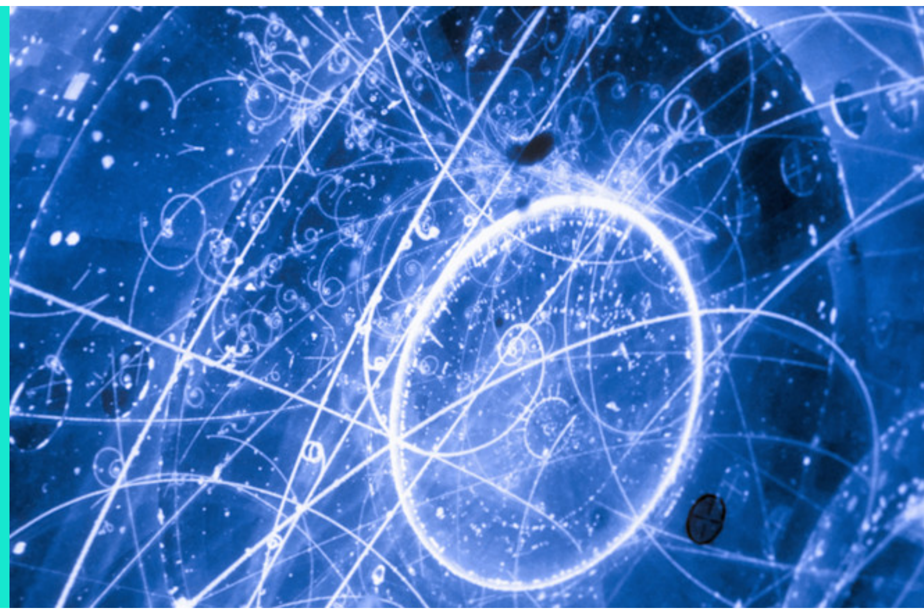
Neutrino-Nucleus Interactions from Reactors to the Cosmos



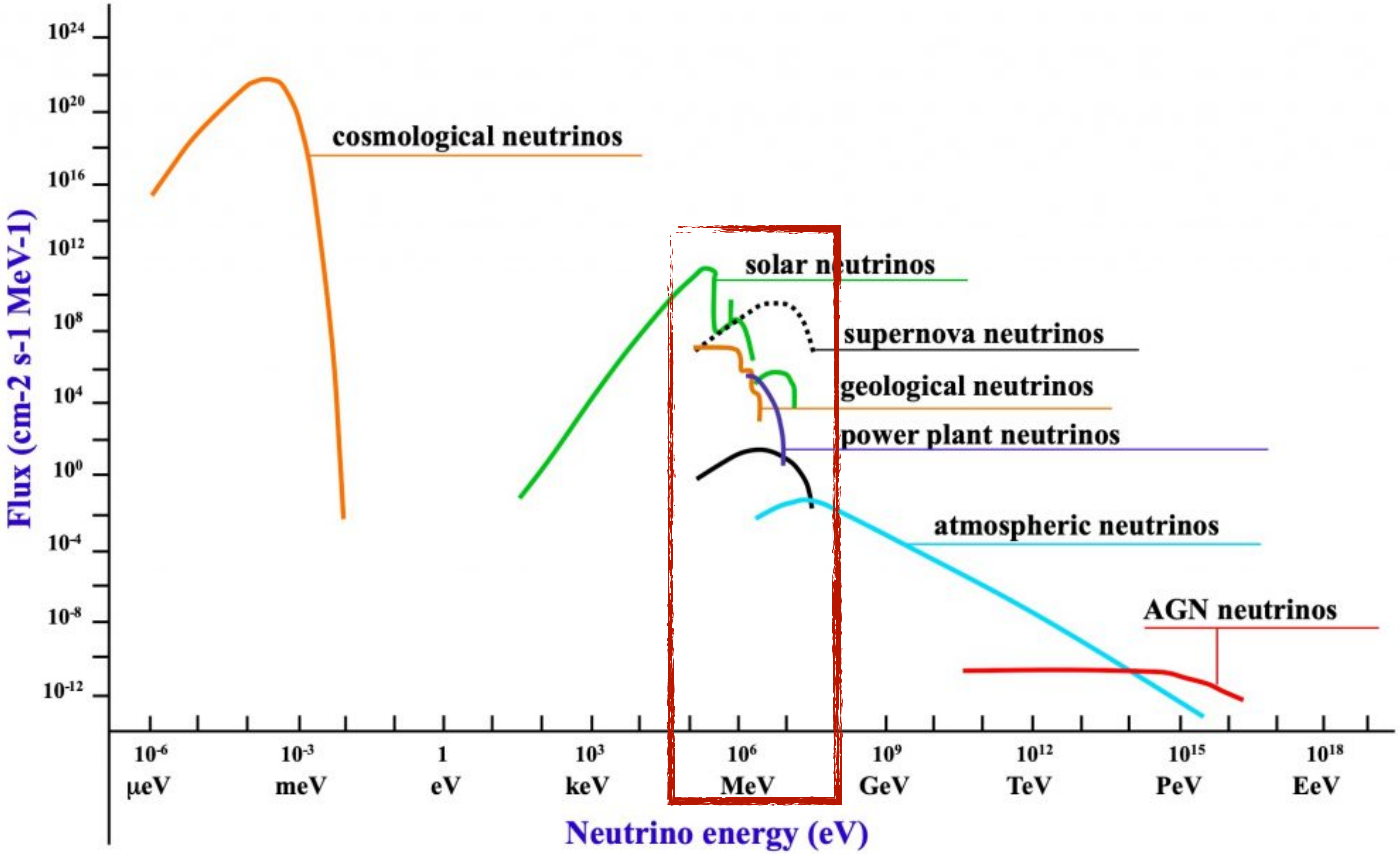
Iván Martínez Soler

IOP Nuclear Physics Conference

April 13, 2026

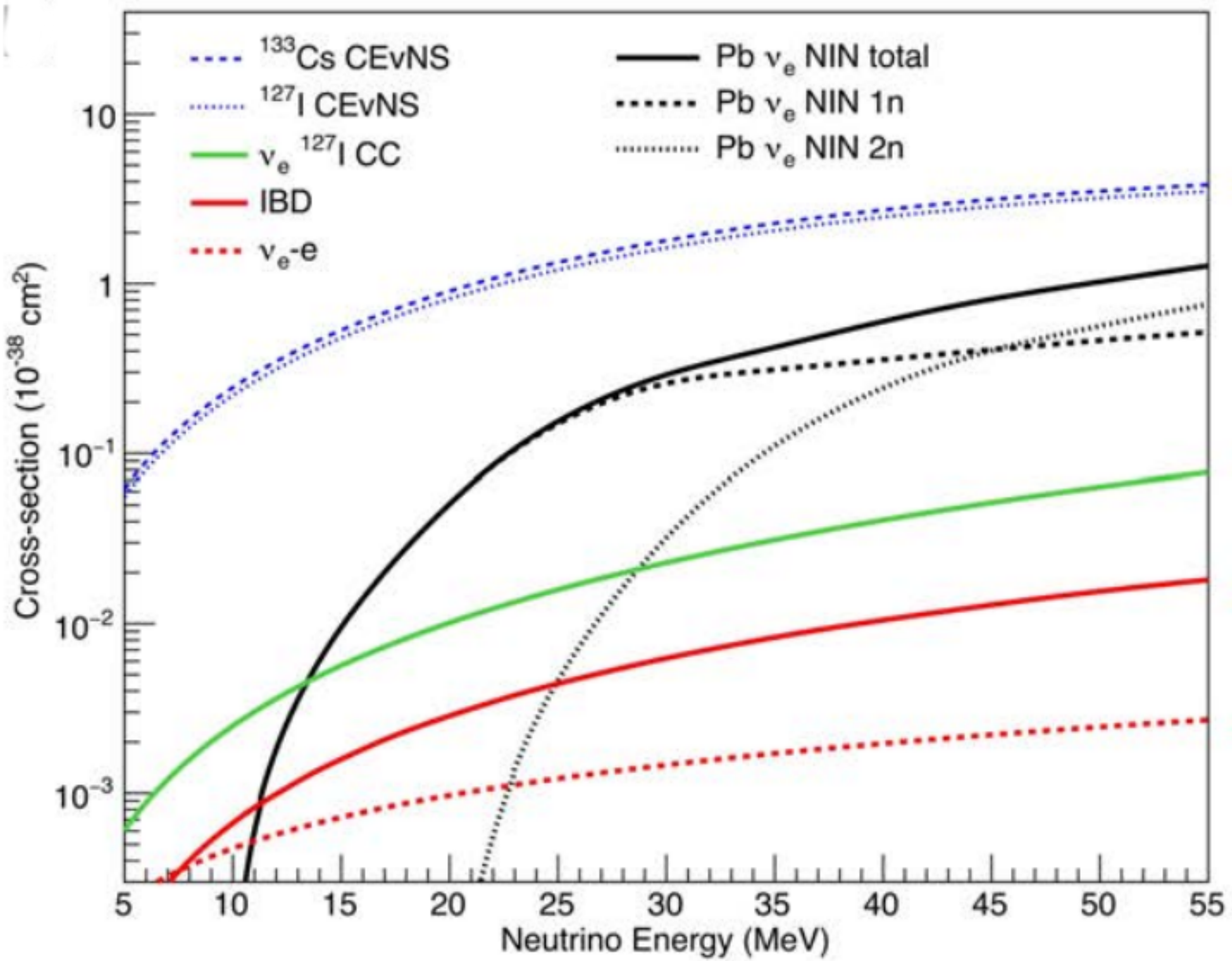
Neutrino Sources

There are multiple neutrino sources, we focus on fluxes around the MeV scale



Coherent Scattering

At MeV energies, coherent interactions dominate neutrino scattering.



COHERENT, Science 357 2017

Coherent Scattering

COHERENT reported the **first observation** of coherent neutrino-nucleus scattering

- Used a neutrino beam created by pion decay

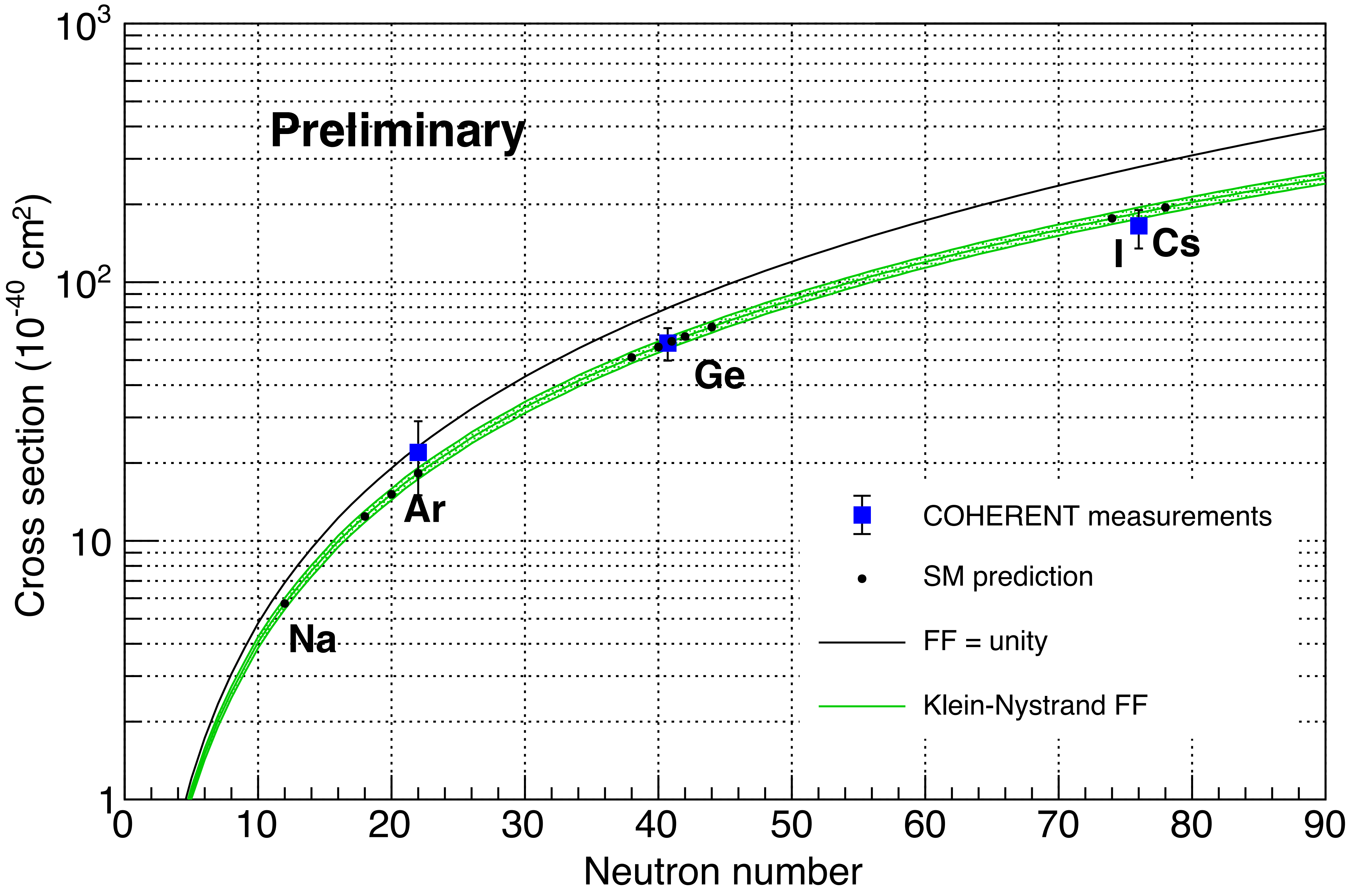
$$\pi^+ \rightarrow \mu^+\nu_\mu \qquad\qquad \mu^+ \rightarrow e\overline{\nu}_\mu\nu_e$$

