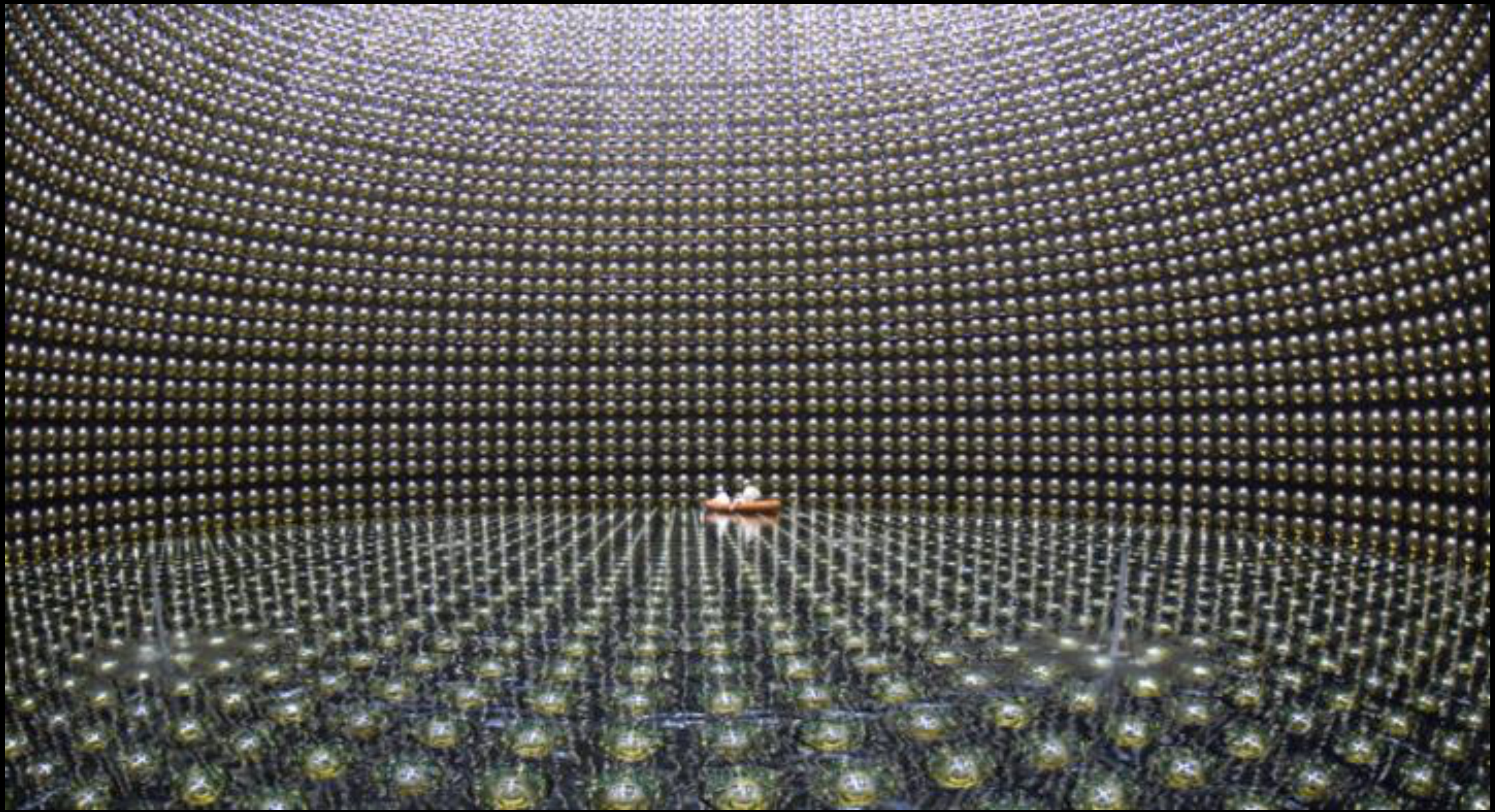
Dark Matter Search in Neutrino Detectors



Super-k

Kenny CY Ng (吳震宇)

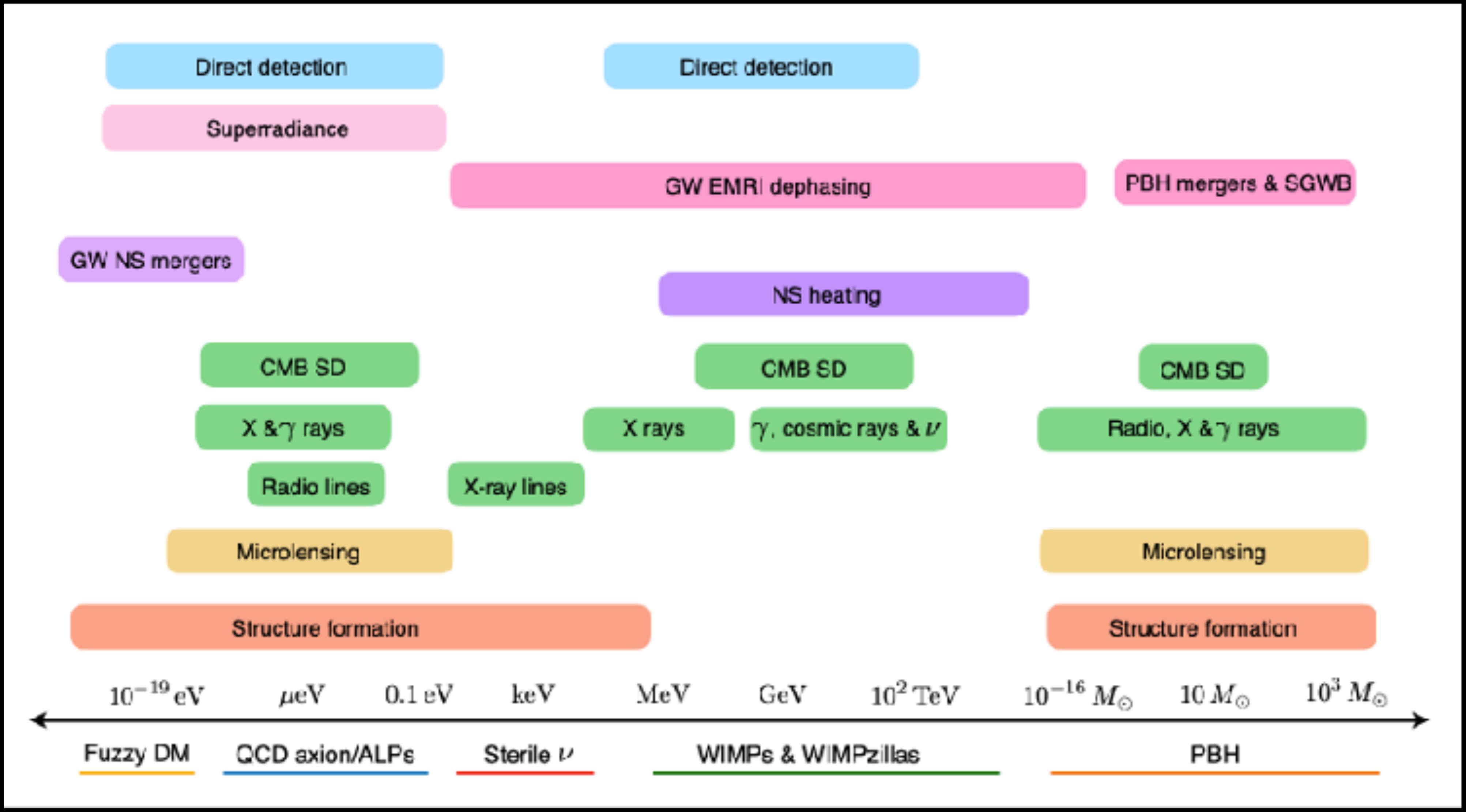
The Chinese University of Hong Kong

17th International Conference on Interconnections between Particle Physics and Cosmology

PPC 2024

14 -18 October 2024, Hyderabad, India

Dark Matter identification

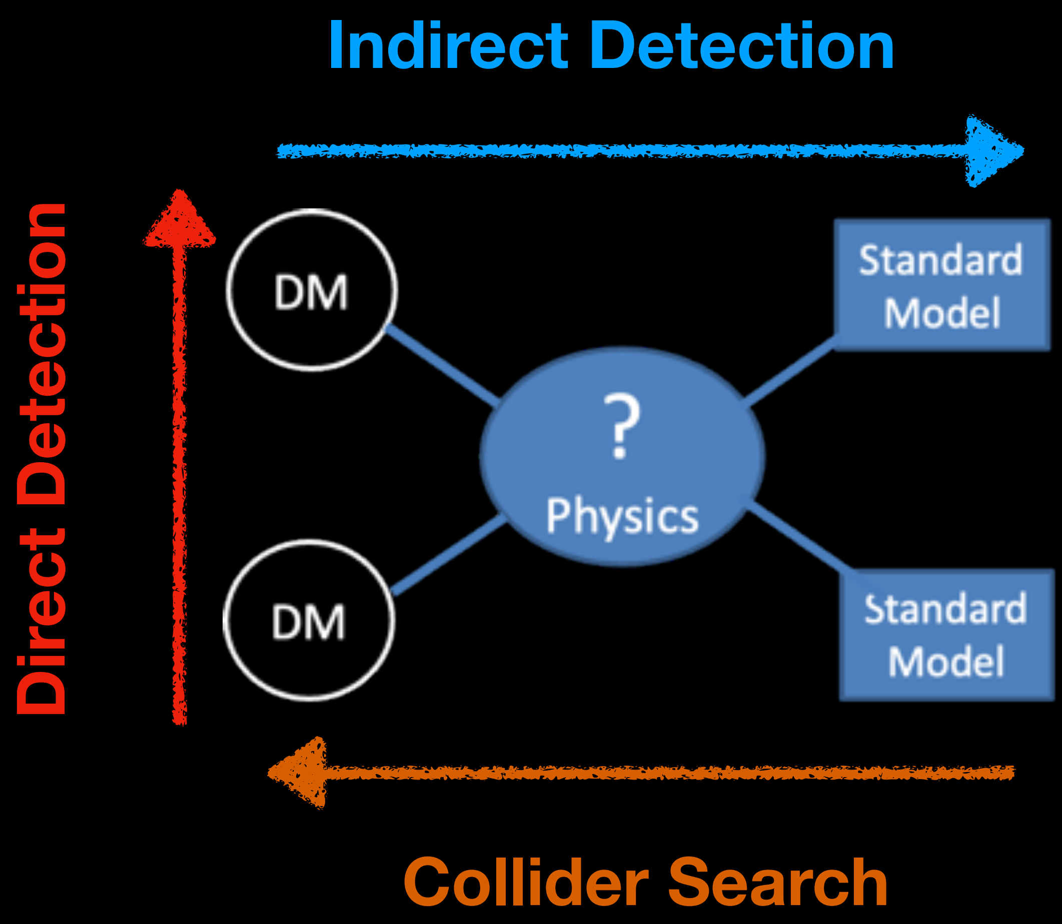


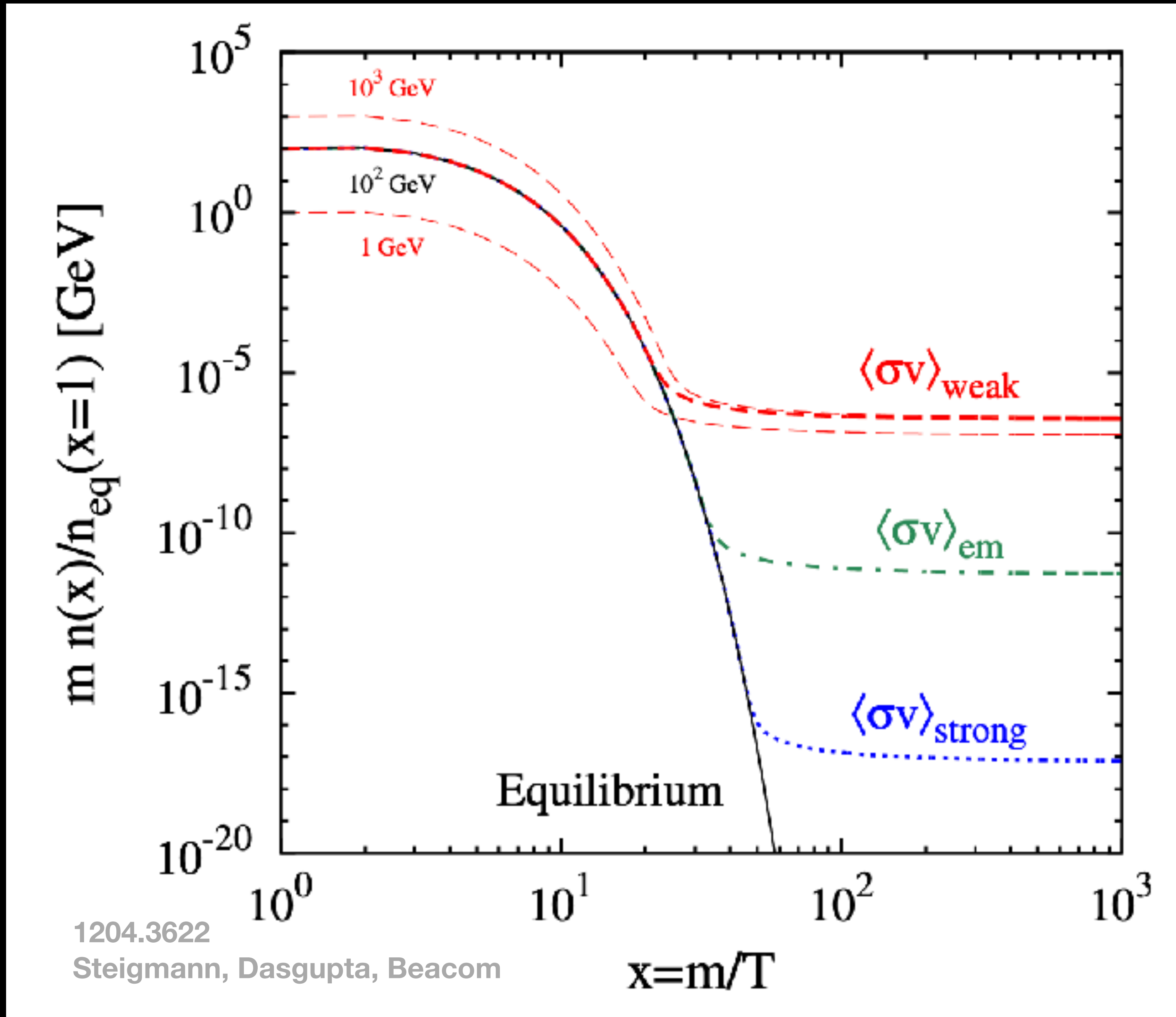
- EuCAPT White Paper, arxiv: 2110.10074

One must try everything

Weakly interacting massive particles (WIMPs)

- **Indirect Detection**
- production by
  - SM + SM -> X + X in the early universe
- sets a definite prediction
  - X + X -> SM + SM
  - 10^{-26}cm^3/s (simplest case)

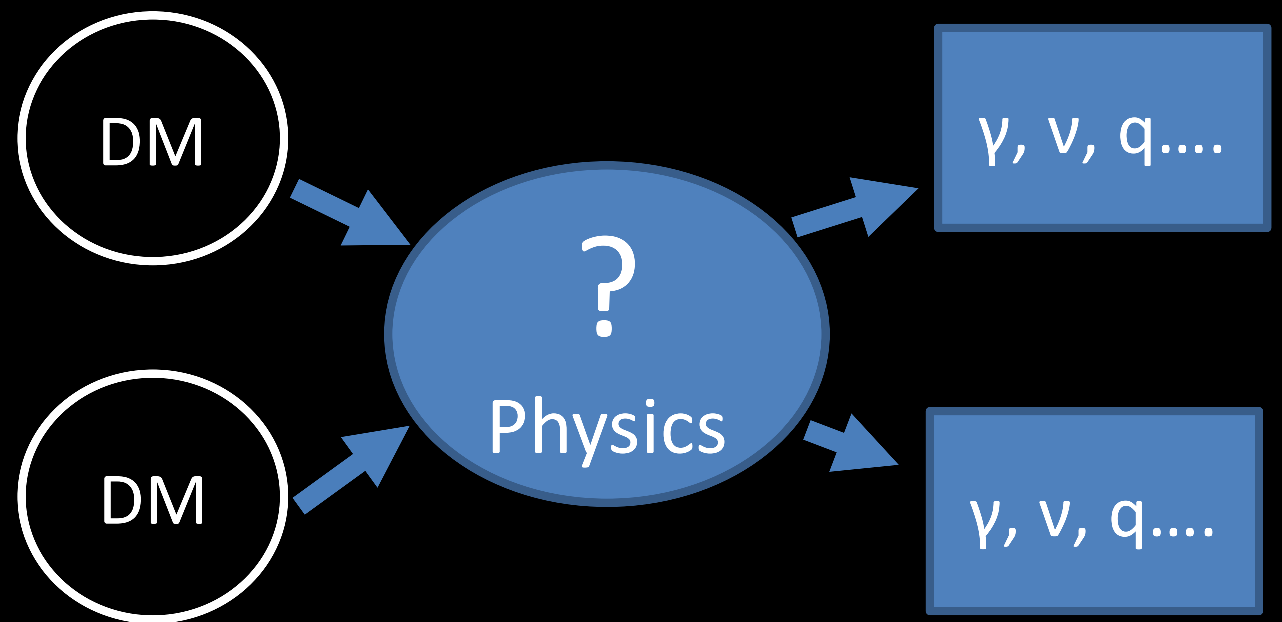




Note: this is the **Total Cross Section**

- 2 to 2, S-wave, spin1/2 majorona DM

Indirect detection



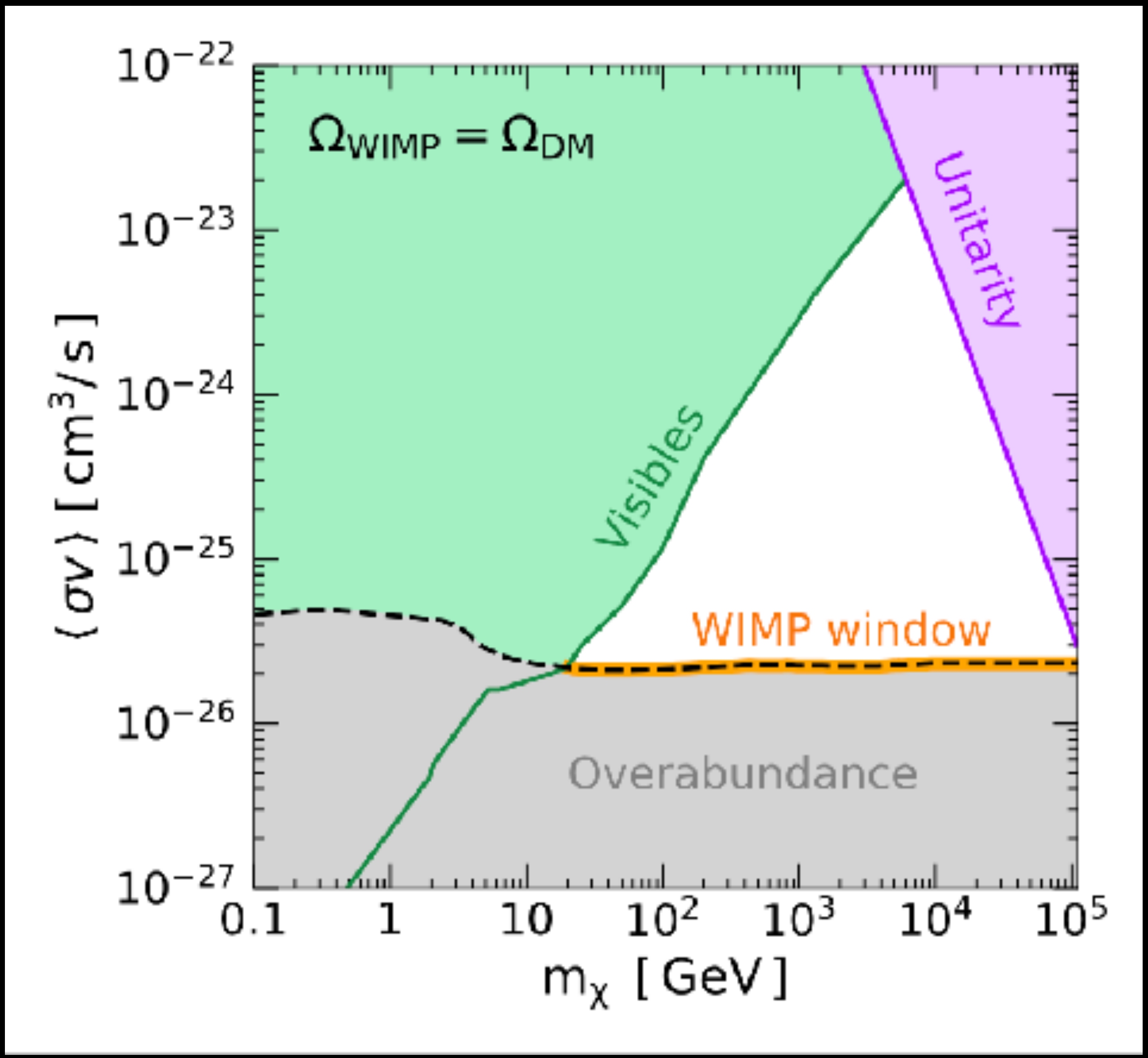
Typical Indirect detection search considers only single Channel

