Extending the event-weighted pulsation search to very faint gamma-ray sources

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Introduction

- Following Bickel+2008, Kerr2011 demonstrated that weighting each event by the probability that it originates from the pulsar when computing Htest improves the pulsation search sensitivity (gtlike+gtsrcprob)

- Limitation: the spectrum of very faint pulsars can not be measured
  - → it is not possible to compute the weights

- This talk presents 2 methods that overcome this limitation by exploring efficiently the pulsar spectral parameter space:
  - simple weights (without prior information)
  - model weights (full spatial and spectral information)

- The methods are tested on a sample of 144 LAT pulsars:
  - 117 (2PC) + 27 detected after 2PC (Hou+2014, Laffon+2014, Smith+2017)
  - Ephemerides provided by the Pulsar Timing Consortium

Simple weights: definition

$$w(E,\vec{\Omega}) = \frac{r_{\rm psr}(E,\vec{\Omega})}{r_{\rm psr}(E,\vec{\Omega}) + r_{\rm bkg}(E,\vec{\Omega})}$$

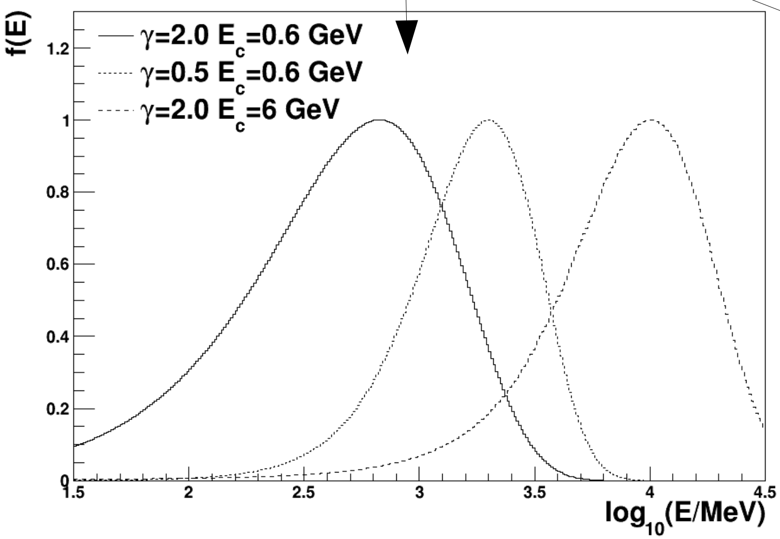
2 assumptions:
- faint pulsar
- uniform background

$$w(E,\vec{\Omega}) = r_{\rm psr}(E,\vec{\Omega})/r_{\rm bkg}(E)$$

simple rewriting to separate the direction dependent part which is derived from the PSF model:

$$w(E,\vec{\Omega}) = f(E) \times g(E,\vec{\Omega})$$

$$g(E,x) = \left(1 + \frac{9x^2}{4\sigma_{\rm psf}(E)^2}\right)^{-2}$$



$$w(E,x,\mu_w) = e^{-2(\log_{10} E - \mu_w)^2} \left(1 + \frac{9x^2}{4\sigma_{\rm psf}(E)^2}\right)^{-2}$$

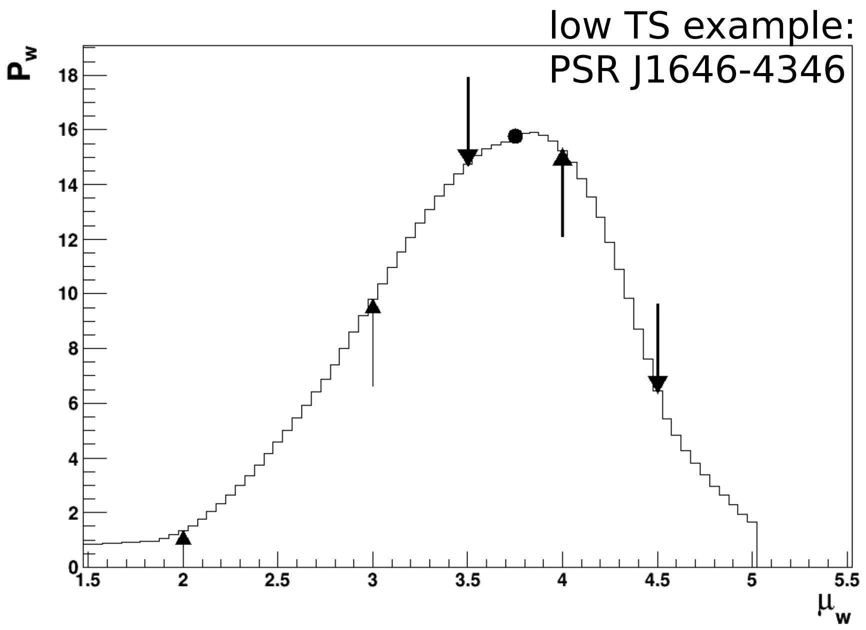
Galactic diffuse spectrum
+ pulsar PLEC spectrum
→ f(E) is gaussian-like (width~0.5)

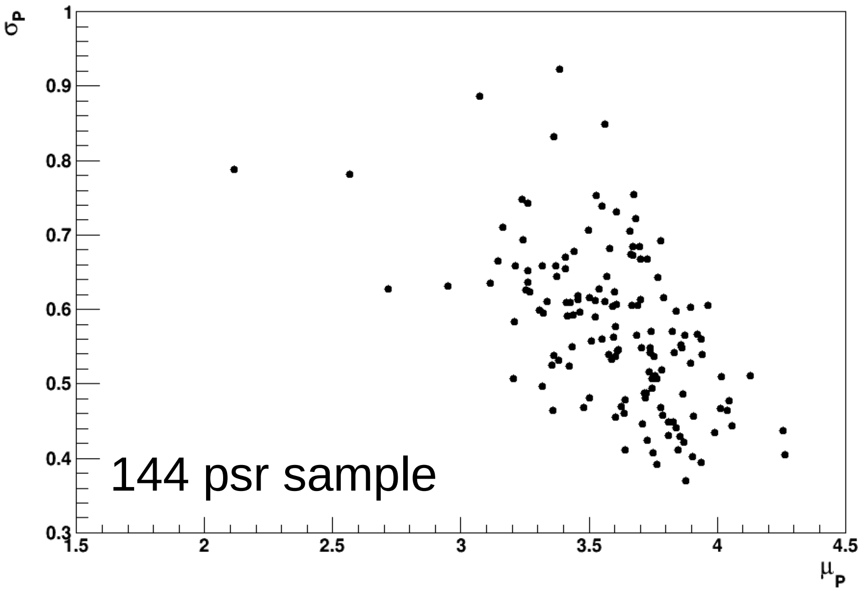
Scan over μ_w to explore the pulsar spectral parameter phase space