- At low momentum transfer, neutrinos probe the entire nucleus

$$\frac{d\sigma^\nu}{dE_R} = [\mathcal{Q}_V^{\mathrm{SM}}]^2\mathcal{F}^2(E_R)\frac{G_F^2 m_N}{4\pi}\left(1-\frac{E_R}{E_\nu}+\frac{E_R^2}{2E_\nu^2}-\frac{m_N E_R}{2E_\nu^2}\right)$$

$\mathcal{F}^2(E_R)$ is the nuclear form factor

$$\mathcal{Q}_V^{\mathrm{SM}} = N-(1-4\sin^2\theta_W)Z$$



COHERENT Collaboration, arXiv:2602.15652

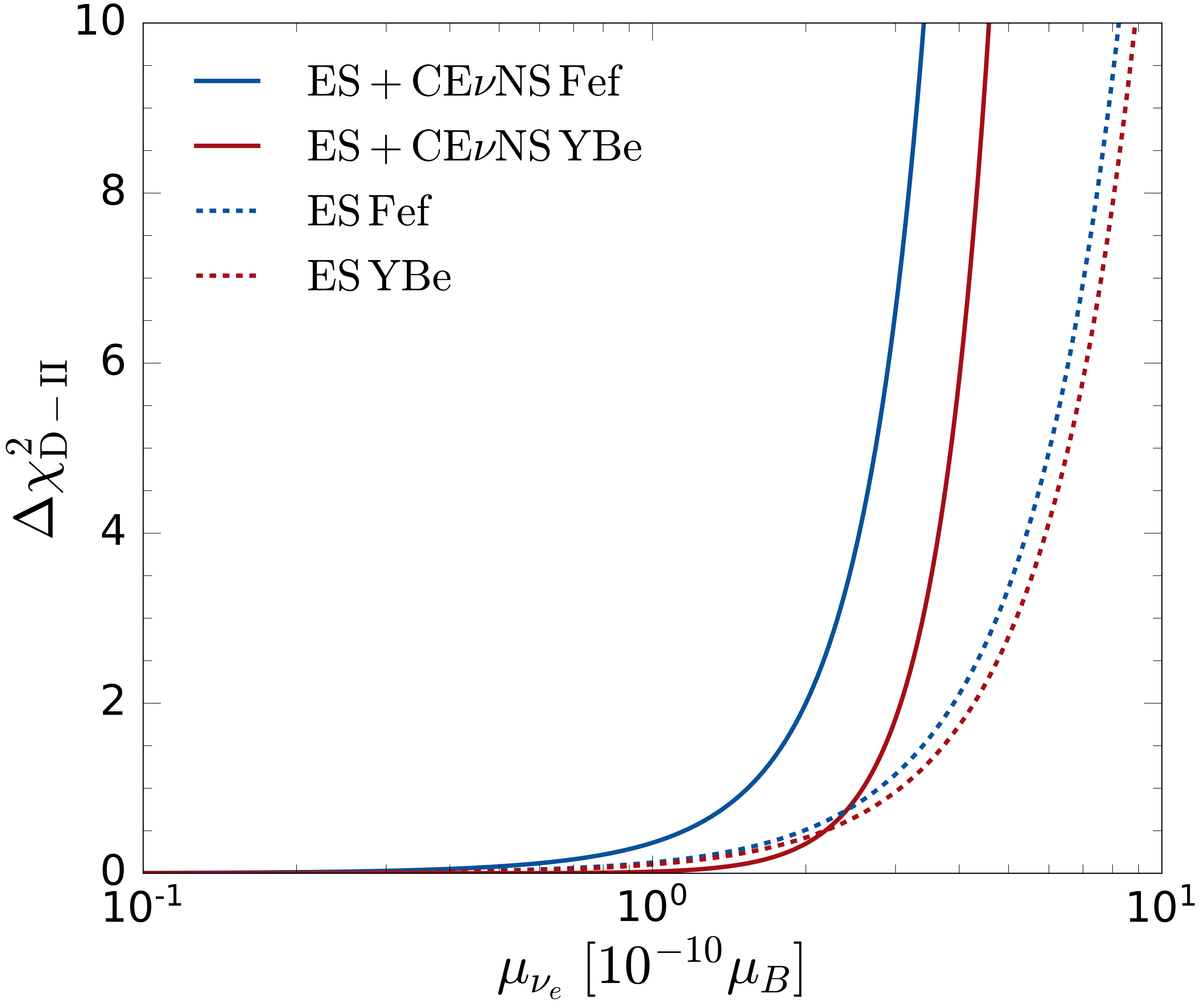
BSM

The measurement of coherent neutrino scattering opens **new opportunities to probe neutrino properties**.

A non-zero neutrino **magnetic moment** would introduce an additional neutrino-proton scattering channel.

$$\frac{d\sigma^{\nu}}{dE_R} = Z^2\mathscr{F}^2(E_R)\left(\frac{\mu_\nu}{\mu_B}\right)^2 \frac{\alpha^2\pi}{m_e^2}\left(\frac{1}{E_R} - \frac{1}{E_\nu}\right)$$

- Fef and YBe correspond to two quenching-factor models
- Uncertainty in $Q(E_R)$ has a significant impact on the results

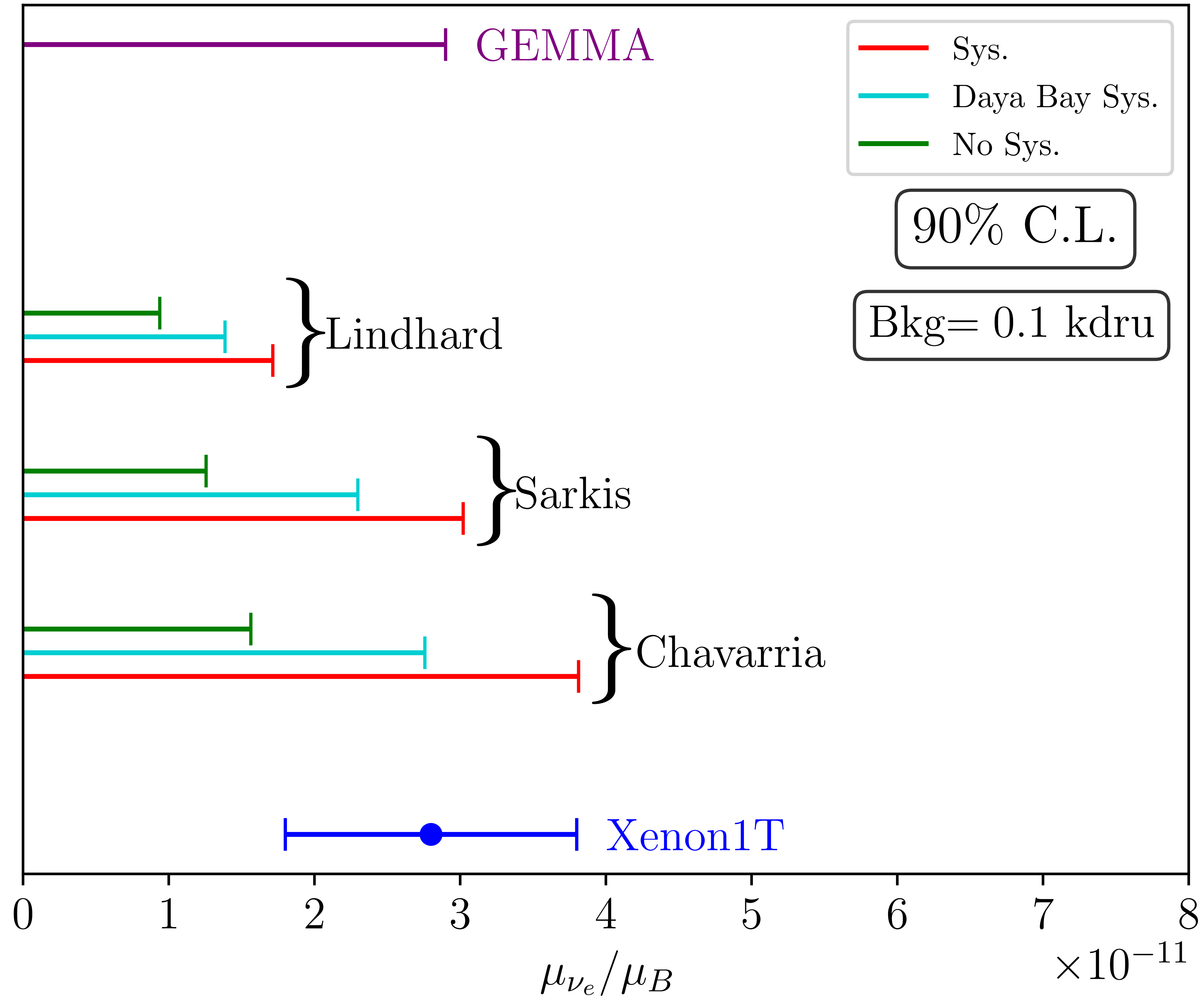


P. Coloma, I. Esteban, M.C. Gonzalez-Garcia, L. Larizgoitia, F. Monrabal, S. Palomarez-Ruiz, JHEP 05 (2022)

BSM

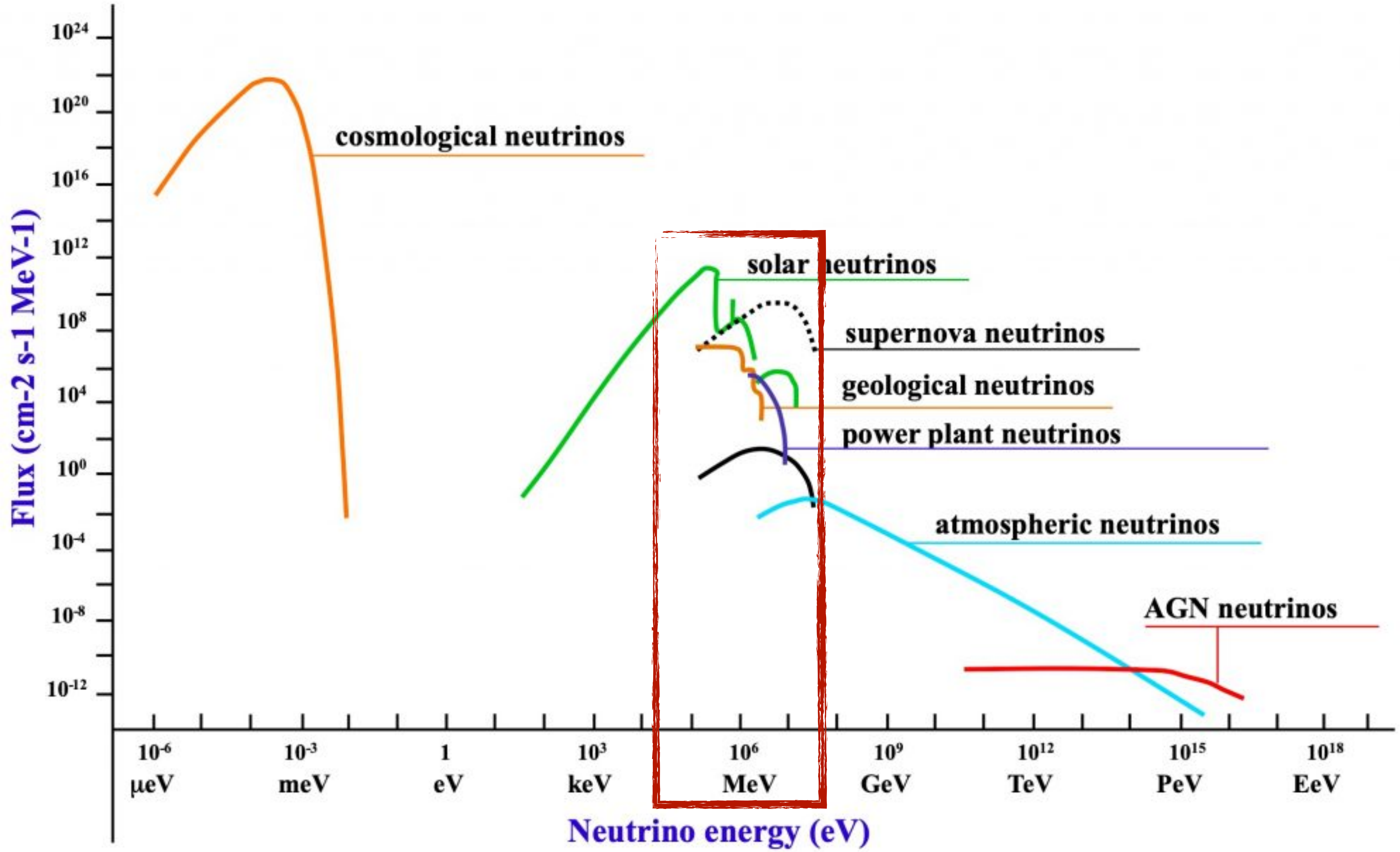
Increased exposure and improved resolution in future detectors will lead enhance the procision of these models.

