Primordial BHs

Main reviews and articles

- astro-ph/0504034 **Primordial Black Holes - Recent Developments**
- astro-ph/0304478 **Gamma Rays from Primordial Black Holes in Supersymmetric Scenarios**
- gr-qc/0304042 **Do black holes radiate?**
- gr-qc/0506078 **Black Holes in Astrophysics**
- arXiv: 0709.2380 **Do evaporating BHs form magnetospheres?**
- arXiv: 0912. 5297 **New cosmological constraints on primordial black holes**
- arXiv: 1403.1198 **PBHs (review)**
- arXiv:1503.01166 **PBHs (review)**
- arXiv:1510.04372 **PBHs (very large review)**

Introduction

The idea was proposed by Hawking (1971)
[however, some discussion appeared also before, see,
for example, Zeldovich & Novikov, 1966].
The idea is that at early times large-amplitude overdensities would overcome internal pressure forces and collapse to form black holes.
The mass of a PBH is close to the Hubble horizon mass.

Of course, we are interested only in PBH formed after inflation.

PBHs may also form at the phase transitions expected in the early universe, in particular, PBH formation can be related to topological defects.

PBH contribute not only to γ-ray, but also to CR and ν background.

Masses from 10^{-5} g up to 10^{5} solar masses.

See introductions in arXiv: 0709. 2380, 0910.1876, astro-ph/0304478

Primordial black holes

$$M_H(t) \approx \frac{c^3 t}{G} \approx 10^{15} \left(\frac{t}{10^{-23}\ \mathrm{s}} \right) g.$$

Primordial black holes (PBH) are formed with masses about the mass inside a horizon at the given moment (particle horizon).

$$T = \frac{\hbar c^3}{8\pi G M k} \approx 10^{-7} \left(\frac{M}{M_\odot} \right)^{-1} \mathrm{K},$$

Hawking radiation

BHs with M>10^{26} g have temperatures lower than the CMB radiation now.

The time for complete evaporation

$$\tau(M) \approx \frac{\hbar c^4}{G^2 M^3} \approx 10^{64} \left(\frac{M}{M_\odot} \right)^3 \mathrm{y}.$$

astro-ph/0504034

Mass-spectrum

$$\frac{dn_{KL}}{dM_i} = \frac{n+3}{4}\sqrt{\frac{2}{\pi}}\gamma^{7/4}\rho_i M_{H,i}^{1/2} M_i^{-5/2}\sigma_H^{-1} \times \exp\left(-\frac{\gamma^2}{2\sigma_H^2}\right)$$

Mass function in the standard model (Kim-Lee)

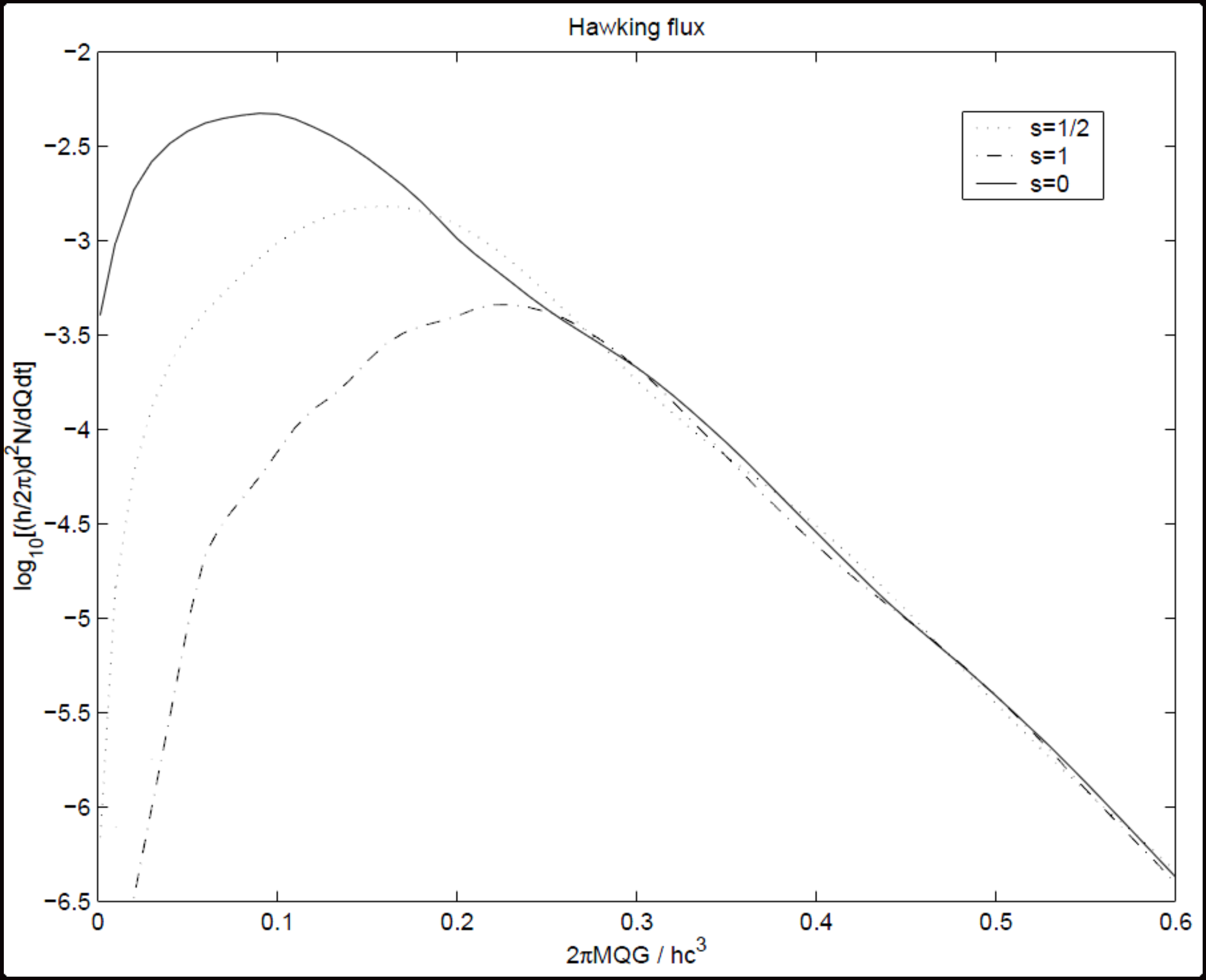
The case n = 1 corresponds to a scale-invariant (Harrison-Zel'dovich) spectrum which yields a Carr initial mass function, $dn/dM_i \sim M_i^{-5/2}$.
As some authors realized, the n = 1 spectrum does not yield a significant PBH abundance when normalized to COBE observations (astro-ph/0304478).

PBH can be considered non-charged, non-rotating as both (spin and charge) are rapidly emitted due to particle creating (Hawking radiation).

astro-ph/0304478

Hawking spectrum

$$\frac{d^2N}{dQdt} = \frac{\Gamma_s}{2\pi\hbar\left(\exp\left(\frac{Q}{kT}\right) - (-1)^{2s}\right)}.$$



For non-rotating, non-charged BH.

Horizontal axis ~Q/kT

T=T(M)

Vertical – $d^2N/dQdt$

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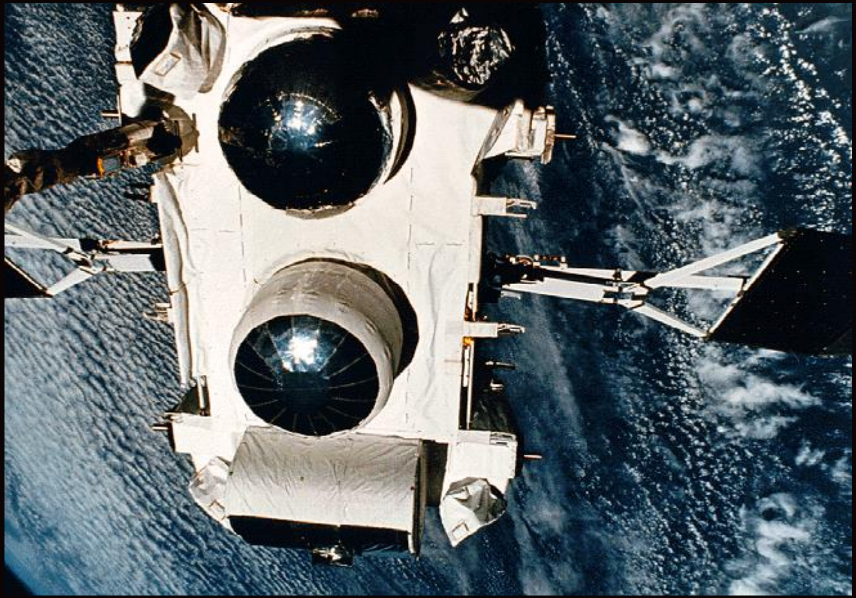
EGRET and constraints on PBH



$$\frac{dF_\gamma}{dE} = 7.3 \times 10^{-14} \left(\frac{E}{100MeV} \right)^{-2.10} \mathrm{cm}^{-3}\mathrm{GeV}^{-1}$$

Background radiation at energies: 30 MeV – 120 GeV.

