Fermi LAT limit on evaporation of individual primordial black holes

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Primordial black holes

- Proposed by
  – Zeldovich, Novikov (1966)
  – Hawking (1971)
- Fluctuations of density in the early Universe
  – Large fluctuations of density (non-gaussianity?)
  – Small pressure states (energy density is dominated by non-relativistic particles)
- Mass range: from Planck mass to the masses of SMBHs
- Uses:
  – Constrain cosmological theories on scales much smaller than CMB
  – Were proposed as the origin of SMBHs at high redshift
  – Were suggested as the origin of stellar mass BHs observed in LIGO / Virgo

Black hole temperature

- Beckenstein (1973)
  - Information loss paradox
  - Generalized entropy S + A / 4
  - BHs have a “temperature” T ~ 1 / M
- Hawking (1975)
  - Black holes emit radiation with thermal spectrum

$$F = \frac{1}{2\pi} \frac{\Gamma_{\rm s}}{e^{E/T} - (-1)^{2s}}$$

  - where

$$T = \frac{M_{\rm P}^2}{8\pi M}$$

Evaporation

- **Temperature**

$$T = \frac{M_P^2}{8\pi M}$$

- **Mass loss ~ emission power**

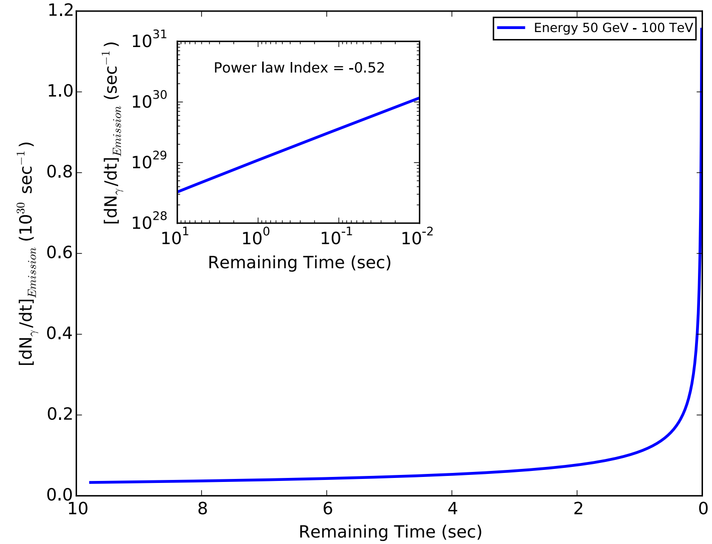
$$\dot{M} \sim R^2 T^4 \sim M^{-2}$$

- **Lifetime**

$$\tau \sim M^3 \sim T^{-3}$$

- **10 MeV, 10^{15} g, lifetime of the Universe**
- **10 GeV, 10^{12} g, 30 years**
- **10 TeV, 10^{9} g, 1 second**

