SNvD 2023@LNGS
International conference on Supernova Neutrino Detection
May 29th to June 1st, 2023
Gran Sasso National Laboratory
Assergi, L'Aquila [Italy]

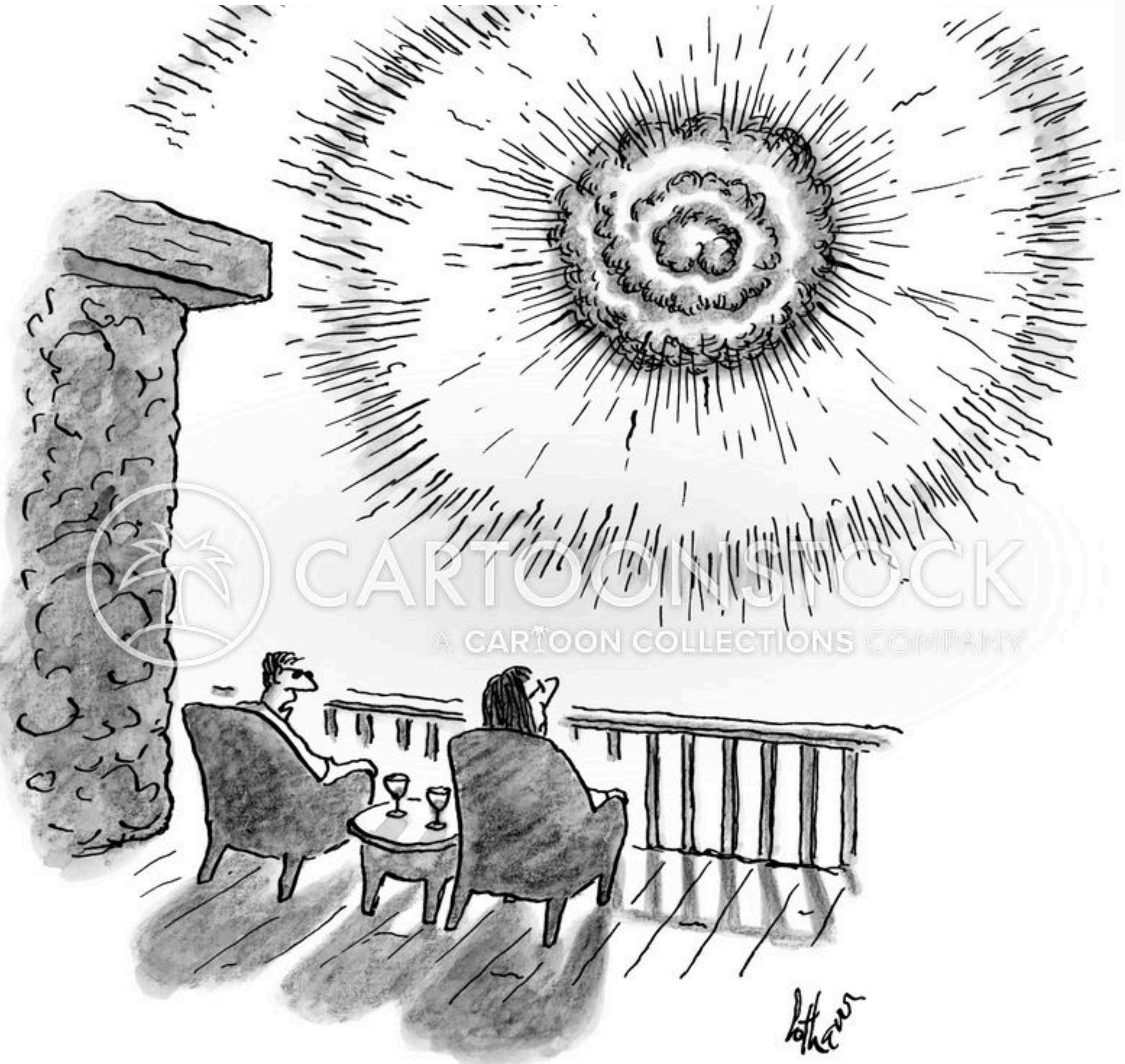

CREDITS: ESA/Hubble & NASA

International conference on Supernova Neutrino Detection

New physics and supernova neutrinos

Manibrata Sen
Max-Planck Institut für Kernphysik, Heidelberg
29/05/23

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

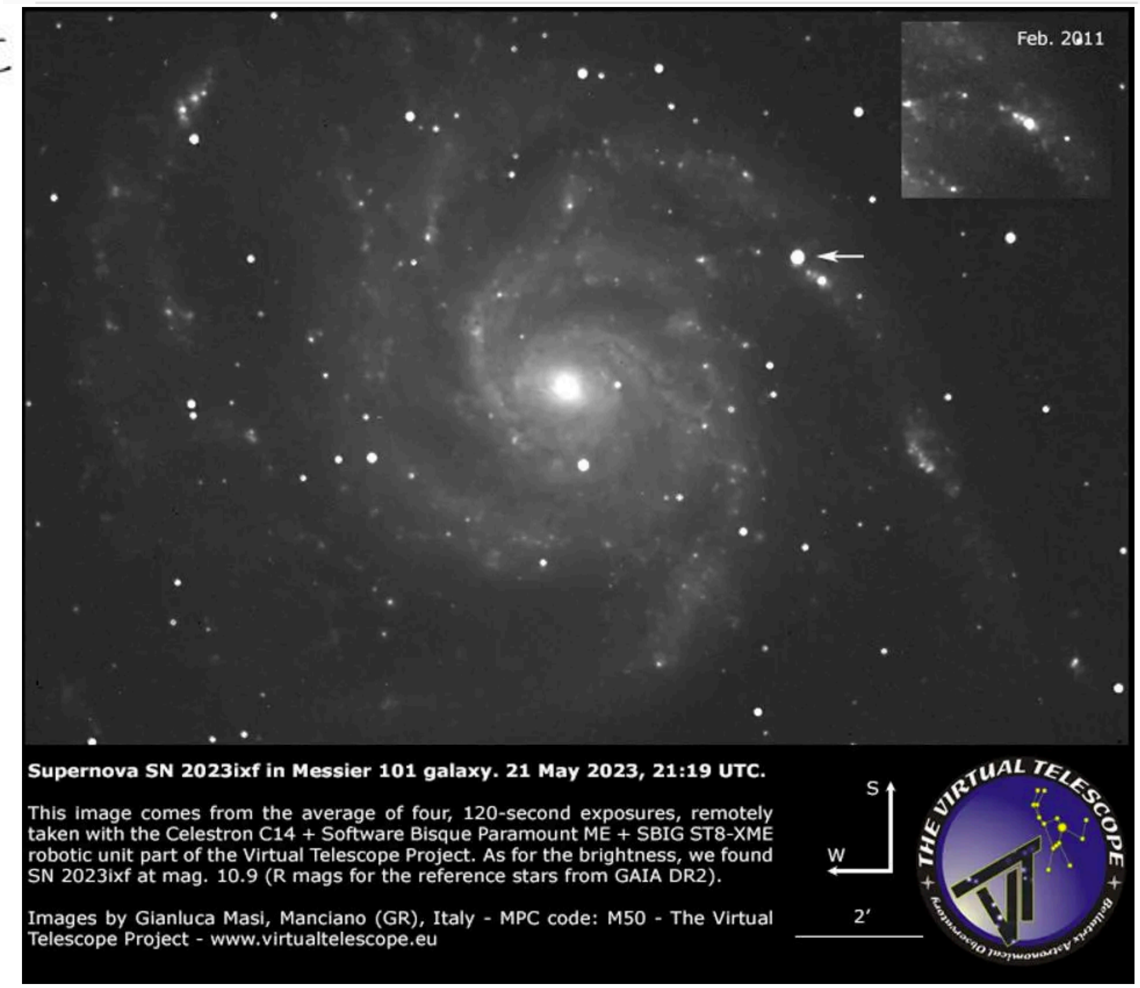


FORBES > INNOVATION > SCIENCE

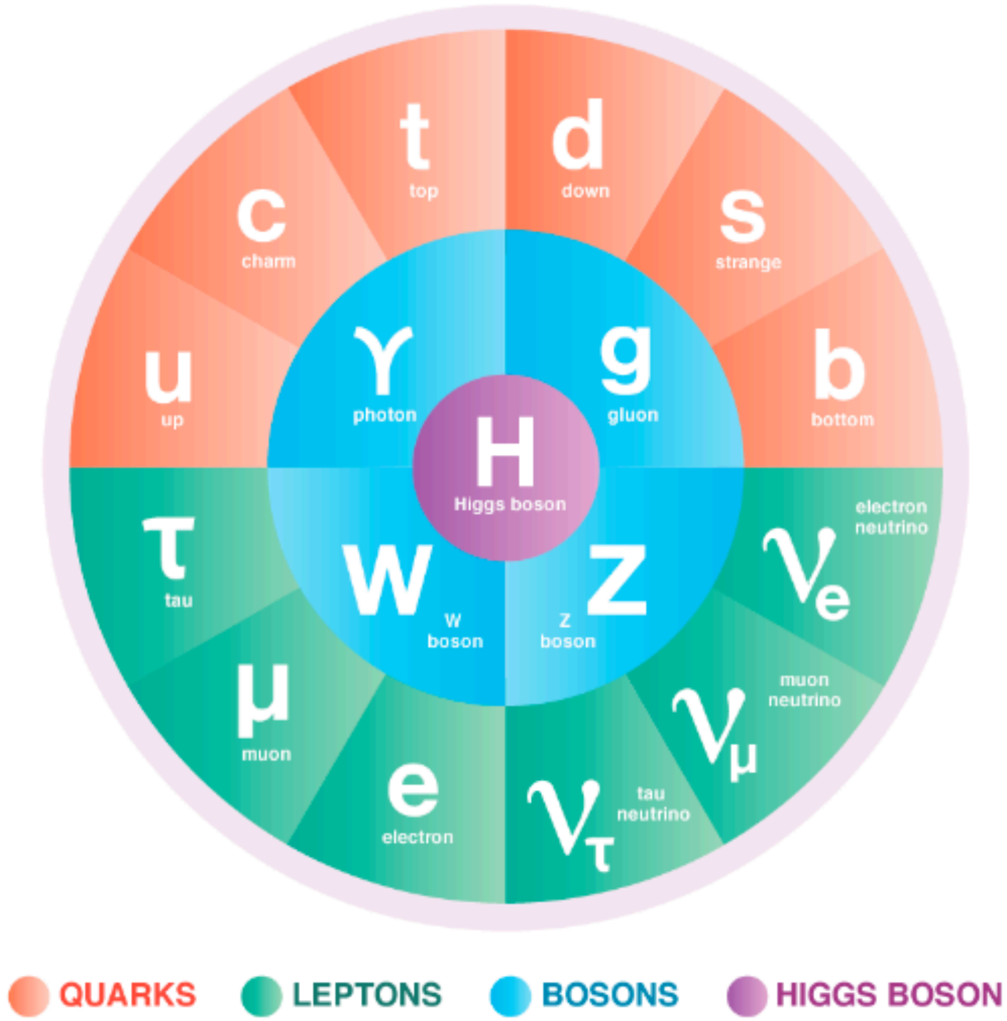
A Very Bright Supernova Just Appeared Near The Big Dipper

Jamie Carter Senior Contributor

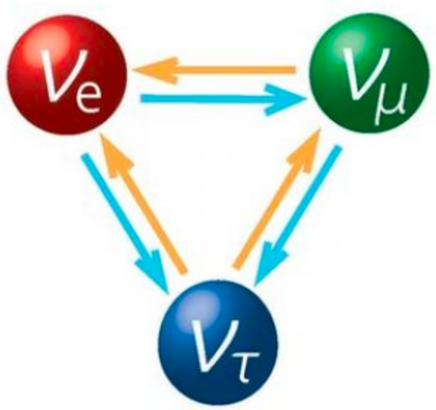
I inspire people to go stargazing, watch the Moon, enjoy the night sky



What is “beyond” the SM (in this talk)?



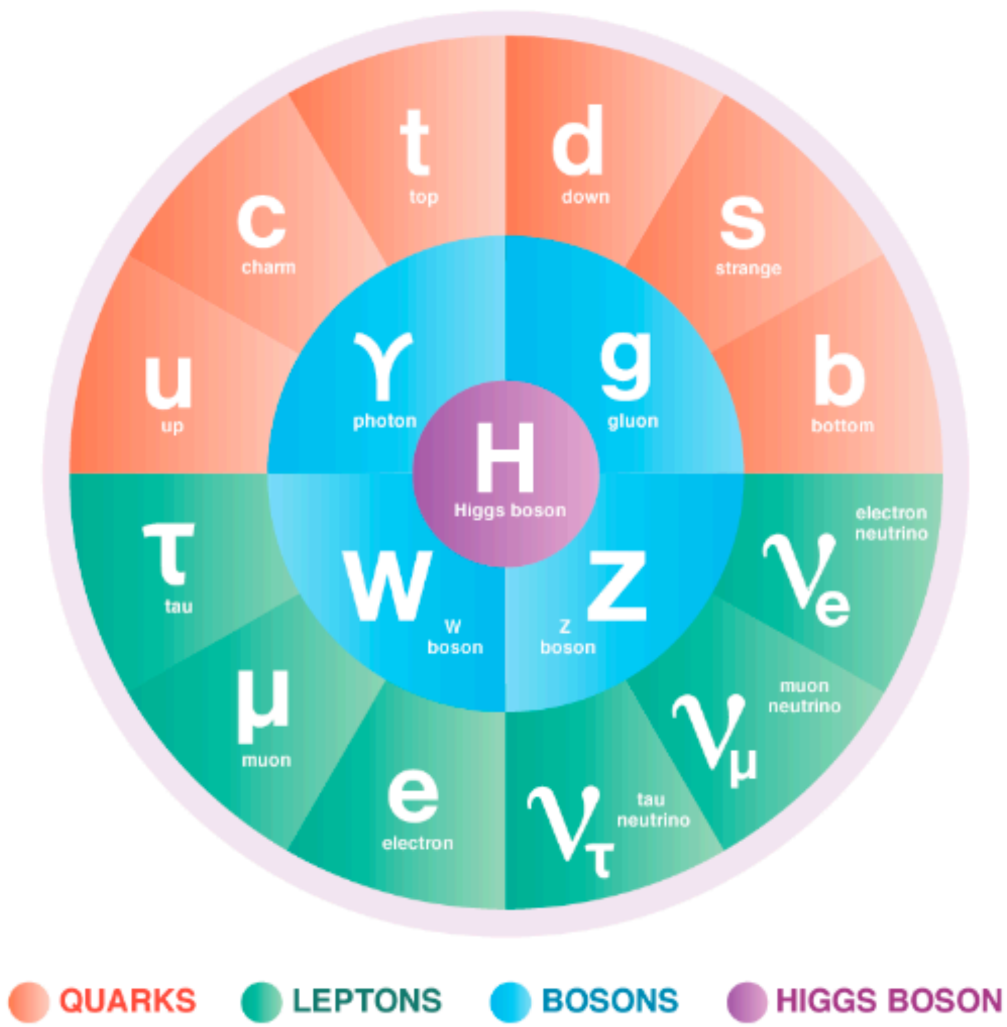
Artwork courtesy of Sandbox Studio, Chicago for Symmetry



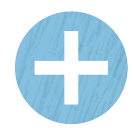
Credit: BBC

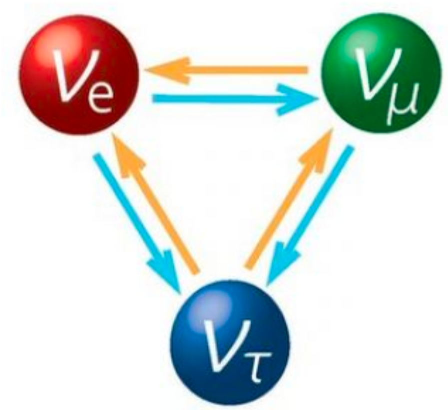
The Standard Model

What is “beyond” the SM (in this talk)?

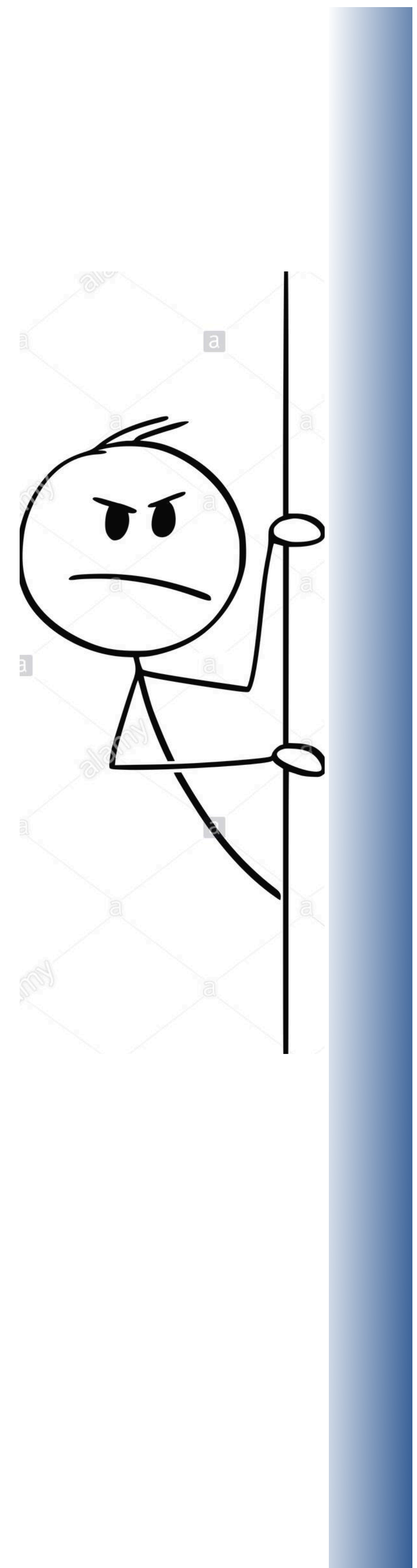


Artwork courtesy of Sandbox Studio, Chicago for Symmetry





Credit: BBC

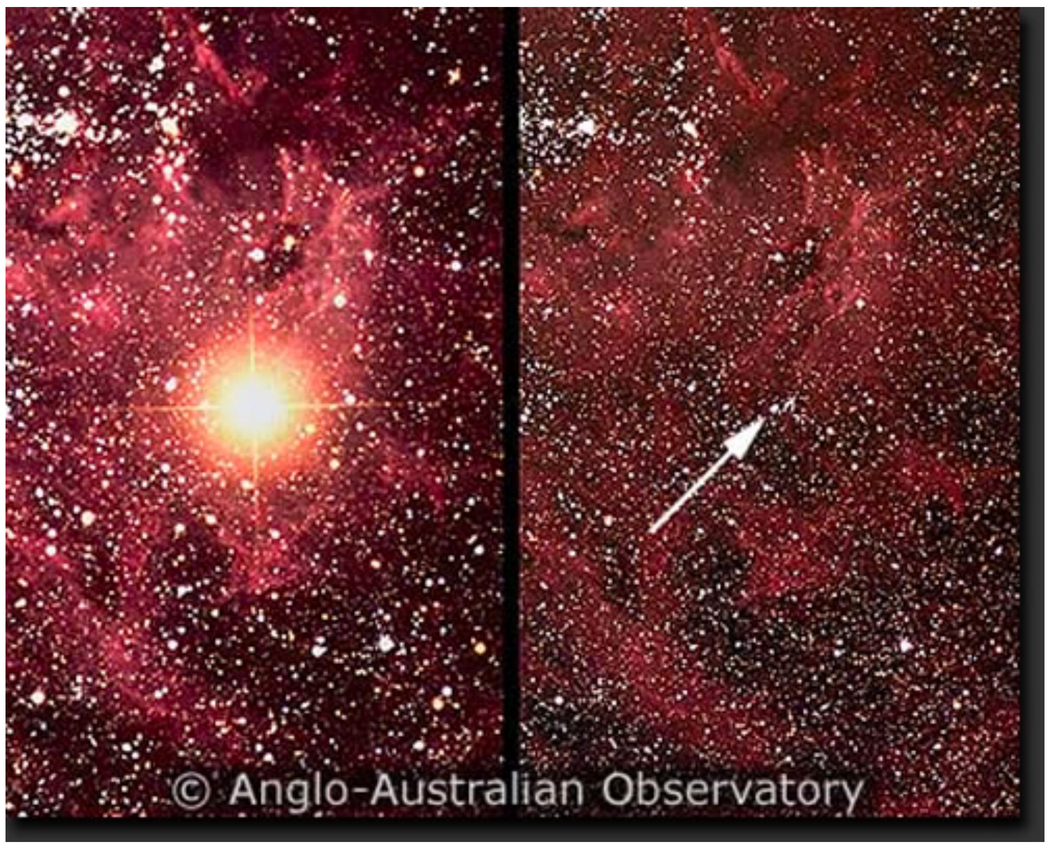


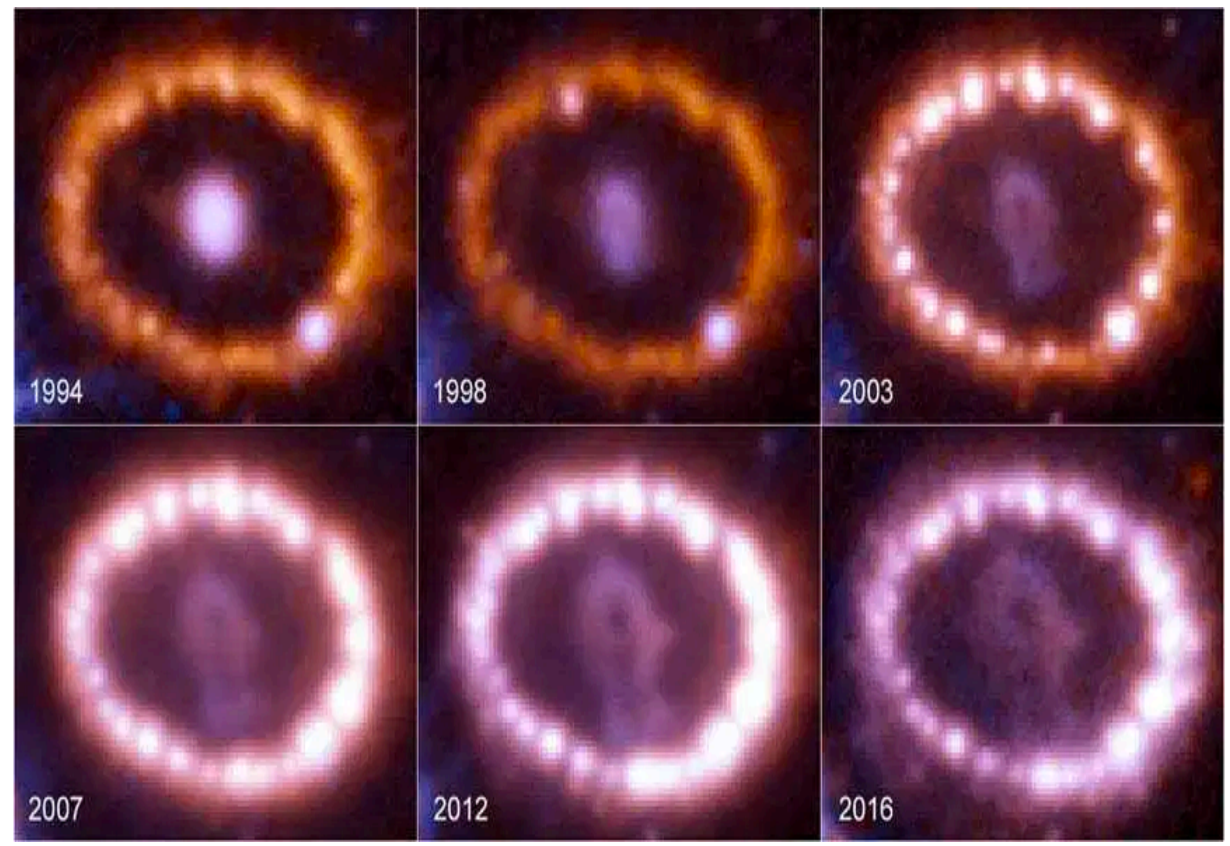
Beyond

The Standard Model

SN1987A: the marvel of the last century

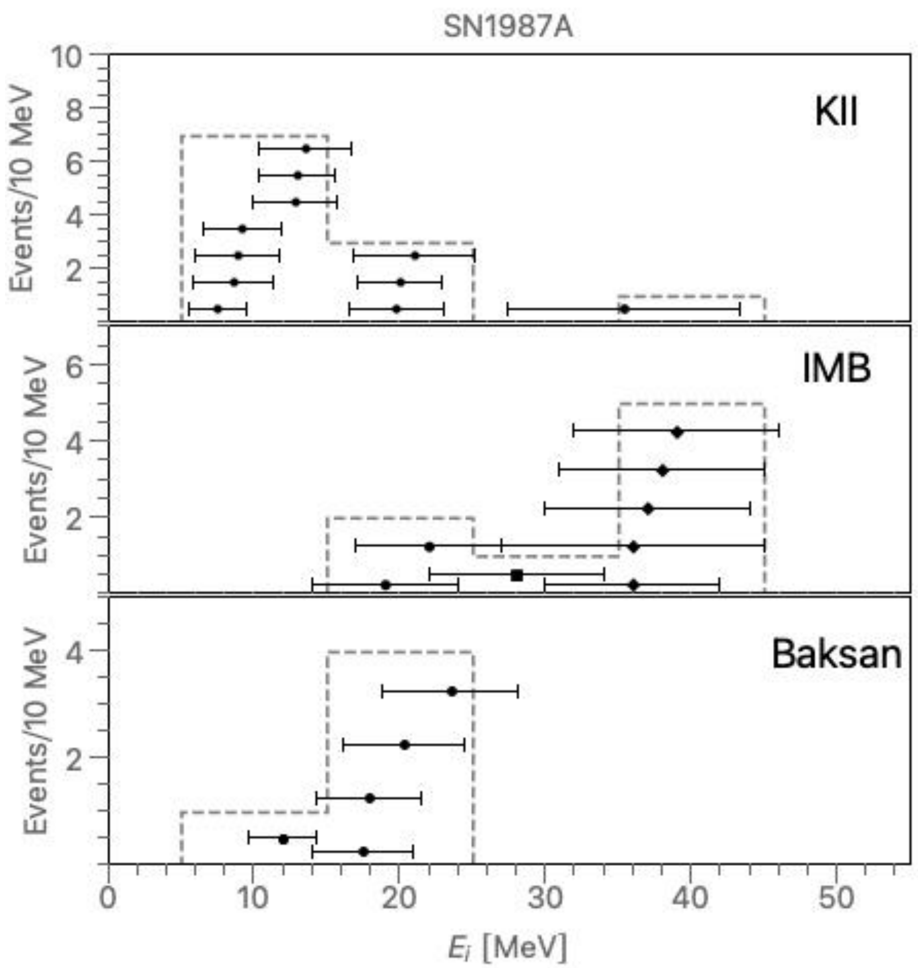
Feb 23, 1987

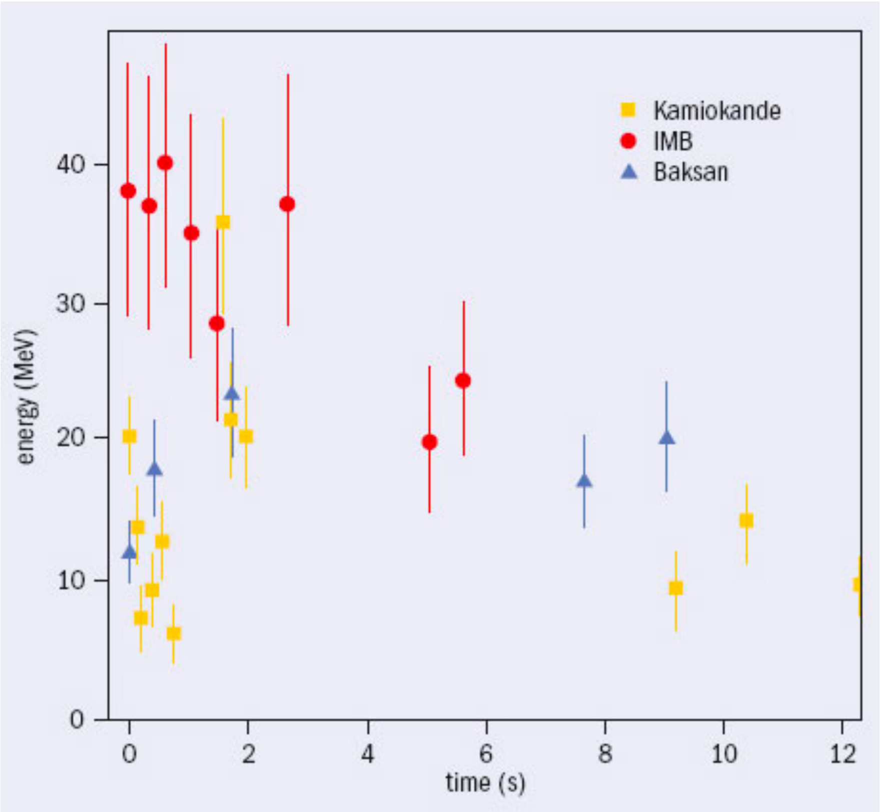




- Took place 168,000 years ago
- In the Large Magellanic Cloud, 50 kpc away. $18M_\odot$ star.

