Constraining the Intergalactic Magnetic Field with Time-Delay Likelihoods in Gamma-Ray Transients

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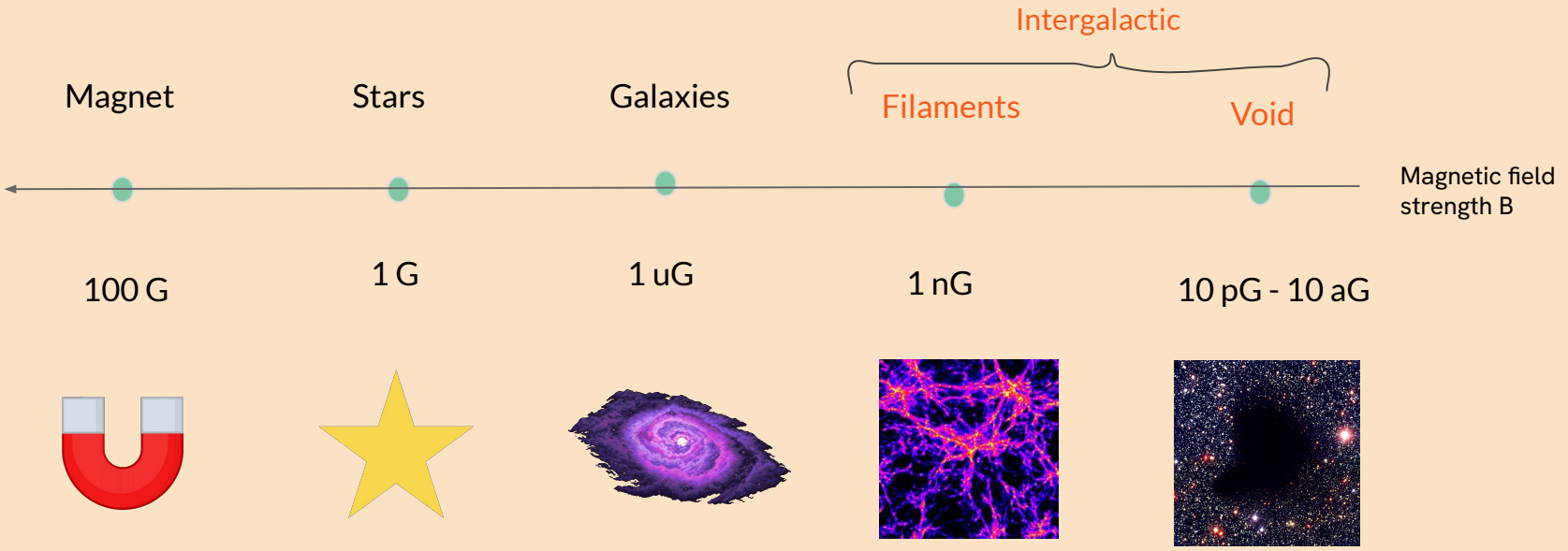
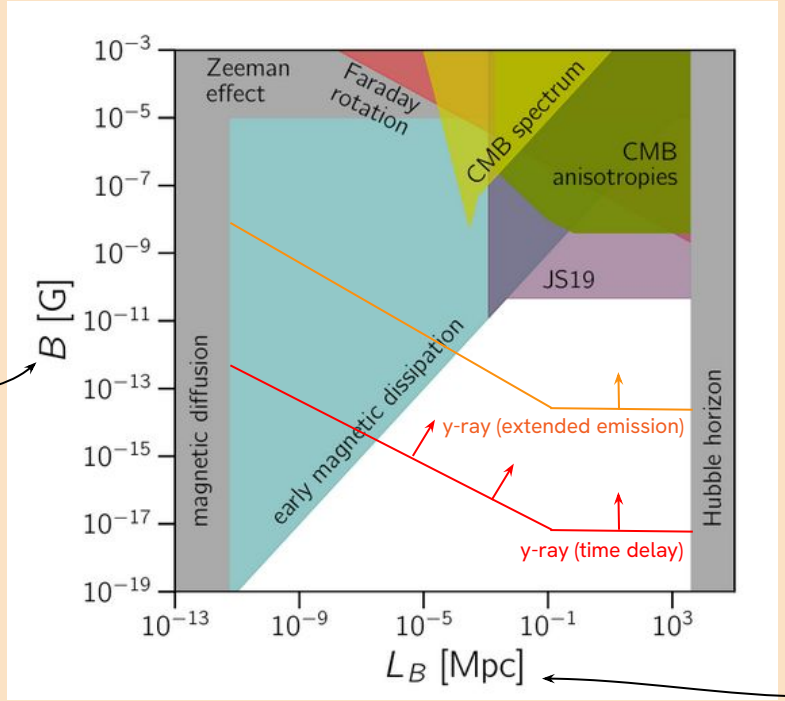
on behalf of the CTAO-LST project

September 2026

What is the Intergalactic Magnetic Field (IGMF) ?

