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Neutrinos from Supernovae

Opportunities, Challenges, Ideas

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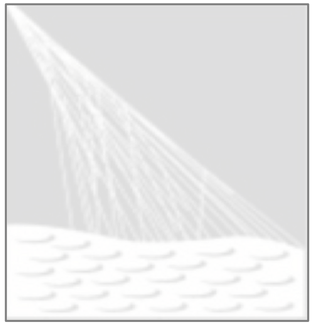
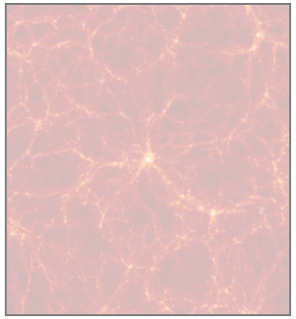
SERB INDIA
Science & Engineering Research Board
Department of Science & Technology
Government of India

MAX-PLANCK-GESELLSCHAFT

Neutrino Sources

human-made nus @
reactors, accelerators
+DM etc. not shown

0.1 - 10^4 TeV	0.1 - 10 GeV	1 - 100 MeV	1 - 10 MeV	0.1 - 1 MeV	0.01 meV
					
Cosmic Accelerators	Atmospheric	**Supernova** **BNS mergers**	Solar	Earth	Early Universe

Proof of Principle

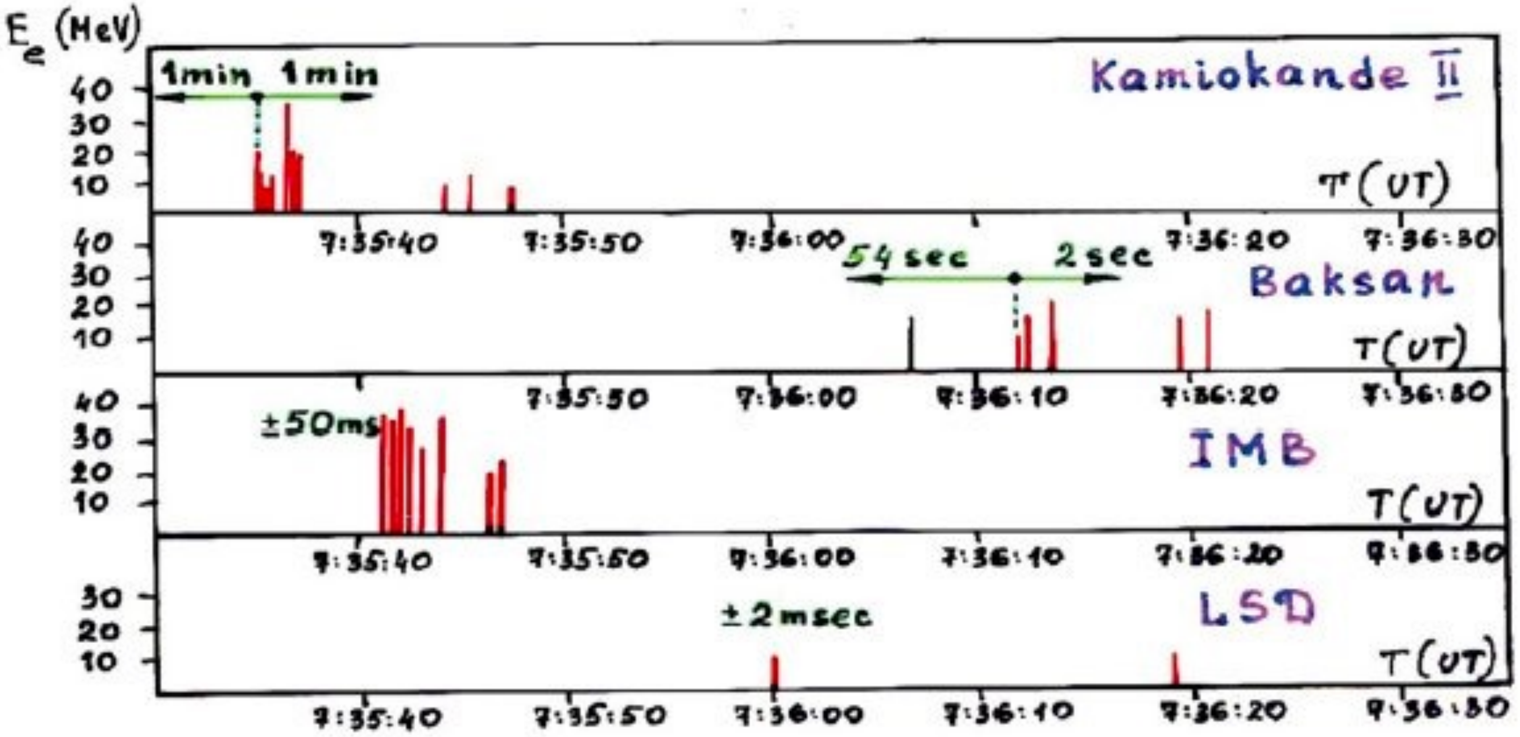


Image credit: Suzuki (2003)

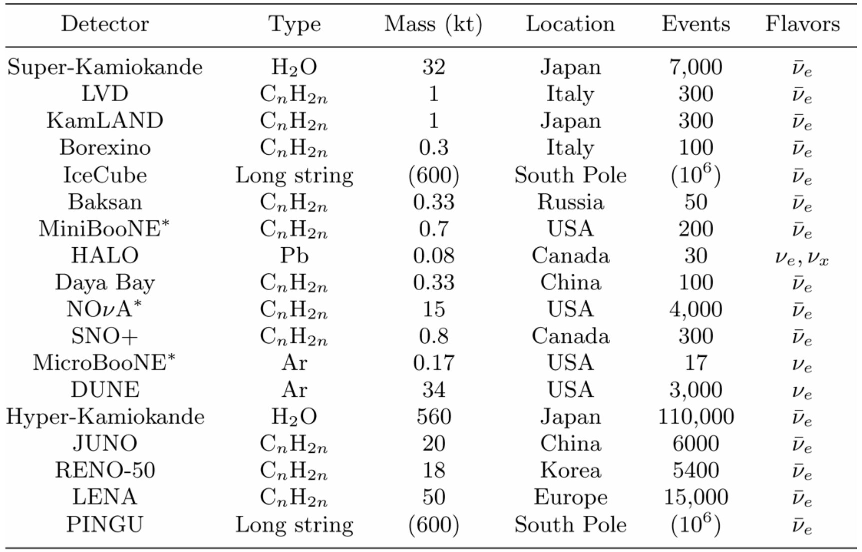
Modelling is driven by SN simulations, though most features are theoretically well-justified

SN1987A is the only data.

SN Neutrino Program

Running

Future

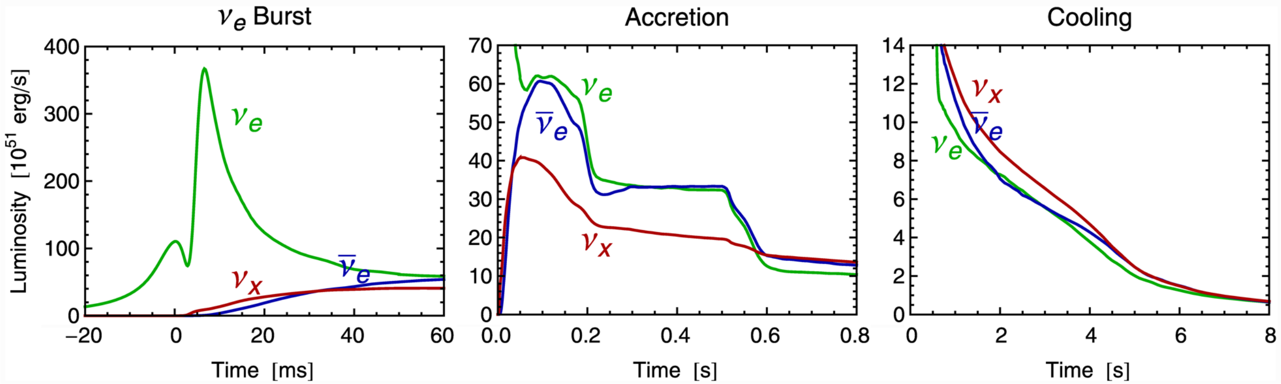


Detector	Type	Mass (kt)	Location	Events	Flavors
Super-Kamiokande	H_2O	32	Japan	7,000	$\bar{\nu}_e$
LVD	C_nH_{2n}	1	Italy	300	$\bar{\nu}_e$
KamLAND	C_nH_{2n}	1	Japan	300	$\bar{\nu}_e$
Borexino	C_nH_{2n}	0.3	Italy	100	$\bar{\nu}_e$
IceCube	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$
Baksan	C_nH_{2n}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

From review by Scholberg (2012)

Several detectors capable of detecting SN neutrinos.
There is a rich science-case.

1d simulation of a 27 M_{sun} star by Garching group
See review by Janka, Melson, and Summa (2016)



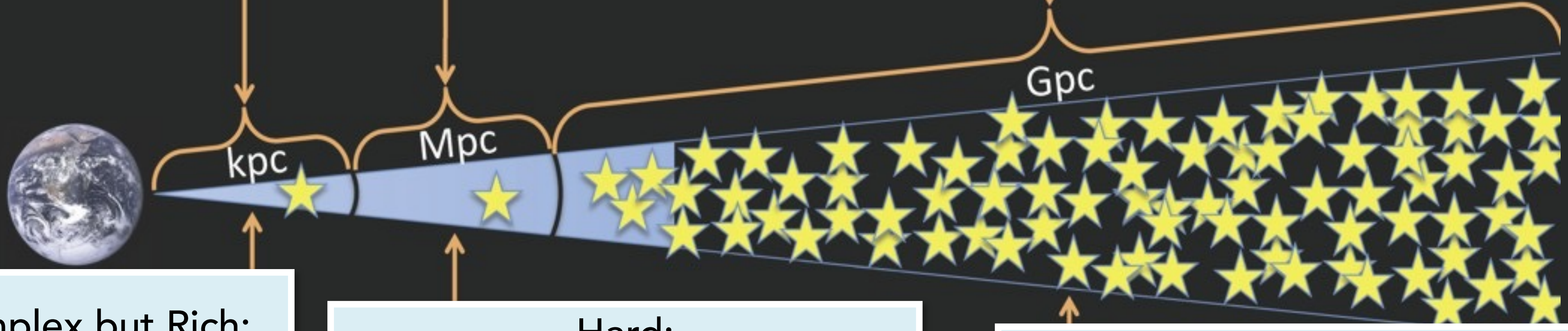
Burst	**Accretion**	**Cooling**
SN standard candle	Collective effects	Nuclear physics
Mass ordering	SN theory	Exotics/Axions
Timing	Mass ordering	Nucleosynthesis
…	Pointing	Shock
	…	…

Here, There, Everywhere

N >> 1 : Burst

N ~ 1 : Mini-Burst

N << 1 : DSNB



Rare & Complex but Rich:
This Talk

Hard:
Need multi-messenger and/or bigger detectors

Hard but Promising:
Gd in SK

Rate ~ 0.01/yr

Rate ~ 1/yr

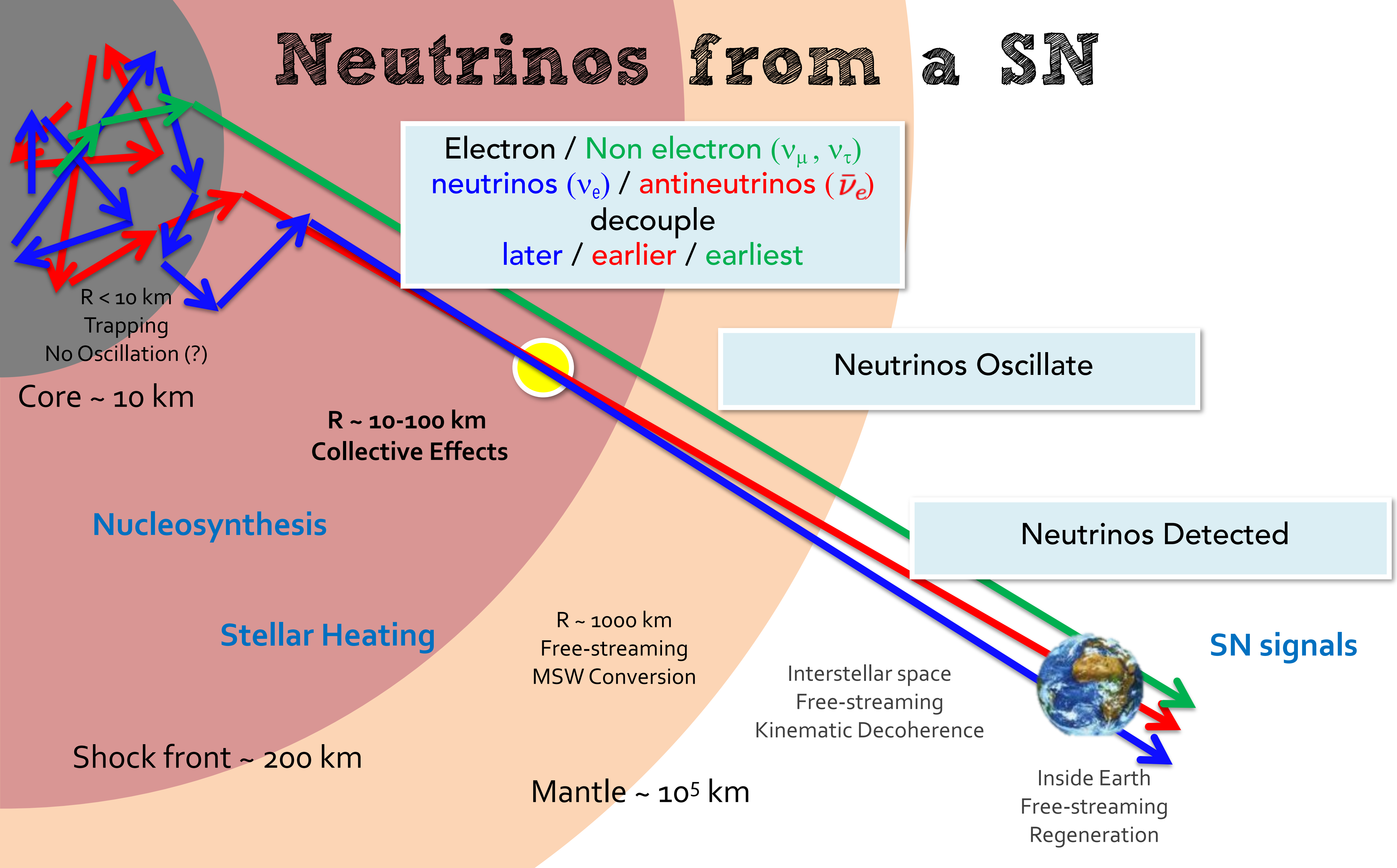
Rate ~ 10^8/yr

high statistics,
all flavors

object identity,
burst variety

cosmic rate,
average emission

Neutrinos from a SN



Electron / Non electron (ν_μ, ν_τ)
neutrinos (ν_e) / antineutrinos $(\bar{\nu}_e)$
decouple
later / earlier / earliest

Neutrinos Oscillate

Neutrinos Detected

R < 10 km
Trapping
No Oscillation (?)

