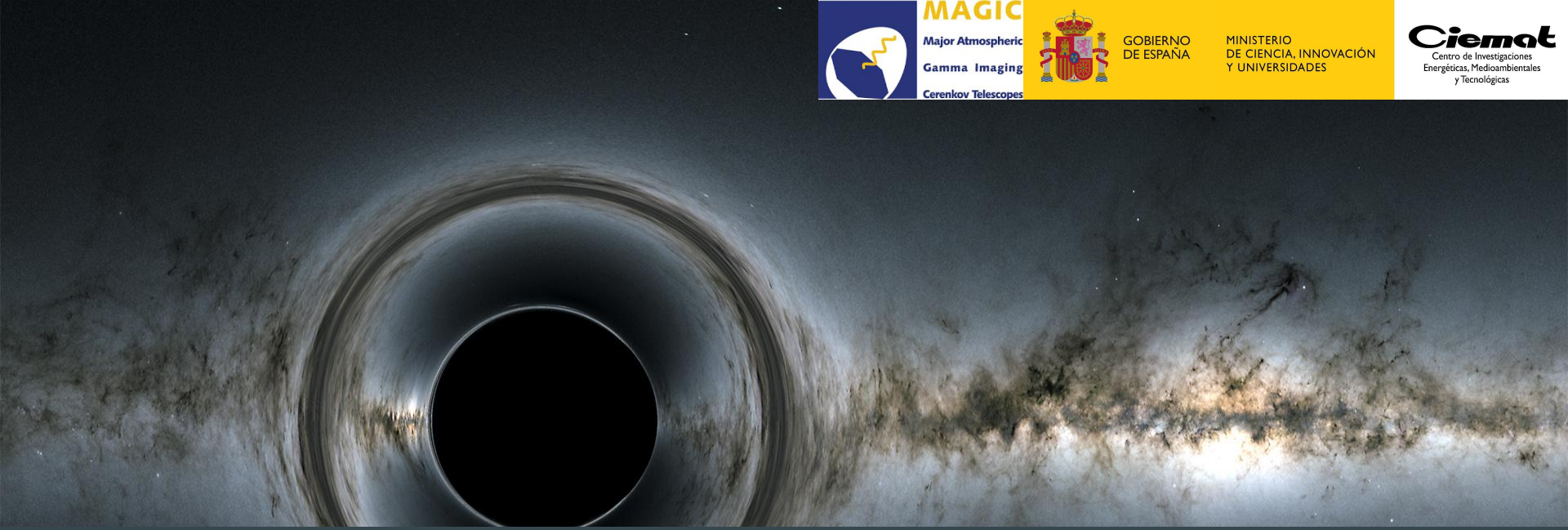


Primordial Black Hole Evaporation Search with MAGIC

TeVPA 2025 - Valencia, Spain

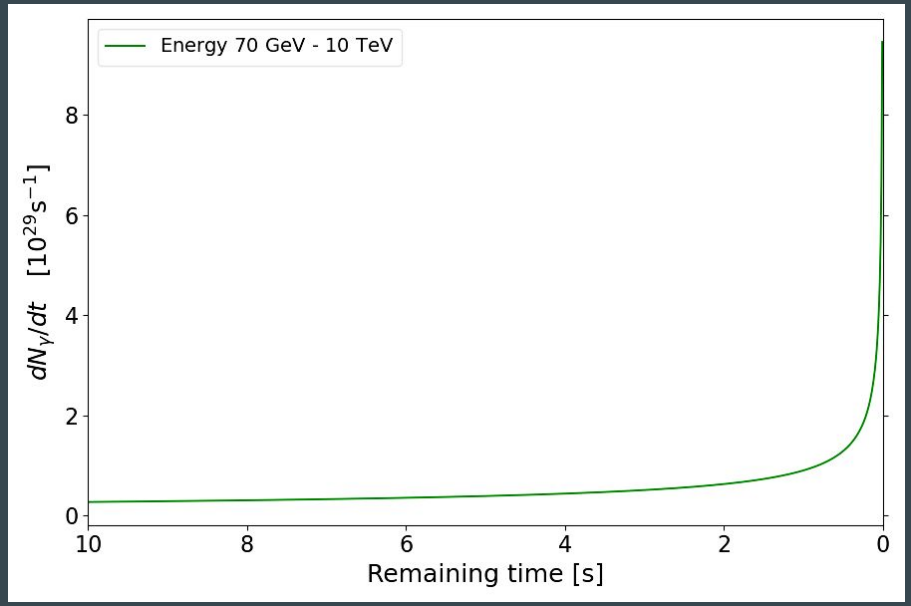
Elia do Souto Espiñeira, Javier Rico
on behalf of the MAGIC Collaboration

Primordial Black Holes: Theory

- PBHs are hypothetical black holes formed in the early Universe.
  - Wide range of initial masses 10^{-8}kg to $10^{5}M_{\odot}$
  - Dark matter candidates
- Black holes radiate particles (black body analogous)

$$T_{\mathrm{BH}} \propto \frac{1}{M_{\mathrm{BH}}}$$

- Hawking radiation negligible for $M_{BH} > M_{\odot}$
- PBHs of initial mass ~ 5.0 x10^{11}kg should be evaporating now → Big burst



