A novel search for Primordial Black Holes with Axions at large volume neutrino detectors

Yongsoo Jho (Yonsei U.)

Based on collaboration with
T.-G. Kim, Y. Park, D.-Y. Cheong and S. Park
(in progress)

2024 Saga-Yonsei Joint Workshop

Axions

Primordial Black Holes

Main keywords of this talk

Axions

Axion in particle physics

Axion is a pseudo-scalar (i.e. axial) particle with CP-odd parity which appears at low energy spectrum of the theory.

Axion in particle physics

Axion is a pseudo-scalar (i.e. axial) particle with CP-odd parity which appears at low energy spectrum of the theory.

Most generic Effective Lagrangian to SM fields:

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a}\frac{g_s^2}{32\pi^2}G\tilde{G} + \frac{1}{4}g^0_{a\gamma}aF\tilde{F} + \frac{\partial_\mu a}{2f_a}\bar{q}c^0_q\gamma^\mu\gamma_5 q - \bar{q}_L M_q q_R + \text{h.c.}\,.$$

Axion in particle physics

Axion is a pseudo-scalar (i.e. axial) particle with CP-odd parity which appears at low energy spectrum of the theory.

Most generic Effective Lagrangian to SM fields:

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a}\frac{g_s^2}{32\pi^2}G\tilde{G} + \frac{1}{4}g^0_{a\gamma}aF\tilde{F} + \frac{\partial_\mu a}{2f_a}\bar{q}c^0_q\gamma^\mu\gamma_5 q - \bar{q}_L M_q q_R + \text{h.c.}\,.$$

It can be (usually) originated from

1) Spontaneously broken accidental symmetries (pseudo-Goldstone boson)
2) Dimensional reduction of higher-dimensional gauge fields
3) Longitudinal mode of anomalous gauge fields in effective field theories

Why axion?

- Axion appears ubiquitously at various UV completions of particle theory.

Why axion?

- **Axion appears ubiquitously at various UV completions of particle theory.**

- **Theoretically,**

  - commonly expected to appear at low energy spectrum of the theory.
  (ex. string theory)

Why axion?

- Axion appears ubiquitously at various UV completions of particle theory.
- Theoretically,

  - commonly expected to appear at low energy spectrum of the theory.
  (ex. string theory)

- Phenomenologically,

  - suggested to resolve Strong CP problem

  - could explain some fraction of dark matter/dark energy?

  - (what else?)

Axions are usually expected to be

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a}\frac{g_s^2}{32\pi^2}G\tilde{G} + \frac{1}{4}g^0_{a\gamma}aF\tilde{F} + \frac{\partial_\mu a}{2f_a}\bar{q}c^0_q\gamma^\mu\gamma_5 q - \bar{q}_L M_q q_R + \text{h.c.}\,.$$

- **Light : since it is usually pseudo-goldstone boson**
  (its precise mass depends on non-perturbative effects)

- **Feebly interact with gauge and matter fields**
  (suppressed by large scale of axion decay constant)

- **Its CP-odd parity determine the shape of the interaction with matter**

QCD axion: special case

- **QCD Axion**
  - Motivation: Strong CP problem solution (Peccei-Quinn mechanism)
  - Models:
    - KSVZ: Heavy quark mediated coupling
    - DFSZ: Direct coupling to SM fermions
  - Triangle anomaly induces photon coupling:

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

  - Mass-coupling relation:

[G. G. Di Cortona et al., JHEP (2016)]

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right) = \left(0.203\frac{E}{N} - 0.39\right)\frac{m_a}{\mathrm{GeV}^2}$$

- **Axion-Like Particles (ALPs)**
  - Motivation: String theory, dark matter, and other BSM phenomena
  - Primary interaction with photons
  - Free parameters: m_a and $g_{a\gamma}$ (+ model dependent g_{ae}, g_{aN})

[S. Aoyama & T. K. Suzuki, PRD (2015)]

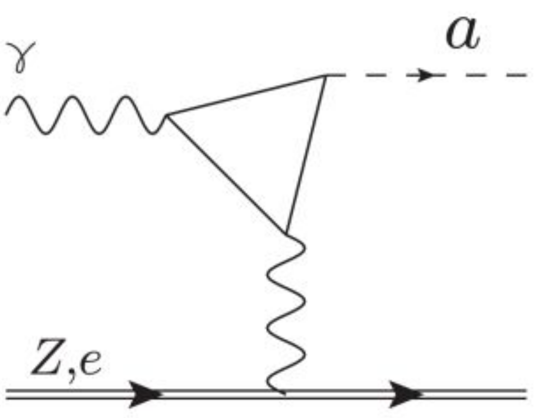


Figure 1: Primakoff process

Primordial Black Holes

Primordial Black Holes

- Expected to be formed from gravitational collapse of large primordial density fluctuations
- A promising and natural candidate for explaining a major fraction of dark matter
- Can be considered a source of various particle emissions through Hawking radiation

