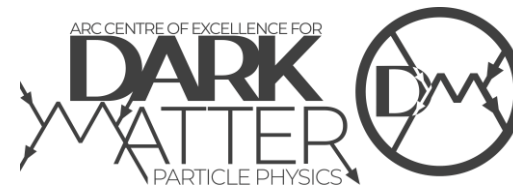


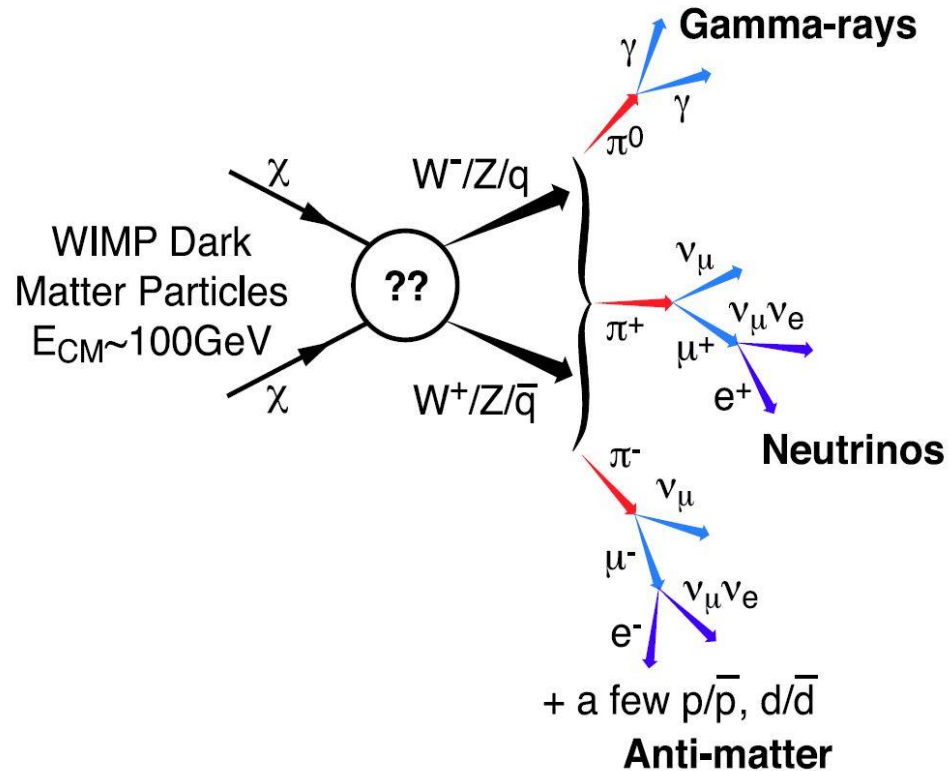
Detecting Dark Matter Annihilation to Neutrinos

Nicole Bell

in collaboration with Matthew Dolan and Sandra Robles



Indirect detection – Detecting dark matter annihilation



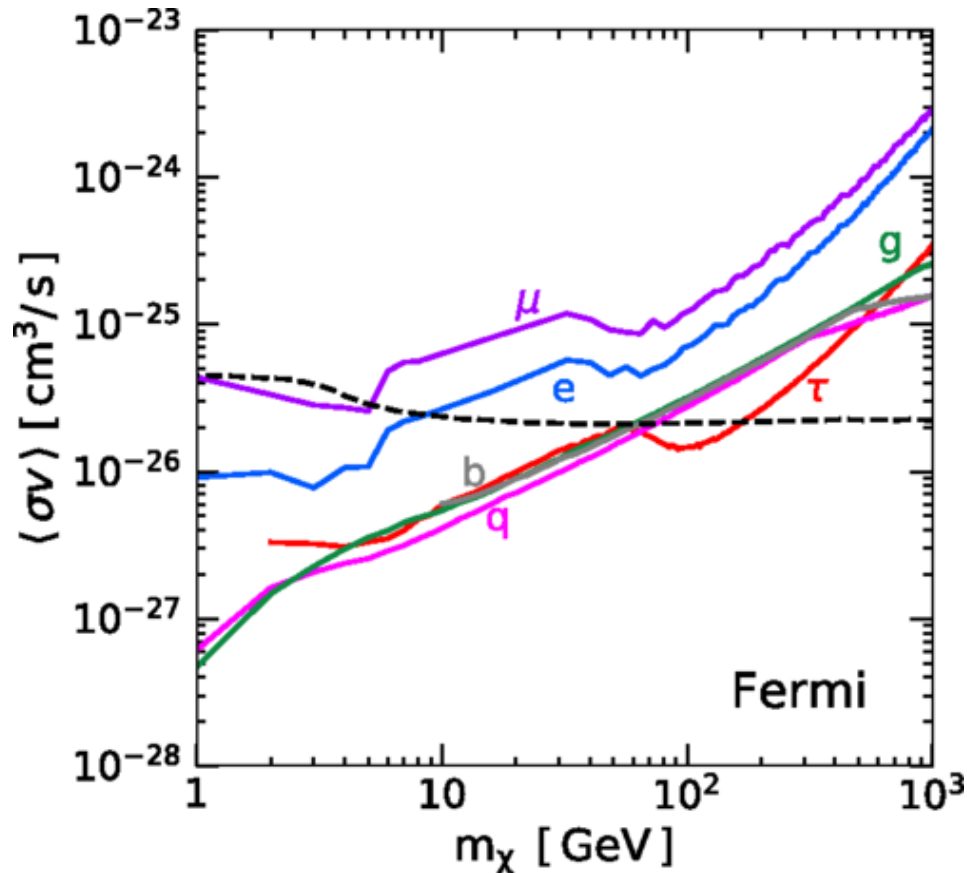
Indirect detection probes the dark matter annihilation cross-section

→ The most direct detect test of the **thermal-relic WIMP paradigm**

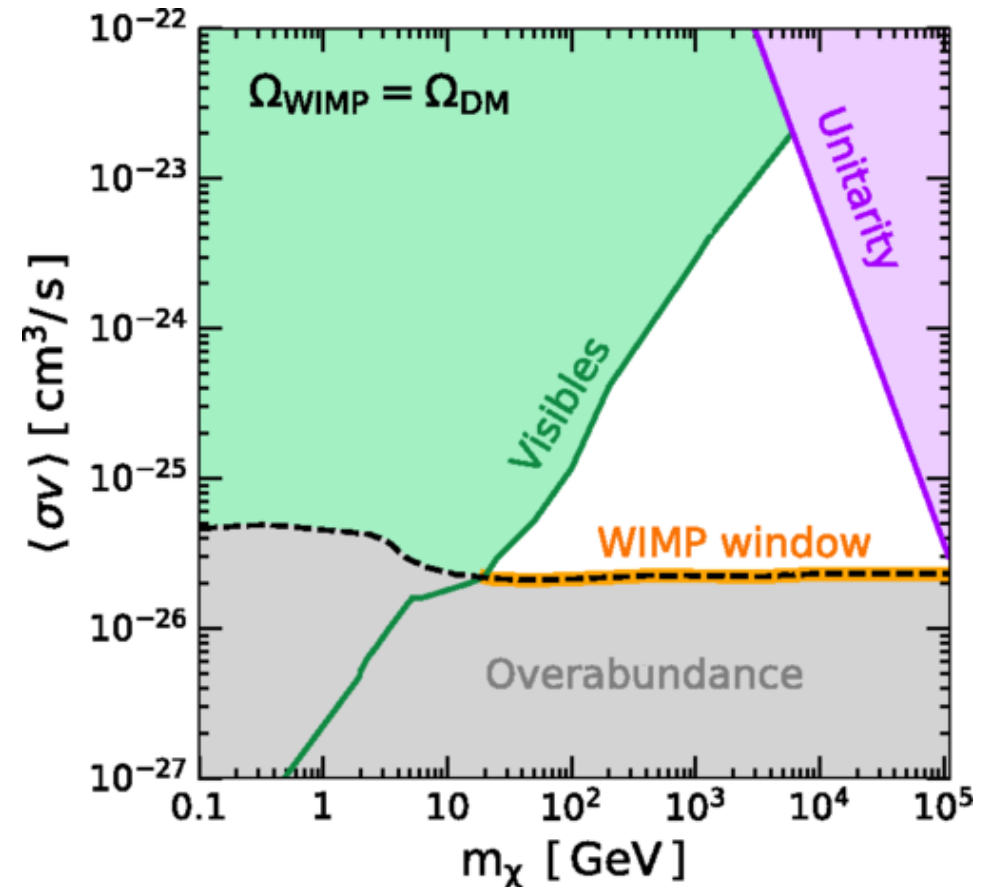
Indirect detection constraints

R. Leane, et al., arXiv:1805.10305

Fermi dSph limits

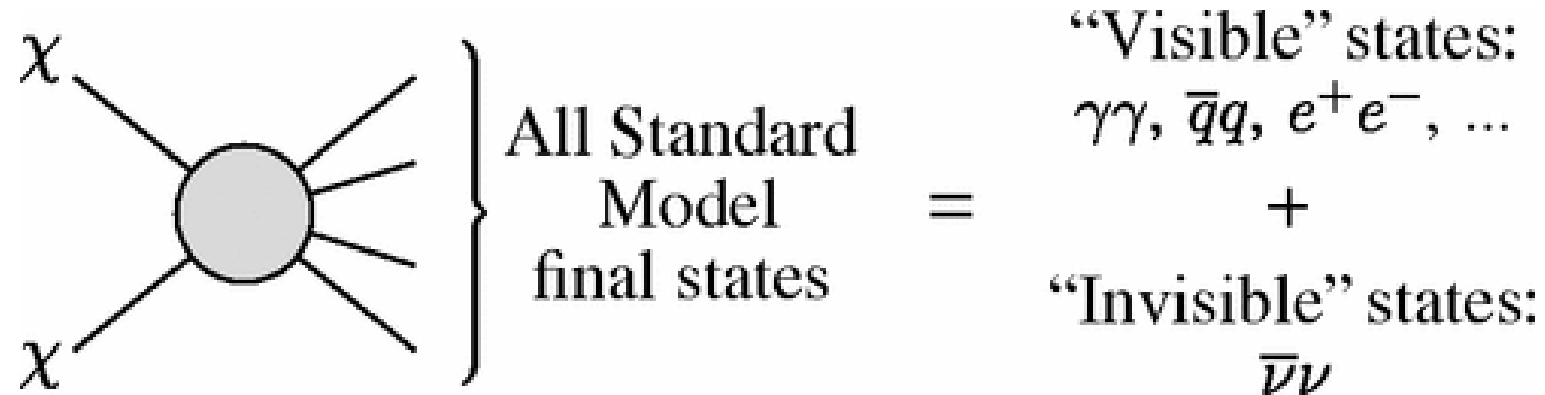


Annihilation to “visible” SM states



Annihilation to neutrinos

- Indirect detection limits – typically neglect the possibility that dark matter may annihilate to “invisible” or hard-to-detect final states.

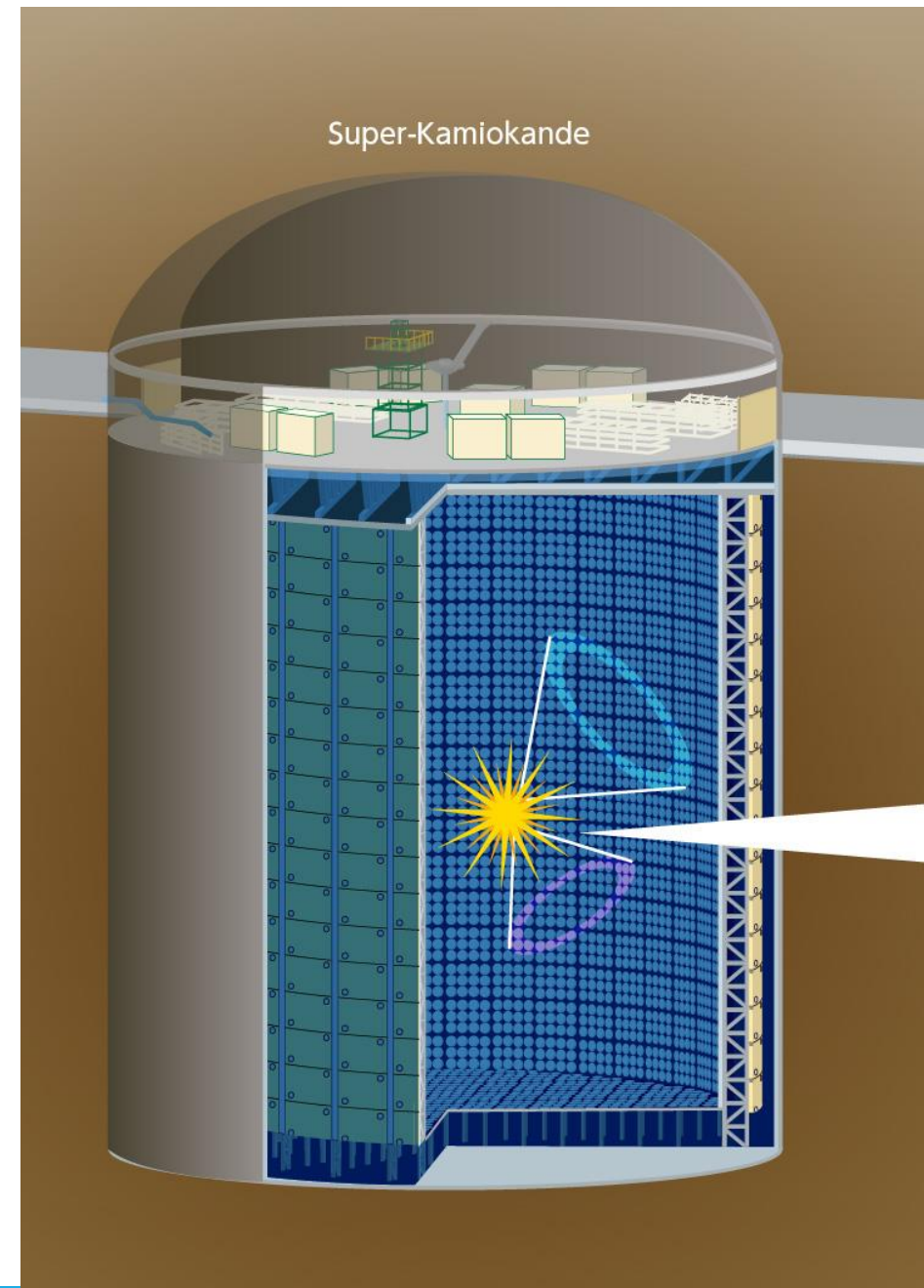


- Can DM annihilate to neutrinos without producing charged fermions?
 - Yes, e.g., “neutrino portal” models
- **Annihilation to neutrinos – can we probe thermal-relic cross sections?**

Hyper-Kamiokande

Can we observe $\chi\chi \rightarrow \nu\bar{\nu}$ above the atmospheric neutrino background?

