
ESO/L Calçada

Additional BSM Effects on the DSNB

Yuber F. Perez-Gonzalez

Towards the Detection of the
Diffuse Supernova Neutrinos

September 18th, 2024

Durham University

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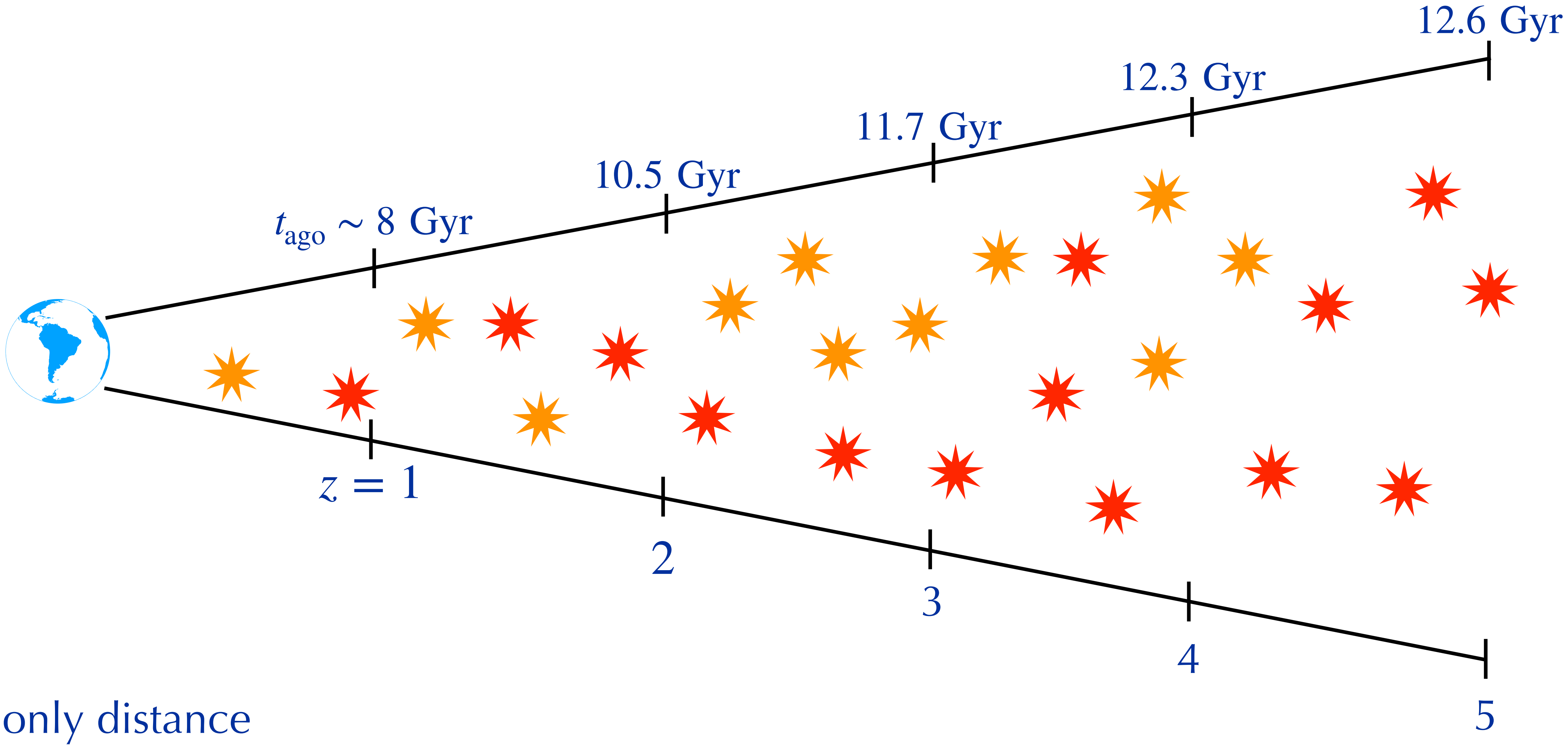
Diffuse Supernova Neutrino Background

Oldest neutrinos within experimental reach!

$$z = 5 \longrightarrow t_{\rm ago} \sim 12.6 \text{ Gyr}$$



Not only distance
but also in time

Compare to PKS 0735+178,
$z = 0.27 \rightarrow t_{\rm ago} = 3.35$ Gyr

Inspired on Beacom

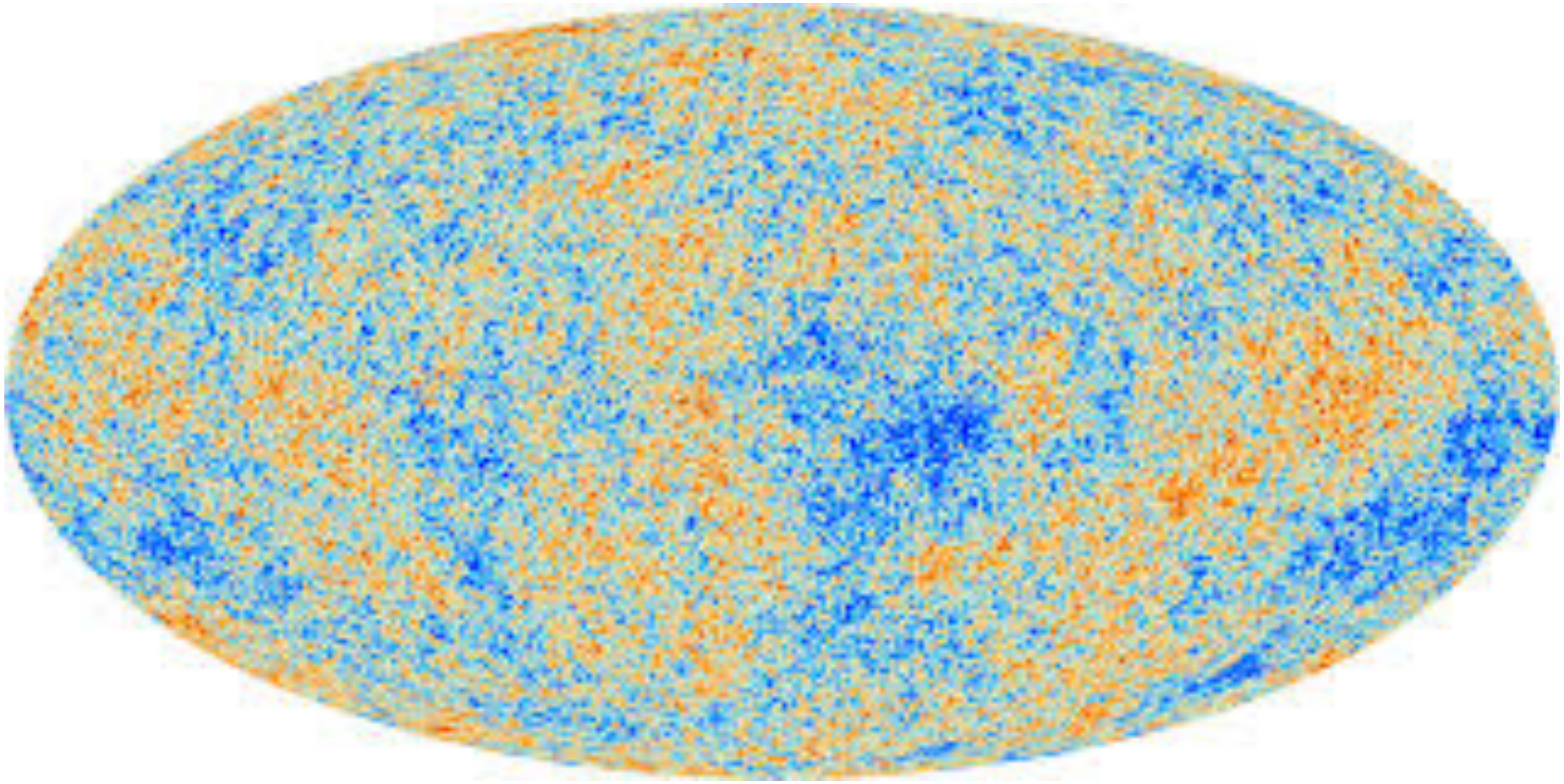
Beacom, Ann.Rev.Nuc.Phys.Sc.2010
Lunardini, Astropart. Phys2016