The upper limit on the density of PBHs

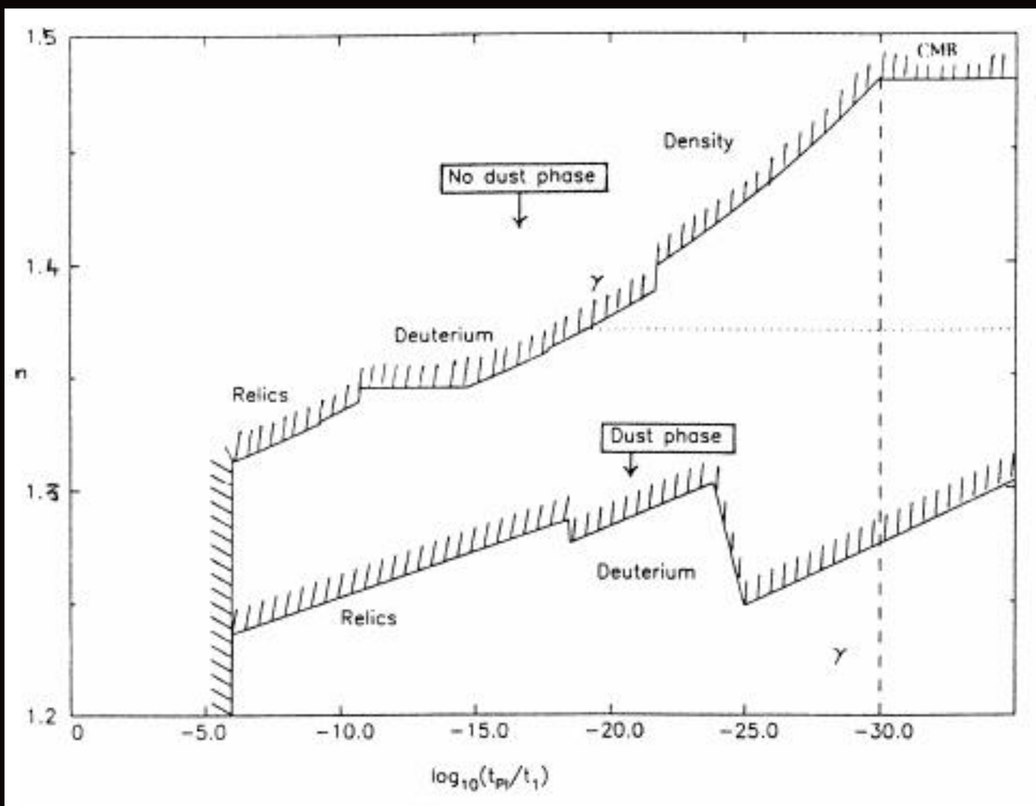
$$\Omega_{\mathrm{PBH}} \leq (5.1 \pm 1.3) \times 10^{-9} h^{-2},$$

astro-ph/0504034

Constraints on cosmological parameters from data on PBH

Data on PBHs in principle can provide constraints on different cosmological parameters related to the density fluctuations.

$$M > M_{\min} = M_P (T_{RH}/T_{Pl})^{-2}$$



For example, on the parameter *n*, characterising the power spectrum of fluctuations.

$$|\delta_k|^2 \approx k^n$$

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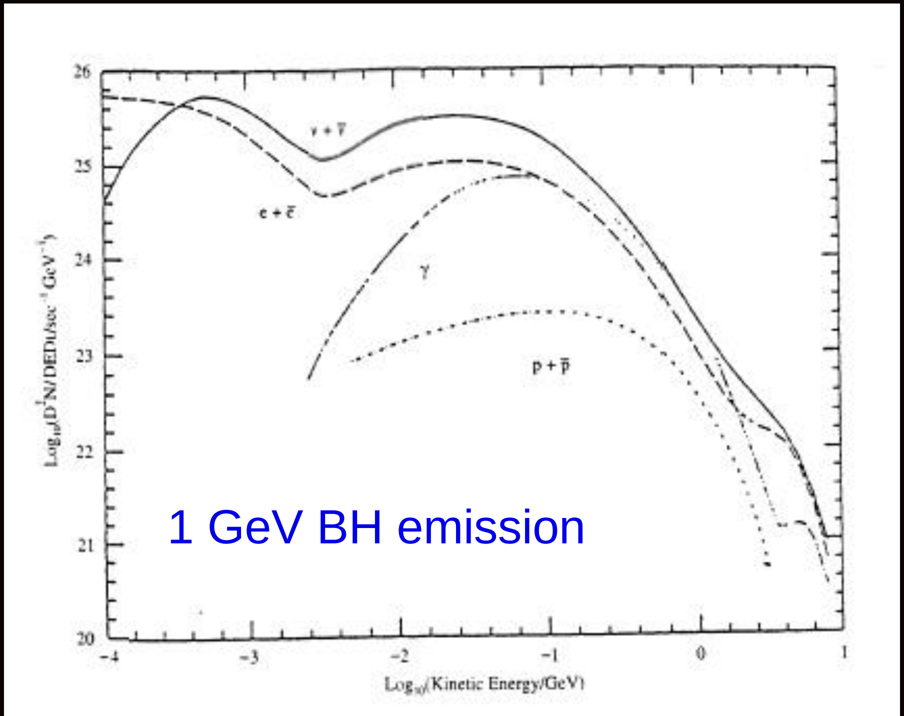
About other constraints see Carr (2005) astro-ph/0504034

Particle emission during PBH evaporation



$$T \approx 10^{26}\left(\frac{M}{g}\right)^{-1} \mathrm{K} \approx \left(\frac{M}{10^{13} g}\right)^{-1} \mathrm{GeV}.$$

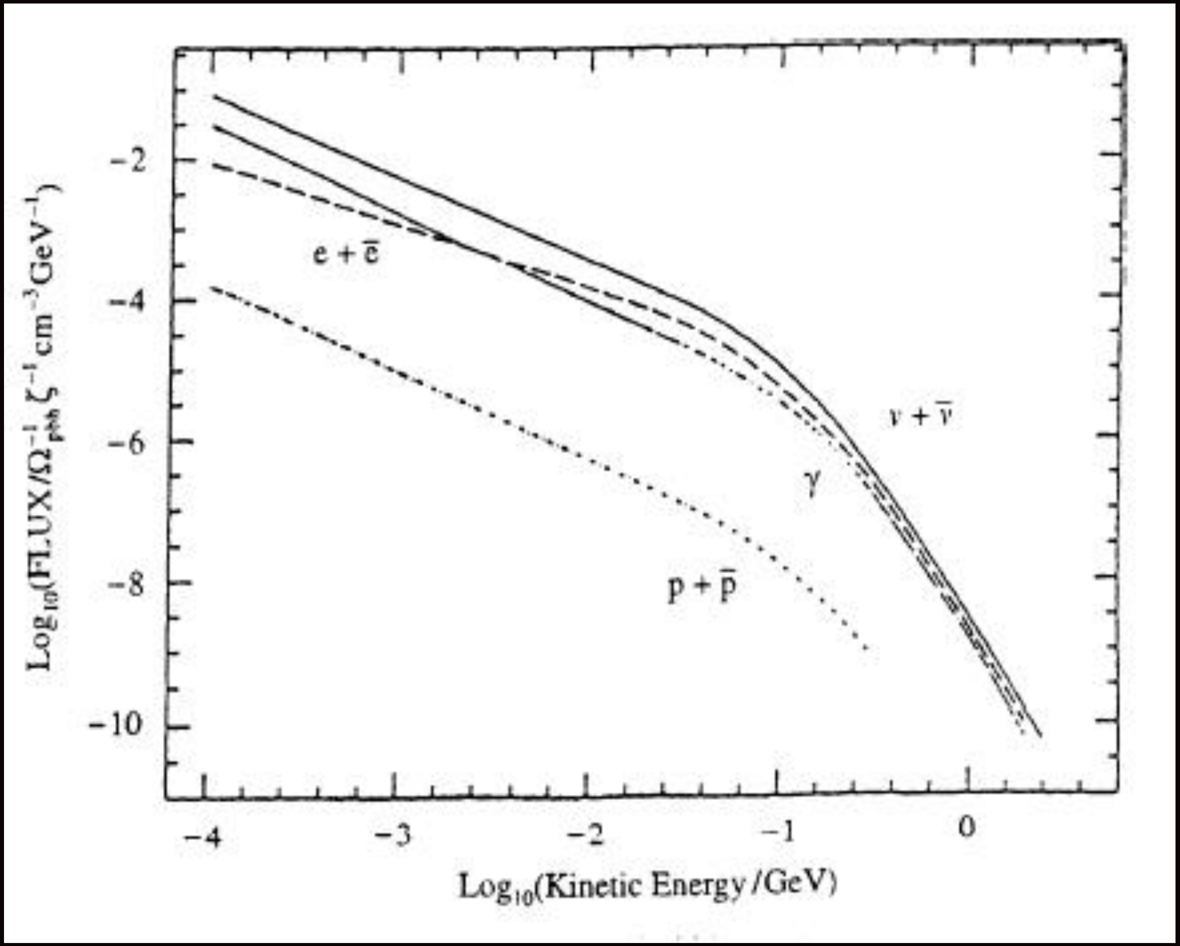
$$\dot{M} = -5 \times 10^{25} (M/g)^{-2} f(M) \; \mathrm{g\,s}^{-1}$$

$$\tau(M) = 6 \times 10^{-27} f(M)^{-1} (M/g)^{3} \; \mathrm{s}.$$

When a BH mass is below 10^{14} g,
it starts to emit hadrons.

astro-ph/0504034

Particle spectrum for uniform distribution of PBHs



BHs uniformly distributed in the Universe.