- We considered reactor neutrinos and a 10kg Si detector
- The setup probes **lower recoil energies** than COHERENT
- The neutrinos are MeV-scale, produced by fission of isotopes isotopes:^{235}U,^{238} U,^{239} Pu,^{241} Pu



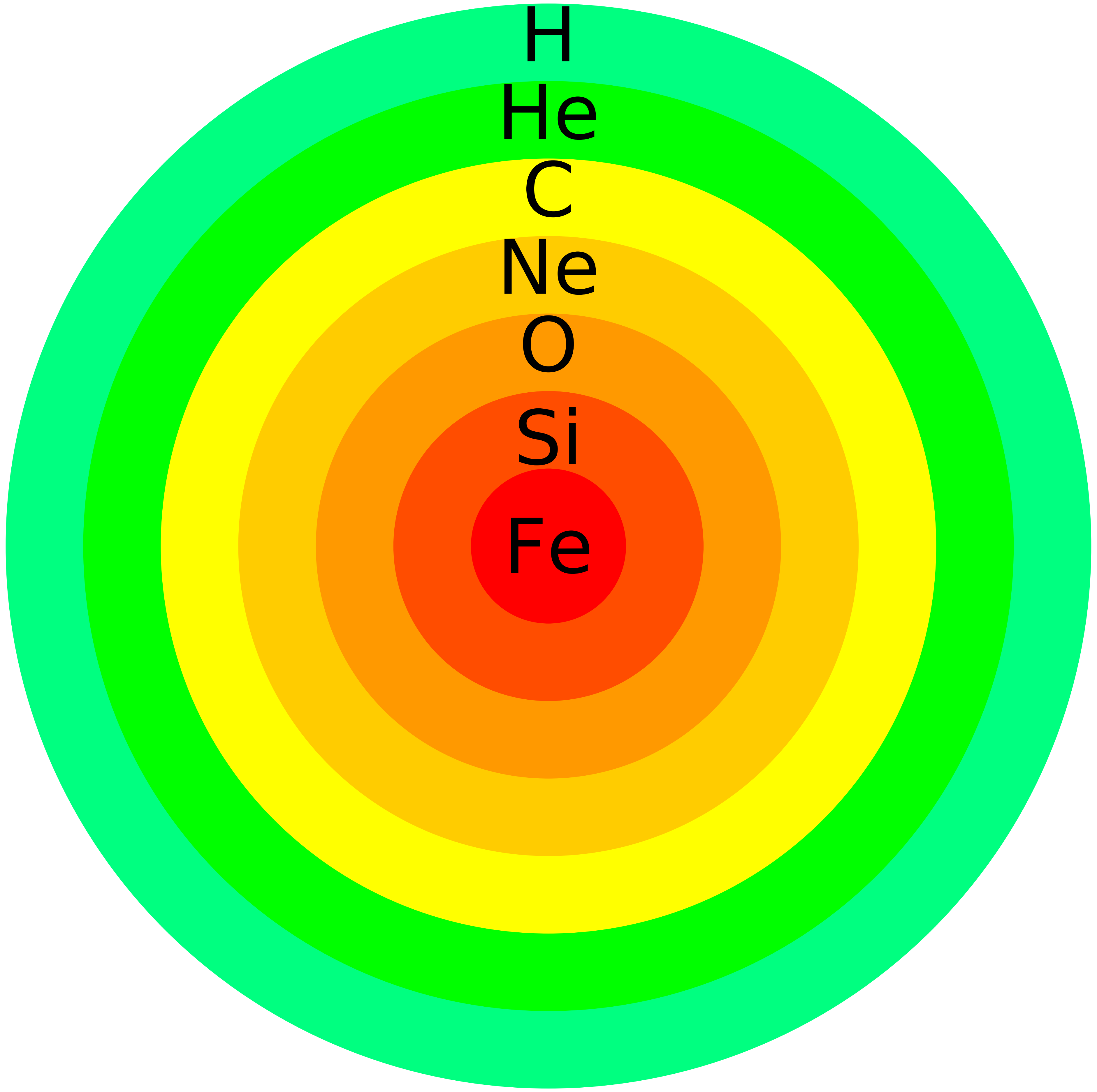
Fernandez-Moroni, Harnik, Machado, IMS, Perez-Gonzalez, Rodrigues and Rosauro-Alcaraz, JHEP 02 (2022)

MeV-scale neutrinos offer a window onto astrophysical sources



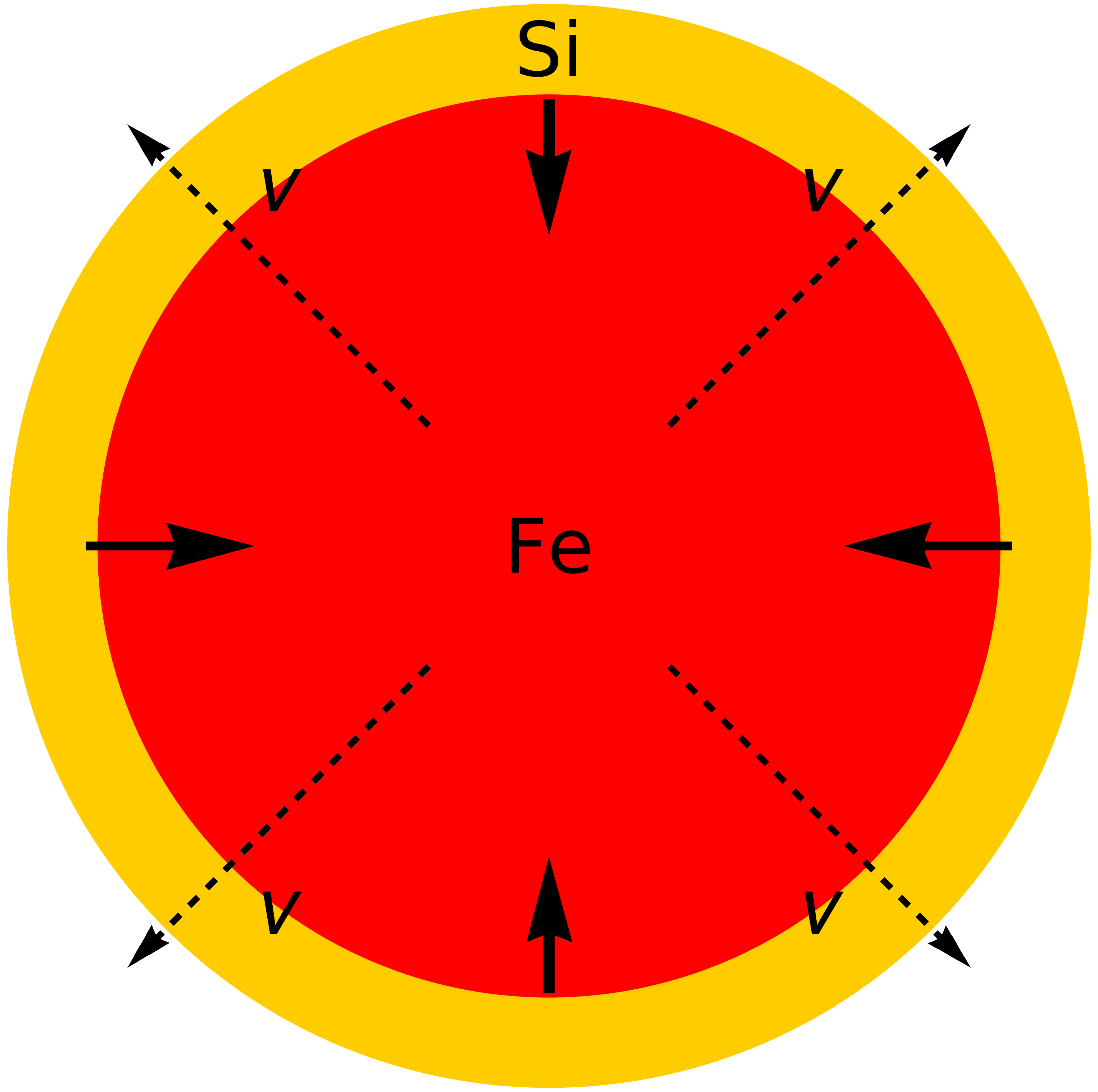
Core-Collapse Supernova

A core-collapse supernova happens at the end of a very massive star ($M > 8M_\odot$)



Core-Collapse Supernova

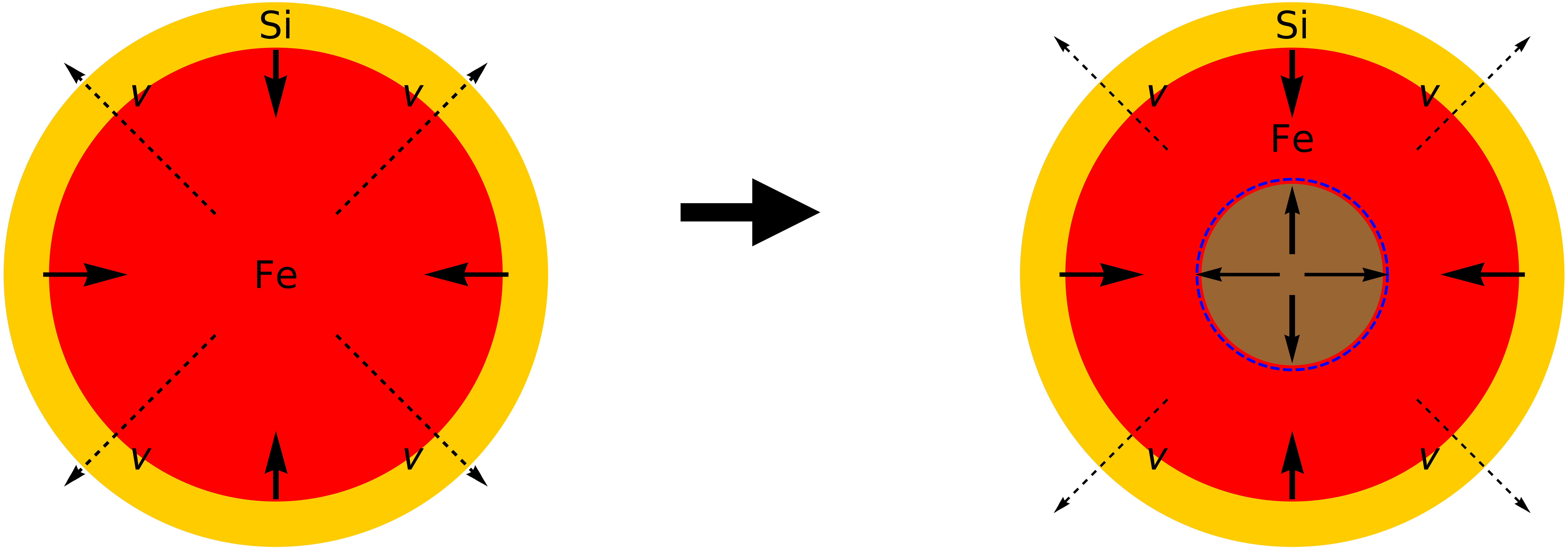
For core masses of $1.44 M_{\odot}$, the electron pressure cannot stabilize the core



