The diffuse supernova neutrino background, a new window to the Universe

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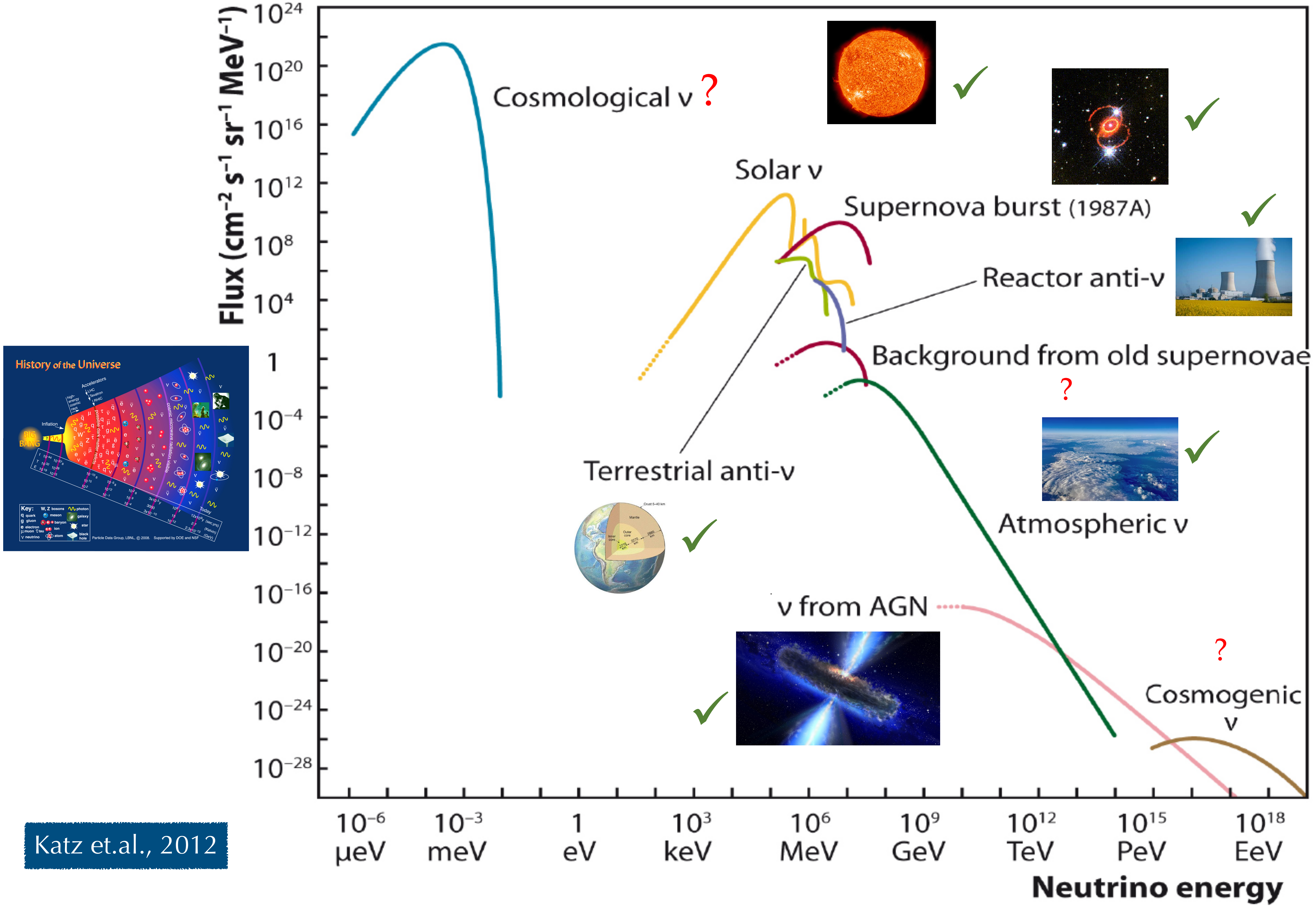
Fermilab

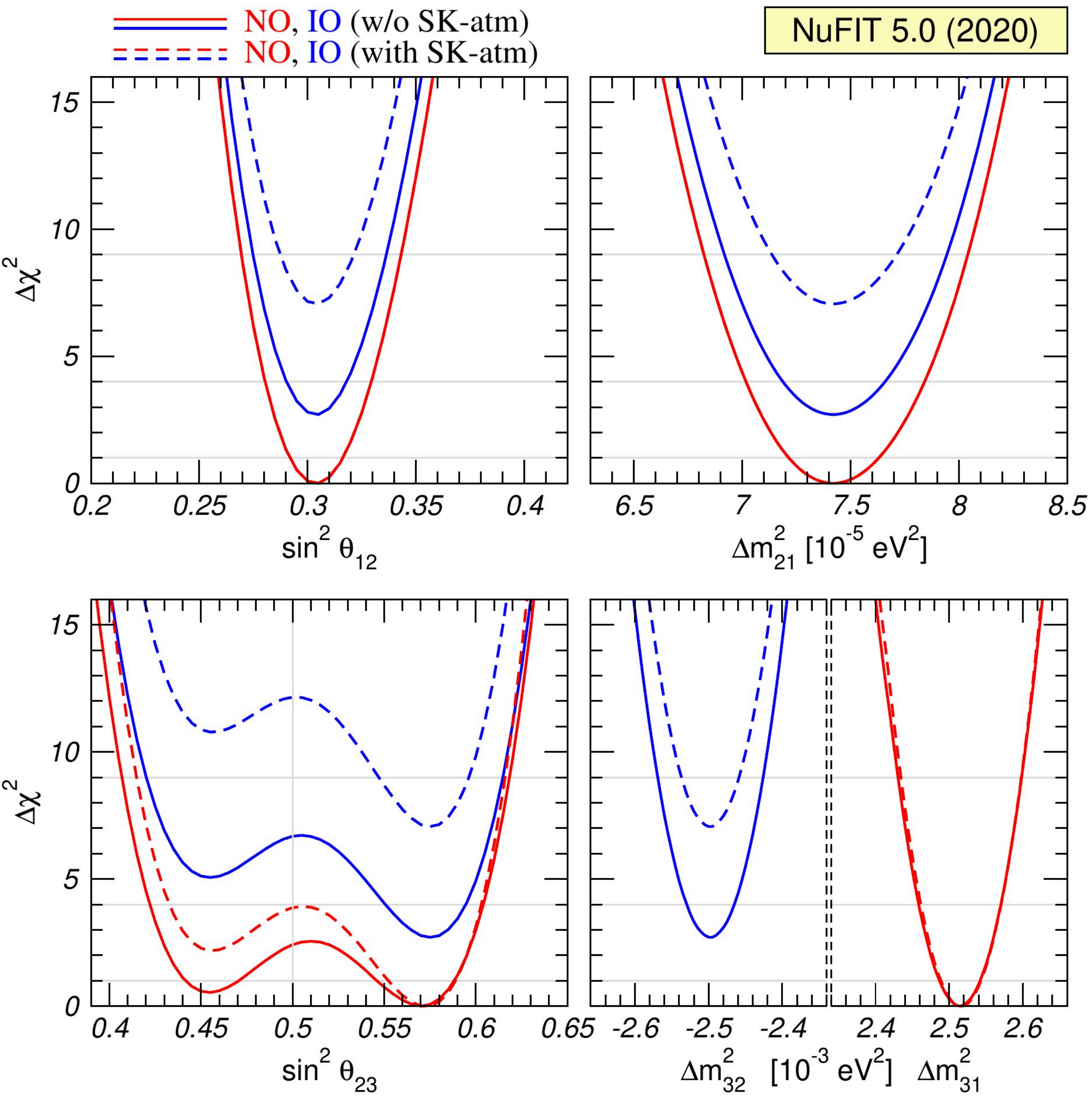
COFI
COLEGIO DE FISICA FUNDAMENTAL E INTERDISCIPLINARIA DE LAS AMERICAS

Northwestern



Katz et.al., 2012

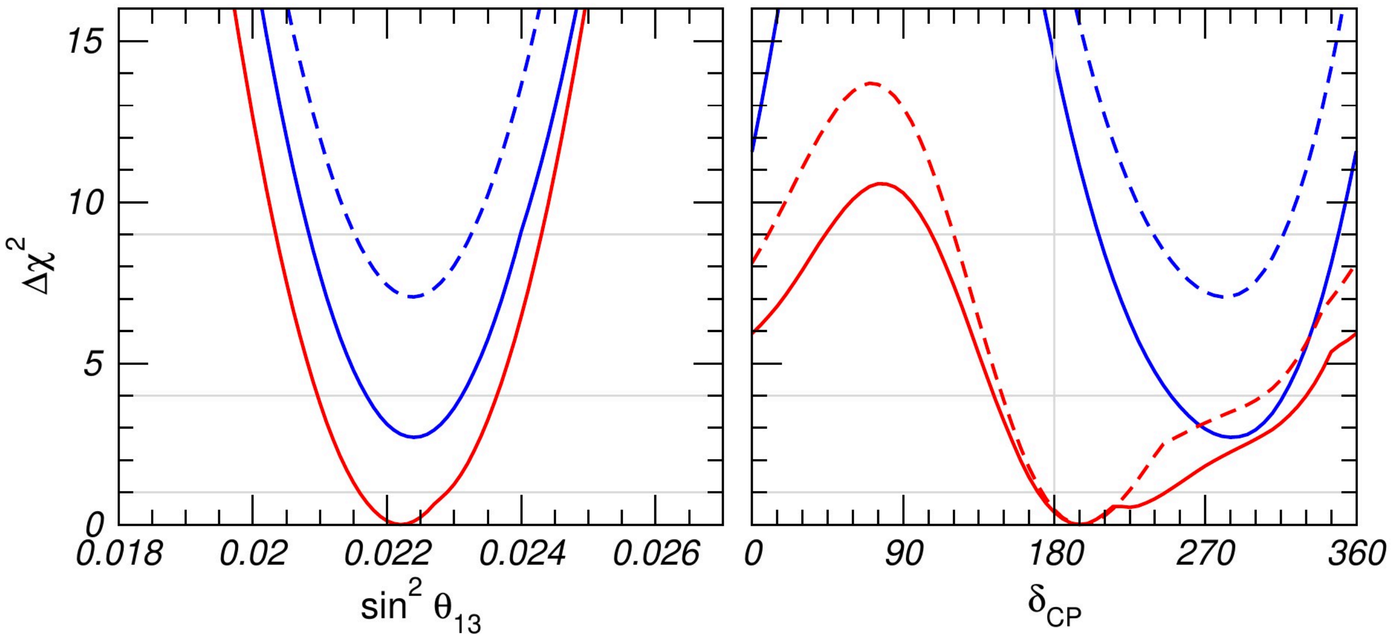
What do we know about neutrino masses and mixing?



$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\,|\nu_i\rangle$$

$$P_{\alpha\beta} = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \exp\left(-i\frac{(m_k^2 - m_j^2)L}{2E}\right)$$

- 3 mixing angles
- 2 non-zero quadratic mass differences

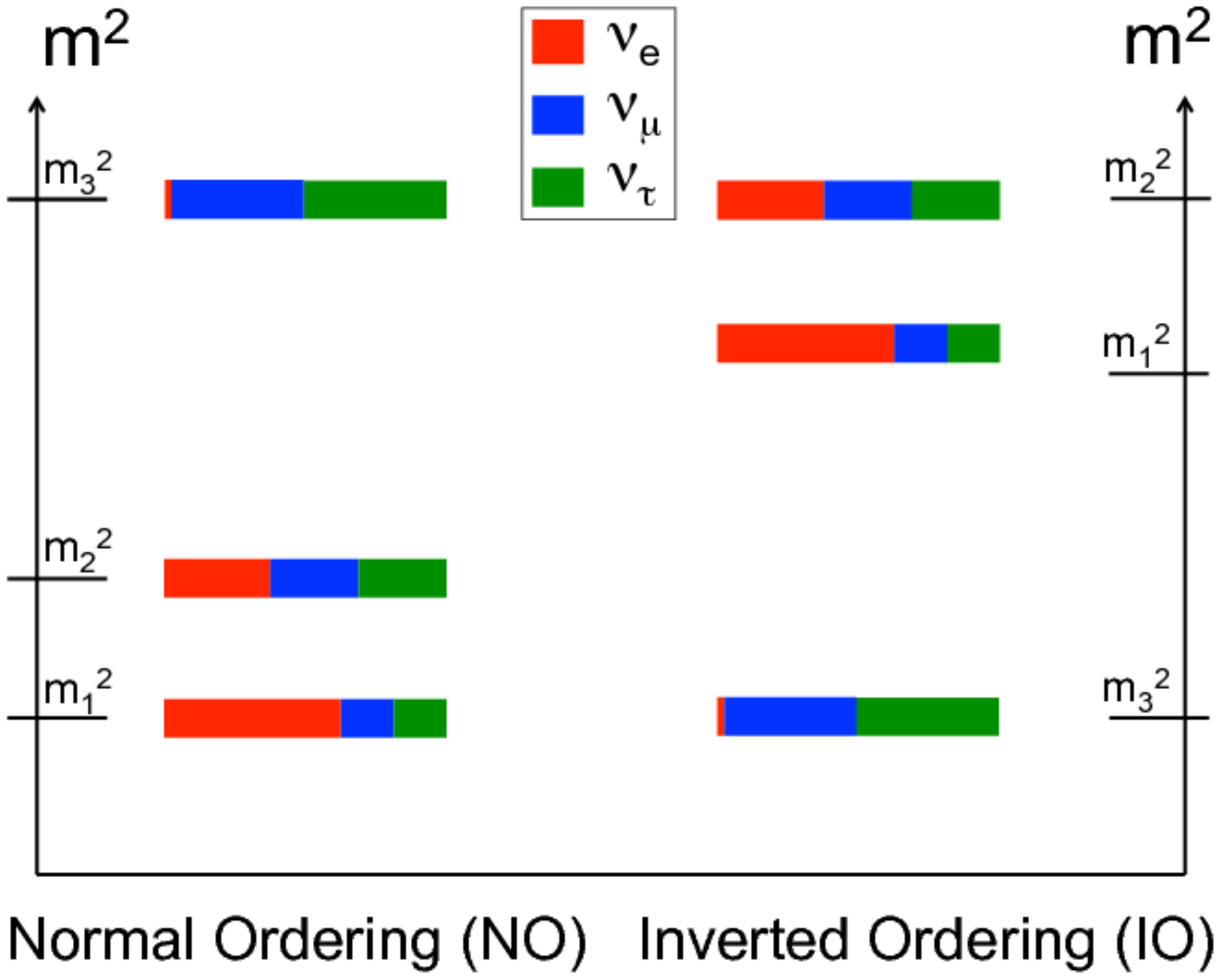


NuFit
JHEP 09 (2020) 178

Erica's talk

What do not we know about neutrino masses and mixing?