PBH evaporation gamma-ray light curve



Ukwatta et al, APh 80 (2016)
arxiv:1510.04372

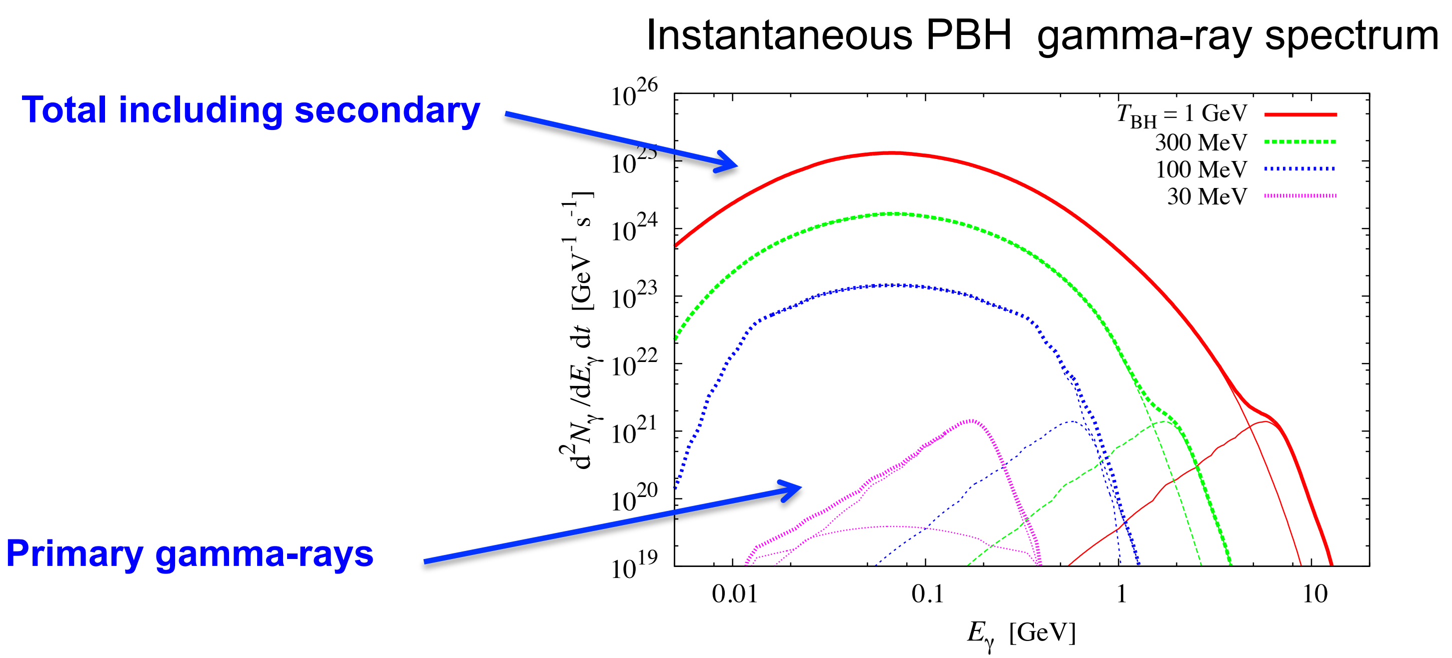
Some numbers

- **Black hole: M = 10^{15} g, T ~ 10 MeV**
  - **Size of a nucleus, 10^{-15} m**
  - **Mass of a 1000 of super large oil tankers**

1000 x

PBH gamma-ray spectrum

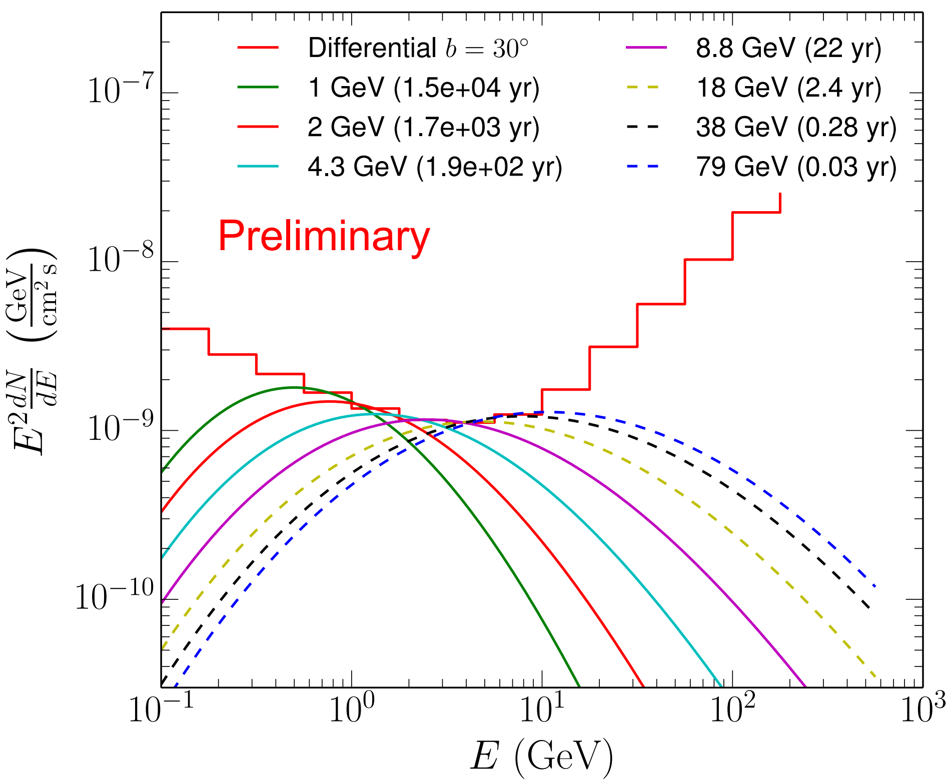
- **PBHs evaporate to all elementary particles available at temperature T**
- **The spectrum has contribution both from primary and secondary (mostly from hadronic cascades) gamma rays**