- Next generation water-Cherenkov detector.
- Currently under construction
- Fiducial volume:
 - Hyper-K: 188 kT
 - Super-K: 22 kT



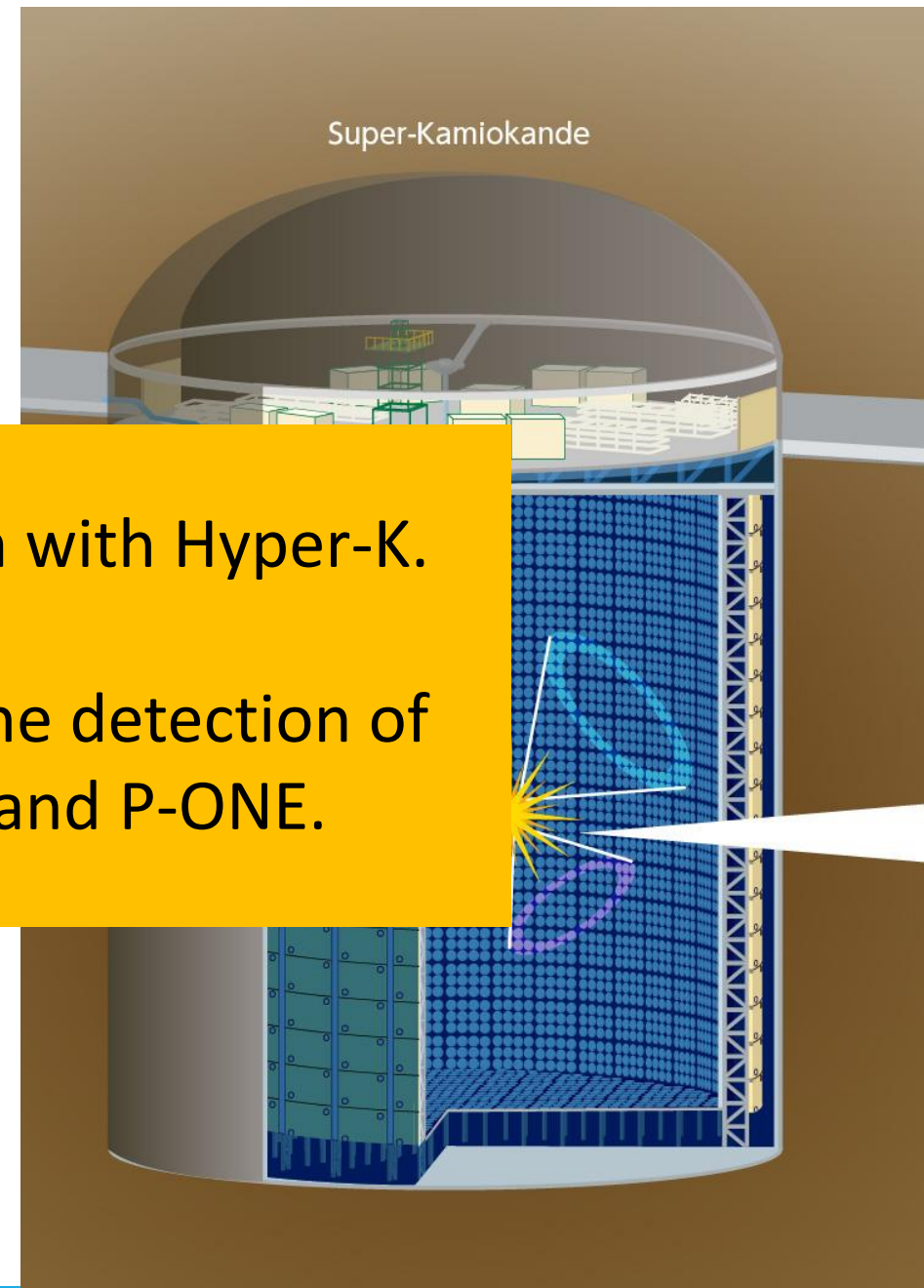
Hyper-Kamiokande

Can we observe $\chi\chi \rightarrow \nu\bar{\nu}$ above the atmospheric neutrino background?

- Ne
- Cu
- Fic
 - Hyper-K: 188 kT
 - Super-K: 22 kT

I focus on low-energy neutrino detection with Hyper-K.

See Stephan Meighen-Berger's talk for the detection of high-mass dark matter with IceCube and P-ONE.



Hyper-K simulation

NFB, M.Dolan, **S.Robles**,

arXiv: 2005.01950; arXiv:2107.04216; arXiv: 2205.14123

Neutrino flux from DM annihilation

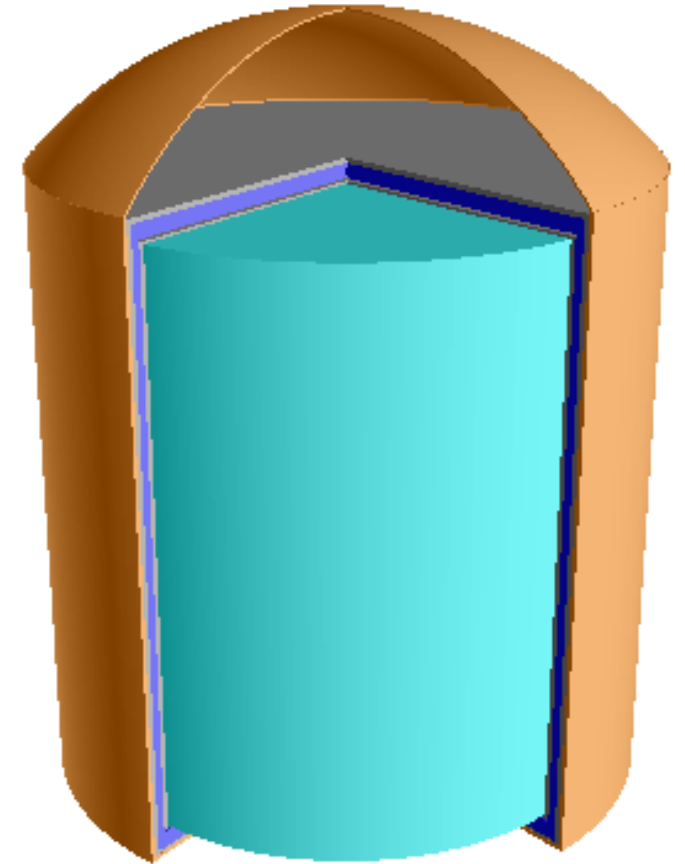
- DarkSUSY

Atmospheric neutrino background

- Honda et al – above 100 MeV
- Fluka – below 100 MeV

Neutrino interactions

- GENIE



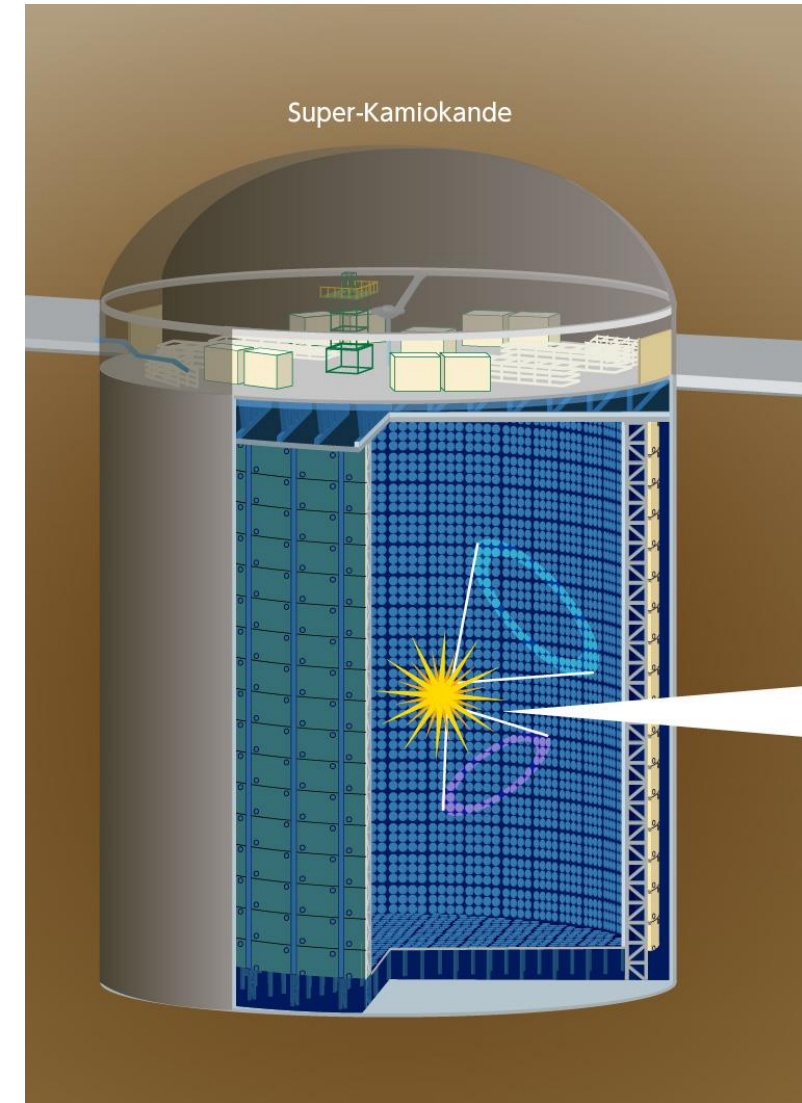
Interactions and event categories

Dominant CC interactions:

- DIS at high energy (> 10 GeV)
- CC-QE (quasi elastic) at low energies (< 1 GeV)
- baryon resonances (1-several GeV)