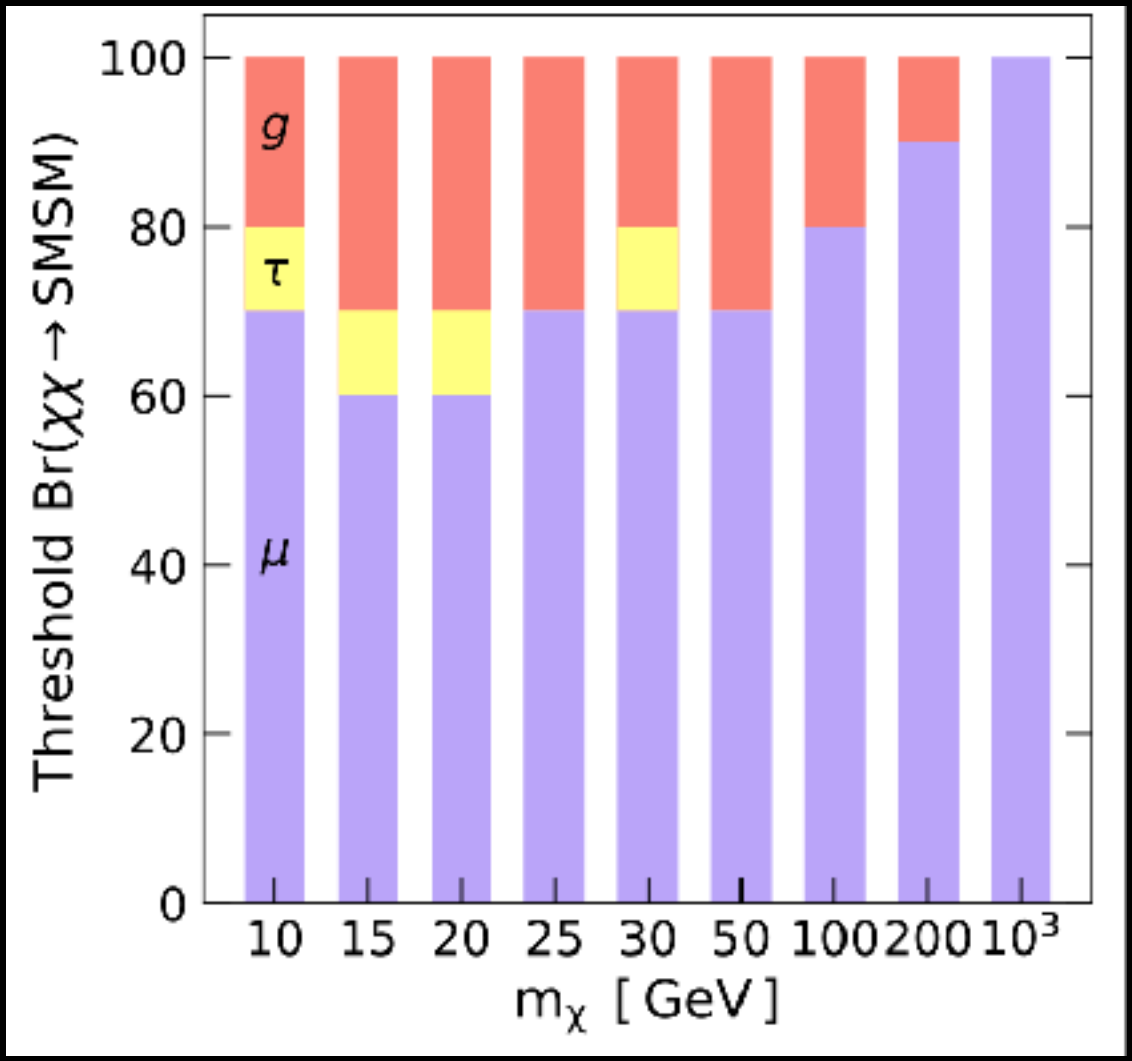
Flux $= \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \int \rho^2 d\ell \frac{dN}{dE}$ **for a specific channel**

$$\langle \sigma v \rangle = Br \times \langle \sigma v \rangle_{tot}$$

Constraints on total cross section

With only visible channels



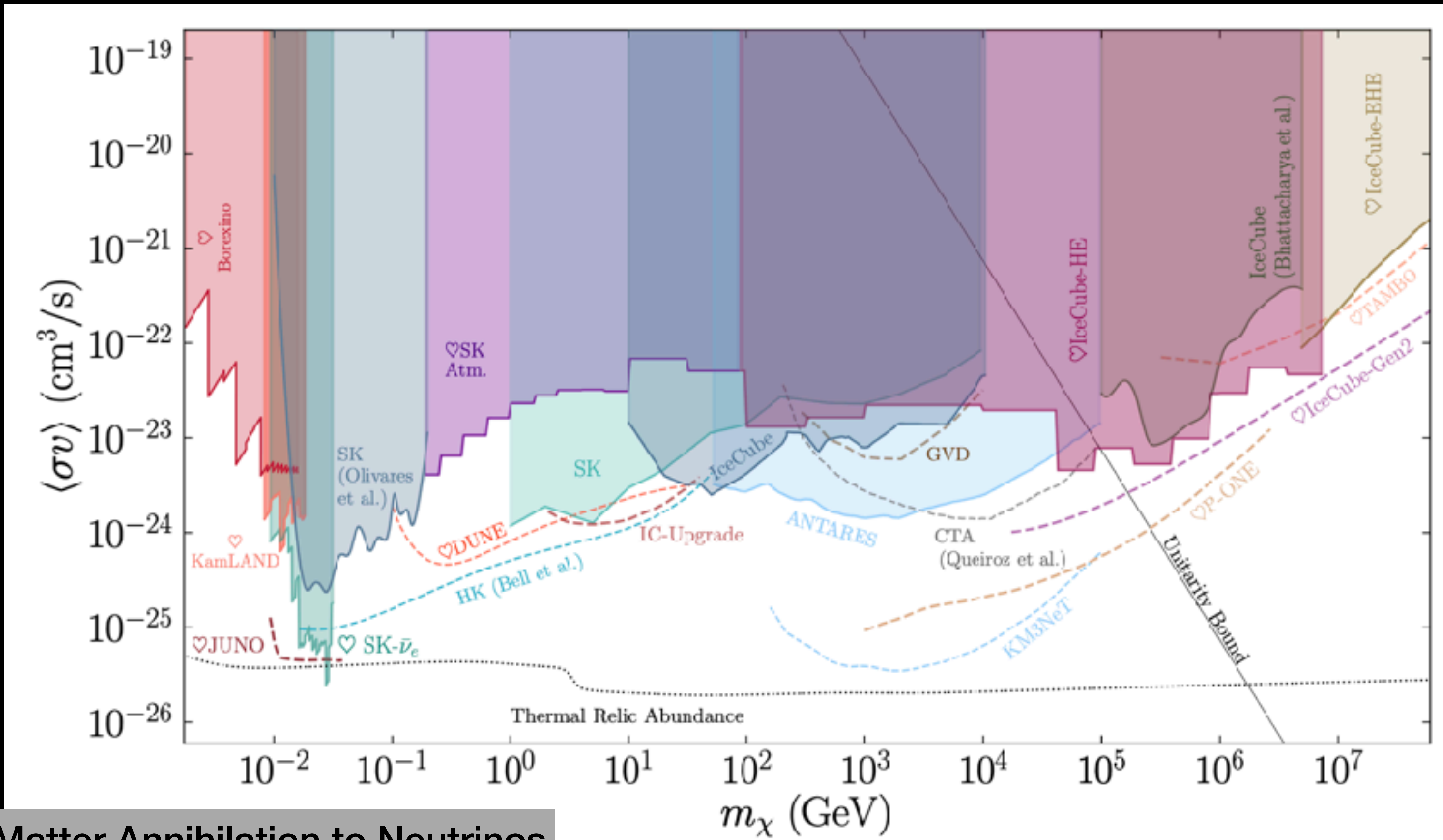


Least constraining combination

1805.10305
Leane, Slatyer, Beacom, KCYN

Neutrinos not included!

Neutrino limits

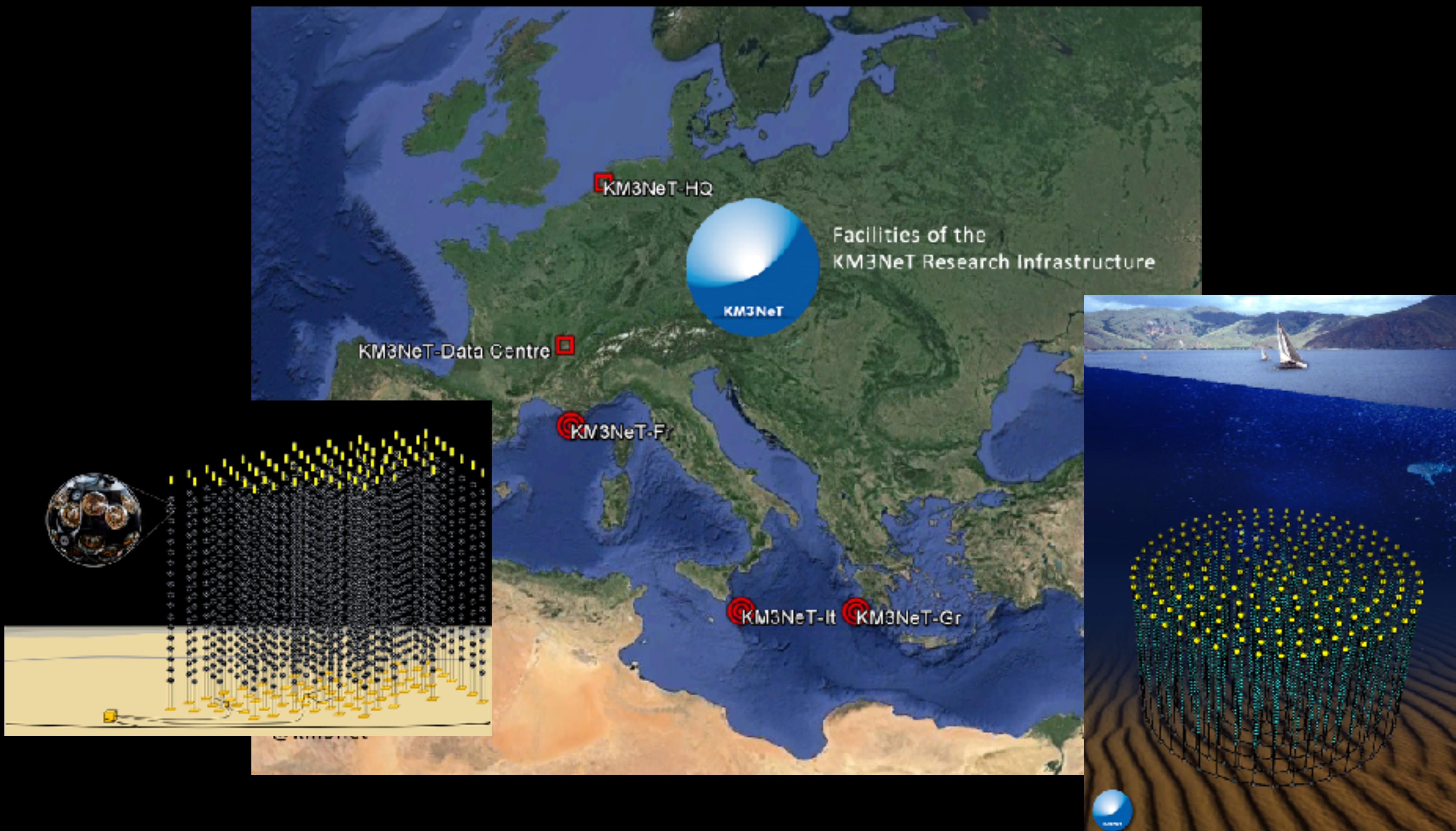


Dark Matter Annihilation to Neutrinos
Arguelles et al ,1912.09486

Neutrinos are the least constraining!
But perhaps the most important for testing WIMP hypothesis

Towards detecting super-GeV dark matter via annihilation to neutrinos
JCAP 08 (2023) 006 [2211.12235]

- L. Salvador Miranda, S. Basegmez du Pree, K.C.Y. Ng, A. Cheek, C. Arina

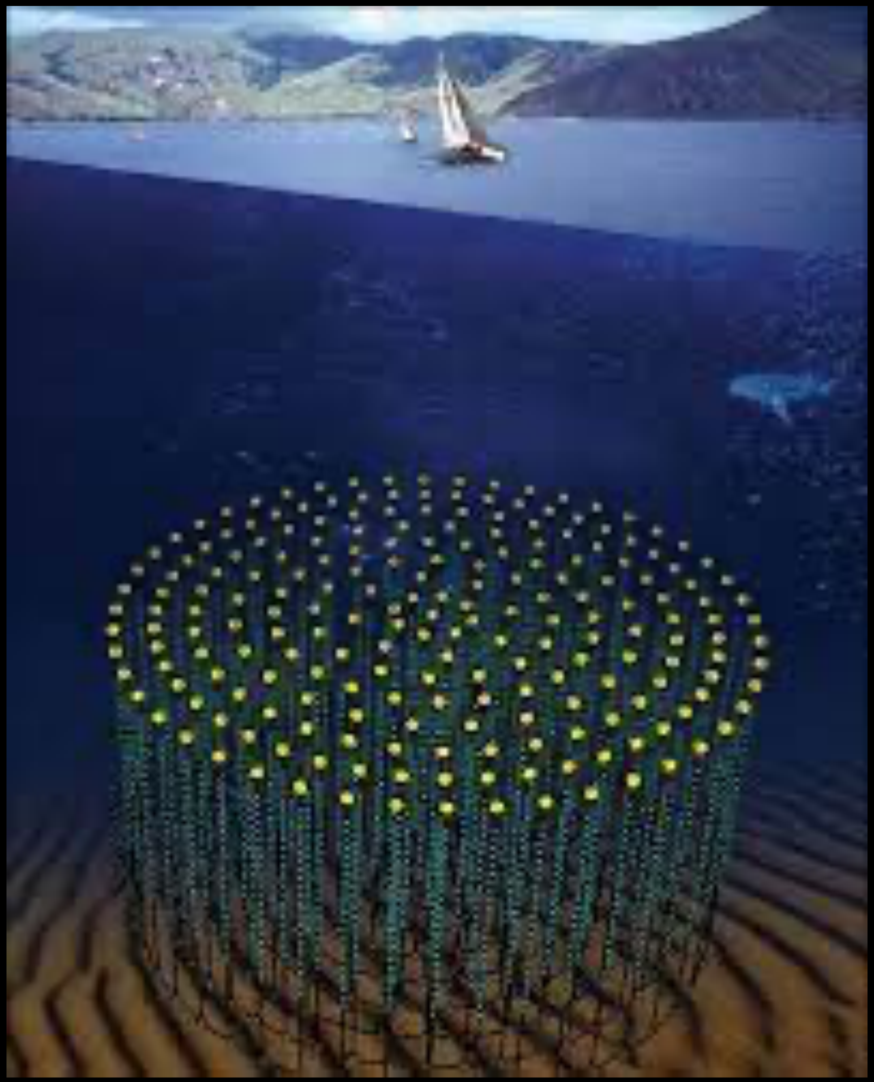


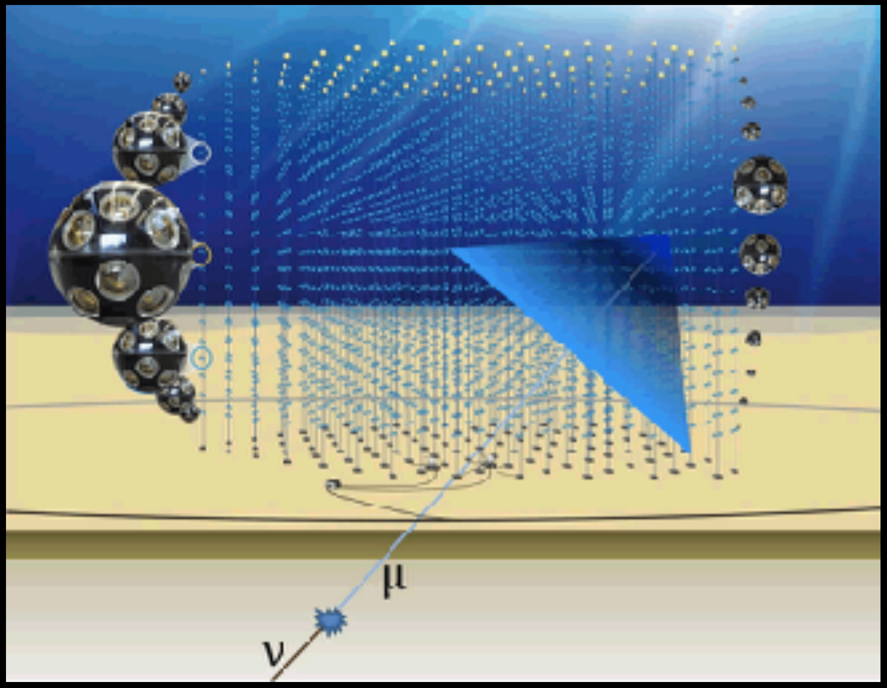
KM3NeT

- Next-gen water Cherenkov neutrino telescope

- ORCA
- ~ 3.7 Mton
- Off-shore France

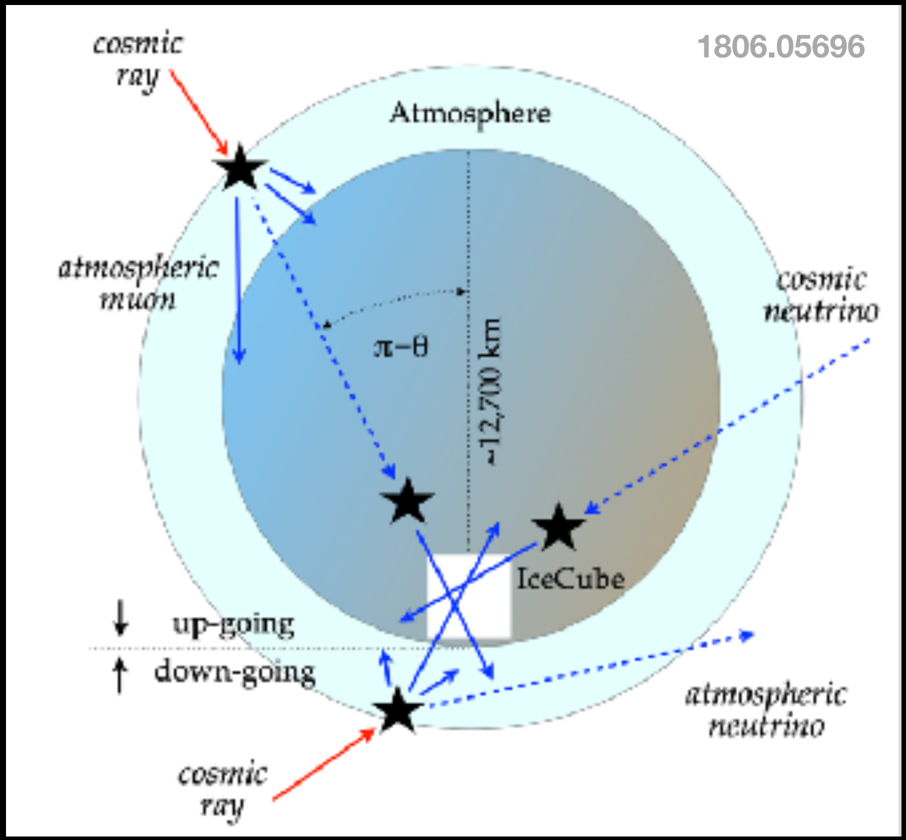
- ARCA
- Off-shore Italy
- 2 building blocks, total ~ 1 Gton