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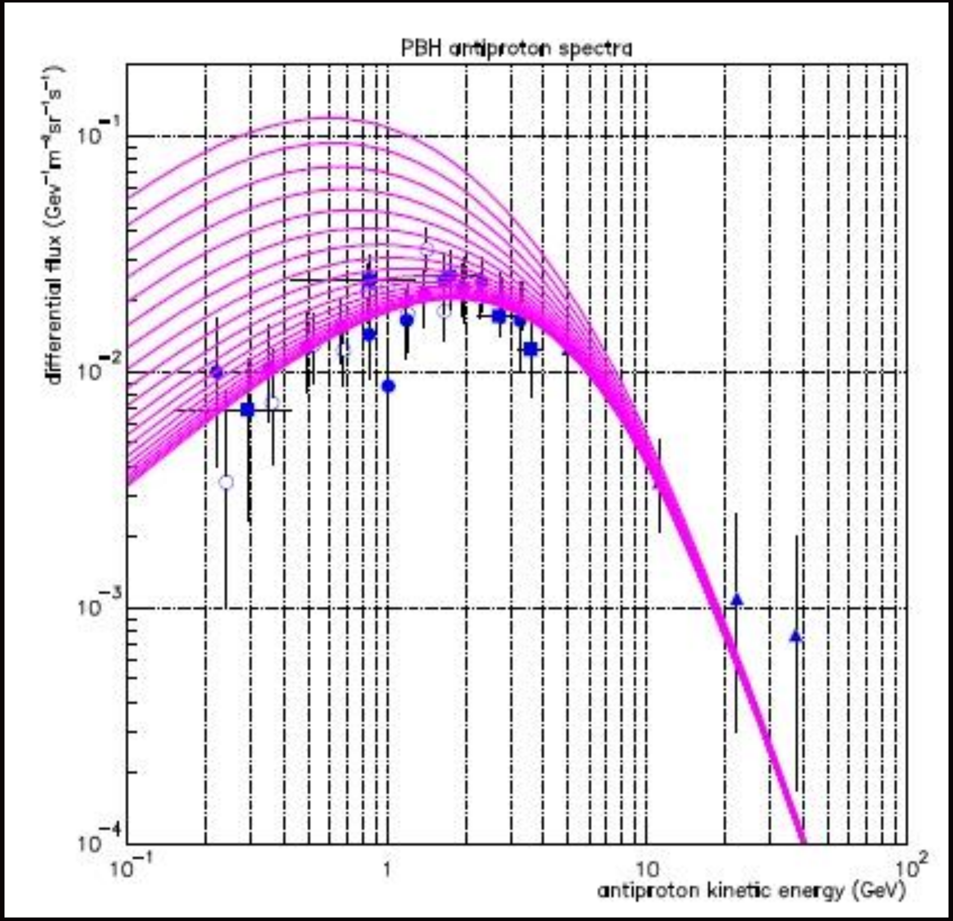
PBH and antiprotons



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Antiprotons are detected in cosmic rays.
They are secondary particles.
Properties of these secondary antiprotons should be different from properties of antiprotons generated during PBH evaporation at energies 0.1-1 GeV.

Comparison between calculations and the observed spectrum of antiprotons provides a limit on the spatial density of PBHs.

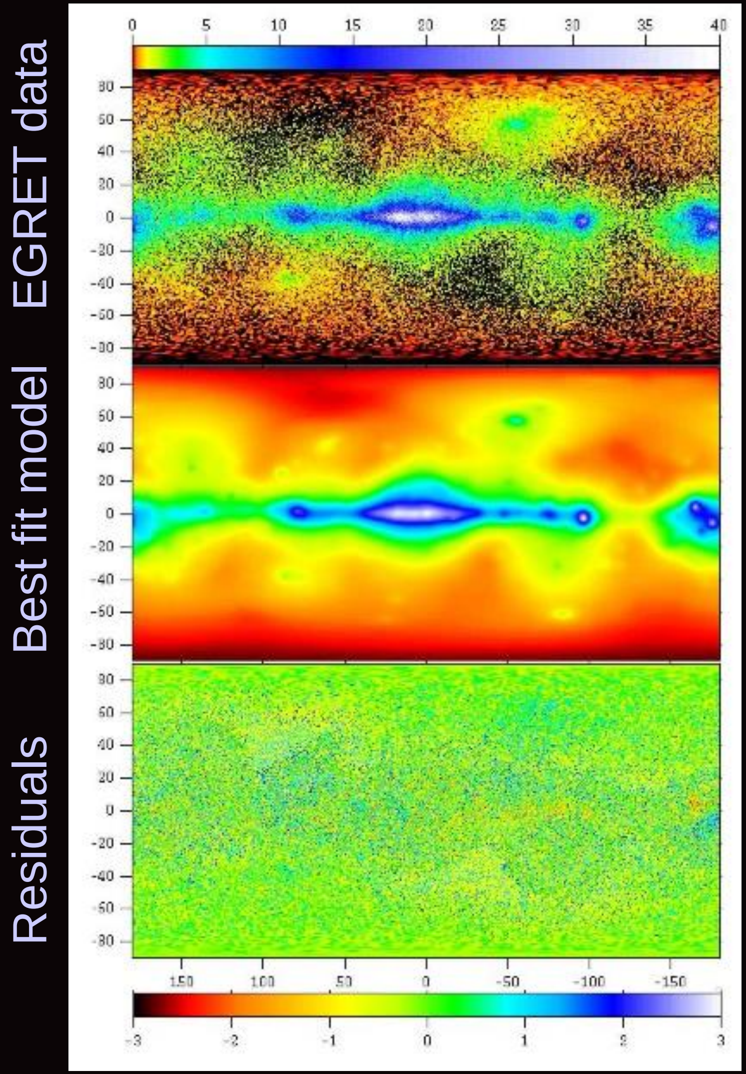
Barrau et al. 2003, taken from Carr 2005

Constraints from galactic γ-ray background

The authors assume that PBHs
are broadly distributed like
dark matter in the halo of our Galaxy.
EGRET data

1. spacetime is 4D;
2. PBHs form through
   a cosmological scenario;
3. most PBHs are presently neutral
   and non-rotating;
4. being part of the dark matter,
   PBHs are distributed alike.

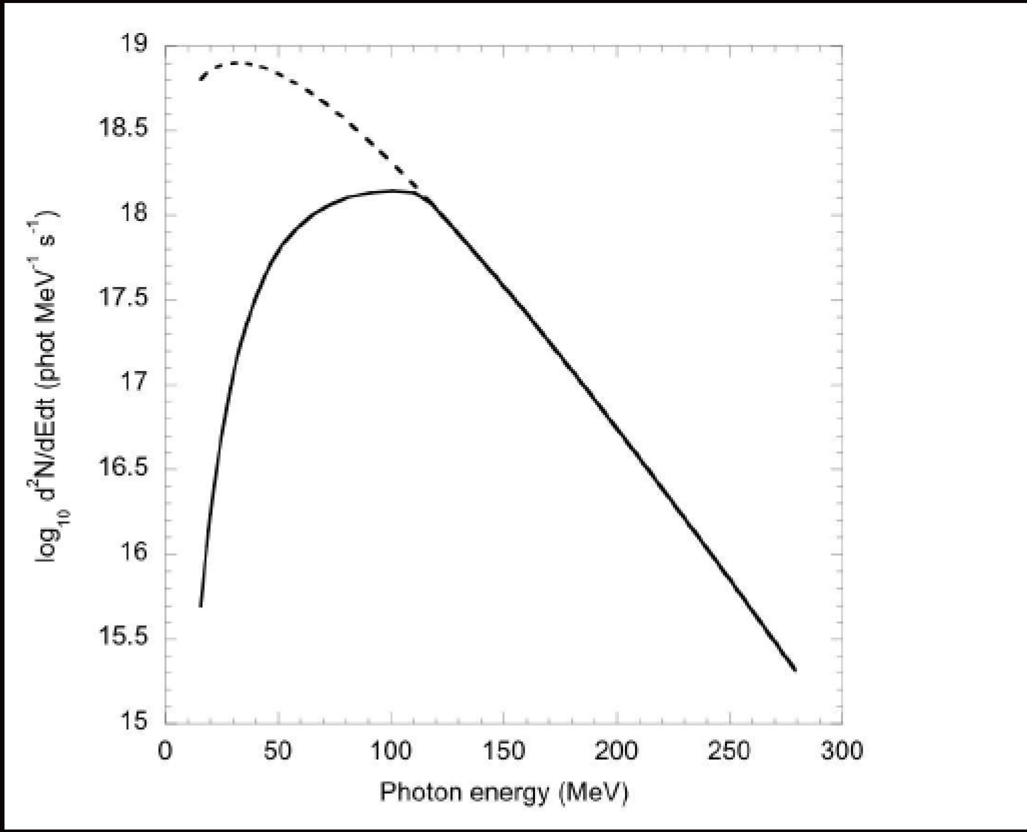
The flux peaks at higher energy
(around 5 kT)
than for a pure blackbody at
the same temperature
(which flux is maximum at 1.59 kT)



