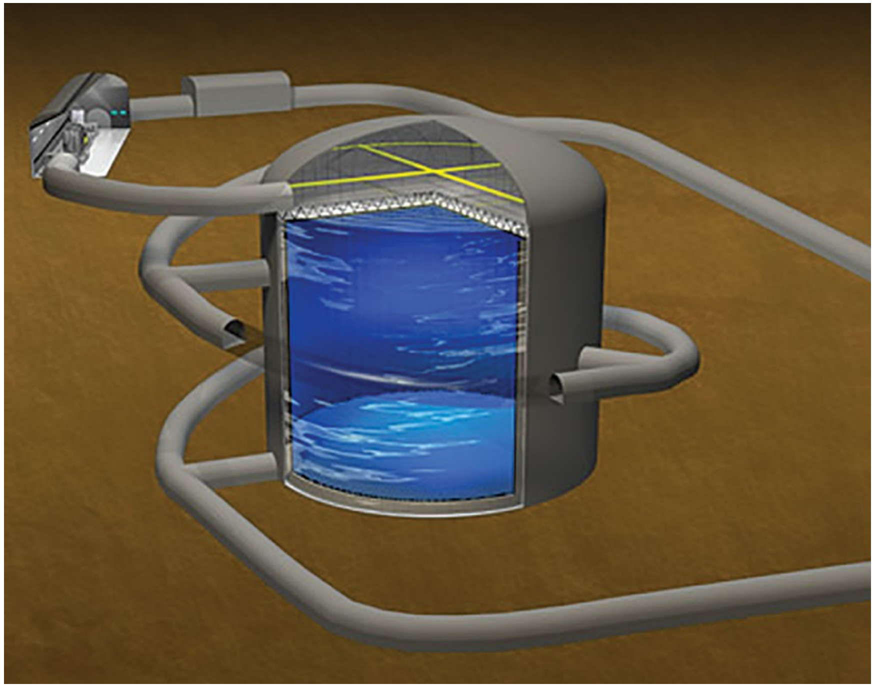
Dark Matter Searches at Hyper-Kamiokande

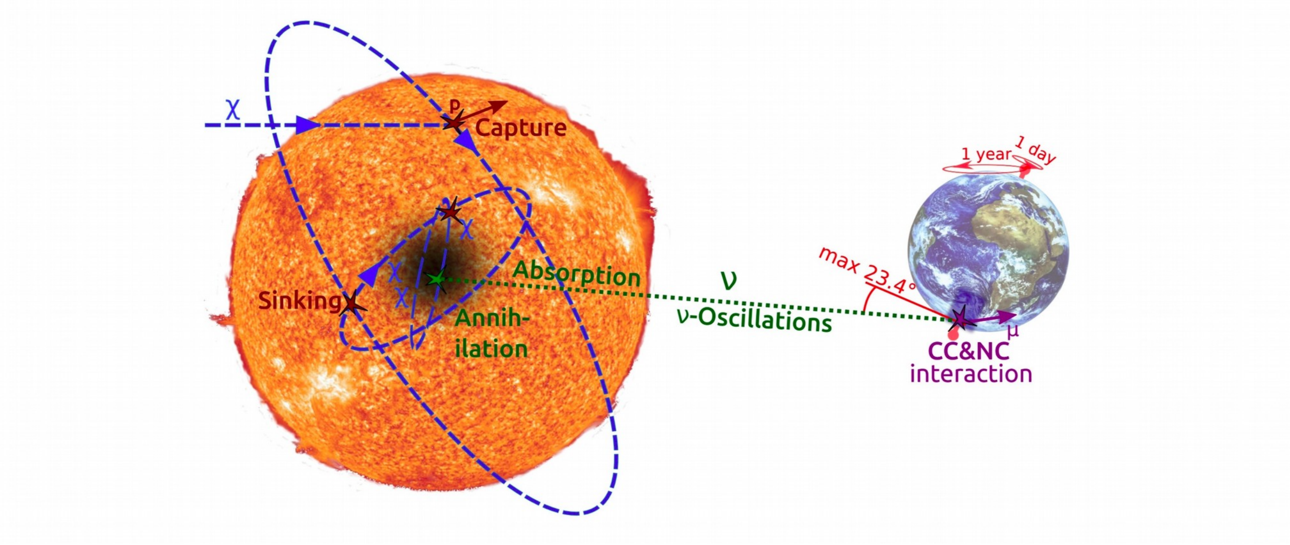


Matthew Dolan
University of Melbourne
Centre of Excellence for Dark Matter Particle Physics

Based on Nicole Bell, MJD, Sandra Robles
2005.01950 (JCAP), 2107.04216 (JCAP) and 2205.14123

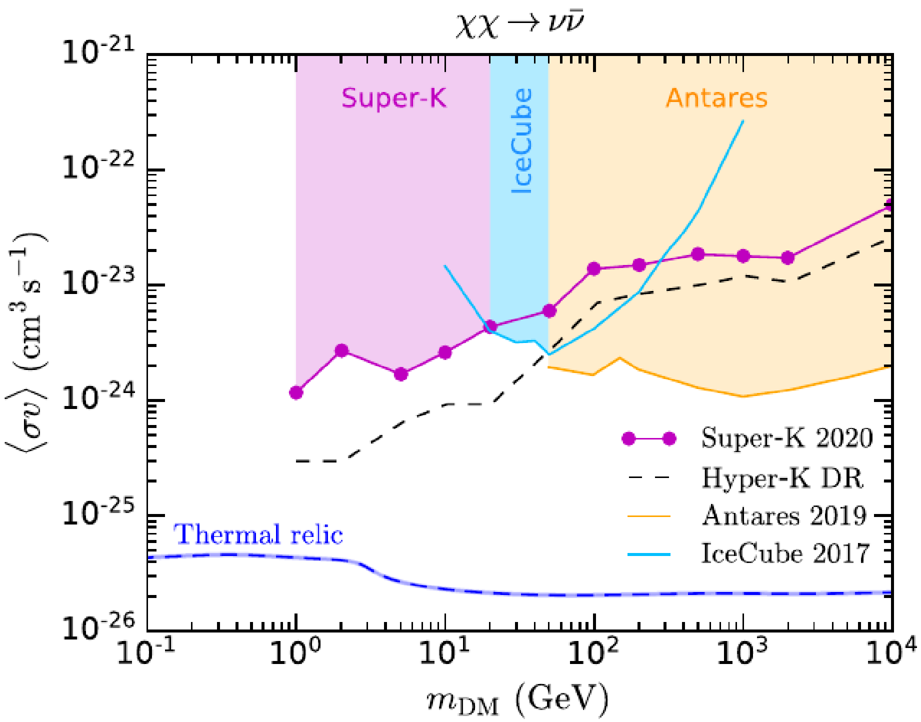
Introduction

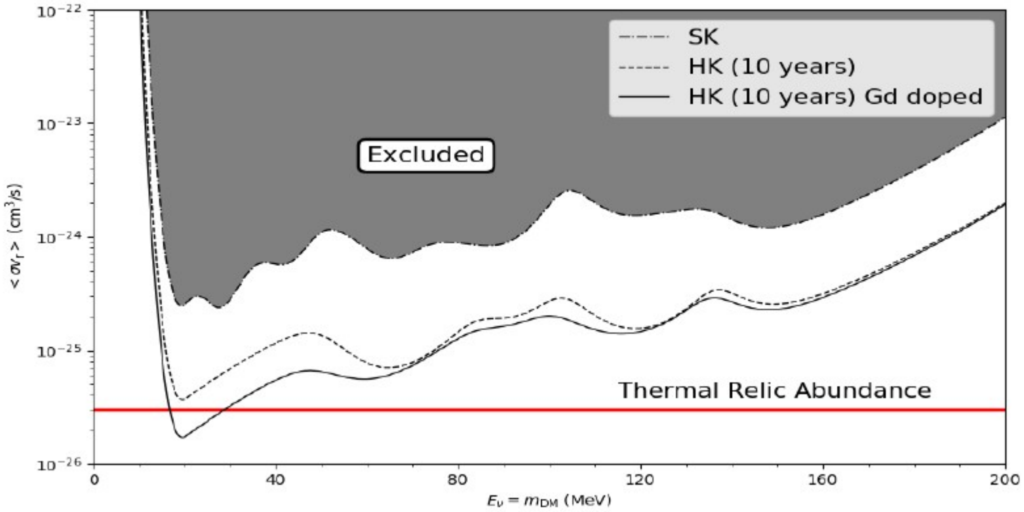
- Large-scale neutrino experiments are sensitive to (annihilating) dark matter: Galactic Centre, Sun, Earth, boosted DM…
- This talk: Hyper-Kamiokande
- Projections for GC and Sun searches, low DM masses, interplay with Diffuse Supernova Neutrino Background.



Current state-of-play: Galactic Centre

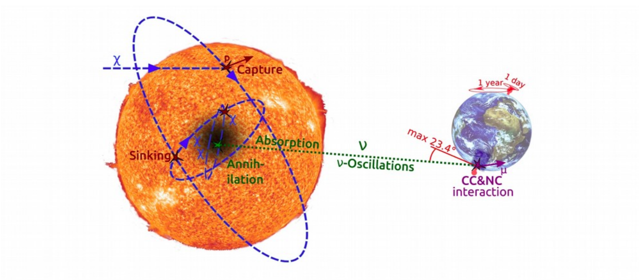
- Dark matter from the Galactic Centre





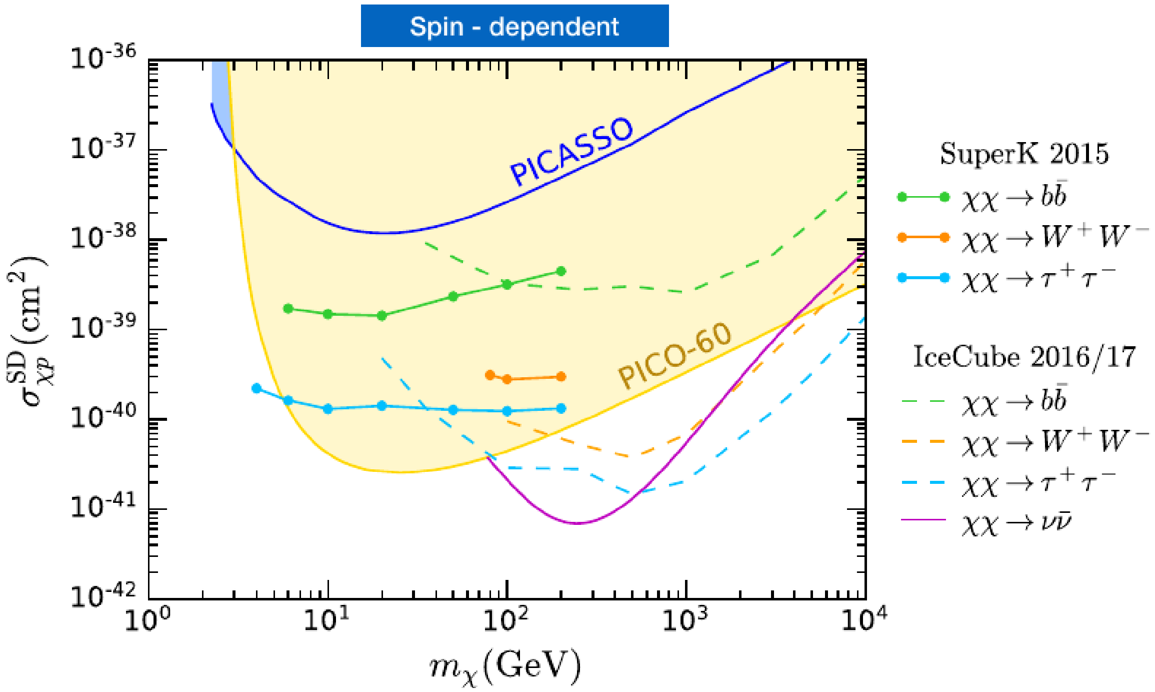
Reinterpret SuperK DSNB search as limit on DM
Rescale to HK

