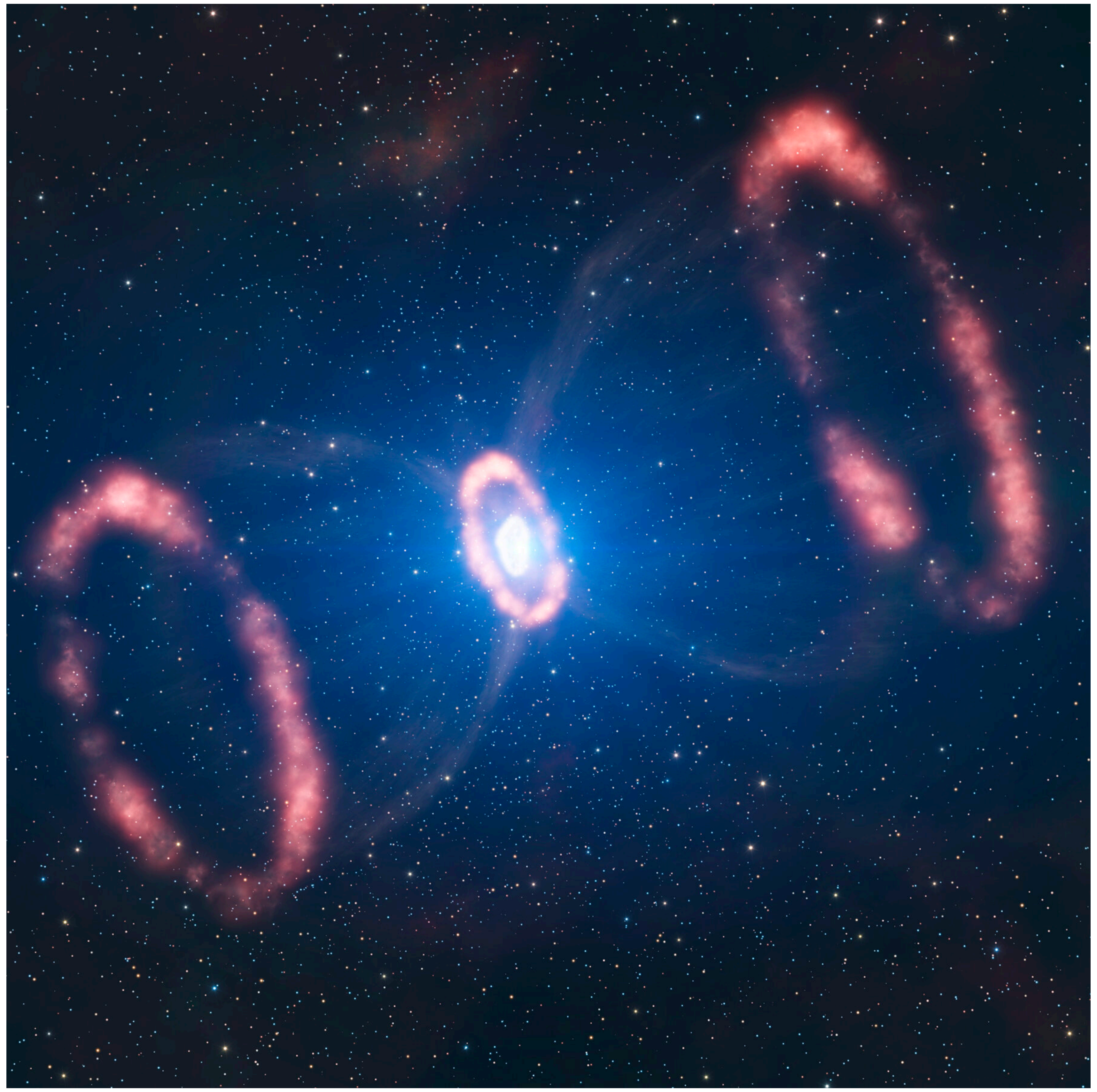
SUPERNOVA NEUTRINOS

Manibrata Sen

Max-Planck-Institut für Kernphysik
Heidelberg

Invisibles23 Workshop
28/08/23



MAX-PLANCK-INSTITUT
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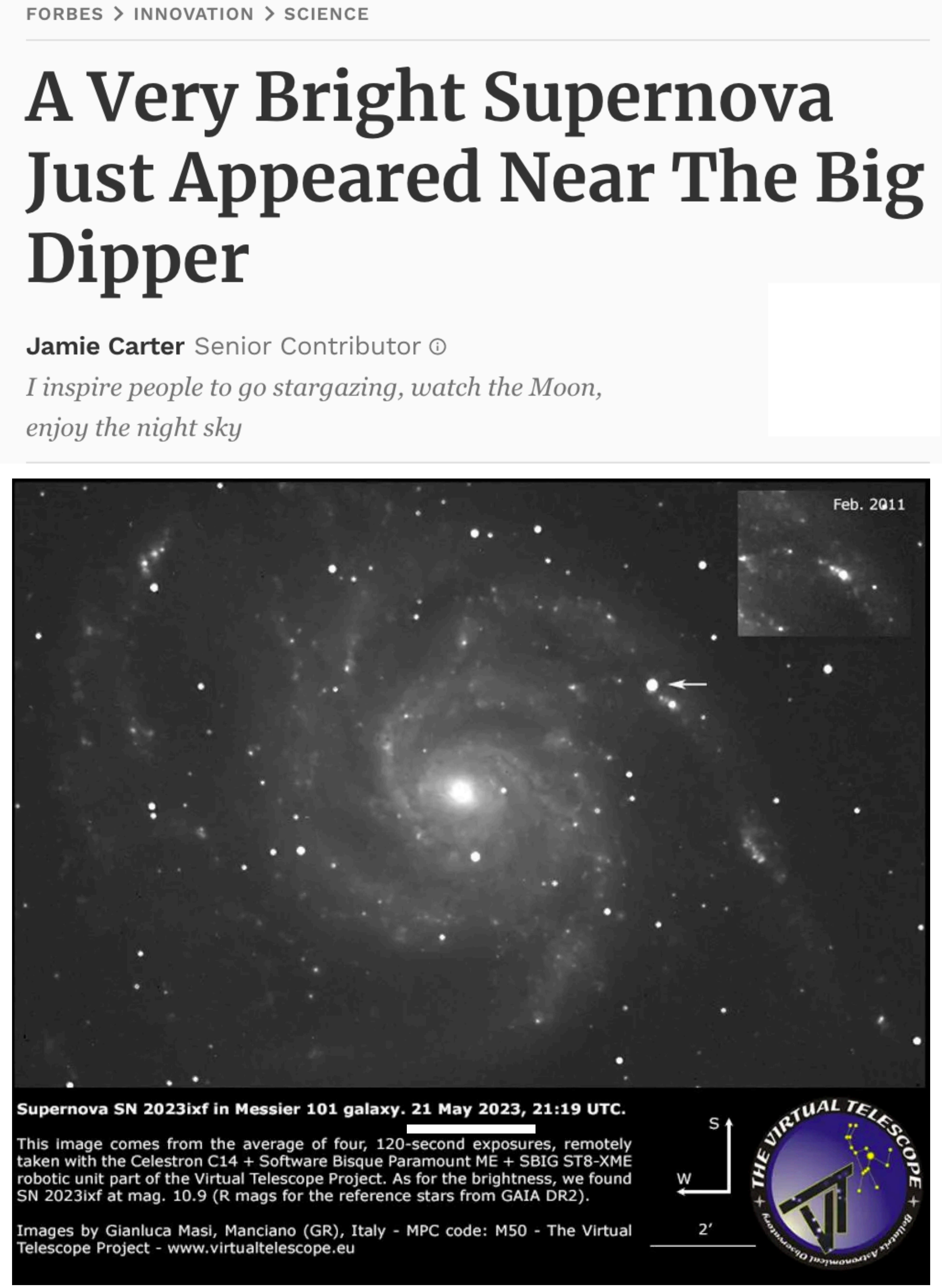
HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Asymmetry
Essential Asymmetries of Nature



FORBES > INNOVATION > SCIENCE

A Very Bright Supernova Just Appeared Near The Big Dipper

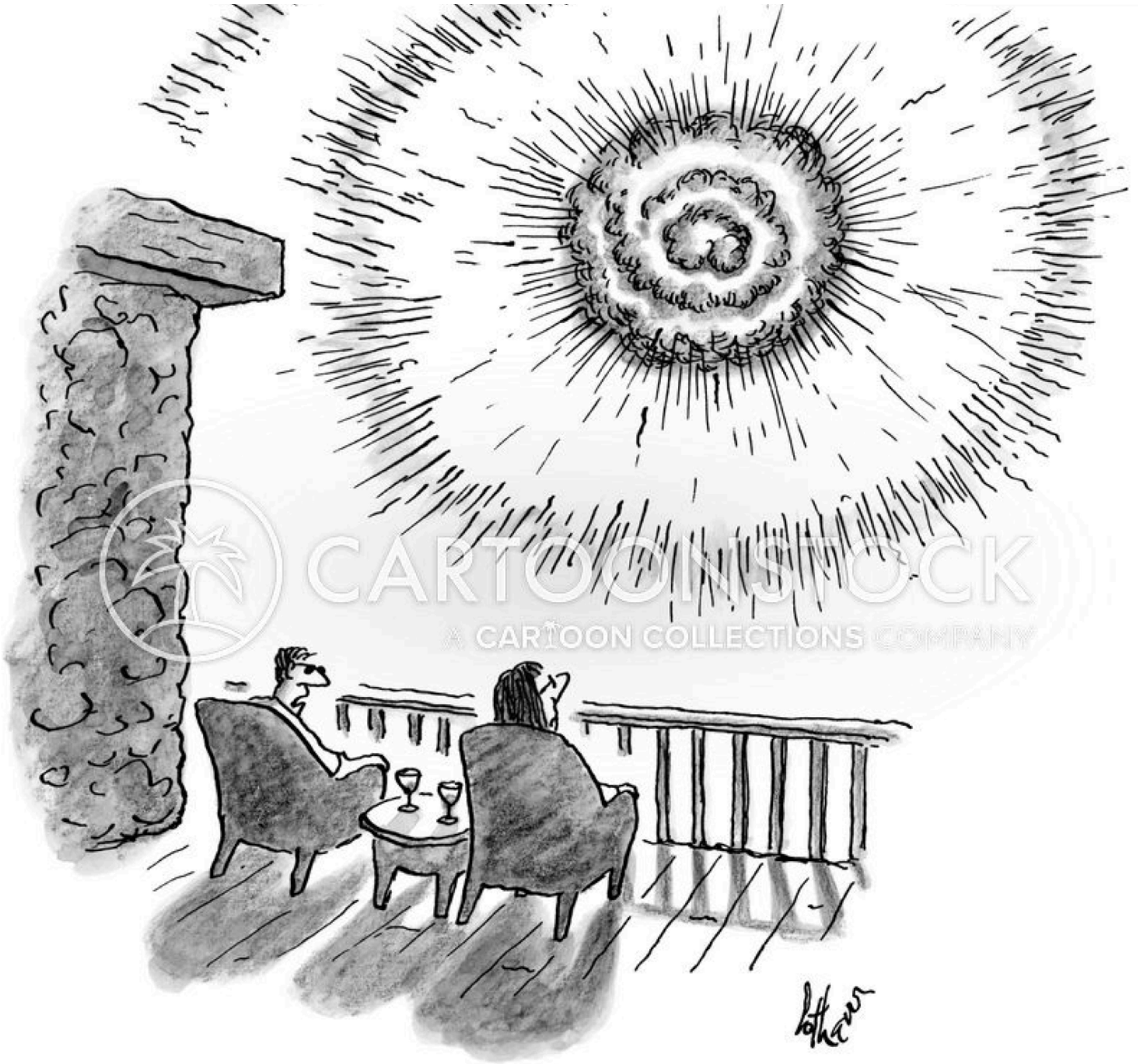
Jamie Carter Senior Contributor

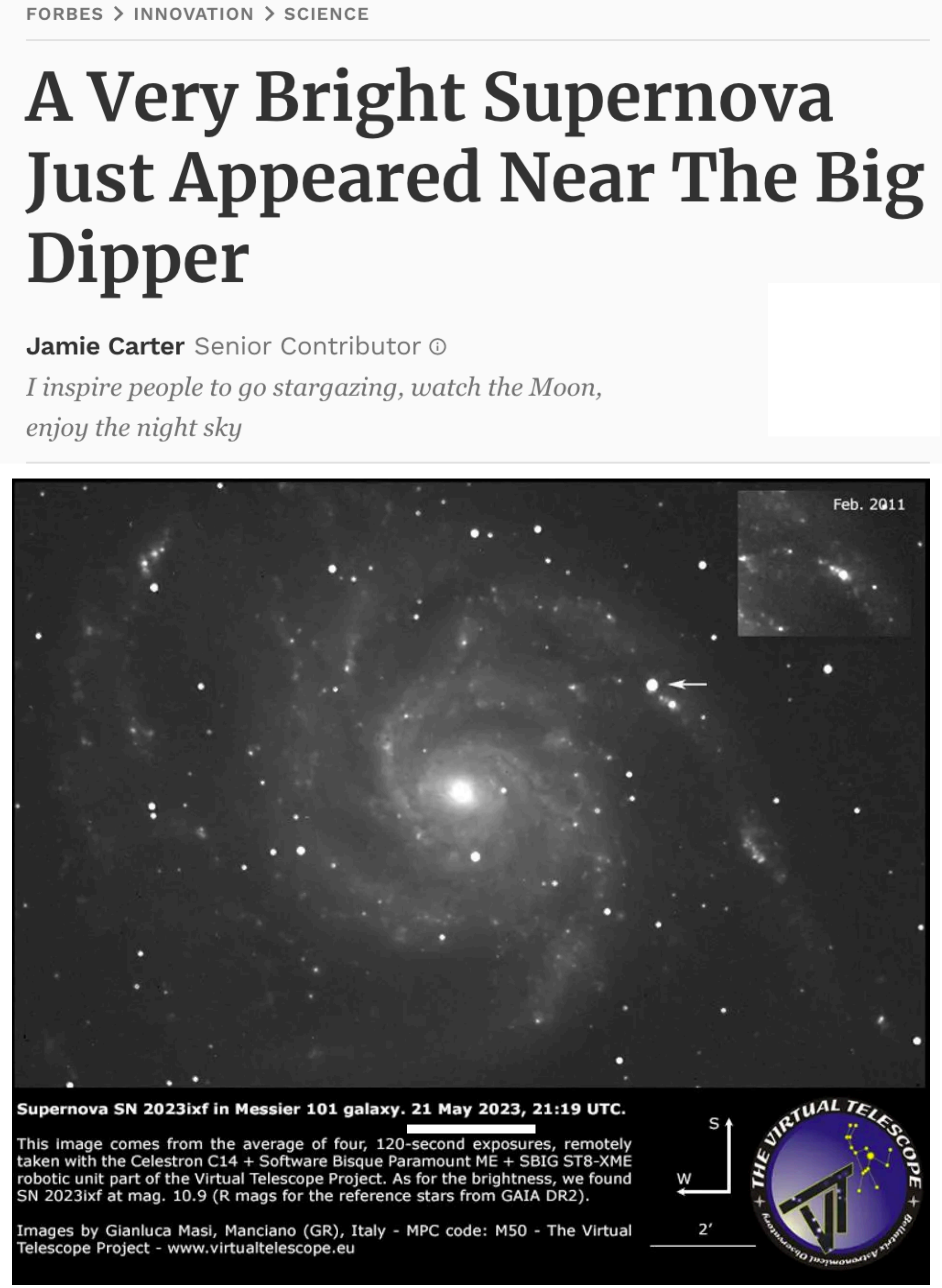
I inspire people to go stargazing, watch the Moon, enjoy the night sky

Supernova SN 2023ixf in Messier 101 galaxy. 21 May 2023, 21:19 UTC.

This image comes from the average of four, 120-second exposures, remotely taken with the Celestron C14 + Software Bisque Paramount ME + SBIG ST8-XME robotic unit part of the Virtual Telescope Project. As for the brightness, we found SN 2023ixf at mag. 10.9 (R mags for the reference stars from GAIA DR2).

Images by Gianluca Masi, Manciano (GR), Italy - MPC code: M50 - The Virtual Telescope Project - www.virtualtelescope.eu

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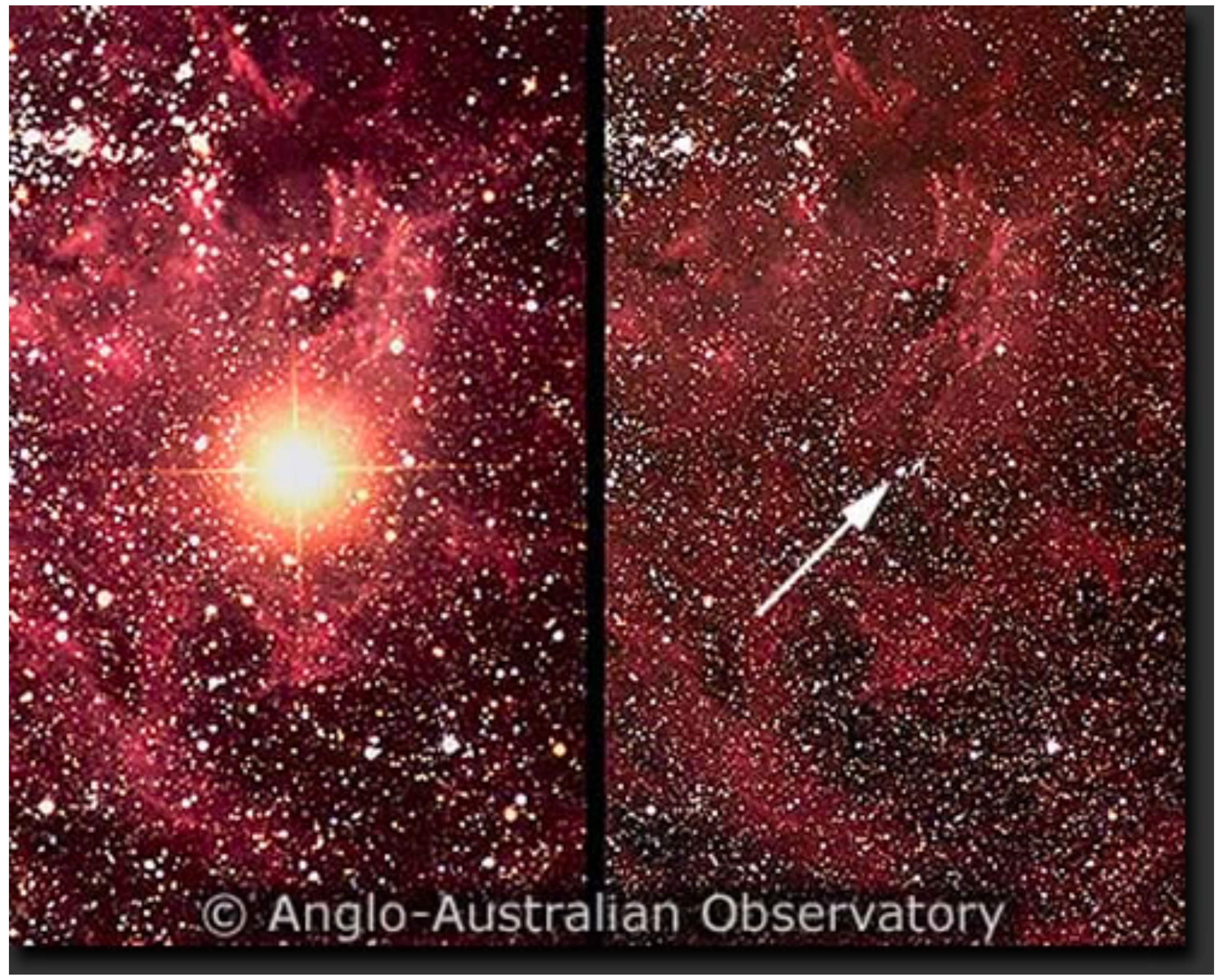
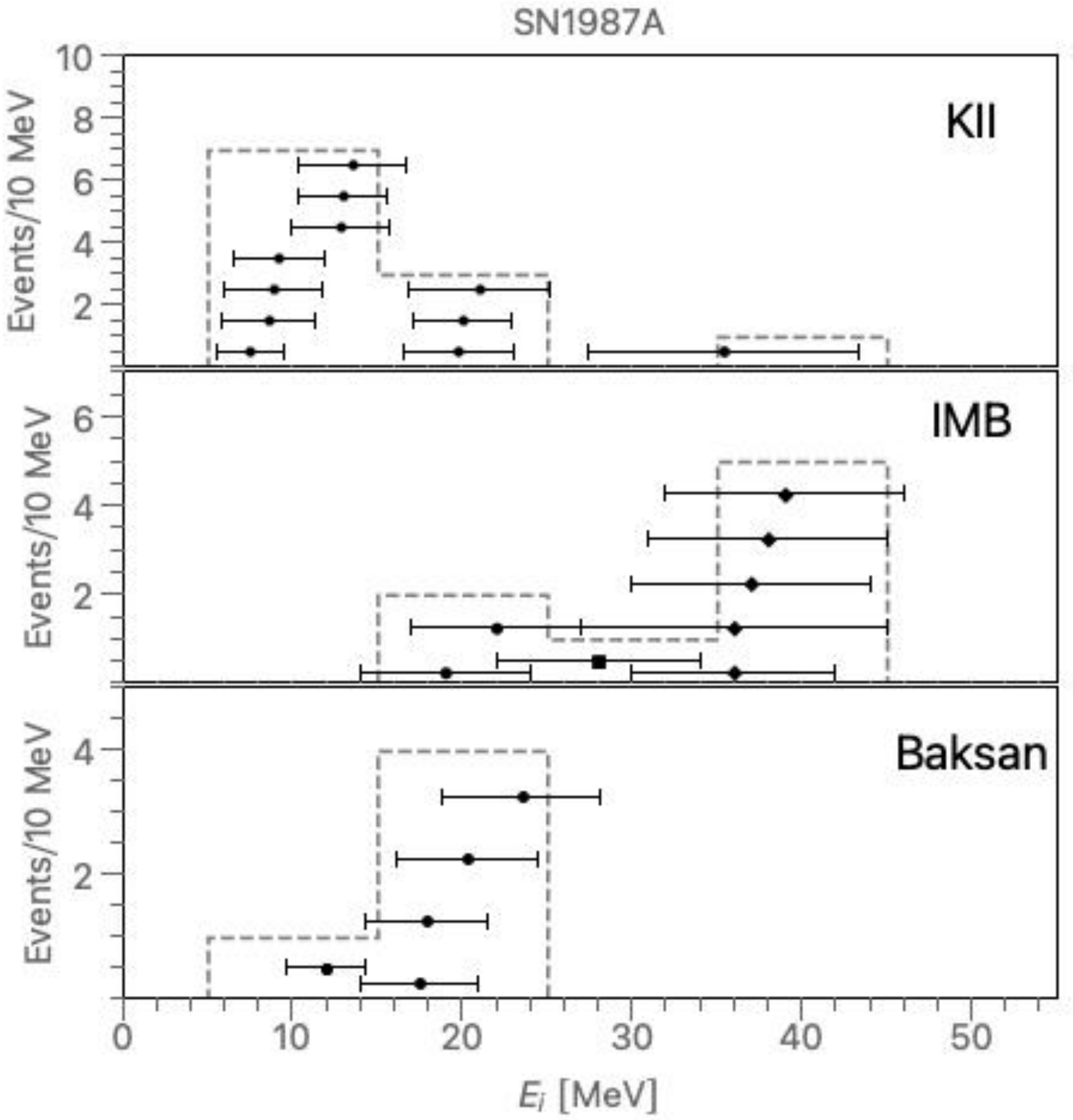
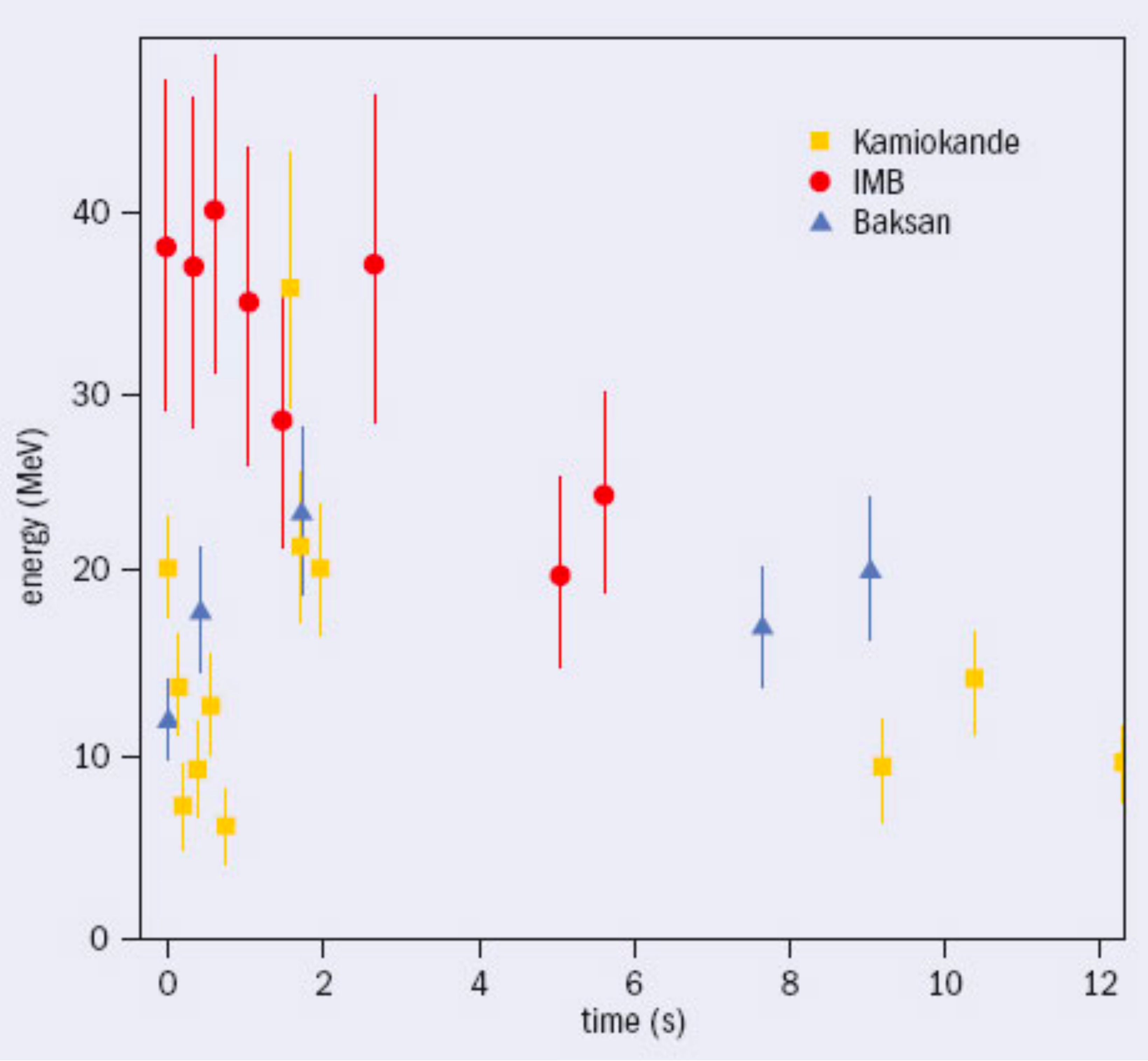
Core-collapse supernova:SN1987A

- SN1987A: in the Large Magellanic Cloud, 50 kpc away. $18 M_\odot$ star.

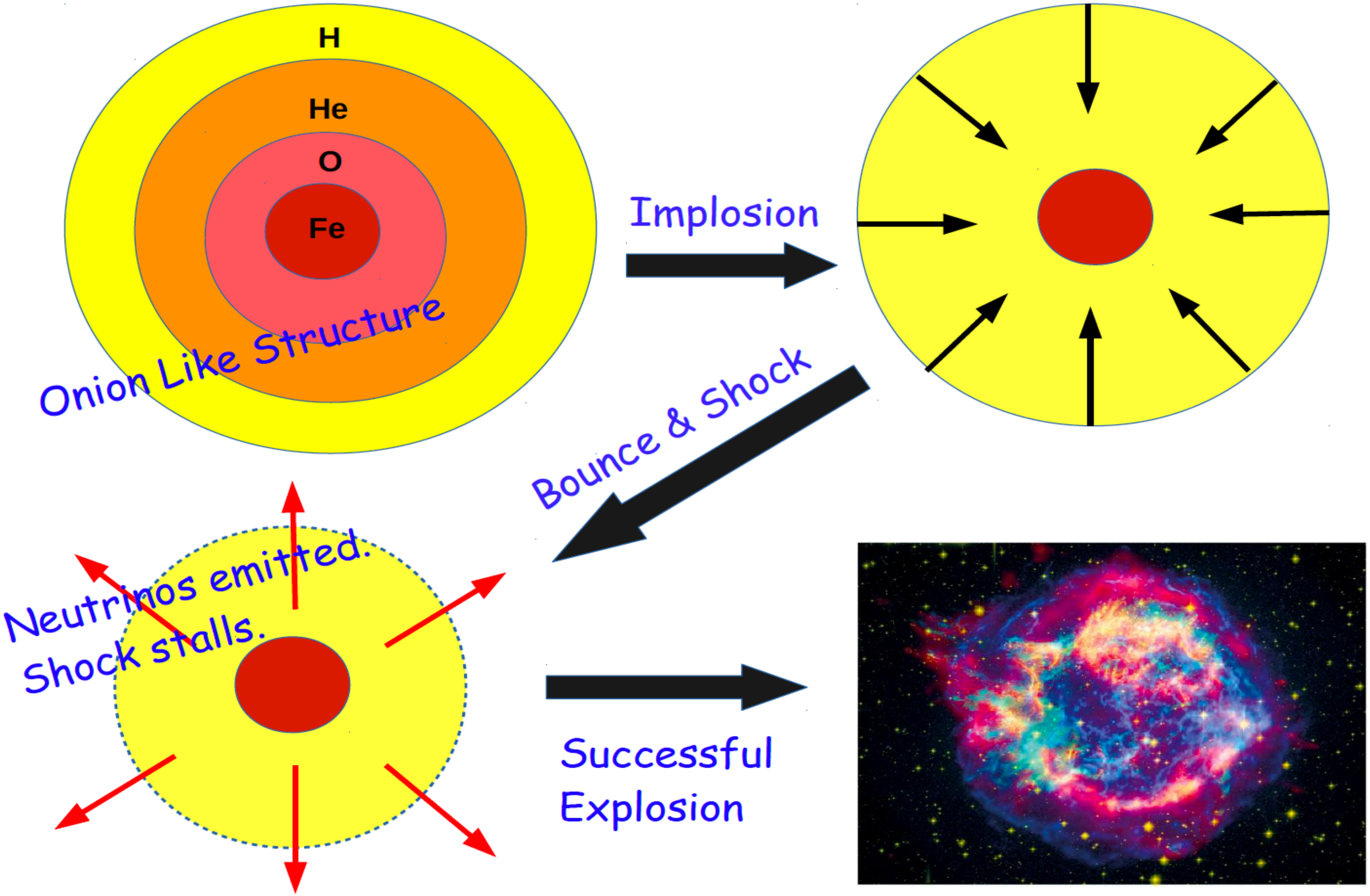






- One of the first examples of multi-messenger astronomy.