Carr et al, PRD 81 (2010), arxiv:0912.5297

Detection radius as a function of temperature

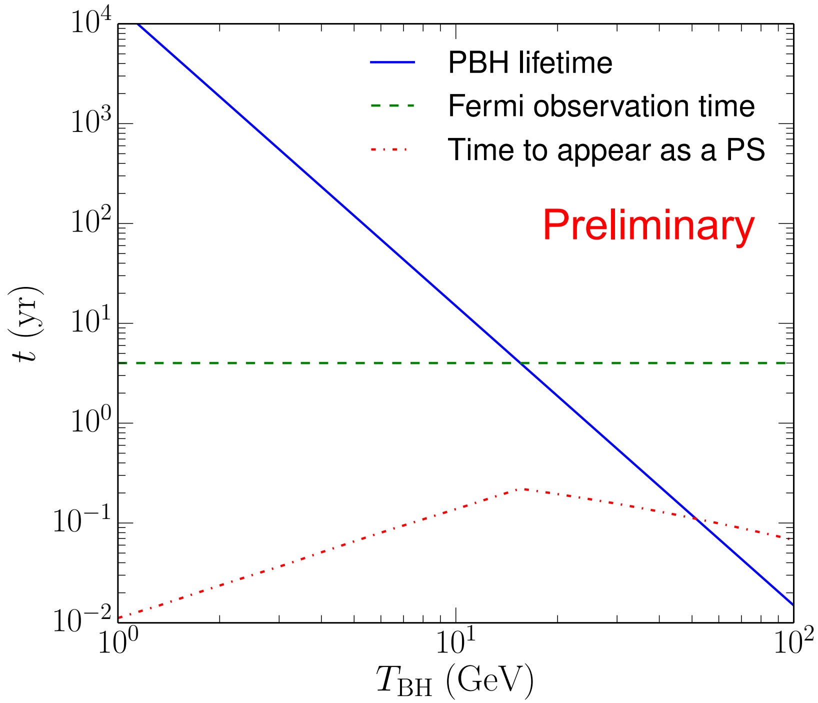
- **To estimate the domain of sensitivity of Fermi LAT to PBHs we compare the PBH spectra with the differential sensitivity**

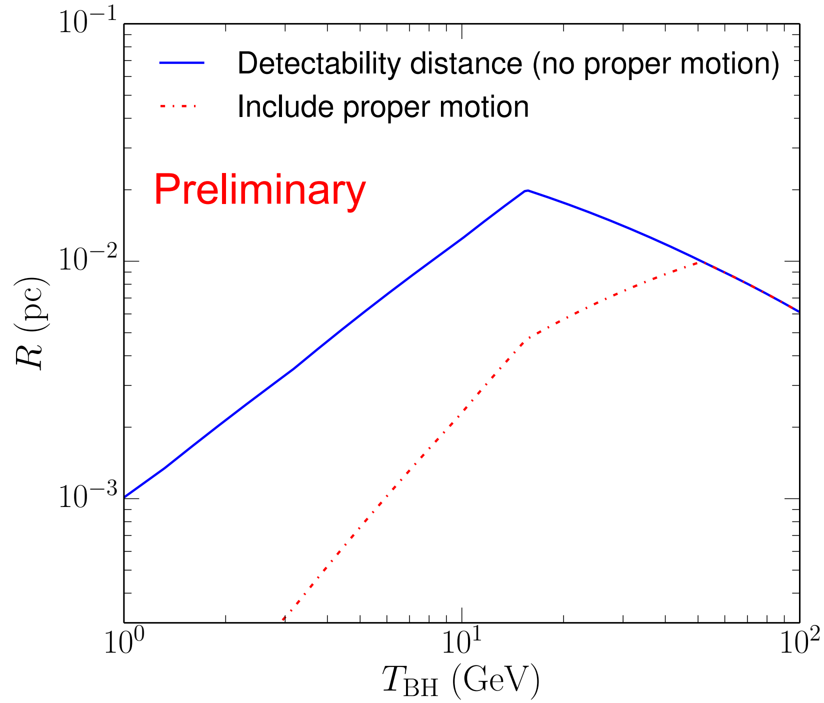


The normalization (and hence the distance to PBH) is chosen such that the spectrum does not exceed the differential sensitivity (4 year P7 rep: the same dataset is used for 3FGL catalog)

Dashed lines – PBH lifetime is shorter than Fermi observations.

