Using neutrinos from relic supernovae to test ν properties

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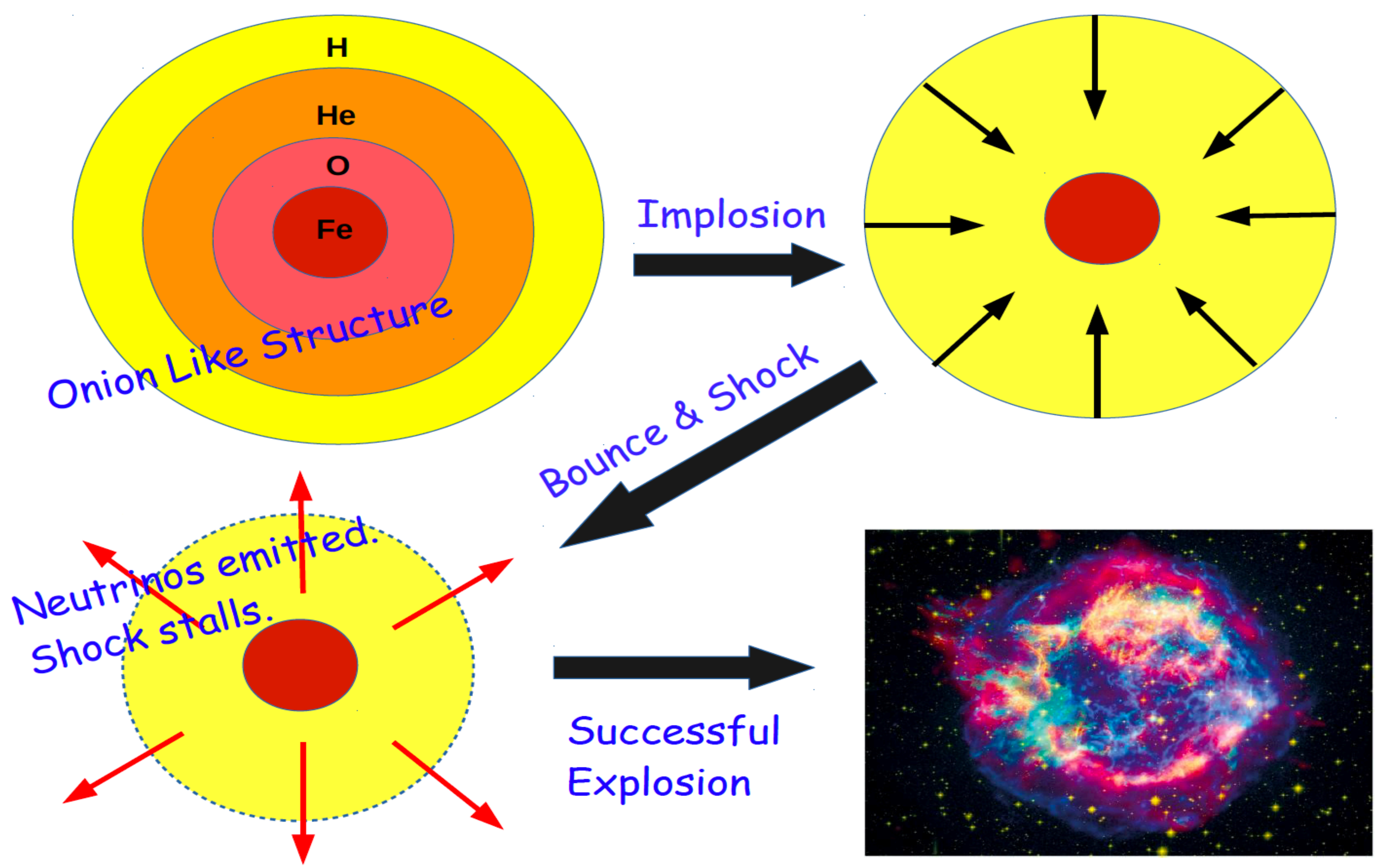
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

NOW 2022
Neutrino Oscillation Workshop

Core-collapse SNe: Mechanism



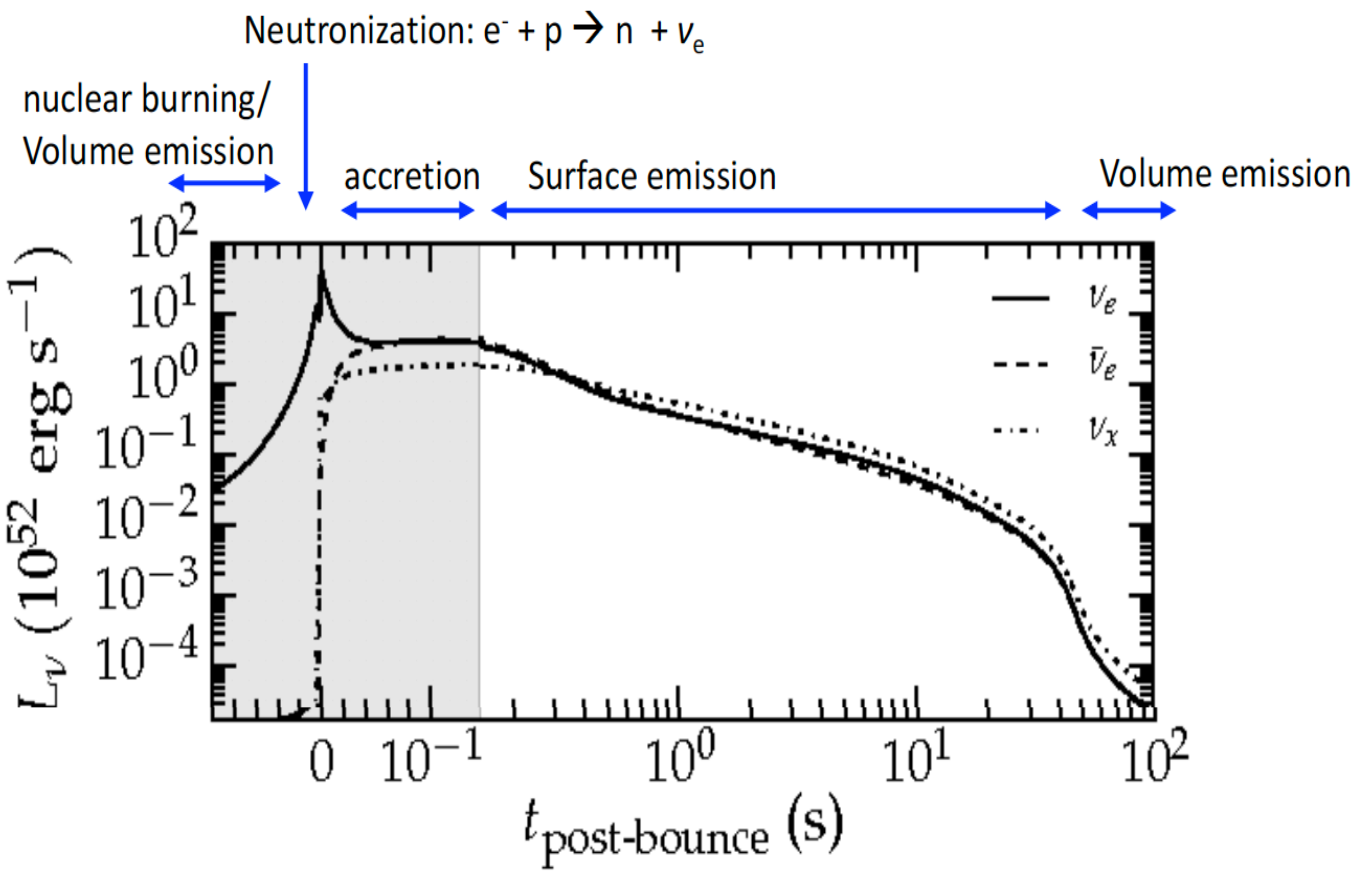


Figure from Roberts and Reddy, Handbook of Supernovae, Springer Intl., 20

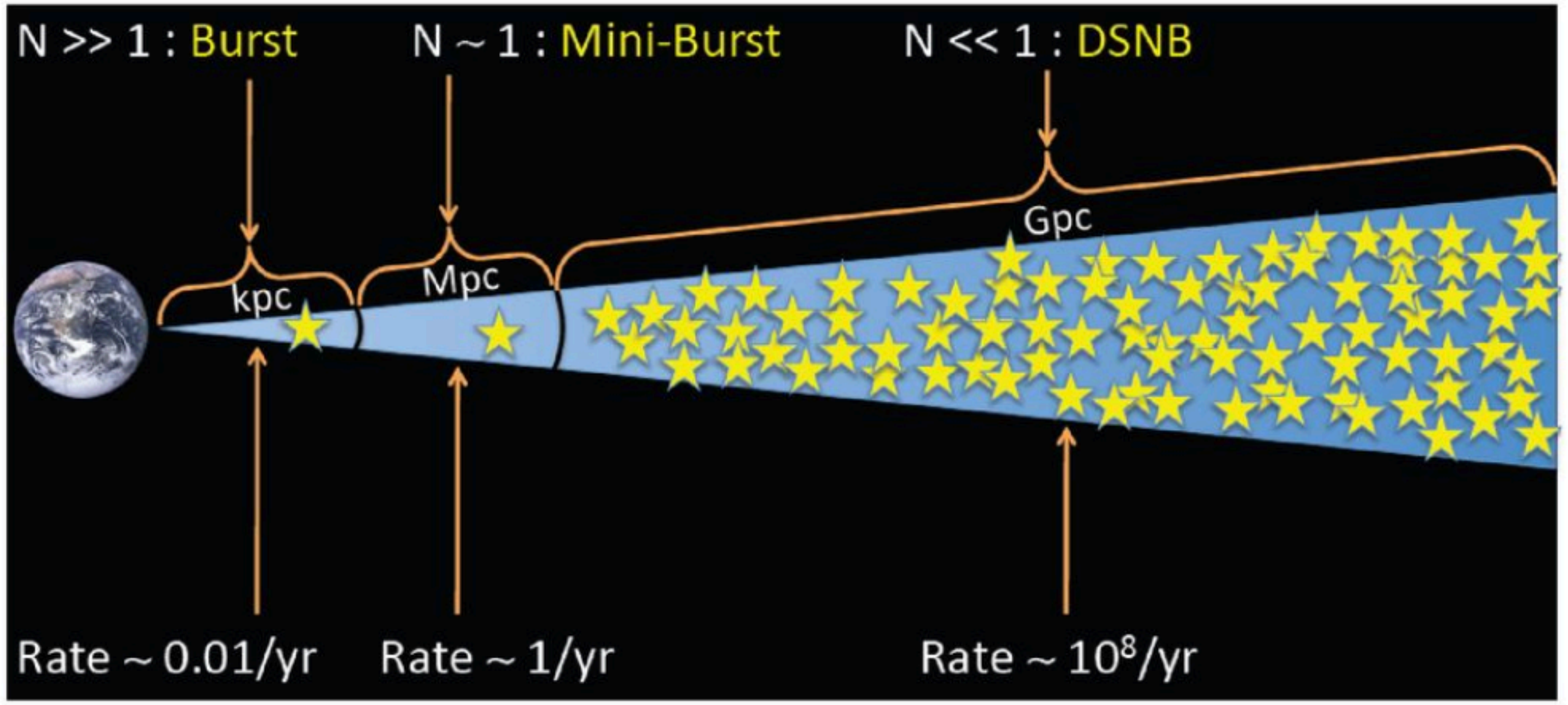
- Core-collapse SNe leading to MeV neutrino emission.
- Almost thermal spectra for different flavors.
- SN1987A: some of the strongest bounds on neutrino properties!

Talks by
B. Dasgupta,
I. Tamborra,
K.Kotake,
L. Johns,
A. Suliga

The Diffuse Supernova Neutrino Background

- A galactic SN is very rare. So, should we wait a lifetime?
- 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?

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

Beacom, Ann.Rev.Nucl.Part.Sci. 2010
Lunardini, Astropart. Phys 2016

SN Neutrino spectra

$$F_{\nu_\beta}(E_\nu) = \frac{1}{E_{0\beta}} \frac{(1+\alpha)^{1+\alpha}}{\Gamma(1+\alpha)} \left(\frac{E_\nu}{E_{0\beta}}\right)^{\alpha} e^{-(1+\alpha)\frac{E_\nu}{E_{0\beta}}}$$

Cosmological SN rate

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

Cosmology

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

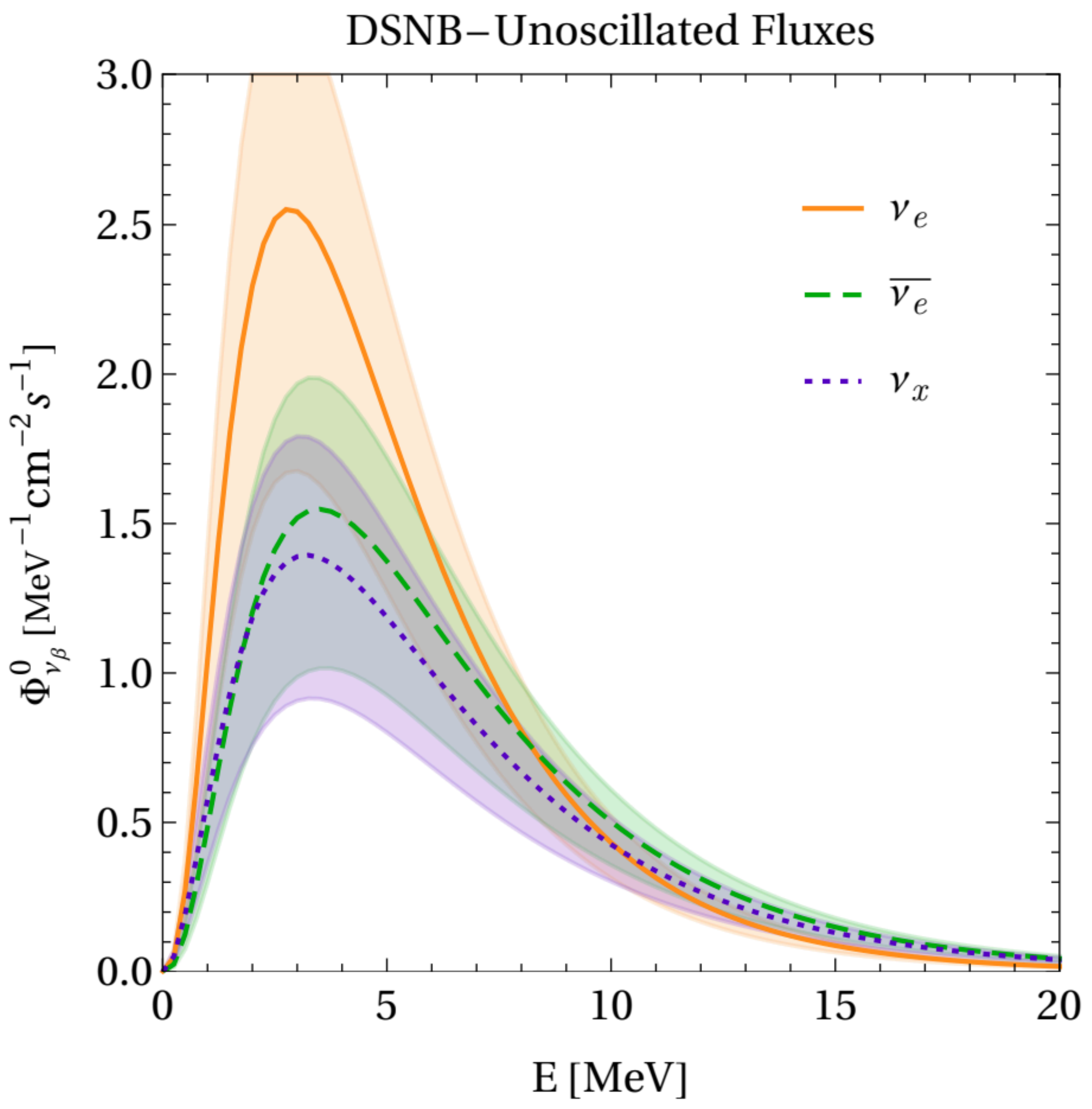
Putting all ingredients together

- The DSNB window ~10-26 MeV.
- 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.

  Atmospheric ν: Low energy tails of ν_e and $\bar{\nu}_e$. Exceeds the DSNB at E~30 MeV.
- Experiments: SK, JUNO, DUNE, HK, Theia, Resnova, many others being considered.