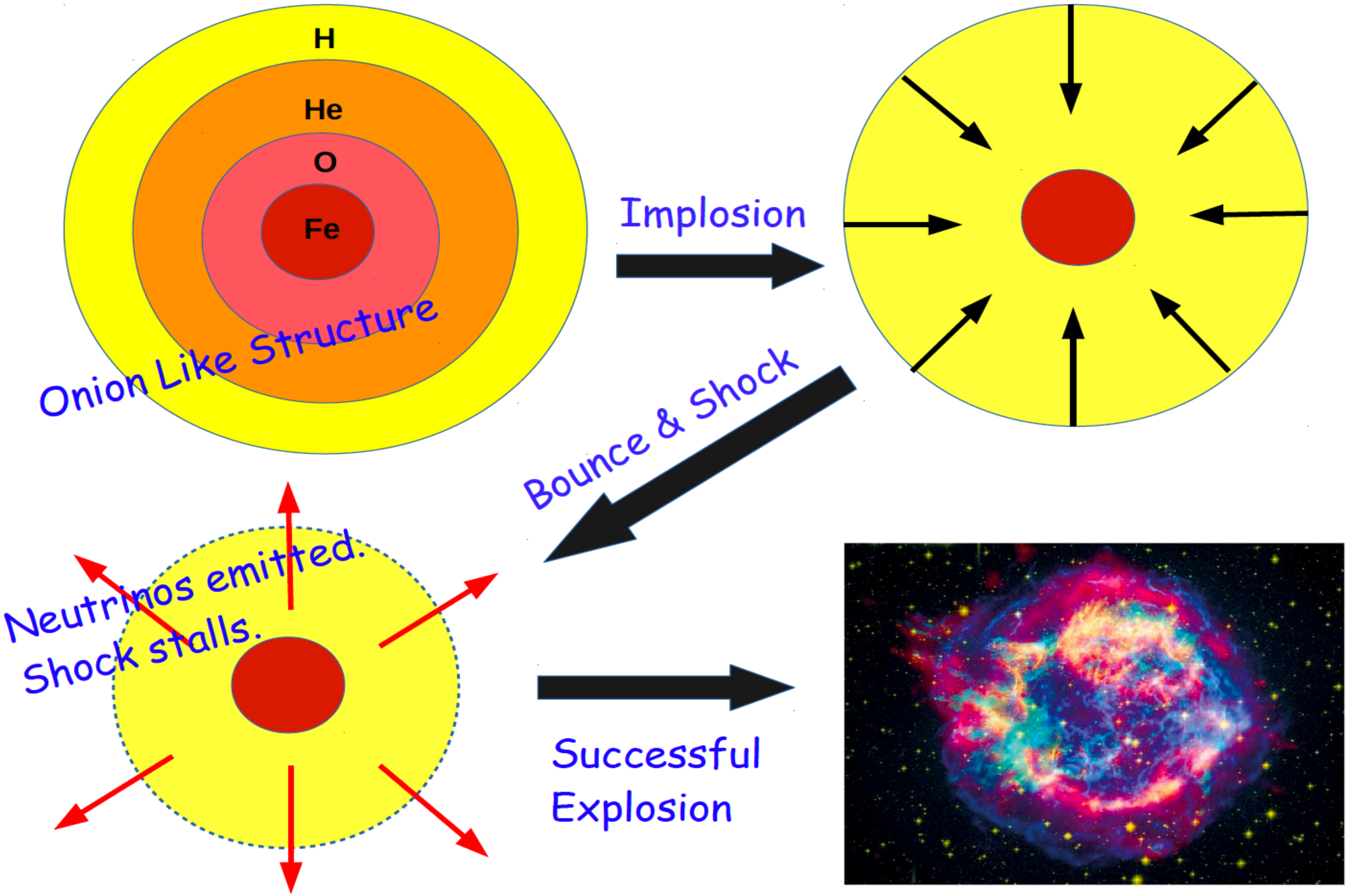
“Many” neutrinos were observed





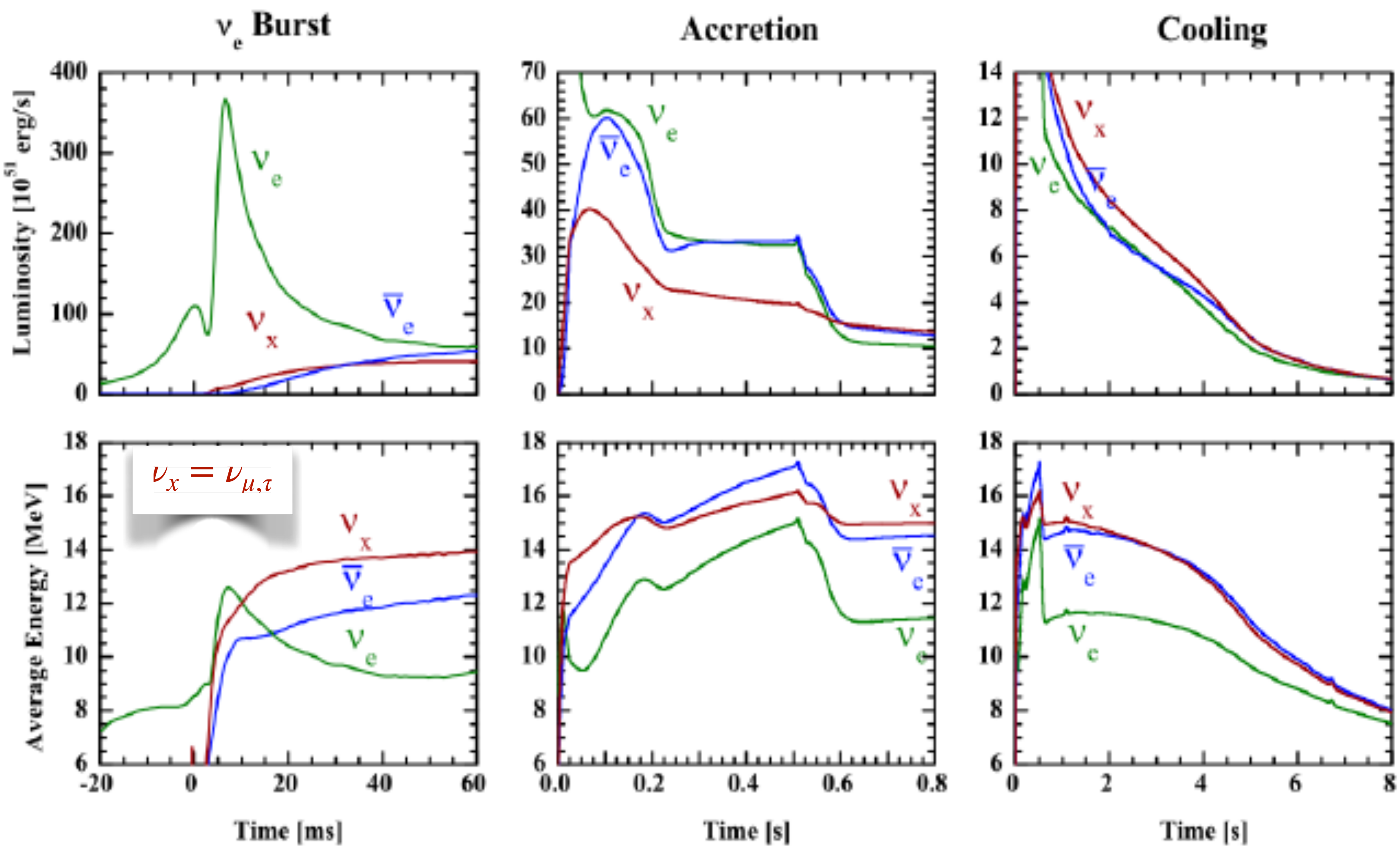
- O(30) events in total.
- One of the first examples of multi-messenger astronomy.
- Neutrinos before photons.
- Not enough statistics, still a coherent picture can be formed!

A supernova engine



Talk by Burrows, Janka for further details

Supernova neutrino luminosity



+
Late time

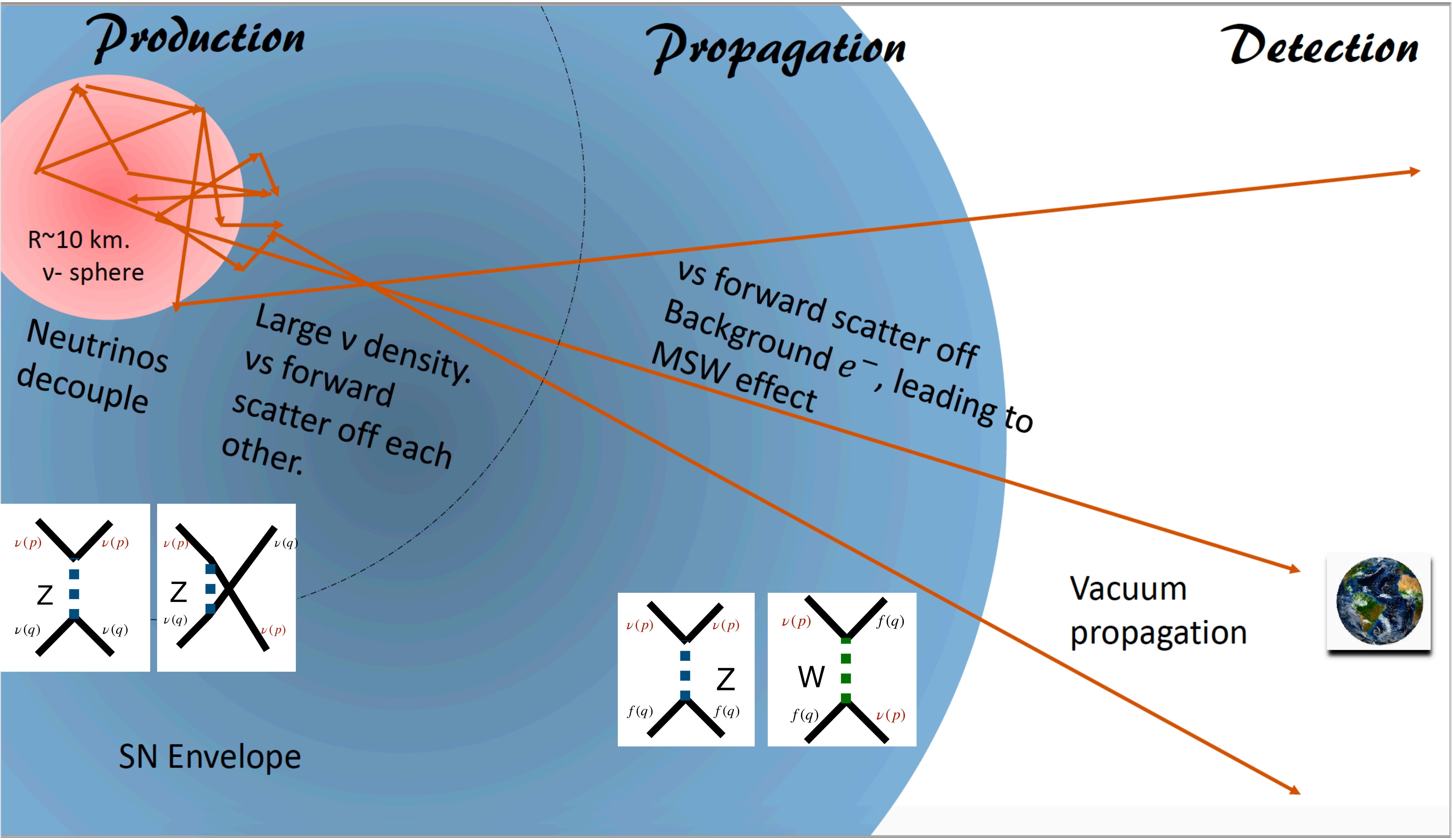
- Mostly ν_e.
- Good laboratory.

- Neutrino self-interactions. Collective oscillations

- Mostly thermal flux

Garching simulations

Neutrino propagation inside a SN



The governing Hamiltonian

- Easier to study the behaviour of the flavour ensemble, through

$$\varrho = \begin{bmatrix} \langle \nu_e | \nu_e \rangle & \langle \nu_e | \nu_x \rangle \\ \langle \nu_x | \nu_e \rangle & \langle \nu_x | \nu_x \rangle \end{bmatrix}$$

- The Eq. of motion $\quad d_t\, \varrho_p(r,p,t) = -i[H_p\,, \varrho_p] + C[\varrho_p]$

$$H_p = \omega_p \quad + \quad \lambda \quad + \quad \mu \int d^3q (1 - \cos\theta_{pq})\, \varrho_q$$

vacuum

$$\frac{\Delta M^2}{2E_p}$$

MSW matter term

$$\lambda = \sqrt{2} G_F\, n_e$$

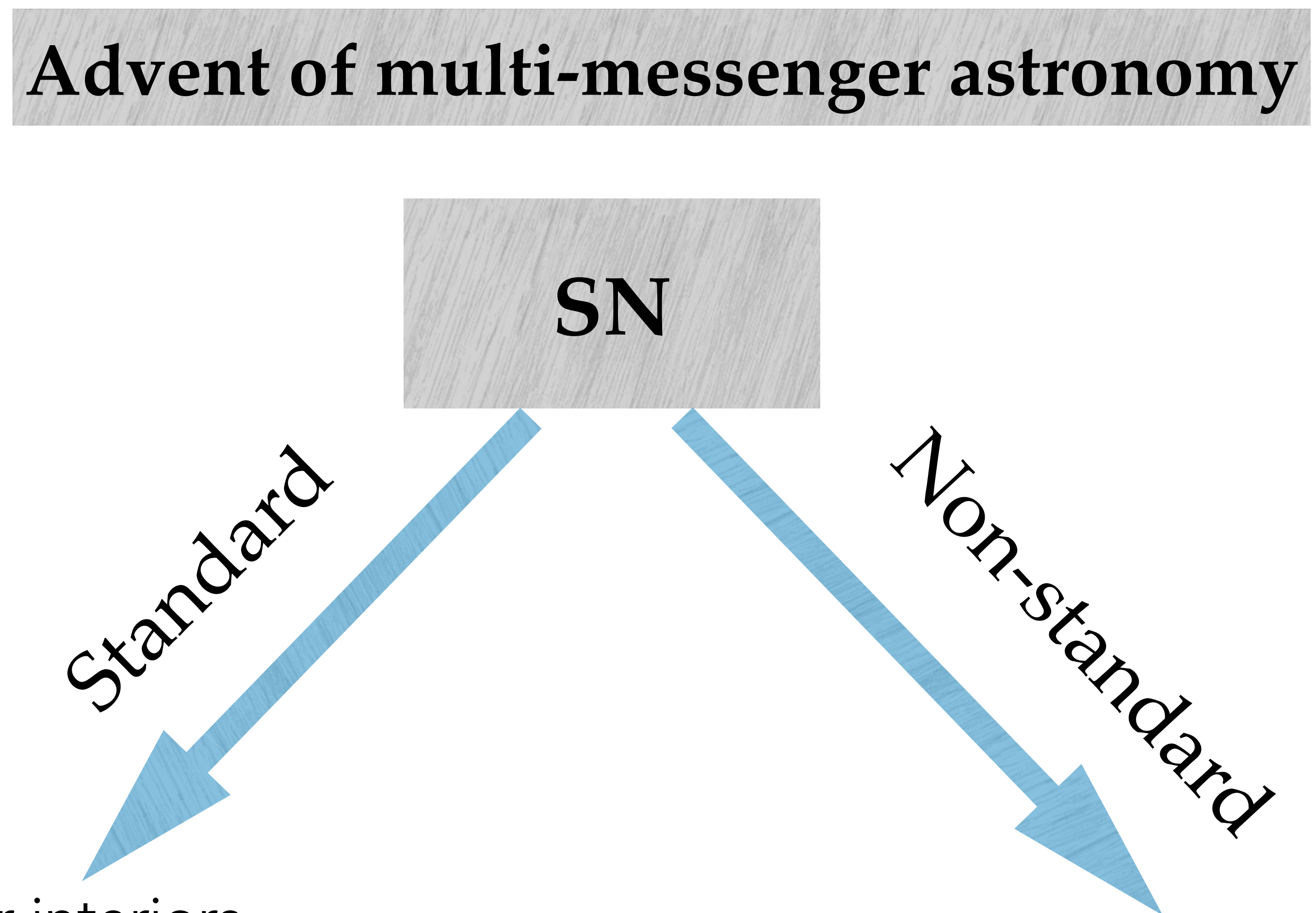
$\nu - \nu$ term

$$\mu = \sqrt{2} G_F\, n_\nu$$

Talk by Kneller for further details

- Collective neutrino oscillations

What sort of a laboratory is the SN?



- νs probe stellar interiors.
- Relevant information about supernova dynamics, shockwave propagation, turbulence.
- Physics of dense neutrino streams. Can lead to "collective oscillations"!

- Non-standard (self)interactions, decay, magnetic moment, millicharge, etc.
- New particles: sterile neutrinos, axions, majorons, etc.
- Any crazy stuff that theorists can think about.

Category of bounds from SN neutrinos

New Physics can

1. Impact on the neutrino luminosity, and average energy, and duration of neutrino burst

2. Impact on the neutrino spectra/ flux

Impact on the neutrino luminosity, and average energy

SN cooling bound

- New modes of energy loss due to weakly coupled particles.
- If $\mathscr{L}_x > \mathscr{L}_\nu \sim 10^{52}\,\mathrm{erg/s}$, then duration of neutrino burst is reduced.
- $g < g_{\min}$: not efficiently produced. $g > g_{\max}$: efficiently trapped and reabsorbed (trapping mechanism needs to be well understood)

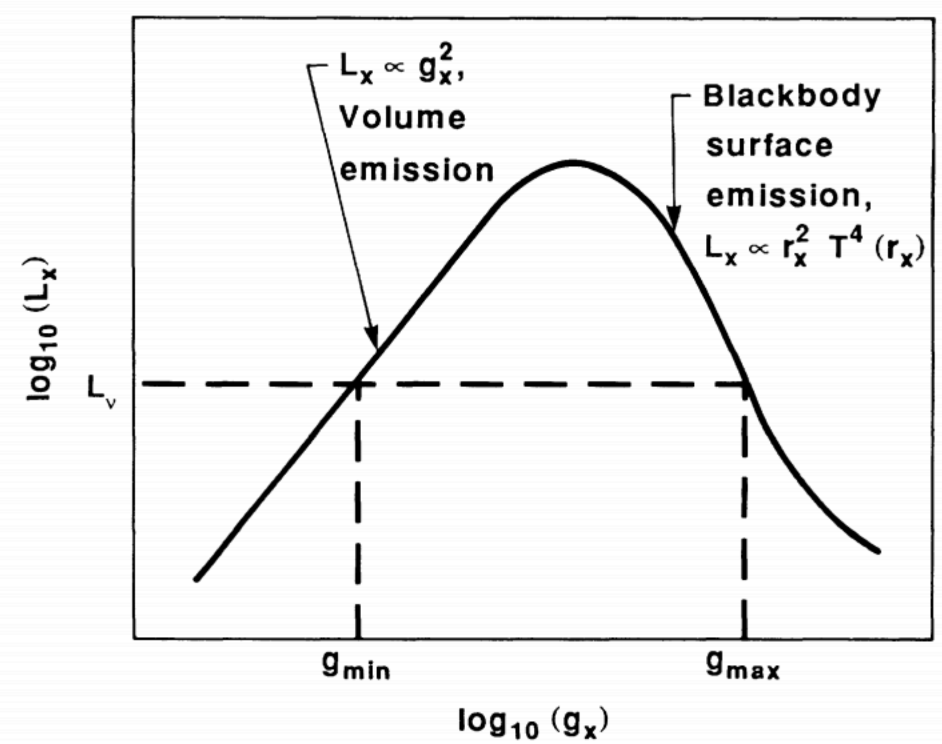


FIG. 1. Schematic dependence of L_x on the coupling strength g_x. The horizontal line denotes the neutrino luminosity L_ν. In the range $g_{\min} < g < g_{\max}$ the LEP emission L_x would exceed L_ν.

Raffelt and Seckel, (PRL 1998)
Raffelt, Stars as laboratories for fundamental physics, UCP (1996)

- Further improvements in treatment recently.