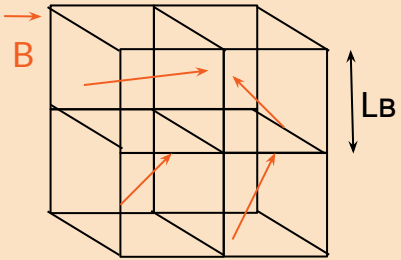


IGMF description

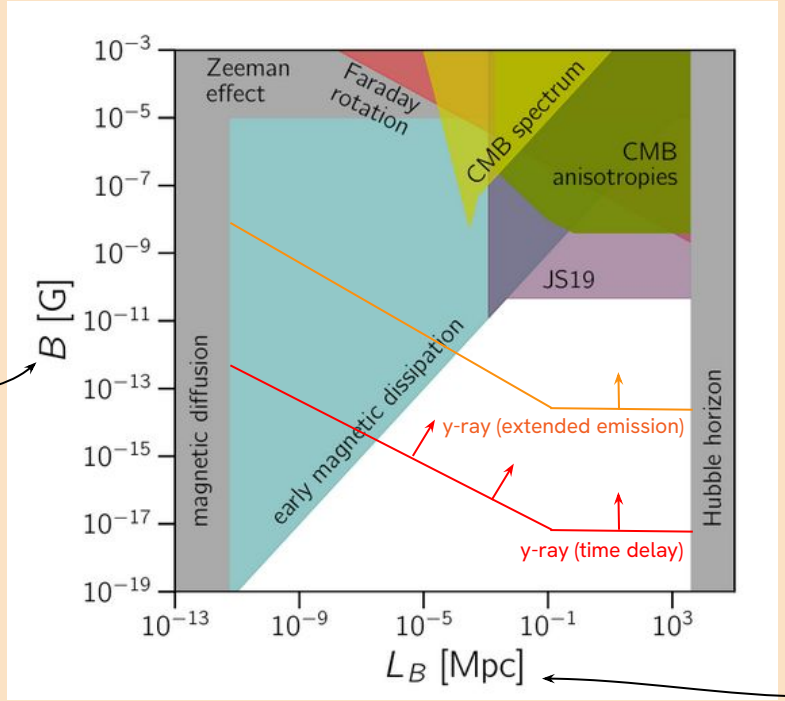


Strength

Length scale



IGMF description and measurement



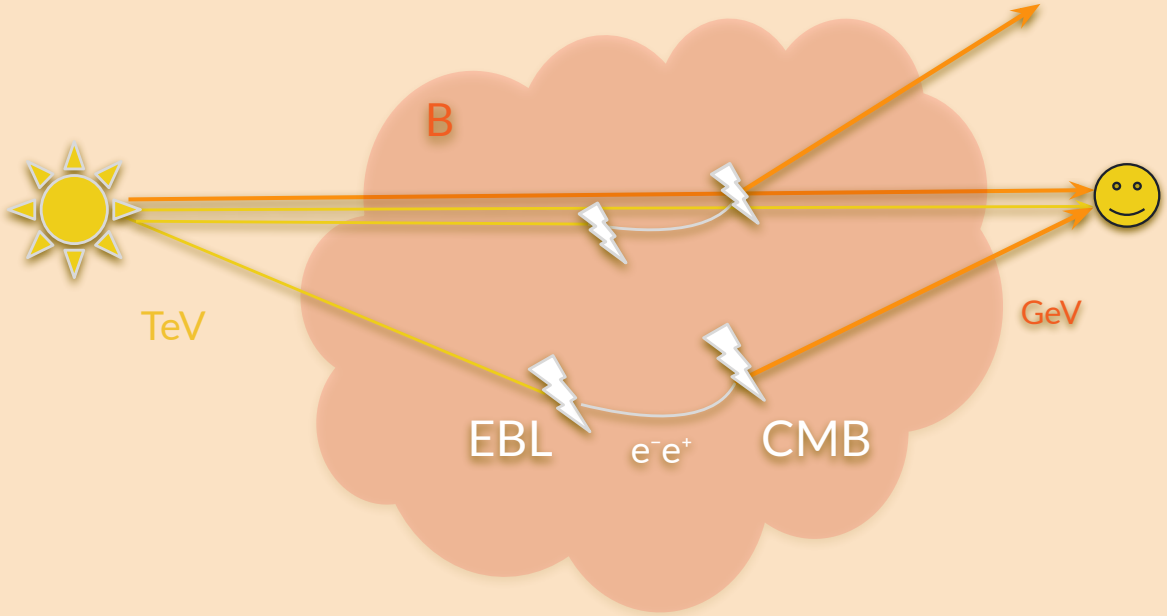
Strength

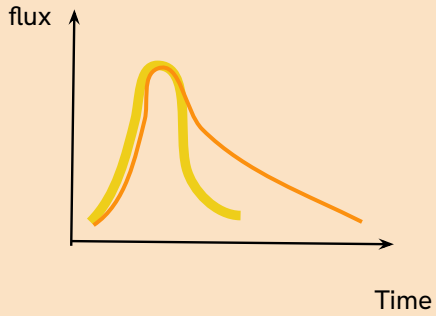
Length scale

Not yet detected, only upper and lower limits in the (B, L) space parameter !!

Measuring the IGMF with gamma-rays

a) Physical process

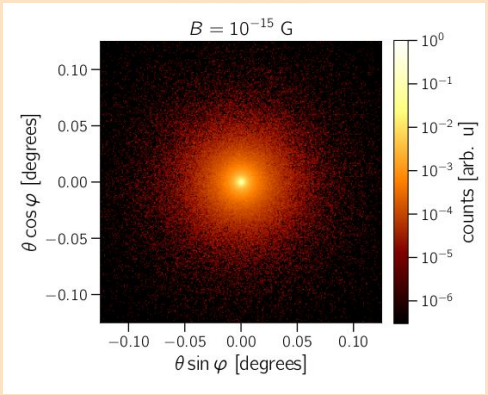




Measuring the IGMF with gamma-rays

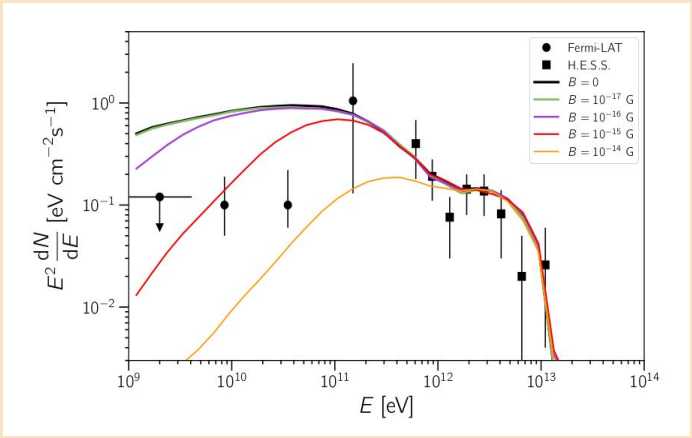
b) What we observe

Extended GeV emission



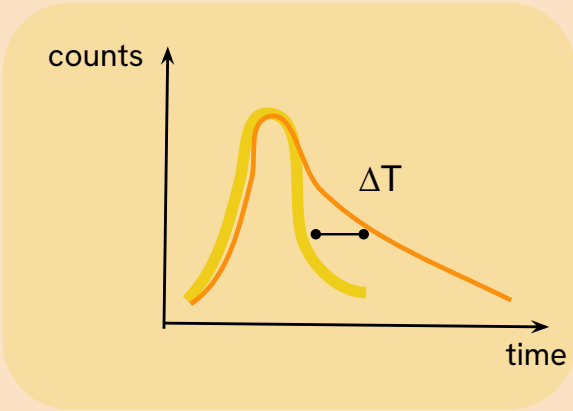
Alves Batista et al. 2022

Missing GeV component in the SED



Alves Batista & Saveliev, 2021

Delayed GeV emission



Almost assumption-free !

