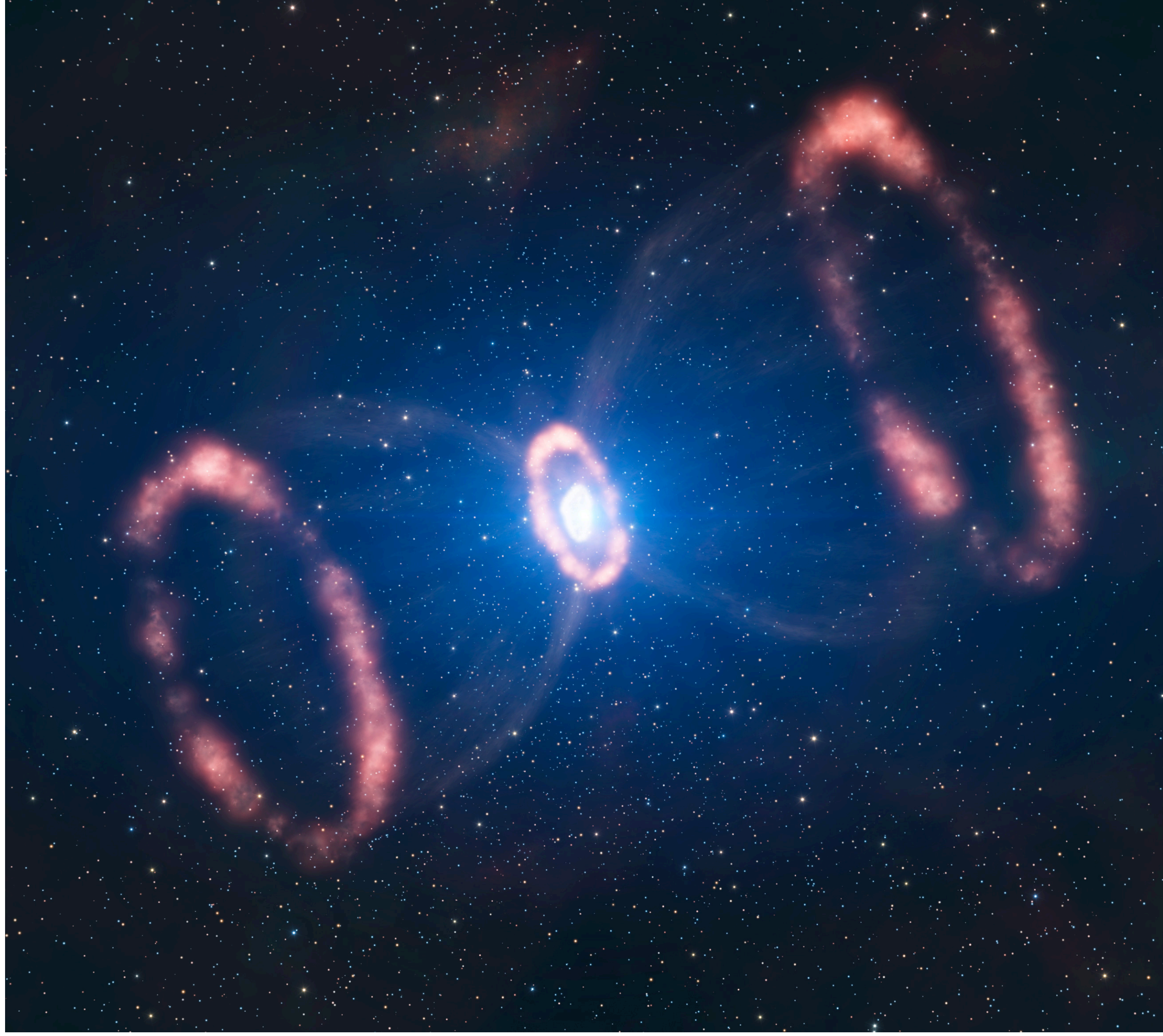
The Diffuse Supernova Neutrino Background as a window to the neutrino past

Yuber F. Perez-Gonzalez

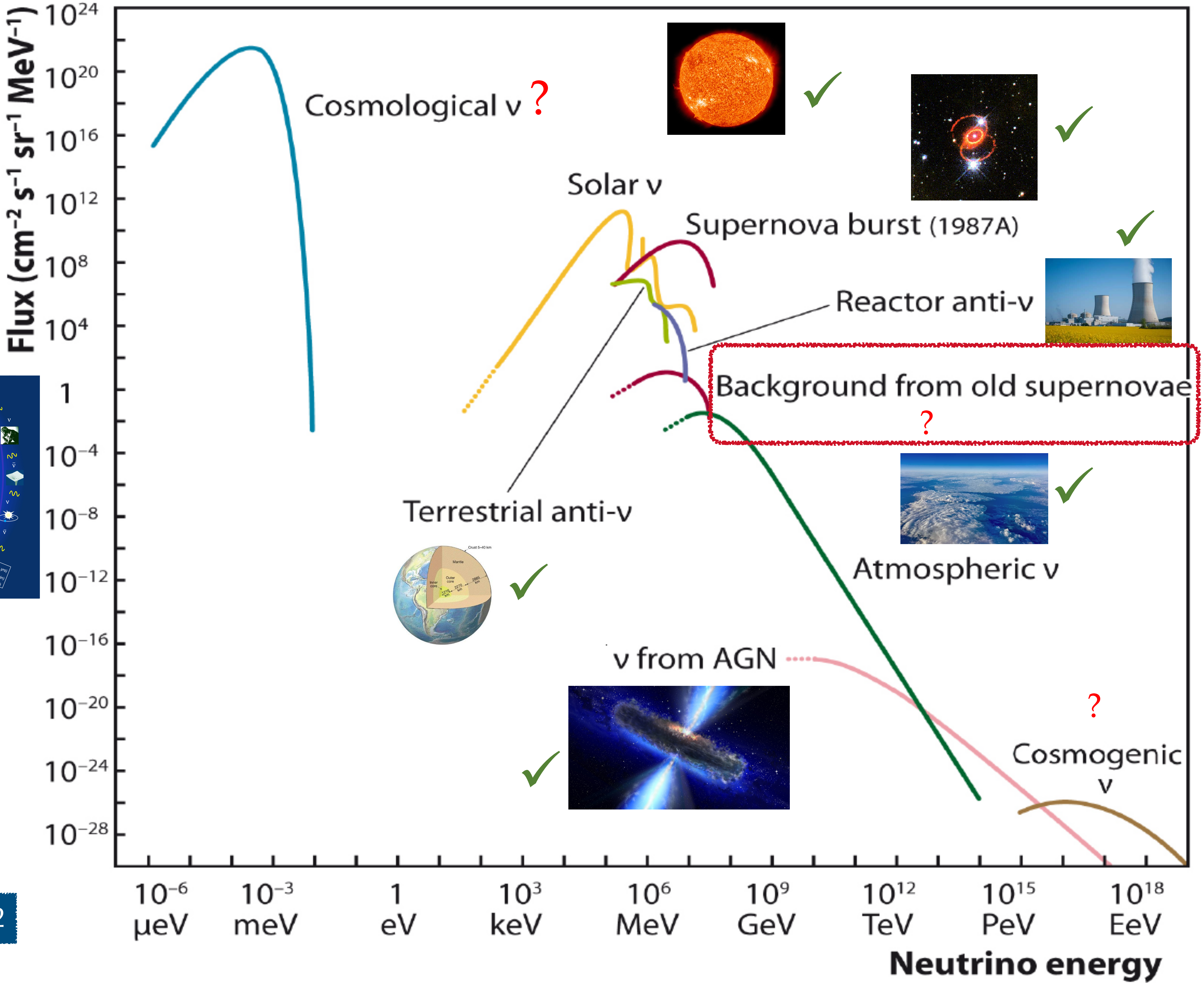


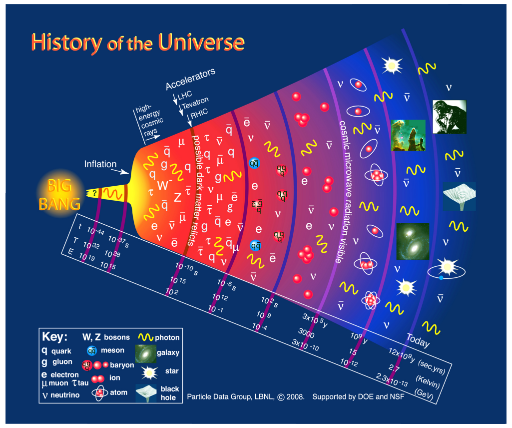
ESO/L. Calçada

CERN Neutrino Platform
March 16th, 2023

Durham University

IP3

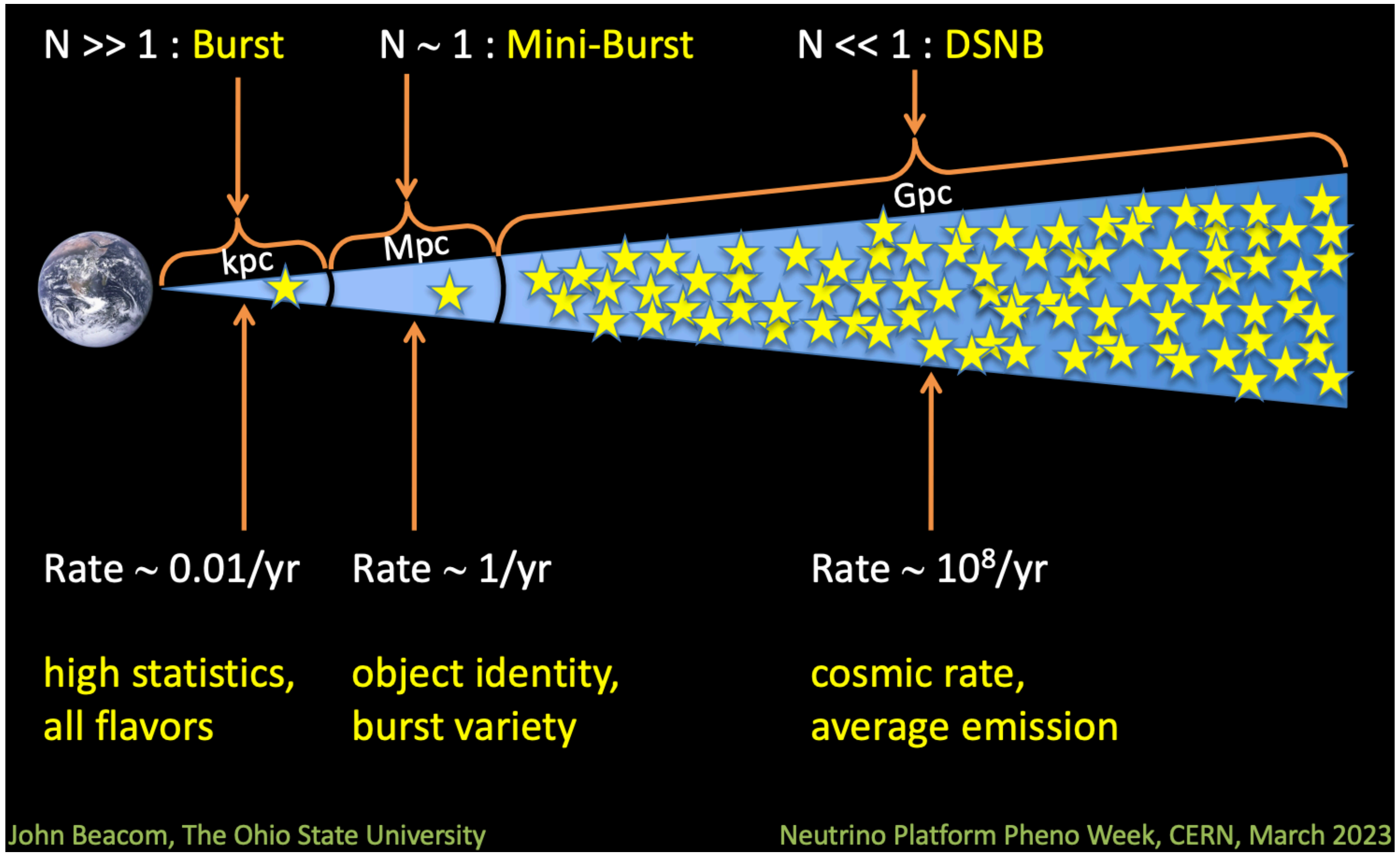




Katz et.al., 2012

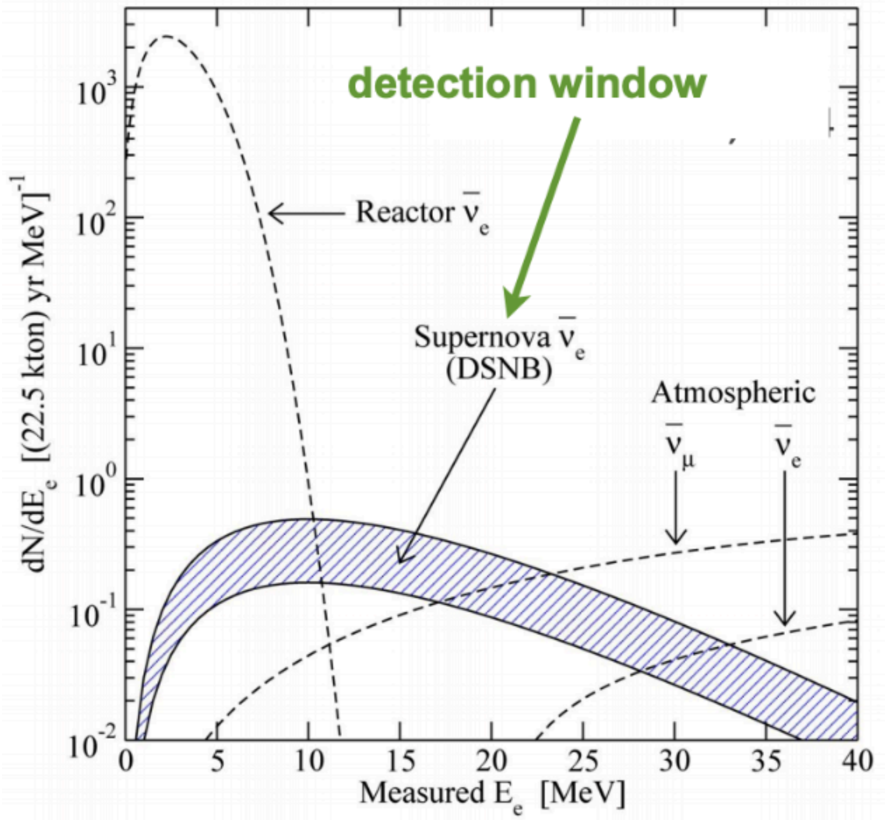
Diffuse Supernova Neutrino Background

- We could look for *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
- "Oldest" neutrinos within reach
  $z = 5 \longrightarrow t_{\rm age} \sim 1\ {\rm Gyr}$



John Beacom, The Ohio State University

Neutrino Platform Pheno Week, CERN, March 2023



What can we learn by measuring the DSNB?

Beacom, Vagins, PRL 2003
Beacom, Ann.Rev.Nuc.Phys.Sc.2010
Lunardini, Astropart. Phys2016

Diffuse Supernova Neutrino Background

$z_{\text{max}} = 5$

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

Neutrino physics

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

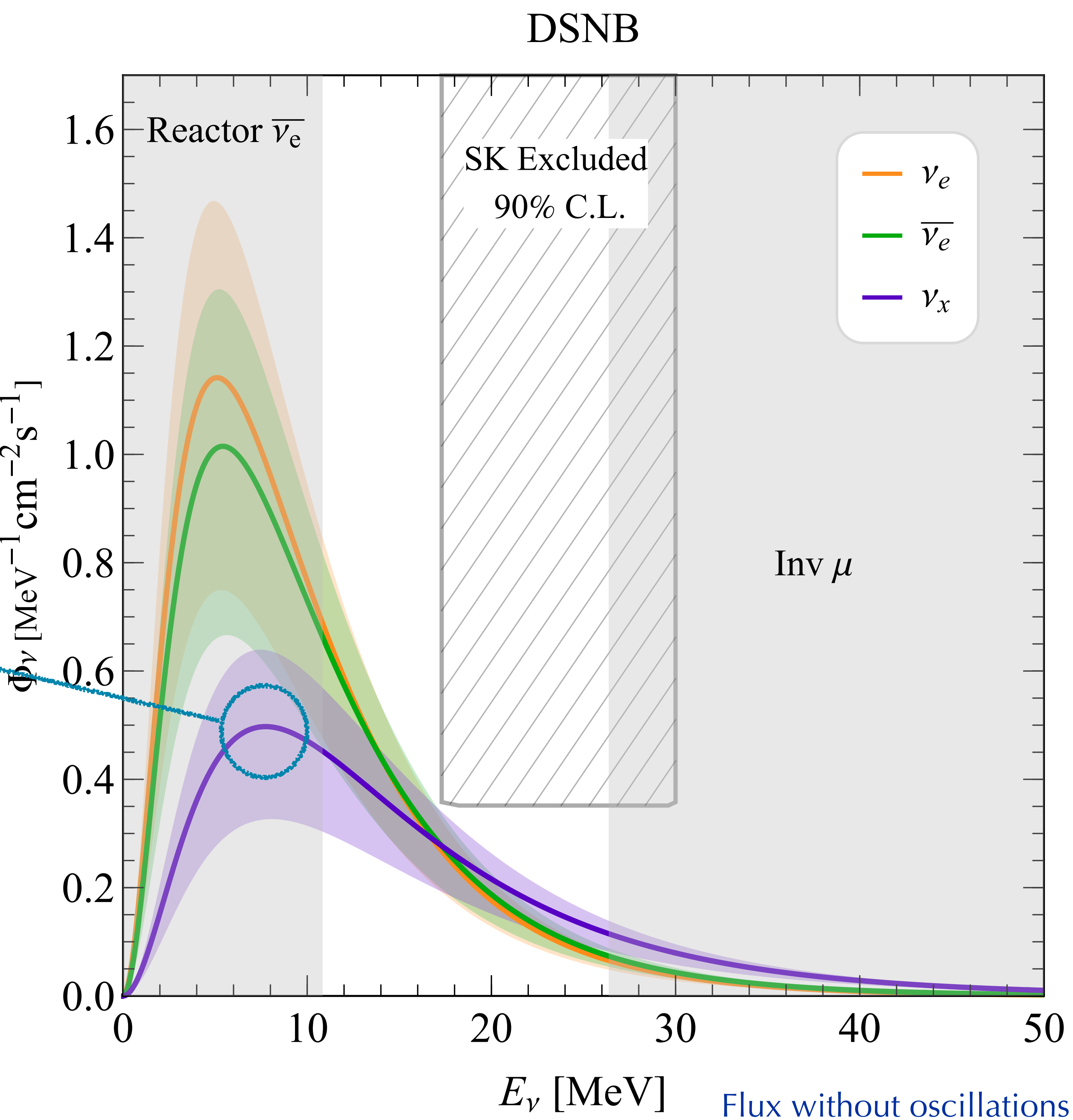
$$F_\nu(E) = \frac{\overset{\text{Total released energy}}{\boxed{E_\nu^{\text{tot}}}}}{6} \frac{120}{7\pi^4} \frac{E_\nu^2}{T_\nu^4} \frac{1}{e^{E_\nu/T_\nu} + 1}$$

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

Diffuse Supernova Neutrino Background

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

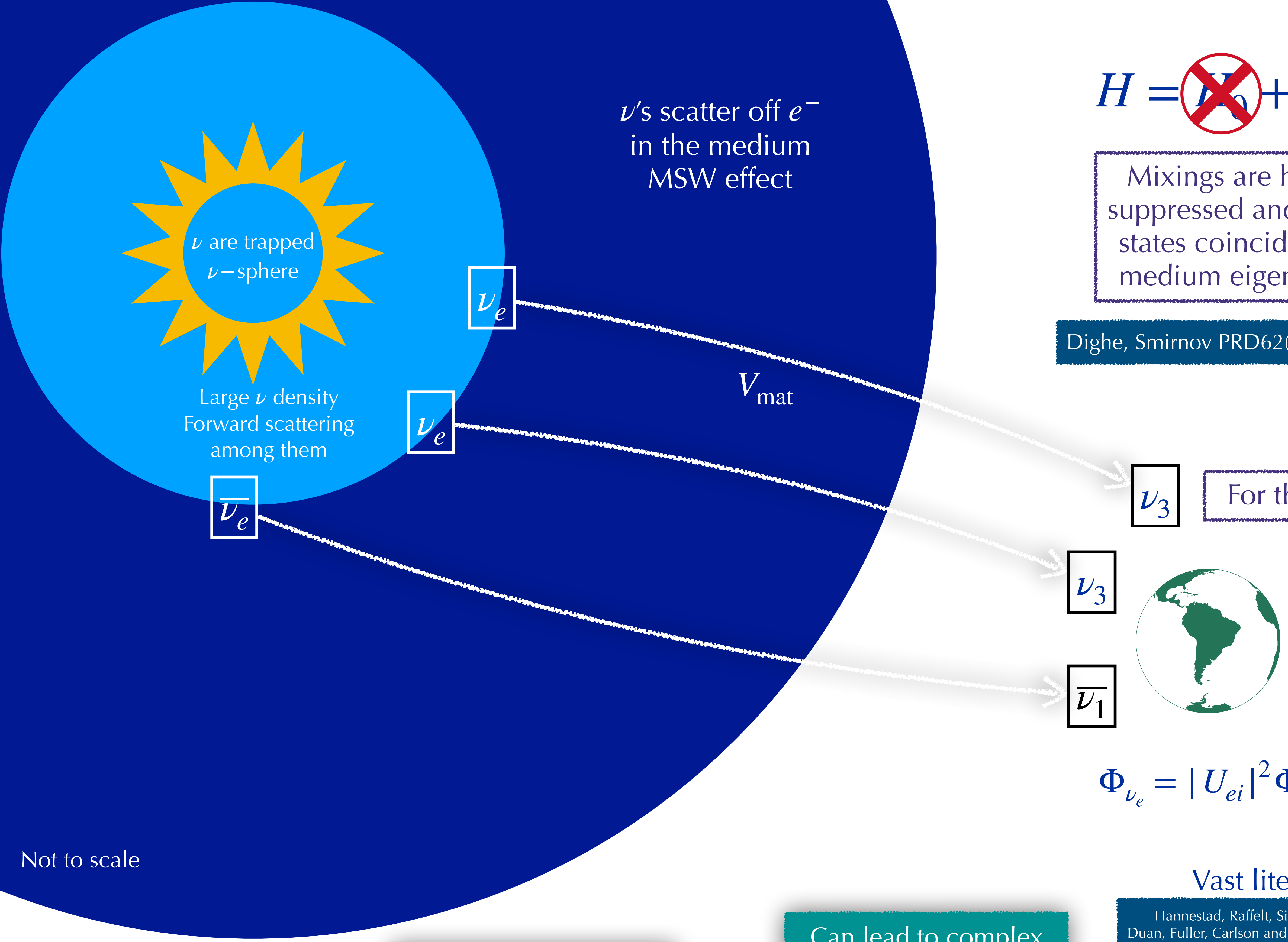
$z_{\max} = 5$



Uncertainty due to the SFR

Flux without oscillations

Oscillations?