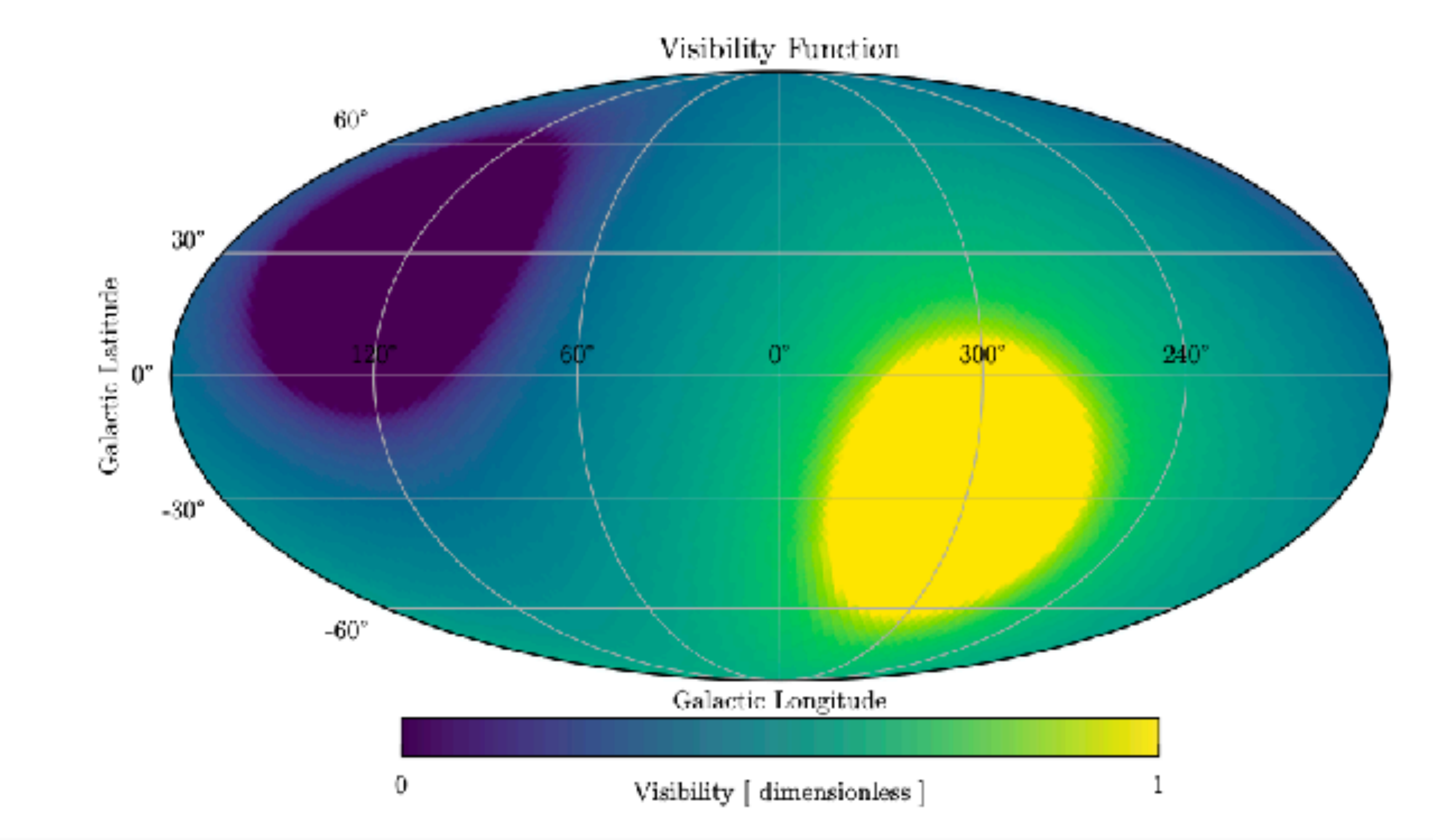


KM3NeT

- Northern hemisphere detector, have a good view of the Galactic Center, GC



- Visibility function:
  - Fraction of time that the GC is below horizon
  - ~ 63% at GC



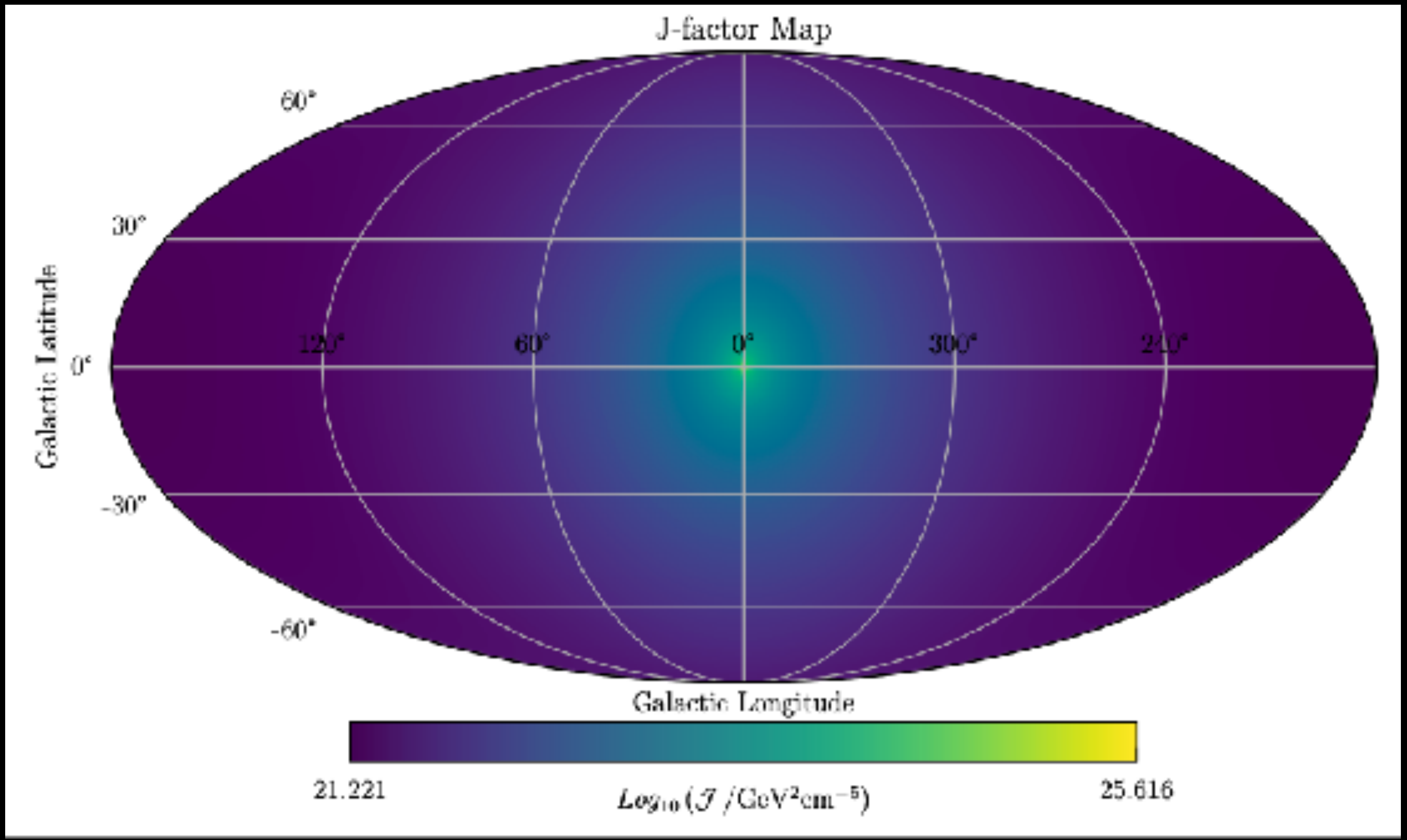
This work
2211.12235

Dark Matter signal

- Dark Matter flux

$$\frac{dI_\nu(\psi)}{dE} = \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \frac{dN_\nu}{dE} \int_0^{l_{max}} \rho_\chi^2[r(l)]dl$$

- J-factor
  - $J = \int \rho^2 d\ell$



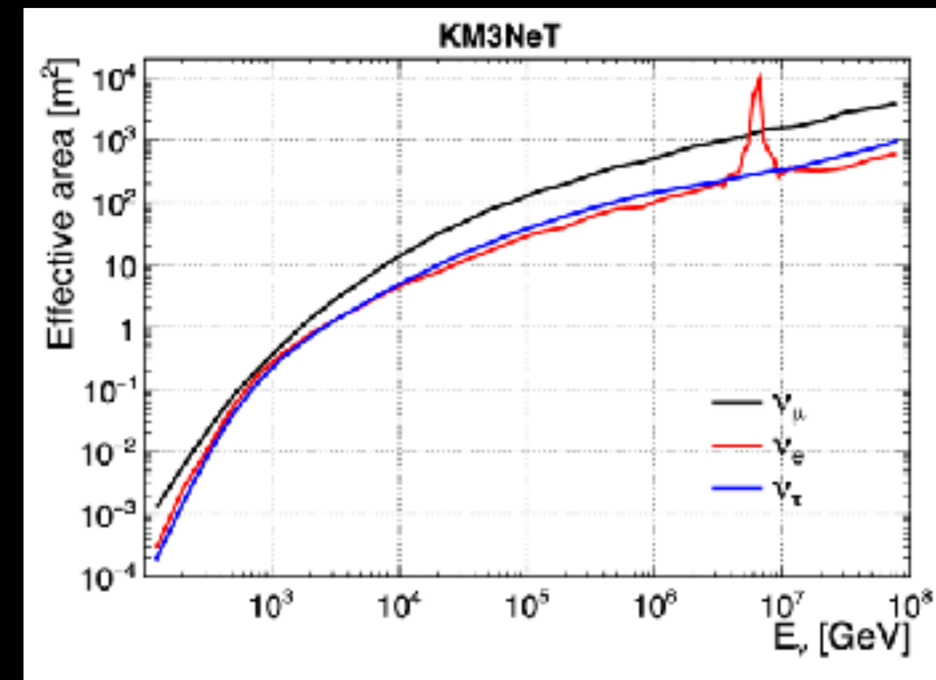
- NFW profile
  - The choice is important

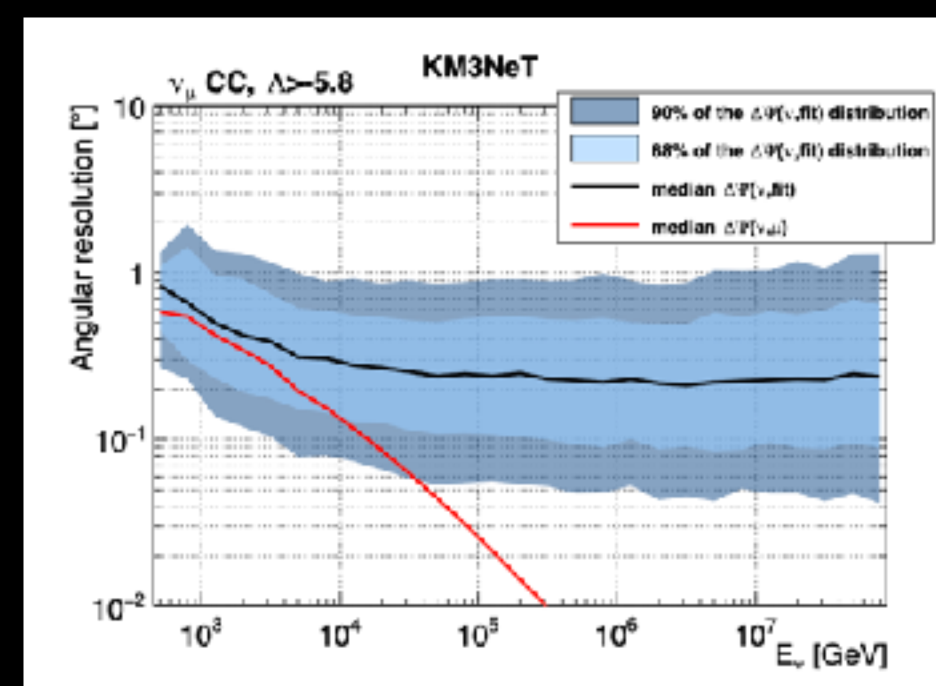
$$\rho_\chi(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

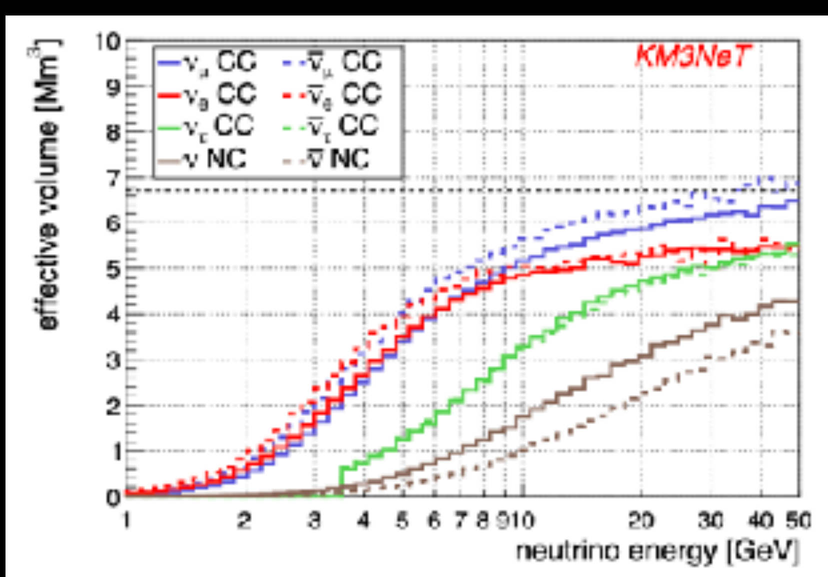
Expected Event rate ber bin

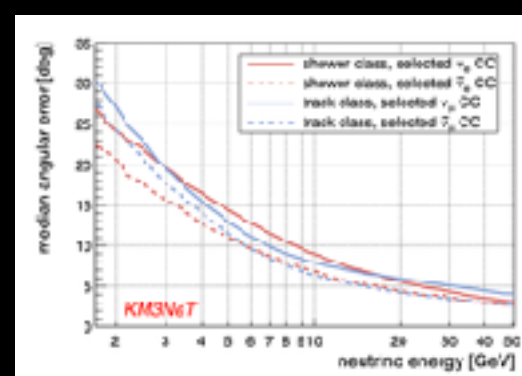
KM3NeT Letter of intent
1601.07459

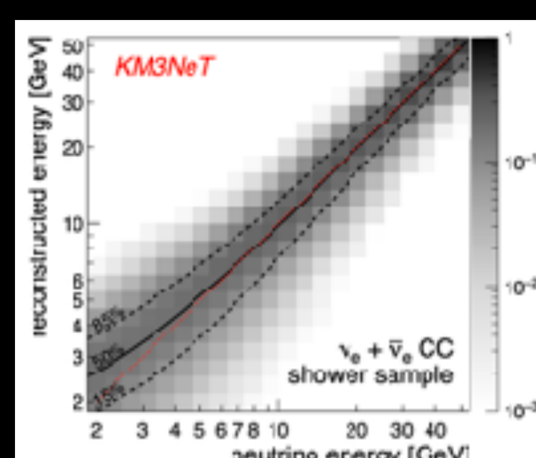
- Effective area
- Angular resolution
  - ARCA: ~ 0.3 degree at 10 TeV
- Energy resolution
  - ARCA: $\Delta \log_{10}(E_\nu) = 0.27$ (tracks)











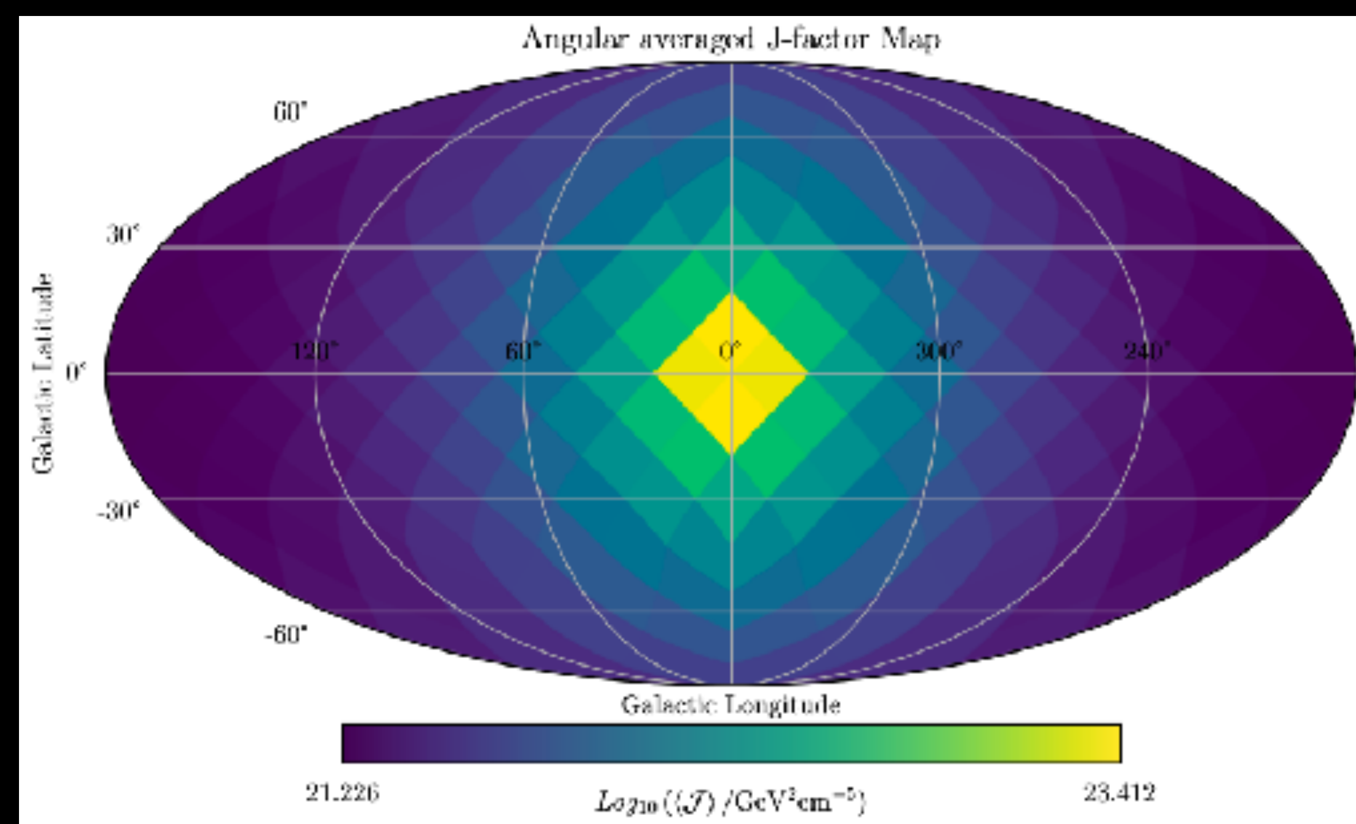
Aiello et al
2103.09885

Expected Event rate ber bin

- Binning in both Energy and Angular
- Two times of the resolution

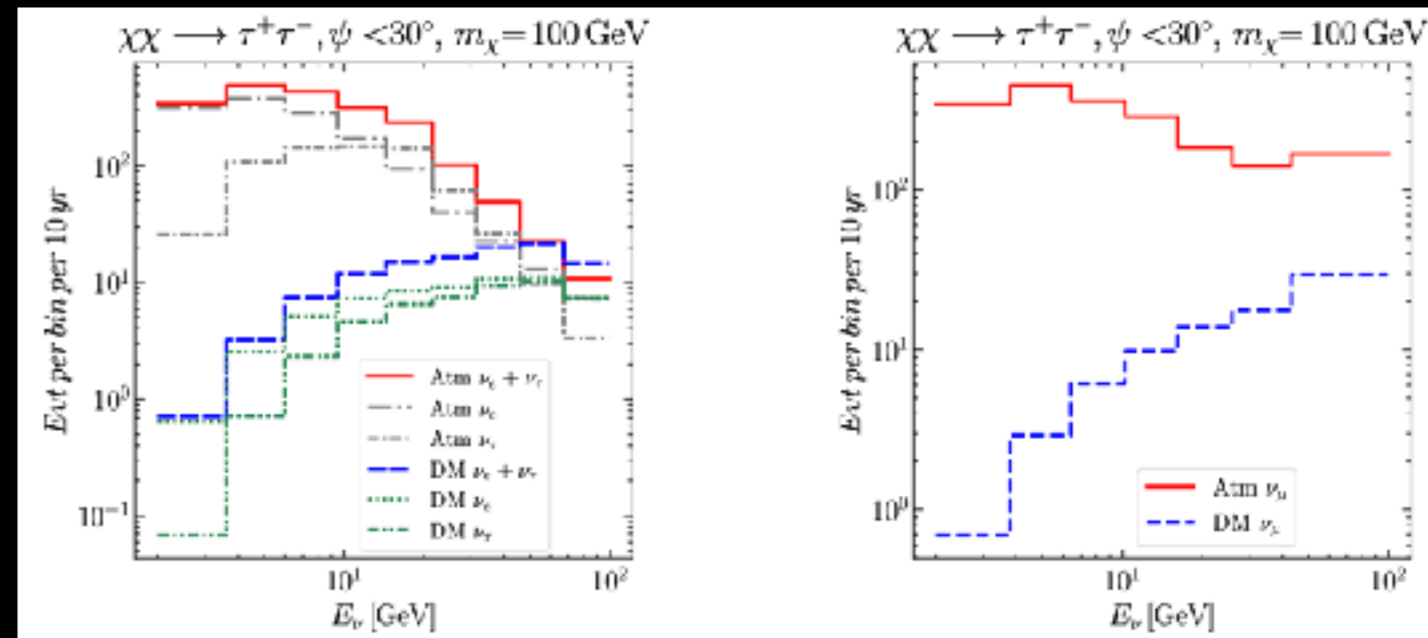
$$n_{ij} = T_{\text{eff}} \int_i dE_\nu \int_j \text{vis}(\Omega)\, d\Omega \frac{dI_\nu}{dE_\nu} A_{\text{eff}} \langle e^{-\tau(E_\nu;\Omega)} \rangle$$