Caputo, Raffelt, Vitagliano (JCAP 2022)

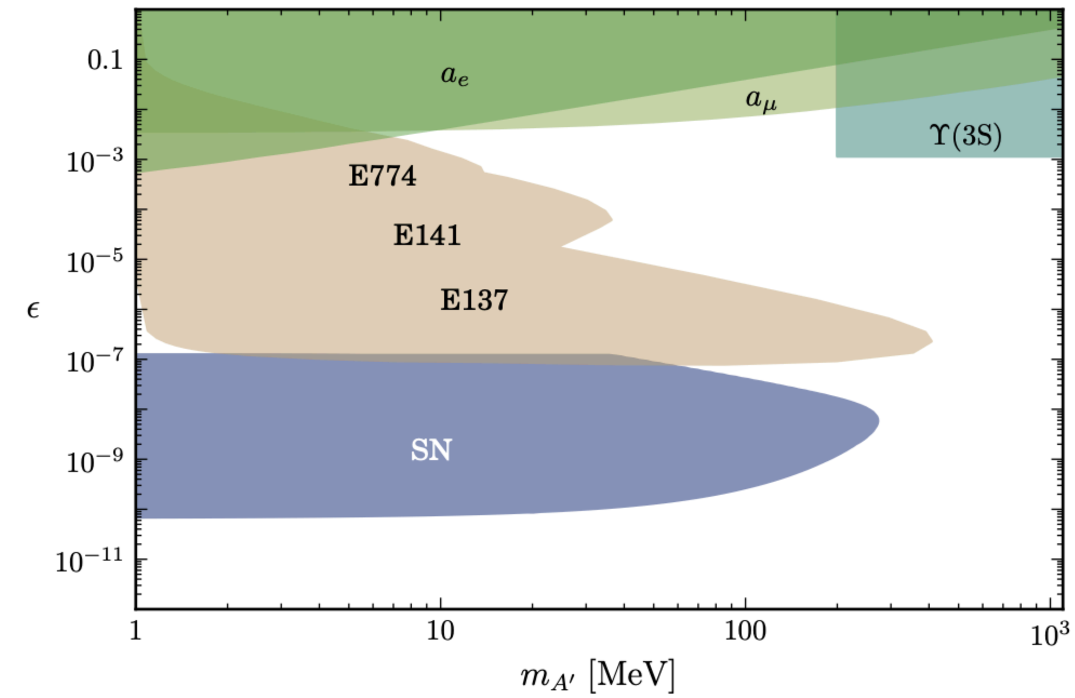
1. The dark photon, and other light friends in SN

Different dark photon models

1. Vanilla Dark photon ~ $\mathscr{L} \supset \frac{1}{4}F'F' + \frac{\epsilon}{2}FF'$

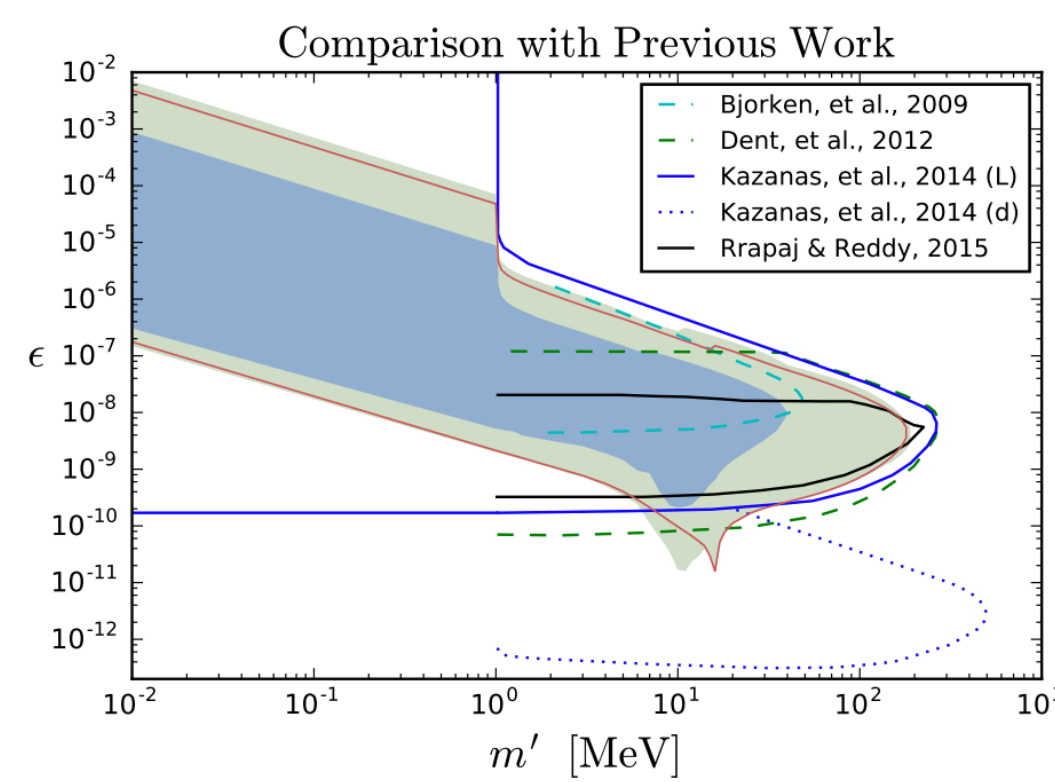
- Consider free-streaming and trapping limit. Main production from $pp \to ppA'$, $np \to npA'$.

Dent, Ferrer, Krauss, arXiv 1201.2683



- Include finite temperature and density effects in A′ production.

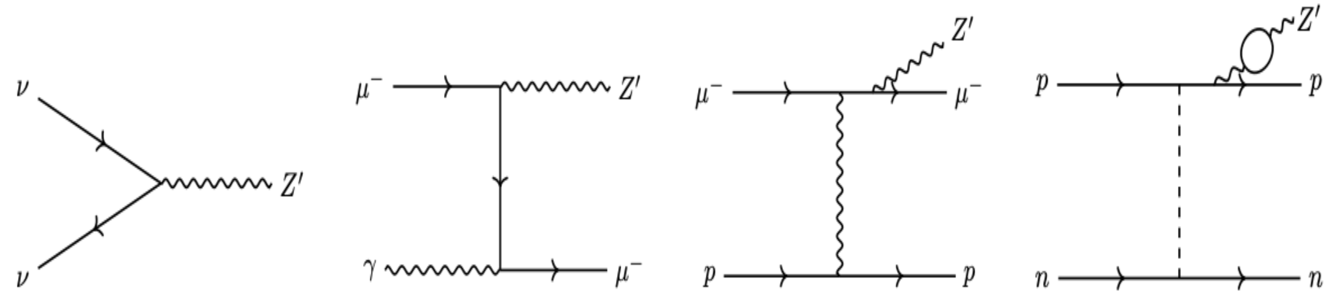
Chang, Essig, McDermott, (JHEP 2017)



- Bounds can be further strengthened by considering decay to e^+e^-, γ, both in the mantle, and near the progenitor surface.

Kazanas, Mohapatra, Nussinov, et al. , (NPB 2015)
DeRocco, Graham, Kasen, et al., (JHEP 2019)

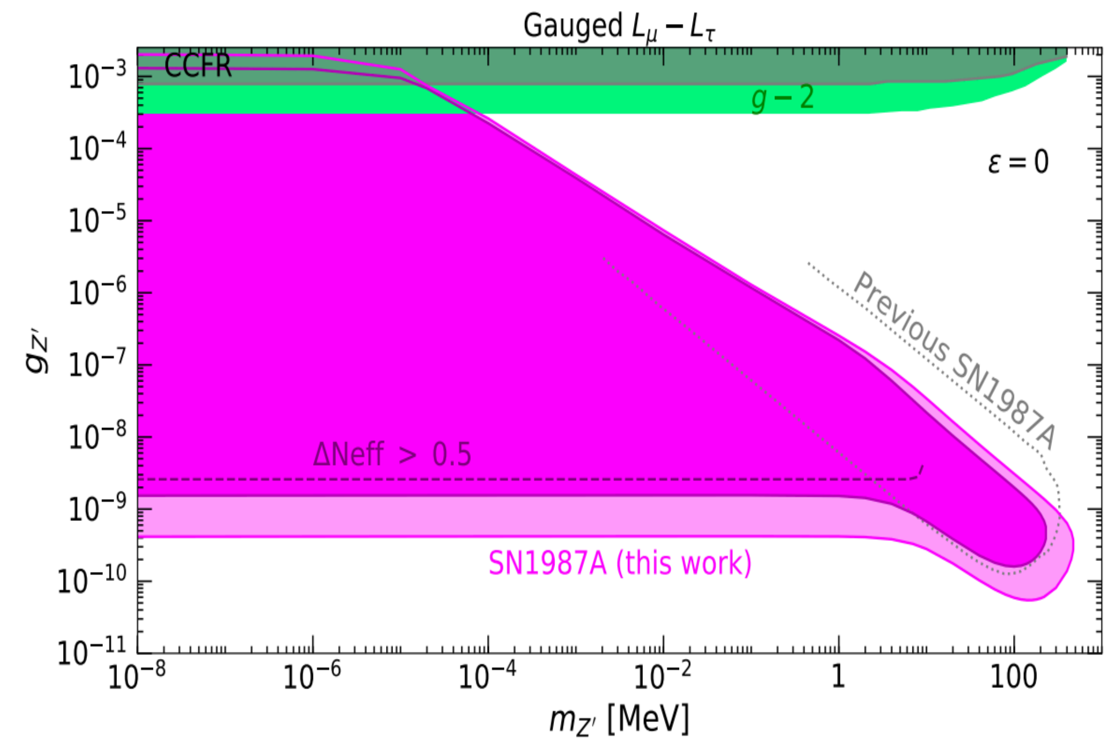
Inclusion of muons from simulations



(a) Pair coalescence (b) Semi-Compton (c) Bremsstrahlung (d) Loop Brem

2. $L_\mu - L_\tau$ gauge boson.

- For lower Z′ masses, semi-Compton process relevant.
- Upper bound fixed by trapping arguments.



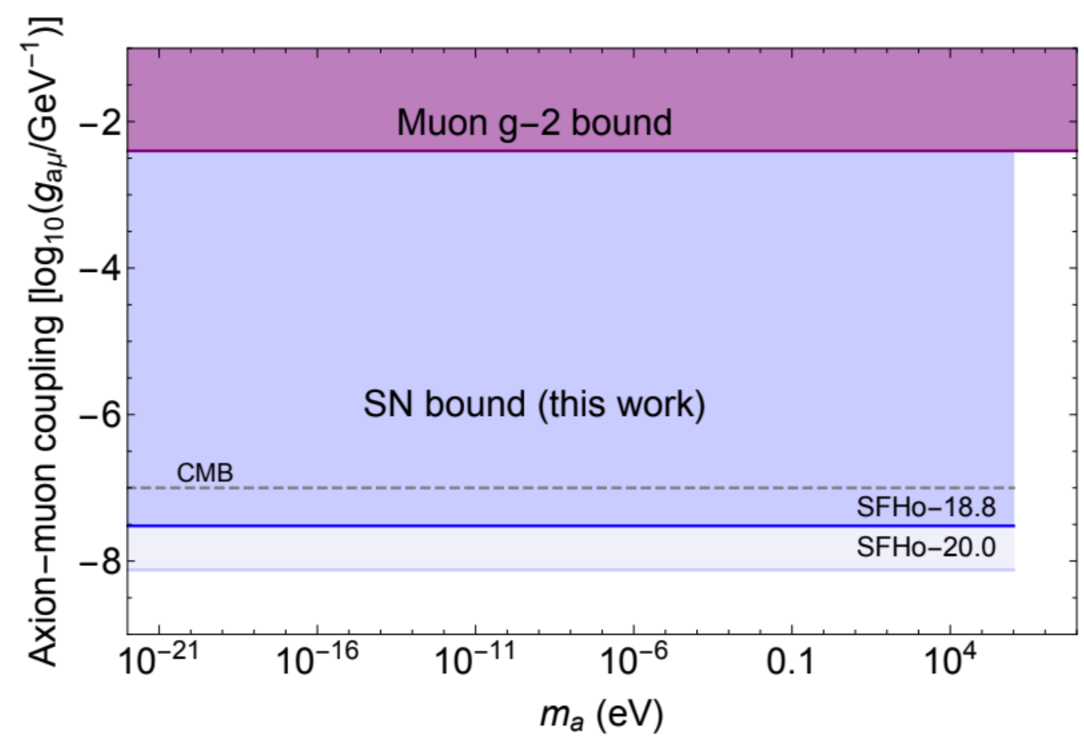
Croon, Ellor, Leane, McDermott, (JHEP 2021)

3. Axion-muon coupling gauge boson.

- Probe of axion physics

$\mu\gamma \to \mu a$

$\mu p \to \mu p a$



Bollig, Rocco, Graham, Janka (PRL 2021)

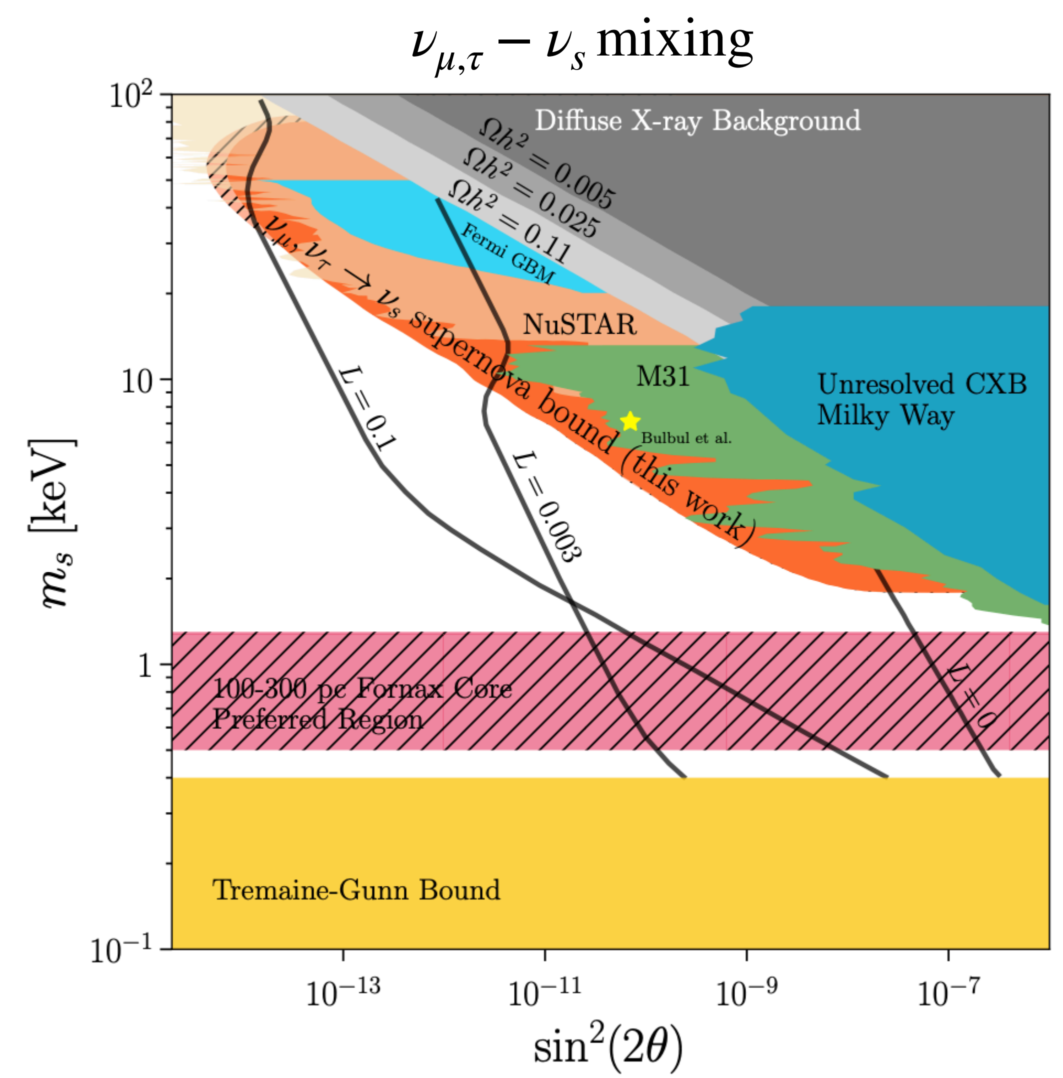
2. Sterile neutrinos in SN

Sterile neutrinos in supernova

- Sterile neutrino production in SN, through
  (i) adiabatic MSW conversion at radii 10-15 km inside neutrinosphere.

  (ii) collisional production due to $\nu_{\mu,\tau} - n$ scattering.

- Interplay of two main parameters: width of the resonance region and the oscillation length, and m.f.p.



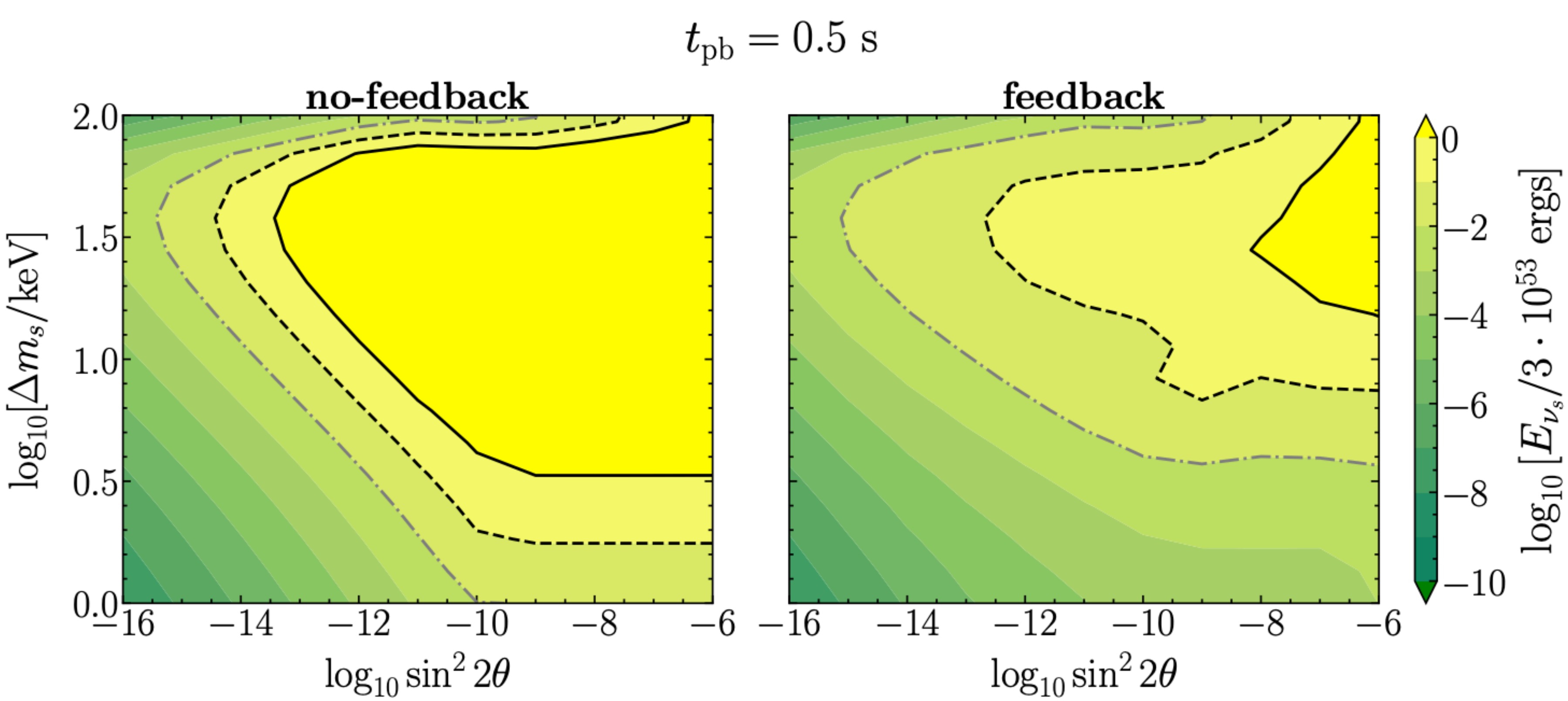
Arguelles, Brdar, Kopp, (PRD 2019)

But…feedback is important

- ν_s is produced from ν_a. This affects the $V_{\rm eff}$, which again affects flavor conversions: feedback.

- Neglecting feedback drastically over-estimates the ν_a lepton number.

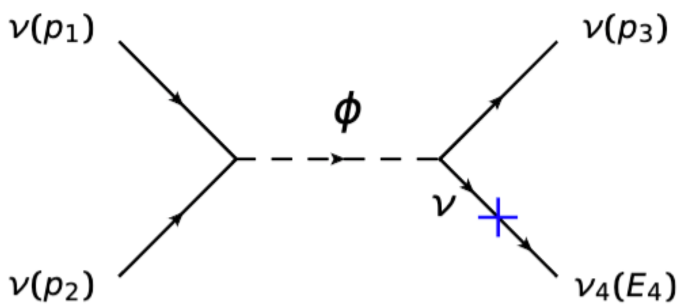
- Including feedback in multi-zone models relaxes SN bounds.

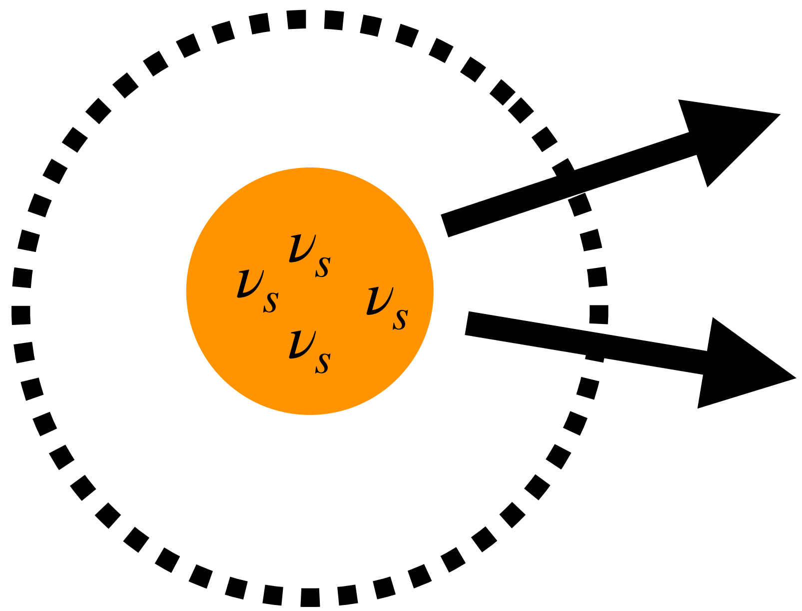


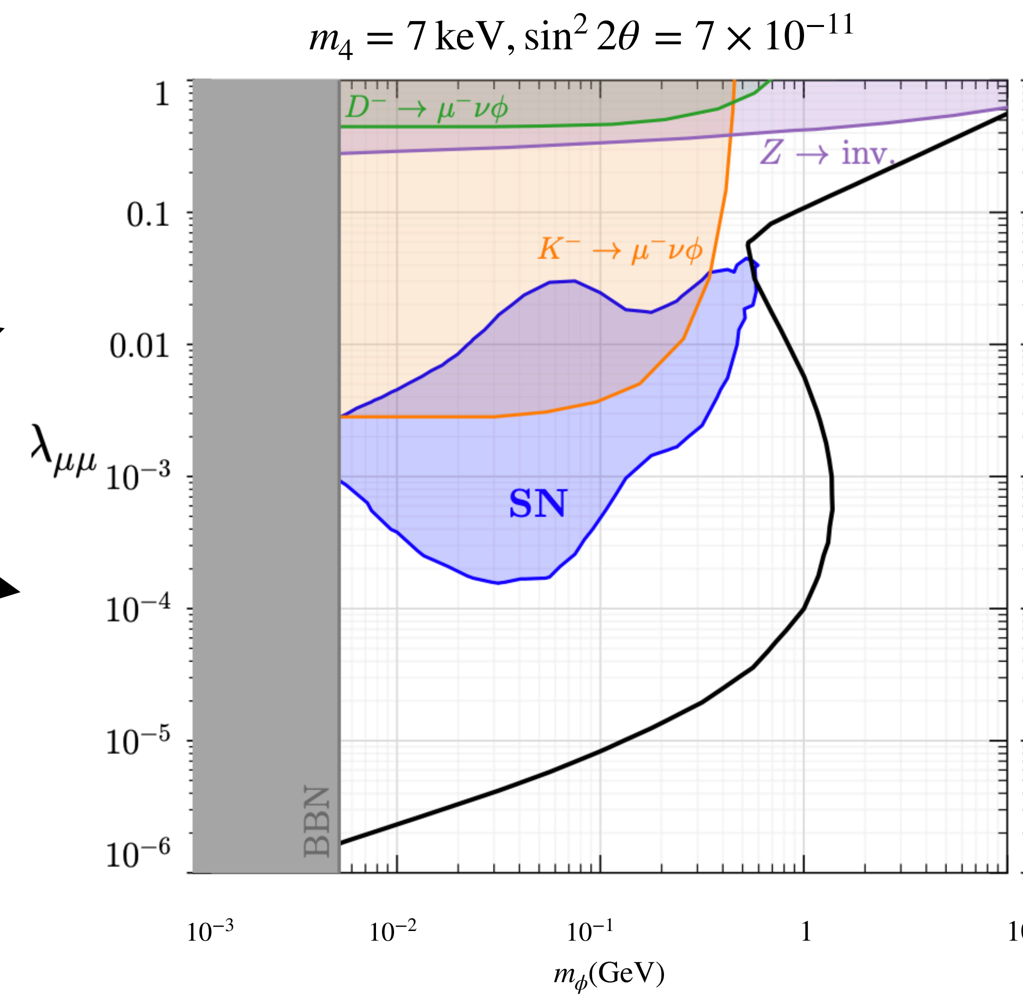
Tamborra, Wu, Suliga, (JCAP 2019)

See also Raffelt and Zhou (PRD 2011), for an earlier discussion of feedback in one-zone models.