*Assuming ΛCDM

See also Ken’ichiro's talk

Diffuse Supernova Neutrino Background

Oldest photons…



Oldest neutrinos, the CνB,
probably not in our lifetime

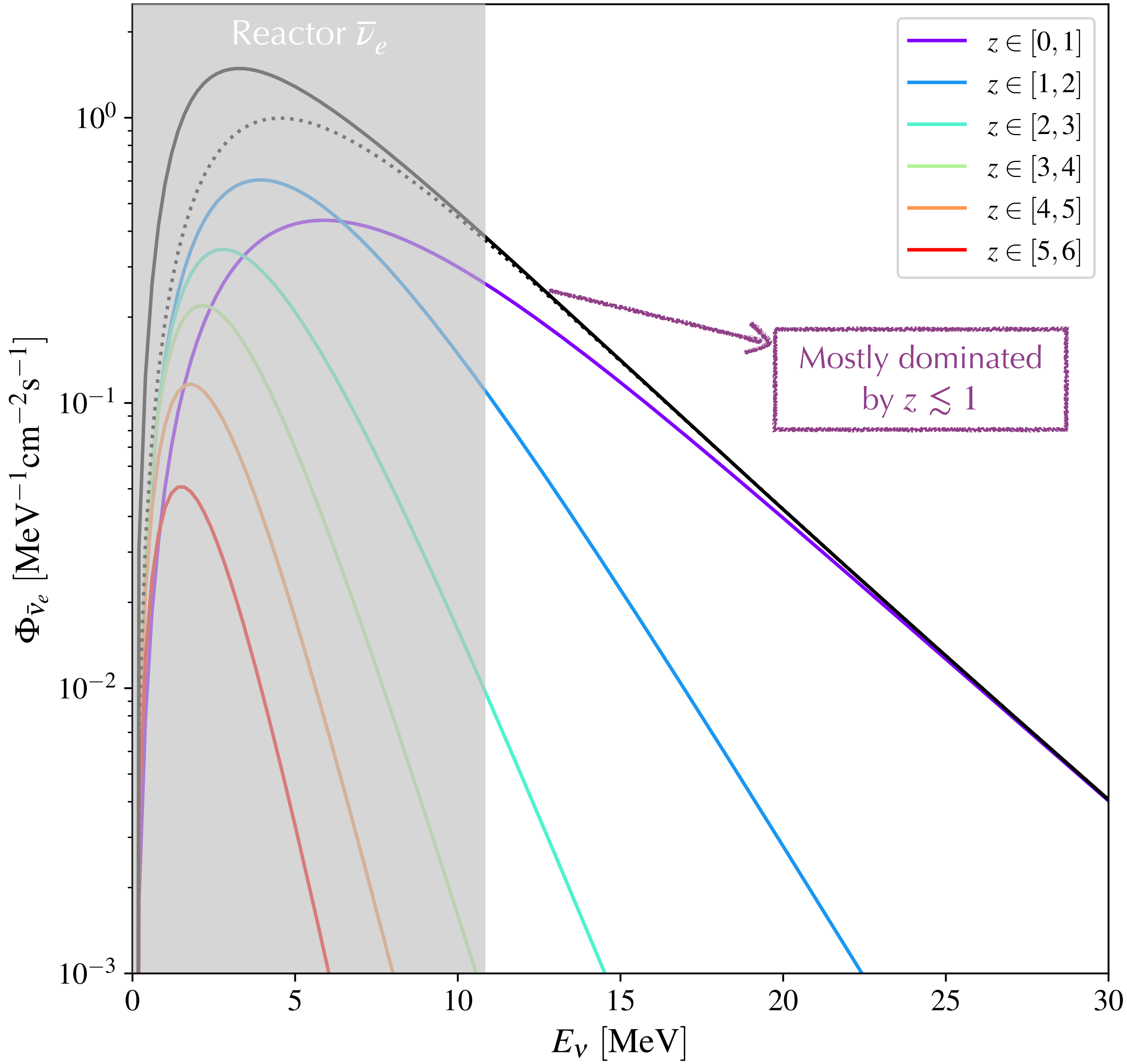
Diffuse Supernova Neutrino Background

We've seen this several times by now…

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

$z_{\max} = 5$

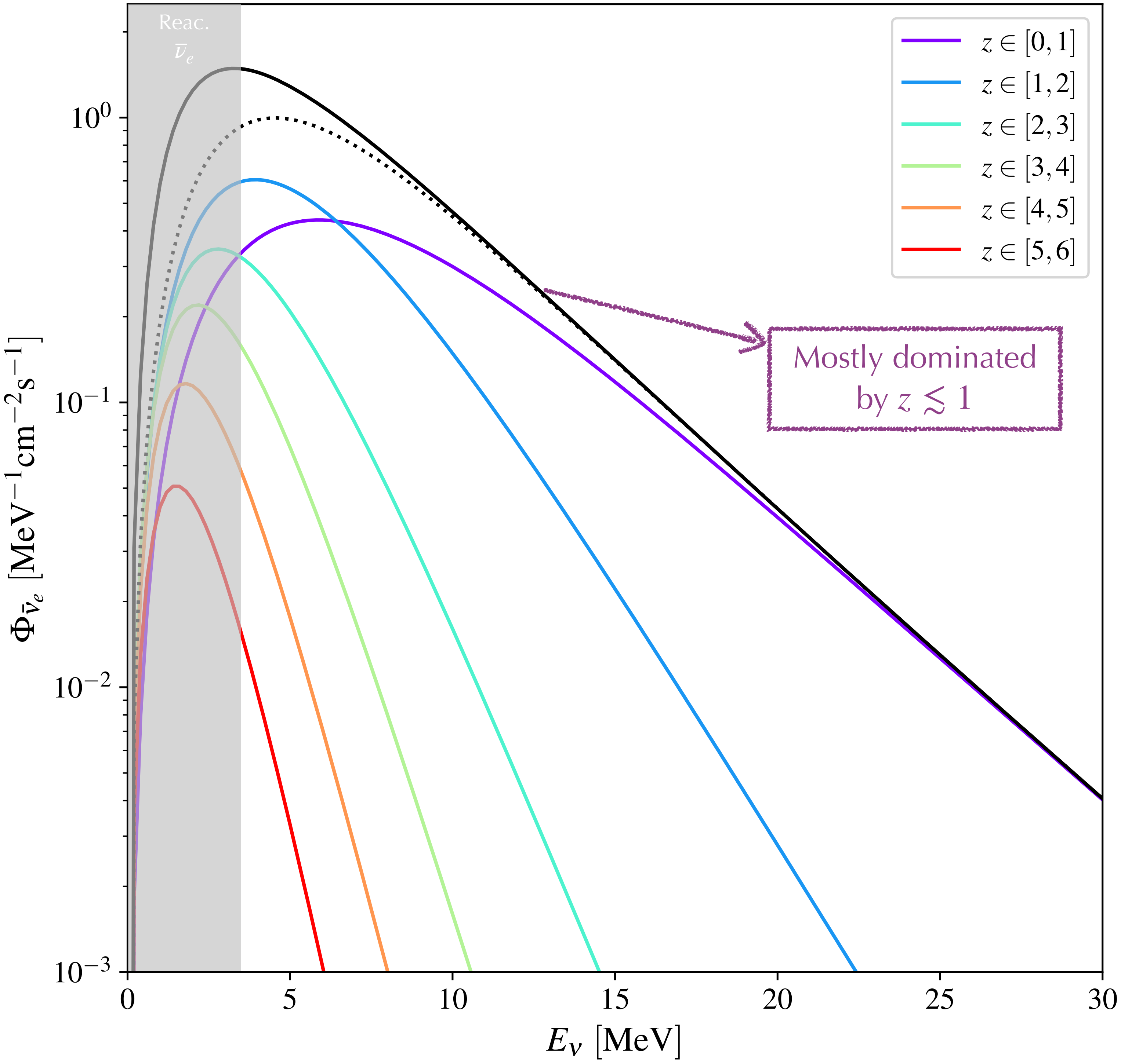
Diffuse Supernova Neutrino Background



Mostly dominated by $z \lesssim 1$

See also Daniel's talk

Diffuse Supernova Neutrino Background



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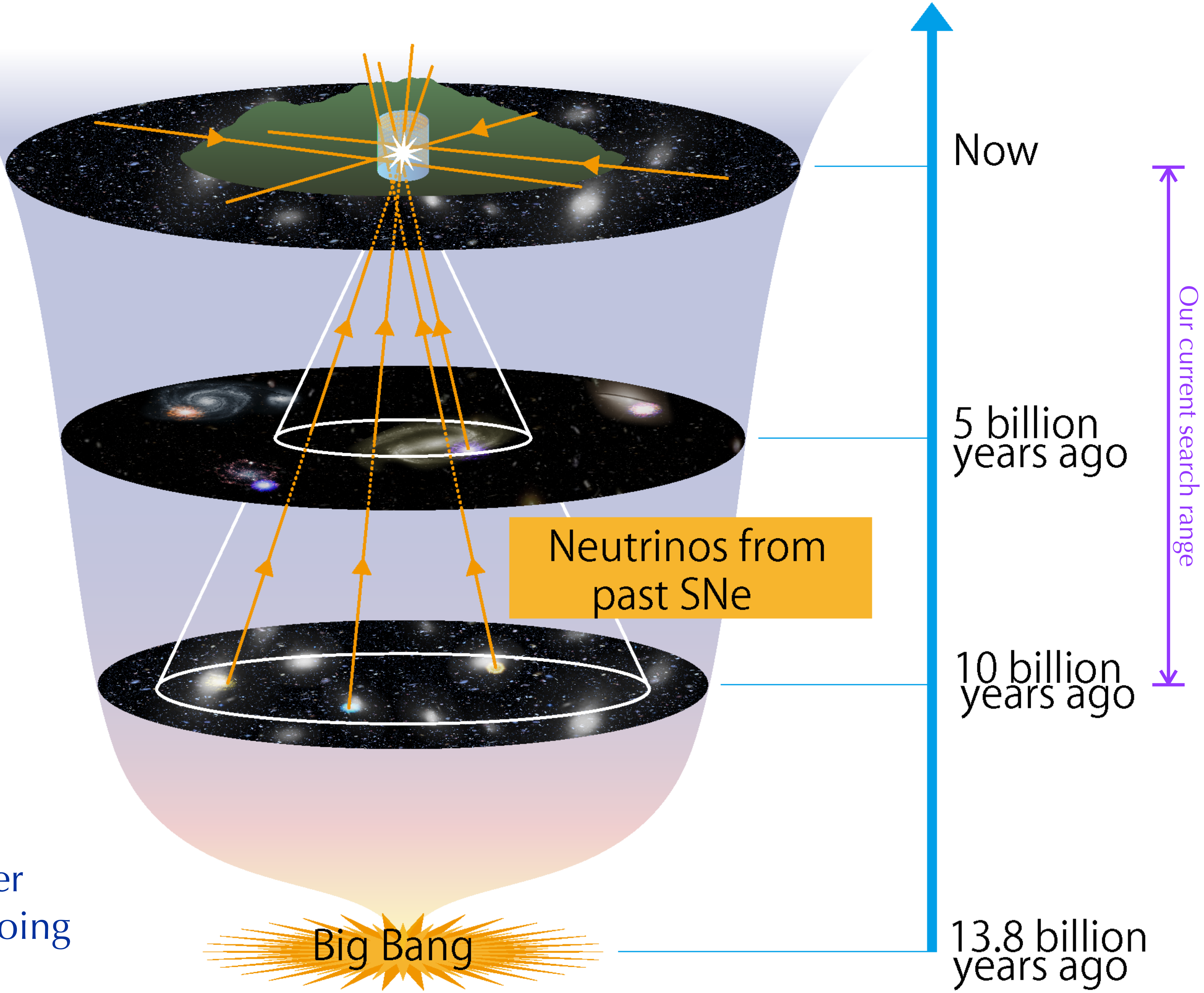
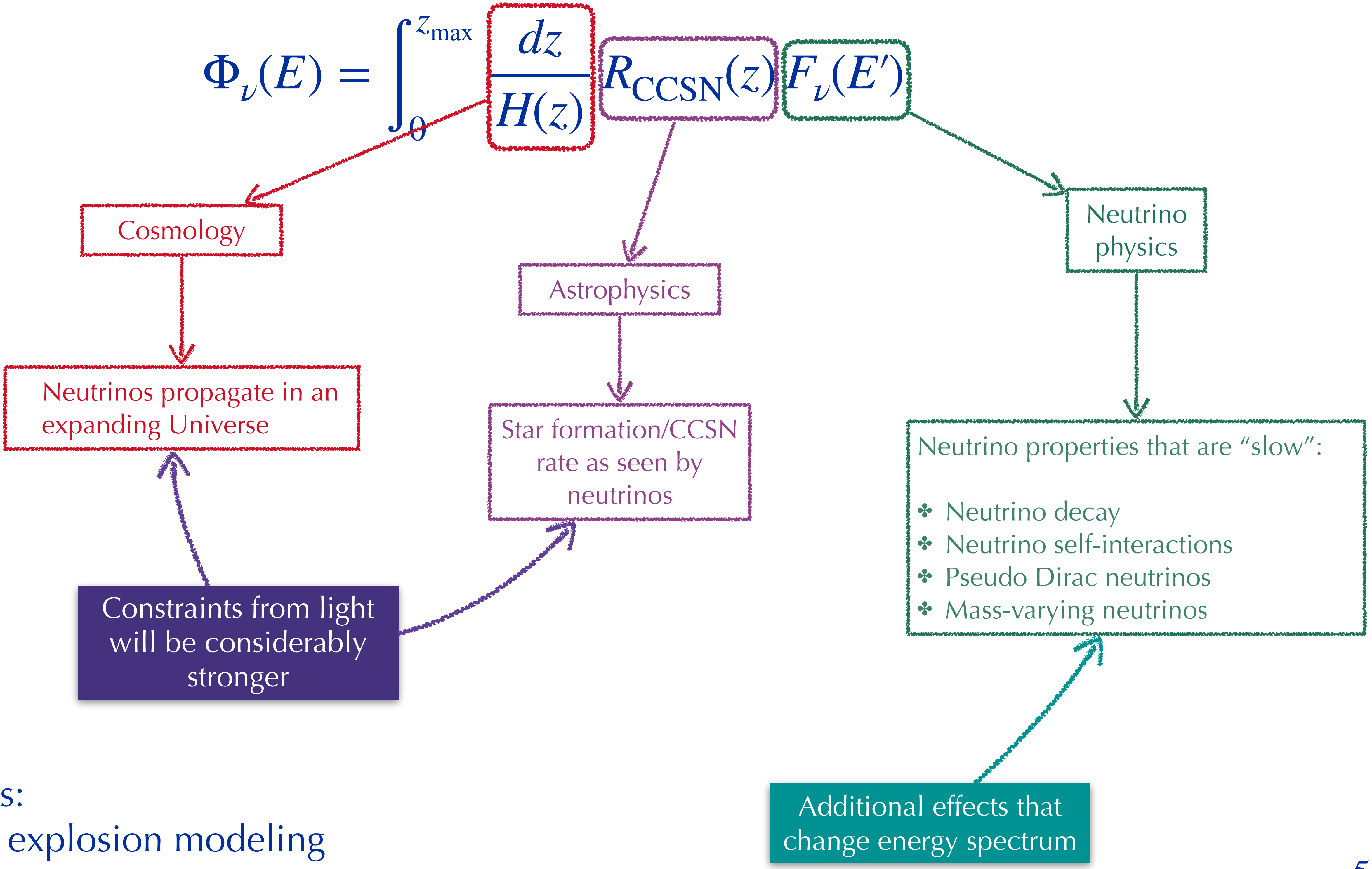


Going to lower energies mean going further back!

What can we learn?

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

We've seen this several times by now…



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

Cosmology

Neutrinos propagate in an expanding Universe

Astrophysics

Star formation/CCSN rate as seen by neutrinos

Neutrino physics

Neutrino properties that are "slow":

- Neutrino decay
- Neutrino self-interactions
- Pseudo Dirac neutrinos
- Mass-varying neutrinos

Constraints from light will be considerably stronger

Additional effects that change energy spectrum

- Caveats:
  - SN explosion modeling
  - Dependence on $f_{\rm BH}, f_{\rm MR}$

$z_{\max} = 5$

What can we learn?

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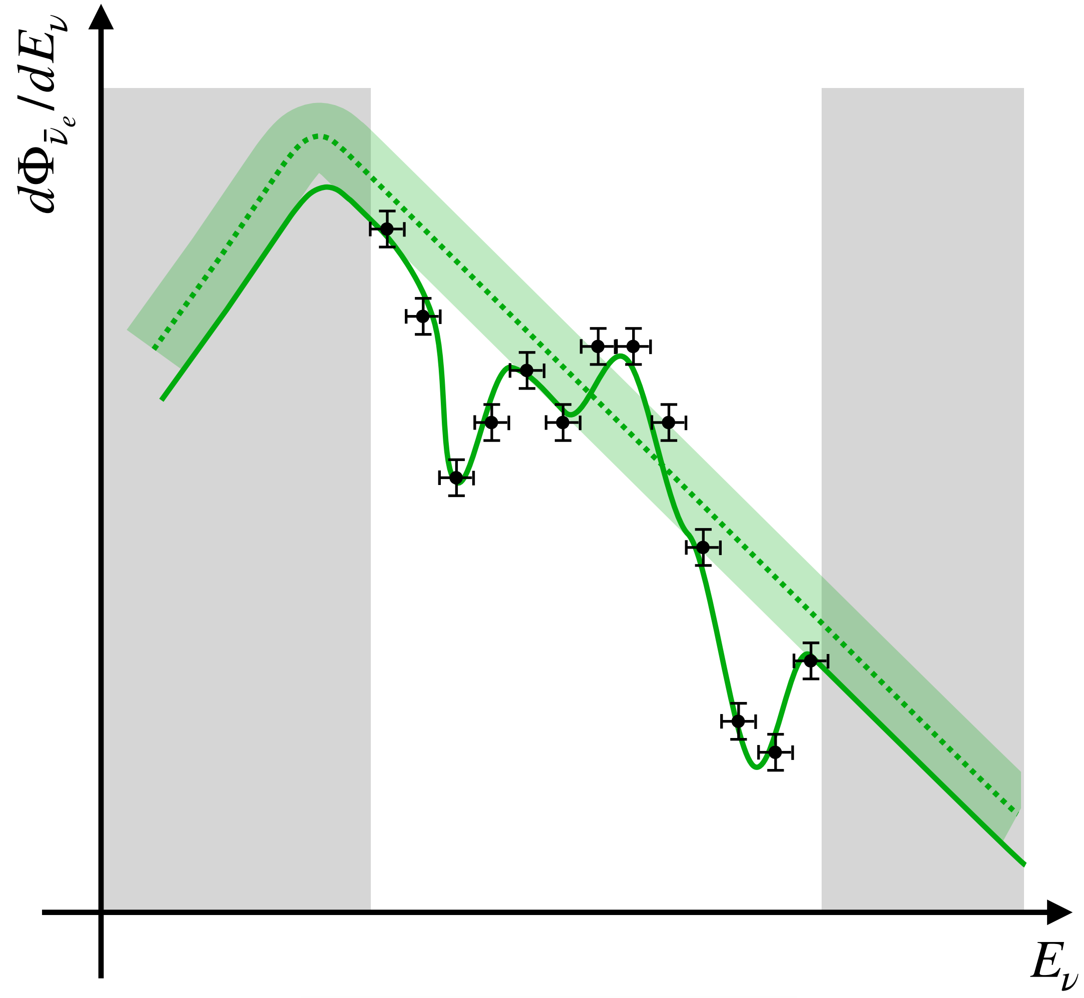
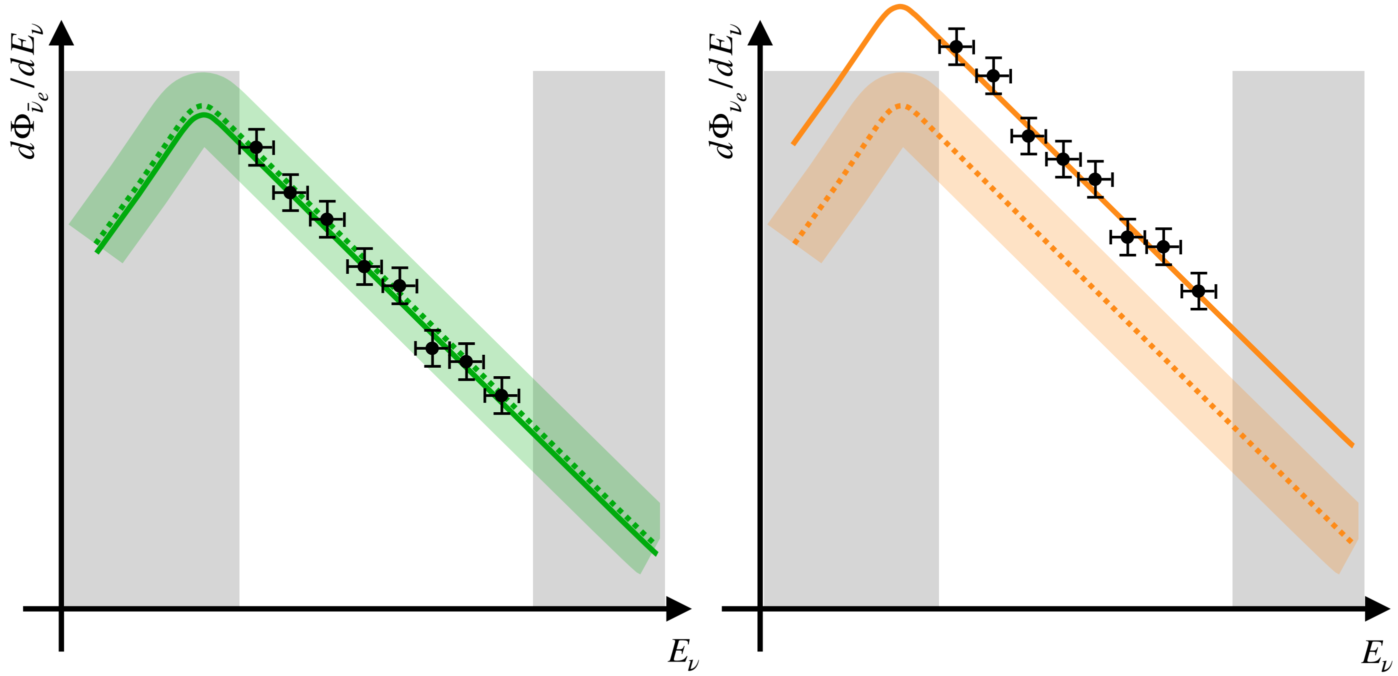


Smocking gun signatures



Mismatch between flavors

This, of course, will
require lots of statistics

Is there anything we can do
with SK (10y) + JUNO?

Here's the homework Pablo asked for!

What can we learn?

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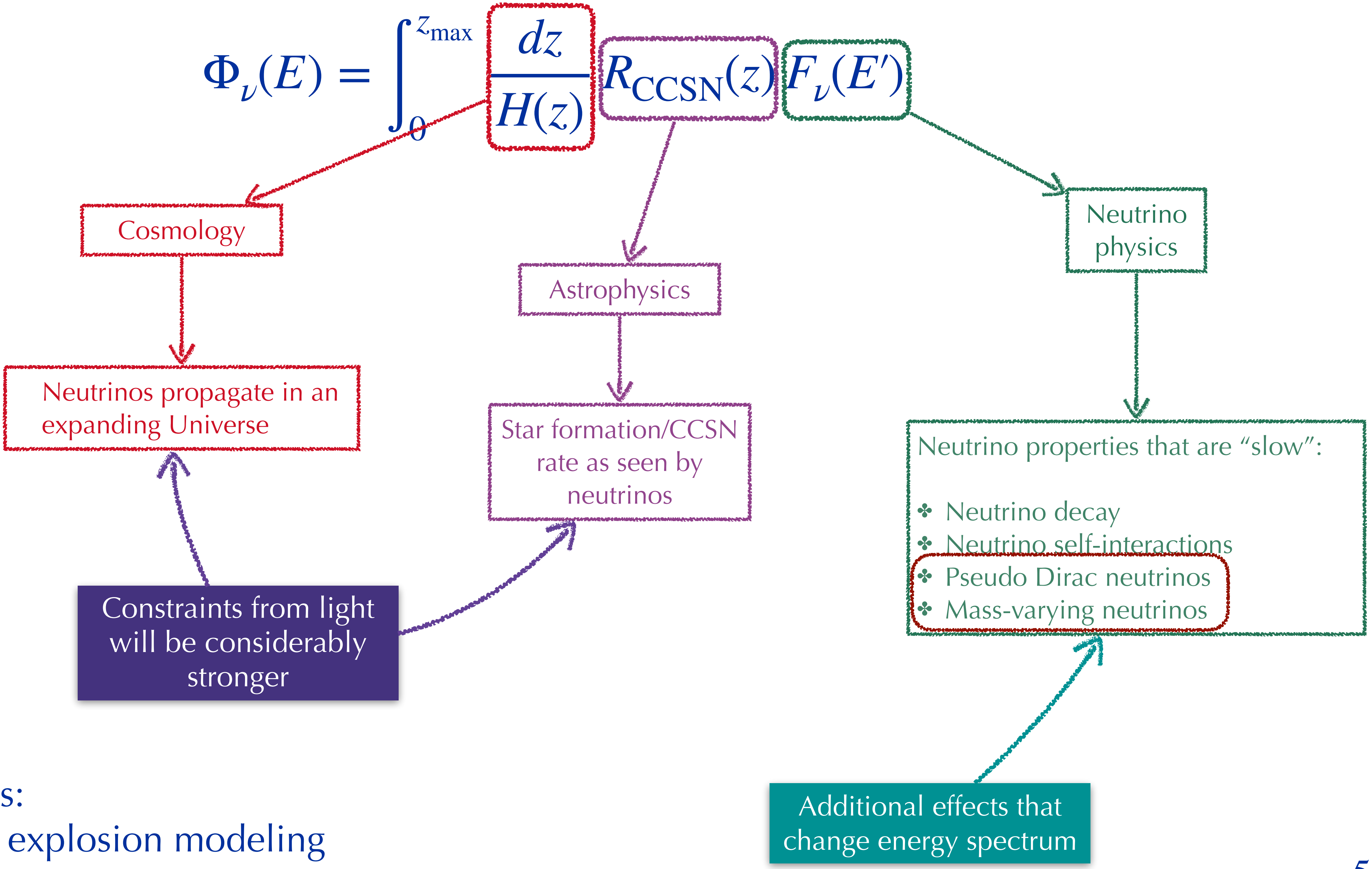
We've seen this several times by now…



