CCAST Postdoctoral Fellow Interview

Department of Physics
The Chinese University of Hong Kong

Qishan LIU (刘琪汕)

Expected Postdoc Collaborator : Yufeng Li(李玉峰)

Resume

South China Normal University (华南师范大学) *September 2013 – June 2017*

School of Physics ＆ Telecommunication Engineering
Major: Physics（物理勷勤创新班）
Supervisor: Prof. Yihang Chen, Prof. Jiahui Huang
Degree: Bachelor of Science

Johannes Gutenberg-Universität Mainz (美因茨大学) *April 2018 – May 2020*

Institute of Physics (THEP)
Major: Physics
Supervisor: Prof. Hubert Spiesberger, Prof. Jens Erler
Degree: Master of Science

The Chinese University of Hong Kong (香港中文大学) *August 2021 – now*

Department of Physics
Major: Physics
Supervisor: Prof. Kenny C. Y. NG , Prof. Mingchung Chu

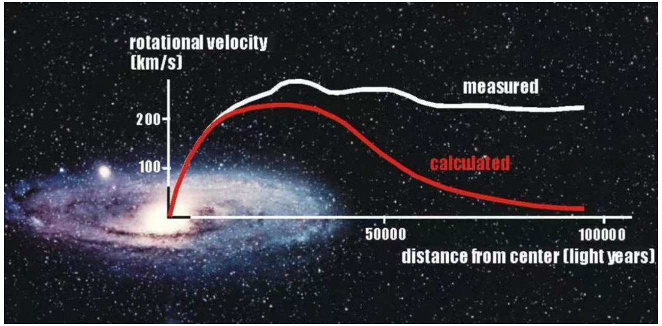
Research Interest:

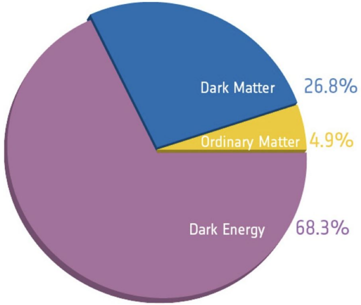
Neutrinos Physics
Dark Matter

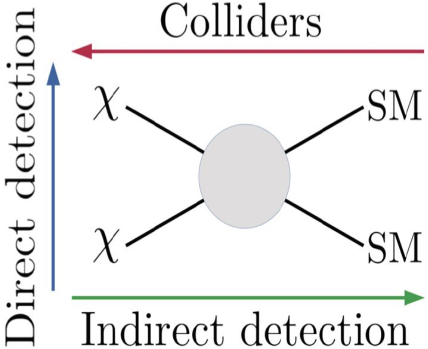
Gravitational Evidence for Dark Matter

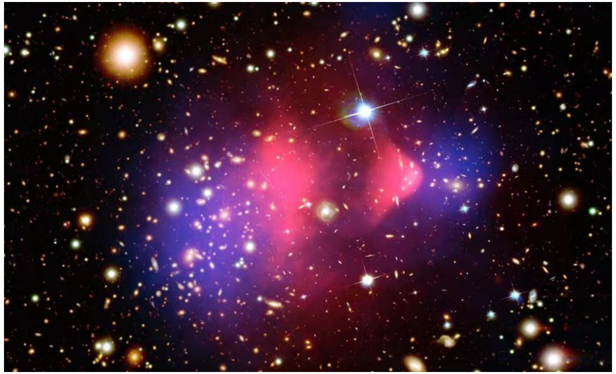
- Rotation Curve
- Collisions of Galaxy Clusters
- Large Structure Formation
- Cosmic Microwave Background

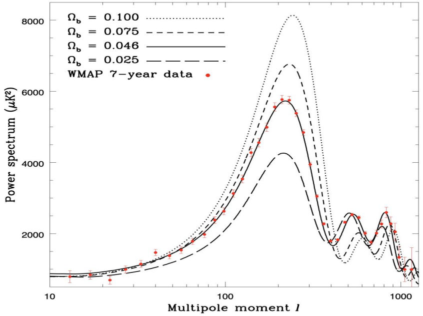
……





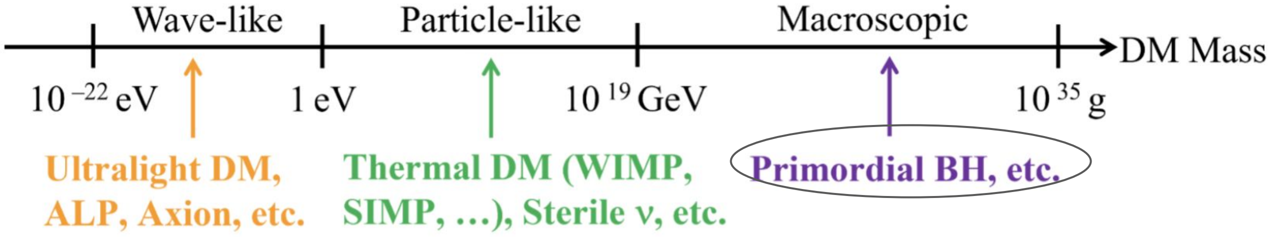






Katherine Garrett & Gintaras Duda, 2010

Theoretical Motivation



Wave-like

Particle-like

Macroscopic

DM Mass

10^{-22} eV

1 eV

10^{19} GeV

10^{35} g

Ultralight DM,
ALP, Axion, etc.

Thermal DM (WIMP,
SIMP, …), Sterile ν, etc.

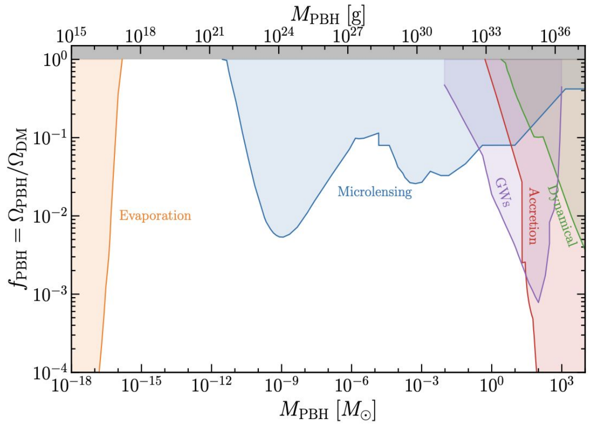
Primordial BH, etc.

Dark matter is non-baryonic, stable, cold, and weakly interacting

- PBHs form due to the gravitational collapse of overdensities
- Lifetime of PBHs can be longer than the age of the Universe

$$t_{\text{evap}} = t_{\text{Universe}} \left(\frac{M_{\text{PBH}}}{5 \times 10^{14} g}\right)^3$$

- PBHs can be non-relativistic
- PBHs are expected to only interact gravitationally



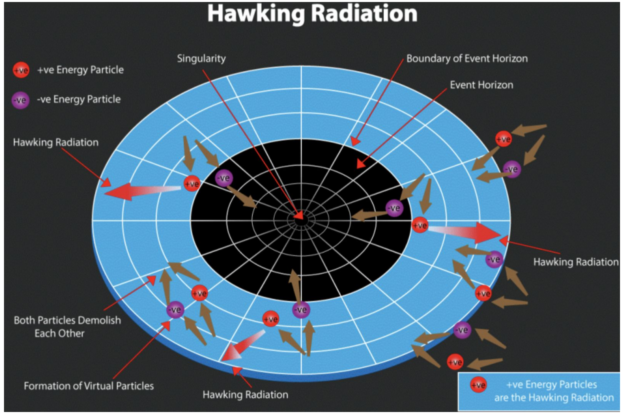
https://github.com/bradkav/PBHbounds.