ν_s DM from neutrino self-interactions







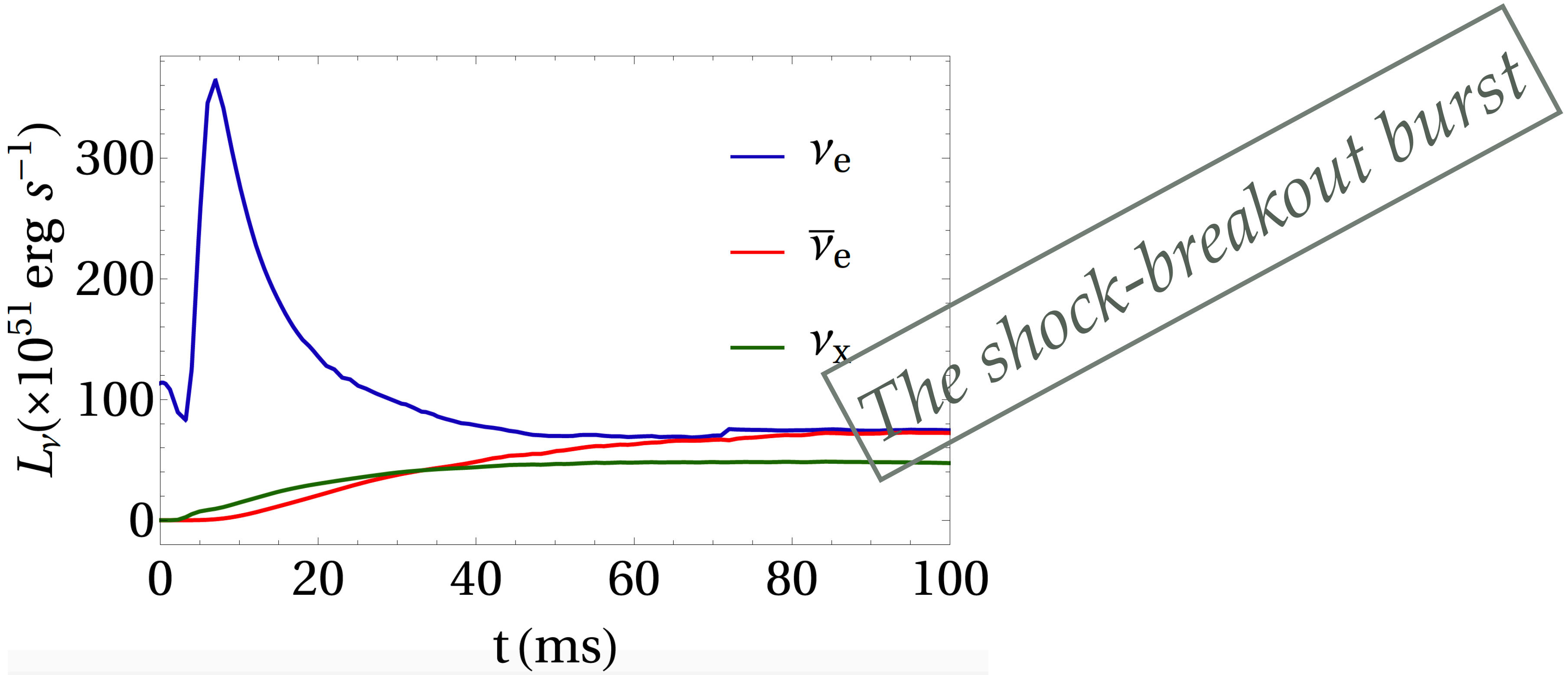
- ν_s can also be produced inside the SN core due to new interactions
  $\mathscr{L} \supset \lambda_{aa} \nu_a \nu_a \phi$
  Lead to additional cooling channels. Strong bounds!

- Bound : $L \lesssim 3 \times 10^{52}\,\mathrm{erg/s}.$

Chen, **MS**, Tuckler, et al. (JCAP 2022)

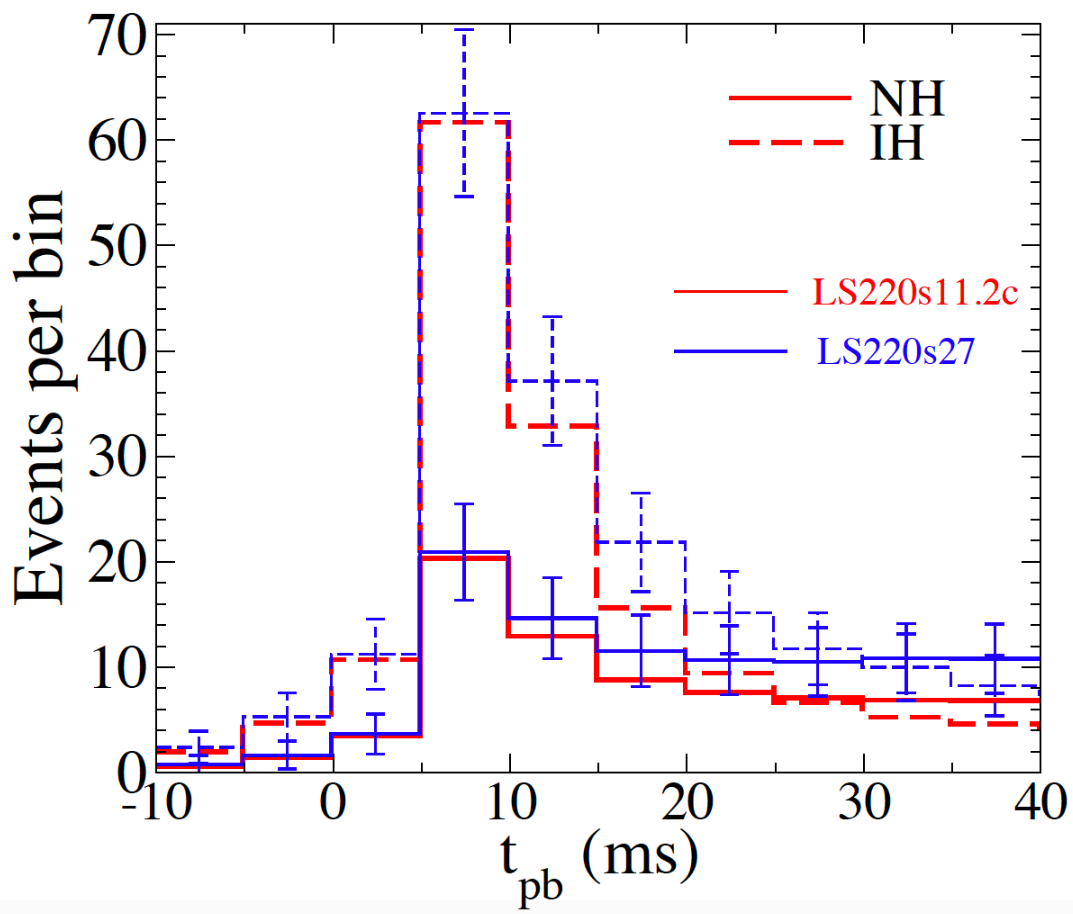
Impact on the neutrino spectra/flux

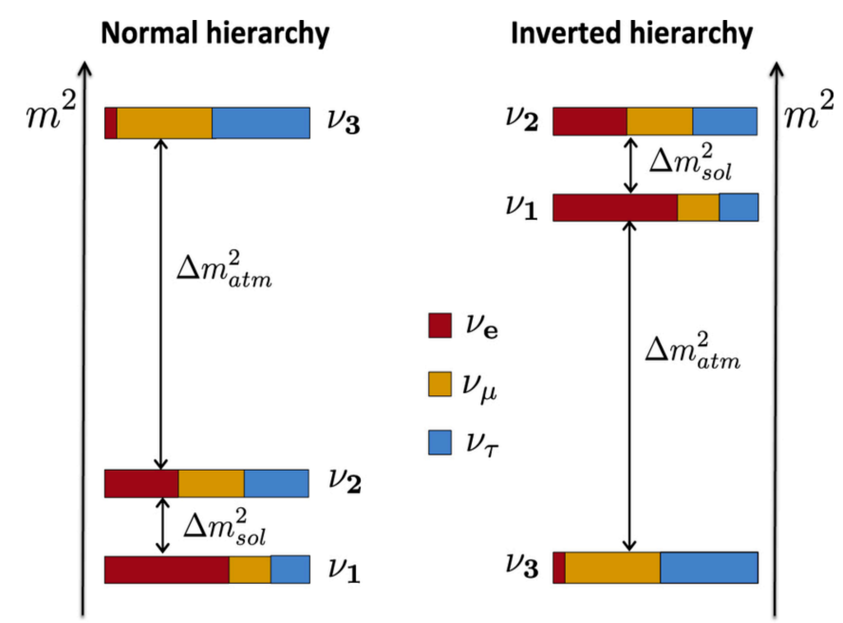
The neutronization burst: a foreward



- Large burst of ν_e in the first ~30 ms post bounce.
- Robust feature of all simulations.
- Large ν_e excess, *hence no collective oscillations within the SM*. (Remember $\nu_e\overline{\nu}_e \leftrightarrow \nu_\mu\overline{\nu}_\mu$!)

Sensitivity to neutrino mass ordering





ν_e is produced as ν_3 (ν_2) in NH (IH).

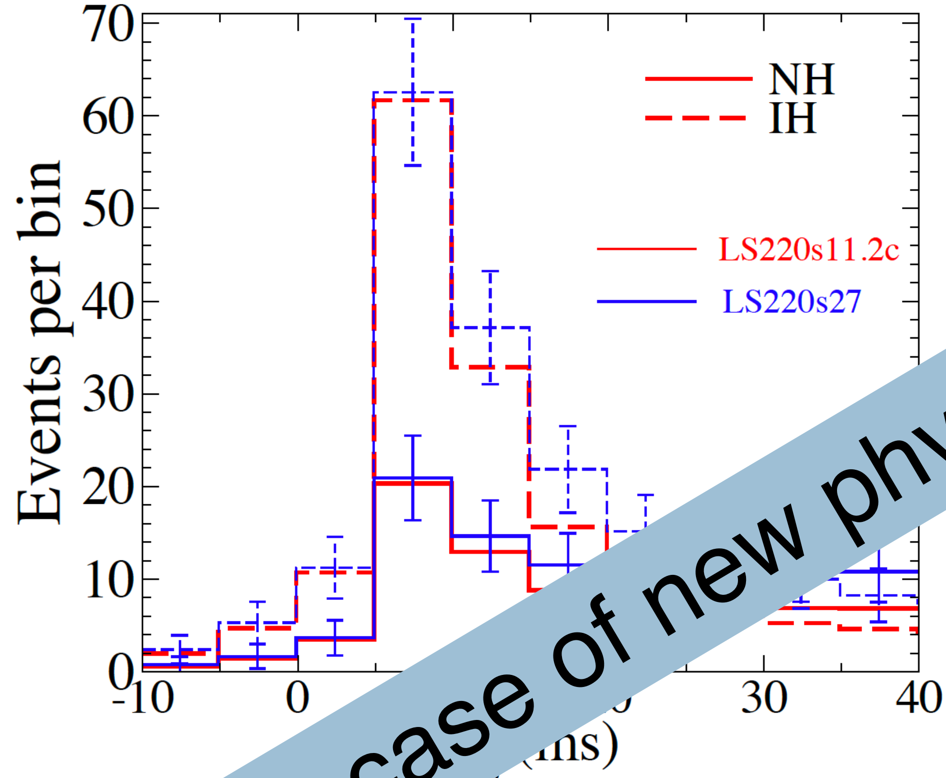
$L_{\nu_e}(R_E) \simeq |U_{e2}|^2 \, L^0_{\nu_e} = 0.2 \, L^0_{\nu_e}$ IH

$L_{\nu_e}(R_E) \simeq |U_{e3}|^2 \, L^0_{\nu_e} = 0.03 \, L^0_{\nu_e}$ NH

Dighe, Smirnov (PRD 2000)

Independent probe of mass ordering!

Sensitivity to neutrino mass ordering



What happens in case of new physics?

$L \ldots \simeq |U_{e2}|^2 \, L^0_{\nu_e} = 0.2 \, L^0_{\nu_e}$ IH

$\ldots_e(R_E) \simeq |U_{e3}|^2 \, L^0_{\nu_e} = 0.03 \, L^0_{\nu_e}$ NH

Independent probe of mass ordering!

3. Non-standard (self)interactions

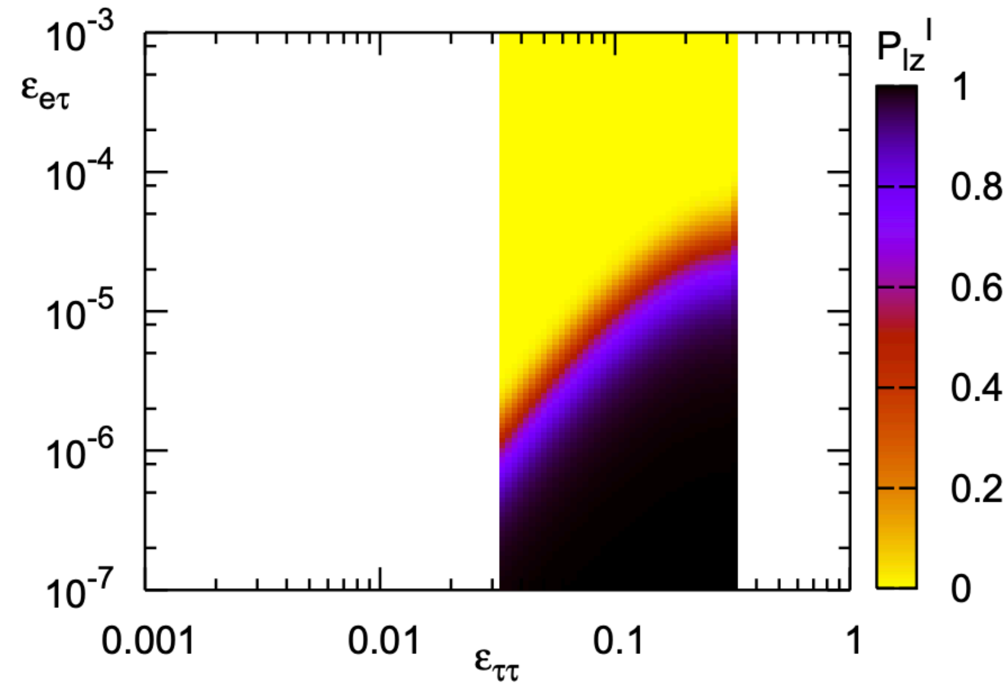
Non-standard interactions

- Presence of NSI can lead to important consequences in dense core
  $\mathscr{L} \supset \varepsilon^{fP}_{\alpha\beta} 2\sqrt{2} G_F \, (\bar{\nu}^{\alpha} \gamma^{\mu} L \, \nu^{\beta}) \, (\bar{f} \gamma_{\mu} P f)$

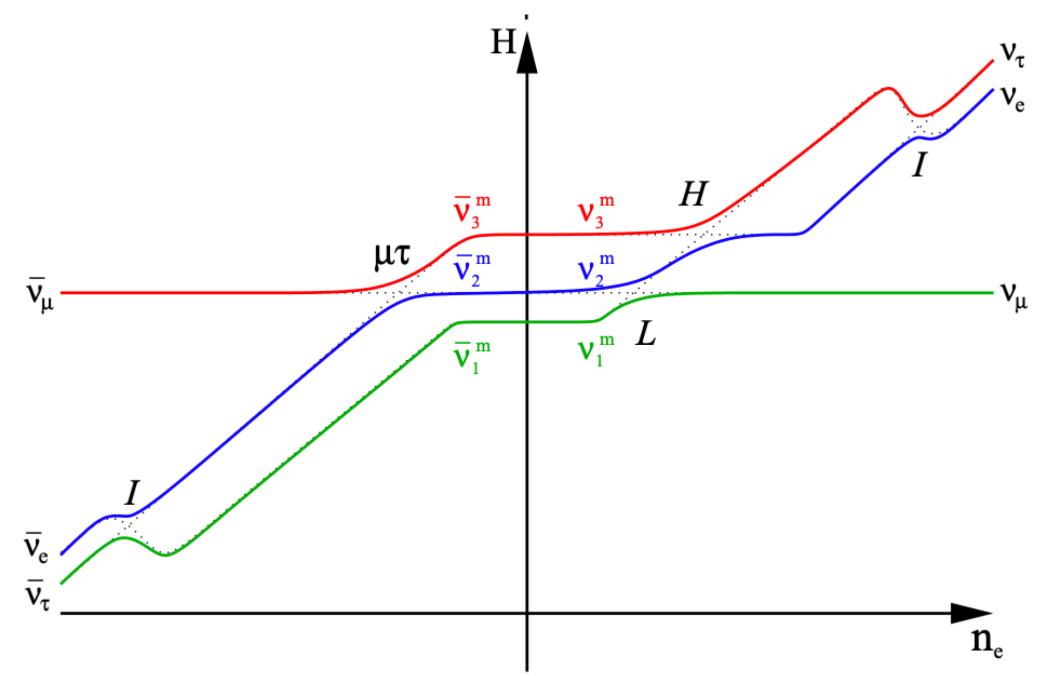
- Extra potential $V = \sqrt{2} G_F N_f \, \varepsilon^{fP}_{\alpha\beta}$

- Leads to an extra resonance ('I' resonance) if $H_{ee} = H_{\mu\mu}, H_{\tau\tau}$. Changes flavor content deep inside the SN.

- Can reduce Y_e during collapse, leading to lower shock energy.



Esteban-Pretel, Tomas, Valle, (PRD 2007)



Amanik, Fuller, (PRD 2007)
See also Amanik, Fuller, Grinstein, Astropart. Phys (2005)

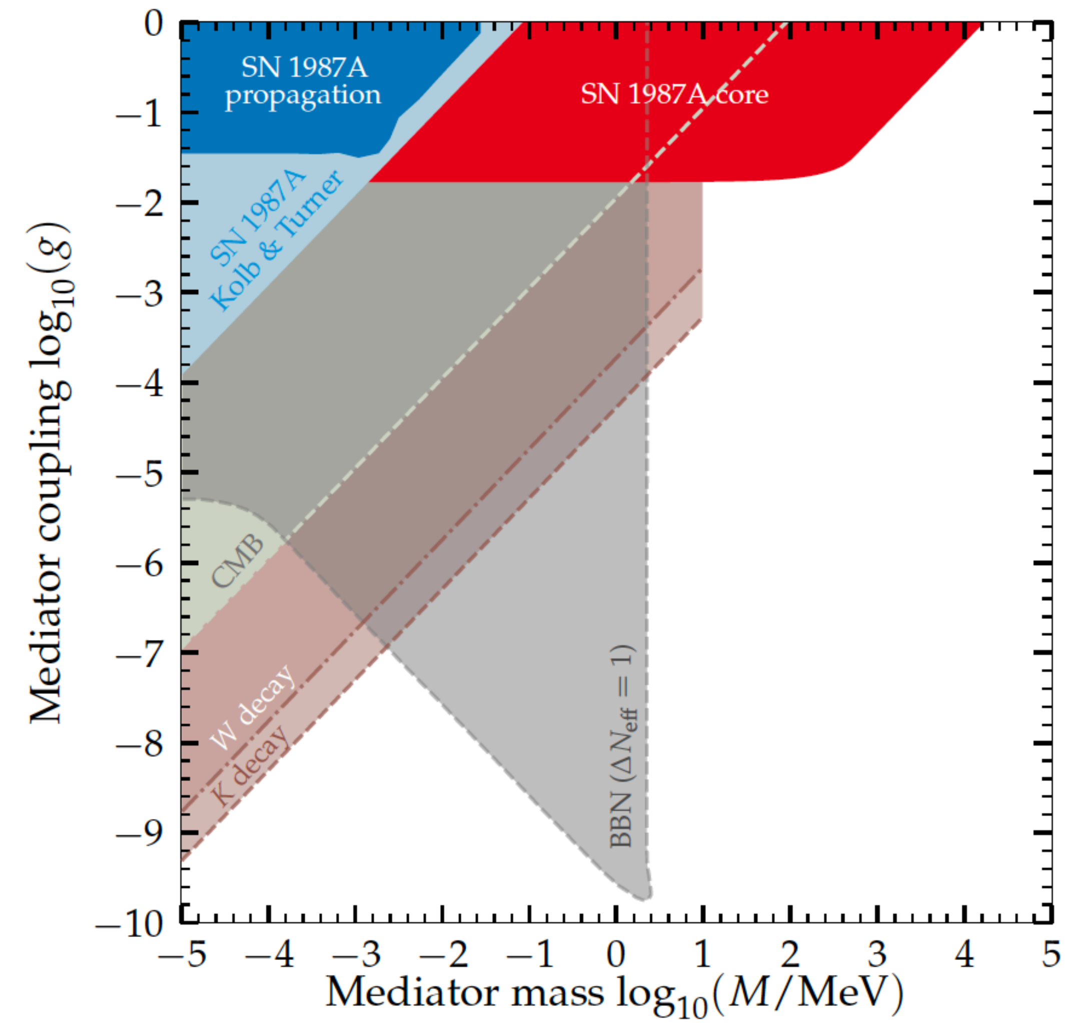
A neutrinophilic ϕ

- Consider a neutrinophilic scalar
  $\mathscr{L} \supset g\,\nu\nu\phi$

- Leads to $\nu\bar{\nu} \to 2\nu 2\bar{\nu}$. Doubles ν number density, but energy is halved. Cannot transfer enough energy to stalled shock (red region).

- Additional bounds from scattering with CνB, and losing energy (blue region).

- Additional bounds due to modification of stellar physics.



Shalgar, Tamborra, Bustamante, (PRD 2020)

Fuller, Mayle, Wilson, Astrophys. J. (1988)
Kachelreiss, Tomas, Valle, (PRD 2000)
Farzan (PRD 2000)

Non-standard self-interactions

- Consider $\mathscr{L} \supset G_F\, (G_{\alpha\beta}\, \bar{\nu}^\alpha \gamma^\mu L \nu^\beta)\, (G_{\eta\delta}\, \bar{\nu}^\eta \gamma^\mu L \nu^\delta)$,

$x = \mu, \tau$

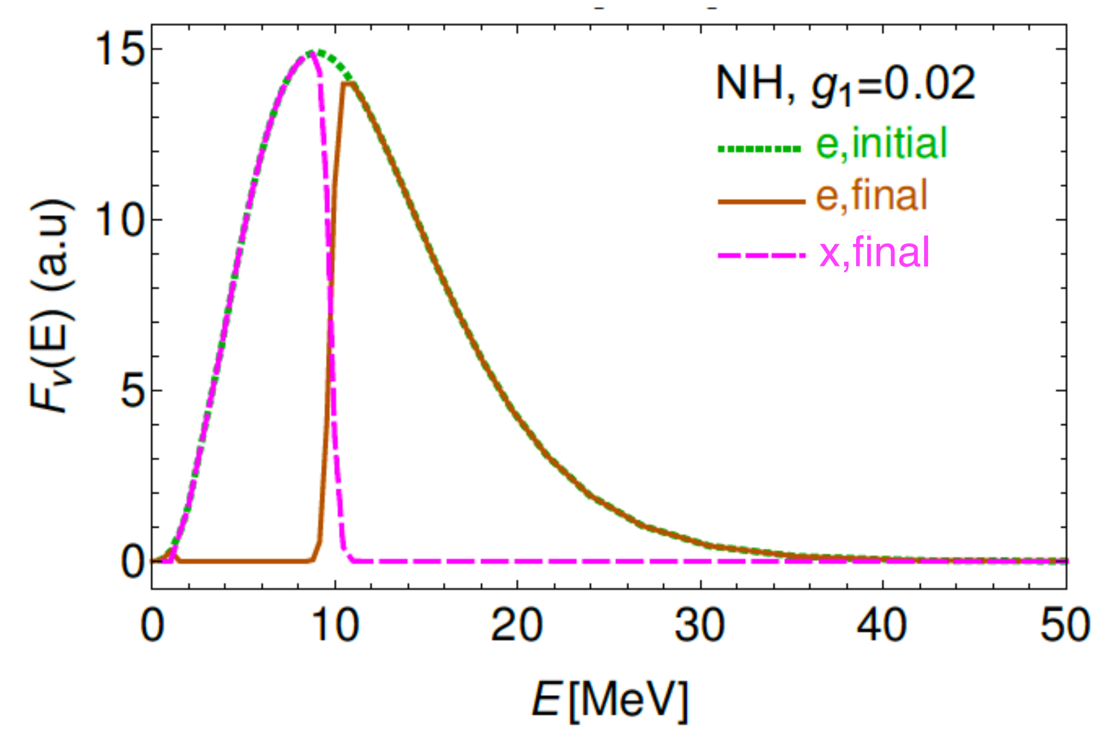
where most generally, $G = \begin{pmatrix} 1 + g_{ee} & g_{ex} \\ g_{ex} & 1 + g_{xx} \end{pmatrix}$.

- Non-linear EoMs, extremely sensitive to νSI.

Raffelt, Sigl (NPB 1993)
Blennow, Mirizzi, Serpico (PRD 2008)

$$i\, d_t\, \varrho_p = \left[H_{\rm vac} + H_{\rm mat} + \sqrt{2} G_F \int d\mathbf{q}\, G\, \varrho_q\, G\, , \varrho_p \right],$$

- $g_{ex} \neq 0$ can populate ν_x from ν_e during neutronization. Cause collective oscillations now, giving distinct spectral splits in neutronization spectra.

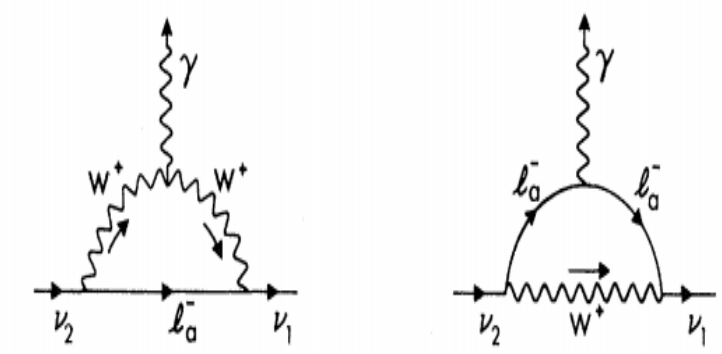


Das, Dighe, **MS** (JCAP 2017)

4. Neutrino decay & properties

Non-standard neutrino decay

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



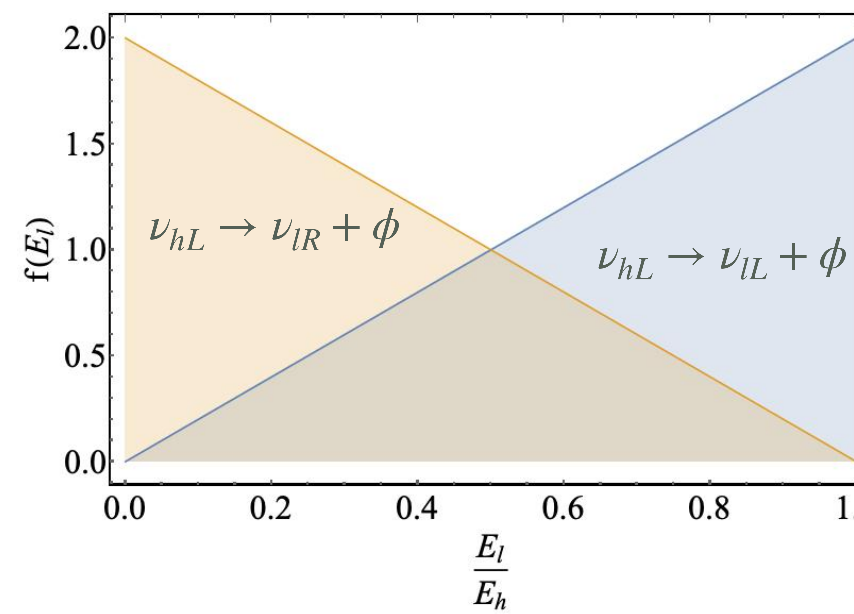
Pal and Wolfenstein PRD (1982)

- New physics can mediate faster decay.

$$\mathscr{L} \supset \nu_h \nu_l \phi + \mathrm{H.c.}$$

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

$\nu_{hL} \rightarrow \nu_{lR} + \phi$ …. Helicity flip. (h.f.)

