Search for PBH evaporations with H.E.S.S.

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

IRFU / CEA-Paris Saclay, Université Paris-Saclay

thomas.tavernier@cea.fr

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Physics assumptions

- Primordial black holes are an hypothetical type of black hole that formed in the early universe.
- Various scenarios :
  - Gaussian density fluctuations $\rightarrow$ gravitational collapse

  $\rightarrow$ Power law mass spectrum

$\rightarrow$ 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 $\sim 5.0x10^{14}$g ($\sim 10^{-19}\mathrm{M}_{\odot}$) should reach there final stage of evaporation now. Possibly emitting bursts of high-energy particles, including gamma radiation in the TeV energy range.

Overview of the analysis

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

- Timescale of a few seconds to few minutes
- Signal of few photons

→ **Analysis steps :**

- Use efficient algorithm to detect such bursts
  - OPTICS algorithm
- Have a reliable estimation of the false positive background
  - Estimated through shuffling several times the timestamps in the data, then running the same algorithm.
- Estimate signal expected with H.E.S.S. from PBH evaporations
  - Using PBH evaporation spectrum, convoluted whith the H.E.S.S. IRF
- Use statistical method to put upper limits on PBH evaporations rate, or eventually claim a signal detection
  - Maximum likelihood ratio
- Use these upper limits to constrain cosmological models

Dataset

- H.E.S.S.-1 observations between January 2004 and January 2013. (GPS & HEGS data set)
- Runs of poor quality (bad weather or technical problems) excluded
- Sources region are excluded
- Use only runs available for both H.E.S.S. analysis chains. (X-check)

- Final dataset : 11494 runs (4924 hours).

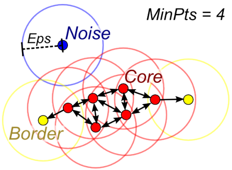
OPTICS Algorithm (3D approach)

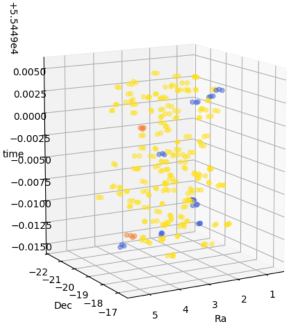
OPTICS : *ordering points to identify the clustering structure*

3 input parameters :

- n : MinPts : minimum number of points in cluster (2)
- ϵ : maximum distance (0.14^o : 2x point source radius definition in H.E.S.S. (was 0.2^o for PA))
- χ_0 : reachability cut (0.05)

4th Parameter for our analysis : Metric to apply for the time dimension.





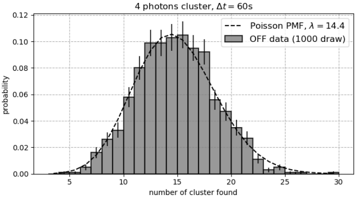
Background estimation

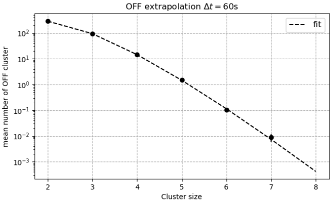
False positive background estimation

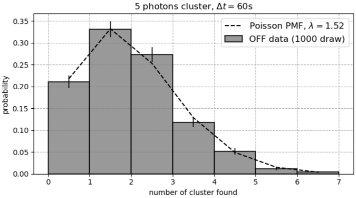
- Shuffling the time of arrivals of photons
- 200 MC realisations for each run (hereafter OFF data)

Probability distribution of the number of clusters in a run :

- Well described by a Poissonian law.
- Can be extrapolated for larger clusters







Expected signal from PBH evaporation

Evaporation spectrum :

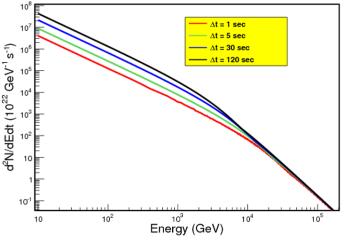
$$\frac{dN}{dE} = \Phi_0 \times \begin{cases} \left(\frac{E}{E_0}\right)^{-\alpha_0} & \text{for} \quad E \leq E_{\rm cut} \\ \left(\frac{E_{\rm cut}}{E_0}\right)^{\alpha_1-\alpha_0} \left(\frac{E}{E_0}\right)^{-\alpha_1} & \text{for} \quad E \geq E_{\rm cut} \end{cases}$$

with :

