International Conference on High Energy Particle & Astroparticle Physics (ICHEPAP2023)

Primordial black holes

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Thanks to my collaborators: Anupam Ray, Regina Caputo, Basudeb Dasgupta, Julian B. Muñoz, Philip Lu, Akash K. Saha, Tracy R. Slatyer, and Volodymyr Takhistov

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- Primordial black hole introduction
- Some primordial black hole detection techniques
  (a) from evaporation
  (b) from lensing
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Primordial black hole introduction

Primordial black holes

What are primordial black holes?

Primordial black holes are exotic compact objects which can form in the early Universe due to large density perturbations (numerous formation models) and/ or due to beyond the Standard Model physics

(Zel'dovich and Novikov Astron. Zhu, 1966, Hawking MNRAS 1971, Carr and Hawking MNRAS 1974, Chapline Nat. 1975 and many others; Shandera, Jeong, and Gebhardt 1802.08206 PRL and Kouvaris, Tinyakov, and Tytgat 1804.06740 PRL; see Bagui et al., 2310.19857 for a recent review)

$$M_{\rm PBH} \approx 10^{15} \left(\frac{t}{10^{-23}\,{\rm s}} \right) {\rm g}$$ (for PBHs formed in the early Universe)

Primordial black holes can have a wide range of masses and can form the entire dark matter density of the Universe

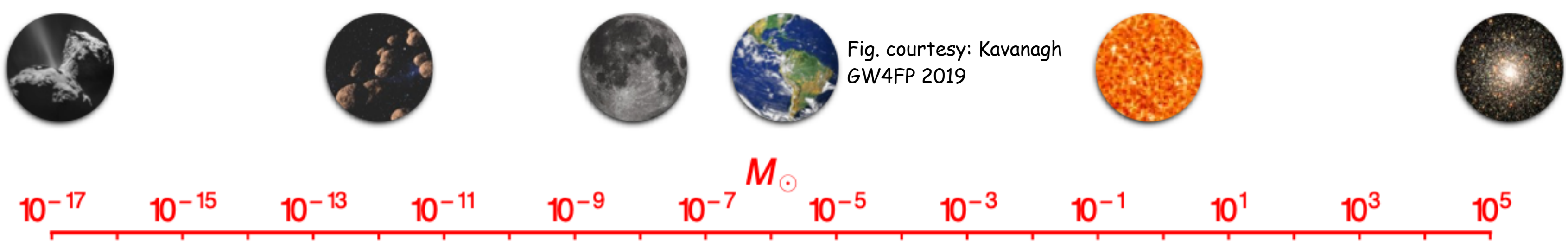
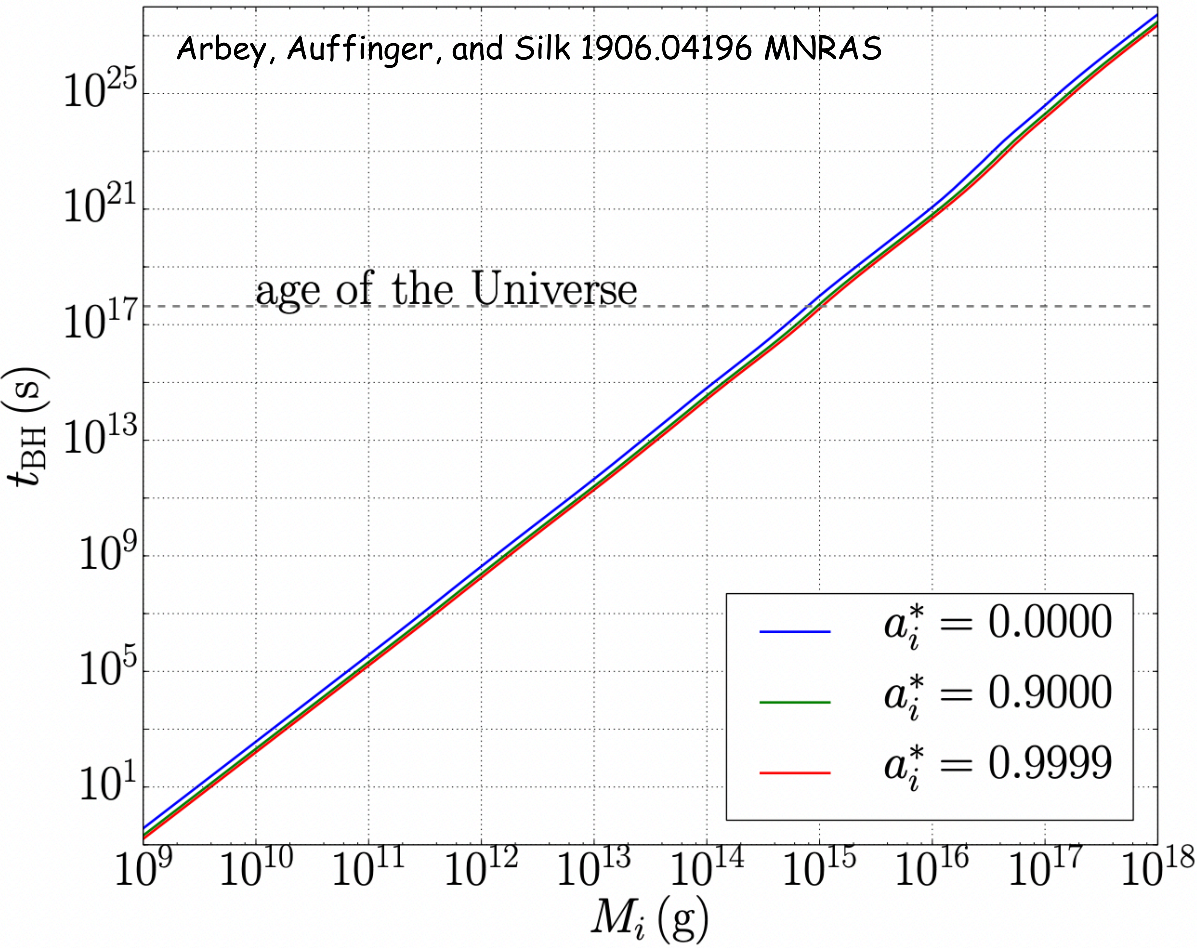


Fig. courtesy: Kavanagh GW4FP 2019

$$1\,M_\odot \approx 2 \times 10^{30}\,{\rm kg} \approx 1.1 \times 10^{57}\,{\rm GeV}$$

Primordial black holes may have a log-normal mass function or a power law mass function and can have a wide range of spins

Masses of primordial black holes for dark matter



PBHs evaporate via Hawking radiation

$$t_{\rm BH} \propto M_{\rm BH}^3$$

Lifetime of a black hole

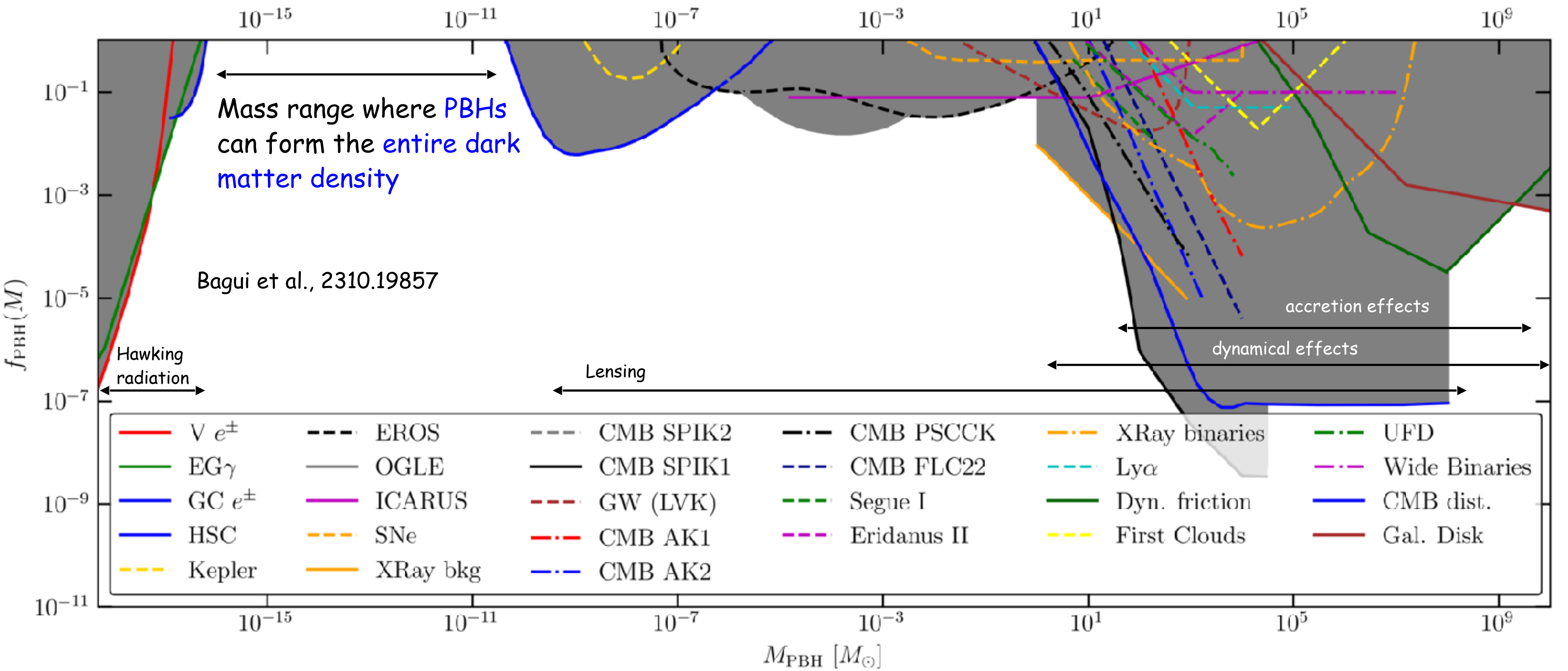
Mass of a black hole

a_i^* = initial spin of the black hole

Minimum mass of non-spinning PBH DM ≈ 6×10^{14} g

Non-zero spin increases the minimum mass of PBH DM

Primordial black hole (PBH) dark matter



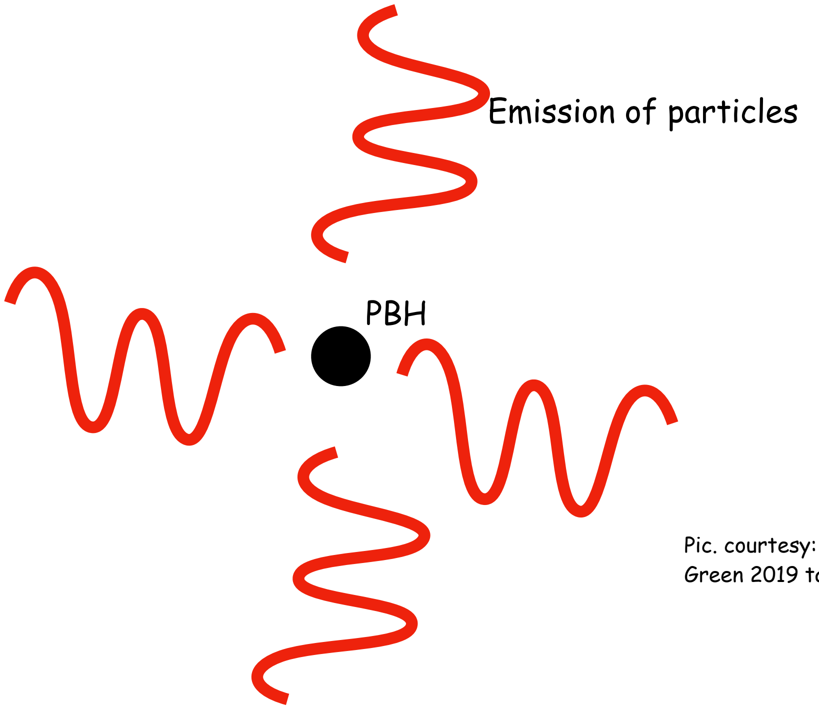
f_{PBH} = fraction of the dark matter in the form of PBHs

Multiple constraints exist over wide range of masses (all of these are not shown for clarity)

I will discuss some of these constraints in the following slides (individual references later)

Constraints involve different phenomenology in different mass ranges

Primordial black holes constraints from evaporation



Pic. courtesy:
Green 2019 talk

Evaporation of primordial black holes

Black holes evaporate to produce Standard Model particles (and possible beyond the Standard Model particles) and can have observable consequences

S. W. Hawking, Nature 248 (1974) 30-31.

S. W. Hawking,, Commun. Math. Phys. 43 (1975) 199-220.

Temperature of the black hole →

$$T_{\rm BH} = 1.06 \left(\frac{10^{10}\,{\rm kg}}{M_{\rm BH}} \right) {\rm GeV}$$

↑ Mass of the black hole

Dimensionless absorption probability for the emitted species → Γ_s

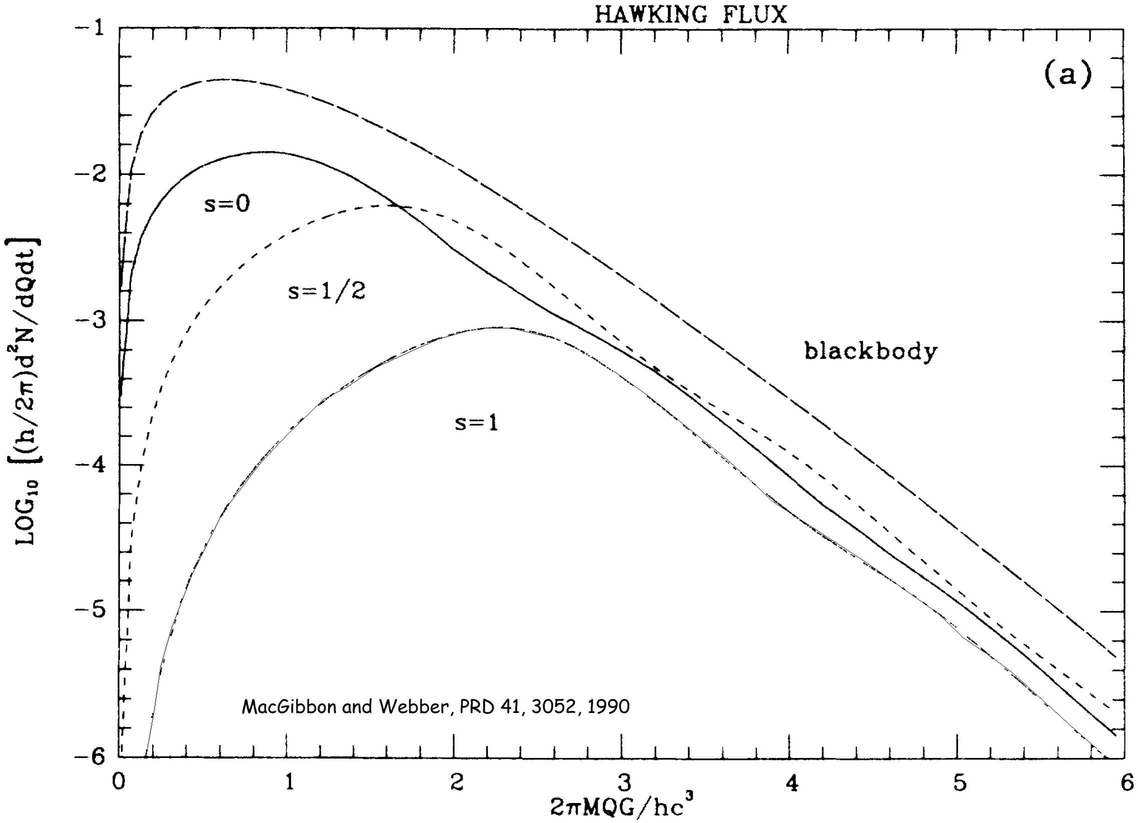
$$\frac{dN_s}{dE} = \frac{\Gamma_{\rm s}}{2\pi} \int dt \, \frac{1}{\exp(E/T_{\rm BH}) - (-1)^{2{\rm s}}}$$

↑ Evaporation energy spectrum of particle of spin s from a non-spinning black hole

Page PRD 16, 8, 2402 - 2411, 1977

See Auffinger 2206.02672 and Page hep-th/0409024 for reviews

Hawking radiation spectrum



Q = total energy of the emitted particles

This is for a non-rotating uncharged black hole

Emission of pion, $e^{\pm}$, and photon via Hawking radiation

The spectrum closely resembles a black-body radiation

The peaks in the flux per particle mode measured at infinity occur at:

$$Q_{\mathrm{s}=0} \approx 2.81\, T_{\mathrm{BH}} \qquad Q_{\mathrm{s}=1/2} \approx 4.02\, T_{\mathrm{BH}} \qquad Q_{\mathrm{s}=1} \approx 5.77\, T_{\mathrm{BH}}$$