Mass ordering?



$|\nu_a\rangle = \tilde{U}_{\alpha a}|\nu_\alpha\rangle$

T2K —> NO
NOvA —> NO
T2K + NOvA —> IO

Kelly, Machado, Parke,
YFPG, and Funchal
2007.08526

- CP phase - CP violation
- Absolute mass values
- Dirac vs Majorana nature

Dirac vs Majorana

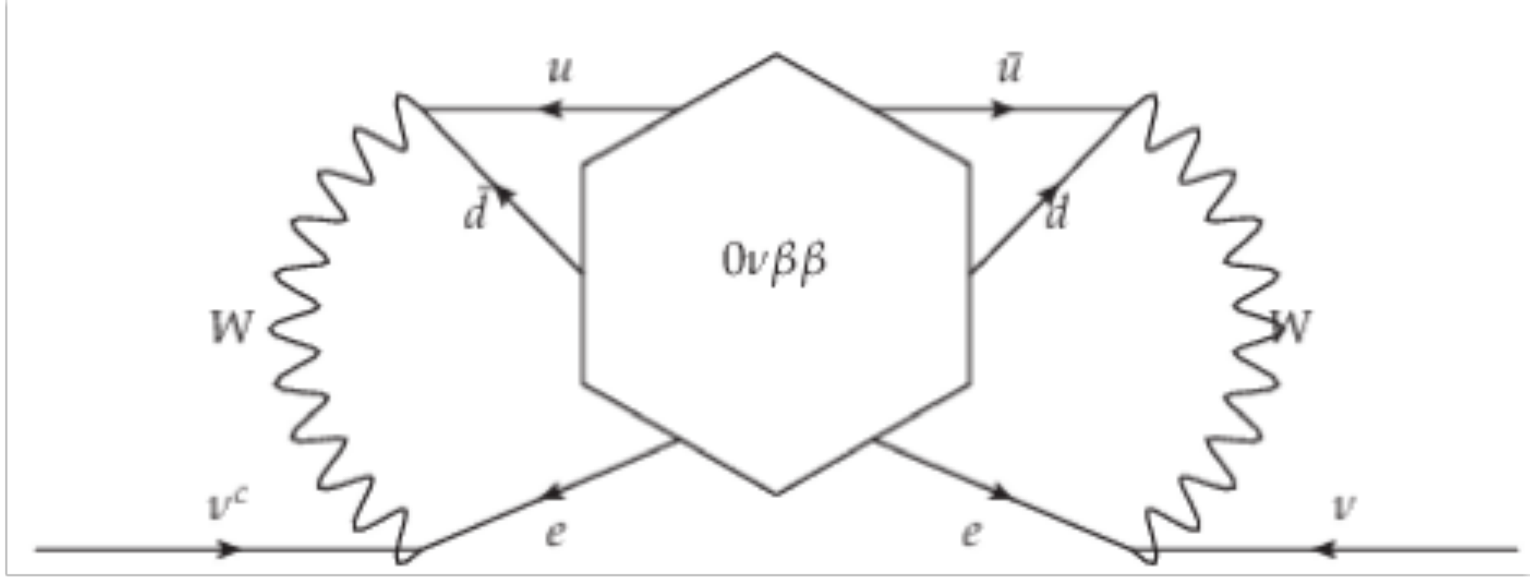
- Neutrino-less double beta decay

Schechter Valle, 1982

$\tau_{1/2} > 10^{27} - 10^{28}$ y

$m_{\beta\beta} < \sim 20$ meV

nEXO, KamLAND2-Zen, Cupid..



- Measure energy and angle distributions of heavy neutrino decay

Balantekin, De Gouvêa, Kayser, 2018

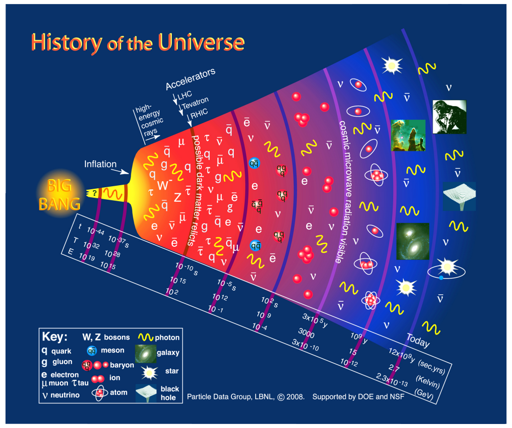
- Detect non-relativistic neutrinos $\nu_a + n \to p^+ + e^-$

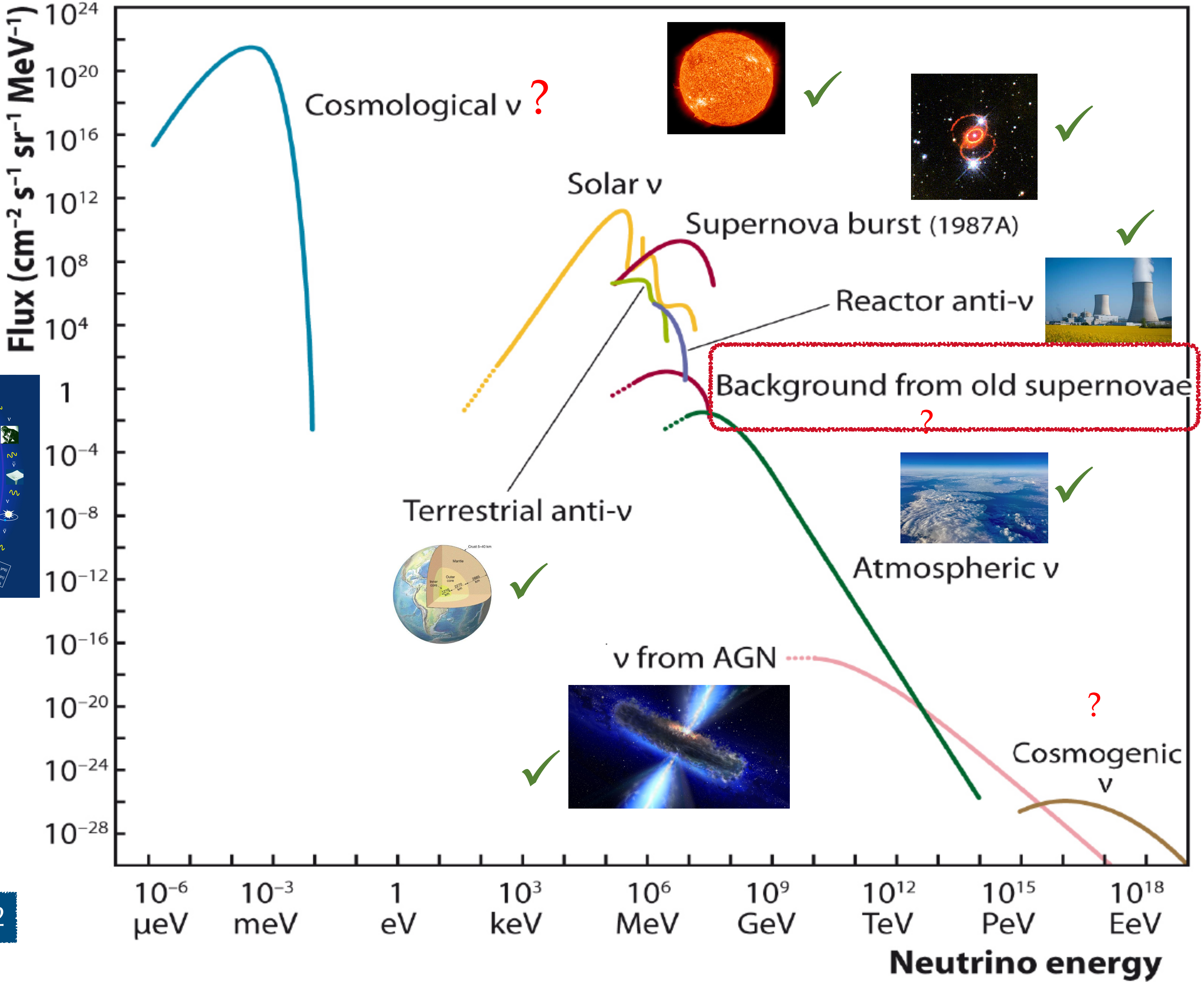
Duda and Gelmini, 2001
Long et.al. 2014

$$\boxed{\Gamma^{\mathrm{M}}_{\mathrm{C}\nu\mathrm{B}} = 2\Gamma^{\mathrm{D}}_{\mathrm{C}\nu\mathrm{B}}}$$

- BSM can hinder the neutrino nature

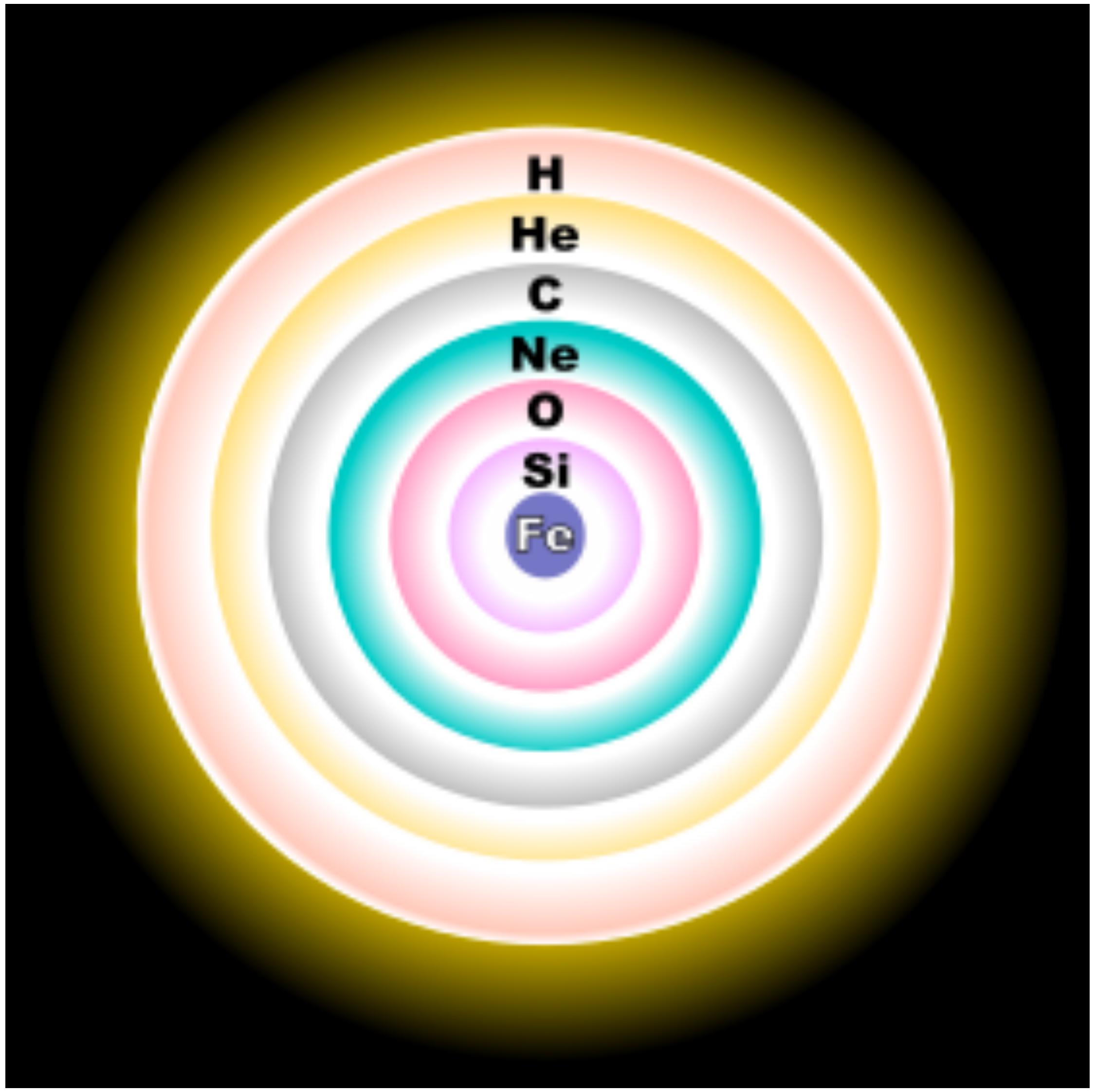
Arteaga, Bertuzzo, YFPG, Funchal, 2017





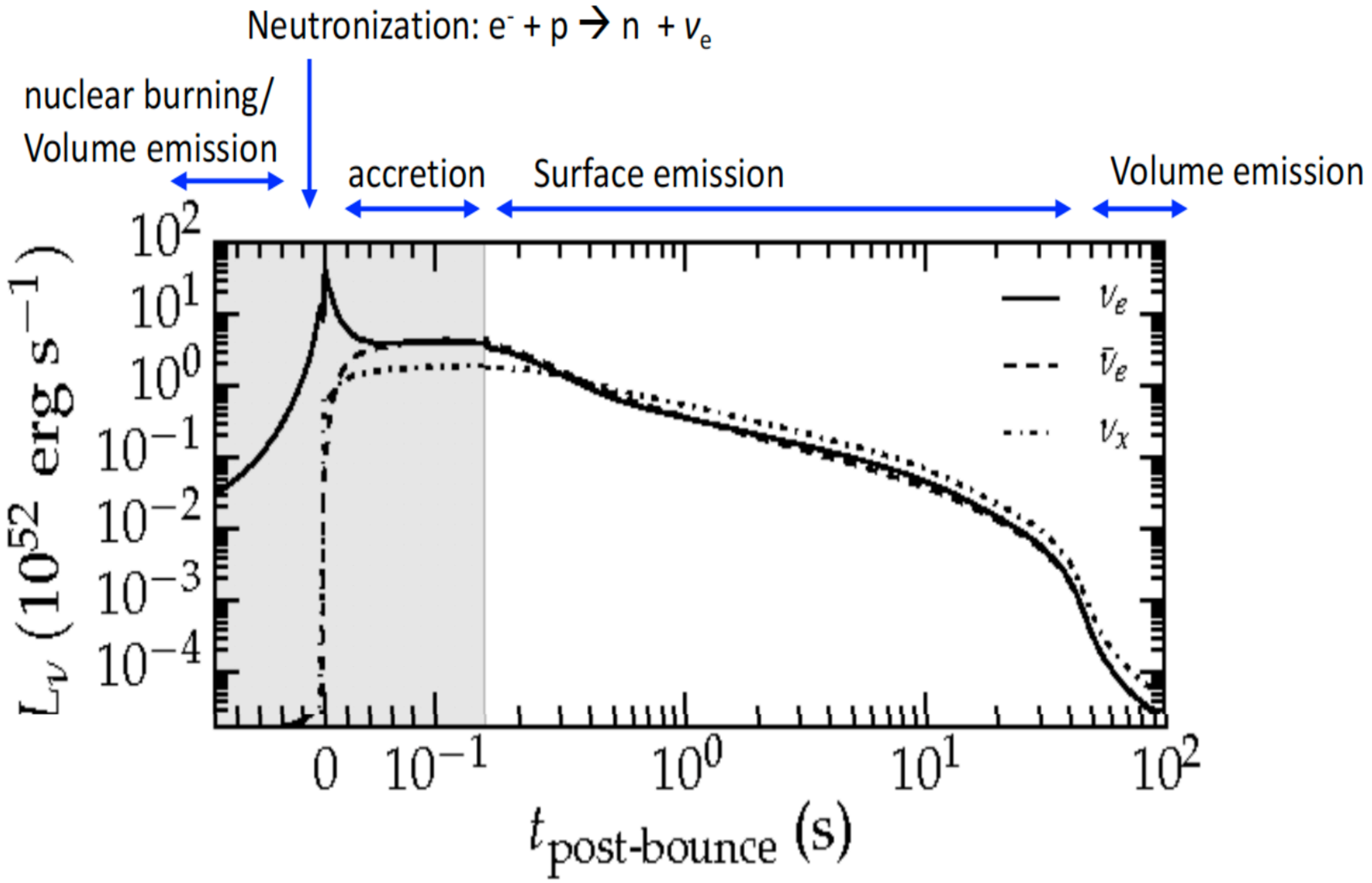
Katz et.al., 2012

Core-collapse Supernovae



$M > 11M_\odot$

- Core composed of iron, cannot continue doing fusion to counterbalance gravity
- MeV neutrinos are emitted
- Dominated by the cooling phase


