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**
- arXiv: 2006.02838, 2007.10722, 2110.02821 **PBHs as dark matter**
- arXiv: 2206.02672, 2211.05767 **PBHs. Large review**
- arXiv: 2310.19857 **GW from 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 γ-ray, but also to X-ray, CR, GW, 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

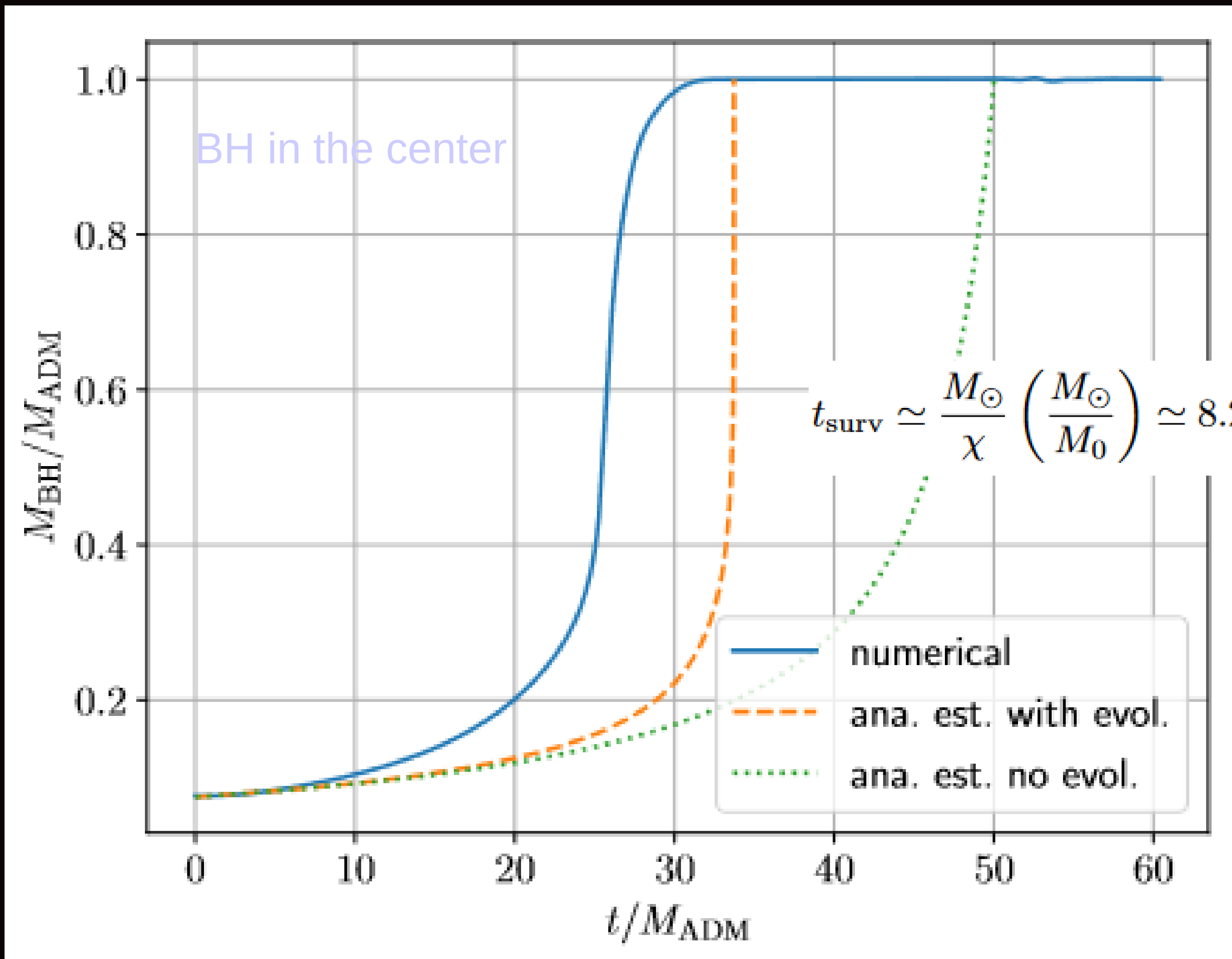
BHs with $M>10^{26}$ g have temperatures lower than the CMB radiation now.

The time for complete evaporation

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

astro-ph/0504034

Tiny black hole inside a neutron star



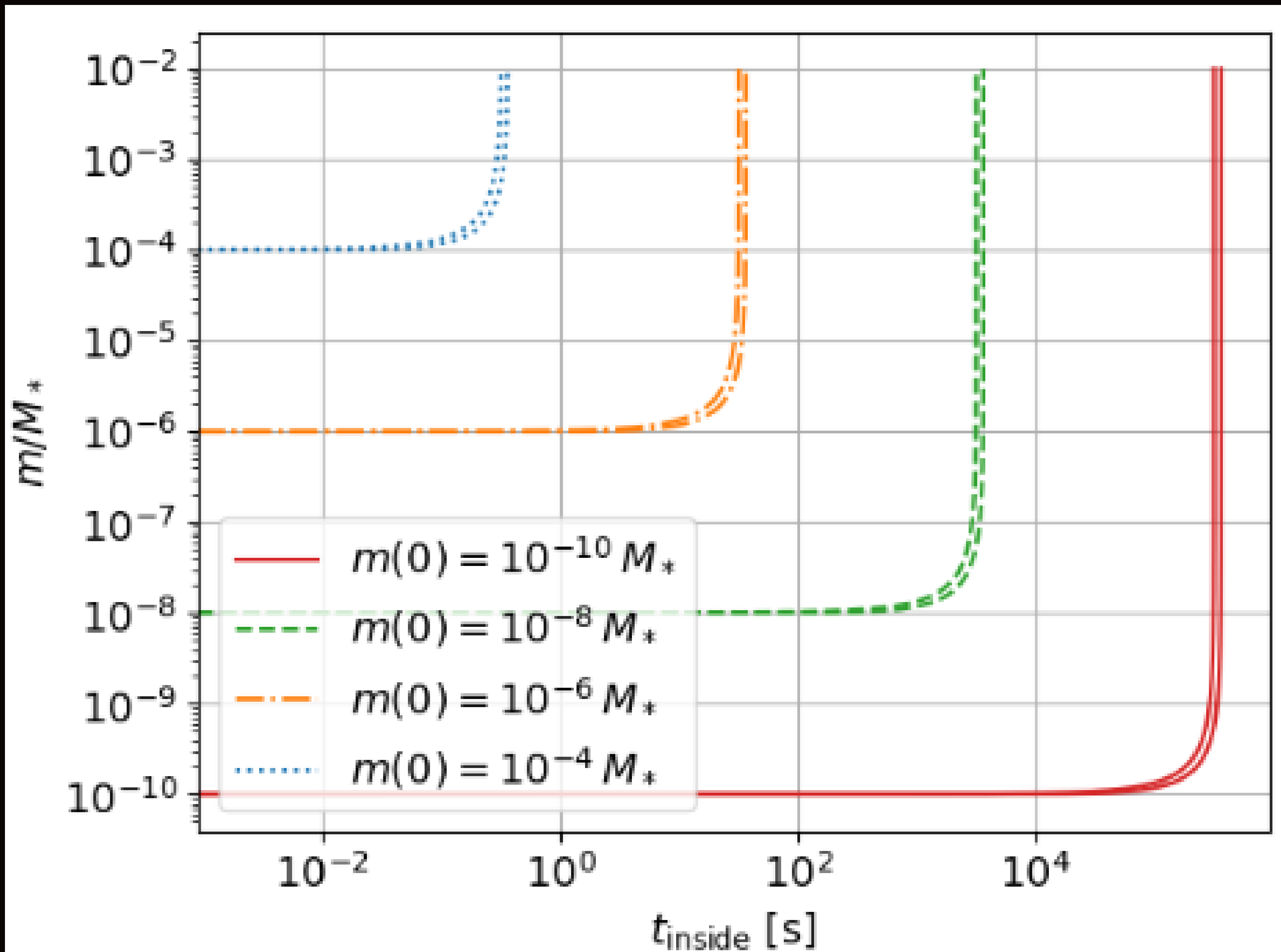
More realistic calculations with more or less realistic EoS and some other effects.

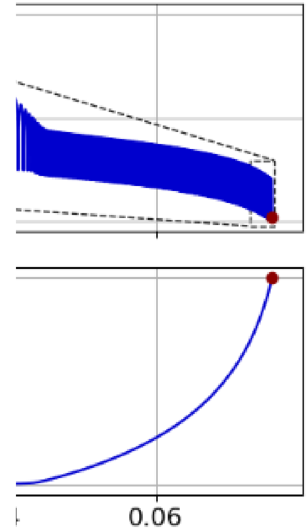
$$t_{\rm surv} \simeq \frac{M_\odot}{\chi}\left(\frac{M_\odot}{M_0}\right) \simeq 8.2\times 10^5\,{\rm s}\left(\frac{10^{-10}M_\odot}{M_0}\right)$$

2110.08285

2102.09574, new results in 2110.08285

NS + PBH = light BH





$(\Gamma = 2,\, a \ll 1)$

$$t_{\rm coll} \simeq \frac{M_*}{m(0)}\,\tau_{\rm dyn}$$

$$)^5\,{\rm s}\left(\frac{10^{-10} M_*}{m(0)}\right)$$

2404.08735. Calculations for larger BHs are presented in 2405.10365

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.).

astro-ph/0304478

Hawking spectrum

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

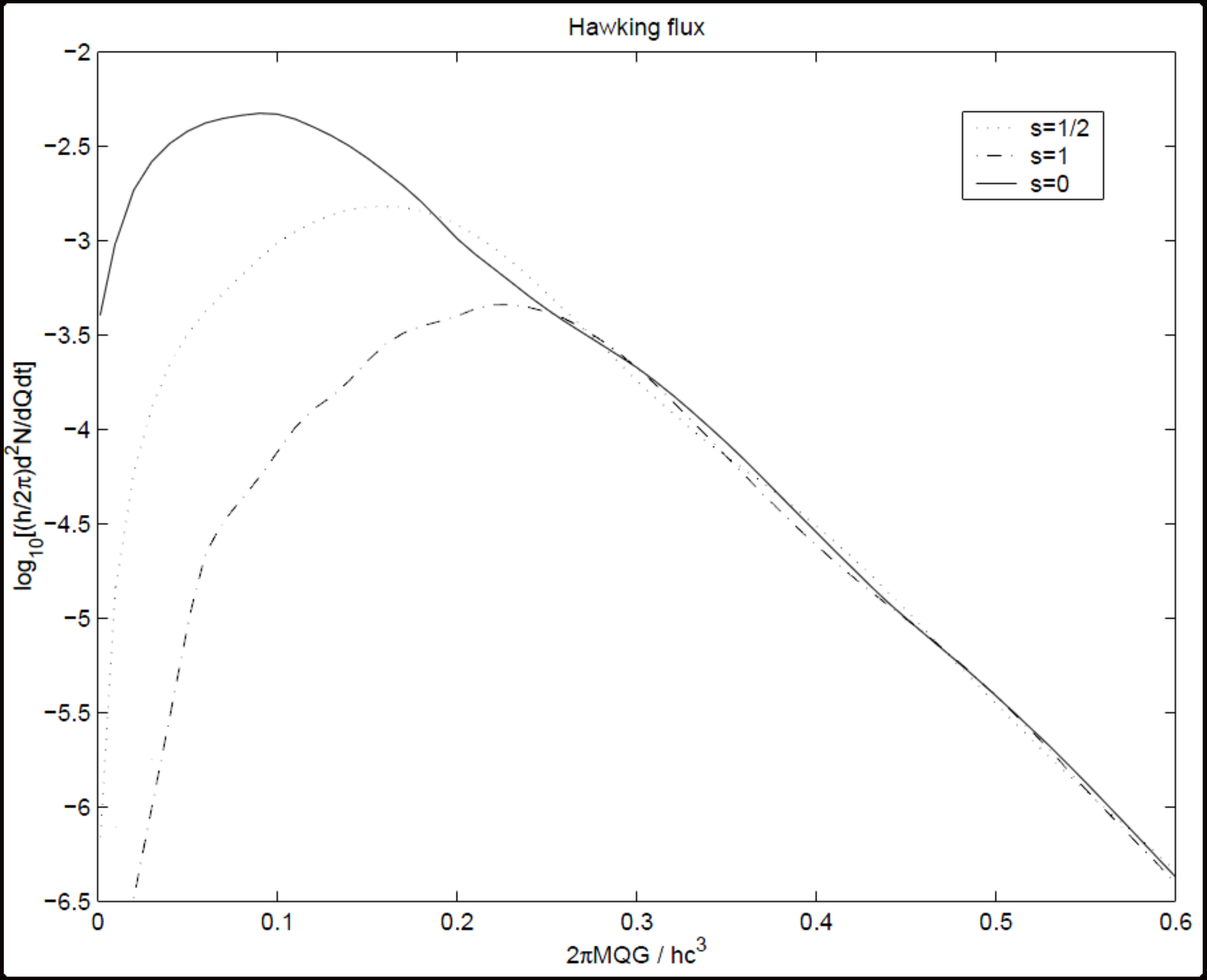
For non-rotating, non-charged BH.

Horizontal axis ~Q/kT

T=T(M)

Vertical – $d^2N/dQdt$

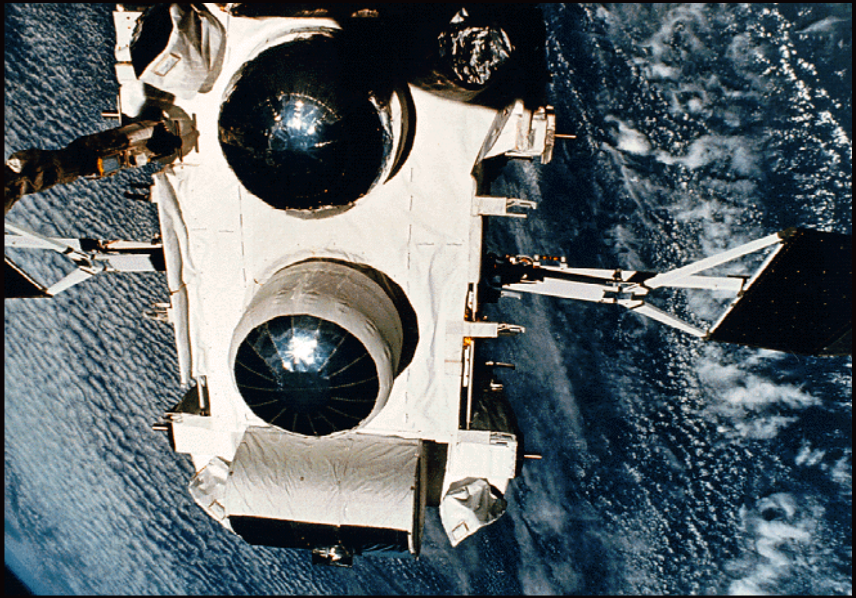
Rem: Spectrum is different in other models of gravity. For example, about BH evaporation in loop quantum gravity see 1808.08857, 2001.08833.



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

astro-ph/0304478

EGRET and constraints on PBH



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

Background radiation at energies: 30 MeV – 120 GeV.

The upper limit on the density of PBHs

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

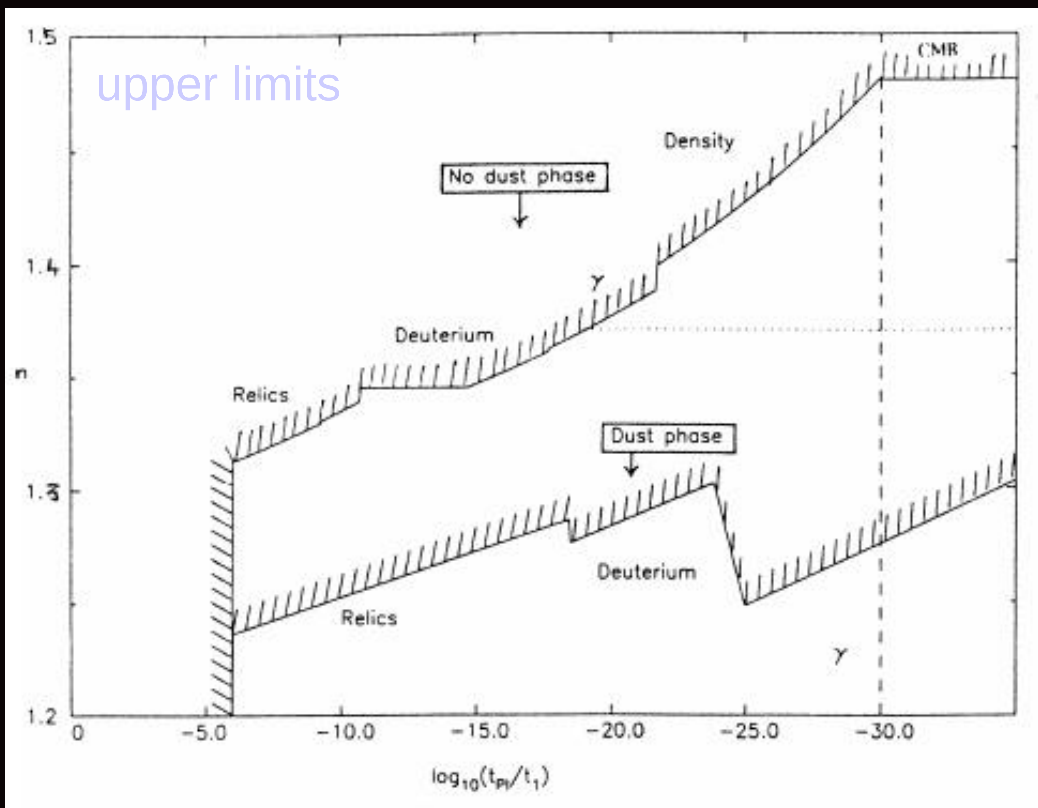
astro-ph/0504034

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.

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

astro-ph/0504034



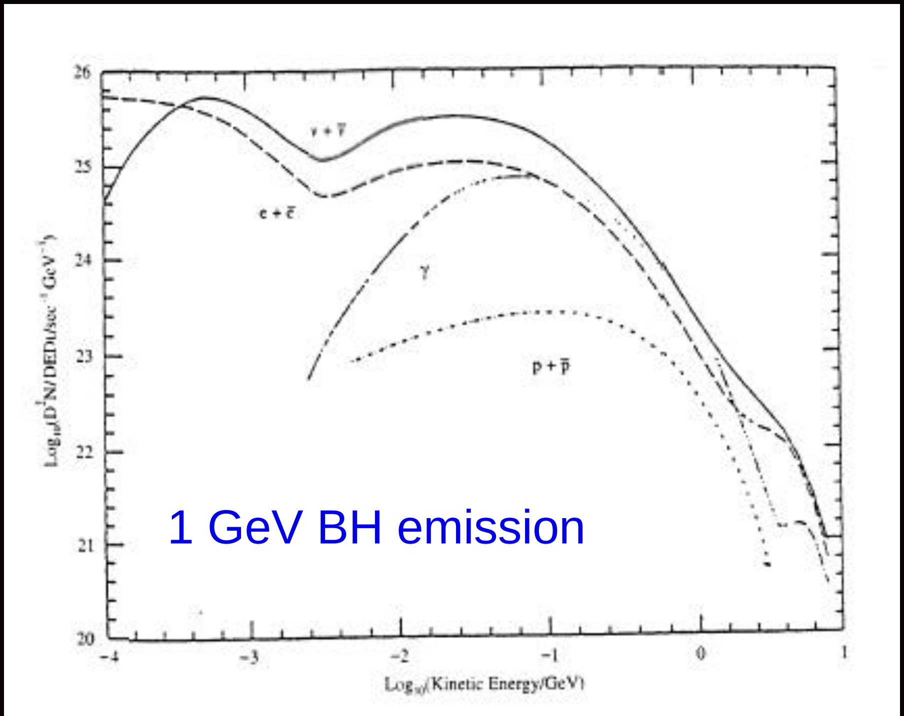
For example, on the parameter *n*, characterizing the power spectrum of fluctuations.