MacGibbon, Carr, and Page PRD 2008

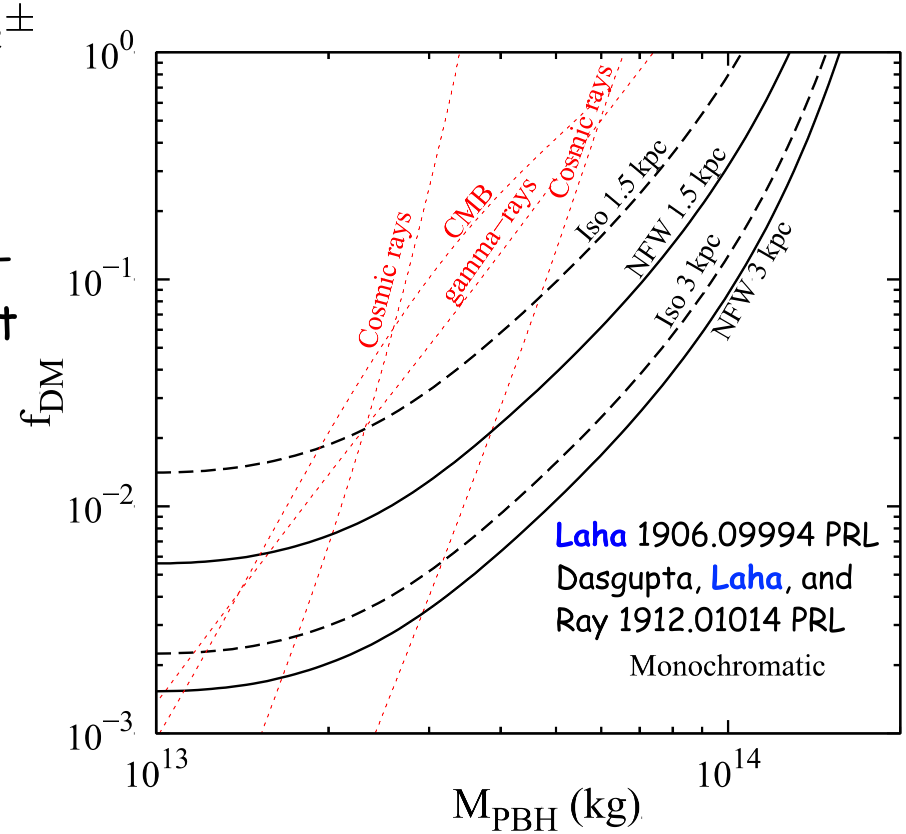
Low-mass PBHs and Galactic Center 511 keV line

Low-mass PBHs can evaporate to produce $e^{\pm}$ pairs

The positrons will lose energy, become non-relativistic, and annihilate with the ambient electrons to produce photons

Galactic Center observations reveal an intense flux of 511 keV and associated continuum gamma-ray photons produced by unknown source(s)

Requiring that the positrons from PBH evaporation do not overshoot the positron luminosity produces one of the strongest limit on their abundance with masses between ~ 10^{13} kg to 10^{14} kg



Similar results in DeRocco and Graham 1906.07740 PRL

See also Keith and Hooper 2103.08611 PRD

$$\frac{dN}{dM} \propto \delta(M - M_{\rm PBH})$$

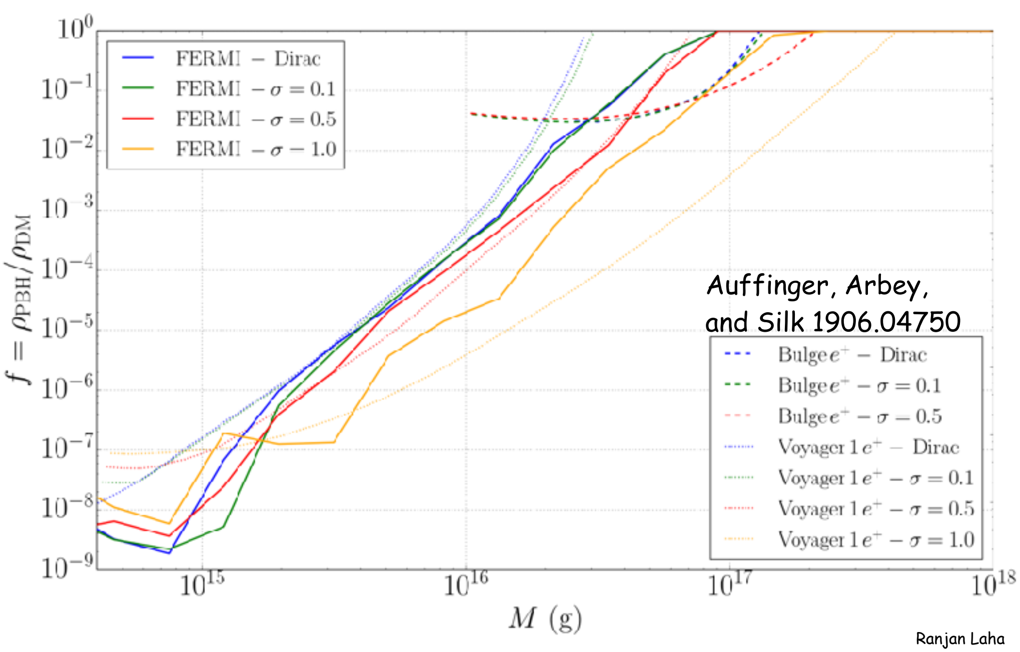
Low-mass primordial black holes and photons

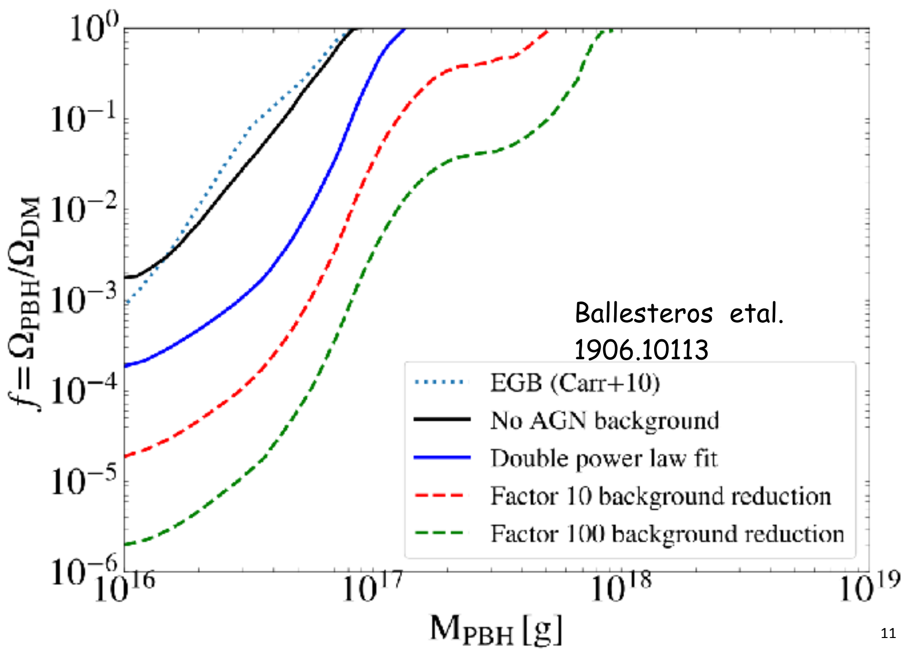
Primordial black holes can evaporate to produce photons

The photons can contribute to the cosmic photon background

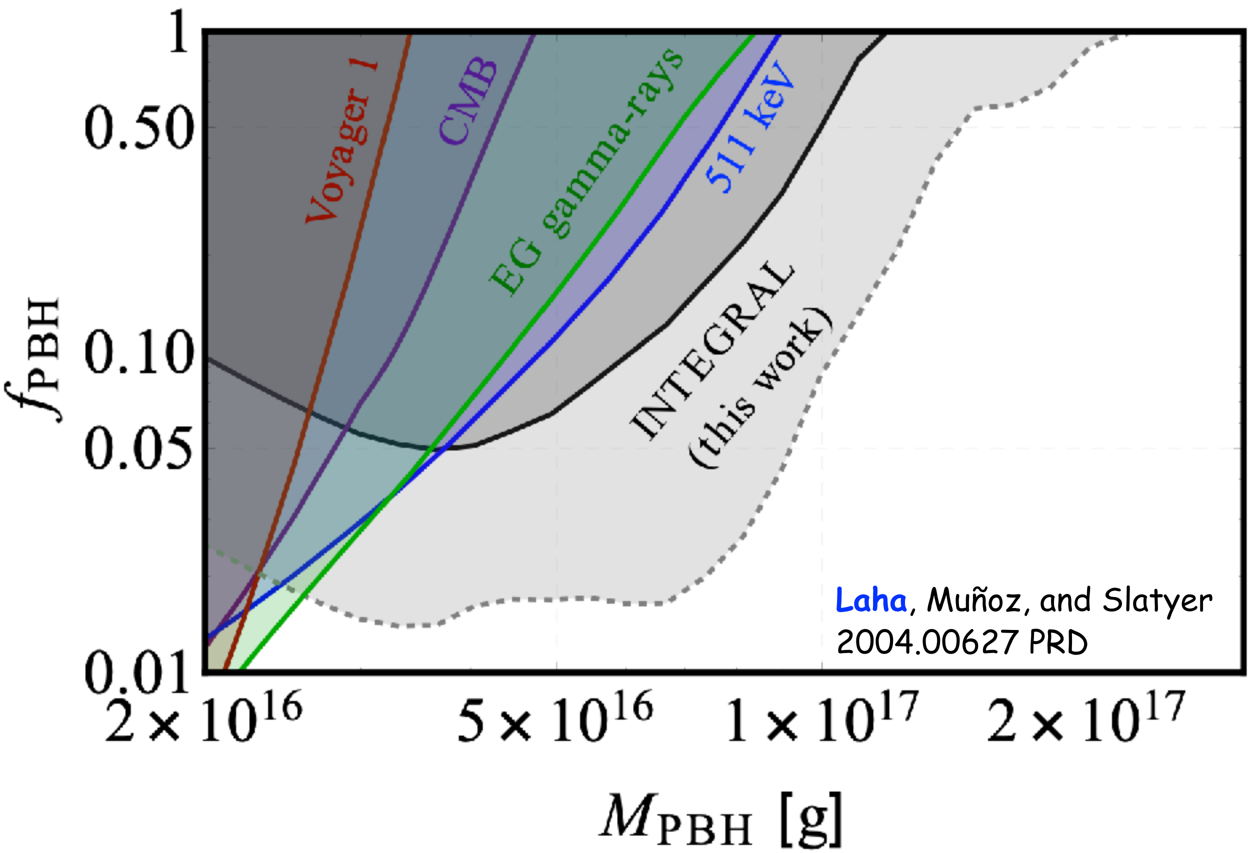
The isotropic gamma-ray background and the cosmic MeV background has been used to constrain the density of primordial black holes

The constraint can be derived by either assuming astrophysical contribution(s) to the photon background or by assuming no modeling (to derive a more conservative limit)





Constraint from angular dependence of the PBH signal and the INTEGRAL gamma-ray data



One of the best probes of low-mass PBHs

This constraint is relatively insensitive to the dark matter profile

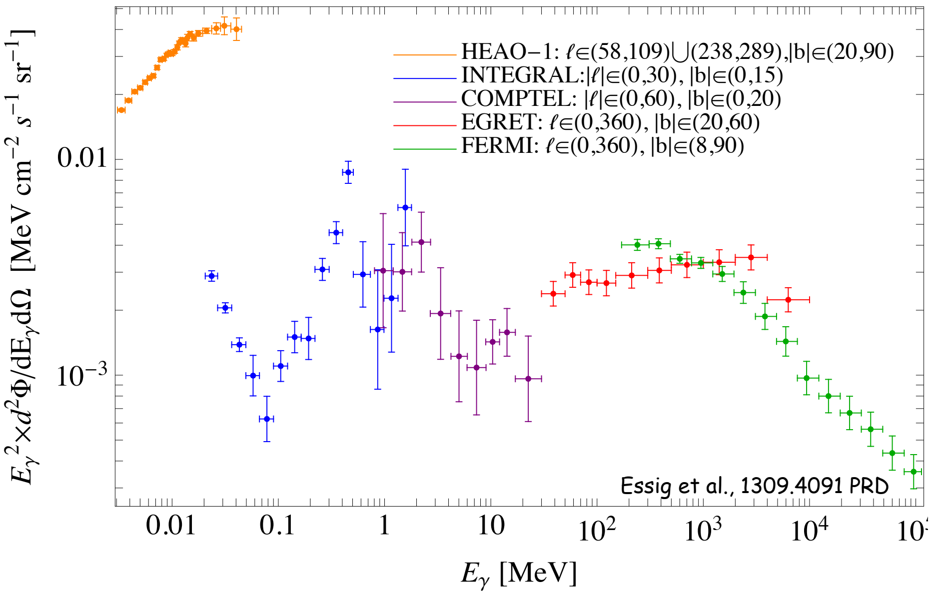
Assumes a mono-chromatic mass function of non-spinning PBHs

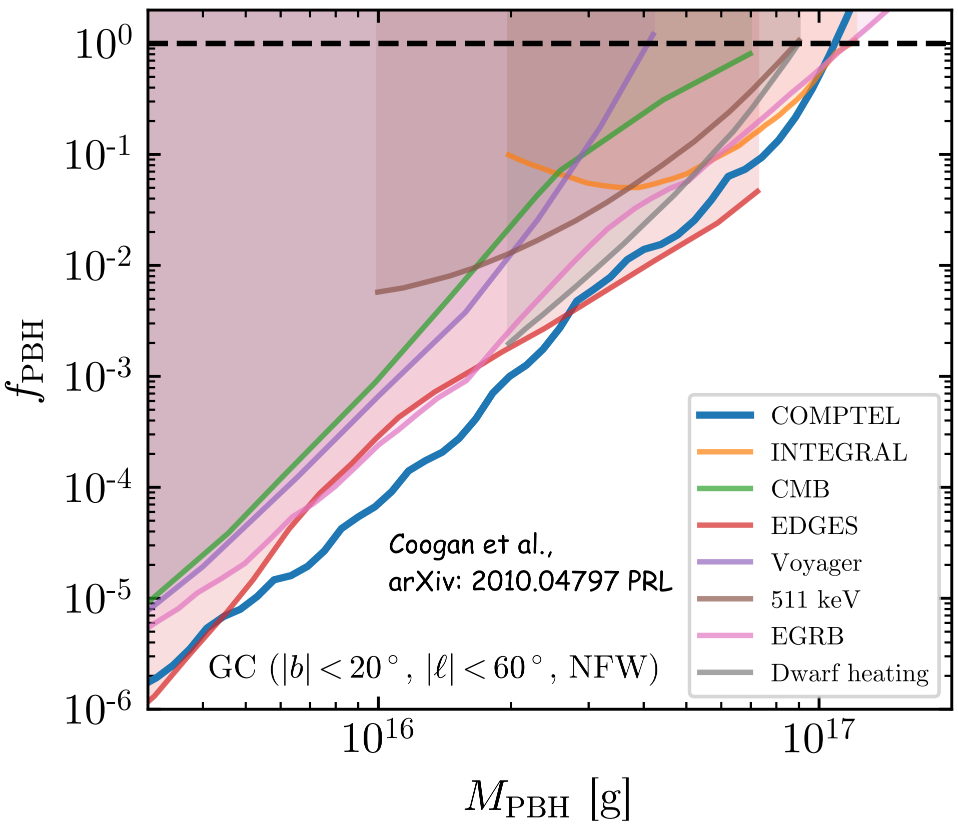
Equally constraining probe for an extended mass function of PBHs and for spinning PBHs

