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

Yuber F. Perez-Gonzalez

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Fermilab

COFI
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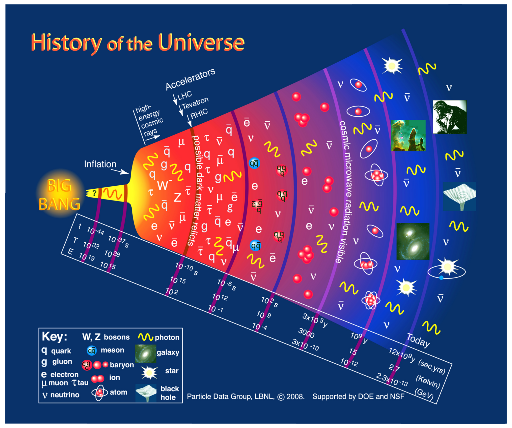
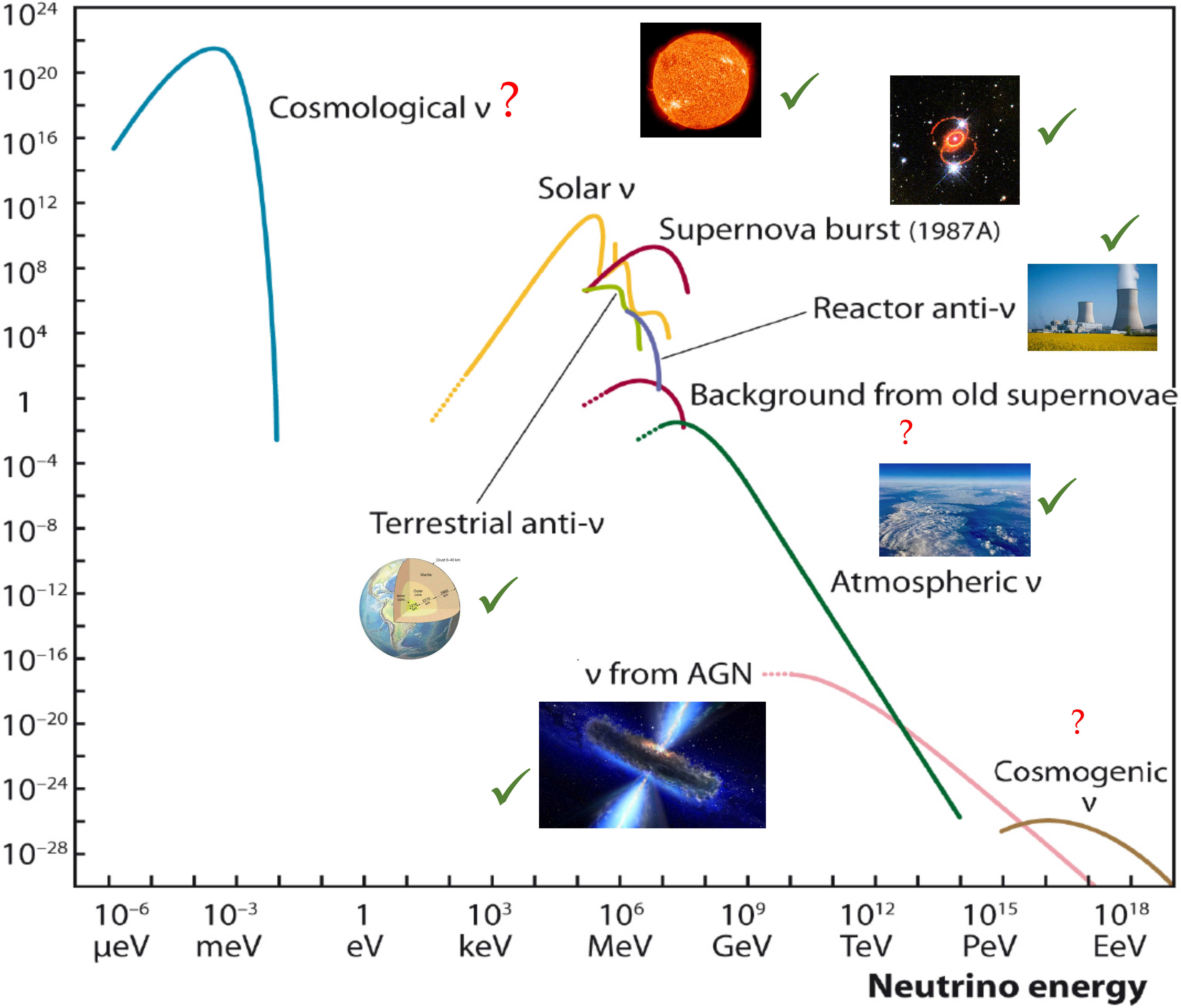
INTERDISCIPLINARIA DE LAS AMERICAS

Northwestern





Katz et.al., 2012

What do we know about neutrino masses and mixing?

Neutrinos oscillate!!

Mixing

$$|\nu_\alpha\rangle = \widetilde{U}^*_{\alpha a}|\nu_a\rangle$$

$$\Delta_{ab} = \frac{\Delta m^2_{ab}}{2E}$$

$$P(\nu_\alpha \to \nu_\beta) = \sum_{a,b} \widetilde{U}^*_{\alpha a}\widetilde{U}_{\beta a}\widetilde{U}_{\alpha b}\widetilde{U}^*_{\beta b}\, e^{i\Delta_{ab}L}$$

$$\Delta m^2_{ab} = m_a^{\nu\,2} - m_b^{\nu\,2}$$

Neutrinos are usually ultrarelativistic

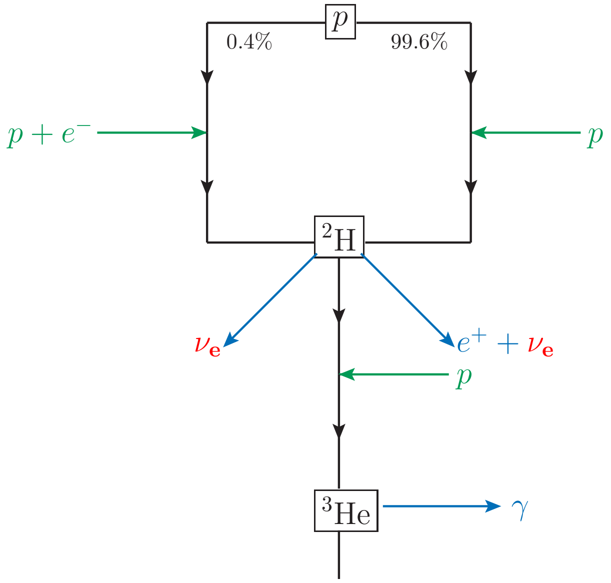
PMNS Mixing matrix

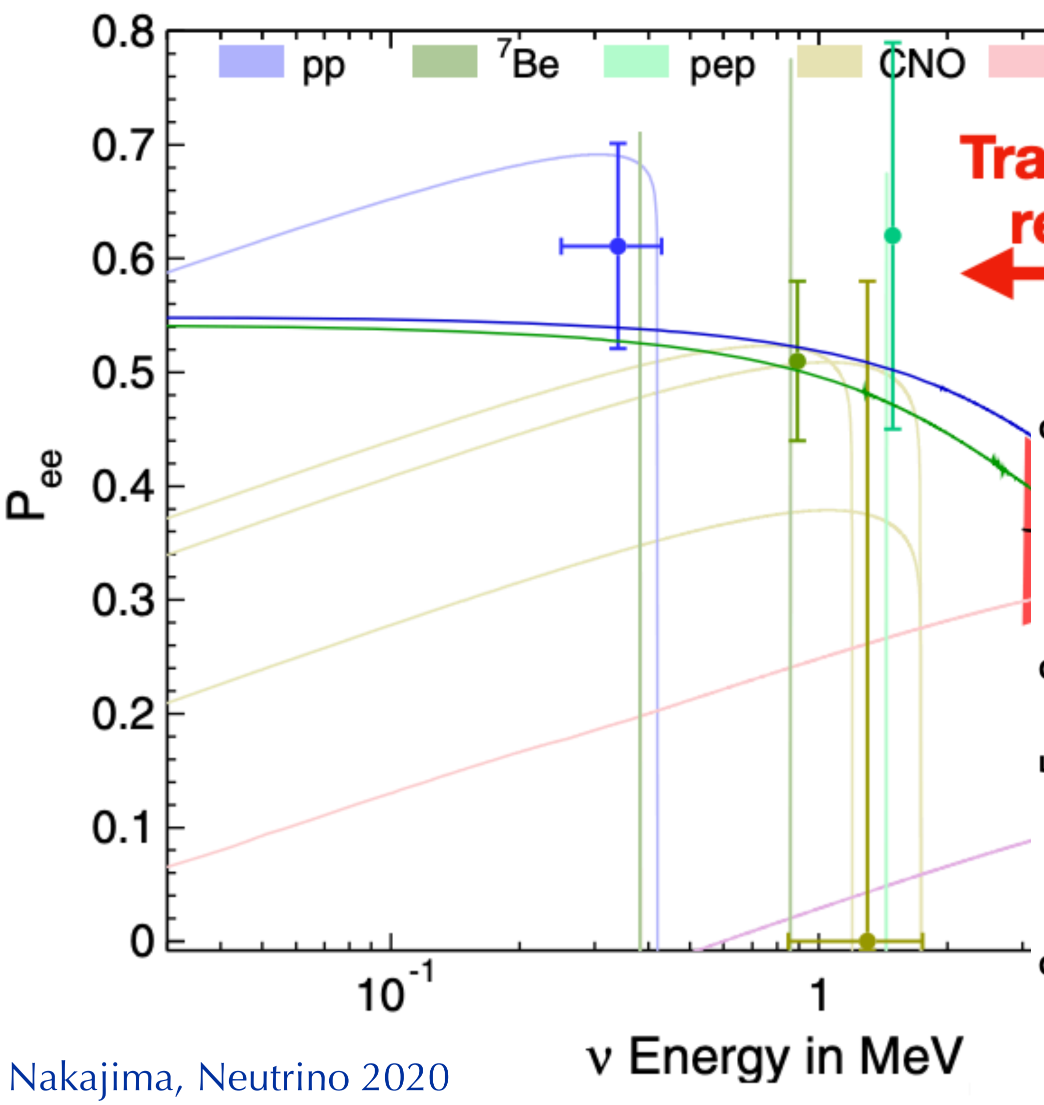
$$\widetilde{U} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}\, e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}\, e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}\, e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}\, e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}\, e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

2 more phases if neutrinos are Majorana

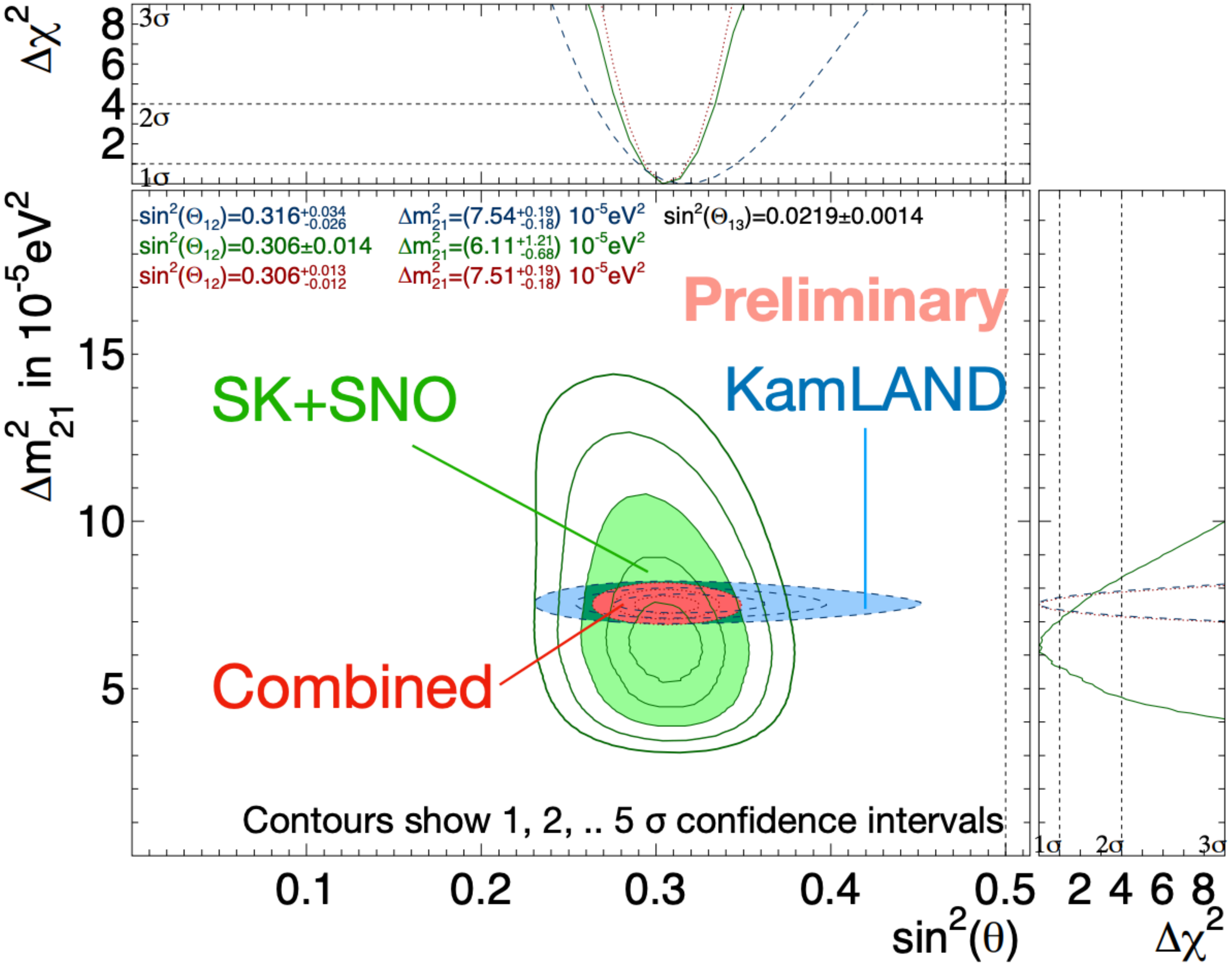
$c_{ij} \equiv \cos\theta_{ij} \quad s_{ij} \equiv \sin\theta_{ij}$

Solar Neutrinos





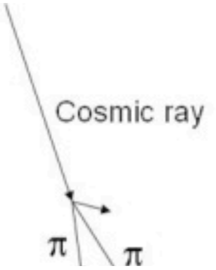
Nakajima, Neutrino 2020



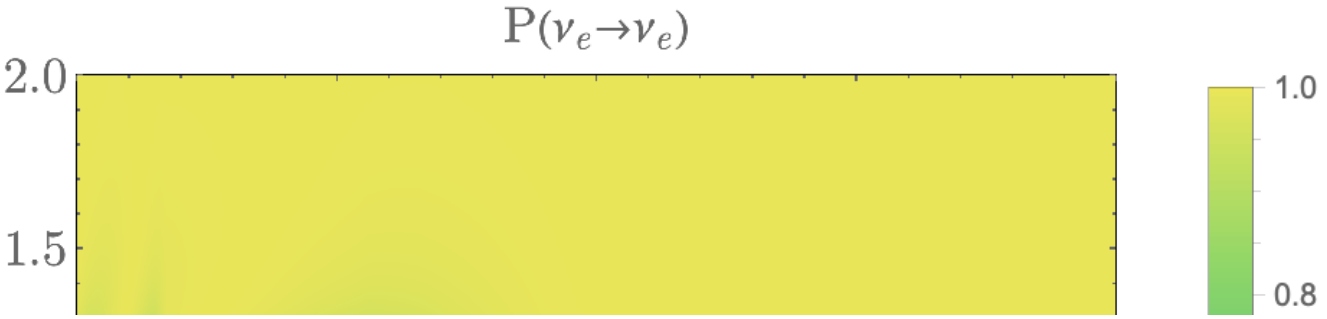
MSW Effect at play: Measurement of Δm^2_{21} and θ_{12}

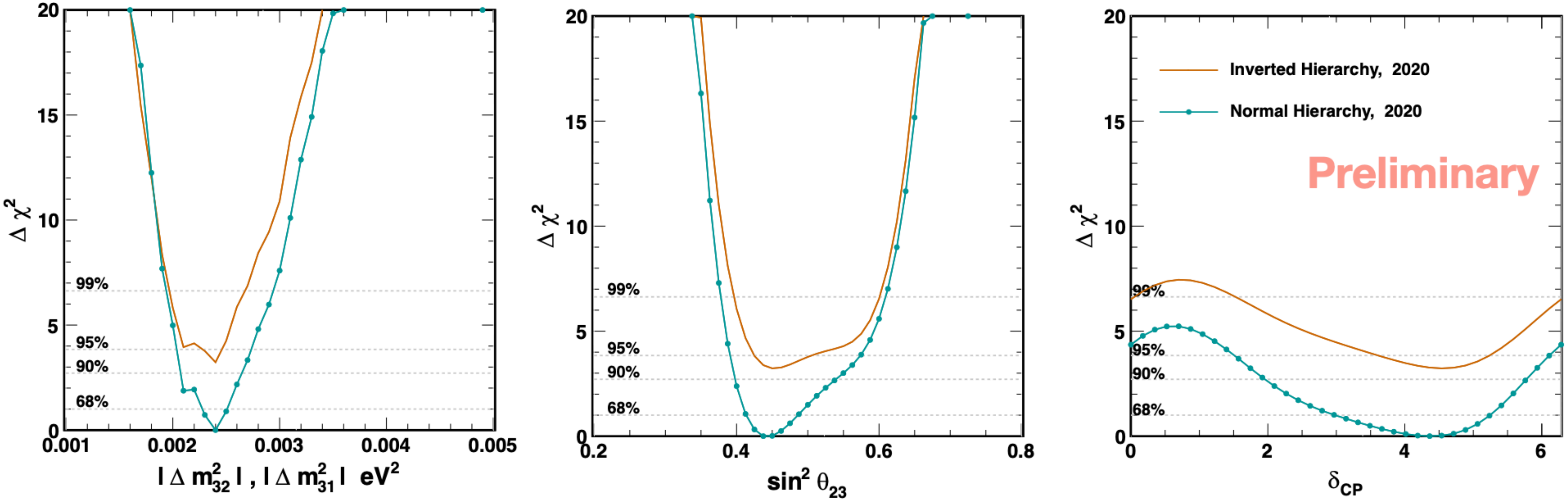
SK, SNO, Borexino…

Atmospheric Neutrinos



Matter effects





Nakajima, Neutrino 2020

Large ranges of the baselines

SK, IceCube…

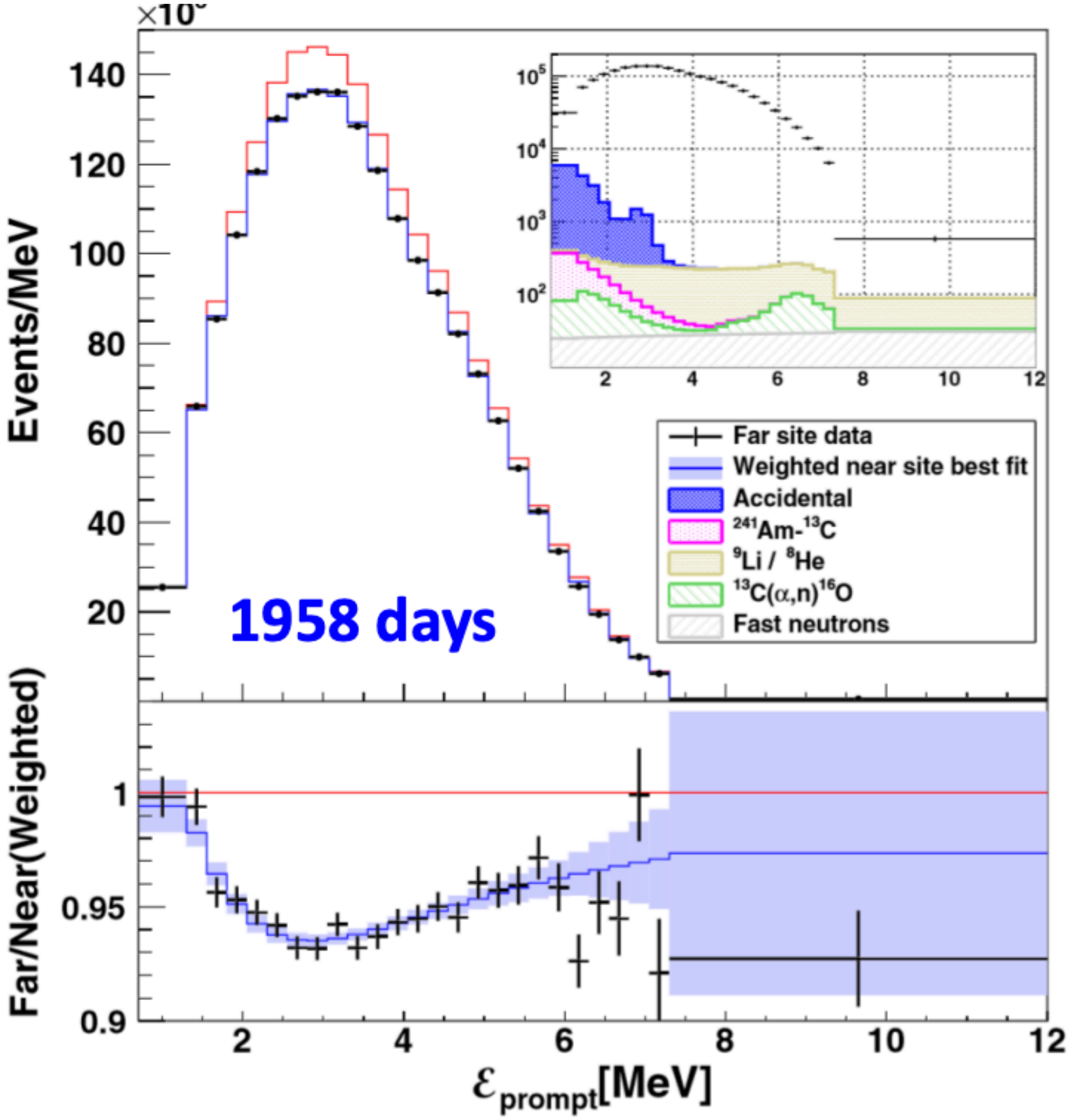
Measurement of Δm^2_{3j}, θ_{23} and δ_{CP}

