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# Adaptive estimation for Hawkes' processes; application to genome analysis

Patricia REYNAUD-BOURET\* and Sophie SCHBATH†

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## Abstract

This article is the result of a fruitful discussion between application and theory. The aim of this paper is to provide a new practical method for the detection of either favored or avoided distances between genomic events along DNA sequences. These events are modeled by a Hawkes' process. The biological problem is actually complex enough to need a non asymptotic penalized model selection approach. But the right shape of penalty cannot be guessed without deep theoretical results. Hence we provide a theoretical penalty that satisfies an oracle inequality even for quite complex families of models. The consecutive theoretical estimator is shown to be adaptive minimax for hölderian functions with regularity in  $(1/2, 1]$ : those aspects have not yet been studied for the Hawkes' process. Moreover we introduce an efficient strategy, named *Islands*, which is not classically used in model selection, but that happens to be particularly relevant to the biological question we want to answer. Since a multiplicative constant in the theoretical penalty is not computable in practice, we provide extensive simulations to find a data-driven penalty. The results obtained on real genomic data are coherent with biological knowledge and eventually refine them.

**Keywords** Hawkes' process, model selection, oracle inequalities, data-driven penalty, minimax risk, adaptive estimation, unknown support, genome analysis.

**Mathematics Subject Classification (2000)** 62G05 62G20 46N60 65C60

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# 1 Introduction

Modeling the arrival times of a particular event on the real line is a common problem in time series theory. In this paper we deal with a very similar but fewly addressed problem: modeling the process of the occurrences of a particular event along a discrete sequence, namely a DNA sequence. Such events could be for instance any given DNA patterns, any genes or any other biological signals occurring along genomes. A huge literature exists on the statistical properties of pattern occurrences along random sequences [14] but our current approach is different. It consists in directly modeling the point process of the occurrences of any kind of events and it is not restricted to pattern occurrences. Our aim is to characterize the dependence, if any, between the event occurrences by pointing out either favored or avoided distances between them, those distances being significantly larger than the classical memory used in the quite popular hidden Markov chain model for instance. At this scale, it is more interesting to use a continuous framework and see occurrences as points. A very interesting model for this purpose is the Hawkes' process [10].

In the most basic self-exciting model, the Hawkes' process  $(N_t)_{t \in \mathbb{R}}$  is defined by its intensity, which satisfies

$$\lambda(t) = \nu + \int_{-\infty}^{t^-} h(t-u) dN_u, \quad (1.1)$$

where  $\nu$  is a positive parameter,  $h$  a nonnegative function with support on  $\mathbb{R}^+$  and  $\int h < 1$  and where  $dN_u$  is the point measure associated to the process. The interested reader shall find in Daley and Vere-Jones' book [7] the main definitions, constructions and models related to point processes in general and Hawkes' processes in particular (see for instance Examples 6.3(c) and 7.2(b) therein).

The intensity  $\lambda(t)$  represents the probability to have an occurrence at position  $t$  given all the past. In this sense, (1.1) basically means that there is a constant rate  $\nu$  to have a spontaneous occurrence at  $t$  but that also all the previous occurrences influence the apparition of an occurrence at  $t$ . For instance an occurrence at  $u$  increases the intensity by  $h(t-u)$ . If the distance  $d = t-u$  is favored, it means that  $h(d)$  is really large: having an occurrence at  $u$  significantly increases the chance of having an occurrence at  $t$ . The intensity given by (1.1) is the most basic case, but variations of it enable us to model self interaction (ie also inhibition) and, in the most general case, to model interaction with another type of event. The drawback is that, by definition, the Hawkes process is defined on an ordered real line (there is a past, a present and a future). But a strand of DNA itself has a direction, fact that makes our approach quite sensible.

The Hawkes' model has been widely used to model the occurrences of earthquake [18]. In this set-up and even for more general counting processes, the statistical inference usually deals with maximum likelihood estimation ([12], [13]). This approach has been

applied to genome analysis: in a previous work [10], Gusto and Schbath's method, named FADO, uses maximum likelihood estimates of the coefficients of  $h$  on a Spline basis coupled with an AIC criterion to select the set of equally spaced knots.

On one hand, the FADO procedure is quite effective, it can manage interactions between two types of events and self excitation or inhibition, ie it works in the most general Hawkes' process framework and produces smooth estimates. However, there are several drawbacks. From a theoretical point of view, AIC criterion is proved to select the right set of knots if first, there exists a true set of knots, and then if the family of possible knots is held fixed whereas the length of the observed sequence of DNA tends to infinity. Moreover from a practical point of view, the criterion seems to behave very poorly when a lot of possible sets of knots with the same cardinality are in competition [9]. FADO has been implemented with equally spaced knots for this reason. Finally it heavily depends on an extra knowledge of the support of the function  $h$ . In practice, we have to input the maximal size of the support, say 10000 bases, in the FADO procedure. Consequently the FADO estimate is a Spline function based on knots that are equally spaced on  $[0, 10000]$ . Actually the estimate of  $h$  will probably be small with some fluctuations but not null until the end of the interval.

On the other hand, our feeling is that if interaction exists, say around the distance  $d = 500$  bases, the function  $h$  to estimate should be really large around  $d = 500$  and if there is no biological reason for any other interaction, then  $h$  should be null anywhere else.

One way to solve this problem of estimation is to use model selection but in its non asymptotic version. Ideally, if the work of Birgé and Massart in [2] was not restricted to the Gaussian case but if it also provides results for the Hawkes' model then it should enable us to find a way of selecting an irregular set of knots with complexity that may grow if the length of the observed sequence becomes larger. The question of the knowledge of the support never appears in Birgé and Massart's work because there is not such a question in a Gaussian model, but one could imagine that their way of selecting sparse models should enable us to select a sparse support too.

However we are not in an ideal world where white noise model and Hawkes' model are equivalent (even heuristically), so there is no way to guess the right way of penalizing in our situation. So the purpose of this article is to provide a first attempt at constructing a penalized model selection in a non asymptotic way for the Hawkes' model. This paper consists in both practical methods for estimating  $h$  that lie on strong theoretical evidences and also in new theoretical results such as oracle inequalities or adaptivity in the minimax sense. Note that up to our knowledge, the minimax aspects of the Hawkes' model have not yet been considered.

Accordingly we restrict ourselves to a simpler case than the FADO procedure. First we focus on the self-exciting model (ie the one given by (1.1)), but we would at least like

that the final estimator remains computable in case of self-inhibition. Then we do not use maximum likelihood estimators since they are not easily handled by model selection procedures, at least from a theoretical point of view (see [6] for the classical case of density estimation). So we provide in this paper theoretical results for penalized projection estimators (i.e. least square estimators) and not for penalized maximum likelihood estimators. At this stage, we would like to emphasize the following fact. It is our belief that theoretical results are the only way to guess the right way of penalizing even if the implemented method is not exactly the one provided by the theory. There is always a gap between practice and theory, but theory provides meaningful formulas. We definitely need those formulas here since, in some cases, the popular AIC criterion is not working. Finally, for technical reasons, we only deal with piecewise constant estimators.

Since the Hawkes' processes are quite popular for modeling earthquakes, financial or economical data, we try to keep a general formalism in most of the sequel (except in the biological applications part). Consequently our method could be applied to many other type of data.

In Section 2, we define the notations and the different families of models. Section 3 states first a non asymptotic result for the projection estimators, since up to our knowledge, these estimators were not yet studied. Then Section 3 gives a theoretical penalty that enables us to select a good estimator in a family of projection estimators. Indeed we prove that our penalized projection estimator satisfies an oracle inequality, hence proving by that result that our estimator is as good as the best projection estimator in the family up to some multiplicative term. However the theoretical penalty is not computable in practice. As a consequence Section 4 provides simulations which validate a method that seems to work well from a practical point of view. Then in Section 5 we apply this method to DNA data. The results match biological evidences and refine them. Section 6 details the adaptive and minimax properties of our estimators. Section 7 is dedicated to more technical results that are at the origin of the ones stated in Section 3. Proofs can be found in Section 8.

## 2 Framework

Let  $(N_t)_t$  be a stationary Hawkes' process on the real line satisfying (1.1). We assume that  $h$  has a bounded support included in  $(0, A]$  where  $A$  is a known positive real number and that

$$p := \int_0^A h(u) du, \quad (2.1)$$

satisfies  $p < 1$ . This condition guarantees the existence of a stationary version of the process (see [11]). Let us remark that, for the DNA applications we have in mind,  $A$  is quite known because it corresponds to a maximal distance from which it is no longer

reasonable to consider a linear interaction between two genomic locations. If there may exist some interaction at longer distances, then it should certainly imply the 3D structure of DNA.

We observe the stationary Hawkes' process  $(N_t)_t$  on an interval  $[-A, T]$ , where  $T$  is a positive real number. Typically  $T$  should be significantly larger than  $A$ . Using this observation, we want to estimate

$$s = (\nu, h), \quad (2.2)$$

assumed to be in

$$\mathbb{L}^2 = \left\{ f = (\mu, g) : g \text{ with support in } (0, A], \quad \|f\|^2 = \mu^2 + \int_0^A g^2(x)dx < +\infty \right\}. \quad (2.3)$$

The introduction of this Hilbert space is related to the fact that we want to use least square estimators.

With these constraints on  $h$ , we can note that (1.1) is equivalent to

$$\lambda(t) = \nu + \int_{t-A}^{t^-} h(t-u)dN_u. \quad (2.4)$$

Now we can introduce intensity candidates: for all  $f = (\mu, g)$  in  $\mathbb{L}^2$ , we define

$$\Psi_f(t) := \mu + \int_{t-A}^{t^-} g(t-u)dN_u. \quad (2.5)$$

In particular, note that  $\Psi_s(t) = \lambda(t)$ . A good intensity candidate should be a  $\Psi_f(\cdot)$  that is close to  $\Psi_s(\cdot)$ . The least-square contrast is consequently defined for all  $f$  in  $\mathbb{L}^2$  by

$$\gamma_T(f) := -\frac{2}{T} \int_0^T \Psi_f(t)dN_t + \frac{1}{T} \int_0^T \Psi_f(t)^2 dt. \quad (2.6)$$

As we will see in Lemma 2, this really defines a contrast, in the statistical sense. Indeed, taking the compensator of the previous formula leads to

$$-\frac{2}{T} \int_0^T \Psi_f(t)\Psi_s(t)dt + \frac{1}{T} \int_0^T \Psi_f(t)^2 dt.$$

Let us consider the last integral in the previous equation:

$$D_T^2(f) := \frac{1}{T} \int_0^T \Psi_f(t)^2 dt. \quad (2.7)$$

Lemma 3 proves that  $D_T^2(\cdot)$  defines a quadratic form on  $\mathbb{L}^2$  such that

$$\|f\|_D := \sqrt{\mathbb{E}(D_T^2(f))} \quad (2.8)$$

is a quadratic norm on  $\mathbb{L}^2$ , equivalent to  $\|f\|$  (see (2.3)). In this sense, we can see  $\gamma_T(f)$  as an empirical version of  $\|f - s\|_D^2 - \|s\|_D^2$ , which is quite classical for a least-square contrast (see the density set-up for instance).

## 2.1 Projection estimator

Let  $m$  be a set of disjoint intervals of  $(0, A]$ . In the sequel  $m$  is called a model and  $|m|$  denotes the number of intervals in  $m$ . One can think of  $m$  as a partition of  $(0, A]$  but there are other interesting cases as we will see later. Let  $S_m$  be the vectorial space of  $\mathbb{L}^2$  defined by

$$S_m = \left\{ f = (\mu, g) \in \mathbb{L}^2 \text{ such that } g = \sum_{I \in m} a_I \frac{\mathbb{1}_I}{\sqrt{\ell(I)}} \text{ with } (a_I)_{I \in m} \in \mathbb{R}^m \right\}, \quad (2.9)$$

where  $\ell(I) = \int \mathbb{1}_I dt$ . We say that  $g$  in the above equation is constructed on the model  $m$ . Conversely, if  $g$  is a piecewise constant function, remark that we can define a resulting model  $m$  by the set of intervals where  $g$  is constant but non zero and a resulting partition by the set of intervals where  $g$  is constant. The projection estimator,  $\hat{s}_m$ , is the least square estimator of  $s$  defined by

$$\hat{s}_m = \operatorname{argmin}_{f \in S_m} \gamma_T(f). \quad (2.10)$$

Model selection intuition usually relies on a bias-variance decomposition of the risk of  $\hat{s}_m$ . So let us define  $s_m$  as the orthogonal projection for  $\|\cdot\|$  of  $s$  on  $S_m$ . Then  $\hat{s}_m$  is a "good" estimate of  $s_m$ , since  $\gamma_T(f)$  is an approximation of  $\|f - s\|_D^2 - \|s\|_D$ . We cannot prove that it is an unbiased estimate, but the intuition applies. So the bias can be more or less identified as  $\|s - s_m\|$ . This is the approximation error of the model  $m$  with respect to  $s$ . The variance, or stochastic error, is not so well defined. In this context, it is not that easy to understand how to choose the best model  $m$ . There is not such a thing as Mallows'  $C_p$  heuristic here. We consequently use the most general form of penalization in the sequel.

## 2.2 Penalized projection estimator

Let  $\mathcal{M}_T$  be a family of sets of disjoint intervals of  $(0, A]$  (i.e. a family of possible models). We denote by  $\#\{\mathcal{M}_T\}$  the total number of models. We define the penalty (or penalty function) by  $\operatorname{pen} : \mathcal{M}_T \rightarrow \mathbb{R}^+$  and we select a model by minimizing the following criteria

$$\hat{m} = \operatorname{argmin}_{m \in \mathcal{M}_T} [\gamma_T(\hat{s}_m) + \operatorname{pen}(m)]. \quad (2.11)$$

Then the penalized projection estimator is defined by

$$\tilde{s} = (\tilde{\nu}, \tilde{h}) = \hat{s}_{\hat{m}}. \quad (2.12)$$

The main problem is now to find a function  $\operatorname{pen} : \mathcal{M}_T \rightarrow \mathbb{R}^+$  that guarantees that

$$\|s - \tilde{s}\|^2 \leq C \inf_{m \in \mathcal{M}_T} \|s - \hat{s}_m\|^2 \quad (2.13)$$

and this either with high probability or in expectation, up to some small residual term and up to some multiplicative term  $C$  that could slightly increase with  $T$ . The previous equation (2.13) is an oracle inequality. If this oracle inequality holds, this will mean that we can select a model  $\hat{m}$ , and consequently a projection estimator  $\tilde{s} = \hat{s}_{\hat{m}}$ , that is almost as good as the best estimator in the family of the  $\hat{s}_m$ 's – whereas this best estimator cannot be guessed without knowing  $s$ . Of course this would tell us nothing if the projection estimators themselves, i.e. the  $\hat{s}_m$ 's, are not sensible. The next section precisely states the properties of the projection estimator and the oracle inequality satisfied by the penalized projection estimator. To conclude Section 2 we precise the different families of models we would like to use and we precisely explain what self-inhibition means in our model.

## 2.3 Strategies

A strategy refers to the choice of the family of models  $\mathcal{M}_T$ . In the sequel, a partition  $\Gamma$  of  $(0, A]$  should be understood as a set of disjoint intervals of  $(0, A]$  such that their union is the whole interval  $(0, A]$ . A regular partition is such that all its intervals have the same length. We say that a model  $m$  is written on  $\Gamma$  if all the extremities of the intervals in  $m$  are also extremities of intervals in  $\Gamma$ . For instance if  $\Gamma = \{(0, 0.25], (0.25, 0.5], (0.50, 0.75], (0.75, 1]\}$  then  $\{(0, 0.25], (0.25, 1]\}$  or  $\{(0, 0.25], (0.75, 1]\}$  are models written on  $\Gamma$ . Now let us give some examples of families  $\mathcal{M}_T$ . Let  $J$  and  $N$  be two positive integers.

**Nested Strategy** Take  $\Gamma$  a dyadic regular partition (i.e. such that  $|\Gamma| = 2^J$ ). Then take  $\mathcal{M}_T$  as the set of all dyadic regular partitions of  $(0, A]$  that can be written on  $\Gamma$ , including the void set. In particular, note that  $\#\{\mathcal{M}_T\} = J + 1$ . We say that this strategy is nested since for two partitions in this family, one of them is always written on the other one.

**Regular strategy** Another natural strategy is to look at all the regular partitions of  $(0, A]$  until some finest partition of cardinal  $N$ . That is to say that one has exactly one model with cardinality  $k$  for each  $k$  in  $\{0, \dots, N\}$ . Here  $\#\{\mathcal{M}_T\} = N + 1$ .

**Irregular strategy** Assume now that we know that  $h$  is piecewise constant on  $(0, A]$  but that we do not know where the cuts of the resulting partition are. We can consider  $\Gamma$  a regular partition such that  $|\Gamma| = N$  and then consider  $\mathcal{M}_T$  the set of all possible partitions written on  $\Gamma$ , including the void set. In this case  $\#\{\mathcal{M}_T\} \simeq 2^N$ .

**Islands strategy** This last strategy has been especially designed to answer our biological problem. We think that  $h$  has a very localized support. The interval  $(0, A]$  is really large and in fact  $h$  is non zero on a really smaller interval or a union of really smaller intervals: the resulting model is sparse. We can consider  $\Gamma$  a regular partition such that  $|\Gamma| = N$  and then consider  $\mathcal{M}_T$  the set of all the subsets of  $\Gamma$ . A typical

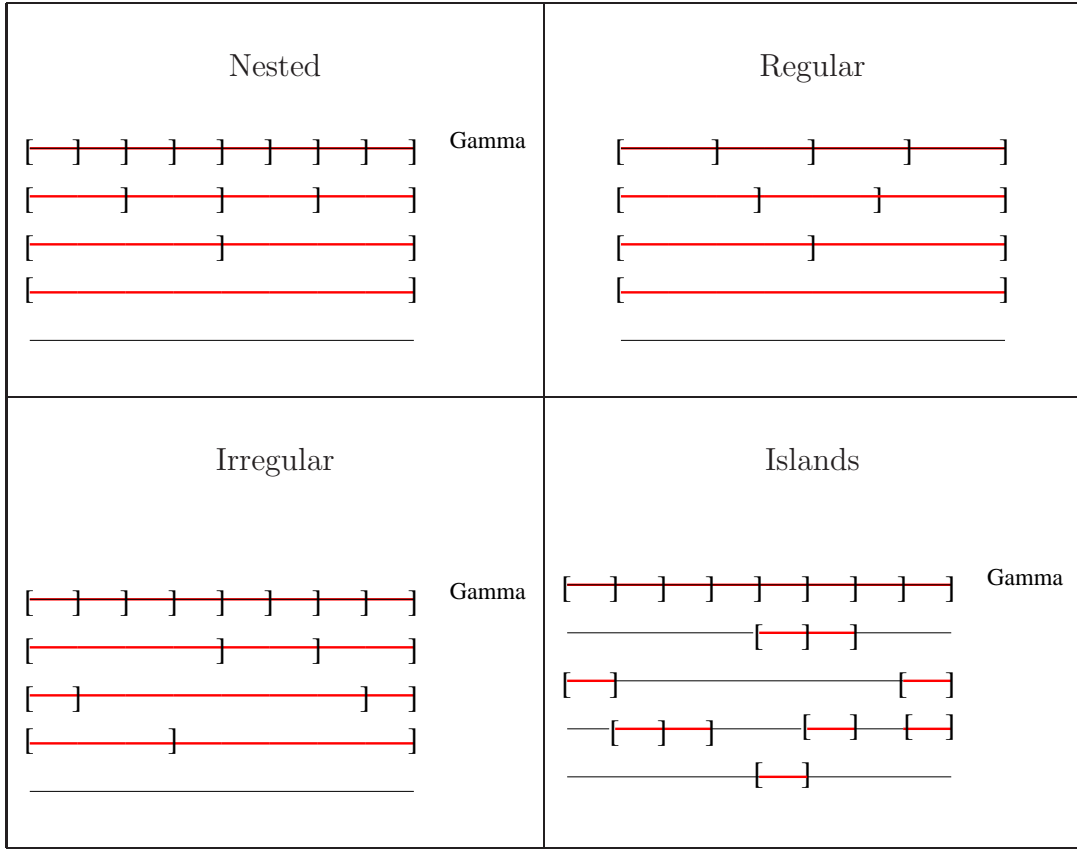


Figure 1: On each line, one can find a model by looking at the collection of red intervals between “[” or “]”. For the *Nested Strategy*, here are all the models for  $J = 3$ . For the *Regular strategy*, here are all the models for  $N = 4$ . For the *Irregular* and *Islands strategies*, these are just some examples of models in the family with  $N = 8$ .

