Unravelling the Mystery of Dark Matter with Black Holes

i) Phys. Rev. Lett. 125, 101101 (2020), ii) Phys. Rev. D 104, 023516 (2021)
iii) 2107.02190 (submitted to JCAP), iv) Phys. Rev. Lett. 126, 141105 (2021)
also, v) JCAP 08 (2019) 018 vi) JCAP 10 (2020) 023,

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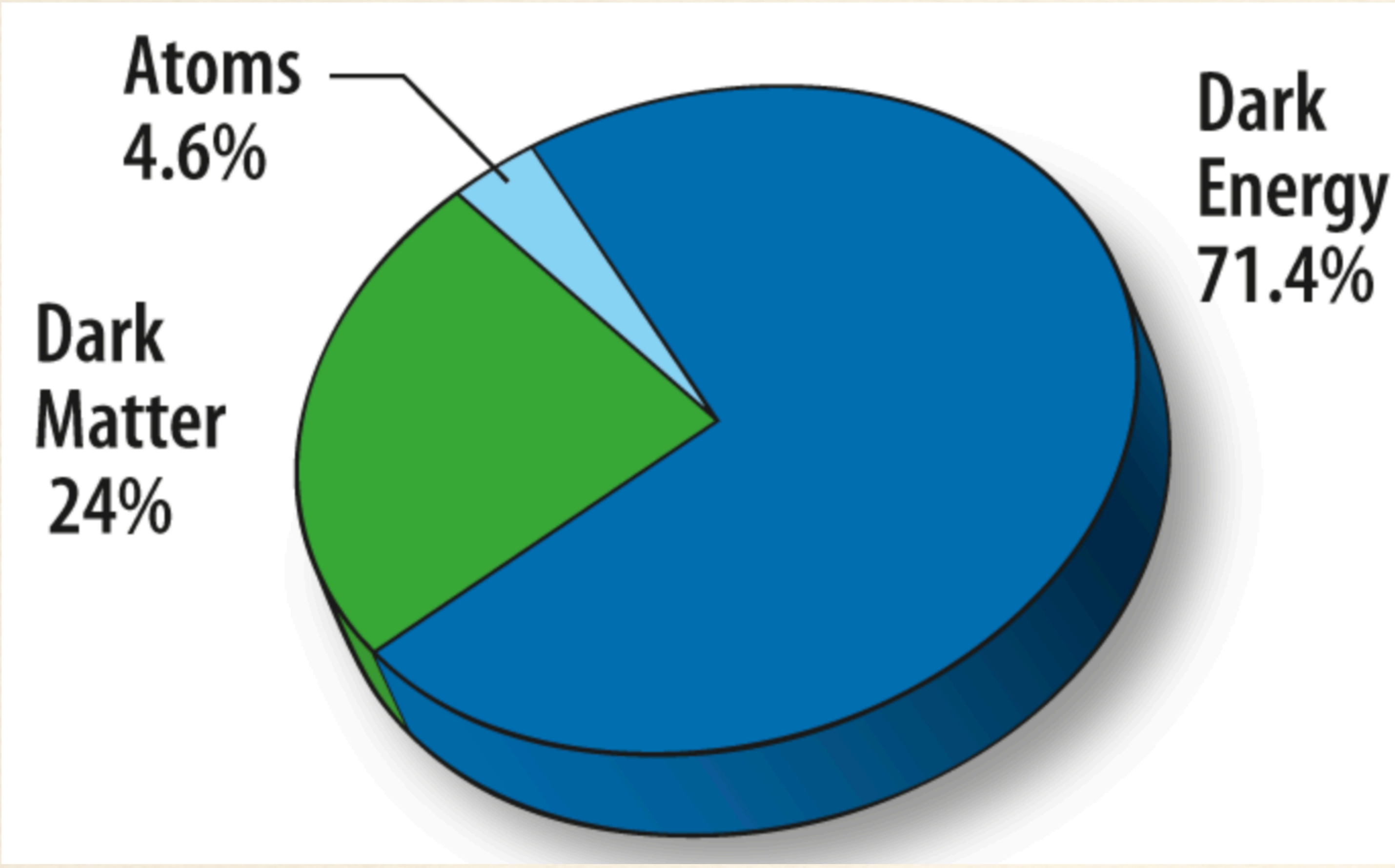
(TIFR, Mumbai)

Work in collaboration with: Basudeb Dasgupta, Ranjan Laha, Julian B. Muñoz, Regina Caputo, Shikhar Mittal, and Girish Kulkarni

LAPTh Seminar, Annecy
09.11.2021

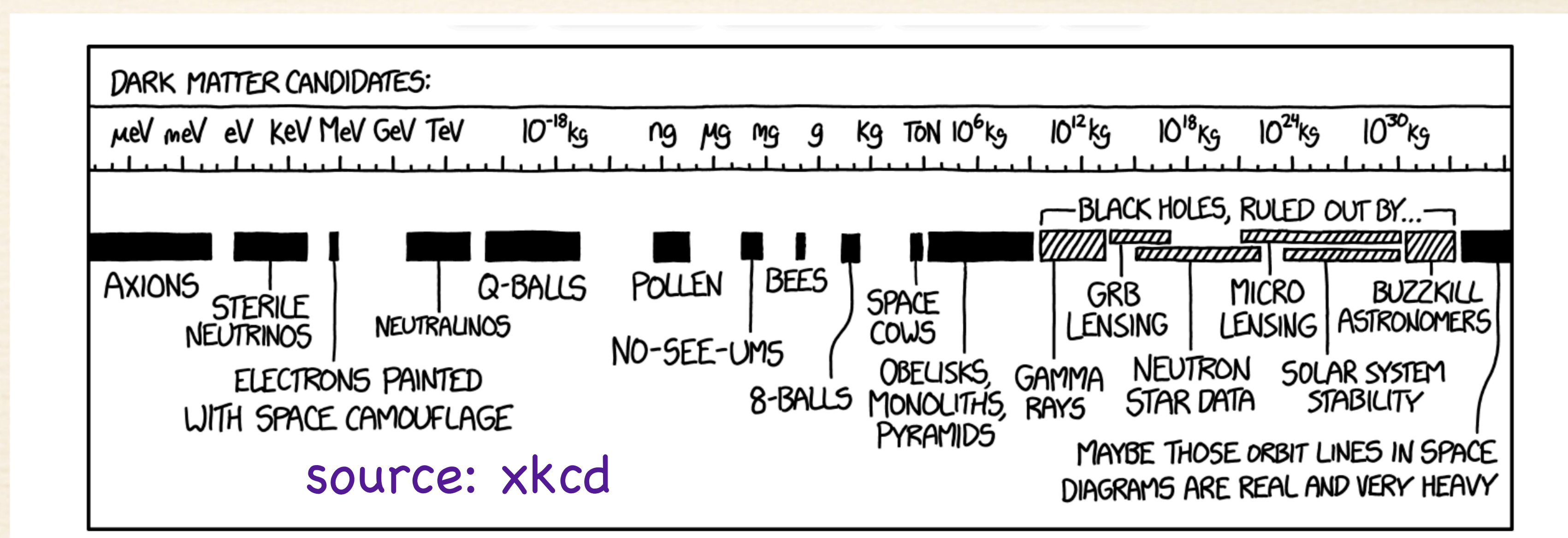
Dark Matter (DM)



- DM is omnipresent in our Universe.

https://wmap.gsfc.nasa.gov/universe/uni_matter.html

- What is DM?



source: xkcd

Outline

- Black Holes can unravel the mystery of DM :

i) Ultra-light PBHs as a viable DM candidate.

(broadly, indirect detection of DM)

- Phys. Rev. Lett. 125, 101101 (2020) : Constraining ultralight PBHs as DM using DSNB searches at Super-Kamiokande & 511 keV gamma-ray line measurement by INTEGRAL.
- Phys. Rev. D 104, 023516 (2021) : Imminent soft gamma-ray telescope AMEGO can exclude asteroid mass PBHs as DM.
- arXiv: 2107.02190 : Constraining ultralight PBHs as DM using EDGES measurement of the global 21-cm signal

ii) Accretion of asymmetric DM can lead to Black Hole formation, testable by GW detectors.

(GW detectors as a probe of particle DM)

- JCAP 08 (2019) 018 : Improved the treatment of DM capture in compact stellar objects in the multiple scattering regime.
- JCAP 10 (2020) 023 : Provided a general treatment of DM capture in compact stellar objects to account for arbitrary mediator masses.
- Phys. Rev. Lett. 126, 141105 (2021) : Continued accumulation of asymmetric DM in compact stars can provide non-primordial sub-Chandrasekhar mass black holes, testable by third-generation GW experiments.

- **Primordial black holes (PBHs):** Exotic compact objects; formed in the early universe possibly by gravitational collapse of over dense regions.

$$\rho_{\rm PBH} \sim \frac{\rm M_{PBH}}{\left(\frac{2\,\rm G\,M_{PBH}}{c^2}\right)^3} \sim 10^{18} \left(\frac{\rm M_\odot}{\rm M_{PBH}}\right)^2 \rm g/cm^3$$

Required density

for PBH formation

average density of Sun $\sim 1.41\, g/cm^3$

$$\rho_c \sim \frac{1}{\rm G\,t^2} \sim 10^6 \left(\frac{1\,s}{\rm t}\right)^2 \rm g/cm^3$$

Cosmological density

PBH forming large density can only be achieved in the very early universe.

PBHs: sirens of the early universe

- Wide range of masses depending on their time of formation

$$M_{\rm PBH} \sim \frac{c^3\, t}{G}$$

time of formation

$$\sim 10^{15}\left(\frac{t}{10^{-23}\,\mathrm{s}}\right)\mathrm{g}$$

PBHs can explain a multitude of Cosmic Conundra.

$t = t_p = 10^{-43}\,\mathrm{s}$ $\quad$ $t = 10^{-5}\,\mathrm{s}$ $\quad$ $t = 1\,\mathrm{s}$

$M_{\rm PBH} \sim 10^{-38}\,M_\odot$ $\quad$ $M_{\rm PBH} \sim 1\,M_\odot$ $\quad$ $M_{\rm PBH} \sim 10^{5}\,M_\odot$

- PBHs that are formed before $\sim 10^{-5}$ s are naturally sub-Solar.
  - PBHs form much much earlier than the first stars.

PBHs as DM

- Primordial black holes (PBHs): One of the earliest proposed DM candidate.

- Detection of gravitational waves in LIGO followed by the subsequent proposals that these black holes can be primordial in nature rekindled the idea of PBHs as DM.

Did LIGO detect dark matter?

Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess[1]

[1] *Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA*

We consider the possibility that the black-hole (BH) binary detected by LIGO may be a signature of dark matter. Interestingly enough, there remains a window for masses $20\,M_\odot \lesssim M_{\rm bh} \lesssim 100\,M_\odot$ where primordial black holes (PBHs) may constitute the dark matter. If two BHs in a galactic halo pass sufficiently close, they radiate enough energy in gravitational waves to become gravitationally bound. The bound BHs will rapidly spiral inward due to emission of gravitational radiation and ultimately merge. Uncertainties in the rate for such events arise from our imprecise knowledge of the phase-space structure of galactic halos on the smallest scales. Still, reasonable estimates span a range that overlaps the $2-53$ Gpc^{-3} yr^{-1} rate estimated from GW150914, thus raising the possibility that LIGO has detected PBH dark matter. PBH mergers are likely to be distributed spatially more like dark matter than luminous matter and have no optical nor neutrino counterparts. They may be distinguished from mergers of BHs from more traditional astrophysical sources through the observed mass spectrum, their high ellipticities, or their stochastic gravitational wave background. Next generation experiments will be invaluable in performing these tests.

Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914

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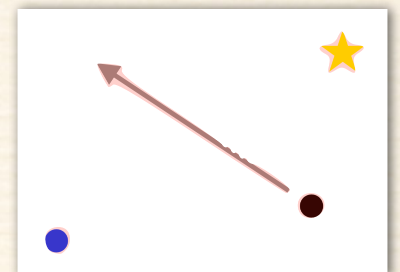
Abstract

We point out that the gravitational-wave event GW150914 observed by the LIGO detectors can be explained by the coalescence of primordial black holes (PBHs). It is found that the expected PBH merger rate would exceed the rate estimated by the LIGO Scientific Collaboration and the Virgo Collaboration if PBHs were the dominant component of dark matter, while it can be made compatible if PBHs constitute a fraction of dark matter. Intriguingly, the abundance of PBHs required to explain the suggested lower bound on the event rate, > 2 events Gpc^{-3}yr^{-1}, roughly coincides with the existing upper limit set by the nondetection of the cosmic microwave background spectral distortion. This implies that the proposed PBH scenario may be tested in the not-too-distant future.

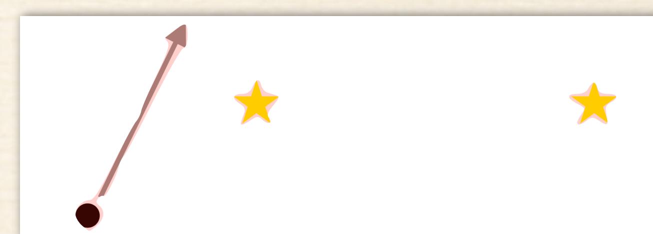
- Multiple techniques have been applied to probe PBHs as DM in various mass ranges.
  - Constraints from Hawking radiation.

  - Constraints from lensing.

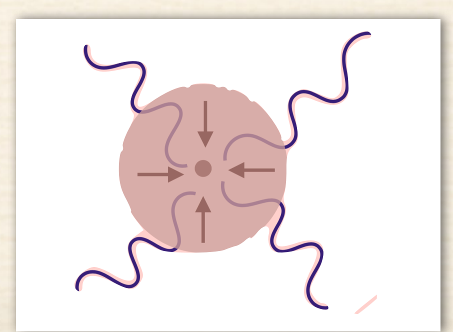


  - Constraints from gravitational waves searches.

  - Constraints from dynamical effects.