Mechanism of a core-collapse supernova



Onion Like Structure

Implosion

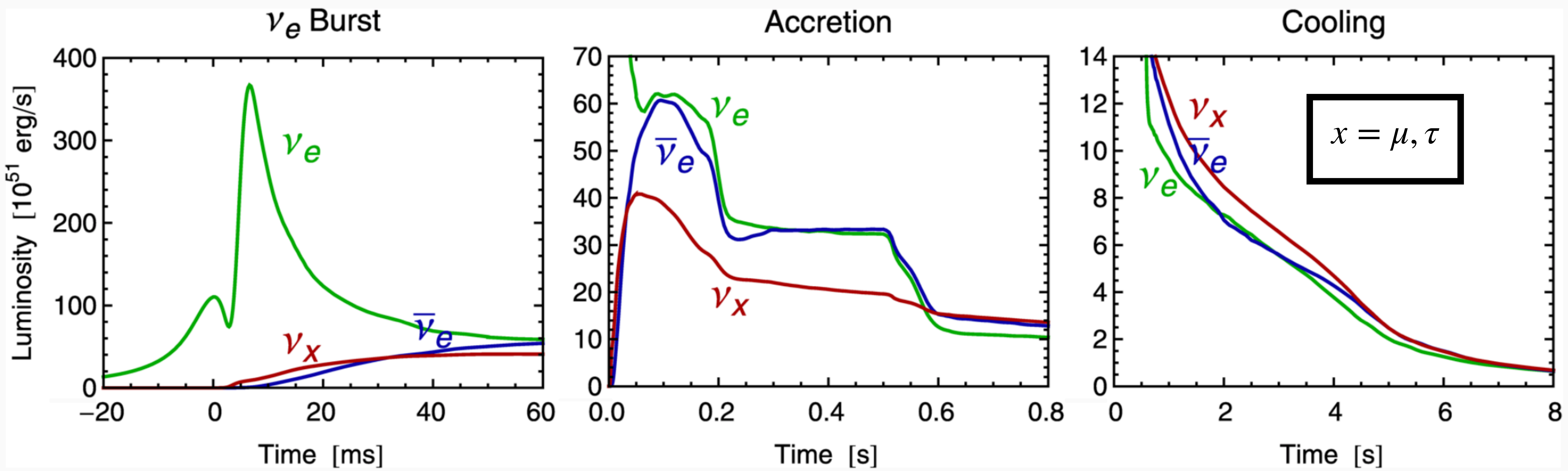
Bounce & Shock

Neutrinos emitted.
Shock stalls.

Successful
Explosion

Neutrino emission from a supernova

Garching simulations



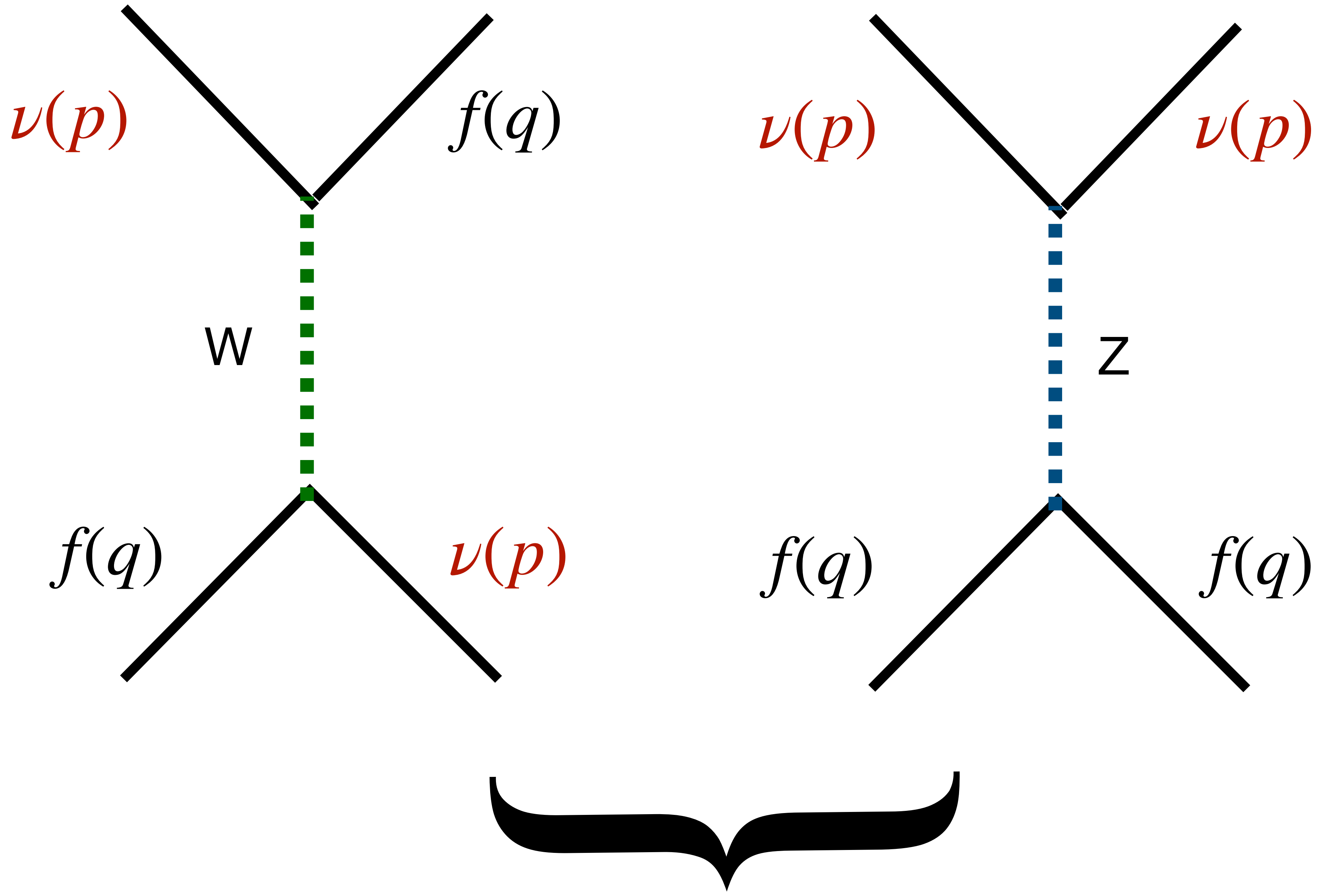
- Mostly ν_e.
- Good laboratory.

- Neutrino self-interactions.
- Collective oscillations

- Mostly thermal flux
- Cooling sensitive to new physics

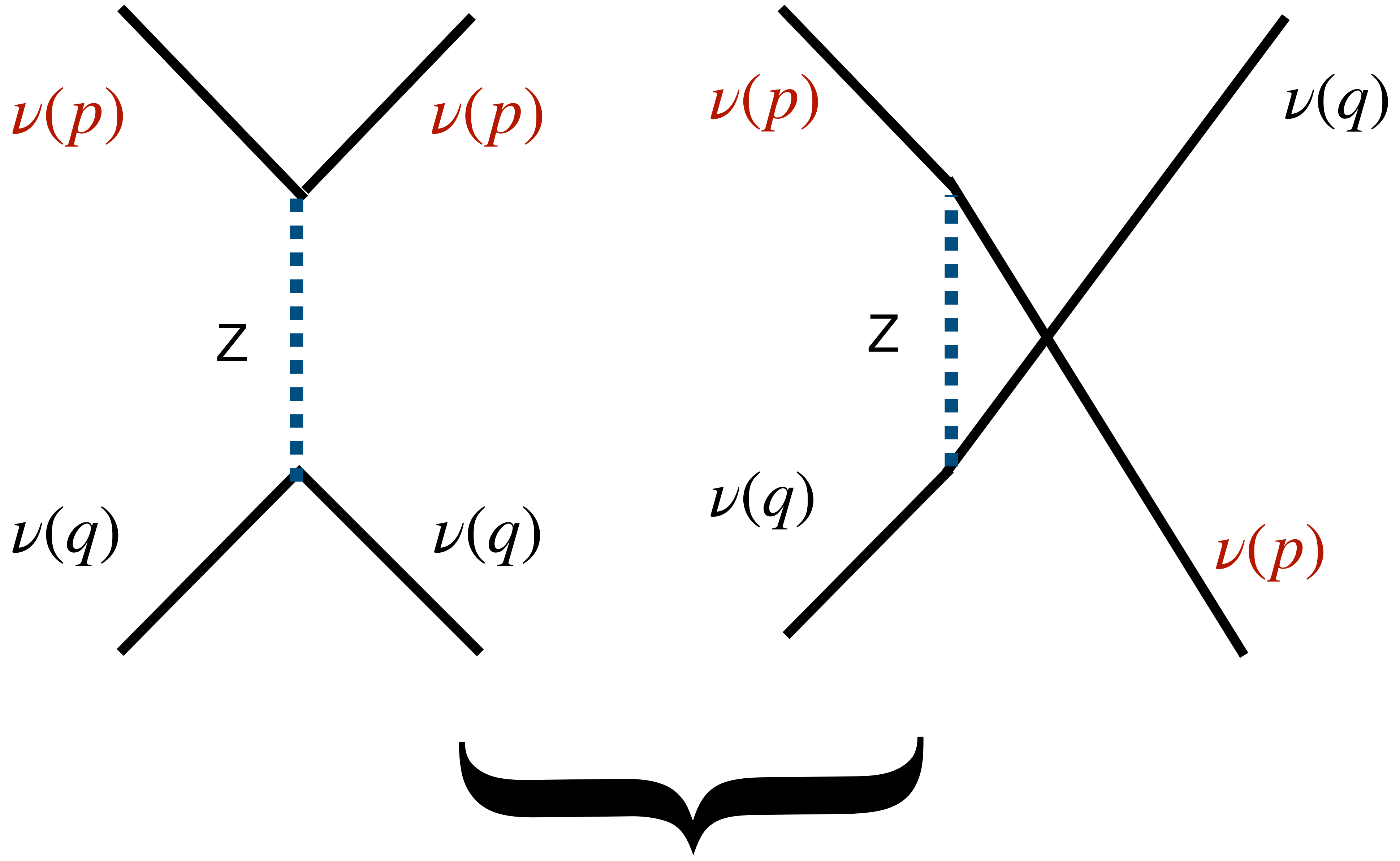
- A core-collapse SN emits almost all of its energy in the form of neutrinos.
- $\sim 10^{58}$ neutrinos are emitted in a period of 10s.

Neutrino propagation through a SN



Same as the Sun

+



Additional potential

- Neutrino density so high that they feel additional potential due to neutrinos. This potential can be between different neutrino flavours.

- Only lab where neutrino self-interactions become important.

Wolfenstein (PRD1978,1979)
Mikheyev and Smirnov (SJNP1985)
Pantaleone (PRD 1992)
Duan, Fuller, Carlson and Qian (PRD 2006,2007)
Hannestad, Raffelt, Sigl and Wong (2006)

Production

Propagation

Detection

R~10 km.
ν- sphere

Neutrinos decouple

$r_{\nu_e} > r_{\bar{\nu}_e} \gg r_{\nu_{\mu,\tau}}$

Large ν density. νs forward scatter off each other.

νs forward scatter off Background e^-, leading to MSW effect

Vacuum propagation

Detectors

SN Envelope

The matrix of densities : (1+3+3 D)

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

$$\varrho(t, r, p) = \begin{bmatrix} \langle \nu_e | \nu_e \rangle & \langle \nu_e | \nu_x \rangle \\ \langle \nu_x | \nu_e \rangle & \langle \nu_x | \nu_x \rangle \end{bmatrix}$$

$\langle \nu_{e,x} | \nu_{e,x} \rangle$ related to net flavour content

$\langle \nu_e | \nu_x \rangle$ encodes flavour oscillations

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

Inelastic Collision term

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

vacuum

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

MSW matter term

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

$\nu - \nu$ term

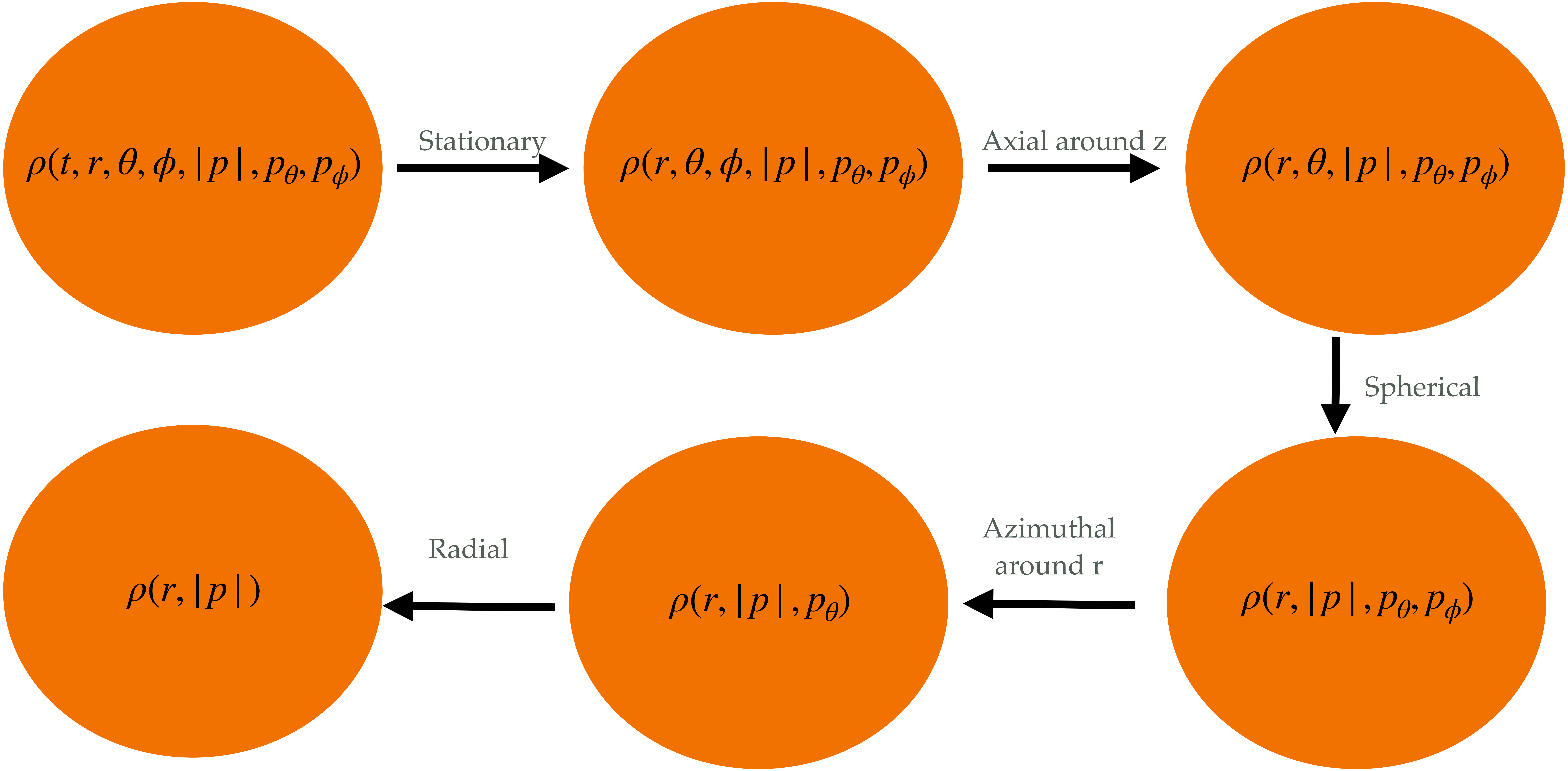
$$\mu = \sqrt{2} G_F n_\nu$$

Coupled, non-linear problem

Three length scales

$\mu \gtrsim \lambda \gg \omega$

Collective oscillations - where do we stand?



$\rho(t, r, \theta, \phi, |p|, p_\theta, p_\phi)$

Stationary

$\rho(r, \theta, \phi, |p|, p_\theta, p_\phi)$

Axial around z

$\rho(r, \theta, |p|, p_\theta, p_\phi)$

Spherical

$\rho(r, |p|, p_\theta, p_\phi)$

Azimuthal
around r

$\rho(r, |p|, p_\theta)$

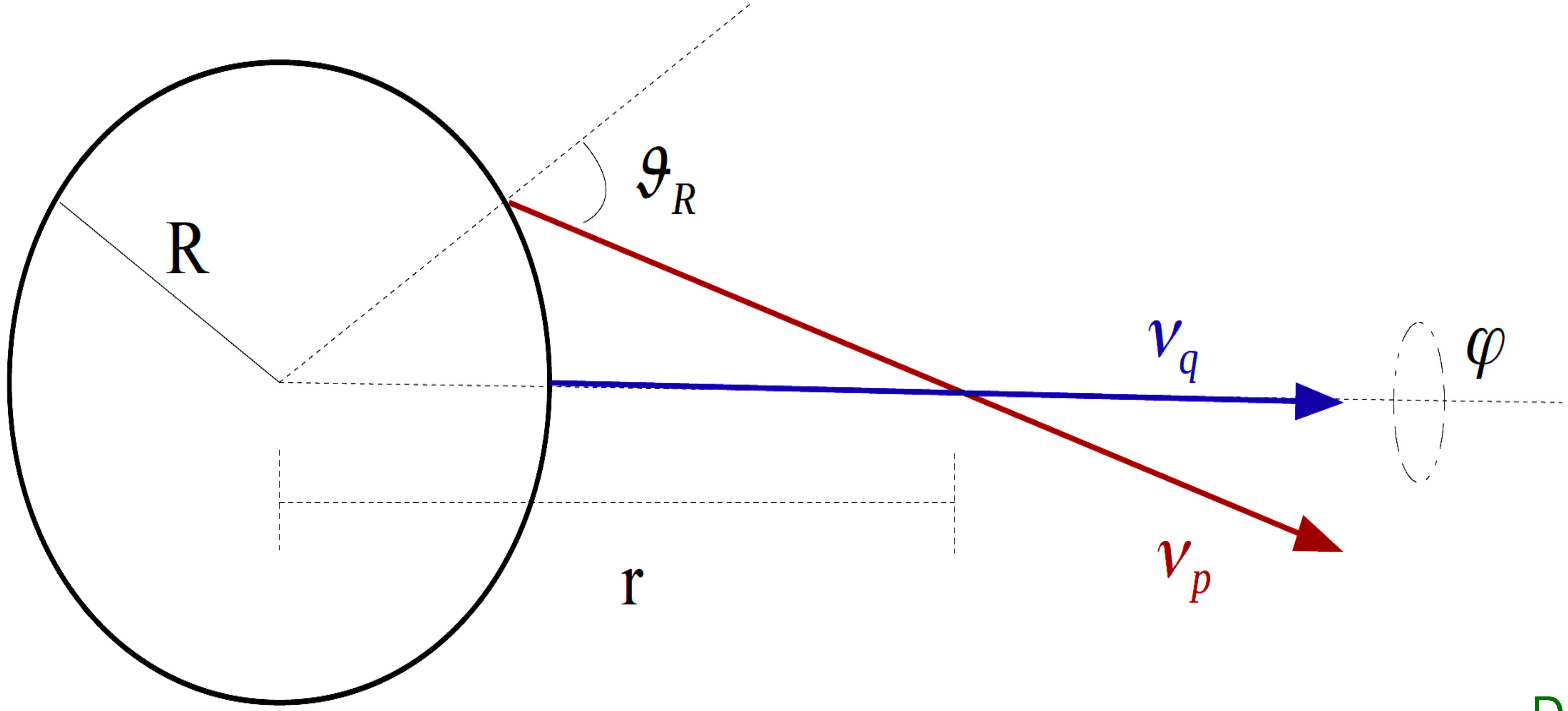
Radial

$\rho(r, |p|)$

Single angle bulb model

Multi-angle bulb model

Collective oscillations: simple single angle model



Duan, Fuller, Carlson and Qian (PRD 2006,2007)
Hannestad, Raffelt, Sigl and Wong (PRD 2006)

- The simplest system demonstrating collective oscillations:

$$\nu: \qquad d_t \varrho_p = -i[\omega_p + \mu(\varrho_q - \overline{\varrho_q}), \varrho_p]$$

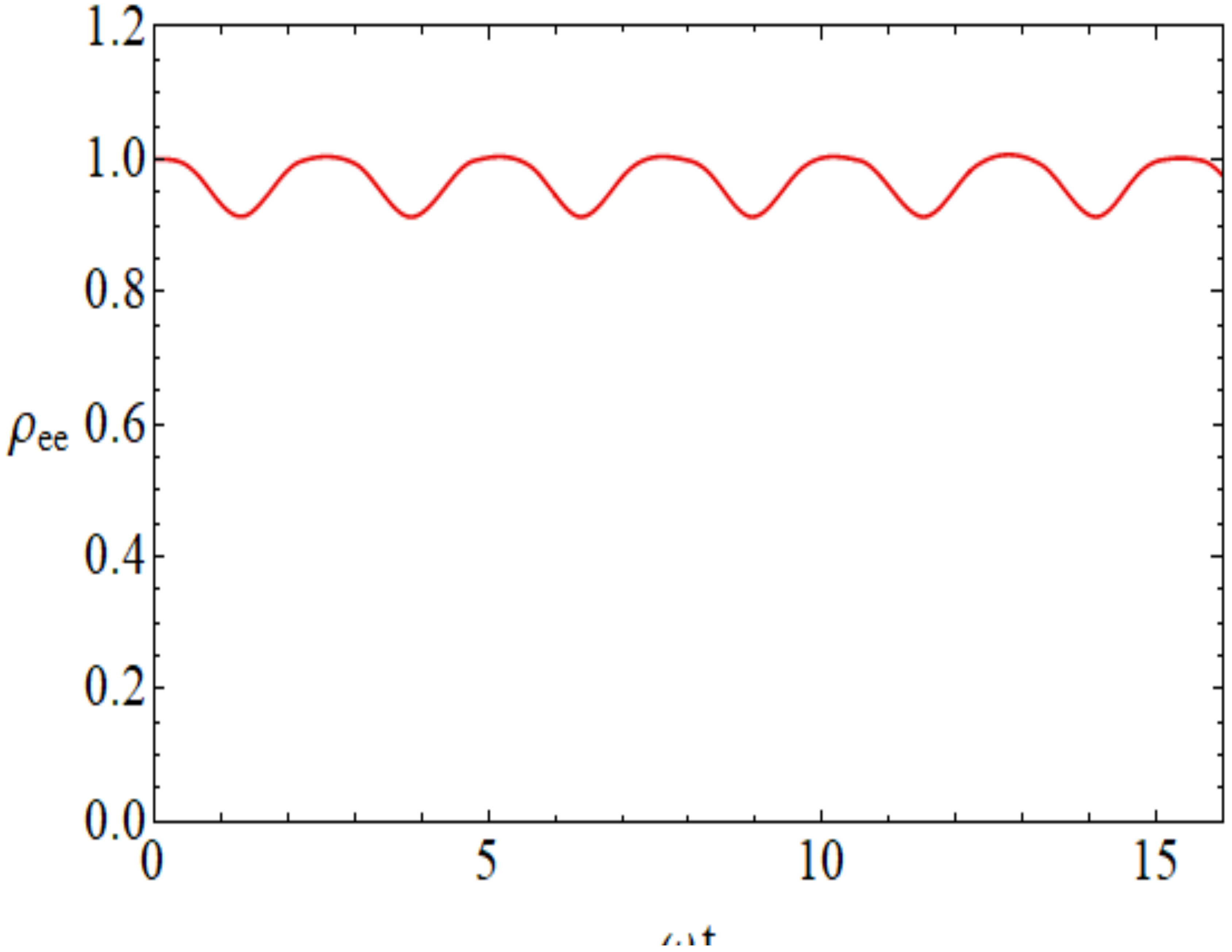
$$\boxed{\omega \gtrsim 0.1\,\mathrm{km}^{-1}}$$

$$\bar{\nu}: \qquad d_t \overline{\varrho_p} = -i[-\omega_p + \mu(\varrho_q - \overline{\varrho_q}), \overline{\varrho_p}]$$

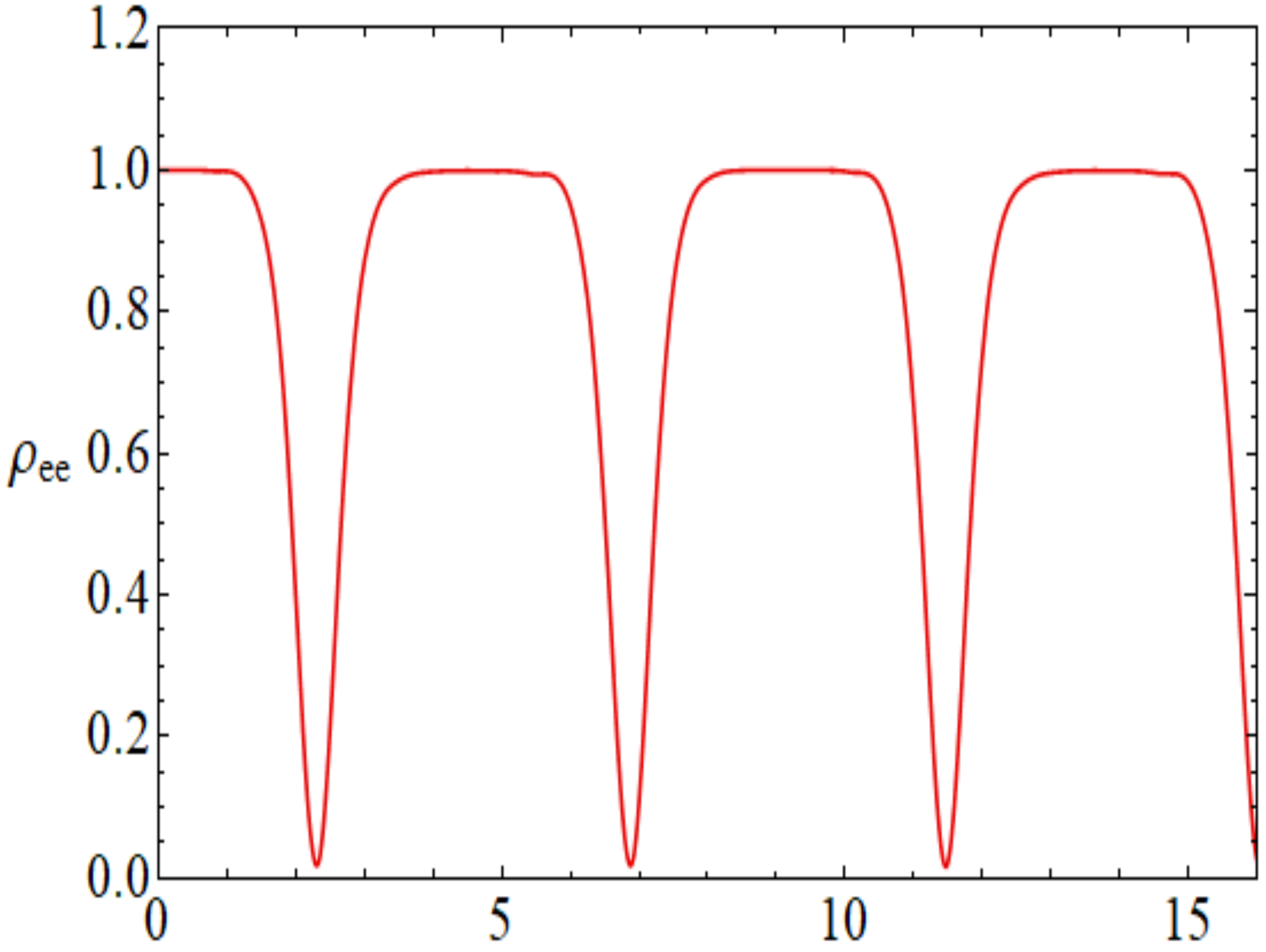
$$\boxed{\mu \gtrsim 10^5\,\mathrm{km}^{-1}}$$

- Rich physics of an interacting neutrino gas: collective oscillations!