$m$  corresponds to a vectorial space  $S_m$  where the functions  $g$  are zero on  $(0, A]$  except on some disjoint intervals which look like several “islands”. In this case  $\#\{\mathcal{M}_T\} = 2^N$ .

Figure 1 gives some more visual examples of the different strategies.

## 2.4 Self-inhibition

The self-interaction can be modeled in a more general way by a process whose intensity is given by

$$\lambda(t) = \left( \nu + \int_{-\infty}^{t^-} h(t-u) dN_u \right)_+ \quad (2.14)$$

where  $h$  may now be negative. We have taken the positive part to ensure that the intensity remains positive. Then the condition  $\int |h| < 1$  is sufficient to ensure the existence of a stationary version of the process (see [4]). When  $h(d)$  is strictly positive there is a self-excitation at distance  $d$ . When  $h(d)$  is strictly negative, then there is a self-inhibition. It is more or less the same interpretation as above (see (1.1)) except that now all the previous occurrences are voting whether they "like" or "dislike" to have a new occurrence at position  $t$ . If this process is not studied in this paper from a theoretical point of view because of major technical issues (except in the remarks following Theorem 2), note that however our projection estimators and penalized projection estimators do not take the sign of  $g$  or  $h$  into account for being computed. That is the reason why we will use our estimators, even in this case, for the numerical results.

Finally we use in the sequel the notation  $\square$  which represents a positive function of the parameters that are written in indices. Each time  $\square_\theta$  is written in some equation, one should understand that there exists a positive function of  $\theta$  such that the equation holds. Therefore the values of  $\square_\theta$  may change from line to line and even change in the same equation. When no index appears,  $\square$  represents a positive absolute constant.

### 3 Main results

For technical reasons we are not able to carefully control the behavior of the projection estimators if  $\nu$  tends to 0 or to infinity, but also if  $p$  (see (2.1)) tends to 1: in such cases, the number of points in the process is either exploding or vanishing. Consequently the theoretical results are proved within a subset of  $\mathbb{L}^2$ . Let us define for all real numbers  $H > 0$ ,  $\eta > \rho > 0$ ,  $1 > P > 0$ , the following subset of  $\mathbb{L}^2$ :

$$\mathcal{L}_{H,P}^{\eta,\rho} = \left\{ f = (\mu, g) \in \mathbb{L}^2 / \mu \in [\rho, \eta], \quad g(\cdot) \in [0, H] \text{ and } \int_0^A g(u)du \leq P \right\}.$$

If we know that  $s$  belongs to  $\mathcal{L}_{H,P}^{\eta,\rho}$  and if we know the parameters  $H, \eta$  and  $\rho$ , then it is reasonable to consider the clipped projection estimator,  $\bar{s}_m$ . If we denote the projection estimator  $\hat{s}_m = (\hat{\nu}_m, \hat{h}_m)$  then  $\bar{s}_m = (\bar{\nu}_m, \bar{h}_m)$  is given, for all positive  $t$ , by

$$\left\{ \begin{array}{l} \bar{\nu}_m = \begin{cases} \hat{\nu}_m & \text{if } \rho \leq \hat{\nu}_m \leq \eta, \\ \rho & \text{if } \hat{\nu}_m < \rho, \\ \eta & \text{if } \hat{\nu}_m > \eta, \end{cases} \\ \bar{h}_m(t) = \begin{cases} \hat{h}_m(t) & \text{if } 0 \leq \hat{h}_m(t) \leq H, \\ 0 & \text{if } \hat{h}_m(t) < 0, \\ H & \text{if } \hat{h}_m(t) > H. \end{cases} \end{array} \right. \quad (3.1)$$

For the clipped projection estimator, we can prove the following result.

**Proposition 1.** *Let  $(N_t)_{t \in \mathbb{R}}$  be a Hawkes' process with intensity given by  $\Psi_s(\cdot)$ . Let  $m$  be a model written on  $\Gamma$  where  $\Gamma$  is a regular partition of  $(0, A]$  such that*

$$|\Gamma| \leq \frac{\sqrt{T}}{(\log T)^3}. \quad (3.2)$$

*Then if  $s$  belongs to  $\mathcal{L}_{H,P}^{\eta,\rho}$ , the clipped projection estimator on the model  $m$  satisfies*

$$\mathbb{E}(\|\bar{s}_m - s\|^2) \leq \square_{H,P,\eta,\rho,A} \left[ \|s_m - s\|^2 + (|m| + 1) \frac{\log T}{T} \right].$$

This result is a control of the risk of the clipped projection estimator on one model. It is not asymptotic so it allows a dependence of  $m$  on  $T$ , as soon as (3.2) is satisfied. There are two terms in the upper bound. The first one  $\|s_m - s\|^2$  has already been identified as the bias of the projection estimator. The second term can be viewed as an upper bound for the stochastic or variance term. Actually this upper bound is almost sharp. If we assume that  $s$  belongs to  $S_m$ , i.e.  $s = s_m$ , then the bias disappears and the quantity  $\mathbb{E}(\|\bar{s}_m - s\|^2)$  –a pure variance term– is in fact upper bounded by a constant times  $|m| \log(T)/T$ . But on the other hand, we have the following result:

**Proposition 2.** *Let  $m$  be a model such that  $\inf_{I \in m} \ell(I) \geq \ell_0$  then there exists a positive constant  $c$  depending on  $A, \eta, P, \rho, H$  such that if  $|m| \geq c$  then*

$$\inf_{\hat{s}} \sup_{s \in S_m \cap \mathcal{L}_{H,P}^{\eta,\rho}} \mathbb{E}_s(\|s - \hat{s}\|^2) \geq \square_{H,P,\eta,\rho,A} \min \left( \frac{|m|}{T}, \ell_0 |m| \right).$$

*The infimum over  $\hat{s}$  represents the infimum over all the possible estimators constructed on the observation on  $[-A, T]$  of a point process  $(N_t)_t$ .  $\mathbb{E}_s$  represents the expectation with respect to the stationary Hawkes' process  $(N_t)_t$  with intensity given by  $\Psi_s(\cdot)$ .*

Hence, when  $s$  belongs to  $S_m$ , the clipped projection estimator has a risk which is lower bounded by a constant times  $|m|/T$  and upper bounded by  $|m| \log(T)/T$ . There is only a loss of a factor  $\log(T)$  between the upper bound and the lower bound. This factor comes from the unboundedness of the intensity. The best control we can provide for the intensity is to bound it on  $[0, T]$  by something of the order  $\log(T)$ . The reader may think to this really similar fact: the sup of  $n$  iid variables with exponential moments can only be bounded with high probability by something of the order  $\log(n)$ . Note also that the clipped projection estimator is minimax up to this logarithmic term.

Now let us turn to model selection, oracle inequalities and penalty choices. As before if we know  $H, \eta$  and  $\rho$ , then it is reasonable to consider the clipped penalized projection

estimator,  $\bar{s}$ . Recall that the penalized projection estimator  $\tilde{s} = (\tilde{\nu}, \tilde{h})$  is given by (2.12). Then the clipped penalized projection estimator,  $\bar{s} = (\bar{\nu}, \bar{h})$ , is given, for all positive  $t$ , by

$$\left\{ \begin{array}{l} \bar{\nu} = \begin{cases} \tilde{\nu} & \text{if } \rho \leq \tilde{\nu} \leq \eta, \\ \rho & \text{if } \tilde{\nu} < \rho, \\ \eta & \text{if } \tilde{\nu} > \eta, \end{cases} \\ \bar{h}(t) = \begin{cases} \tilde{h}(t) & \text{if } 0 \leq \tilde{h}(t) \leq H, \\ 0 & \text{if } \tilde{h}(t) < 0, \\ H & \text{if } \tilde{h}(t) > H. \end{cases} \end{array} \right. \quad (3.3)$$

The next Theorem provides an oracle inequality in expectation (see (2.13)).

**Theorem 1.** *Let  $(N_t)_{t \in \mathbb{R}}$  be a Hawkes' process with intensity  $\Psi_s(\cdot)$ . Assume that we know that  $s$  belongs to  $\mathcal{L}_{H,P}^{\eta,\rho}$ . Moreover assume that all the models in  $\mathcal{M}_T$  are written on  $\Gamma$ , a regular partition of  $(0, A]$  such that (3.2) holds. Let  $Q > 1$ . Then there exists a positive constant  $\kappa$  depending on  $\eta, \rho, P, A, H$  such that if*

$$\forall m \in \mathcal{M}_T, \quad \text{pen}(m) = \kappa Q (|m| + 1) \frac{\log(T)^2}{T}, \quad (3.4)$$

then

$$\mathbb{E}(\|\bar{s} - s\|)^2 \leq \square_{\eta,\rho,P,A,H} \inf_{m \in \mathcal{M}_T} \left[ \|s - s_m\|^2 + (|m| + 1) \frac{\log(T)^2}{T} \right] + \square_{\eta,\rho,P,A,H} \frac{\#\{\mathcal{M}_T\}}{T^Q}.$$

The form of the penalty is a constant times  $|m| \log(T)^2/T$ , i.e. it is equal to the variance term up to some logarithmic factor. Remark also that choosing the penalty as a constant times the dimension leads to an oracle inequality in expectation. The multiplicative constant is not an absolute constant but something that depends on all the parameters that were introduced ( $H, \eta, P$ , etc). This is actually classical. Even in the Gaussian nested case (see [3]), Mallows'  $C_p$  multiplicative constant is  $2\sigma^2$  where  $\sigma^2$  is the variance of the Gaussian noise. The form is simpler than in our case but still an unknown parameter  $\sigma^2$  appears. With respect to the Gaussian case, remark that there is also some loss due to logarithmic terms. Finally, for readers who are familiar with model selection techniques, we do not refined the penalty with the use of weights, because the concentration formulas we use to derive the penalty expression are not concentrated enough to allow a real improvement by using those weights. The Gaussian concentration inequalities do not apply to Hawkes' processes, even if there are some attempts at proving similar results [17]. As a consequence, we are not able to treat families of models as complex as in [2].

## 4 Numerical results on simulated data

The main drawback of the previous theoretical results is that the penalty is not computable in practice. Even if the formula for the factor  $\kappa$  is known, it heavily depends on the extra knowledge of parameters ( $H, \eta, P$ , etc) that cannot be guessed in practice. On the contrary,  $A$  is a meaningful quantity, at least for our biological purpose. The aim of this section to find a performant implementable method of selection, based on the following theoretical fact: (3.4) proves that a constant times the dimension of the model should work.

### 4.1 Compared methods

We consider only three strategies (regular, irregular and islands) since for computational reasons one cannot use a model  $m$  with more than 25 intervals. The nested strategy would lead to at most 5 models in the family. Consequently we do not use this strategy in practice. Since we are looking for a penalty that is inspired by (3.4), we compare our penalized methods to the most naive approach, namely the hold-out procedure described below. As said in the Introduction (Section 1), the log-likelihood contrast coupled with an AIC penalty (see for instance [10]) is only adapted to functions  $g$  defined on regular partitions, so we do not consider this method here.

Moreover, the truncated estimators are designed for minimax theoretical purposes, but of course they depend on parameters ( $H$  etc.) that cannot be guessed in practice. Therefore in this section we only use non truncated estimators (see (2.10),(2.11),(2.12)).

**Hold-out** The naive approach is based on the following fact (which can be made completely and theoretically explicit in the case  $h > 0$ ). We know (see Lemma 2) that  $\gamma_T$  is a contrast. We know also that  $\mathbb{E}(\gamma_T(f)) = \|f - s\|_D^2 - \|s\|_D^2$ . Moreover we know that the projection estimators  $\hat{s}_m$  behave nicely (see Proposition 1). Now we would like to select a model  $\hat{m}$  such that  $\hat{s}_{\hat{m}}$  is as good as the best possible  $\hat{s}_m$ . So one way to select a good model  $m$  should be to observe a second independent Hawkes process with the same  $s$  and to compute the minimizer of  $\gamma_{T,2}(\hat{s}_m)$  over  $\mathcal{M}_T$  (where  $\hat{s}_m$  is computed with the first process and  $\gamma_{T,2}$  is our contrast but computed with the second process). However we do not have in practice two independent Hawkes processes at our disposal. But one can cut  $[-A, T]$  in two almost independent pieces. Indeed the points of the process in  $[-A, T/2 - A]$  and in  $[T/2, T]$  can be equal to those of independent stationary Hawkes processes and this with high probability (see [17]). Hence in the sequel whenever the Hold-out estimator is mentioned, and whatever the family  $\mathcal{M}_T$  is, it is referring to the following procedure.

1. Cut  $[-A, T]$  into two pieces:  $H_1$  refers to the points of the process on  $[-A, T/2 - A]$ ,  $H_2$  refers to the points of the process on  $[T/2, T]$ .

2. Compute  $\hat{s}_m$  for all the  $m$  in  $\mathcal{M}_T$  by minimizing the least-square contrast  $\gamma_{T,1}$  on  $S_m$  computed with only the points of  $H_1$ , ie

$$\forall f \in \mathbb{L}^2, \quad \gamma_{T,1}(f) = -\frac{2}{T} \int_0^{T/2-A} \Psi_f(t) dN_t + \frac{1}{T} \int_0^{T/2-A} \Psi_f(t)^2 dt,$$

3. Compute  $\gamma_{T,2}(\hat{s}_m)$  where  $\gamma_{T,2}$  is computed with  $H_2$ , i.e.,

$$\forall f \in \mathbb{L}^2, \quad \gamma_{T,2}(f) = -\frac{2}{T} \int_{T/2+A}^T \Psi_f(t) dN_t + \frac{1}{T} \int_{T/2+A}^T \Psi_f(t)^2 dt,$$

and find  $\hat{m} = \arg \min_{m \in \mathcal{M}_T} \gamma_{T,2}(\hat{s}_m)$ .

4. The Hold-out estimator is defined by  $\tilde{s}^{HO} := \hat{s}_{\hat{m}}$ .

**Penalized** Theorem 1 shows that theoretically speaking a penalty of the type  $K(|m|+1)$  should work. However the theoretical constant is not only not computable, it is also too large for practical purpose. So one needs to consider Theorem 1 as a result that guides our intuition towards the right shape of penalty and one should not consider it as a sacred and not improvable way of penalizing. Therefore we investigate two ways of finding the right penalty.

1. The first one follows the conclusions of [3]. In the *Regular strategy*, there exists at most one model per dimension. If there exists a true model  $m_0$ , then for  $|m|$  large (larger than  $|m_0|$ )  $\gamma_T(\hat{s}_m)$  should behave like  $-k(|m|+1)$ . So there is a “minimal penalty” as defined by Birgé and Massart of the form  $\text{pen}_{\min} = k(|m|+1)$ . In this situation their rule is to take  $\text{pen}(m) = 2 * \text{pen}_{\min}(m)$ .

We find a  $\hat{k}$  by doing a least-square regression for large values of  $|m|$  so that

$$\gamma_T(\hat{s}_m) \simeq -\hat{k}(|m|+1).$$

Then we take

$$\hat{m} = \operatorname{argmin}_{m \in \mathcal{M}_T} \gamma_T(\hat{s}_m) + 2\hat{k}(|m|+1),$$

and we define  $\tilde{s}^{\min} := \hat{s}_{\hat{m}}$ .

Let us remark that the framework of [3] is Gaussian and i.i.d. It is in our opinion completely out of reach to extend these theoretical results here. However, at least in the *Regular strategy*, the concentration formula that lies at the heart of our proof is really close to the one used in [3] (see (8.9)), which tends to prove that their method could work here.

For the *Irregular* and *Islands strategy*, as a preliminary step, we need to find the best data-driven model per dimension i.e.

$$\hat{m}_D = \operatorname{argmin}_{m \in \mathcal{M}_T, |m|=D} \gamma_T(\hat{s}_m).$$

Then one can plot as a function of  $D$ ,  $\gamma_T(\hat{s}_{\hat{m}_D})$ . In [3], they also obtain another kind of minimal penalty of the form  $\text{pen}_{\min} = k(D+1)(\log(|\Gamma|/D) + 5)$  when the *Irregular strategy* is used. But for very small values of  $|\Gamma|$  (as here) we would not see the difference between this form of penalty and the linear form. Moreover theoretically speaking we are not able to justify, even heuristically, such a form of penalty for large values of  $|\Gamma|$ . Indeed the concentration formula in our case (see (8.9) in the proofs Section 8) is quite different for such a complex family: for really complex families, the parameter  $x$  in (8.9) should depend on the model  $m$ .

So we have decided that we will use the same penalty as before even in the *Irregular* and *Islands strategies*. That is to say that we find a  $\hat{k}$  by doing a least-square regression for large value of  $D$  so that

$$\gamma_T(\hat{s}_{\hat{m}_D}) \simeq -\hat{k}(D+1).$$

Then we take

$$\hat{m} = \operatorname{argmin}_{m \in \mathcal{M}_T} \gamma_T(\hat{s}_m) + 2\hat{k}(|m| + 1),$$

and we define  $\tilde{s}^{\min} := \hat{s}_{\hat{m}}$  even for the *Irregular* and *Islands strategies*.

