Diffuse SN neutrino background: ubiquitous and driving fundamental physics

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Network for Neutrinos, Nuclear Astrophysics and Symmetries (N3AS) seminar, 09/01/2020

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.

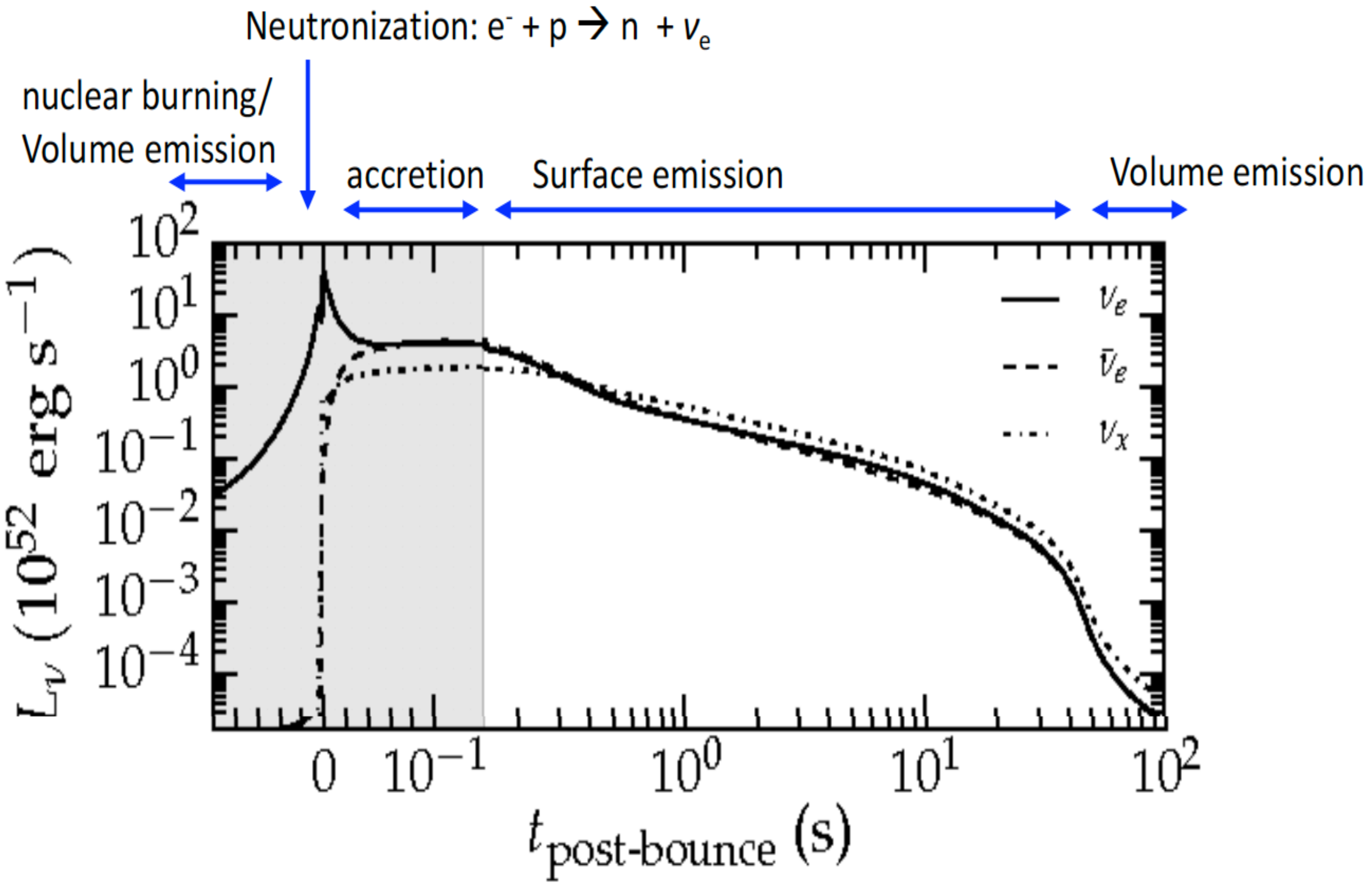
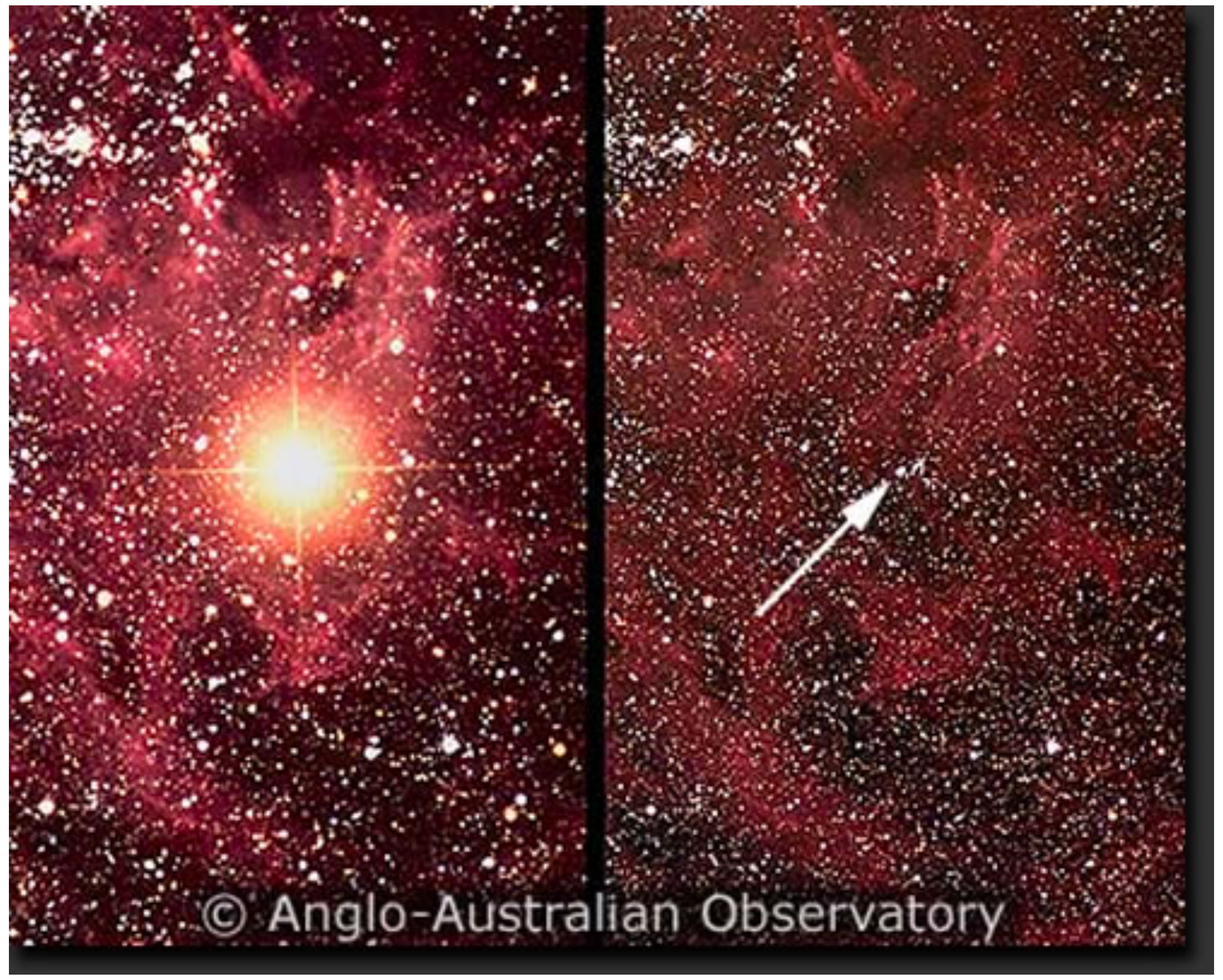
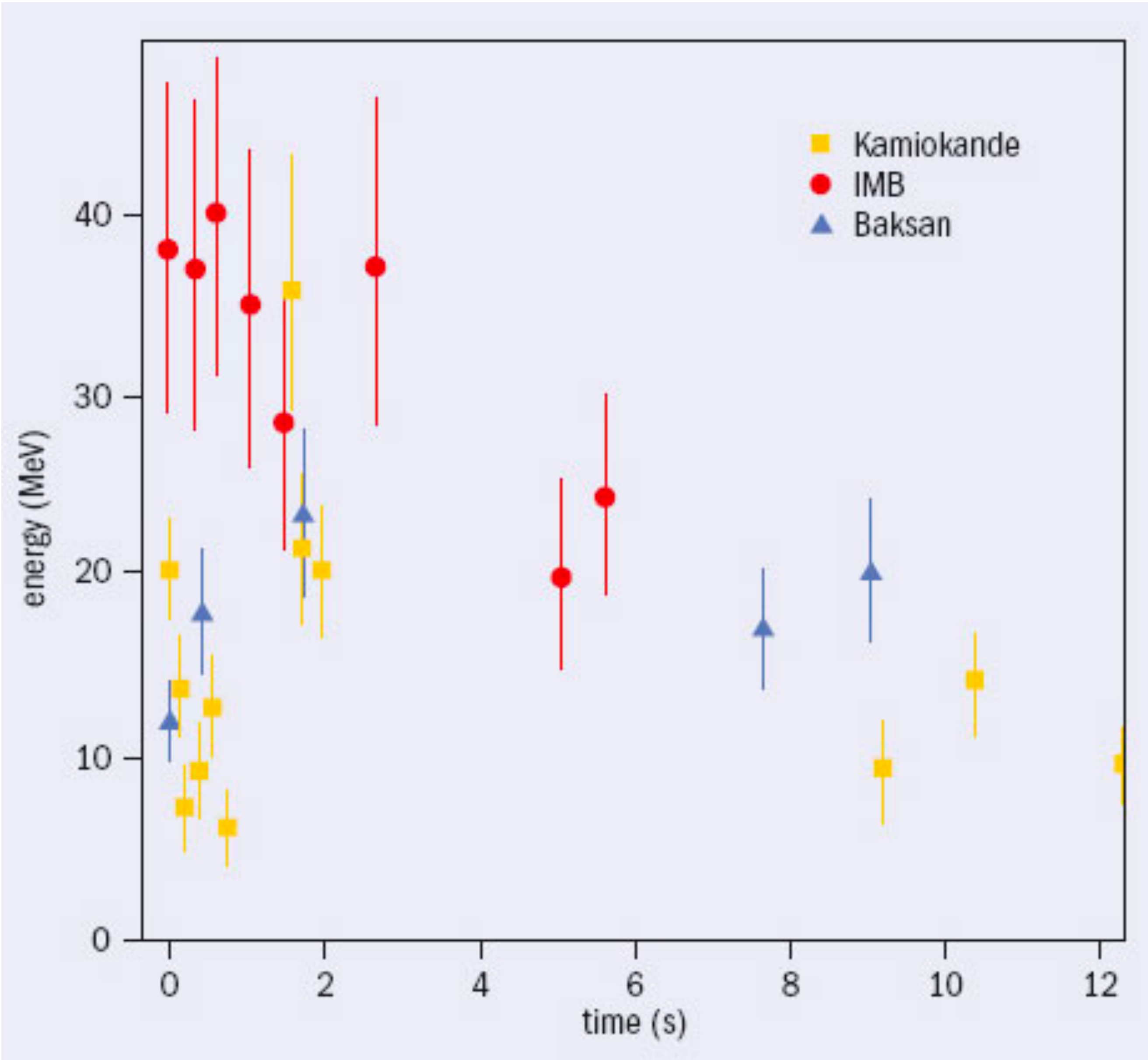