Hawking Temperature

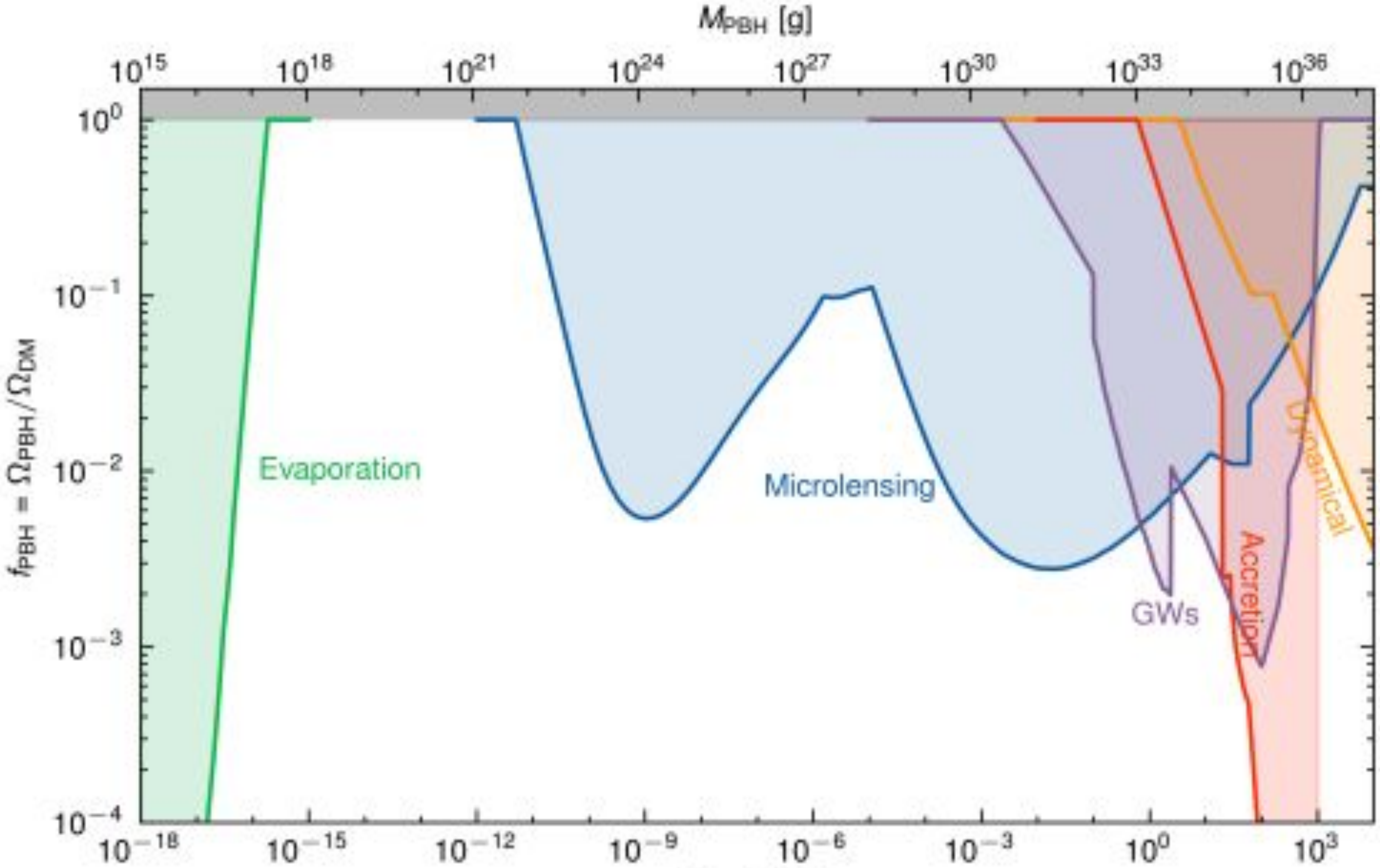
$$k_B T_{\mathrm{PBH}} = \frac{\hbar c^3}{8\pi G M_{\mathrm{PBH}}} \sim 1.06 \left(\frac{10^{16}\mathrm{g}}{M_{\mathrm{PBH}}} \right) \mathrm{MeV} \sim 10^{10} \left(\frac{10^{16}\mathrm{g}}{M_{\mathrm{PBH}}} \right) \mathrm{K}$$

Emission rate of Hawking radiation

$$\frac{\mathrm{d}^2 N_\chi}{\mathrm{d}E \mathrm{d}t} = \frac{g_\chi}{2\pi} \frac{\Gamma(E, M_{\mathrm{PBH}})}{e^{E/k_{\mathrm{B}} T_{\mathrm{PBH}}} - (-1)^{2s_\chi}}$$

- g_χ: Degree of freedom of χ
- s_χ: Spin of χ
- $\Gamma(E, M_{\mathrm{PBH}})$: Greybody factor

Ballpark of PBH as a DM candidate



Our question: Can we probe the ballpark of PBH DM with Axions?