Project milestones

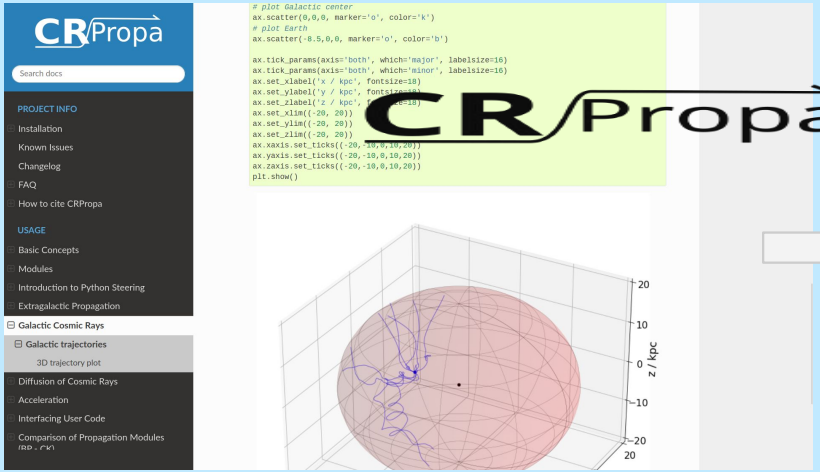
Extract the time delay distribution induced by the IGMF **from simulations**

Building a framework to analyse our model in energy and time bin

Compare data and model in energy and time binning : **Binned likelihood**

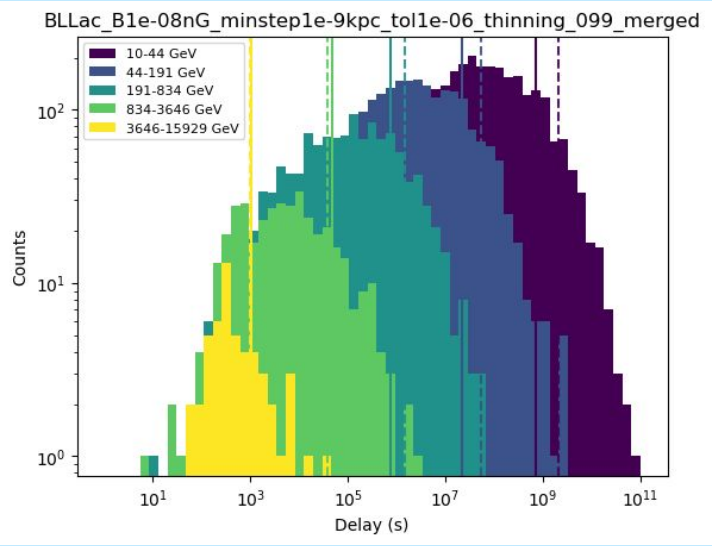
Extend the model to **include additional physical parameters**

1) Extracting time delay distribution from simulations



JCAP (2022) no. 09, 035; arXiv:2208.00107.

Distribution of the photon's delay given a B :



Dashed line :

$$T_{\rm delay} \simeq \frac{7\times10^5\kappa(1-\tau_\theta^{-1})(1+z)^{-5}}{\left[\frac{E_\gamma}{0.1\ {\rm TeV}}\right]^{-5/2}\left[\frac{B_0}{10^{-18}\ {\rm G}}\right]^2}\ {\rm s}, \qquad \lambda'_B \gg D_e$$

Neronov, Semikov 2009

2) Building our model in energy and time bin

a) Expected signal

$$\text{Expected signal}(E', t' \mid B) = \int dE \int dt \int dd \; \mathbf{IRF}(E',E) \times \mathbf{SED} \times \mathbf{EBL}(E) \times \mathbf{F}(t) \times \mathbf{P}(d,E \mid B) \times \delta(t' - (t + d))$$

the instrument response of the detector.

Intrinsic source spectrum

the effects of gamma-ray absorption by the EBL

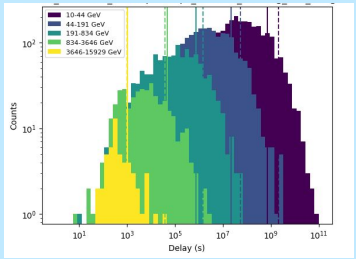
Intrinsic light curve

effects caused by the IGMF

2) Building our model in energy and time bin

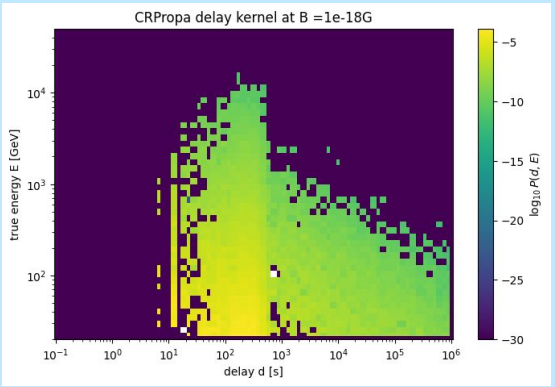
b) Energy-delay matrix

$$\text{Expected signal}(E', t' \mid B) = \int dE \int dt \int dd \quad IRF(E',E) \times SED \times EBL(E) \times F(t) \times \mathbf{P(d,E \mid B)} \times \delta(t' - (t + d))$$



Distribution of the delay given a B extracted from simulations

P(d,E | B)



3) Compare data and model in energy and time bins

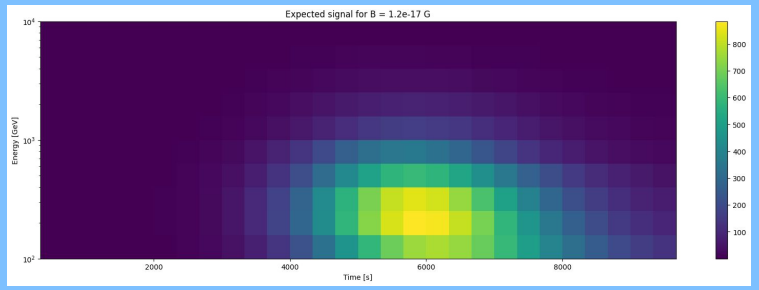
=> Binned likelihood approach

MODEL

Expected signal(E', t' | B) = $\int$ IRF(E',E) × SED x EBL(E) × F(t) × P(d,E | B) × δ(t' - (t + d)) dE dt dd

"how many photons should I expect in bin (energy, time) given B"