Energy integrated photon emission in the last 10s before the PBH's total evaporation

$$\tau(M_{\mathrm{BH}}) \approx 10^{67} \left(\frac{M_{\mathrm{BH}}}{M_{\odot}}\right)^{3} \mathrm{yr}$$

MAGIC telescopes

- +20 years in operation. Rich archival data.
- Energy threshold ~ 50GeV (in this work >70GeV used).
- 3.5° FoV
- Angular resolution ~0.1°. Energy resolution ~15%.
- 2004 MAGIC-I, 2009 MAGIC-II and 2012 upgrade*.

*J. Aleksić et al. (2006a)
J. Aleksić et al. (2006b)

Photo credit: Urs Leutenegger

Unbiased archival transient search

1. Sky divided in circular cells equal to MAGIC's PSF (0.15° radius at high E).
    a. This allows for longer monitoring in time of the same coordinates.
2. Cells close to known TeV sources are removed.
3. Observed gamma-like events vs time from a cell.
4. Time binning of 2, 10, 100 and 1000s.

1. Gamma-like background model
    a. From instrument response function (IRF) and overall camera rate
2. Number of expected gamma-like background events computed for the same cell and time bin.

Comparison of observed vs expected events in each time/space bin → p-value

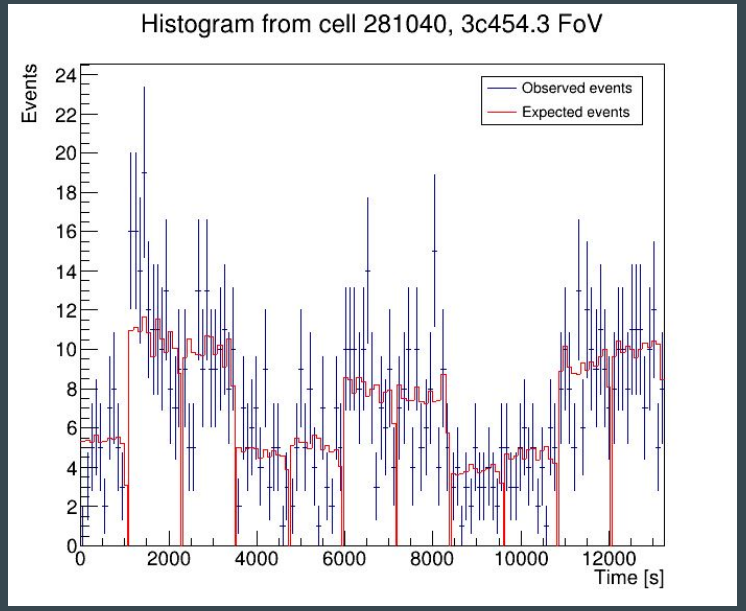
MAGIC observations

- Need validated IRFs for the whole FoV.
  - Stable telescope performance period
- Data analysed corresponds to 3 periods, from 2013 to 2014 and from 2016 to 2018.
- Stereo mode observations.
- Quality cuts were applied to exclude bad weather, high moonlight or technical issues.
- MAGIC runs ~20min.
- Remaining dataset amounts to 2076.5h.

Dates	N. runs	After quality cuts	Effective time
2013-07-27 - 2014-06-18 2014-07-05 - 2014-08-05	3722	957.8h	876.2h
2016.04.29 - ~2017.08.02	4400	1118.7h	773.9h
Total	**8122**	**2076.5h**	**1650.1h**

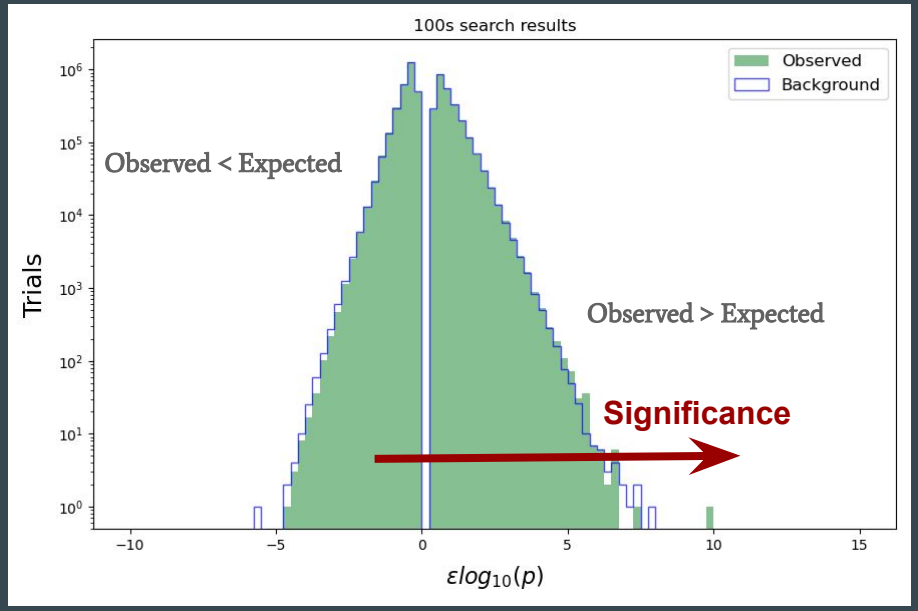
Burst search results

No PBH evaporation found with significance >5σ after correcting for trials.