Simple weights: scan

- Pulsation search = find the maximum of $P_w = -\log_{10} P(x>\text{Htest})$ when varying μ_w , with the minimum number of trials

- $P_w(\mu_w)$ is gaussian-like around its maximum: $2<\mu<4.5$ and $0.3<\sigma<1$





6-trial algorithm:
- try 3 test values: 2,3,4 (↑)
- try 2 test values: max +- 0.5 (↓)
- try gaussian peak position (•) defined by the 3 previous tests
- correct for the number of trials

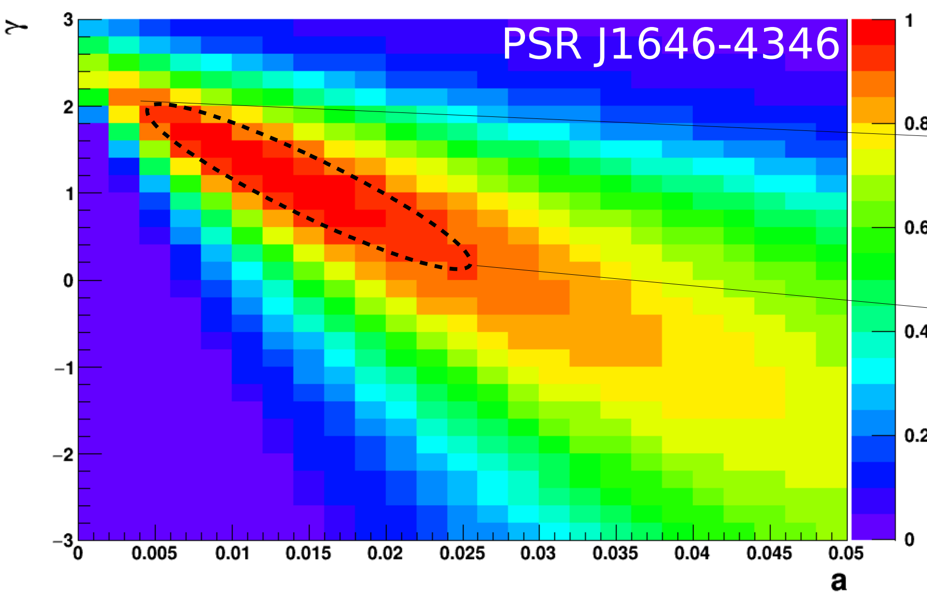
$$P_s = \max_{\mu_w \text{ scan}} P_w - \log_{10} 6$$

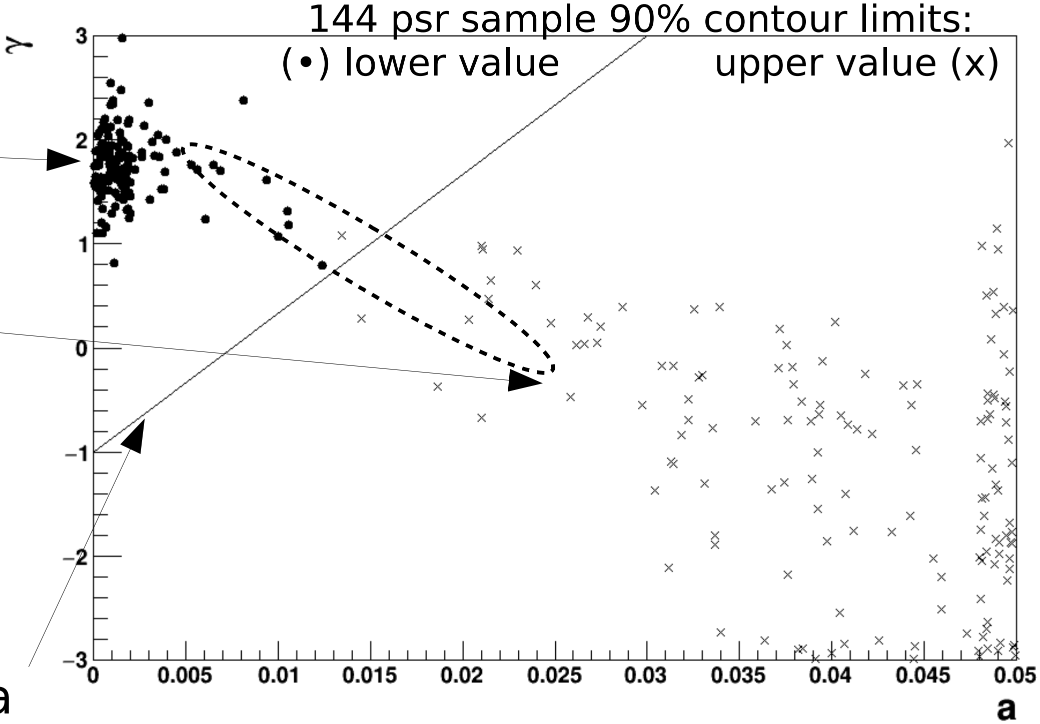
Model weights: method

- Standard binned spectral fit of the RoI centered on the pulsar (gtlike)
  - → N_{pulsar} and N_{total} maps to derive the weights
  - one set of weight maps for each PSF event type