ν are trapped
$\nu-$sphere

Large ν density
Forward scattering
among them

ν's scatter off e^-
in the medium
MSW effect

$V_{\rm mat}$

ν_e → ν_3

ν_e → ν_3

$\overline{\nu_e}$ → $\overline{\nu_1}$

Not to scale

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

Mixings are highly suppressed and flavor states coincide with medium eigenstates

Dighe, Smirnov PRD62(2000)033007

For the NO

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

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

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)
…

See Basudev and Pedro's talk

Detecting the DSNB

This is a "guaranteed" flux

Why haven't we detected it?

Number of events

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.

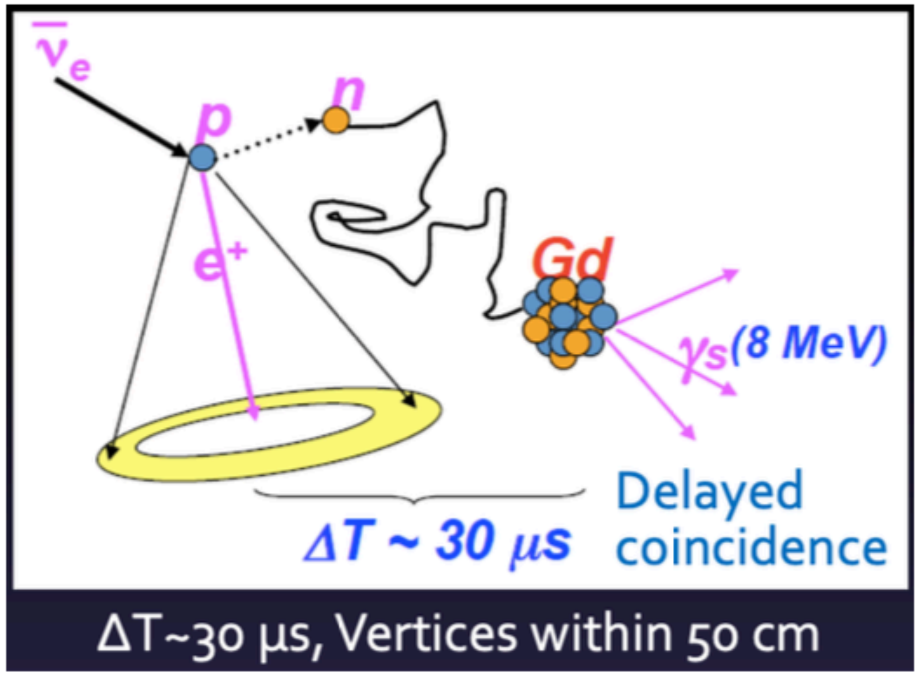
$$N_i = N_{\text{tar}} T \int dE^r dE^t \Phi_\alpha \sigma_\alpha \epsilon(E^t, E^r) + \text{Bkg}_i$$

SK, SK-Gd and HK

- 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

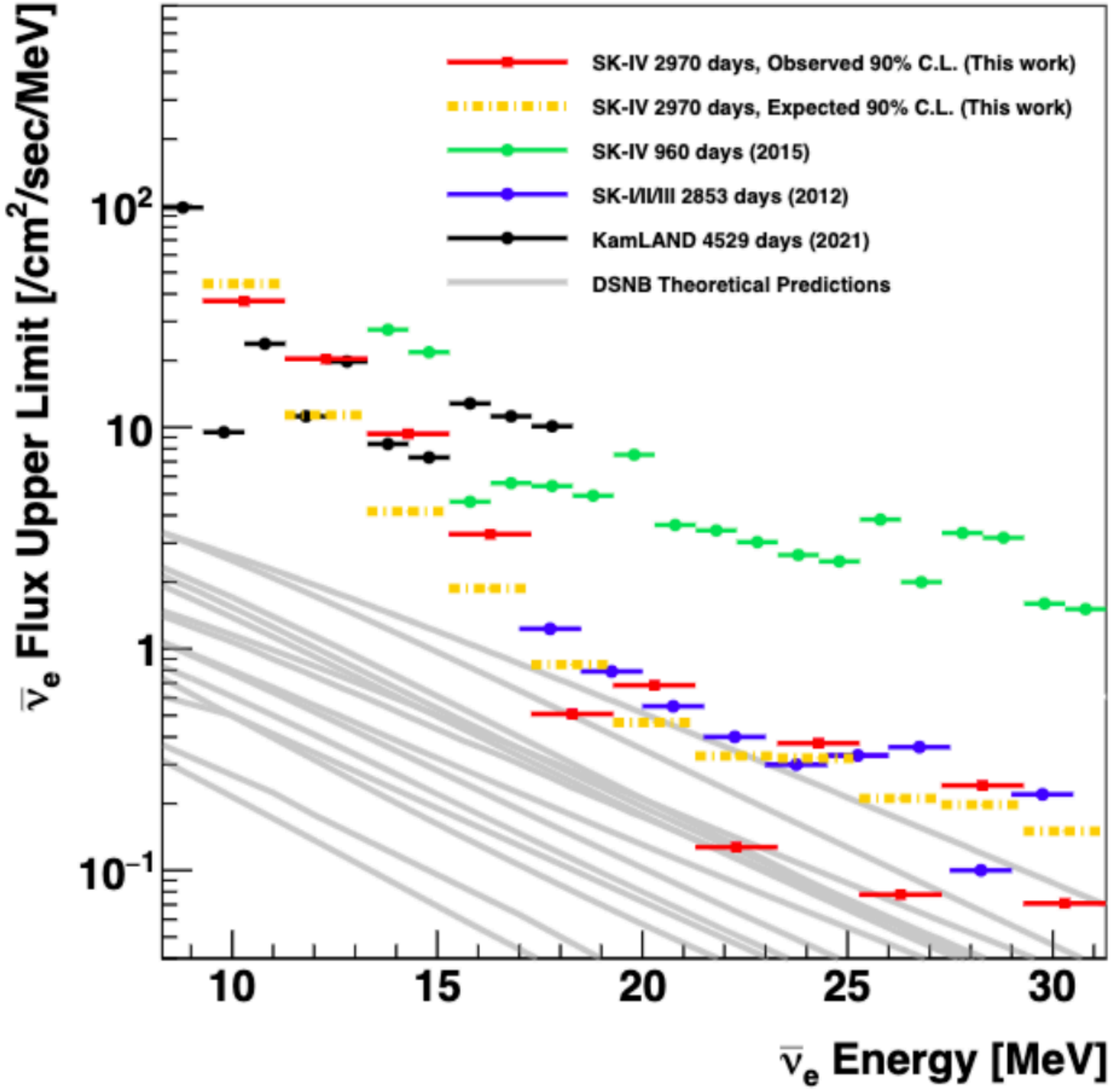
- Dope with Gadolinium!



ΔT~30 μs, Vertices within 50 cm

Beacom, Vagins, PRL 2003

Last limits from SK



Abe et.al. PRD104(2021)12

What could we learn by measuring the DSNB?

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

- Neutrinos propagate in an expanding Universe → Cosmology?

- Star Formation Rate as seen by neutrinos

Constraints from light will be considerably stronger

- Neutrino properties that are "slow":
  - Neutrino decay
  - Pseudo Dirac neutrinos
  - Mass-varying neutrinos
  - Neutrino self-interactions

de Gouvêa, Martinez-Soler, YFPG, Sen,
2007.13748
2205.01102

Das, YFPG, Sen, 2205.11522

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No time for this, unfortunately…
See Ivan's talk!

de Gouvêa, Martinez-Soler, YFPG, Sen,
2007.13748
2205.01102

Das, YFPG, Sen, 2205.11522

Neutrino Decay

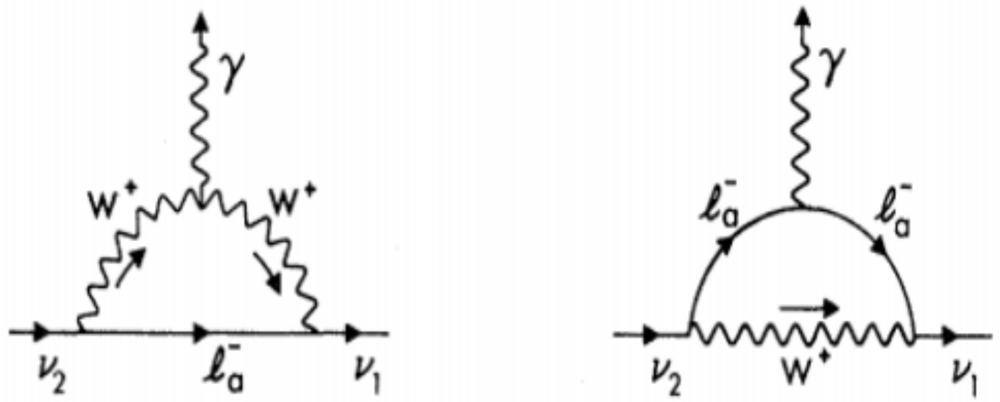
Neutrino Decay

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

- Neutrinos have a lifetime, even in the SM

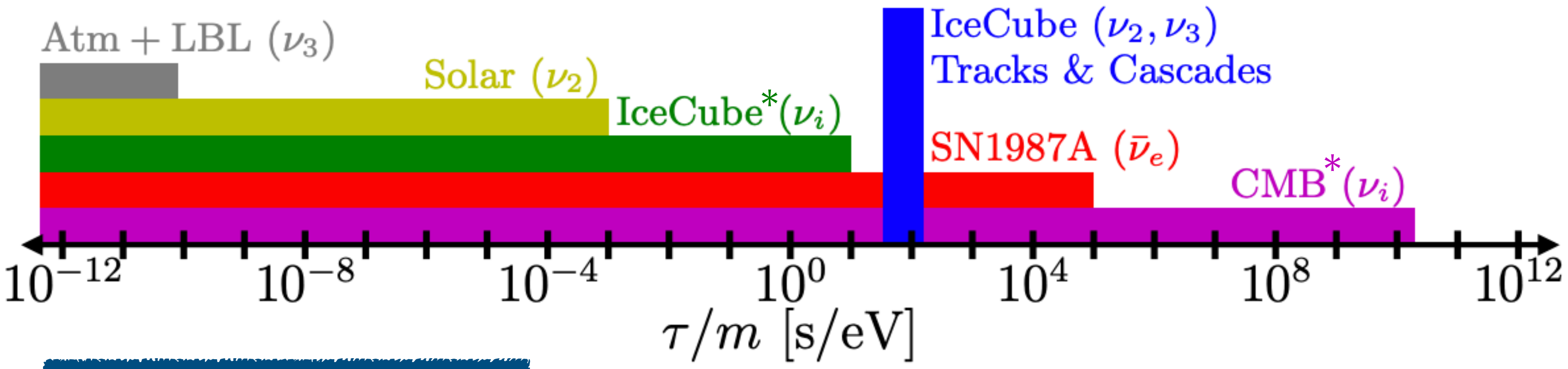
$$\Gamma \sim 10^{-45}\ \mathrm{s}^{-1} \longrightarrow$$

Way longer than the age of the Universe



Pal and Wolfenstein (PRD1982)

- However, if BSM exists, it can modify the neutrino lifetime:



Abdullahi, Denton
PRD 102, 023018 (2020)

$^*\tau_1/m_1 \gtrsim 6\times10^3$ s/eV

$^*\tau_0 \gtrsim 10^7$ s, two decay

$\tau_0 \gtrsim 10^5$ s (10^2 s) for one decay — atm (sol)

Gonzalez-Garcia and Maltoni (0802.3699)
Gomes, Gomes and Peres (1407.5640)
Abrahão et al (1506.02314)

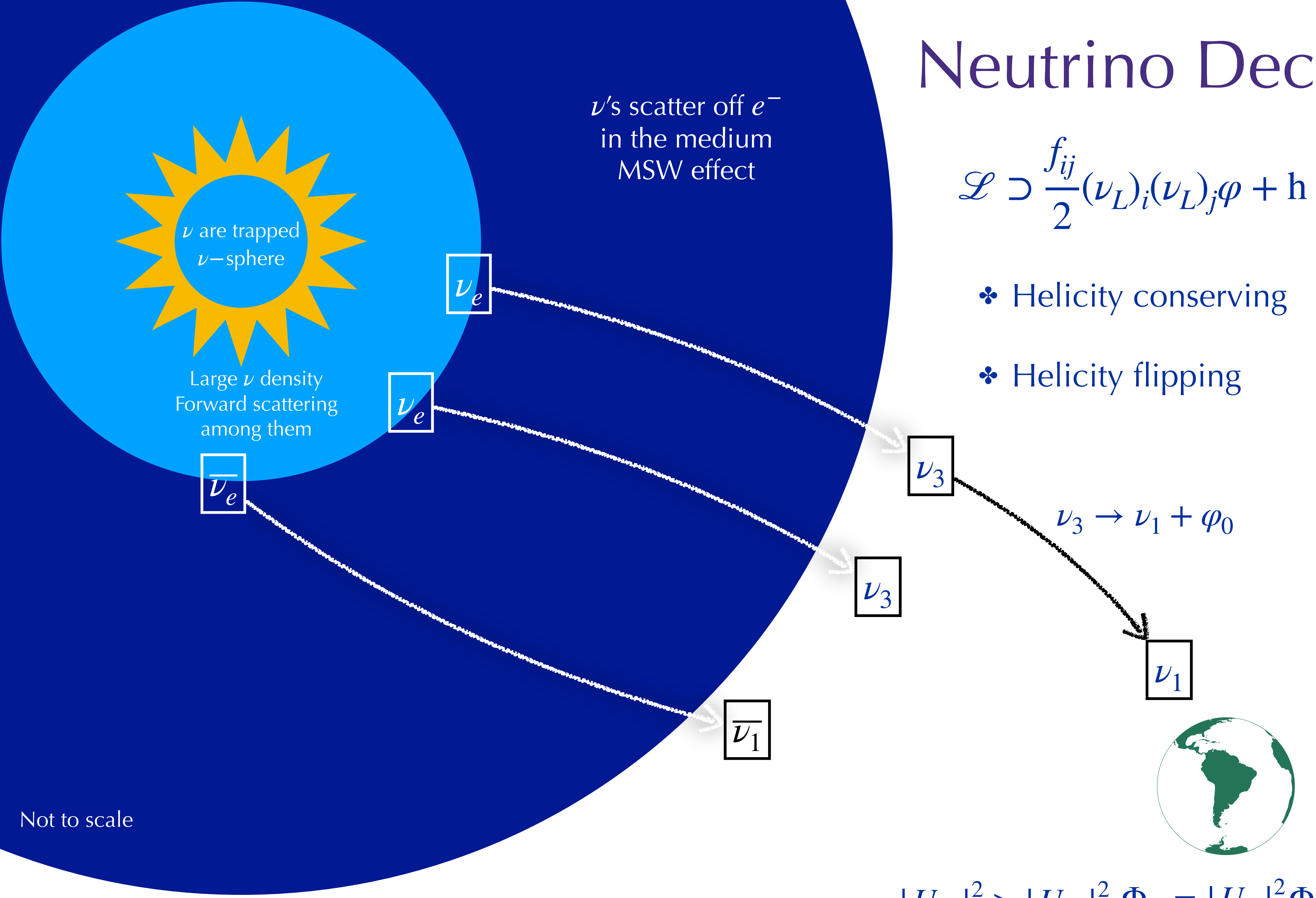
SNO (1812.01088)
Berryman, de Gouvea, Hernandez (1411.0308)

Bustamante, Beacom, Murase (1610.02096)
Denton, Tamborra (1805.05950)
Bustamante (2004.06844)
…

SK (PRL '87)
Kachelriess, Tomas and Valle (0001039)
Farzan ('02)

Escudero and Fairbairn (1907.05425)
Chacko, Dev, Du, Poulin and Tsai (1909.05275)
Chen et al (2203.09075)

Neutrino Decay



$$\mathscr{L} \supset \frac{f_{ij}}{2}(\nu_L)_i(\nu_L)_j\varphi + \mathrm{h.c.}$$

- Helicity conserving
- Helicity flipping

$$|U_{e1}|^2 > |U_{e3}|^2 \ \Phi_{\nu_e} = |U_{ei}|^2 \Phi_{\nu_i}$$

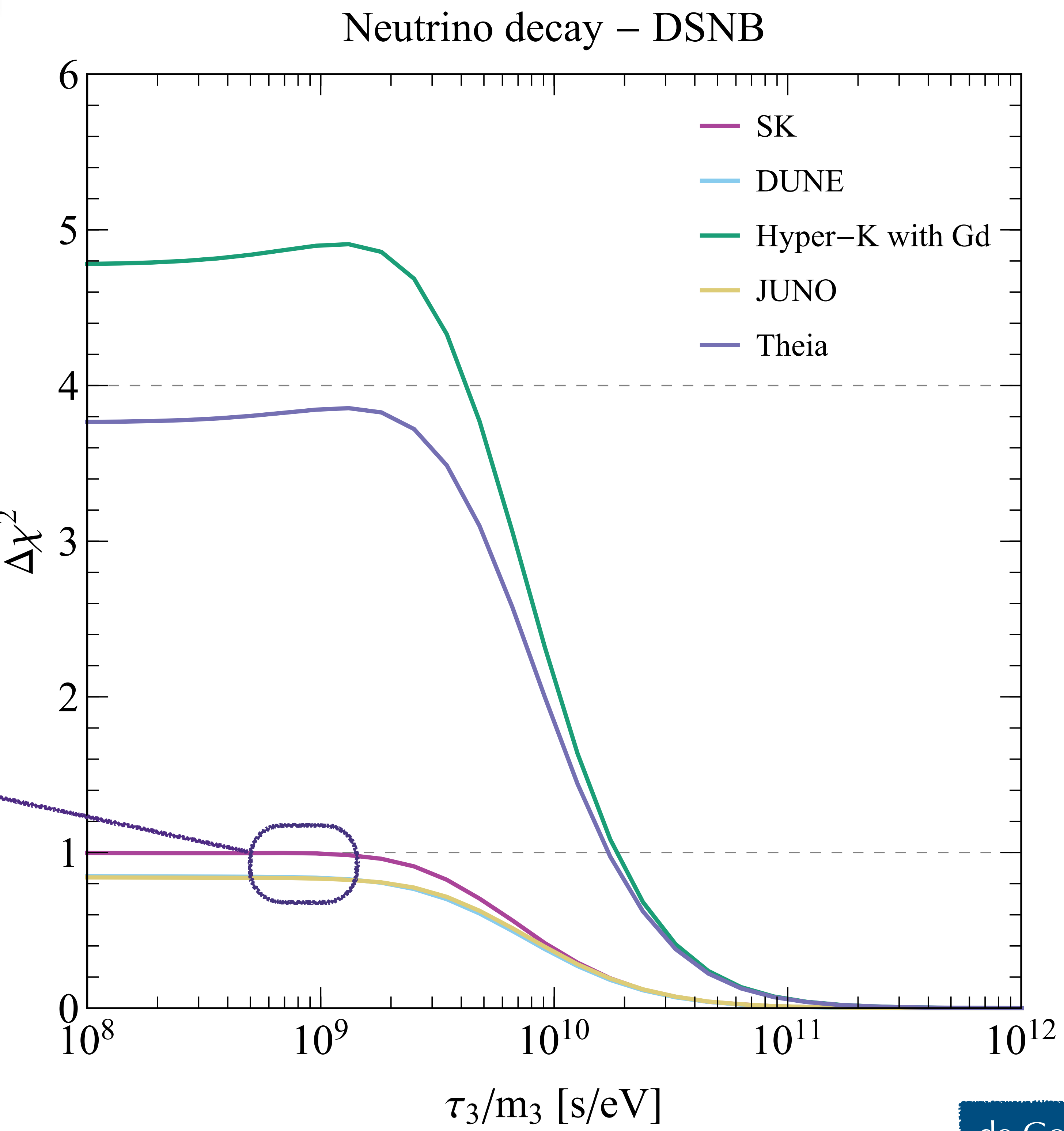
Enhancement

For the NO

Ando (0307169)
Fogli et at (0401227)

For galactic SNe: De Gouvêa, Martinez-Soler, Sen, PRD 2019

Future sensitivity - 10 y



$\tau_3/m_3 \lesssim 10^9$ s/eV

@ 2σ — 10 yr

Small statistics in these experiments

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

Pseudo-Dirac Neutrinos

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

Soft lepton number violation

Also technically natural case

$$\nu_{\alpha L} = \frac{1}{\sqrt{2}}\underbrace{U_{\alpha j}}_{\text{PMNS matrix}}(\underbrace{\nu_j^+ + i\,\nu_j^-}_{\text{Mass eigenstates}})$$

Active neutrinos are a ~50-50 combination of two states

See Babu's talk

---

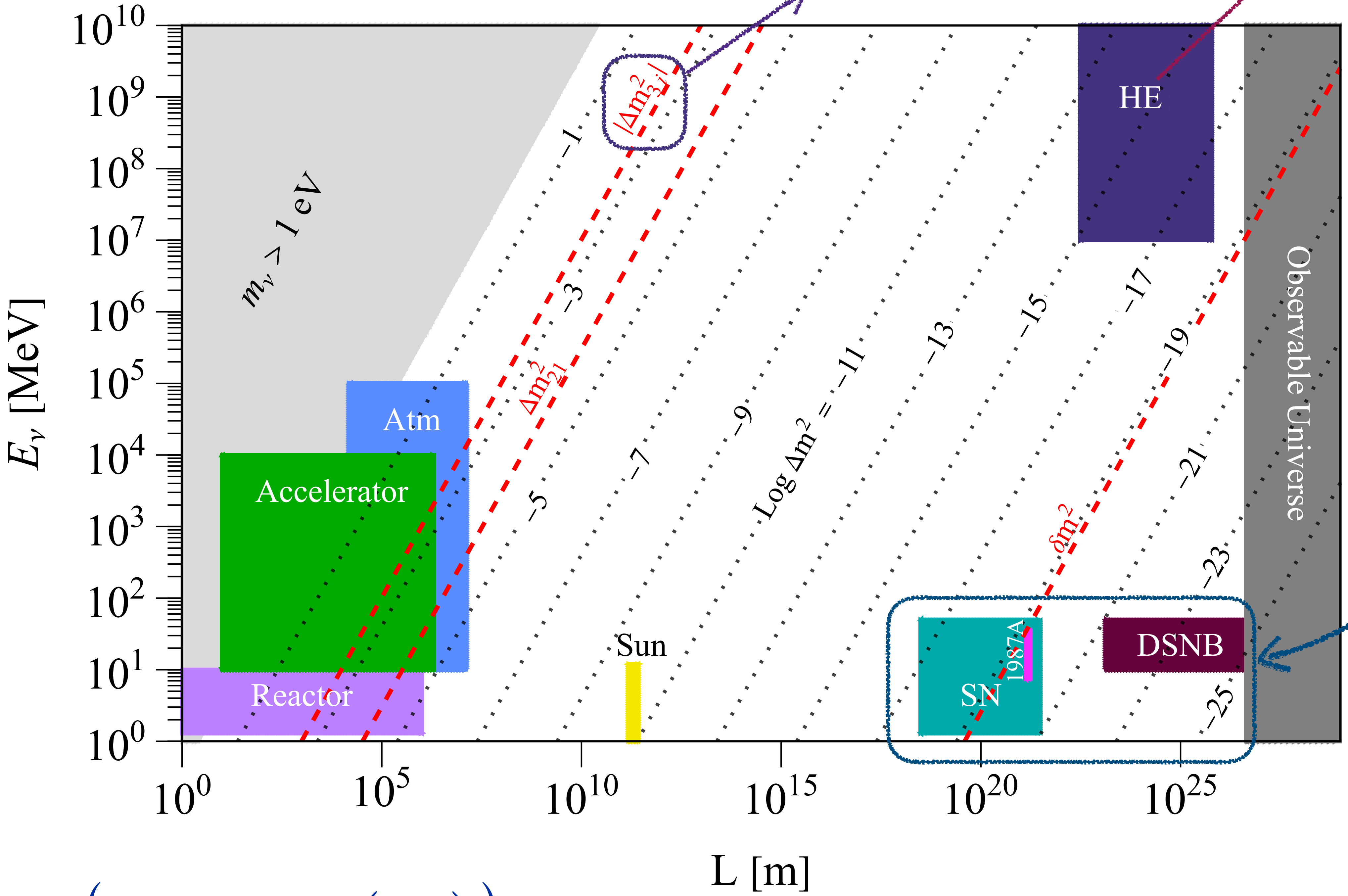
*I use "pseudo-Dirac" to describe active-sterile pairs

Pseudo-Dirac Neutrinos

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

Oscillation length

See Bhupal's talk



SN neutrinos are sensitive to very tiny mass differences!