Detectability radius and lifetime





- **If we include the motion of PBHs relative to the Earth, then most of PBHs with temperatures below ~ 50 GeV would appear as moving gamma-ray sources**

Search for PBHs in 3FGL catalog

- **Search for candidates of PBHs in the 3FGL Fermi-LAT catalog**
  - **Association: exclude sources associated with known astrophysical sources or with |b| < 10°**
  - **Spectrum: Exclude sources with spectra inconsistent with PBHs**
    - **In 3FGL there are fluxes reported in 5 energy bands: cut on $\chi^2 < 11.3$ (95% confidence for 5 - 2 = 3 d.o.f.)**
  - **Proper motion: 2σ global cut on proper motion (for 318 sources with consistent spectra)**

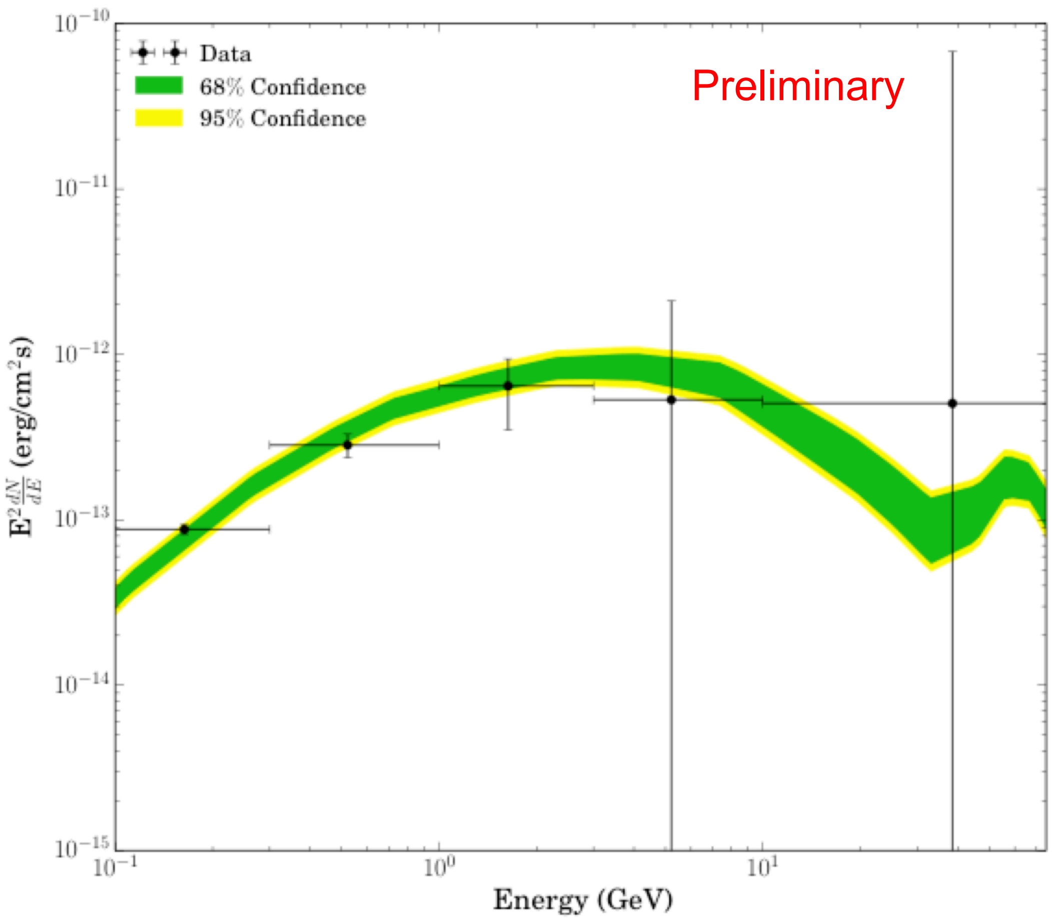
Initial

3033 Sources → **Association** → 1010 Sources → **Spectrum** → 318 Sources → **Proper Motion** → 1 Source!

