Searching for Dark Matter with Hyper-Kamiokande

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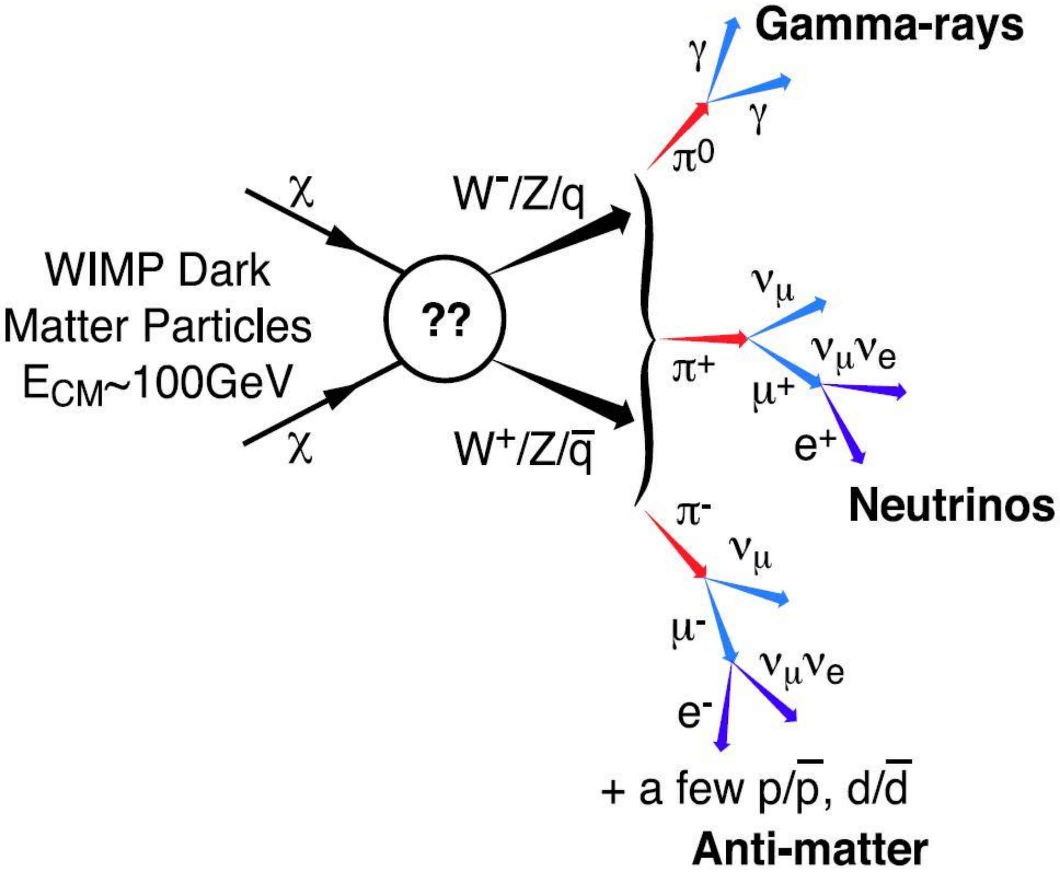
in collaboration with Matthew Dolan and Sandra Robles

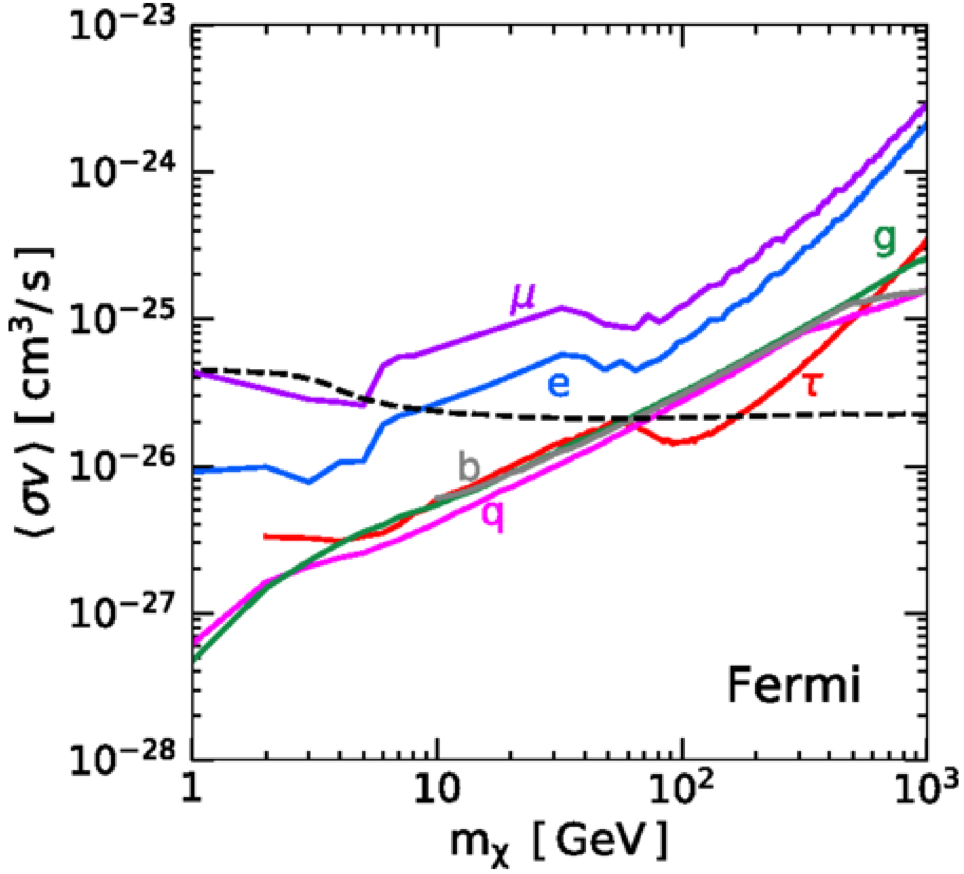
Indirect detection – Detecting dark matter annihilation



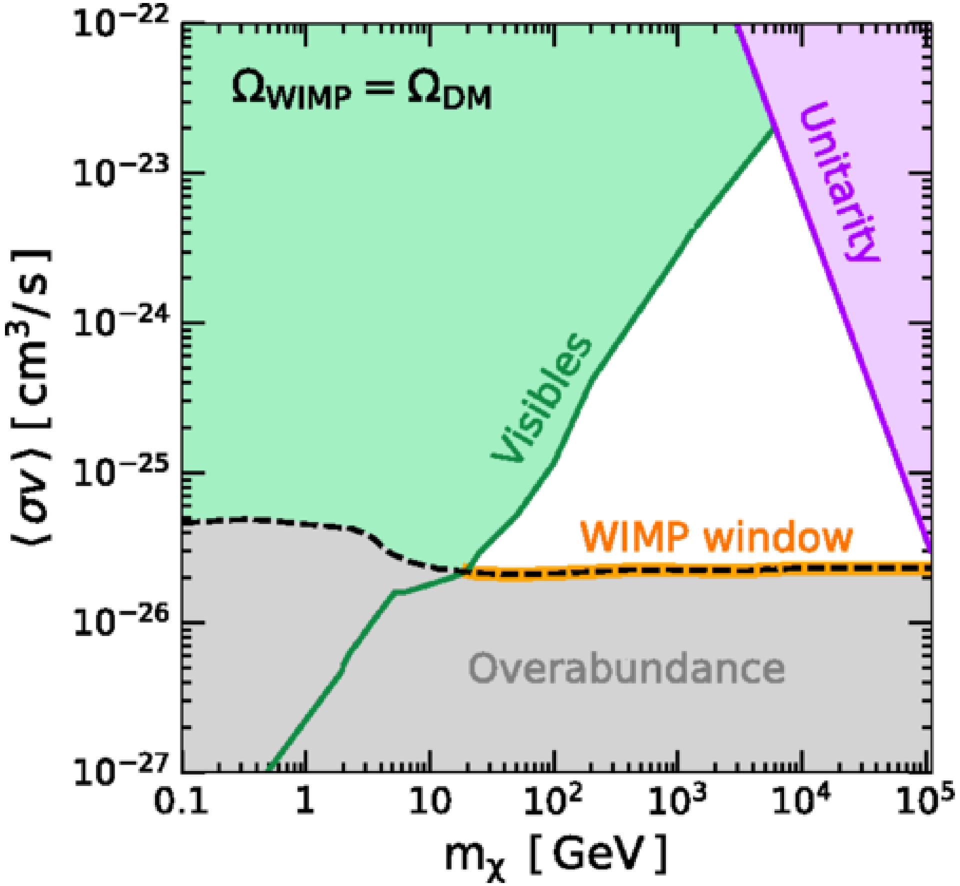
Indirect detection constraints

R. Leane, et al., arXiv:1805.10305

Fermi dSph limits

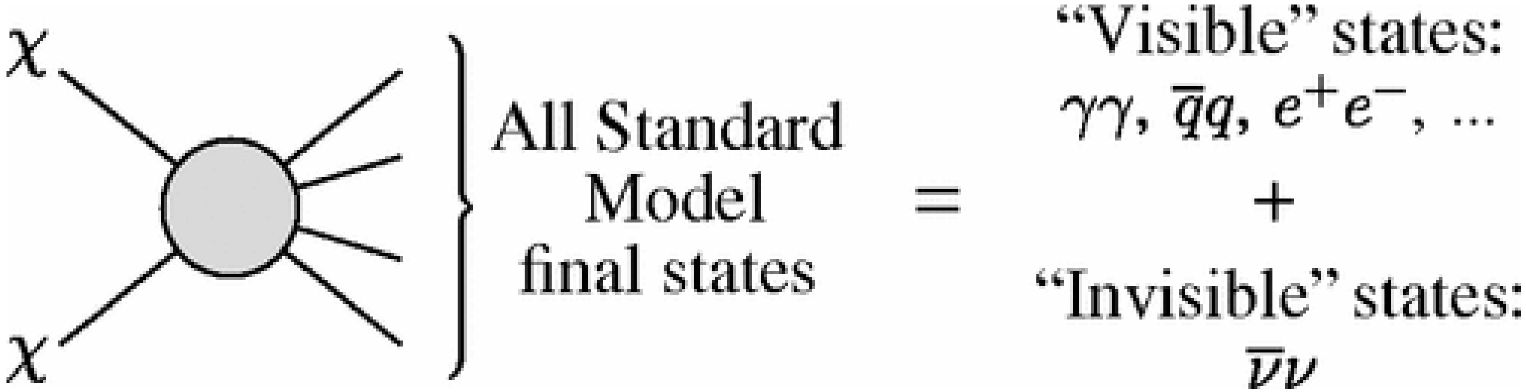


Annihilation to "visible" SM states



Annihilation to neutrinos

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



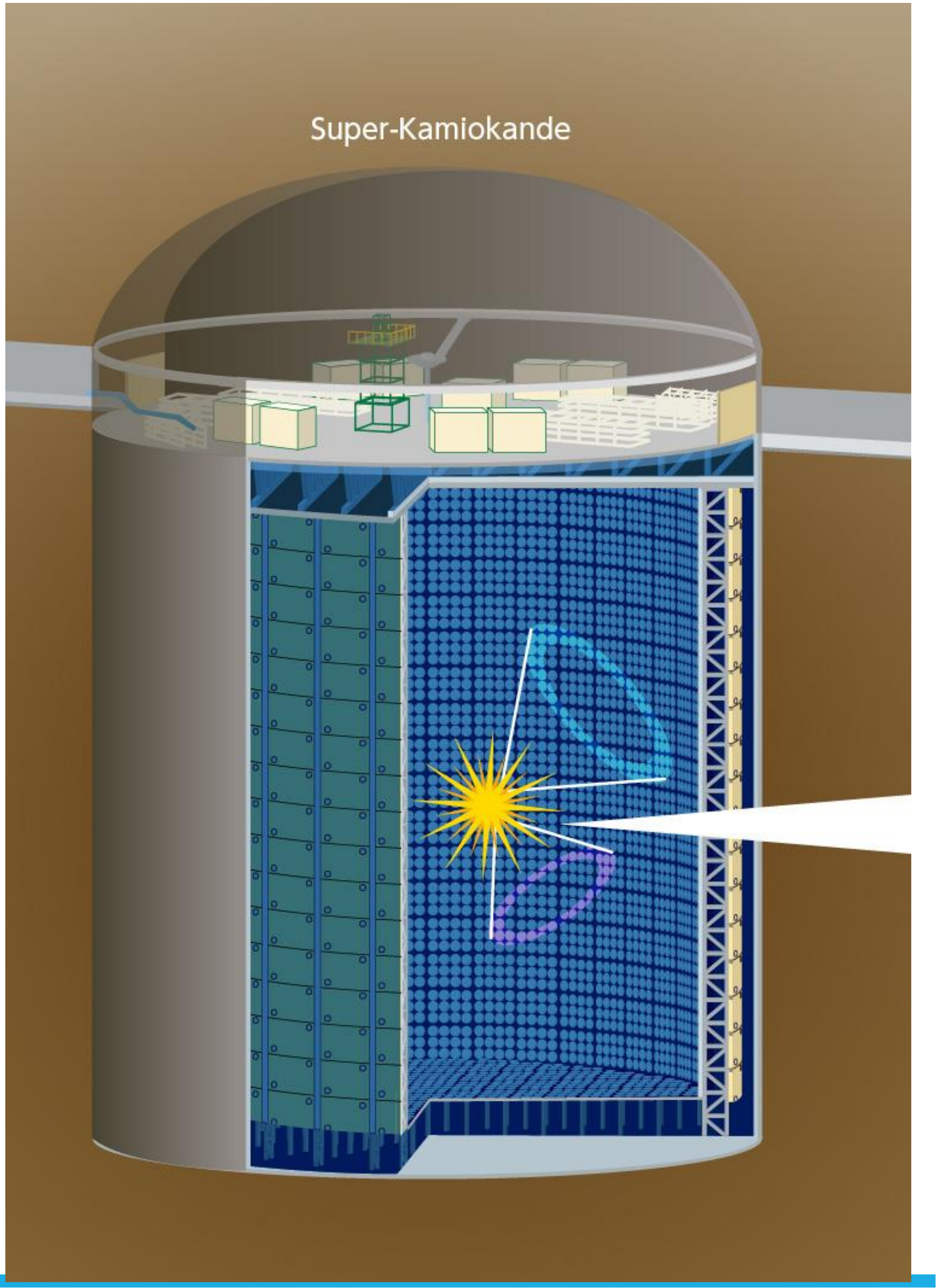
All Standard Model final states $=$ “Visible” states: $\gamma\gamma$, $\bar{q}q$, e^+e^-, … $+$ “Invisible” states: $\bar{\nu}\nu$

- 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 $\chi\chi \to \nu\bar{\nu}$ above the atmospheric neutrino background?