Constraints on PBH from COMPTEL observations

COMPTEL performed observations between ~ 1991 to ~ 2000

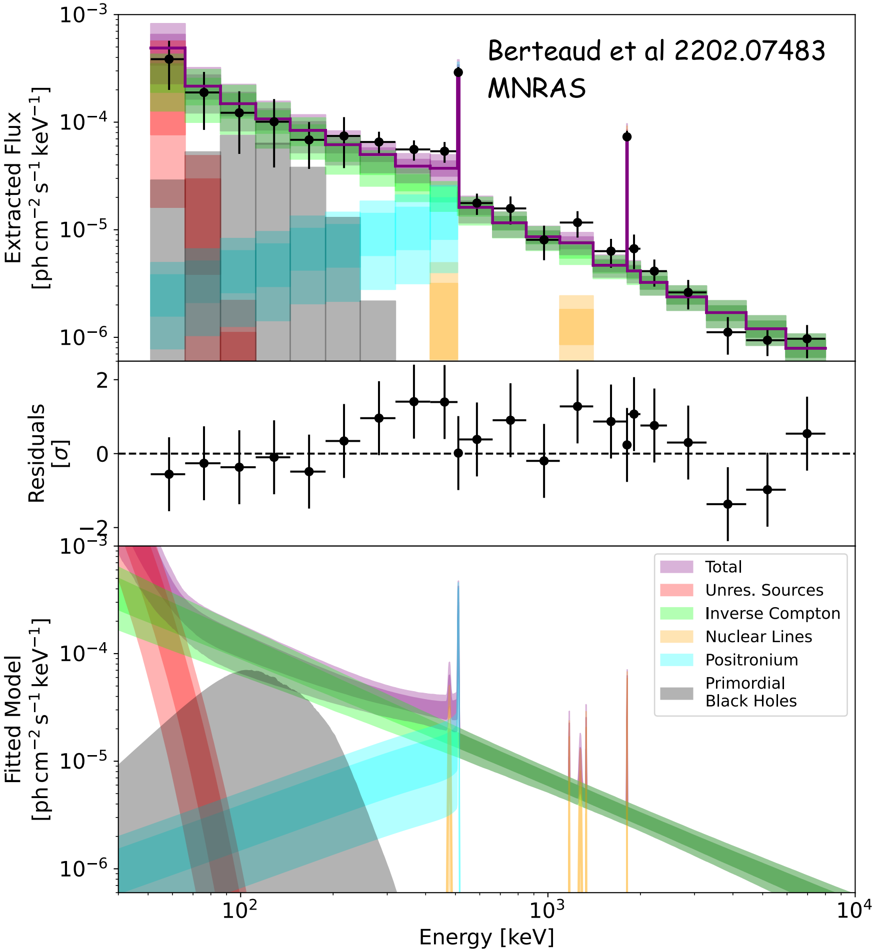
Sensitive between 0.75 to 30 MeV

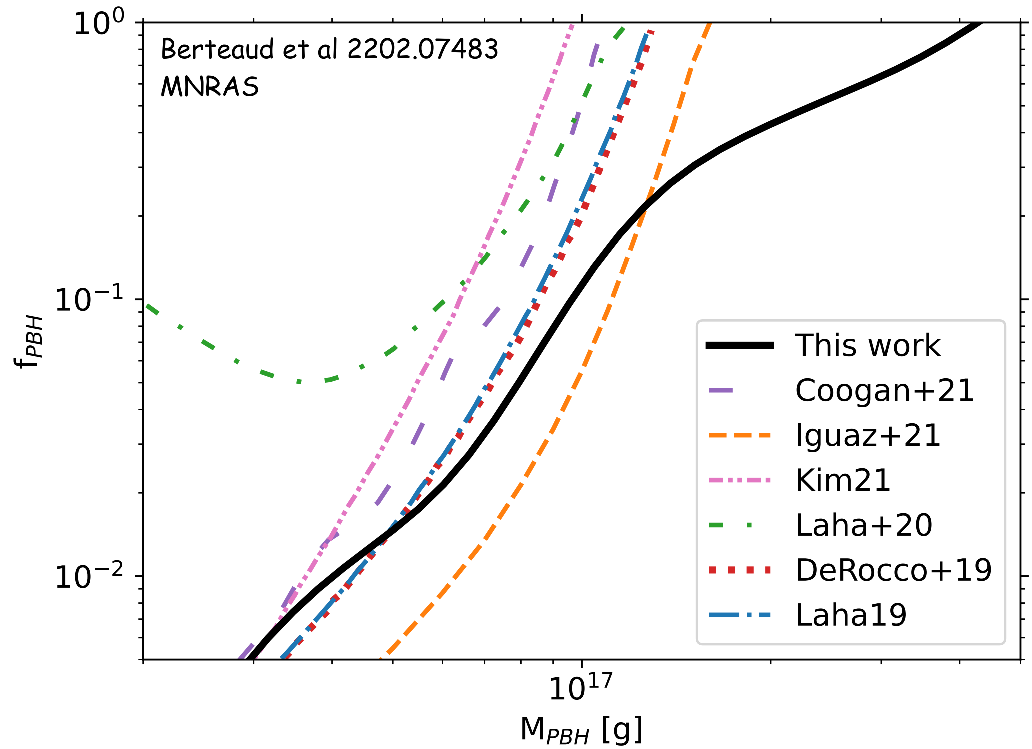




Strong constraints on PBH DM density using archival COMPTEL observations

Constraints on PBH from 16 years of INTEGRAL/ SPI observations



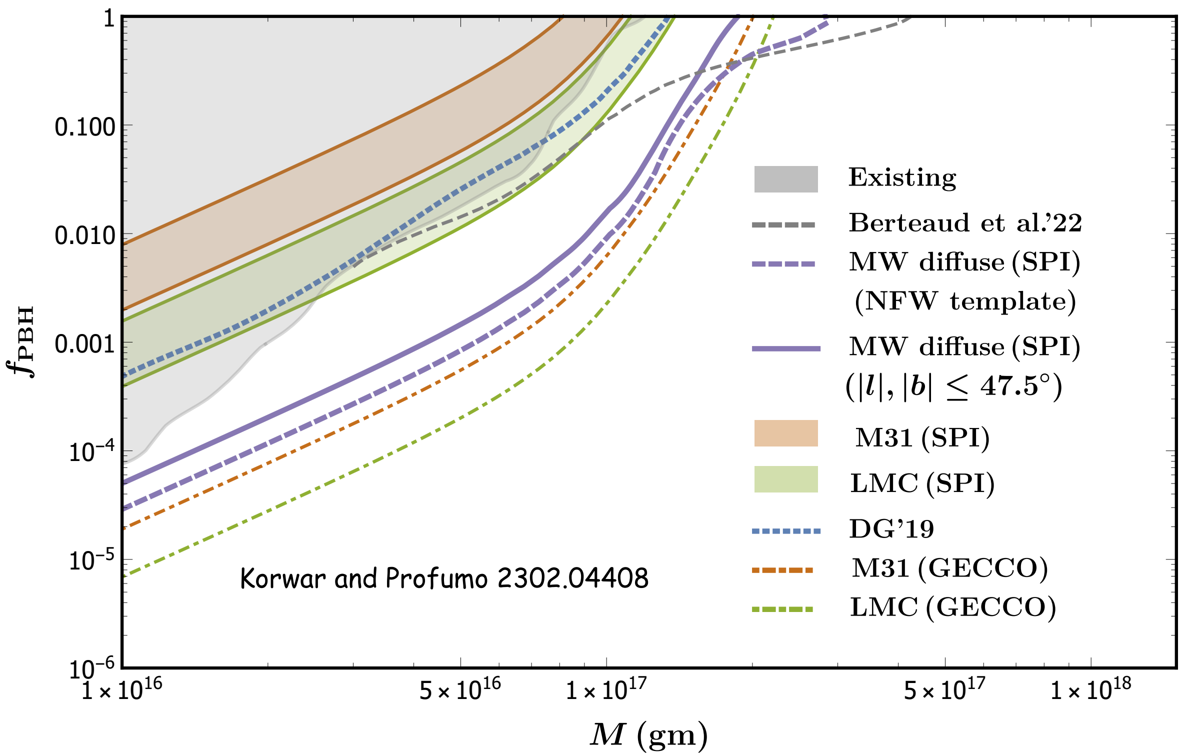


Observation of diffuse soft gamma-rays from the inner galaxy and its fit using various astrophysical components

No excess observed in the entire energy range

Strong constraints on PBH DM density

Constraints on PBH from gamma-ray observations of the Milky Way and LMC



Constraint on PBH DM using various observations of the Milky Way and Large Magellanic Cloud

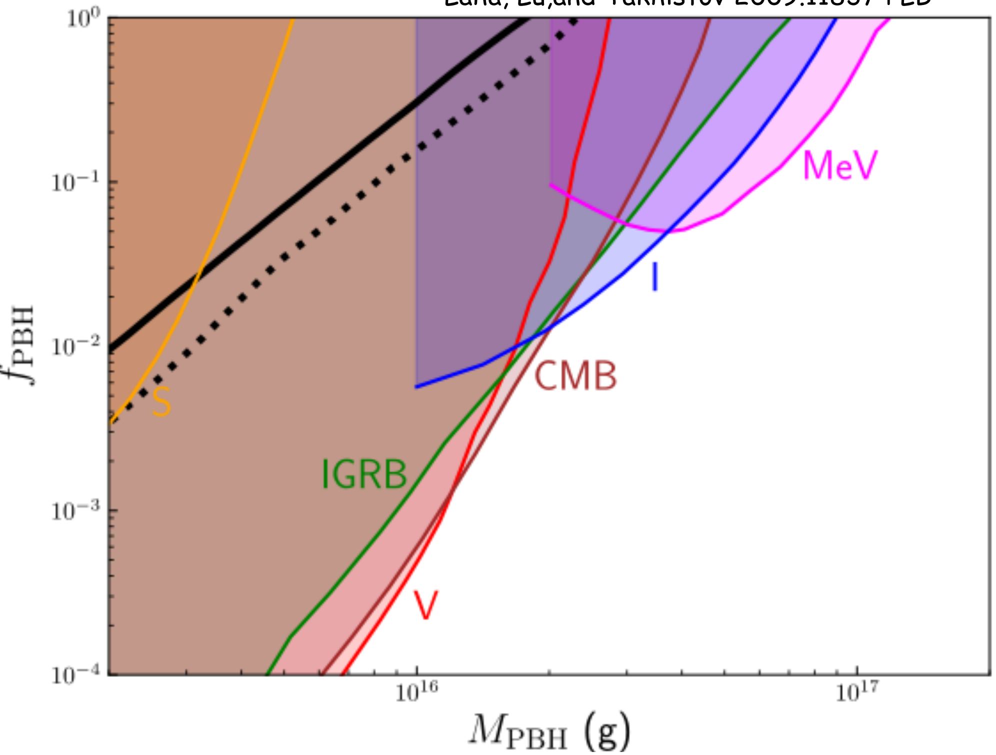
Some other probes of low-mass PBHs

(1) 21 cm measurements: Effect of energy injection due to Hawking radiation (Saha and Laha 2112.10794 PRD, Clark et al., 1803.09390 PRD; Halder and Pandey 2101.05228; Mittal et al. 2107.02190 JCAP)

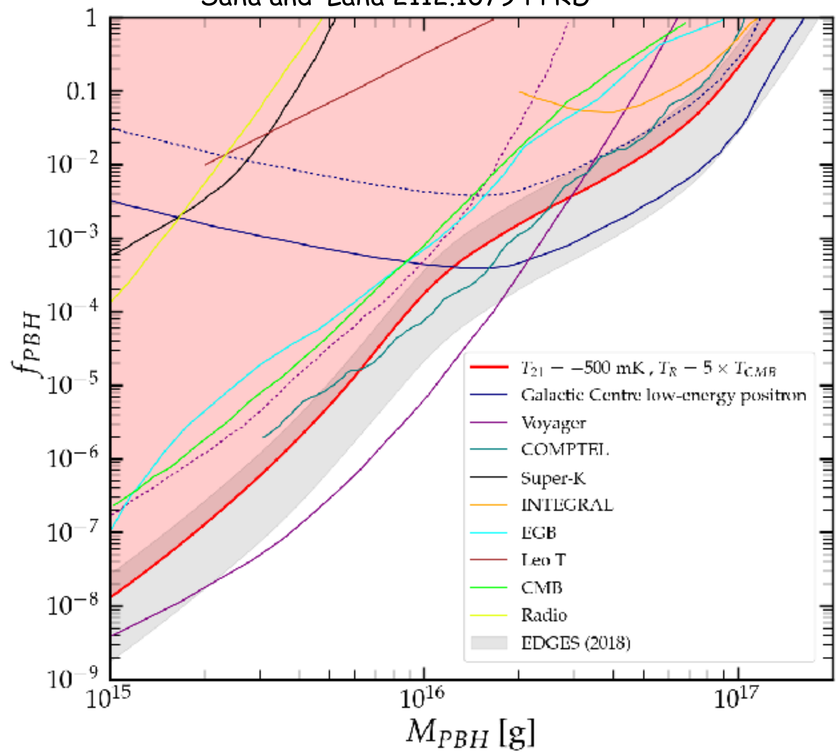
(2) Leo-T: gas heating (Kim 2007.07739; Laha, Lu,and Takhistov 2009.11837 PLB)

(3) Radio observations: synchrotron or inverse Compton energy losses of $e^{\pm}$ from PBH evaporation can be observed via radio telescopes (Chan and Lee 2007.05677 MNRAS; Dutta, Kar, and Strigari 2010.05977)

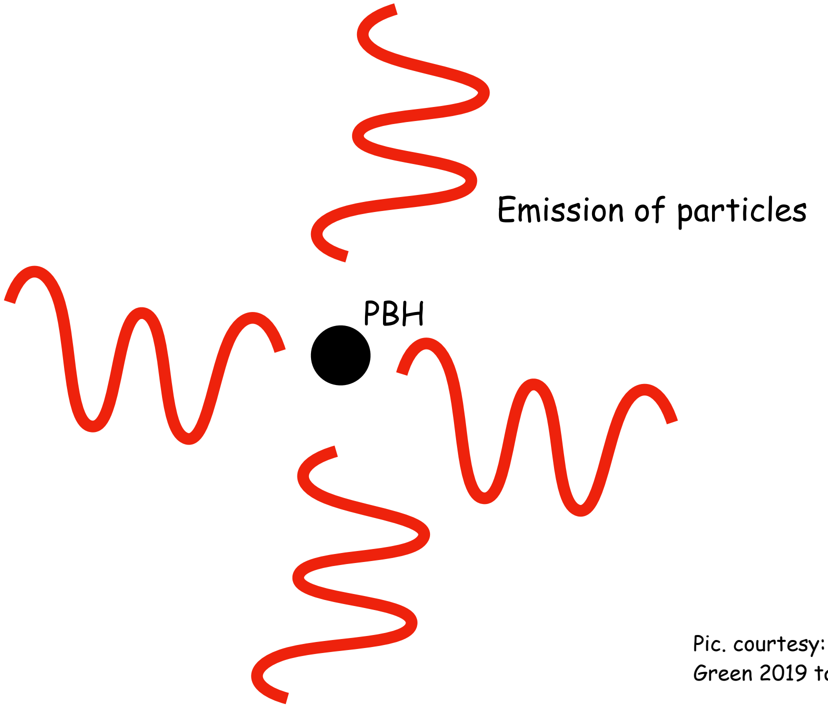
Laha, Lu,and Takhistov 2009.11837 PLB



Saha and Laha 2112.10794 PRD

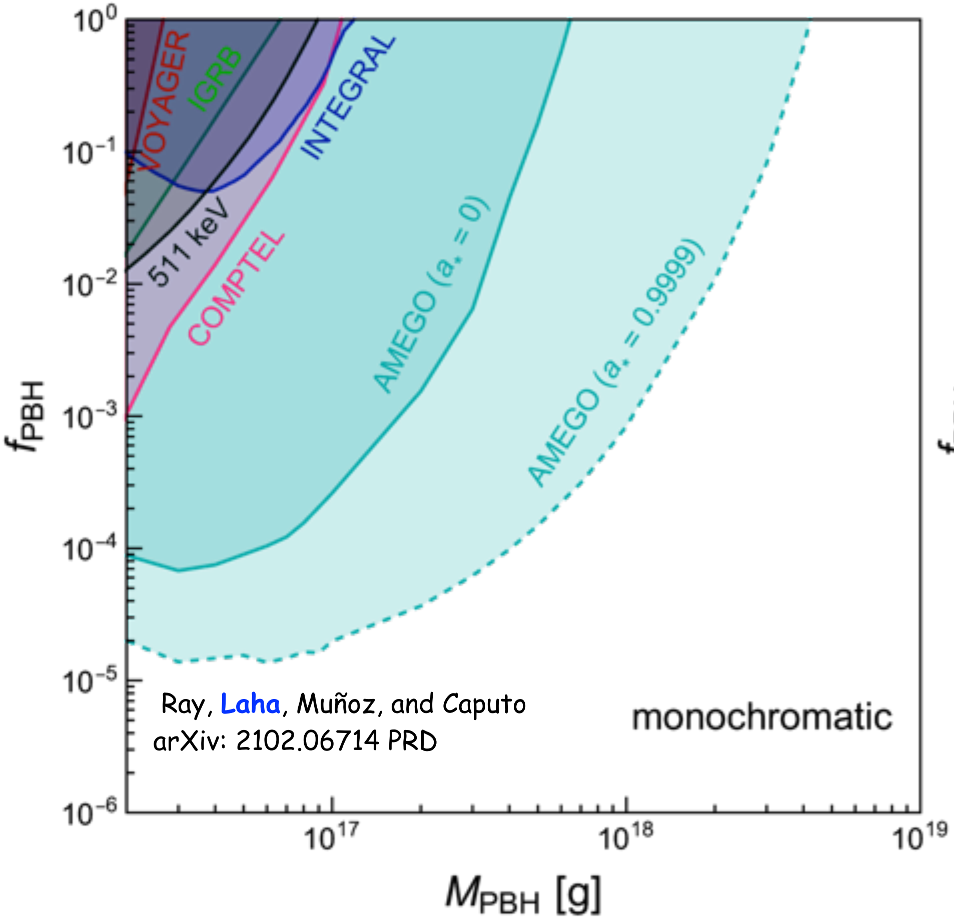


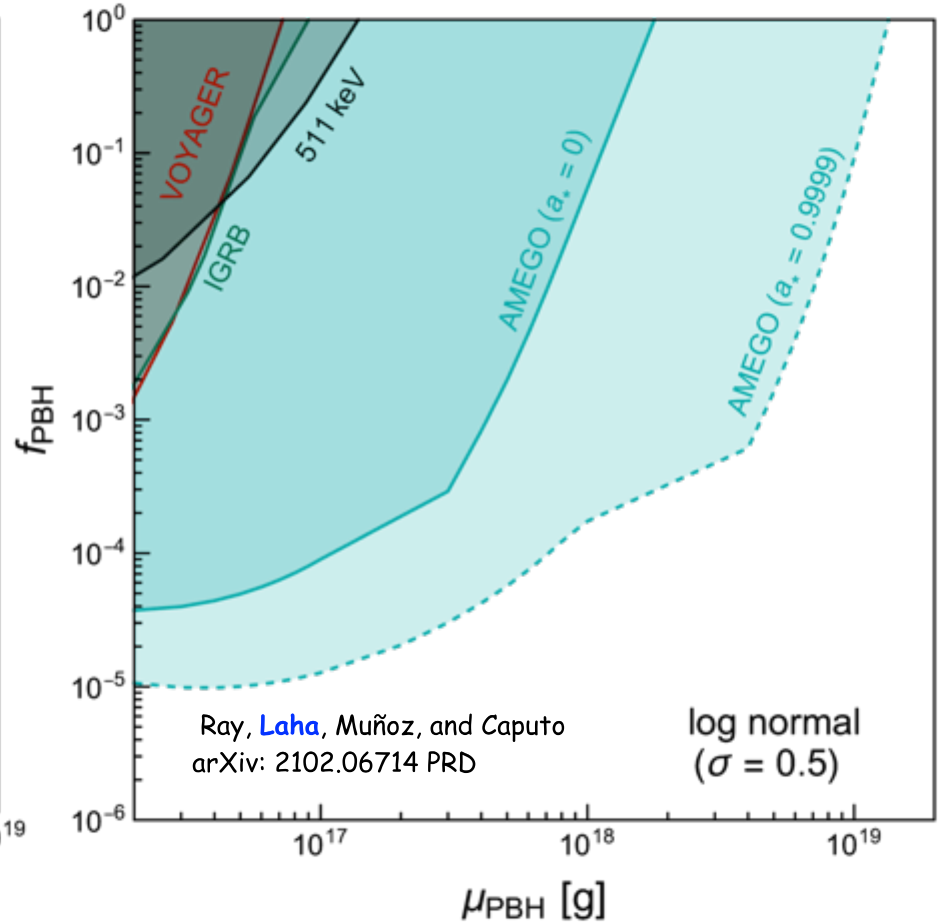
Primordial black holes discovery prospects from evaporation