Neutronization: $e^- + p \rightarrow n + \nu_e$

nuclear burning/ Volume emission

accretion

Surface emission

Volume emission

Figure from Roberts and Reddy, Handbook of Supernovae, Springer Intl., 2017

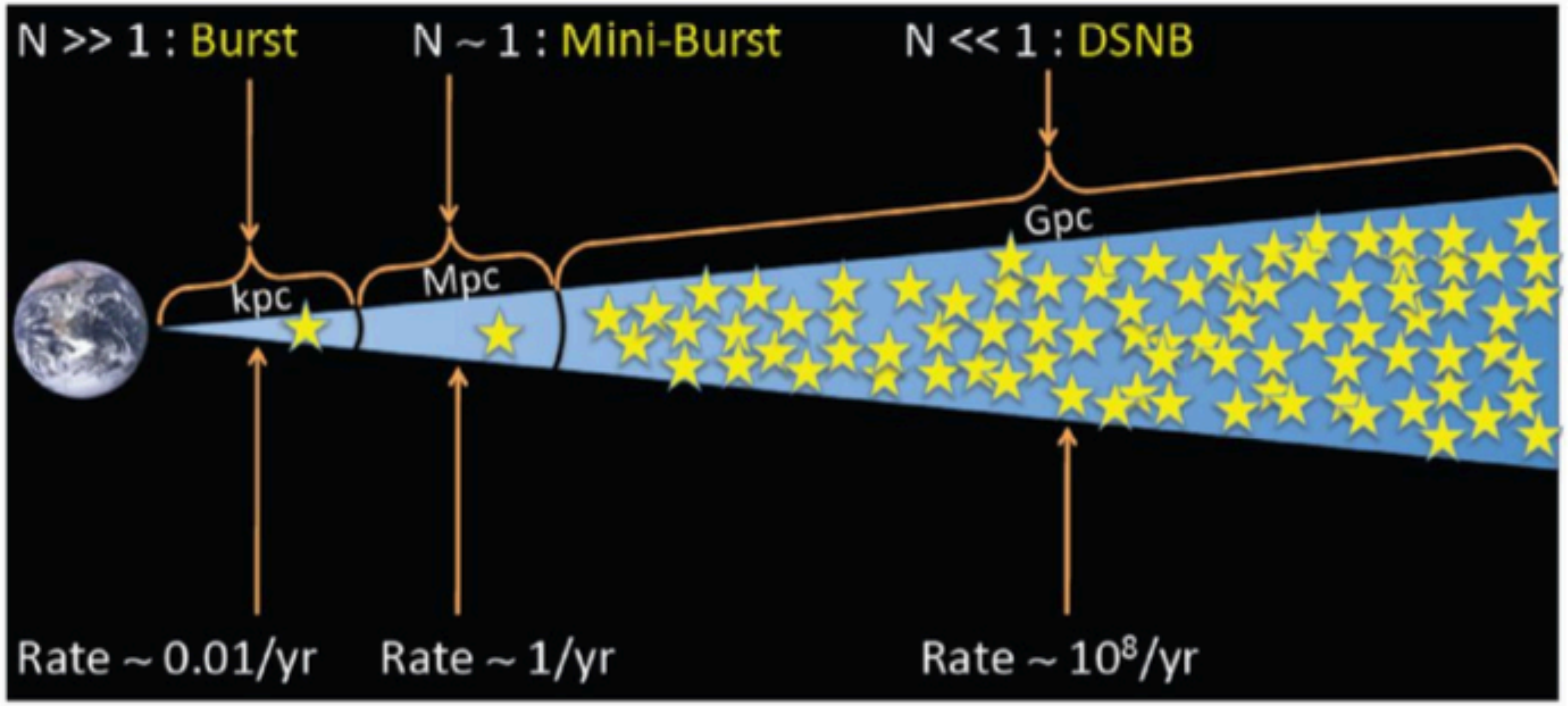
Core-collapse Supernovae

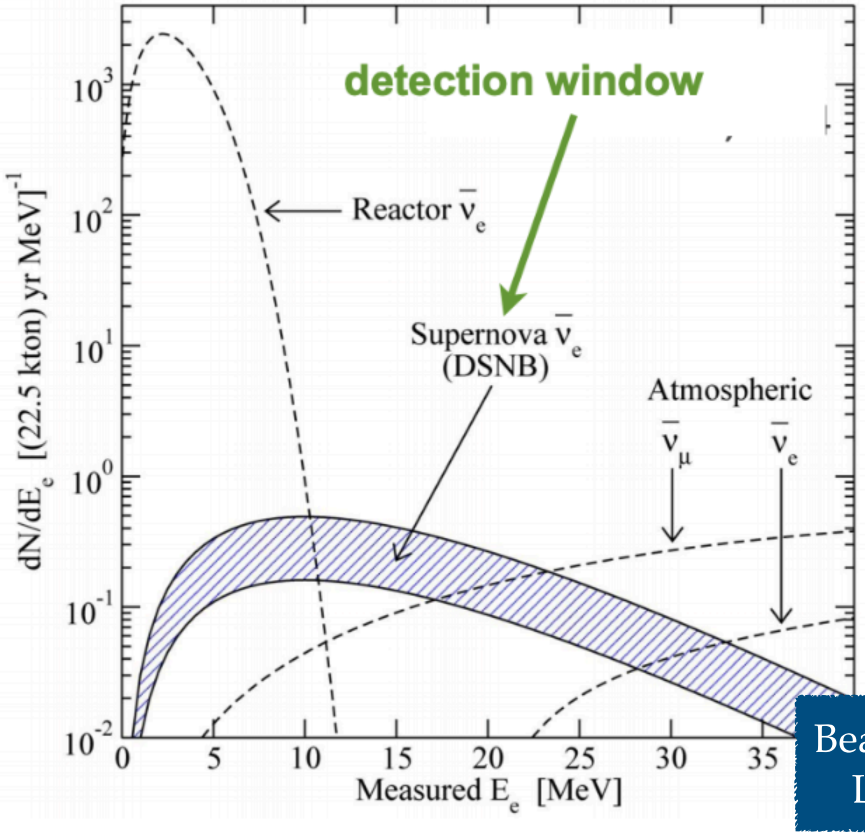
- Galactic SNe are rare, 3 per century
- Last event was the SN1987a
- O(30) neutrino events were measured
- Future SNe could make our detectors "shine like a Christmas tree" —> O(10k) events!
- When will the next galactic SN be?

Diffuse Supernova Neutrino Background

- We could look at all the SNe that have exploded in the Universe
- This should create a diffuse (isotropic and time independent) neutrino flux
- New frontier in neutrino astrophysics

John Beacom, TAUP2011



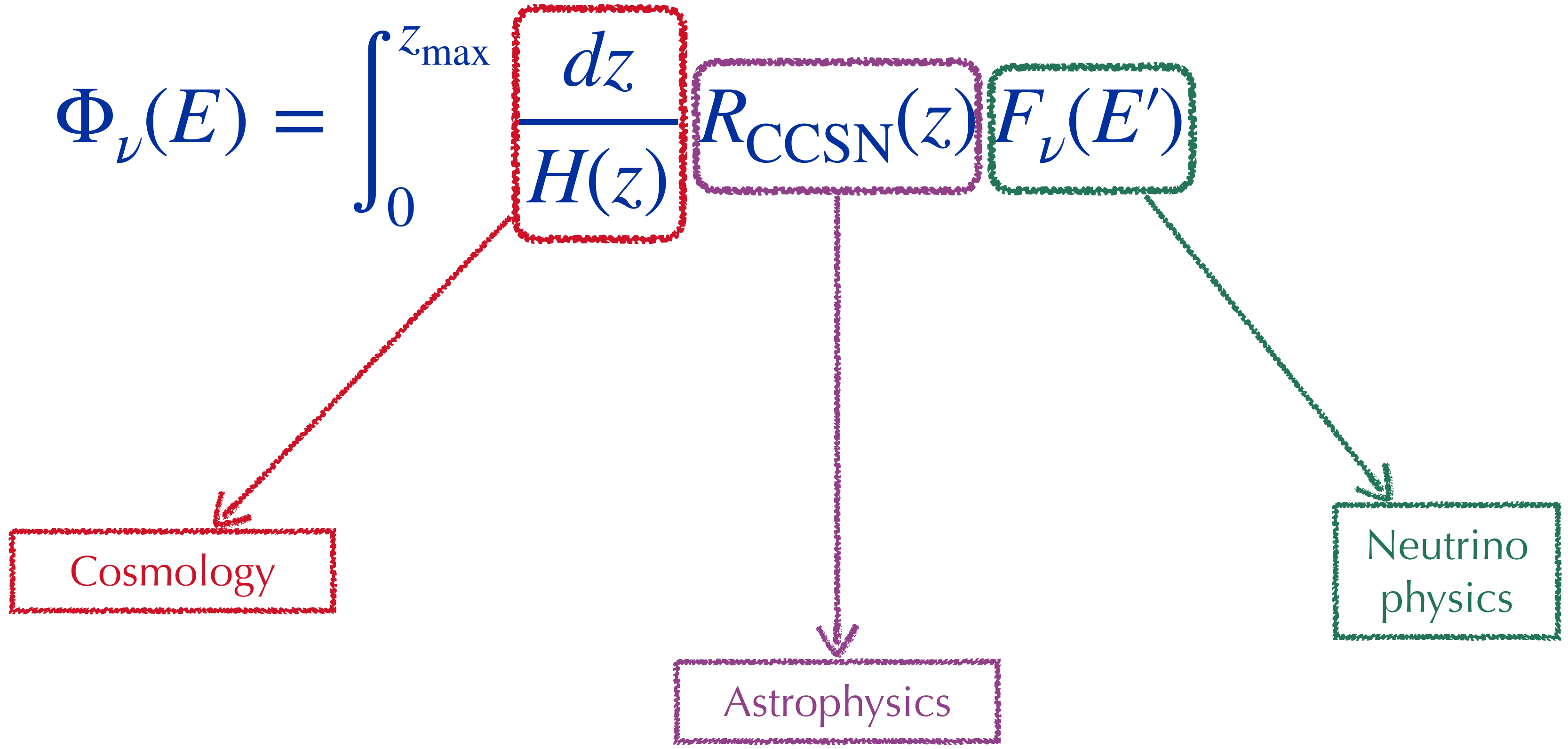


Beacom, Ann.Rev.Nuc.Phys.Sc.2010
Lunardini, Astropart. Phys2016

What can we learn by measuring the DSNB?