Figure from Roberts and Reddy, Handbook of Supernovae, Springer Intl., 2017

SN 1987A: "Many" neutrinos were observed



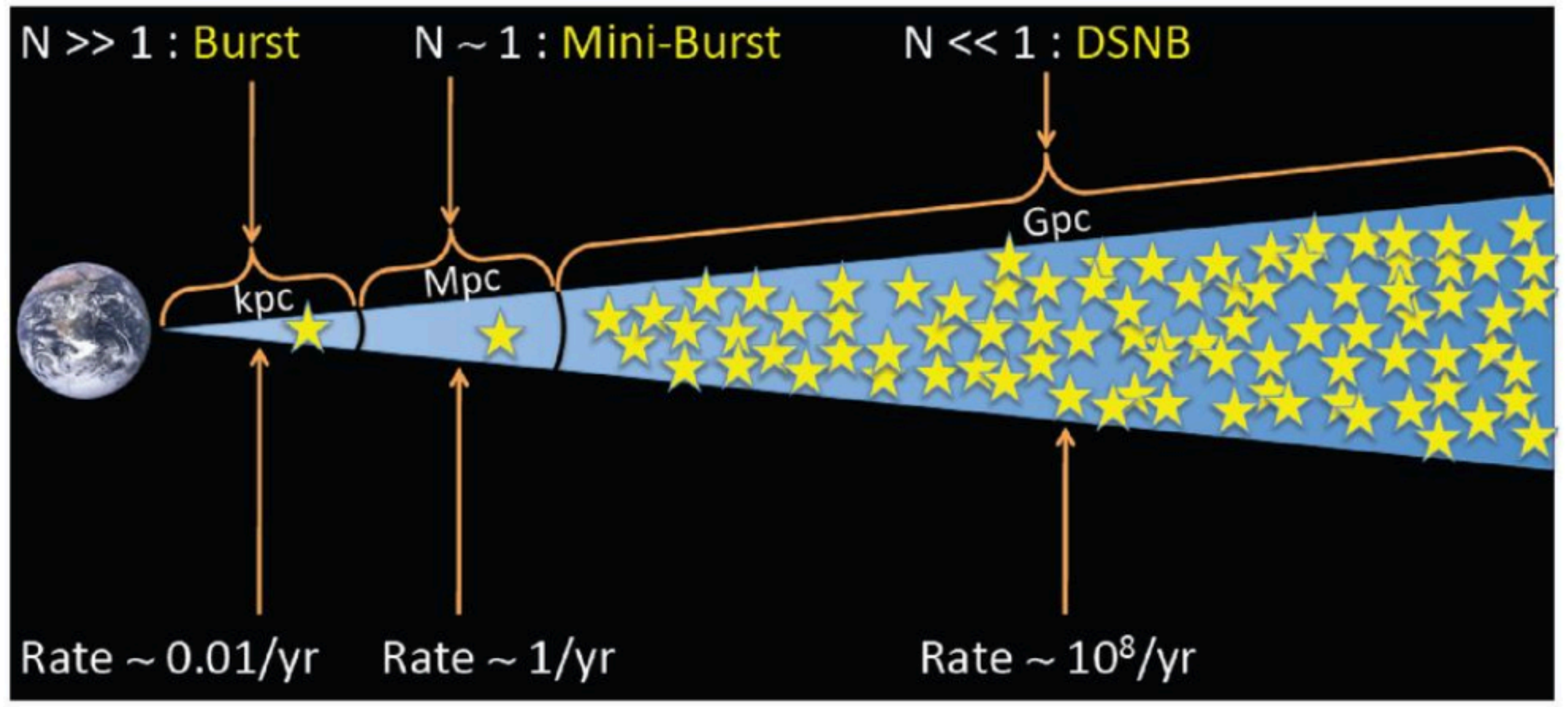


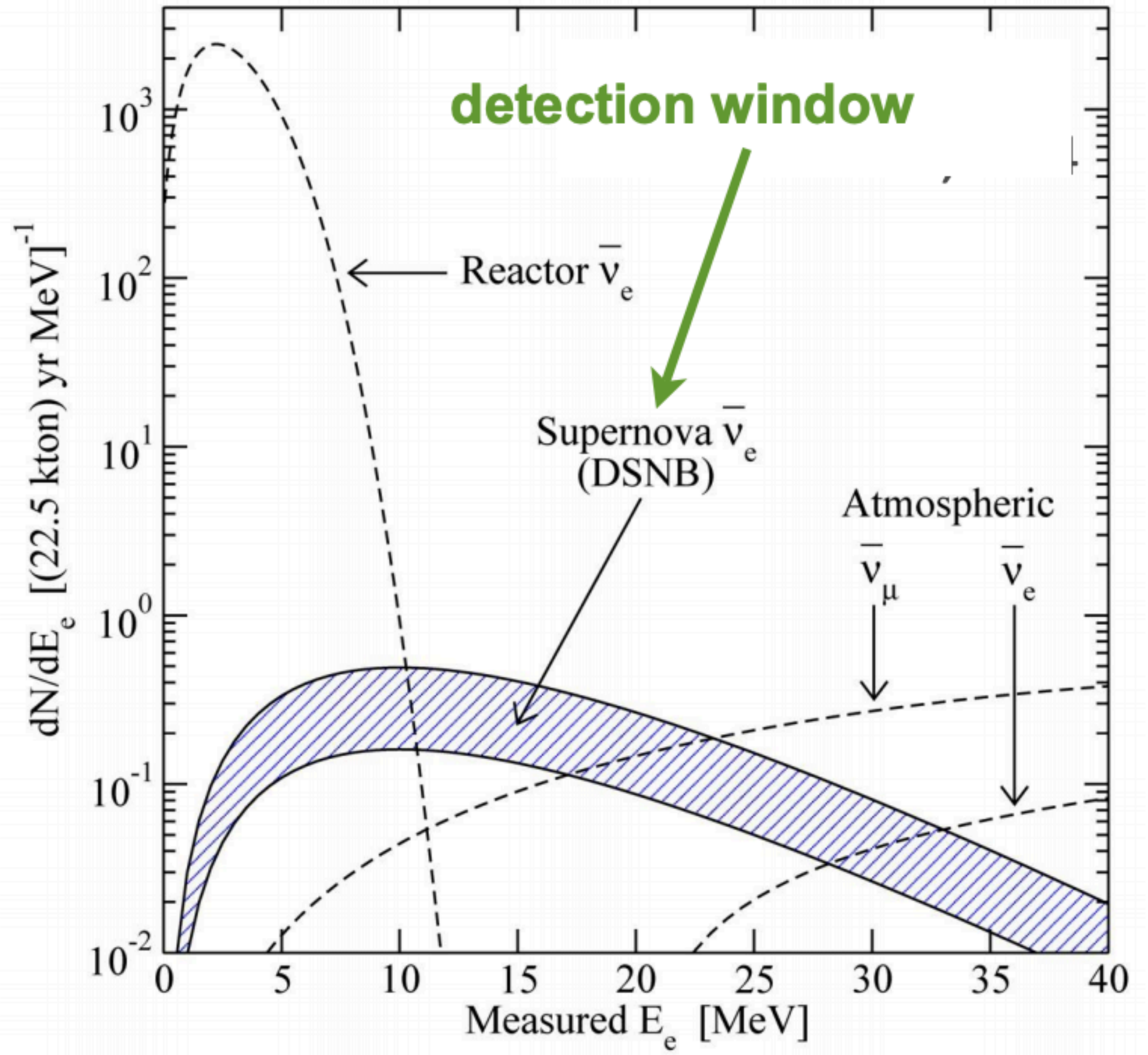
- O(30) events in total.
- One of the first examples of multi-messenger astronomy.
- Not enough statistics, still some of the strongest bounds on neutrino properties!
- A future galactic SN will have O(10k) events in detectors! Surely, we can capitalize on that!
- Extremely rare to have one. So do we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





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

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

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

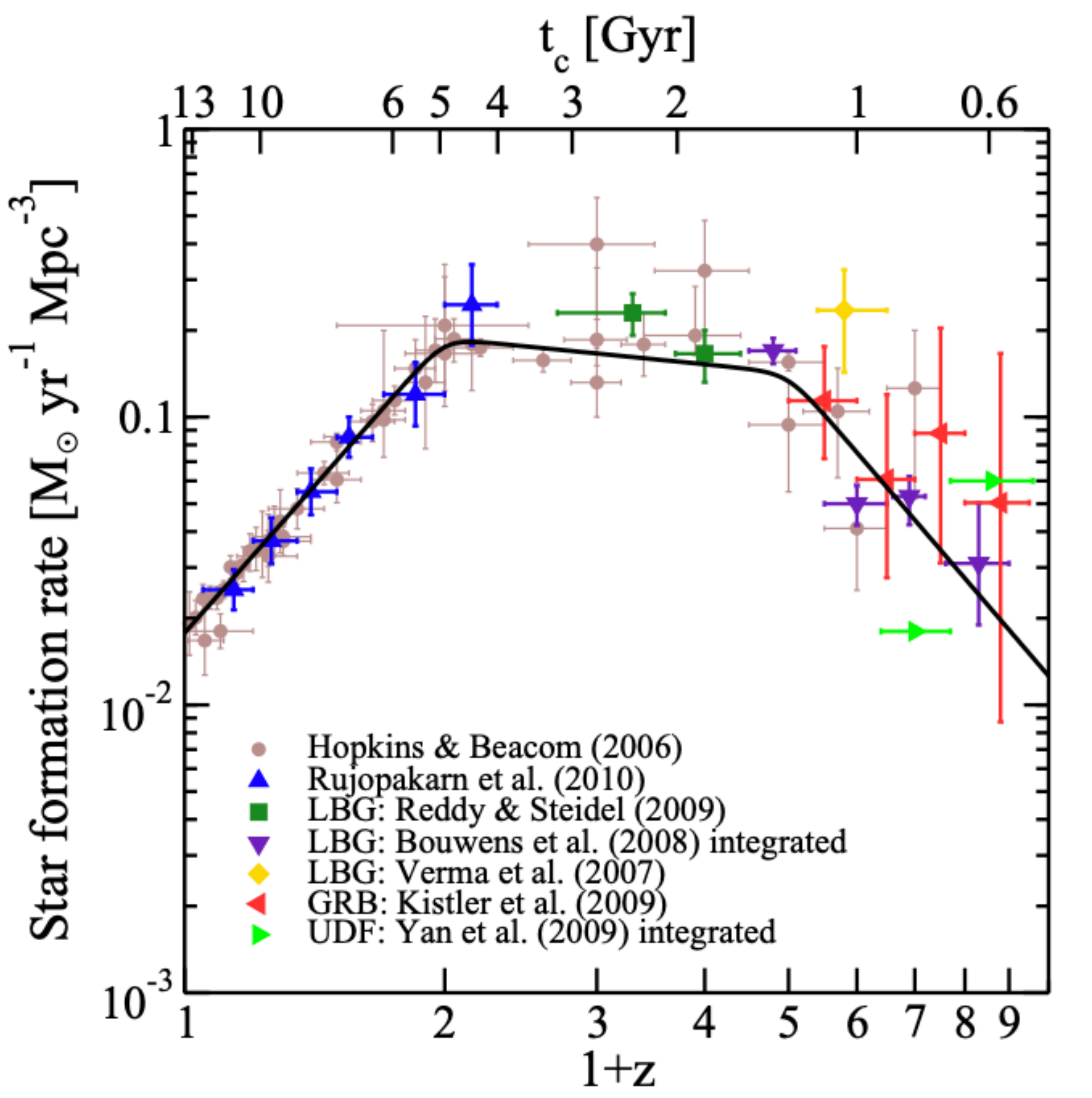
$$B = (1+z_1)^{1-\alpha/\beta}$$

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

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

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

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



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

Ingredient 3: Neutrino spectra

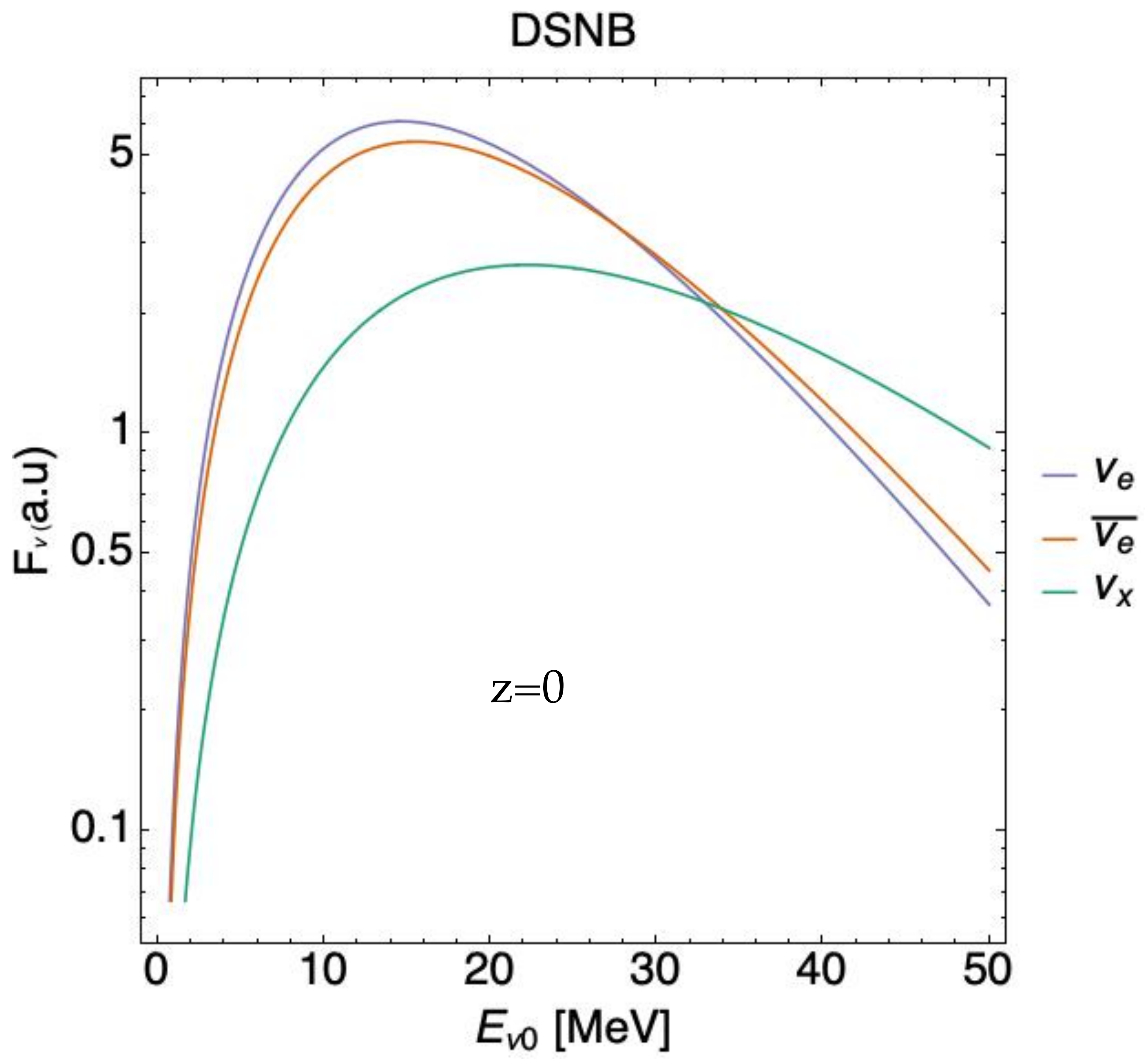
- Assume an approximately thermal spectra, characteristic of late-time phase.

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

- 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 $\leftrightarrow \nu_x$

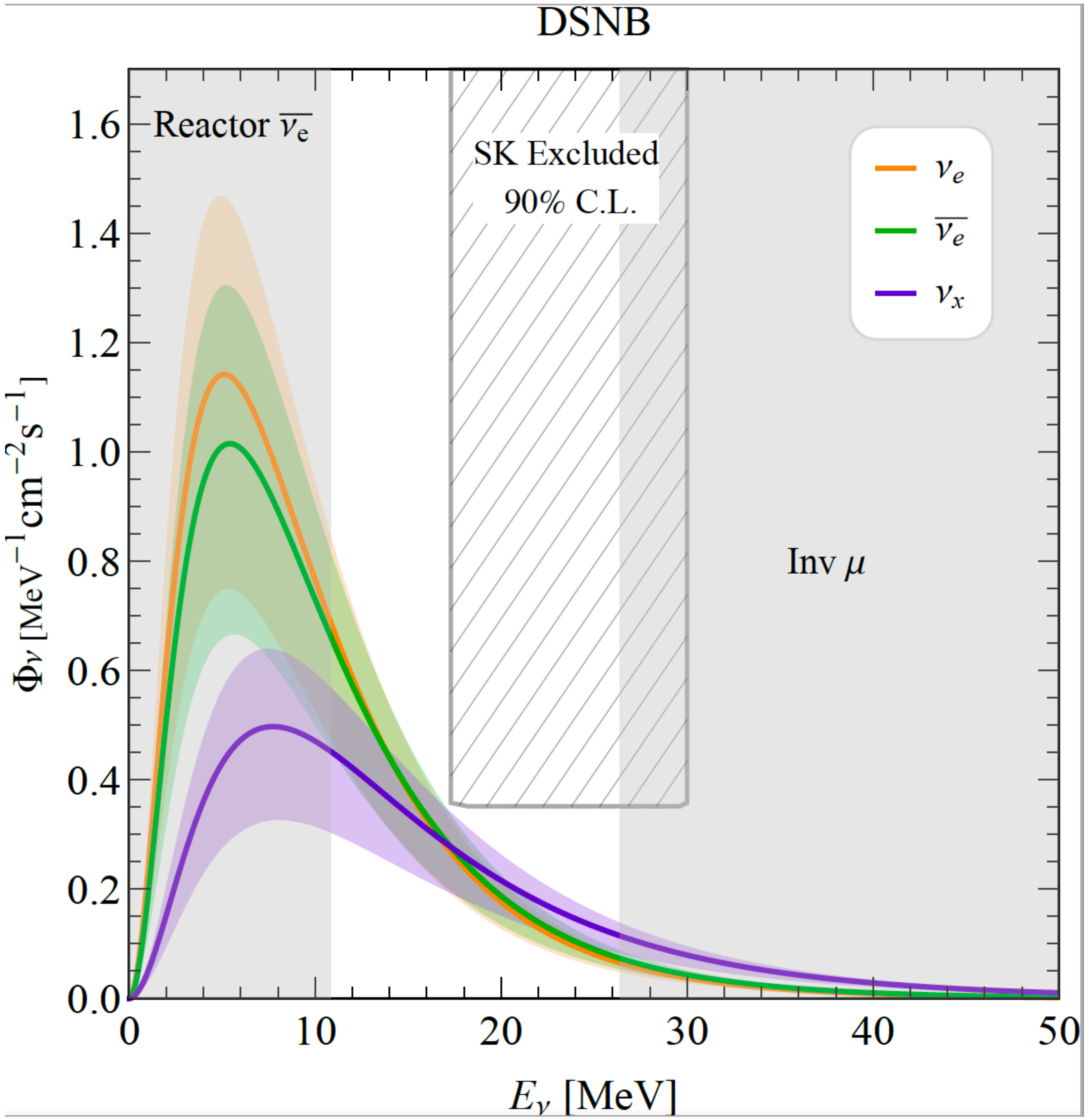
- Temperature hierarchy $T_{\nu_e} < T_{\bar{\nu}_e} < T_{\nu_x}$