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



Hyper-K simulation

Neutrino flux from DM annihilation

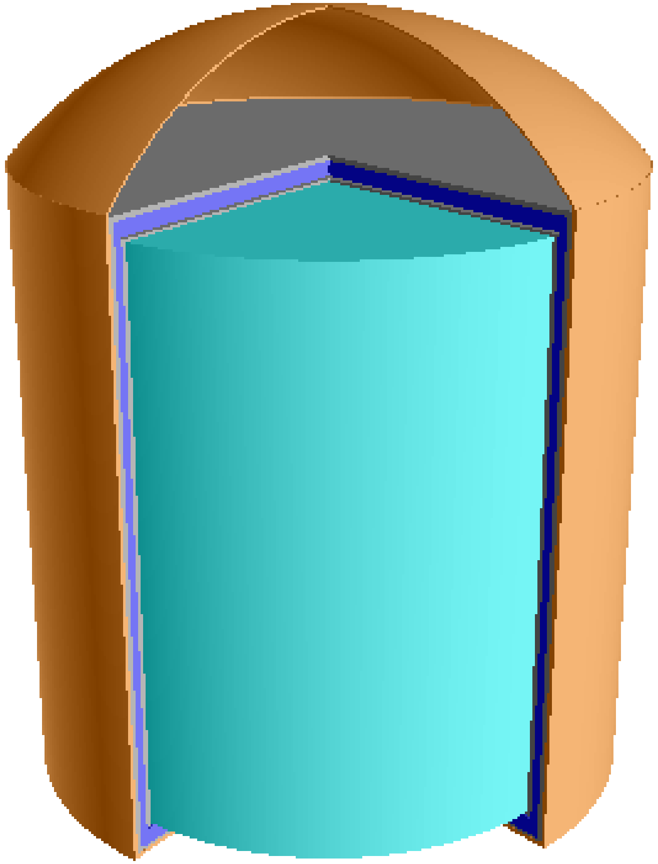
- DarkSUSY

Atmospheric neutrino background

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

Neutrino interactions

- GENIE



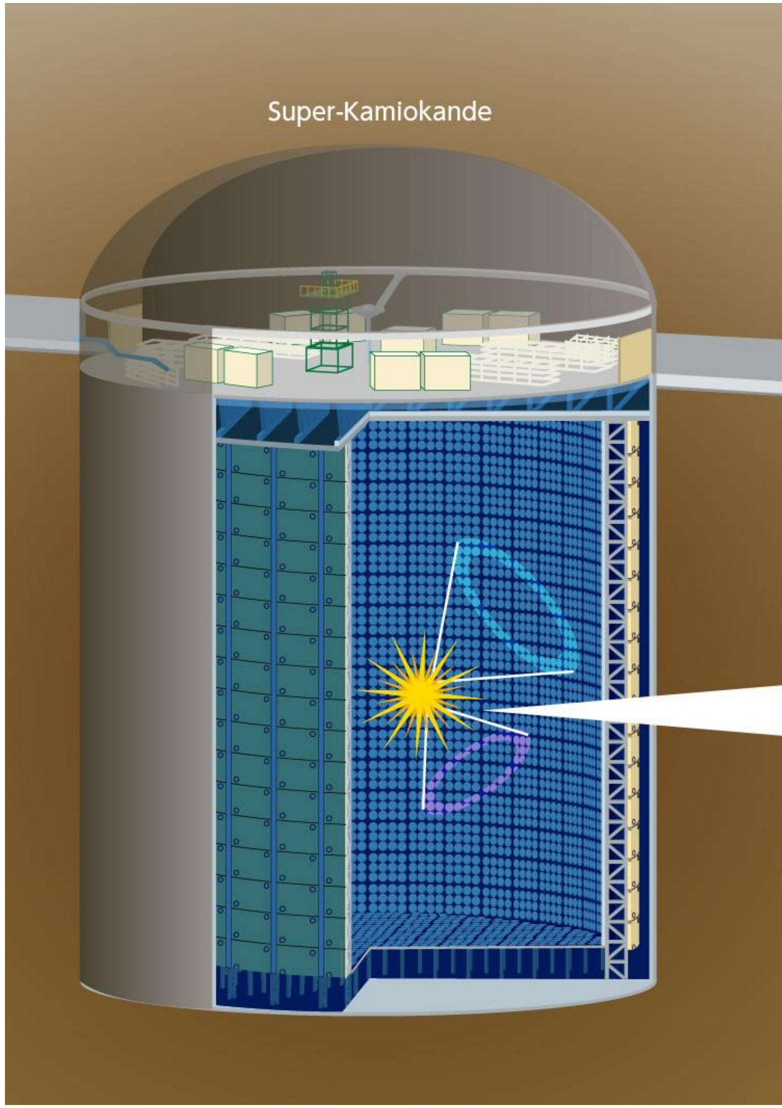
Interactions and event categories

Dominant CC interactions:

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

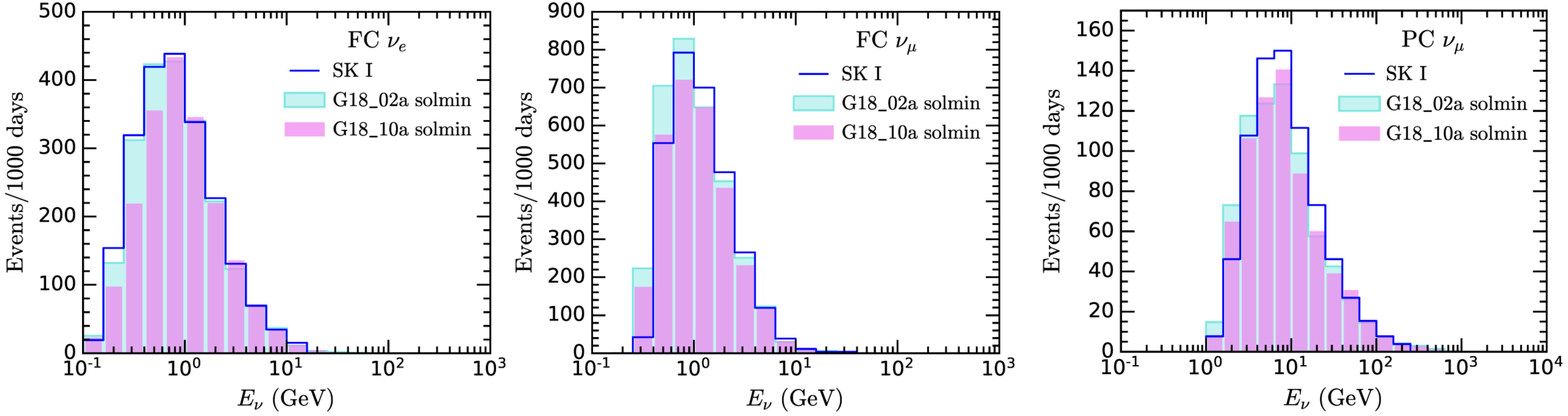
Event important categories

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



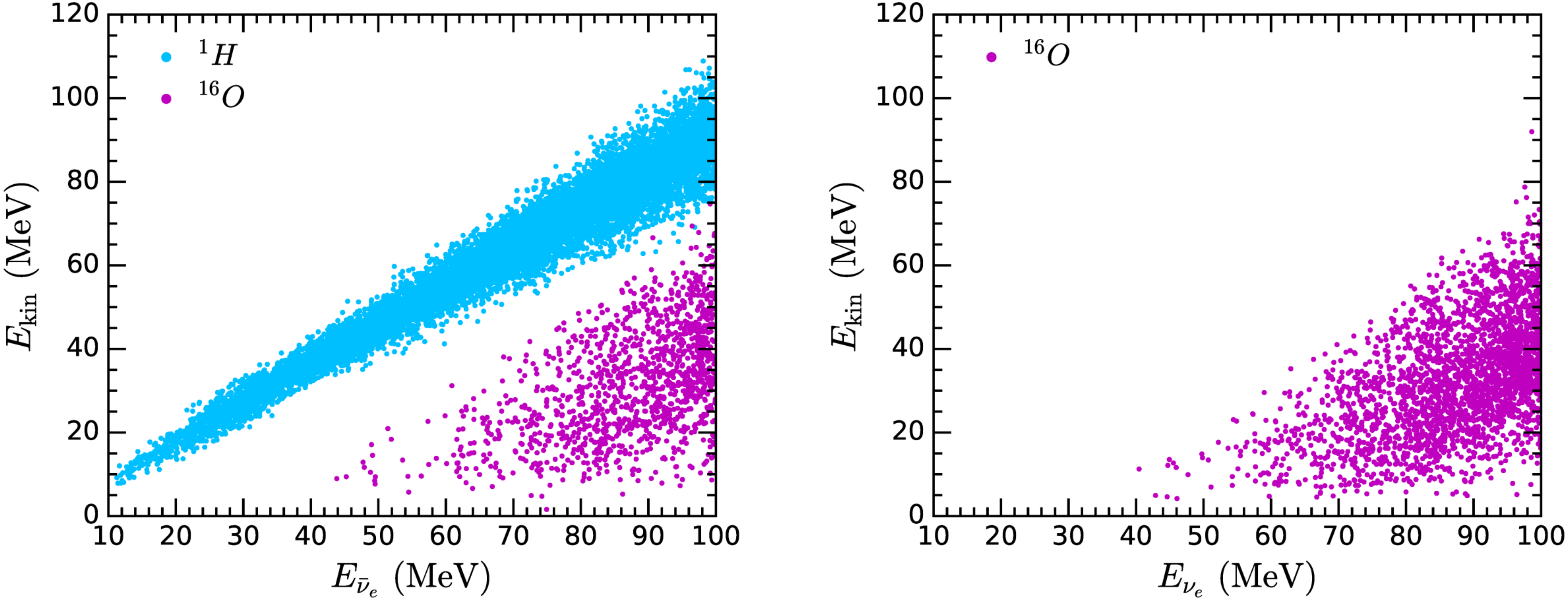
Simulation validated against Super-K data