Diffuse Supernova Neutrino Background

$z_{\max} = 5$



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

Cosmology

Astrophysics

Neutrino physics

Cosmology

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

H_0 → Hubble parameter
Ω_{x} → Distinct components
w → Dark Energy EOS

Cosmology

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

H_0 → Hubble parameter
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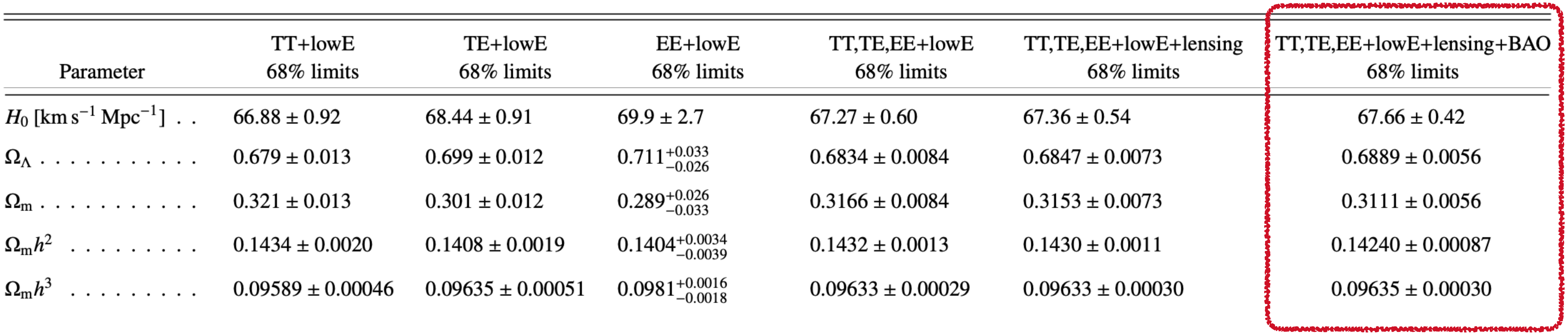
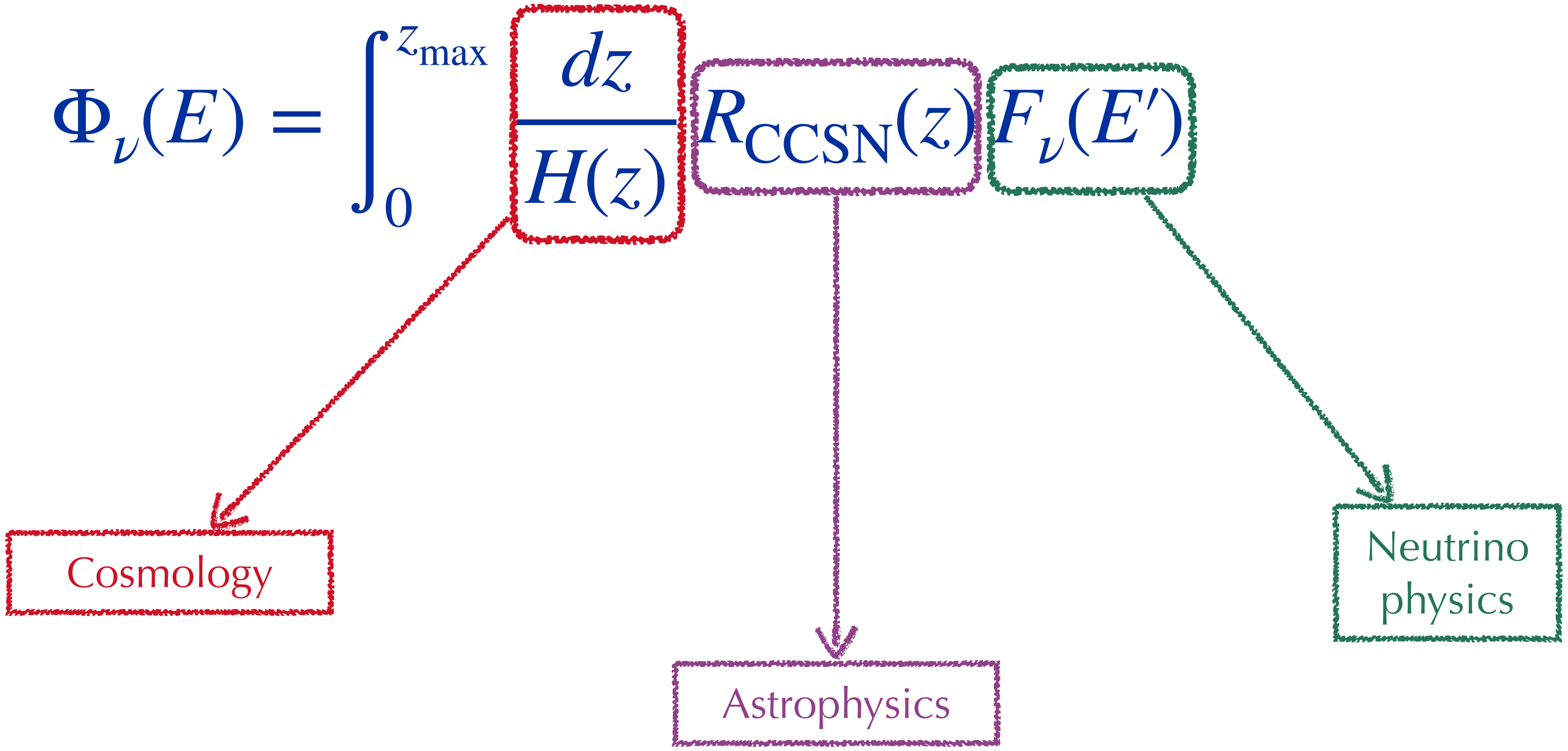


Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
H_0 [km s^{-1} Mpc^{-1}] . .	66.88 ± 0.92	68.44 ± 0.91	69.9 ± 2.7	67.27 ± 0.60	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.679 ± 0.013	0.699 ± 0.012	$0.711^{+0.033}_{-0.026}$	0.6834 ± 0.0084	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.321 ± 0.013	0.301 ± 0.012	$0.289^{+0.026}_{-0.033}$	0.3166 ± 0.0084	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1434 ± 0.0020	0.1408 ± 0.0019	$0.1404^{+0.0034}_{-0.0039}$	0.1432 ± 0.0013	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09589 ± 0.00046	0.09635 ± 0.00051	$0.0981^{+0.0016}_{-0.0018}$	0.09633 ± 0.00029	0.09633 ± 0.00030	0.09635 ± 0.00030

Planck 2018

Diffuse Supernova Neutrino Background

$z_{\rm max} = 5$



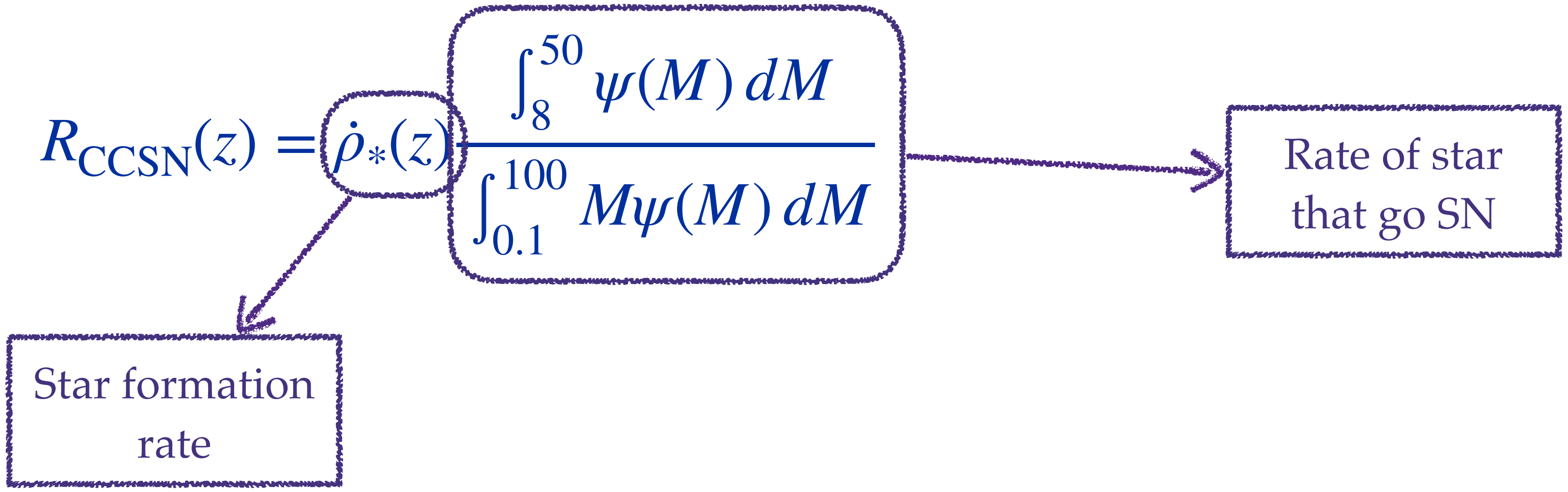
$$\Phi_\nu(E) = \int_0^{z_{\rm max}} \boxed{\frac{dz}{H(z)}}\, \boxed{R_{\rm CCSN}(z)}\, \boxed{F_\nu(E')}$$

Cosmology

Astrophysics

Neutrino physics

Astrophysics



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

Rate of star that go SN

Star formation rate

Astrophysics

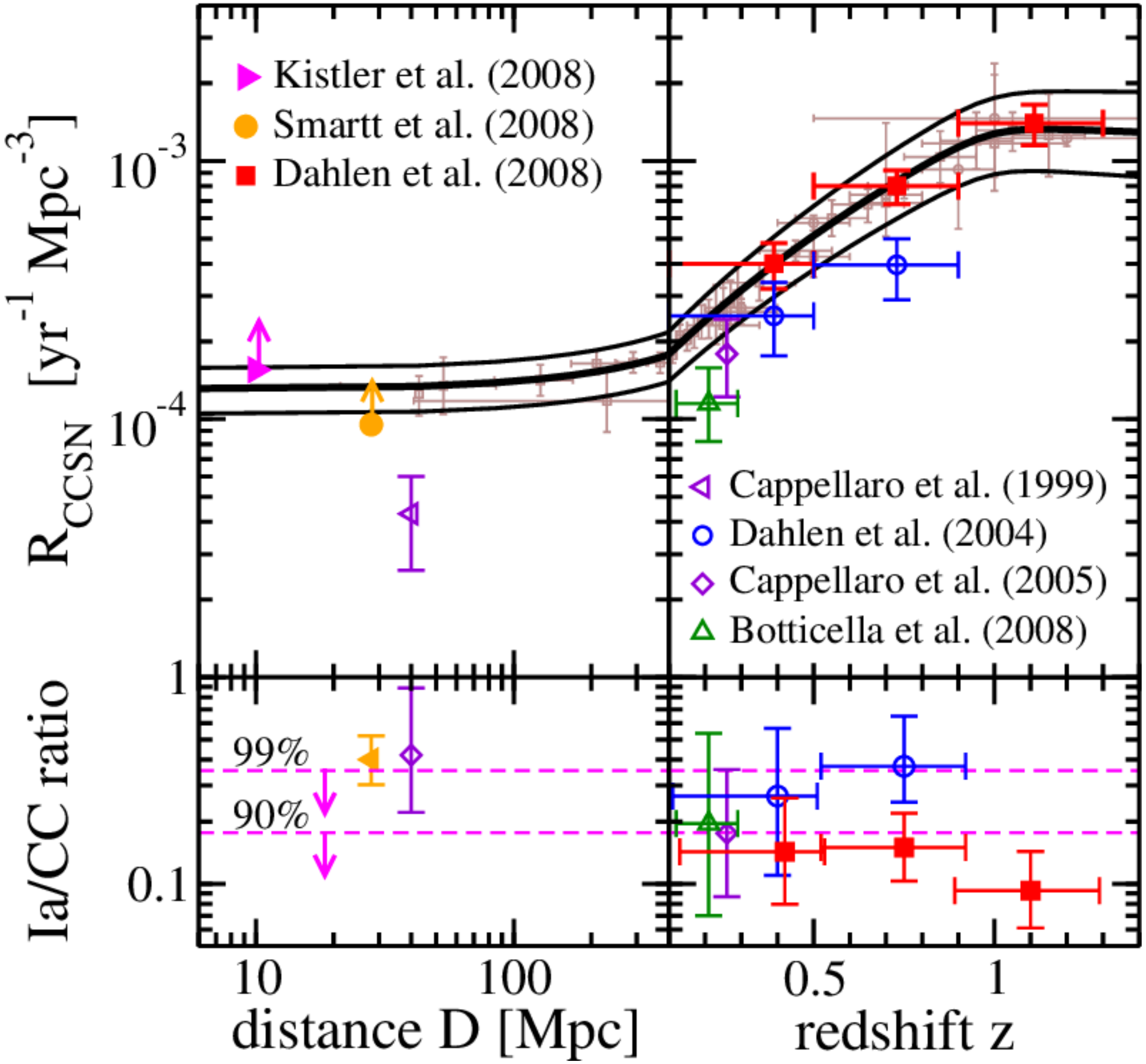
$$\dot{\rho}_*(z) = \dot{\rho}_0 \left[(1+z)^{-10\,\alpha} + \left(\frac{1+z}{B}\right)^{-10\,\beta} + \left(\frac{1+z}{C}\right)^{-10\,\gamma} \right]^{-1/10}$$

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

Star formation rate

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

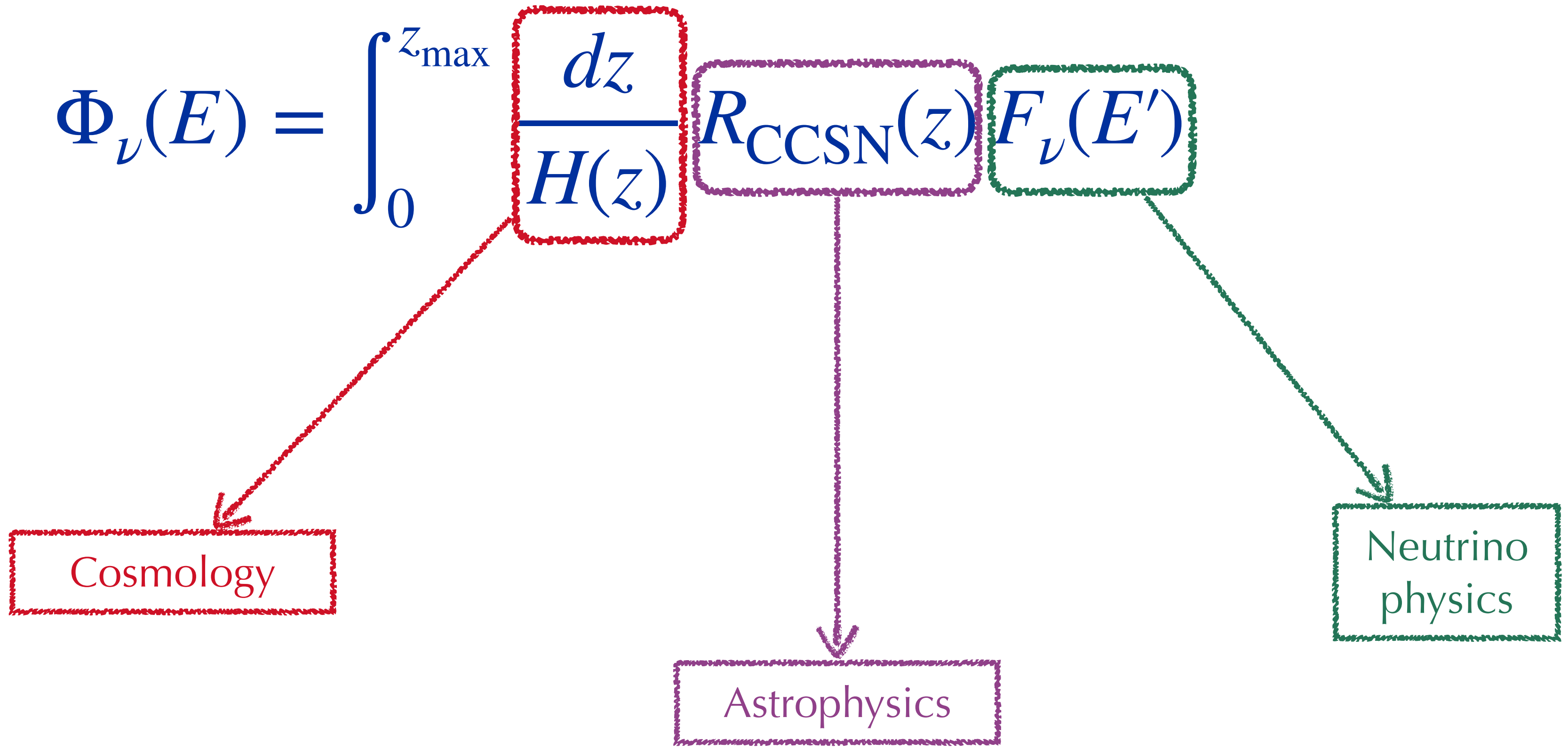
Cosmic SFR pretty well known from data in the UV and the far-infrared