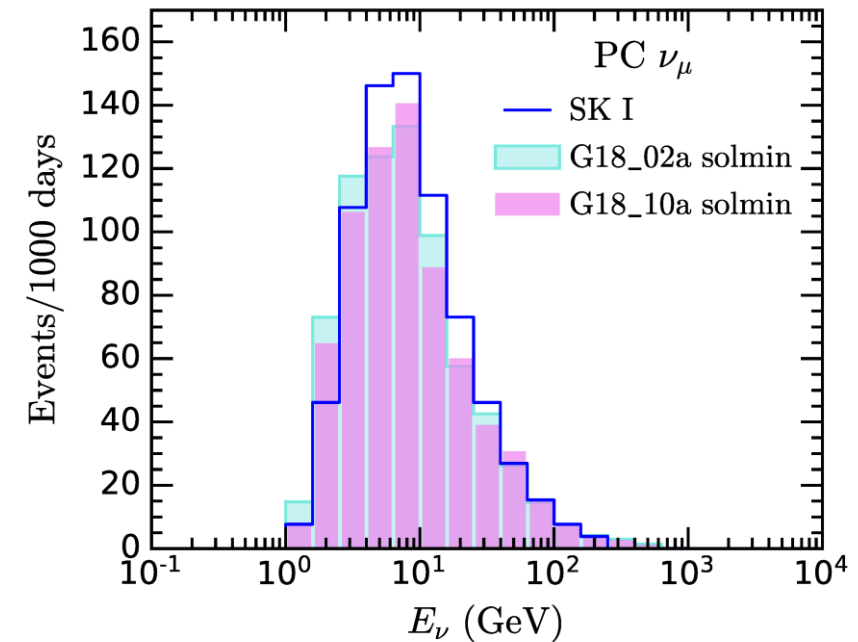
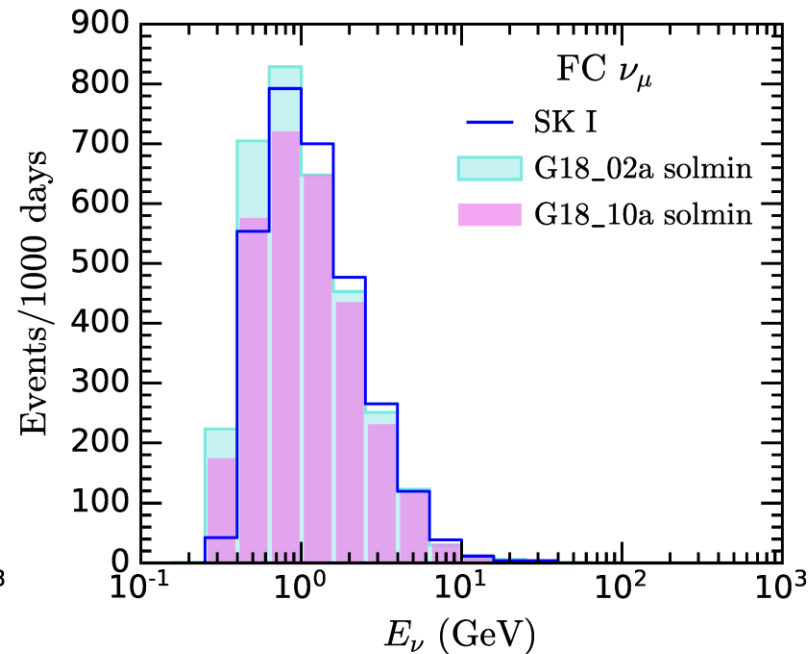
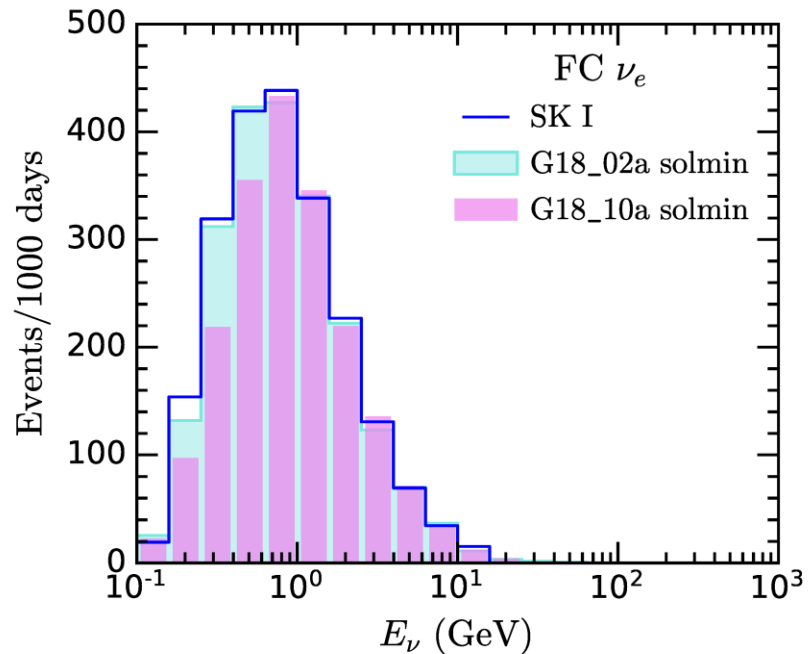
Event important categories

- Fully contained (FC) – all energy deposited
- Partially contained (PC) – muon leaving the detector
- Upward through going muons ($up-\mu$) – created in rock near the detector – important for high energy neutrinos



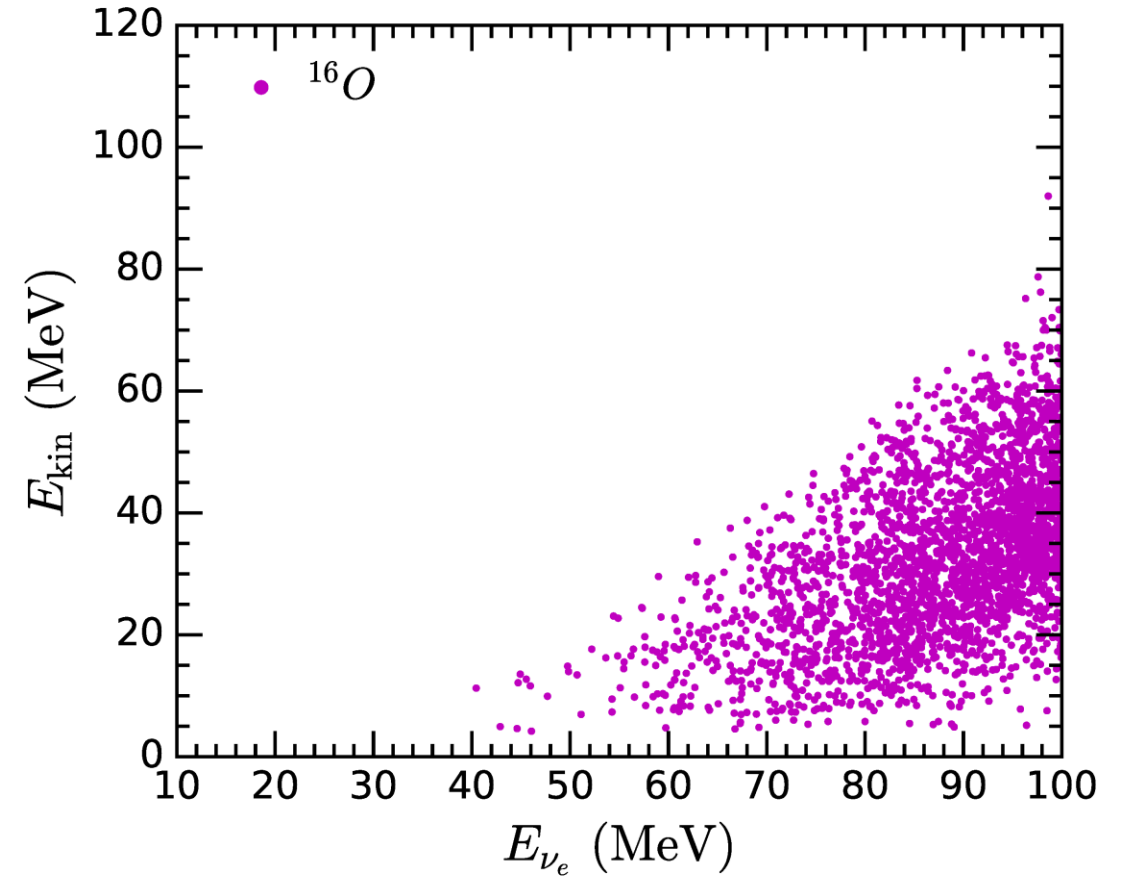
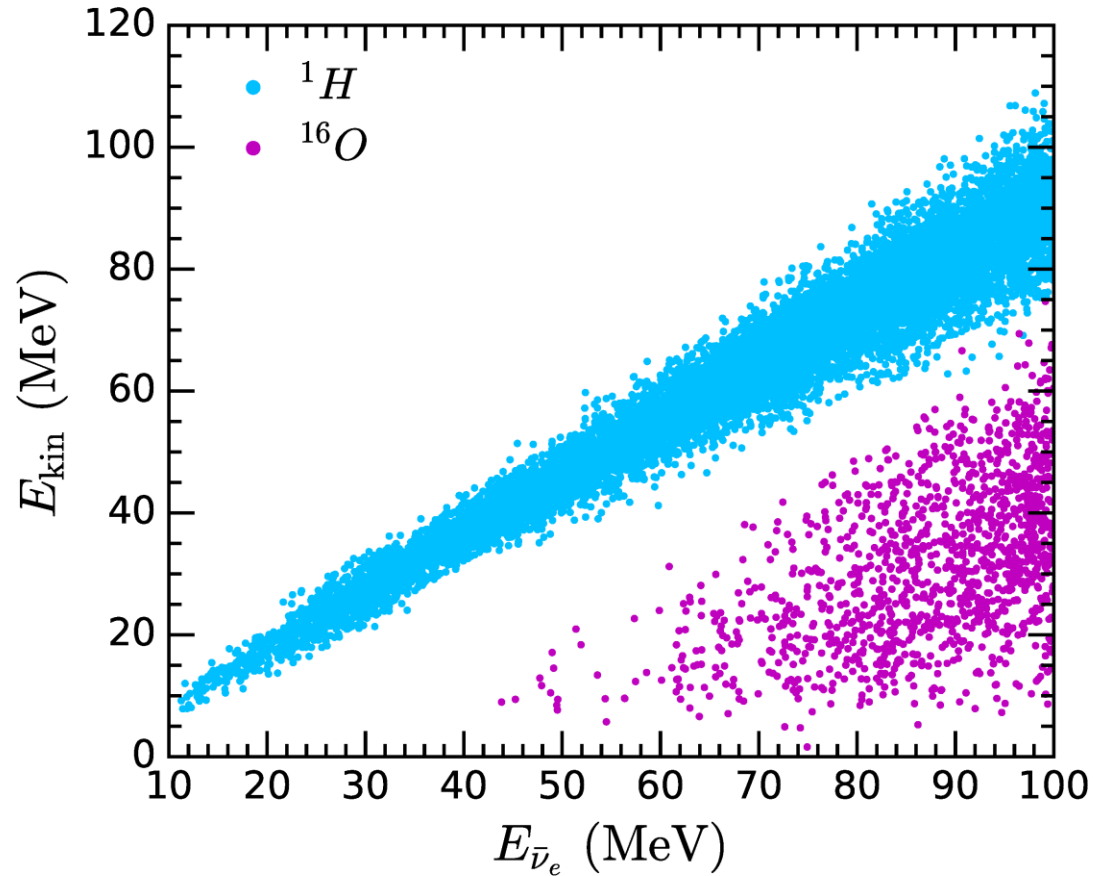
Simulation validated against Super-K data

Reproduced the atmospheric neutrino background rates measured by Super-K

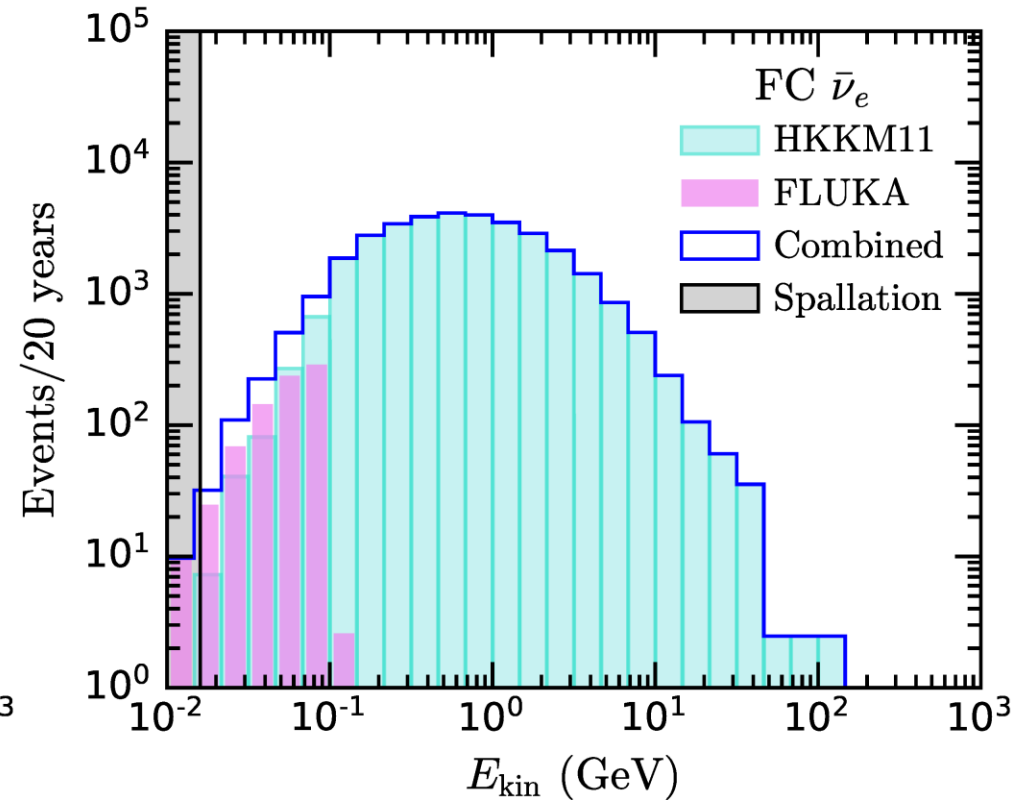
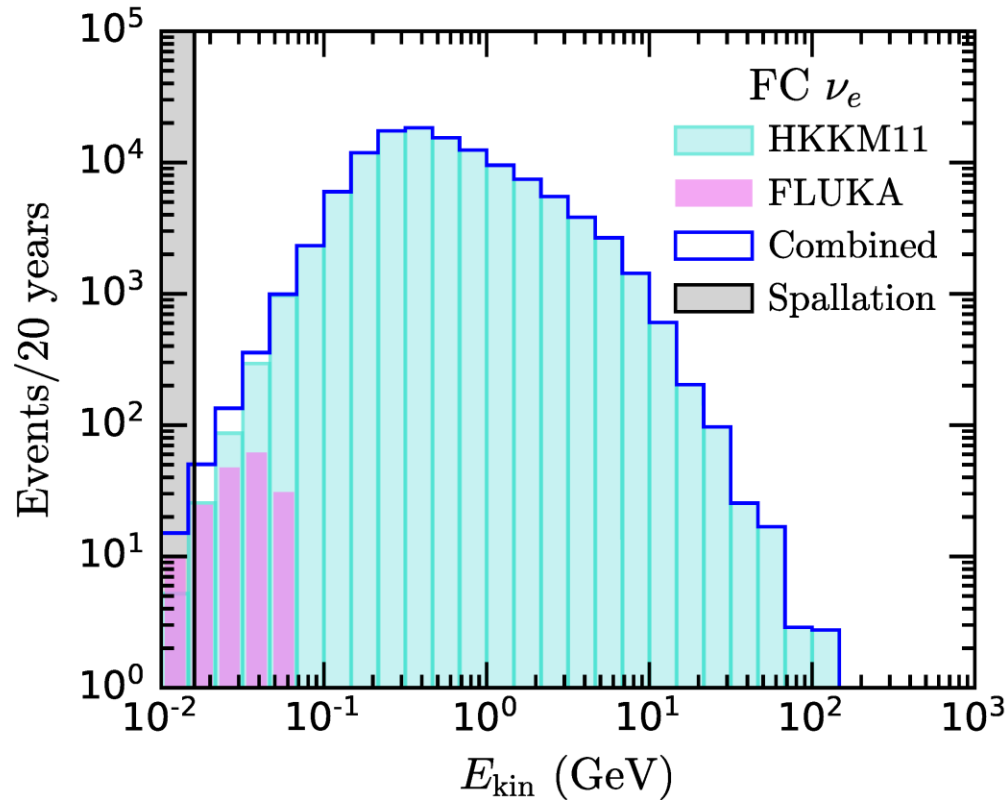