Reactor Antineutrinos

Chooz power plant

DAYA BAY, RENO, Double-Chooz…

Measurement of Δm^2_{3j}, θ_{13}



$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

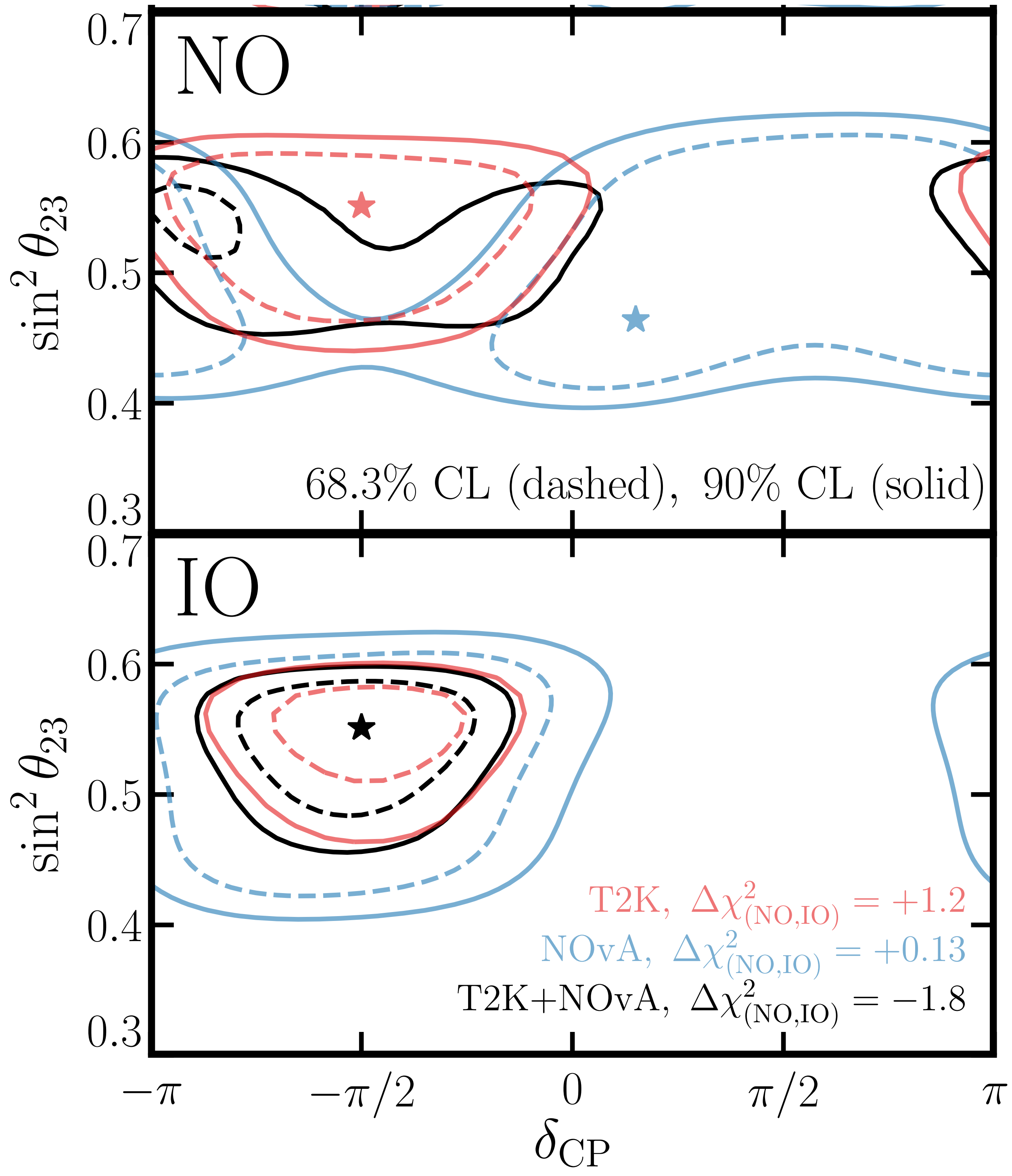
$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}\ \text{eV}^2$$

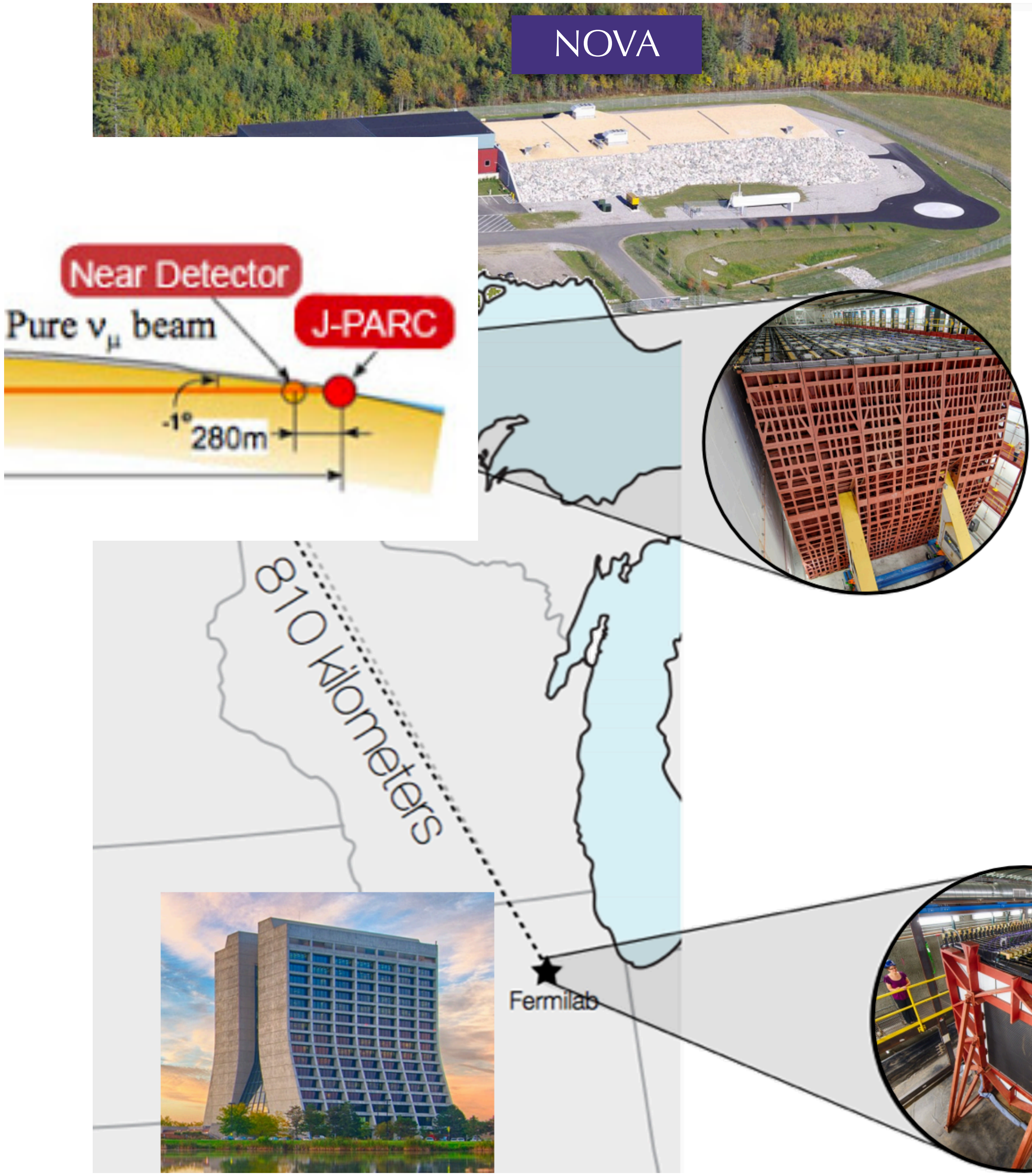
$$\Delta m^2_{32} = (2.47 \pm 0.07) \times 10^{-3}\ \text{eV}^2\ \text{(NO)}$$

$$\Delta m^2_{32} = (-2.58 \pm 0.07) \times 10^{-3}\ \text{eV}^2\ \text{(IO)}$$

Jiajie Ling (SYSU), Neutrino 2020

Accelerator Neutrinos





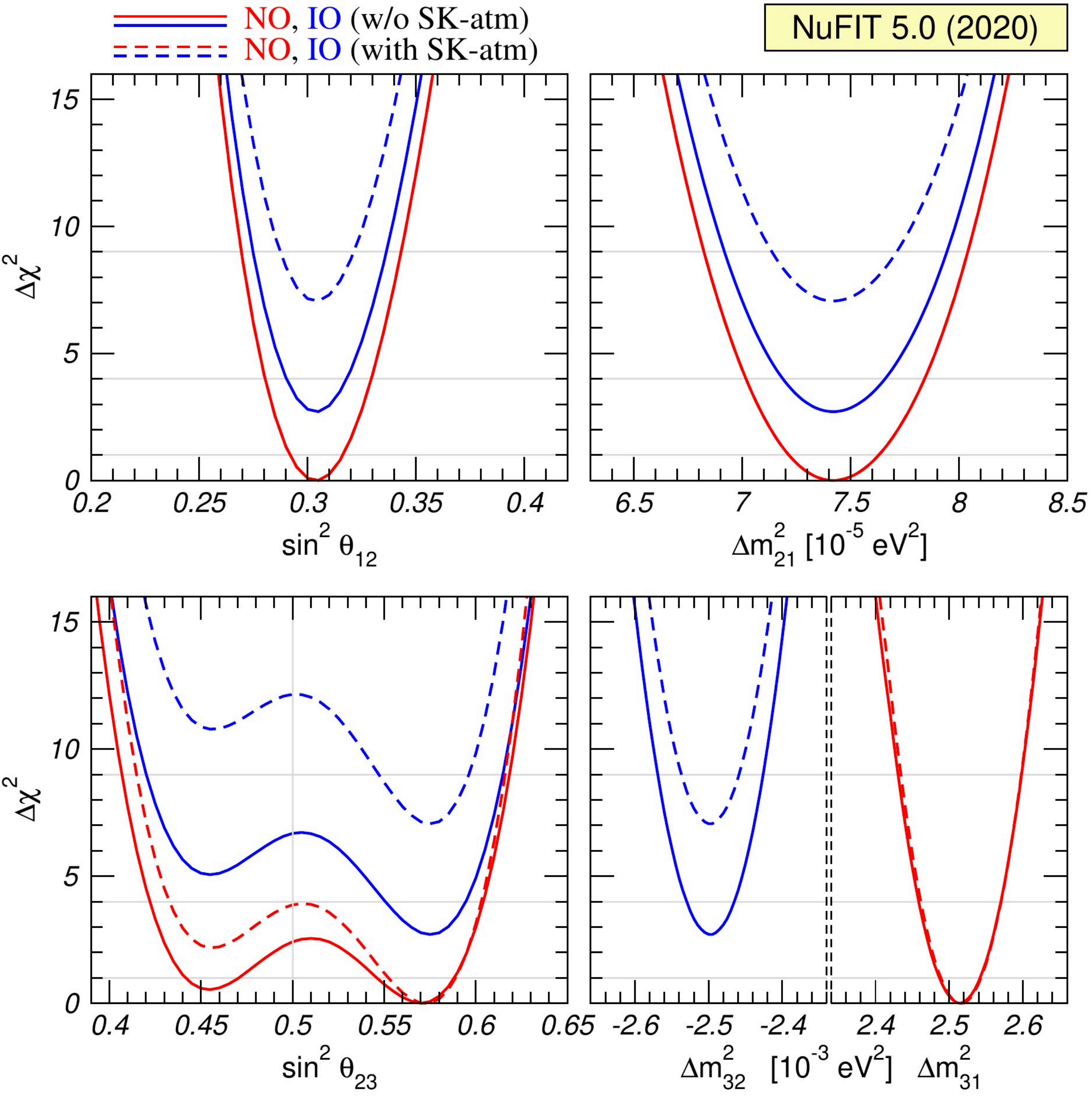
Kelly, Machado, Parke, YFPG, and Funchal 2007.08526

MINOS, T2K, NOvA…
DUNE

Alex Himmel, Neutrino 2020

Measurement of Δm^2_{3j}, θ_{23} and δ_{CP}

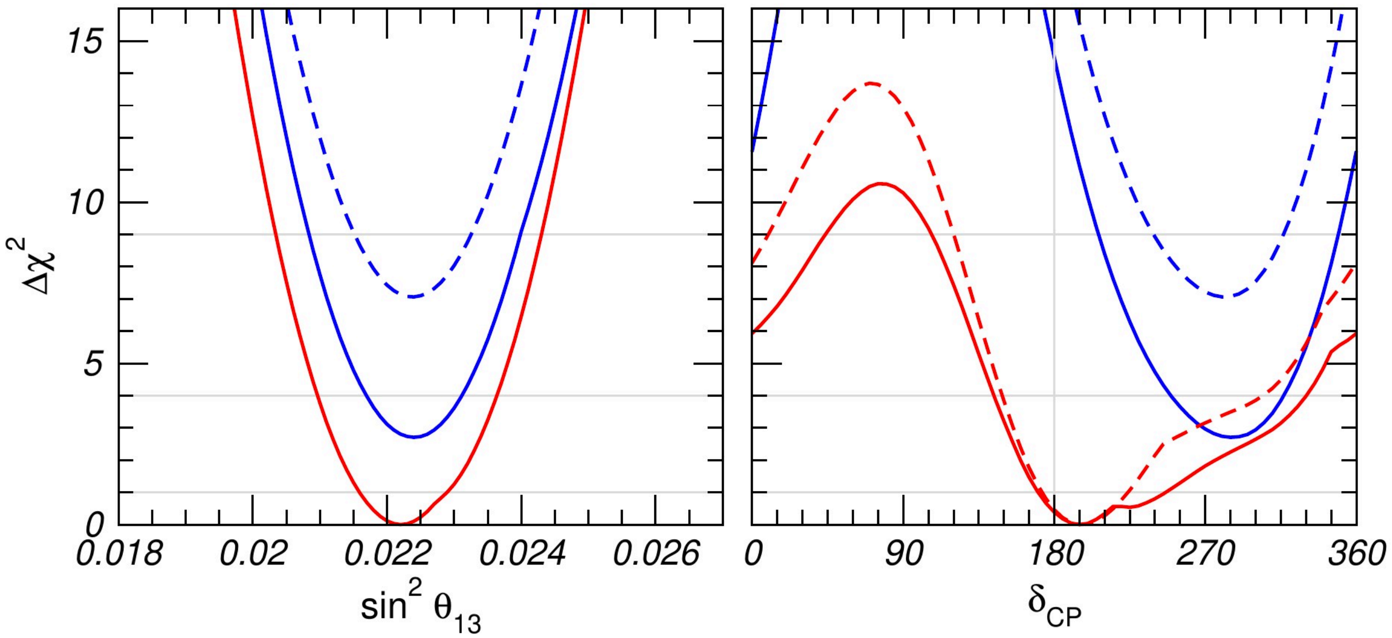
What do we know about neutrino masses and mixing?



Other global fits

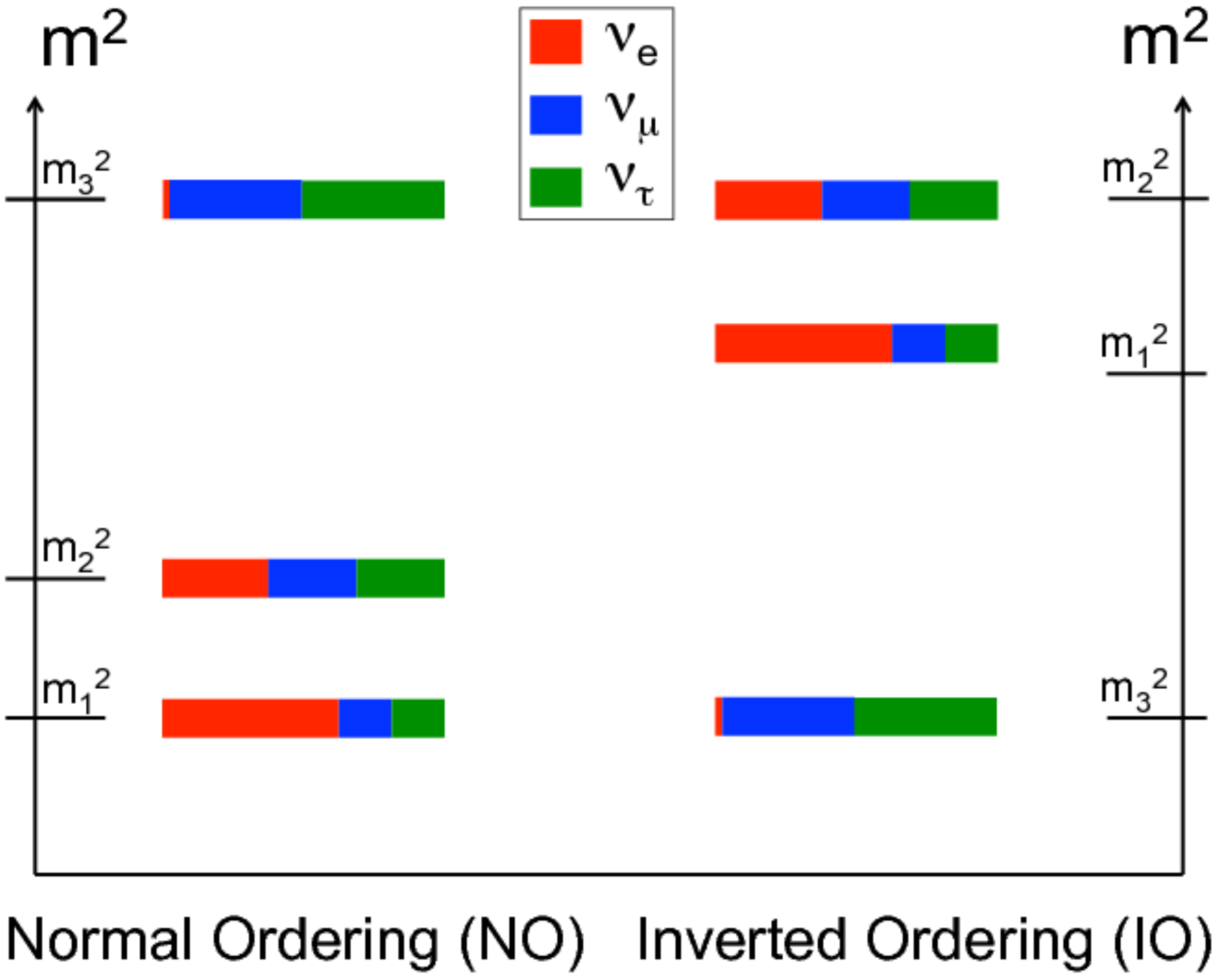
Valencia group
2006.11237

Bari group
2003.08511



NuFit
JHEP 09 (2020) 178

What do not we know about neutrino masses and mixing?



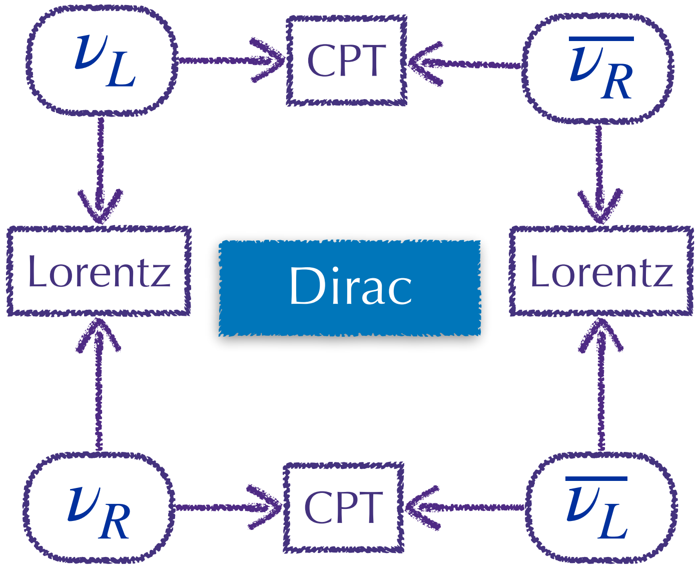
$|\nu_a\rangle = \tilde{U}_{\alpha a}|\nu_\alpha\rangle$

Mass ordering?

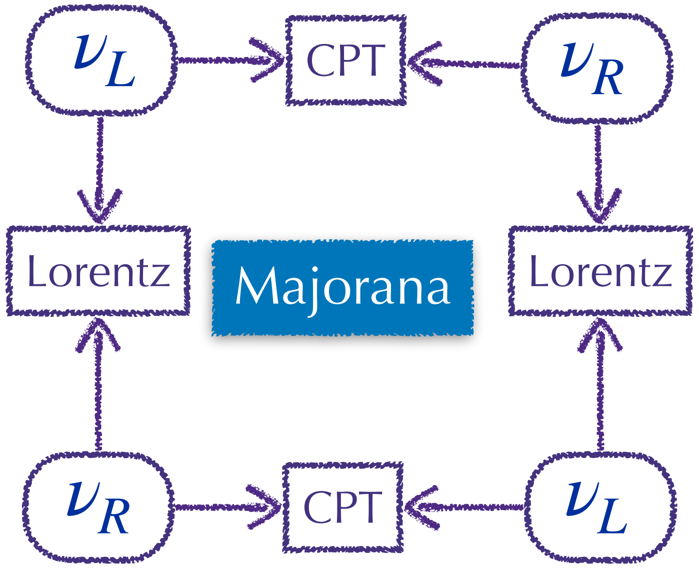
- CP phase - CP violation
- Absolute mass values
- Dirac vs Majorana nature

- Reactor anomalies
- MiniBoone + LSND

Dirac or Majorana, that is the question….



4 degrees of freedom



2 degrees of freedom

Nightmare scenario: Neutrinos are Majorana but effectively act as Dirac

↓

Pseudo-Dirac

Why don't we know?

↓

Weak interactions are chiral and neutrinos are ultrarelativistic

$$|\nu_e\rangle \sim |L\rangle + \frac{m_\nu}{E}|R\rangle$$

Dirac or Majorana, that is the question….

