Search for PBH evaporations with H.E.S.S. – ICRC 2019

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Physics assumptions

- Primordial black holes are an hypothetical type of black hole that formed in the early universe.
- Various scenarios :
  - Density fluctuations → gravitational collapse
  - Inflation related scenarios

  → Mass from Planck scale to few tens of solar masses.

→ The idea that PBH may account for a significant fraction of the invisible mass experiences a renewed popularity.

- According to Hawking Radiation process :
  - PBHs with an initial mass of $\sim 5.0x10^{14}$g ($\sim 10^{-19}\mathrm{M}_{\odot}$) should be evaporating now with bursts of high-energy particles, including gamma radiation in the TeV energy range.

Black Hole evaporation – Hawking Radiation

BH Thermodynamics

- J. Bekenstein :
  - BH entropy was $\propto$ Area of its event horizon
- S. Hawking :
  - black-body radiation

$$T_{\rm BH} = \frac{M_p^2}{8\pi M_{\rm BH}}$$

$\rm M_p$: Planck mass
$M_{\rm BH}$: PBH mass

Hawking radiation process

- negligible for M $\sim \rm M_\odot$
- TeV burst at final stage of evaporation (last 10-100 second of their lifetime)

Overview of the analysis

→ **Goal of the analysis** :
search TeV γ-ray bursts

- Timescale of a few seconds
- Signal of few photons

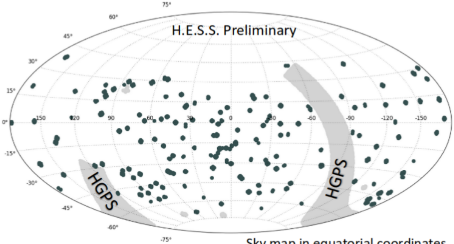
- Use efficient algorithm to detect such bursts
- Have a reliable estimation of the false positive background
- Estimate signal expected with H.E.S.S. from PBH evaporations
- Use analysis results to put upper limits on PBH evaporations rate, or eventually claim a signal detection

Data set used :

Use of H.E.S.S. I extragalactic data [1] ($|b| > 10^\circ$) from 01/2004 to 01/2013

H.E.S.S. extragalactic survey data set :

- 6250 runs
- 2860 hours of observation



Sky map in equatorial coordinates

1. F. Brun et al. for the HESS collaboration, Fermi Symposium 2017

Current limits on PBH evaporation

Currents upper limits on PBH evaporation rate ($\dot{\rho}_{\rm PBH}$) lie between $10^4 - 10^5 pc^{-3} yr^{-1}$

Early HESS analysis in 2013

(ICRC talk and paper draft)

- UL for 1s time scale : $\sim 8 \times 10^4 pc^{-3} yr^{-1}$
- UL for 30s time scale : $\sim 1.4 \times 10^4 pc^{-3} yr^{-1}$

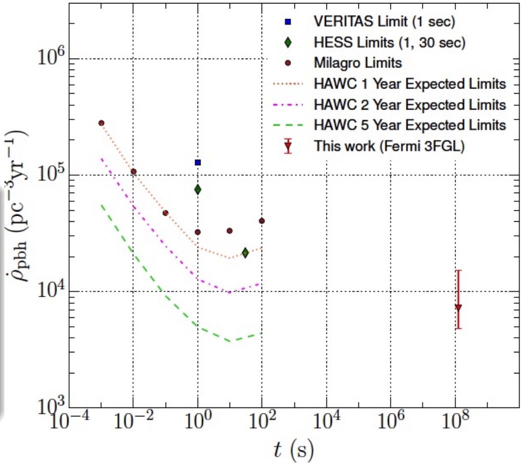


Figure from *Search for Gamma-Ray Emission from Local Primordial Black Holes with the Fermi Large Area Telescope (Fermi LAT, ApJ 2018)*

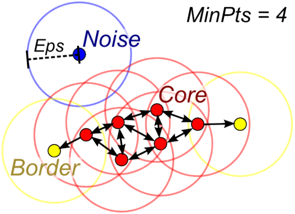
Burst detection algorithm : a 3D approach

DBSCAN : *density-based spatial clustering of applications with noise*

2 input parameters :

- MinPts : minimum number of points in cluster
- eps : maximum distance

3rd Parameter for our analysis : Metric to apply for the time dimension.