Reproduced the atmospheric neutrino background rates measured by Super-K

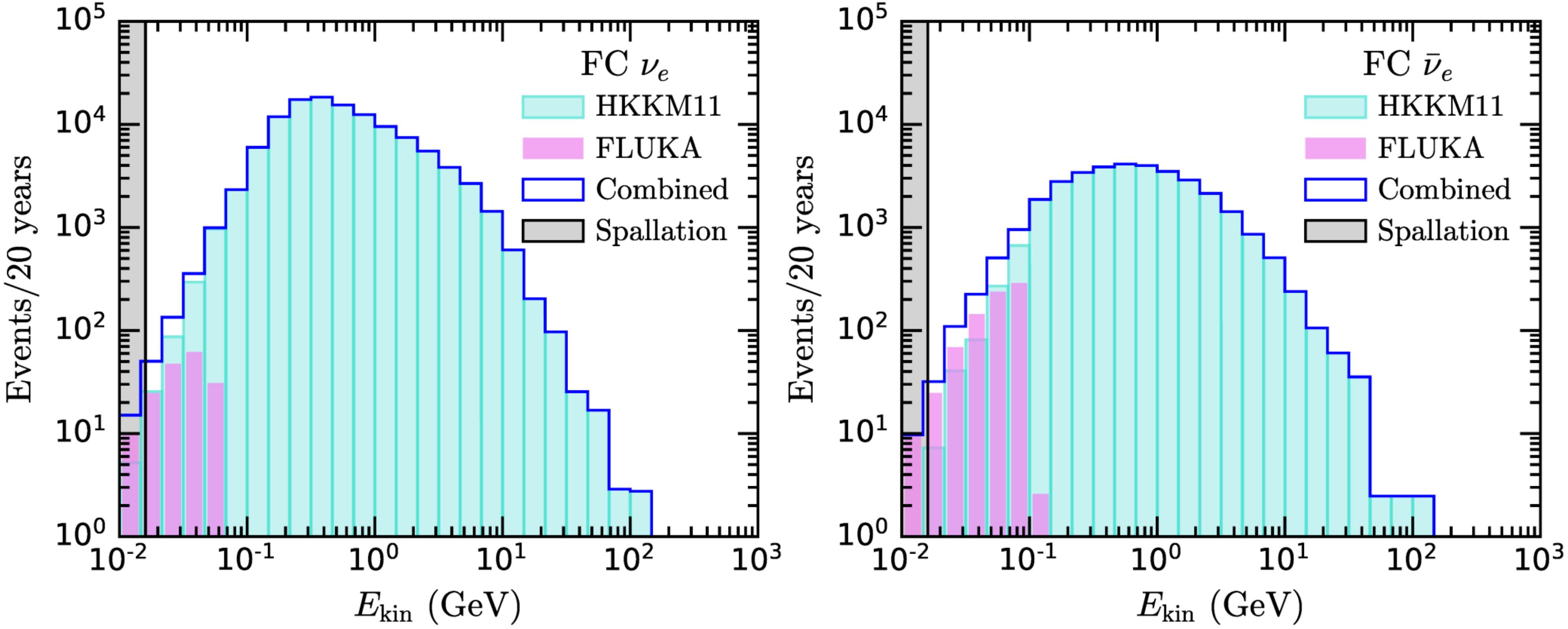


NFB, Dolan, Robles, arXiv: 2005.01950

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



Atmospheric neutron background

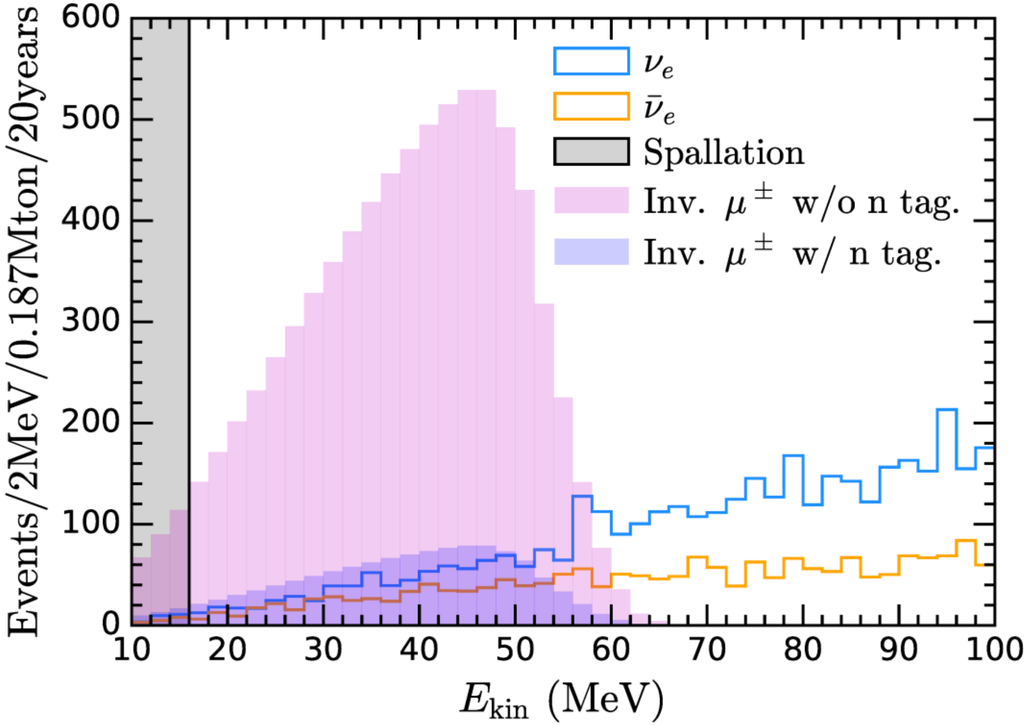


NFB, Dolan, Robles, arXiv: 2005.01950

Neutron tagging to remove invisible muons

"Invisible muons" are an important background at sub-GeV energies

- $\mu^{\pm}$ 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 $\overline{\nu}_e$ or event.

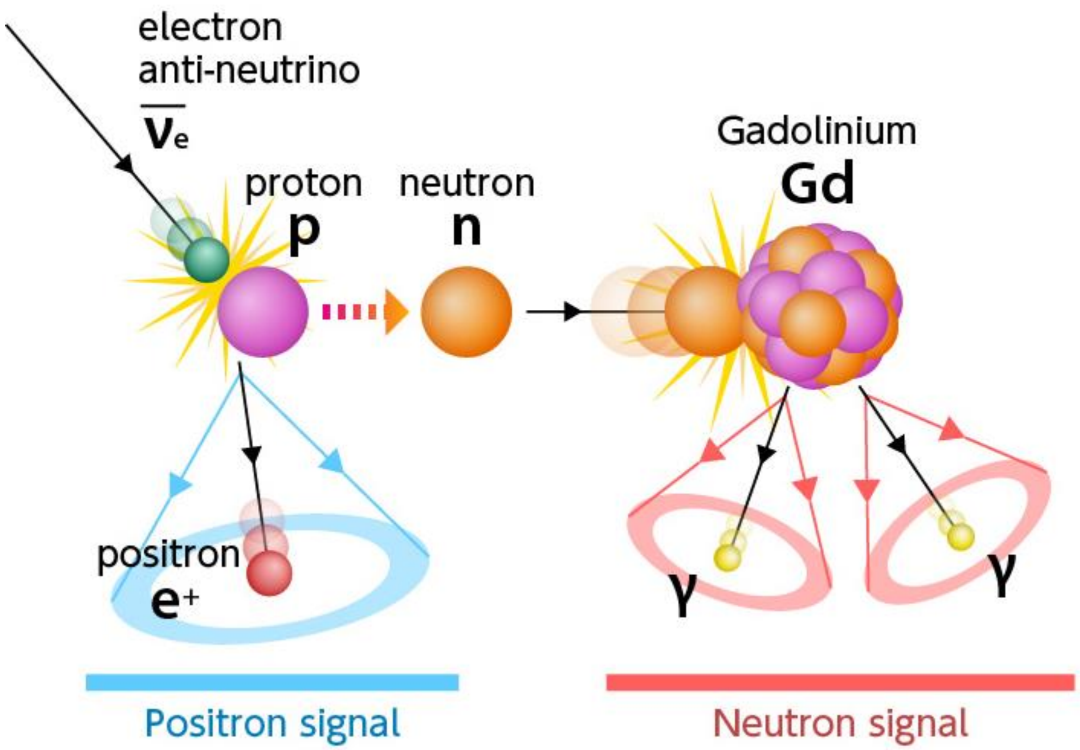


NFB, Dolan, Robles, arXiv: 2005.01950

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

$$\overline{\nu}_e + p \rightarrow n + e^{+}$$

Neutron tagging on Gadolinium



Gadoliniun has a large neutron capture cross section.

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

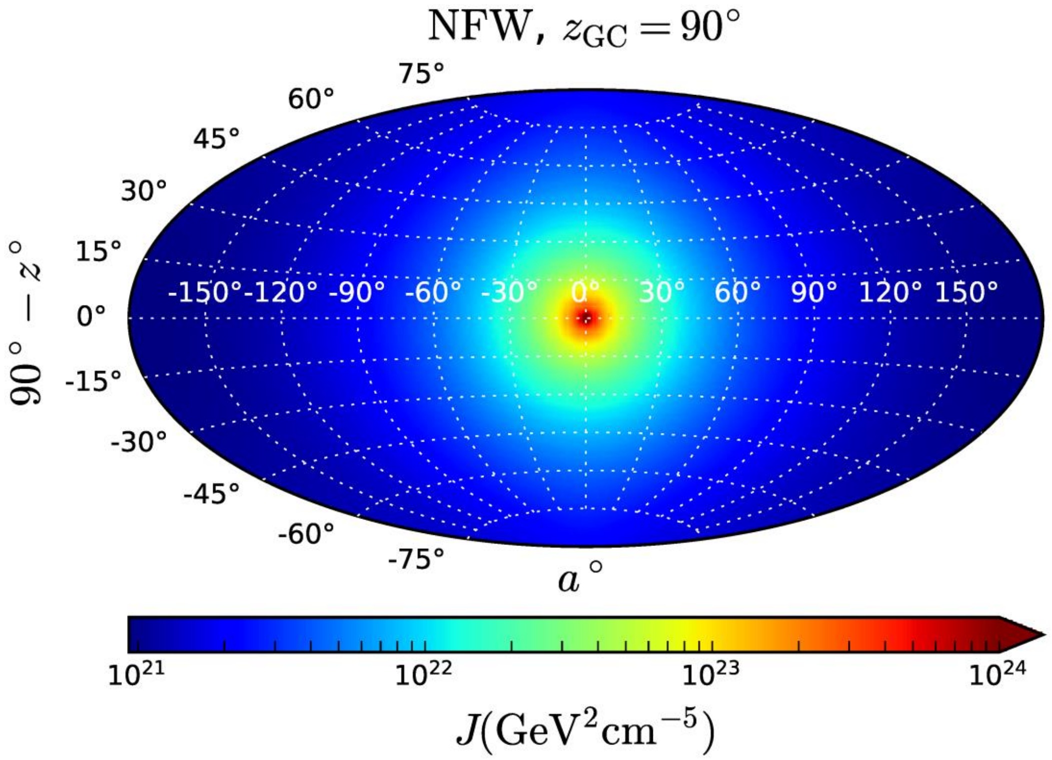
Neutron tagging on Hydrogen is possible too:

$$n + p \rightarrow d + \gamma(2.2\ \mathrm{MeV})$$

DM annihilation to neutrinos in the Galactic Centre

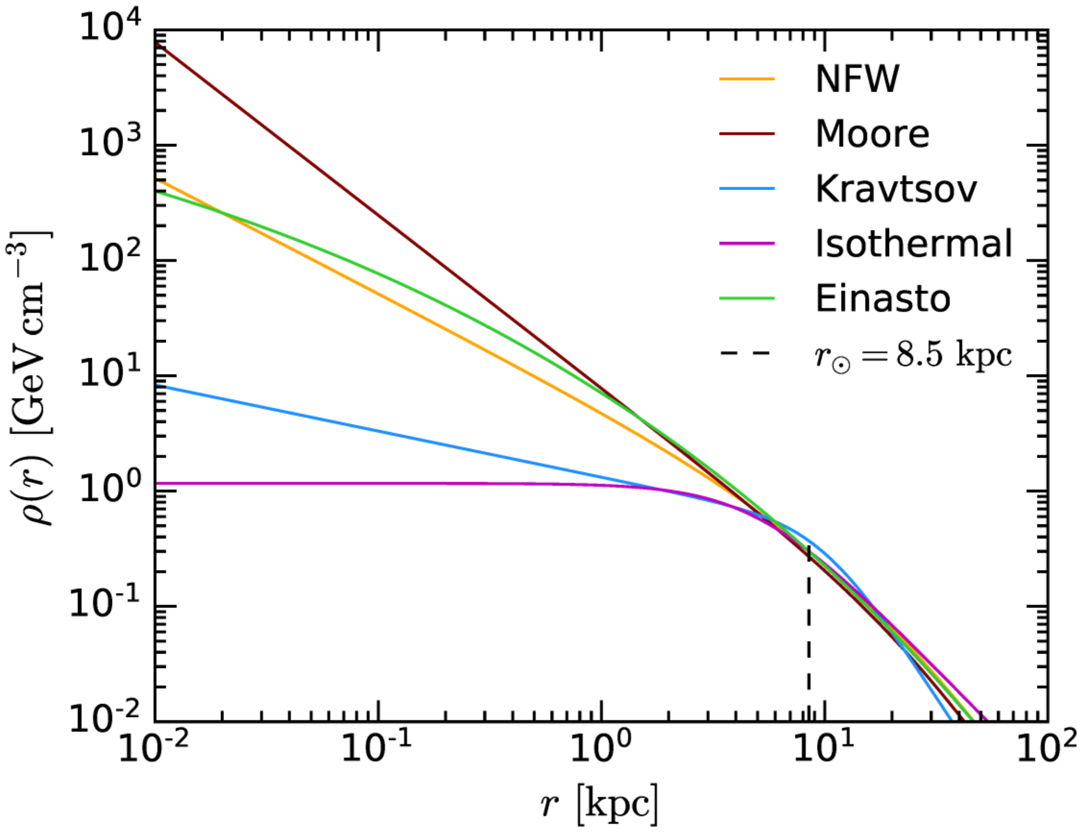
Dark matter annihilation signal

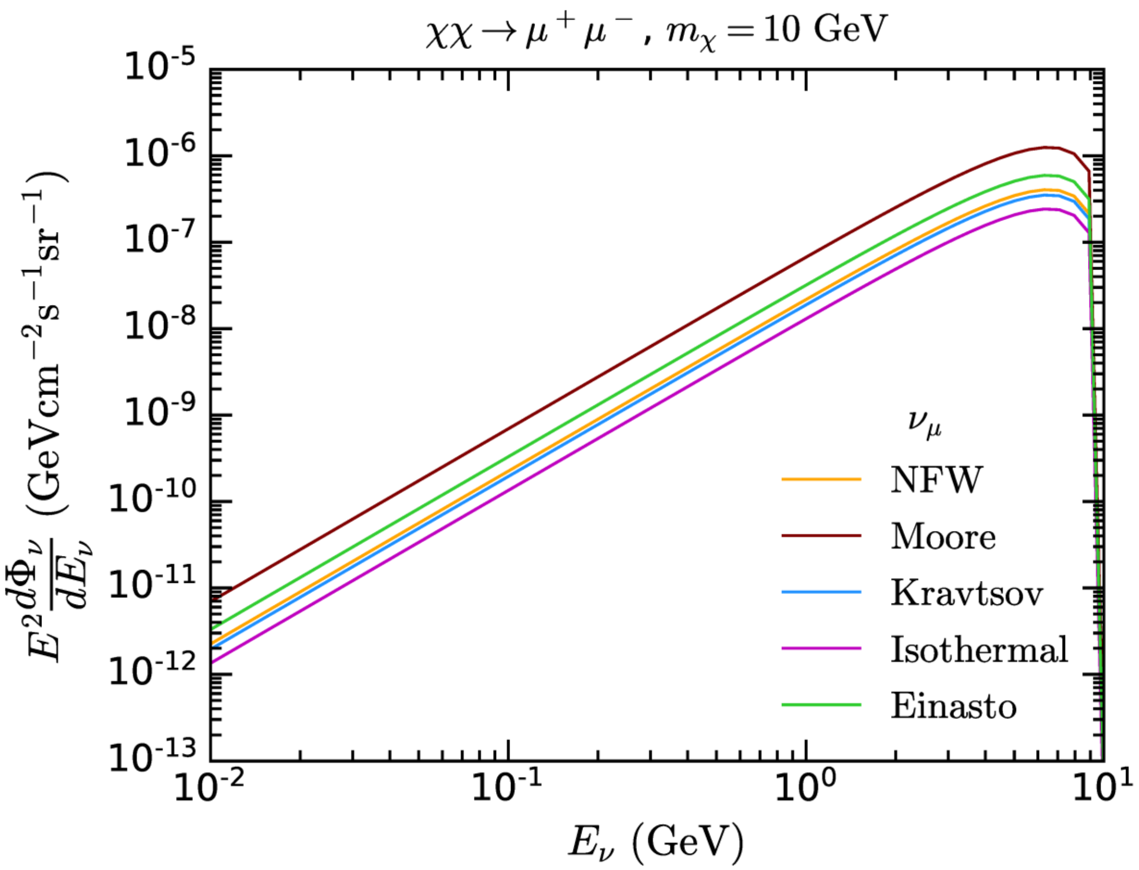
$$\frac{d\Phi_{\nu\Delta\Omega}}{dE_\nu} = \underbrace{\langle\sigma v\rangle}_{\text{Annihilation cross section}} \underbrace{\frac{J_{\Delta\Omega}}{8\pi m_{DM}^2}}_{\text{Integral of (density)}^2\text{ along line of sight}} \underbrace{\frac{dN_\nu}{dE_\nu}}_{\text{Spectrum per annihilation}}$$