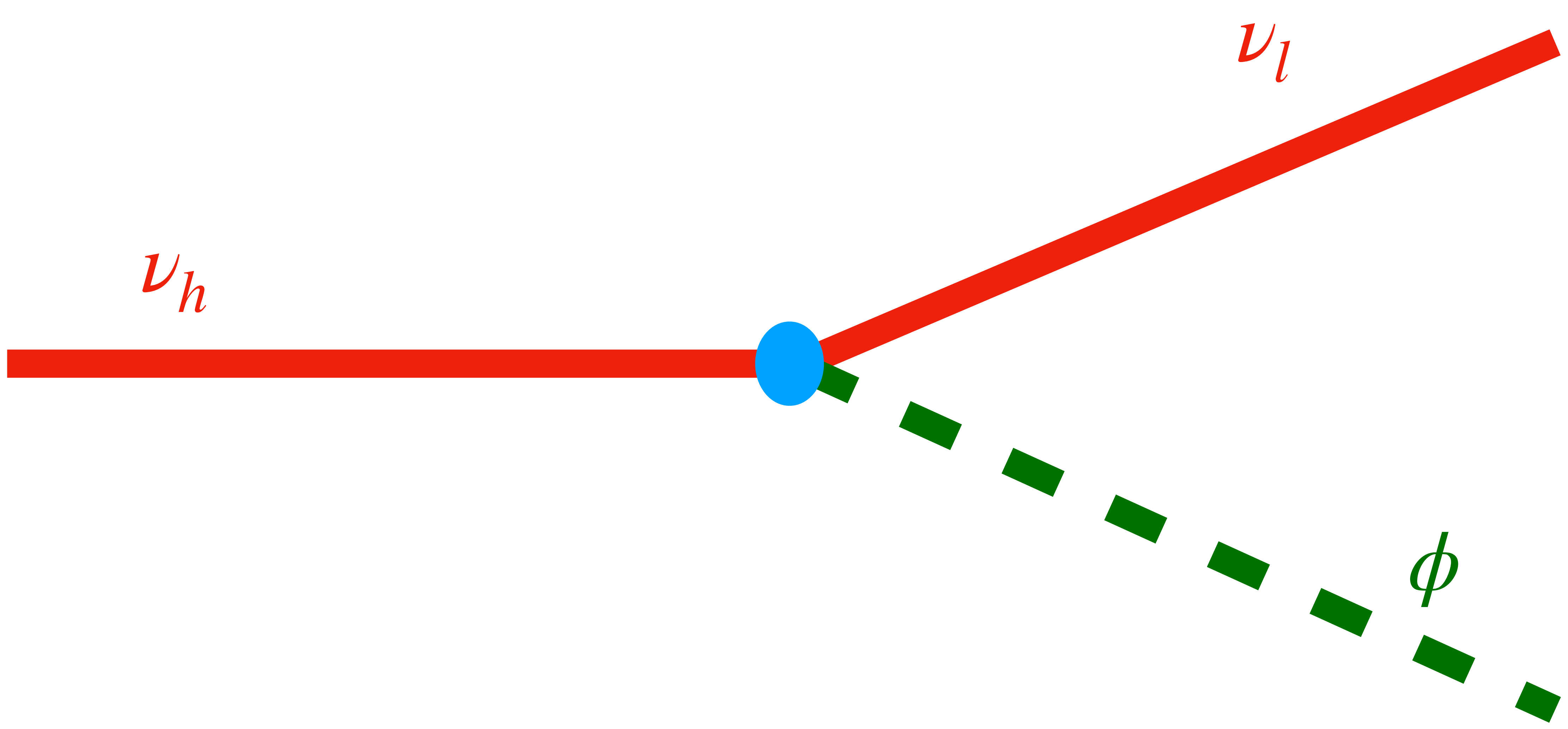
The DSNB as a late Universe laboratory

Multidisciplinary aspects of understanding the supernova neutrinos:

- Particle physics aspects: Neutrino physics in dense media, neutrino properties (this talk), 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…

Based on (1) de Gouvea, Martinez-Soler, Perez-Gonzalez, **MS**, PRD 2020
(2) de Gouvea, Martinez-Soler, Perez-Gonzalez, **MS**, arXiv:2205.01102
(3) Das, **MS**, PRD 2021
(4) Das, Perez-Gonzalez, **MS**, arXiv:2204.11885

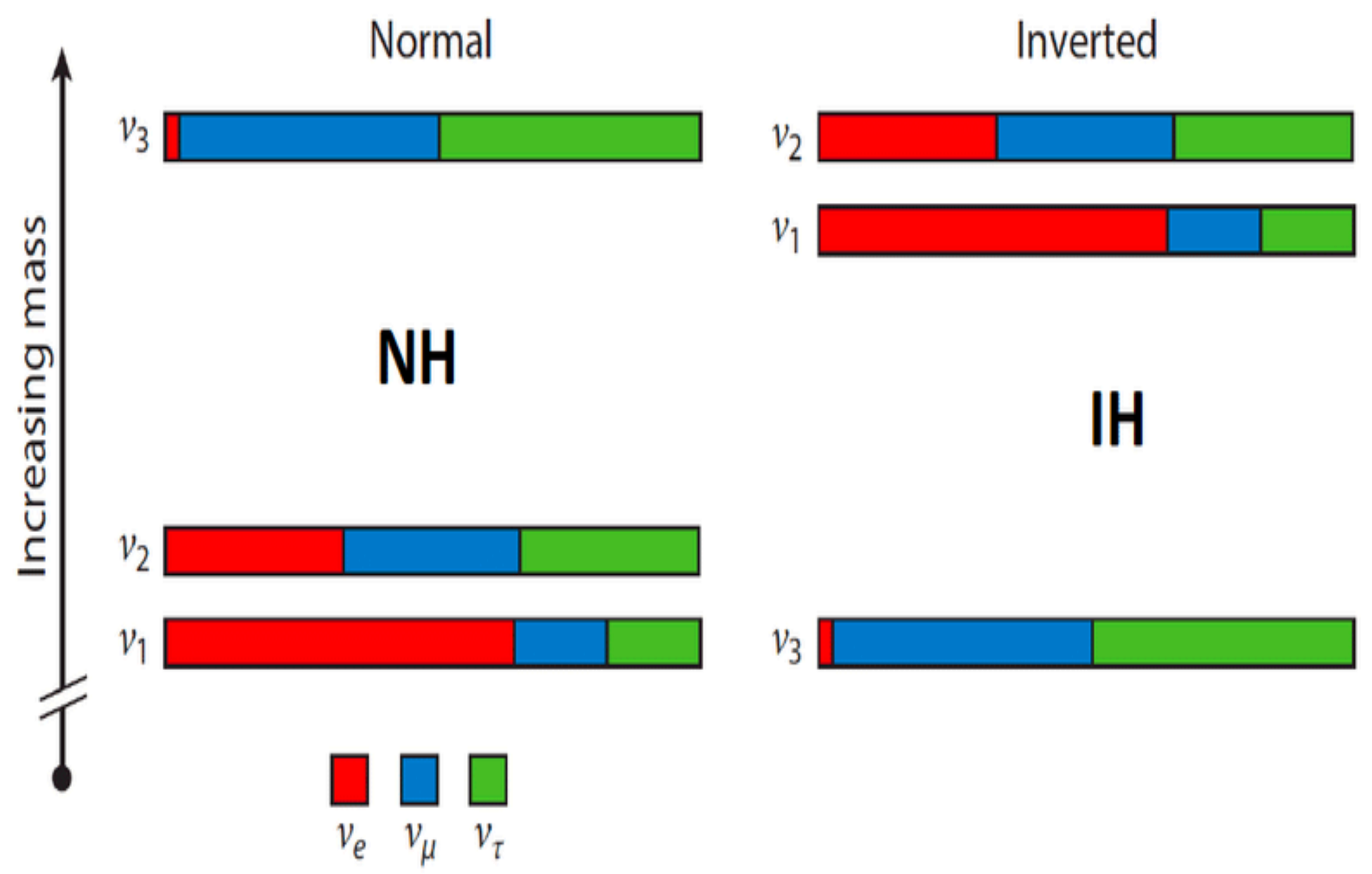
1. Neutrino Decay



1. Neutrino Decay

- Massive neutrinos can decay to lighter through new physics

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



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

$\nu_l \equiv \nu_1$

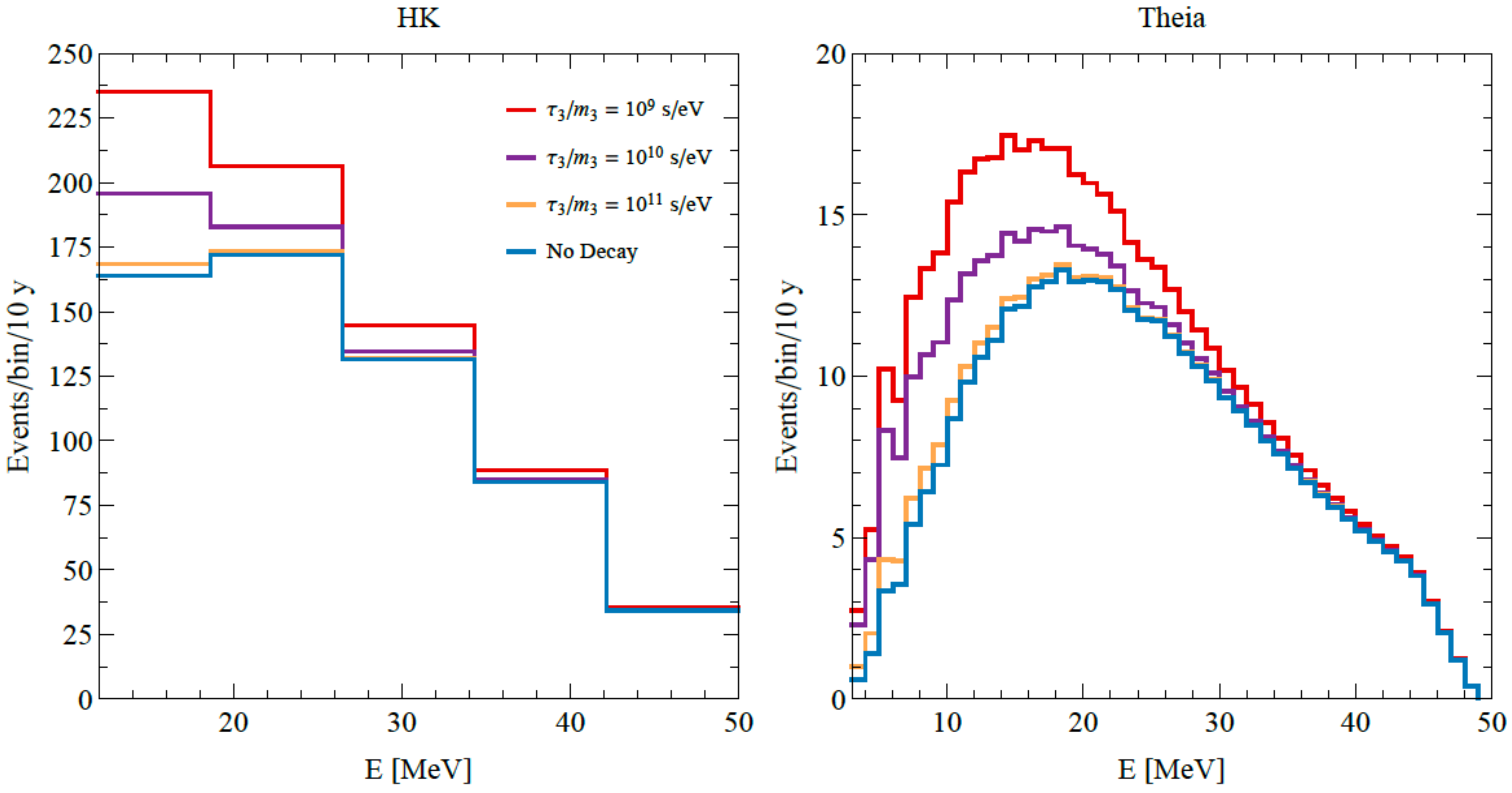
$\nu_h \equiv \nu_3$

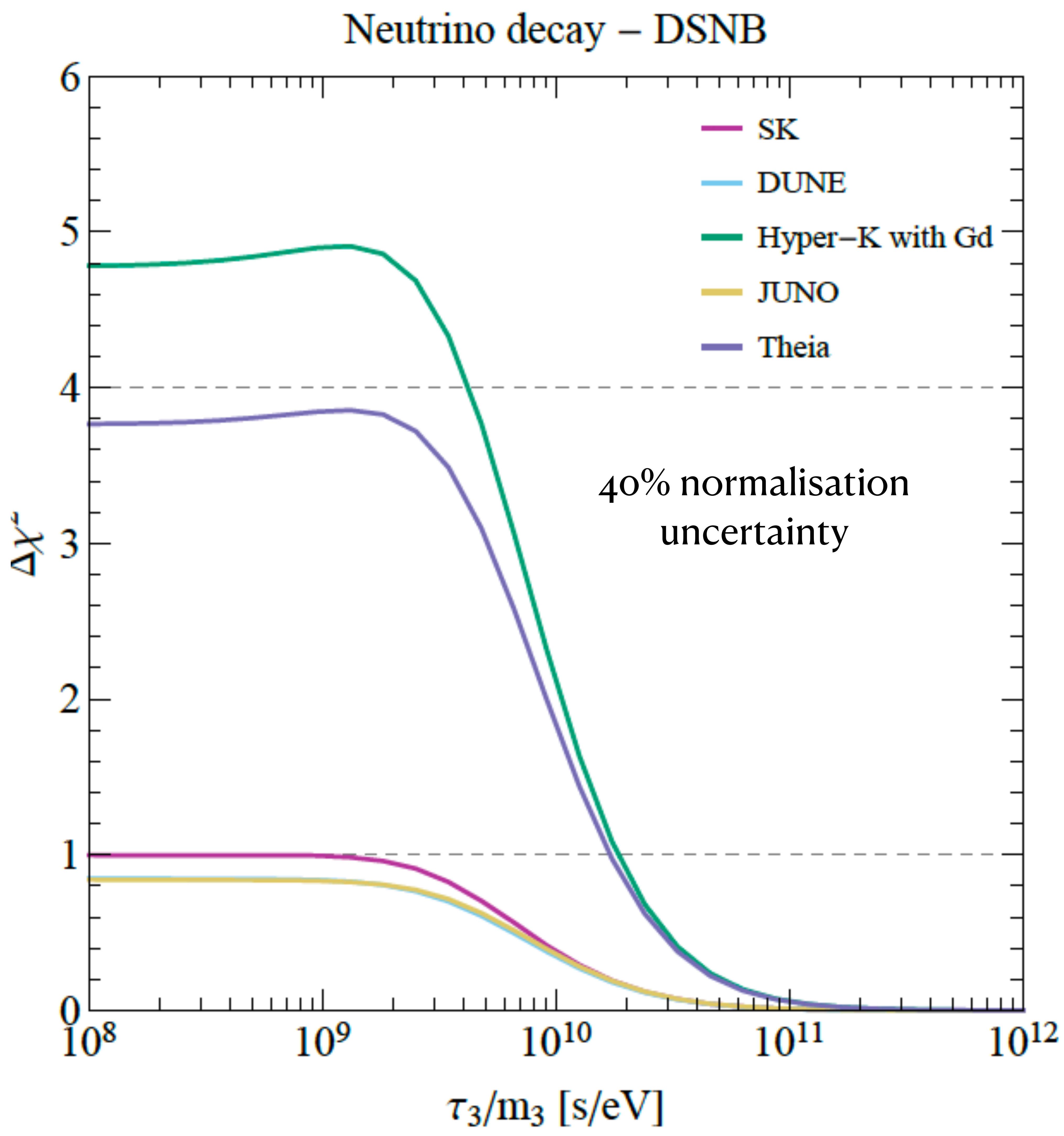
$\nu_e \sim |U_{e1}|^2 \sim 0.7\, \nu_e^{\rm in}$