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Pseudo-Dirac Neutrinos

Pseudo-Dirac Neutrinos*

Let's consider the Dirac+Majorana Lagrangian

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

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

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

Soft lepton number violation

Also technically natural case

$$\nu_{\alpha L} = \frac{1}{\sqrt{2}} U_{\alpha j} (\nu_j^+ + i\,\nu_j^-)$$

PMNS matrix

Mass eigenstates

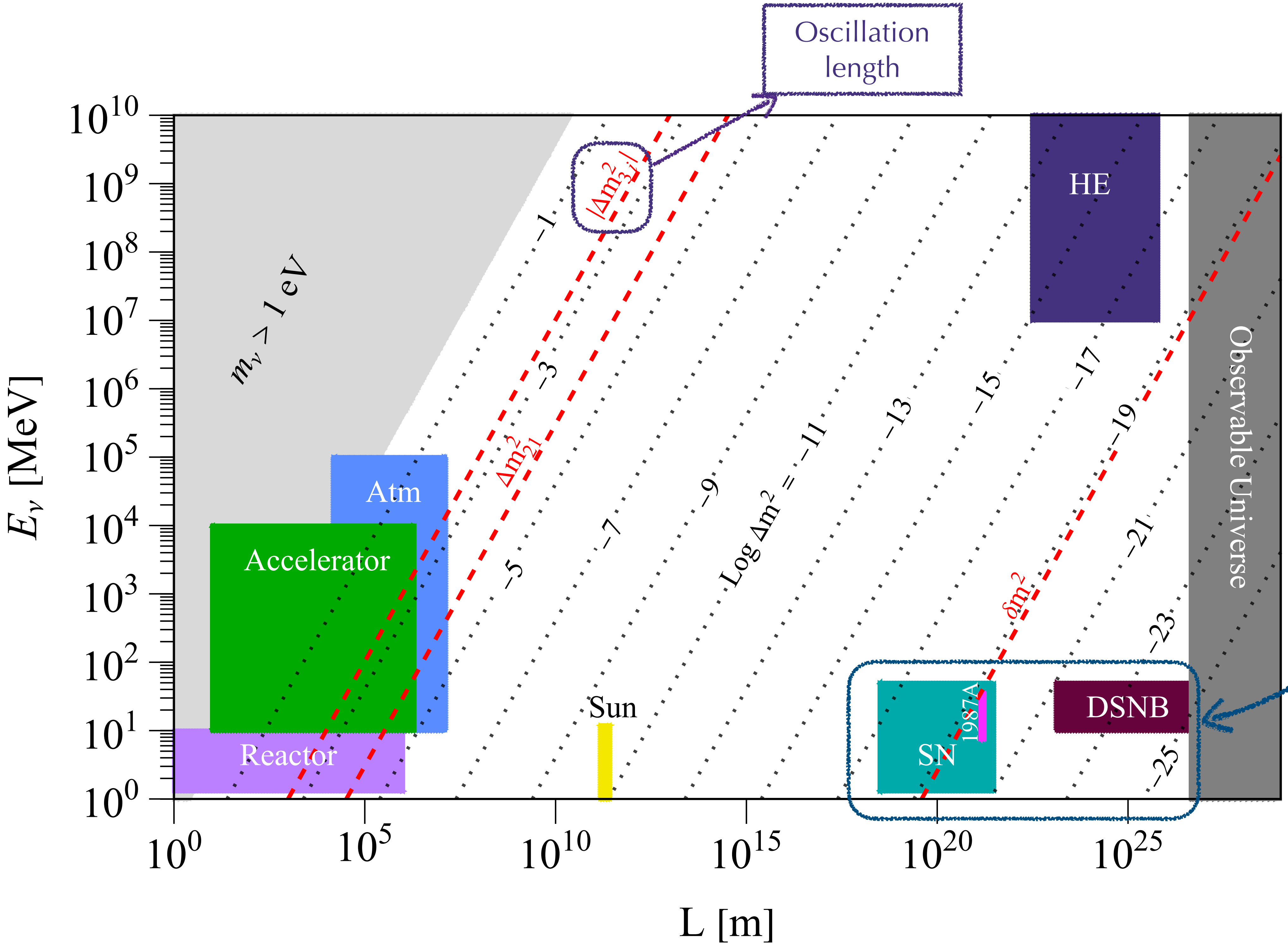
Active neutrinos are a ~50-50 combination of two mass eigenstates

---

*I use "pseudo-Dirac" to describe active-sterile pairs

Pseudo-Dirac Neutrinos

$$P_{ee} = P_{aa}(E_\nu; L, \delta m^2) \sum_k \left| U_{ek} \right|^4$$



DSNB neutrinos are sensitive to very tiny mass differences!

Inspired on 0307151

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

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

Pseudo-Dirac Neutrinos

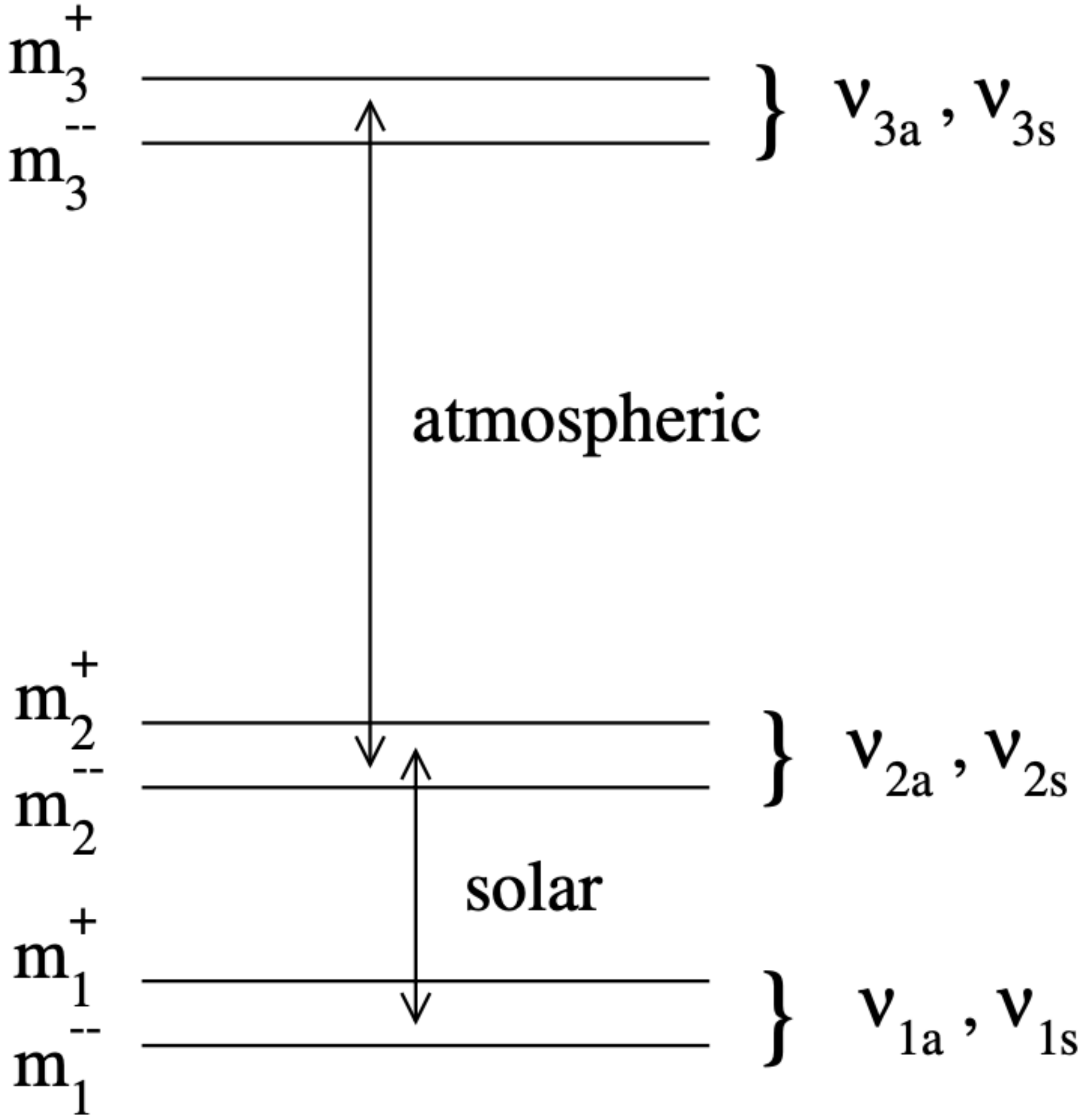
$$m_{ks}^2 = m_k^2 + \frac{1}{2}\delta m_k^2$$

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

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

Limits on δm_k^2

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



Beacom et.al. 0307151

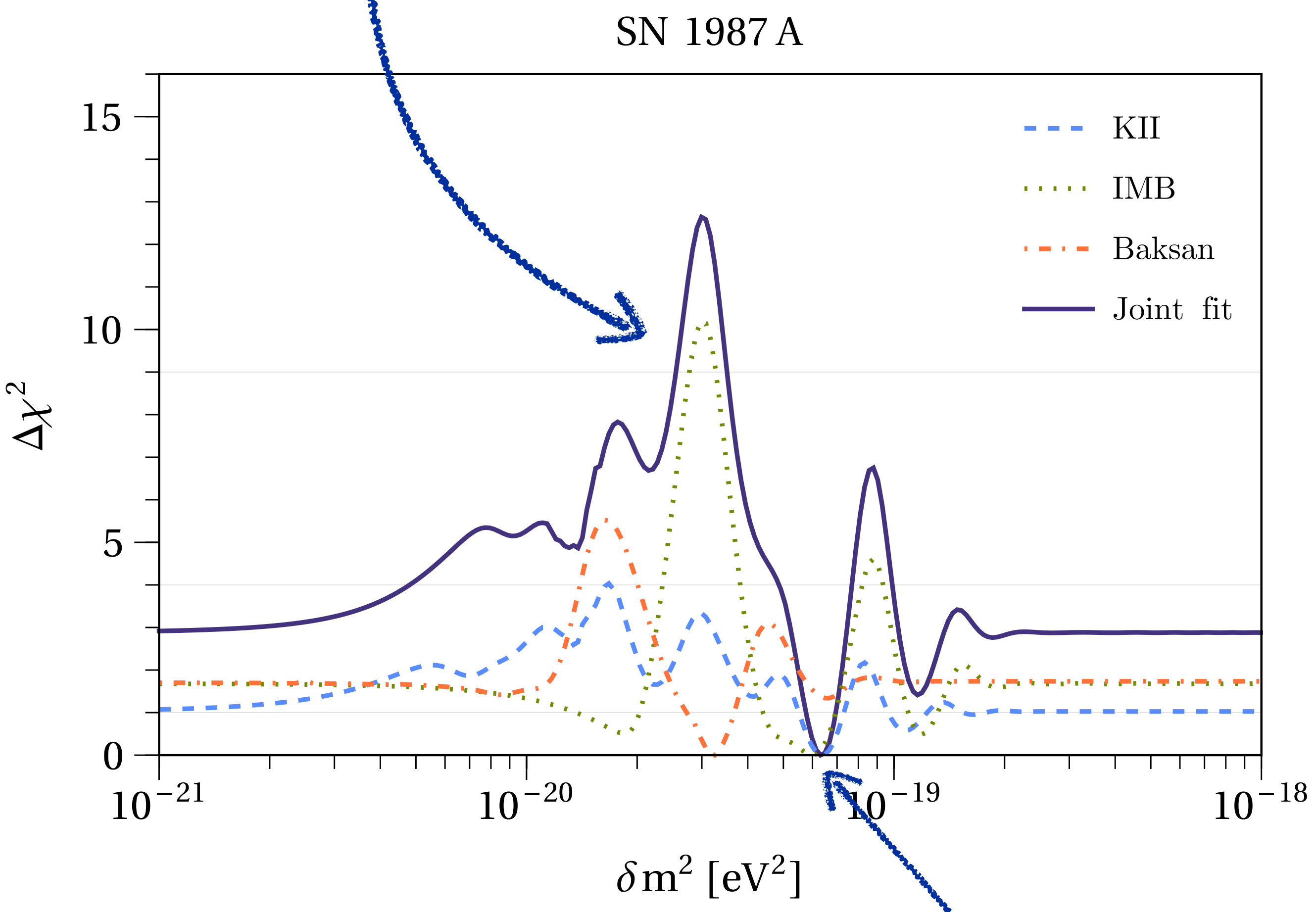
SN1987A

Mild preference for a non-zero δm_k^2

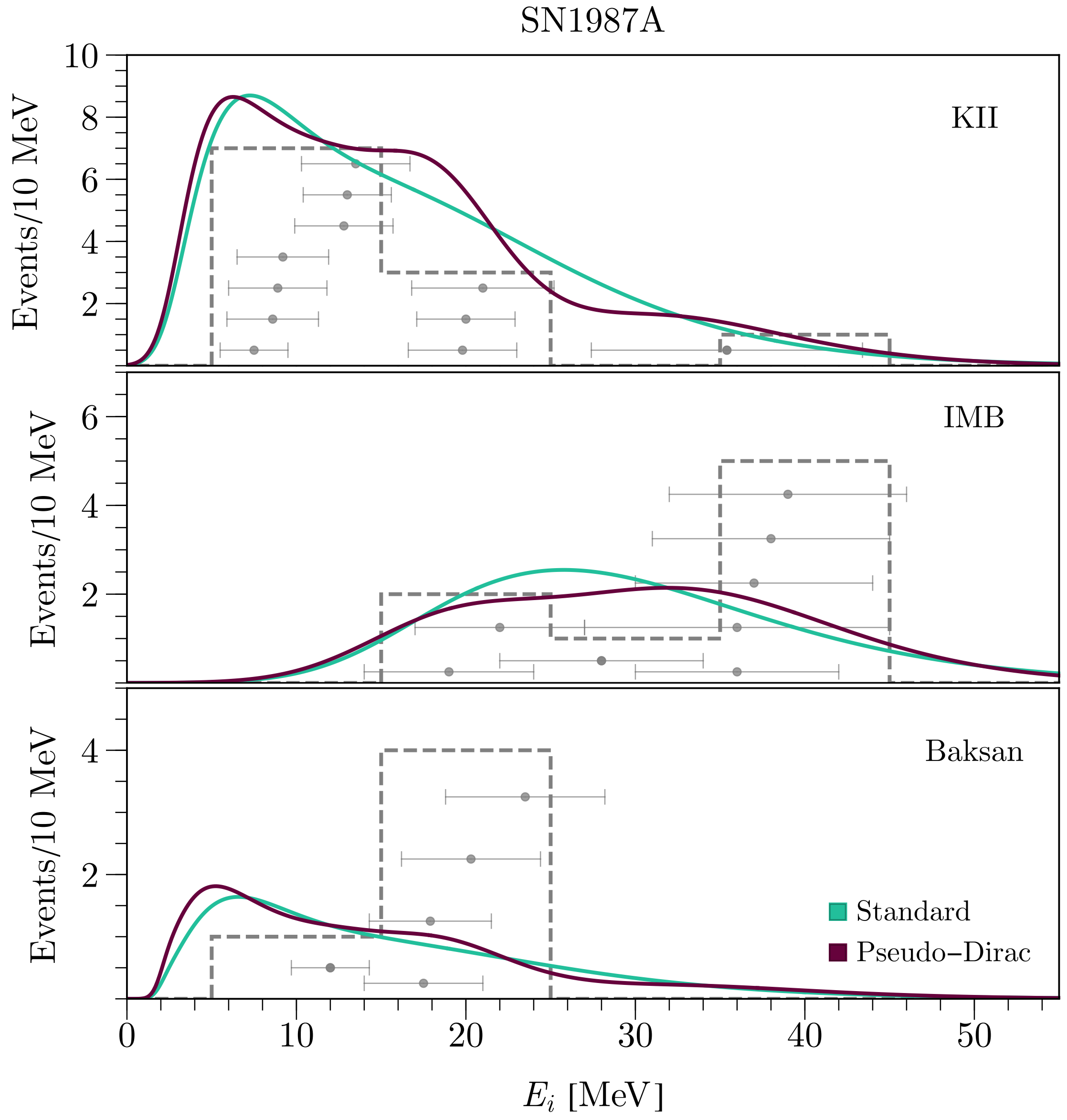
$\Delta\chi^2 \approx 3$

We can exclude a range a more than 3σ!