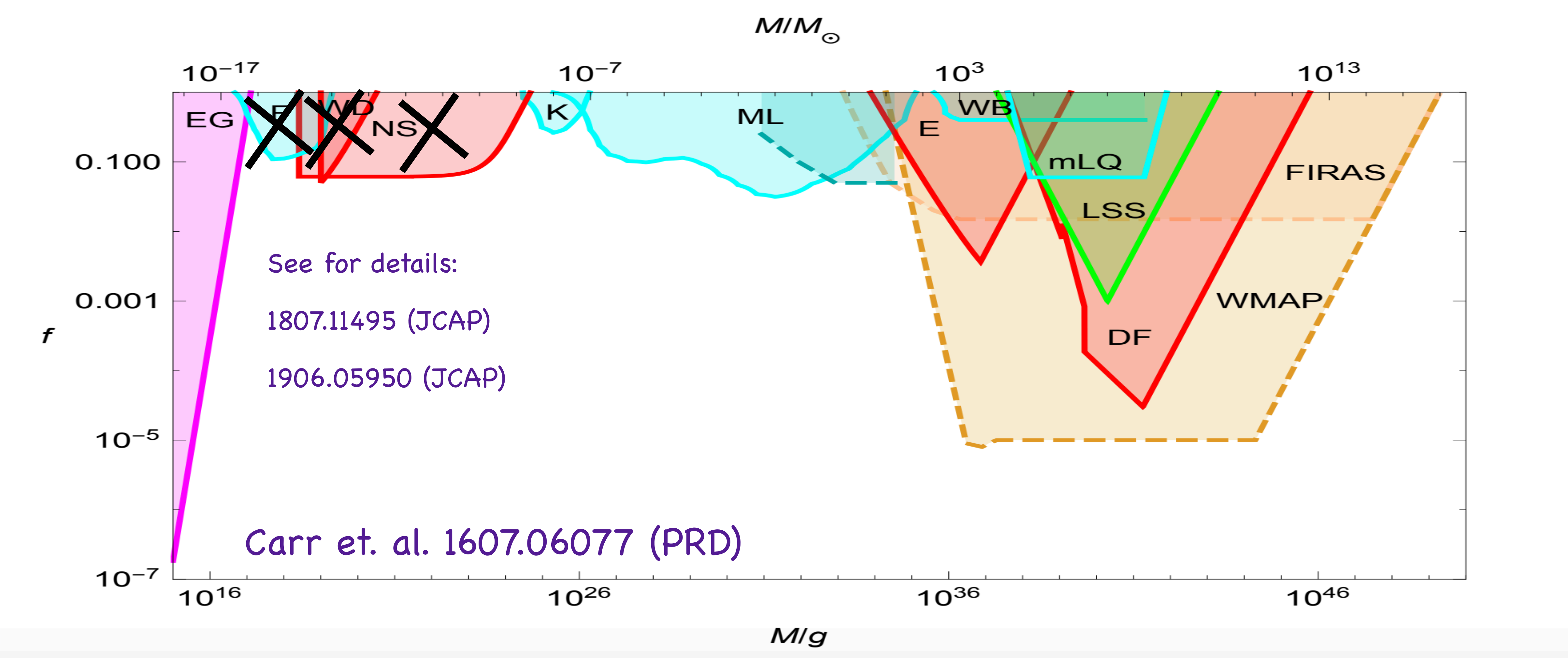


  - Constraints from accretion.



Pic. Courtesy:
Anne Green

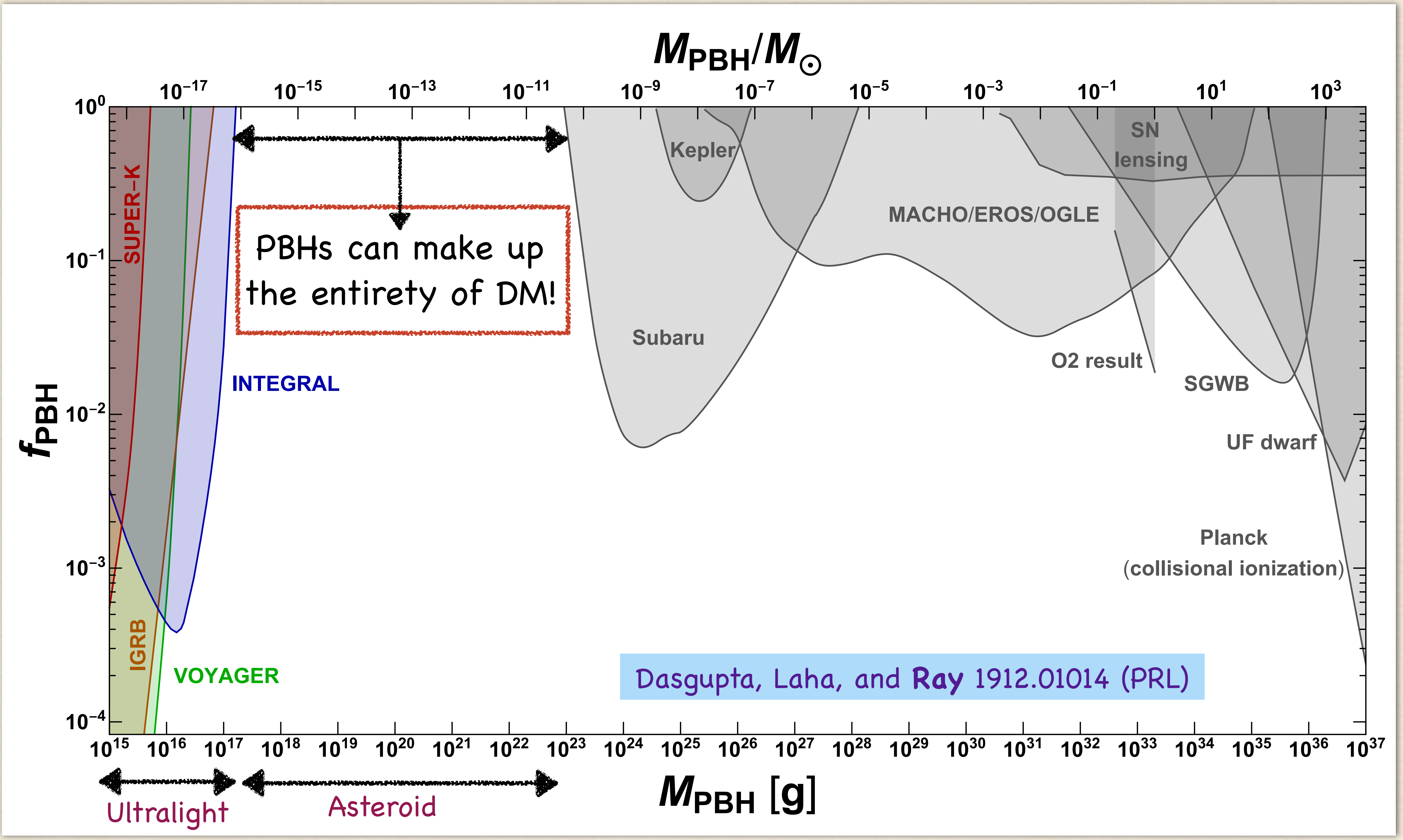
PBHs as DM (in 2016-2017)



In recent years,

- Multiple exclusion limits are shown to be ineffective.
- Many existing limits are significantly revised.
- Many new exclusion limits are added especially in the ultralight mass window.

PBHs as DM (in 2020-)

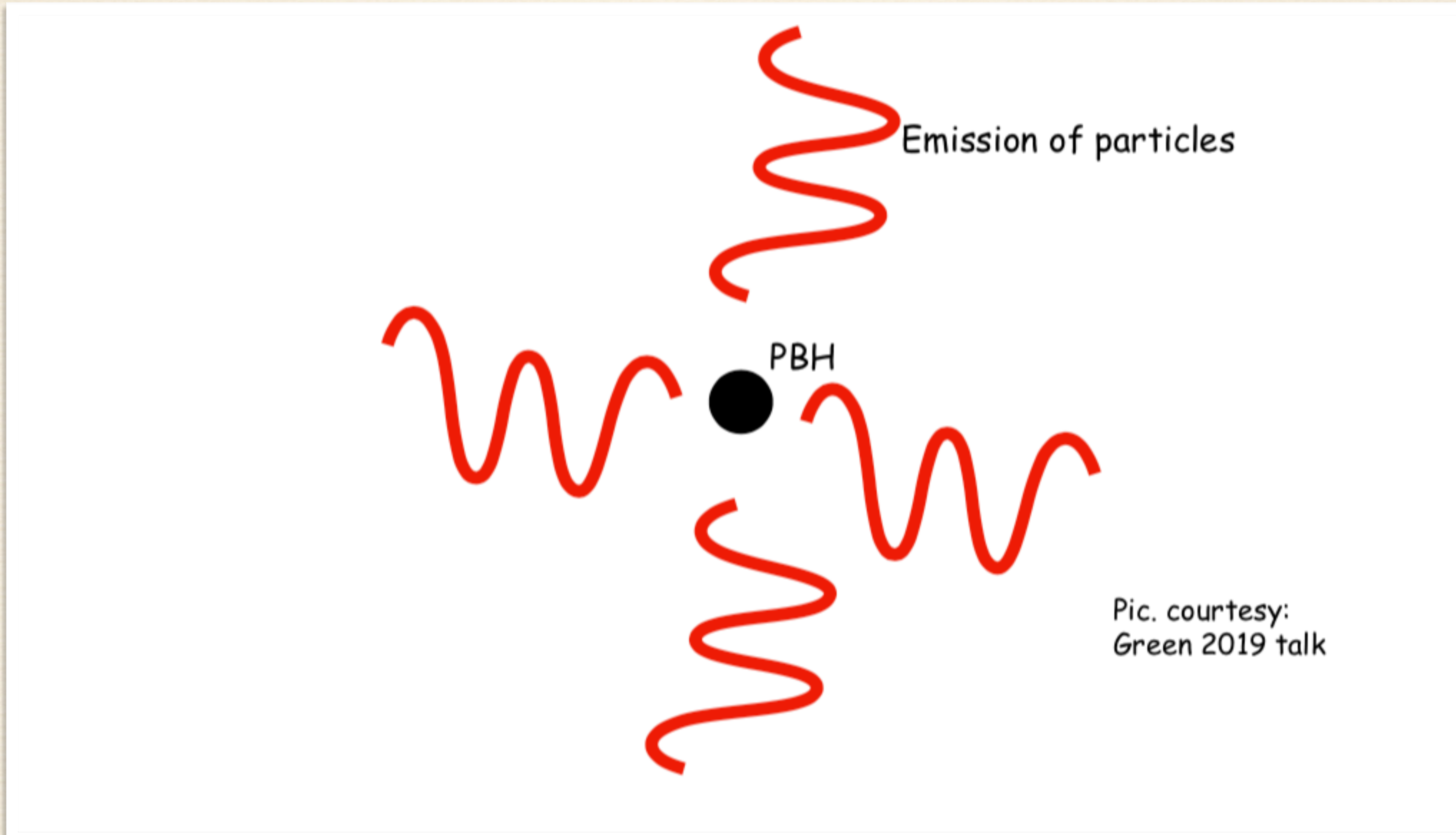


See also Carr et. al. 2002.12778, Carr et. al. 2006.02838, Green et. al. 2007.10722, and https://github.com/bradkav/PBHbounds.

Summary

- Neutrino (positron) emission from PBHs and subsequent non-detection at Super-Kamiokande (INTEGRAL) put stringent exclusion on fraction of DM composed of ultralight PBHs ($10^{15} - 10^{17}$ g). Phys. Rev. Lett. 125, 101101 (2020)
- Angular momentum of PBHs has a significant impact on the evaporation constraints; rotating PBHs as a DM is an interesting aspect to study. Phys. Rev. Lett. 125, 101101 (2020)
- PBHs in the asteroid mass range ($10^{17} - 10^{23}$ g) can be all of DM; observations of low energy Galactic Center photons by the upcoming soft-gamma ray telescopes, such as AMEGO, can close this mass window by almost an order of magnitude. Phys. Rev. D 104, 023516 (2021)
- EDGES measurement of the global 21-cm signal provide world-leading exclusion on PBHs as DM in the entire ultralight mass window. arXiv: 2107.02190

Hawking radiation from PBHs



Formalism

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

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

- PBHs emit particle by Hawking radiation and spectrum of these emitted particles follow a black body like distribution:

Greybody factor

Dimensionless Spin parameter ∈ [0,1]

$$\frac{d^2N}{dEdt} = \frac{1}{2\pi} \frac{\Gamma_s(E, M_{\text{PBH}}, a_*)}{\exp\left[E'/T_{\text{PBH}}\right] - (-1)^{2s}}$$

Spin of the emitted particle

temperature of PBH

$$\boxed{E' = E - m\Omega}$$

Effective energy of the emitted particle

angular velocity of PBH

$E' \gg T_{\text{PBH}}$
emission exponentially suppressed

Arbey, Auffinger 1905.04268 (EPJC) BlackHawk: A public code for calculating the Hawking evaporation spectra

Page, PRD, 13, 198, 1976

MacGibbon and Webber, PRD, 41, 3052, 1990

MacGibbon, Carr, Page, PRD, 0709.2380 (PRD)

- Temperature of a uncharged, rotating PBH

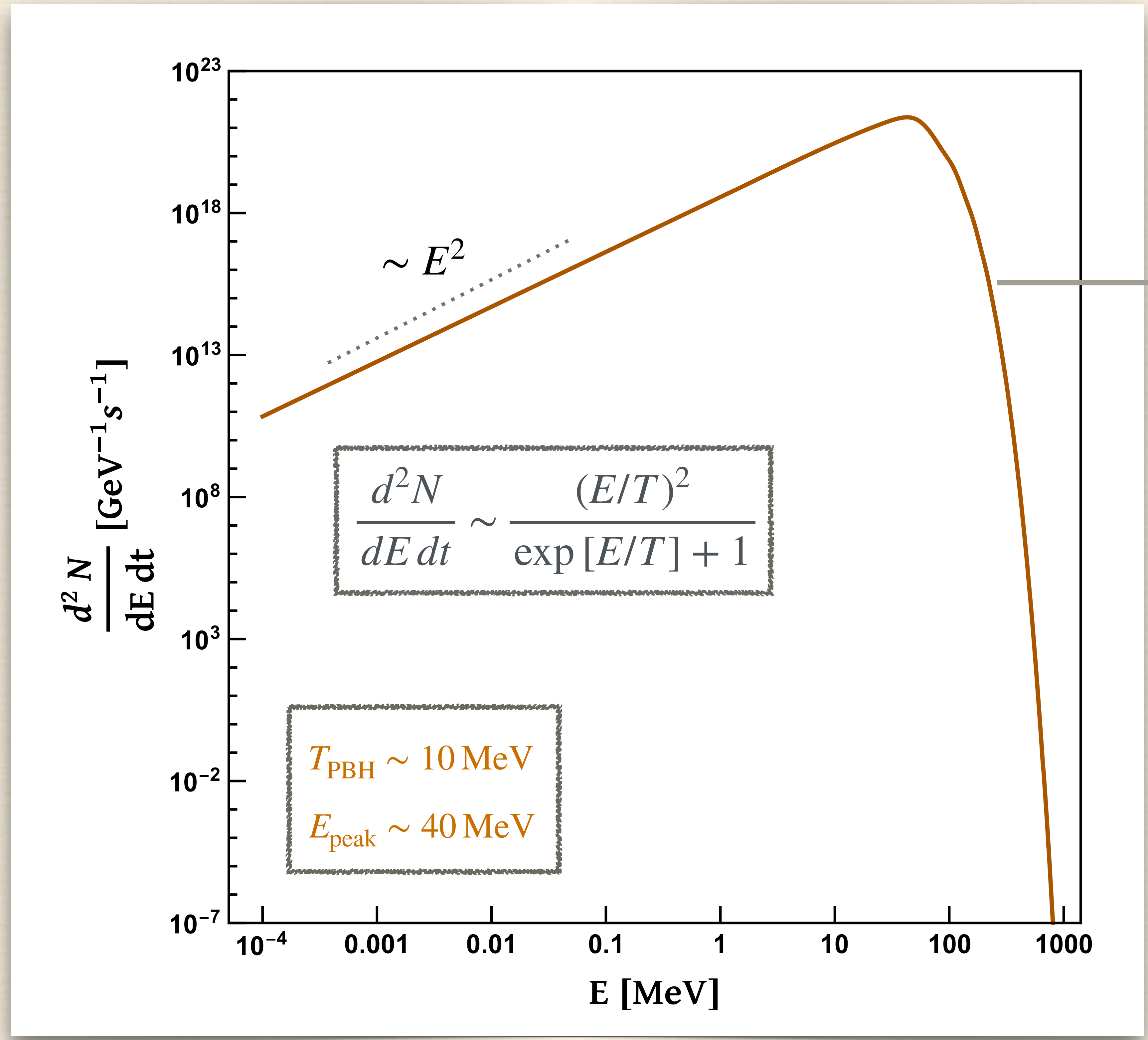
$$T_{\rm PBH} = \frac{1}{4\pi G M_{\rm PBH}} \frac{\sqrt{1-a_*^2}}{1+\sqrt{1-a_*^2}}$$

- For a uncharged, non-rotating PBH,

$$T_{\rm PBH} = \frac{1}{8\pi G M_{\rm PBH}} = 1\,{\rm GeV}\left(\frac{10^{13}\,{\rm g}}{{\rm M}_{\rm PBH}}\right)$$

Emission of particles peaks at:

$$E_{s=0} \sim 2.81\, T_{\rm PBH} \qquad E_{s=1/2} \sim 4.02\, T_{\rm PBH} \qquad E_{s=1} \sim 5.77\, T_{\rm PBH}$$



emission exponentially suppressed $E \gg T_{\rm PBH}$

Emitted neutrino spectrum via Hawking radiation for a PBH of mass 10^{15} g and $a_* = 0$.