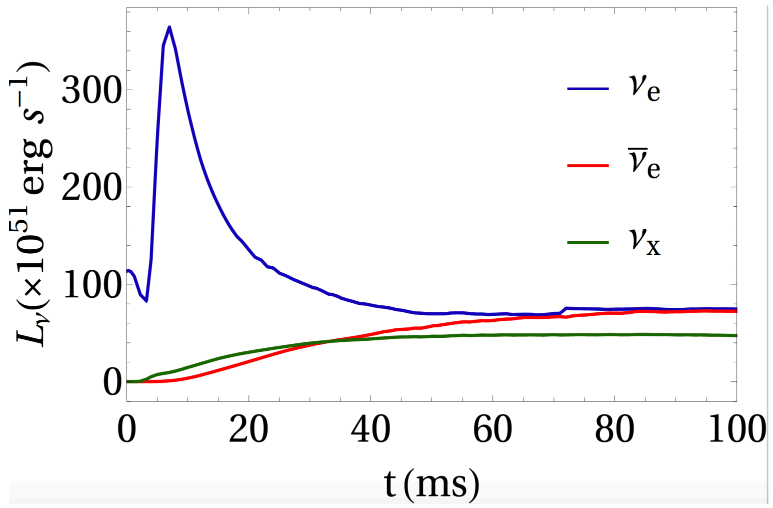


Use the neutronization flux to

(i) Put some of the tightest bound on this decay.

(ii) Distinguish between Dirac and Majorana nature.

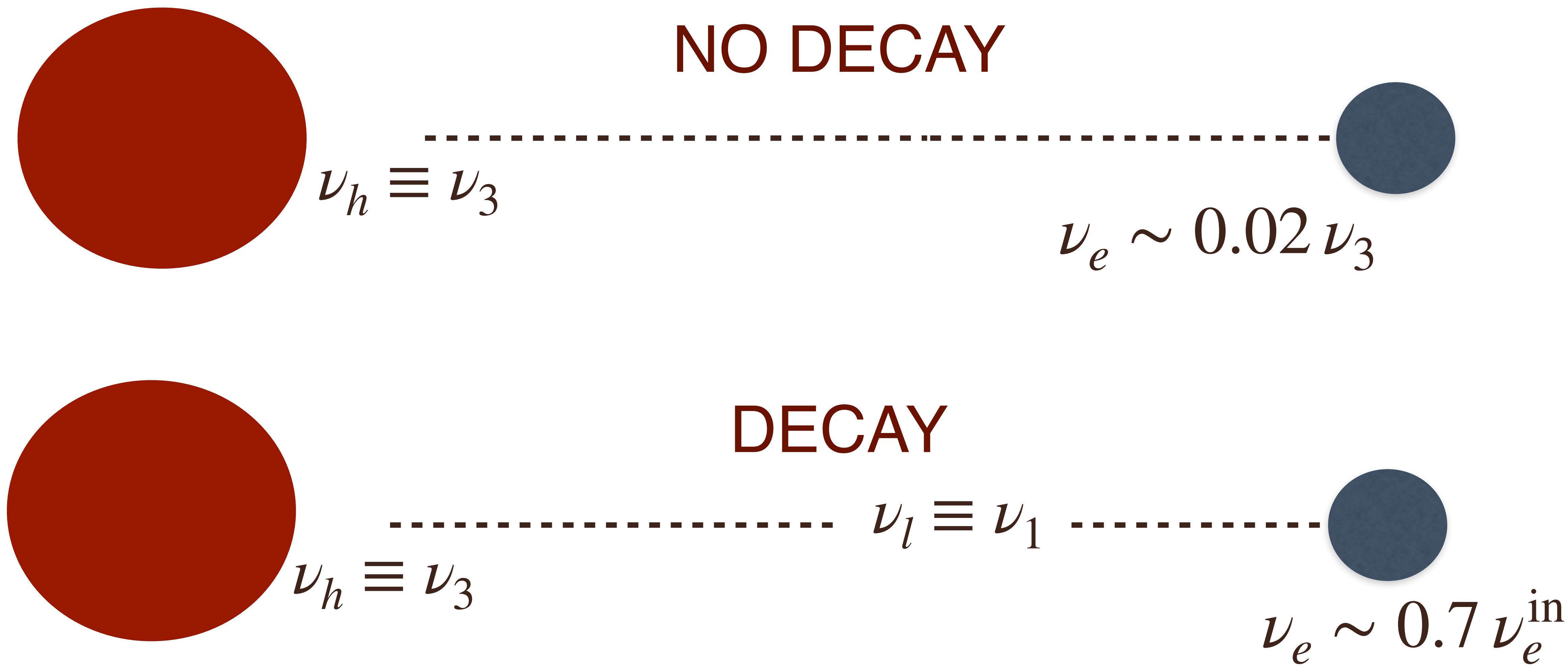
The game plan



Normal Ordering

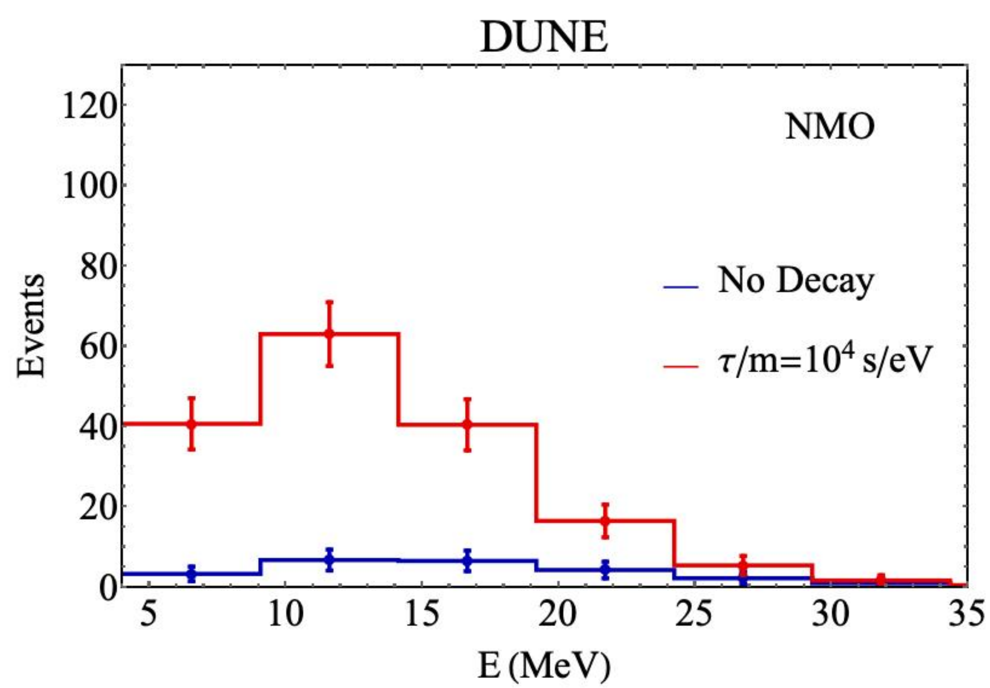
Ando PRD (2004)
de Gouvea, Martinez-Soler, **MS** (PRD 2019)

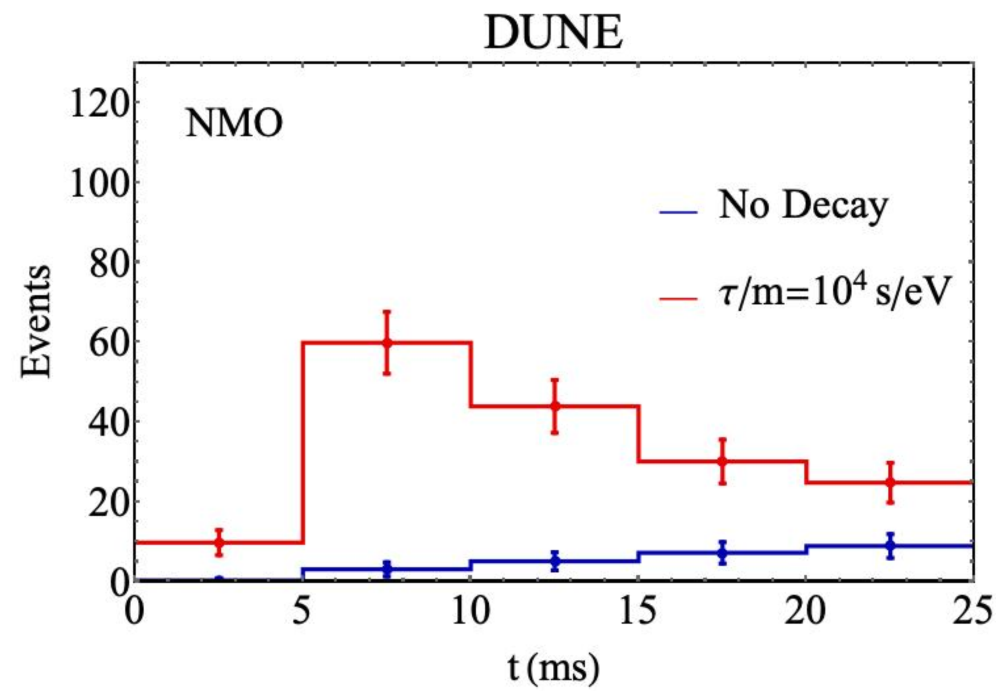
For a detailed theoretical framework of neutrino decay, see Lindner, Ohlsson, Winter, (NPB 2002)

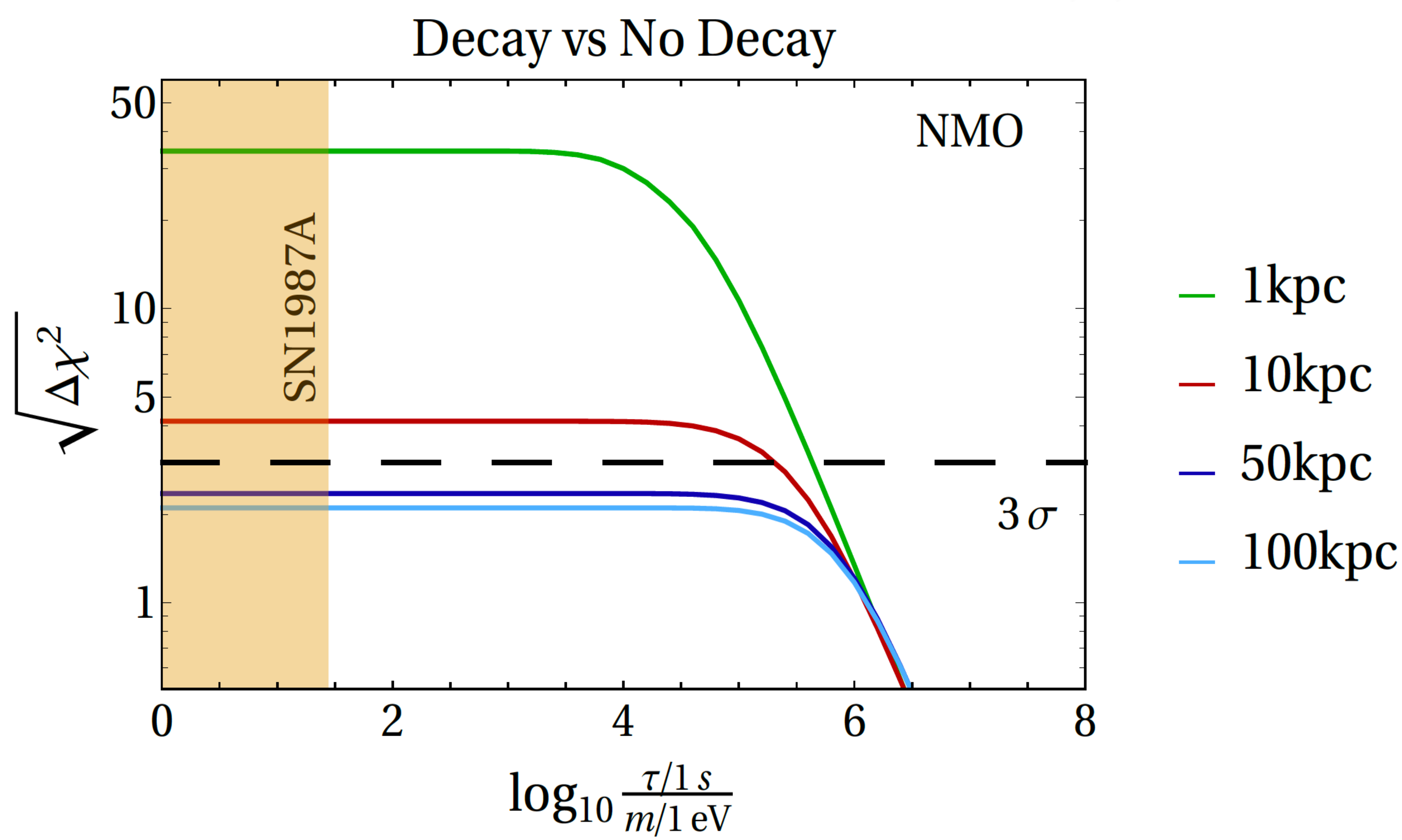


Enhancement in spectra

Simulated data in DUNE

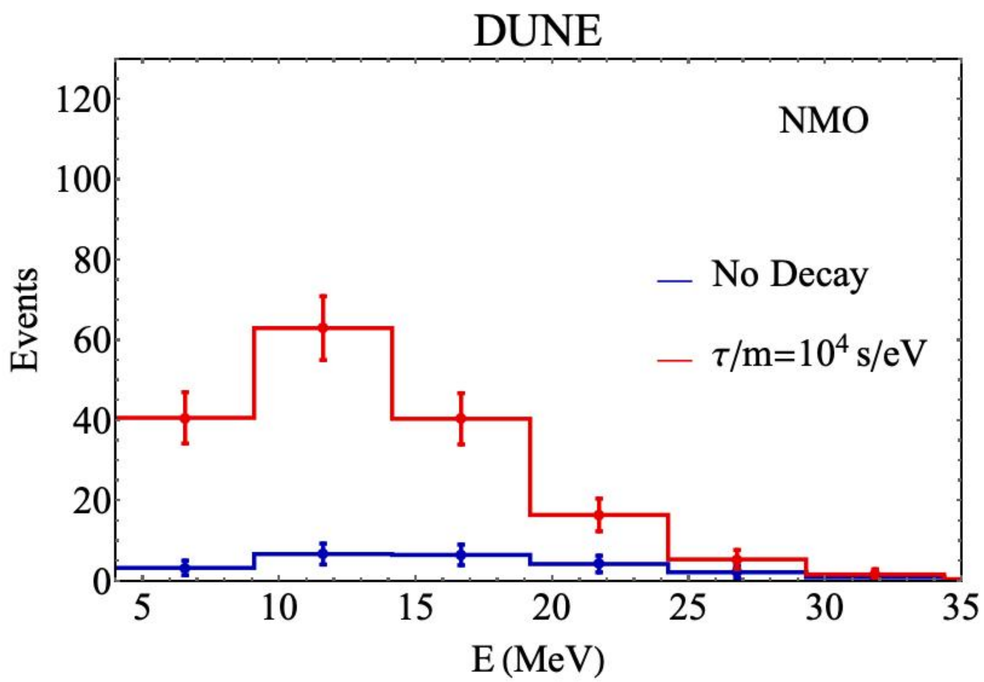


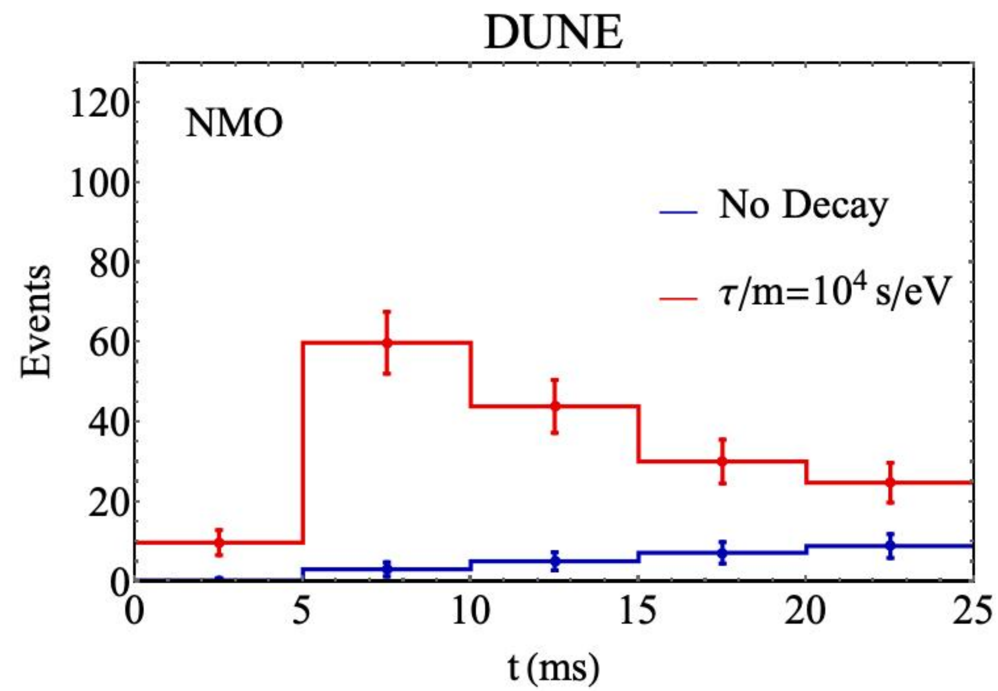


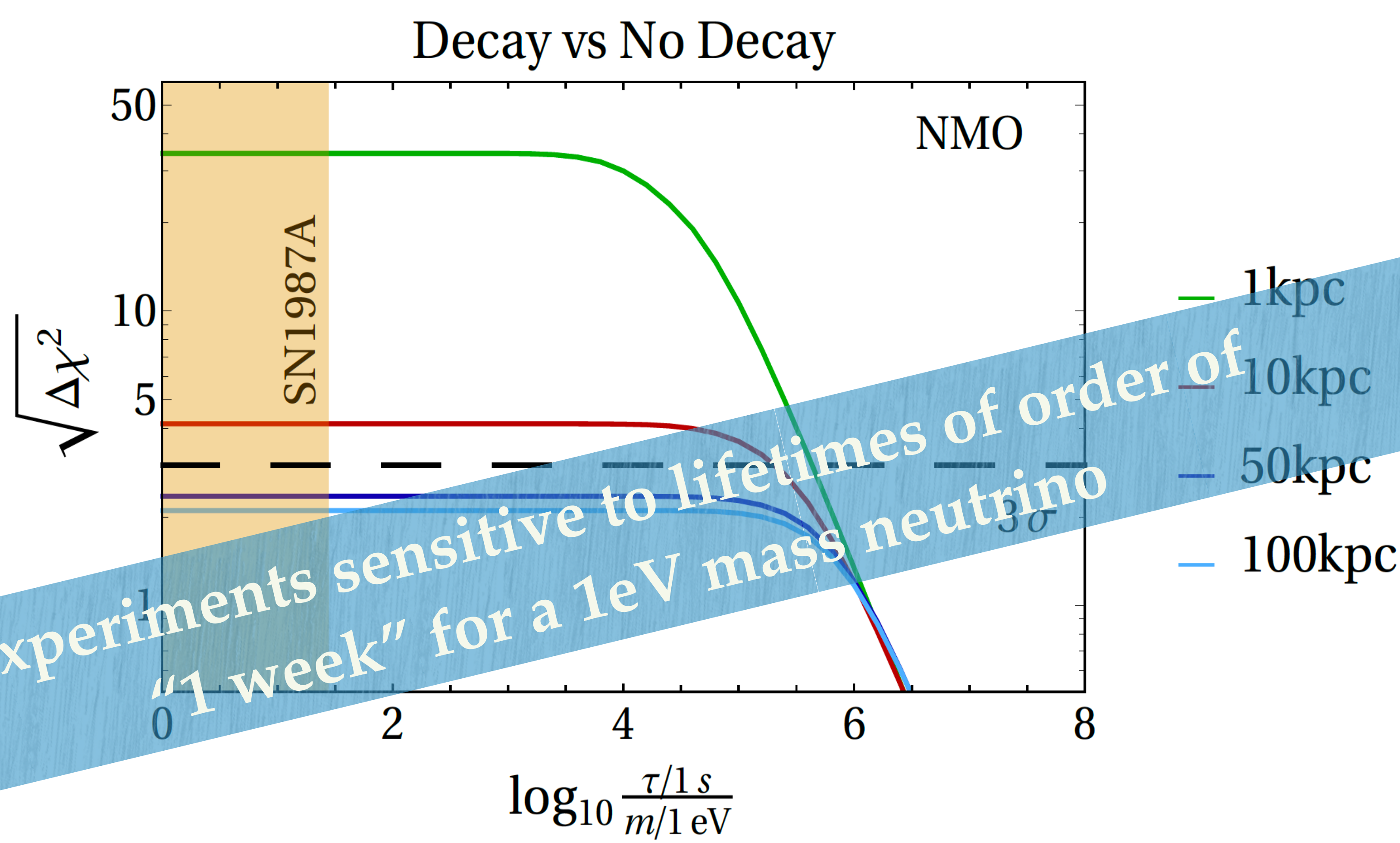


de Gouvea, Martinez-Soler, **MS** (PRD 2019)

Simulated data in DUNE







Experiments sensitive to lifetimes of order of "1 week" for a 1eV mass neutrino

de Gouvea, Martinez-Soler, **MS** (PRD 2019)

Dirac vs Majorana

$$\mathscr{L}_{\text{Dir}} \supset \nu_h \nu_l^c \phi + \text{H.c.}$$

- $\nu_{hL} \to \nu_{lL} + \phi$
- $\nu_{hL} \to \nu_{lR} + \phi$

acts as an “inert” neutrino and cannot be observed.

$$\mathscr{L}_{\text{Maj}} \supset \nu_h \nu_l \phi + \text{H.c.}$$

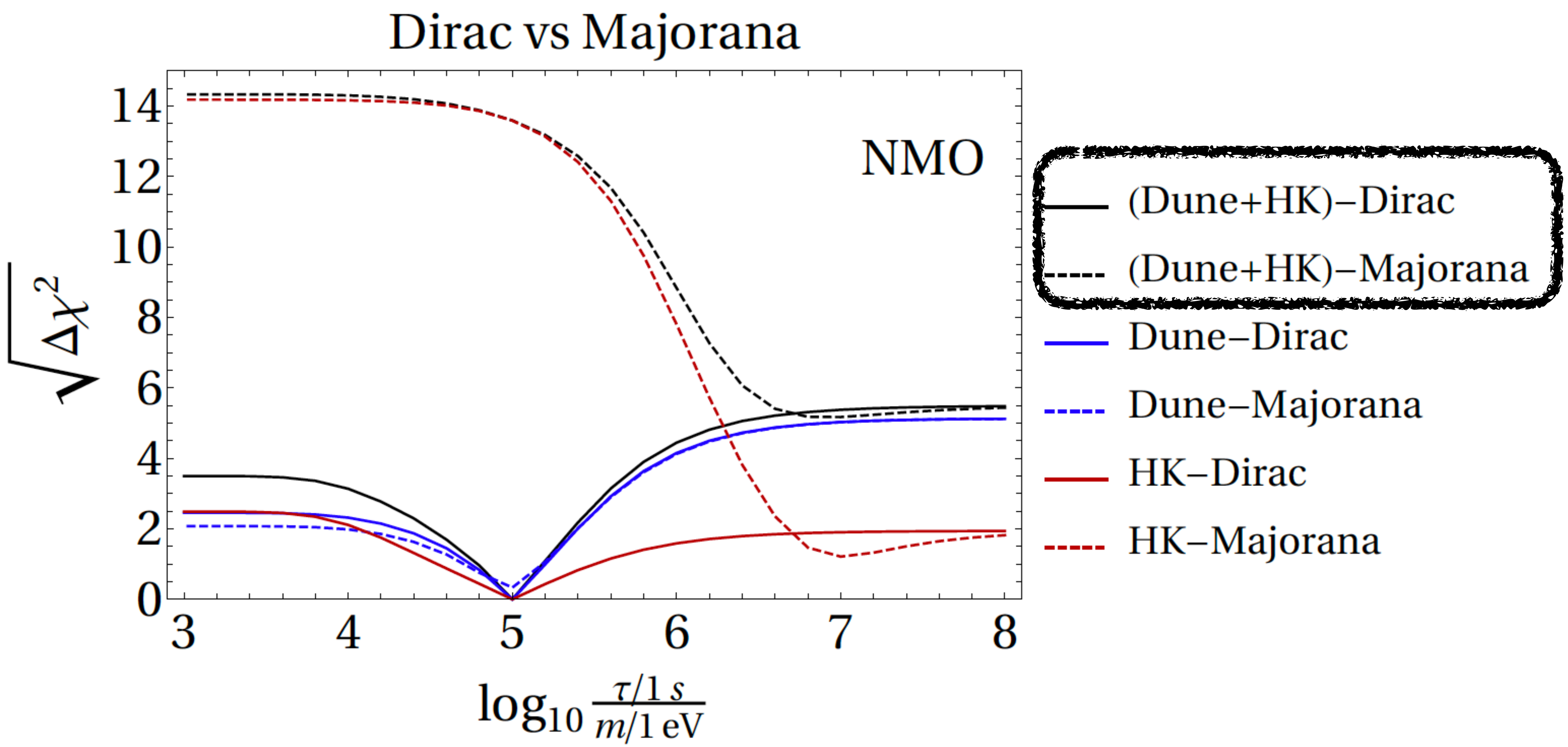
- $\nu_{hL} \to \nu_{lL} + \phi$
- $\nu_{hL} \to \nu_{lR} + \phi$

acts as the “antineutrino” - produces an e^+ on interaction—observable

Different signatures in detectors sensitive to ν_e and $\overline{\nu}_e$.