Core-Collapse Supernova

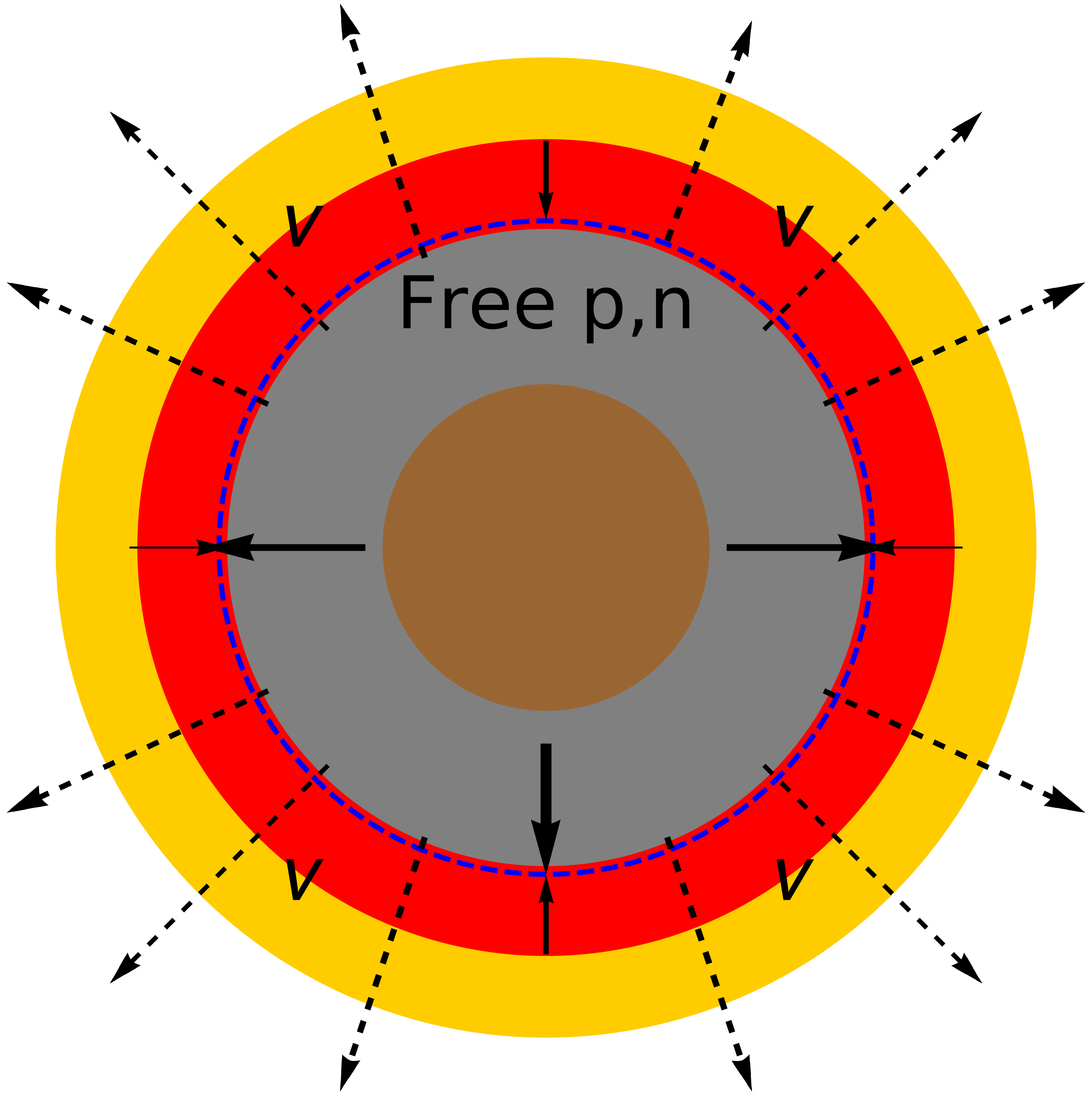
For core masses of $1.44 M_{\odot}$, the electron pressure cannot stabilize the core

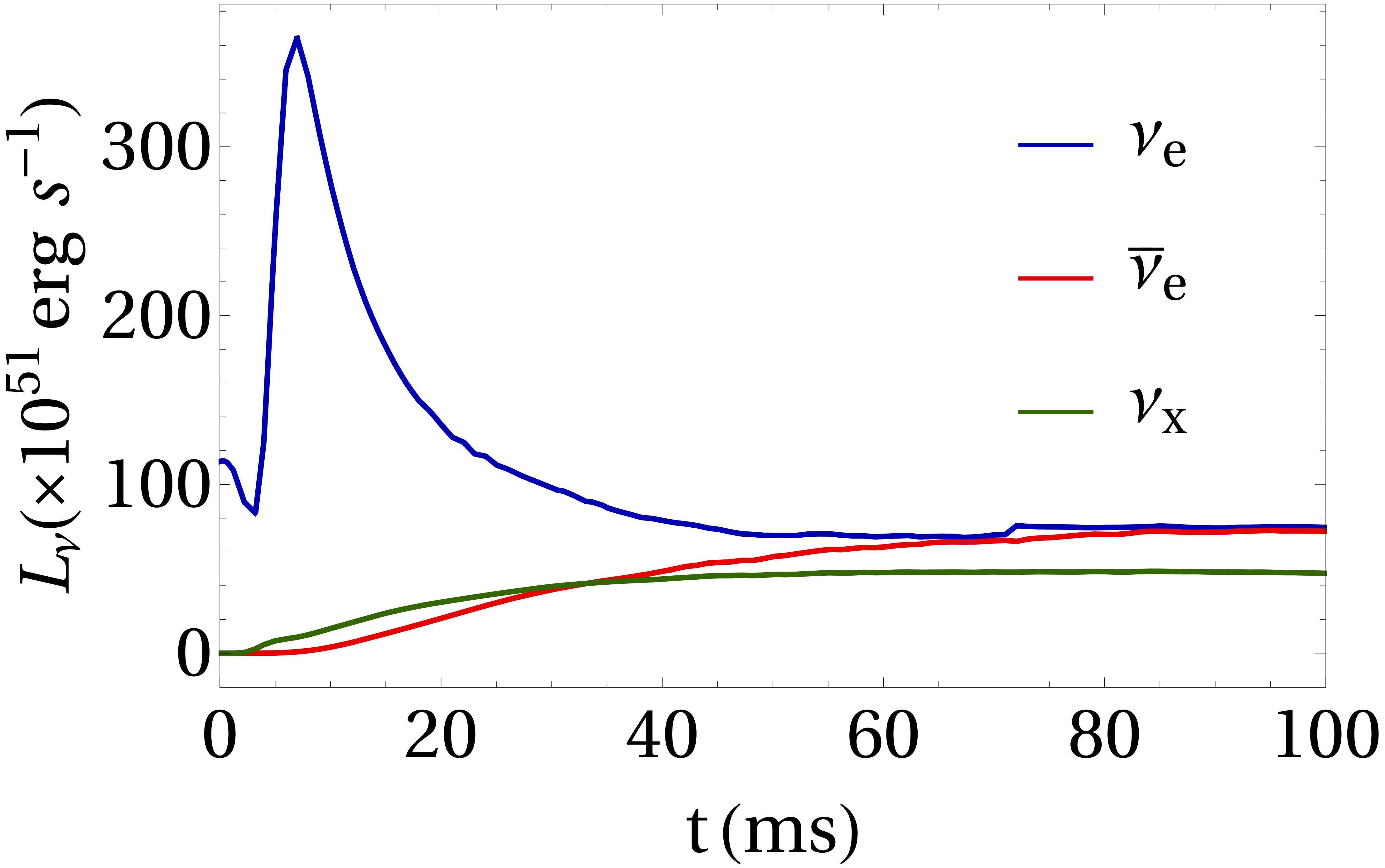
Near nuclear densities ($\rho \sim 10^{14}$g/cm^{3}), the core bounces launching a shock wave outwards



Core-Collapse Supernova

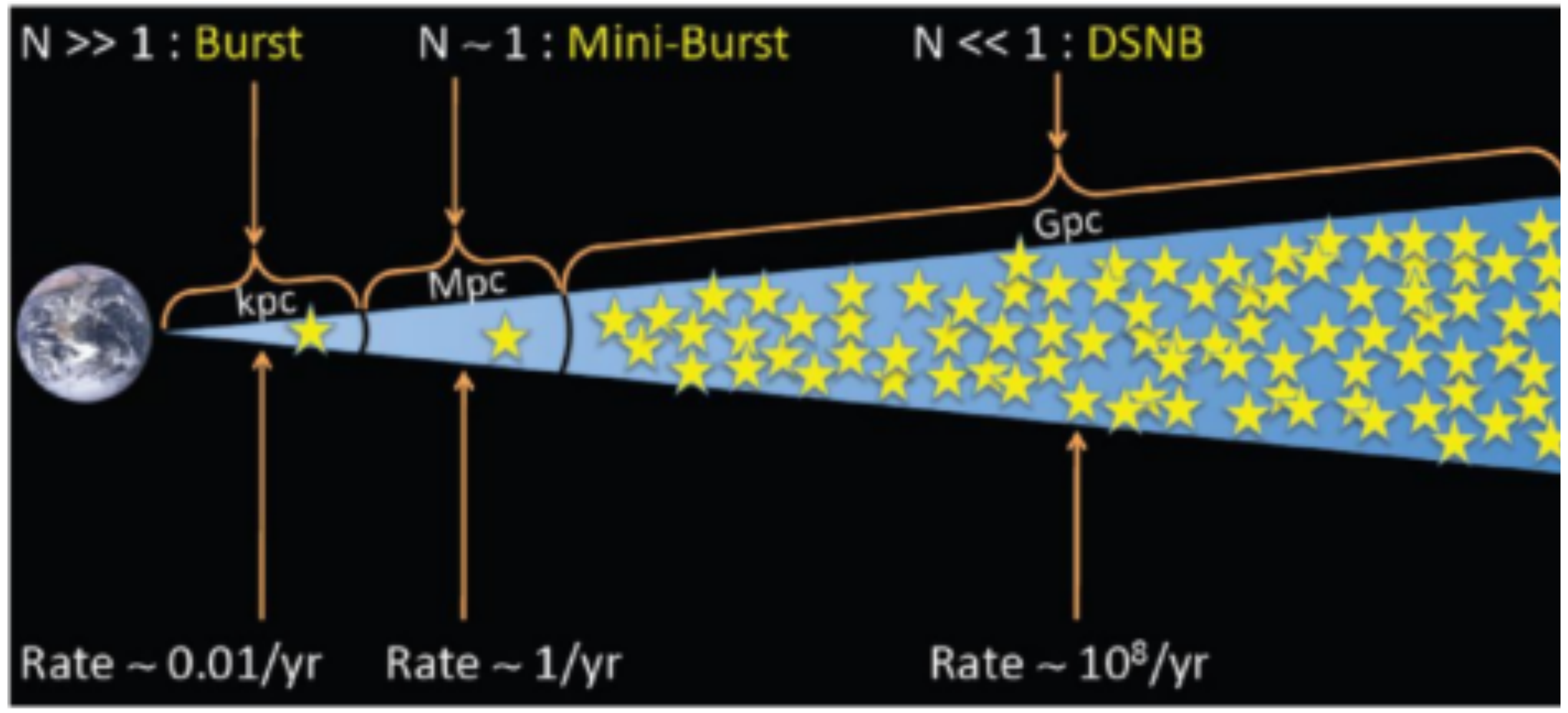
Free electrons are captured by free protons, leading to a large neutrino production





DSNB

Core-collapse supernova are rare events



Beacom TAUP 2011

The **Diffuse Supernova Neutrino Background** (DSNB) includes contributions from all CCSN in the observable universe

- It forms an isotropic and time-independent astrophysical neutrino flux
- The DSNB has not yet been observed.

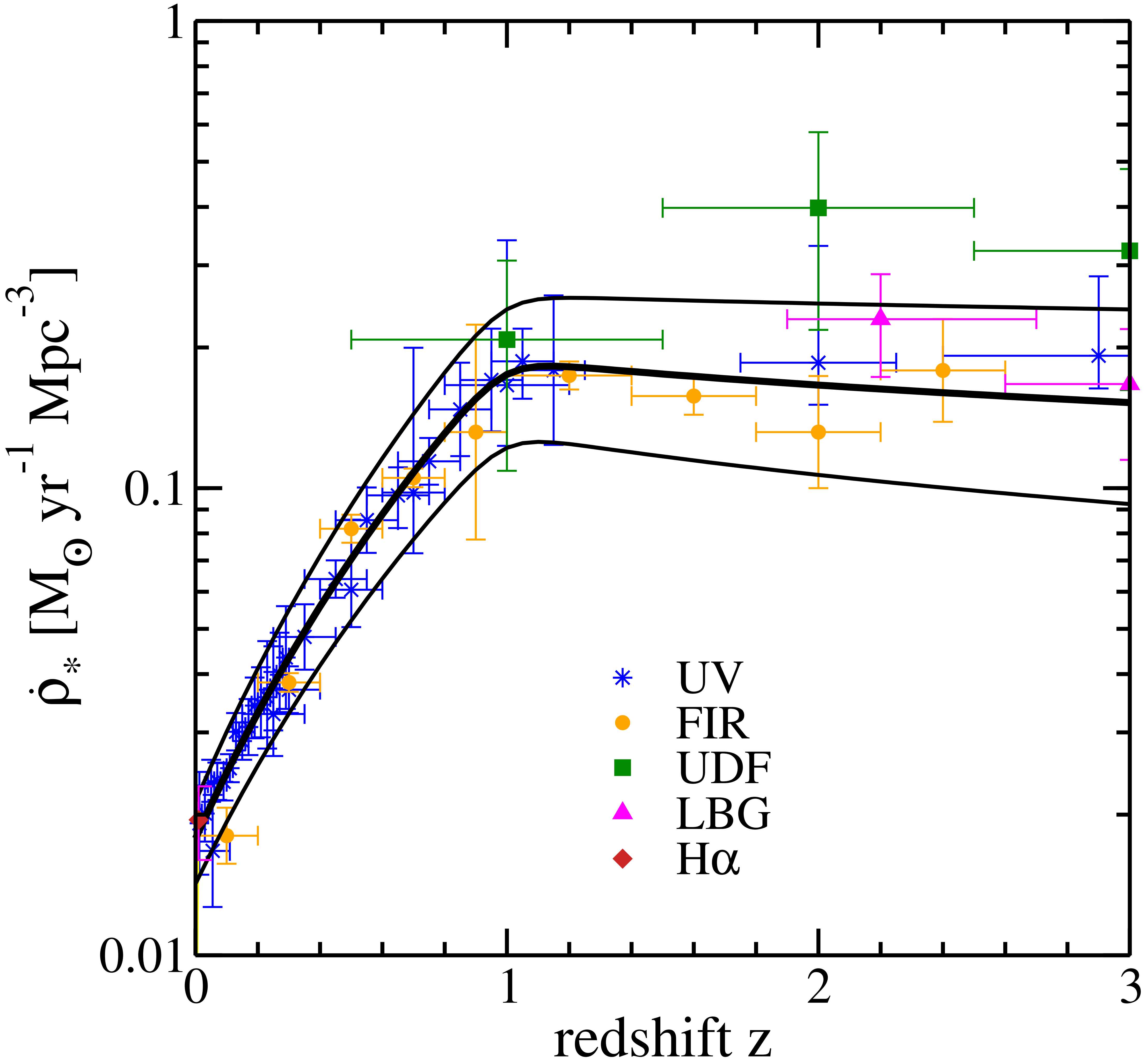
DSNB

The core-collapse supernova rate as a function of the redshift is determined by the **star formation rate (SFR)**

$$R_{CCSN}(z) = \rho_*(z)\frac{\int_8^{50}\psi(M)\,dM}{\int_{0.1}^{100}M\psi(M)\,dM}$$