Hawking Radiation

At the event horizon of a black hole, quantum fluctuations can create particle-antiparticle pairs

$$\left.\frac{d^2N_i(E,t)}{dtdE}\right|_{\text{primary}} = \frac{g_i}{2\pi}\frac{\Gamma_i\left(E,M_{\rm PBH}\right)}{e^{E/T_{\rm BH}}\pm 1}$$

A.Arbey & J.Auffinger,2019



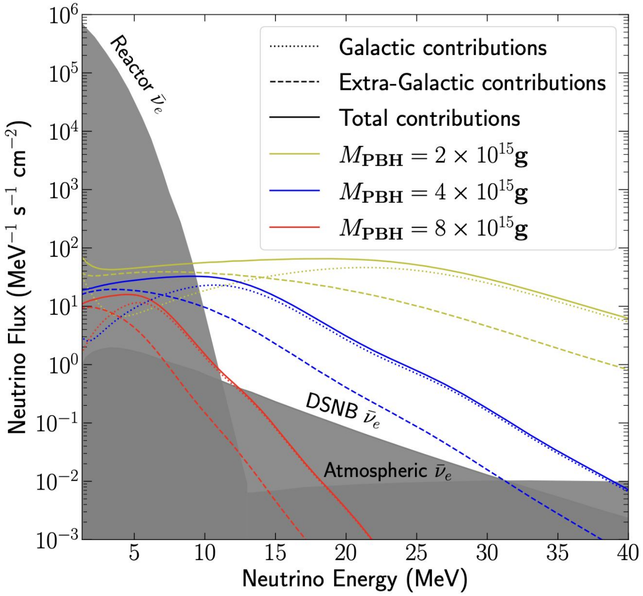
S. W. Hawking, 1974

The differential neutrino flux can be separated into the galactic and extragalactic contribution

- $$\frac{d\Phi_{\rm MW}}{dE_\nu} = \frac{d^2N_\nu}{dE_\nu dt}\frac{f_{\rm PBH}}{M_{\rm PBH}}\int\frac{d\Omega}{4\pi}\int_0^{\ell_{\rm max}} d\ell\,\rho_{\rm NFW}(r(\ell,\phi))$$
- $$\frac{d\Phi_{\rm EG}}{dE_\nu} = \frac{f_{\rm PBH}\rho_{\rm DM}}{M_{\rm PBH}}\int_0^{z_{\rm max}}\frac{cdz}{H(z)}\frac{d^2N_\nu((1+z)E_\nu,t)}{dE_\nu dt}$$

Constraints on PBHs by Neutrino Fluxes Upper limits

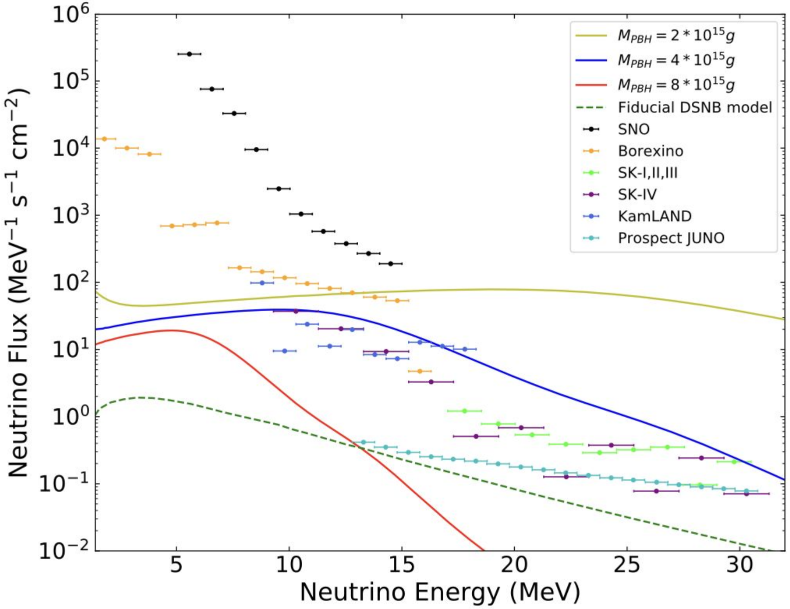
PBHs evaporation as a function of energy with $f_{PBH} = 1$, assuming a monochromatic mass distribution and 0 spin.



Atmospheric $\bar{\nu}_e$[K. et al.2018]

DSNB $\bar{\nu}_e$[Moller2018]

Reactor $\bar{\nu}_e$[Battistoni2005]



SNO[Aharmim et al.2004]

Borexino [M. et al.2021]

SK-I,II,III[K. et al.2012]

SK-IV[K. et al.2021]

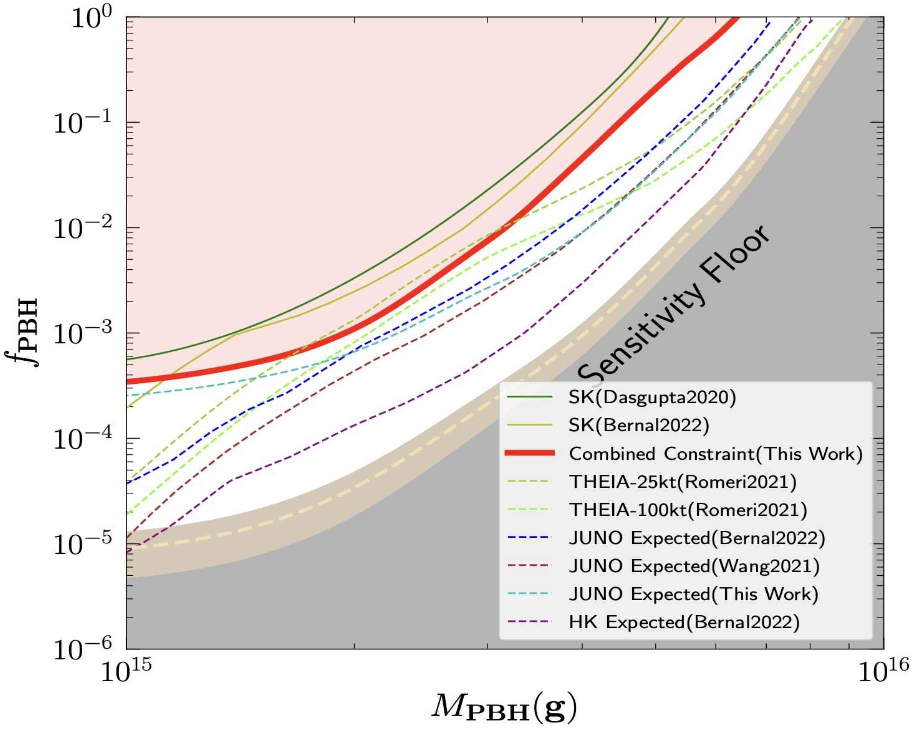
KamLAND[Abe et al.2022]