2. On the other hand, the choice of  $\hat{m}$  by  $\tilde{s}^{\min}$  was not completely satisfactory when using the *Islands* or *Irregular strategies* (see the comments on the simulations hereafter). But on the contrast curve:  $D \rightarrow \gamma_T(\hat{s}_{\hat{m}_D})$ , we could see a perfectly clear angle at the true dimension. So we have decided to compute  $-\bar{k} = \frac{\gamma_T(\hat{s}_\Gamma) - \gamma_T(\hat{s}_{\hat{m}_1})}{|\Gamma| - 1}$  and to choose

$$\hat{m} = \operatorname{arg} \min_{m \in \mathcal{M}_T} \gamma_T(\hat{s}_m) + \bar{k}(|m| + 1).$$

We define  $\tilde{s}^{\text{angle}} := \hat{s}_{\hat{m}}$ . This seems to be a proper automatic way to obtain this angle without having to look at the contrast curve. It is still based on the fact that a multiple of the dimension should work. This has only been implemented for the *Irregular* and *Islands strategies*.

This angle method may be viewed as the “extension” of the L-curve method in inverse problems where one chooses the tuning parameter at the point of highest curvature.

Table 1 summarizes our 8 different estimators.

## 4.2 Simulated design

We have simulated Hawkes processes with parameters  $(\nu, h)$ , with  $\nu$  in  $\{0.001, 0.002, 0.003, 0.004, 0.005\}$ ,  $h$  having a bounded support in  $(0, 1000]$  (i.e.  $A = 1000$ ) and on a sequence of length

Methods	Strategy	Selection
1	<i>Regular</i> $N = 15$	minimal penalty $\tilde{s}^{min}$
2	<i>Irregular</i> $ \Gamma  = 15$	angle method $\tilde{s}^{angle}$
3	<i>Irregular</i> $ \Gamma  = 15$	minimal penalty $\tilde{s}^{min}$
4	<i>Islands</i> $ \Gamma  = 15$	angle method $\tilde{s}^{angle}$
5	<i>Islands</i> $ \Gamma  = 15$	minimal penalty $\tilde{s}^{min}$
6	<i>Regular</i> $N = 15$	Hold-Out $\tilde{s}^{HO}$
7	<i>Irregular</i> $ \Gamma  = 15$	Hold-Out $\tilde{s}^{HO}$
8	<i>Islands</i> $ \Gamma  = 15$	Hold-Out $\tilde{s}^{HO}$

Table 1: Table of the different methods.

$[-A, T]$  with  $T = 100000$  or  $T = 500000$ . The fact that the process is or not stationary does not seem to influence our procedure with this relatively short memory (indeed  $T \geq 100A$ ).

The functions  $h$  have been designed so that we can see the influence of  $p$  (2.1) on the estimation procedure. So  $f_1 = 0.004\mathbb{1}_{[200,400]}$  is a piecewise constant nonnegative function on the regular partition  $\Gamma$  ( $|\Gamma| = 15$ ) with integral 0.8 and we have tested  $h = c * f_1$  with  $c$  in  $\{0.25, 0.5, 0.75, 1\}$  (i.e.  $p = 0.2, 0.4, 0.6$  and  $0.8$  respectively). We have also tested a possibly negative function  $f_2 = 0.003\mathbb{1}_{[200,800/3]} - 0.003\mathbb{1}_{[2000/3,2200/3]}$  that is piecewise constant on  $\Gamma$ . Note that (see Section 2.4) the sign of  $h$  should not affect the method (penalized least-square criterion) whereas the log-likelihood may have some problems each time  $\Psi_f()$  remains negative on a large interval. The parameter of importance here is the integral of the absolute value, which is here  $\int |f_2| = 0.8$  and we have tested  $h = f_2$ . Finally the method itself should not be affected by a smooth function  $h$ : we have used  $f_3$  a nonnegative continuous function (in fact the mixture of two Gaussian densities) with integral equal to 0.8 and we have tested once again  $h = f_3$ .

Remark that the mean number of observed points belongs to  $[125, 12500]$  which corresponds to the number of occurrences we could observe in biological data.

### 4.3 Results

The quality of the estimation procedures is measured thanks to two criteria: the risk of the estimators and the associated oracle ratio.

- We call *Risk* of an estimator the Mean Square Error of this estimator over 100 simulations, i.e. we compute for each simulation  $\|s - \hat{s}\|^2$  and next we compute the average over 100 simulations. Note that with the range of our parameters, the error of estimation of  $\nu$  will be really negligible with respect to the error of estimation for

$h$ , so that  $\|s - \hat{s}\|^2 \simeq \int_0^A (h - \hat{h})^2$ .

- The Oracle Risk is for each method the minimal risk, i.e.  $\min_{m \in \mathcal{M}_T} Risk(\hat{s}_m)$ . All our methods give an estimator  $\tilde{s}$  that is selected among a family of  $\hat{s}_m$ 's. The Oracle ratio is the ratio of the risk of  $\tilde{s}$  divided by the Oracle Risk, i.e.

$$\frac{Risk(\tilde{s})}{\min_{m \in \mathcal{M}_T} Risk(\hat{s}_m)}.$$

If the oracle ratio is 1, then the risk of  $\tilde{s}$  is the one of the best estimator in the family. Note that the definition of  $\mathcal{M}_T$  and even the definition of  $\hat{s}_m$  appearing in the Oracle ratio may change from one method to another one.

Figure 2 gives the *Risk* of our estimators for  $h = 0.5 * f_1$  for various  $\nu$  and  $T$ . We first clearly see that the risk decreases when  $T$  increases whatever the method. Then we see that the "best methods" are Methods 1, 2 and 4, i.e. the *Regular strategy* with minimal penalty and the *Irregular* and *Islands Strategies* with the angle method. For the *Irregular* and *Islands Strategies*, the minimal penalty seems to behave like the Hold-out Strategies. There seems also to be a slight improvement when  $\nu$  becomes larger, tending to prove that, if the mean total number of points  $\mathbb{E}(N[0, T]) = \nu T / (1 - p)$  grows, the estimation is improved –at least in our range of parameters. Figure 3 gives the Oracle Ratio of our estimators in the same context. The oracle ratio is really close to 1 for Methods 1, 2 and 4 when  $T = 500000$  whatever  $\nu$  is. Remark that the Oracle Ratio for the Hold-Out estimators (methods 6,7,8) is not that large but since the estimators  $\hat{s}_m$  are computed with half of the data, their risks are not as small as the projection estimators used in the penalty methods. This explains why the *Risk* of the Hold-Out methods is large when the Oracle Ratio is close to 1. The Oracle Ratio is improving when  $T$  becomes larger for our three favorite methods (namely 1, 2, 4).

Figure 4 gives the variation of the risk with respect to  $p$  (2.1). Since  $h = c * f_1$  and since  $c$  varies, the Rescaled *Risk*,  $Risk/c^2$ , gives (up to some negligible term corresponding to  $\nu$ ) the risk of  $\tilde{h}/c$  as an estimator of  $f_1$ . We clearly see that when  $T$  or  $c$  becomes larger the Rescaled *Risk* is decreasing. So it definitely seems that if the mean total number of points grows, the estimation is improving. Methods 1, 2 and 4 seem to be still the more precise ones. Figure 5 gives the oracle ratio in the same situation. Once again there is an improvement when  $T$  grows at least for our three favorite methods (1, 2 and 4) and the Oracle ratio is 1 when  $T = 500000$  and  $c = 0.8$ . The same comment about a good Oracle Ratio for the Hold-out methods apply.

Figure 6 gives the frequency of the chosen dimension, namely  $|\hat{m}| + 1$  for the different methods. Clearly methods 1, 2 and 4 are correctly choosing the true dimension in most of the simulations when the other methods overestimate the true dimension.

Finally Figure 7 shows the resulting estimators of Methods 1, 2 and 4 on one simulation. In particular, before penalizing, note that one clearly sees an angle on the contrast

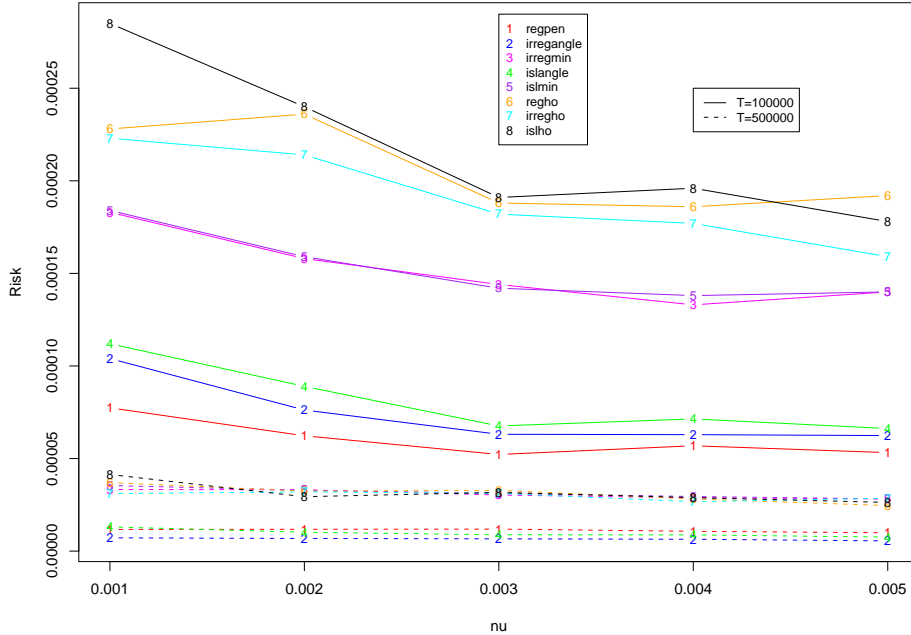


Figure 2: Risk of the 8 different methods for  $h = 0.5 * f_1$  for different values of  $\nu$  and  $T$ .

curve at the true dimension and that penalizing by the angle method (method 2 and 4) gives an automatic way to find the position of this angle.

Figure 8 shows the results for the possibly negative function  $f_2$  and only for our three favorite methods (1,2,4). For this function only and because the true dimension is 16 for Method 1, we use for Method 1,  $|\Gamma| = 25$ . Note that (i) Method 1 and 4 select the right dimension whereas Method 2 (*Irregular Strategy*) does not see the negative jump and that (ii) it is also more easy to detect the precise position of the fluctuations on the sparse estimate given by Method 4 (compared to Method 1). For sake of simplicity we do not give the risk values, but it is sufficient to note that, for all the methods, they are small (with a slight advantage for Method 4) and that the oracle ratios are close to 1.

Figure 9 gives the same results for the smooth function  $f_3$ . Of course since the projection estimators are piecewise constant, they cannot look really close to  $f_3$ . But in any case, Method 1 and more interestingly Method 4 gives the right position for the spikes whereas Method 2 does not see the smallest bump.

Finally let us conclude the simulations by noting that the penalized projection estimators with the *Islands strategy* and the angle penalty (Method 4) seems to be an appropriate method for detecting local spikes and bumps in the function  $h$  and even negative jumps.

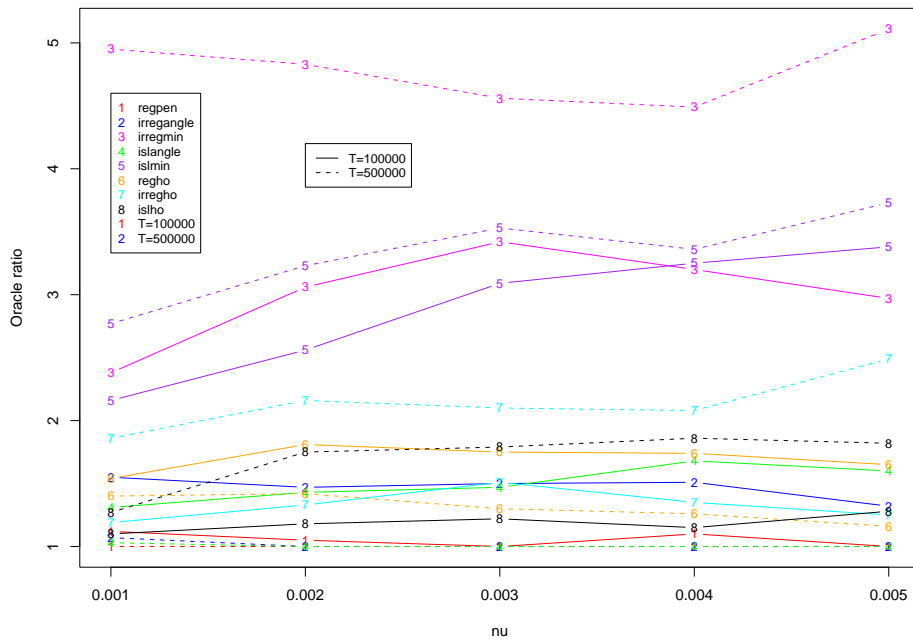


Figure 3: Oracle ratio of the 8 different methods for  $h = 0.5 * f_1$  for different values of  $\nu$  and  $T$ .

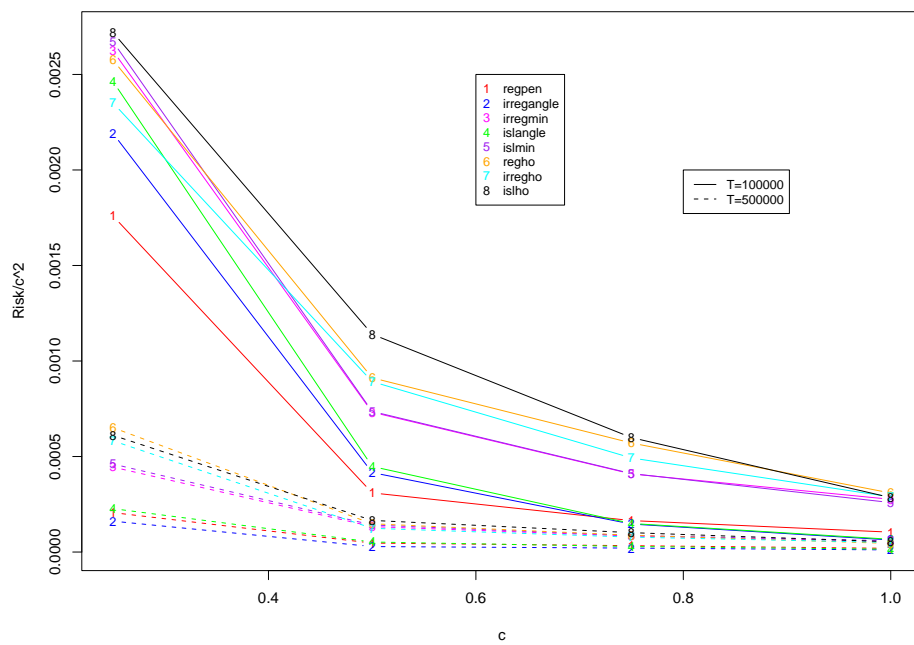


Figure 4: Rescaled Risk ( $Risk/c^2$ ) of the 8 different methods for  $h = c * f_1$  and  $\nu = 0.001$ , for different values of  $c$  and  $T$ .

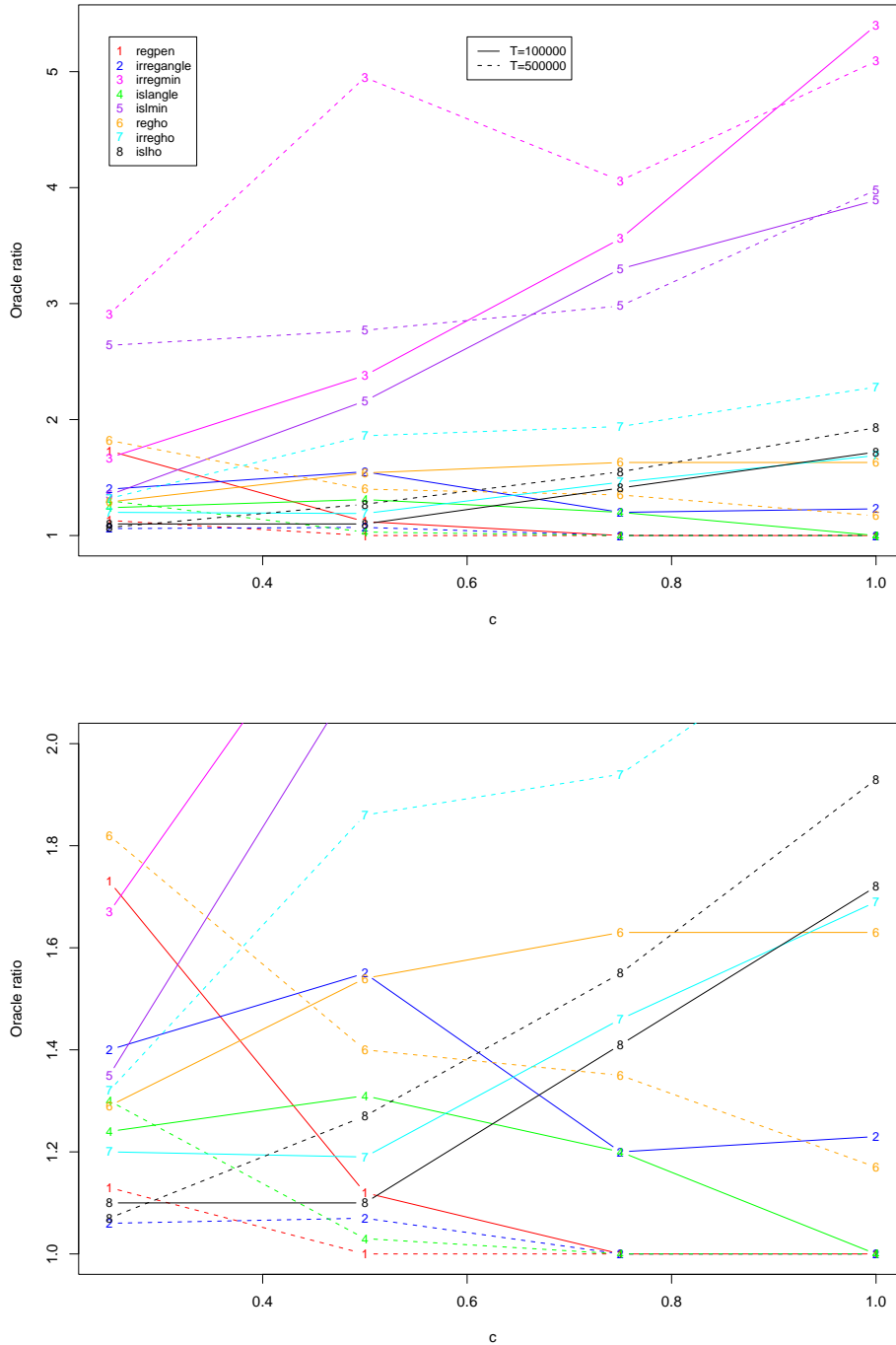


Figure 5: Oracle ratio of our estimators for  $h = c * f_1$  and  $\nu = 0.001$  for different values of  $c$  and  $T$  (top). The bottom picture zooms in on the top picture for oracle ratio between 1 and 2.