Pic. courtesy:
Green 2019 talk

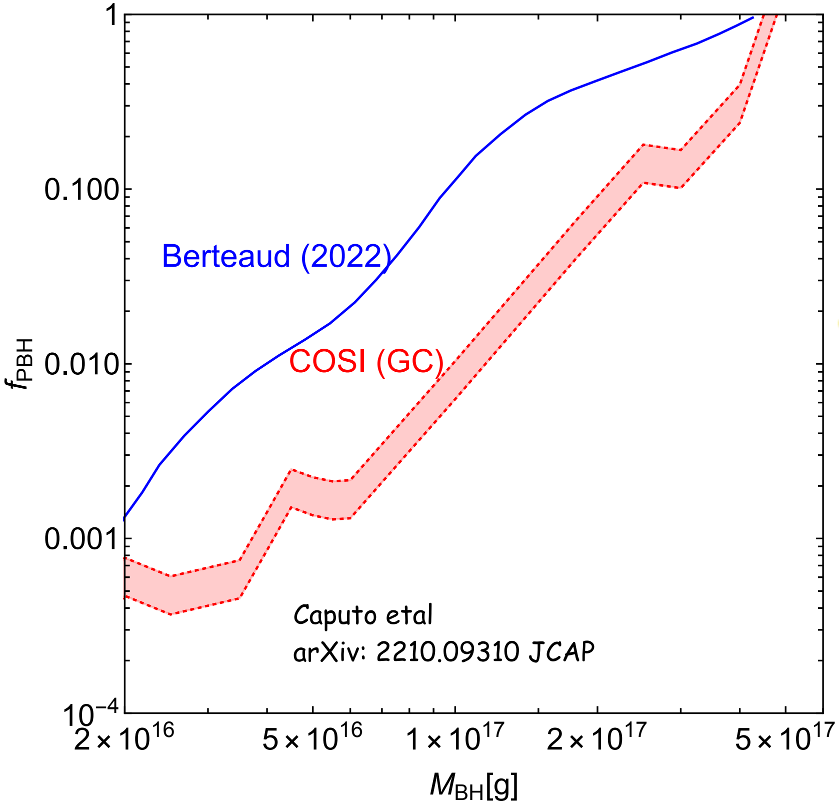
Projections in PBH parameter space using an AMEGO-like experiment

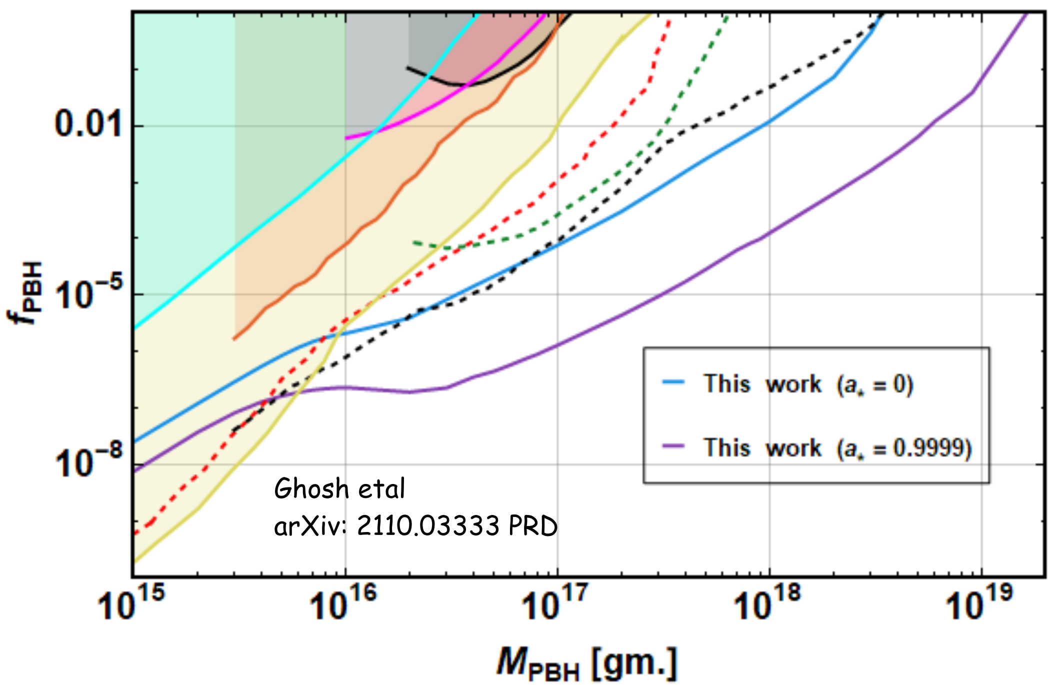




Very promising discovery probe for PBH DM

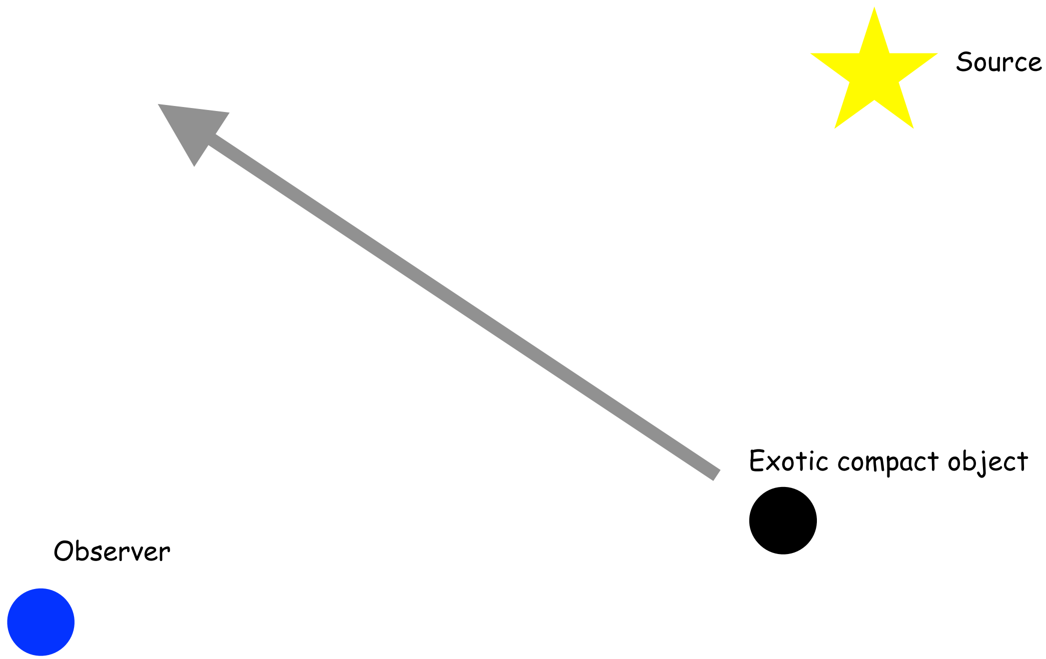
Projections in PBH parameter space using COSI and XGIS-THESEUS





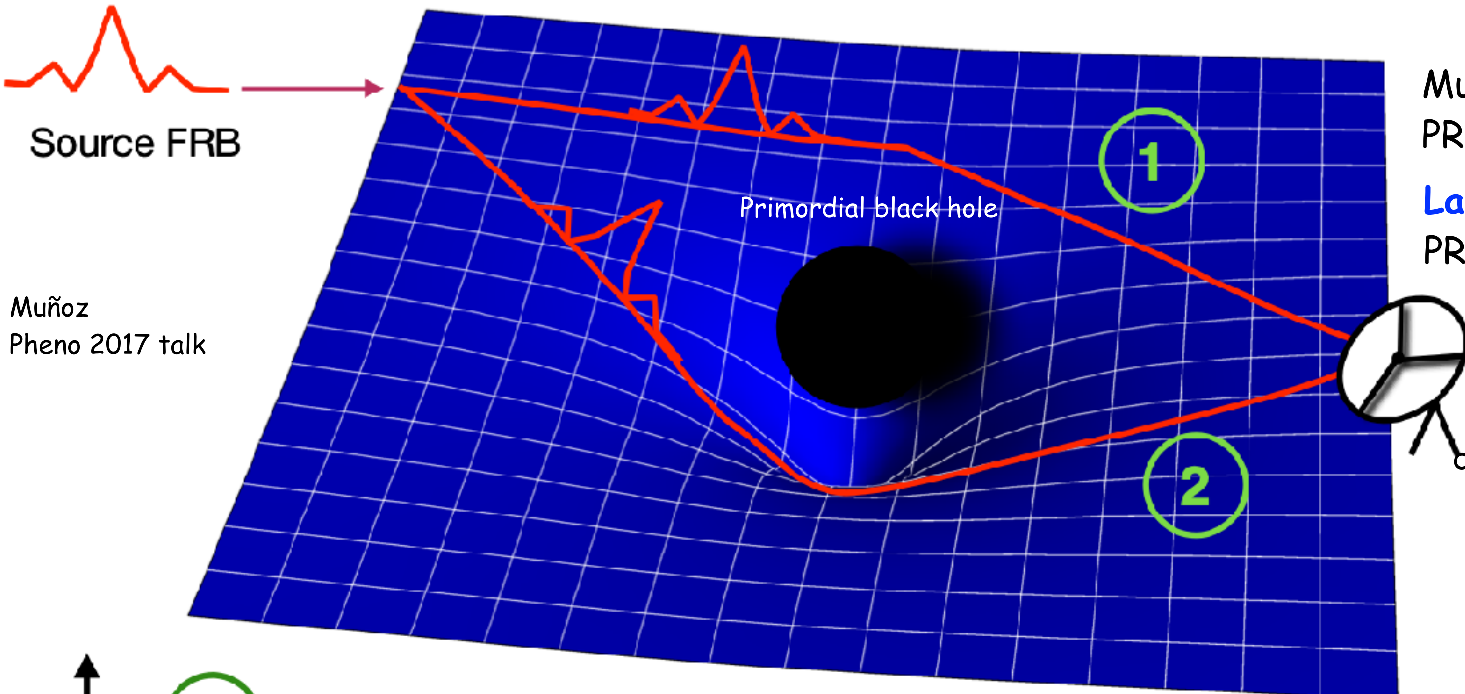
Very promising discovery probe for PBH DM

Primordial black holes constraints from lensing



Pic. courtesy:
Green 2019 talk

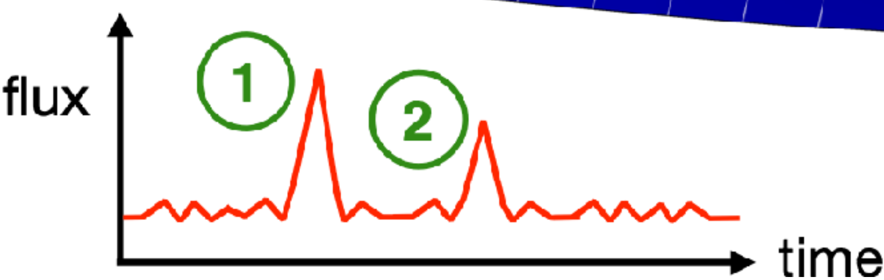
Lensing of fast radio bursts (FRBs)



Muñoz etal., 1605.00008
PRL

Laha 1812.11810
PRD

Muñoz
Pheno 2017 talk



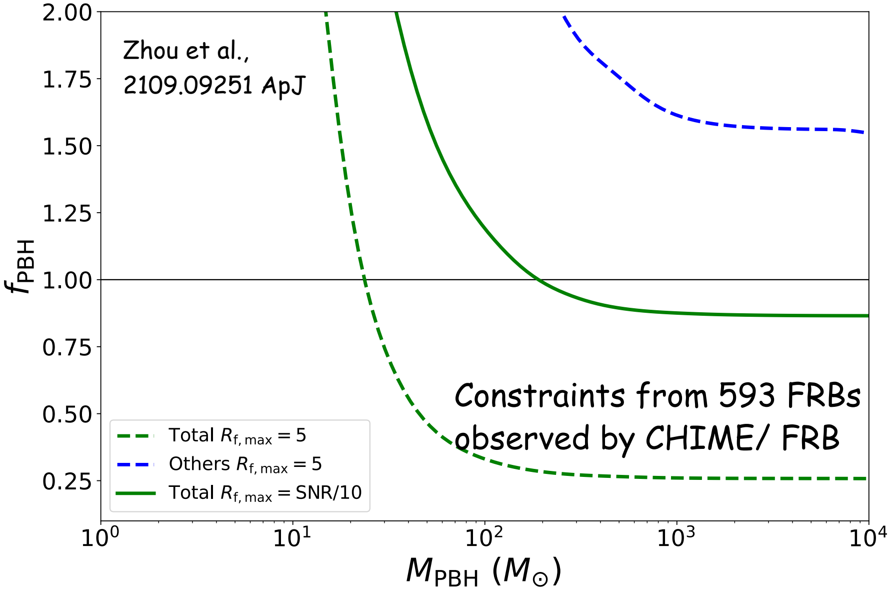
Two images of the original burst

Depending on the lensing parameters
(i) the images might be temporally separated and
(ii) the images need to be magnified enough to be detectable

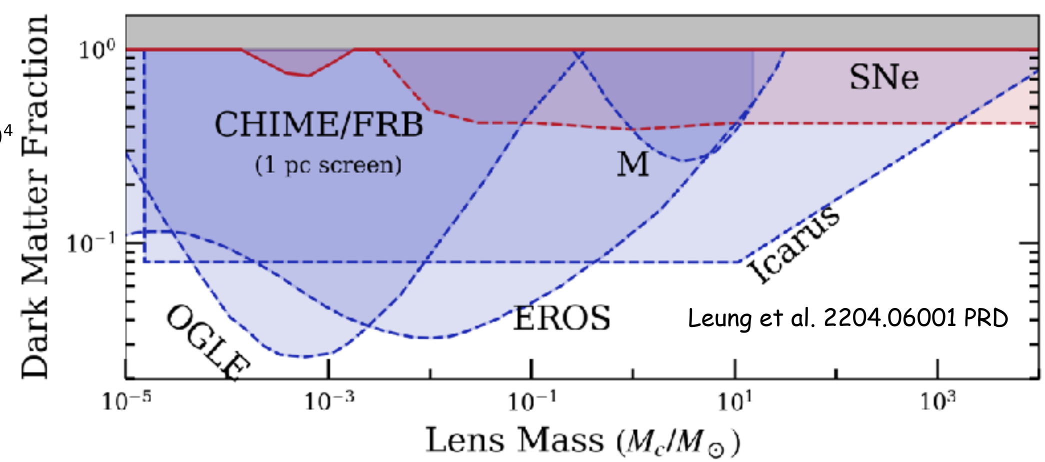
Aim to lens the main burst and the mini-bursts

Constraints from lensing of observed fast radio bursts

- Multiple authors have studied lensing of FRBs to constrain PBH dark matter (Sammons et al. 2002.12533 ApJ, Zhou et al. 2103.08510 MNRAS, Sammons et al. 2210.09487 MNRAS, Zhou et al. 2311.15848)



- CHIME/ FRB collaboration used an interferometric method to search for lensed FRB in the time-domain and achieved sensitivity to sub-solar mass PBHs (Leung et al. 2204.06001)

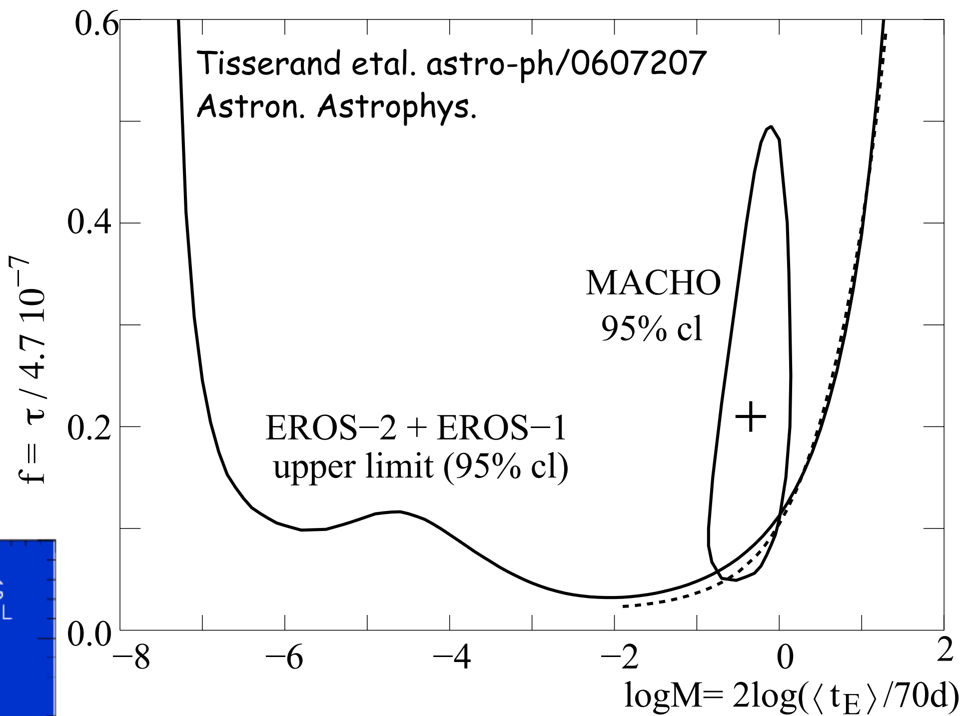


- There has been investigations about capabilities of current/ near-future radio telescopes to probe lensed FRBs (Ho et al. 2304.04990 ApJ, Leung et al. 2204.06001 PRD)