$\delta m_k^2 \sim [2.55,3.01] \times 10^{-20}\ \mathrm{eV}^2$



$\delta m_k^2 = 6.31 \times 10^{-20}\ \mathrm{eV}^2$



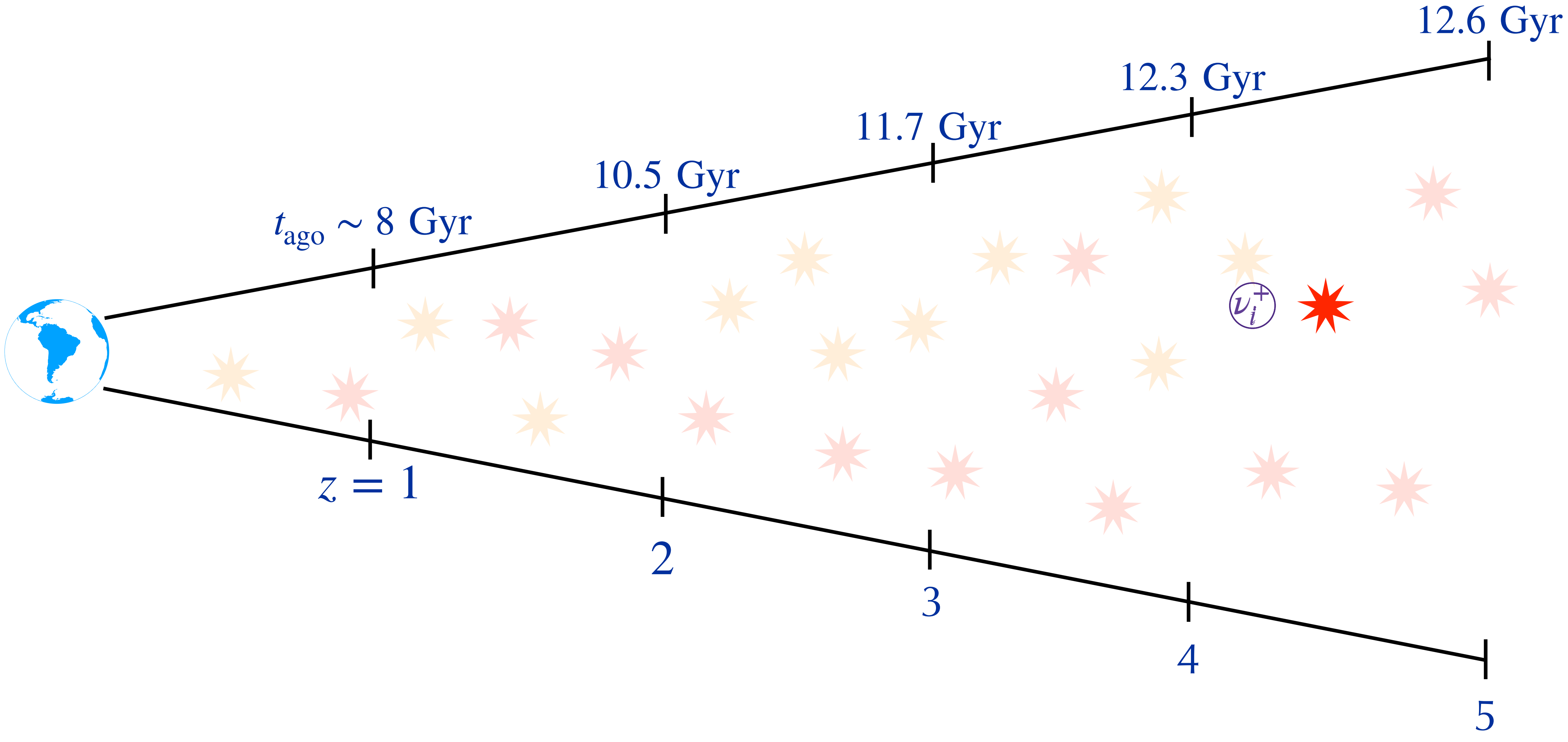
Active-sterile oscillations ease the tension

Martinez-Soler, YFPG, Sen
PRD105(2022)095019

Pseudo-Dirac Neutrinos — DSNB

Oldest neutrinos within experimental reach!

$z = 5 \longrightarrow t_{\rm ago} \sim 12.6$ Gyr



Inspired on Beacom

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

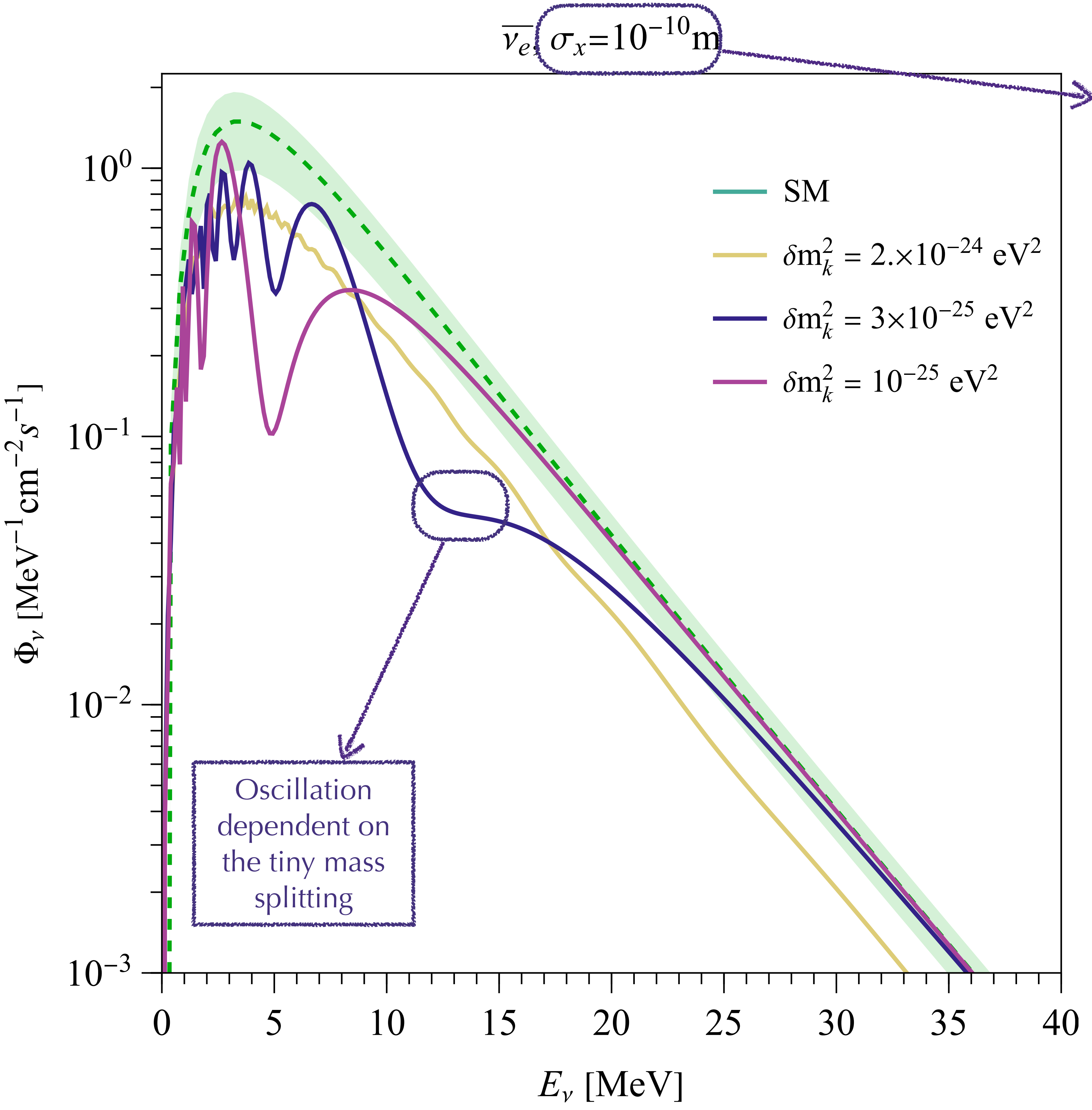
*Assuming ΛCDM

Pseudo-Dirac Neutrinos — DSNB

Caveats:

- We assume all δm_k^2 are the same for all three generations, and there is maximal mixing between the PD pair
- We assume MSW happens as in the standard case. PD oscillations only starts to matter much later. We do not include fast flavor oscillations.
- The general trend doesn't depend on the specifics, since we're looking for an additional energy dependence on the events