- Explore the pulsar spectral parameter phase space $\mathrm{d}N/\mathrm{d}E \propto (E/E_0)^{\gamma} e^{a(E_0^{\beta} - E^{\beta})}$
  - (a,γ) scan: fix a and γ → spectral fit → find normalization
  - → compute the weights → compute the pulsation significance P_w

- P_w 90% contour looks like an ellipse:

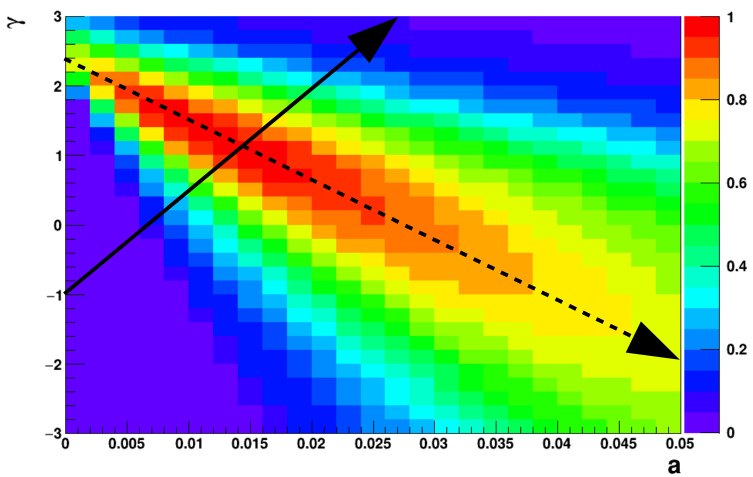


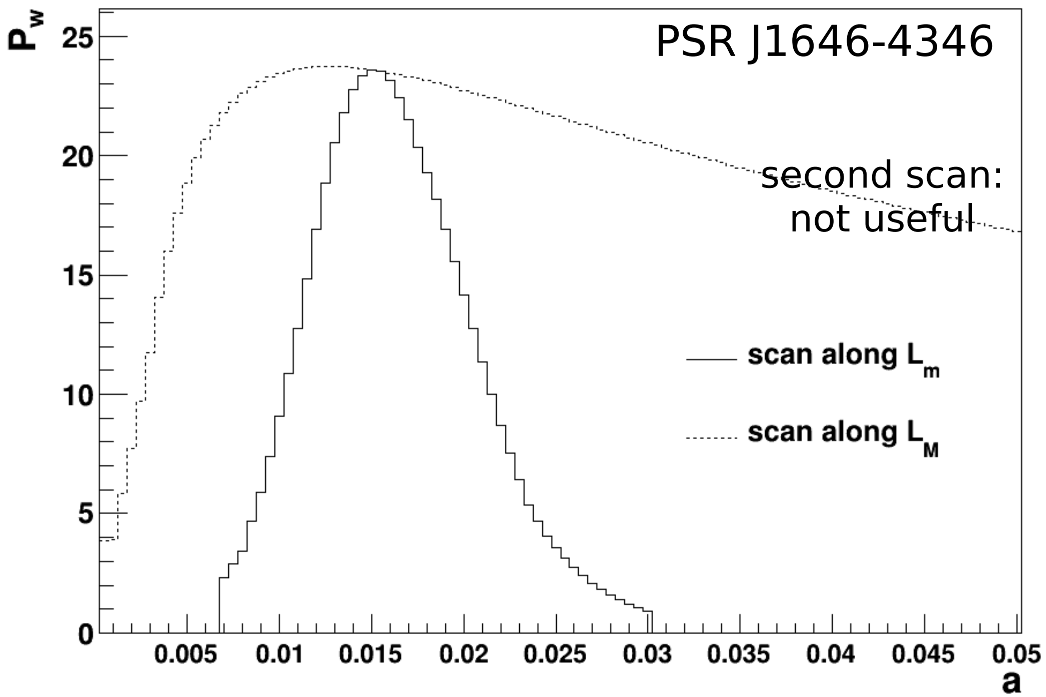


In order to cross the 90% region, one can scan along γ = -1+133.33 a

Model weights: scan

- Pulsation search:
  - find the maximum of P_w when varying a along the “minor axis”
    - around the maximum, P_w(a) is gaussian-like → 6-trial algorithm
  - scan along the major axis:
    - at least two additional trials for an average gain <5% → not useful