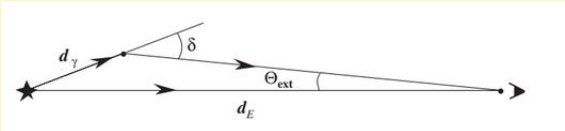
DATA

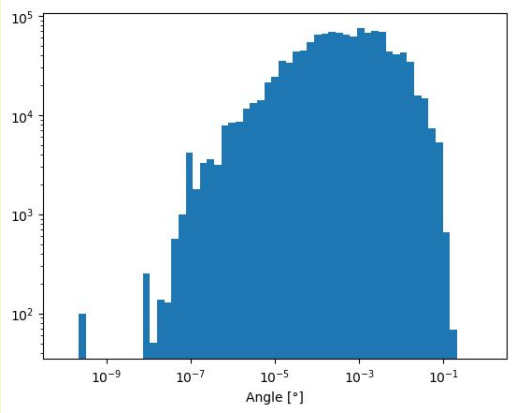


2D Binning (energy, time) of observed counts

Advantage of the method : the intrinsic light curve and the spectrum index are our free parameter, thus we have minimal assumptions

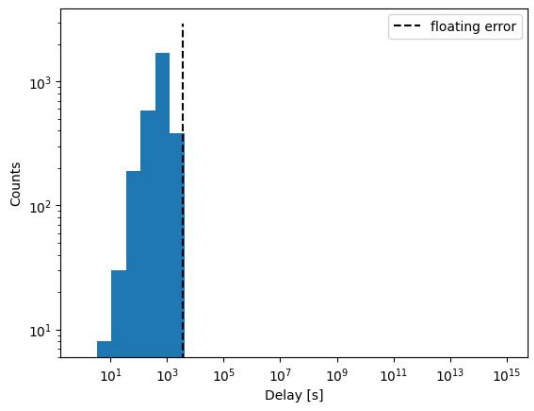
1) CRPropa simulation checks





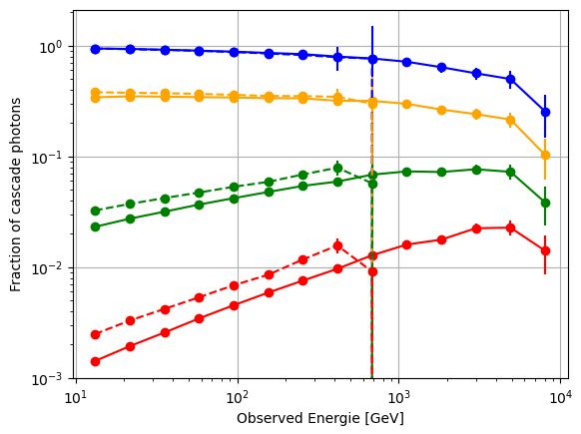
Θext distribution of cascade photons

Double-precision error



Delay distribution of primary photons

different spectral index (color)
\+ different redshift (---)

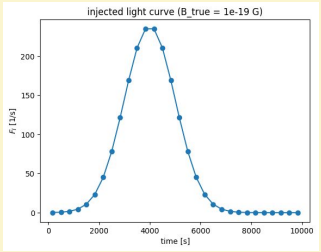


Fraction of cascade photons for different spectral index

2) Binned Likelihood test

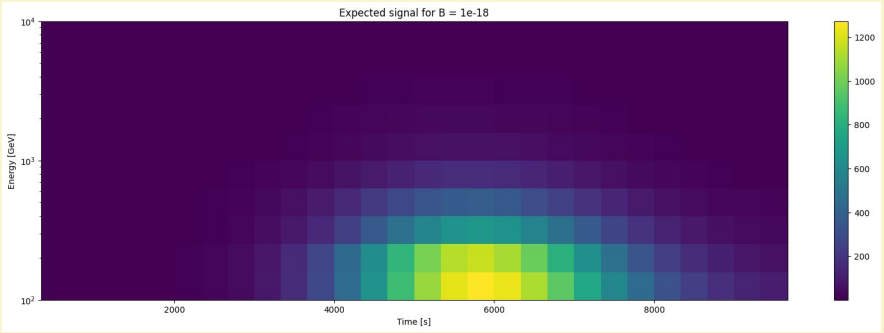
a) Generating simulated data for a B

Simulated intrinsic spectrum

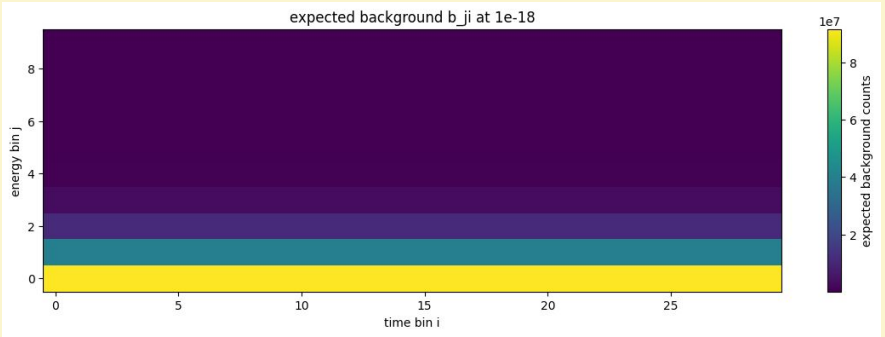


spectral index constant in time

Expected signal(E', t' | B) = $\int dE \int dt \int dd$ IRF(E',E) × SED x EBL(E) × F(t) × P(d,E | B) × δ(t' - (t + d))