Signal: Axions from PBHs

- **Our Scenario**
  - PBH as the majority of DM
  - Axions are emitted from PBHs
- **Axions from PBHs**
  - Galactic contribution

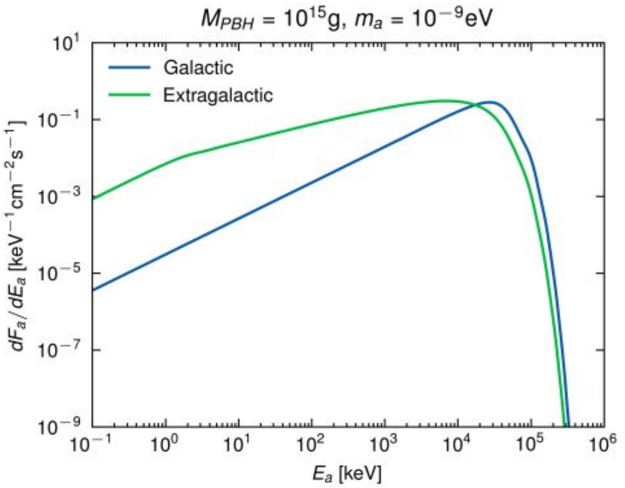
$$\frac{\mathrm{d}F_a}{\mathrm{d}E_a} = \frac{1}{4\pi}\int \mathrm{d}k\mathrm{d}\Omega \frac{f_{\mathrm{PBH}}\rho(x[k,\varphi])}{M_{\mathrm{PBH}}}\frac{\mathrm{d}^2 N_a}{\mathrm{d}E_a \mathrm{d}t}$$

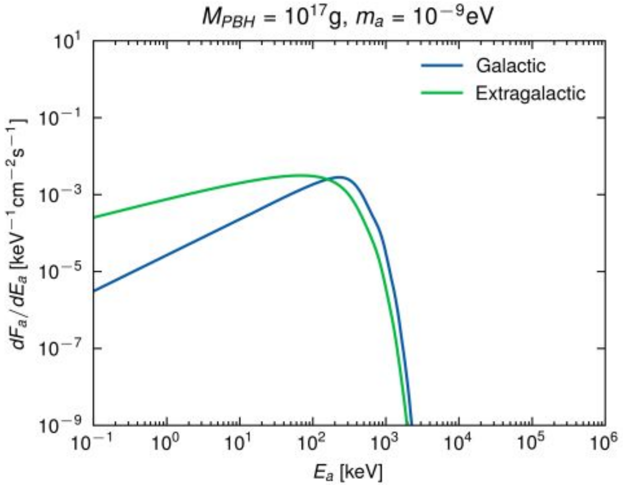
  - Extragalactic contribution ($E_a \gg m_a$)

[B. J. Carr et al., PRD (2010)]

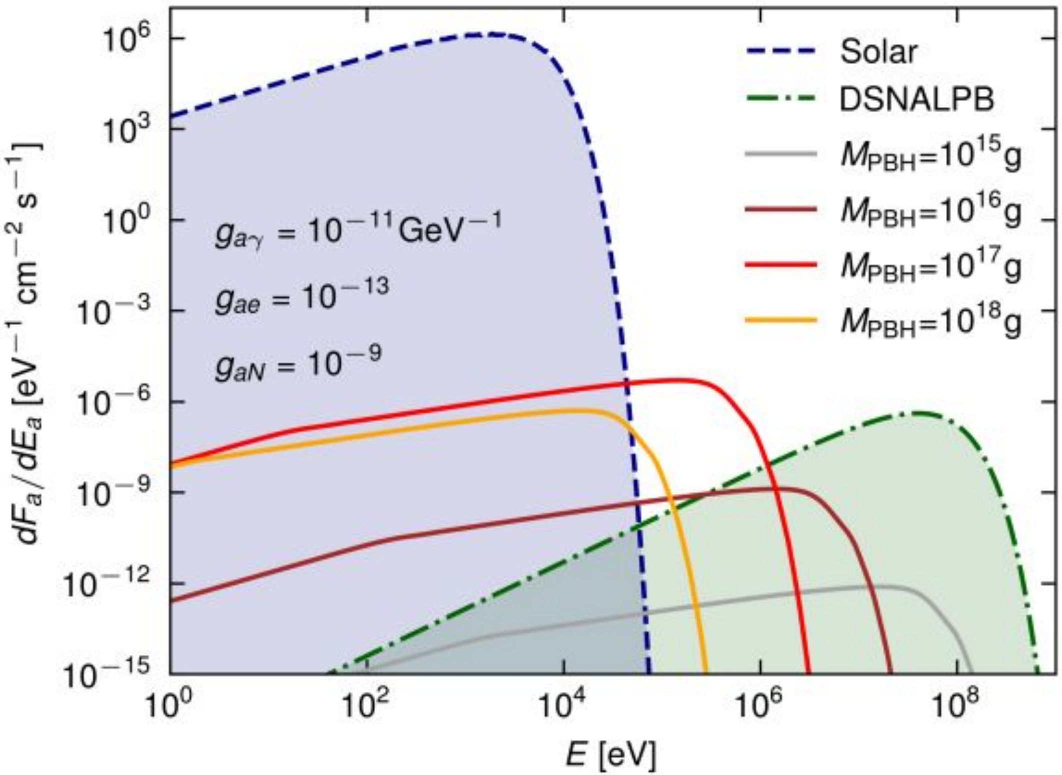
[Y. Jho, **TGK**, J.-C. Park, S. C. Park and Y. Park [2212.11977]]