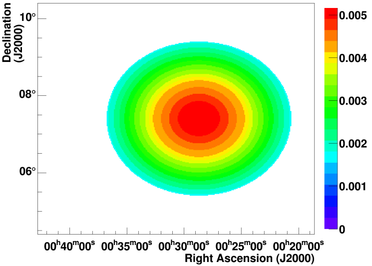
- $E_{\rm cut} = 38.(\frac{1}{\Delta t})^{1/3.}$ TeV

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

Assuming the predicted PBH evaporation spectral shape, 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 a size of $N_{\rm obs}$ photons observed during the run

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

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.
- $\dot{\rho}_{\rm PBH}$ the PBH evaporation density rate

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

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.

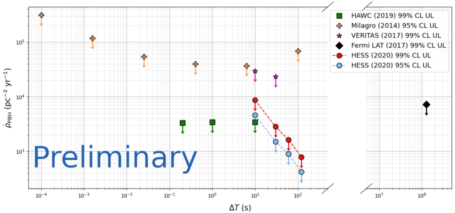
$$TS = -2ln\left(\frac{\mathcal{L}_{H_1}}{\mathcal{L}_{H_0}}\right) = 2 \times \sum_{n_{\mathrm{ON}}} M + n_{\mathrm{ON}}\left(ln(n_{\mathrm{OFF}}) - ln(n_{\mathrm{OFF}} + M)\right)$$

Results : Limits on PBH evaporation rate

- Analysis was ran for 10s, 30s, 60s, 120s time scales
- No significant PBH evaporation signal ($\sigma < 0.5$)

Preliminary best 99% C.L upper limit :
$\dot{\rho}_{\mathrm{PBH}} < 700\ \mathrm{pc}^{-3}\mathrm{yr}^{-1}$

- 4924 hours of HESS data
- HAP photon list



Cosmological interpretation : assumptions

- PBH creation induced by Gaussian density fluctuations
- initial mass distribution described by a power law :

$$\frac{d\rho_{PBH}}{d\mathrm{M}_i} = \frac{\rho_0}{\mathrm{M}_*}\left(\frac{\mathrm{M}_i}{\mathrm{M}_*}\right)^{-\beta}$$

with :
M_i the initial mass of PBHs
M_* the initial mass of PBHs at the final stage of evaporation here and now.

- $2 < \beta < 3$

ρ_0 is given by $\rho_0 = (\beta - 2)\frac{\Omega_{\mathrm{PBH}}\rho_c}{M_*}$
where Ω_{PBH} is the fraction of the critical density ρ_c

Cosmological interpretation : assumptions

Local rate of evaporation is given by [Halzen et al 1991]

$$\dot{\rho}_{\mathrm{PBH}} \simeq \frac{\alpha(M_*)}{M_*^3}\eta\rho_0 \simeq \frac{\alpha(M_*)}{M_*^4}\eta(\beta-2)\Omega_{\mathrm{PBH}}\rho_c$$

where :

- $\alpha(M)$ counts the degrees of freedom of the particles contributing to the energy loss as a function of the black-hole mass
- η is the ratio between the global and local dark matter densities.

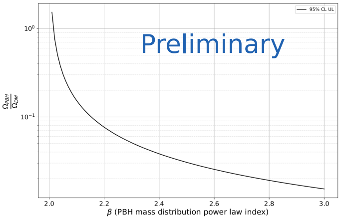
using

- $\eta > 1.6 \times 10^4$ [bovy 2012]
- $\alpha(M_*) > 10^{17}$ kg^3 s^{-1}

Our upper limits of $\dot{\rho}_{\mathrm{PBH}}$ constrains the product $(\beta-2)\Omega_{\mathrm{PBH}}$

Cosmological limits on $\Omega_{\rm PBH}$

- $\frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} < 1$ for most values of *beta*
- It would require fine tuning for these object to be responsible for the major part of the invisible mass



Summary

- Analysis summary :
  - Analysis was ran on ~5000 hours of H.E.S.S data for $\Delta t = 10$, 30, 60 and 120 seconds using HAP analysis chain.
  - No hint of signal.
  - 99% CL upper limits lies between 6.5×10^3 and 7.0×10^2 pc^{-3} yr^{-1} is competitive with previous measurements
- Assuming PBH are induced by Gaussian density fluctuations and follows Hawking's evaporation process : PBHs are unlikely to participate significantly in the missing mass of the universe.