NFB, Dolan, Robles, arXiv: 2005.01950

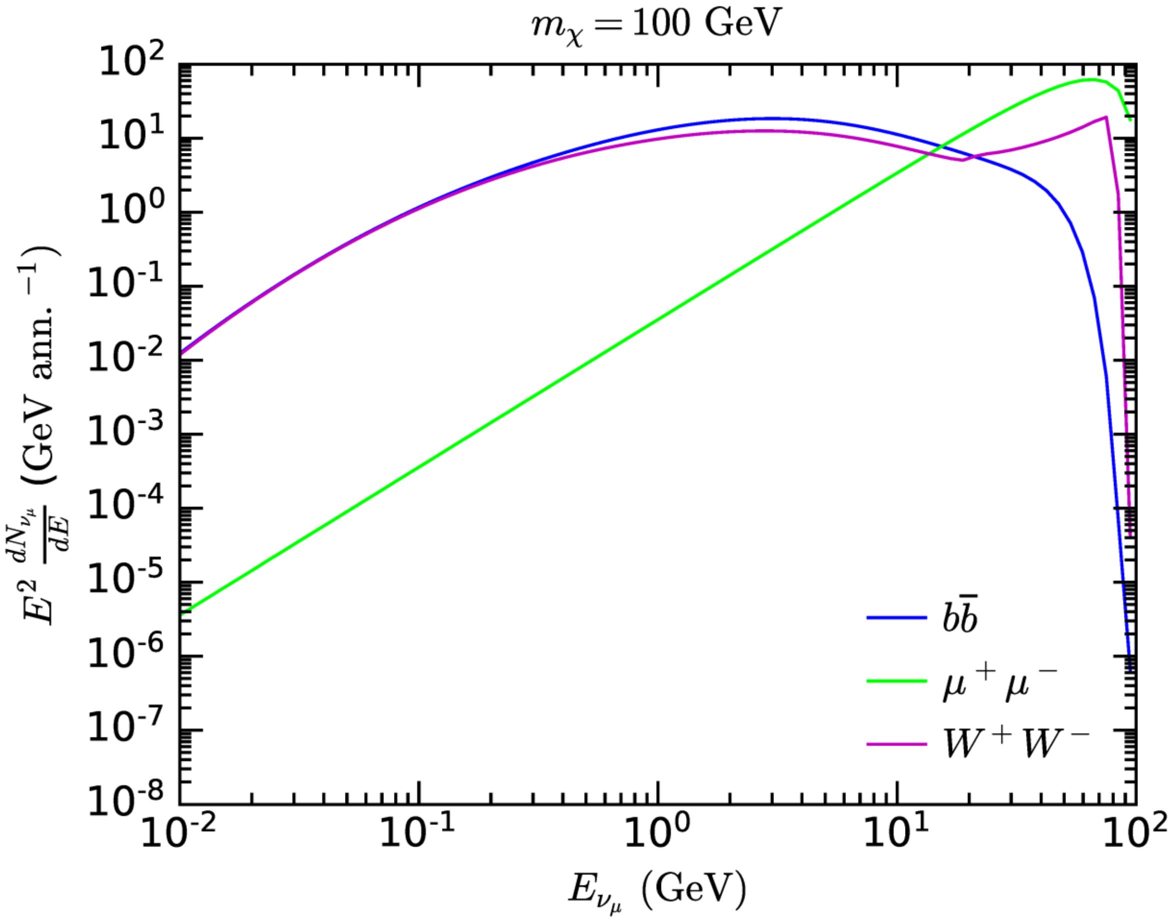
Dependence on halo profile is mild, as we undertake an all-sky analysis





