

# 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)**
- • arXiv: 2002.12778 **Constraints on PBHs**

# 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  $\gamma$ -ray, but also to CR and  $\nu$  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

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

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

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

Hawking radiation

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

The time for complete evaporation

$$\tau = \frac{2\pi G^2 M^3}{\hbar c^4}$$

# 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).

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

In different models of PBHs formation the spectrum can have different shape (power law, log-normal, etc.).

# Hawking spectrum

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

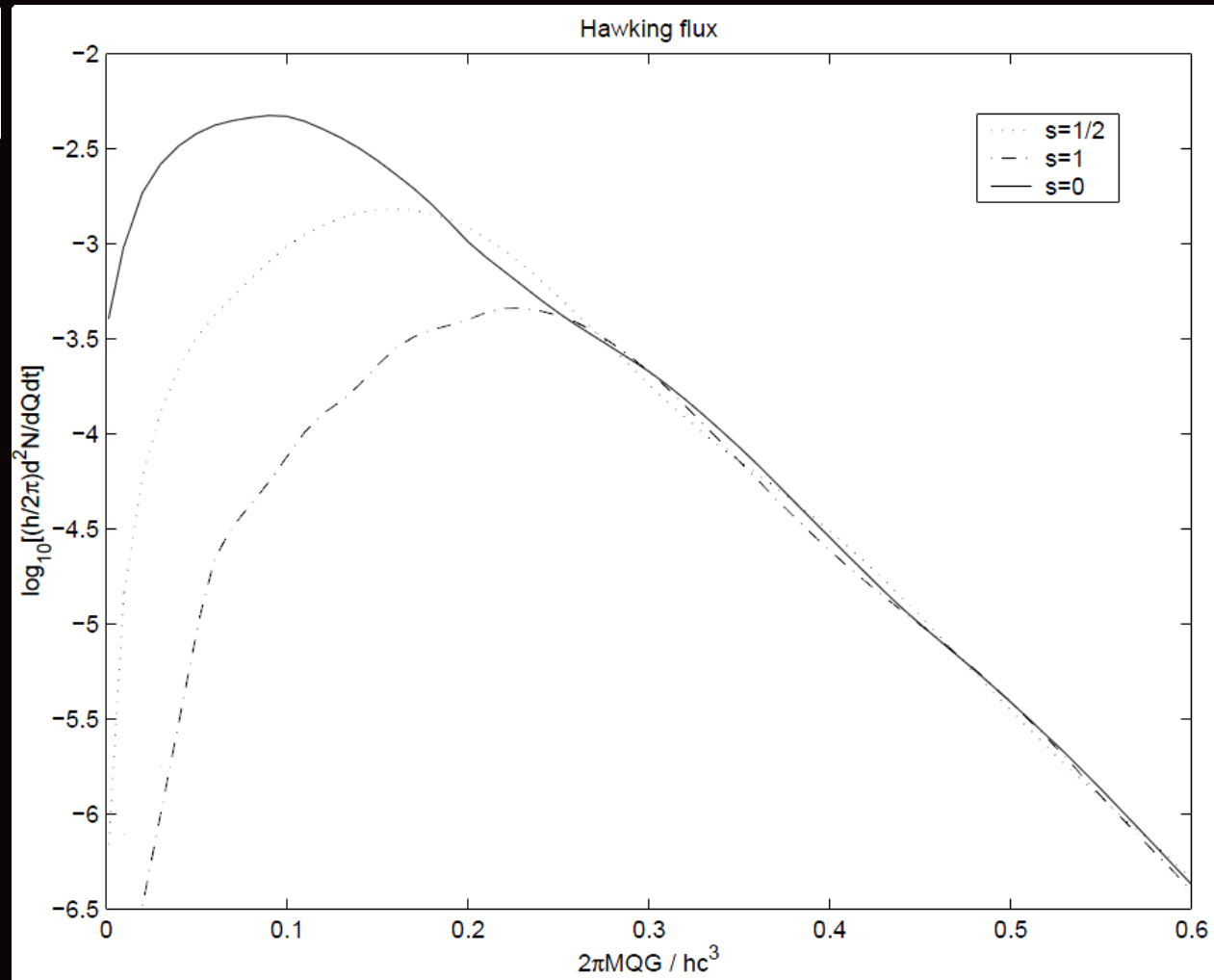
For non-rotating,  
non-charged BH.

Horizontal axis  $\sim Q/kT$

$T=T(M)$

Vertical –  $d^2 N/dQ dt$

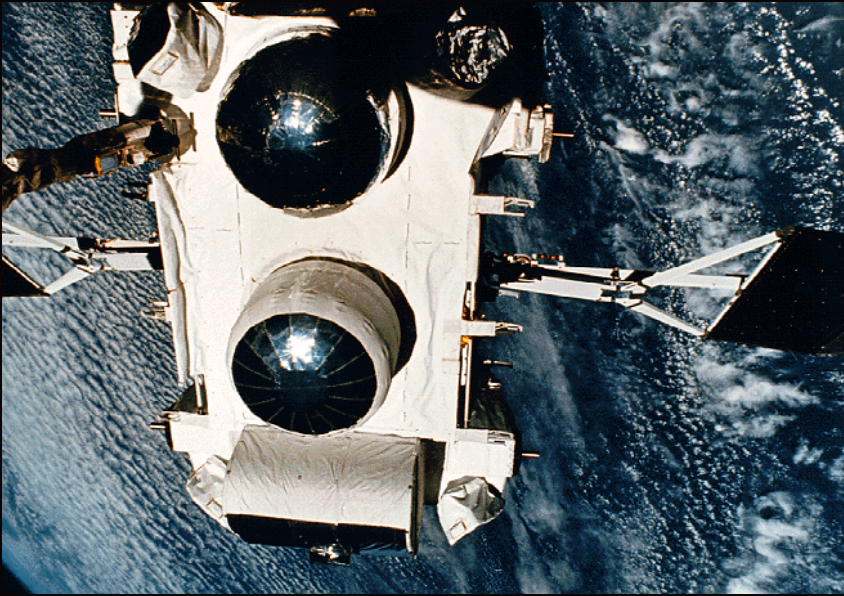
*Rem: Spectrum is  
different in other models  
of gravity. For example,  
about BH evaporation  
in loop quantum gravity  
see 1808.08857, 2001.08833.*



Rem: rotation is not important for  
actively evaporating BHs (1906.04196).

astro-ph/0304478

# EGRET and constraints on PBH



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

Background radiation at energies:  
30 MeV – 120 GeV.

The upper limit on the density of PBHs

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

# Constraints on cosmological parameters from data on PBH

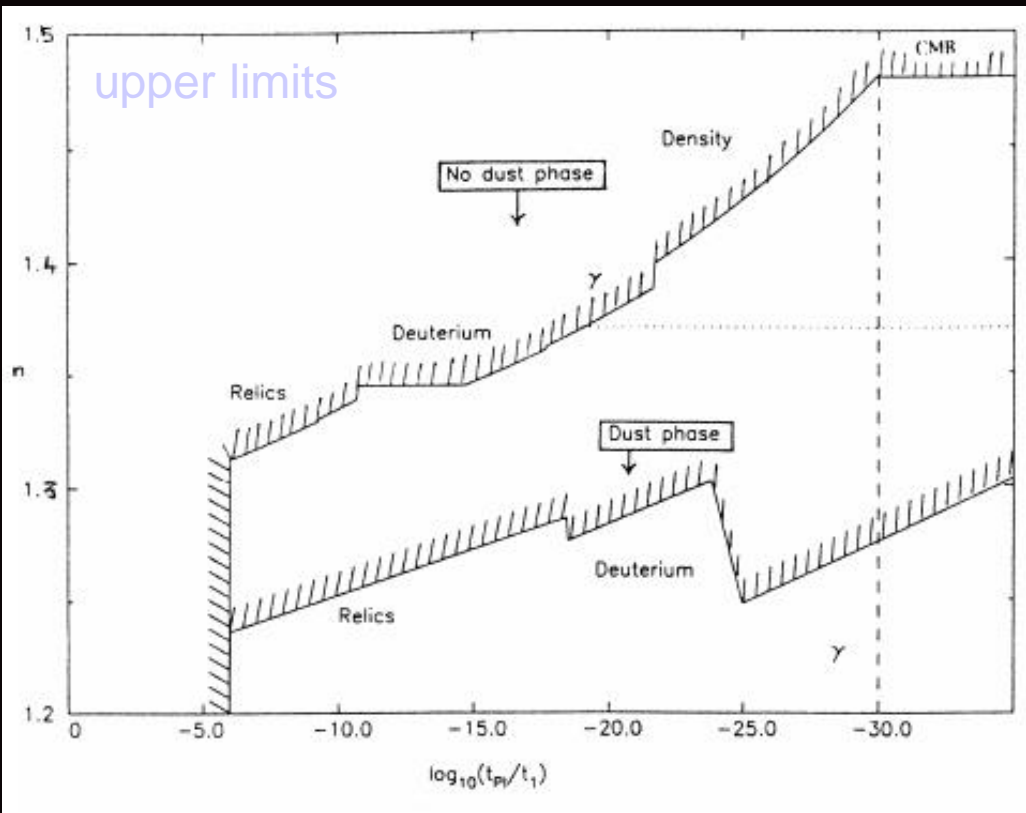
Data on PBHs in principle can provide constraints on different cosmological parameters related to the density fluctuations.

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

For example, on the parameter  $n$ , characterizing the power spectrum of fluctuations.

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

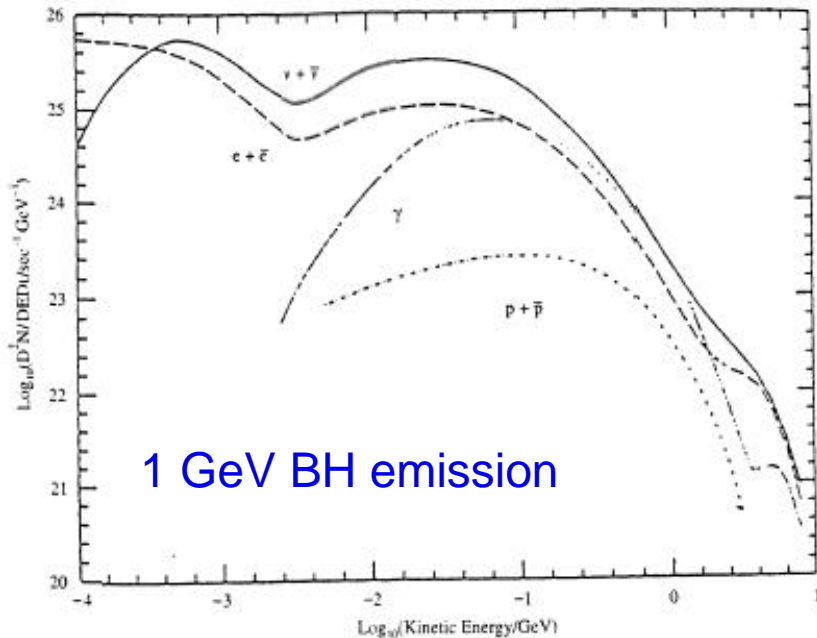
$t_1$  – re-heating time



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



# Particle emission during PBH evaporation



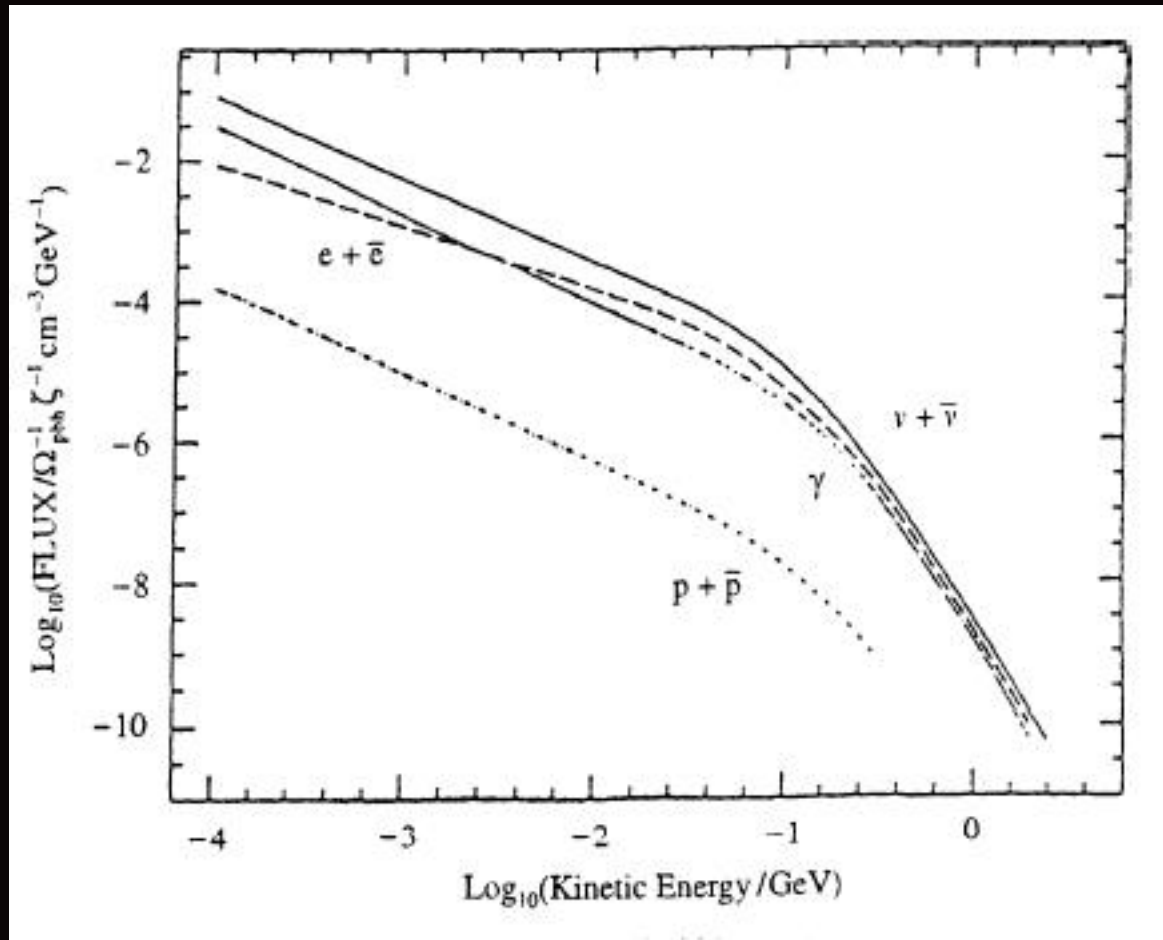
$$T \approx 10^{26} \left( \frac{M}{g} \right)^{-1} \text{ K} \approx \left( \frac{M}{10^{13} g} \right)^{-1} \text{ GeV.}$$

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

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

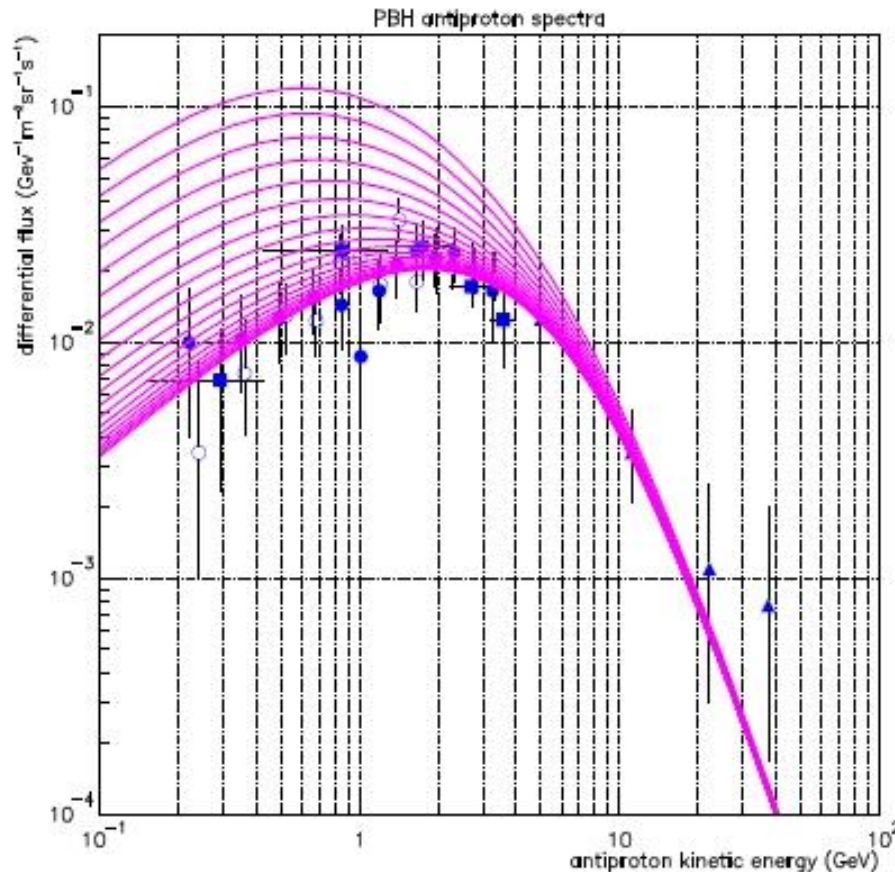
When a BH mass is below  $10^{14} \text{ g}$ , it starts to emit hadrons.

