Valentina De Romeri

(IFIC Valencia - UV/CSIC)

Signatures of primordial black hole dark matter at DUNE and THEIA

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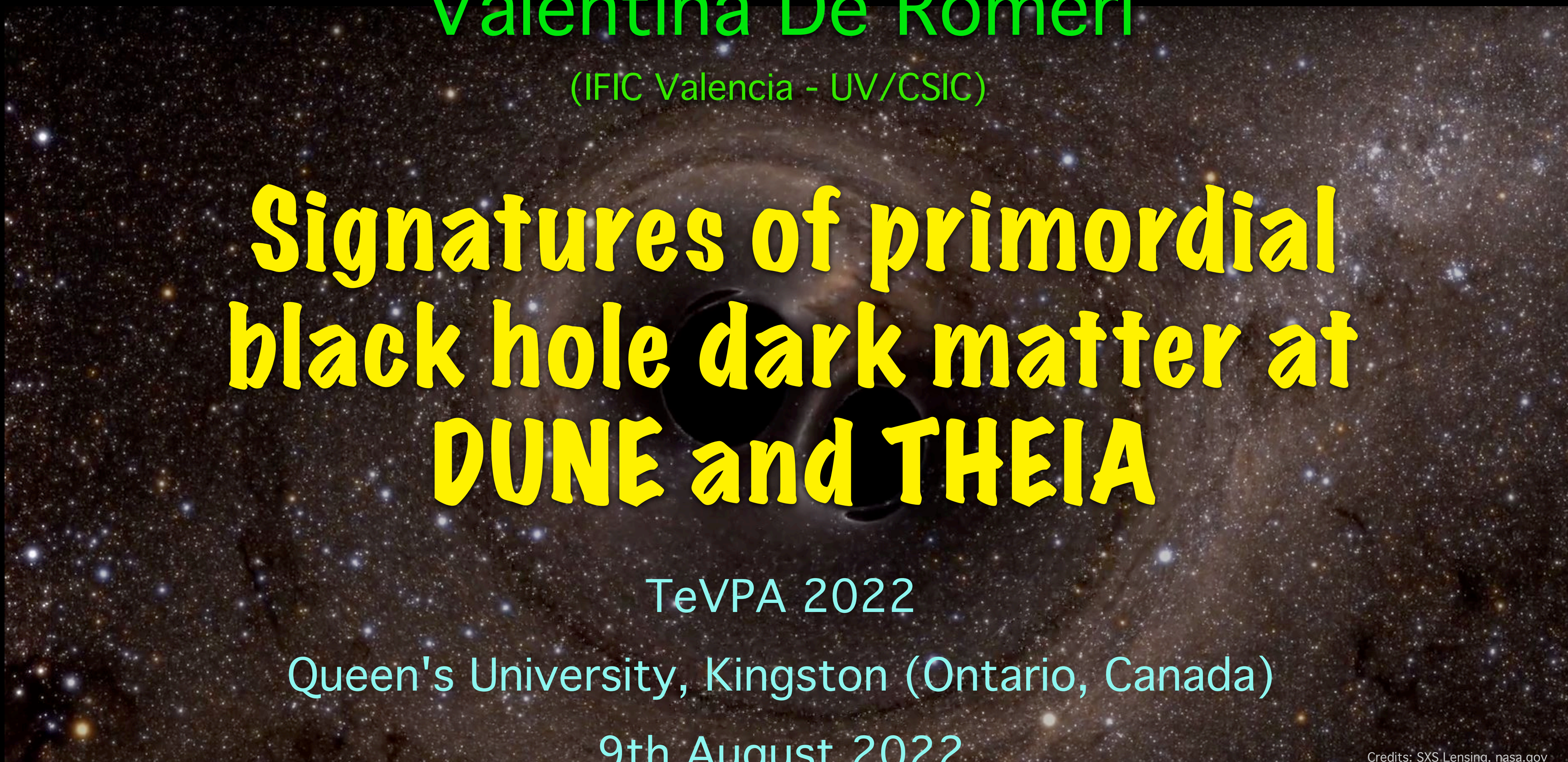