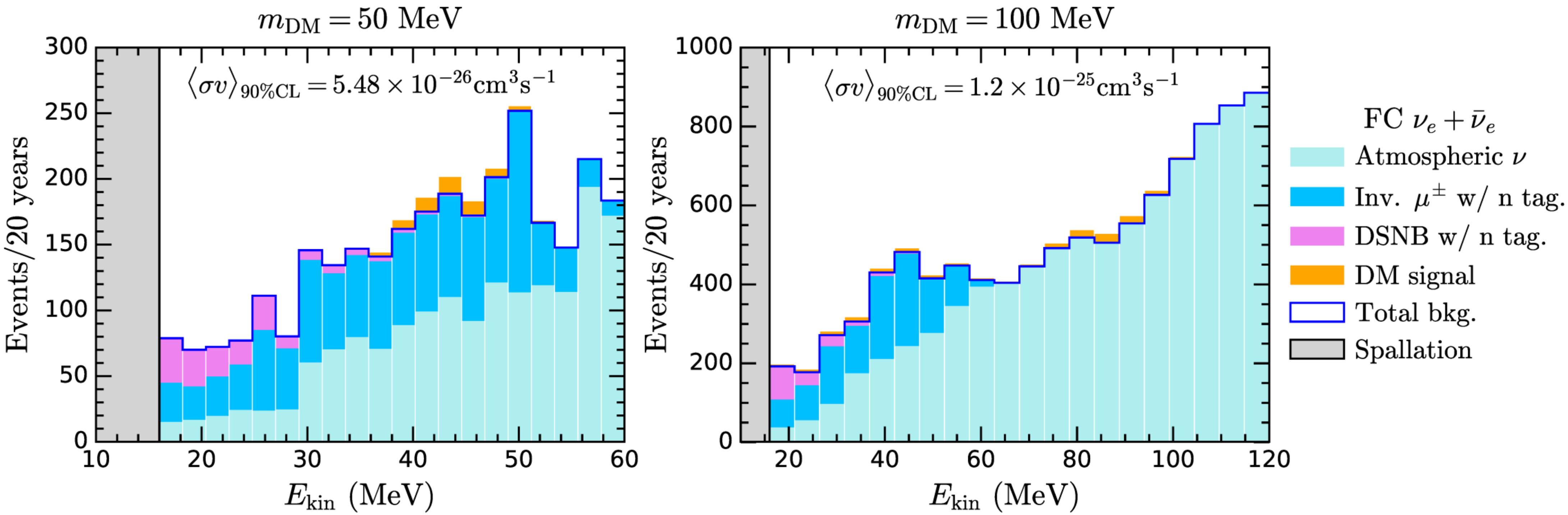
NFB, Dolan, Robles, arXiv: 2005.01950

Annihilation spectrum



NFB, Dolan, Robles, arXiv: 2005.01950

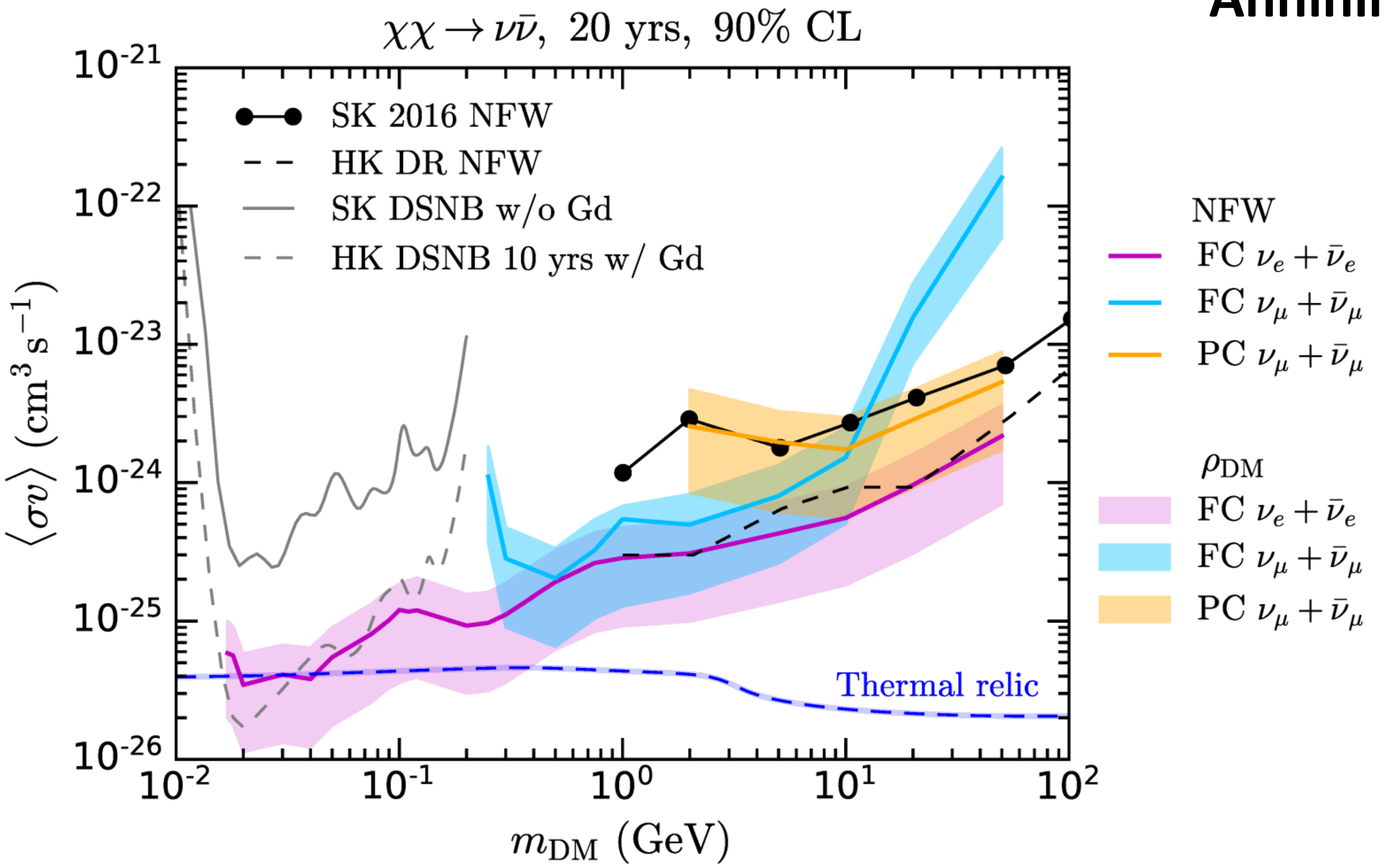
Annihilation signal and backgrounds



NFB, Dolan, Robles, arXiv: 2005.01950

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

Annihilation to "visible" SM states

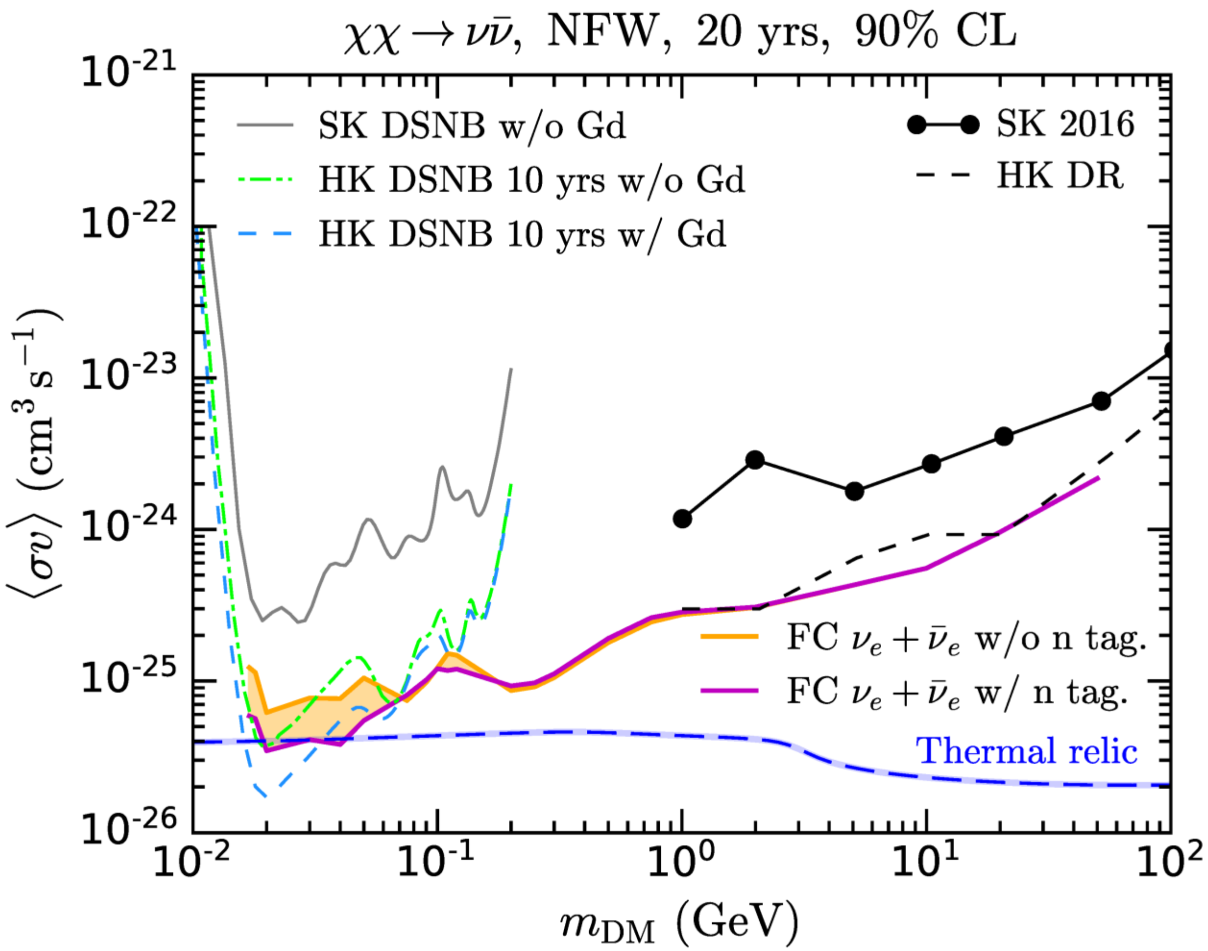


Thermal relic sensitivity for DM mass of ~ 30 MeV

NFW – central lines
Isothermal – upper
Moore - lower

NFB, Dolan, Robles, arXiv: 2005.01950

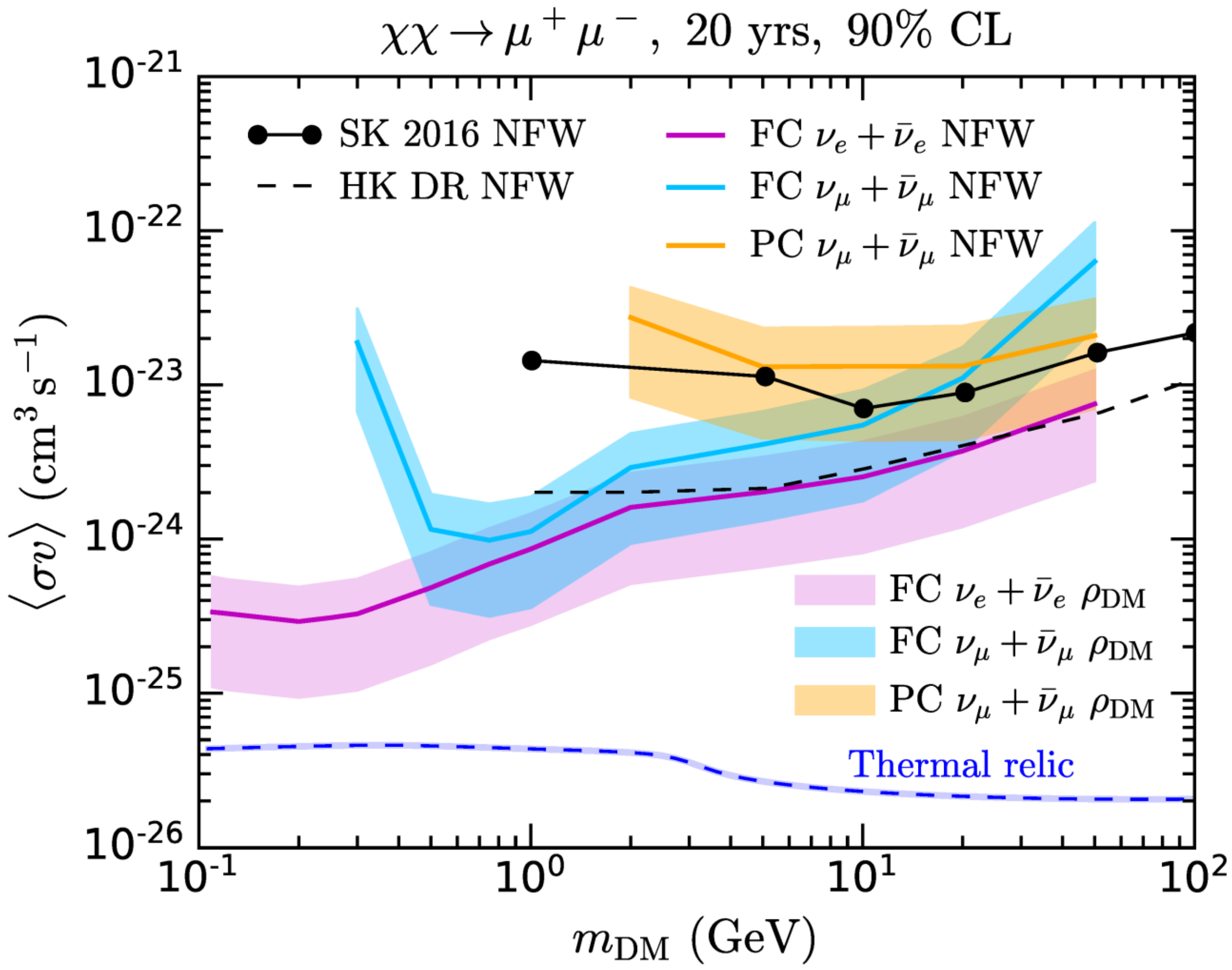
With and w/out neutron tagging



Assumes 70% tagging efficiency

NFB, Dolan, Robles, arXiv: 2005.01950

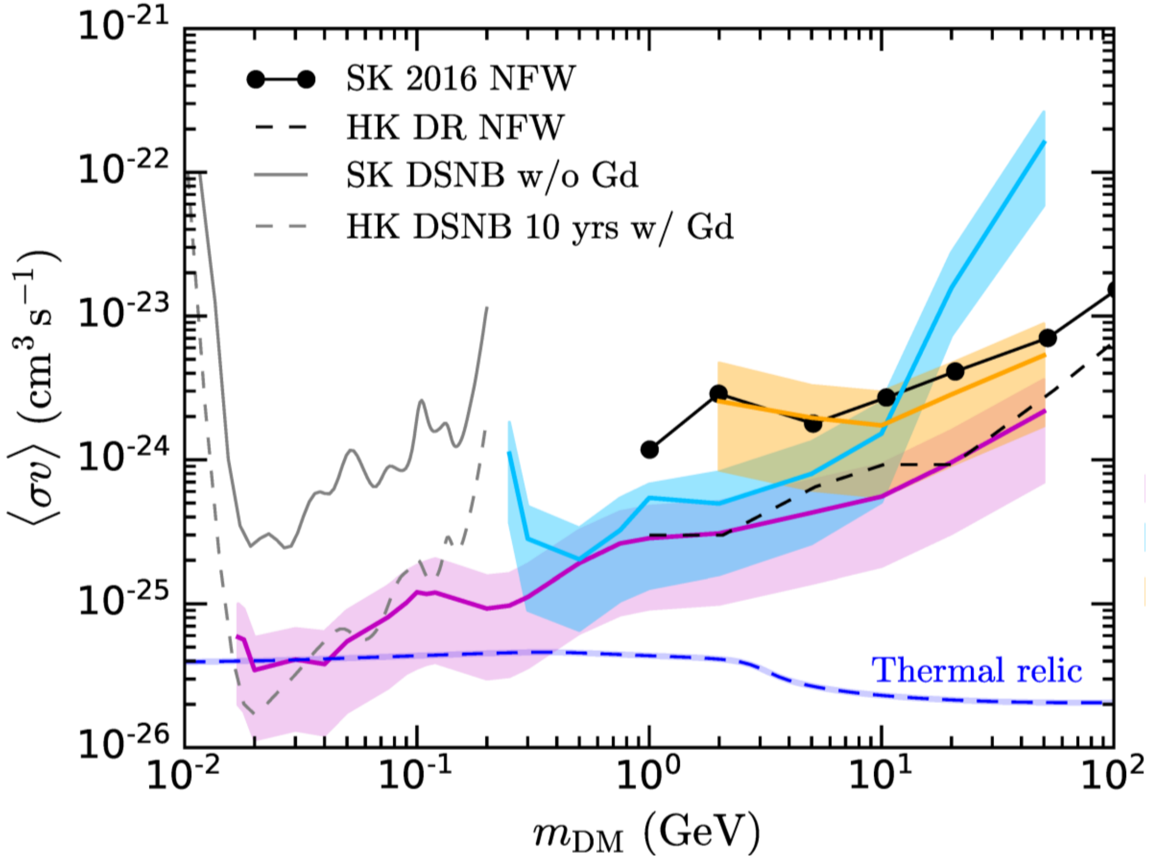
Cross section limits: $\chi\chi \rightarrow \mu^+\mu^-$



NFB, Dolan, Robles, arXiv: 2005.01950

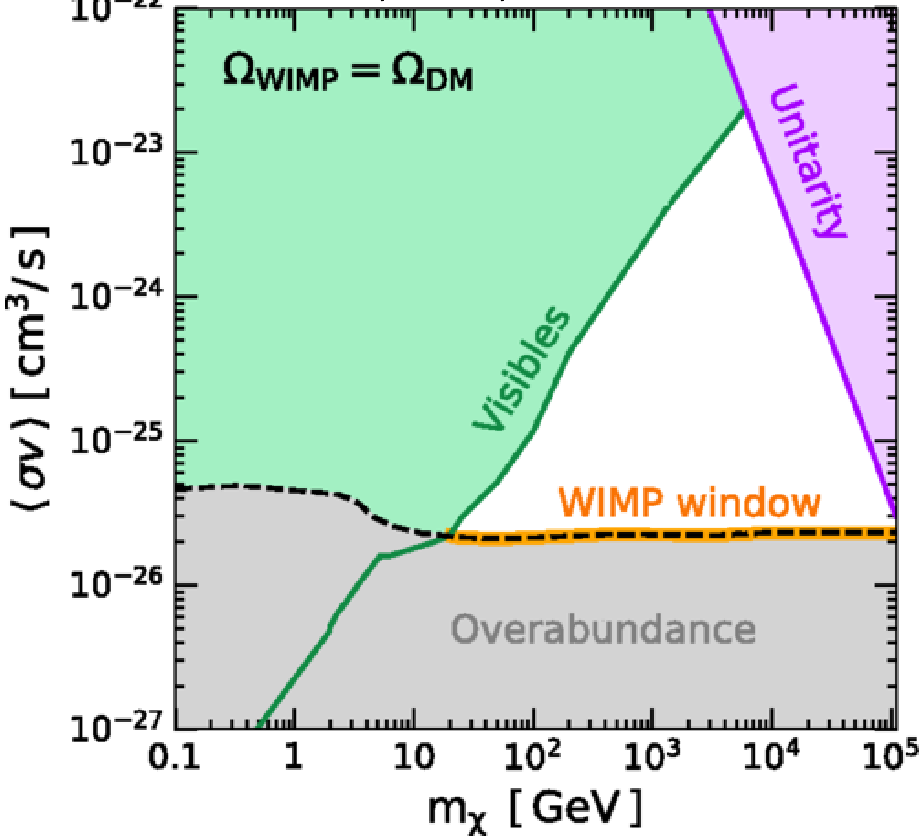
Conservative indirect detection limits

Annihilation to “invisible” SM states



Annihilation to “visible” SM states

R. Leane, et al., arXiv:1805.10305



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

Diffuse Supernova Neutrino Background

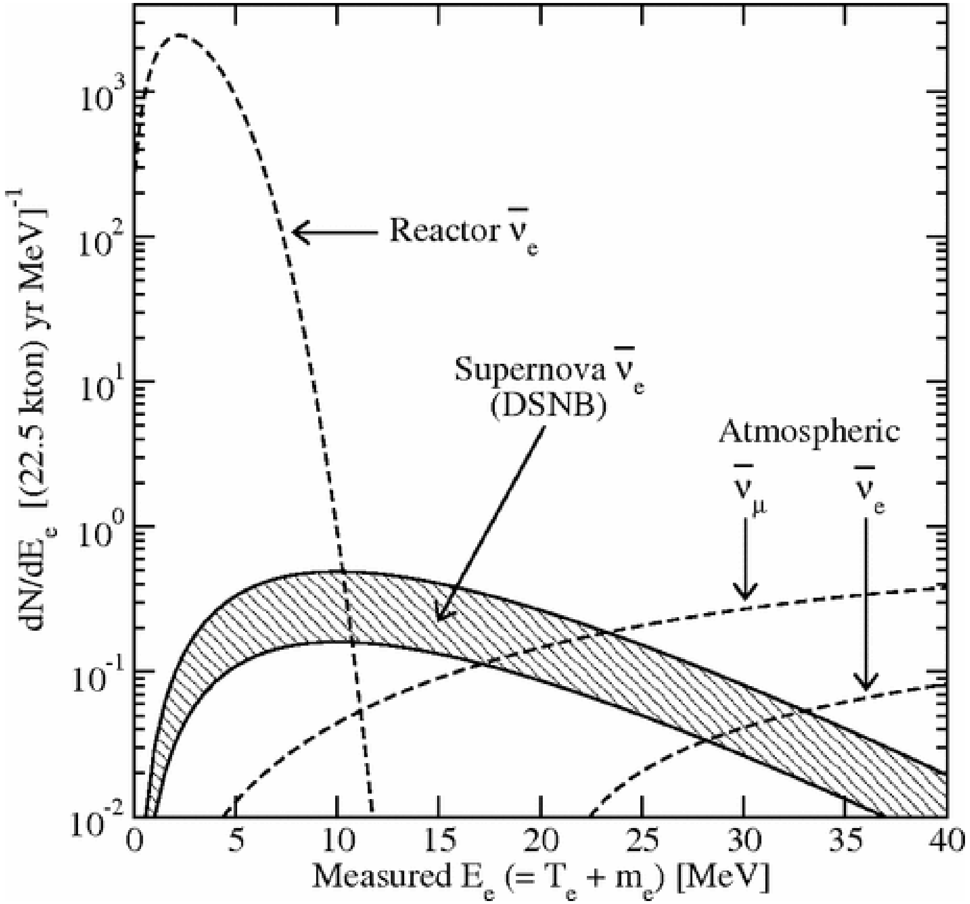
- Core collapse supernovae release gravitational binding energy in the form of neutrinos: 3×10^{53} erg