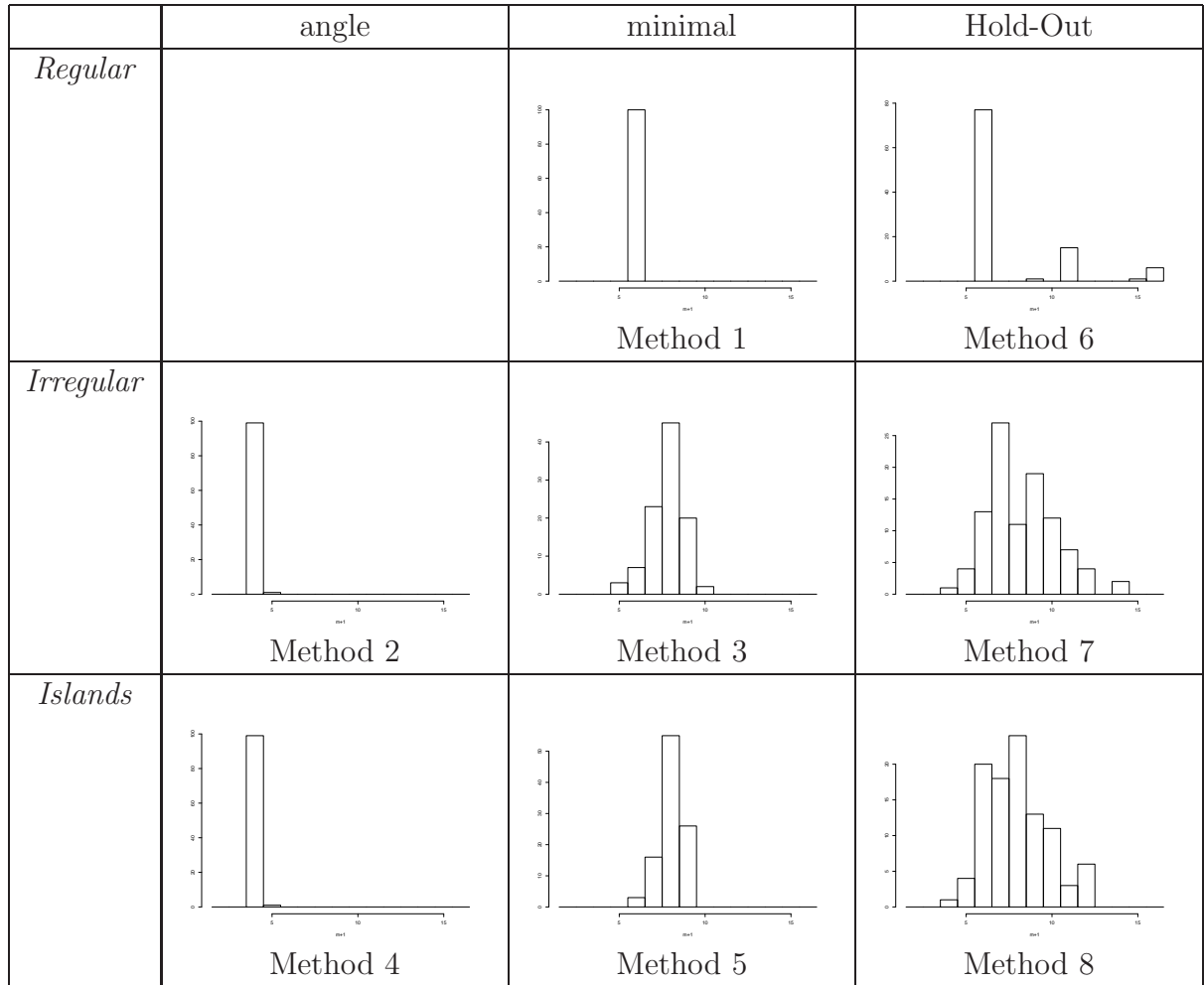


Figure 6: Frequency of the chosen dimension  $|\hat{m}| + 1$  for the different methods when  $T = 500000$ ,  $\mu = 0.001$  and  $h = 0.5 * f_1$ . Note that the true dimension is 6 for the *Regular* method (chosen in 100% of the simulations by Method 1) and 4 for the *Irregular* and *Islands* methods (chosen in more than 95% of the simulations by Methods 2 and 4)

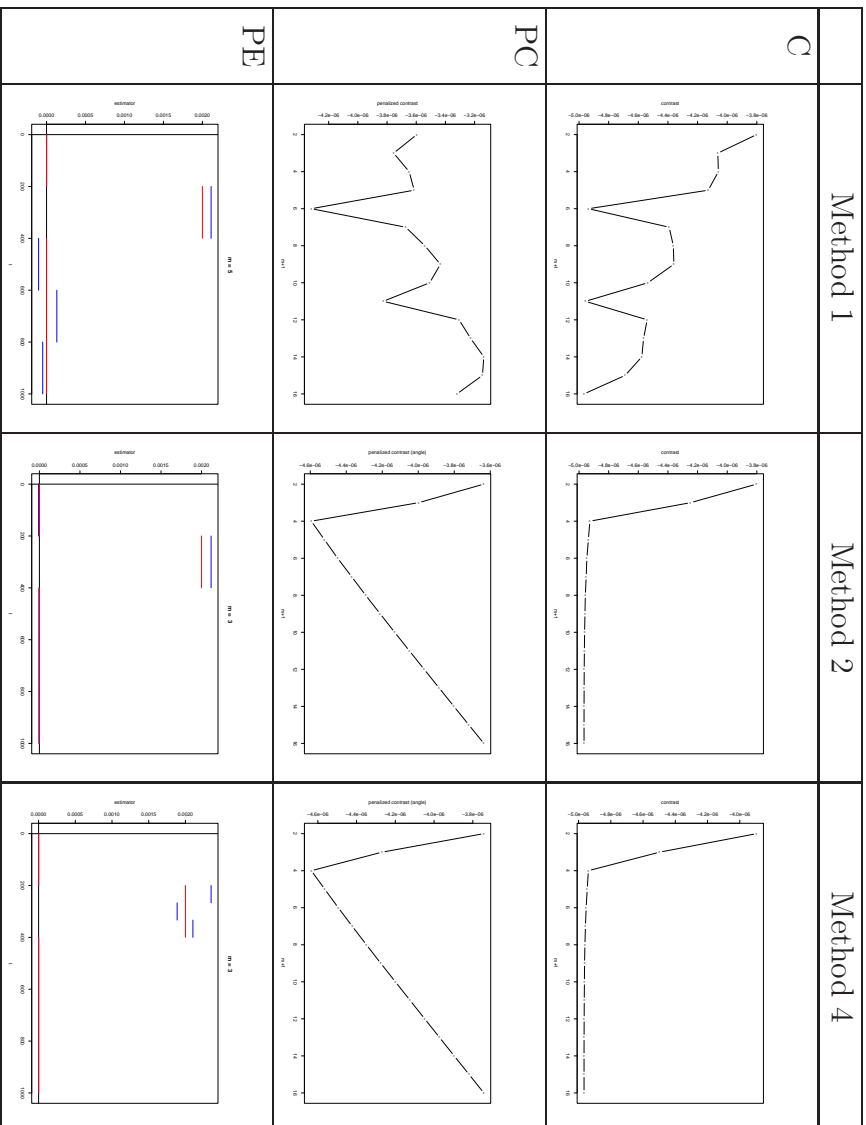


Figure 7: Contrast (C) and penalized contrast (PC) as a function of the dimension for the three favorite methods on one simulation with  $T = 500000$ ,  $\mu = 0.001$  and  $h = 0.5 * f_1$ . The chosen estimators (PE) are in blue whereas the function  $h = 0.5 * f_1$  is in red.

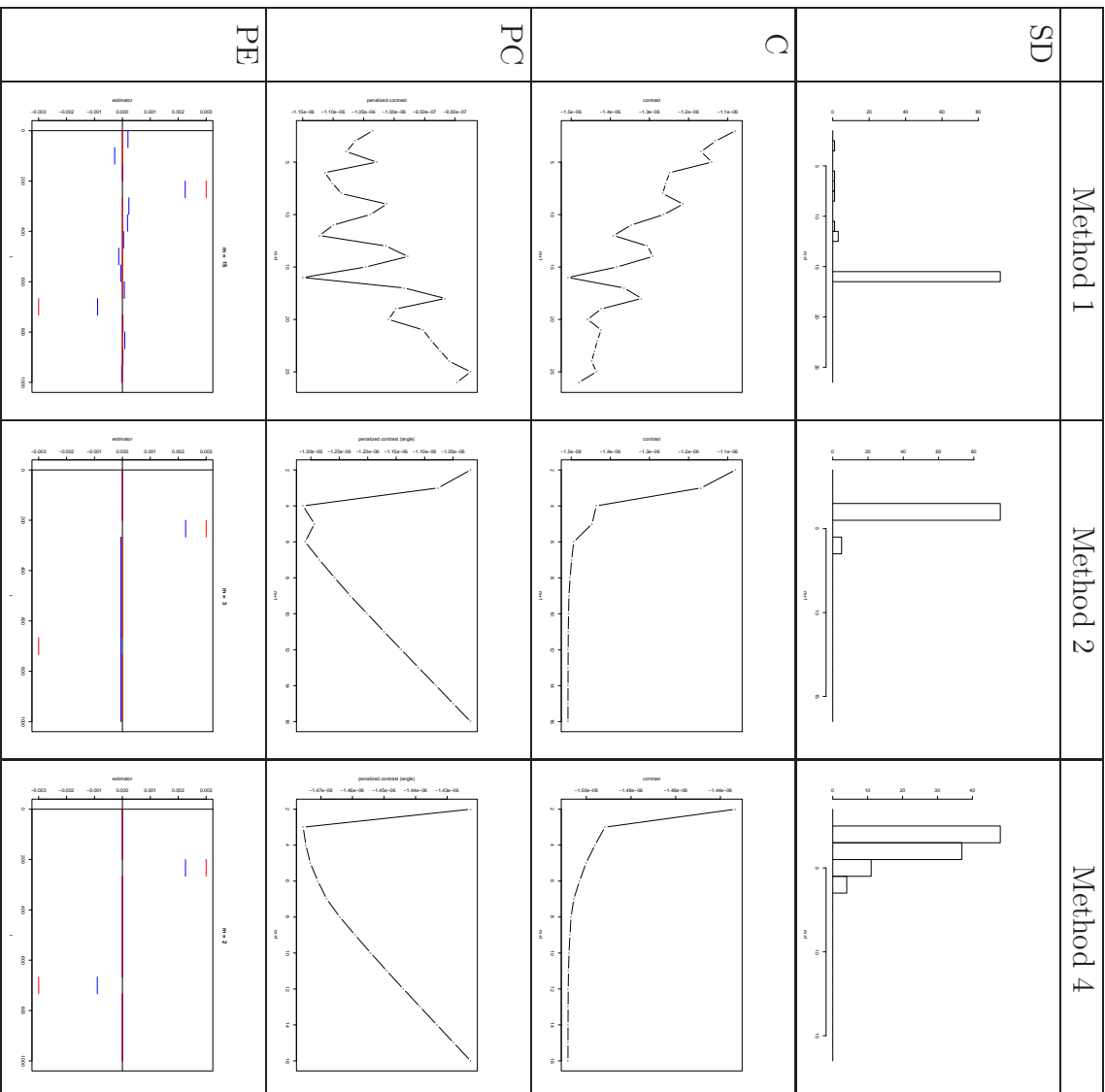


Figure 8: Histogram of the selected dimension over 100 simulations (SD). Contrast (C) and penalized contrast (PC) as a function of the dimension for the three favorite methods on one simulation with  $T = 500000$ ,  $\mu = 0.001$  and  $h = f_2$ . The true dimension is 16 for method 1 (*Regular*), 6 for method 2 (*Irregular*) and 3 for method 4 (*Islands*). The chosen estimators (PE) are in blue whereas the function  $h = f_2$  is in red.

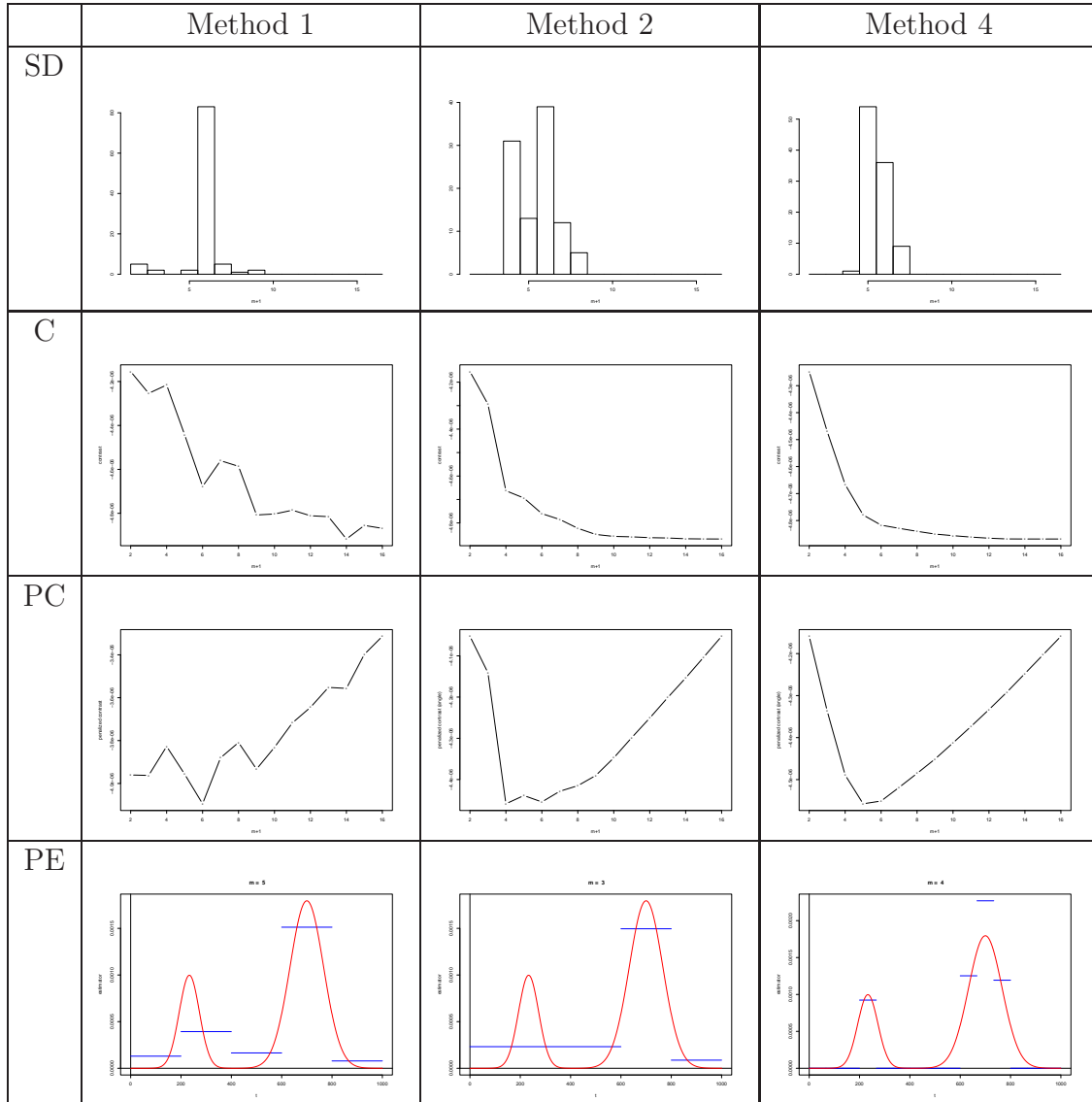


Figure 9: Histogram of the selected dimension over 100 simulations (SD). Contrast (C) and penalized contrast (PC) as a function of the dimension for the three favorite methods on one simulation with  $T = 500000$ ,  $\mu = 0.001$  and  $h = f_3$ . The chosen estimators (PE) are in blue whereas the function  $h = f_3$  is in red.

## 5 Applications on real data

We have applied the penalized (angle method) estimation procedure with the *Island strategy* to two data sets related to occurrences of genes or DNA motifs along both strands of the complete genome of the bacterium *Escherichia coli* ( $T = 9\,288\,442$ ). In both cases, we used  $A = 10\,000$  as the longest dependence between events and the finest partition corresponds to  $|\Gamma| = 15$ .

The first process corresponds to the occurrences of the 4290 genes. Figure 10 (top) gives the associated contrast and penalized contrast, together with the chosen estimator of  $h$  ( $\hat{m} = 4$  and  $\hat{\nu} = 3.64 \cdot 10^{-4}$ ). The shape of this estimator tells us that

- gene occurrences seem to be uncorrelated down to 2600 basepairs,
- they are avoided at a short distance ( $\sim 0$ –500 bps) and
- favored at distances  $\sim 700$ –2000 bps apart.

This general trend has been refined by shortening the support  $A$  to 5000 and then to 2000 (see Figure 11). It then clearly appears both a negative effect at distances less than 250 bps, and a positive one around 1000 bps. This is completely coherent with biological observations: genes on the same strand do not usually overlap, they are about 1000 bps long in average, and there are few intergenic regions along bacterial genomes (compact genomes).

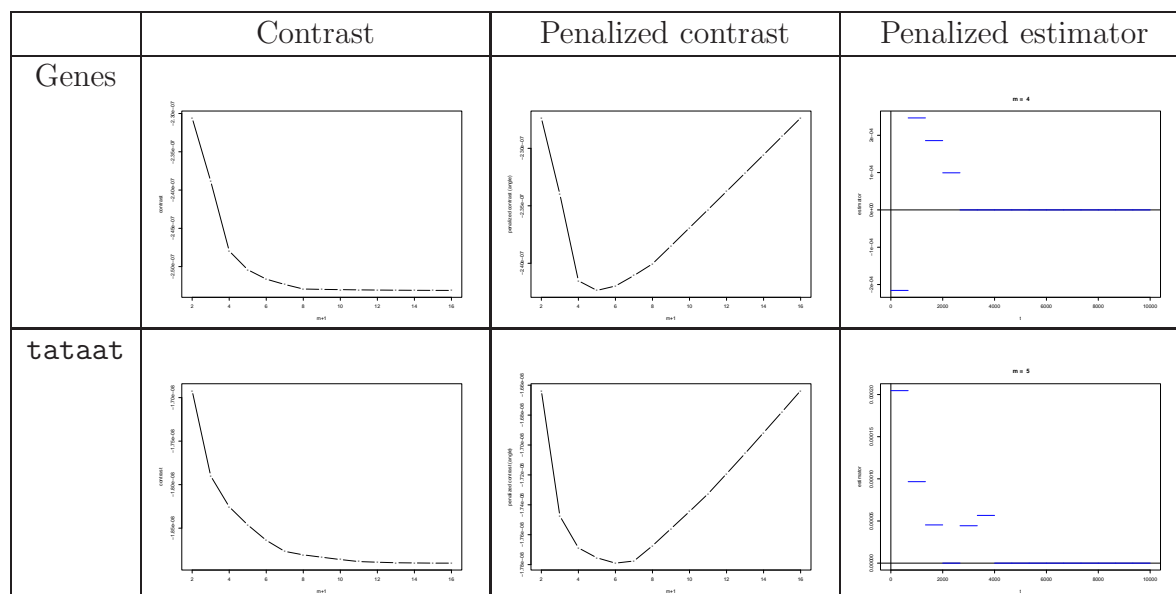


Figure 10: Contrasts, penalized contrasts and chosen estimators for both *E. coli* datasets

The second process corresponds to the 1036 occurrences of the DNA motif `tataat`. Figure 10 (bottom) gives the associated contrast and penalized contrast, together with the chosen estimator of  $h$  ( $\hat{m} = 5$  and  $\hat{\nu} = 7.82 \cdot 10^{-5}$ ). The shape of the estimator suggests that

- occurrences seem to be uncorrelated down to 4000 basepairs,
- favored at distances  $\sim 0$ –1500 bps and 3000 bps apart,
- highly favored at a short distance apart (less than 600 bps).