Collective oscillations: effects of non-linearity



Suppressed mixing angle

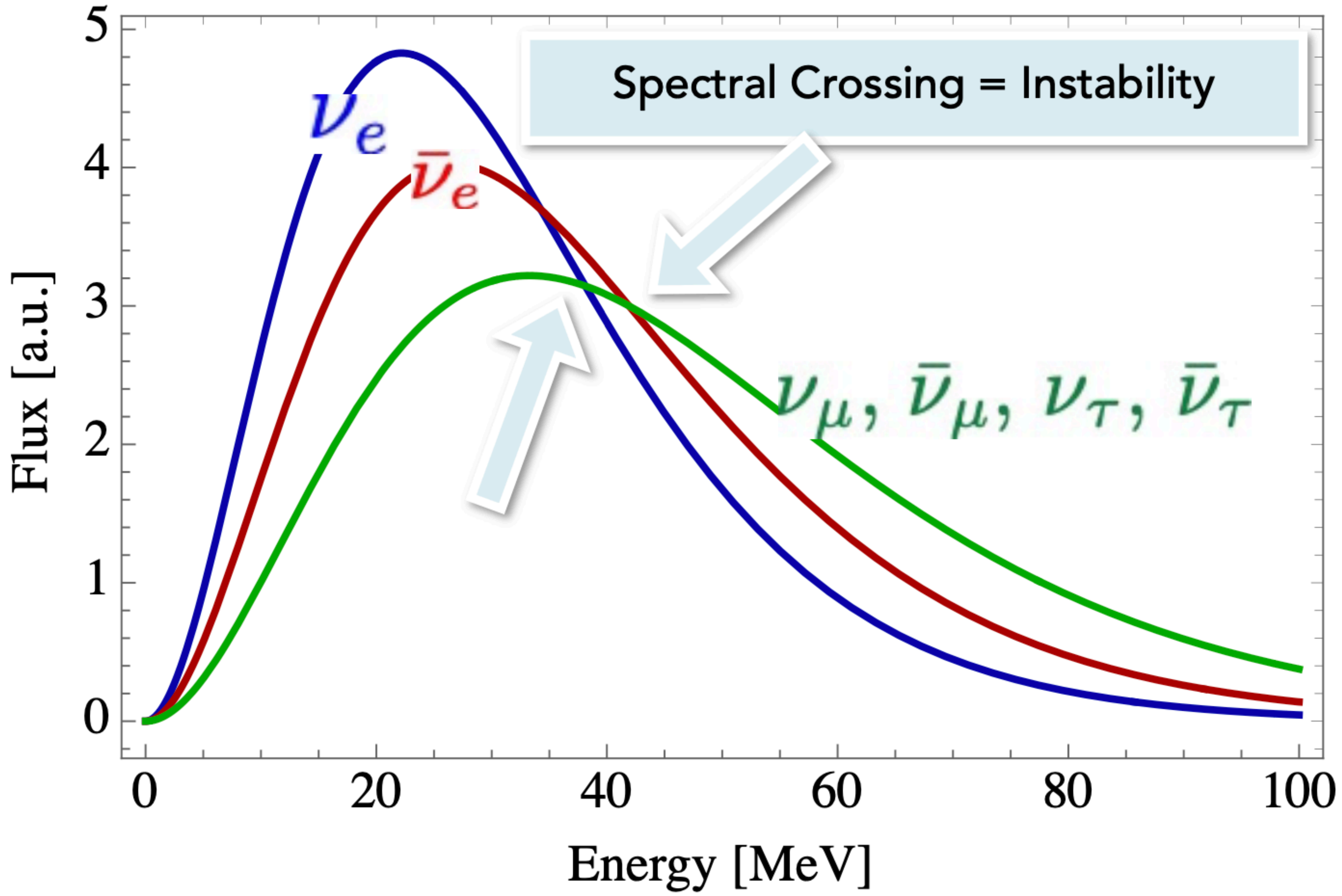


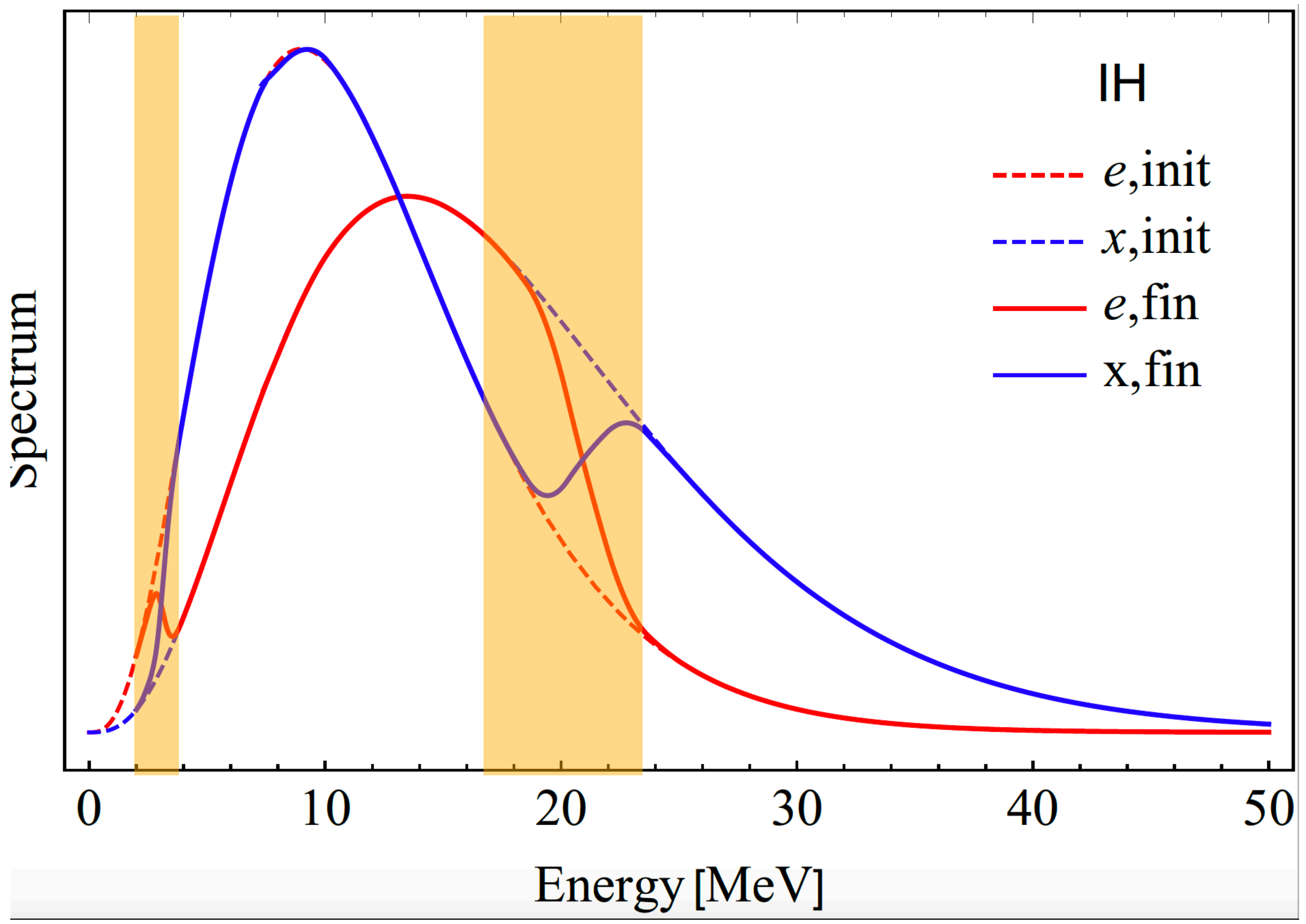
Large change even with small mixing angle

- When neutrino density is high, oscillations are synchronized.
- As density lowers, system is unstable. Oscillations grow at a rate $\sqrt{\omega\mu} \sim 10^3\omega$. Bipolar oscillations - Slow collective oscillations!
- Oscillations can occur for extremely tiny mixing angles. and occur at $\mathcal{O}(100\,\mathrm{km})$ from the core.

Duan, Fuller, Carlson and Qian (PRD 2006,2007)
Hannestad, Raffelt, Sigl and Wong (PRD 2006)

Spectral swaps





- Bipolar instability occurs if there is a spectral crossing.
- Spectral crossing leads to spectral swaps.
- Smoking-gun signatures of these collective oscillations.

Duan, Fuller, Carlson and Qian (PRL 2006)
Dasgupta, Dighe, Raffelt and Smirnov (PRL 2009)
Dasgupta, Dighe, Mirizzi and Raffelt (PRD 2008)
Friedland (PRL 2010)

Collective oscillations - where do we stand?

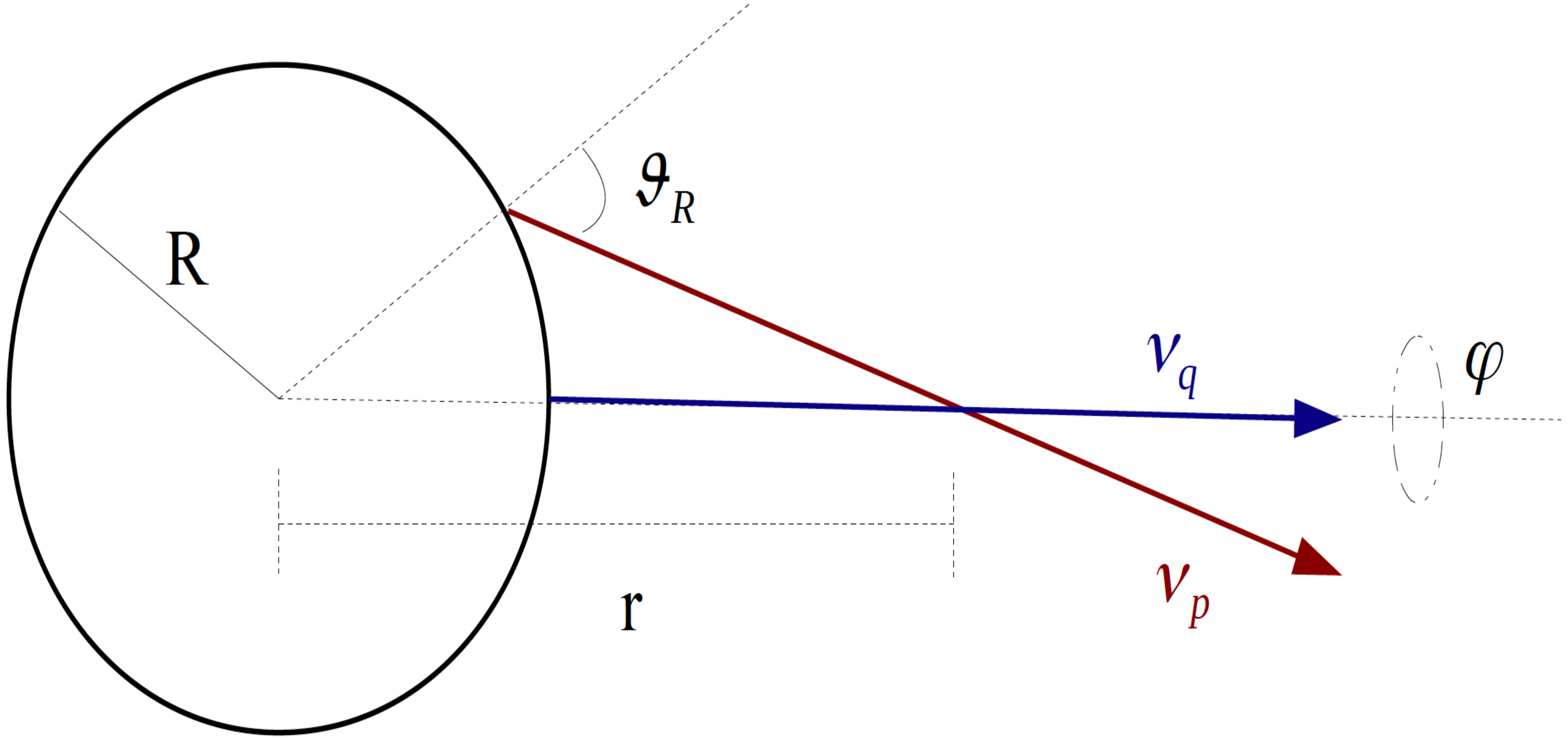
$$\begin{tikzcd}
\rho(t,r,\theta,\phi,|p|,p_\theta,p_\phi) \arrow[r, "\text{Stationary}"] & \rho(r,\theta,\phi,|p|,p_\theta,p_\phi) \arrow[r, "\text{Axial around z}"] & \rho(r,\theta,|p|,p_\theta,p_\phi) \arrow[d, "\text{Spherical}"] \\
\rho(r,|p|) & \rho(r,|p|,p_\theta) \arrow[l, "\text{Radial}"'] & \rho(r,|p|,p_\theta,p_\phi) \arrow[l, "\text{Azimuthal around r}"']
\end{tikzcd}$$

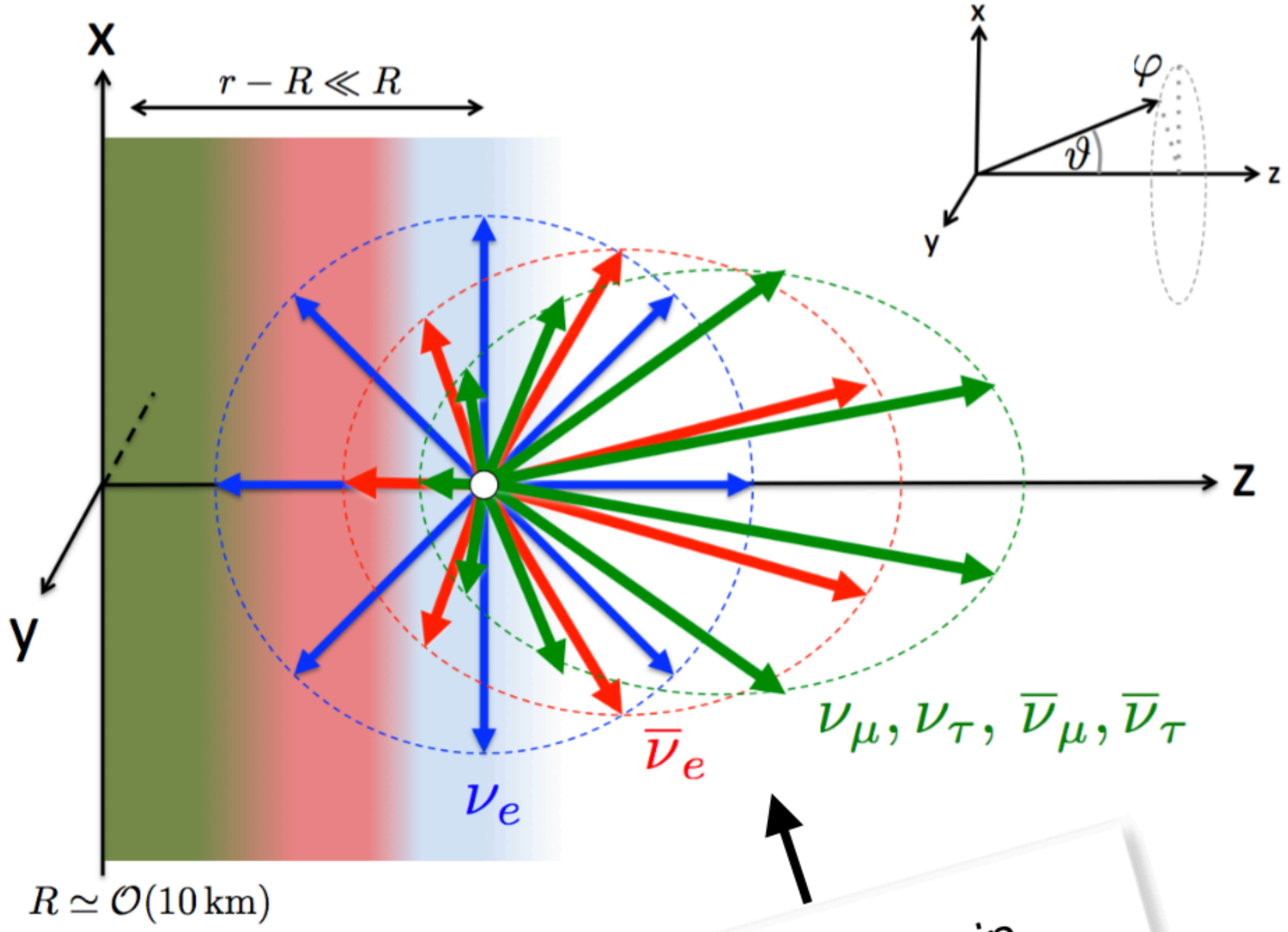
Symmetry imposed suppresses certain class of solutions.

Feature of the non-linear nature of the equations!

Raffelt,Sarikas, Seixas (PRL 2013)
Raffelt,Seixas (PRD 2014)
Chakraborty, Mirizzi (PRD 2014)
Mirizzi (PRD 2013)
Abbar, Duan, Shalgar (PRD 2015)
Duan, Shalgar (Phys. Lett. 2015)
Mirizzi, Mangano, Saviano (PRD 2015)
Dasgupta, Mirizzi (PRD 2015)
Sawyer (2005, 2009, 2012)
+many more…..

Fast flavour conversions: setup





$E_{\nu_x} > E_{\bar{\nu}_e} > E_{\nu_e}$

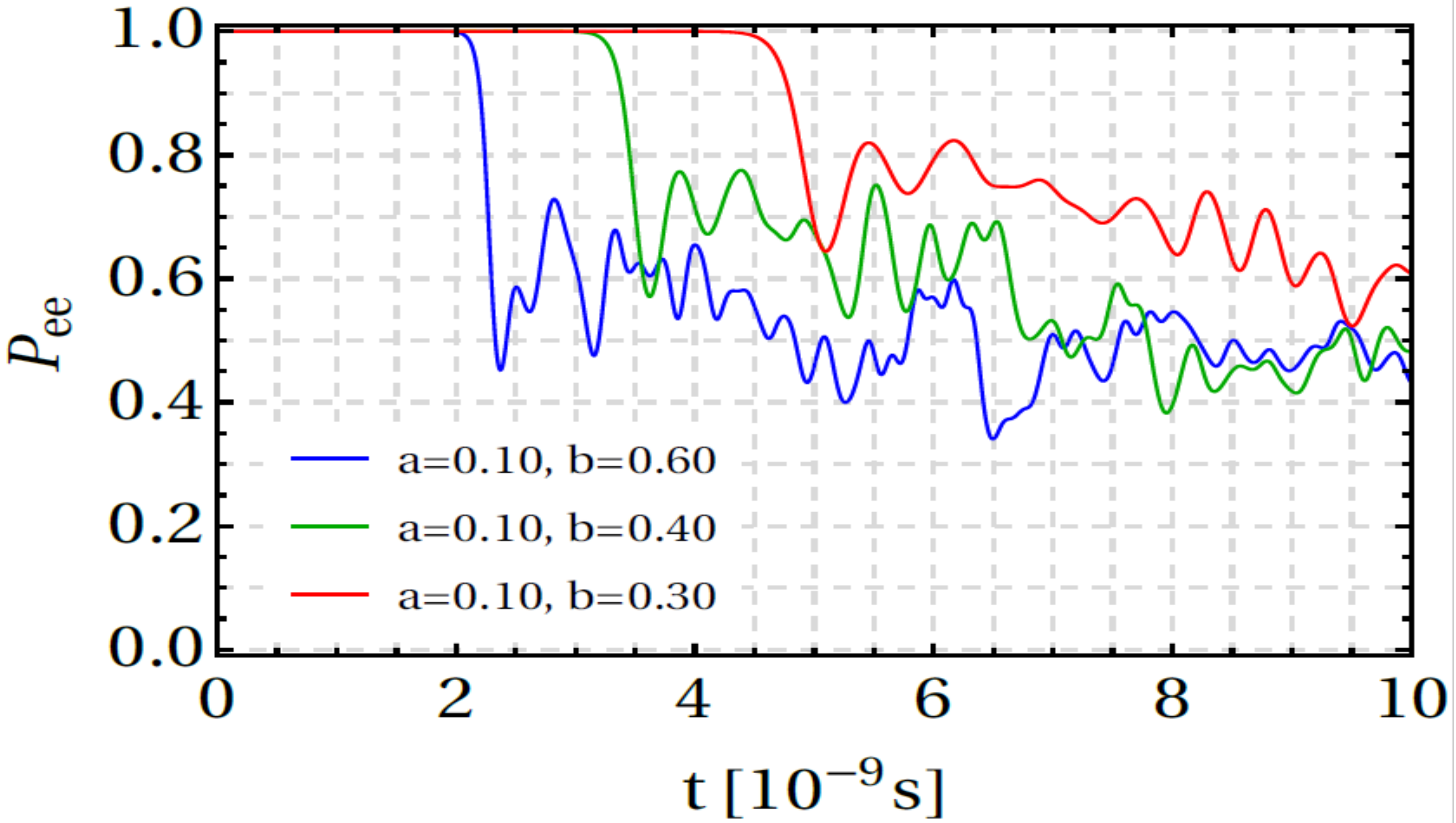
Anisotropy in angular distribution

- Discard the concept of a distinct neutrino-sphere.

Dasgupta, Mirizzi, **MS** (JCAP 2017)

- Flavour dependent free-streaming. Leads to different angular distributions for different flavours - crossing in angular spectra!

Fast flavour conversions



Dasgupta, Mirizzi, **MS** (JCAP 2017)

- Rapid flavour conversions, with a rate *proportional to the neutrino density* (μ). Rate 10^3 times slow bipolar conversions.

Chakraborty, Izaguirre, Raffelt (JCAP 2016)

- Operative just a *few cm* outside the neutrino decoupling region.
- Crossing in angular distribution a necessary component.

Morinaga (PRD 2022)
Dasgupta (PRL, 2022)

Why are these collective oscillations relevant?

- Provides a method of converting ν_μs to ν_es deep inside a star.

- We have $\langle E_{\nu_\mu} \rangle > \langle E_{\nu_e} \rangle$. This can lead to net heating of matter outflow, since the ν_e can deposit energy. Can be crucial for reheating the stalled shockwave.

- Or it can accelerate neutrino cooling by conversion of ν_es to ν_μs. Hinder explosion?

- Such conversions are not suppressed by tiny mixing angles.

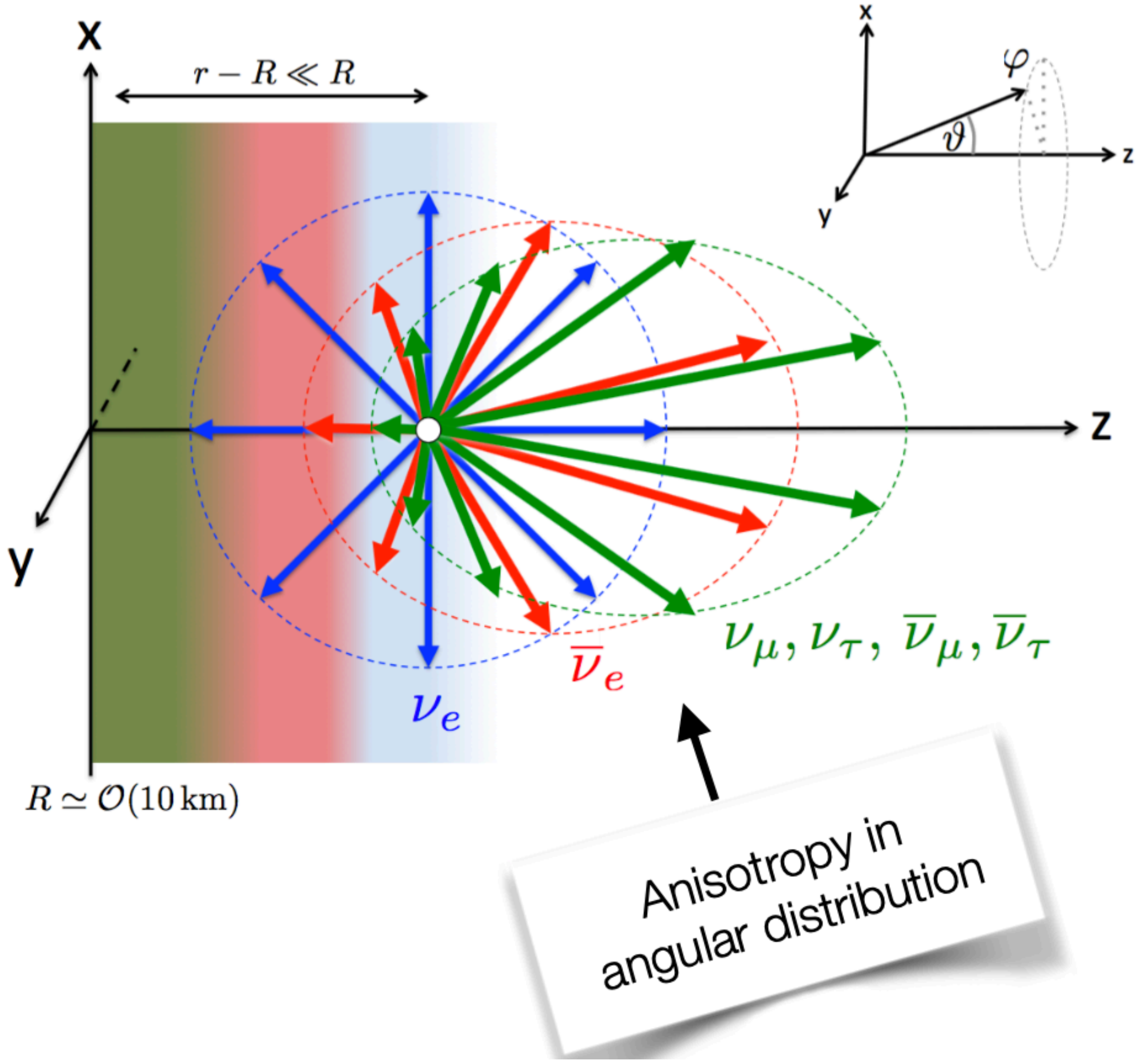
- $\nu_e + n \to p + e^-, \quad \bar{\nu}_e + p \to n + e^+$
  Can change the n/p ratio through charged current interactions of ν. Relevant for nucleosynthesis.

Fast conversions and collisions

- Fast conversions require different neutrino angular distributions.

- This requires them to have different collisional rates

$$d_t \varrho_p(r,p,t) = -i[H_p, \varrho_p] + C[\varrho_p]$$



Anisotropy in angular distribution

- Collisions create the conditions for fast conversions, but do they damp these oscillations?

Capozzi, Dasgupta, Mirizzi, **MS**, Sigl (PRL 2019)

- Intense investigations underway.

Martin, Carlson, et al (PRD 2021)
Tamborra, Shalgar (PRD 2021, PRD 2023),
Johns (PRL 2022), Johns, Xiong (PRD 2022)
Zhong, Wu, et al (PRD 2023) + …

Open questions - Probing the tip of the iceberg

- Final outcome of flavour conversions?

Bhattacharya, Dasgupta (PRL 2021, PRD 2022), Wu et al (PRD 2021), Nagakura, Ziazhen (PRL 2022, PRD 2023) + …

- Method to detect the presence of fast flavour conversions in SN simulations.

Dasgupta, Mirizzi, **MS** (PRD 2019)
Glas, Capozzi, **MS** et al, (PRD 2020),Abbar (JCAP 2020),
Abbar, Capozzi et al (PRD 2021), Johns, Nagakura (PRD 2021) + …

- Application to SN heating mechanism

Dasgupta, O’Connor, Ott (PRD 2011), Ehring, Abbar, et al (PRL 2023), Nagakura (PRD 2023)

- Extension to three flavours.

Capozzi, **MS** et al (PRL 2021, PRD 2022), Tamborra, Shalgar (PRD 2021), Richers, Wilcox(PRD 2021)

- Impact on r-process nucleosynthesis.

