Disentangling Sub-GeV DM from the Diffuse Supernova Neutrino Background using Hyper-Kamiokande

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with
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arXiv: 2205.14123

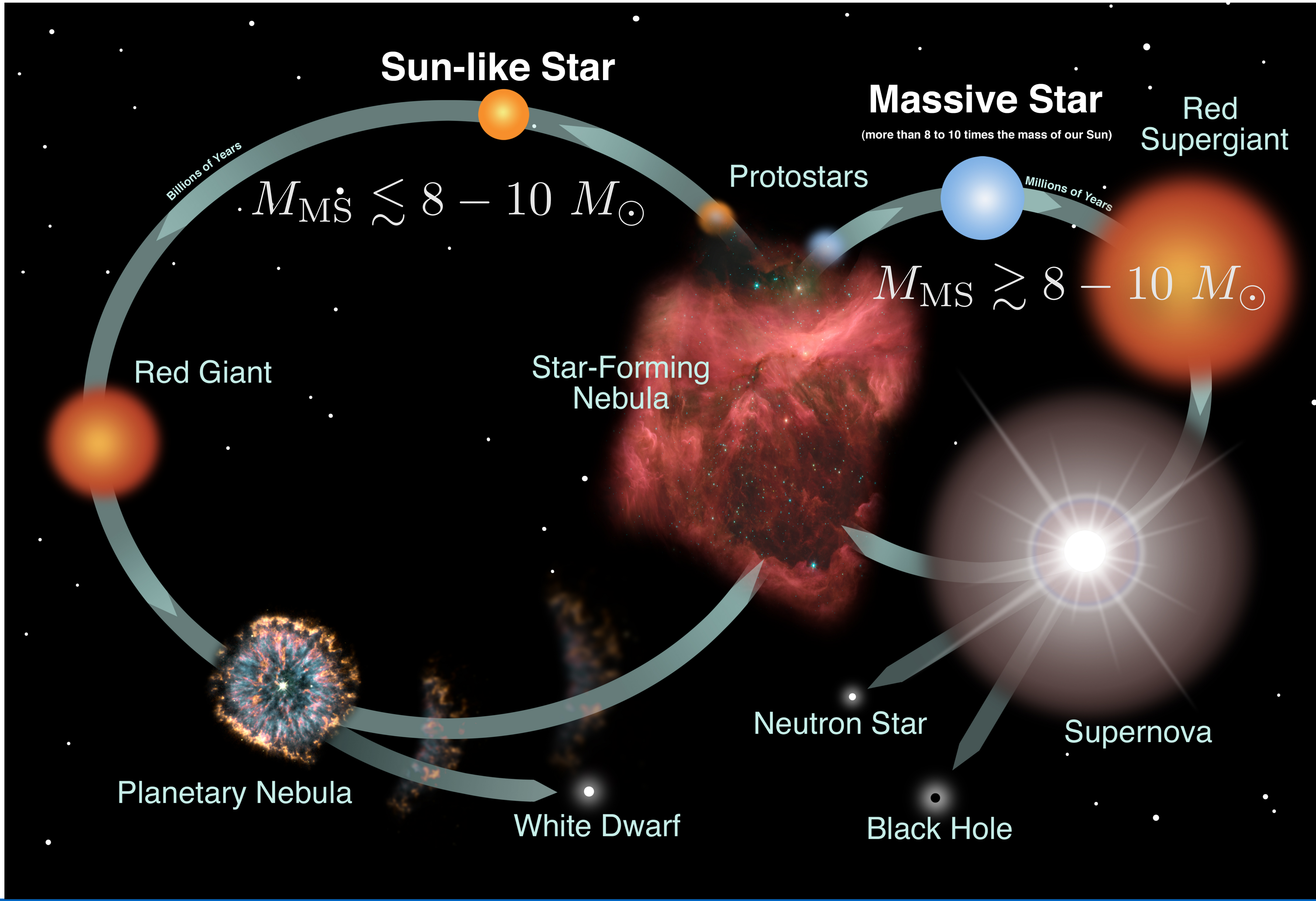
Introduction

- Massive stars $M_\star \gtrsim 8-10\ M_\odot$ live relatively short lives
- Die in core-collapse supernova explosions

➡ Remnant: Neutron star

➡ ~99% of the energy from the SN released as neutrinos (all flavours)

Credit: NASA

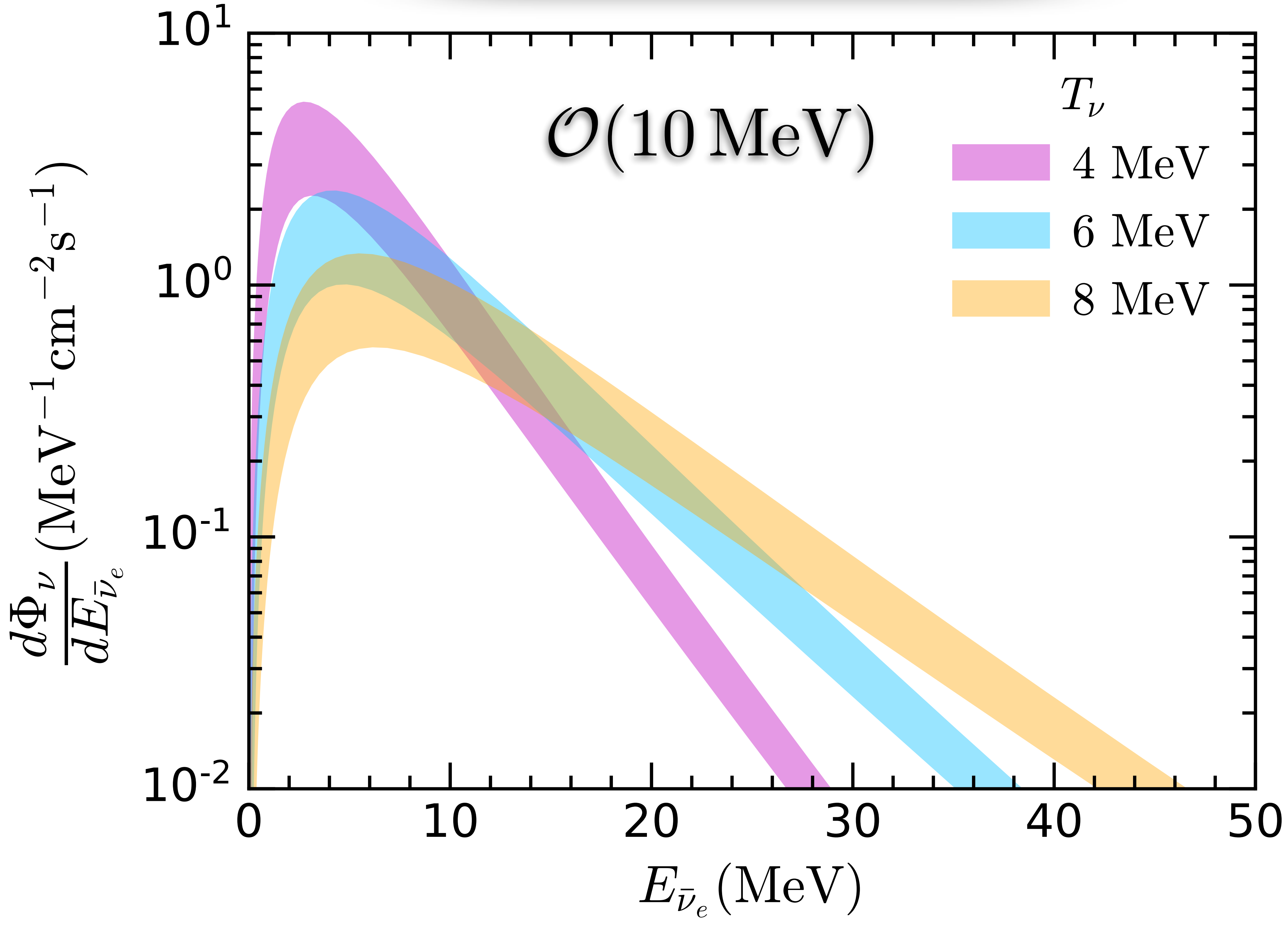


Introduction

Diffuse Supernova Neutrino Background (DSNB)

- Neutrinos from all previous core-collapse supernovae
  - ➡ Isotropic signal
- DSNB flux
  - ➡ obtained by redshifting neutrino spectrum from single SN according to the SN rate
- Traces star formation rate
- Not discovered yet

DSNB neutrino flux

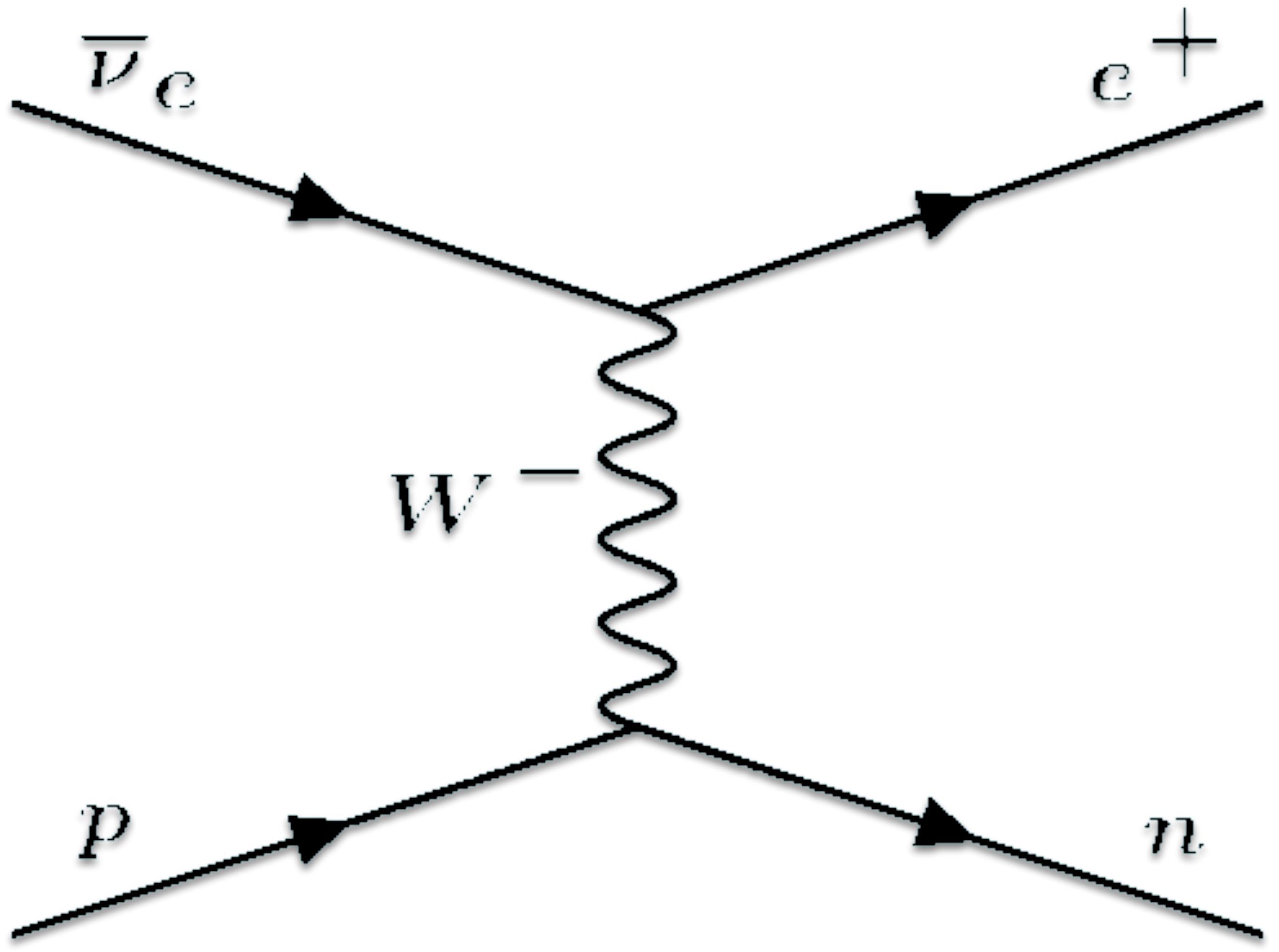


Introduction

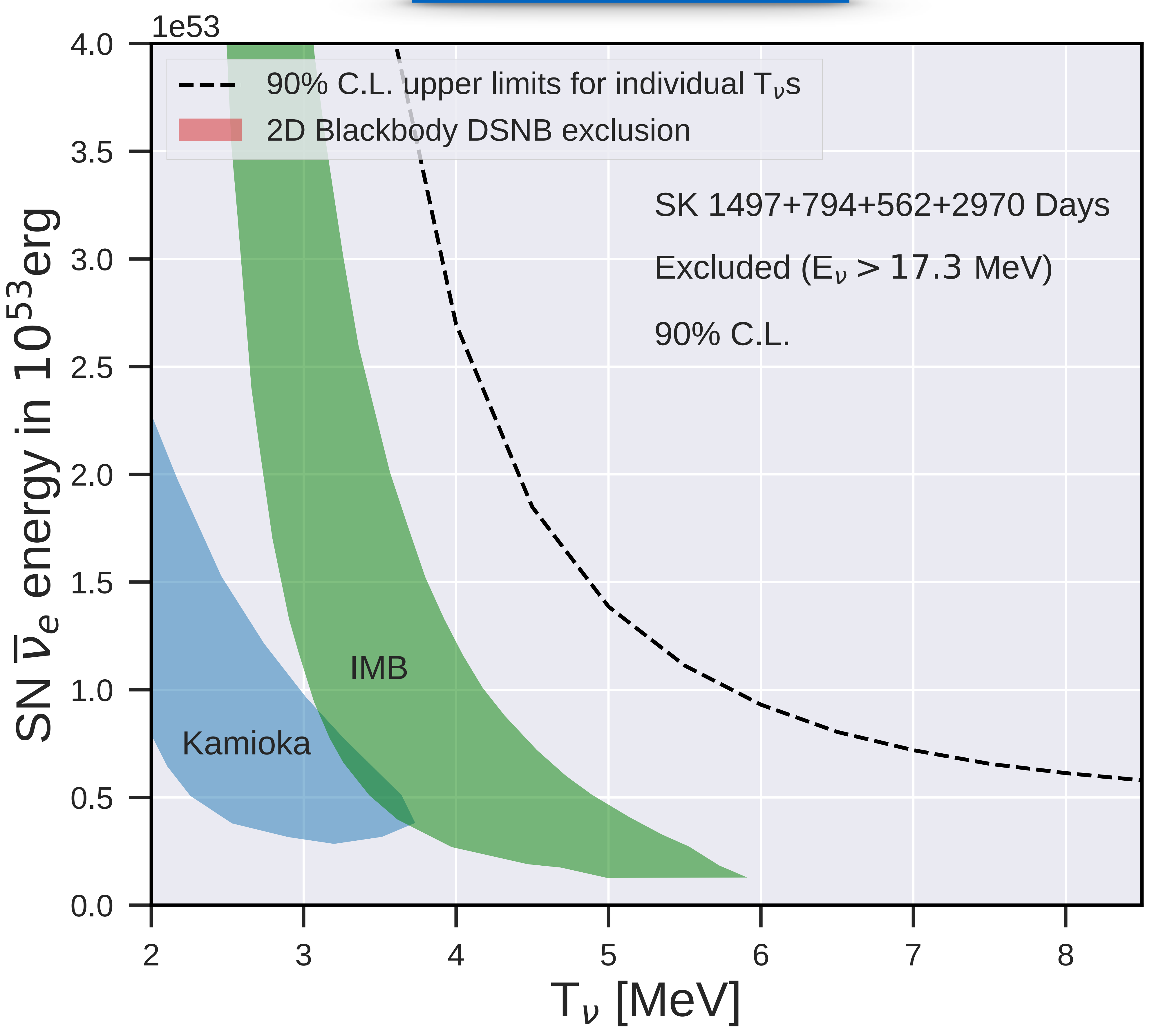
DSNB searches

- Detection
  - ➡ Water Cherenkov detectors (SuperK, HyperK)
  - ➡ Liquid argon (DUNE) and scintillator (JUNO)
- Water Cherenkov detectors
  - ➡ Dominant channel inverse beta decay

$$\bar{\nu}_e + p \to e^+ + n$$



SuperK-IV



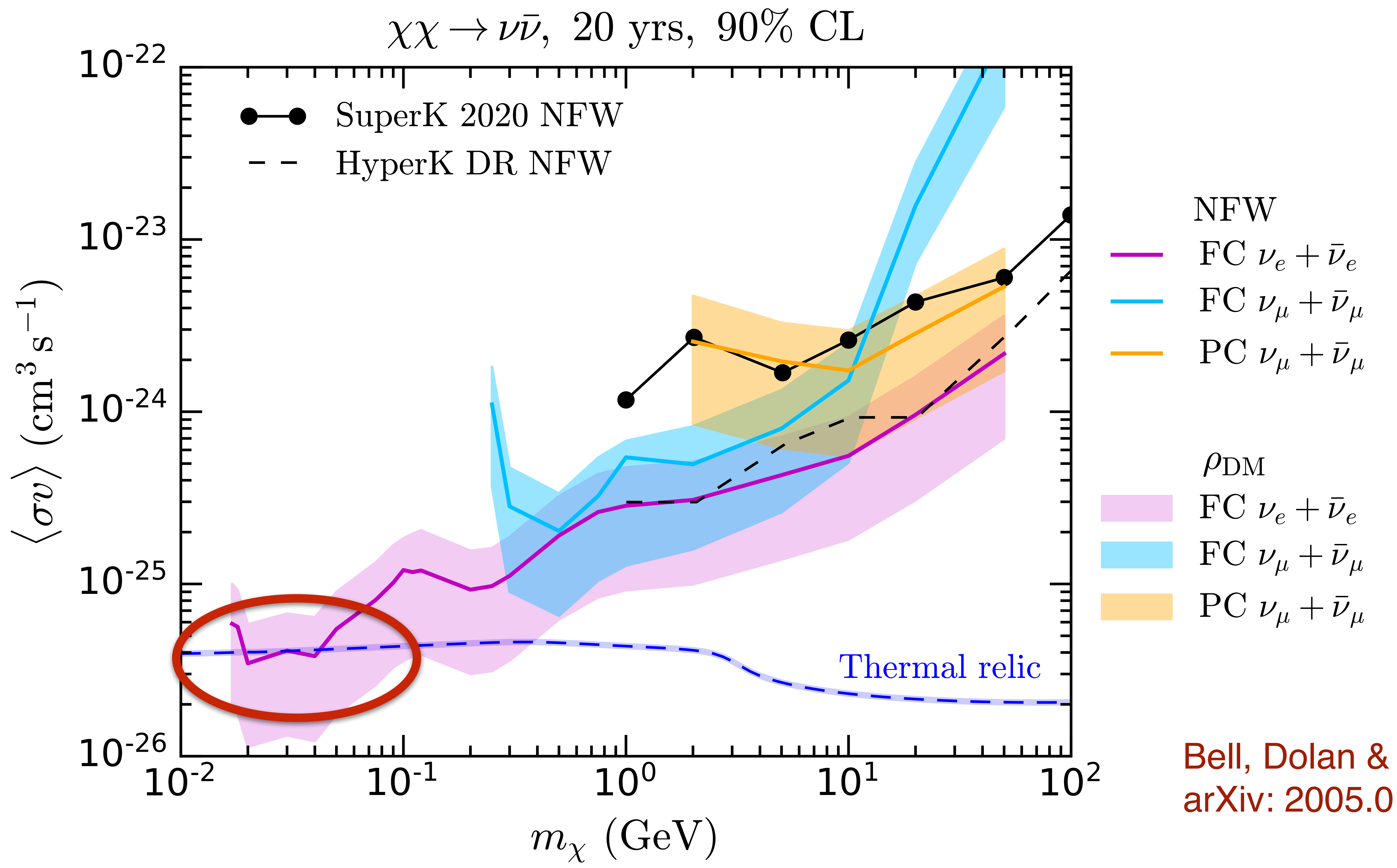
SuperK Collaboration arXiv: 2109.11174

Introduction

- HyperK should be able to probe thermal annihilation cross-sections for DM of mass ~ 20 - 40 MeV for annihilation into neutrinos.

