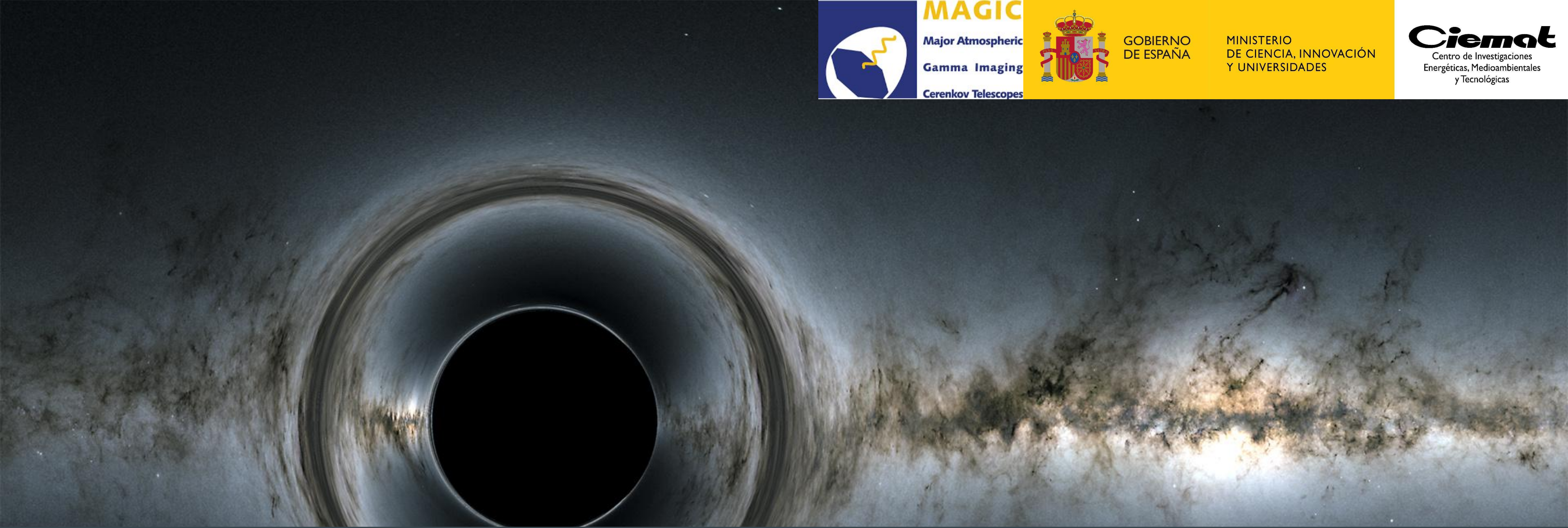

MAGIC Major Atmospheric Gamma Imaging Cerenkov Telescopes

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Primordial Black Hole Evaporation Signal Searches with MAGIC

TeVPA 2026 - Tendo, Japan

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

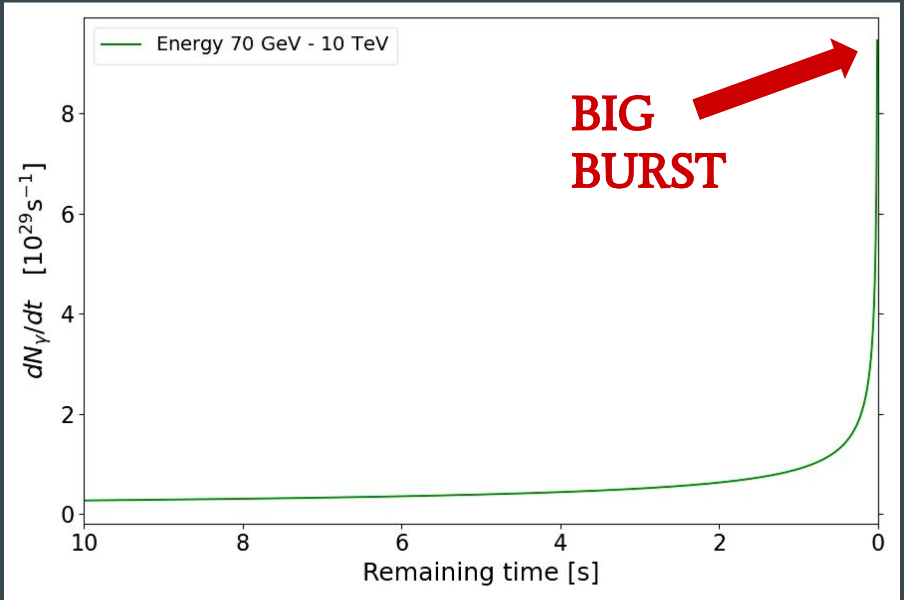
Primordial Black Holes: Theory

- 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)