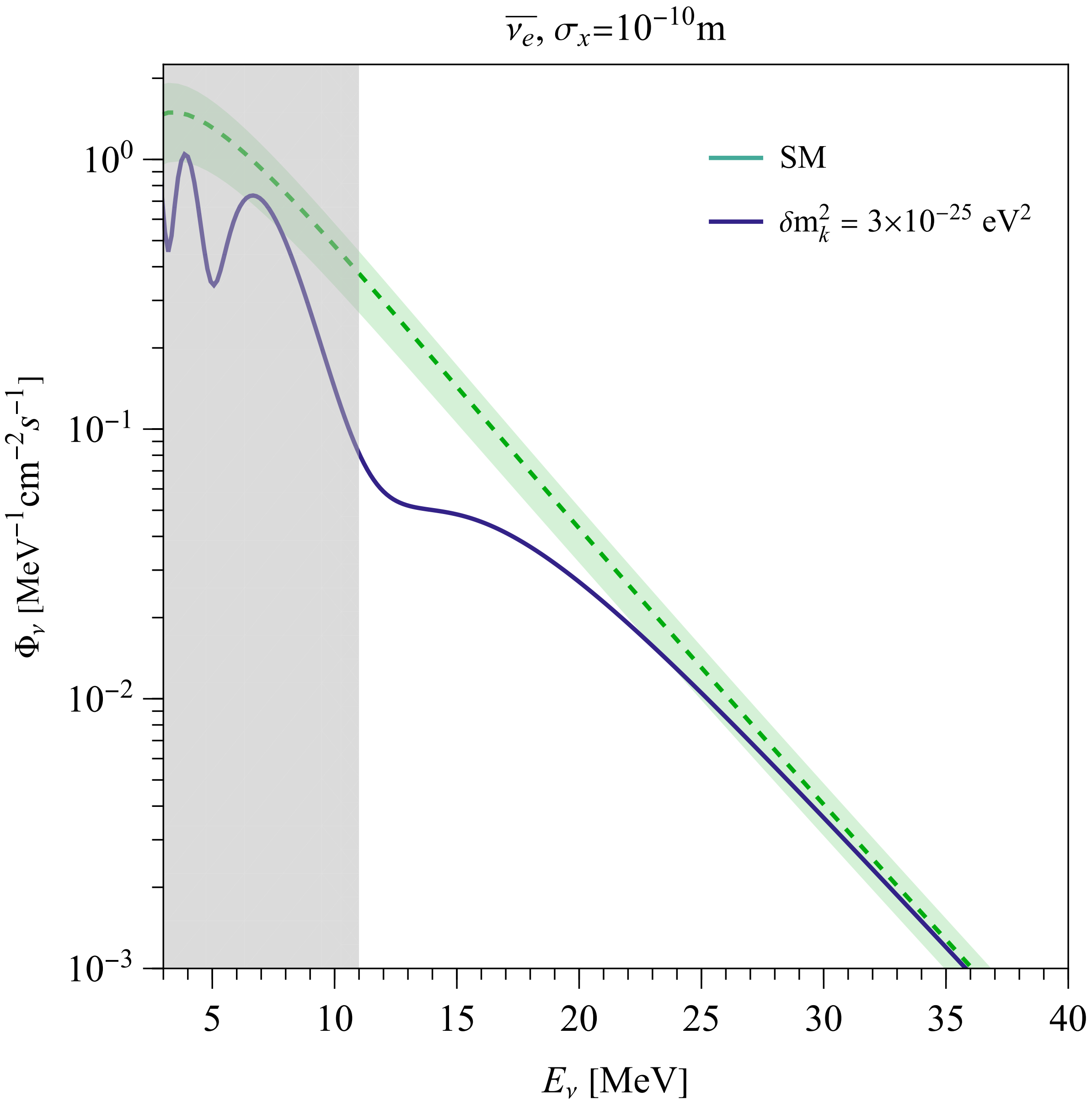
Pseudo-Dirac Neutrinos — DSNB

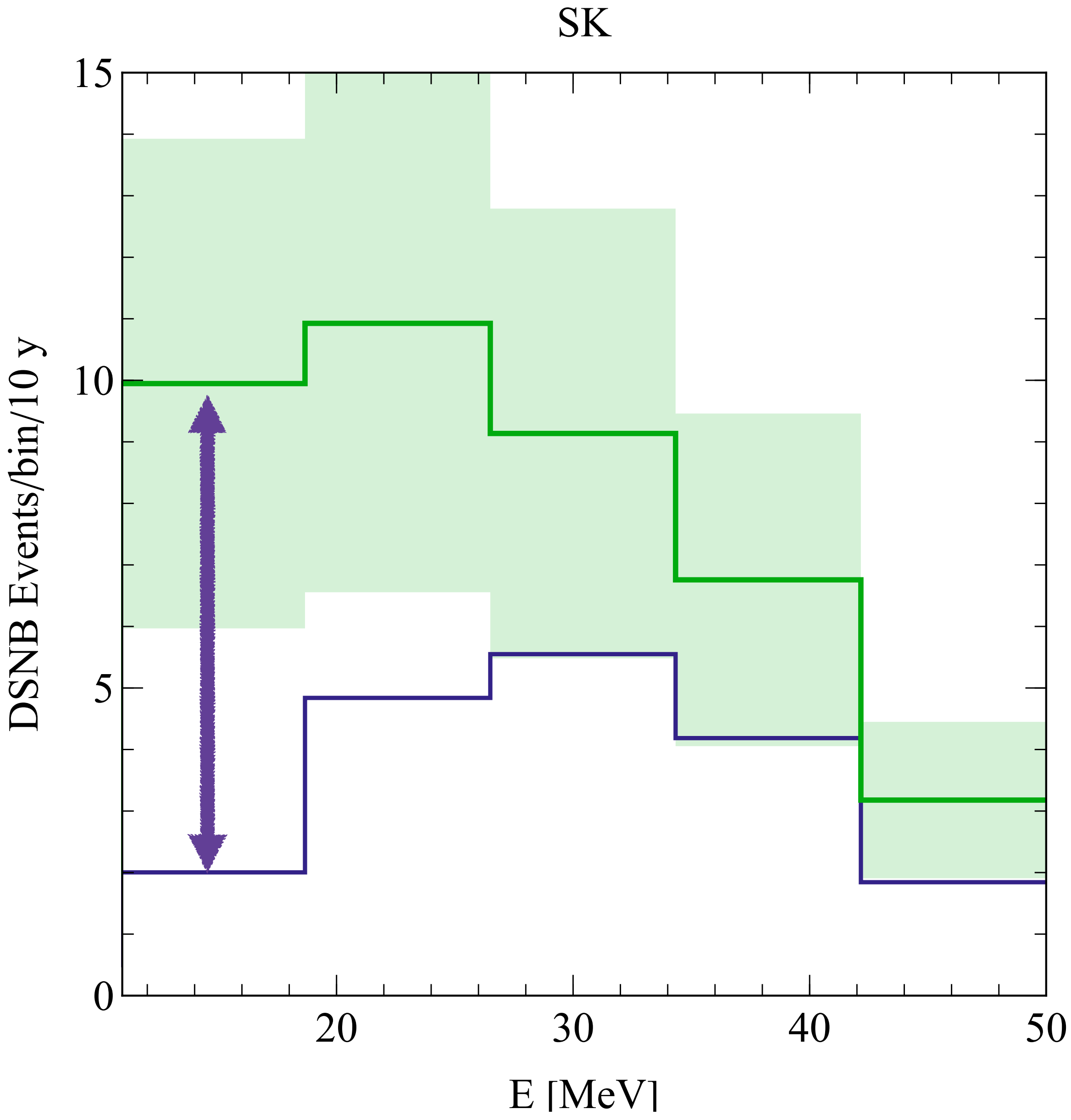


Fixed wave packed size

Oscillation dependent on the tiny mass splitting

Pseudo-Dirac Neutrinos — DSNB

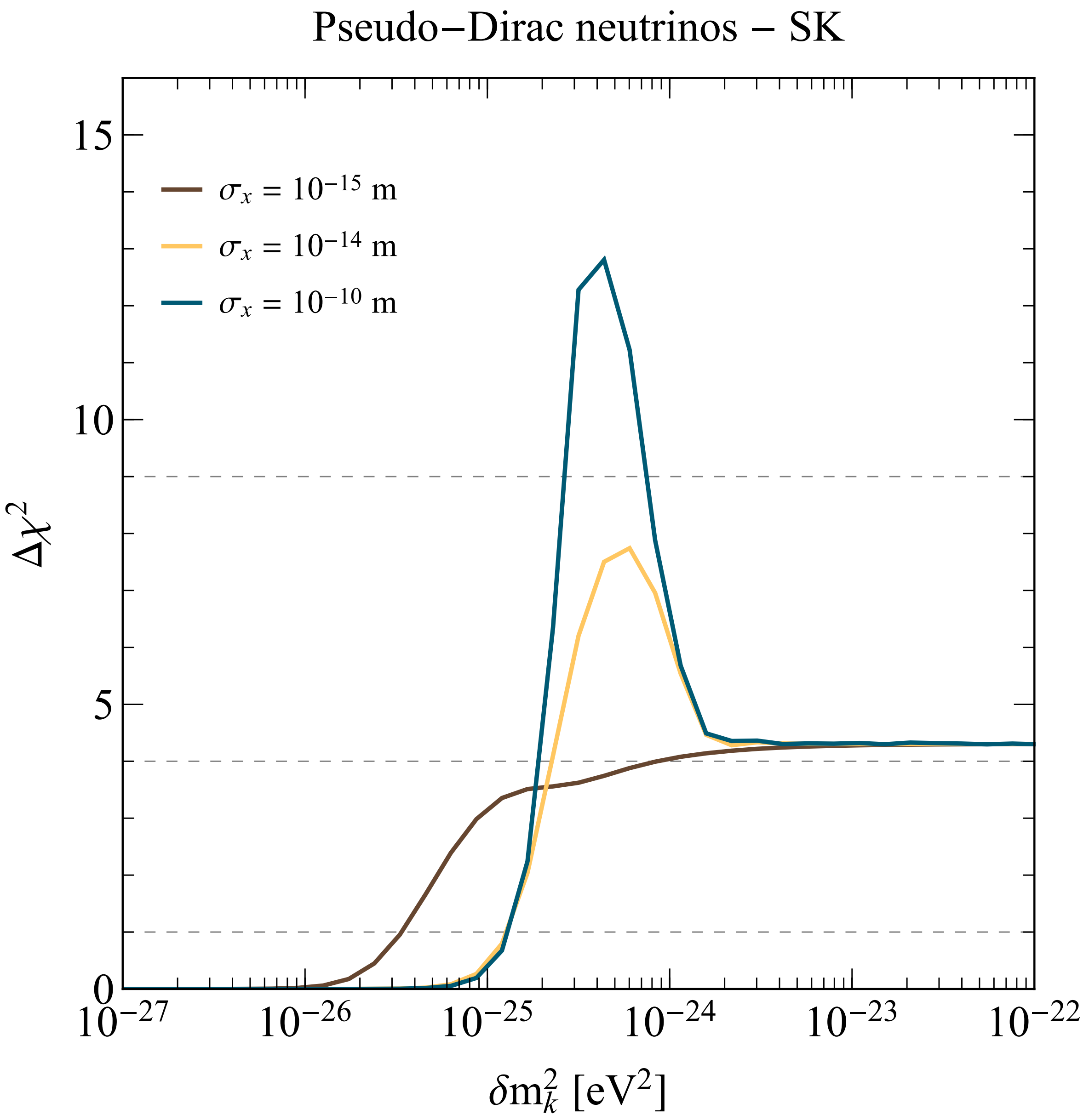


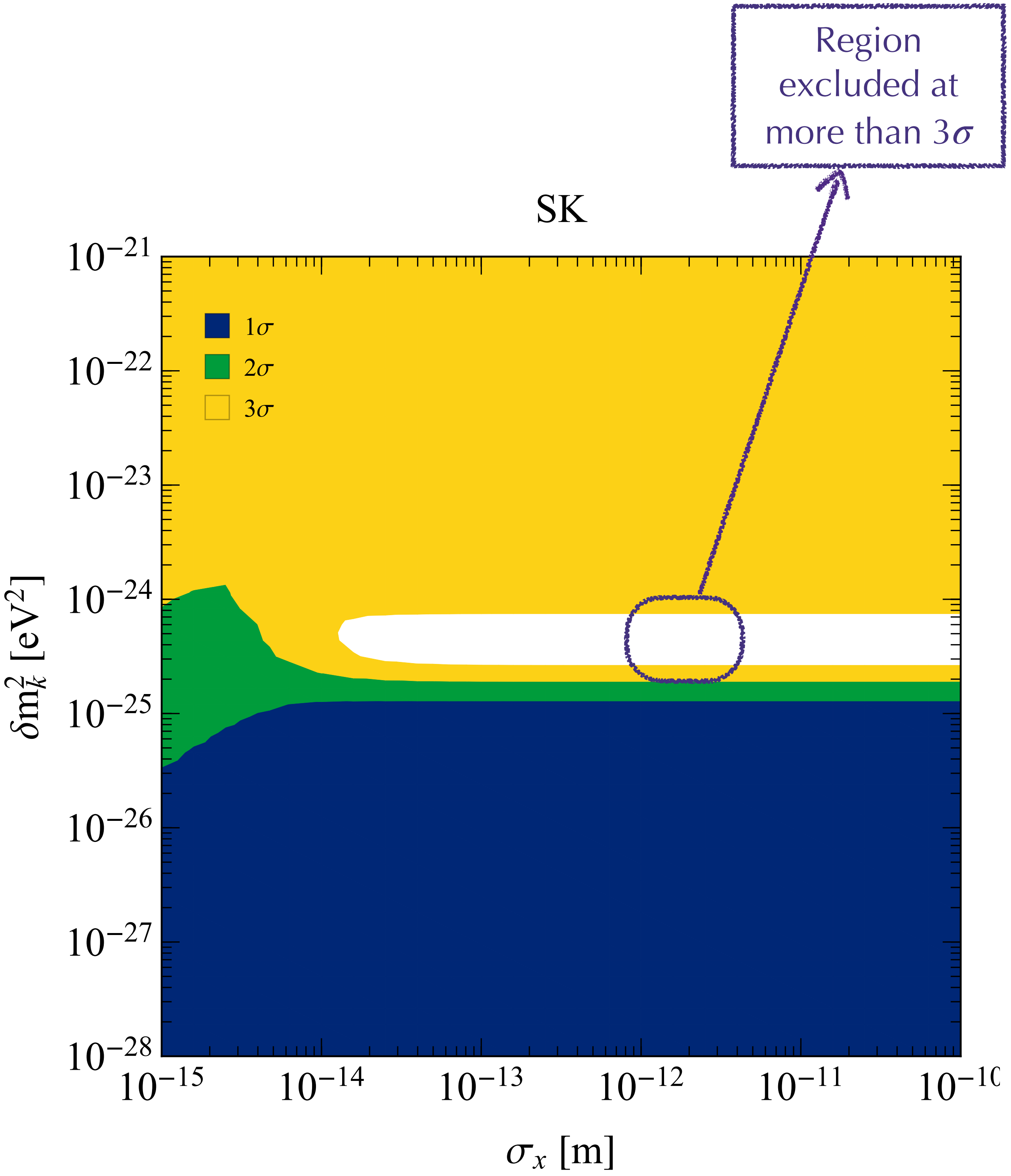


de Gouvêa, Martinez-Soler, YFPG, Sen, 2007.13748

Pseudo-Dirac Neutrinos

- 40% Normalization uncertainty
- Inv μ, atm ν's




Region excluded at more than 3σ

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

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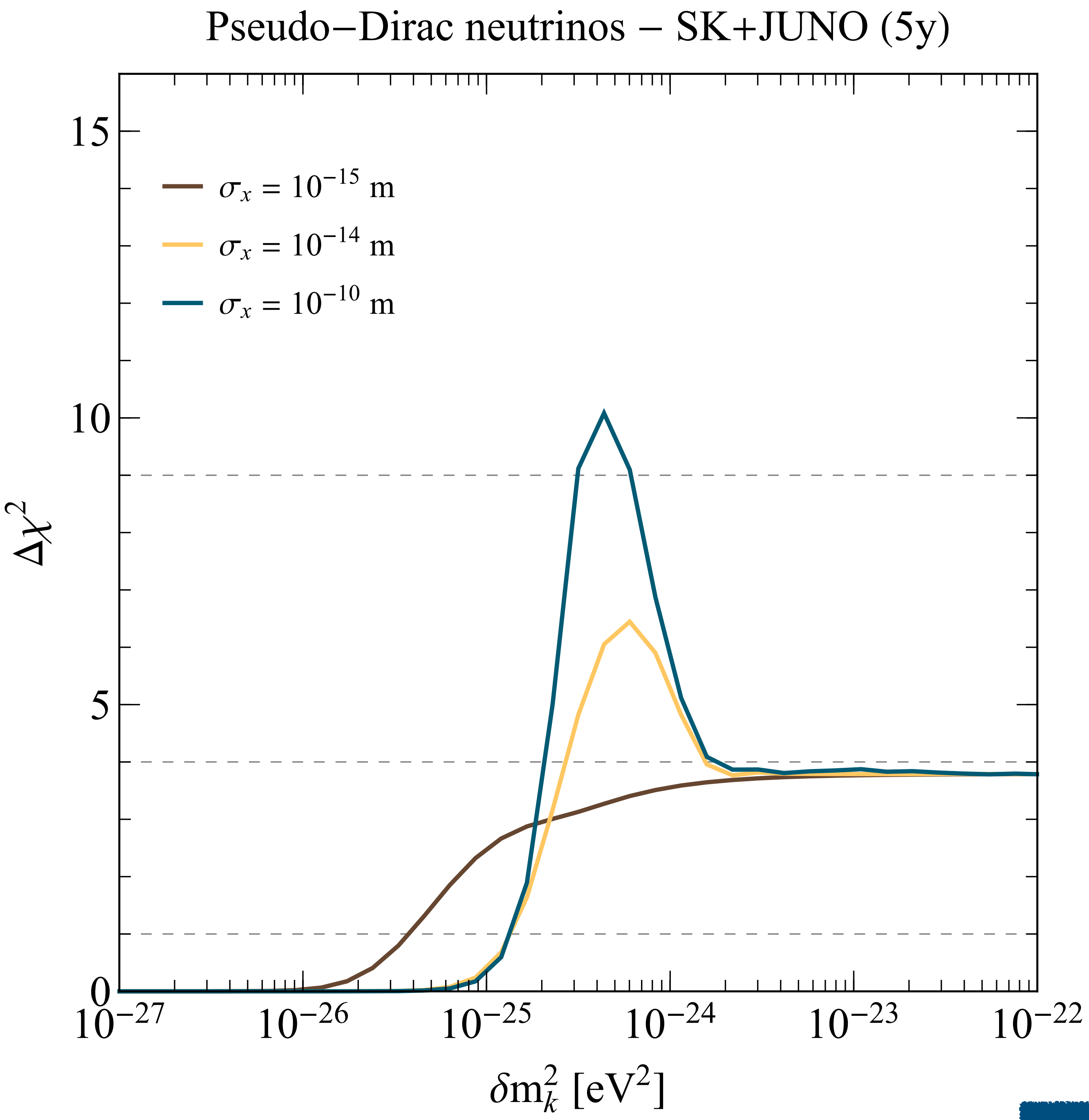


de Gouvêa, Martinez-Soler, YFPG, Sen, 2007.13748

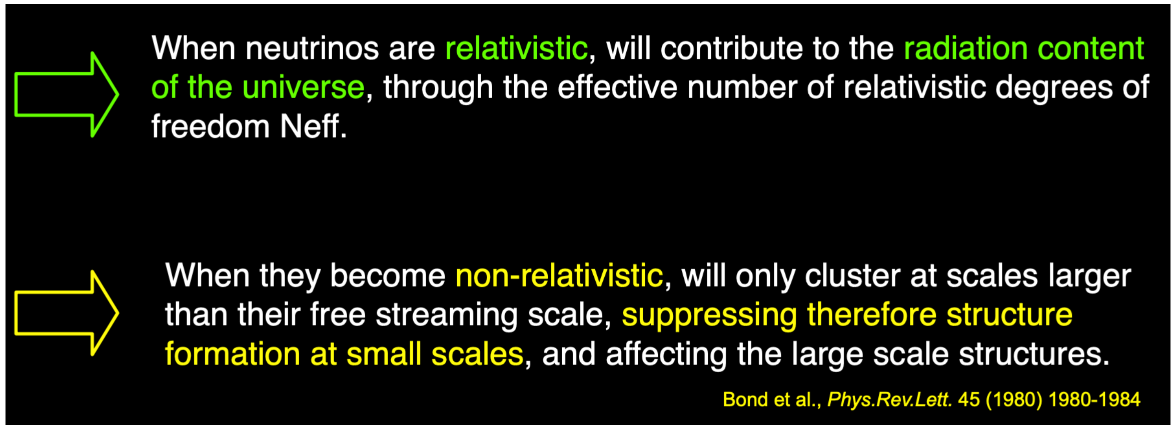
Mass-varying Neutrinos

Neutrino masses in Cosmology

Di Valentino, talk at
CERN neutrino
platform, 2023

- How neutrino mass is measured?

More neutrinos more
expansion of the Universe



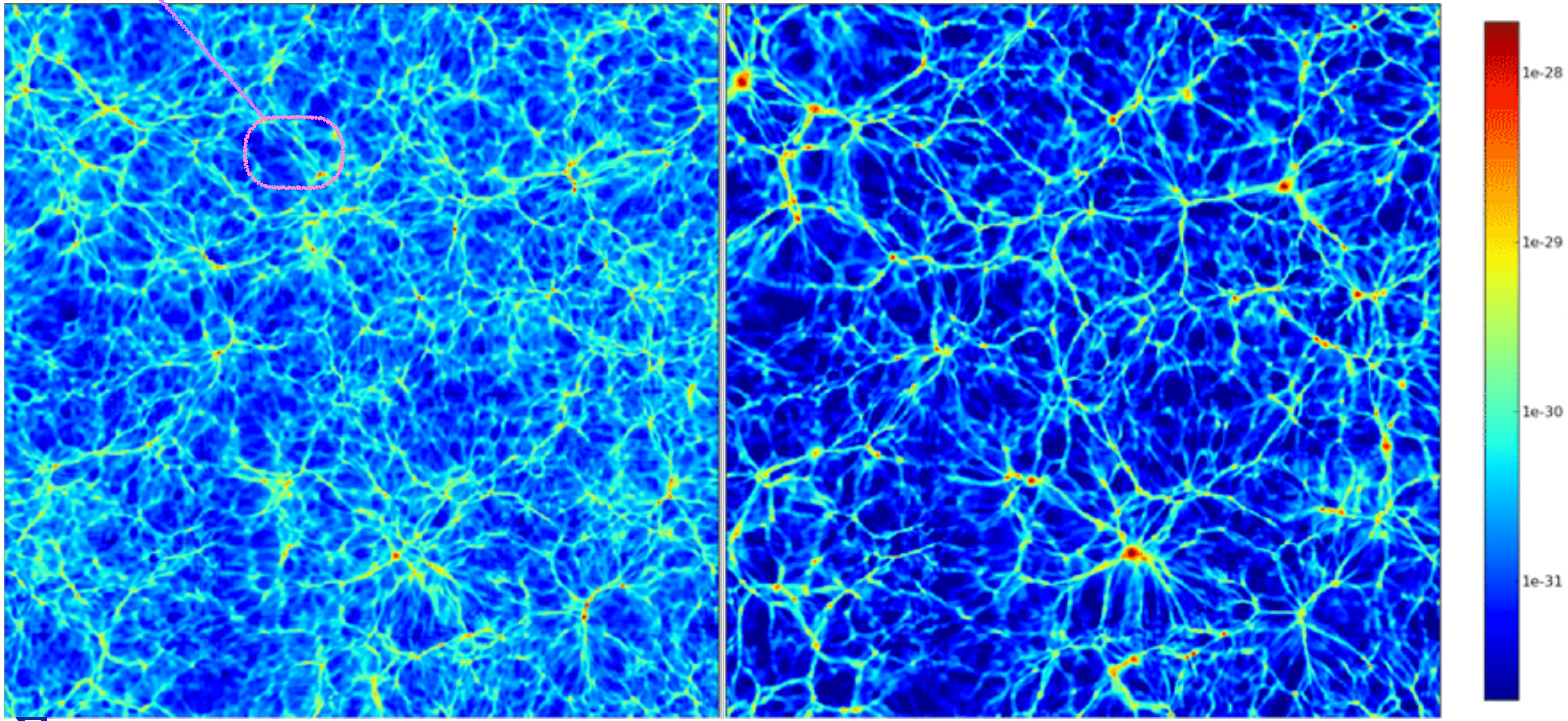
When neutrinos are relativistic, will contribute to the radiation content of the universe, through the effective number of relativistic degrees of freedom Neff.

When they become non-relativistic, will only cluster at scales larger than their free streaming scale, suppressing therefore structure formation at small scales, and affecting the large scale structures.