Expected signal counts for a B



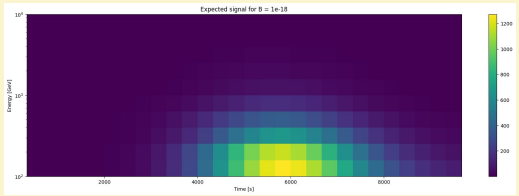
Background counts

2) Binned Likelihood test

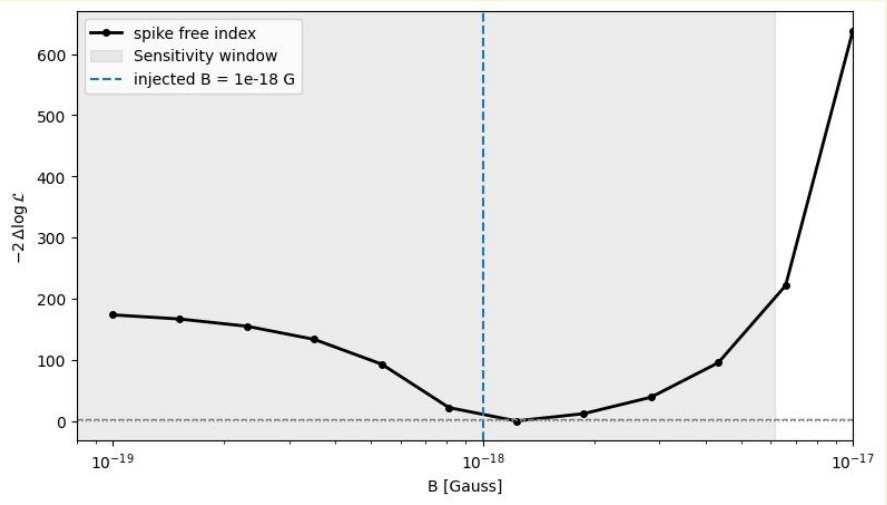
b) Recovering the injected B value

Simulated data

B = 1e-18G



Vs Model =



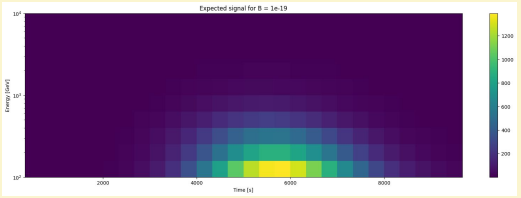
Likelihood curve

2) Binned Likelihood test

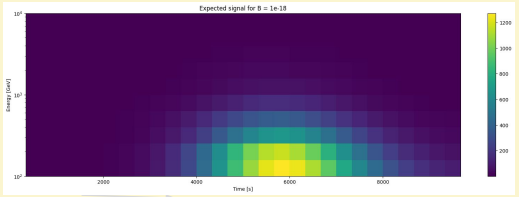
b) Recovering the injected B value

Simulated data

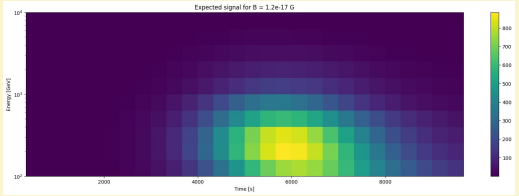
B = 1e-19G



B = 1e-18G

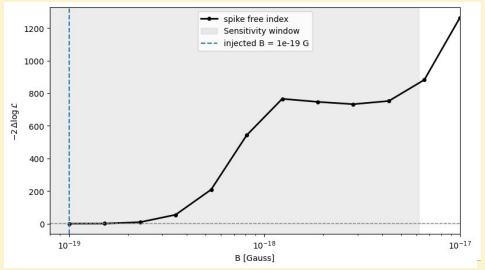


B = 1e-17G



Vs Model

=



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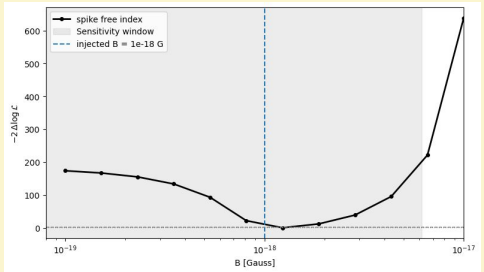

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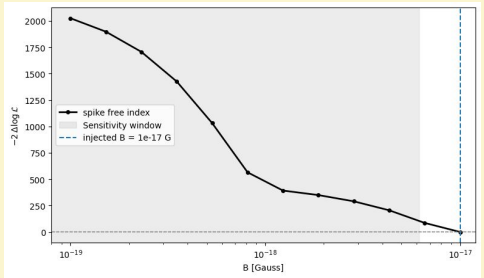