MS, Qian et al(ApJ 2021), George, Wu, et al (PRD 2022), Friedland, Mukhopadhyay (Phys, Lett. 2023)

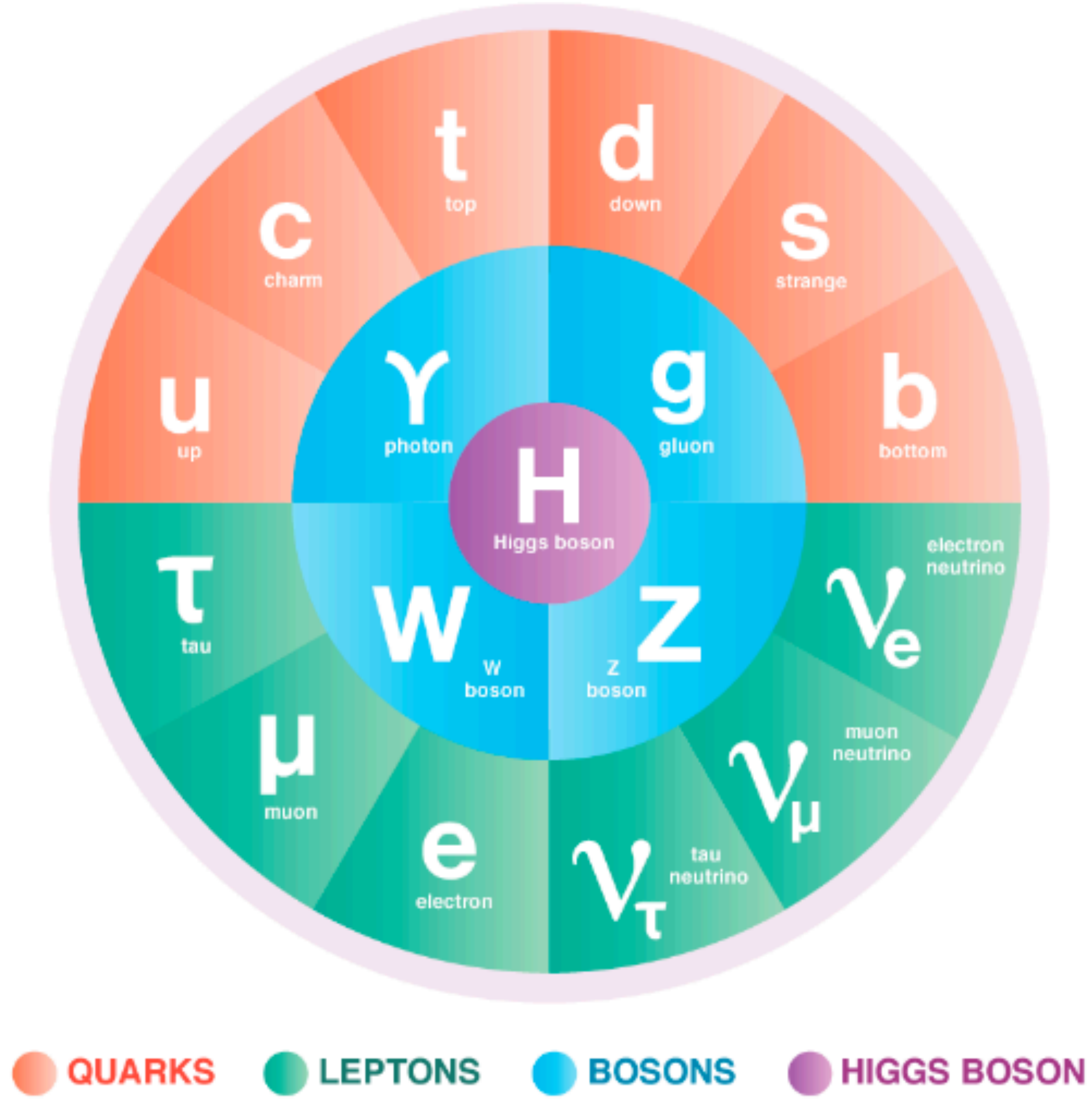
- Analytical approaches

Dasgupta, **MS** (PRD 2018), Dasgupta, Bhattacharya (PRD 2022), Padilla-Gay, Tamborra, Raffelt (PRL 2022), Fiorillo, Raffelt (PRD 2023)

- Many-body physics

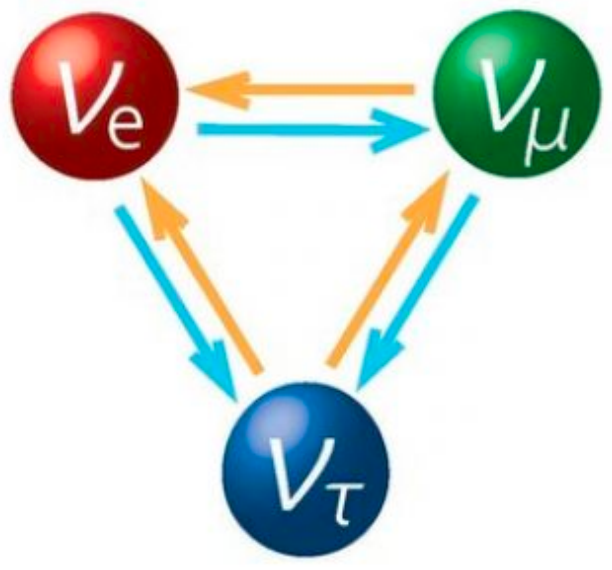
Balantekin and Pehlivan, (PRD 2011), Patwardhan, Cervia, Balantekin (PRD 2019), Xiong (PRD 2022), Martin, Roggero et al (PRD 2022), Siwach, Suliga, Balantekin (PRD 2023), +…

Sensitive to new physics

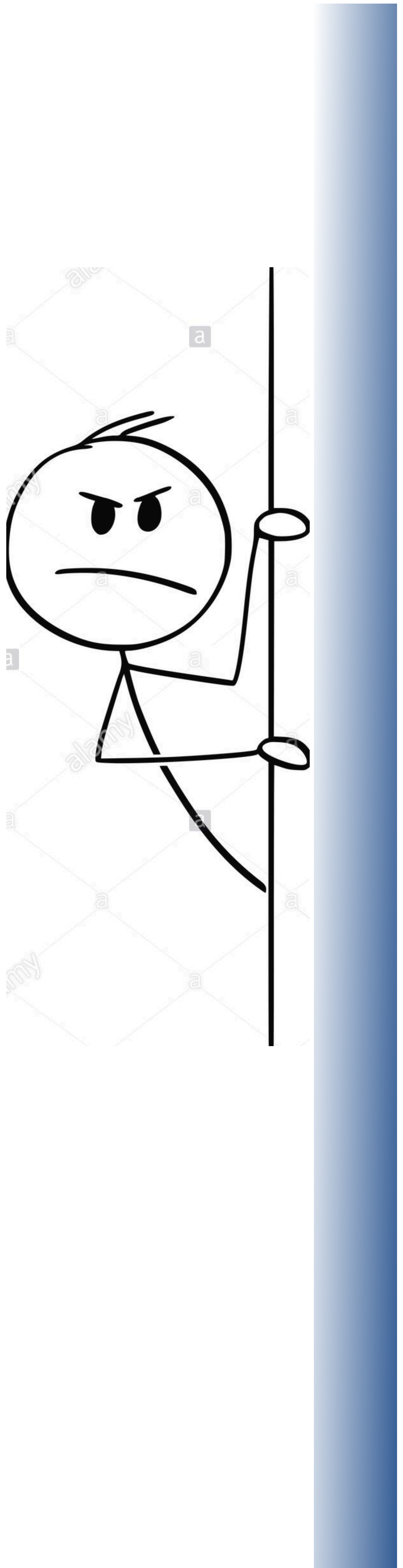


Artwork courtesy of Sandbox Studio, Chicago for Symmetry

+



Credit: BBC



Beyond

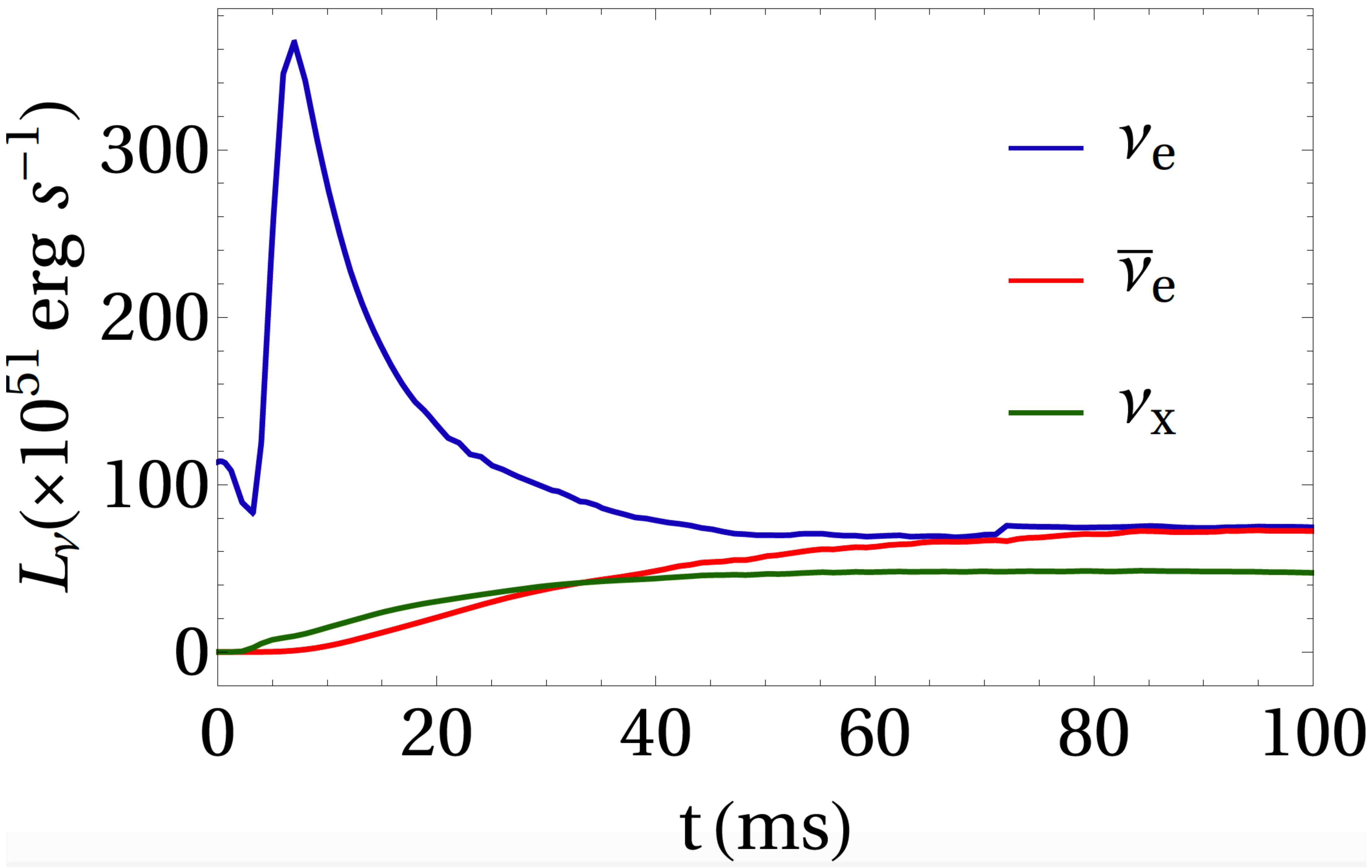
The Standard Model

Sensitive to new physics

New Physics can have an

1. Impact on the neutrino spectra/ flux, e.g. neutrino properties.
2. Impact on the neutrino luminosity, and average energy, and duration of neutrino burst - cooling bounds, e.g., new particles.

Probe of new physics - neutronization burst



- Large burst of ν_e in the first ~30 ms post bounce. Robust feature of all simulations.
- Almost negligible amount of $\bar{\nu}_e$ and $\nu_{x=\mu,\tau}$.
- Not affected by collective oscillations due to large $\nu - \bar{\nu}$ asymmetry.

Sensitive to neutrino mass-ordering

- ν_e propagates as the heaviest state due to matter (MSW) effects.

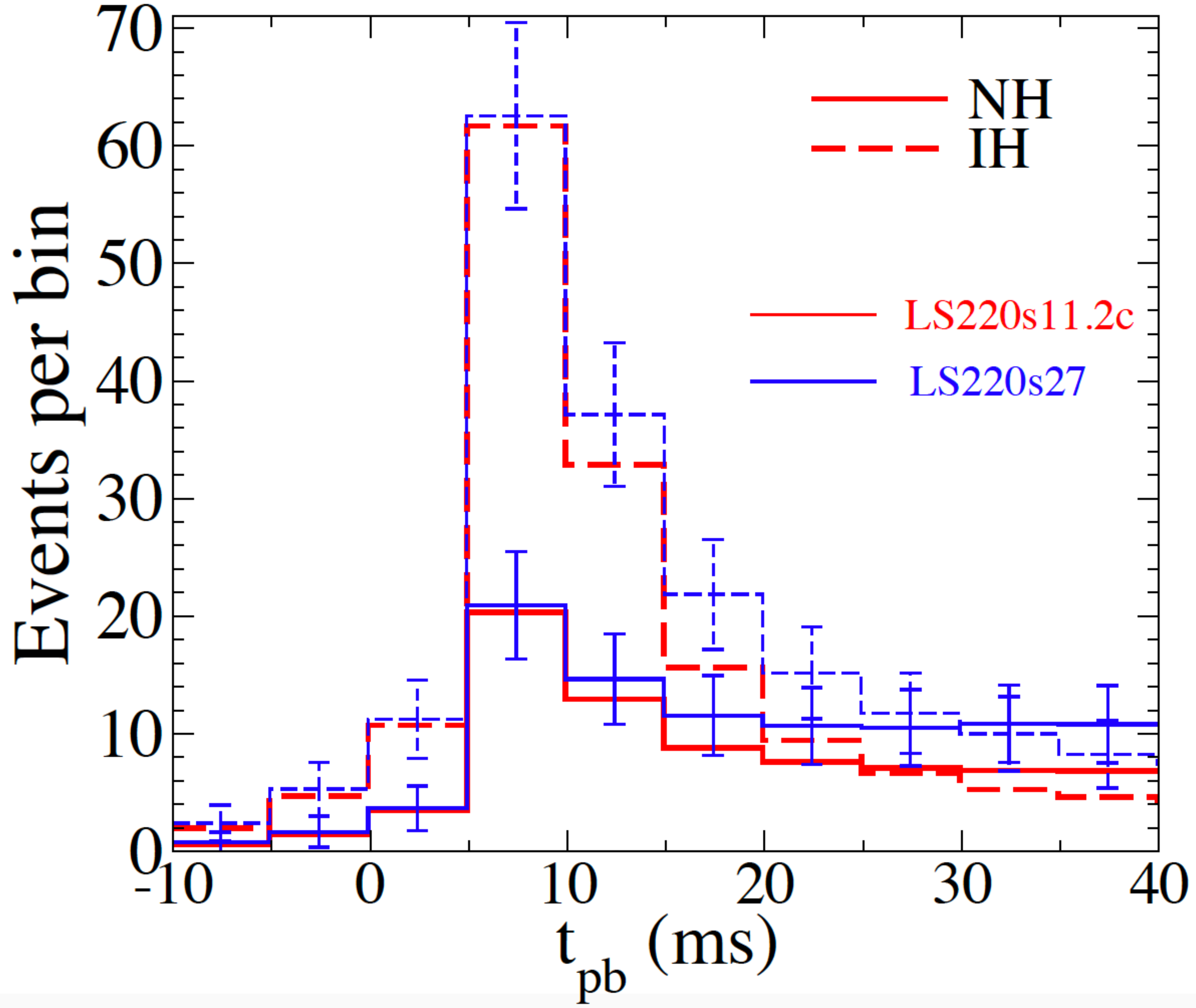
- In NMO, $\nu_e \equiv \nu_3$.

$$L_{\nu_e} \simeq |U_{e3}|^2 L_{\rm orig} = 0.02\, L_{\rm orig}$$

In IMO, $\nu_e \equiv \nu_2$.

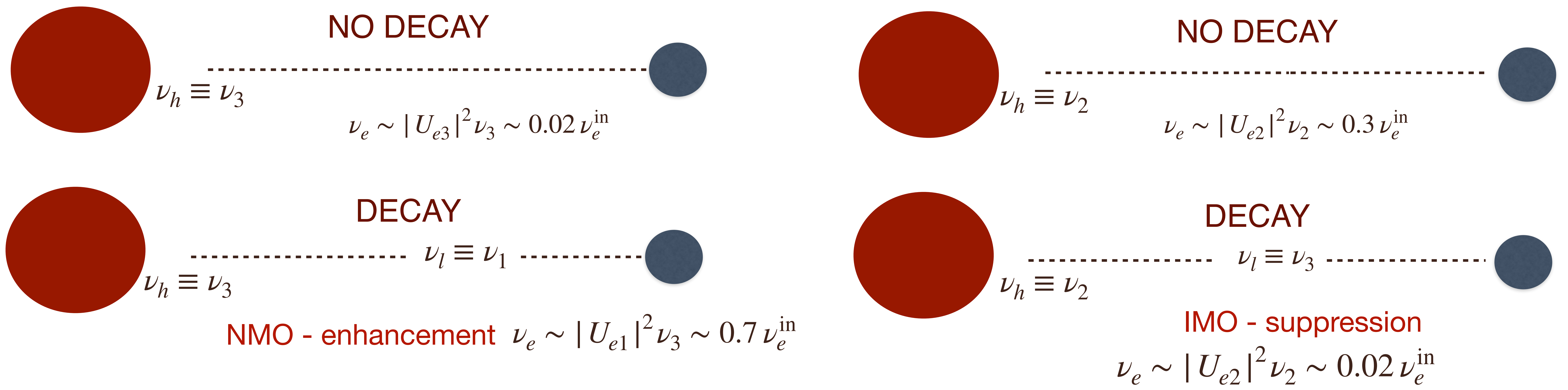
$$L_{\nu_e} \simeq |U_{e2}|^2 L_{\rm orig} = 0.3\, L_{\rm orig}$$

- Independent probe of mass ordering!



Dighe and Smirnov (PRD 2000)

1. Neutrino decay



NO DECAY

$\nu_h \equiv \nu_3$

$\nu_e \sim |U_{e3}|^2 \nu_3 \sim 0.02\, \nu_e^{\rm in}$

NO DECAY

$\nu_h \equiv \nu_2$

$\nu_e \sim |U_{e2}|^2 \nu_2 \sim 0.3\, \nu_e^{\rm in}$

DECAY

$\nu_h \equiv \nu_3$ $\nu_l \equiv \nu_1$

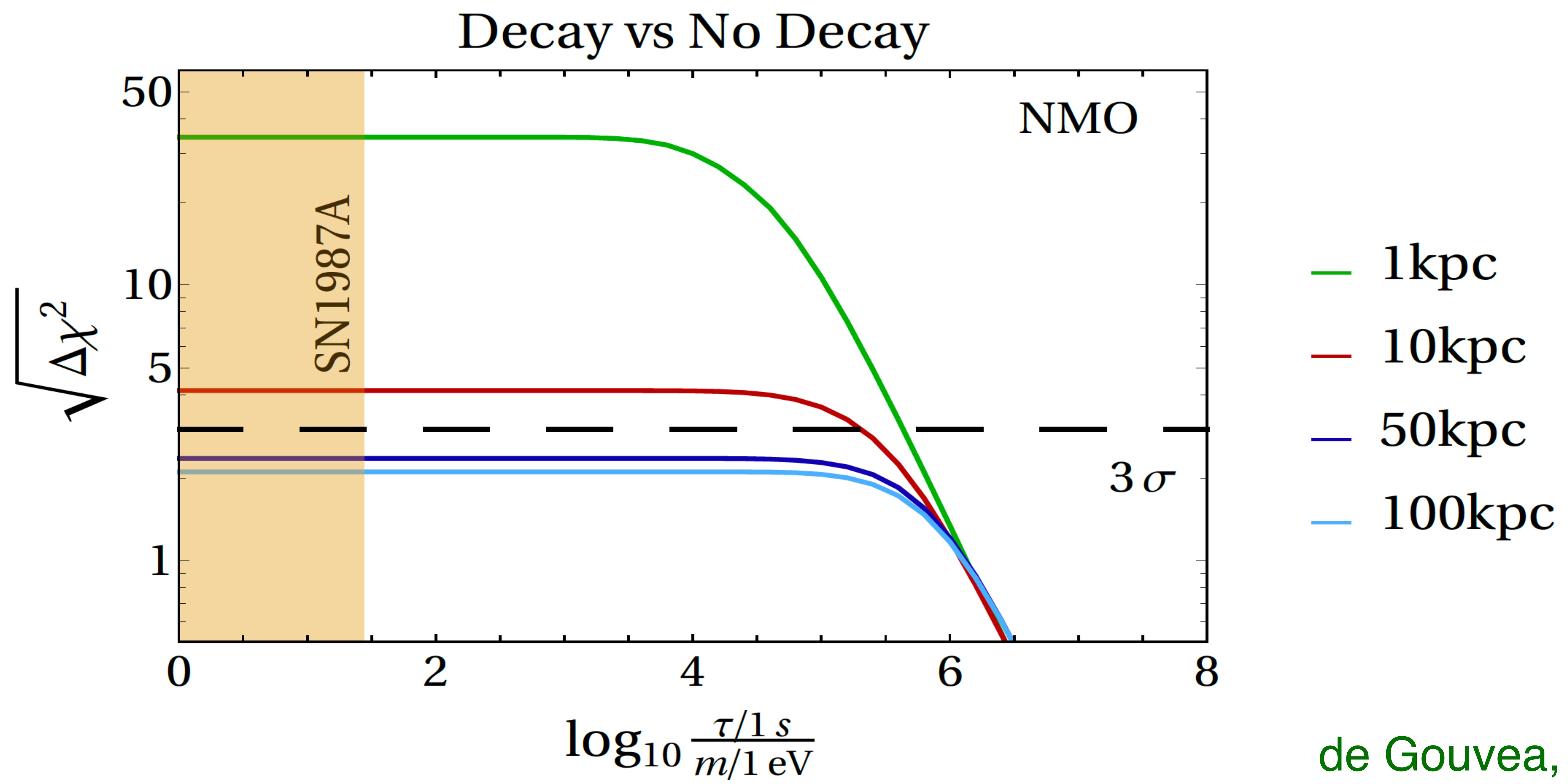
NMO - enhancement $\nu_e \sim |U_{e1}|^2 \nu_3 \sim 0.7\, \nu_e^{\rm in}$

DECAY

$\nu_h \equiv \nu_2$ $\nu_l \equiv \nu_3$

IMO - suppression

$\nu_e \sim |U_{e2}|^2 \nu_2 \sim 0.02\, \nu_e^{\rm in}$



- Strongest bounds on non-standard neutrino decay $\nu_{\rm h} \to \nu_{\rm l} + \phi$
- Confuse mass ordering determination

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

2. Dirac vs Majorana

Wrong helicity neutrino

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

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

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

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

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

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

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

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

- Different signatures in detectors sensitive to ν_e and $\bar{\nu}_e$.
- Look at DUNE and HK

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

3. Neutrino secret self-interactions (NSSI)

$x = \mu, \tau$

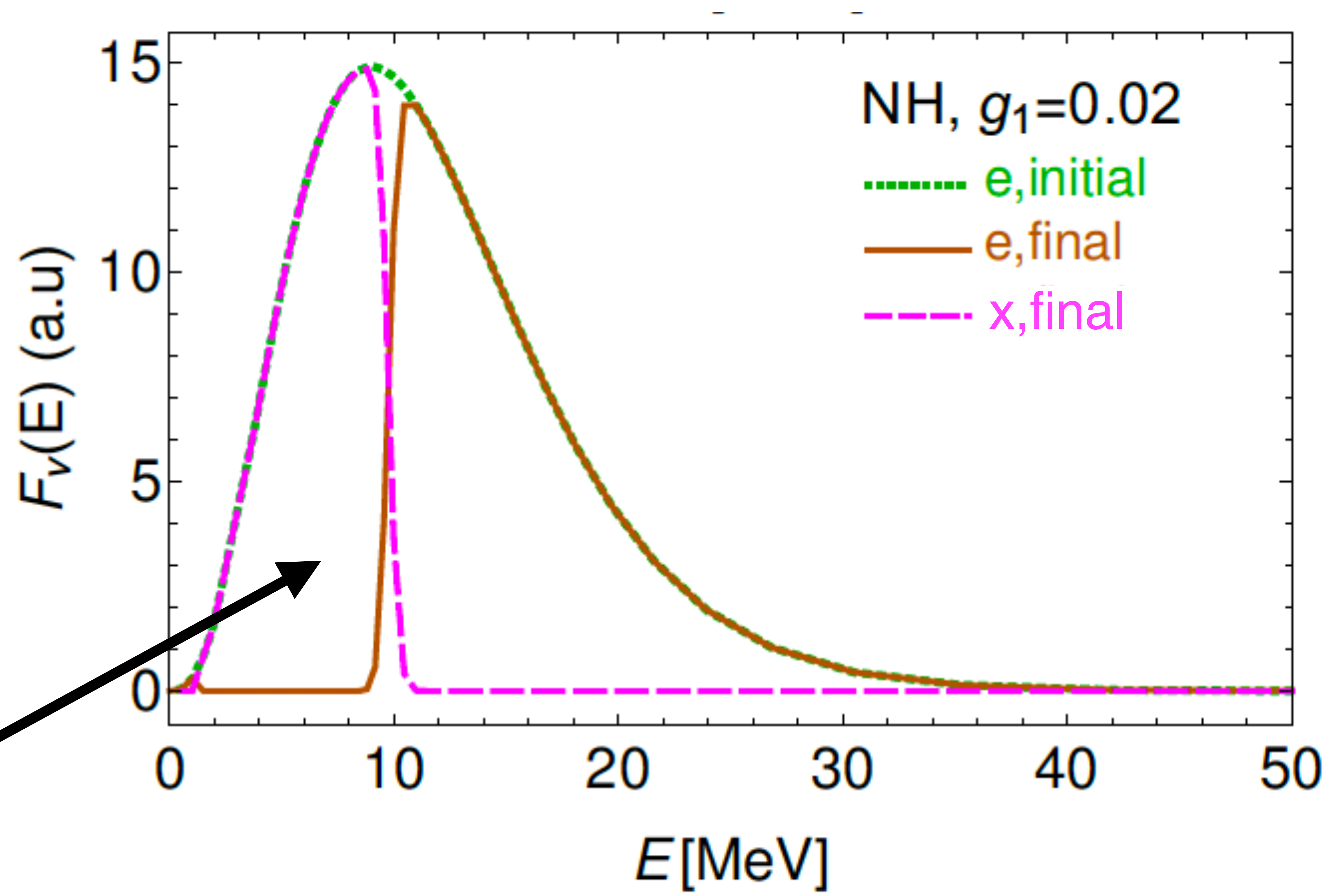
- Consider $\mathscr{L} \supset G_F\,(G_{\alpha\beta}\,\bar{\nu}^{\alpha}\gamma^{\mu}L\,\nu^{\beta})\,(G_{\eta\delta}\,\bar{\nu}^{\eta}\gamma^{\mu}L\,\nu^{\delta})$,

  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.

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

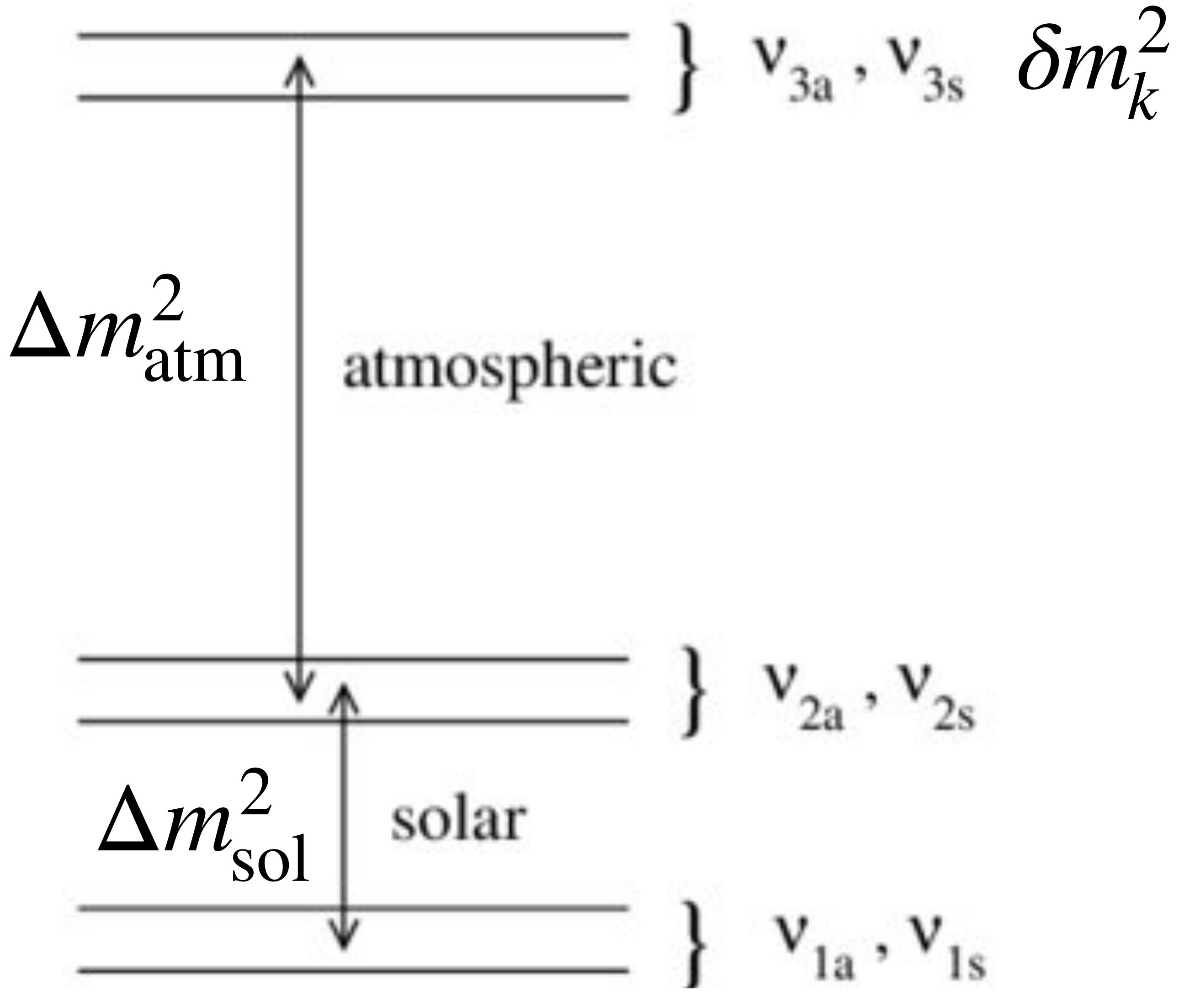
- $g_{ex} \neq 0$ can populate ν_x
  from ν_e during neutronization.



