Diffuse SN neutrino background: a possible contender for fundamental physics probes

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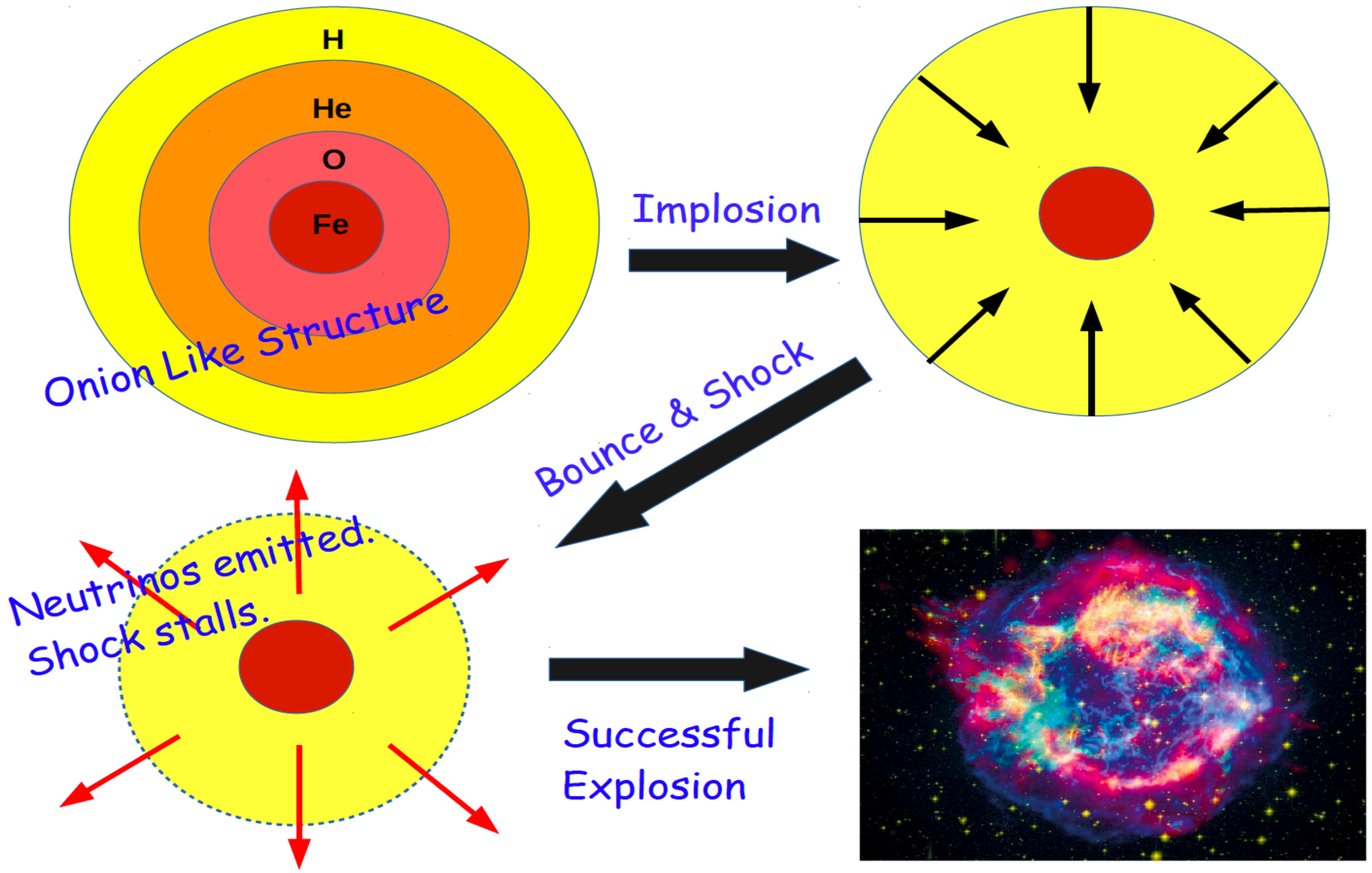
Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

Core-collapse SNe: Mechanism



Neutrino flux from a typical SN

- Core-collapse SNe, collapse of iron core in a massive star, leading to MeV neutrino emission.

- Dominated by cooling phase neutrinos. Almost thermal spectra for different flavors.

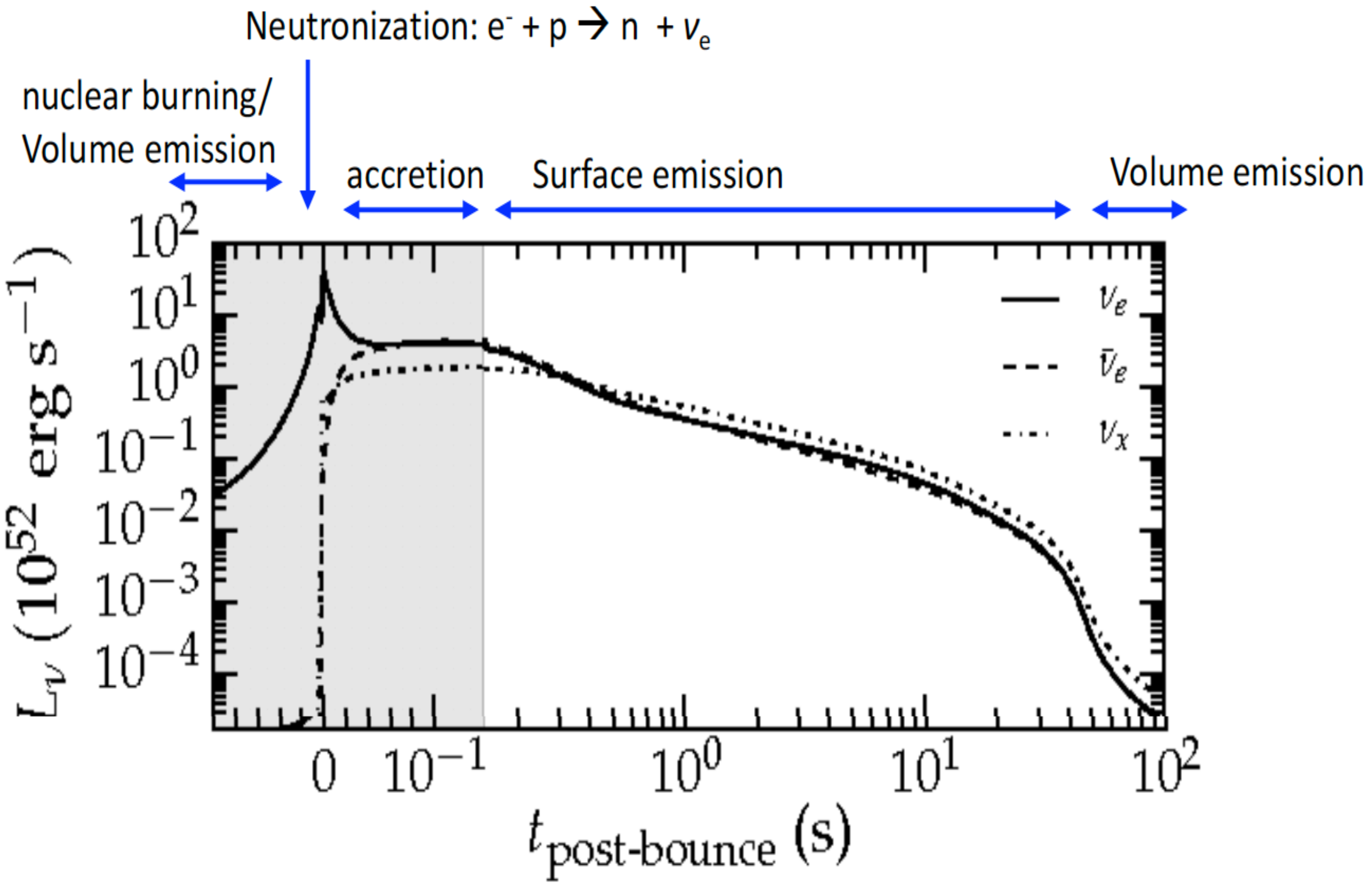
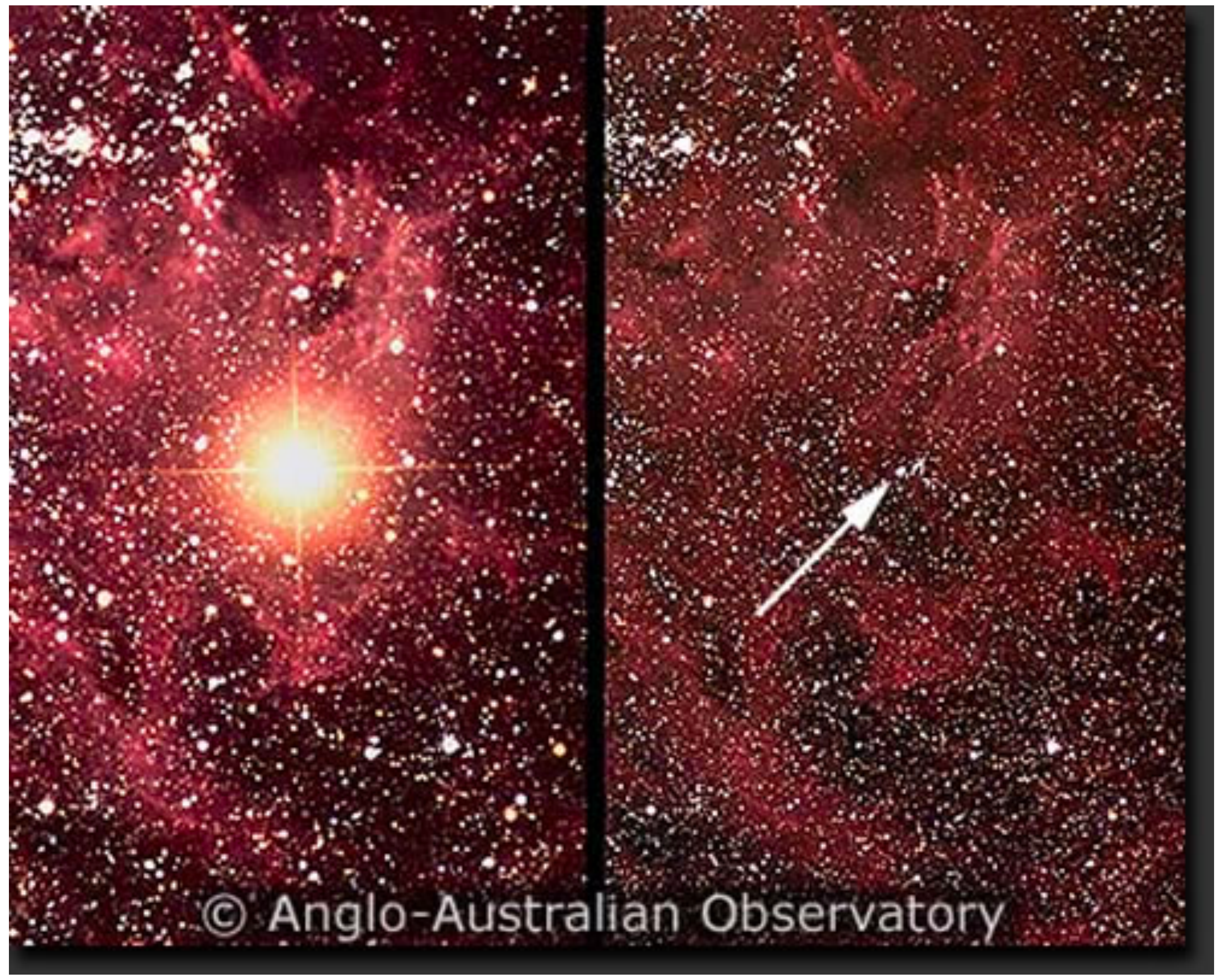
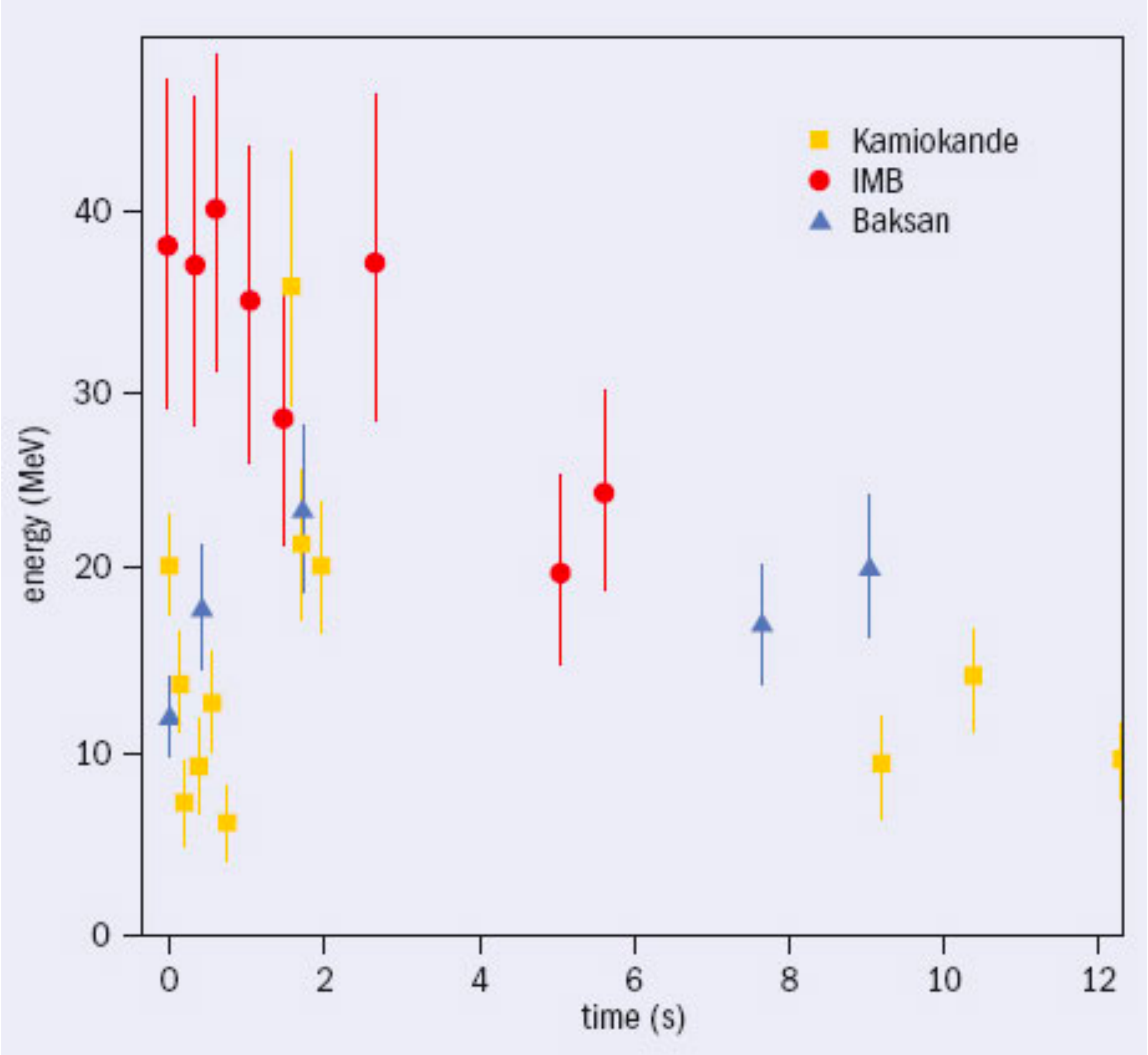


Figure from Roberts and Reddy, Handbook of Supernovae, Springer Intl., 2017

SN 1987A: "Many" neutrinos were observed





- O(30) events in total.
- One of the first examples of multi-messenger astronomy.
- Not enough statistics, still some of the strongest bounds on neutrino properties!
- A future galactic SN will have O(10k) events in detectors! Surely, we can capitalize on that!
- Extremely rare to have one. So do we wait a lifetime?

The Diffuse Supernova Neutrino Background

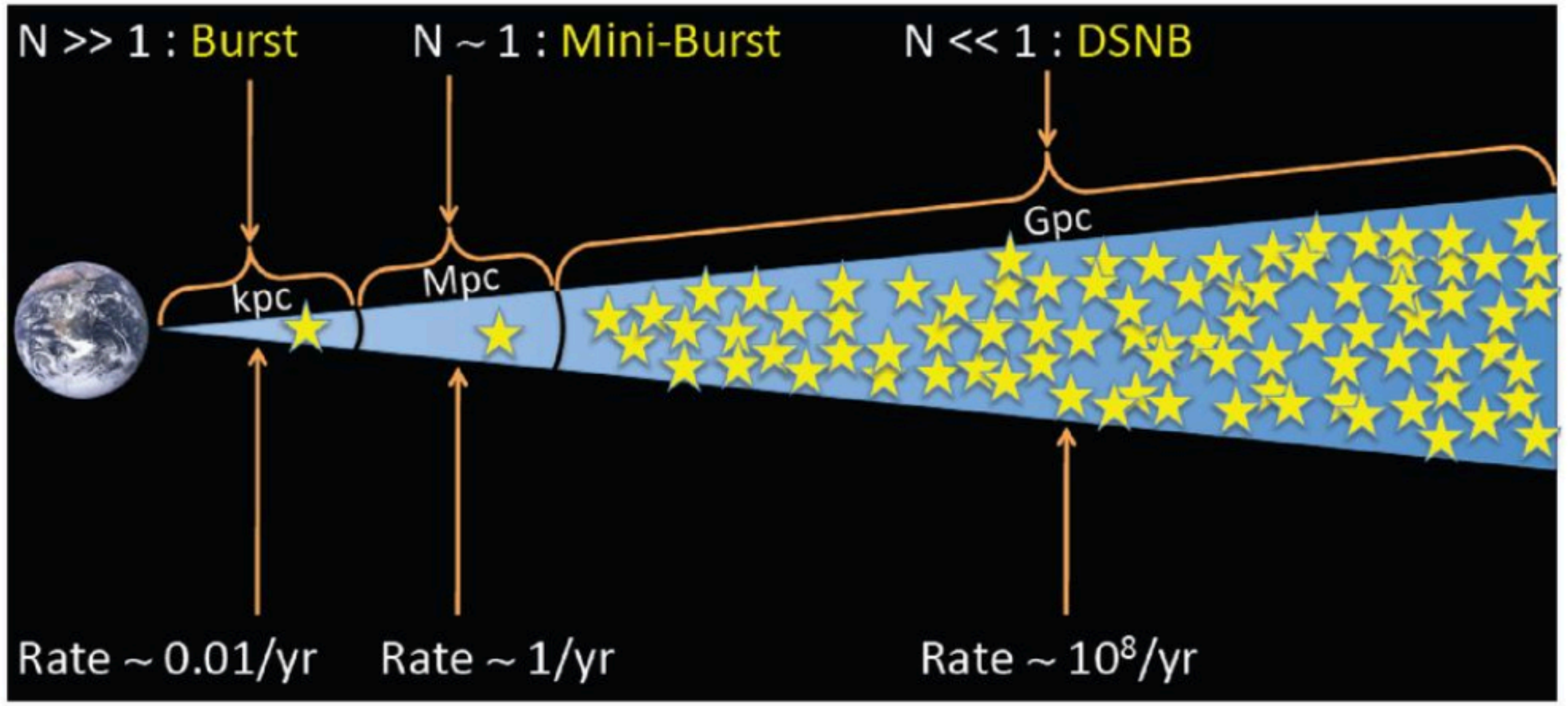
- We can be more inclusive, and look to the distant Universe for more SNe.

- Not that rare. On an average, there is 1 SN going off per second. The neutrino emission produces the DSNB.

- Detectable neutrino flux, mostly from stars upto redshift z~1, but extends upto z~6.

- Opens up a new frontier in neutrino astronomy.