$$\frac{\mathrm{d}F_a}{\mathrm{d}E_a} \simeq \frac{f_{\mathrm{PBH}}\rho_{\mathrm{DM}}}{M_{\mathrm{PBH}}}\int \mathrm{d}t(1+z(t))\left[\frac{\mathrm{d}^2 N_a}{\mathrm{d}E\mathrm{d}t}\right]_{E=(1+z(t))E_a}$$





PBH-Axions vs. Other source of Axions in the universe (from astrophysical processes)



- **Axions from the Sun**

[T. Dafni et al., Phys. Rev. D 99 035037 (2019)]

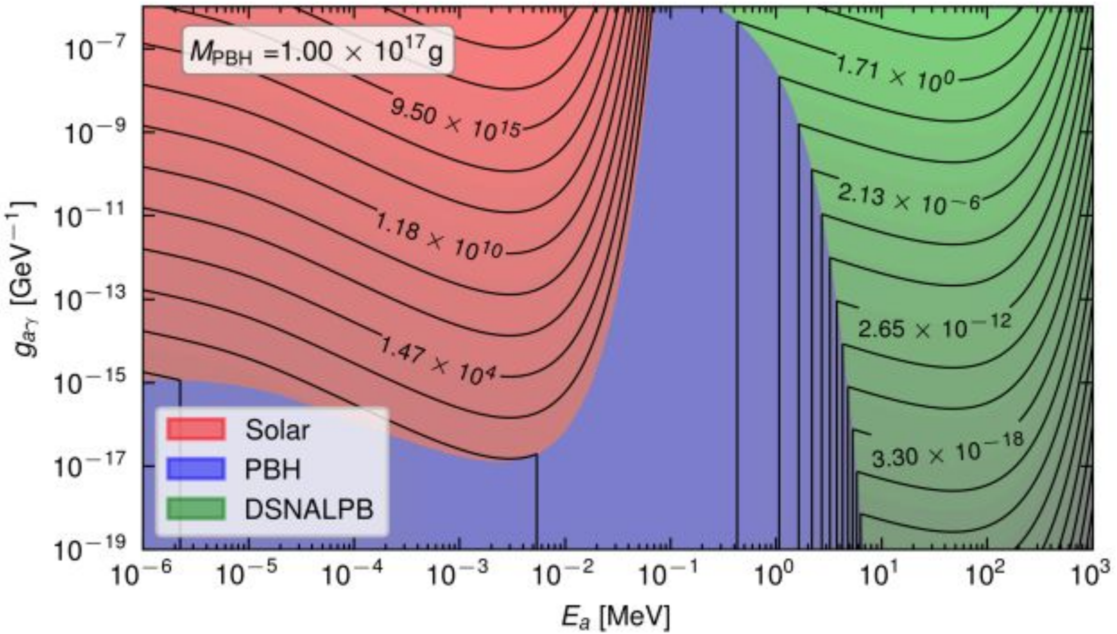
$$\left(\frac{\mathrm{d}F_a}{\mathrm{d}E_a}\right)_{\mathrm{sun}} = \frac{\mathrm{d}F_a^P}{\mathrm{d}E_a} + \frac{\mathrm{d}F_a^C}{\mathrm{d}E_a} + \frac{\mathrm{d}F_a^B}{\mathrm{d}E_a} + \frac{\mathrm{d}F_a^A}{\mathrm{d}E_a}$$