Core ~ 10 km

R ~ 10-100 km
Collective Effects

Nucleosynthesis

Stellar Heating

Shock front ~ 200 km

R ~ 1000 km
Free-streaming
MSW Conversion

Mantle ~ 10^5 km

Interstellar space
Free-streaming
Kinematic Decoherence

Inside Earth
Free-streaming
Regeneration

SN signals

SN Neutrino Oscillations

$$i\left(\partial_t + \mathbf{v}_\mathbf{p}\cdot\partial_\mathbf{p}\right)\rho_\mathbf{p} = +\left[\frac{\mathsf{M}^2}{2E},\,\rho_\mathbf{p}\right] + \sqrt{2}G_\mathrm{F}\left[\mathsf{L},\rho_\mathbf{p}\right] + \sqrt{2}G_\mathrm{F}\int\frac{d^3\mathbf{q}}{(2\pi)^3}\left(1-\hat{\mathbf{p}}\cdot\hat{\mathbf{q}}\right)\left[\rho_\mathbf{q}-\bar{\rho}_\mathbf{q},\rho_\mathbf{p}\right]$$

Vacuum oscillations depend on neutrino mass matrix M
Overall minus sign for antineutrinos

MSW effect depends on ordinary matter density L, i.e. mainly electron density

Collective effects depends on the neutrino density

$$\omega = \frac{\Delta m^2}{2E}$$

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

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

In general, a 7 dimensional problem
3 momentum (E, θ_p, ϕ_p) + 3 space (r, θ, ϕ) + 1 time (t)
Dimensionality of calculations denoted by $n_p + n_x + n_t$

Collective Oscillation: Instability

When density is high

$$\mu = G_F n_\nu \gg \frac{\Delta m^2}{2E} = \omega$$

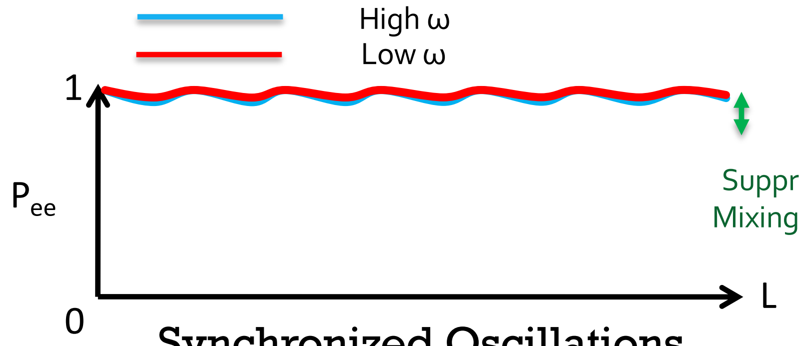
the collective oscillations have small amplitude

As neutrino density gets lower

$$G_F\, n_\nu \gtrsim \frac{\Delta m^2}{2E}$$

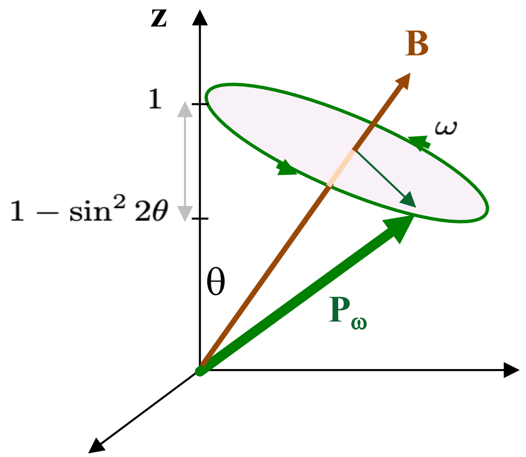
the system can be unstable

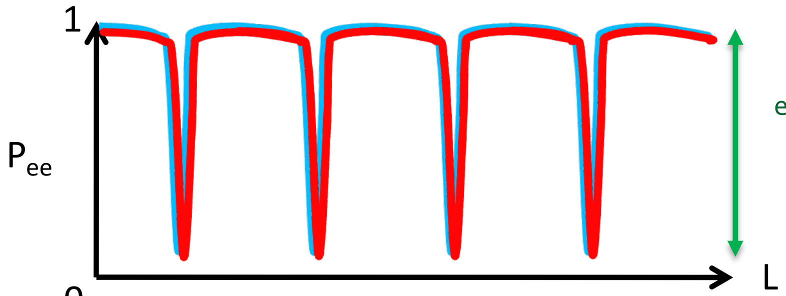
Instability grows at rate sqrt($\omega\mu$) … (slow) or proportional to μ … (fast)



Suppressed Mixing Angle

Synchronized Oscillations





Large Change even with Small Mixing Angle

Bipolar/Fast Instability

Pioneering work by Pantaleone, Kostelecky, Samuel in the 90s
Second-wave in 2005-06 by Duan, Fuller, Carlson, Qian + others
Fast Oscillations by Sawyer (2015)
Chakraborty, Hansen, Izaguirre, Raffelt (2016)
Dasgupta, Mirizzi, Sen (2016)

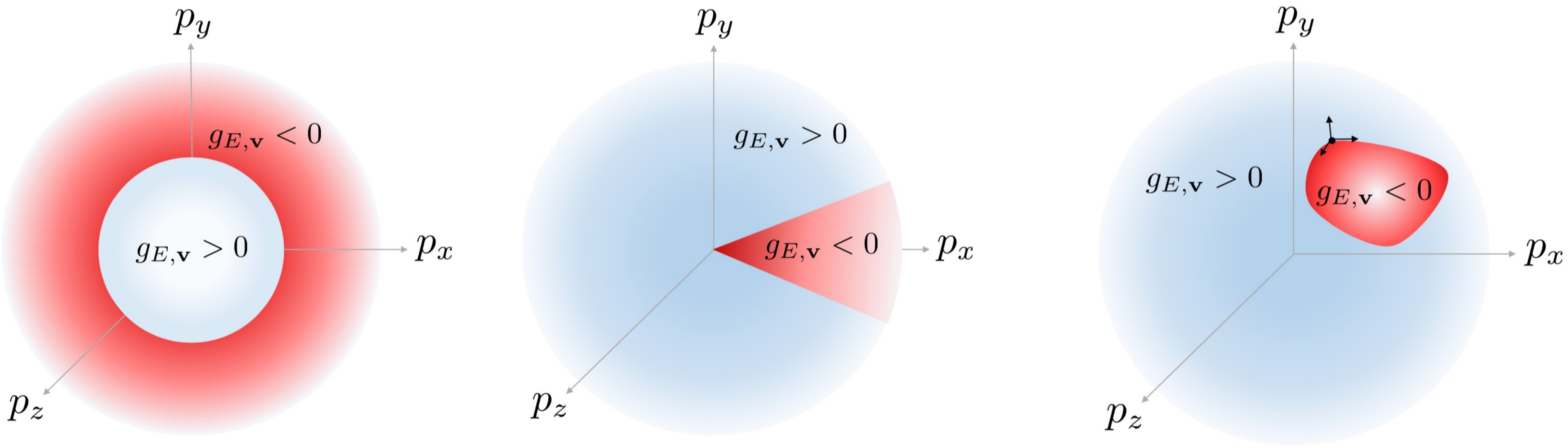
Crossing Theorem

Collective instability occurs *only if* momentum distributions of any two flavors *cross each other* around some momentum

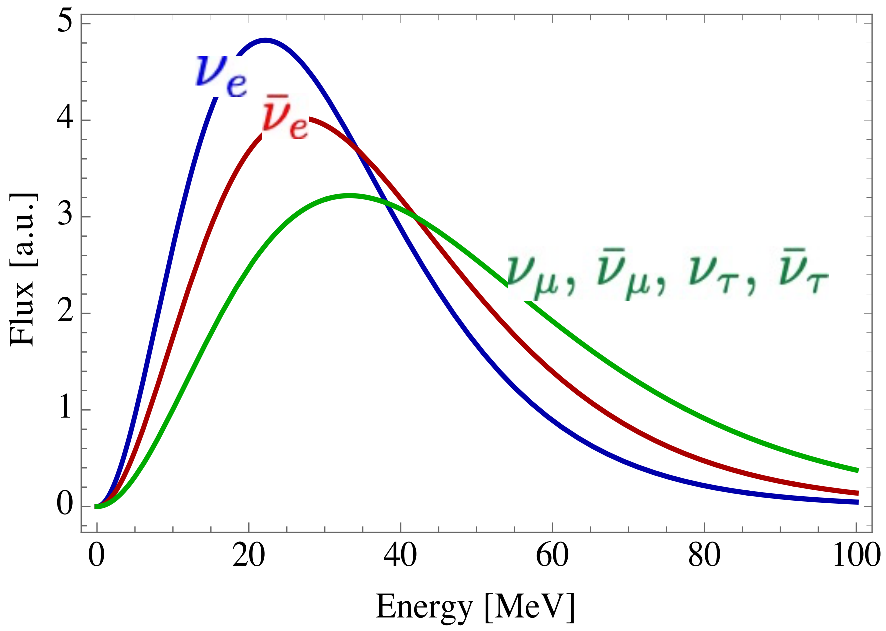
This is related to the positive-definiteness of a matrix

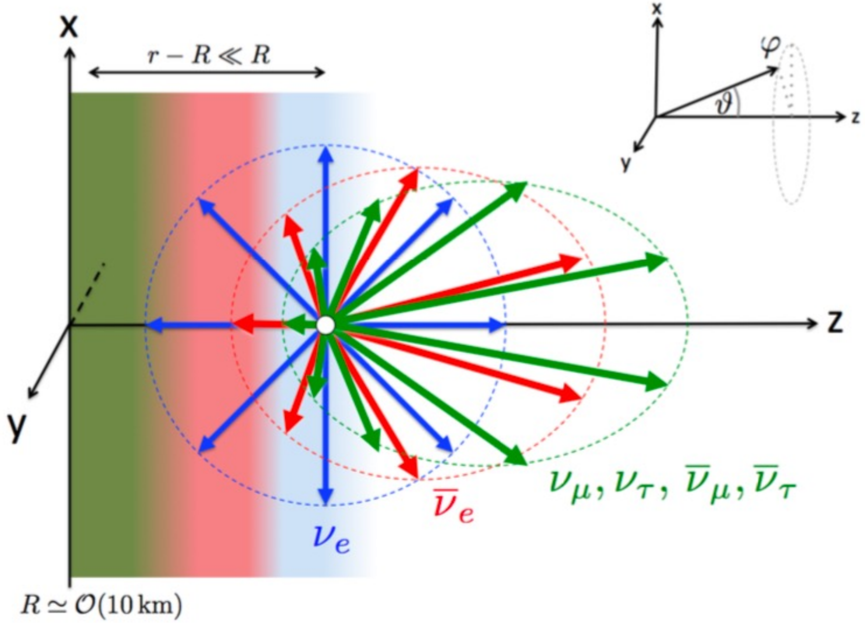
Dasgupta (2110.00192 ; PRL 2022)
Morinaga (PRD, 2022)

$$g_\Gamma = \sqrt{2}G_\mathrm{F}\begin{cases} f_{\nu_e,\mathbf{p}} - f_{\nu_\mu,\mathbf{p}} & \text{for } E > 0 \\ f_{\bar{\nu}_\mu,\mathbf{p}} - f_{\bar{\nu}_e,\mathbf{p}} & \text{for } E < 0 \end{cases}$$



Why crossings exist





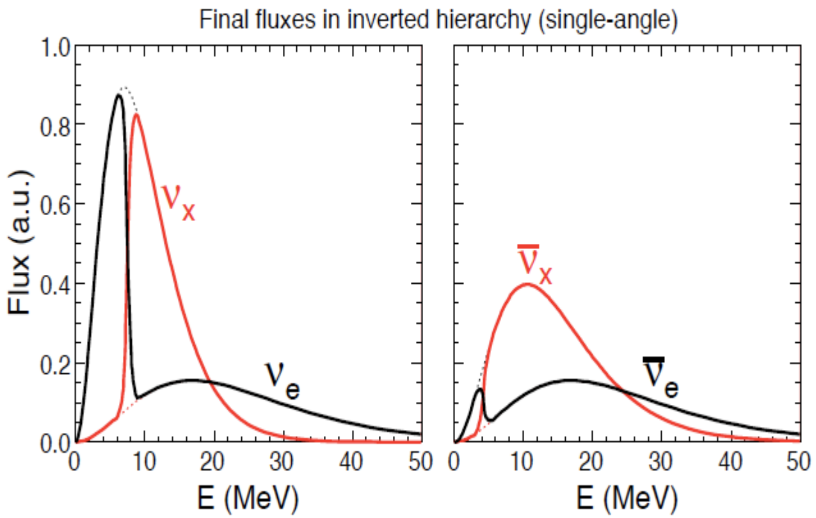
Different flavors have different energy spectrum

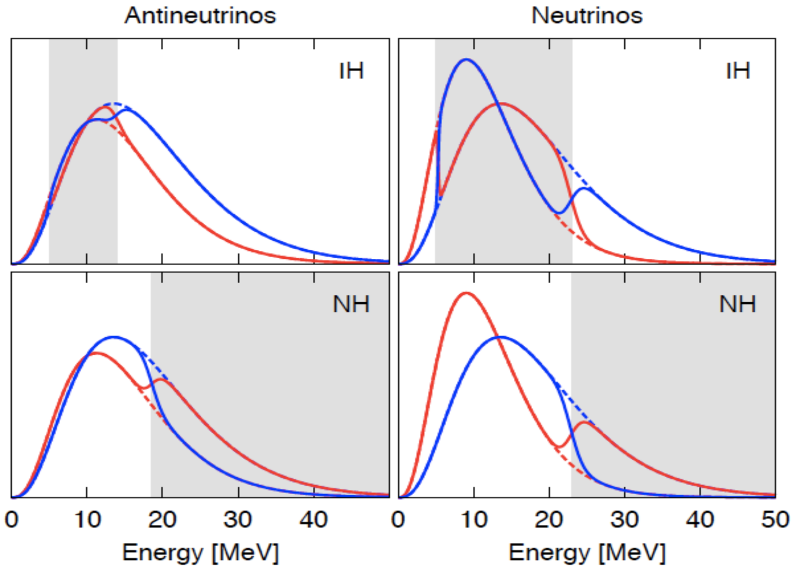
Crossing leads to (slow) instability

Different flavors have different angular distribution

Crossing leads to (fast) instability

Spectral Swaps due to Slow Effects





Portions of the energy spectra get exchanged

Initially thought to occur for Inverted ordering

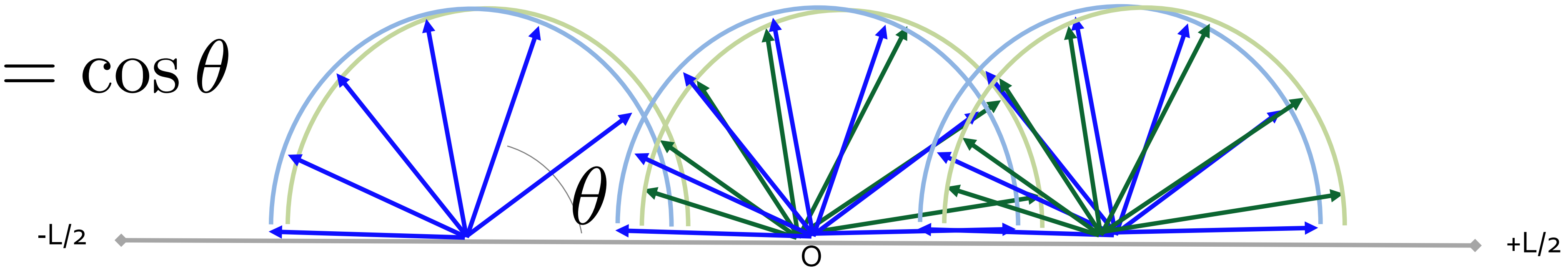
Later realized that this occurs for both orderings and there can be multiple spectral splits

Seminal papers by Duan, Fuller, Carlson, Qian (2005, 2006, 2007)
Raffelt and Smirnov (2007, 2007)
Fogli, Lisi, Marrone, Mirizzi (2008)

Dasgupta, Dighe, Raffelt, Smirnov (2009)
Friedland (2010)

Fast Oscillation : Numerics

$$v = \cos\theta$$



1 dimensional box of length L

$$(\partial_t + v\partial_z)\mathsf{S}_v = \mu_0 \int_{-1}^{+1} dv' G_{v'}\,(1 - vv')\,\mathsf{S}_{v'} \times \mathsf{S}_v$$

Neutrinos labeled by velocity emitted in electron or muon state at a small region of size L