Limits from DSNB

- Non-observations of Hawking radiated neutrinos in the DSNB searches at Super-Kamiokande/KamLAND set robust and stringent exclusion limits on ultralight PBHs as DM.

- Galactic and extragalactic contribution to the PBH flux for monochromatic mass distribution:

fraction of DM composed of PBHs

$$F_{\rm gal} = \int \frac{d\Omega}{4\pi} \int_{E_{\rm min}}^{E_{\rm max}} dE \frac{d^2N}{dEdt} \int_0^{l_{\rm max}} dl \, \frac{f_{\rm PBH}\, \rho_{\rm MW}\left(r(l,\psi)\right)}{M_{\rm PBH}}$$

Galactic flux from PBHs

DM density profile of the Milky Way

$$F_{\rm eg} = \int_{t_{\rm min}}^{t_{\rm max}} \int_{E_{\rm min}}^{E_{\rm max}} dt\, dE\, (1+z(t)) \frac{f_{\rm PBH}\, \rho_{\rm DM}}{M_{\rm PBH}} \frac{d^2N}{dEdt}\bigg|_{E \to (1+z(t))\,E}$$

extra-Galactic flux from PBHs

average DM density of the universe

Conservative upper limit on $f_{\rm PBH}$

$$\boxed{F_{\rm gal} + F_{\rm eg} \leq \text{ DSNB flux upper limit}}$$

***can be improved by background modeling

- Current upper limits on the DSNB flux :

Bays et al. 1111.5031 (PRD)

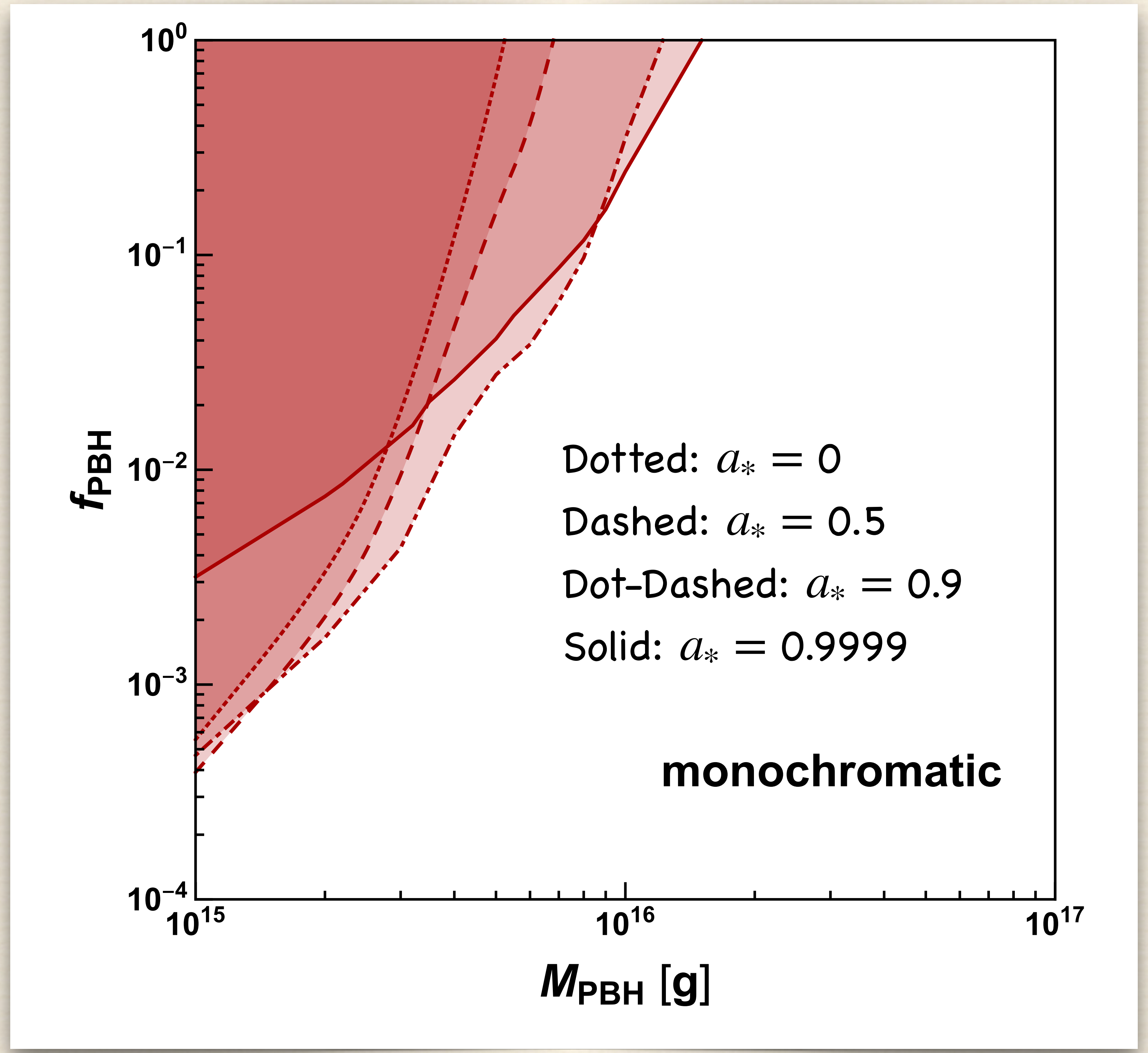
- 2.9 $\bar{\nu}_e \, \mathrm{cm}^{-2}\, \mathrm{s}^{-1}$ in the energy range of 17.8 MeV to 91.3 MeV from Super-Kamiokande.

- 139 $\bar{\nu}_e \, \mathrm{cm}^{-2}\, \mathrm{s}^{-1}$ in the energy range of 8.3 MeV to 31.8 MeV from KamLAND.

Gando et al. 1105. 3516 (APJ)

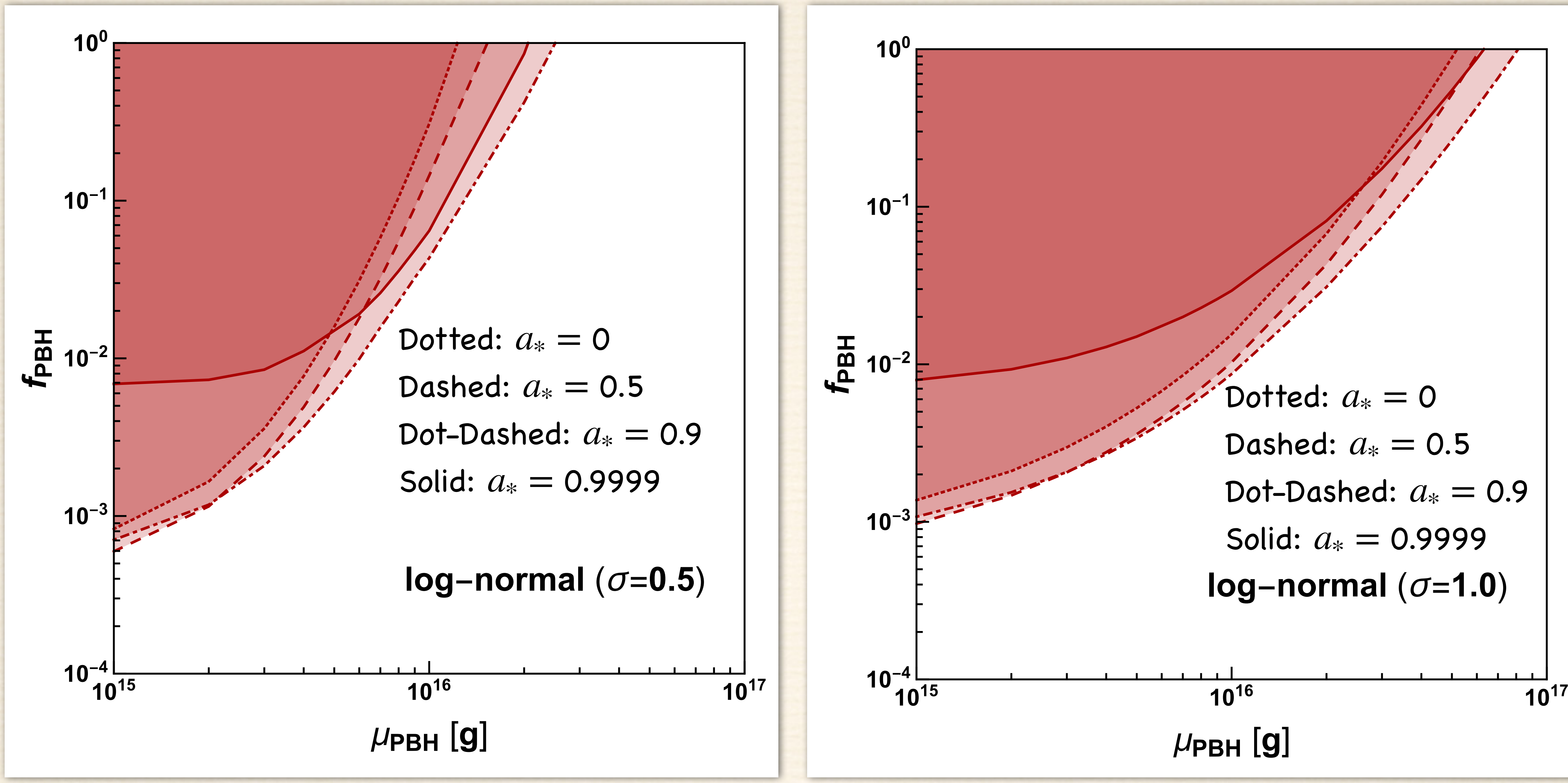
- Both, Super-Kamiokande and KamLAND upper limits exclude ultralight PBHs to form solitary component of DM. However, the exclusions obtained from Super-Kamiokande is stronger in the entire mass range.

Dasgupta, Laha, and **Ray** 1912.01014 (PRL)



Upper limit on fraction of DM composed of PBHs, from DSNB searches at Super-Kamiokande for a monochromatic mass distribution of PBHs.

Dasgupta, Laha, and **Ray** 1912.01014 (PRL)



Upper limit on fraction of DM composed of PBHs, from DSNB searches at Super-Kamiokande for an extended (log-normal) mass distribution of PBHs.

See also Wang et. al. 2010.16053 (PRD), De Romeri et al 2106.05013 for projected exclusion limits using upcoming neutrino detectors: Jiangmen Underground Neutrino Observatory (JUNO), Deep Underground Neutrino Experiment (DUNE) and THEIA.

Summary of the Neutrino Derived Results

- Non-observations of Hawking radiated neutrinos in the DSNB searches at Super-Kamiokande exclude monochromatic non-rotating (maximally rotating) PBHs to form the solitary component of DM up to 5×10^{15} (10^{16}) g.

- Covers more mass window for PBHs that have rotation or which follow an extended mass distributions.

- Very robust to uncertainties in the DM density profiles and to a variety of astrophysical uncertainties that are inevitably associated with photons or any other charged particles.

- Near-future loading of gadolinium in Super-Kamiokande and Hyper-Kamiokande will improve upon the results. Stay tuned!

Limits from INTEGRAL

- INTEGRAL measurement of the 511 keV gamma ray line indicates the total positron injection rate within the Galactic bulge is $\sim 10^{50}\ \mathrm{yr}^{-1}$.

- Positron injection rate from PBHs for monochromatic mass distribution:

fraction of DM composed of PBHs

$$\Gamma = \int_{m_e}^{3\,\mathrm{MeV}} dE \frac{d^2N}{dEdt} \int_0^{r_{\max}} \frac{f_{\mathrm{PBH}}\, \rho_{\mathrm{MW}}(r)}{M_{\mathrm{PBH}}} d^3r$$