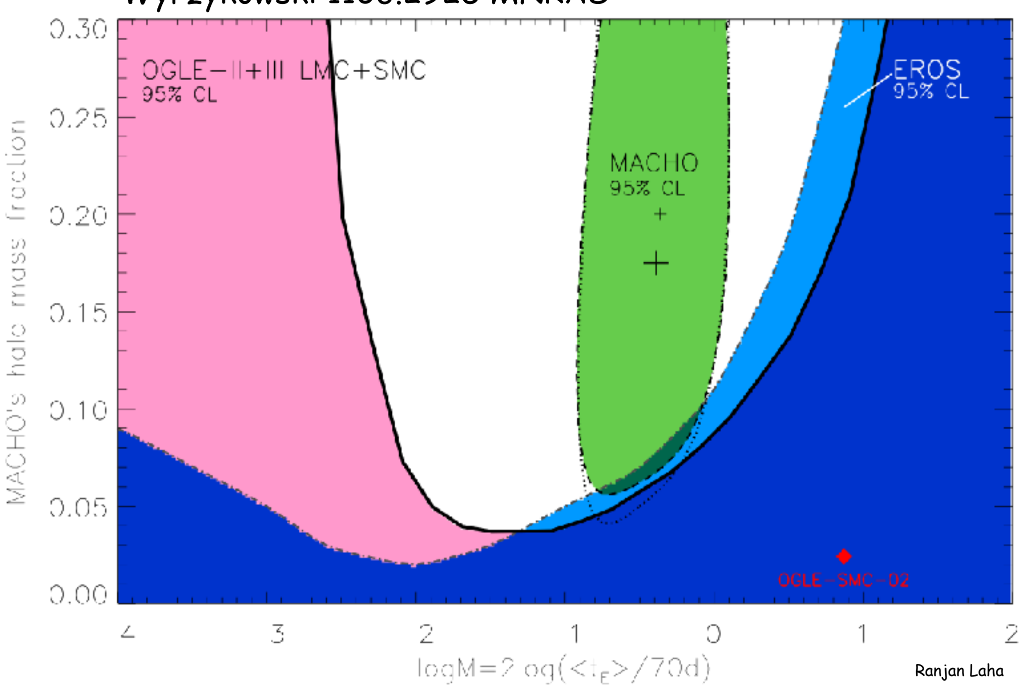
Constraints from microlensing of stars in the Magellanic Clouds

Various collaborations have observed microlensing of stars in the Magellanic Clouds in order to discover massive astrophysical compact halo objects

(Tisserand etal. astro-ph/0607207 A&A,
Wyrzykowski 1106.2925 MNRAS,
Alcock etal. astro-ph/0011506 ApJL)



Wyrzykowski 1106.2925 MNRAS

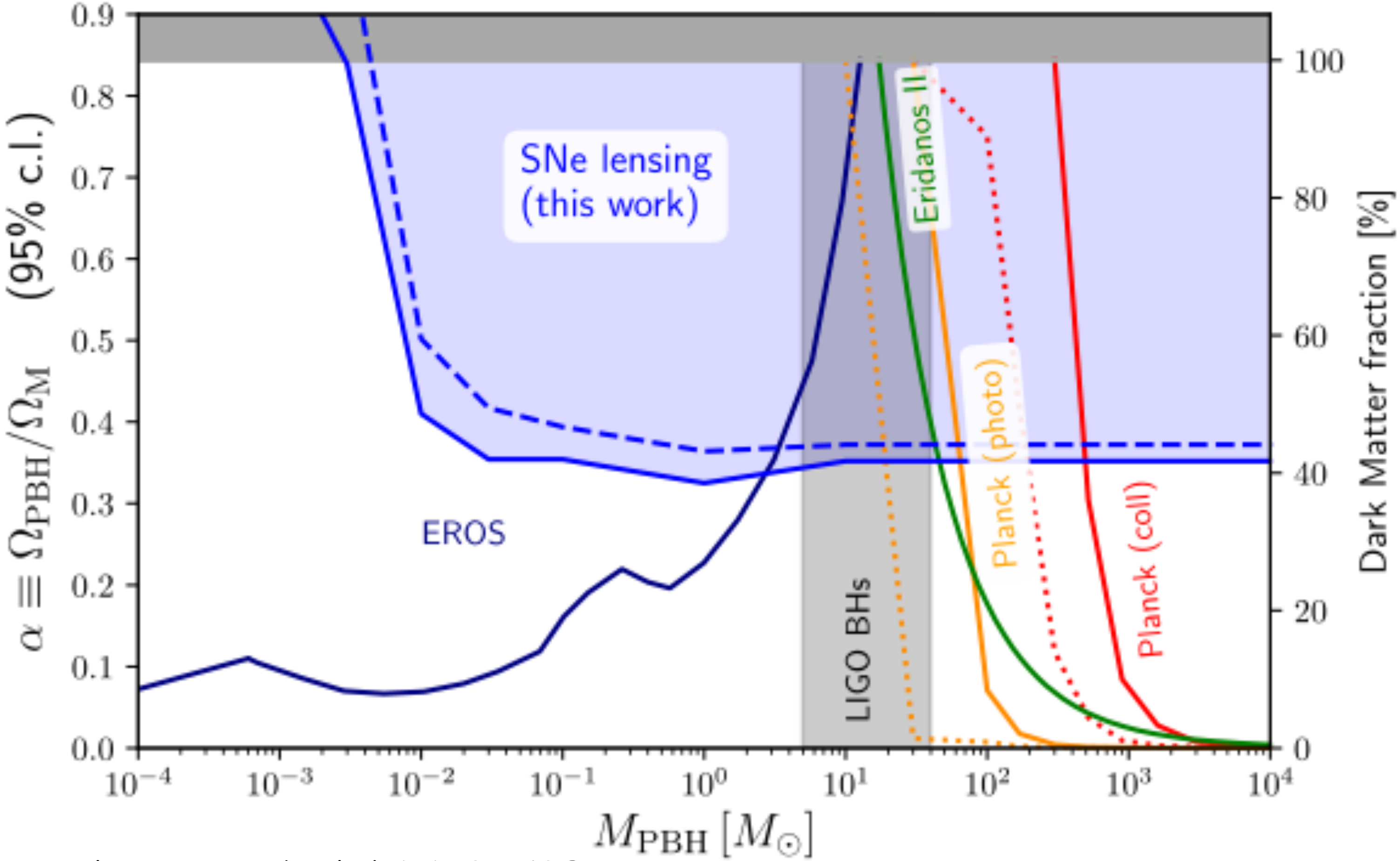


Final results from OGLE-II + III data for Large and Small Magellanic Clouds

Constraint from supernova lensing

Gravitational lensing of type Ia supernova can be used to constrain compact objects near the line of sight

Some caveats regarding these constraints were also put forward in the literature
(Garcia-Bellido, Cleese, and Fleury 1712.06574 Phys. Dark Univ., Bosca et al., 2205.00991 JCAP)

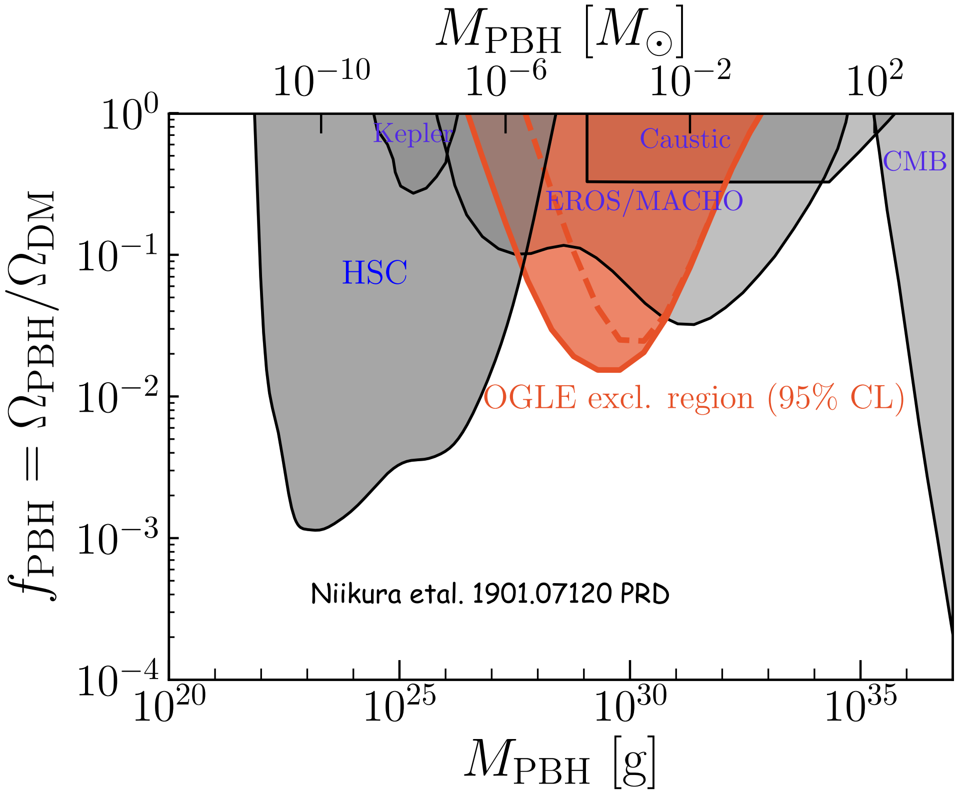


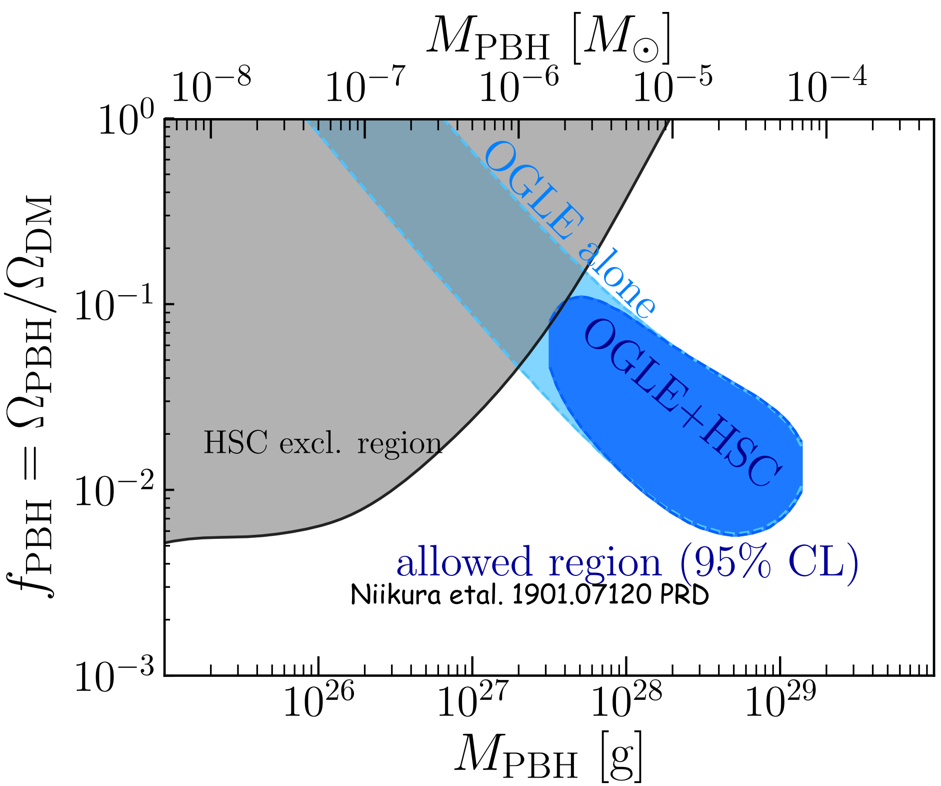
See earlier study in Metcalf and Silk astro-ph/0612253 PRL

Zumalacarregui and Seljak 1712.02240 PRL

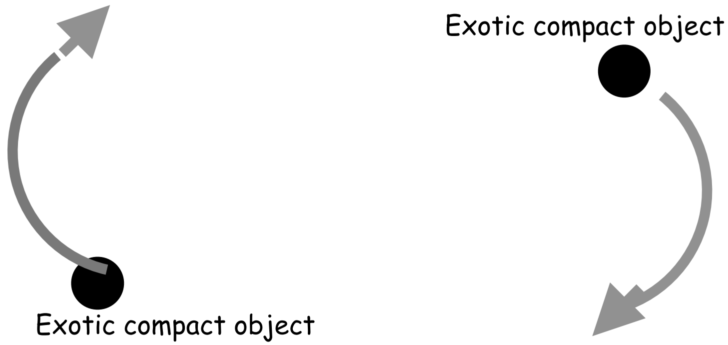
Constraints from microlensing of stars in M31 and Galactic bulge

- Microlensing of stars in M31 can constrain low-mass compact objects (Niikura etal. 1701.02151 Nat. Astron., Montero-Camacho etal. 1906.05950 JCAP, Katz etal. 1807.11495 JCAP, and Smyth etal. 1910.01285)
- Important to take into account the finite size of the source and wave optics effect
- Observation of microlensing of stars in the Galactic bulge by OGLE 5-year data-set can constrain PBHs; it has also discovered intriguing events: either exotic compact objects or free-floating planets (Niikura etal. 1901.07120 PRD)





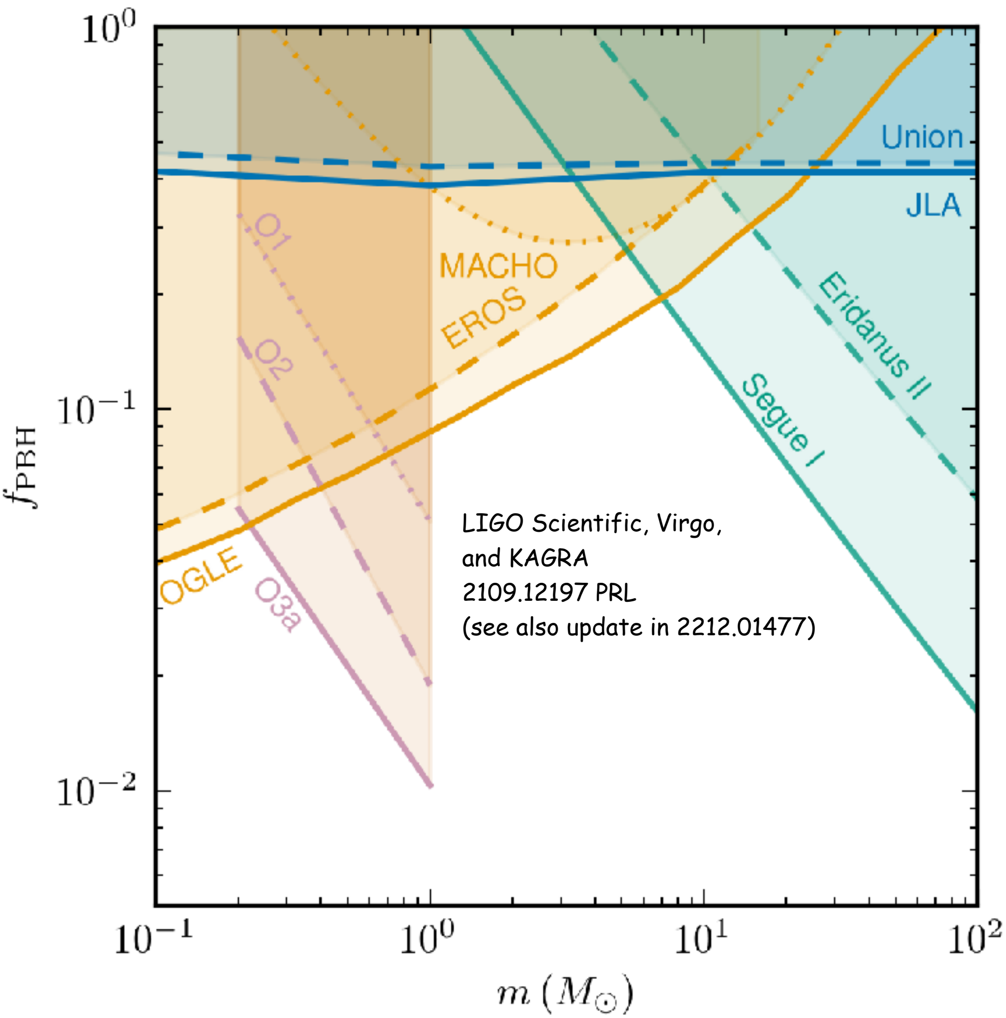
Primordial black holes constraints from gravitational waves



Pic. courtesy:
Green 2019 talk

Constraints from gravitational waves

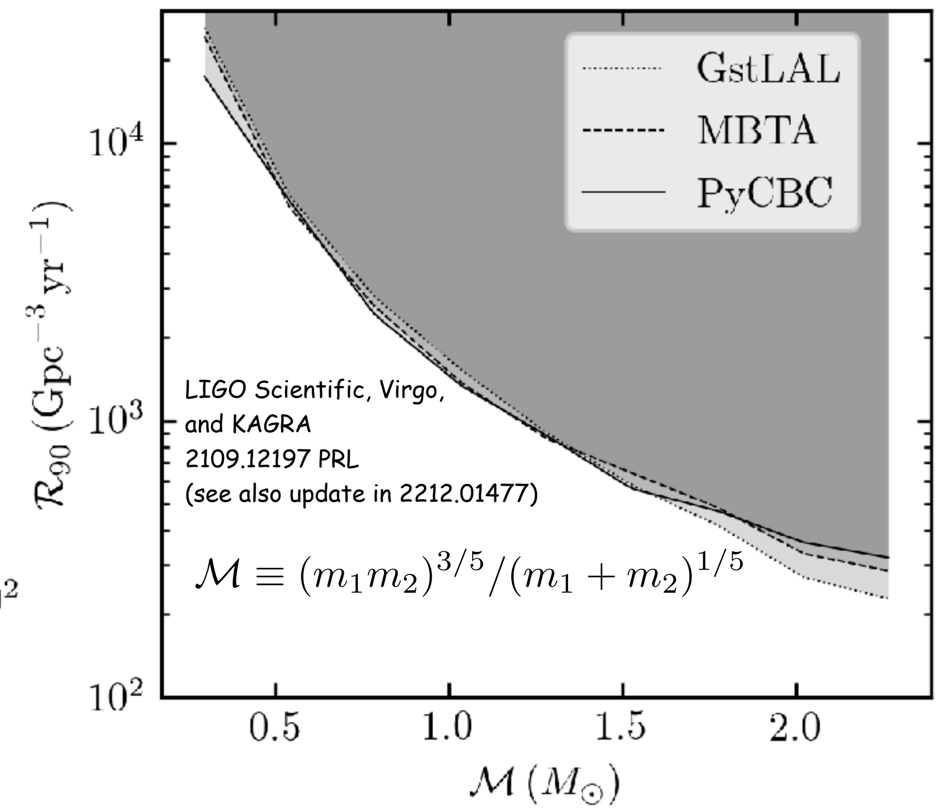
- Gravitational waves from sub-solar ultracompact binaries can be detected by the LIGO Scientific, Virgo and KAGRA collaboration