Example of an event light curve from the application of the archival search on a single night of observations of one source

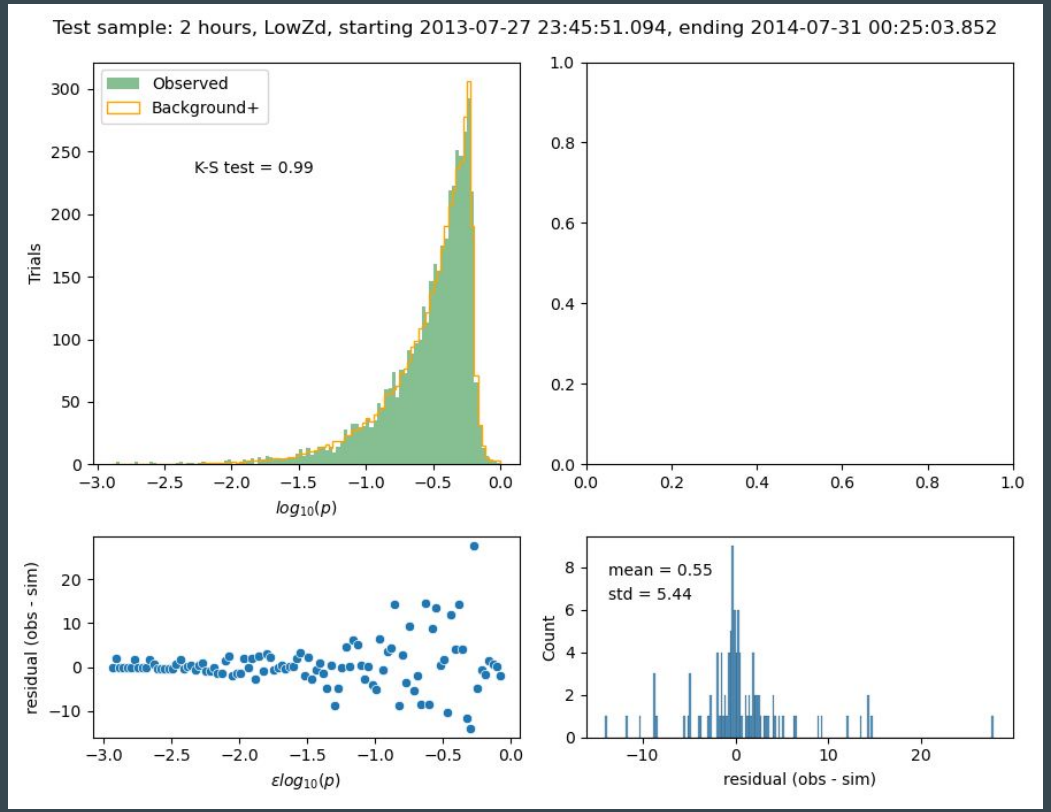
p-values



Distribution of p-values from the 100s burst search over a year of observations. ε = -1 for $N_{obs} > N_{exp}$ and ε = 1 for $N_{obs} < N_{exp}$

Burst search results

- Systematic uncertainties tested on the left side.
- Kolmogorov-Smirnov test applied to multiple 2h long samples
  - The observed p-value distribution follows the one from the expected background. ✅
- Background model validated → Calculate upper limits.



Primordial Black Holes: Spectrum

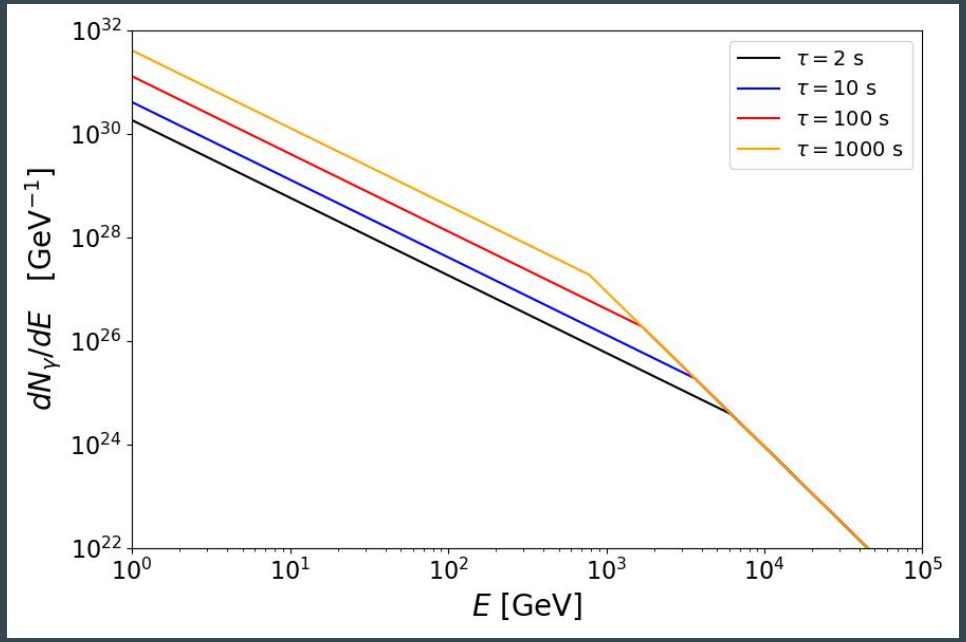
PBH evaporation gamma-ray spectrum:

$$T_{\mathrm{BH}} > 50\,\mathrm{GeV}$$

$$\tau = 4.8 \times 10^{11} \left(\frac{T_{\mathrm{BH}}}{\mathrm{GeV}}\right)^{-3}\ \mathrm{s}$$

$$\frac{dN_\gamma}{dE_\gamma} \approx 9 \times 10^{35} \begin{cases} \left(\frac{1\mathrm{GeV}}{T_{\mathrm{BH}}}\right)^{3/2} \left(\frac{1\mathrm{GeV}}{E_\gamma}\right)^{3/2} \mathrm{GeV}^{-1}\ for\ E_\gamma < T_{\mathrm{BH}} \\ \left(\frac{1\mathrm{GeV}}{E_\gamma}\right)^{3} \mathrm{GeV}^{-1}\ for\ E_\gamma = T_{\mathrm{BH}} \end{cases}$$

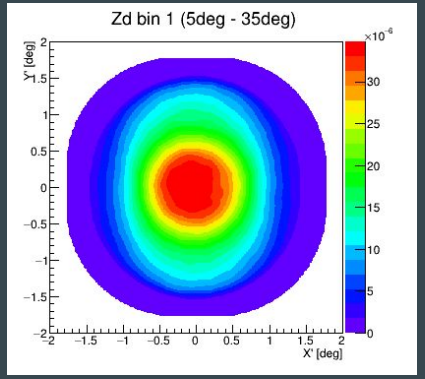
Petkov et al. (2008)

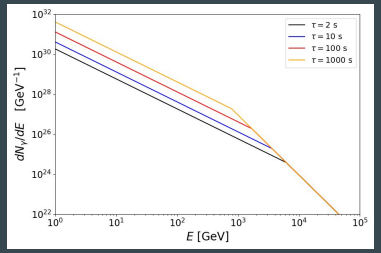


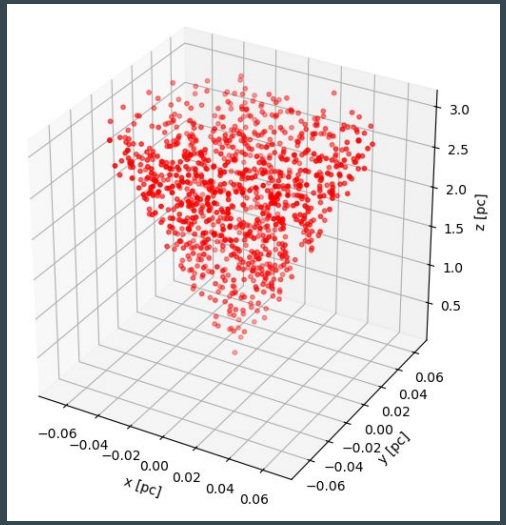
Time-integrated photon energy spectrum for different burst timescales τ

Analysis

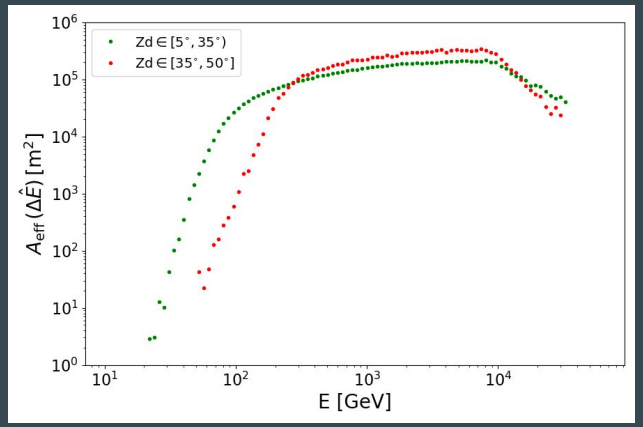
Knowing the PBH spectrum and MAGIC's IRF for the observation periods.