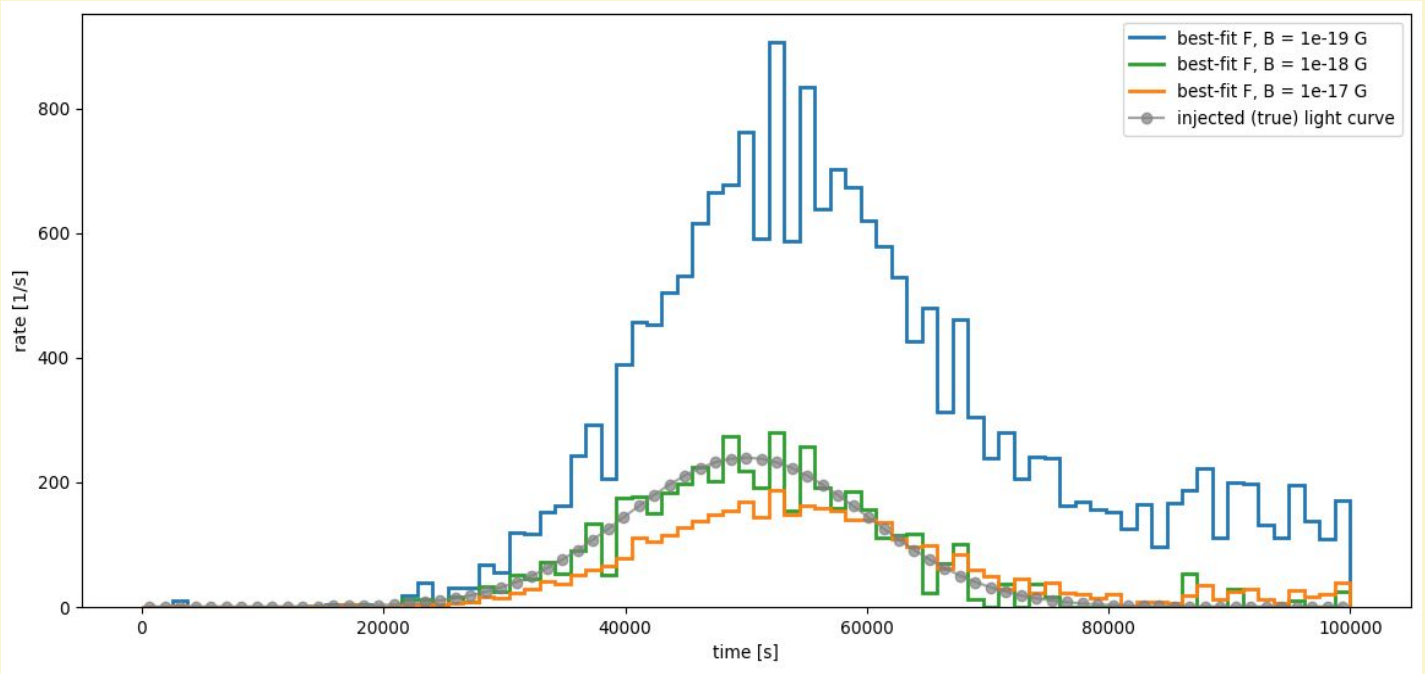
Likelihood curves

3) Setting intrinsic LC and spectrum index as free parameters

a) Recovering the Intrinsic light curve

For the simulated data generated with B = 1e-18 G

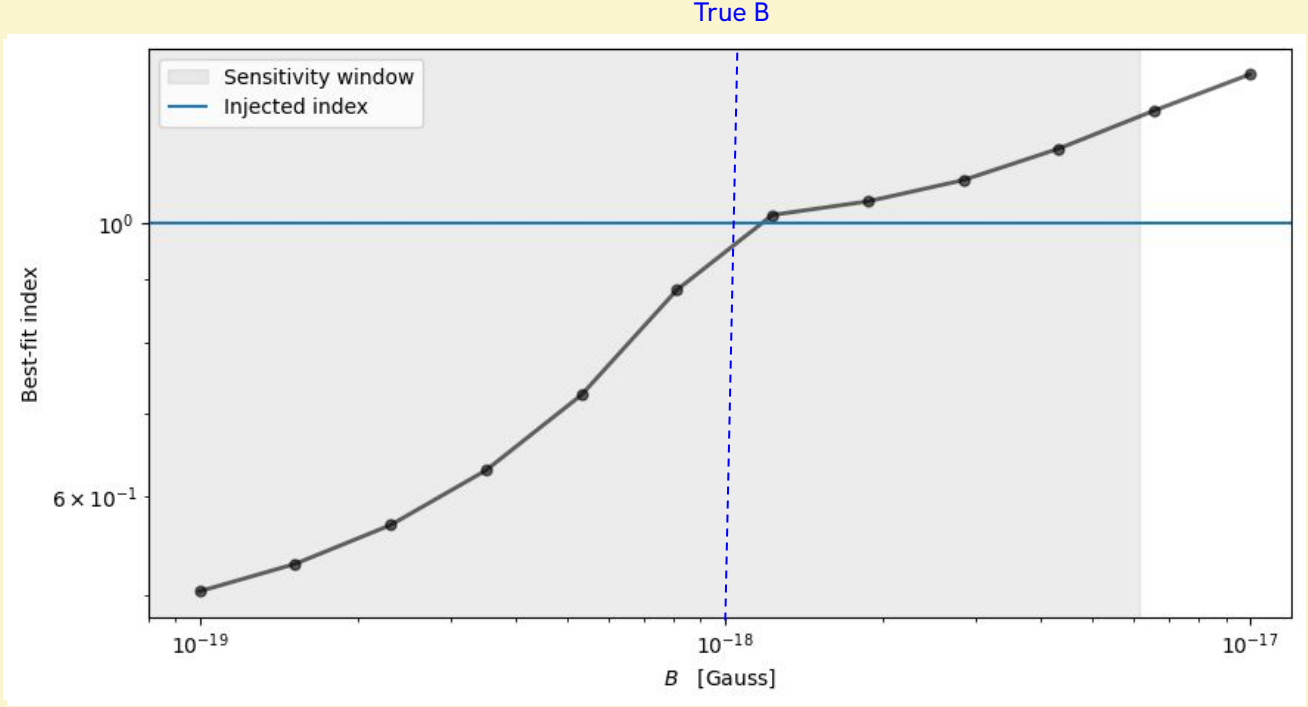
Colored curves : best fit intrinsic light curve for different value of B



3) Setting intrinsic LC and spectrum index as free parameters

b) Intrinsic spectrum index

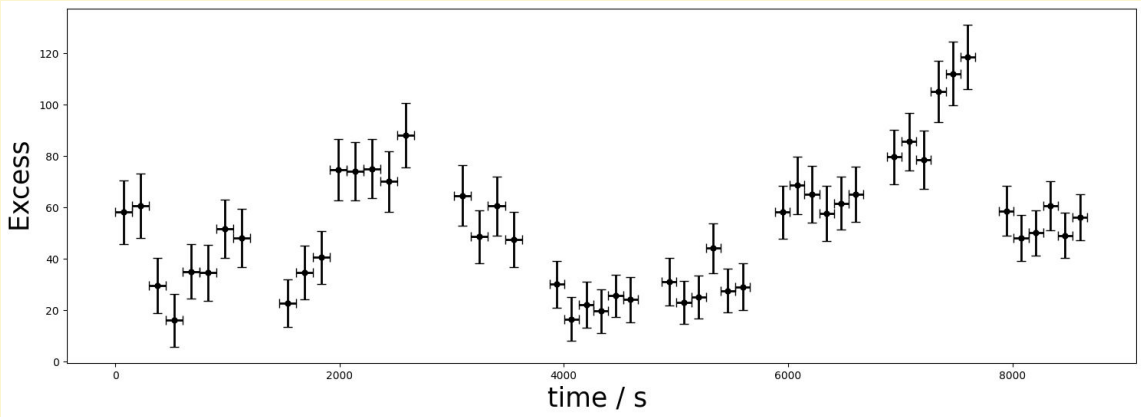
For the fake data generated with B = 1e-18 G



4) Prospect on BLLac

- Extragalactic (z =0.07)
- Intranight variability AGN
- Very high energy

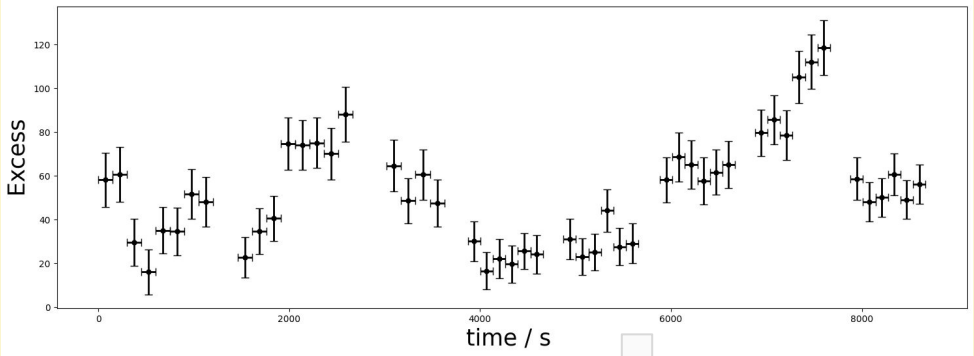
Light Curve Of BLLac during the night of 2021.08.08 with LST



https://arxiv.org/pdf/2309.09715

4) Prospect on BLLac

Light Curve Of BLLac during the night of 2021.08.08 with LST



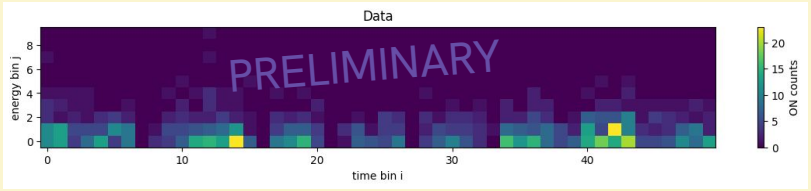
https://arxiv.org/pdf/2309.09715

Selected thanks to the catalog Varcat of Cyann Plard!