# Particle spectrum for uniform distribution of PBHs



BHs uniformly distributed in the Universe.

# PBH and antiprotons



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.

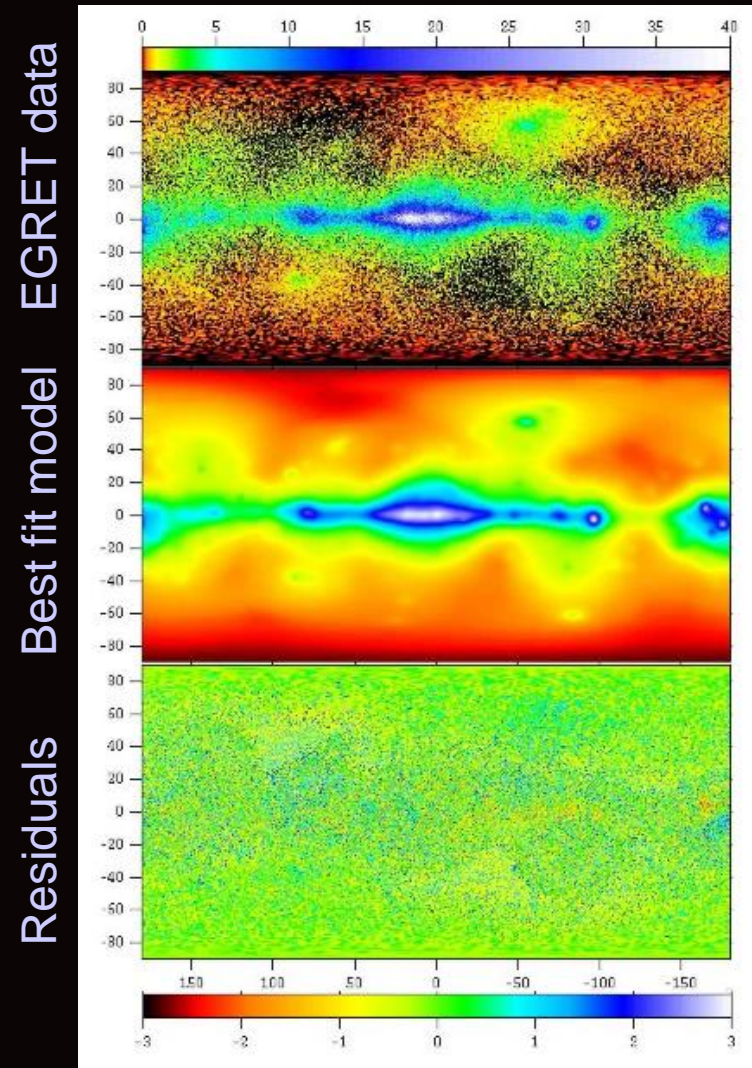
Recently, positron spectrum measured by Voyager-1 was used to put constraints on the PBH number (1807.03075).

# Constraints from galactic $\gamma$ -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  $5\text{ kT}$ ) than for a pure blackbody at the same temperature (which flux is maximum at  $1.59\text{ kT}$ )



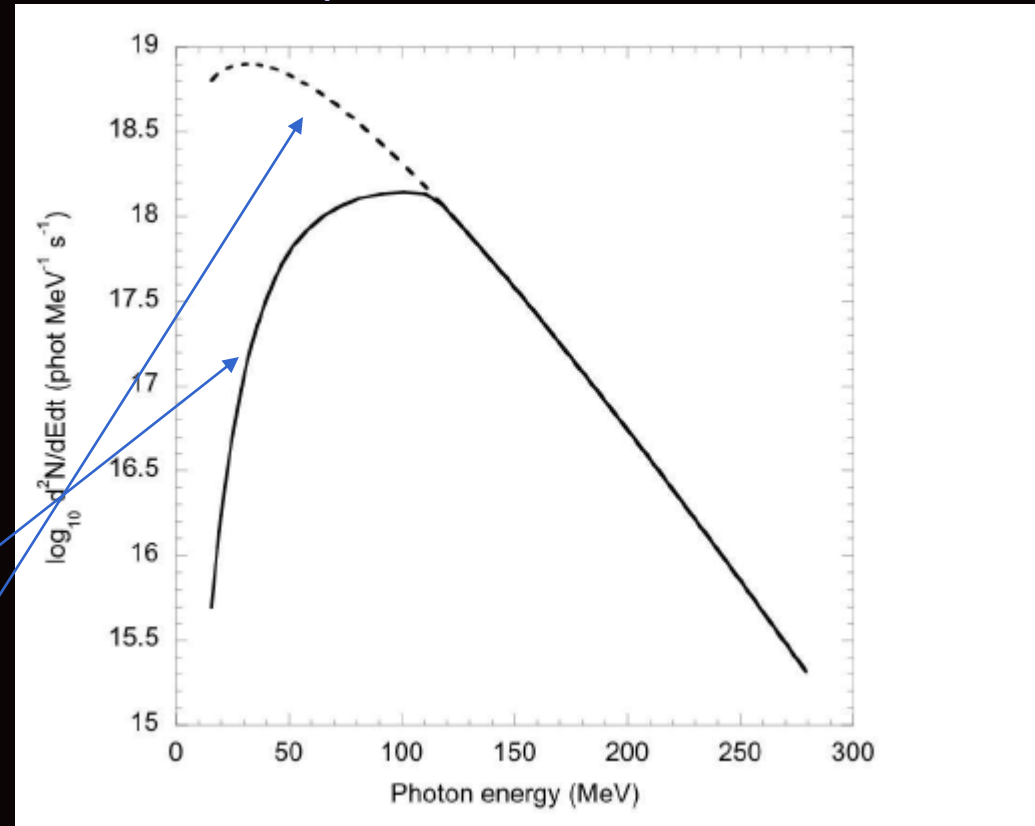
# The spectrum

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 quasi-planckian spectrum at unexpectedly high energy, peaking at about 100 MeV

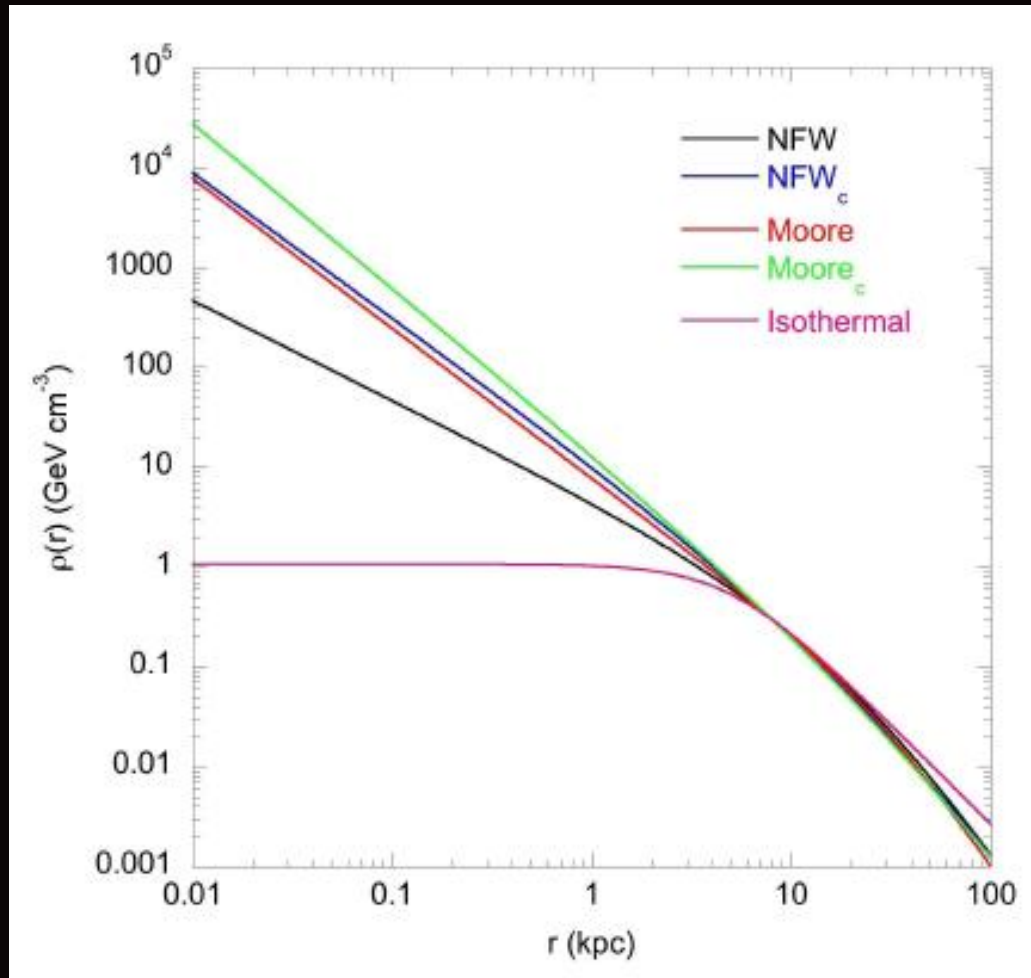
BH spectrum  
(MacGibbon&Webber 1990)

Blackbody spectrum  
with the same temperature

Spectrum of a  $kT=20$  MeV BH



# Density distribution



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



# Results and limits

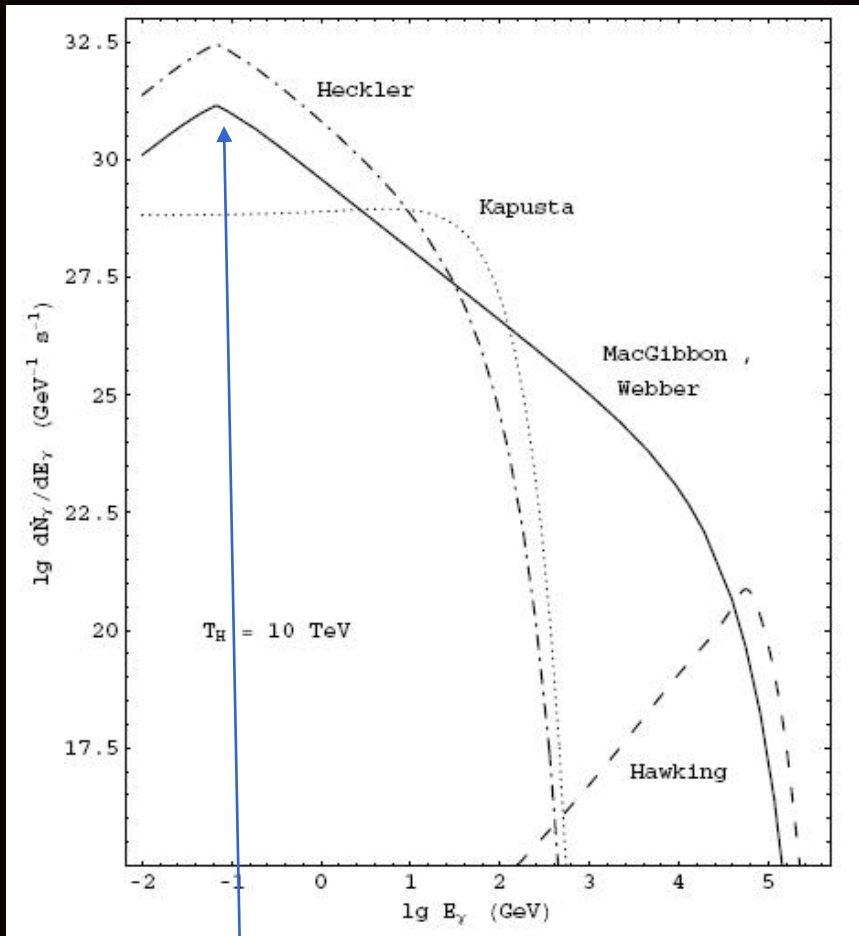
DM distribution	$f(M_\star)$	$\Omega_{PBH}(M_\star)$	$\beta(M_\star)$
Moore	$6.04 \pm 0.05 \cdot 10^{-9}$	$1.38 \cdot 10^{-9}$	$0.98 \cdot 10^{-27}$
Moore <sub>c</sub>	$1.07 \pm 0.07 \cdot 10^{-9}$	$0.24 \cdot 10^{-9}$	$0.17 \cdot 10^{-27}$
NFW	$6.70 \pm 0.05 \cdot 10^{-9}$	$1.53 \cdot 10^{-9}$	$1.08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

Upper limits for the local PBH density are:

$3.3 \cdot 10^7 - 2.1 \cdot 10^8$  per  $\text{pc}^3$ .

Explosion rate  $\sim 0.06 \text{ pc}^{-3} \text{ yr}^{-1}$ .