John Beacom, TAUP2011



DSNB=Diffuse Supernova Neutrino Background

How to estimate the DSNB?

$$\Phi_\nu(E) = \int_0^{z_{\max}} \frac{dz}{H(z)} R_{\rm CCSN}(z)\, F_\nu\big(E(1+z)\big)$$

Neutrino spectra

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

Cosmological SN rate

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

Cosmology

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

Ingredient 1: Cosmology

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
σ_8	0.8118 ± 0.0089	0.793 ± 0.011	0.796 ± 0.018	0.8120 ± 0.0073	0.8111 ± 0.0060	0.8102 ± 0.0060

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

- Underlying cosmology is well constrained from Planck 2018 data.
- Parameters provide a normalisation to the spectra

PLANCK 2018

Ingredient 2: Star formation Rate

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

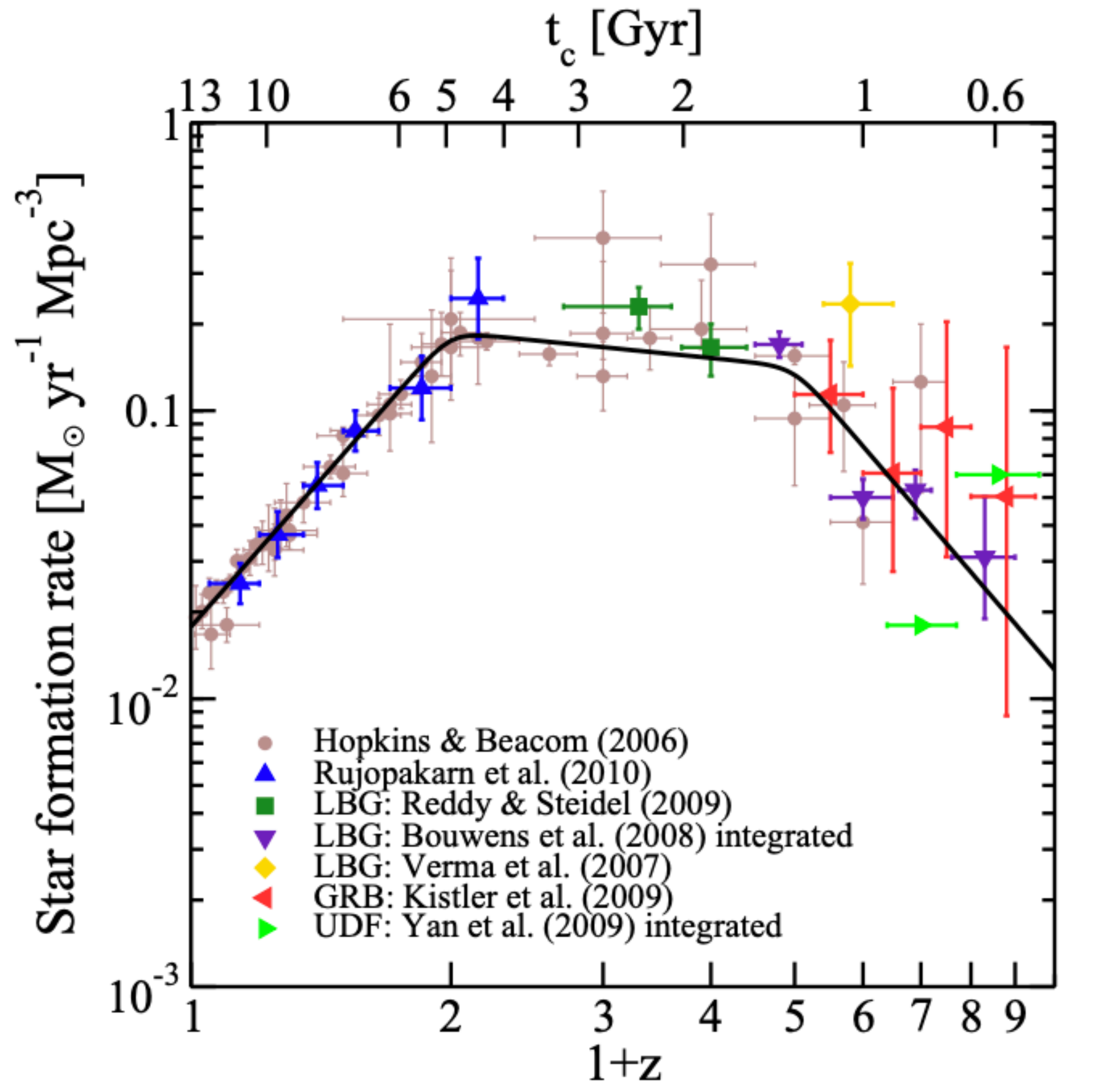
$$\dot{\rho}_*(z) = \dot{\rho}_0 \left[(1+z)^{-10\alpha} + \left(\frac{1+z}{B}\right)^{-10\beta} + \left(\frac{1+z}{C}\right)^{-10\gamma} \right]^{-1/10}$$

$$B = (1+z_1)^{1-\alpha/\beta}$$

$$C = (1+z_1)^{(\beta-\alpha)/\gamma}(1+z_2)^{1-\beta/\gamma}$$

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

Here $\psi(M) \sim M^{-2.35}$ is the initial mass distribution function



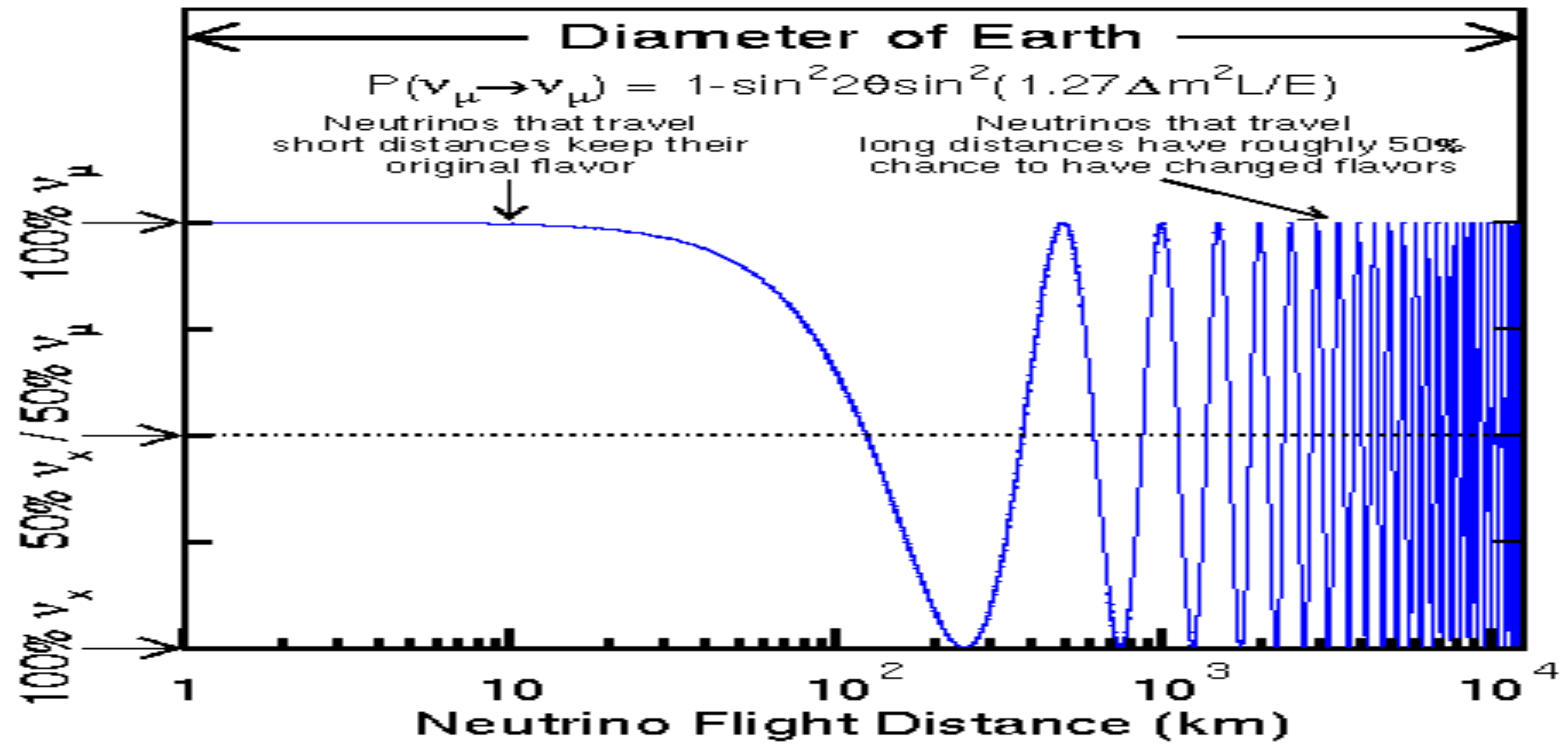
Analytic fits[a]	$\dot{\rho}_0$	α	β	γ	z_1	z_2
Upper	0.0213	3.6	-0.1	-2.5	1	4
Fiducial	0.0178	3.4	-0.3	-3.5	1	4
Lower	0.0142	3.2	-0.5	-4.5	1	4

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

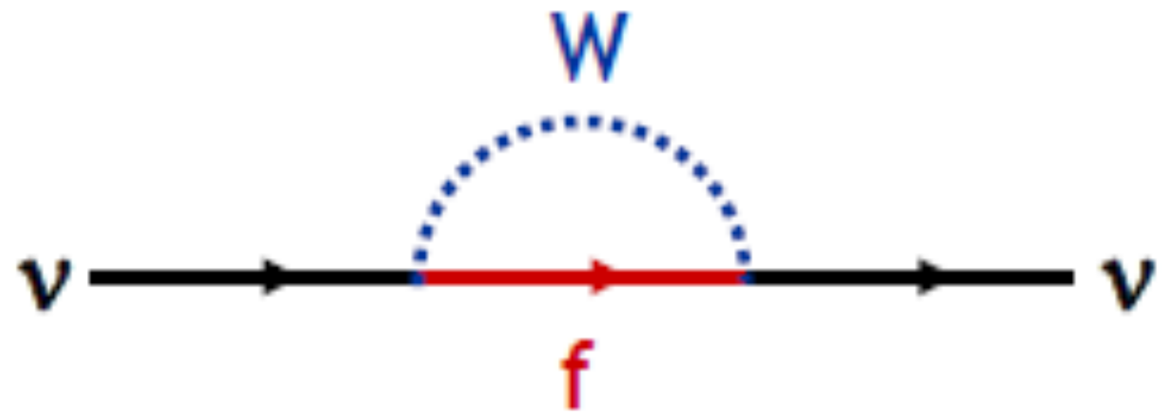
A brief detour into ν oscillations: 2 flavors

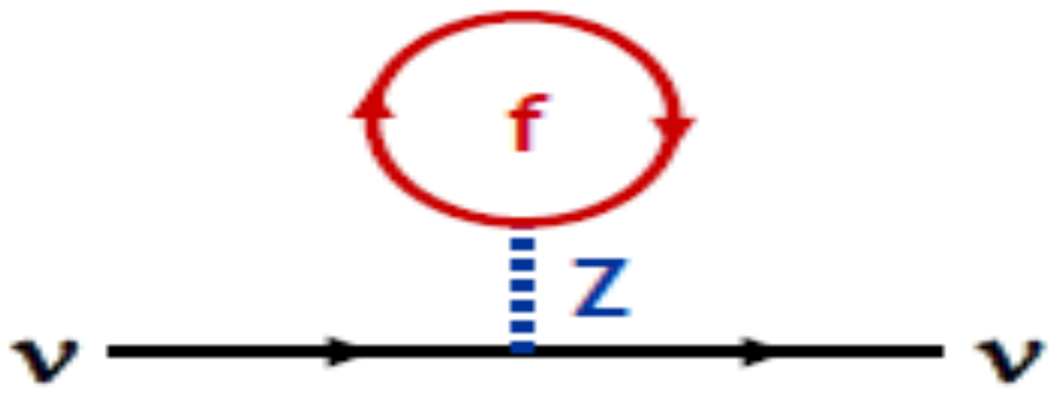
In vacuum

$$i d_t \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \frac{\Delta m^2}{2\mathrm{E}} \begin{pmatrix} \cos 2\theta & \sin 2\theta \\ \sin 2\theta & -\cos 2\theta \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$



While traveling through matter





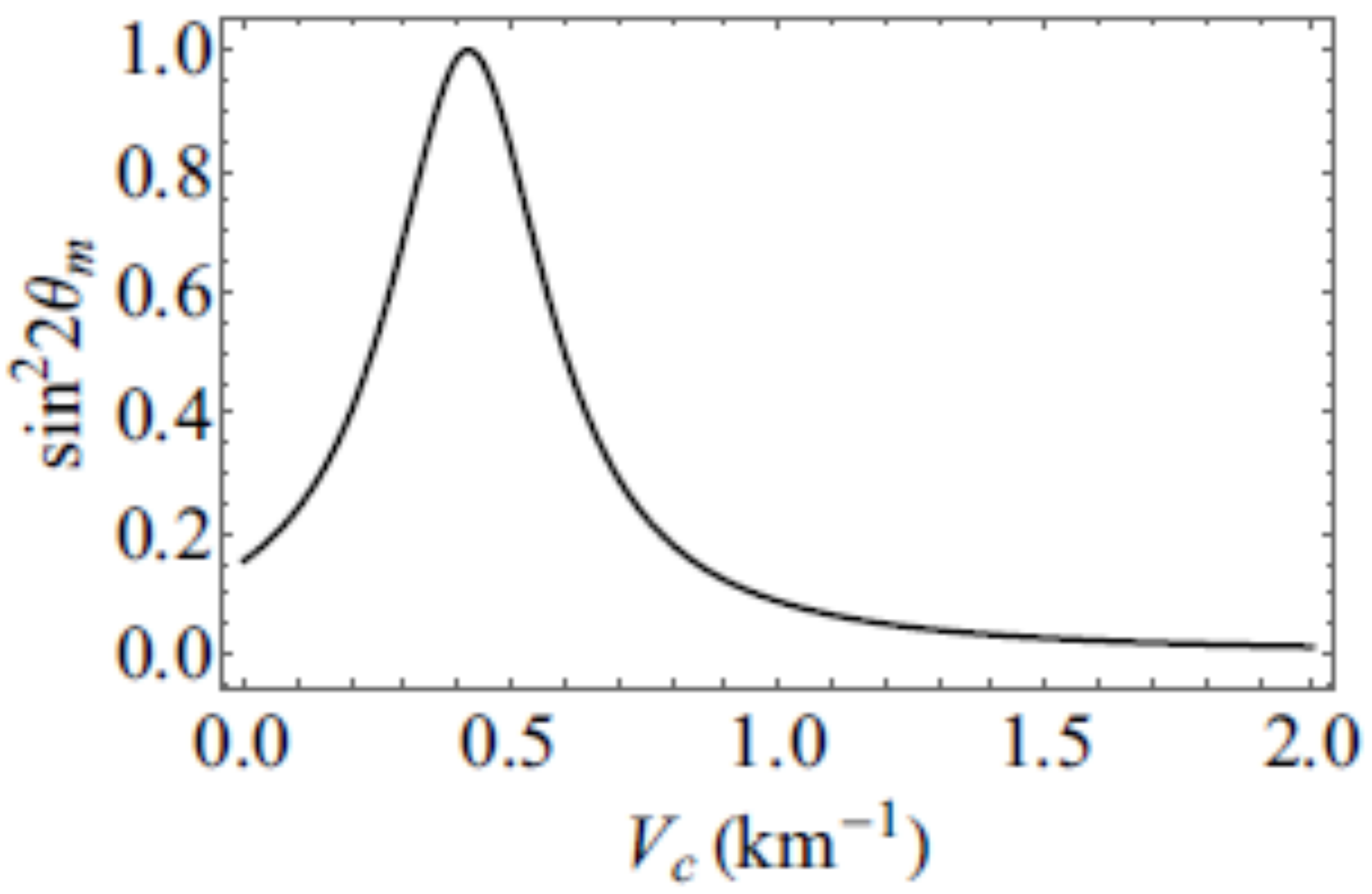
Wolfenstein (PRD 1977)
Mikheyev and Smirnov (Sov.J.Nuc.Phys. 1985)

$$i d_t \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \frac{\Delta m^2}{2\mathrm{E}} \cos 2\theta + \sqrt{2}\, G_F\, (n_e - n_n/2) & \frac{\Delta m^2}{2\mathrm{E}} \sin 2\theta \\ \frac{\Delta m^2}{2\mathrm{E}} \sin 2\theta & -\frac{\Delta m^2}{2\mathrm{E}} \cos 2\theta - \sqrt{2}\, G_F\, n_n/2 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

MSW flavor conversions

- Effective mixing angle in matter:

$$\sin 2\theta_M = \frac{\frac{\Delta m^2}{2E}\sin 2\theta}{\sqrt{\left(\frac{\Delta m^2}{2E}\cos 2\theta - V(r)\right)^2 + \left(\frac{\Delta m^2}{2E}\sin 2\theta\right)^2}}$$



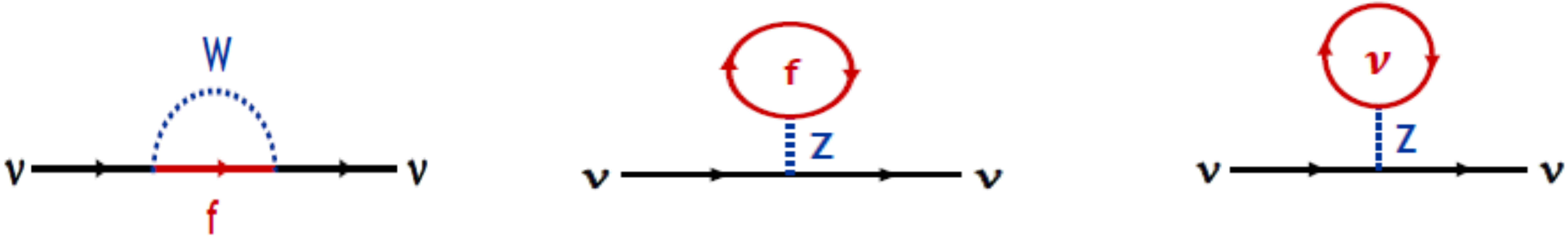
- Enhanced flavor conversions when

$$\frac{\Delta m^2}{2E}\cos 2\theta = V(r)$$

- Rate of oscillations $\propto \omega = \frac{\Delta m^2}{2E}$
- Solution of the solar neutrino problem.

Wolfenstein (PRD 1977)
Mikheyev and Smirnov (Sov.J.Nuc.Phys. 1985)

How is the story different for a SN



• Neutrino density so high that they feel additional potential. Only lab where neutrino self-interactions become important.

• This makes flavor evolution a complicated non-linear problem.

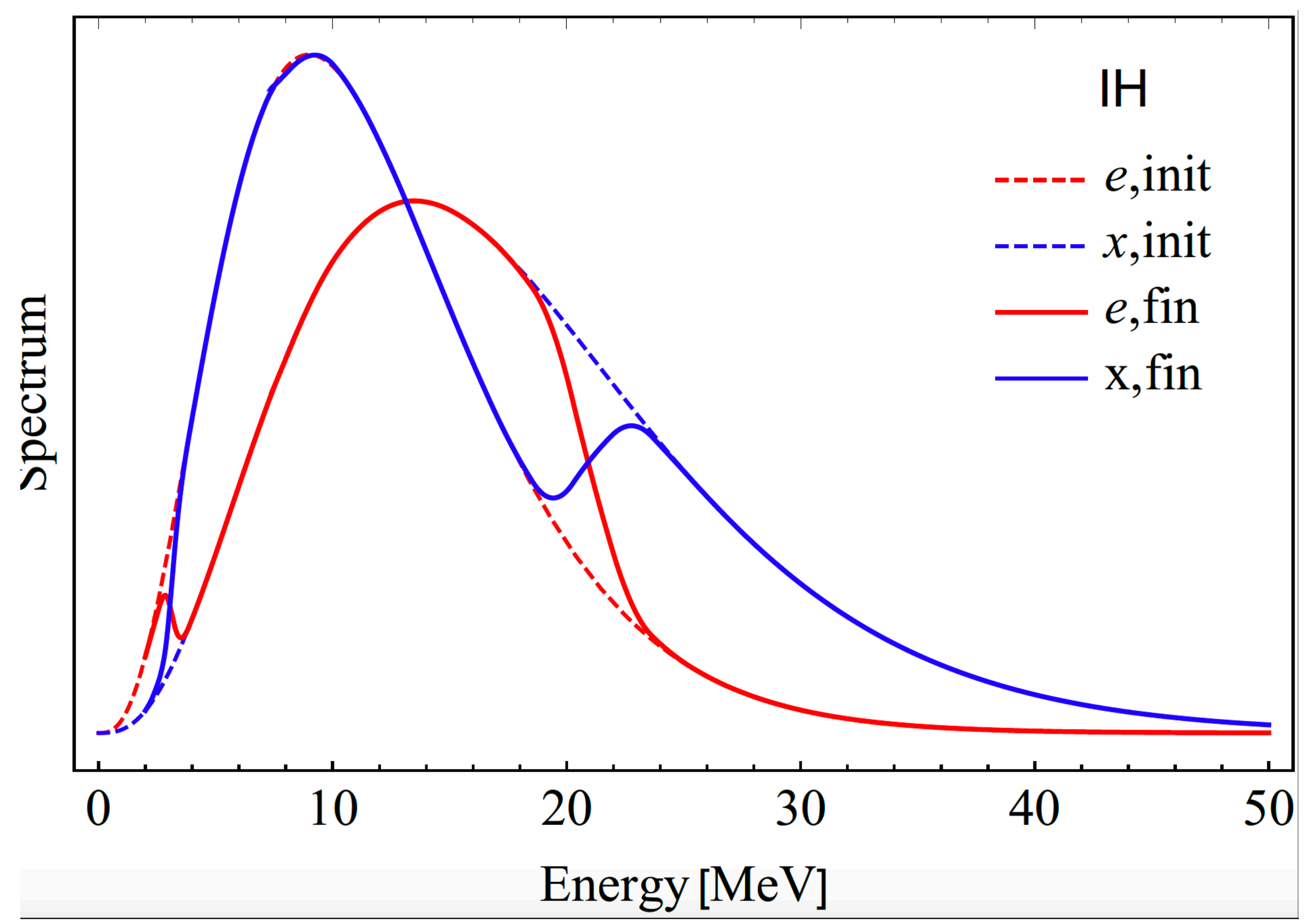
$$H = \frac{M^2}{2E} + \sqrt{2}G_F \begin{pmatrix} N_e - \frac{N_n}{2} & 0 \\ 0 & -\frac{N_n}{2} \end{pmatrix} + \sqrt{2}G_F \begin{pmatrix} N_{\nu_e} & N_{\langle \nu_e | \nu_\mu \rangle} \\ N_{\langle \nu_\mu | \nu_e \rangle} & N_{\nu_\mu} \end{pmatrix}$$

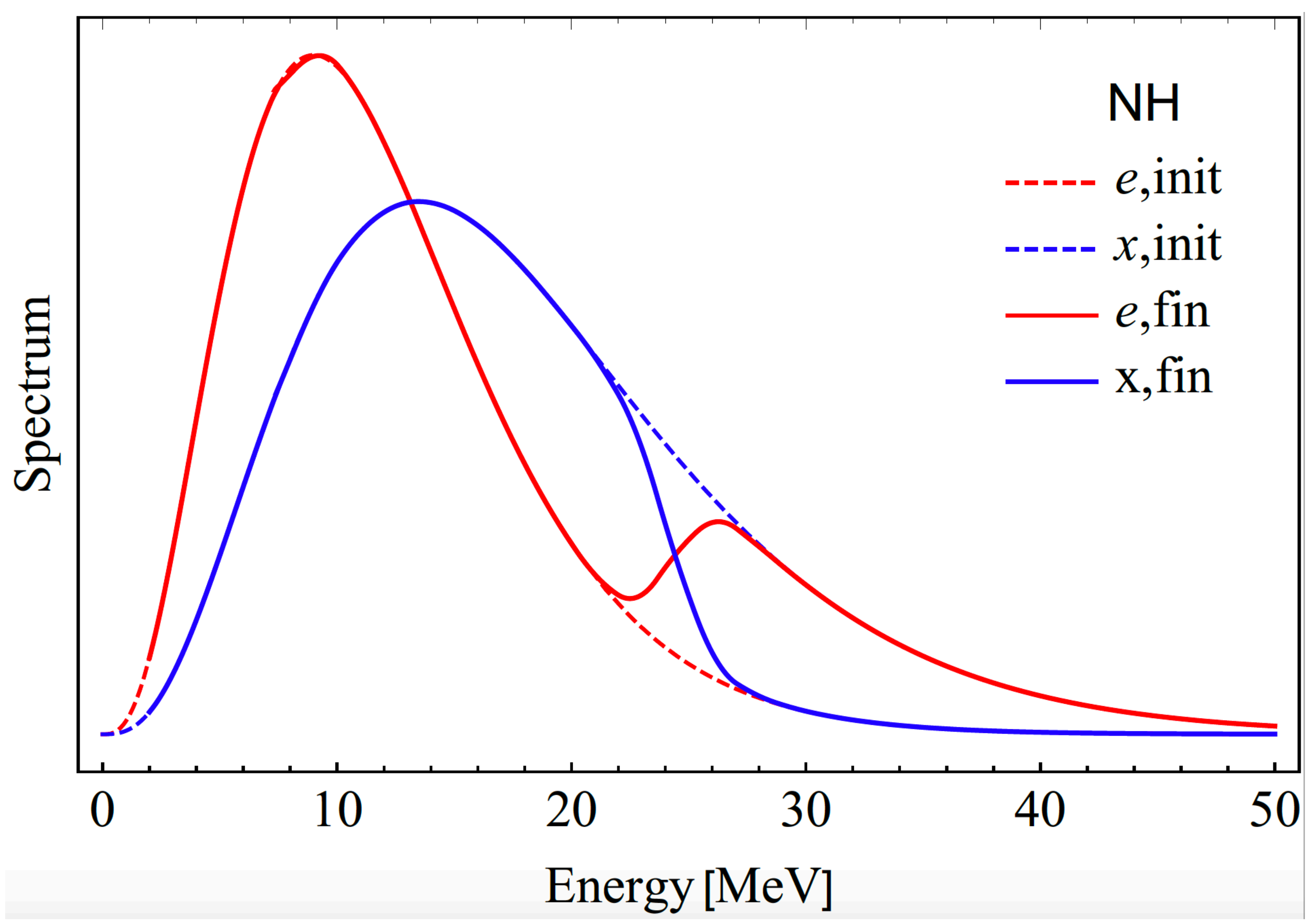
↑ Mass term in flavor basis: causes vacuum oscillations

↑ Wolfenstein's weak potential, causes MSW "resonant" conversion together with vacuum

↑ Flavor-off-diagonal potential, caused by flavor oscillations. (J.Pantaleone, PLB 287:128,1992)

Collective oscillations: Spectral Swaps





- Collective oscillations lead to large 'spectral swaps': smoking gun signal of collective oscillations.