Hopkins, Beacom, ApJ2006
Yuksel, Kistler, Beacom, Hopkins, ApJ2008
Horiuchi, Beacom, Dwek, PRD2009

Diffuse Supernova Neutrino Background

$z_{\max} = 5$



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

Cosmology

Astrophysics

Neutrino physics

Neutrino physics

Total released energy

Assume a Fermi-Dirac distribution. Characteristic of the late-time phase

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

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

Neutrino physics

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

$$T_{\nu_e} < T_{\bar\nu_e} < T_{\nu_x}$$

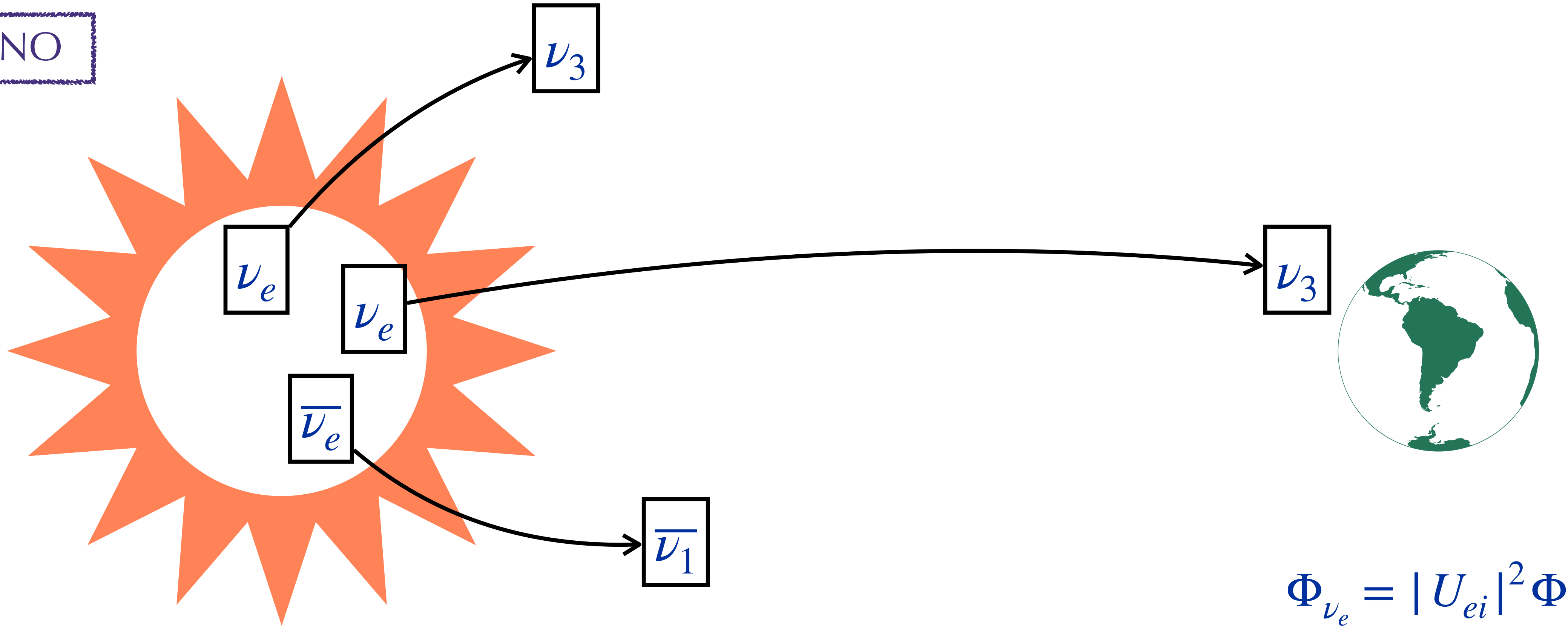
Oscillations? → Dominated by MSW effect

$$H = \cancel{H_0} + V_{\rm mat}$$

Mixings are highly suppressed and flavor states coincide with medium eigenstates

Dighe, Smirnov PRD62(2000)033007

For the NO

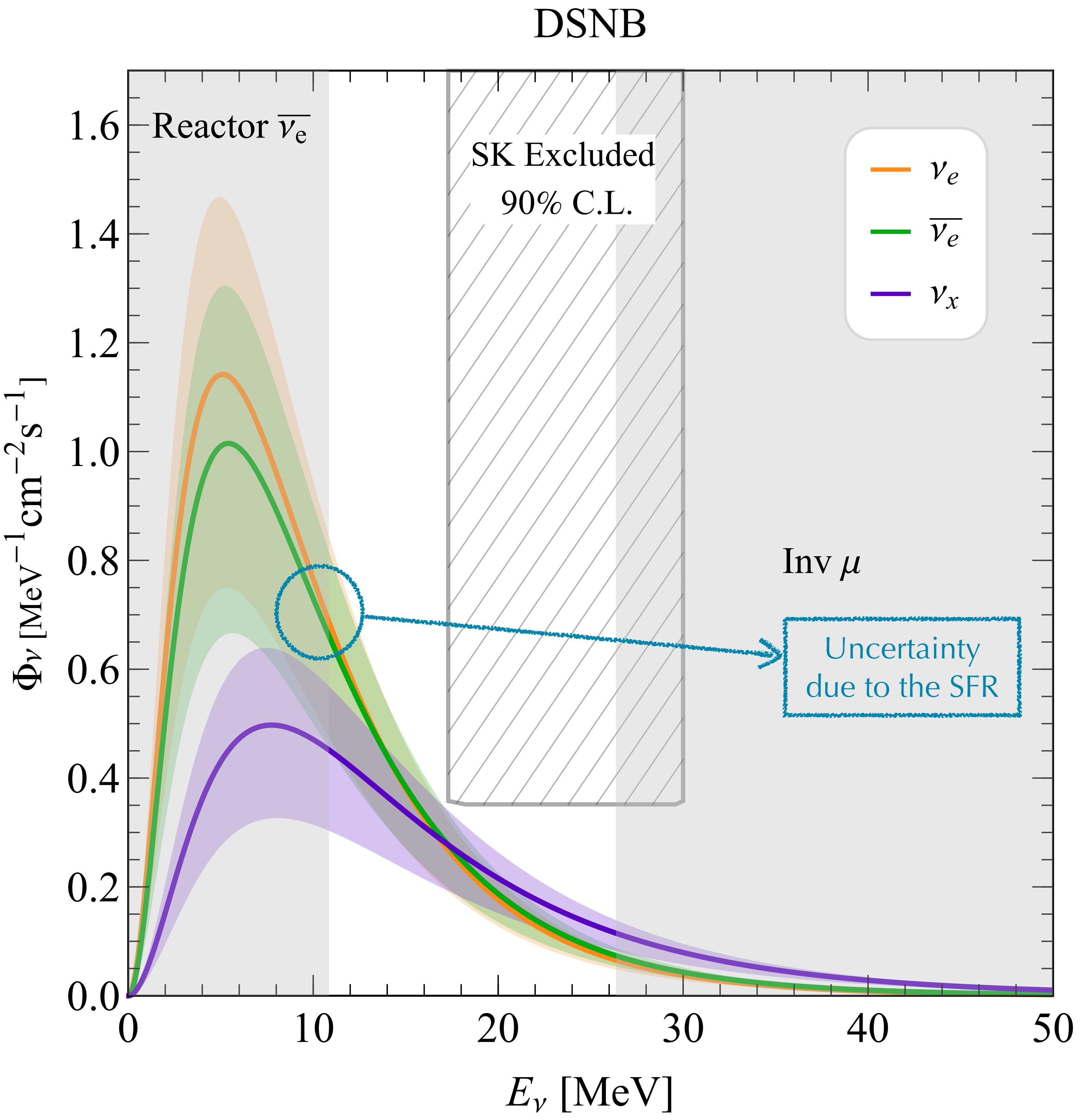


$$\Phi_{\nu_e} = |U_{ei}|^2\,\Phi_{\nu_i}$$

Diffuse Supernova Neutrino Background

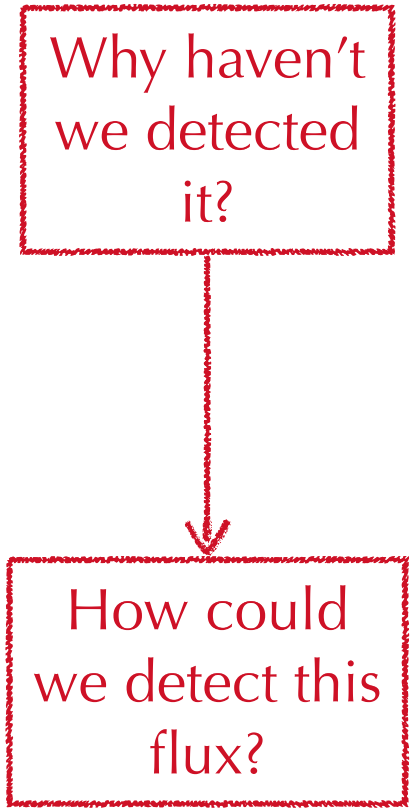
This is a “guaranteed” flux

Why haven’t we detected it?



Uncertainty due to the SFR

Detecting the DSNB



Why haven't we detected it?

How could we detect this flux?

Backgrounds…

- There are many sources of background in the DSNB energy window
- Next generation experiments should be able to identify the DSNB
  - ✦ SK-Gd, JUNO, HK, DUNE, THEIA
- Backgrounds will depend on the detector.

Number of events

$$N_i = N_{\rm tar} T \int dE^r dE^t \Phi_\alpha \sigma_\alpha \epsilon(E^t, E^r) + {\rm Bkg}_i$$

SK, SK-Gd and HK

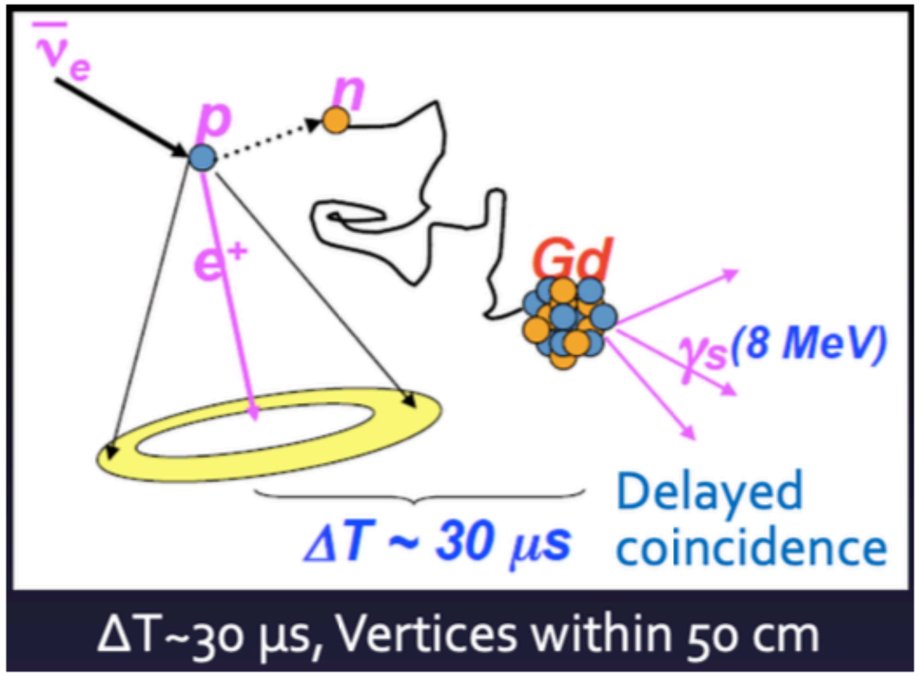
de Gouvêa, Martinez-Soler, YFPG, Sen, 2007.13748

- Main channel for detection, IBD, $\overline{\nu_e} + p^+ \to n + e^+$

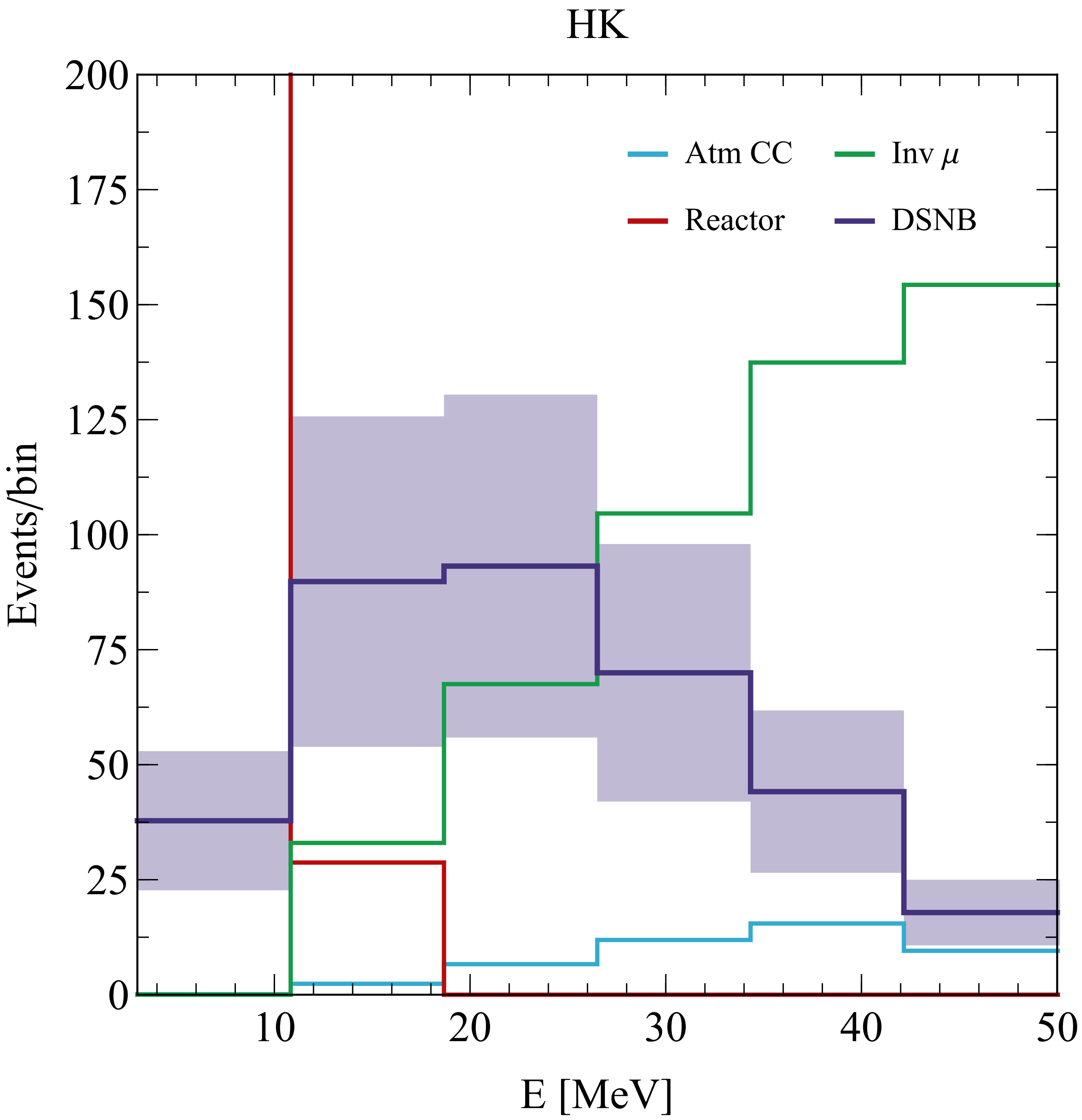
- **Backgrounds:**
  - $E_\nu < 10$ MeV, reactor antineutrinos
  - $E_\nu > 10$ MeV, muon spallation, atm neutrinos, invisible muon decay , NC

- Dope with Gadolinium!