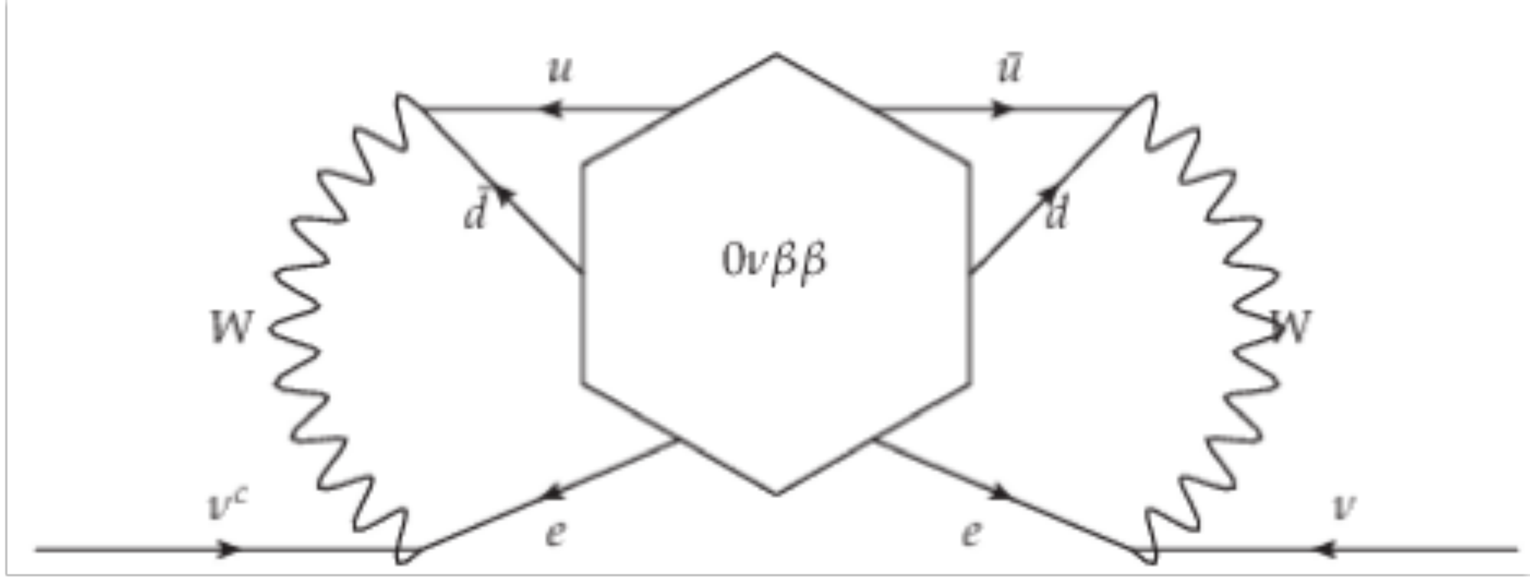
- Neutrino-less double beta decay

Schechter Valle, 1982

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

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

nEXO, KamLAND2-Zen, Cupid..



- Measure energy and angle distributions of heavy neutrino decay

Balantekin, De Gouvêa, Kayser, 2018

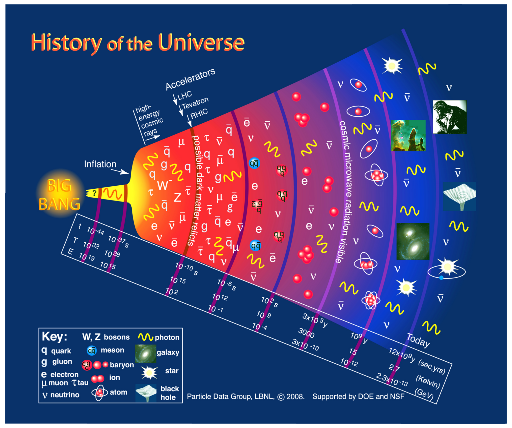
- Detect non-relativistic neutrinos $\nu_a + n \rightarrow p^+ + e^-$

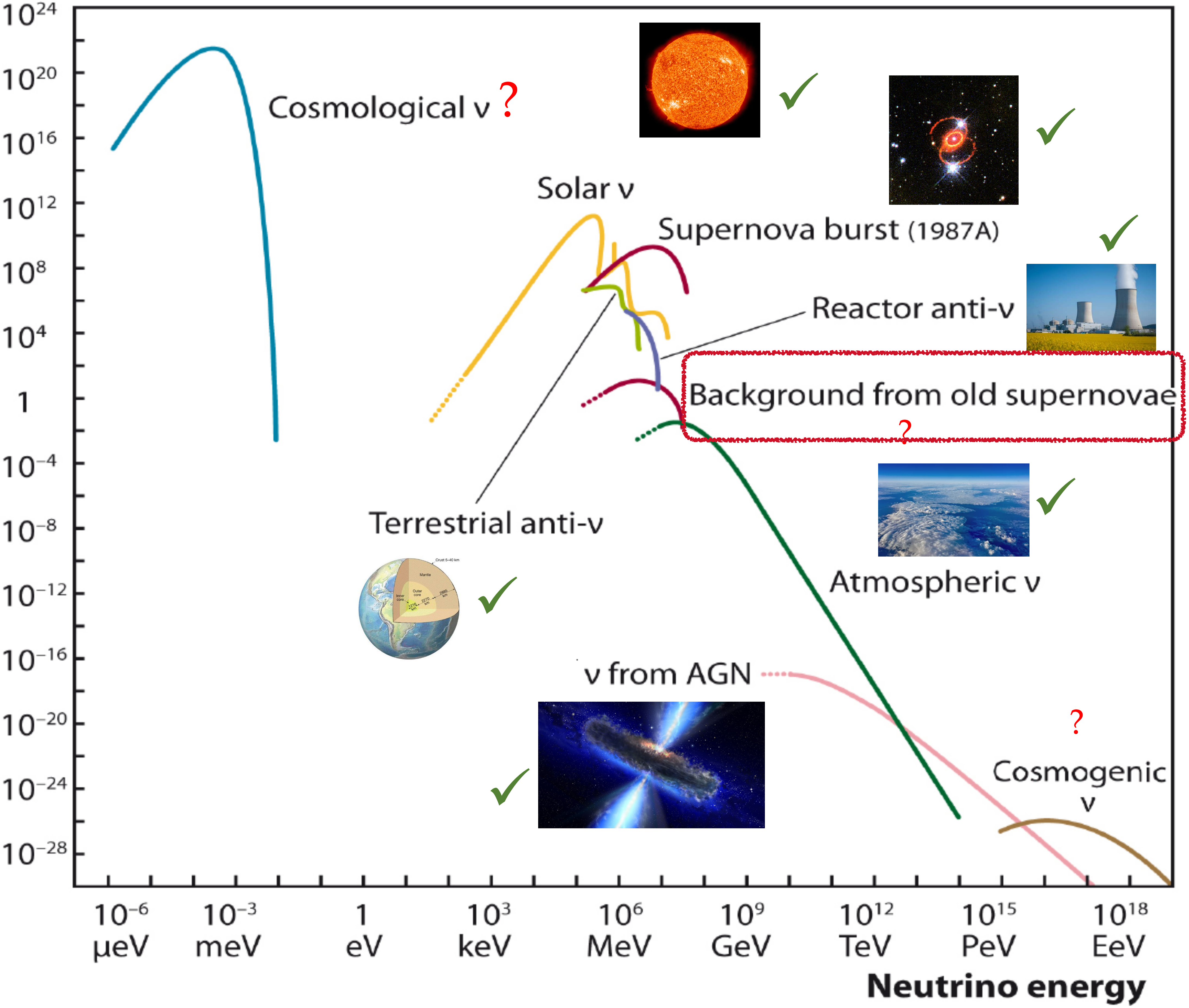
Duda and Gelmini, 2001
Long et.al. 2014

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

- BSM can hinder the neutrino nature

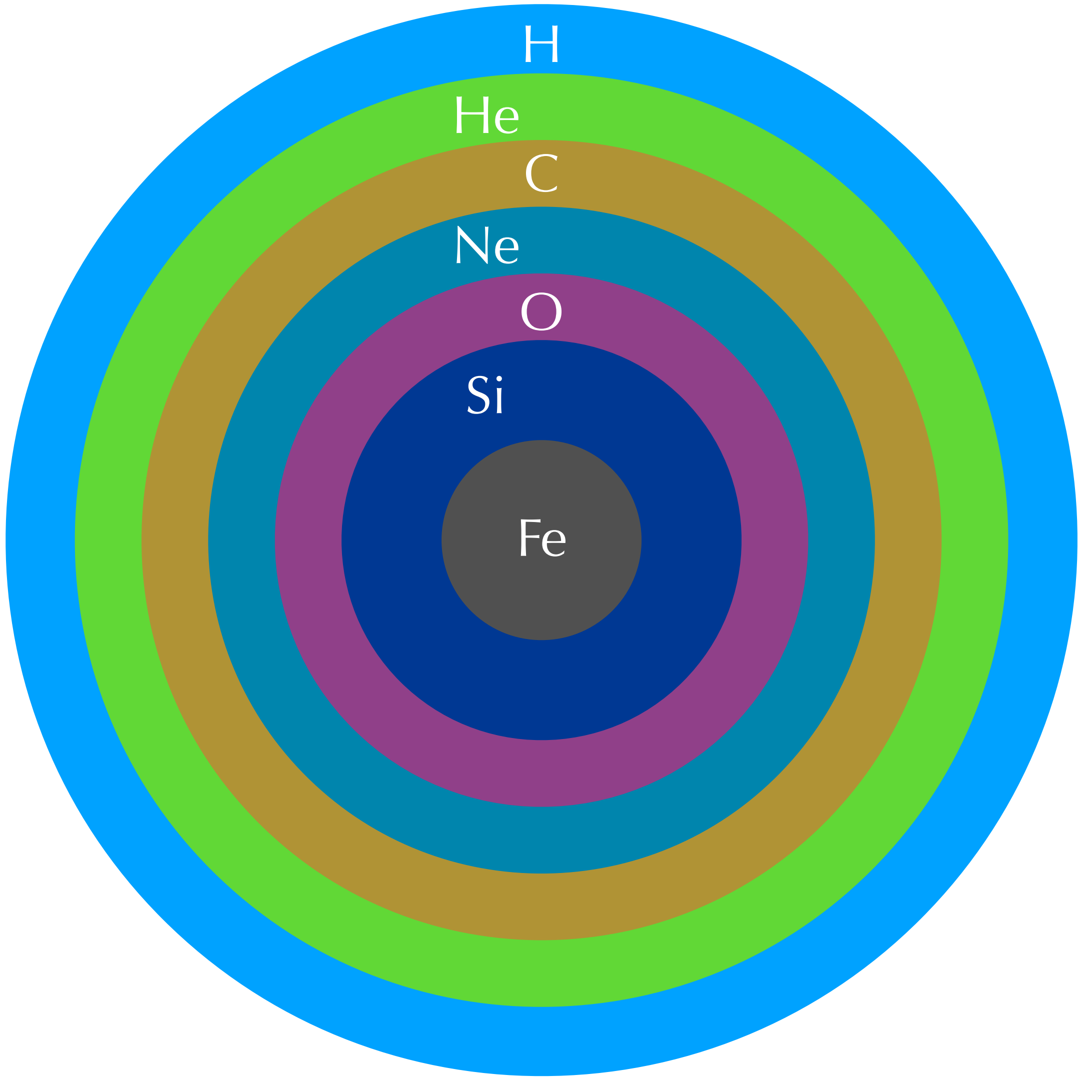
Arteaga, Bertuzzo, YFPG, Funchal, 2017





Katz et.al., 2012

Core-collapse Supernovae

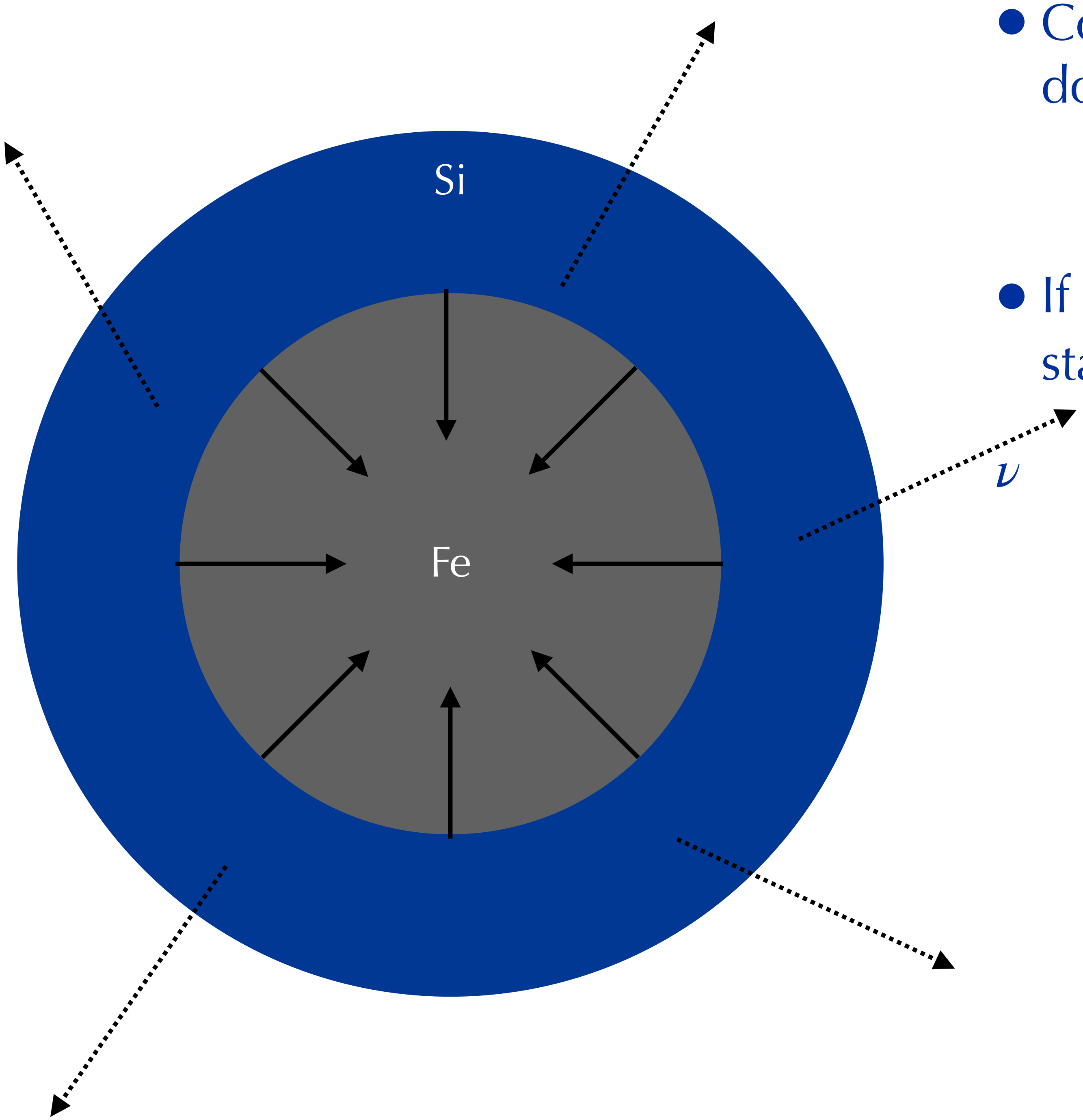


$M > 11 M_\odot$

- Core composed of iron, cannot continue doing fusion to counterbalance gravity

- If $M_c > 1.44 M_\odot$ electron pressure cannot stabilize the core

Core-collapse Supernovae



$M > 11M_\odot$

Janka et. al. 2006

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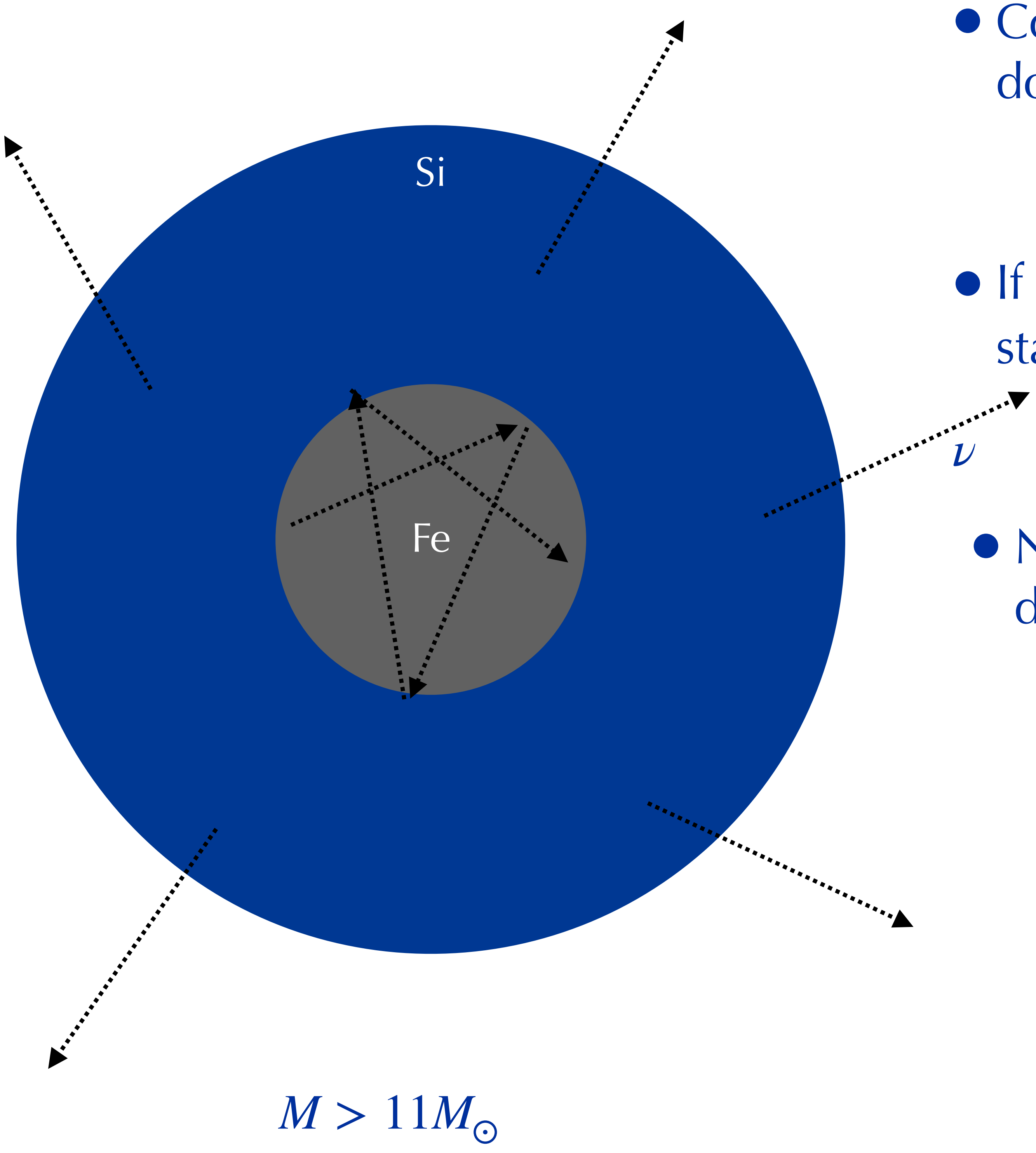
Core-collapse Supernovae



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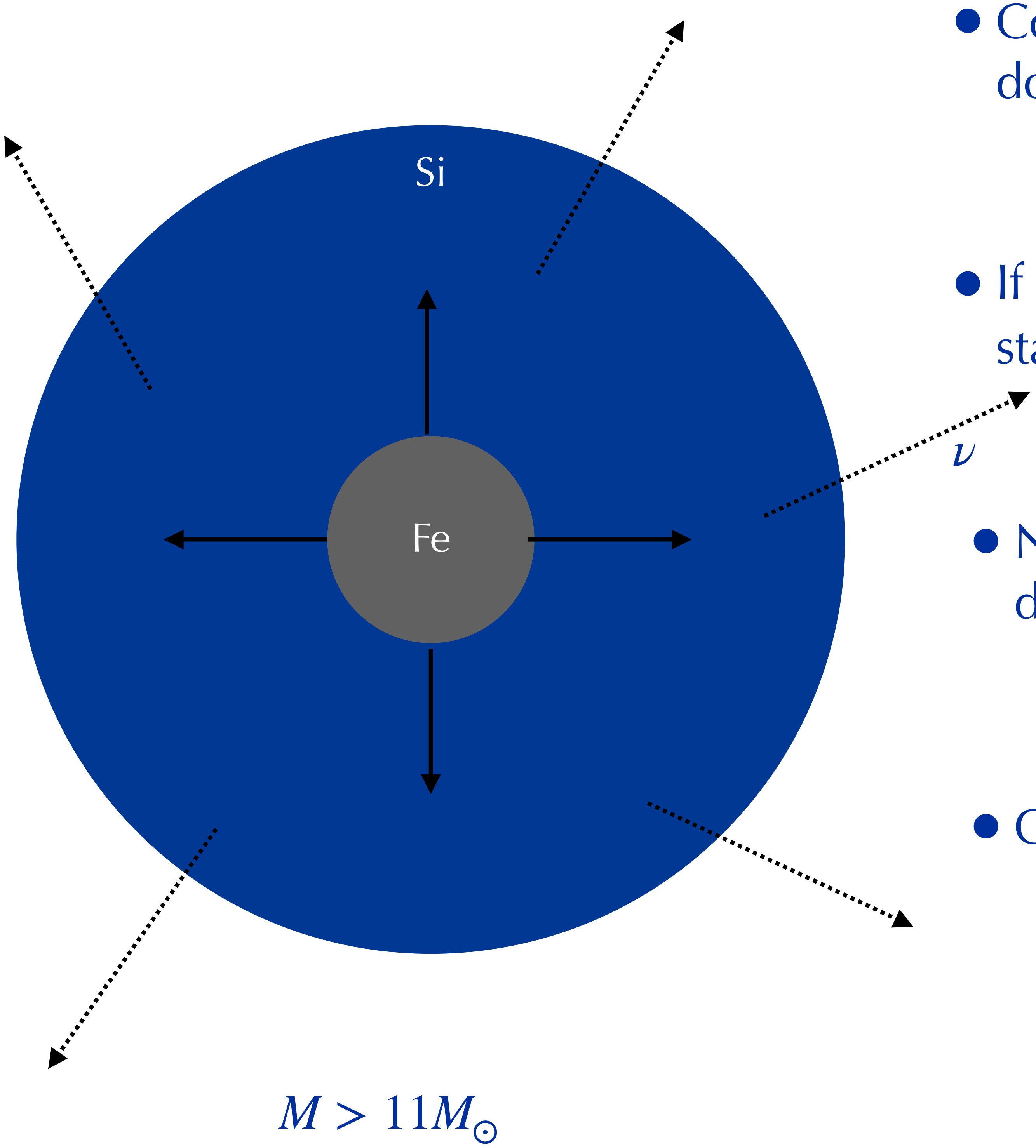
- Neutrinos can get trapped in the core if the density is large enough