Bond et al., *Phys.Rev.Lett.* 45 (1980) 1980-1984

They tend to not
contribute to grav collapse

Less structures
for $\sum m_\nu > 0$

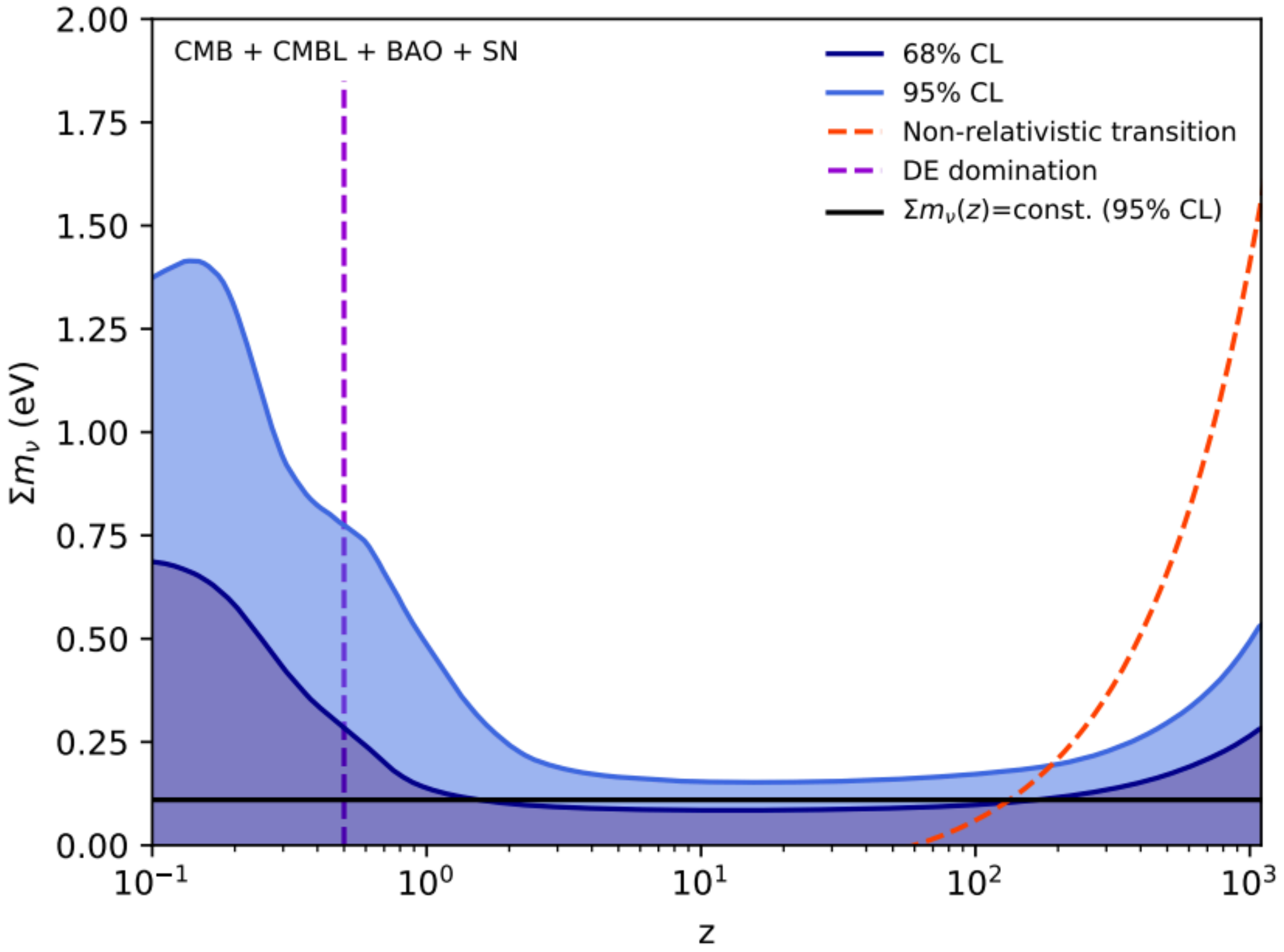


$\sum m_\nu = 1.9$ eV

Lesgourges, Physics 3, 57

Neutrino masses in Cosmology

- ✴ Cosmology doesn’t forbid (yet) massless neutrinos at different redshifts
- ✴ Weaker constraints for smaller redshifts
- ✴ At “z=0” we observe oscillations



Lorenz et al, PRD 104(2021)122518

Koksbang, Hannestad, JCAP09(2017) 014

Neutrino masses in Cosmology — Current status

✴ Recent DESI results

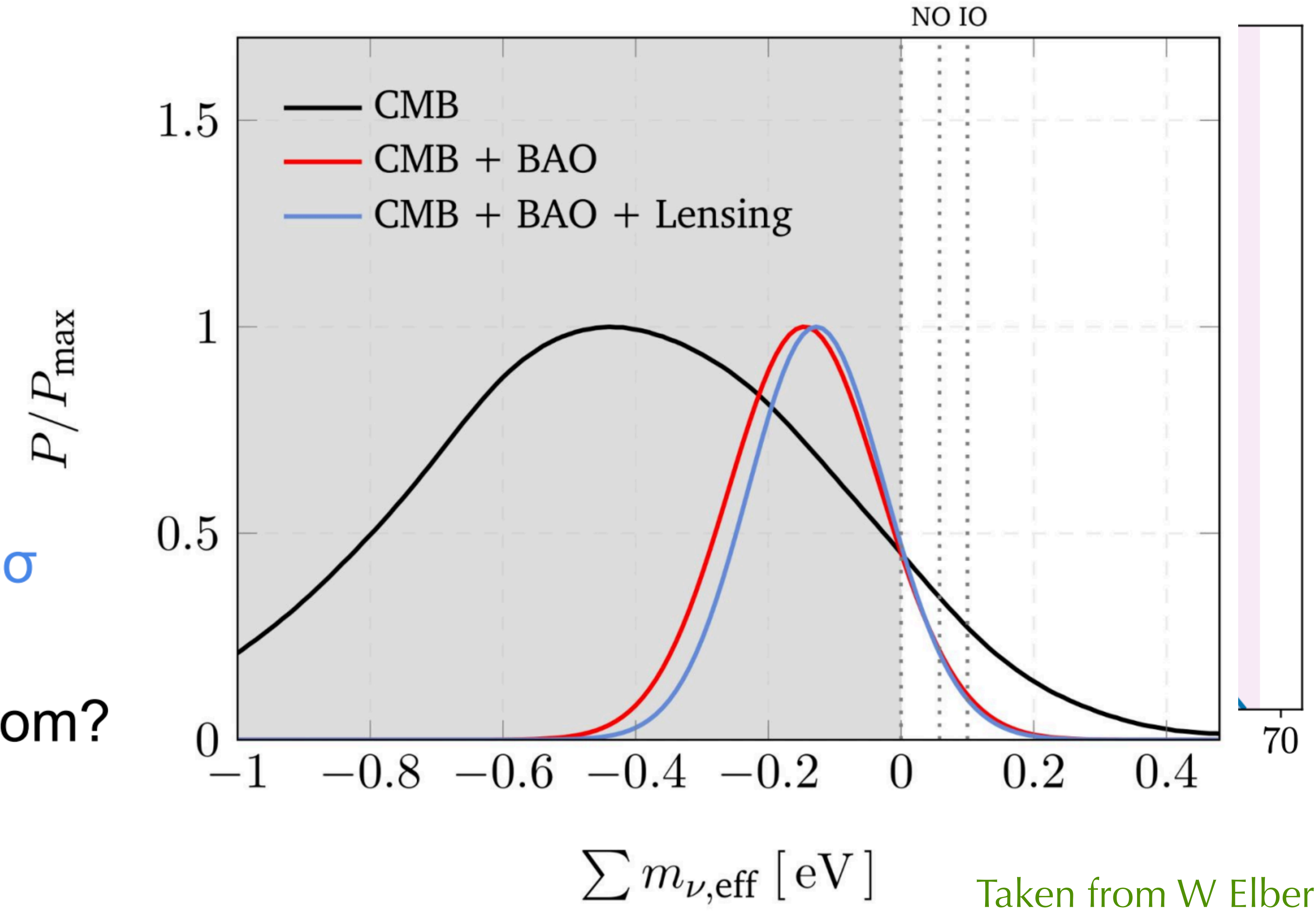
Tension with oscillations:

CMB alone: 1.9σ

CMB + BAO: 2.6σ

CMB + BAO + Lensing: 2.8σ

1) Where is this coming from?
2) What does it mean?

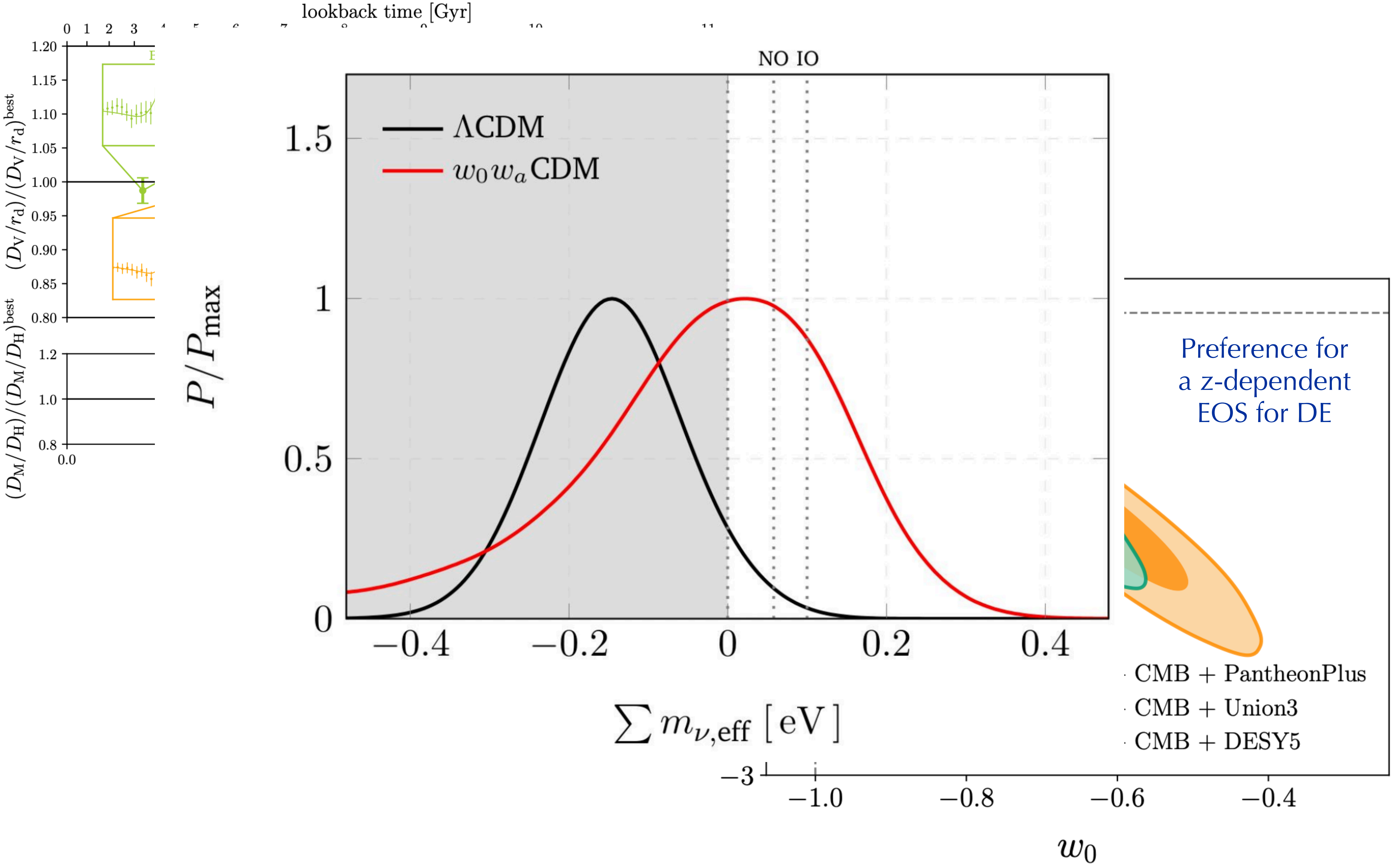


Taken from W Elbers, Neutrino 2024

$$\sum m_\nu < 0.072\,\mathrm{eV}$$

Conflict with terrestrial experiments?

Neutrino masses in Cosmology — Current status



Preference for a z-dependent EOS for DE

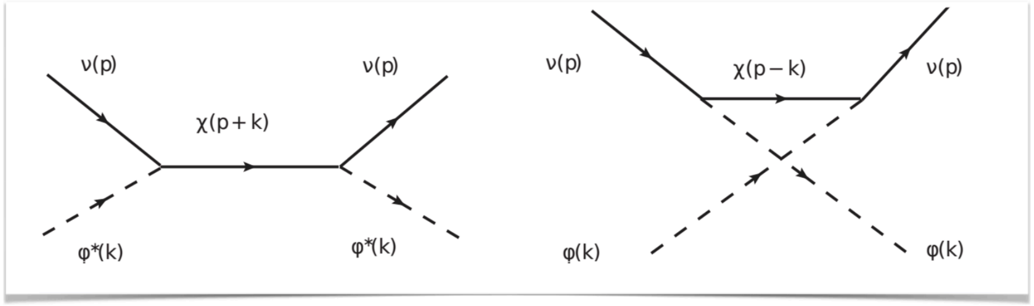
What if neutrino masses different at earlier times?

An example of a model:

A model of dark neutrino mass

- Consider massless neutrinos scattering off ultralight scalar DM ϕ through a fermionic mediator χ.

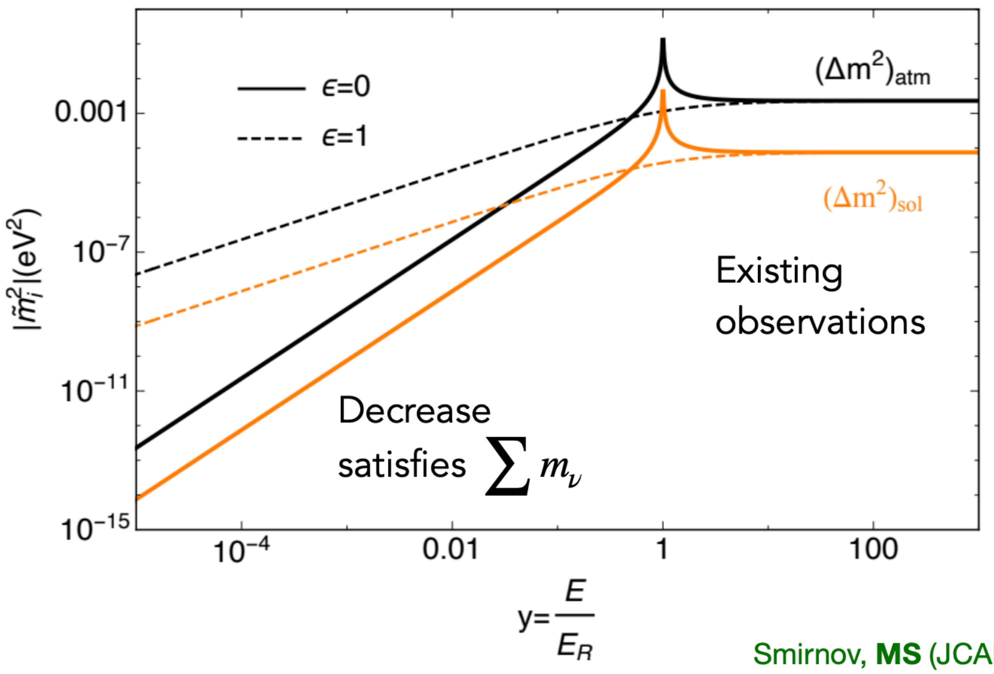
$$\mathscr{L} \supset \sum_{\alpha=e,\mu,\tau} \sum_{k} g_{\alpha k} \bar{\chi}_{kR} \nu_{\alpha L} \phi^* + m_{\chi k} \bar{\chi}_{kR} \chi_{kL} + \mathrm{h.c.}$$



The effective potential

$$V_{\alpha\beta} = \sum_{k} g_{\alpha k} g^*_{\beta k} \left[\frac{\bar{n}_\phi (2Em_\phi - m^2_{\chi k})}{(2Em_\phi - m^2_{\chi k})^2 + (m_\chi \Gamma_{\chi k})^2} + \frac{n_\phi}{2Em_\phi + m^2_{\chi k}} \right],$$

$$E_R = \frac{m^2_\chi}{2m_\phi}$$



Smirnov, **MS** (JCAP 2024)

$$\tilde{m}^2_{\alpha\beta} = 2y\, E_R \sum_k \frac{g_{\alpha k}\, g^*_{\beta k}}{2m^2_\chi} (n_\phi + \bar{n}_\phi) \left[\frac{(1-\epsilon)(y-1)}{(y-1)^2 + \frac{\Gamma^2_{\chi k}}{m^2_\chi}} + \frac{1+\epsilon}{1+y} \right]$$

where $\epsilon \equiv \frac{n_\phi - \bar{n}_\phi}{n_\phi + \bar{n}_\phi}, \quad (\epsilon = -1 \div 1),$

Neutrino masses depend on the DM density

Dispersion for massless neutrinos: E= p(z) + V(z)

M. Sen, NOW2024

Below z=1000, neutrinos effectively massless.
Can explain DESI results.

Can the DSNB give us some hint about these discrepancies?

What if neutrino masses were different in the past?