Associated with a solar flare

Search for PBHs in Fermi Catalogs

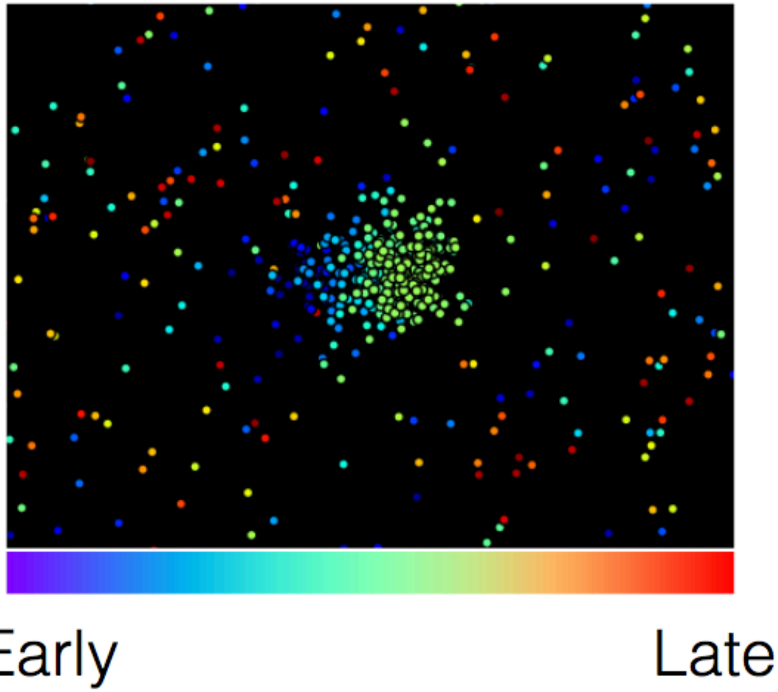
- Compare the PBH spectra with 3FGL spectra
  - An example of a matching spectrum (J0342.8-1321)



Example of a PS with a proper motion

- Background photons come at random times
- Photons from a moving PS have a correlated shift

Energy: >3 GeV
Color: Arrival time



Detection of Proper Motion

- To check the existence of a proper motion of a PS, we add two additional parameters in the PS model: velocity in the sky, and check the significance of the new parameters.
- We maximize the likelihood:

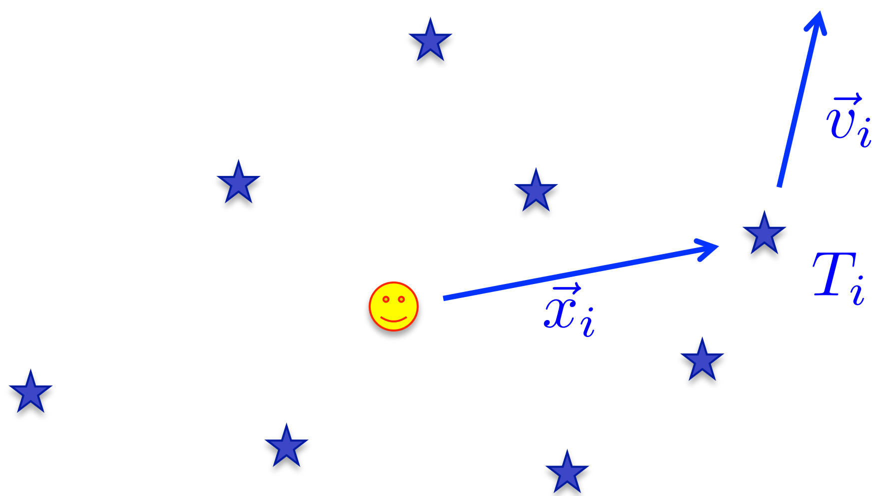
$$L = \prod_{i=1}^{N} w_i \times \exp\left\{-\frac{(\vec{x_i} - \vec{x_0} - \vec{v_0} t_i)^2}{\sigma_i^2}\right\}$$

to find x_0 and v_0. x_i are the coordinates of photons, t_i are the arrival times.