Janka et. al. 2006

Core-collapse Supernovae



Janka et. al. 2006

- Core composed of iron, cannot continue doing fusion to counterbalance gravity
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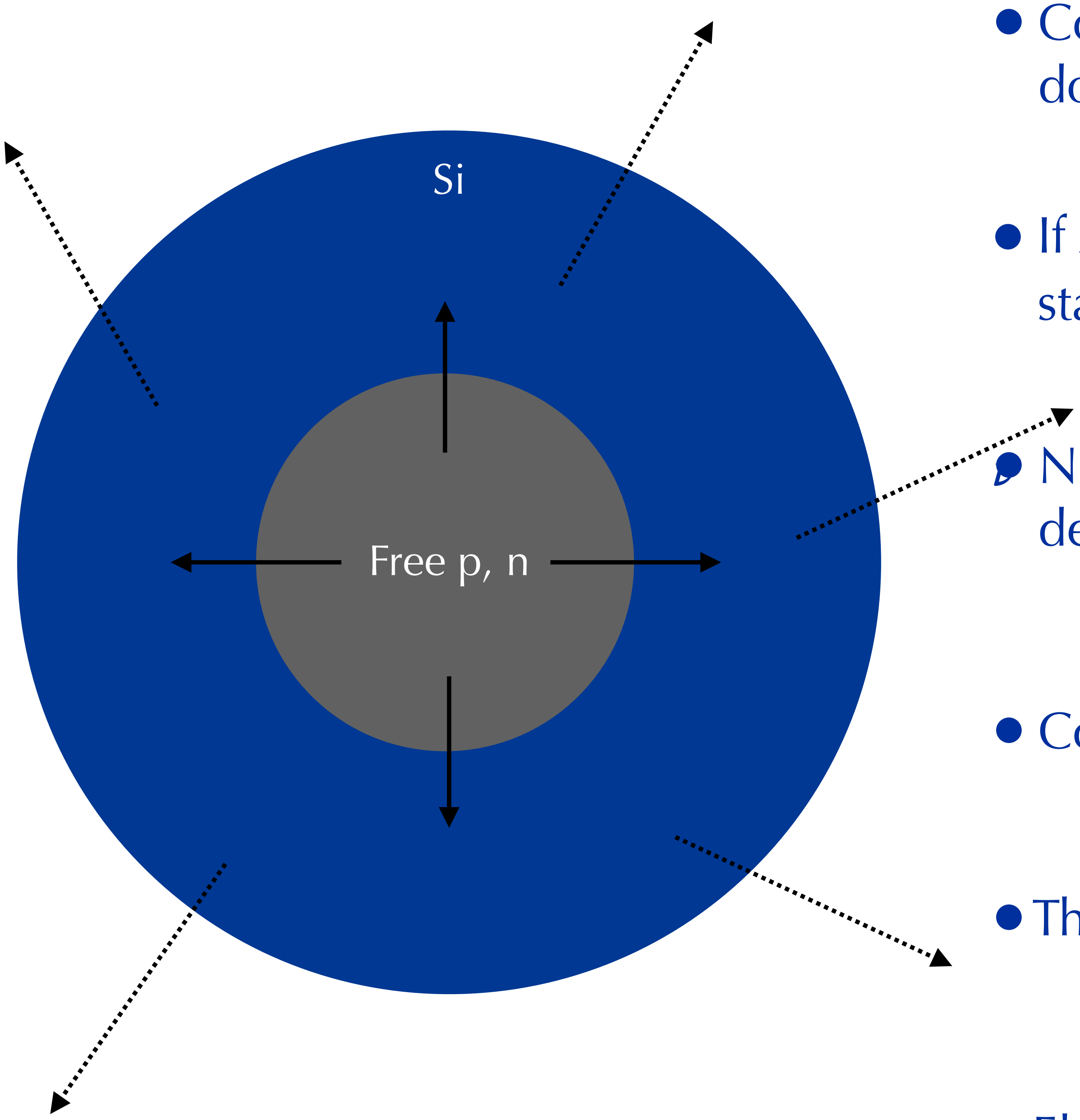
- Core bounces back creating a shockwave

Core-collapse Supernovae



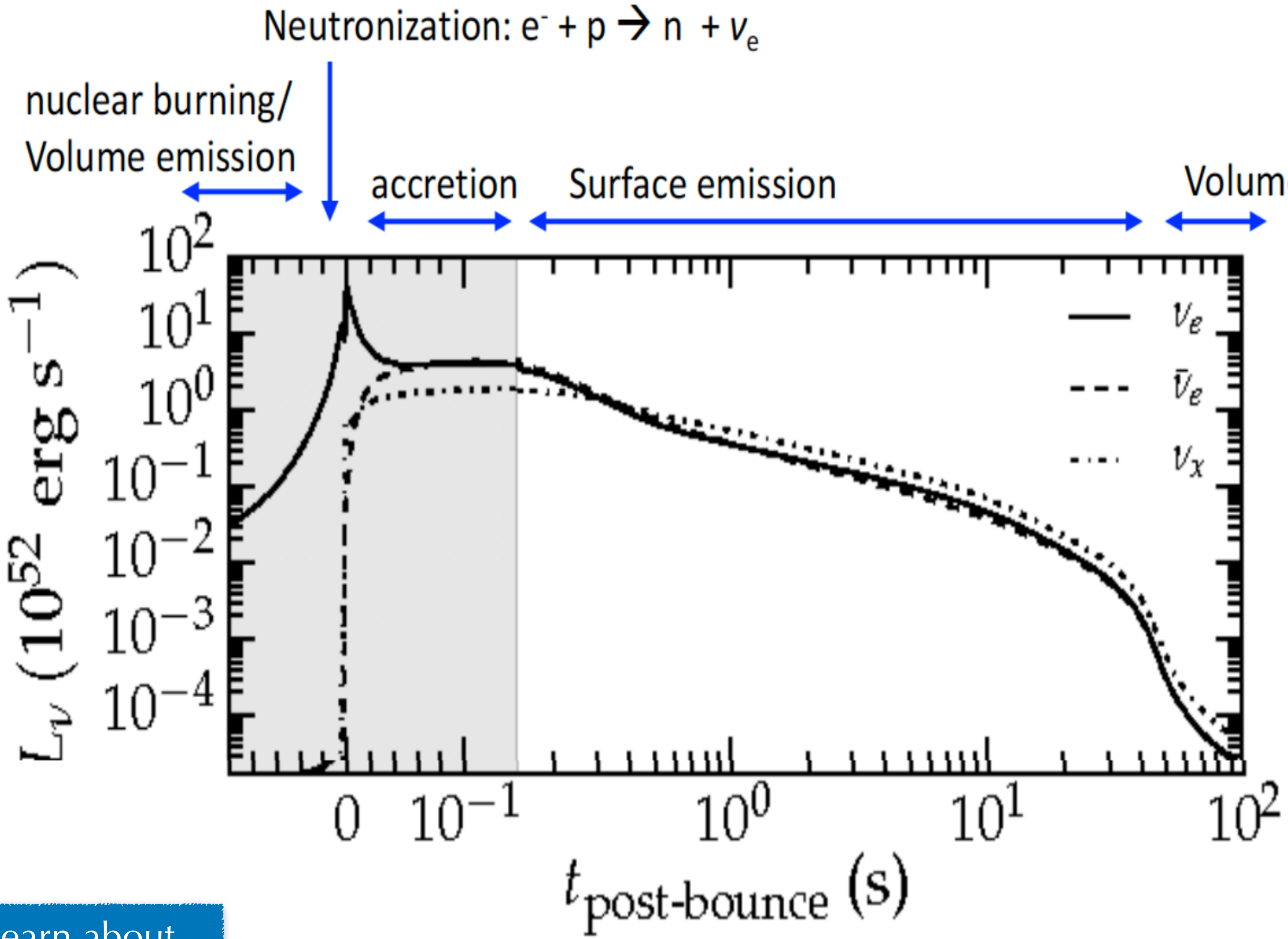
$M > 11M_{\odot}$

Janka et. al. 2006

- Core composed of iron, cannot continue doing fusion to counterbalance gravity
- If $M_c > 1.44M_{\odot}$ electron pressure cannot stabilize the core
- Neutrinos can get trapped in the core if the density is large enough
- Core bounces back creating a shockwave
- The shockwave dissociate the heavy nuclei
- Electrons are captured by free protons producing a large quantity of neutrinos

Core-collapse Supernovae

- MeV neutrinos are emitted



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

nuclear burning/ Volume emission

accretion

Surface emission

Volume emission

We could learn about mass ordering, δ_{CP}…

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

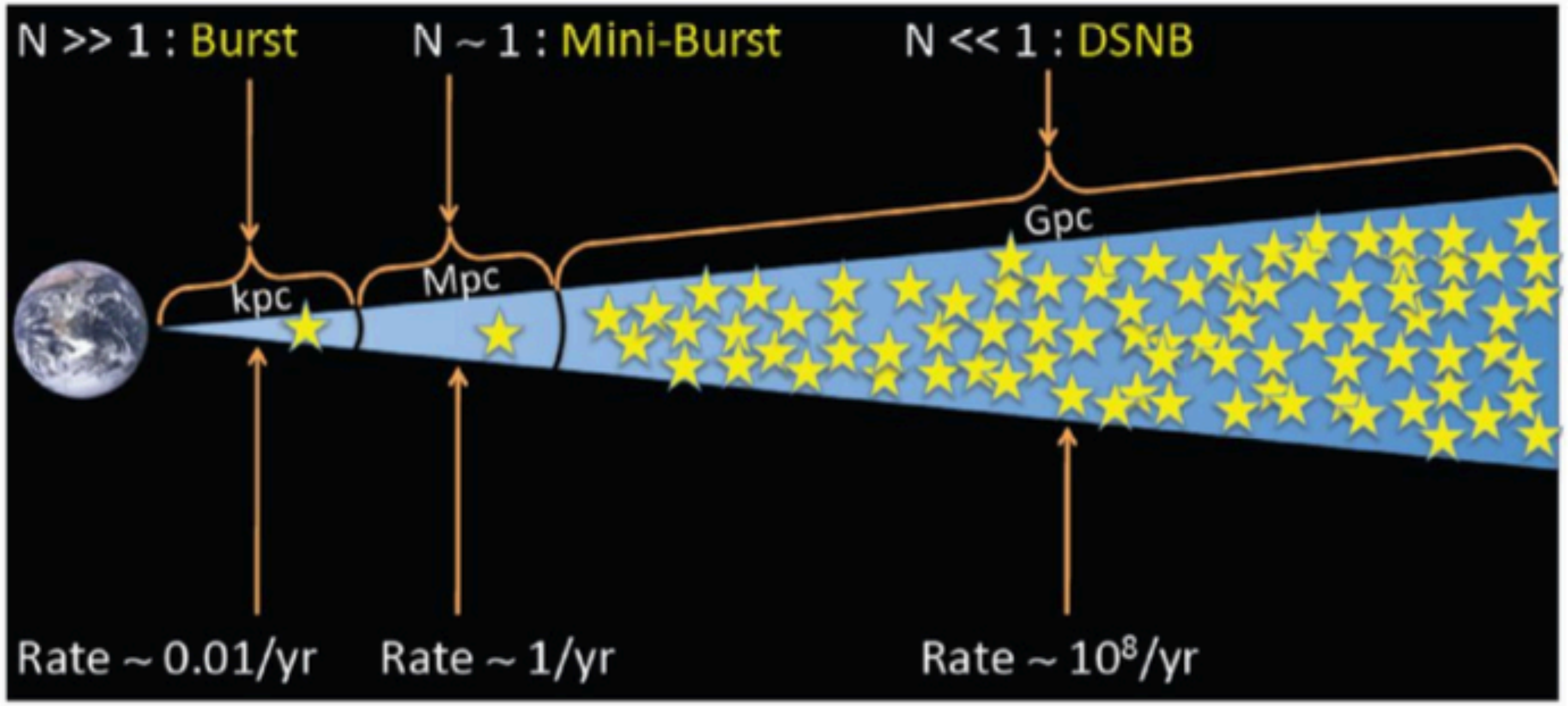
- Instead, we could look at *all* the SNe that have exploded in the Universe

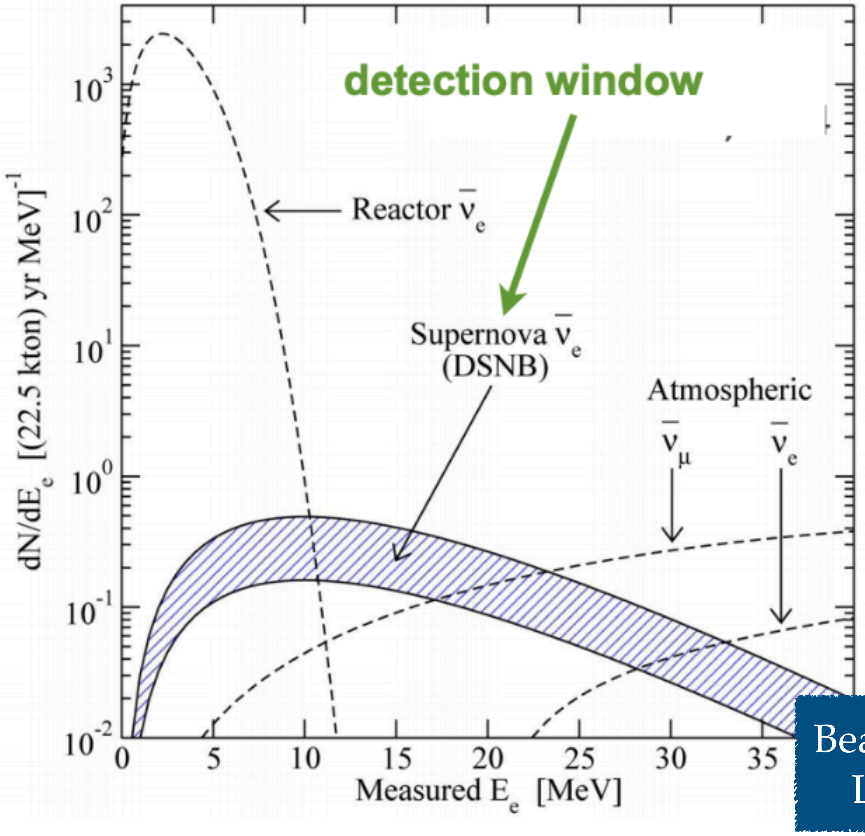
- This should create a diffuse (isotropic and time independent) neutrino flux

- New frontier in neutrino astrophysics

What can we learn by measuring the DSNB?

John Beacom, TAUP2011

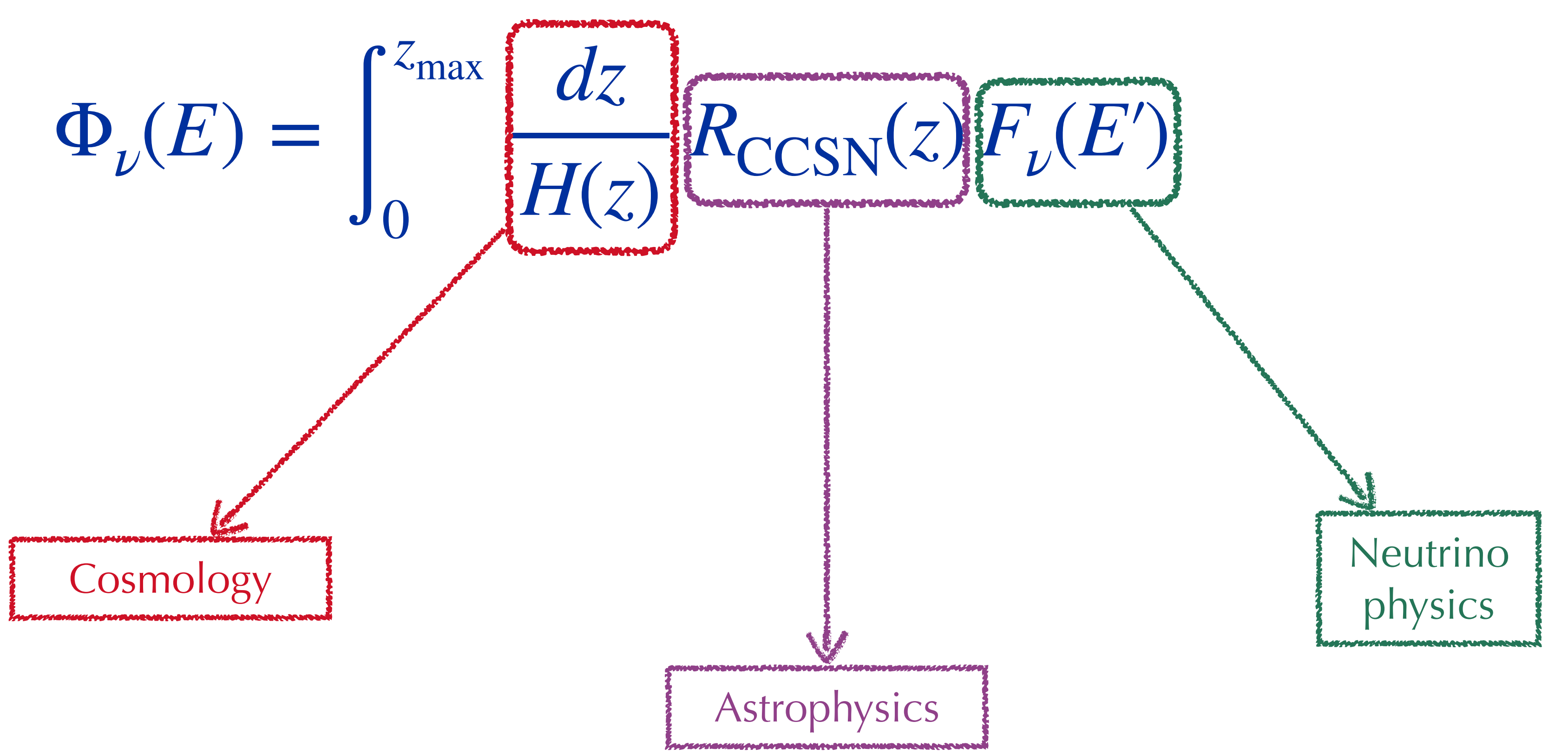




Beacom, Ann.Rev.Nuc.Phys.Sc.2010
Lunardini, Astropart. Phys2016

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

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
$\Omega_{\rm x}$ → Distinct components
w → Dark Energy EOS

Cosmology

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

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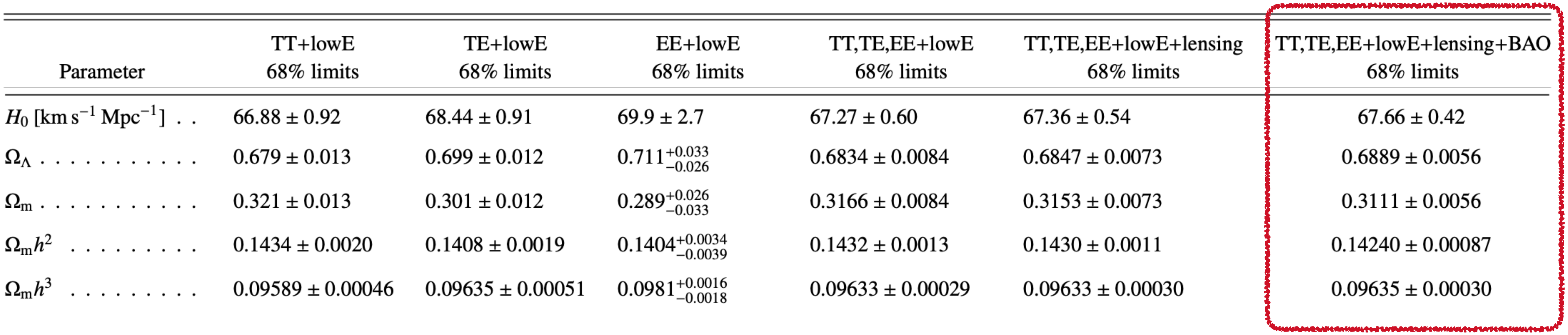
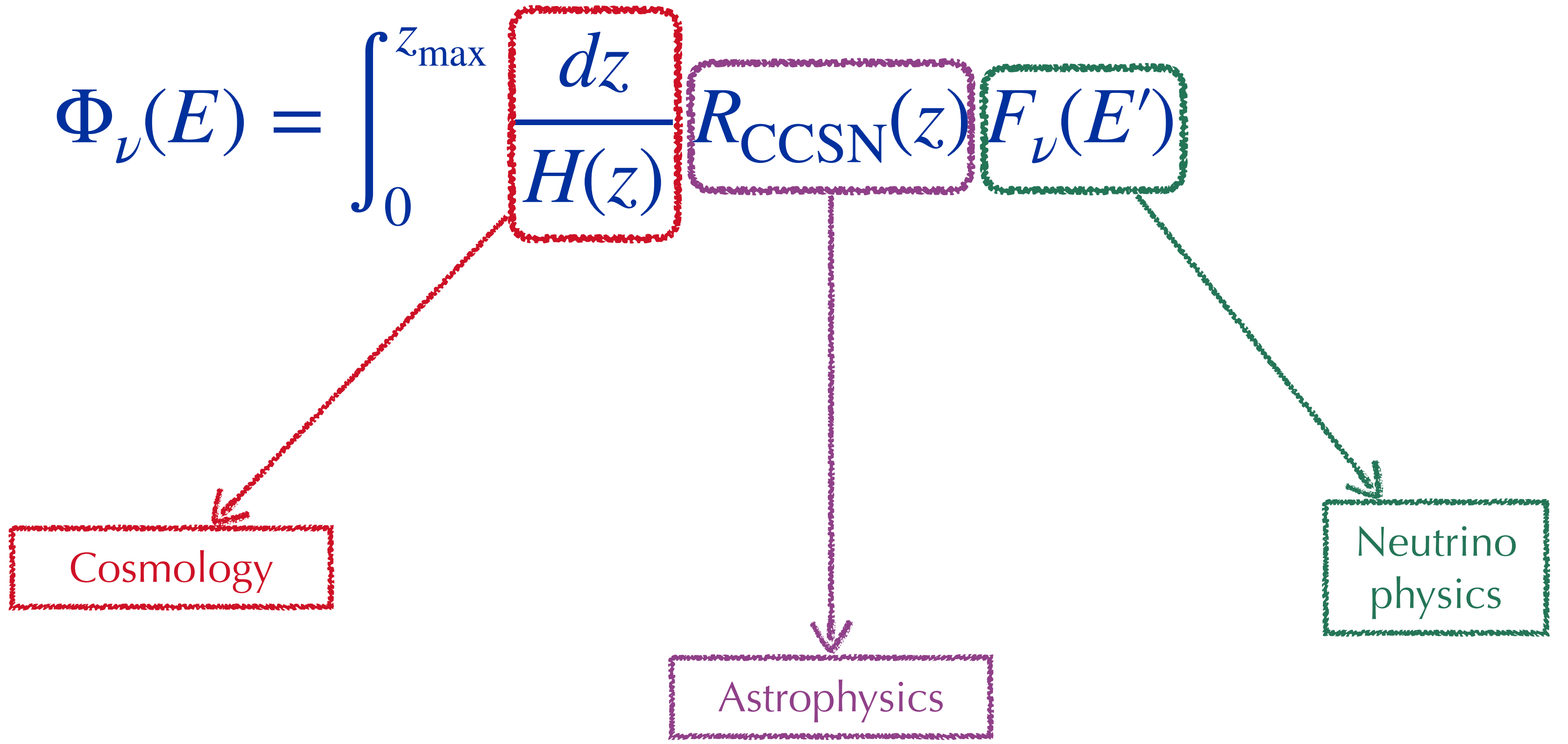


Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
H_0 [km s^{-1} Mpc^{-1}] . .	66.88 ± 0.92	68.44 ± 0.91	69.9 ± 2.7	67.27 ± 0.60	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.679 ± 0.013	0.699 ± 0.012	$0.711^{+0.033}_{-0.026}$	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

$z_{\max} = 5$



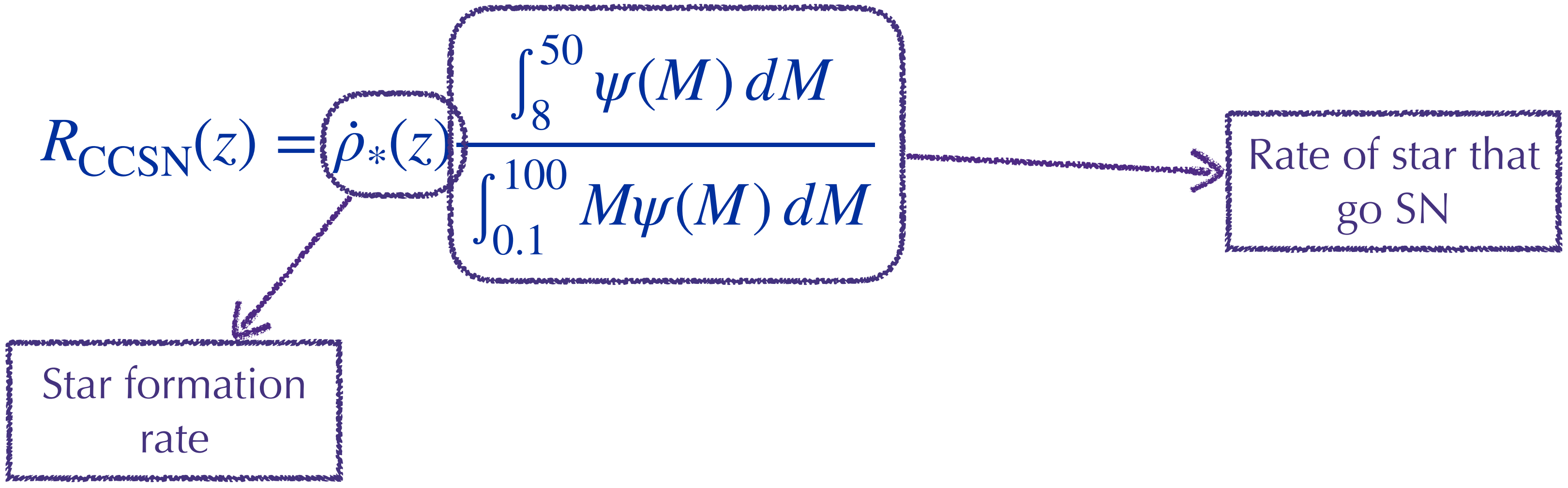
$$\Phi_\nu(E) = \int_0^{z_{\max}} \boxed{\frac{dz}{H(z)}}\,\boxed{R_{\mathrm{CCSN}}(z)}\,\boxed{F_\nu(E')}$$

Cosmology

Astrophysics

Neutrino physics

Astrophysics



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

Star formation rate

Rate of star that go SN

Astrophysics

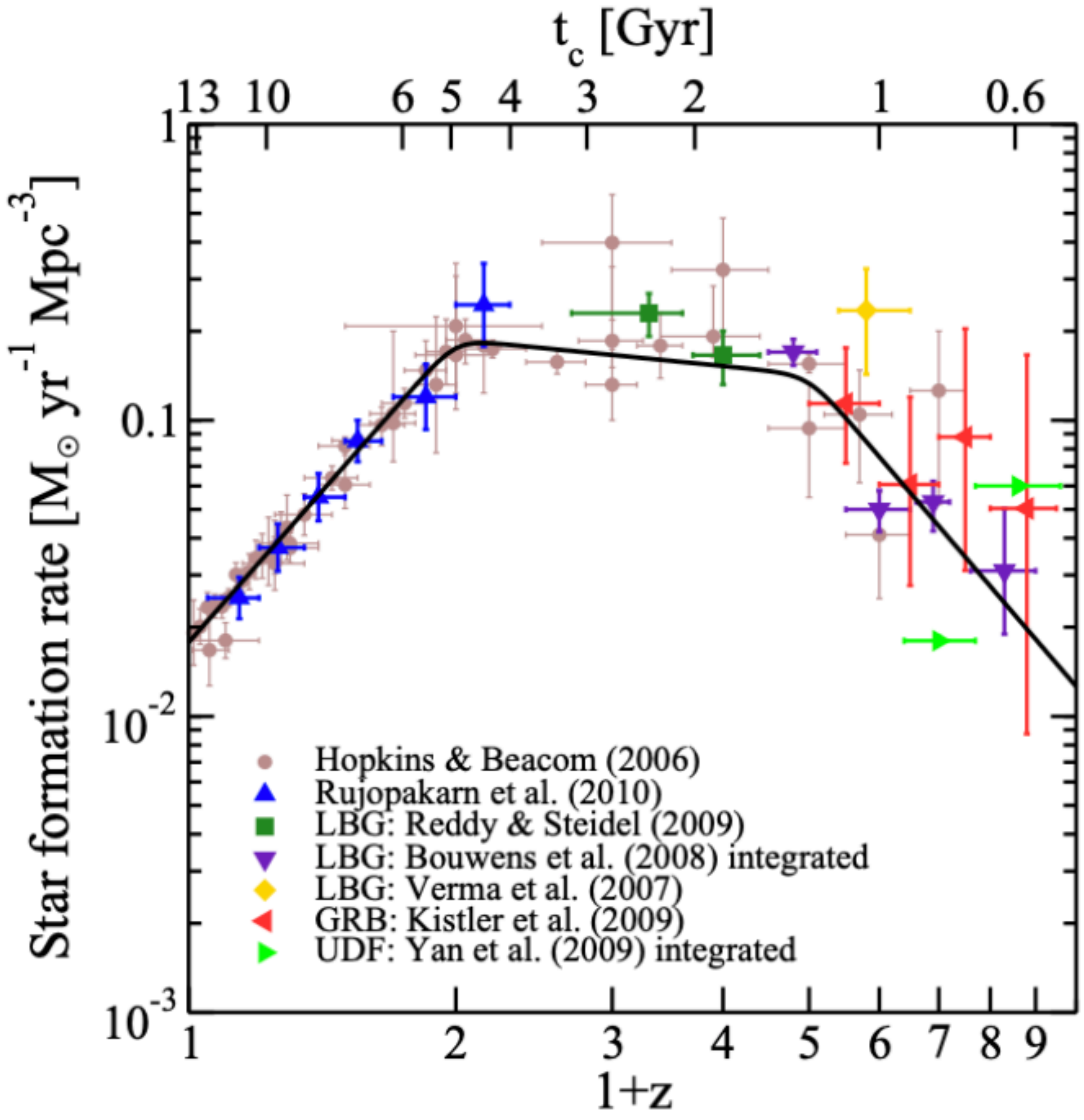
$$\dot{\rho}_*(z) = \dot{\rho}_0 \left[(1+z)^{-10\,\alpha} + \left(\frac{1+z}{B}\right)^{-10\,\beta} + \left(\frac{1+z}{C}\right)^{-10\,\gamma} \right]^{-1/10}$$

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

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

$z_{\rm max} = 5$

$$\Phi_\nu(E) = \int_0^{z_{\rm max}} \underbrace{\boxed{\frac{dz}{H(z)}}}_{\text{Cosmology}} \underbrace{\boxed{R_{\rm CCSN}(z)}}_{\text{Astrophysics}} \underbrace{\boxed{F_\nu(E')}}_{\text{Neutrino physics}}$$

Neutrino physics

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

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

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

Neutrino physics

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

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

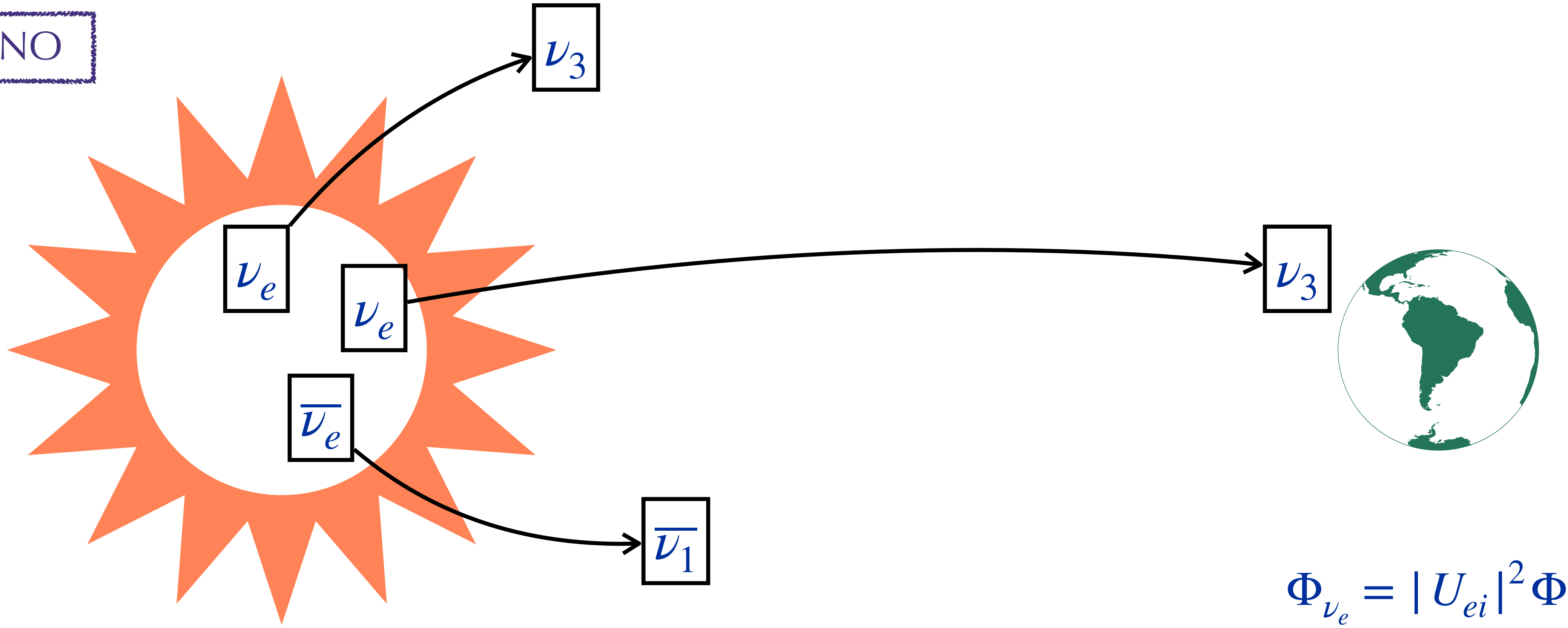
Oscillations? → Dominated by matter effects

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

Mixings are highly suppressed and flavor states coincide with medium eigenstates

Dighe, Smirnov PRD62(2000)033007

For the NO

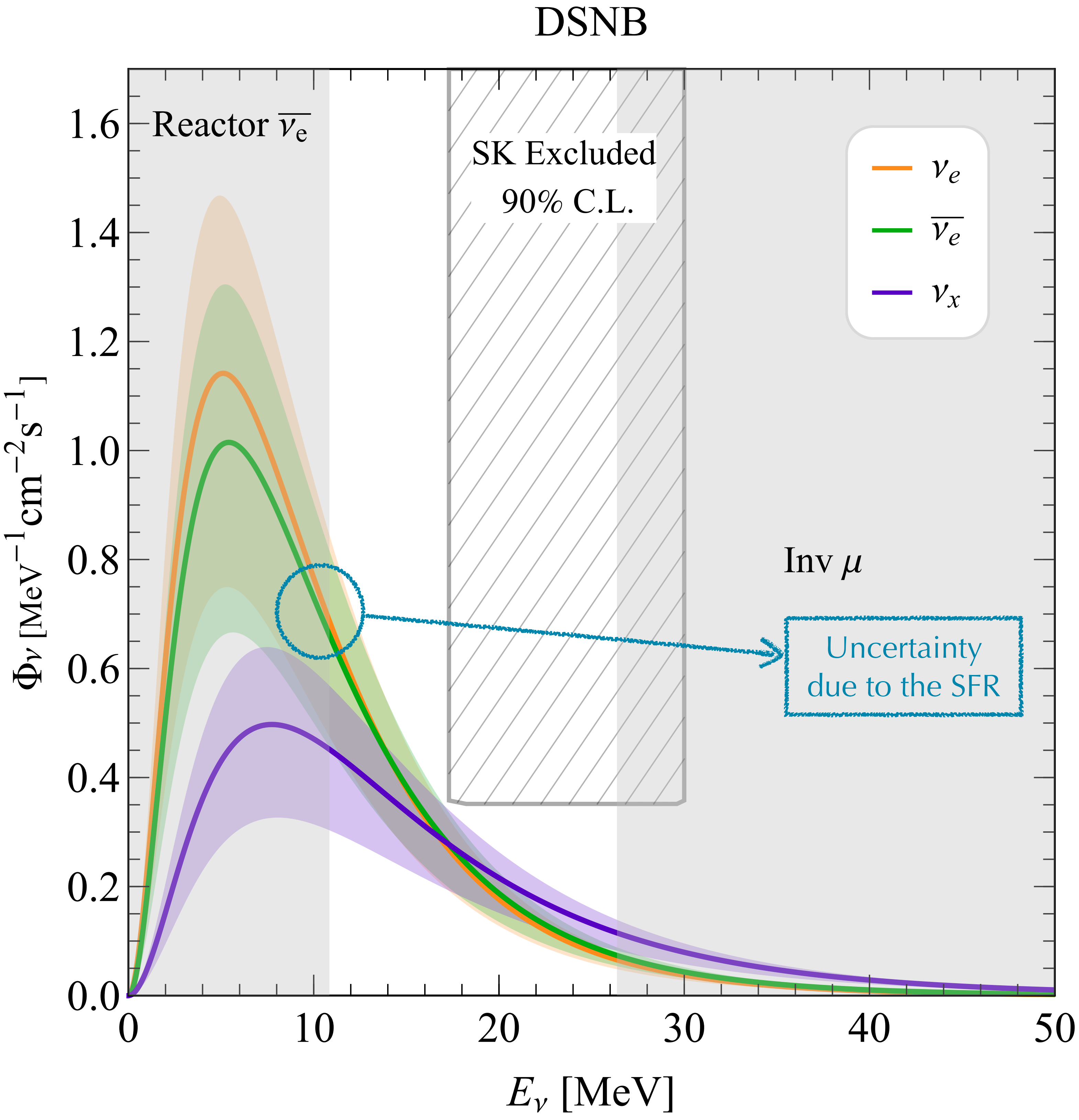


$$\Phi_{\nu_e} = |U_{ei}|^2\,\Phi_{\nu_i}$$

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…

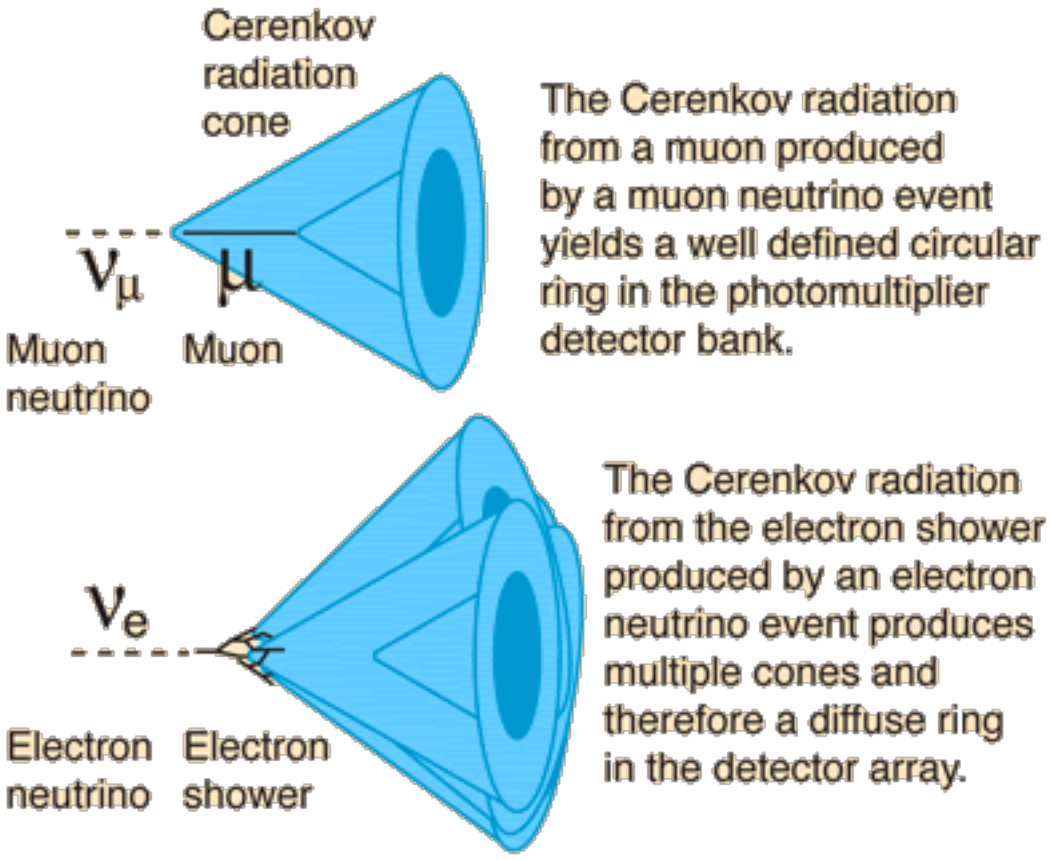
- There are many sources of background in the DSNB energy window
- Next generation experiments should be able to identify the DSNB
  - ✦ SK-Gd, HK, DUNE, THEIA
- Backgrounds will depend on the detector.

Number of events

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

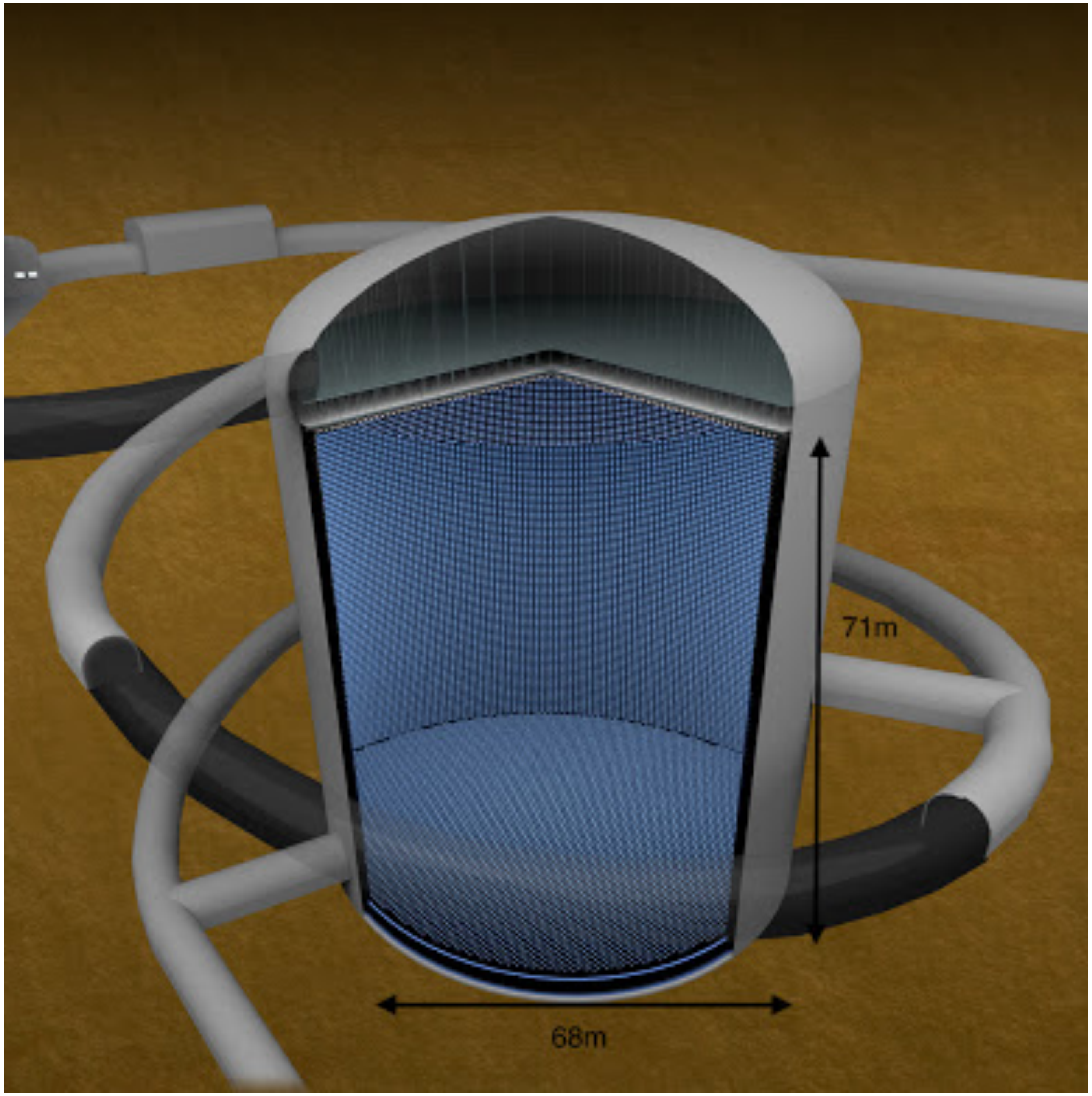
SK, SK-Gd and HK

- HK: 187kt and 10 years of data



The Cerenkov radiation from a muon produced by a muon neutrino event yields a well defined circular ring in the photomultiplier detector bank.