arXiv: 0906.1648

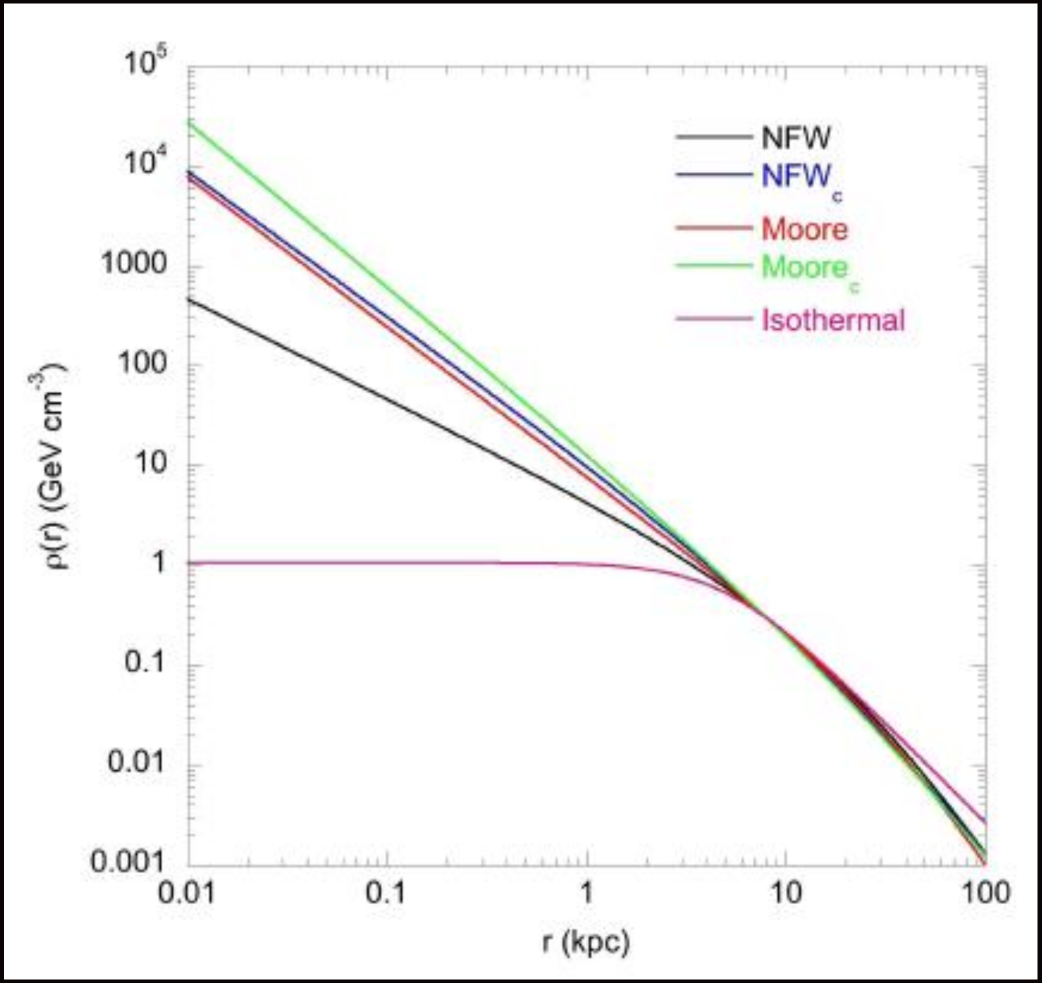
The spectrum

Since the typical temperature of PBHs born in the early Universe and that end its life at present time is about 20 MeV, a distinctive signature of quantum black holes would be a quasiplanckian spectrum at unexpectedly high energy, peaking at about 100 MeV



arXiv: 0906.1648

Density distribution



It was assumed that
PBH follow the DM distribution.
Several different variants
have been used.

arXiv: 0906.1648

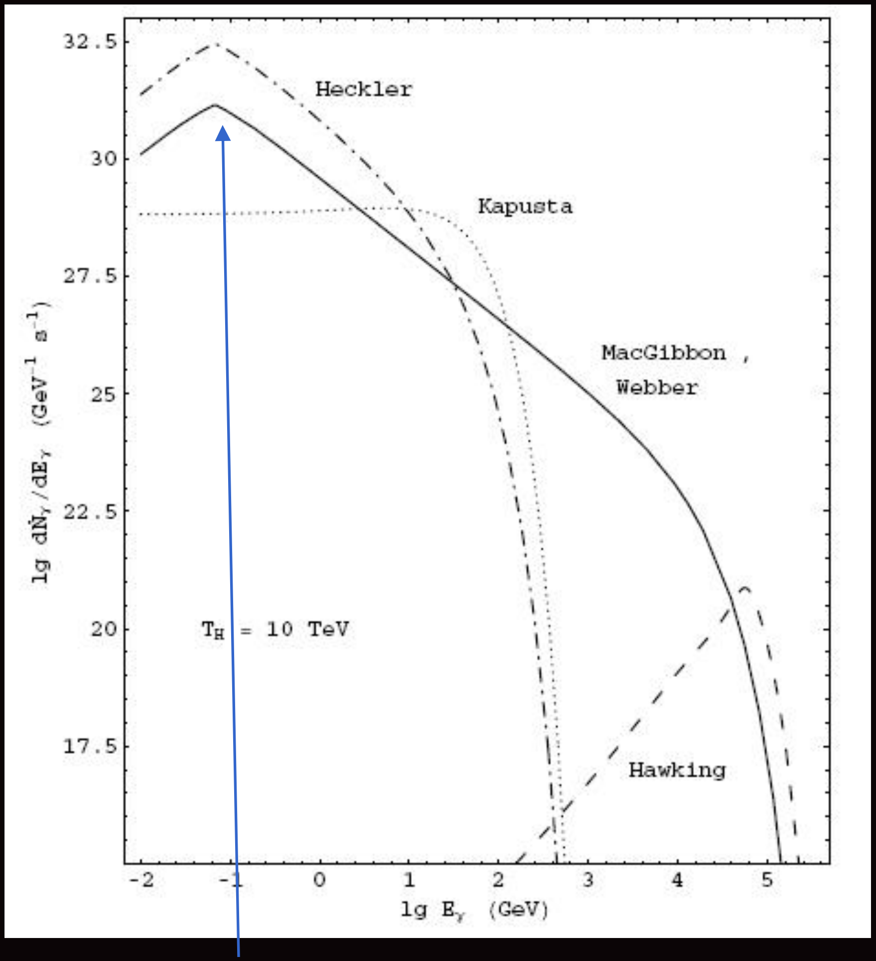
Results and limits

DM distribution	$f(M_\star)$	$\Omega_{PBH}(M_\star)$	$\beta(M_\star)$
Moore	$6.04 \pm 0.05\ 10^{-9}$	$1.38\ 10^{-9}$	$0.98\ 10^{-27}$
Moore_c	$1.07 \pm 0.07\ 10^{-9}$	$0.24\ 10^{-9}$	$0.17\ 10^{-27}$
NFW	$6.70 \pm 0.05\ 10^{-9}$	$1.53\ 10^{-9}$	$1.08\ 10^{-27}$
NFW_c	$1.93 \pm 0.08\ 10^{-9}$	$0.44\ 10^{-9}$	$0.31\ 10^{-27}$
isothermal	$11.62 \pm 0.04\ 10^{-9}$	$2.65\ 10^{-9}$	$1.87\ 10^{-27}$

Upper limits for the local PBH density are:
$3.3\ 10^7 - 2.1\ 10^8$ per pc^3.
Explosion rate ~0.06 pc^{-3} yr^{-1}.

arXiv: 0906.1648

Spectra in different models



$$E_\gamma \simeq m_{\pi^0}/2 \approx 68\,\mathrm{MeV}$$

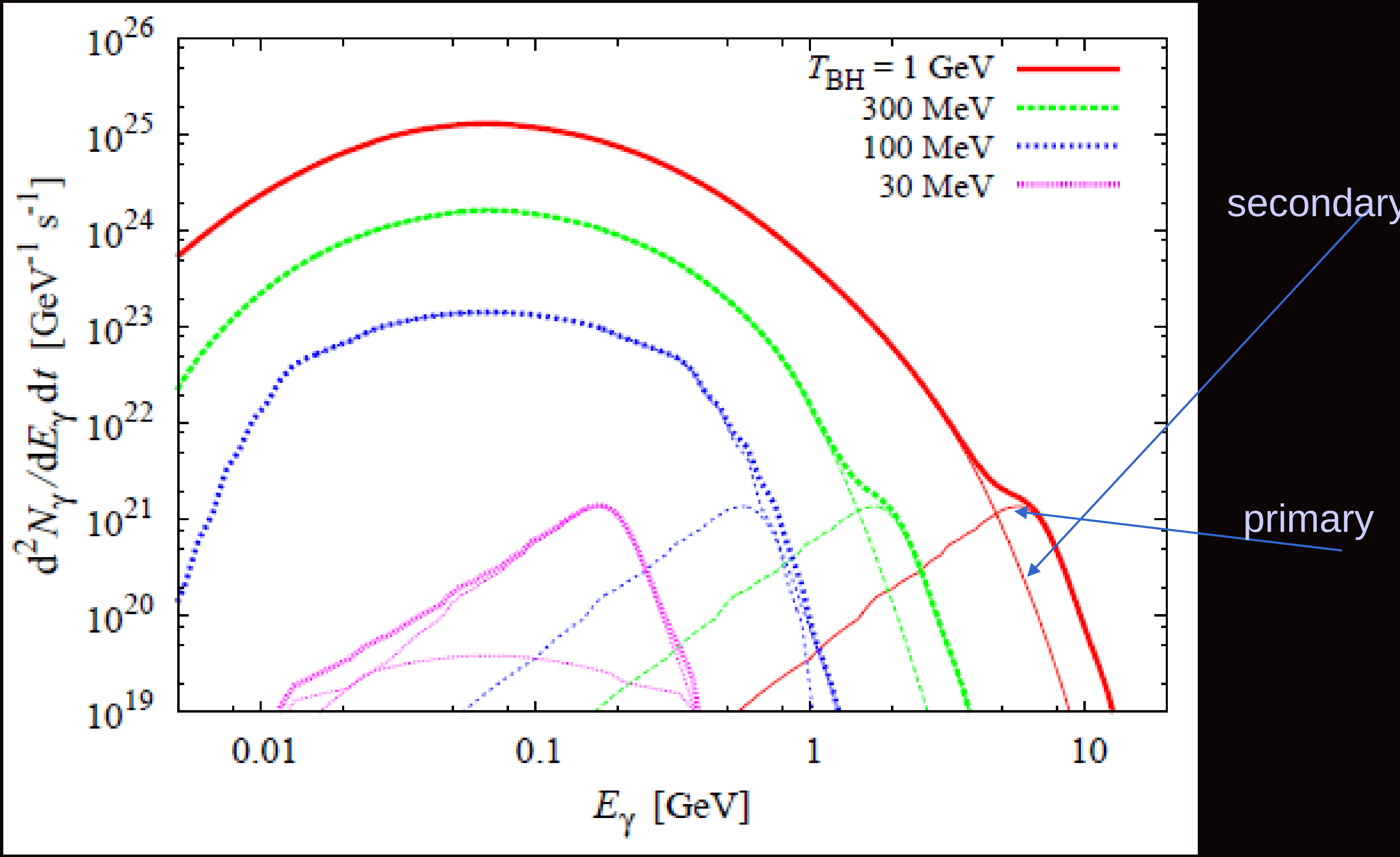
The spectrum can be non-thermal.
This is due to creation of particles which then demonstrate series of transformations (decays) and interactions; only at the very end we have photons.
And their spectrum is different from the thermal (i.e. from the blackbody).