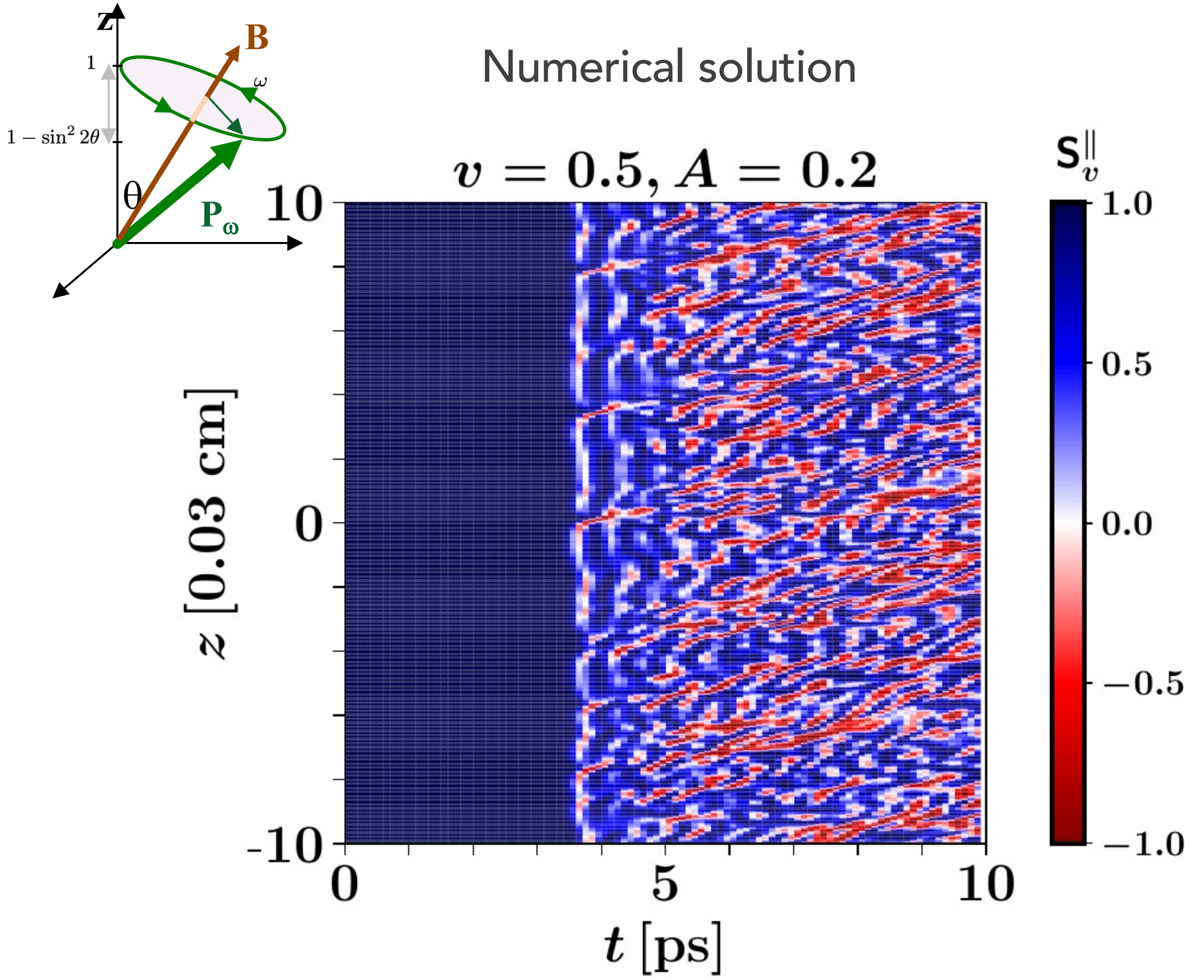
Net-emission at velocity v is $G_v = f_e(v) - f_{muon}(v)$

which is the difference of phase space distributions of the two flavors at each v.

1+1+1d calculation Bhattacharyya and Dasgupta (PRD 2020 ; PRL 2021, 2205.05129)

Fast Mixing due to Fast Instability

Numerical solution



Bhattacharyya and Dasgupta (PRD, 2020 ; PRL 2021)

Analytical Understanding via Coarse-graining

$$\partial_t \langle M_n \rangle = \frac{\langle M_1 \rangle}{2} \left(\partial_n^2 \langle M_n \rangle + \frac{1}{n} \partial_n \langle M_n \rangle \right)$$

A diffusion of the “difference of flavors” to higher multipoles of emission angle (i.e., momentum)

Several other groups have since obtained similar results

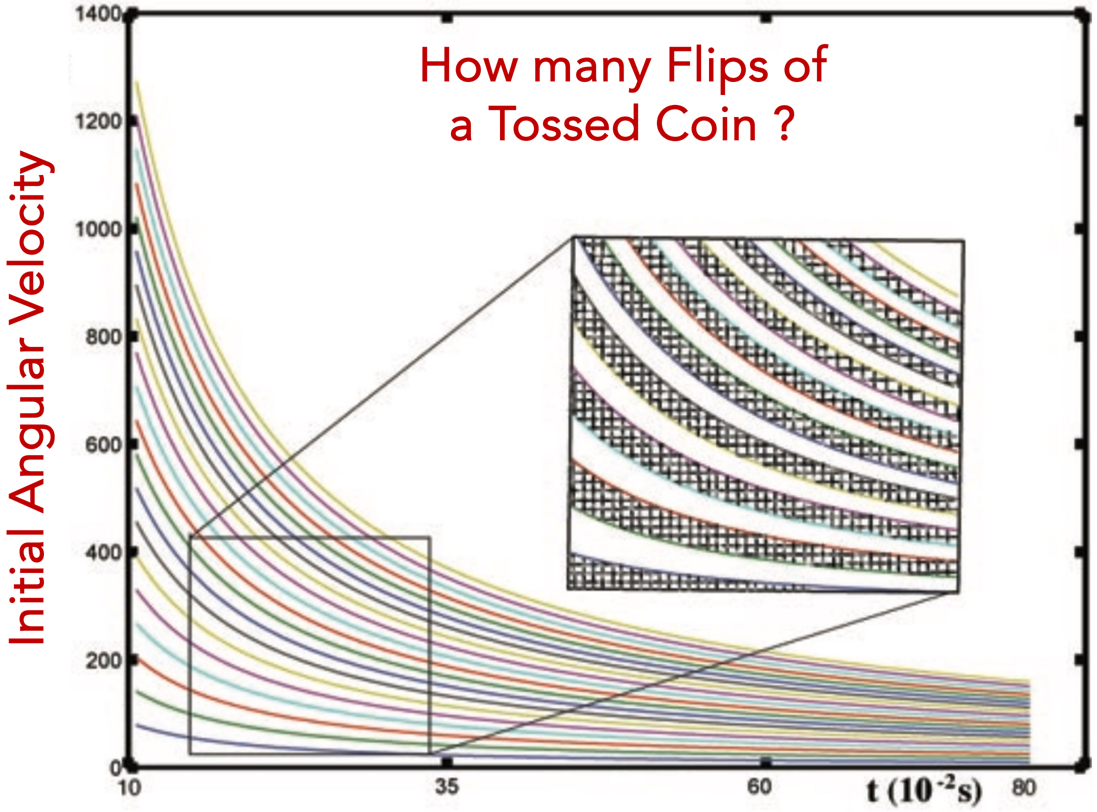
- Richers et al. @ Berkeley
- Wu et al. @ Taiwan
- Sigl @ Hamburg

Survival Probability starts at 1

Oscillates coherently a few times

And then decoheres

Probability from Certainty



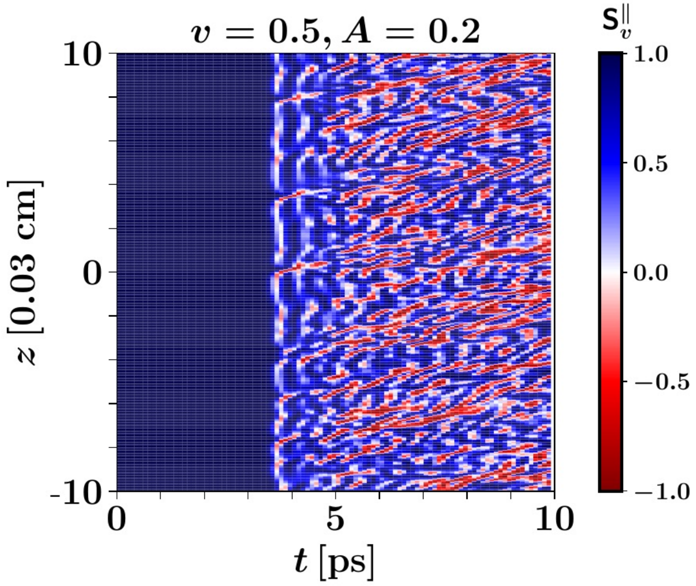
How many Flips of
a Tossed Coin ?

Time in air ~ Initial Velocity

Fig. from Diaconis, Holmes, Mongomery (2007)

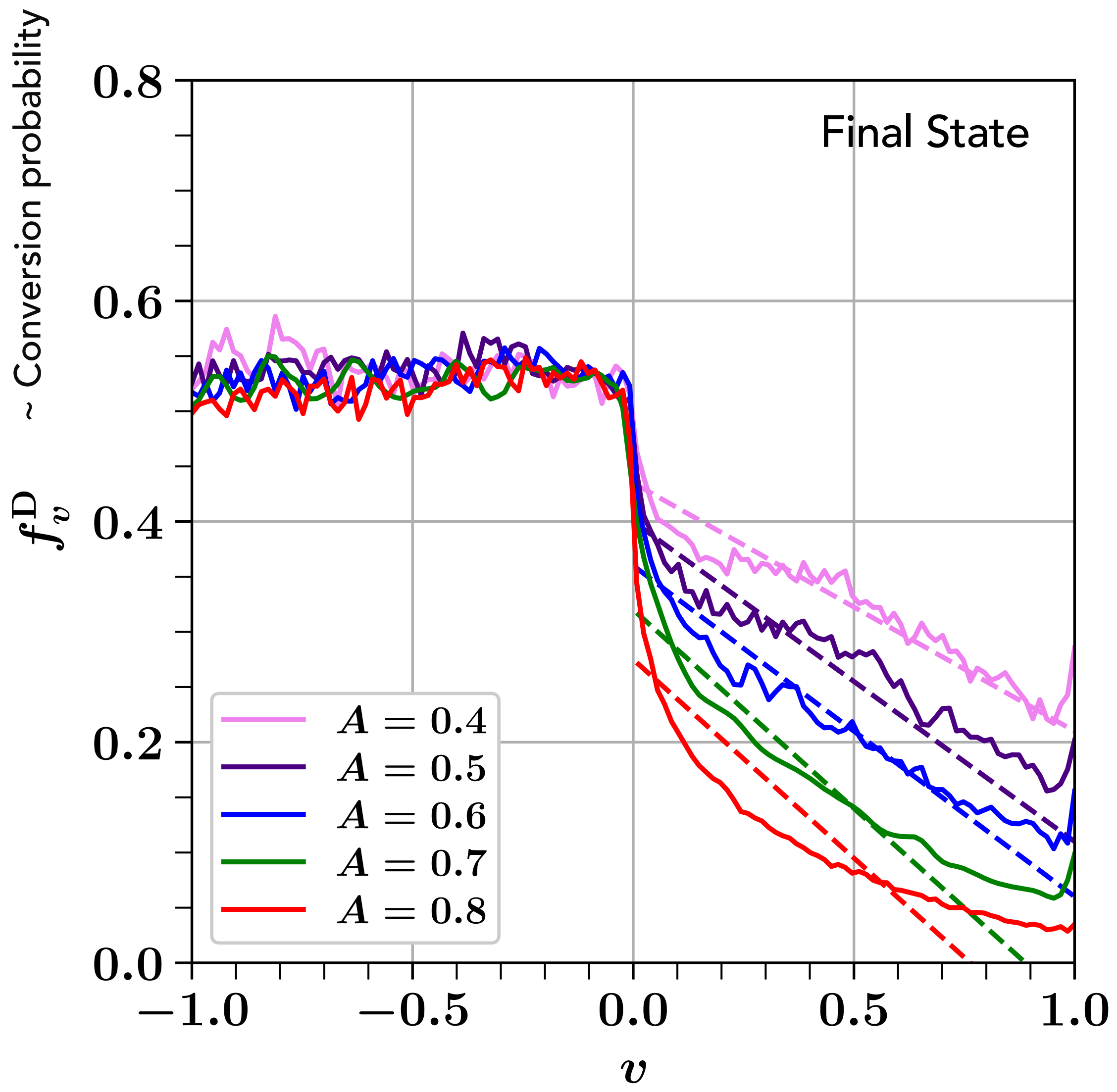
Coarse-grained measurements
lead to probabilities via strong averaging
over deterministic possibilities

Coarse-graining can lead to
apparent irreversibility even if
the evolution is reversible



Coarse-grained
probability

Fast Depolarization



$$f_v^{\mathrm{D}} \approx \begin{cases} \frac{1}{2} - \frac{A}{4} - \frac{3A}{8}\,v, & \text{if } v > 0 \\ \frac{1}{2}, & \text{if } v < 0 \end{cases}$$

Bhattacharyya and Dasgupta (PRL, 2021)

Can approximately predict the spatially coarse-grained degree of flavor mixing *without* full numerical solution.

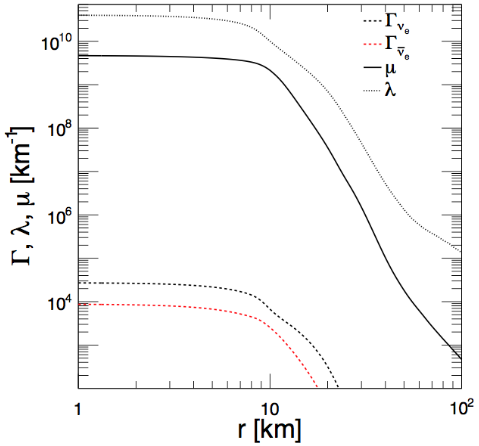
If you do not know how to include collective oscillations in your SN neutrino analysis what should you do?

Assume "Flavor Equilibrium" if Crossing Exists

Bhattacharyya and Dasgupta (PRL, 2021)

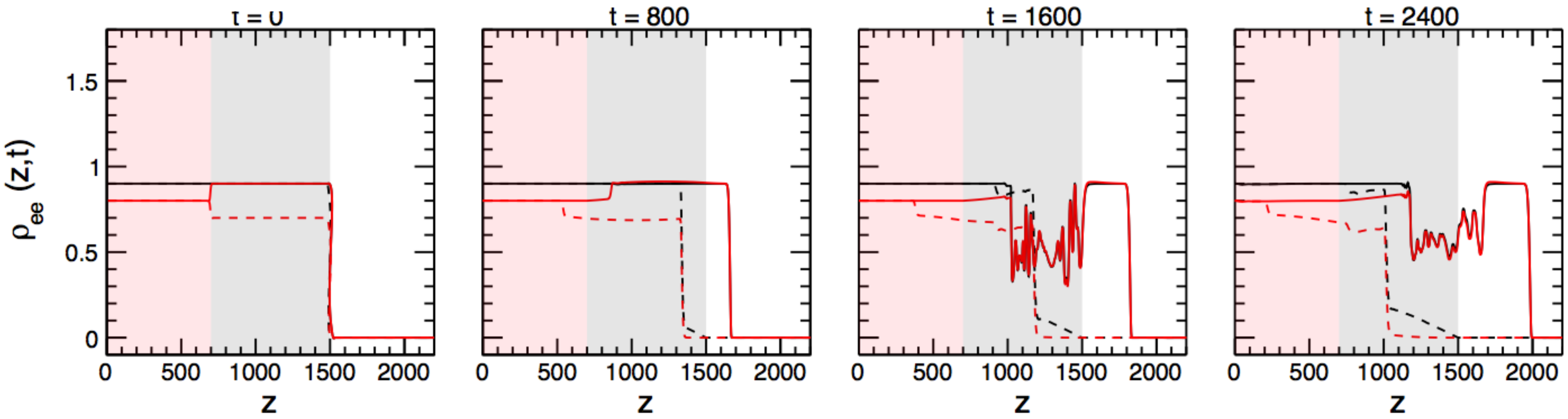
Caution: This is very simplified advice but a good starting point
One should do better : Partial Flavor Equilibrium
Need more realism: Contact your favorite SN Neutrino Physicist

Collisions vs. Oscillations



Collisions can be strong enough to create a difference between electron neutrinos and antineutrinos.
Yet, may not damp oscillations.

Capozzi, Dasgupta, Mirizzi, Sen (2018)
See also Johns (2021)
Martin, Carlson, Cirigliano, Duan (2021)
Sasaki, Takiwaki (2021)
Shalgar and Tamborra (2021)



Do fast conversions, once generated, penetrate the SN core?

Related work

- Mean-field treatment via Wigner fns.