# Spectra in different models



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

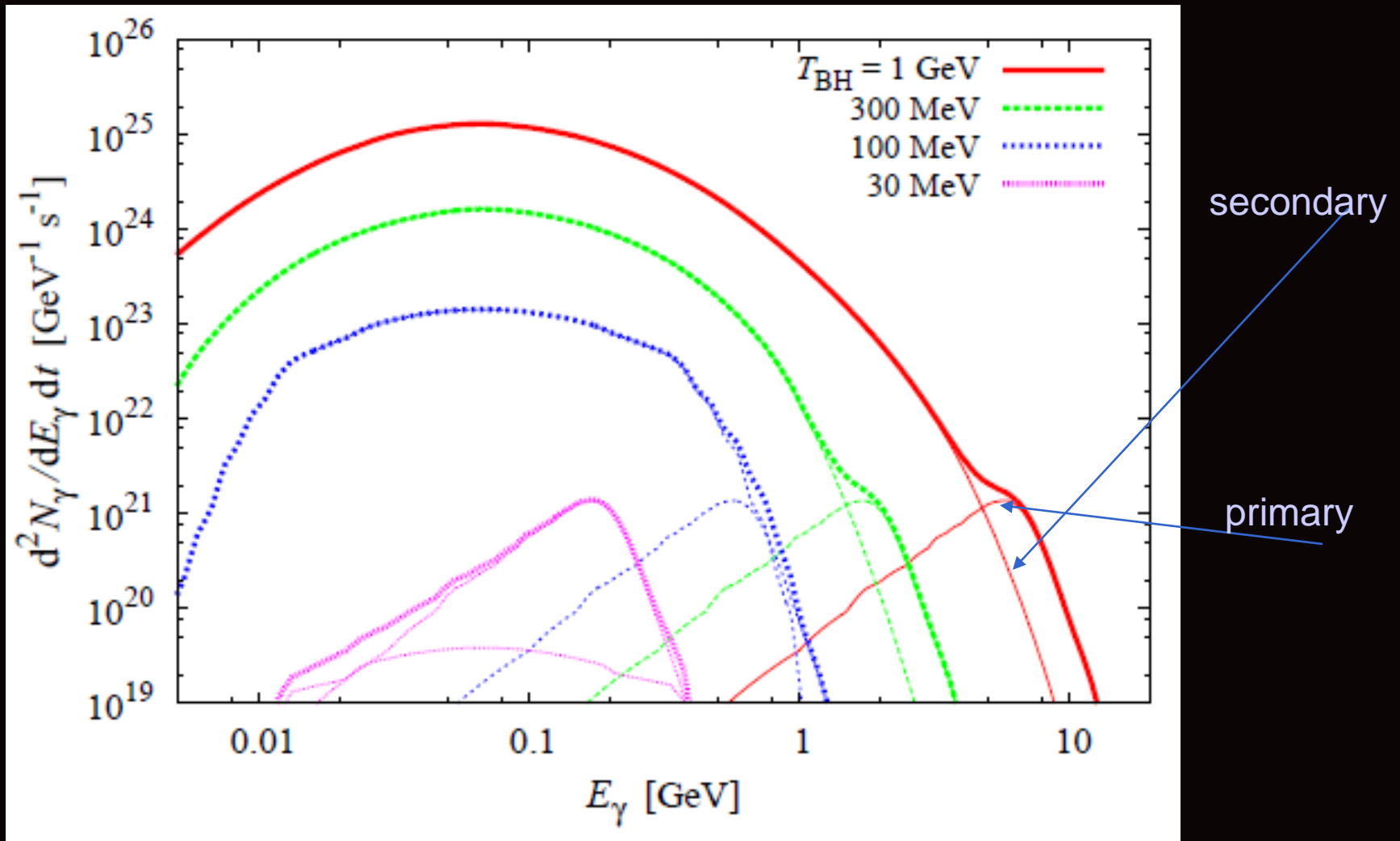
The spectrum can be non-thermal. This is due to creation of particles which then demonstrate series of transformations (decays) and interactions; only at the very end we have photons. And their spectrum is different from the thermal (i.e. from the blackbody).

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

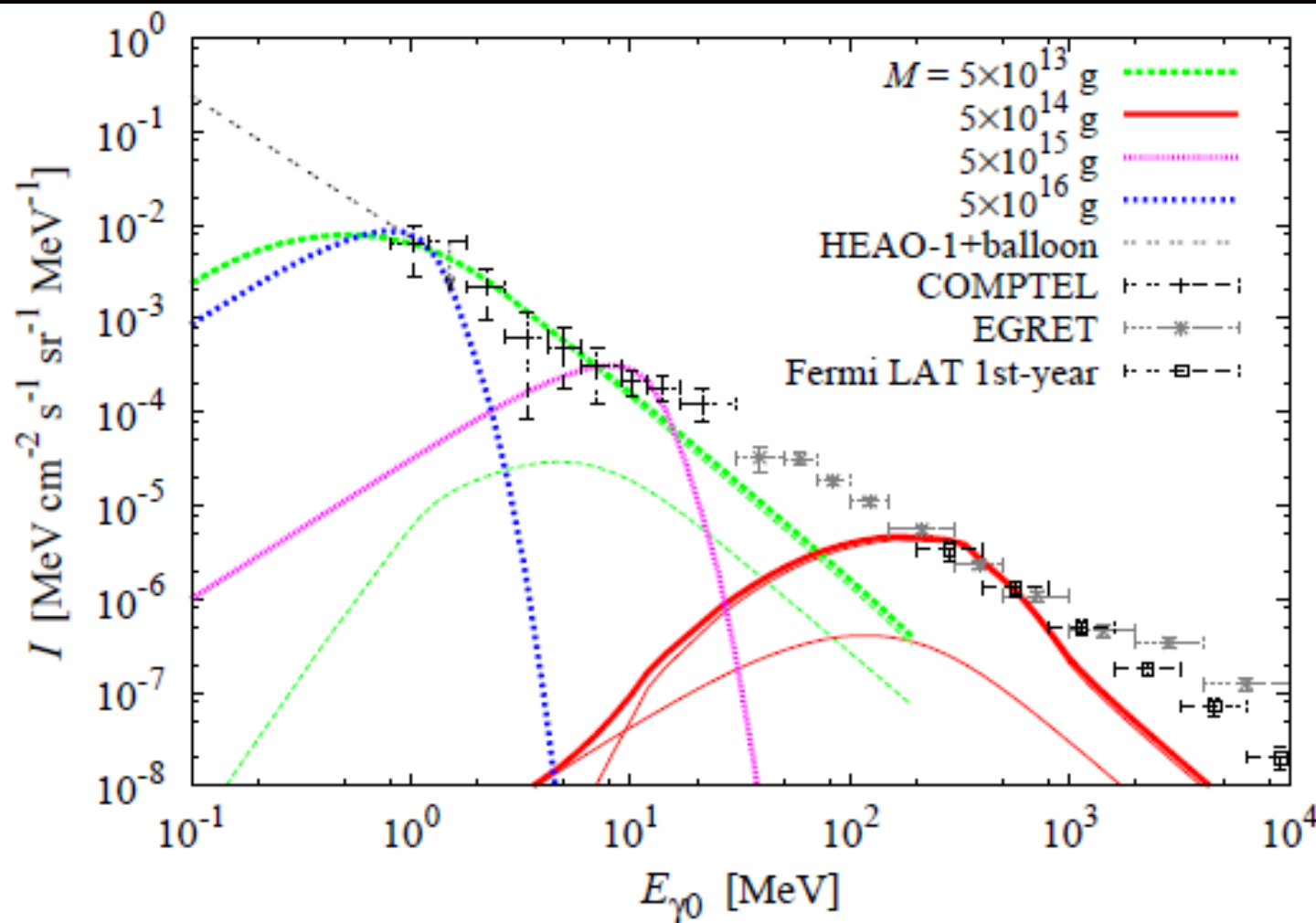
Note, that  $\gamma$ -ray limits are made for PBH with  $T \sim 20 \text{ MeV}$ , so effects of photospheres are not important. But they can be important for UHECRs. Effects can be strong at  $T_{\text{BH}} \sim \Lambda_{\text{QCD}} \sim 300 \text{ MeV}$



# Emission rate of photons

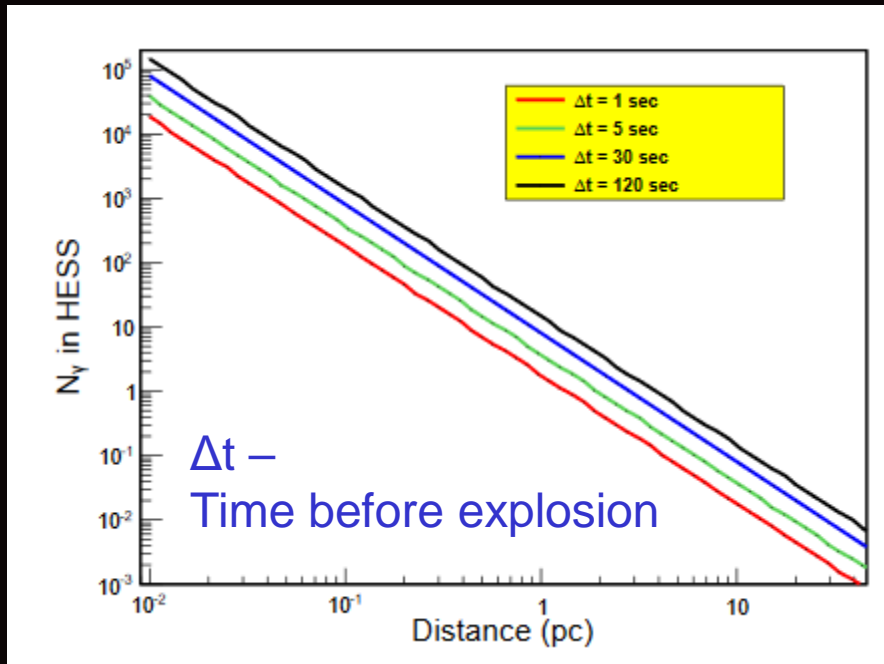


# Gamma-ray background



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

# Constraints from H.E.S.S.



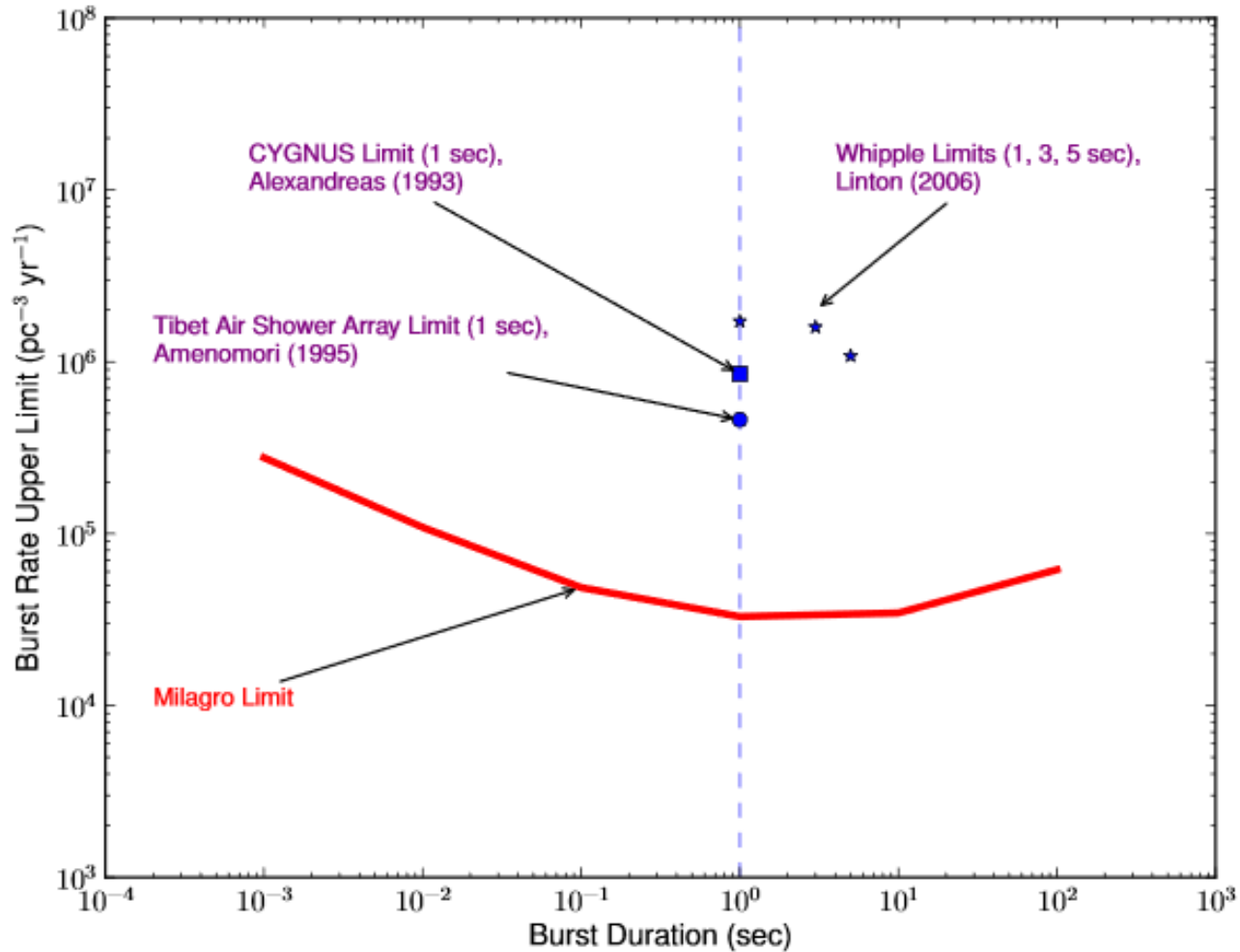
Nothing detected.

Upper limits can be derived.

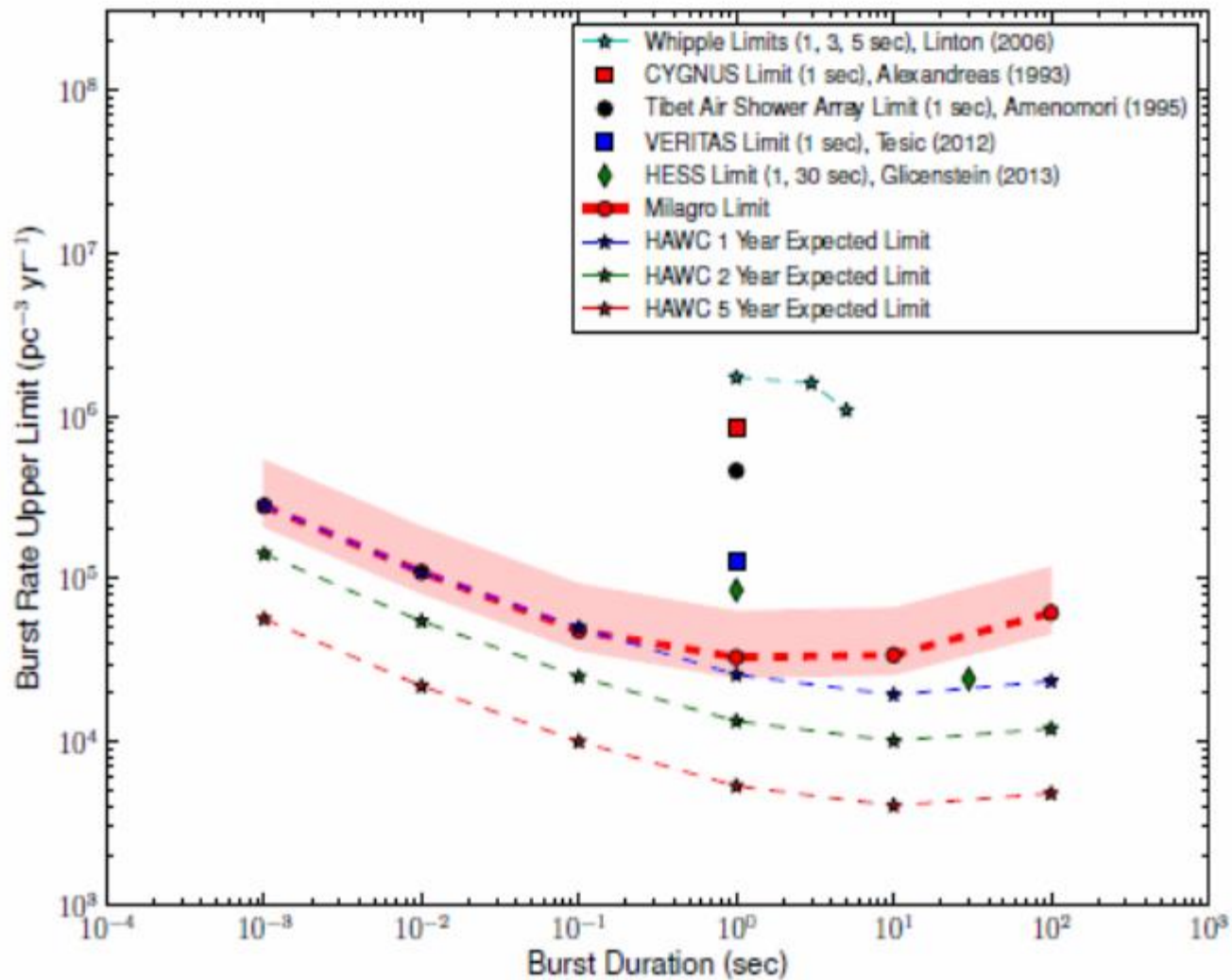
At the moment these limits are not very constraining. However, with HESS-2 it will be possible to obtain more interesting limits.