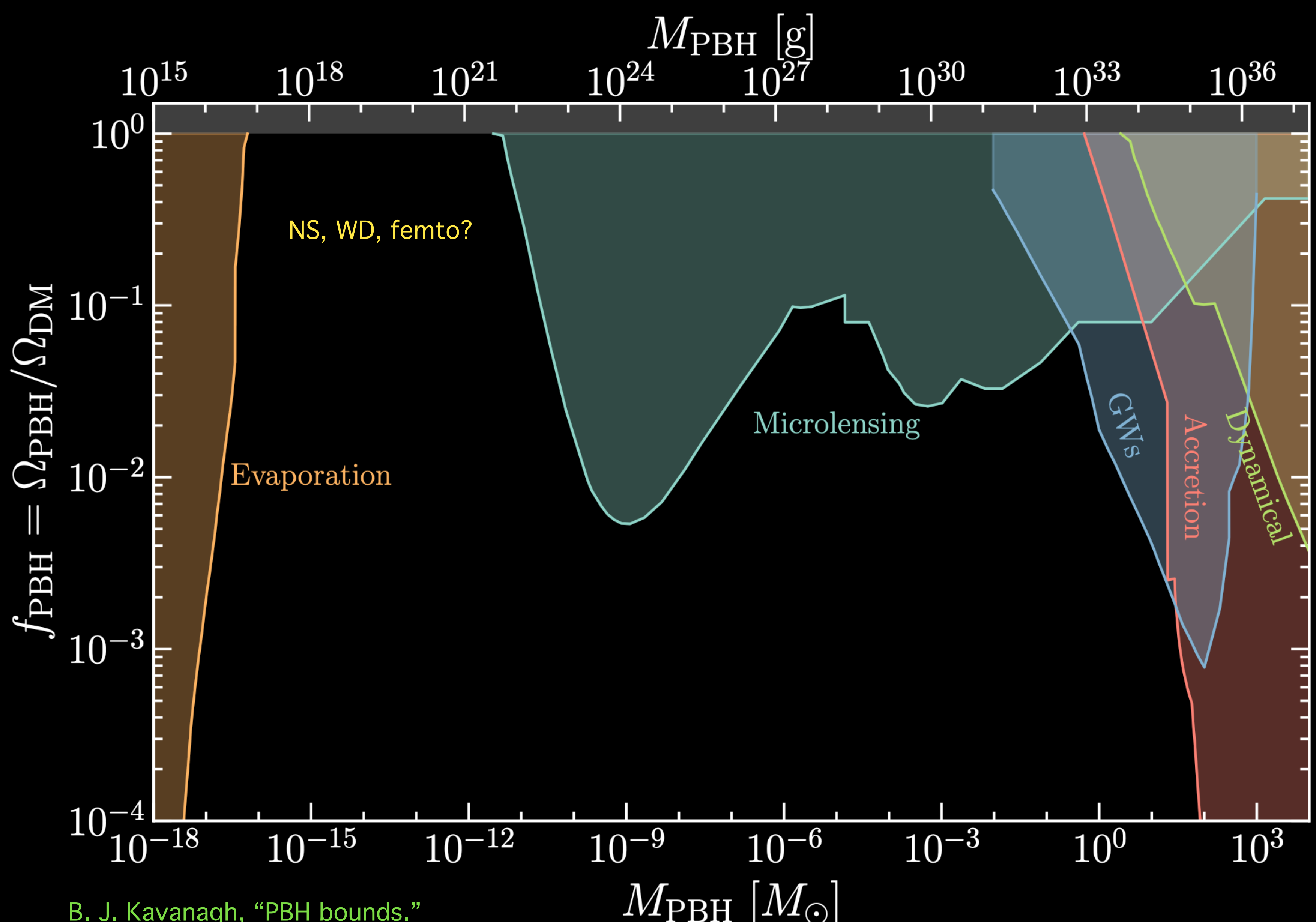
Credits: SXS Lensing, nasa.gov

Based on JCAP10(2021)051 in collaboration with Pablo Martínez-Miravé, Mariam Tórtola

Primordial black hole dark matter

Primordial black holes are formed from collapse of primordial inhomogeneities in the early Universe before the BBN epoch. They constitute one of the earliest proposed and appealing DM candidates.

Hawking (1971), Zeldovich, Novikov (1966), Y. B. . N. Zel'dovich, I. D., (1967), Chapline (1975)



B. J. Kavanagh, "PBH bounds."
https://github.com/bradkav/PBHbounds.

Primordial Black Holes evaporation

- Black holes are thought to evaporate via Hawking radiation, emitting particles near their event horizons.

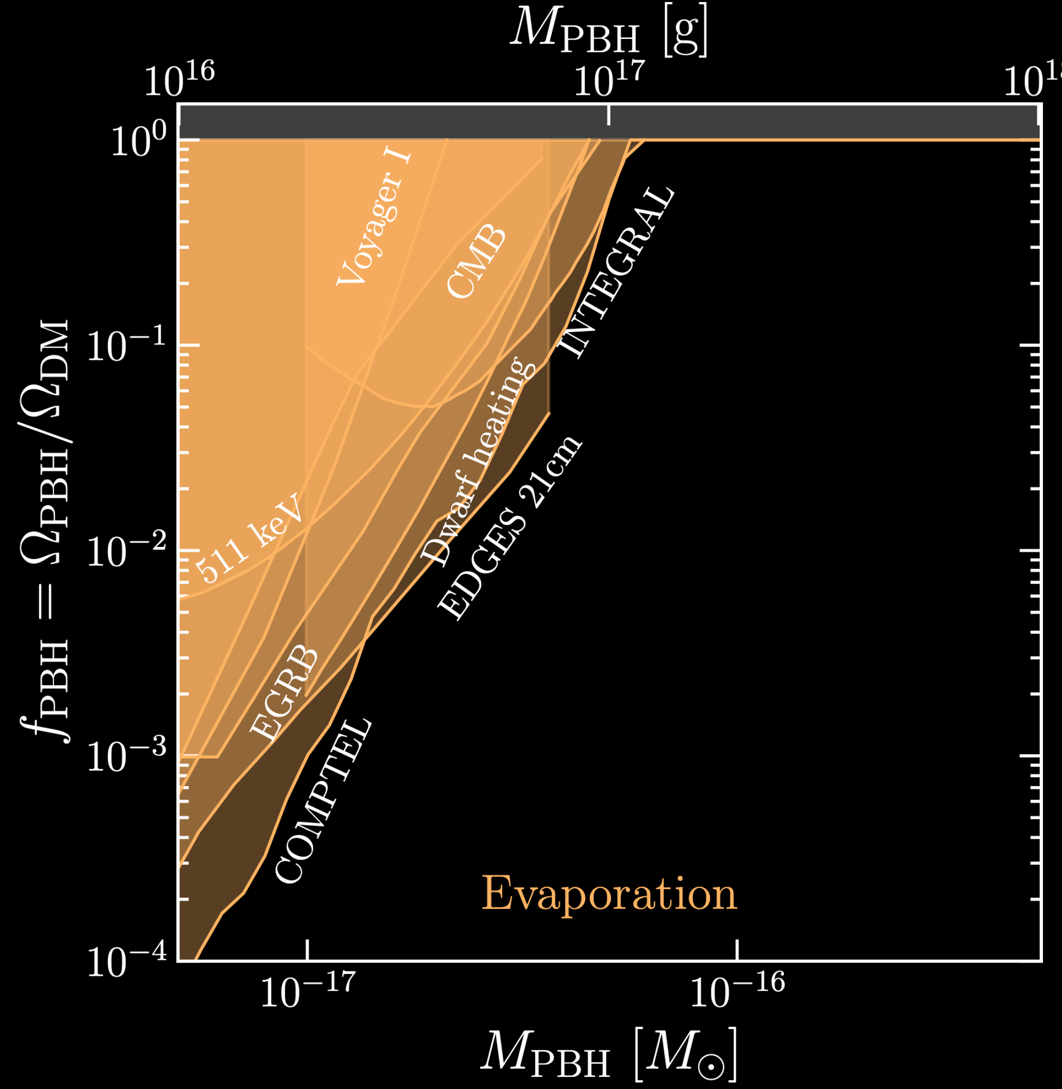
Hawking (1974, 1975)

- Very light non-rotating (maximally rotating) PBHs with $M_{PBH} < 5\ (7) \times 10^{14}$ g are expected to have completely evaporated by now.