However, the situation is not that clear (see recent criticism in arXiv: 0709.2380).

Note, that γ-ray limits are made for PBH with T~20MeV, so effects of photospheres are not important.
But they can be important for UHECRs.
Effects can be strong at $T_{BH}\sim\Lambda_{QCD}\sim300$ MeV

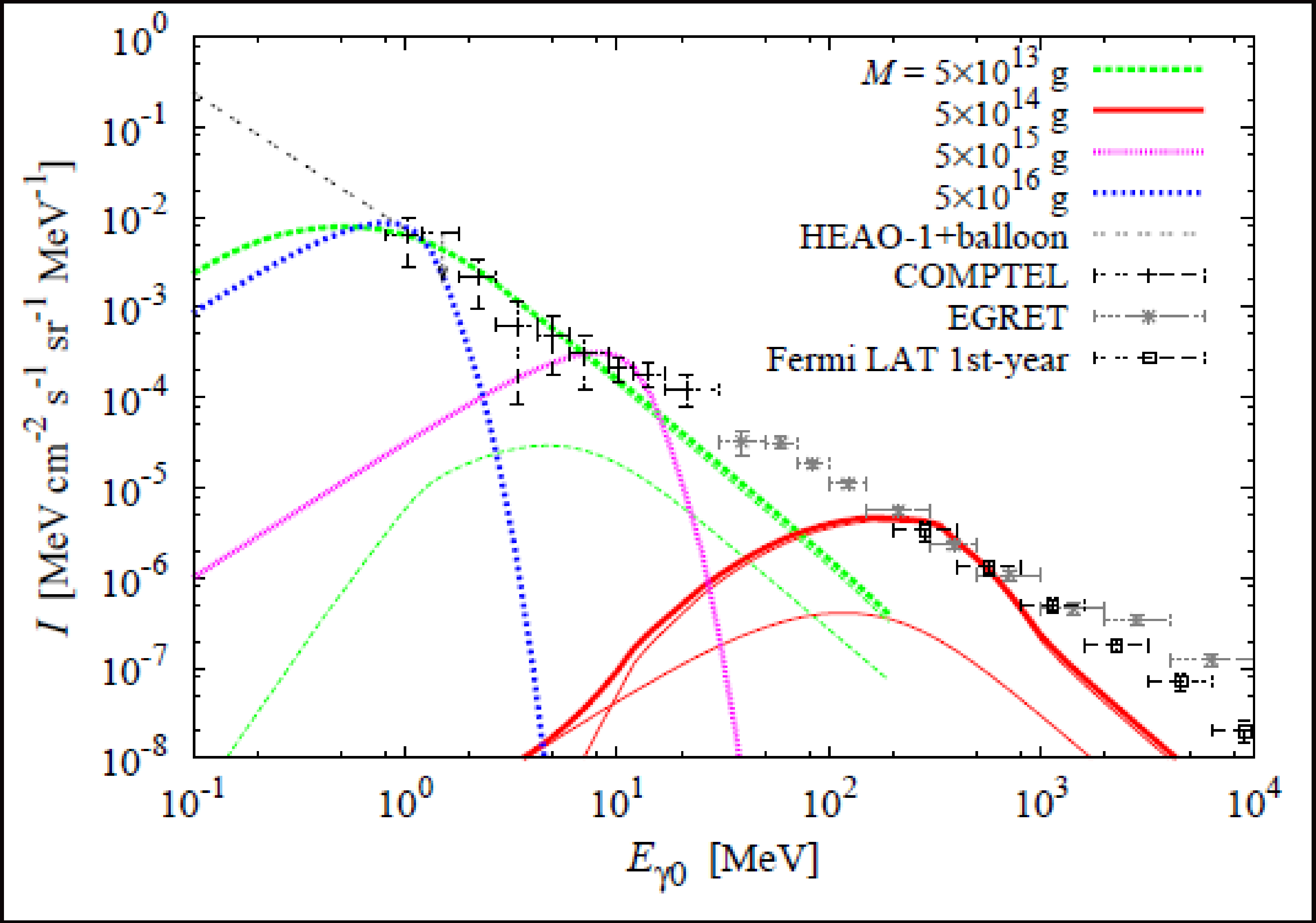
arXiv: 0706.3778

Emission rate of photons



0912.5297

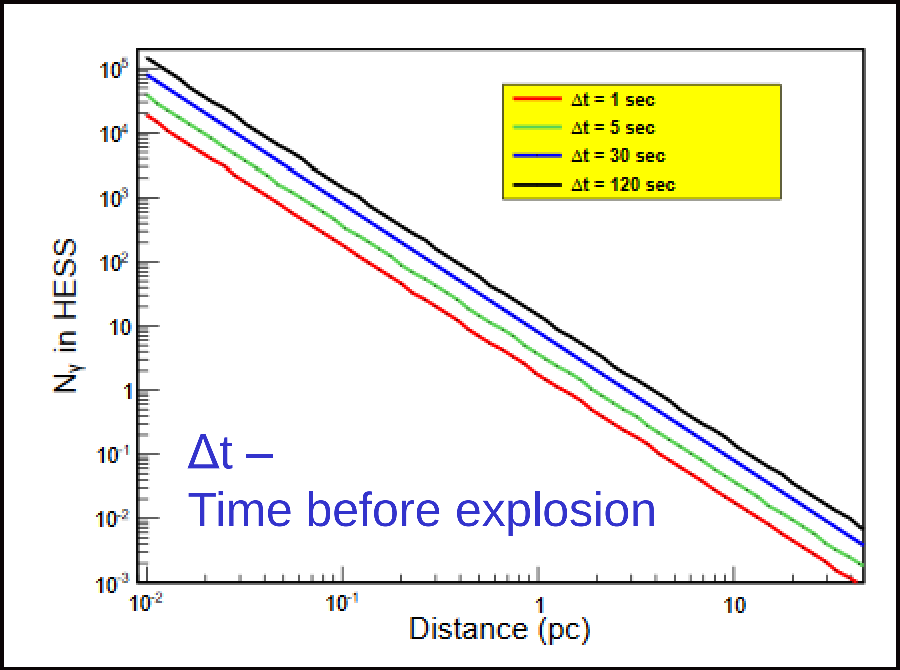
Gamma-ray background



$\Omega_{PBH} < 5\ 10^{-10}$

0912.5297

Constraints from H.E.S.S.



Nothing detected.

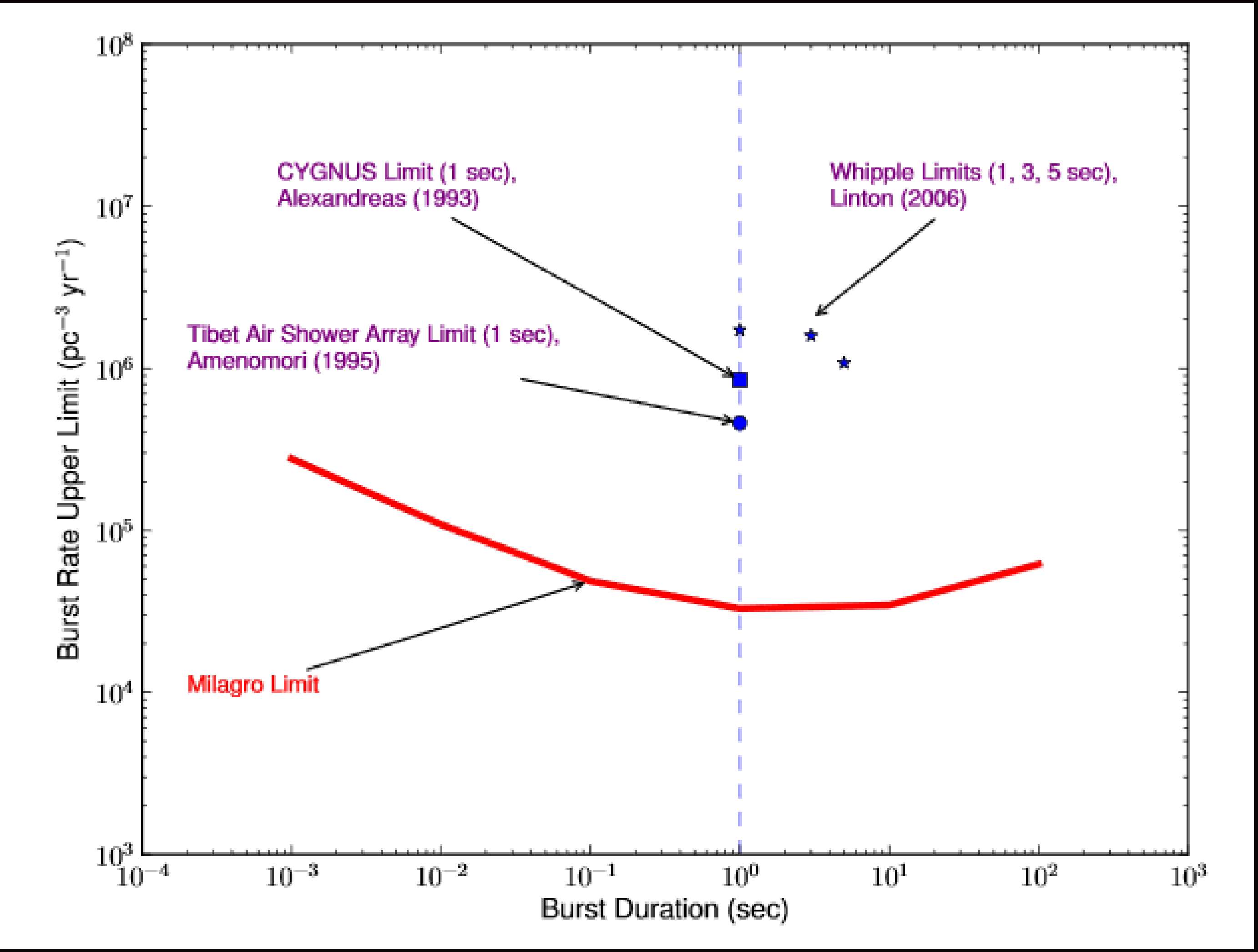
Upper limits can be derived.