- Weights w_i represent a probability that a photon belongs to the PS (rather than other PS or the diffuse background)
- We estimate the significance of v_0 by shuffling randomly the arrival times of the photons.

PBH limits

- Since no PBH candidates were detected in the Fermi-LAT data we put a limit on the PBH evaporation rate
- Monte Carlo simulation
  - Generate PBHs with a distribution over temperature, position, velocity
  - Increase the density of PBHs until the non-detection probability is less than 1%



MC simulation

- Generate PBHs with density distribution corresponding to stationary distribution of PBHs

$$\frac{d\rho}{dt} = \frac{d\rho}{dT}\frac{dT}{dt} = const.$$

$$\frac{d\rho}{dT} \propto \dot{T}^{-1} \propto T^{-4}$$

- Velocity distribution is Gaussian with
  - V_{av} equal to the disk rotation velocity (250 km/s)
  - σ_v equal to the dark matter dispersion (270 km/s)
- Distance up to 0.08 pc (constant spatial density)
- Add the PBHs (one at a time) to the gamma-ray data and perform the same analysis steps as in the detection algorithm

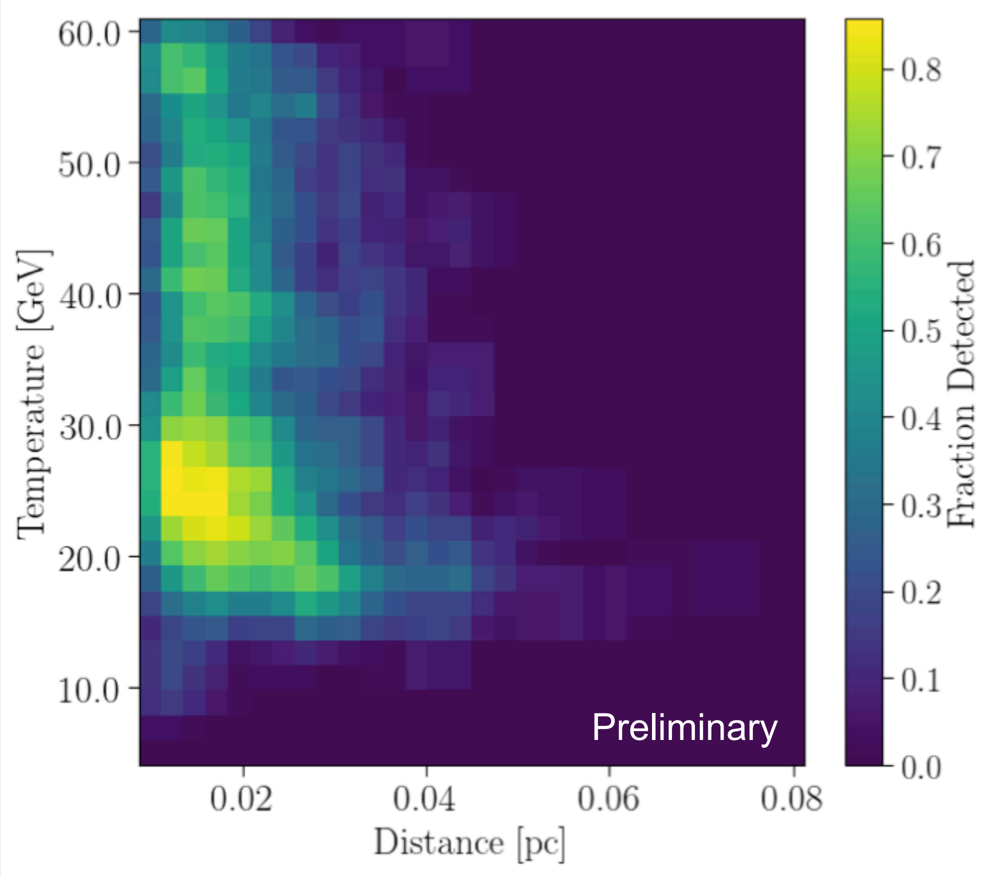
Detection of PBHs in MC simulation

- **Perform the same analysis steps on the generated PBHs as in the search of PBH candidates in the 3FGL catalog**
  - **Apply the standard Fermi-LAT point source detection algorithm (gtlike);**
  - **Check for associations with 3FGL sources (chance coincidence). Exclude sources within 10^{o} from the Galactic plane;**
  - **Check that the spectrum is consistent with PBH spectra;**
  - **Check that the measured velocity is larger than 2σ global significance (taking into account 318 3FGL sources with spectra consistent with PBHs).**