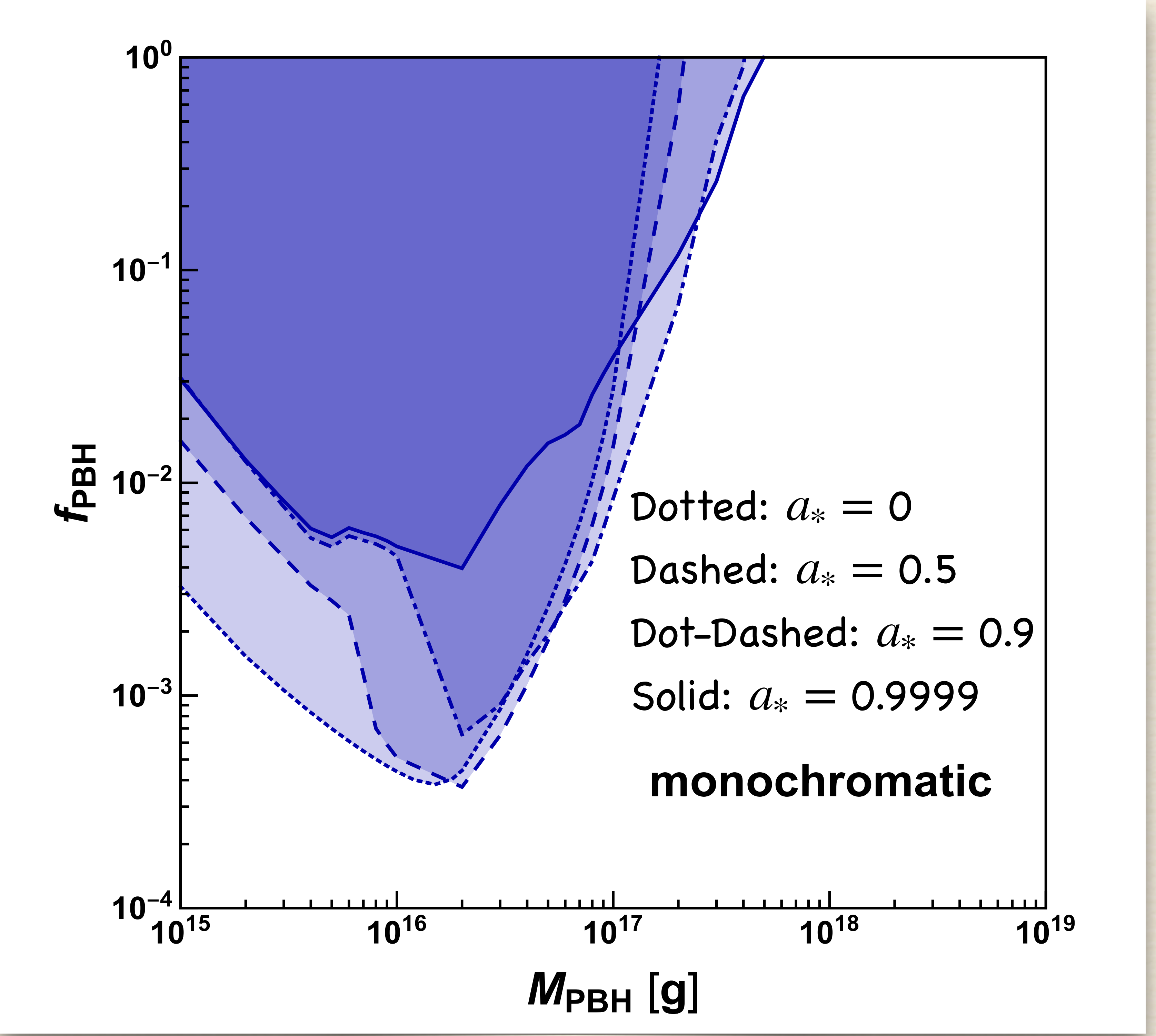
Galactic positron injection rate

DM density profile of the Milky Way

Conservative upper limit on f_{PBH}

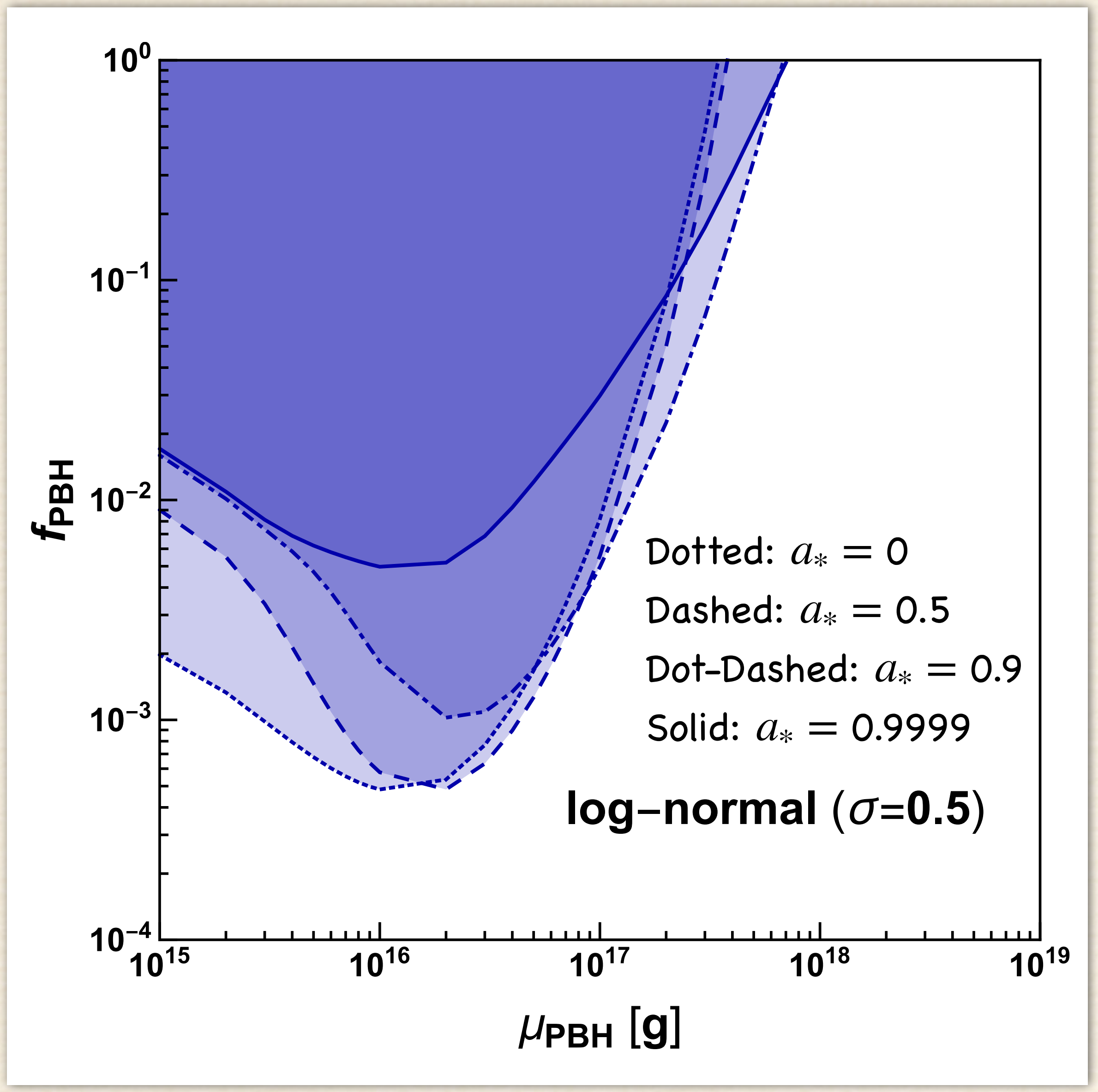
$$\boxed{\Gamma \leq 10^{50}\,\mathrm{yr}^{-1}}$$

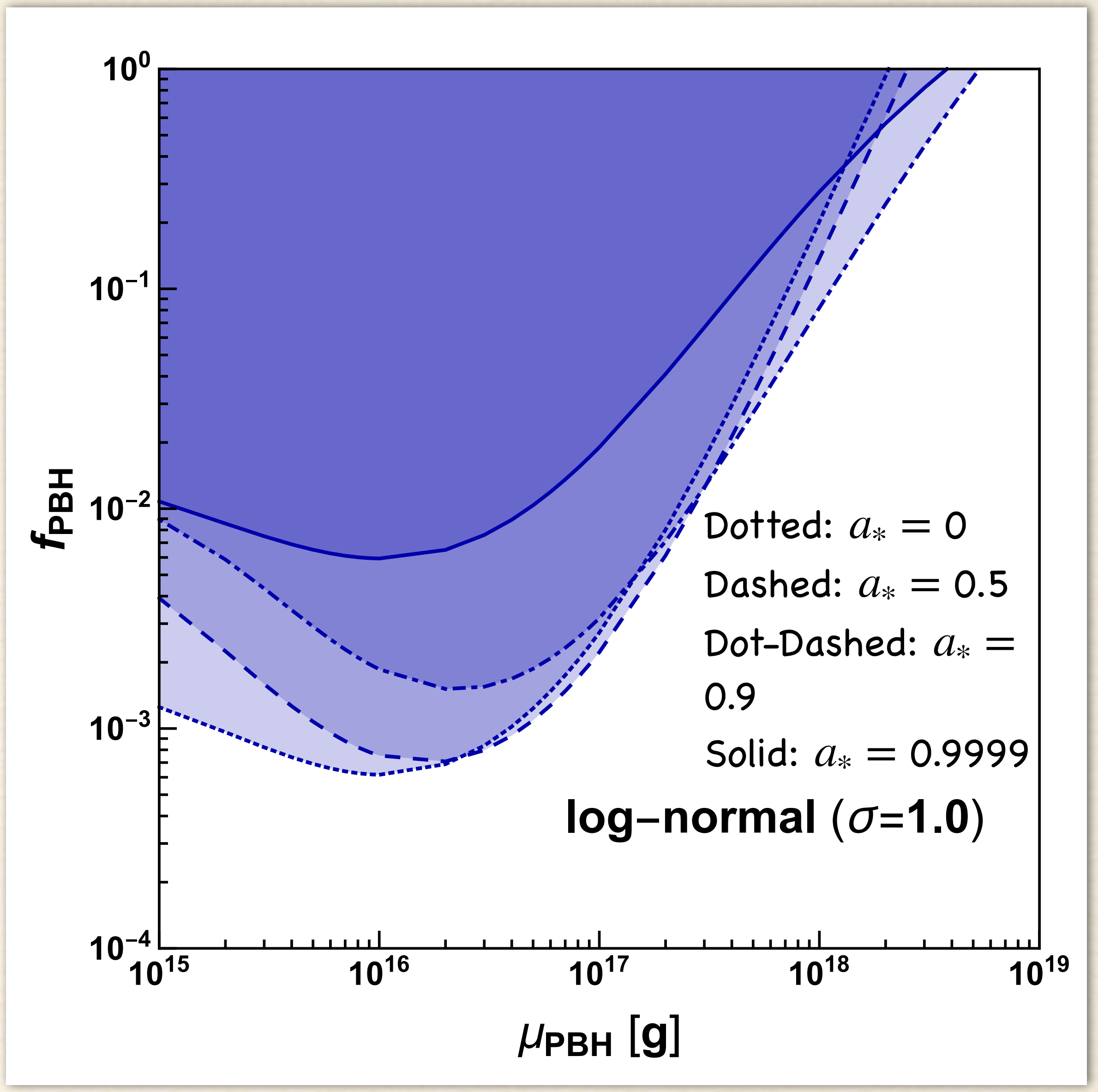
Dasgupta, Laha, and **Ray** 1912.01014 (PRL)



Upper limit on fraction of DM composed of ultralight PBHs, from 511 keV gamma-ray line measurement by INTEGRAL telescope for a monochromatic mass distribution of PBHs.

Dasgupta, Laha, and **Ray** 1912.01014 (PRL)



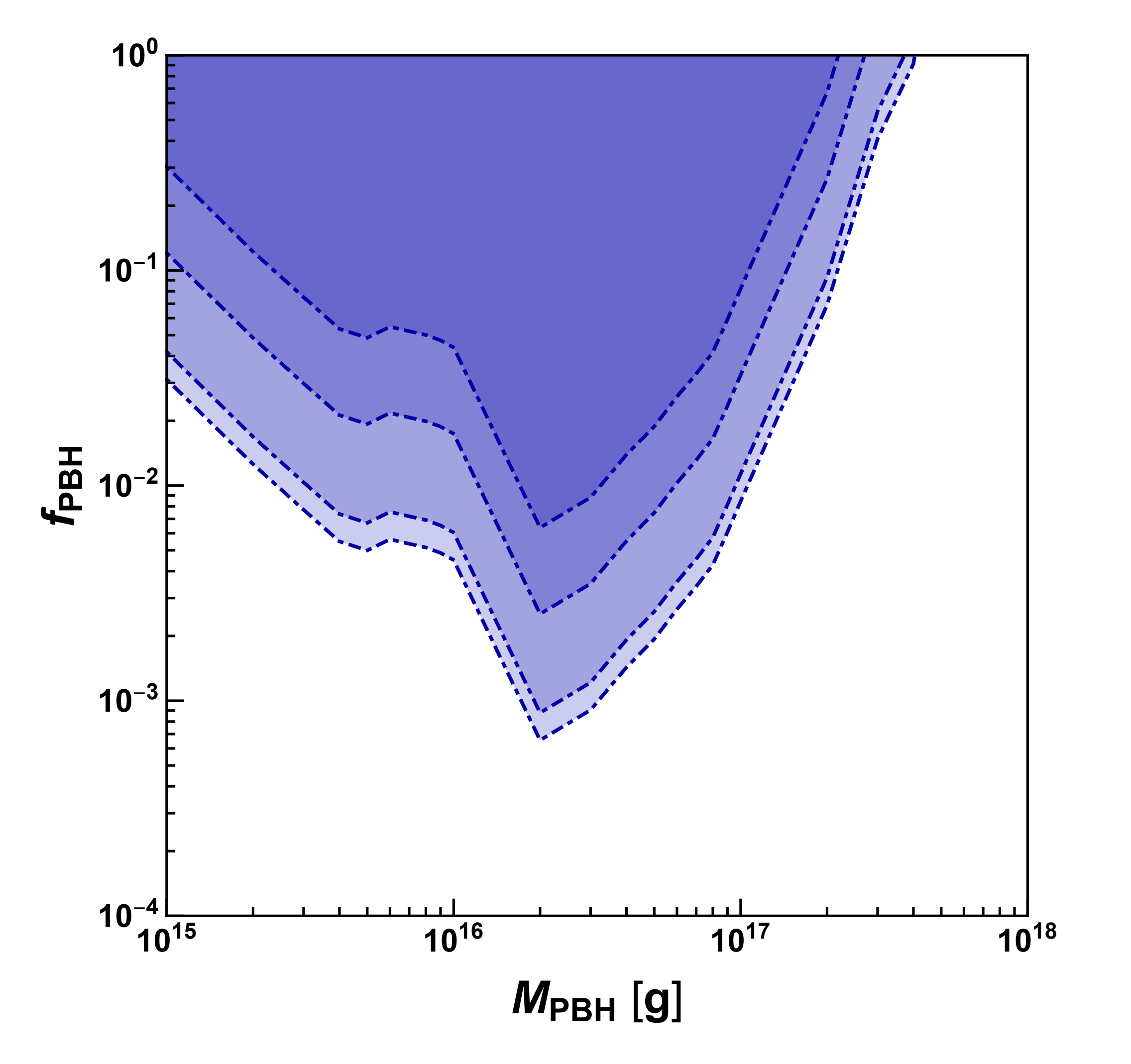


Upper limit on fraction of DM composed of ultralight PBHs, from 511 keV gamma-ray line measurement by INTEGRAL telescope for an extended mass distribution of PBHs.

See also Laha 1906.09994 (PRL), and De Rocco et al 1906.07740 (PRL) for similar exclusion limits for non-rotating PBHs. See also Seigert et al 2109.03791 (MNRAS) for an update.

Dasgupta, Laha, and **Ray** 1912.01014 (PRL)

- Astrophysical uncertainties in the positron derived constraints:
  - Unknown propagation distance (r_{max}) of the emitted positrons in the Galactic centre.
  - Choice of DM density profiles.



NFW with $r_{\text{max}} = 3.5\,\text{kpc}$ strongest upper limit

Isothermal with $r_{\text{max}} = 1.5\,\text{kpc}$ weakest upper limit

Positron derived constraints @INTEGRAL can vary up to an order of magnitude due to the astrophysical uncertainties. Shown for $a_* = 0.9$ but same for every value of spin.