- *Approximately* equally partitioned among flavours

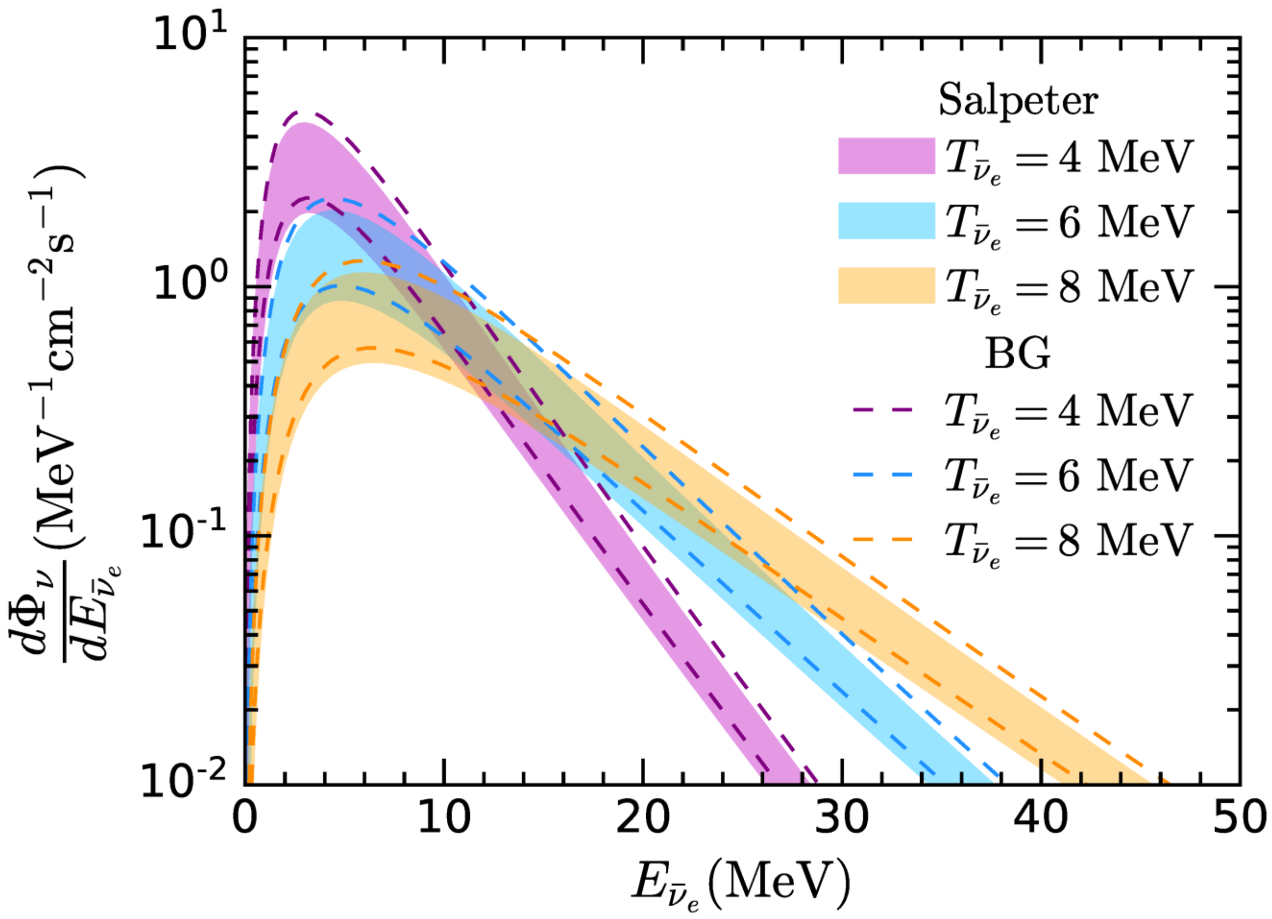
- Neutrinos diffuse out over ~ 10 seconds.
- Thermal spectra with T ~ 6 MeV

- 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.

Beacom and Vagins, Phys.Rev.Lett 2004



DSNB antineutrino spectrum



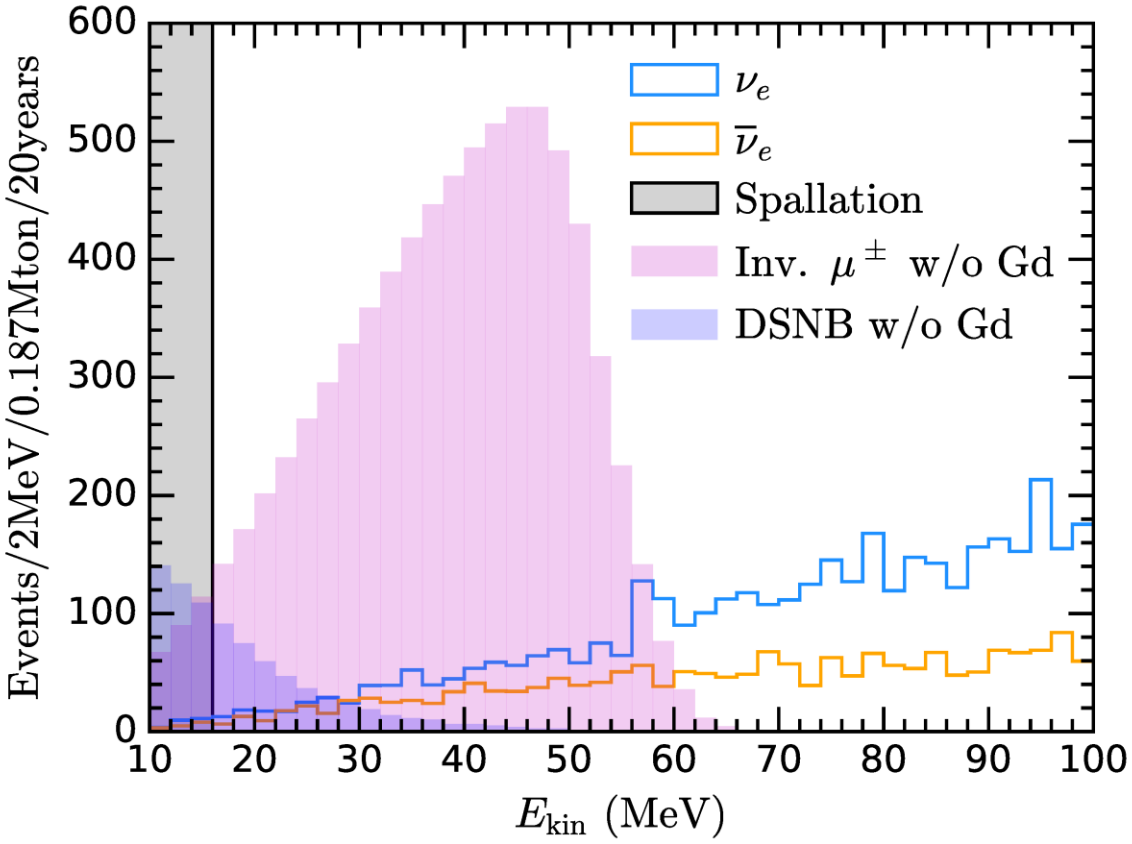
Width of bands determined by upper and lower limits on the start formation rate.

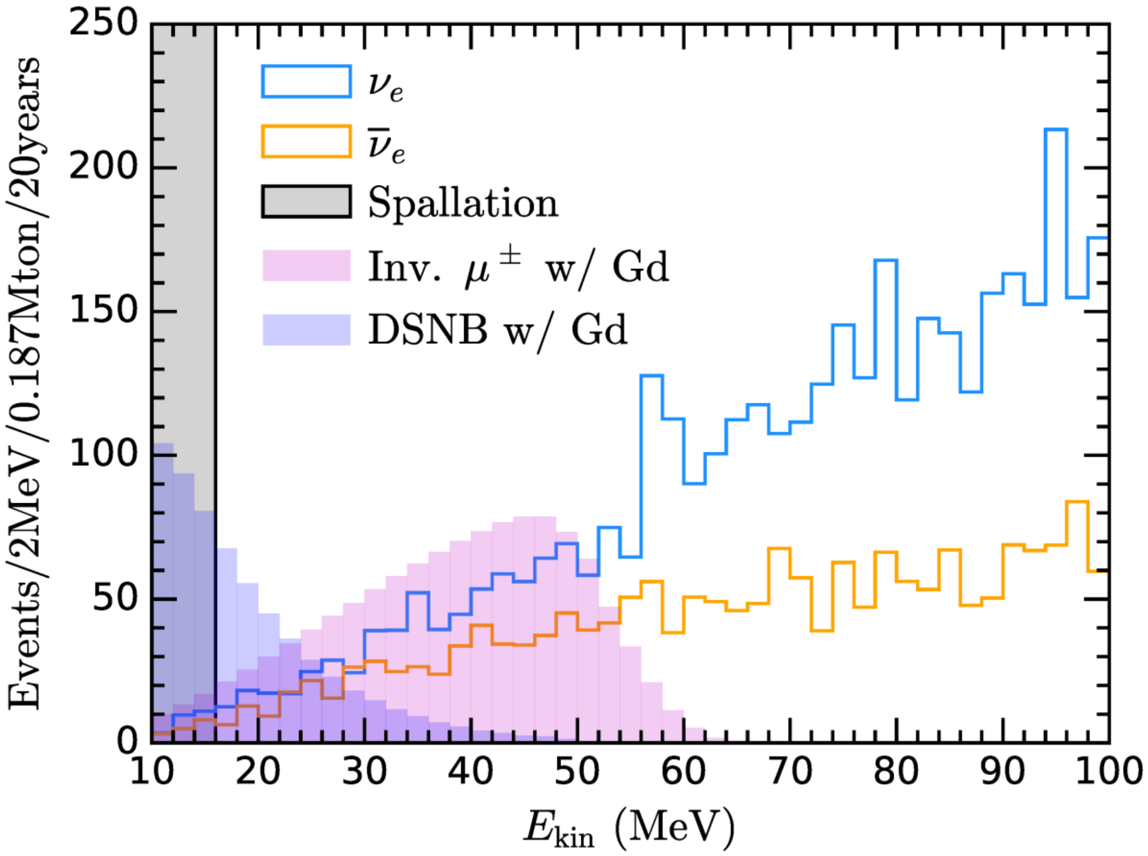
Little dependence on the choice of initial mass function (IFM), Salpeter vs Baldry-Glazebrook