D. N. Page (1976), MacGibbon+ (2008)

- A large number of constraints have been derived on the abundance of light PBH in the 10^{15}–10^{17} g mass range, from the non-observation of their evaporation products: γ rays, electrons/positrons and neutrinos.

- Further constraints: from CMB and BBN, the EDGES measurements of 21cm absorption, or the heating of interstellar medium.



B. J. Kavanagh, "PBH bounds." https://github.com/bradkav/PBHbounds.

Carr (1976), Lehoucq+ (2009), Wright (1996), Ballesteros+ (2019), Laha+ (2020), Boudaud&Cirelli (2019), Dasgupta+ (2019), DeRocco& Graham (2019), Laha (2019), Clark+ (2017), Stöcker+ (2018), Acharya&Khatri (2020), Keith+ (2020), Clark+ (2018), Hektor+ (2018), Carr+ (2010), Coogan+ (2020) …

Neutrinos from PBH evaporation

A rotating BH emits elementary particles following a blackbody-like distribution.
We rely on the public tool *BlackHawk* to compute both the instantaneous and the full time-dependent emission of neutrinos from a PBH of a given mass and spin.

Arbey and Auffinger (2019)

Two contributions:

- Primary: neutrinos directly emitted in the evaporation of the PBH
- Secondary: stems from the hadronization and subsequent decay of the primary particles

Both PBHs in the galactic halo and outside contribute to the differential neutrino flux from PBH evaporation:

Galactic contribution

(NFW)

$$\frac{d\phi^{\nu}_{\rm gal}}{dE} = \frac{f_{\rm PBH}}{M_{\rm PBH}} \frac{d^2N}{dE dt} \int \frac{1}{4\pi} d\Omega \int \boxed{\rho_{\rm MW}\left[r(\ell,\psi)\right]} d\ell$$

Extragalactic contribution

(E$_0$ = neutrino energy at the source)

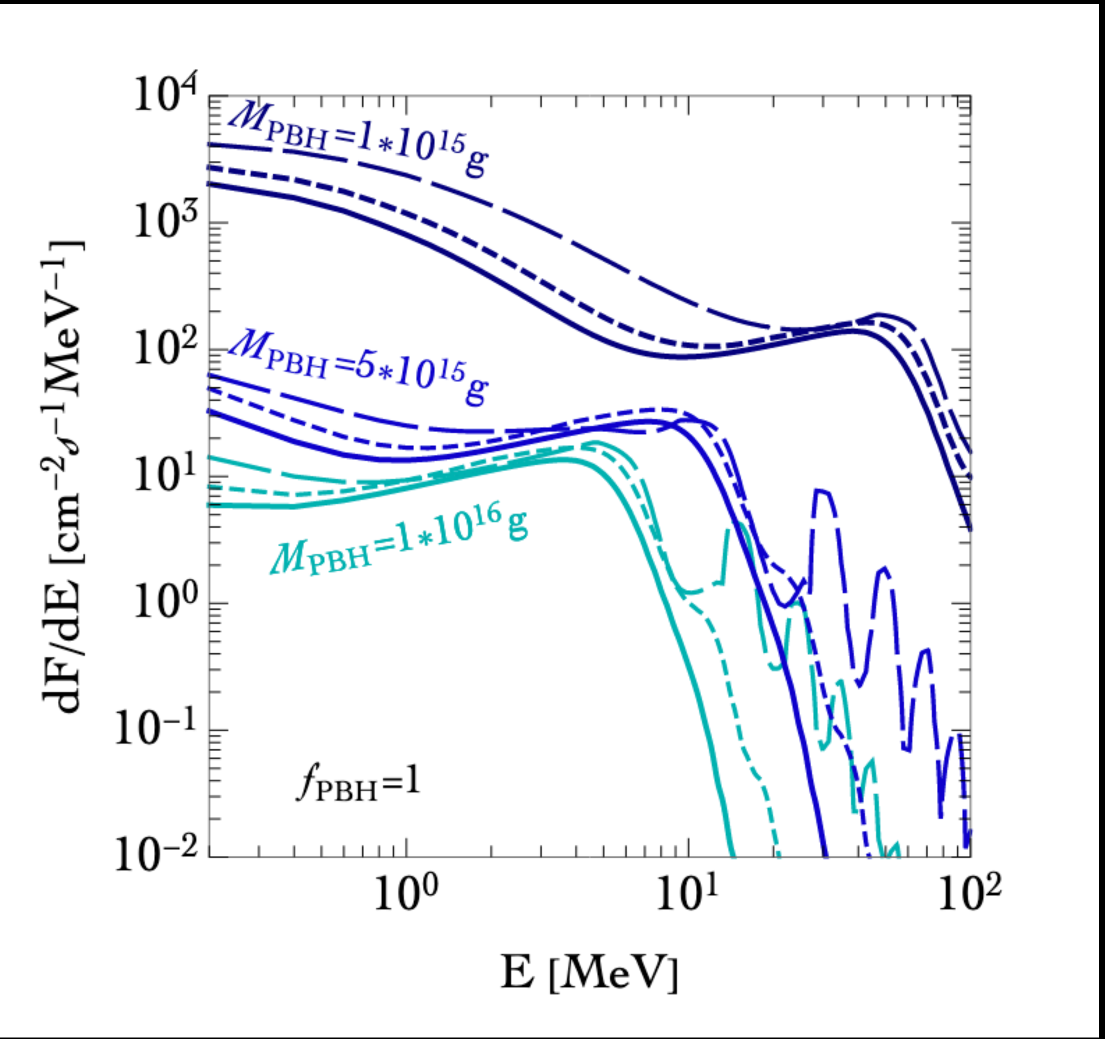
$$\frac{d\phi^{\nu}_{\rm exg}}{dE} = \frac{f_{\rm PBH}\,\bar{\rho}_{\rm DM}}{M_{\rm PBH}} \int_{t_{\rm min}}^{t_{\rm max}} dt [1+z(t)] \left.\frac{d^2N}{dE_0 dt}\right|_{\boxed{E_0=[1+z(t)]E}}$$