NFB, Dolan, Robles, arXiv: 2005.01950

Lepton energy (E_{kin}) vs neutrino energy (E_{ν})



Atmospheric neutrino background



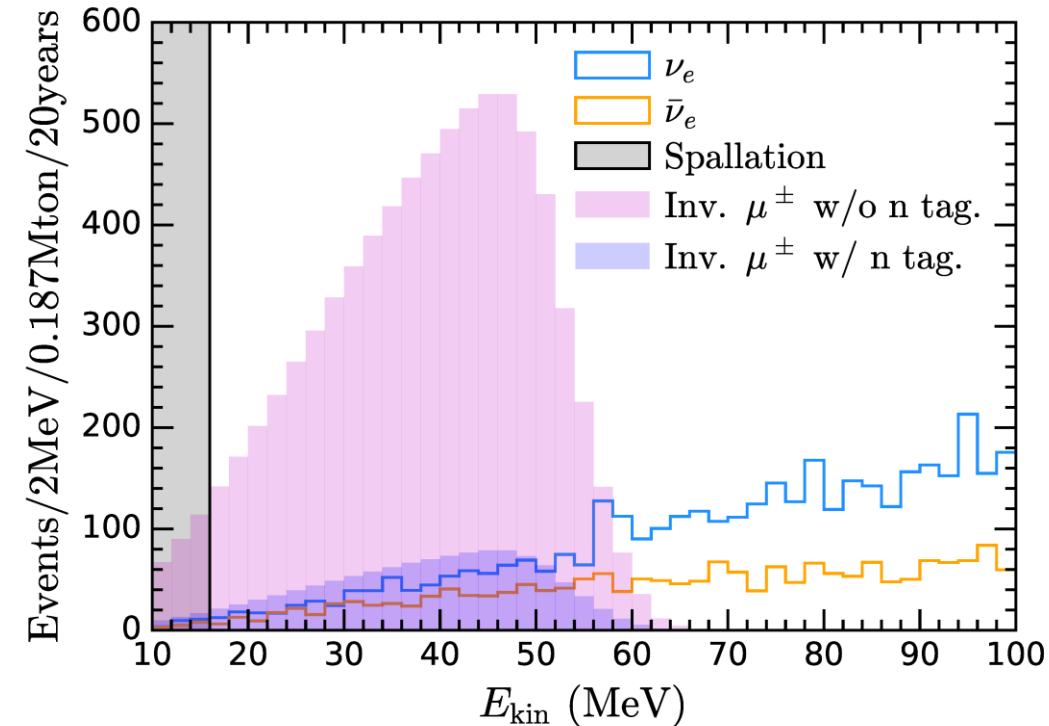
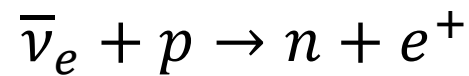
NFB, Dolan, Robles, arXiv: 2005.01950

Neutron tagging to remove invisible muons

“Invisible muons” are an important background at sub-GeV energies

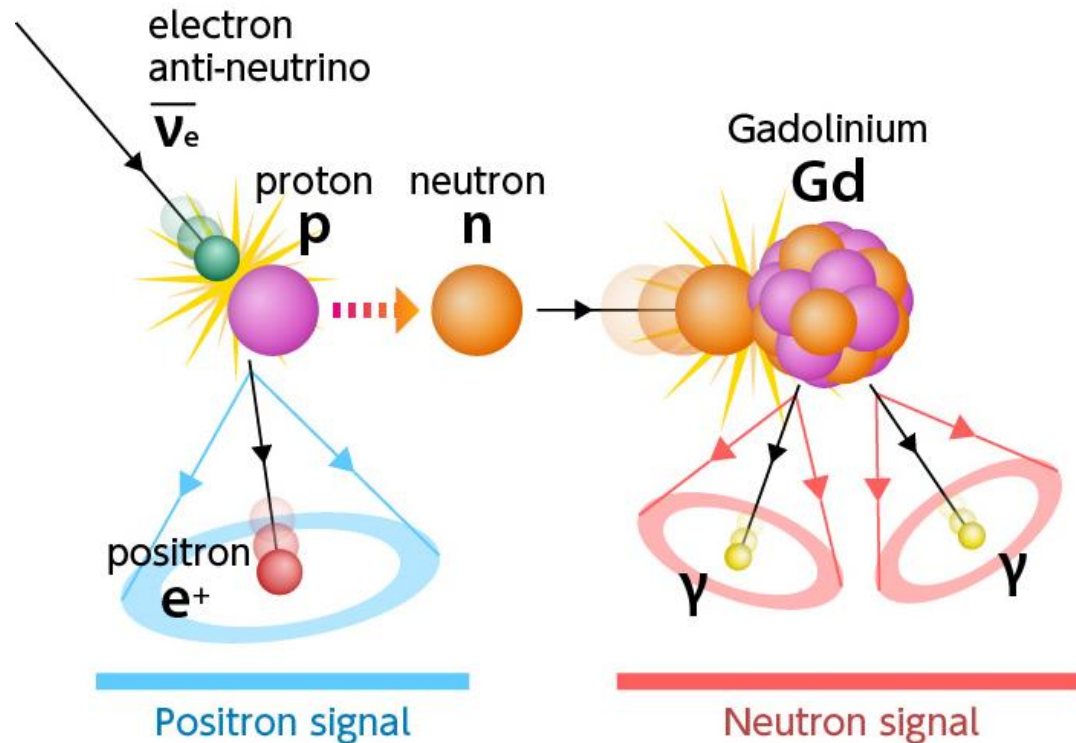
- μ^\pm of energy < 50 MeV (produced from interaction of low energy atm neutrinos) are invisible in the detector
- When they decay, the resulting e^\pm cannot be associated with the parent muon.
- Looks like a ν_e or $\bar{\nu}_e$ event.

Neutron tagging allows invisible muons to be distinguished from true IBD:



NFB, Dolan, Robles, arXiv: 2005.01950

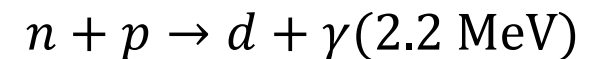
Neutron tagging on Gadolinium



Gadolinium has a large neutron capture cross section.

It de-excites via emission of an easily identifiable photon cascade of 8 MeV.

Neutron tagging on Hydrogen is possible too:



DM annihilation to neutrinos in the Galactic Centre

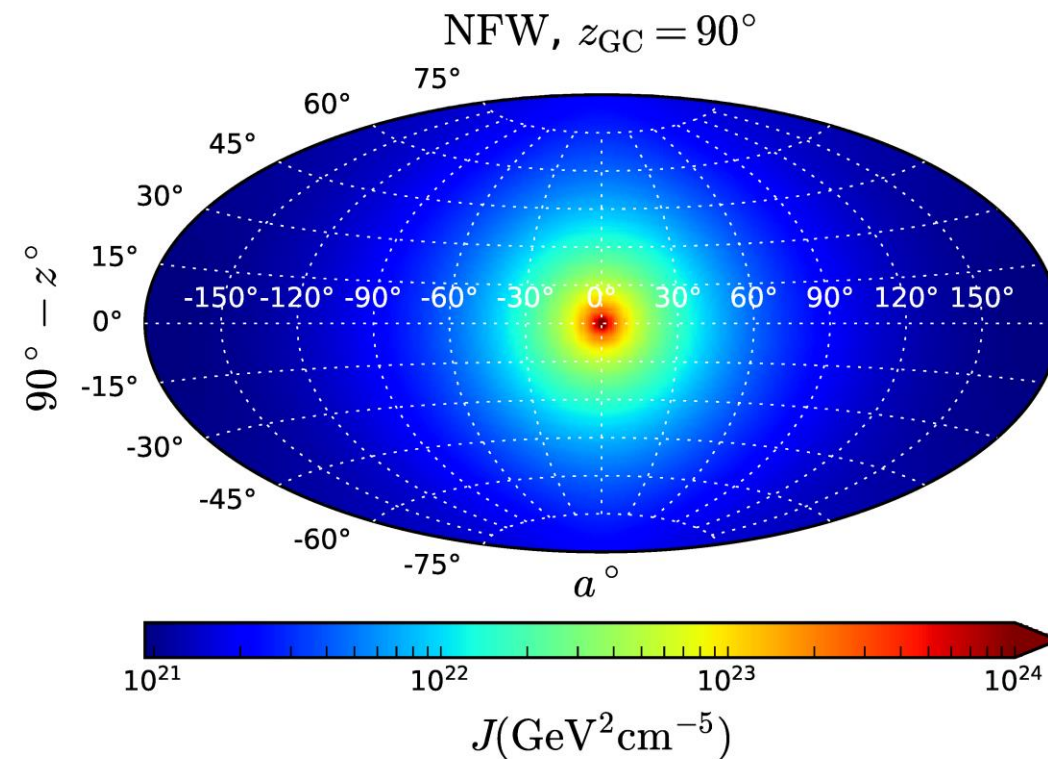
Dark matter annihilation signal

$$\frac{d\Phi_{\nu\Delta\Omega}}{dE_{\nu}} = \langle\sigma v\rangle \frac{J_{\Delta\Omega}}{8\pi m_{DM}^2} \frac{dN_{\nu}}{dE_{\nu}}$$

Annihilation cross section

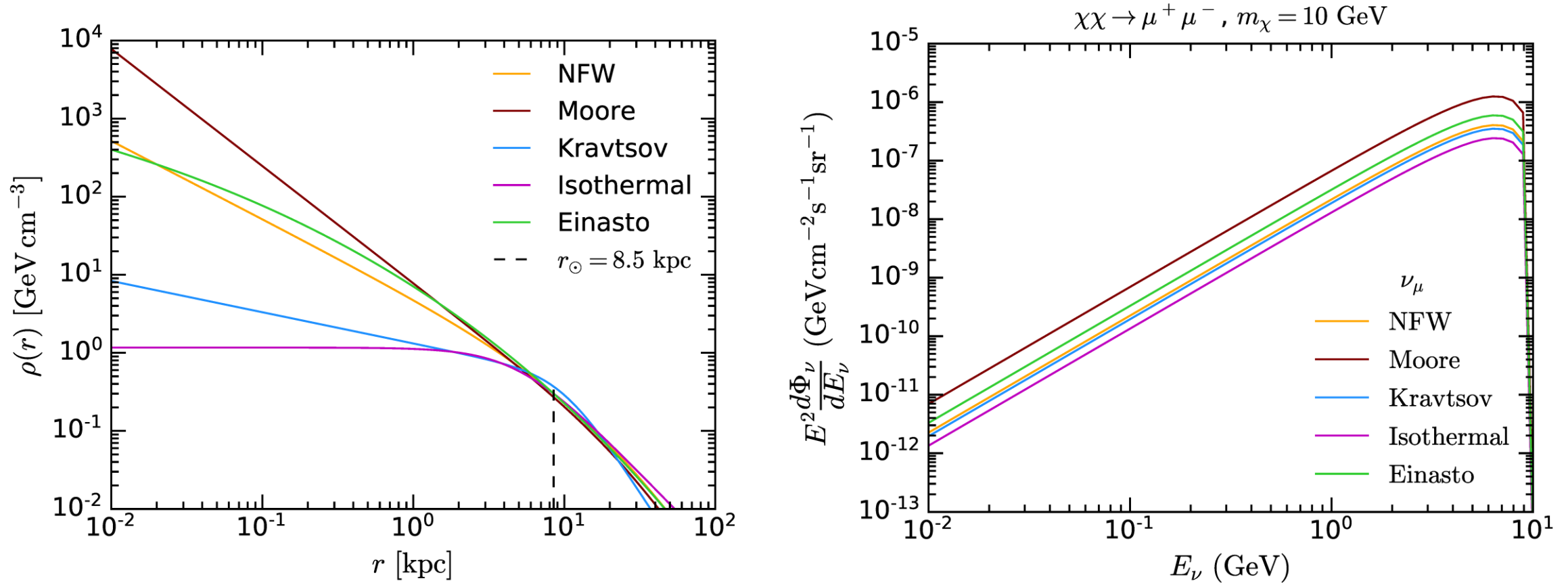
Integral of (density)² along line of sight