JUNO[Abusleme et al.2022]

DSNB[Moller2018]

The Sensitivity Floor for Primordial Black Holes Neutrino

- Since the DSNB is unavoidable, it is difficult for neutrino detectors to detect the PBH DM above $9 \times 10^{15}\ g$
- The JUNO experiment could potentially extend the constraints on PBHs up to masses of approximately $8 \times 10^{15}\ g$
- To probe PBH as 100% of the DM beyond the mass range, need other messengers

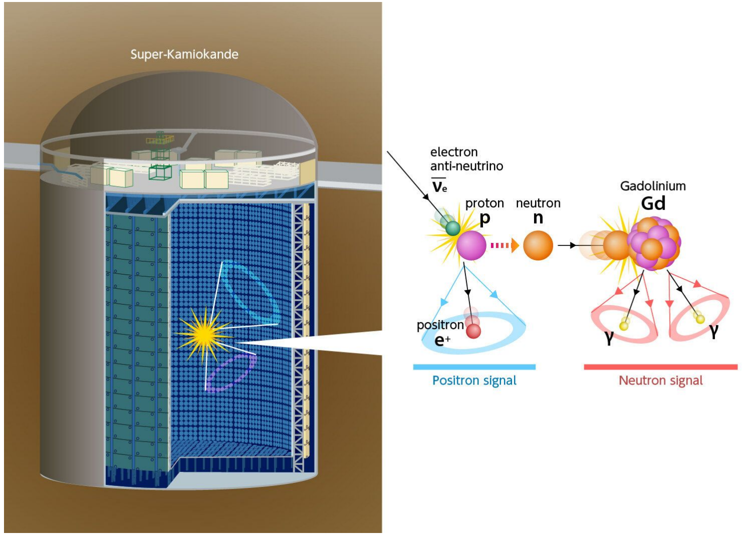


Inverse Beta Decay Directionality

- Water Cherenkov Detectors

No directionality before because positrons direction is mostly isotropic

Adding Gadolinium make it possible

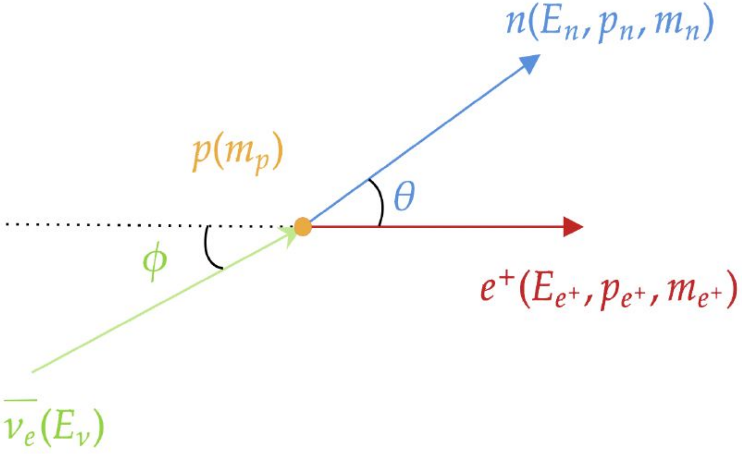


- ~49,000 barns for Gd (30μs for capture with ~8MeV gamma cascade)
- 0.3 barns for H (200μs for capture with a 2.2MeV gamma ray)

KINEMATICS OF INVERSE BETA DECAY

$$\begin{bmatrix} E_\nu \\ E_\nu \cos\phi \\ E_\nu \sin\phi \\ 0 \end{bmatrix} + \begin{bmatrix} m_\mathrm{p} \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} E_\mathrm{n} \\ p_\mathrm{n} \cos\theta \\ p_\mathrm{n} \sin\theta \\ 0 \end{bmatrix} + \begin{bmatrix} E_e \\ p_e \\ 0 \\ 0 \end{bmatrix}$$

$$\bar{\nu_e} + p \rightarrow e^+ + n$$



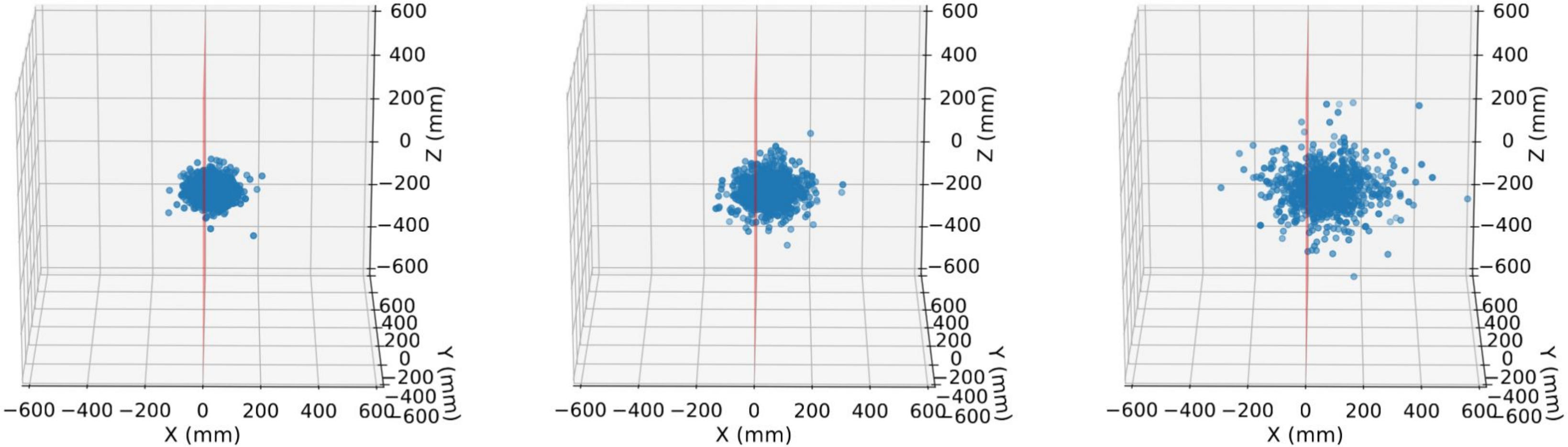
Five equations (2D):

$$\begin{cases} E_\nu + m_\mathrm{p} & = E_\mathrm{n} + E_e \\ E_\nu \cos\phi & = p_\mathrm{n}\cos\theta + p_e \\ E_\nu \sin\phi & = p_\mathrm{n}\sin\theta \\ m_e^2 & = E_e^2 - p_e^2 \\ m_\mathrm{n}^2 & = E_\mathrm{n}^2 - p_\mathrm{n}^2 \end{cases}$$