Assumption: the DM is distributed isotropically at sufficiently large scales.
The exg differential neutrino flux over the full sky is estimated as the redshifted sum over all epochs emission.

Neutrinos from PBH evaporation

Total differential ν_e flux from PBHs. We assume a monochromatic PBH mass distribution and different PBH spins.

- Heavier PBHs lead to reduced fluxes, shifted towards smaller neutrino energies.
- The dominant (smooth) contribution to the flux stems from particles emitted with no additional angular momentum apart from their intrinsic spin.
- Peaks at higher energies: radiation of particles with higher angular momentum, leading to a substantial enhancement of the flux if the latter is aligned with the PBH one.



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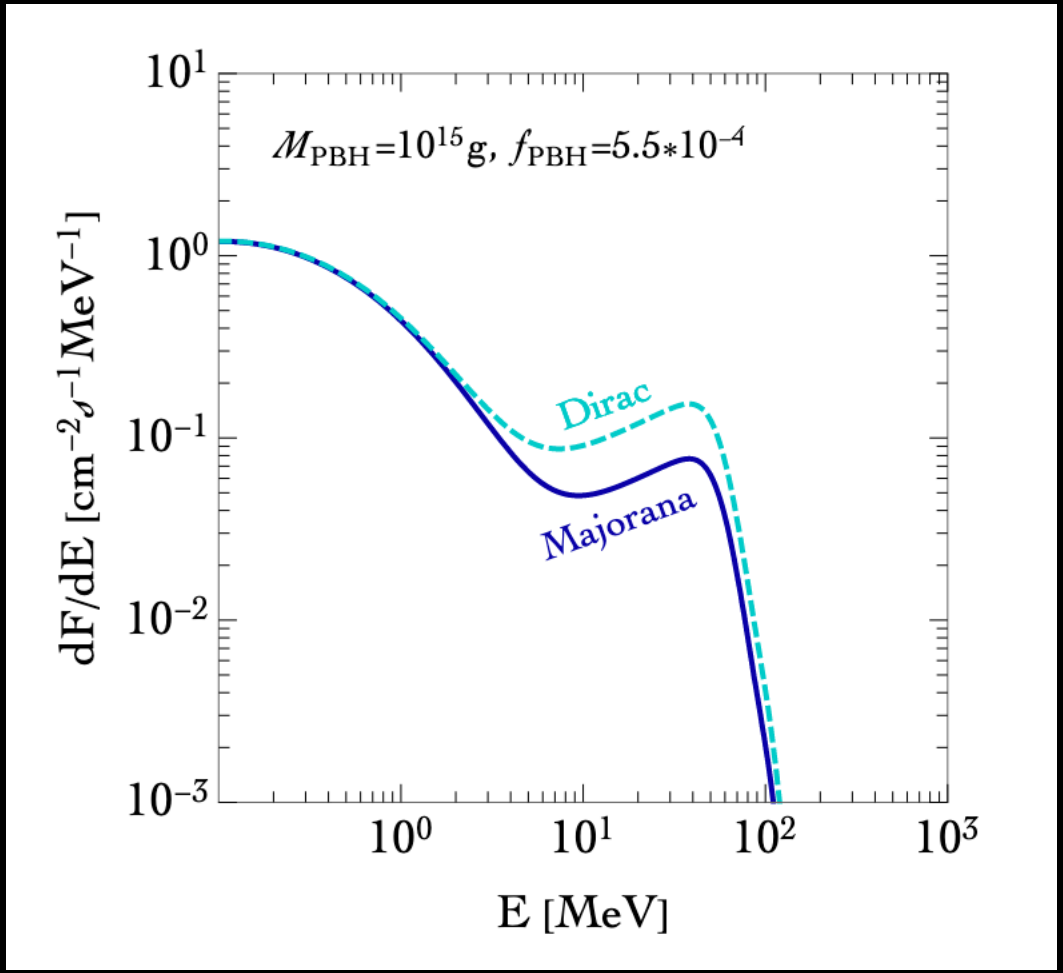
Neutrinos from PBH evaporation

The PBH evaporation rate depends on the total number of degrees of freedom of the emitted particles, as well as on their masses.