- **Axions from the DSNe (DSNALPB)**

[C. Calore et al., Phys. Rev. D 102 123005 (2020)]

$$\left(\frac{\mathrm{d}F_a}{\mathrm{d}E_a}\right)_{\mathrm{DSNe}} = \left(\frac{\mathrm{d}F_a}{\mathrm{d}E_a}\right)_{\gamma\to a} + \left(\frac{\mathrm{d}F_a}{\mathrm{d}E_a}\right)_{NN\to a}$$

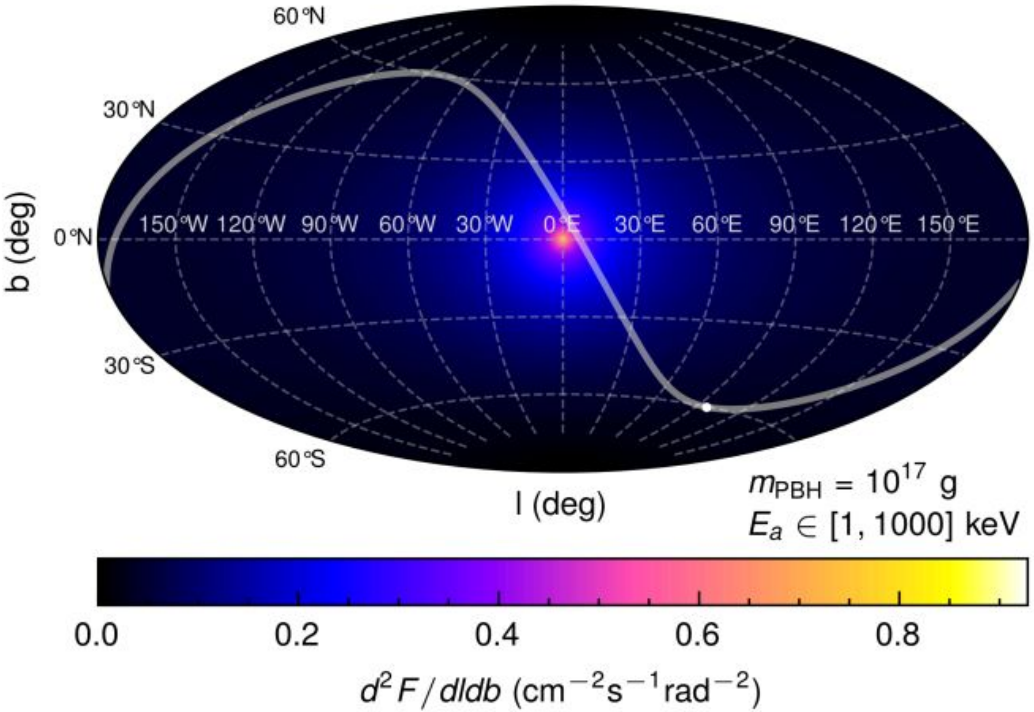
Are PBH-Axions dominate over other possible sources of relativistic axions from astrophysical process?

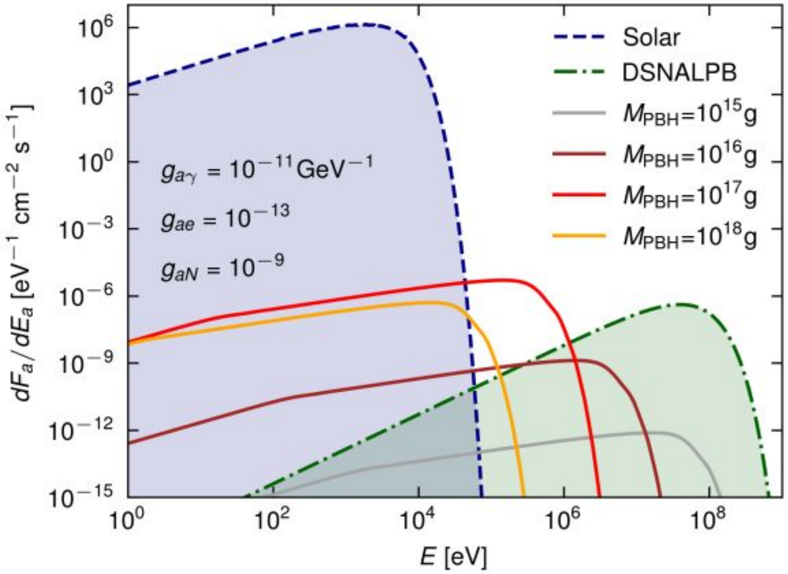


- The colored regions represent dominant axion sources.
- The number on contour represents the differential axion flux from each source.
- Assume KSVZ-like ALPs