Seven parameters:

the momenta p_e, p_n, particle energies E_ν, E_e, E_n, and the two angles θ and ϕ

Geant4 Simulation for Neutron Capture Positions



Neutron capture positions in Gd-loaded water 20 MeV (left), 50 MeV (middle) and 80 MeV (right) neutron momenta are emitted along the x-axis

Some neutron directionality remains even after diffusion (3D)

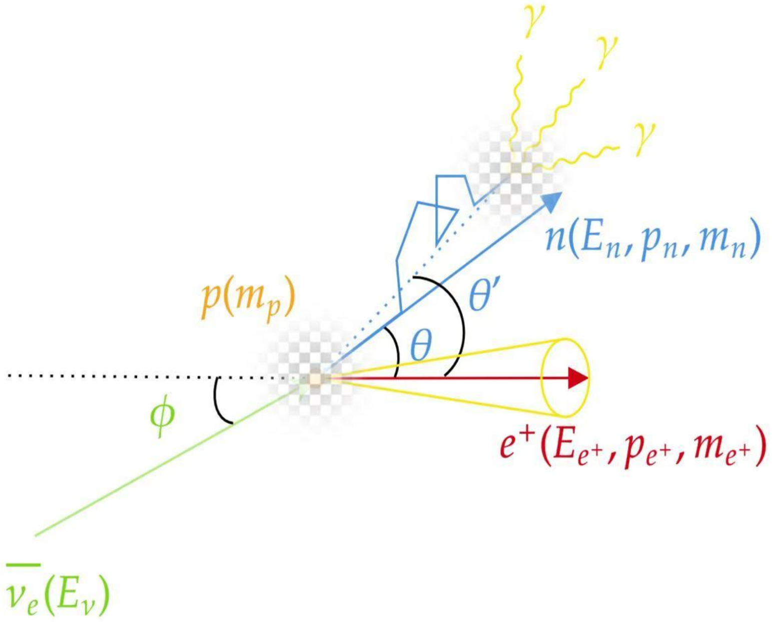
The asymmetry is larger for larger neutron momentum

Vertex Resolution

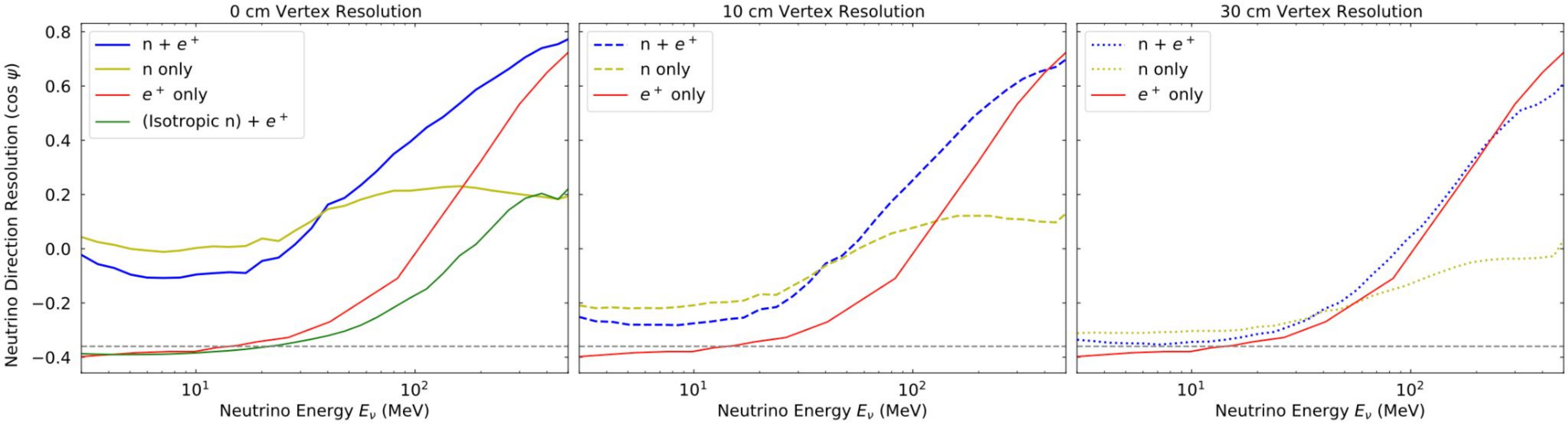
If the vertex resolution >> neutron capture distance —> No direction!

Neutron capture distance ~ 10cm at 50 MeV

Vertex resolution ≳ 30cm



Neutron Capture Information in Improving IBD Angular Resolution



Vertex resolution ↓ —> reconstruction ↓

Neutron diffusion in water makes it impossible to reconstruct at the event-by-event level but possible to statistically infer the direction of the neutrinos using multiple events

Conclusion

In the first study, we present the first estimate of the neutrino sensitivity floor for primordial black hole dark matter.

It is generally believed that the IBD events carry **no directional** information within a water Cherenkov detector. In the second study, we introduce a novel method to improve the reconstruction of neutrino direction by combining information from both the positron and the neutron capture position.

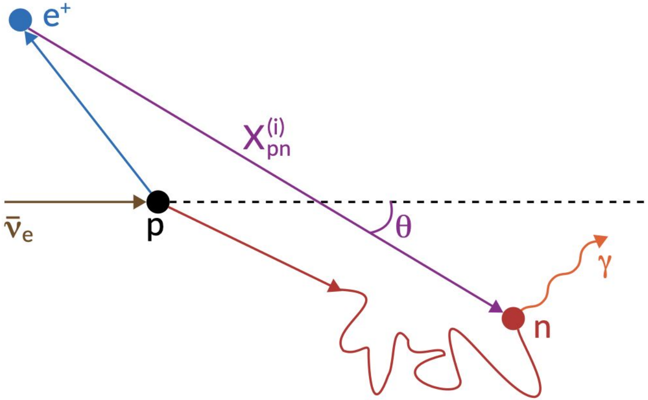
This improved directional information is important for supernova pointing applications, enabling early detection capabilities and is also invaluable in the search for dark matter.

Research Plan

1. Fundamental analysis of commissioning data.
2. Developing and optimizing inverse beta decay neutrino direction reconstruction in JUNO.
3. Using neutrino direction reconstruction for supernova pointing.
4. Investigating the detection of the diffuse supernova neutrino background.
5. Utilizing JUNO to search for signatures of boosted dark matter.

IBD Neutrino Direction Reconstruction

- **Simulations in Geant4**: Simulating the neutron diffusion in liquid scintillator environment.
- **Reconstruction Methodology**:
  - Try to distinguish the Cherenkov light from scintillator light.
  - Evaluate the impact of detector performance
  - Explore the use of machine learning to enhance the reconstruction.
- **Physics Applications**: supernova pointing, and dark matter.