Putting all ingredients together

- The DSNB window ~10-26 MeV.
- Uncertainty due to SFR.
- Main backgrounds to keep in mind:

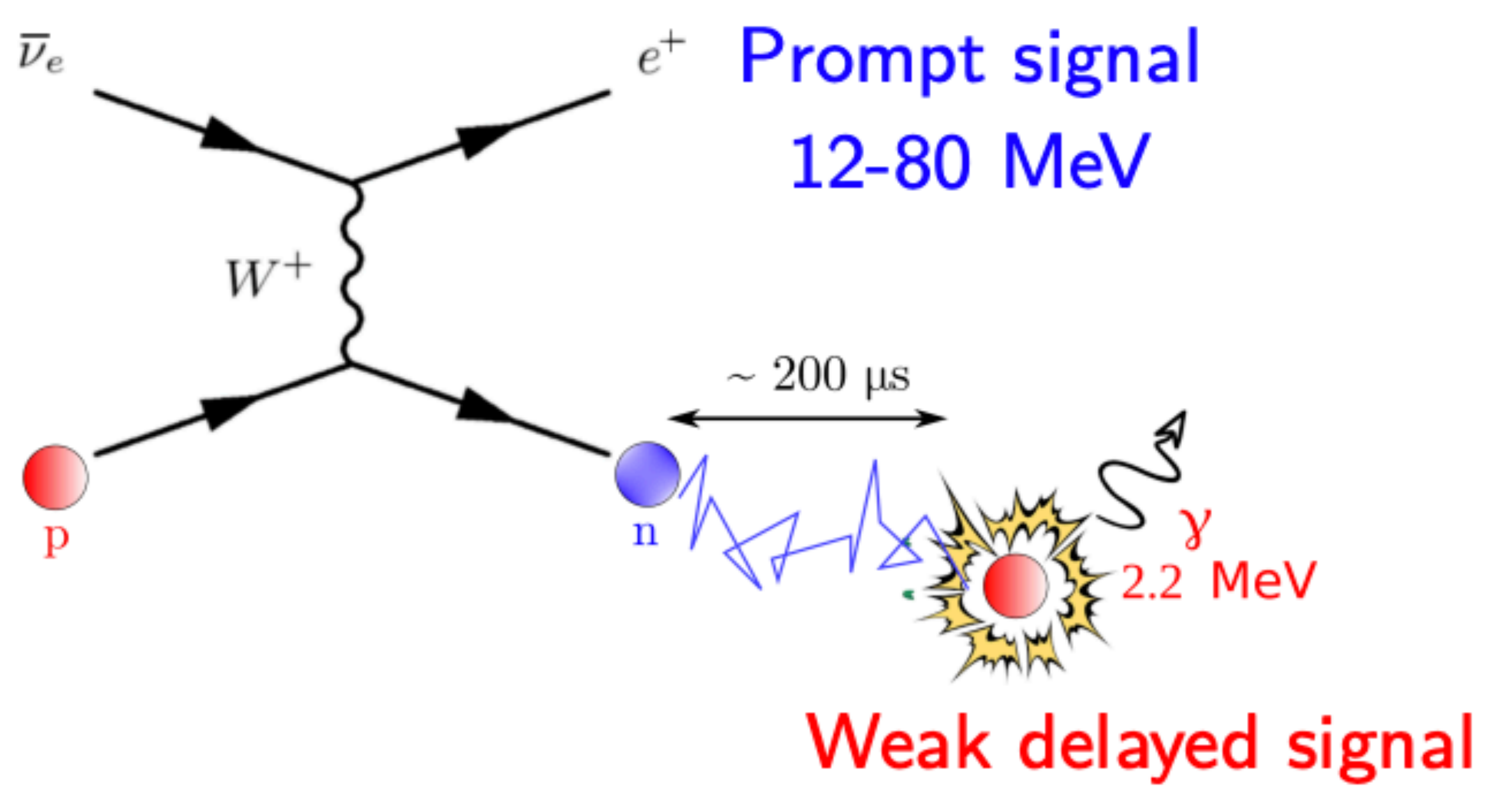
  Solar ν_e: extends upto ~20 MeV (can be reduced by directional information).
  Geo $\bar{\nu}_e$: Mostly dominates low energy ~ 4 MeV background.
  Reactor $\bar{\nu}_e$: extends upto ~10 MeV. Ineliminable.
  Atmospheric ν: Low energy tails of ν_e and $\bar{\nu}_e$. Exceeds the DSNB at E~30 MeV. Ineliminable.



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



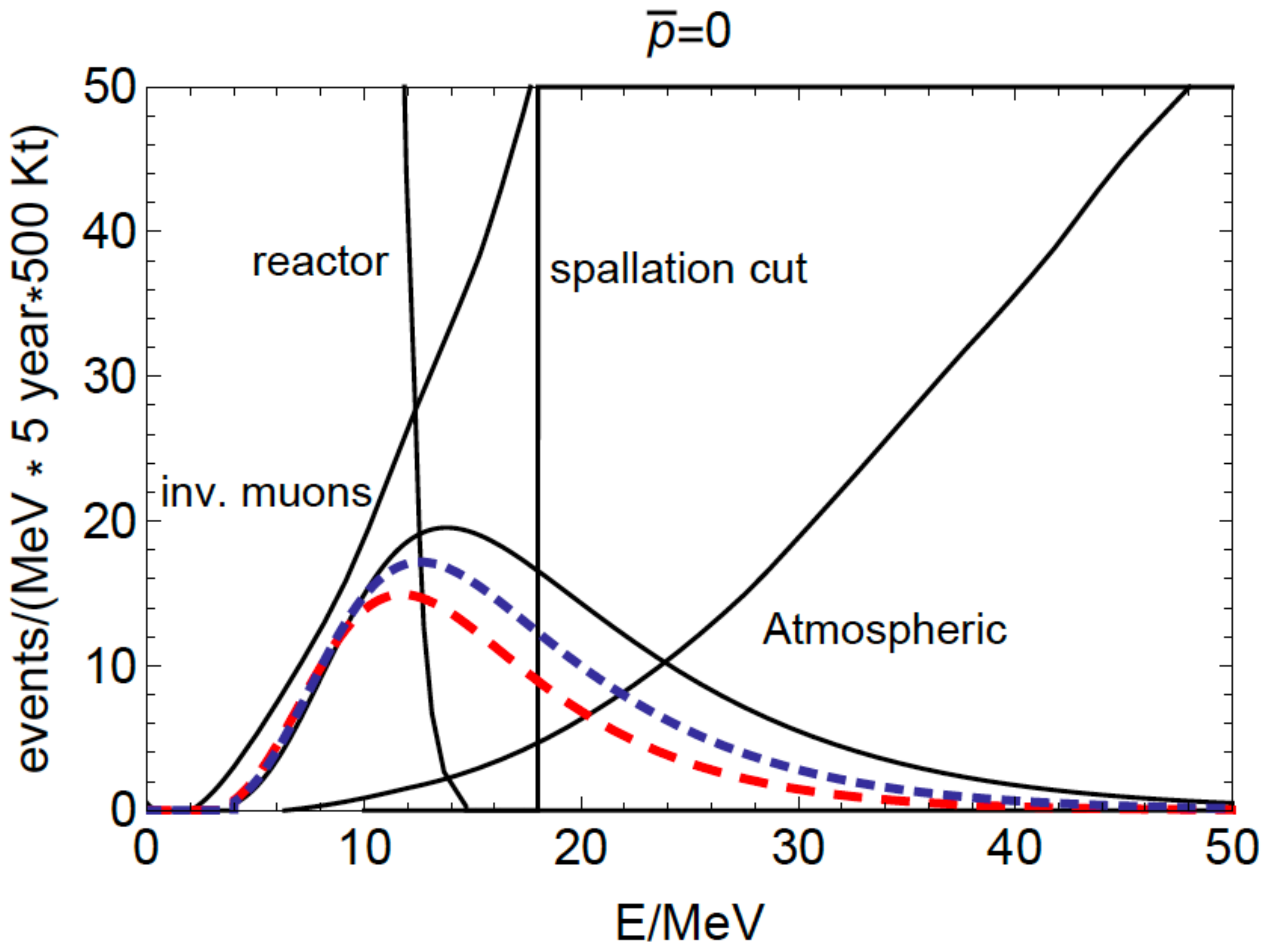
- Spallation backgrounds: radioactivity induced by cosmic muon spallation in water: $\mu + O \to \mu + X$. Substantial background ~ 20 MeV.

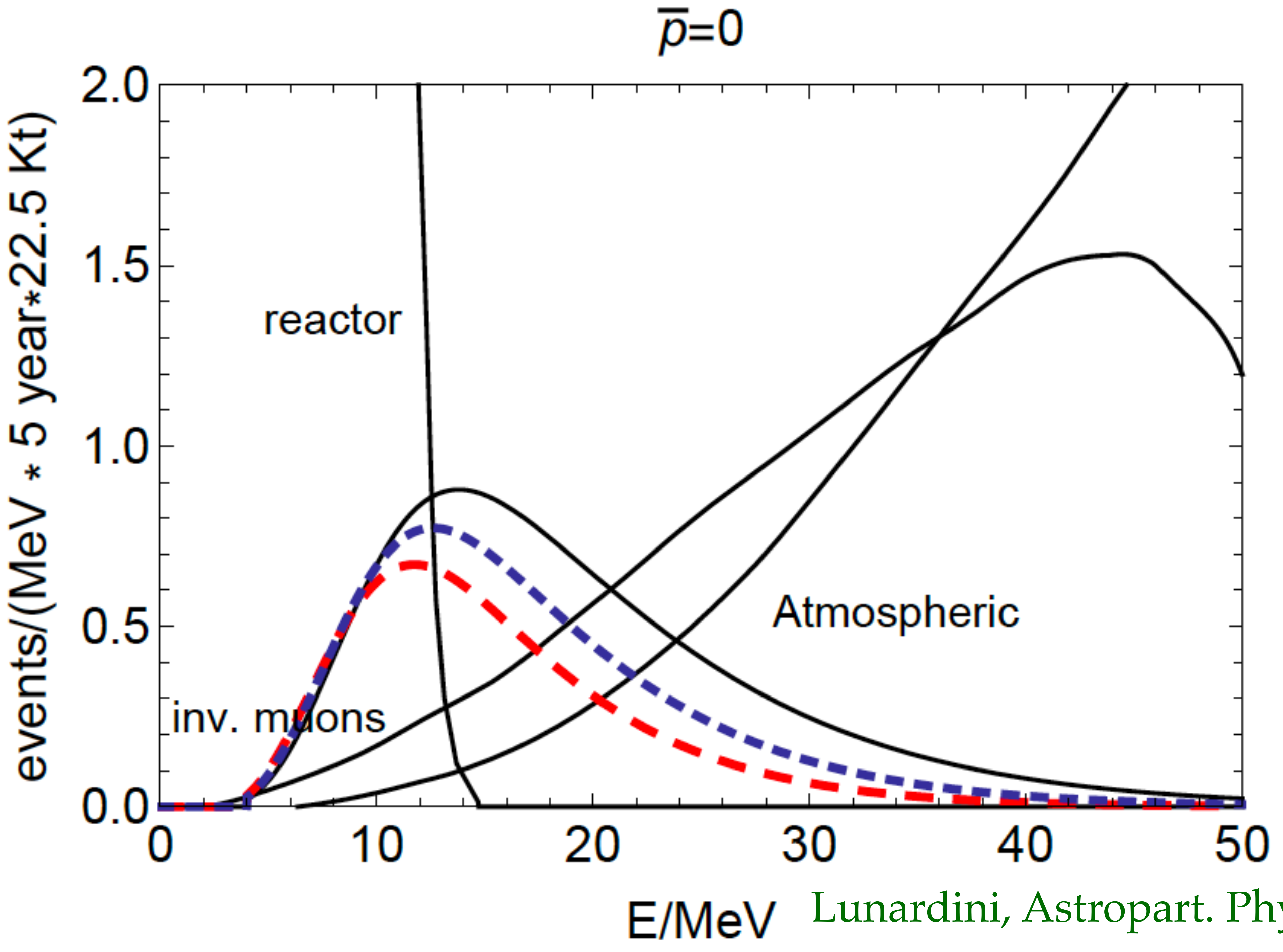
- Invisible muons: $\nu_\mu + N \to \mu + N'$. If muon energy is below Cherenkov threshold, it can only be detected through decay.

- Low energy atmospheric neutrinos. Isotropic background.

Gd doping: GADZOOKS!