The Cerenkov radiation from the electron shower produced by an electron neutrino event produces multiple cones and therefore a diffuse ring in the detector array.



McDonald, Klein, Ward
Scientific American 288(2003)4

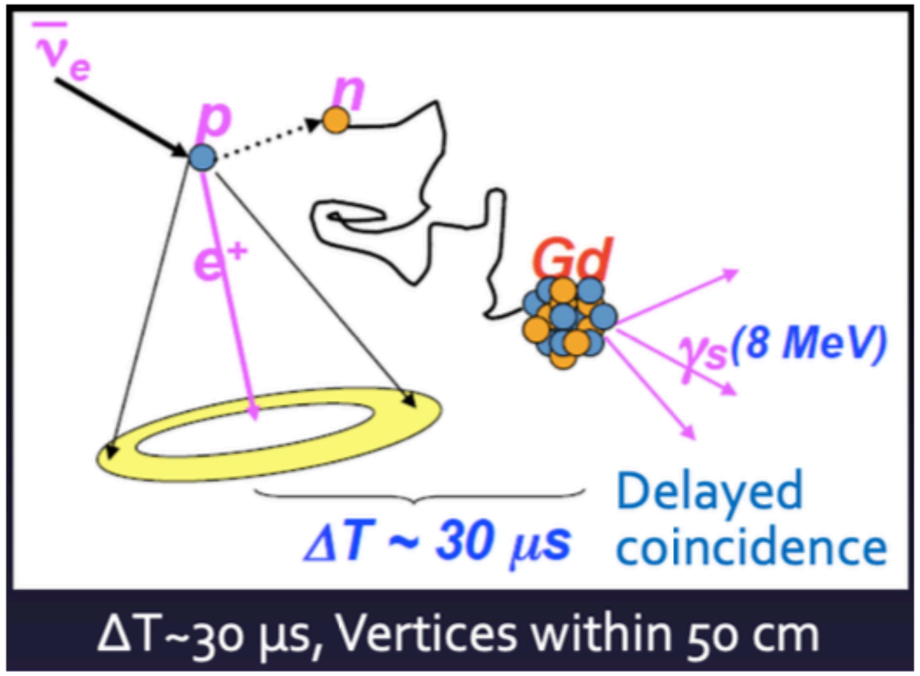
SK, SK-Gd and HK

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

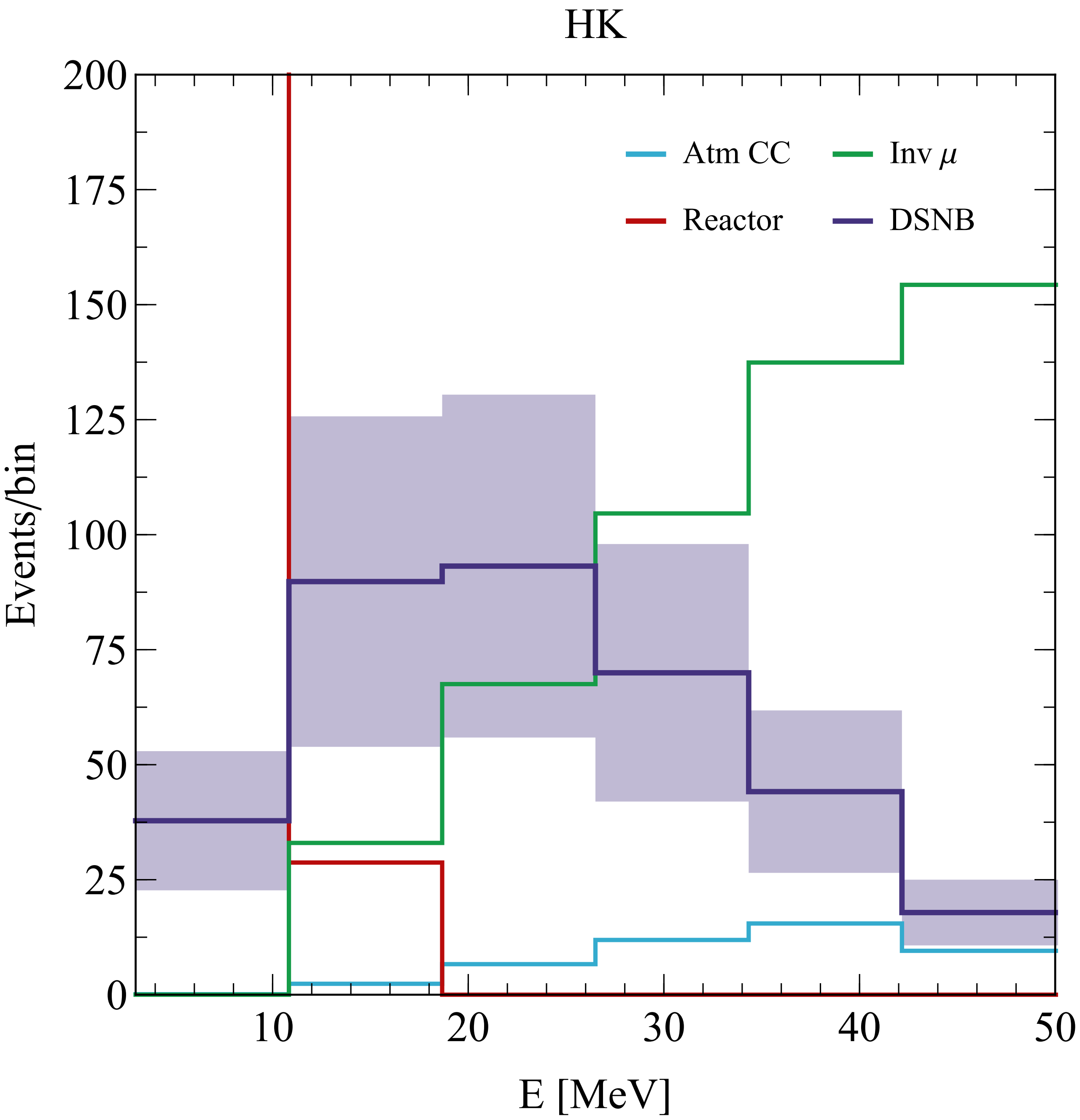
- Main channel for detection, IBD, $\overline{\nu_e} + p^+ \to n + e^+$

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

- Dope with Gadolinium!

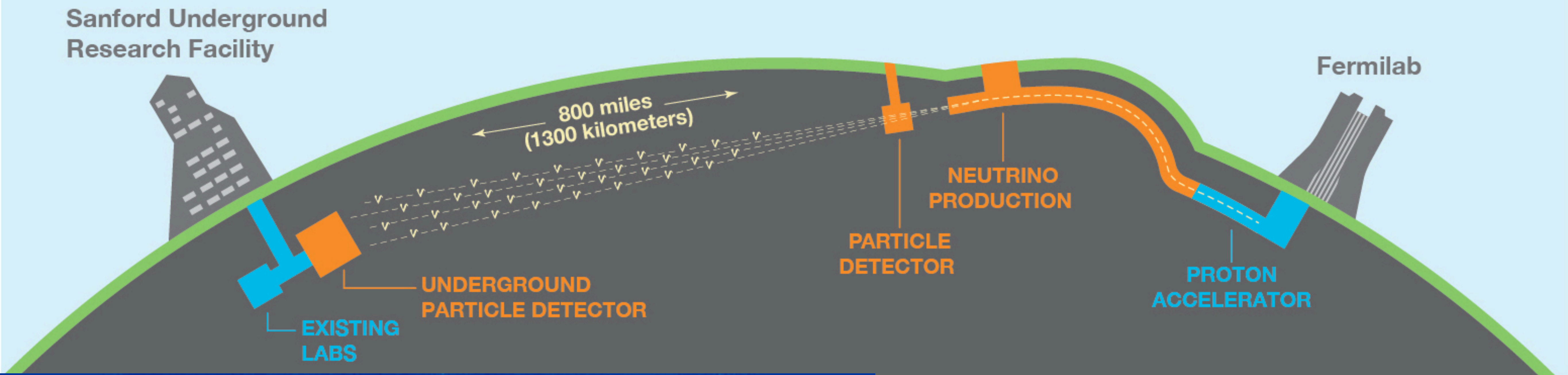


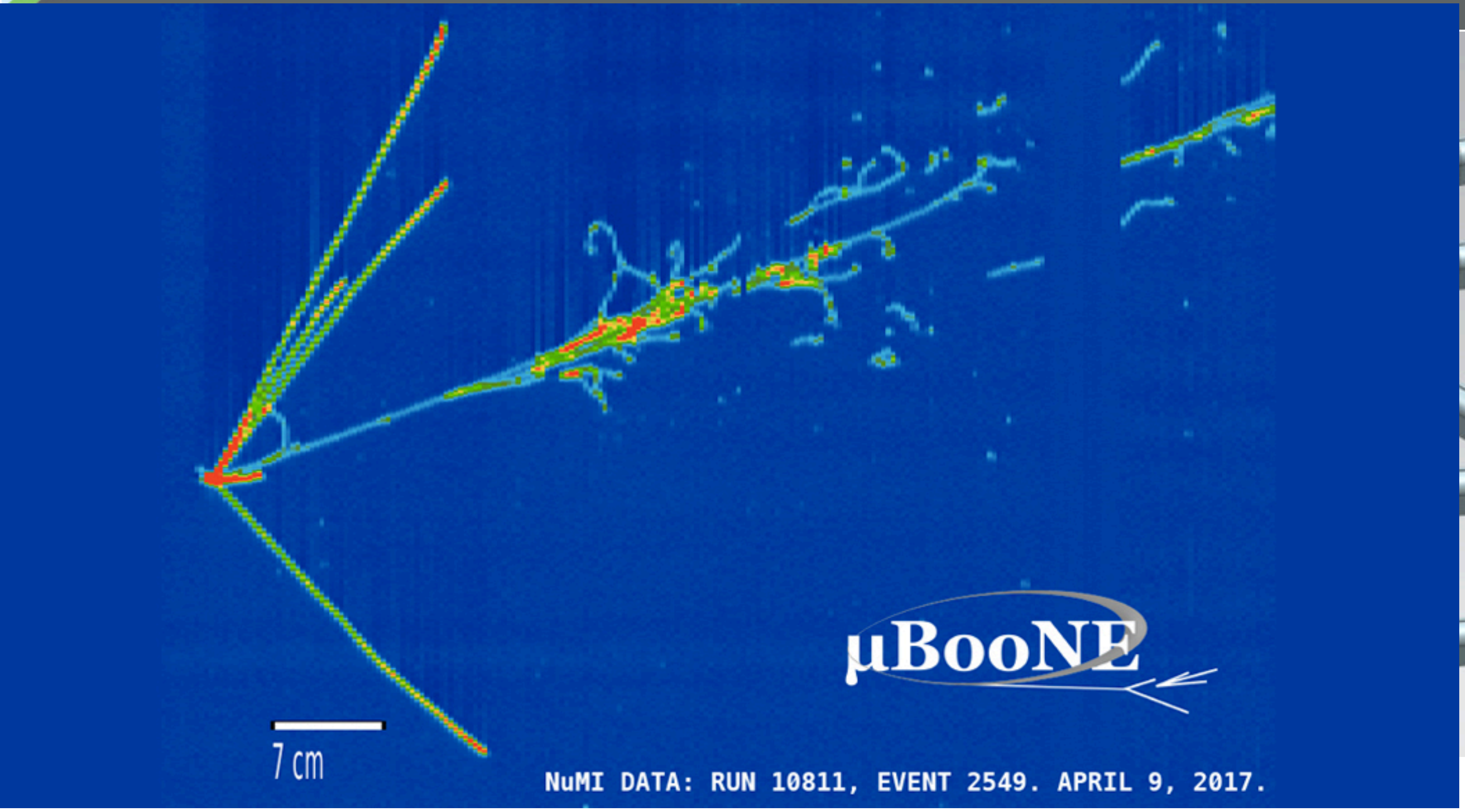
ΔT~30 μs, Vertices within 50 cm

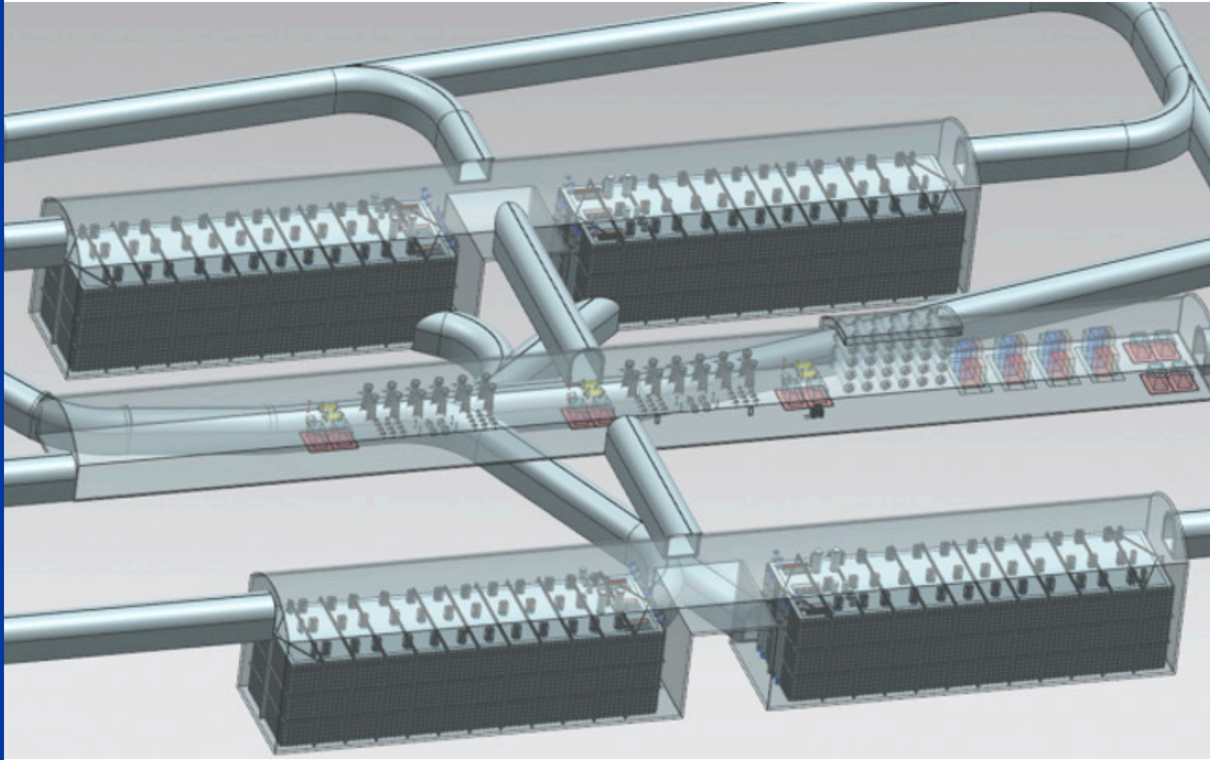


DUNE

- DUNE: 40kt and 10 years







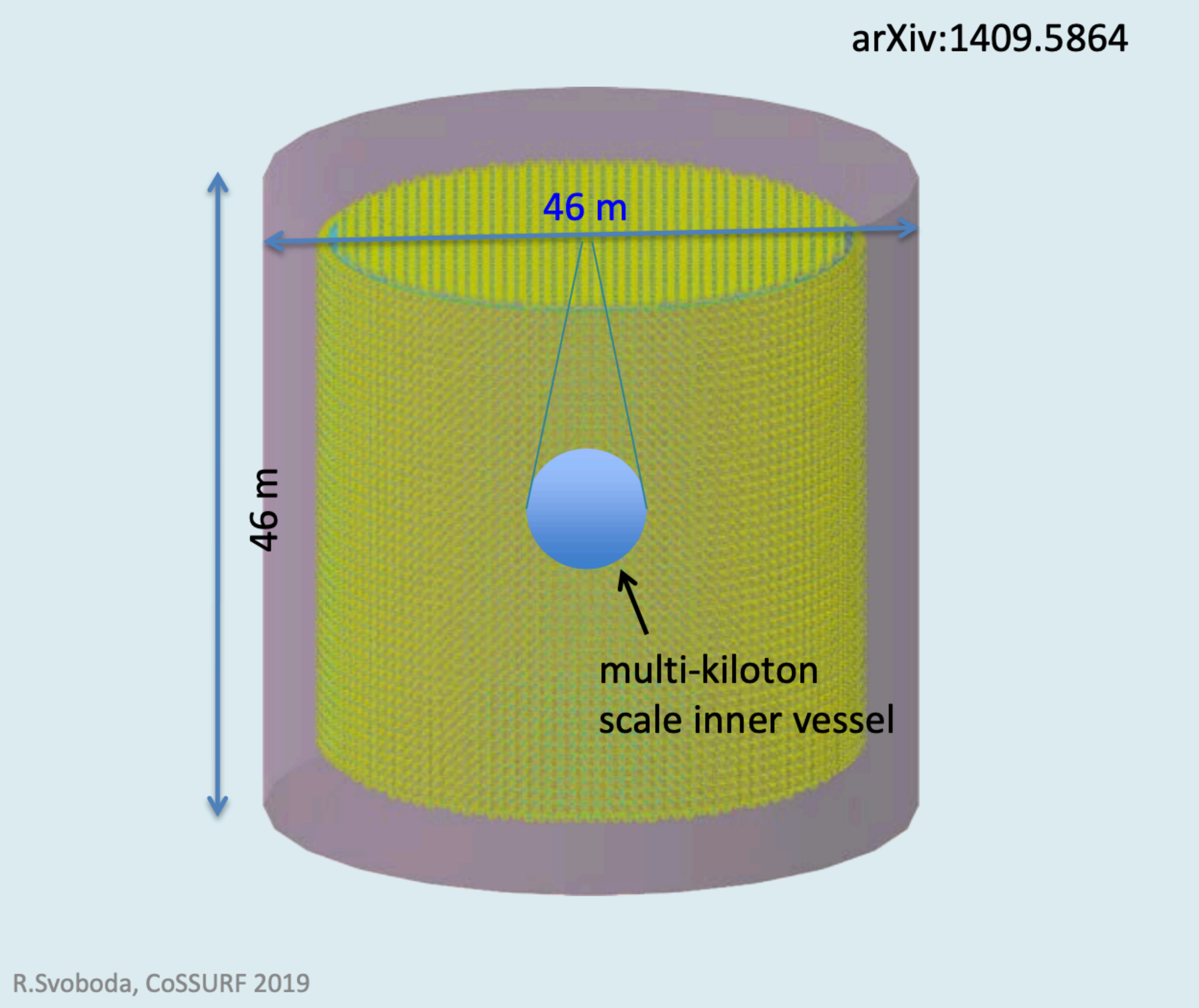
Water-based Liquid Scintillator - THEIA

Scintillation:
Luminescence caused by ionizing radiation

- Combination of techniques, H_2O + LS

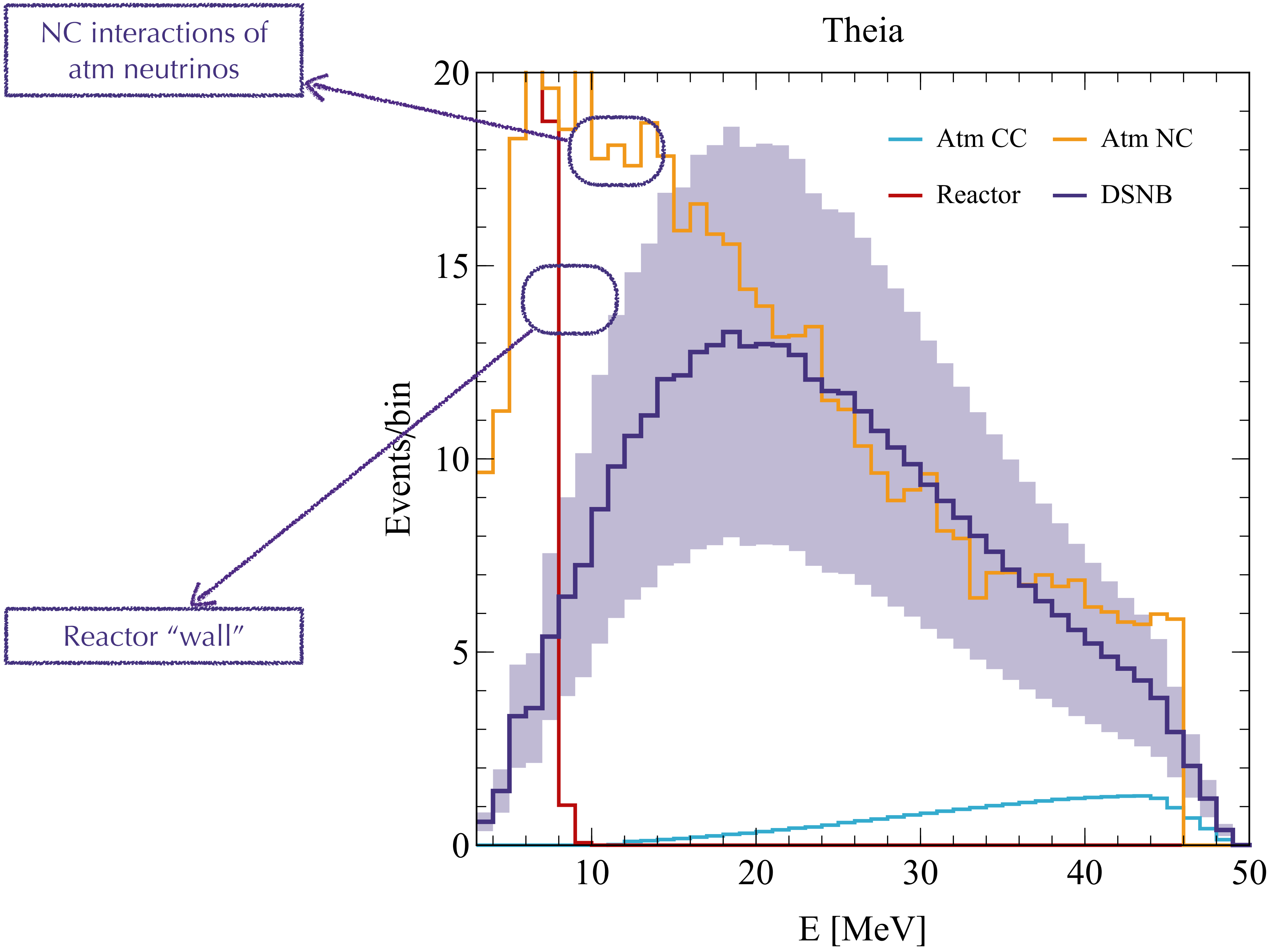
- **Backgrounds:**
  - 9Li from muon spallation, NC atms, neutrons…