Simulated PBH bursts within MAGIC's FoV up to 3pc for a time of 3 years and $\dot{\rho} = 1.9 \times 10^5 \mathrm{pc}^{-3}\mathrm{yr}^{-1}$



$$g(r, \mathrm{Zd}, \tau, \epsilon) = \frac{1}{4\pi r^2} \int_0^\infty dE \frac{dN(\tau)}{dE} \epsilon A_{\mathrm{eff}}(E|\Delta\hat{E}, \mathrm{Zd})$$

Analysis

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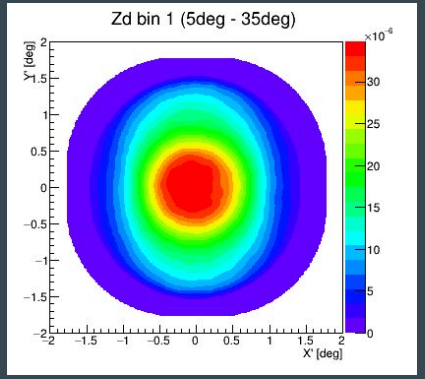
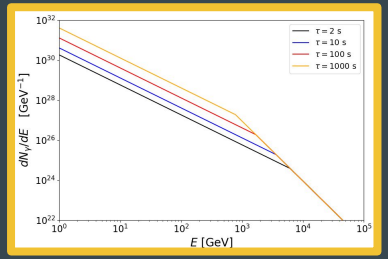
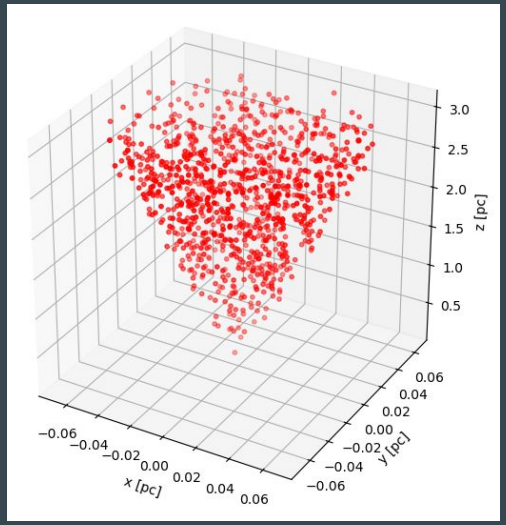




Spectrum



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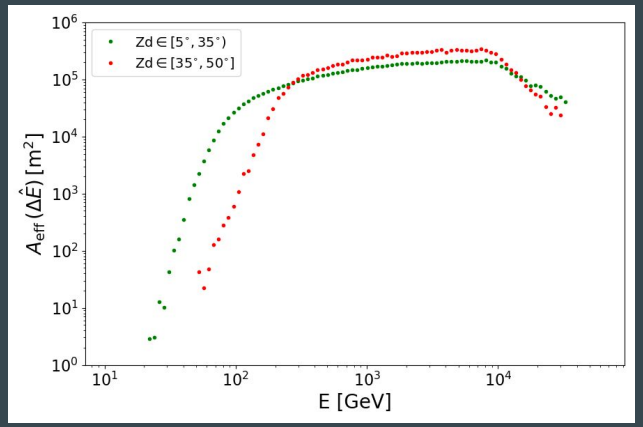

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Analysis

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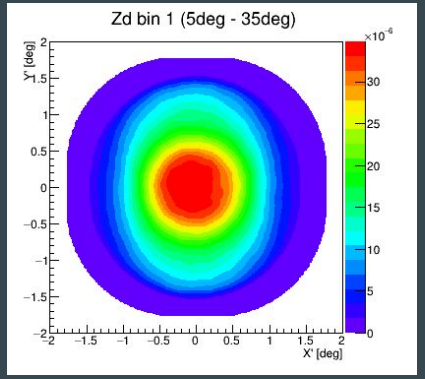

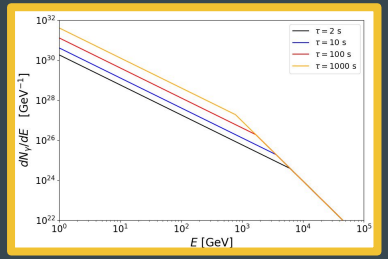

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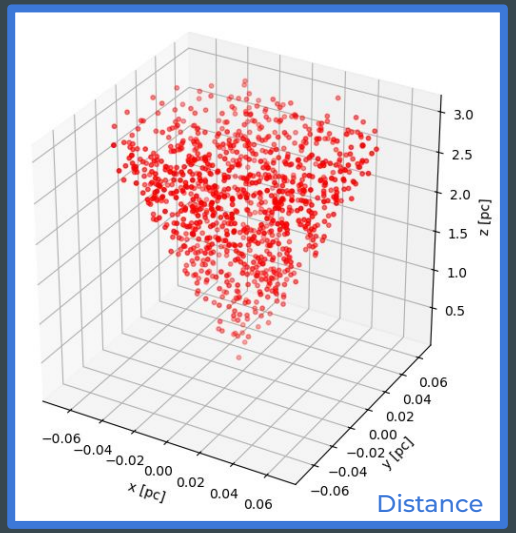