- Neutrinos are considered to be massless (non-zero masses would make a very small difference) and with a Majorana nature.
- We do not include the effect of neutrino mixing in our analysis.
- Flavour conversions would only affect the secondary components.
- Considering neutrino mixing would reduce the total differential flux by less than ~ 2%



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Monochromatic vs extended mass distribution

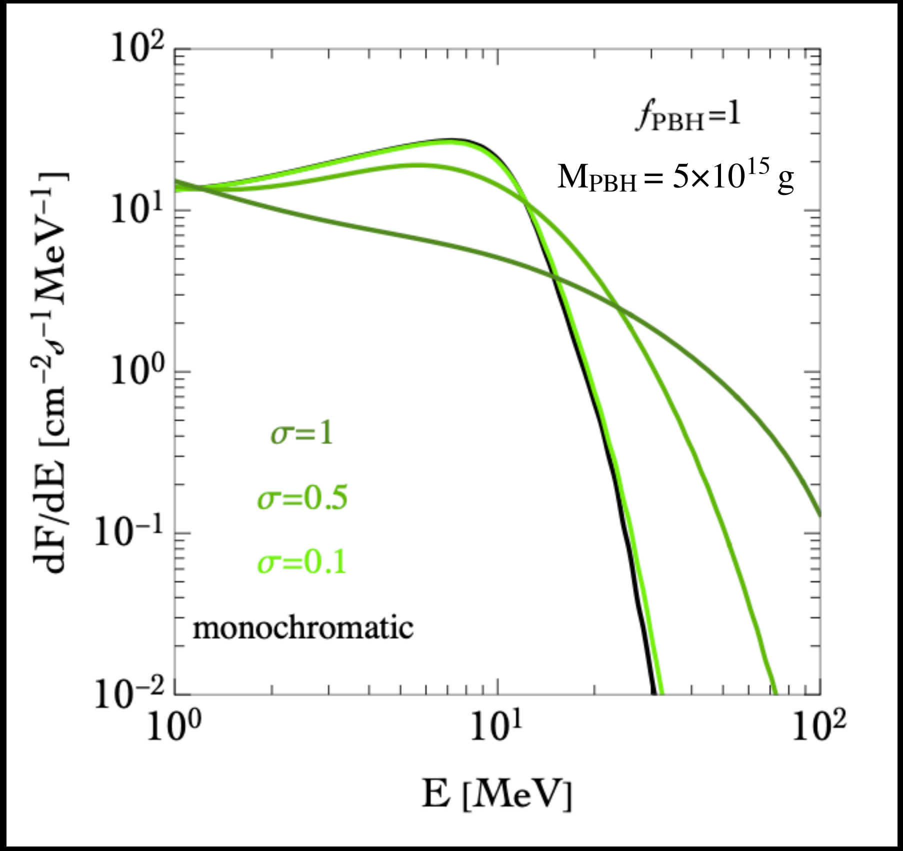
A large variety of formation mechanisms predicts extended mass distributions for PBHs.
A common approximation to the true mass distribution generated from a peak in the power spectrum of primordial fluctuations is the log-normal distribution for the comoving number density:

M_c: critical mass (referring to the position of the peak)

$$\frac{dN_{\rm PBH}}{dM_{\rm PBH}} = \frac{1}{\sqrt{2\pi}\sigma M_{\rm PBH}} \exp\left[-\frac{\ln\left(M_{\rm PBH}/M_c\right)^2}{2\sigma^2}\right]$$

width of the distribution

The larger the distribution width, the more the typical "peak" from the galactic primary contribution is smoothed down and, as a result, the flux is still sizeable at larger energies



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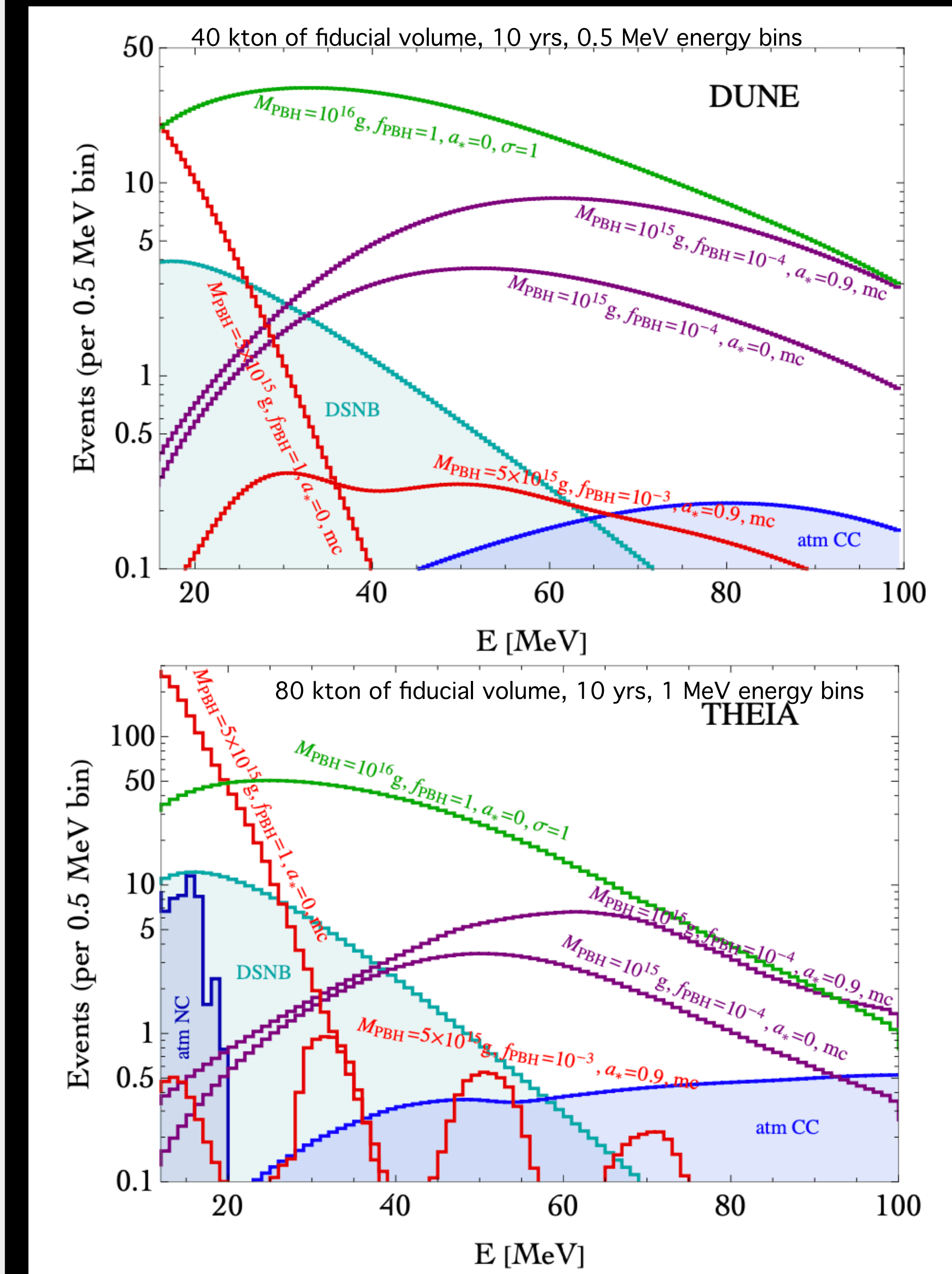
Event spectra at future facilities