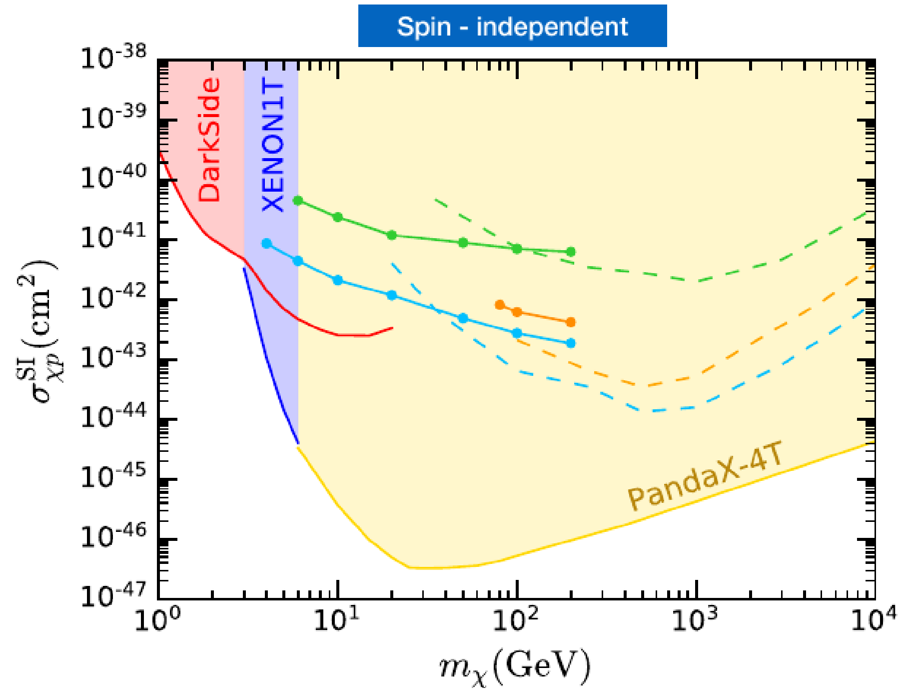
Del Campo et al, 1805.09830, 1711.05283
Palomares-Ruiz, Pascoli 0710.5420



State-of-play: Sun

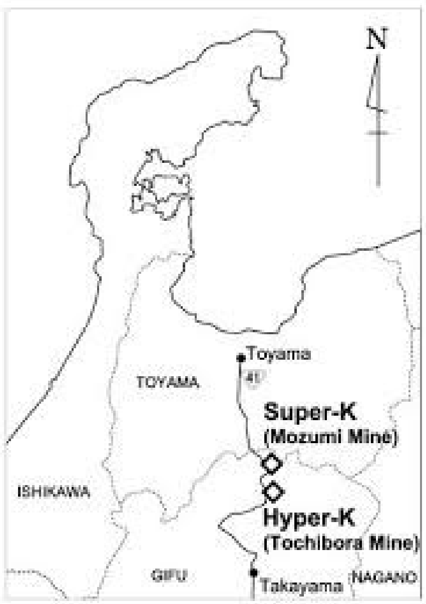
- Dark matter annihilating in the Sun



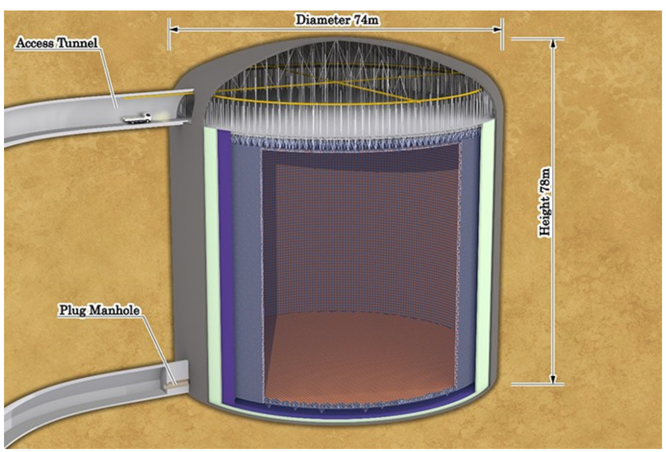


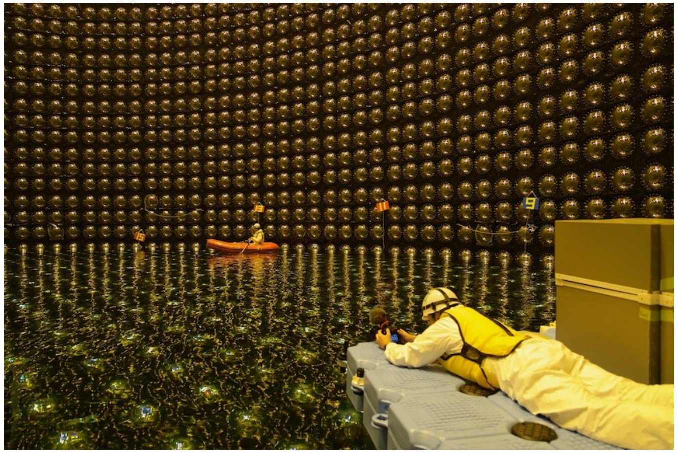
Sensitive/competitive primarily to spin-dependent nucleon scattering

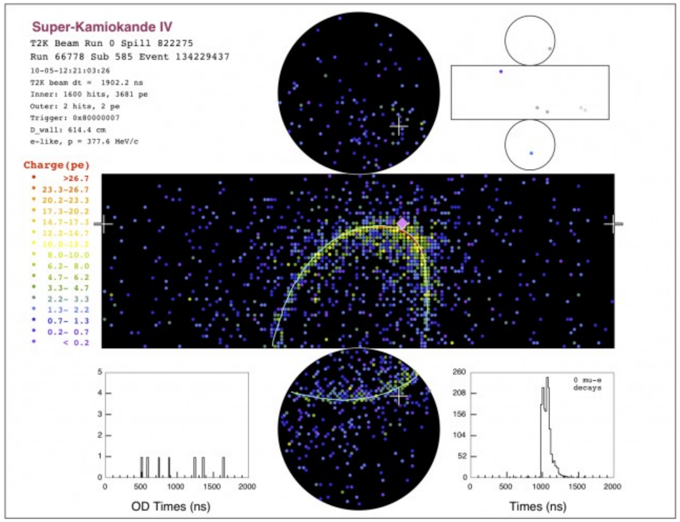
The Hyper-Kamiokande Experiment



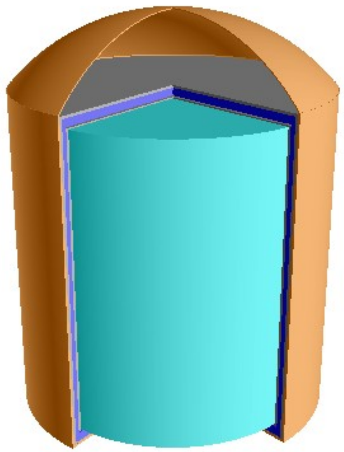
- Kamiokande → SuperKamiokande → HyperKamiokande
- Large-scale water Cherenkov detector
- 187kt fiducial volume – 8x SuperK
- Tochibora mine (600m), shallower site than Mozumi mine (1000m)
- Under construction, commencing 2027.
- Design report: 1805.04163





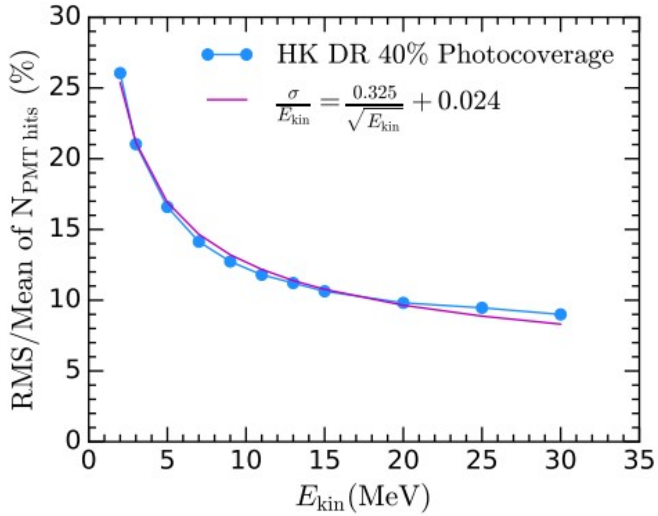


Simulation and Validation

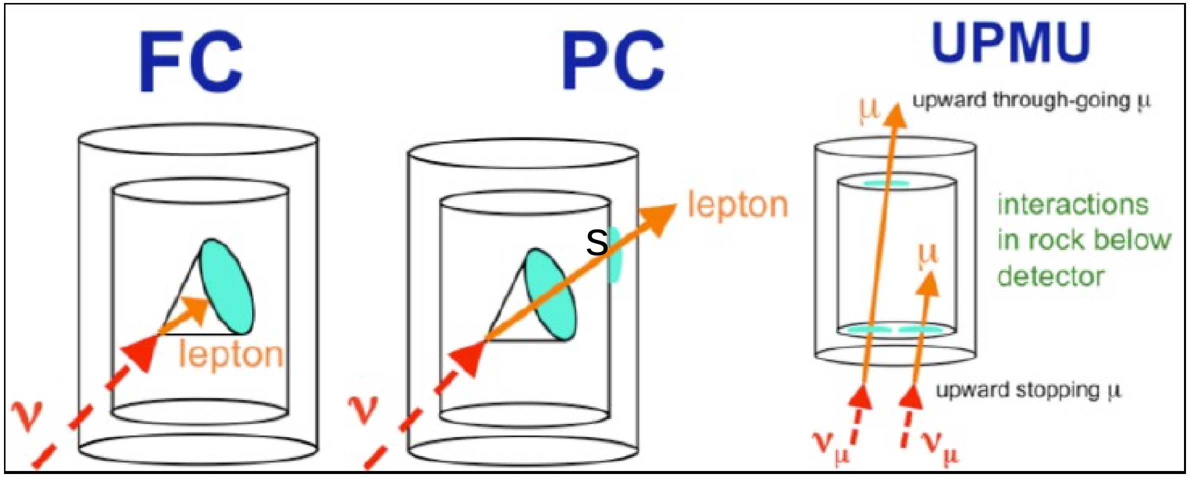


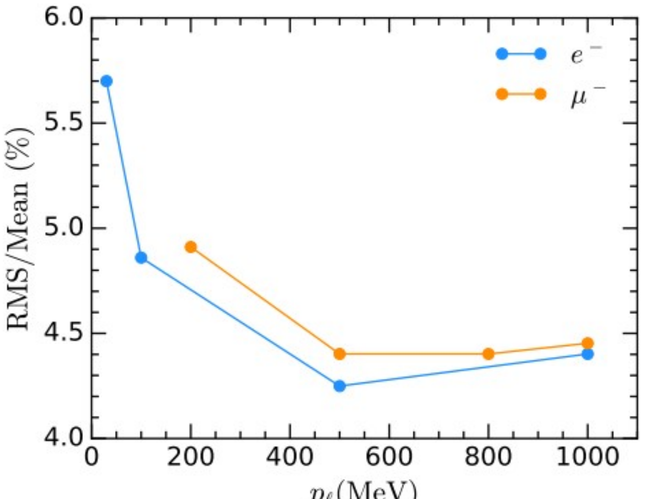
SuperK: 39m X 42m
HyperK: 68m x 71m

Smearing and resolution
from Design Report



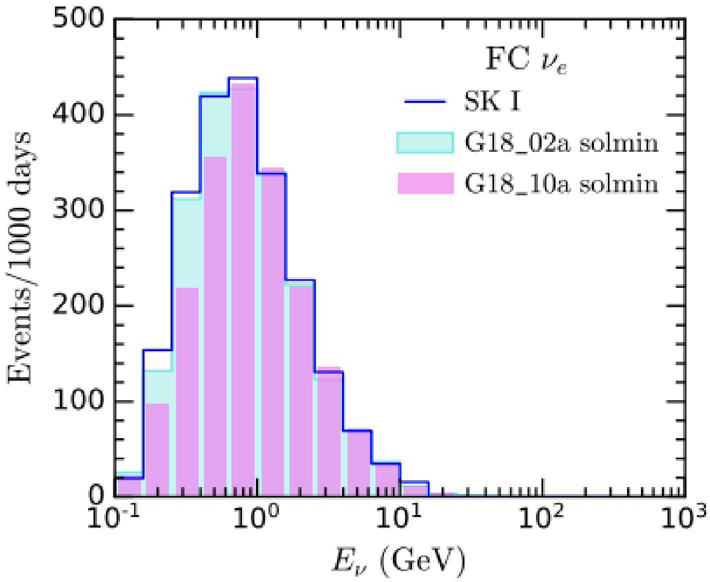
- In-house detector simulation (ROOT) and event generation (GENIE)
  - Distinguish electron and muons, but not charge
  - Fully Contained (FC) and Partially Contained (PC)
- Upward-going muons (UpMu): Through-going and Stopping