$\psi(M) \sim M^{-2.35}$ Star density

The SFR shows a maximum for $z \sim 1$



Horiuchi, Beacom, Qwek (2009)

DSNB

The diffuse neutrino flux is given by the integral of the **SFR along the whole history of the universe**

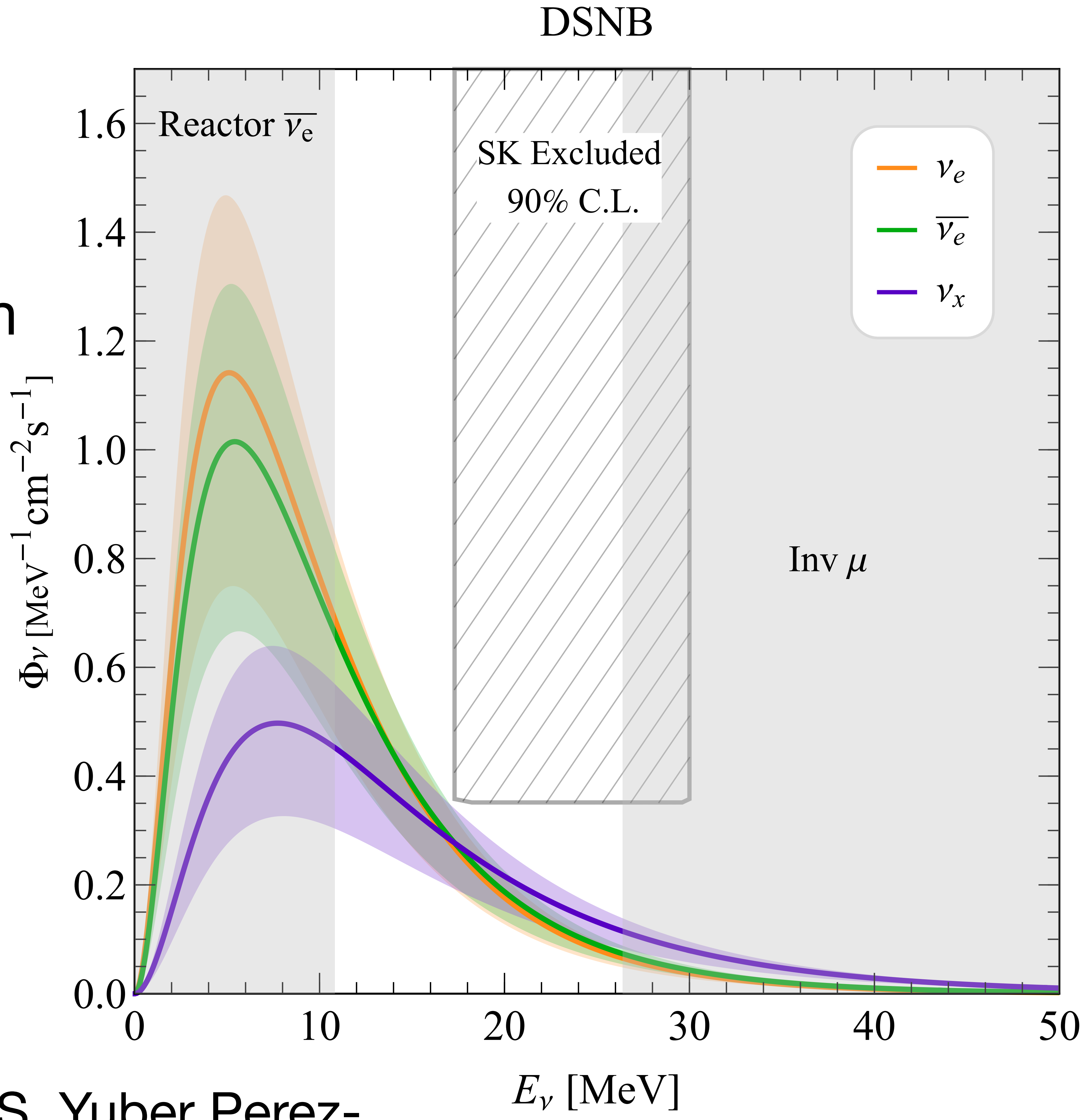
$$\Phi_\nu(E) = \int_0^{z_{\max}} \frac{dz}{H(z)} R_{CCSN}(z) F_\nu(E')$$

For the neutrino spectra is considered a Fermi-Dirac distribution

$$F_\nu(E) = \frac{E_\nu^{\mathrm{tot}}}{6} \frac{120}{7\pi^4} \frac{E_\nu^2}{T_\nu^4} \frac{1}{e^{E_\nu/T_\nu}+1}$$

The neutrino "temperature" depends on the interaction rate

$$T_{\nu_e} < T_{\overline{\nu}_e} < T_{\nu_x}$$



Andre de Gouvea, IMS, Yuber Perez-Gonzalez, Manibrata Sen, PRD 102 (2020)

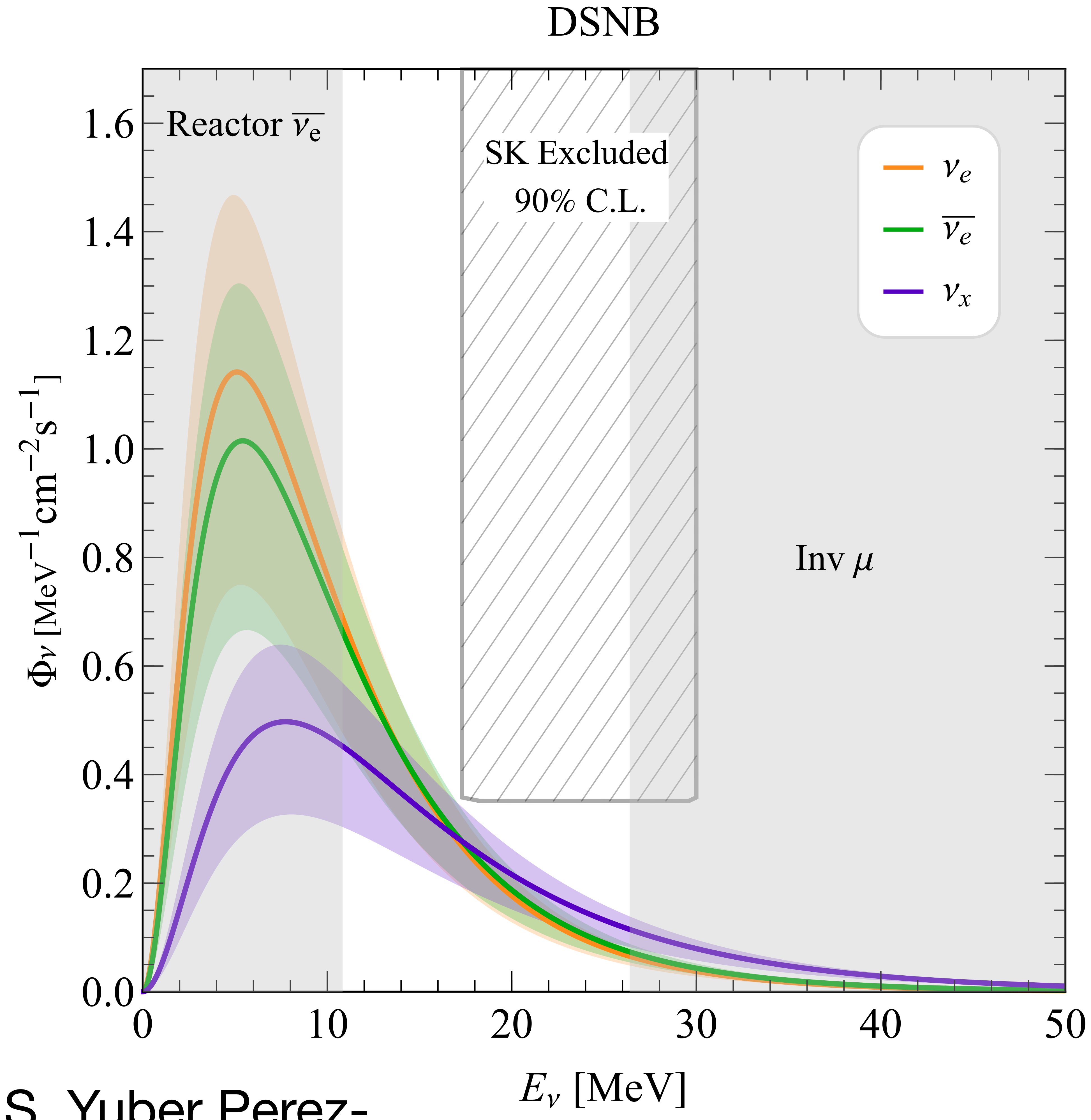
DSNB

The diffuse neutrino flux is given by the integral of the SFR along the whole history of the universe

$$\Phi_\nu(E) = \int_0^{z_{\max}} \frac{dz}{H(z)} R_{CCSN}(z) F_\nu(E')$$

We need to account for the **expansion of the universe**

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)} + (1-\Omega_m-\Omega_\Lambda)(1+z)^2}$$



Andre de Gouvea, IMS, Yuber Perez-Gonzalez, Manibrata Sen, PRD 102 (2020)

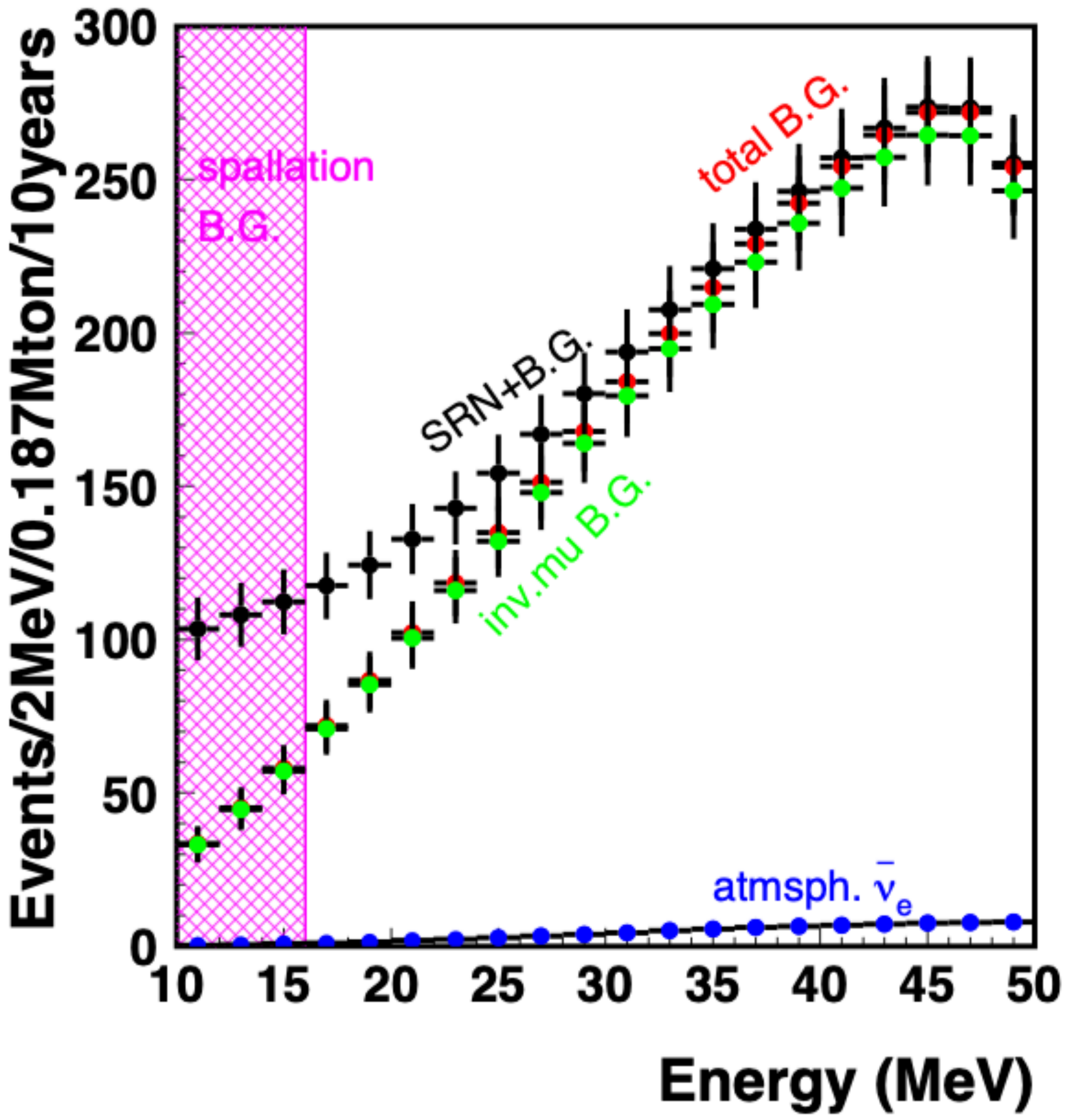
DSNB Detection

Most of the experiments proposed consider **Inverse Beta Decay** (IBD) as the main detection channel