- Cause collective oscillations now, giving distinct spectral splits
  in neutronization spectra.

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

4. Pseudo-Dirac neutrinos



- Neutrinos have sub-dominant Majorana mass terms.

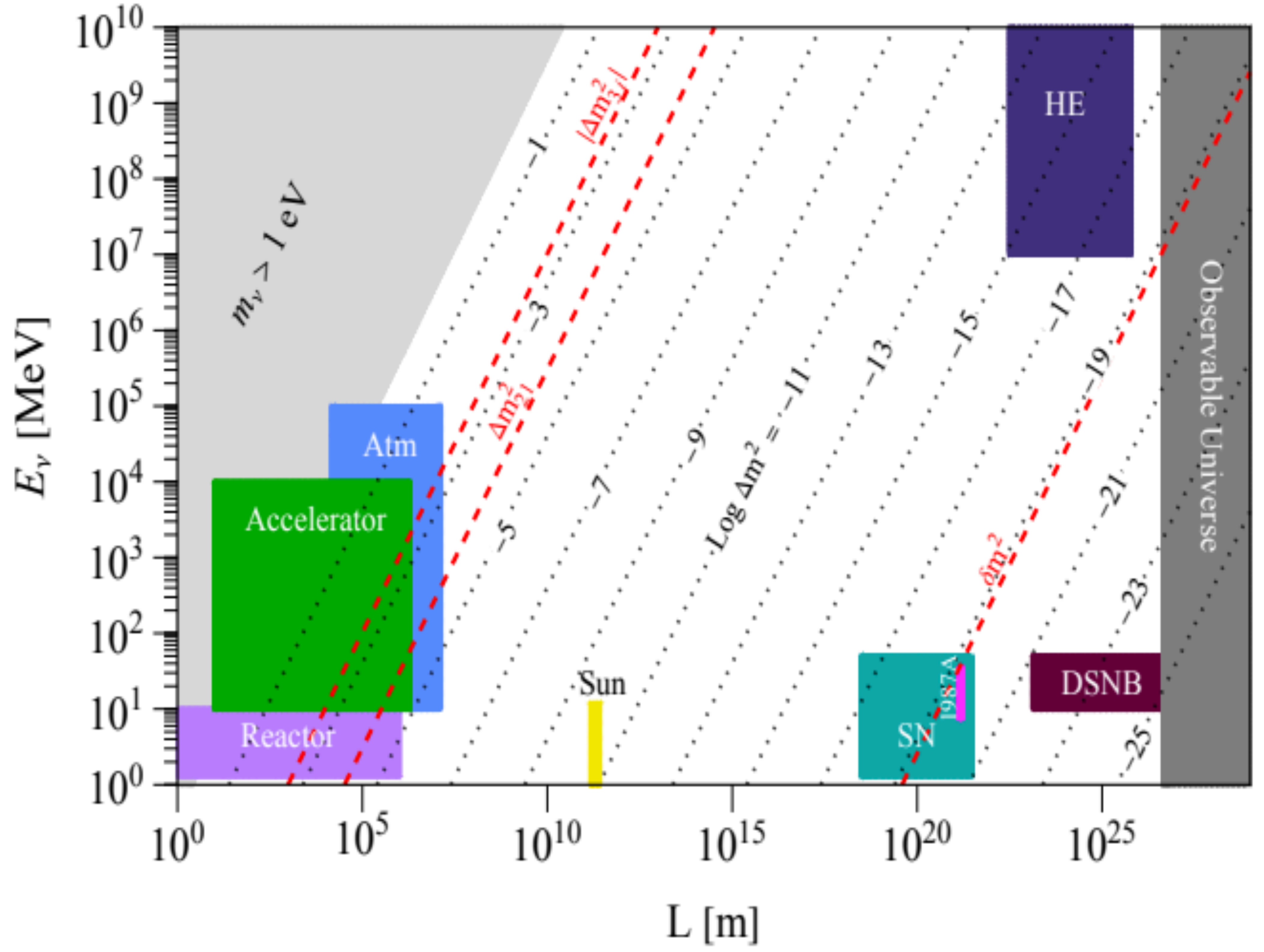
Generic Majorana mass matrix $\begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}$.

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

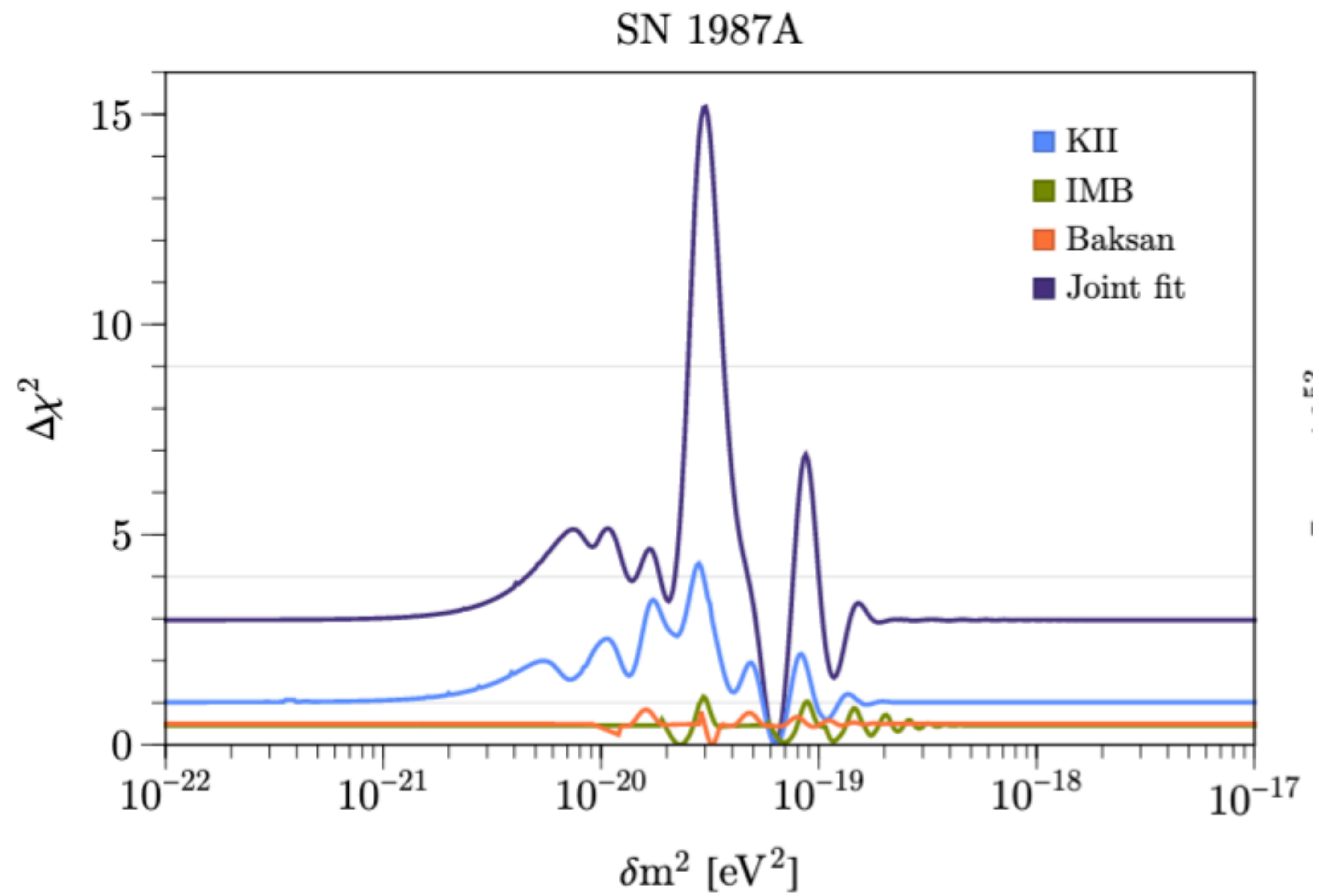
$$\nu_{\alpha L} = \frac{1}{\sqrt{2}} U_{\alpha j}(\nu_{js} + i\,\nu_{ja})$$

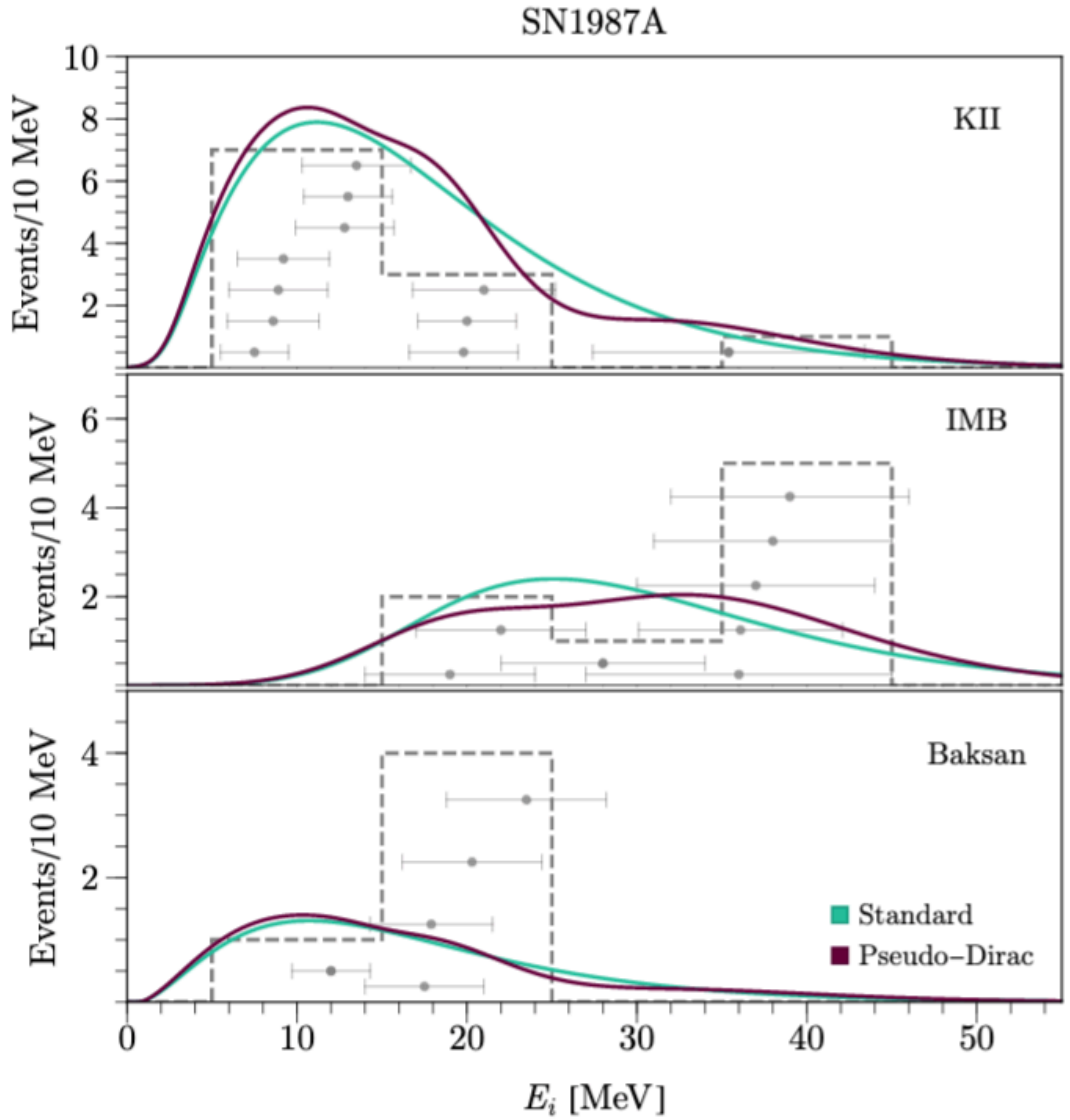
- Oscillations driven by this tiny δm_k^2 .



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

Pseudo-Dirac neutrinos: SN1987A





- Rules out $\delta m^2 \sim [2.5, 3.] \times 10^{-20} \mathrm{eV}^2$ by $\Delta\chi^2 \gtrsim 15$.

- 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)

New physics constraints: SN cooling bound

- New modes of energy loss due to weakly coupled particles (x).

- If $\mathscr{L}_x > \mathscr{L}_\nu \sim 10^{52}\,\mathrm{erg/s}$, then duration of neutrino burst is reduced from ~10s.

- $g < g_{\min}$: not efficiently produced.

  $g > g_{\max}$: efficiently trapped and reabsorbed.

- Further improvements in treatment recently.

Caputo, Raffelt, Vitagliano (JCAP 2022)

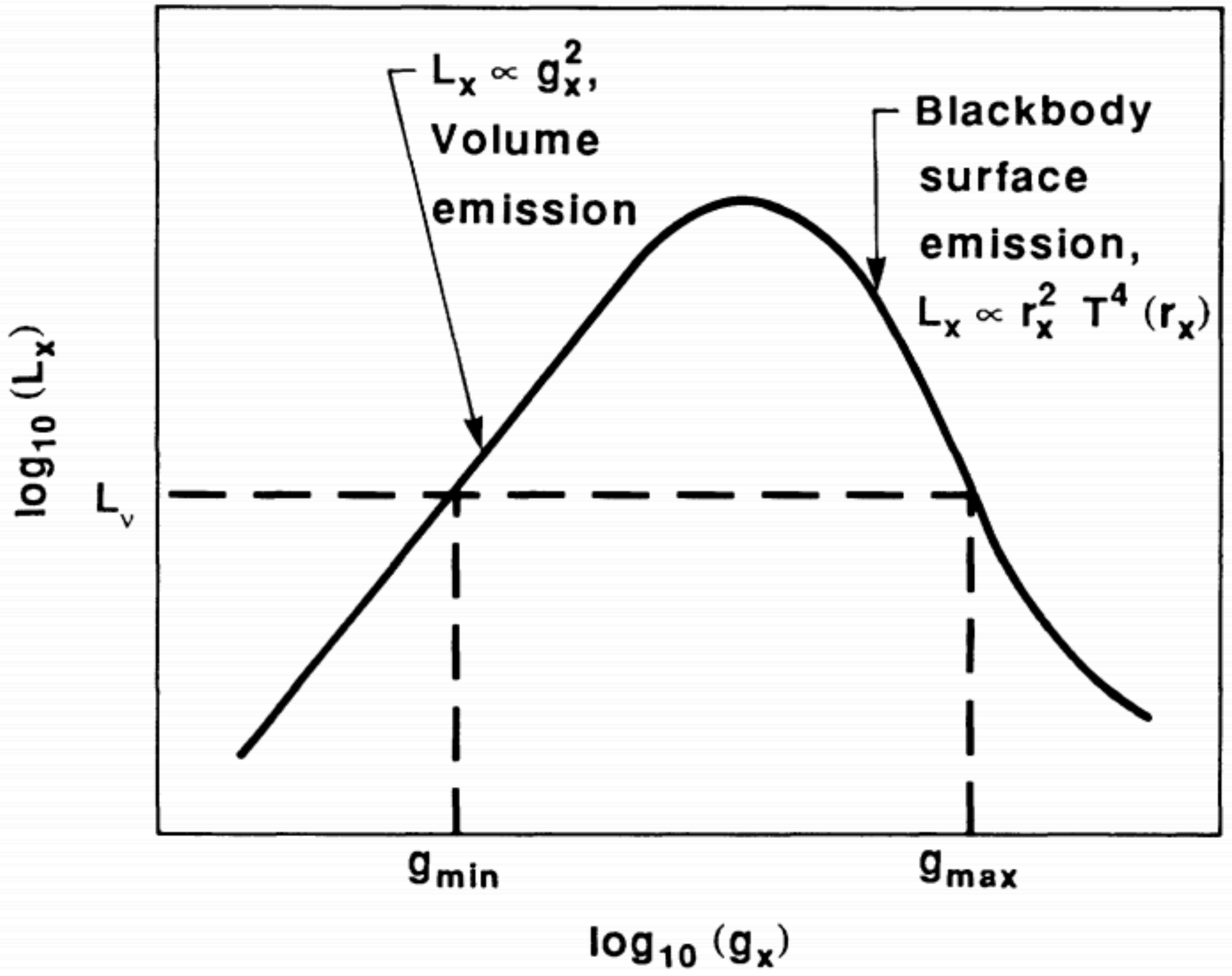
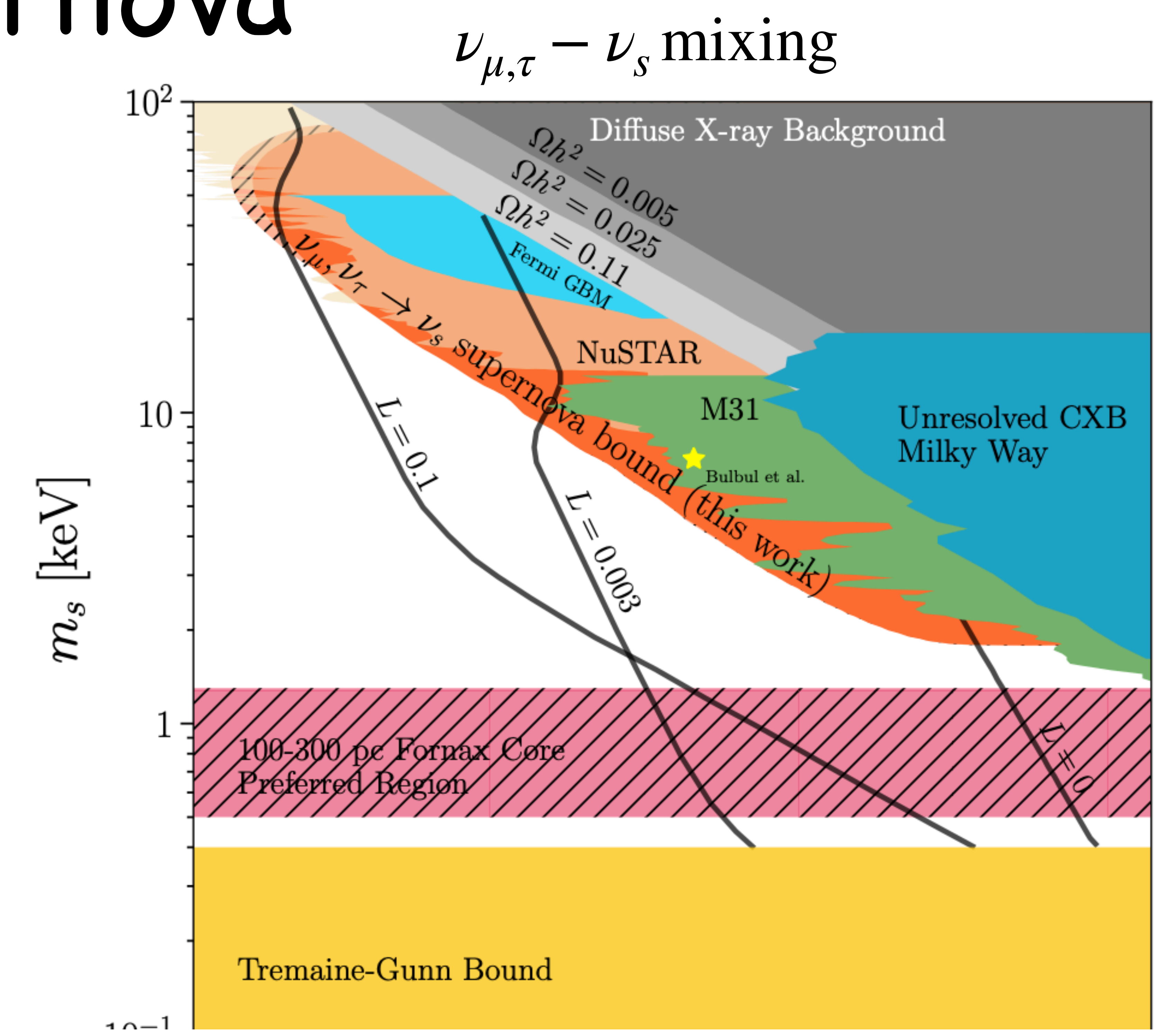


FIG. 1. Schematic dependence of L_x on the coupling strength g_x. The horizontal line denotes the neutrino luminosity L_ν. In the range $g_{\min} < g < g_{\max}$ the LEP emission L_x would exceed L_ν.

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

5. Sterile neutrinos in supernova



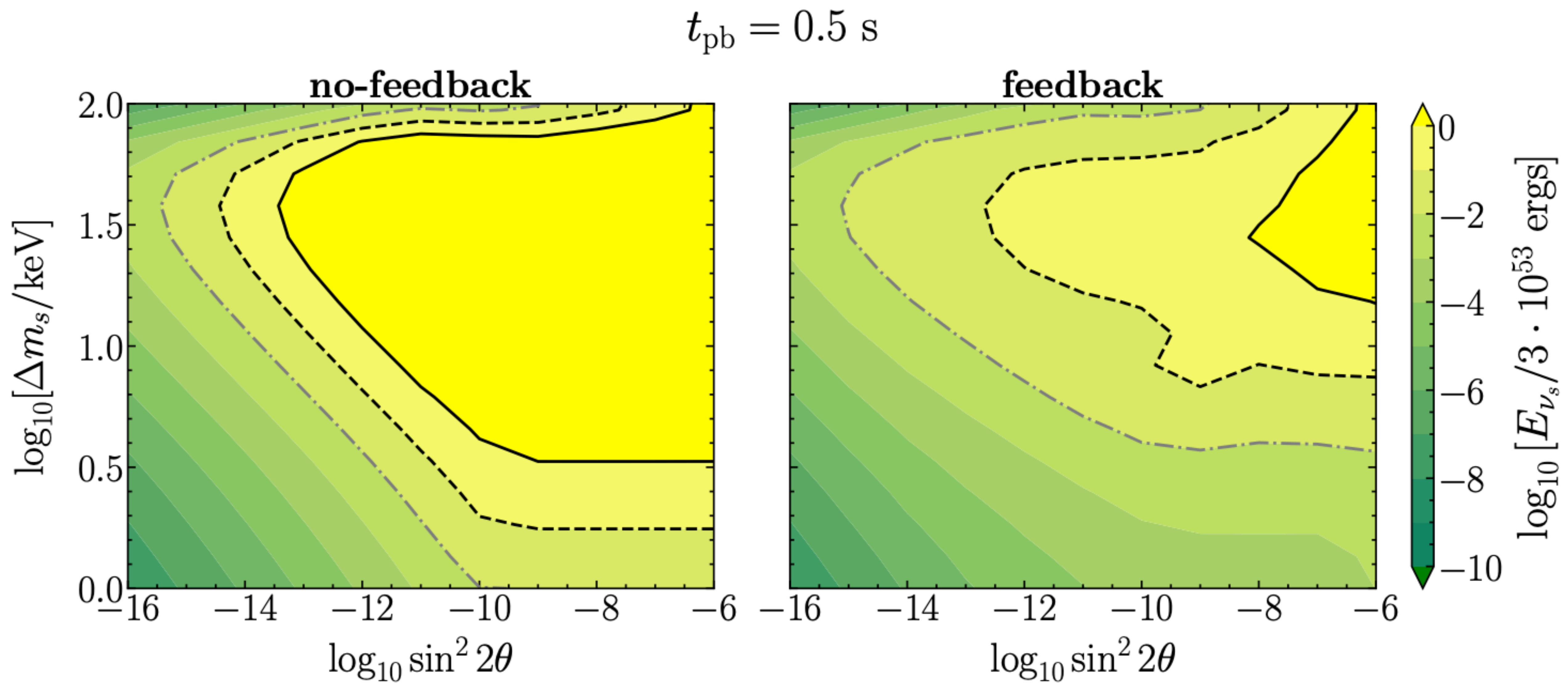
- keV sterile neutrino production in SN, through

  (i) adiabatic MSW conversion at radii 10-15 km inside neutrinosphere

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

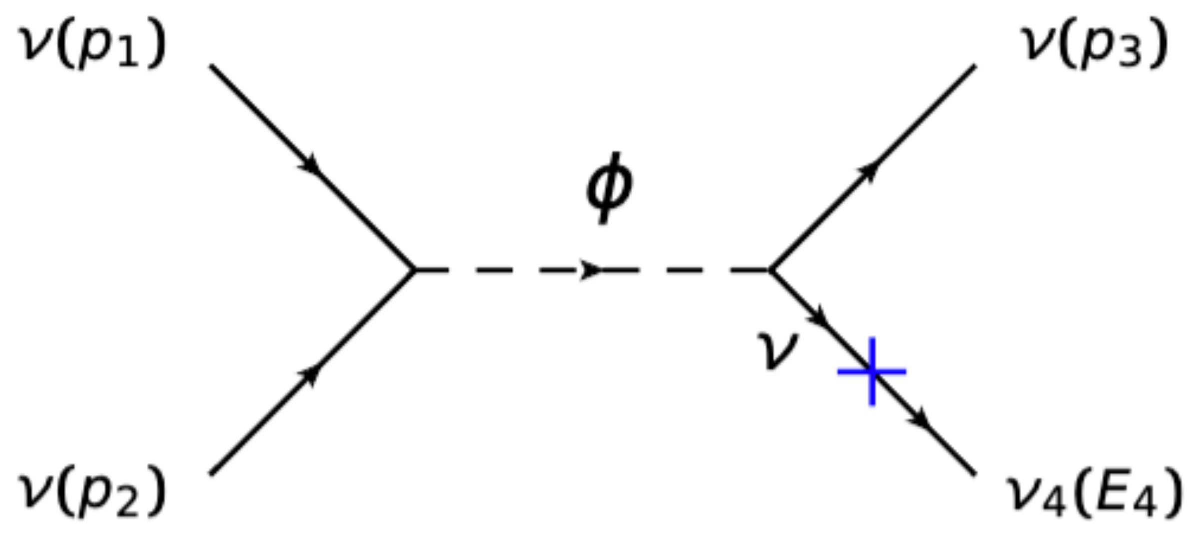
- ν_s is produced from ν_a. This affects the V_{eff}, which again affects flavor conversions.

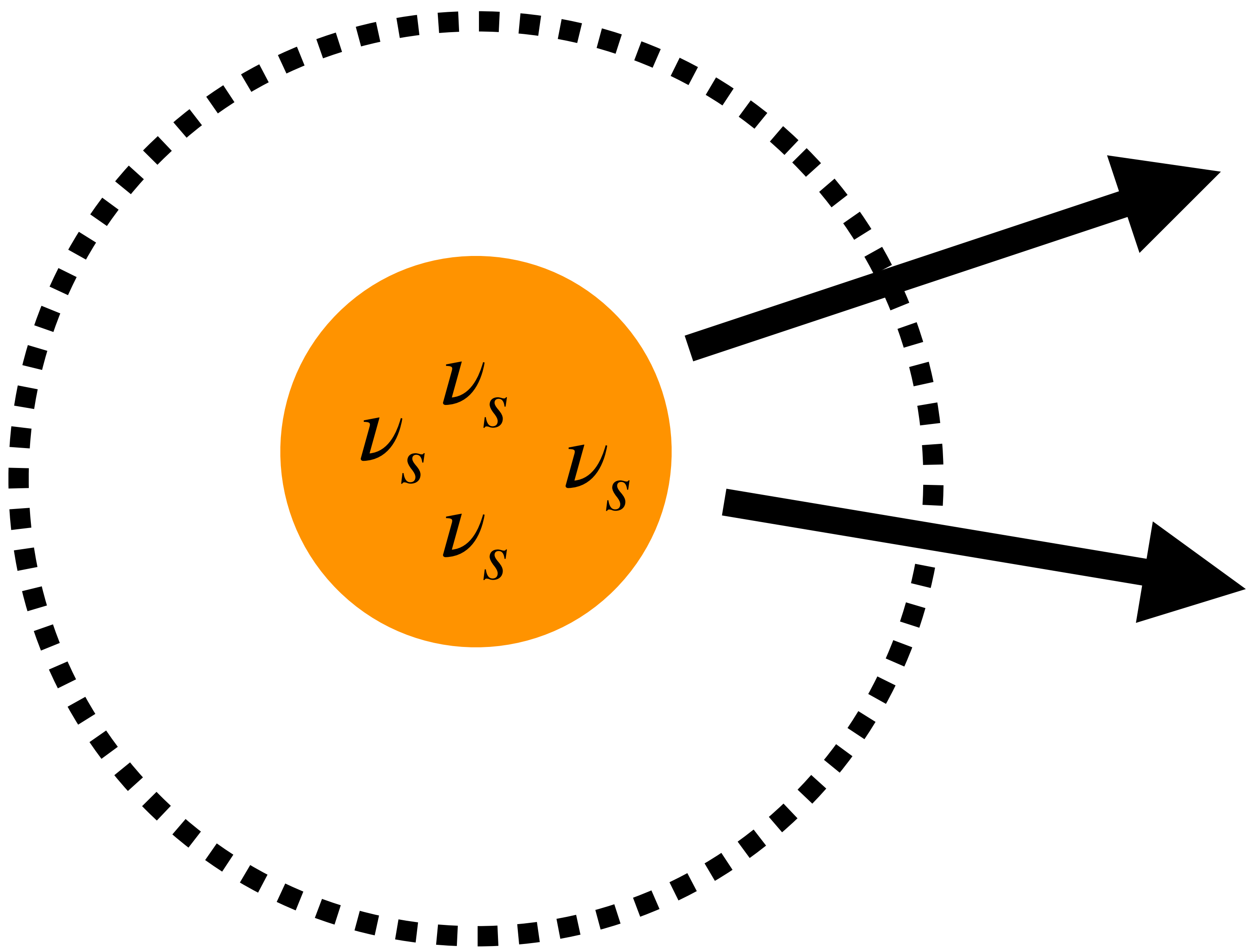
- Feedback is important! Reduces bounds.