Fogli, Lisi, Mirizzi, Montaninio, PRD 2004

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

Constraints on neutrino lifetime

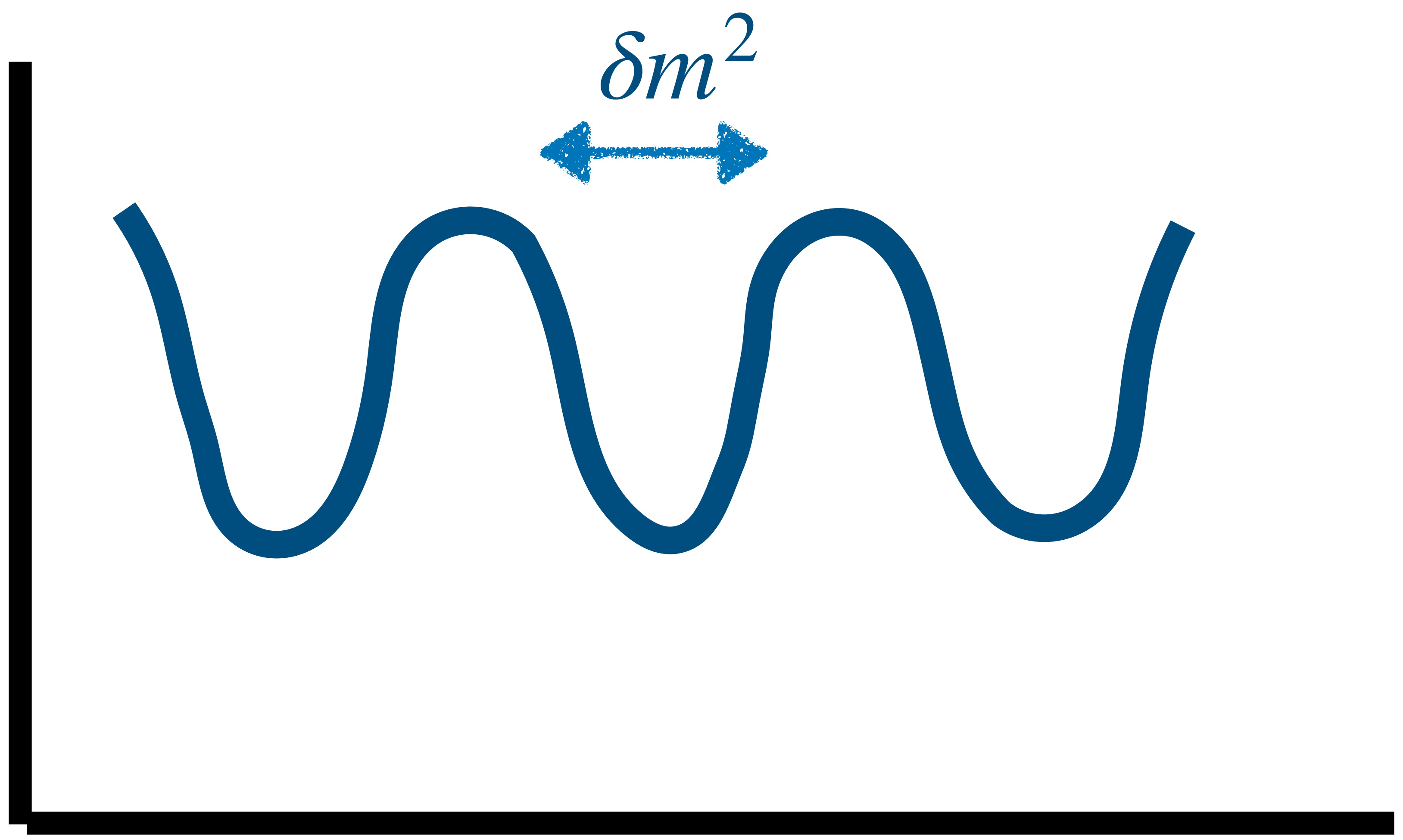




de Gouvea, Martinez-Soler, Perez-Gonzalez, MS, PRD 2020

- HK and Theia can put some of the strongest constraints on neutrino lifetime. At 2-σ, $\tau_3/m_3 \sim 10^9\,\mathrm{s/eV}$.
- This is comparable to the bounds from CMB.

2. Pseudo-Dirac Neutrinos



2. Pseudo(quasi) Dirac Neutrinos

- Neutrinos have sub-dominant Majorana mass terms.

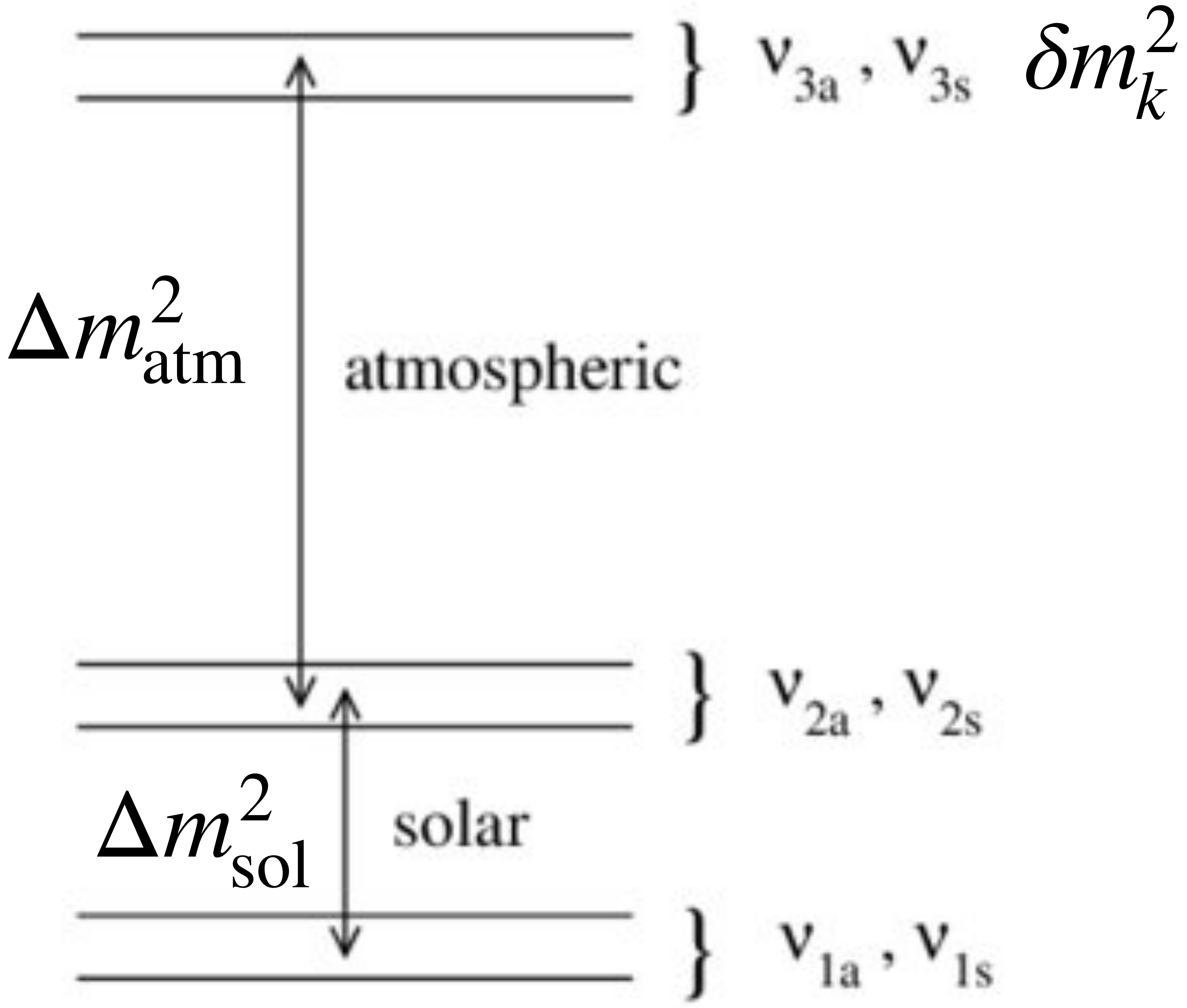
  Generic Majorana mass matrix $\begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}$.

  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

Oscillations due to pseudo Dirac Neutrinos

- δm_k^2 will lead to oscillations at very large distances.

- Flavor oscillation probability induced by $\Delta m^2_{\rm sol}$ and $\Delta m^2_{\rm atm}$ over a large distance gets averaged.

$$P(\nu_\beta \to \nu_\gamma) = P_{aa}(z,E)\left|U_{\beta k}\right|^2 \left|U_{\gamma k}\right|^2$$

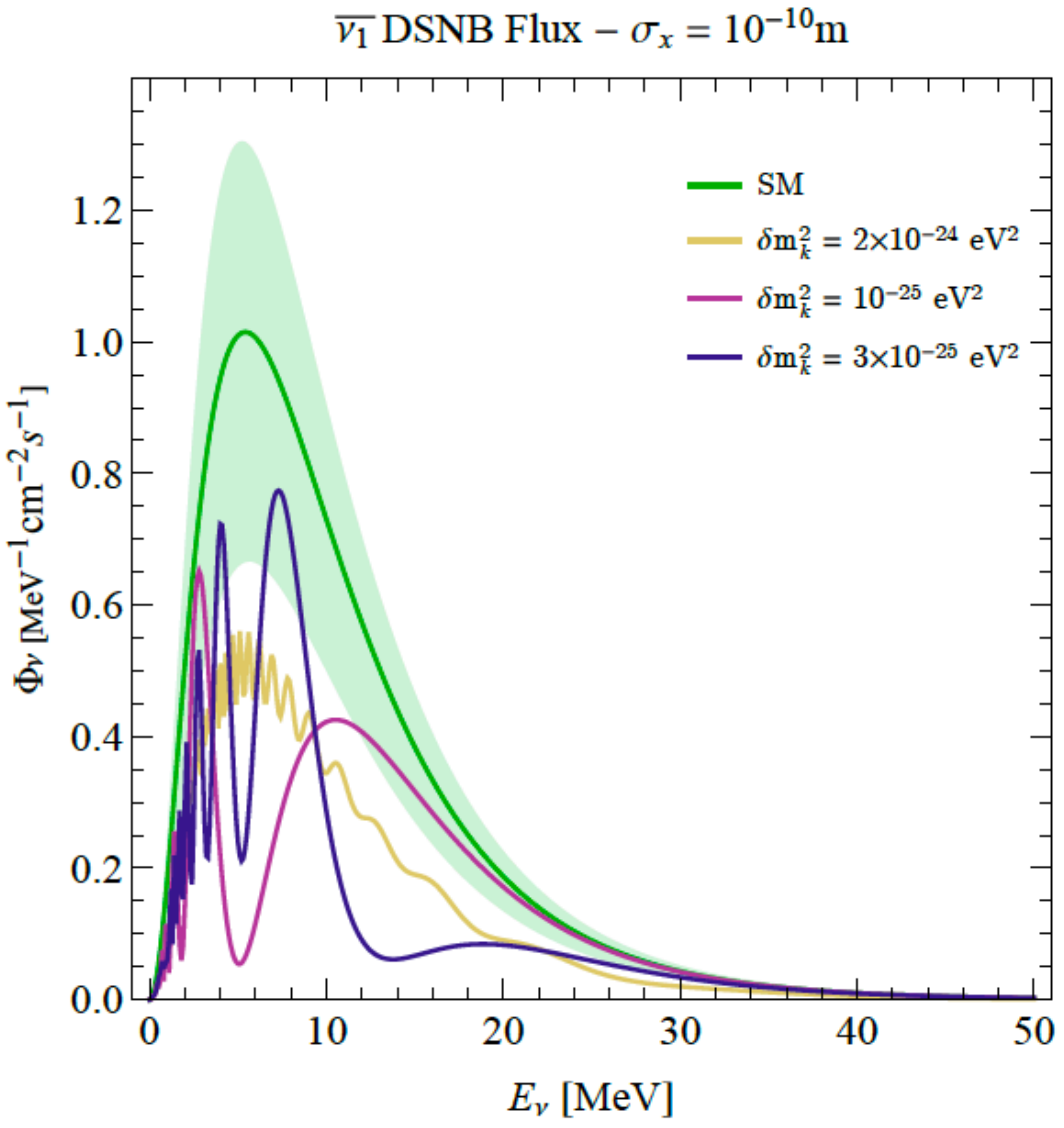
- The active-sterile probability, driven by δm_k^2 is

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

- Wave-packet separation decoherence also becomes important.

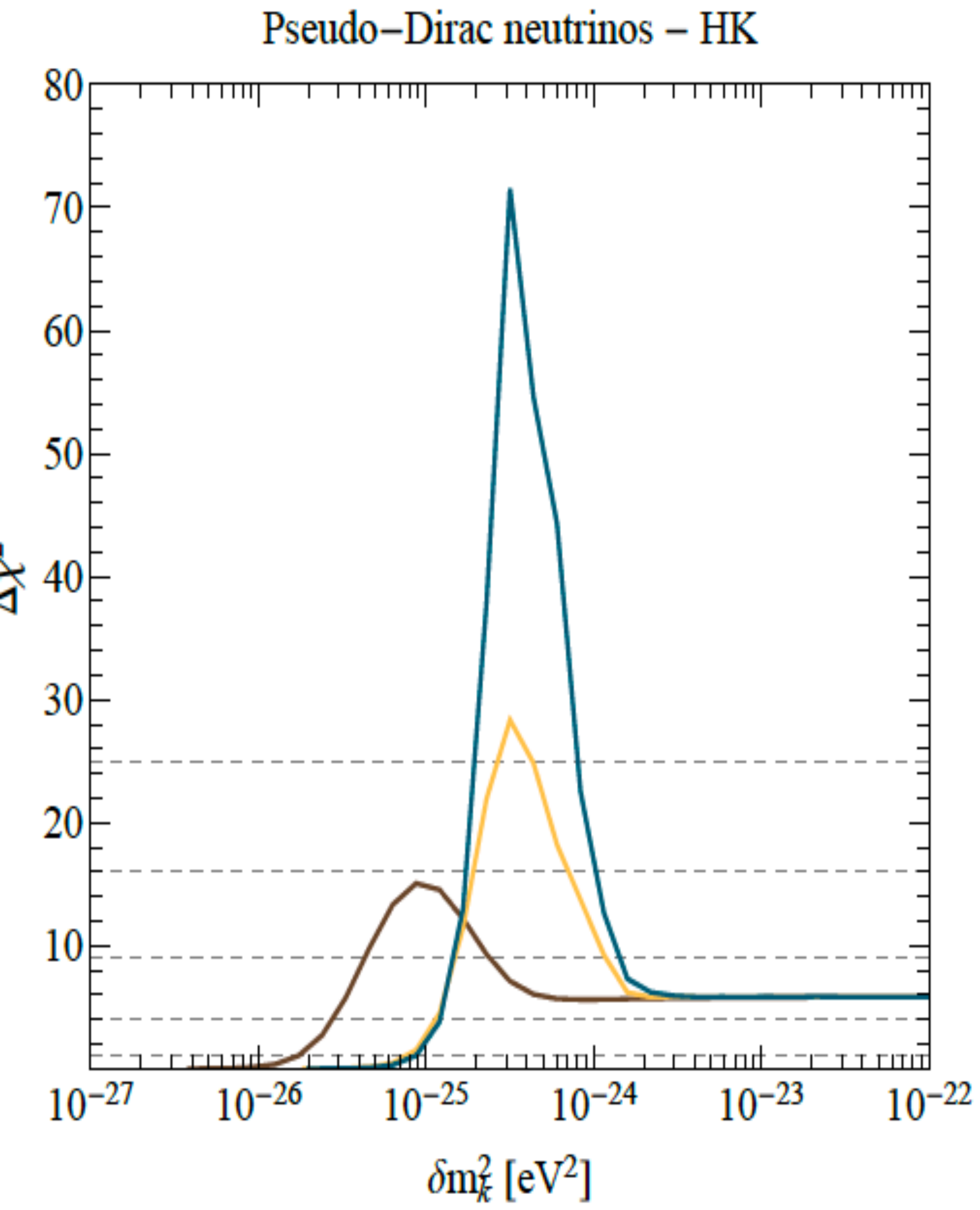
$$L_{\rm osc} = \frac{4\pi E}{\delta m_k^2} \approx 8.03\ \text{Gpc}\left(\frac{E}{10\ \text{MeV}}\right)\left(\frac{10^{-25}\ \text{eV}^2}{\delta m_k^2}\right),$$