Detection efficiency

- Calculate the detection efficiency as a function of distance and temperature (integrate over velocity distribution)
- We use it to calculate the average detection efficiency

$$\epsilon = \frac{\int \epsilon(R,T)\,\frac{R^2}{T^4}\,dR\,dT}{\int \frac{R^2}{T^4}\,dR\,dT}$$



Calculation of the limit

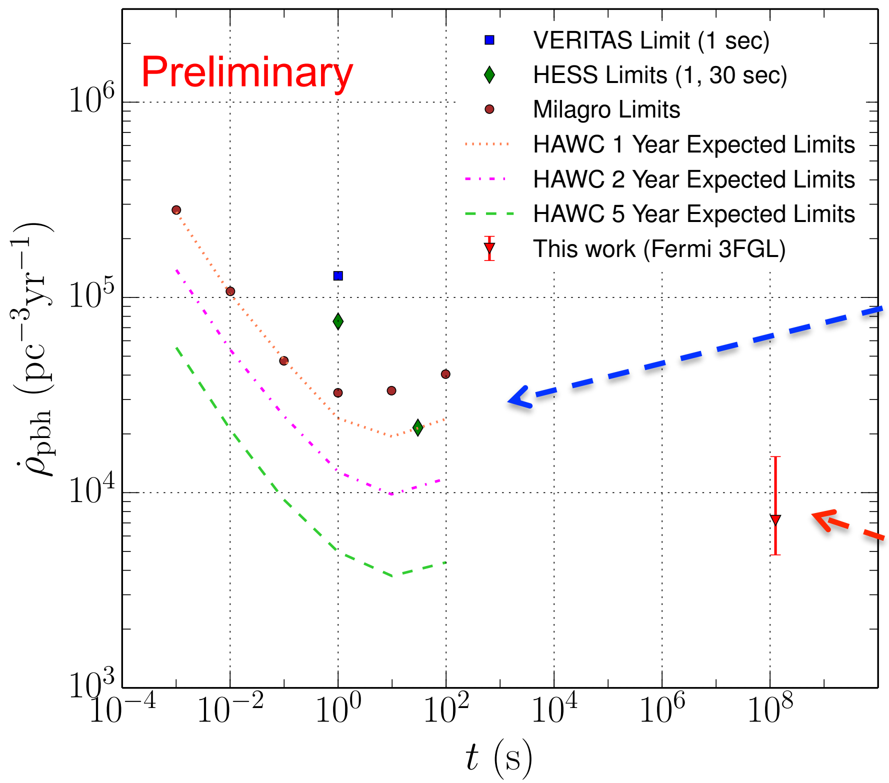
- Number of detections is $N = \rho\epsilon V$
- 99% upper confidence (observing not more than 1 candidate) corresponds to $N < 6.64$
- Which we express as a limit on the evaporation rate

$$\dot{\rho}_{\rm PBH} < 7.2 \times 10^3 \ {\rm pc}^{-3} \ {\rm year}^{-1}$$

- We estimate the systematic uncertainty by taking bracketing values on velocities and normalization of the PBH spectrum

Model	Spectrum Normalization	Orbital Velocity ($\mathrm{km\,s^{-1}}$)	DM Halo Velocity ($\mathrm{km\,s^{-1}}$)	Limit
Aggressive	$\frac{0.45}{0.35}$	100	150	$4.8 \times 10^3\ \mathrm{pc^{-3} yr^{-1}}$
Conservative	$\frac{0.25}{0.35}$	300	350	$15.3 \times 10^3\ \mathrm{pc^{-3}\ yr^{-1}}$