Look at DUNE and HK

Distinguishing capacity: Dirac(D) vs Majorana (M)



- Simulate data consistent with Dirac neutrinos and $\tau/m = 10^5\mathrm{s/eV}$.

- A combination of DUNE+ HK can distinguish between Dirac and Majorana neutrinos at 5σ.

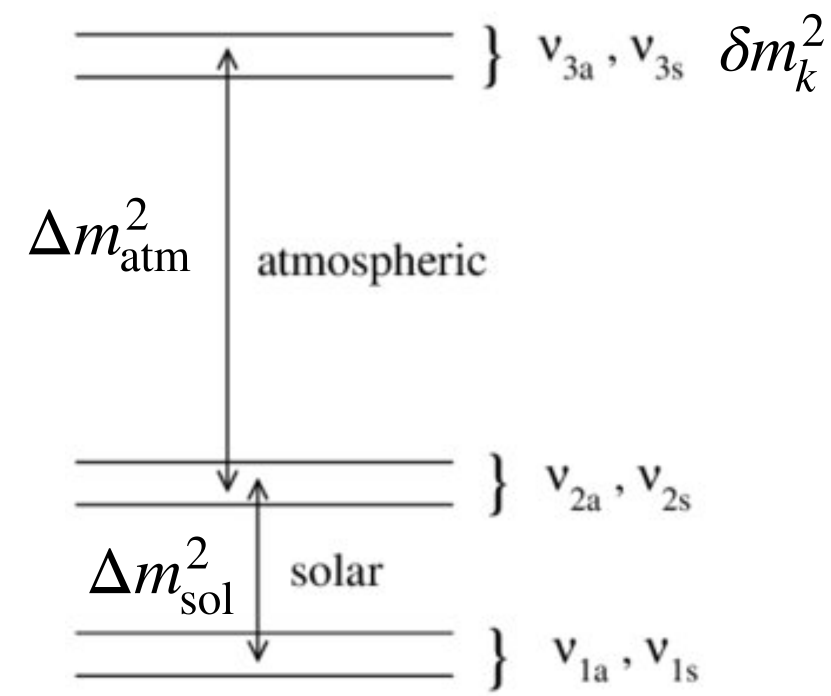
de Gouvea, Martinez-Soler, **MS** (PRD 2019)

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 : $m_{L,R} \ll m_D$



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

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

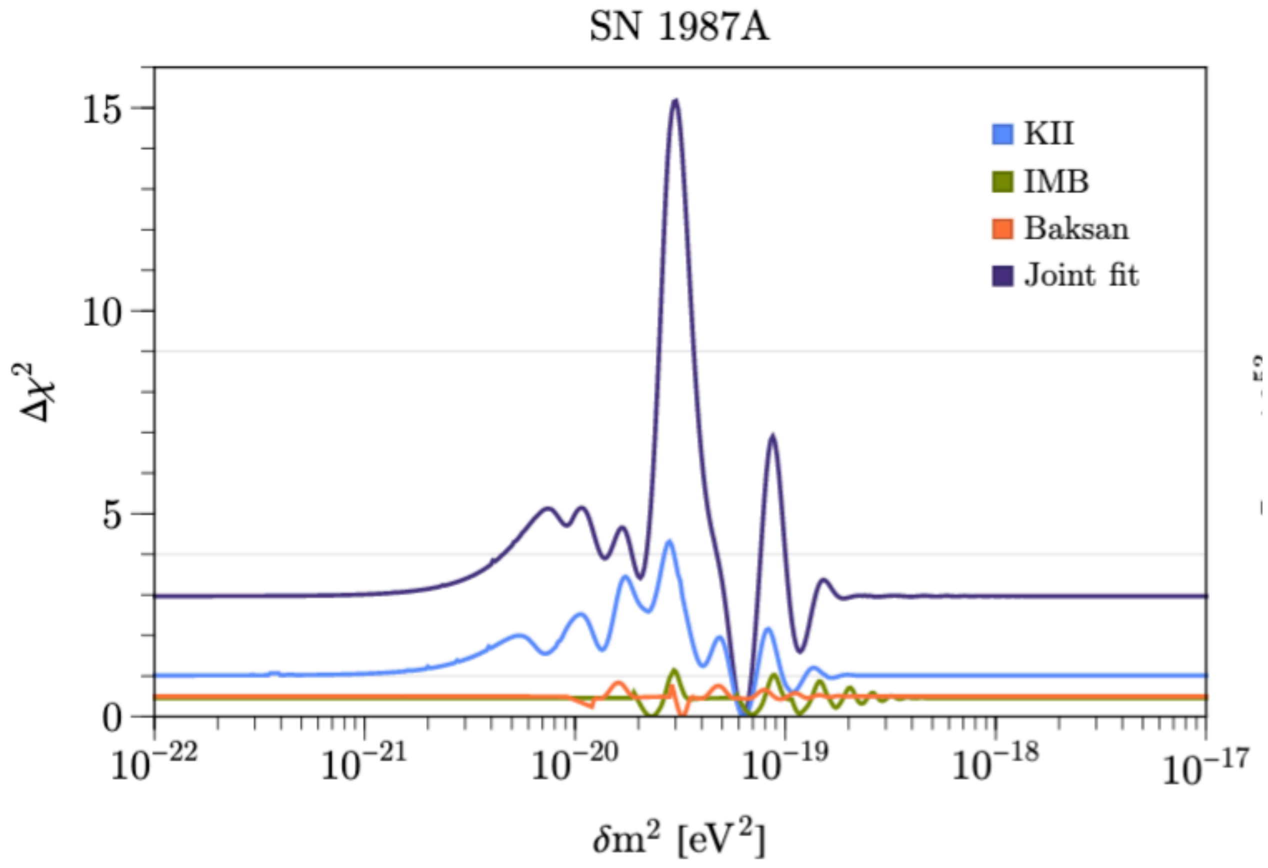
- Maximally mixed active and sterile states. Oscillations driven by this tiny mass.

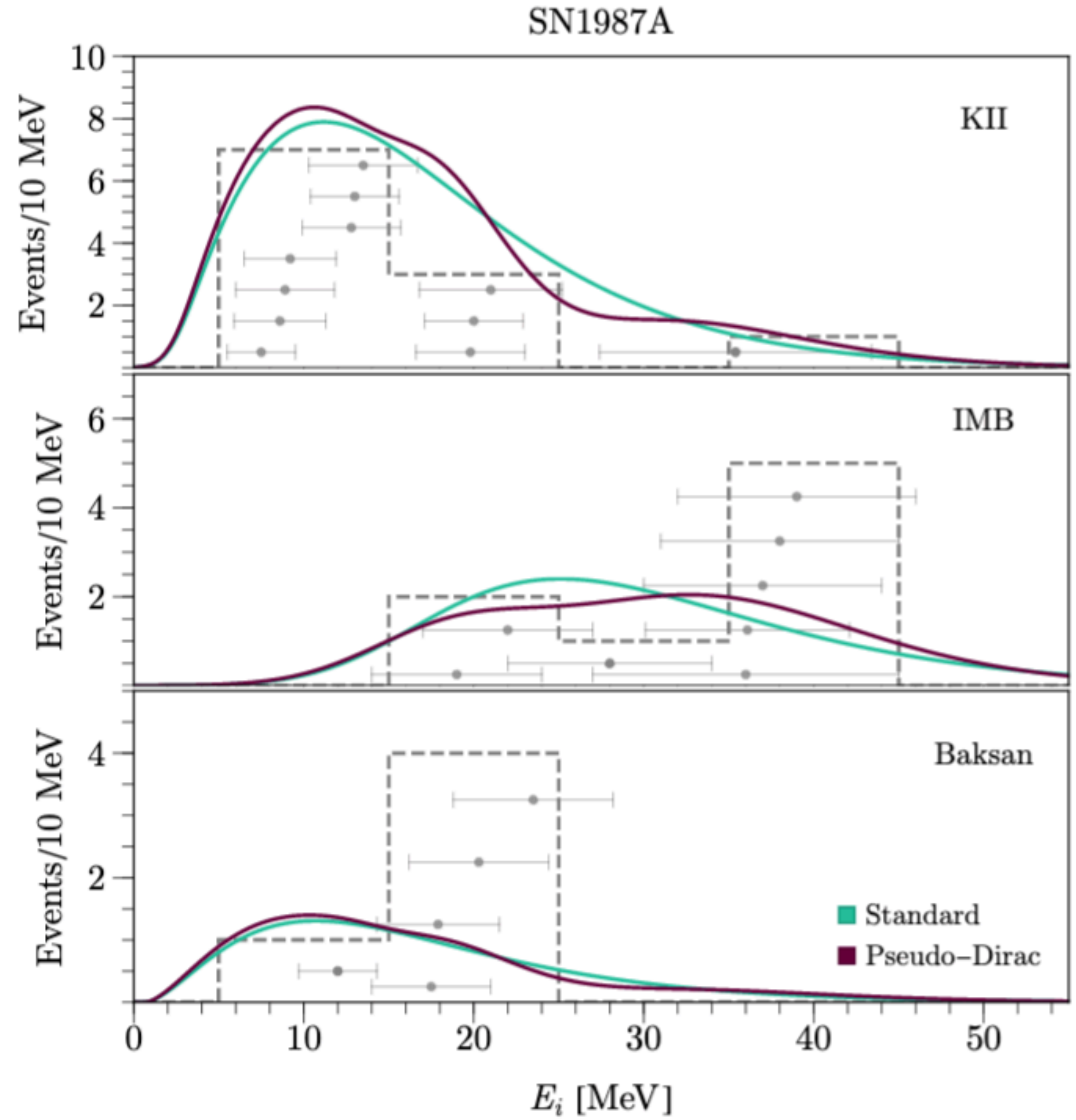
Martinez-Soler, Perez-Gonzalez, **MS** (PRD 2022)

Bounds:

1. Solar neutrinos $\delta m^2 = 10^{-12}\,{\rm eV}^2$
   de Gouvea, Huang, Jenkins (PRD 2009)
2. Atmospheric neutrinos
   $\delta m^2 > 10^{-4}\,{\rm eV}^2$
   Beacom, Bell, et al. (PRL 2004)
3. High energy astrophysical neutrinos
   $10^{-18}\,{\rm eV}^2 < \delta m^2 < 10^{-12}\,{\rm eV}^2$
   Esmaili, Farzan, (JCAP 2012)

Pseudo-Dirac neutrinos: SN1987A





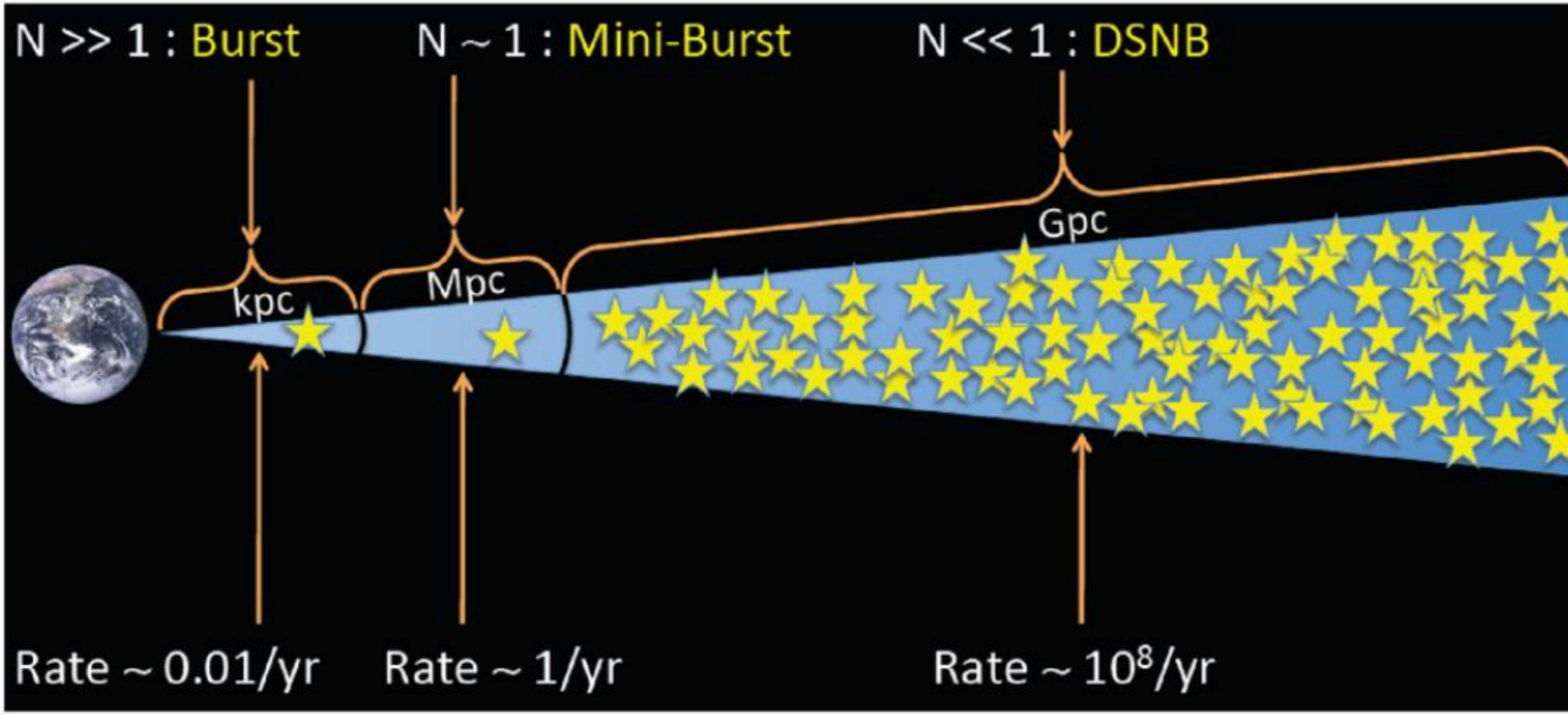
Rules out $\delta m^2 \sim [2.5, 3.] \times 10^{-20} \mathrm{eV}^2$ by more than 3σ.

Slight preference for $\delta m^2 = 6.31 \times 10^{-20} \mathrm{eV}^2$ over the un-oscillated scenario by $\Delta\chi^2 \approx 3$.

Martinez-Soler, Perez-Gonzalez, **MS** (PRD 2022)

Neutrinos from all supernovae

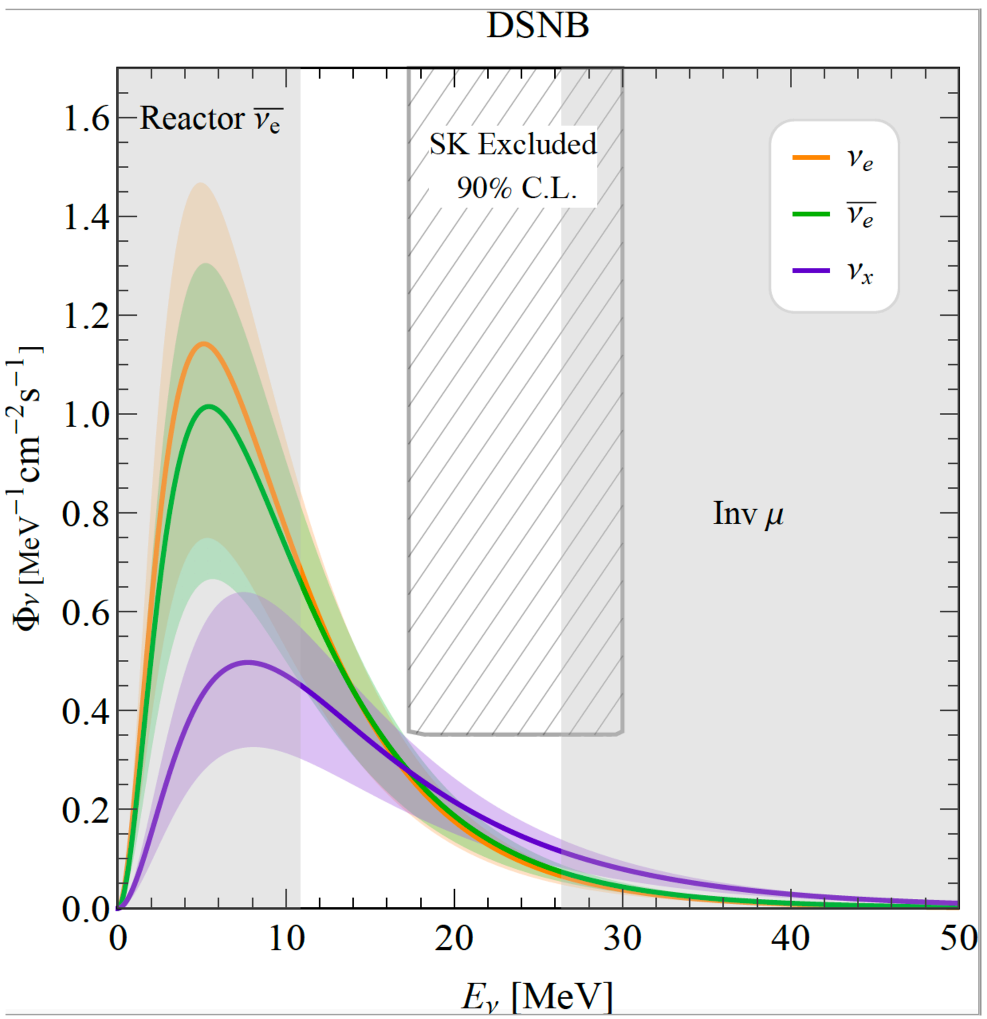
John Beacom, TAUP2011

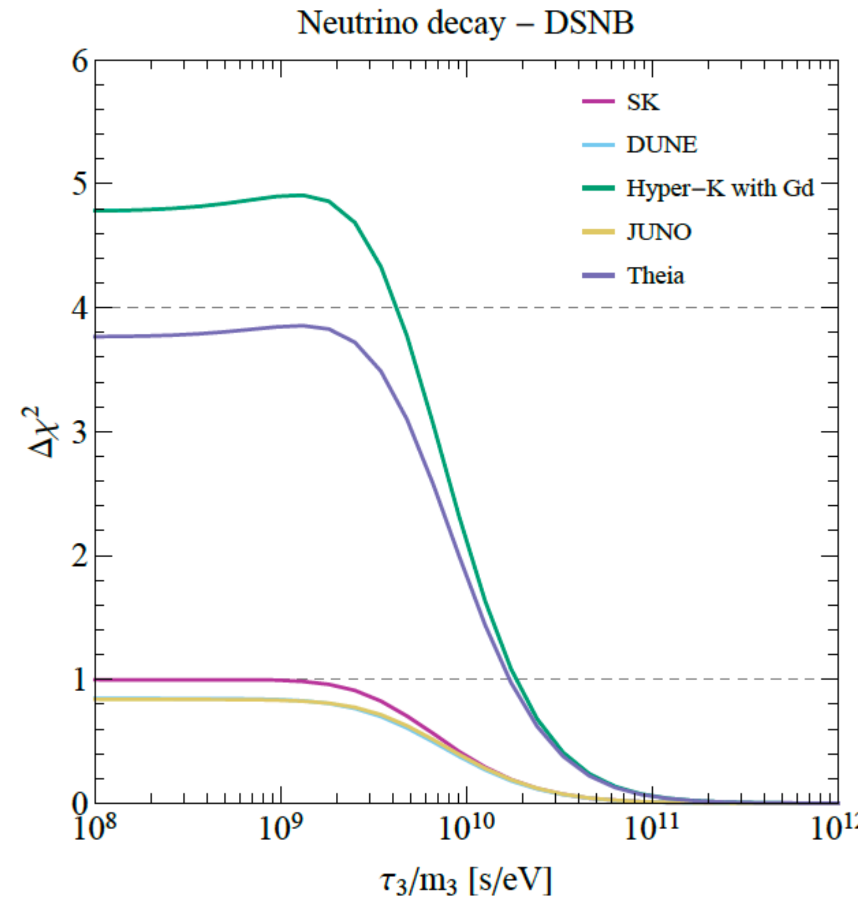


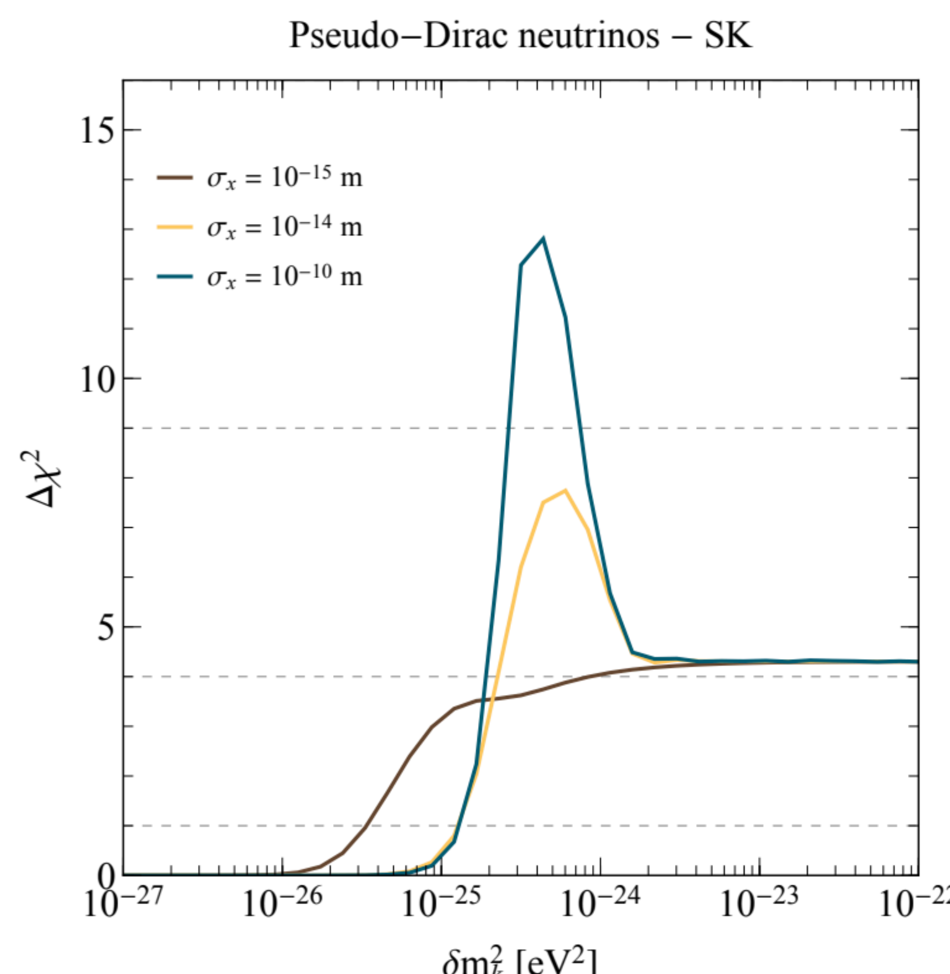
DSNB=Diffuse Supernova Neutrino Background

Talk by Horiuchi for further details

Finally, the DSNB: an omnipresent laboratory

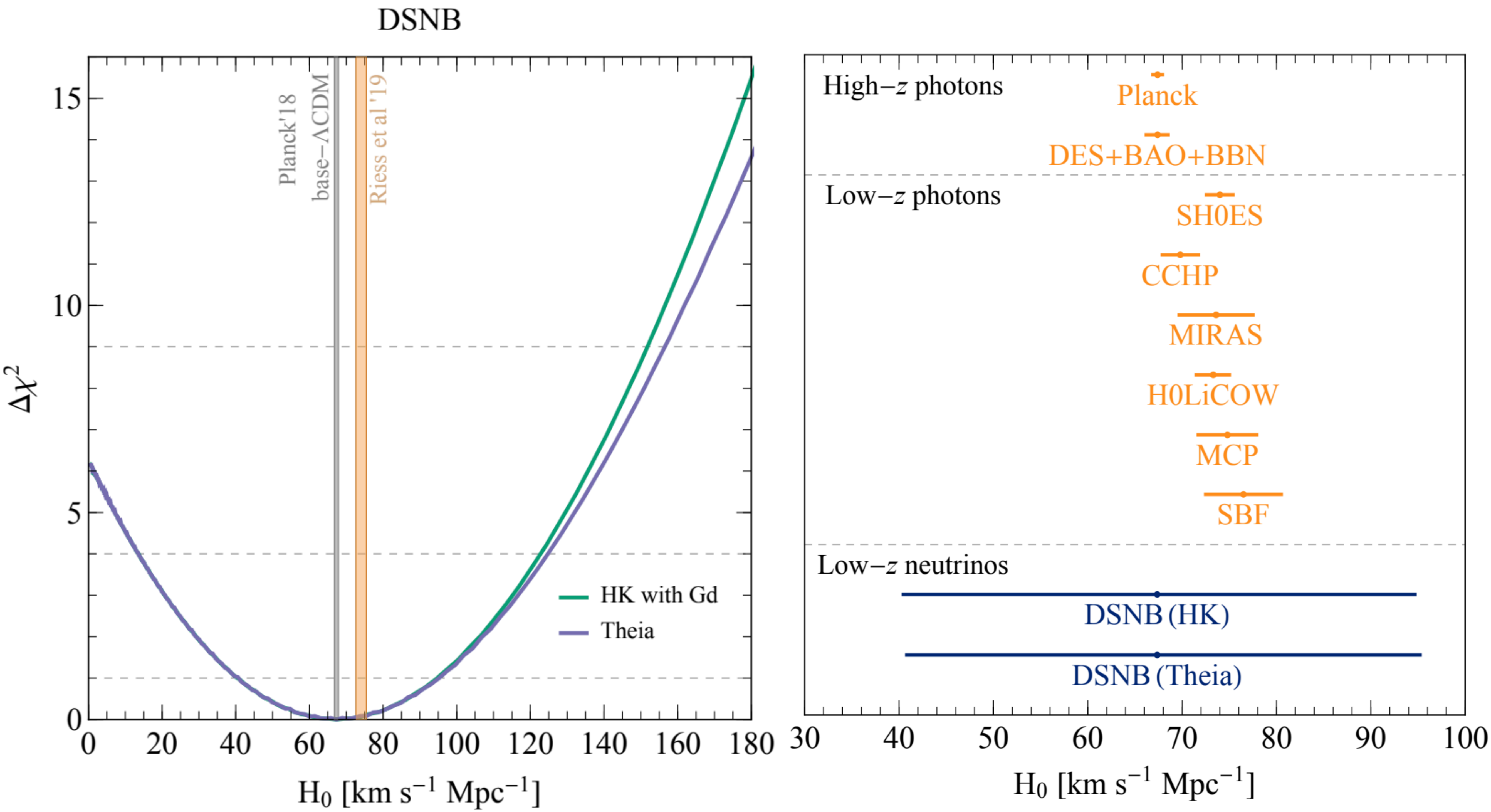






de Gouvea, Martinez-Soler, Perez-Gonzalez , **MS** (PRD 2020)