DM profiles

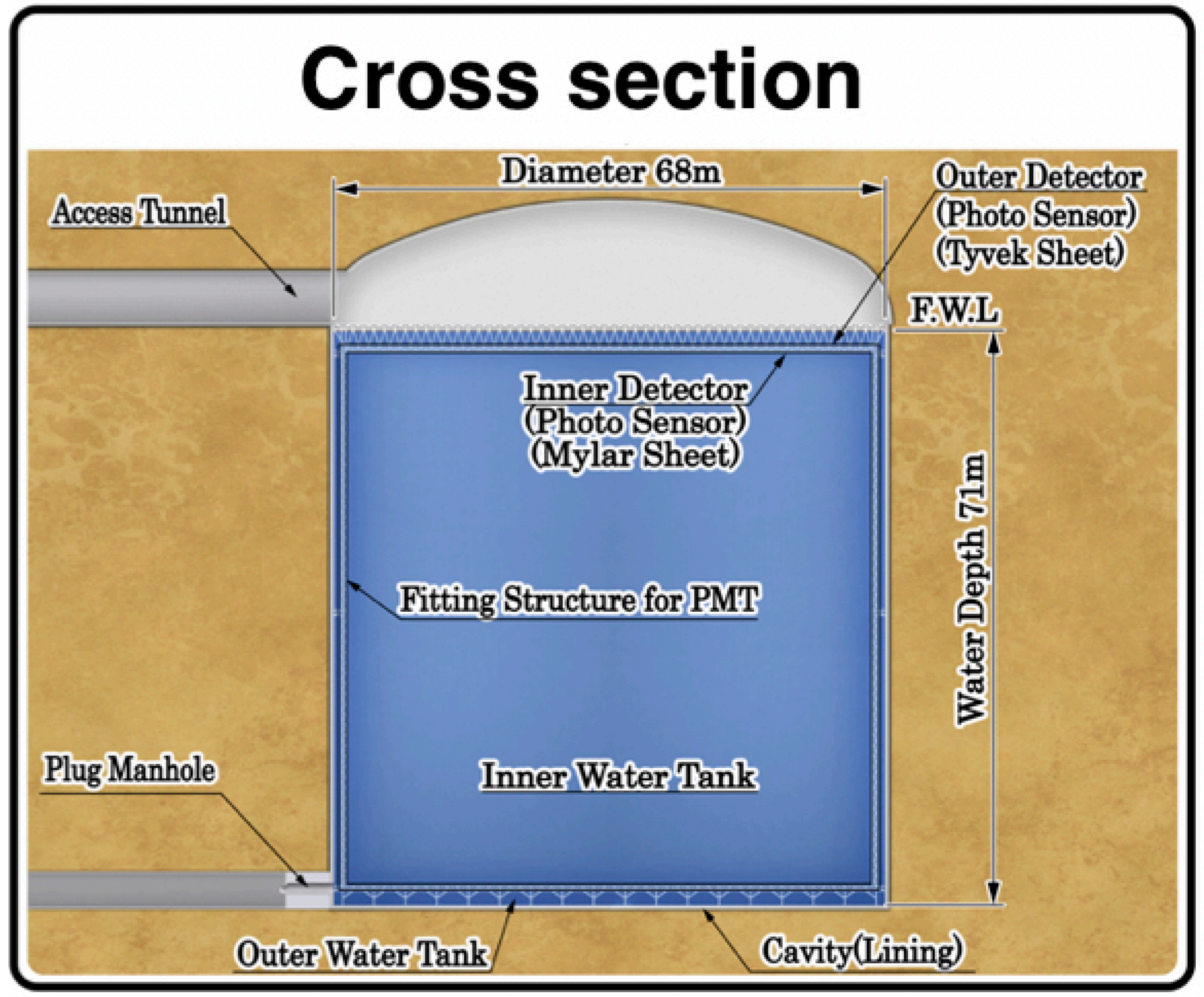
- Isothermal
- NFW
- Moore

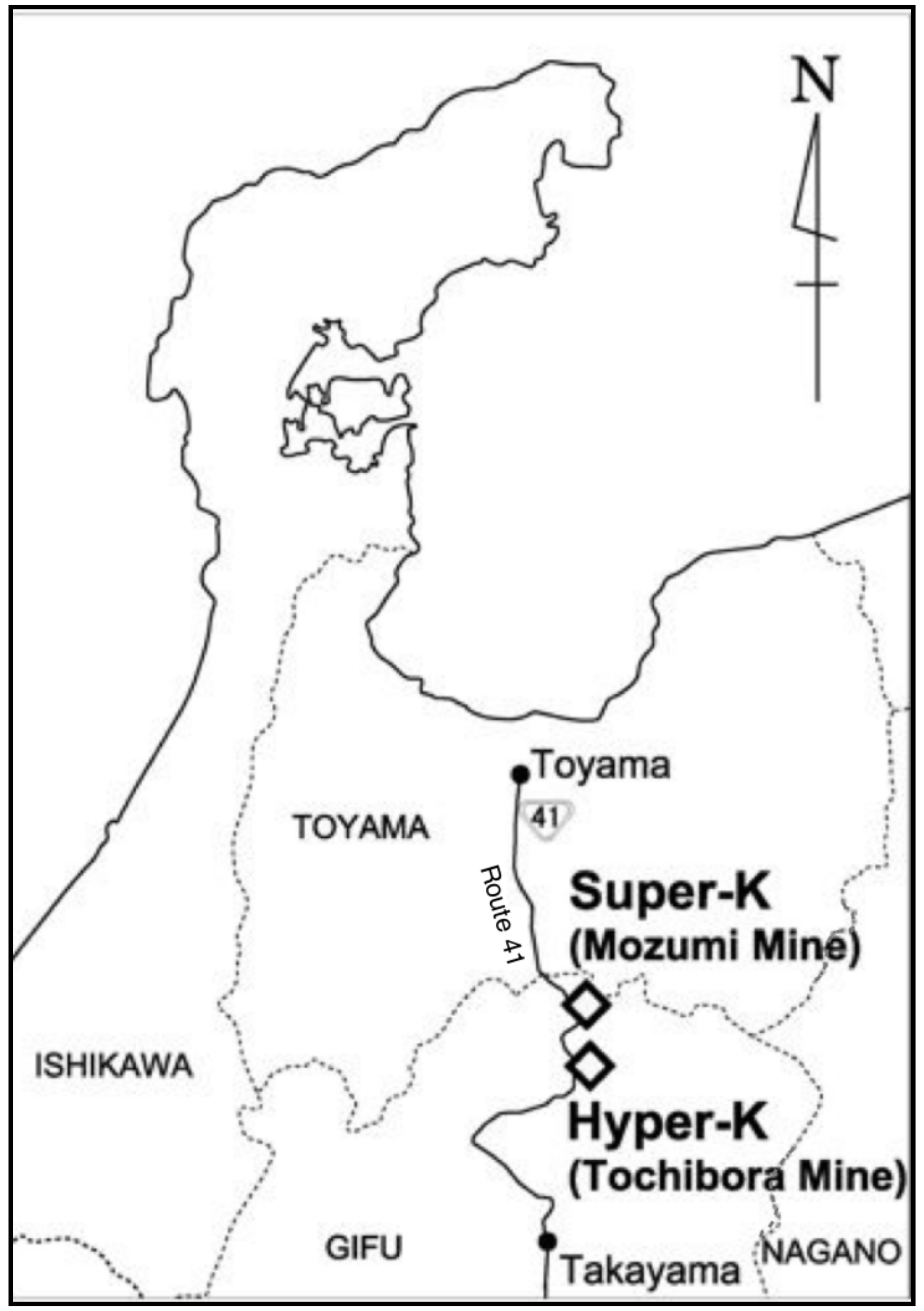


Bell, Dolan & SR
arXiv: 2005.01950

Hyper-Kamiokande

- 3rd generation underground water Cherenkov detector
  - ➡ Kamiokande (1983-1996) - 1987 first detection of supernova neutrinos 
  - ➡ Super-Kamiokande (1996-present) - 1998 discovery of neutrino oscillations 
- 188 kton fiducial volume ~ 8.4 times larger than SuperK
- High-QE PMTs
- Less overburden ~ 650m (SuperK 1000m)





HyperK Design Report
arXiv:1805.04163

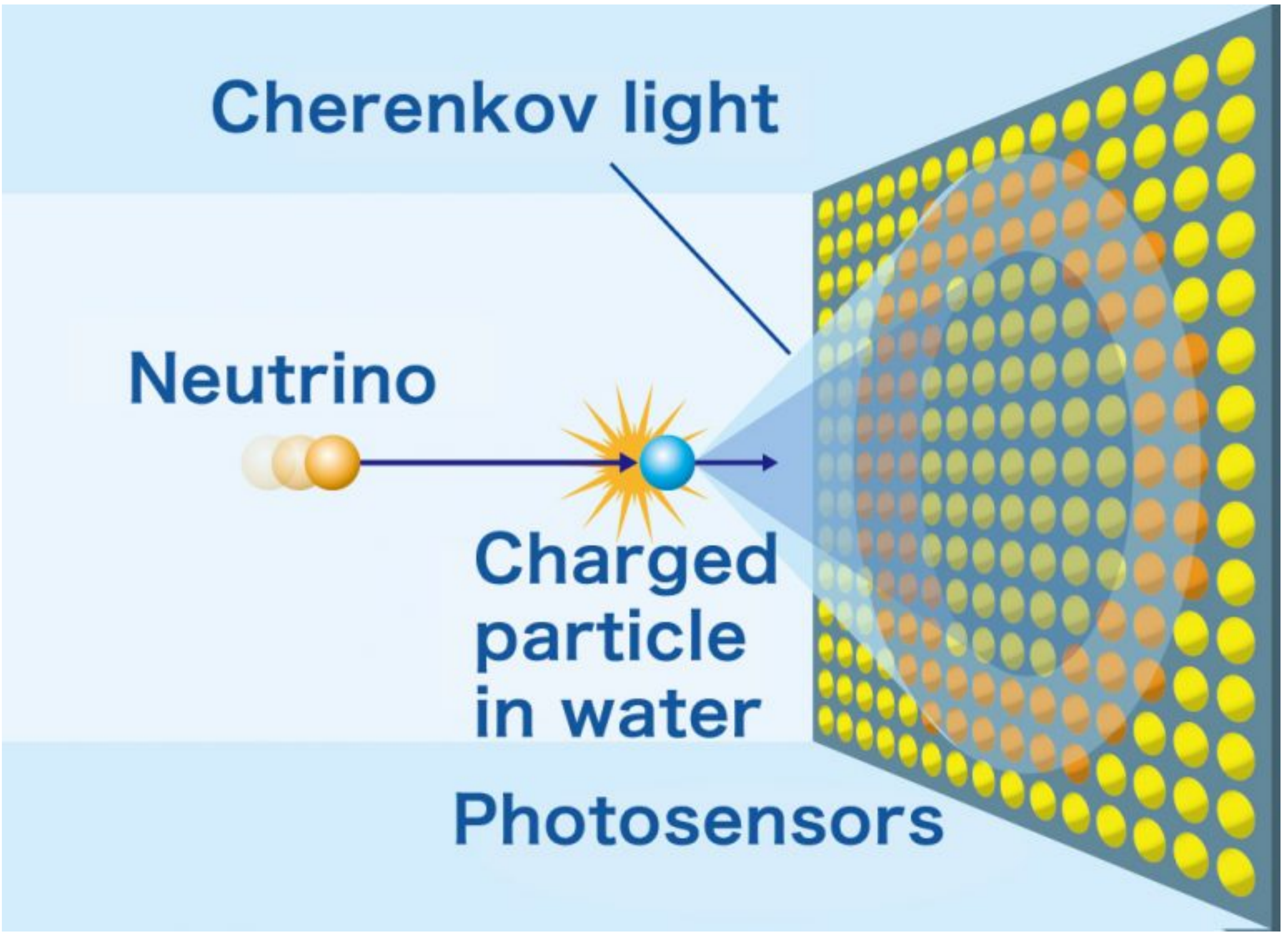
http://www.hyper-k.org/en/detector/detector-detail.html

Can neutrinos from DM annihilation contribute a significant background to DSNB searches?