Spectrum per annihilation



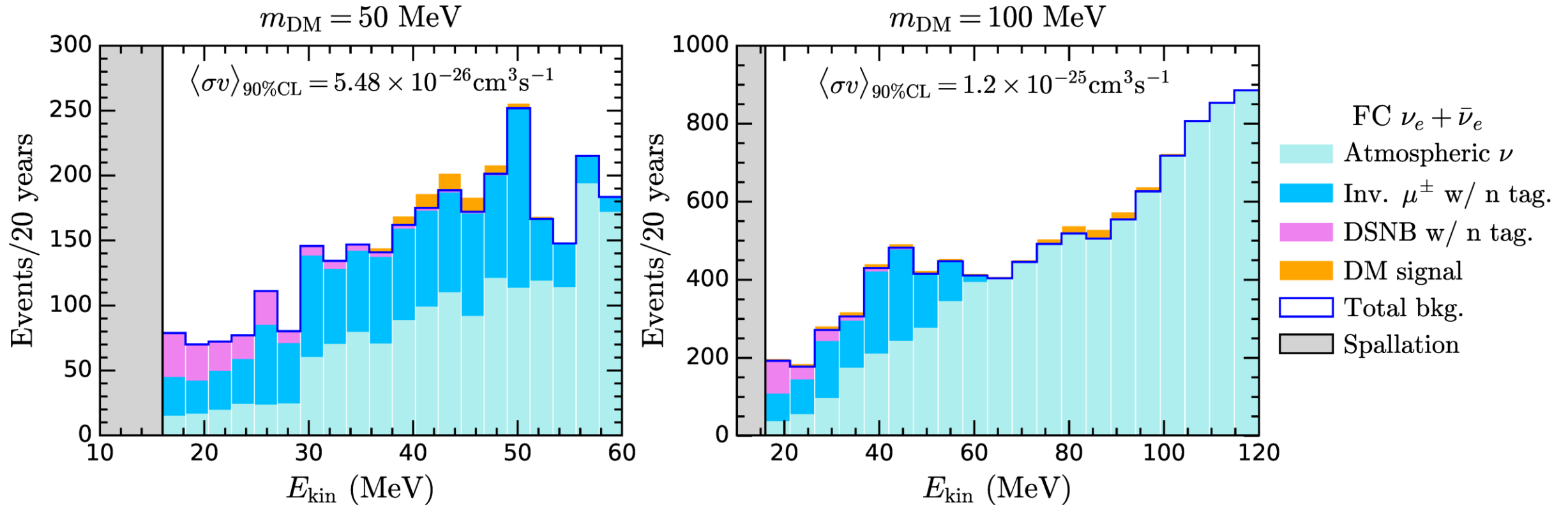
NFB, Dolan, Robles, arXiv: 2005.01950

Dependence on halo profile is mild, as we undertake an all-sky analysis



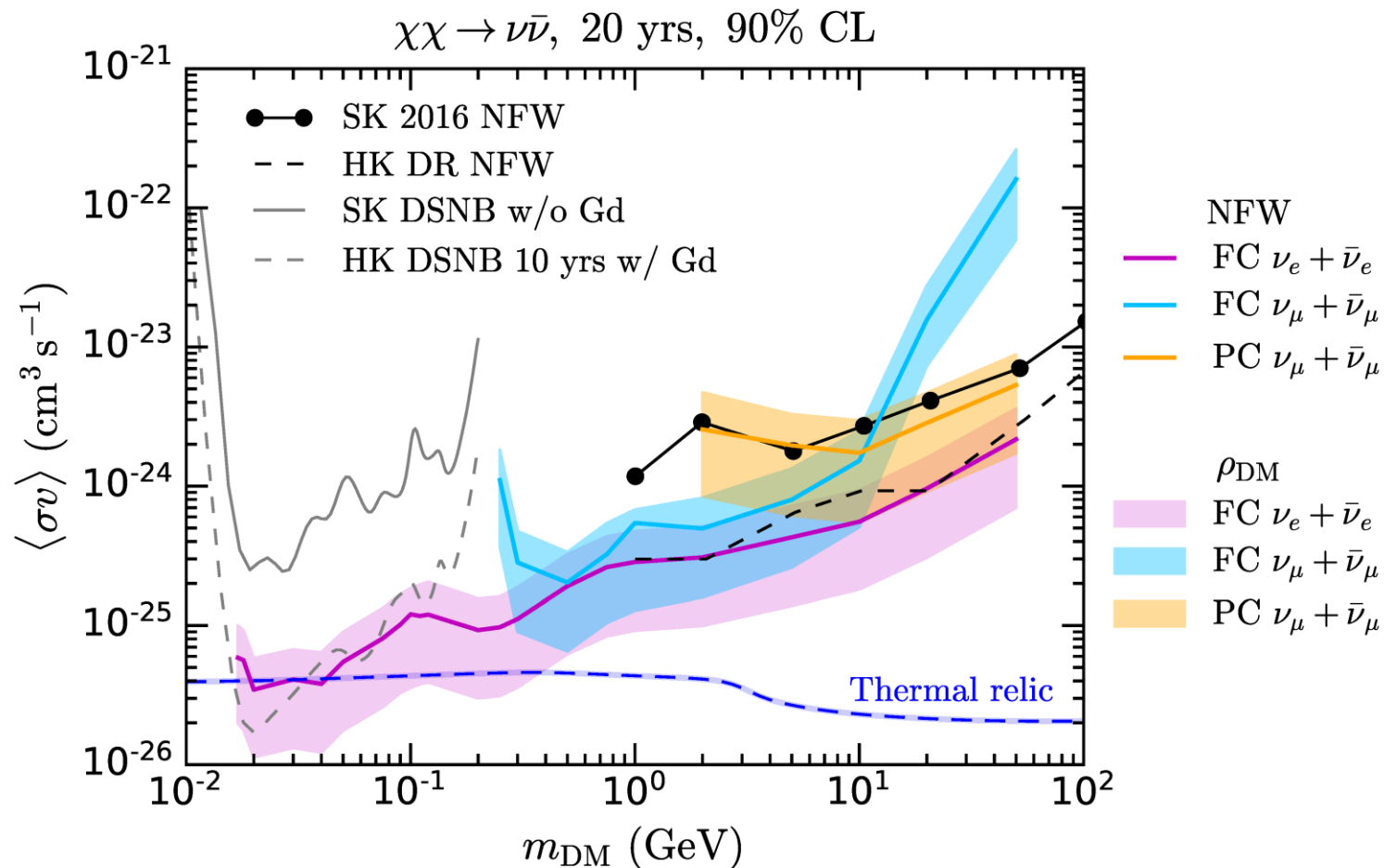
NFB, Dolan, Robles, arXiv: 2005.01950

Annihilation signal and backgrounds



NFB, Dolan, Robles, arXiv: 2005.01950

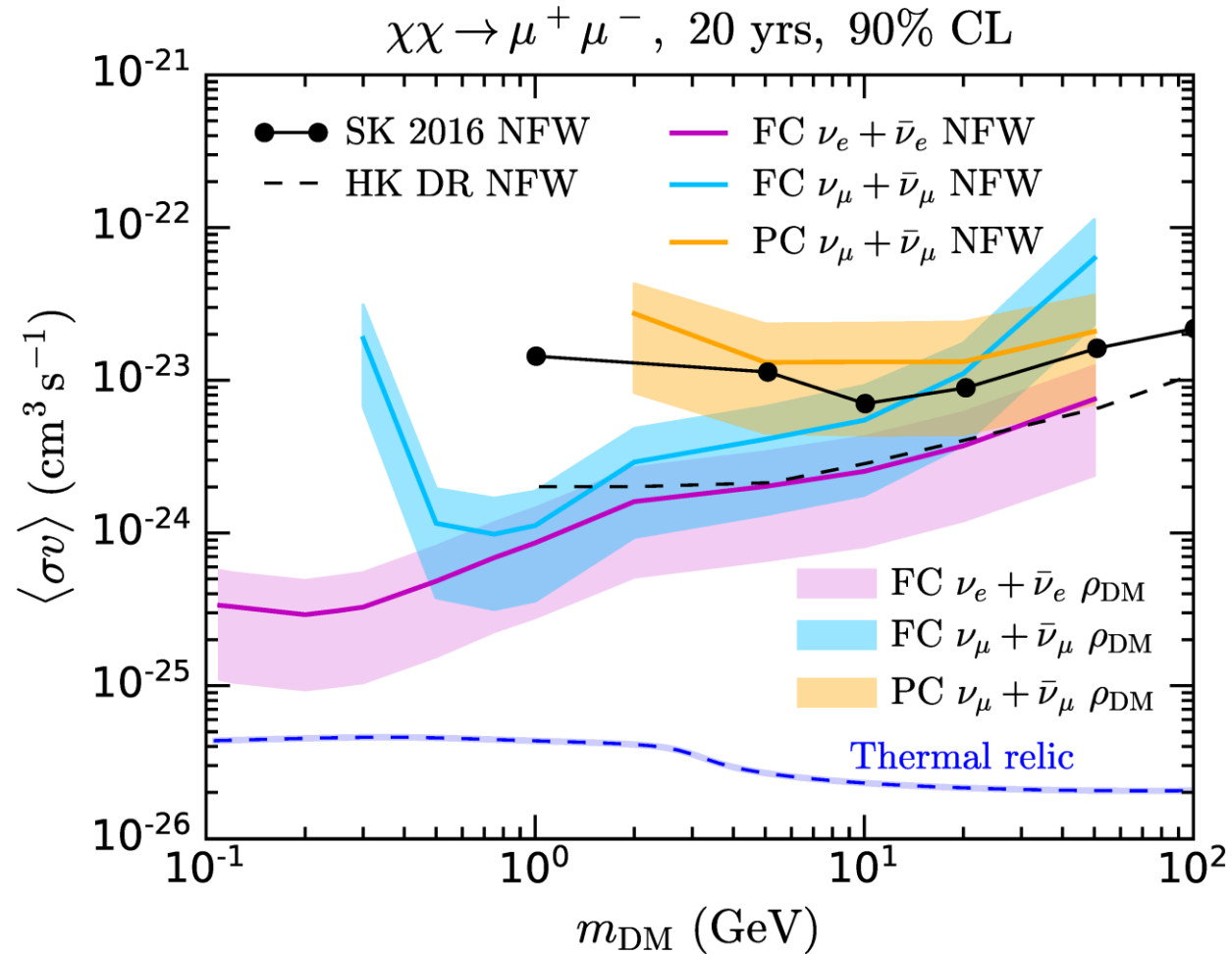
Annihilation cross section limits: $\chi\chi \rightarrow \nu\bar{\nu}$



Thermal relic sensitivity for
DM mass of ~ 30 MeV

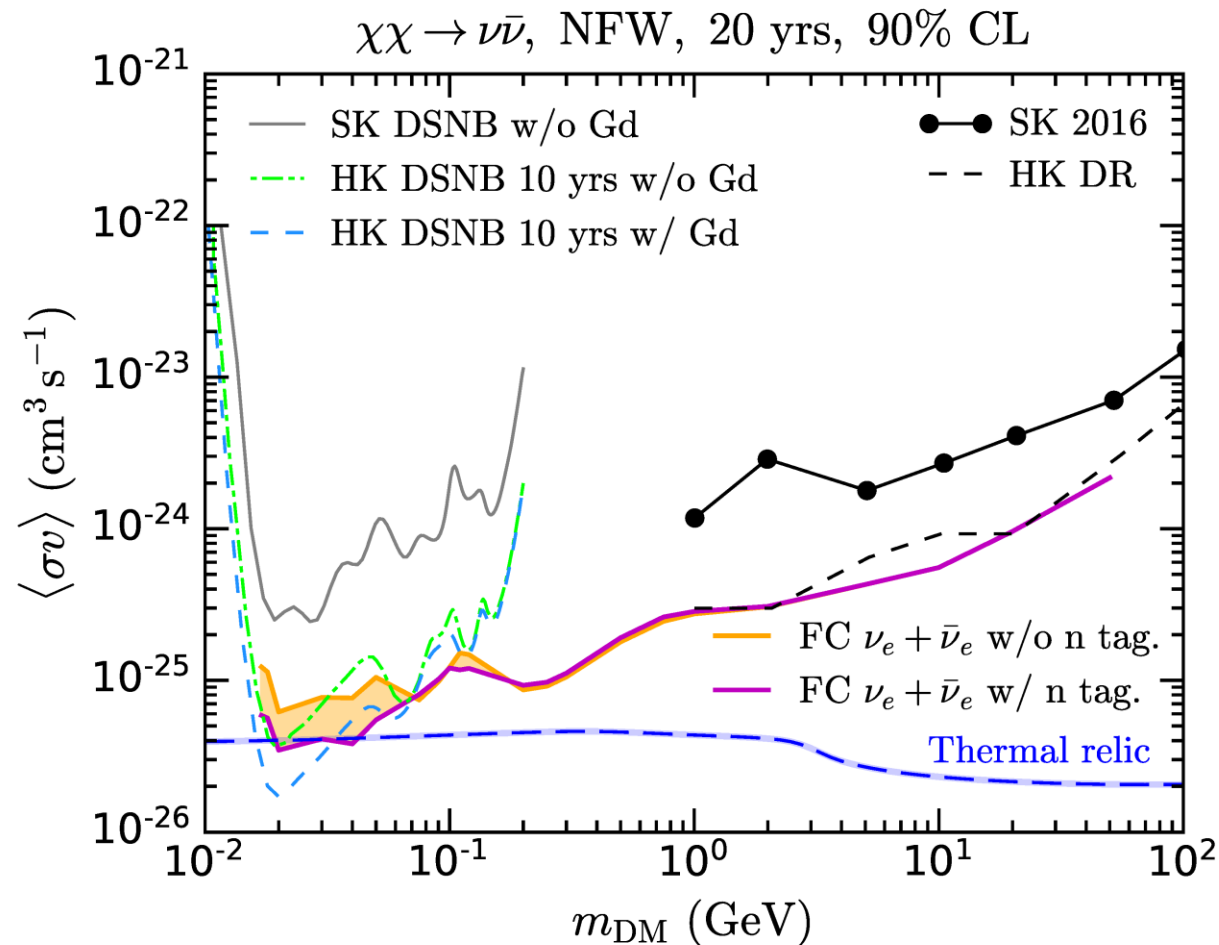
NFW – central lines
Isothermal – upper
Moore - lower