Exotica 1: The Hubble Parameter



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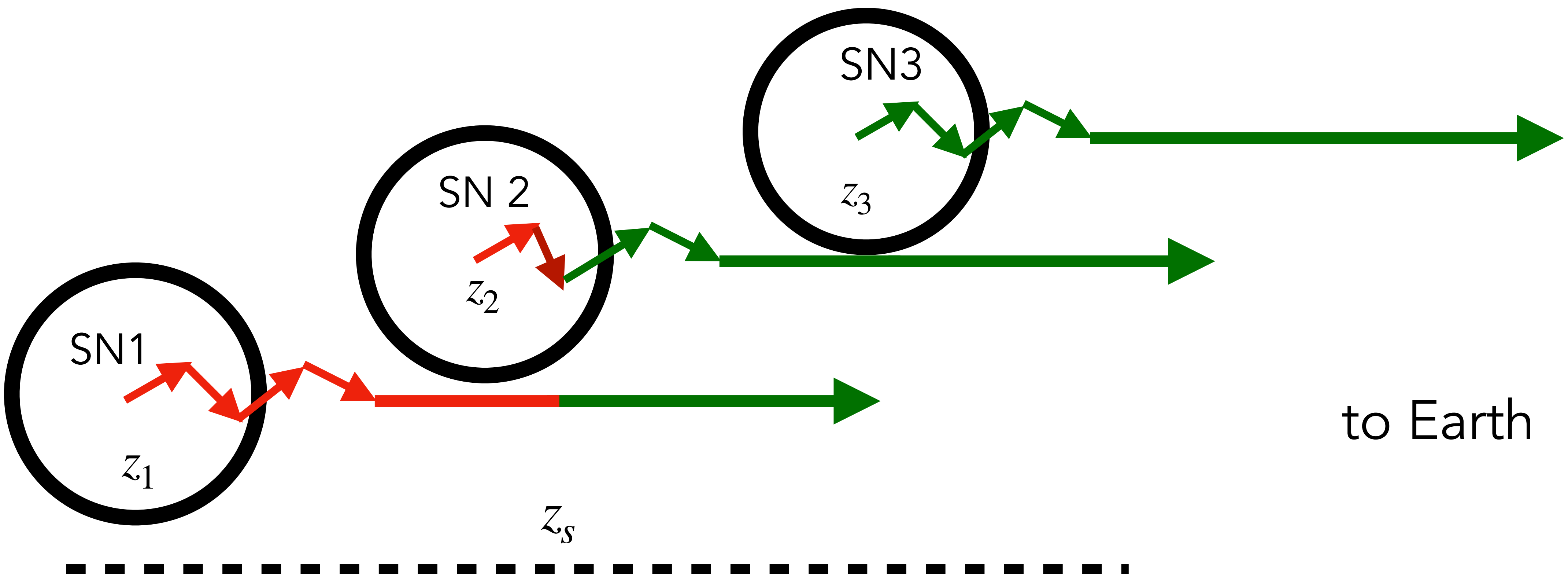
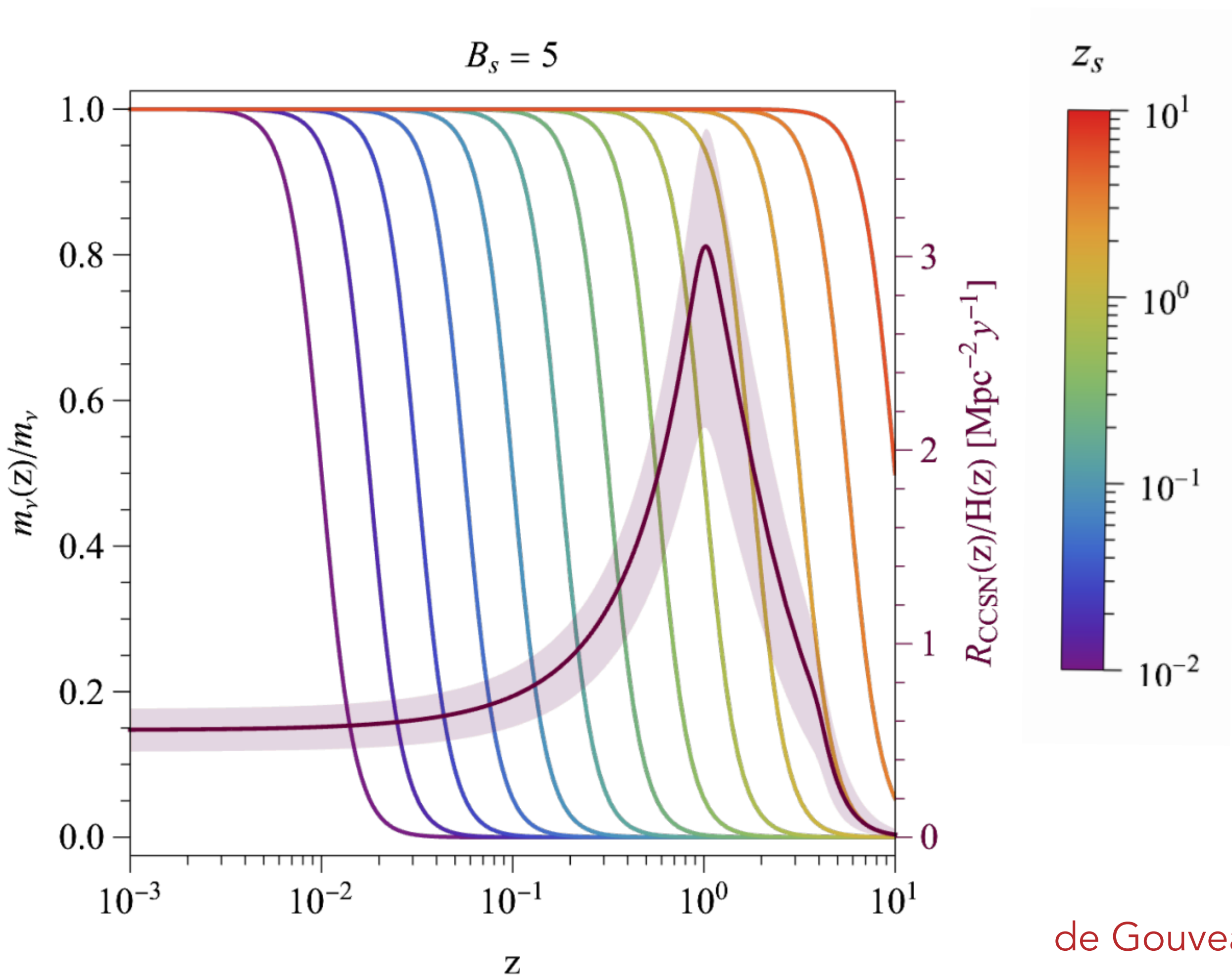
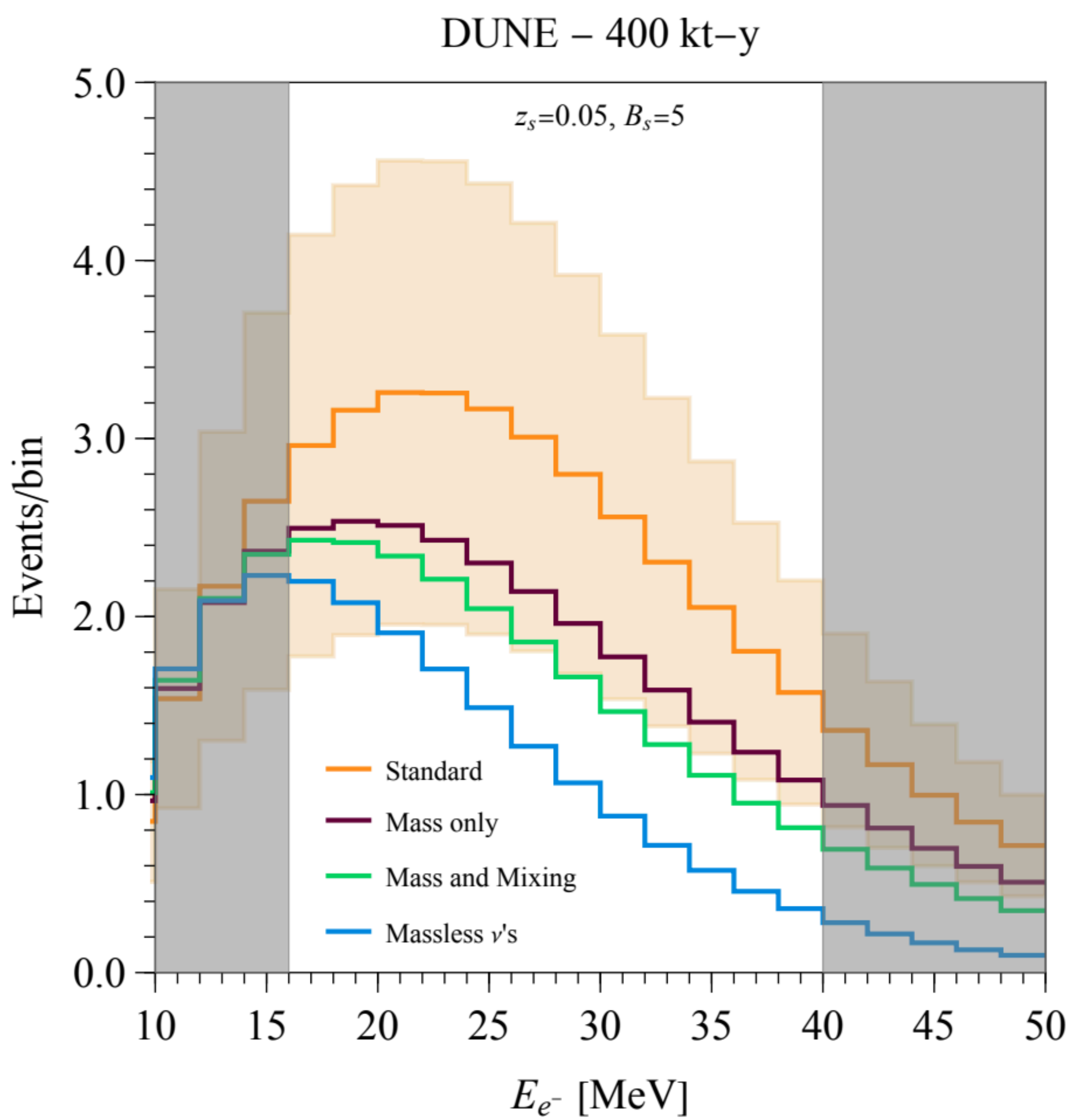
Exotica 2: Redshift dependent neutrino mass





de Gouvea, Martinez-Soler, Perez-Gonzalez , **MS** (PRD 2022)

Exotica 2: Redshift dependent neutrino mass



de Gouvea, Martinez-Soler, Perez-Gonzalez , **MS** (PRD 2022)

Other new physics–an incomplete list

- Axions, and axion-like particles. Raffelt, Stars as laboratories for fundamental physics, UCP (1996); Jaeckel, Spannowsky, (PLB 2016); Lucente, Carenza, Fischer, et al. (JCAP 2020)

  Majorons and other feebly interacting scalars. Kachelreiss, Tomas, Valle, (PRD 2000); Farzan (PRD 2000); Fiorillo, Raffelt, Vitagliano, 2209.11773

- Neutrino magnetic moment: bounds $\mu_D < 10^{-12}\mu_B$. Barbieri, Mohapata, (PRL 1988); Jana, **MS**, Silva (JCAP 2022)

- Radiative decays: $\nu \to \nu'\gamma$, gives a coincident γ-ray flare. Bounds $\tau/m > 10^{15}\,\mathrm{s/eV}$. Raffelt, Stars as laboratories for fundamental physics, UCP (1996)

- Time of flight delay due to neutrinos: $m_\nu < 20\,\mathrm{eV}$. Zatsepin, JETP Lett (1968)

  More precise time measurements narrow it to O(1)eV. Hansen, Lindner, Scholer, (PRD 2020); Pompa, Capozzi, et al (PRL 2022)

  Talk by Pompa for further details

- If ν have millicharge, their path can be bent by galactic B field, causing a time delay, $e_\nu < 10^{-17} e\,(1\mu G/B)$ Barbiellini, Cocconi, Nature (1987)

Conclusion

- A core-collapse SN is one of the best astrophysical laboratories for fundamental neutrino physics.

- Can use neutrino luminosity constraints to put bounds on exotic new particles.

- Better understanding of the underlying neutrino physics can be leveraged to use the signal to put some of the best bounds on non-standard neutrino properties, as well as the nature of neutrinos.

- Till a galactic SN takes place, one can utilize the constant availability of the DSNB to already probe some of these physics.

Thank you!

Backup

Estimating the DSNB

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

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

SN Neutrino spectra

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

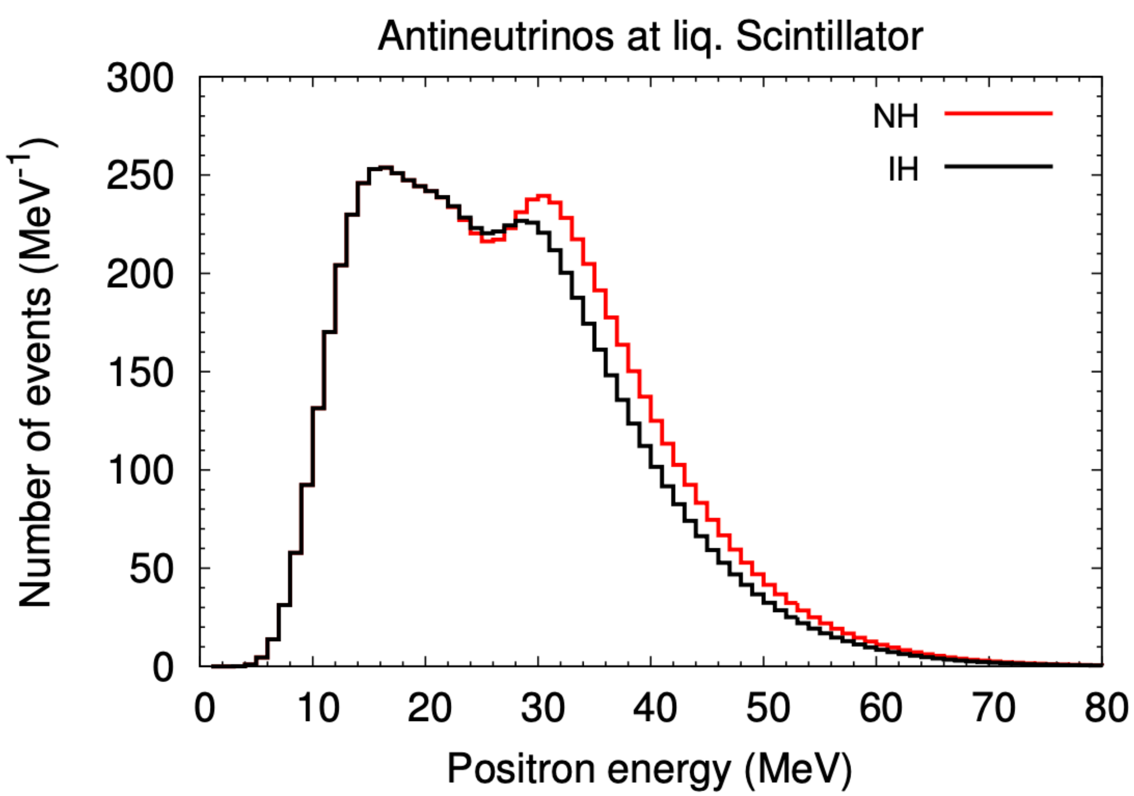
Cosmological SN rate

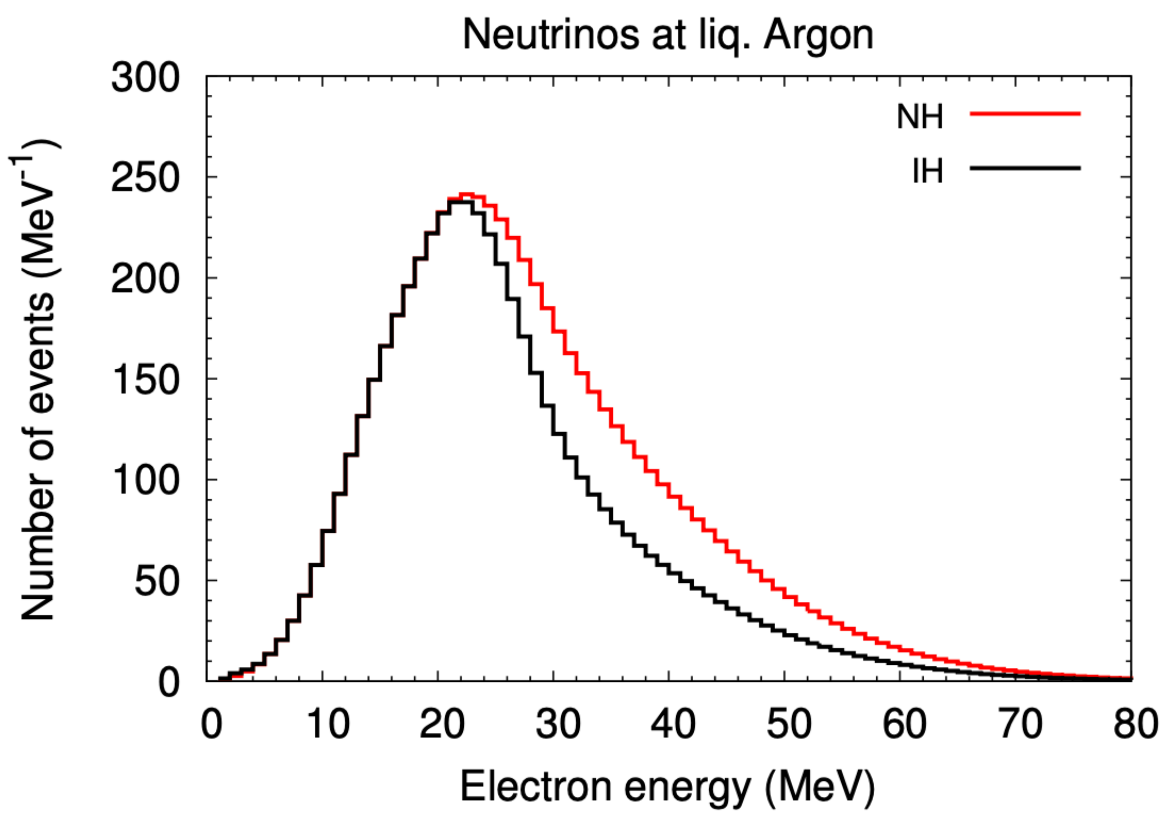
$$R_{\rm CCSN}(z) = \dot{\rho}_{\rm SFR}(z) \frac{\int_8^{50} \psi_{\rm IMF}(M)\, dM}{\int_{0.1}^{100} M\psi_{\rm IMF}(M)\, dM}\,.$$

Cosmology

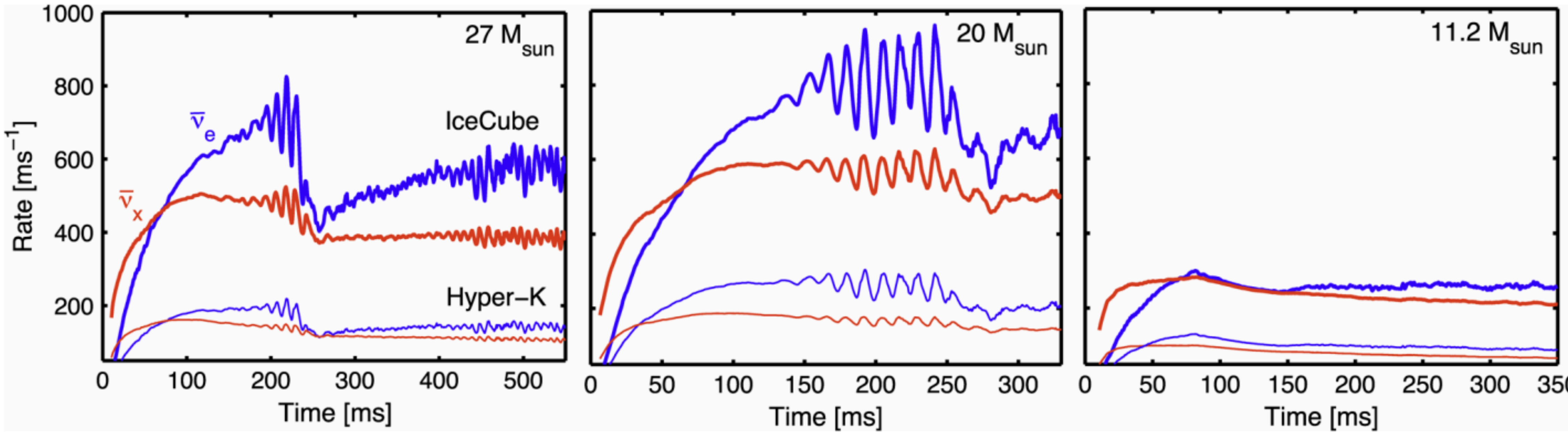
$$H(z) = H_0 \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)} + (1-\Omega_m-\Omega_\Lambda)(1+z)^2}$$

Signature of spectral splits





SASI effects



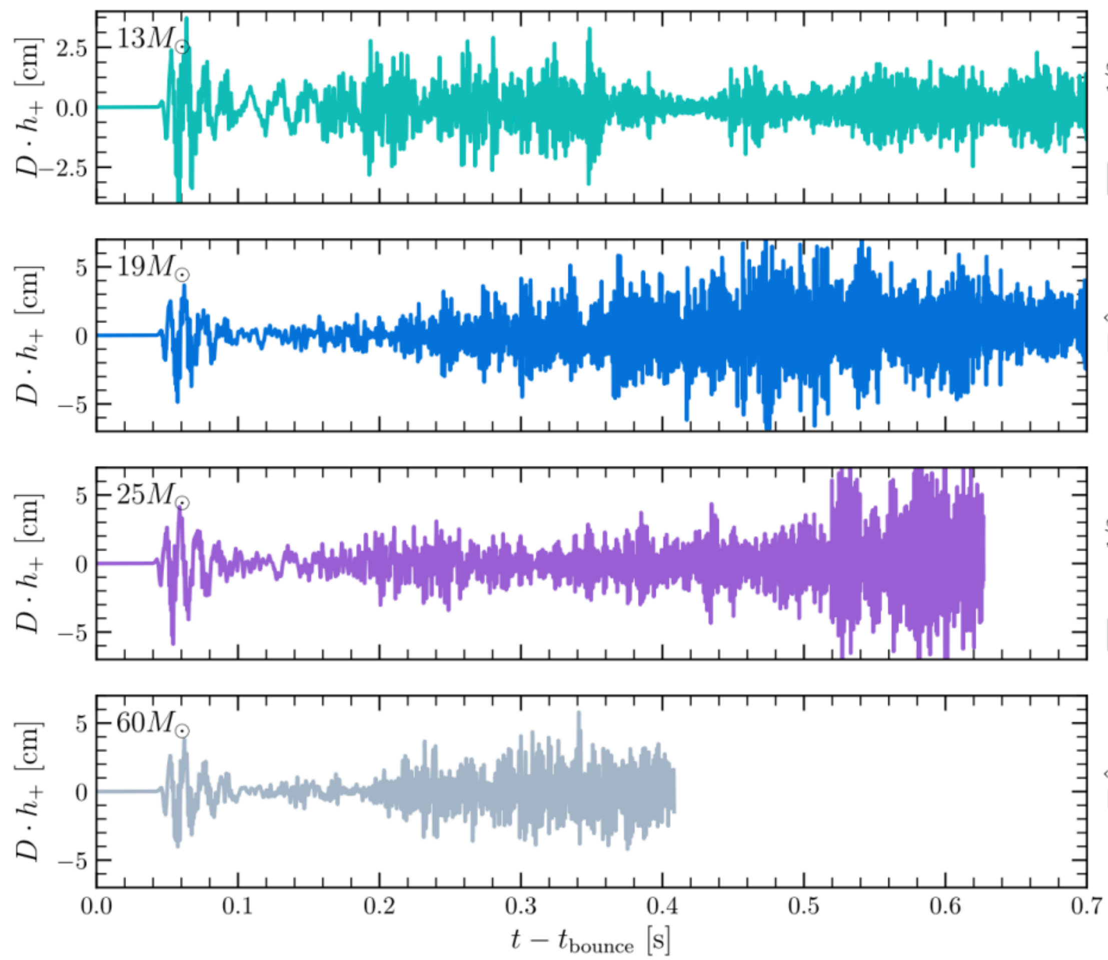
$27\ M_{sun}$ star Multiple SASI episodes and convection