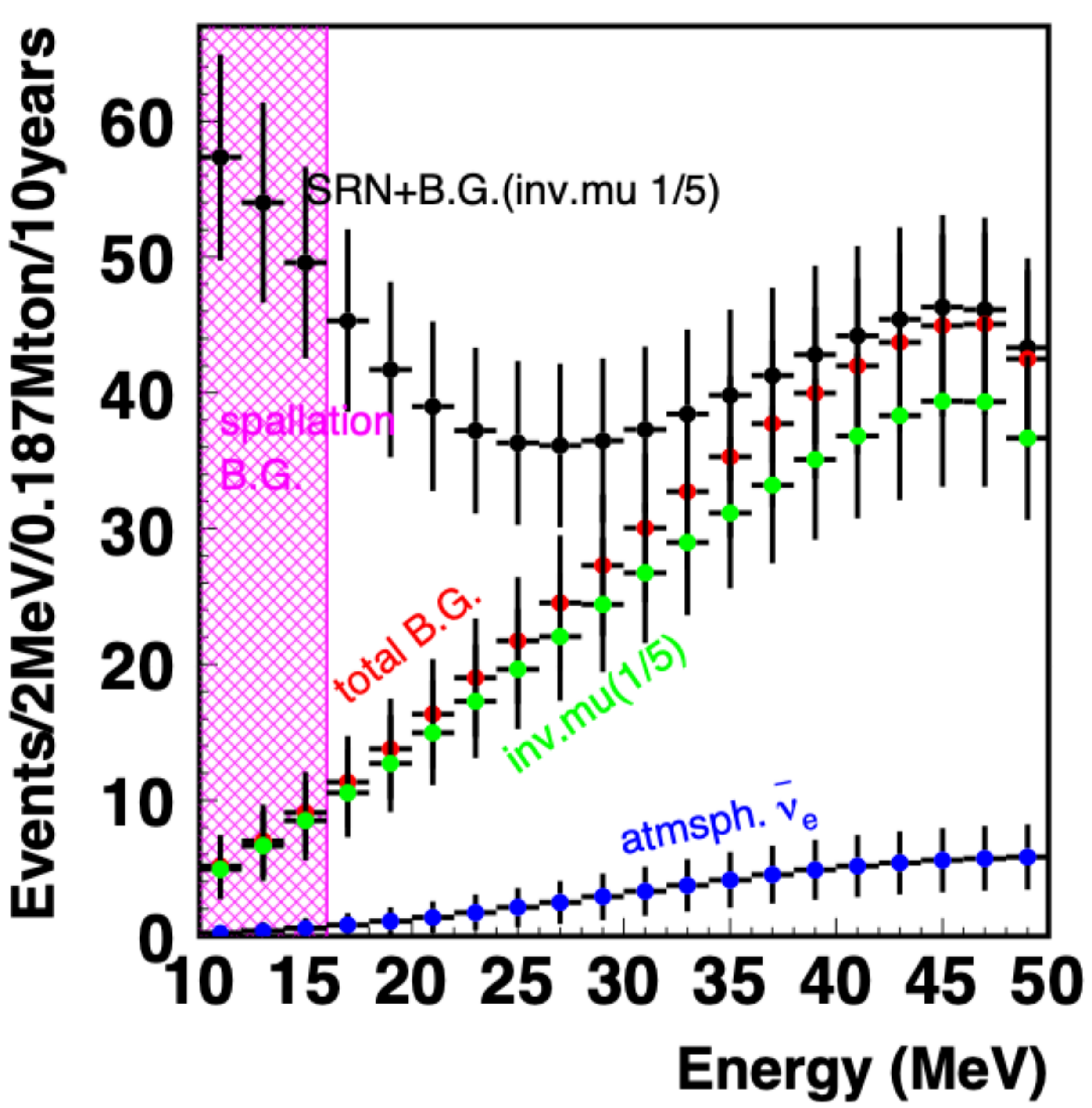
$$\overline{\nu}_e + p \rightarrow n + e^+$$

To identify the signal and suppress background, experiments **search for coincident positron-neutron detection.**

No Neutron Detection



Neutron Detection

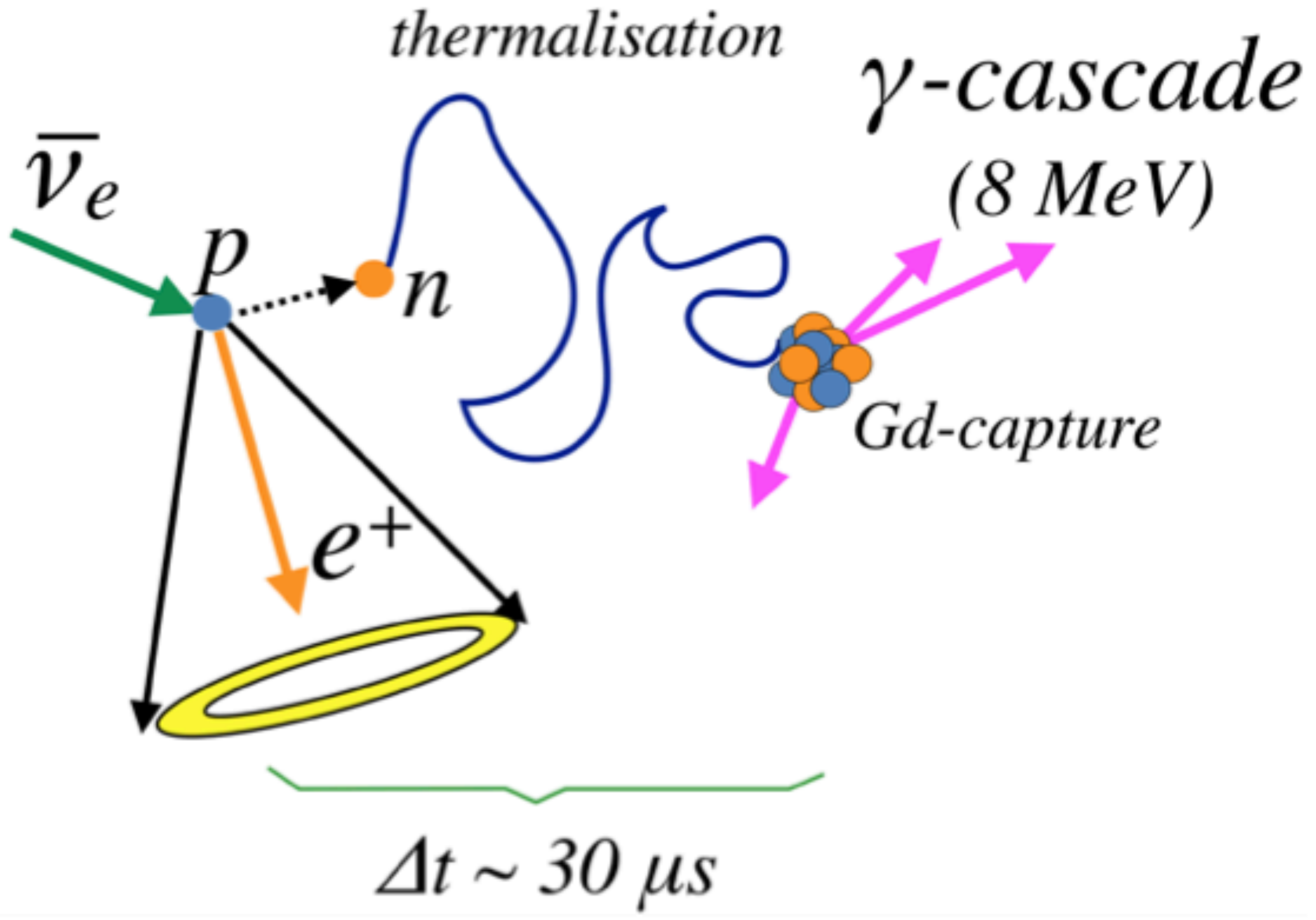


Hyper-Kamiokande Collaboration, arXiv:1805.04163

DSNB Detection

In water Cherenkov detectors, **neutron tagging is achieved via gadolinium** (Gd) doping

- Gadolinio has a large neutron-absorption cross-section
- Neutron capture produces an ~8 MeV γ-ray cascade.
- Experiments search for Cherenkov radiation from e^+ and γ cascade