Cross section limits: $\chi\chi \rightarrow \mu^+\mu^-$



NFB, Dolan, Robles, arXiv: 2005.01950

With and w/out neutron tagging

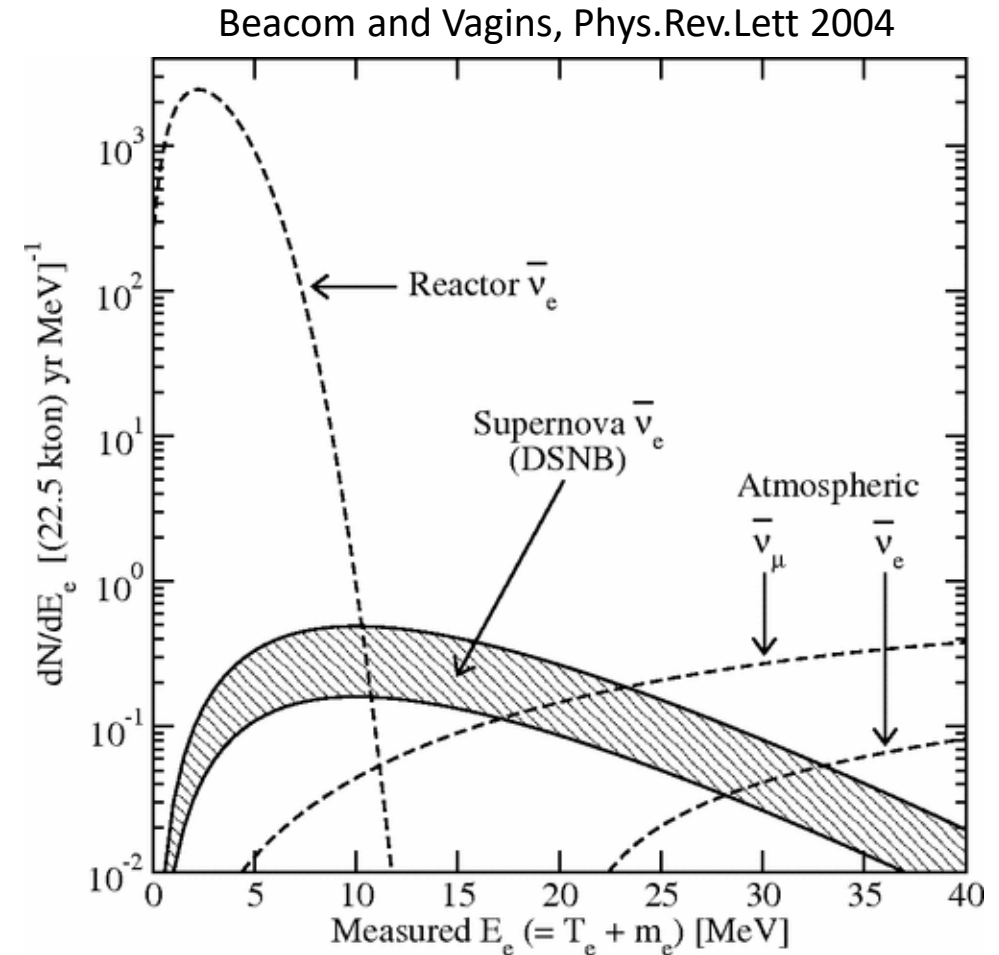


Assumes 70%
tagging efficiency

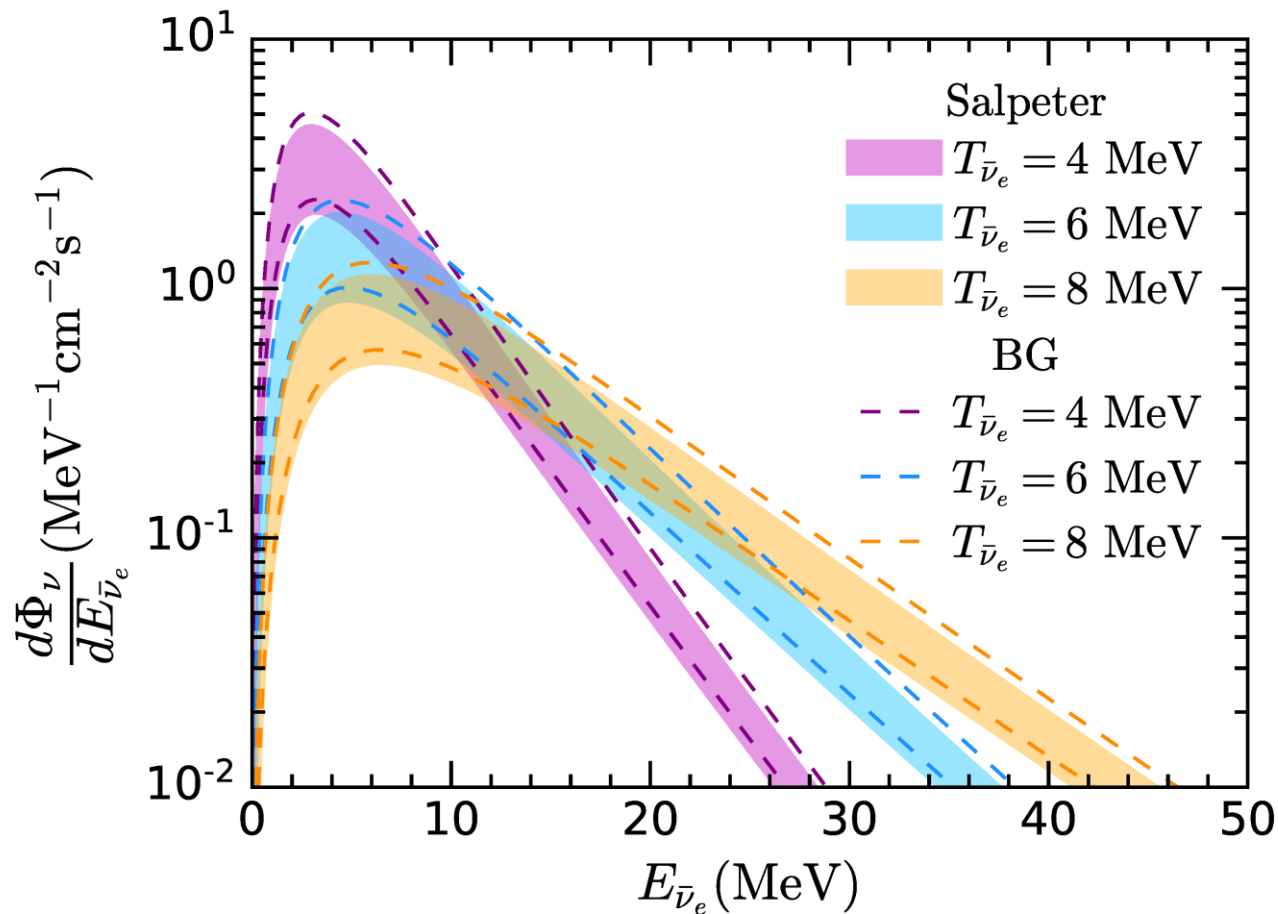
Dark Matter pollution of the Diffuse Supernova Neutrino Background (DSNB)

Diffuse Supernova Neutrino Background

- Core collapse supernovae release gravitational binding energy in the form of neutrinos: 3×10^{53} erg
- *Roughly* equally partitioned among flavours
- Neutrinos diffuse out over ~ 10 seconds.
- Thermal spectra with $T \sim 6$ MeV
- Galactic supernova are rare (~ 1 per century). But detection of the *diffuse flux of neutrinos from extra galactic supernovae (DSNB)* is just around the corner.



DSNB antineutrino spectrum

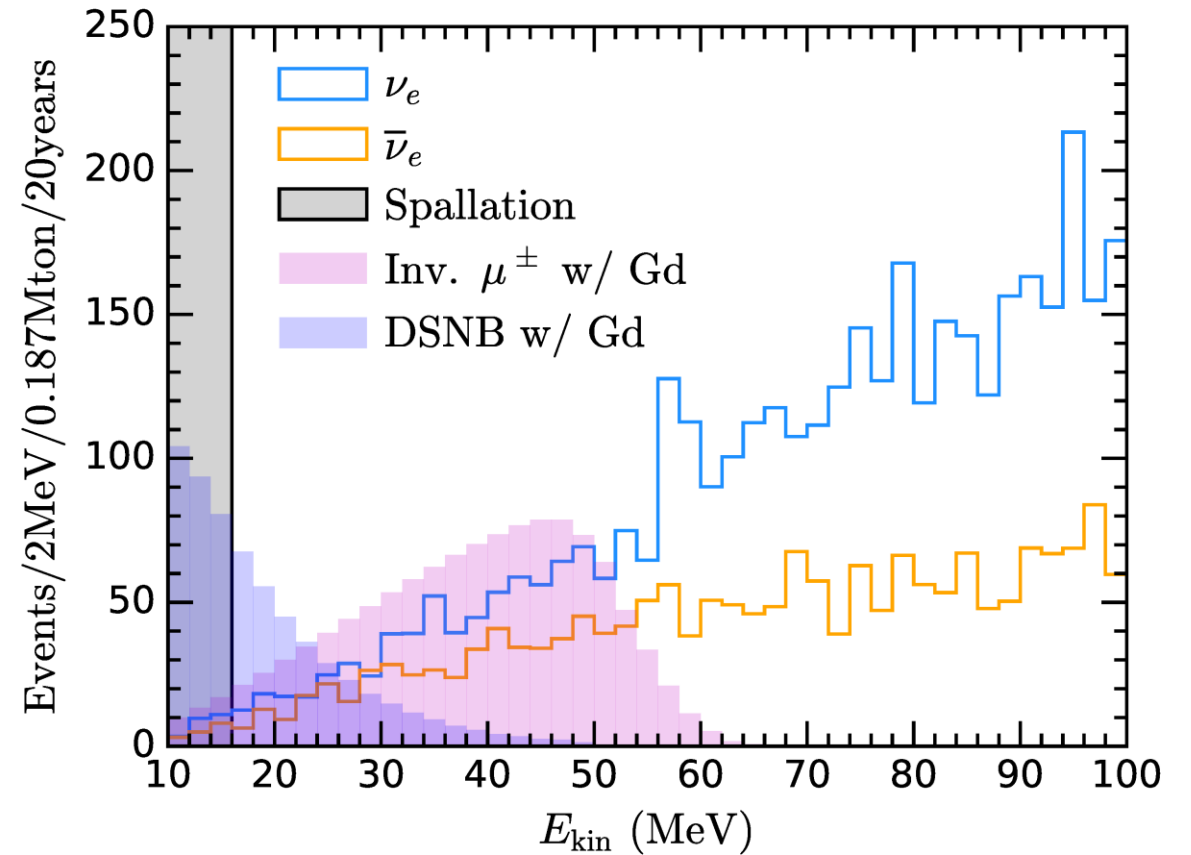
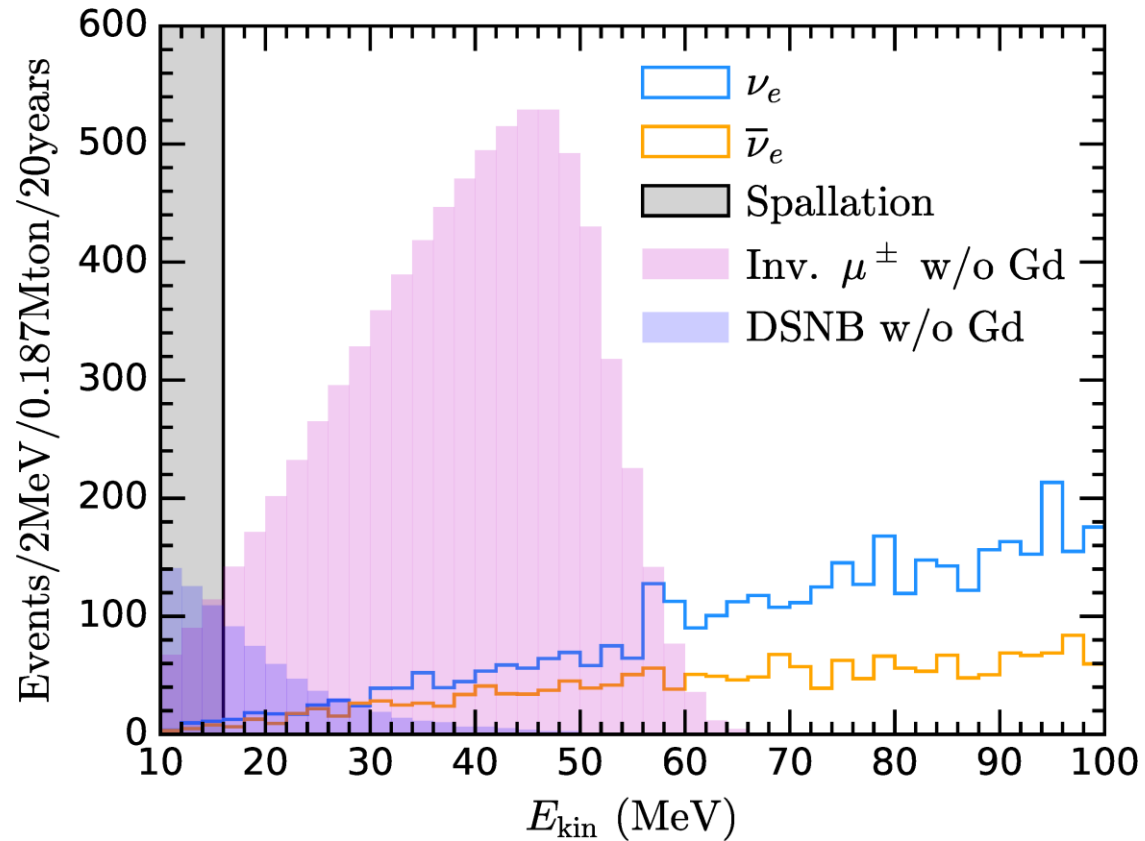