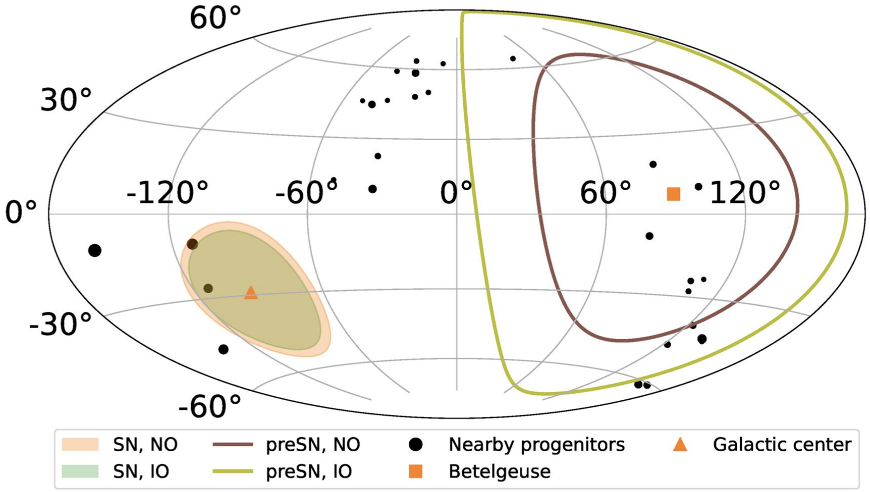


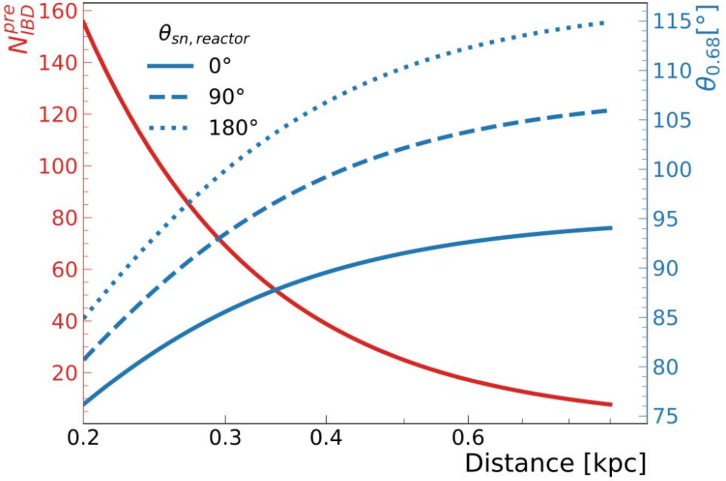
Hui-Ling Li et al., 2020

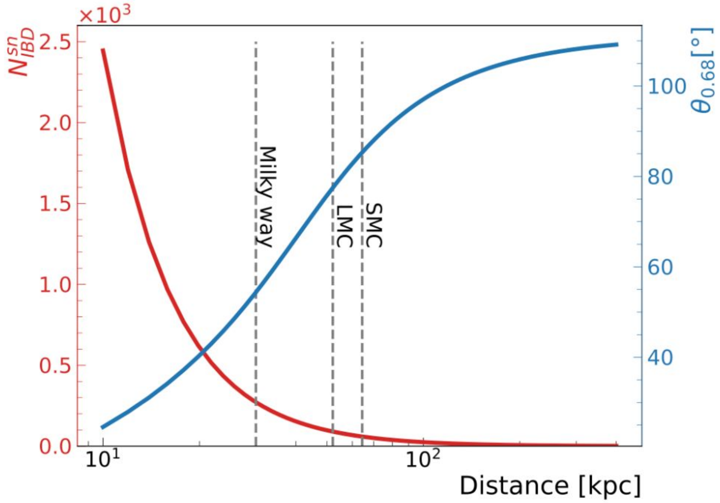
Mainak Mukhopadhyay et al., 2020

Supernova Pointing

- **Neutrino fluxes and the expected visible energy spectra for different model**
- **The pointing ability by analyzing the IBD events**





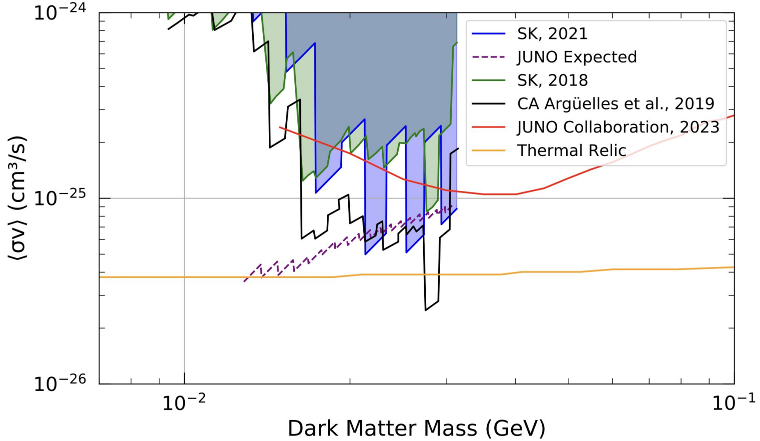


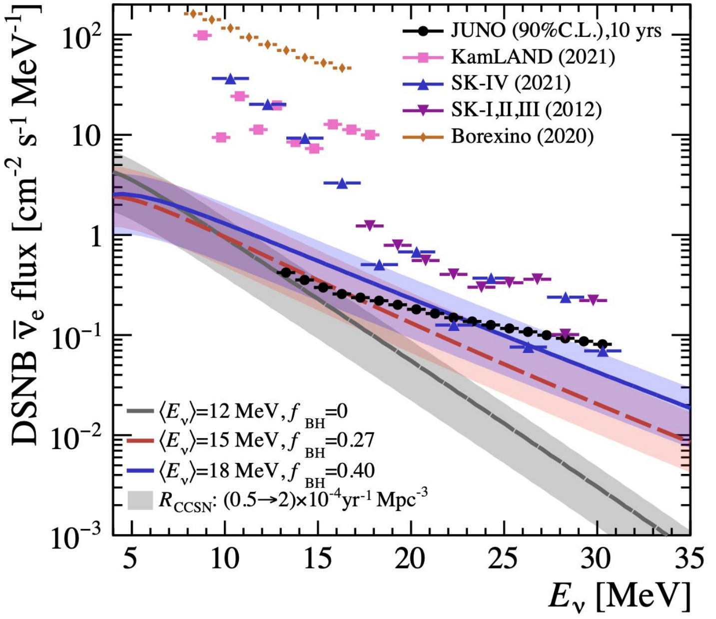
JUNO Collaboration, 2023

Searching for the Diffuse Supernova Neutrino Background

The DSNB is a faint flux of neutrinos from all past supernovae in the universe. JUNO's sensitivity to DSNB will complement searches at other detectors:

- **Signal Detection**
- **Background Suppression**
- **Spectral Analysis**
- **Search for Dark Matter**