- THEIA: 100kt - 10 years of data taking



R.Svoboda, CoSSURF 2019

Water-based Liquid Scintillator - THEIA


NC interactions of atm neutrinos

Reactor “wall”

Better energy resolution

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

Constraints from light will be considerably stronger

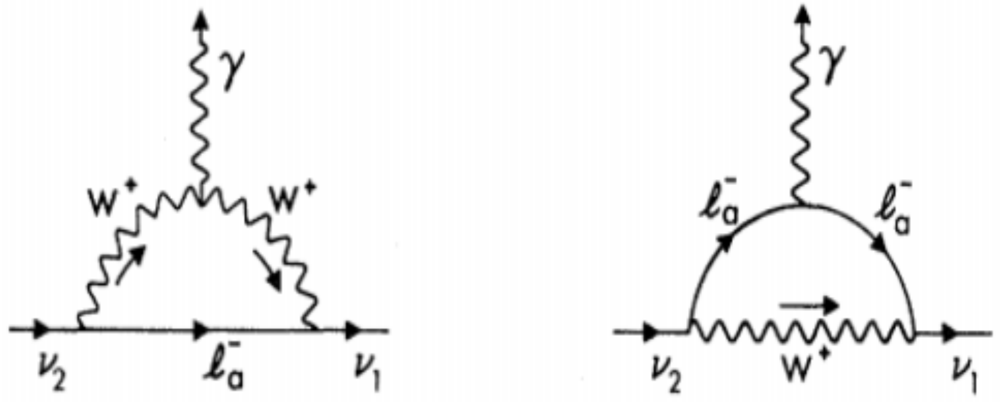
de Gouvêa, Martinez-Soler, YFPG, Sen, 2007.13748

Neutrino Decay

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

- Neutrinos have a lifetime, even in the SM

$\Gamma \sim 10^{-45}\ \mathrm{s}^{-1} \longrightarrow$ Way longer than the age of the Universe



Pal and Wolfenstein (PRD1982)

- However, if 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)

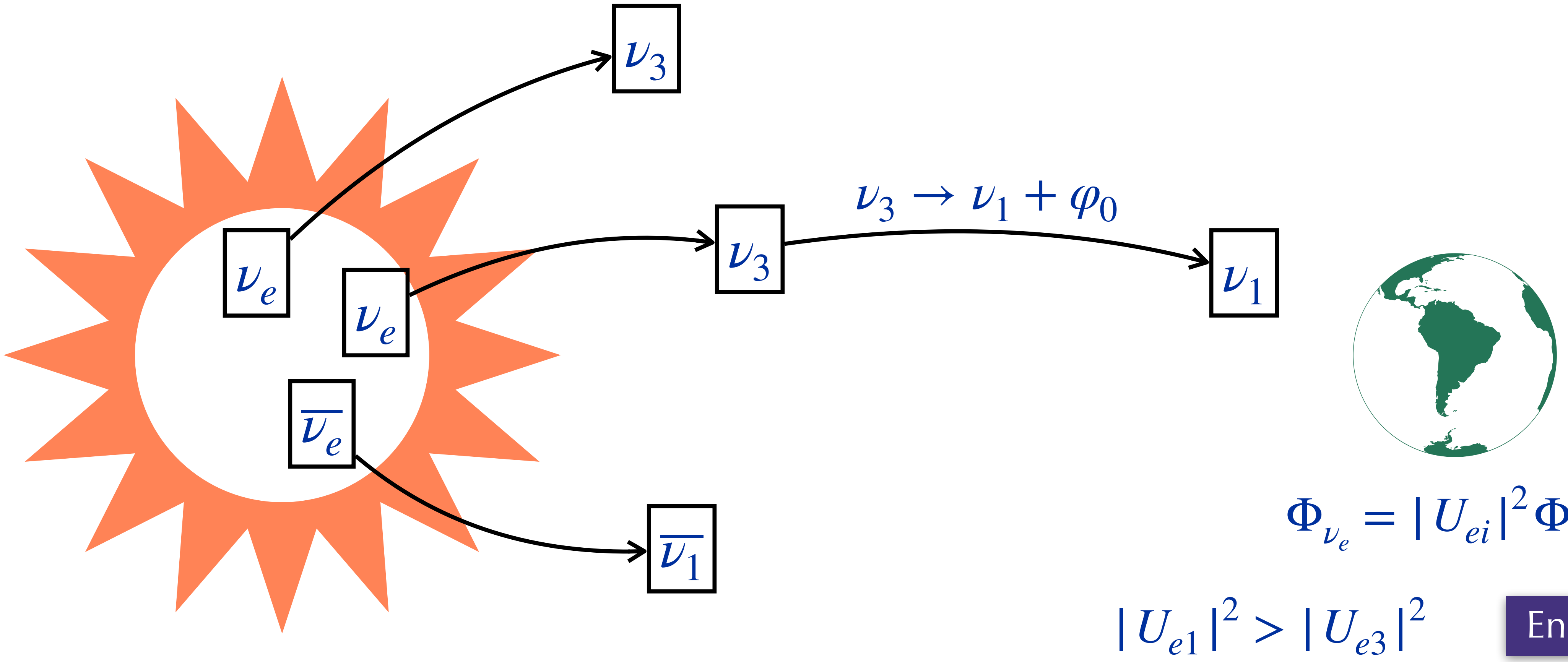
Neutrino Decay

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 $\nu_{3_L} \to \nu_{1_R} + \varphi_0$



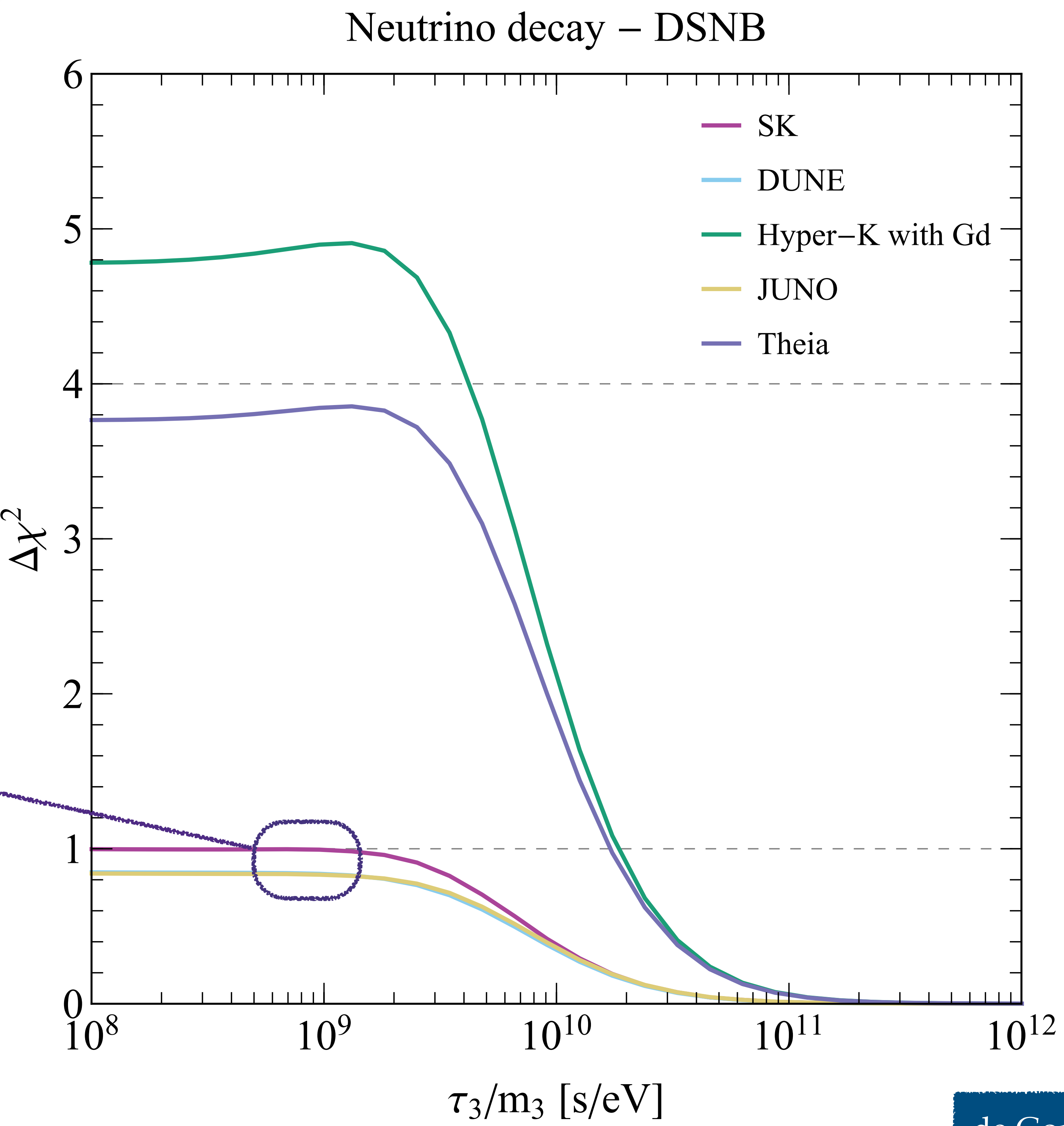
$$\Phi_{\nu_e} = |U_{ei}|^2\Phi_{\nu_i}$$

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

Enhancement

Future sensitivity

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



Small statistics in these experiments

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

Pseudo-Dirac Neutrinos

Let's consider the Dirac+Majorana Lagrangian

$$\mathscr{L}_Y = -\frac{\sqrt{2}M_D}{v}\overline{L}\tilde{H}N_R + \frac{1}{2}\overline{N^c}MN + \mathrm{h.c.}$$

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

- $M_R = 0 \rightarrow$ 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

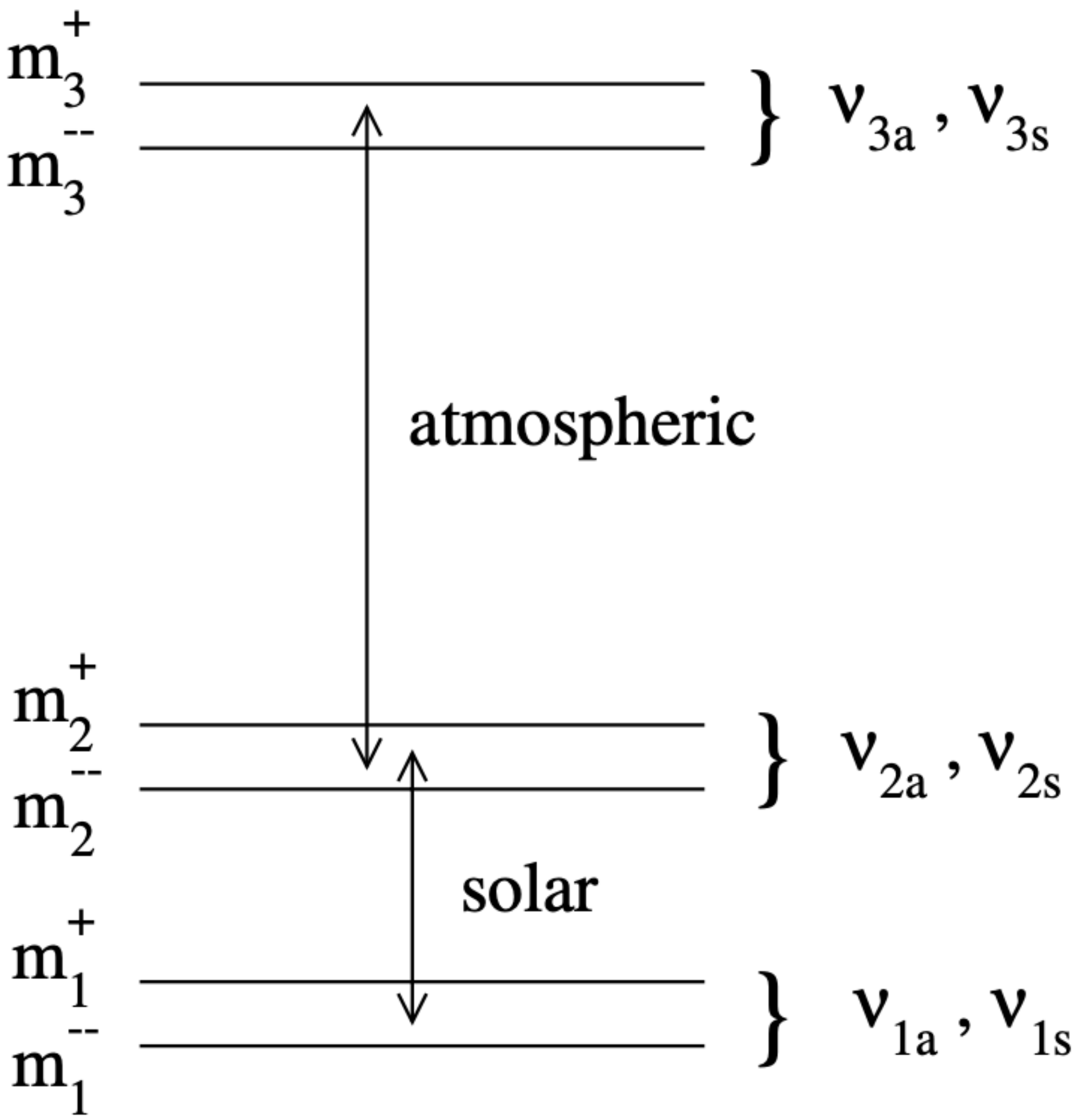
$$m_{ks}^2 = m_k^2 + \frac{1}{2}\delta m_k^2$$

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

δm_k^2 → 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



Beacom et.al. 0307151

Pseudo-Dirac Neutrinos

Neutrinos have propagated distances of order Gpc

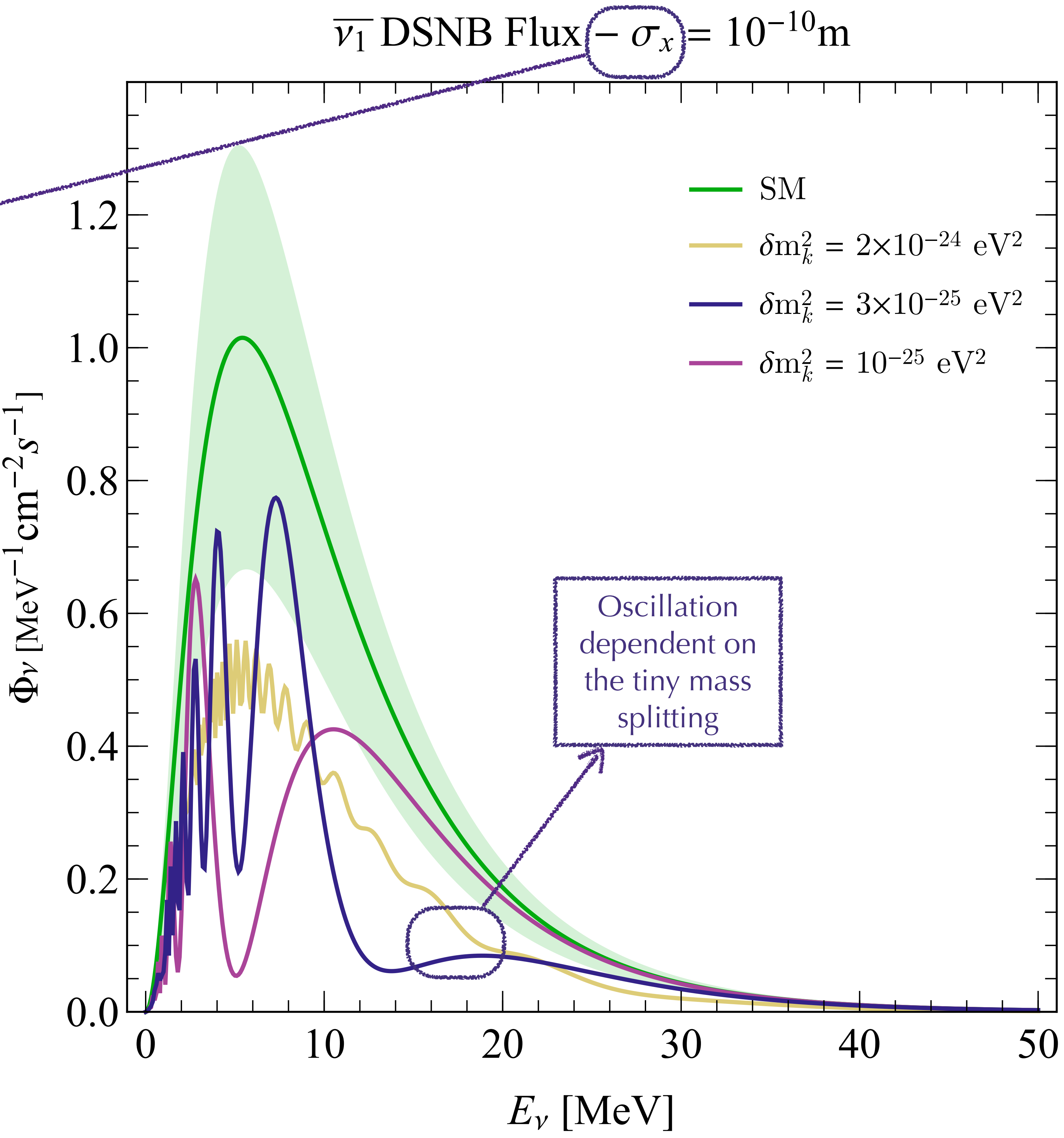
$$P_{k\beta}(z,E) = \frac{1}{2}\,|U_{\beta k}|^2 \left(1 + \exp\left\{-\frac{L_3(z)^2}{L_{\rm coh}^2}\right\} \cos\left(\frac{\delta m_k^2}{2E} L_2(z)\right)\right)$$

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

Oscillation and decoherence lengths

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

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



Fixed wave packed size

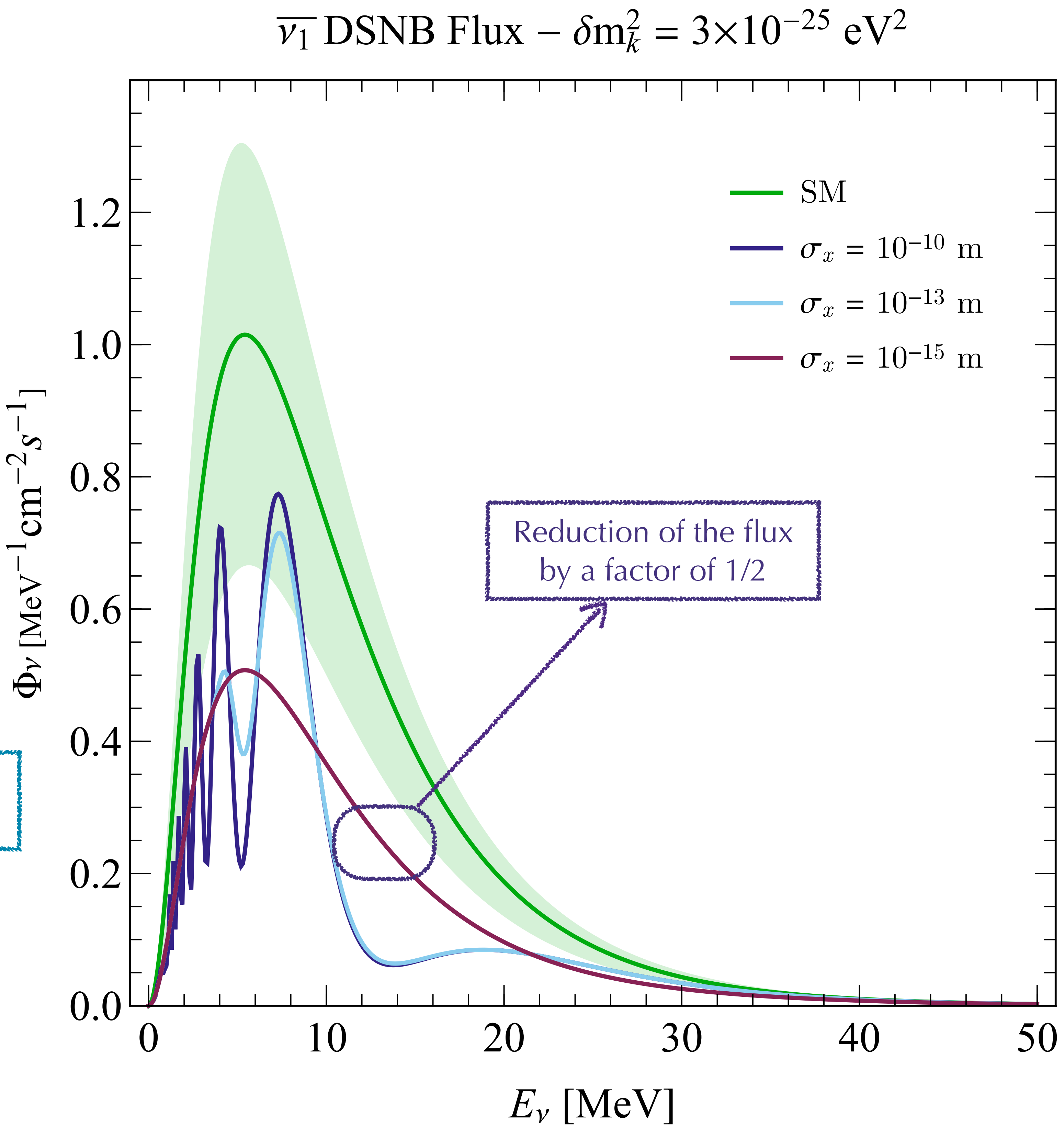
Oscillation dependent on the tiny mass splitting

Decoherence?