Width of bands determined by upper and lower limits on the start formation rate.

Little dependence on the choice of initial mass function (IFM), Salpeter vs Baldry-Glazebrook

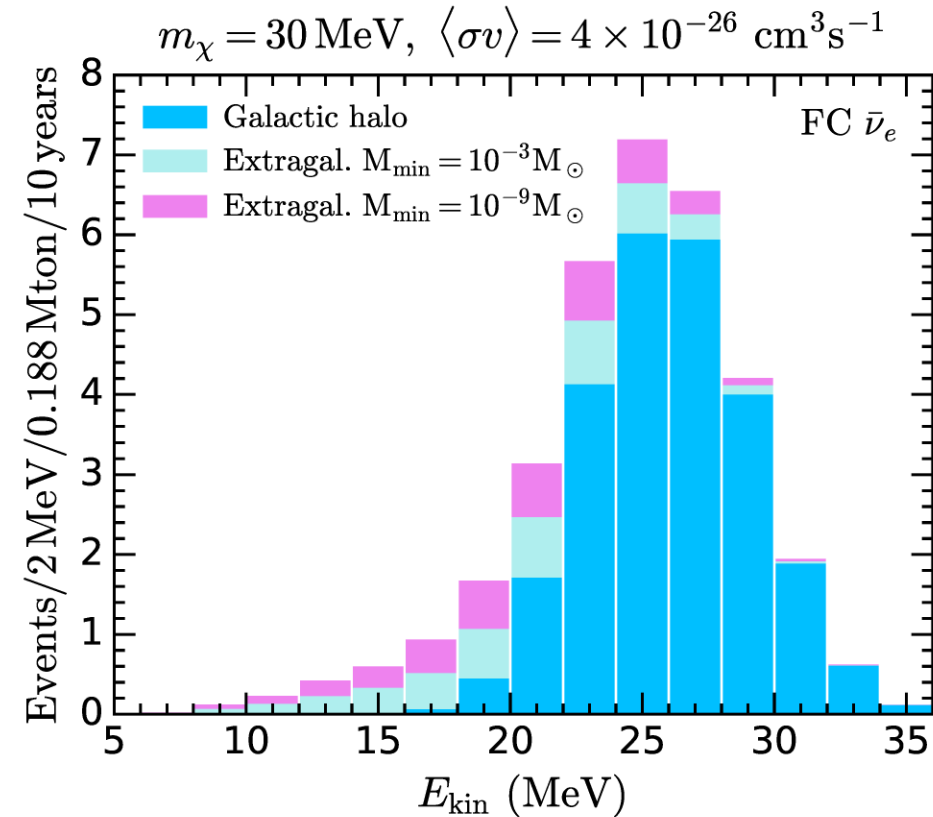
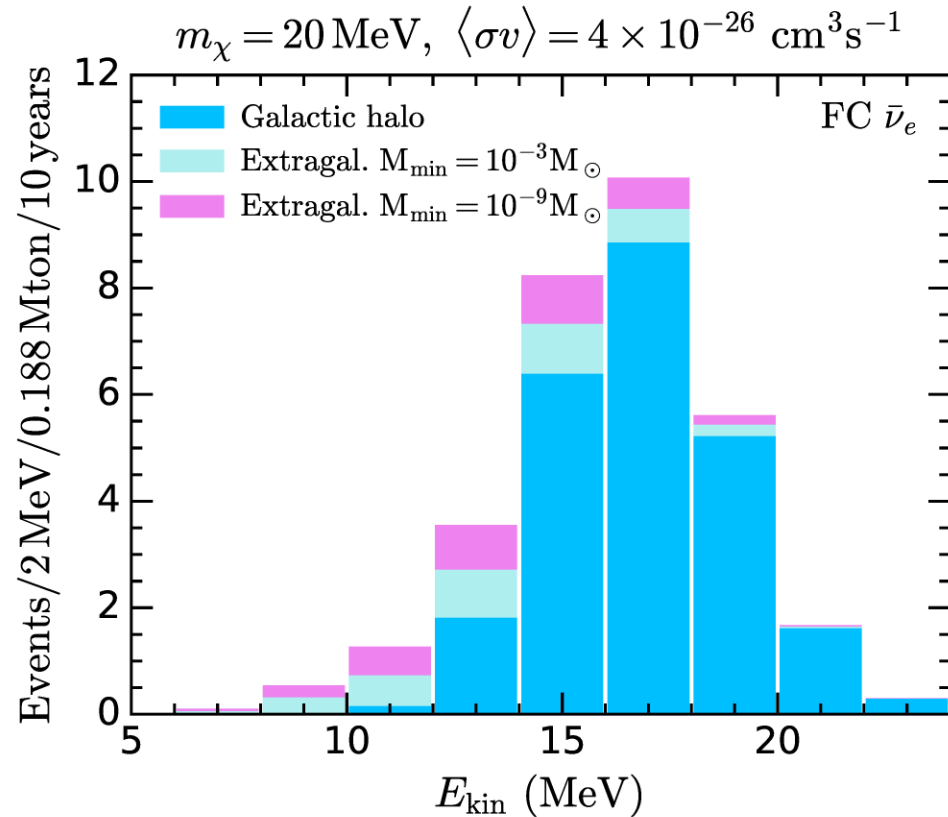
Neutron tagging

Critical for DSNB model discrimination

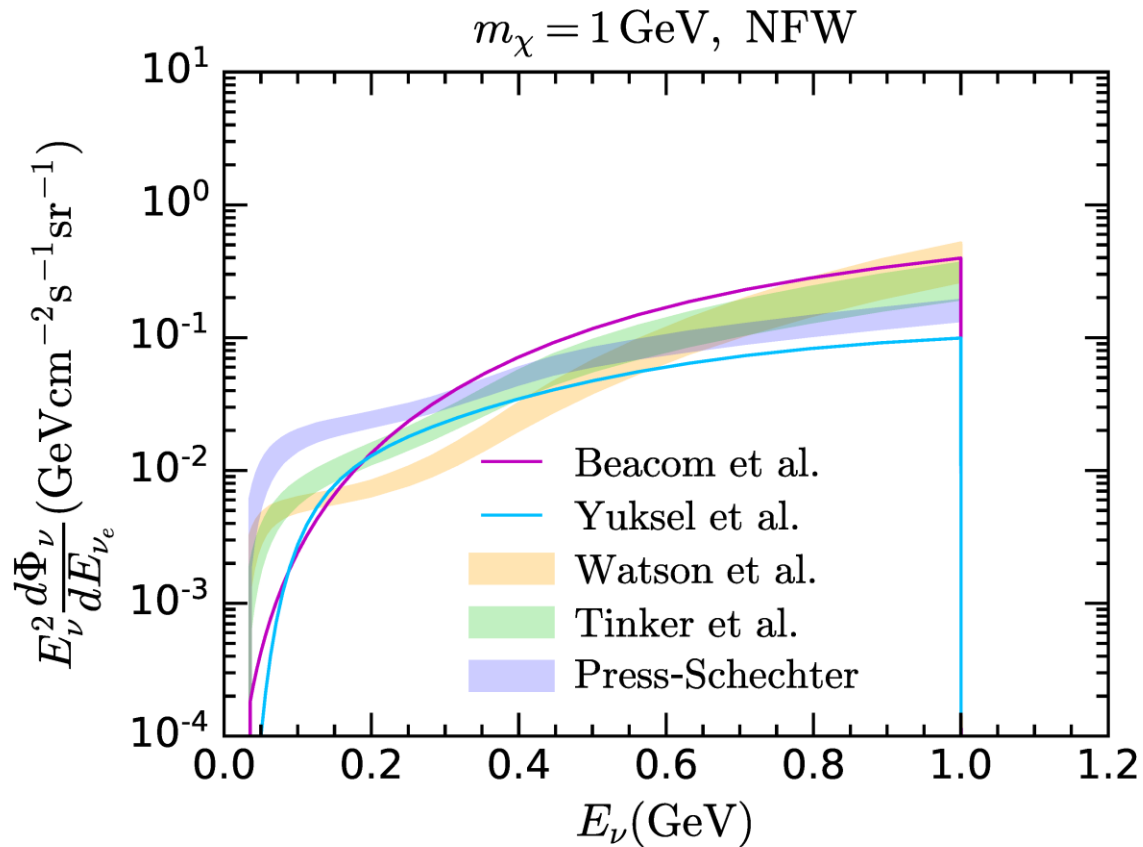


NFB, Dolan, Robles

Galactic + extragalactic DM annihilation



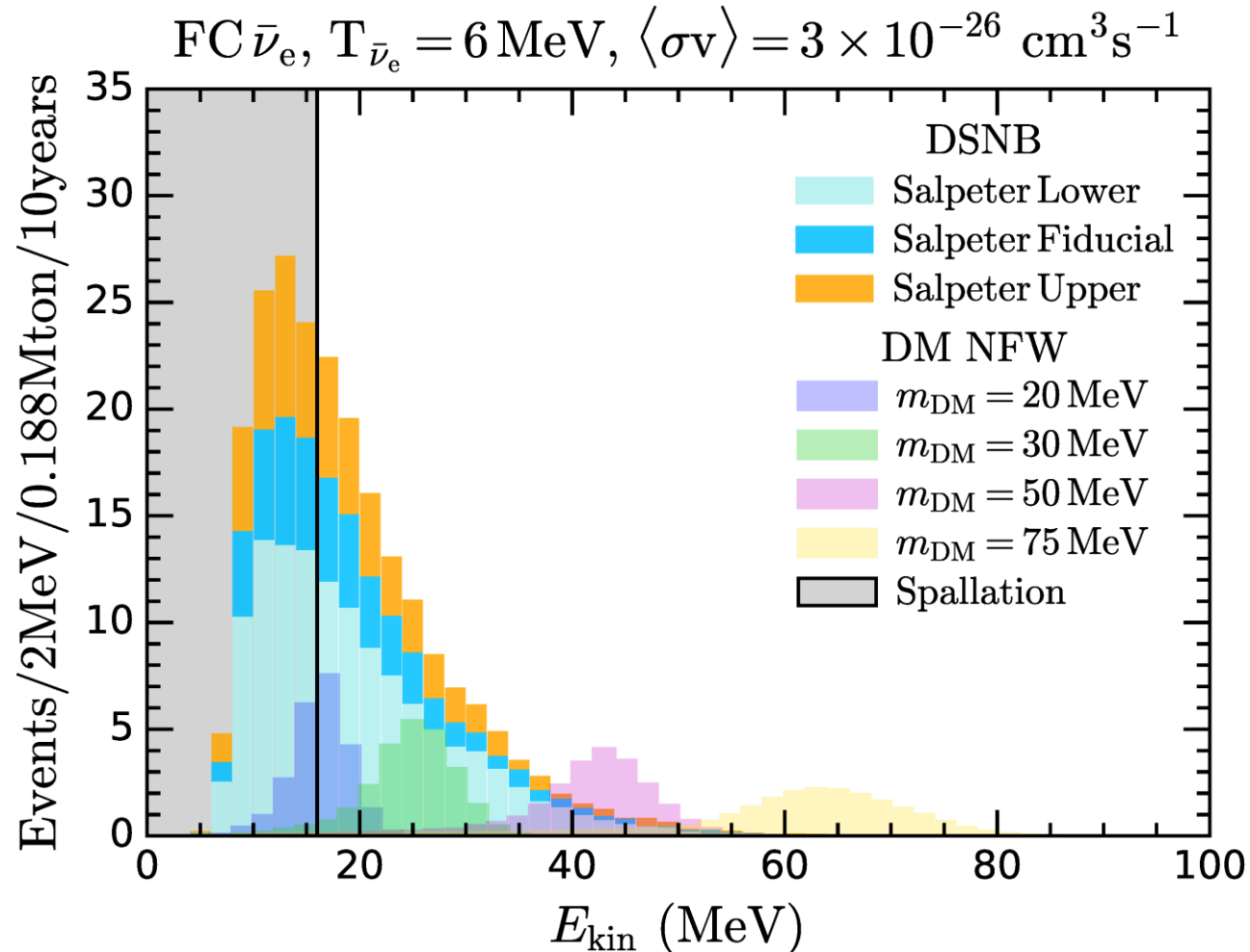
Dark Matter – extra galactic flux



$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\langle\sigma v\rangle}{2} \frac{c}{4\pi H_0} \frac{\Omega_{DM}^2 \rho_c^2}{m_{DM}^2} \int_0^{z_{up}} dz \frac{\Delta^2}{h(z)} \frac{dN_\nu(E'_\nu)}{dE'_\nu}$$