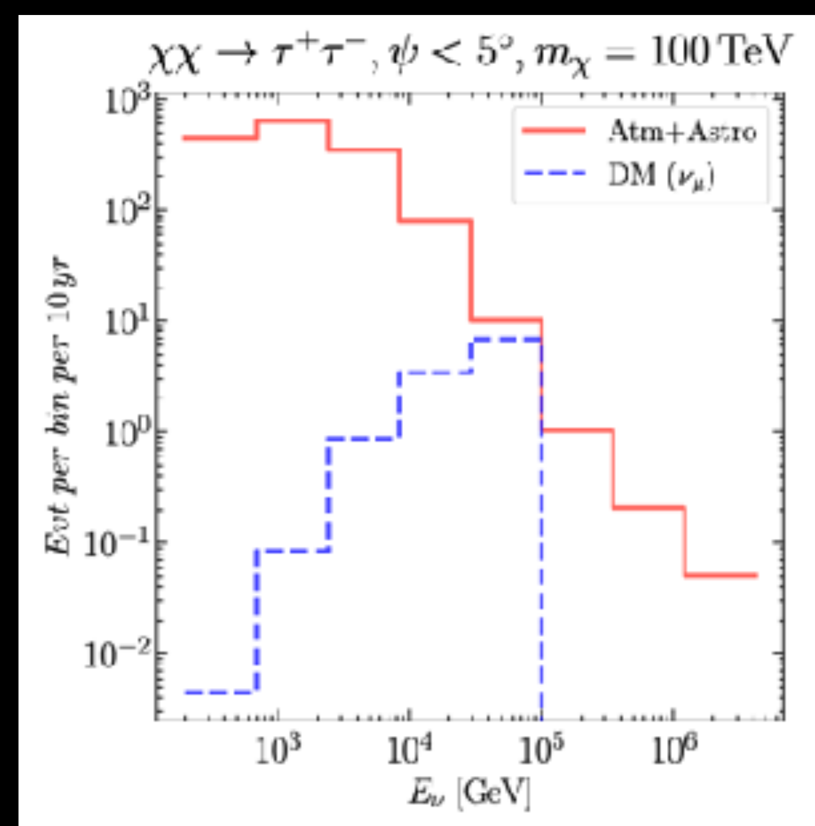
- T_{eff} = 10 years
- $\text{vis}(\Omega)$: visibility function vs sky position
- A_{eff} detector effective area
- $\langle e^{-\tau} \rangle$ neutrino absorption through energy, only relevant at very high energy



Backgrounds

- Atmospheric neutrinos
  - Honda et al, 1502.03916
  - Sinegovskaya et al, 1407.3591
- Astrophysical neutrinos
  - 10-years Icecube best fit, 1908.09551
  - Results not are sensitive to isotropic diffuse astrophysical neutrinos.

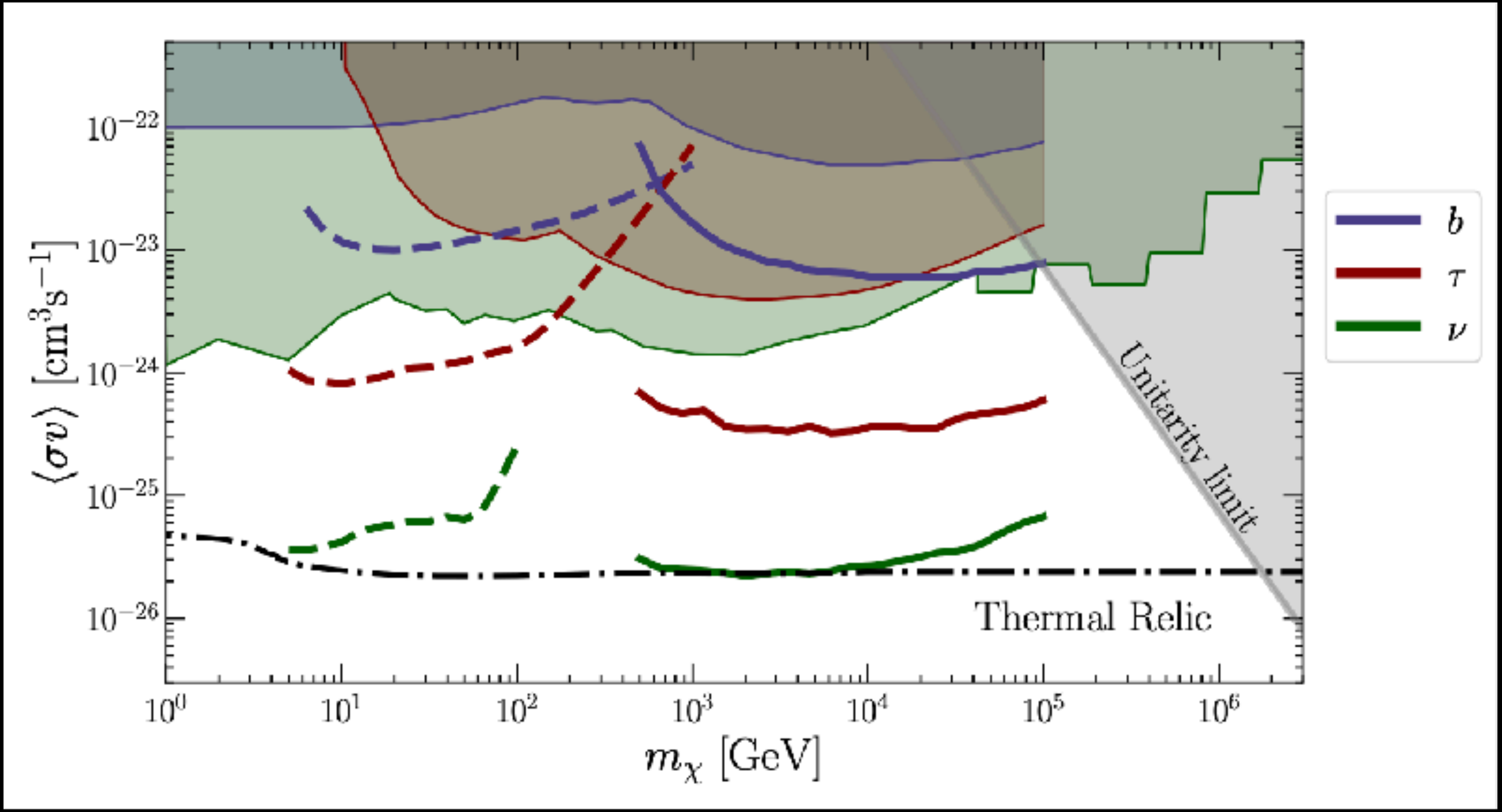




This work
2211.12235

Mock Likelihood analysis

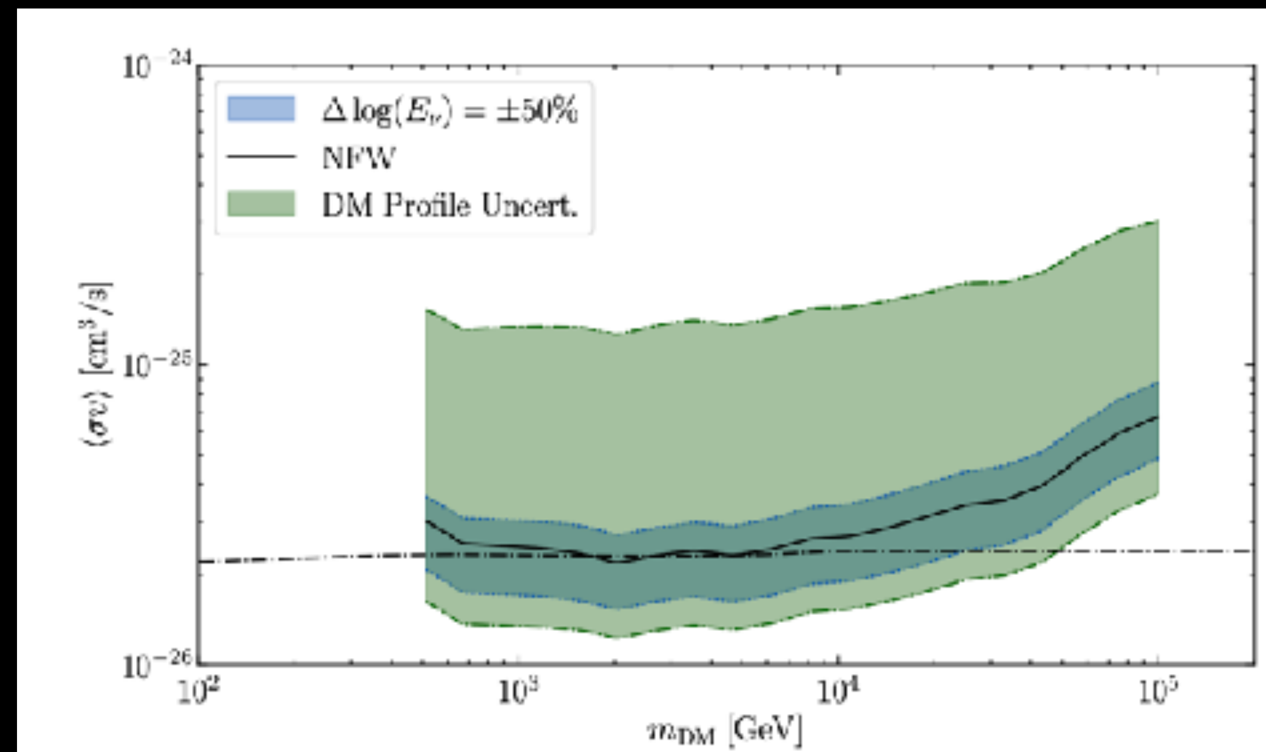
- Atmospheric neutrino + 10 years IceCube isotropic diffuse astrophysical background



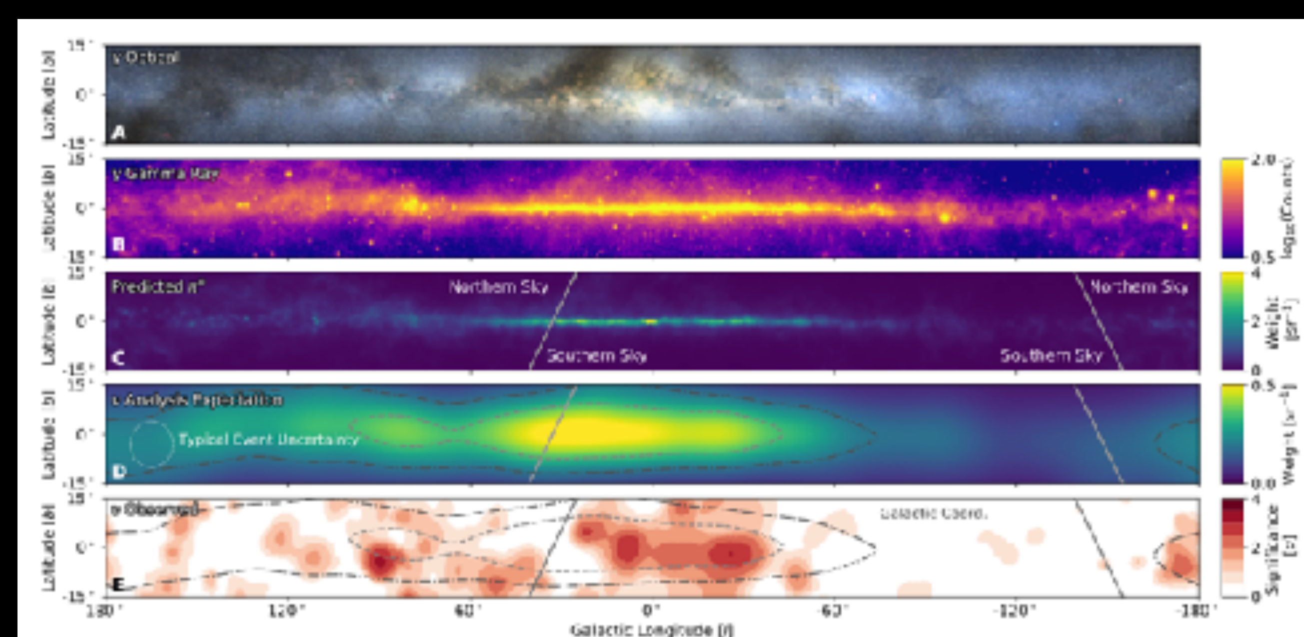
This work
2211.12235

The uglies

- The result will depends a lot on the profile assumption.

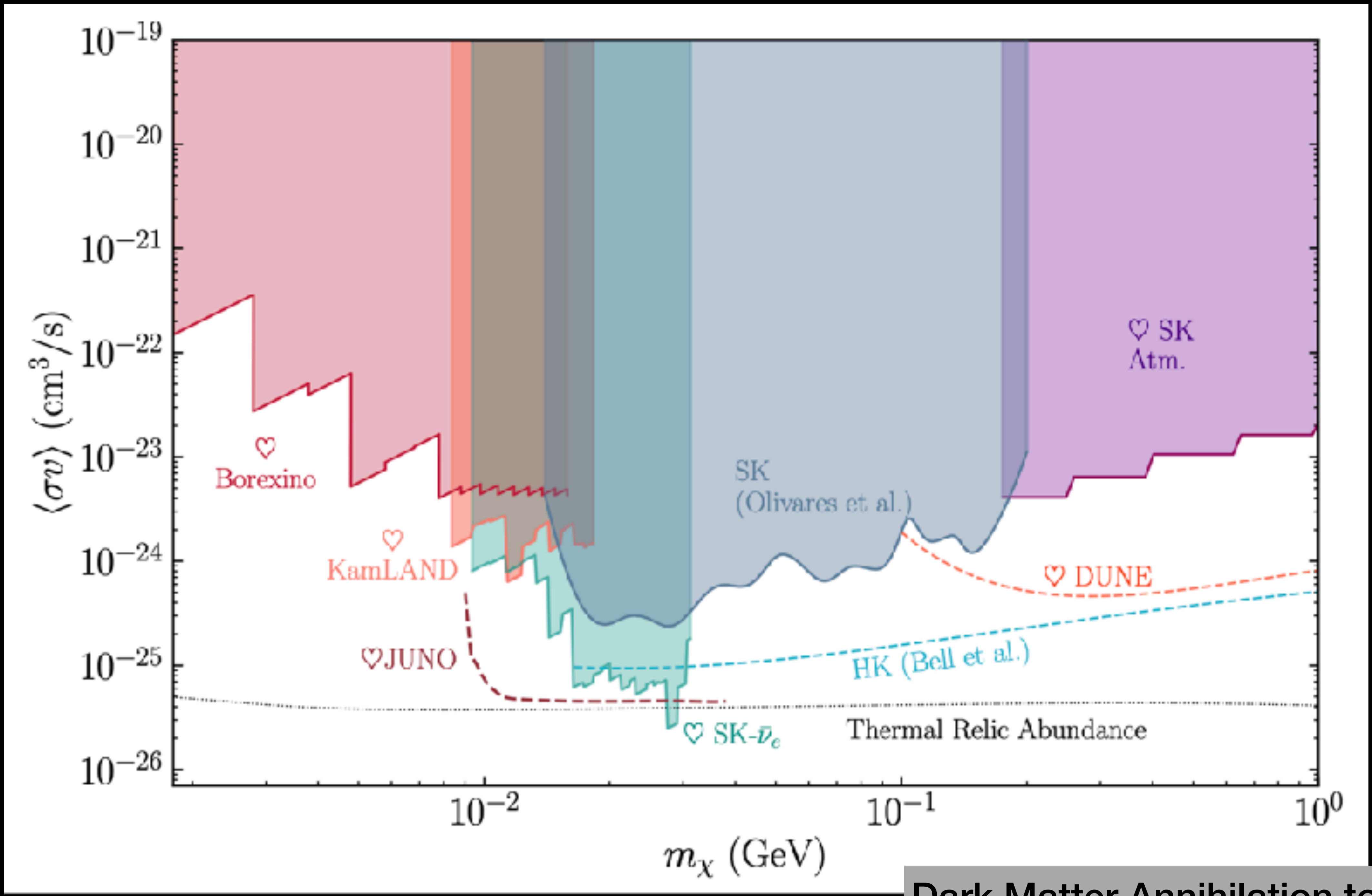


- Galactic plane/center component?



- Diffuse component is fine
- A peak at GC will be confusing

MeV Scale



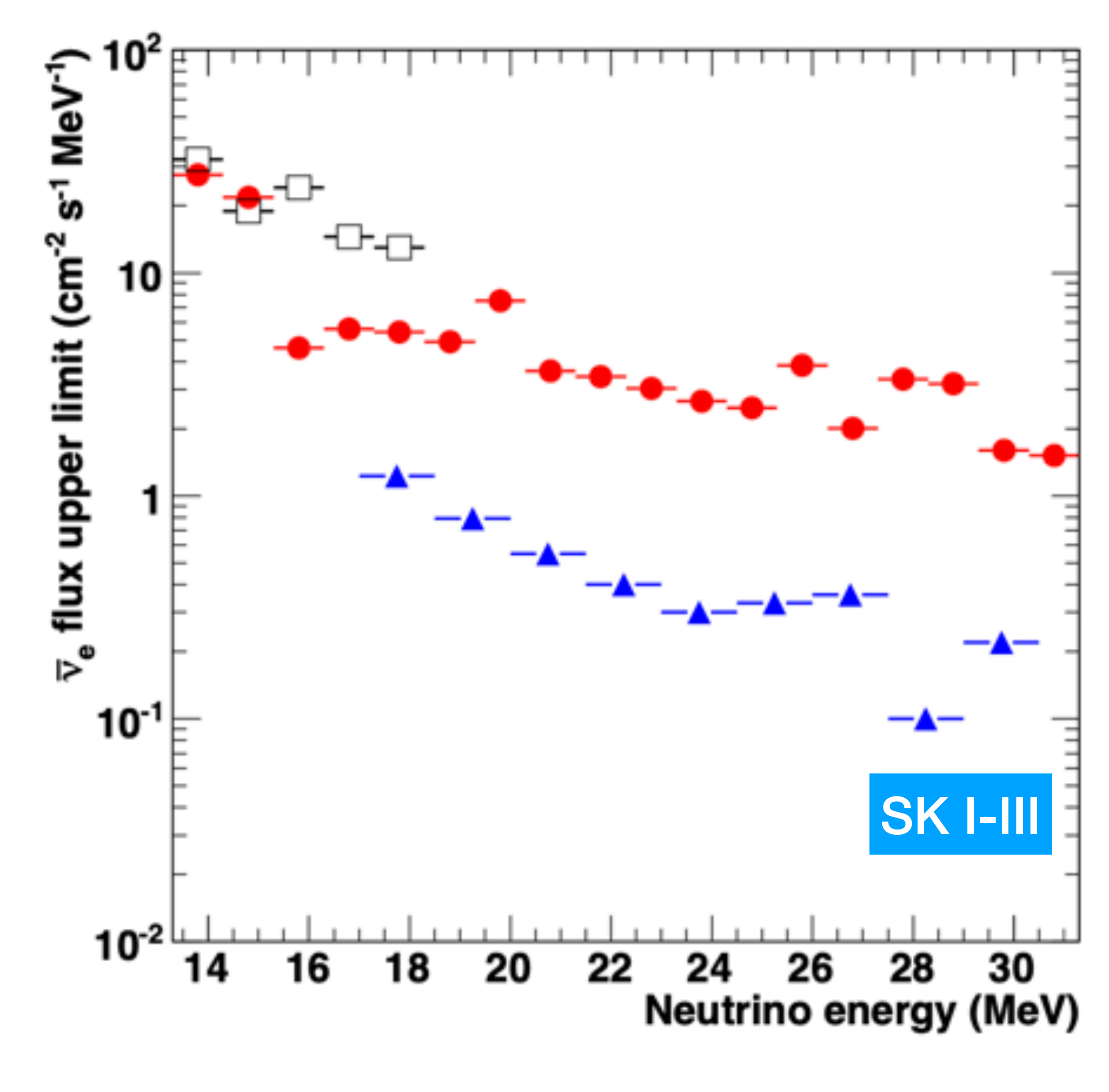
Dark Matter Annihilation to Neutrino
Arguelles et al ,1912.09486