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

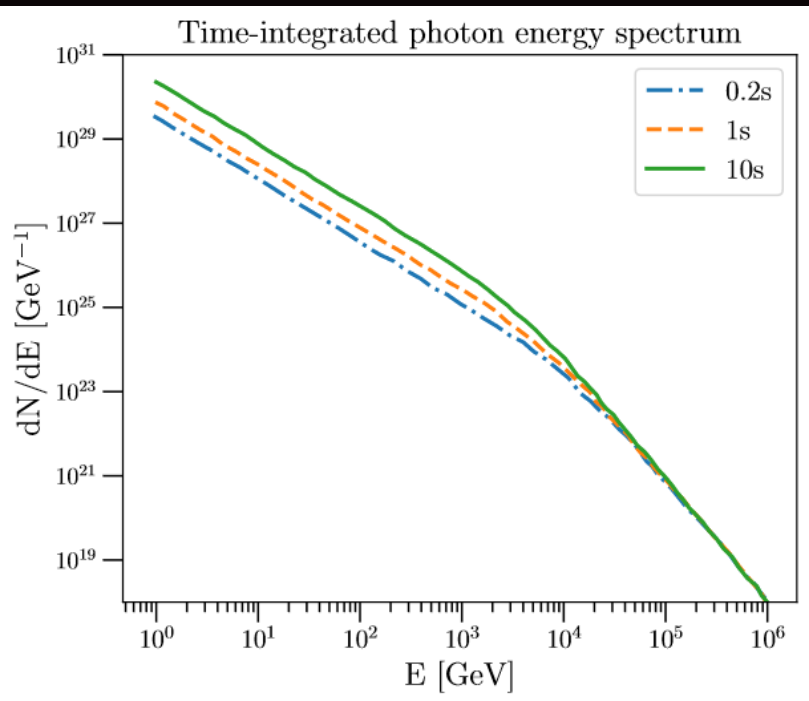
# Milagro limits



# Joint limits



# HAWC limits



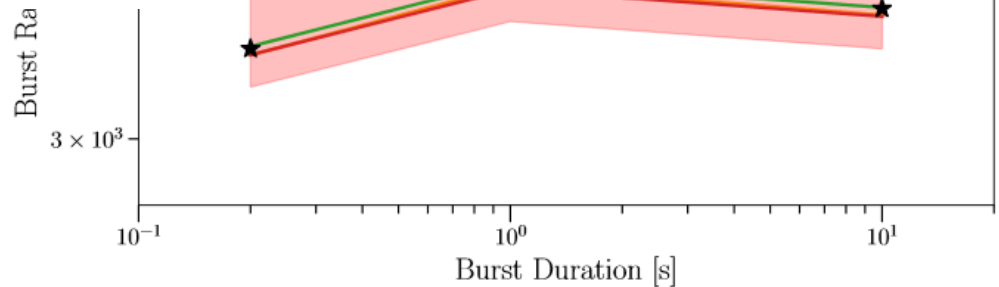
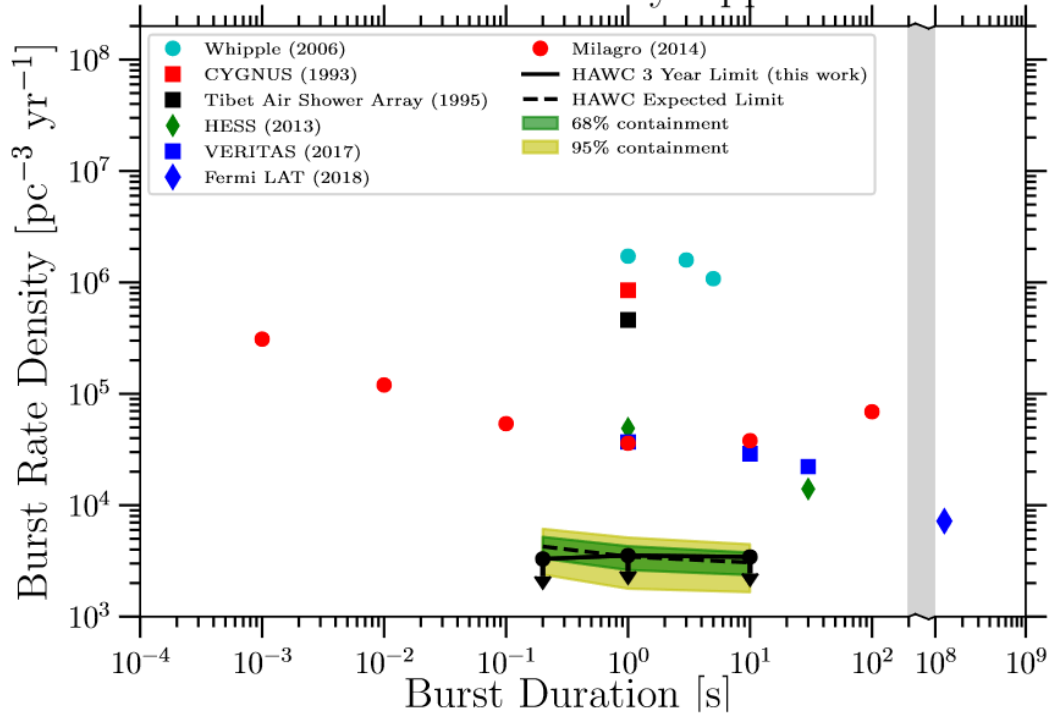
Burst duration	Burst Rate Upper Limit
0.2 s	$3300^{+300}_{-100} \text{ pc}^{-3} \text{ yr}^{-1}$
1 s	$3500^{+400}_{-200} \text{ pc}^{-3} \text{ yr}^{-1}$
10 s	$3400^{+400}_{-100} \text{ pc}^{-3} \text{ yr}^{-1}$

300 GeV - 100 TeV  
959 day of observations.

Experiment	Burst Rate Upper Limit	Search Duration	Reference
Milagro	$36000 \text{ pc}^{-3} \text{ yr}^{-1}$	1 s	[27]
VERITAS	$22200 \text{ pc}^{-3} \text{ yr}^{-1}$	30 s	[19]
H.E.S.S.	$14000 \text{ pc}^{-3} \text{ yr}^{-1}$	30 s	[14]
Fermi-LAT	$7200 \text{ pc}^{-3} \text{ yr}^{-1}$	$1.26 \times 10^8 \text{ s}$	[20]
<b>HAWC 3 yr.</b>	<b><math>3400 \text{ pc}^{-3} \text{ yr}^{-1}</math></b>	<b>10 s</b>	<b>This Work</b>

# HAWC limits

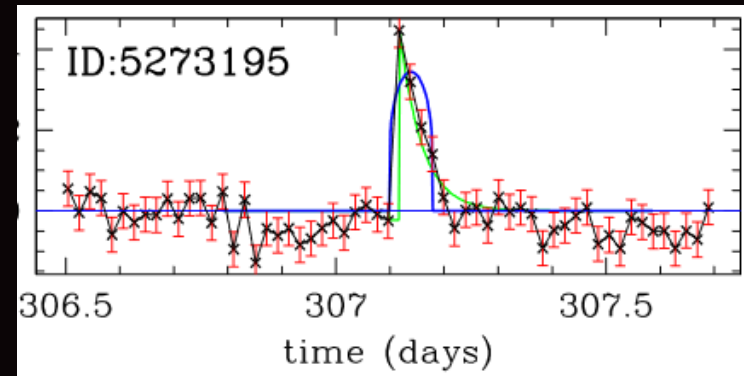
PBH Burst Rate Density Upper Limits



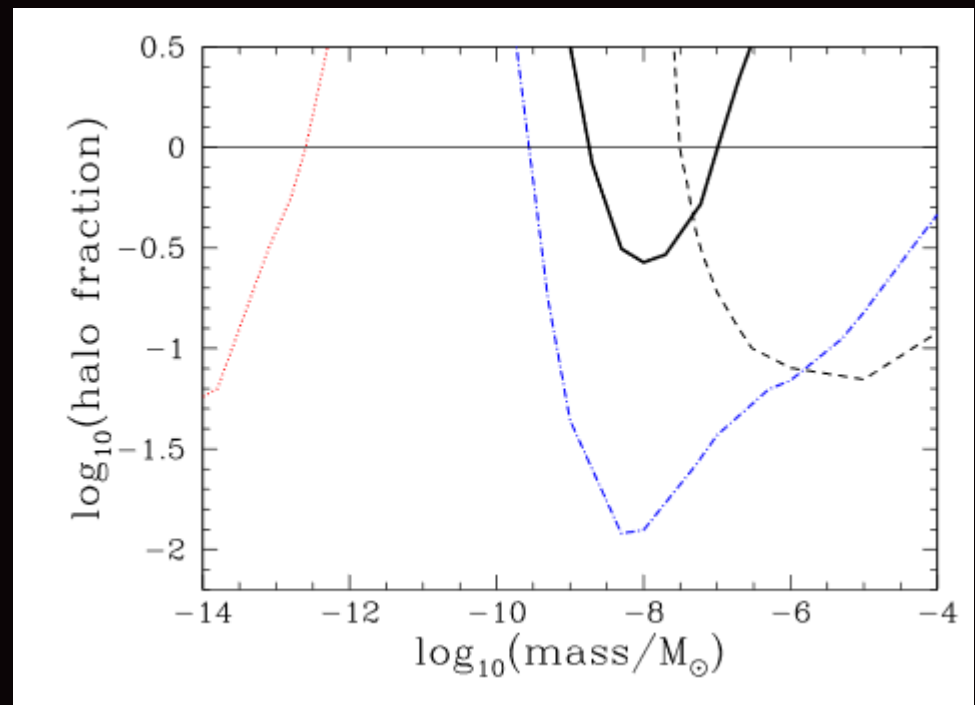
# Limits from the Kepler data

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  
 $2 \cdot 10^{-10} M_{\text{solar}} < M_{\text{BH}} < 2 \cdot 10^{-6} M_{\text{solar}}$



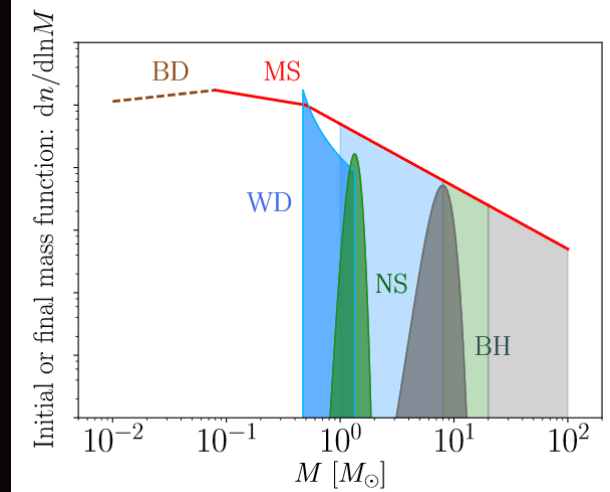
Solid black is the new limit.  
It excludes the mass range  
 $10^{-9} M_{\text{solar}} < M_{\text{BH}} < 10^{-7} M_{\text{solar}}$   
I.e., PBHs from this range  
cannot explain halo DM.  
The allowed range is  
 $10^{-13} M_{\text{solar}} < M_{\text{BH}} < 10^{-9} M_{\text{solar}}$





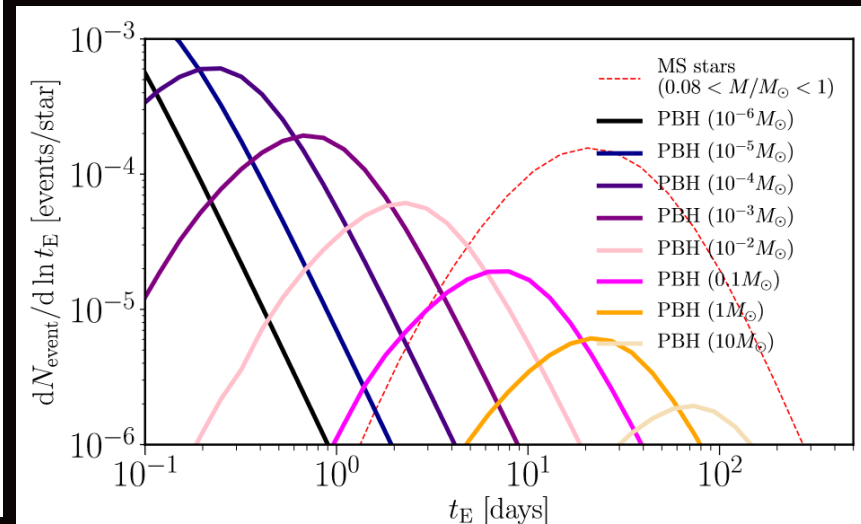
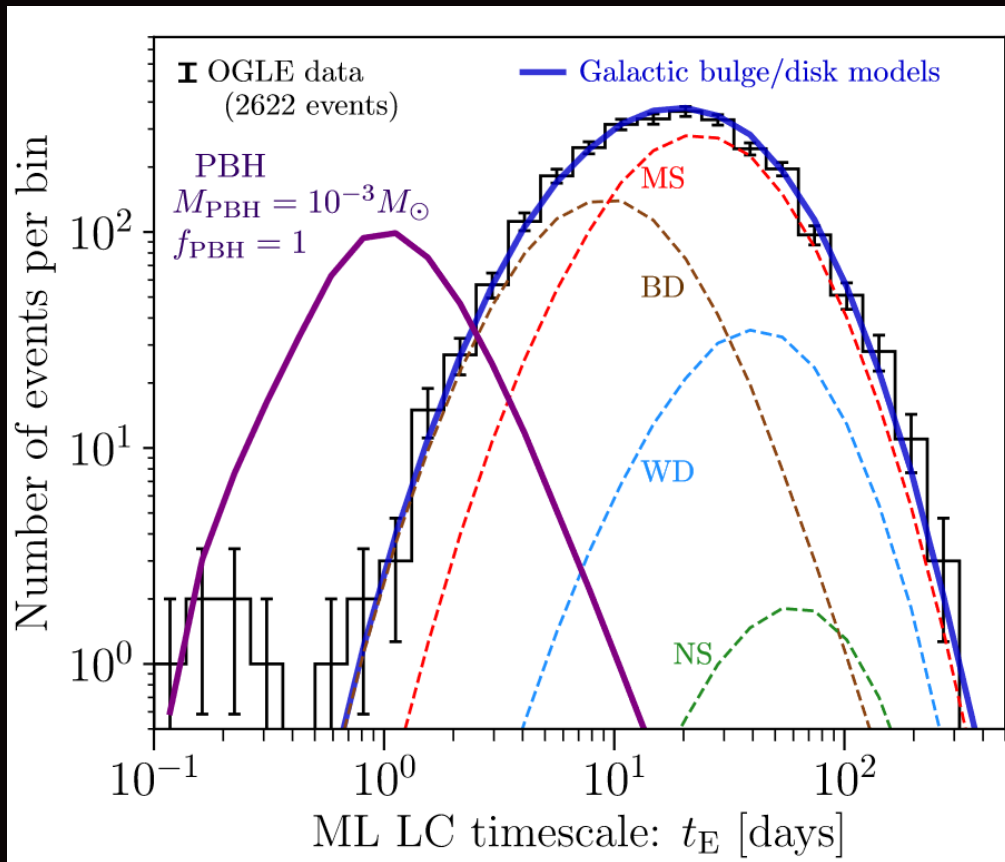
# OGLE limits from lensing