- Independent analysis of the data carried out by Nitz and Wang:

2007.03583 PRL
2102.00868 ApJ
2106.08979 PRL
2202.11024 PRD

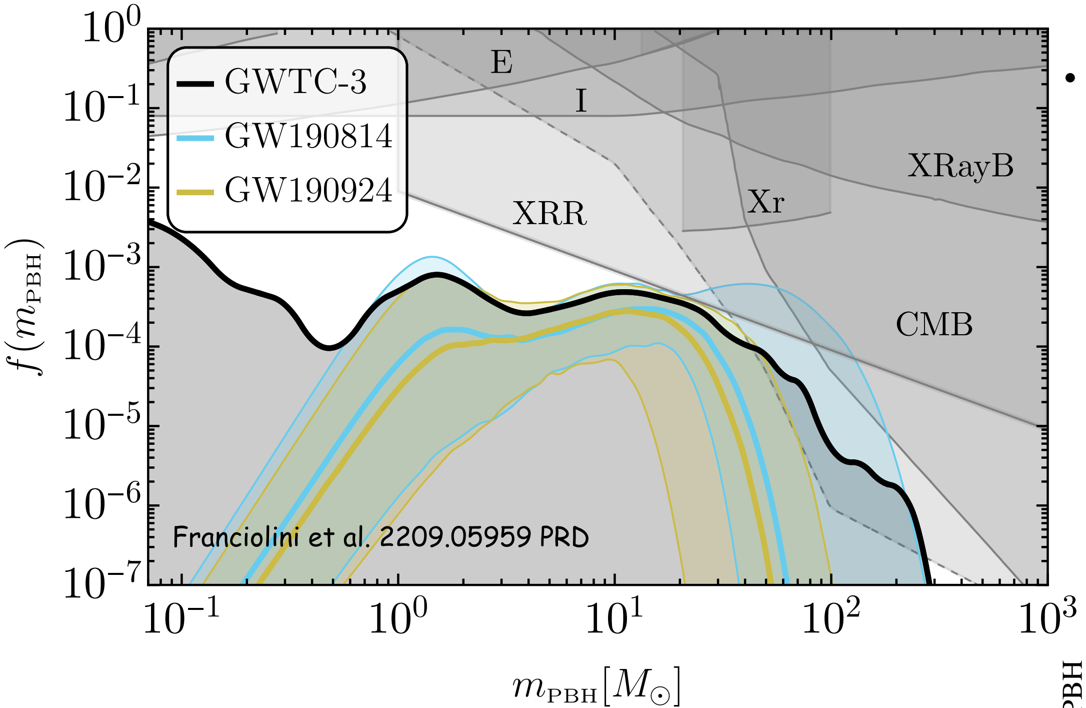
$\mathcal{R}_{90}$ = 90% C.L. upper limit on the merger rate



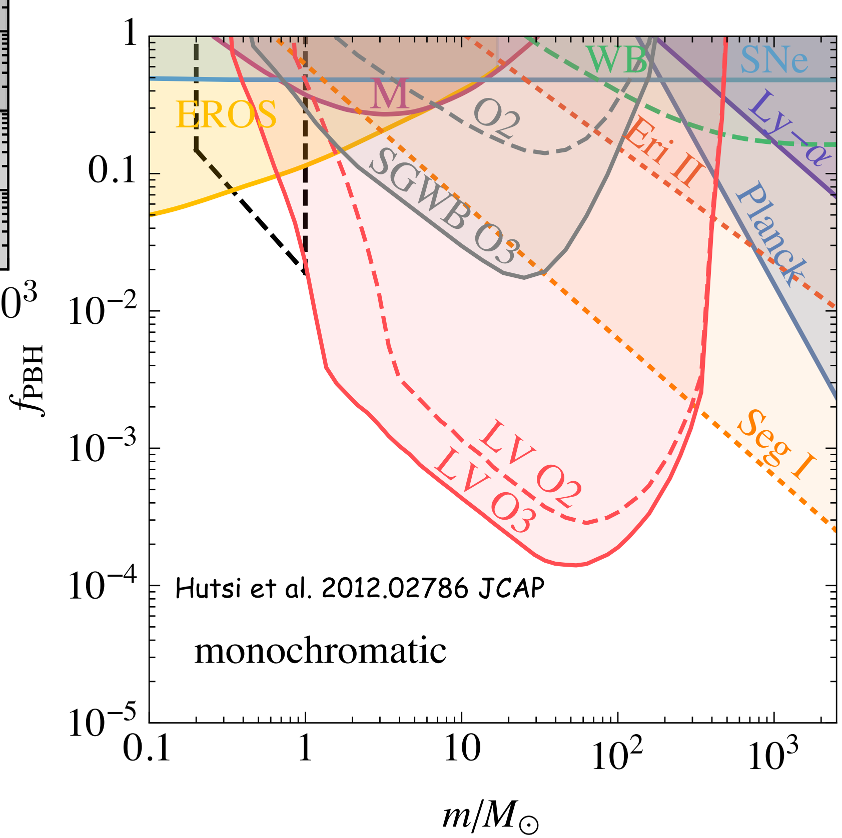
Earlier studies in
LIGO Scientific and Virgo 1808.04771 PRL, Magee etal. 1808.04772 PRD, LIGO Scientific and Virgo 1904.08976 PRL

Constraints from gravitational waves

- Constraint from non-observation of the stochastic gravitational wave background and from binary black hole mergers

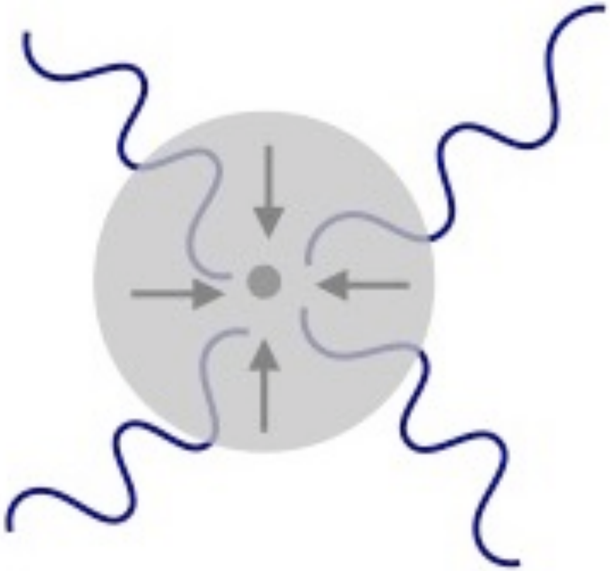


- PBHs do not make up the majority of dark matter in the mass range being probed by current gravitational wave observatories



See
Bird etal. 1603.00464 PRL
Sasaki etal. 1603.08338 PRL
Raidal, Spethmann, Vaskonen, and Veermae 1812.01930 JCAP
Kavanagh, Gaggero, and Bertone 1805.09034 PRD
Raidal, Vaskonen, and Veermae 1707.01480 JCAP and many others

Primordial black holes constraints from accretion



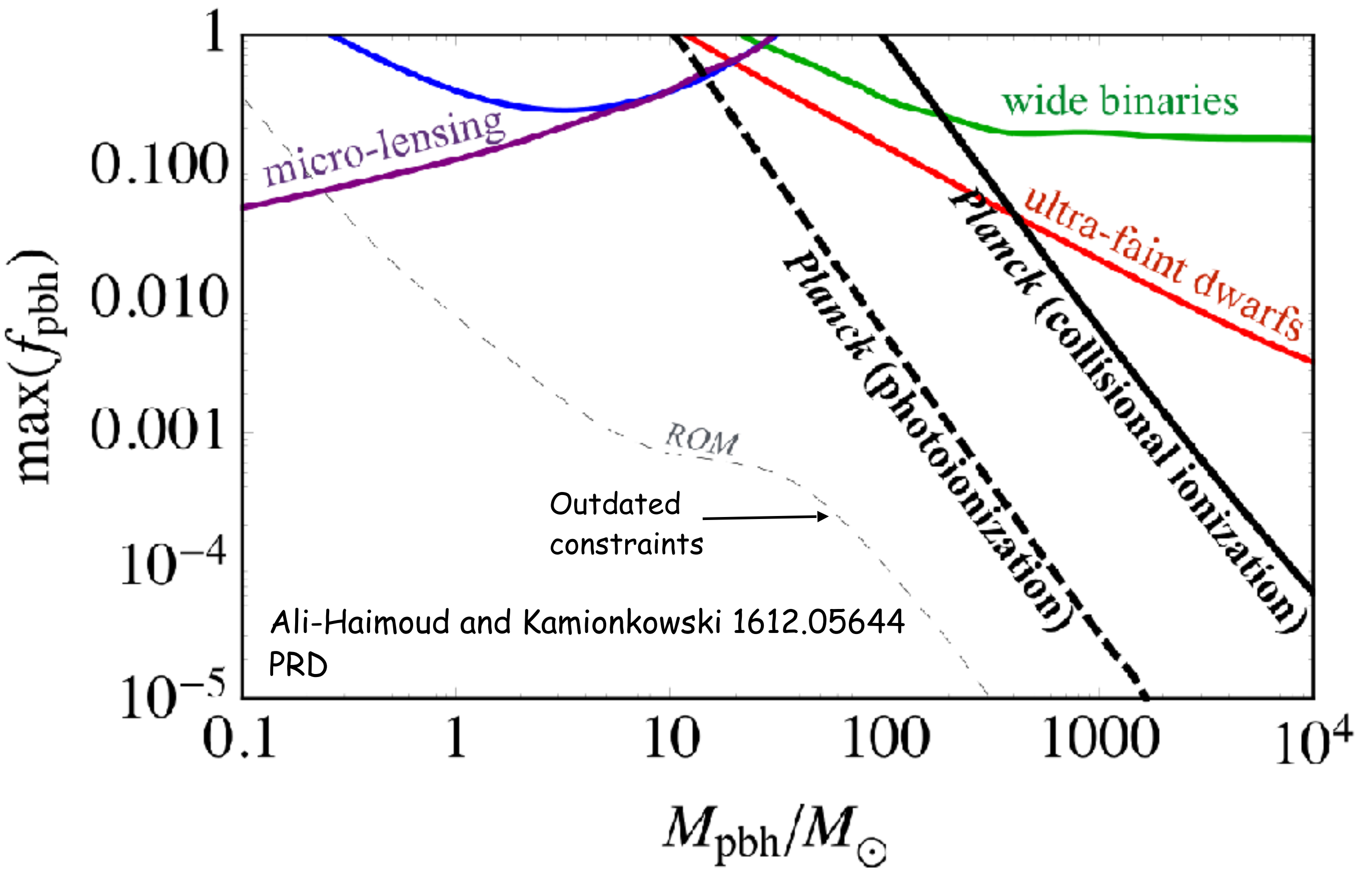
Pic. courtesy:
Green 2019 talk

Constraint from cosmic microwave background

Accretion of primordial gas on PBHs leads to emission of photons which can be detected via cosmic microwave background

Significant uncertainties in accretion

"Collisional ionization": radiation from the PBH does not ionize the local gas



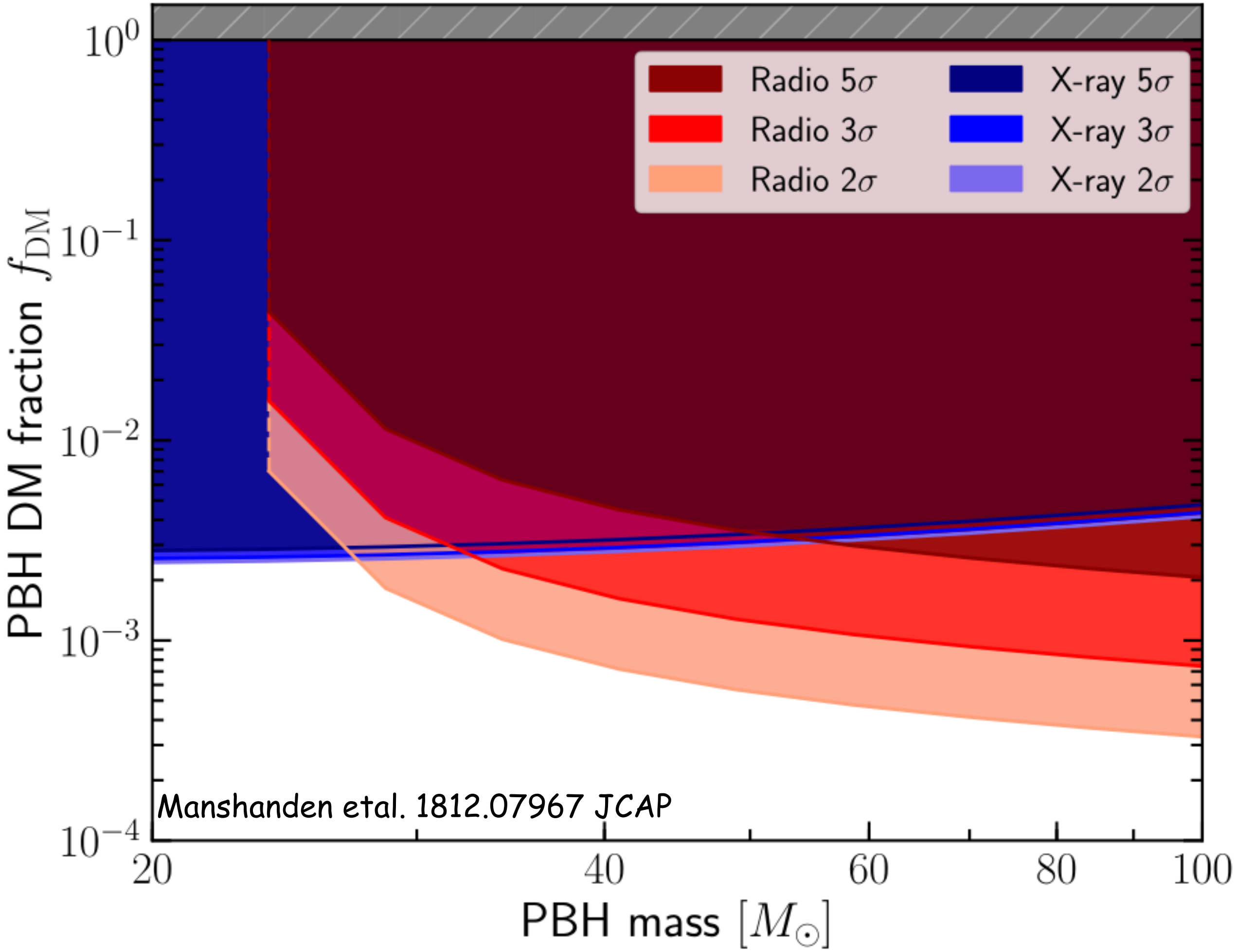
"Photoionization": local gas is ionized due to the PBH radiation

Other related works: Horowitz 1612.07264
Aloni, Blum and Flauger 1612.06811 JCAP
Poulin etal. 1707.04206 PRD
Abe, Tashiro, and Tanaka 1901.06089 PRD
Nakama, Carr, and Silk 1710.06945 PRD
Serpico et al. 2002.10771 PRR
Piga et al. 2210.14934 JCAP
Facchinetti etal. 2212.07969 PRD

Constraint from X-ray and radio point sources

Accretion of interstellar gas on PBHs leads to emission of photons which can be detected as point sources in the X-ray and radio sky

Significant uncertainties in accretion



These type of constraints have been disputed Hektor, Hutsi, and Raidal 1805.06513 AA

Other related works:
Gaggero etal. 1612.00457 PRL
Inoue and Kusenko 1705.00791 JCAP
Lu et al., 2007.02213 ApJL
Takhistov et al., 2111.08699 MNRAS L

Exploding primordial black holes

Exploding primordial black holes

- An interesting phenomenology of primordial black holes is detecting these exotic objects at or near the moment of its disappearance due to Hawking radiation