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

t_1 – re-heating time

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

Particle emission during PBH evaporation



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

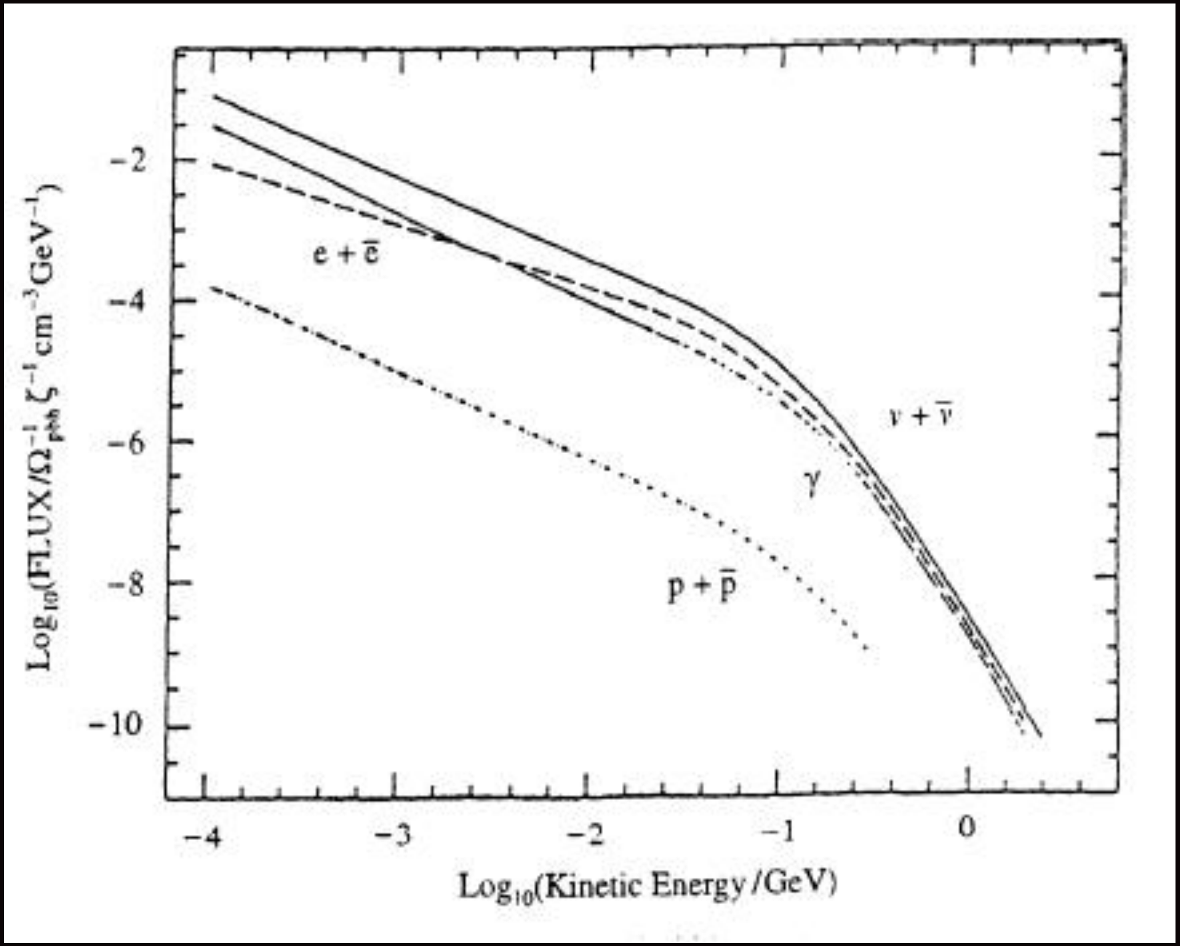
$$\dot{M} = -5 \times 10^{25} (M/g)^{-2} f(M) \ \mathrm{g\ s^{-1}}$$

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

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

astro-ph/0504034

Particle spectrum for uniform distribution of PBHs

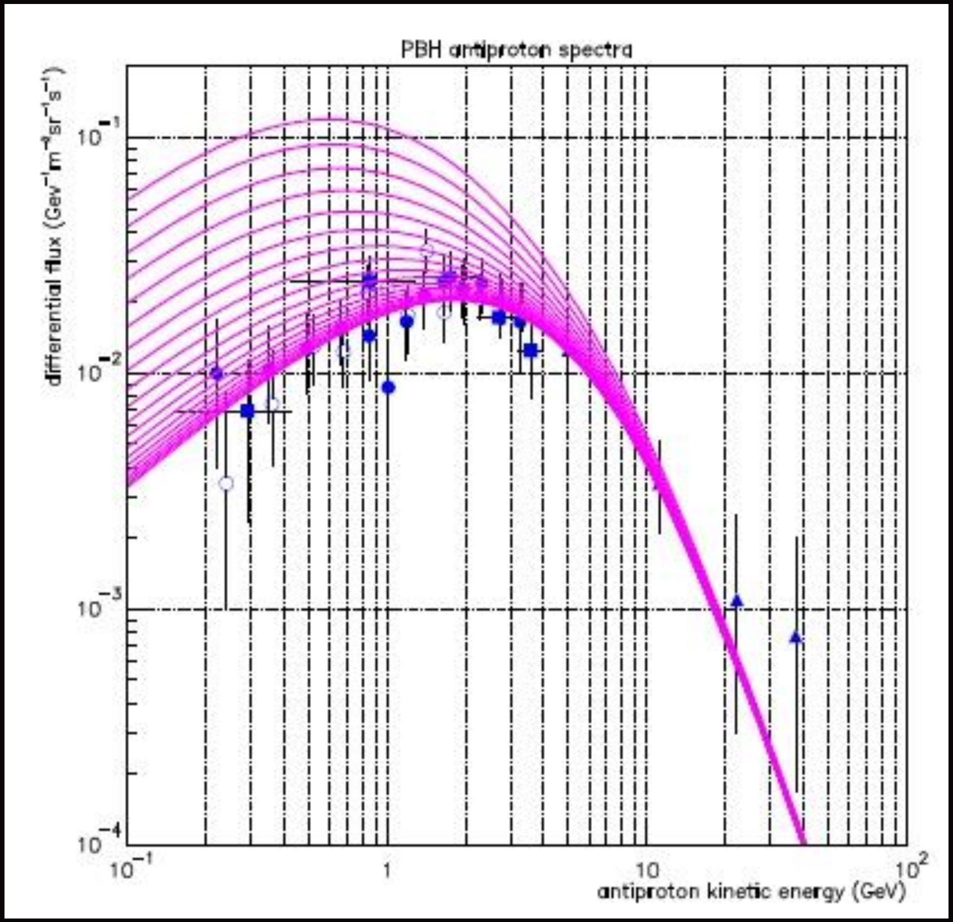


BHs uniformly distributed in the Universe.

astro-ph/0504034

PBH and antiprotons

astro-ph/0504034



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).

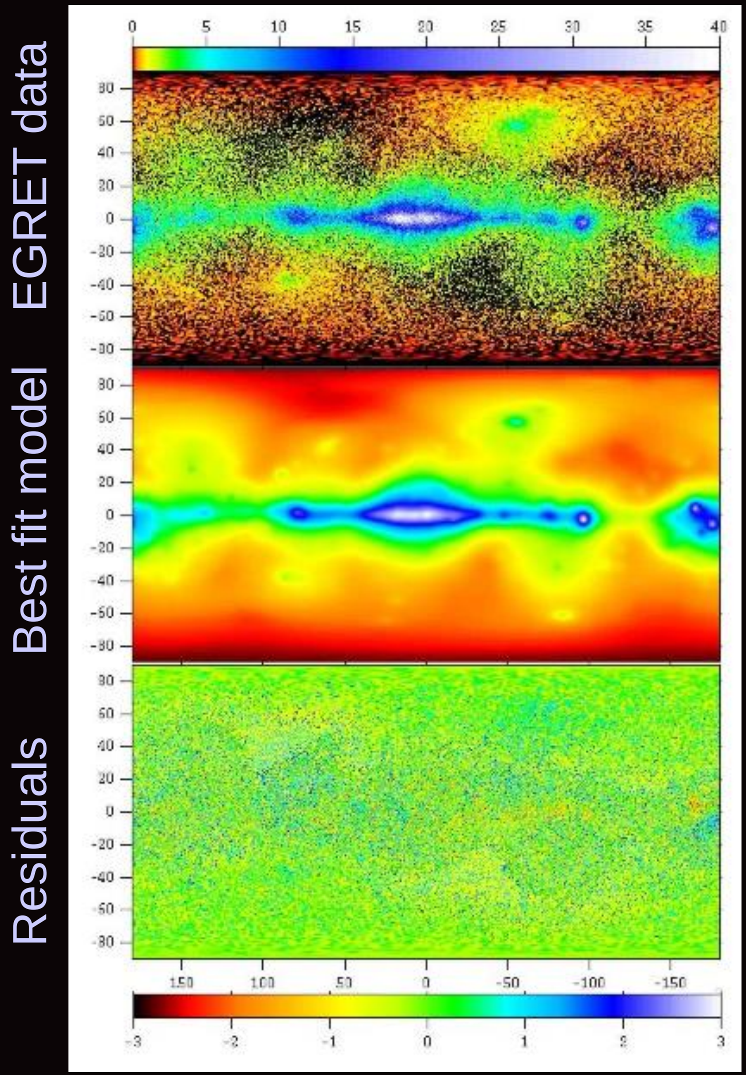
Barrau et al. 2003, taken from Carr 2005

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.

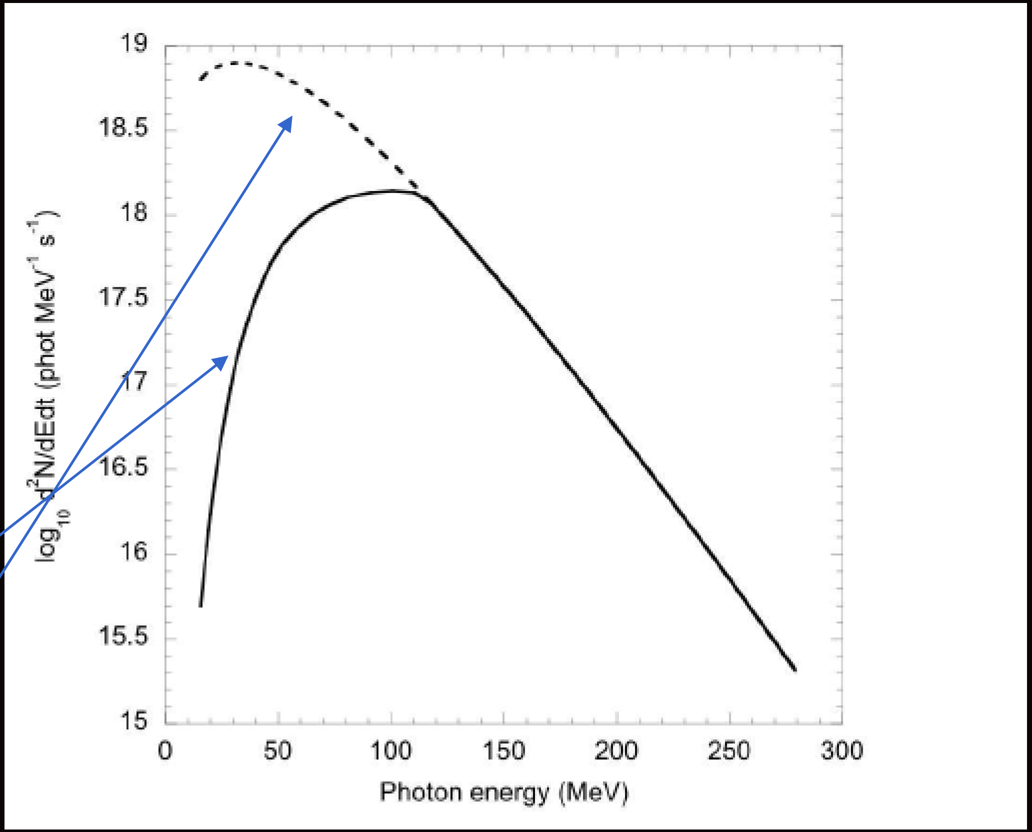
The flux peaks at higher energy
(around 5 kT)
than for a pure blackbody at
the same temperature
(which flux is maximum at 1.59 kT)



arXiv: 0906.1648

The spectrum

Spectrum of a kT=20 MeV BH



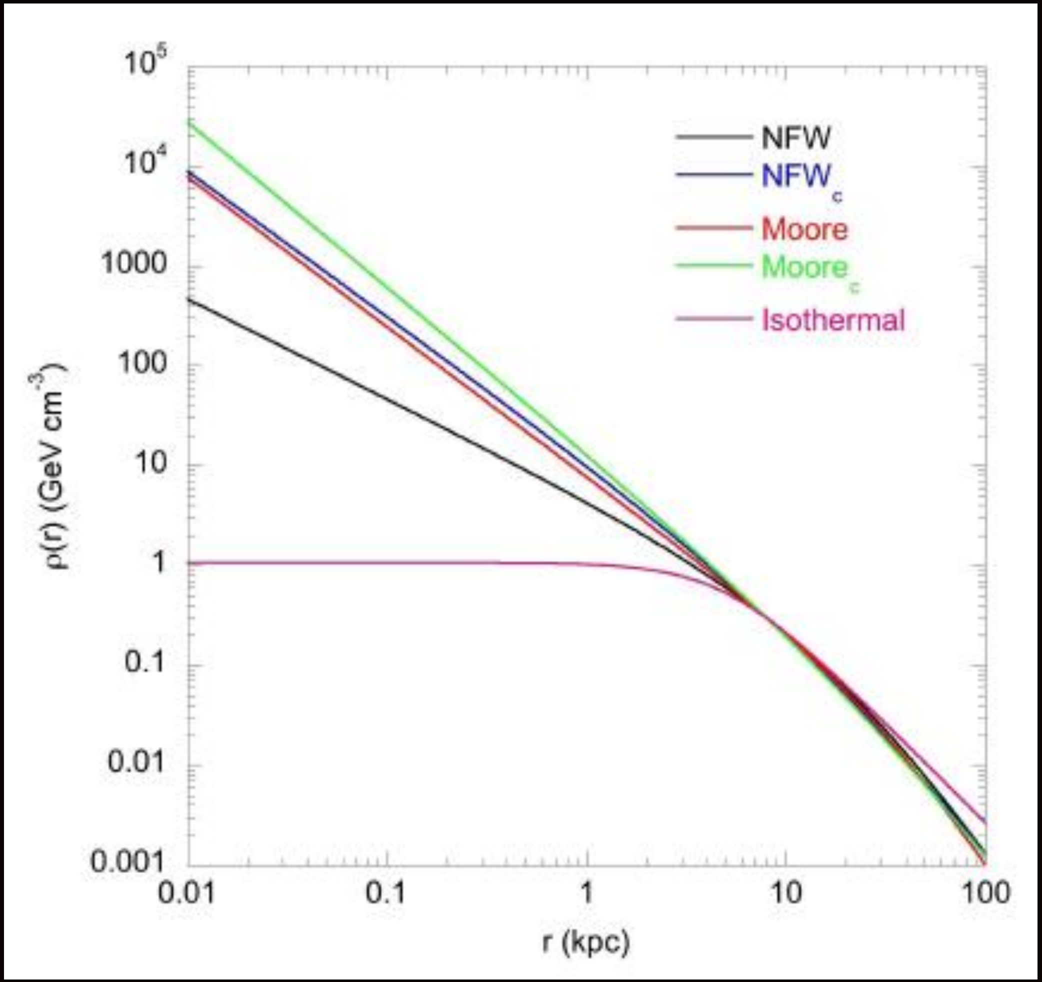
Since the typical temperature
of PBHs born in the early Universe
and that end its life at present time
is about 20 MeV,
a distinctive signature of
quantum black holes would be
a quasi-planckian spectrum at
unexpectedly high energy,
peaking at about 100 MeV

BH spectrum
(MacGibbon&Webber 1990)

Blackbody spectrum
with the same temperature

arXiv: 0906.1648, see a public code description in 1905.04268

Density distribution



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

arXiv: 0906.1648

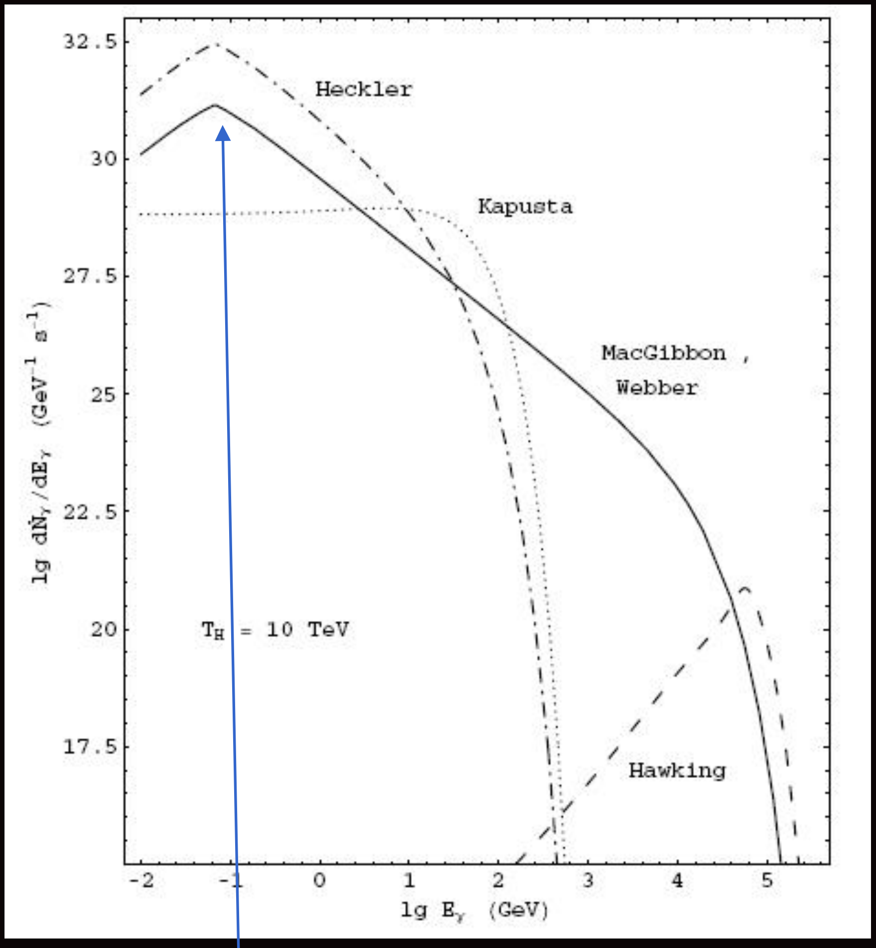
Results and limits

DM distribution	$f(M_*)$	$\Omega_{PBH}(M_*)$	$\beta(M_*)$
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



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

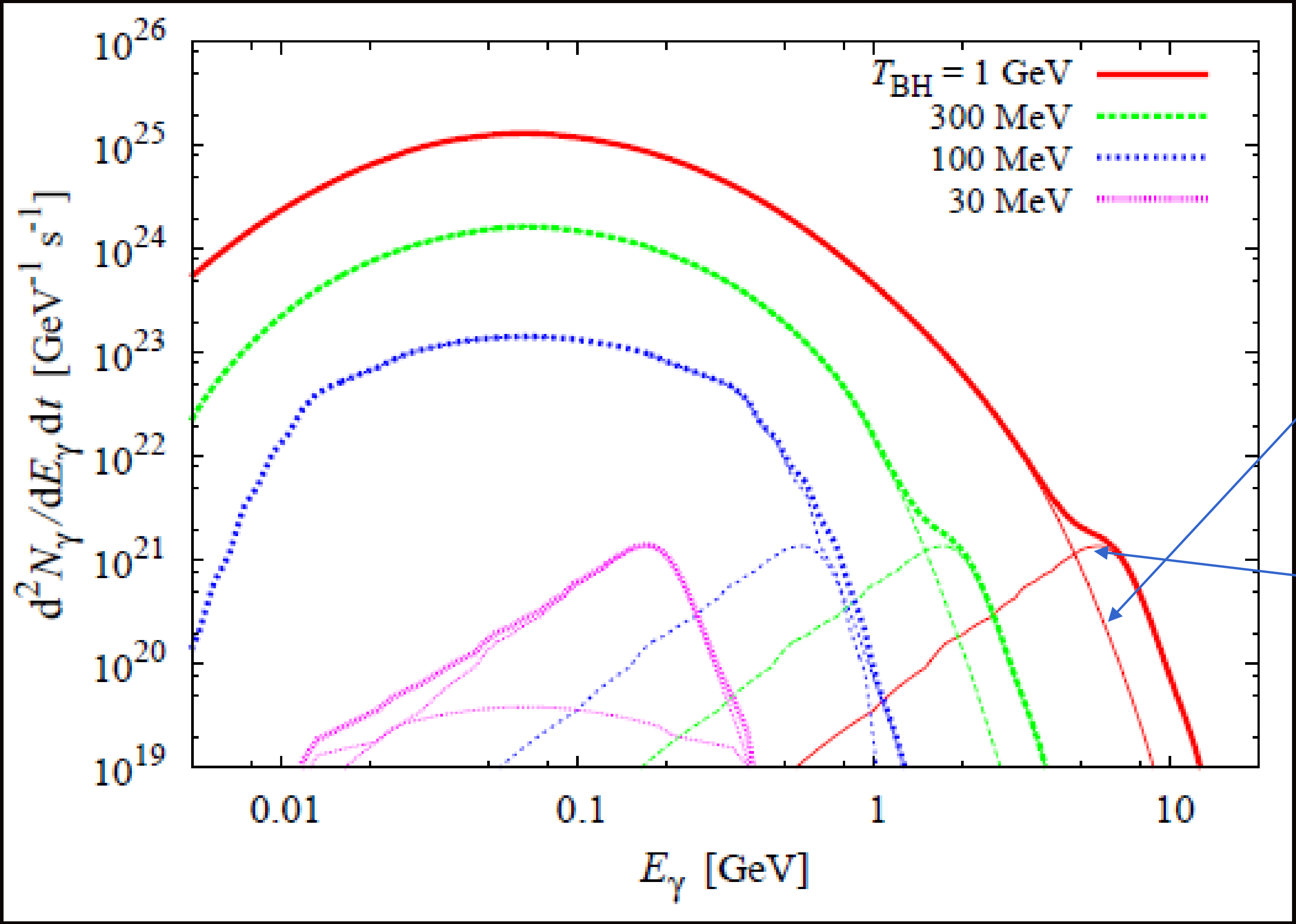
The spectrum can be non-thermal.
This is due to creation of particles which then demonstrate series of transformations (decays) and interactions; only at the very end we have photons.
And their spectrum is different from the thermal (i.e. from the blackbody).