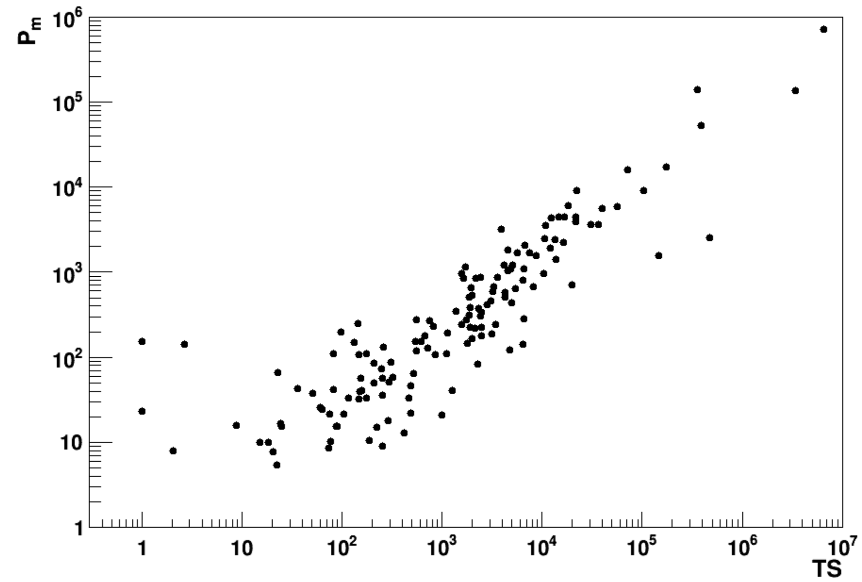


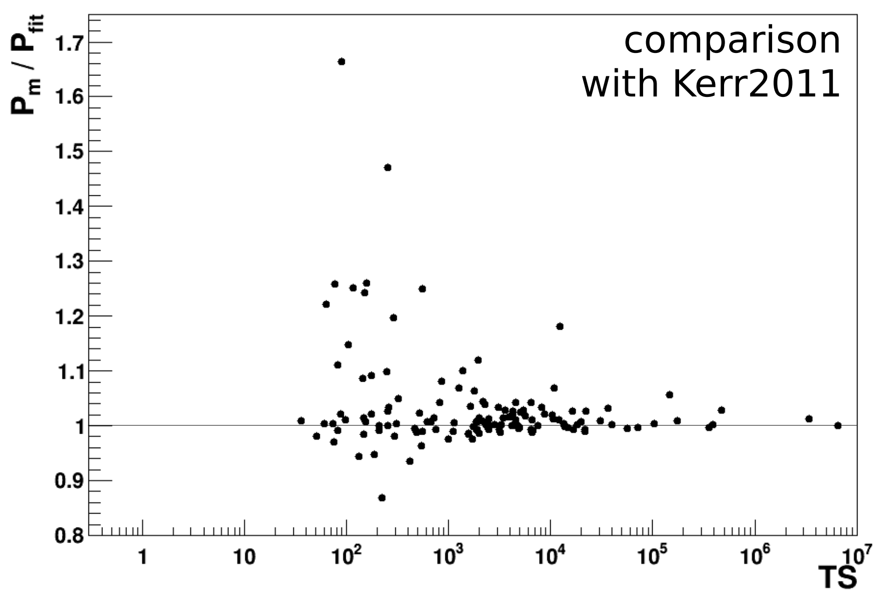
Model weights: “minor-axis” scan
with 6-trial algorithm

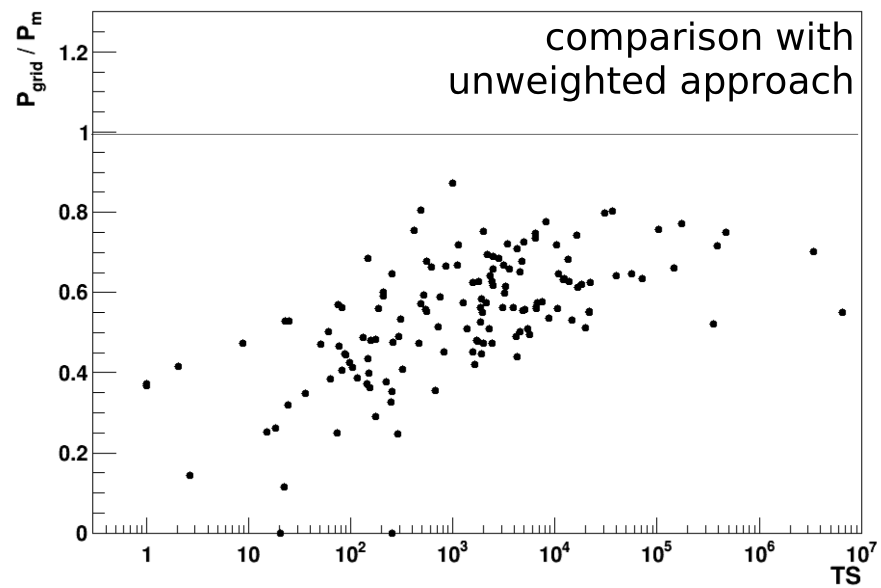
$$P_m = \max_{L_m \text{ scan}} P_w - \log_{10} 6$$

Model weights: results

- Pulsation is detected for all 144 pulsars, including 12 with TS<25
- Compared to original Kerr2011
  - same performance on average
  - >20% gain for 8 pulsars
    - likely due to off-pulse emission
- Compared to unweighted approach:
  - >2 gain for low TS pulsars