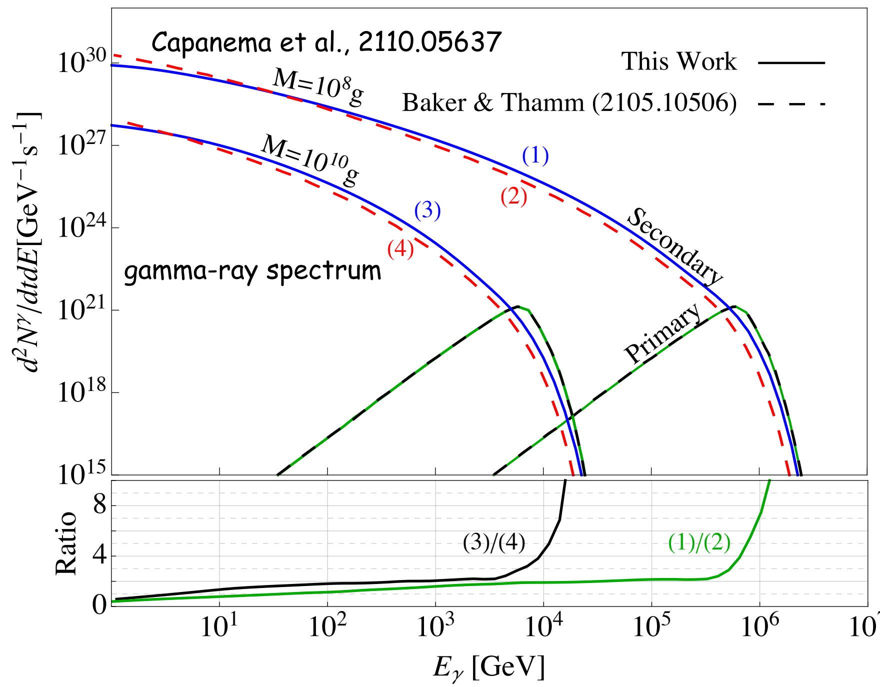
- These primordial black holes will not contribute to the dark matter content of the Universe; instead these results can be used to test various early Universe cosmology models: these primordial black holes have an initial mass $\lesssim (5-6) \times 10^{14}\,\mathrm{g}$

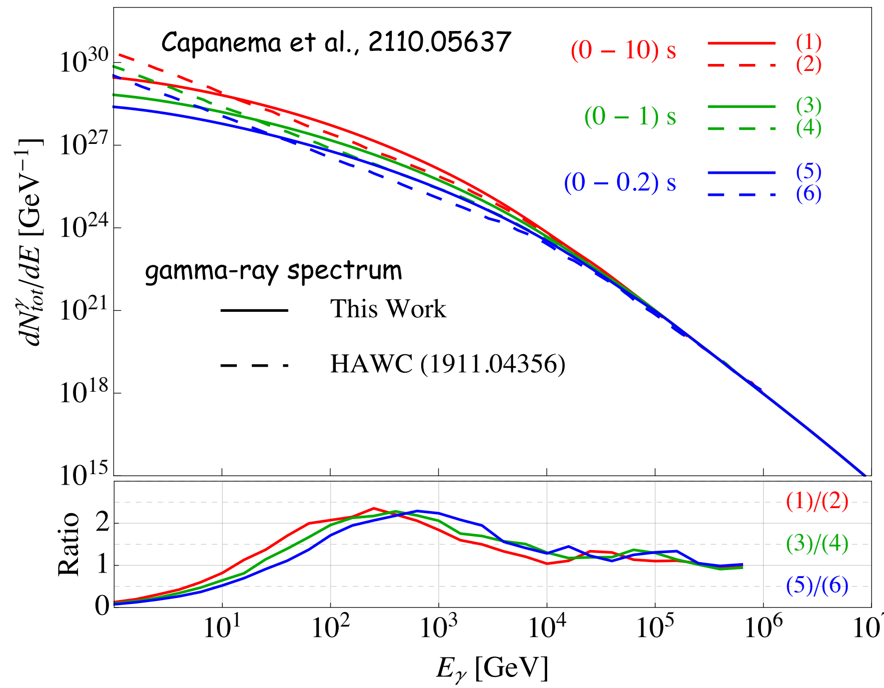
- As the black hole Hawking evaporates, its mass decreases and it produces very high energy particles for a short duration which can be detected: a brief and bright flash before disappearance

- Searches are typically sensitive to exploding primordial black holes which are located very close: $d_{\mathrm{L}} \lesssim 10^{-4}\,\mathrm{pc}$

- Dedicated searches conducted by Fermi-LAT (arXiv: 1802.00100), VERITAS (arXiv: 1709.00307), Milagro (arXiv: 1407.1686), HAWC (arXiv: 1911.04365), and HESS (arXiv: 1909.01620)

Exploding primordial black holes



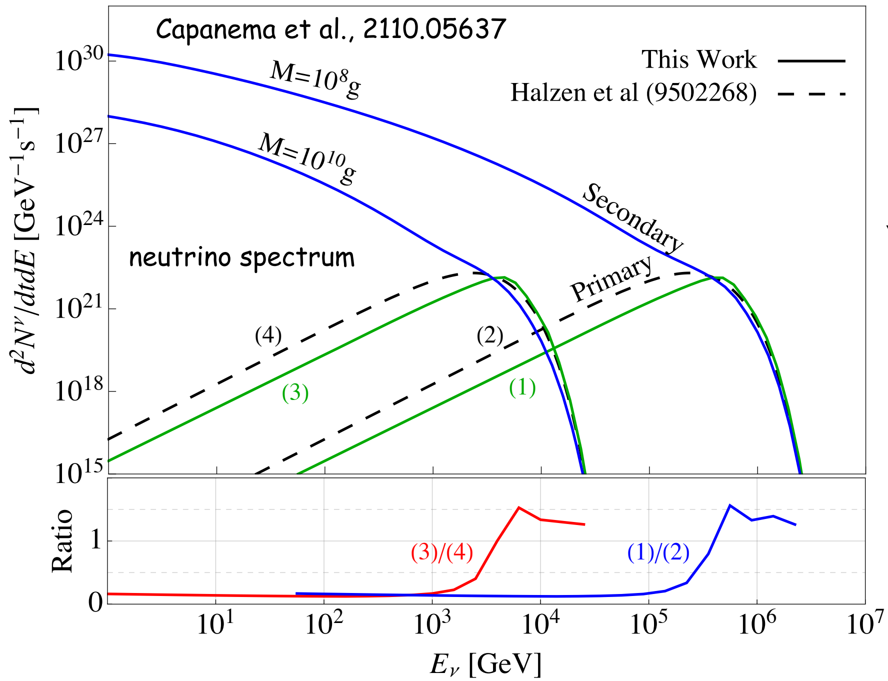


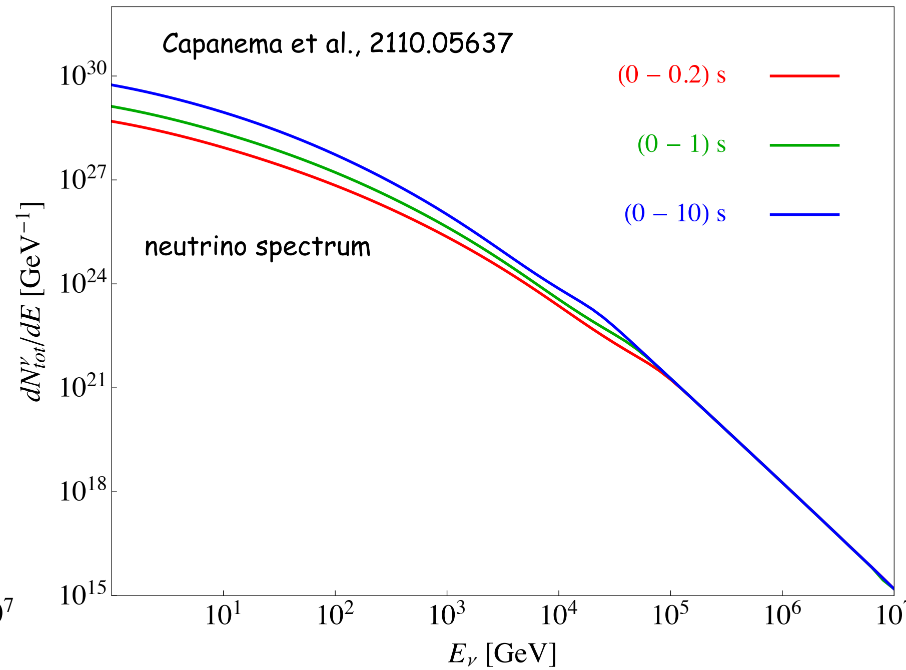
$$10^8\,\mathrm{g} \equiv 4 \times 10^{-4}\,\mathrm{sec\ before\ disappearance}$$

$$10^{10}\,\mathrm{g} \equiv 400\,\mathrm{sec\ before\ disappearance}$$

- A detailed understanding of hadronisation at high energies is essential to derive the correct spectrum, especially at higher photon or neutrino energies
- These spectrum only include the emission of Standard Model particles

Exploding primordial black holes





$$10^8\,\mathrm{g} \equiv 4 \times 10^{-4}\,\mathrm{sec\ before\ disappearance}$$

$$10^{10}\,\mathrm{g} \equiv 400\,\mathrm{sec\ before\ disappearance}$$

- HAWC data implies the local PBH burst rate density $\dot{\rho}_{\rm max} \lesssim 1200\,\mathrm{pc}^{-3}\,\mathrm{yr}^{-1}$ at 90% C.L.
- IceCube data implies the local PBH burst rate density $\dot{\rho}_{\rm max} \lesssim 4 \times 10^6\,\mathrm{pc}^{-3}\,\mathrm{yr}^{-1}$ at 90% C.L.
- Neutrino limits are important if PBHs are embedded in a dense medium

from Capanema et al., 2110.05637

Conclusions

- Primordial black hole (PBH) is a well motivated dark matter candidate and/ or an early Universe relic
- There are large regions of the parameter space where PBHs can make up the entire dark matter density or a substantial portion of it
- It is important to probe this entire parameter space to as small a cosmic density as possible

Questions & comments:
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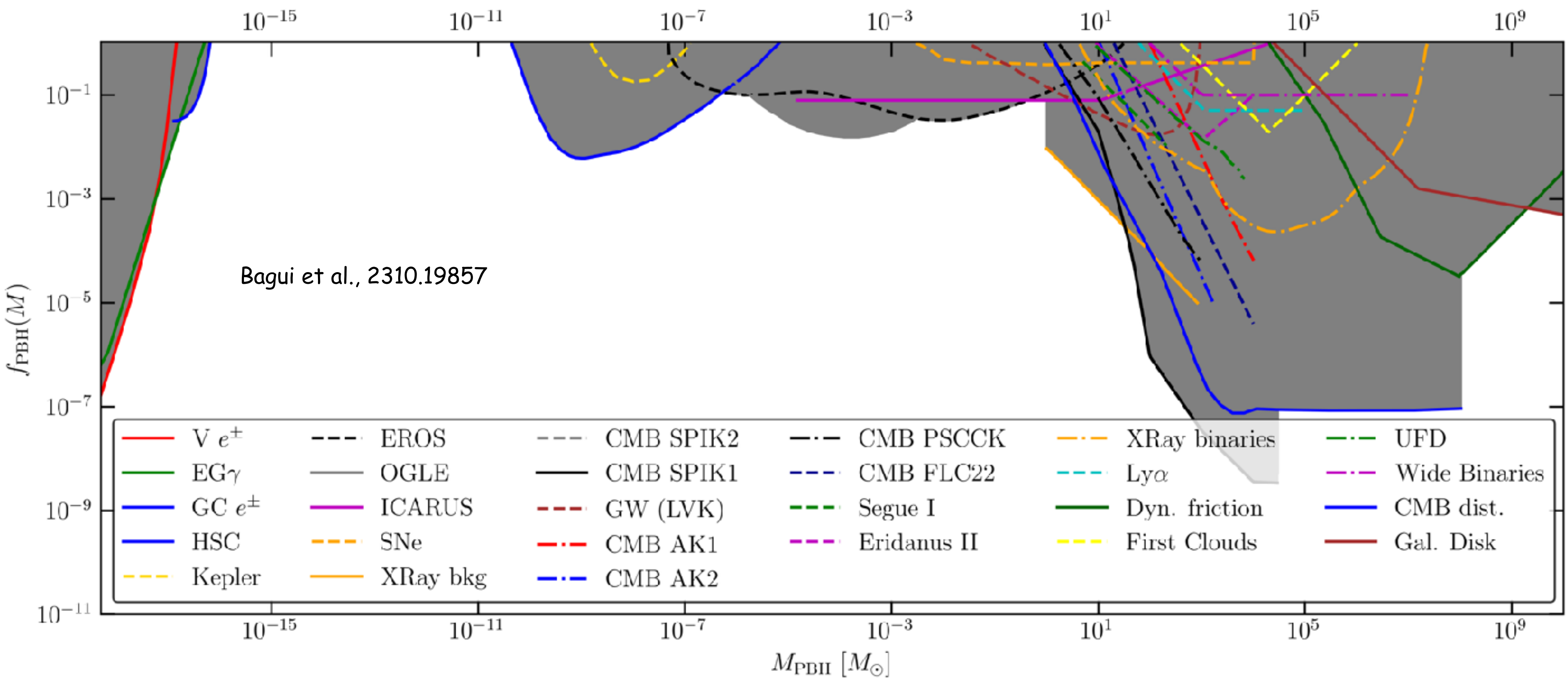


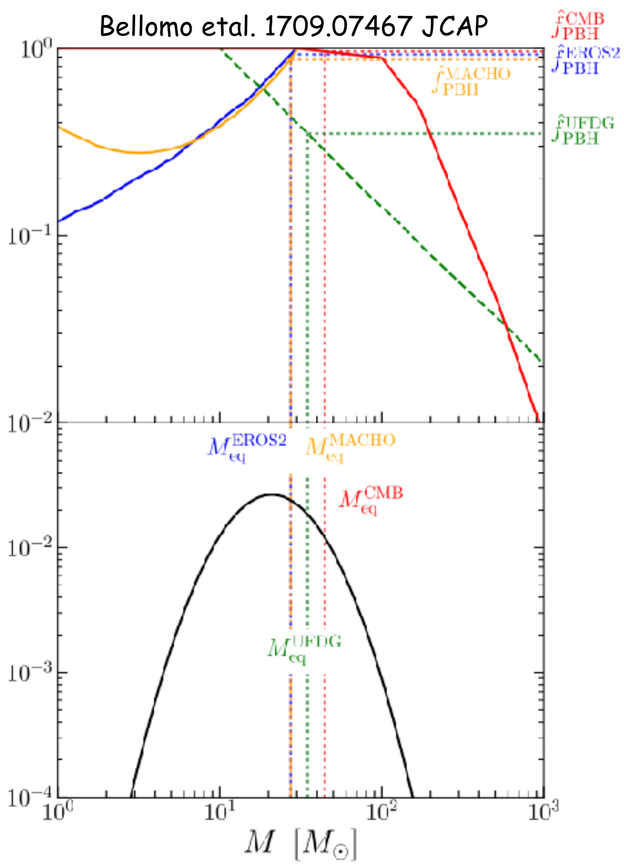
Extended mass functions of primordial black holes

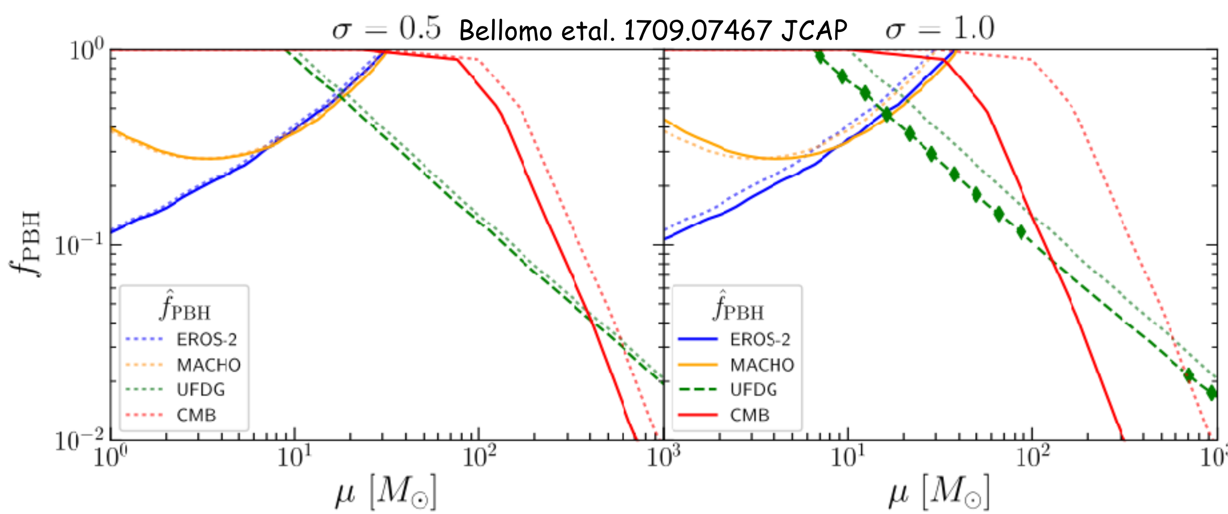
Impact of the primordial black hole mass function

All the constraints presented earlier are for monochromatic mass function of primordial black holes

Many techniques have been proposed in order to convert the monochromatic mass function constraints into constraints on the extended mass functions (Carr etal. 1705.05567 PRD, Green 1609.01143 PRD, Kuhnel & Freese 1701.07223 PRD, Bellomo etal. 1709.07467 JCAP)

Primordial black holes with extended mass functions can also form the entire dark matter density (Bhaumik & Jain 1907.04125 JCAP and many others)





$$\frac{d\Phi_{\rm PBH}}{dM_{\rm PBH}} = \frac{e^{-[\ln^2(M_{\rm PBH}/\mu)]/2\sigma^2}}{\sqrt{2\pi}\sigma M_{\rm PBH}}$$