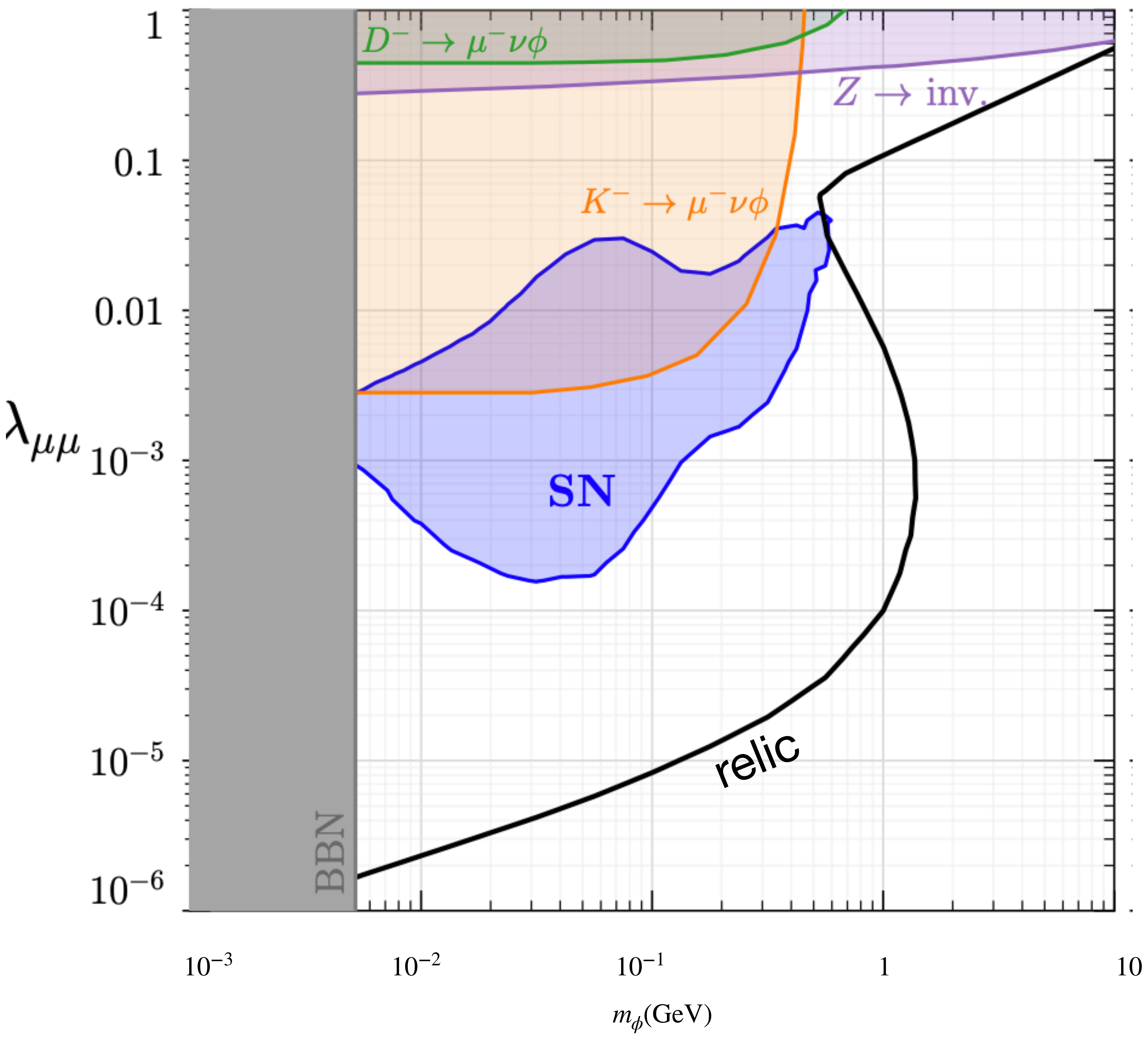
Arguelles, Brdar, Kopp, (PRD 2019)
Tamborra, Wu, Suliga, (JCAP 2019)
Raffelt and Zhou (PRD 2011),

Sterile neutrino DM from neutrino self-interactions





$m_4 = 7\,\mathrm{keV}, \sin^2 2\theta = 7 \times 10^{-11}$



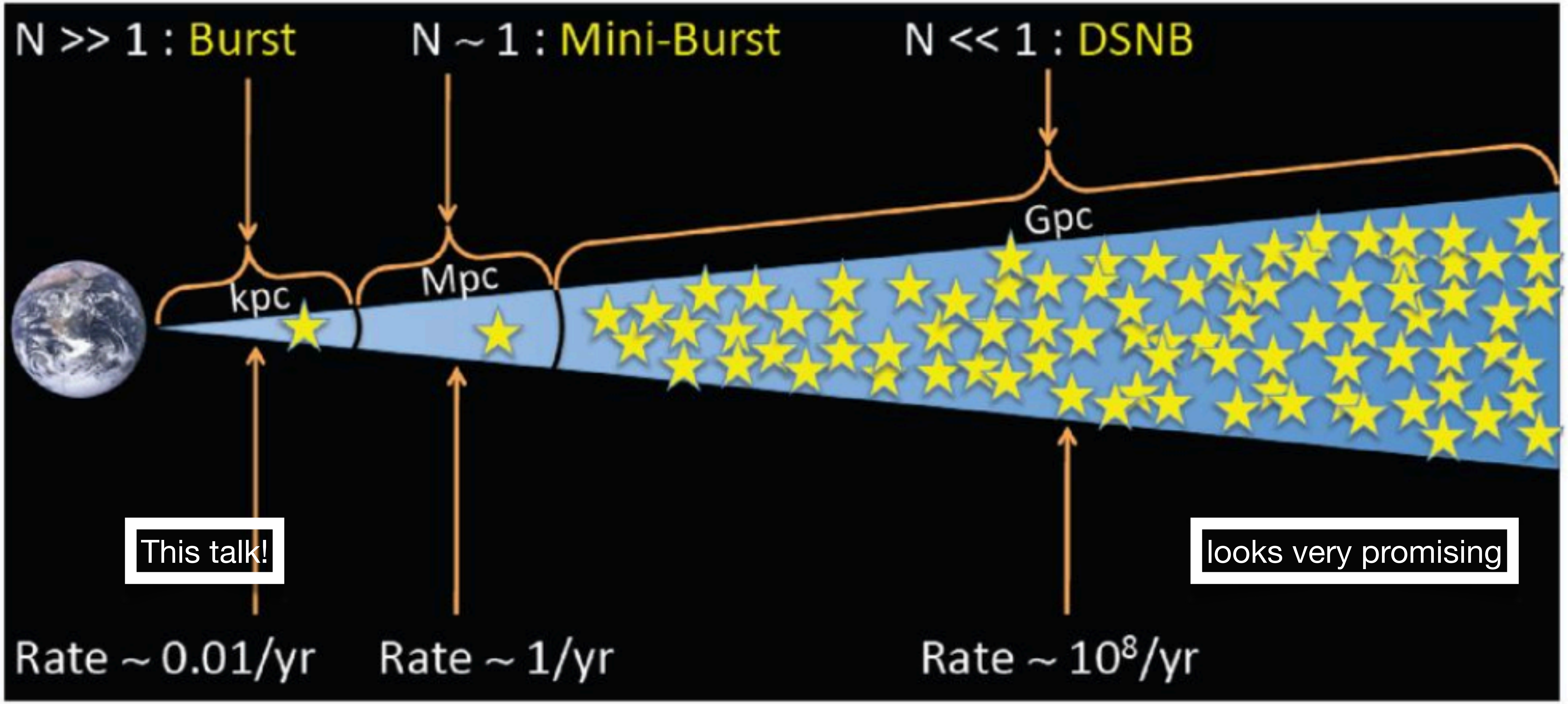
Chen, **MS**, Tuckler, et al. (JCAP 2022)

- 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!

Relic neutrinos from supernovae

John Beacom, TAUP2011



This talk!

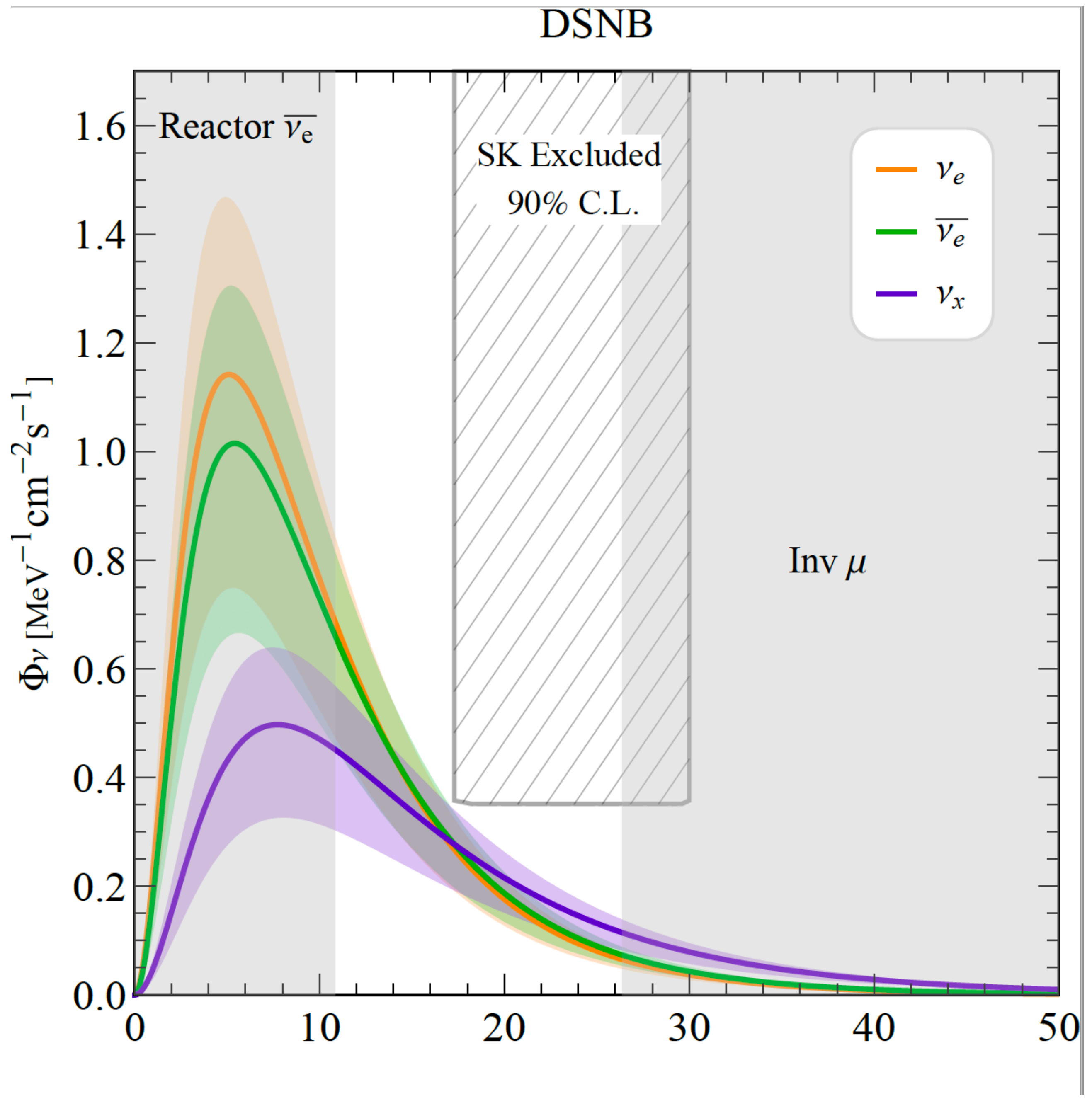
looks very promising

DSNB=Diffuse Supernova Neutrino Background

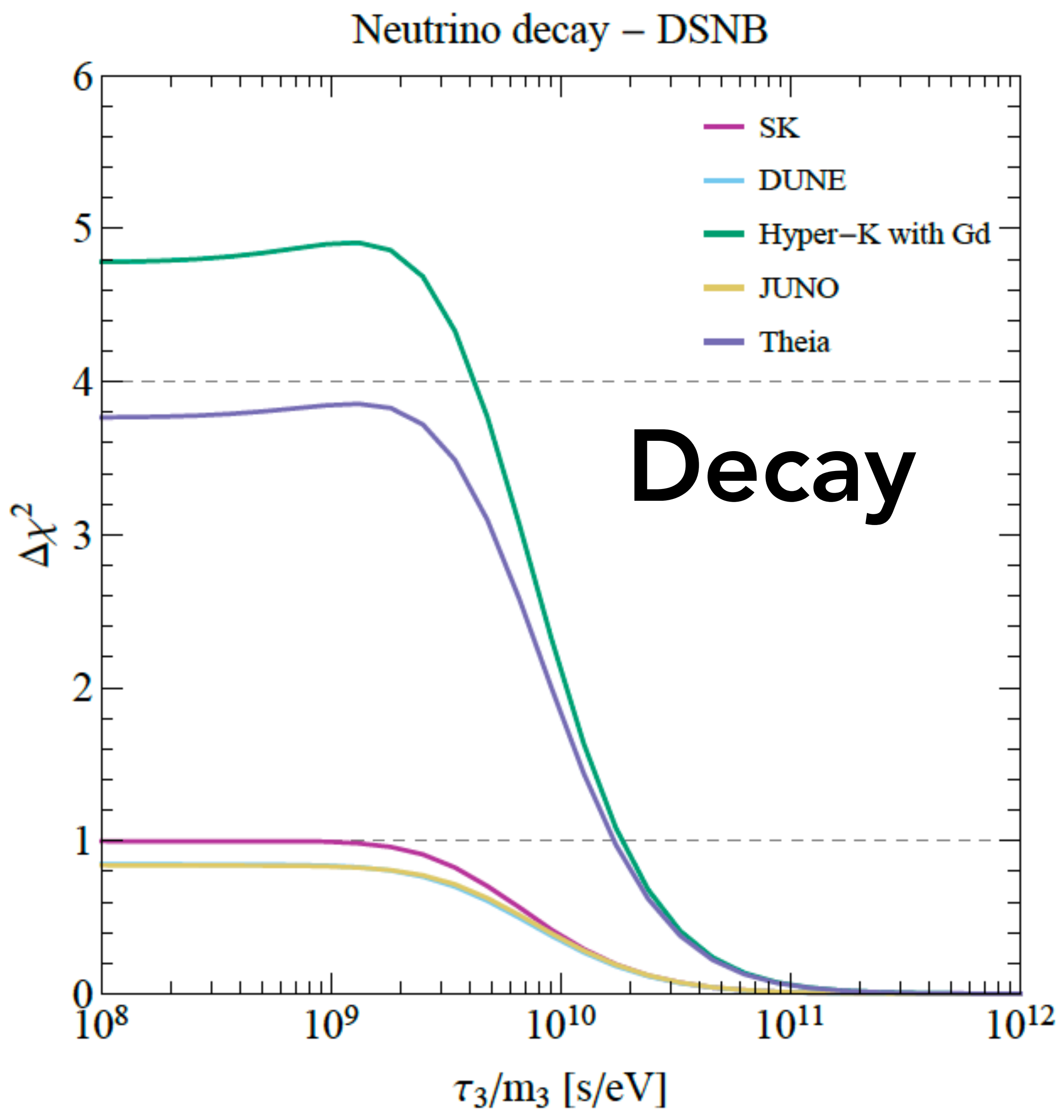
SuperNovaE Neutrinos

Next giant leap in multi-messenger physics.

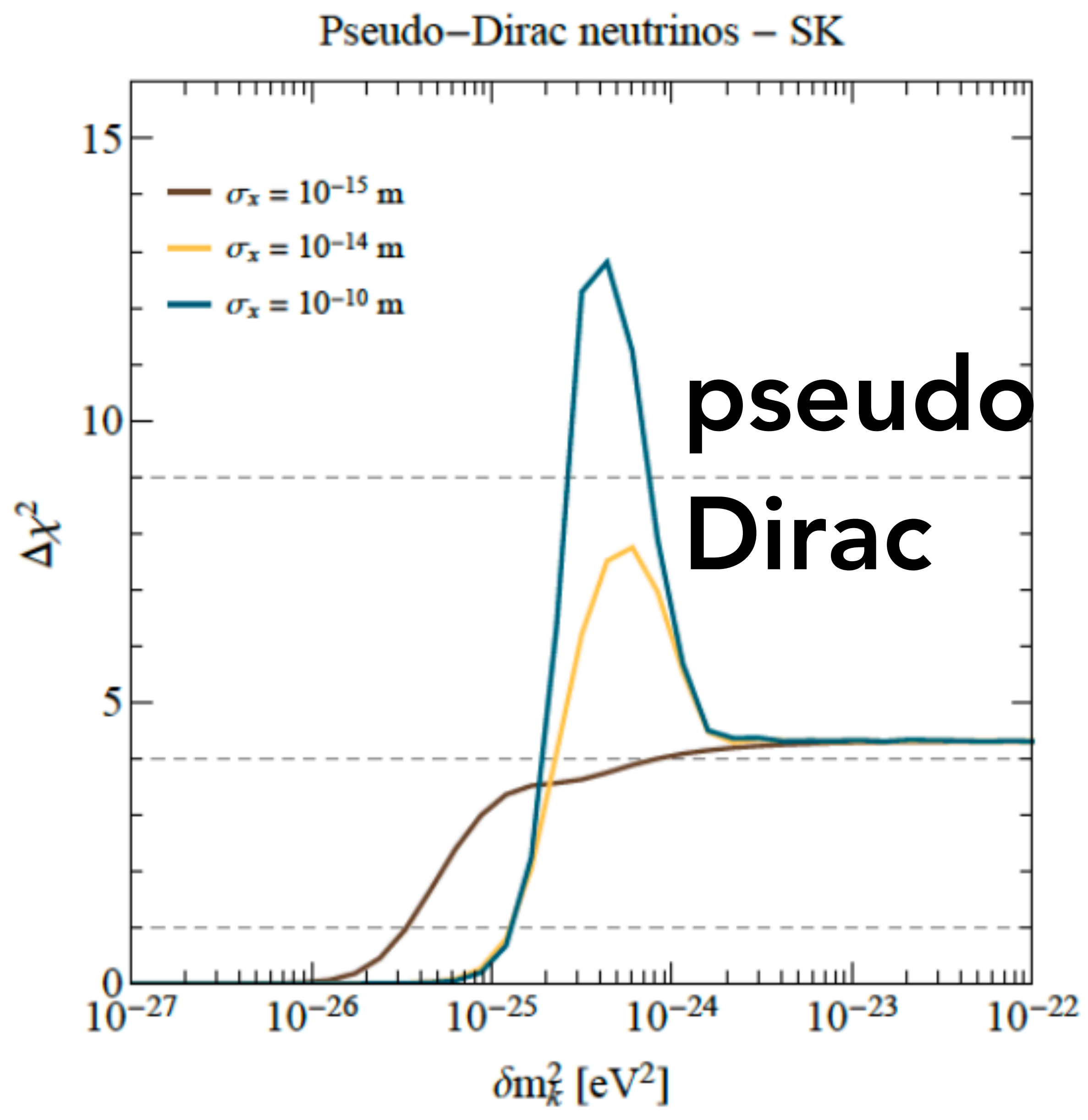
Detection around the corner!



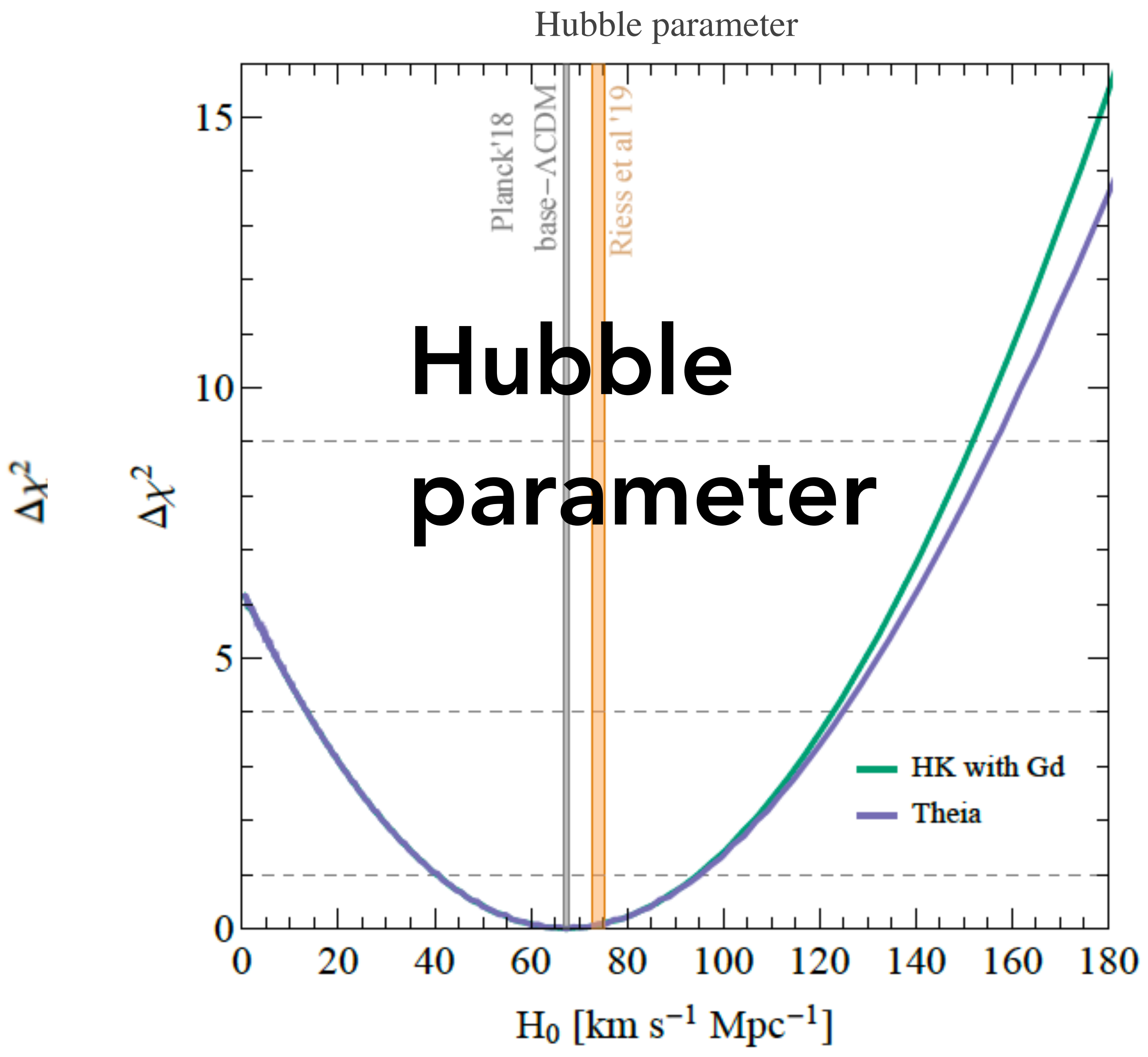
de Gouvea, Martinez-Soler, Perez-Gonzalez, **MS** (PRD 2020, 2022),
Das, **MS** (PRD 2021),
Das, Perez-Gonzalez, **MS** (PRD 2022)



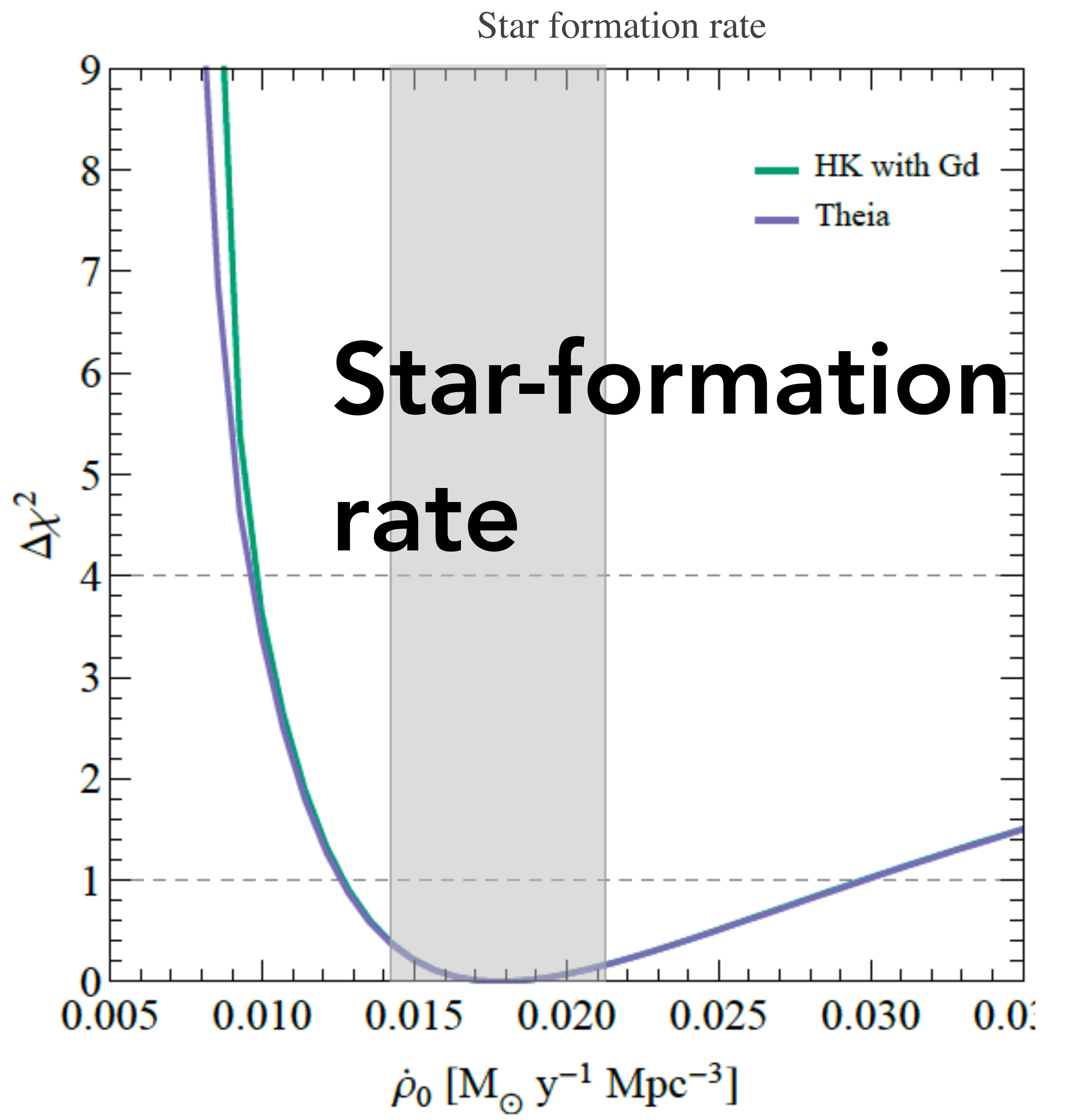
Decay



pseudo Dirac



Hubble parameter



Star-formation rate

Final thoughts

- Core-collapse SNe are one of the very few places where $\nu - \nu$ interactions are relevant. Physics of is collective neutrino oscillations not yet understood completely.

- Slow collective oscillations - operative at $\mathcal{O}(100)\,\mathrm{km}$ from the core. Rate 10^3 times faster than vacuum oscillations. Not suppressed by small mixing angles.

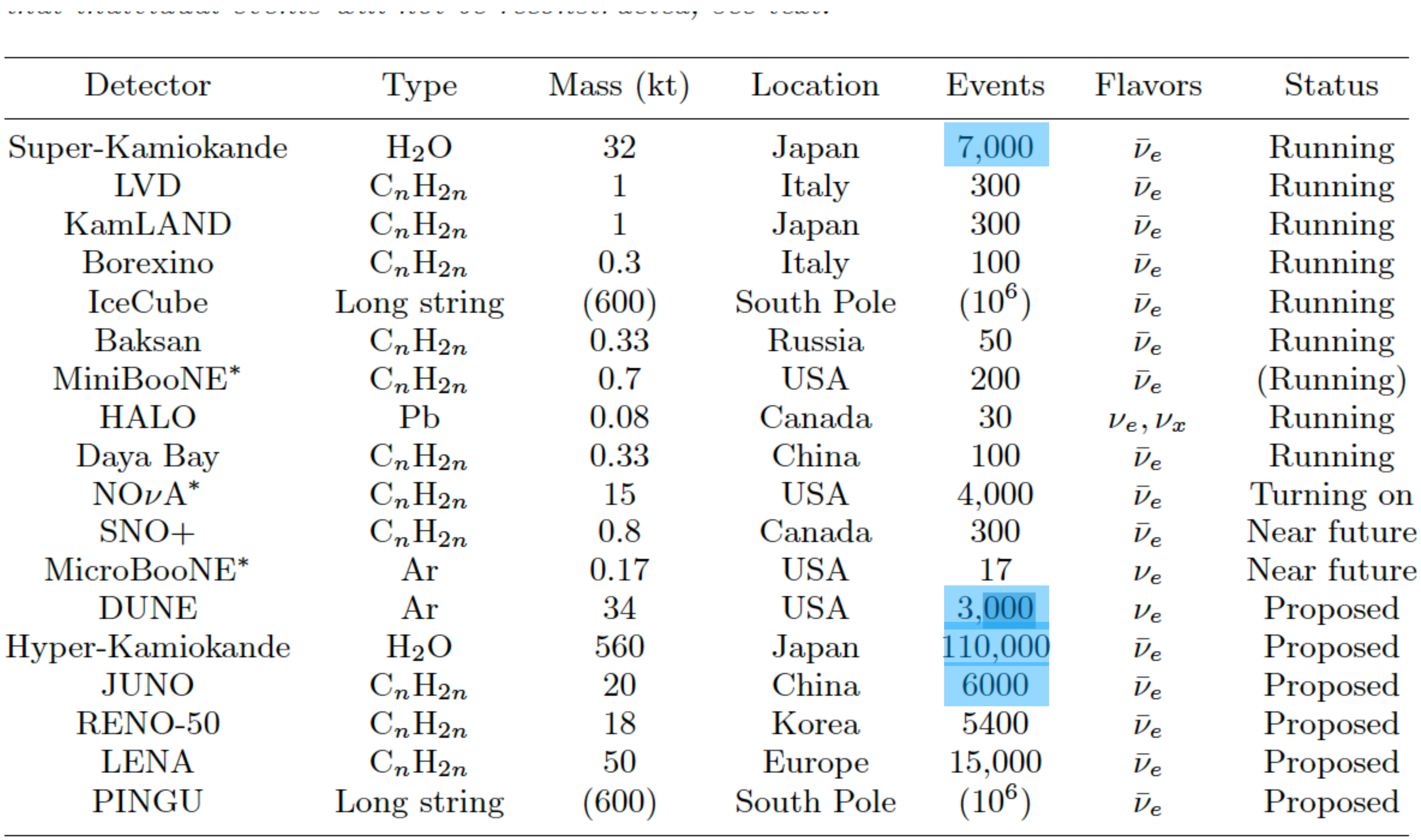
- Fast flavour conversions: a type of collective oscillations causing rapid flavour conversions near the core of the SN $\mathcal{O}(10)\,\mathrm{cm}$. Rate 10^3 times faster than slow collective oscillations.