Summary of the Positron Derived Results

- Precise measurement of the 511 keV gamma-ray line by the space based telescope INTEGRAL provide world-leading exclusions on ultralight PBHs as DM. It excludes monochromatic non-rotating (maximally rotating) PBHs to form the sole component if DM up to $\sim 10^{17}$ (6×10^{17}) g.
- Stronger than the Extra-Galactic gamma-ray background (EGRB) constraints (Carr et al. 0912.5297 (PRD)), which were thought to be the most stringent for almost a decade.
- Strongly depends on uncertainties in DM density profile as well as unknown positron propagation distance, and can vary by an order of magnitude because of these uncertainties.
- Identification of the astrophysical sources of these low-energy positrons will significantly strengthen the exclusion limits.

Projected limits from AMEGO

- PBHs in the asteroid mass range ($10^{17} - 10^{23}$ g) can make up the entire fraction of DM density as the exclusion limits in this mass widow are now refutable.

Katz et al 1807.11495 (JCAP), Montero-Camacho et al 1906.05950 (JCAP)

- Observations of Galactic Center ($|\, l \,| \leq 5^{\circ}, |\, b \,| \leq 5^{\circ}$) photons in the energy interval of 0.15 - 5 MeV by the imminent telescopes, such as AMEGO (All-sky Medium Energy Gamma-ray Observatory), can close the asteroid mass window by almost an order of magnitude.

- Excludes monochromatic non-rotating (maximally rotating) PBHs to form the sole component of DM up to 7×10^{17} (4×10^{18}) g by assuming no evaporation signal is present in the data. Covers more more mass window for extended mass distributions.

See also, Coogan, Morrison, and Profumo 2010.04797 (PRL)

- Galactic and extragalactic contribution to the PBH flux for monochromatic mass distribution:

l : Galactic longitude
b : Galactic latitude

fraction of DM composed of PBHs

$$\frac{d\phi_{\rm gal}}{dE} = \frac{f_{\rm PBH}}{4\pi M_{\rm PBH}} \frac{d^2N}{dEdt} \int_0^{s_{\rm max}} \rho_{\rm MW}\left[r(s,l,b)\right] ds\, d\Omega$$

Galactic flux from PBHs

DM density profile of the Milky Way

$$d\Omega = \cos[b]\, dl\, db$$

$$\frac{d\phi_{\rm eg}}{dE} = \frac{f_{\rm PBH}\,\rho_{\rm DM}}{M_{\rm PBH}} \frac{\Delta\Omega}{4\pi} \int_0^{\infty} \frac{dz}{H(z)} \frac{d^2N}{dEdt}\bigg|_{E\to(1+z)E}$$

Extragalactic flux from PBHs

solid angle under consideration

Hubble expansion rate at redshift z

- Galactic and extragalactic astrophysical backgrounds:

Bartels et al 1703.02546 (JCAP)

$$\phi_{\rm gal}^{\rm bkg} = A_{\rm bkg}\left(\frac{E}{1\,\mathrm{MeV}}\right)^{-\alpha}\exp\left[-\left(\frac{E}{E_c}\right)^{\gamma}\right]$$

Galactic astrophysical background

Galactic background parameters:

$A_{\rm bkg} = 0.013\,\mathrm{MeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\mathrm{sr}^{-1}$

$\alpha = 1.8$

$E_c = 20\,\mathrm{MeV}$

$\gamma = 2.0$

extra-Galactic background parameters:

$A_{\rm bkg}^{\rm eg} = 0.004135\,\mathrm{MeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\mathrm{sr}^{-1}$

$\alpha_{\rm eg} = 2.8956$

$$\phi_{\rm eg}^{\rm bkg} = A_{\rm bkg}^{\rm eg}\left(\frac{E}{1\,\mathrm{MeV}}\right)^{-\alpha_{\rm eg}}$$

Ballesteros et al 1906.10113 (PLB)

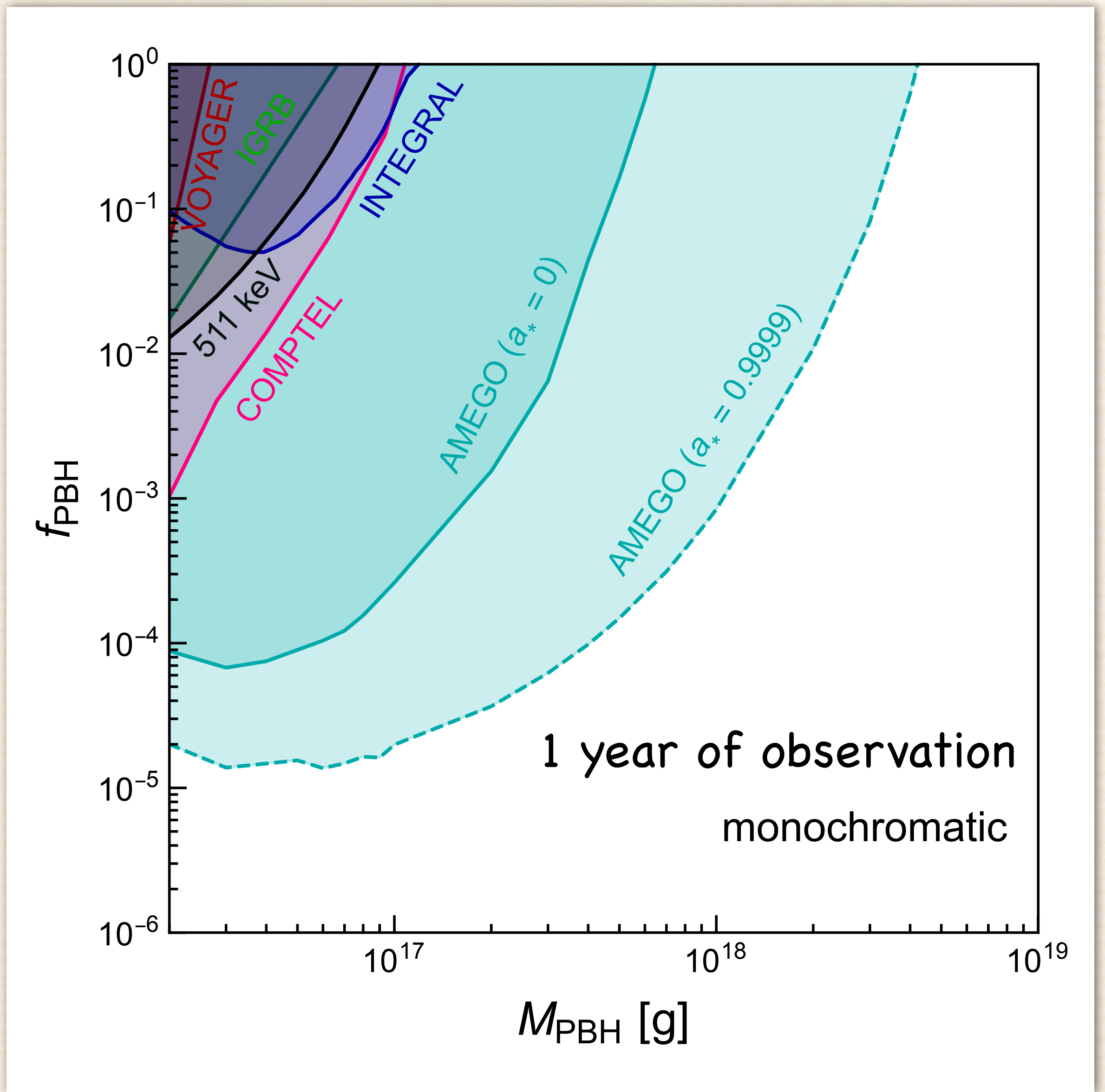
extra-Galactic astrophysical background

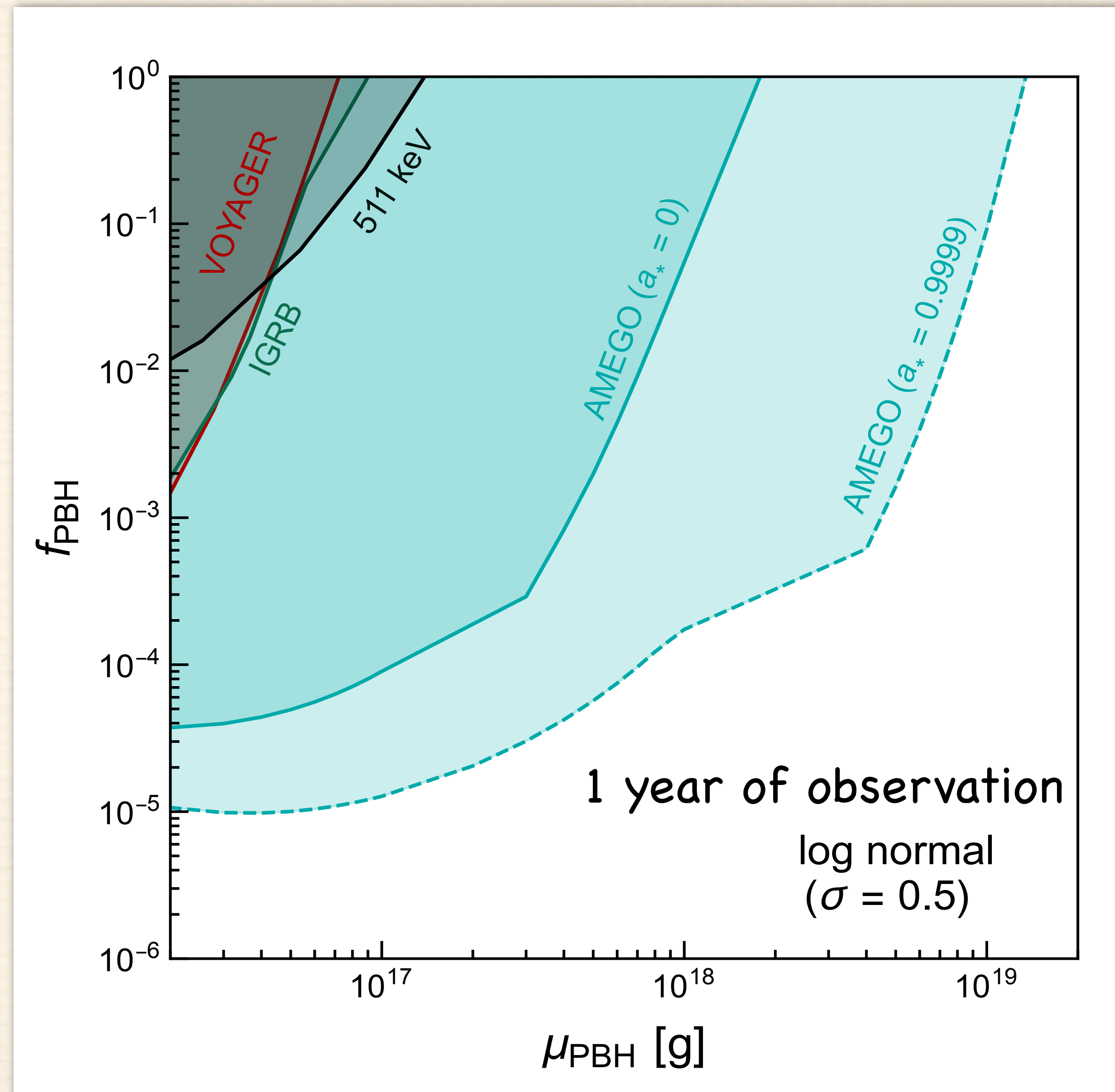
- 6 background parameters, and 1 signal parameter.

- Applied a Fisher forecasting with marginalising over all astrophysical background parameters to compute the projected exclusion limits on fraction of DM composed of PBHs.

closes the "mass gap" by almost an order of magnitude

Ray, Laha, Muñoz, Caputo 2102.06714 (PRD)





Projected upper limit on fraction of DM composed of asteroid mass PBHs, from non-observations of Galactic Center MeV photons by AMEGO.

Limits from EDGES

- EDGES (Experiment to Detect the Global EoR Signature) measurement of the global 21-cm signal can be used to set a world-leading exclusion on the fraction of DM composed of ultralight PBHs.
- Improved upon the prior analysis (Clark et al 1803.09390 (PRD)) by considering : i) the effect of the X-ray heating of the intergalactic medium, and ii) using the full spectral shape of the global 21-cm signal.
- Unlike the other two probes, it uses all emission channels (photons, positrons, electrons, and neutrinos) from PBHs.
- Excludes $f_{\rm PBH} \geq 10^{-9.7}$ at 95% CL for monochromatic non-rotating PBHs of mass 10^{15} g, and probes up to PBH masses of 2×10^{17} g, setting the leading exclusion till date in the entire ultralight mass window.

- Hawking emitted particles from PBHs interact with the baryons of the intergalactic medium; provides an additional heating and ionization — damps the amplitude of the 21-cm signal

$c \rightarrow$ Heating and Ionization

average DM density of the universe

$$q_c = \frac{f_{\rm PBH}\,\rho_{\rm DM}}{M_{\rm PBH}} \int dE \left[f_c\left(E_\gamma, z\right)\, E_\gamma \left.\frac{d^2N}{dE\,dt}\right|_\gamma + 2 f_c\left(E_e - m_e, z\right)\,\left(E_e - m_e\right)\left.\frac{d^2N}{dE\,dt}\right|_{e^\pm}\right]$$

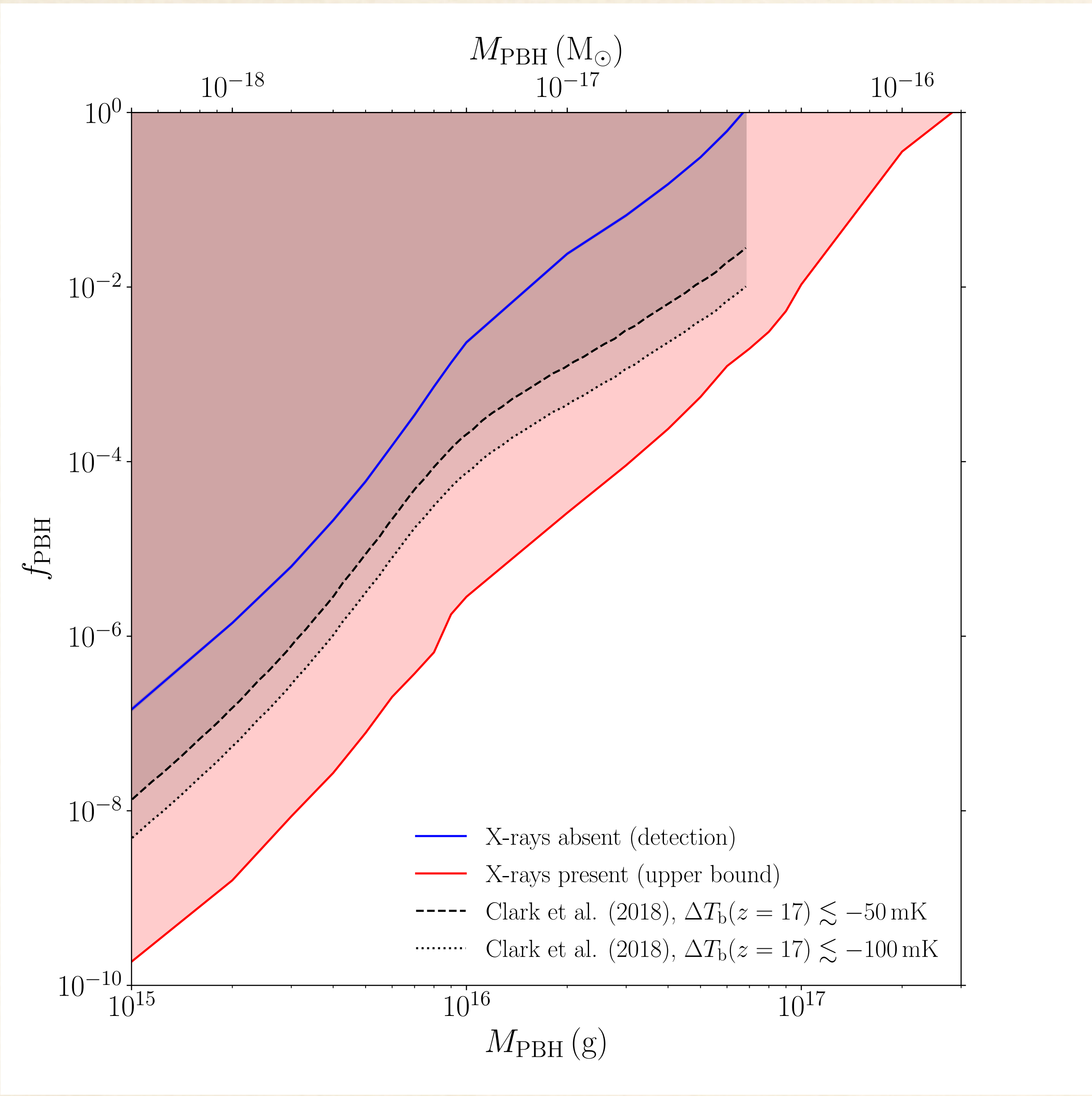
Power density (energy per unit volume per unit time) to a particular channel "c"