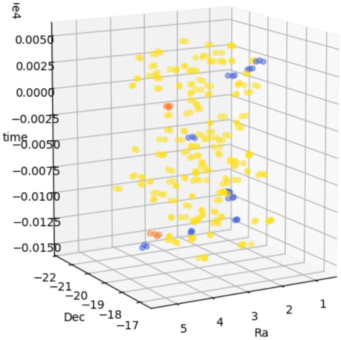
clusters with important number of photons might extend beyond the PSF and Δt

- 2d level to exclude photons outside the limits

DBSCAN output

Cluster parameters :

- minimum γ-Like in cluster $= 2$
- eps $\sim$ 2*80%PSF $= 0.2^o$
- $\Delta T = 10$ s



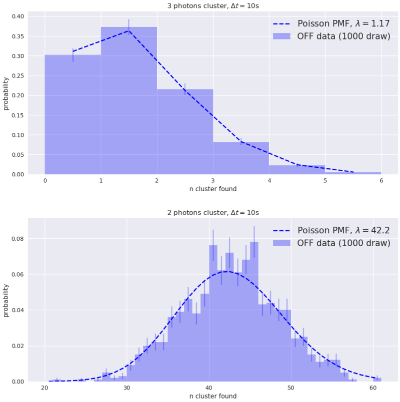
Background estimation

False positive background estimation

- Shuffling the time of arrivals of photons
- $\sim$ 50 MC realisations for each run (hereafter OFF data)

Probability distribution of the number of clusters in a run :

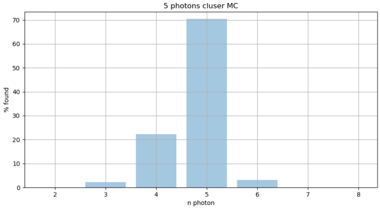
- Well described by a Poissonian law.



Algorithm efficiency

Algorithm efficiency :

- 1000 MC injection of 5 photons cluster in the data (2 per run in 500 runs)
    - 2D Gaussian dist. in Ra Dec ($\sigma = 0.1^\circ$)
    - uniform dist. in time
- efficiency of $\sim$ 98 %



Expected signal from PBH evaporation

Evaporation spectrum :

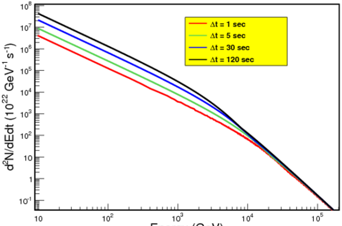
$$\frac{dN}{dE} = \Phi_0 \times \begin{cases} \left(\frac{E}{E_0}\right)^{-\alpha_0} & \text{for} \quad E \leq E_{\text{cut}} \\ \left(\frac{E_{\text{cut}}}{E_0}\right)^{\alpha_1 - \alpha_0} \left(\frac{E}{E_0}\right)^{-\alpha_1} & \text{for} \quad E \geq E_{\text{cut}} \end{cases}$$

with :

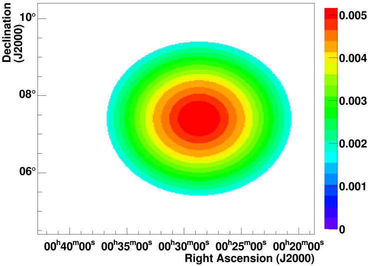
- $E_{\text{cut}} = 38.(\frac{1}{\Delta t})^{1/3.}$ TeV

See J.H. MacGibbon & B.R. Webber (1990)

Assuming the predicted PBH evaporation spectral shape (duration of 10 seconds), the expected number of photons is computed for each run using the HESS IRFs.