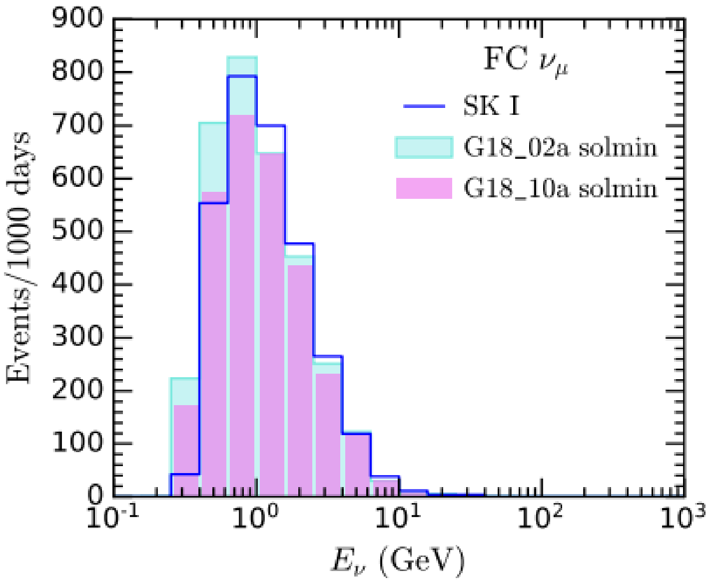


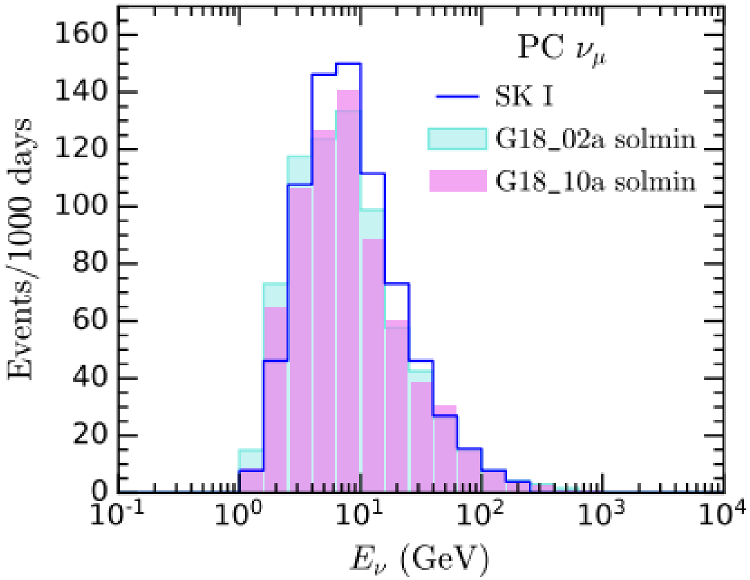


Simulation and Validation

- Use HKMM11 and FLUKA atmospheric neutrino fluxes
- Fully and Partially Contained
- Simulation validated against SKI atmospheric neutrino measurements
- Dependence on generator tune



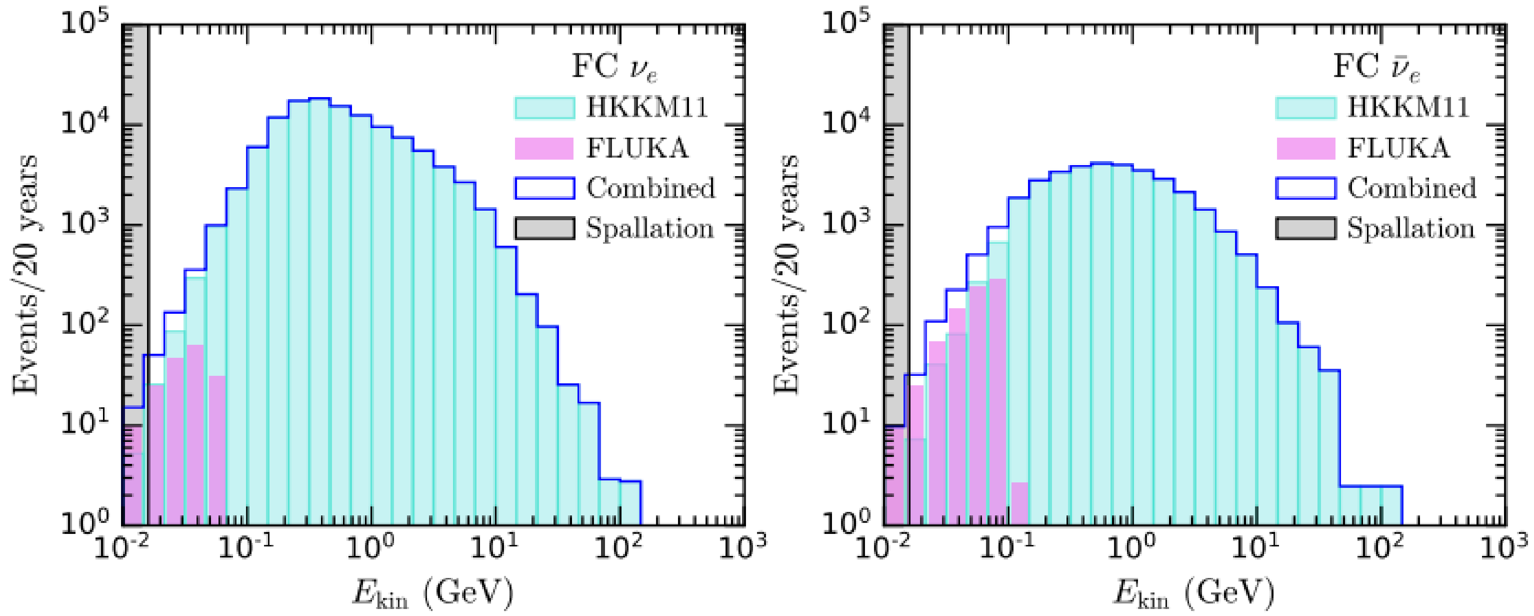




SKI: hep-ex/0501064

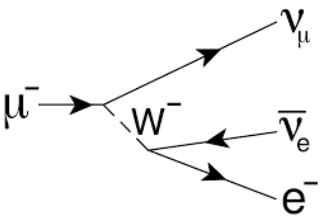
Simulation and Validation

- Scale up SK simulation to HK parameters from Design Report
- Include neutrino oscillations for Normal Hierarchy and PREM Earth model.
- Predictions for atmospheric neutrino fluxes (i.e. backgrounds) at HyperKamiokande.

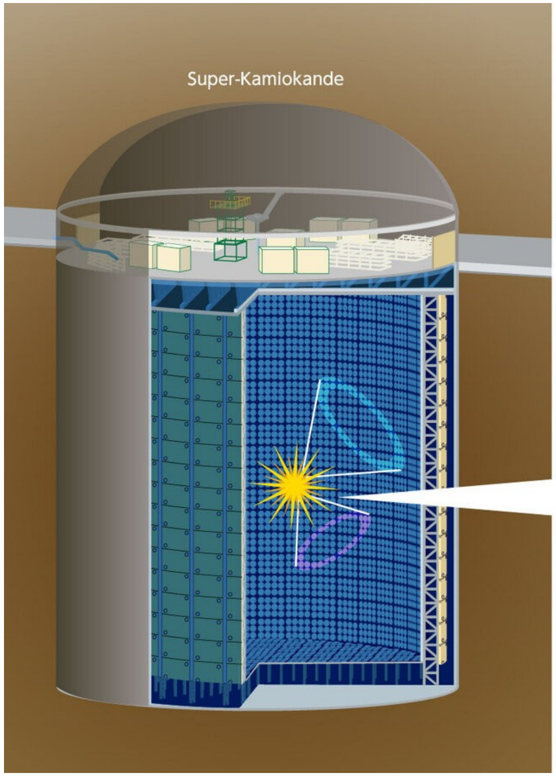


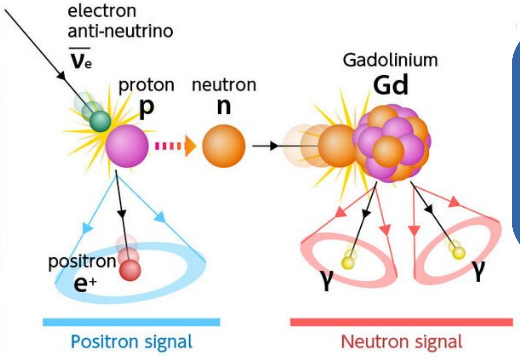
Low Energy: Invisible Muons and DSNB

- Low energies: muon decay below Cherenkov threshold
- Michel spectrum for resulting electrons: “invisible muons”



- Diffuse Supernova Neutrino Background: all neutrinos that have been emitted by core-collapse supernovae.
- Inverse-beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$



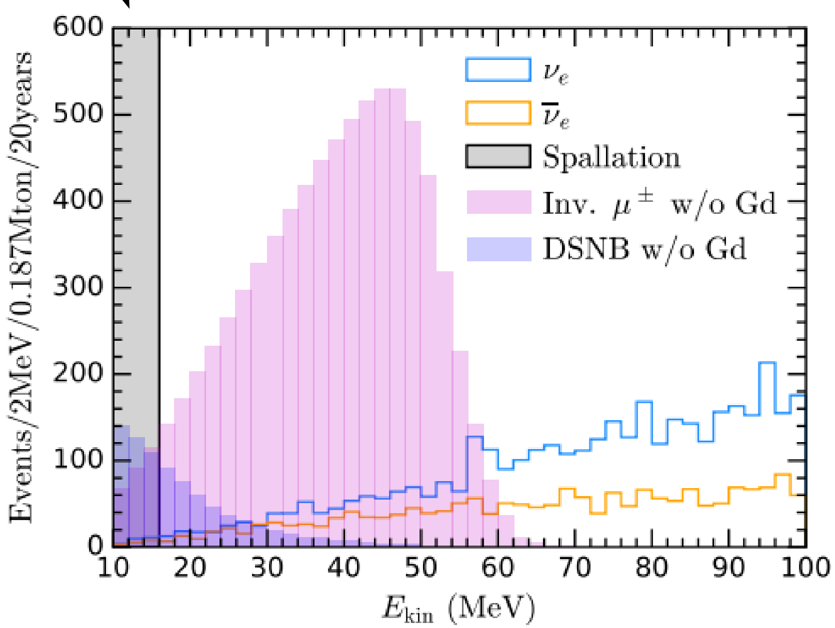


- Neutron-tagging allows suppression of invisible muon and spallation backgrounds
- Hydrogen capture: $n + p \rightarrow d + \gamma(2.2\ \mathrm{MeV})$
- Gadolinium doping (in progress at SK)