next

Background for DSNB searches

Image credit: ICRR (Institute for Cosmic Ray Research), The University of Tokyo

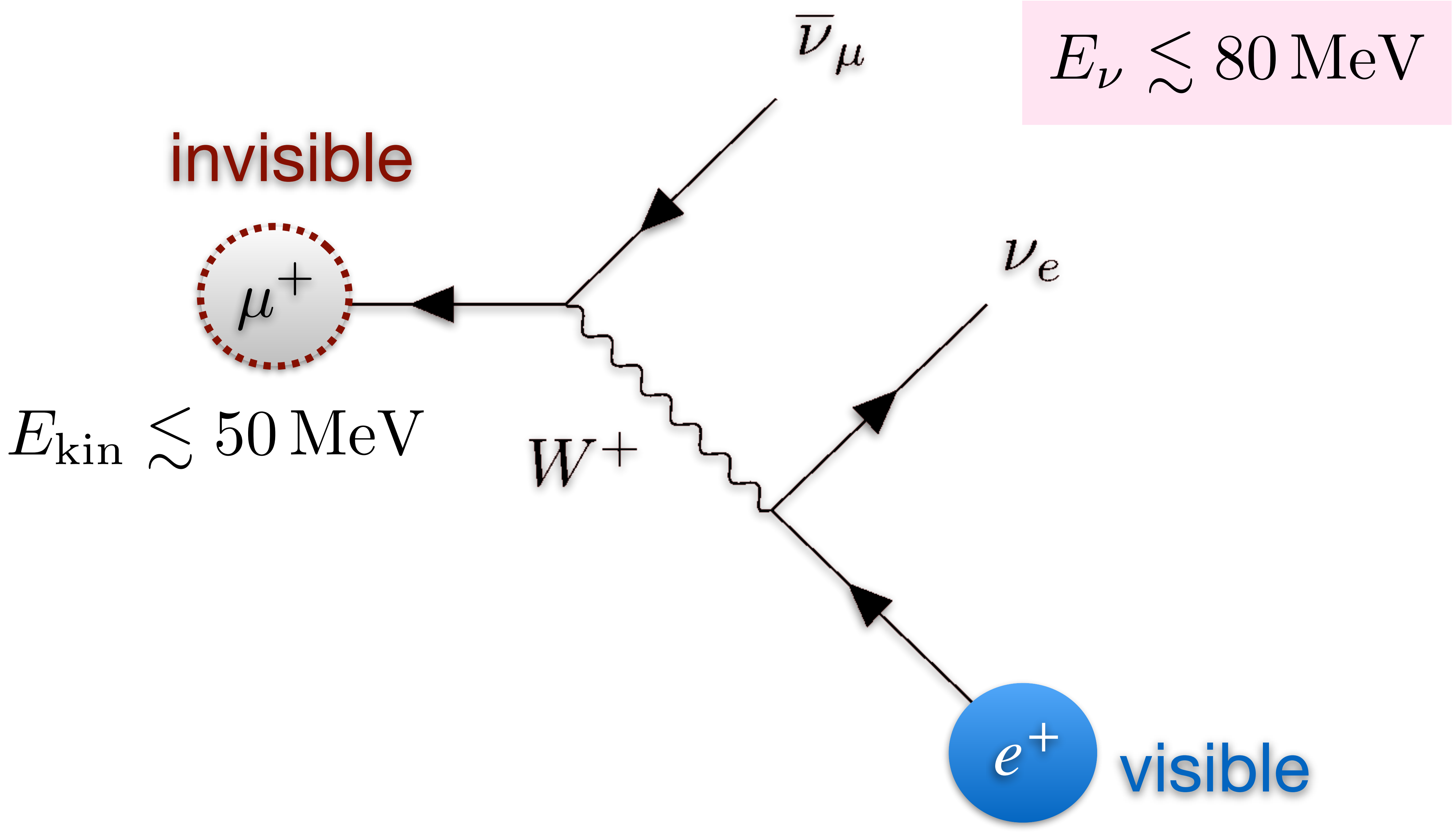


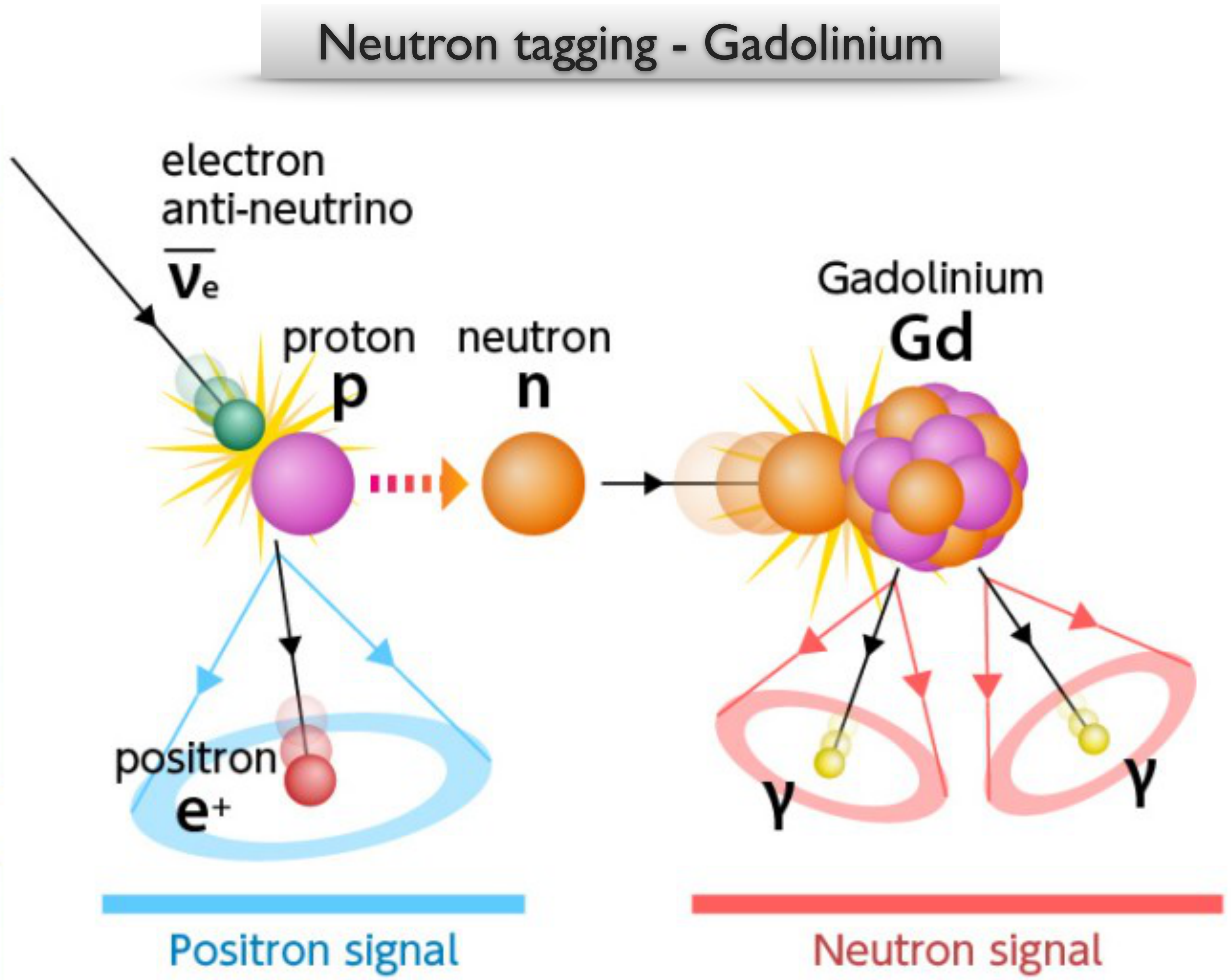
- Charged current interactions

$$\nu_\ell + N \to \ell + N'$$

Background for DSNB searches

- Invisible Muons





- Muon induced spallation $E_\nu \lesssim 16\,\mathrm{MeV}$
- Elastic scattering (Neutral current interactions)

$$\nu + e \to \nu + e$$

DM Signal

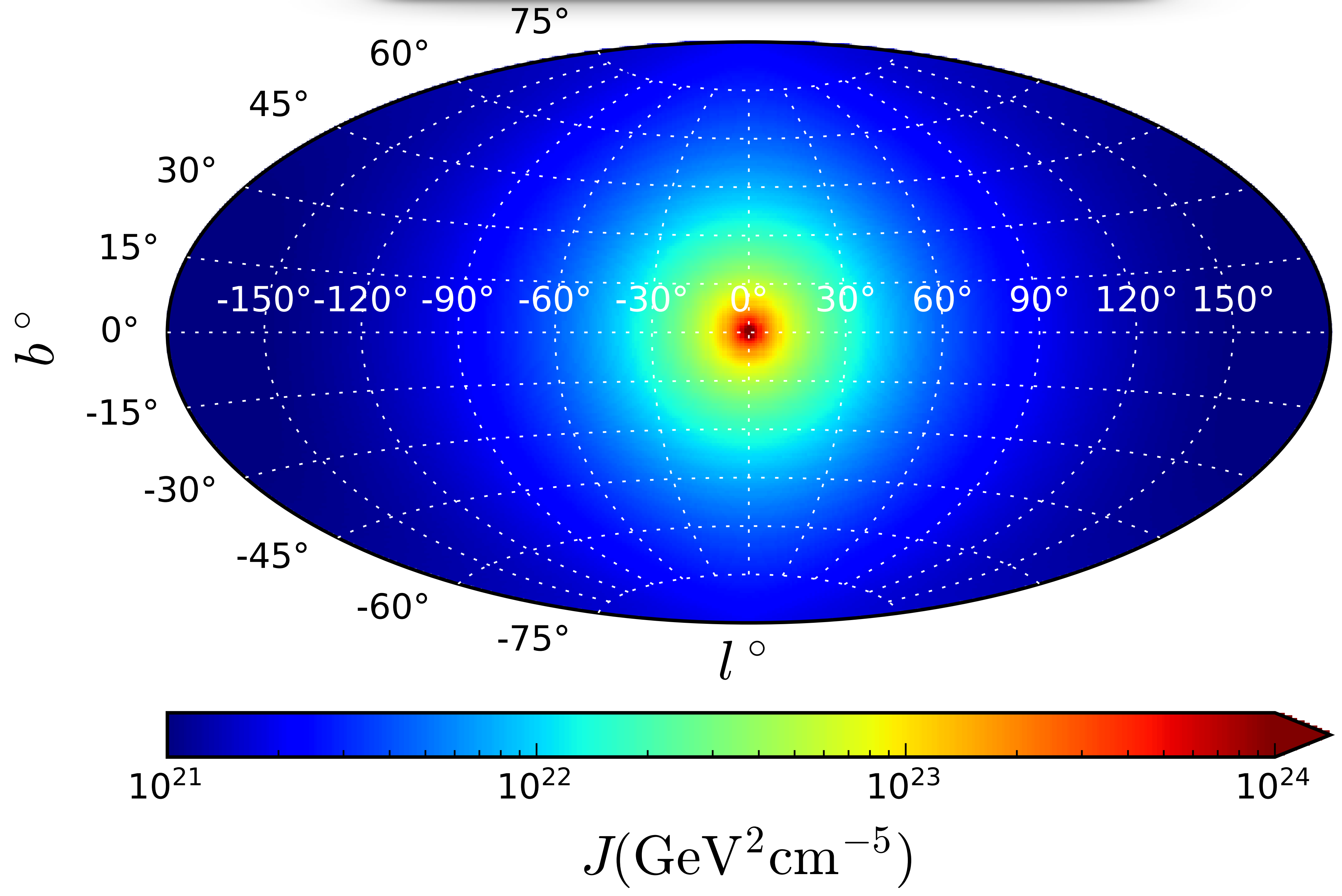
Neutrino flux from DM annihilation in the Galactic halo

$$\frac{d\Phi_\nu}{dE_\nu}(E_\nu, b, l) = \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \frac{dN_\nu}{dE_\nu} J(b,l)$$

DM particles producing vs along the l.o.s.

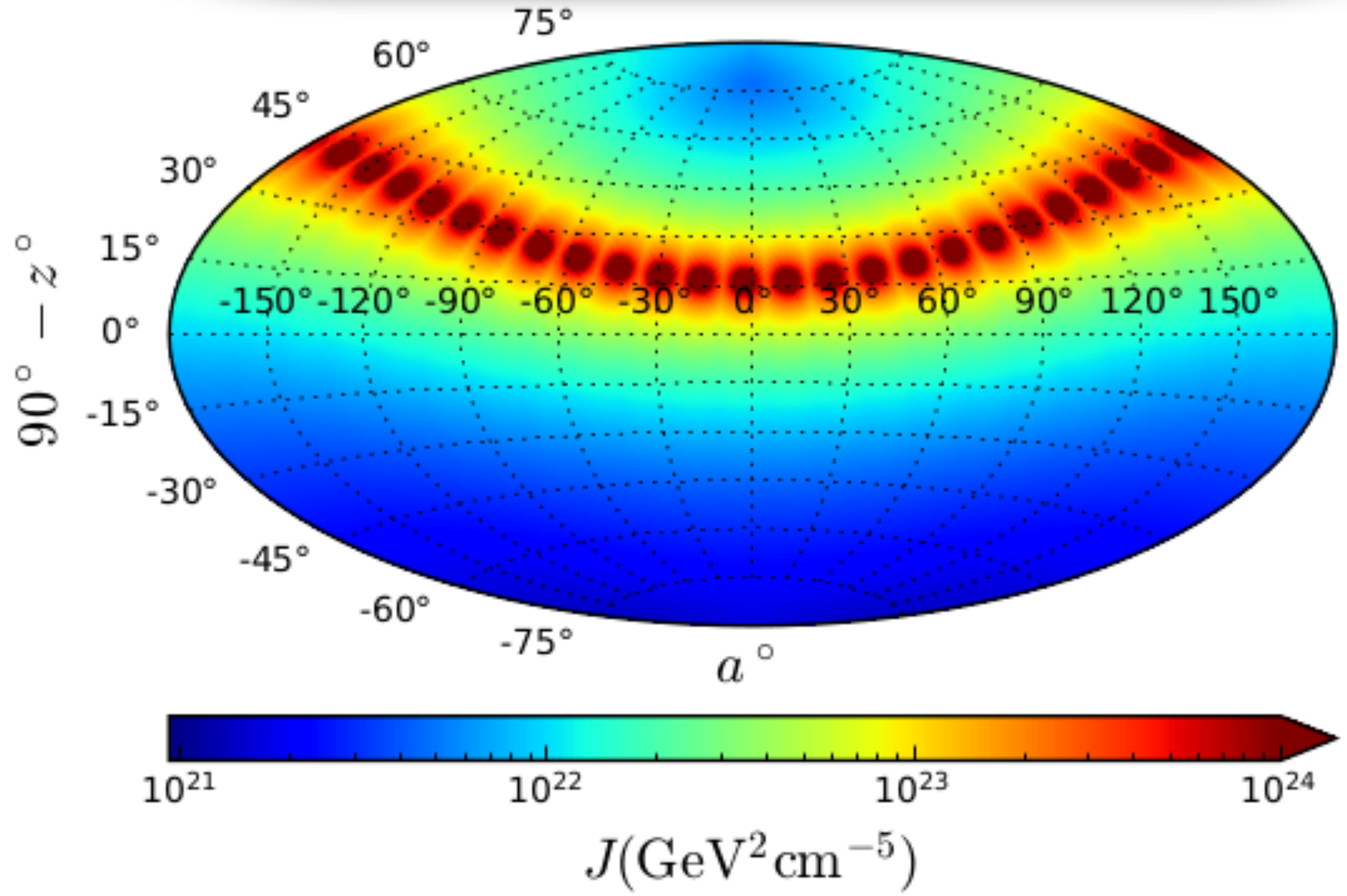
Differential neutrino spectrum

Galactic coordinates



Tracking the GC

Horizontal coordinates @ HyperK



DM Signal

Neutrino flux from extragalactic DM annihilation

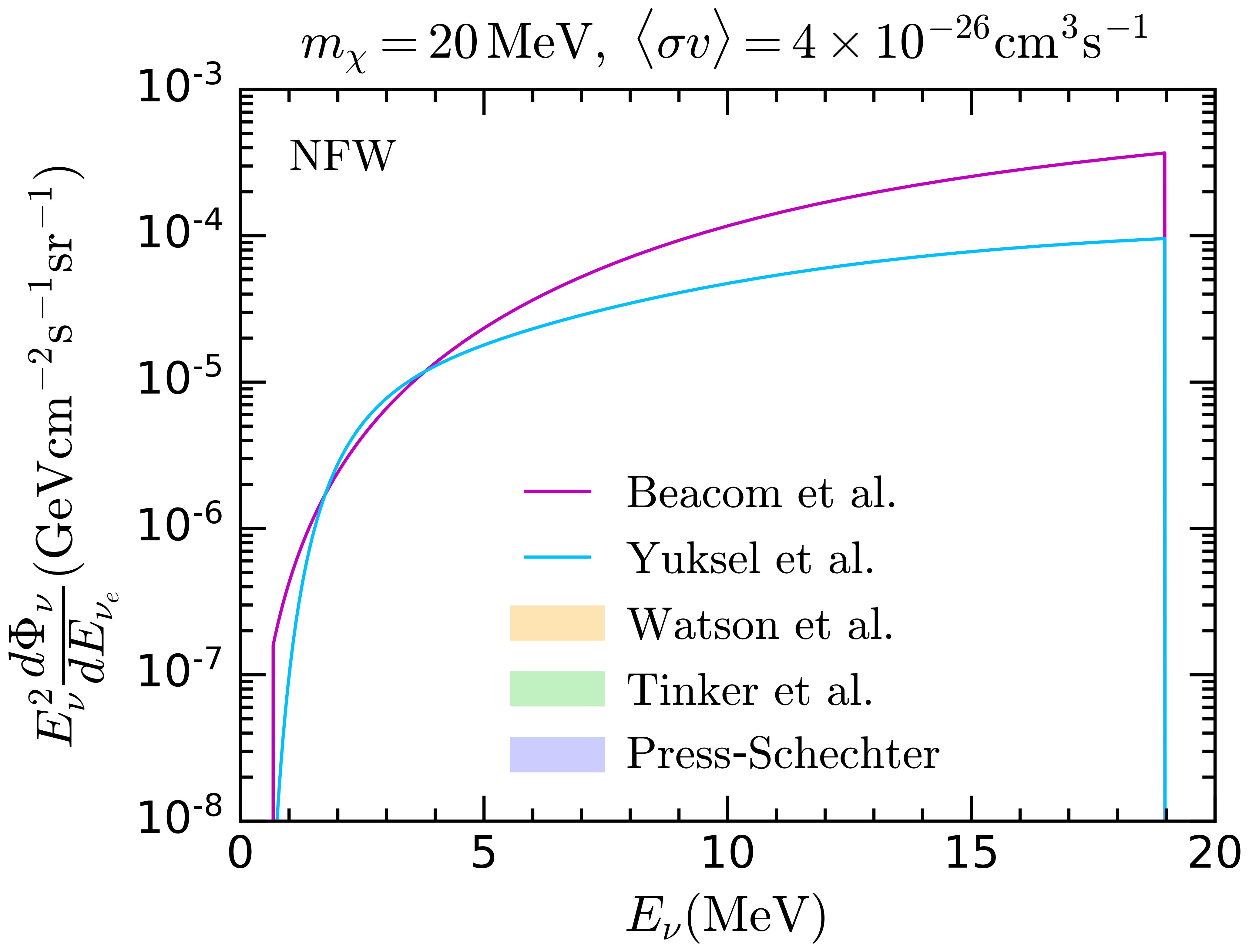
- Isotropic signal

Enhancement due to DM clustering

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\langle\sigma v\rangle}{2}\frac{c}{4\pi H_0}\frac{\Omega^2_{\mathrm{DM},0}\rho^2_{c,0}}{m^2_\chi}\int_0^{z_{up}} dz \frac{\Delta^2(z)}{\sqrt{\Omega_{m,0}(1+z)^3+\Omega_{\Lambda,0}}}\frac{dN_\nu(E'_\nu)}{dE'_\nu}$$

Differential neutrino spectrum

Beacom, Bell & Mack astro-ph/0608090



- Assumptions
  - ➡ DM density profile
  - ➡ DM clustering factor (halo mass function)

DSNB Signal

Neutrino flux from core-collapse supernovae

- Isotropic signal from all previous core-collapse SNe
- Core-collapse SN rate

$$R_{CCSN}(z) = \dot{\rho}_\star(z) \frac{\int_8^{50} \xi(M)dM}{\int_{0.1}^{100} M\xi(M)dM}$$

Star Formation Rate

Initial Mass Function

- DSNB flux

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

- Neutrino spectrum

$$\frac{dN_{\bar{\nu}_e}}{dE'_{\bar{\nu}_e}} = f(T_{\bar{\nu}_e}, E_{\bar{\nu}_e})$$

Neutrino temperature

- Assumptions
  - ➡ Star Formation Rate (SFR)
  - ➡ Initial Mass Function (IMF)

Horiuchi, Beacom & Dwek, arXiv: 0812.3157

Can neutrinos from DM annihilation contribute a significant background to DSNB searches?