Inspired on 0307151

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

$$L_{\rm osc} = \frac{4\pi E_\nu}{\delta m^2} \sim 20\,\text{kpc}\left(\frac{E_\nu}{25\text{MeV}}\right)\left(\frac{10^{-19}\text{eV}^2}{\delta m^2}\right)$$

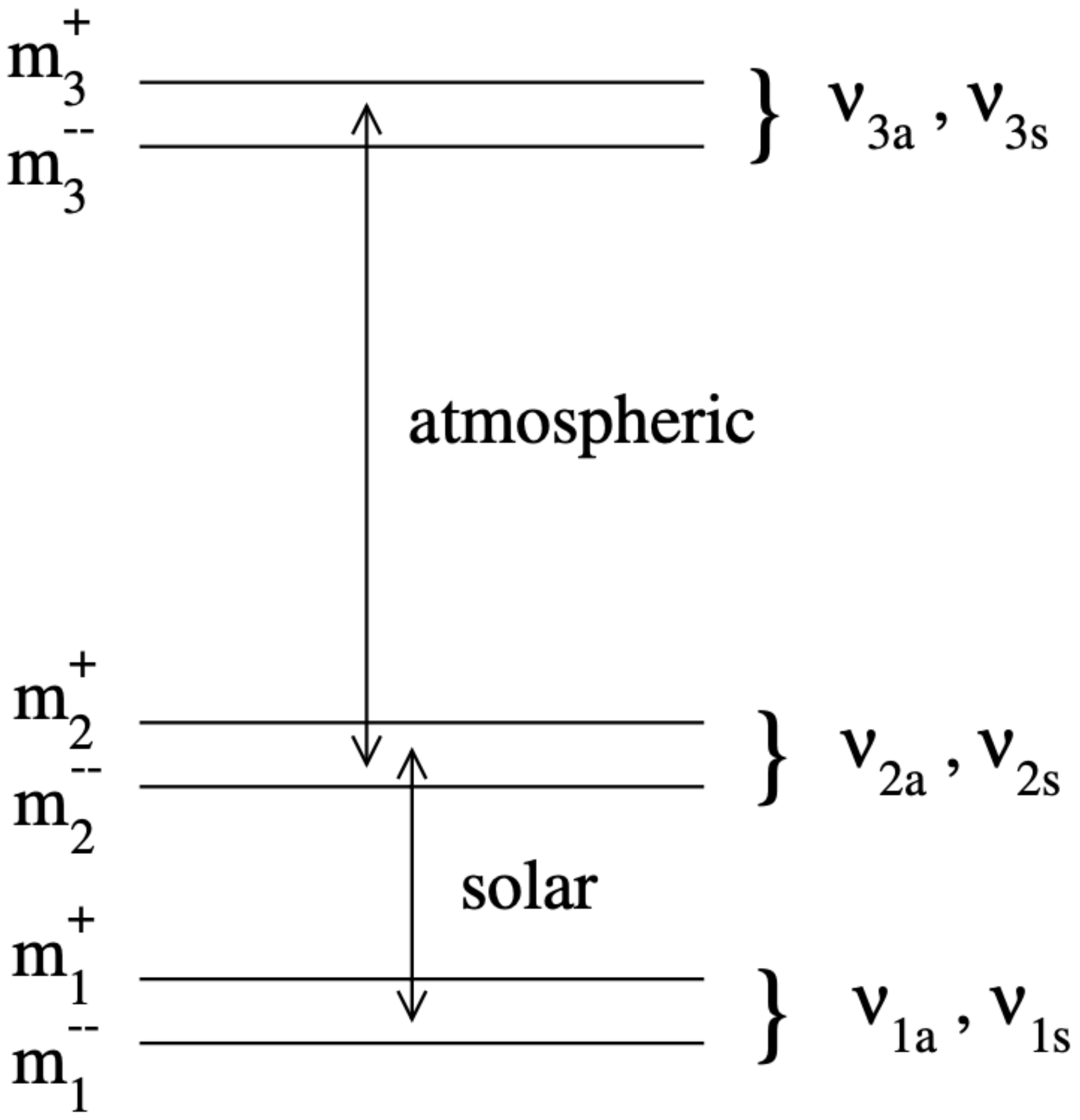
Pseudo-Dirac Neutrinos

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

$\delta m_k^2 \rightarrow$ 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

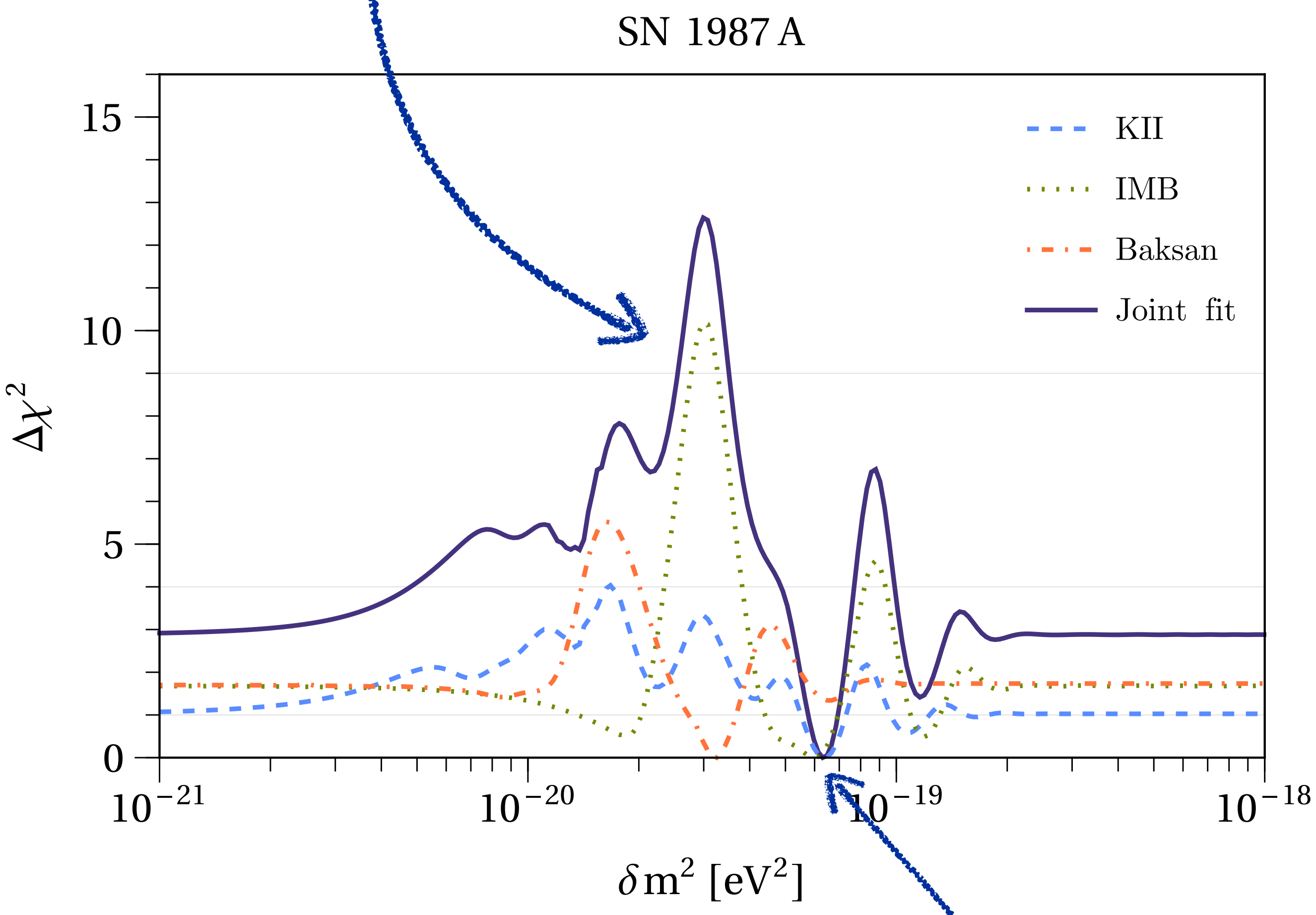
SN1987A

Mild preference for a non-zero δm_k^2

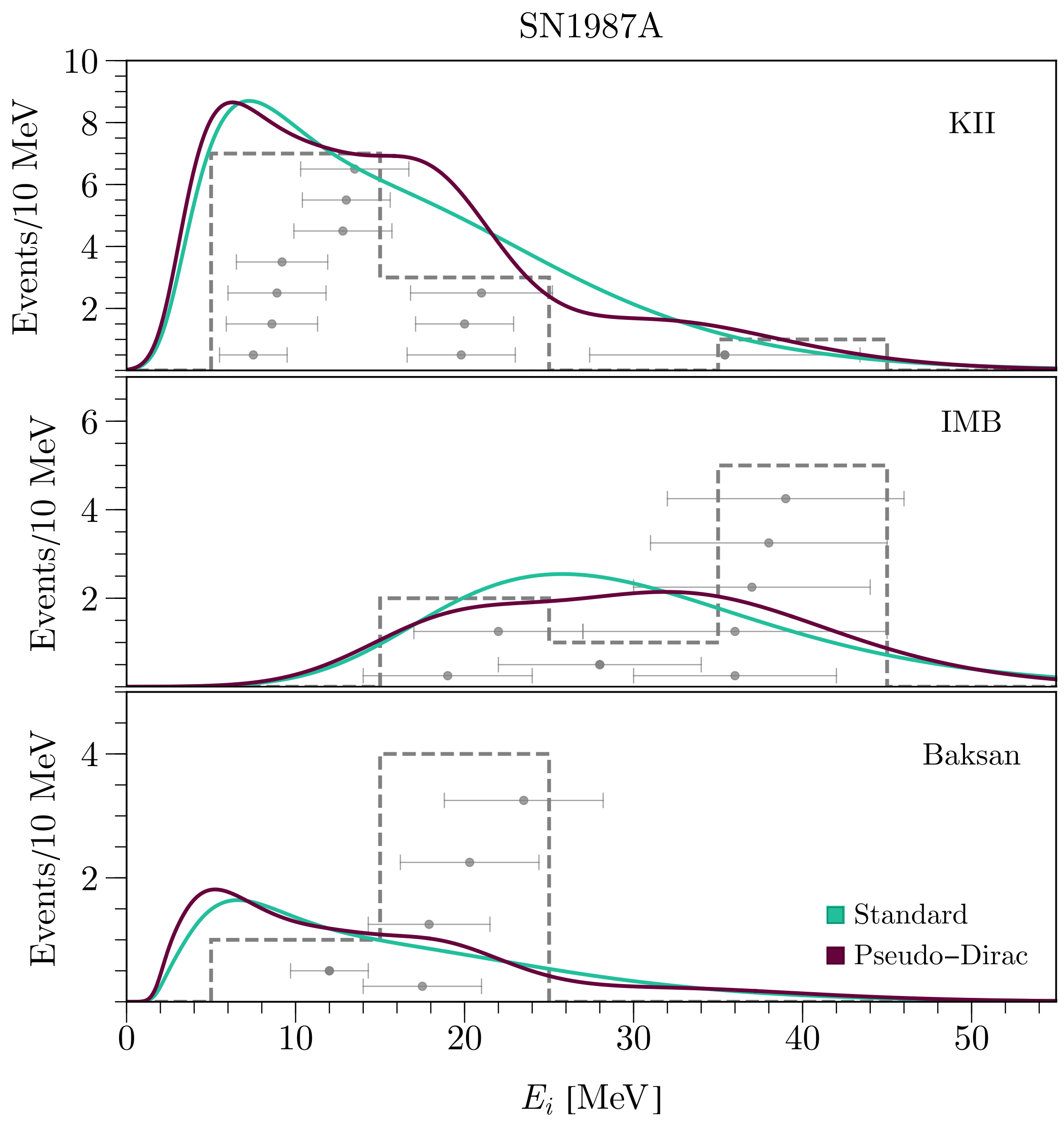
$\Delta\chi^2 \approx 3$

We can exclude a range a more than 3σ!

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



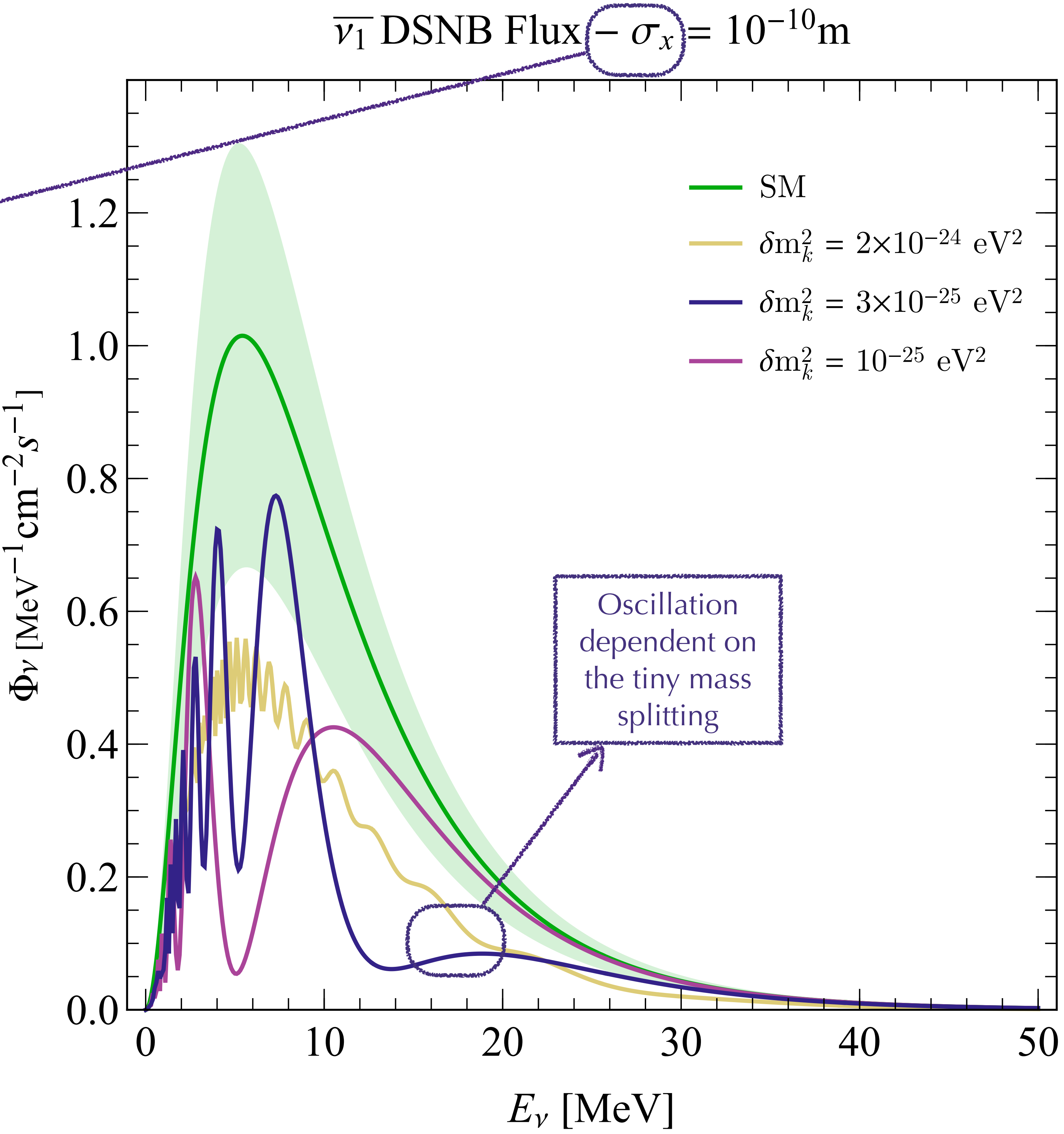
$\delta m_k^2 = 6.31 \times 10^{-20}$ eV^2