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

- Hawking radiation negligible for $M_{BH} > M_\odot$

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



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

PBHs of initial mass ~ 5.0 x10^{14} g should be evaporating now (assuming SM and no spin)

Primordial Black Holes: Spectrum

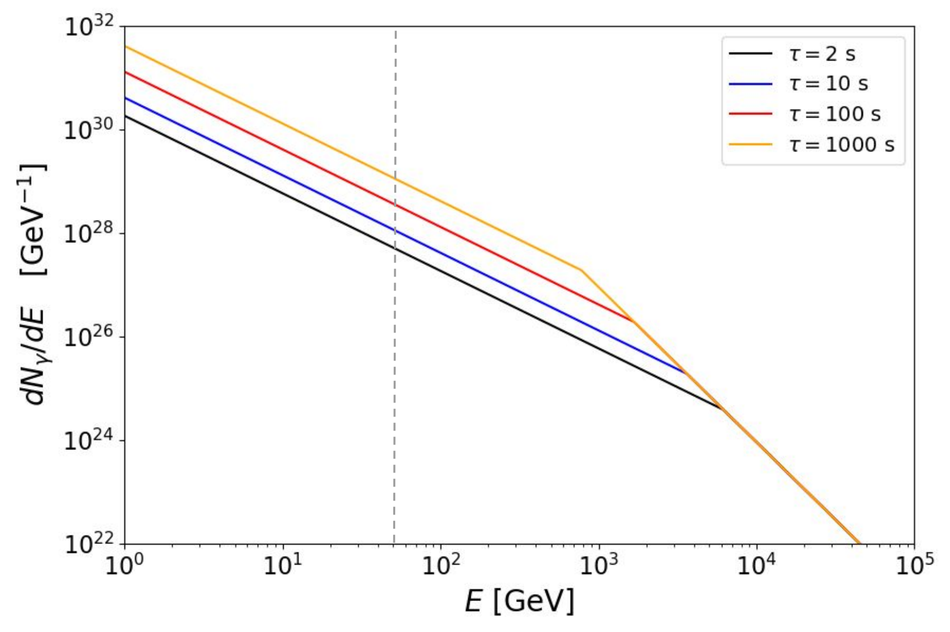
PBH evaporation gamma-ray spectrum:

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

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

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

Petkov et al. (2008)



Time-integrated photon energy spectrum for different burst timescales τ.

No effect on final burst even if initial PBH spin ~0.99

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

MAGIC dataset

- 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 effective time amounts to **1650.1h.**

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**

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.

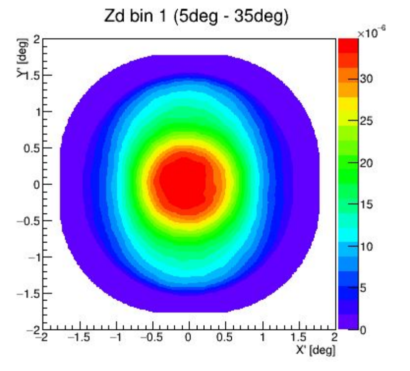
1. Gamma-like background model
    a. From instrument response function (IRF) and **overall camera rate**
2. Number of expected **gamma-like background events** computed for the same cell and time bin.