next

DSNB flux

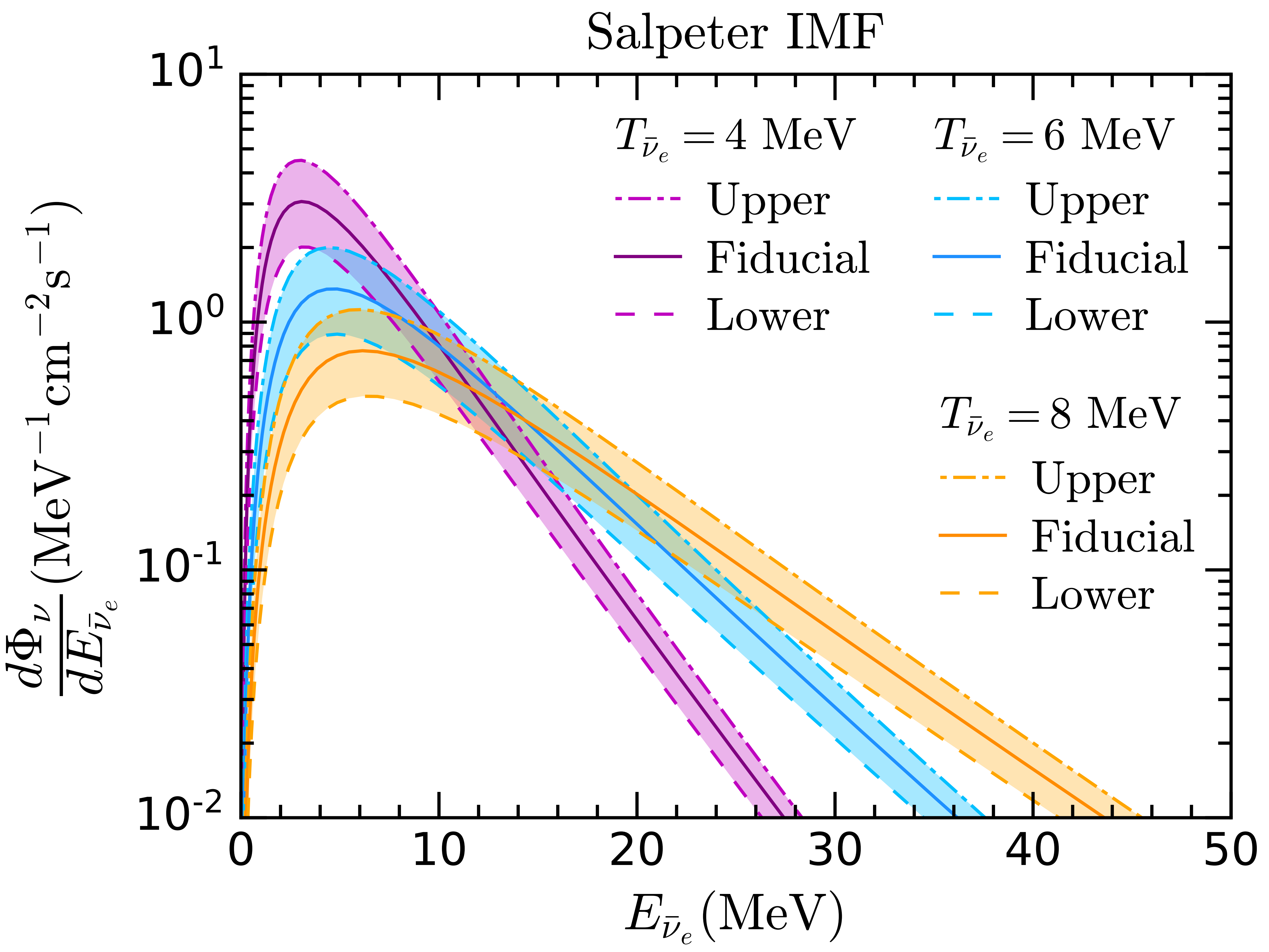
- Salpeter IMF
- SFR: continuous broken power law

$$\dot{\rho}_\star(z) = \dot{\rho}_0 \left[(1+z)^{\alpha\eta} + \left(\frac{1+z}{B}\right)^{\beta\eta} + \left(\frac{1+z}{C}\right)^{\gamma\eta} \right]^{1/\eta}$$

➡ Fits from Hubble and GRB data

SFR Fits	$\dot{\rho}_0$	α	β	γ
Upper	0.0213	3.6	-0.1	-2.5
Fiducial	0.0178	3.4	-0.3	-3.5
Lower	0.0142	3.2	-0.5	-4.5

Horiuchi, Beacom & Dwek, arXiv: 0812.3157

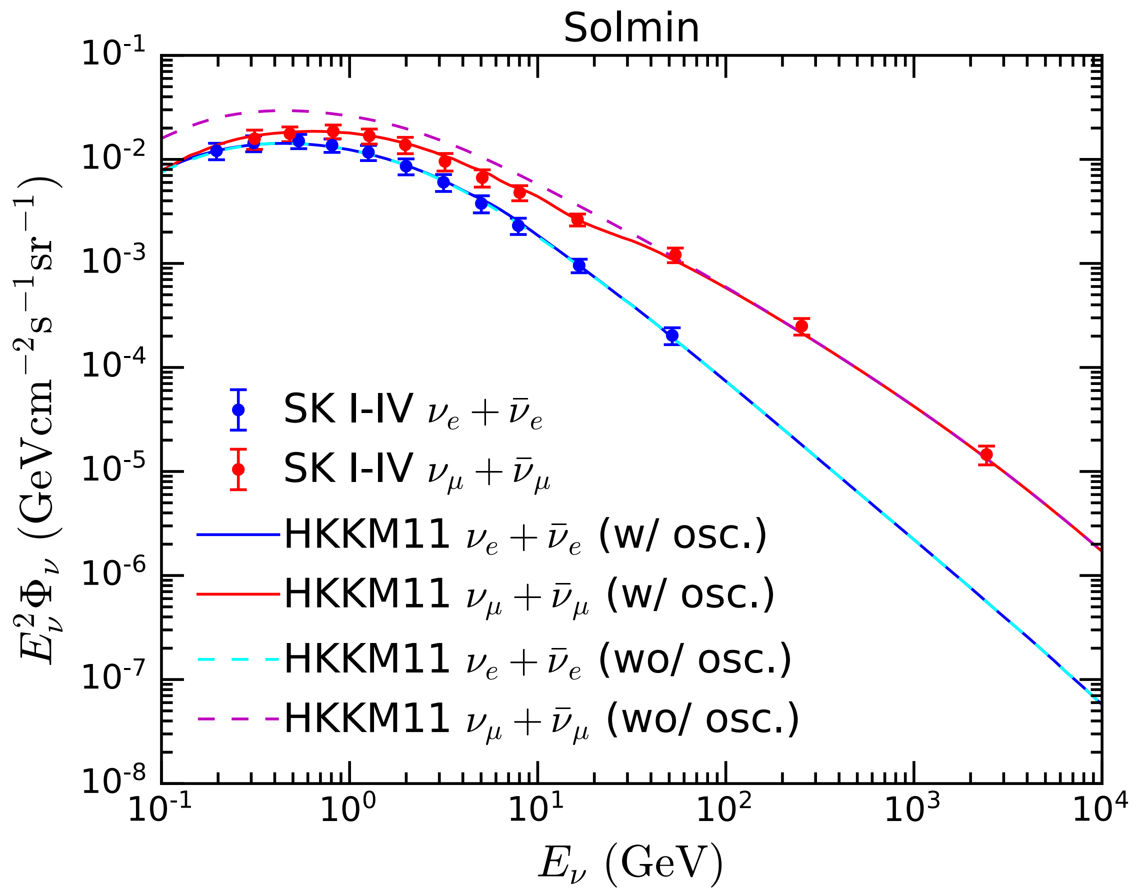


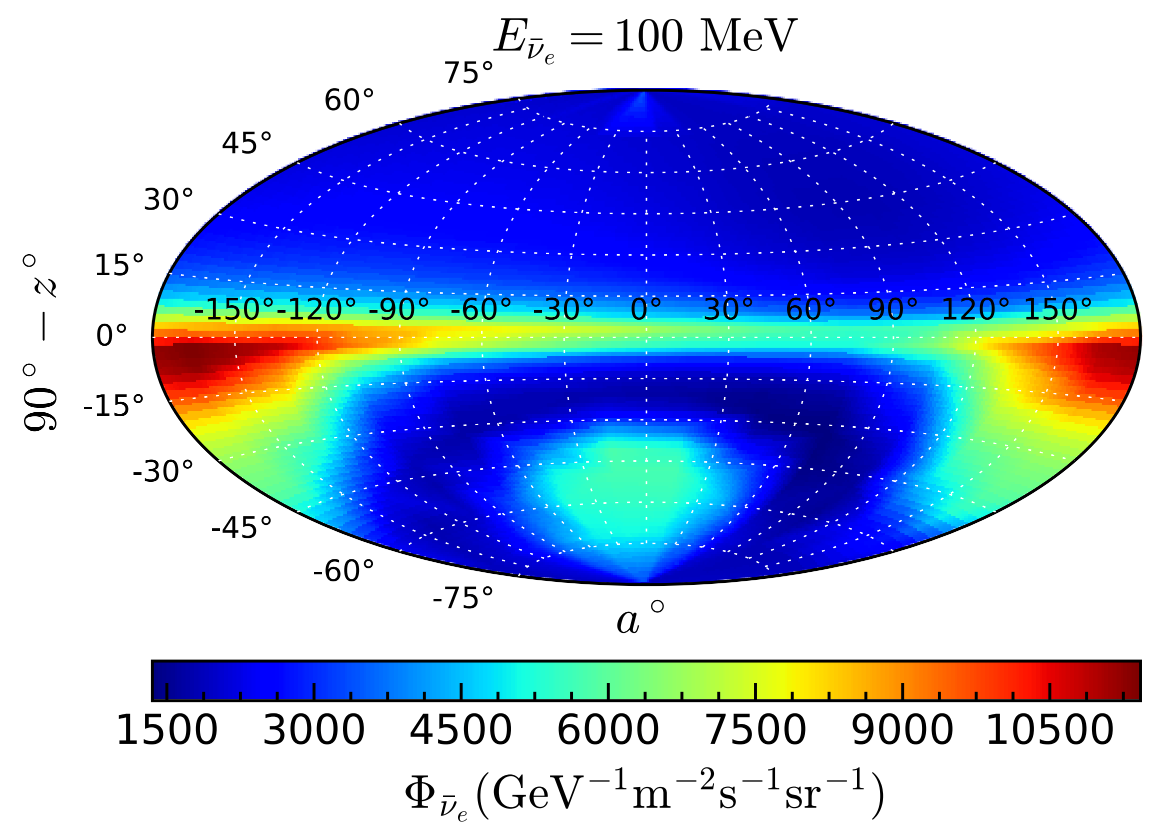
Detector simulation

- GENIE neutrino Monte Carlo event generator

  Andreopoulus et al. arXiv:1510.05494

- ROOT geometry package - detector geometry

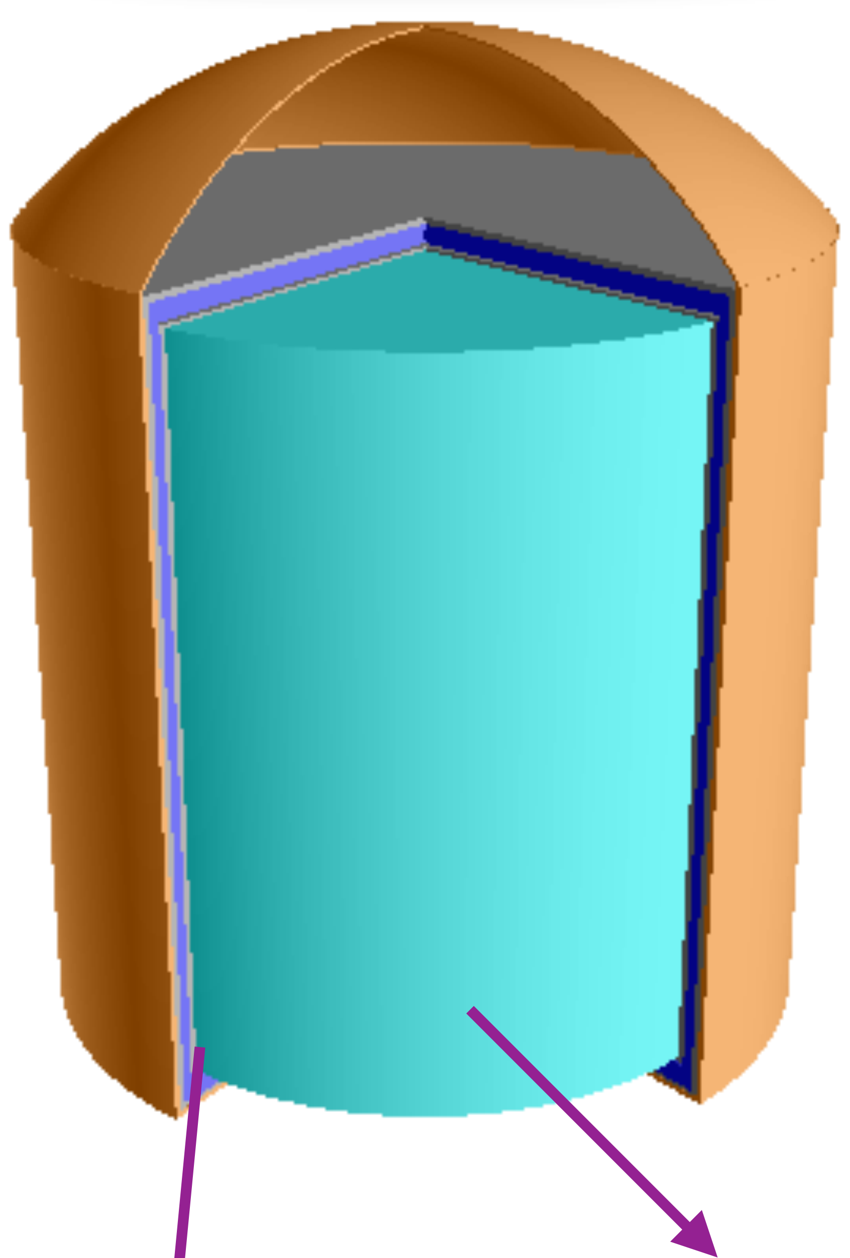




$$\Phi_\nu(E_\nu, z, a)$$

Atmospheric ν 4D flux
HKKM11: arXiv:1102.2688

HyperK



- ✓ Water
- ✓ Stainless steel
- ✓ Concrete
- ✓ Standard rock

Inner Detector

Outer Detector

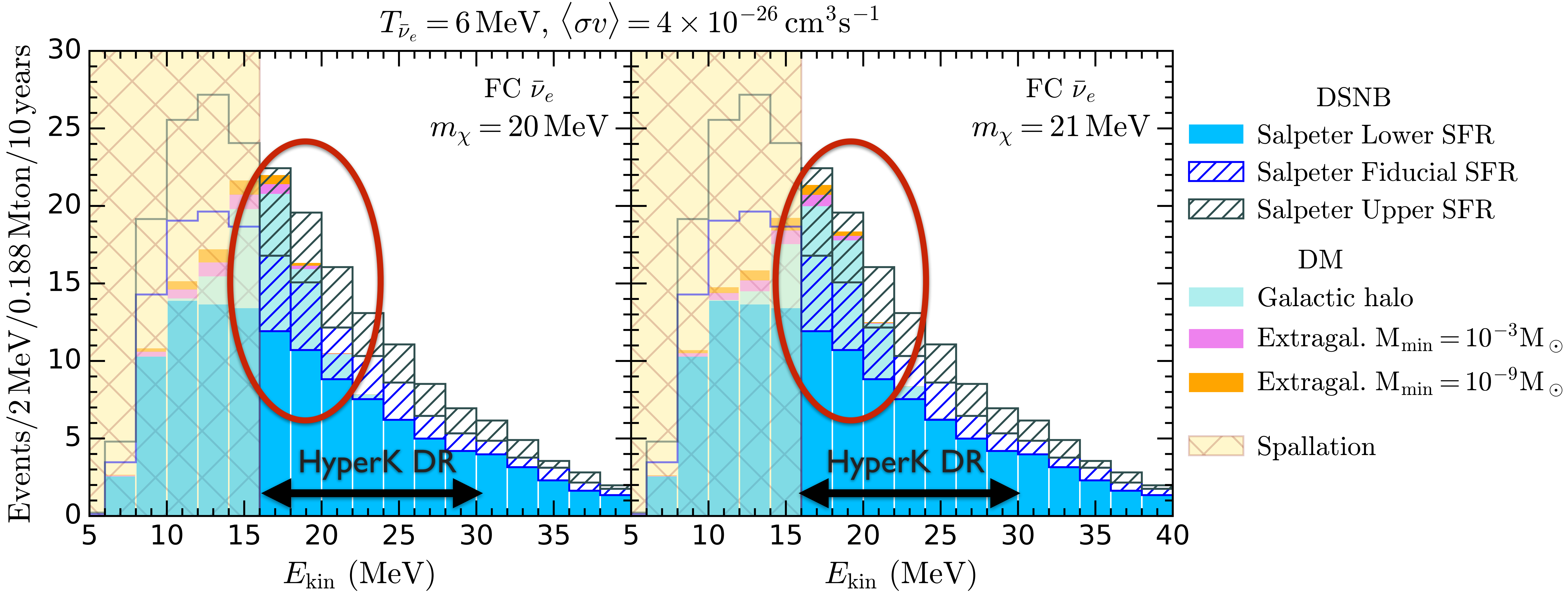
UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

