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

Thomas Tavernier,
J.F. Glicenstein, F. Brun

IRFU / CEA-Paris Saclay, Université Paris-Saclay

thomas.tavernier@cea.fr

31 juillet 2019
Primordial black holes are an hypothetical type of black hole that formed in the early universe.

Various scenarios:
- Density fluctuations $\rightarrow$ gravitational collapse
- Inflation related scenarios
  $\rightarrow$ Mass from Planck scale to few tens of solar masses.

$\rightarrow$ 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 $\sim 5.0 \times 10^{14} \text{g} \left(\sim 10^{-19} \text{M}_\odot\right)$ 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

\[ T_{BH} = \frac{M_p^2}{8\pi M_{BH}} \]

- $M_p$ : Planck mass
- $M_{BH}$ : PBH mass

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

---

1. F. Brun et al. for the HESS collaboration, Fermi Symposium 2017
Current limits on PBH evaporation

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

Early HESS analysis in 2013 (ICRC talk and paper draft)
- UL for 1s time scale: $\sim 8 \times 10^4 \text{pc}^{-3} \text{yr}^{-1}$
- UL for 30s time scale: $\sim 1.4 \times 10^4 \text{pc}^{-3} \text{yr}^{-1}$

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 $\Delta t$

- 2d level to exclude photons outside the limits
Cluster parameters:

- minimum $\gamma$-Like in cluster = 2
- $\epsilon = 2\times80\%PSF = 0.2^\circ$
- $\Delta T = 10$ 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:

- 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:

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

with:

- \( E_{\text{cut}} = 38 \cdot \left( \frac{1}{\Delta t} \right)^{1/3} \) 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.
Expected signal from PBH evaporation

The information we really need:

Number $M$ of cluster with $N_{\text{obs}}$ 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:

- $\Omega$ 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

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

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:

\[
\frac{\mathcal{L}_{H_1}}{\mathcal{L}_{H_0}} = \prod_{n_{ON} \in \text{Data}} \frac{\mathcal{P}(n_{ON} | \lambda = n_{OFF} + M(n_{\text{phot}}, \rho_{\text{PBH}}))}{\mathcal{P}(n_{ON} | \lambda = n_{OFF})}
\]

Where \( M(n_{\text{phot}}, \rho_{\text{PBH}}) \) is the expected excess.

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

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

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

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

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 $2.5 \times 10^4$ 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

<table>
<thead>
<tr>
<th>n run</th>
<th>MJD</th>
<th>$n_{\text{phot}}$</th>
<th>$N_{\text{ON}}$</th>
<th>$&lt; N_{\text{OFF}} &gt;$</th>
<th>$\mathcal{P}$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>41246</td>
<td>54334.054355</td>
<td>5</td>
<td>4.0</td>
<td>0.52</td>
<td>0.00181121</td>
<td>3.11</td>
</tr>
<tr>
<td>42153</td>
<td>54379.886926</td>
<td>2</td>
<td>240.0</td>
<td>281.44</td>
<td>0.001036</td>
<td>3.28</td>
</tr>
<tr>
<td>29794</td>
<td>53704.8957049</td>
<td>5</td>
<td>4.0</td>
<td>0.32</td>
<td>0.000317</td>
<td>3.60</td>
</tr>
<tr>
<td>20440</td>
<td>53116.8205595</td>
<td>2</td>
<td>342.0</td>
<td>297.36</td>
<td>0.000883</td>
<td>3.32</td>
</tr>
<tr>
<td>32116</td>
<td>53871.7584333</td>
<td>6</td>
<td>2.0</td>
<td>0.04</td>
<td>0.0007686</td>
<td>3.36</td>
</tr>
<tr>
<td>73033</td>
<td>56099.7745254</td>
<td>8</td>
<td>1.0</td>
<td>0.0</td>
<td>0.0004129</td>
<td>3.53</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 $> 5\sigma$