$\bar{\nu}_e$ flux upper limits

- Inverse Beta Decay
  - $\bar{\nu}_e + p \rightarrow e^+ + n$

- Diffuse $\bar{\nu}_e$ flux upper limits
  - From diffuse supernova neutrinos search

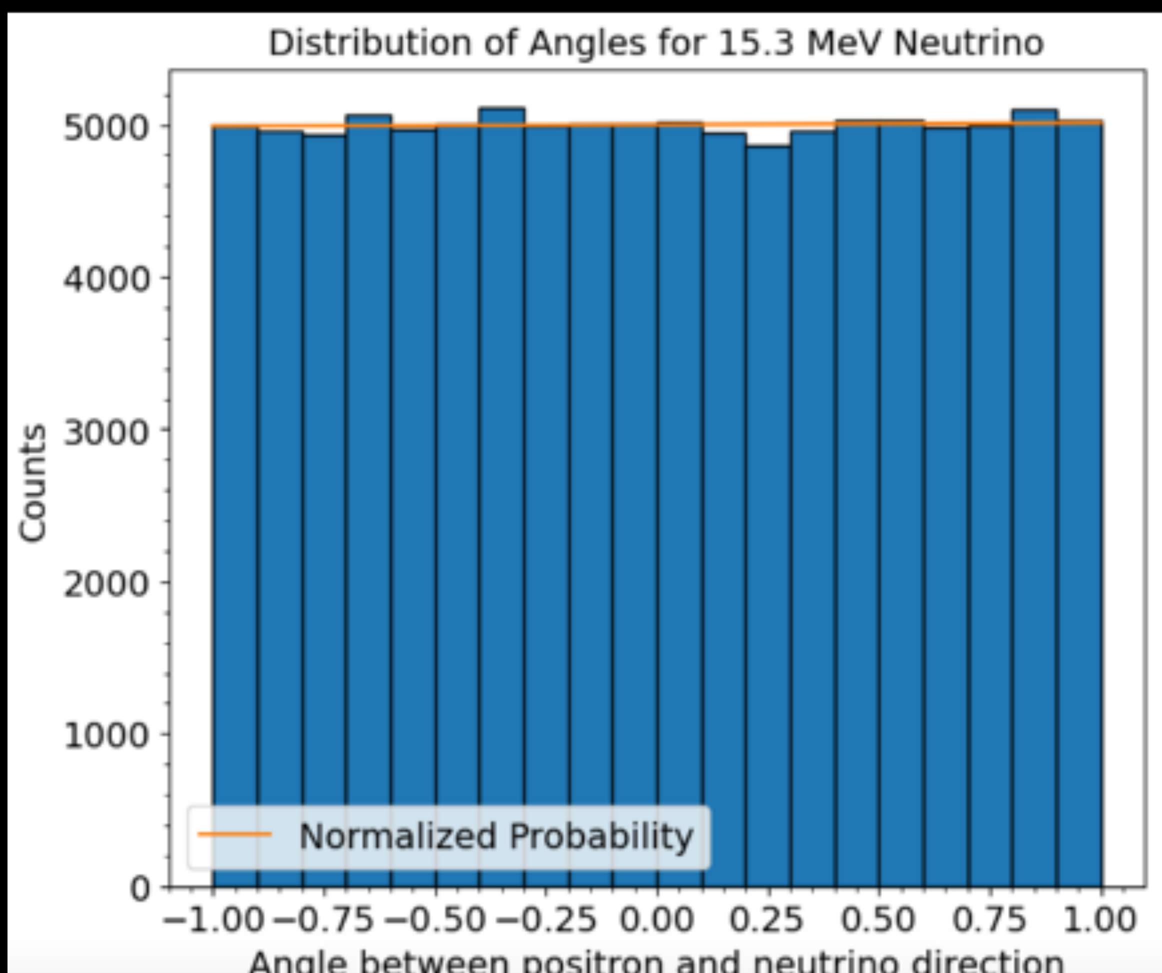
- The "strong" limit is really just dominated by one data point!



Super-K
1311.3738

Inverse beta cross section

- Positrons from IBD does not point
  - Vogel, Beacom 1999



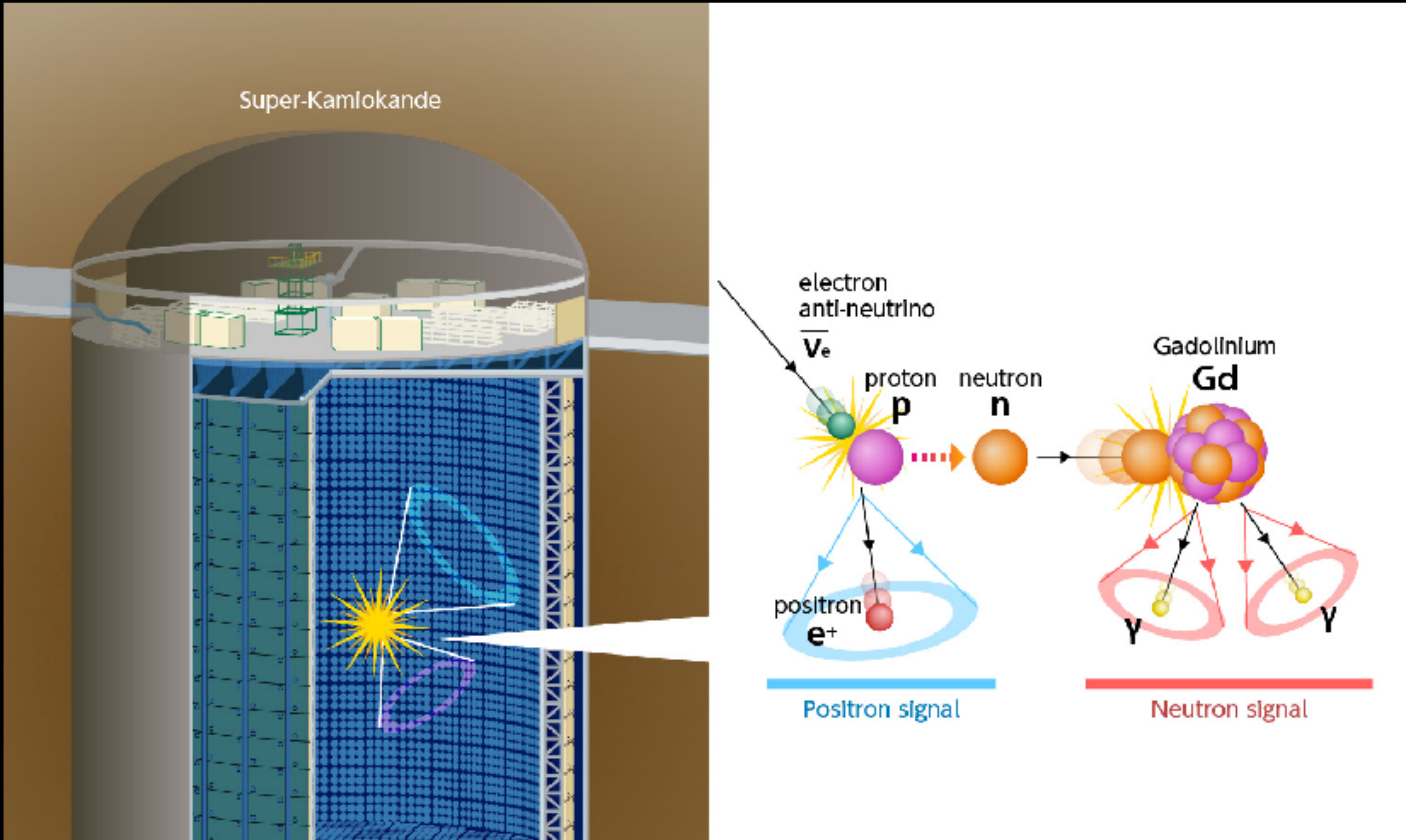
Positron angular distribution from cross section

E_ν	$\sigma(\bar{\nu}_e p)$	$\langle E_e \rangle$	$\langle \cos\theta \rangle$	E_ν	$\sigma(\bar{\nu}_e p)$	$\langle E_e \rangle$	$\langle \cos\theta \rangle$
1.806	0	–	–	8.83	0.511	7.46	−0.015
2.01	0.00351	0.719	−0.021	9.85	0.654	8.47	−0.013
2.25	0.00735	0.952	−0.025	11.0	0.832	9.58	−0.010
2.51	0.0127	1.21	−0.027	12.3	1.05	10.8	−0.007
2.80	0.0202	1.50	−0.027	13.7	1.33	12.2	−0.003
3.12	0.0304	1.82	−0.027	15.3	1.67	13.7	0.0006
3.48	0.0440	2.18	−0.027	17.0	2.09	15.5	0.005
3.89	0.0619	2.58	−0.026	19.0	2.61	17.4	0.010
4.33	0.0854	3.03	−0.025	21.2	3.24	19.5	0.015
4.84	0.116	3.52	−0.024	23.6	4.01	21.8	0.021
5.40	0.155	4.08	−0.023	26.4	4.95	24.4	0.028
6.02	0.205	4.69	−0.022	29.4	6.08	27.3	0.036
6.72	0.269	5.38	−0.020	32.8	7.44	30.5	0.044
7.49	0.349	6.15	−0.018	36.6	9.08	34.1	0.054
8.36	0.451	7.00	−0.016	40.9	11.0	38.0	0.065

Strumia, Vissani
astro-ph/0302055

Super-k + Gd

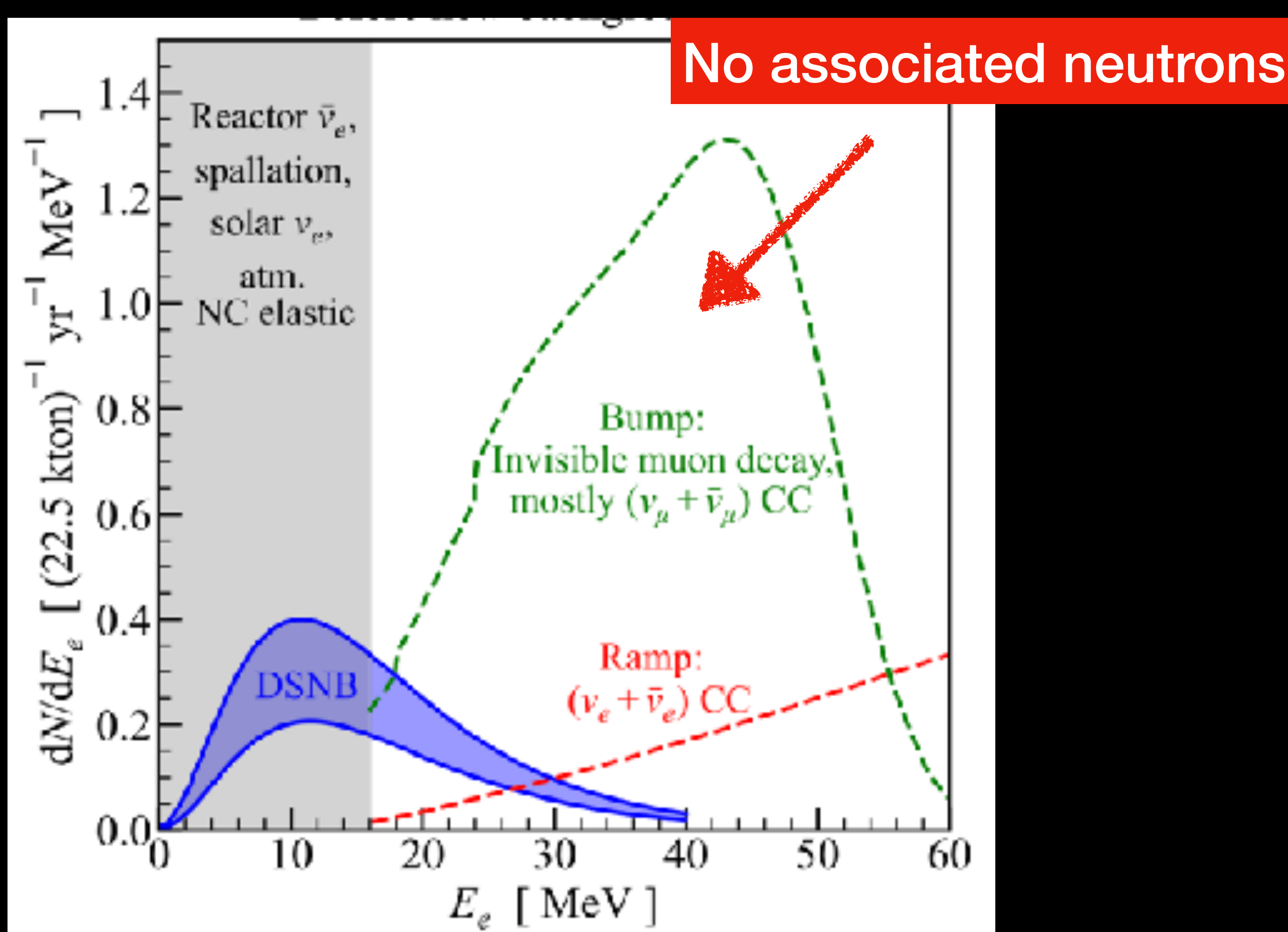
Beacom, Vagin 2004



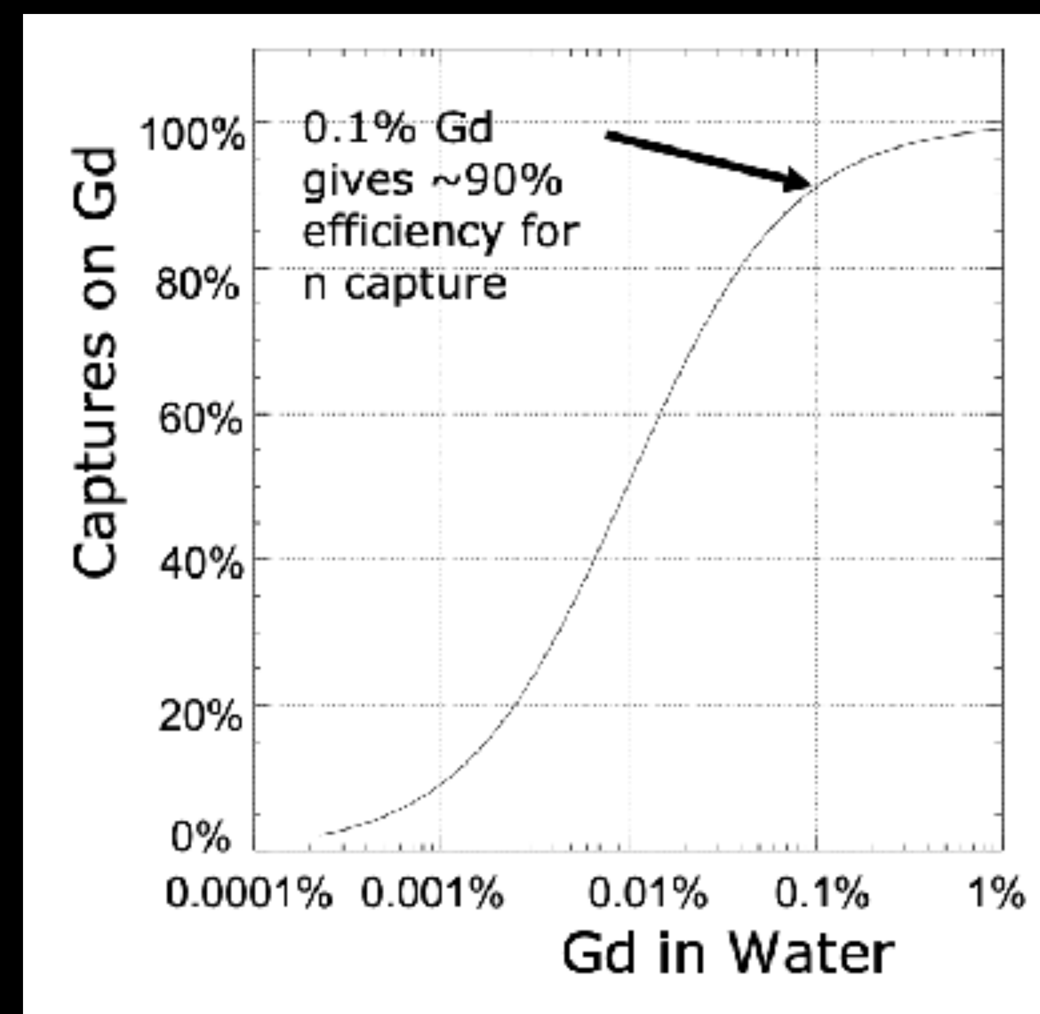
Neutron tagging reduce background

Super-k Gd project

- SK: 2109.00360
  - 0.01% Gd
- SK: 2403.07796
  - 0.033% Gd
- Could enable the detection of diffuse supernova neutrino background (DSNB)
- 2.3 sigma (Neutrino 2024)



Zhou, Beacom 2024

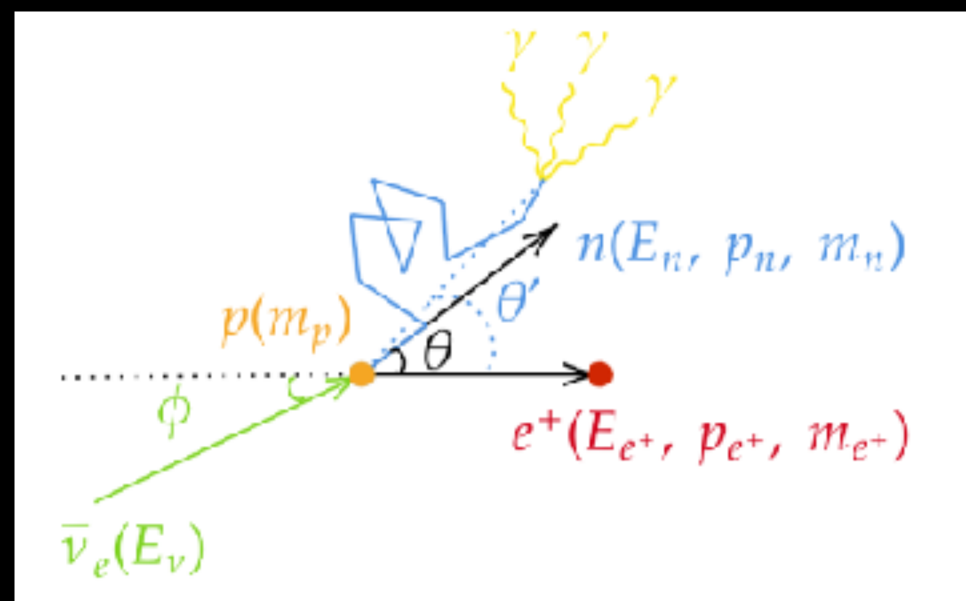


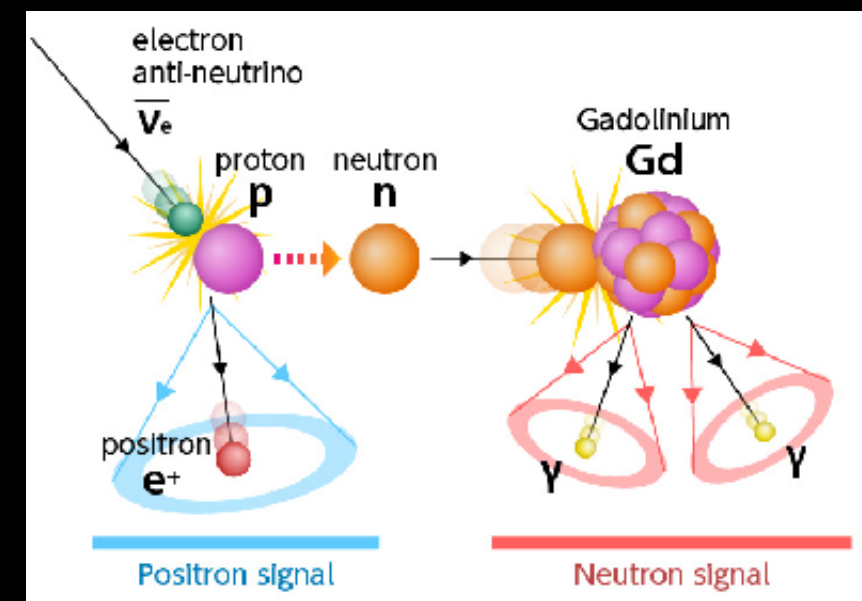
https://pos.sissa.it/282/982/pdf

Can Neutrons help reconstruct IBD?