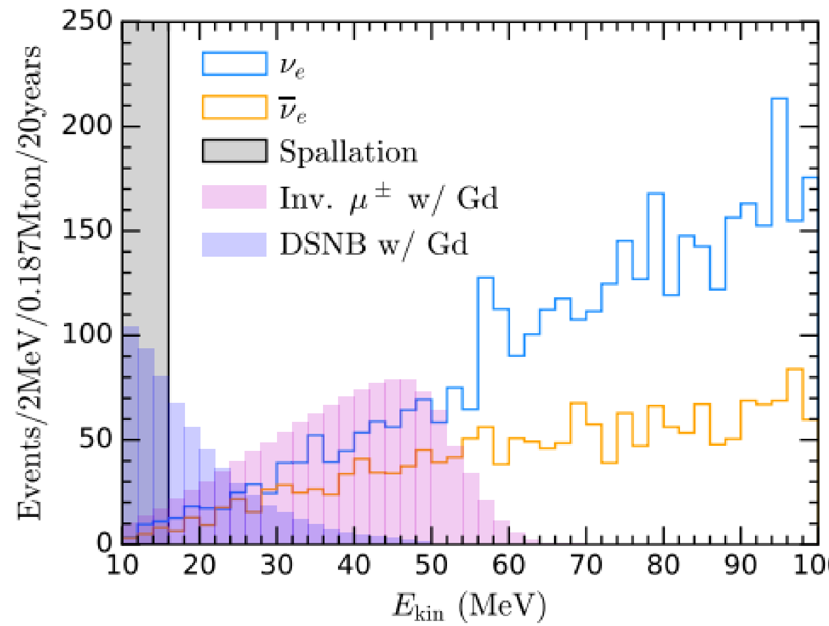
HyperK: Low Energy backgrounds

Below 16 MeV: spallation dominated

Without neutron tagging



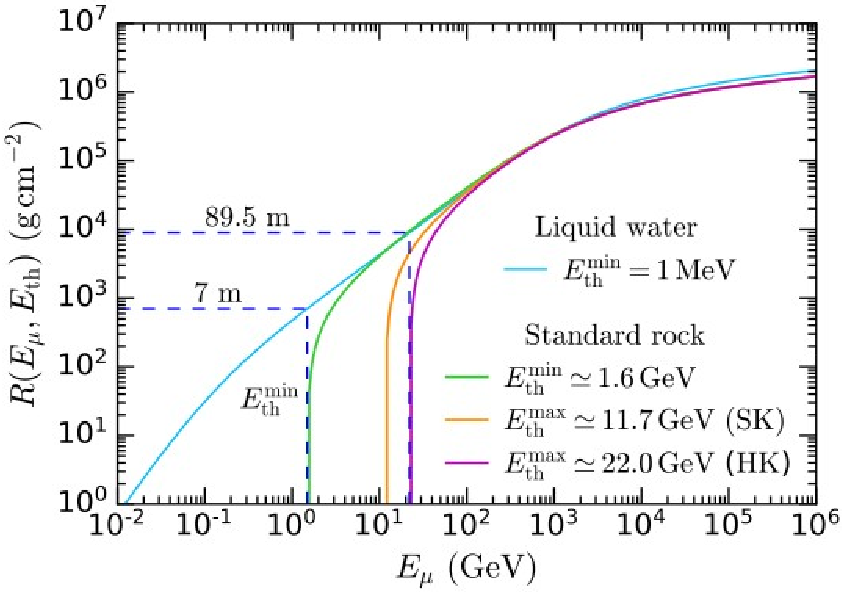
With neutron tagging



Invisible muons and DSNB backgrounds taken from HyperK Design Report.
Atmospheric neutrinos from simulations.

Simulation and Validation

- Upward-going muons: $\nu_\mu + N \to \mu + N'$
- From neutrino interactions with surrounding rock.
- Can be through-going or stopping.
- Minimum 7m path-length in ID: min 1.6 GeV energy (SK)



$$P(E_\nu, E_{th}) = N_A \int_0^{1-E_{th}/E_\nu} \int_0^1 \frac{d^2\sigma_\nu}{dxdy} R(E_\mu, E_{th}) dx\, dy,$$

Probability for neutrino with energy E_ν to produce muon that reaches detector with energy above threshold

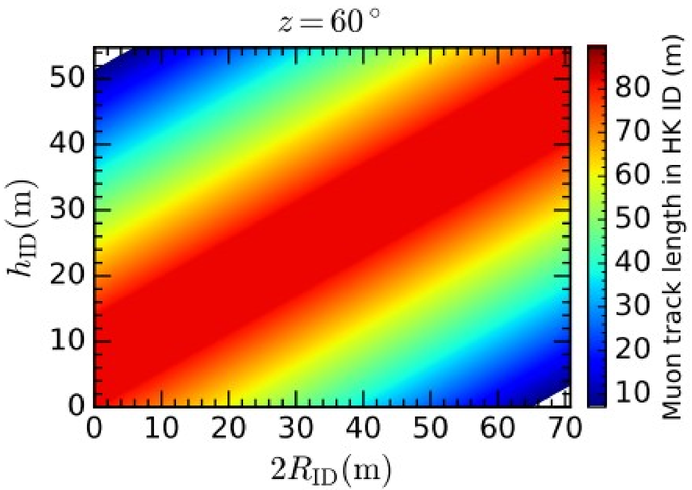
Differential cross-section

Distance travelled by muon before reaching threshold energy

Honda, Mori 1987

Simulation and Validation

- Upward-going muons: $\nu_\mu + N \to \mu + N'$
- From neutrino interactions with surrounding rock.
- Can be through-going or stopping.
- Minimum 7m path-length in ID: min 1.6 GeV energy (SK)



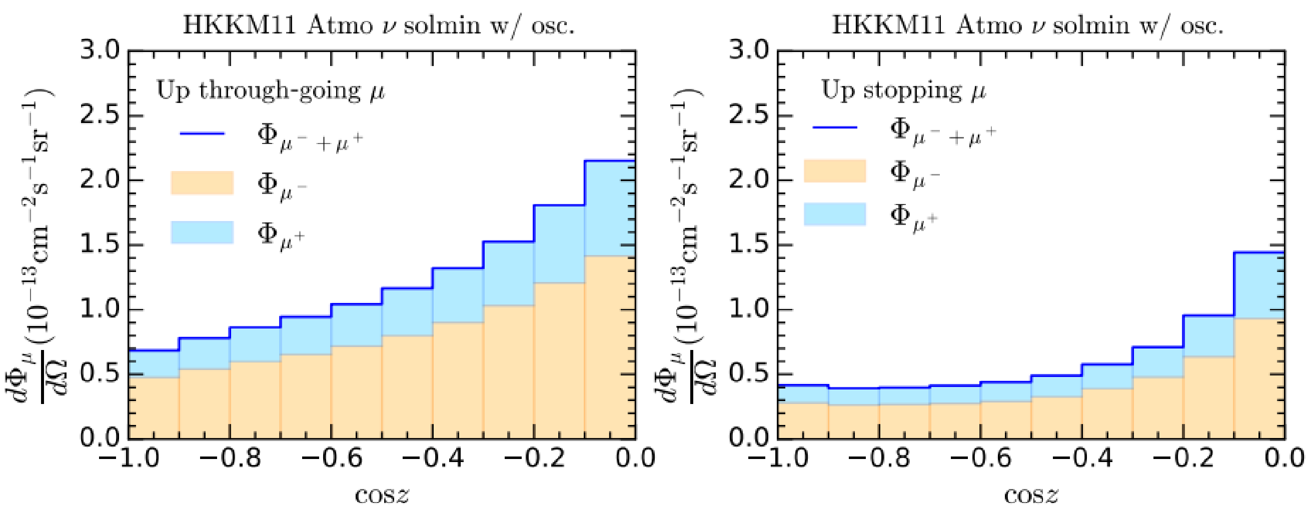
$$\frac{d\Phi_\mu(E_{\rm th}, \cos z)}{d\Omega} = \int_{E_{\rm th}}^{\infty} dE_\nu \, P(E_\nu, E_{\rm th}) \frac{d^2\Phi_\nu(E_\nu, \cos z)}{dE_\nu d\Omega}.$$

Average over all muon path lengths:

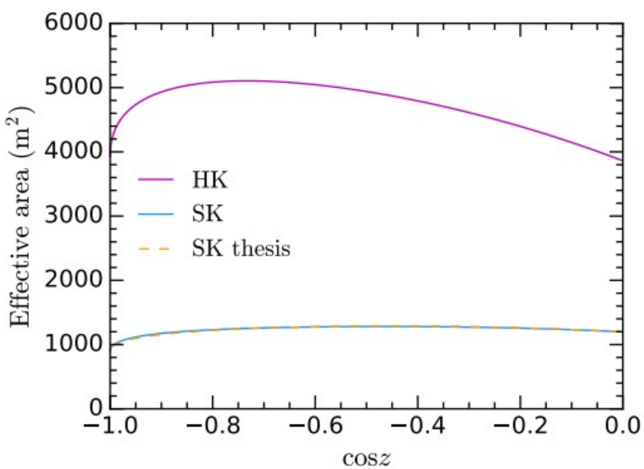
$$\frac{d\Phi_\mu(\cos z)}{d\Omega} = \frac{\sum_i \frac{d\Phi_\mu(E_{\rm th}(x_i), \cos z)}{d\Omega} \Theta(x_i - 7)}{\sum_i \Theta(x_i - 7)}$$

Upward-going Muons

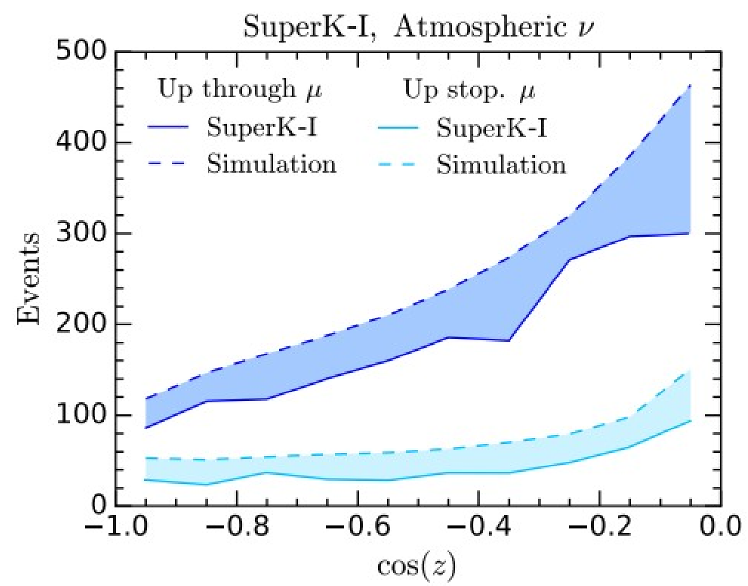
Expected fluxes



Compare with SK data



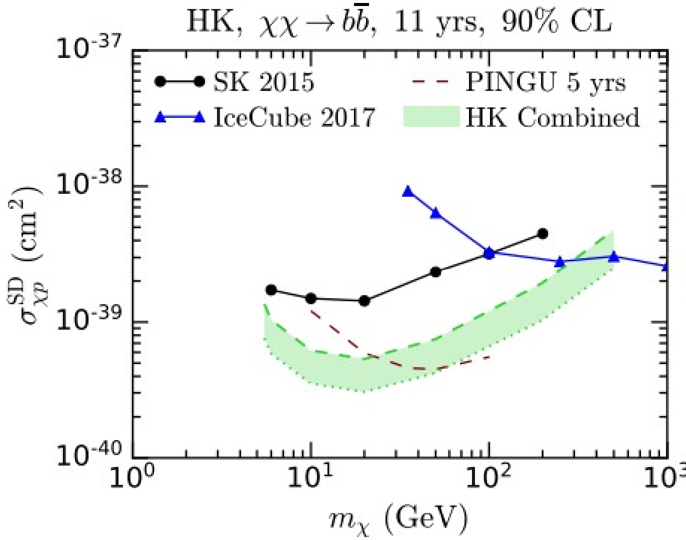
Detector effective area

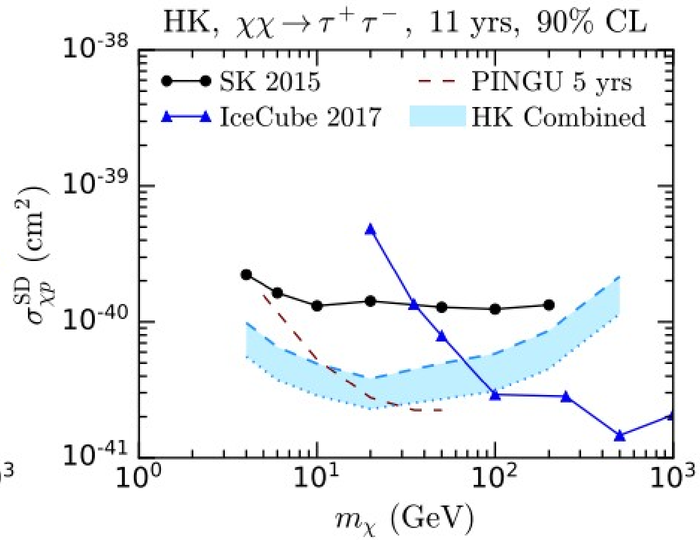


T Tanaka, PhD Thesis (2011)