NFB, Dolan, Robles, arXiv: 2205.14123

Neutron tagging

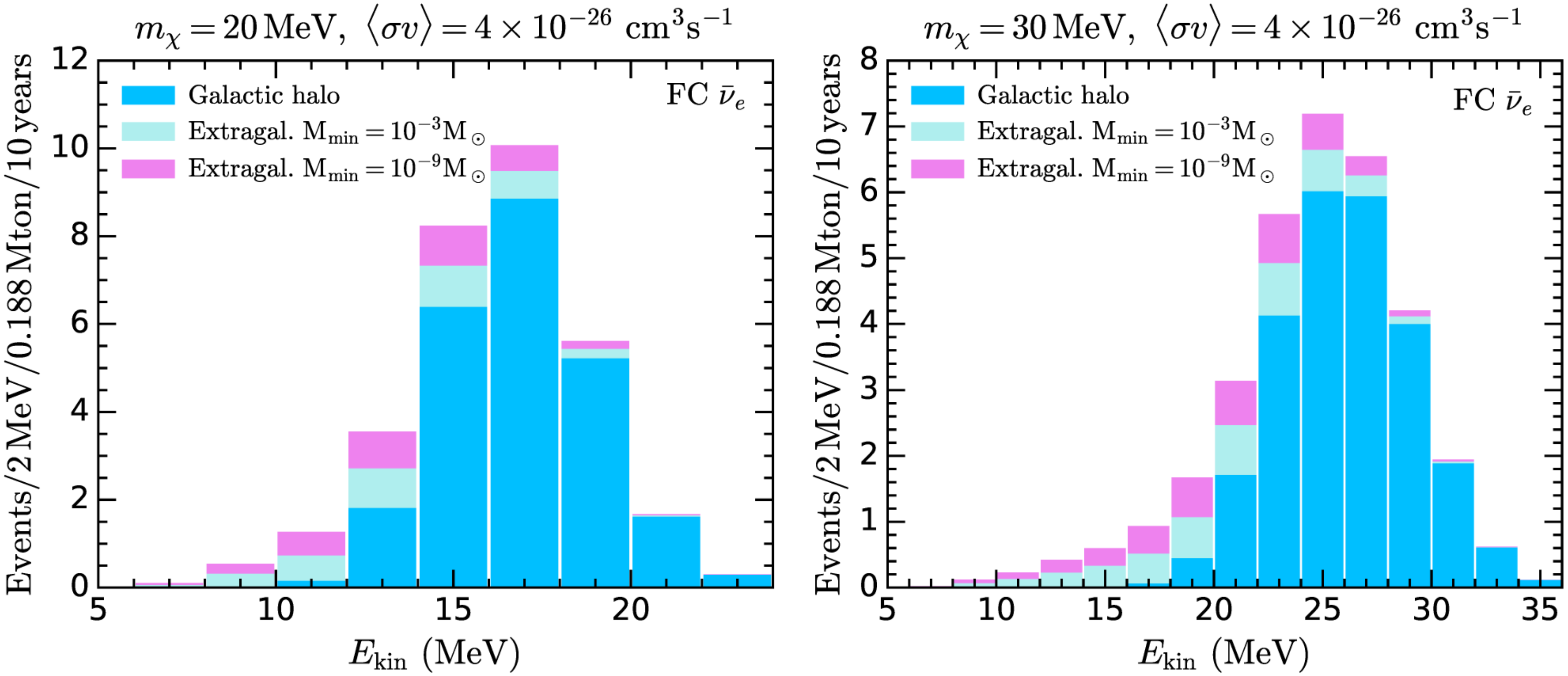
Critical for DSNB model discrimination





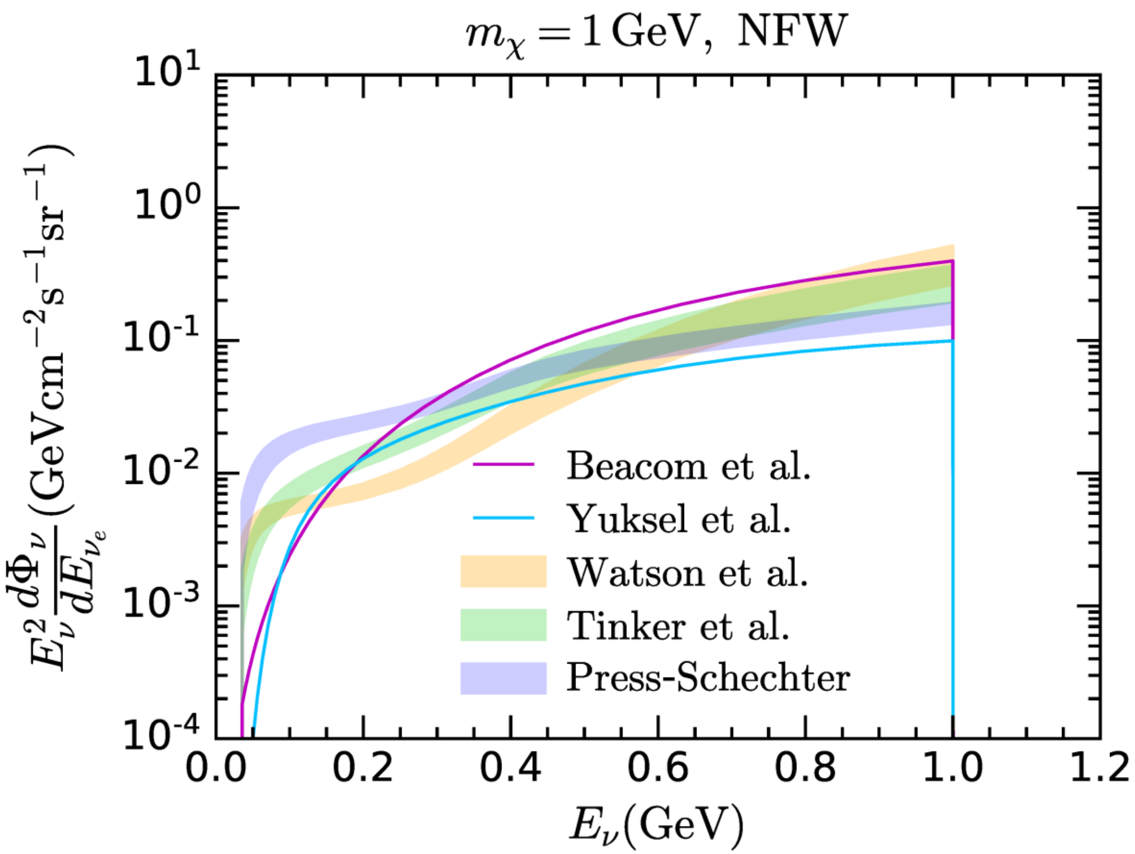
NFB, Dolan, Robles

Galactic + extragalactic DM annihilation



NFB, Dolan, Robles, arXiv: 2205.14123

Dark Matter – extra galactic flux

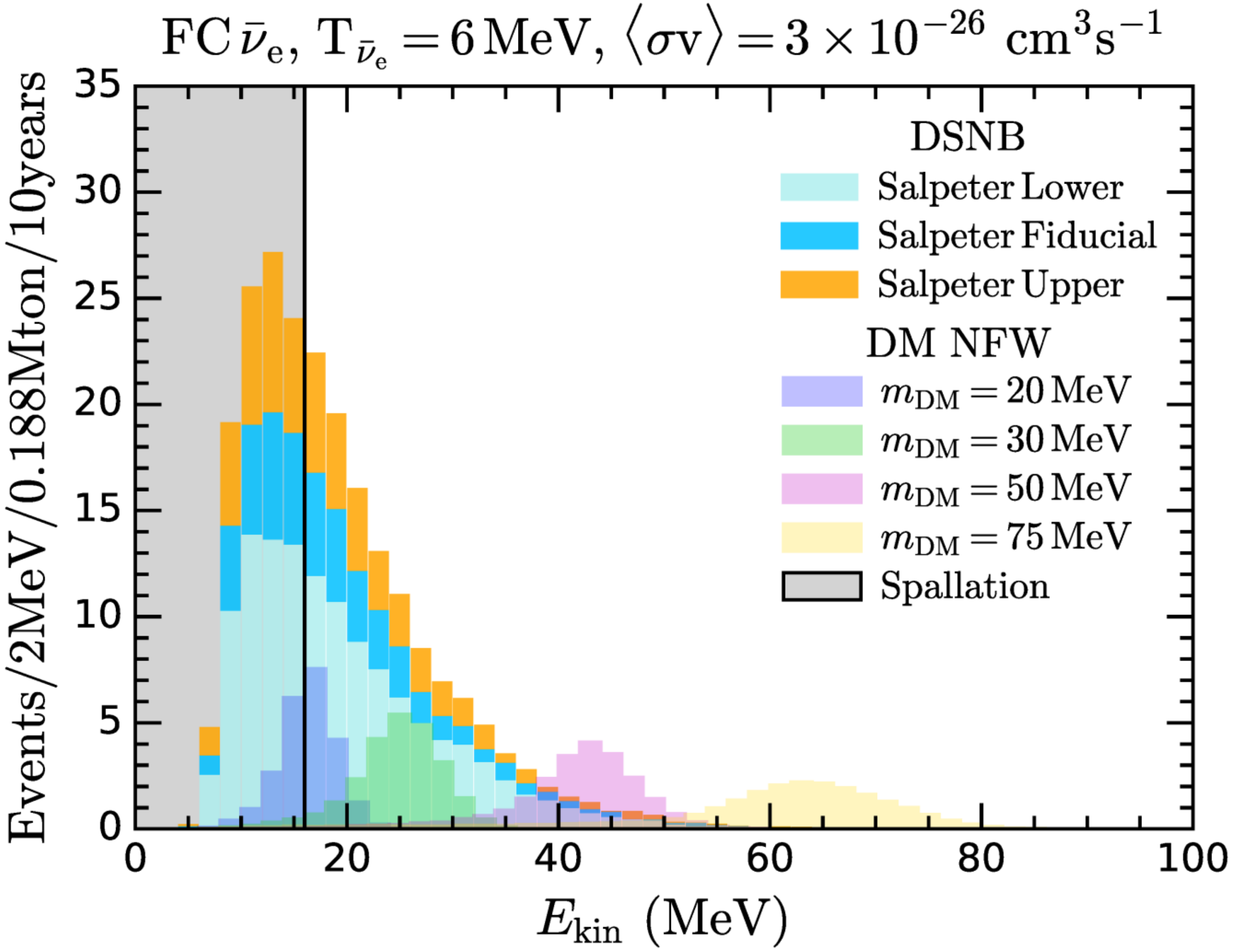


$$\frac{d\Phi_\nu}{dE_{nu}} = \frac{\langle\sigma v\rangle}{2}\frac{c}{4\pi H_0}\frac{\Omega_{DM}^2\rho_c^2}{m_{DM}^2}\int_0^{z_{up}} dz\,\frac{\Delta^2}{h(z)}\frac{dN_\nu(E_\nu')}{dE_\nu{}'}$$