Comparison with limits from Cherenkov telescopes



Cherenkov telescopes timescale – several seconds

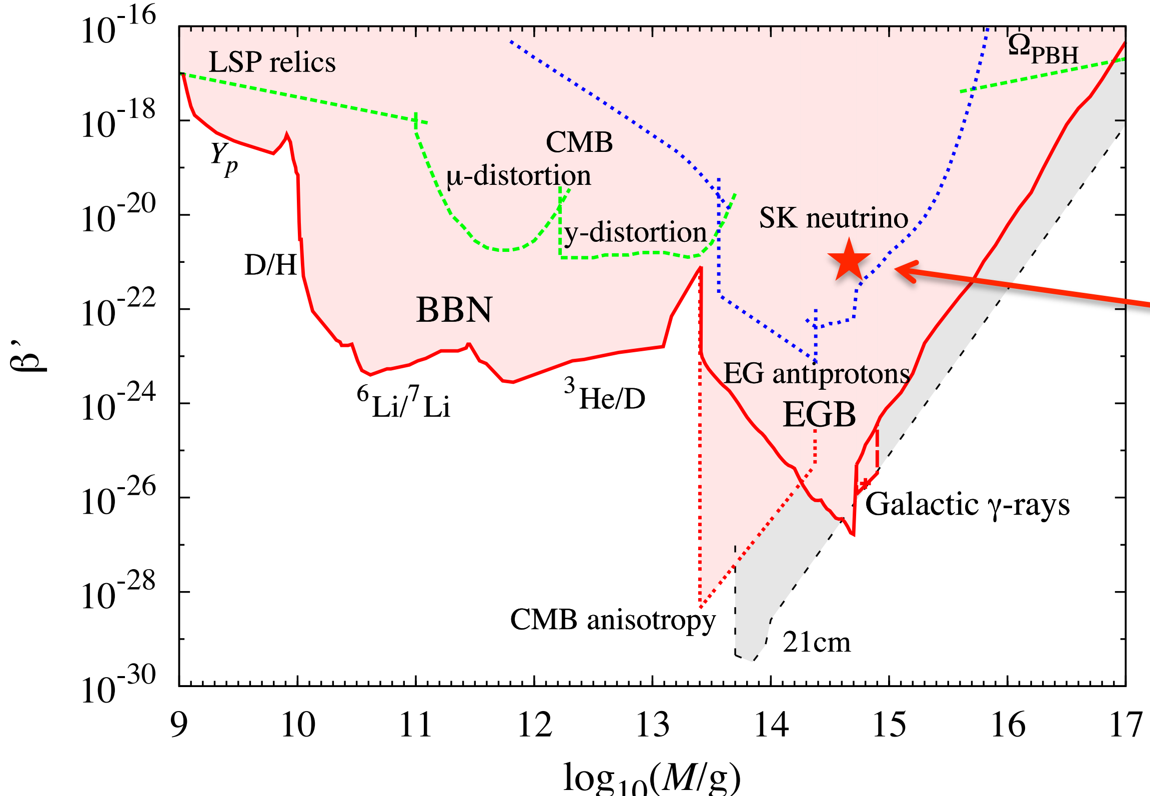
Fermi LAT timescale – several years

$$\dot{\rho}_{\rm PBH} < (7.2^{+8.1}_{-2.4}) \times 10^3 \ {\rm pc}^{-3} \ {\rm yr}^{-1}$$

- **Fermi LAT limit is better than existing limits on individual PBHs, it is comparable to expected HAWC limit after 2 to 5 years of observations**

Comparison with other limits

- **The limit on local PBH evaporations can be translated to the average energy density of PBHs Ω, which in turn can be related to the energy density of PBHs at the time of formation β'.**



Fermi LAT limit on individual PBHs (this work)

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Final remarks and conclusions

- Fermi LAT is sensitive to individual PBHs with temperatures around few tens of GeV
- The lifetimes of these PBHs are several years
  - Within the radius of sensitivity of Fermi LAT, these PBHs will appear as moving PS
- We have developed a new algorithm to search for proper motion of Fermi LAT point sources
- We checked that in the 3FGL catalog there are no PBH candidates (sources without association that have consistent spectra and significant proper motion)
- We put a 99% confidence upper limit on PBH evaporation

$$\dot{\rho}_{\rm PBH} < (7.2^{+8.1}_{-2.4}) \times 10^3 \ {\rm pc}^{-3} \ {\rm yr}^{-1}$$

- which is more constraining than the existing limits from Cherenkov telescopes