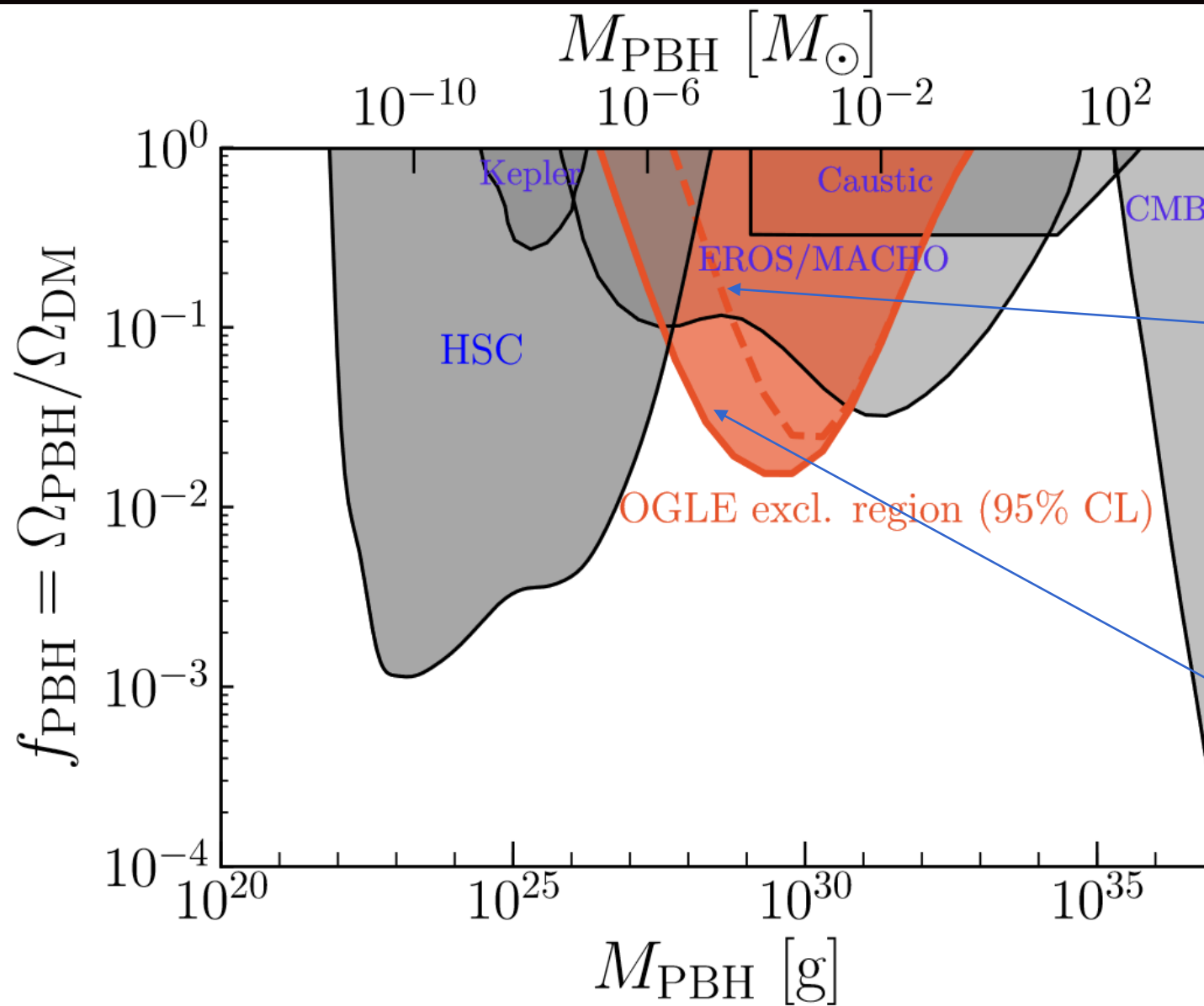
Six “suspicious” ultrashort (few hours) events are detected. They correspond to masses about an earth-like planet. Potentially, they can be PBHs.



MS : WD : NS : BH = 1 : 0.15 : 0.013 : 0.0068

+~0.1 free-floating Jupiter-mass planet per MS star

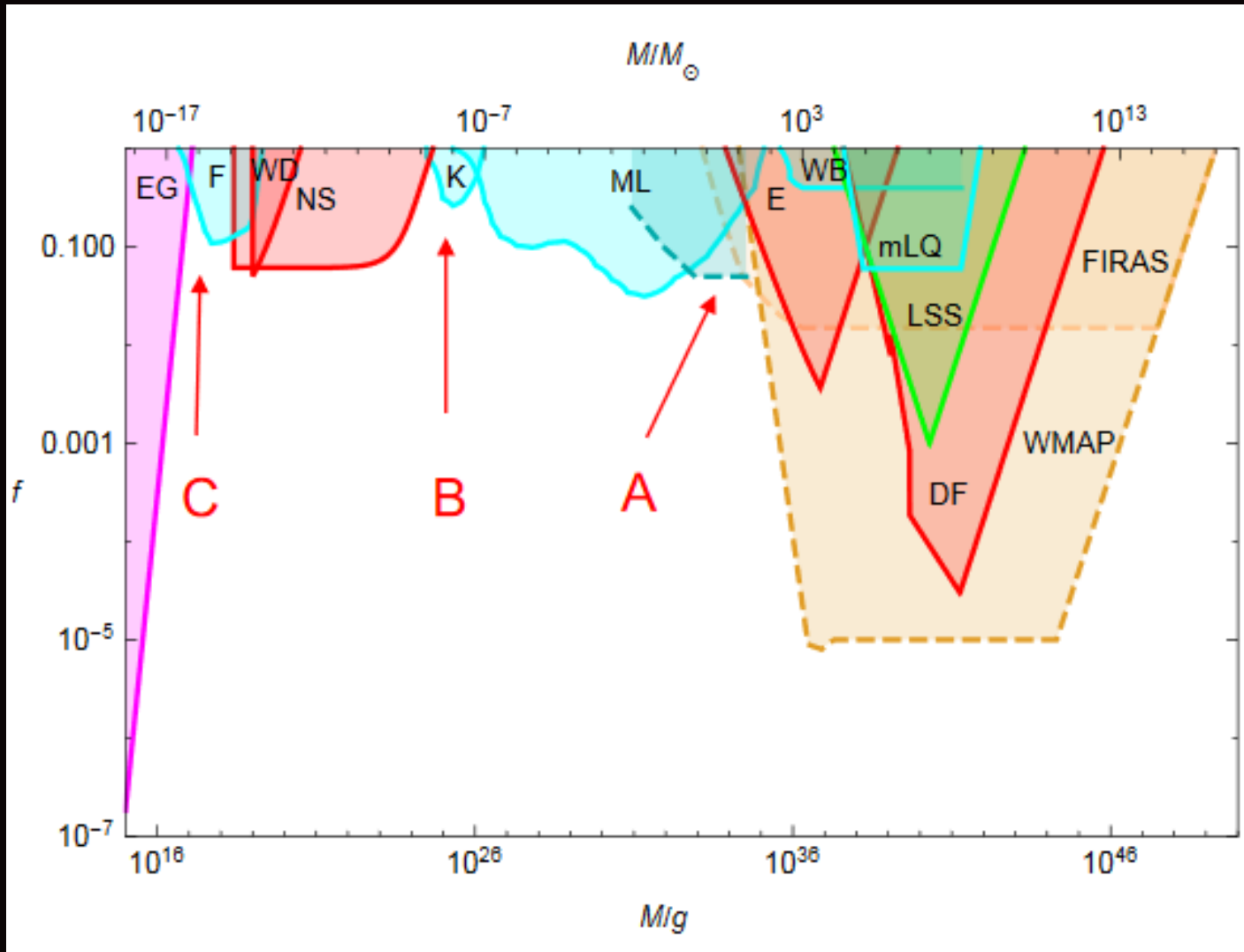




If 4 shortest  
OGLE events  
are excluded  
from the  
analysis.

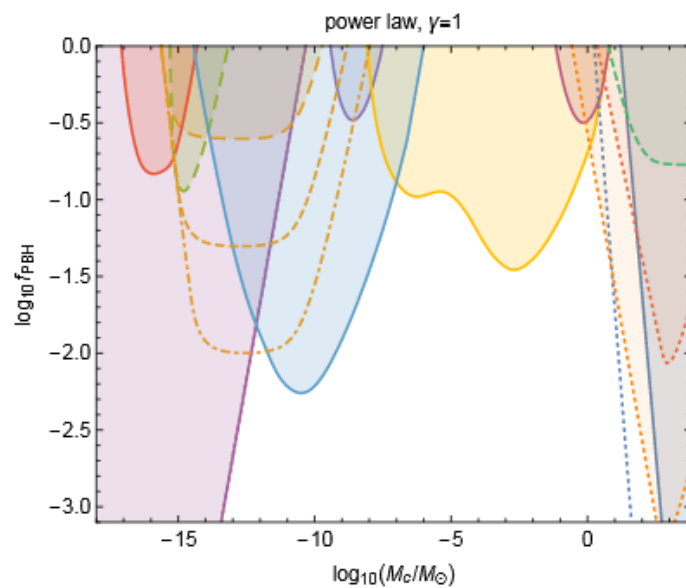
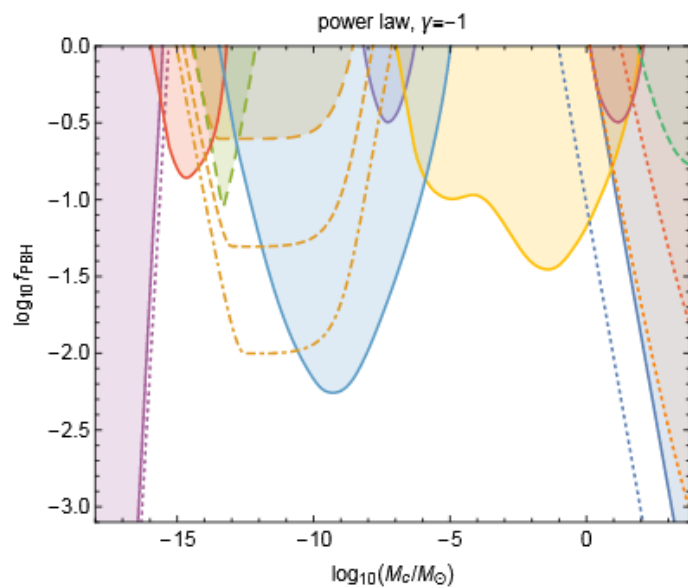
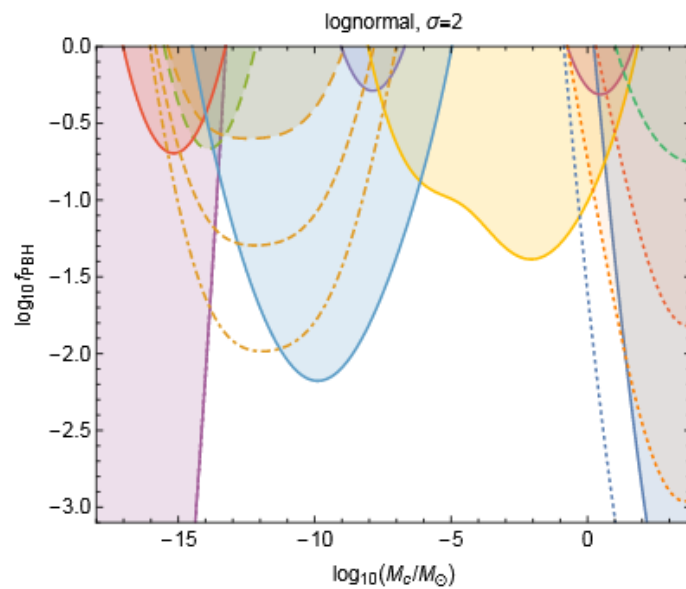
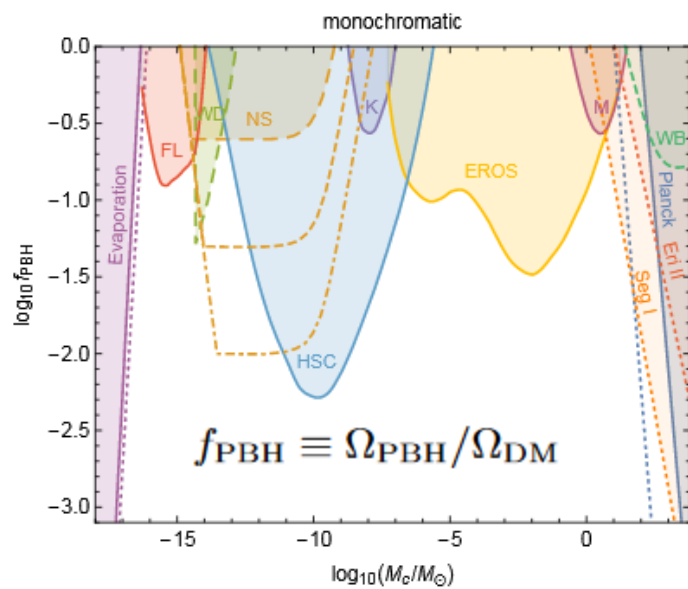
Assuming  
that no PBHs  
were  
detected  
by OGLE

# Limits on PBHs of different masses



Three  
“windows”  
are marked.

All constraints  
are for  
monochromatic  
mass functions  
 $\Delta M \sim M$ .