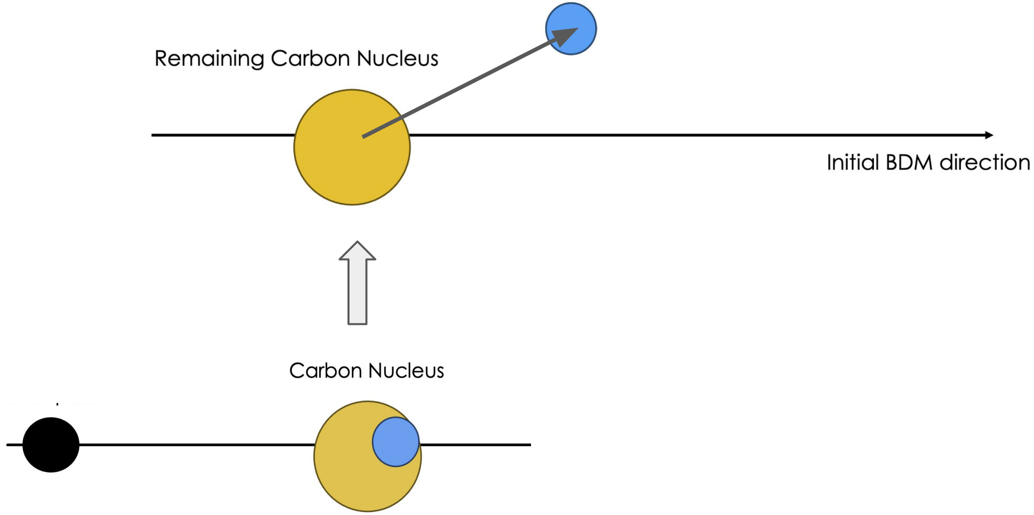


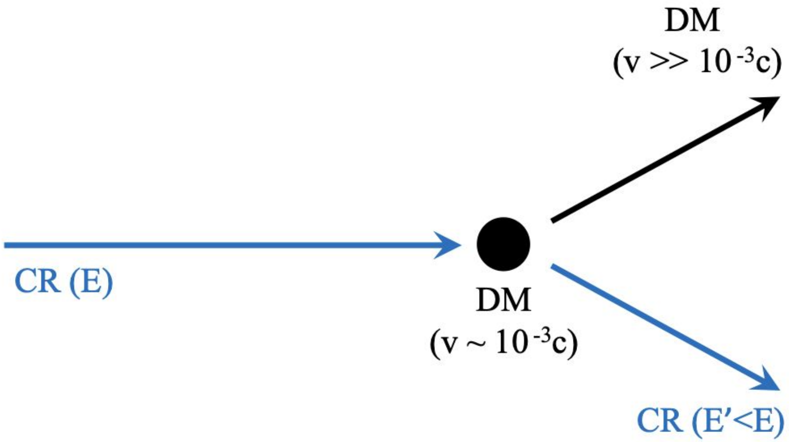


JUNO Collaboration, 2022

Boosted Dark Matter in JUNO

- **Signal Characteristics**
- **Background Rejection**
- **Parameter Space Exploration**





Boosted DM could trigger neutrino detectors, and possibly leave a directional signature.

Works

Qishan Liu, Kenny C.Y. Ng. Neutron Capture Information in Improving IBD Angular Resolution. 2025, First author. This paper will soon be posted on arXiv. It is generally believed that there is no directionality of neutrinos in inverse beta decay within a water Cherenkov detector. In this study, we introduce a novel method to improve the reconstruction of neutrino direction by combining information from both the positron and the neutron capture position.

Chun-Ming Yip, Xu-Run Huang, Ming-chung Chu, and **Qishan Liu**, Measuring the Low-Energy Weak Mixing Angle with Supernova Neutrinos. 2025, Forth author. This paper will soon be posted on arXiv. We propose a method to determine the low-energy weak mixing angle by the neutrino flux from a nearby core-collapse supernovathrough the coherent elastic neutrino-nucleus scattering in Argo experiment. Such a measurement is valuable for the search for new physics.

Chingam Fong, Kenny C.Y. Ng, **Qishan Liu**. Searching for Particle Dark Matter with eROSITA Early Data. 2024, Third author.

Qishan Liu, Kenny C.Y. Ng. Sensitivity floor for primordial black holes in neutrino searches. Physical Review D [J]. 2024, First author.

Iwata, Geoffrey Z., Hu, Yinan, Wickenbrock, Arne, Sander, Tilmann, Muthuraman, Muthuraman, Chirumamilla, Venkata Chaitanya, Groppa, Sergiu, **Liu, Qishan** and Budker, Dmitry. Biomagnetic signals recorded during transcranial magnetic stimulation (TMS)-evoked peripheral muscular activity. Biomedical Engineering / Biomedizinische Technik [J]. 2022, Eighth author.

Yanxin Lu, **Qishan Liu**, Yihang Chen, Zefeng Chen, Dan-Wei Zhang, Hanying Deng, Shi-Liang Zhu, Peng Han, Nian-Hai Shen, Thomas Koschny, and Costas M. Soukoulis. Topological Transition Enabled by Surface Modification of Photonic Crystals. ACS Photonics [J]. 2021, Co-first author.

Xiaochao Zheng, Jens Erler, **Qishan Liu**, Hubert Spiesberger. Accessing weak neutral-current coupling using positron and electron beams at Jefferson Lab. The European Physical Journal A [J]. 2021, Third author.

A. Accardi et al. An experimental program with high duty-cycle polarized and unpolarized positron beams at Jefferson Lab. The European Physical Journal A [J]. 2021, Rank by the last name.

Jia-Hui Huang, Guang-Zhou Guo, Hao-Yu Xie, **Qi-Shan Liu**, Fang-Qing Deng. Spontaneous breaking of (2 + 1)-dimensional Lorentz symmetry by an antisymmetric tensor. Modern Physics Letters A [J]. 2008, Forth author.

Work Experience:

Research Assistant in Dmitry Budker Group - Helmholtz Institute, Johannes Gutenberg University, Mainz (February 2020- December 2020)
Teaching Assistant in The Chinese University of Hong Kong (August 2021 – July 2024)
Lectures:
Topics in Theoretical Physics (Astroparticle Physics) （研究生课程）
Engineering Physics: Mechanics and Thermodynamics（本科生课程）
Astronomy（本科生课程）

Other Experience:

Master Project about selecting tiny Higgs signal from a huge background, ‘from simple cuts to modern machine learning techniques’, directed by Dr. Christian Schmitt (TEAP, JGU, August 2019)

Attend a workshop on dark matter physics in the Department of Physics and Astronomy at University of California, Riverside (April 2023)

Visit and join a symposium discussing Dark Matter related research topics in the University of California, Irvine, Department of Physics (April 2023)

Oral presentation in the APS April Meeting 2023, Minneapolis (April 2023)

Oral presentation in the 29th International Workshop on Weak Interactions and Neutrinos (WIN 2023), Sun Yat-sen University (July 2023)

Give a lecture on 'Standard Model of Particle Physics' to postgraduate students at The Chinese University of Hong Kong (October 5th, 2023)