After shortening the support  $A$  to 5000 (see Figure 11), the shape of the chosen estimator shows that there actually are 3 types of favored distances: very short distances (less than 300 bps), around 1000 bps and around 3500 bps. This trend is again coherent with the fact that (i) the motif `tataat` is self-overlapping (two successive occurrences can occur at a distance 5 apart), (ii) this motif is part of the most common promoter of *E. coli* meaning that it should occur in front of the majority of the genes (and these genes seem to be favored at distances around 1000 bps apart from the previous example), (iii) some particular successive genes (operons) can be regulated by the same promoter (this could explain the third bump).

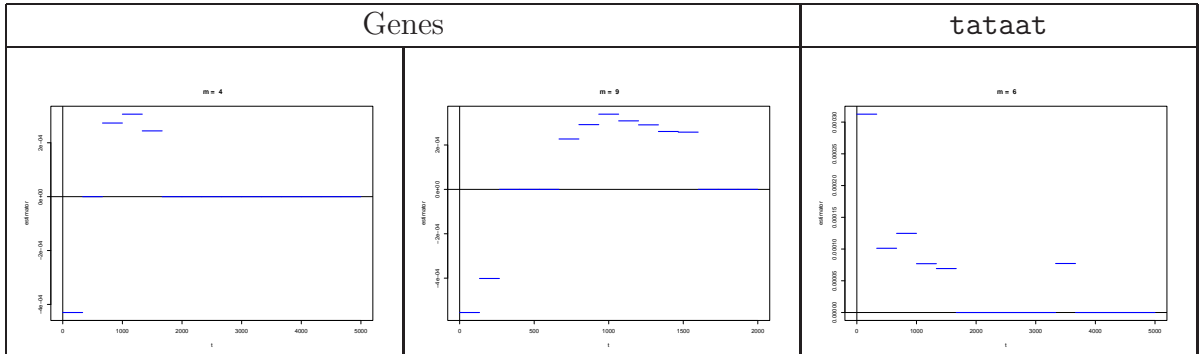


Figure 11: Chosen estimators for both *E. coli* datasets for different values of  $A$ :  $A = 5000$  (left, right) and  $A = 2000$  (middle).

Our results are in agreement with the ones obtained by [10]. Compared to the later, the advantages of our new approach are the capability to have a better idea of the support  $A$  of the function  $h$  and the capability to consider irregular partitions leading to models of smaller dimension. The limitation is essentially that we only consider piecewise constant estimators, but this is enough to get a general trend on favored or avoided distances within a point process.

## 6 Minimax properties

The theoretical procedures of Proposition 1 and Theorem 1 have more theoretical properties than just an oracle inequality. This section provides their minimax properties. In particular, even if it has not been implemented for technical reasons that were described above, the *Nested strategy* leads to an adaptive minimax estimator. Such kind of estimators were not known in the Hawkes model, as far as we know.

### 6.1 Hölderian functions

First, one can prove the following lower bound.

**Proposition 3.** *Let  $L > 0$  and  $1 \geq a > 0$ . Let*

$$\mathcal{H}_{L,a} = \left\{ s = (\nu, h) \in \mathbb{L}^2 / \quad \forall x, y \in (0, A], \quad |h(x) - h(y)| \leq L|x - y|^a \right\}.$$

Then

$$\inf_{\hat{s}} \sup_{s \in \mathcal{H}_{L,a} \cap \mathcal{L}_{H,P}^{\eta,\rho}} \mathbb{E}_s(\|s - \hat{s}\|^2) \geq \square_{H,P,A,\eta,\rho,a} \min \left( L^{\frac{2}{2a+1}} T^{-\frac{2a}{2a+1}}, 1 \right).$$

The infimum over  $\hat{s}$  represents the infimum over all the possible estimators constructed on the observation on  $[-A, T]$  of a point process  $(N_t)_t$ .  $\mathbb{E}_s$  represents the expectation with respect to the stationary Hawkes' process  $(N_t)$  with intensity given by  $\Psi_s(\cdot)$ .

But on the other hand, let us consider the clipped projection estimator  $\bar{s}_m$  with  $m$  a regular partition of  $(0, A]$  such that

$$|m| \simeq (T/\log(T))^{1/(2a+1)}.$$

If the function  $h$  is in  $\mathcal{H}_{L,a} \cap \mathcal{L}_{H,P}^{\eta,\rho}$  with  $a \in (1/2, 1]$ , then, applying Proposition 1,  $\bar{s}_m$  satisfies

$$\mathbb{E}(\|\bar{s}_m - s\|^2) \leq \square_{H,P,A,\eta,\rho,L,a} \left( \frac{\log(T)}{T} \right)^{2a/(2a+1)}.$$

Compared with the lower bound of the minimax risk (Proposition 3), we only lose a logarithmic factor. The clipped projection estimators are minimax on  $\mathcal{H}_{L,a} \cap \mathcal{L}_{H,P}^{\eta,\rho}$ , with  $a \in (1/2, 1]$ , up to some logarithmic term. We cannot go beyond  $a = 1/2$  because one needs  $|m| \ll \sqrt{T}$ , in Proposition 1.

Of course, we need to know  $a$  to find  $\bar{s}_m$ , so  $\bar{s}_m$  is not adaptive with respect to  $a$ . But the clipped penalized projection estimator  $\bar{s}$  with the *Nested strategy* can be adaptive with respect to  $a$ . It is sufficient to take  $J \simeq \log_2(\sqrt{T}/\log(T)^3)$  to guarantee (3.2). Then we apply Theorem 1 with  $Q = 1.1$  for instance. Since  $\#\{\mathcal{M}_T\} = J + 1$  is of the order  $\log(T)$ , we obtain that

$$\mathbb{E}(\|\bar{s} - s\|^2) \leq \square_{H,\eta,P,A,\rho} \inf_{m \in \mathcal{M}_T} \left[ \|s - s_m\|^2 + (|m| + 1) \frac{\log(T)^2}{T} \right].$$

If  $h$  is in  $\mathcal{H}_{L,a} \cap \mathcal{L}_{H,P}^{\eta,\rho}$  with  $a \in (1/2, 1]$ , then there exists  $m$  in  $\mathcal{M}_T$  such that

$$|m| \simeq (T/\log(T))^{1/(2a+1)},$$

and consequently

$$\mathbb{E}(\|\bar{s} - s\|)^2 \leq \square_{H,\eta,P,\rho,A,L,a} \left( \frac{\log(T)^2}{T} \right)^{2a/(2a+1)}.$$

Therefore, the clipped penalized projection estimator  $\bar{s}$  with the *Nested strategy* and the theoretical penalty given by (3.4) is adaptive minimax on  $\{\mathcal{H}_{L,a} \cap \mathcal{L}_{H,P}^{\eta,\rho}, a \in (1/2, 1]\}$  up to some logarithmic term.

## 6.2 Irregular and Islands sets

Let us apply Theorem 1 to the *Irregular strategy* and *Islands strategy*. In both cases, the limiting factor here is  $\#\{\mathcal{M}_T\}$ . Take  $N \leq \log_2(T)$ , then  $\#\{\mathcal{M}_T\} \leq T$  and if  $Q \geq 2$  we obtain that

$$\mathbb{E}(\|\bar{s} - s\|)^2 \leq \square_{H,P,A,\eta,\rho} \inf_{m \in \mathcal{M}_T} \left[ \|s - s_m\|^2 + (|m| + 1) \frac{\log(T)^2}{T} \right].$$

To measure performances of those estimators, one needs to introduce a set of sparse functions  $h$ , functions that are difficult to estimate with a *Nested strategy*. A piecewise function  $h$  is usually thought as sparse if the resulting partition is irregular with few intervals. So we define the Irregular set by:

$$S_{\Gamma,D}^{irr} := \cup_{m \text{ partition written on } \Gamma, |m|=D} S_m, \quad (6.1)$$

Then, if  $s$  belongs to  $S_{\Gamma,D}^{irr}$ , using the *Irregular strategy*, the clipped penalized projection estimator satisfies

$$\mathbb{E}(\|\bar{s} - s\|)^2 \leq \square_{H,P,\eta,\rho,A} D \frac{\log(T)^2}{T}.$$

But for our biological purpose, the sparsity lies in the support of  $h$ . So we define the Islands set by

$$S_{\Gamma,D}^{isl} := \cup_{m \subset \Gamma, |m|=D} S_m, \quad (6.2)$$

Then, if  $s$  belongs to  $S_{\Gamma,D}^{isl}$ , using the *Islands strategy*, the clipped penalized projection estimator also satisfies

$$\mathbb{E}(\|\bar{s} - s\|)^2 \leq \square_{H,P,\eta,\rho,A} D \frac{\log(T)^2}{T}.$$

On the other hand it is possible to compute lower bounds for the minimax risk over those sets.

**Proposition 4.** *Let  $\Gamma$  be a partition of  $(0, A]$  such that  $\inf_{I \in \Gamma} \ell(I) \geq \ell_0$ . Let  $|\Gamma| = N$  and let  $D$  be a positive integer such that  $N \geq 4D$ . If  $D \geq c_2(A, \eta, P, \rho, H) > 1$ , for  $c_2$  some positive constant depending on  $A, \eta, P, \rho, H$ , then*

$$\inf_{\hat{s}} \sup_{s \in S_{\Gamma, D}^{isl} \cap \mathcal{L}_{H, P}^{\eta, \rho}} \mathbb{E}_s(\|s - \hat{s}\|^2) \geq \square_{H, P, A, \eta, \rho} \min\left(\frac{D \log\left(\frac{N}{D}\right)}{T}, D\ell_0\right),$$

and

$$\inf_{\hat{s}} \sup_{s \in S_{\Gamma, D}^{irr} \cap \mathcal{L}_{H, P}^{\eta, \rho}} \mathbb{E}_s(\|s - \hat{s}\|^2) \geq \square_{H, P, A, \eta, \rho} \min\left(\frac{D \log\left(\frac{N}{D}\right)}{T}, D\ell_0\right).$$

The infimum over  $\hat{s}$  represents the infimum over all the possible estimators constructed on the observation on  $[-A, T]$  of a point process  $(N_t)_t$ .  $\mathbb{E}_s$  represents the expectation with respect to the stationary Hawkes' process  $(N_t)$  with intensity given by  $\Psi_s(\cdot)$ .

To clarify the situation it is better to take  $N = |\Gamma| \simeq \log(T)$ . If  $D \simeq \log(T)^a$  with  $a < 1$  then the lower bound on the minimax risk is of the order  $\log(T)^a \log \log T / T$  when the risk of the clipped penalized projection estimator (for both strategies) is upper bounded by  $\log(T)^{a+2}/T$ , and this whatever  $a$  is. So our estimator matches the rate  $1/T$  up to a logarithmic term. Of course the most fundamental part is this logarithmic term. Think however that there exists some function  $h$  in those sets, such that the function belongs to  $S_{\Gamma}$  but to none of the other spaces  $S_m$  for  $m$  in the family  $\mathcal{M}_T$  described by the *Nested Strategy*. Consequently, a clipped penalized estimator with the *Nested Strategy* would have an upper bound on the risk of the order  $\log(T)^3/T$ , by applying Theorem 1. So the *Irregular* and *Islands* strategies have not only good practical properties, but there is also definitely a theoretical improvement in the upper bound of the risk.

## 7 Technical results

### 7.1 Oracle inequality in probability

The following result is actually the one at the origin of Theorem 1.

**Theorem 2.** *Let  $(N_t)_{t \in \mathbb{R}}$  be a Hawkes' process with intensity  $\Psi_s(\cdot)$ . Let  $H, \eta$  and  $A$  be positive known constants such that  $s = (\nu, h)$  satisfies  $\nu \in [0, \eta]$  and  $h(\cdot) \in [0, H]$ .*

*Moreover assume that the family  $\mathcal{M}_T$  satisfies*

$$\inf_{m \in \mathcal{M}_T} \inf_{I \in m} \ell(I) \geq \ell_0 > 0.$$

*Let  $\mathcal{S}$  be a subspace of  $\mathbb{L}^2$  containing all the piecewise constant functions constructed on the models of  $\mathcal{M}_T$ . Let  $R > r > 0$  be positive real numbers, let  $\mathcal{N}$  be a positive integer*

and let us consider the following event

$$\mathcal{B} = \left\{ \forall t \in [0, T], \quad N([t - A, t]) \leq \mathcal{N} \quad \text{and} \quad \forall f \in \mathcal{S}, \quad r^2 \|f\|^2 \leq D_T^2(f) \leq R^2 \|f\|^2 \right\},$$

where  $N([t - A, t])$  represents the number of points of the Hawkes process  $(N_t)_t$  in the interval  $[t - A, t]$ . We set  $\Lambda = (\eta + HN)R^2/r^2$  and we consider  $\varepsilon$  and  $x$  any arbitrary positive constants. If for all  $m \in \mathcal{M}_T$

$$\text{pen}(m) \geq (1 + \varepsilon)^2 \Lambda \frac{|m| + 1}{T} (1 + 3\sqrt{2x})^2,$$

then on  $\mathcal{B}$  with probability larger than  $1 - 3\#\{\mathcal{M}_T\}e^{-x}$ , the following inequality holds for all  $m \in \mathcal{M}_T$ :

$$r^2 \frac{\varepsilon}{1 + \varepsilon} \|\tilde{s} - s\|^2 \leq \left( R^2 + \frac{r^2}{1 + \varepsilon} \right) \|s - s_m\|^2 + \text{pen}(m) + \square_\varepsilon \Lambda \frac{x}{T} + \square_\varepsilon \frac{1 + \mathcal{N}^2/\ell_0}{r^2 T^2} x^2.$$

This result is really the most fundamental to understand how the Hawkes' process can be easily handled once we only focus on a nice event, namely  $\mathcal{B}$ . We have “hidden” in  $\mathcal{B}$  the fact that the intensity of the process is unbounded: on  $\mathcal{B}$ , the number of points per interval of length  $A$  is controlled, so the intensity is bounded on this event. We have also “hidden” in  $\mathcal{B}$  the fact that we are working with a natural norm, namely  $D_T$ , which is random and which may eventually behave badly: on  $\mathcal{B}$ ,  $D_T$  is equivalent to the deterministic norm  $\|\cdot\|$ . Moreover  $\mathcal{B}$  is observable, so if one observes that we are on  $\mathcal{B}$ , this theorem shows that a penalty of the type a factor times the dimension can work really well to select the right dimension. Indeed, note that if, in the family  $\mathcal{M}_T$ , there is a “true” model  $m$  (meaning that  $s = s_m$ ) and if the penalty is correctly chosen, then the result proves that  $\|\tilde{s} - s\|^2$  is of the same order as the lower bound on the minimax risk on  $m$ , namely  $|m|/T$  (see Proposition 2 for the precise lower bound). In that sense, this is an oracle inequality. The procedure is adaptive because it can select the right model without knowing it. But of course this hides something of importance. If  $\mathcal{B}$  is not that frequent, then the result is completely useless from a theoretical point of view since one cannot guarantee that the risk of the penalized estimator and even the risk of the projection estimators themselves are small.

In fact, we will see in the next subsection that the choices of  $\mathcal{N}$ ,  $R$ ,  $r$ ,  $\mathcal{M}_T$  are really important to control  $\mathcal{B}$ . In particular we are not able at the end to manage families of models with a very high complexity as in [2] or in most of the other works in model selection (see Theorem 1 and Section 6). This is probably due to a lack of independency and boundedness in the process itself.

Note also that the result of Theorem 2 remains true for the more general process defined by (2.14) once we replace  $\mathcal{B}$  by  $\mathcal{B} \cap \mathcal{B}'$  where  $\mathcal{B}' = \{\forall t \leq T, \lambda(t) > 0\}$ . But of course then,  $\mathcal{B}'$  is not observable. This tends to prove that even in case of self-inhibition a penalty of the type a constant times the dimension is working.

## 7.2 Control of $\mathcal{B}$

The assumptions of Theorem 1 are in fact a direct consequence of the assumptions needed to control  $\mathcal{B}$ , as shown in the following result.

**Proposition 5.** *Let  $s \in \mathcal{L}_{H,P}^{\eta,\rho}$  and  $R$  and  $r$  such that*

$$R^2 > 2 \max \left( 1, \frac{\eta}{(1-P)^2} (\eta A + (1-P)^{-1}) \right) \quad \text{and} \quad r^2 < \min \left( \frac{\rho}{4}, \frac{1-P}{8A\eta+1} \right).$$

Moreover let

$$\mathcal{N} = \frac{4 \log(T)}{P - \log P - 1}.$$

Let us finally assume that  $\mathcal{S}$ , defined by Theorem 2, is included in  $S_\Gamma$  where  $\Gamma$  is a regular partition of  $(0, A]$  such that

$$|\Gamma| \leq \frac{\sqrt{T}}{(\log T)^3}.$$

Then, under the assumptions of Theorem 2, there exists  $T_0 > 0$  depending on  $\eta, \rho, P, A, R$  and  $r$ , such that for all  $T > T_0$ ,

$$\mathbb{P}(\mathcal{B}^c) \leq \square_{\eta,P,A} \frac{1}{T^2}.$$

## 8 Proofs

### 8.1 Contrast and norm

First let us show a very useful result, that is recursively used in the following proofs.

**Lemma 1.** *Let  $(N_t)_{t \in \mathbb{R}}$  be a Hawkes process with intensity  $\Psi_s(\cdot)$ . Let  $g$  be a function on  $\mathbb{R}_+$  such that  $\int_0^{+\infty} g(u) du$  is finite. Then for all  $t$ ,*

$$\begin{aligned} \mathbb{E} \left[ \left( \int_{-\infty}^t g(t-u) dN_u \right)^2 \right] &= \frac{\nu^2}{(1-p)^2} \left( \int_0^{+\infty} g(u) du \right)^2 + \int_{\mathbb{R}} |\mathcal{F}g(-w)|^2 f_N(w) dw \\ &\leq \frac{\nu^2}{(1-p)^2} \left( \int_0^{+\infty} g(u) du \right)^2 + \frac{\nu}{(1-p)^3} \int_0^{+\infty} g^2(u) du, \end{aligned}$$

where

$$f_N(w) = \frac{\nu}{2\pi(1-p) |1 - \mathcal{F}h(w)|^2},$$

is the spectral density of  $(N_t)_{t \in \mathbb{R}}$ .