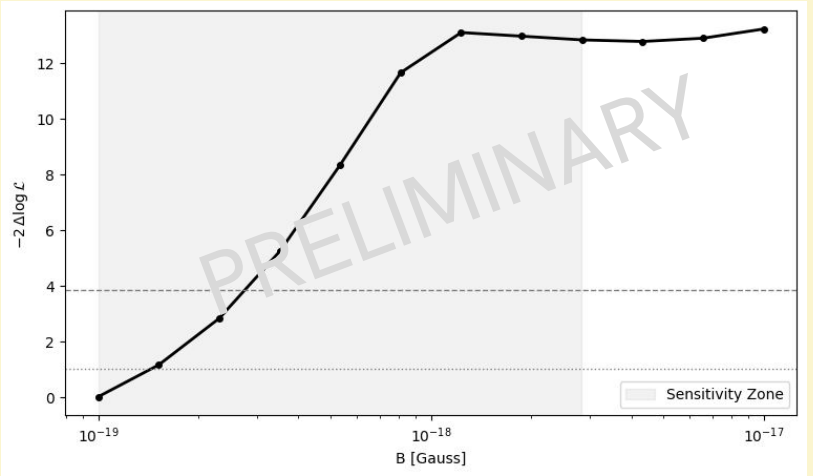
https://gitlab.cta-observatory.org/cyann.plard/gammaliv#

4) Prospect on BLLac

BLLac during the night of 2021.08.08



Vs Model =



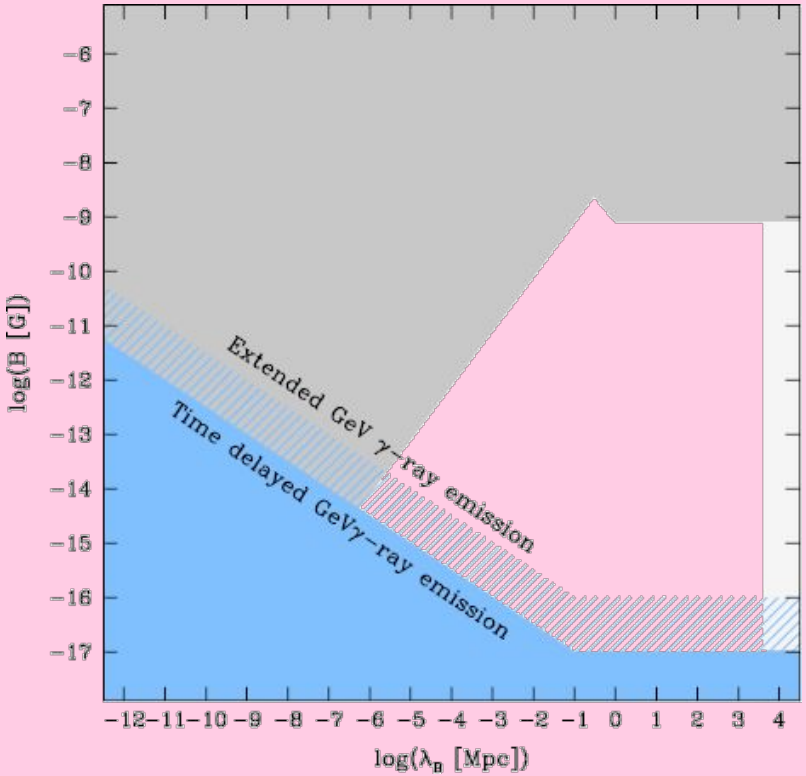
Test statistic against no delay :
loglkl (no delay) = 208.850
loglkl (best B) = 246.557
TS = null - best = -37.707

Take home message

- Using a **binned likelihood approach** lets us study time delays with minimal assumptions regarding the intrinsic light curve and spectral index of the source.
- Delayed emission studies especially with **transients** allow us to avoid complex assumptions about long-term source behavior

What's next

- Apply the method to a selected list of events recorded with the LST.
- Extend the statistical framework to include simultaneously the different effects induced by the IGMF



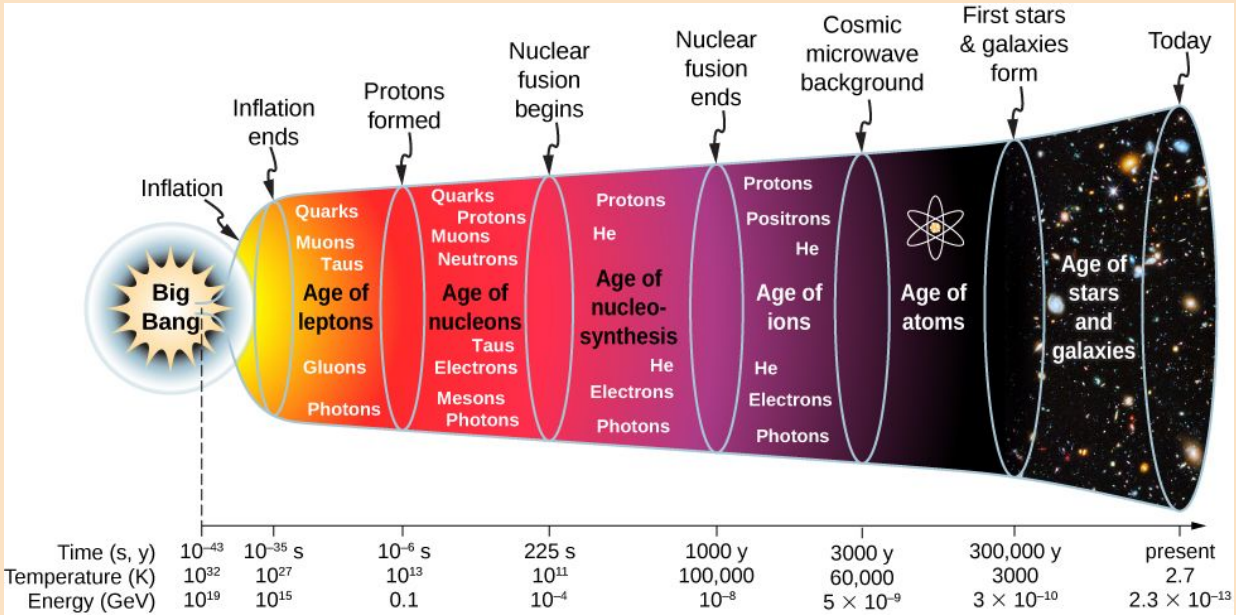
Thanks !