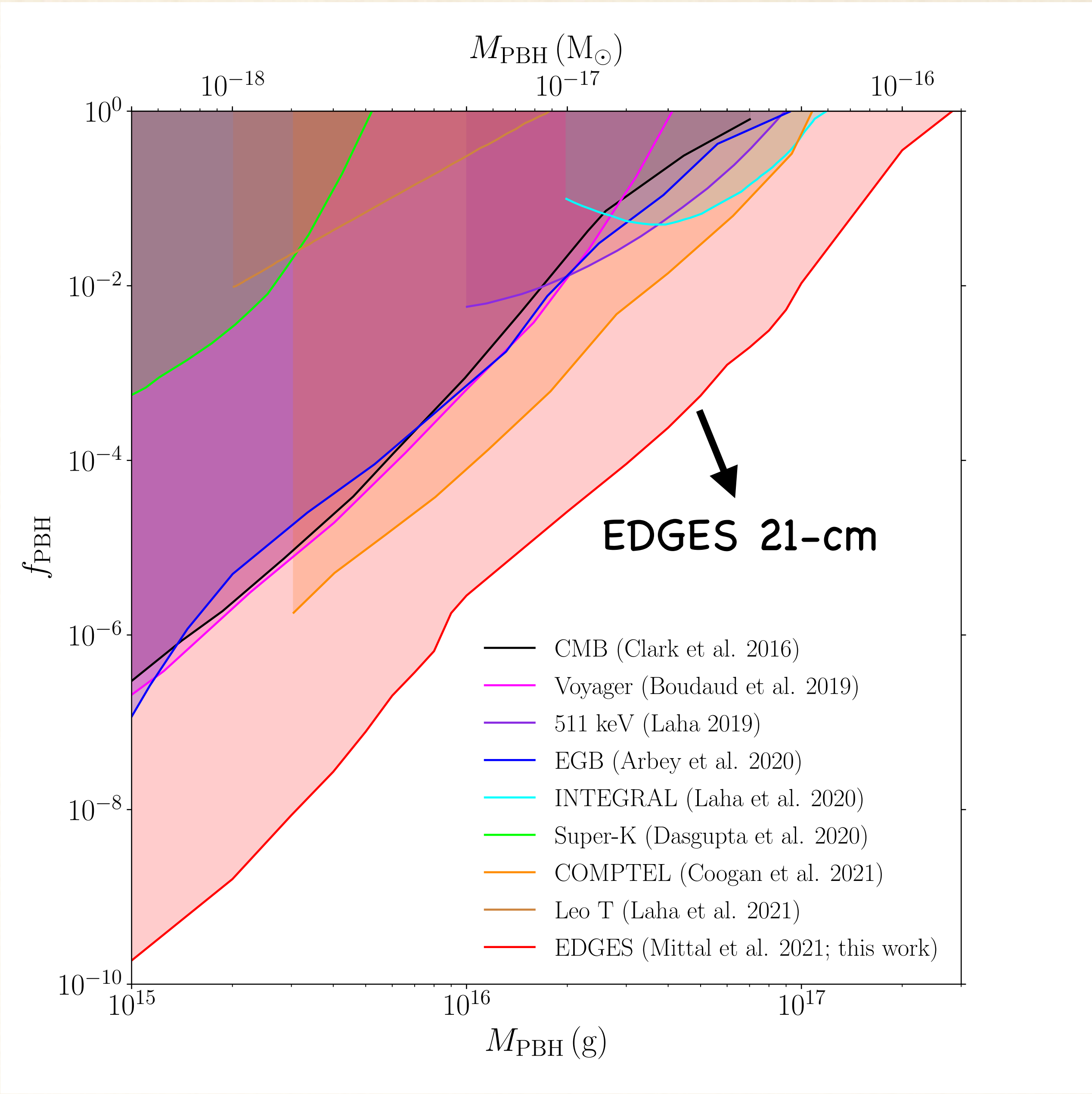
counts electrons and positrons

$f_c(E_k, z)$: ratio of the energy deposited into channel "c" to the injected energy as a function of the kinetic energy of the emitted particles E_k and redshift z.

Liu et al 1904.09296 (PRD), Liu et al 1604.02457 (PRD),...

Mittal, **Ray,** Kulkarni, Dasgupta 2107.02190





Upper limit on fraction of DM composed of ultralight PBHs, from EDGES observation of global 21-cm signal.

Summary & Conclusions

- PBH as a dominant component of DM had been written a few years ago, however, such a conclusion is premature.
- PBHs can make up a large or even entire fraction of the present day DM density over a wide mass range.
- Ultralight PBHs emit particle via Hawking radiation, act as a decaying DM, and can be probed via searching these Hawking emitted particles in various space as well as ground based detectors.
- DSNB searches at the existing neutrino detectors, measurement of the 511 keV gamma-ray line, observations of the Galactic Center photons by the imminent telescopes, and 21-cm Cosmology provide world-leading exclusions on ultralight PBHs as DM.

Still, a wide mass window remains unexplored. Many more ideas to come!

Mergers as a Probe of Particle DM

Dasgupta, Laha, and **Ray** 2009.01825 (PRL)

Phys. Rev. Lett. 126, 141105 (2021)

Probing Particle DM with GW detectors

- Recent discoveries of unusually low mass objects in the GW detectors pose a very fundamental questions about their origin.

(Stellar or Primordial?)

GW190814: Gravitational Waves from the Coalescence of a 23 $M_\odot$ Black Hole with a 2.6 $M_\odot$ Compact Object

LIGO Scientific Collaboration and Virgo Co

(Dated: June 24, 2020)

ABSTRACT

We report the observation of a compact binary coalescence involving a compact object with a mass of $2.50 - 2.67\,M_\odot$ (all measurements q The gravitational-wave signal, GW190814, was observed during LIG run on August 14, 2019 at 21:10:39 UTC and has a signal-to-noise ratio of 25 in the three-detector network. The source was localized to 18.5 deg^2 at a distance of 241^{+41}_{-45} Mpc; no electromagnetic counterpart has been confirmed to date. The source has the most unequal mass ratio yet measured with gravitational waves, $0.112^{+0.008}_{-0.009}$, and its secondary component is either the lightest black hole or the heaviest neutron star ever discovered in a double compact-object system. The dimensionless

REPORT

A noninteracting low-mass black hole–giant star binary system

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BH mass: $3.3^{+2.8}_{-0.7}\,M_\odot$

+also, secondary components of GW200105 & GW200115 can be low mass BHs!

GW190425: Observation of a Compact Binary Coalescence with Total Mass $\sim 3.4 M_\odot$

On 2019 April 25, the LIGO Livingston detector observed a compact binary coalescence with signal-to-noise ratio 12.9. The Virgo detector was also taking data that did not contribute to detection due to a low signal-to-noise ratio, but were used for subsequent parameter estimation. The 90% credible intervals for the component masses range from 1.12 to 2.52 $M_\odot$ (1.46–1.87 $M_\odot$ if we restrict the dimensionless component spin magnitudes to be smaller than 0.05). These mass parameters are consistent with the individual binary components being neutron stars. However, both the source-frame chirp mass $1.44^{+0.02}_{-0.02}\,M_\odot$ and the total mass $3.4^{+0.3}_{-0.1} M_\odot$ of this system are significantly larger than those of any other known binary neutron star (BNS) system. The possibility that one or both binary components of the system are black holes cannot be ruled out from gravitational-wave data. We discuss possible

- Detection of a sub-Chandrasekhar mass ($< 1.4\ M_\odot$) BH is usually thought as a smoking gun signature of its primordial origin.

- Non-annihilating DM with non-zero interaction strength with nuclei, a vanilla scenario, is sufficient to produce sub-Chandrasekhar mass non-primordial BHs.

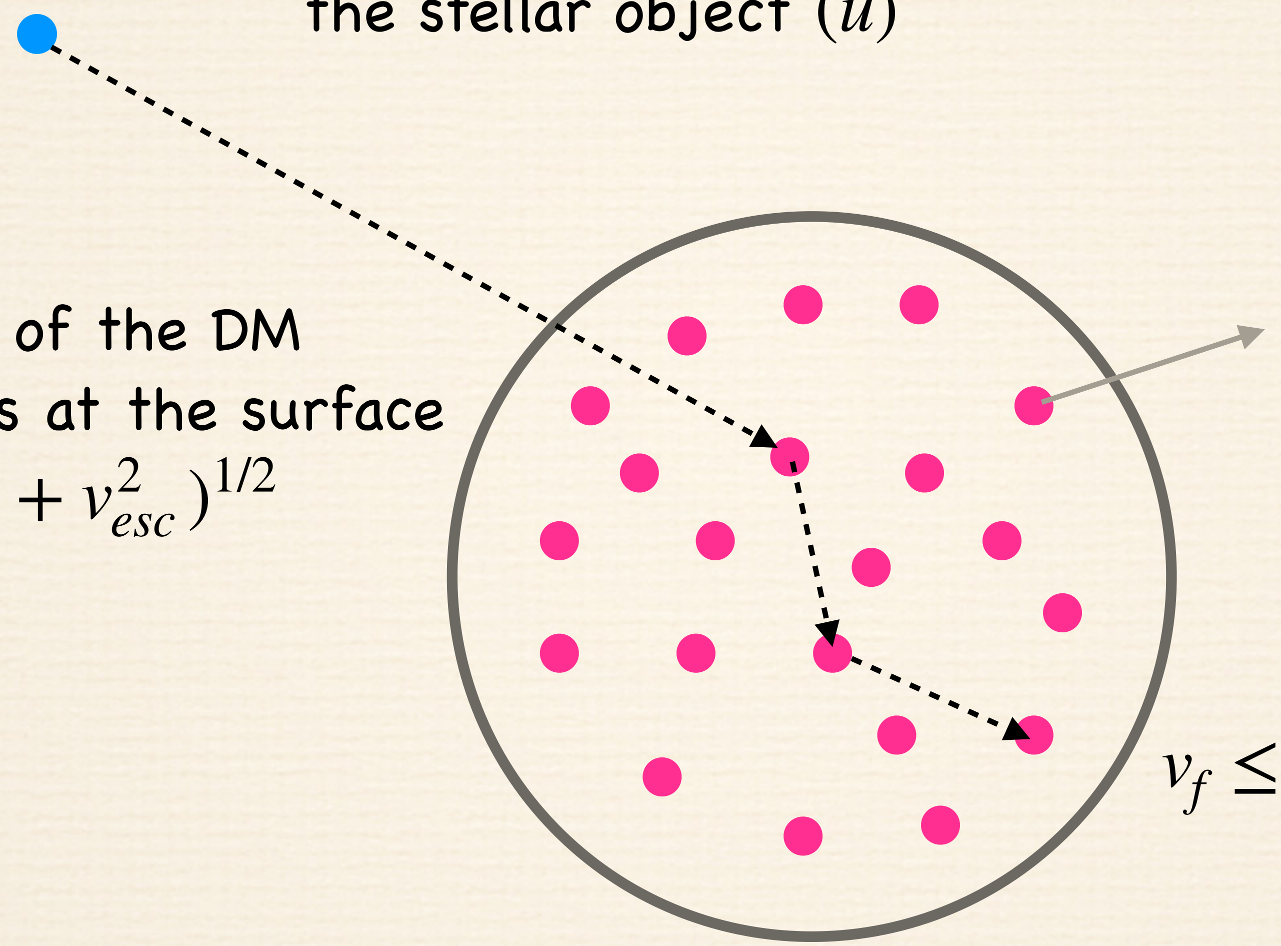
- Origin of a low mass BH (transmuted or primordial) can easily be tested via several simple yet powerful probes.

- Cosmic evolution of the binary merger rates, especially, measurement of binary merger rates at higher redshifts can conclusively determine the origin of low mass BHs, and therefore, can test the particle DM hypothesis.

Formation of low mass transmuted BHs

$\boxed{\text{Dark Core Collapse}}$

DM accretion in stellar objects



v_f : final velocity of the DM particles

$v_{\rm esc}$: escape velocity of the stellar object

Press & Spergel (1985), Gould (1987),...

Gould (1987),...

- Baryonic capture rate of incoming DM particles:

$$\sigma^{\rm sat}_{\chi n} = \frac{\pi R^2}{N_n}$$

Scattering cross section

$$\underbrace{C}_{\text{Capture rate (assumes single scattering)}} = \underbrace{\frac{\rho_\chi}{m_\chi}\int \frac{f(u)du}{u}\left(u^2 + v_{\rm esc}^2\right)}_{\text{Incoming DM flux}} \underbrace{N_n}_{\text{Number of targets}} \,\mathrm{Min}\left[\sigma_{\chi \rm n}, \underbrace{\sigma^{\rm sat}_{\chi \rm n}}_{\text{geometrical cross section}}\right] \mathrm{g}_1(\mathrm{u})$$

Capture rate (assumes single scattering)

Incoming DM flux

Number of targets

geometrical cross section

Capture Probability
$P\left(v_f \leq v_{\rm esc}\right)$

*For a detailed treatment of multiple scattering, see Dasgupta, Gupta, and **Ray** 1906.04204 (JCAP)

*See Dasgupta, Gupta, and **Ray** 2006.10773 (JCAP) for estimation of the capture probability for interactions mediated via arbitrary mass mediators.

- Dark core collapse:

See Genolini, Serpico, Tinyakov 2006.16975 (PRD) for an updated estimation of another transmutation channel via small PBH transit.