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 $T_{BH} \sim \Lambda_{QCD} \sim 300$ MeV

arXiv: 0706.3778

Emission rate of photons

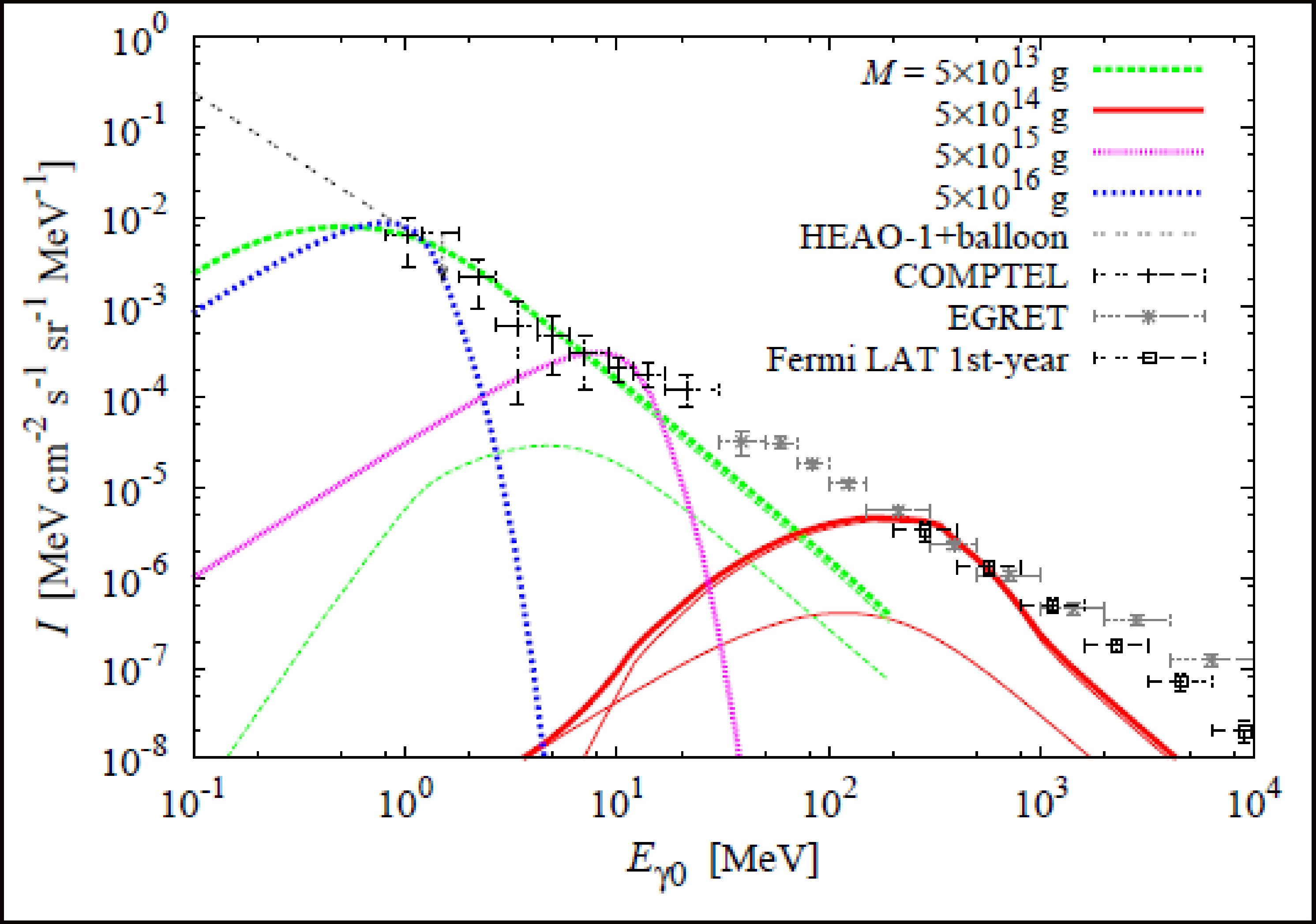


secondary

primary

0912.5297

Gamma-ray background



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

0912.5297

Emission from exploding PBHs

$$\dot{N}_\gamma \simeq 1.4 \times 10^{29} \left(\frac{T_{\rm BH}}{\rm TeV}\right)^{1.6} {\rm sec}^{-1}$$

$$\phi_\gamma \simeq 1.2 \times 10^{-9} \left(\frac{\rm pc}{d}\right)^2 \left(\frac{T_{\rm BH}}{\rm TeV}\right)^{1.6} {\rm sec}^{-1}{\rm cm}^{-2}$$

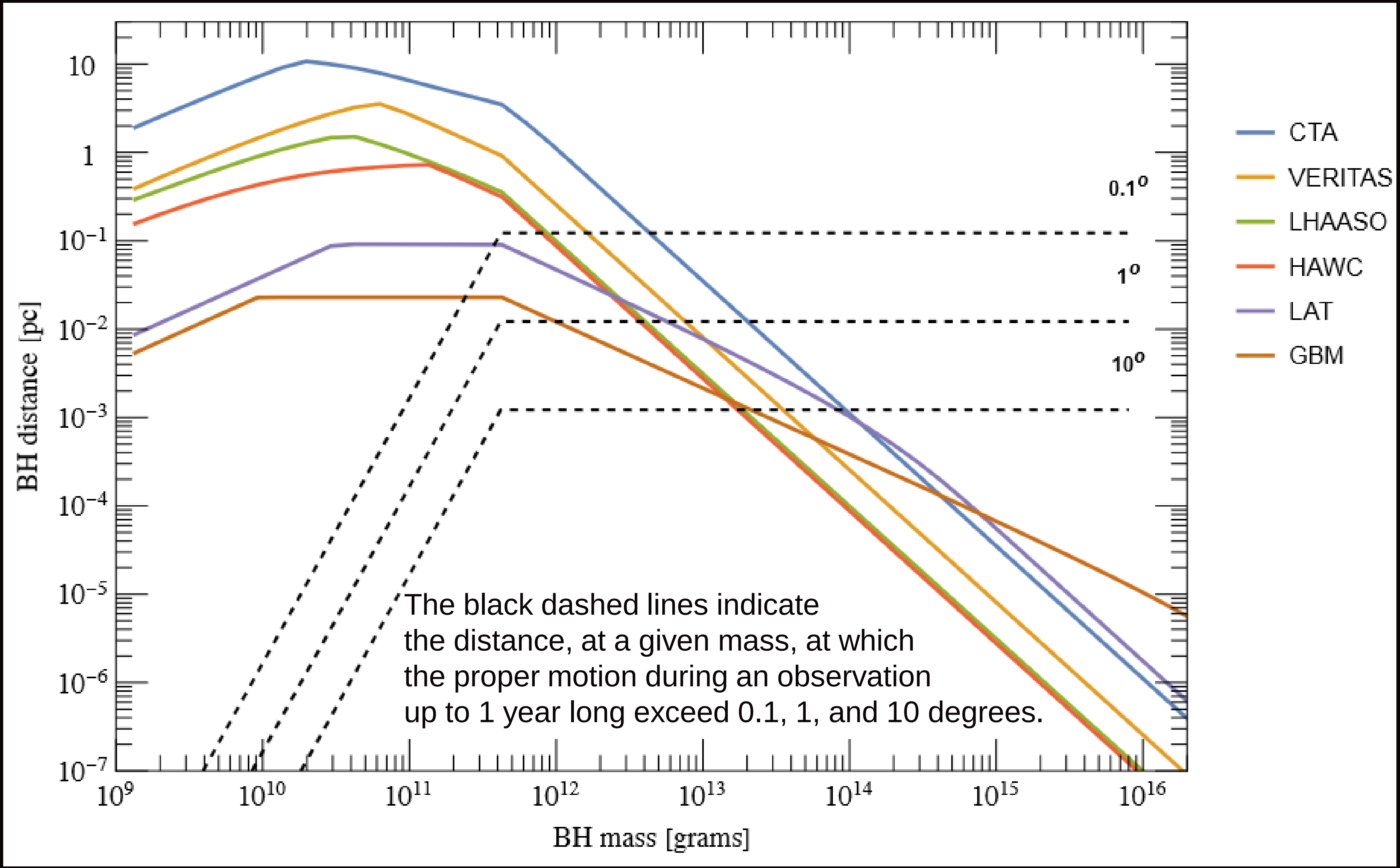
$$\frac{dM_{\rm BH}}{dt} = -\frac{\alpha(M_{\rm BH})}{M_{\rm BH}^2},$$

$$\phi_\gamma \simeq 1.1 \times 10^{-9} \left(\frac{\rm pc}{d}\right)^2 \left(\frac{10^{10}\ {\rm g}}{M_{\rm BH}}\right)^{1.6} {\rm sec}^{-1}{\rm cm}^{-2}$$

The maximum possible rate of explosions
for different mass functions is <~0.01-0.1 per yr per pc^3.

2307.06467

Detectabilty by modern detectors

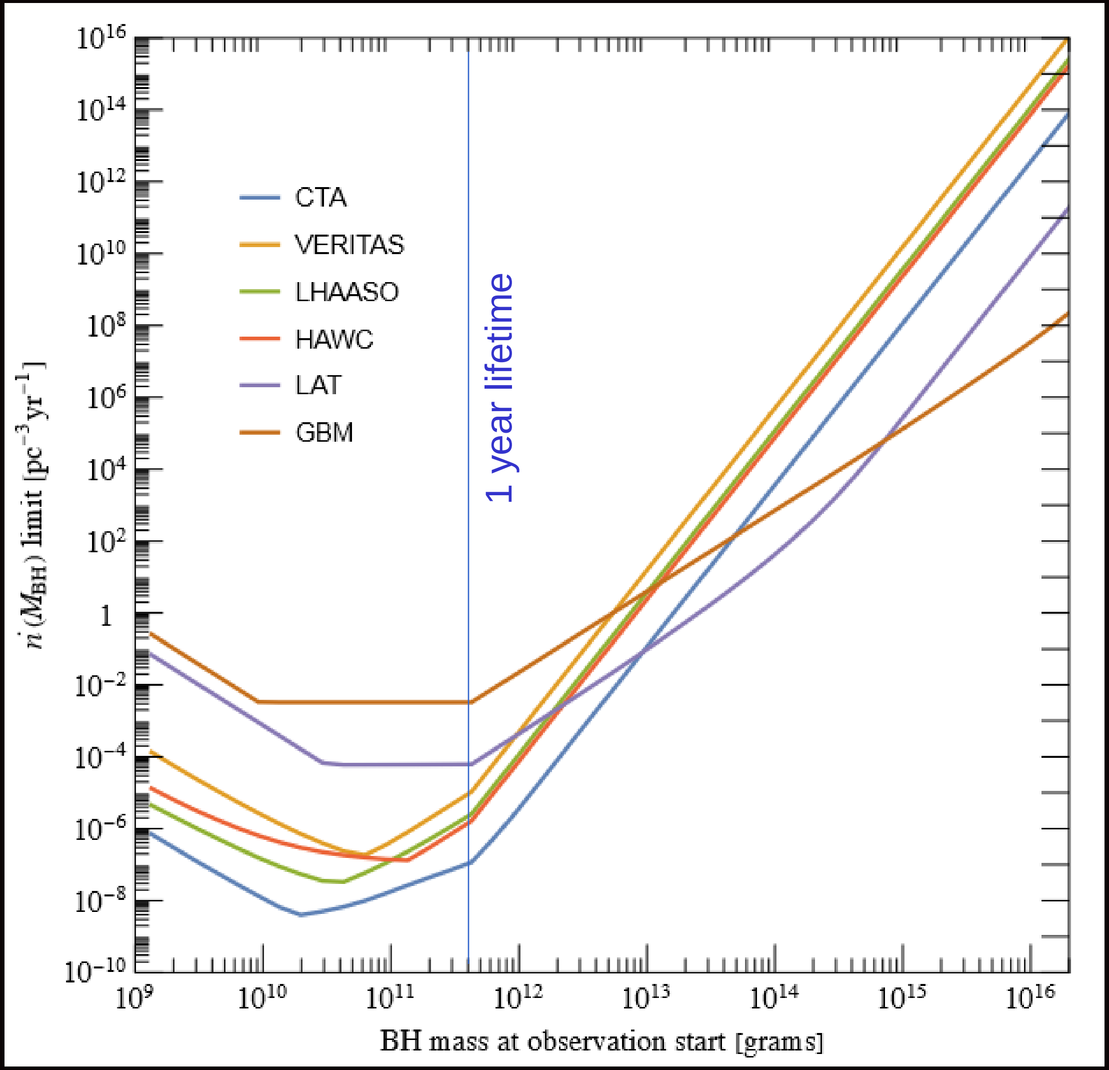


2307.06467

Rate limits for modern instruments

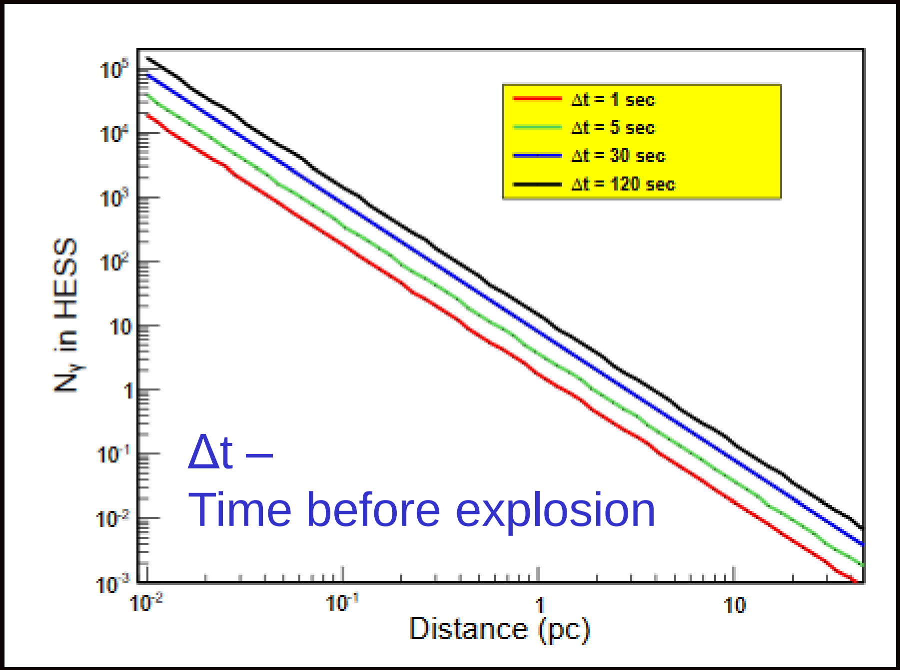
$$\dot{n}(M) = \frac{3}{T_{\rm obs} \cdot d^3(M) \cdot \Omega_{\rm fov}}$$

Here M is the mass at the start of observations.



2307.06467

Constraints from H.E.S.S.



Nothing detected.

Upper limits can be derived.

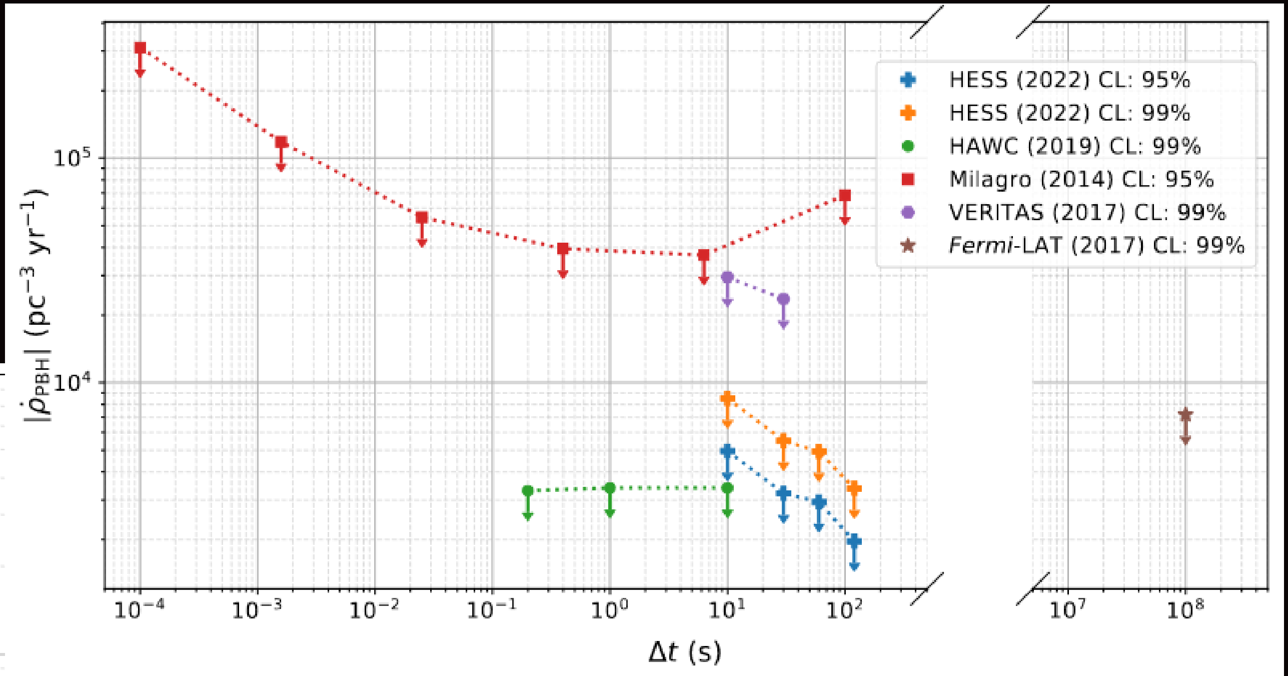
At the moment these limits are not very constraining. However, with HESS-2 it will be possible to obtain more interesting limits.

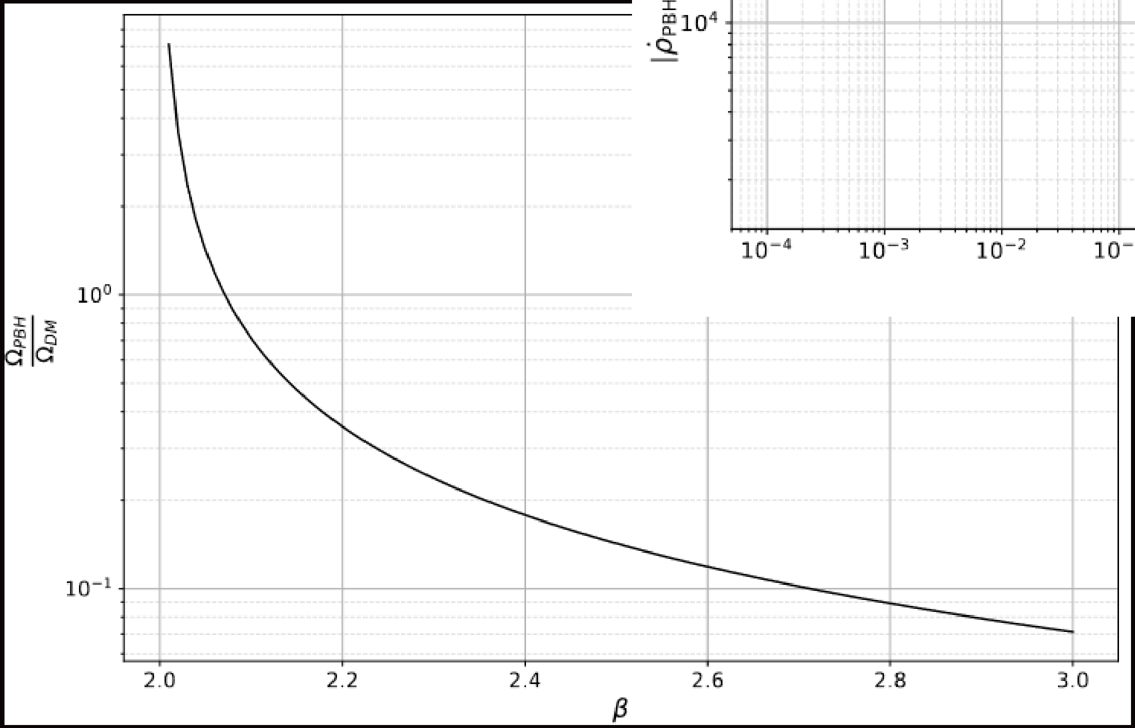
The preliminary upper limit on the explosion rate is $\dot{\rho}_{\mathrm{PBH}} < 1.4 \times 10^4 \mathrm{pc}^{-3}\mathrm{yr}^{-1}$ at the 95% CL for $\tau = 30\,\mathrm{s}$. The sensitivity limit, defined in section 5.3 is $1.7 \times 10^4 \mathrm{pc}^{-3}\mathrm{yr}^{-1}$. By comparison, the preliminary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

1307.4898

New limits from H.E.S.S.

$$\frac{dN_{\rm PBH}}{dM_i} = \frac{\rho_0}{M_*}\left(\frac{M_i}{M_*}\right)^{-\beta}$$