Active-sterile oscillations ease the tension

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

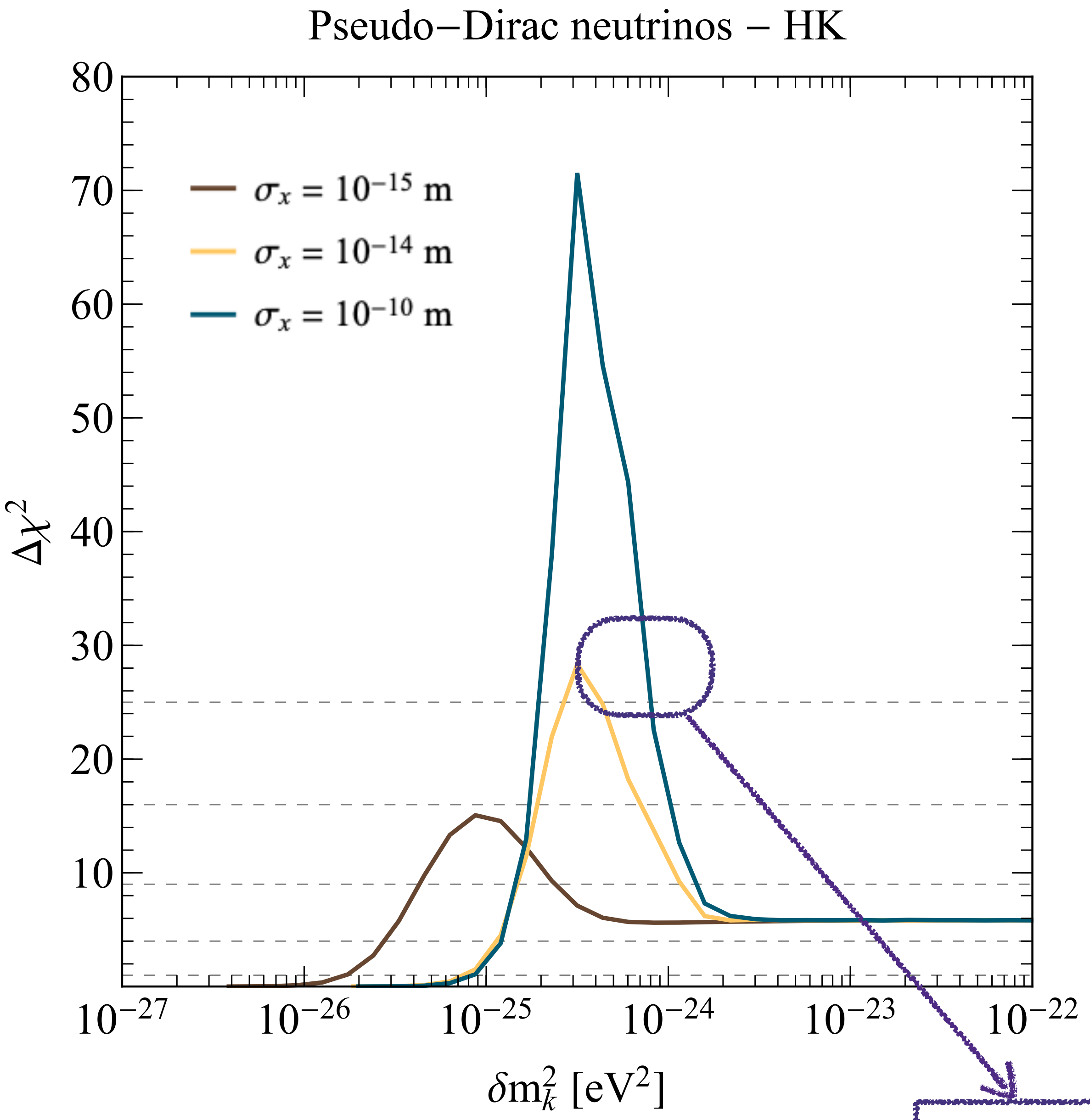
Pseudo-Dirac Neutrinos



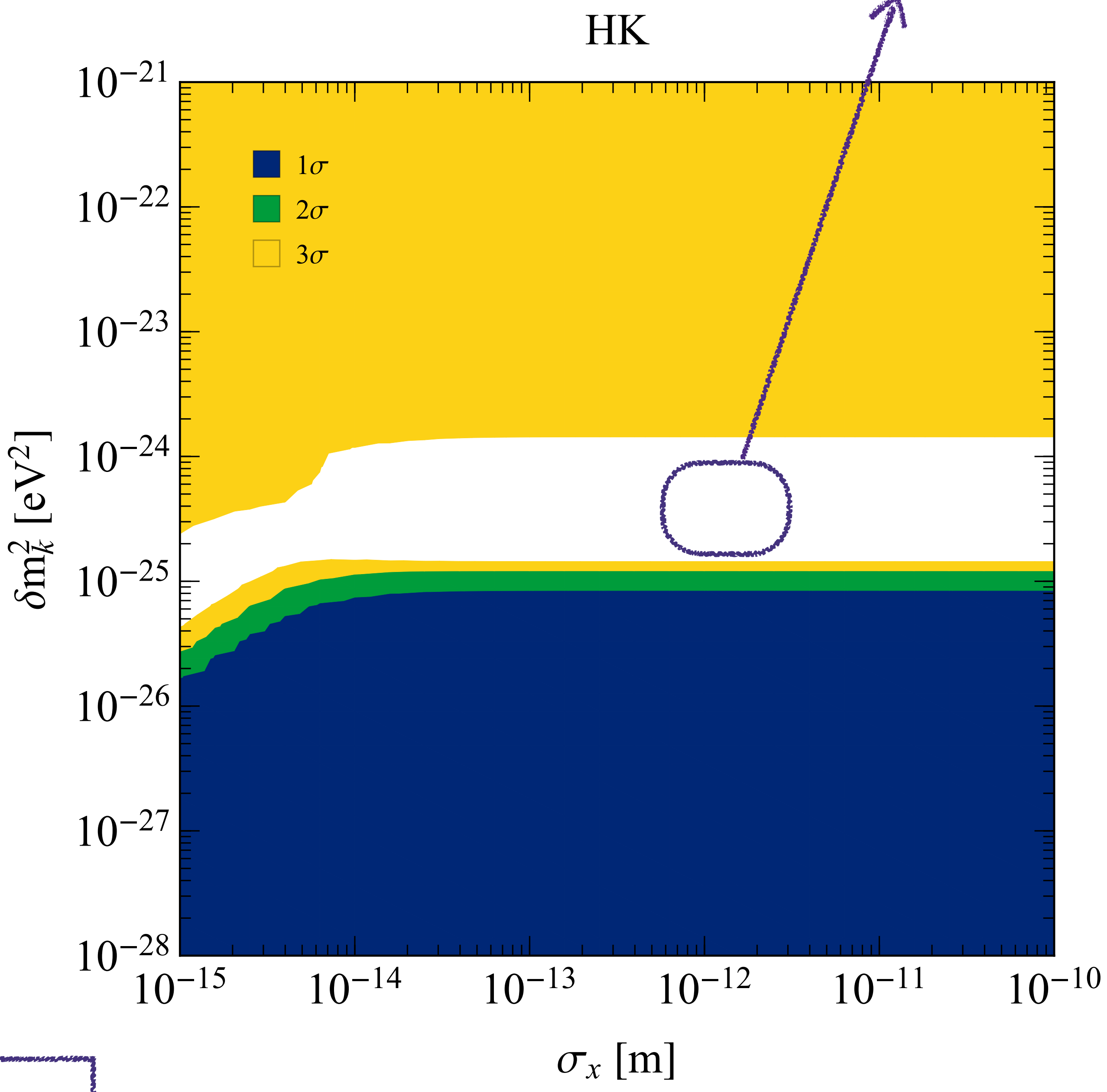
Fixed wave packed size

Oscillation dependent on the tiny mass splitting

Pseudo-Dirac Neutrinos



Large sensitivities



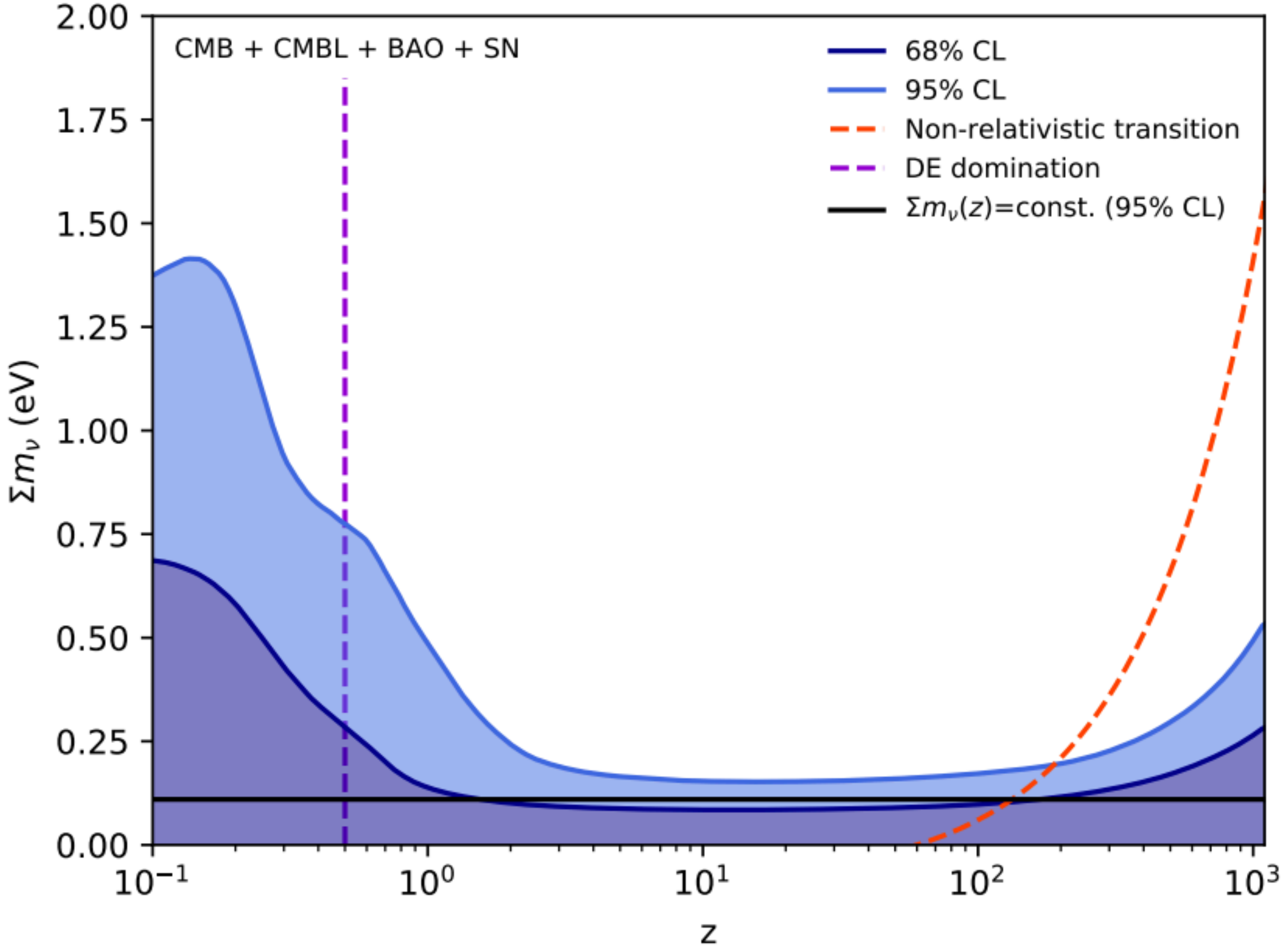
Region excluded at more than 3σ

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

Mass-varying Neutrinos

Mass-varying neutrinos

- ✴ 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

Mass-varying neutrinos

What if neutrino masses were different in the past?

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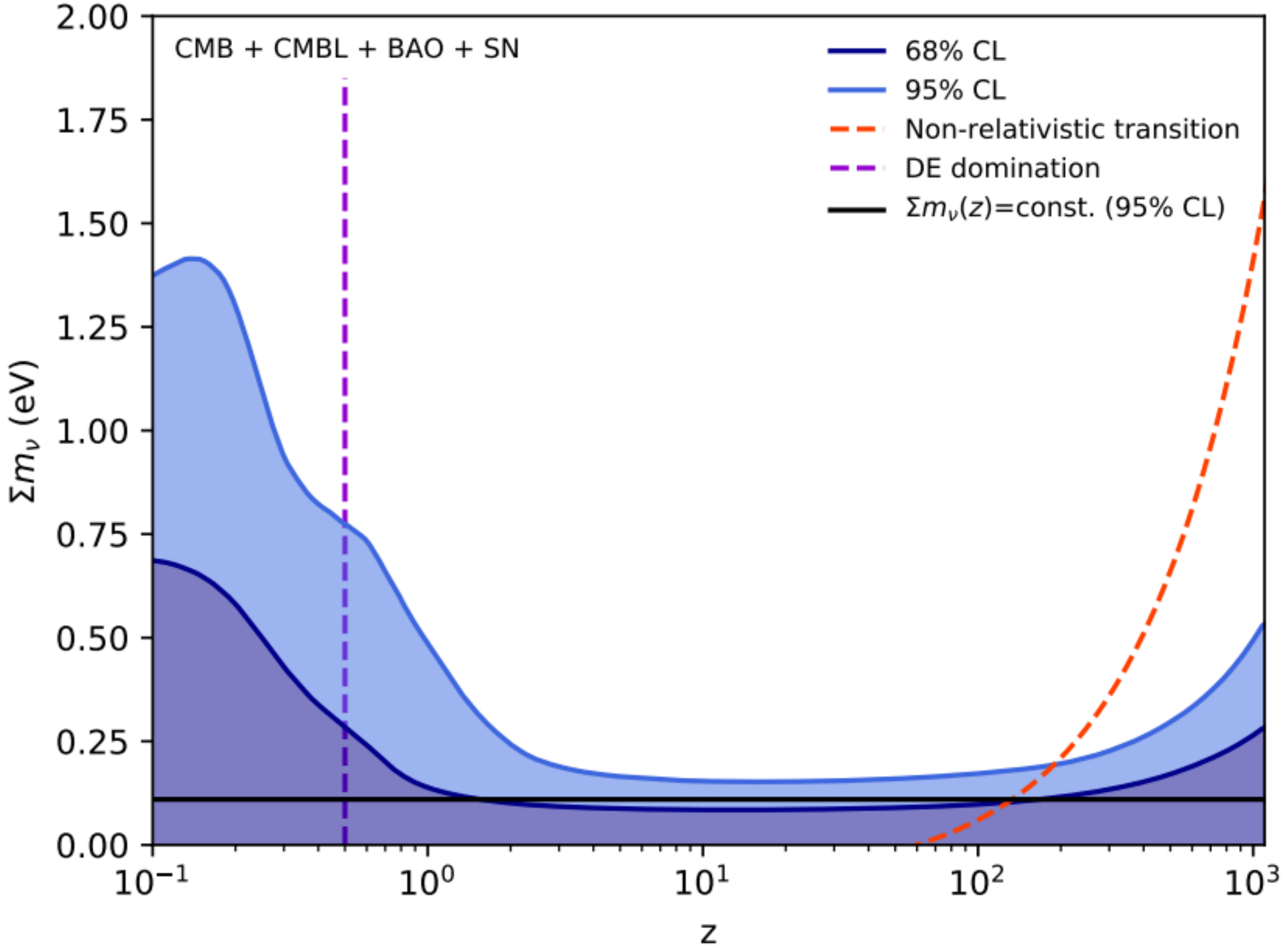


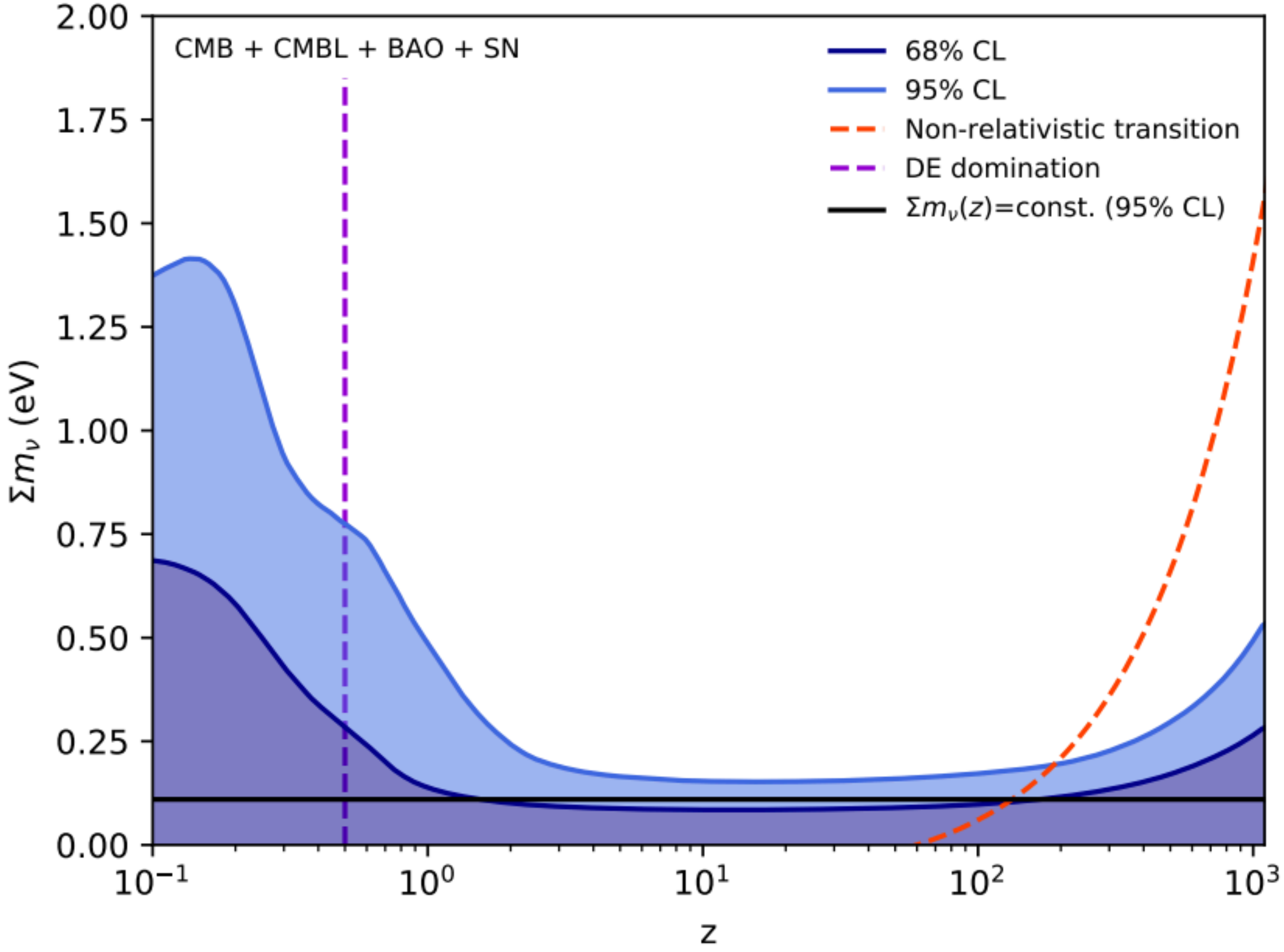
Lorenz et al, PRD 104(2021)122518

Mass-varying neutrinos

What if neutrino masses were different in the past?

- ✳ Cosmology doesn't forbid (yet) massless neutrinos at different redshifts
- ✳ Weaker constraints for smaller redshifts
- ✳ At "z=0" we observe oscillations
- ✳ Let's assume a purely phenomenological approach:

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



Lorenz et al, PRD 104(2021)122518

B_s → how fast

z_s → when

Koksbang, Hannestad, JCAP09(2017) 014

See Manibrata's talk for an example of a model

Mass-varying neutrinos

What if neutrino masses were different in the past?

- ✳ Let's assume a purely phenomenological approach:

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

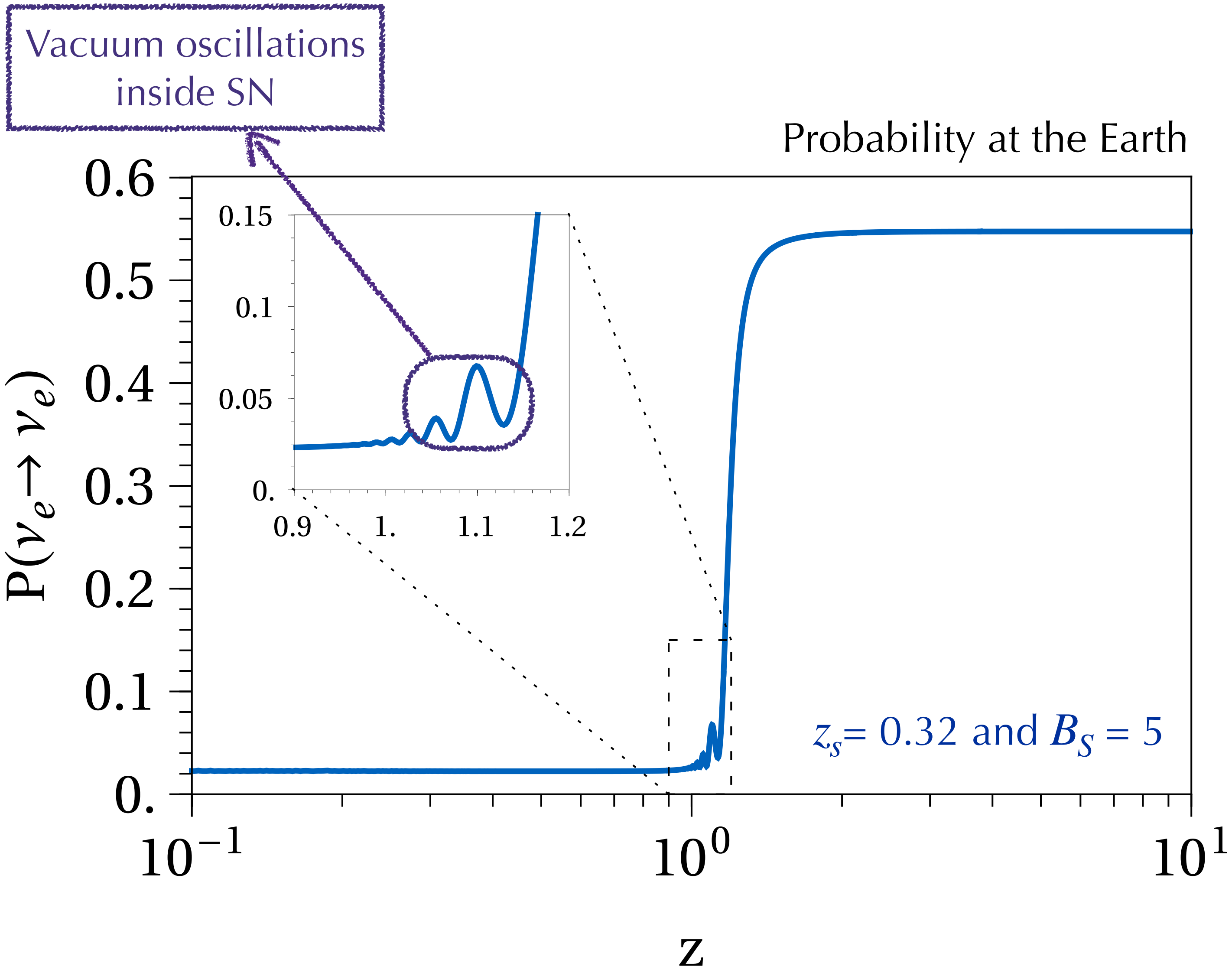
B_s → how fast
z_s → when

DSNB fluxes at the Earth

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

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

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


Vacuum oscillations inside SN

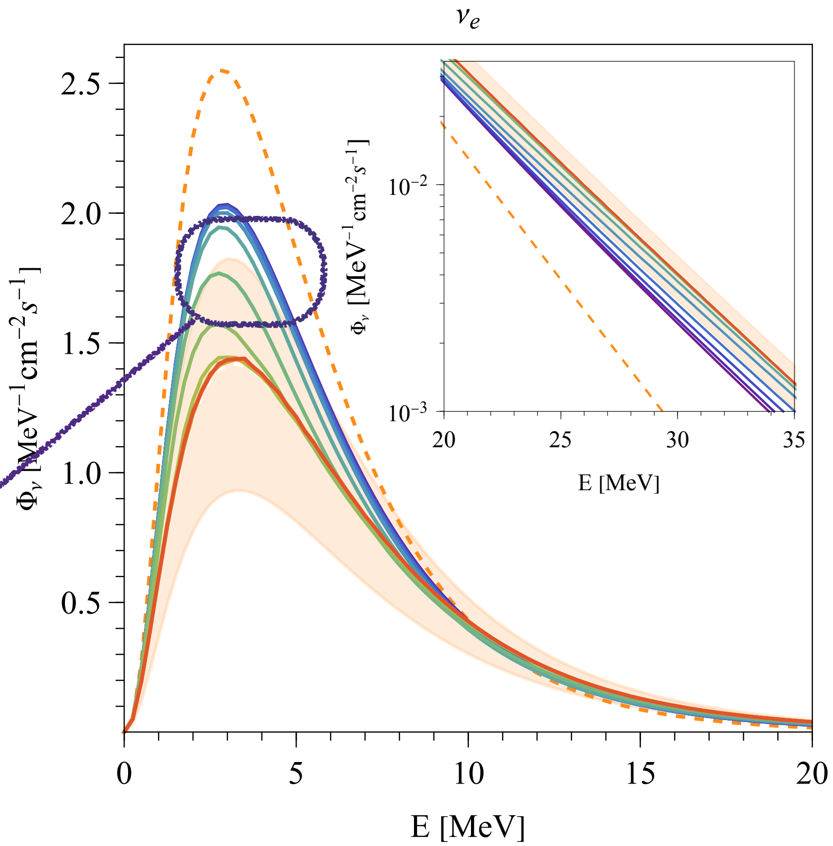
Probability at the Earth

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

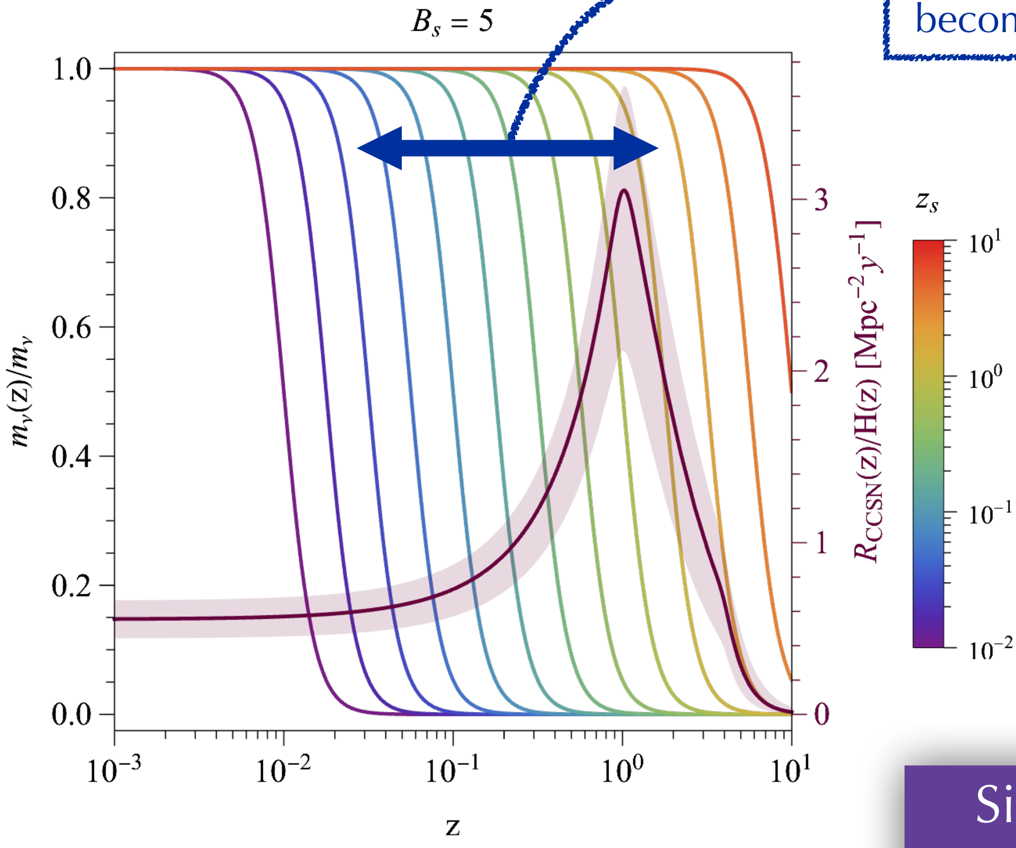
de Gouvêa, Martinez-Soler, YFPG, Sen, 2205.01102