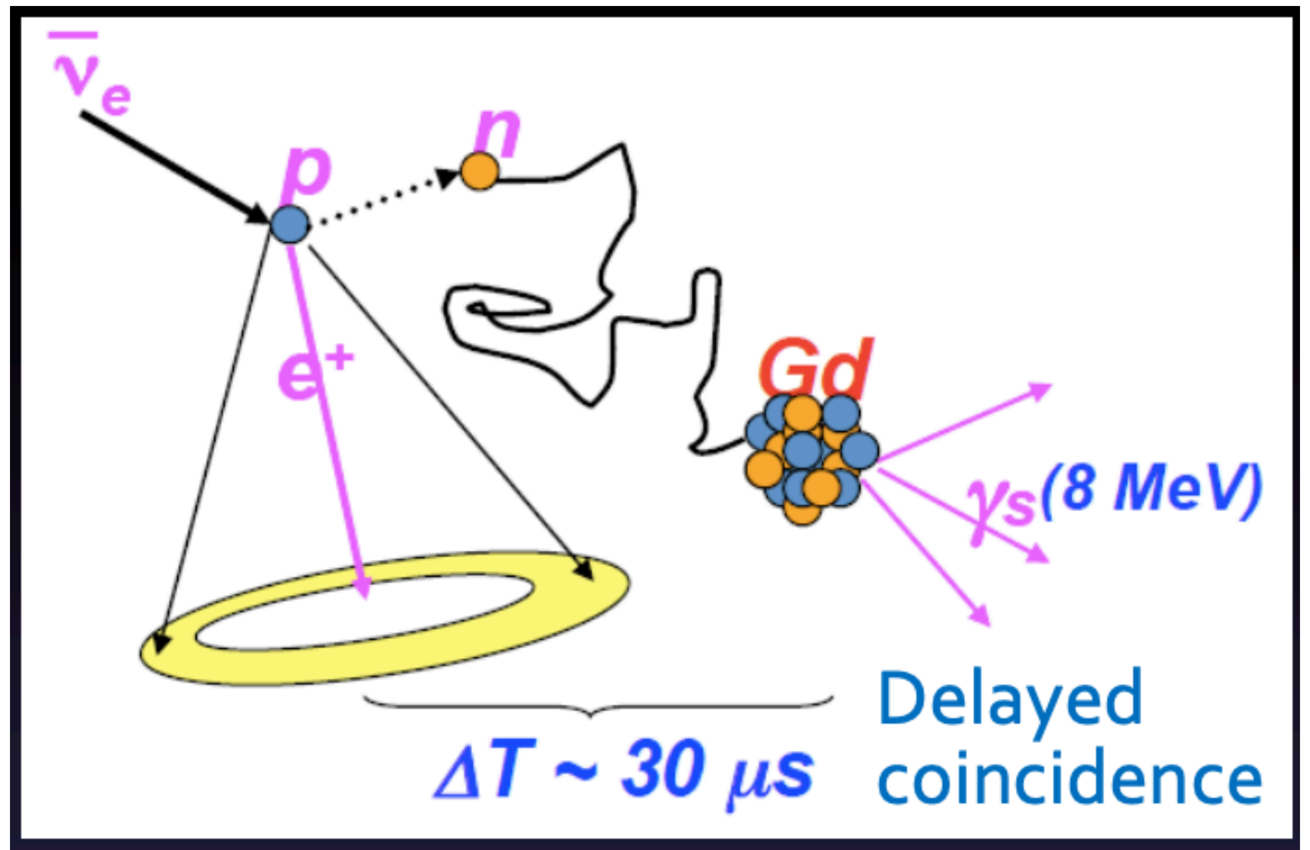
Beacom, Vagins, PRL2004





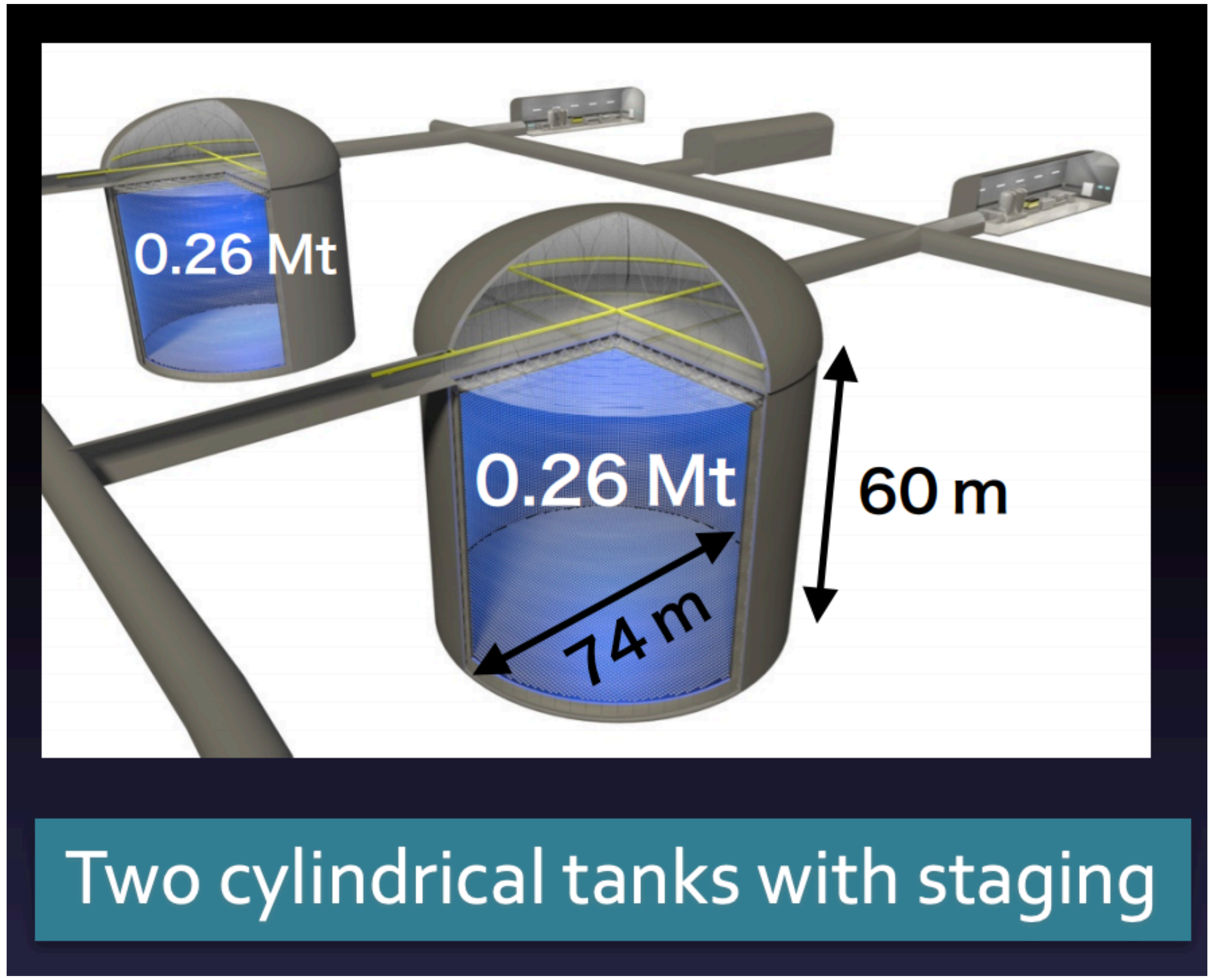
Lunardini, Astropart. Phys2016

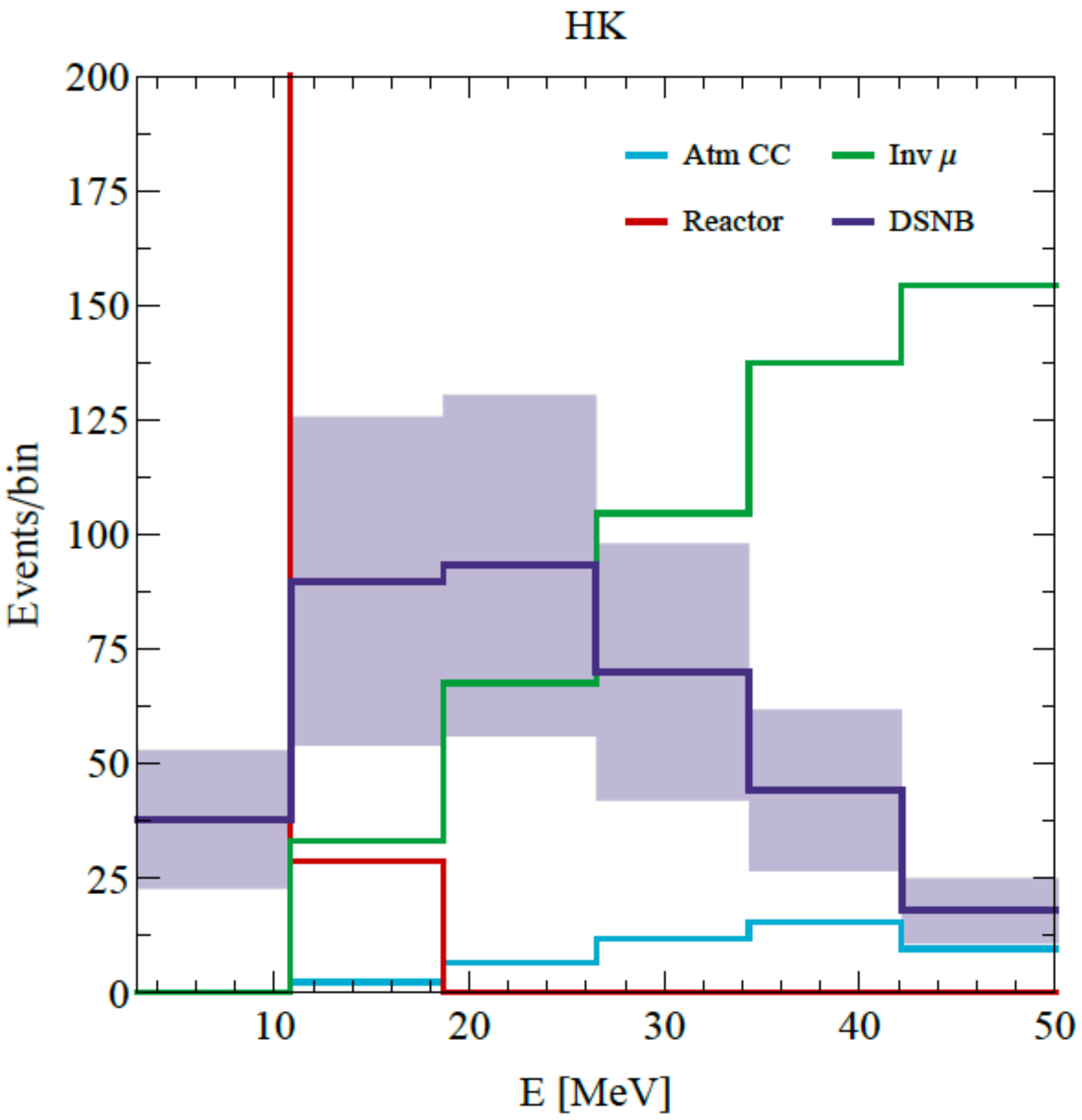
- Solution: Gd doping.
- Reduces energy threshold.
- Background due to spallation will be subtracted almost completely and the one due to invisible muons will be reduced by a factor of 5.



ΔT~30 μs, Vertices within 50 cm

Future Detection: Hyper-Kamiokande + Gd

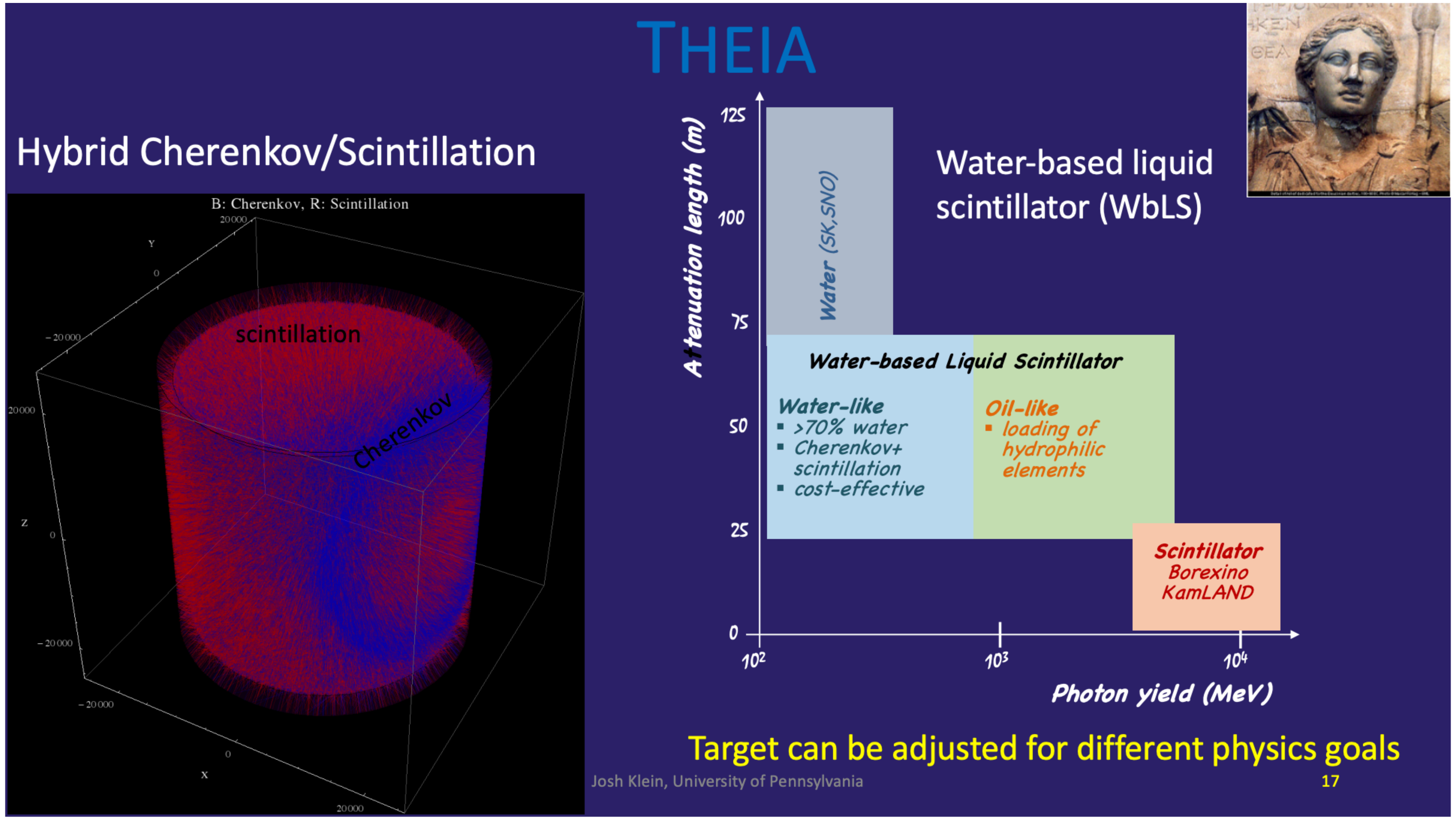


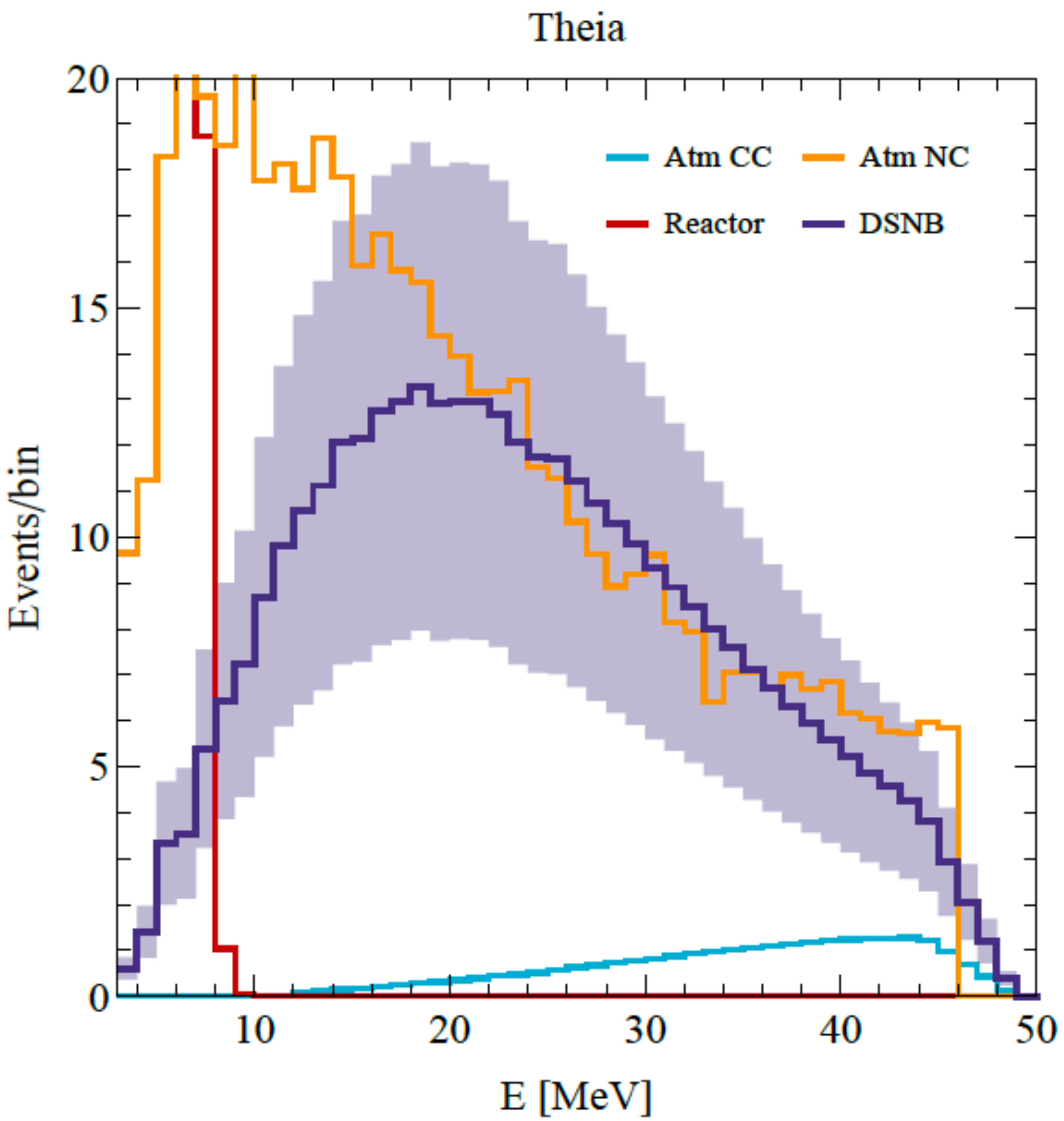


- HK enriched with Gd provides excellent detection prospects.
- Results with 1 tank with 10 years of data taking.
- Backgrounds same as SK.