Predicted ν_e event rate from PBH evaporation at the DUNE far detector, mainly sensitive to the ν_e component of the PBH neutrino flux via the process

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}K^*$$

Bckgs: solar neutrinos (<16 MeV) and CC atm neutrinos (>30 MeV).

▶ SNOwGLoBES

DUNE collab. Abi+ (2020)
http://www.phy.duke.edu/~schol/snowglobes
DSNB: de Gouvêa+ Phys. Rev. D 102 (2020) 123012

THEIA is a proposal for a water-based liquid scintillator (obtained by adding ultra-pure water to an organic scintillator). The dominant reaction channel will be IBD: $\bar{\nu}_e + p \rightarrow e^+ + n$

Bckgs: solar neutrinos, CC atm neutrinos, reactor neutrinos and NC high-energy atmospheric neutrinos.

Theia collab. M. Askins+, EPJC 80 5 (2020)

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Statistical analysis

We assume the following least-squared functions:

$$\chi^2_{\rm DUNE} = \sum_i \left(\frac{N_i^{\rm PBH} + (1+\alpha) N_i^{\rm atmCC} + (1+\beta) N_i^{\rm DSNB} - N_i^{\rm atmCC} - N_i^{\rm DSNB}}{\sqrt{N_i^{\rm PBH} + N_i^{\rm atmCC} + N_i^{\rm DSNB}}} \right)^2 + \left(\frac{\alpha}{\sigma_\alpha}\right)^2 + \left(\frac{\beta}{\sigma_\beta}\right)^2$$

The nuisance parameters α and β account for uncertainties on the backgrounds (DSNB and atm CC). We fix their standard deviations to $\sigma_\alpha = 0.35$ and $\sigma_\beta = 0.35$.

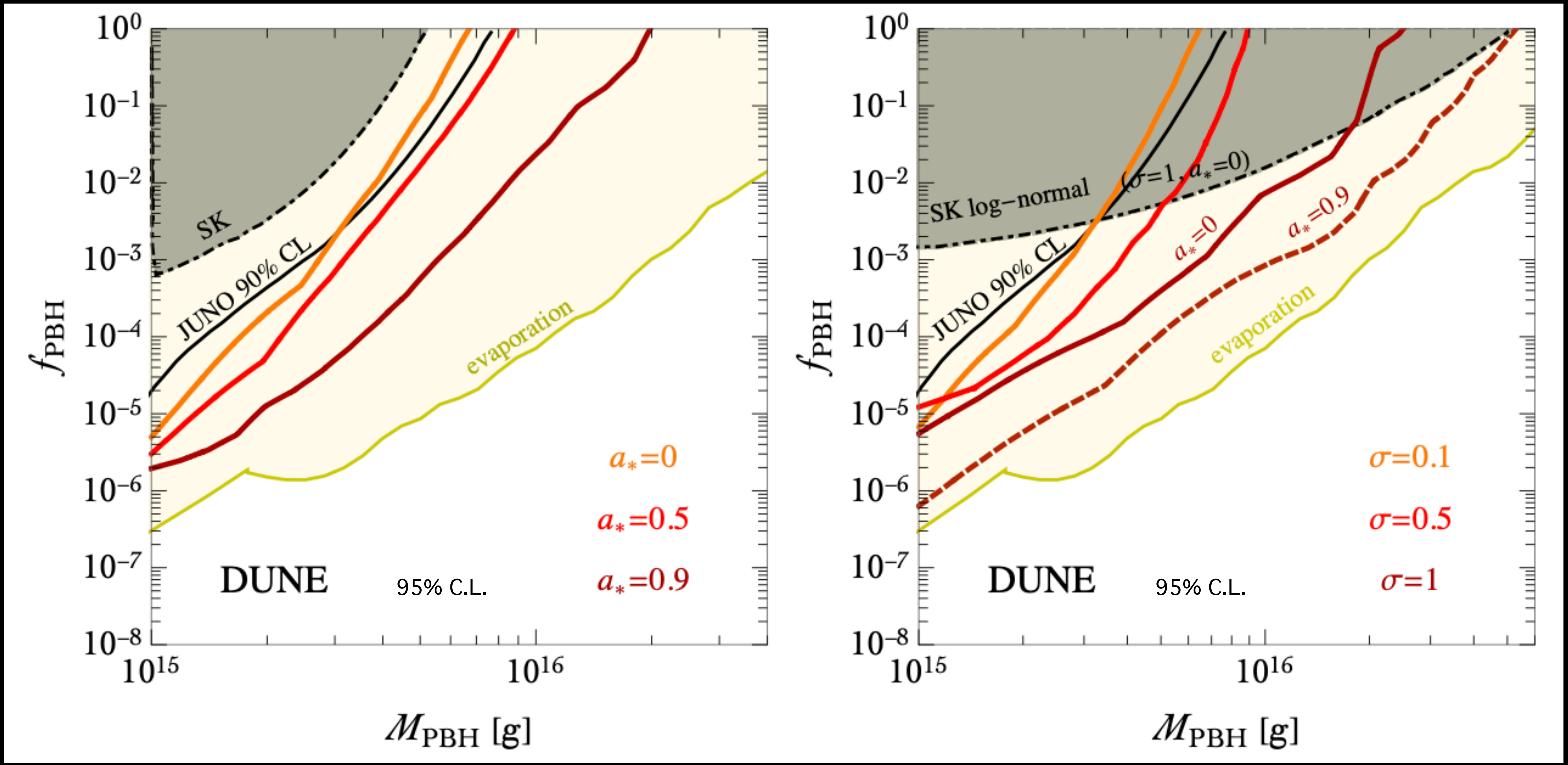
Battistoni+, Astropart. Phys. 23 (2005) 526–534
Sawatzki+, Phys. Rev. D 103 no. 2, (2021)
Guo, Phys. Rev. D 99, 073007
De Gouvêa+, Phys. Rev. D 102 (2020) 123012