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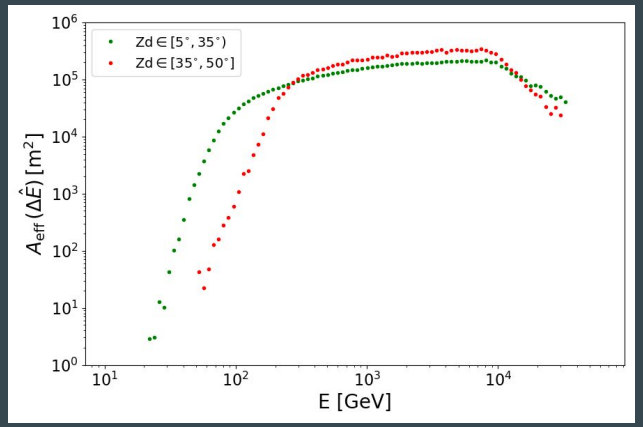

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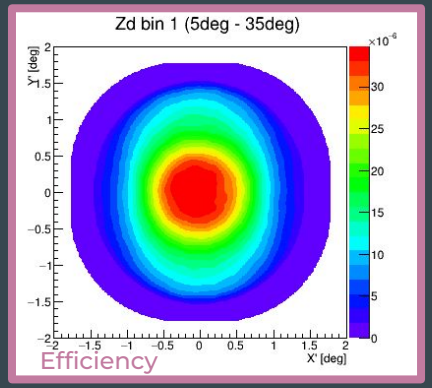
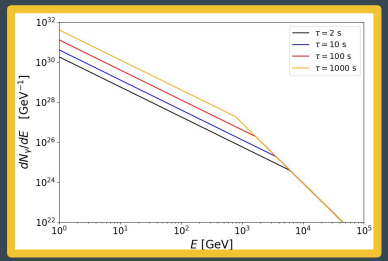
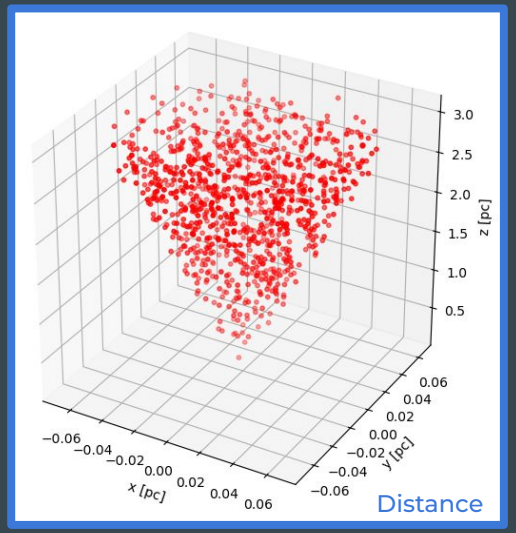




Spectrum



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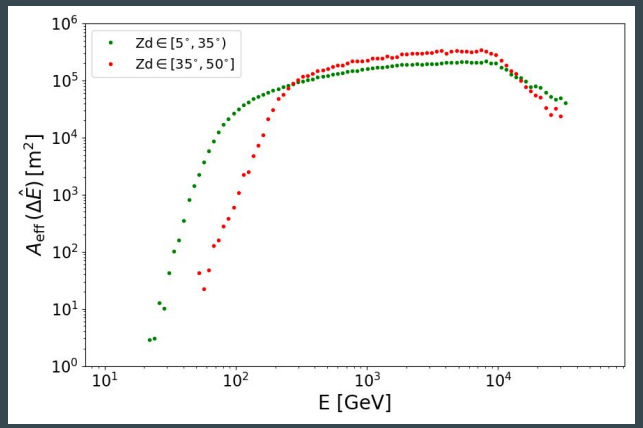

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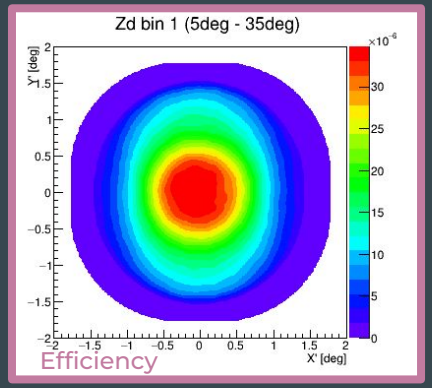