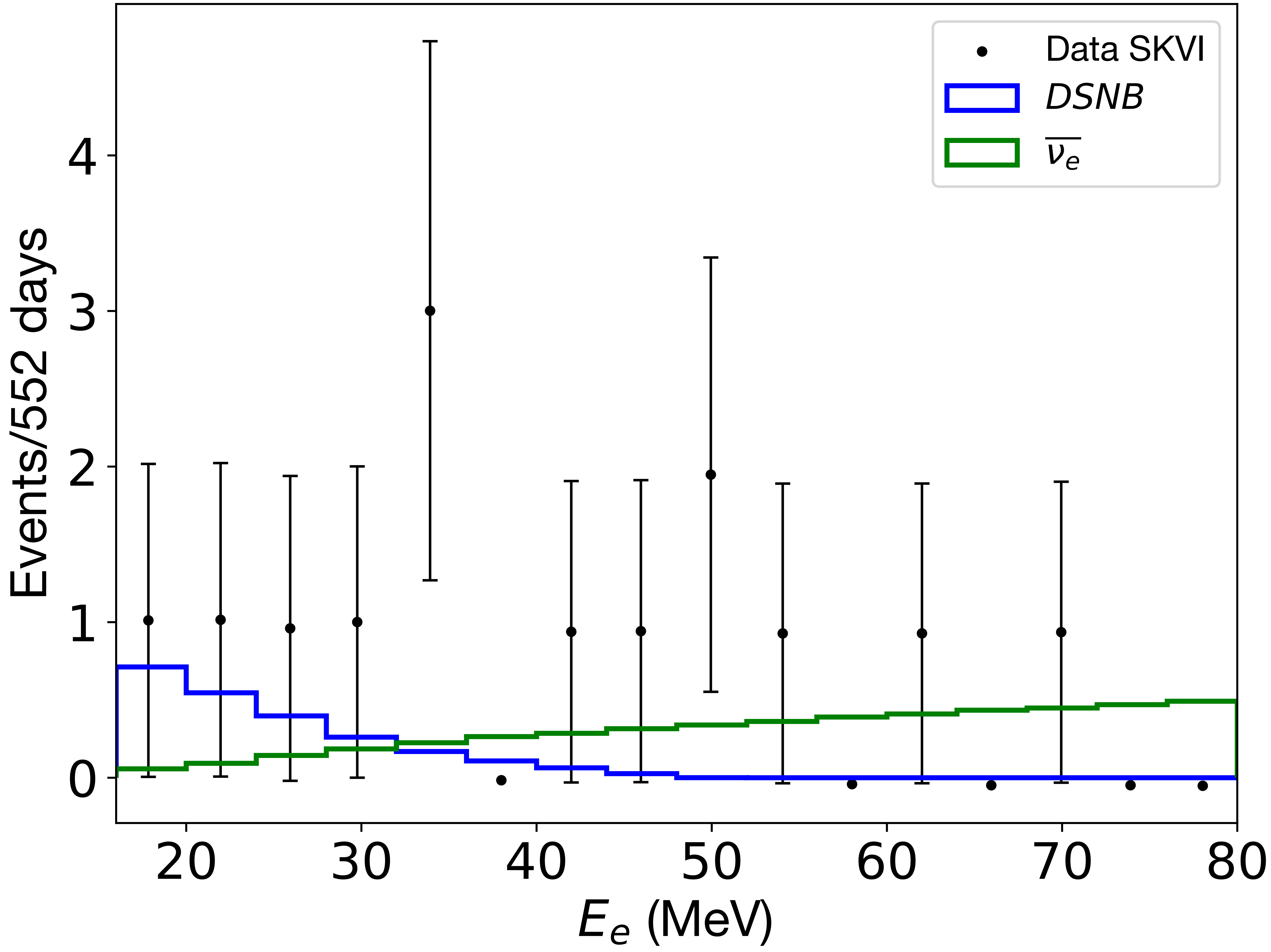


DSNB Detection

Irreducible backgrounds persist despite neutron tagging

Atmospheric anti-electron neutrinos

- Significant at energies > 35 MeV



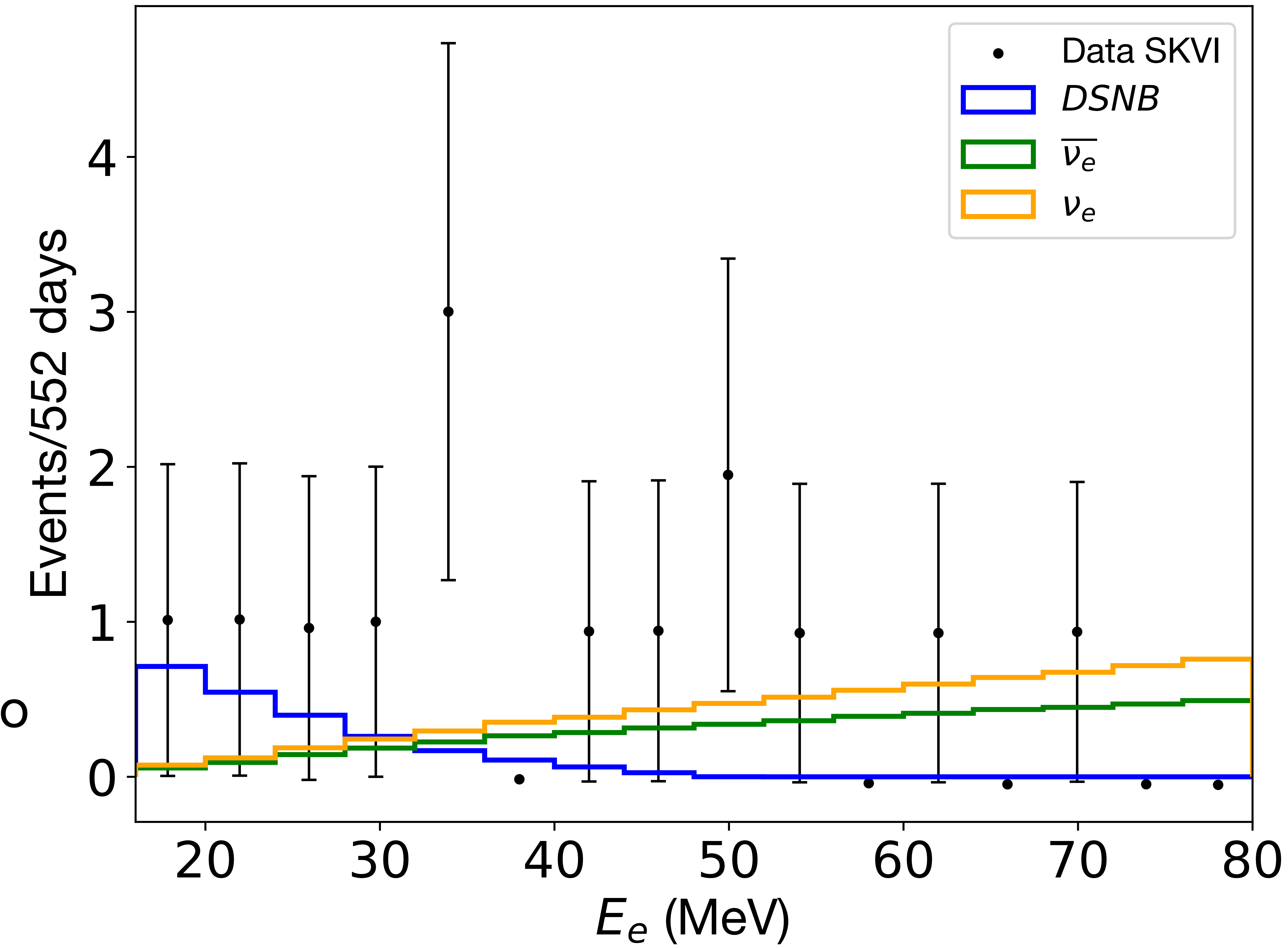
DSNB Detection

ν_e charge-current interaction with ^{16}O lead neutrons through **nuclear effects**

$$\nu_e + ^{16}O \rightarrow e^- + n + X$$

Primary driven by FSI and 2p2h interactions

- We have simulated this background using Nuwro



DSNB Detection

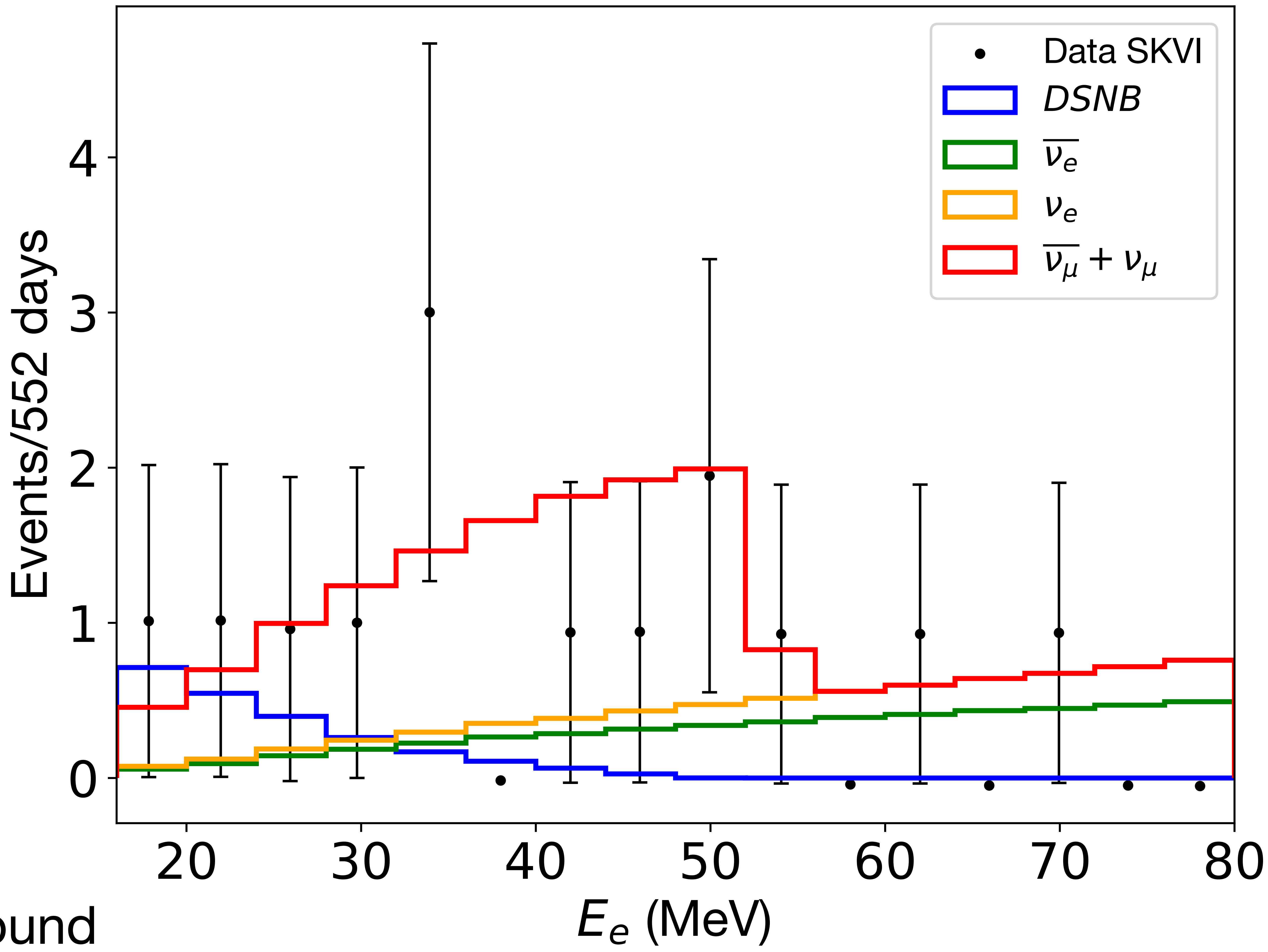
Charge-current interactions of ν_μ and $\overline{\nu_\mu}$ with ^{16}O occur at energies above ~100MeV

$$\overline{\nu_\mu} + ^{16}O \rightarrow \mu^+ + n + X$$

$\mu^\pm$ with energies < 150MeV **do not emit cherenkov radiation**

$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu_\mu}$$

- These events can mimic IBD signals
- They are reconstructed at energies below 50 MeV
- FSI and 2p2h processes contribute to the background



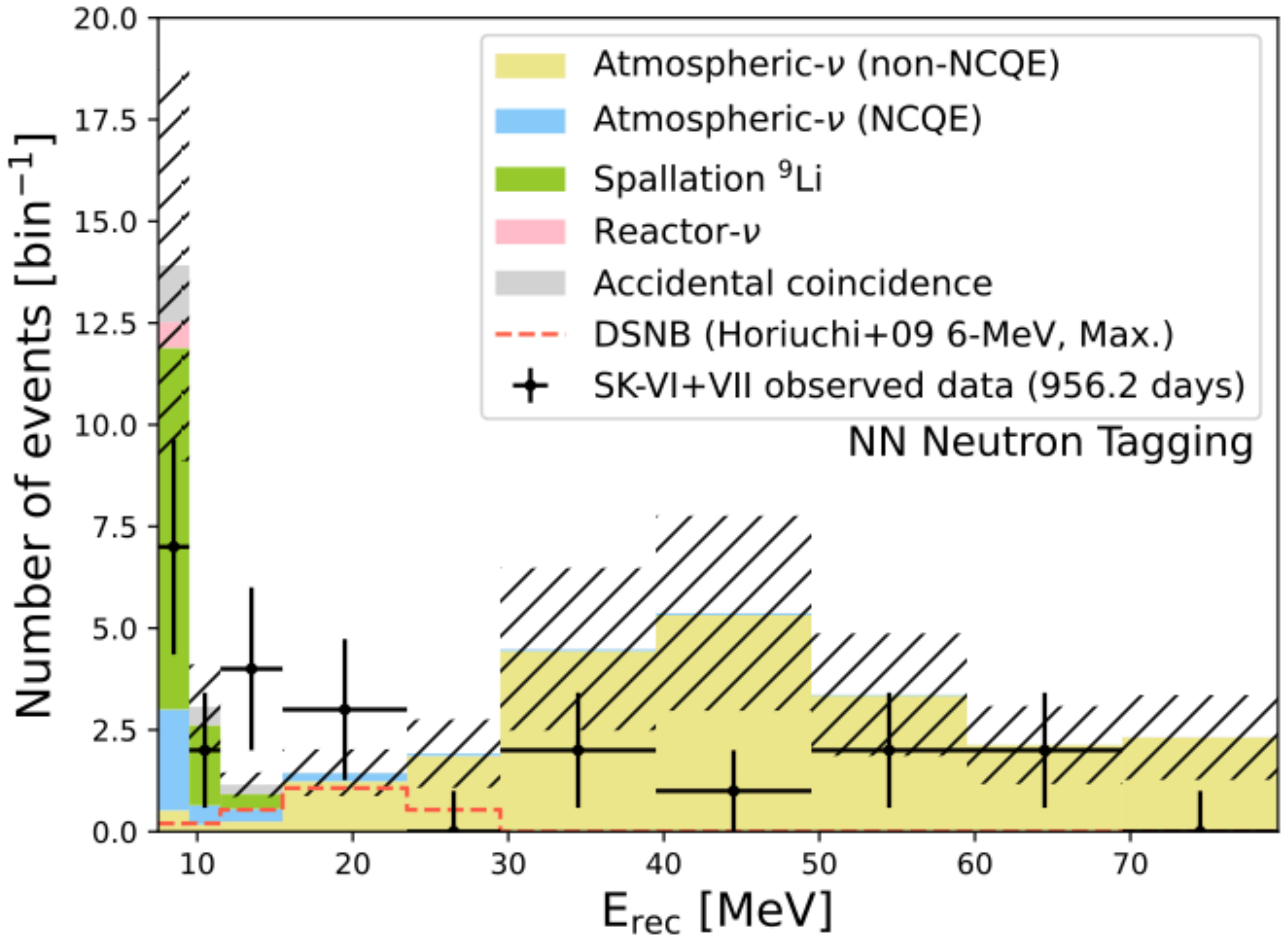
DSNB Detection

Additional background sources affect signal detection at energies below 20MeV

- Atmospheric neutrino Neutral Current Interactions

$$\nu(\overline{\nu}) +^{16} O \rightarrow \nu(\overline{\nu}) + n +^{15} O*$$

- Spallation from cosmic muons
- Reactor neutrinos



Super-Kamiokande, arXiv:2511.02222

Why Detect the DSNB?