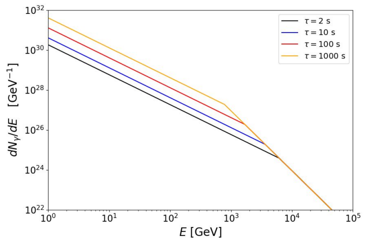
Compute p-values

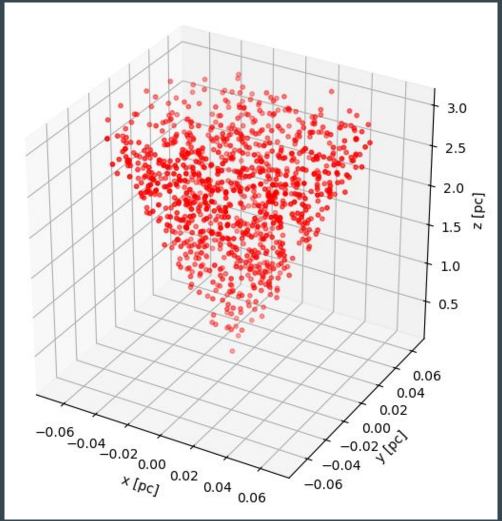
Search for individual PBH bursts

Simulation

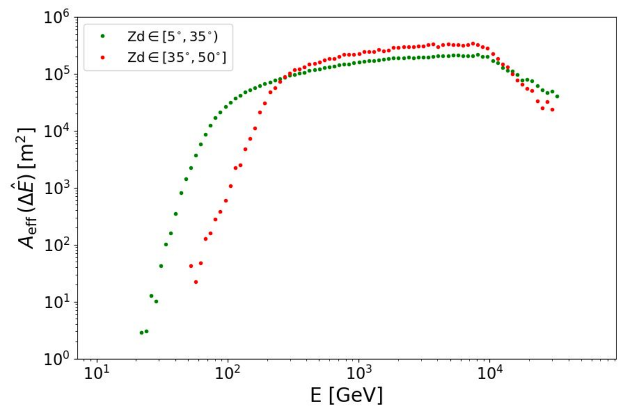
Knowing the PBH spectrum and MAGIC's IRF for the observation periods.







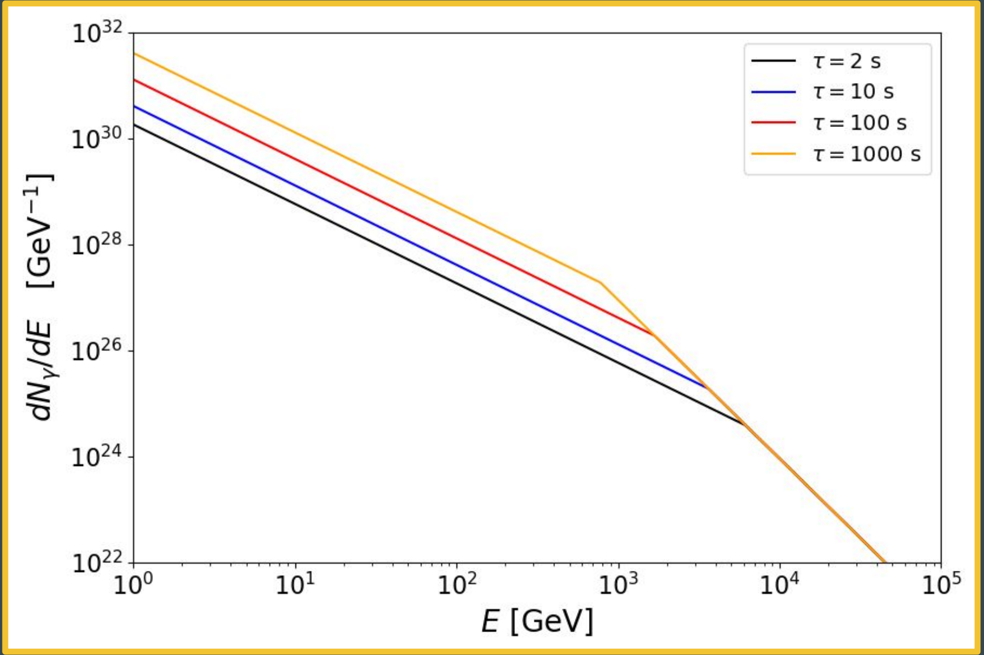
Simulated PBH bursts within MAGIC's FoV up to 3pc for a time of 3 years and $\dot{\rho} = 1.9 \times 10^5 \mathrm{pc}^{-3}\mathrm{yr}^{-1}$



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

Simulation

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



Spectrum

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

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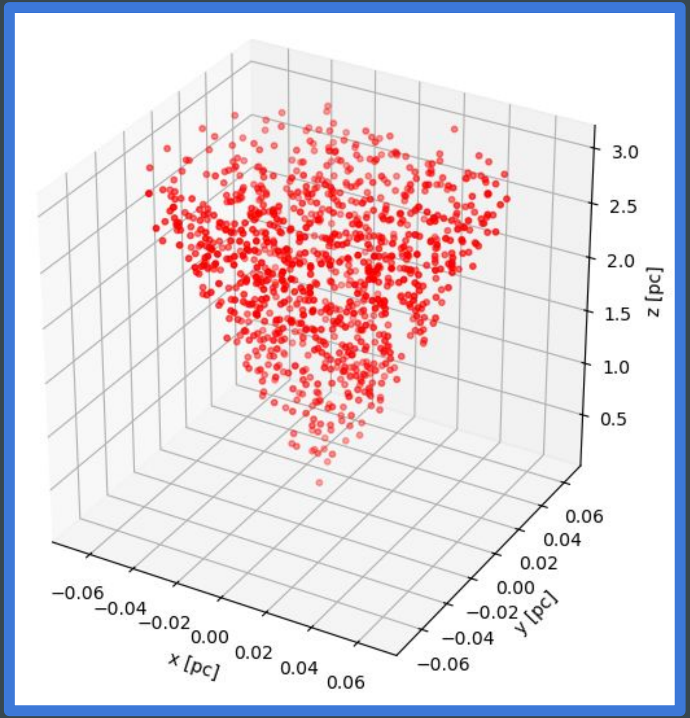