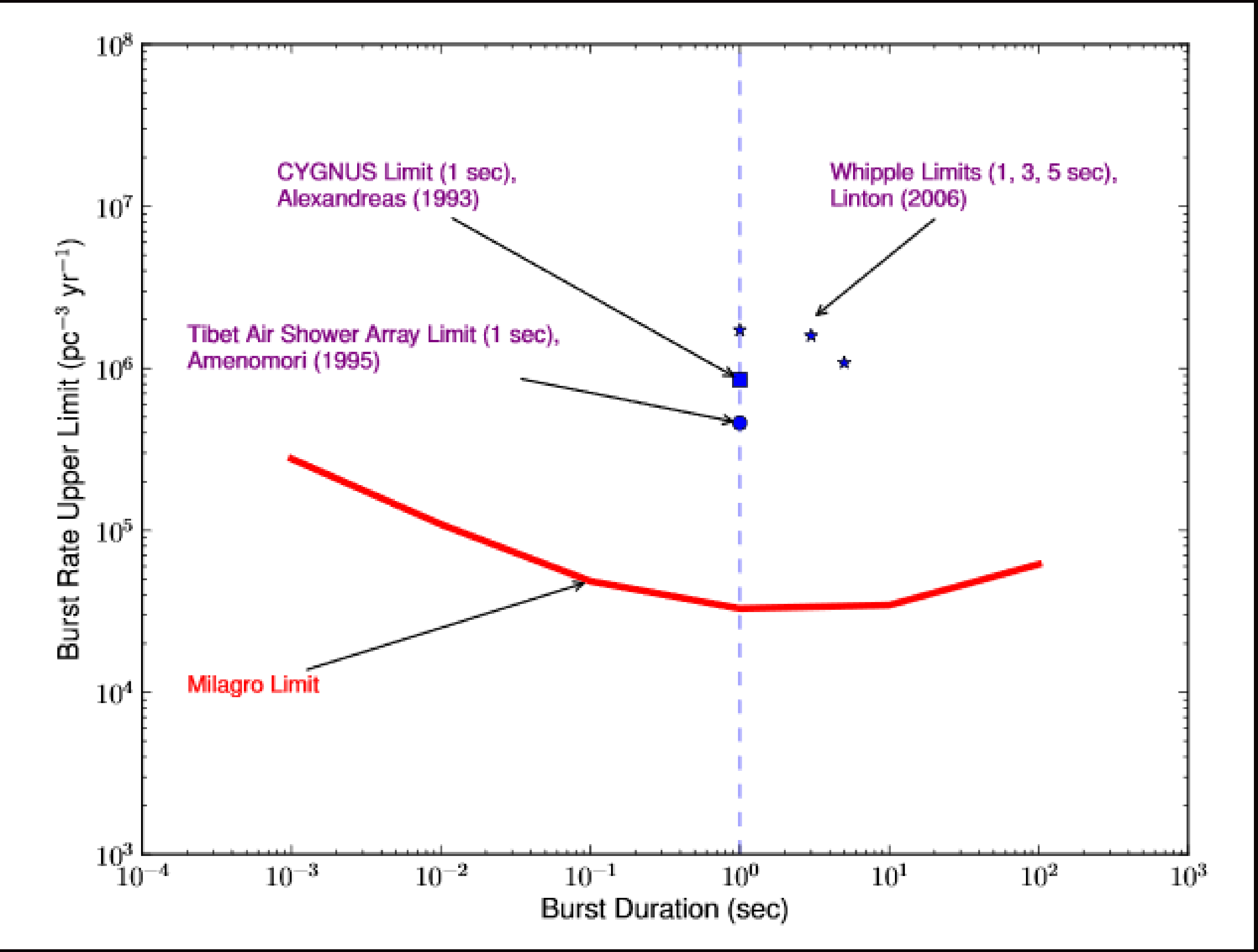


$$\rho_0 = (\beta - 2)\frac{\Omega_{\rm PBH}\rho_c}{M_*}$$

$$|\dot{\rho}_{\rm PBH}| \simeq \frac{\alpha(M_*)}{M_*^3}\eta\rho_0$$

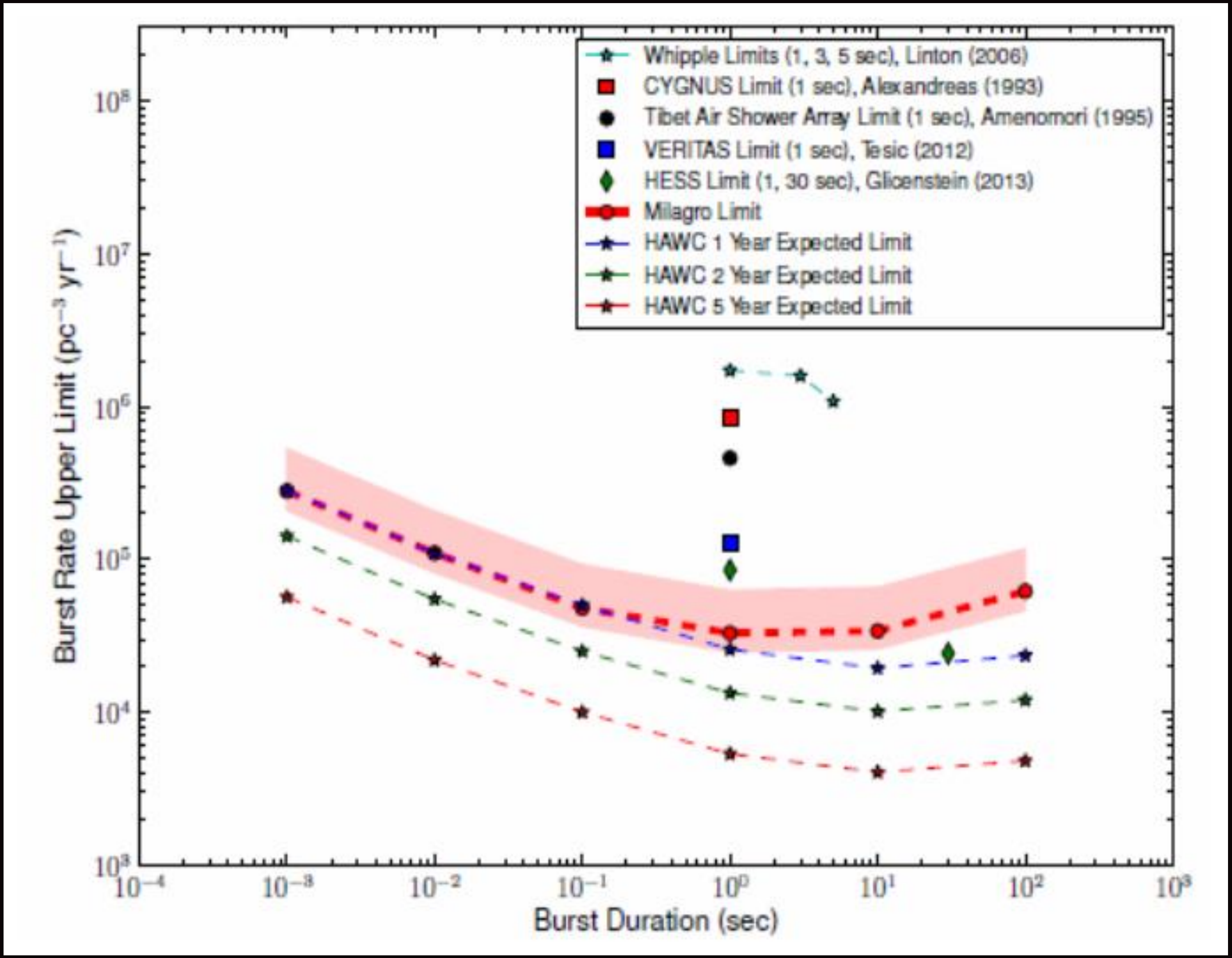
2303.12855

Milagro limits



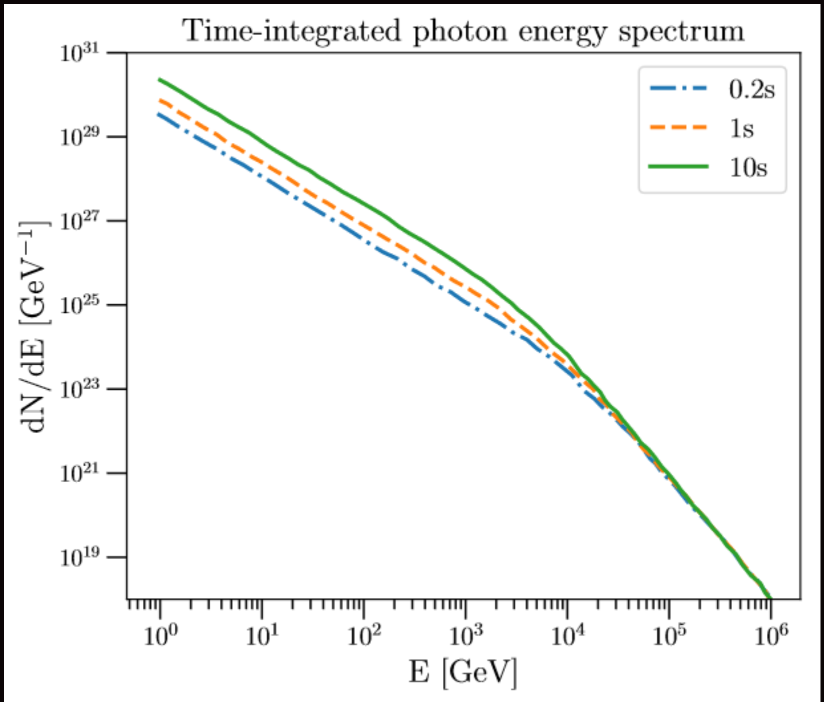
1308.4912

Joint limits



1503.01166

HAWC limits



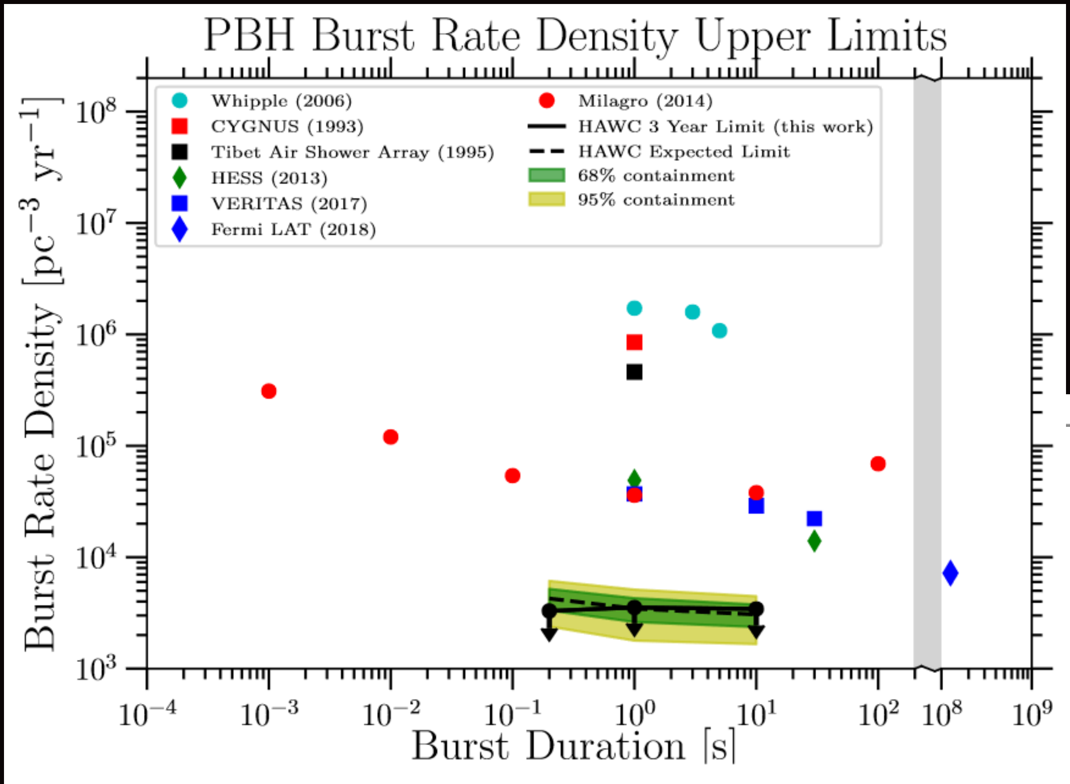
Burst duration	Burst Rate Upper Limit
0.2 s	$3300\ ^{+300}_{-100}\ \mathrm{pc^{-3}yr^{-1}}$
1 s	$3500\ ^{+400}_{-200}\ \mathrm{pc^{-3}yr^{-1}}$
10 s	$3400\ ^{+400}_{-100}\ \mathrm{pc^{-3}yr^{-1}}$

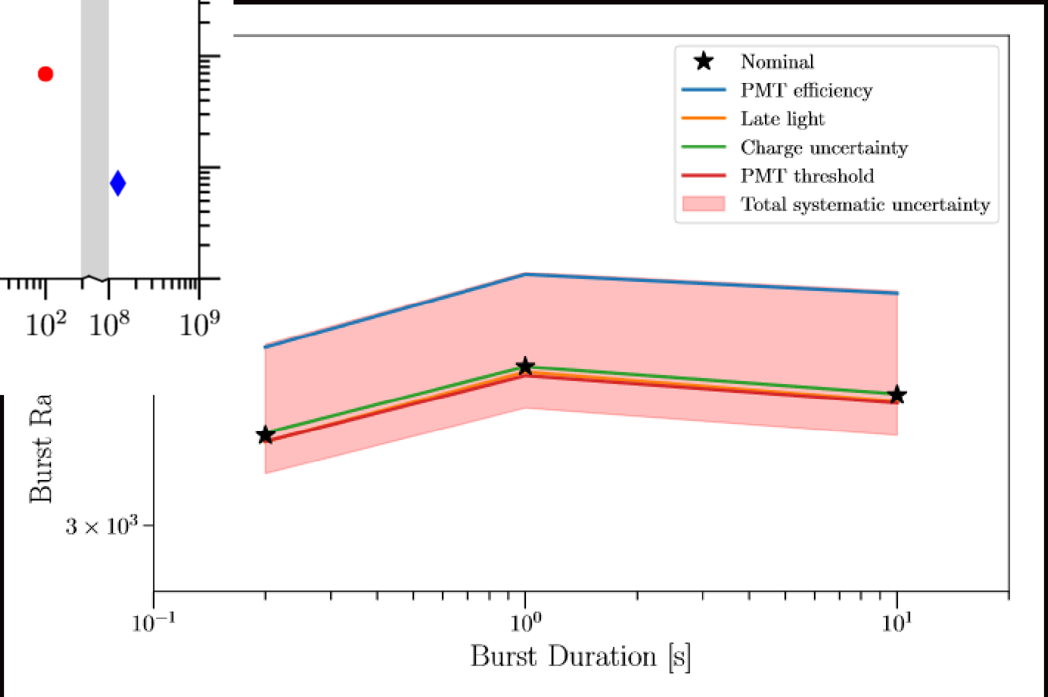
300 Gev - 100 TeV
959 day of observations.

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

1911.04356

HAWC limits





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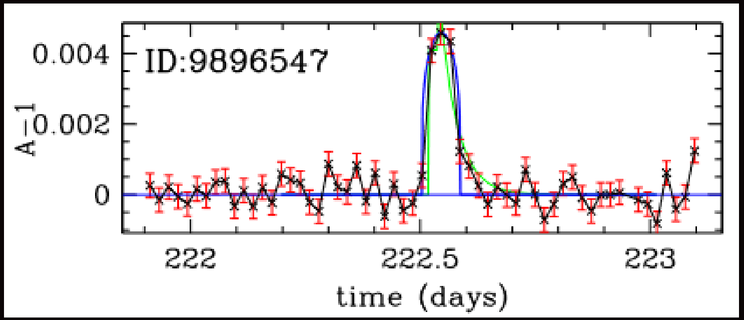
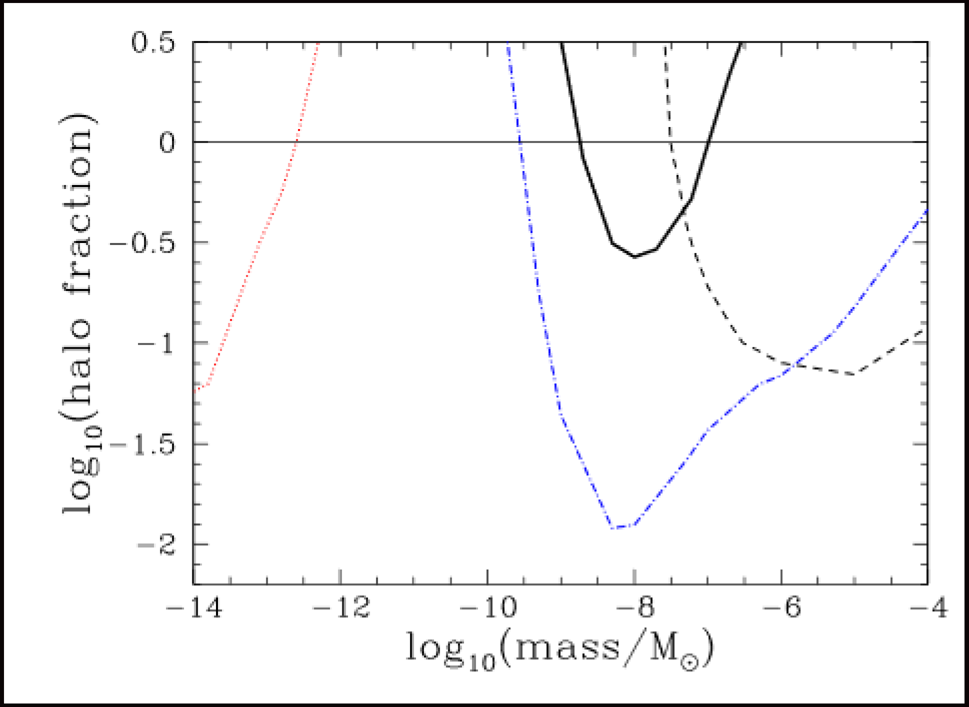
Limits from the Kepler data

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



In this work, the authors probe the mass range of PBHs $2\ 10^{-9}\ M_{solar} < M_{BH} < 10^{-7}\ M_{solar}$

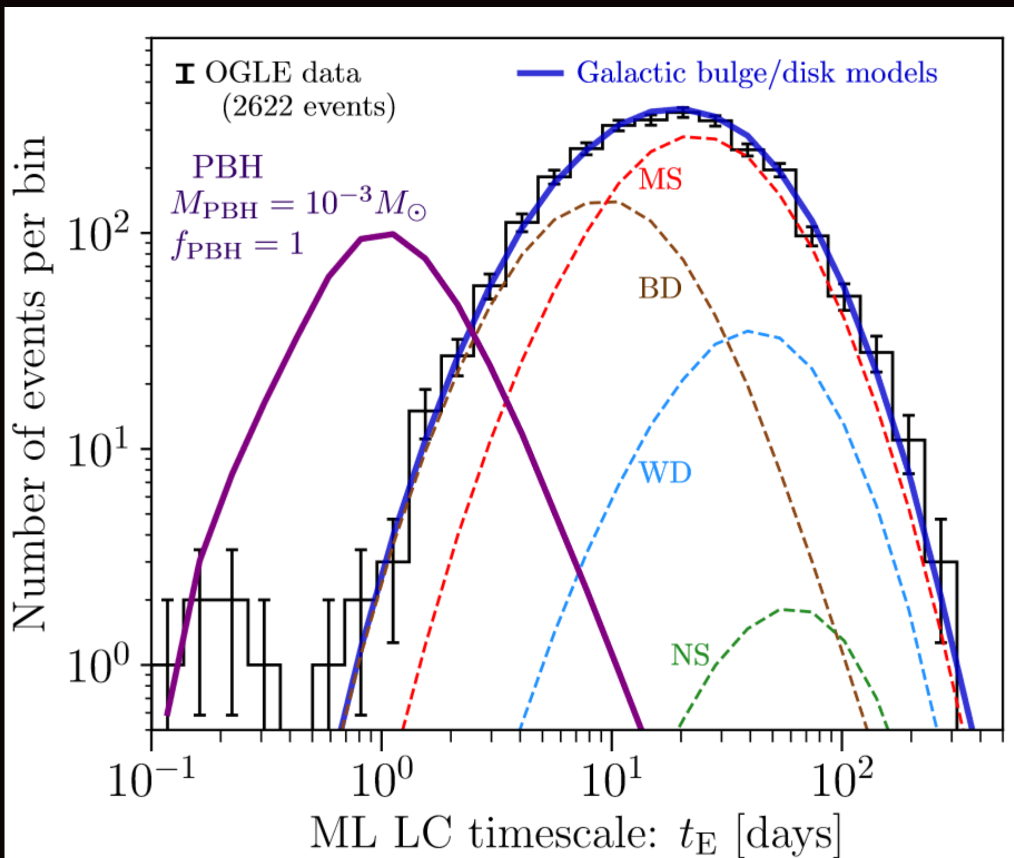


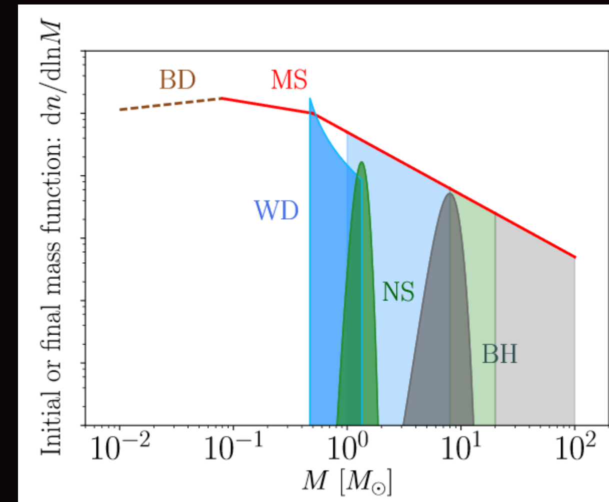
Solid black is the new limit.
It excludes the mass range
$10^{-9}\ M_{solar} < M_{BH} < 10^{-7}\ M_{solar}$
I.e., PBHs from this range
cannot explain halo DM.
The allowed range is
$10^{-13} M_{solar} < M_{BH} < 10^{-9}\ M_{solar}$

1307.5798

OGLE limits from lensing

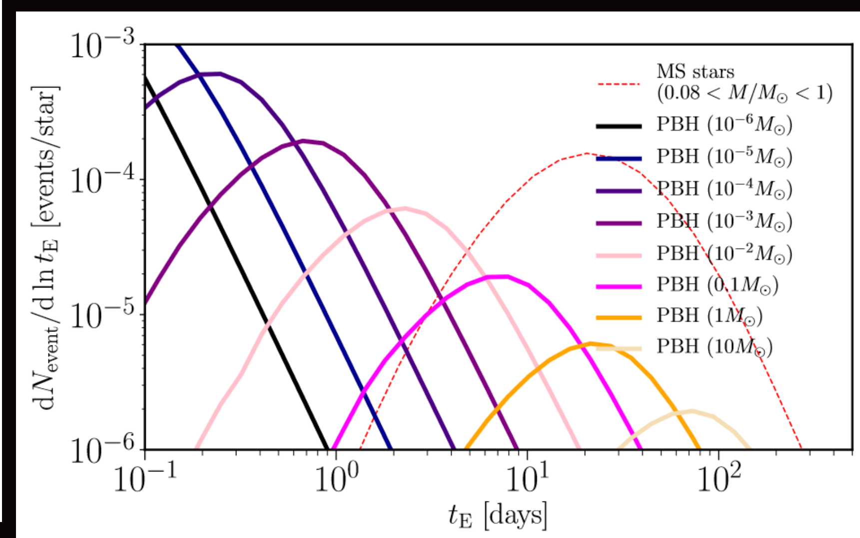
Six “suspicious” ultrashort (few hours) events are detected. They correspond to masses about an earth-like planet. Potentially, they can be PBHs.