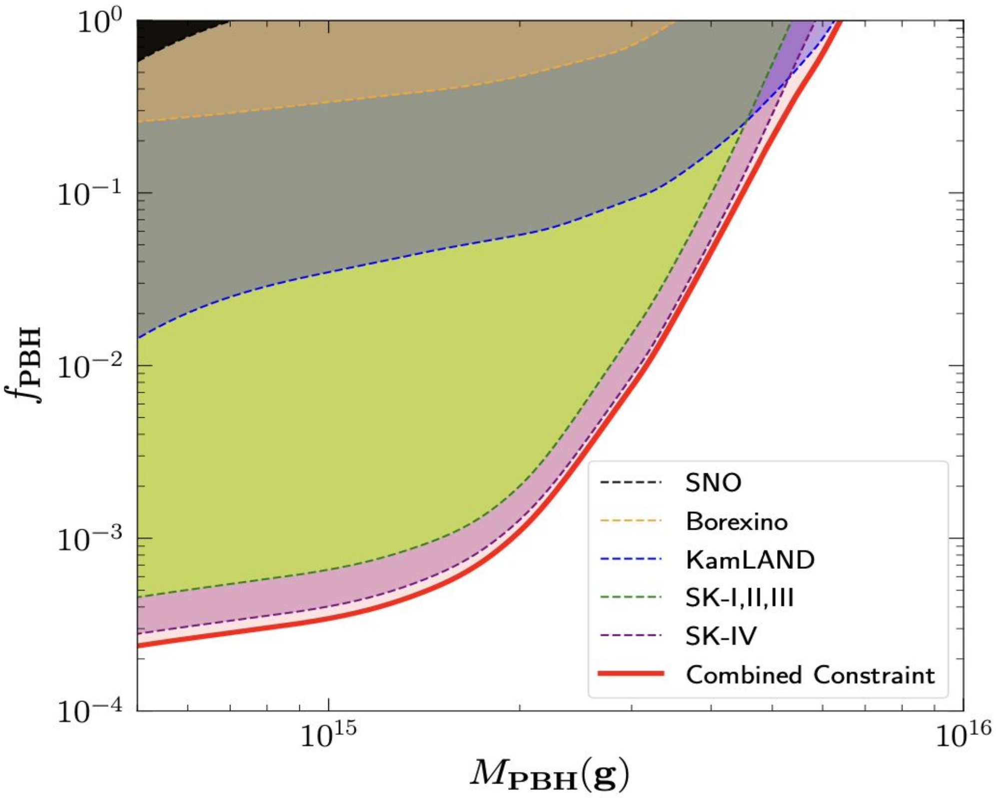
Oral presentation in the Scientific Committee of the International Symposium on Cosmology and Particle Astrophysics at the Chinese University of Hong Kong (November 2023)

Give a lecture on "Astrophysics II (Dark matter & astroparticles)" in SURIP Summer School 2024 (May 23rd 2024)

Give a talk on " Dark Matter Indirect Detections via Neutrinos" in Institute of High Energy Physics, Chinese Academy of Sciences (December 25th 2024)

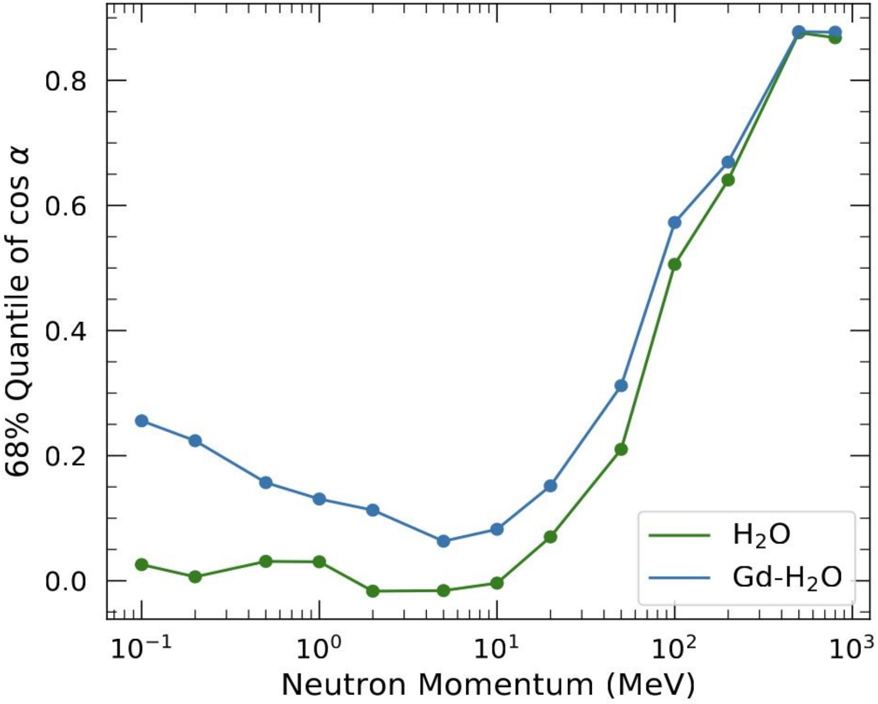
Backup Slides

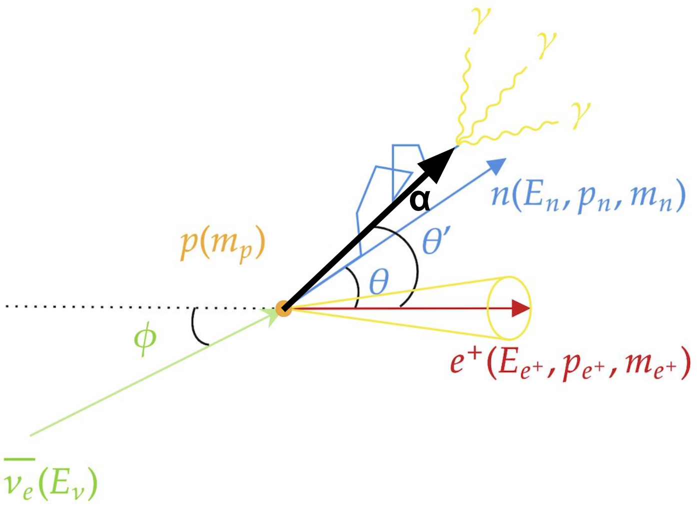
Current Upper Bounds on PBHs



- PBHs alone cannot account for the entirety of DM up to masses of 6.4 × 10^15 g.
- This has an enhancement of 20% compared to the previous upper limits.
- Neutrino searches are robust with respect to DM density profiles due to the all-sky nature of the search.
- Completely different systematics associated with propagation of electromagnetic messengers.

Geant4 simulation





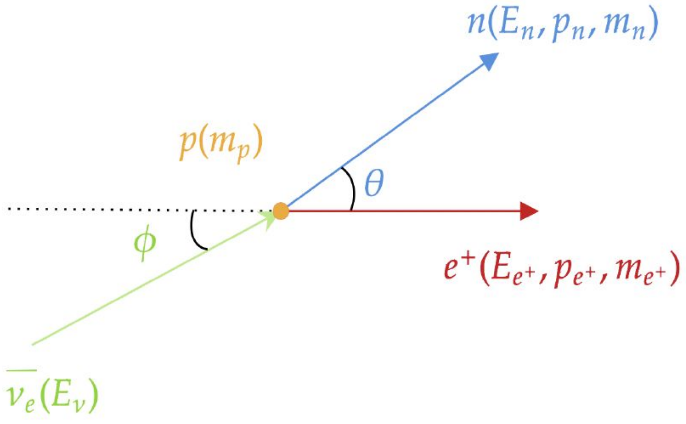
A neutron vector constructed by connecting the original point and the capture position point.