$$g_{ae}, g_{aN} \sim \frac{\alpha}{16\pi} g_{a\gamma}$$

Directionality

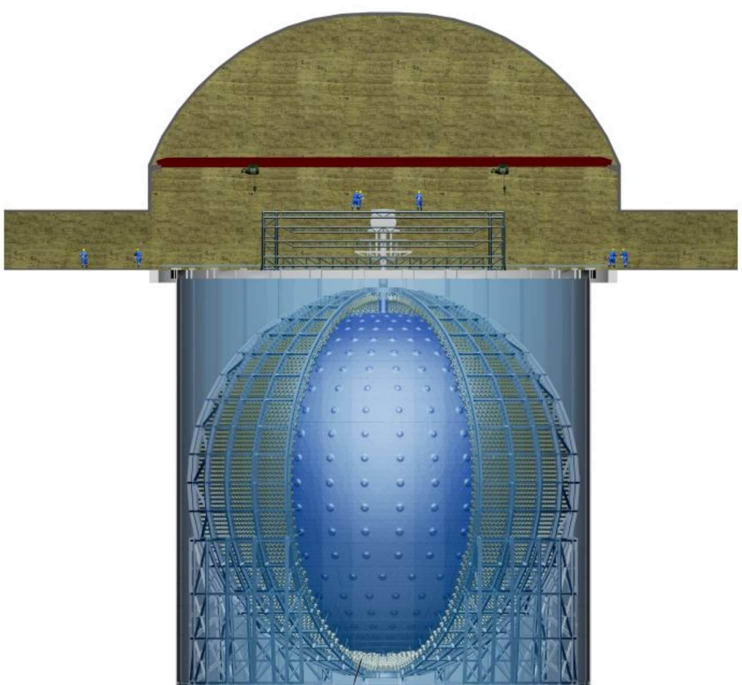


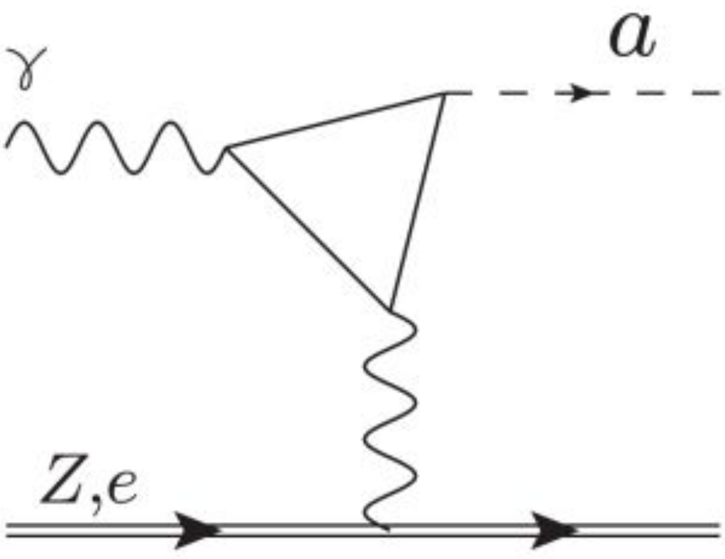


How to detect (PBH-)Axions?

Large volume neutrino detector: ex. JUNO, Hyper-K, DUNE, etc.

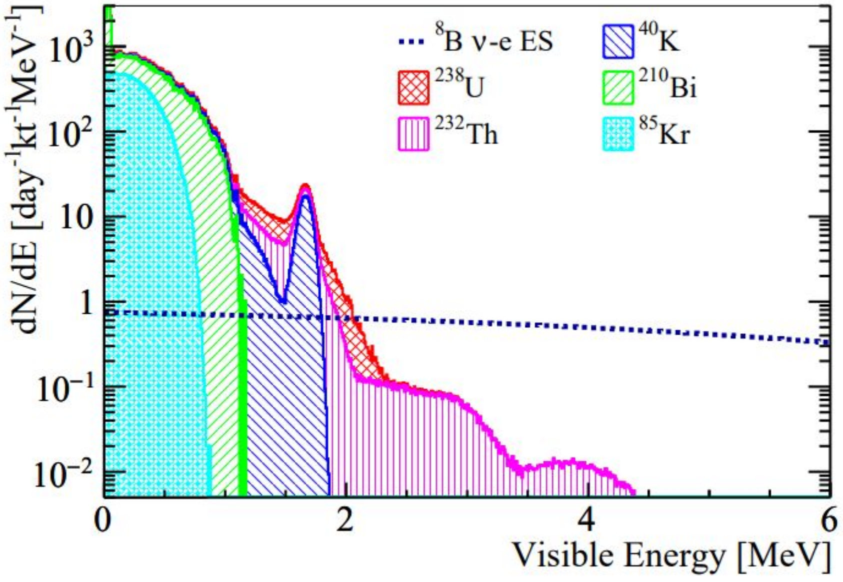
Signal: Inverse primakoff process in the detector ⇒ A hard photon + soft e,N recoils