- Impact strongest in the accretion phase, where there is a hierarchy in the flavors.

Duan, Fuller, Carlson and Qian (PRL 2006)
Smirnov and Raffelt (PRD 2007)
Dasgupta, Dighe, Smirnov and Raffelt (PRL 2008)
Friedland (PRL 2010)

Ingredient 3: Neutrino spectra

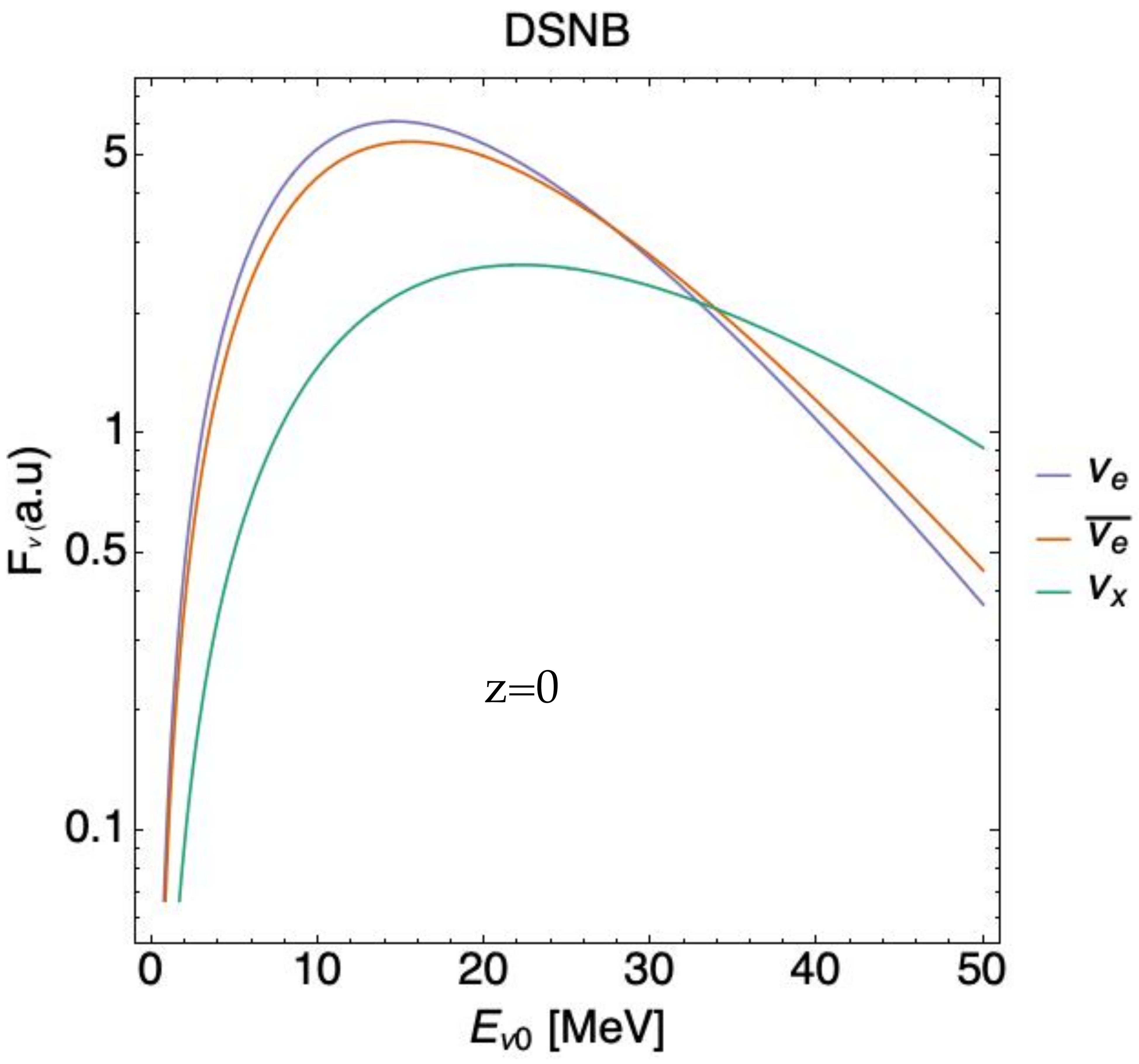
- Assume an approximately thermal spectra, characteristic of late-time phase.

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

- Could be processed by collective neutrino oscillations, however effect is not very large. Hence ignore.

- Only assume adiabatic MSW transition, so
  heaviest neutrino $\leftrightarrow \nu_e$
  lightest neutrinos $\leftrightarrow \nu_x$

- Temperature hierarchy $T_{\nu_e} < T_{\bar{\nu}_e} < T_{\nu_x}$



$$\Phi_\nu(E) = \int_0^{z_{\max}} \frac{dz}{H(z)}\, R_{\mathrm{CCSN}}(z)\, F_\nu\big(E(1+z)\big)$$

Putting all ingredients together

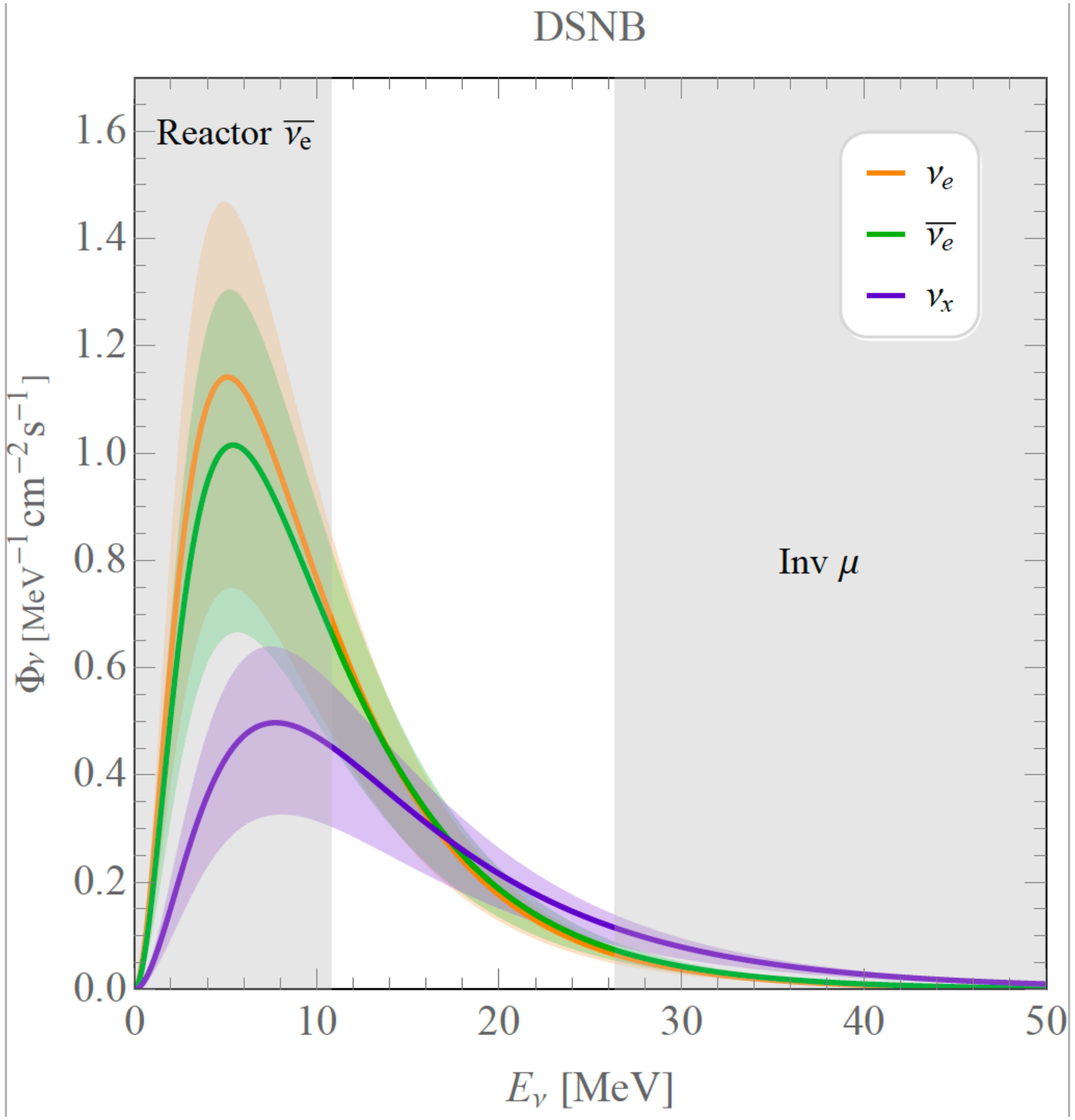
- The DSNB window ~10-26 MeV.

- Uncertainty due to SFR.

- Main backgrounds to keep in mind:

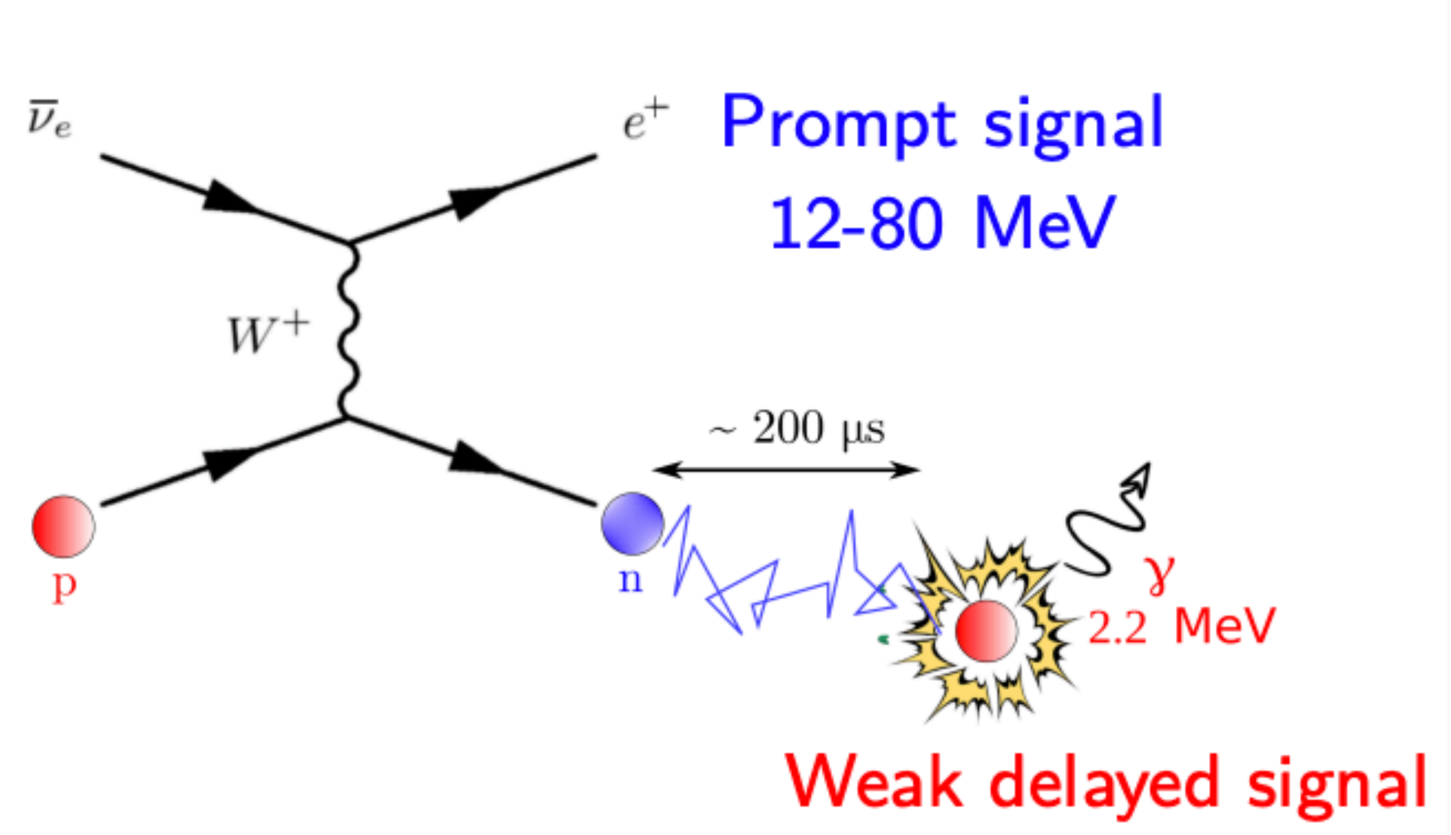
  Solar ν_e: extends upto ~20 MeV (can be reduced by directional information).
  Geo $\bar{\nu}_e$: Mostly dominates low energy ~ 4 MeV background.

  Reactor $\bar{\nu}_e$: extends upto ~10 MeV. Ineliminable.
  Atmospheric ν: Low energy tails of ν_e and $\bar{\nu}_e$. Exceeds the DSNB at E~30 MeV. Ineliminable.



Detecting the DSNB + backgrounds: Super-K

- Event rate $N_i = N_{\rm tar}(\Delta\, t) \int_{\rm bin\, i} dE^{\rm rec} \int_{\rm all} dE^{\rm true}\, \Phi_\nu\, \sigma_\nu\, \epsilon(E^{\rm true}, E^{\rm rec})$

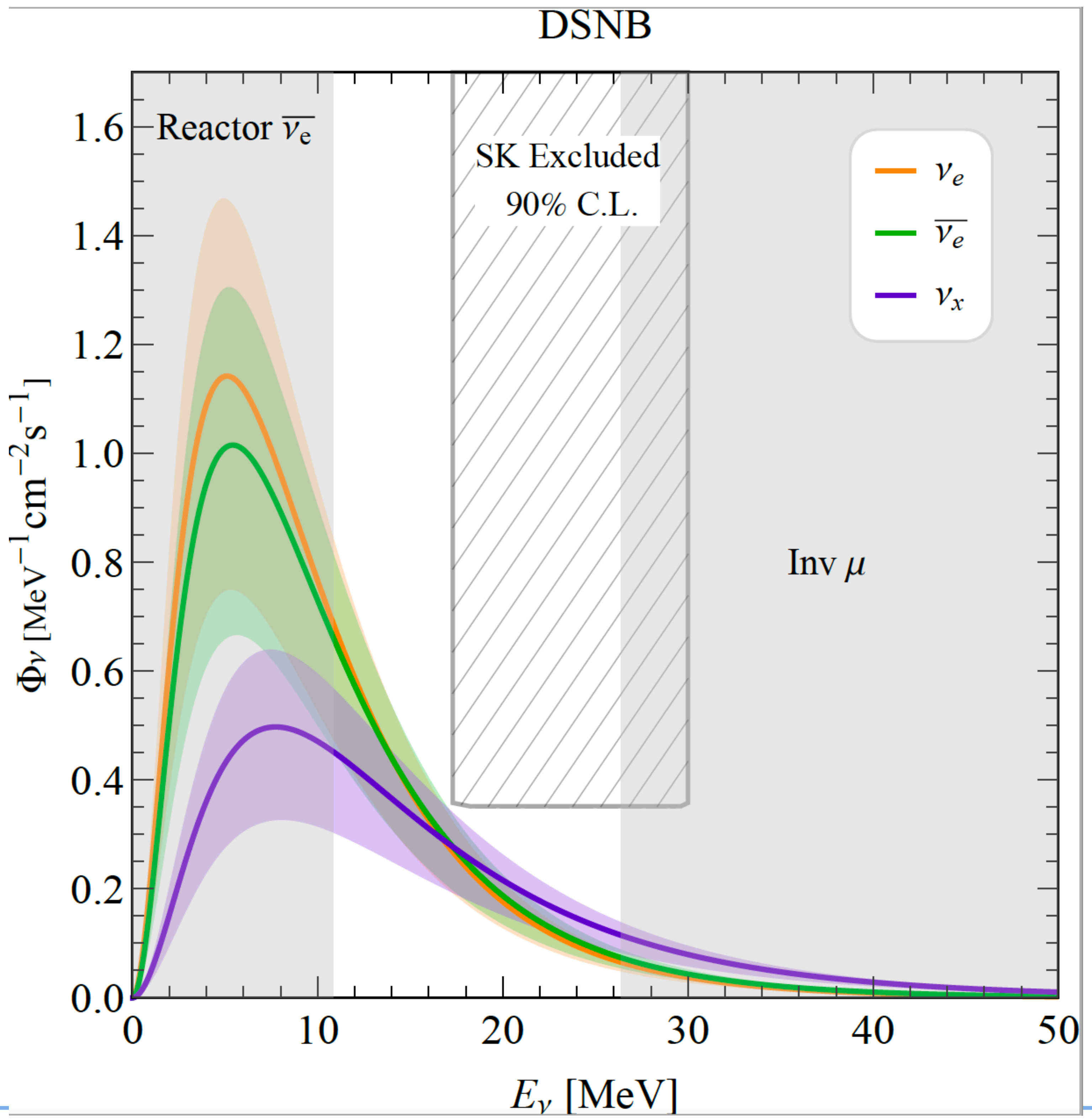


- Main channel is IBD: $\bar{\nu}_e + p \rightarrow e^+ + n$

- Spallation backgrounds: radioactivity induced by cosmic muon spallation in water: $\mu + O \rightarrow \mu + X$. Substantial background ~ 20 MeV.

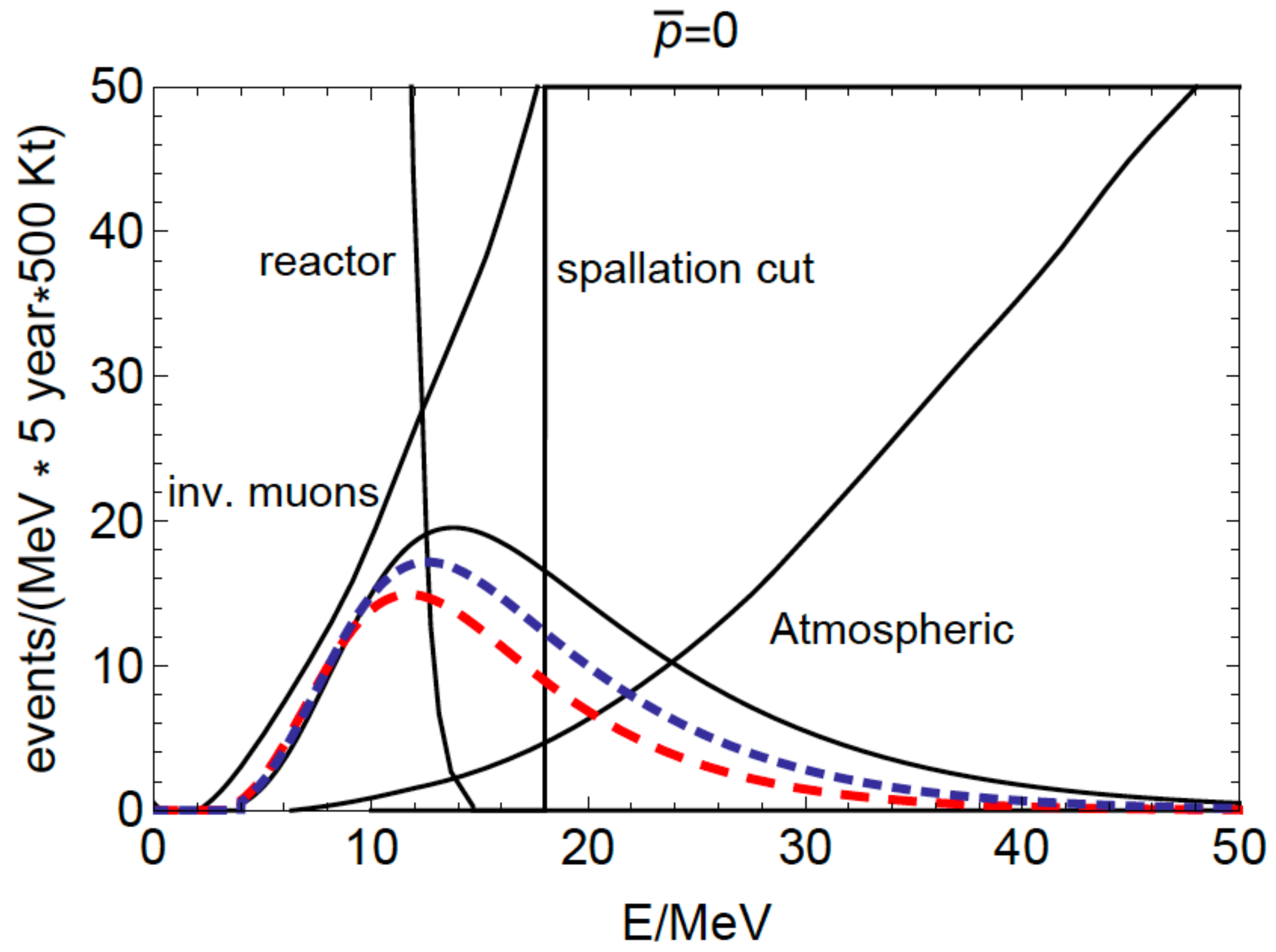
- Invisible muons: $\nu_\mu + N \rightarrow \mu + N'$. If muon energy is below Cherenkov threshold, it can only be detected through decay.