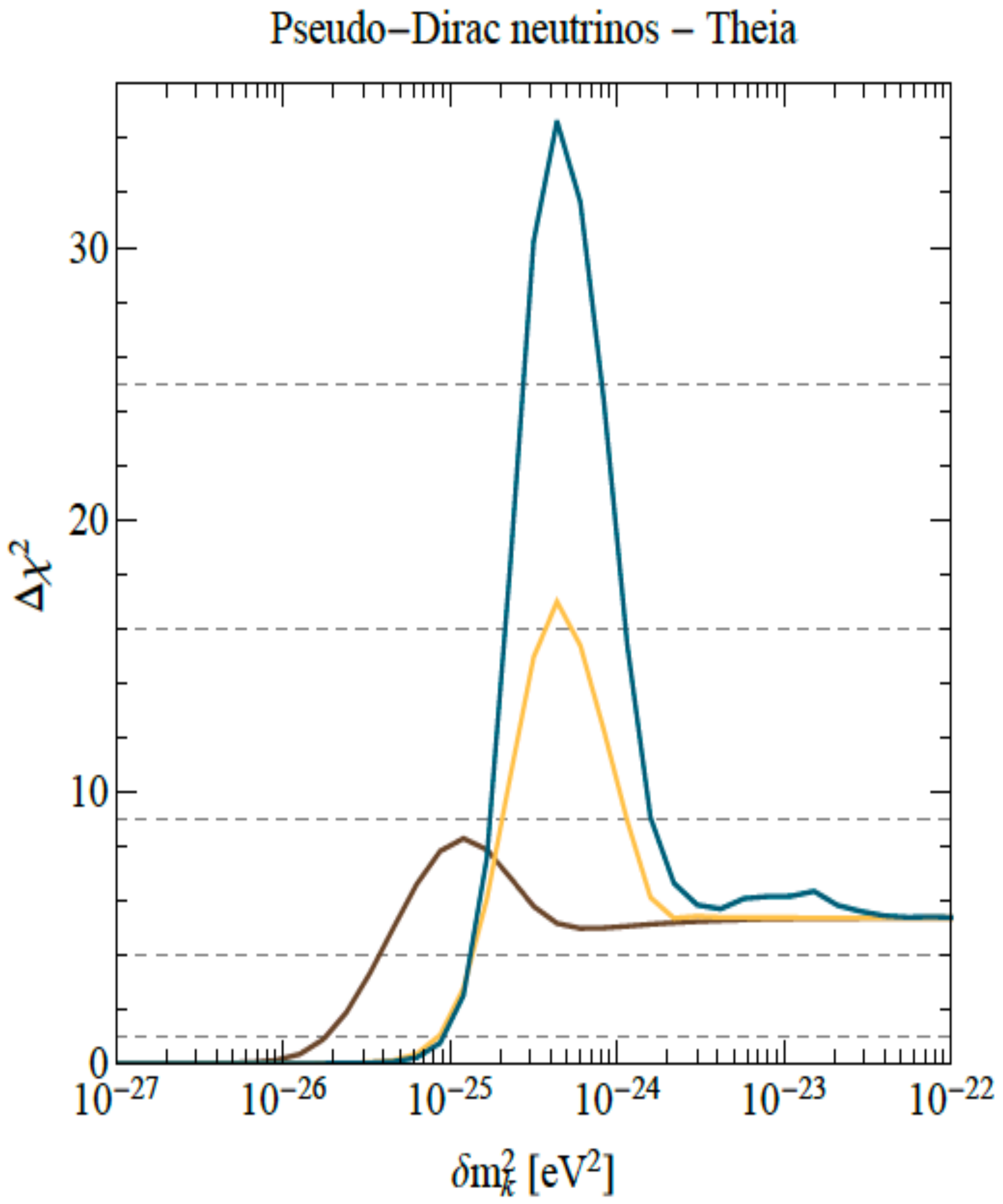
$$L_{\rm coh} = \frac{4\sqrt{2}E^2}{|\delta m_k^2|}\sigma_x \approx 180\ \text{Gpc}\left(\frac{E}{10\ \text{MeV}}\right)^2\left(\frac{10^{-25}\ \text{eV}^2}{\delta m_k^2}\right)\left(\frac{\sigma_x}{10^{-12}\ \text{m}}\right).$$

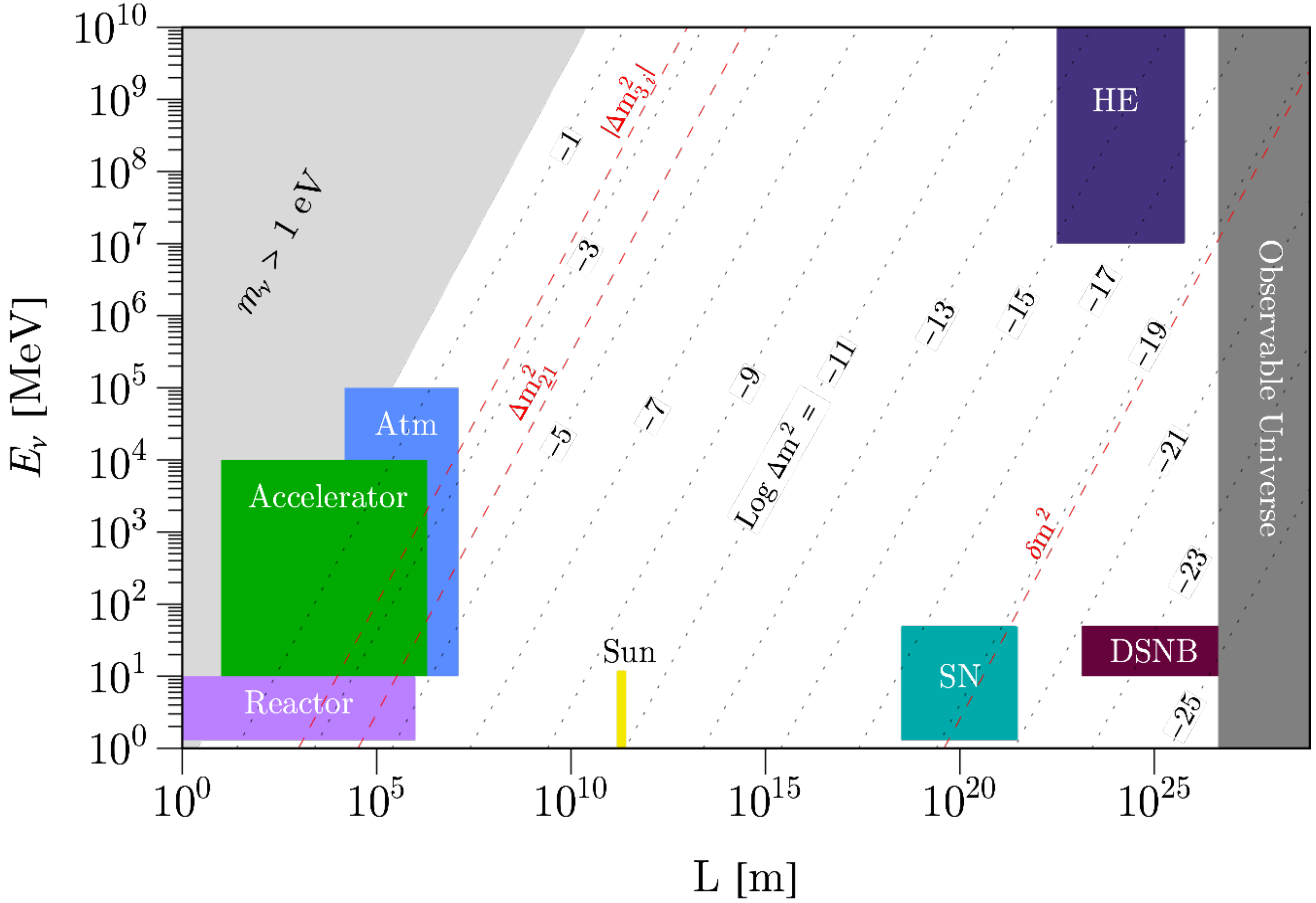


Increasing δm^2 reduces $L_{\rm osc}$ and $L_{\rm coh}$, and causes more oscillations

Sensitivity to tiny mass-squared differences







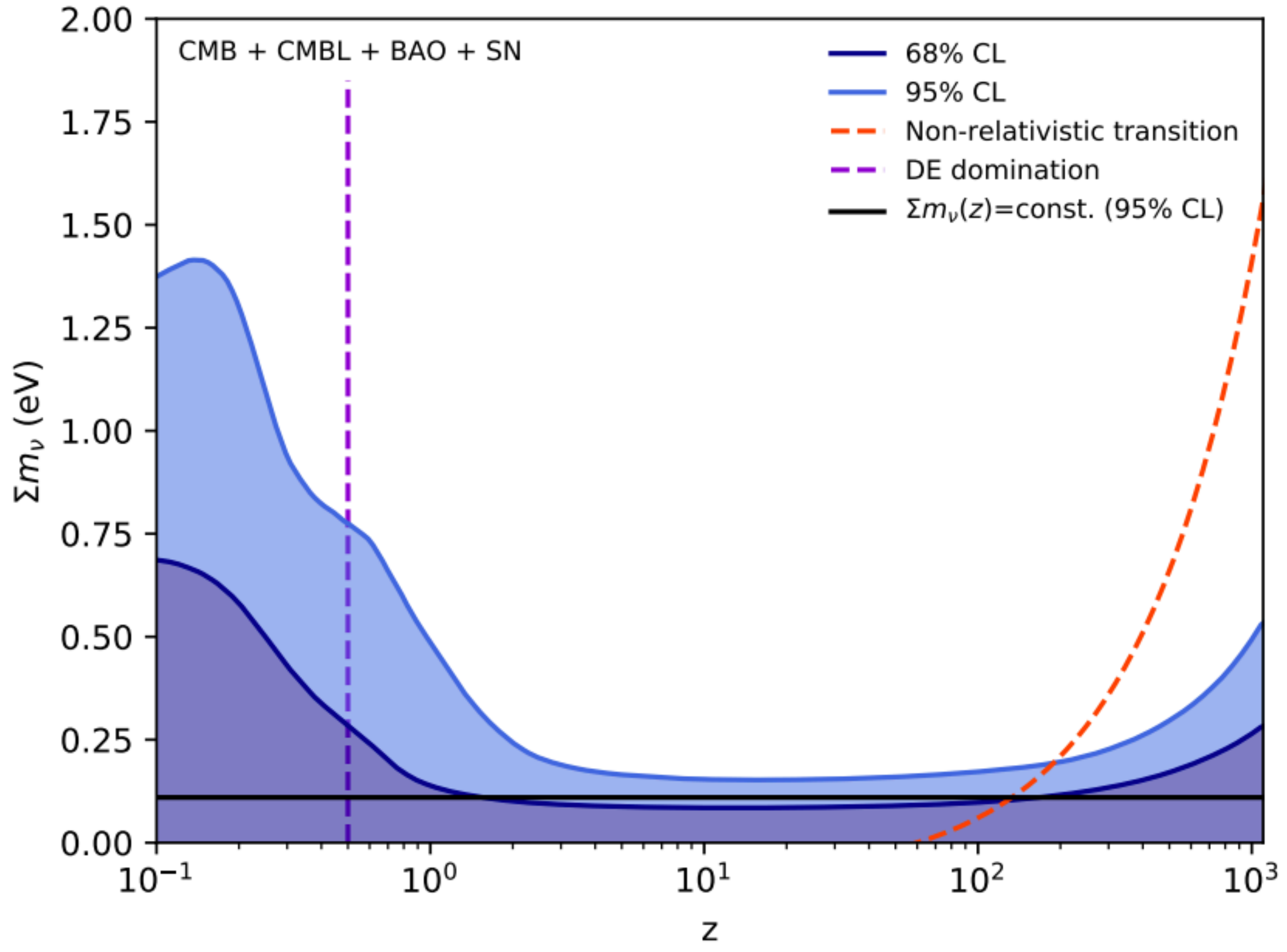
- DSNB sensitive to $\delta m^2 \sim \mathcal{O}(10^{-25}\,\mathrm{eV}^2)$ with a high significance - tiniest values constrained so far.

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

3. Origin of neutrino mass

3. Redshift dependent neutrino mass

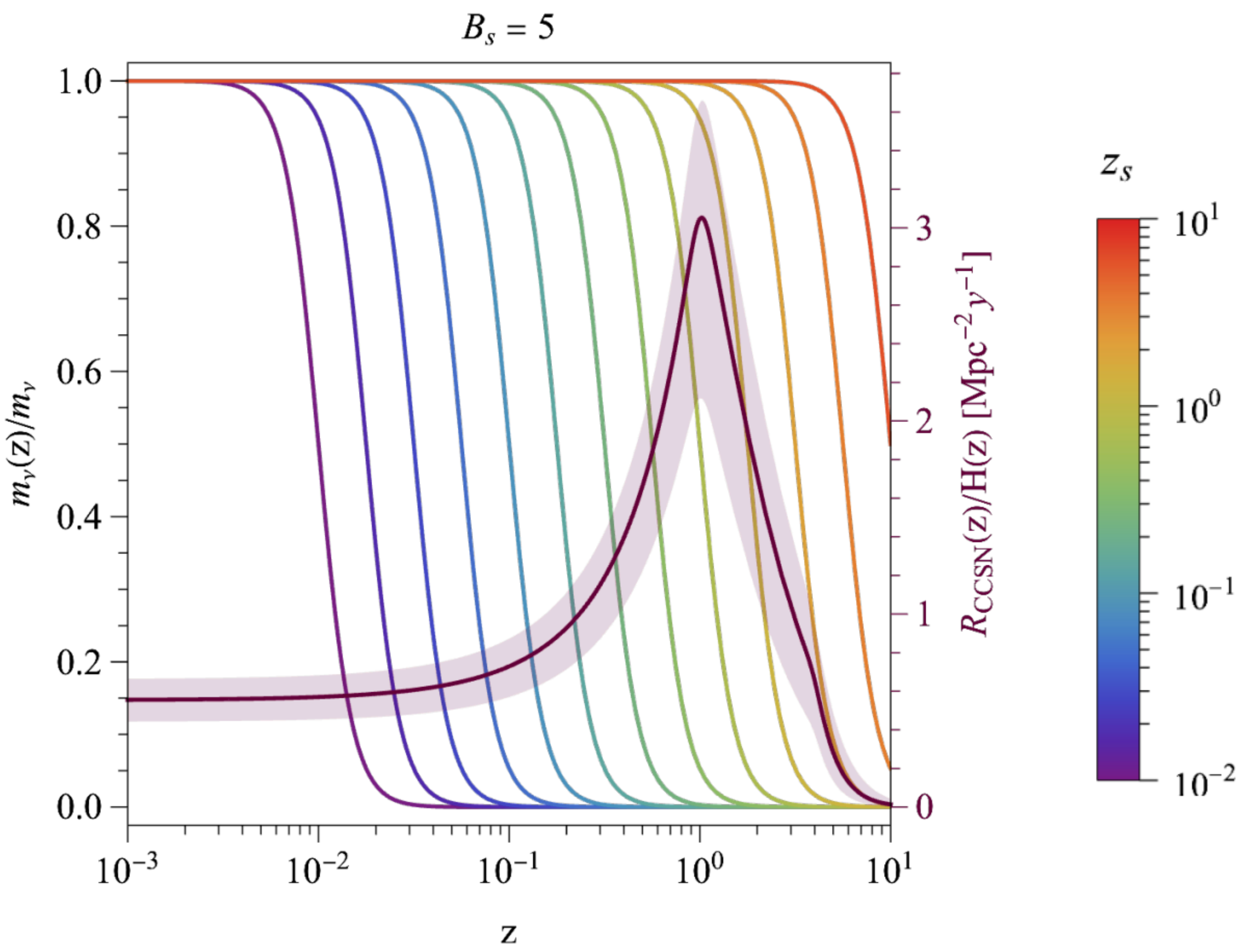
- Can the neutrino mass be redshift dependent?
- Use $\sum m_\nu$ as a function of redshift.
- Consider bounds from
  1. CMB temperature, polarization and lensing data from Planck.
  2. BAO from 6dF, SDSS, BOSS,…
  3. Type Ia SN from Pantheon.
- Bound on $\sum m_\nu$ increases at very low redshifts.
- This could arise in models where the neutrino mass is generated at low redshifts due to a phase transition.
- If the neutrino mass is indeed generated at low redshifts, are there any other probes?



Dvali, Funcke, PRD 2016
Lorenz,Funcke,Löffler, Calabrese, PRD 2021
Lorenz,Funcke,Calabrese,Hannestad PRD 2019

See today's plenary talk by M.Lattanzi

Mass variation parameterization



- We stay agnostic of the mechanism causing mass variation:
  coupling to light scalar, phase transition, etc.