- Little dependence on neutrino energy and mixing angle. Fascinating consequences for SN explosion and nucleosynthesis.

- Supernova - as a laboratory for tests of beyond-the-Standard-Model: neutrino decays, Dirac-Majorana nature, non-standard interactions, new particles, and so on.

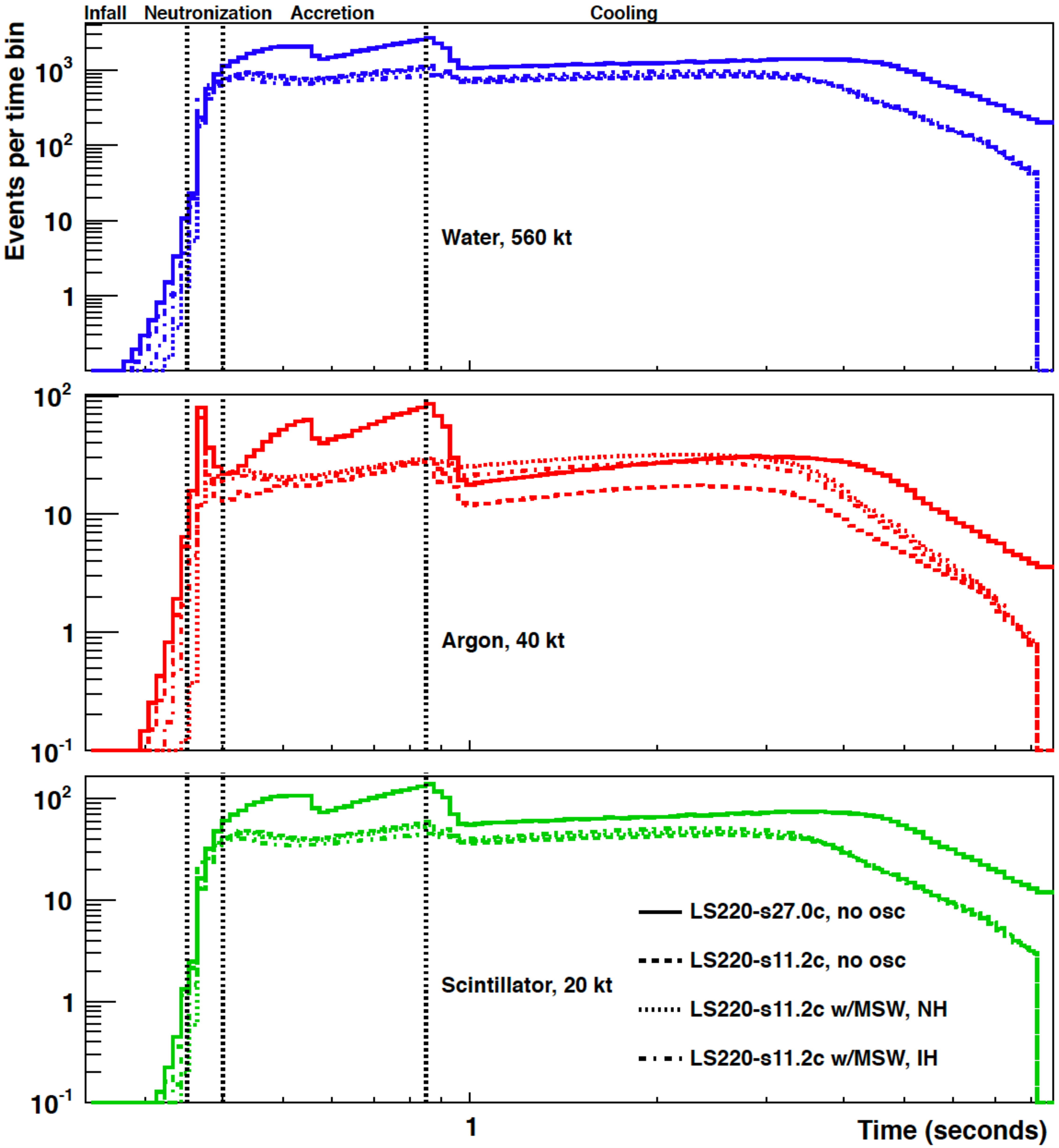
THANK YOU!

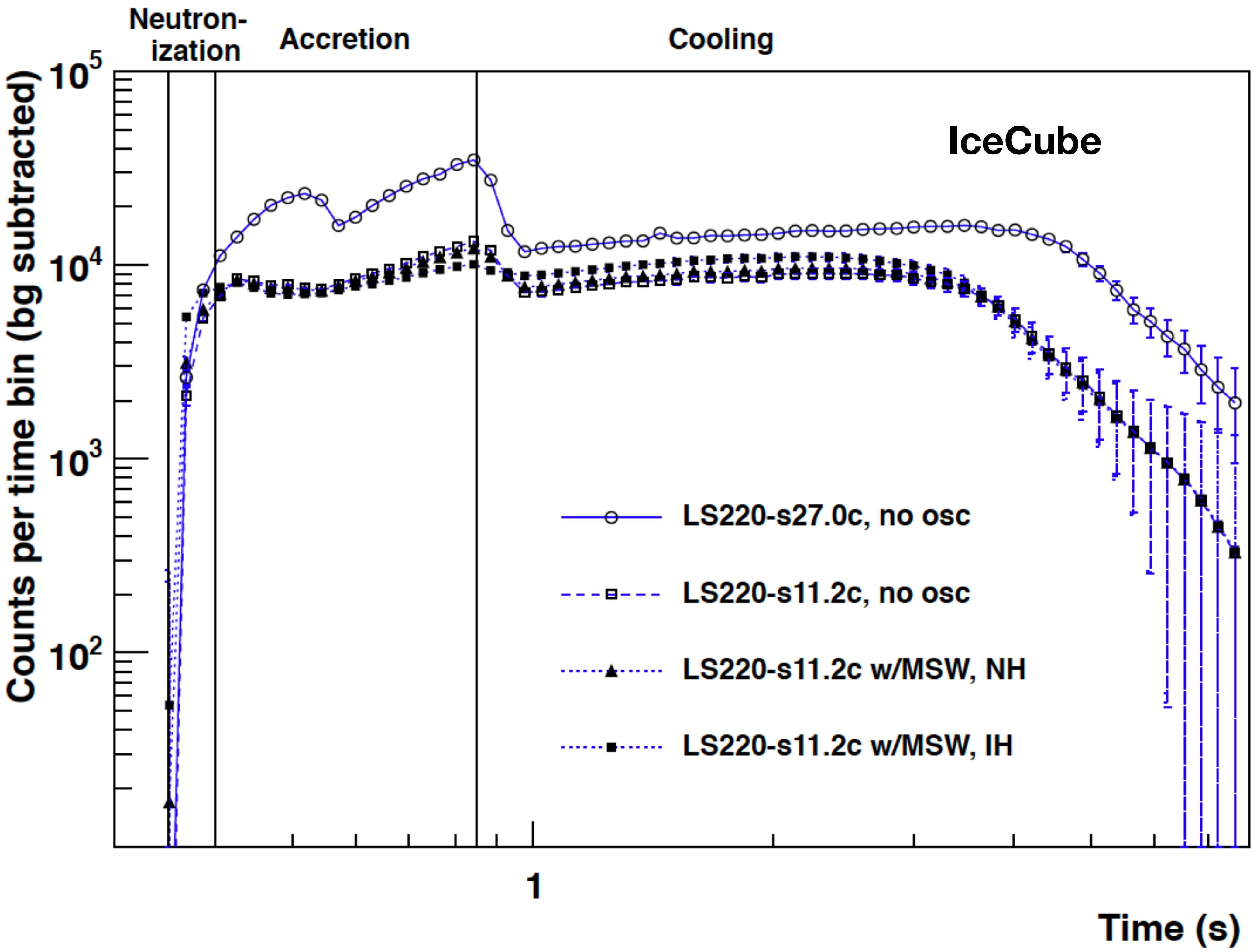
Future event rates in detectors



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

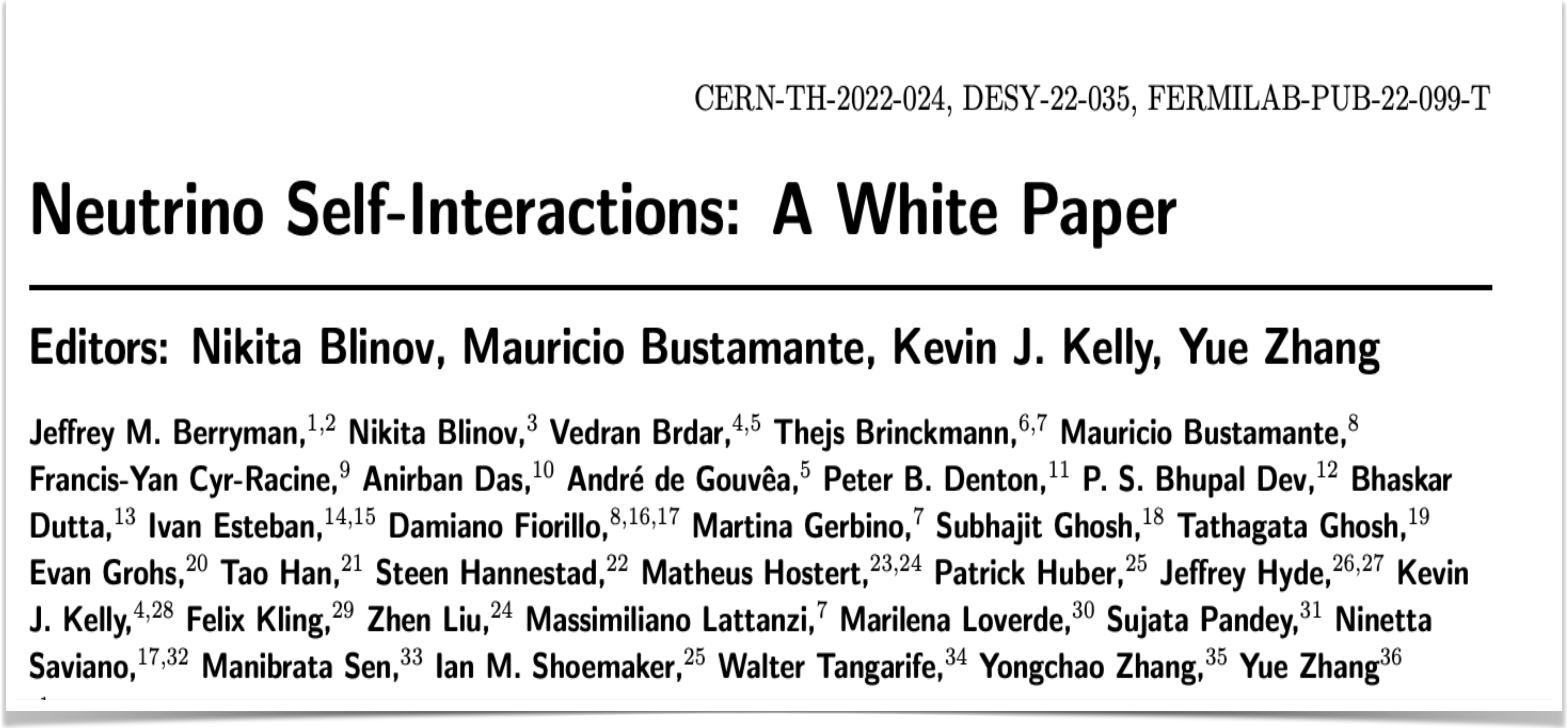
Future event rates in detectors





d=10 kpc

3. Neutrino secret self-interactions (NSSI)

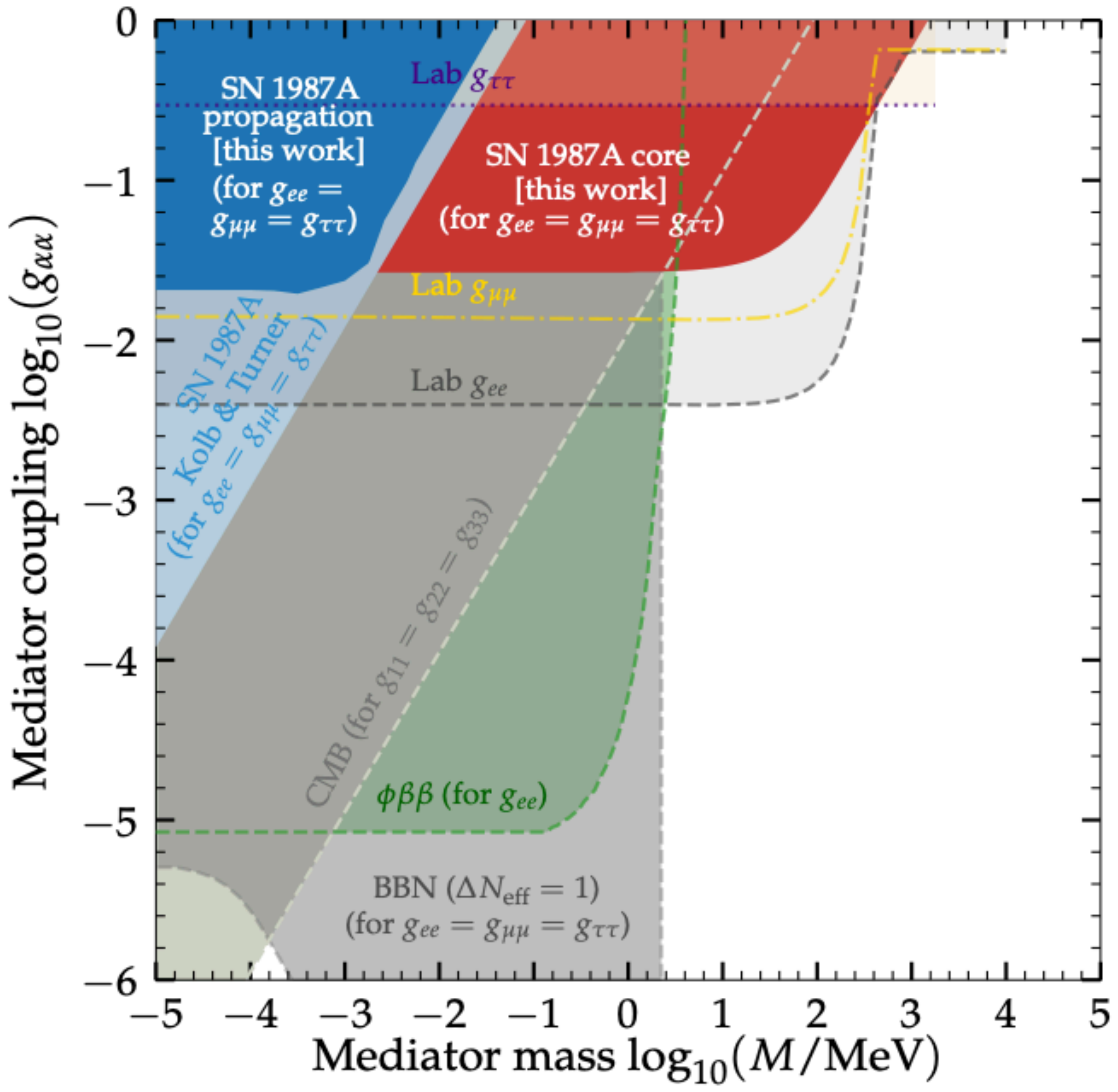


CERN-TH-2022-024, DESY-22-035, FERMILAB-PUB-22-099-T

Neutrino Self-Interactions: A White Paper

Editors: Nikita Blinov, Mauricio Bustamante, Kevin J. Kelly, Yue Zhang

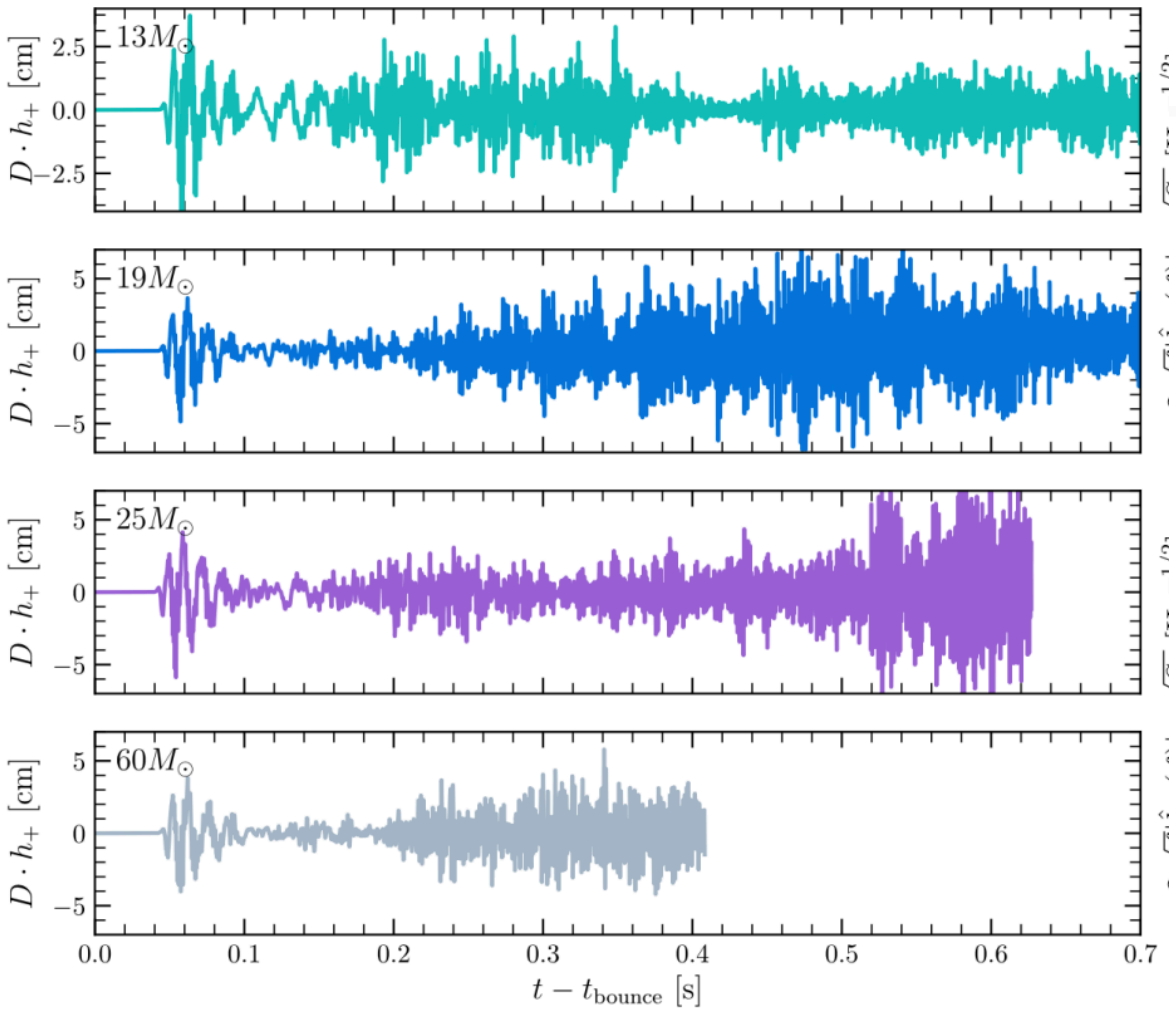
Jeffrey M. Berryman,[1,2] Nikita Blinov,[3] Vedran Brdar,[4,5] Thejs Brinckmann,[6,7] Mauricio Bustamante,[8] Francis-Yan Cyr-Racine,[9] Anirban Das,[10] André de Gouvêa,[5] Peter B. Denton,[11] P. S. Bhupal Dev,[12] Bhaskar Dutta,[13] Ivan Esteban,[14,15] Damiano Fiorillo,[8,16,17] Martina Gerbino,[7] Subhajit Ghosh,[18] Tathagata Ghosh,[19] Evan Grohs,[20] Tao Han,[21] Steen Hannestad,[22] Matheus Hostert,[23,24] Patrick Huber,[25] Jeffrey Hyde,[26,27] Kevin J. Kelly,[4,28] Felix Kling,[29] Zhen Liu,[24] Massimiliano Lattanzi,[7] Marilena Loverde,[30] Sujata Pandey,[31] Ninetta Saviano,[17,32] Manibrata Sen,[33] Ian M. Shoemaker,[25] Walter Tangarife,[34] Yongchao Zhang,[35] Yue Zhang[36]



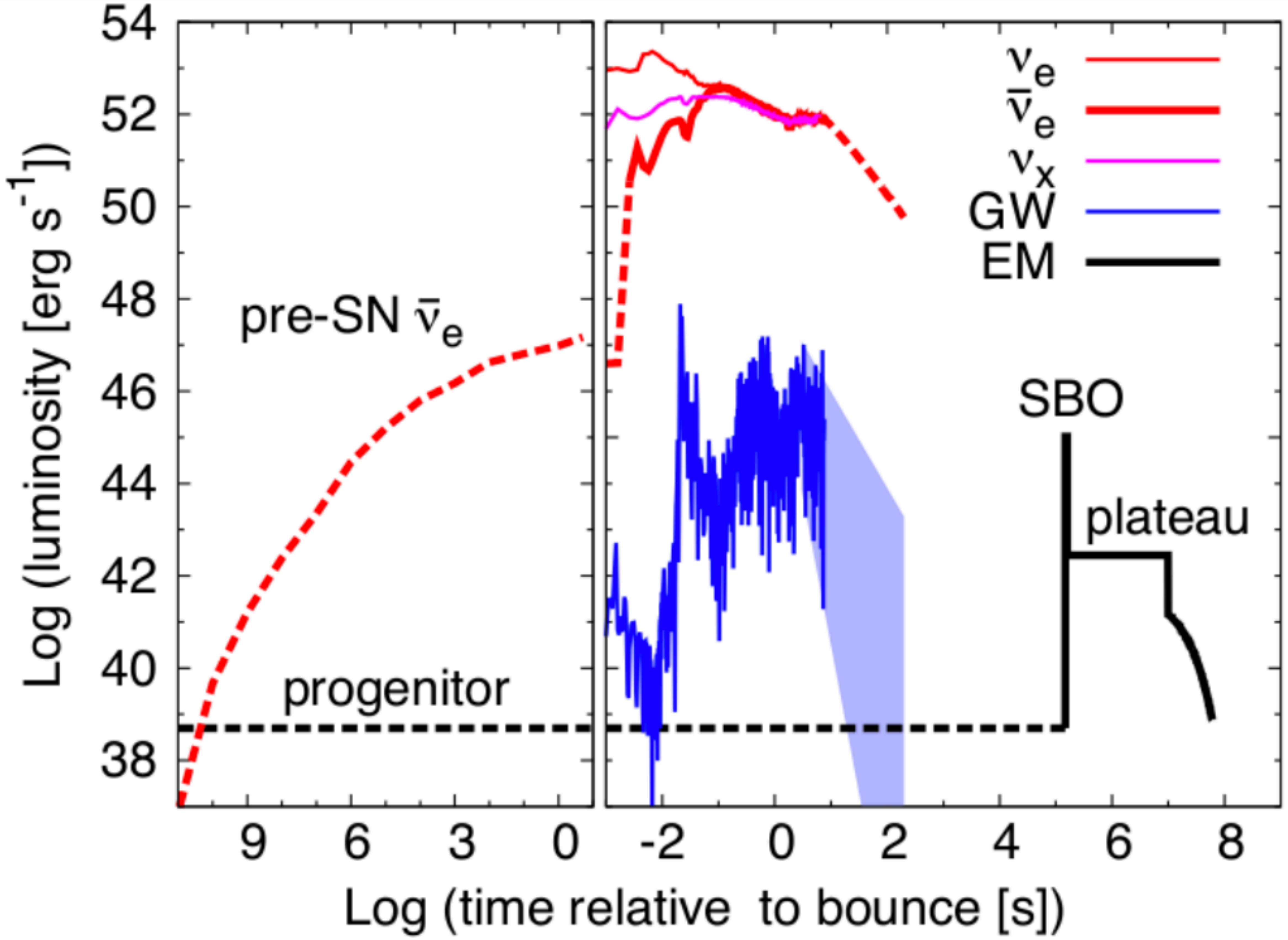
- Scatterings with the cosmic neutrino background could have down-scattered the neutrinos from SN1987A (blue shaded).
- Non-trivial impact on neutrino spectra through collective oscillations.