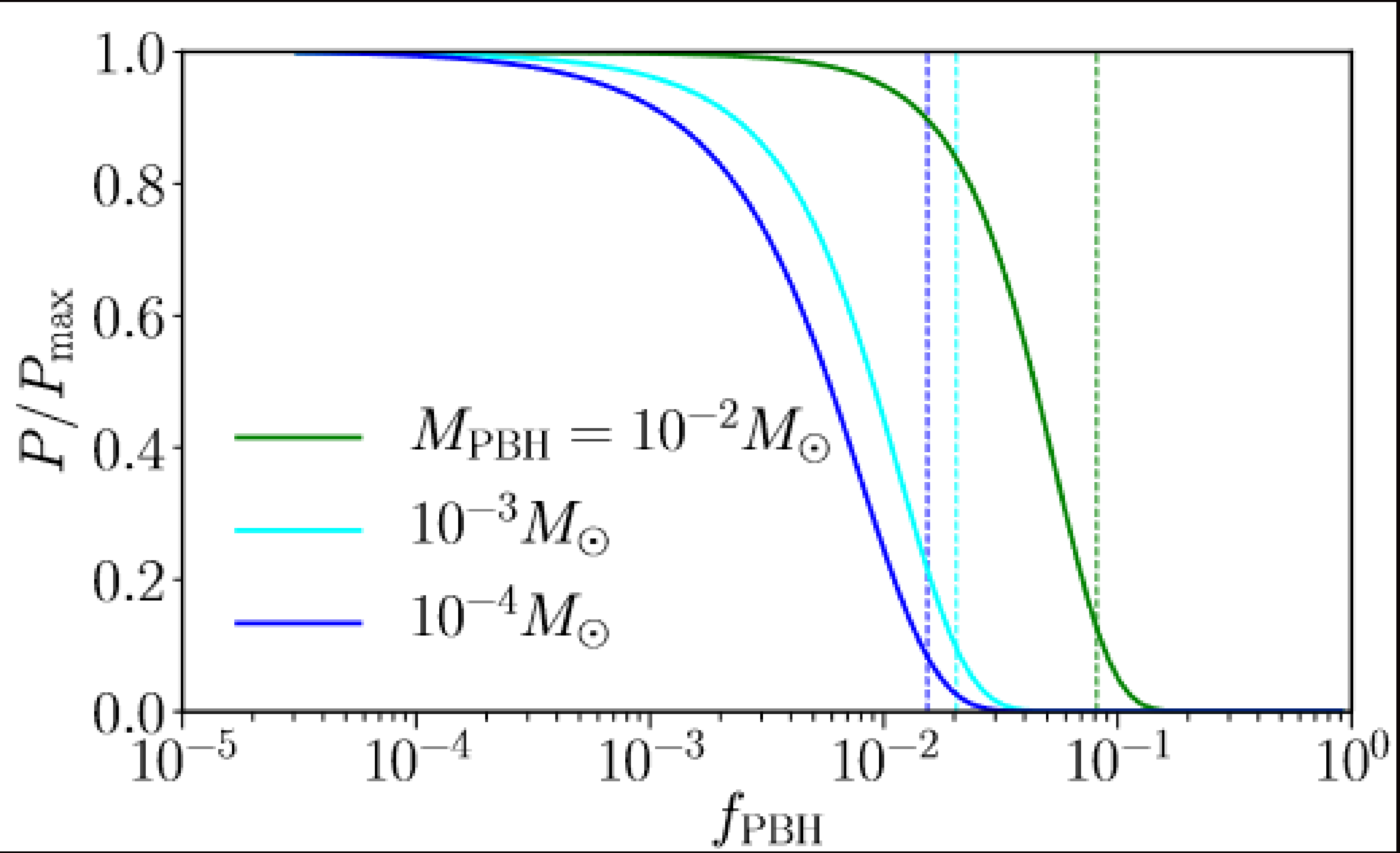
MS : WD : NS : BH = 1 : 0.15 : 0.013 : 0.0068

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

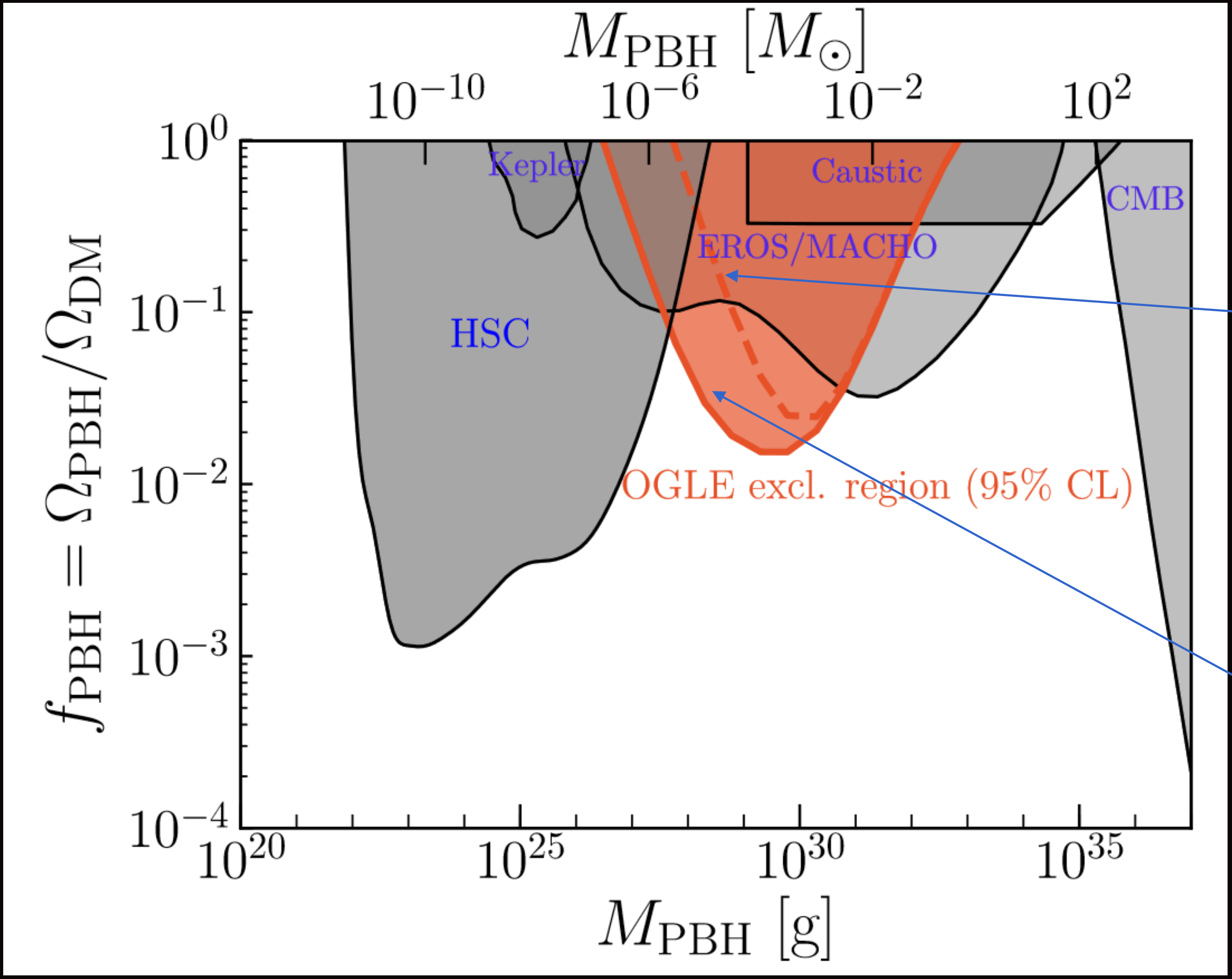


1901.07120

Limits from OGLE



1901.07120

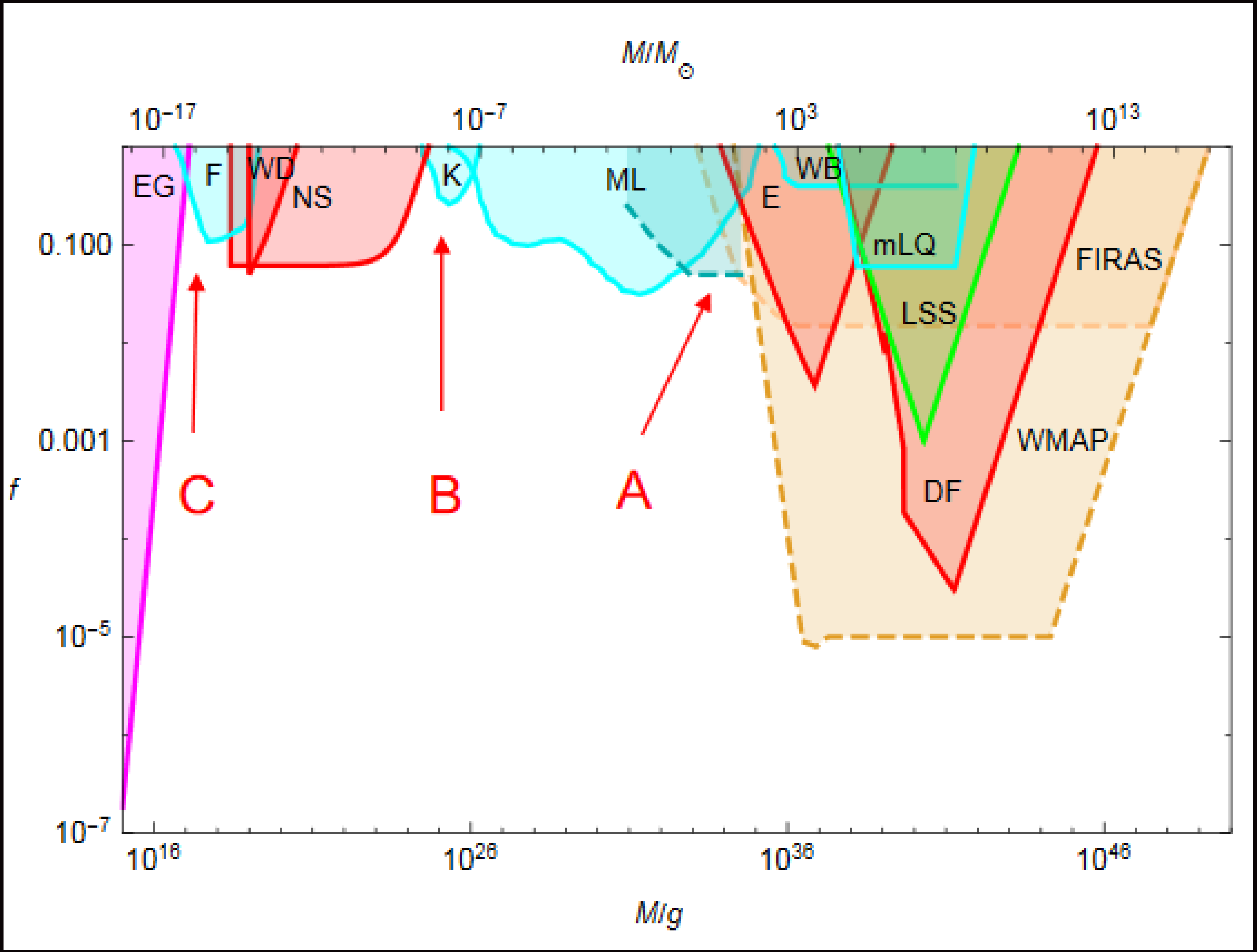


If 4 shortest OGLE events are excluded from the analysis.

Assuming that no PBHs were detected by OGLE

1901.07120

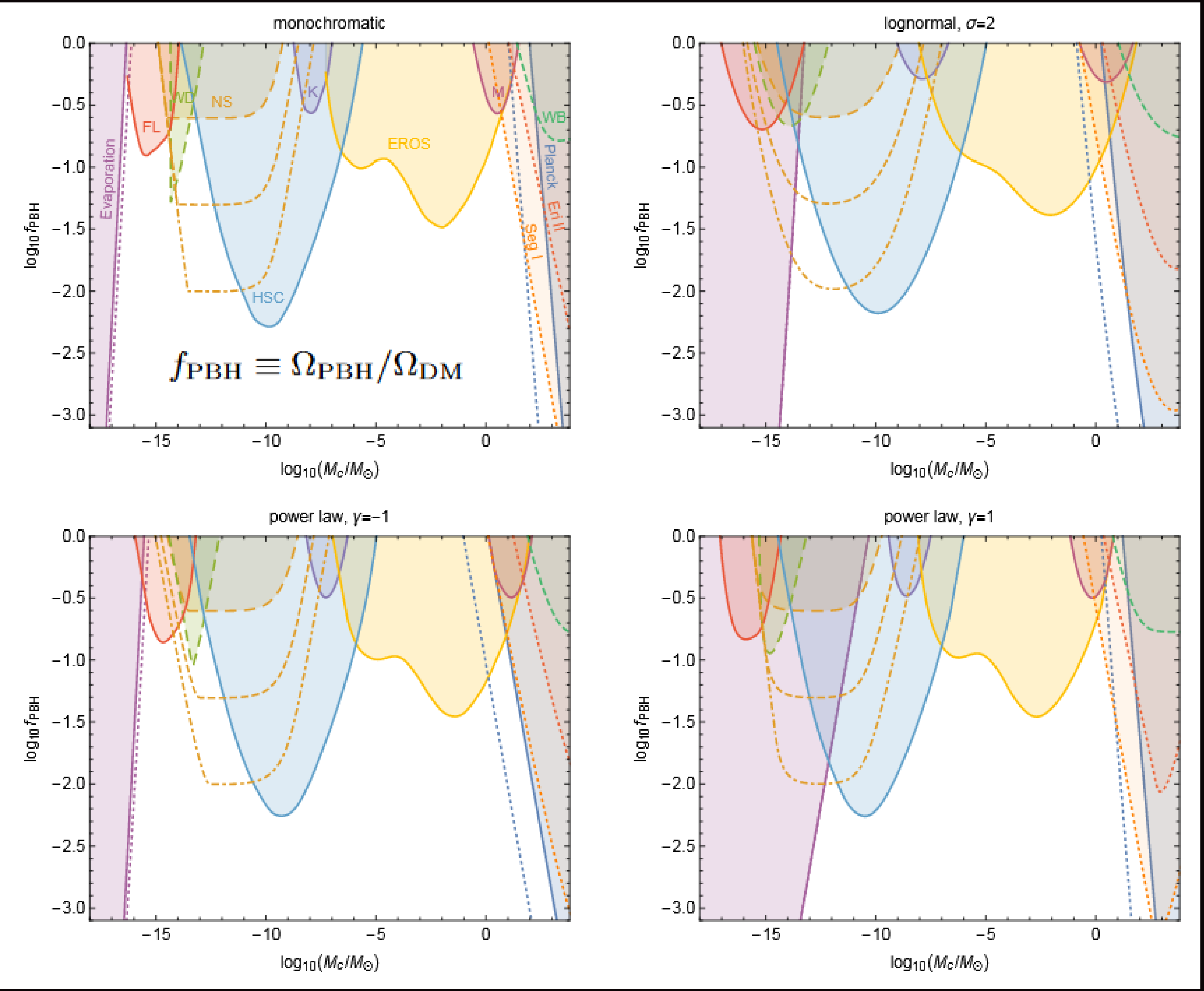
Limits on PBHs of different masses



Three "windows" are marked.

All constraints are for monochromatic mass functions ΔM~M.

1607.06077, see a review in 1901.07803


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
$f_{\rm PBH} \equiv \Omega_{\rm PBH}/\Omega_{\rm DM}$
$\log_{10} f_{\rm PBH}$
$\log_{10}(M_c/M_\odot)$

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.

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

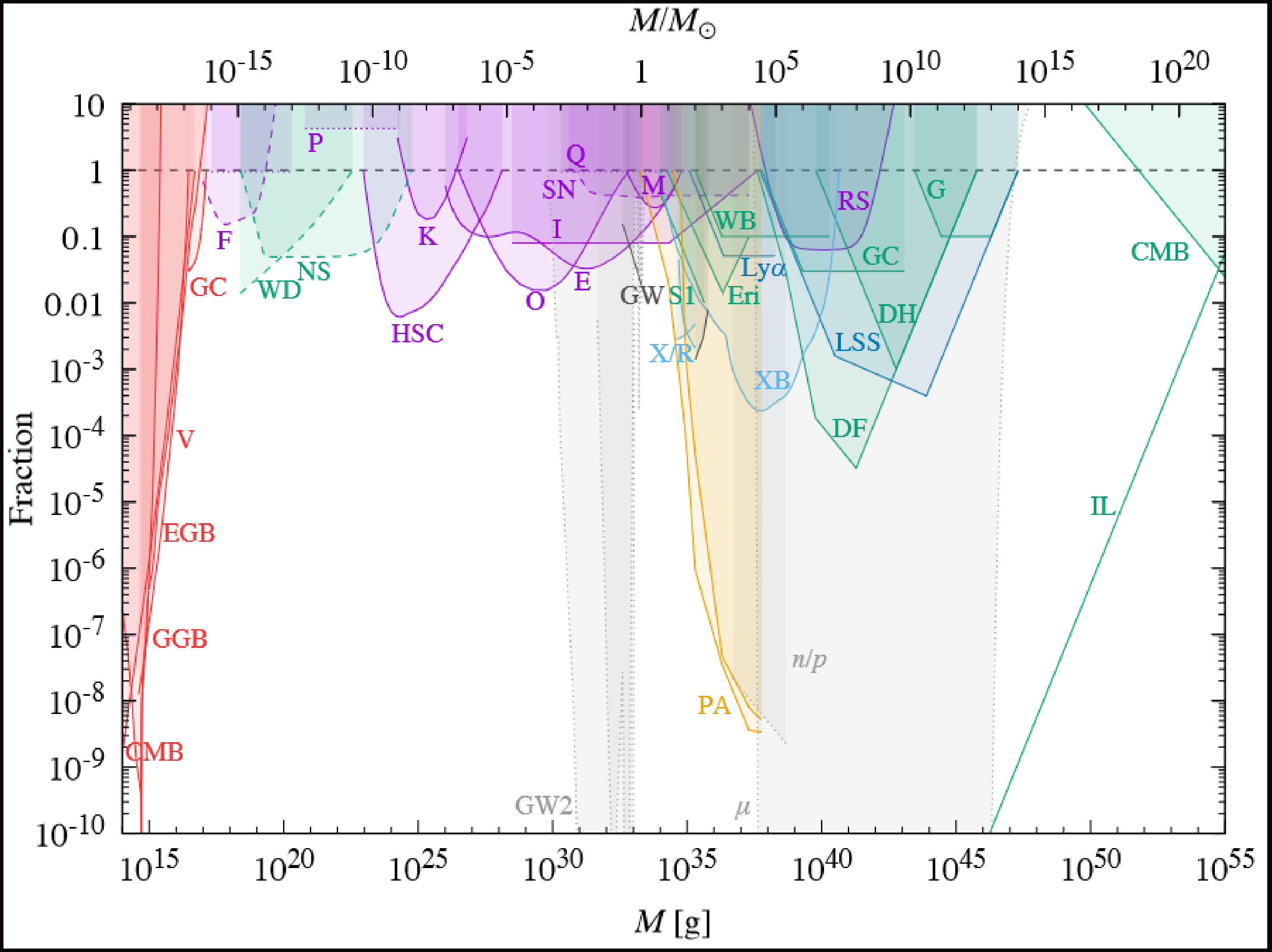
$$\psi(M) = \frac{f_{\rm PBH}}{\sqrt{2\pi}\sigma M} \exp\left(-\frac{\log^2(M/M_c)}{2\sigma^2}\right)$$