Birol, Pehlivan, Balantekin, Kajino (2018)
Stirner, Sigl, Raffelt (2018)
Vlasenko, Fuller, Cirigliano (2014)
Volpe, Vaananen, Espinoza (2013)
Cardall (2008)

- Wavepackets/Kinematic decoherence

Akhmedov, Kopp, Lindner (2017)
Hansen, Smirnov (2016)

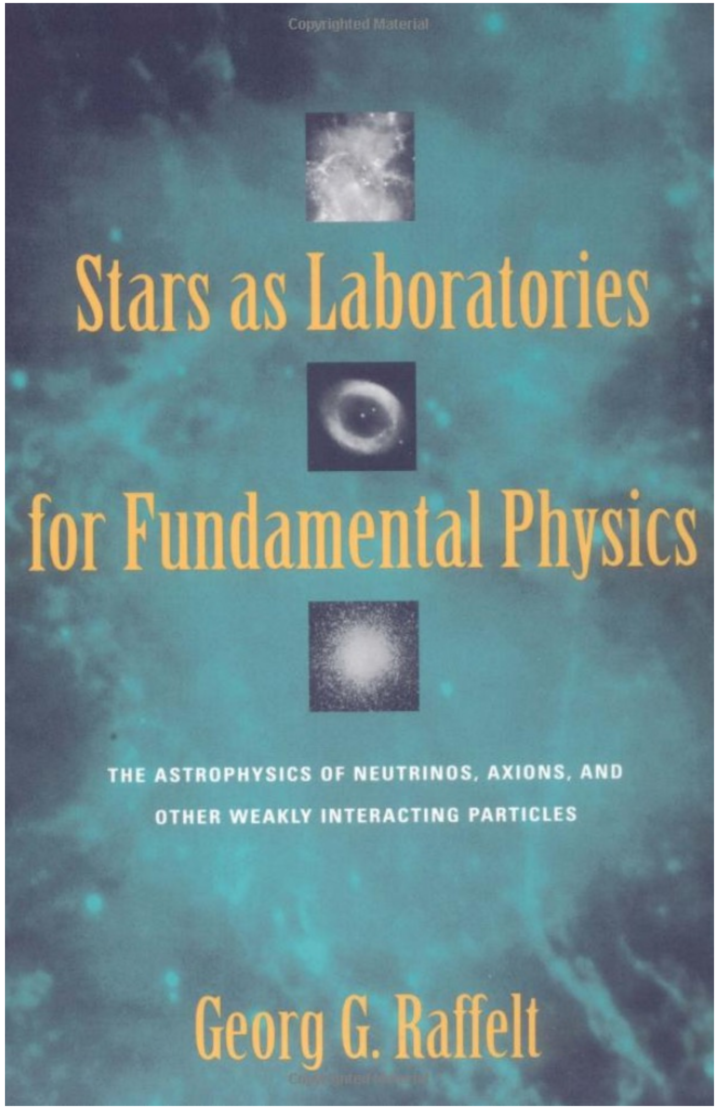
- Sterile nus, NSI, BSM, …

Skipping non-standard physics for lack of space and time

- Interpretation of collective effects

Hansen and Smirnov (2018)
Morinaga and Yamada (2017)

Fundamental Physics with Stars



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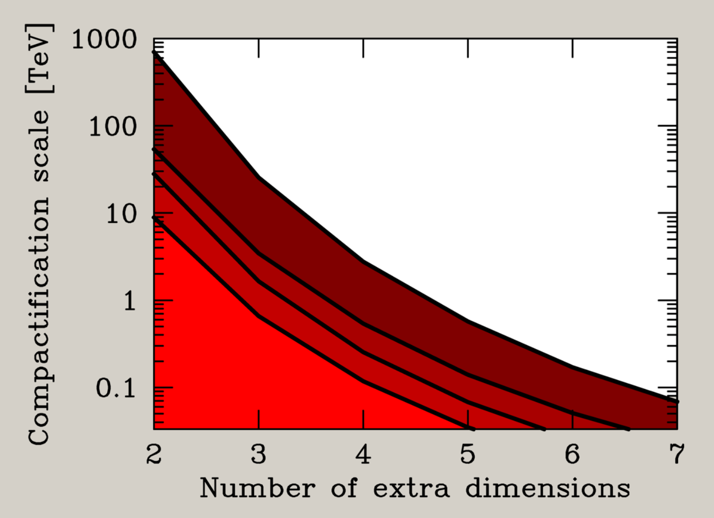
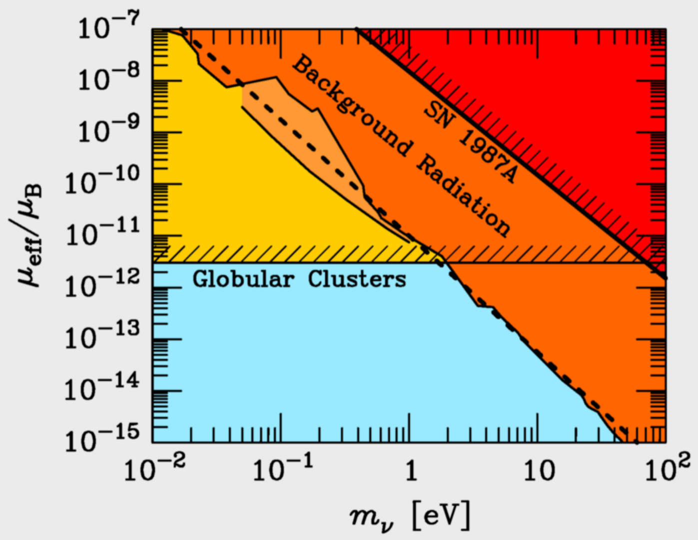
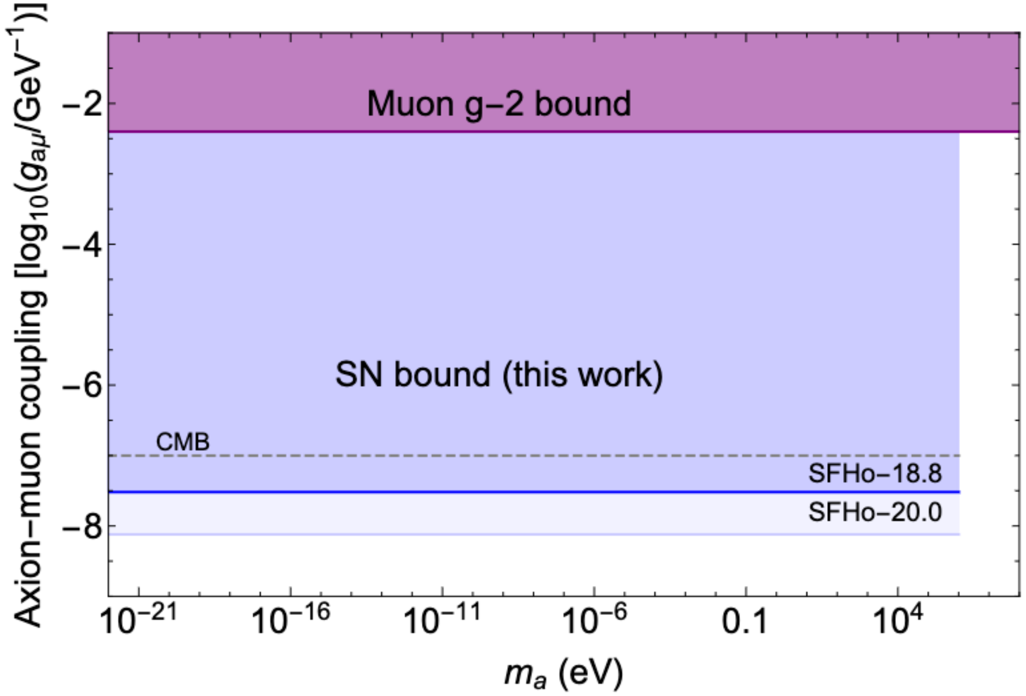




New Ingredients: e.g. Muons

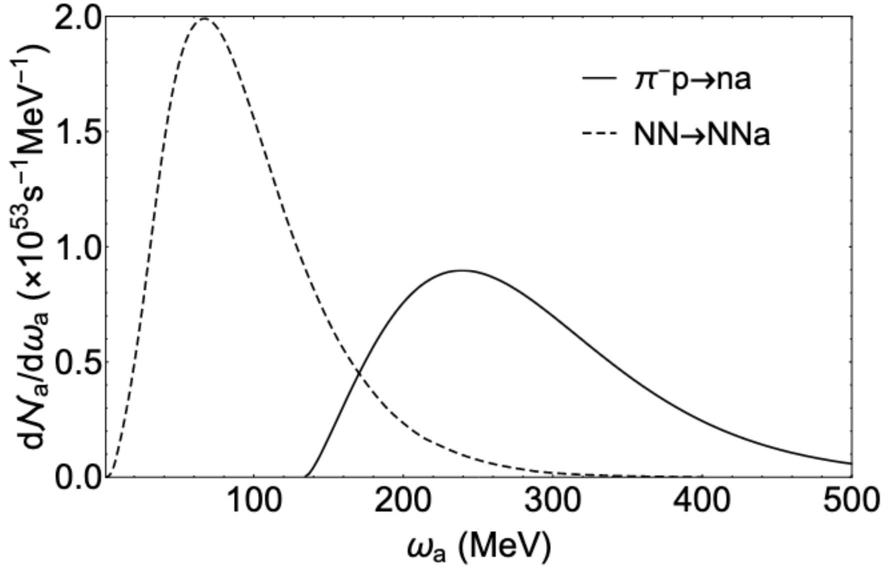
Temperature in SN ~ 30-60 MeV.
Muons are not heavily suppressed.
Can use this to put bounds on BSM physics coupling to muons, e.g., an axion coupling to muons, or a light feebly interacting $L_e - L_\mu$ boson.



Bollig et al. (PRL, 2017)
Bolling, de Rocco, Graham, Janka (PRL, 2017)
Croon, Elor, Leane, McDermott (2020)
Caputo, Raffelt, Vitagliano (PRD, 2022)

Better limits from better models of SN, and inclusion of previously ignored physical effects

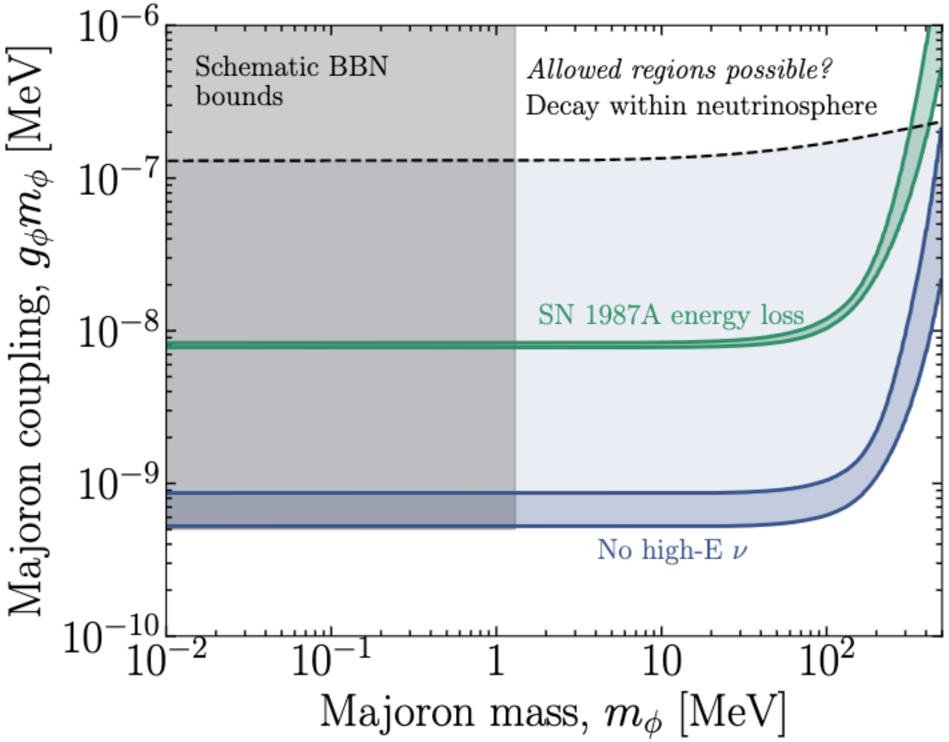
New Processes : e.g. NN -> NNa



Newly considered processes that produce axions more prominently at higher energies.

Fore, Reddy (PRC, 2020)
Carenza, Fore, Gianotti, Mirizzi, Reddy (PRL, 2020)

New Arguments: e.g. HENs

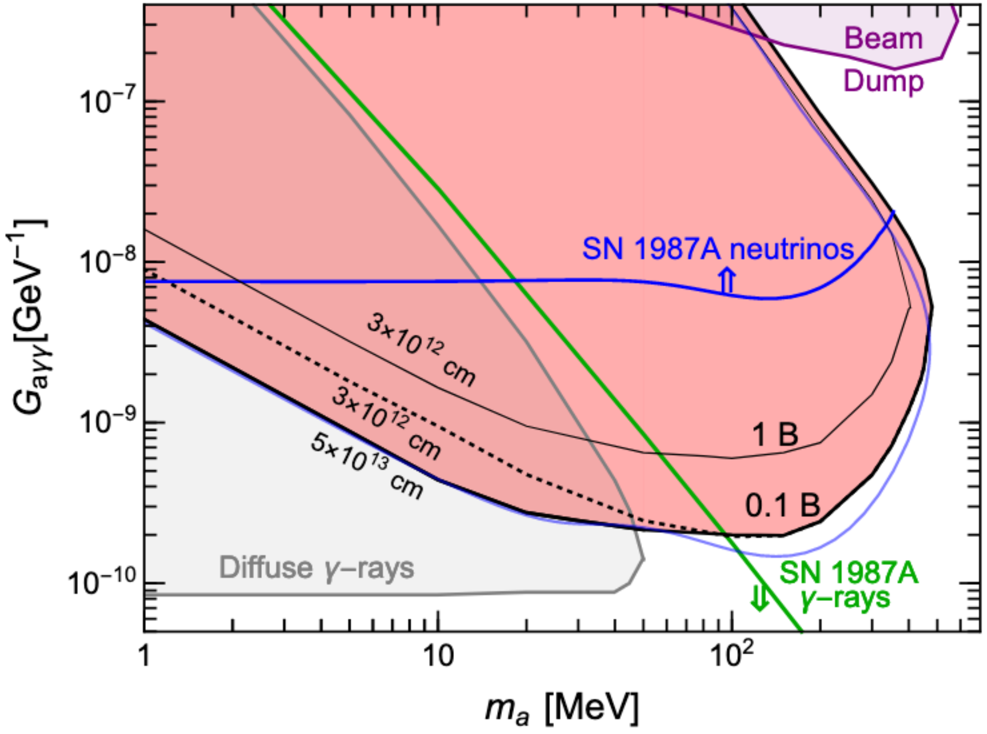


Fiorillo, Raffelt, Vitagliano (2209.11773)

A Majoron not only steals energy from core of SN, it can also decay back into high-E neutrinos.

Non-observation of high-E neutrinos from SN gives stronger bounds than cooling.