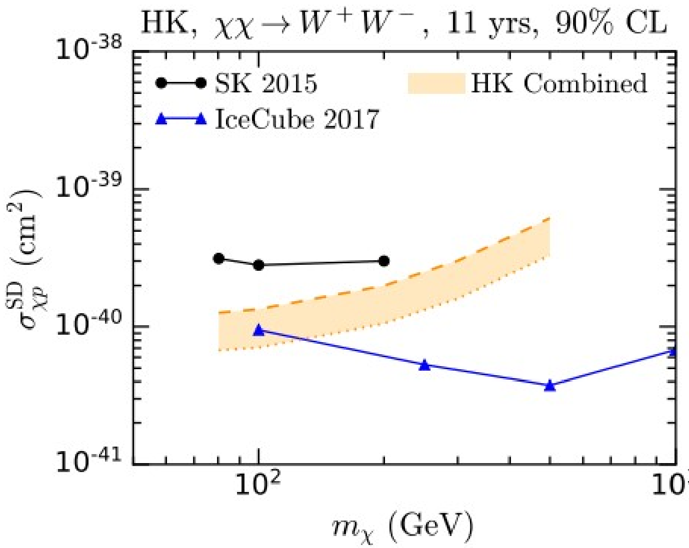
Spin-Dependent (Solar) Projections

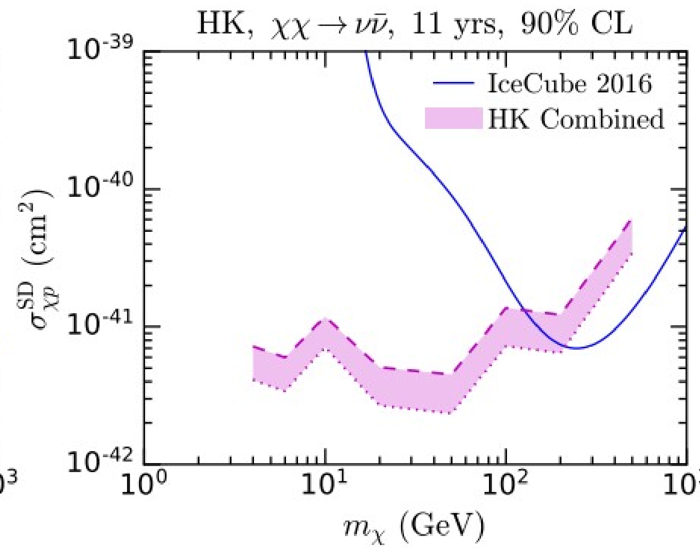
- Projections for 11 years at HK
- Combination over event categories
- Dashed: current SK systematic errors
- Dotted: half current SK systematic errors



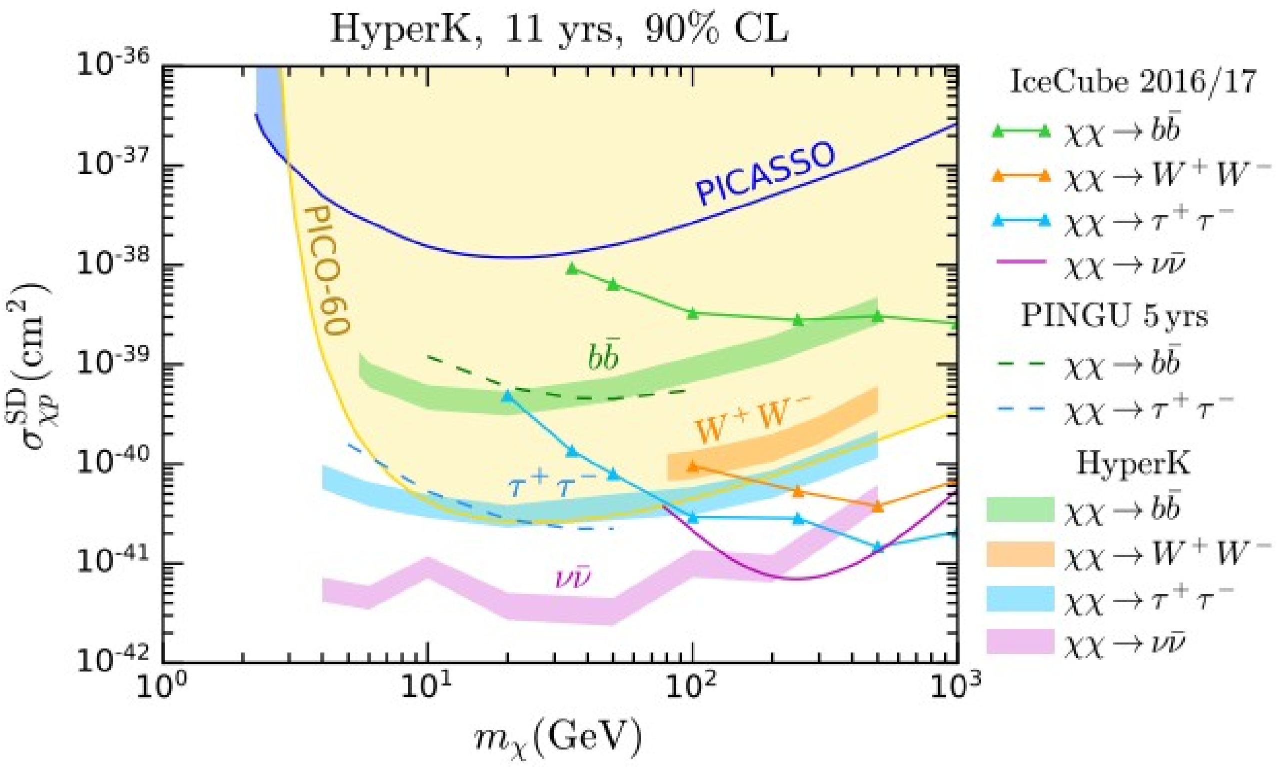


- Improve on SuperK by ~3
- Consistent with Earth search projections in HyperK Design Report



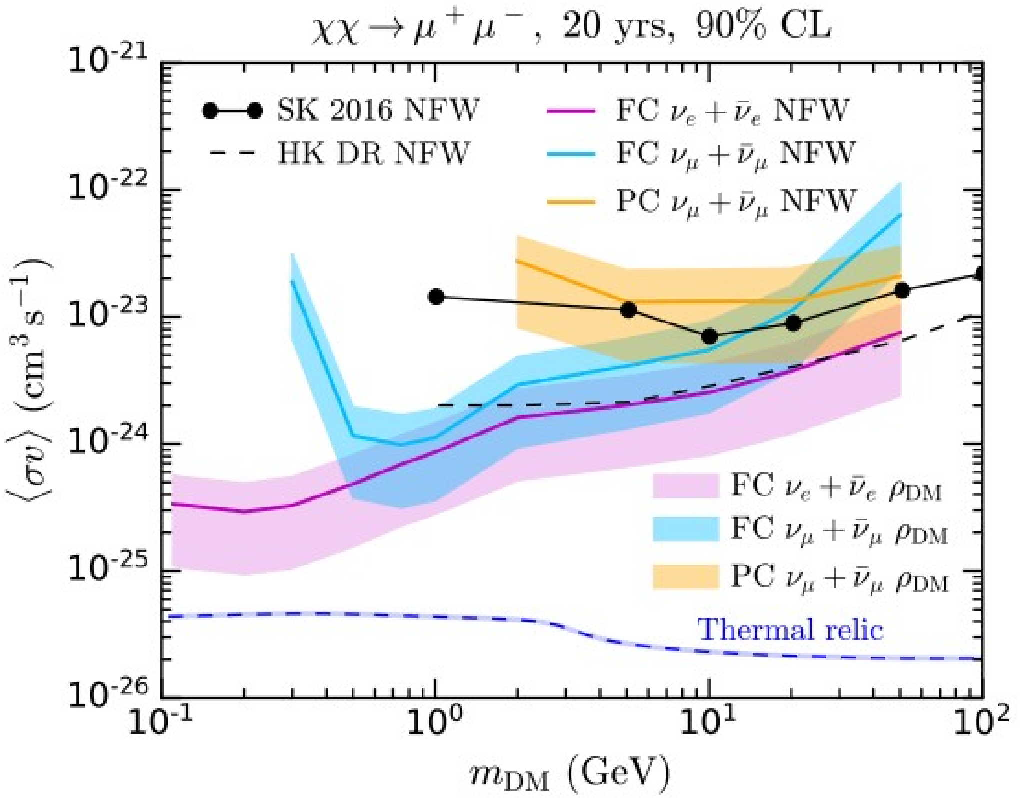


Spin-Dependent (Solar) Projections



- Low mass cutoff: evaporation from Sun.
- Most parameter space already constrained by direct detection (PICO-60)
- Icecube more sensitive at high masses
- Can rule out some parameter space for neutrinos, taus

Galactic Centre Search Projections: Muons

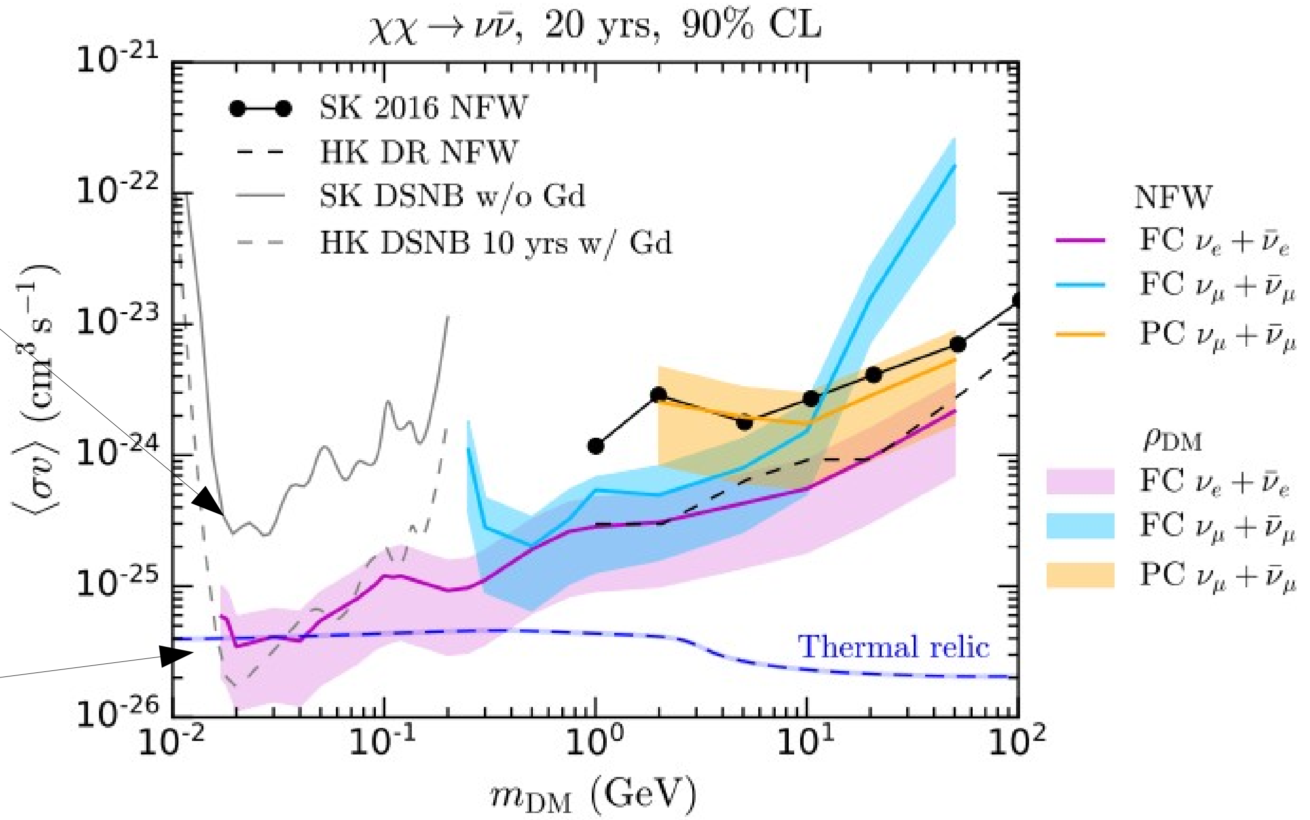


- Impact of alternate DM halo profiles shown by coloured bands
  - Isothermal (top): Worse by ~2
  - Moore (bottom): Better by ~2