- The mass variation is parameterized

$$m_\nu(z) = \frac{m_\nu}{1 + (z/z_s)^{B_s}}.$$

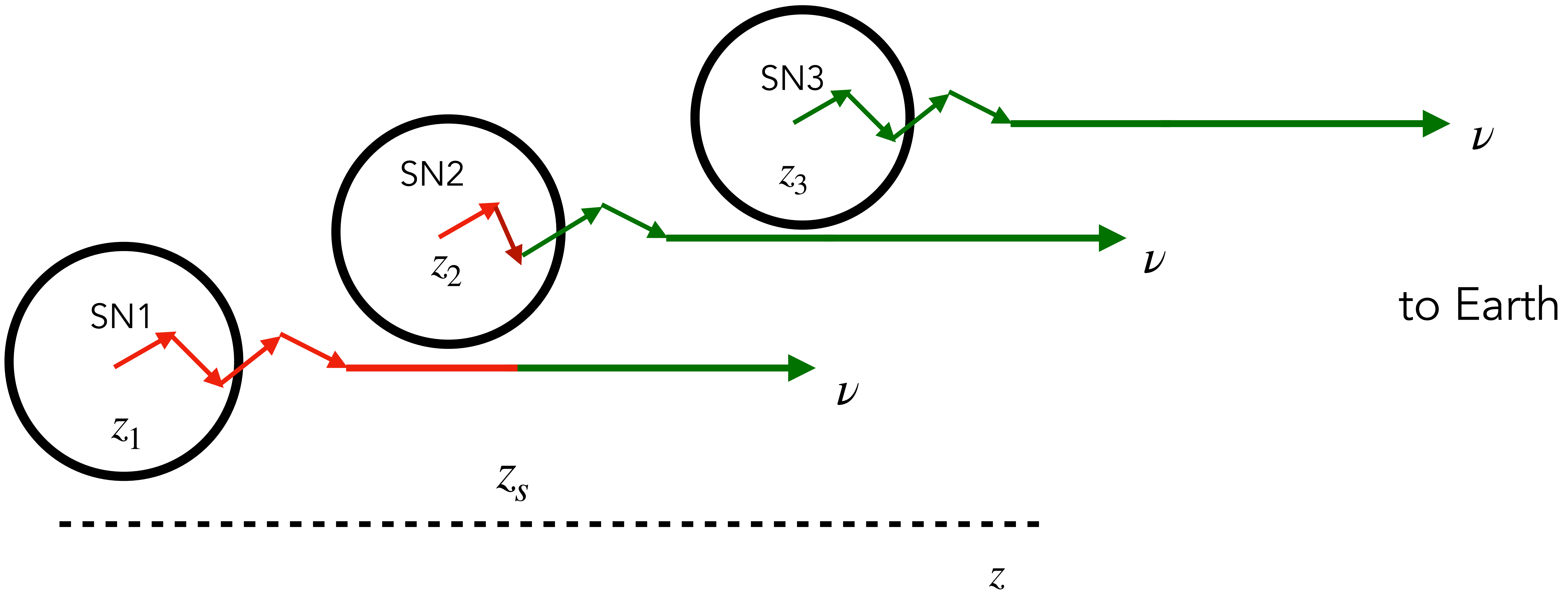
z_S indicates redshift when mass switches on.

B_s governs the width of transition.

- Effect on DSNB is stronger if m_ν switches on when the R_{CCSN} peaks, i.e., around $z_S \sim 1$

de Gouvea, Martinez-Soler, Perez-Gonzalez, MS, arXiv:2205.01102

Physics of neutrio propagation as mass varies



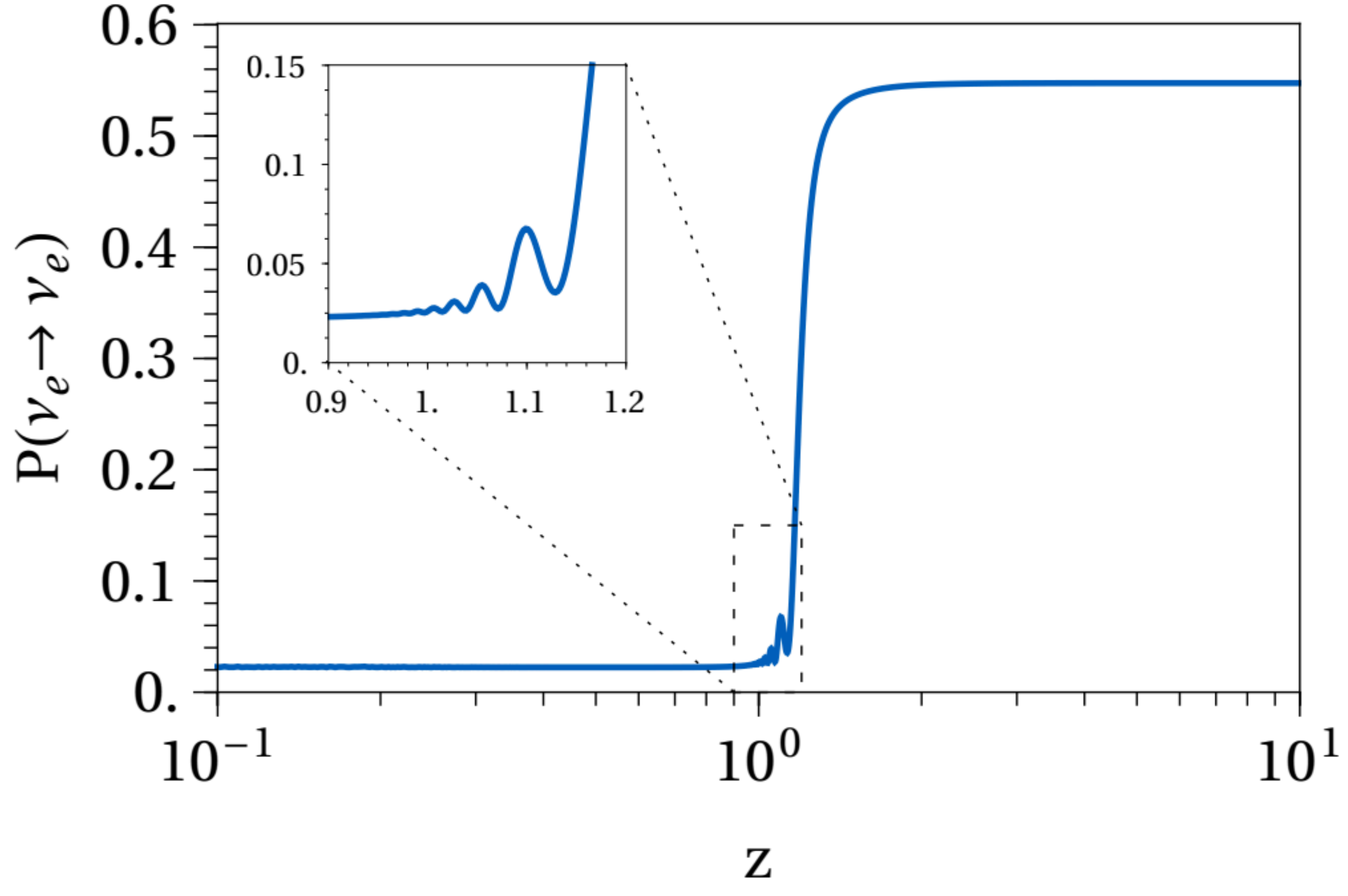
- For massless neutrinos, flavor and mass eigenstates are identical.

- As neutrino mass switches on while in vacuum, propagation changes depending on what the neutrino encounters: matter effects, vacuum, etc.

- This changes the probability of a certain flavor arriving at Earth.

Neutrino probability calculation

- Solve the neutrino propagation inside a SN to obtain probability



Neutrino probability calculation

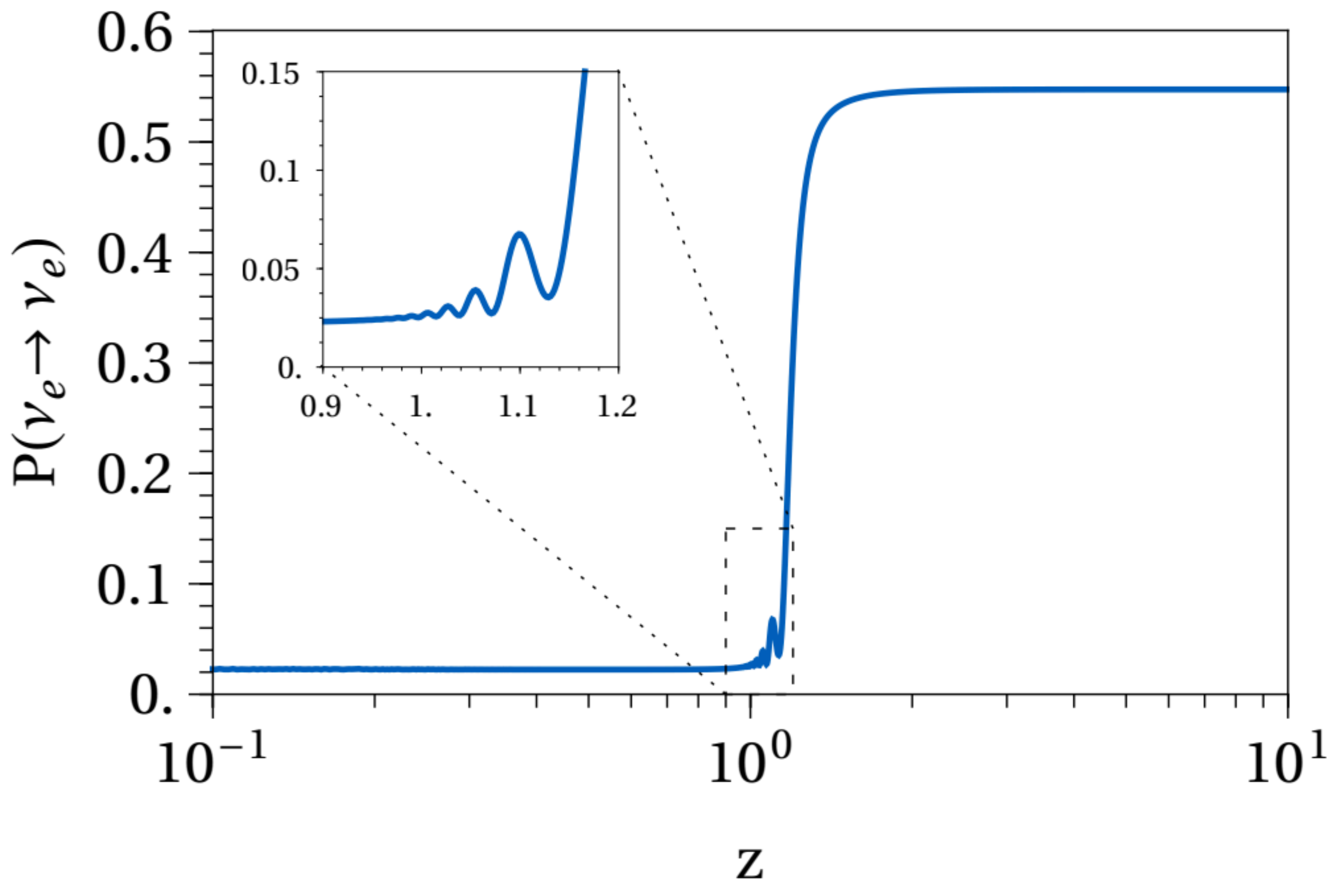
- Solve the neutrino propagation inside a SN to obtain probability

- As neutrino mass switches on while in vacuum, propagation similar to vacuum, hence $P_{ee}(\nu_e) = \sum_k |U_{ek}|^4 = 0.57$

- Contrast with MSW matter propagation:

For massive neutrinos, in NMO,
$P_{ee}(\nu_e) \sim |U_{e3}|^2 = 0.02$ and $P_{ee}(\bar{\nu}_e) \sim |U_{e1}|^2 = 0.67$

For massive neutrinos, in IMO,
$P_{ee}(\nu_e) \sim |U_{e2}|^2 = 0.3$ and $P_{ee}(\bar{\nu}_e) \sim |U_{e3}|^2 = 0.03$



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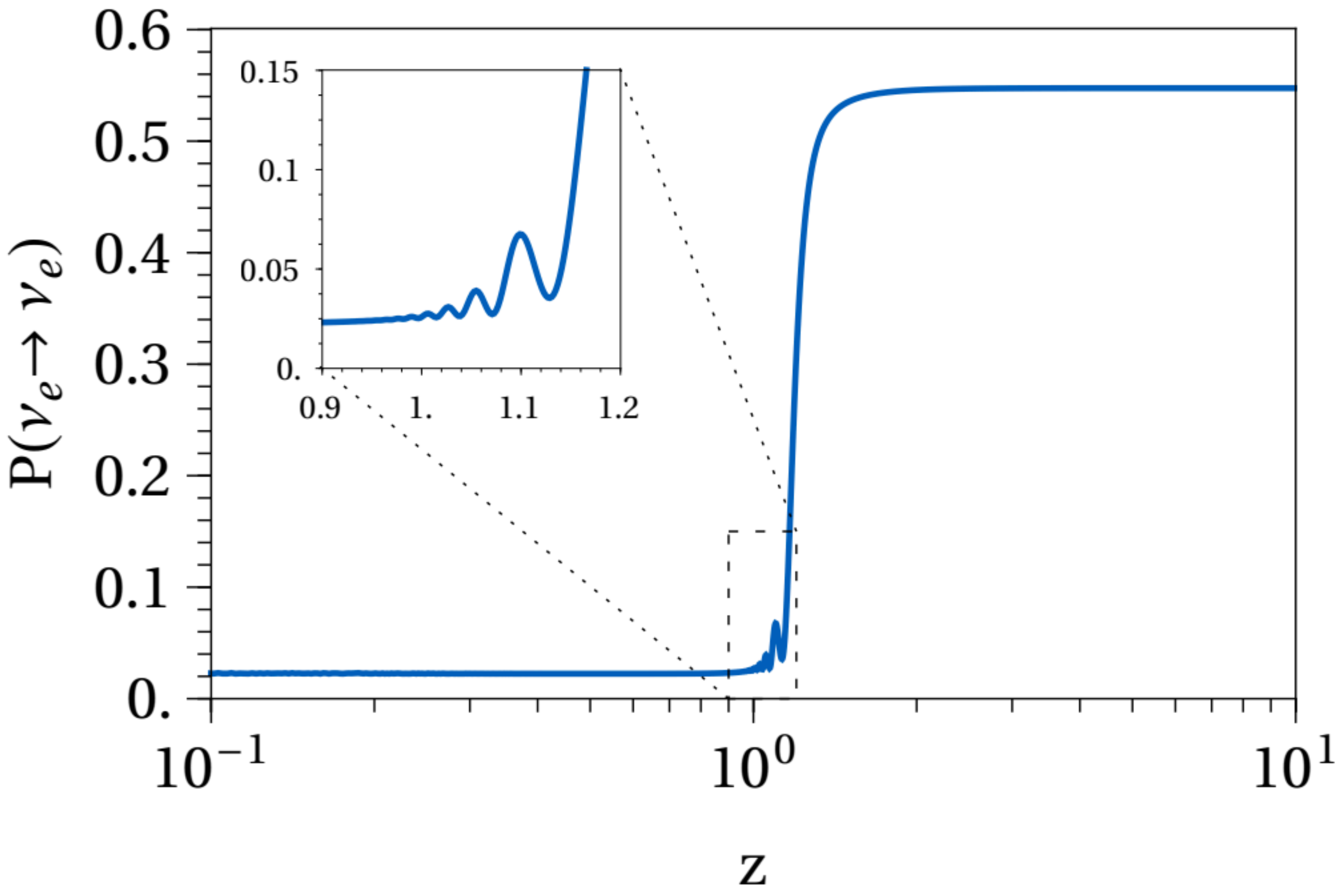
  For massive neutrinos, in IMO,
  $P_{ee}(\nu_e) \sim |U_{e2}|^2 = 0.3$ and $P_{ee}(\bar{\nu}_e) \sim |U_{e3}|^2 = 0.03$