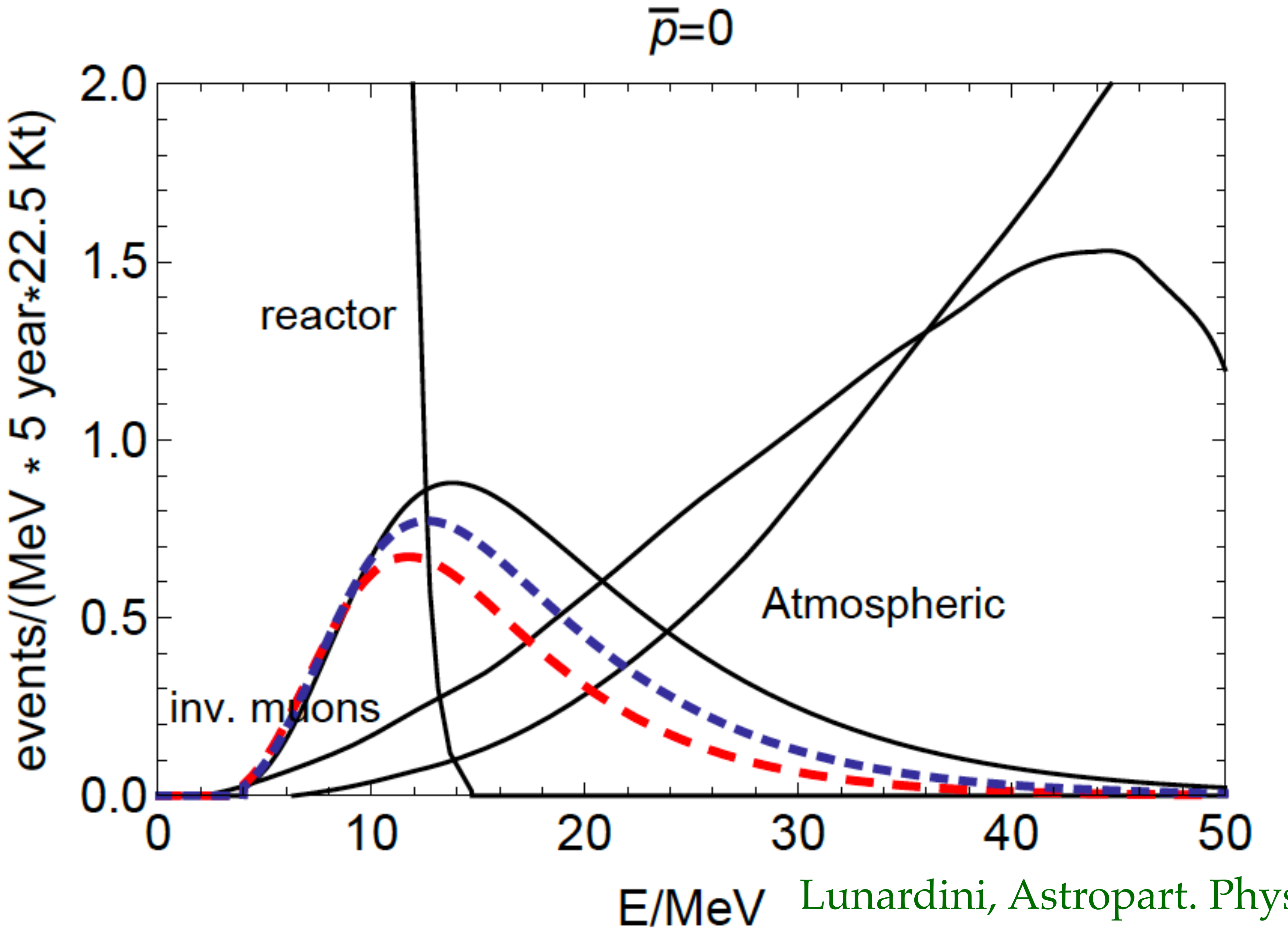
- Low energy atmospheric neutrinos. Isotropic background.



Gd doping: GADZOOKS!

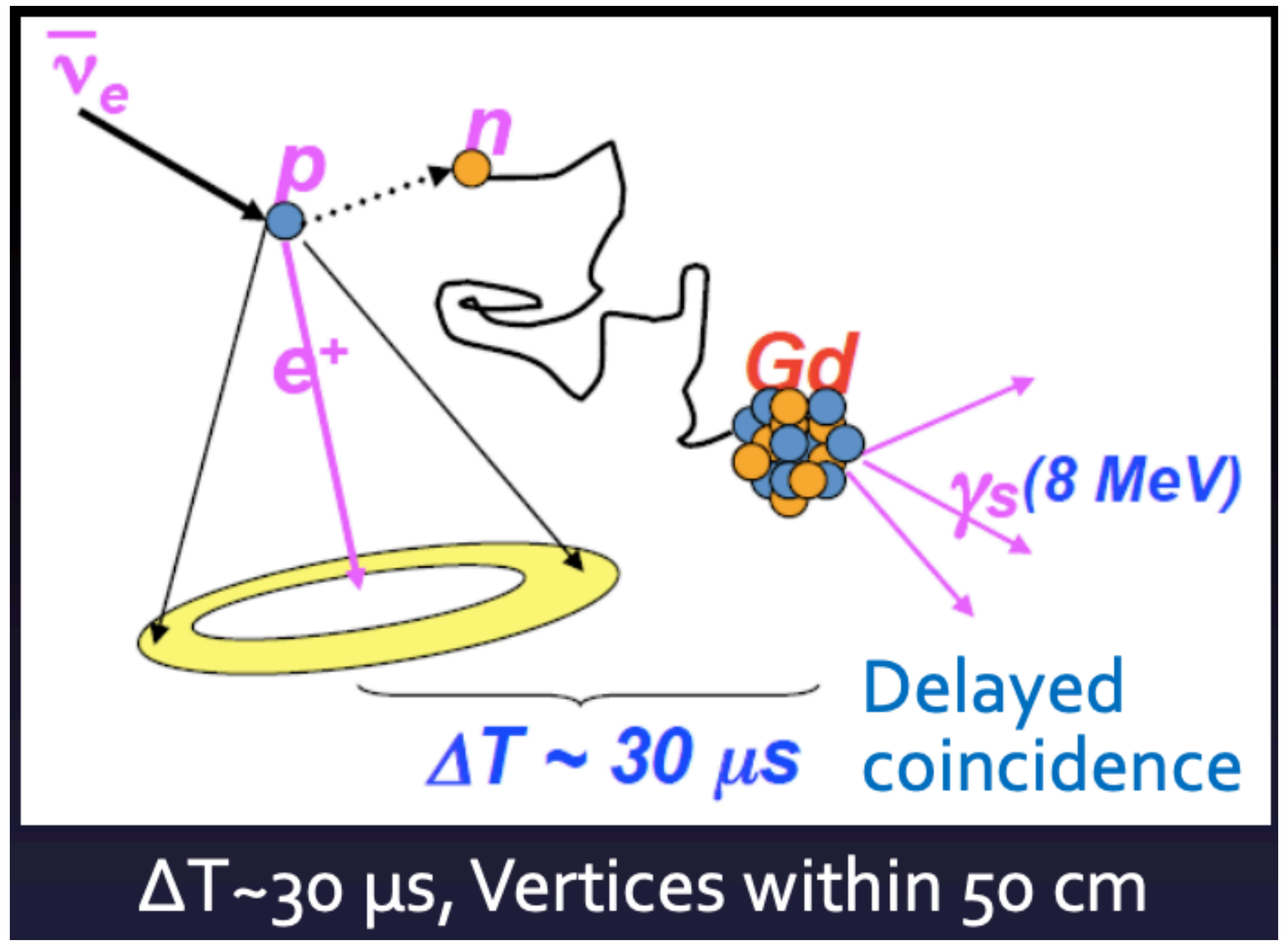
Beacom, Vagins, PRL2004



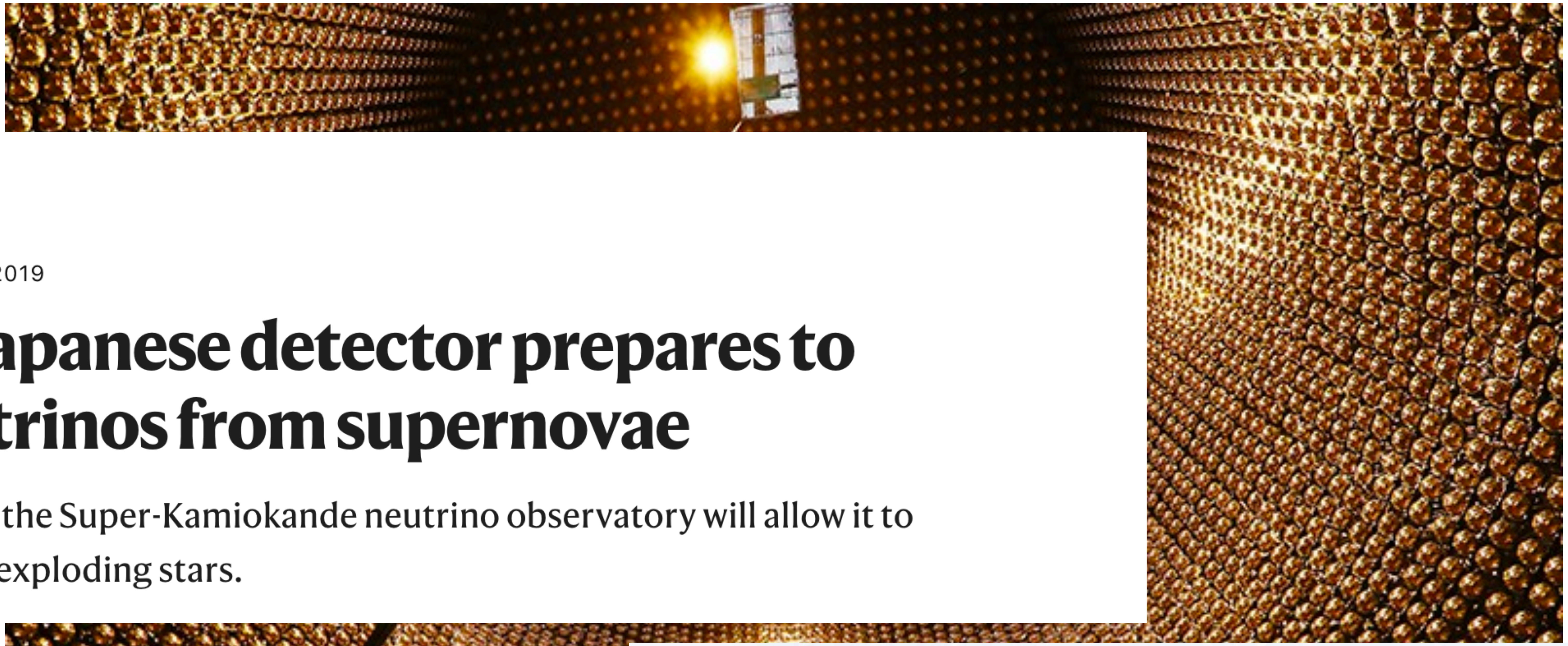


Lunardini, Astropart. Phys2016

- Solution: Gd doping.
- Reduces energy threshold.
- Background due to spallation will be subtracted almost completely and the one due to invisible muons will be reduced by a factor of 5.



The Diffuse Supernova Neutrino Background

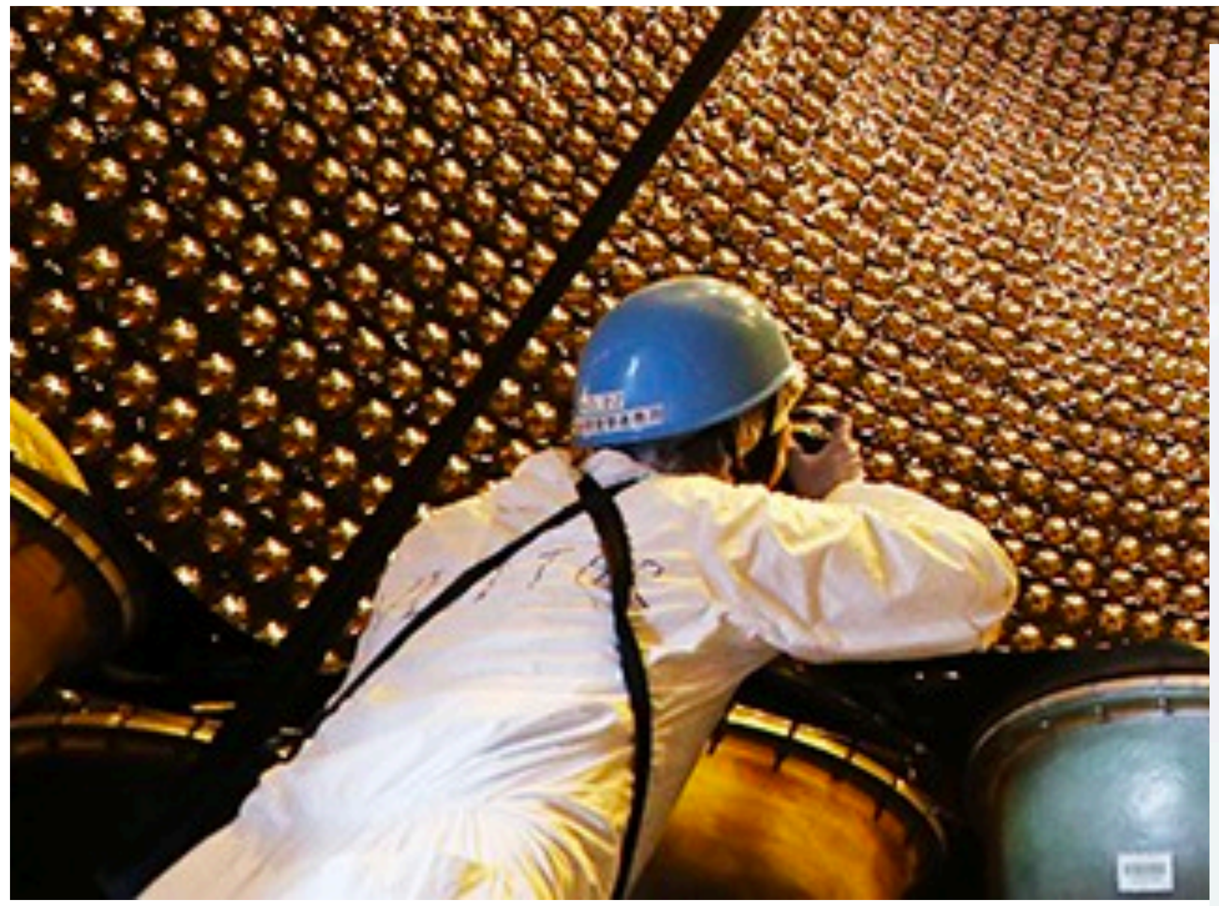


nature > news > article

NEWS · 27 FEBRUARY 2019

Gigantic Japanese detector prepares to catch neutrinos from supernovae

Recent upgrades to the Super-Kamiokande neutrino observatory will allow it to trace the history of exploding stars.



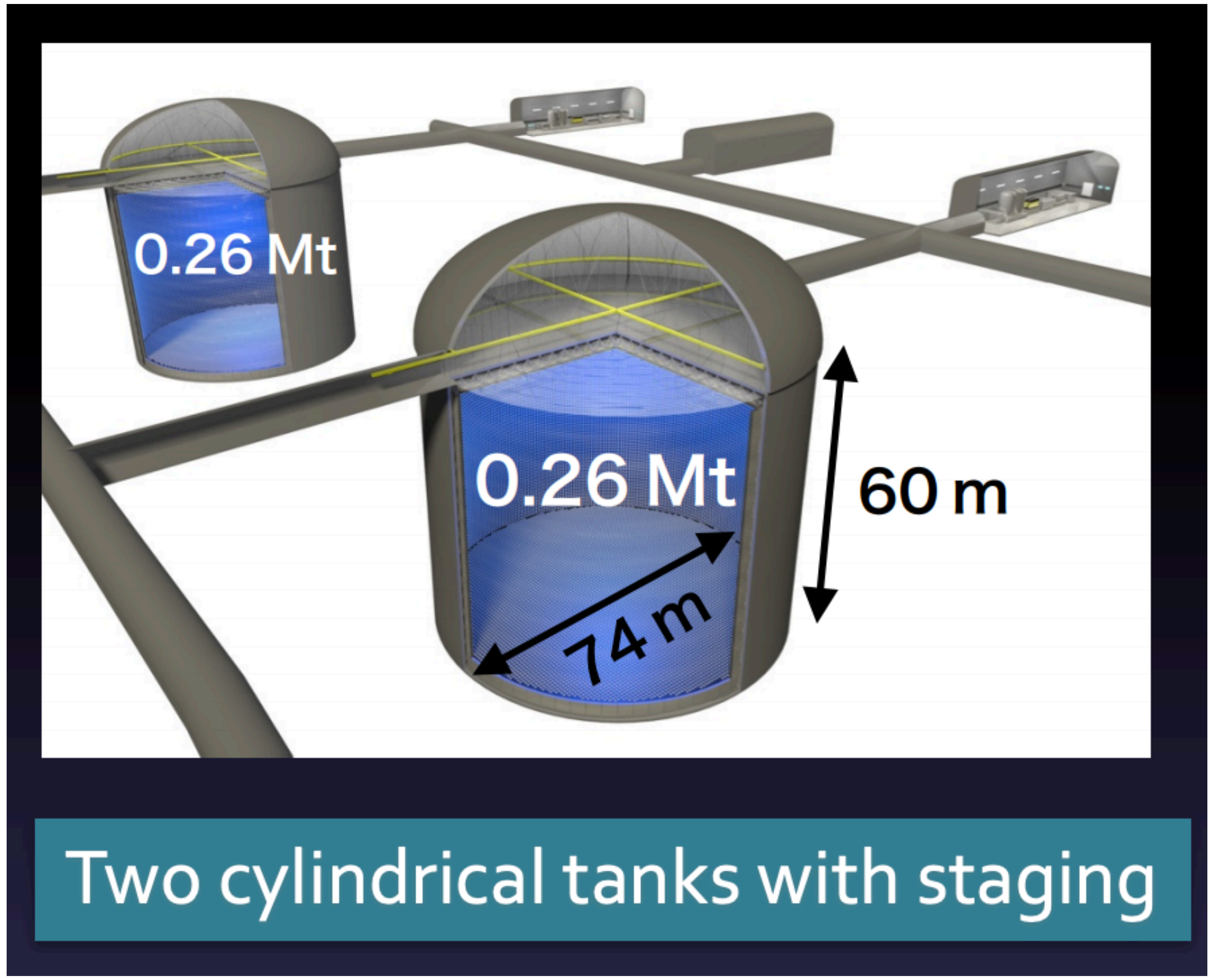
Introduction of Gadolinium into Super-Kamiokande and the Start of New Observations

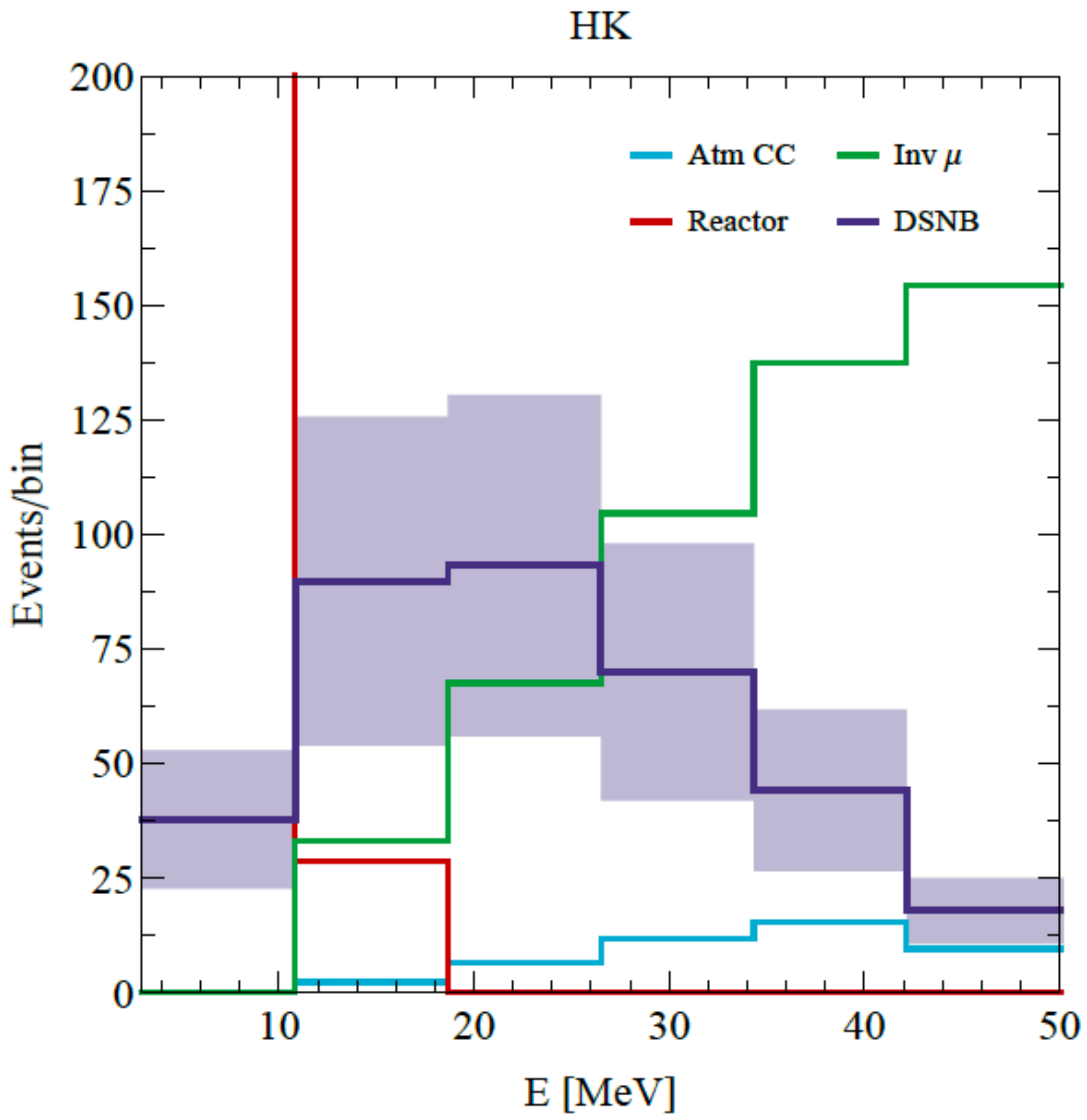
August 21, 2020
Super-Kamiokande Collaboration

The rare earth element gadolinium has recently been introduced into the Super-Kamiokande (SK) detector, starting a new period of observations. The addition of gadolinium improves SK's ability to observe the sea of neutrinos, known as "supernova relic neutrinos", produced by supernova explosions that have occurred since the beginning of the universe. In addition, gadolinium will improve SK's ability to observe the burst of neutrinos from any supernovae occurring in our galaxy and will improve its other research topics, such as the discrimination of atmospheric neutrinos from antineutrinos and the observation of manmade neutrinos. This release explains the details of the recent gadolinium loading in SK.

What about the future?