Goldman (1989), McDermott (1103.5472), Kouvaris (1104.0382),…, Kouvaris (1804.06740), Dasgupta (2006.10773),…

Total number of captured DM particles $\geq$ Number of particles required for black hole formation

$$t_{\rm age}\, C\left(m_\phi, m_\chi, \sigma_{\chi n}\right) \qquad \mathrm{Max}\left[N_\chi^{\rm self}, N_\chi^{\rm cha}\right]$$

age of the stellar object

required number of DM particles for self-gravitating collapse

Chandrasekhar limit

$$N_\chi^{\rm self} = 4.8\times 10^{41}\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)^{5/2}\left(\frac{T}{10^5\,\mathrm{K}}\right)^{3/2}$$

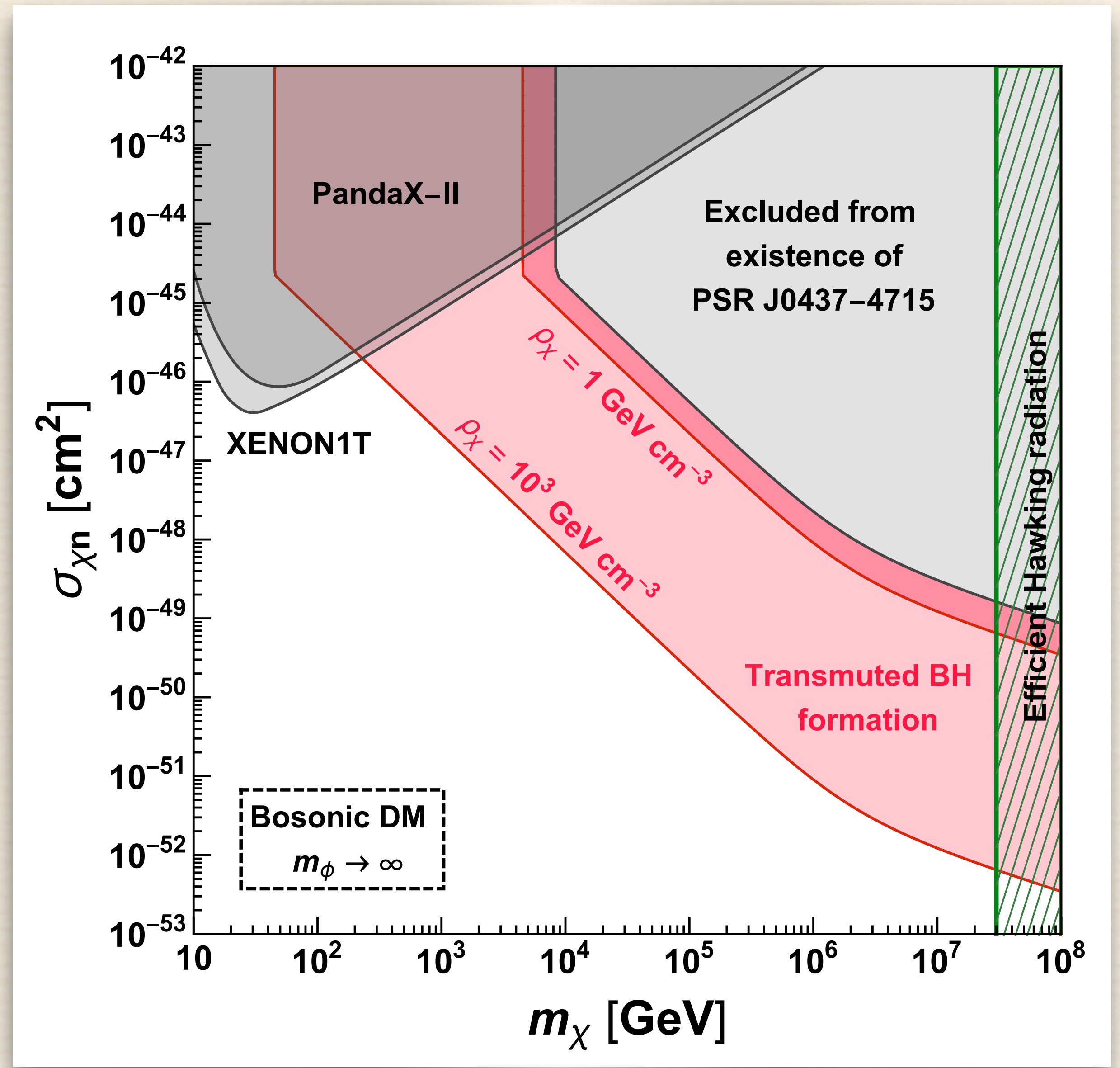
$$N_\chi^{\rm cha} = 1.5\times 10^{34}\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)^{2} \quad \text{Bosonic DM}$$

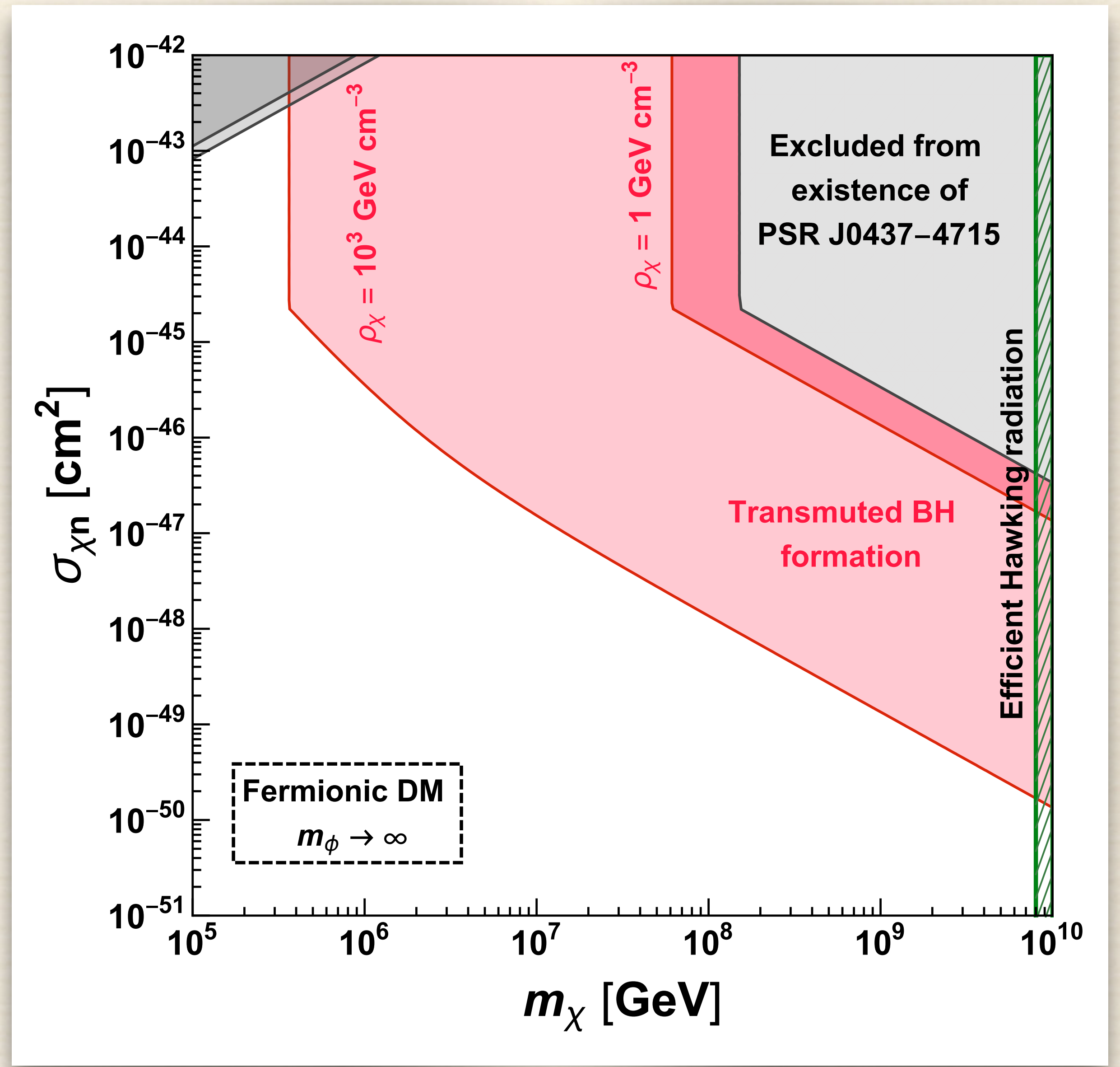
$$N_\chi^{\rm cha} = 1.8\times 10^{51}\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)^{3} \quad \text{Fermionic DM}$$

$N_\chi^{\rm cha}$: depends on DM spin (boson/fermion)

parameter space for transmuted BH formation is different for bosonic and fermionic DM

Dasgupta, Laha, and **Ray** 2009.01825 (PRL)





Parameter space for transmuting a 1.3 $M_\odot$ neutron star to a comparable mass ($\leq$ 1.3 $M_\odot$) BH for non-annihilating bosonic (left)/fermionic (right) DM. Contact interaction between DM and stellar nuclei is assumed in these plots.

Tests for the origin of low mass BHs

(Transmuted or Primordial)

- Cosmic evolution of the binary merger rates. ✓
- Mass distribution of the compact objects.

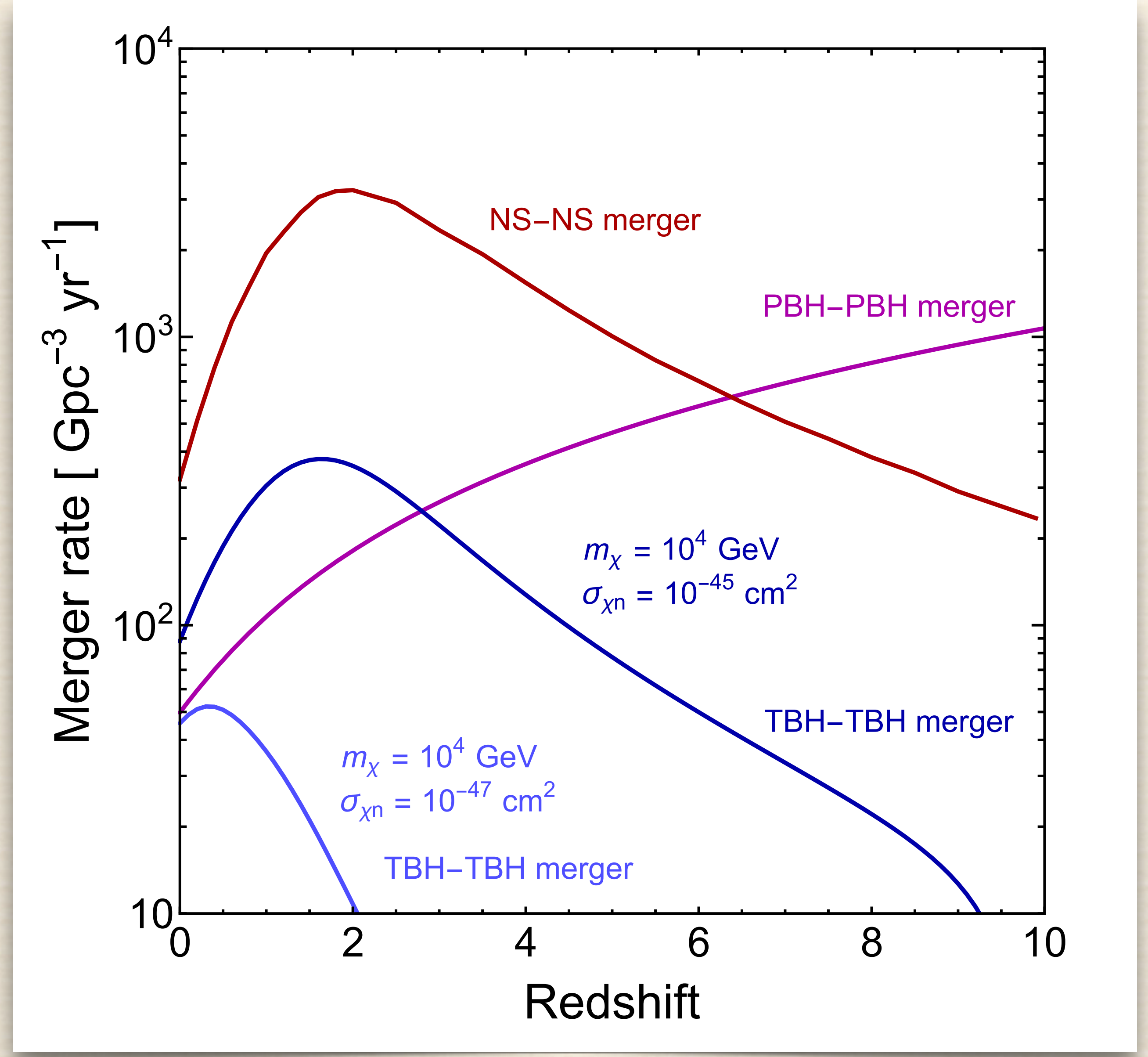
  See also Takhitsov, Fuller, Kusenko 2008.12780 (PRL)

- Ambient DM density around the compact objects.

Cosmic evolution of the binary merger rates

- Redshift dependence of the binary merger rates can be used as a probe to determine the origin of low mass BHs

Mergers as a probe of particle DM



Distinct redshift dependence of the binary NS, PBH and transmuted BH (TBH) merger rates, especially at higher redshifts can be measured by the upcoming third generation GW experiments (Pre-DECIGO, Einstein Telescope).

Dasgupta, Laha, and **Ray** 2009.01825 (PRL)

Summary & Conclusions

- sub-Chandrasekhar mass BH is not a smoking gun signature of its primordial origin.

- Non-annihilating DM with non-zero interaction strength with nuclei is sufficient to produce a sub-Chandrasekhar mass BH of non-primordial origin.