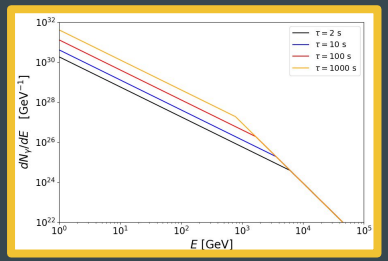

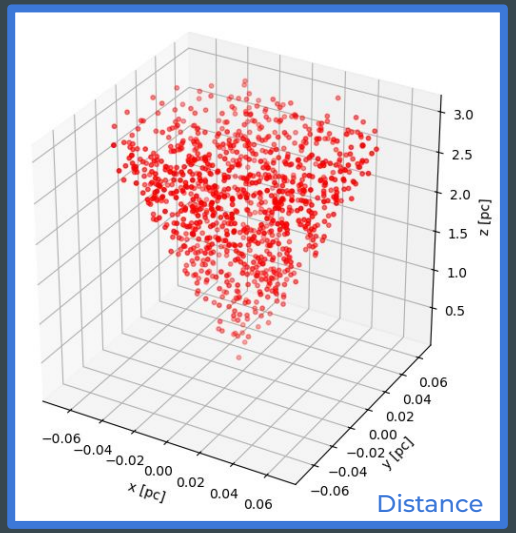

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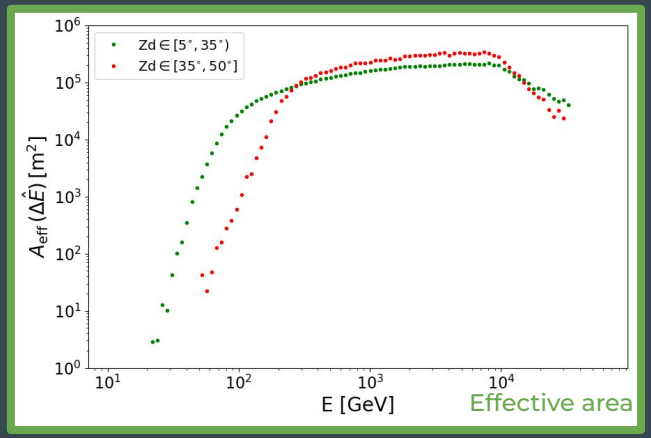

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Analysis

Following the procedure in Albert et al. (2020), for a given evaporation rate density $\dot{\rho}$.

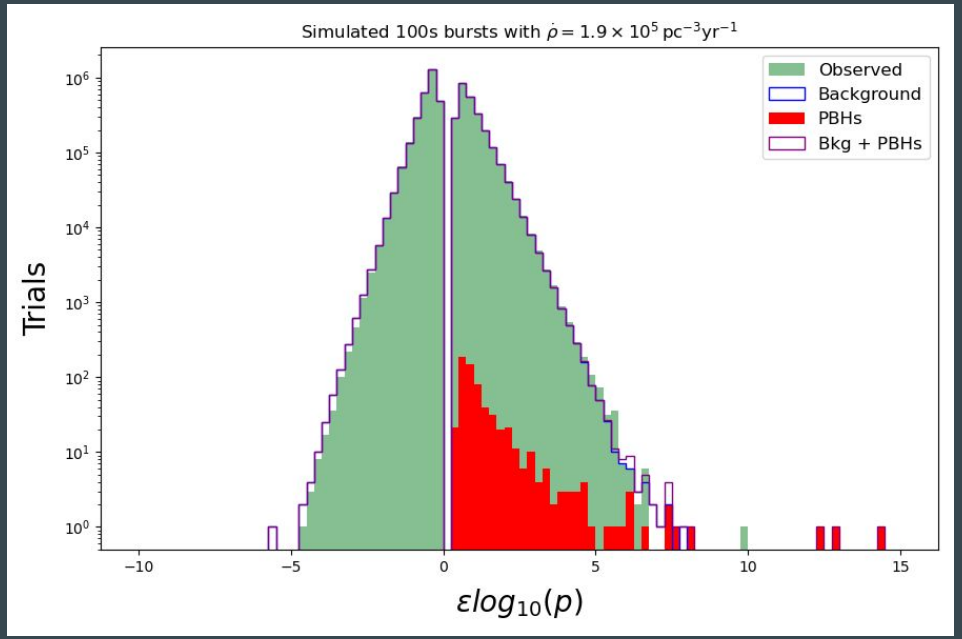
The number of gamma-rays from PBHs is simulated for the cells and time bins of our search.

If the number of expected background counts for a bin is B, the p-value from the simulated PBHs is