Future Detection: Hyper-Kamiokande + Gd

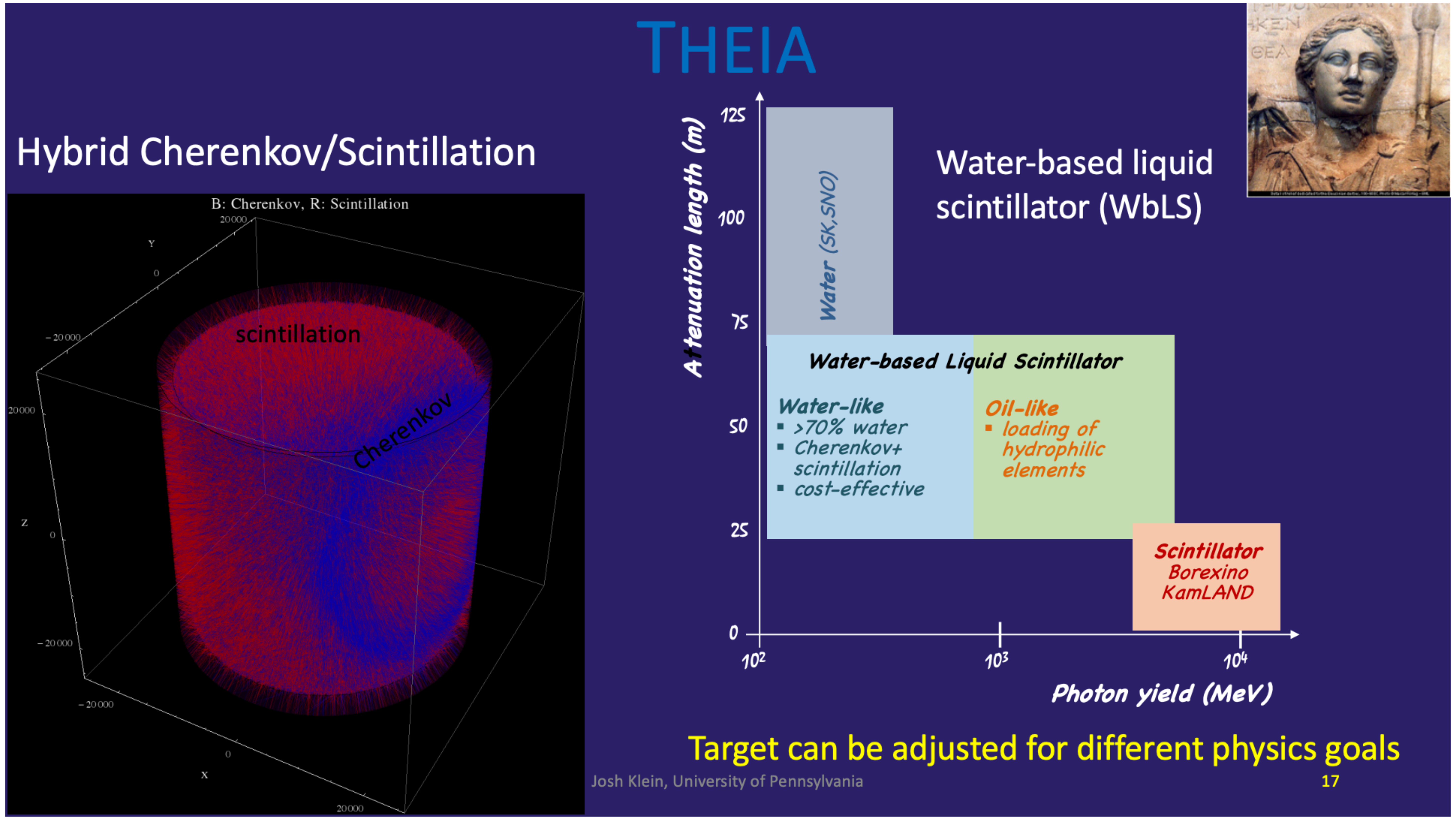


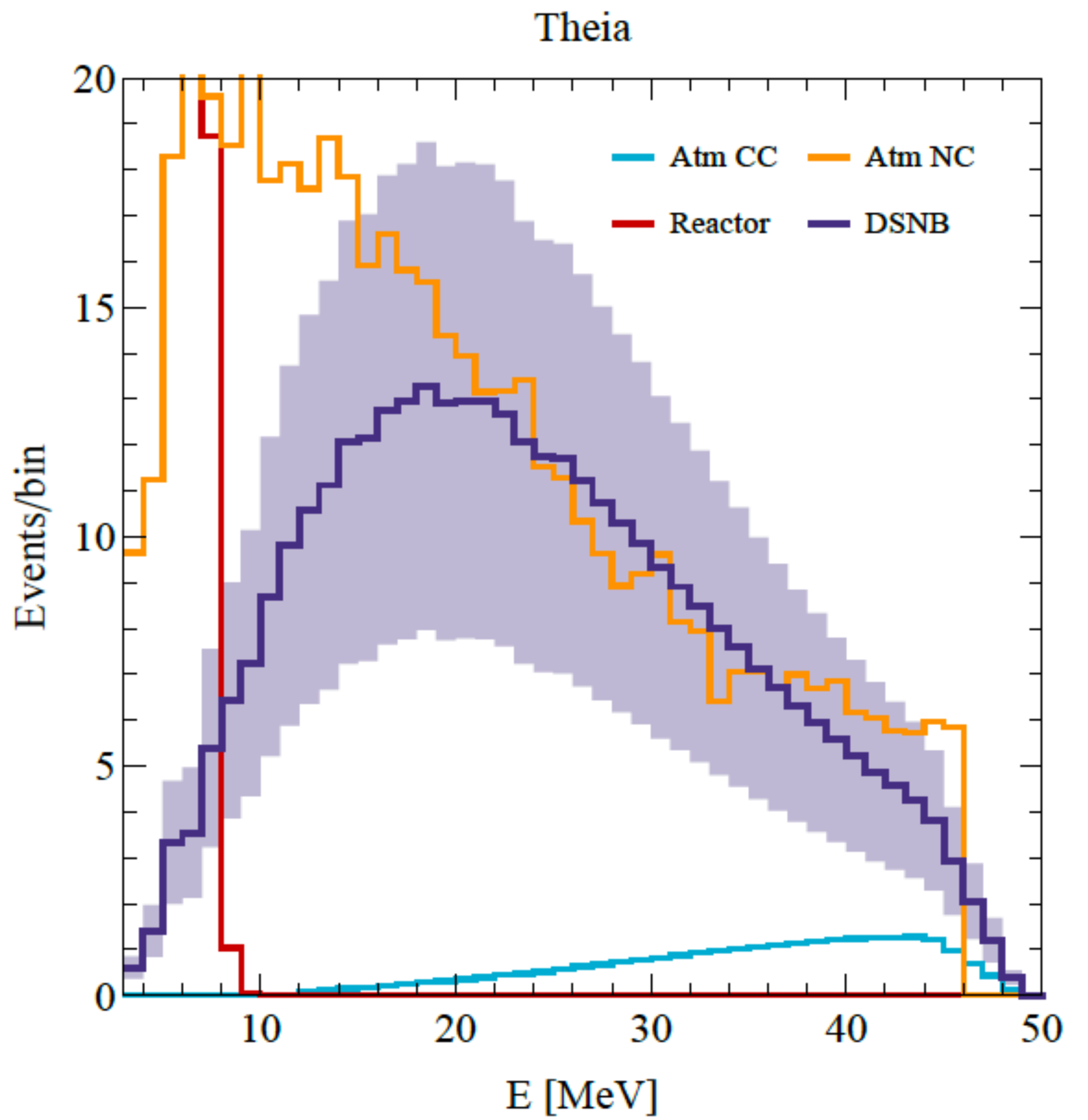


- HK enriched with Gd provides excellent detection prospects.
- Results with 1 tank with 10 years of data taking.
- Backgrounds same as SK.

de Gouvea, Martinez-Soler, Perez-Gonzalez, MS, PRD 2020

Future Detection: Theia





de Gouvea, Martinez-Soler, Perez-Gonzalez, MS, PRD 2020

- 100 kT detector, with 10 years of data-taking
- Low energy resolution of scintillator, and high-energy reconstruction techniques for Cherenkov detector.
- Major background: NC interactions of ν on C nuclei. Prompt signal in recoil + delayed signal due to absorption of emitted neutron. Can be reduced using Cherenkov/Scintillation ratio.

Fundamental Physics Probes

Multidisciplinary aspects of understanding the supernova neutrinos:

- Particle physics aspects: Neutrino physics in dense media, neutrino properties, anomalous cooling mechanism due to new physics,…
- Astrophysics: Star formation rates, including life and birth cycles, constraints on new sources, neutron star equation of state, nucleosynthesis,…
- Cosmology: SN distance indicators, fundamental cosmology parameters, dark matter physics,…
- Multi-messenger aspect: adds to information from photons and gravity waves.

All these channels can open up with a future detection of the DSNB.

Neutrino Decay

$$\Phi_\nu(E) = \int_0^{z_{\max}} \frac{dz}{H(z)} R_{\mathrm{CCSN}}(z)\, F_\nu\big(E(1+z)\big)$$

Changes spectra

Neutrino Properties: Decay

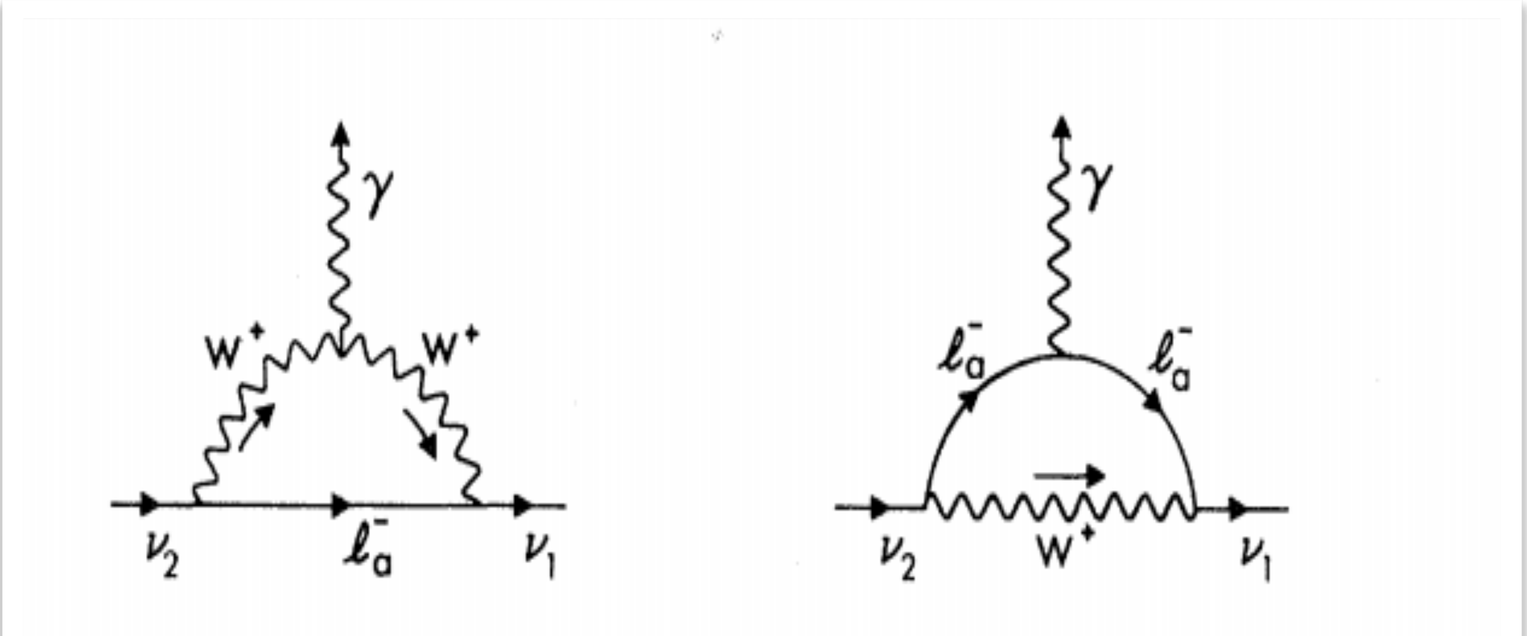
- Massive neutrinos can decay to lighter ones even within the SM. Age longer than universe.

- New physics can mediate faster decay.

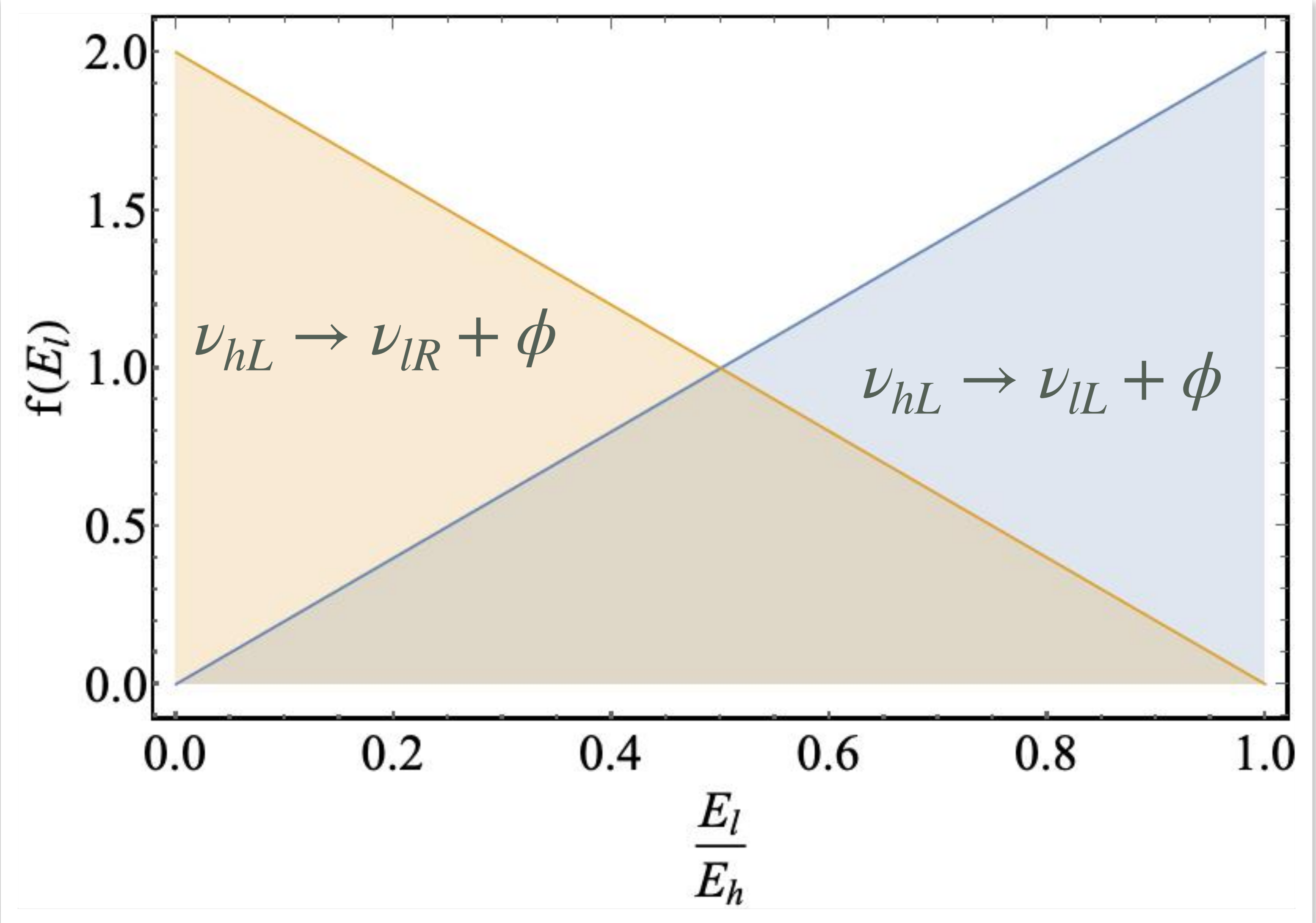
$$\mathscr{L} \supset \bar{\nu}_l \nu_h \, \varphi + \mathrm{H.c.}$$

$\nu_{hL} \rightarrow \nu_{lL} + \varphi$ …. Helicity cons. (h.c.)
$\nu_{hL} \rightarrow \nu_{lR} + \varphi$ …. Helicity flip. (h.f.)

- In ν_h rest frame, the daughter that shares the same helicity as the parent is emitted preferrentially along the parent helicity direction.



Pal and Wolfenstein (PRD1982)

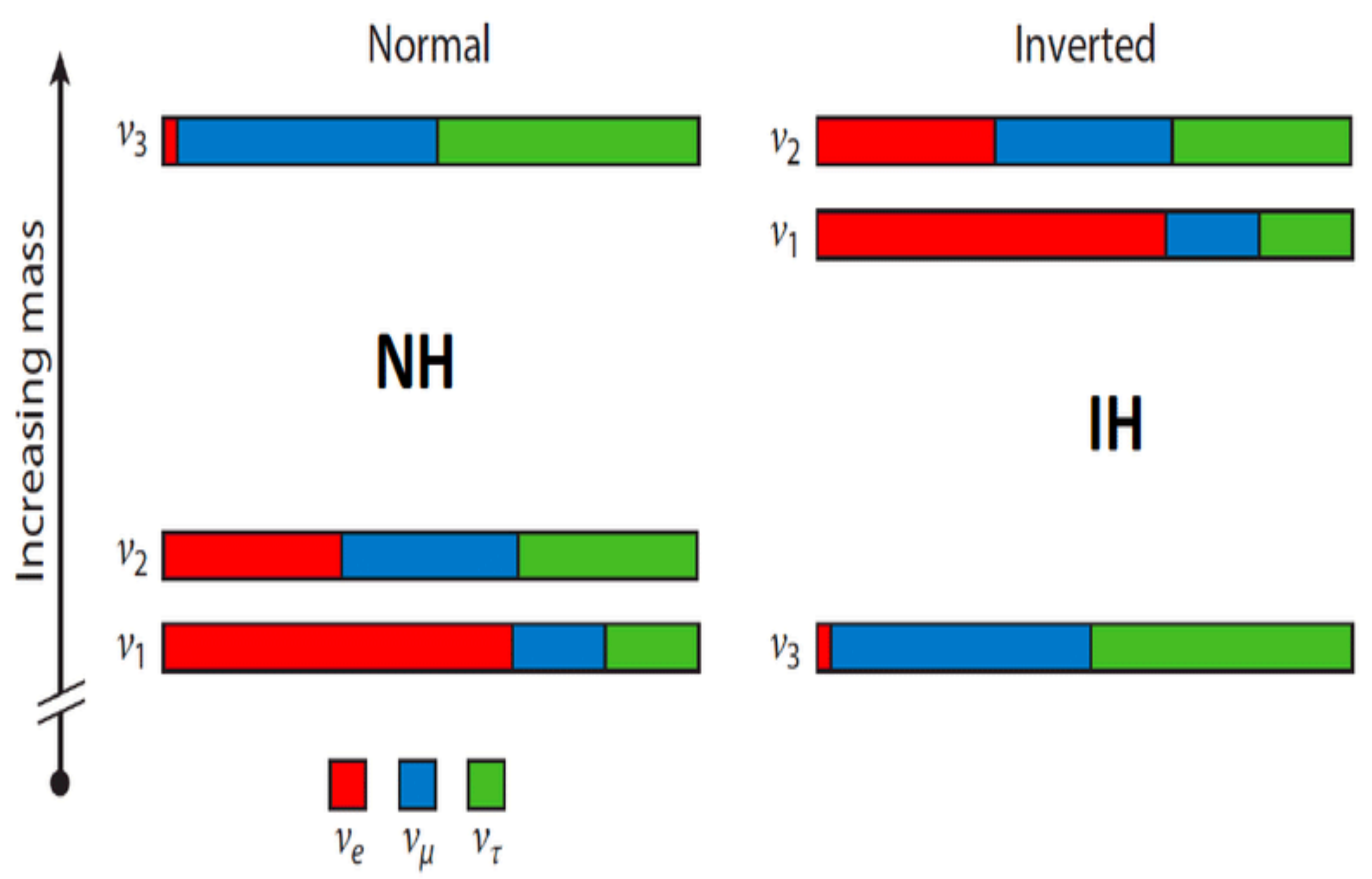


de Gouvea, Martinez-Soler, MS, PRD2020

How does neutrino decay work?