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

Future Detection: Theia





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

- 100 kT detector, with 10 years of data-taking
- Low energy resolution of scintillator, and high-energy 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.

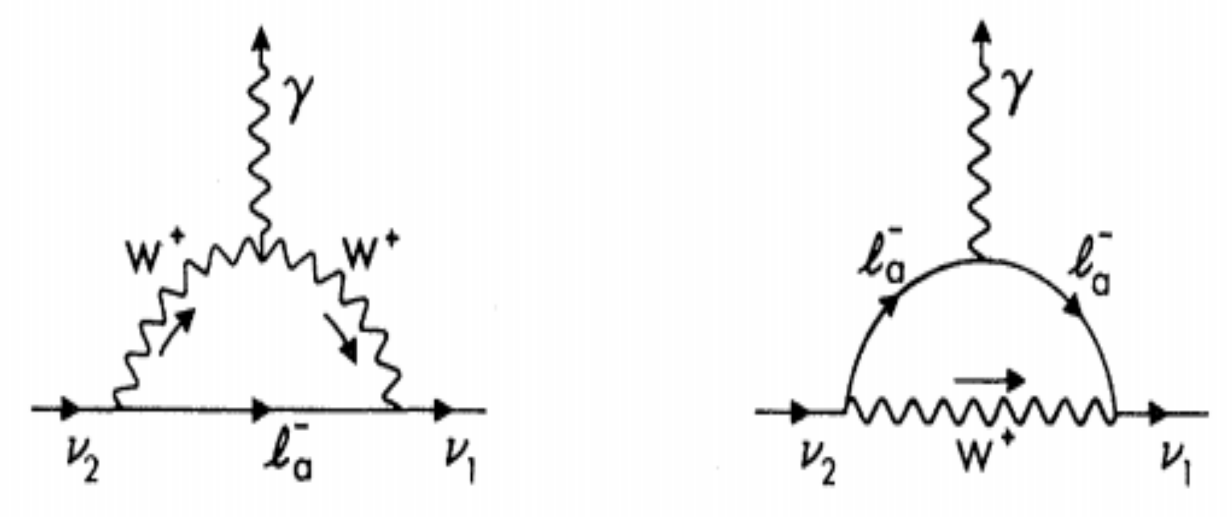
- New physics can mediate faster decay.

$$\mathscr{L} \supset \nu_l \mathbf{P_L} \nu_h \, \varphi + \mathrm{H.c.}$$

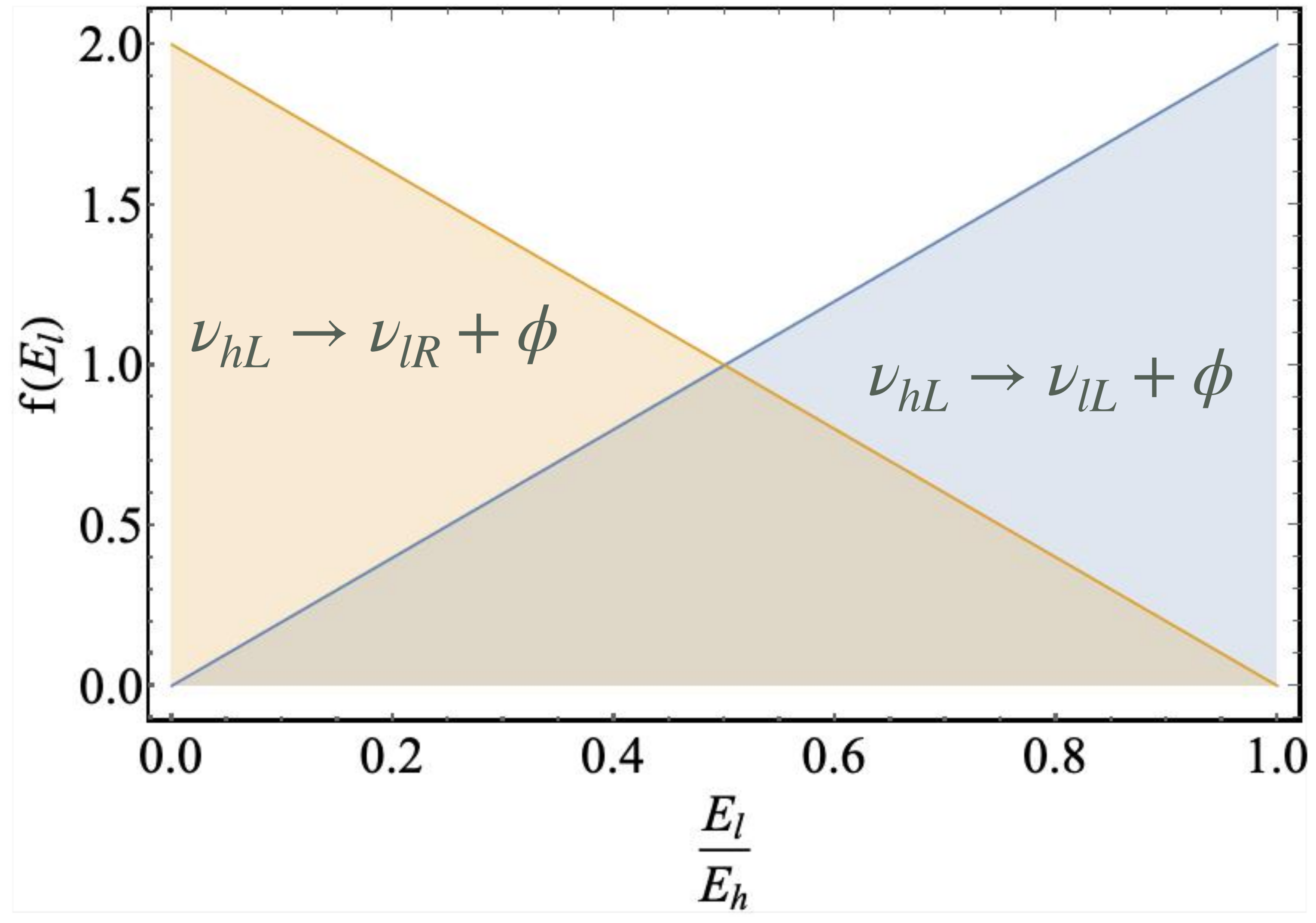
$\nu_{hL} \to \nu_{lL} + \varphi$ …. Helicity cons. (h.c.)

$\nu_{hL} \to \nu_{lR} + \varphi$ …. 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)

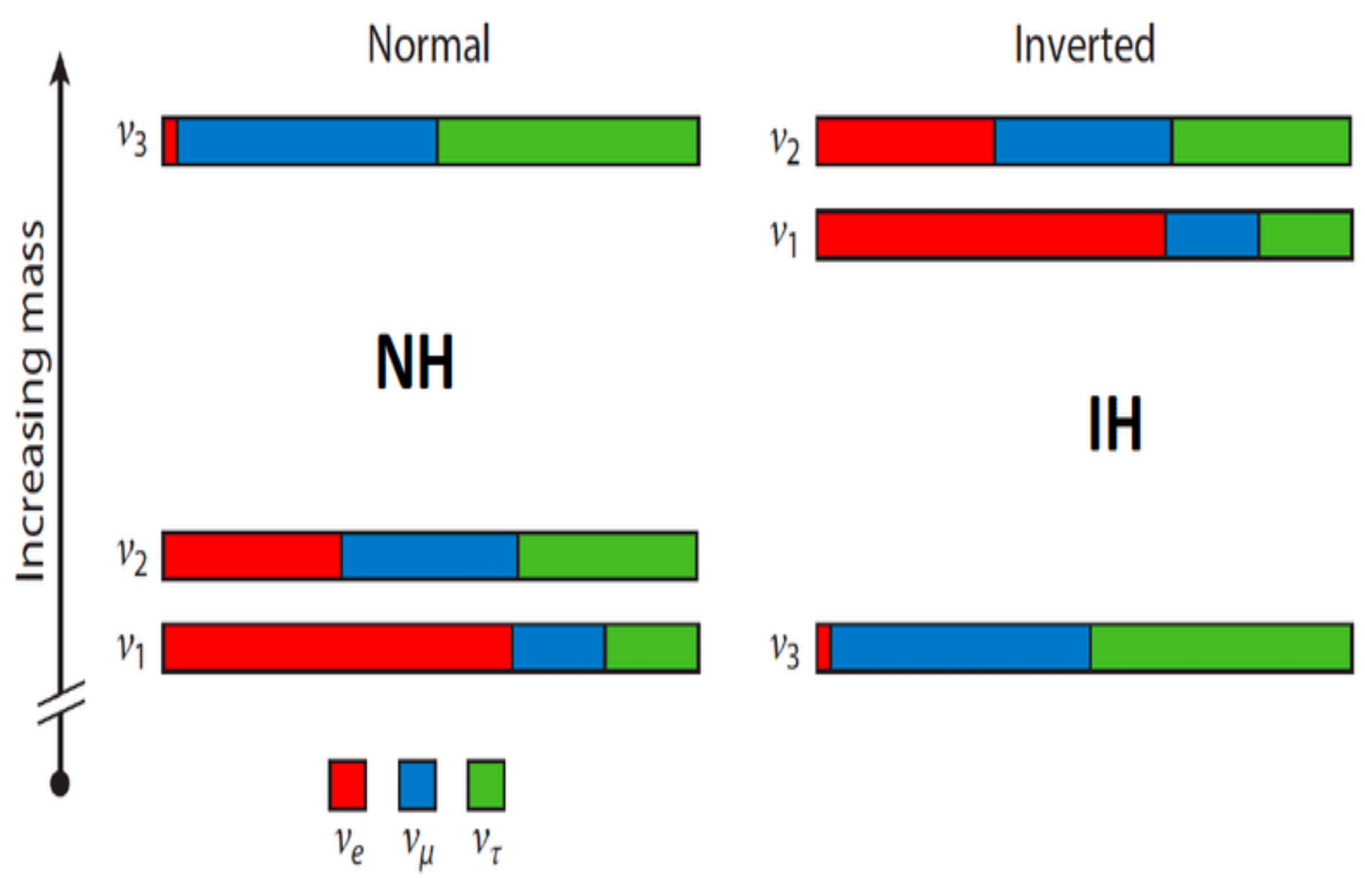


de Gouvea, Martinez-Soler, MS, PRD2020

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

$\nu_l \equiv \nu_1$

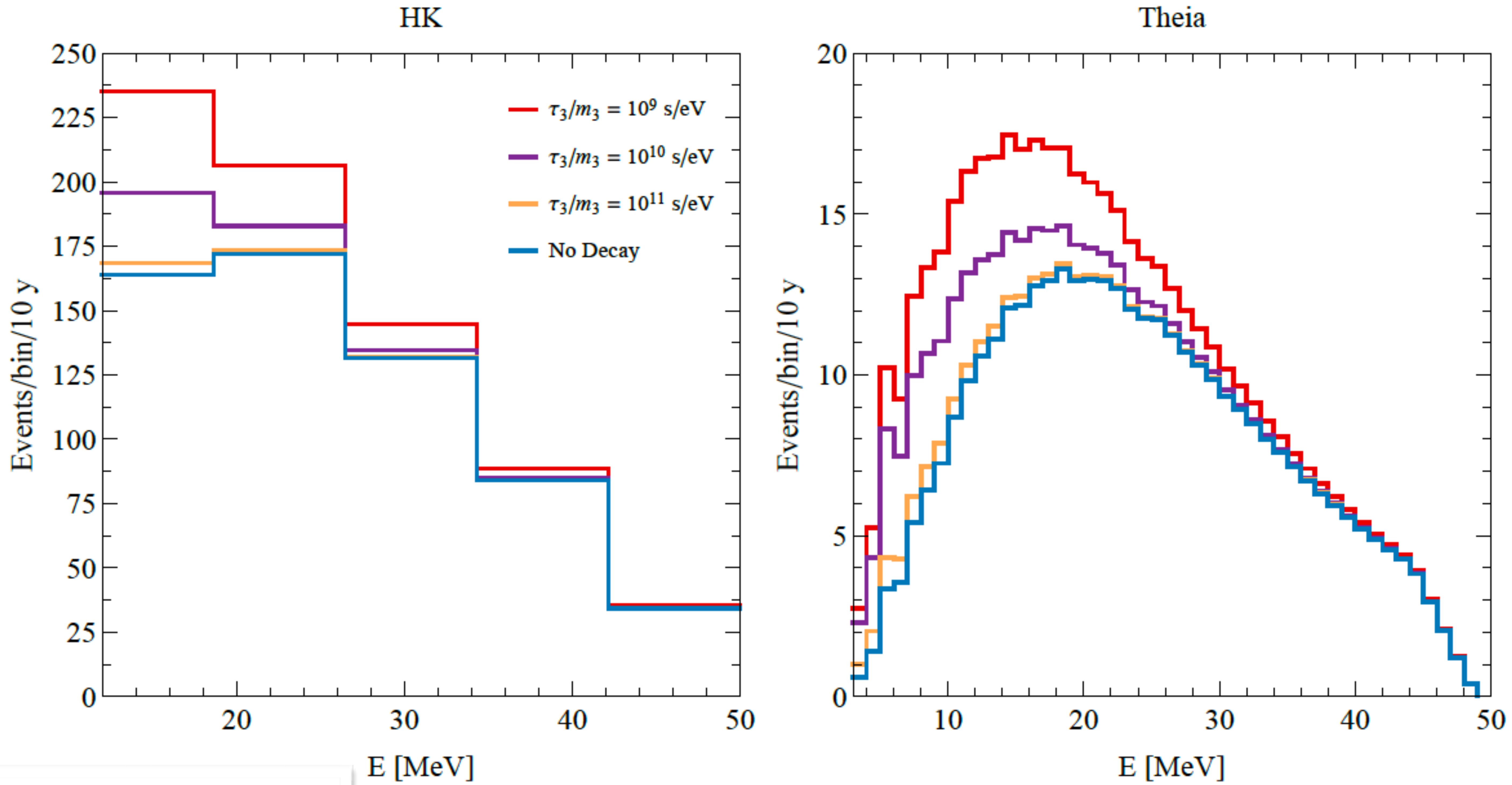
$\nu_h \equiv \nu_3$

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

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.