*Remark (Notation):*  $\mathcal{F}h$  is the Fourier transform of  $h$ , i.e.  $\mathcal{F}h(x) = \int_{\mathbb{R}} e^{ixt} h(t) dt$ .

**Proof.** Let  $\phi_t(u) = \mathbb{1}_{u < t} g(t - u)$ . We know (see [5, p 123]) that

$$\text{Var} \left[ \int_{\mathbb{R}} \phi_t(u) dN_u \right] = \int_{\mathbb{R}} |\mathcal{F}\phi_t(w)|^2 f_N(w) dw.$$

Moreover, since  $g$  has a positive support,  $\mathcal{F}\phi_t(w) = e^{iwt} \mathcal{F}g(-w)$ . Hence

$$\text{Var} \left[ \int_{\mathbb{R}} \phi_t(u) dN_u \right] = \int_{\mathbb{R}} |\mathcal{F}g(-w)|^2 f_N(w) dw.$$

But we also know that (see [11])

$$\lambda = \mathbb{E}(\lambda(t)) = \frac{\nu}{1-p}.$$

Consequently

$$\begin{aligned} \mathbb{E} \left[ \left( \int_{-\infty}^t g(t-u) dN_u \right)^2 \right] &= \text{Var} \left[ \int_{\mathbb{R}} \phi_t(u) dN_u \right] + \left( \mathbb{E} \left( \int_{\mathbb{R}} \phi_t(u) dN_u \right) \right)^2 \\ &= \text{Var} \left[ \int_{\mathbb{R}} \phi_t(u) dN_u \right] + \left( \lambda \int_0^{+\infty} g(u) du \right)^2, \end{aligned}$$

which gives the first part of the Lemma. The second part is due to Plancherel's identity and the fact that  $f_N$  is upper bounded by  $\nu/[2\pi(1-p)^3]$  since  $h$  is nonnegative. ■

**Lemma 2.** Let  $(N_t)_{t \in \mathbb{R}}$  be a Hawkes process with intensity  $\Psi_s(\cdot)$ . Then the functional given by

$$\forall f \in \mathbb{L}^2, \quad \gamma_T(f) = -\frac{2}{T} \int_0^T \Psi_f(t) dN_t + \frac{1}{T} \int_0^T \Psi_f(t)^2 dt,$$

is a contrast, i.e.  $\mathbb{E}(\gamma_T(f))$  is minimal for  $f = s$ .

To show this, we need the forthcoming lemma.

**Lemma 3.** The functional  $D_T^2$  is a quadratic form on  $\mathbb{L}^2$  and its expectation  $\|\cdot\|_D^2$  (see (2.8)) is the square of a norm on  $\mathbb{L}^2$  satisfying

$$\forall f \in \mathbb{L}^2, \quad L\|f\| \leq \|f\|_D \leq K\|f\|, \tag{8.1}$$

where

$$K^2 = 2 \max \left[ 1, \frac{\nu}{(1-p)^2} \left( \nu A + \frac{1}{1-p} \right) \right] \quad \text{and} \quad L^2 = \min \left[ \frac{\nu}{4}, \frac{1-p}{8A\nu+1} \right].$$

**Proof.**[Lemma 3]  $D_T^2$  is a quadratic form since  $\frac{1}{T} \int_0^T \Psi_f(t) \Psi_k(t) dN_t$ , its associated form, is bilinear and symmetric in  $f$  and  $k$ .

Moreover one can compute  $\|f\|_D^2$ : if  $f = (\mu, g)$ ,

$$\begin{aligned} \mathbb{E}(D_T^2(f)) &= \frac{1}{T} \int_0^T \mathbb{E} \left[ \left( \mu + \int_{-\infty}^t g(t-u) dN_u \right)^2 \right] dt \\ &= \frac{1}{T} \int_0^T \mathbb{E} \left[ \mu^2 + 2\mu \int_{-\infty}^t g(t-u) dN_u + \left( \int_{-\infty}^t g(t-u) dN_u \right)^2 \right] dt \\ &= \frac{1}{T} \int_0^T \left( \mu^2 + 2\mu \lambda \int_{-\infty}^t g(t-u) du + \mathbb{E} \left[ \left( \int_{-\infty}^t g(t-u) dN_u \right)^2 \right] \right) dt \\ &= \mu^2 + 2\mu \lambda \int_0^{+\infty} g(u) du + \frac{1}{T} \int_0^T \mathbb{E} \left[ \left( \int_{-\infty}^t g(t-u) dN_u \right)^2 \right] dt. \end{aligned}$$

Let us use the first part of Lemma 1. This gives that

$$\|f\|_D^2 = \mathbb{E}(D_T^2(f)) = \mu^2 + 2\mu \lambda \int_0^{+\infty} g(u) du + \lambda^2 \left( \int_0^{+\infty} g(u) du \right)^2 + \int_{\mathbb{R}} |\mathcal{F}g(-w)|^2 f_N(w) dw. \quad (8.2)$$

This is a quadratic norm on  $\mathbb{L}^2$ : indeed,  $\|f\|_D^2 \geq 0$  and its associated form

$$\forall f, k \in \mathbb{L}^2, \quad \frac{1}{2} (\|f+k\|_D^2 - \|f\|_D^2 - \|k\|_D^2) = \frac{1}{T} \mathbb{E} \left[ \int_0^T \Psi_f(t) \Psi_k(t) dN_t \right] \quad (8.3)$$

is bilinear and symmetric. It remains to prove that  $\|f\|_D^2 = 0$  implies  $f = 0$ , which is automatic if we prove (8.1). Refining the computations of Lemma 1, one can easily check that for all  $w$

$$0 < c = \frac{\nu}{2\pi(1-p)(1+p)^2} \leq f_N(w) \leq C = \frac{\nu}{2\pi(1-p)^3}. \quad (8.4)$$

By (8.2) and (8.4), one has

$$\left( \mu + \lambda \int_0^A g(x) dx \right)^2 + c \int_{\mathbb{R}} |\mathcal{F}g(-w)|^2 dw \leq \|f\|_D^2 \leq \left( \mu + \lambda \int_0^A g(x) dx \right)^2 + C \int_{\mathbb{R}} |\mathcal{F}g(-w)|^2 dw.$$

By Plancherel's identity,  $\int_{\mathbb{R}} |\mathcal{F}g(-w)|^2 dw = 2\pi \int_0^A g^2(x) dx$ . Consequently

$$\left( \mu + \lambda \int_0^A g(x) dx \right)^2 + 2\pi c \int_0^{+\infty} g^2(x) dx \leq \|f\|_D^2 \leq \left( \mu + \lambda \int_0^A g(x) dx \right)^2 + 2\pi C \int_0^{+\infty} g^2(x) dx.$$

- For the upper bound, remark that

$$\left( \mu + \lambda \int_0^A g(x) dx \right)^2 \leq 2\mu^2 + 2\lambda^2 \left( \int_0^A g(x) dx \right)^2,$$

which implies by Cauchy-Schwarz' inequality that

$$\left(\mu + \lambda \int_0^A g(x)dx\right)^2 \leq 2\mu^2 + 2\lambda^2 A \int_0^A g^2(x)dx.$$

So  $K^2 = \max(2, 2\lambda^2 A + 2\pi C)$  works.

- For the lower bound, one has for all  $\theta > 0$

$$\left(\mu + \lambda \int_0^A g(x)dx\right)^2 \geq (1 - \theta)\mu^2 + \left(1 - \frac{1}{\theta}\right)\lambda^2 \left(\int_0^A g(x)dx\right)^2.$$

Then if  $\theta < 1$ , this implies, by Cauchy-Schwarz' inequality, that

$$\left(\mu + \lambda \int_0^A g(x)dx\right)^2 \geq (1 - \theta)\mu^2 + \left(1 - \frac{1}{\theta}\right)A\lambda^2 \int_0^A g^2(x)dx.$$

Hence we obtain for all  $0 < \theta < 1$

$$\|f\|_D^2 \geq (1 - \theta)\mu^2 + \left[2\pi c + \left(1 - \frac{1}{\theta}\right)A\lambda^2\right] \int_0^A g^2(x)dx.$$

Taking  $\theta$  such that  $2\pi c + (1 - \frac{1}{\theta})A\lambda^2 = \pi c$ , this implies that

$$\|f\|_D^2 \geq \frac{\pi c}{A\lambda^2 + \pi c}\mu^2 + \pi c \int_0^A g^2(x)dx.$$

But  $\pi c \geq \nu/4$  and

$$\frac{\pi c}{A\lambda^2 + \pi c} \geq \frac{1 - p}{8A\nu + 1}.$$

Hence  $L^2 = \min(\nu/4, (1 - p)(8A\nu + 1)^{-1})$  works. ■

**Proof.[Lemma 2]** Let us compute  $\mathbb{E}(\gamma_T(f))$ . As  $\lambda(t) = \Psi_s(t)$ , one can write by the martingale properties of  $dN_t - \Psi_s(t)dt$  and by (8.3) that

$$\begin{aligned} \mathbb{E}(\gamma_T(f)) &= \mathbb{E}\left[-\frac{2}{T} \int_0^T \Psi_f(t)dN_t\right] + \mathbb{E}(D_T^2(f)) \\ &= \mathbb{E}\left[-\frac{2}{T} \int_0^T \Psi_f(t)\Psi_s(t)dt\right] + \|f\|_D^2 \\ &= \|f - s\|_D^2 - \|s\|_D^2. \end{aligned}$$

Consequently  $\mathbb{E}(\gamma_T(f))$  is minimal when  $f = s$  since Lemma 3 proves that  $\|\cdot\|_D$  is a norm. ■

## 8.2 Proof of Theorem 2

**Proof.** Let  $m$  be a fixed partition of  $\mathcal{M}_T$ . By construction, we obtain

$$\gamma_T(\tilde{s}) + \text{pen}(\hat{m}) \leq \gamma_T(\hat{s}_m) + \text{pen}(m) \leq \gamma_T(s_m) + \text{pen}(m). \quad (8.5)$$

Let us denote for all  $f$  in  $\mathbb{L}^2$ ,

$$\nu_T(f) = \frac{1}{T} \int_0^T \Psi_f(t)(dN_t - \Psi_s(t)dt),$$

which is linear in  $f$ . Then (2.6) becomes  $\gamma_T(f) = D_T^2(f - s) - D_T^2(s) - 2\nu_T(f)$  and (8.5) leads to

$$D_T^2(\tilde{s} - s) \leq D_T^2(s_m - s) + 2\nu_T(\tilde{s} - s_m) + \text{pen}(m) - \text{pen}(\hat{m}). \quad (8.6)$$

By linearity of  $\nu_T$ ,  $\nu_T(\tilde{s} - s_m) = \nu_T(\tilde{s} - s_{\hat{m}}) + \nu_T(s_{\hat{m}} - s_m)$ . Now let us control each term in the right hand side of (8.6).

1. Let us begin with  $A_1 = 2\nu_T(\tilde{s} - s_{\hat{m}})$ . For all  $m'$  in  $\mathcal{M}_T$ , we set

$$W_{m'} = \sup_{f \in S_{m'}} \frac{\nu_T(f)}{\|f\|}. \quad (8.7)$$

Thus  $A_1 \leq 2\|\tilde{s} - s_{\hat{m}}\|W_{\hat{m}}$ . Therefore, for all  $\theta > 0$ , one has the following upper bound

$$A_1 \leq \theta\|\tilde{s} - s_{\hat{m}}\|^2 + \frac{1}{\theta}W_{\hat{m}}^2. \quad (8.8)$$

Now we need to control  $W_{\hat{m}}$  which is doubly random: for fixed  $m$ ,  $W_m$  is random but the choice  $\hat{m}$  is random too. So one needs to control each  $W_{m'}$ 's to control  $W_{\hat{m}}$ .

To do so, we first need to find a simpler form for  $W_{m'}$ . Note that

$$\{(1, 0)\} \cup \left\{ \left( 0, \frac{\mathbb{1}_I}{\sqrt{\ell(I)}} \right), I \in m' \right\}$$

is an orthonormal basis of  $S_m$  for  $\|\cdot\|$ . For all  $I \in m'$ , let us denote

$$N_I(t) = \Psi_{(0, \mathbb{1}_I)}(t).$$

Then

$$\begin{aligned} W_{m'} &= \sup_{\mu^2 + \sum_{I \in m'} a_I^2 = 1} \left[ \frac{1}{T} \int_0^T \left( \mu + \sum_{I \in m'} a_I \frac{N_I(t)}{\sqrt{\ell(I)}} \right) (dN_t - \Psi_s(t)dt) \right] \\ &= \sup_{\mu^2 + \sum_{I \in m'} a_I^2 = 1} \left[ \mu \frac{1}{T} \int_0^T (dN_t - \Psi_s(t)dt) + \sum_{I \in m'} a_I \frac{1}{T} \int_0^T \frac{N_I(t)}{\sqrt{\ell(I)}} (dN_t - \Psi_s(t)dt) \right] \\ &= \sqrt{\left( \int_0^T \frac{1}{T} (dN_t - \Psi_s(t)dt) \right)^2 + \sum_{I \in m'} \left( \int_0^T \frac{N_I(t)}{T\sqrt{\ell(I)}} (dN_t - \Psi_s(t)dt) \right)^2} \end{aligned}$$

Let  $\mathcal{T}$  be defined by

$$\mathcal{T} = \left\{ t \geq 0 \middle/ N([t - A, t]) > \mathcal{N} \quad \text{or} \quad \exists f \in \mathcal{S}, \quad \frac{1}{T} \int_0^t \Psi_f(u)^2 du > R^2 \|f\|^2 \right\}$$

and let  $\tau$  be the stopping time defined by

$$\tau = \inf\{t \geq 0, t \in \mathcal{T}\}.$$

It is quite easy to see that if  $t$  belongs to  $\mathcal{T}$  then there exist  $t' < t$  such that  $t'$  belongs to  $\mathcal{T}$ . Hence  $\tau$  does not belong to  $\mathcal{T}$  and since  $\int_0^t \Psi_f(u)^2 du$  is increasing in  $t$ , saying that we restrict ourselves to  $\mathcal{B}$  implies that  $\tau \geq T$ . Finally we can write that on  $\mathcal{B}$ ,  $W_{m'} = Z_{m'}$  defined by

$$Z_{m'} = \sqrt{\left( \int_0^T \frac{1}{T} \mathbb{1}_{t \leq \tau} (dN_t - \Psi_s(t) dt) \right)^2 + \sum_{I \in m'} \left( \int_0^T \frac{N_I(t)}{T \sqrt{\ell(I)}} \mathbb{1}_{t \leq \tau} (dN_t - \Psi_s(t) dt) \right)^2}.$$

Written in this way, this is a  $\chi^2$ -type statistics as defined in [16], since the  $N_I(\cdot)$ 's are predictable processes and so is  $\mathbb{1}_{t \leq \tau}$ . So Corollary 2 of [16] gives that with probability larger than  $1 - 2e^{-x}$ ,

$$Z_{m'} \leq \sqrt{C_{m'}} + 3\sqrt{2vx} + bx$$

where

$$C_{m'} = \int_0^T \left[ \frac{1}{T^2} + \sum_{I \in m'} \frac{N_I^2(t)}{T^2 \ell(I)} \right] \mathbb{1}_{t \leq \tau} \Psi_s(t) dt, \quad v = \|C_{m'}\|_\infty$$

and where  $b$  is a deterministic constant that should satisfy

$$b^2 \geq \mathbb{1}_{t \leq \tau} \left[ \frac{1}{T^2} + \sum_{I \in m'} \frac{N_I^2(t)}{T^2 \ell(I)} \right].$$

But on  $\{\tau \geq T\}$  one has for all  $t \leq T$

$$\Psi_s(t) \leq \eta + HN.$$

So

$$C_{m'} \leq (\eta + HN) \frac{1}{T} \left( D_T^2((1, 0)) + \sum_{I \in m'} \frac{D_T^2((0, \mathbb{1}_I))}{\ell(I)} \right).$$

Moreover on  $\{\tau \geq T\}$ , for all  $f$  in  $\mathcal{S}$ ,  $D_T^2(f) \leq R^2 \|f\|^2$ , this implies that

$$C_{m'} \leq (\eta + HN) R^2 \frac{|m'| + 1}{T}.$$

Using  $\ell_0$ , one has that  $b^2 = (1 + \mathcal{N}^2/\ell_0)/T^2$  works. Finally, on  $\mathcal{B}$ , with probability larger than  $1 - 2\#\{\mathcal{M}_T\}e^{-x}$ ,

$$W_{\hat{m}} \leq \sqrt{(\eta + HN)R^2 \frac{|\hat{m}| + 1}{T} (1 + 3\sqrt{2x})} + \frac{\sqrt{1 + \mathcal{N}^2/\ell_0}}{T}x. \quad (8.9)$$

Let us go back to  $A_1$ : for all  $\theta > 0$ , we obtain the following upper bound

$$A_1 \leq \theta \|\tilde{s} - s_{\hat{m}}\|^2 + \frac{1}{\theta} \left[ (1 + \varepsilon)(\eta + HN)R^2 \frac{|\hat{m}| + 1}{T} (1 + 3\sqrt{2x})^2 + (1 + \varepsilon^{-1}) \frac{1 + \mathcal{N}^2/\ell_0}{T^2} x^2 \right], \quad (8.10)$$

inequality which holds on  $\mathcal{B}$  with probability larger than  $1 - 2\#\{\mathcal{M}_T\}e^{-x}$ .

2. Let us control now  $A_2 = 2\nu_T(s_{\hat{m}} - s_m)$ . To do so, we need to control all the  $V_{m'} = \nu_T(s_{m'} - s_m)$ . But on  $\mathcal{B}$ ,  $V_{m'} = U_{m'}$  where

$$U_{m'} = \frac{1}{T} \int_0^T \mathbb{1}_{t \leq \tau} \Psi_{s_{m'} - s_m}(t) (dN_t - \Psi_s(t)dt).$$

So one can use Corollary 1 of [16]: with probability larger than  $1 - e^{-x}$ ,

$$U_{m'} \leq \sqrt{2vx} + \frac{b}{3}x,$$

where  $v$  and  $b$  are constants such that for all  $t \leq T$ ,

$$v \geq \frac{1}{T^2} \int_0^T \mathbb{1}_{t \leq \tau} \Psi_{s_{m'} - s_m}(t)^2 \Psi_s(t) dt \quad \text{and} \quad b \geq \mathbb{1}_{t \leq \tau} \frac{1}{T} |\Psi_{(s_{m'} - s_m)}(t)|.$$

As we stop all the processes in  $\tau$ , we obtain that the following choices work:

$$v = \frac{(\eta + HN)R^2}{T} \|s_{m'} - s_m\|^2 \quad \text{and} \quad b = \frac{2HN}{T},$$

since the infinite norm of  $s_m$  is also bounded by  $H$ .