Snowmass white paper 2022

Neutrinos and gravitational waves



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



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

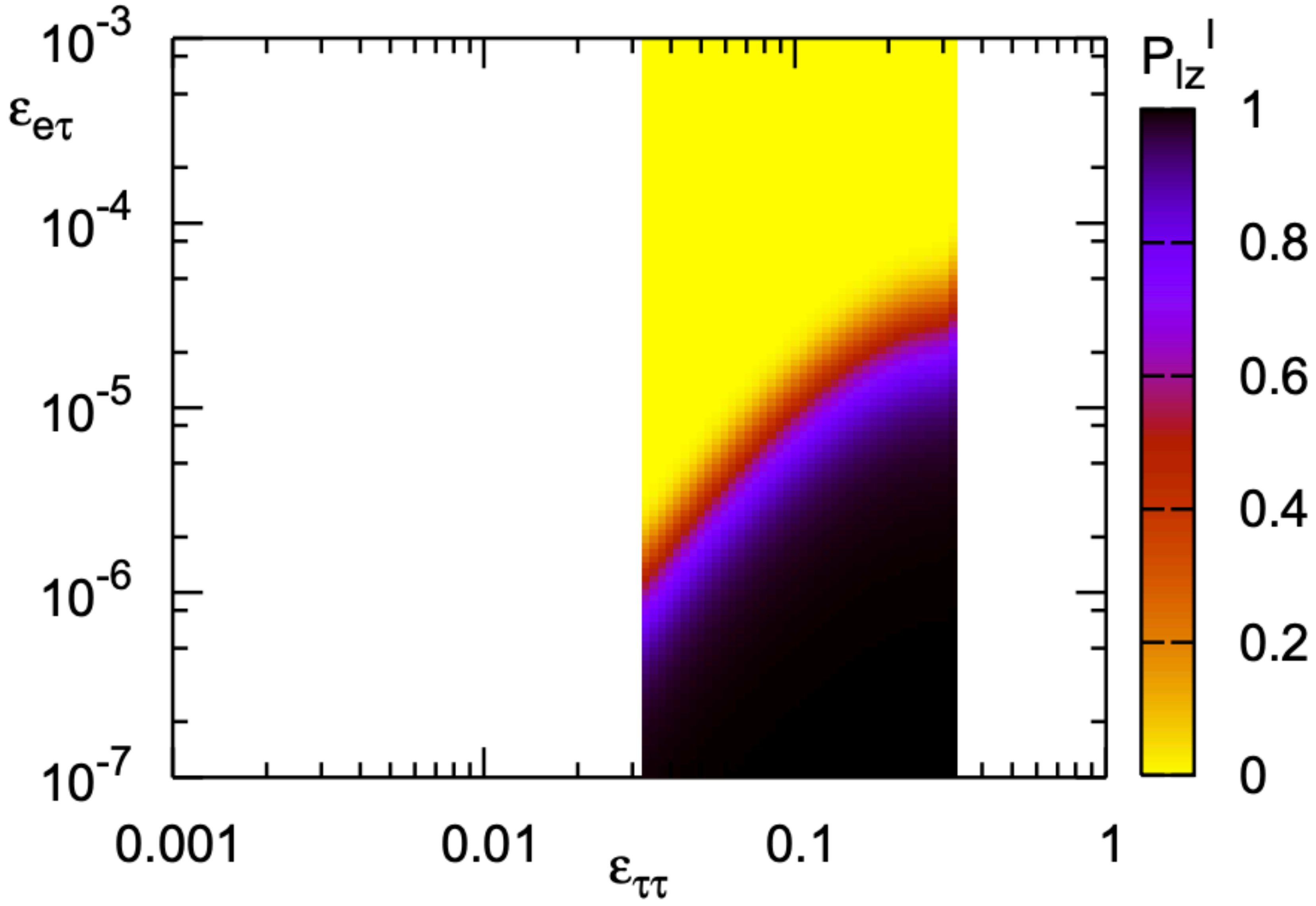
Non-standard Interactions

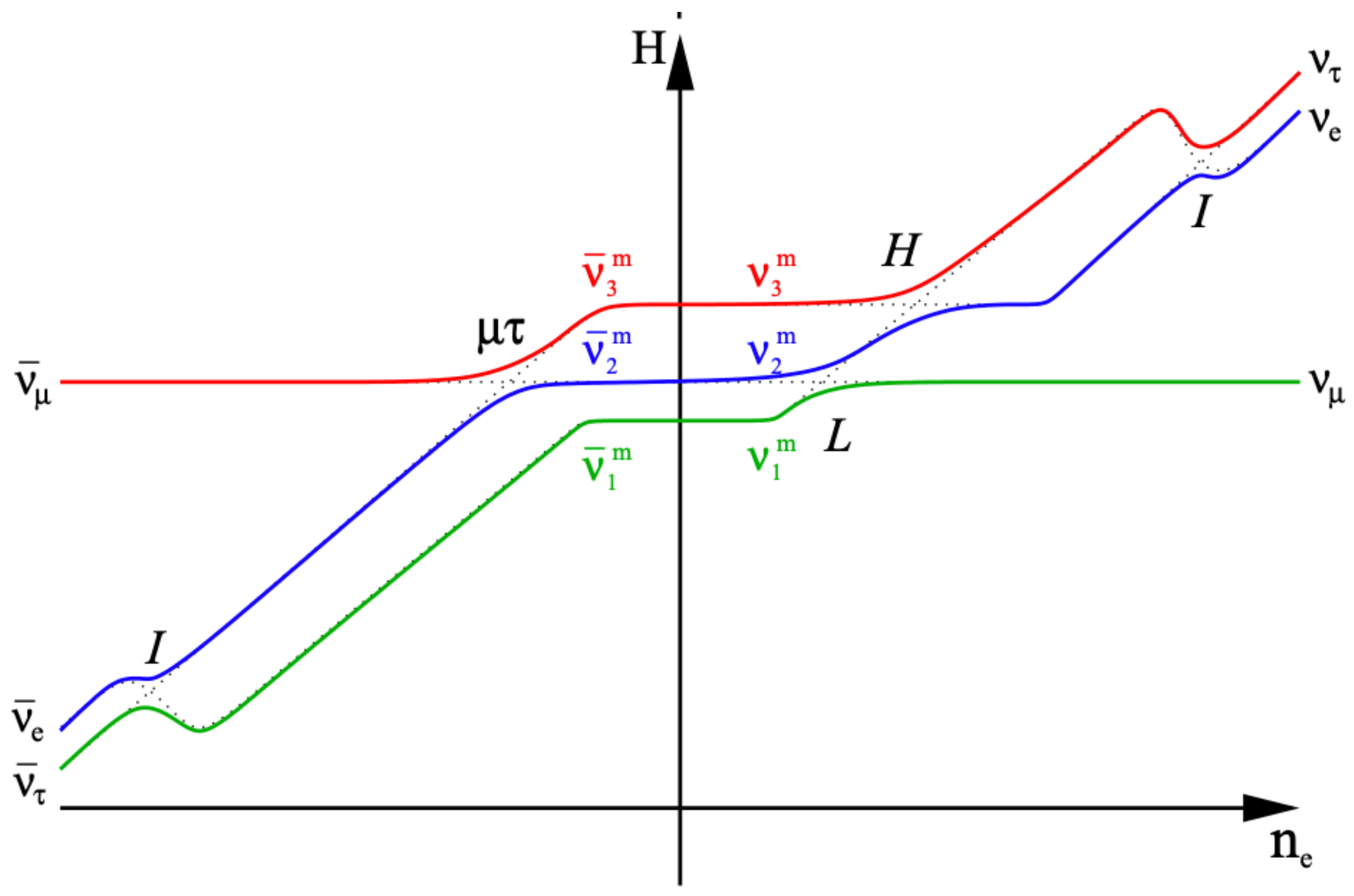
- Presence of NSI can lead to important consequences in dense core
  $\mathscr{L} \supset \varepsilon^{fP}_{\alpha\beta}\, 2\sqrt{2}G_F\, (\bar{\nu}^{\alpha}\,\gamma^{\mu} L\,\nu^{\beta})\,(\bar{f}\gamma_{\mu} P f)$

- 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.

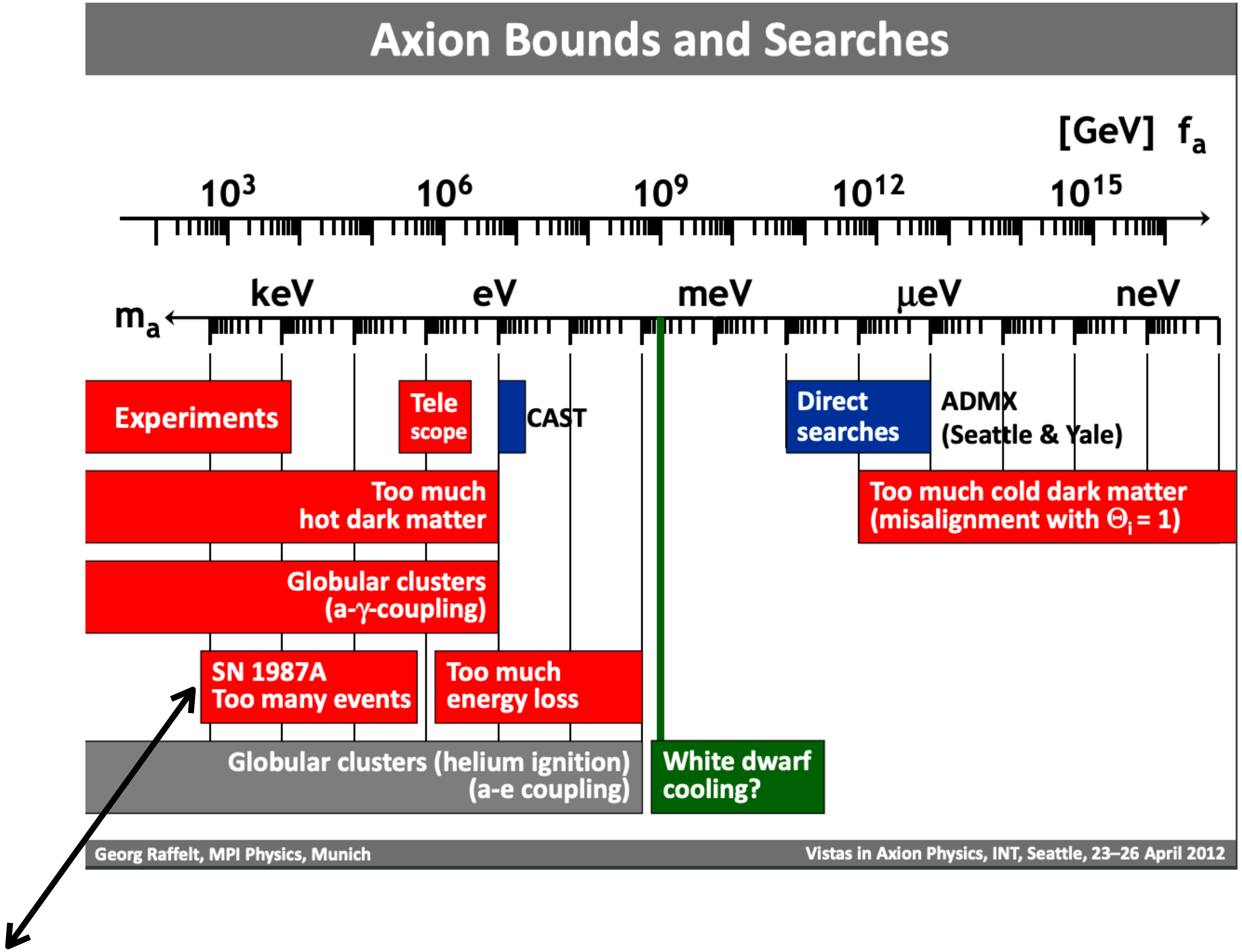
- Can reduce Y_e during collapse, leading to lower shock energy.





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

Axion bounds

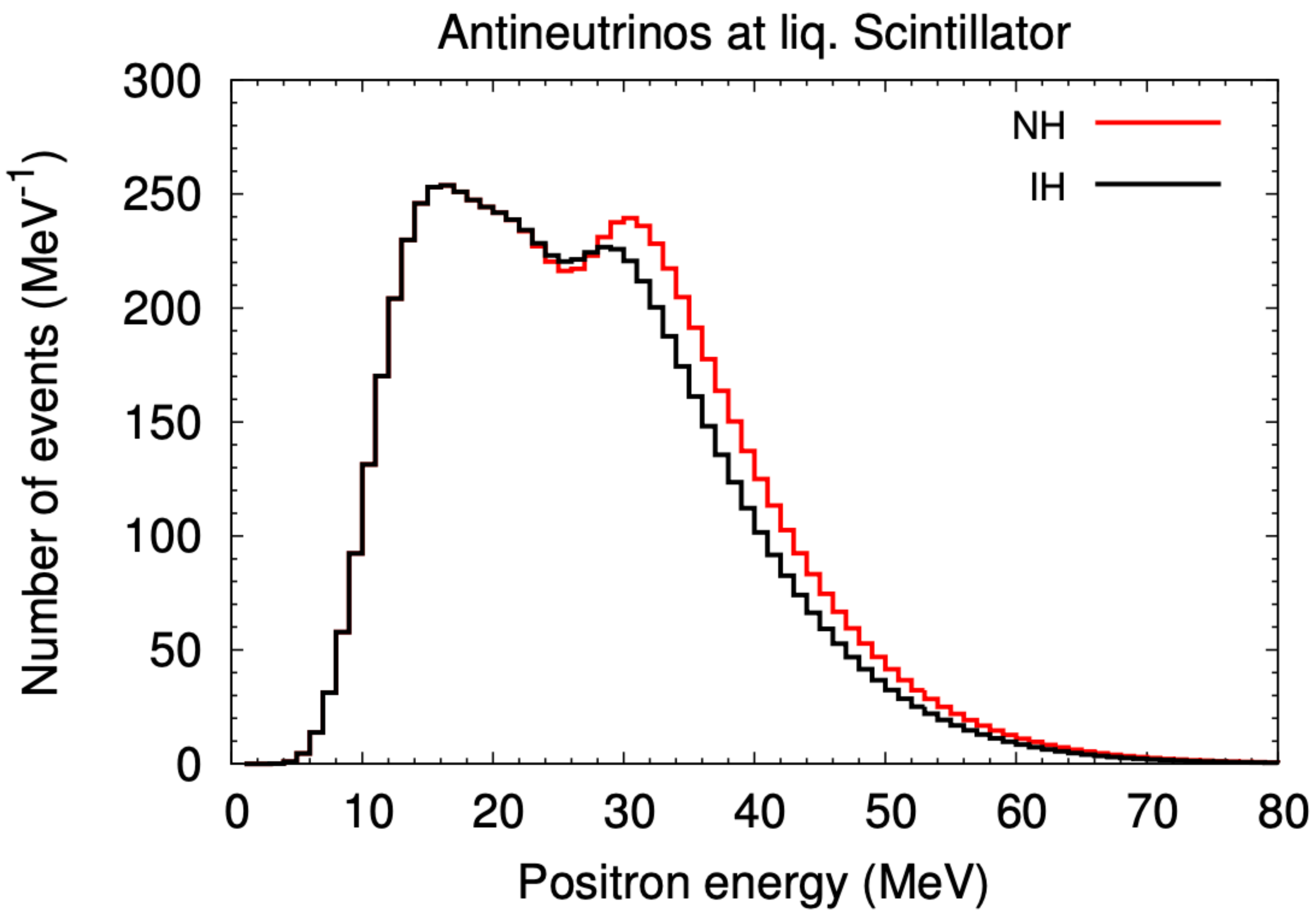

Axion Bounds and Searches

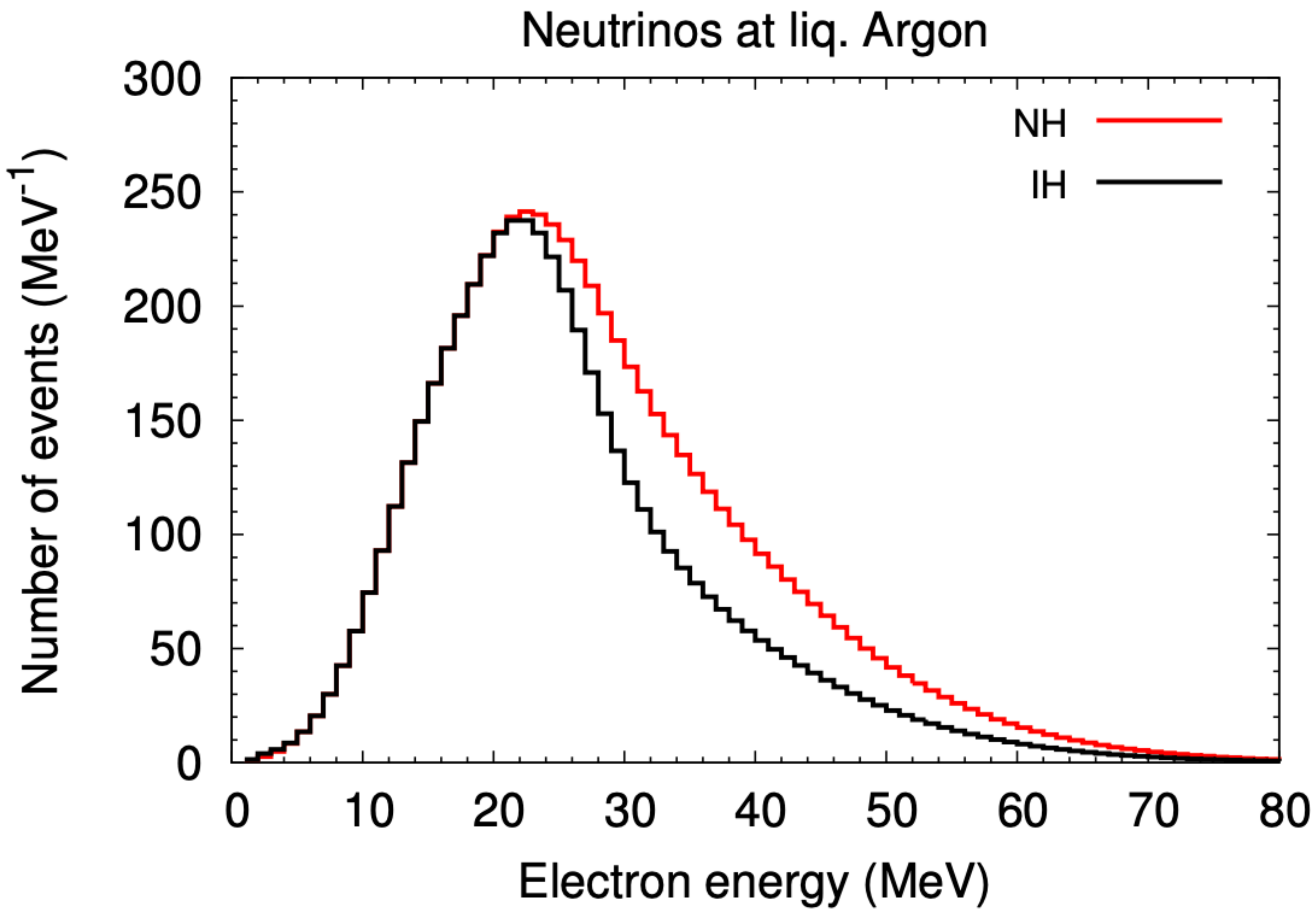
Georg Raffelt, MPI Physics, Munich

Vistas in Axion Physics, INT, Seattle, 23–26 April 2012

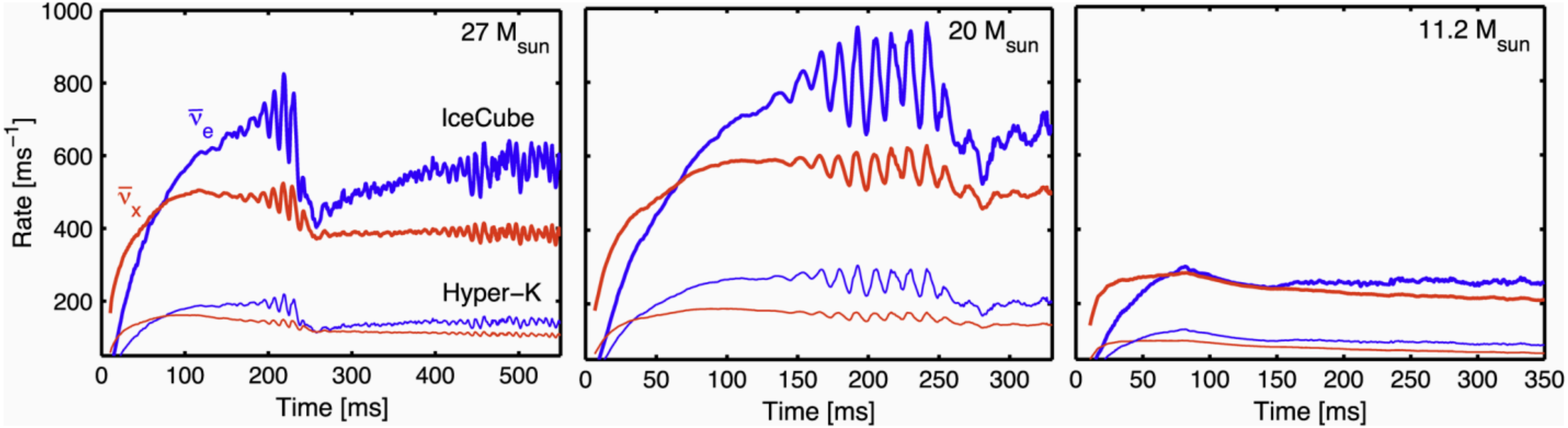
Too many events due to absorption on O, and subsequent γ emission.

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

Earth-matter effects

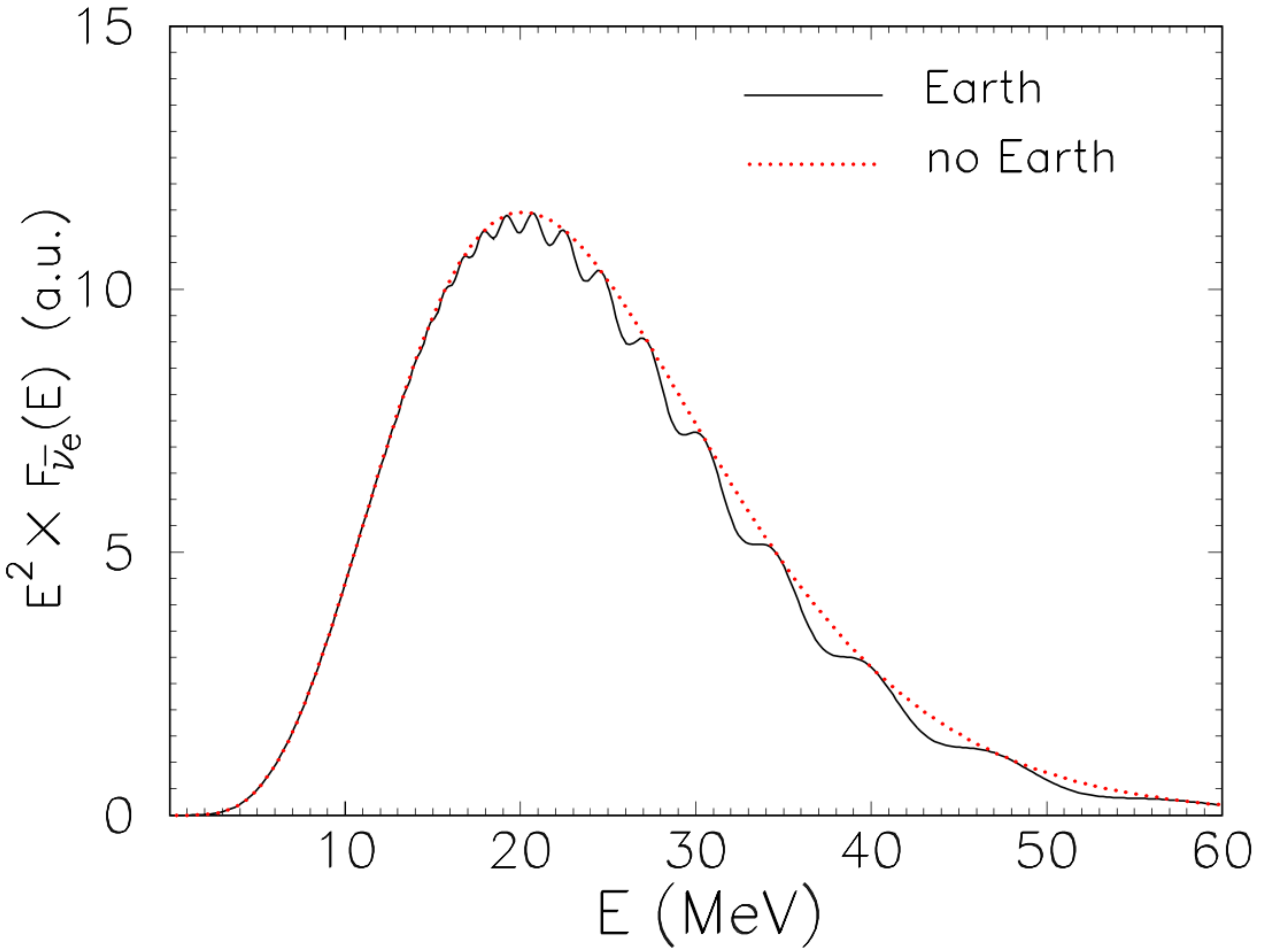
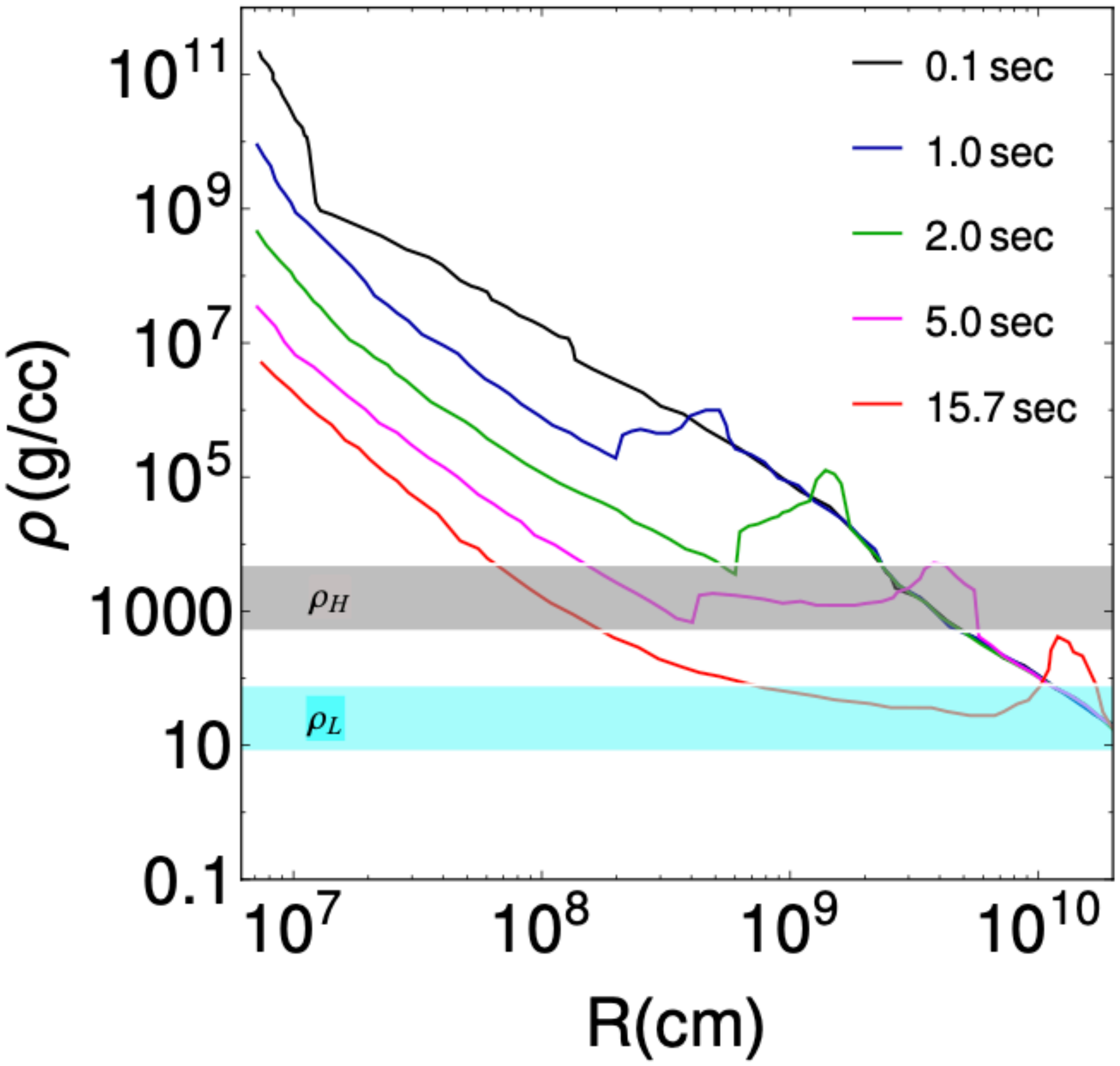


Fig. 39. – Observable signal $E^2 F_{\bar{\nu}_e}$ with (continuous curve) and without (dotted curve) Earth crossing.

SN density profile



Many-body picture: SN oscillations

Flavour isospin operator

$$\begin{aligned} a_e(\mathbf{p}) &= \cos\theta\, a_1(\mathbf{p}) + \sin\theta\, a_2(\mathbf{p}) \\ a_x(\mathbf{p}) &= -\sin\theta\, a_1(\mathbf{p}) + \cos\theta\, a_2(\mathbf{p}) \end{aligned}$$

Flavour isospin operator

$$J^+_{\mathbf{p}} = a_e^\dagger(\mathbf{p}) a_x(\mathbf{p}) \ , \qquad J^-_{\mathbf{p}} = a_x^\dagger(\mathbf{p}) a_e(\mathbf{p}) \ , \qquad J^z_{\mathbf{p}} = \frac{1}{2}\left(a_e^\dagger(\mathbf{p}) a_e(\mathbf{p}) - a_x^\dagger(\mathbf{p}) a_x(\mathbf{p})\right)$$

Vacuum term:

$$\begin{aligned} H_{\text{vac}} &= \sum_{\mathbf{p}} \left(\frac{m_1^2}{2p} a_1^\dagger(\mathbf{p}) a_1(\mathbf{p}) + \frac{m_2^2}{2p} a_2^\dagger(\mathbf{p}) a_2(\mathbf{p}) \right) \\ &= \sum_{\omega} \omega \vec{B} \cdot \vec{J}_\omega \ , \end{aligned}$$

$$\vec{B} = (0,0,-1)_{\text{mass}} = (\sin 2\theta, 0, -\cos 2\theta)_{\text{flavor}} .$$

Self-int term:

$$\begin{aligned} H_{\nu\nu} = \frac{G_F}{\sqrt{2}V} \sum_{\mathbf{p}} \sum_{\mathbf{q}} (1 - \cos\vartheta_{\mathbf{pq}}) [\, & a_e^\dagger(\mathbf{p}) a_e(\mathbf{p}) a_e^\dagger(\mathbf{q}) a_e(\mathbf{q}) + a_x^\dagger(\mathbf{p}) a_x(\mathbf{p}) a_x^\dagger(\mathbf{q}) a_x(\mathbf{q}) \\ & + a_x^\dagger(\mathbf{p}) a_e(\mathbf{p}) a_e^\dagger(\mathbf{q}) a_x(\mathbf{q}) + a_e^\dagger(\mathbf{p}) a_x(\mathbf{p}) a_x^\dagger(\mathbf{q}) a_e(\mathbf{q})) \,] \end{aligned}$$

$$H_{\nu\nu} = \frac{\sqrt{2} G_F}{V} \sum_{\mathbf{p},\mathbf{q}} (1 - \cos\vartheta_{\mathbf{pq}})\, \vec{J}_{\mathbf{p}} \cdot \vec{J}_{\mathbf{q}}$$

Balantekin and Pehlivan, PRD 2011.

Many-body picture: SN oscillations

- Combined neutrino Hamiltonian (vacuum + self-interactions)

$$H_\nu = \sum_\omega \omega \vec{B} \cdot \vec{J}_\omega + \mu(r) \vec{J} \cdot \vec{J}.$$

$$\mu = \frac{\sqrt{2} G_F}{V} \ .$$

Constant of motion:

$$h_\omega = \vec{B} \cdot \vec{J}_\omega + 2\mu \sum_{\omega' (\neq \omega)} \frac{\vec{J}_\omega \cdot \vec{J}_{\omega'}}{\omega - \omega'} \ .$$

$$\vec{P}_{\mathbf{p}} = 2 \langle \vec{J}_{\mathbf{p}} \rangle \xrightarrow{\langle \mathcal{O}_1 \mathcal{O}_2 \rangle = \langle \mathcal{O}_1 \rangle \langle \mathcal{O}_2 \rangle} \frac{d}{dt} \vec{P}_\omega = (\omega \vec{B} + \mu \vec{P}) \times \vec{P}_\omega$$

Balantekin and Pehlivan, PRD 2011.