At the moment these limits are not very constraining. However, with HESS-2 it will be possible to obtain more interesting limits.

The preliminary upper limit on the explosion rate is $\dot{\rho}_{\rm PBH} < 1.4 \times 10^4 {\rm pc}^{-3}{\rm yr}^{-1}$ at the 95% CL for $\tau = 30\,{\rm s}$. The sensitivity limit, defined in section 5.3 is $1.7 \times 10^4 {\rm pc}^{-3}{\rm yr}^{-1}$. By comparison, the preliminary upper limit obtained with the $\tau = 1\,{\rm s}$ search time-window is $\dot{\rho}_{\rm PBH} < 4.9 \times 10^4 {\rm pc}^{-3}{\rm yr}^{-1}$ (95% CL).

1307.4898

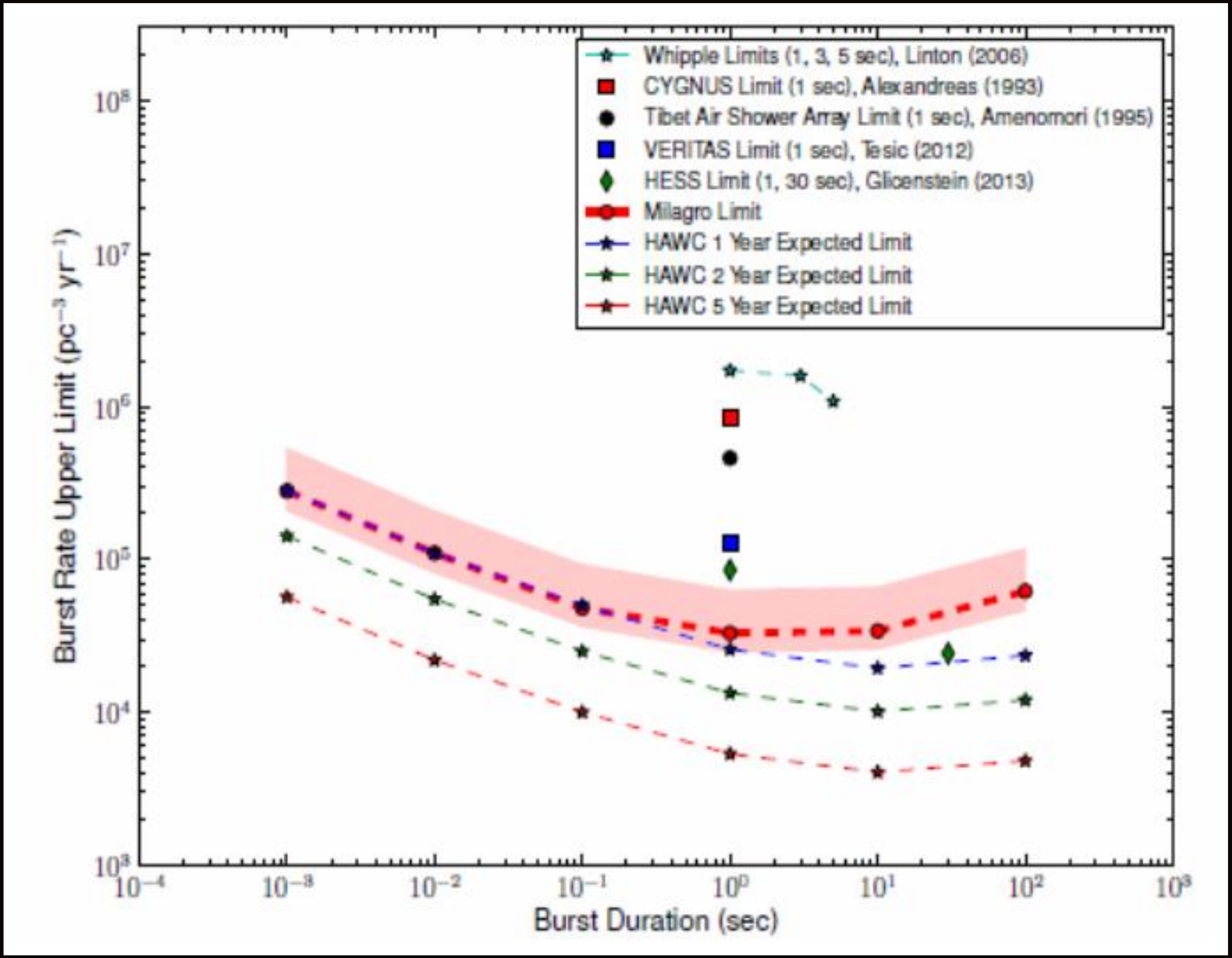
Milagro limits



See also 1507.01648 about future limits from HAWC.

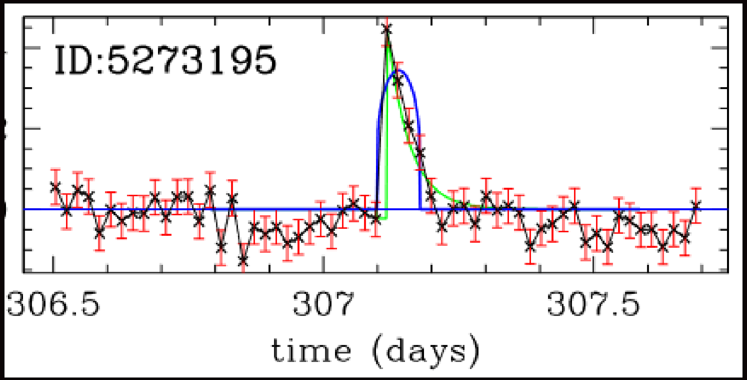
1308.4912

Joint limits



1503.01166

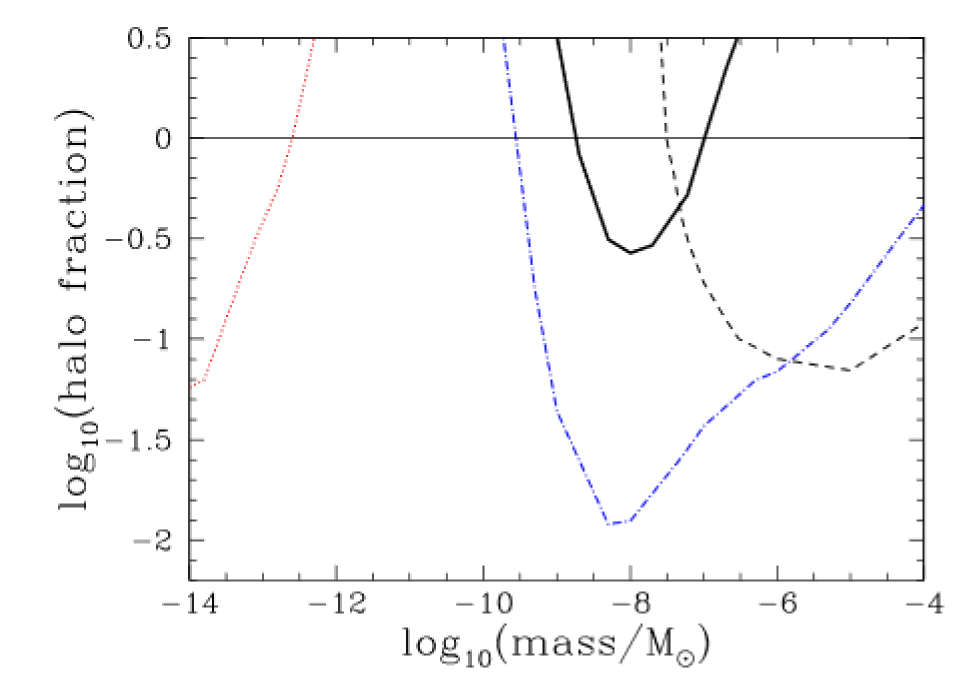
Limits from the Kepler data



Limits are based on lensing searches.
The idea was to put new limits on PBHs
as dark matter candidates looking for MACHOs.