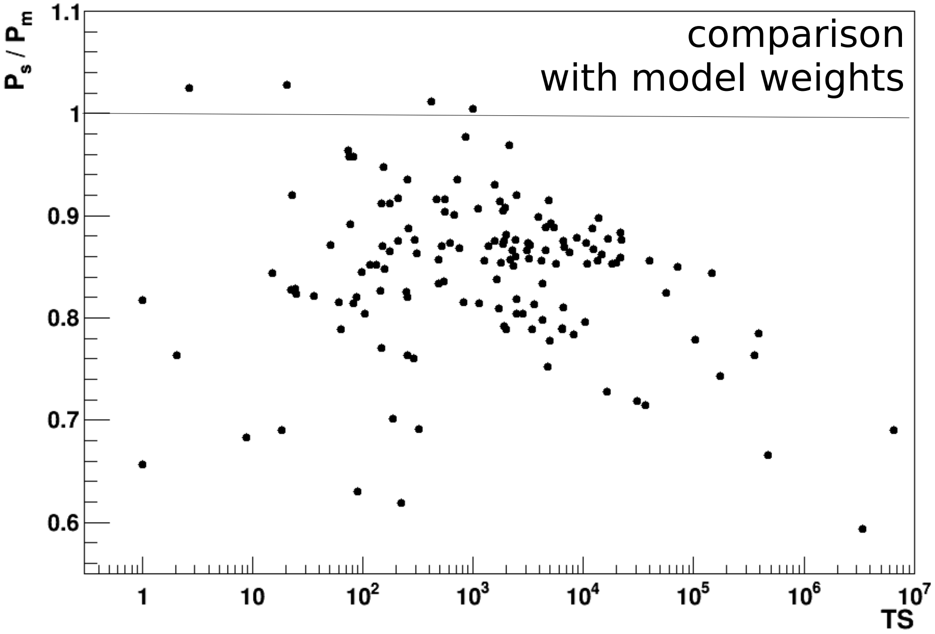


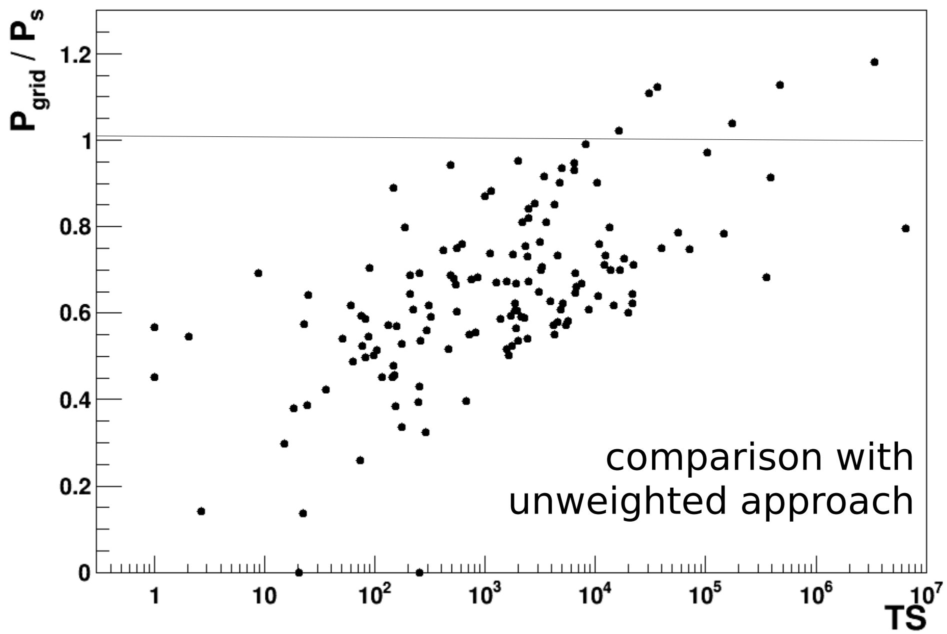




Simple weights: results

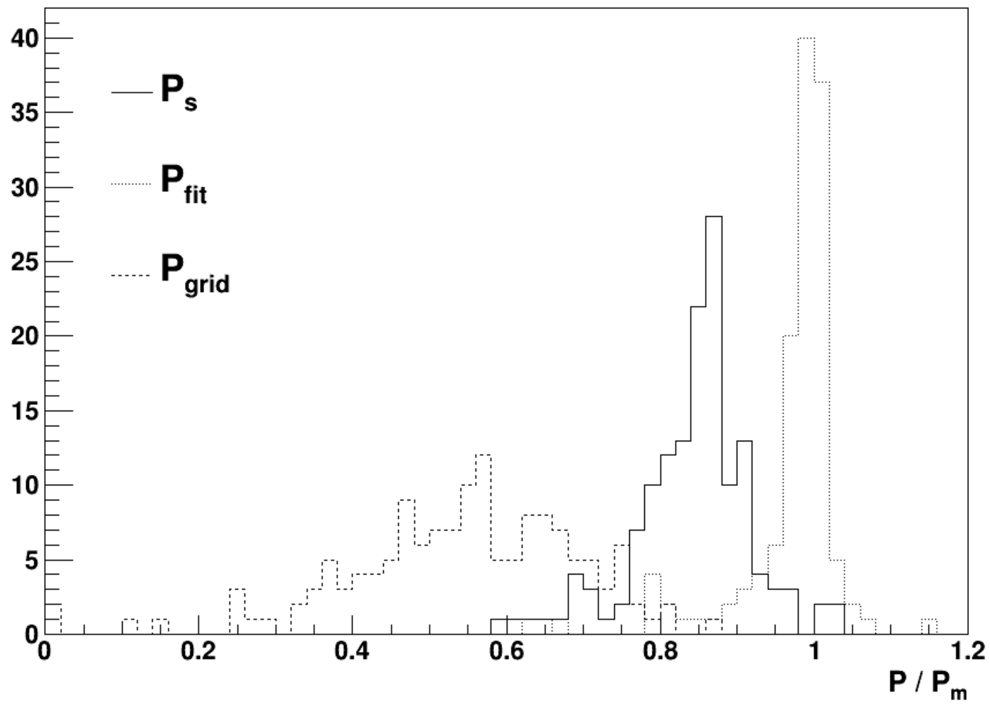
- Pulsation is detected for all 144 pulsars, including 12 with TS<25
- Less powerful than model weights
  - -15% for the bulk of pulsars, larger loss at low TS
- Compared to unweighted approach: >~1.5 gain for low TS pulsars





Conclusions

- The simple and model weight methods are both able to detect pulsation from all pulsars, including the TS<25 ones
- The model weight method has the same sensitivity as Kerr2011
  - it can do even better when off-pulse emission is present
- The simple weight method is a little less sensitive but the loss of performance is relatively small compared to the simplicity of its implementation and its rapidity of execution (no gtlike required)



Major-axis scan

- Scanning along the major axis of the 90% ellipse:
  - compared to the a-position found in the previous step, the optimal a can be either lower of higher → at least 2 additional trials
  - relative gain is modest (<10% if the first scan crosses the 90% ellipse)
  - → for ~4-sigma pulsars, the major axis scan is not useful on average