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

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

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

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

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.

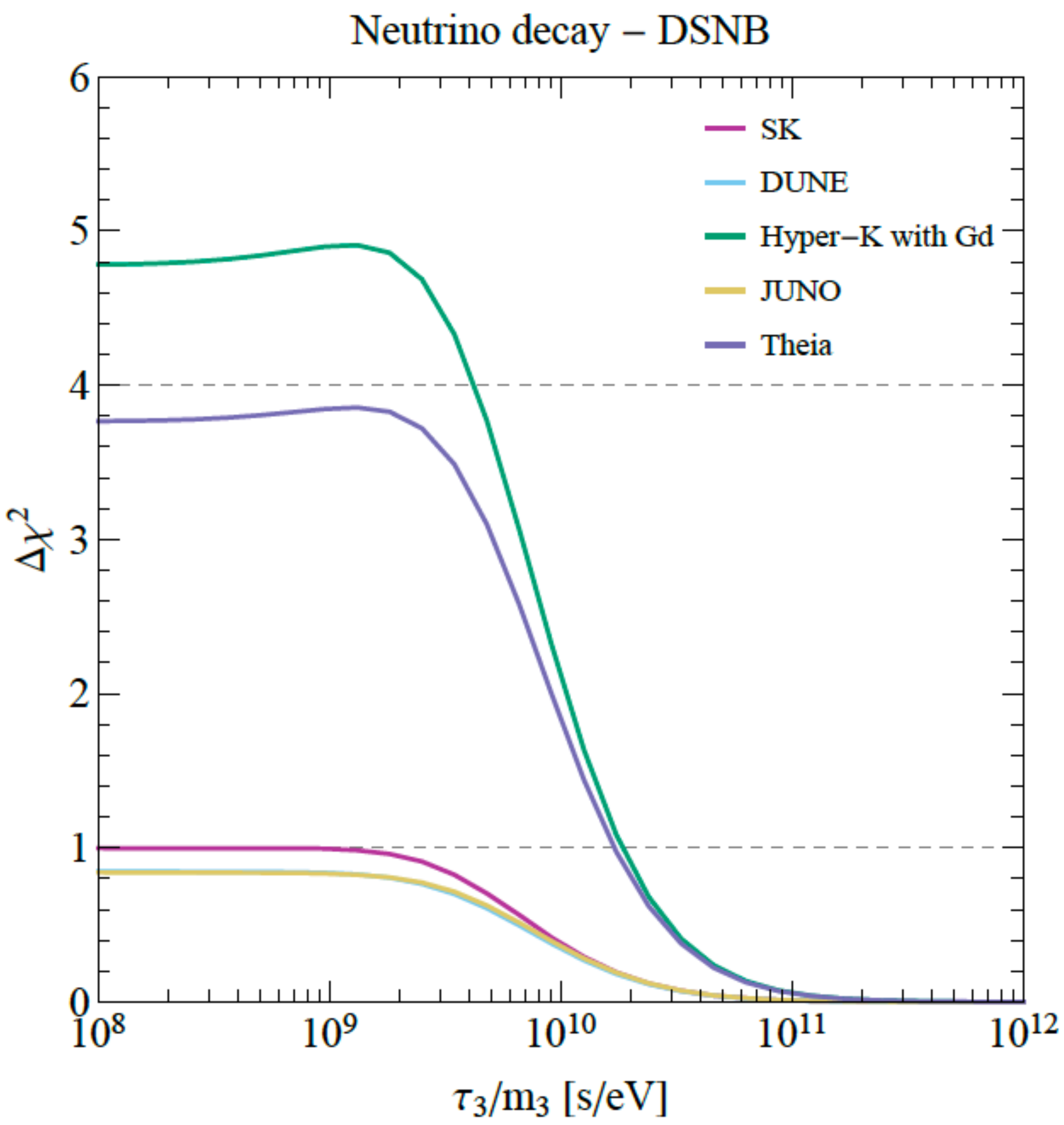
  Gonzalez-Garcia, Maltoni, PLB2008 + …

- 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, 2007.13748

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 are Dirac, but have sub-dominant Majorana mass terms.
  Oscillations driven by this tiny mass.

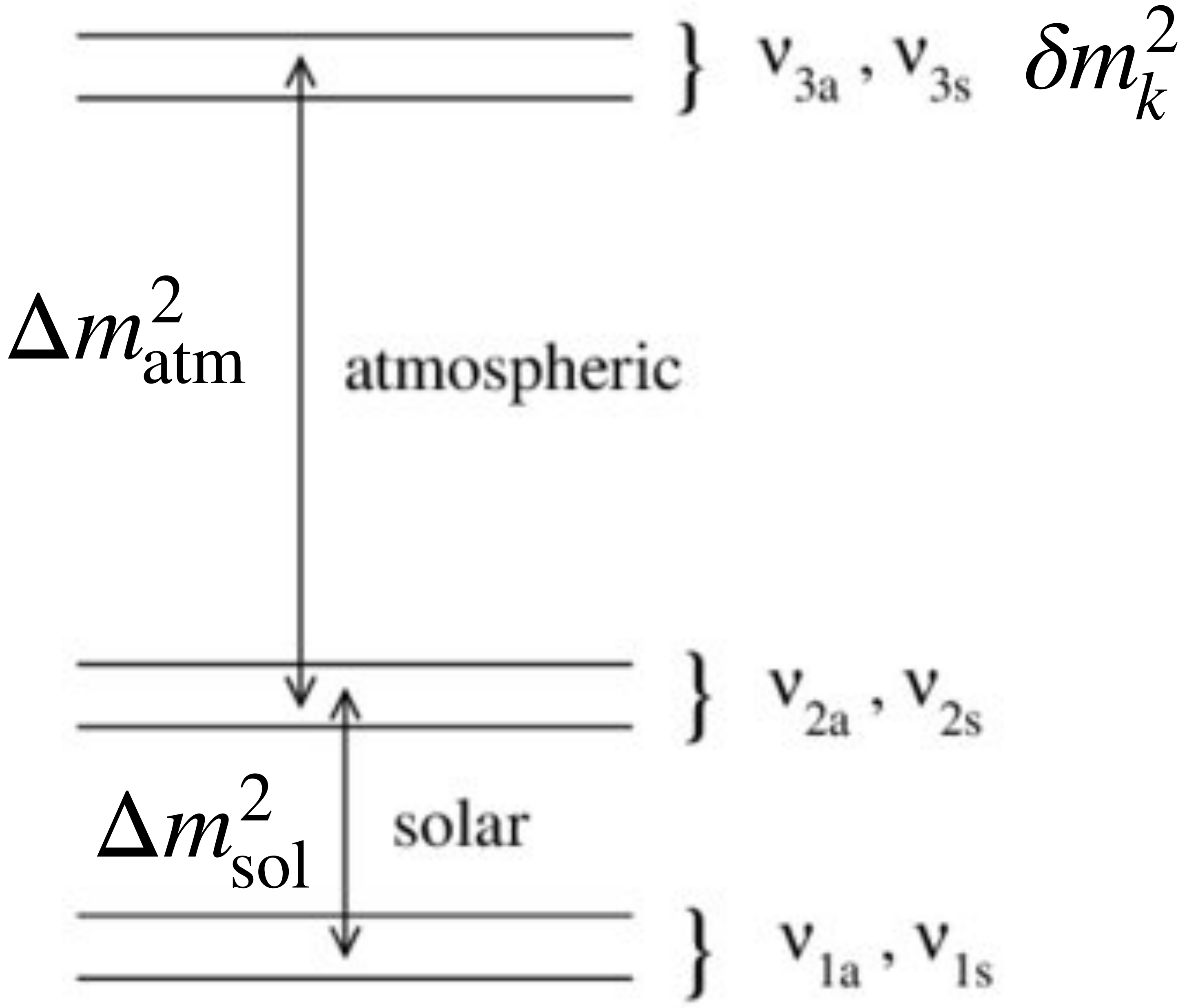
- Generic Majorana mass matrix $\begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}$.

  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 $\Delta m^2_{\rm atm}$.

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

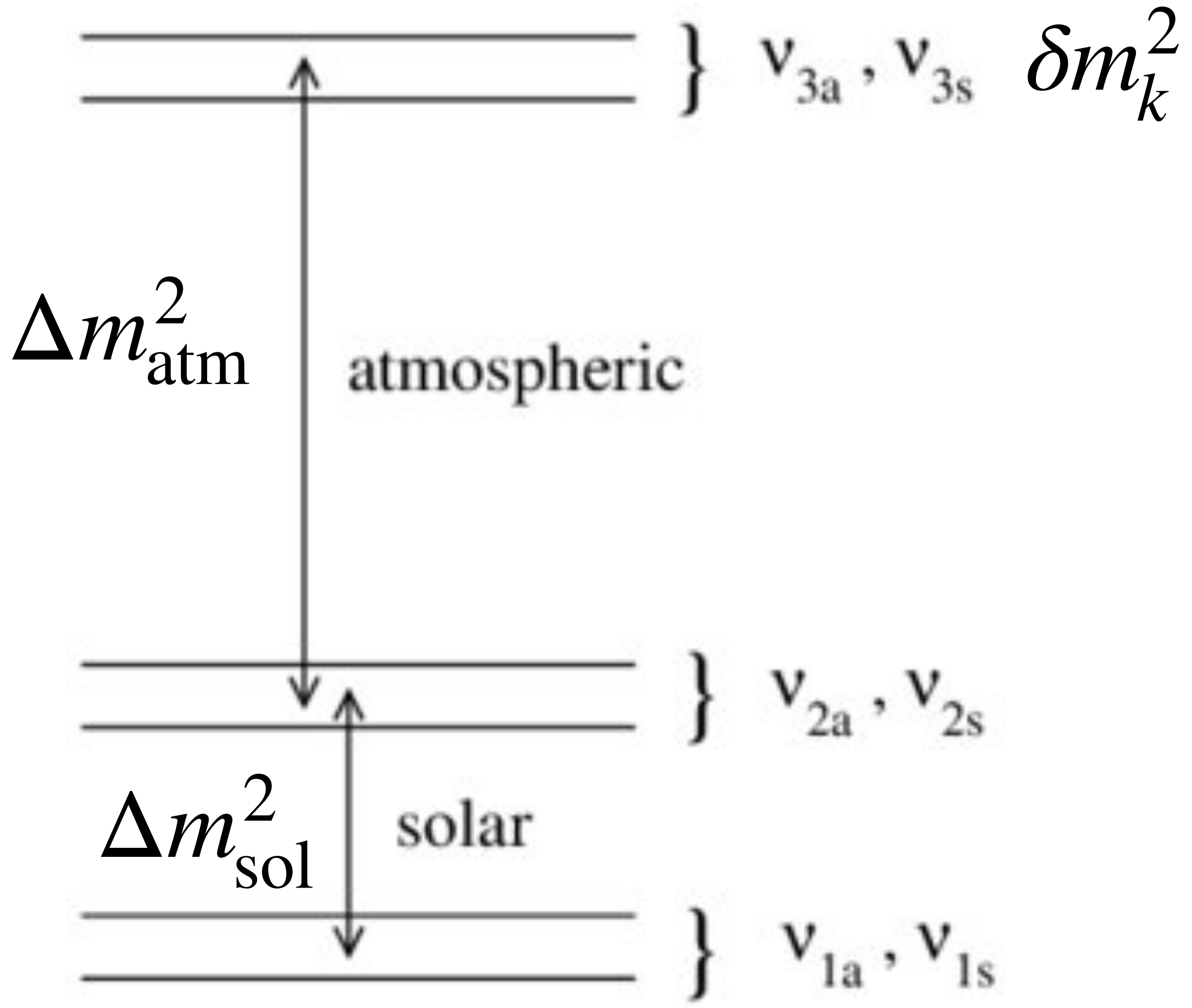
- Maximally mixed active and sterile states.



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 $\nu_i \to \nu_\beta$

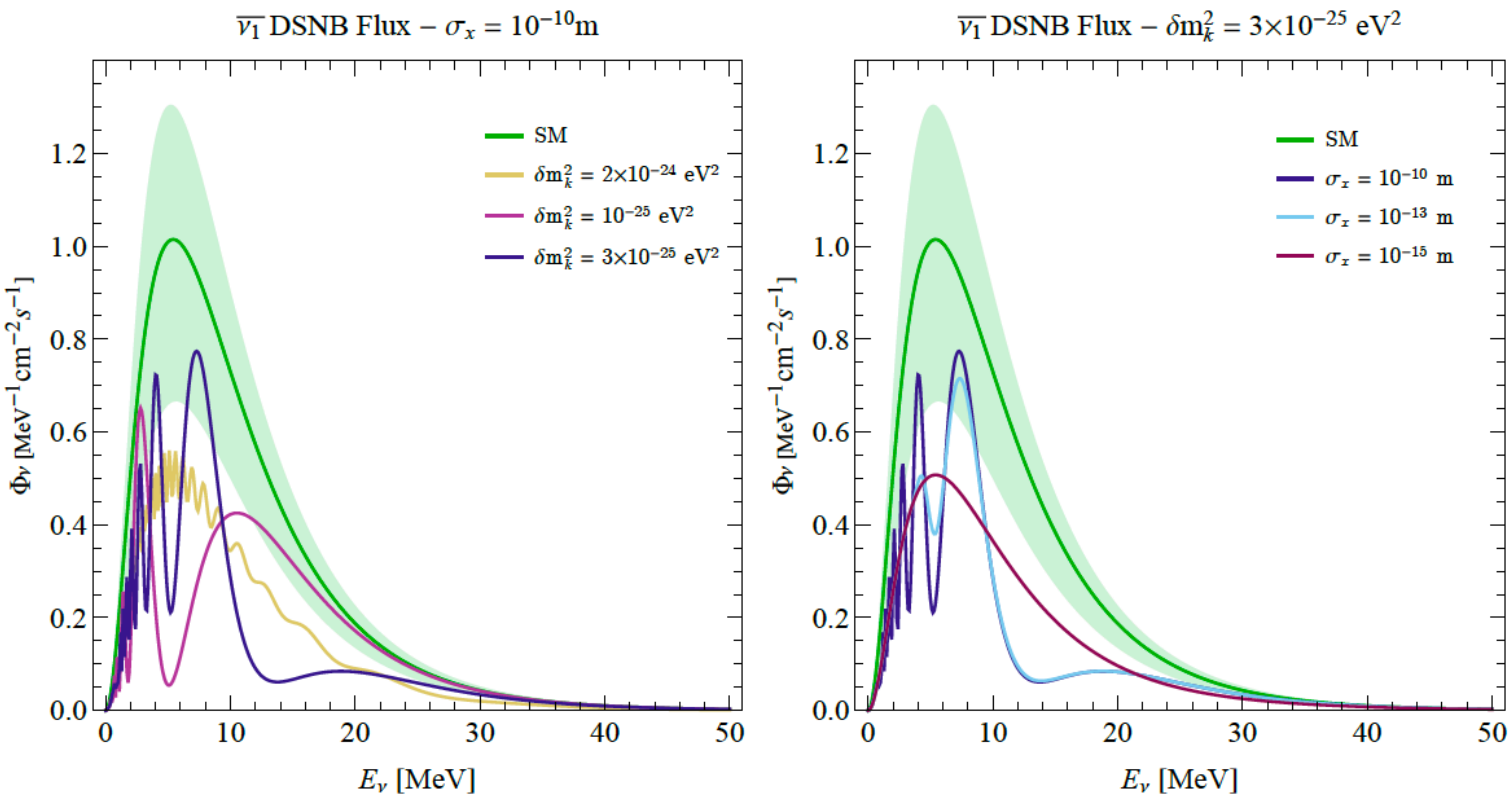
$$P_{i\beta}(z,E) = \frac{1}{2}|U_{\beta k}|^2\left(1+e^{-\left(\frac{L_3(z)}{L_{\rm coh}}\right)^2}\cos\left(\frac{L_2(z)}{L_{\rm osc}}\right)\right)$$

A smaller σ_x can cause decoherence.