New Arguments: e.g. Ejecta Energy

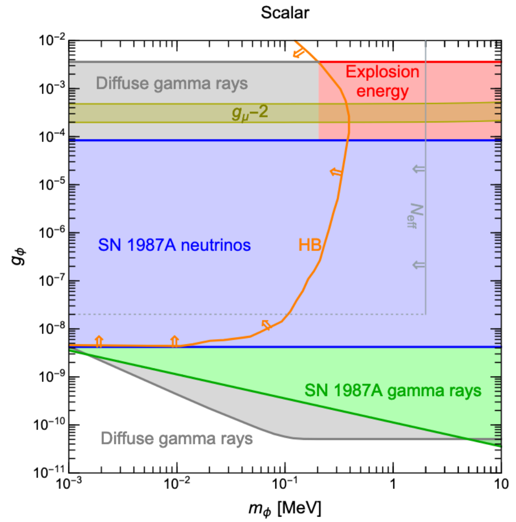


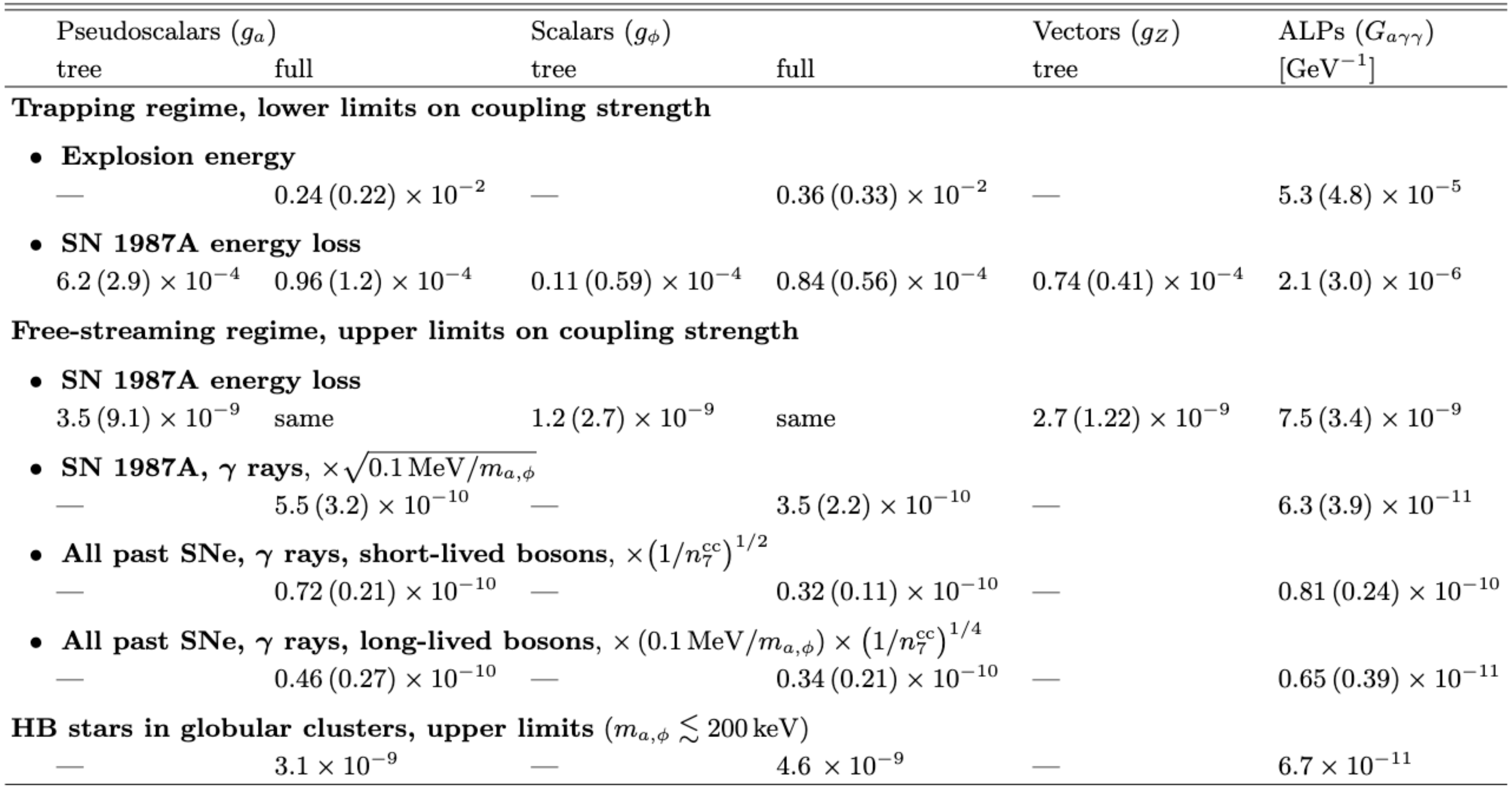
Caputo, Janka, Raffelt, Vitagliano (PRL, 2022)

A BSM particle produced in SN not only cools but also interacts and redeposits energy in ejecta

Observed ejecta energy can give stronger or complementary bounds.

SN Bounds Galore

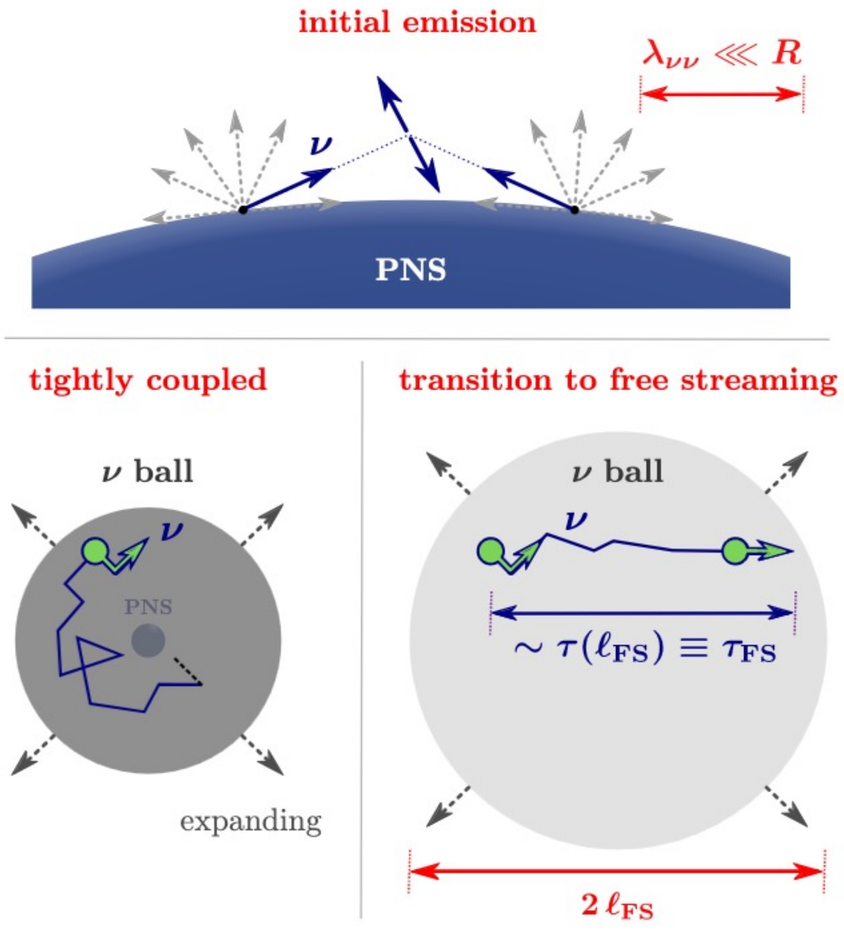




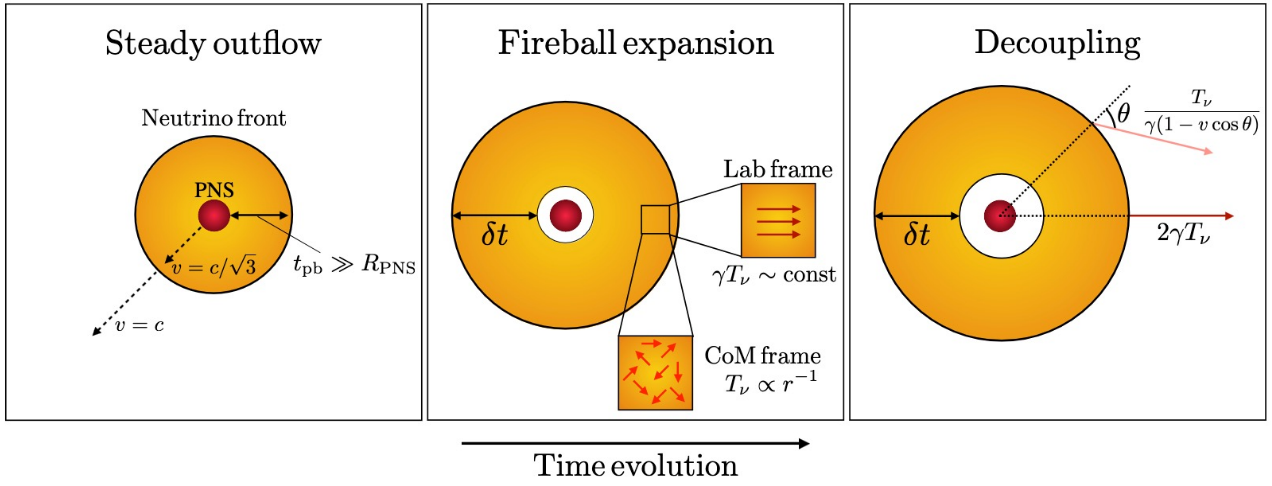
Pseudoscalars (g_a)		Scalars (g_ϕ)		Vectors (g_Z)	ALPs ($G_{a\gamma\gamma}$)
tree	full	tree	full	tree	[GeV^{-1}]
Trapping regime, lower limits on coupling strength					
• **Explosion energy**					
—	$0.24\,(0.22)\times10^{-2}$	—	$0.36\,(0.33)\times10^{-2}$	—	$5.3\,(4.8)\times10^{-5}$
• **SN 1987A energy loss**					
$6.2\,(2.9)\times10^{-4}$	$0.96\,(1.2)\times10^{-4}$	$0.11\,(0.59)\times10^{-4}$	$0.84\,(0.56)\times10^{-4}$	$0.74\,(0.41)\times10^{-4}$	$2.1\,(3.0)\times10^{-6}$
Free-streaming regime, upper limits on coupling strength					
• **SN 1987A energy loss**					
$3.5\,(9.1)\times10^{-9}$	same	$1.2\,(2.7)\times10^{-9}$	same	$2.7\,(1.22)\times10^{-9}$	$7.5\,(3.4)\times10^{-9}$
• **SN 1987A, γ rays**, $\times\sqrt{0.1\,\mathrm{MeV}/m_{a,\phi}}$					
—	$5.5\,(3.2)\times10^{-10}$	—	$3.5\,(2.2)\times10^{-10}$	—	$6.3\,(3.9)\times10^{-11}$
• **All past SNe, γ rays, short-lived bosons**, $\times(1/n_7^{\rm cc})^{1/2}$					
—	$0.72\,(0.21)\times10^{-10}$	—	$0.32\,(0.11)\times10^{-10}$	—	$0.81\,(0.24)\times10^{-10}$
• **All past SNe, γ rays, long-lived bosons**, $\times(0.1\,\mathrm{MeV}/m_{a,\phi})\times(1/n_7^{\rm cc})^{1/4}$					
—	$0.46\,(0.27)\times10^{-10}$	—	$0.34\,(0.21)\times10^{-10}$	—	$0.65\,(0.39)\times10^{-11}$
HB stars in globular clusters, upper limits ($m_{a,\phi}\lesssim200\,\mathrm{keV}$)					
—	3.1×10^{-9}	—	$4.6\ \times10^{-9}$	—	6.7×10^{-11}

Caputo, Raffelt, Vitagliano (PRD, 2022)
Cerdeno, Cermeno, Farzan (2023)
+ many more papers … apologies for incomplete list

Puzzle: Neutrino Interactions



Chang, Isteban, Beacom, Thompson, Hirata (2206.12426)
+ previous papers …

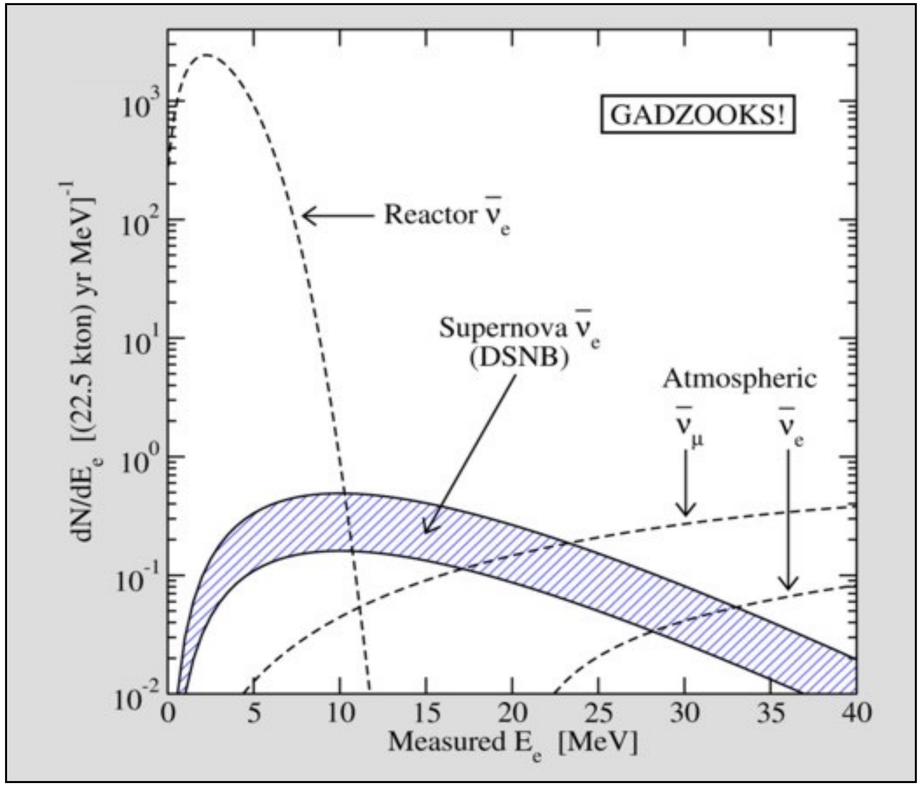


Neutrino secret interactions do not alter the duration or energetics of the burst

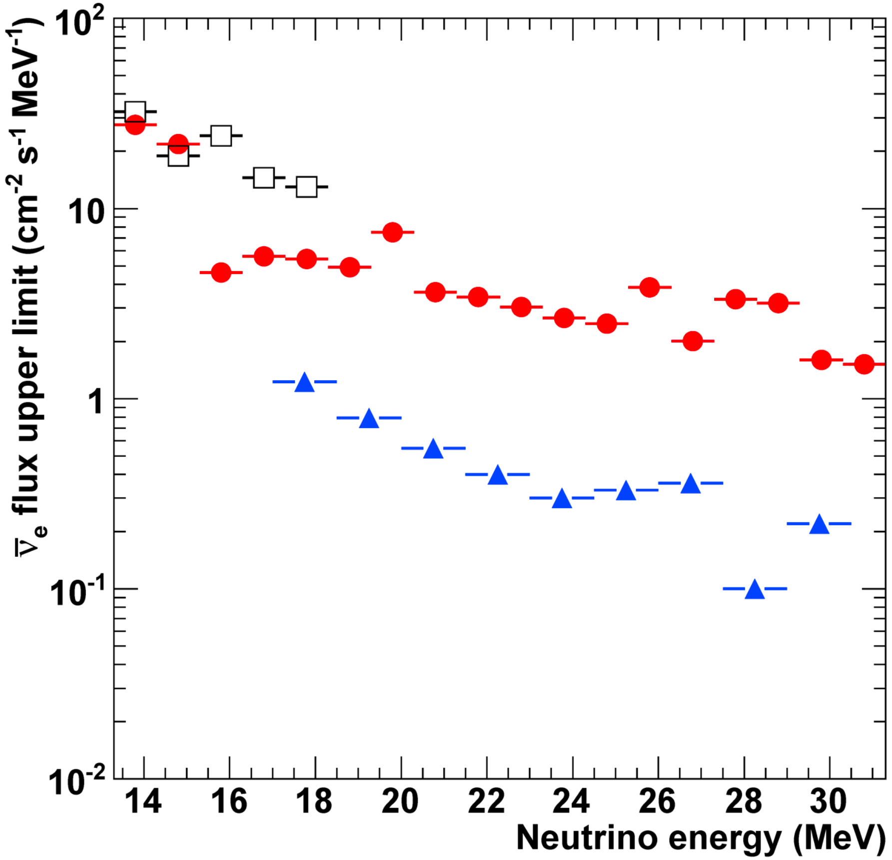
Fiorillo, Raffelt, Vitagliano (2307.15115)
see also Dicus, Nussinov, Pal, Teplitz (PLB 1989)

What more can we learn?