GC Search Projections: Neutrinos

Limit and projection from SK DSNB search

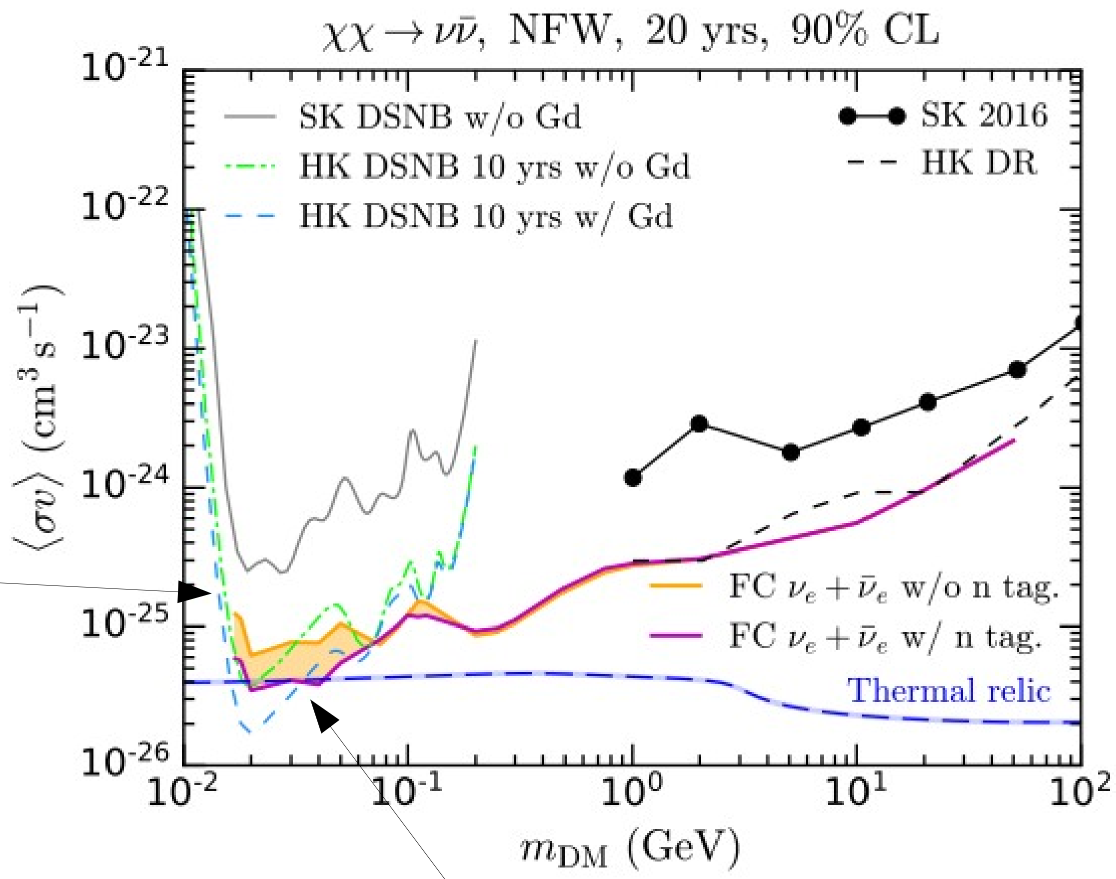
0710.5420
1805.09830
Palomares-Ruiz, Pascoli, Olivares-Campo et al



HyperK sensitive to thermal annihilation cross-sections at low masses.

- Impact of alternate DM halo profiles shown by coloured bands
  - Isothermal (top): Worse by ~2
  - Moore (bottom): Better by ~2

GC Search Projections: Neutron tagging



Limit and projection from SK DSNB search
Green: w/out tagging
Blue/ w /tagging

0710.5420
1805.09830
Palomares-Ruiz, Pascoli, Olivares-Campo

Neutron tagging key to achieving thermal relic sensitivity

Dark Matter Pollution in the DSNB

- Previous assumption: DSNB a known component of background at low DM masses.
  - Calculating the DSNB flux:

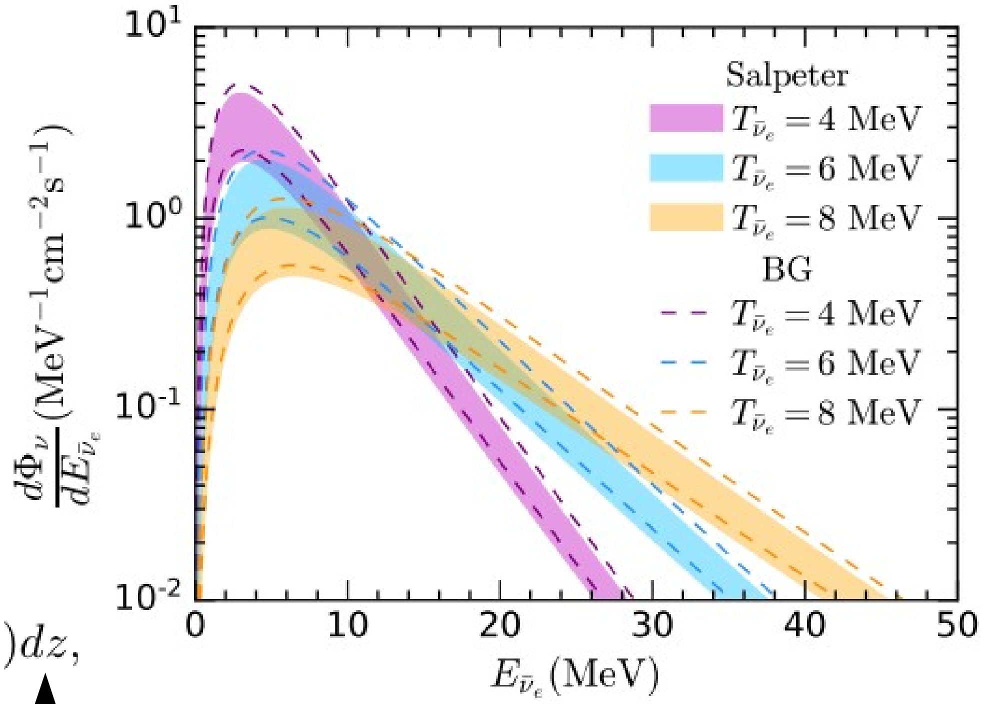
Neutrino emission per SN

CCSN rate

$$\frac{d\Phi_{\overline{\nu}_e}}{dE_{\overline{\nu}_e}} = \frac{c}{H_0}\int_0^{z_{\max}} \frac{R_{CCSN}(z)}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}} \frac{dN_{\overline{\nu}_e}}{dE'_{\overline{\nu}_e}}(E'_{\overline{\nu}_e})dz,$$

Redshift factor

Integrated over time



Requires choice of
- Initial Mass Function (Salpeter)
- Upper, Fiducial, Lower SFR rates
- Effective neutrino temperature for neutrino emission: Fermi-Dirac distribution

e.g. Beacom 1004.3311, Mirizzi *et al* 1508.00785

Bell, MJD, Robles 2205.14123

DSNB Search at SuperK-IV

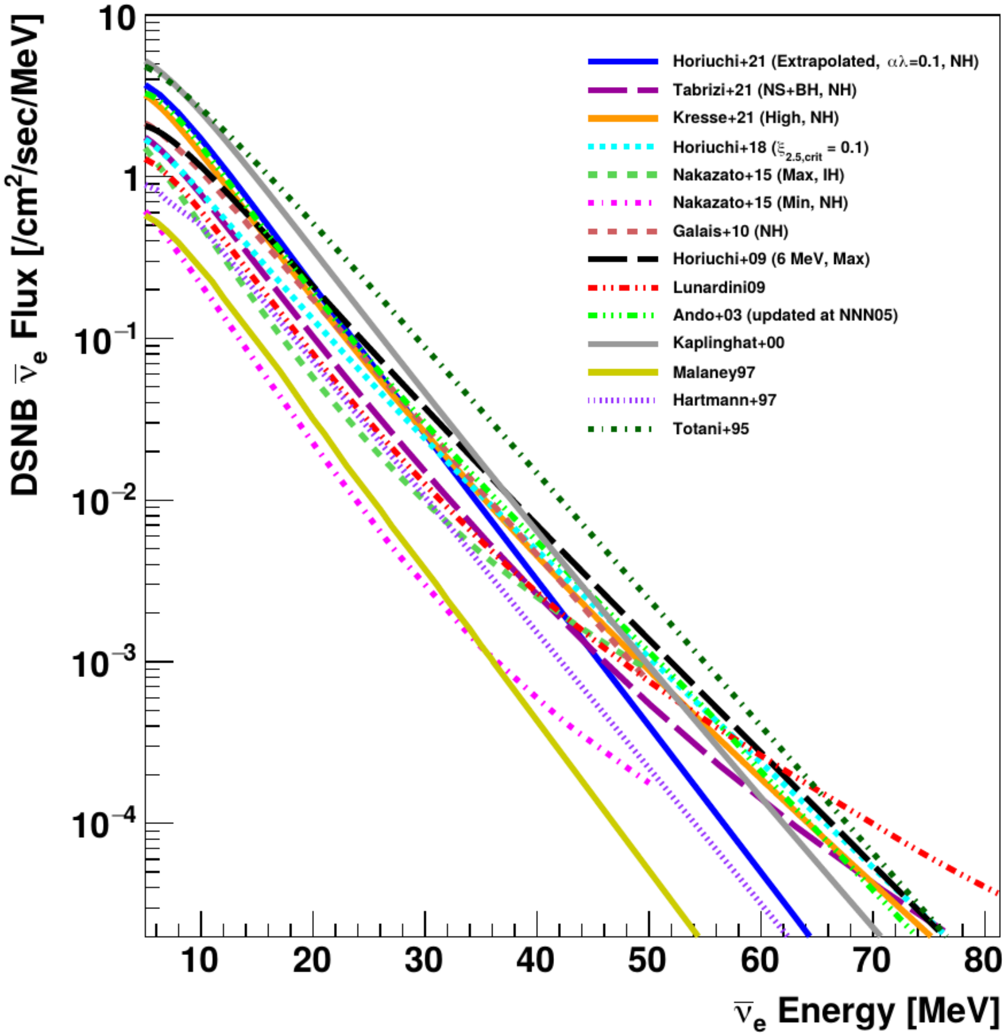
- Previous assumption: DSNB a known component of background at low DM masses.
  - Calculating the DSNB flux

Neutrino emission per SN

CCSN rate

$$\frac{d\Phi_{\overline{\nu}_e}}{dE_{\overline{\nu}_e}} = \frac{c}{H_0}\int_0^{z_{\max}} \frac{R_{CCSN}(z)}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}} \frac{dN_{\overline{\nu}_e}}{dE'_{\overline{\nu}_e}}(E'_{\overline{\nu}_e})dz,$$