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

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

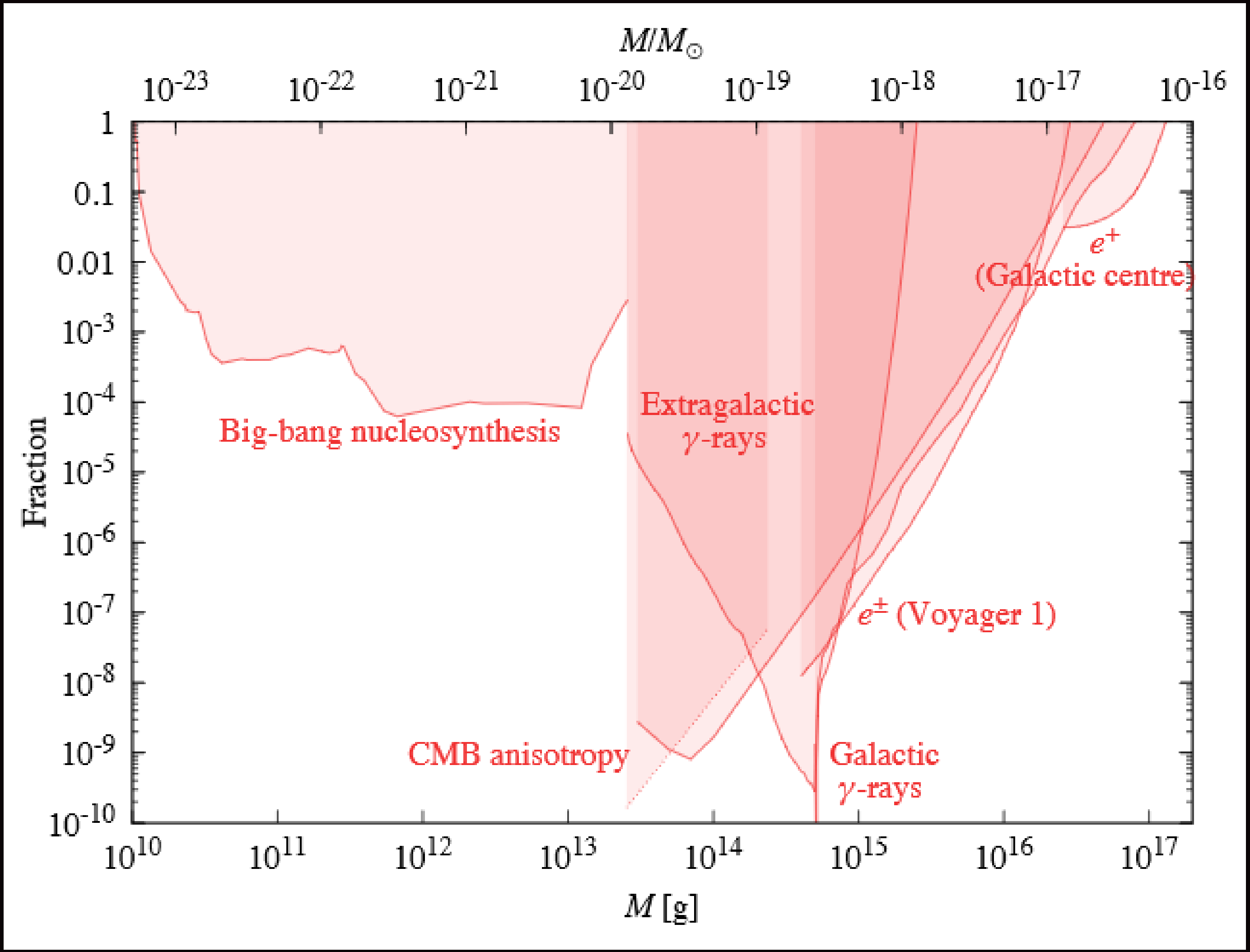
1705.05567, Subaru limits (HSC) are criticized in 1910.01285