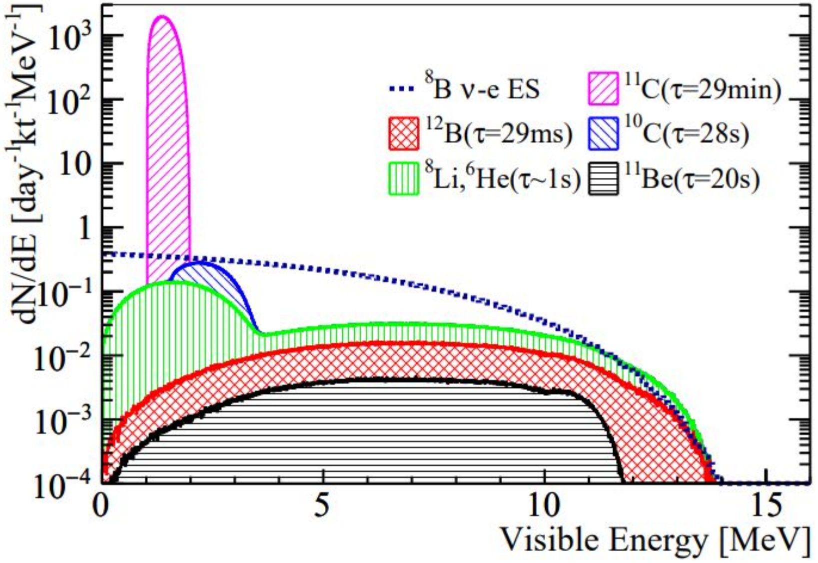




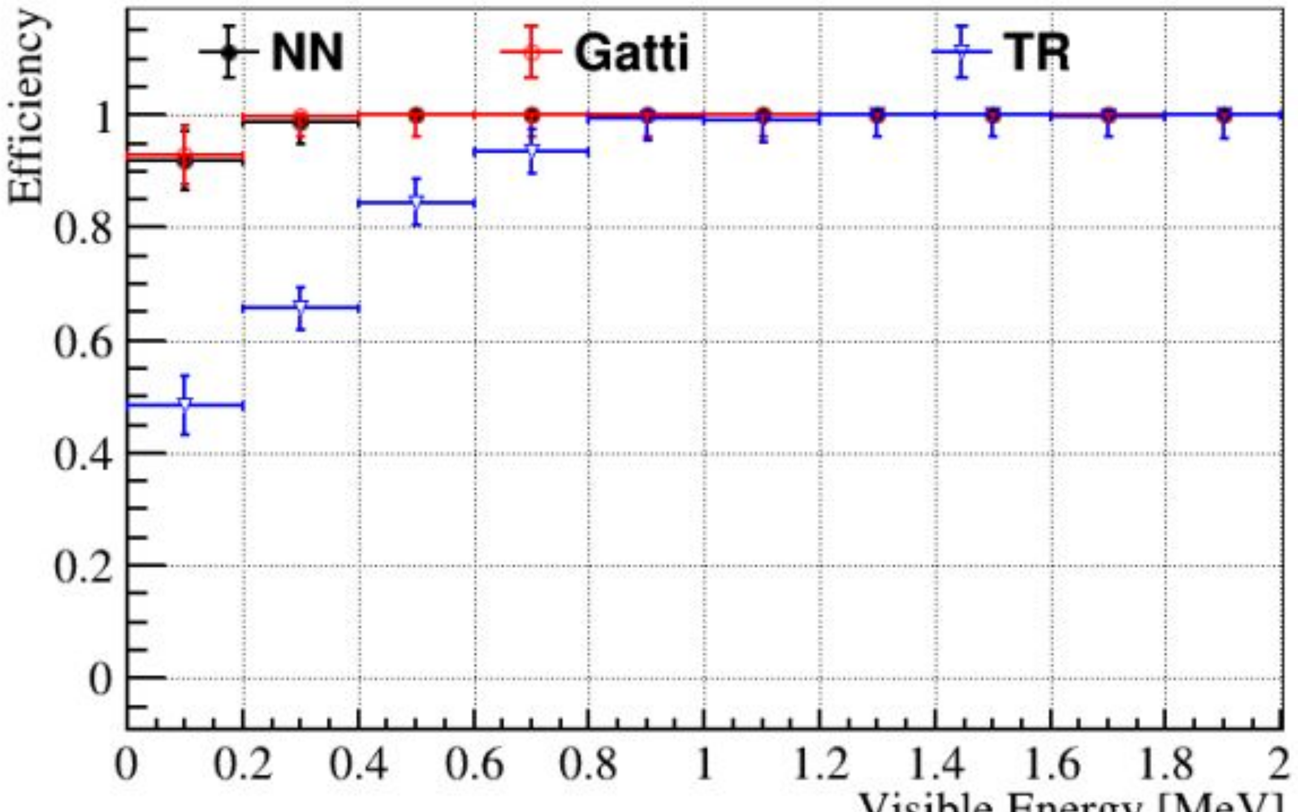
A possible background in the detector?