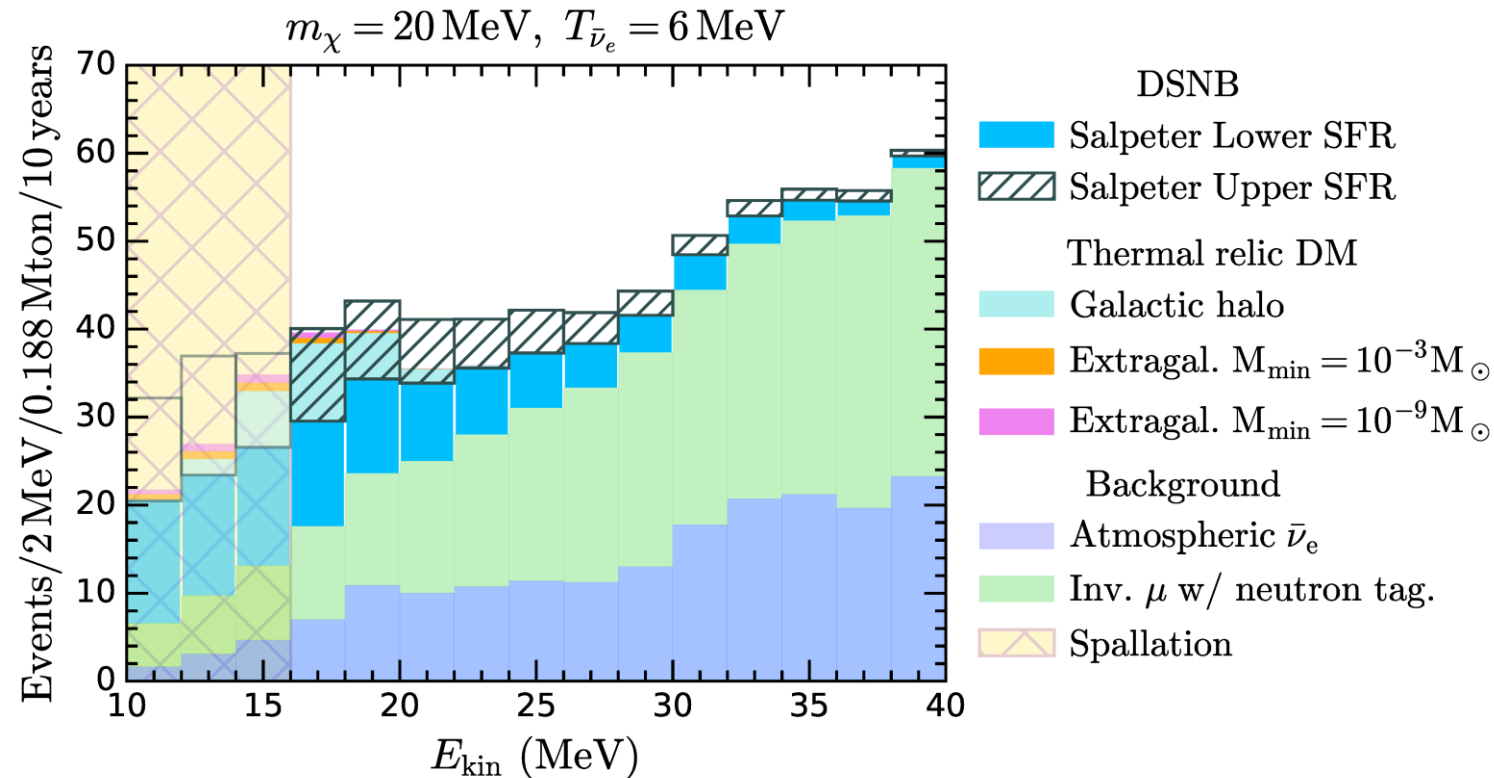
Dependence on the choice of the Halo clustering factor Δ^2 .

DSNB + DM



A dark matter contribution impairs the ability to do model discrimination with the DSNB.

DSNB + DM + atmospheric nu background



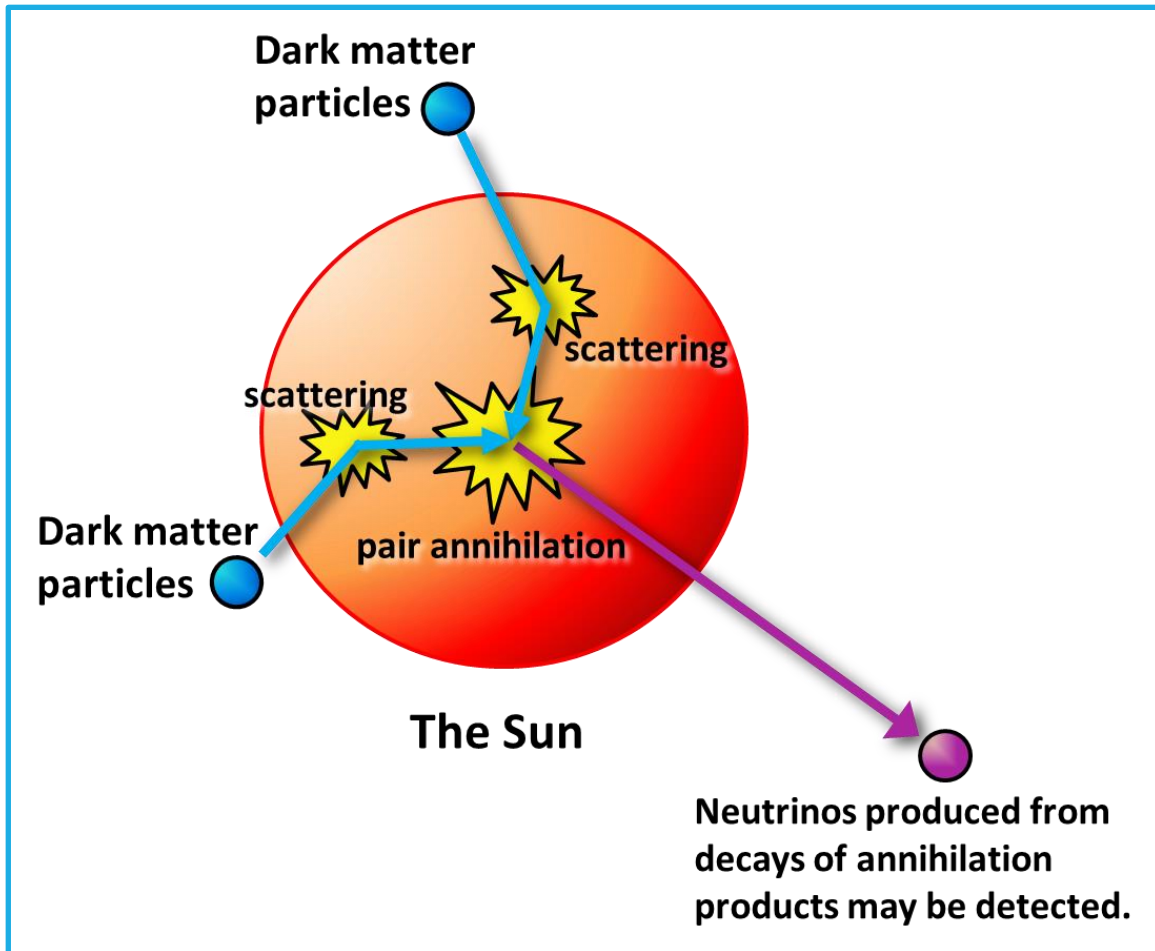
A possible DM signal makes DSNB model discrimination difficult:

High SFR looks like **Low-SFR + DM**

DM annihilation to neutrinos in the Sun

Dark Matter Capture in Stars

→ an alternative approach to Dark Matter Direct Detection experiments



- Dark matter scatters, loses energy, becomes gravitationally bound to star
- Accumulates and annihilates in centre of the star → neutrinos escape

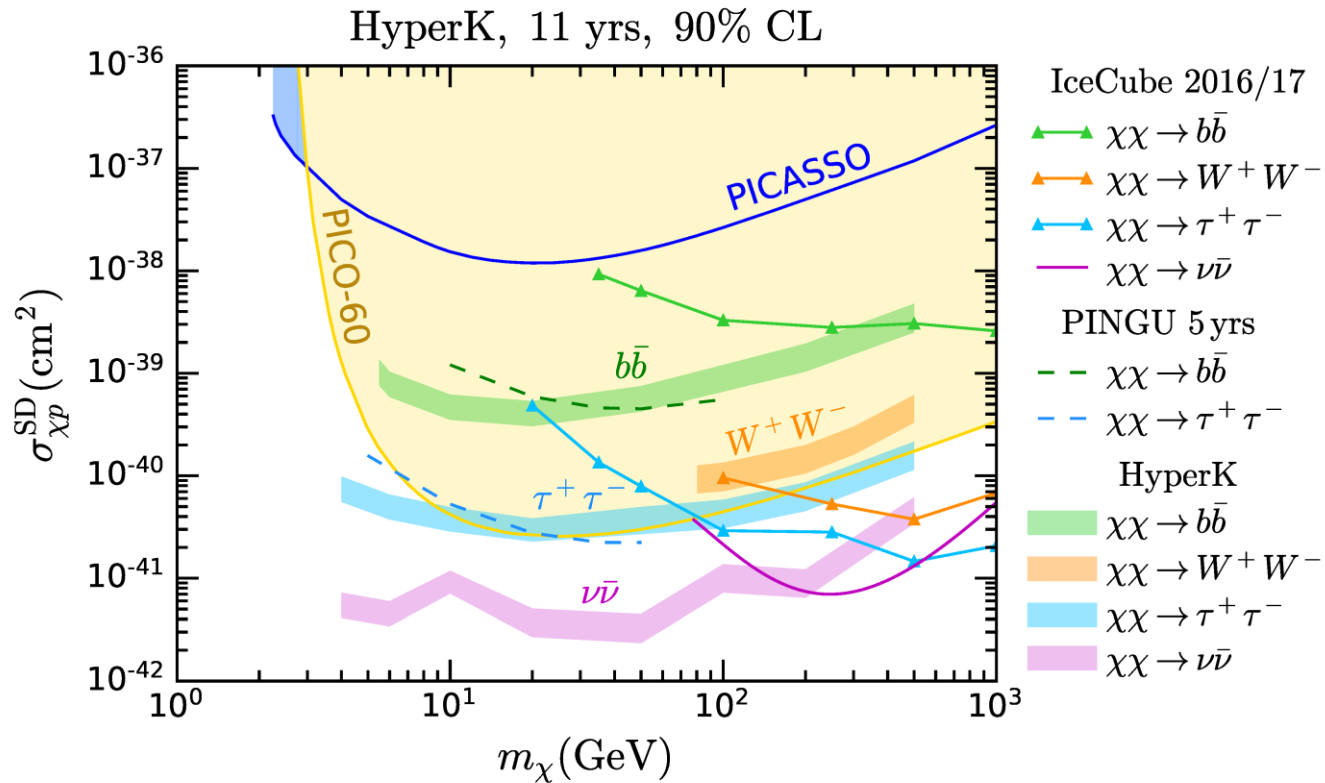
In equilibrium:

Annihilation rate = Capture rate

- controlled by DM-nucleon scattering cross section
- **probes the same quantity as dark matter direct detection experiments**

Dark matter annihilation in the Sun

Spin-Dependent (SD)



Spin-dependent (SD) interactions:
 - solar DM searches competitive or better than direct detection experiments

Spin-independent (SI) interactions:
 - direct detection experiments win.

Summary

- Indirect detection limits on DM annihilation to neutrinos
 - Hyper-K will probe thermal-relic cross section for $m_{\text{DM}} \lesssim 30$ MeV
- Detection of the Diffuse Supernova Background
 - Hyper-K will make a high-statistics detection of the DSNB.
 - Model discrimination will require backgrounds (including a possible DM contribution) to be understood.
- DM annihilation to neutrinos in the Sun
 - For spin-dependent scattering, solar WIMP searches surpass direct detection (for certain masses/annihilation channels).