# 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.

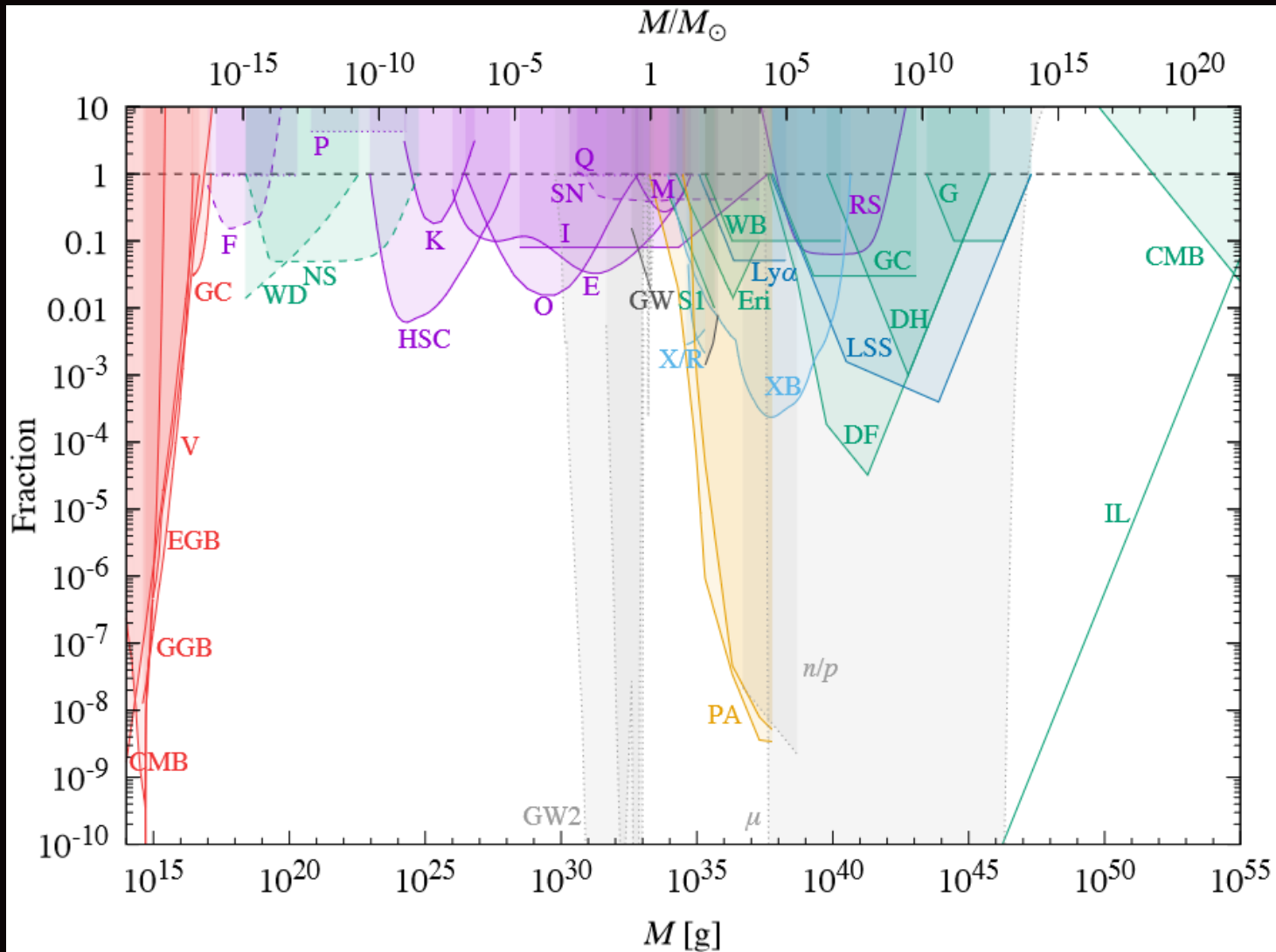
$$f_{\text{PBH}} \equiv \frac{\Omega_{\text{PBH}}}{\Omega_{\text{DM}}} = \int dM \psi(M)$$