DSNB



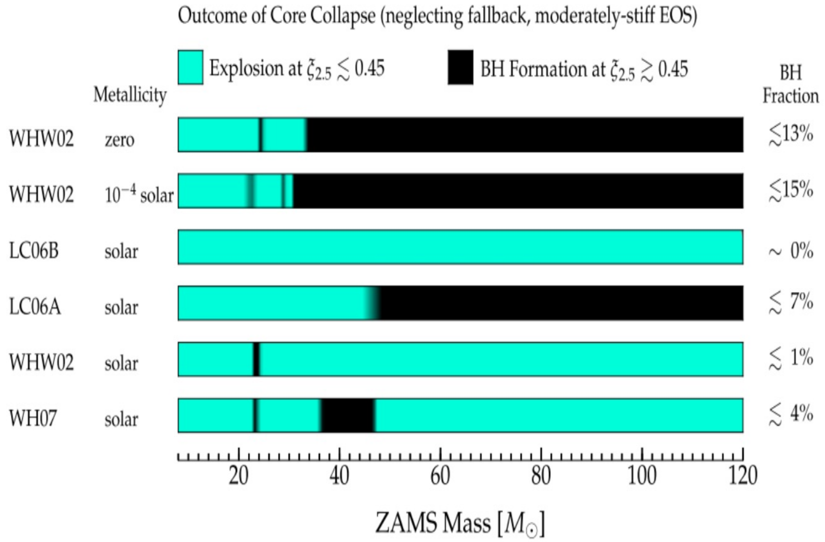
Zeldovic (1964), Bisnovatyi-Kogan and Seidov (1982)
Plot from Beacom and Vagins (2003)
See reviews by Lunardini (2010) and Beacom (2010)



Super-Kamiokande Collaboration (2013)

We may be close to detecting the DSNB.
With Gd upgrade of Super-K this can be very promising.

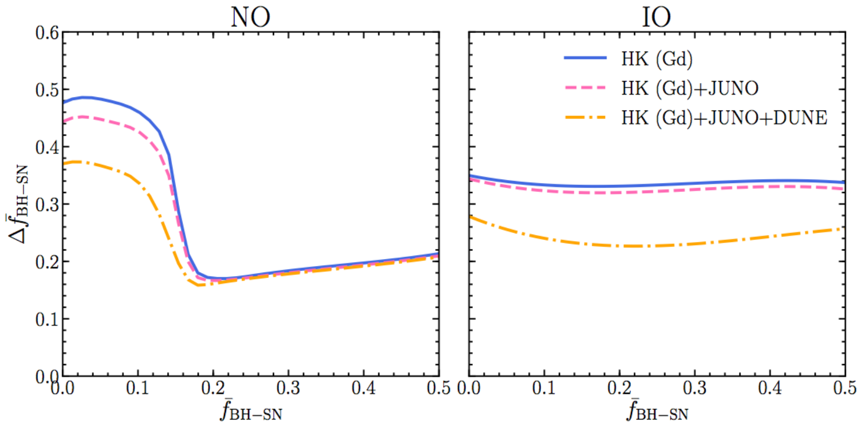
Are there failed SN?



Some supernovae are not expected to explode

O'Connor and Ott (2013)

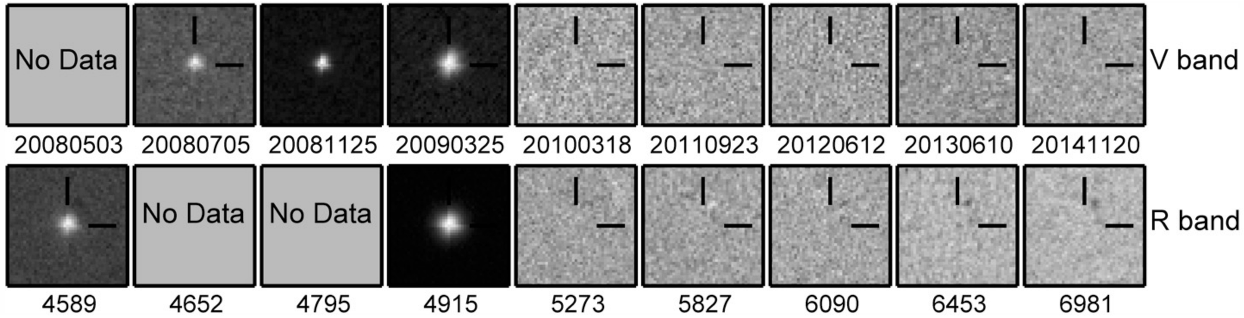
Ertl, Janka, Woosley, Sukhbold, Ugliano (2016)



DSNB is sensitive to the failed SN fraction

Lunardini (2009)

Moller, Suliga, Tamborra, Denton (2018)

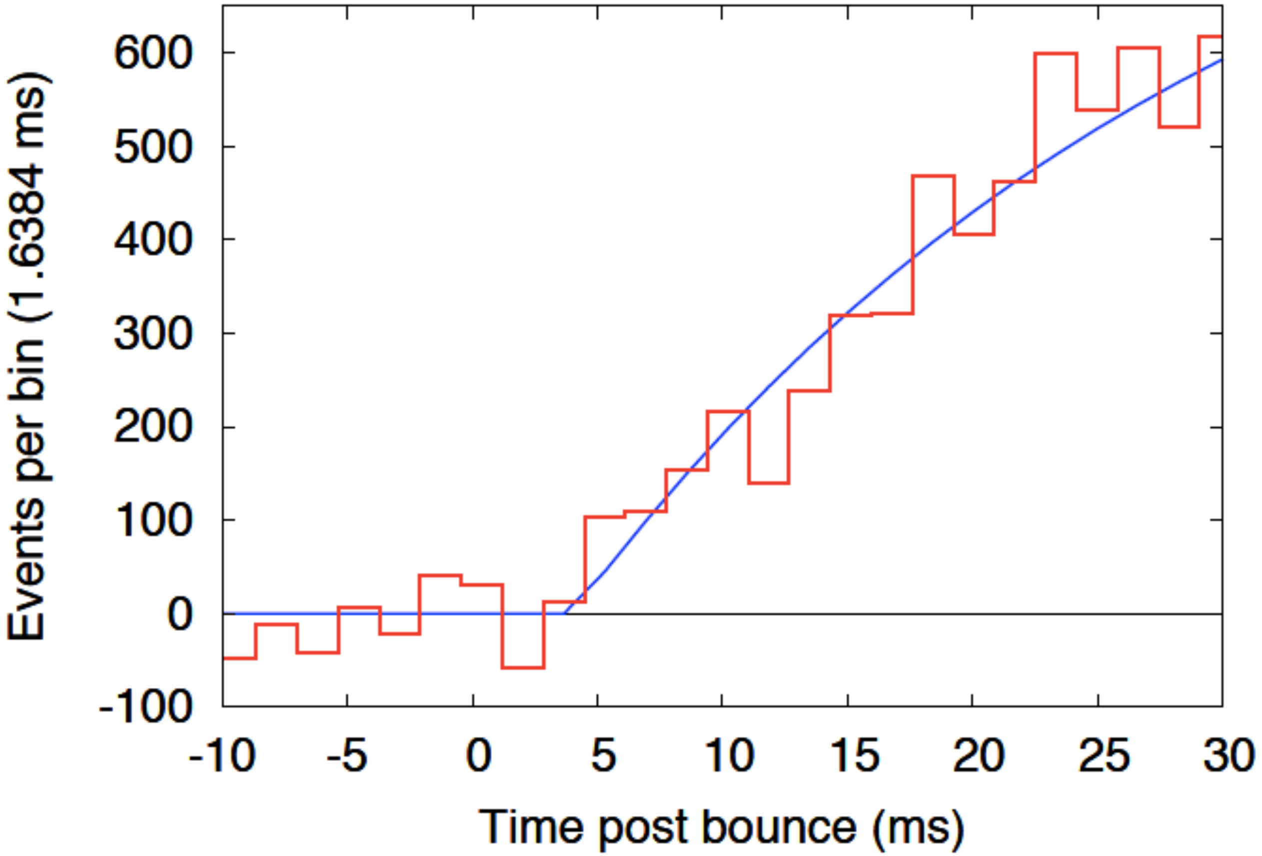


SN without a bang

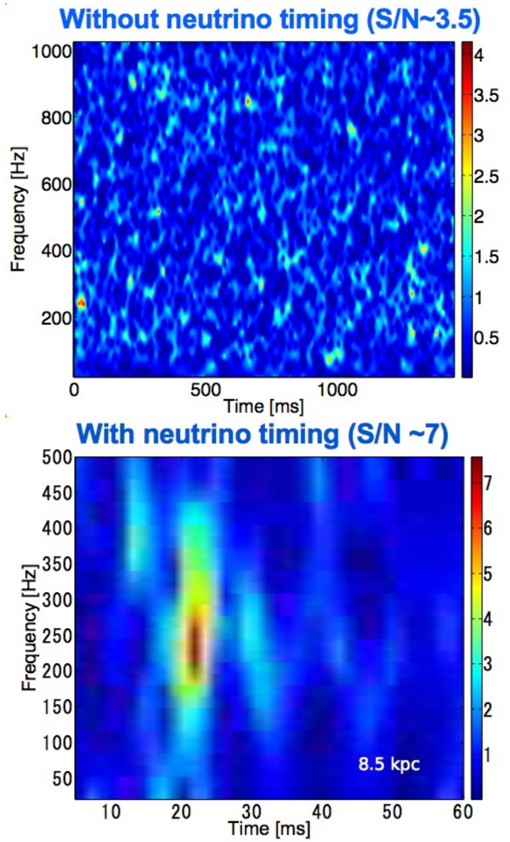
Gerke, Kochanek, Stanek (2014)

Reynolds, Fraser, Gilmore (2015)

Timing



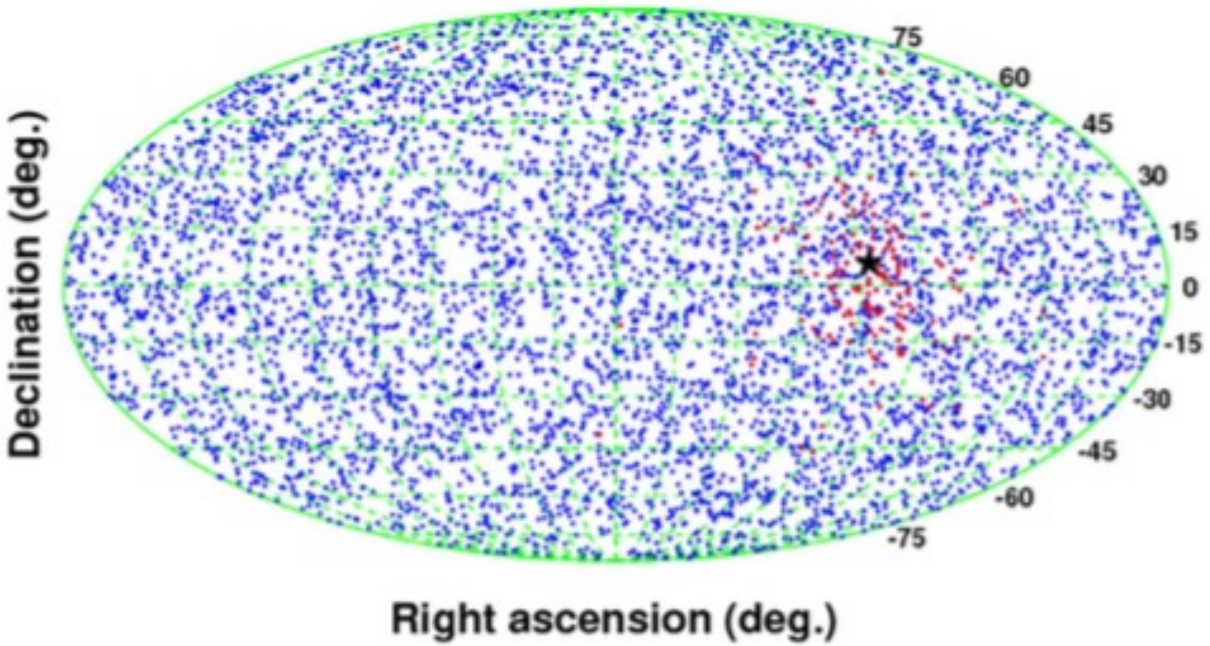
Pagliaroni, Vissani, Coccia, Fulgione (2009)
Plot from Halzen and Raffelt (2009)



Nakamura, Horiuchi, Tanaka, Hayama,
Takiwaki, Kotake (2016)

Improved ability to spot the signal with different messengers

Pointing



Using directionality of elastic scattering events and subtraction of tagged inverse beta "background"

Beacom and Vogel (1998)

Beacom and Vagins (2000)

Tomas, Semikox, Raffelt, Kachelriess, Dighe (2003)

Plot from Abe at al. for Super-K (2016)

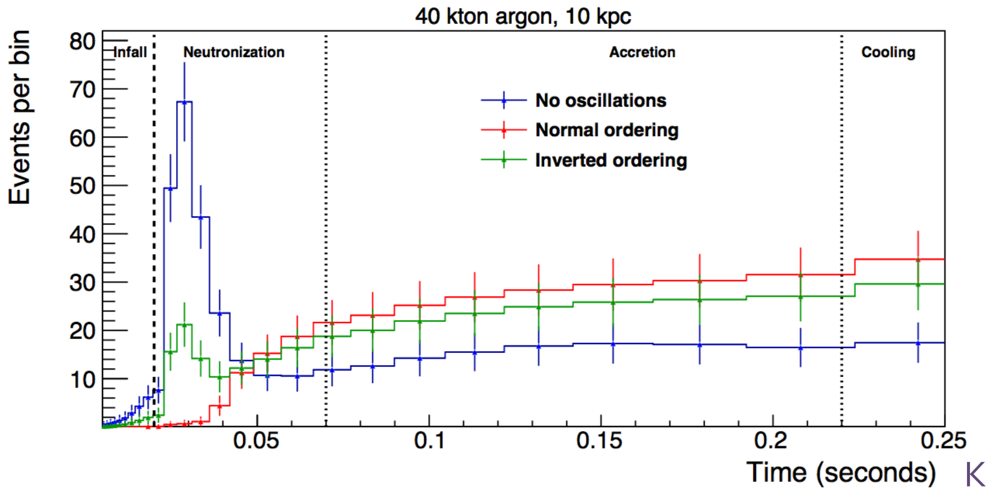
For triangulation: see Beacom and Vogel (1998)

Muhlbeier, Nunokawa, and Zukanovich Funchal (2013)

Brdar, Lindner, Xu (2018)

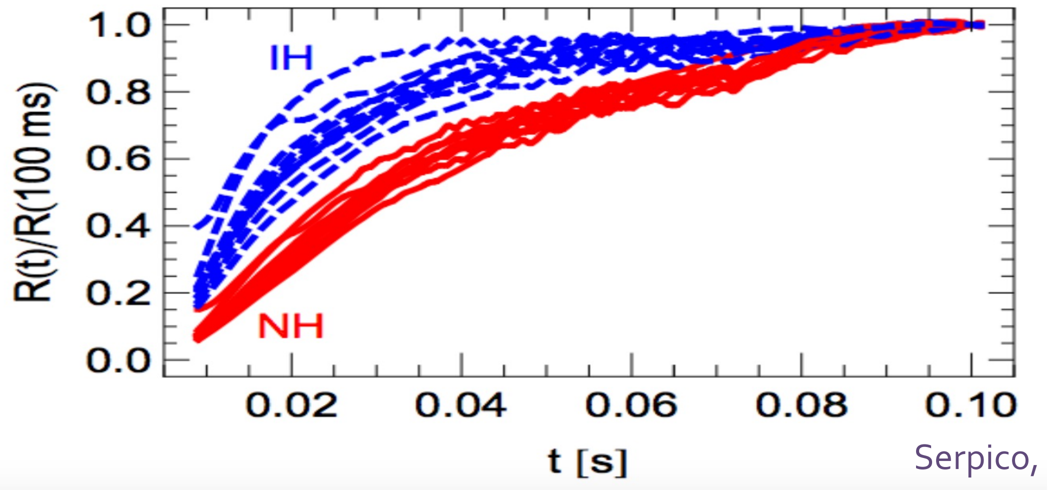
Pointing accuracy of a few degrees for SN at 10 kpc

Mass Ordering



No neutronization peak seen in electron neutrinos for inverted mass ordering

Plot from E. Worcester's talk at Neutrino 2018
Wallace, Burrows, Dolence (2015)
Kachelriess, Tomas, Buras, Janka, Marek, Rampp (2004)