- HK: 187kt and 10 years of data



ΔT~30 μs, Vertices within 50 cm

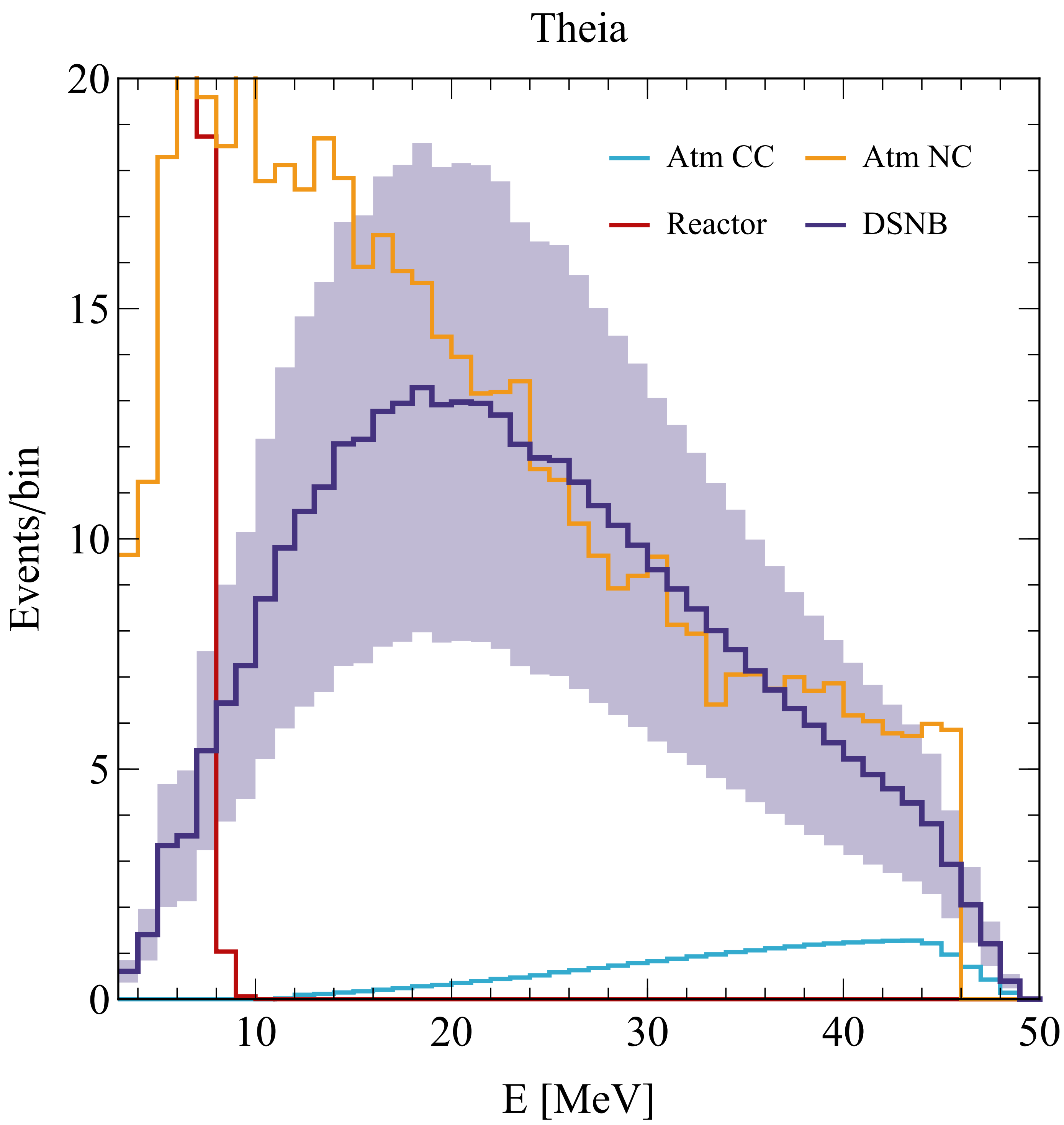


Water-based Liquid Scintillator - THEIA

- Combination of techniques, H20 + LS

- **Backgrounds:**
  - ✤ 9Li, muon spallation, NC aims, neutrons…

- THEIA: 100kt - 10 years of data taking



What can we learn by measuring the DSNB?

We can look at the Universe's history though neutrino's eyes

- Neutrinos propagate in an expanding Universe → Cosmology?
- Star Formation Rate as seen by neutrinos

Constraints from light will be considerably stronger

- Neutrino properties that are "slow":
  - Neutrino decay
  - Pseudo Dirac neutrinos

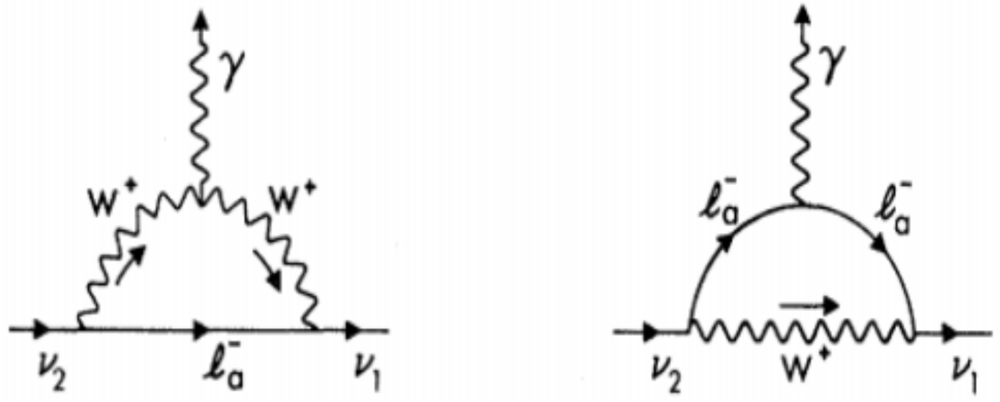
de Gouvêa, Martinez-Soler, YFPG, Sen, 2007.13748

Neutrino Decay

- Neutrinos have a lifetime, even in the SM

Pakvasa and Valle ('03), Pal and Wolfenstein ('82), Petcov, Marciano and Sanda ('77)

$\Gamma \sim 10^{-45}$ s → Way longer than the age of the Universe



Pal and Wolfenstein (PRD1982)

- However, in BSM exists, it can modify the neutrino lifetime:
  - ✳ Solar neutrinos: $\tau_2/m_2 \gtrsim 10^{-3}$ s/eV, and $\tau_1/m_1 \gtrsim 10^{-4}$ s/eV
  - ✳ Atms neutrinos: $\tau_3/m_3 \gtrsim 10^{-10}$ s/eV
  - ✳ CMB: $\tau_\nu > 4 \times 10^8\ \mathrm{s}(m_\nu/0.005\ \mathrm{eV})^3$
  - ✳ SN1987a: $\tau_\nu/m_3 \gtrsim 3 \times 10^1$ s/eV

SNO (1812.01088)
Berryman, de Gouvea, Hernandez (1411.0308)

Gonzalez-Garcia and Maltoni (0802.3699)
Gomes, Gomes and Peres (1407.5640)

Escudero and Fairbairn (1907.05425)
Chacko, Dev, Du, Poulin and Tsai (1909.05275)

Kachelriess, Tomas and Valle (0001039)
Farzan ('02)

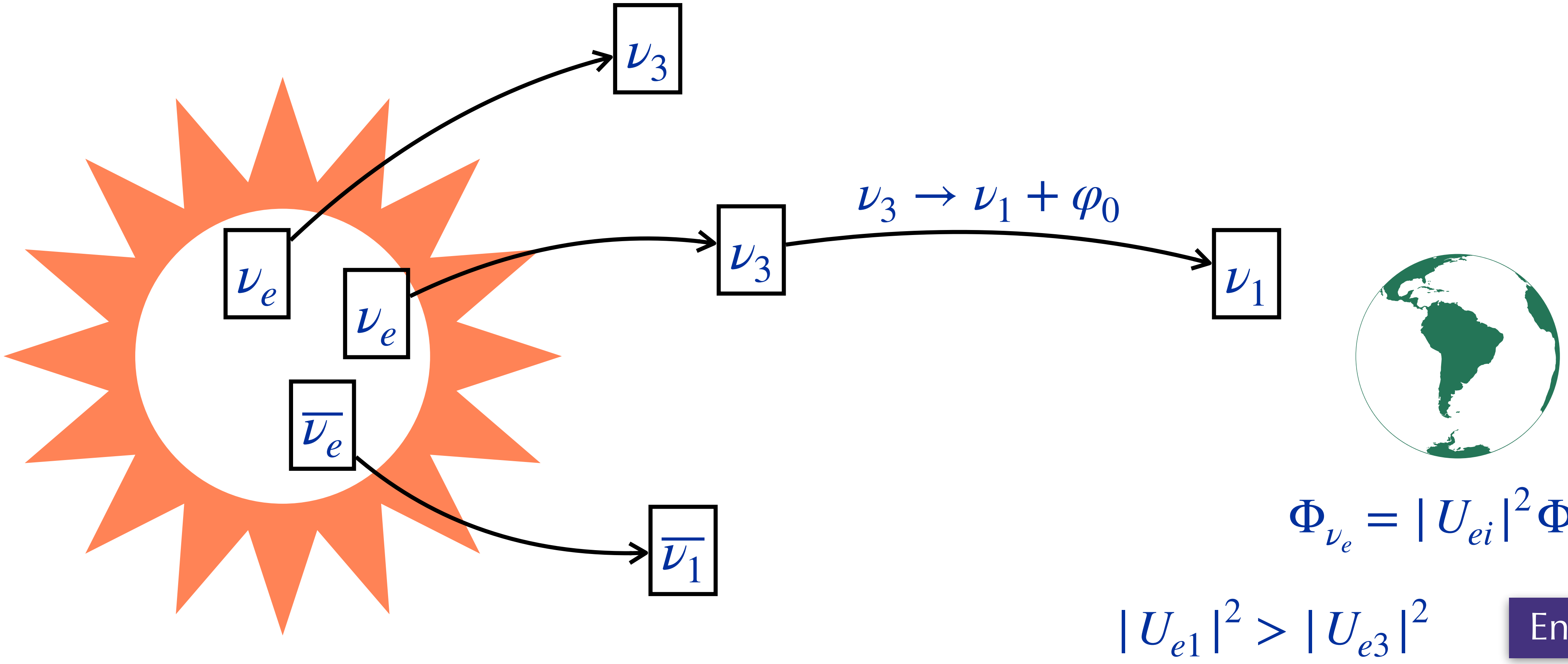
Neutrino Decay

Assume neutrinos to be Majorana

Consider an invisible neutrino decay

$$\mathscr{L} \supset \frac{f_{ij}}{2}(\nu_L)_i(\nu_L)_j\varphi + \mathrm{h.c.}$$

- Helicity conserving $\nu_{3_L} \to \nu_{1_L} + \varphi_0$
- Helicity flipping $\nu_{3_L} \to \nu_{1_R} + \varphi_0$