Normal Ordering

$\nu_3 \to \nu_1 \varphi$



NO DECAY

$\nu_h \equiv \nu_3$

$\nu_e \sim |U_{e3}|^2 \sim 0.02\, \nu_3$

Enhancement in spectra

DECAY

$\nu_l \equiv \nu_1$

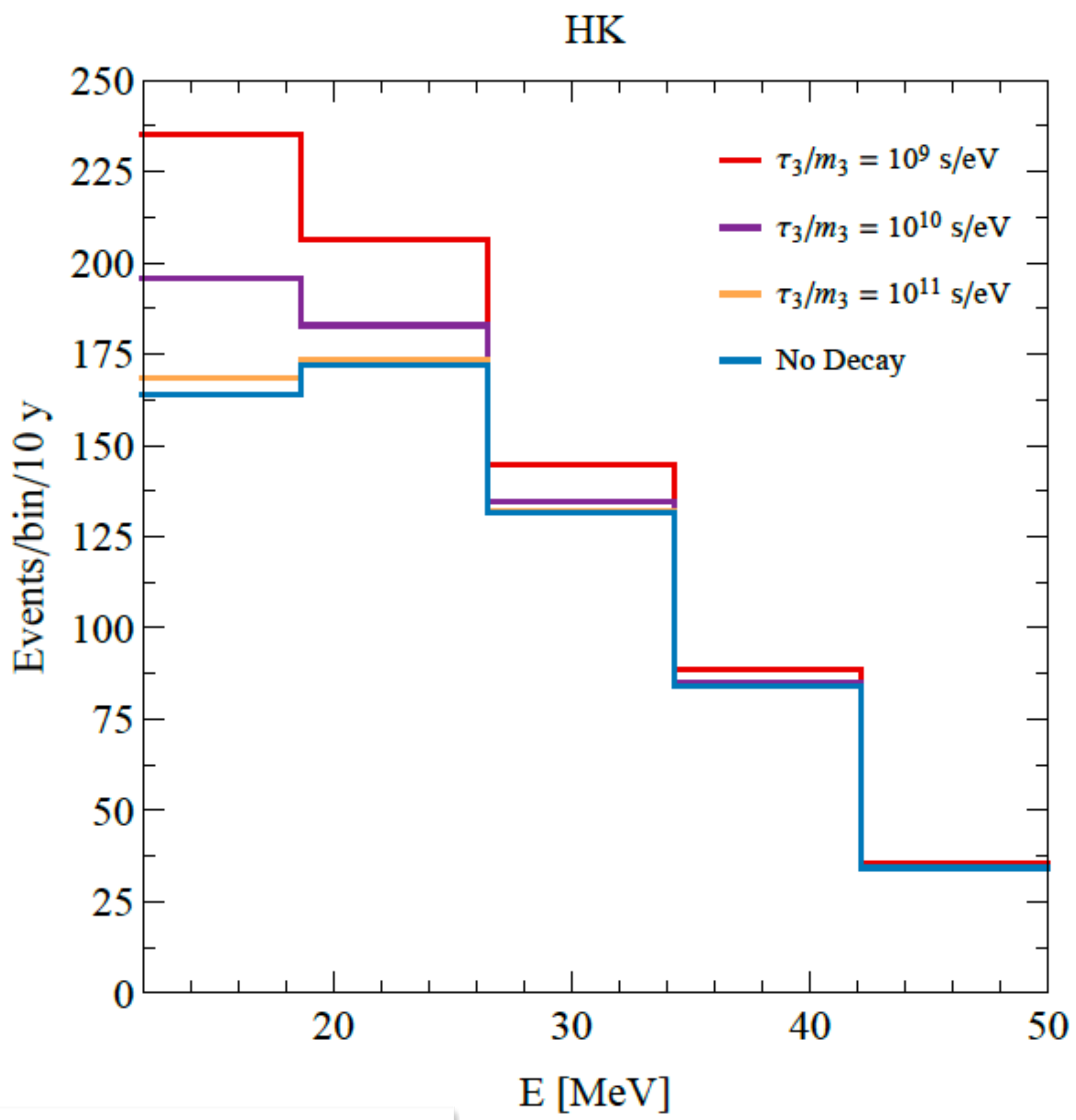
$\nu_h \equiv \nu_3$

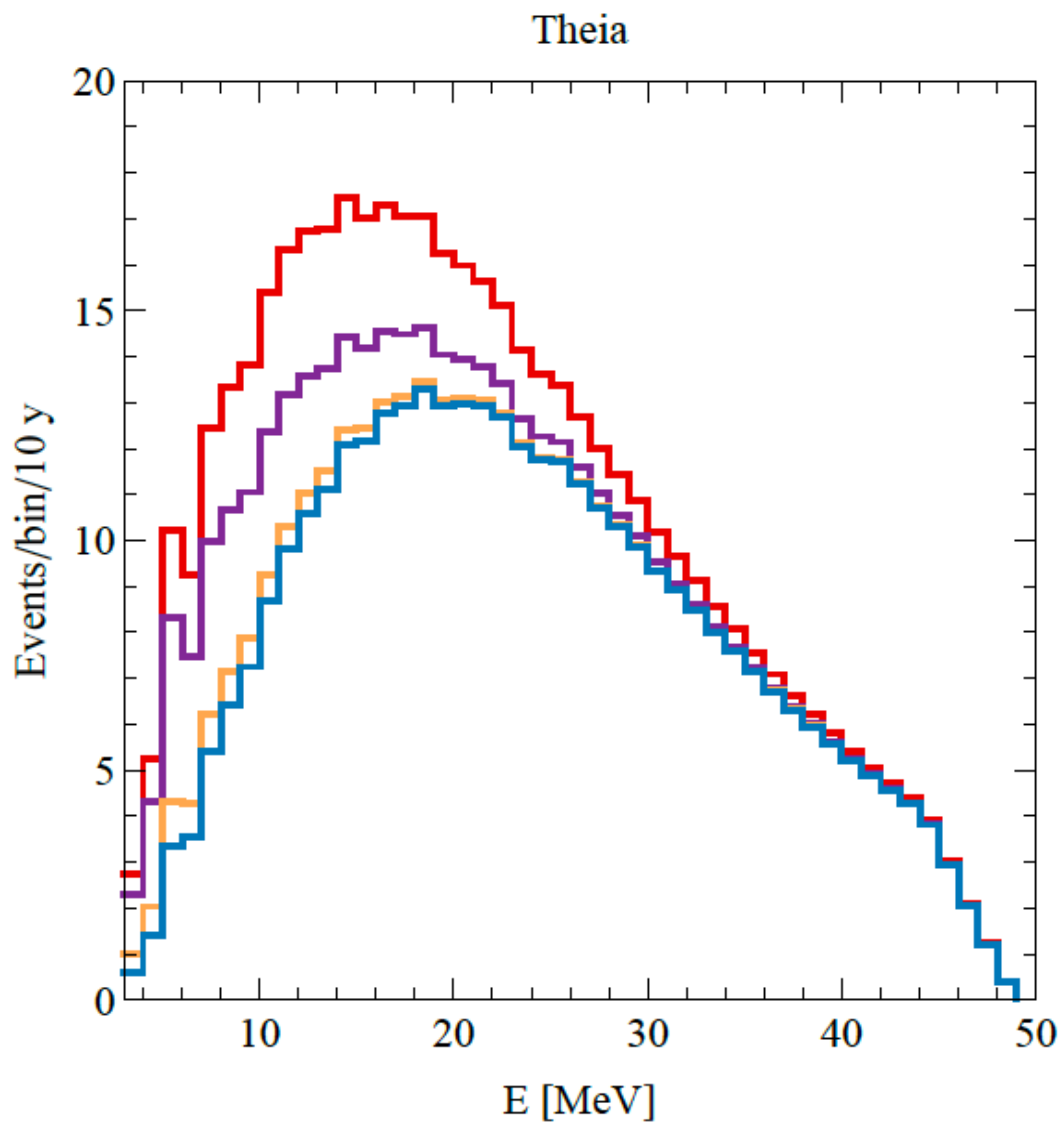
$\nu_e \sim |U_{e1}|^2 \sim 0.7\, \nu_e^{\text{in}}$

Simulated data at HK & Theia

- Consider Majorana neutrinos for maximum impact.
  Two channels:
  1. $\nu_{3L} \to \nu_{1L} + \varphi$
  2. $\nu_{3L} \to \nu_{1R}\,(\bar{\nu}_{1R}) + \varphi$

- ν_{1R} acts as anti-neutrinos, and detected as well.





$$\Phi_{\nu_3}(E) = \int_0^{z_{\max}} \frac{dz'}{H(z')} R_{\rm CCSN}(z')\, F_{\nu_3}\left(E(1+z')\right) e^{-\Gamma(E)\zeta(z')}$$

$$\Phi_{\nu_2}(E) = \int_0^{z_{\max}} \frac{dz'}{H(z')} R_{\rm CCSN}(z')\, F_{\nu_2}\left(E(1+z')\right)$$

$$\Phi_{\nu_1}(E) = \int_0^{z_{\max}} \frac{dz'}{H(z')} \Big\{ R_{\rm CCSN}(z')\, F_{\nu_1}\left(E(1+z')\right) + \int_E^{\infty} dE' \left[\Phi_{\nu_3}(E')\,\Gamma(E')\,\psi_{\rm h.c.}(E',E) + \Phi_{\bar{\nu}_3}(E')\,\Gamma(E')\,\psi_{\rm h.f.}(E',E)\right] \Big\}$$

de Gouvea, Martinez-Soler, Perez-Gonzalez, MS, PRD 2020

Constraints on neutrino lifetime

- HK and Theia can put some of the strongest constraints on neutrino lifetime. At 2-σ, $\tau_3/m_3 \sim 10^9$ s/eV .

- Solar bounds: $\tau_2/m_2 > 10^{-3}$ s/eV.
  $\tau_3/m_3 > 10^{-5}$ s/eV.

  Berryman, de Gouvea, Hernandez, PRD2015
  Funcke, Vitagliano, Raffelt PRD2020 + …

- Long baseline: $\tau_3/m_3 > 10^{-10}$ s/eV.

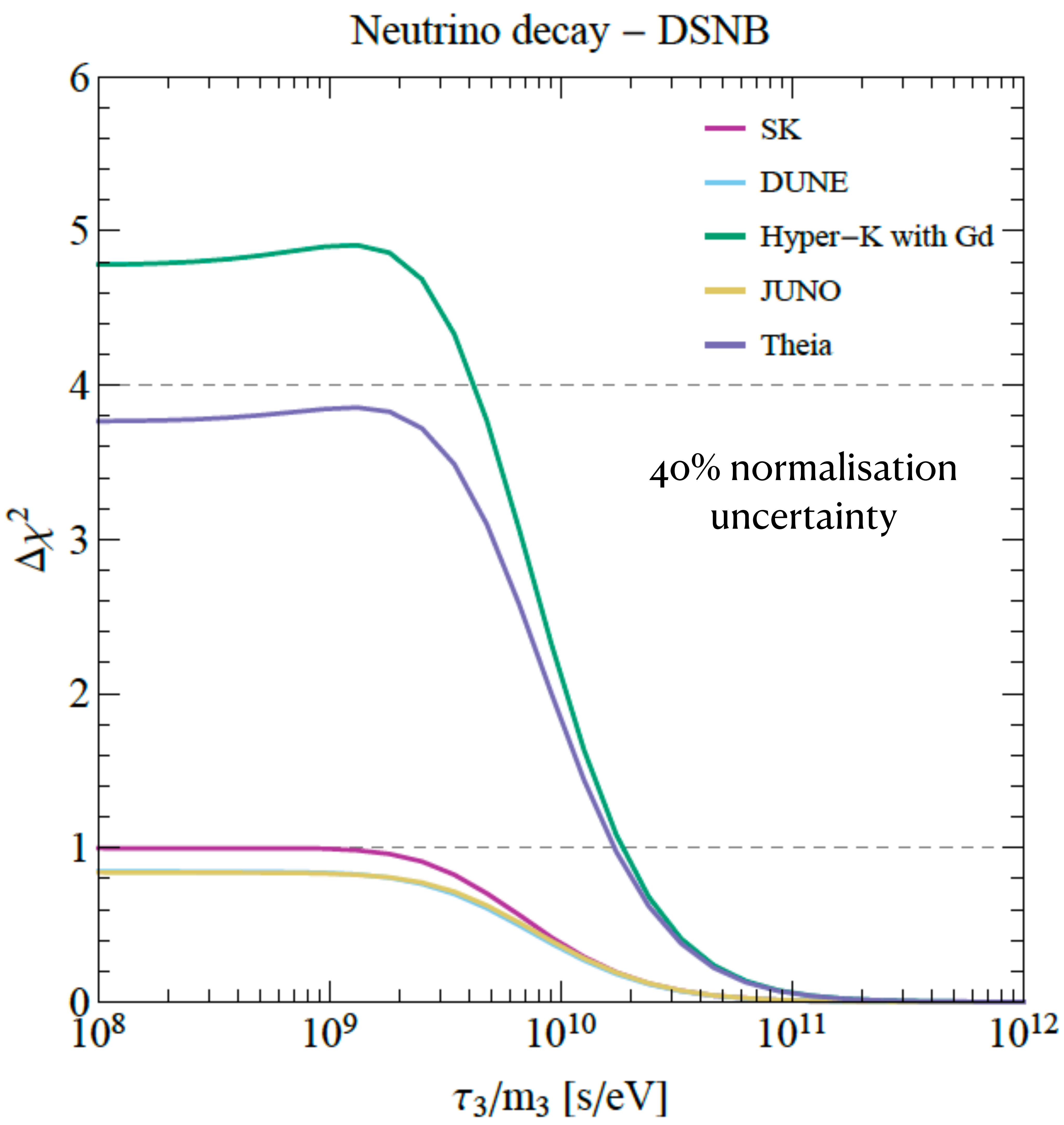
  Gonzalez-Garcia, Maltoni, PLB2008 + …

- IceCube: $\tau_3/m_3 \sim 10^2$ s/eV

  Denton, Tamborra PRL2018

- CMB: $\tau/m \sim 10^9$ s/eV

  Escudero, Fairbairn PRD2019



de Gouvea, Martinez-Soler, Perez-Gonzalez, MS, PRD 2020

Pseudo-Dirac Neutrinos

$$\Phi_\nu(E) = \int_0^{z_{\max}} \frac{dz}{H(z)} R_{\mathrm{CCSN}}(z)\, F_\nu\big(E(1+z)\big)$$

Undergoes oscillations

Pseudo Dirac Neutrinos

- Neutrinos have sub-dominant Majorana mass terms.

  Generic Majorana mass matrix $\begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}$.

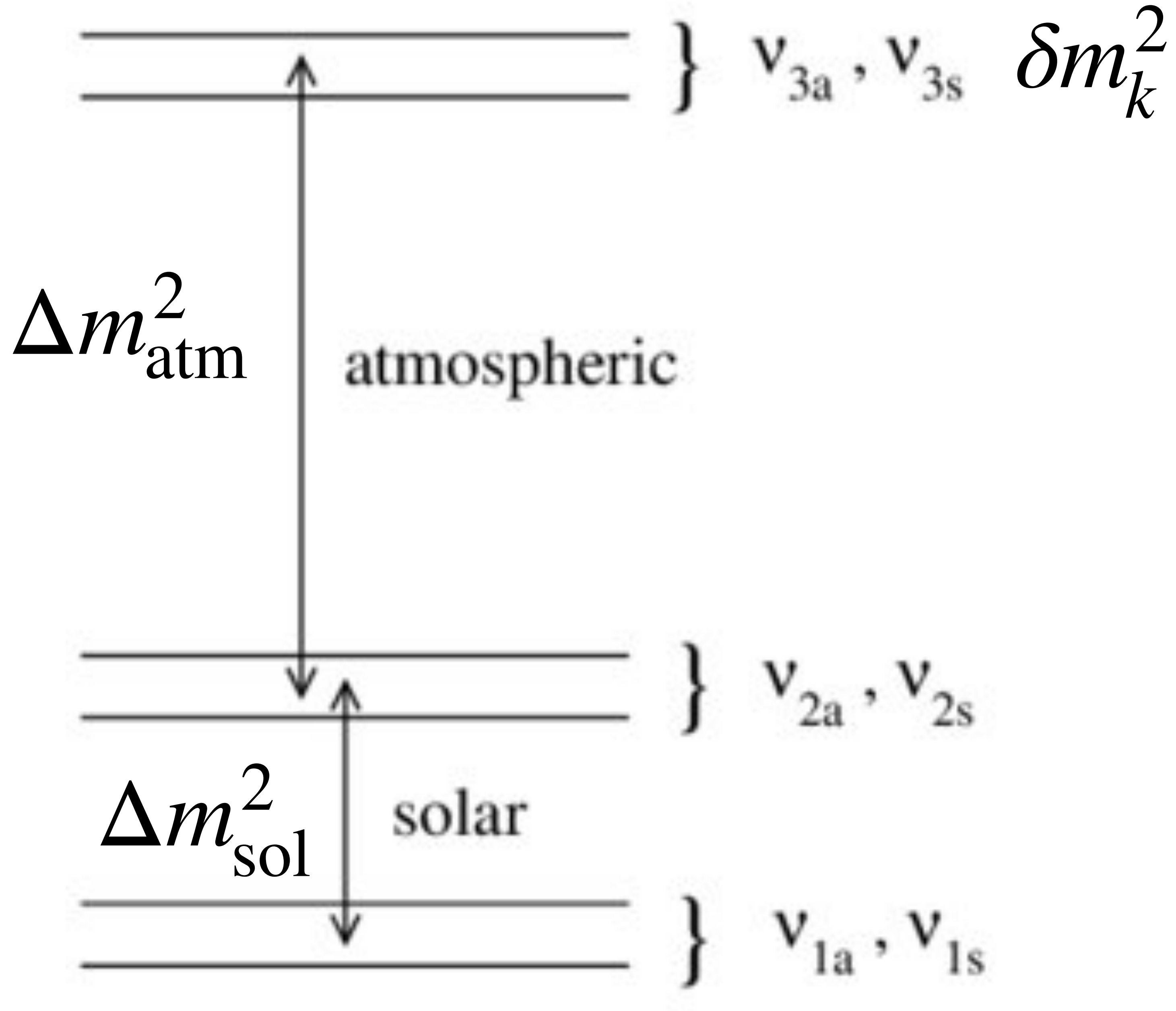
  Pseudo-Dirac limit : $m_{L,R} \ll m_D$

  Kobayashi, Lim, PRD2001

- 3 pairs of quasi-degenerate states, separated by δm_k^2, which is much smaller than the usual $\Delta m^2_{\rm sol}$ and $\Delta m^2_{\rm atm}$.

$$\nu_{\alpha L} = \frac{1}{\sqrt{2}} U_{\alpha j}(\nu_{js} + i\,\nu_{ja})$$

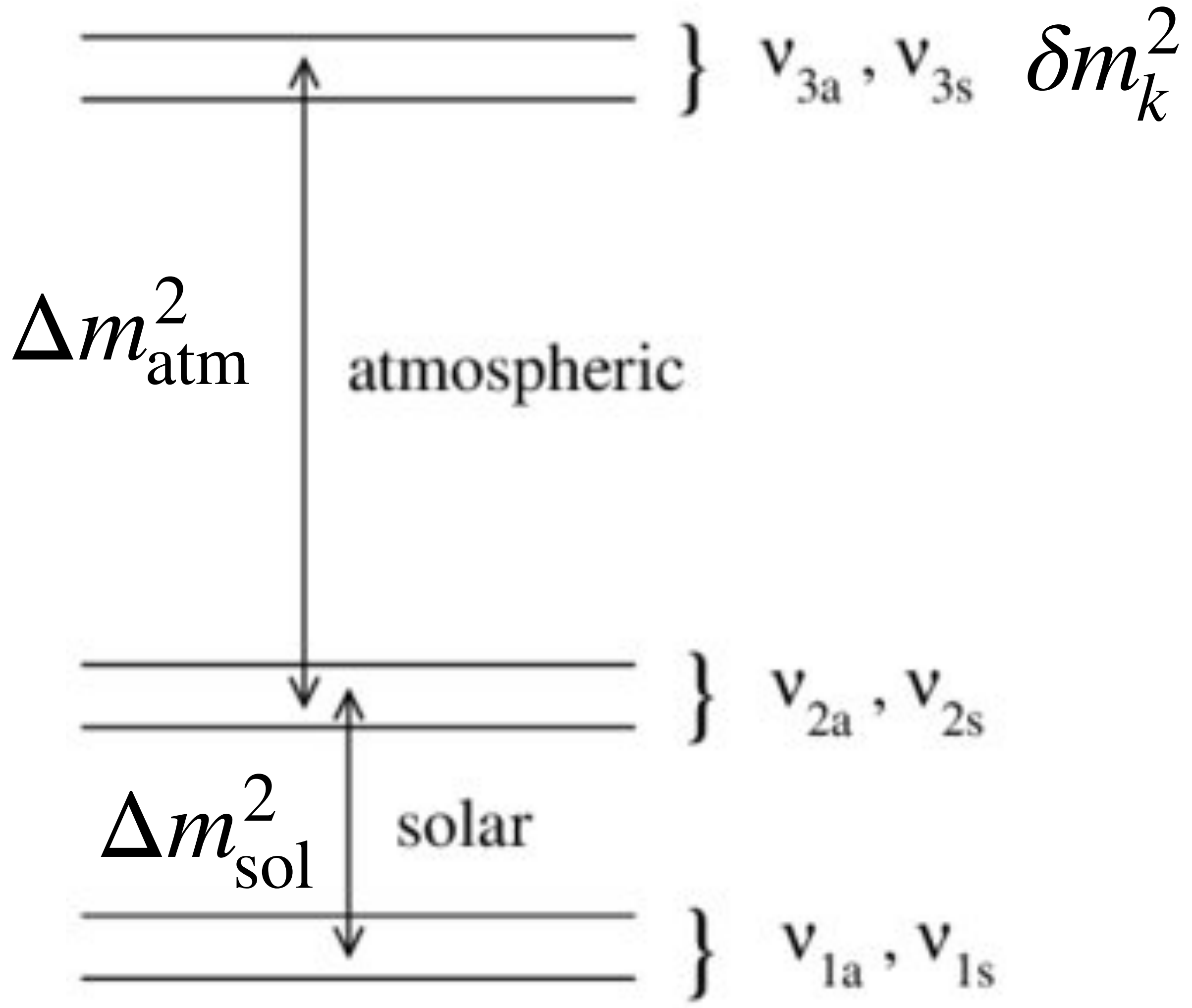
- Maximally mixed active and sterile states. Oscillations driven by this tiny mass.



Bounds:

1. Solar neutrinos $\delta m^2 = 10^{-12}\,{\rm eV}^2$
   de Gouvea, Huang, Jenkins, PRD2009
2. Atmospheric neutrinos $\delta m^2 > 10^{-4}\,{\rm eV}^2$
   Beacom, Bell, et al., PRL2004
3. High energy astrophysical neutrinos $10^{-18}\,{\rm eV}^2 < \delta m^2 < 10^{-12}\,{\rm eV}^2$
   Esmaili, Farzan, JCAP2012

Pseudo Dirac Neutrinos



- δm_k^2 will lead to oscillations at very large distances. Wave-packet separation decoherence also becomes important.

- Probability for $\nu_i \to \nu_\beta$

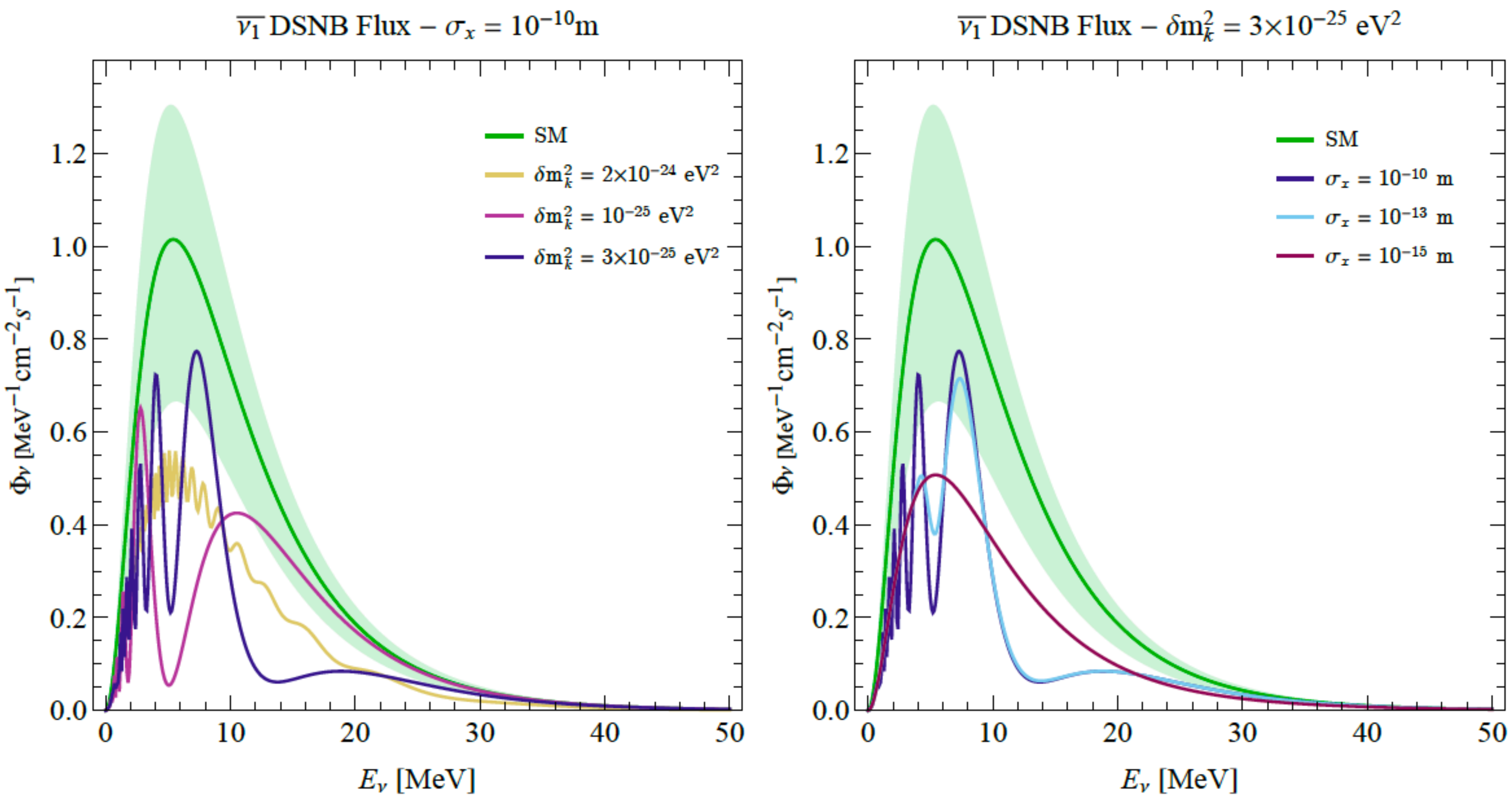
$$P_{i\beta}(z,E) = \frac{1}{2}|U_{\beta i}|^2 \left(1 + e^{-\left(\frac{L(z)}{L_{\rm coh}}\right)^2} \cos\left(\frac{L(z)}{L_{\rm osc}}\right)\right)$$

A smaller σ_x can cause decoherence.