$$p = \mathrm{P}(n \geq N; B) = \sum_{n=N}^{\infty} \frac{B^n e^{-B}}{n!}$$

The model distribution is defined as

$$H_{\mathrm{model}}(p) = H_{\mathrm{Bkg}}(p) + H_{\mathrm{PBH}}(p)$$



Test statistic and upper limits

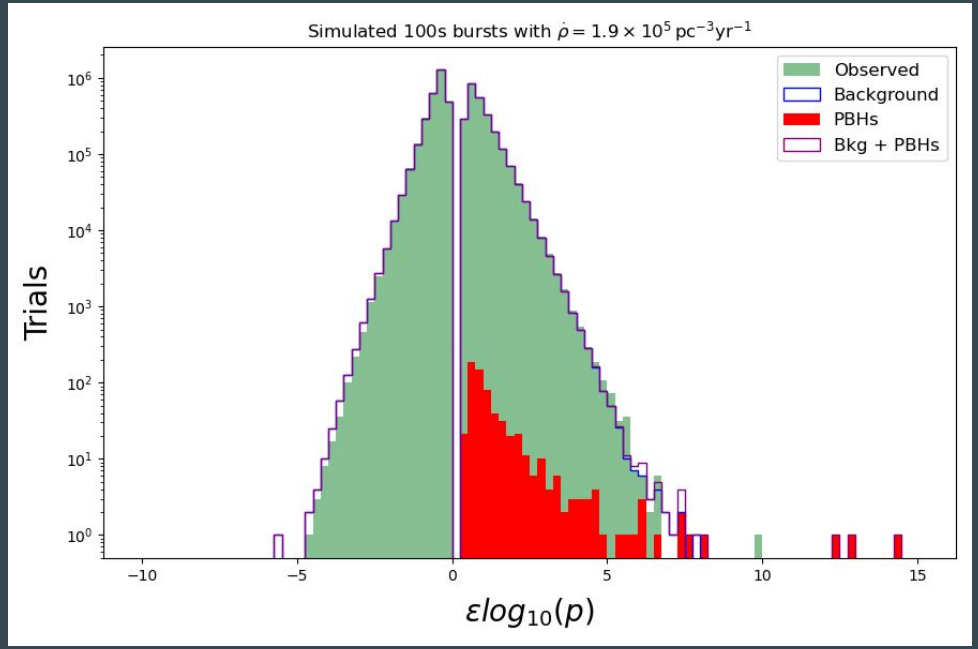
To calculate the upper limits on $\dot{\rho}$ we define a test statistic

$$TS = 2[\ln \mathcal{L}_1 - \ln \mathcal{L}_0]$$

with

$$\ln \mathcal{L}_0 = \sum_b [H_{\text{data}}(b) \ln(H_{\text{bkg}}(b)) - H_{\text{bkg}}(b)]$$

$$\ln \mathcal{L}_1 = \sum_b [H_{\text{data}}(b) \ln(H_{\text{model}}(b)) - H_{\text{model}}(b)]$$

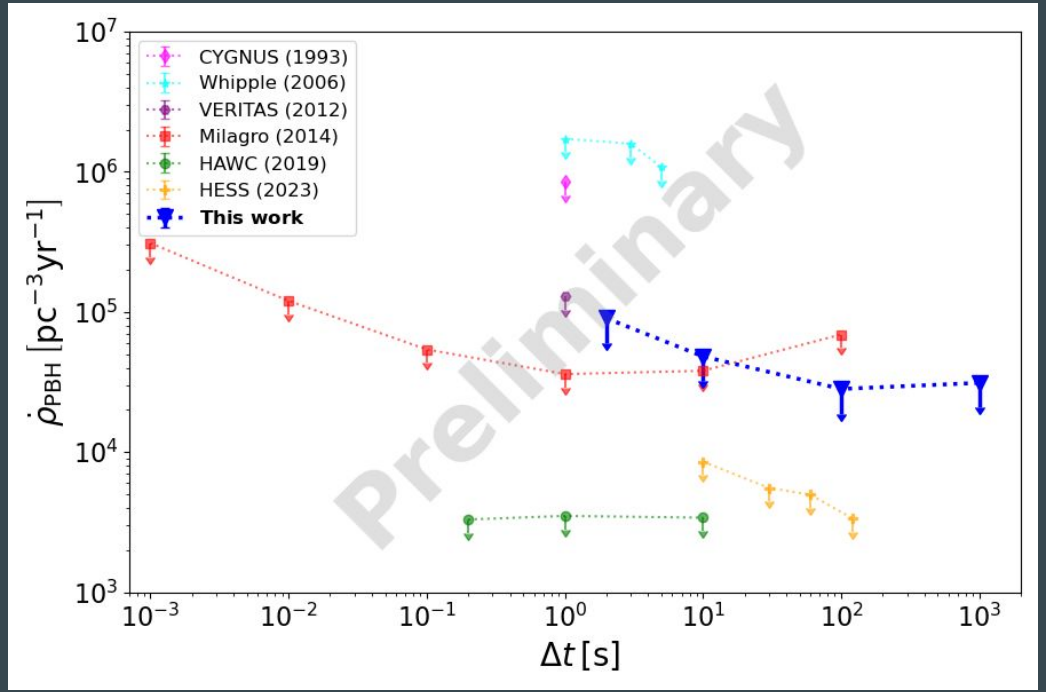


PBH evaporation rate density upper limits

- 2076.5h of data after quality cuts.
- Timescales of 2, 10, 100 and 1000s were explored.
- No evaporation signal found.

Best 99% CL upper limit:

$$\dot{\rho} = 28203\,\mathrm{pc}^{-3}\mathrm{yr}^{-1}$$



Future work

- Add more data.
  - Two more periods can already be added (+ ~1500 raw hours).
- Simulate PBHs with different spins and initial mass distribution.

Thank you for your attention