Kepler is sensitive to PBHs in the mass range
$2\ 10^{-10}\ M_{solar} < M_{BH} < 2\ 10^{-6}\ M_{solar}$

Solid black is the new limit.
It excludes the mass range
$10^{-9}\ M_{solar} < M_{BH} < 10^{-7}\ M_{solar}$
I.e., PBHs from this range
cannot explain halo DM.
The allowed range is
$10^{-13} M_{solar} < M_{BH} < 10^{-9}\ M_{solar}$



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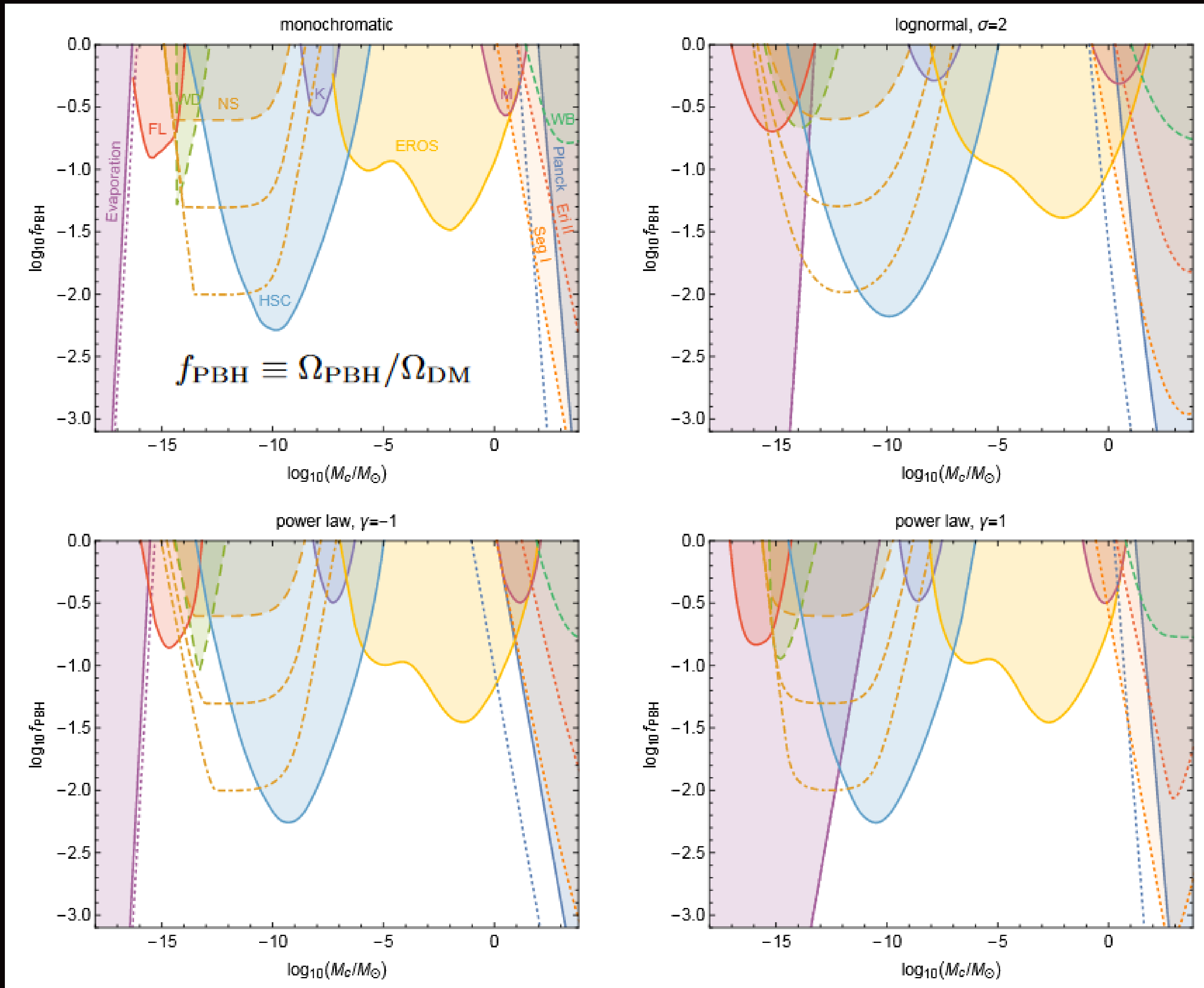

monochromatic
lognormal, σ=2
power law, γ=−1
power law, γ=1
Evaporation
FL
WD
NS
K
HSC
EROS
M
WB
Planck
Eri II
Seg I
$f_{\rm PBH} \equiv \Omega_{\rm PBH}/\Omega_{\rm DM}$
$\log_{10} f_{\rm PBH}$
$\log_{10}(M_c/M_\odot)$
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
−15
−10
−5
0

1705.05567

Legend to the previous plot

The purple region on the left is excluded by evaporations,
the red region by femtolensing of gamma-ray bursts (FL),
the brown region by neutron star capture (NS) for different values of the dark matter density in the cores of globular clusters,
the green region by white dwarf explosions (WD),
the blue, violet, yellow and purple regions by the microlensing results from Subaru (HSC), Kepler (K), EROS and MACHO (M), respectively.
The dark blue, orange, red and green regions on the right are excluded by Planck data, survival of stars in Segue I (Seg I) and Eridanus II (Eri II), and the distribution of wide binaries (WB), respectively.
The black dashed and solid lines show, respectively, the combined constraint with and without the constraints depicted by the colored dashed lines.

$$f_{\rm PBH} \equiv \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} = \int {\rm d}M\, \psi(M)$$

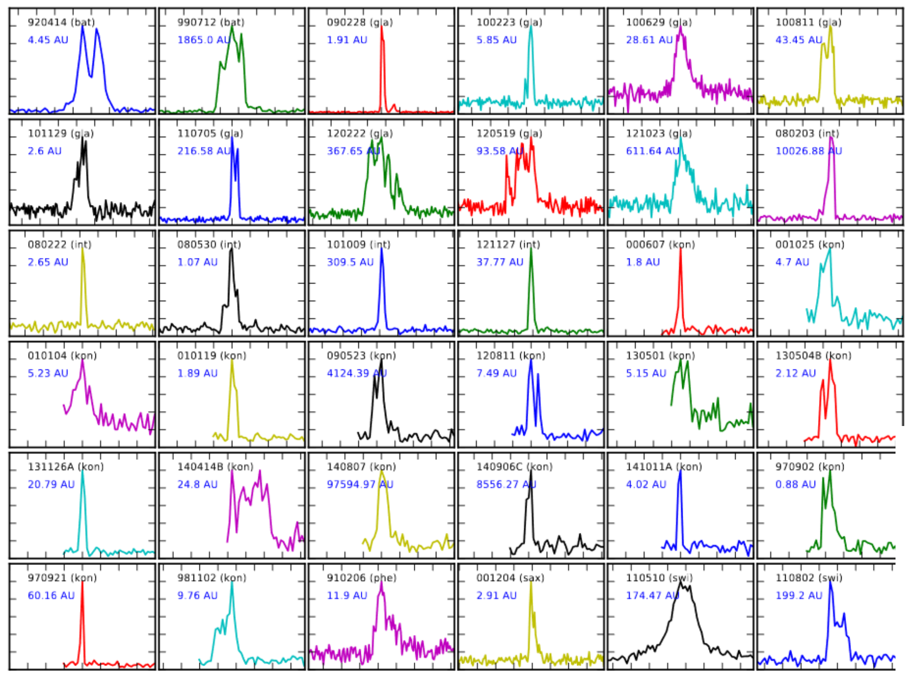
$$\psi(M) = \frac{f_{\rm PBH}}{\sqrt{2\pi}\sigma M} \exp\left(-\frac{\log^2(M/M_c)}{2\sigma^2}\right)$$

$$\psi(M) \propto M \frac{{\rm d}n}{{\rm d}M}$$

$$\psi(M) \propto M^{\gamma-1}$$

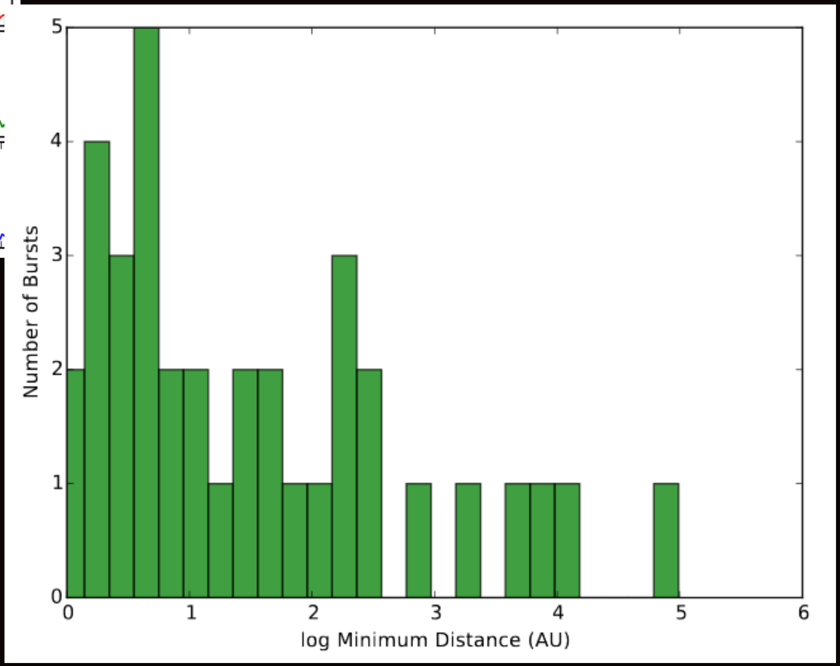
1705.05567

Searches with GRB network of detectors



With IPN the authors try to put limits on the distance to short gamma-ray bursts.

It is expected that PBHs evaporation is visible from short distances.



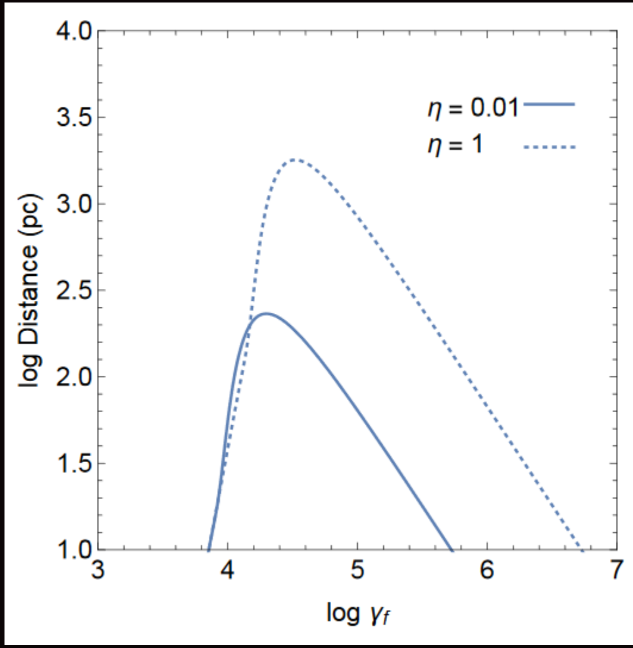
The are some (36) candidates with possibly small distances (<1 pc). But these are LOW limits.
I.e., it is still very uncertain if these bursts are related to PBHs.