One fundamental question is the **origin of the neutrino masses**. To explain that, we can consider the SM as an effective field theory

$$\mathscr{L}_{eff} = \mathscr{L}_{SM} + \frac{\mathscr{L}_{d=5}}{\Lambda} + \cdots$$

- At d=5, we have the Weinberg operator

$$\mathscr{L}^{\nu}_{mass} \supset Y_\nu \bar{L}_L \tilde{\phi} N_R + \frac{1}{2} M_R \bar{N}^c_R N_R + h.c.$$

Type-I seesaw:
- Introduce right-handed neutrinos
- Allow L number violation

- For $M_R >> v$

$$m_\nu \sim \frac{Y_\nu^\dagger Y_\nu v^2}{M_R} \qquad m_N \approx M_R + \mathcal{O}\left(m_\nu\right)$$

- Heavy neutrinos can hardly be tested
- There are other scenarios where the Majorana mass can take smaller values

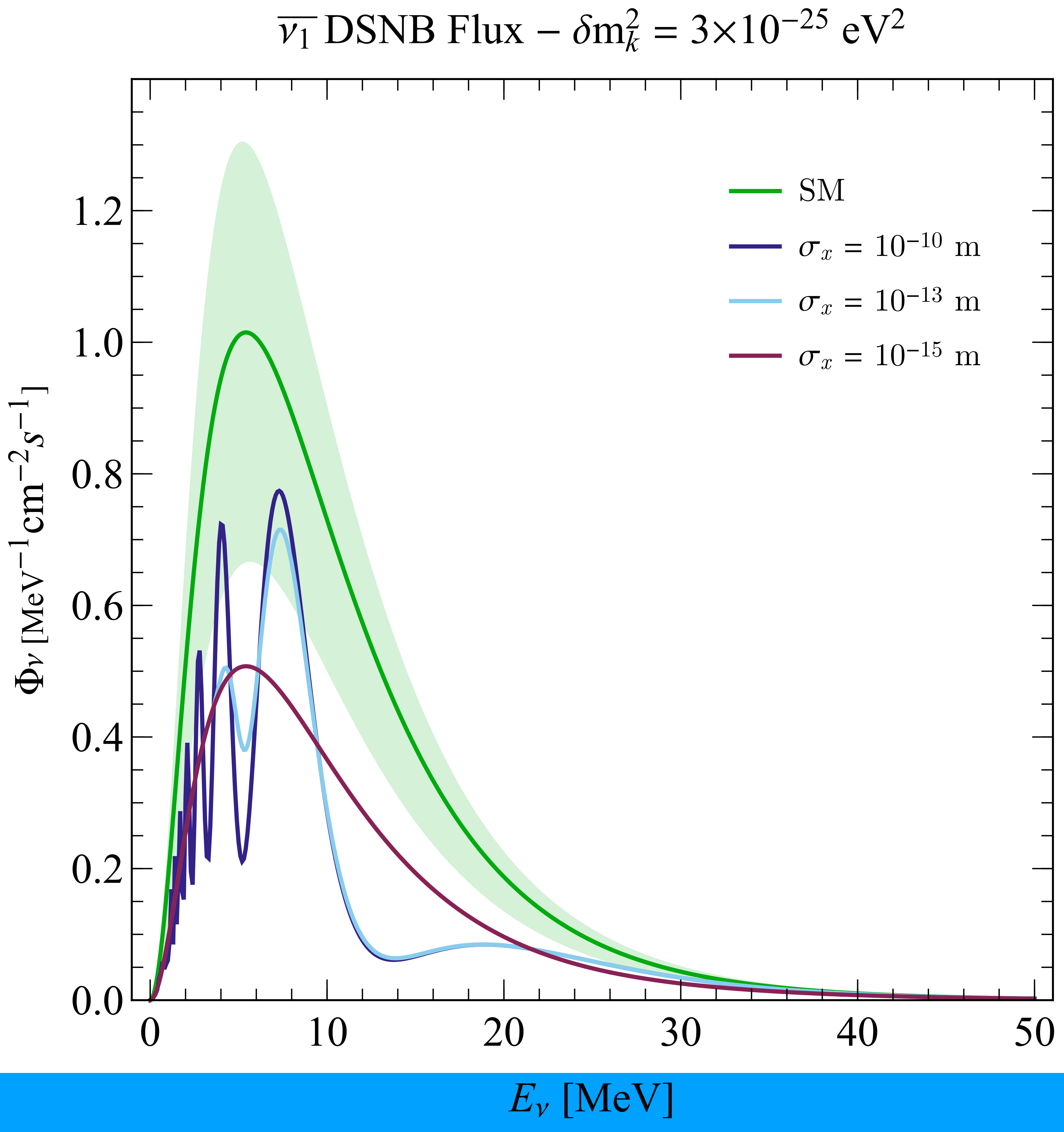
Pseudo-Dirac neutrinos

In the scenario where $M_R << M_D$, we get an **oscillation between active and sterile state** over astrophysical scales

This scenario predicts a small mass difference between active and sterile states

$$m_{ks}^2 = m_k^2 + \frac{1}{2}\delta m_k^2$$
$$m_{ka}^2 = m_k^2 - \frac{1}{2}\delta m_k^2$$

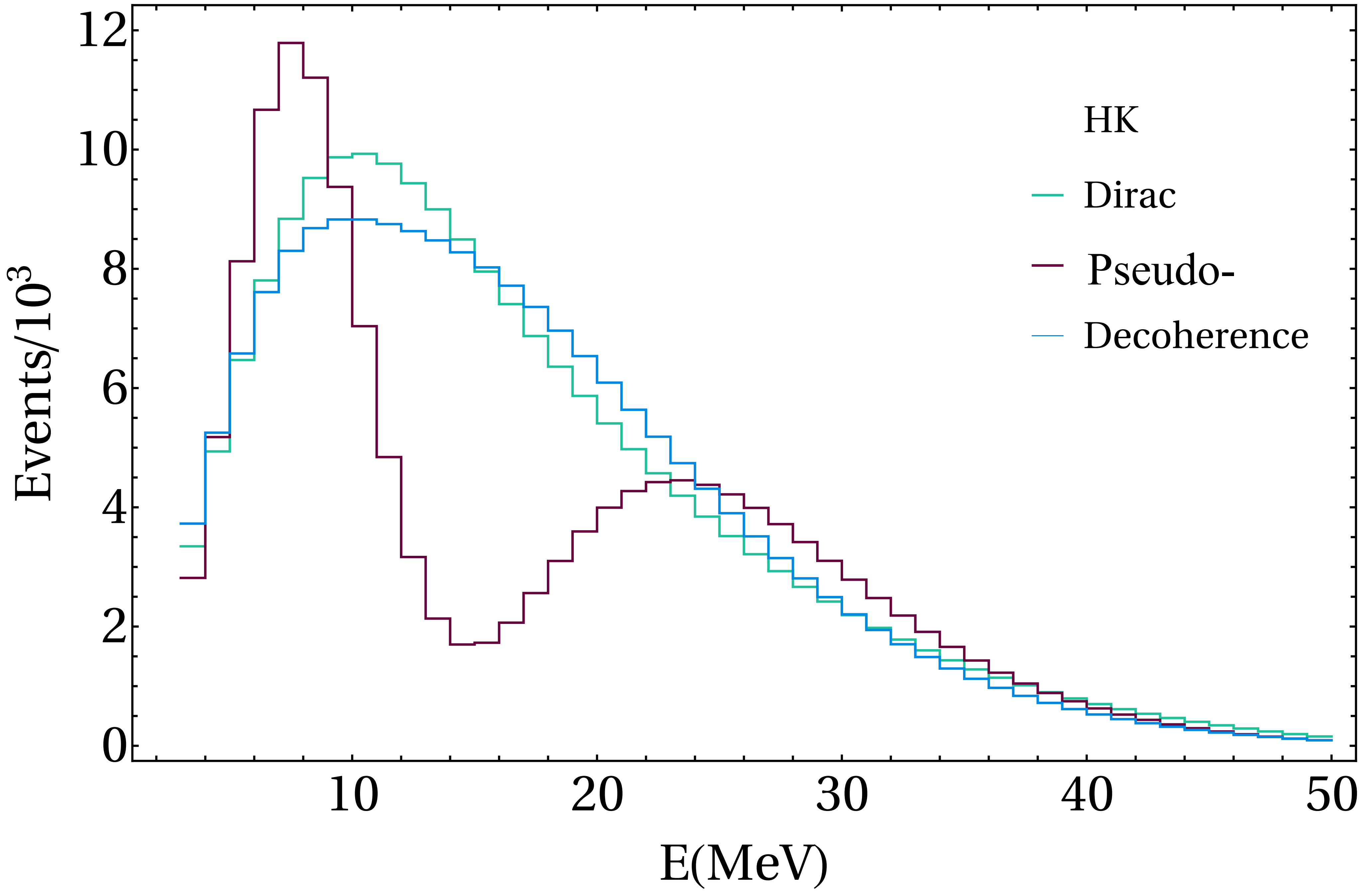
Andre de Gouvea, IMS, Yuber Perez-Gonzalez, Manibrata Sen, PRD 102 (2020)



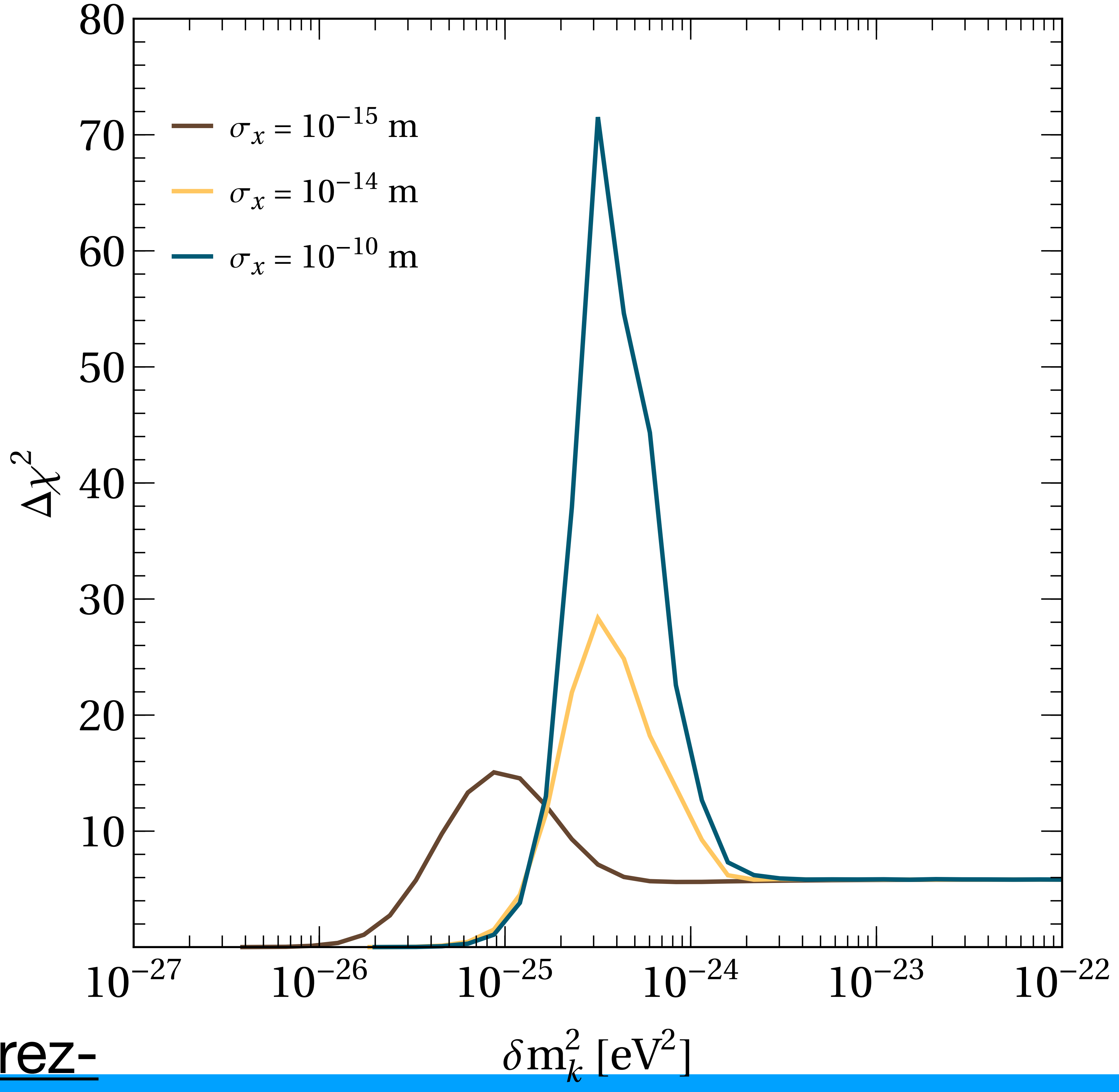
Pseudo-Dirac neutrinos

We have explored the sensitivity of a **future detector**: Hyper-Kamiokande

Neutrinos detection via IBD



HK can probe tiny mass splittings with a significance



Andre de Gouvea, IMS, Yuber Perez-Gonzalez, Manibrata Sen, PRD 102 (2020)

Conclusions

- The study of **neutrino cross sections** provides a powerful tool to probe neutrino **properties** and to identify new neutrino **sources**.

- **Coherent elastic neutrino–nucleus scattering** has now been observed with multiple sources and target nuclei, enabling sensitivity to new neutrino properties, such as magnetic moments and non-standard interactions.

- At MeV energies, neutrino detectors open the possibility of observing new astrophysical signals, including the **Diffuse Supernova Neutrino Background** (DSNB).

- A precise understanding of neutrino–oxygen scattering at very low energies is essential for future **low-threshold detectors** and astrophysical neutrino searches.

Thanks!