- Counting variables

$$
\begin{aligned}
E_\nu + m_p &= E_n + E_e \\
E_\nu \cos\phi &= p_n \cos\theta + p_e \\
E_\nu \sin\phi &= p_n \sin\theta
\end{aligned}
$$





- 2D problem
- 3 equations
- 5 variables
  - E_ν , E_e , E_n , θ , ϕ

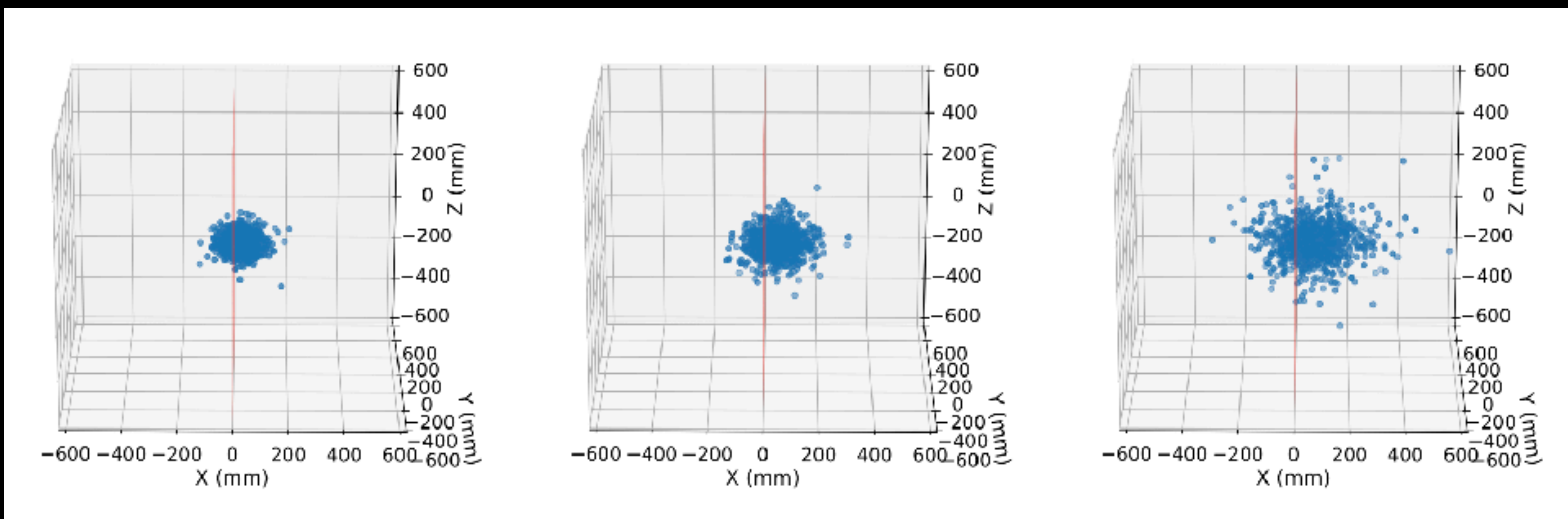
- **Positron energy is already measured**
- **Just need one more!**
- **Neutron angle or neutron momentum**

Unfortunately, Neutron diffuse in water

Can Neutron help reconstruct IBD?

Preliminary

- With Qishan Liu@CUHK
- Geant4 simulation
- 0.1% Gd in Water by weight



Neutron momentum | 20MeV | 50MeV | 80MeV

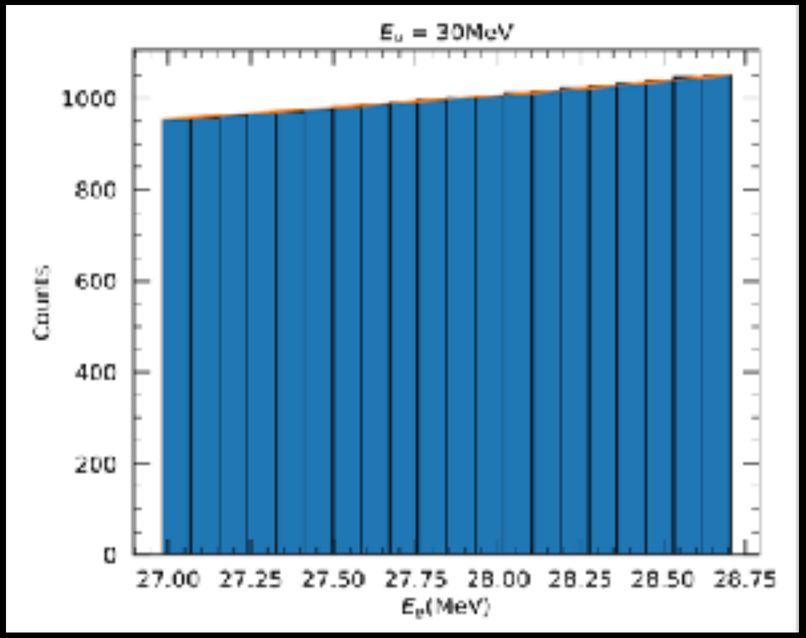
- Some neutron directionality remains even after diffusion

Can Neutron help reconstruct IBD?

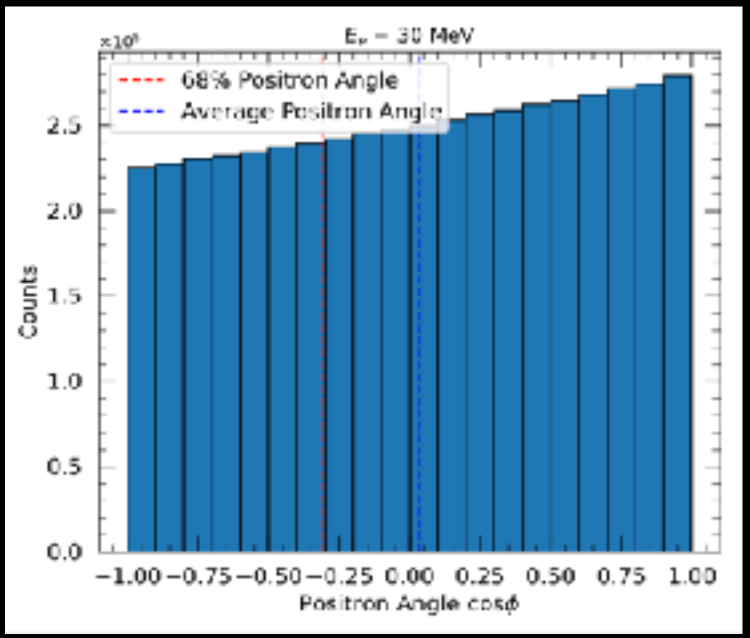
Preliminary

- Full blind reconstruction difficult
- **For targeted search**
  - **Fixed direction and/or fixed energy (e.g., Dark matter)**
  - Using only *neutron capture direction*

Cross sections distributions



Positron energy



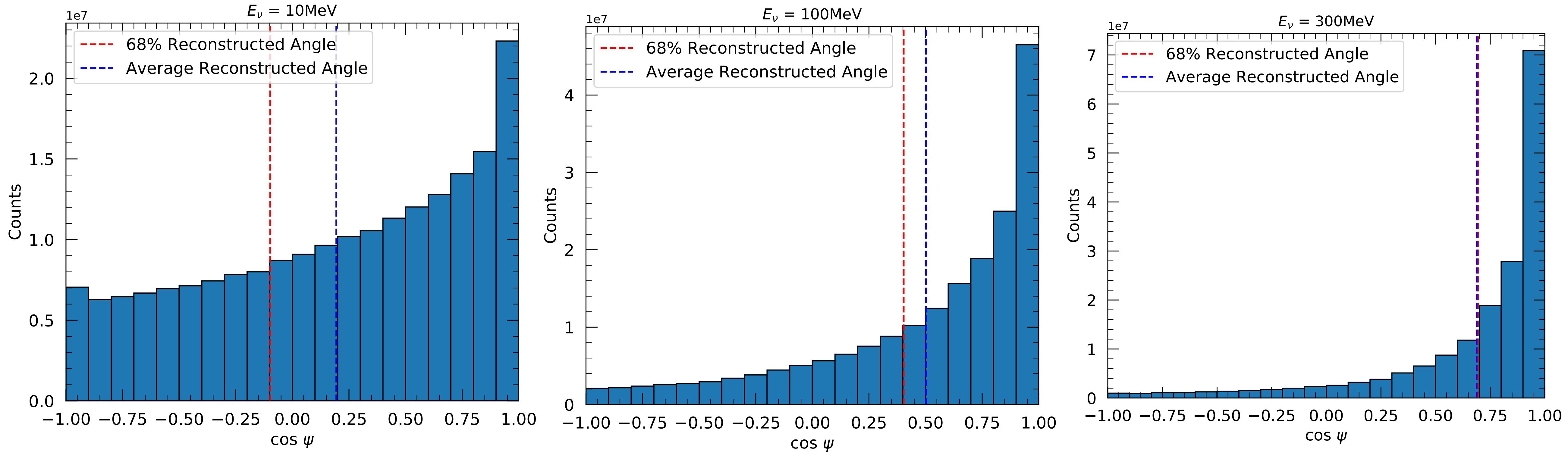
Positron angle

+

Neutron Diffusion and Capture

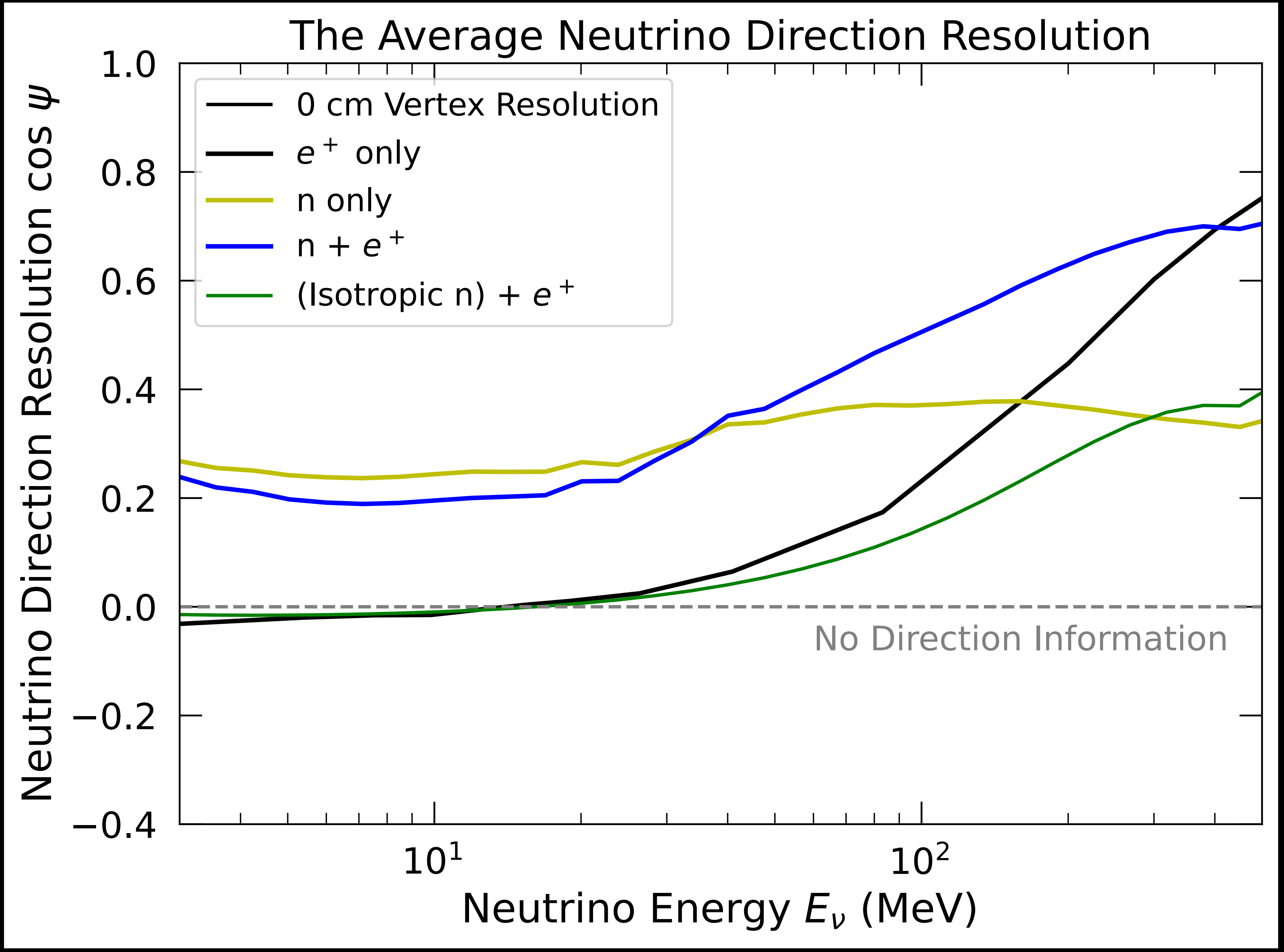
Reconstructed neutrino direction

Preliminary



The ideal scenario (theoretically best case)

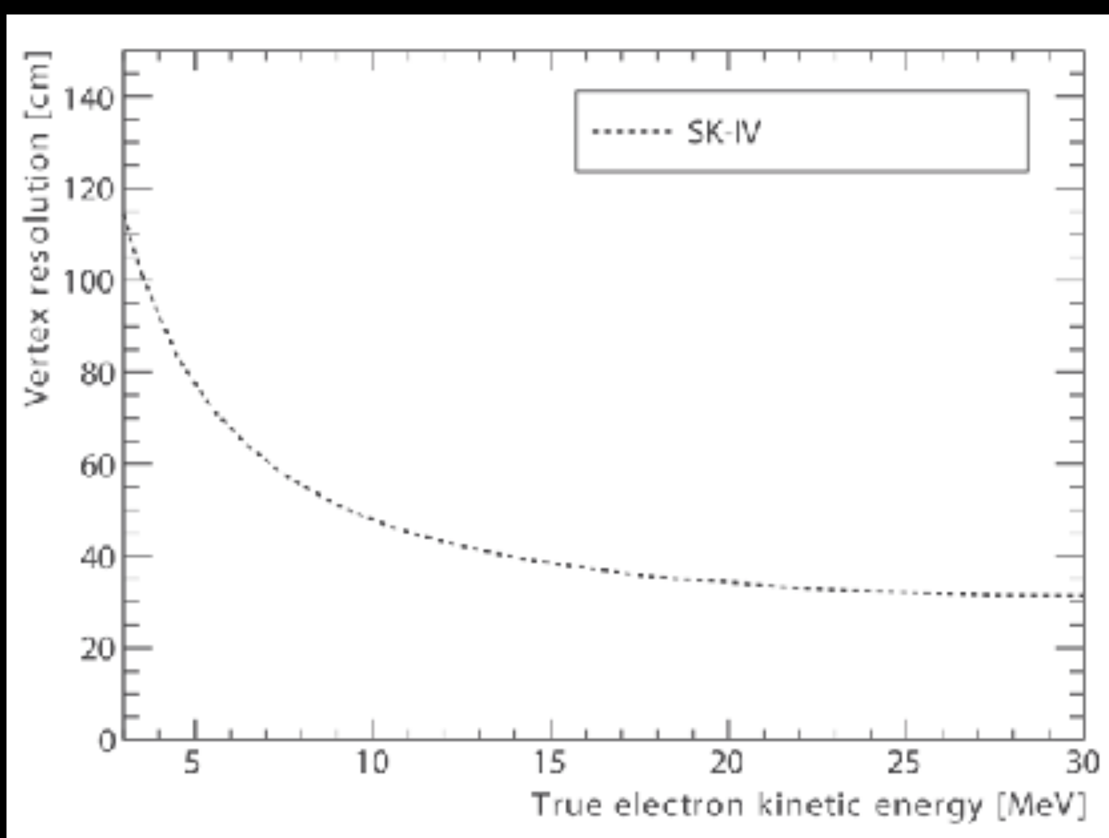
- At low energies, neutron carries most of the direction
- Positrons direction dominates at higher energy
  - Also starts to deviate from quasi-elastic regime



Vertex resolution

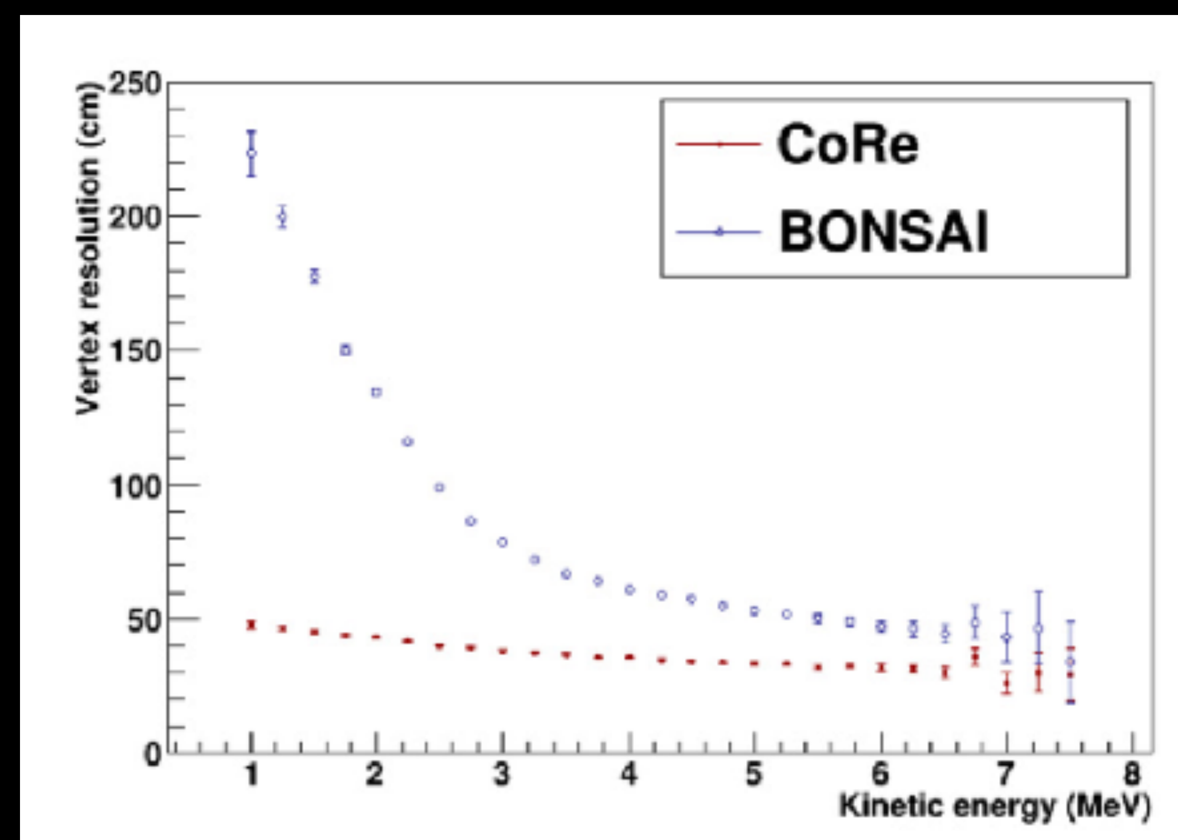
- The IBD reaction vertex and the neutron capture position needs to be reconstructed.

Super-K solar neutrino search



https://journals.aps.org/prd/pdf/10.1103/PhysRevD.109.092001

Reconstruction taking into account neutron capture light



Kneale et al 2023

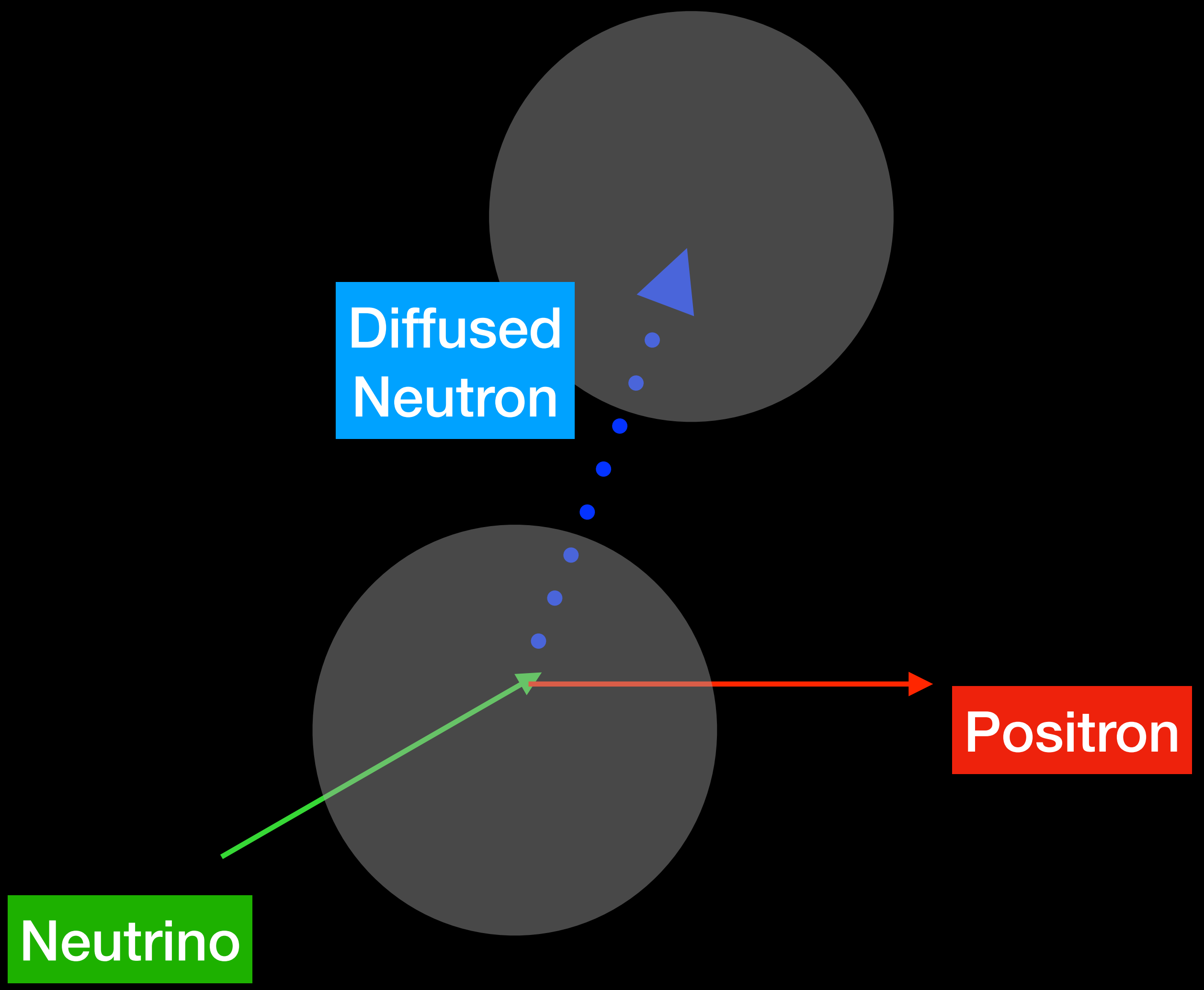
Vertex resolution

- If the vertex error >> neutron displaced vertex
  - No direction!