Consequently, on  $\mathcal{B}$  with probability larger than  $1 - \#\{\mathcal{M}_T\}e^{-x}$

$$\nu_T(s_{\hat{m}} - s_m) \leq \|s_{\hat{m}} - s_m\| \sqrt{2 \frac{(\eta + HN)R^2}{T} x} + \frac{2HN}{3T} x. \quad (8.11)$$

But  $\|s_{\hat{m}} - s_m\| \leq \|s_{\hat{m}} - s\| + \|s - s_m\|$ . Thus

$$\begin{aligned} A_2 &\leq 2\|s_{\hat{m}} - s\| \sqrt{2 \frac{(\eta + HN)R^2}{T} x} + 2\|s - s_m\| \sqrt{2 \frac{(\eta + HN)R^2}{T} x} + \frac{2HN}{3T} x \\ &\leq \theta \|s_{\hat{m}} - s\|^2 + \theta \|s_m - s\|^2 + \frac{4}{\theta} \frac{(\eta + HN)R^2}{T} x + \frac{2HN}{3T} x \\ &\leq \theta \|s_{\hat{m}} - s\|^2 + \theta \|s_m - s\|^2 + \left( \frac{4}{\theta} + \frac{2}{3R^2} \right) \frac{(\eta + HN)R^2}{T} x. \end{aligned} \quad (8.12)$$

Now let us go back to (8.6). Using (8.10) and (8.12), we obtain on  $\mathcal{B}$  with probability larger than  $1 - 3\#\{\mathcal{M}_T\}e^{-x}$  that

$$\begin{aligned} D_T^2(\tilde{s} - s) &\leq D_T^2(s_m - s) + \theta[\|\tilde{s} - s_{\hat{m}}\|^2 + \|s_{\hat{m}} - s\|^2] + \theta\|s - s_m\|^2 + \\ &+ \frac{1}{\theta} \left[ (1 + \varepsilon)(\eta + HN)R^2 \frac{|\hat{m}| + 1}{T} \left(1 + 3\sqrt{2x}\right)^2 + (1 + \varepsilon^{-1}) \frac{1 + \mathcal{N}^2/\ell_0}{T^2} x^2 \right] + \\ &+ \left( \frac{4}{\theta} + \frac{2}{3R^2} \right) \frac{(\eta + HN)R^2}{T} x + \text{pen}(m) - \text{pen}(\hat{m}). \end{aligned}$$

But on  $\mathcal{B}$ , one has  $D_T^2(f) \geq r^2\|f\|^2$ . Moreover  $s_{\hat{m}}$  is the orthogonal projection of  $s$  on  $S_{\hat{m}}$  for  $\|\cdot\|$ . Consequently

$$\begin{aligned} (r^2 - \theta)\|\tilde{s} - s\|^2 &\leq (R^2 + \theta)\|s - s_m\|^2 + \frac{(1 + \varepsilon)}{\theta} (\eta + HN)R^2 \frac{|\hat{m}| + 1}{T} \left(1 + 3\sqrt{2x}\right)^2 + \text{pen}(m) - \text{pen}(\hat{m}) \\ &+ \left( \frac{4}{\theta} + \frac{2}{3R^2} \right) \frac{(\eta + HN)R^2}{T} x + \frac{(1 + \varepsilon^{-1})}{\theta} \frac{1 + \mathcal{N}^2/\ell_0}{T^2} x^2. \end{aligned}$$

Choosing  $\theta = r^2/(1 + \varepsilon)$  leads to the result. ■

### 8.3 Proof of Proposition 5

**Proof.** Through this proof, the value of  $T_0$  will change from line to line but the dependency in the parameter is clearly written. We keep the notations of the previous proof. First let us introduce

$$\mathcal{B}_0 = \left\{ \forall t \in [0, T], \quad N([t - A, t]) \leq \mathcal{N} \right\}, \quad (8.13)$$

and

$$\mathcal{B}_1 = \left\{ \forall f \in \mathcal{S}, \quad r^2\|f\|^2 \leq D_T^2(f) \leq R^2\|f\|^2 \right\}. \quad (8.14)$$

Then  $\mathbb{P}(\mathcal{B}^c) \leq \mathbb{P}(\mathcal{B}_0^c) + \mathbb{P}(\mathcal{B}_1^c \cap \mathcal{B}_0)$ .

- First let us control  $\mathcal{B}_0^c$ . Let

$$\mathcal{B}'_0 = \left\{ \forall k \in \left\{ 0, \dots, \left\lfloor \frac{T}{A} \right\rfloor + 1 \right\}, \quad N([(k-1)A, kA]) \leq \frac{\mathcal{N}}{2} \right\},$$

where  $\lfloor x \rfloor$  denotes the largest integer smaller than  $x$ . Then  $\mathcal{B}'_0 \subset \mathcal{B}_0$  and  $\mathbb{P}(\mathcal{B}_0^c) \leq \mathbb{P}(\mathcal{B}'_0^c)$ . But by stationnarity,

$$\mathbb{P}(\mathcal{B}'_0^c) \leq \left( \left\lfloor \frac{T}{A} \right\rfloor + 2 \right) \mathbb{P} \left( N([-A, 0]) \geq \frac{\mathcal{N}}{2} \right).$$

Proposition 2.1 of [17] tells us how to control the deviation of the number of points per interval of fixed length (here  $A$ ). Hence there exists a positive increasing function in  $p$  (see (2.1)), namely  $m_p(z)$ , such that

$$\mathbb{P}\left(N([-A, 0]) \geq \frac{\mathcal{N}}{2}\right) \leq e^{-\frac{\mathcal{N}z}{2}} e^{\nu A m_p(z)}, \quad (8.15)$$

for all  $z \leq p - \log p - 1$ . In particular one can take  $z = P - \log P - 1$  and replace  $m_p(z)$  by  $m_P(z)$  in (8.15). With  $\mathcal{N}$  as in the proposition, one gets that

$$\mathbb{P}(\mathcal{B}_0^c) \leq \frac{\square_{\eta, A, P}}{T^2}.$$

- Now let us control  $\mathbb{P}(\mathcal{B}_1^c \cap \mathcal{B}_0)$ . Let us introduce

$$\mathcal{B}'_1 = \left\{ \forall I \in \Gamma, \left| \frac{1}{T} \int_0^T [N_I(t) - \mathbb{E}(N_I(t))] dt \right| \leq x_I \right\}, \quad (8.16)$$

and

$$\mathcal{B}''_1 = \left\{ \forall (I, I') \in \Gamma^2, \left| \frac{1}{T} \int_0^T [N_I(t)N_{I'}(t) - \mathbb{E}(N_I(t)N_{I'}(t))] dt \right| \leq x_{I, I'} \right\}, \quad (8.17)$$

where  $N_I(t) = \Psi_{(0, \mathbb{1}_I)}(t)$  and where the  $x_I$ 's and  $x_{I, I'}$ 's are positive numbers that will be chosen later. The control of these events is based on the following lemma which is a direct consequence of Case 3 of Proposition 3.3 of [17].

**Lemma 4.** *Let  $g$  be a function of the points of  $(N_t)_{t \in \mathbb{R}}$  lying in  $[-A, 0)$  with values in  $[-B, B]$ . Let  $(\theta_t)_{t \in \mathbb{R}}$  be the flow induced by  $(N_t)_{t \in \mathbb{R}}$  i.e.  $g \circ \theta_t$  is the same function as before, but now the points are lying in  $[-A + t, t)$ . Then there exists a positive constant  $T_0(P, A)$  such that for all  $T \geq T_0(P, A)$*

$$\mathbb{P}\left(\left| \frac{1}{T} \int_0^T g \circ \theta_t dt \right| \geq |\mathbb{E}g| + 2\sqrt{\frac{c_1 \text{Var}(g) A \log(T)^2}{T(P - \log P - 1)}} + \frac{c_2 B A \log(T)^2}{T(P - \log P - 1)}\right) \leq \frac{\square_{\eta, P}}{T^3},$$

where  $c_1$  and  $c_2$  are absolute constants.

First, let us control  $\mathbb{P}(\mathcal{B}'_1^c \cap \mathcal{B}_0)$  by applying the previous lemma to

$$g = \min(N_I, \mathcal{N}) - \mathbb{E}(N_I).$$

As  $\mathbb{E}(N_I) = \nu \ell(I)(1 - p)^{-1}$ , there exists  $T_0(\eta, p, A)$  such that for all  $T \geq T_0$ ,

$$\mathbb{E}(N_I) \leq \mathcal{N}.$$

Thus  $B = \mathcal{N}$  works in Lemma 4 as soon as  $T$  is large enough. Moreover

$$\text{Var}(g) \leq \mathcal{N} \mathbb{E}(N_I).$$

Finally, by stationnarity,

$$|\mathbb{E}(g)| \leq \mathbb{E}(N_I \mathbb{1}_{N_I \geq \mathcal{N}}) = \mathbb{E}(N_I(0) \mathbb{1}_{N_I(0) \geq \mathcal{N}}).$$

If  $\mathcal{B}_0''$  denotes  $\{N([-A, 0]) \leq \mathcal{N}\}$ , then

$$|\mathbb{E}(g)| \leq \mathbb{E}(N_I(0) \mathbb{1}_{\mathcal{B}_0''^c}).$$

Consequently, we set for all  $\delta > 0$

$$x_I = \mathbb{E}(N_I(0) \mathbb{1}_{\mathcal{B}_0''^c}) + \delta \mathbb{E}(N_I) + \left[ \frac{c_1 \mathcal{N}}{\delta} + c_2 \mathcal{N} \right] \frac{A \log(T)^2}{T(P - \log P - 1)}.$$

By Lemma 4, one has then that

$$\mathbb{P}(\mathcal{B}_1'^c \cap \mathcal{B}_0) \leq |\Gamma| \frac{\square_{\eta, P}}{T^3} \leq \square_{\eta, P} \frac{1}{T^2 \sqrt{T}}.$$

Now, let us control  $\mathbb{P}(\mathcal{B}_1''^c \cap \mathcal{B}_0)$  by applying Lemma 4 to

$$g = \min(N_I N_{I'}, \mathcal{N}^2) - \mathbb{E}(N_I N_{I'}).$$

First remark that

$$\mathbb{E}(N_I N_{I'}) \leq \mathbb{E}(N([-A, 0])^2).$$

Let us apply Lemma 1, then

$$\mathbb{E}(N_I N_{I'}) \leq \mathbb{E}(N([-A, 0])^2) \leq \frac{\nu^2 A^2}{(1-p)^2} + \frac{\nu A}{(1-p)^3} \leq \frac{\eta^2 A^2}{(1-P)^2} + \frac{\eta A}{(1-P)^3}.$$

So there exists  $T_0(\eta, P, A)$  such that for all  $T \geq T_0$ ,  $\mathbb{E}(N_I N_{I'}) \leq \mathcal{N}^2$ . Thus  $B = \mathcal{N}^2$  works in Lemma 4 as soon as  $T$  is large enough. Moreover

$$\text{Var}(g) \leq \mathcal{N}^2 \mathbb{E}(N_I N_{I'}).$$

Finally

$$\begin{aligned} |\mathbb{E}(g)| &\leq \mathbb{E}(N_I(0) N_{I'}(0) \mathbb{1}_{N_I(0) N_{I'}(0) \geq \mathcal{N}^2}) \\ &\leq \mathbb{E}(N_I(0) N_{I'}(0) \mathbb{1}_{\{N_I(0) \geq \mathcal{N} \text{ or } N_{I'}(0) \geq \mathcal{N}\}}) \leq \mathbb{E}(N_I(0) N_{I'}(0) \mathbb{1}_{\mathcal{B}_0''^c}). \end{aligned}$$

Consequently

$$x_{I, I'} = \mathbb{E}(N_I(0) N_{I'}(0) \mathbb{1}_{\mathcal{B}_0''^c}) + \delta \mathbb{E}(N_I N_{I'}) + \left[ \frac{c_1 \mathcal{N}^2}{\delta} + c_2 \mathcal{N}^2 \right] \frac{A \log(T)^2}{T(P - \log P - 1)},$$

gives for  $T \geq T_0(\eta, P, A)$

$$\mathbb{P}(\mathcal{B}_1''^c \cap \mathcal{B}_0) \leq |\Gamma|^2 \frac{\square_{\eta, P}}{T^3} \leq \square_{\eta, P} \frac{1}{T^2}.$$

Finally we proved that

$$\mathbb{P}((\mathcal{B}_1'' \cap \mathcal{B}_1')^c \cap \mathcal{B}_0) \leq \square_{\eta, P} \frac{1}{T^2}.$$

- Now it remains to prove that for  $T$  large enough,  $\mathcal{B}_1'' \cap \mathcal{B}_1' \subset \mathcal{B}_1$ . Let  $f \in \mathcal{S} = S_\Gamma$ ,  $f \neq 0$ . Then we can write  $f = (\mu, g)$  where

$$g = \sum_{I \in \Gamma} \frac{a_I}{\sqrt{\ell(I)}} \mathbb{1}_I.$$

Doing the same kind of development as in the proof of Lemma 1, one has

$$D_T^2(f) - \|f\|_D^2 = 2\mu \left[ \frac{1}{T} \int_0^T [\Psi_{(0, g)}(t) - \mathbb{E}(\Psi_{(0, g)}(t))] dt \right] + \frac{1}{T} \int_0^T [\Psi_{(0, g)}(t)^2 - \mathbb{E}(\Psi_{(0, g)}(t)^2)] dt.$$

So one has

$$\begin{aligned} |D_T^2(f) - \|f\|_D^2| &\leq 2|\mu| \sum_{I \in \Gamma} \frac{|a_I|}{\sqrt{\ell(I)}} \left| \frac{1}{T} \int_0^T (N_I(t) - \mathbb{E}(N_I)) dt \right| + \\ &+ \sum_{I, I' \in \Gamma} \frac{|a_I|}{\sqrt{\ell(I)}} \frac{|a_{I'}|}{\sqrt{\ell(I')}} \left| \frac{1}{T} \int_0^T (N_I(t)N_{I'}(t) - \mathbb{E}(N_I N_{I'})) dt \right|. \end{aligned}$$

On  $\mathcal{B}_1'' \cap \mathcal{B}_1'$  this gives

$$|D_T^2(f) - \|f\|_D^2| \leq 2|\mu| \sum_{I \in \Gamma} \frac{|a_I|}{\sqrt{\ell(I)}} x_I + \sum_{I, I' \in \Gamma} \frac{|a_I|}{\sqrt{\ell(I)}} \frac{|a_{I'}|}{\sqrt{\ell(I')}} x_{I, I'}.$$

Let us introduce

$$g_+ = \sum_{I \in \Gamma} \frac{|a_I|}{\sqrt{\ell(I)}} \mathbb{1}_I.$$

Then for  $T \geq T_0(\eta, P, A)$

$$|D_T^2(f) - \|f\|_D^2| \leq M_1 + M_2 + M_3,$$

where

$$\begin{aligned} M_1 &= 2|\mu| \delta \mathbb{E}(\Psi_{(0, g_+)}(0)) + \delta \mathbb{E}(\Psi_{(0, g_+)}(0)^2), \\ M_2 &= 2|\mu| \mathbb{E}(\Psi_{(0, g_+)}(0) \mathbb{1}_{\mathcal{B}_0''^c}) + \mathbb{E}(\Psi_{(0, g_+)}(0)^2 \mathbb{1}_{\mathcal{B}_0''^c}), \end{aligned}$$

and

$$M_3 = \left( \sum_{I \in \Gamma} \frac{2|\mu||a_I|}{\sqrt{\ell(I)}} \left[ \frac{c_1 \mathcal{N}}{\delta} + c_2 \mathcal{N} \right] + \sum_{I, I' \in \Gamma} \frac{|a_I|}{\sqrt{\ell(I)}} \frac{|a_{I'}|}{\sqrt{\ell(I')}} \left[ \frac{c_1 \mathcal{N}^2}{\delta} + c_2 \mathcal{N}^2 \right] \right) \frac{A \log(T)^2}{T(P - \log P - 1)}.$$

First let us remark that  $2|\mu|\mathbb{E}(\Psi_{(0, g_+)}(0)) + \mathbb{E}(\Psi_{(0, g_+)}(0)^2) = \|(|\mu|, g_+)\|_D^2 - \mu^2$ . By Lemma 3, this is less than

$$K^2 \|(|\mu|, g_+)\|^2 \leq 2 \max \left( 1, \frac{\eta}{(1-P)^2} (\eta A + (1-P)^{-1}) \right) \|f\|^2.$$

Let us take  $\delta = (\log T)^{-1}$ . This gives

$$M_1 \leq \square_{\eta, P, A} \frac{\|f\|^2}{\log T}.$$

Next remark also that

$$\Psi_{(0, g_+)}(0) \leq N([-A, 0]) \sup_{I \in \Gamma} \frac{|a_I|}{\sqrt{\ell(I)}}.$$

But integrating (8.15), one obtains that

$$\mathbb{E}(N([-A, 0])^2 \mathbb{1}_{\mathcal{B}_0^{c'}}) \leq \square_{\eta, P, A} \frac{\log T}{T^4} \quad \text{and} \quad \mathbb{E}(N([-A, 0]) \mathbb{1}_{\mathcal{B}_0^{c'}}) \leq \square_{\eta, P, A} \frac{1}{T^4}.$$

Keeping in mind that  $\ell(I) = A/|\Gamma|$  it remains

$$M_2 \leq \square_{\eta, P, A} \frac{\|f\|^2}{T^3}.$$

Finally

$$M_3 \leq \square_{\eta, P, A} |\Gamma|^2 \delta \mathcal{N}^2 \frac{(\log T)^2}{T} \|f\|^2 = \square_{\eta, P, A} \frac{\|f\|^2}{\log T}.$$

Hence we obtain that for  $T > T_0(A, \eta, P)$

$$|D_T^2(f) - \|f\|_D^2| \leq \square_{\eta, P, A} \frac{\|f\|^2}{\log T}.$$

Using Lemma 3, this gives

$$L^2 - \frac{\square_{\eta, P, A}}{\log T} \leq \frac{D_T^2(f)}{\|f\|^2} \leq K^2 + \frac{\square_{\eta, P, A}}{\log T}.$$

The assumptions on  $R^2$  and  $r^2$  imply that for  $T \geq T_0(A, \eta, P, \rho, R^2, r^2)$

$$r^2 \leq L^2 - \frac{\square_{\eta, P, A}}{\log T} \leq \frac{D_T^2(f)}{\|f\|^2} \leq K^2 + \frac{\square_{\eta, P, A}}{\log T} \leq R^2.$$

This gives that  $\mathcal{B}'_1 \cap \mathcal{B}''_1 \subset \mathcal{B}_1$  and this concludes the proof.