Log-normal mass function

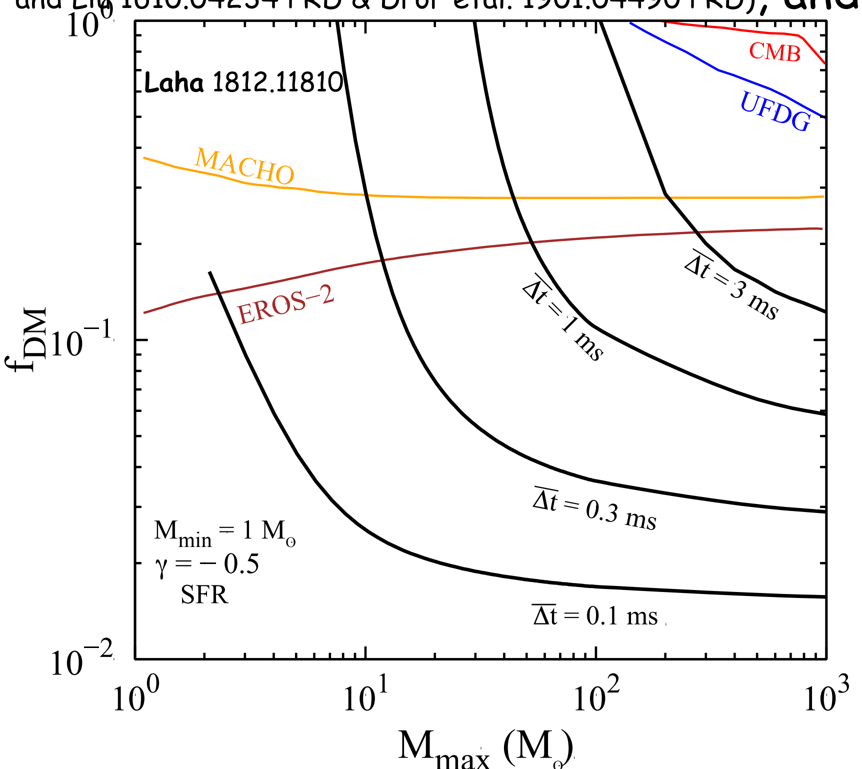
Future probes

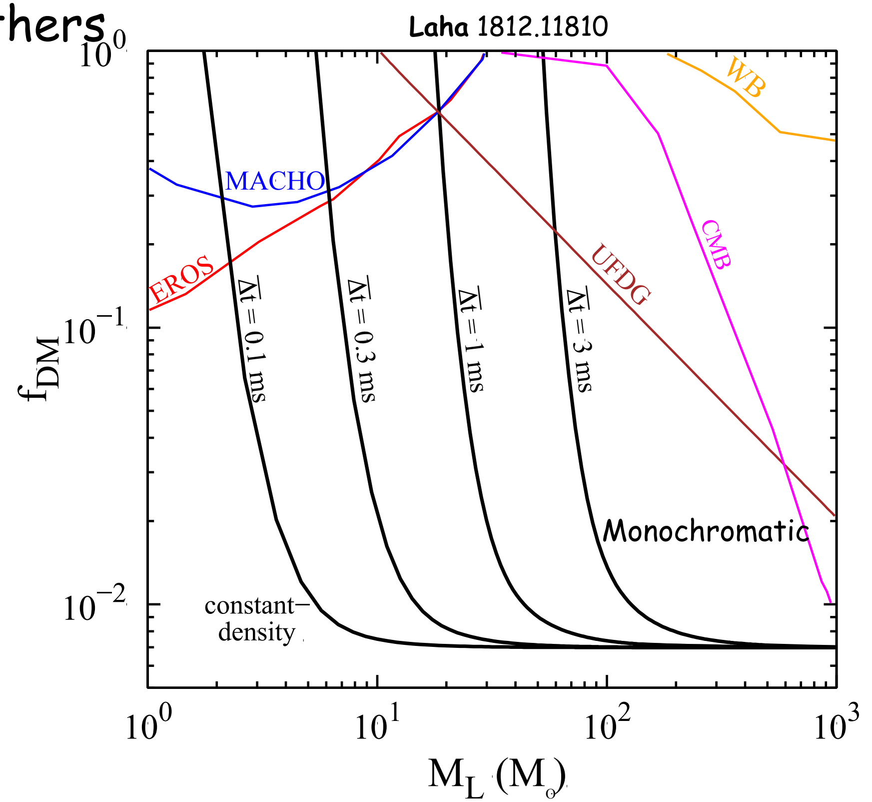
Future of primordial black hole detection

Detection of primordial black holes at any cosmic density will give us a probe of one of the earliest cosmological era

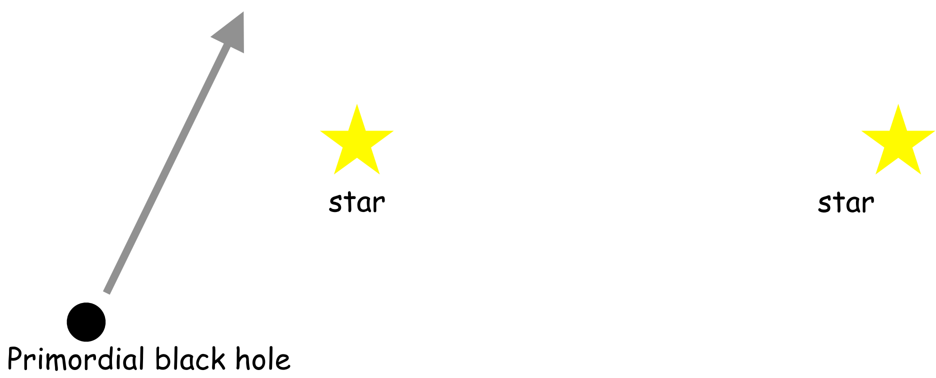
Important to probe the smallest f_{PBH} value possible

Various near future probes proposed: lensing of fast radio bursts (Munoz etal. 1605.00008 PRL, Laha 1812.11810), lensing of X-ray bursts (Bai and Orlofsky 1812.01427 PRD), lensing of gamma-ray bursts (Katz etal. 1807.11495 JCAP), GRB lensing parallax (Jung and Kim 1908.00078), pulsar timing (Schutz and Liu 1610.04234 PRD & Dror etal. 1901.04490 PRD), and many others





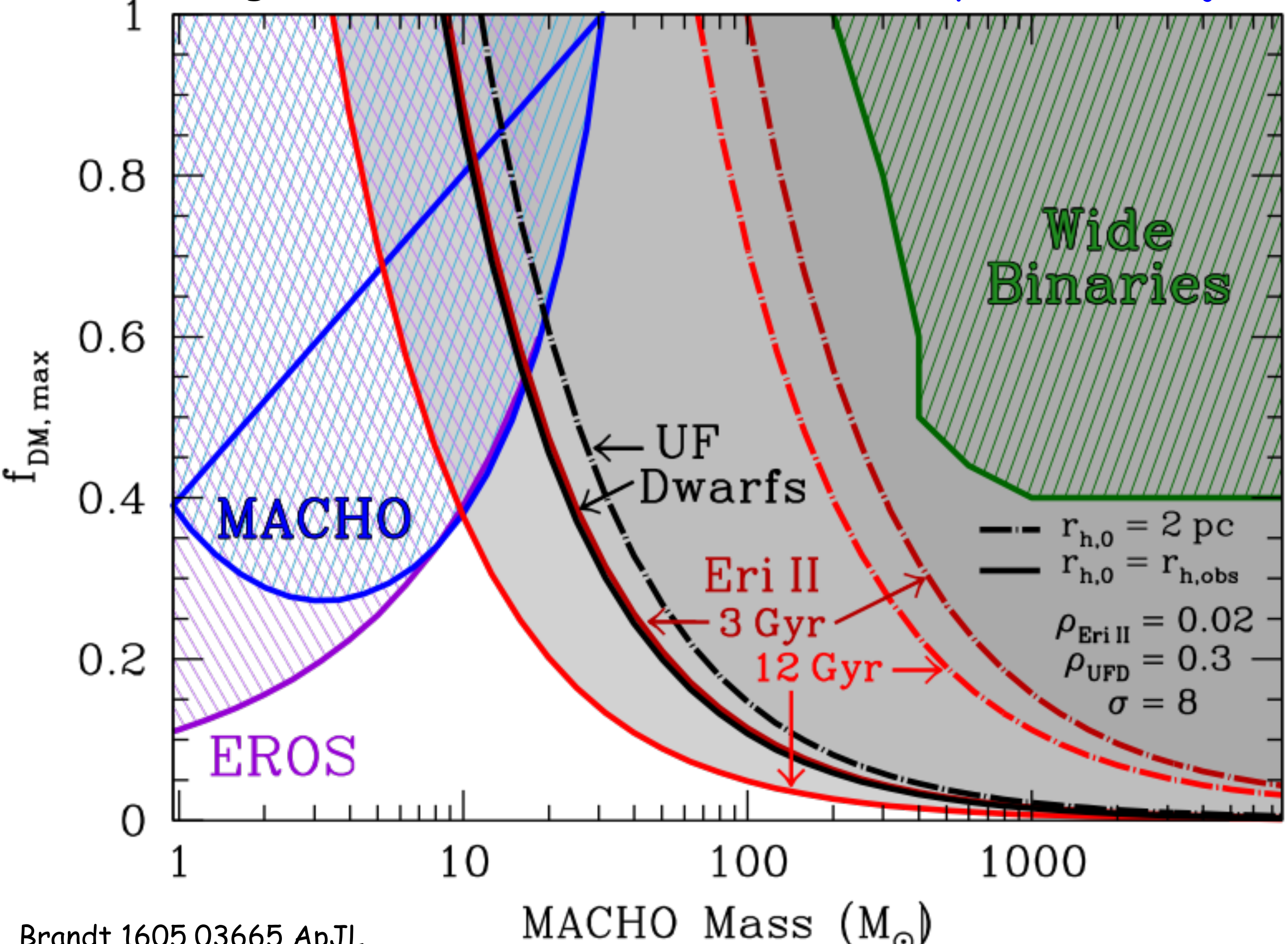
Primordial black holes constraints from dynamical effects



Pic. courtesy:
Green 2019 talk

Constraint from Eridanus II and ultra-faint dwarf galaxies

Dynamical heating of the central star cluster of Eridanus II and stars in compact ultra-faint galaxies can constrain massive compact halo objects (MACHOs)/ PBHs



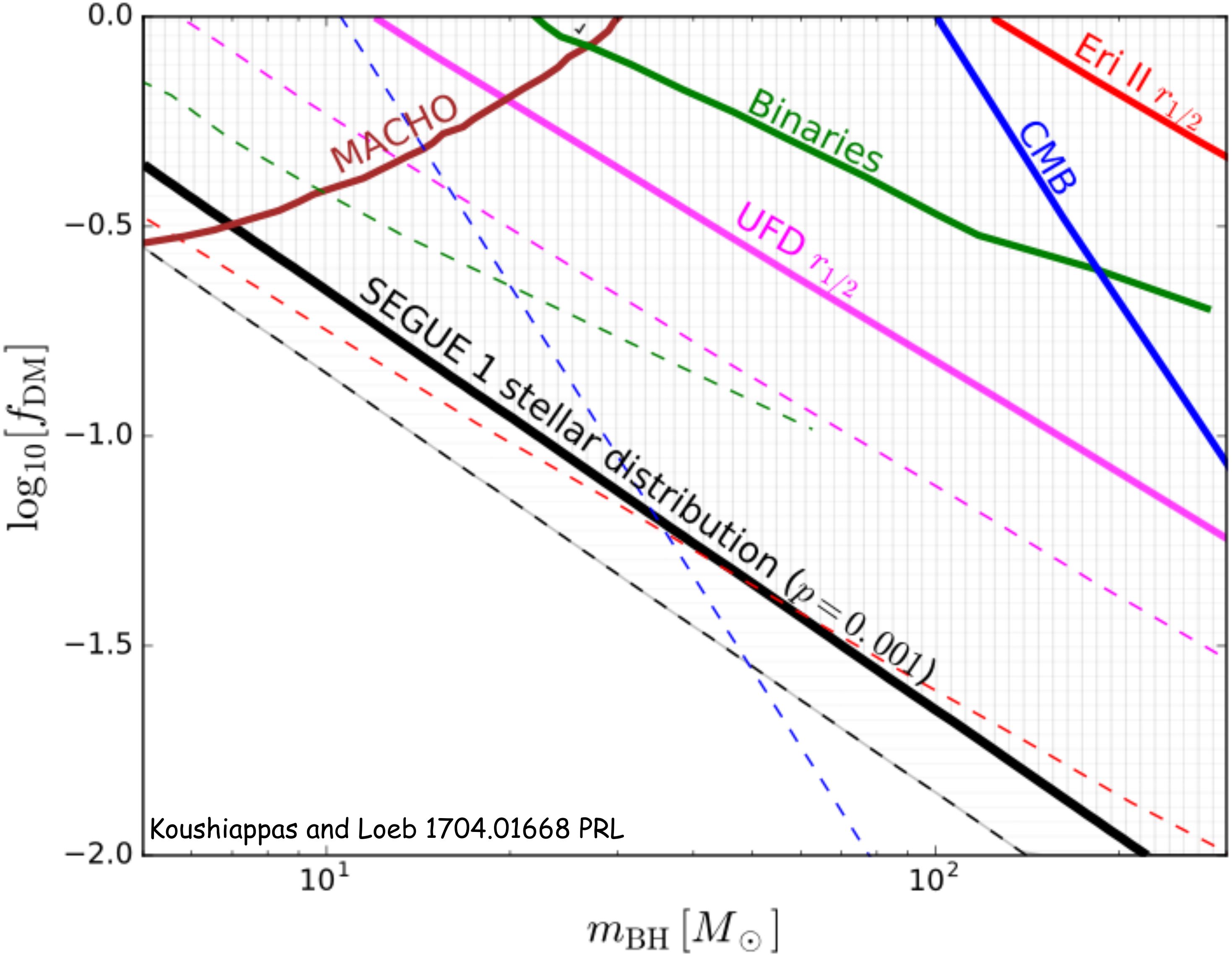
Various astrophysical uncertainties exist, however, the constraints are robust

Further studies in Zhu etal. 1710.05032 MNRAS and Stegmann etal. 1910.04793 MNRAS

Brandt 1605.03665 ApJL

Constraint from Segue 1

Dynamical heating will cause a lack of stars at the center of the galaxy: observed stellar density constrain massive compact halo objects (MACHOs)/ PBHs

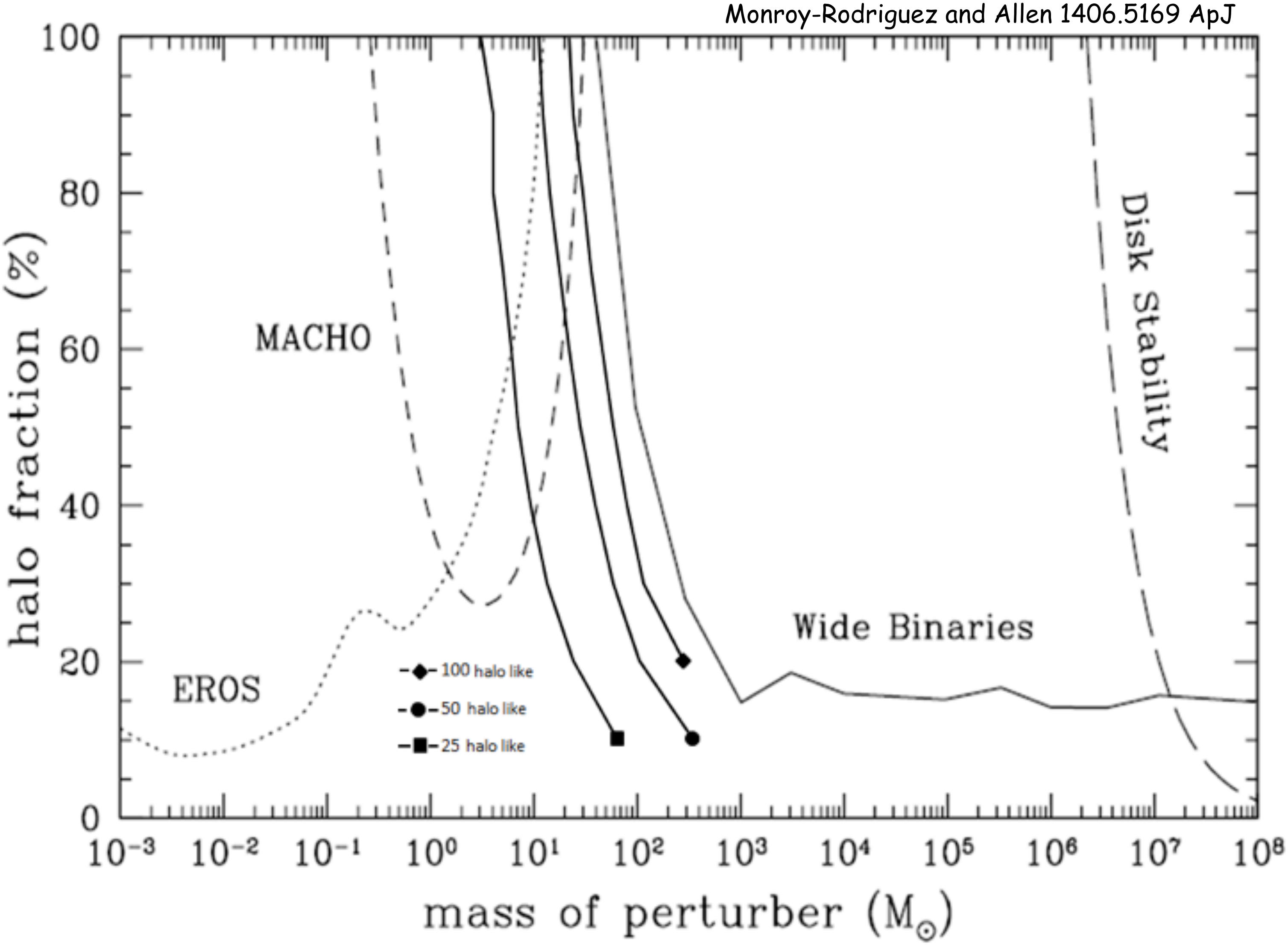


Further studies in Zhu etal. 1710.05032 MNRAS and Stegmann etal. 1910.04793 MNRAS

Constraint from wide binaries

Gravitational perturbations will cause a disruption in wide binary stars: observations constrain massive compact halo objects (MACHOs)/ PBHs

Monroy-Rodriguez and Allen 1406.5169 ApJ



Earlier studies in Yoo etal. astro-ph/ 0307437 ApJ and Quinn etal. 0903.1644 MNRAS Lett.