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

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

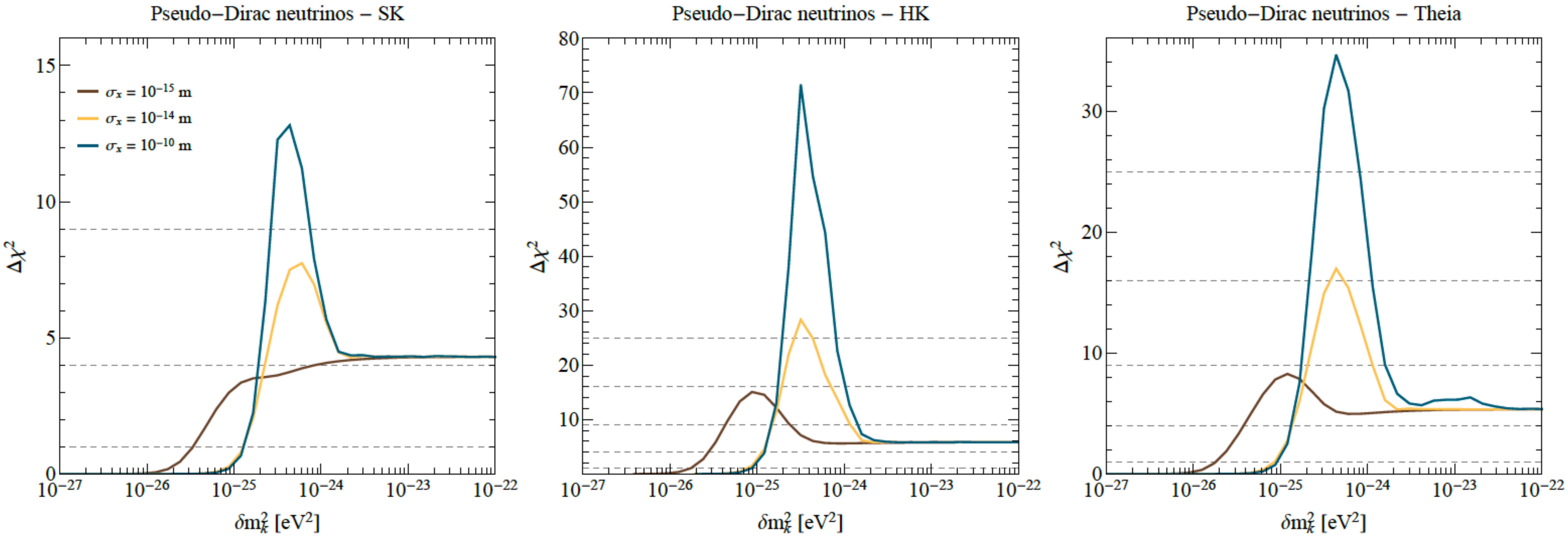
Oscillations due to pseudo-Dirac nature



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



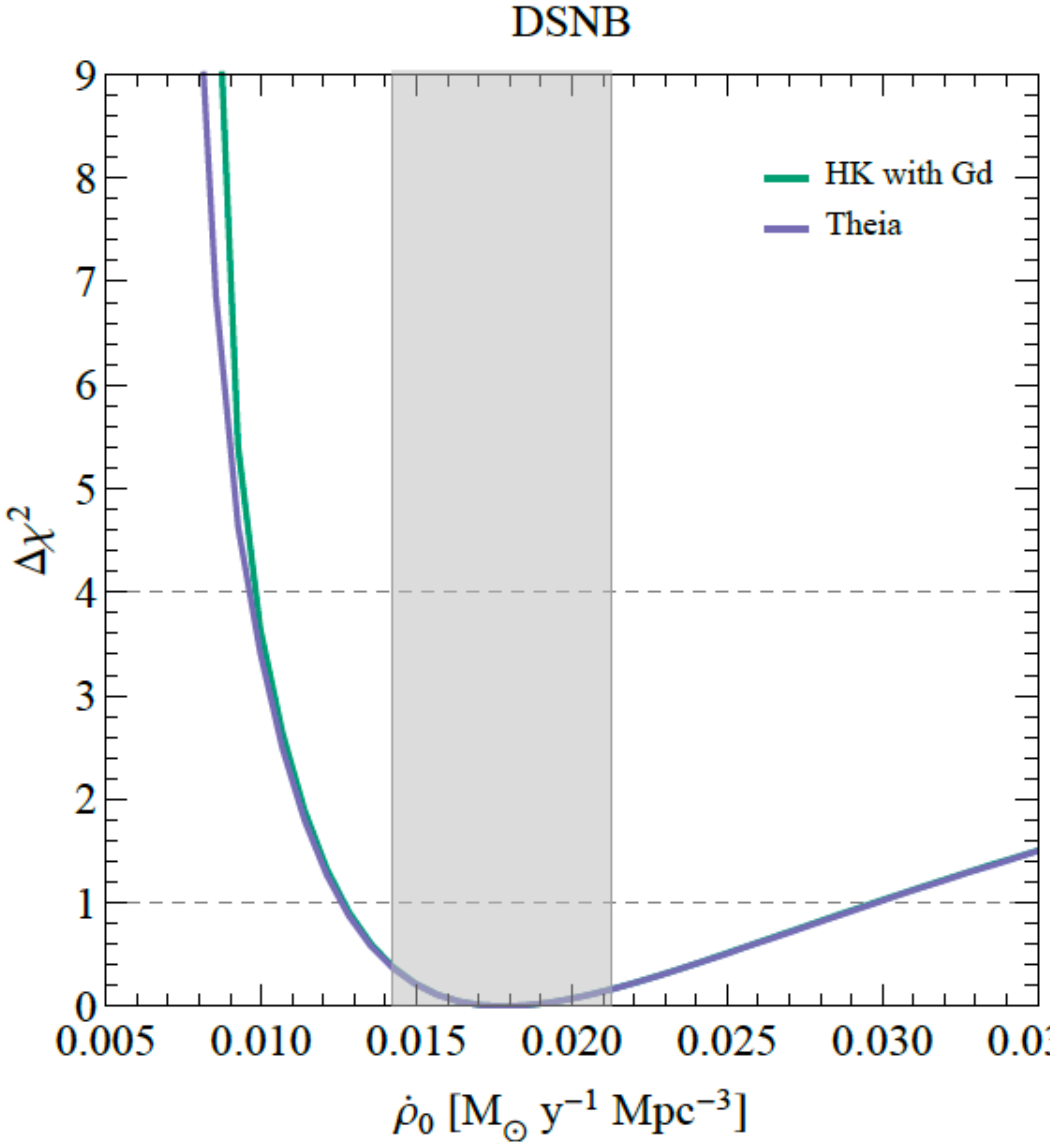
de Gouvea, Martinez-Soler, Perez-Gonzalez, MS, 2007.13748

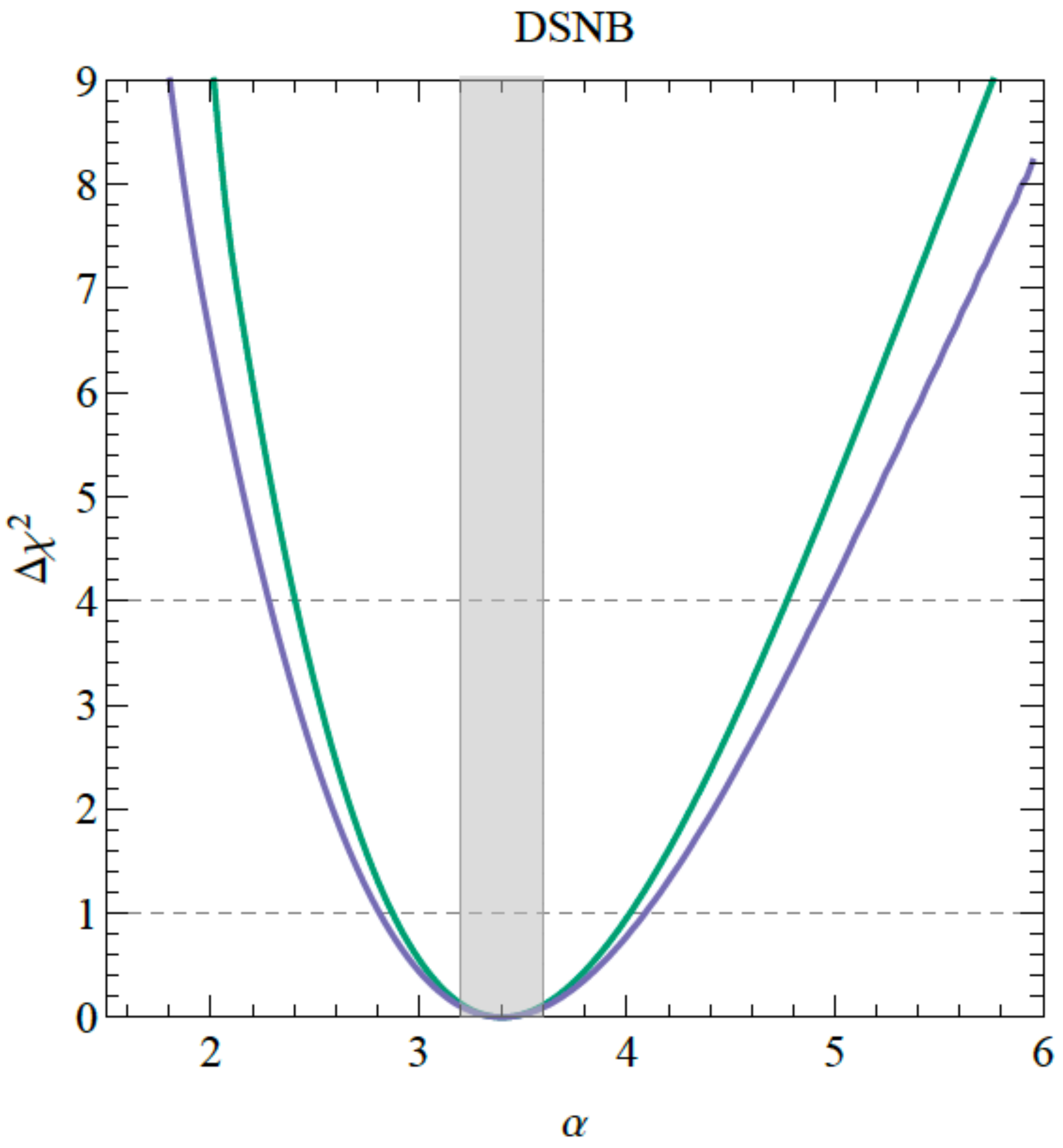
- DSNB sensitive to $\delta m^2 \sim \mathcal{O}(10^{-25}\,\mathrm{eV}^2)$ with a high significance.
- Even if δm^2 is too tiny for oscillations, DSNB is still sensitive to decoherence for small σ_x

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





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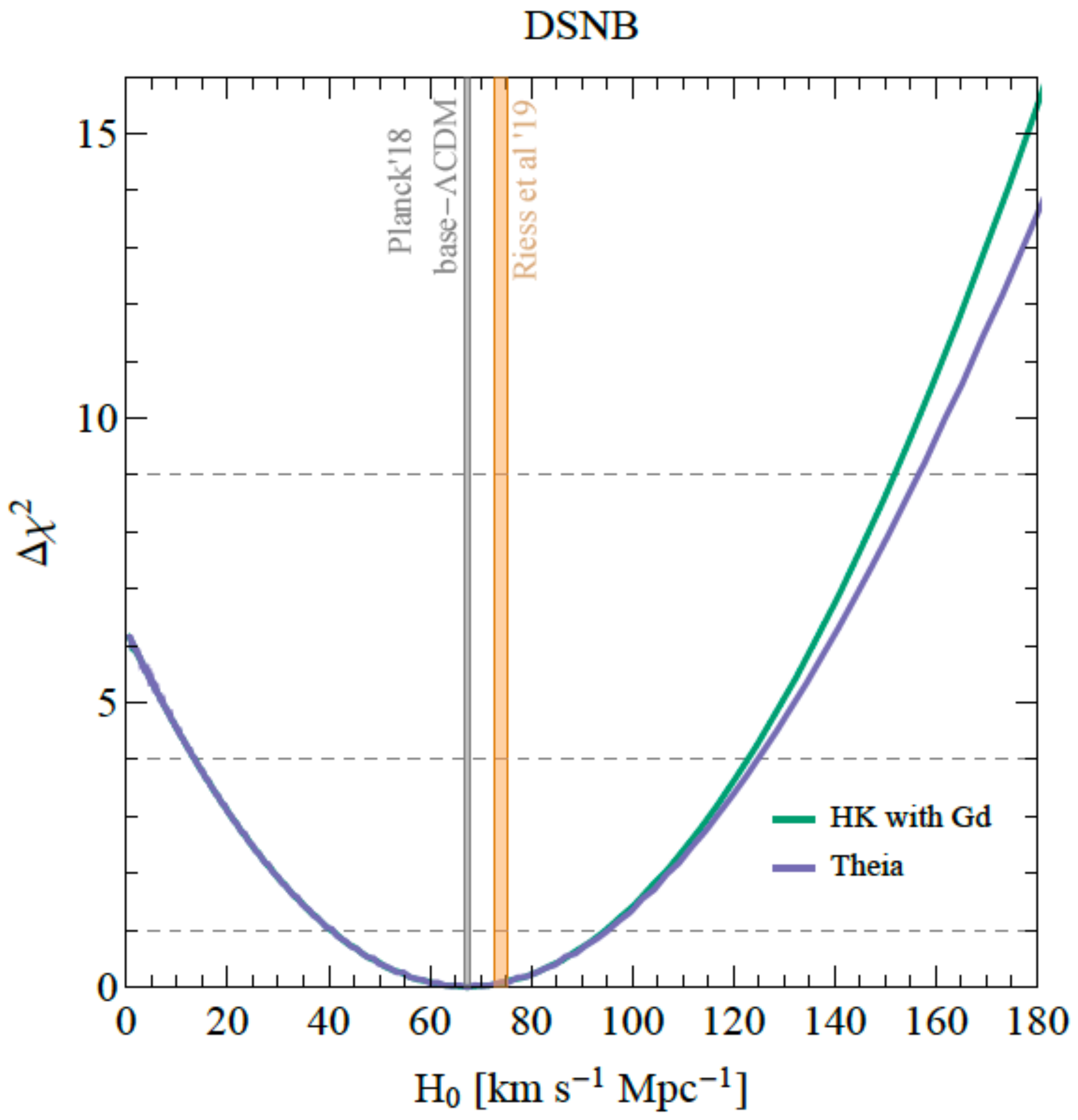
$$\dot{\rho}_*(z) = \dot{\rho}_0 \left[(1+z)^{-10\alpha} + \left(\frac{1+z}{B}\right)^{-10\beta} + \left(\frac{1+z}{C}\right)^{-10\gamma} \right]^{-1/10}$$