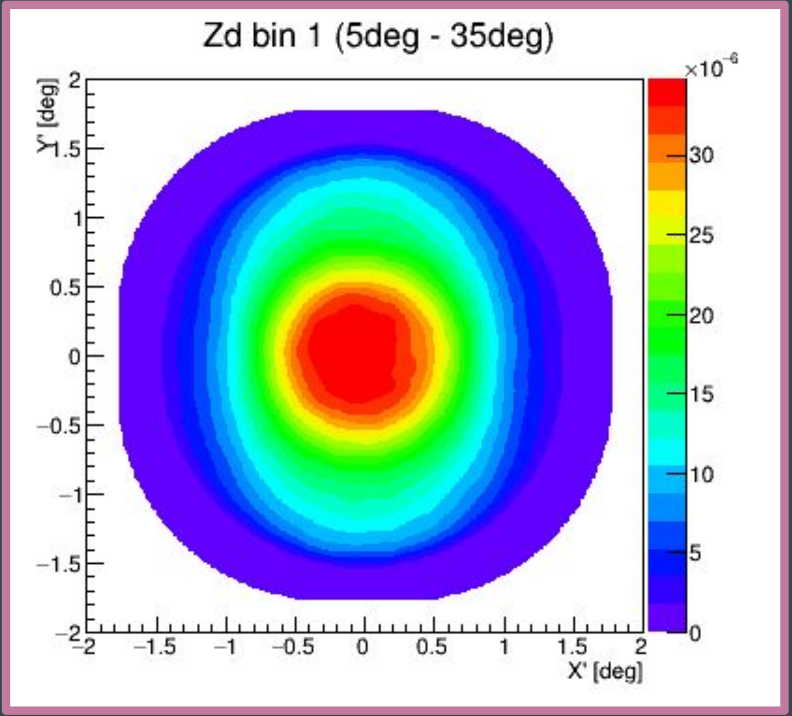
Distance

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

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

Simulation

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



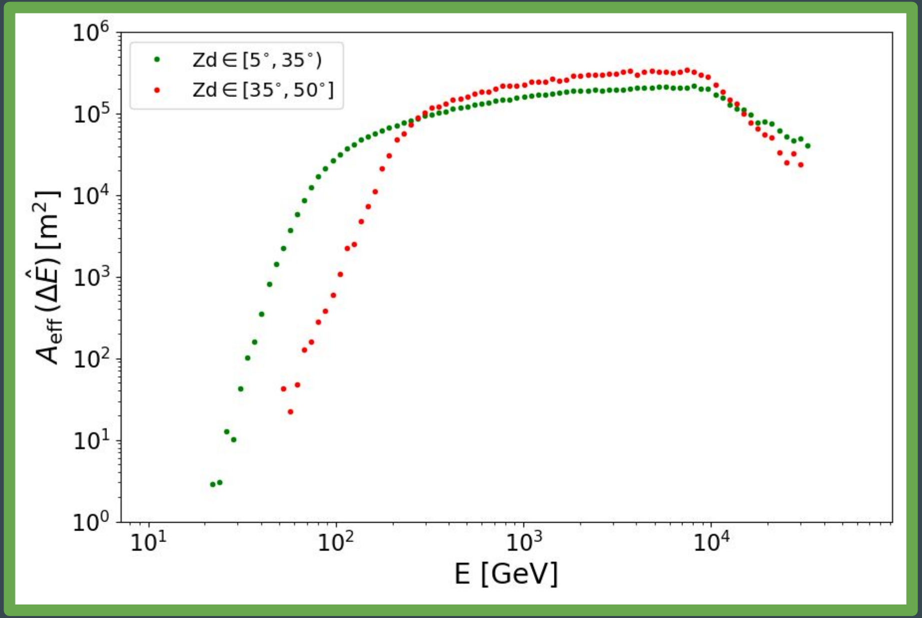
Relative gamma-ray detection efficiency map of MAGIC.

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

Efficiency

Simulation

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

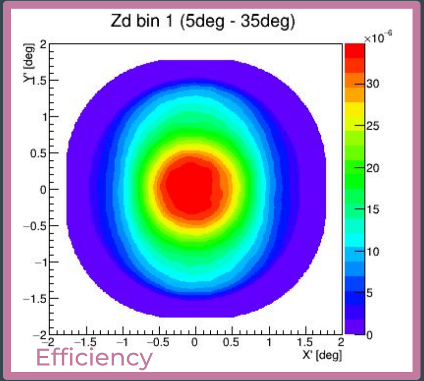


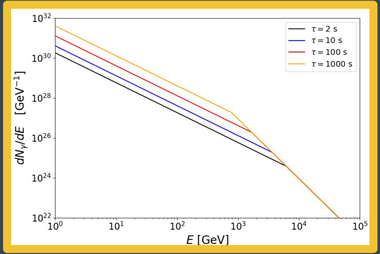
Effective area

MAGIC's effective area for the dataset used.