When was the IGMF possibly born ?

Primordial origin : born during inflation, phase transitions... then diluted with cosmic expansion.

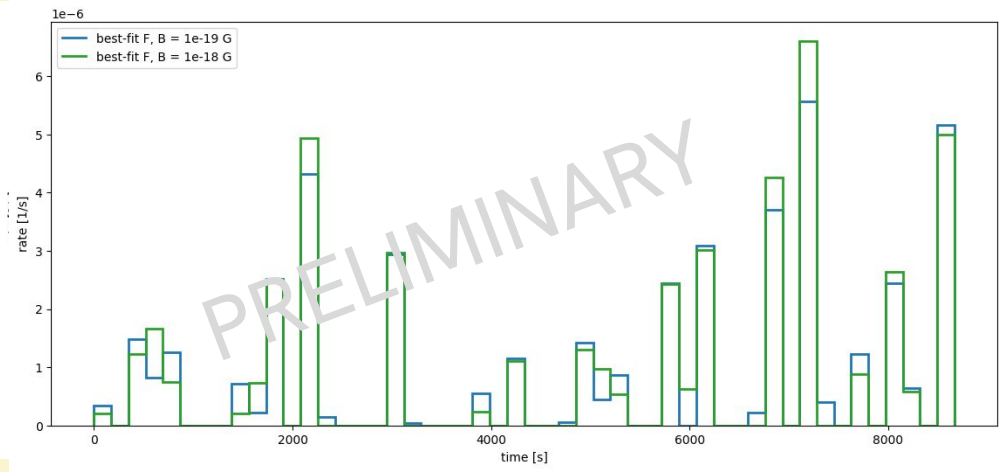
vs

Astrophysical origin : generated by astrophysical objects then spread through cosmic structures

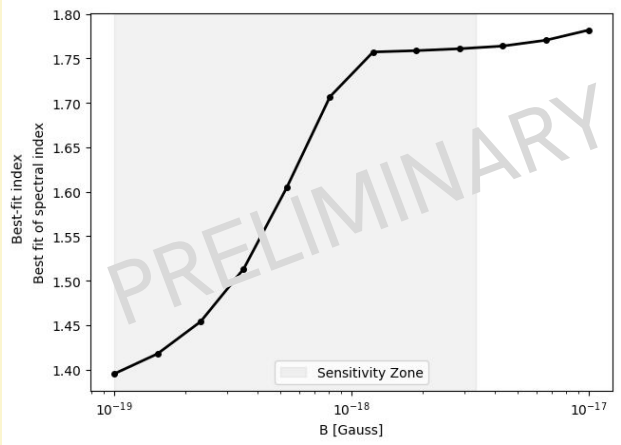


4) Prospect on BLLac

Intrinsic Light Curve



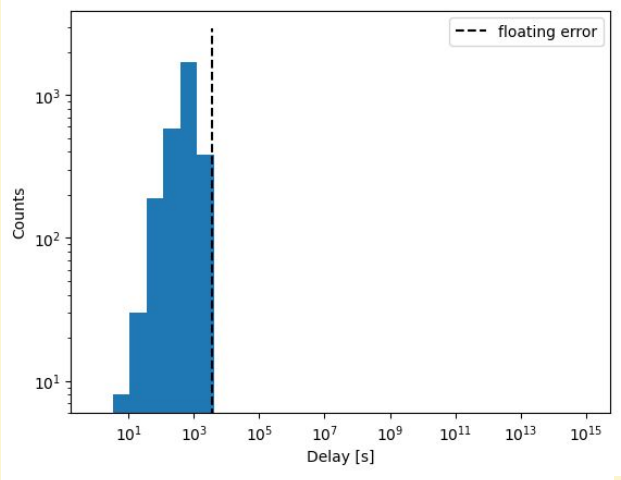
Intrinsic spectrum index



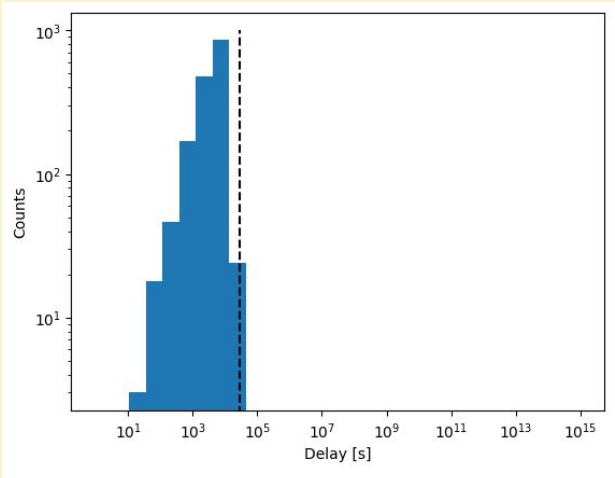
1) Precision error from simulations

- **Double-precision:** relative error ~1e−16 per propagation step

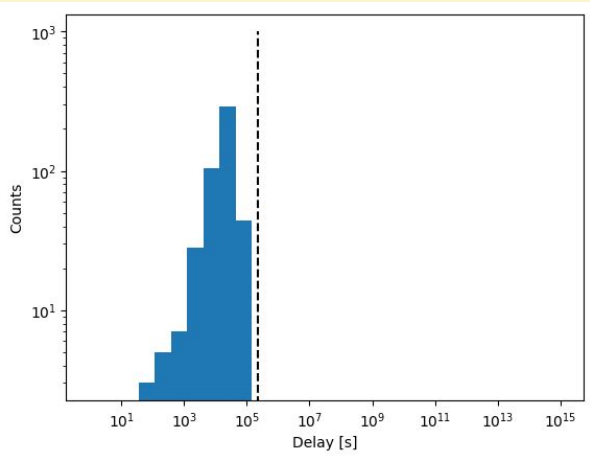
Delay distribution of primary photons with redshift



z=0.1



z=0.3



z=1.0

1) Check of the interpolation