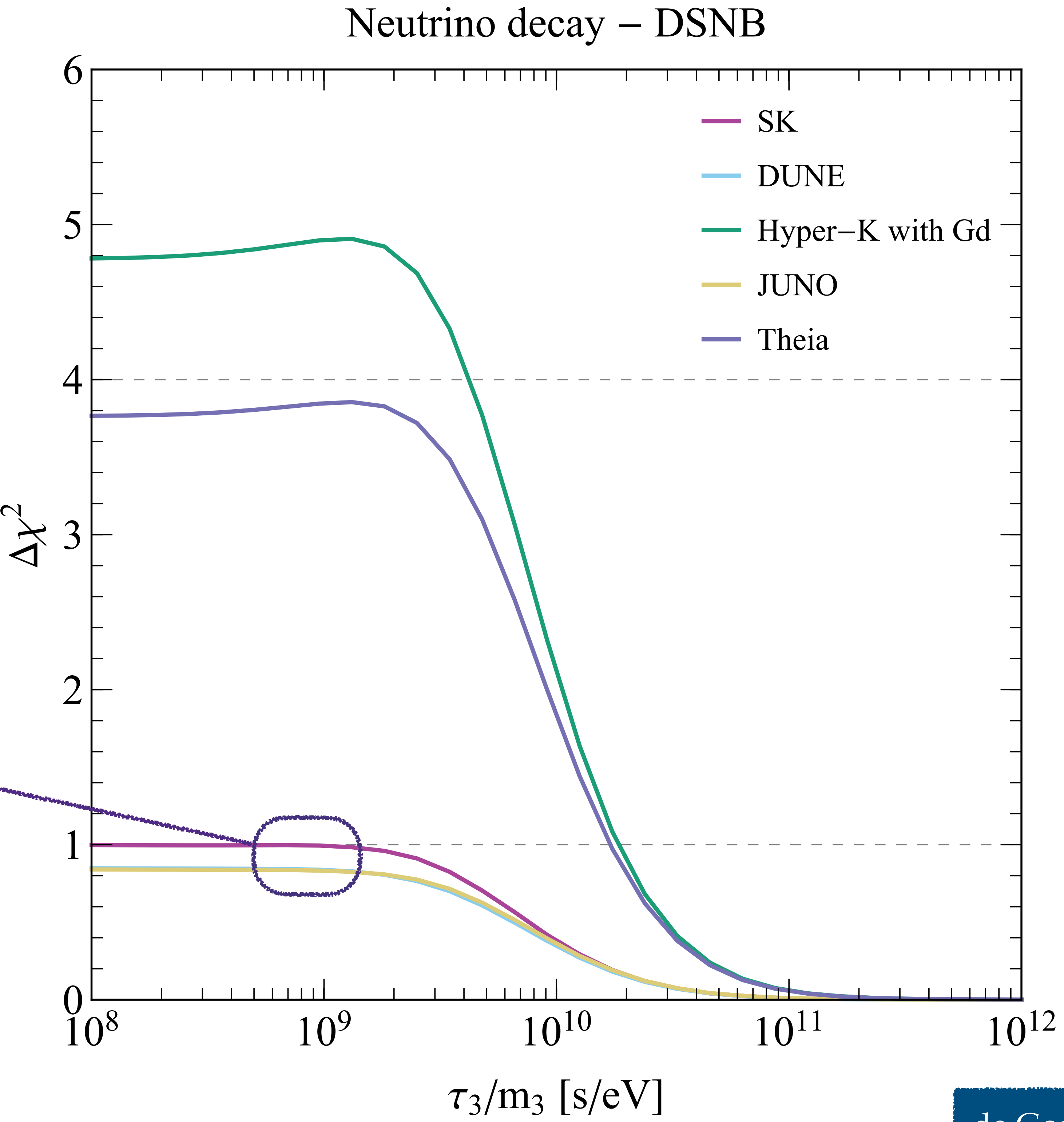
$$\Phi_{\nu_e} = |U_{ei}|^2 \Phi_{\nu_i}$$

$$|U_{e1}|^2 > |U_{e3}|^2$$

Enhancement

Future sensitivity

$$\tau_3/m_3 \lesssim 10^{10}\ \mathrm{s/eV} \left(\frac{L}{1\ \mathrm{Gpc}}\right)\left(\frac{10\ \mathrm{MeV}}{E_\nu}\right)$$



Other experiments barely would have something to say

de Gouvêa, Martinez-Soler, YFPG, Sen, 2007.13748

Pseudo-Dirac Neutrinos

Let's consider the Dirac+Majorana Lagrangian

$$\mathscr{L}_Y = \frac{1}{2}\overline{N^c} M N + \mathrm{h.c.}$$

$$M = \begin{pmatrix} 0_3 & M_D \\ M_D & M_R \end{pmatrix}$$

- ✣ $M_R = 0 \rightarrow$ Dirac neutrinos
- ✣ $M_R \gg M_D \rightarrow$ Usual type I seesaw
- ✣ $M_R \ll M_D \rightarrow$ PseudoDirac neutrinos

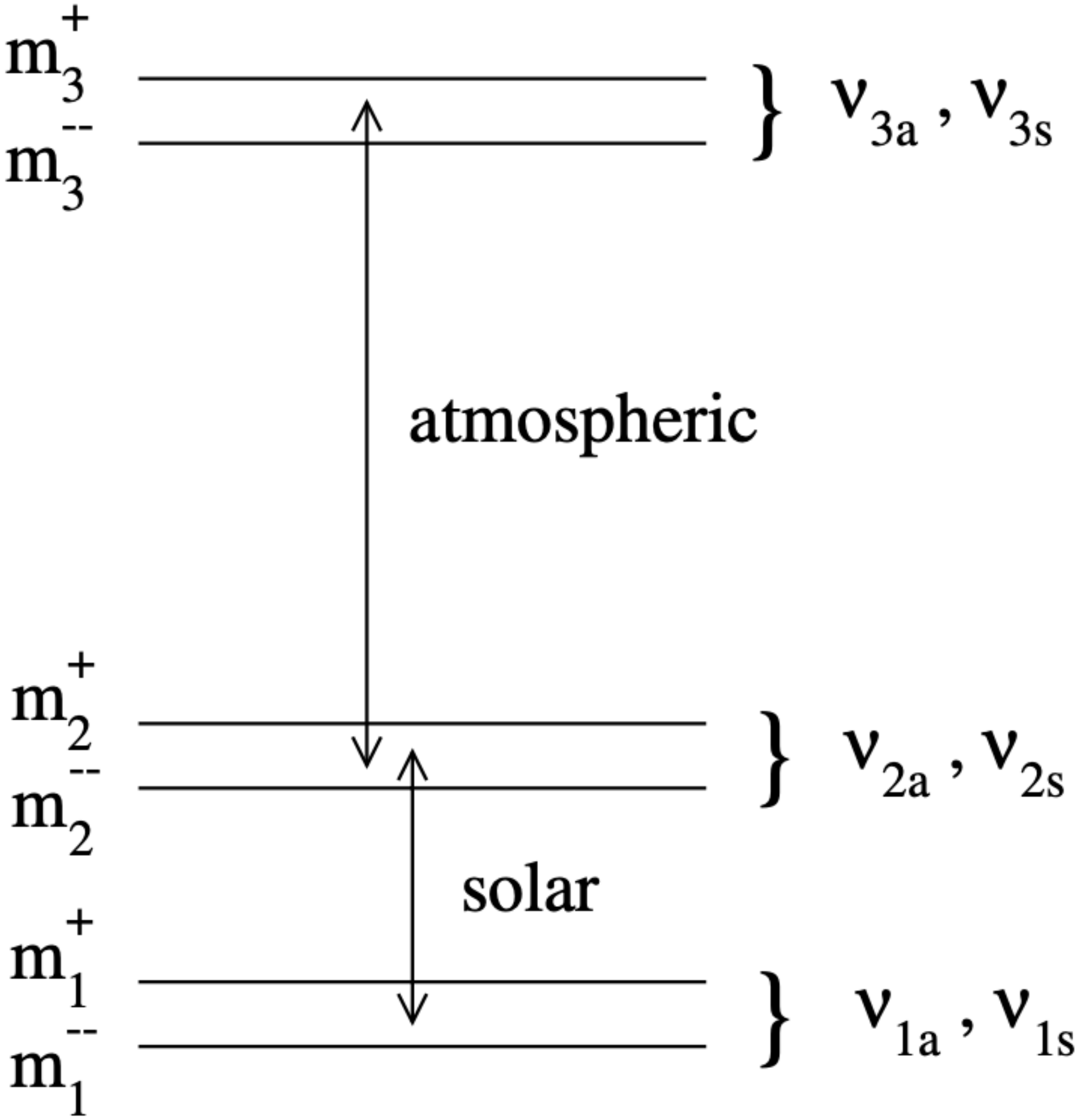
$$\nu_{\alpha L} = \frac{1}{\sqrt{2}} \underbrace{U_{\alpha j}}_{\text{PMNS matrix}} (\underbrace{\nu_{js} + i\,\nu_{ja}}_{\text{Mass eigenstates}})$$

Active neutrinos are a ~50-50 combination of two states

Pseudo-Dirac Neutrinos

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

$\delta m_k^2 \rightarrow$ tiny but non-zero mass difference



Limits on δm_k^2

- Solar neutrinos $\delta m_k^2 \lesssim 10^{-12}\ \mathrm{eV}^2$
  - de Gouvêa et.al. 0906.1611, Donini et.al. 1106.0064
- Atms neutrinos $\delta m_k^2 \lesssim 10^{-4}\ \mathrm{eV}^2$
  - Beacom et.al. 0307151
- HE neutrinos
  $10^{-18}\ \mathrm{eV}^2 \lesssim \delta m_k^2 \lesssim 10^{-12}\ \mathrm{eV}^2$
  - de Gouvêa et.al. 0906.1611, Donini et.al. 1106.0064

Pseudo-Dirac Neutrinos

Neutrinos have propagated distances of order Gpc

$$P_{k\beta}(z,E) = \frac{1}{2}|U_{\beta k}|^2 \left(1 + \exp\left\{-\frac{L_3(z)^2}{L_{\rm coh}^2}\right\} \cos\left(\frac{\delta m_k^2}{2E} L_2(z)\right)\right)$$

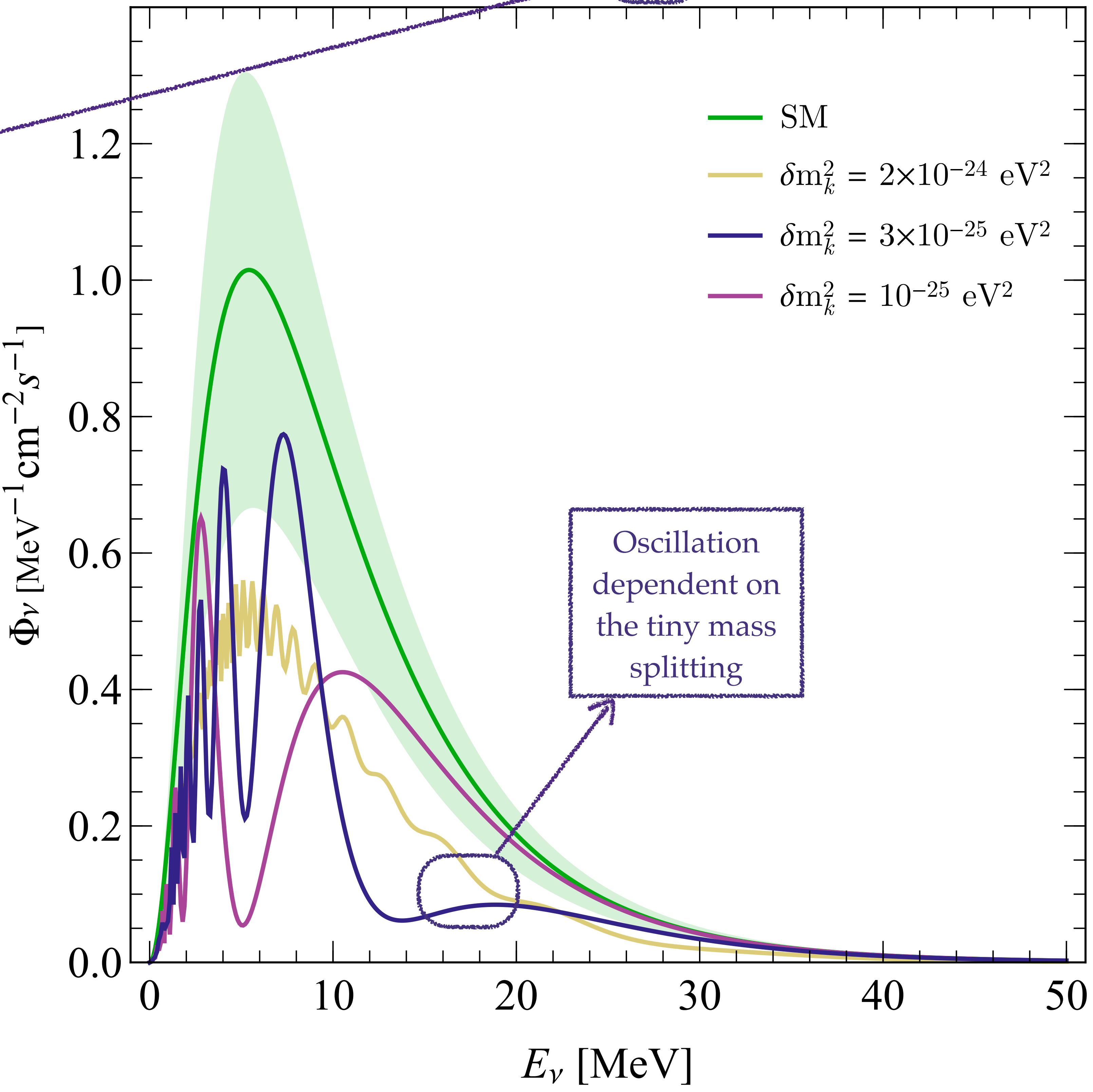
$\boxed{L_n(z)}$ → Distances including the expansion of the Universe

Oscillation and decoherence lengths

$$L_{\rm osc} = \frac{4\pi E}{\delta m_k^2} \approx 8.03 \text{ Gpc} \left(\frac{E}{10 \text{ MeV}}\right)\left(\frac{10^{-25}\text{ eV}^2}{\delta m_k^2}\right)$$

$$L_{\rm coh} = \frac{4\sqrt{2}E^2}{|\delta m_k^2|}\sigma_x \approx 180 \text{ Gpc} \left(\frac{E}{10 \text{ MeV}}\right)^2\left(\frac{10^{-25}\text{ eV}^2}{\delta m_k^2}\right)\left(\frac{\sigma_x}{10^{-12}\text{ m}}\right)$$