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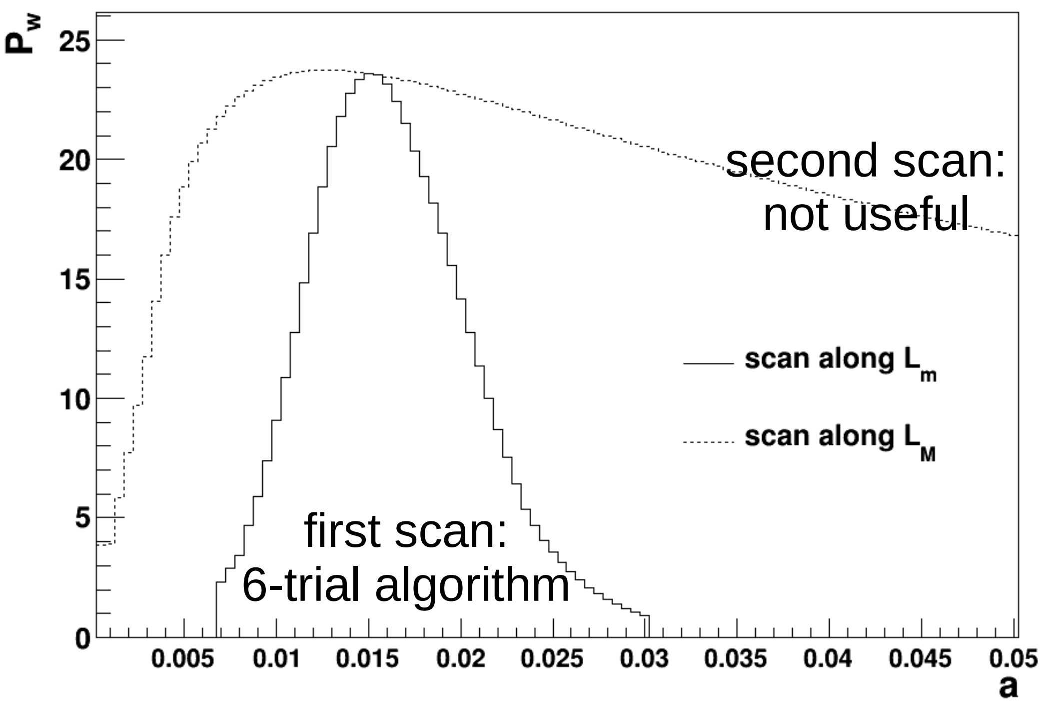
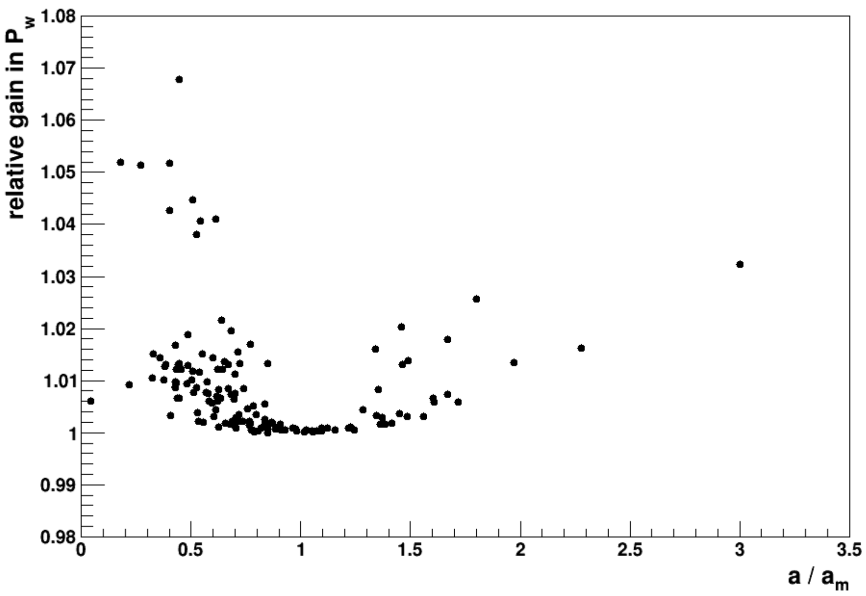


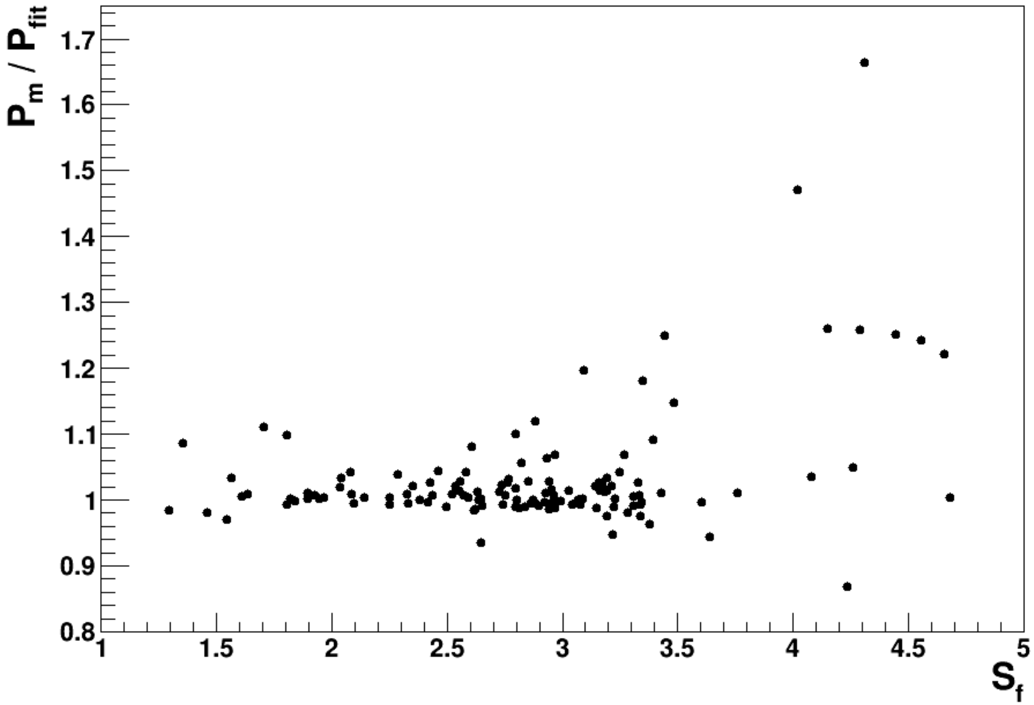


Soft-and-flat estimator

- For some TS>60 pulsars, the model weight method finds better weights than the ones obtained with the result of gtlike
- It could be explained by a significant off-pulse emission, which can have a rather soft and flat spectrum