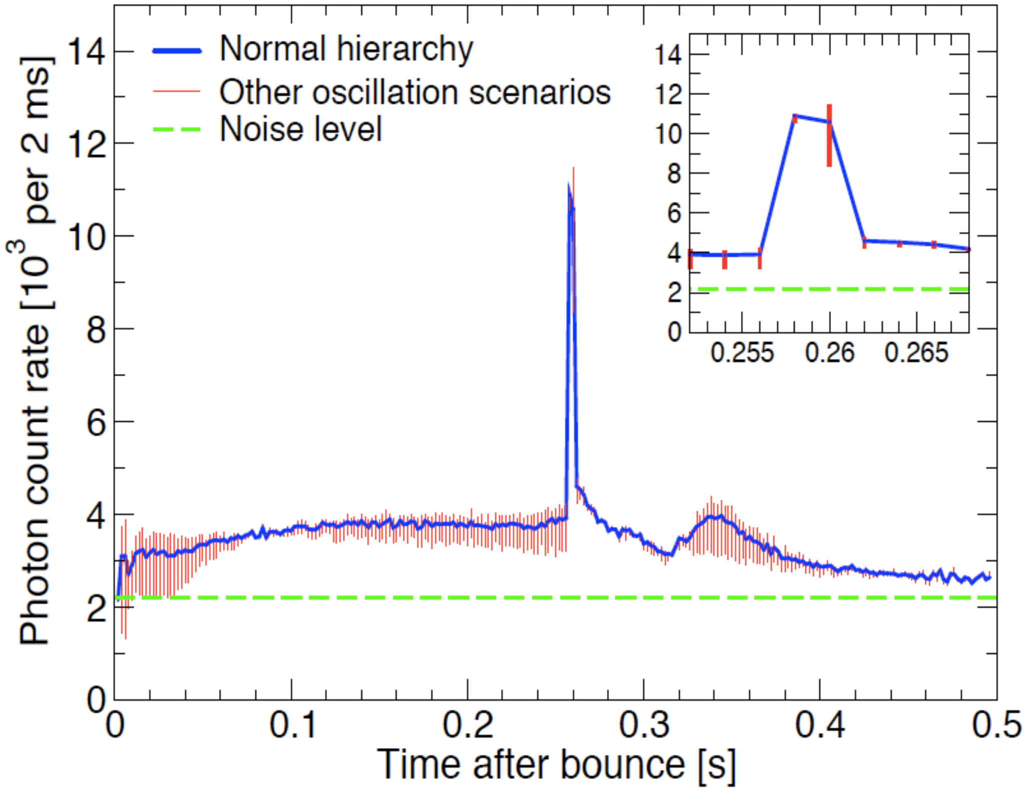
Electron antineutrino signal rises faster for inverted ordering

Note: This can change if fast conversions occurs in the accretion phase

Serpico, Chakraborty, Fischer, Hudepohl, Janka, Mirizzi (2011)

Neutronization burst can reveal the neutrino mass ordering

QCD transition in SN

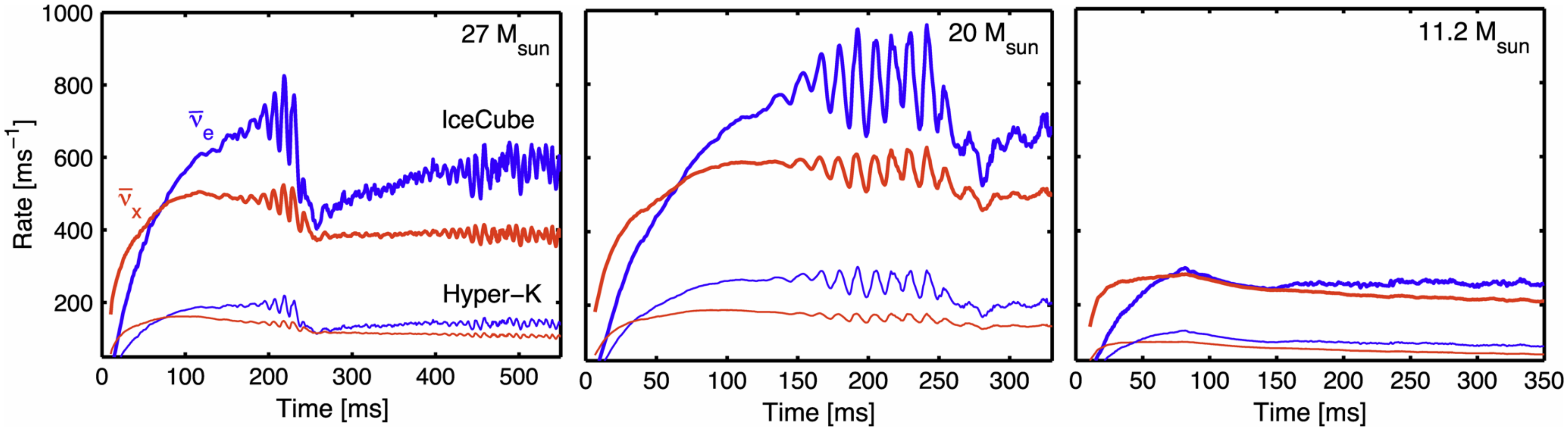


Dasgupta, Fischer, Horiuchi, Liebendoerfer, Mirizzi, Sagert, Schaffner-Bielich (2009)

Simulation by Sagert, Fischer, Hempel, Pagliara, Schaffner-Bielich, Mezzacappa, Thielemann, Liebendoerfer (2008)

Neutrino telescopes are exquisitely sensitive to anything
that affects the electron antineutrino lightcurve

SASI Signatures



27 M_{sun} star
Multiple SASI episodes and convection

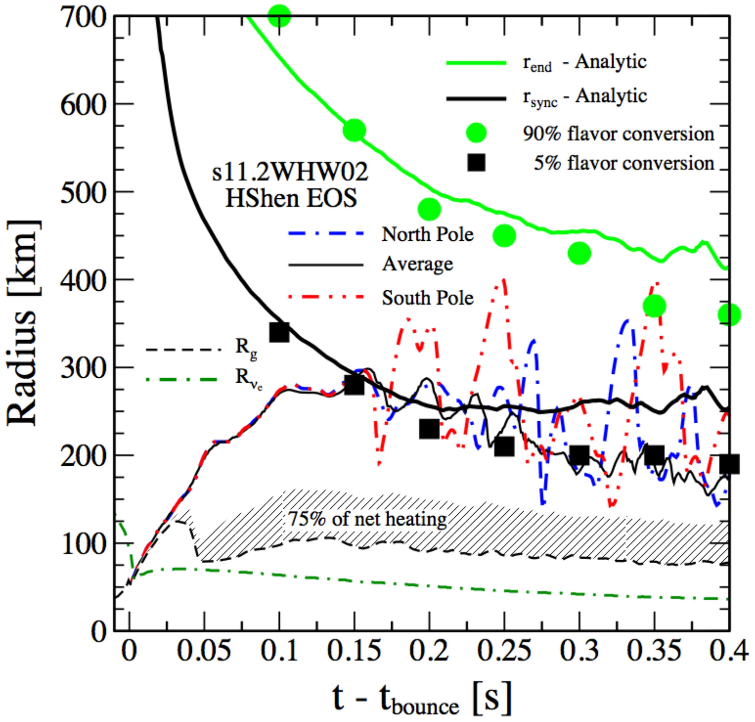
20 M_{sun} star
Single SASI episode and convection

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

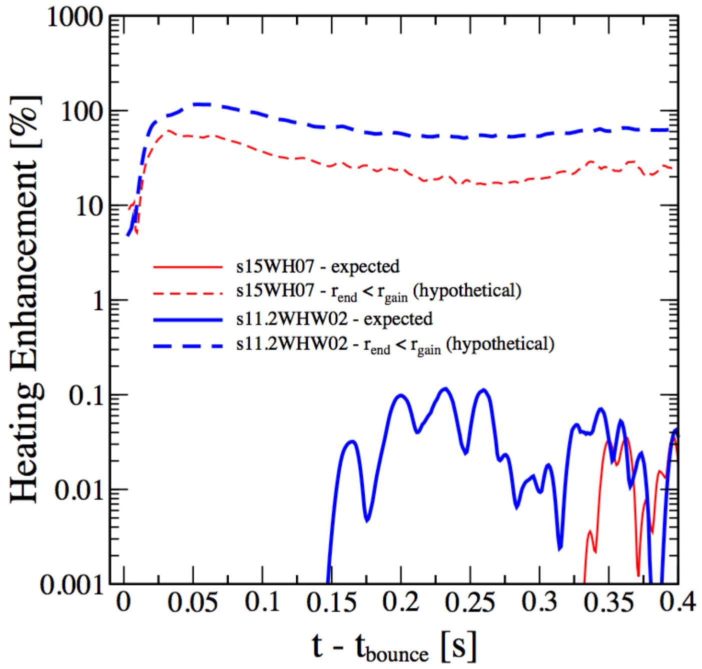
Tamborra, Raffelt,Hanke, Janka, Mueller (2014)
Tamborra, Hanke, Mueller, Janka, Raffelt (2013)

The next galactic SN may reveal distinct signatures of the neutrino mechanism

Fast Conversions = Heating



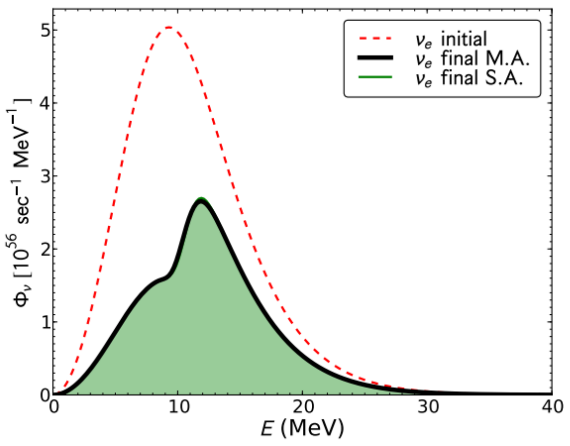
Not possible with slow conversions that occur above r_gain

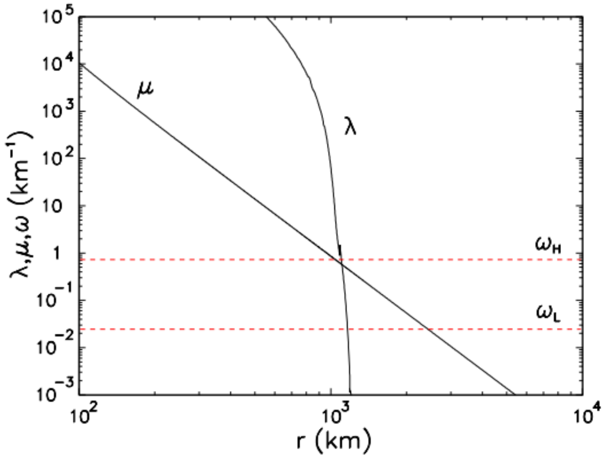


May be possible if fast conversions that occur below r_gain!

Dasgupta, O’Connor, Ott (2011)

O-Mg-Ne Supernovae

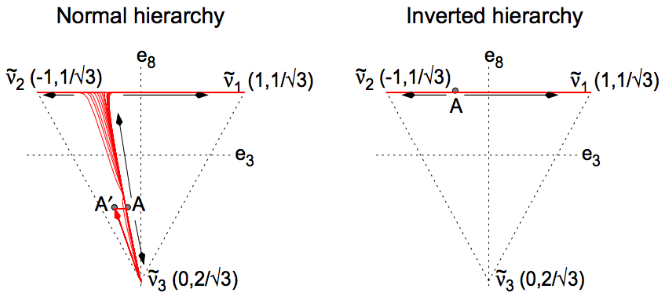




Duan, Fuller, Carlson, Qian (2007)
Duan, Fuller, Carlson, Qian (2008)
Dasgupta, Dighe, Mirizzi, Raffelt (2008)
Cherry, Fuller, Carlson, Duan, Qian (2010)

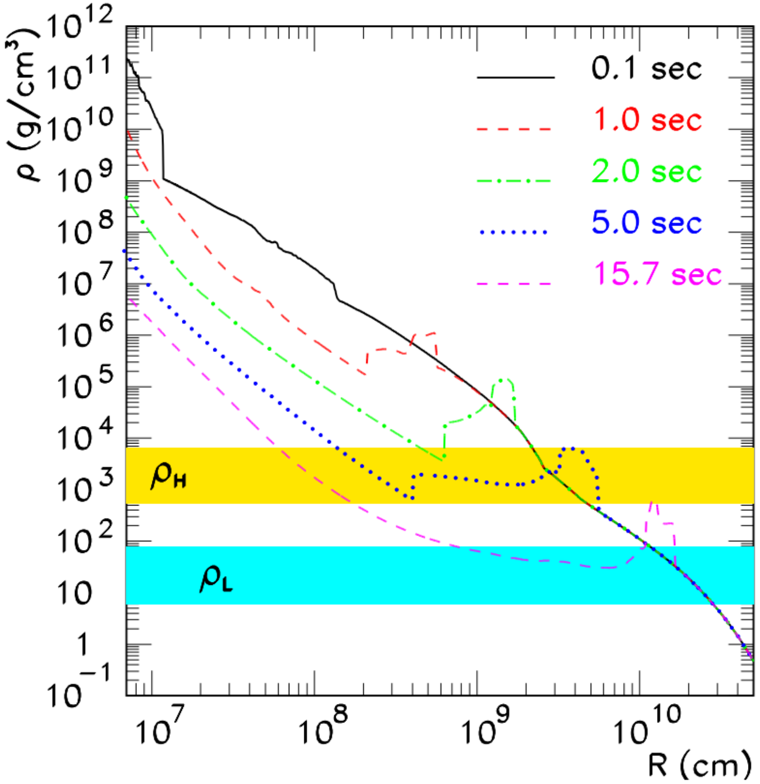
Star has sharply falling matter density, so MSW resonance occurs before (slow) collective effects.

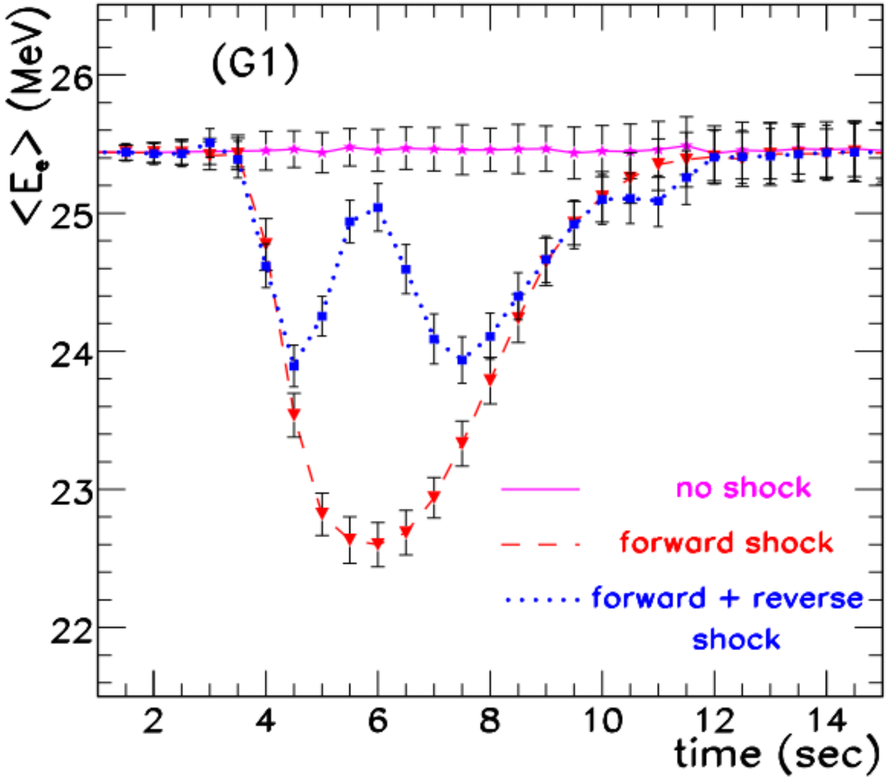
Explained using synchronized MSW



Application of 3 flavor formalism by Dasgupta and Dighe (2007)