Solar neutrino interact with electrons could be a possible source of background?

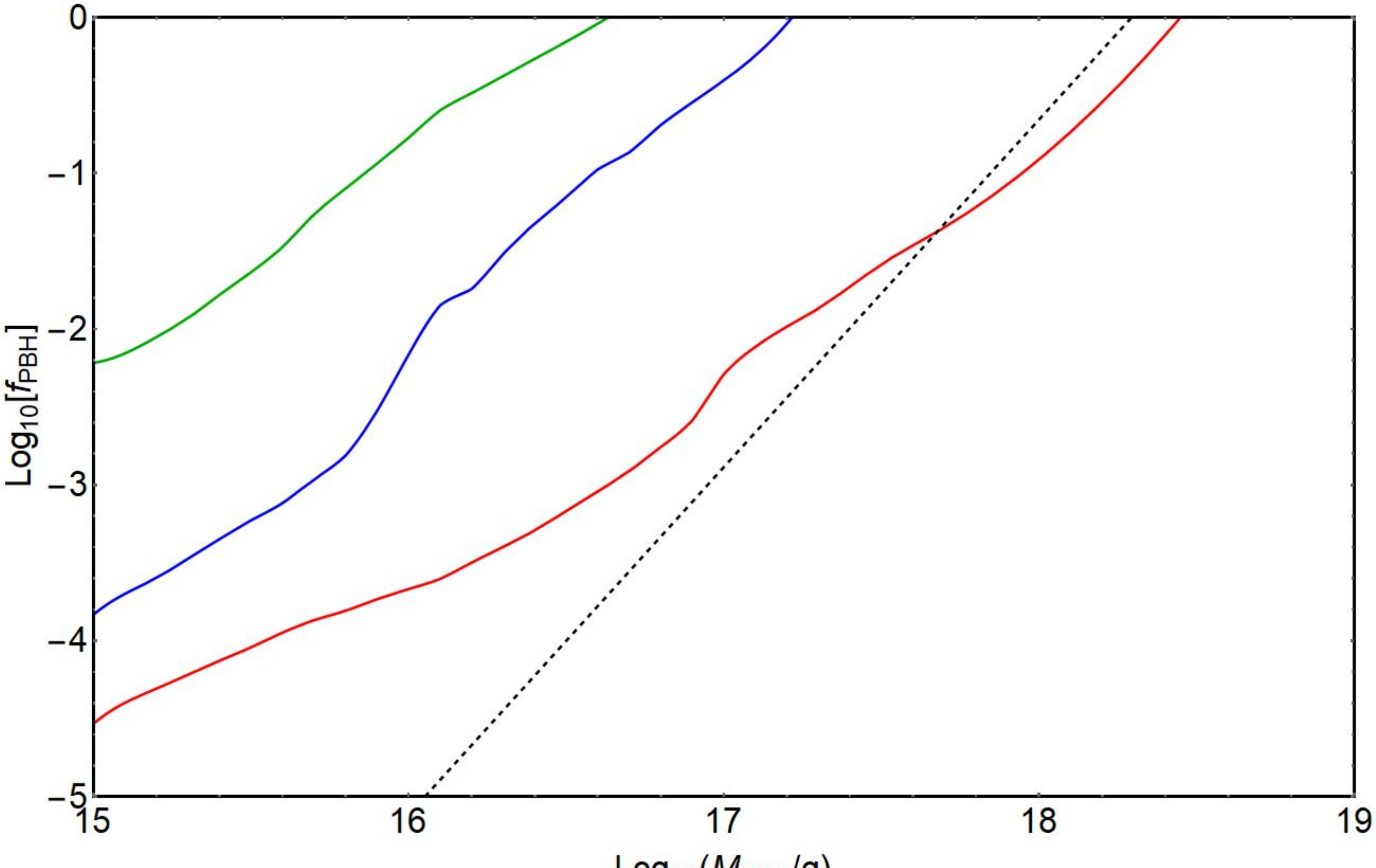




e/gamma discrimination efficiencies at water cherenkov detectors



Expected Sensitivity to PBH abundance



Conclusion

Axions and PBHs are both interesting and motivated topics in particle physics.
In this talk, we discuss the feasibility of the probe of PBH Dark matte scenarios in the presence of Axion, of Axion-like particles in the low energy spectrum.

The Water-Cherenkov detector for neutrino physics are expected to have a great potential to be sensitive Axion detections in the PBH DM ballpark window especially.