1512.01264

Radio transients. BHs and extra dimensions

Low-frequency (8-meter wavelength) antenna – ETA.
According to Blandford (1977) low-frequency radio observations can provide a limit much better than gamma-ray observations.
The limit strongly depends on the Lorentz factor of the fireball.

Depending on parameters a burst ~0.1s long can be detected from the distance ~hundreds parsec.



The limit is $4.2 \times 10^{-7}\,\mathrm{pc^{-3}\,yr^{-1}}$

for Lorentz factor of $10^{4.5}$

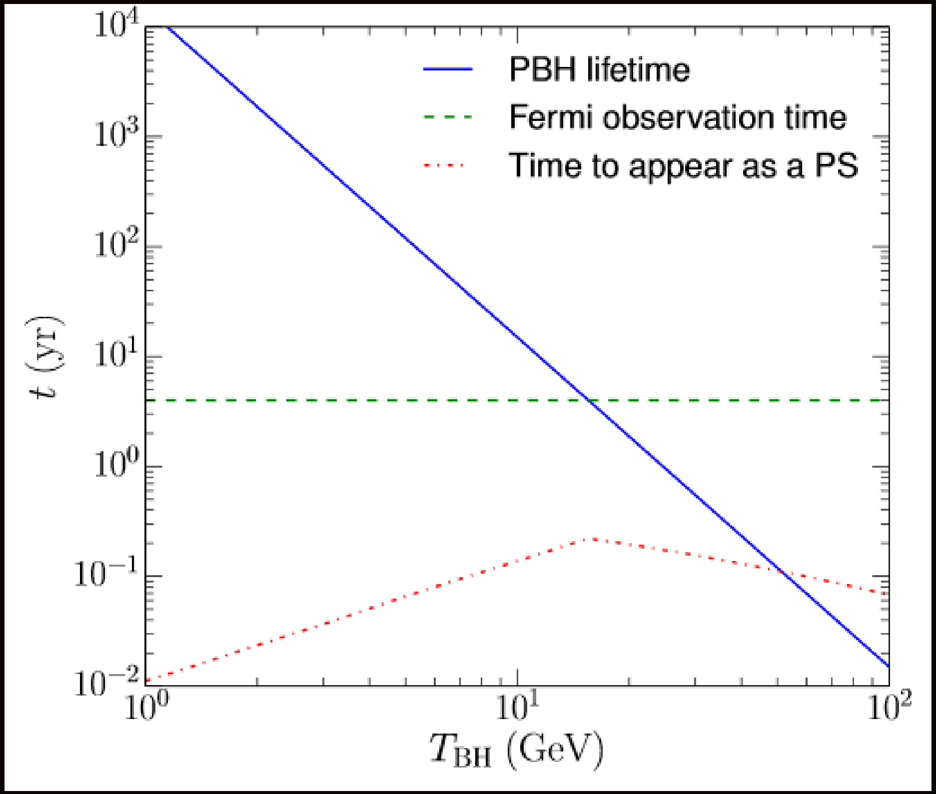
$$\eta M c^2 = \eta \mu L c^4 / G \qquad \mu = GM/Lc^2$$

$$\gamma_f = \frac{\frac{1}{2}kT}{m_e c^2} = \frac{\hbar c}{16\pi G m_e}\frac{1}{M} \approx 10^5\left(\frac{10^{11}\ \mathrm{g}}{M}\right)$$

1608.01945

Fermi limits

LAT is sensitive to evaporating BHs within 0.03 pc with T~16 GeV (mass 6×10^{11} g).
Life time is months-years. Some must already disappear during Fermi observations.
Sources might show spectral and brightness evolution.
And they must move (as they are close)!



$$< 7.2 \times 10^3\ \mathrm{pc}^{-3}\mathrm{yr}^{-1}$$

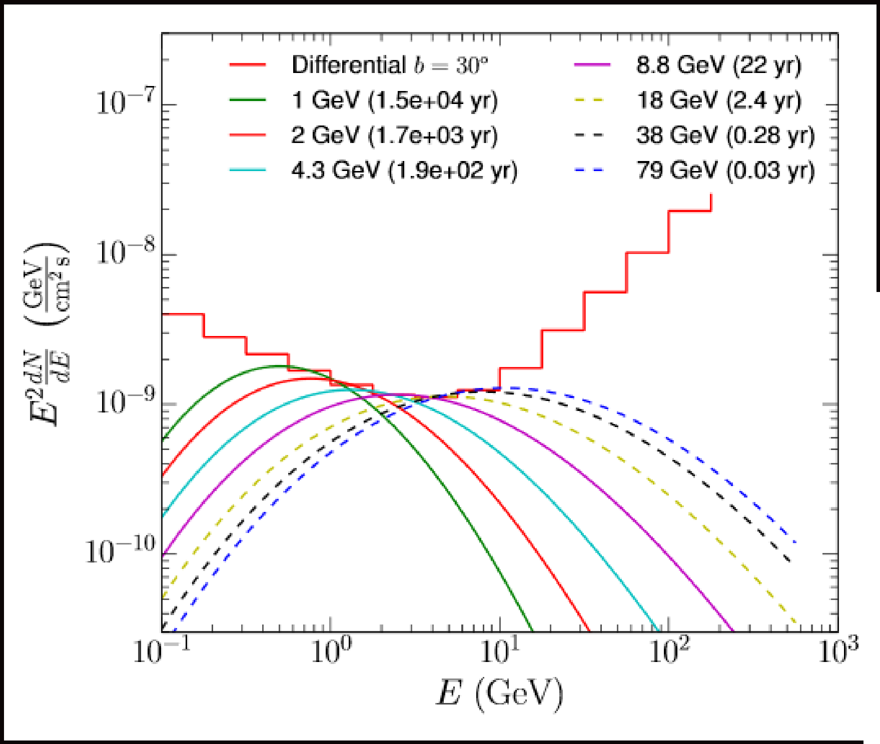
$$T_{\rm BH} = \frac{\hbar c^3}{8\pi G M k} \approx 10^{-7} \left(\frac{M}{M_\odot}\right)^{-1} K,$$

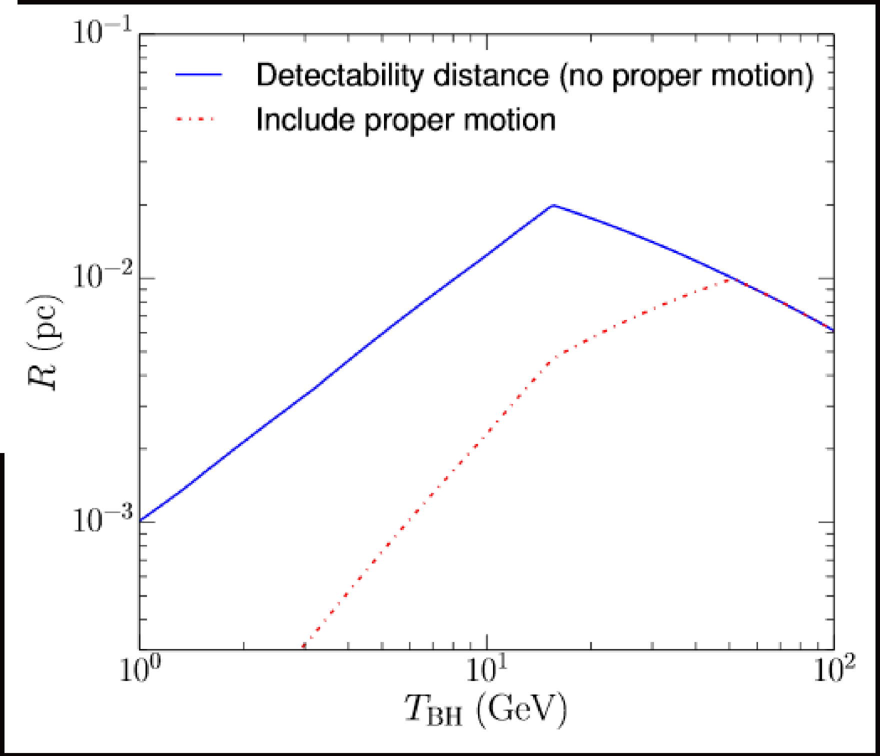
$$M(t) \approx 10^{15} \left(\frac{t}{10^{-23}\mathrm{s}}\right) \mathrm{g}.$$

$$\tau \approx 400 \left(\frac{M}{10^{10}\mathrm{g}}\right)^3 \mathrm{s}.$$

1802.00100

Sensitivity of Fermi to PBHs





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Calculations of the limit

$$\dot{\rho}_{\rm PBH} = const.$$

$$\frac{d\rho_{\rm PBH}}{dT} \propto T^{-4}.$$

$$f = \frac{\int_{16.4\ {\rm GeV}}^{60\ {\rm GeV}} T^{-4}\, dT}{\int_{5\ {\rm GeV}}^{60\ {\rm GeV}} T^{-4}\, dT}.$$

$$N = \rho\epsilon V,$$

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

$$\dot{\rho}_{\rm PBH} < f\frac{6.64}{\epsilon V t} = 7.2\times 10^3\ {\rm pc}^{-3}\ {\rm year}^{-1}.$$

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

1802.00100