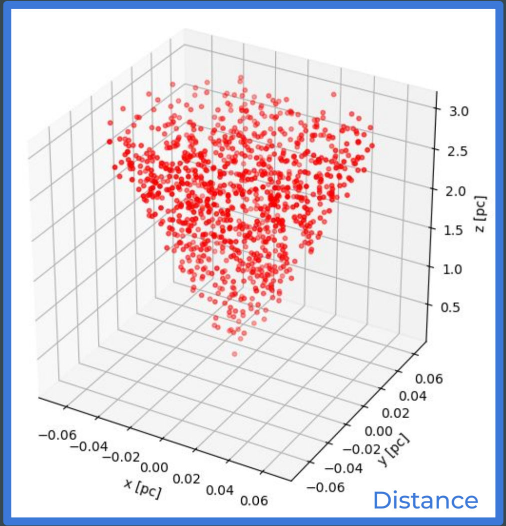
$$g(r, \mathrm{Zd}, \tau, \epsilon) = \frac{1}{4\pi r^2} \int_0^\infty dE \frac{dN(\tau)}{dE} \epsilon \underline{A_{\mathrm{eff}}(E|\Delta\hat{E}, \mathrm{Zd})}$$

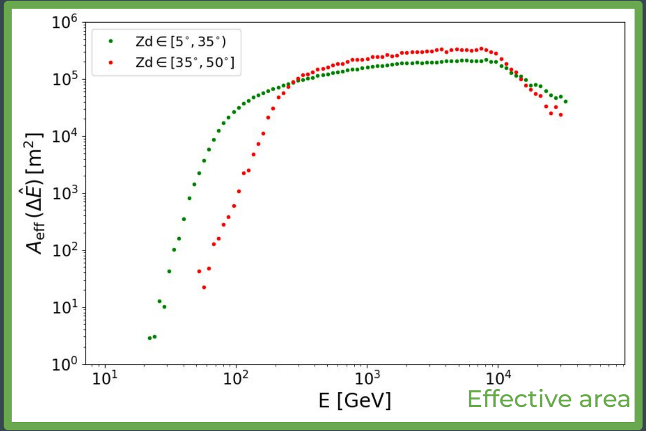
Simulation





Spectrum





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FEED IT TO THE PIPELINE!

Analysis

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

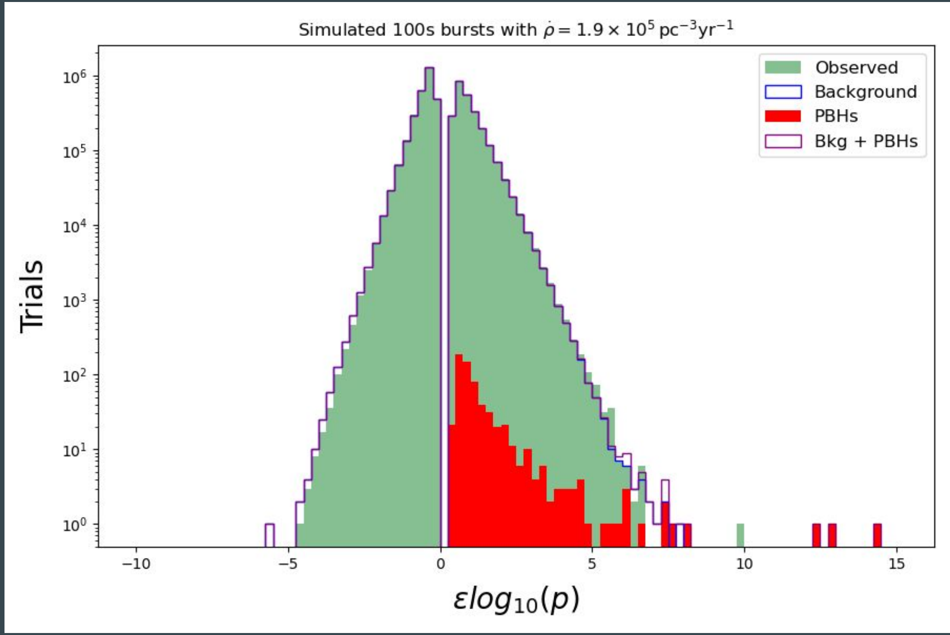
- Create a distribution of p-values:
  - Observed events
  - Background events
  - Simulated PBH events
- Calculate **upper limits** on $\dot{\rho}$ (99 and 95% CL)
- Using H_{Data}, H_{Bkg} and H_{Model}