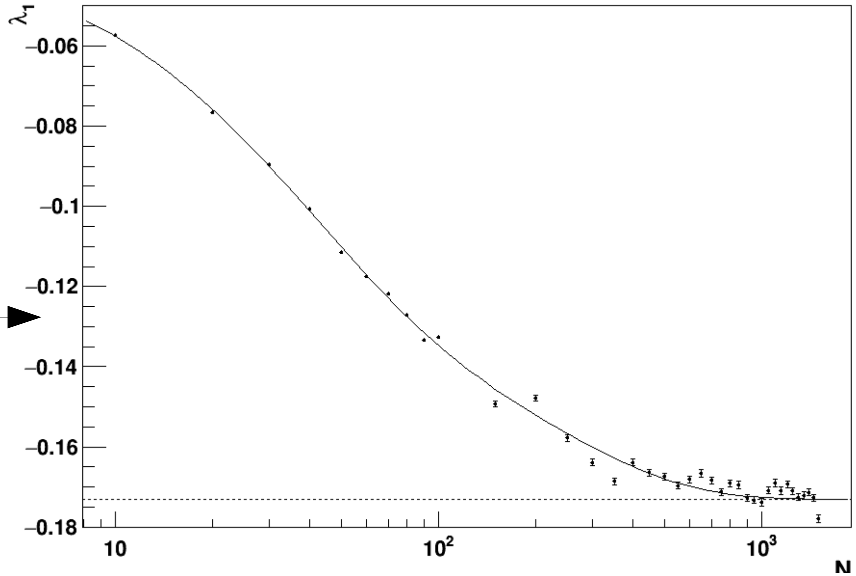
- find a soft-and-flat estimator:
  - curvature significance ? : no, it doesn't measure the curvature itself
  - we build a simple estimator:

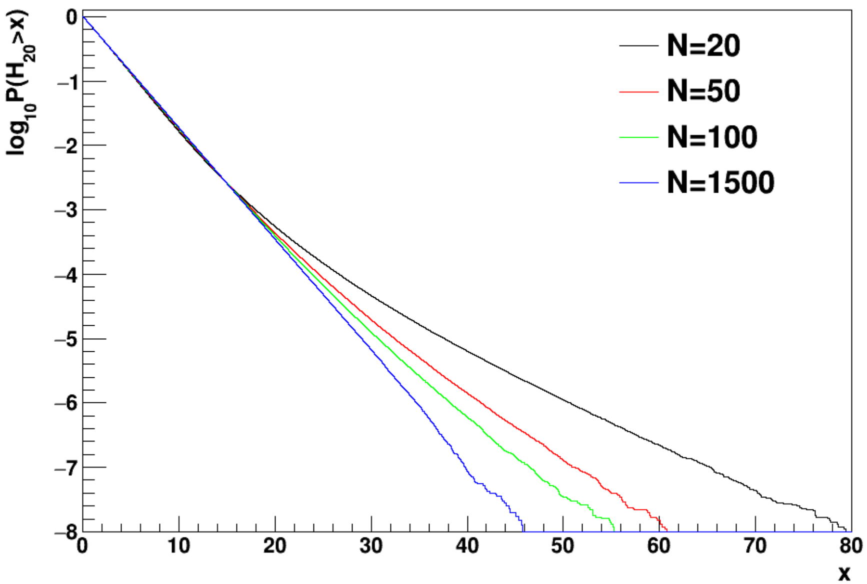
$$S = \gamma + \log_{10} E_c \longrightarrow S_f = 0.576(\gamma + \delta\gamma) + 0.817 \log_{10}(E_c + \delta E_c)$$

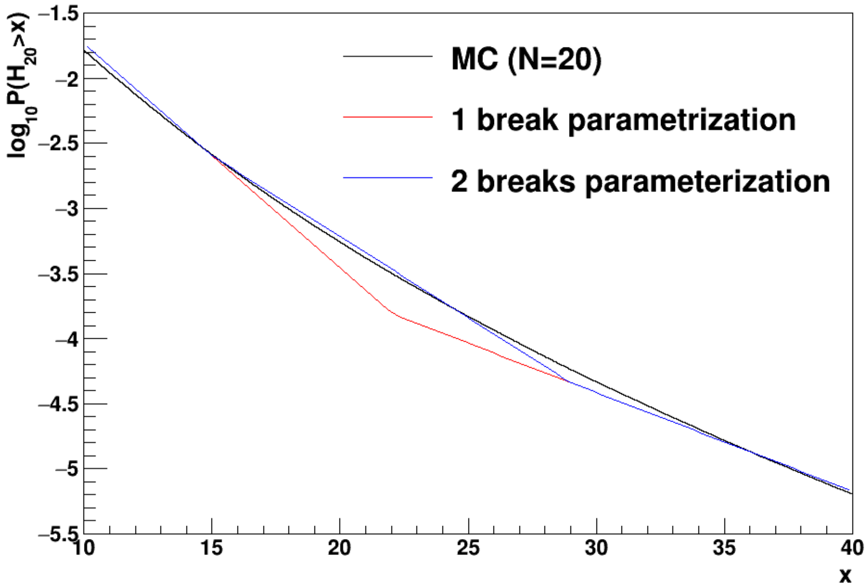


unweighted Htest calib

- de Jager+1989,2010, Kerr2011 provided the asymptotic behavior P(H>x)~exp(-0.4x)
- We ran 10^9 MC realizations to calibrate P(H>x) for small data size N
- x>30 slope parameterization
- P(H>x) approximated by a double broken linear polynomial