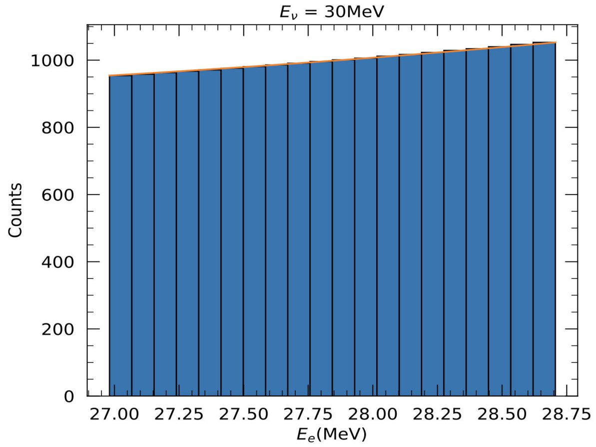
The angle **α** is the angle between the neutron vector and the original direction

Higher momentum neutrons preserve more directional information

IBD Angular Reconstruction Steps before Diffusion

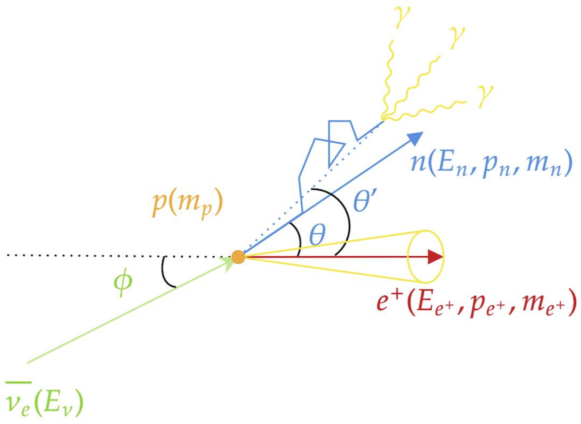
- Fix Neutrino energy (e.g., Dark matter)
- 20 evenly spaced Positron energies
- The contribution of the positron energies are weighted by the differential cross section
- Given neutrino and positron energy, using kinematic to solve everything (2D)

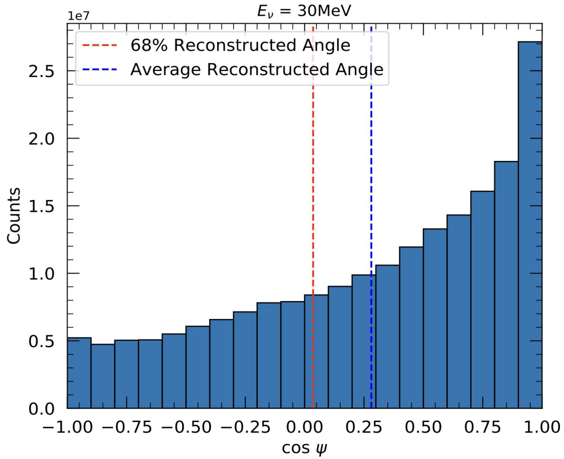




IBD Angular Reconstruction Steps after Diffusion

- Simulate neutron diffusion with momenta value from 1 to 800 MeV at intervals of 1 MeV, each constituting 10000 events
- Match the corresponding neutron momentum and their diffusion simulations
- Calculate 10000 neutron capture angles relative to the positron direction
- Given neutron capture angles and positron energy, using kinematic to reconstruct (3D)





J Factor in DM Annihilation

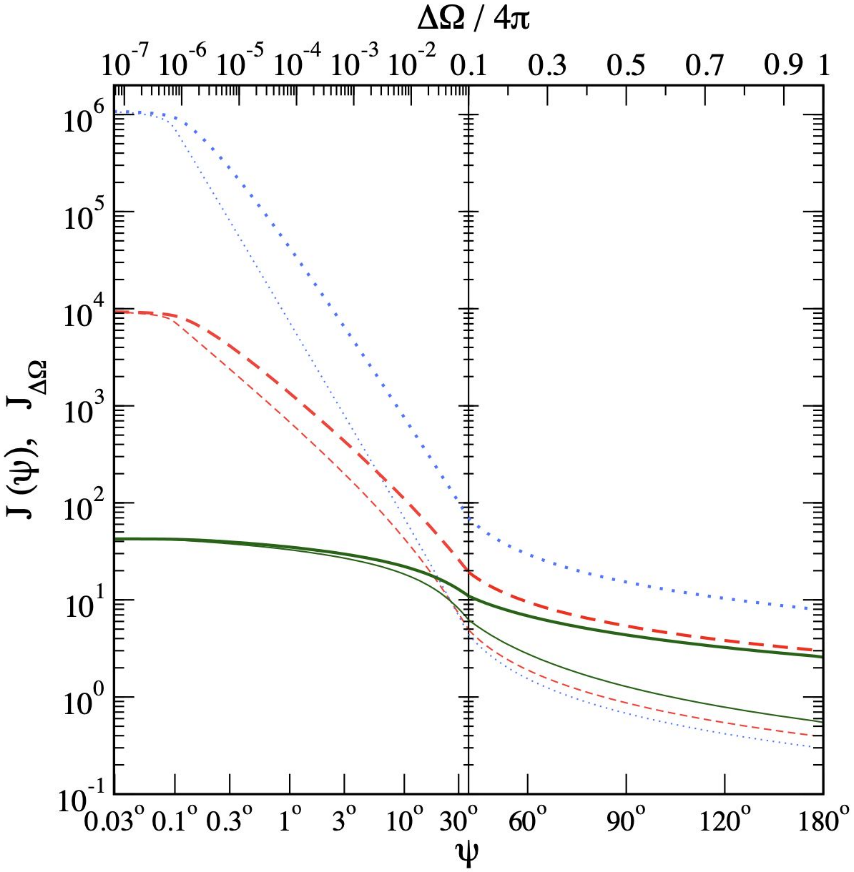
The average intensity of DM annihilation products

$$\frac{d\Phi_{\Delta\Omega}}{dE} = \frac{\langle \sigma_A v \rangle}{2} \mathcal{J}_{\Delta\Omega} \frac{R_{sc}\rho_{sc}^2}{4\pi m_\chi^2} \frac{dN}{dE}$$

Directional information can increase the average J Factor

$$\mathcal{J}_{\Delta\Omega} = \frac{1}{\Delta\Omega} \int_{\cos\psi}^{1} \mathcal{J}(\psi')\, 2\pi\, d(\cos\psi')$$

$$\Delta\Omega = 2\pi(1 - \cos\psi)$$



Moore, NFW and Kravtsov in order of dotted, dashed and solid lines

Hasan Yuksel et al., 2007