Mass-varying neutrinos

In the NO*



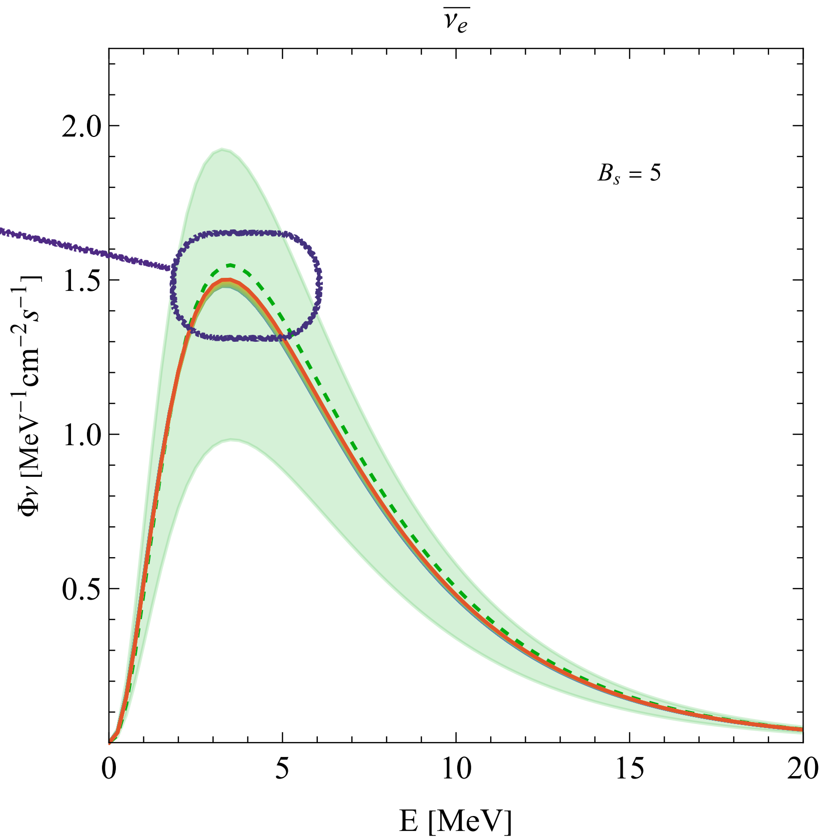
Significant modification on ν_e spectra

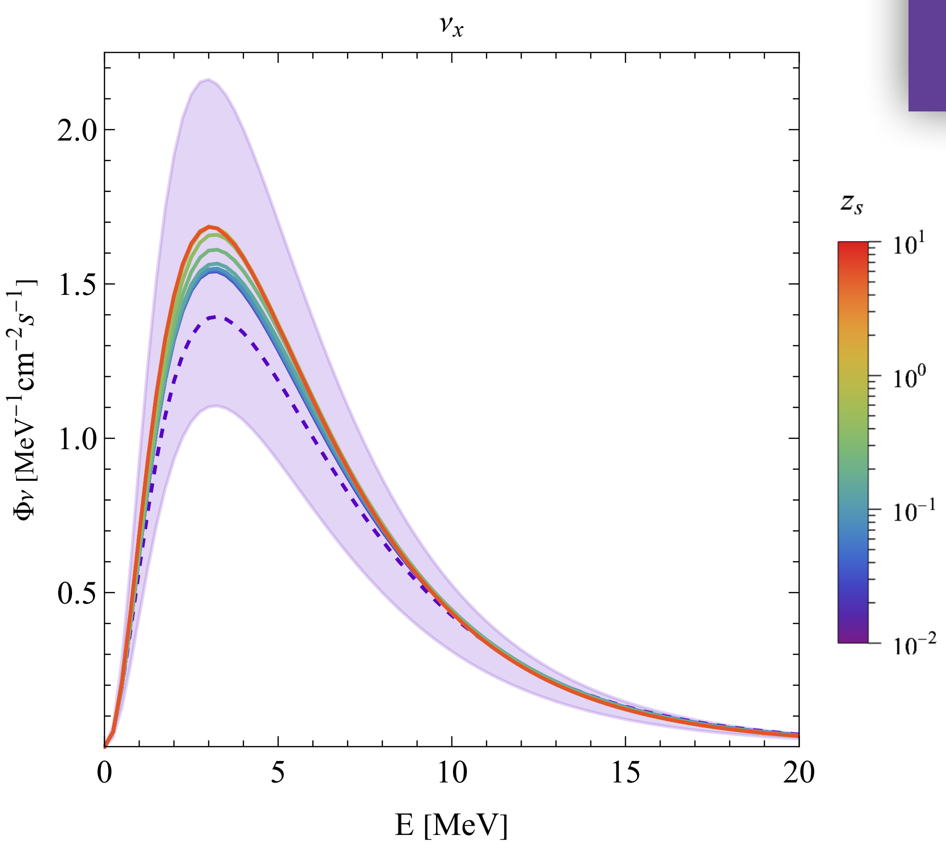


Dependence on when neutrinos become massive

Simultaneous measurements could tell us!

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





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

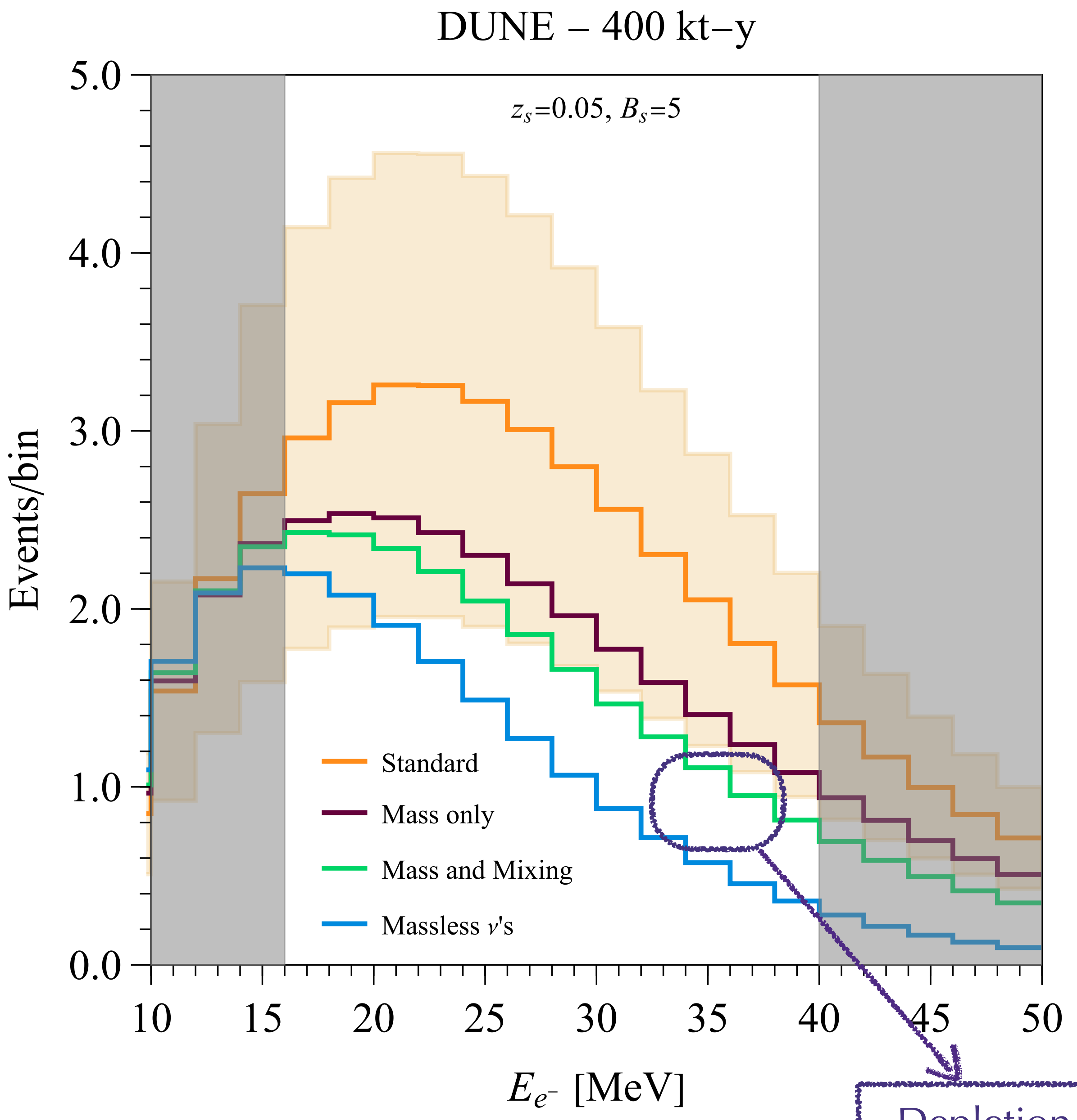
$$|U_{e3}|^2 = 0.02$$

*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…

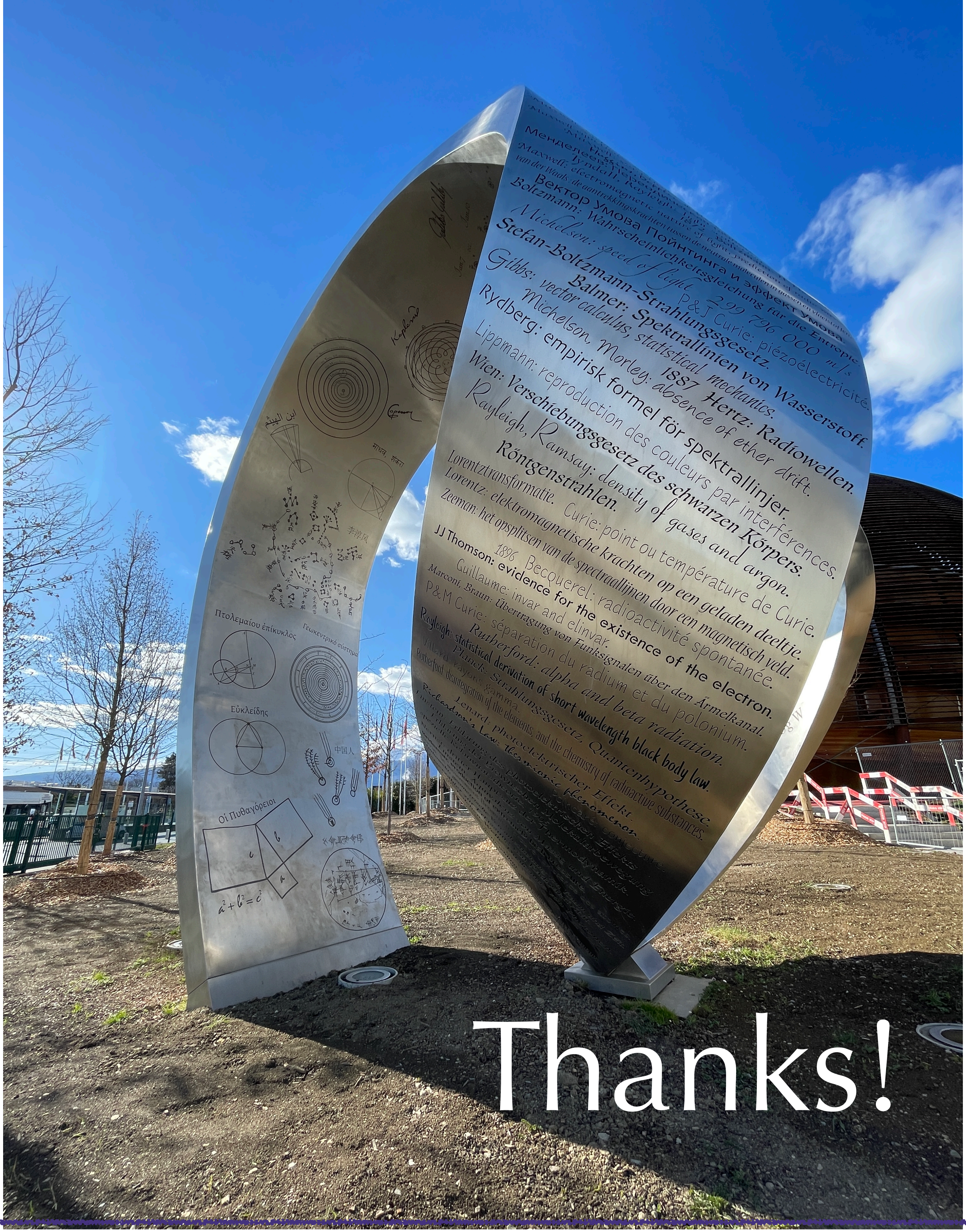
However, there is a clear strategy for the future!*

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

*If the ordering is normal

Conclusions

- SN MeV neutrinos are a complementary window in our era of multi-observational astrophysics
- The DSNB are the oldest neutrinos within experimental reach!
- Measuring the DSNB is *guaranteed*: These neutrinos should be detectable in the next generation of experiments
- Backgrounds are the biggest concern for detection, but many people are working on reducing them
- If we detect the DNSB, we can test “slow” neutrino properties, decay, oscillations spanning Gpc distances, time varying masses.

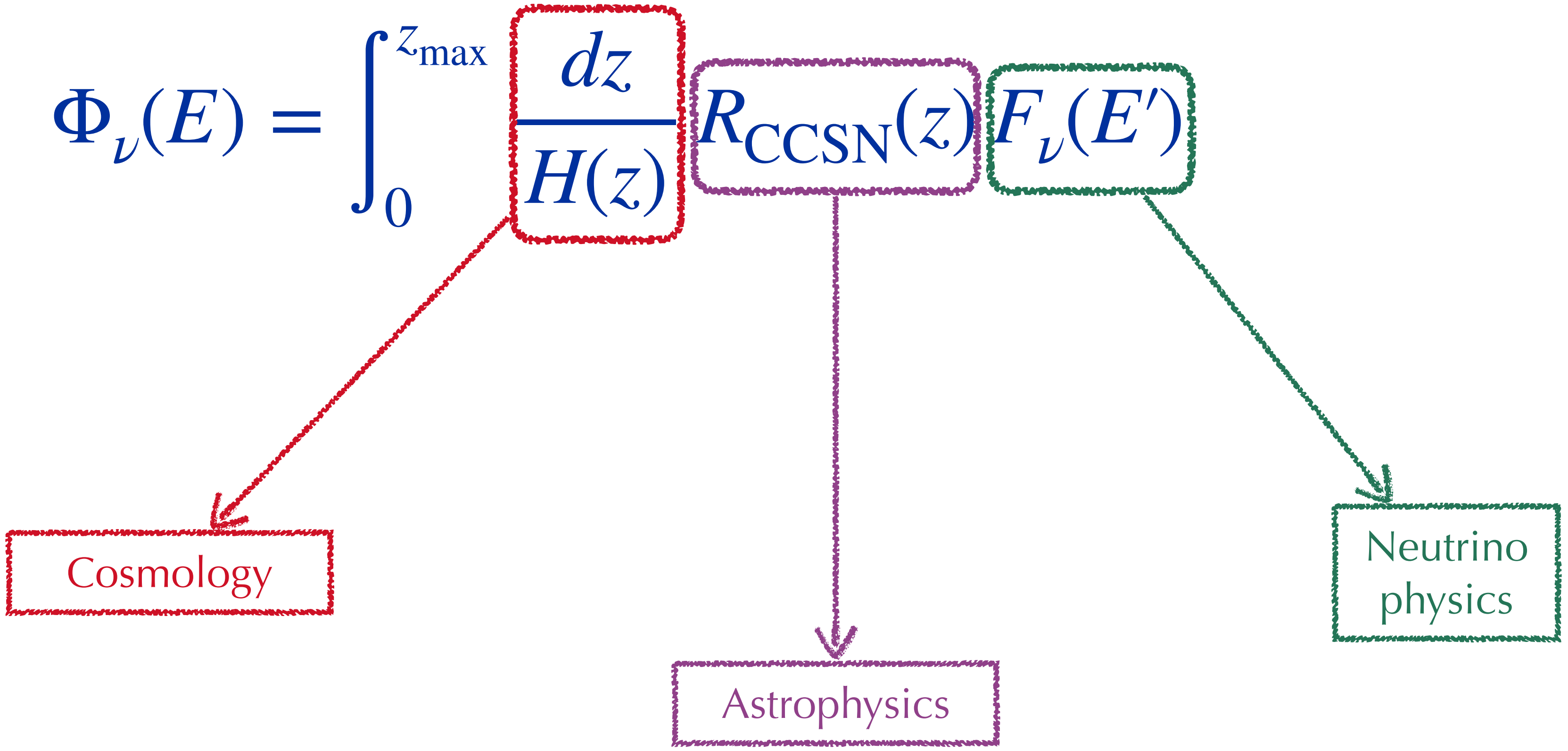

Вектор Умова Пойнтинга и эффект Умова
Boltzmann: Wahrscheinlichkeitsgleichung für die Entropie
Michelson: speed of light 299 796 000 m/s
P&J Curie: piézoélectricité.
Stefan-Boltzmann-Strahlungsgesetz.
Balmer: Spektrallinien von Wasserstoff.
Gibbs: vector calculus, statistical mechanics.
Michelson, Morley: absence of ether drift.
1887 Hertz: Radiowellen.
Rydberg: empirisk formel för spektrallinjer.
Lippmann: reproduction des couleurs par interférences.
Wien: Verschiebungsgesetz des schwarzen Körpers.
Rayleigh, Ramsay: density of gases and argon.
Röntgenstrahlen.
Lorentztransformatie. Curie: point ou température de Curie.
Lorentz: elektromagnetische krachten op een geladen deeltje.
Zeeman: het opsplitsen van de spectraallijnen door een magnetisch veld.
1896 Becquerel: radioactivité spontanée.
JJ Thomson: evidence for the existence of the electron.
Guillaume: invar and elinvar.
Marconi, Braun: Übertragung von Funksignalen über den Ärmelkanal.
P&M Curie: séparation du radium et du polonium.
Rutherford: alpha and beta radiation.
Rayleigh: statistical derivation of short wavelength black body law.
Planck: Strahlungsgesetz. Quantenhypothese.
Rutherford: disintegration of the elements, and the chemistry of radioactive substances.
Lenard: photoelektrischer Effekt.
Πτολεμαίου έπίκυκλος
Γεωκεντρικό σύστημα
Εὐκλείδης
Οἱ Πυθαγόρειοι
$a^2+b^2=c^2$
中国人
Kepler

Thanks!