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

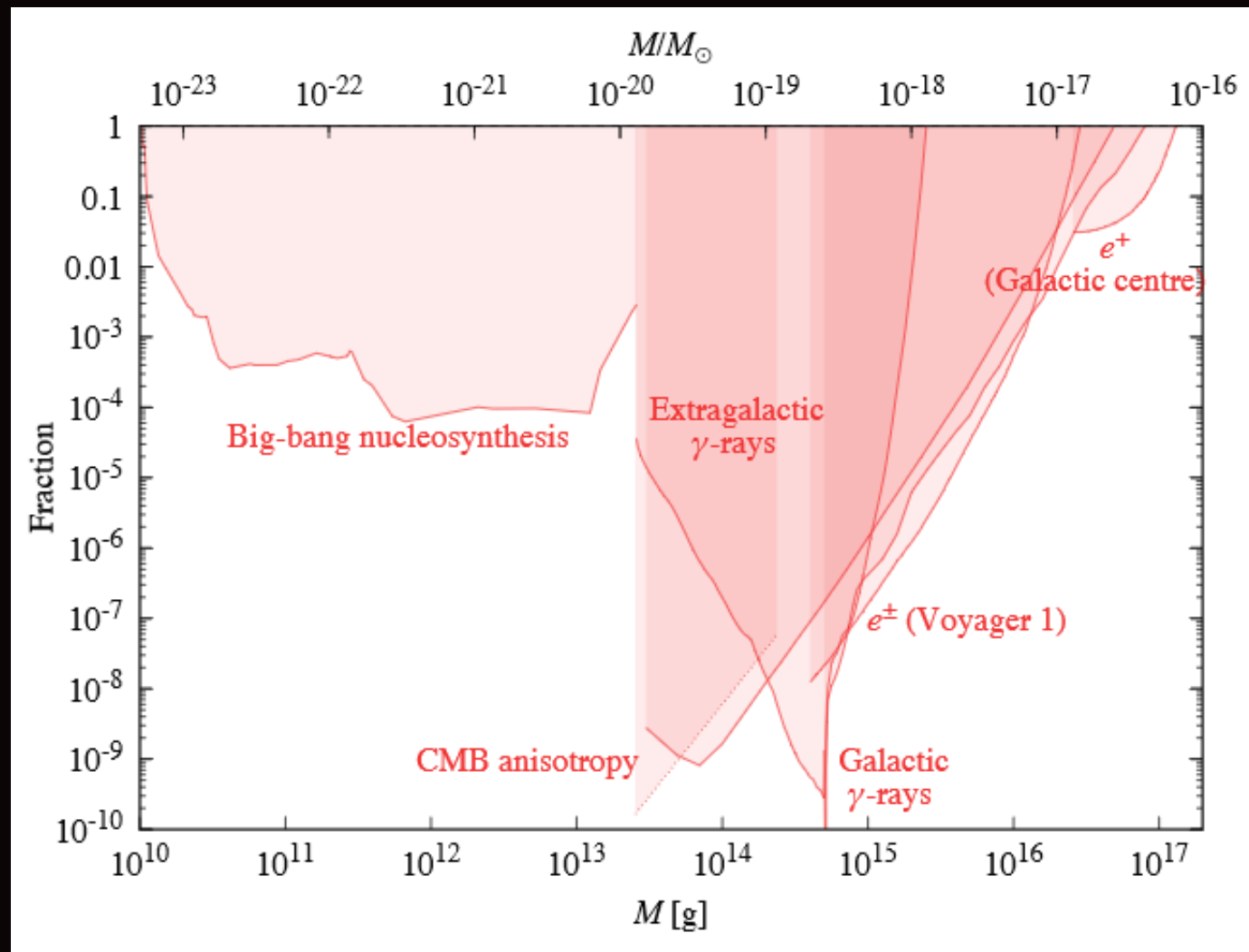
$$\psi(M) \propto M \frac{dn}{dM}$$

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

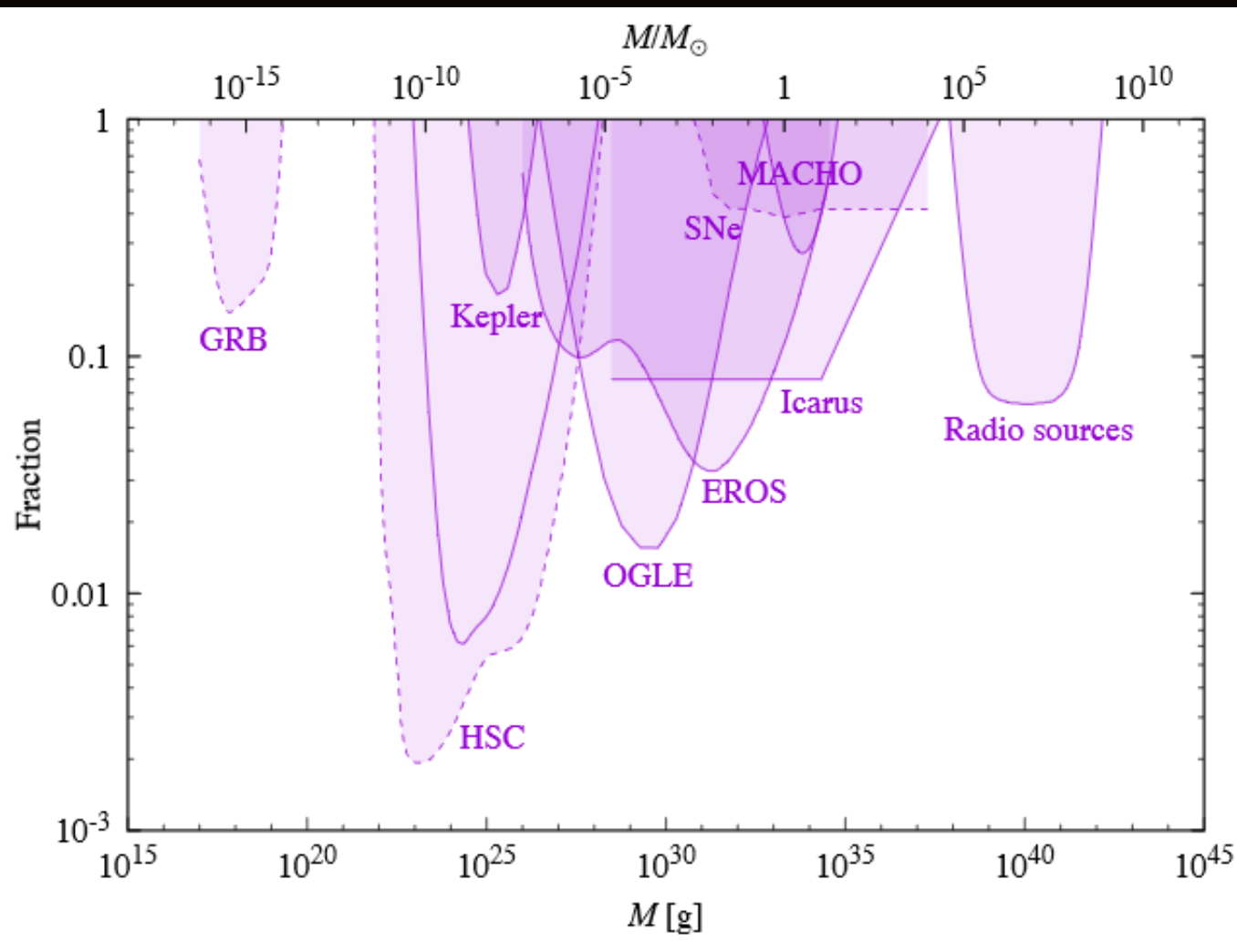
# More limits



# Evaporative constraints on PBHs

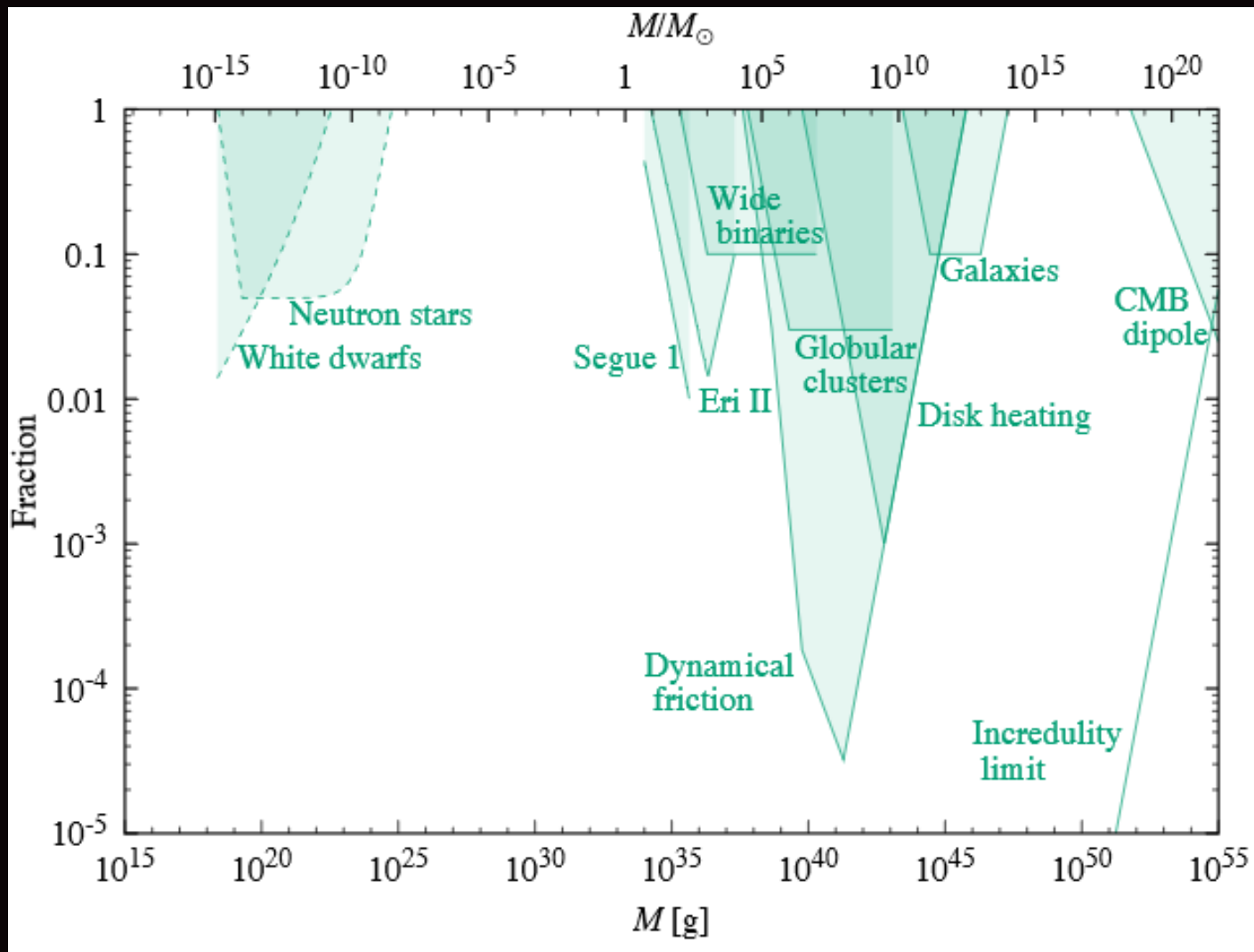


# Lensing constraints + SNe+ GRBs

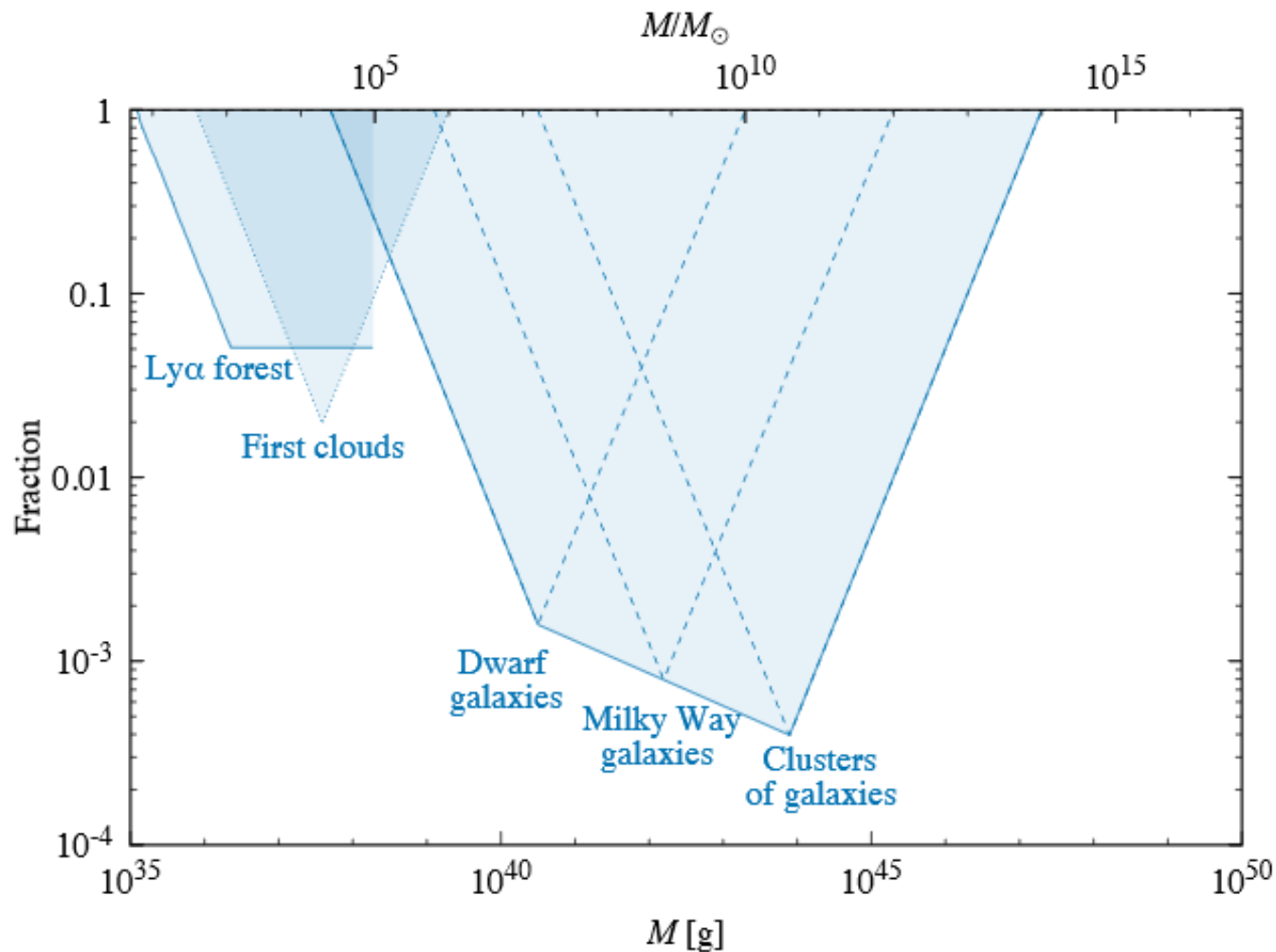




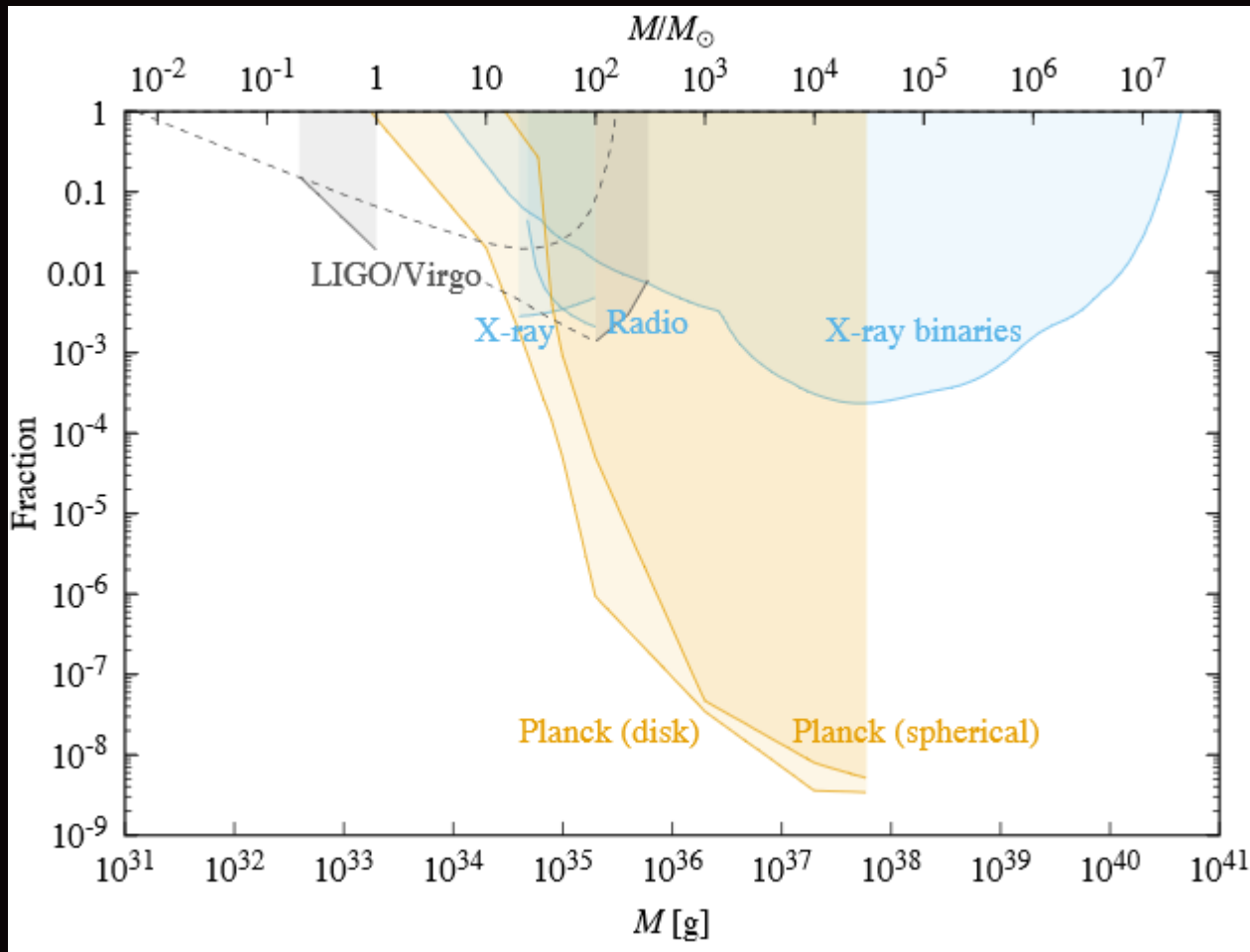
# Dynamical constraints



# Large-scale structure constraints



# Other constraints



Accretion (cyan and yellow) and gravitational wave (grey) constraints from LIGO

# Optimistic scenarios

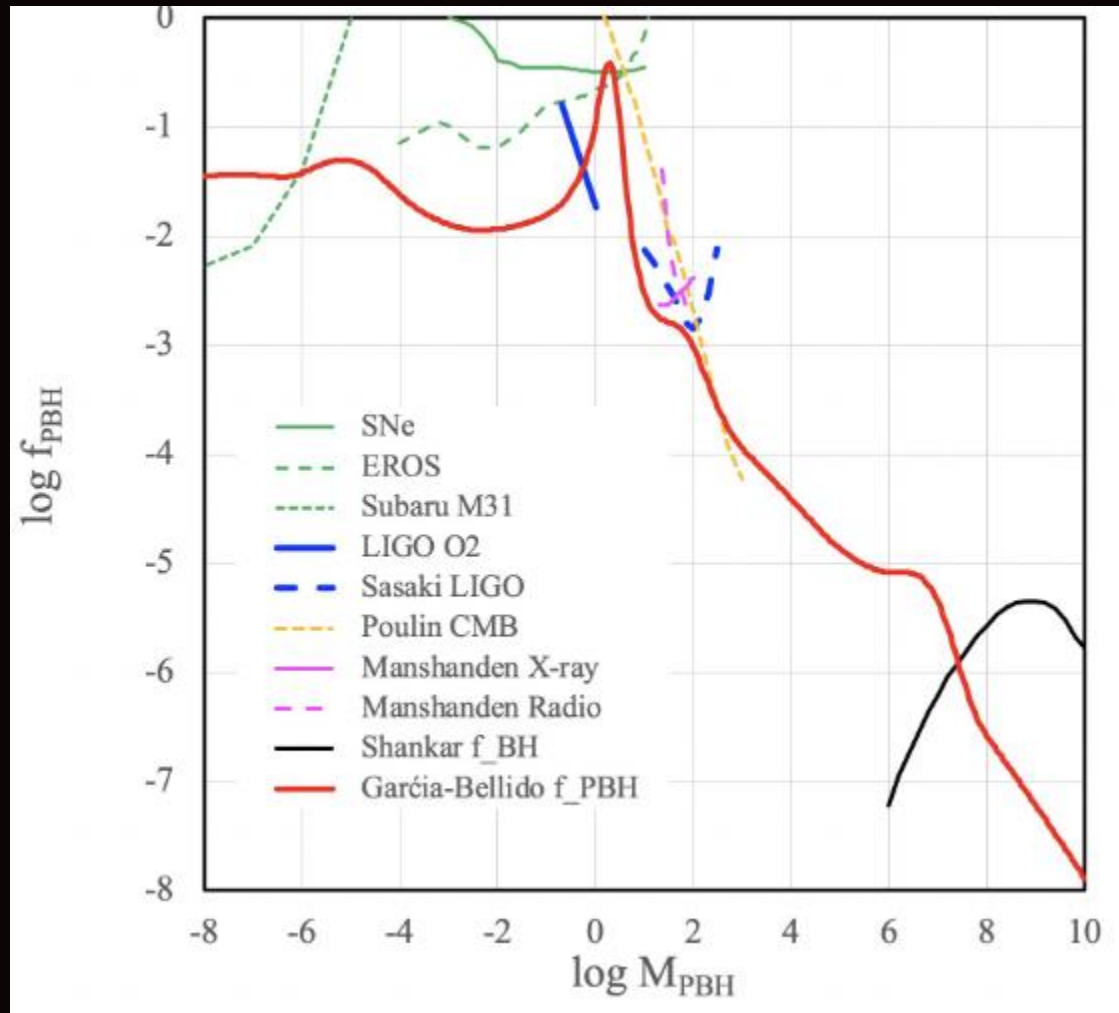
Still, there scenarios in which PBHs are numerous enough to explain the DM.

In such models many other observations appearance of PBHs are possible:

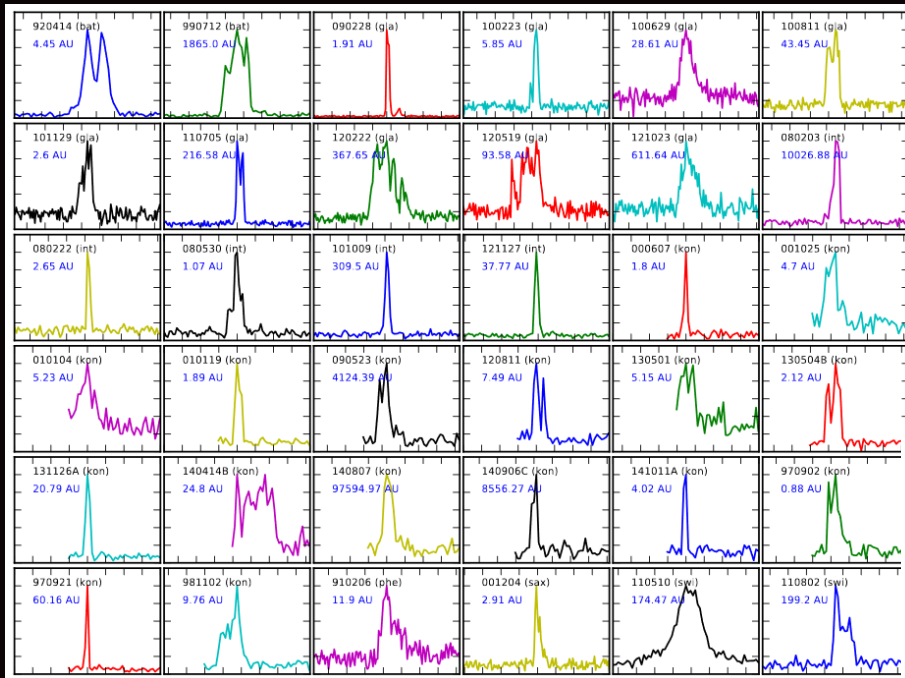
- GW signals;
- Accretion (2003.05150)

PBHs, then, can play role in:

- SMBH formation,
- re-ionization,
- etc.



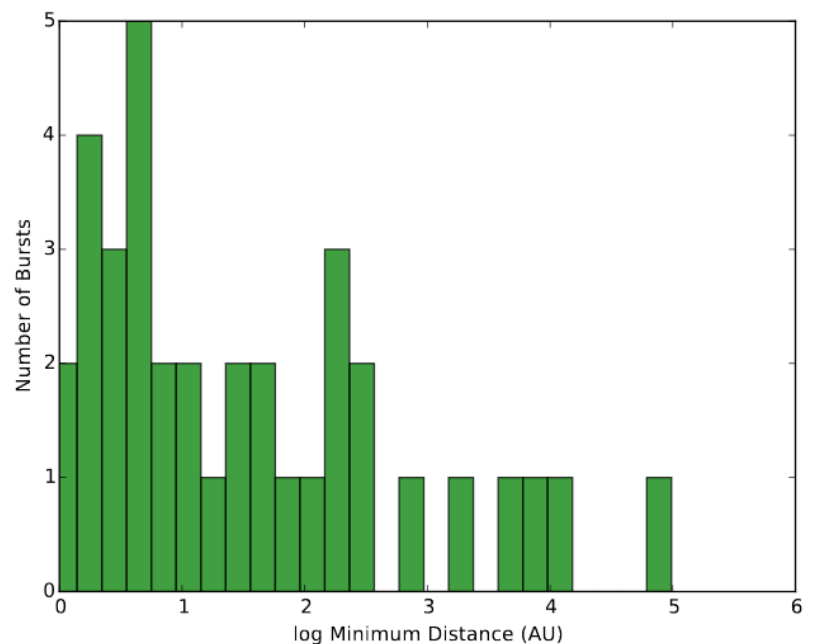
# Searches with GRB network of detectors