- ✓ Kinematics
- ✓ Vertex of the interaction

- ✓ Tracking leptons & pions
- ✓ Smearing

Bell, Dolan & SR
arXiv: 2005.01950

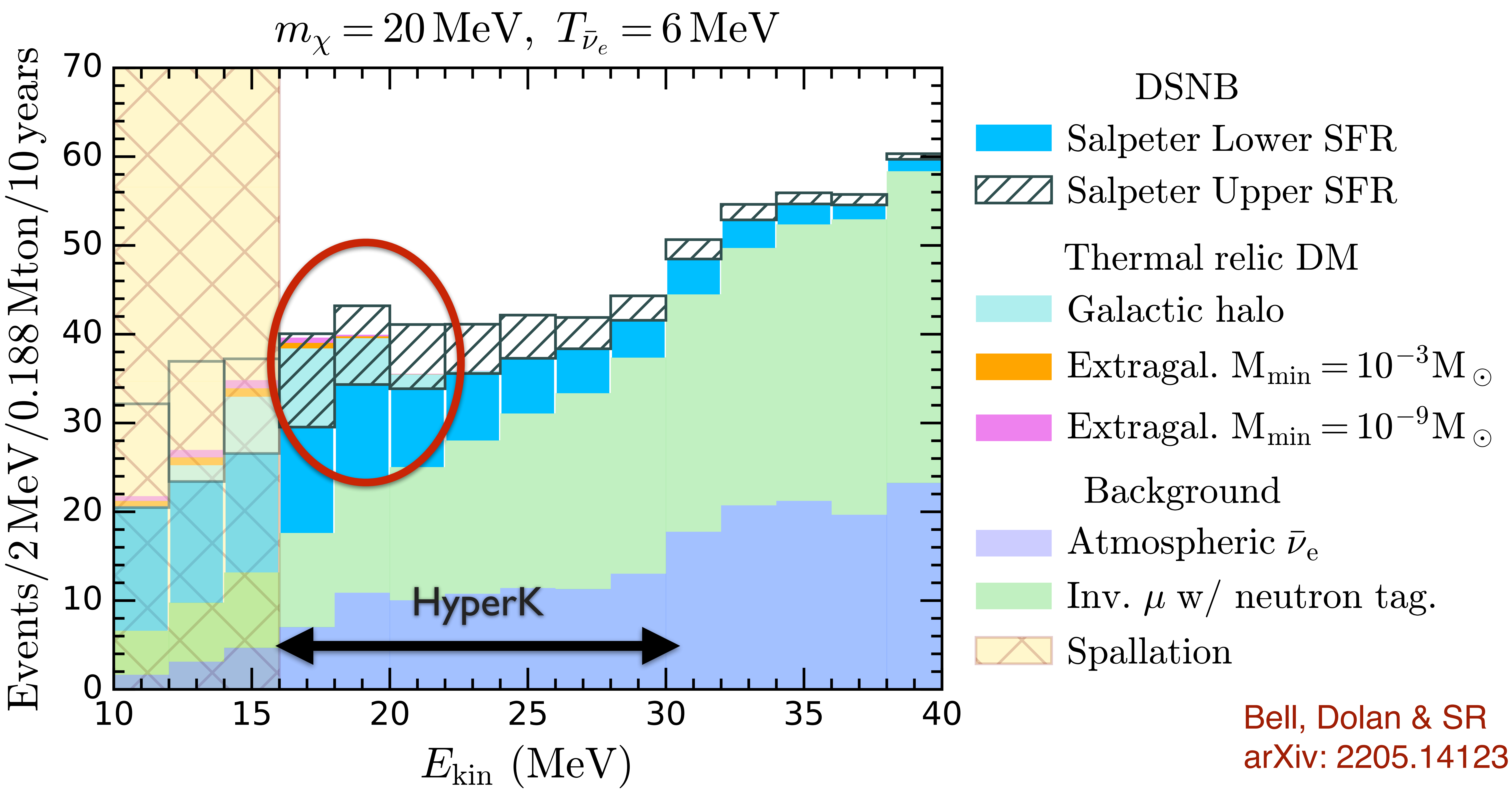
DSNB and DM events @ HyperK



Bell, Dolan & SR
arXiv: 2205.14123

Expected signal and background @ HyperK

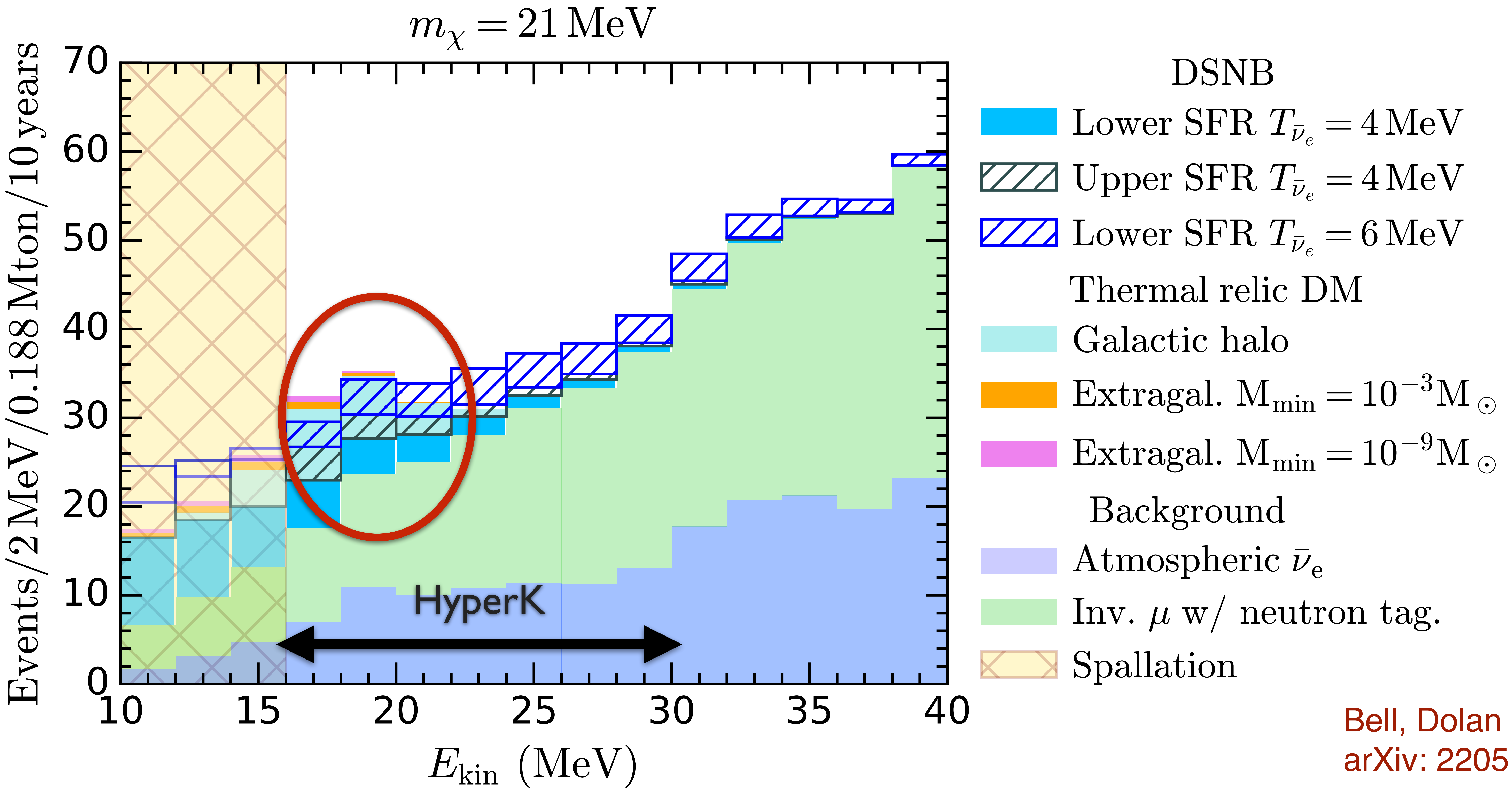
DSNB + DM → wrong SFR at 90% CL



Bell, Dolan & SR
arXiv: 2205.14123

Expected signal and background @ HyperK

DSNB + DM → wrong SFR or wrong T_ν at 95% CL

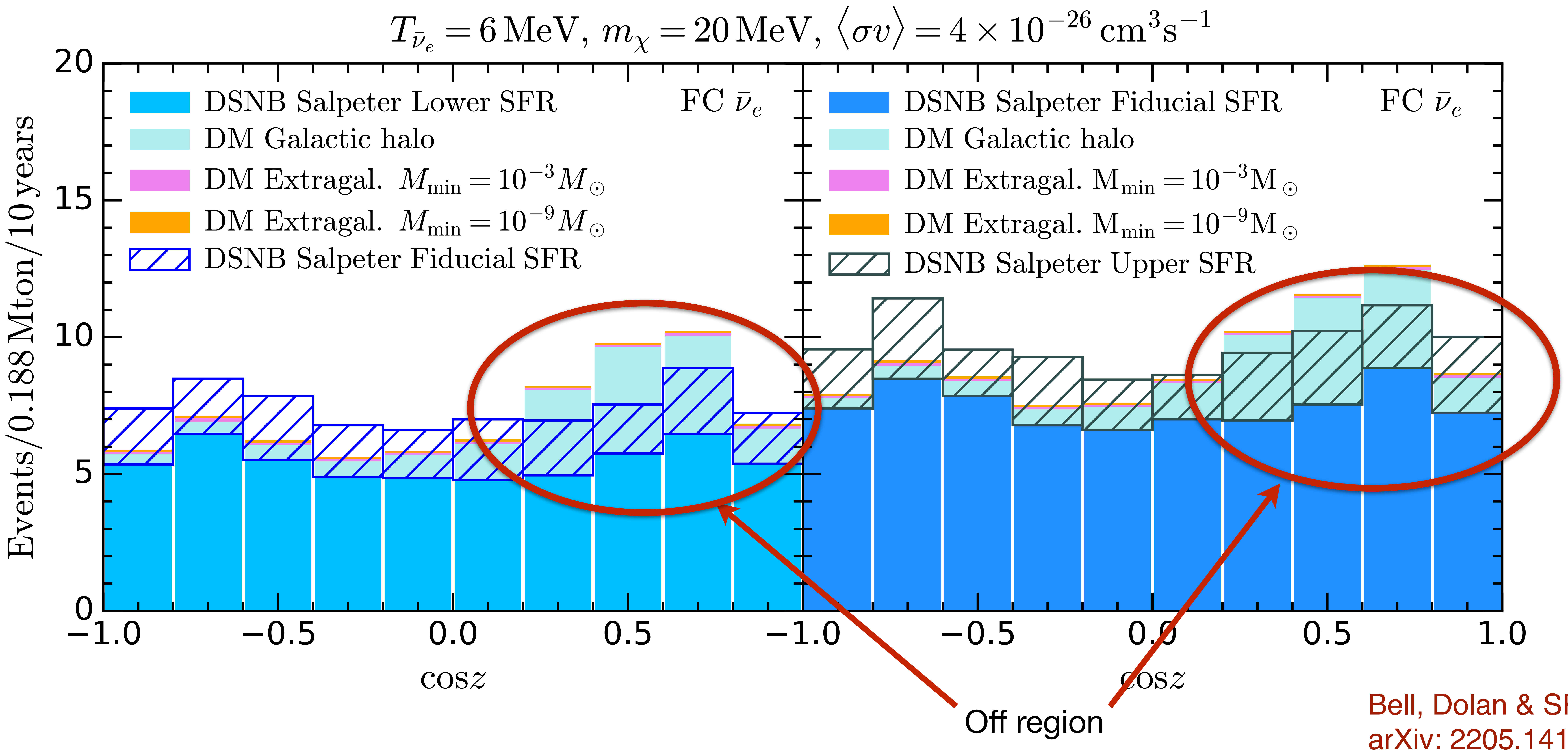


Bell, Dolan & SR
arXiv: 2205.14123

Is there a way to reliably disentangle DSNB and DM signals?

next

On-off analysis @ Hyper-K



Bell, Dolan & SR
arXiv: 2205.14123

Summary

- Pollution from neutrinos from light DM annihilation

  ➡ could lead to incorrect inferences about the astrophysics behind the DSNB and potentially missing a sub-GeV DM signal.

- Using our dedicated simulation of the HyperK detector, we have shown that this could occur.
- Fortunately, a simple on-off analysis can help in detecting the presence of DM.
- This technique can be applied to other experiments that have sensitivity to the DSNB (JUNO and DUNE).

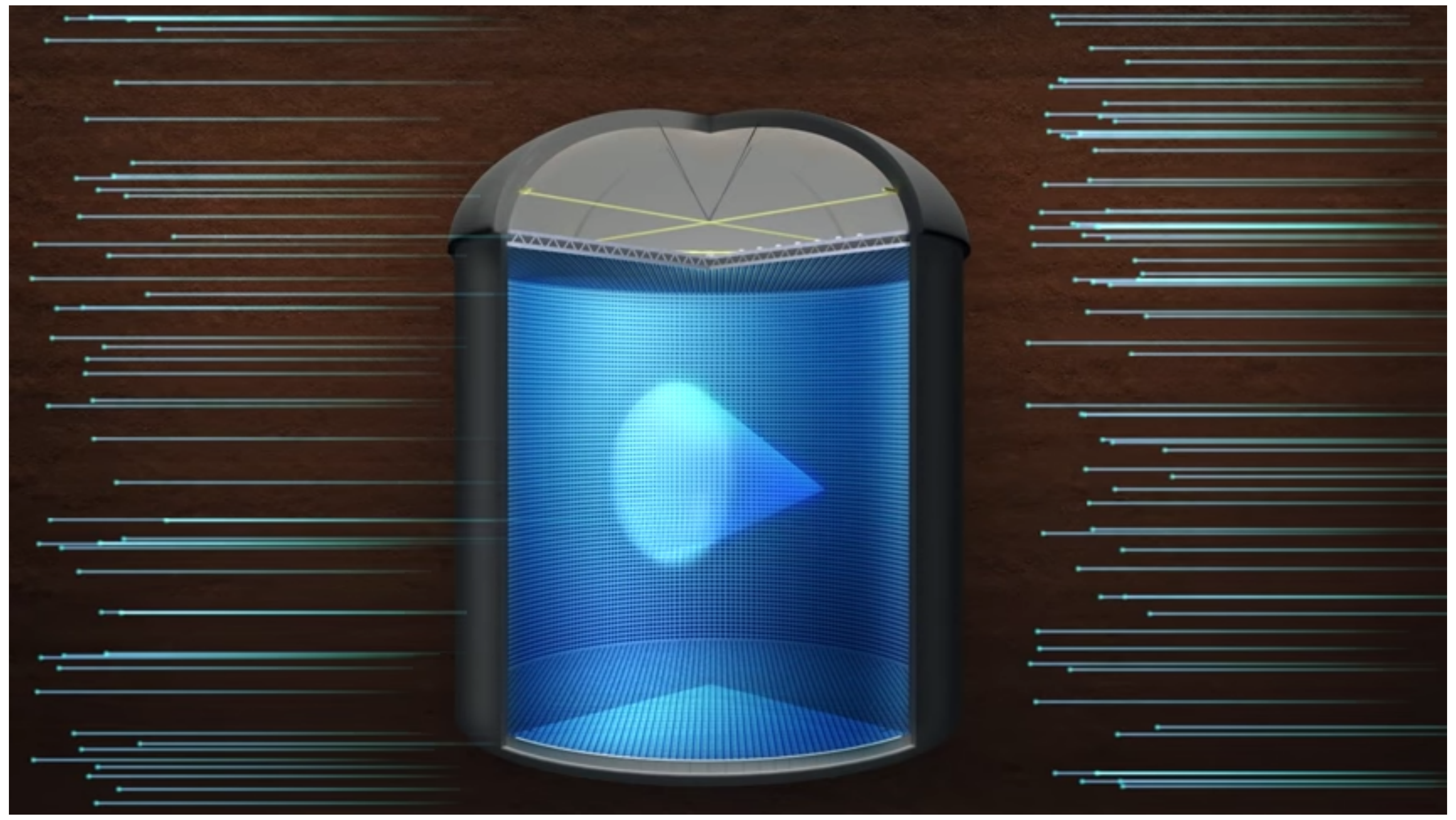


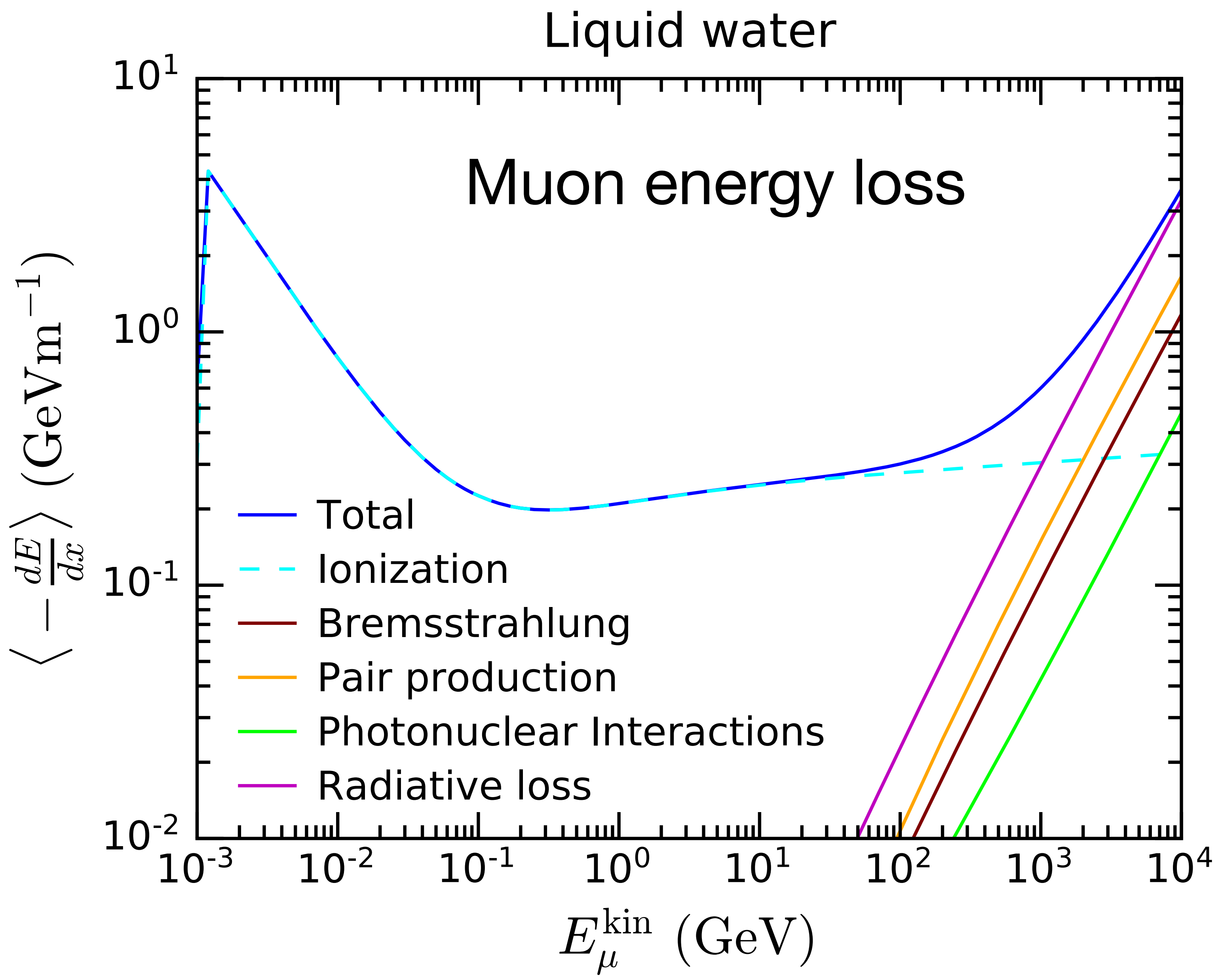
Image credit: ICRR (Institute for Cosmic Ray Research), The University of Tokyo