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

NFB, Dolan, Robles, arXiv: 2205.14123

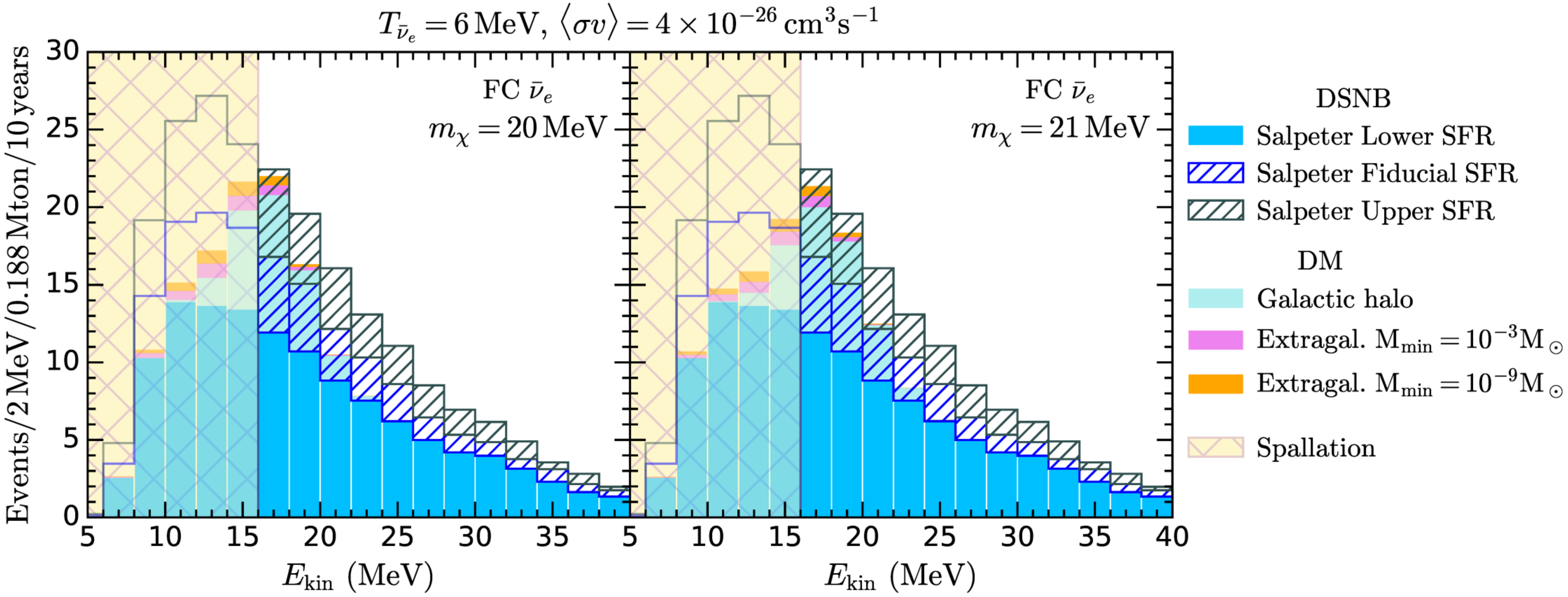
DSNB + DM



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

NFB, Dolan, Robles, arXiv: 2205.14123

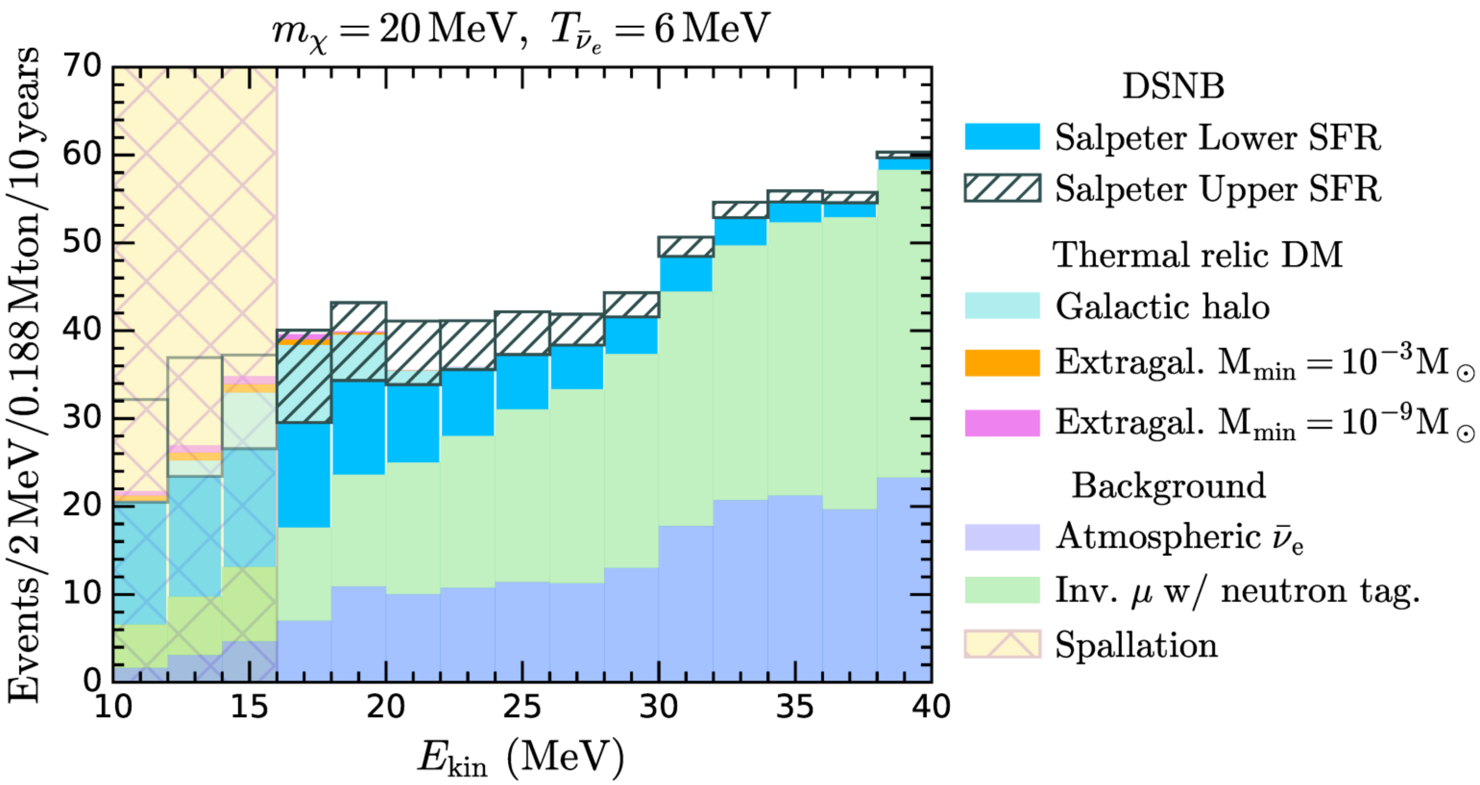
DSNB + DM



In the signal region, **High-SFR** looks like **Low-SFR + DM**

NFB, Dolan, Robles, arXiv: 2205.14123

DSNB + DM + atmospheric nu background

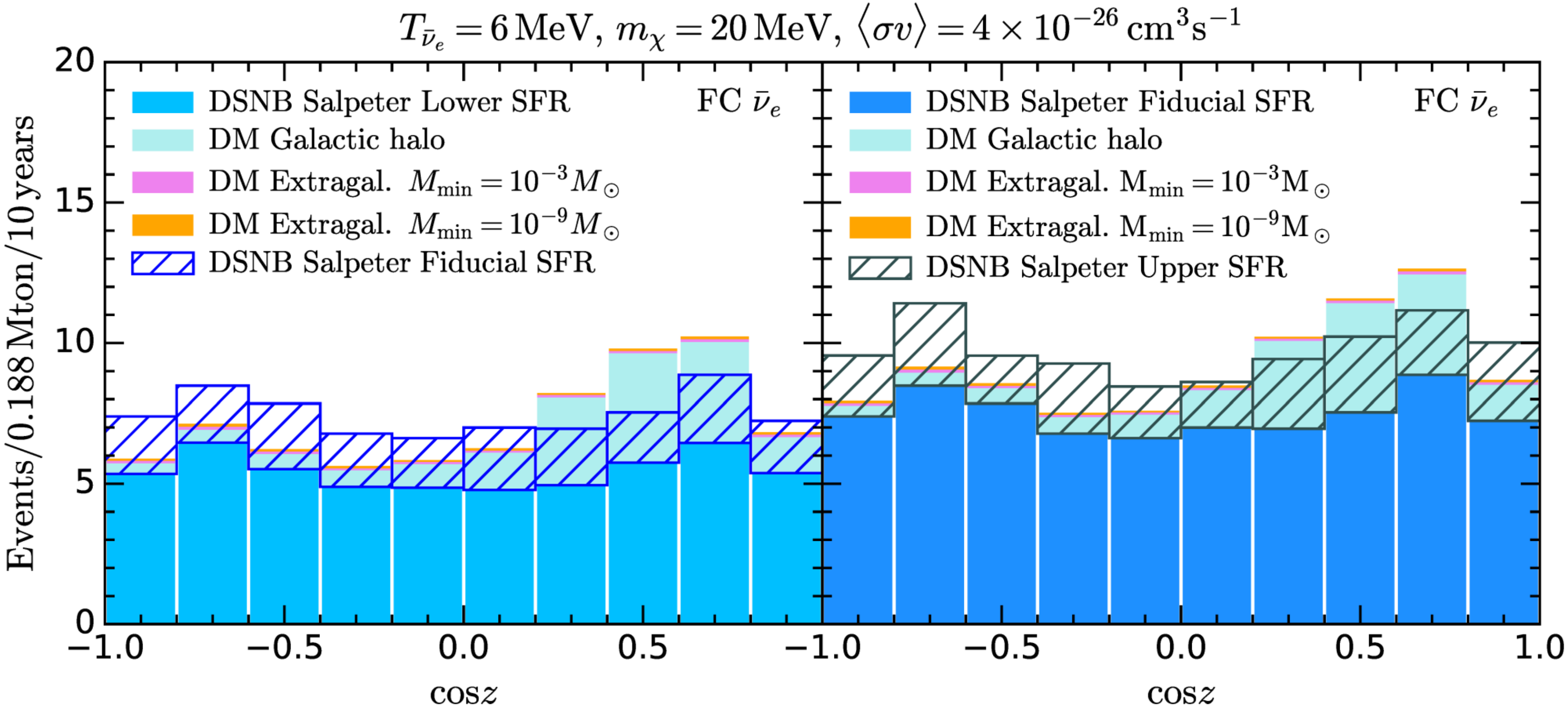


A possible DM signal makes DSNB model discrimination difficult:

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

NFB, Dolan, Robles, arXiv: 2205.14123

Angular dependence

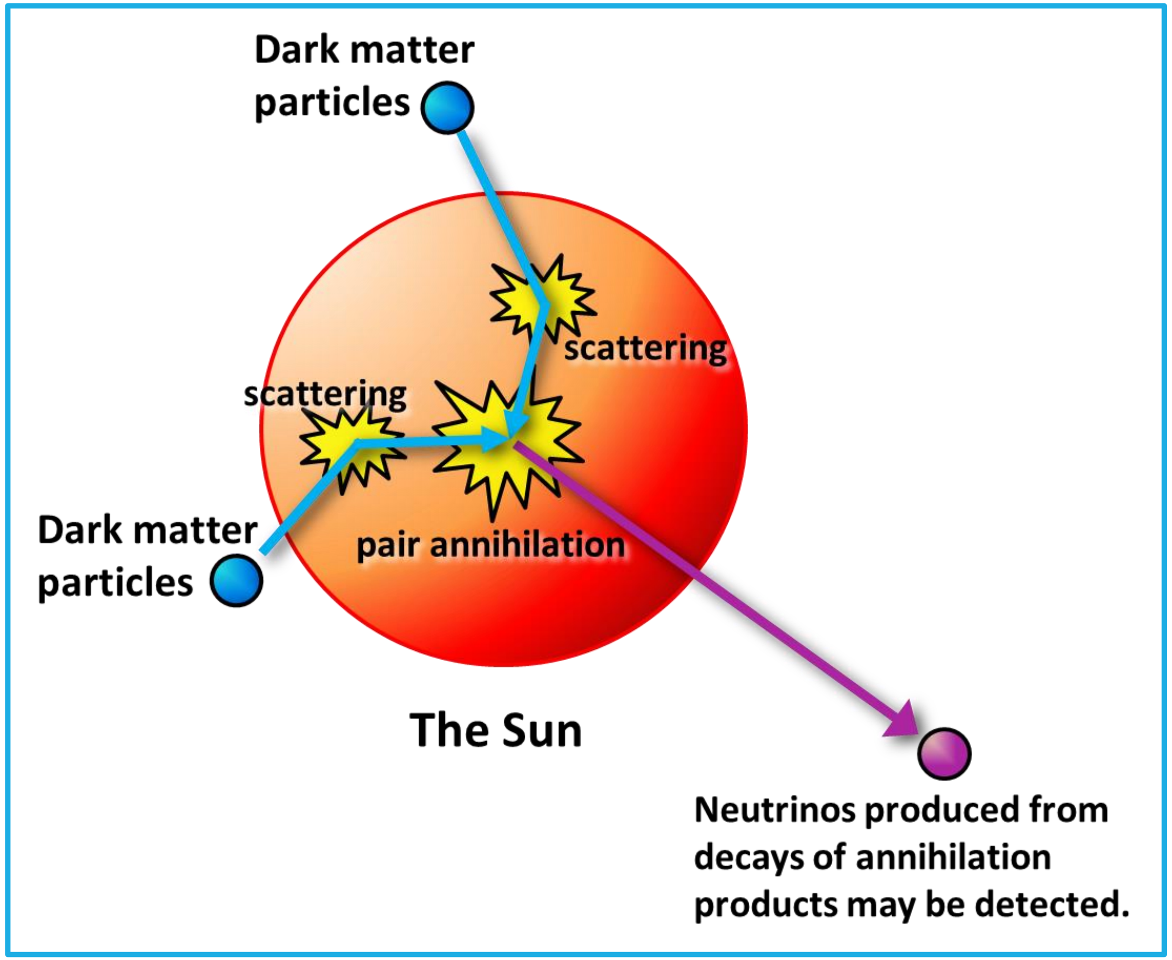


NFB, Dolan, Robles, arXiv: 2205.14123

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

Capture, annihilation, evaporation

DM number density depends on Capture, Annihilation & Evaporation rates:

$$\frac{dN_\chi}{dt} = C - AN_\chi^2 - EN_\chi$$

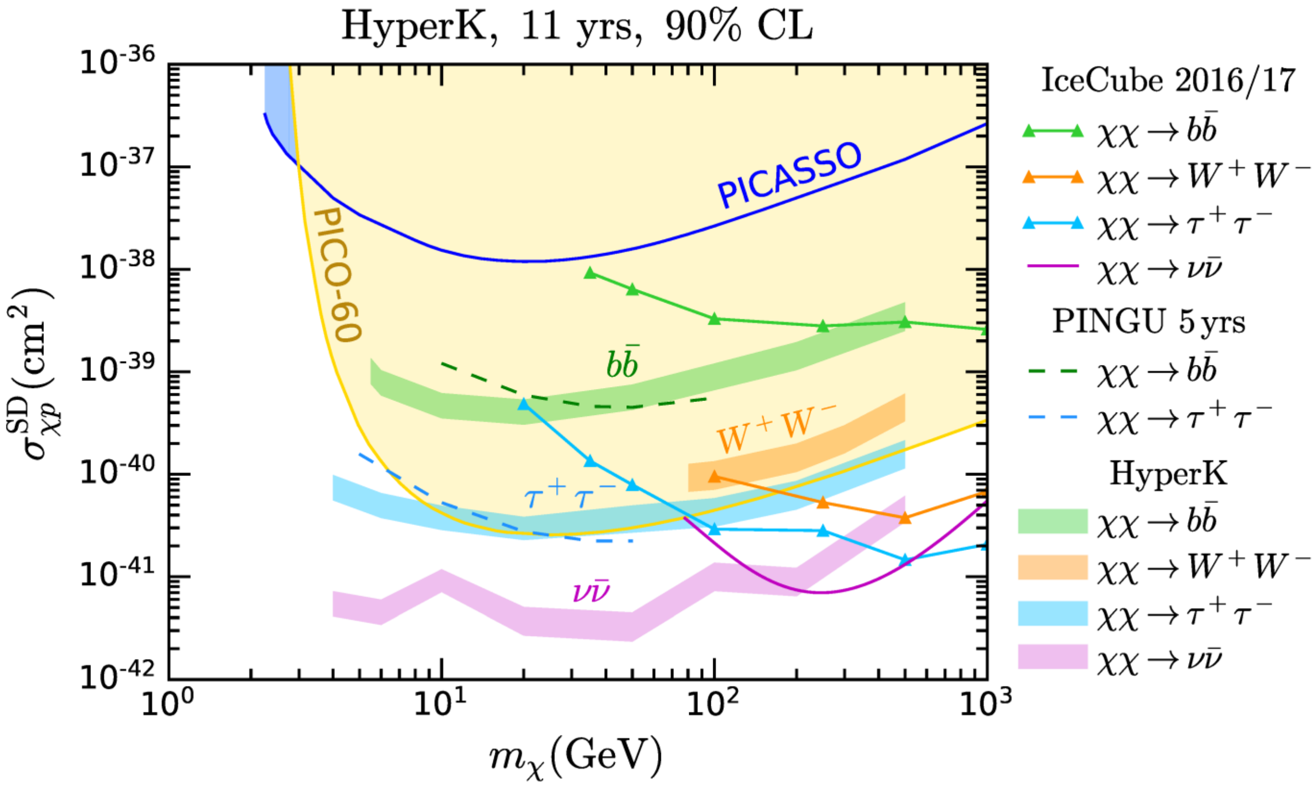
Neglecting evaporation (negligible in the Sun for $m_\chi > 4$ GeV) we have

→ $N_\chi(t) = \sqrt{\frac{C}{A}} \tanh\left(\frac{t}{\tau_{eq}}\right)$ where $\tau_{eq} = 1/\sqrt{CA}$

Capture-annihilation equilibrium when $t \gg \tau_{eq}$: $\Gamma_{ann} = \frac{1}{2}AN_\chi^2 = \frac{1}{2}C$

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.

NFB, Dolan & Robles, arXiv:2107.04216

Summary

- Indirect detection limits on DM annihilation to neutrinos
  - Hyper-K will probe thermal-relic cross section for $m_{\mathrm{DM}} \lesssim 30$ 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. Angular dependence will help.

- DM annihilation to neutrinos in the Sun
  - For SD scattering, solar WIMP searches currently beat direct detection for certain masses. But the direct detection searches will eventually win.