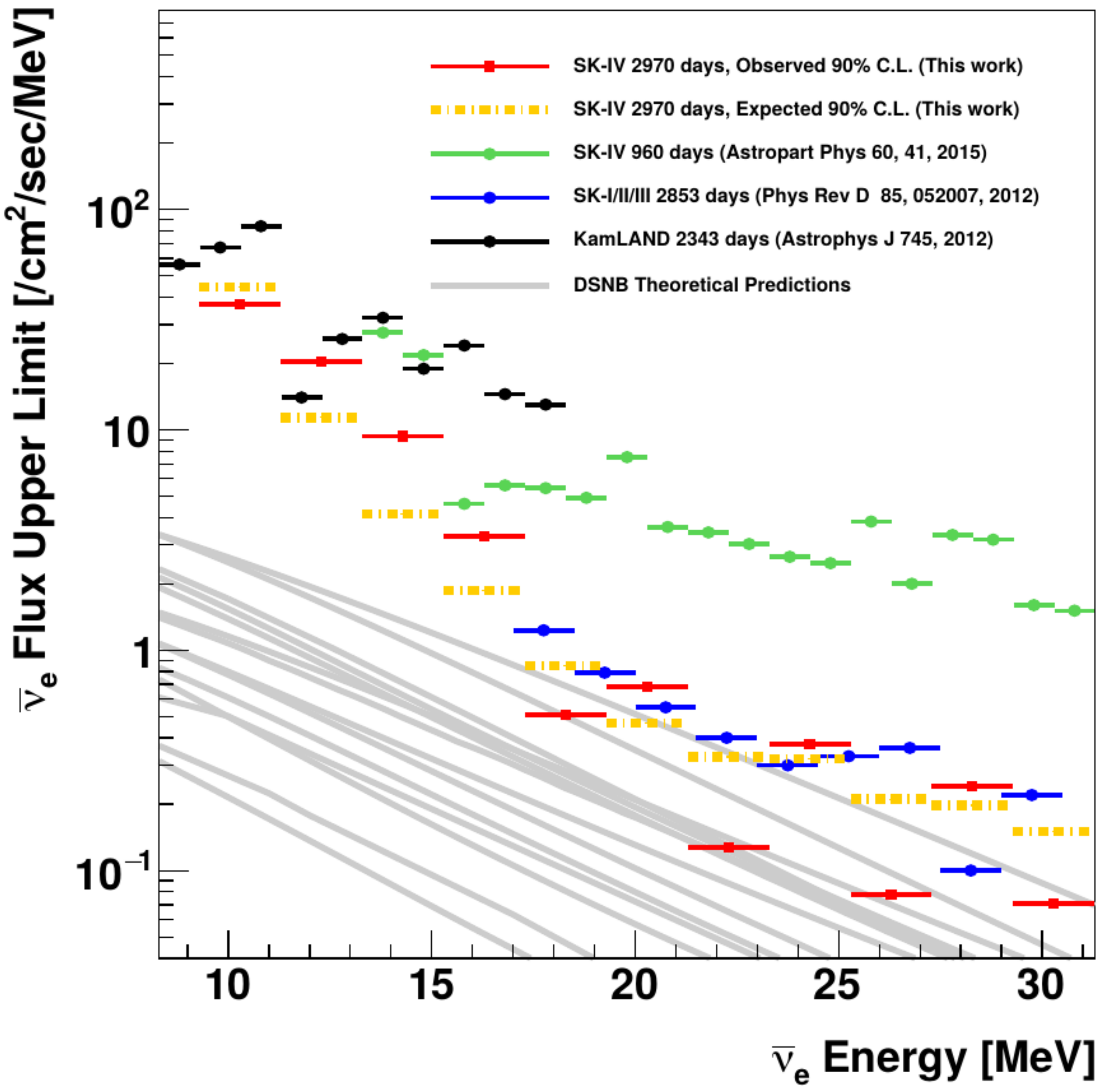
Redshift factor

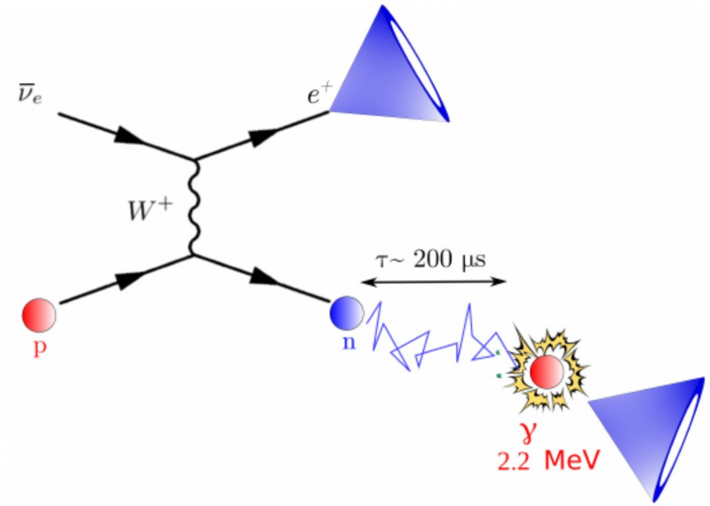


SuperK 2109.11174

e.g. Beacom 1004.3311, Mirizzi *et al* 1508.00785

DSNB Search at SuperK-IV



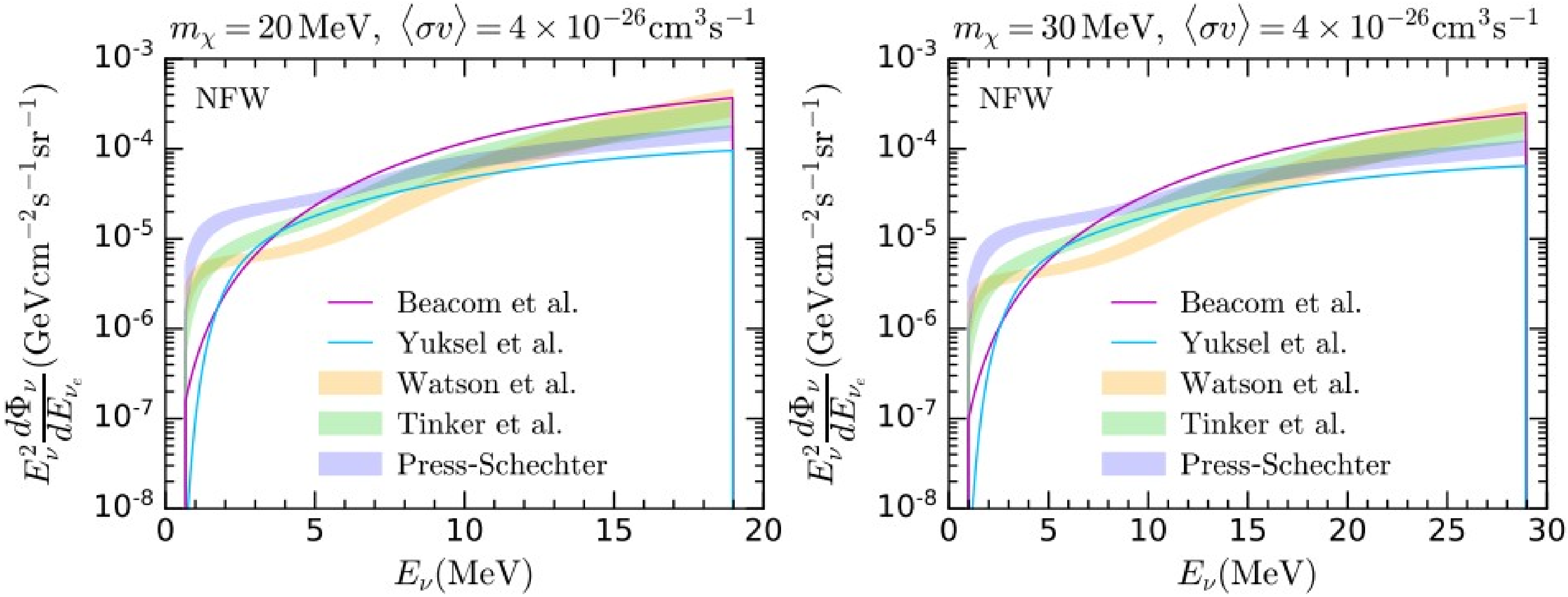


Neutron tagging using hydrogen

SuperK 2109.11174

Dark Matter: Extragalactic Component

- Primary source of DM neutrinos: Galactic Centre
- Secondary, diffuse flux: Extragalactic DM annihilation



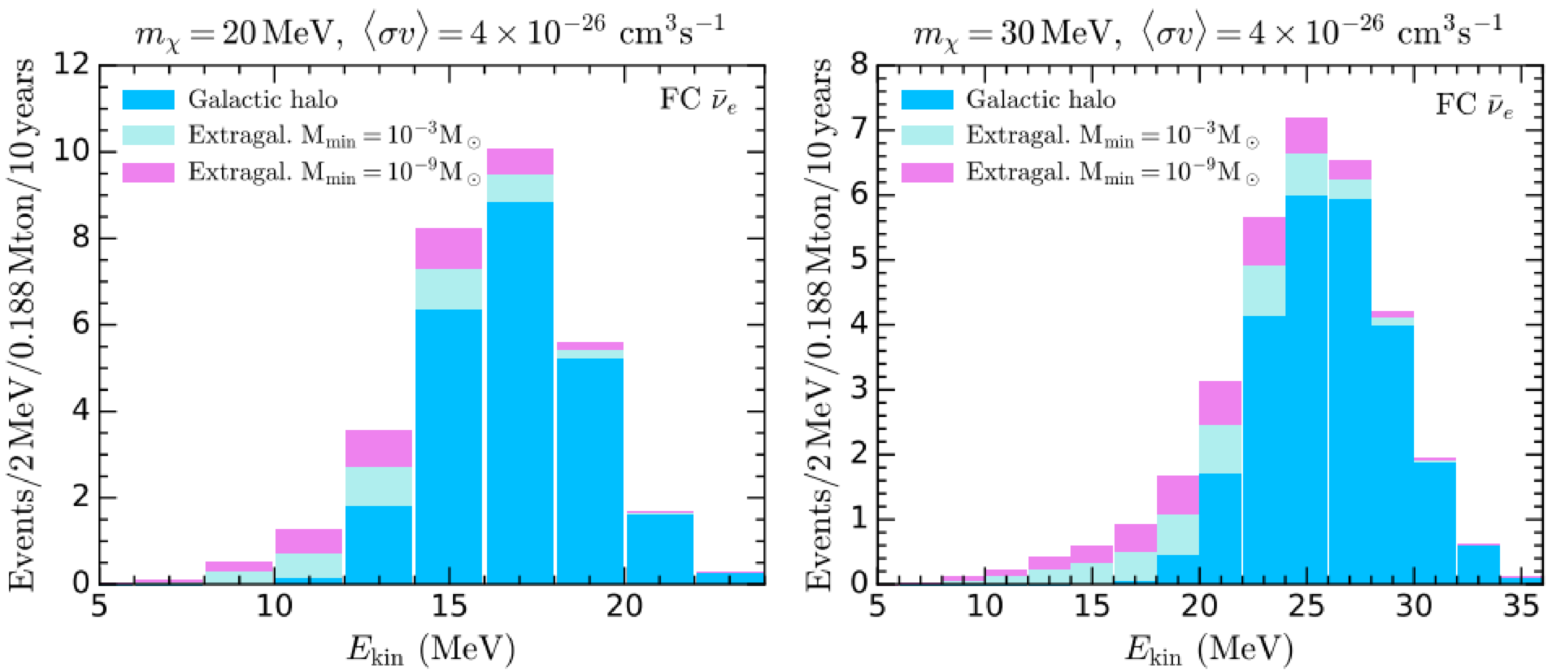
$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\langle\sigma v\rangle}{2}\frac{c}{4\pi H_0}\frac{\Omega^2_{\mathrm{DM},0}\rho^2_{c,0}}{m^2_\chi}\int_0^{z_{up}} dz\,\frac{\Delta^2(z)}{h(z)}\frac{dN_\nu(E'_\nu)}{dE'_\nu}$$

$$h(z) = \sqrt{\Omega_{m,0}(1+z)^3 + \Omega_{\Lambda,0}}$$

$\Delta^2(z)$ Halo boost factor: single halo contribution weighted by halo mass function