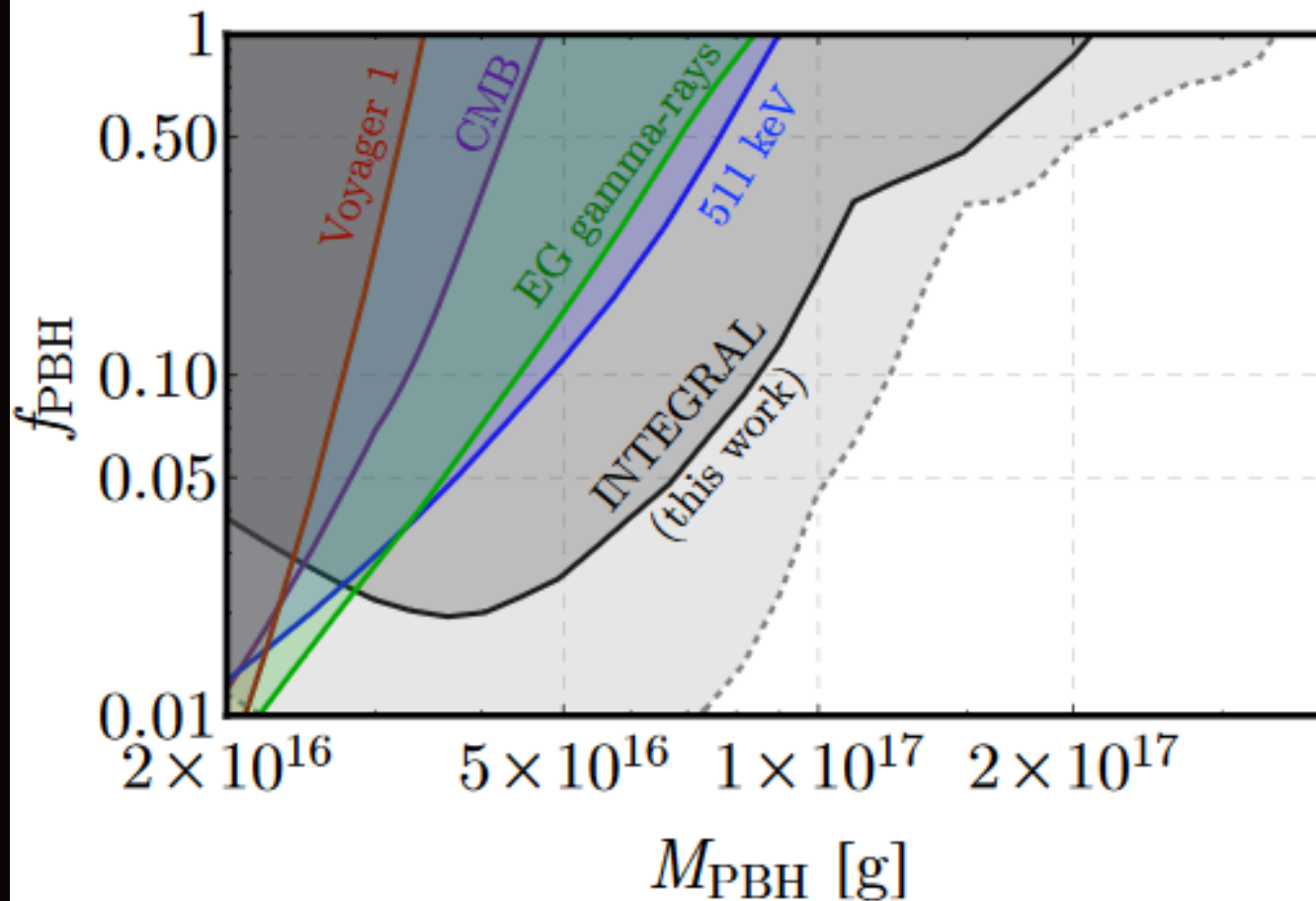
With IPN the authors try to put limits on the distance to short gamma-ray bursts.

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

There 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.



# INTEGRAL limits



PBHs with masses below  $2 \times 10^{17}$  g cannot be responsible for all DM.

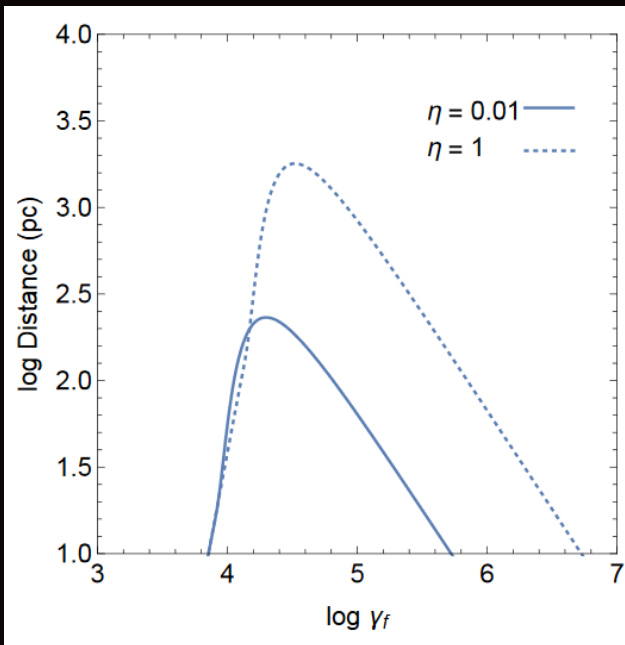
# Radio transients. BHs and extra dimensions

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  $4.2 \times 10^{-7} \text{ pc}^{-3} \text{ yr}^{-1}$

for Lorentz factor of  $10^{4.5}$

L- size of an extra dimension

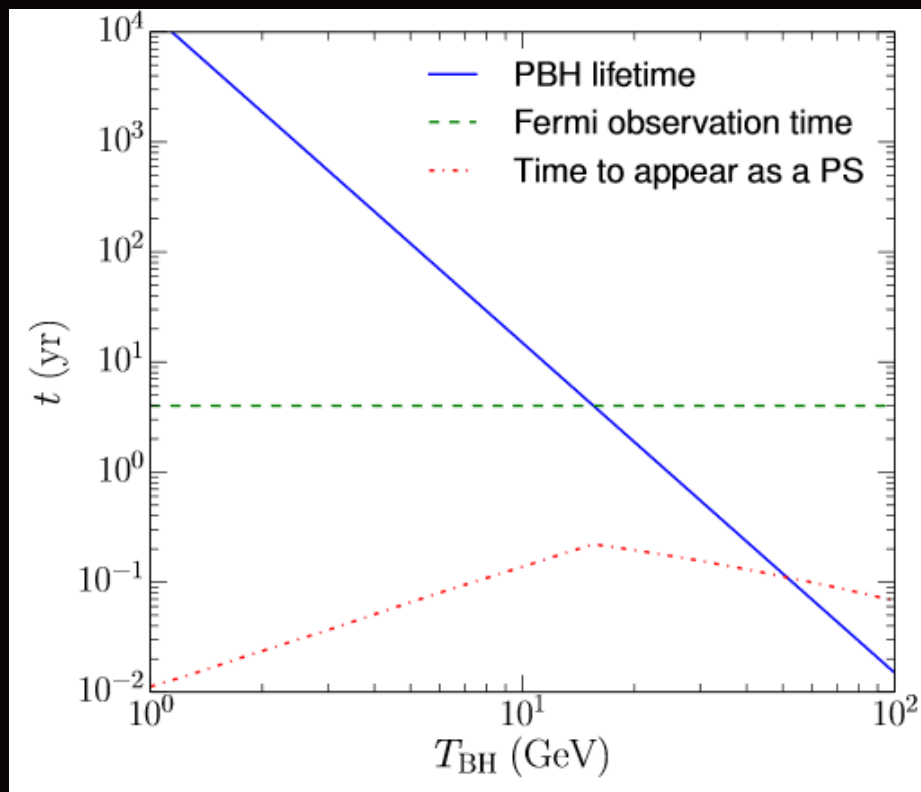
$$\eta M c^2 = \eta \mu L c^4 / G$$

$$\mu = G M / L c^2$$

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

# Fermi limits

LAT is sensitive to evaporating BHs within 0.03 pc with  $T \sim 16$  GeV (mass  $6 \times 10^{11}$  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)!



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

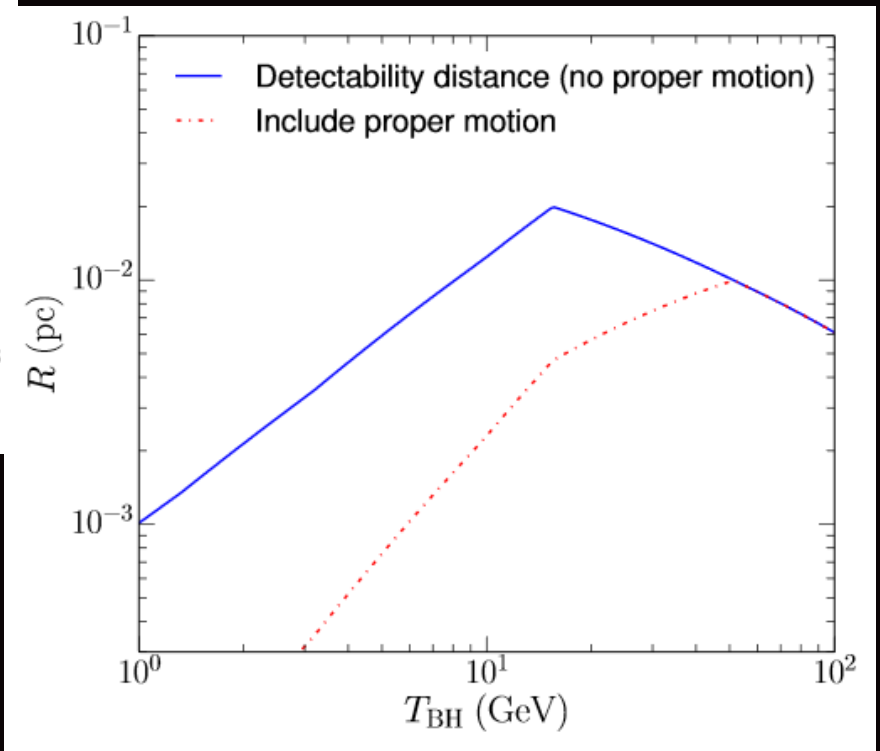
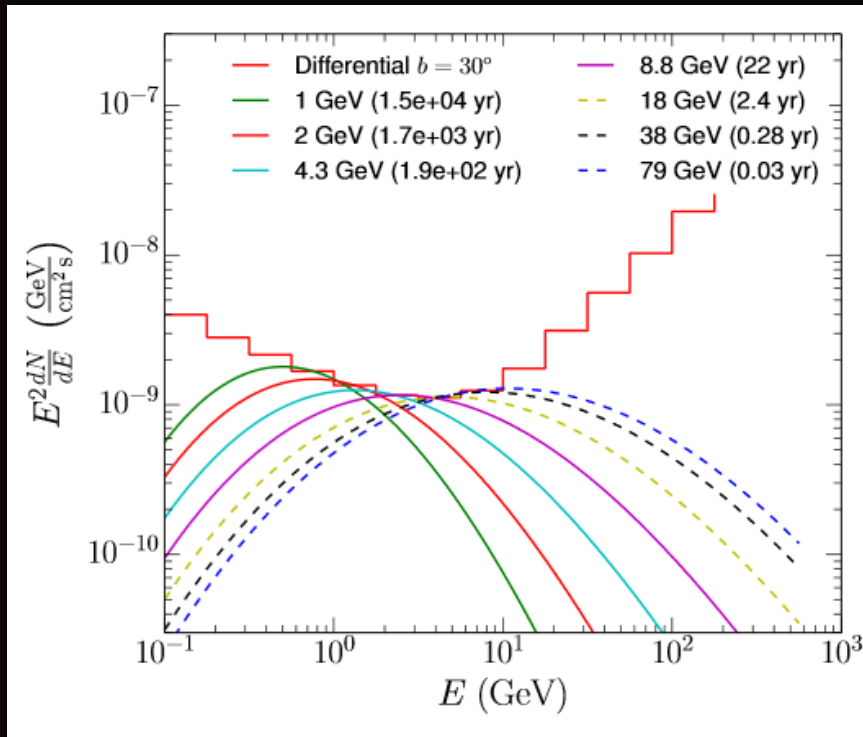
$$T_{\text{BH}} = \frac{\hbar c^3}{8\pi G M k} \approx 10^{-7} \left( \frac{M}{M_{\odot}} \right)^{-1} K$$

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

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



# Sensitivity of Fermi to PBHs



# Calculations of the limit

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

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

All BHs with initial temperature >16.4 GeV evaporate in 4 years.

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

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

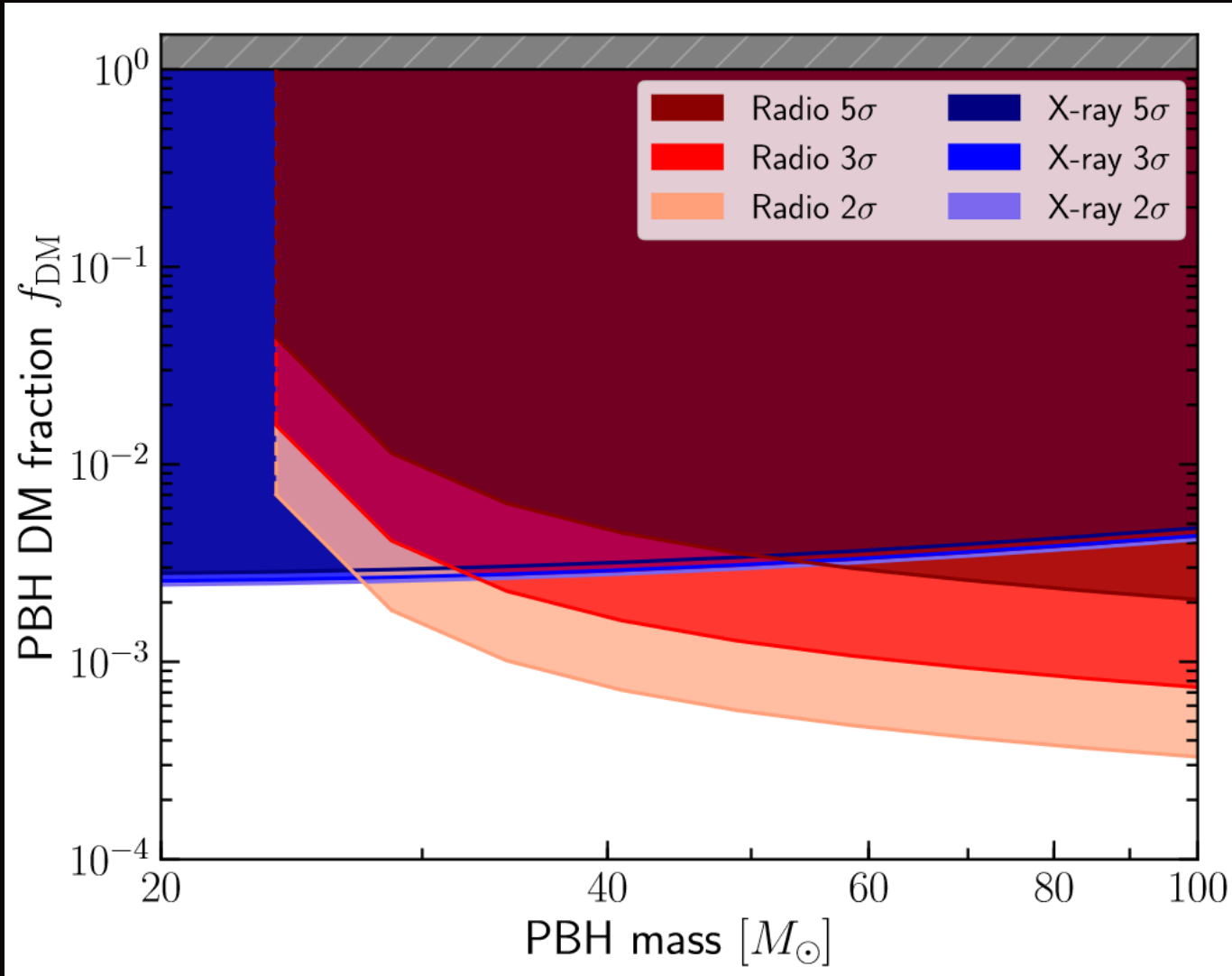
N=6.64 is 99% confidence limit based on 1 source.

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

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

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

# Limits from accretion



Based on observations of the Galactic center region.