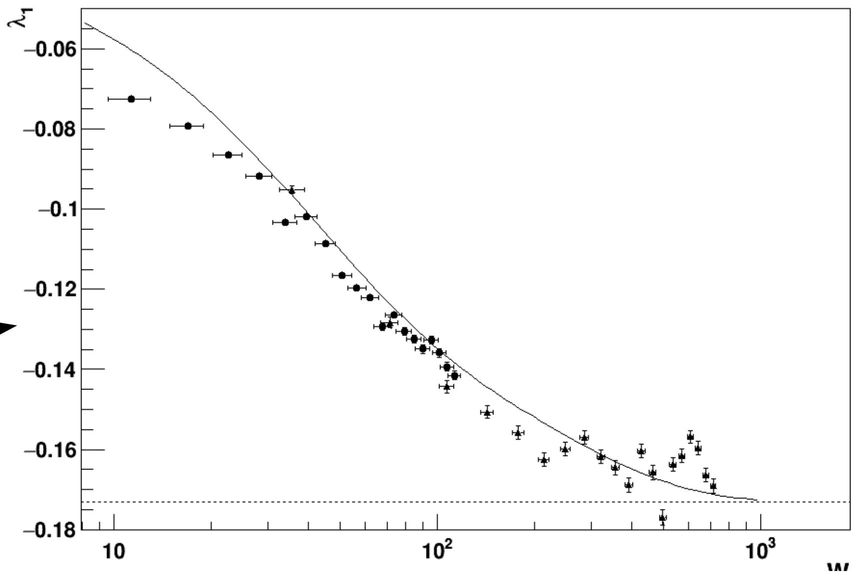


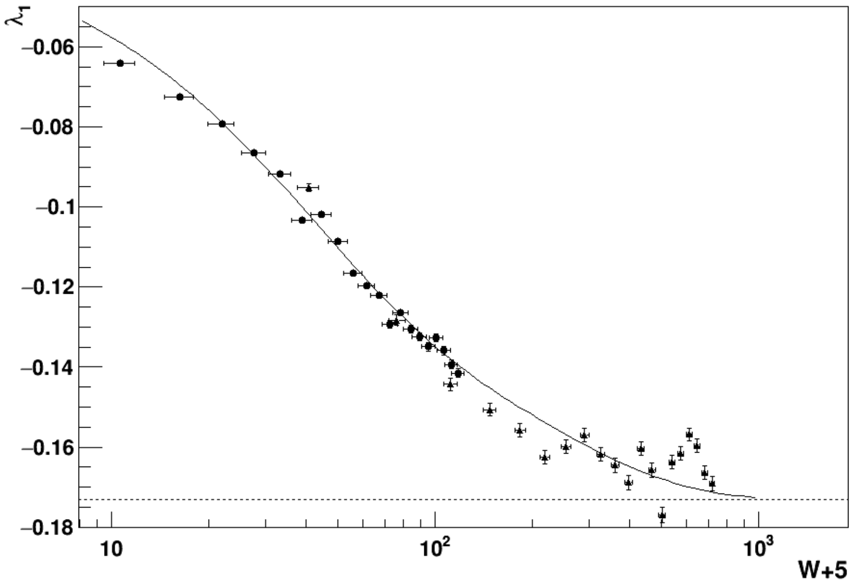


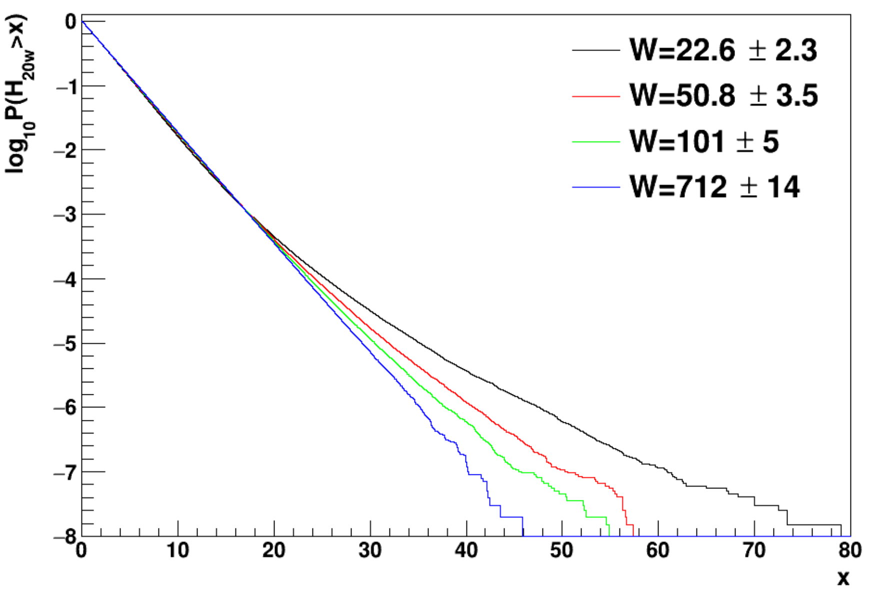


weighted Htest calibration

- When going from unweighted to weighted Htest: N → sum of weights
- Weighted Htest is invariant under weight global scaling → compute W=sum of weights under the prescription that max w = 1
- x>30 slope almost follows unweighted parameterization
- W → W+5 works fine







Htest calibrations

Unweighted Htest:

$$\lambda_0 = -0.398405/\log(10) = -0.173025$$

$$\lambda_1(N) = \lambda_0 + 0.0525796e^{-N/215.170} + 0.086406e^{-N/35.5709}$$

$$\log_{10} P(H_{20} > x) \sim \begin{cases} \lambda_0 x & \text{if } x < 15, \\ 15\lambda_0 + \frac{\lambda_0+\lambda_1(N)}{2}(x-15) & \text{if } 15 < x < 29 \\ 22\lambda_0 + \lambda_1(N)(x-22) & \text{if } x > 29. \end{cases}$$

Unweighted Htest (same as unweighted case except N → W+5):

$$\log_{10} P(H_{20w} > x) \sim \begin{cases} \lambda_0 x & \text{if } x < 15, \\ 15\lambda_0 + \frac{\lambda_0+\lambda_1(W+5)}{2}(x-15) & \text{if } 15 < x < 29 \\ 22\lambda_0 + \lambda_1(W+5)(x-22) & \text{if } x > 29. \end{cases}$$