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

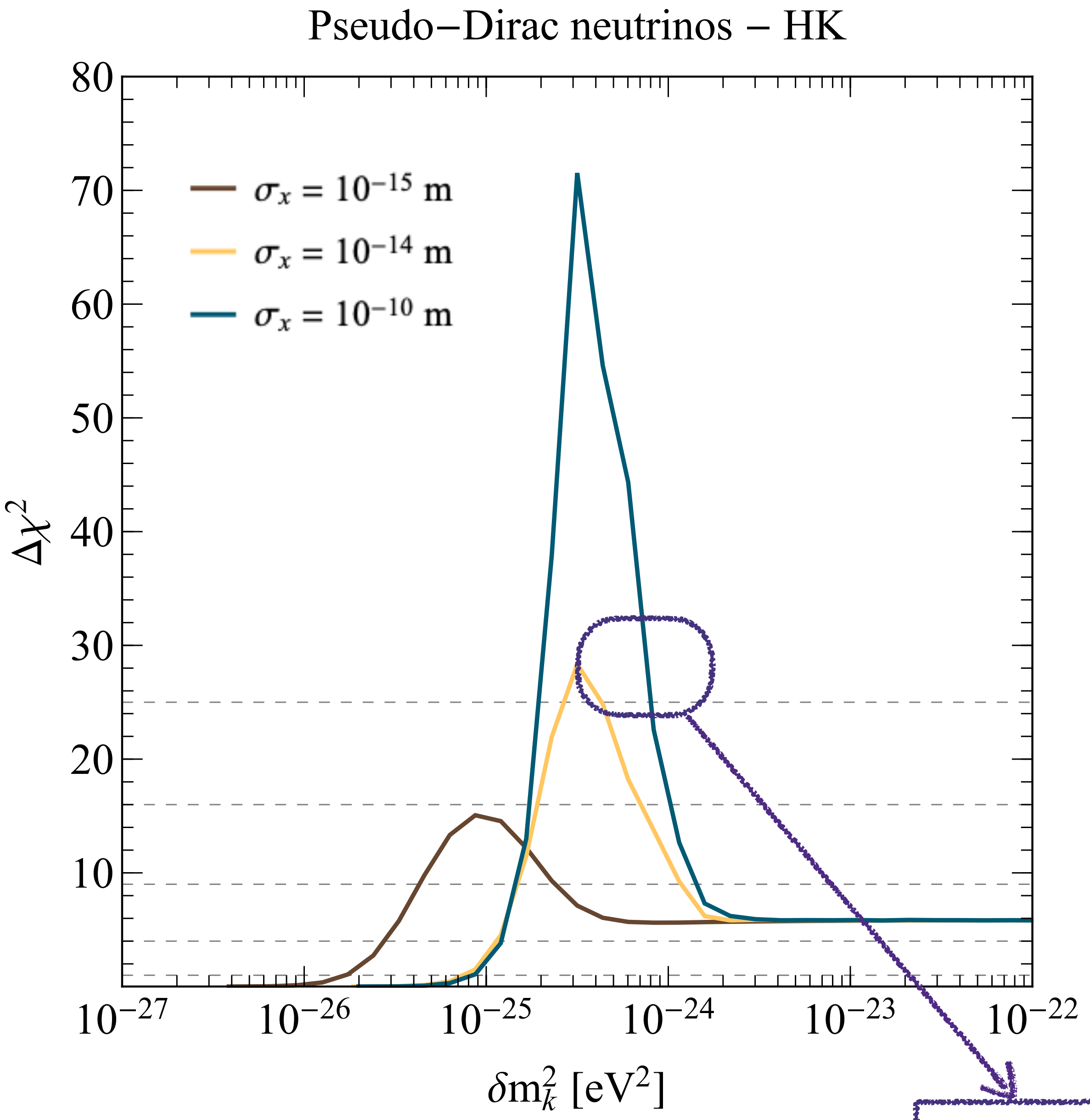
$$\approx 0.0023 \left(\frac{E}{10 \text{ MeV}}\right)\left(\frac{\sigma_x}{10^{-15} \text{ m}}\right)$$

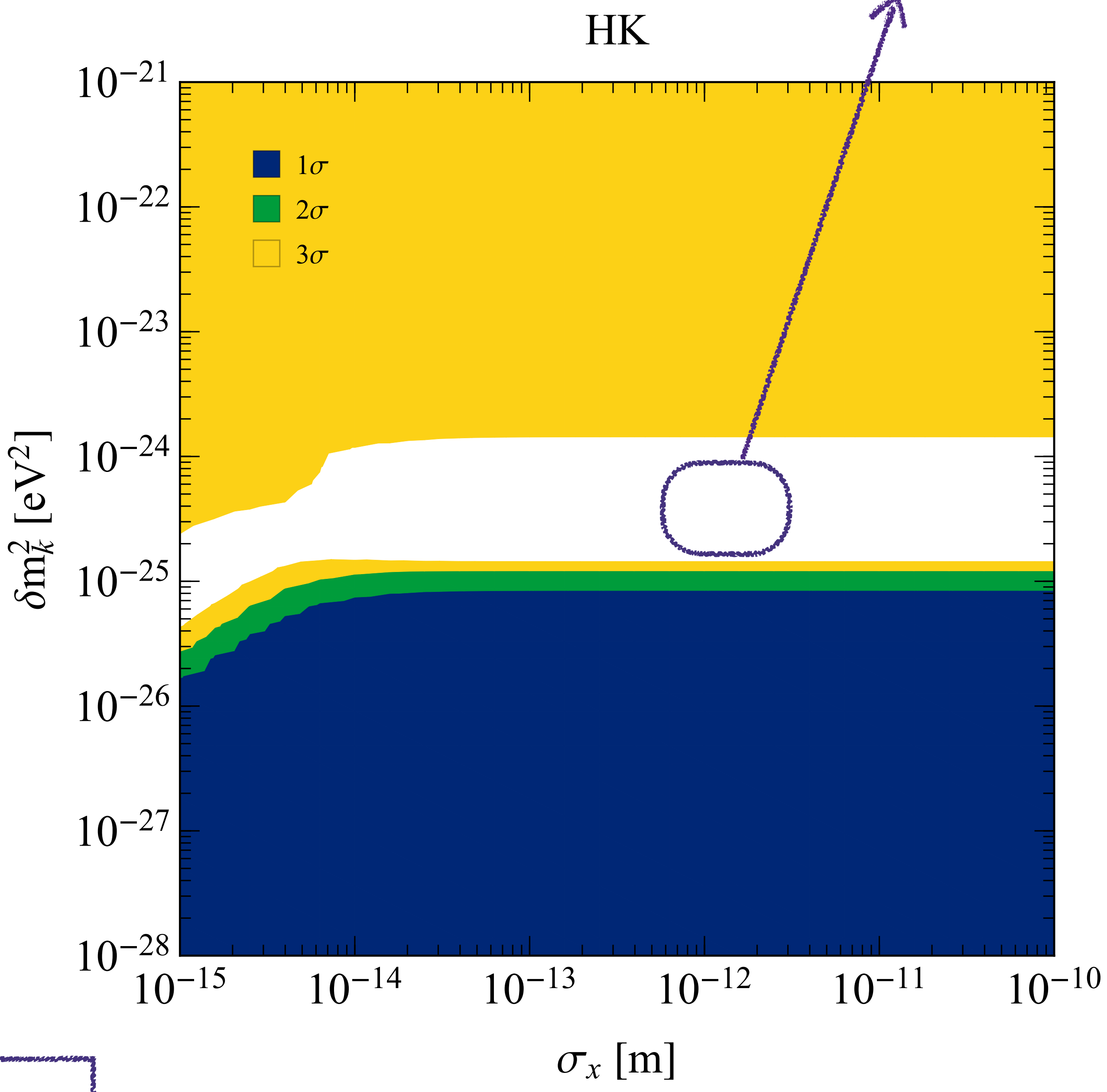
$\sigma_x \gg 1$ fm → It is expected to be at least



Reduction of the flux by a factor of 1/2

Pseudo-Dirac Neutrinos





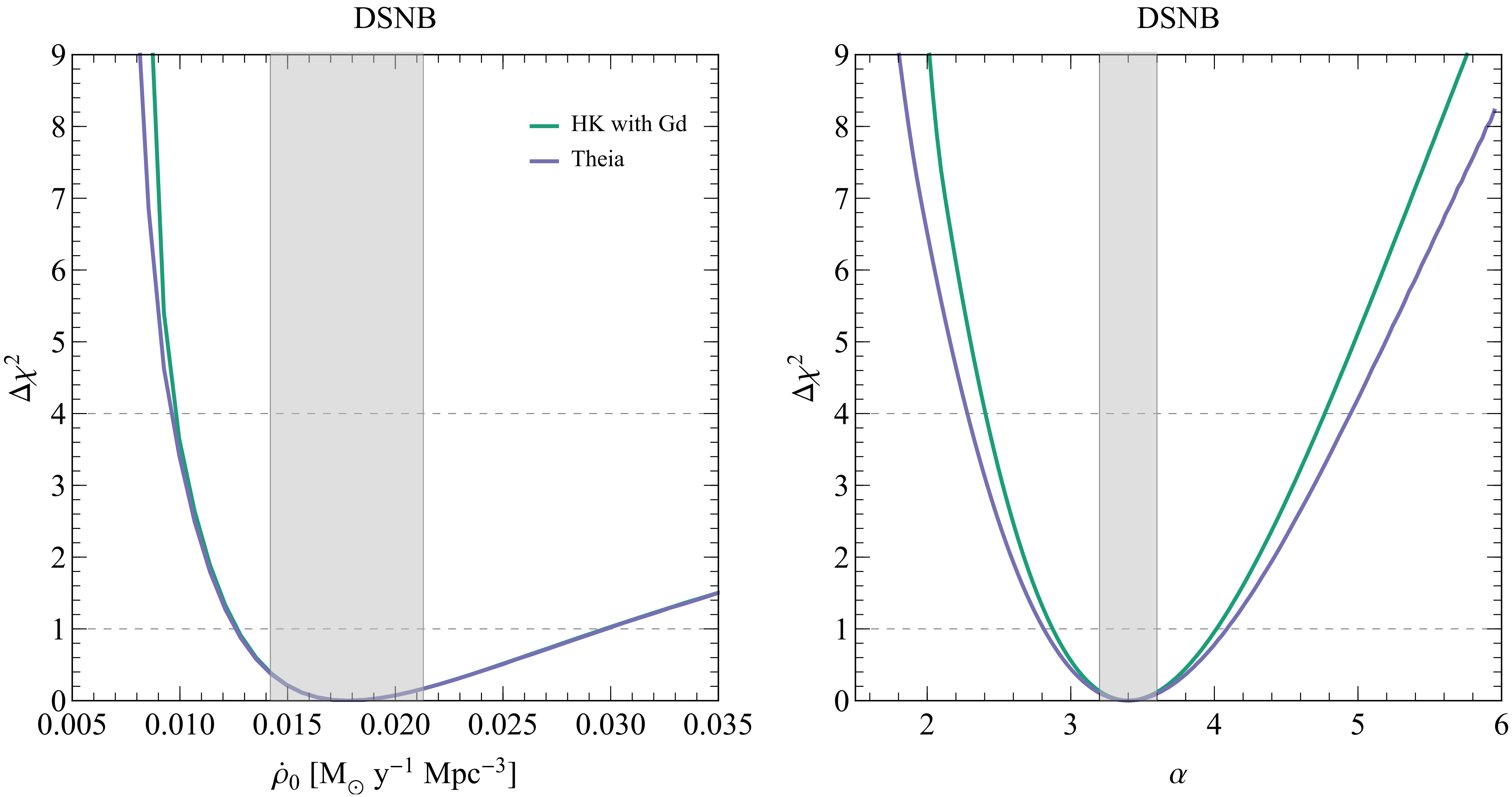
Region excluded at more than 3σ

Large sensitivities

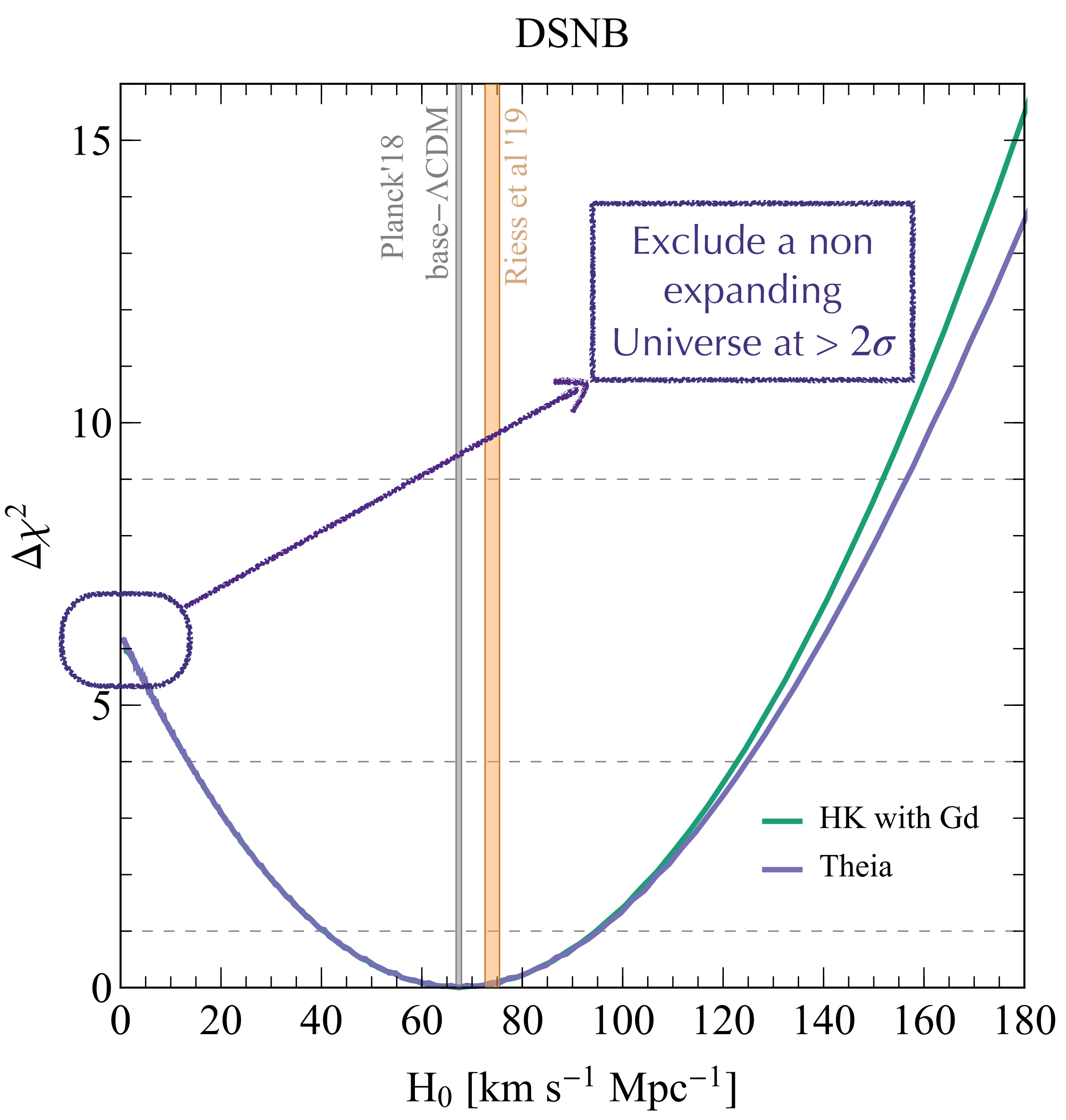
de Gouvêa, Martinez-Soler, YFPG, Sen, 2007.13748

Astrophysics

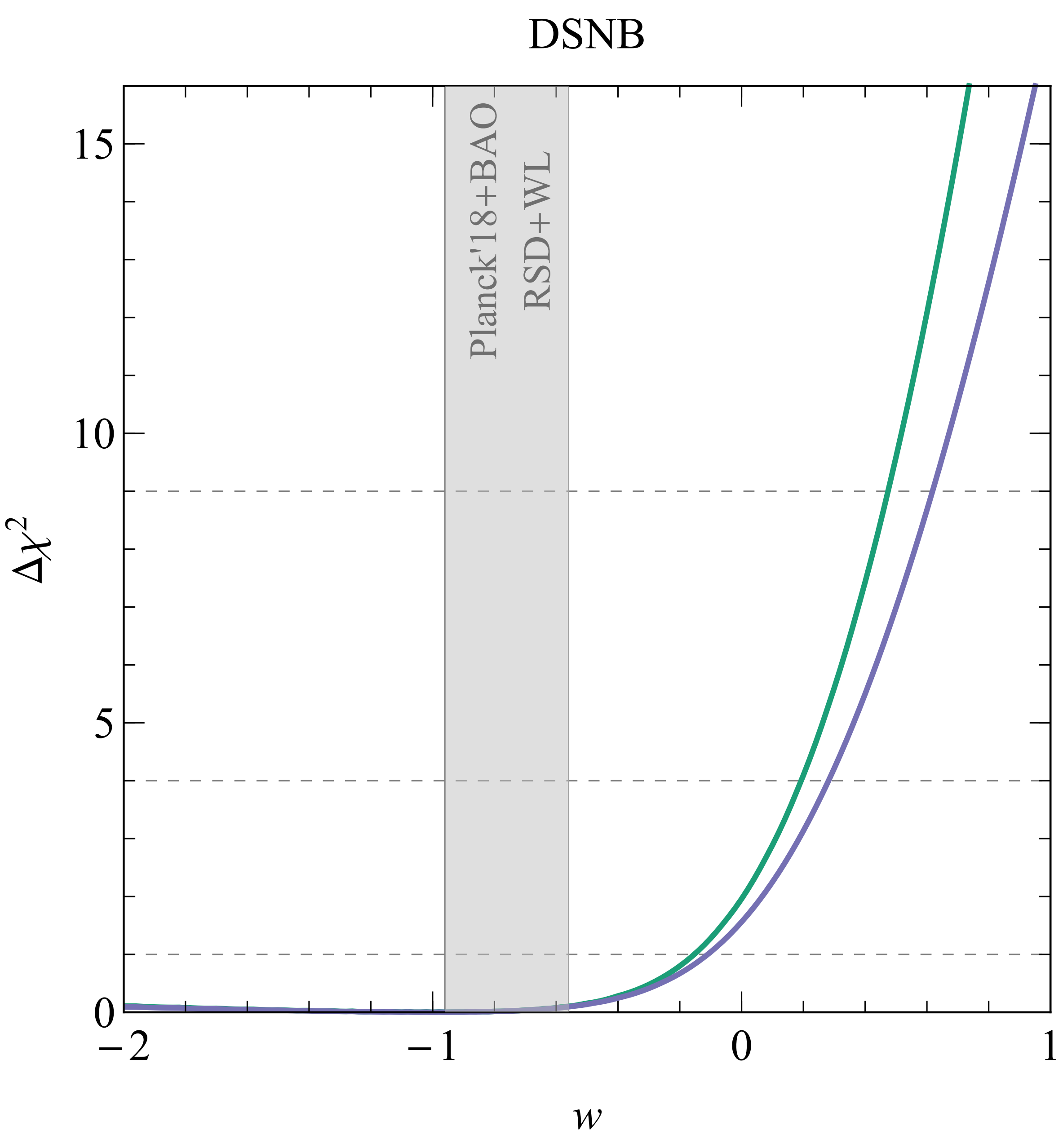
$$\dot{\rho}_*(z) = \dot{\rho}_0 \left[(1+z)^{-10\,\alpha} + \left(\frac{1+z}{B} \right)^{-10\,\beta} + \left(\frac{1+z}{C} \right)^{-10\,\gamma} \right]^{-1/10}$$



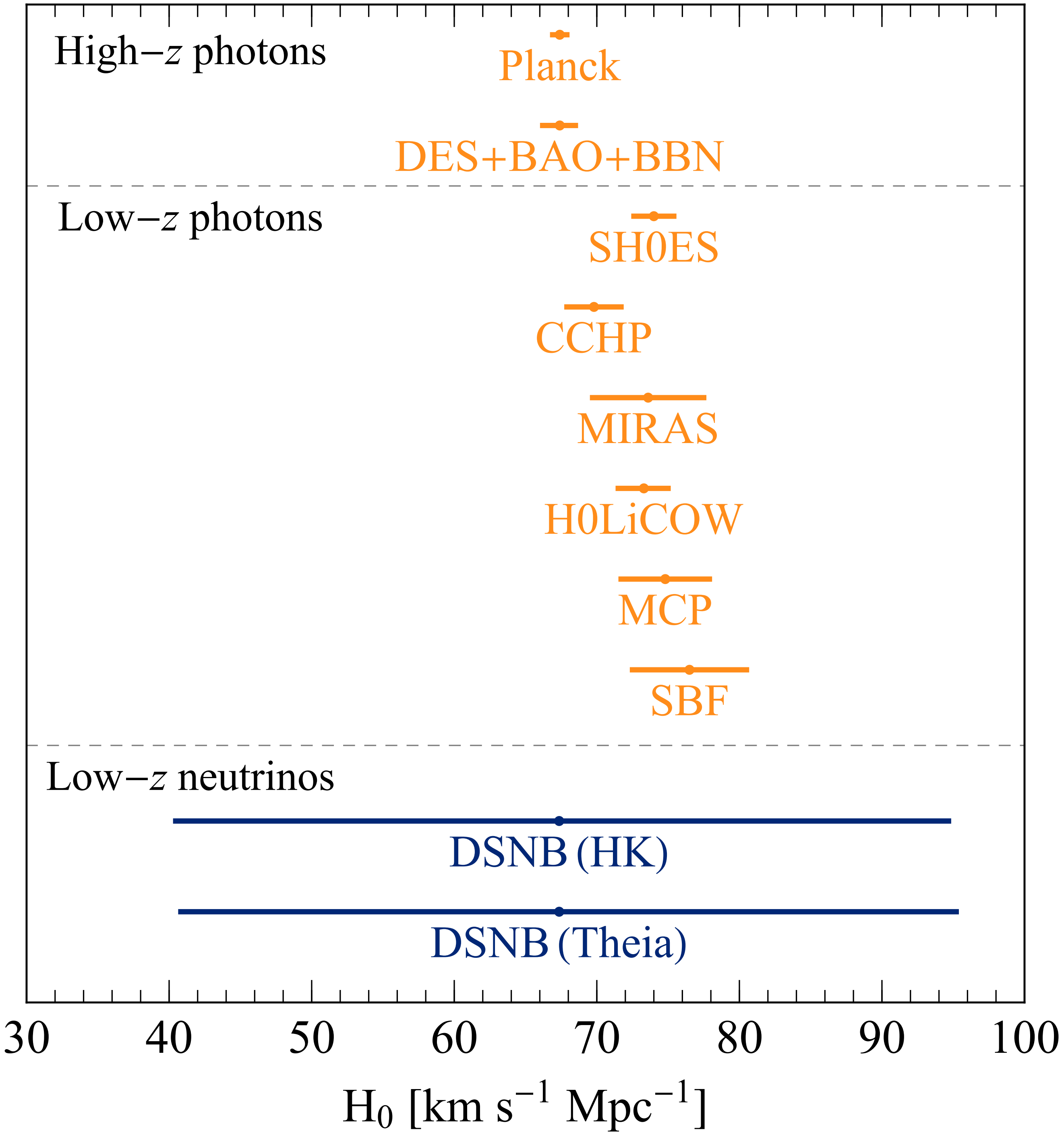
Cosmology…



Exclude a non expanding Universe at $> 2\sigma$



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

Thanks!