Backup

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

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
Ω_{x} → Distinct components
w → Dark Energy EOS

Diffuse Supernova Neutrino Background

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
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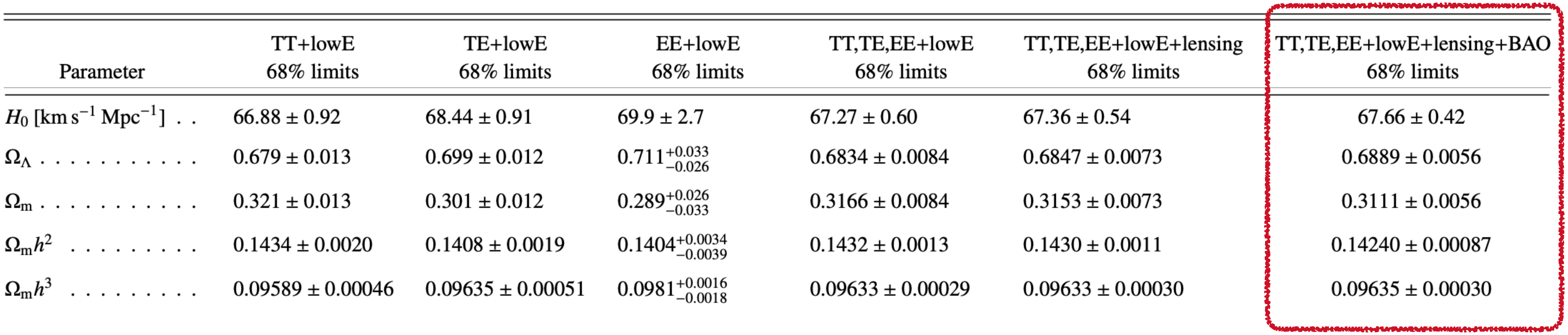


Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
H_0 [km s^{-1} Mpc^{-1}] . .	66.88 ± 0.92	68.44 ± 0.91	69.9 ± 2.7	67.27 ± 0.60	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.679 ± 0.013	0.699 ± 0.012	$0.711^{+0.033}_{-0.026}$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

$z_{\max} = 5$

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

Astrophysics

$$R_{\text{CCSN}}(z) = \underbrace{\boxed{\dot{\rho}_*(z)}}_{\text{Star formation rate}} \underbrace{\boxed{\frac{\int_8^{50} \psi(M)\, dM}{\int_{0.1}^{100} M\psi(M)\, dM}}}_{\text{Rate of star that go SN}}$$

Astrophysics

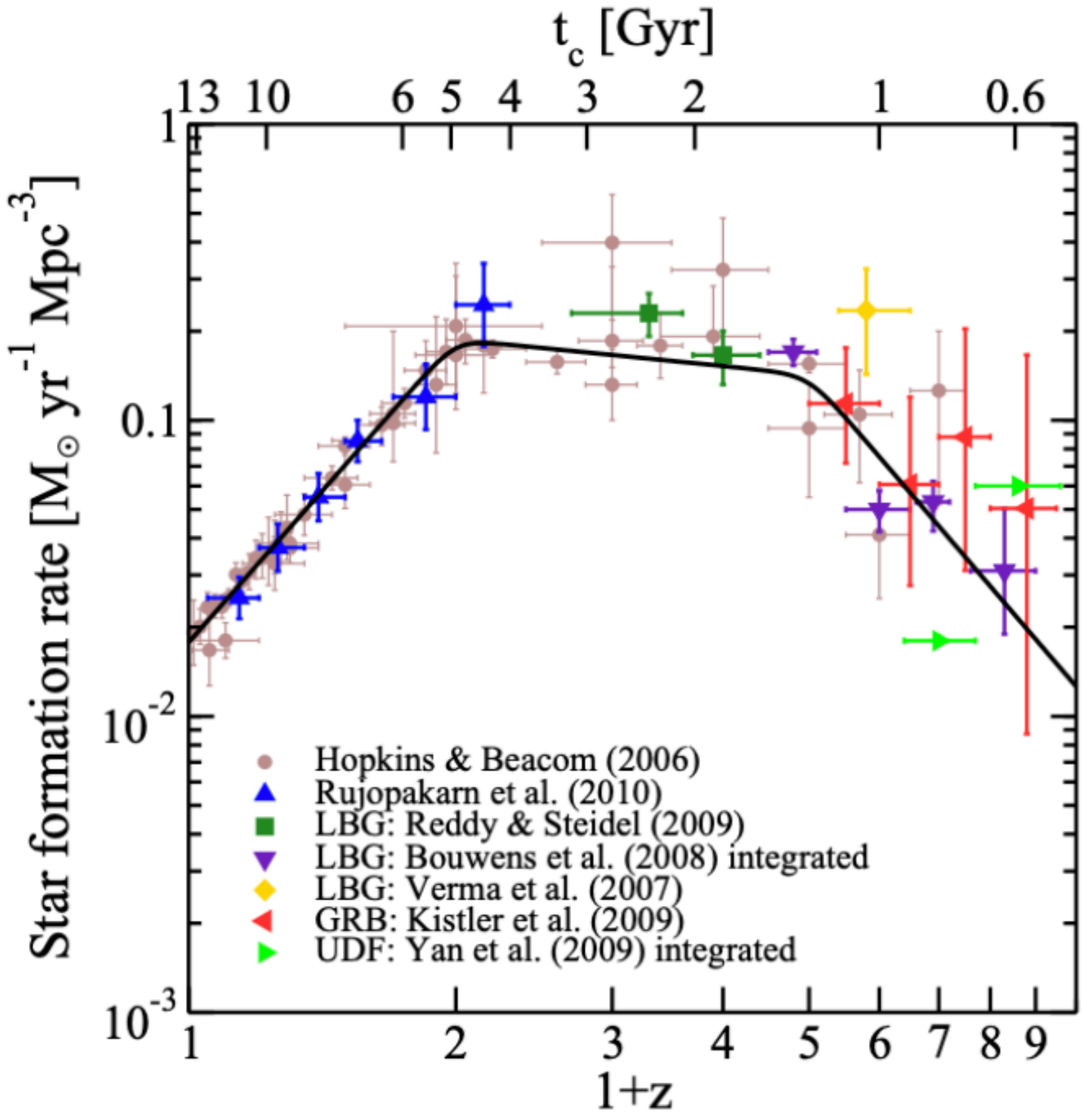
$$\dot{\rho}_*(z) = \dot{\rho}_0 \left[(1+z)^{-10\,\alpha} + \left(\frac{1+z}{B} \right)^{-10\,\beta} + \left(\frac{1+z}{C} \right)^{-10\,\gamma} \right]^{-1/10}$$

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

Star formation rate

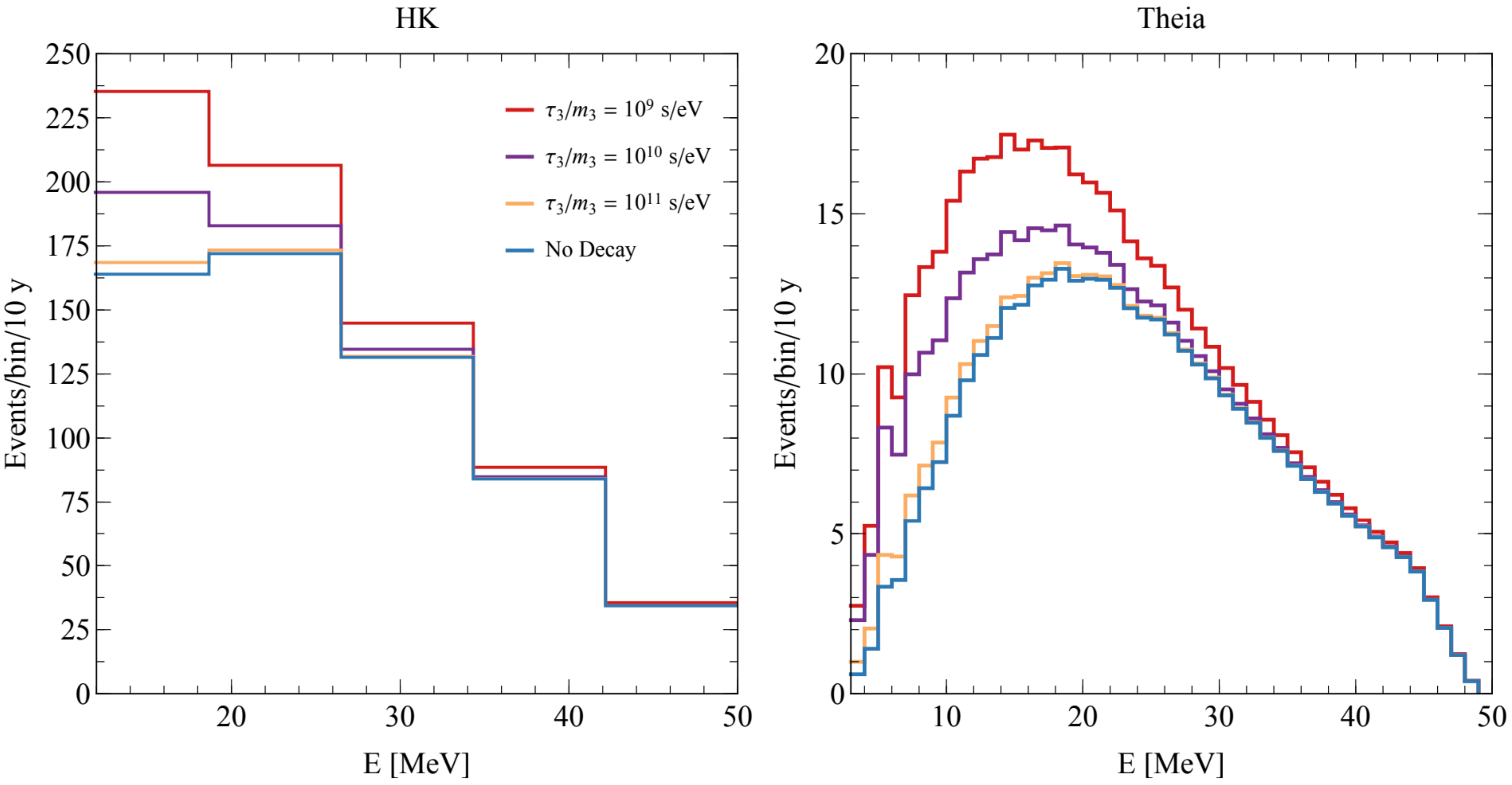
$$\psi(M) \sim M^{-2.35}$$

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

Decay


HK
Theia
Events/bin/10 y
E [MeV]
τ_3/m_3 = 10^9 s/eV
τ_3/m_3 = 10^{10} s/eV
τ_3/m_3 = 10^{11} s/eV
No Decay
0
25
50
75
100
125
150
175
200
225
250
20
30
40
50
0
5
10
15
20
10
20
30
40
50

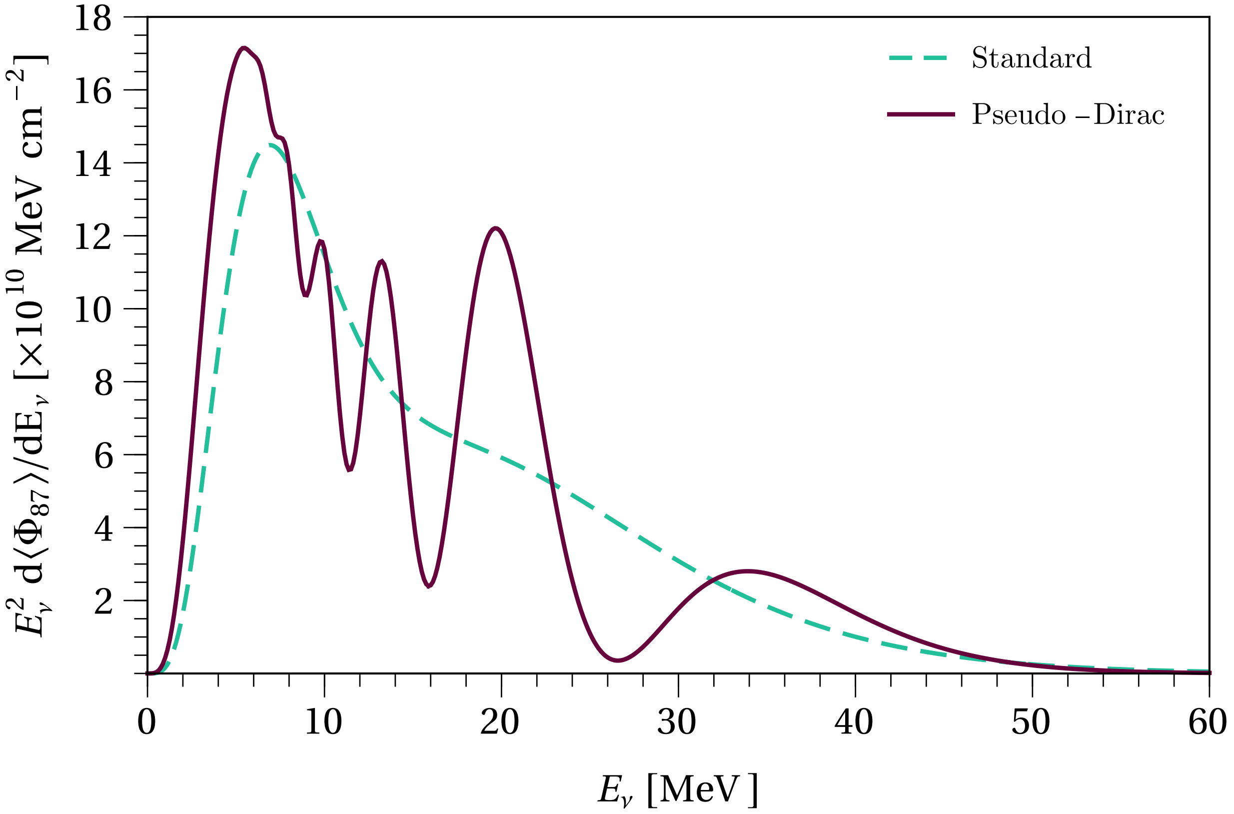
SN1987A — Analysis

$\sigma_x = 10^{-13}$ m

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

Alpha-fit spectra

$\alpha = 2.3$



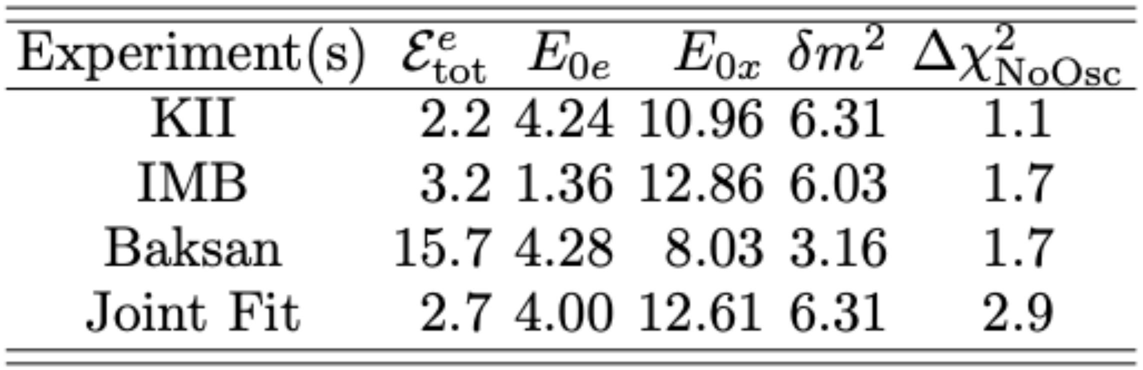
$\bar{\nu}_e$ fluence at the Earth

$$\frac{d\Phi_{87}}{dE_\nu} = \frac{\mathscr{E}^e_{\rm tot}}{4\pi d^2} P_{aa}\left[\bar{p}\frac{\phi_e}{E_{0e}} + r_{xe}\,(1-\bar{p})\frac{\phi_x}{E_{0x}}\right]$$

$$r_{xe} = \frac{\mathscr{E}^x_{\rm tot}}{\mathscr{E}^e_{\rm tot}} = 1$$

Unbinned likelihood

$$\mathscr{L} = e^{-N_{\rm tot}}\prod_i^{N_{\rm obs}} dE_i\left[\frac{dS}{dE_i} + \frac{dB}{dE_i}\right]$$



Experiment(s)	$\mathcal{E}^e_{\rm tot}$	E_{0e}	E_{0x}	δm^2	$\Delta\chi^2_{\rm NoOsc}$
KII	2.2	4.24	10.96	6.31	1.1
IMB	3.2	1.36	12.86	6.03	1.7
Baksan	15.7	4.28	8.03	3.16	1.7
Joint Fit	2.7	4.00	12.61	6.31	2.9

Following: Vissani, J.Phys.G 2015

Pseudo-Dirac Neutrinos

Neutrinos have propagated distances of order Gpc

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

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

Oscillation and decoherence lengths

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

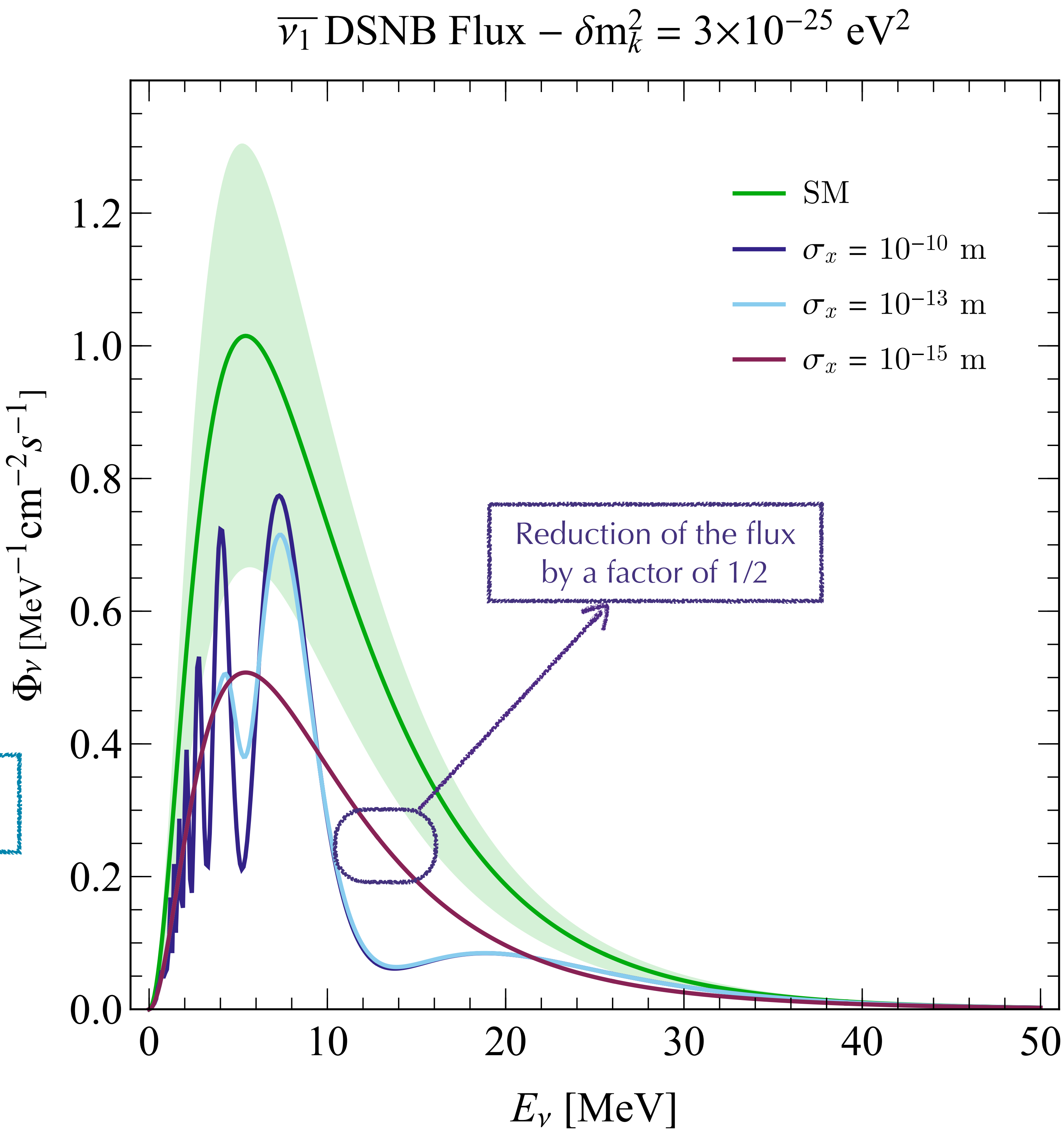
$$L_{\mathrm{coh}} = \frac{4\sqrt{2}E^2}{|\delta m_k^2|}\sigma_x \approx 180 \text{ Gpc} \left(\frac{E}{10 \text{ MeV}}\right)^2 \left(\frac{10^{-25} \text{ eV}^2}{\delta m_k^2}\right) \left(\frac{\sigma_x}{10^{-12} \text{ m}}\right)$$

Decoherence?

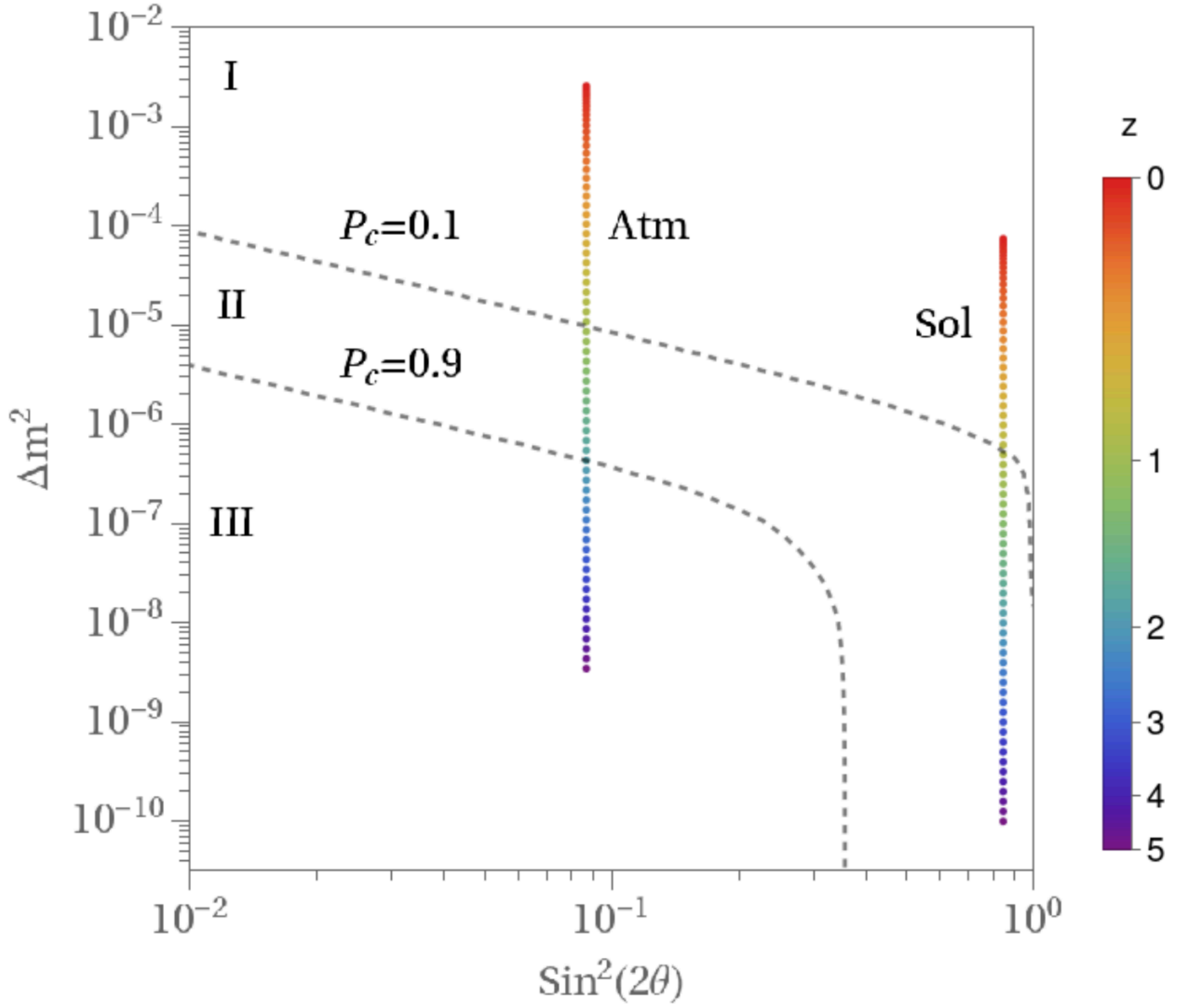
$$\frac{L_{\rm coh}}{L_{\rm osc}} = \frac{\sqrt{2}}{\pi} E\sigma_x$$