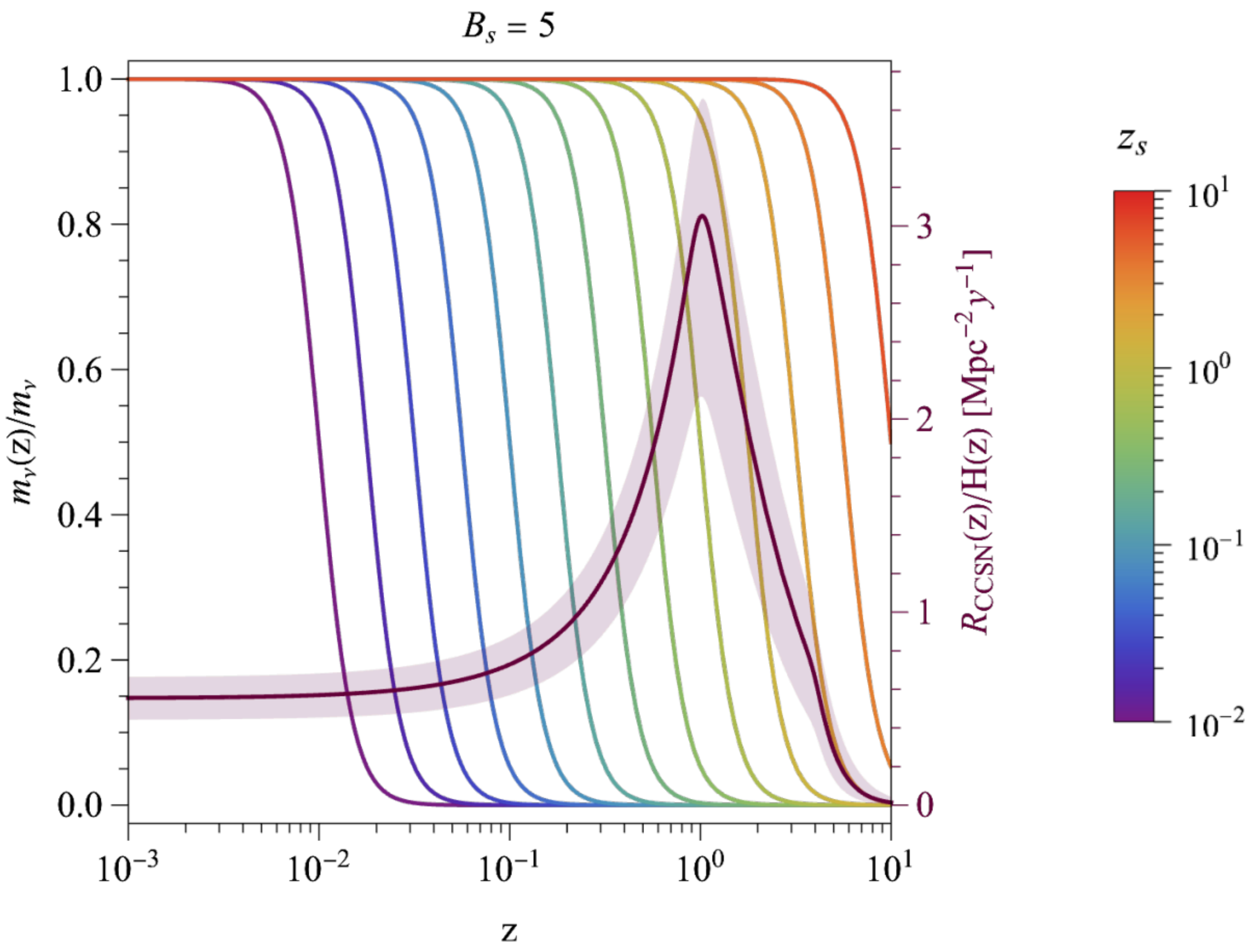


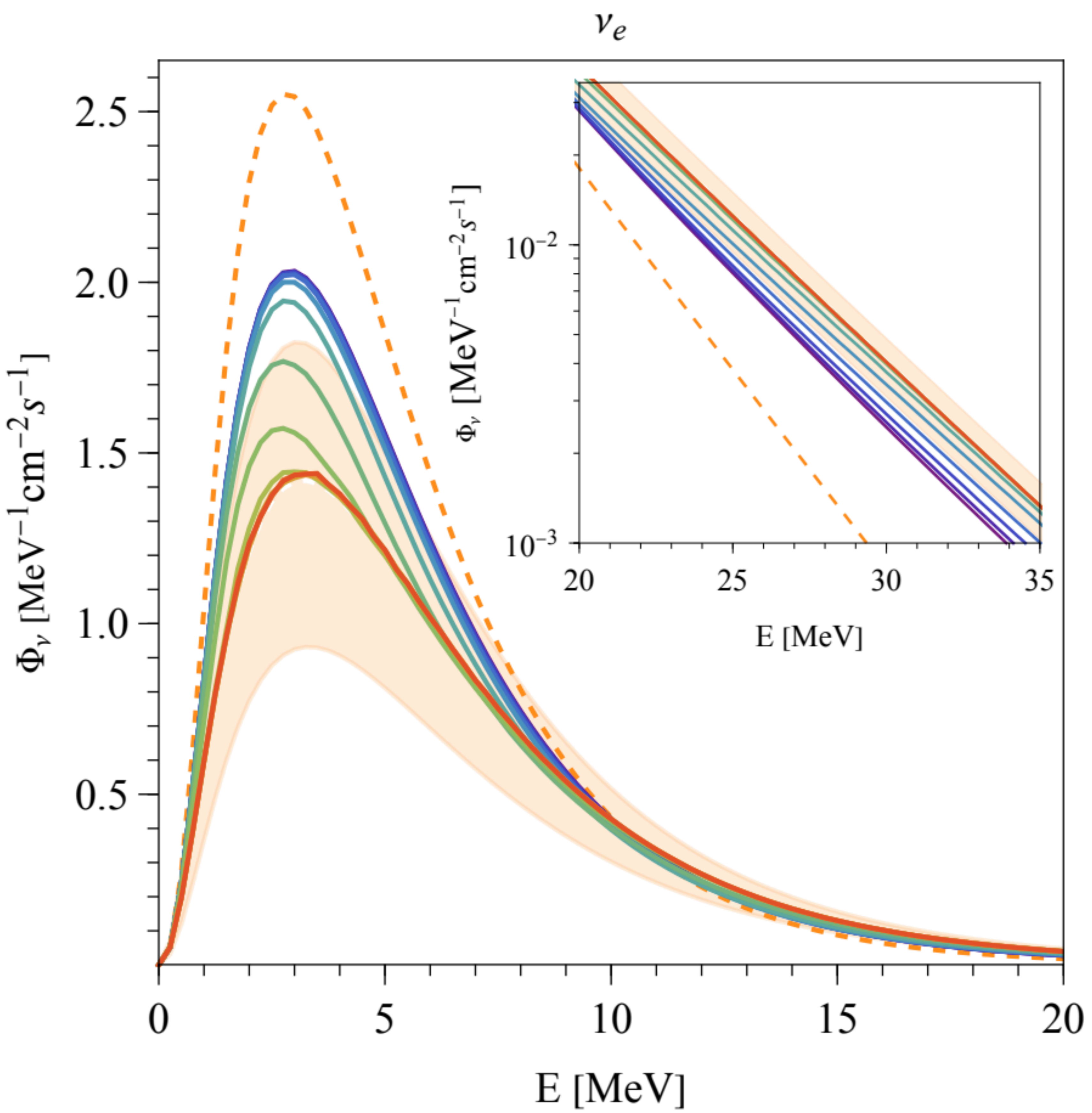
- The net DSNB flux at Earth

$$\Phi_{\nu_e}(E) = \int_0^{z_{\max}} \frac{dz}{H(z)} R_{\rm CCSN}(z) \left\{ P_{ee}(z)\phi^0_{\nu_e} + (1 - P_{ee}(z))\phi^0_{\nu_x} \right\} \longrightarrow \boxed{\text{Impact strongest for } \nu_e \text{ at NMO}}$$

$$\Phi_{\bar{\nu}_e}(E) = \int_0^{z_{\max}} \frac{dz}{H(z)} R_{\rm CCSN} \left\{ \overline{P_{ee}}(z)\phi^0_{\bar{\nu}_e} + (1 - \overline{P_{ee}}(z))\phi^0_{\nu_x} \right\} \longrightarrow \boxed{\text{Almost null effect in both orderings, since } \bar{\phi}_{\nu_e} \sim \phi_{\nu_x}}$$

DSNB spectral difference due to mass variation



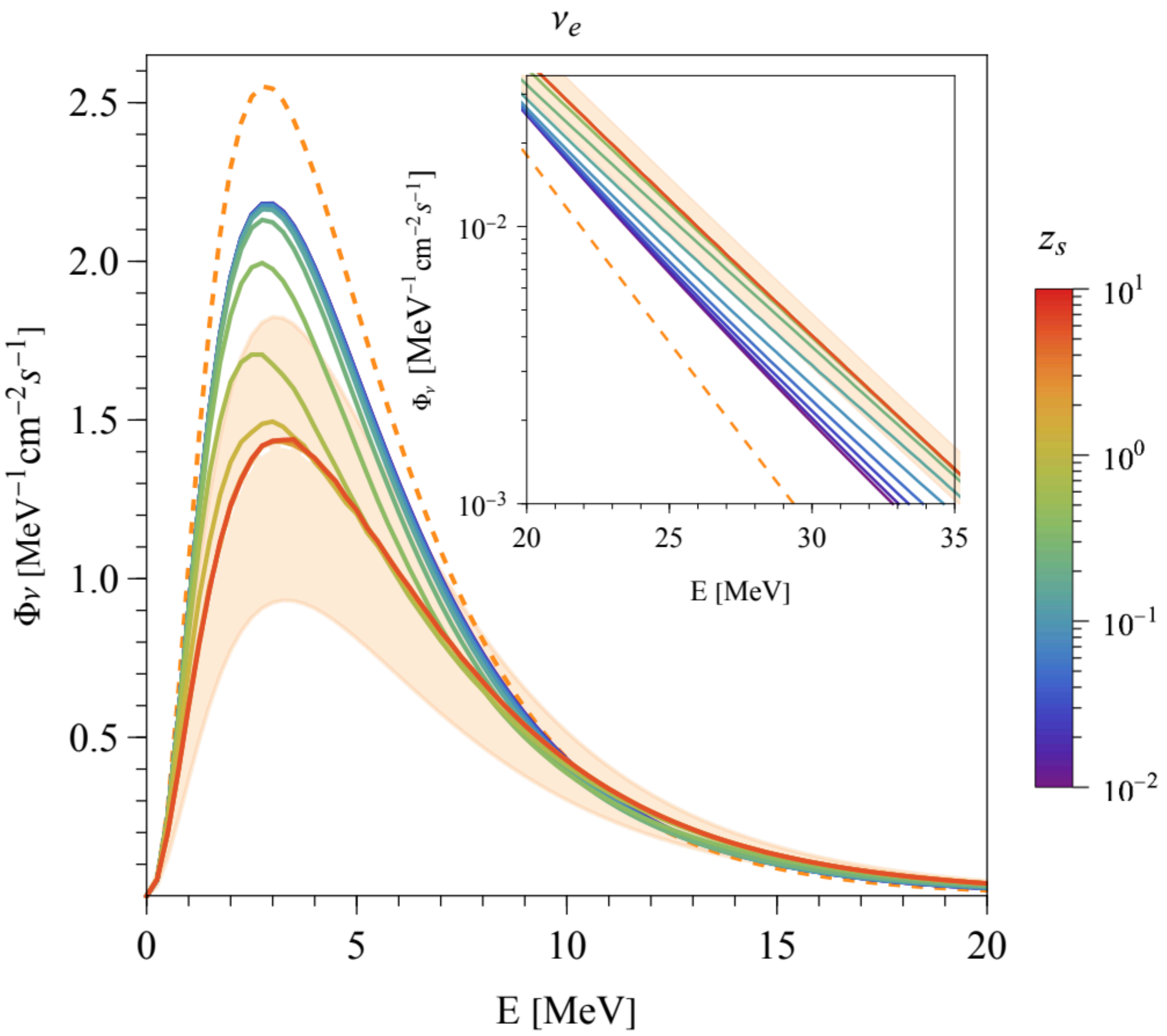


- Effect is strongest when mass switches on at low redshift, since maximum contribution comes from massless neutrinos.

- For $z_s \sim 0.01$, DSNB spectra can be a factor of 1.5 or so larger.

de Gouvea, Martinez-Soler, Perez-Gonzalez, MS, arXiv:2205.01102

What happens if the mixing angles vary similarly?



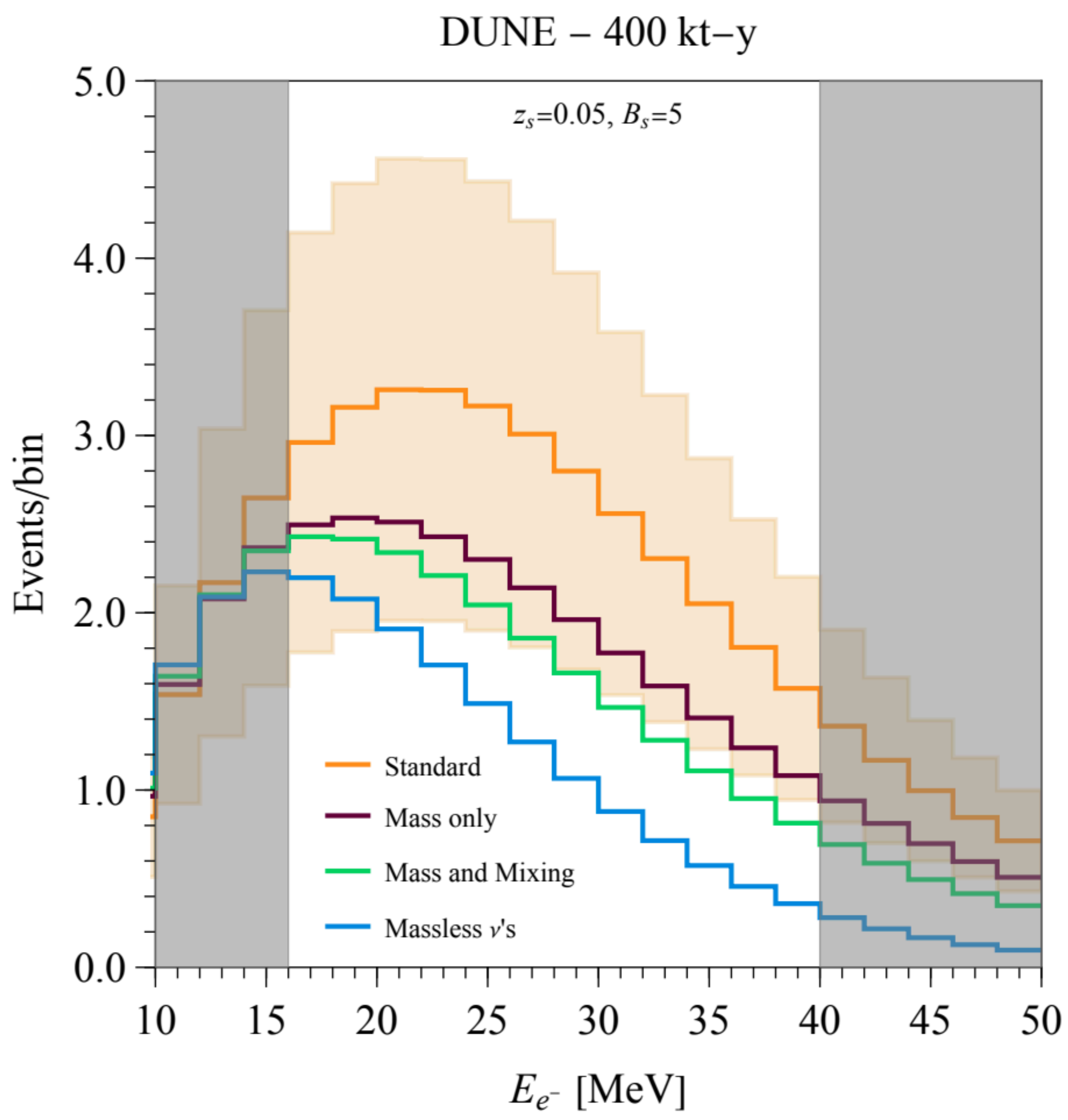
- A similar variation can be induced in mixing angles as well,

$$\theta_{ij}(z) = \frac{\theta_{ij}}{1 + (z/z_s)^{B_s}} .$$

- Combined effect of mass, and mixing variation is stronger.

de Gouvea, Martinez-Soler, Perez-Gonzalez, MS, arXiv:2205.01102

Event spectra in a DUNE like detector



- Currently, one needs to be very "optimistic" for this effect to show up.