$\overline{\nu_1}$ DSNB Flux $-\ \sigma_x = 10^{-10}$m



Fixed wave packed size

Oscillation dependent on the tiny mass splitting

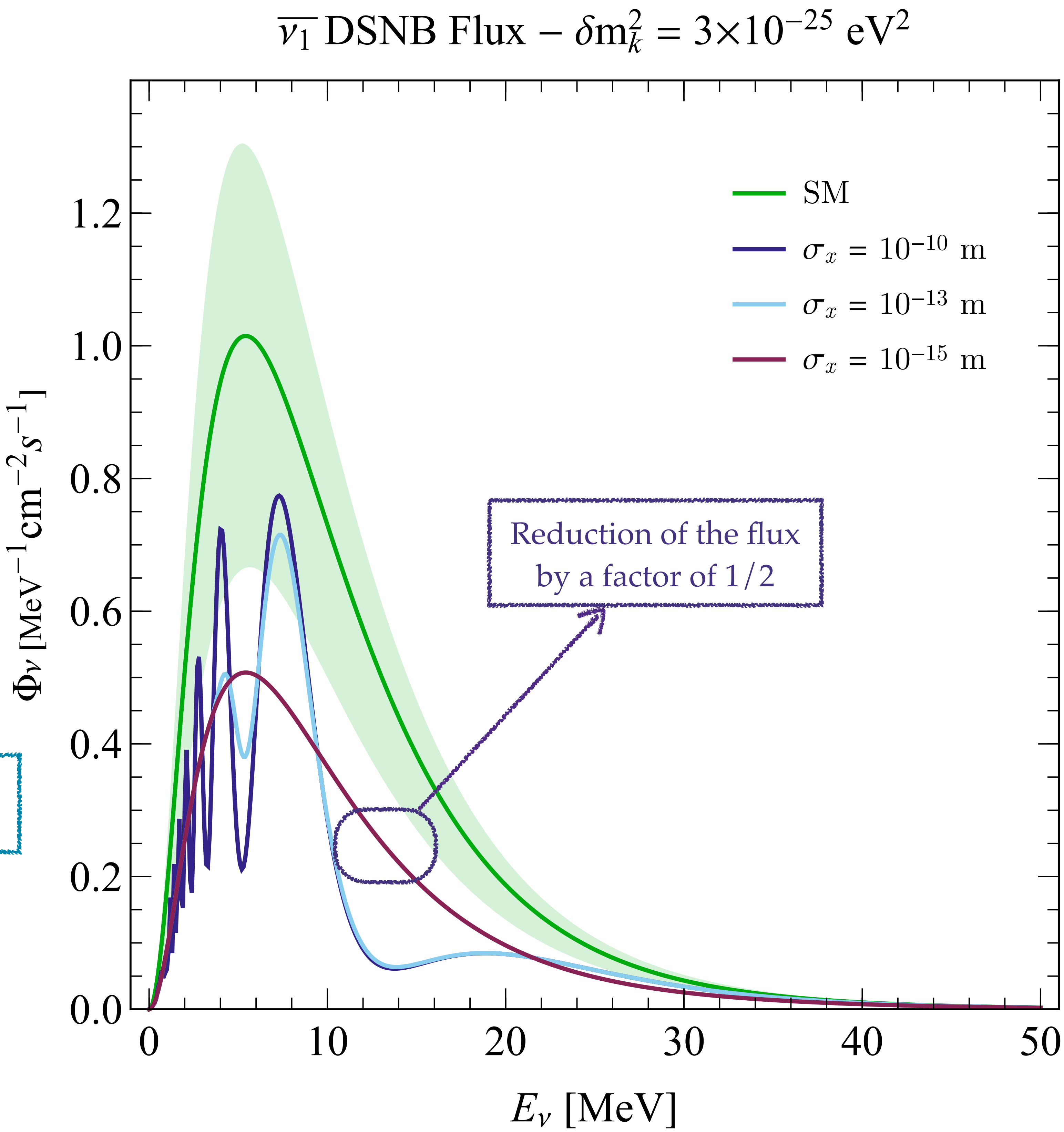
Decoherence?

$$\frac{L_{\rm coh}}{L_{\rm osc}} = \frac{\sqrt{2}}{\pi} E\sigma_x$$

$$\approx 0.0023 \left(\frac{E}{10\ \text{MeV}}\right)\left(\frac{\sigma_x}{10^{-15}\ \text{m}}\right)$$

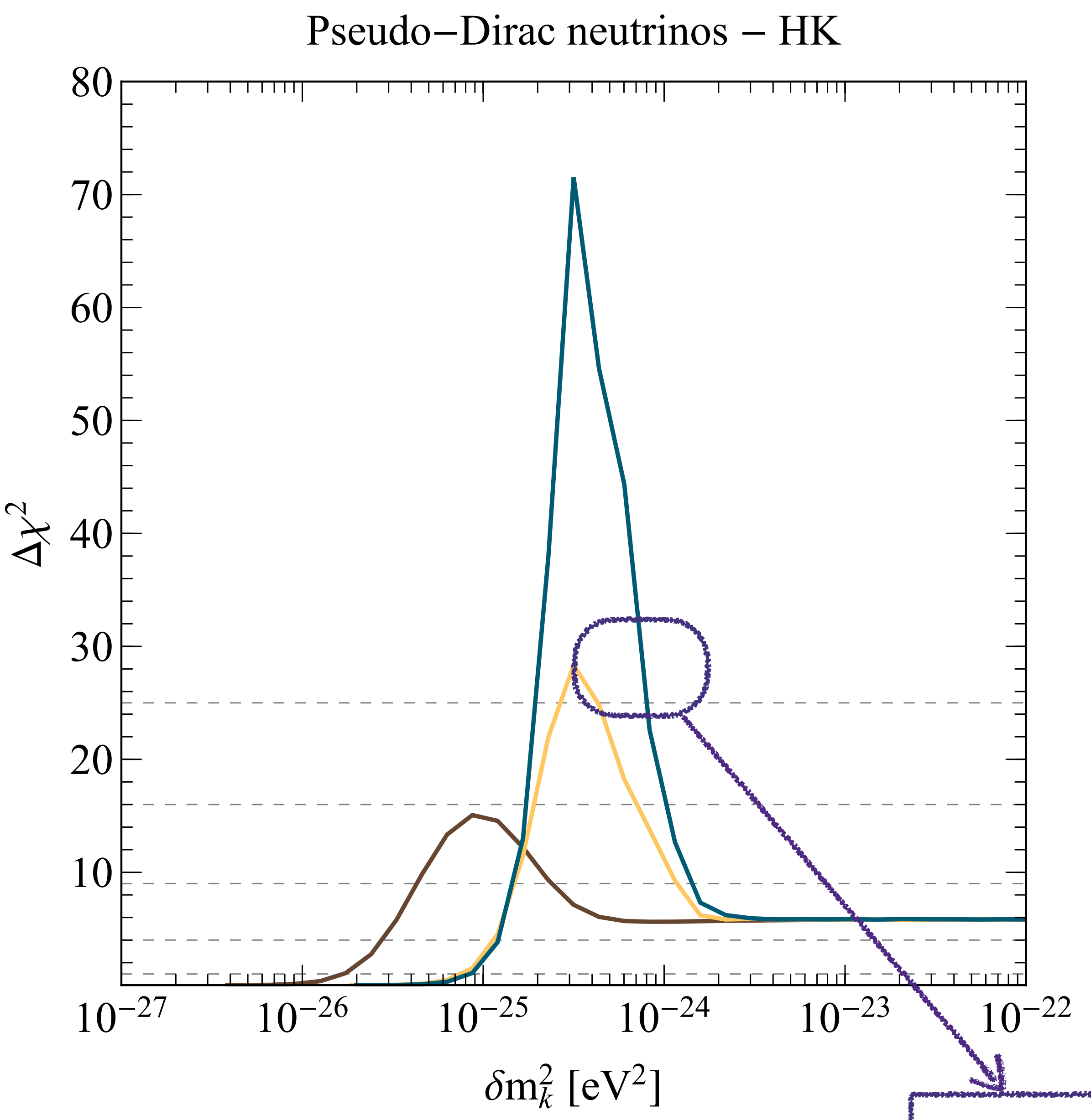
$\sigma_x \gg 1\ \text{fm}$

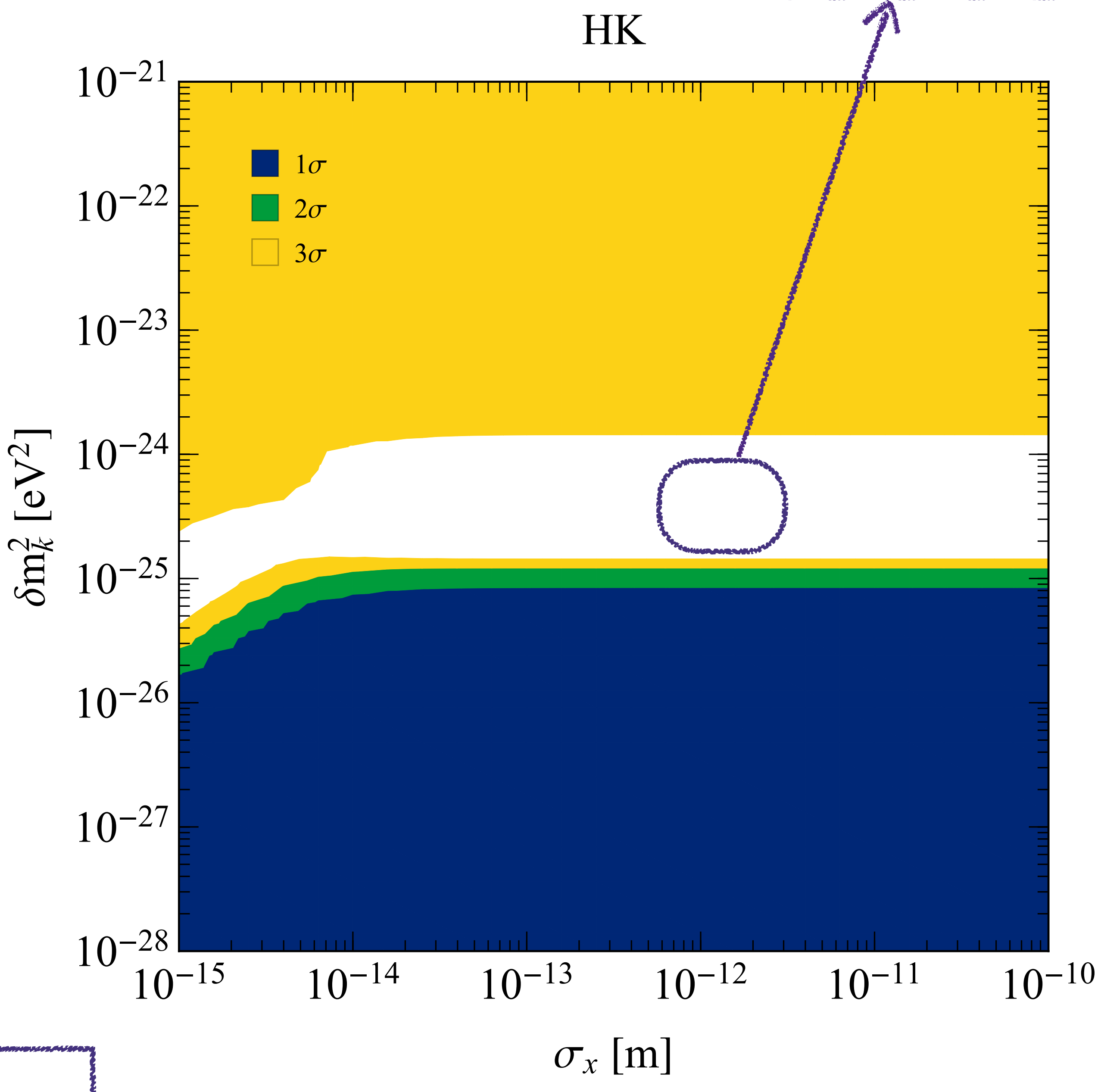
It is expected to be at least



Reduction of the flux by a factor of 1/2

Pseudo-Dirac Neutrinos



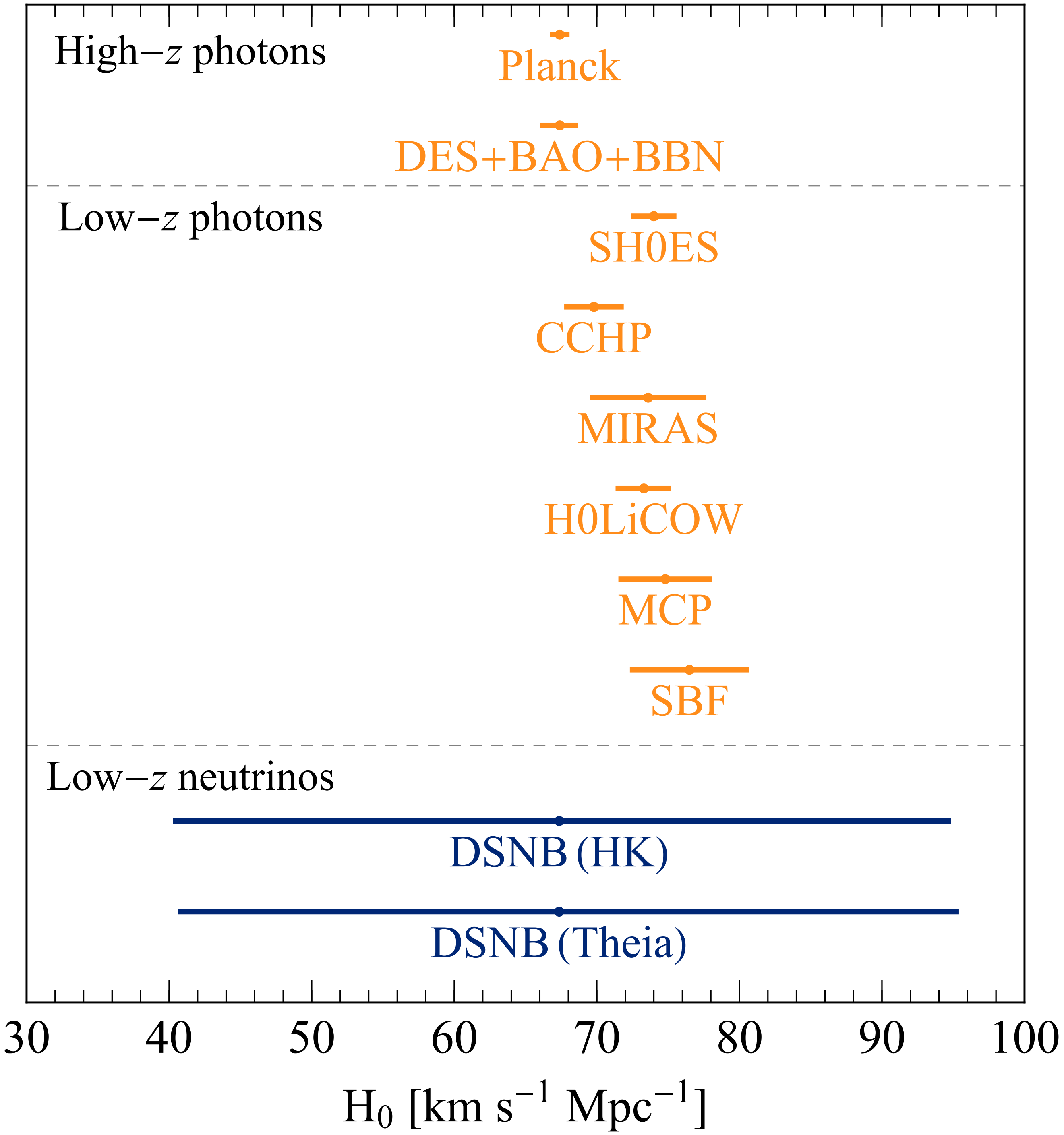


Region excluded at more than 3σ

Large sensitivities

de Gouvêa, Martinez-Soler, YFPG, Sen, 2007.13748

Cosmology…



Limited by uncertainties in the SFR

Conclusions

- Measuring the DSNB is *guaranteed*: These neutrinos should be detectable in the next generation of experiments
- Backgrounds are the biggest concern for detection, there could be more than those we have thought so far
- If we detect the DNSB, we can test "slow" neutrino properties, decay, oscillations spanning Gpc distances.
- Moreover, we could test the expansion of the Universe and the star formation rate considering the DSNB

¡Gracias!