Mass-varying neutrinos

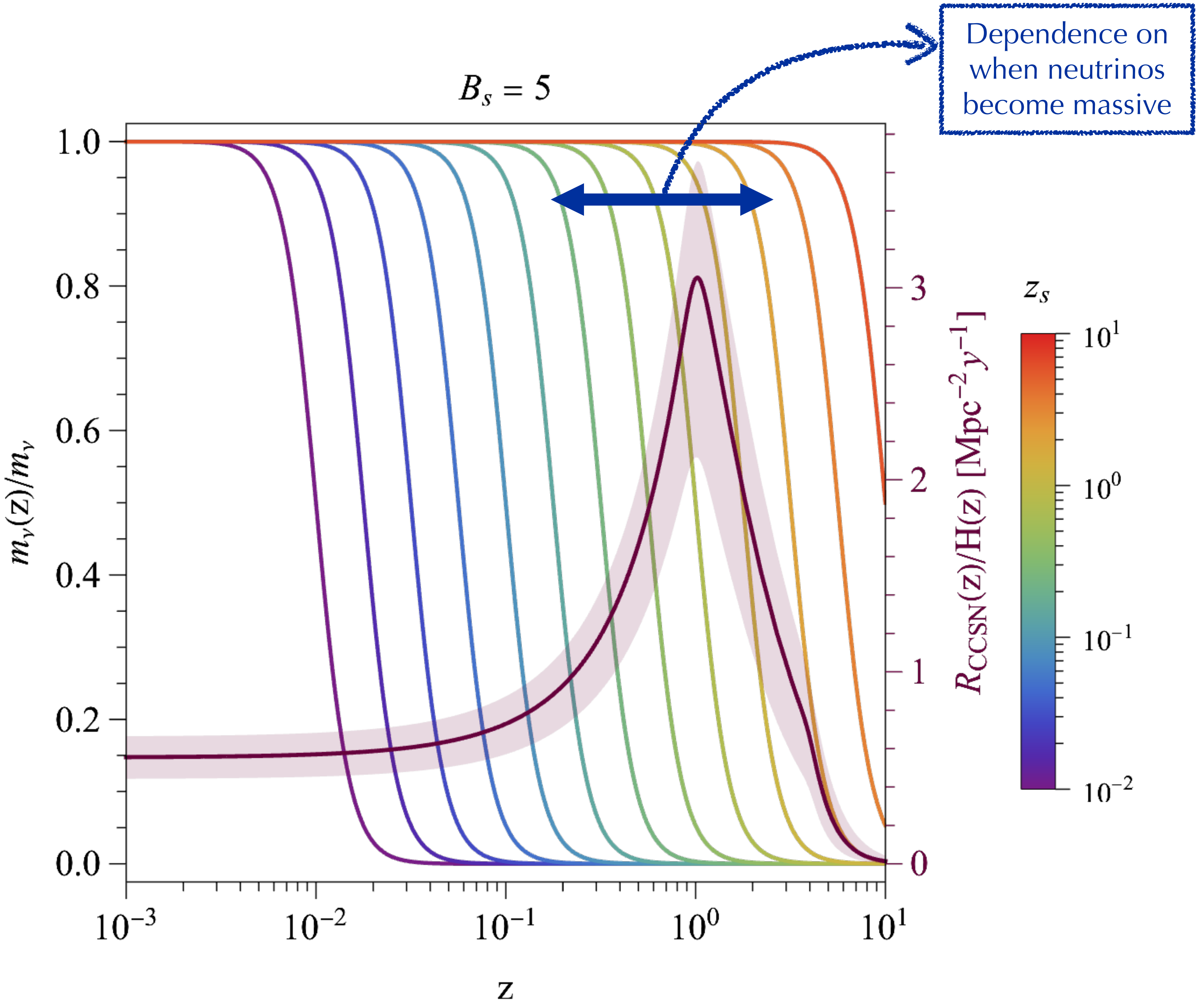
What if neutrino masses were different in the past?

- Let's assume a purely phenomenological approach:

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

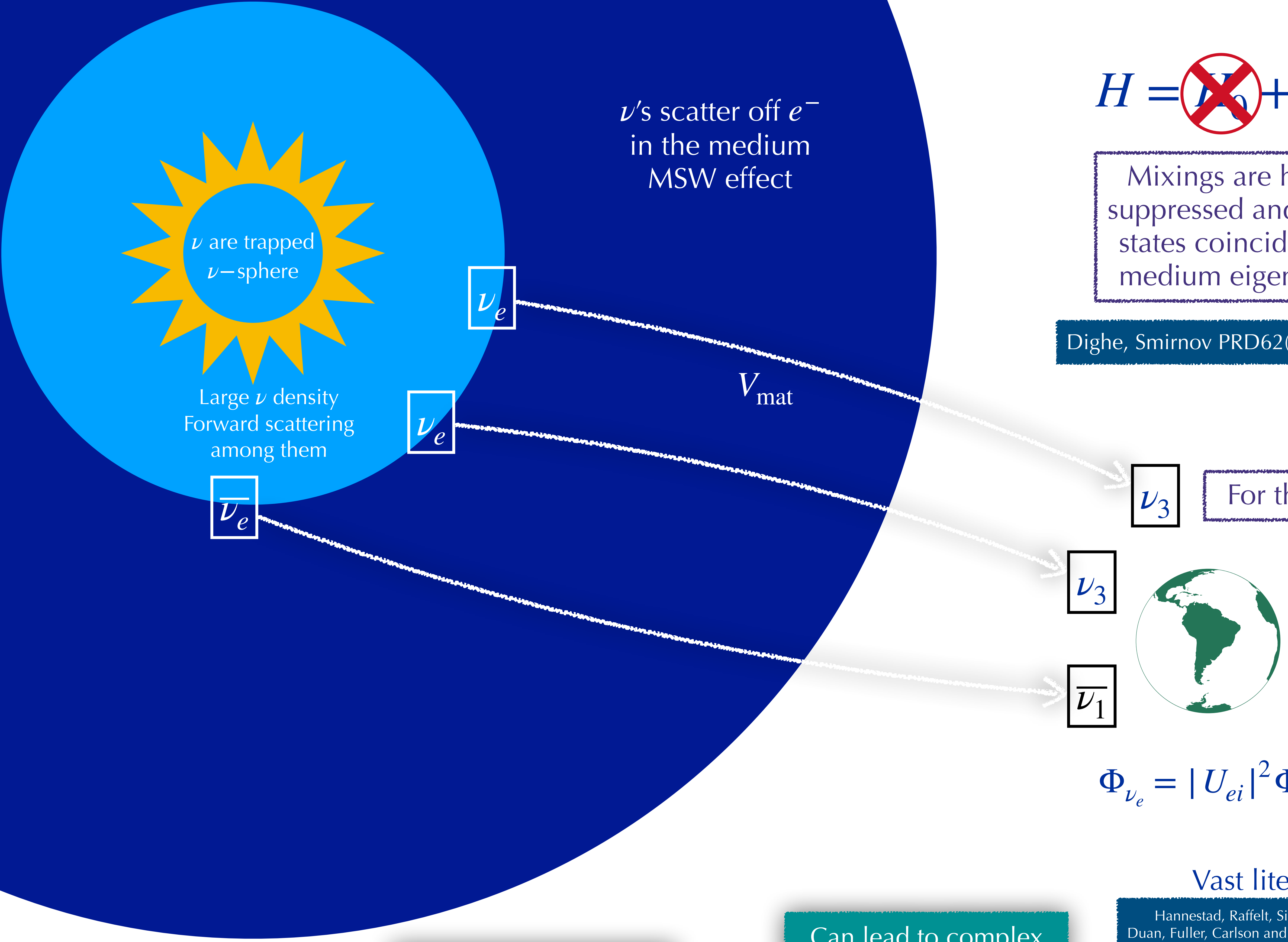
B_s → how fast

z_s → when



Modification of matter effects inside the SN

de Gouvêa, Martinez-Soler, YFPG, Sen, 2205.01102



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

Mixings are highly suppressed and flavor states coincide with medium eigenstates

Dighe, Smirnov PRD62(2000)033007

For the NO

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

Vast literature:

Hannestad, Raffelt, Sigland Wong (2006)
Duan, Fuller, Carlson and Qian (PRD 2006,2007)
Duan, Fuller, Carlson and Qian (PRL 2006)
Dasgupta, Dighe, Raffelt and Smirnov (PRL 2009)
Friedland (PRL 2010)
Capozzi, Dasgupta, Mirizzi, Sen, Sigl (PRL 2019)
…

Collective oscillations → Can lead to complex modifications to the neutrino spectra

Not to scale

Mass-varying neutrinos

What if neutrino masses were different in the past?

- ✳ Let's assume a purely phenomenological approach:

$$m_\nu(z) = \frac{m_\nu}{1 + (z/z_s)^{\mathrm{B}_s}}$$

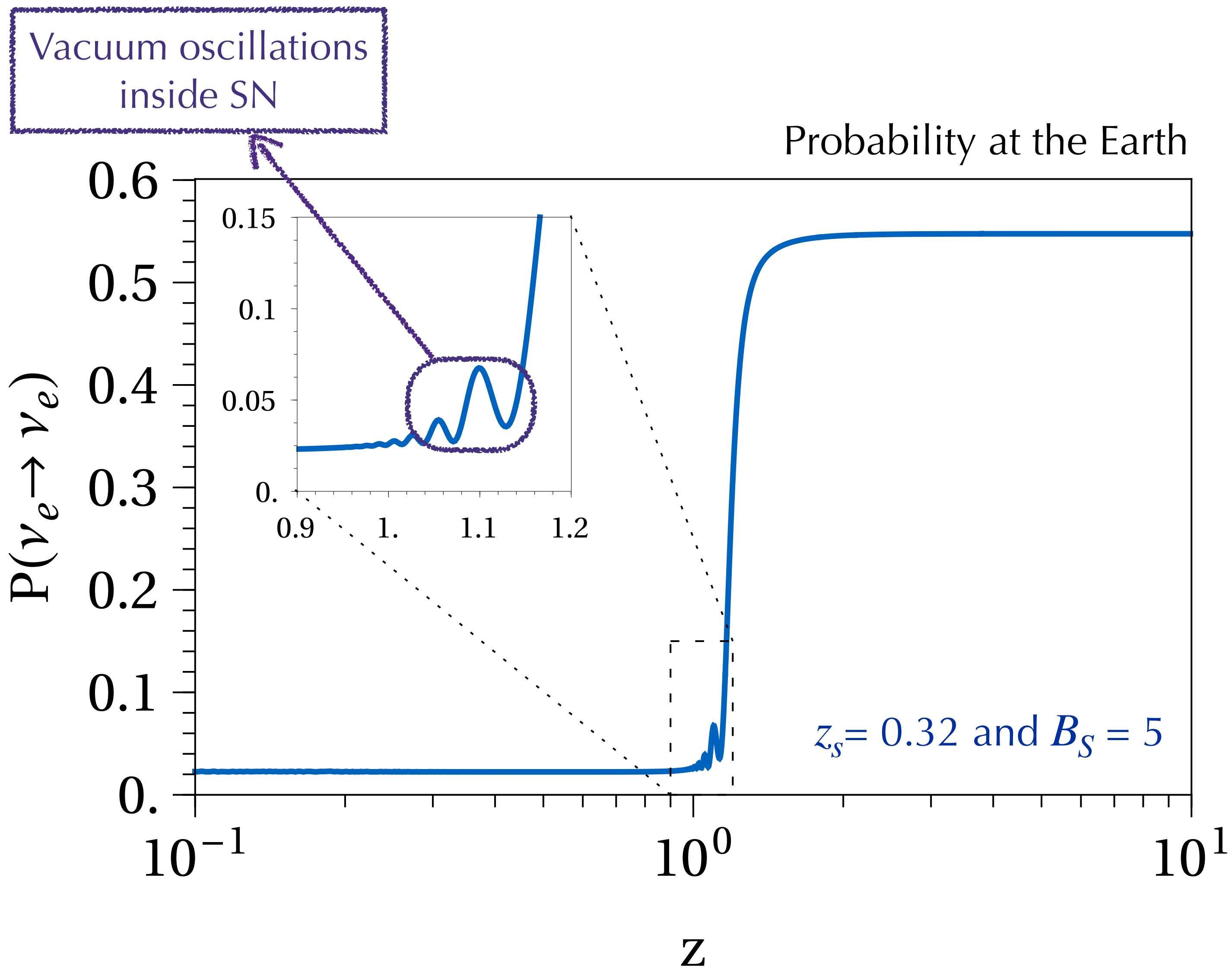
B_s → how fast
z_s → when

DSNB fluxes at the Earth

$$\Phi_{\nu_e}(E) = \int_0^{z_{\max}} \frac{dz}{H(z)} R_{\mathrm{CCSN}}(z)\left\{P_{ee}(z)\phi^0_{\nu_e} + (1 - P_{ee}(z))\phi^0_{\nu_x}\right\}$$

$$\Phi_{\bar{\nu}_e}(E) = \int_0^{z_{\max}} \frac{dz}{H(z)} R_{\mathrm{CCSN}}(z)\left\{\overline{P_{ee}}(z)\phi^0_{\bar{\nu}_e} + (1 - \overline{P_{ee}}(z))\phi^0_{\nu_x}\right\}$$

$$\Phi_{\nu_x}(E) = \int_0^{z_{\max}} \frac{dz}{H(z)} R_{\mathrm{CCSN}}(z)\frac{1}{4}\left\{(1 - P_{ee}(z))\phi^0_{\nu_e} + (1 - \overline{P_{ee}}(z))\phi^0_{\bar{\nu}_e} + (2 + P_{ee}(z) + \overline{P_{ee}}(z))\phi^0_{\nu_x}\right\}$$


Vacuum oscillations inside SN

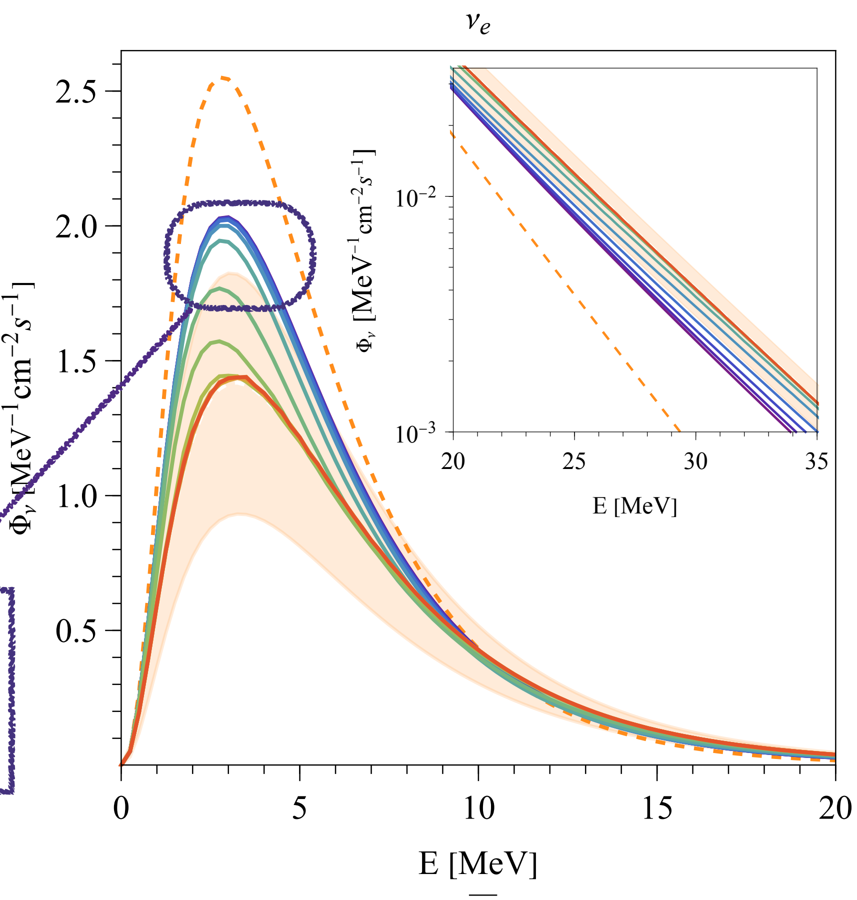
Probability at the Earth

$\phi^0_{\nu_e,\bar{\nu}_e,\nu_x} \longrightarrow$ Fluxes at the neutrino sphere

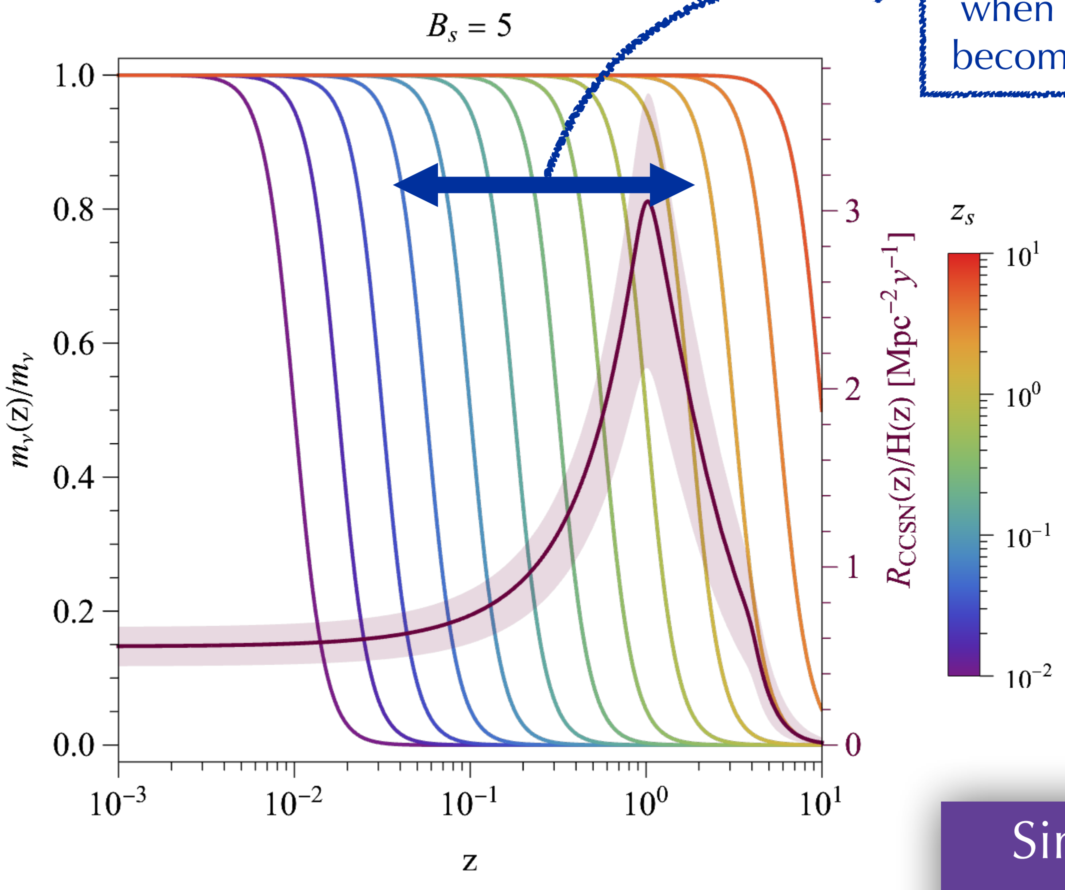
de Gouvêa, Martinez-Soler, YFPG, Sen, 2205.01102