- But, there is a correlation:

  1. Expect a reduction in number of ν_e events in a DUNE like detector, in energy above 20-sh MeV.

  2. In parallel, there would be no change in the $\bar{\nu}_e$ event rate in a HK/JUNO like detector.

- With better astrophysical modelling, and improved detectors, this will become a possibility. So, stay tuned.

de Gouvea, Martinez-Soler, Perez-Gonzalez, MS, arXiv:2205.01102

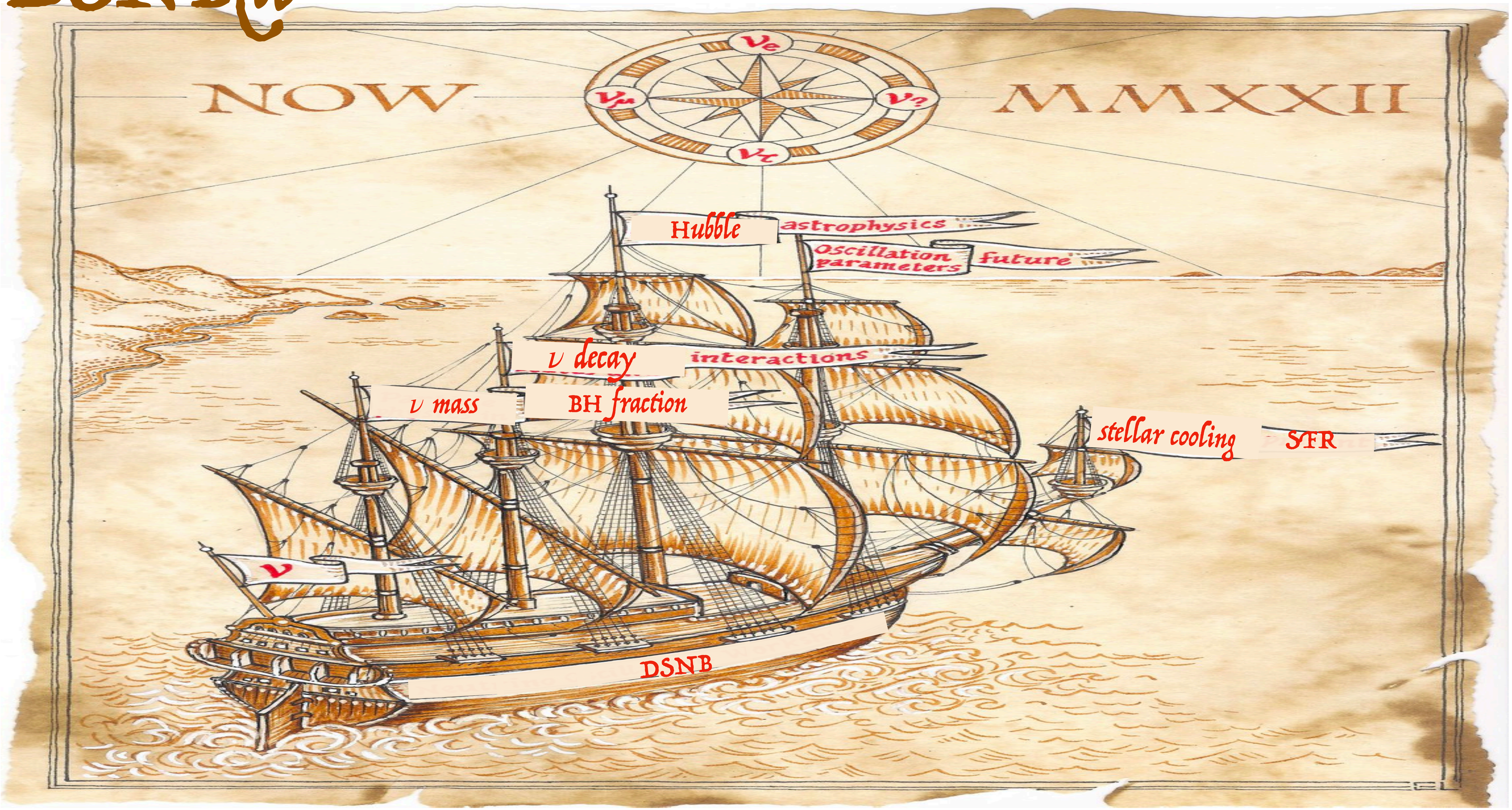
Conclusions

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

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

Conclusions

DSNB@



Original picture adapted and edited from NOW22 workshop logo

Backup

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

Star formation Rate

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

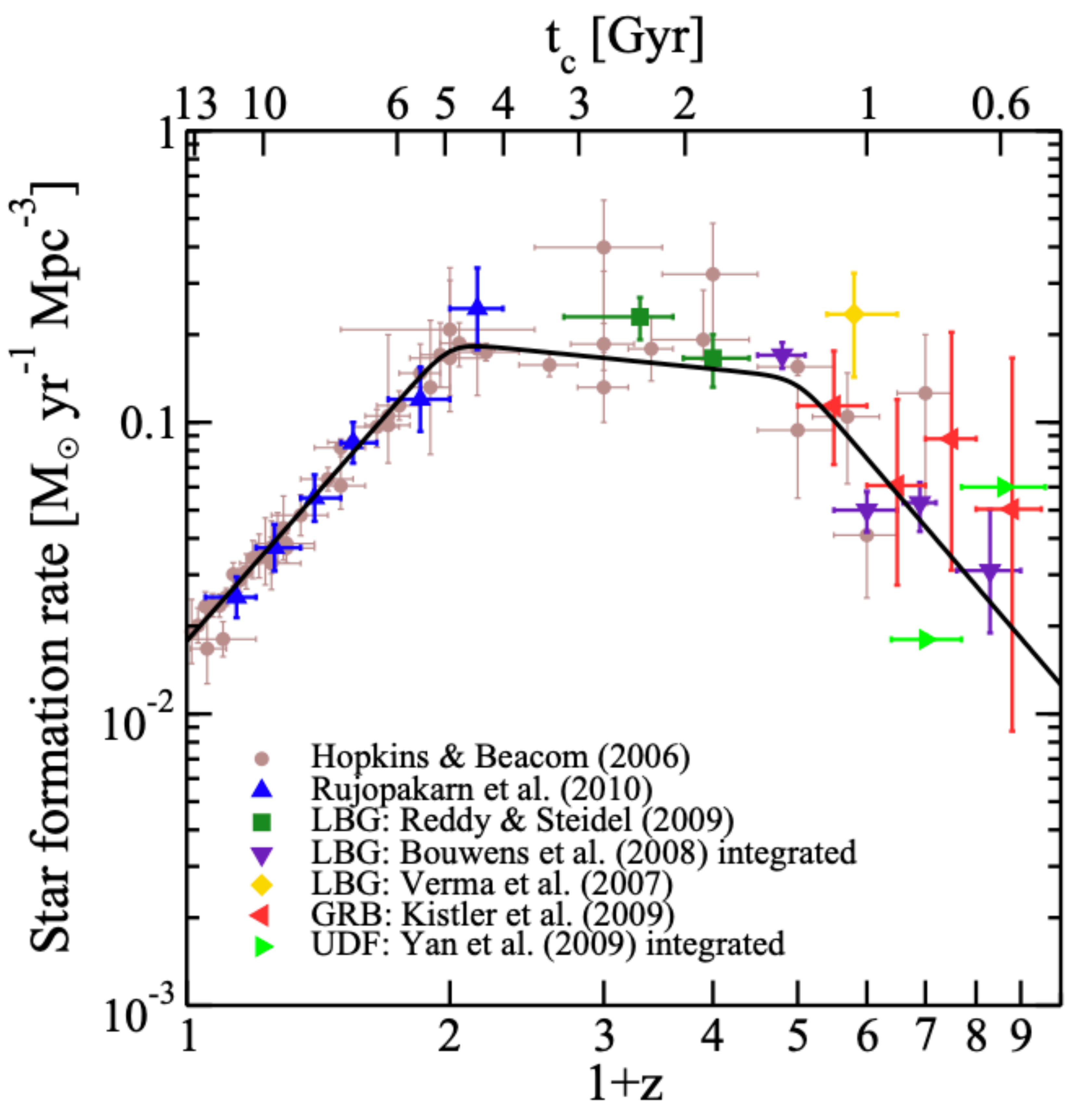
$$\dot{\rho}_*(z) = \dot{\rho}_0 \left[(1+z)^{-10\,\alpha} + \left(\frac{1+z}{B}\right)^{-10\,\beta} + \left(\frac{1+z}{C}\right)^{-10\,\gamma} \right]^{-1/10}$$

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

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

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

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

Neutrino spectra

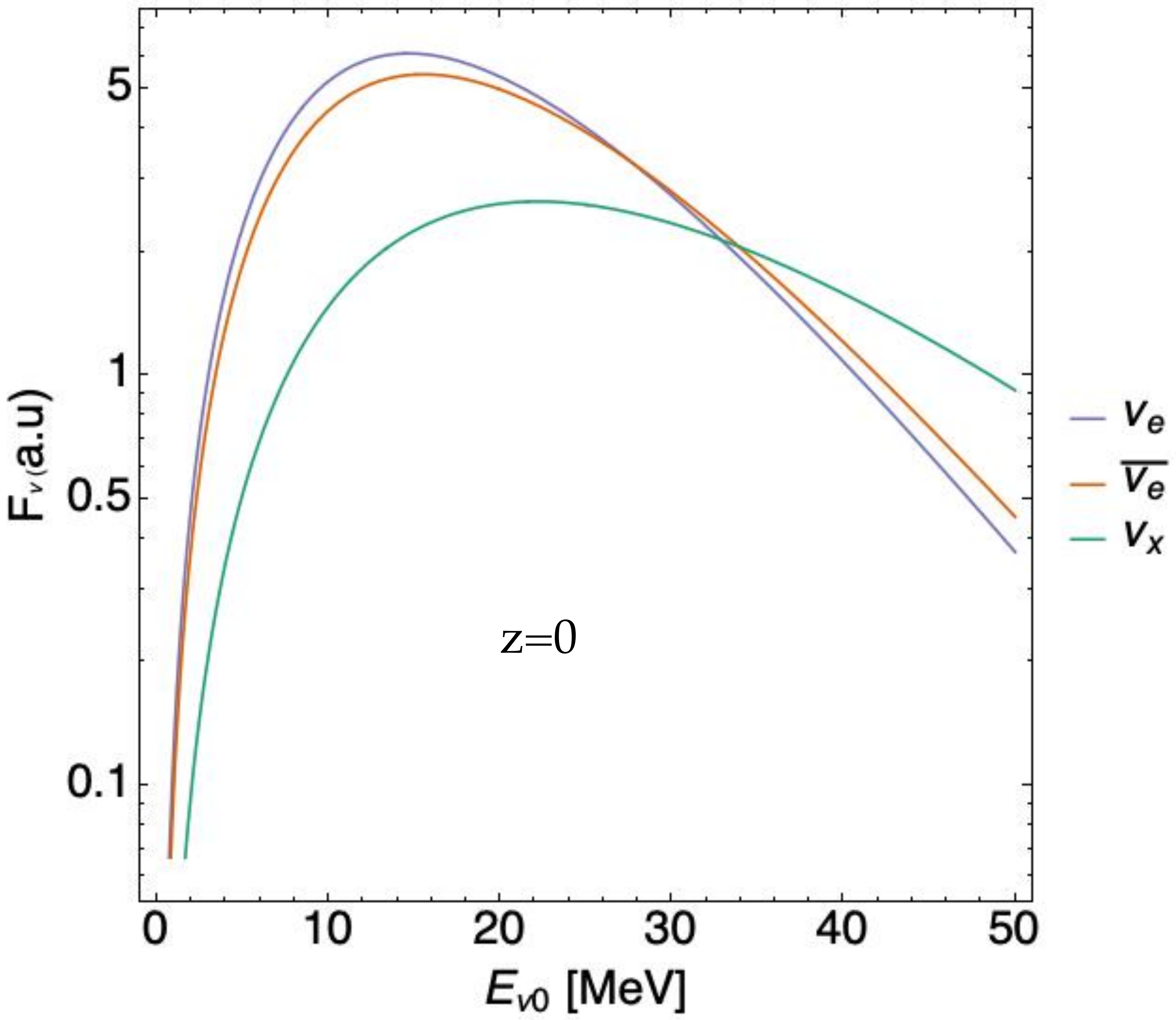
- Assume an approximately thermal spectra, characteristic of late-time phase.

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

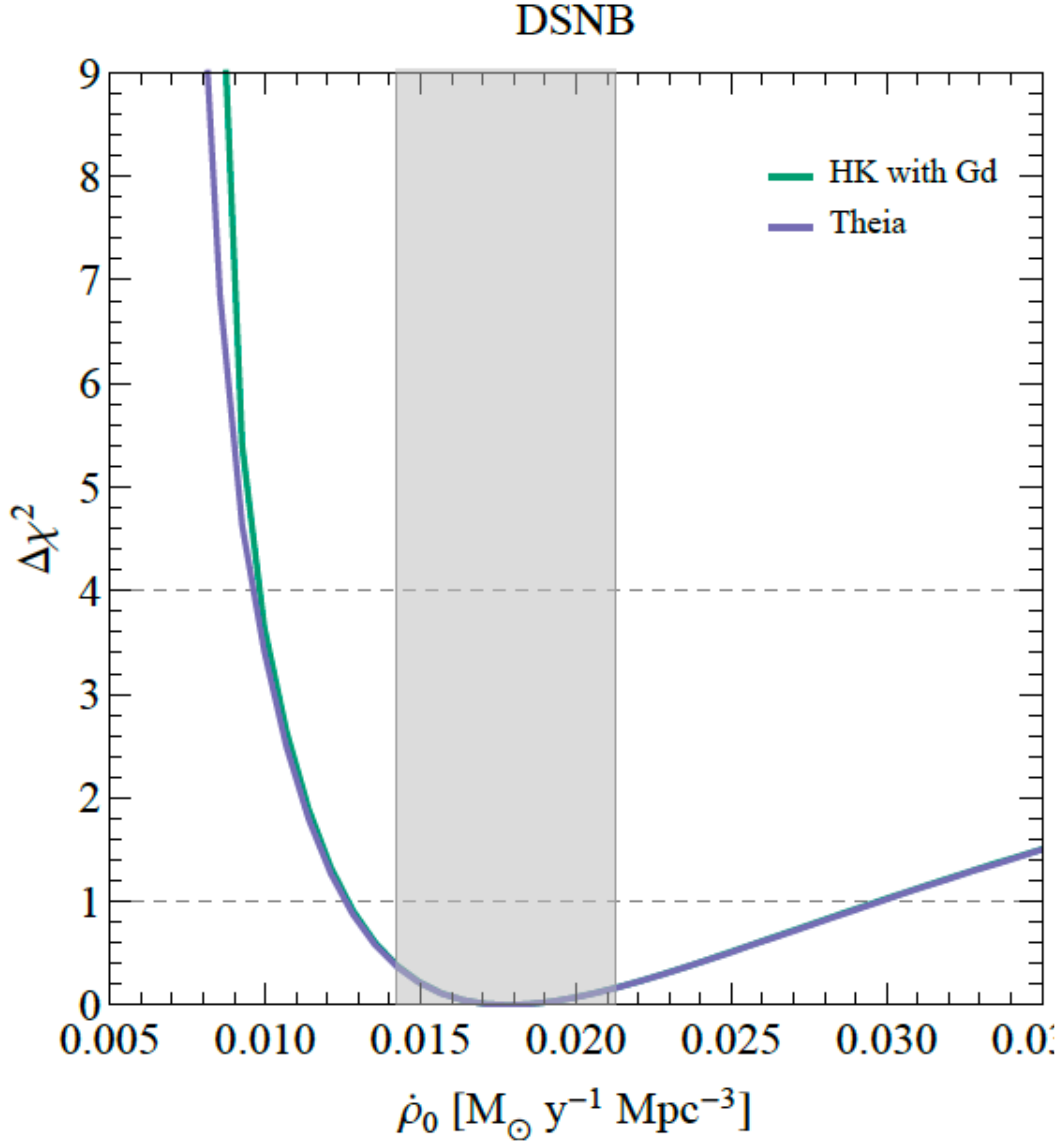
- Could be processed by collective neutrino oscillations, however effect is not very large. Hence ignore.

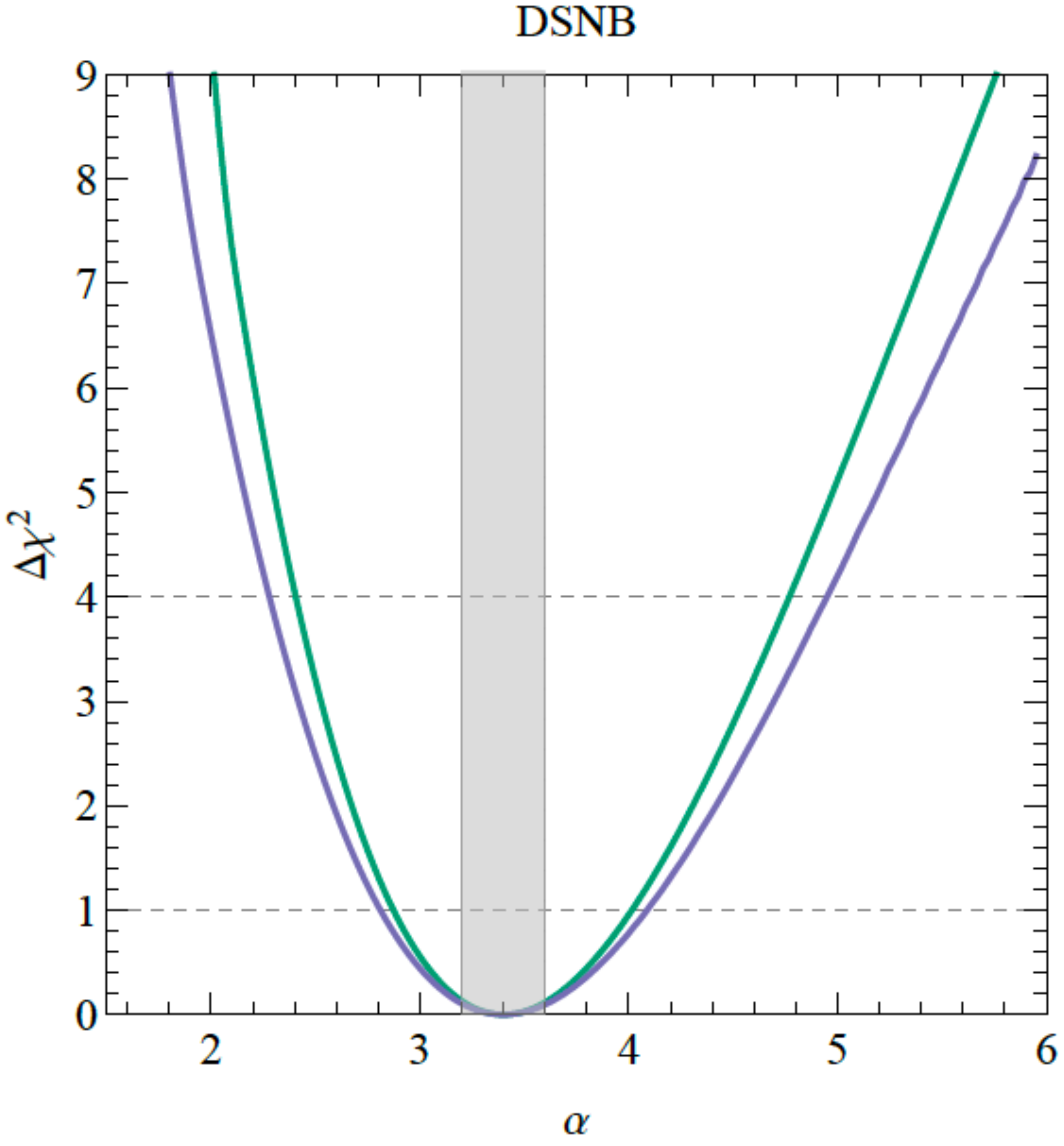
- Only assume adiabatic MSW transition, so
  heaviest neutrino $\leftrightarrow \nu_e$
  lightest neutrinos $\leftrightarrow \nu_x$