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

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



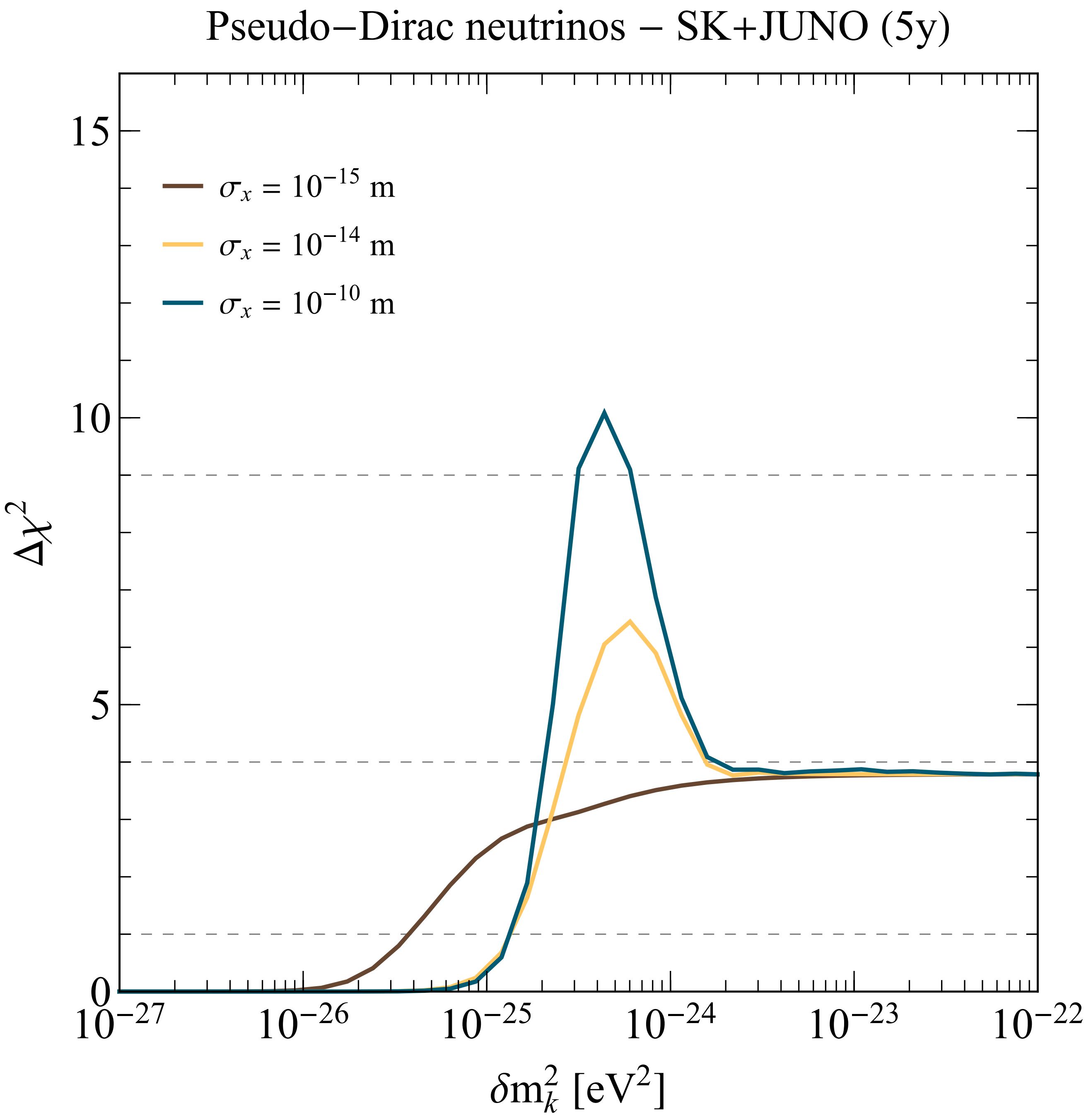
Reduction of the flux by a factor of 1/2



10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
Δm^2
I
II
III
P_c=0.1
P_c=0.9
Atm
Sol
10^{-2}
10^{-1}
10^{0}
$\mathrm{Sin}^2(2\theta)$
z
0
1
2
3
4
5

Pseudo-Dirac Neutrinos

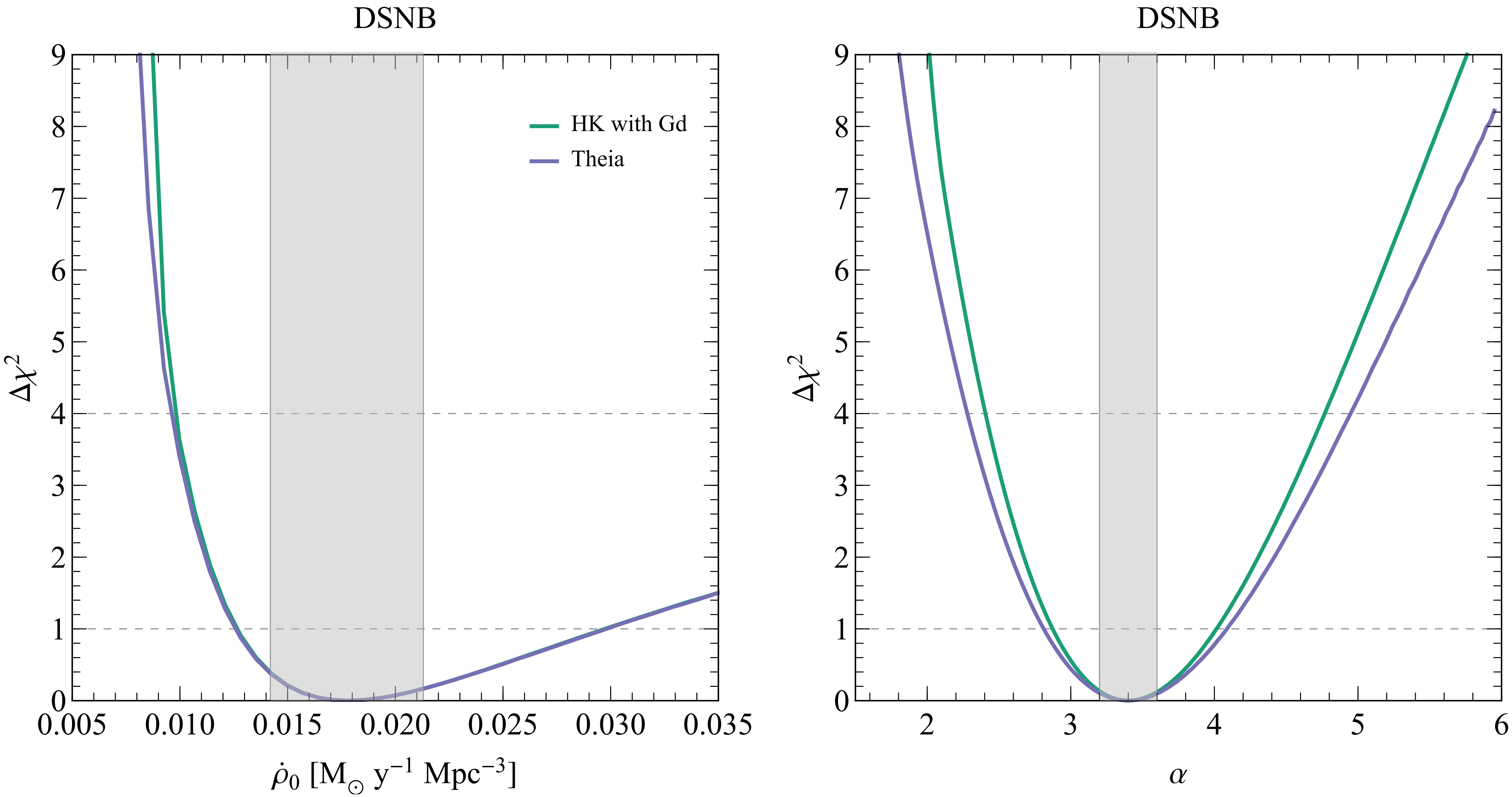
Stronger constraints in the next decade



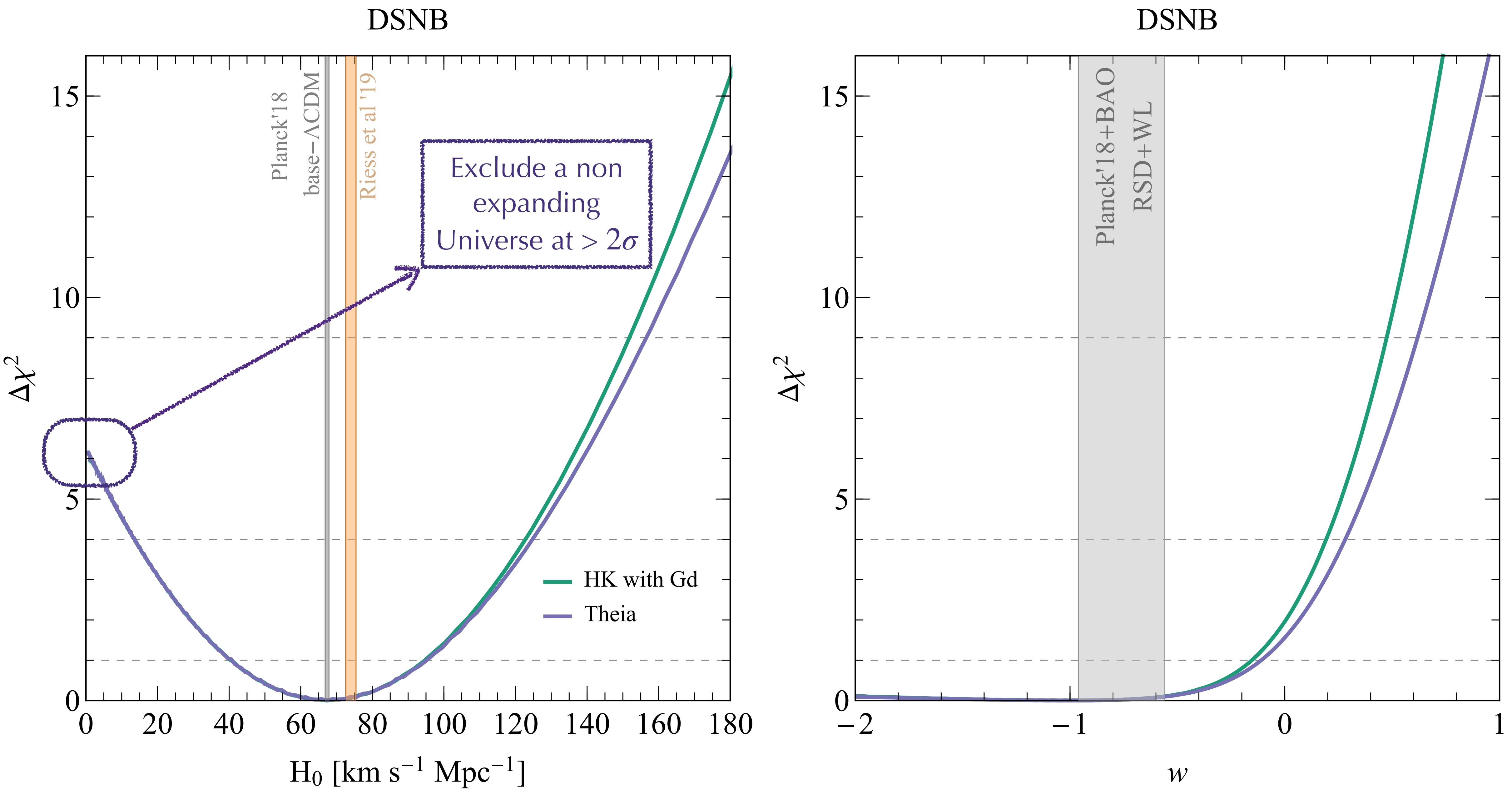
de Gouvêa, Martinez-Soler, YFPG, Sen, 2007.13748

Astrophysics

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

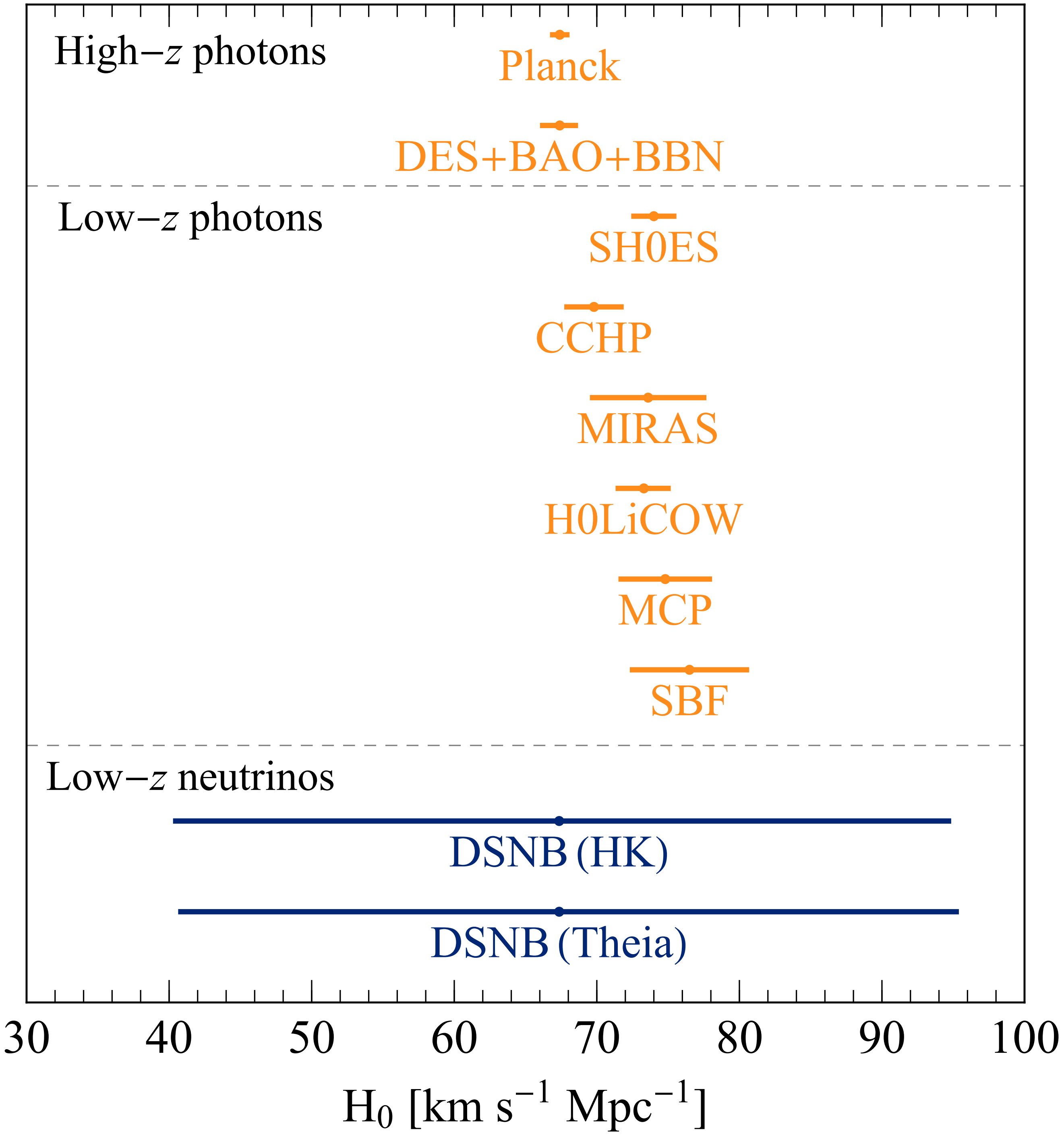


Cosmology…



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

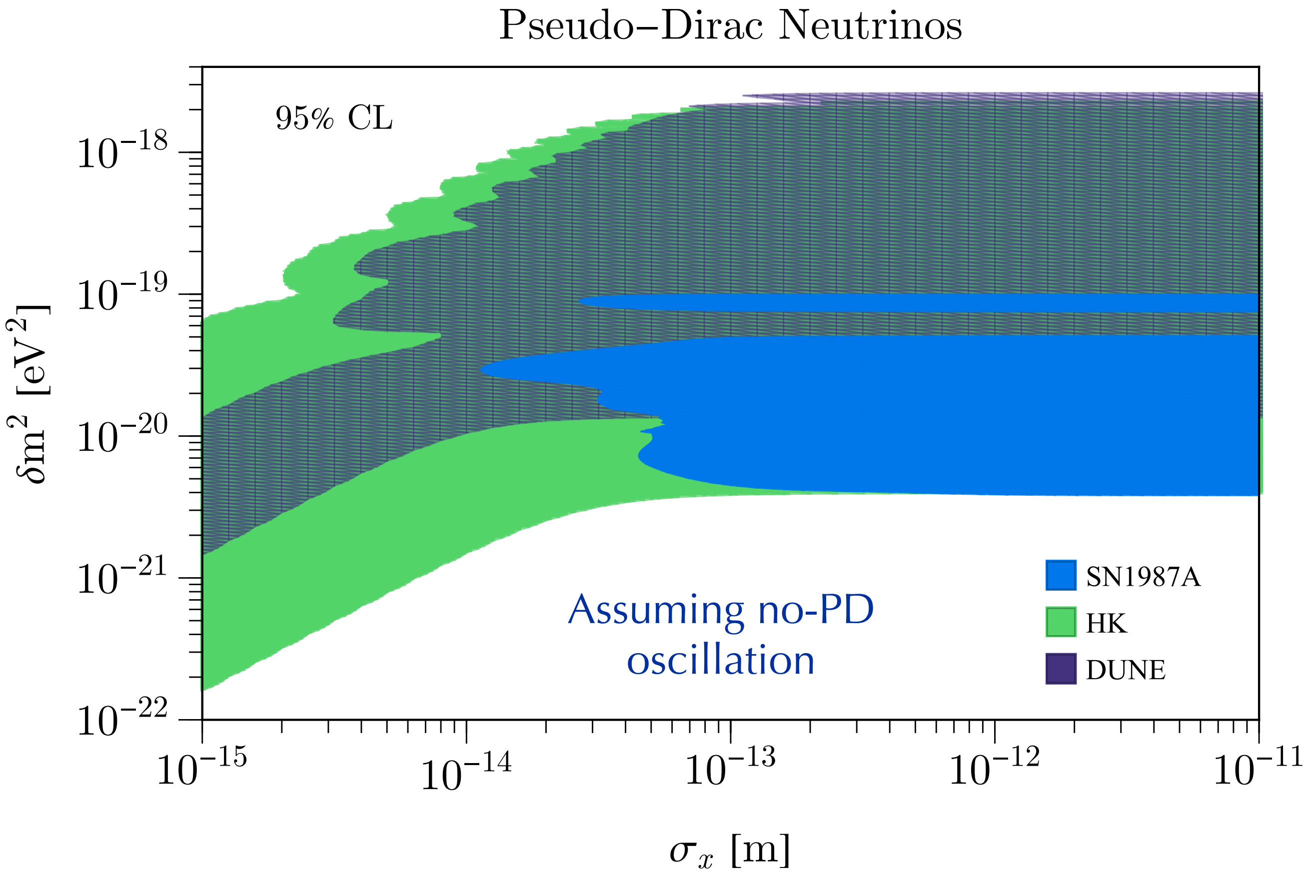
Cosmology…



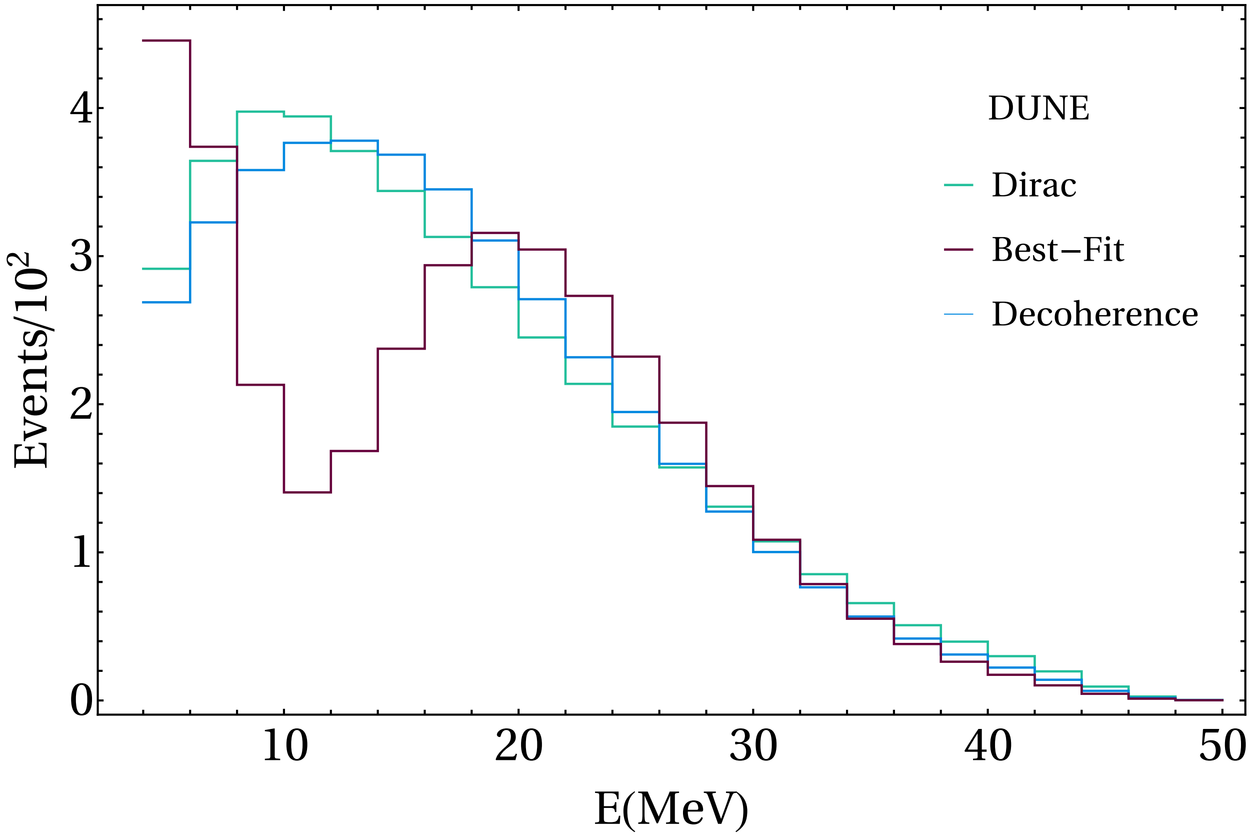
Limited by uncertainties in the SFR

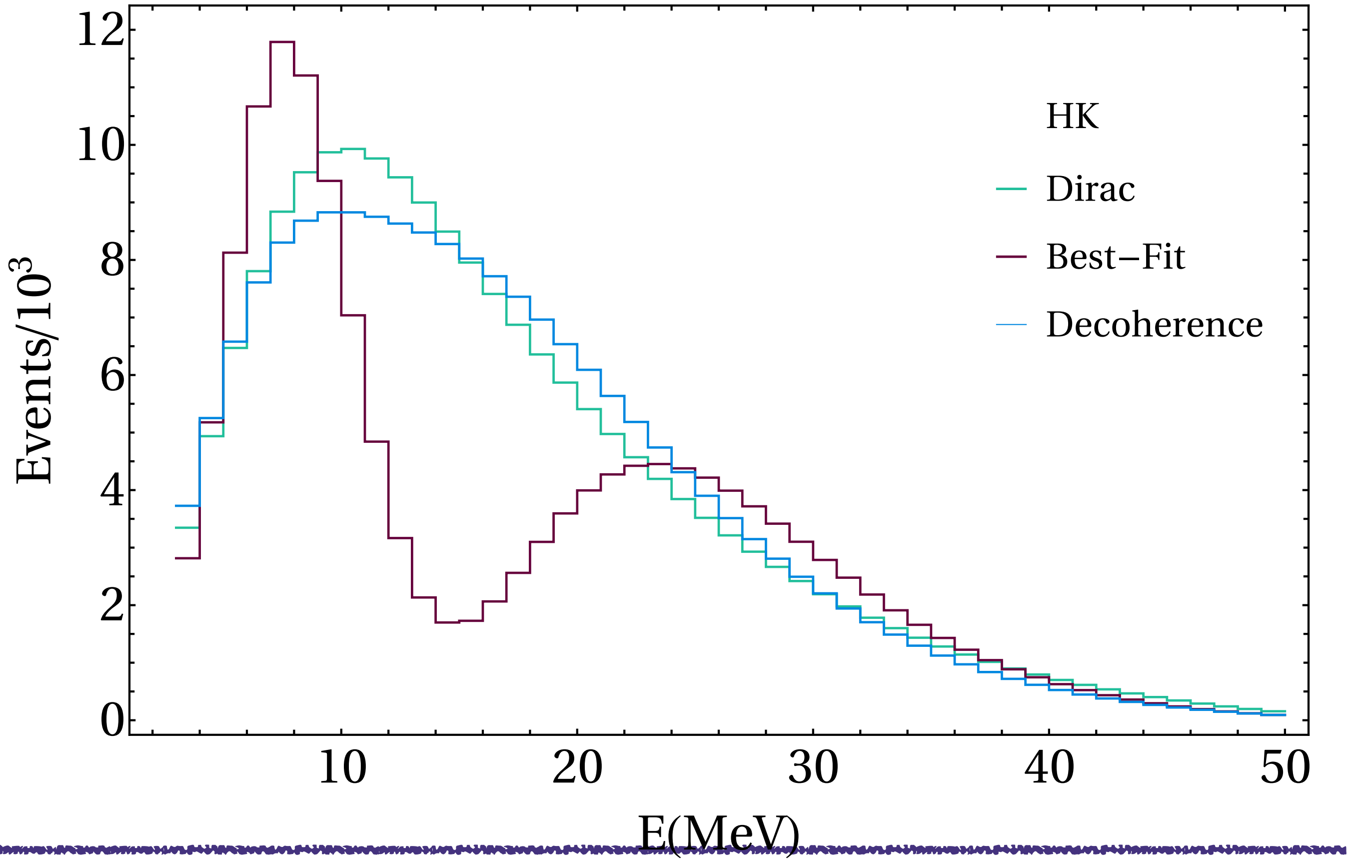
Future SN? Pseudo-Dirac

Do we need to wait (a lifetime) for a galactic SN?