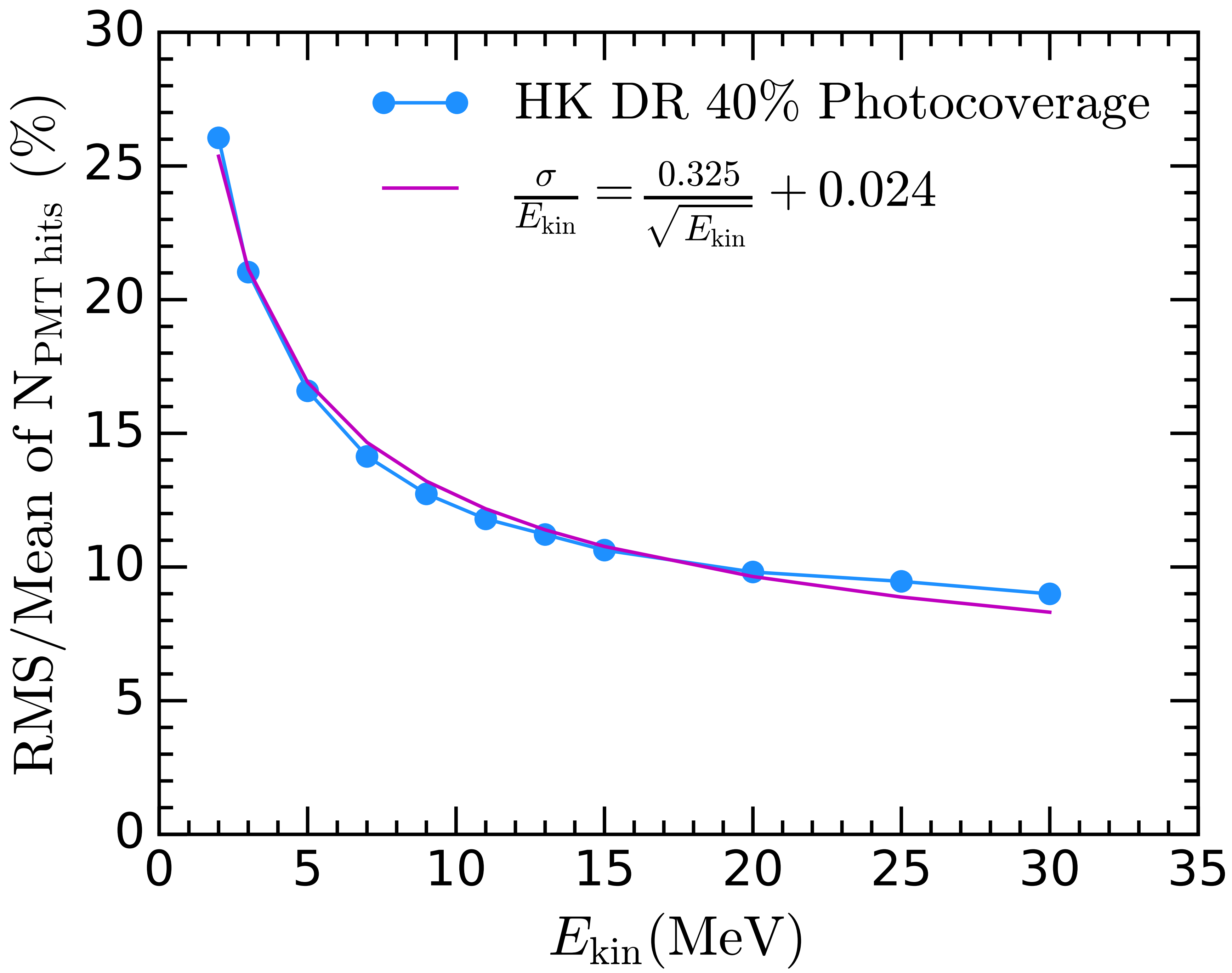
Thank you for your attention!

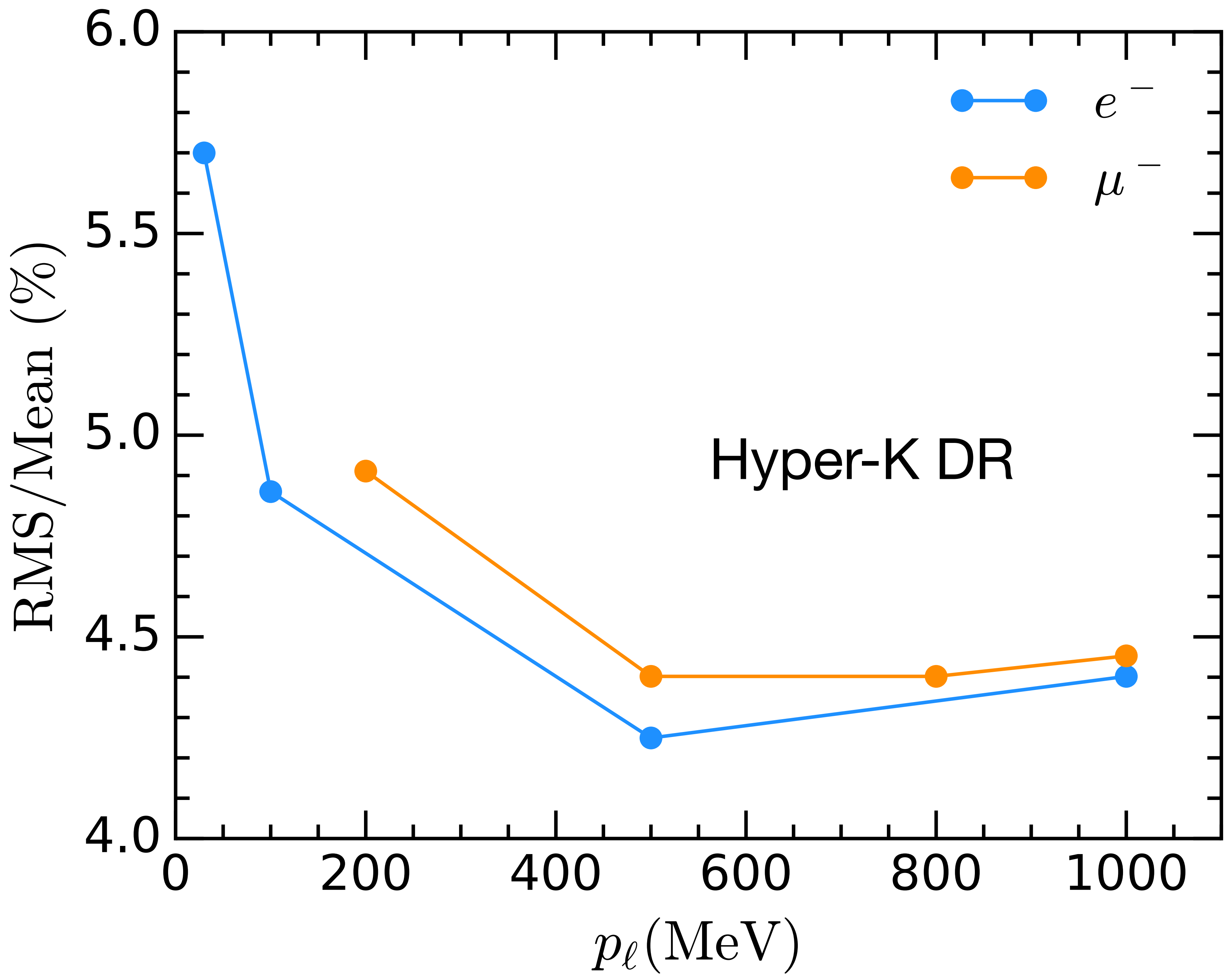
Backup

Detector simulation - FC & PC

- Tracking final leptons and pions
  - ➡ Event categories: FC, PC
- Smearing

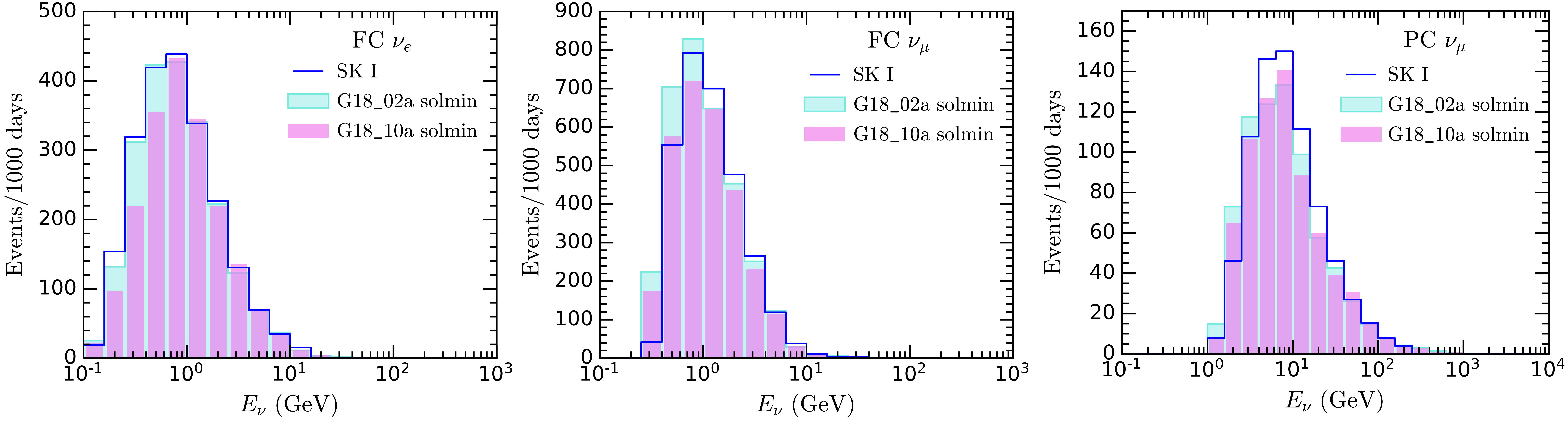






Detector simulation - FC and PC events

✓ Validation against atmospheric neutrinos events expected at Super-K



SuperK-I hep-ex/0501064

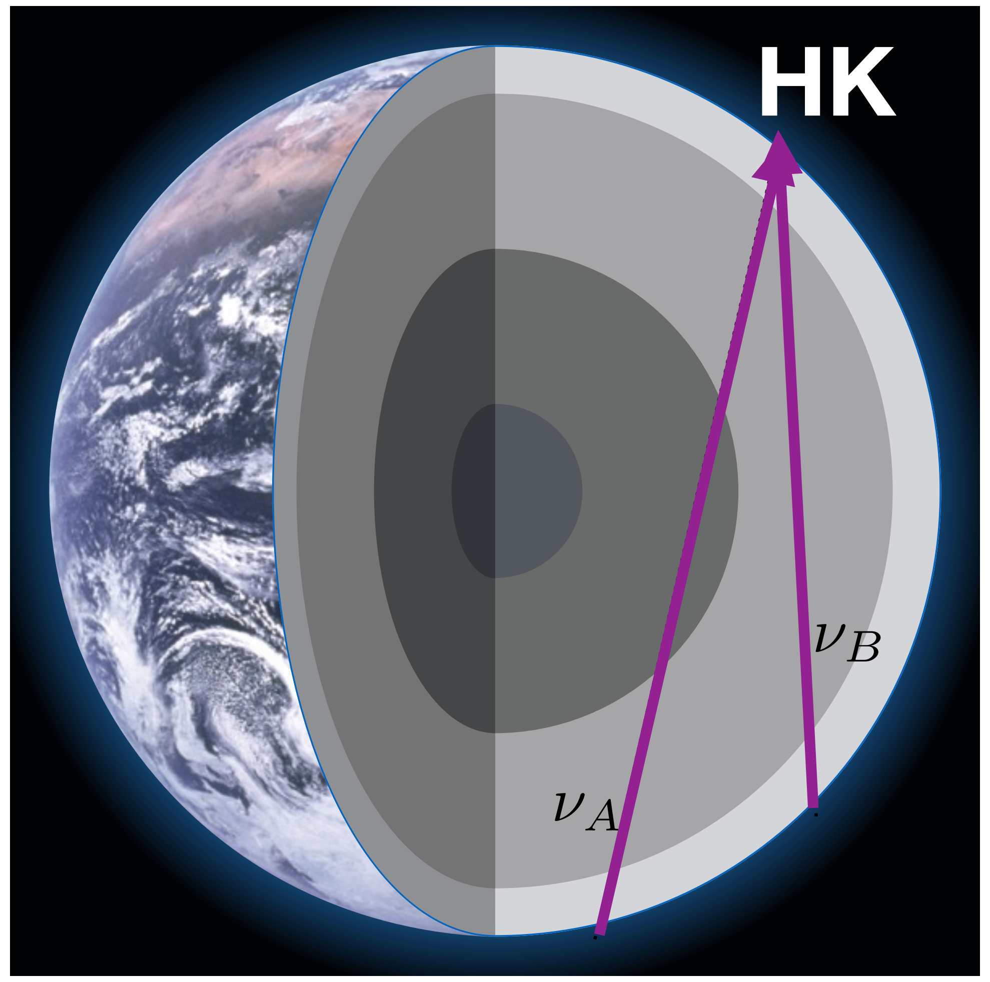
Bell, Dolan & SR
arXiv: 2005.01950

Background simulation

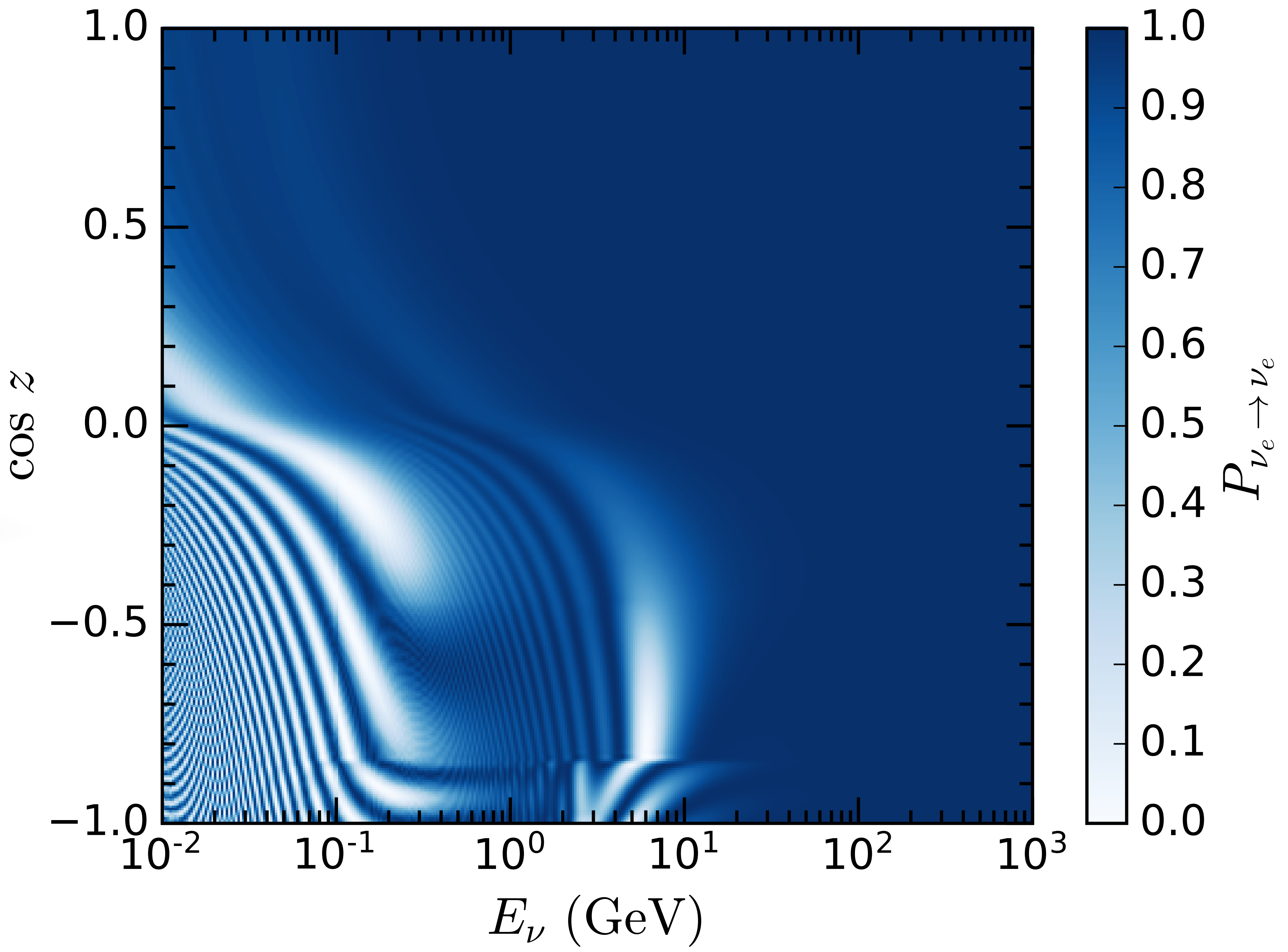
Neutrino oscillations at HyperK depth — nuCraft + Earth PREM model