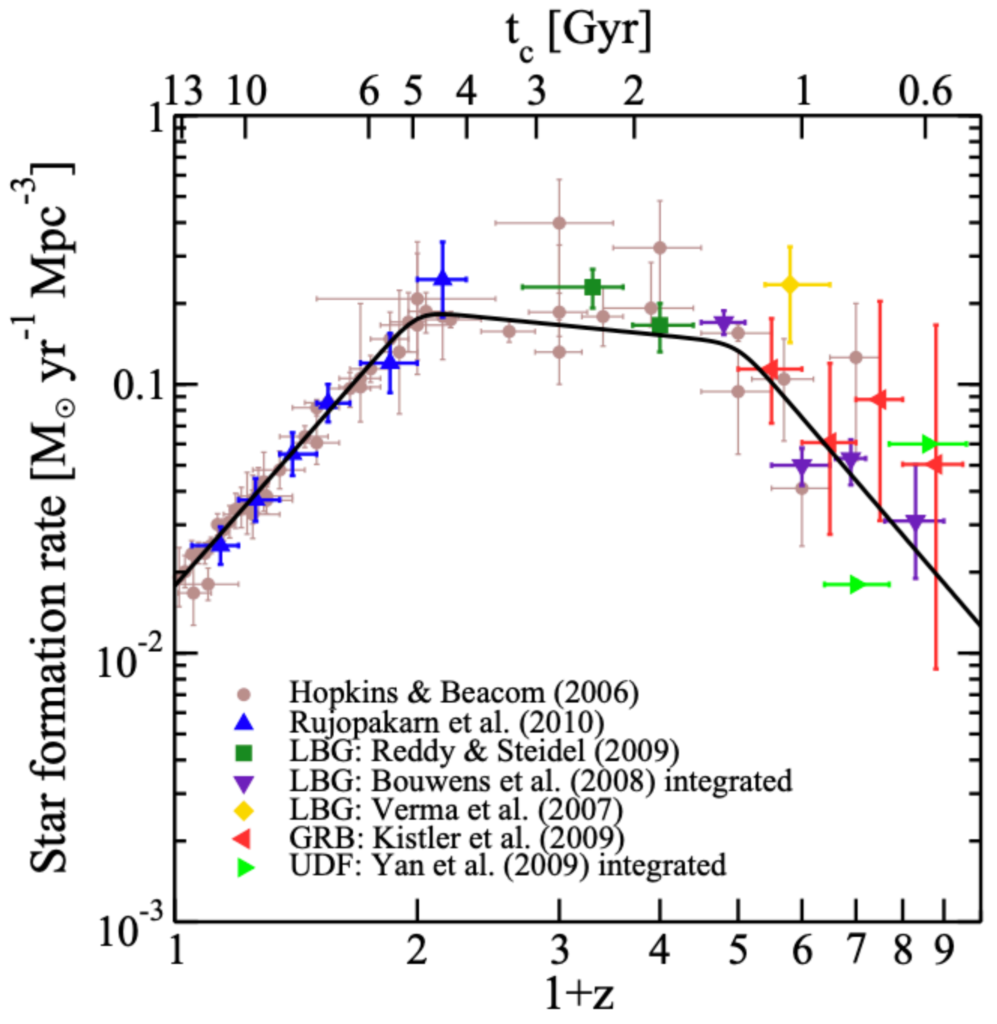
- Temperature hierarchy $T_{\nu_e} < T_{\bar{\nu}_e} < T_{\nu_x}$



Astrophysics: Cosmic star formation rate





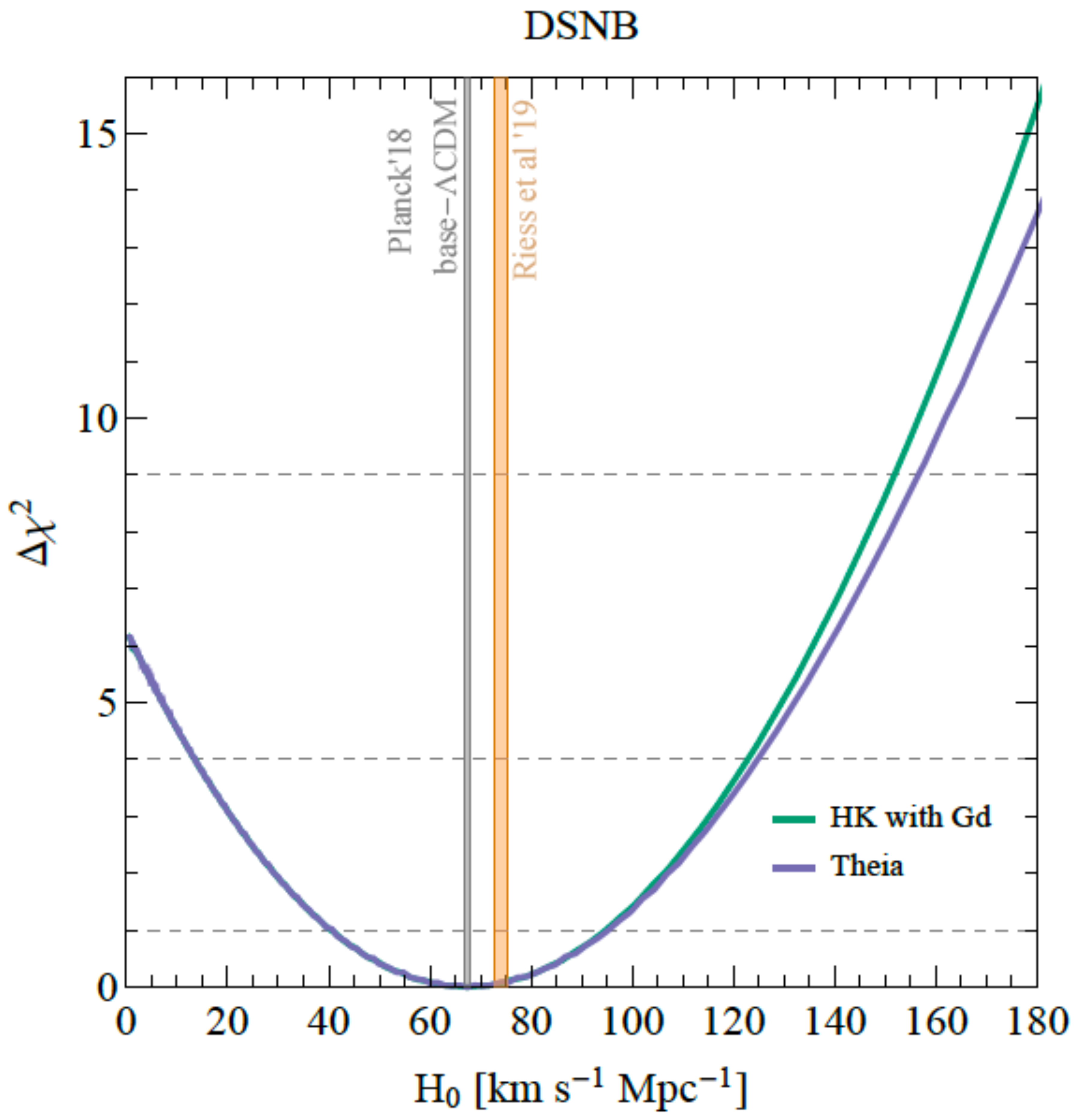


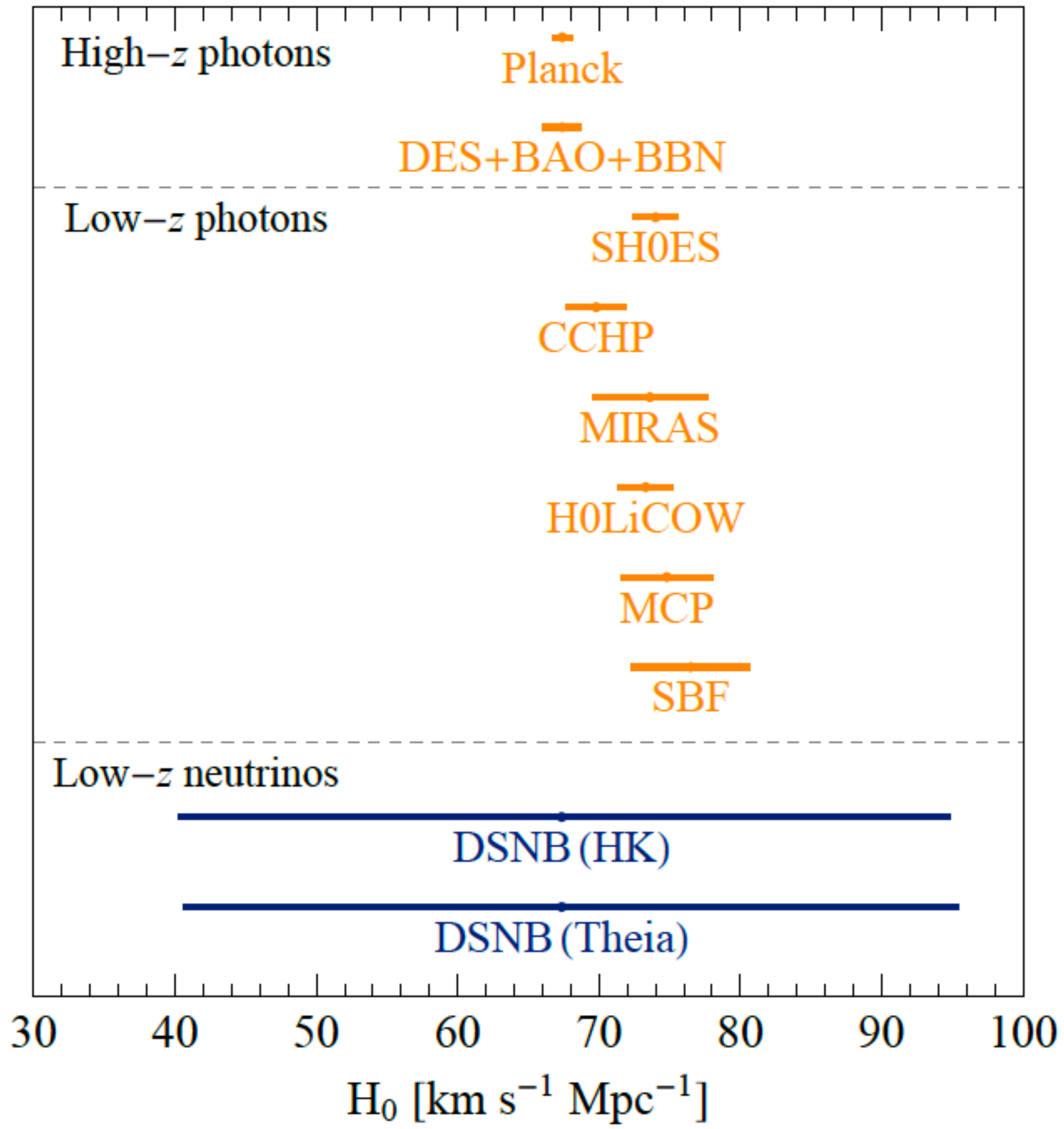
$$\dot{\rho}_*(z) = \dot{\rho}_0 \left[(1+z)^{-10\alpha} + \left(\frac{1+z}{B}\right)^{-10\beta} + \left(\frac{1+z}{C}\right)^{-10\gamma} \right]^{-1/10}$$

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

Cosmology: Hubble Parameter





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- 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.

Redshift dependent mass: adiabaticity

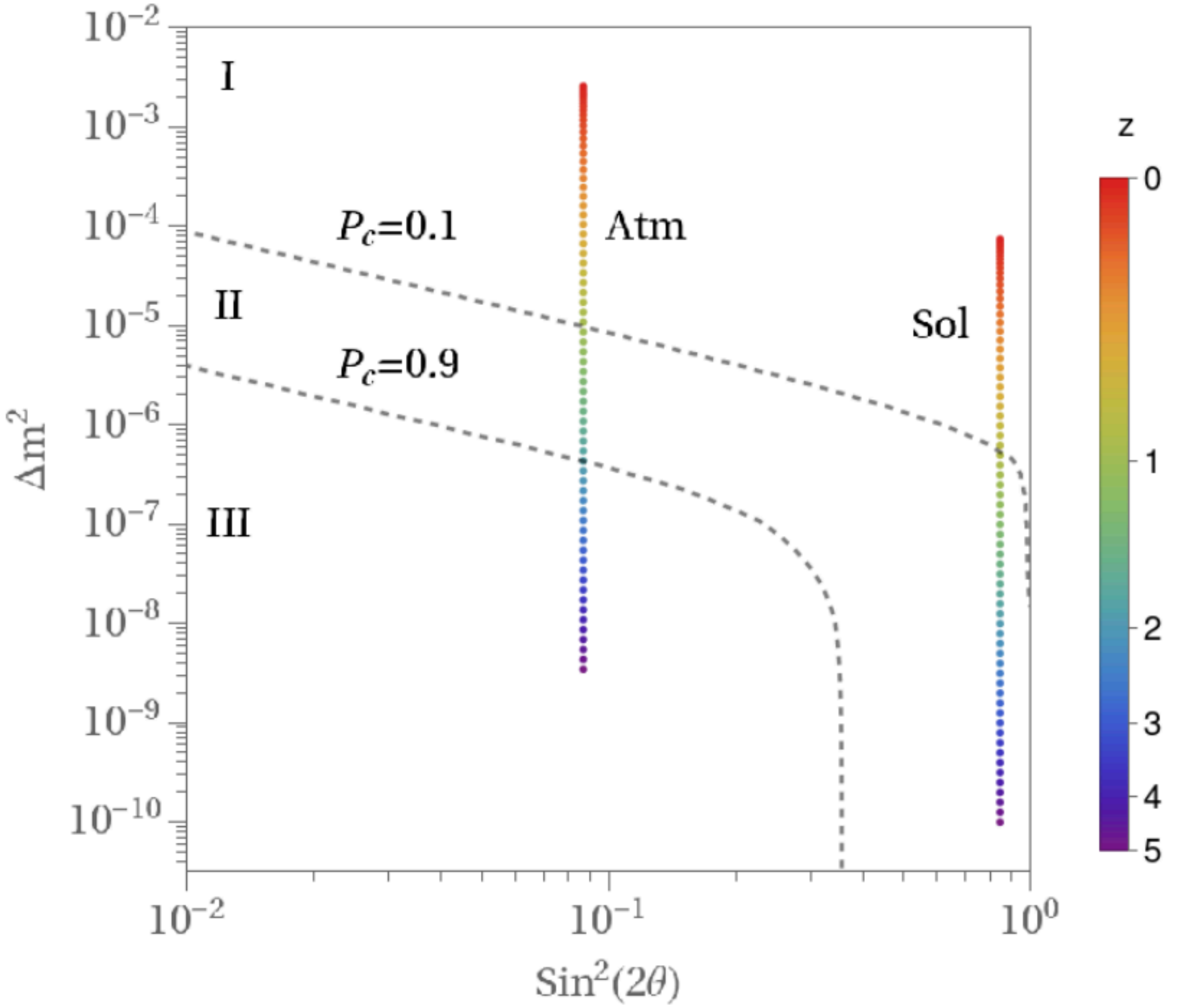

FIG. 2: Constant crossing probability contours in the $\sin^2 2\theta \times \Delta m^2$–plane. These define three regions: (I) $P_c < 0.1$, (II) $0.1 < P_c < 0.9$, and (III) $P_c > 0.9$. The color scale indicates the values of the two independent mass-squared differences as a function of the redshift of neutrino production. For the mass variation, we make use of Eq. (III.1) with $z_s = 0.32$ and $B_s = 5$.