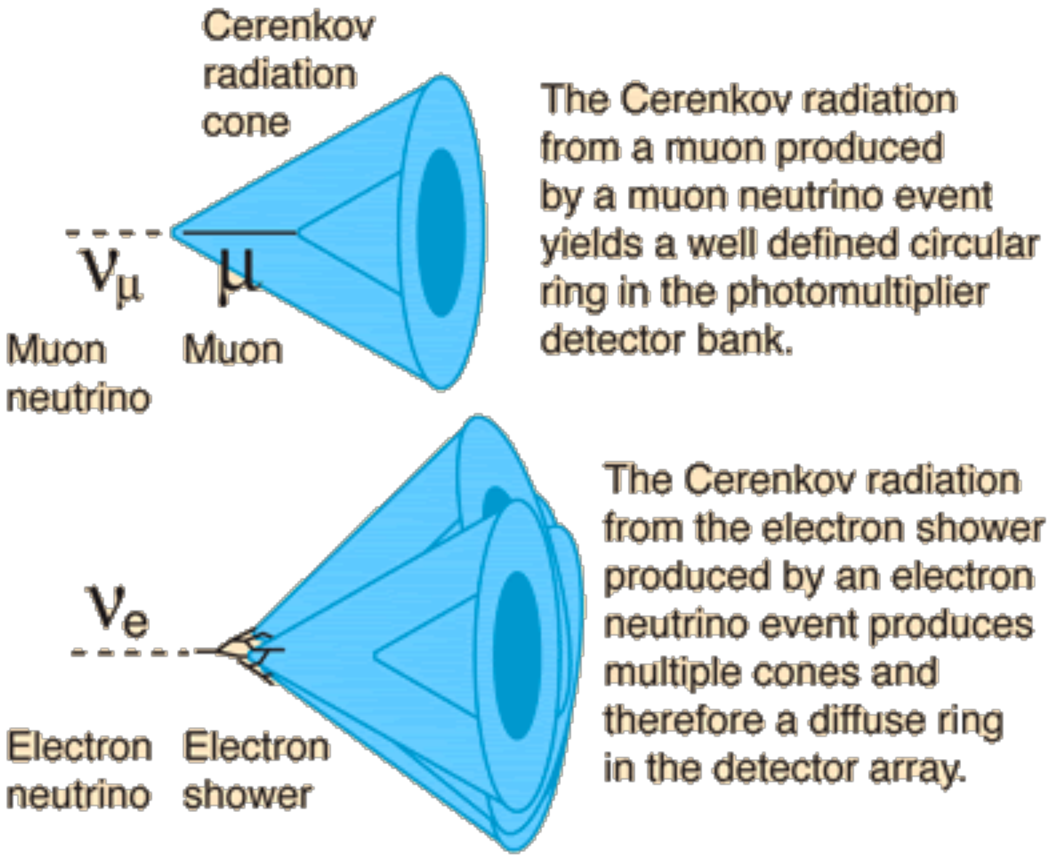
Martinez-Soler, YFPG, Sen
PRD105(2022)095019





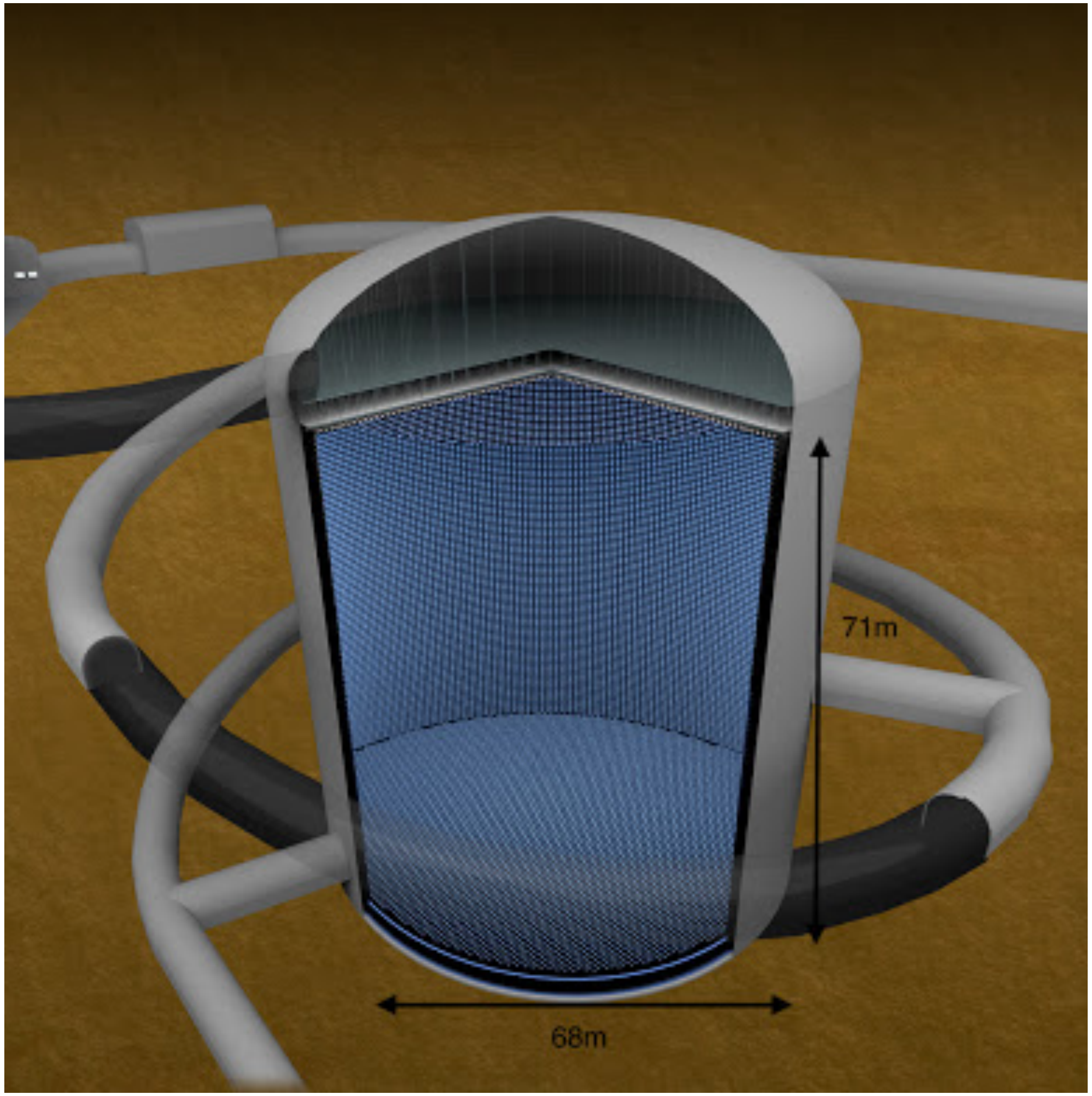
SK, SK-Gd and HK

- 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.

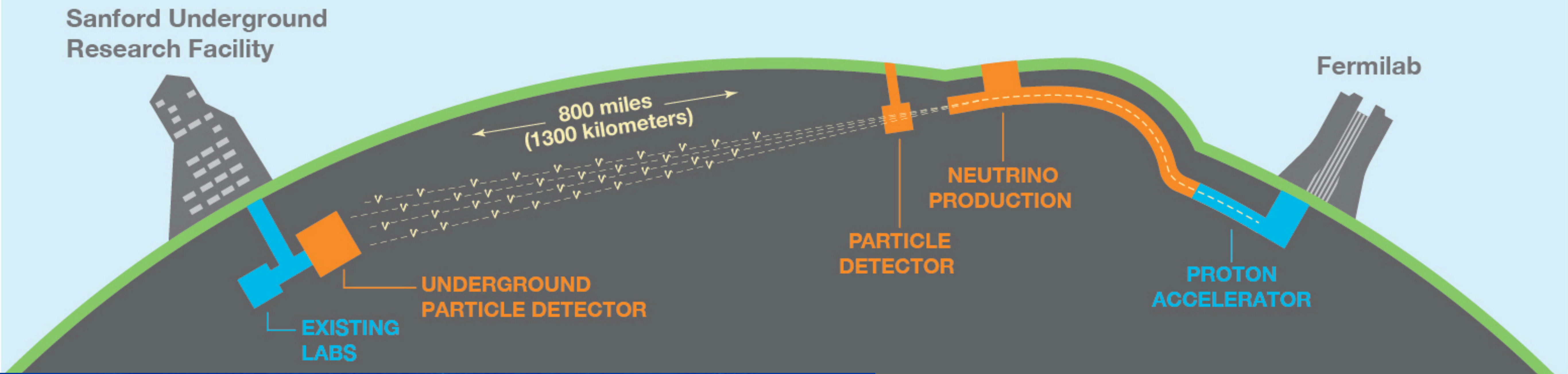
The Cerenkov radiation from the electron shower produced by an electron neutrino event produces multiple cones and therefore a diffuse ring in the detector array.

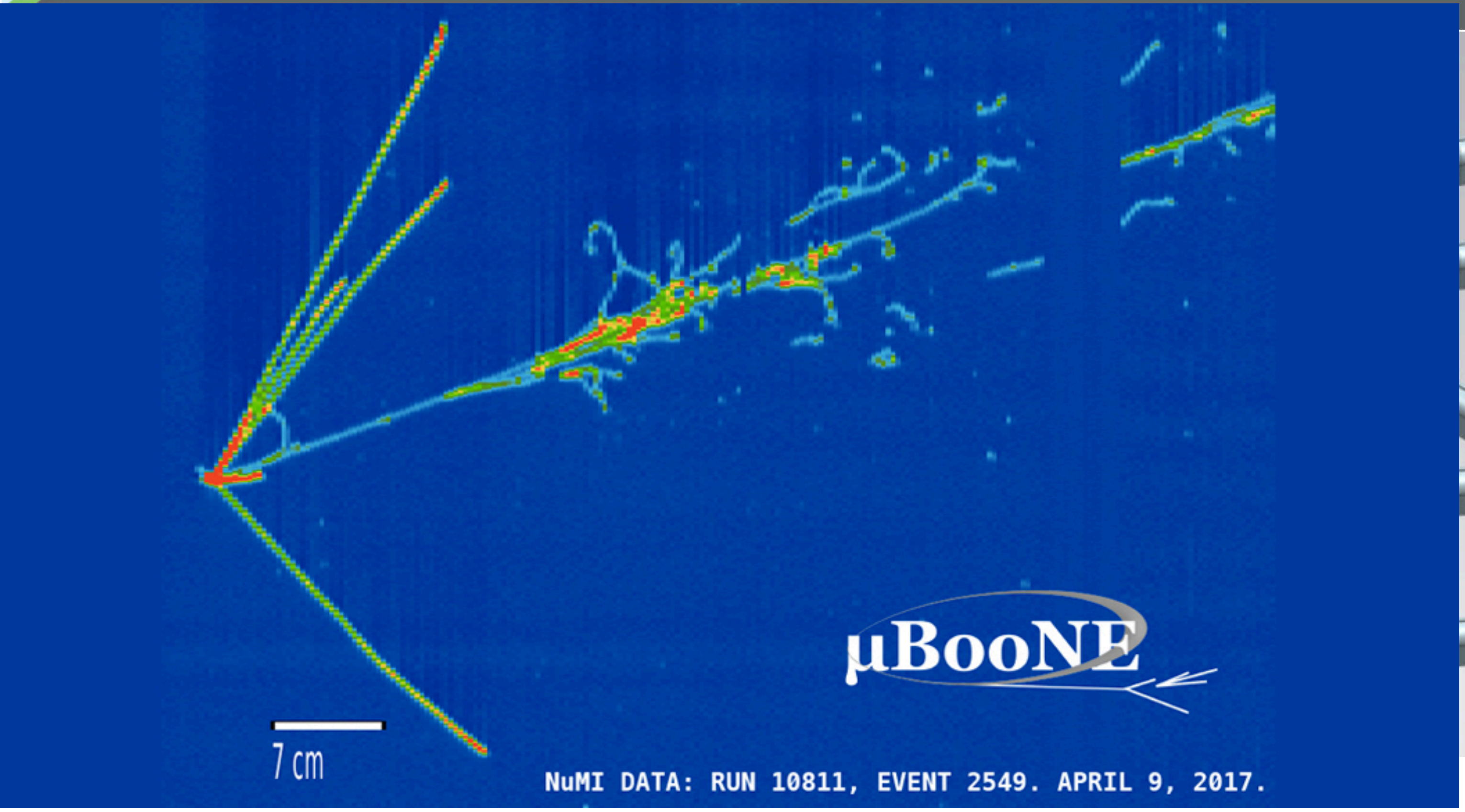


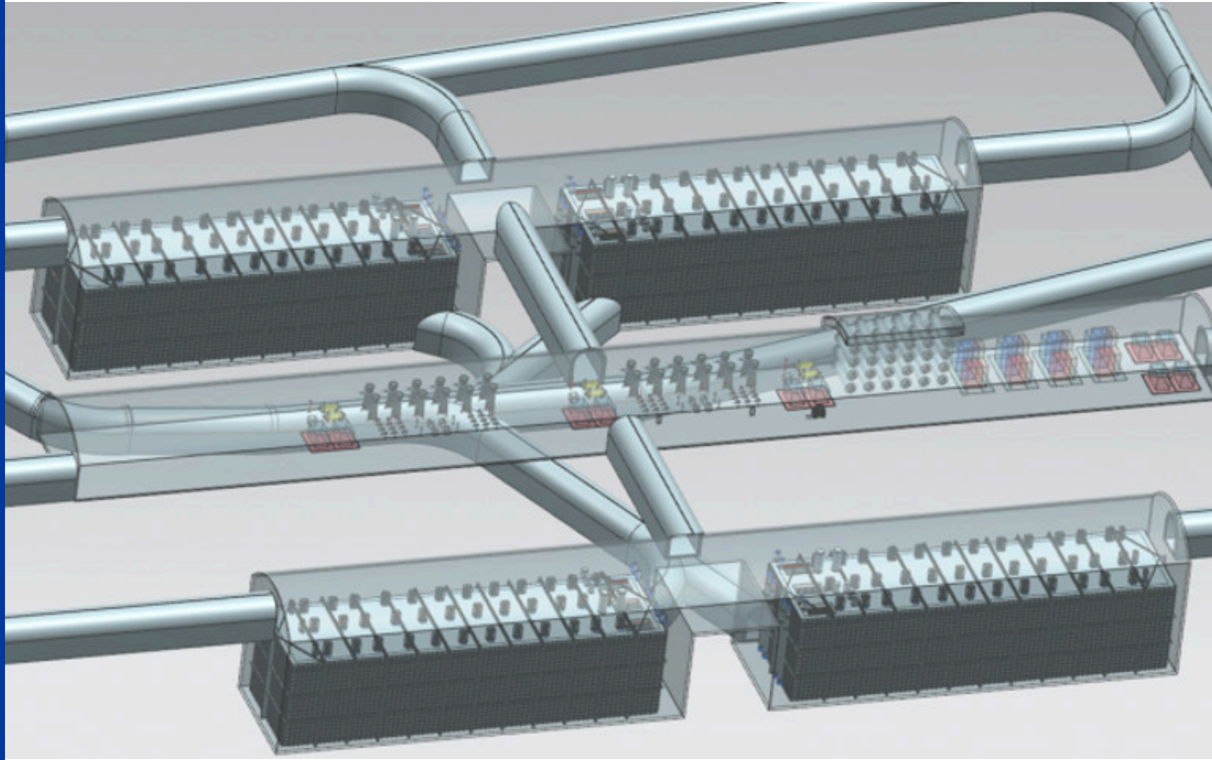
McDonald, Klein, Ward
Scientific American 288(2003)4

DUNE

- DUNE: 40kt and 10 years



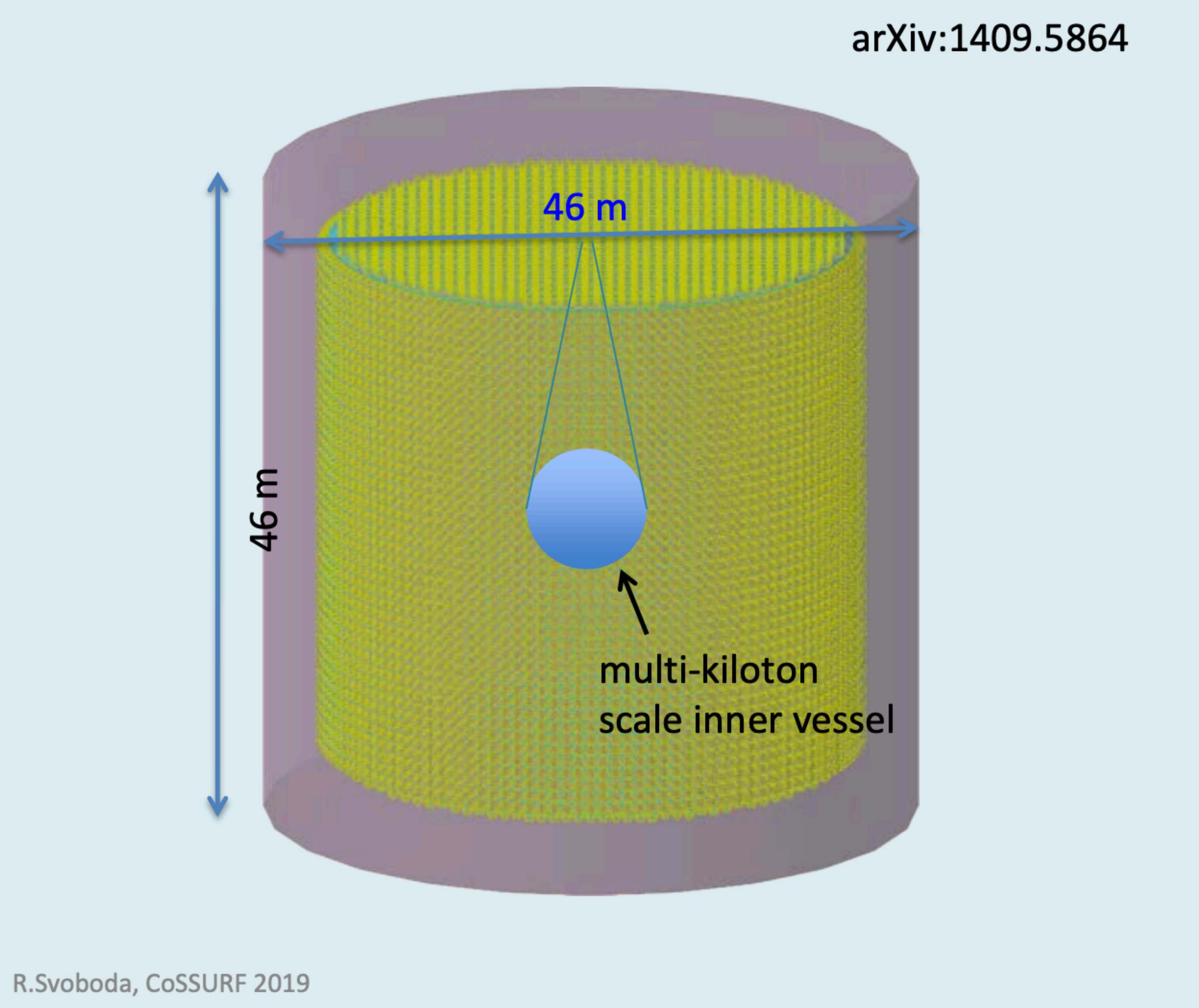




Water-based Liquid Scintillator - THEIA

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