- Neutron displacement
  - ~ 10cm @ 100 MeV

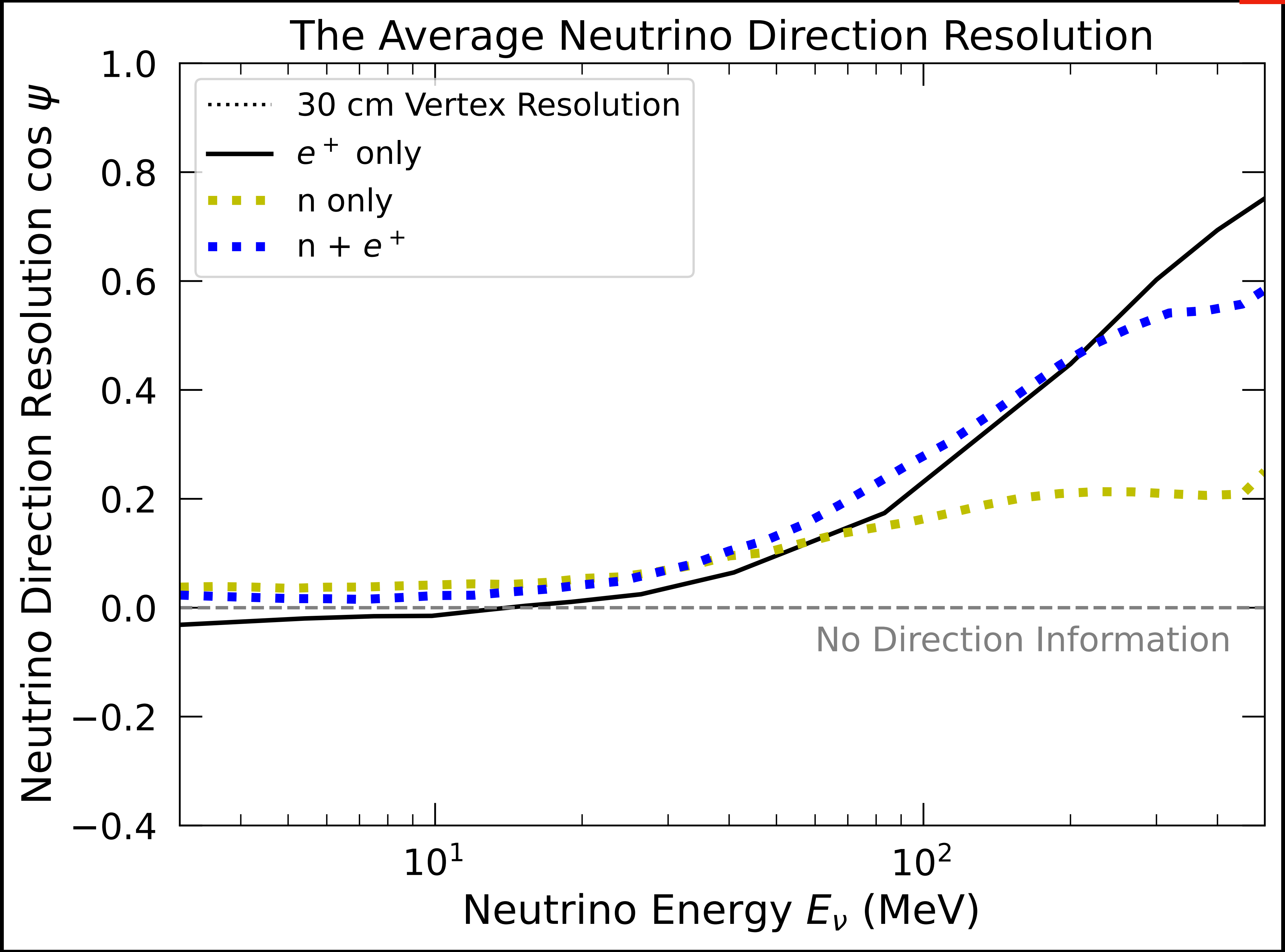
- ***
- Actually no need to reconstruct two vertices
- Just need the neutron final direction
- Similar ideas in Liquid Scintillators
  - Mukhopadhyay et al 2004.02045
  - Li et al 2003.03982
  - Fischer et al 1504.05466

Vertex reconstruction uncertainty ~ 3D Gaussian approx.



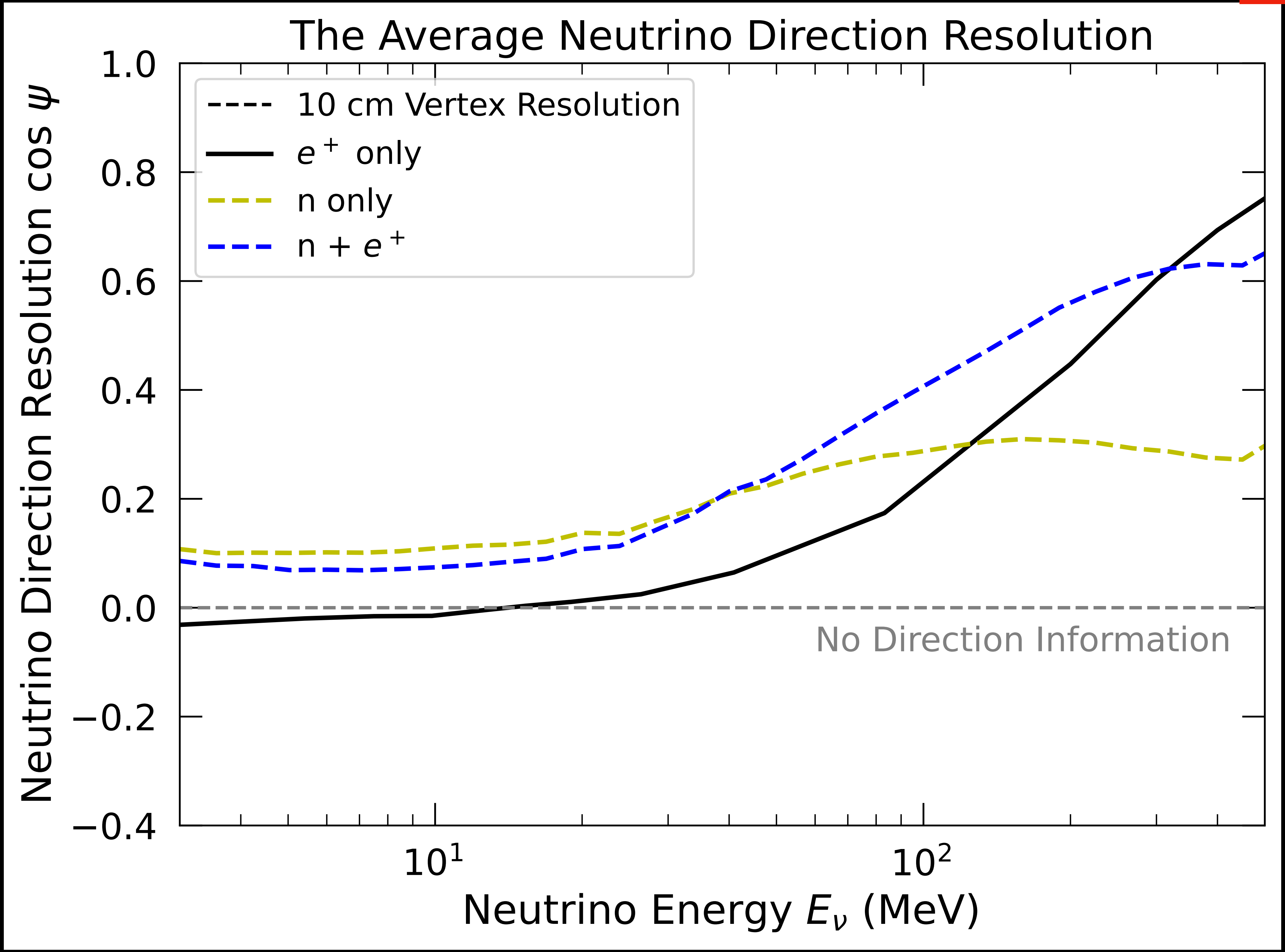
30 cm vertex error

Preliminary



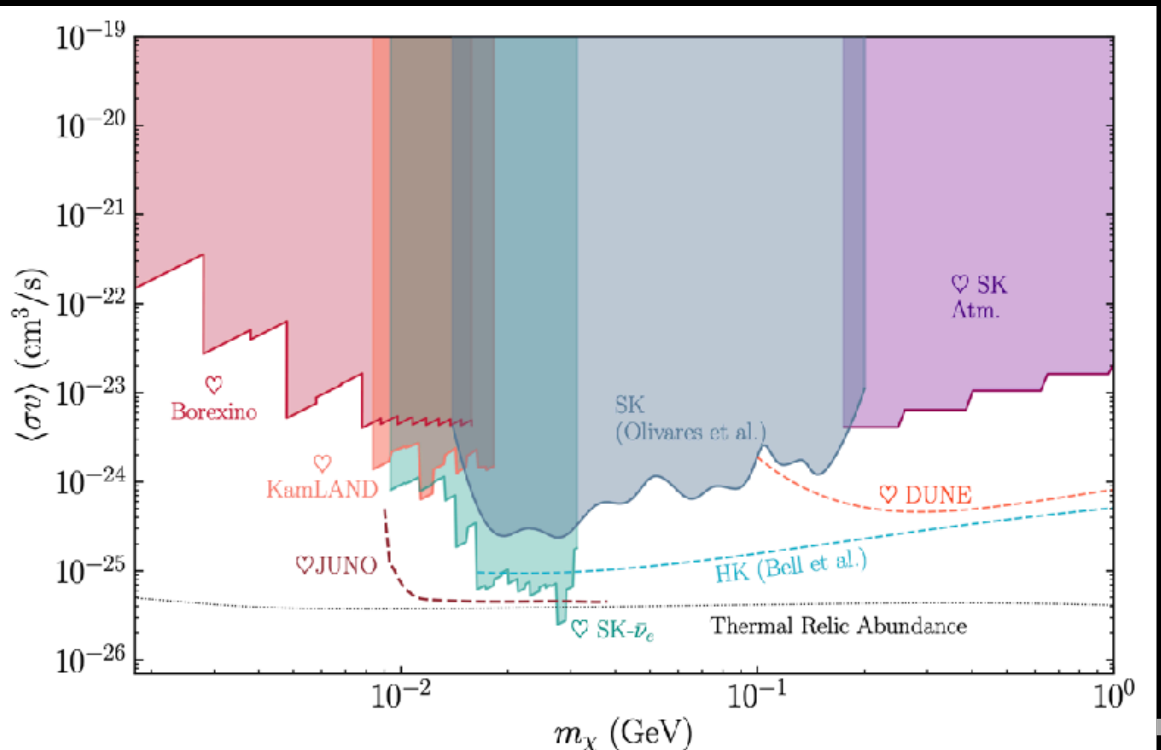
10 cm vertex error

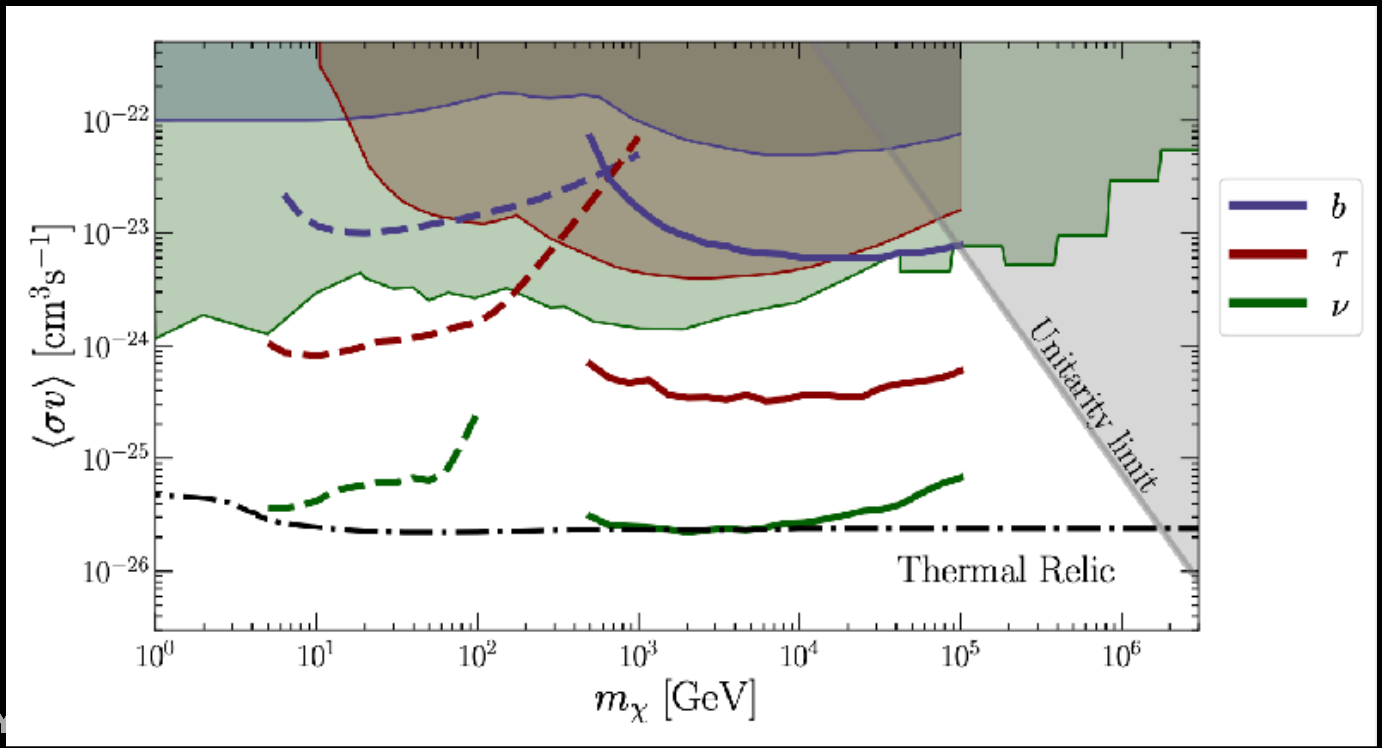
Preliminary



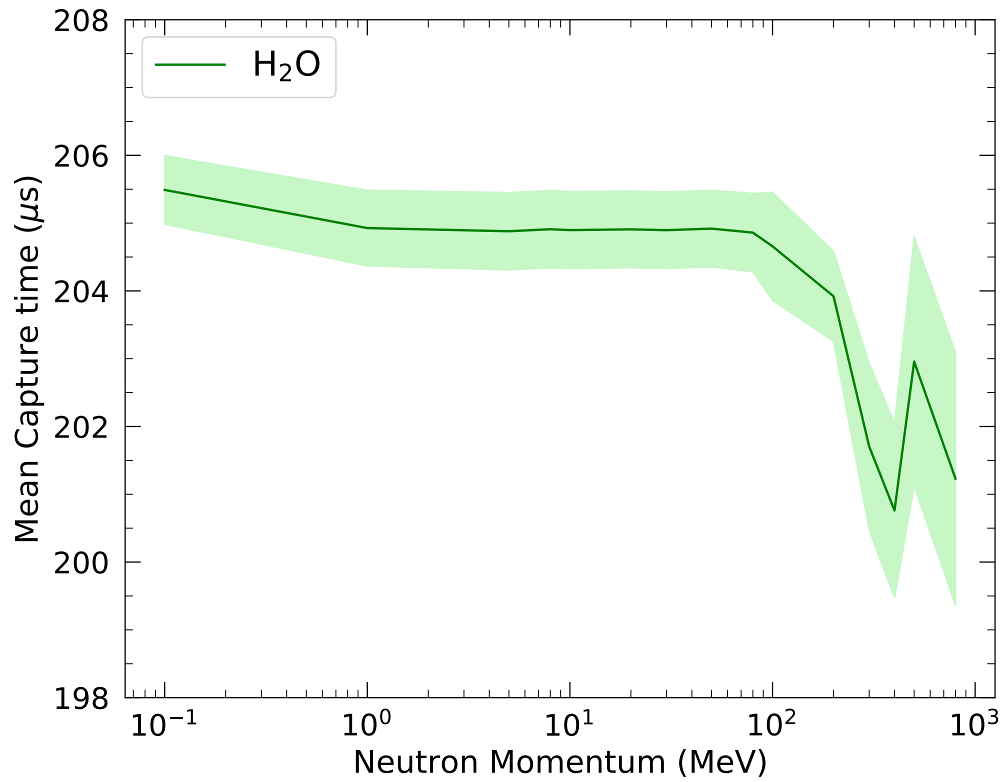
Conclusion

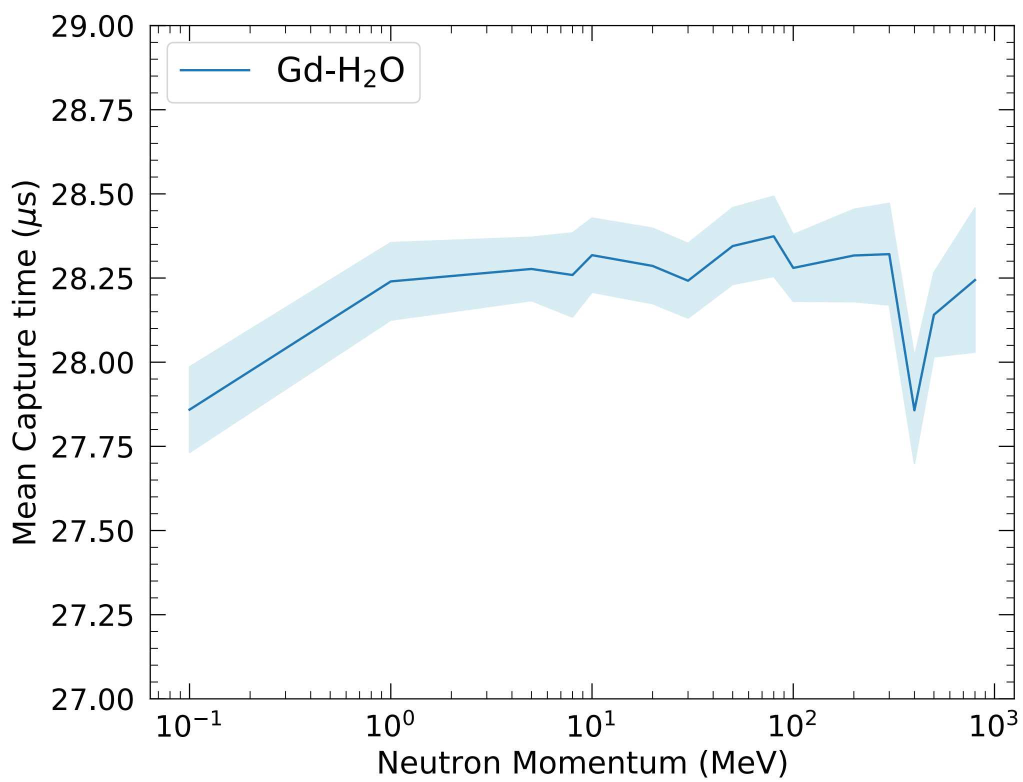
- Even for the simplest WIMP scenario, the total annihilation cross section is not fully constrained
- Neutrino channel is THE bottleneck
- KM3NeT, with its visibility to GC could test the WIMP model
- Hard to push further without new ideas at MeV-GeV range.
  - Improved reconstruction?   Machine Learning?