More limits



2002.12778, see also 2006.02838 and 2007.10722 about PHBs as dark matter

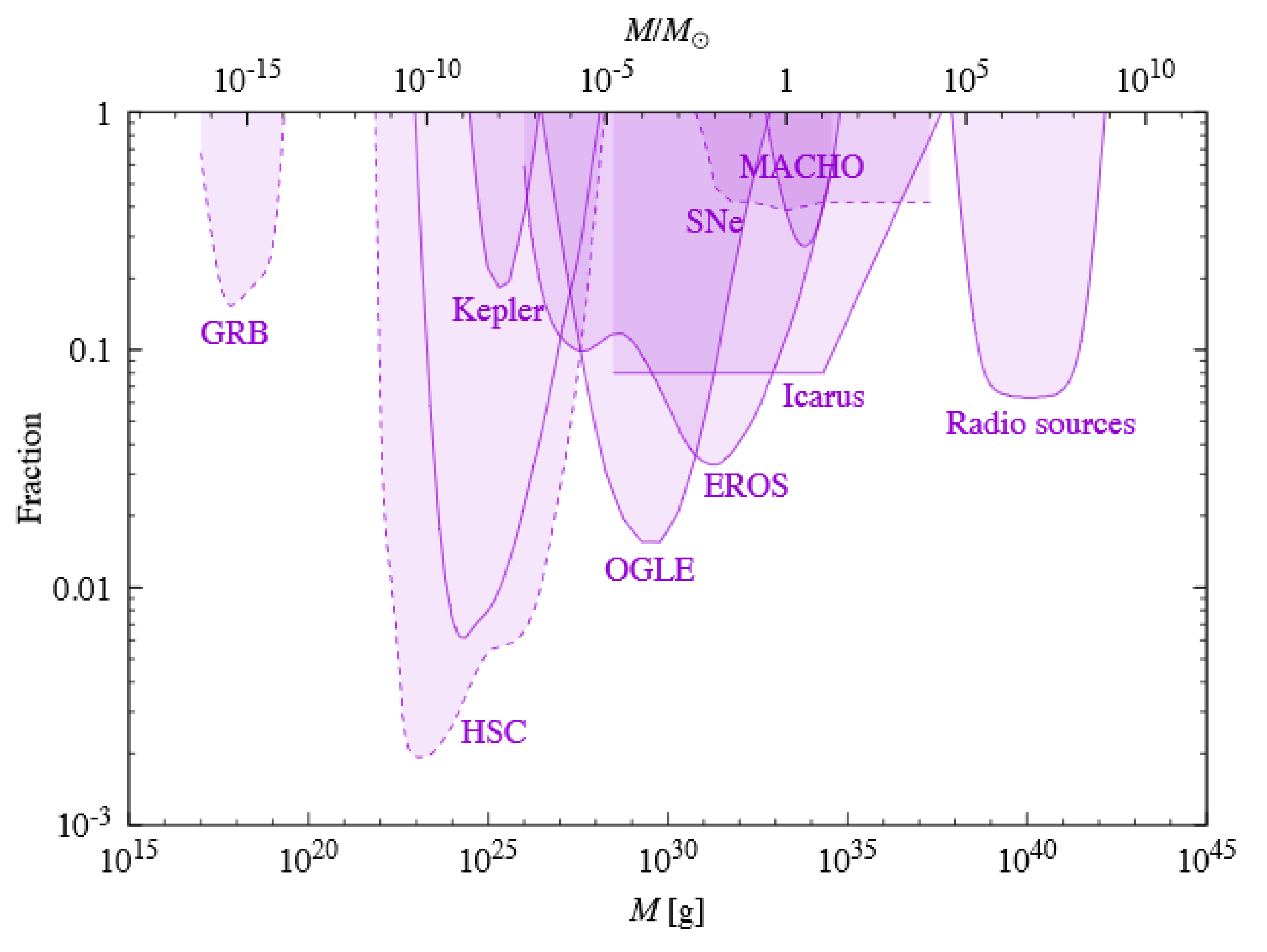
Evaporative constraints on PBHs



New limits on BBN in 2006.03608

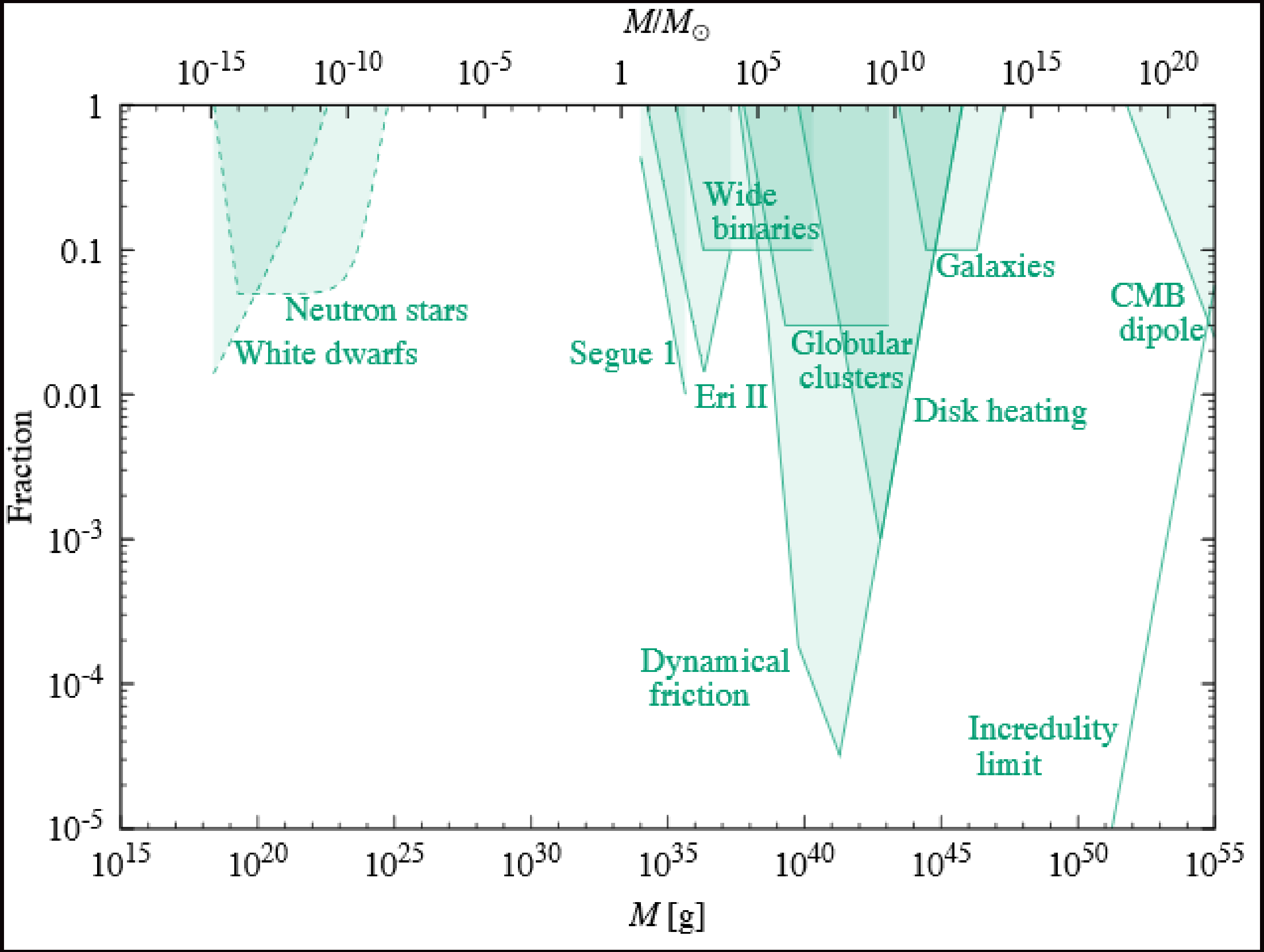
2002.12778

Lensing constraints + SNae+ GRBs



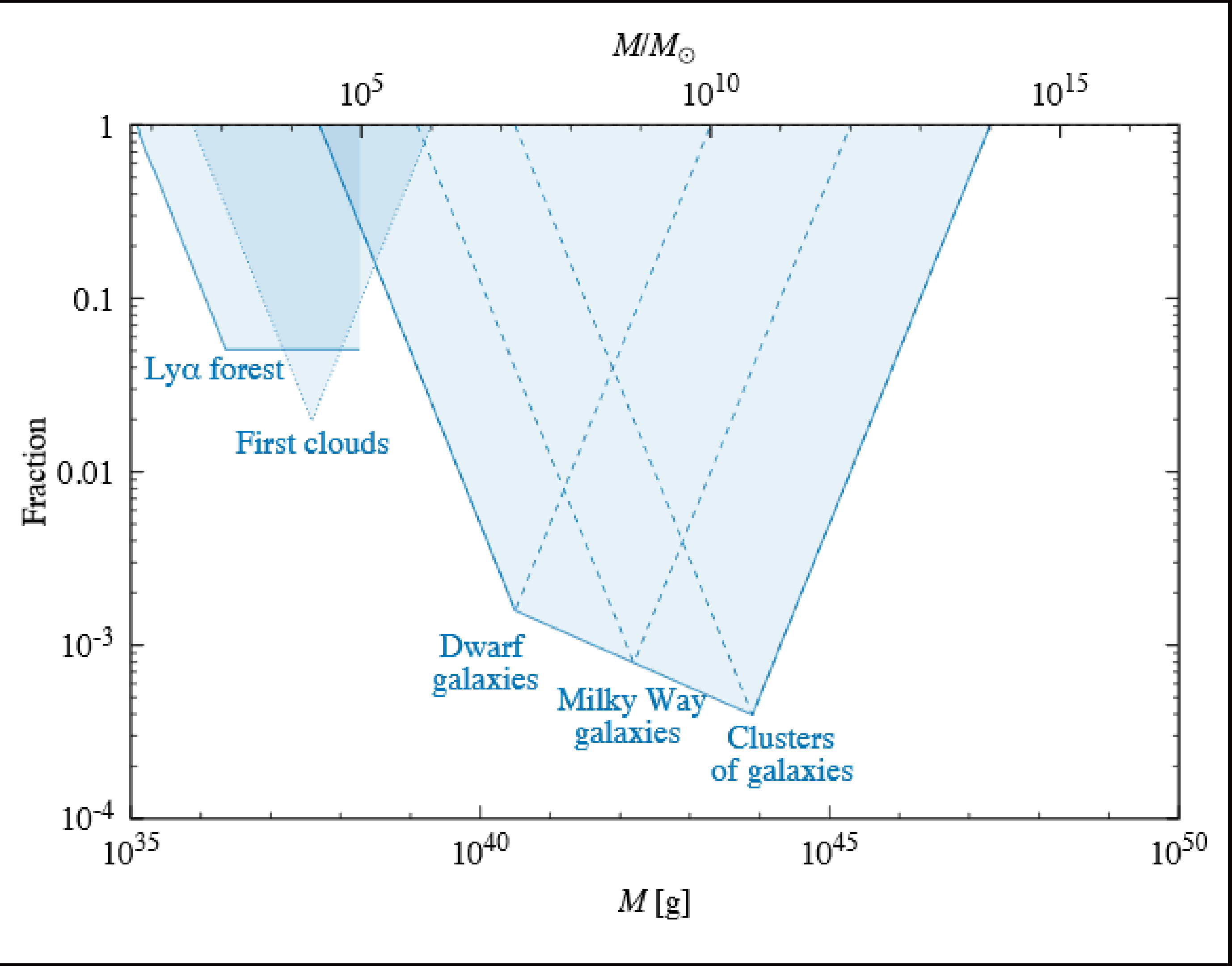
2002.12778

Dynamical constraints



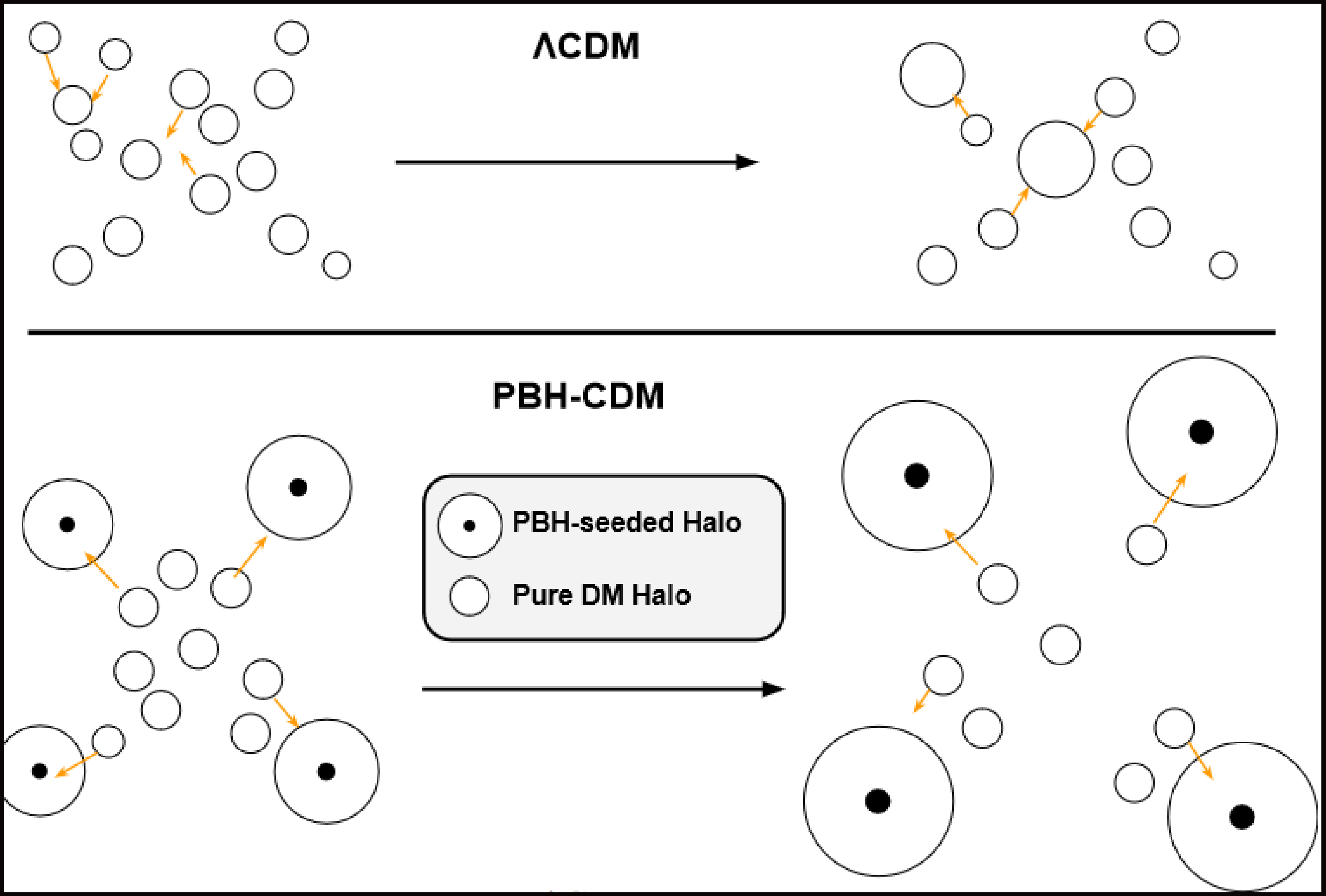
2002.12778

Large-scale structure constraints



2002.12778

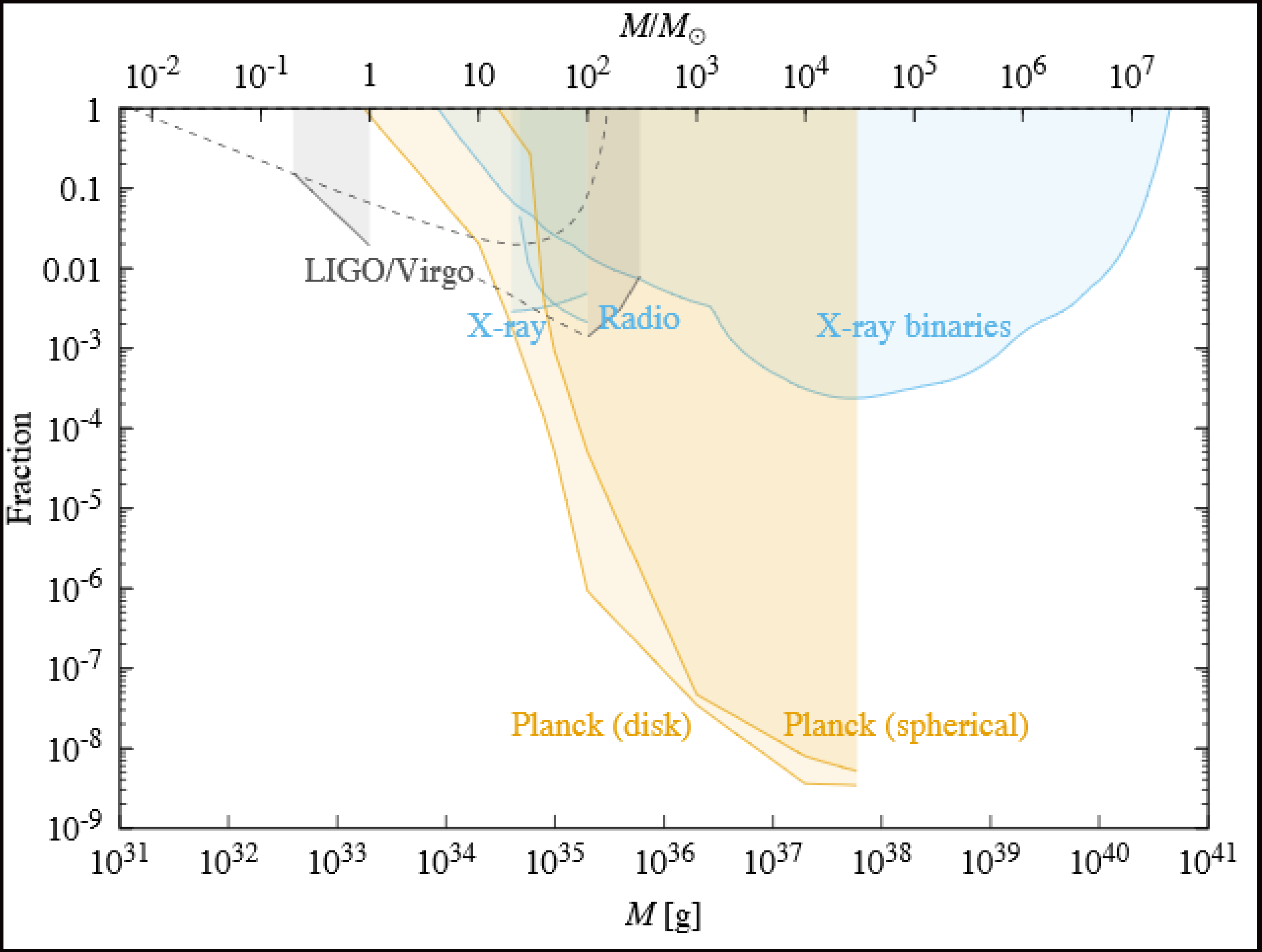
Halo growth under the PBH influence



$M_{PBH} \sim 10^6\ M_{sun}$

2405.11381

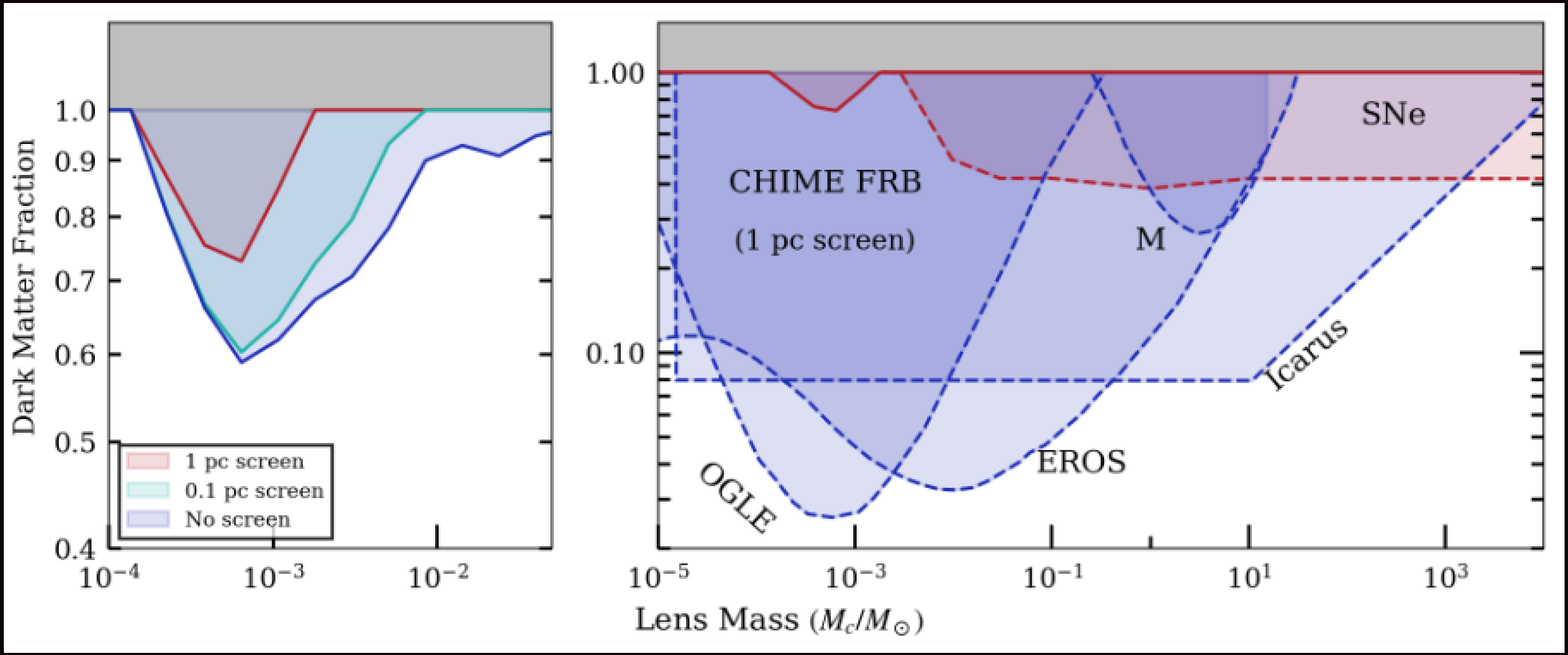
Other constraints



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

2002.12778 An update in arXiv: 2205.14722

FRB constraints



lensing delays of $10^{-9} - 10^{-1}$ sec,
corresponding to PBHs in the mass range of $10^{-4} - 10^{4}$ Msun.

2204.06001

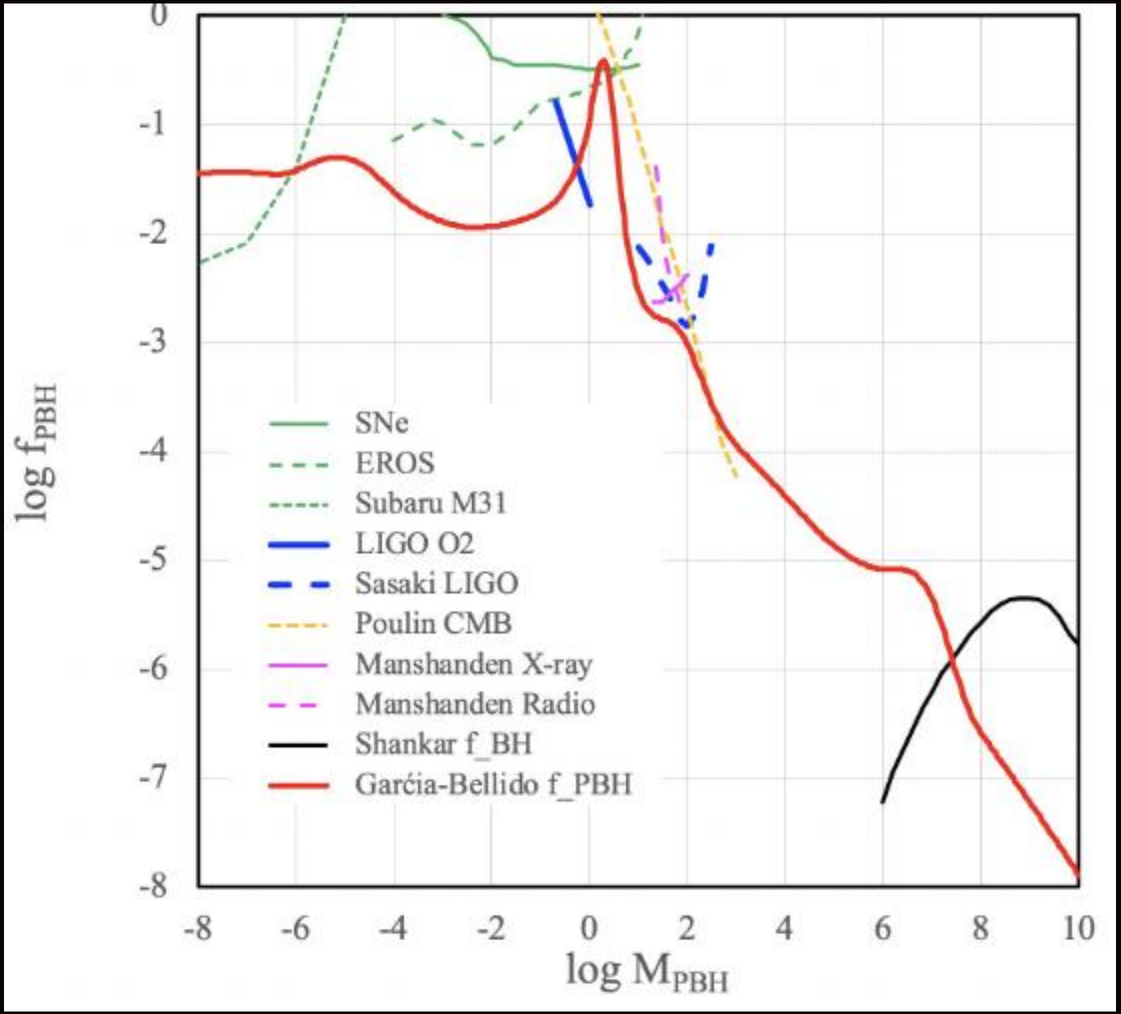
Optimistic scenarios

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

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

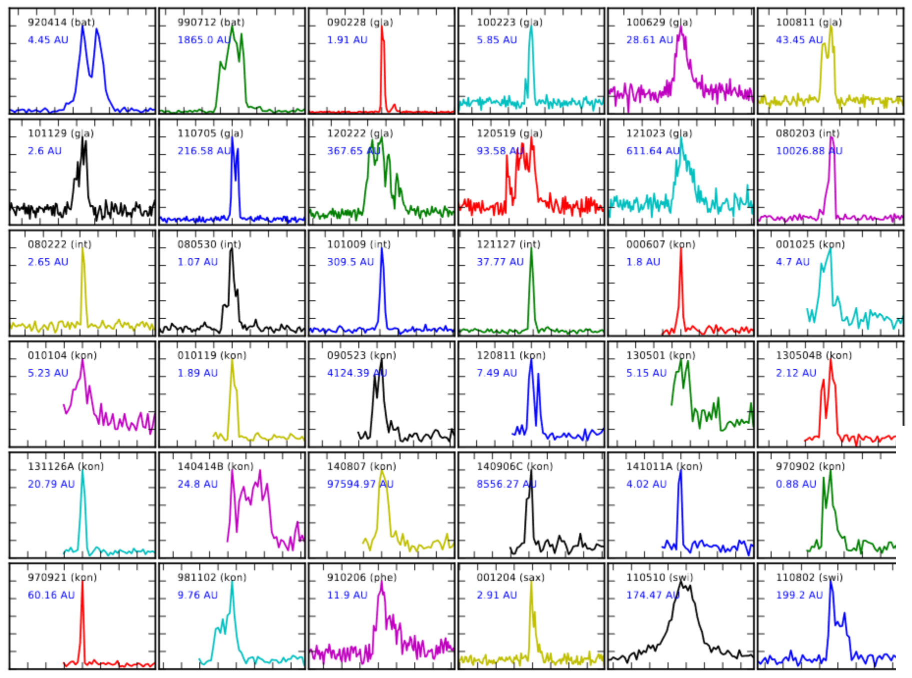
- GW signals;
- Accretion (2003.05150)

PBHs, then, can play role in:
- SMBH formation,
- re-ionization,
etc.



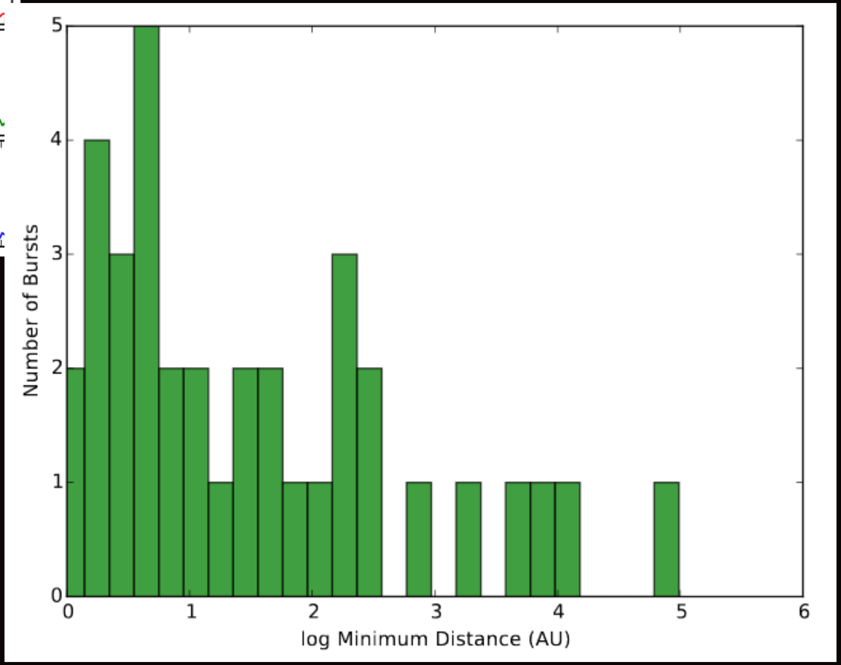
2003.05150

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.

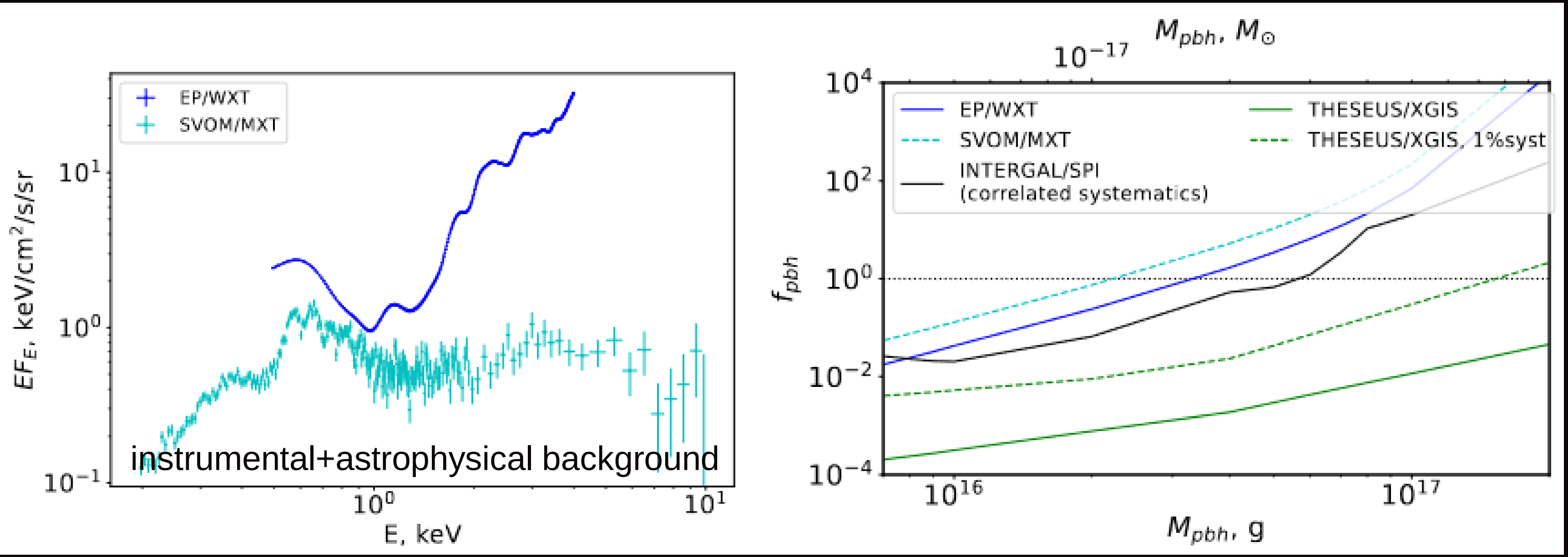


The are some (36) candidates with possibly small distances (<1 pc). But these are LOW limits. I.e., it is still very uncertain if these bursts are related to PBHs.

1512.01264

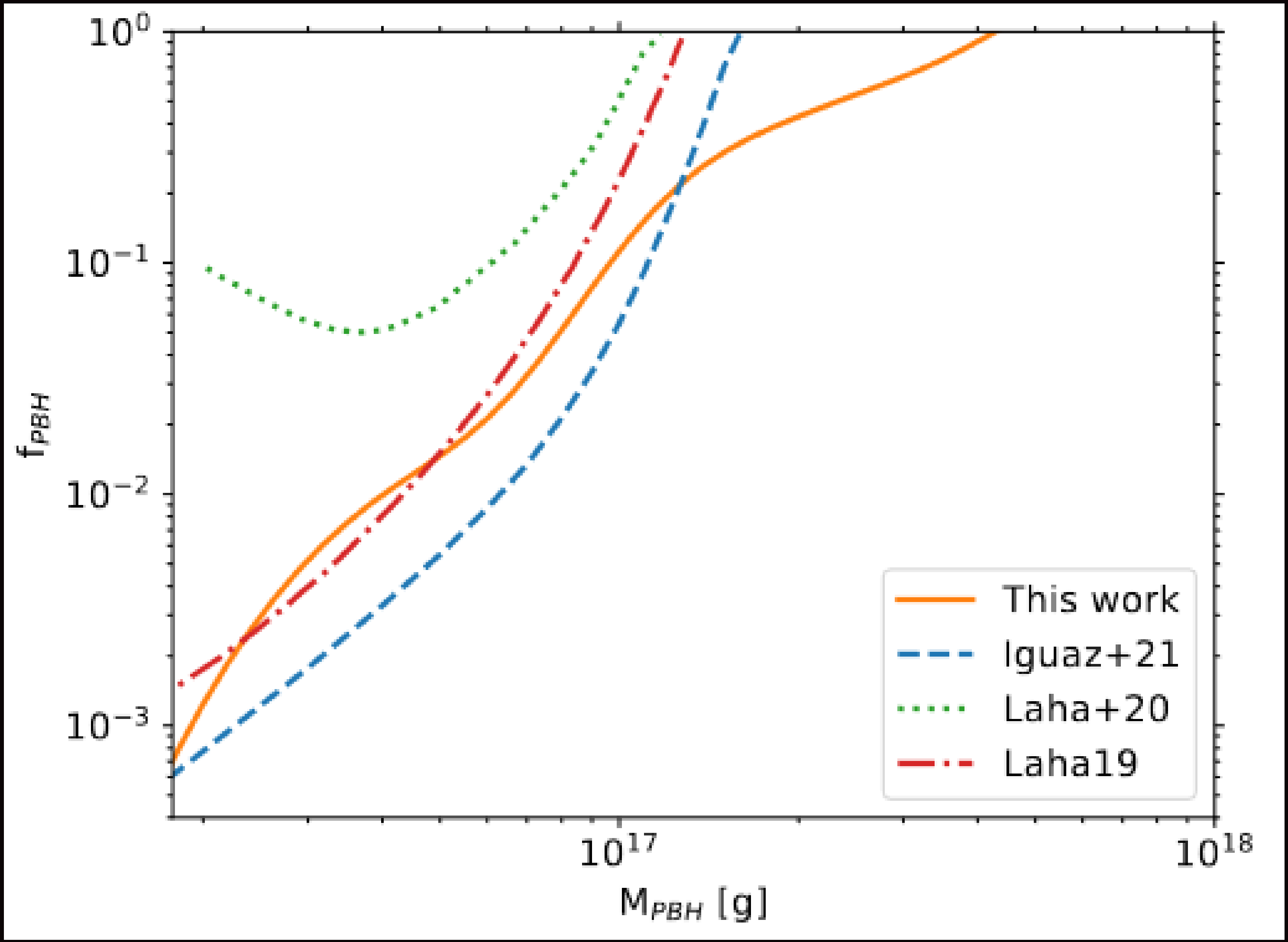
X-ray limits

$$T_H = 1/(4\pi/G_N M_{pbh}) \simeq 1.06 \times (10^{16}\text{g}/\text{M}_{pbh})\ \text{MeV}$$



2311.05942

INTEGRAL limits

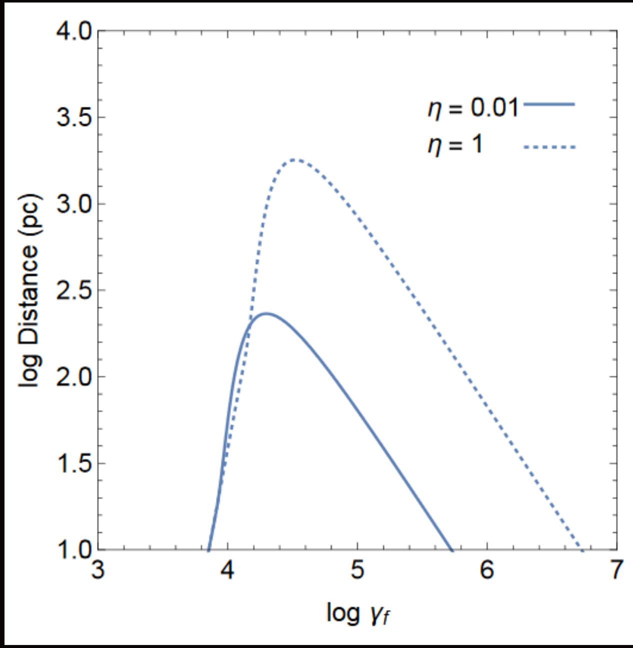


2202.07483. Earlier Integral limits see in 2004.00627

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

for Lorentz factor of $10^{4.5}$

L- size of an extra dimension

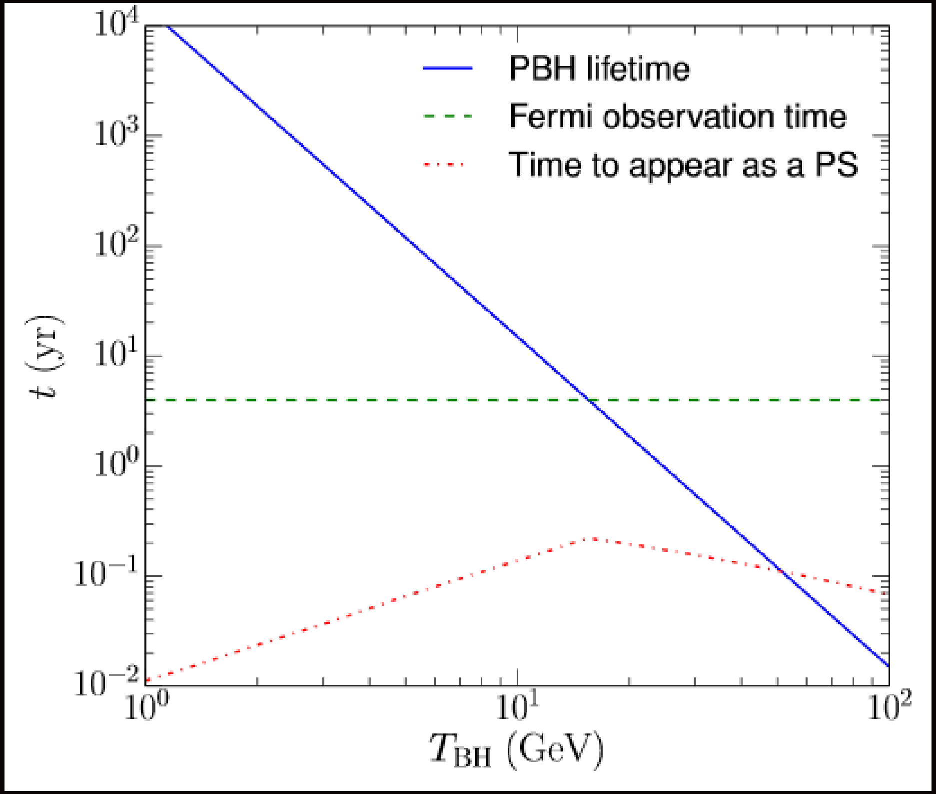
$$\eta M c^2 = \eta \mu L c^4 / G \qquad \mu = GM/Lc^2$$

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

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)!