Low Mass Dark Matter: Neutrino Spectrum

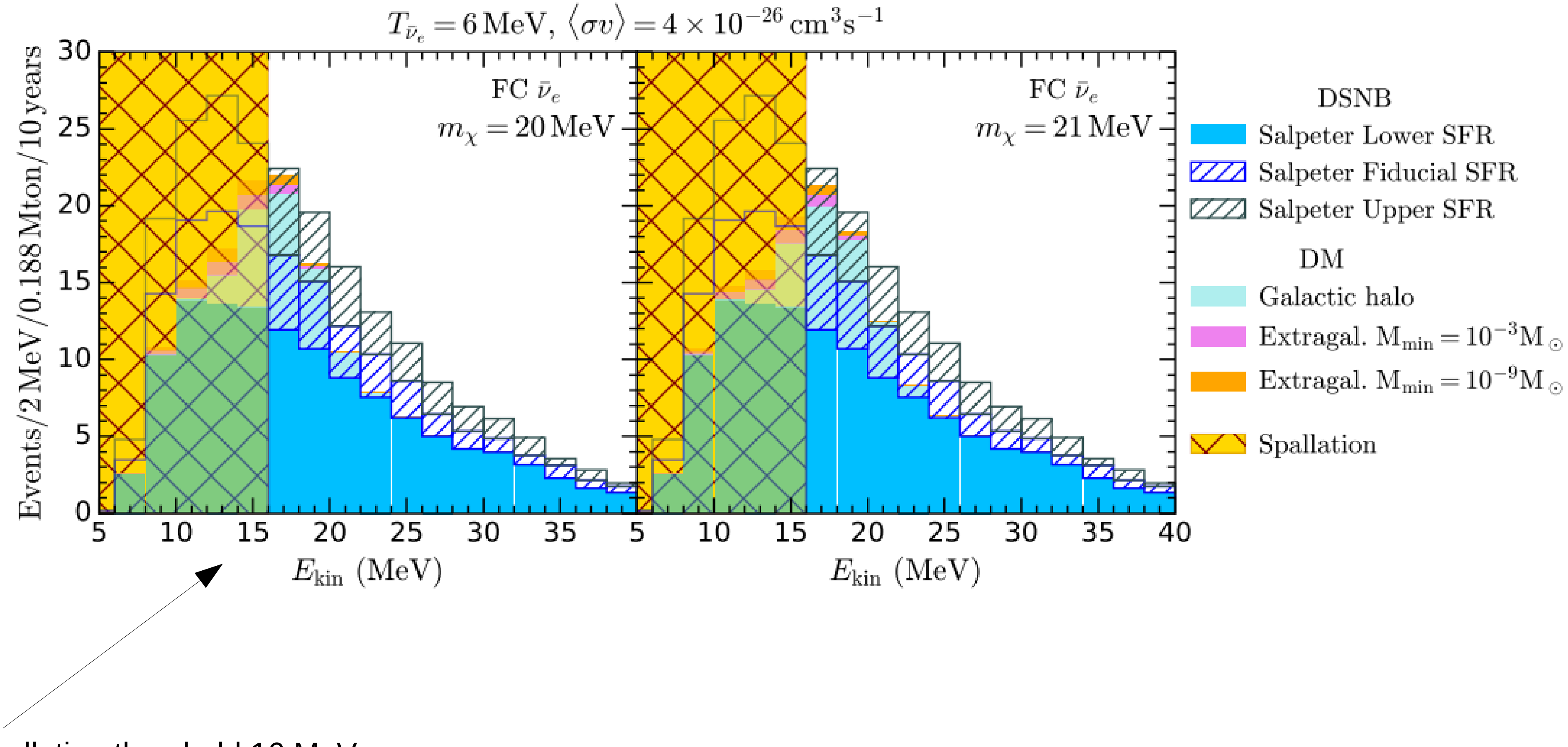
Neutrino spectrum for low mass thermal DM
Kinetic energy of resulting positron:



- Peak corresponds to scattering off hydrogen (oxygen below threshold)
- Extragalactic component redshifted to lower energies

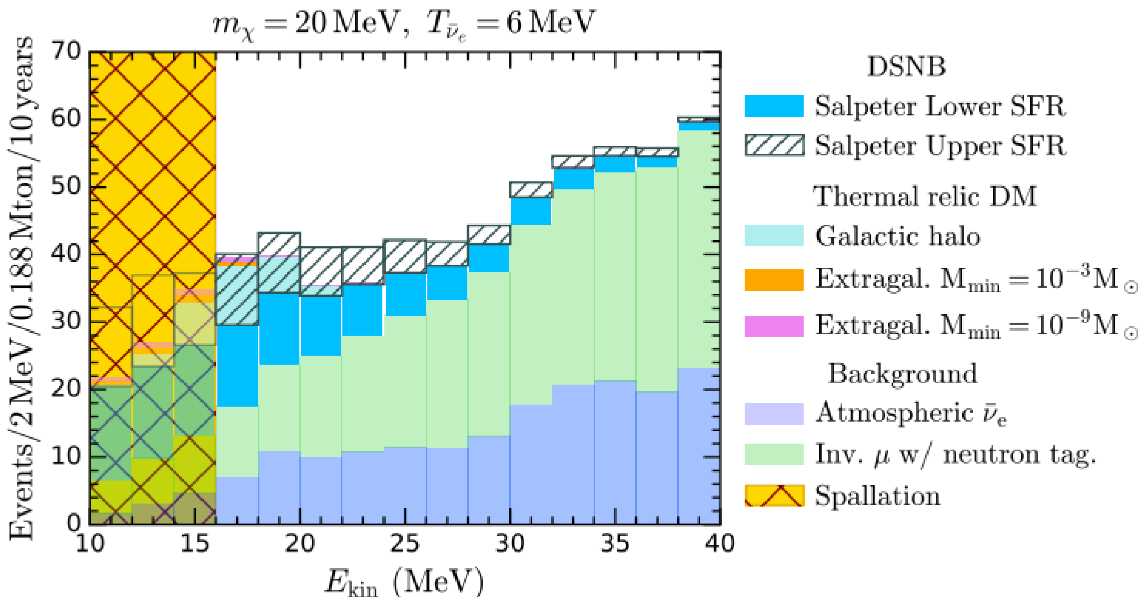
Dark Matter Pollution in the DSNB

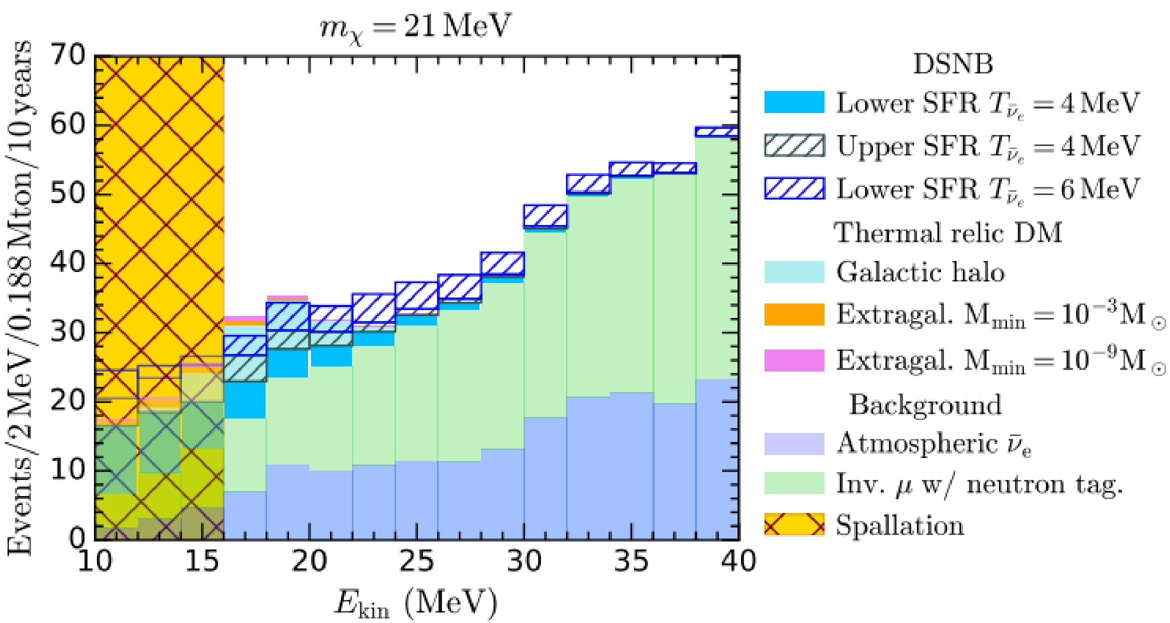
- HyperK DSNB analysis window 16-30 MeV
- 10 years run-time, no neutron-tagging: 3.3 sigma detection of DSNB.
- With 20 MeV thermal DM: 6.3 sigma excess above background.



Spallation threshold 16 MeV
SK: 12 MeV (deeper site)

Dark Matter Pollution in the DSNB



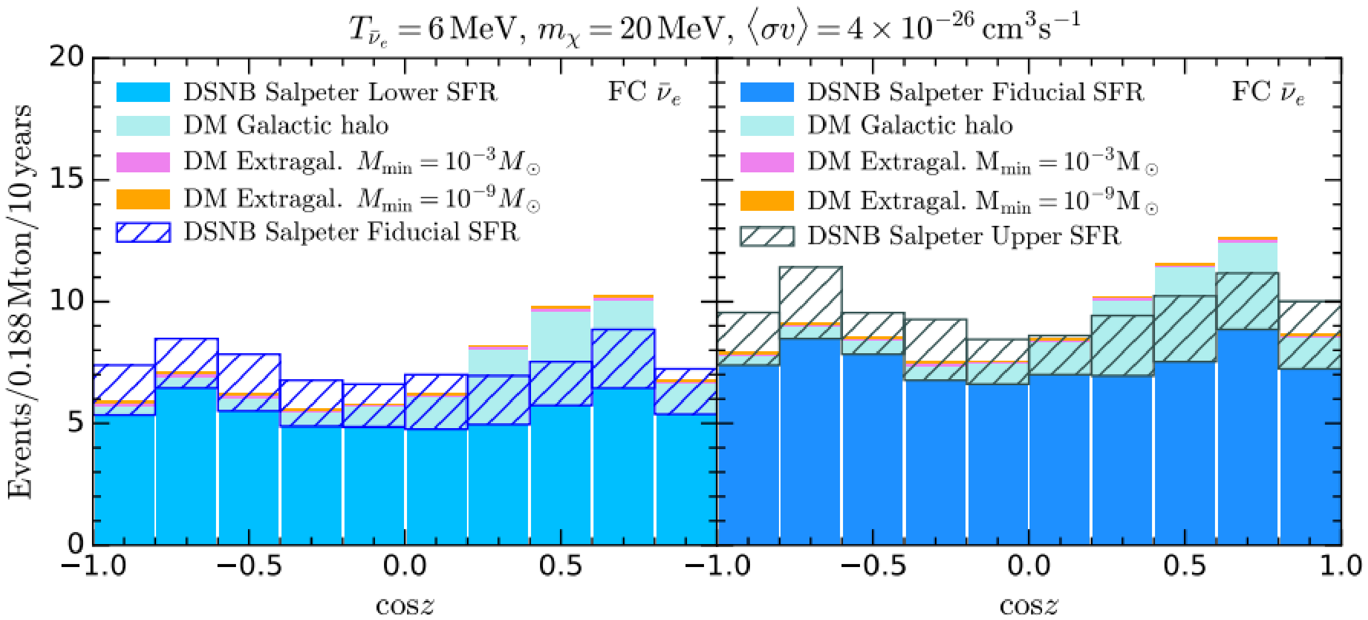


- Neutron tagging → model discrimination
- Presence of DM can lead to some DSNB parameters being wrongly ruled out
  - Or some being incorrectly favoured
    - DM mass ~20-25 MeV

$$TS = -2 \ln \frac{\mathcal{L}_p\left(\mathcal{D}_A(S_2)|S1\right)}{\mathcal{L}_p\left(\mathcal{D}_A(S_1)|S2\right)}$$

DM and the DSNB: Angular Information

Lower SFR (blue)
Fiducial SFR
(hatched)



Fiducial SFR (blue)
Upper SFR
(hatched)

- Dark matter flux primary origin is Galactic Centre.
- DSNB flux is isotropic.
- Simple on-off analysis mitigates effects of DM on DSNB.
- More sophisticated angular analysis possible?

Outlook

- Hyper-Kamiokande: next-generation water Cherenkov detector starting ~2027.
  - HyperK will improve SK's spin-dependent cross-section limits by ~3.
- HyperK will probe thermal relic cross-sections for light dark matter (<40MeV) annihilating into neutrinos.
- Dark matter could be background in DSNB searches at HyperK – and other experiments?
  - Also other possibilities – boosted DM, DM annihilations in Earth...