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

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

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

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

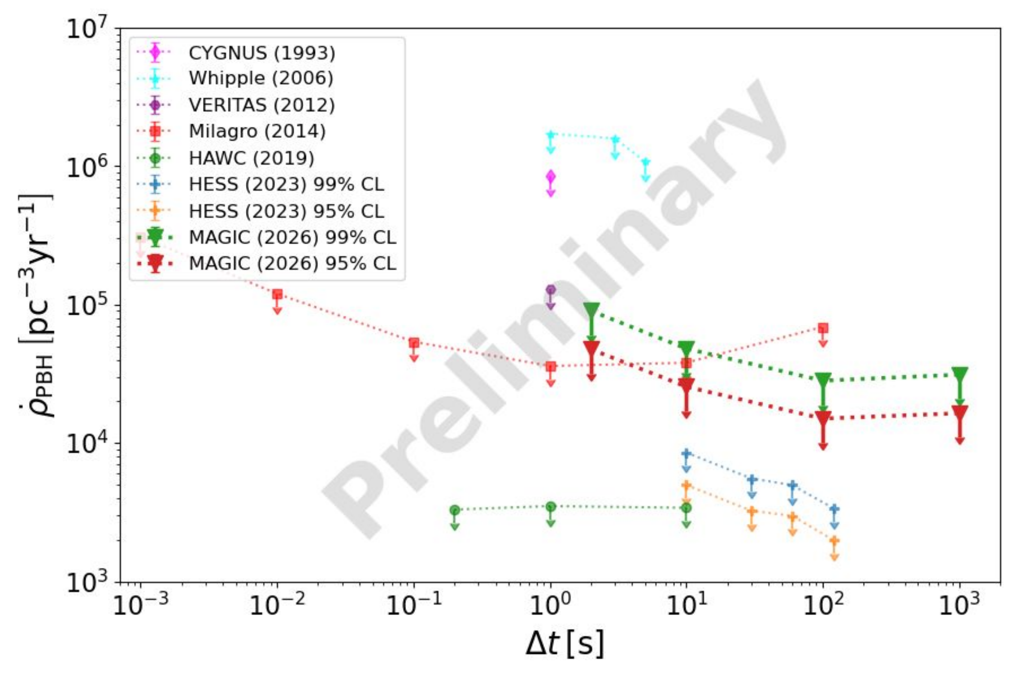


PBH evaporation rate density upper limits

- 1650.1h of effective time analyzed.
- Timescales of 2, 10, 100 and 1000s were explored.
- Sensitive up to 2pc.
- No evaporation signal over 5σ after corrections.

Best 95% CL upper limit:

$$\dot{\rho} = 15010\,\mathrm{pc}^{-3}\mathrm{yr}^{-1}$$



Dark Matter Fraction

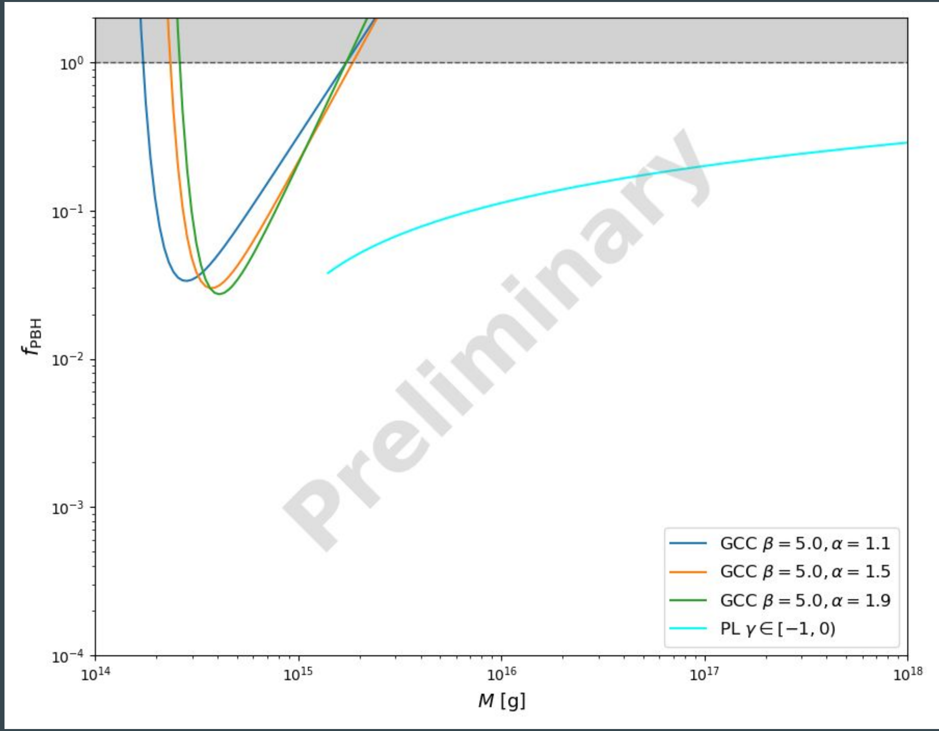
$f_{PBH} = \Omega_{PBH}/\Omega_{DM}$

- Assuming monochromatic:
  - **Limit to past** Ω_{PBH} with $M = 5 \cdot 10^{14}$g
  - Unrealistic
- Assuming extended mass functions:
  - Power law (PL) (scale invariant density fluctuations, cosmic strings).
  - Generalized critical collapse (GCC).

$$\phi_{\rm PL}(M_i) \propto M_i^{\gamma-1}, \qquad \gamma = 2w/(1+w)$$ 1)

$$\phi_{\rm GCC}(M_i) = \frac{\beta}{\mu\,\Gamma(\alpha\beta)}\left(\frac{M_i}{\mu}\right)^{\alpha-1}\exp\left[-\left(\frac{M_i}{\mu}\right)^{\beta}\right], \qquad \beta>0,\ \alpha>1$$

$$\bar{M} = \mu\left(\frac{\alpha-1}{\beta}\right)^{1/\beta}$$



Upper limits on the current fraction of DM composed by PBHs assuming two extended mass formation functions and the evaporation rate density obtained in this work

1) w = equation of state of the Universe when PBH form

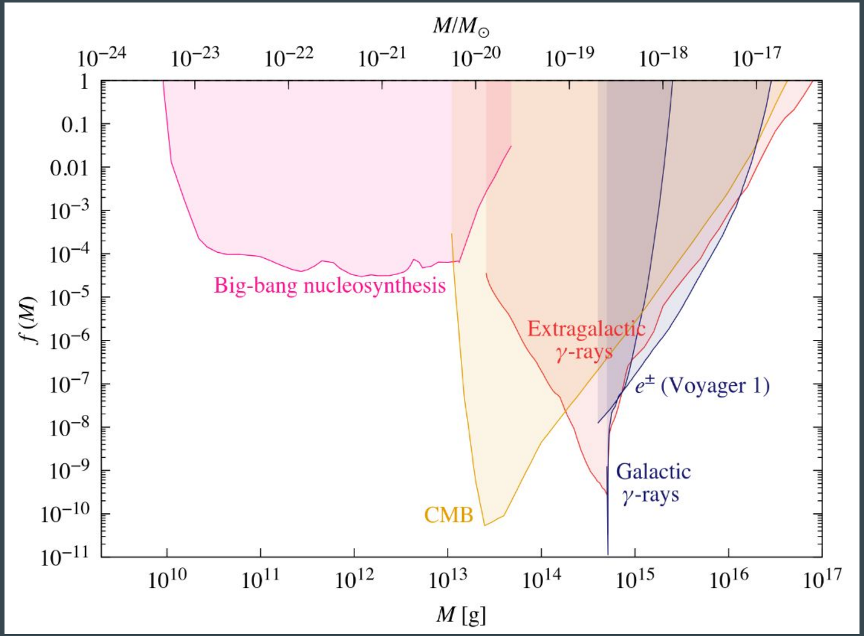
Summary and outlook

- ~1650 hours of effective time MAGIC data analyzed.
  - Currently no more data can be added.
  - Single burst search loses power with more data.
- Obtained 95% CL upper limits on current f_{PBH}.
- Spin distribution has no significant effect.
- Limits from burst search always less constraining than from gamma-ray background:
  - Best for PBH detection.
  - Recommended live detection analysis + multimessenger alert.