$$\chi^2_{\rm THEIA} = \sum_i \left(\frac{N_i^{\rm PBH} + (1+\alpha) N_i^{\rm atmCC} + (1+\beta) N_i^{\rm DSNB} + (1+\gamma) N_i^{\rm atmNC} - N_i^{\rm atmCC} - N_i^{\rm DSNB} - N_i^{\rm atmNC}}{\sqrt{N_i^{\rm PBH} + N_i^{\rm atmCC} + N_i^{\rm DSNB} + N_i^{\rm atmNC}}} \right)^2 + \left(\frac{\alpha}{\sigma_\alpha}\right)^2 + \left(\frac{\beta}{\sigma_\beta}\right)^2 + \left(\frac{\gamma}{\sigma_\gamma}\right)^2 . \quad (12)$$

σ_γ refers to the atm NC background, and is fixed to 30%.

KamLAND Collaboration, Astrophys. J. 745 (2012) 193
Cheng+, Phys. Rev. D 103 (Mar, 2021) 053002

PBH sensitivities at DUNE



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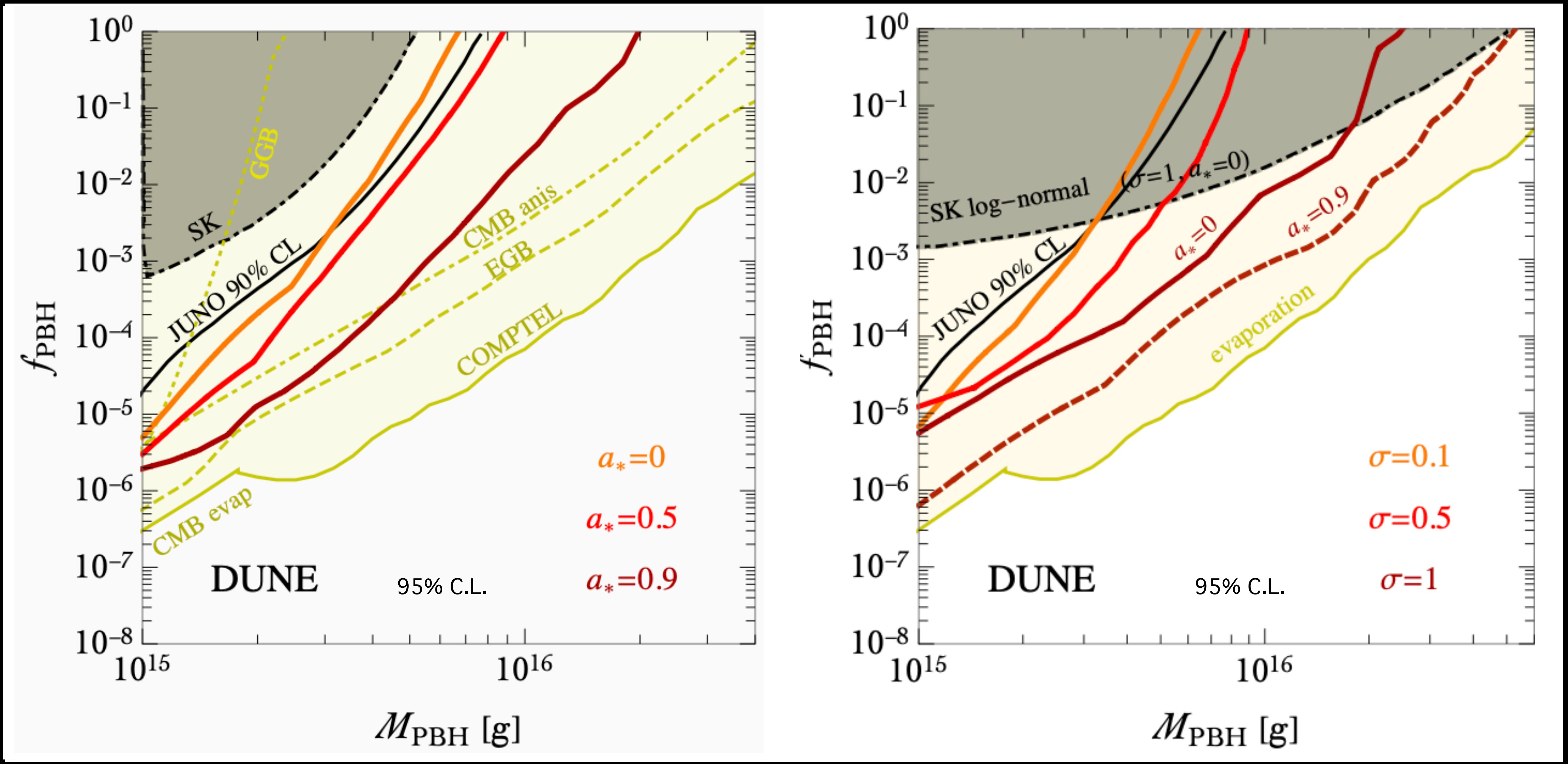
Super-Kamiokande: current bound from neutrinos

Dasgupta+, Phys. Rev. Lett. 125, 101101
See also: Bernal+ 2203.14979

Evaporation bounds: mainly extragalactic γ–ray background, CMB and MeV extragalactic γ-ray background and soft γ rays from COMPTEL.