Mass-varying neutrinos

In the NO*



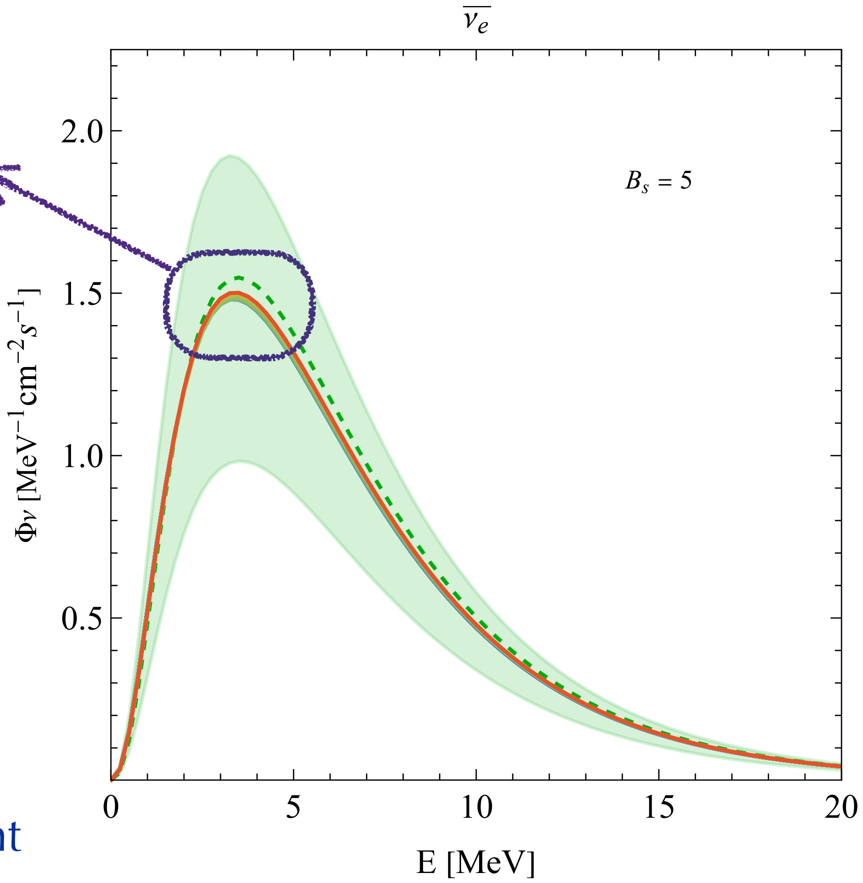
Significant modification on ν_e spectra

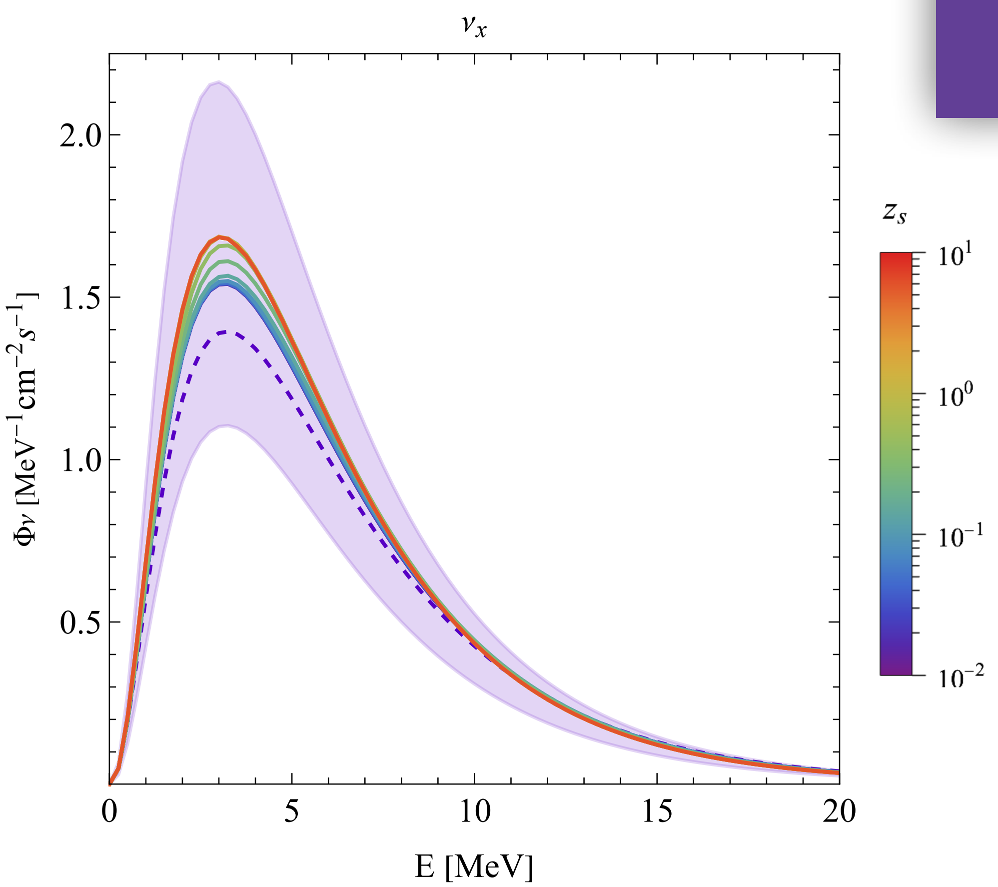


Dependence on when neutrinos become massive

Simultaneous measurements could tell us!

NO modification on $\bar{\nu}_e$ spectra!





$\sum_k |U_{ek}|^2 = 0.57$

$|U_{e3}|^2 = 0.02$

$|U_{e1}|^2 = 0.67$

$f_{\rm BH} = 0.22$

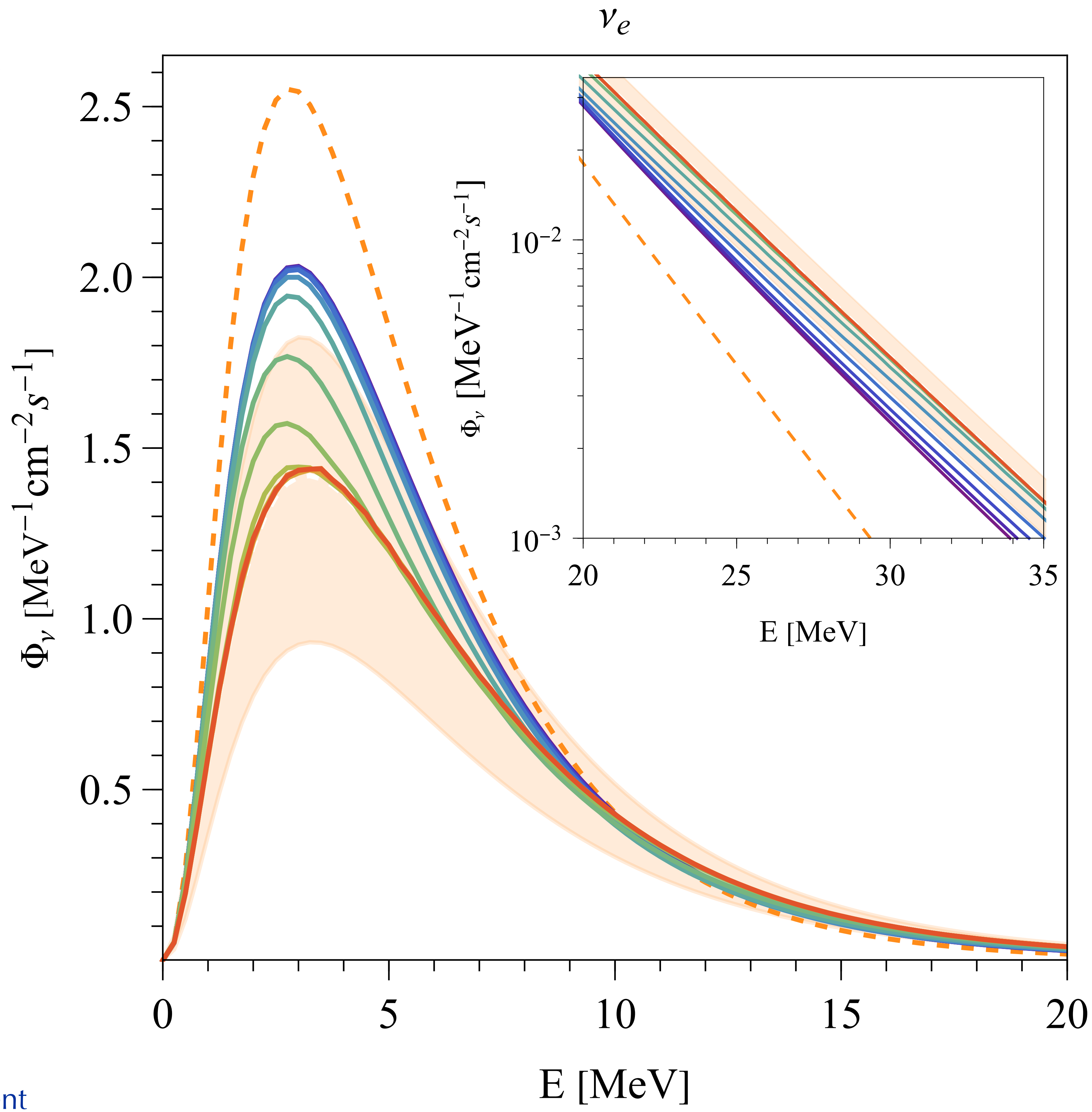
CCSNe $\rightarrow 12M_\odot$

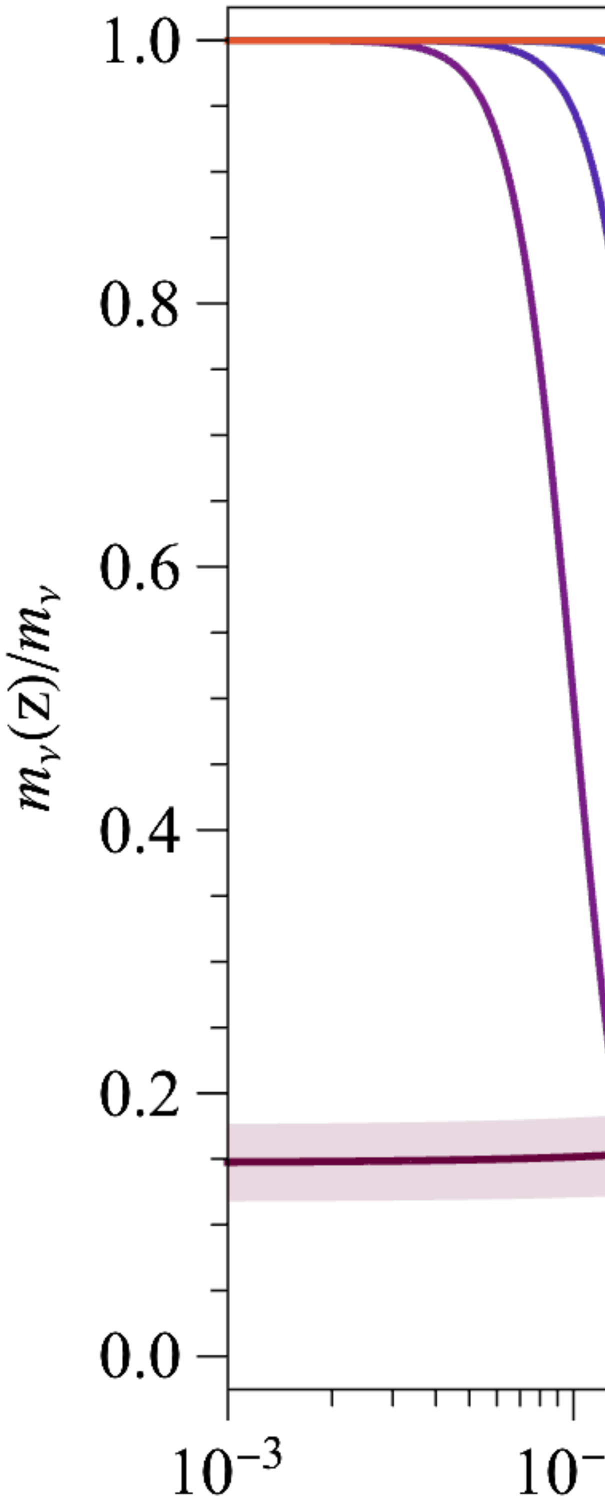
Failed SN $\rightarrow 40M_\odot$

*For IO is different

Mass-varying neutrinos

In the NO*



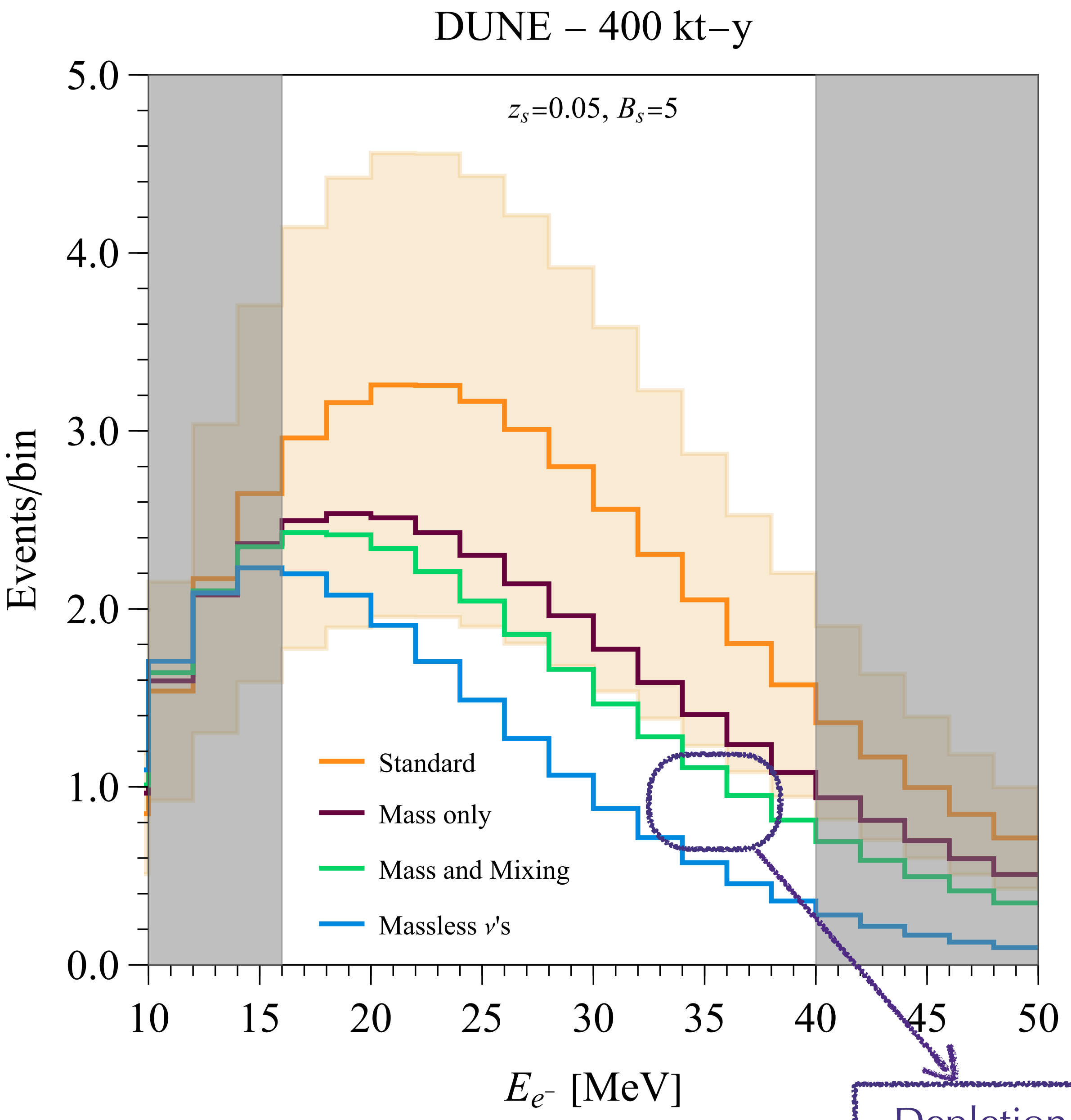


*For IO is different

Mass-varying neutrinos

An example in a DUNE-like experiment

Few events and big backgrounds…



Depletion in the observable energy window…

However, there is a clear strategy for the future!*

- Measurement of $\bar{\nu}_e$ helps with constraining uncertainties
- Then measure ν_e to test this hypothesis

*If the ordering is normal

Conclusions

- The DSNB are the oldest neutrinos within experimental reach!
- If we detect the DNSB, we can test "slow" neutrino properties, such as oscillations spanning Gpc distances, time varying masses.
- Of course, there are important uncertainties that affect the DSNB prediction, so we need to be careful when talking about BSM searches
- Still, there might be "smoking gun" signatures that might not be (very much) affected by those uncertainties
- We are considering the scenario where neutrino masses were bigger at earlier times
- All information is crucial!

Thanks!