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

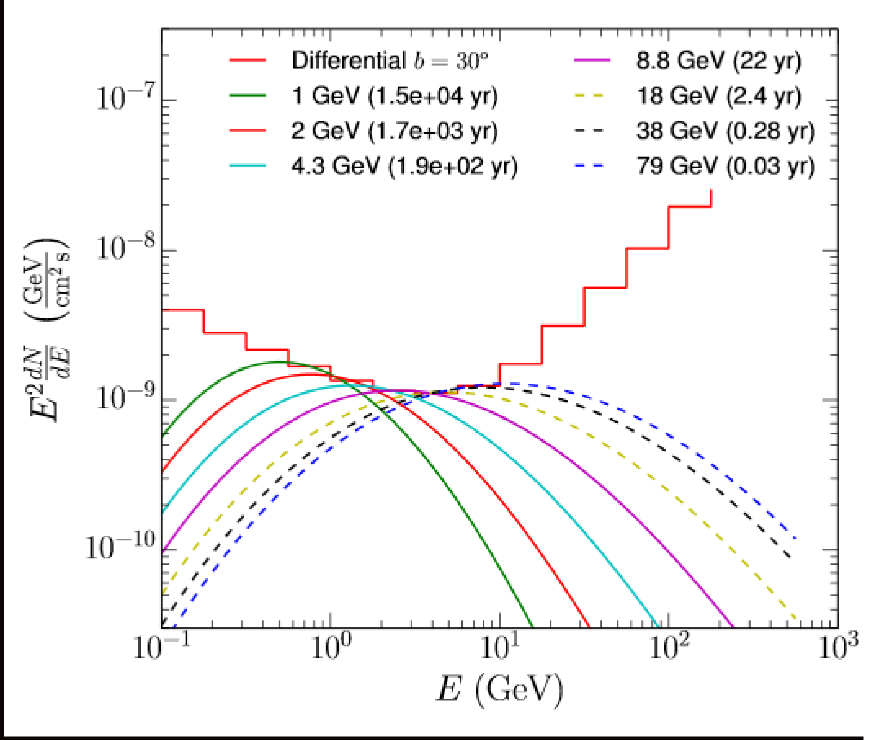
$$T_{\rm BH} = \frac{\hbar c^3}{8\pi G M k} \approx 10^{-7}\left(\frac{M}{M_\odot}\right)^{-1} K,$$

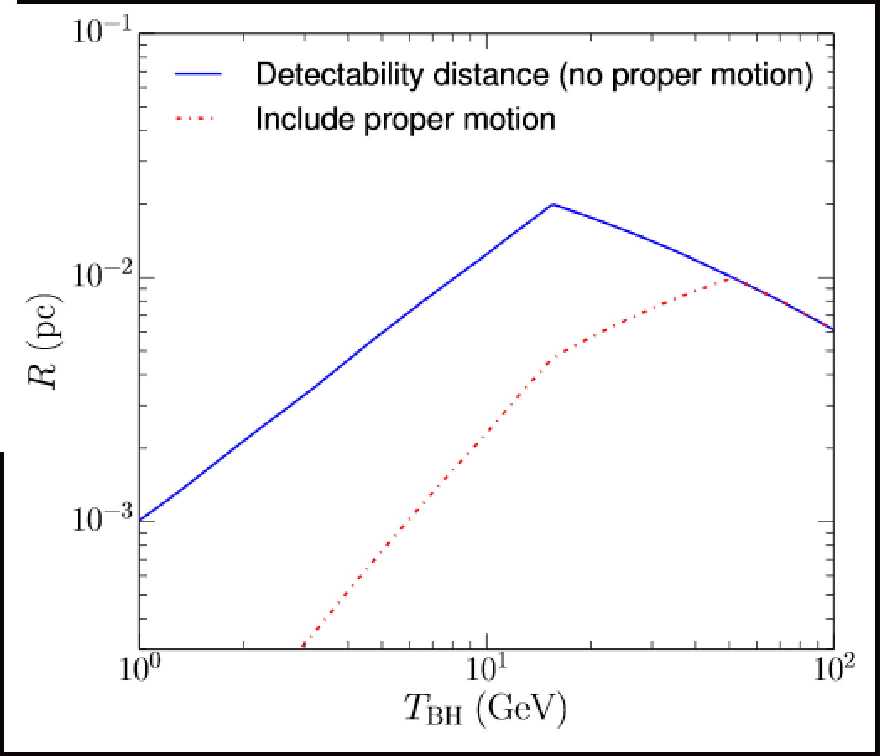
$$M(t) \approx 10^{15}\left(\frac{t}{10^{-23}\mathrm{s}}\right)\ \mathrm{g}.$$

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

1802.00100

Sensitivity of Fermi to PBHs





1802.00100, sensitivity of future instruments is analyzed in 2204.05337

Calculations of the limit

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

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

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

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

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

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

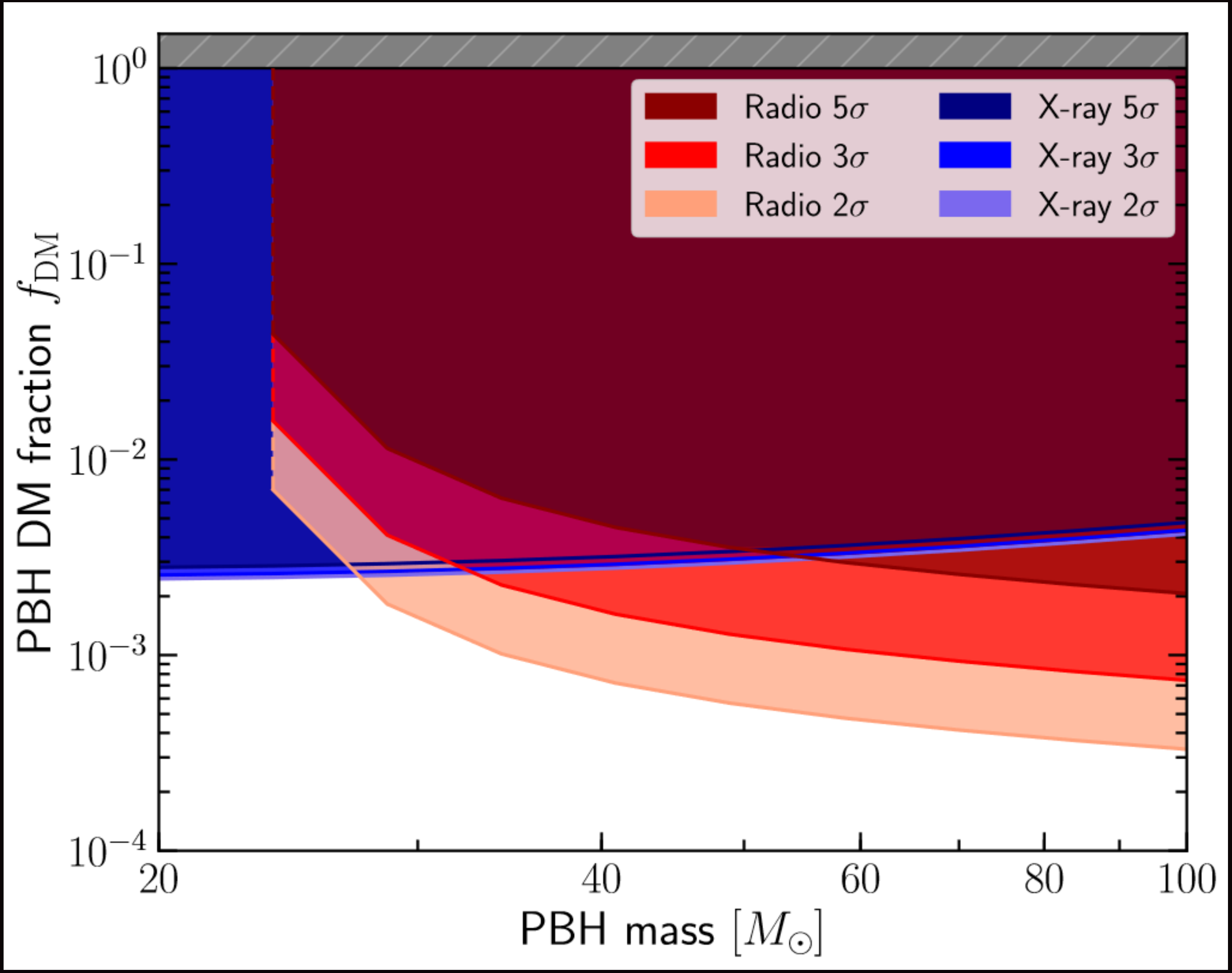
N=6.64 is 99% confidence limit based on 1 source.

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

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

1802.00100

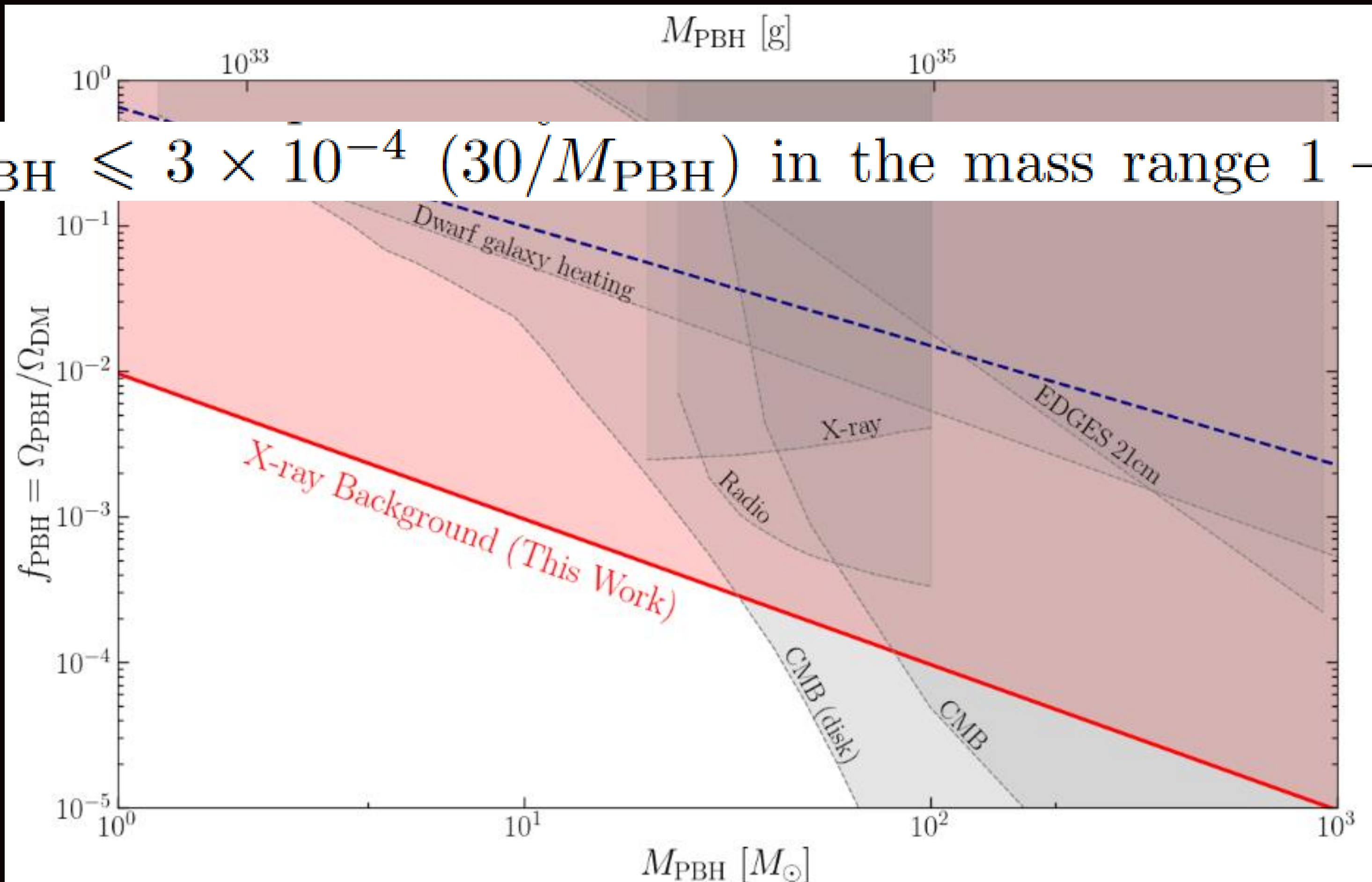
Limits from accretion



Based on observations of the Galactic center region in radio and X-rays.

1812.07967, see also 1805.06513

Limits from accretion. Background

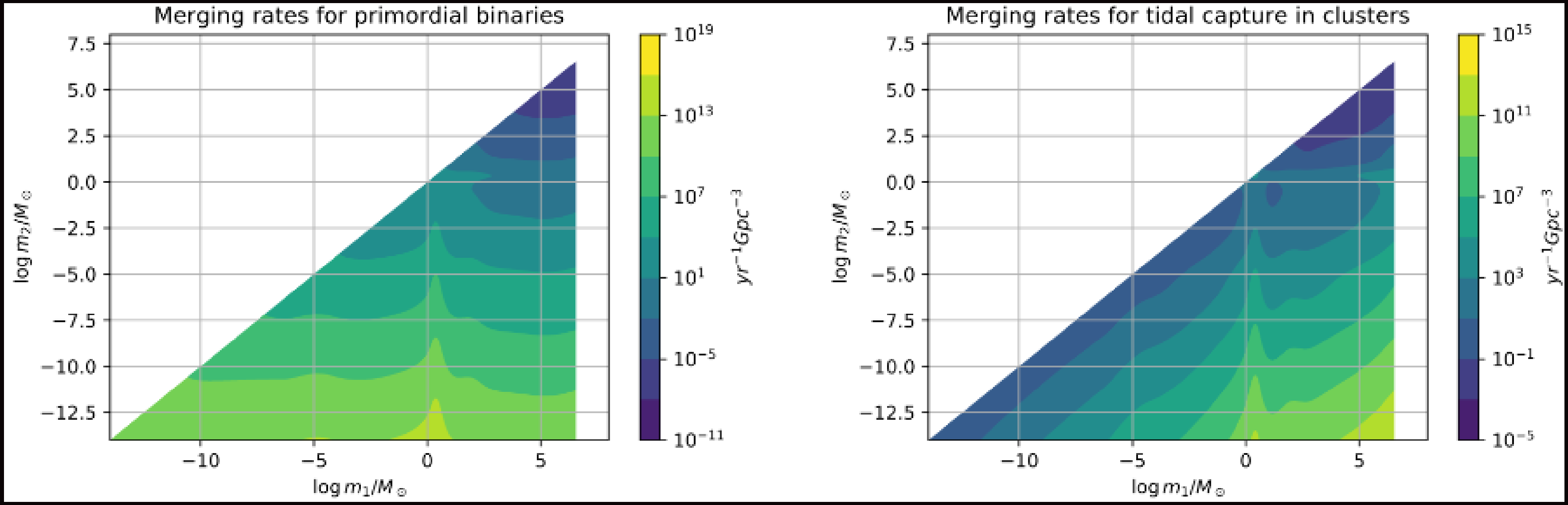


$$f_{\rm PBH} \leqslant 3 \times 10^{-4}\ (30/M_{\rm PBH})\ \text{in the mass range}\ 1 - 1000\, M_\odot$$

Most of the CXB/CRB emission comes from PBHs
in DM mini-halos (Mh <~ 10^6 M) at early epochs (z > 6)

2209.09907

GW signals from primordial BHs



PBHs can form pairs and then coalesce producing GW signals.
Potentially, it can help to explain peculiar properties of some sources.

(to compare: NS-NS merger rate is ~100/yr/Gpc^3

2310.19857

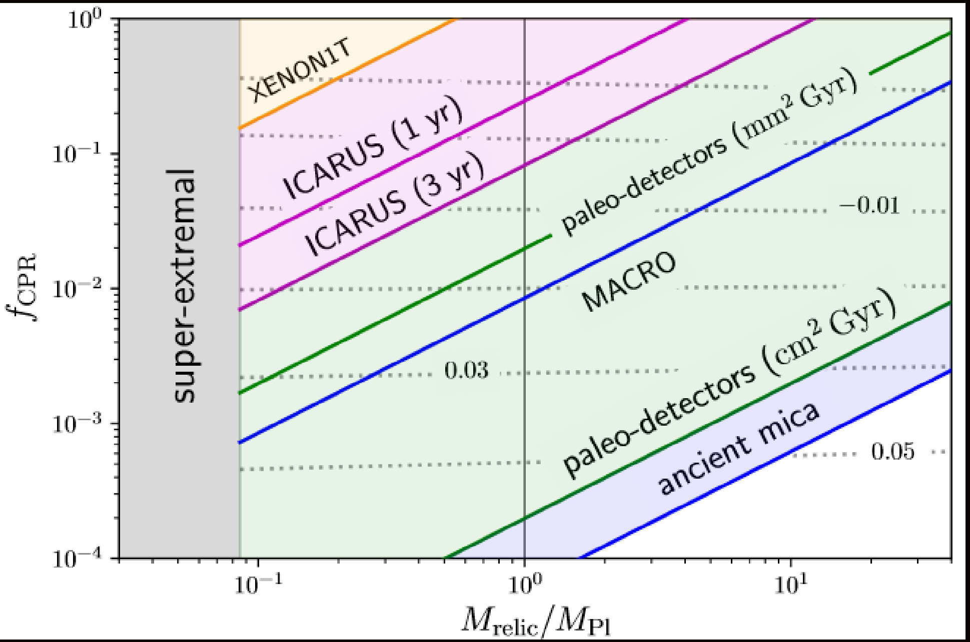
Do BHs evaporate completely?

The idea that BHs do not evaporate completely was proposed long ago (MacGibbon 1987)

Charged relics with $m \sim m_{Pl}$ can exist:

$$N \simeq 0.23\ \mathrm{yr}^{-1} f_{\mathrm{CPR}} \left(\frac{M_R}{M_{\mathrm{Pl}}}\right)^{-1} \left(\frac{\rho_{\mathrm{DM}}}{0.3\ \mathrm{GeV/cm^3}}\right) \left(\frac{v_{\mathrm{DM}}}{300\ \mathrm{km/s}}\right) \left(\frac{A_{\mathrm{eff}}}{1\ m^2}\right) \varepsilon$$

$$K \sim \frac{1}{2} M_R v_{\mathrm{DM}}^2 \simeq 6 \times 10^{16}\ \mathrm{eV} \quad (M_R \simeq M_{\mathrm{Pl}})$$



2405.00546