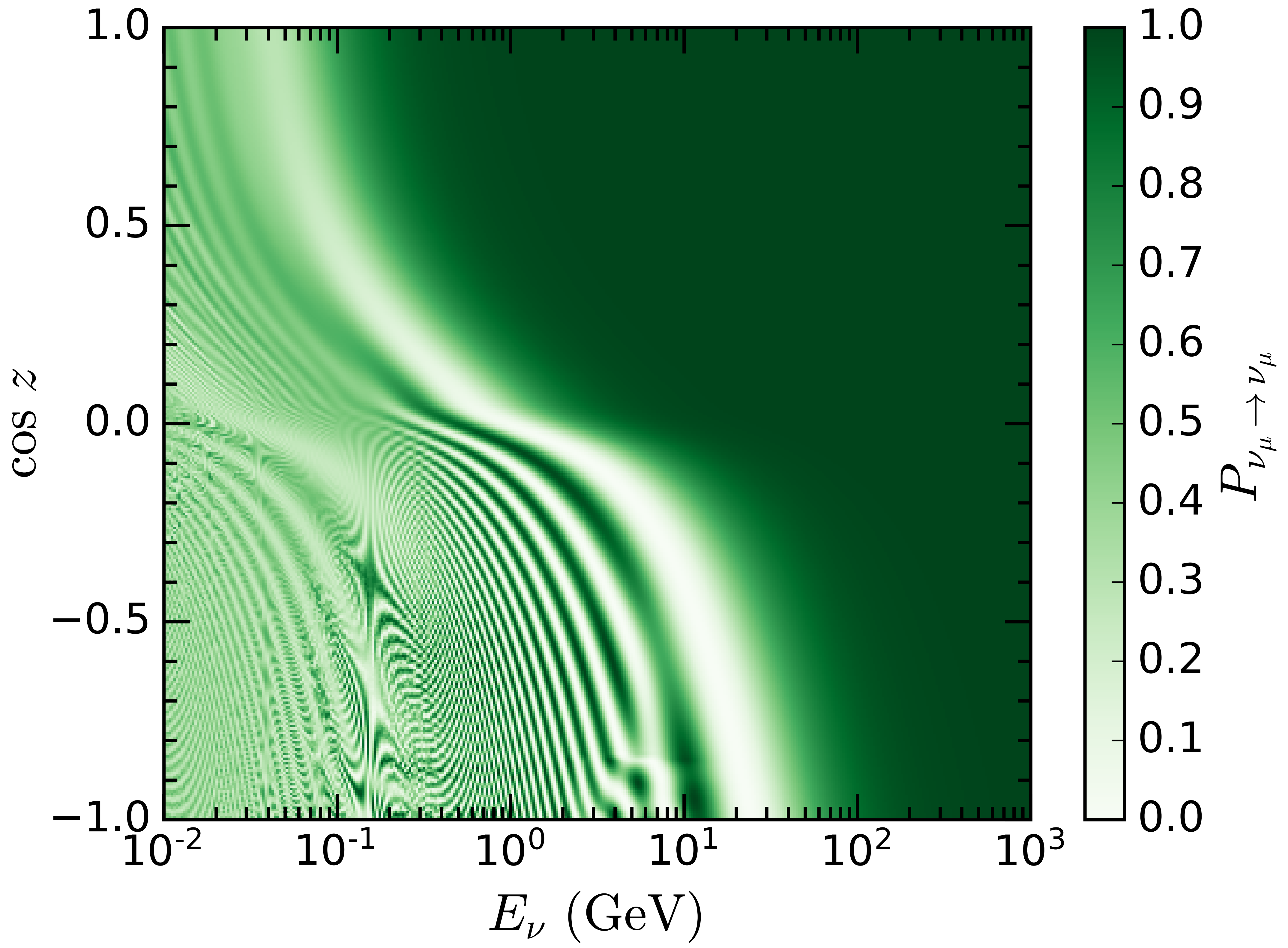
Wallraff & Wiebusch, arXiv:1409.1387

- Normal hierarchy
- Oscillations parameters from PDG



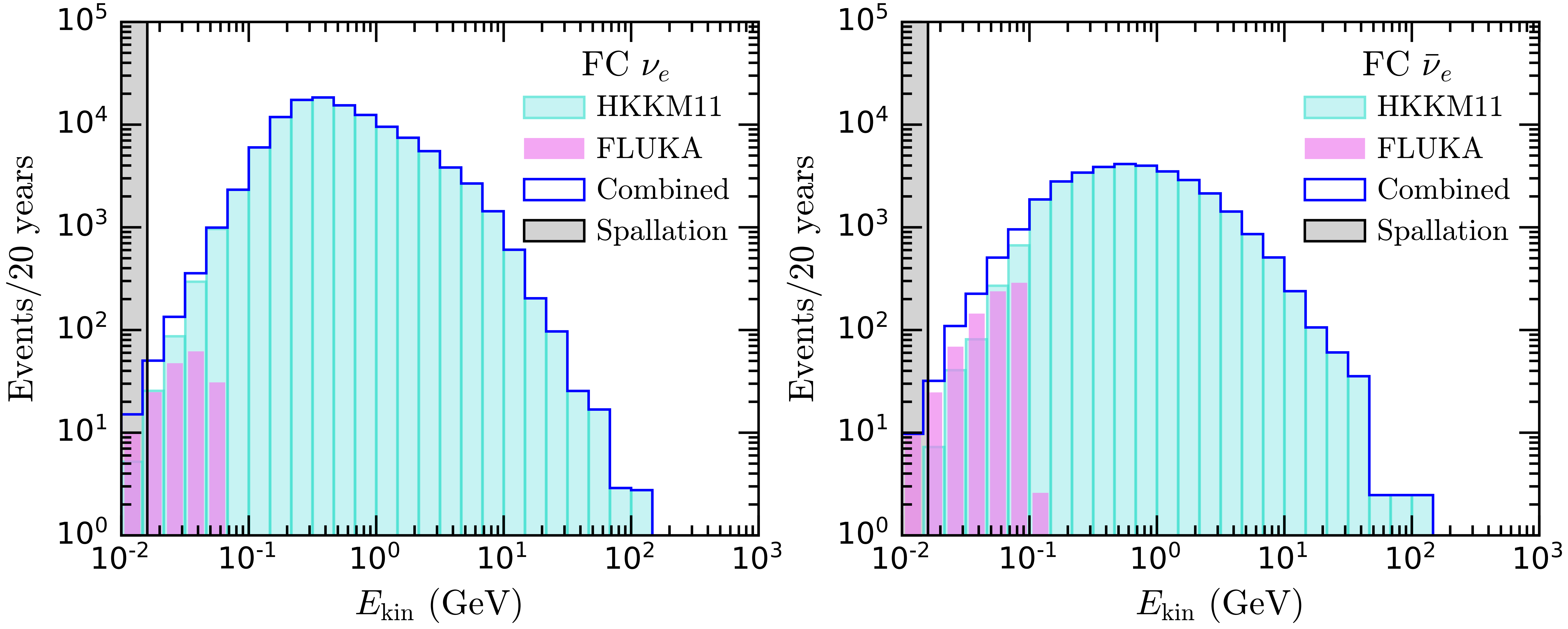
Altitude





Atmospheric neutrinos @ HyperK

FLUKA (13 MeV —100 MeV) + HKKM11 (100 MeV — 1TeV)



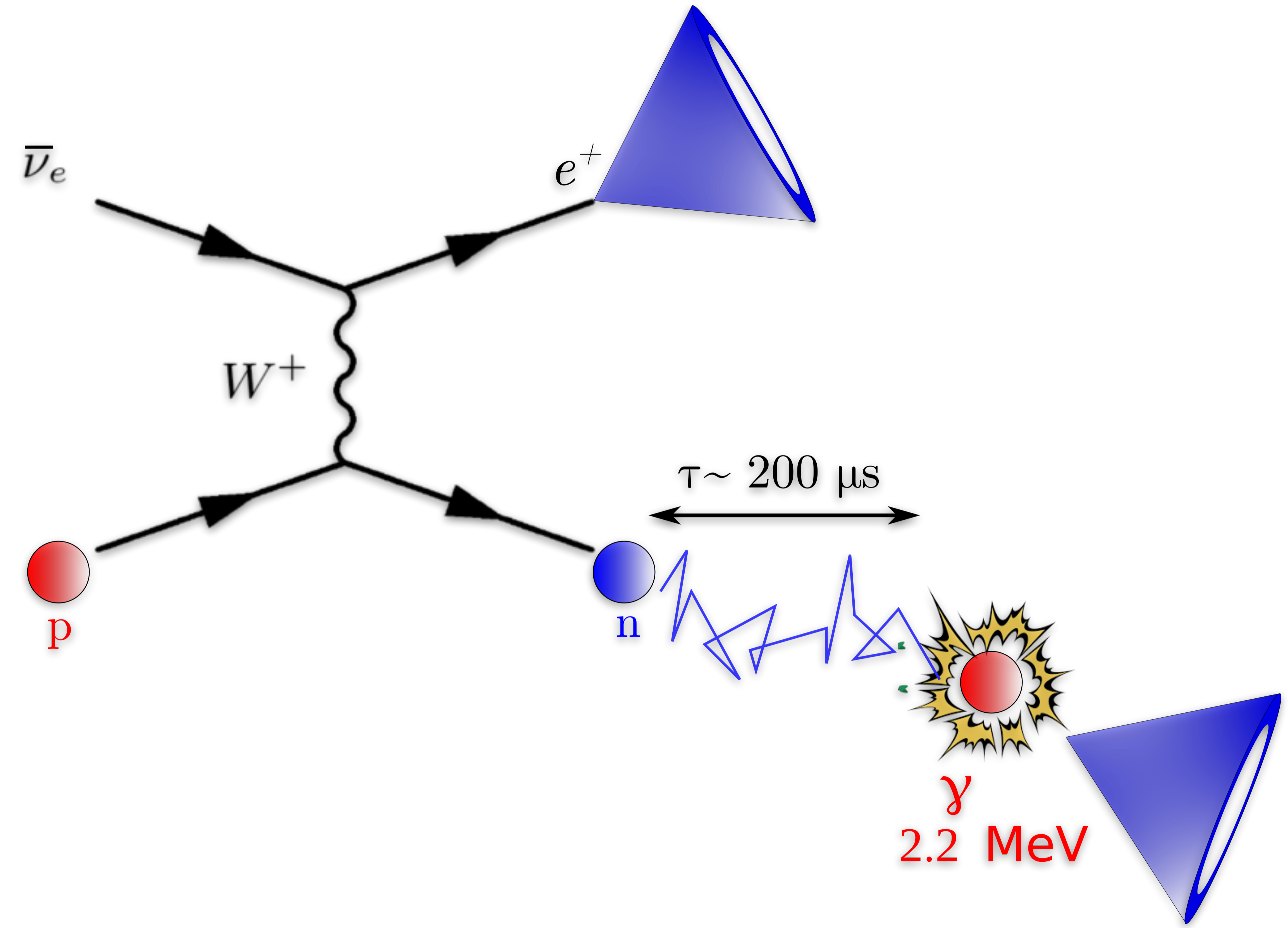
FLUKA LowE: Battistoni et al., Astropart. Phys. 23 (2005) 526

Bell, Dolan & SR
arXiv: 2005.01950

Background for DSNB searches

- Neutron tagging - hydrogen

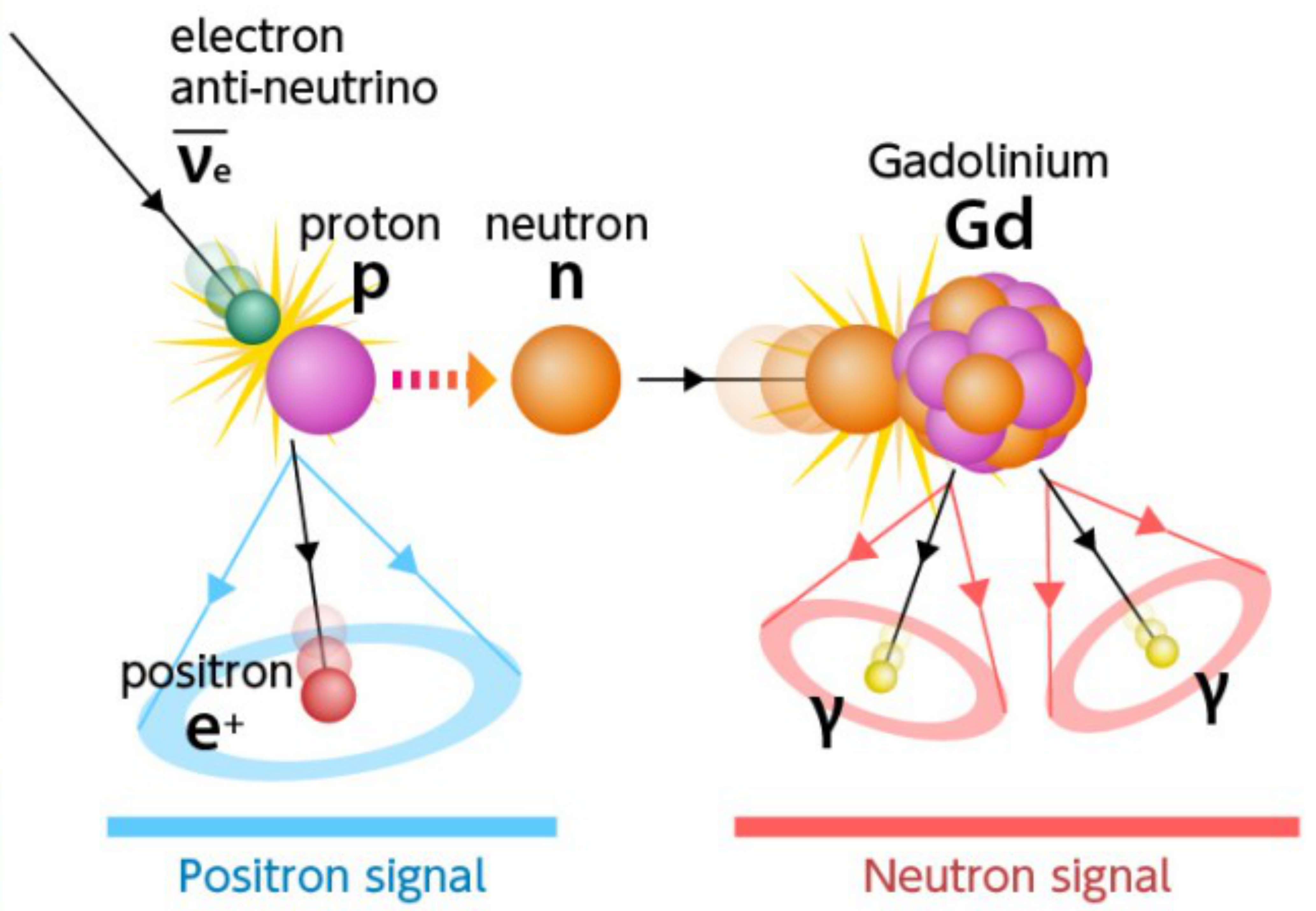
➡ Detection efficiency at SuperK ~20%



SuperK Collaboration arXiv: 2109.11174

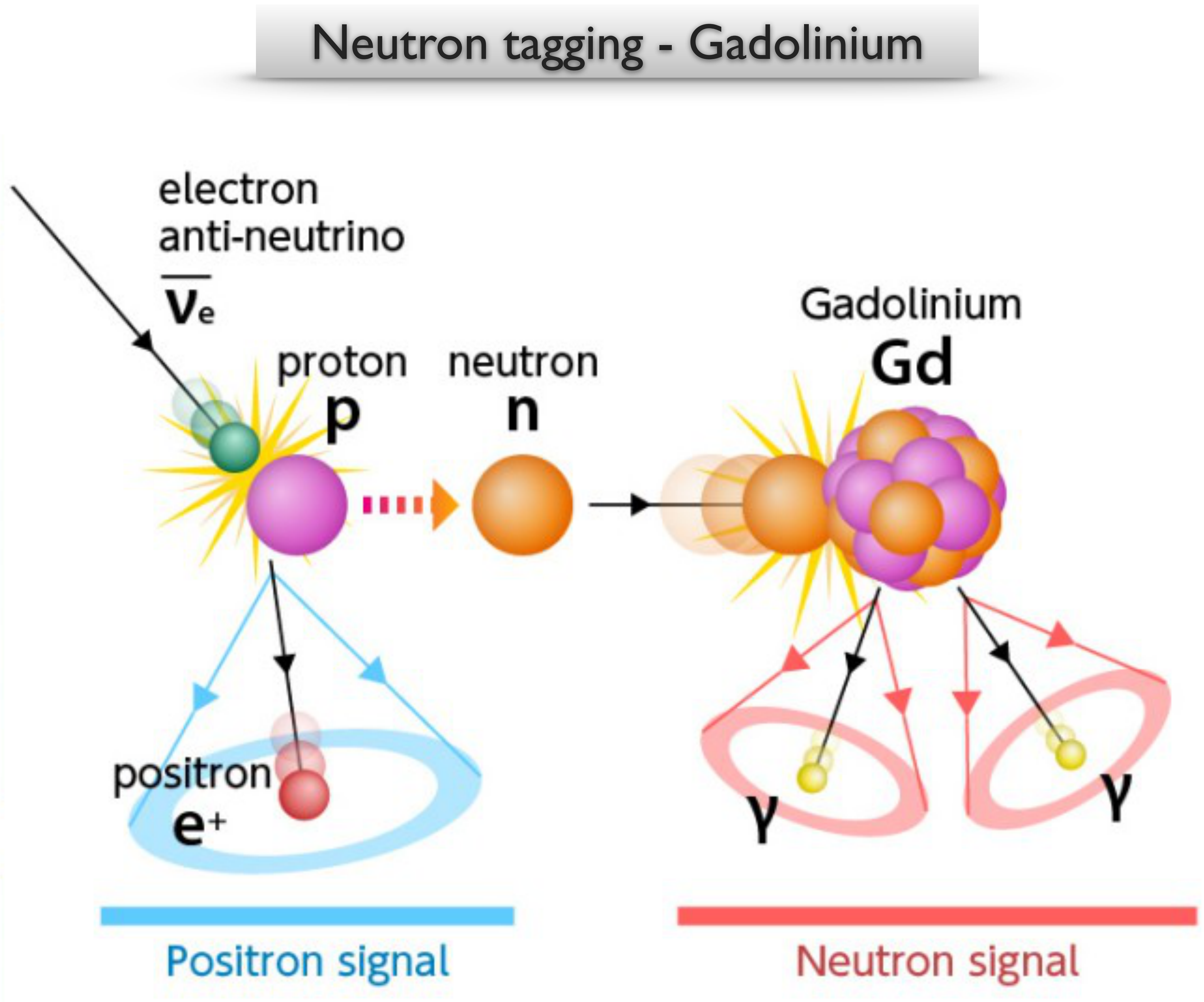
- SuperK has been upgraded to include gadolinium