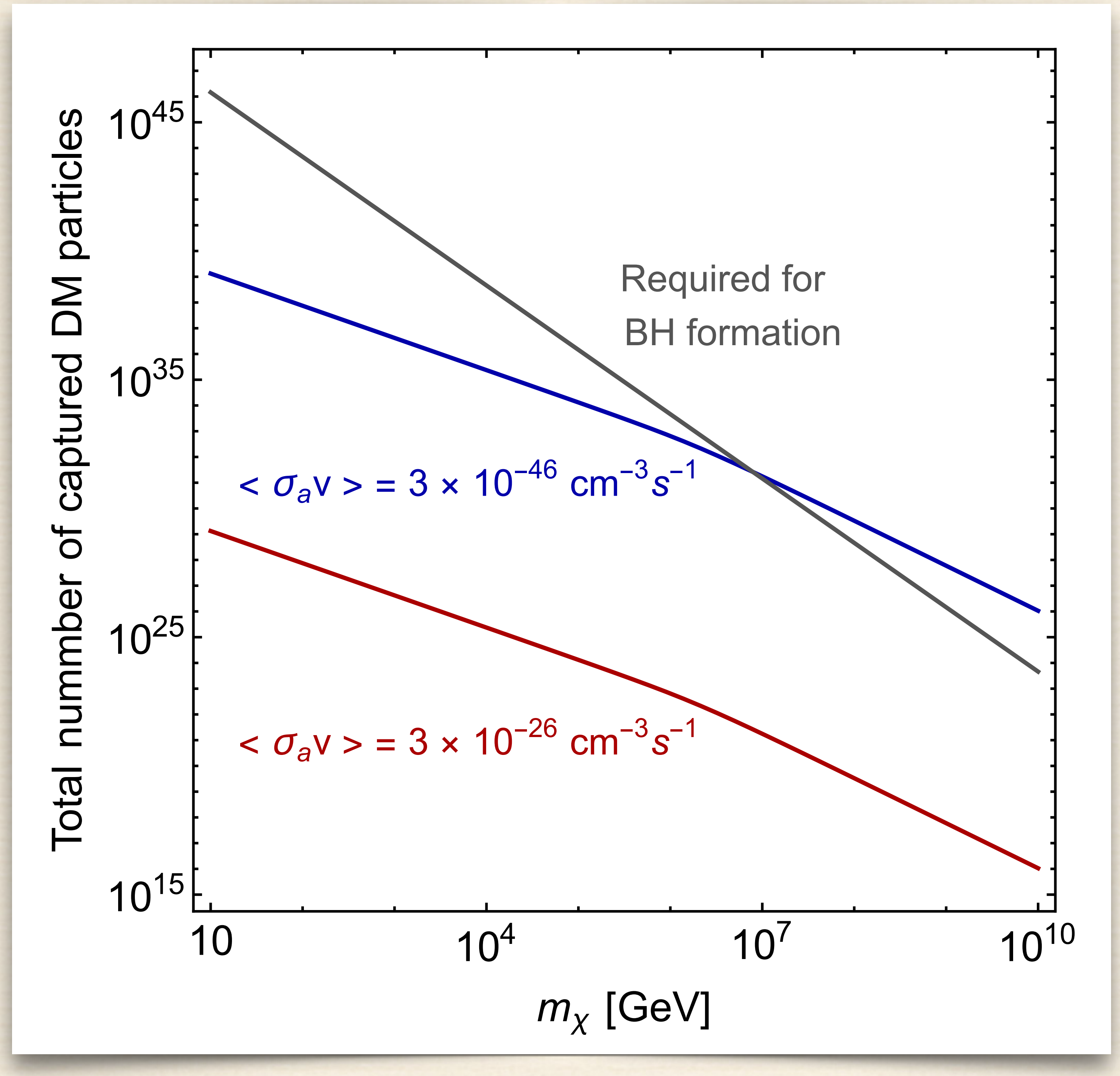
- With remarkable advances in GW astronomy, we have already started to observe unusually low mass BHs; measurements of the binary merger rates, especially at high redshifts by the upcoming GW experiments will settle their origin, and hence, can test the particle DM hypothesis.

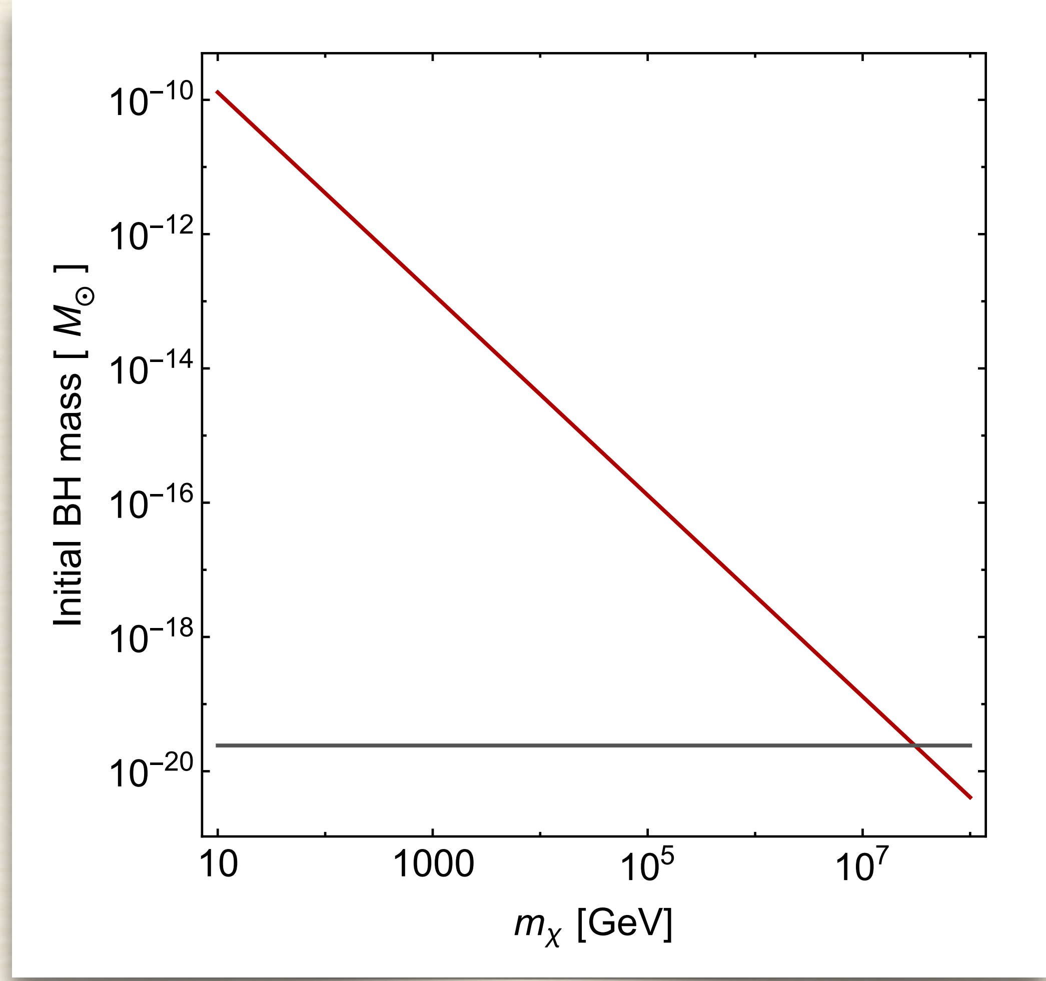
- LIGO can act as a "direct detection" experiment of particle dark matter! (In prep.)

Thanks!

Questions & Comments: anupam.ray@theory.tifr.res.in

Back Up Slides

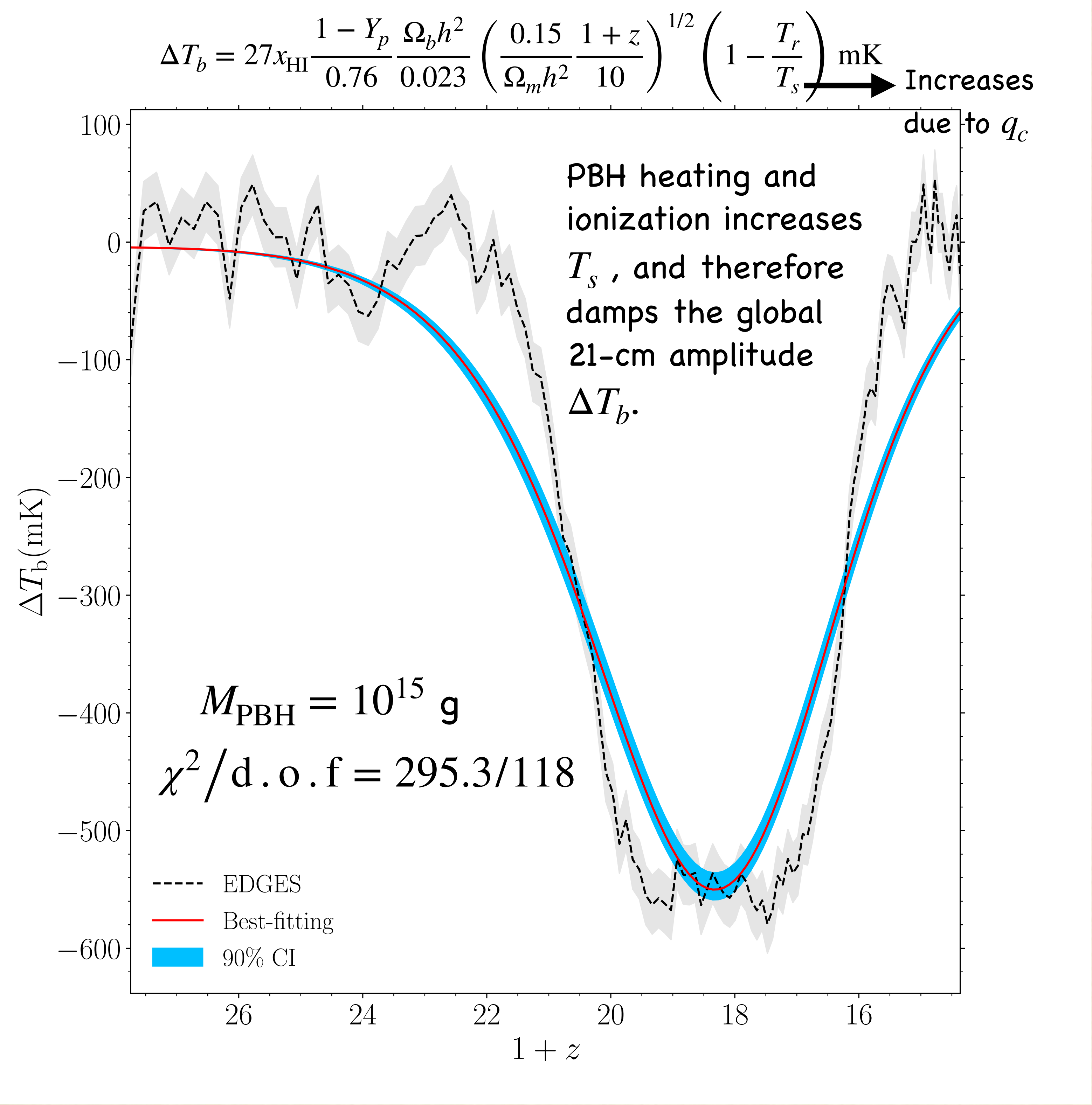




Baumgarte et al 2101.12220,
Richards et al 2102.09574
Schnauck et al 2110.08285

$$\tau_{\text{swallow,max}} = 10^6\,\mathrm{s}\left(\frac{10^{-10}\,\mathrm{M}_\odot}{\mathrm{M}_{\text{init,BH}}}\right)$$

Mittal, **Ray,** Kulkarni, Dasgupta 2107.02190



Best-fitting values:

$\log f_\alpha = 0.02^{+0.007}_{-0.007}$

$\log(T_{\rm vir} \times 10^{-4}) = 0.25^{+0.001}_{-0.001}$

$\log f_X = 0.50^{+0.01}_{-0.01}$

$\log \zeta_{\rm ERB} = -1.27^{+0.02}_{-0.02}$

$\log f_{\rm PBH} \leq -9.73$

f_α : Ly-α background

$T_{\rm vir}$: Virial temp of DM halo

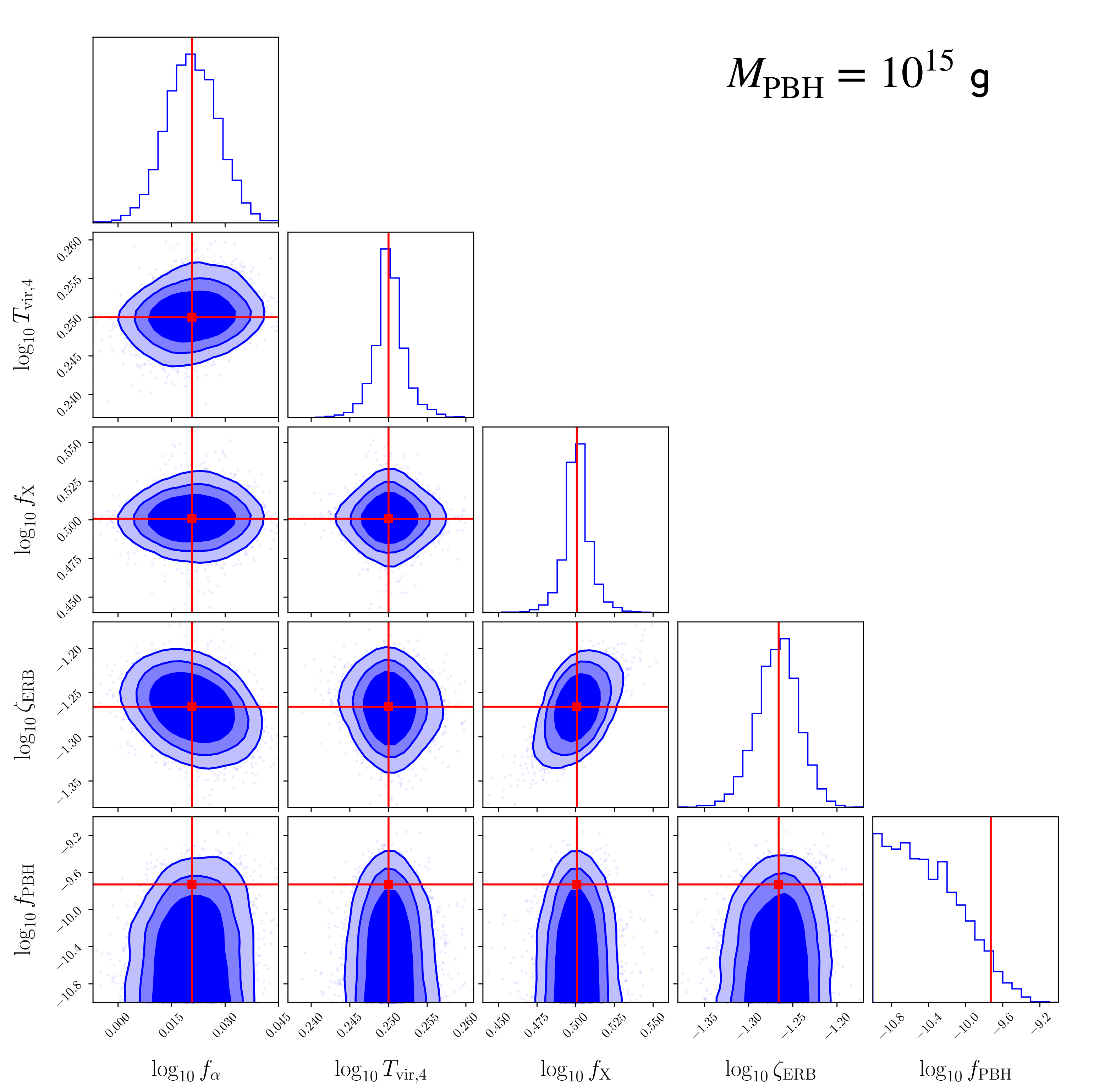
f_X : X-ray background

$\zeta_{\rm ERB}$: Excess radio background

$f_{\rm PBH}$: Fraction of DM in the form of PBHs

Best fit to the EDGES measurement of the global 21-cm signal for monochromatic non-rotating PBHs of mass 10^{15} g.

Mittal, **Ray,** Kulkarni, Dasgupta 2107.02190



Marginalised posterior distribution of the parameters for monochromatic non-rotating PBHs of mass 10^{15} g.

Best-fitting values:

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