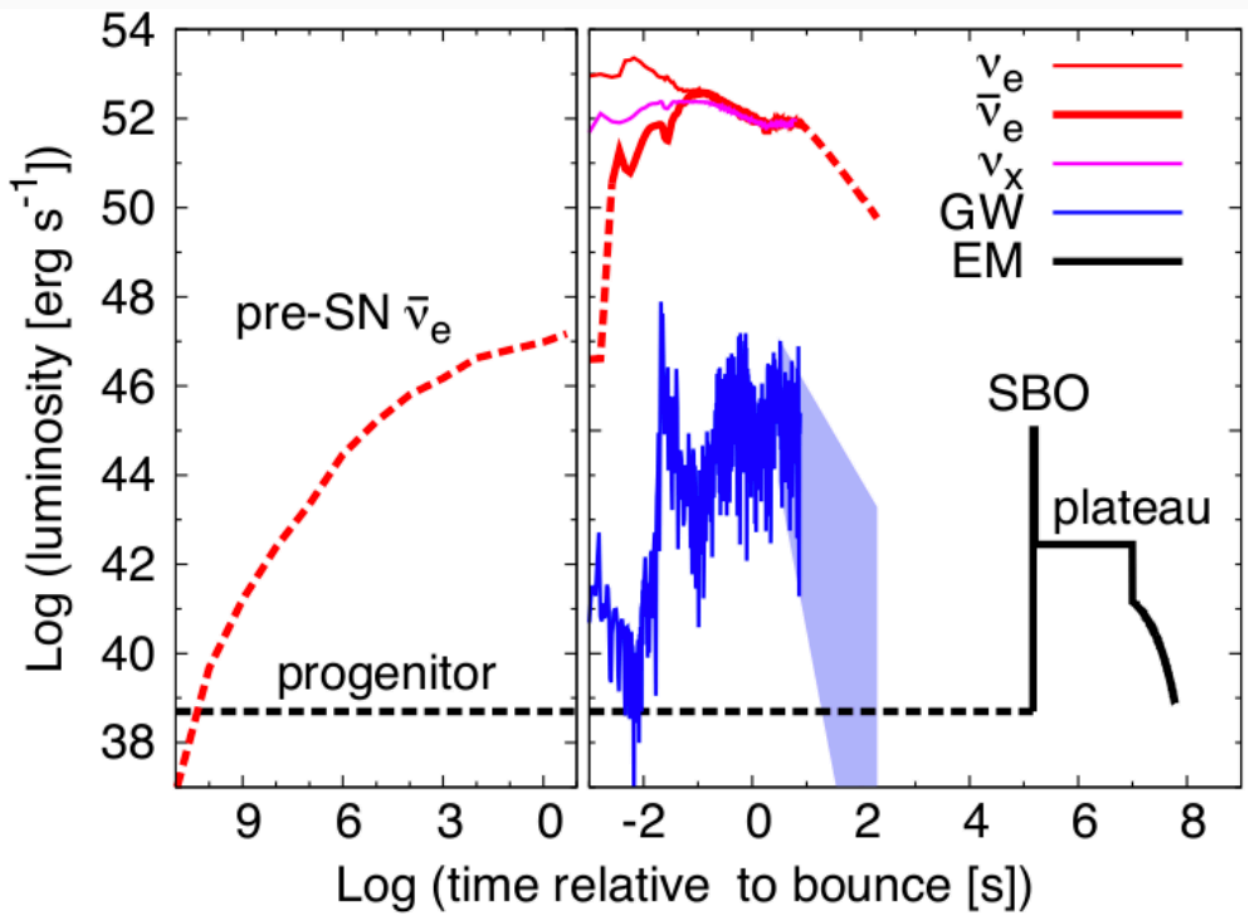
$20\ M_{sun}$ star Single SASI episode and convection

$11.2\ M_{sun}$ star No SASI episode; only convection

Neutrinos and gravitational waves

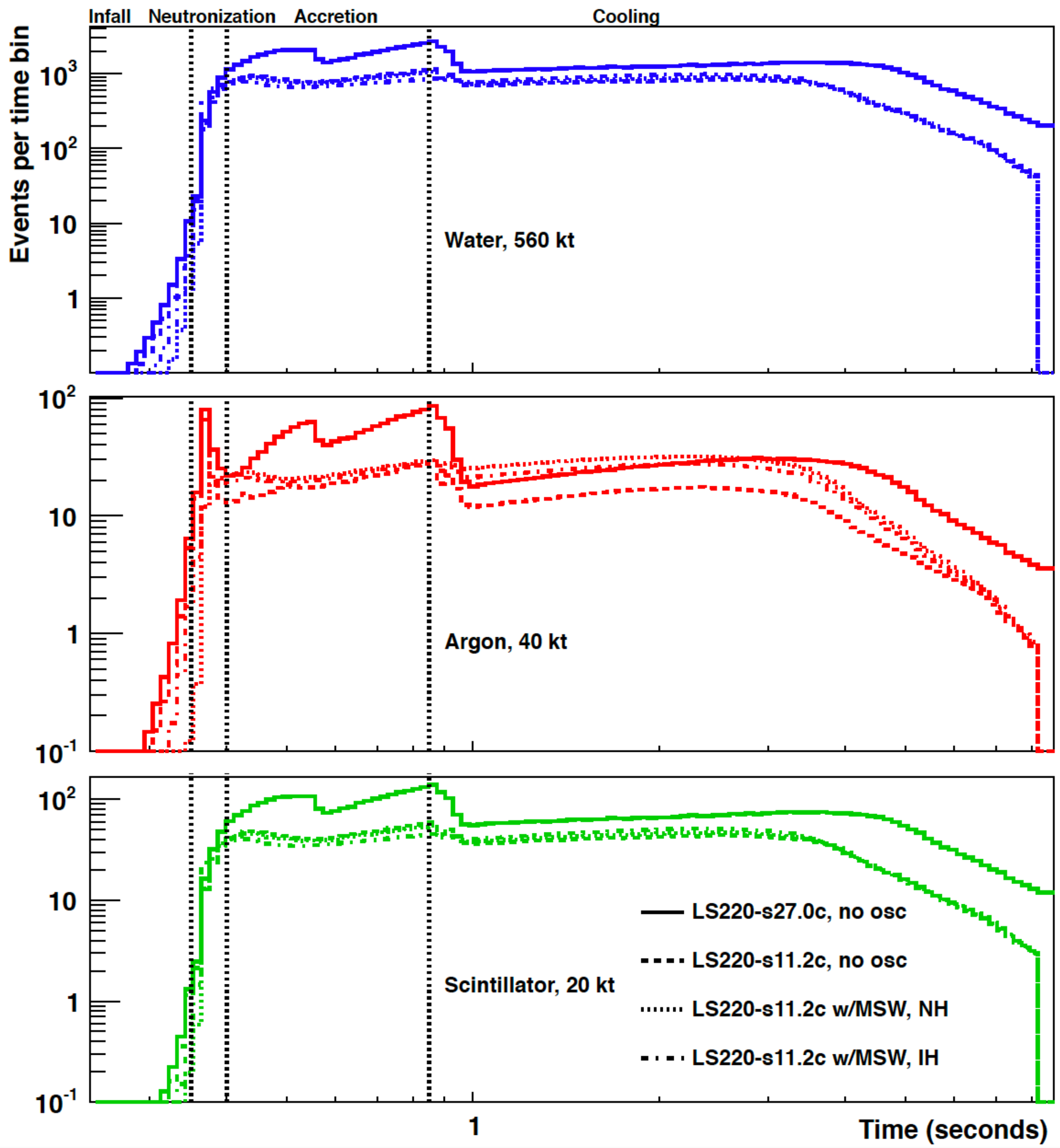
$17\,M_\odot$ progenitor at d=10 kpc

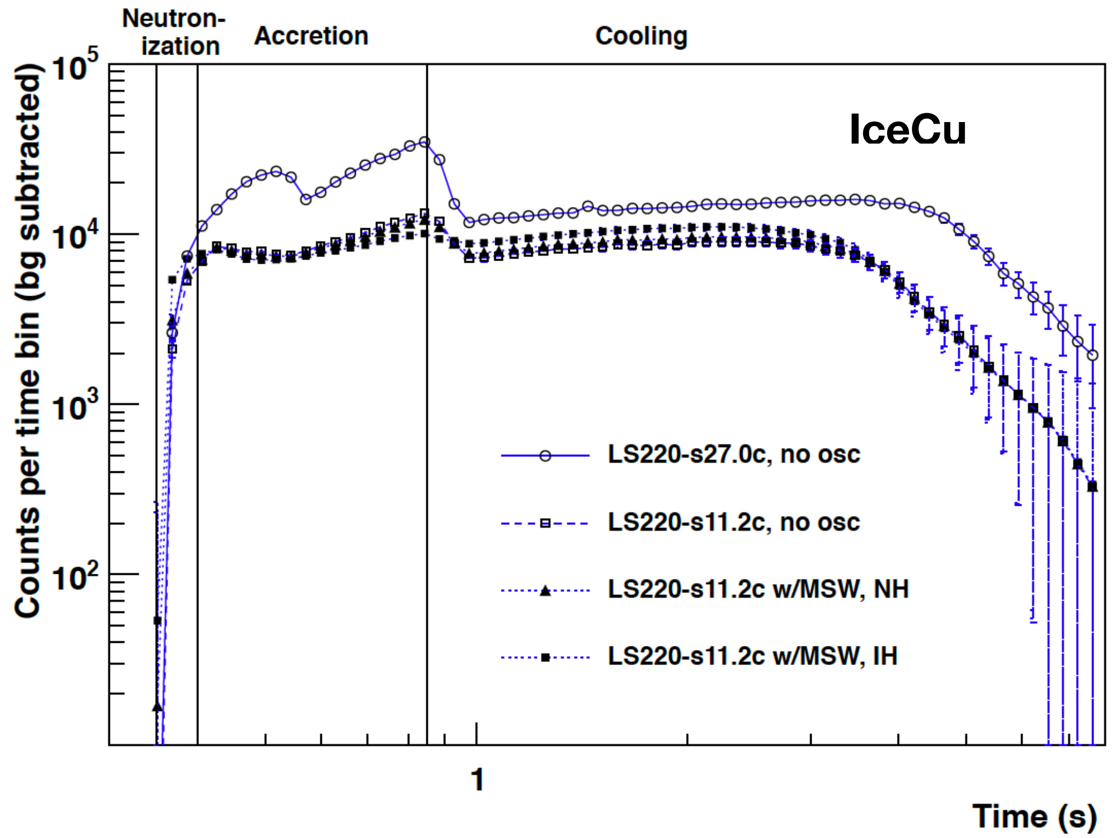




$$\frac{dE_{\rm GW}}{dt} \sim \varepsilon^2 \frac{c^5}{G}\left(\frac{r_{\rm Sh}}{R}\right)^2\left(\frac{\upsilon}{c}\right)^6$$

Future event rates in detectors





d=10 kpc

Future event rates in detectors

Detector	Type	Mass (kt)	Location	Events	Flavors	Status
Super-Kamiokande	H_2O	32	Japan	7,000	$\bar{\nu}_e$	Running
LVD	C_nH_{2n}	1	Italy	300	$\bar{\nu}_e$	Running
KamLAND	C_nH_{2n}	1	Japan	300	$\bar{\nu}_e$	Running
Borexino	C_nH_{2n}	0.3	Italy	100	$\bar{\nu}_e$	Running
IceCube	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$	Running
Baksan	C_nH_{2n}	0.33	Russia	50	$\bar{\nu}_e$	Running
MiniBooNE*	C_nH_{2n}	0.7	USA	200	$\bar{\nu}_e$	(Running)
HALO	Pb	0.08	Canada	30	ν_e, ν_x	Running
Daya Bay	C_nH_{2n}	0.33	China	100	$\bar{\nu}_e$	Running
NOνA*	C_nH_{2n}	15	USA	4,000	$\bar{\nu}_e$	Turning on
SNO+	C_nH_{2n}	0.8	Canada	300	$\bar{\nu}_e$	Near future
MicroBooNE*	Ar	0.17	USA	17	ν_e	Near future
DUNE	Ar	34	USA	3,000	ν_e	Proposed
Hyper-Kamiokande	H_2O	560	Japan	110,000	$\bar{\nu}_e$	Proposed
JUNO	C_nH_{2n}	20	China	6000	$\bar{\nu}_e$	Proposed
RENO-50	C_nH_{2n}	18	Korea	5400	$\bar{\nu}_e$	Proposed
LENA	C_nH_{2n}	50	Europe	15,000	$\bar{\nu}_e$	Proposed
PINGU	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$	Proposed

Neutrino parameters

NuFIT 5.2 (2022)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
	$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
	$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.406 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
	$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
	$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00059}$	$0.02029 \to 0.02391$	$0.02219^{+0.00060}_{-0.00057}$	$0.02047 \to 0.02396$
	$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.12}$	$8.19 \to 8.89$	$8.57^{+0.12}_{-0.11}$	$8.23 \to 8.90$
	$\delta_{CP}/^\circ$	197^{+42}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.511^{+0.028}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.025}$	$-2.581 \to -2.408$
		Normal Ordering (best fit)		**Inverted Ordering ($\Delta\chi^2 = 6.4$)**	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.012}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
	$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
	$\sin^2\theta_{23}$	$0.451^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.569^{+0.016}_{-0.021}$	$0.412 \to 0.613$
	$\theta_{23}/^\circ$	$42.2^{+1.1}_{-0.9}$	$39.7 \to 51.0$	$49.0^{+1.0}_{-1.2}$	$39.9 \to 51.5$
	$\sin^2\theta_{13}$	$0.02225^{+0.00056}_{-0.00059}$	$0.02052 \to 0.02398$	$0.02223^{+0.00058}_{-0.00058}$	$0.02048 \to 0.02416$
	$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.94$
	$\delta_{CP}/^\circ$	232^{+36}_{-26}	$144 \to 350$	276^{+22}_{-29}	$194 \to 344$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.507^{+0.026}_{-0.027}$	$+2.427 \to +2.590$	$-2.486^{+0.025}_{-0.028}$	$-2.570 \to -2.406$

Earth-matter effects

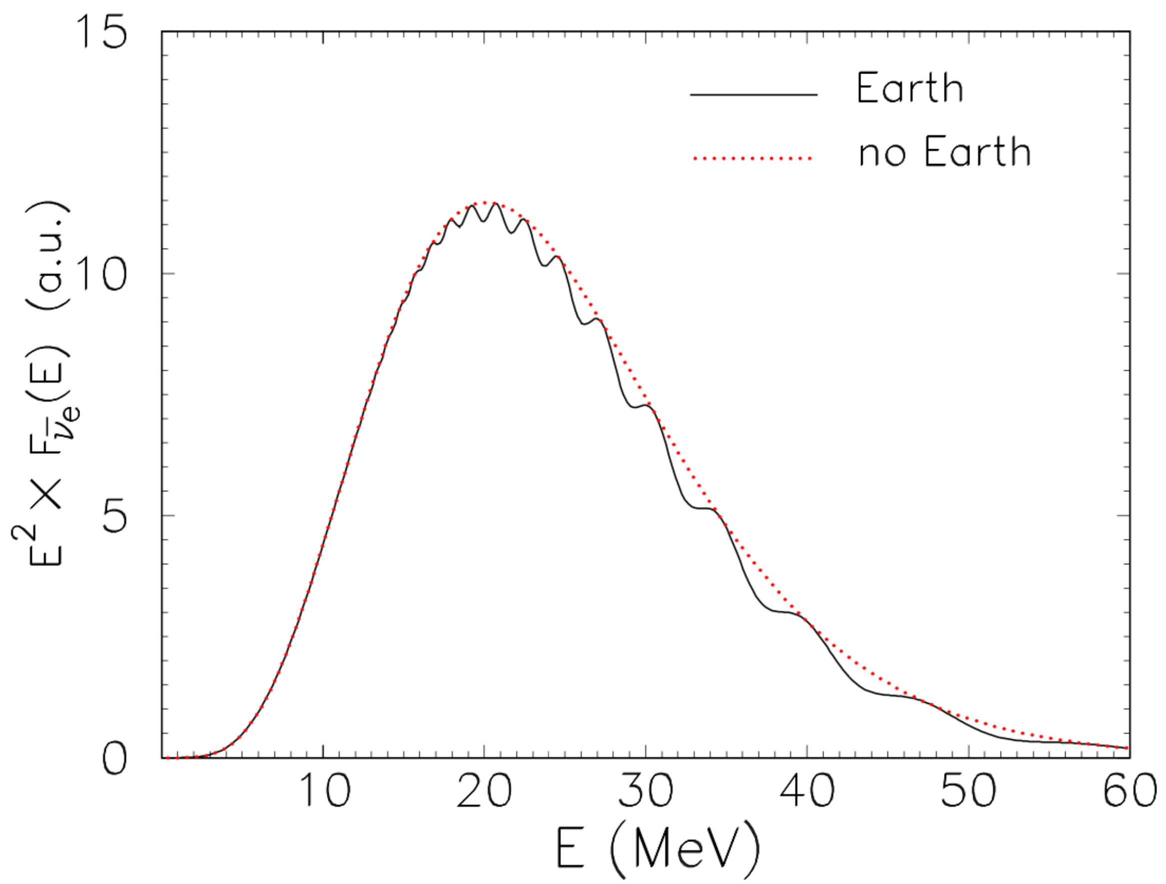
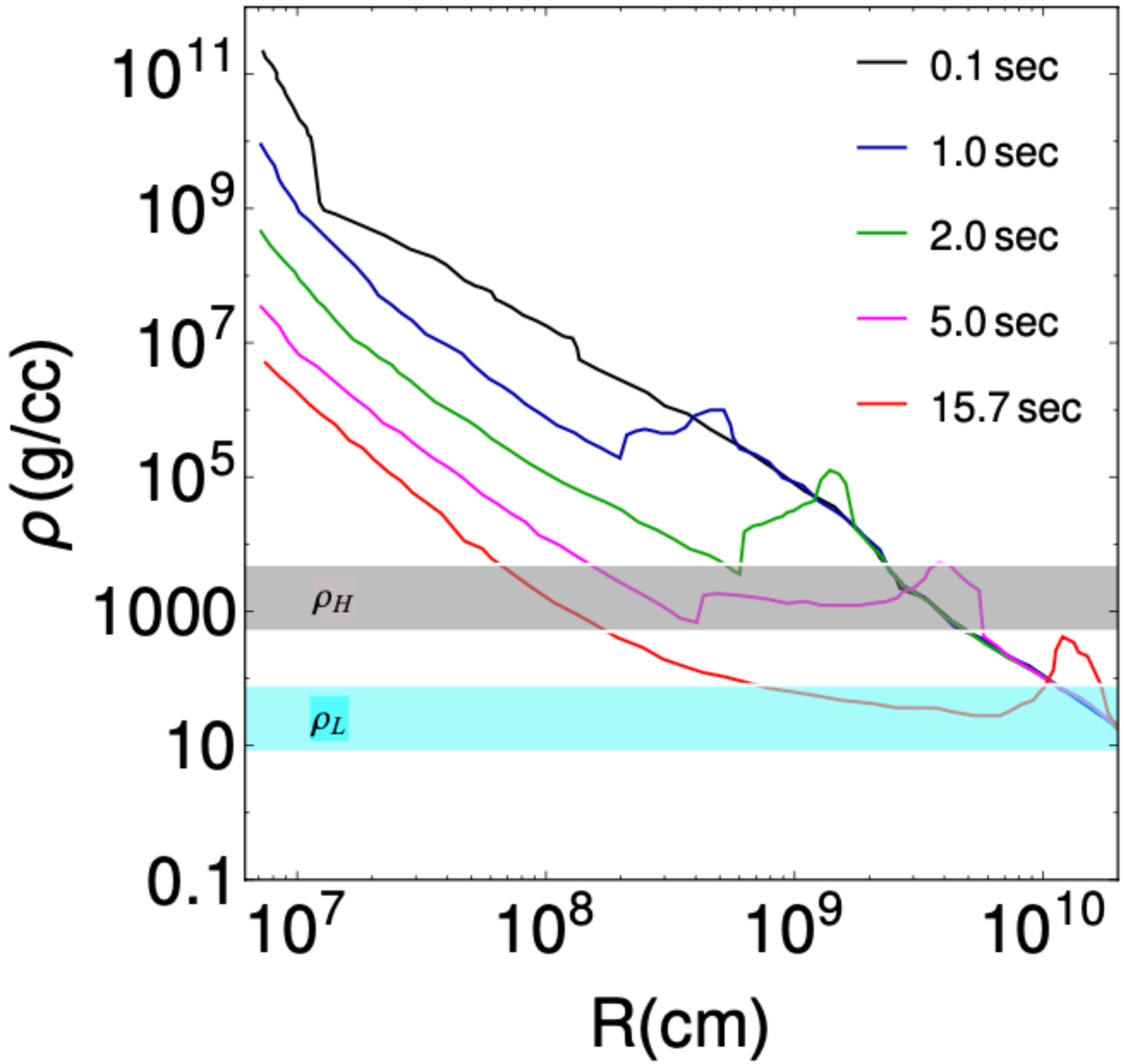
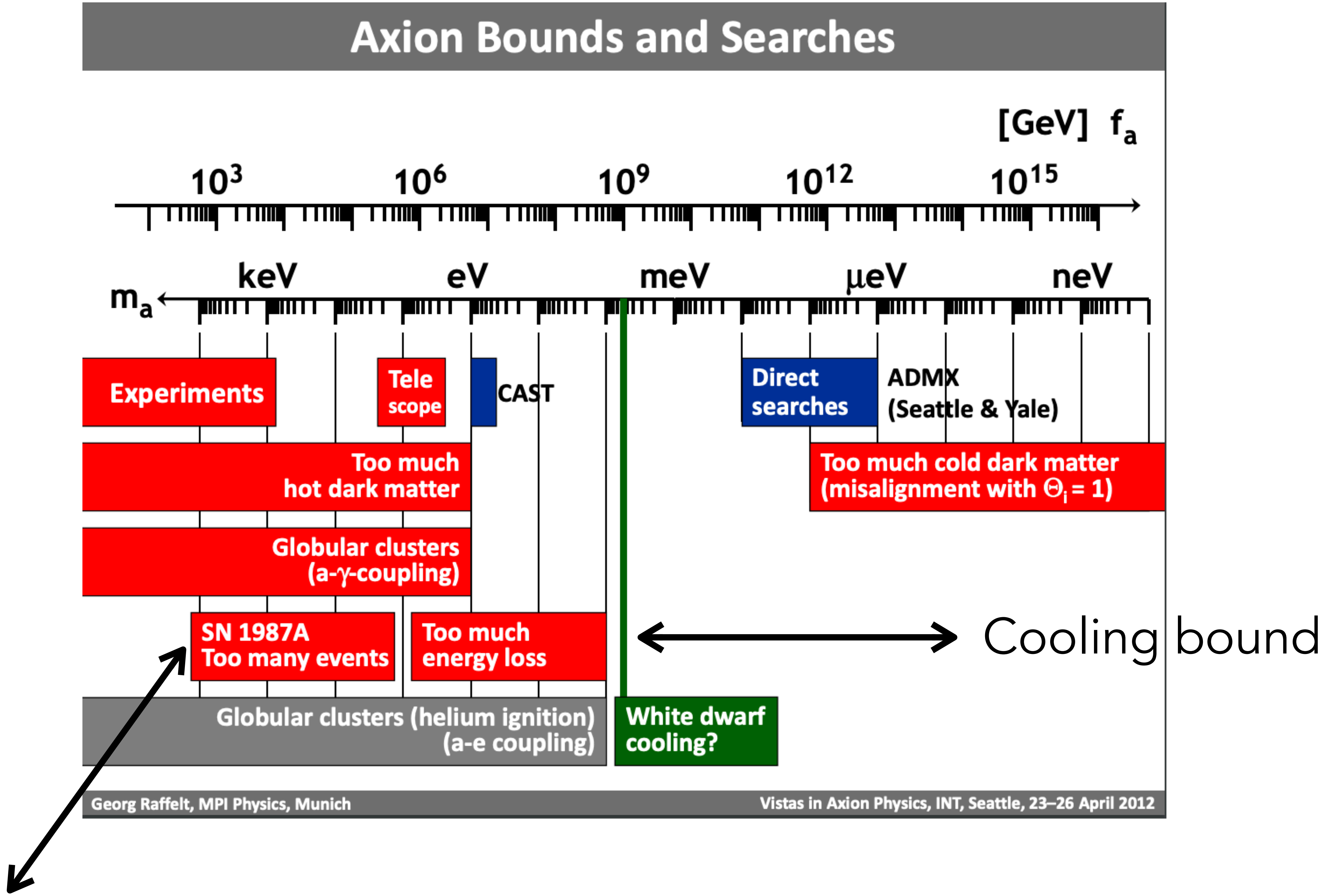


Fig. 39. – Observable signal $E^2 F_{\bar{\nu}_e}$ with (continuous curve) and without (dotted curve) Earth crossing.

SN density profile



Axion bounds



Too many events due to absorption on O, and subsequent γ emission.