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

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

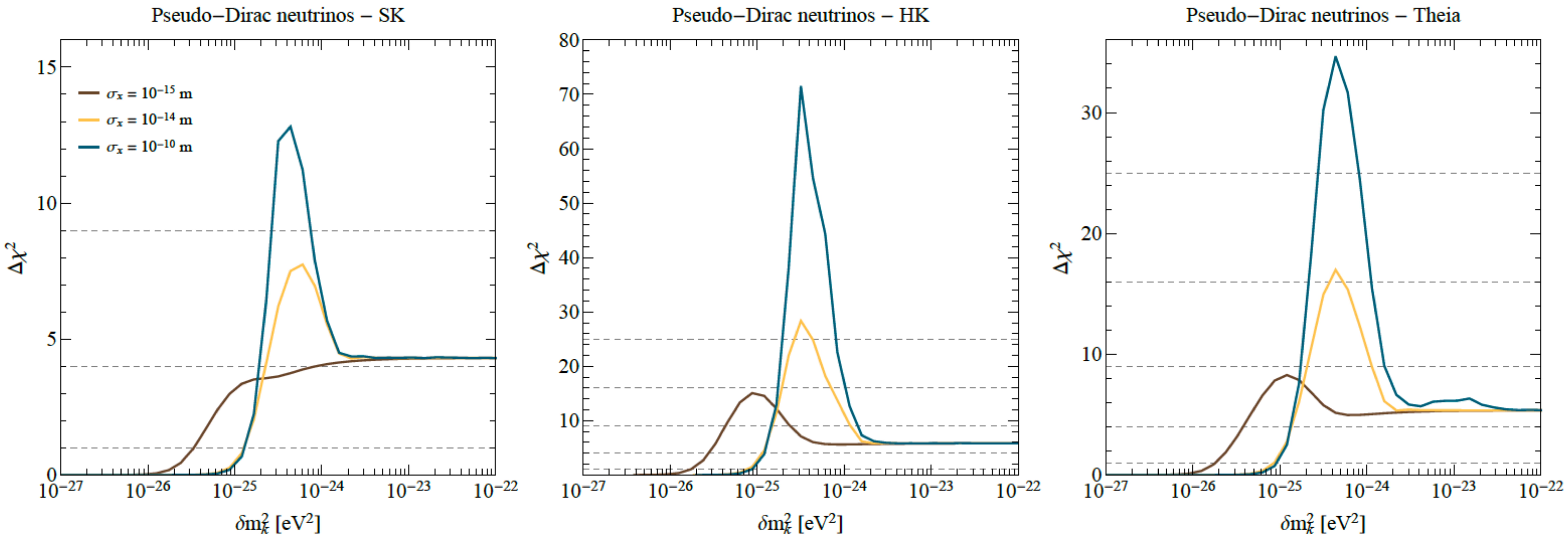
Oscillations due to pseudo-Dirac nature



Increasing δm^2 reduces $L_{\rm osc}$ and $L_{\rm coh}$, and causes more oscillations

Decreasing σ_x reduces $L_{\rm coh}$, and causes more decoherence

Sensitivity to tiny mass-squared differences



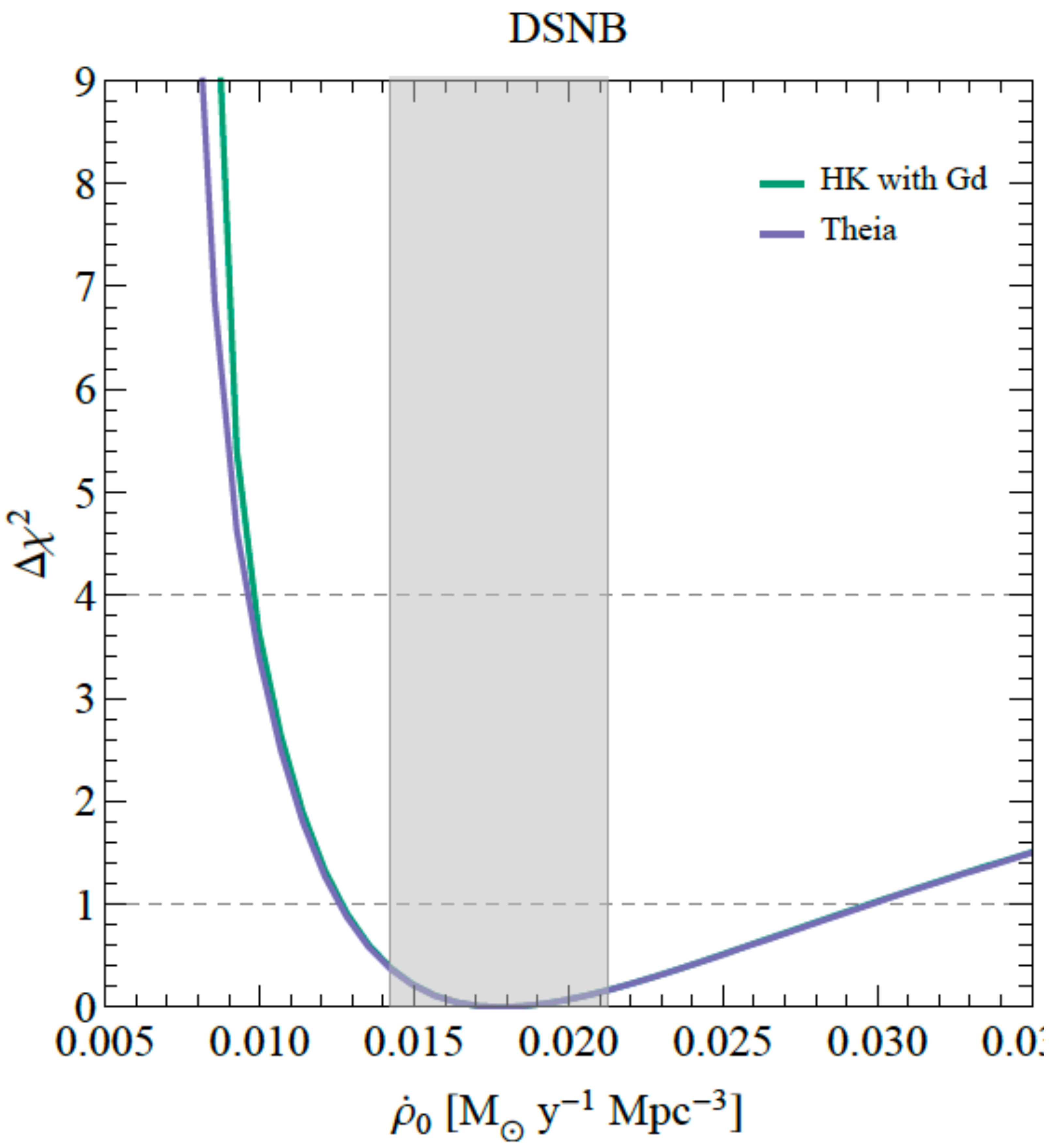
- DSNB sensitive to $\delta m^2 \sim \mathcal{O}(10^{-25}\,\mathrm{eV}^2)$ with a high significance.
- Even if δm^2 is too tiny for oscillations, DSNB is still sensitive to decoherence for small σ_x

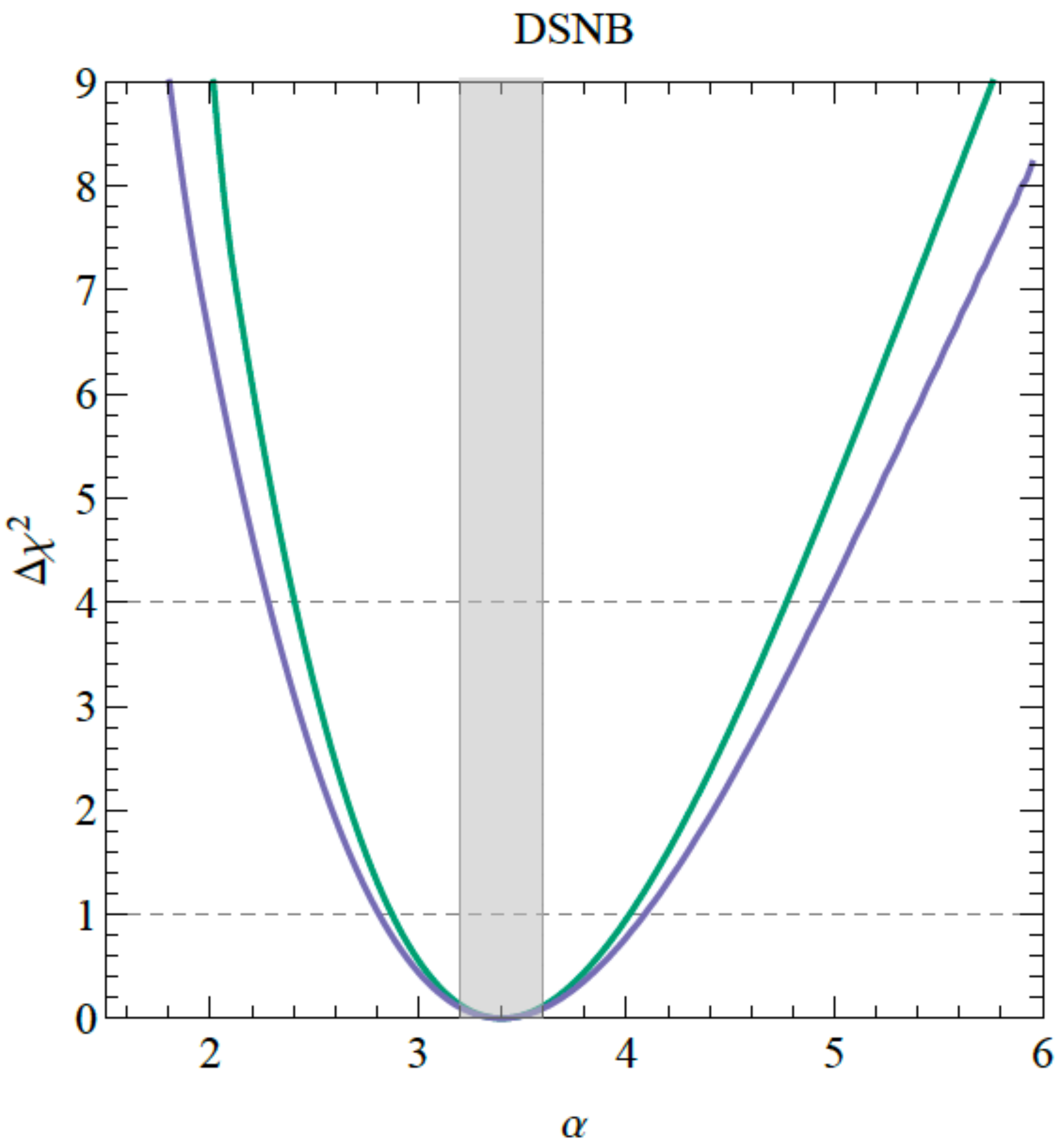
de Gouvea, Martinez-Soler, Perez-Gonzalez, MS, PRD 2020

Star formation Rate

$$\Phi_\nu(E) = \int_0^{z_{\max}} \frac{dz}{H(z)}\, R_{\rm CCSN}(z)\; F_\nu\big(E(1+z)\big)$$

Astrophysics: Cosmic star formation rate





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

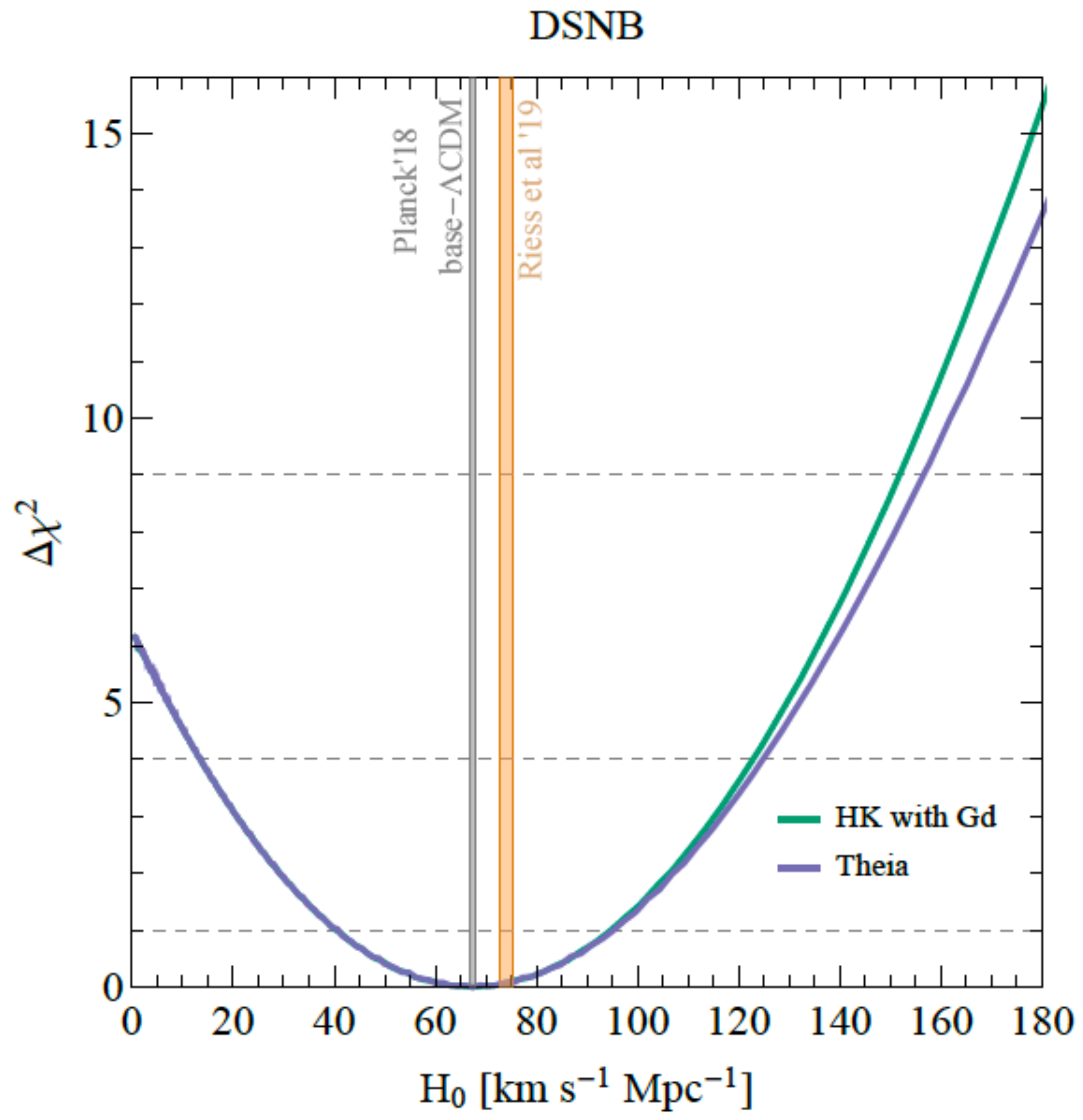
At the 2σ level, the results obtained from the DSNB are almost competetive with those obtained from decades of astronomical surveys.

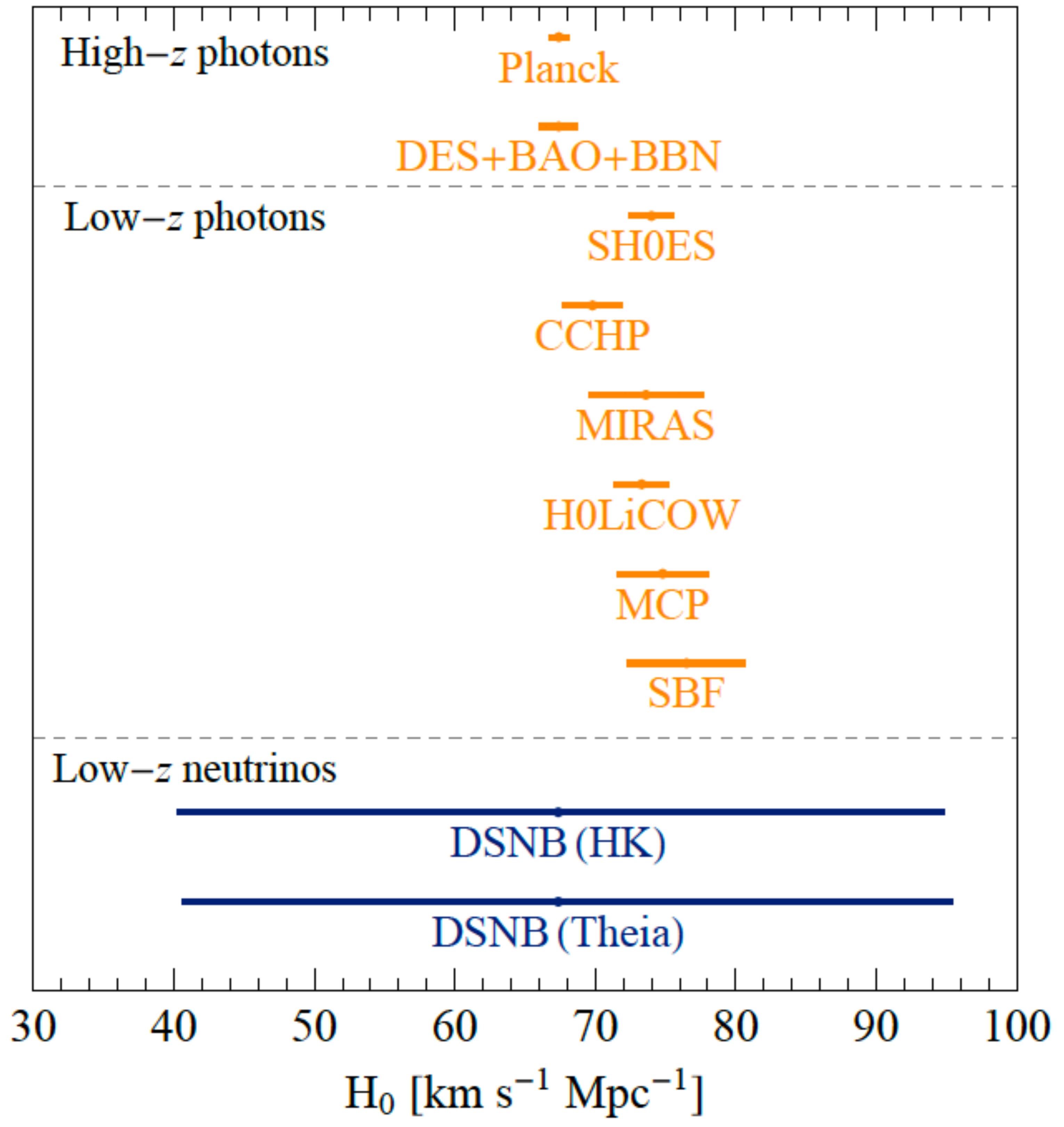
de Gouvea, Martinez-Soler, Perez-Gonzalez, MS, PRD 2020

Hubble constant

$$\Phi_\nu(E) = \int_0^{z_{\max}} \frac{dz}{H(z)} R_{\rm CCSN}(z)\ F_\nu\big(E(1+z)\big)$$

Cosmology: Hubble Parameter





de Gouvea, Martinez-Soler, Perez-Gonzalez, MS, PRD 2020

- Distance yardstick using neutrinos. Can confirm expanding Universe after 10 years of running.
- Measure H_0 at 40% level, which is the systematic uncertainty.
- Caveat: Relies on an independent redshift dependent measurement of the SFR.

Conclusions

- The DSNB opens up a plethora of avenues for neutrino astronomy, next giant leap from the Sun and SN1987A.

- A future detection can provide neutrino only measurement of expansion rate of the Universe, complementary to measurement with photons and gravity waves.

- Competetive constraints on cosmological star formation rate, and hence the rate of core-collapse SNe in the Universe.

- Crucial for testing extreme neutrino properties, which cannot be tested otherwise.

- Other constraints discussed in the literature: black-hole fraction (primordial as well as astrophysical), alternate cosmological models, models of neutrino emission, and propagation, any new exotic physics in the neutrino sector.

Thank You!

Variation with <E> and alpha

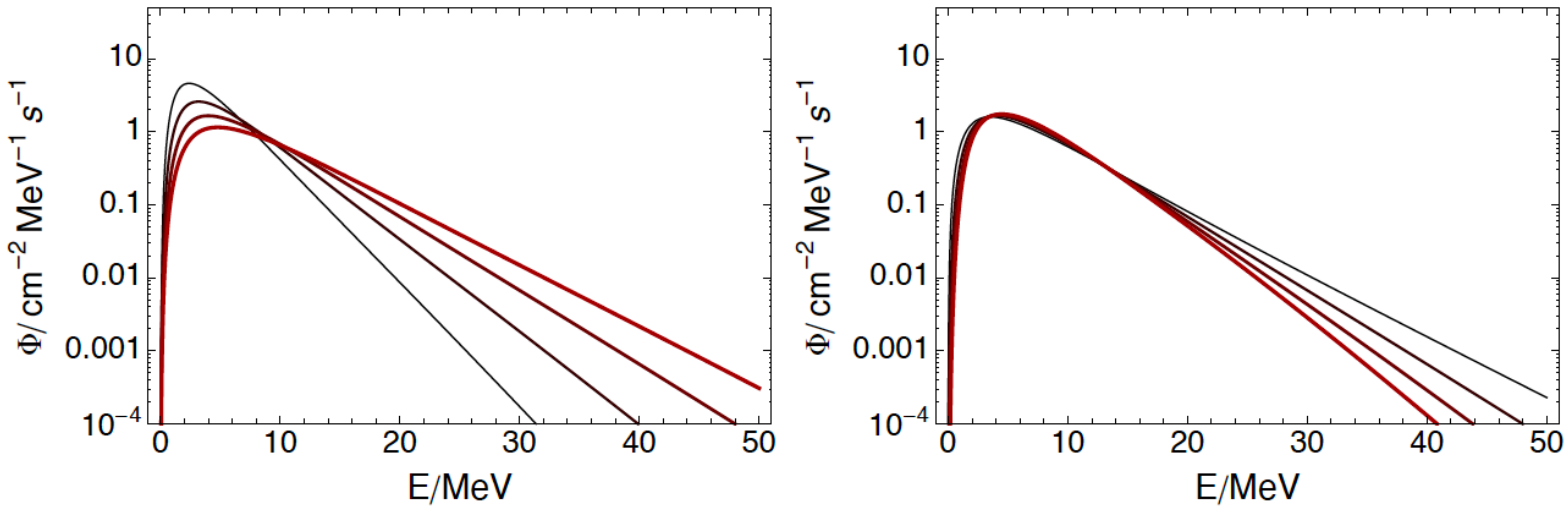


Figure 10: Examples of unoscillated flux, Φ^0_w ($w = e, \bar{e}, x$) (Eq. (15)), for different spectral parameters E_{0w}, α_w. Left: the curves of increasing thickness (increasing color intensity) correspond to $E_{0w} = 9, 12, 15, 18$ MeV, with $\alpha_w = 3$. Right: the curves of increasing thickness (increasing color intensitiy) correspond to $\alpha_w = 2, 3, 4, 5$ with $E_{0w} = 15$ MeV.