JUNO: Wang+, Phys. Rev. D 103 no. 4, (2021) 043010

PBH sensitivities at DUNE



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Super-Kamiokande: current bound from neutrinos Dasgupta+, Phys. Rev. Lett. 125, 101101 See also: Bernal+ 2203.14979

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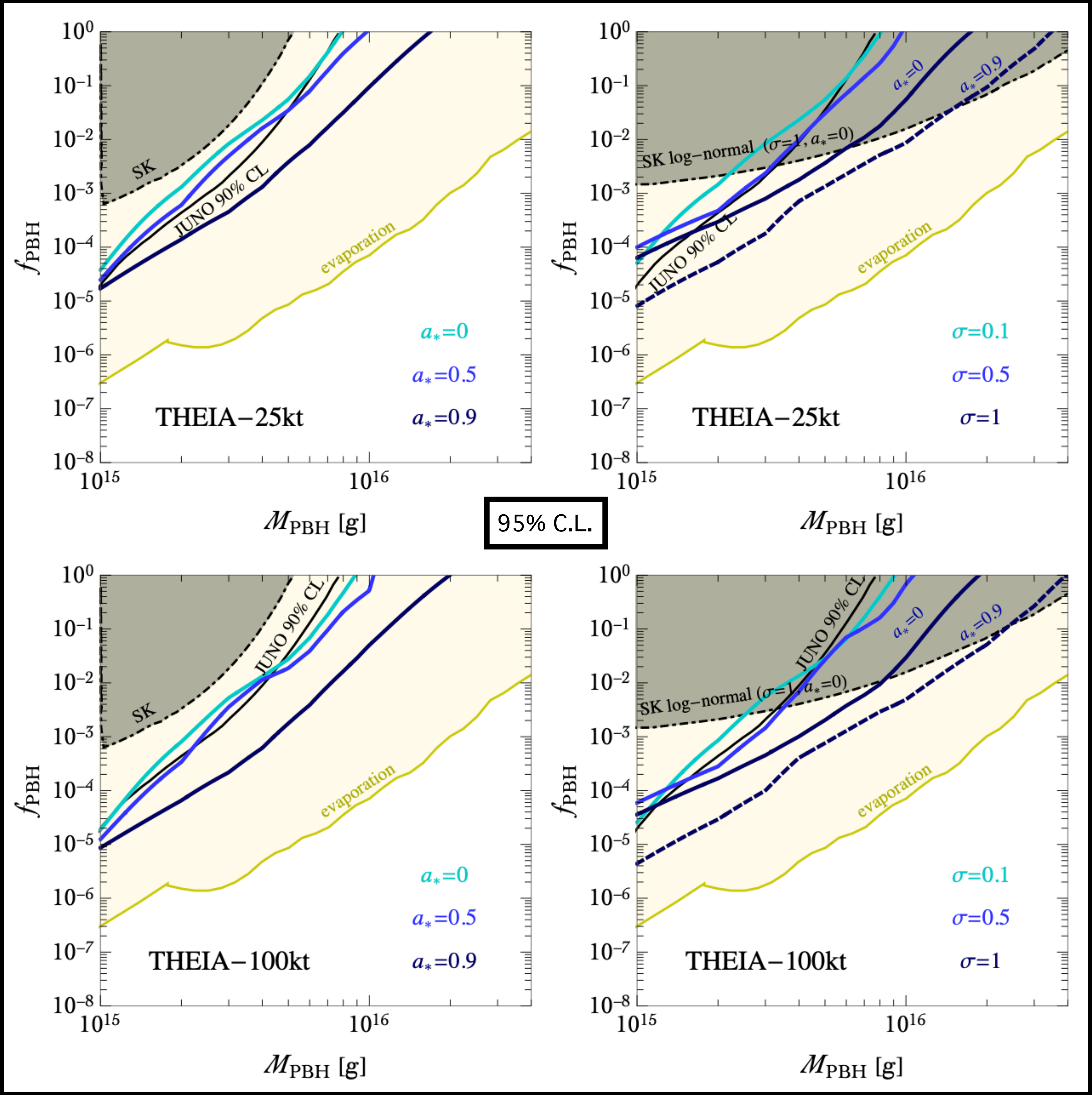
JUNO: Wang+, Phys. Rev. D 103 no. 4, (2021) 043010

PBH sensitivities at Theia



Conclusions

- Primordial black holes are a viable dark matter candidate, whose masses can span over several orders of magnitude.
- Light PBHs with masses in the range $10^{15} - 10^{17}$ g would evaporate and produce sizeable fluxes of MeV neutrinos via Hawking radiation.
- We have explored the possibility of detecting neutrinos from PBH evaporation with the future neutrino experiments DUNE and THEIA.
- Our analysis shows that both DUNE and THEIA could considerably improve the existing bounds from Super-Kamiokande on the abundance of PBHs with masses between $10^{15} - 10^{16}$ g, and even allow to probe heavier PBHs up to $\sim 5 \times 10^{16}$ g.
- Next-generation neutrino facilities could set competitive bounds on the PBH parameter space, complementary to existing limits from other cosmic messengers.
- The quest for PBH dark matter at future neutrino experiments like DUNE and THEIA could be easily included in their physics programmes, leveraging existing supernova neutrino analyses.


Thank you!
Credits: SXS Lensing, nasa.gov