MCRateMap_65536



Expected signal from PBH evaporation

The information we really need :

Number M of cluster with N_{obs} photons observed during the run

$$M(N_{\text{obs}}) = \int d\Omega \int_0^{T_{\text{run}}} dt \int_0^{\infty} dr r^2 \dot{\rho}_{\text{PBH}} P(N_{\text{obs}}|\mu(r))$$

Where :

- Ω is the solid angle of the H.E.S.S. field of view
- r is the distance of the PBH
- $\mu(r)$ is the mean number of photons seen with H.E.S.S.
- $\dot{\rho}_{\text{PBH}}$ the PBH evaporation density rate

$$M(N_{\text{obs}}) = \Omega T_{\text{run}} \dot{\rho}_{\text{PBH}} \frac{(r_0\sqrt{N_0})^3}{2} \frac{\Gamma(N_{\text{obs}} - 3/2)}{\Gamma(N_{\text{obs}} + 1)}$$

where N_0 is the mean number of photons seen for a PBH evaporation at given distance r_0

Significance test and Upper limits estimation

Feldman-Cousins test :

$$\frac{\mathcal{L}_{H_1}}{\mathcal{L}_{H_0}} = \prod_{n_{\mathrm{ON}} \in \mathrm{Data}} \frac{\mathcal{P}(n_{\mathrm{ON}} | \lambda = n_{\mathrm{OFF}} + M(n_{\mathrm{phot}}, \dot{\rho}_{\mathrm{PBH}}))}{\mathcal{P}(n_{\mathrm{ON}} | \lambda = n_{\mathrm{OFF}})}$$

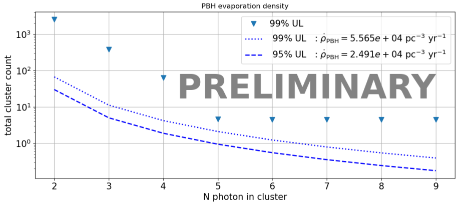
Where $M(n_{\mathrm{phot}}, \dot{\rho}_{\mathrm{PBH}})$ is the expected excess.

$$TS = -2ln\left(\frac{\mathcal{L}_{H_1}}{\mathcal{L}_{H_0}}\right) = 2 \times \sum_{n_{\mathrm{ON}}} M + n_{\mathrm{ON}}\left(ln(n_{\mathrm{OFF}}) - ln(n_{\mathrm{OFF}} + M)\right)$$

Results

- 2860 hours of observation
- $\Delta T = 10$ second

No significant PBH evaporation signal ($\sigma < 0.1$)



Preliminary 95% C.L upper limit : $2.49 \times 10^4 pc^{-3} yr^{-1}$

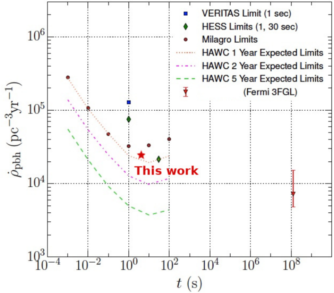


Figure from *Search for Gamma-Ray Emission from Local Primordial Black Holes with the Fermi Large Area Telescope (Fermi LAT, ApJ 2018)*

Summary

- Analysis was ran on 2860 hours of extragalactic H.E.S.S data for $\Delta t = 10$ s
- No hint of signal.
- Preliminary 95% upper limit of 2.5×10^4 pc^{-3} yr^{-1} is competitive with previous limits
- Upcoming :
  - Find optimal time scale
  - More data

Other output of the analysis

Is there significant burst in the data ?

- here for $\Delta t = 30$ sec

n run	MJD	n_{phot}	N_{ON}	$< N_{\mathrm{OFF}} >$	$\mathcal{P}$	σ
...						
41246	54334.054355	5	4.0	0.52	0.00181121	3.11
42153	54379.886926	2	240.0	281.44	0.001036	3.28
29794	53704.8957049	5	4.0	0.32	0.000317	3.60
20440	53116.8205595	2	342.0	297.36	0.000883	3.32
32116	53871.7584333	6	2.0	0.04	0.0007686	3.36
73033	56099.7745254	8	1.0	0.0	0.0004129	3.53
...						

We expect a lot of such event from background fluctuation due to the number or trials. However it could be interesting to see if there is any match with known GRBs or FRBs.

No clustered photon event with significance $> 5\sigma$