■

**Proof.[Proposition 1]** We apply Theorem 2 to a family that is reduced to only one model  $m$ . If the inequality is true for the non truncated estimator and if we know the bounds on  $s$  then the inequality is necessarily true for the truncated estimator, which is closer to  $s$  than  $\tilde{s}$ . Then the penalty is not needed to compute the estimator but it appears nevertheless in the oracle inequality. Next we integrate the inequality in  $x$ , in order to derive an oracle inequality in expectation on  $\mathcal{B}$ . The choices of the parameters in Proposition 5 allows us to control the probability of  $\mathcal{B}^c$  and we can bound  $\|s - \bar{s}_m\|^2$  by  $\eta^2 + H^2A$  on  $\mathcal{B}^c$ . ■

**Proof.[Theorem 1]** We apply Theorem 2 to  $\tilde{s}$ . Since  $\bar{s}$  is closer to  $s$  than  $\tilde{s}$ , the inequality is also true for  $\bar{s}$ . We choose  $x = Q \log(T)$  and  $\mathcal{N}, R, r$  according to Proposition 5. Then on the intersection of  $\mathcal{B}$  and the event of probability  $1 - 3\#\{\mathcal{M}_T\}e^{-x}$ , the upper bound for the expectation is true. On the complementary we bound  $\|\bar{s} - s\|$  by  $\eta^2 + H^2A$  and the probability of the complementary of the event by

$$\square_{\eta, P, A, \rho, H} \left( \frac{1}{T^2} + \frac{\#\{\mathcal{M}_T\}}{T^Q} \right)$$

■

## 8.4 Proof of Propositions 2, 3 and 4

We first need two important lemmas.

**Lemma 5.** *Let  $f = (\mu, g)$  and  $s = (\nu, h)$  be two elements of  $\mathbb{L}^2$  such that  $\mu, \nu > 0$ ,  $g, h \geq 0$ ,  $\int g < 1$  and  $\int h < 1$ . Let  $\mathbb{P}_f^{[-A, T]}$ , respectively  $\mathbb{P}_s^{[-A, T]}$ , be the distribution of a stationnary Hawkes process with intensity  $\Psi_f(\cdot)$ , respectively  $\Psi_s(\cdot)$ , restricted to  $[-A, T]$ . Then the Kullback-Leibler distance satisfies*

$$\mathbb{K}(\mathbb{P}_f^{[-A, T]}, \mathbb{P}_s^{[-A, T]}) = \mathbb{E}_f \left( \int_0^T \phi \left[ \log \left( \frac{\Psi_s(t)}{\Psi_f(t)} \right) \right] \Psi_f(t) dt \right) + \mathbb{K}(\mathbb{P}_f^{[-A, 0]}, \mathbb{P}_s^{[-A, 0]}),$$

where  $\phi(u) = e^u - u - 1$  and  $\mathbb{E}_f$  represents the expectation with respect to  $\mathbb{P}_f^{[-A, T]}$ . Moreover if  $f$  and  $s$  belong to  $\mathcal{L}_{H, P}^{\eta, \rho}$  and if  $A\|h\|_\infty \leq P - \log P - 1$ , then

$$\mathbb{K}(\mathbb{P}_f^{[-A, T]}, \mathbb{P}_s^{[-A, T]}) \leq TC_1 \|f - s\|^2 + C_2,$$

where  $C_1$  and  $C_2$  are positive constants depending only on  $A, H, P, \eta, \rho$ .

**Proof.** Let us denote by  $\mathbb{P}_f^{[0,T]}|_{[-A,0]}$  the conditional distribution of the points of the process lying in  $[0, T]$  conditionnally to the family of points lying in  $[-A, 0]$ . Then the classical decomposition of the Kullback-Leibler distance with respect to the marginals gives the following decomposition.

$$\mathbb{K}(\mathbb{P}_f^{[-A,T]}, \mathbb{P}_s^{[-A,T]}) = \mathbb{E}_f \left[ \ln \frac{d\mathbb{P}_f^{[0,T]}|_{[-A,0]}}{d\mathbb{P}_s^{[0,T]}|_{[-A,0]}} \right] + \mathbb{K}(\mathbb{P}_f^{[-A,0]}, \mathbb{P}_s^{[-A,0]}).$$

Next we combine Example 7.2(b) with Proposition 7.2.III of [7] to obtain that the conditional likelihood ratio is

$$\frac{d\mathbb{P}_f^{[0,T]}|_{[-A,0]}}{d\mathbb{P}_s^{[0,T]}|_{[-A,0]}} = \exp \left( \int_0^T \ln [\Psi_f(t)/\Psi_s(t)] dN_t - \int_0^T \Psi_f(t) dt + \int_0^T \Psi_s(t) dt \right).$$

Using the martingale properties and the fact that the intensity is predictable, one gets the first equation of Lemma 5. Now to upper bound the Kullback-Leibler distance, we need first to remark that  $\forall x > -1, \log(1+x) \geq x/(1+x)$  which gives that

$$\mathbb{E}_f \left( \int_0^T \phi \left[ \log \left( \frac{\Psi_s(t)}{\Psi_f(t)} \right) \right] \Psi_f(t) dt \right) \leq \mathbb{E}_f \left( \int_0^T \frac{(\Psi_s(t) - \Psi_f(t))^2}{\Psi_s(t)} dt \right) \leq \frac{T}{\rho} \|f - s\|_D^2.$$

It is important to note that here (and only here)  $\|\cdot\|_D$  is computed with respect to  $f$  and not  $s$ . Now it remains to use Lemma 3 and to upperbound the constants depending on  $f$  by constants depending on  $A, H, P, \eta, \rho$  to obtain the first part of the inequality.

Then it remains to upper bound  $\mathbb{K}(\mathbb{P}_f^{[-A,0]}, \mathbb{P}_s^{[-A,0]})$ . It is easy to see that in fact if we denote by  $N$  the process on  $[-2A, 0]$ , then  $N = N_1 \cup N_2$  where  $N_2$  is the process on  $[-2A, -A)$  and  $N_1$  is the process on  $[-A, 0]$ . Then if we denote by  $d\mathcal{P}$  the law of a homogeneous Poisson process with intensity 1 on  $[-A, 0]$ , one see that

$$d\mathbb{P}_f^{[-A,0]}(N_1) = \mathbb{E}_{f, N_2} \left[ \exp \left( \int_{-A}^0 \ln [\Psi_f(t)] dN_1(t) - \int_{-A}^0 [\Psi_f(t) - 1] d(t) \right) \right] d\mathcal{P}(N_1),$$

where  $\mathbb{E}_{f, N_2}$  means that we integrate with respect to the  $N_2$  component with the stationary law of a Hawkes process with intensity  $\Psi_f()$ . Consequently,

$$\mathbb{K}(\mathbb{P}_f^{[-A,0]}, \mathbb{P}_s^{[-A,0]}) = \mathbb{E}_{f, N_1} \left( \ln \left( \frac{\mathbb{E}_{f, N_2} \exp \left( \int_{-A}^0 \ln [\Psi_f(t)] dN_1(t) - \int_{-A}^0 \Psi_f(t) d(t) \right)}{\mathbb{E}_{s, N_2} \exp \left( \int_{-A}^0 \ln [\Psi_s(t)] dN_1(t) - \int_{-A}^0 \Psi_s(t) d(t) \right)} \right) \right).$$

So, since  $\Psi_f()$  is positive,

$$\mathbb{K}(\mathbb{P}_f^{[-A,0]}, \mathbb{P}_s^{[-A,0]}) \leq A_1 + A_2$$

with

$$A_1 = \mathbb{E}_{f, N_1} \left( \ln \mathbb{E}_{f, N_2} \left[ \exp \left( \int_{-A}^0 \ln[\Psi_f(t)] dN_1(t) \right) \right] \right)$$

and

$$A_2 = \mathbb{E}_{f, N_1} \left( \ln \mathbb{E}_{s, N_2} \left[ \exp \left( \int_{-A}^0 \Psi_s(t) dt - \int_{-A}^0 \ln \Psi_s(t) dN_1(t) \right) \right] \right).$$

For  $A_1$ , we can upper bound it on  $\mathcal{L}_{H, \rho}^{\eta, \rho}$ .

$$A_1 \leq \mathbb{E}_{f, N_1} \left( \ln \mathbb{E}_{s, N_2} \left[ (\rho + H(N_1 + N_2))^{N_1} \right] \right).$$

But for all integer  $l$  one can upper bound  $\mathbb{E}_{s, N_2} [N_2^l]$  by  $l! \mathbb{E}(\exp(zN_2))/z^l$  and we know that this is a bounded quantity by Proposition 2.1 of [17] for  $z = P - \log P - 1$ . Hence

$$\begin{aligned} \mathbb{E}_{s, N_2} \left[ (\rho + H(N_1 + N_2))^{N_1} \right] &= \sum_{l=0}^{N_1} \binom{N_1}{l} (\rho + HN_1)^{N_1-l} H^l \mathbb{E}_{s, N_2} (N_2^l) \\ &\leq \square_{A, H, \eta, \rho, P} \sum_{l=0}^{N_1} l! \binom{N_1}{l} (\rho + HN_1)^{N_1-l} (H/z)^l \\ &\leq \square_{A, H, \eta, \rho, P} N_1! (\rho + H/z + HN_1)^{N_1}. \end{aligned}$$

Hence  $A_1 \leq \square_{A, H, \eta, \rho, P} \mathbb{E}_f(N_1^2)$  and  $\mathbb{E}_f(N_1^2)$  is bounded by similar arguments. It remains to bound  $A_2$ . But

$$\begin{aligned} \mathbb{E}_{s, N_2} \left[ \exp \left( \int_{-A}^0 \Psi_s(t) dt - \int_{-A}^0 \ln \Psi_s(t) dN_1(t) \right) \right] &\leq \mathbb{E}_{s, N_2} \left[ e^{A(\rho + \|h\|_\infty(N_1 + N_2)) - \ln(\rho)N_1} \right] \\ &\leq \mathbb{E}_{s, N_2} \left[ e^{A\|h\|_\infty N_2} \right] e^{A\rho + AHN_1 - \ln(\rho)N_1}. \end{aligned}$$

So if  $A\|h\|_\infty \leq P - \log P - 1$ , Proposition 2.1 of [17] gives an upperbound for  $\mathbb{E}_{s, N_2} [e^{A\|h\|_\infty N_2}]$ , namely  $\mathbb{E}_{s, N_2} [e^{zN_2}]$  with  $z = P - \log P - 1$  which is bounded by some constant depending on  $A, H, \rho, \eta, P$ . As previously

$$A_2 \leq \square_{A, H, \eta, \rho, P} \mathbb{E}_f(N_1) \leq \square_{A, H, \eta, \rho, P} \frac{\eta A}{1 - P}.$$

This concludes the proof. ■

**Lemma 6.** *Let  $\mathcal{S}$  be a family of possible  $s$  such that  $\Psi_s(\cdot)$  is the intensity of a stationary Hawkes process, and such that  $s$  belongs to  $\mathcal{L}_{H, \rho}^{\eta, \rho}$ . Let  $\delta > 0$  and let  $\mathcal{C} \subset \mathcal{S}$  be a finite family such that for all  $f = (\mu, g) \in \mathcal{C}$ ,  $A\|g\|_\infty \leq P - \log P - 1$ . Then there exists  $\zeta_1$  and  $\zeta_2$  two particular positive functions of  $\eta, \rho, A, P, H$  such that if for all  $f \neq f'$  in  $\mathcal{C}$*

$$\frac{\zeta_1 \log |\mathcal{C}| - \zeta_2}{T} \geq \|f - f'\|^2 \geq \delta \quad \text{then} \quad \inf_{\hat{s}} \sup_{s \in \mathcal{S}} \mathbb{E}_s(\|\hat{s} - s\|^2) \geq \frac{\delta(1 - \alpha)}{4}.$$

**Proof.** First it is very classical to obtain that

$$\inf_{\hat{s}} \sup_{s \in \mathcal{S}} \mathbb{E}_s(\|\hat{s} - s\|^2) \geq \frac{1}{4} \inf_{\hat{s} \in \mathcal{C}} \sup_{s \in \mathcal{C}} \mathbb{E}_s(\|\hat{s} - s\|^2).$$

But

$$\mathbb{E}_s(\|\hat{s} - s\|^2) \geq \delta \mathbb{P}_s(\hat{s} \neq s).$$

So

$$\inf_{\hat{s}} \sup_{s \in \mathcal{S}} \mathbb{E}_s(\|\hat{s} - s\|^2) \geq \frac{\delta}{4} \inf_{\hat{s} \in \mathcal{C}} \left( 1 - \inf_{s \in \mathcal{C}} \mathbb{P}_s(\hat{s} = s) \right).$$

It remains to apply Birgé's Lemma [1], by upper bounding the mean Kullback-Leibler distance on  $\mathcal{C}$ . Using Lemma 5, it remains only to choose  $\zeta_1$  and  $\zeta_2$  according to  $\mathcal{C}_1$  and  $\mathcal{C}_2$ . This concludes the proof.  $\blacksquare$

**Proof.** It is now sufficient to apply the previous Lemma for good choices of  $\mathcal{C}$ .

**Proposition 2** Let  $m$  be a model and let  $\mathcal{P}_0$  be the maximal collection of subsets of  $m$ , such that for all  $\mathcal{I} \neq \mathcal{I}'$  in  $\mathcal{P}_0$ ,  $|\mathcal{I} \Delta \mathcal{I}'| \geq \theta |m|$ , then by [8], one has that  $\log |\mathcal{P}_0| \geq \sigma |m|$ , for  $\theta$  and  $\sigma$  some absolute constants.

Let

$$\mathcal{C}_0 = \left\{ f_{\mathcal{I}} = \left( \rho, \sum_{I \in \mathcal{I}} \frac{\varepsilon}{\sqrt{\ell(I)}} \mathbb{1}_I \right), \mathcal{I} \in \mathcal{P}_0 \right\},$$

where  $\varepsilon$  is a positive real number that will be chosen later. To ensure that  $\mathcal{C}_0 \subset \mathcal{L}_{H,P}^{\eta,\rho}$  we need that  $\varepsilon \leq \min(H, P/A) \sqrt{\ell_0}$ . Moreover to apply Lemma 6 we need that  $\varepsilon \leq (P - \log P - 1) \sqrt{\ell_0}/A$ .

Now, for all  $f_{\mathcal{I}}, f_{\mathcal{I}'}$  in  $\mathcal{C}_0$ ,

$$\|f_{\mathcal{I}} - f_{\mathcal{I}'}\|^2 = |\mathcal{I} \Delta \mathcal{I}'| \varepsilon^2 \geq \theta D \varepsilon^2.$$

Moreover

$$\|f_{\mathcal{I}} - f_{\mathcal{I}'}\|^2 \leq \varepsilon^2 D.$$

Finally taking

$$\varepsilon^2 = \min \left( \frac{(\zeta_1 D - \zeta_2) \sigma}{TD}, \ell_0 \min(H, P/A, (P - \log P - 1)/A)^2 \right),$$

and applying Lemma 6 gives the result.

**Proposition 4** Let  $\Gamma$  be a partition of  $(0, A]$  and let us concentrate first on the Islands set. Let  $\mathcal{P}_1$  be the maximal collection of subsets of  $\Gamma$  with cardinal  $D$ , such that for all  $\mathcal{I} \neq \mathcal{I}'$  in  $\mathcal{P}_1$ ,  $|\mathcal{I} \Delta \mathcal{I}'| \geq \theta D$ , then by the appendix of [15], one has that  $\log |\mathcal{P}_1| \geq \sigma D \log \frac{N}{D}$ , for  $\theta$  and  $\sigma$  some absolute constants. Let

$$\mathcal{C}_1 = \left\{ f_{\mathcal{I}} = \left( \rho, \sum_{I \in \mathcal{I}} \frac{\varepsilon}{\sqrt{\ell(I)}} \mathbb{1}_I \right), \mathcal{I} \in \mathcal{P}_1 \right\}.$$

Then the same computations as before give the result for the Islands set. But note that the set  $\mathcal{C}_1$  is also included in  $S_{\Gamma, (2D+1)}^{irr}$ . Consequently the lower bound is also valid up to some multiplicative constant for  $S_{\Gamma, (2D+1)}^{irr}$ .

**Proposition 3** For the h"olderian family, let  $\varphi$  be a positive continuous function on  $\mathbb{R}$ , null outside  $(0, A]$  and such that for all  $x, y \in \mathbb{R}$ ,  $|\varphi(x) - \varphi(y)| \leq |x - y|^a$ . Remark that a quantity that only depends on  $\varphi$  actually depends on  $A$  and  $a$ .

Let  $m$  be a regular partition of  $(0, A]$  in  $D$  pieces. Let  $\varphi_D(x) = LD^{-a}\varphi(Dx)$ . Let  $\mathcal{P}_0$  be defined as before and

$$\mathcal{C}_2 = \left\{ s_{\mathcal{I}} = \left( \rho, \sum_{I \in \mathcal{I}} \varphi_D(x - u_I) \right), \mathcal{I} \in \mathcal{P}_0 \right\},$$

where  $u_I$  is the left extremity of  $I$ . To ensure that  $\mathcal{C}_2 \subset \mathcal{L}_{H,p}^{\eta,\rho}$  and that  $\|g\|_{\infty} \leq (P - \log P - 1)/A$ , we need that  $D \geq c(A, a, H, P)L^{1/a}$ , for some positive continuous function  $c$ .

But for all  $s_{\mathcal{I}}, s_{\mathcal{I}'}$  in  $\mathcal{C}_2$ ,

$$\|s_{\mathcal{I}} - s_{\mathcal{I}'}\|^2 = |\mathcal{I} \Delta \mathcal{I}'| L^2 D^{-2a-1} \int \varphi^2 \geq \theta L^2 D^{-2a} \int \varphi^2.$$

Moreover

$$\|s_{\mathcal{I}} - s_{\mathcal{I}'}\|^2 \leq L^2 D^{-2a} \int \varphi^2.$$

But note that for  $D$  large enough  $\zeta_1 \sigma D - \zeta_2 \geq \zeta' D$  for some other constant  $\zeta'$ .

It remains to choose

$$D = \square_{H,P,A,\rho,\eta,a} \max \left[ (TL^2)^{1/(2a+1)}, L^{1/a} \right],$$

to obtain the result. ■

## 9 Conclusion

We proposed a method based on model selection principle for Hawkes' processes that is proved to be adaptive minimax with respect to certain classes of functions. The theoretical penalty cannot be used in practice but it helped us to design a method – namely the *Islands strategy* coupled with angle penalty – that seems to be really adapted to our biological problem. In particular it allows us to estimate the right range of interaction.

This work is preliminary and asks for several developments. First it is necessary to treat interaction with another type of events (for instance promoter/genes) with the *Islands strategy*. Next a test procedure should be applied to know whether the function  $h$  is really non zero. This would be equivalent to testing whether there exists an interaction or not.

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