➡ Detection efficiency > 70%

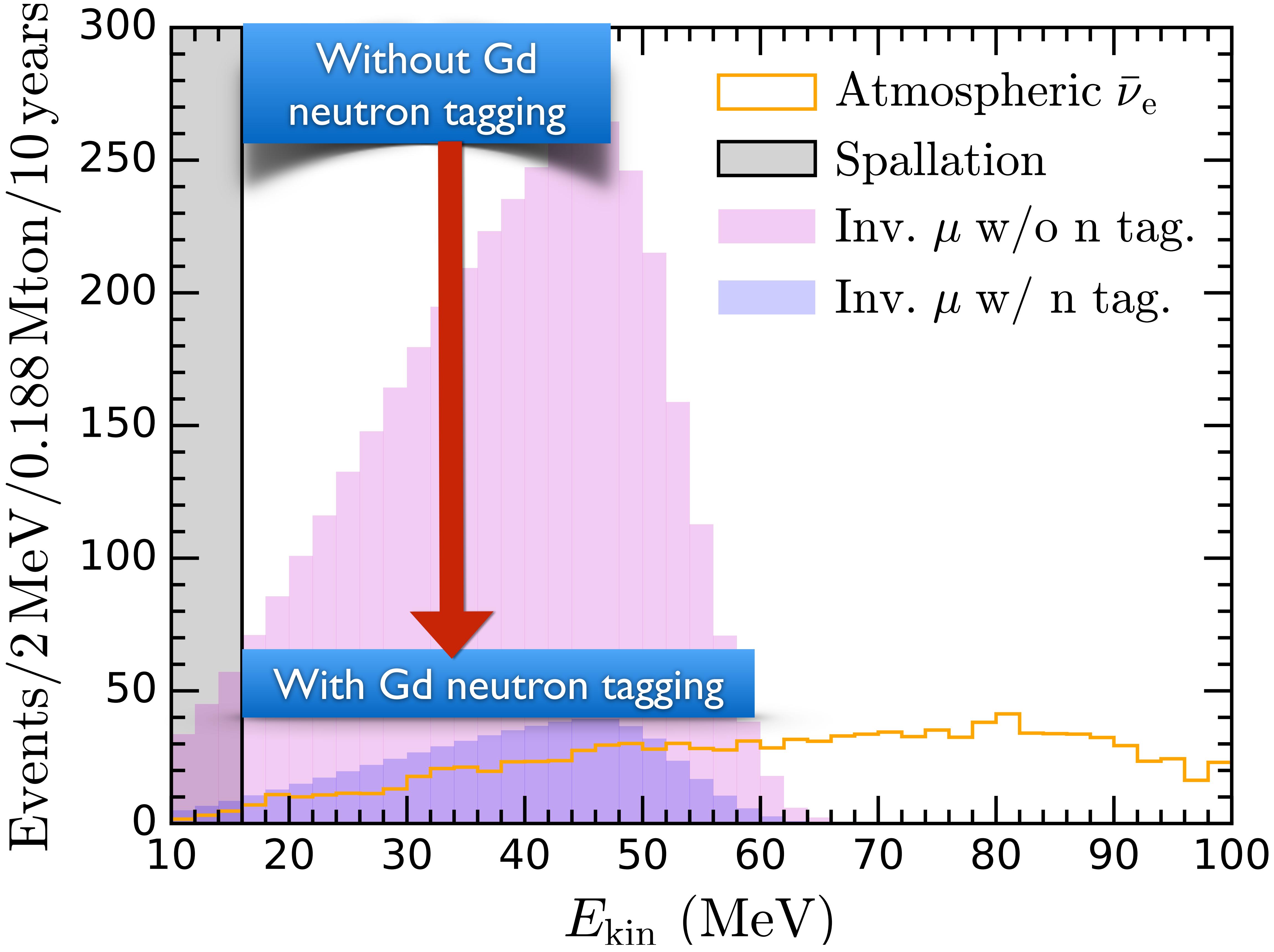


Background for DSNB searches

- Invisible muons from HyperK design report

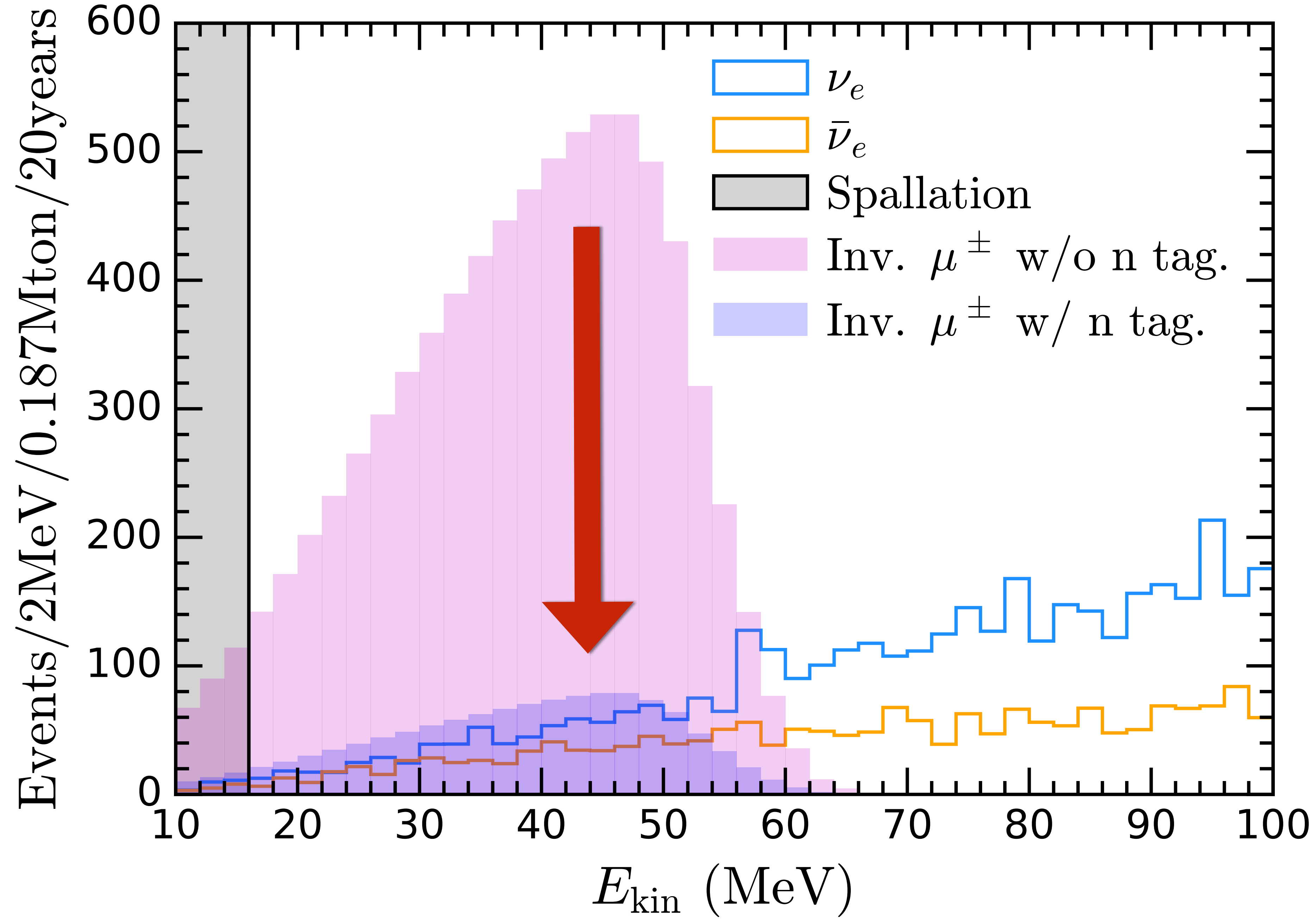


- Background at HyperK



HyperK projected sensitivity

Neutron tagging - Gadolinium loading



Bell, Dolan & SR
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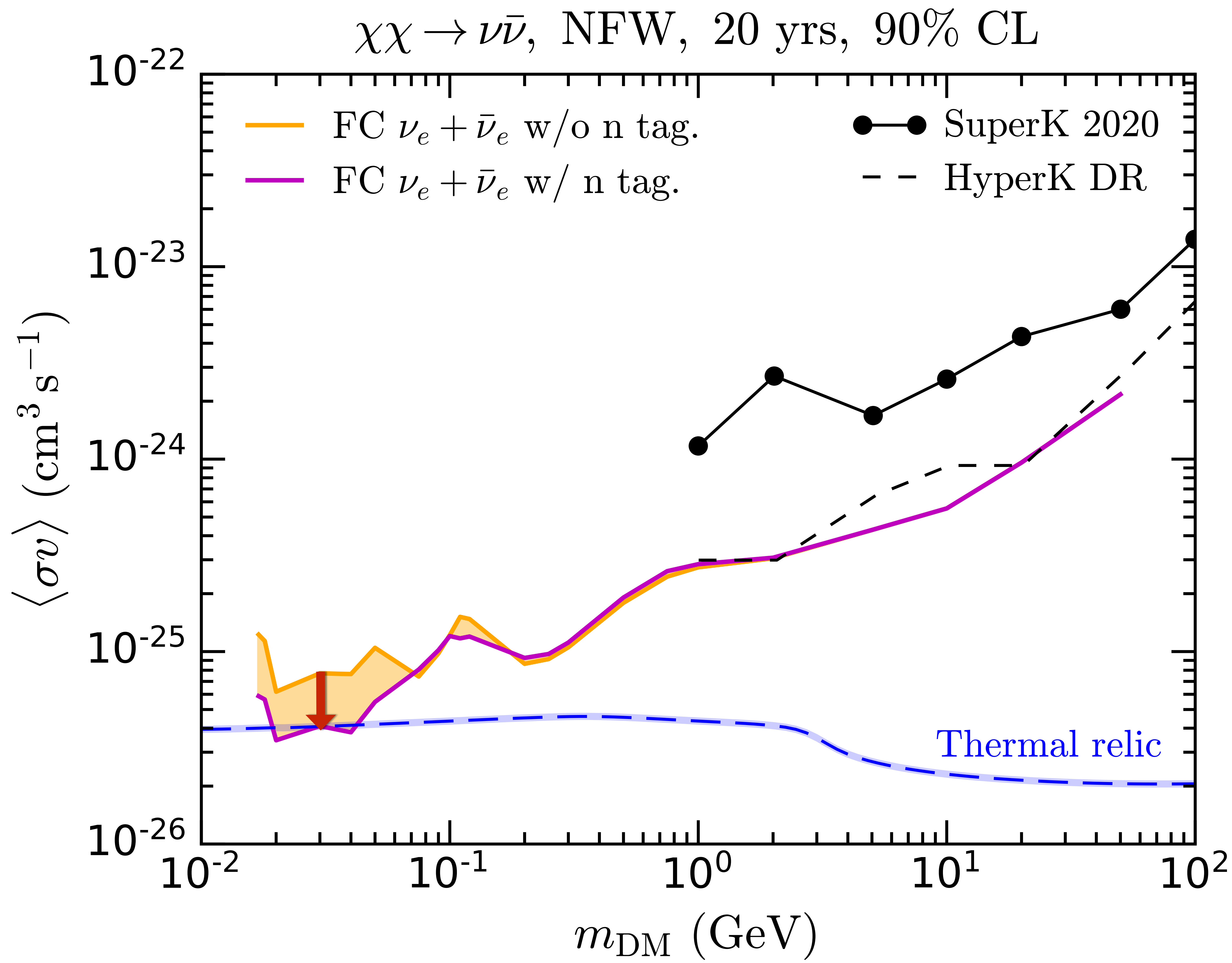


DSNB Signal

Neutrino flux from core-collapse supernovae

Core-collapse SN rate

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

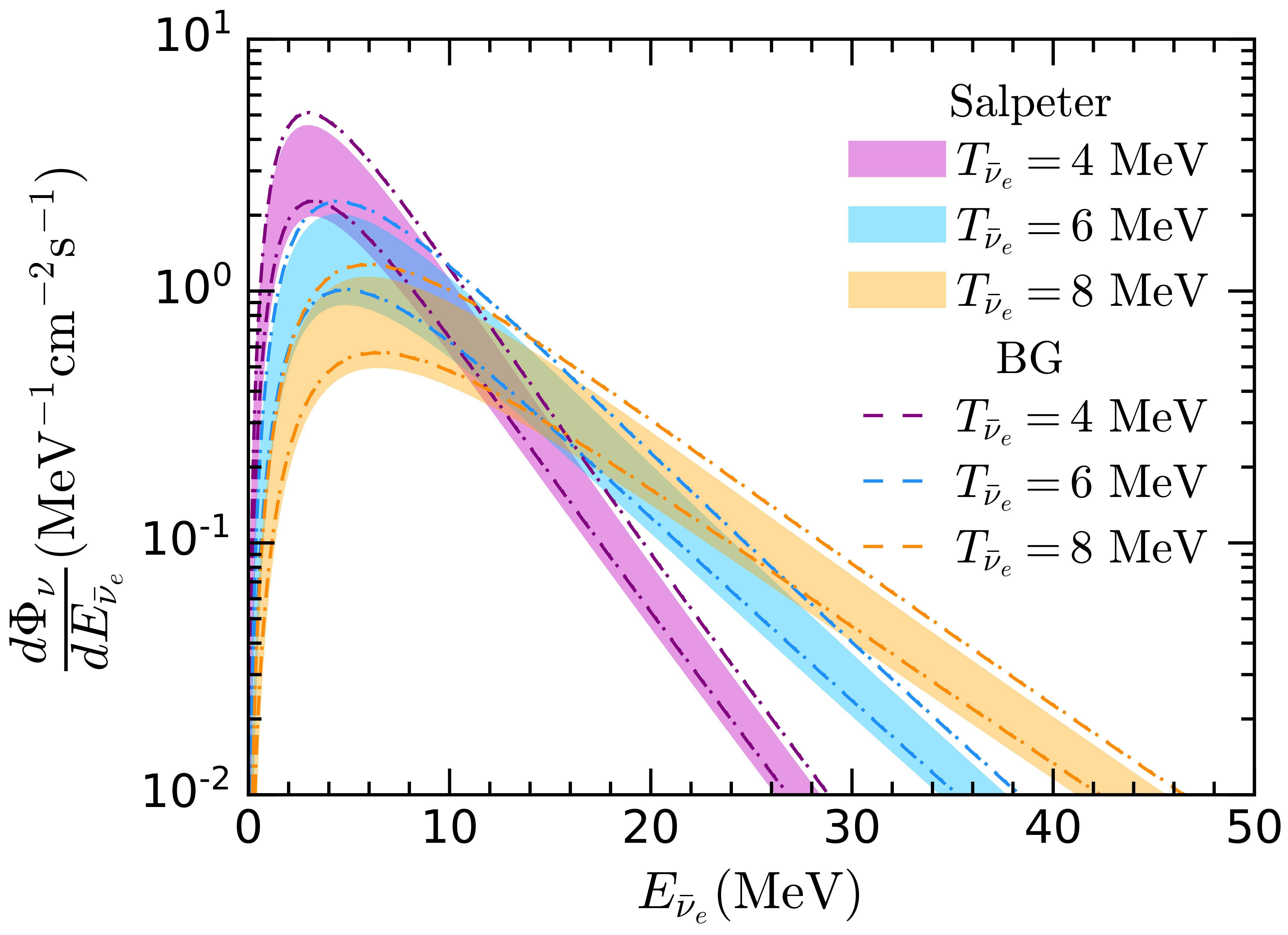
$$\frac{dN_{\bar{\nu}_e}}{dE'_{\bar{\nu}_e}}(E'_{\bar{\nu}_e}) = \frac{120}{7\pi^4}\frac{E_\nu^{tot}}{6}\frac{E'^2_{\bar{\nu}_e}}{T^4_{\bar{\nu}_e}}\frac{1}{e^{E'_{\bar{\nu}_e}/T_{\bar{\nu}_e}}+1}$$

Differential neutrino spectrum

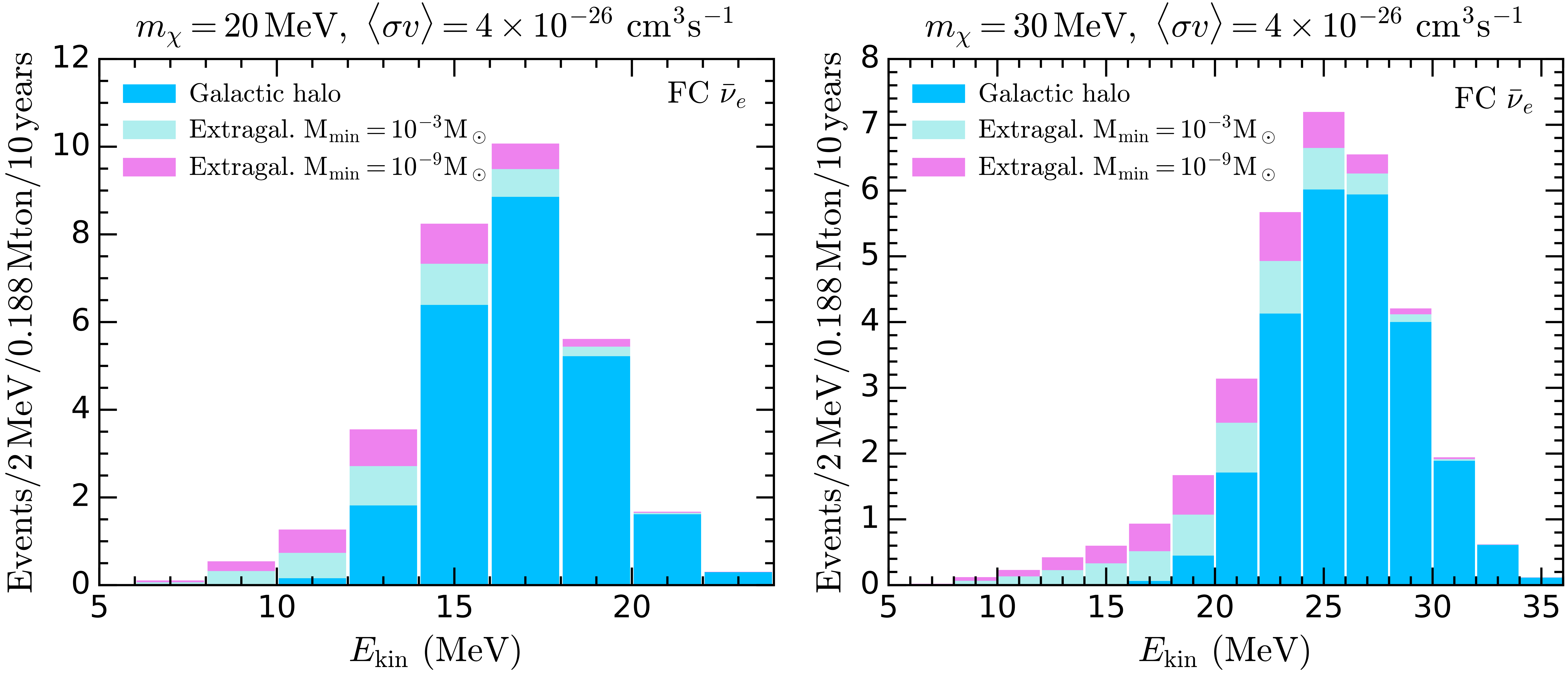
Horiuchi, Beacom & Dwek, arXiv: 0812.3157

- Rather insensitive to the IMF

➡ Salpeter, Kroupa, Baldry-Glazebrook (BG)



Expected DM events @ HyperK



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