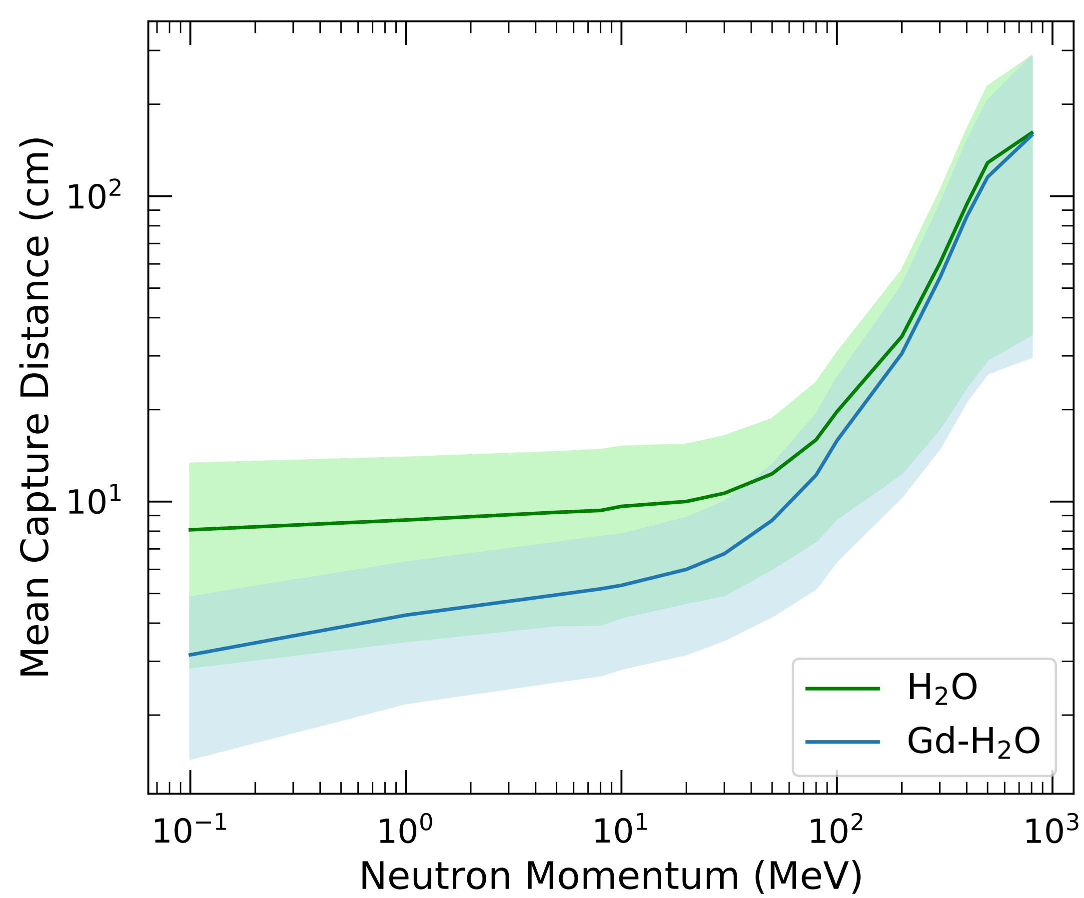


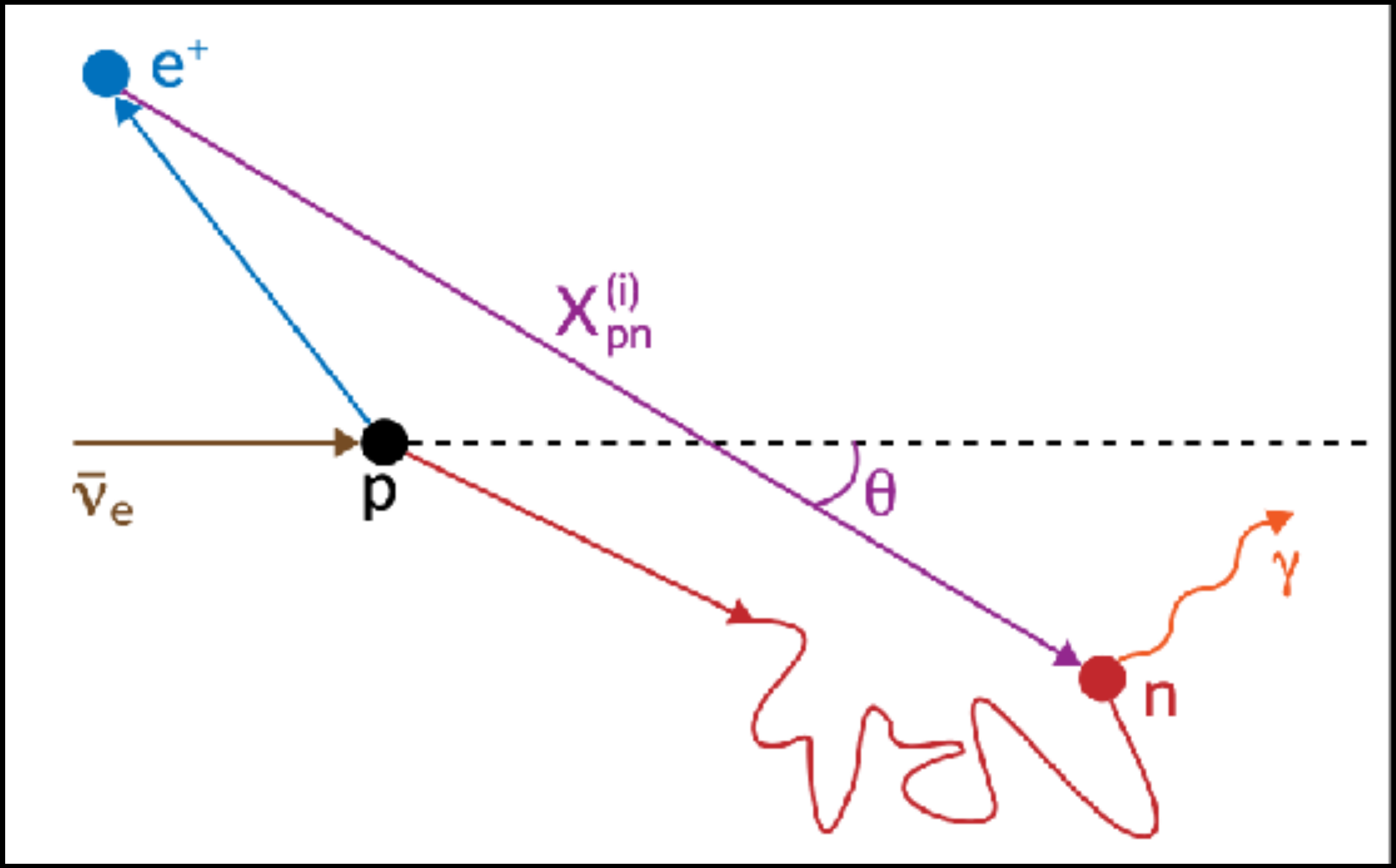


Capture time and distance

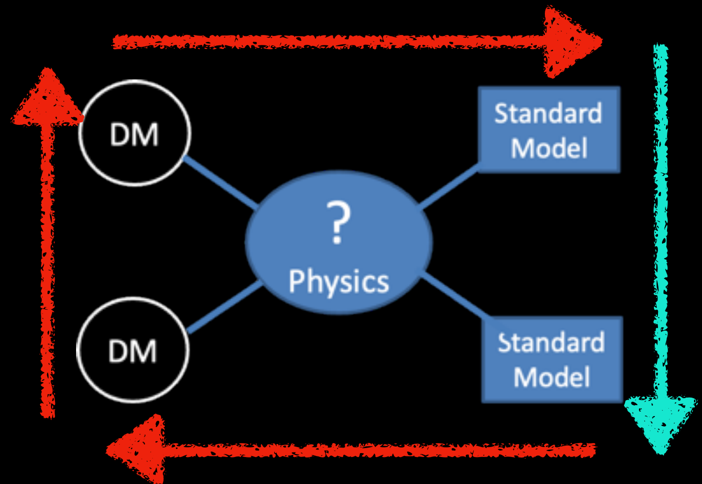






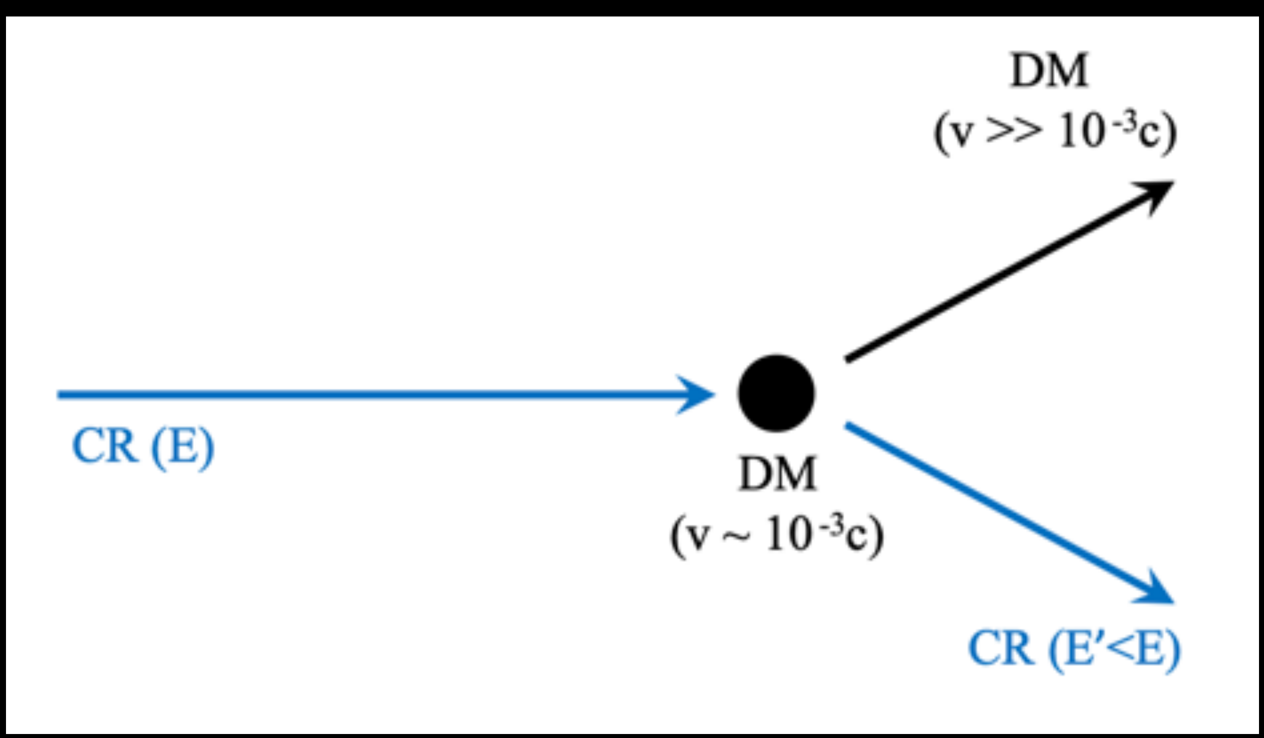


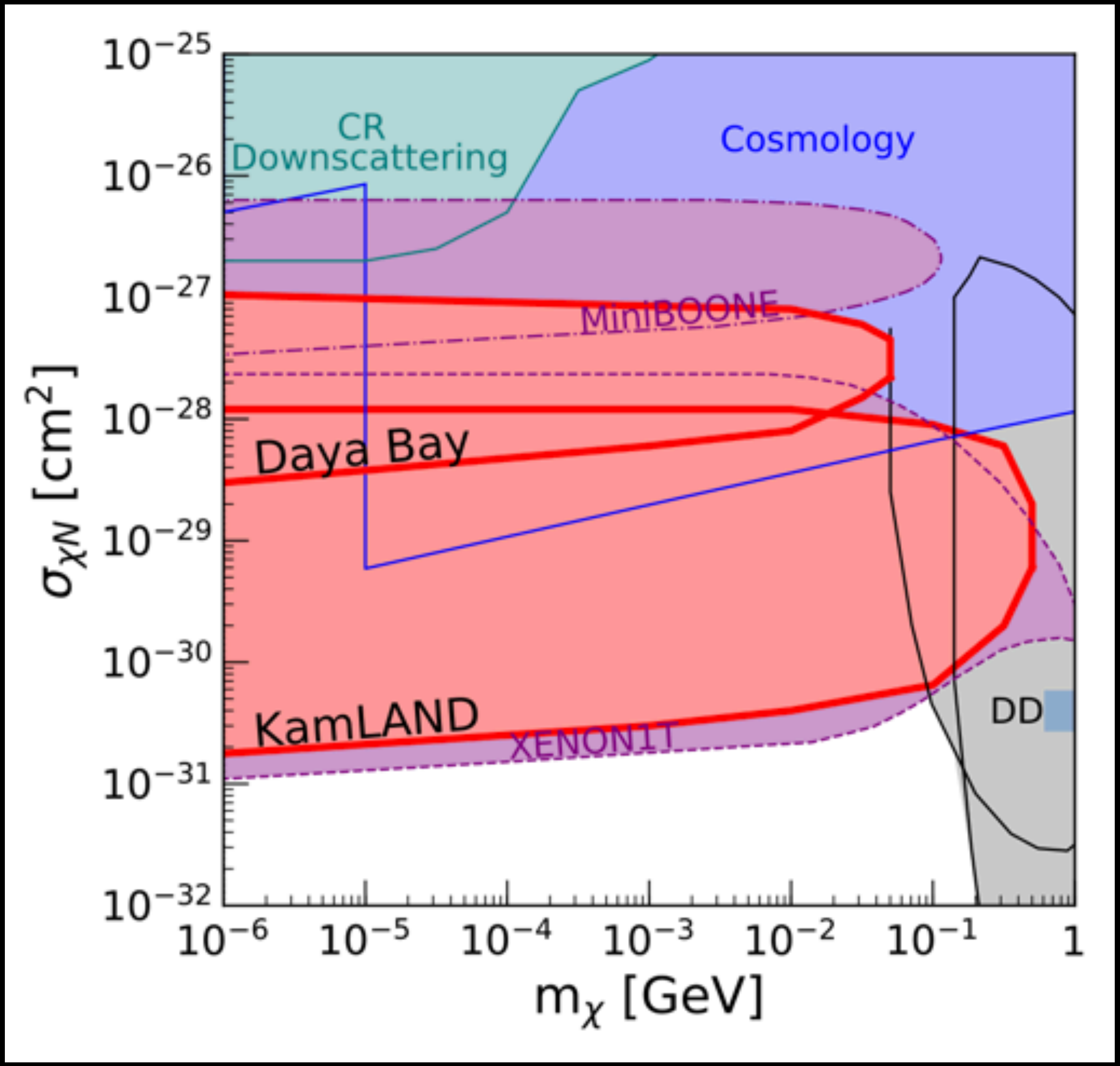
e+
$X_{pn}^{(i)}$
θ
γ
n
p
$\bar{\nu}_e$



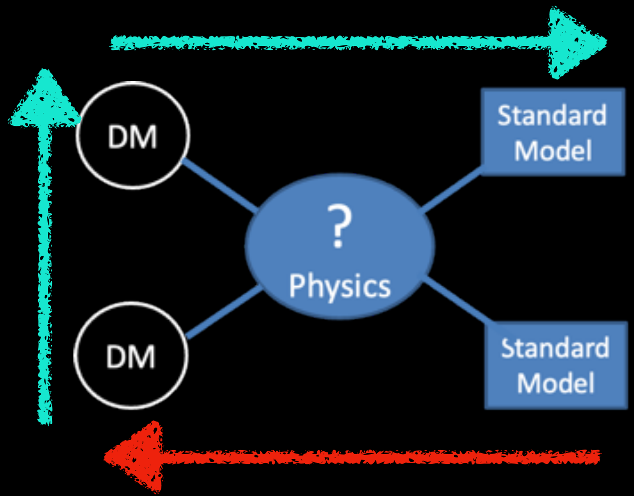
Boosted Dark Matter

- GeV-TeV range
- Neutrino floor is closing
  - Coherent scattering of solar, atm, SN neutrinos
- New opportunities at low energies?

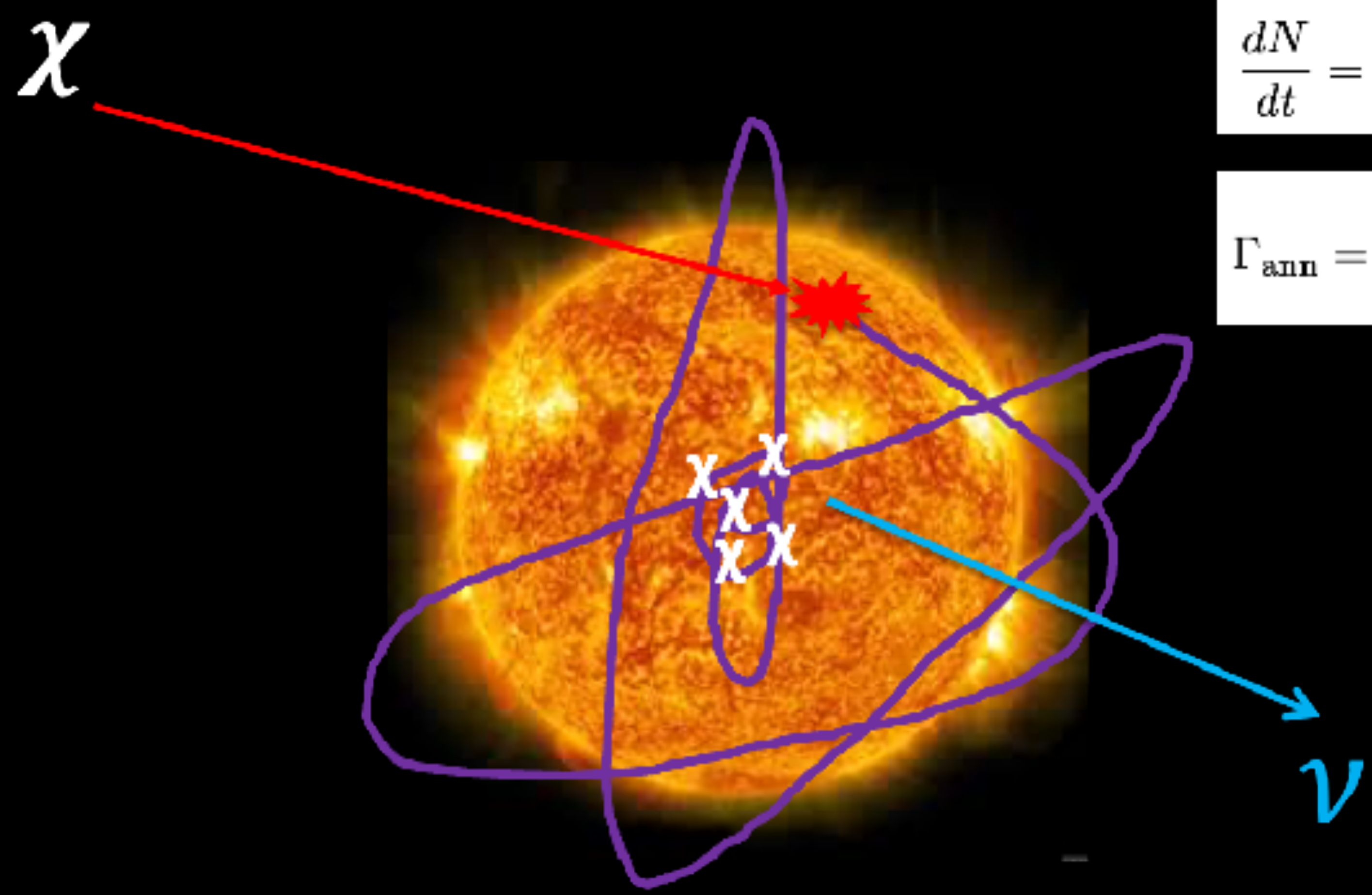




Cappiello and Beacom 1906.11283

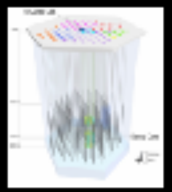


Solar WIMPs



$$\frac{dN}{dt} = \Gamma_{\rm cap} - C_{\rm ann} N^2$$

$$\Gamma_{\rm ann} = \frac{1}{2} C_{\rm ann} N^2 = \frac{1}{2}\Gamma_{\rm cap}$$



Press, Spergel (1985)
Krauss, Freese, Press, Spergel (1985)
Silk, Olive, Srednicki (1985)