Variation with redshift

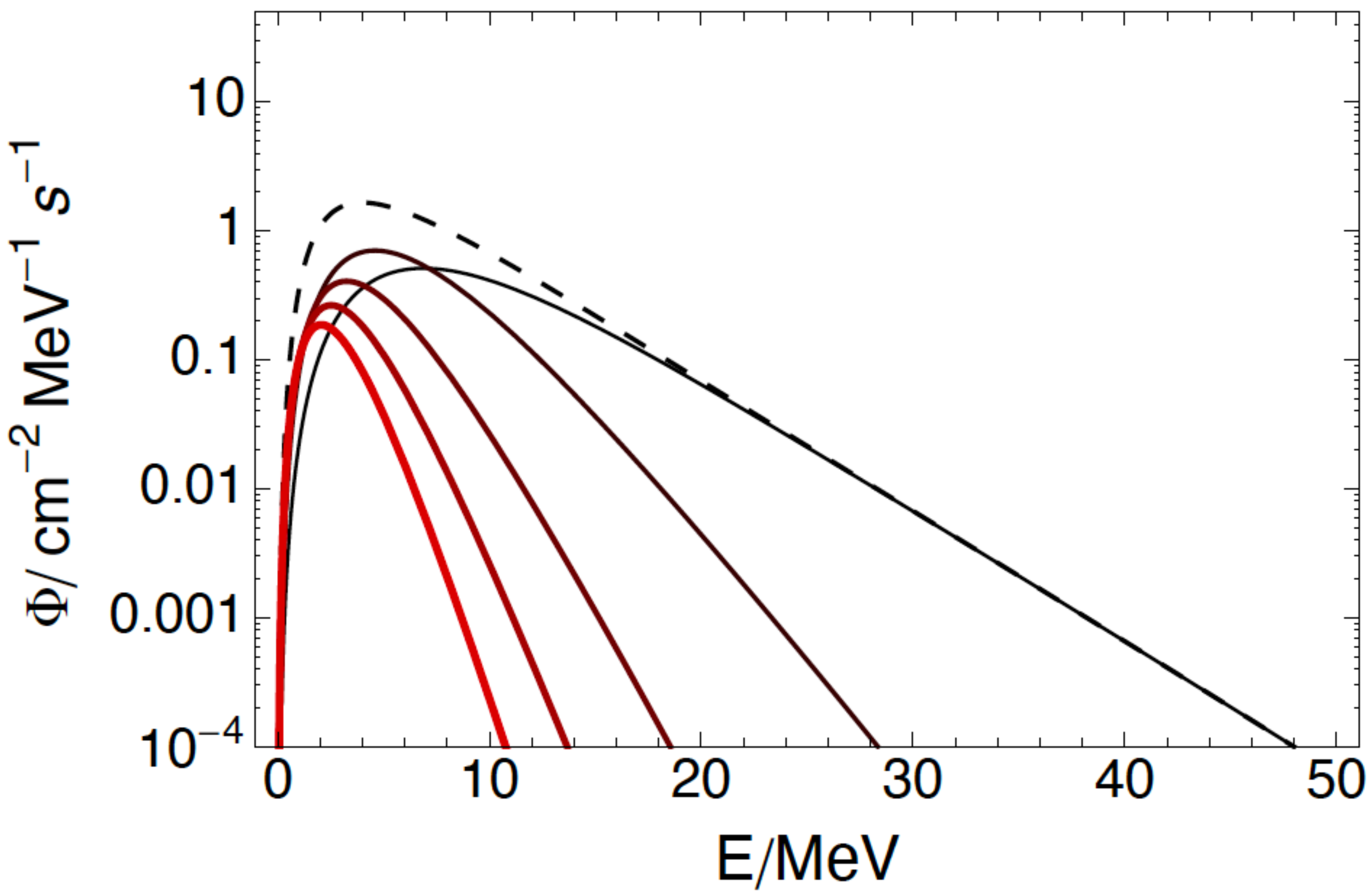
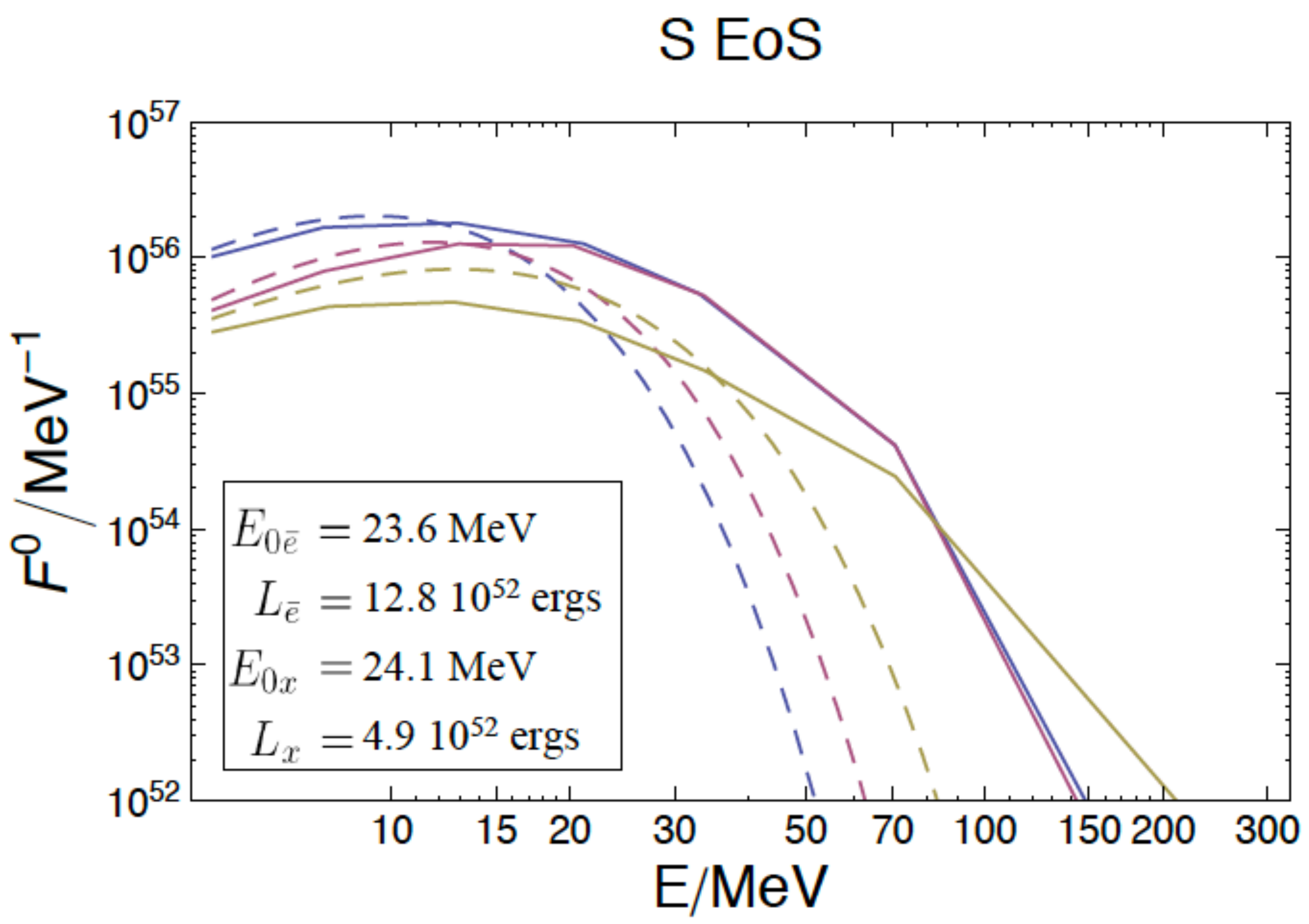
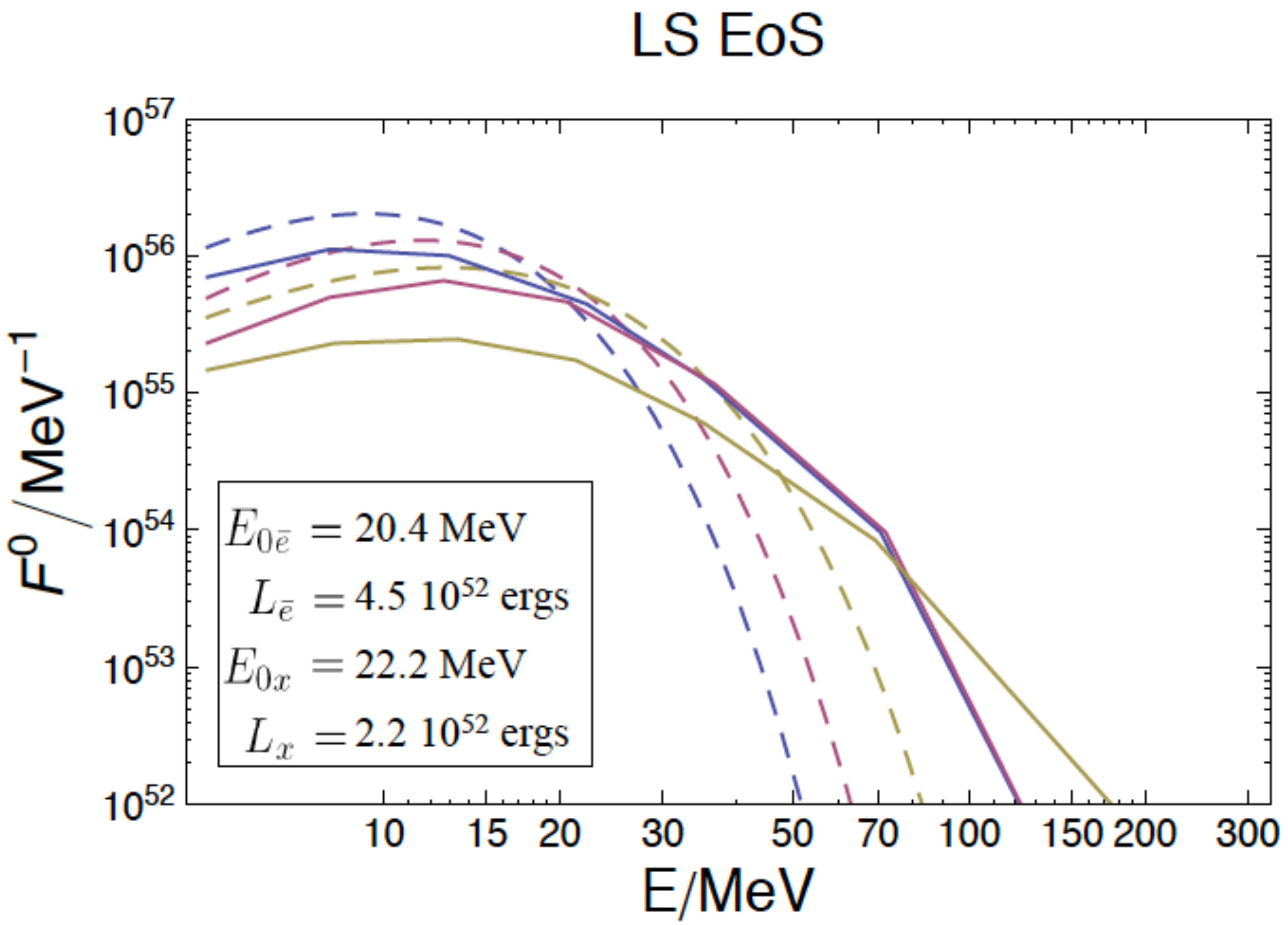


Figure 13: The contribution to the *unoscillated* $\bar{\nu}_e$ flux of sources in bins of increasing redshift, for the best fit SNR parameter $\beta = 3.28$ [59]. The solid curves from thinner to thicker (darker to lighter color) refer to the intervals: $z = 0 - 1$, $z = 1 - 2$, $z = 2 - 3$, $z = 3 - 4$ and $z = 4 - 5$. The dashed line is the total flux integrated over all redshifts. The parameters of the H case were used (Table 1).

Failed Supernovae





- Stars with $M > 25 - 40\,M_\odot$ can end up forming a failed SN.
- Neutrino spectra can be more energetic due to rapid contraction of the PNS before collapse.
- 'S' EoS is stiffer, so stronger core-bounce and hence more energetic neutrinos.

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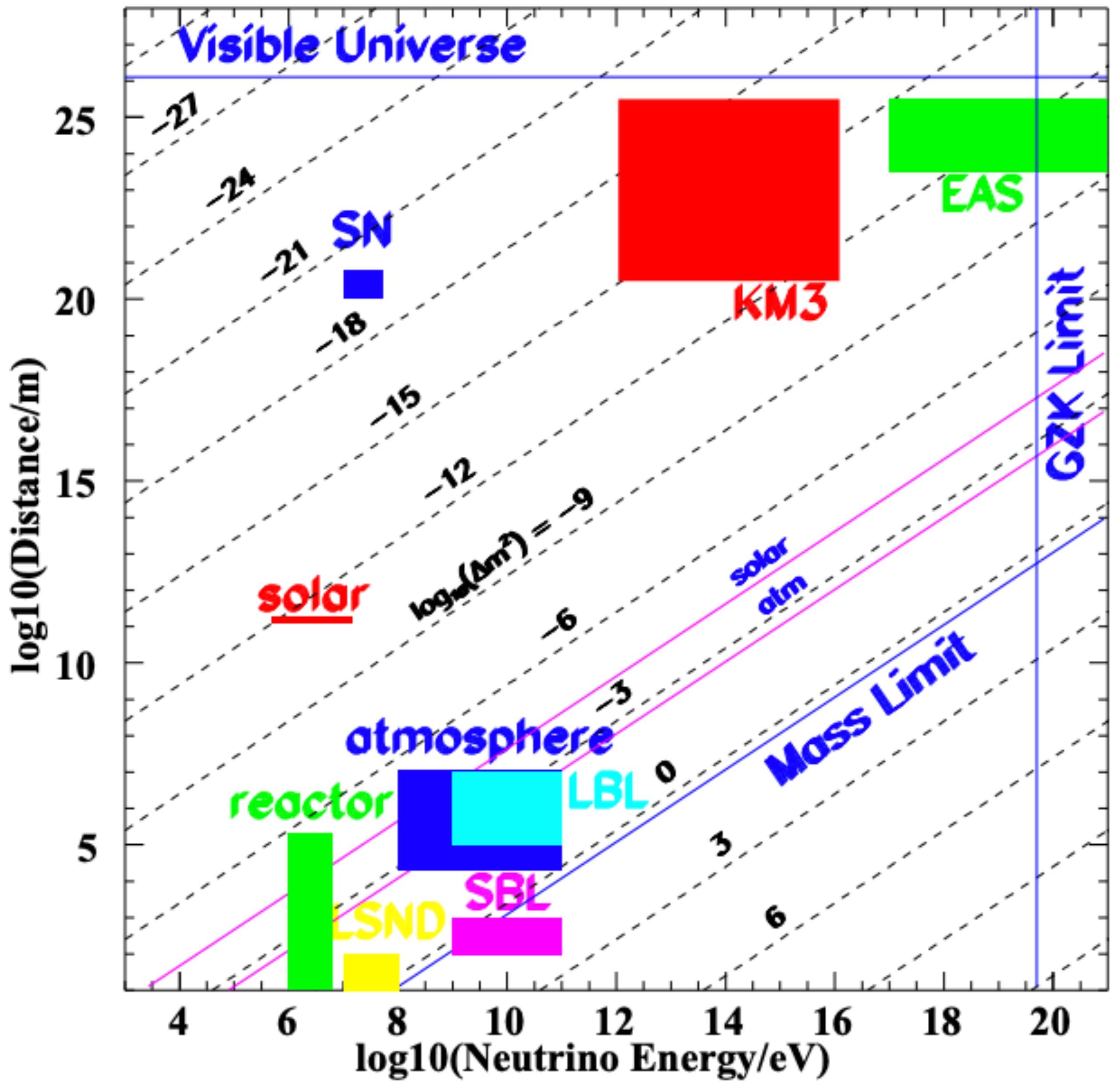
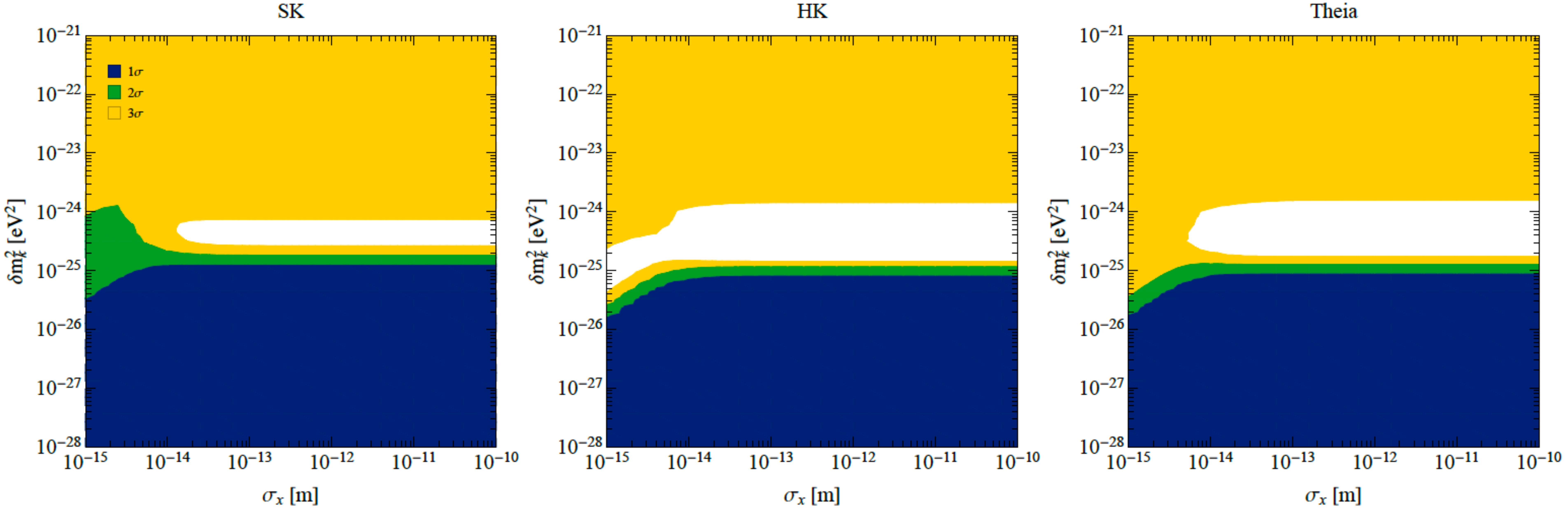
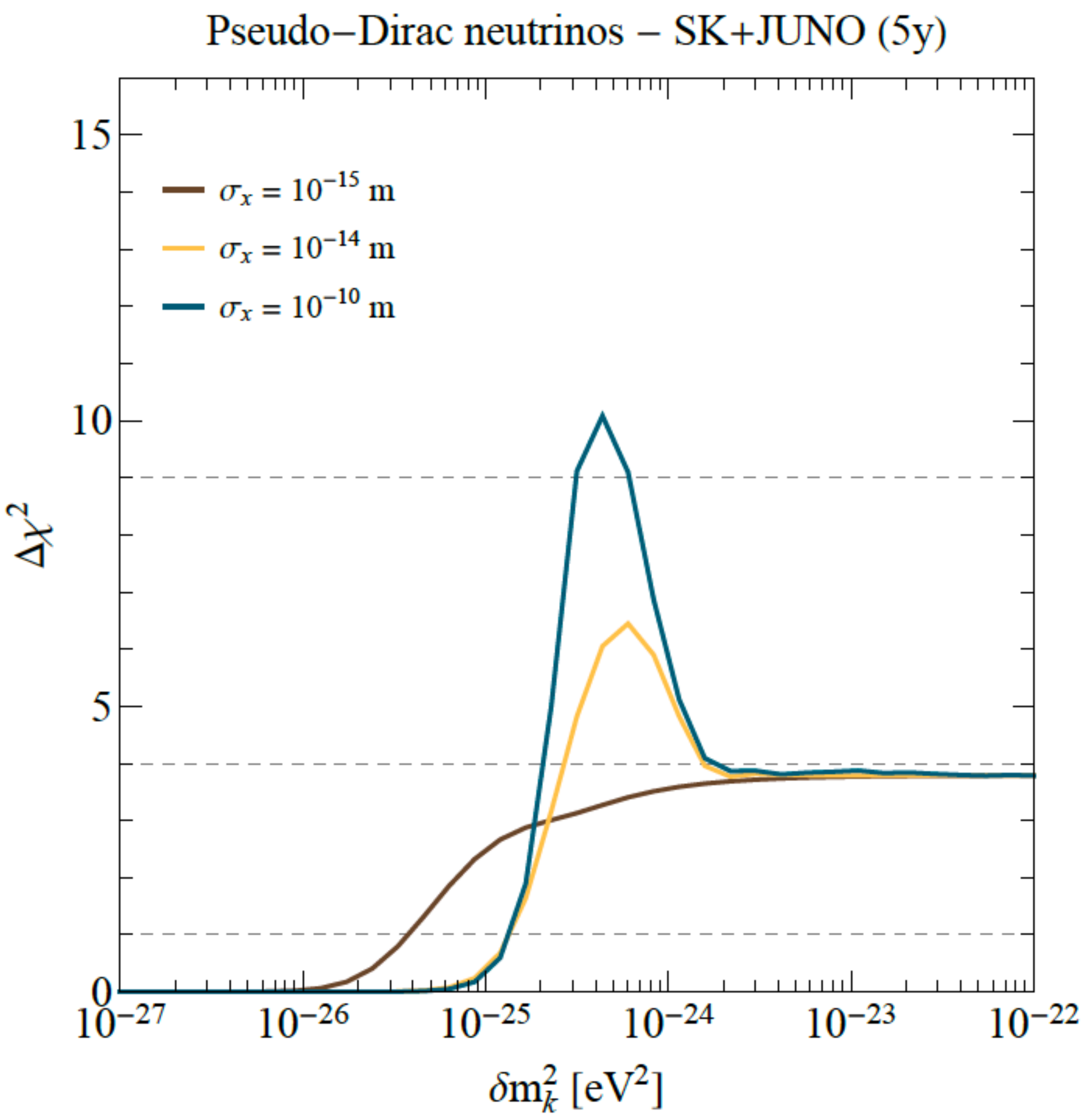


Beacom, Bell, et al., PRL2004

de Gouvea, Martinez-Soler, Perez-Gonzalez, MS, 2007.13748



Pseudo-Dirac Constraints by SK+JUNO in 5 years



de Gouvea, Martinez-Soler, Perez-Gonzalez, MS, 2007.13748