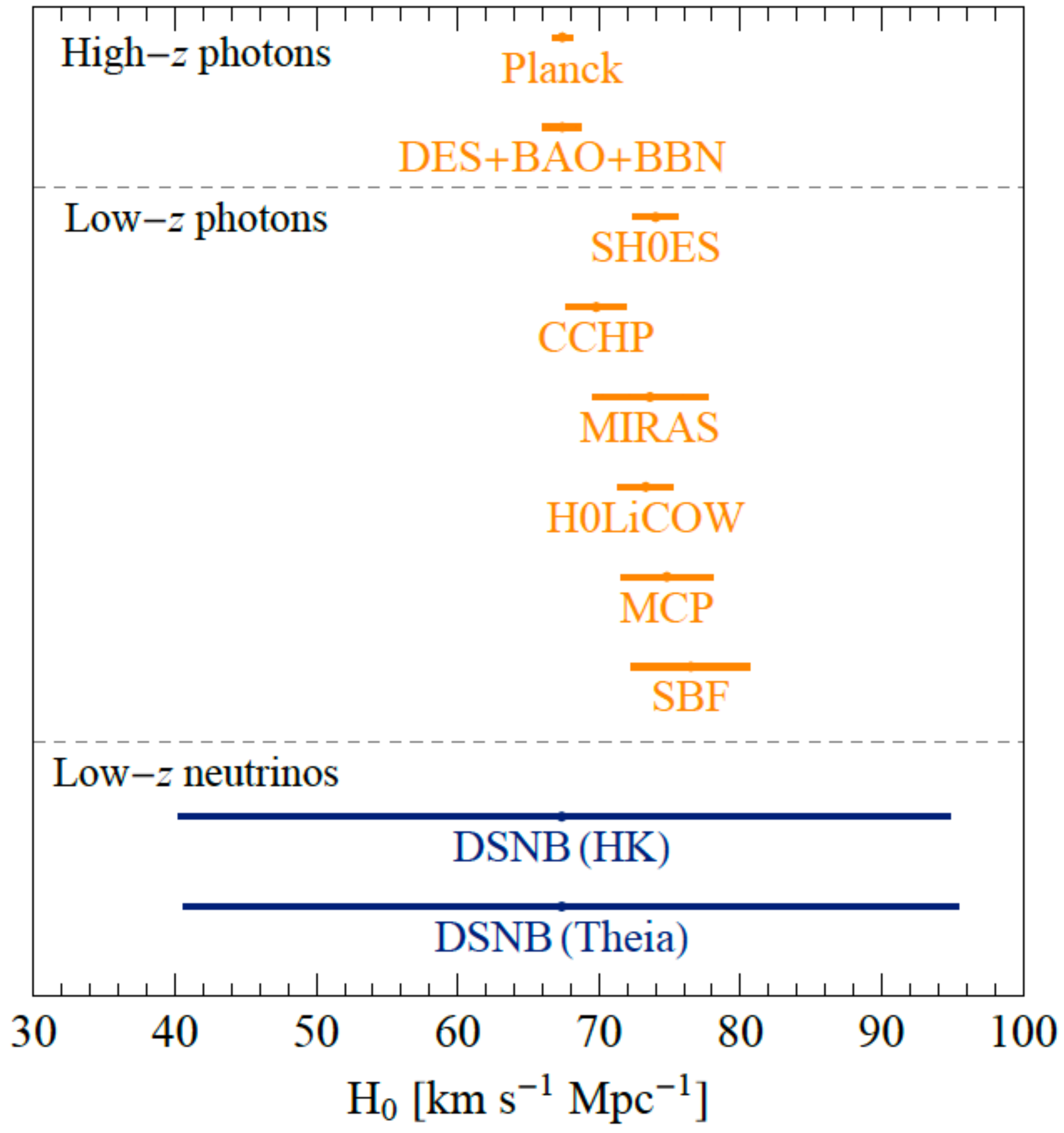
At the 2σ level, the results obtained from the DSNB are almost competetive with those obtained from decades of astronomical surveys.

Hubble constant

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

Cosmology: Hubble Parameter





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

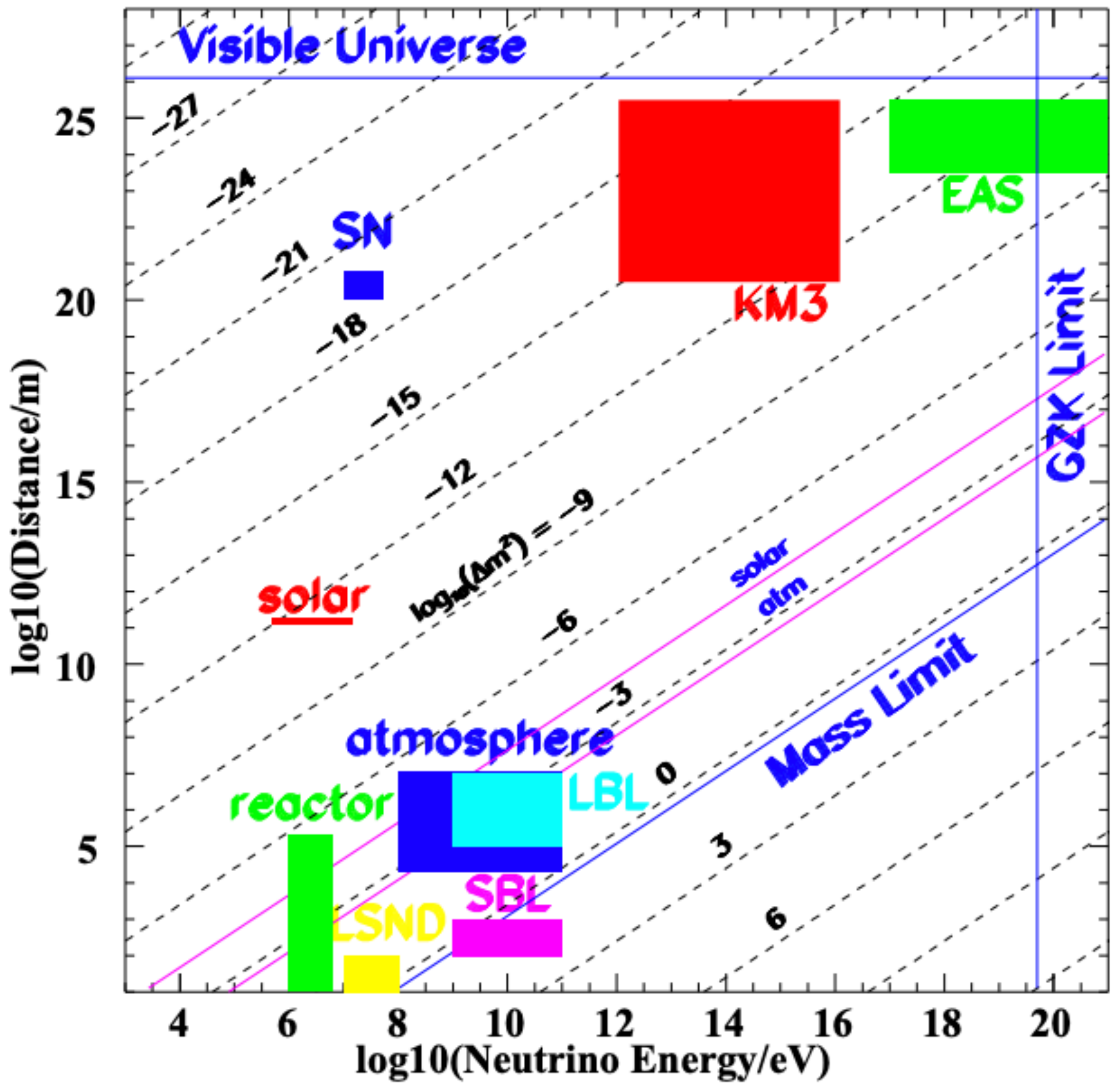
- Distance yardstick using neutrinos. Can confirm expanding Universe after 10 years of running.
- Measure H_0 at 40% level, which is the systematic uncertainty.
- Caveat: Relies on an independent redshift dependent measurement of the SFR.

Conclusions

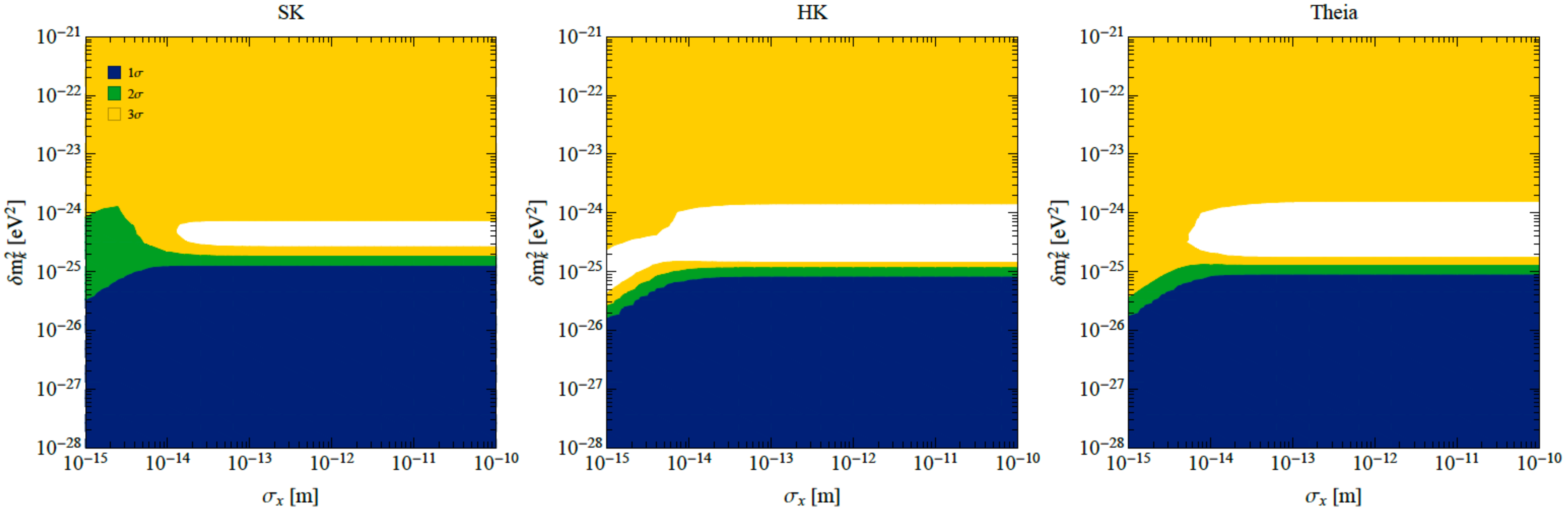
- The DSNB opens up a plethora of avenues for neutrino astronomy, next giant leap from the Sun and SN1987A.
- A future detection can provide neutrino only measurement of expansion rate of the Universe, complementary to measurement with photons and gravity waves.
- Competetive constraints on cosmological 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!

Pseudo-Dirac Constraints

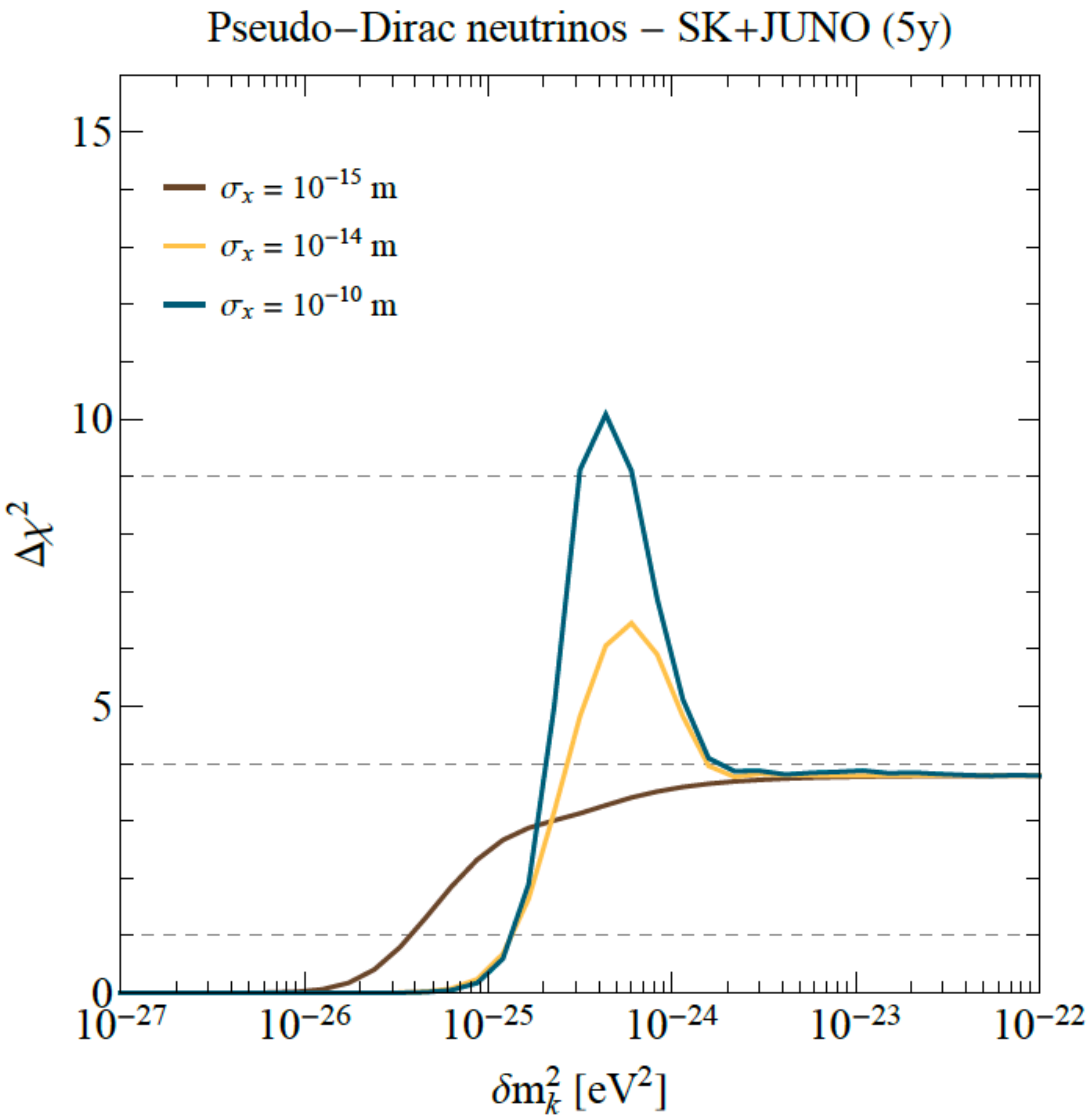


Beacom, Bell, et al., PRL2004



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