Thank you for your attention

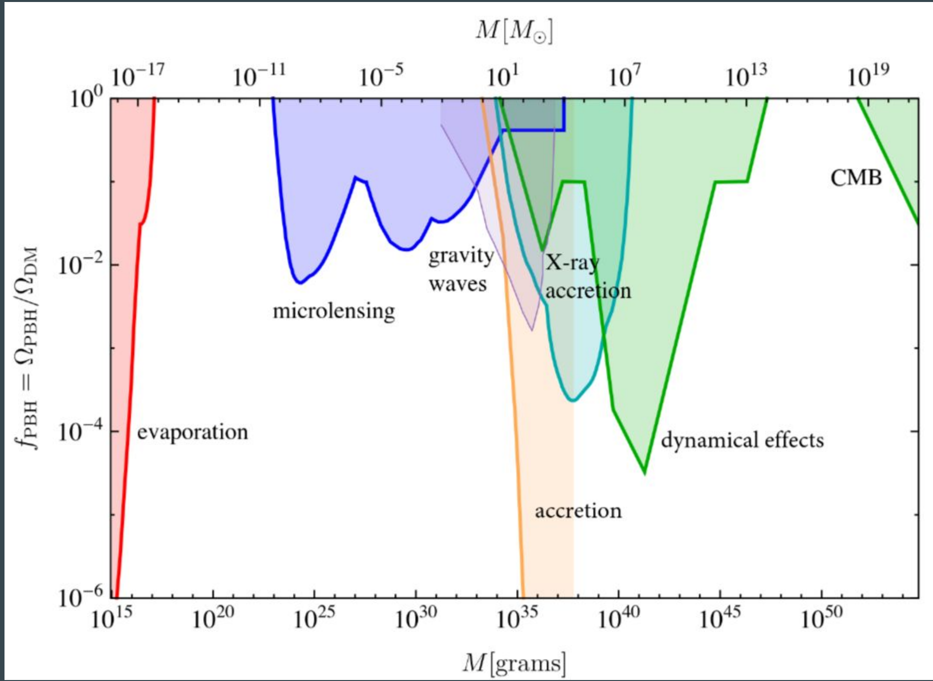
PBHs as DM: General view

Carr et al. 2021



Evaporation constraints on f_{PBH} at time of formation.

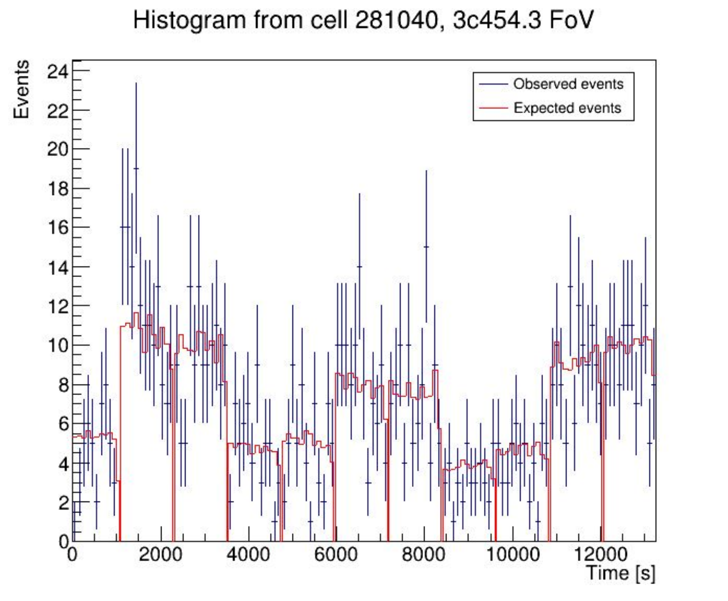
Carr et al. 2024



Constraints on f_{PBH} as a function of mass, M, assuming all PBHs have the same mass.

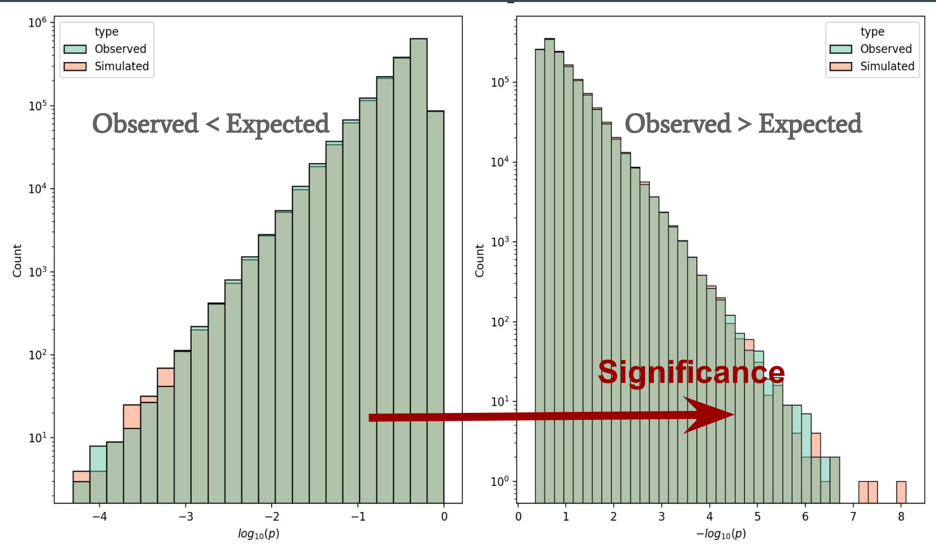
Burst search results

Applied search to dataset → 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 the whole dataset of observations.