Shock Wave

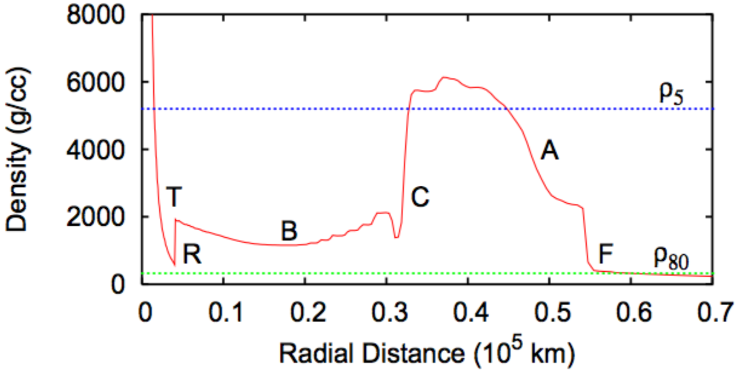


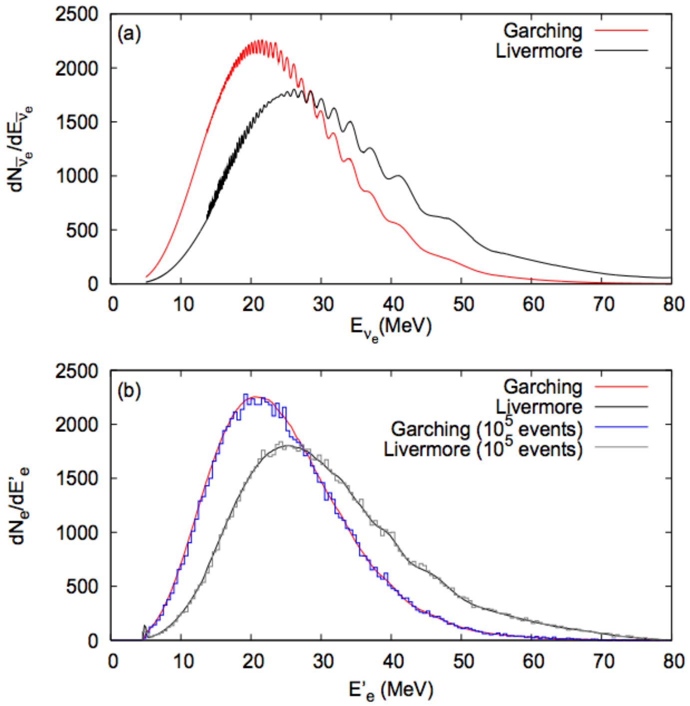


Schirato and Fuller (2002)
Tomas, Kachelriess, Raffelt, Dighe, Janka, Scheck (2004)

Shockwave propagation leads to dips/bumps in observed average E

Phase Effects



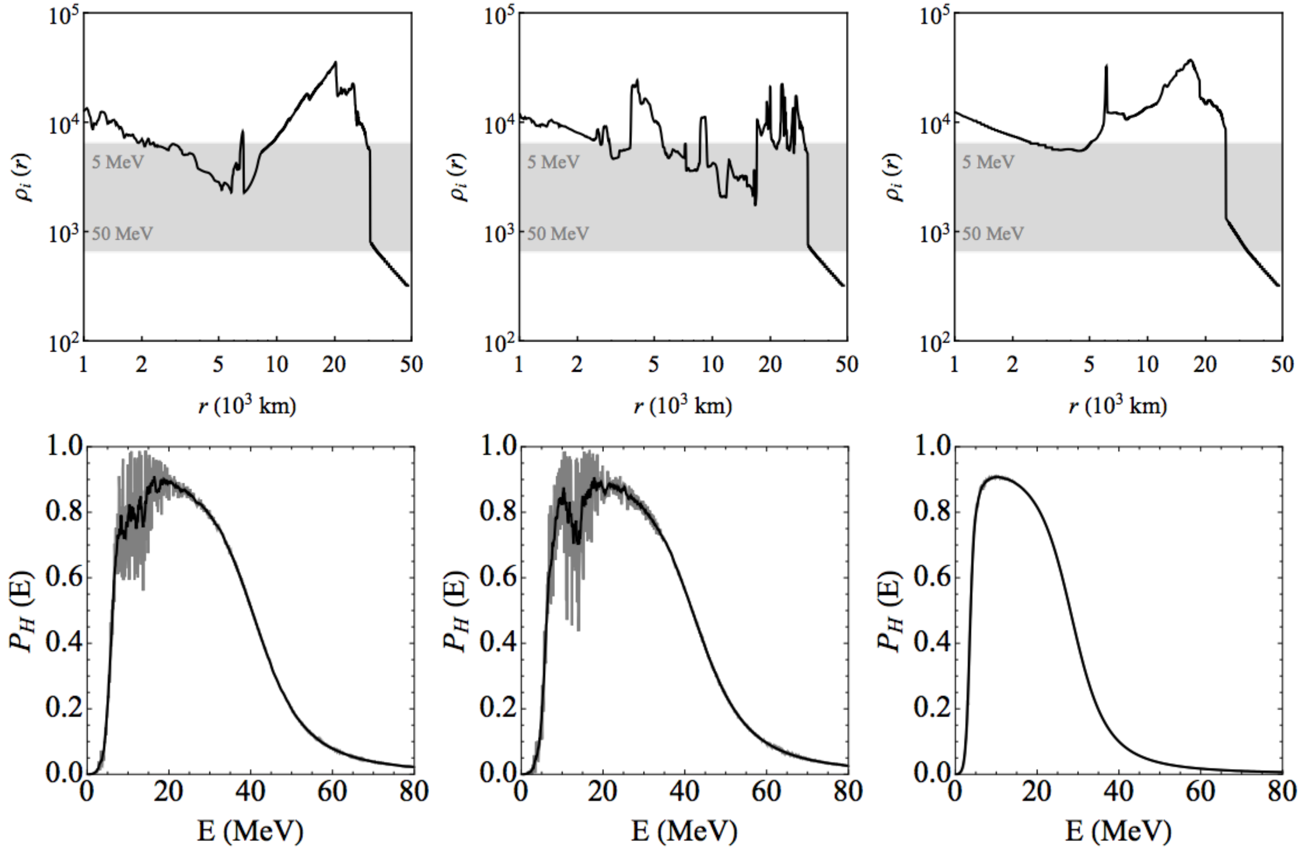


Density profile is not monotonic. There are multiple resonances. Some of them are close enough and lead to interference features with large wavelength in 1/E

Typically gets averaged out due to finite energy resolution

Dasgupta and Dighe (2005)

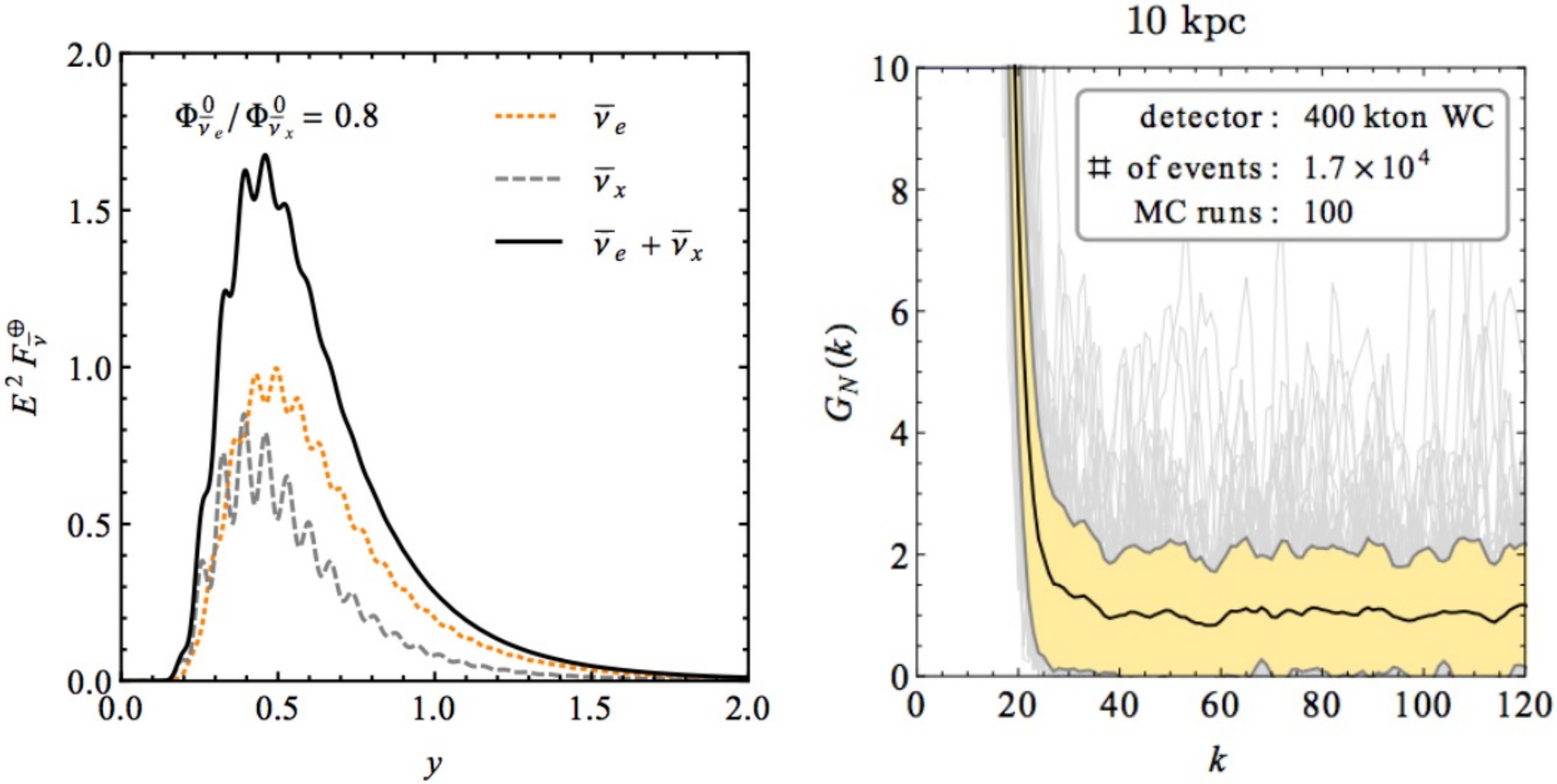
Turbulence



Plot from Borriello, Chakraborty, Janka, Lisi, Mirizzi (2013)
Fogli, Lisi, Mirizzi, Montanino (2006)
Friedland and Gruzinov (2006)

Survival probabilities are highly stochastic quantities during certain time-windows

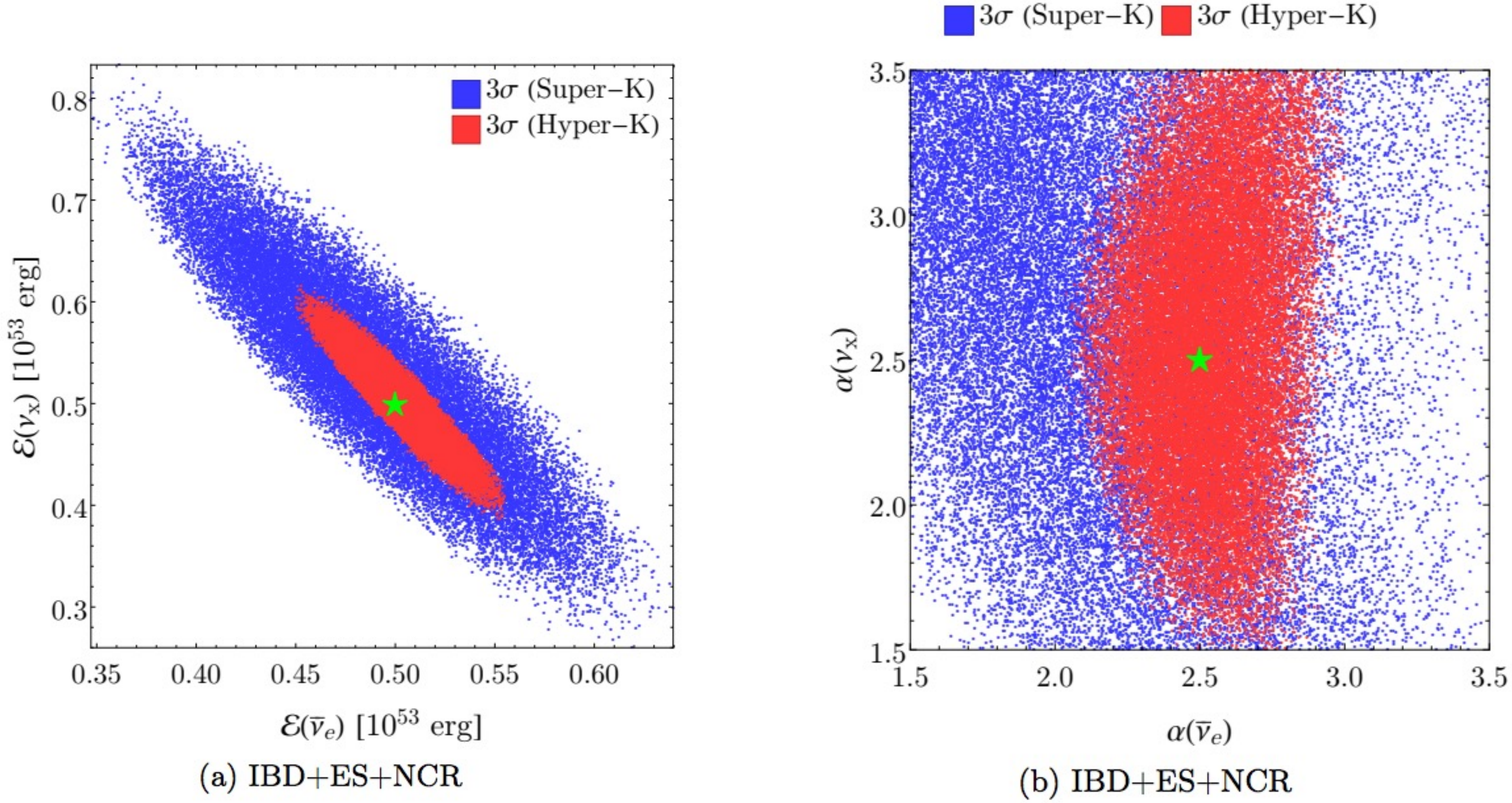
Earth Matter Effects



Energy-dependent regeneration in Earth depends on spectral differences between flavors and encodes neutrino mass ordering. May be hard to see.

Boriello, Chakraborty, Mirizzi, Serpico, Tamborra (2012)
Lunardini, Smirnov (2001)

SN Flux Reconstruction



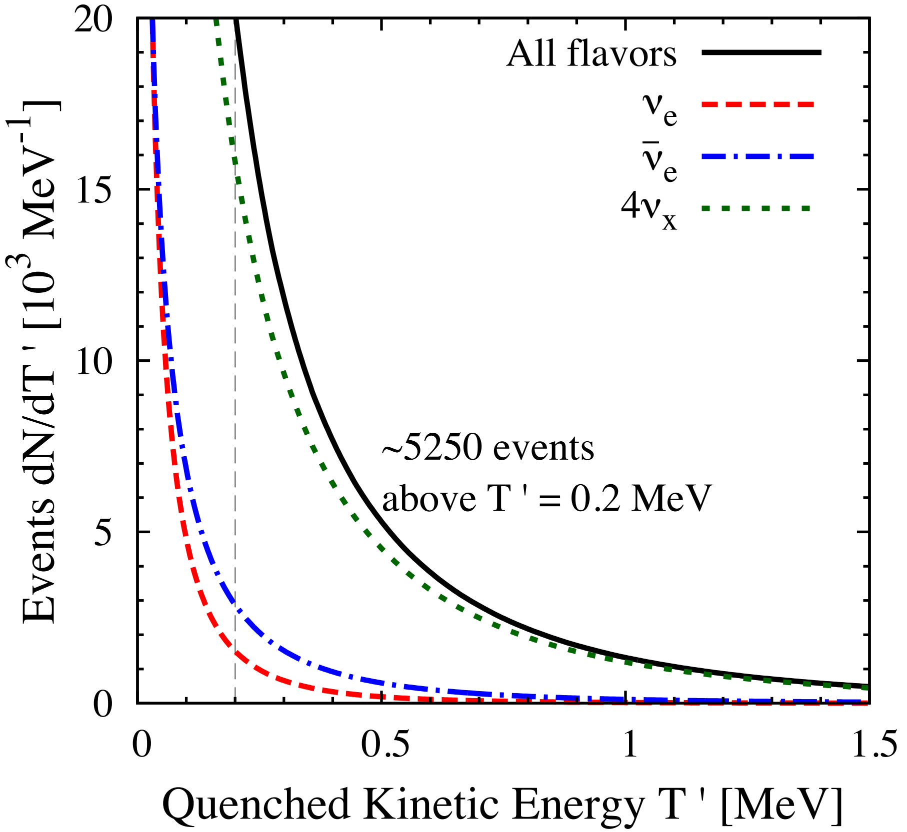
(a) IBD+ES+NCR

(b) IBD+ES+NCR

May be possible to reconstruct fluxes with unknown pinching

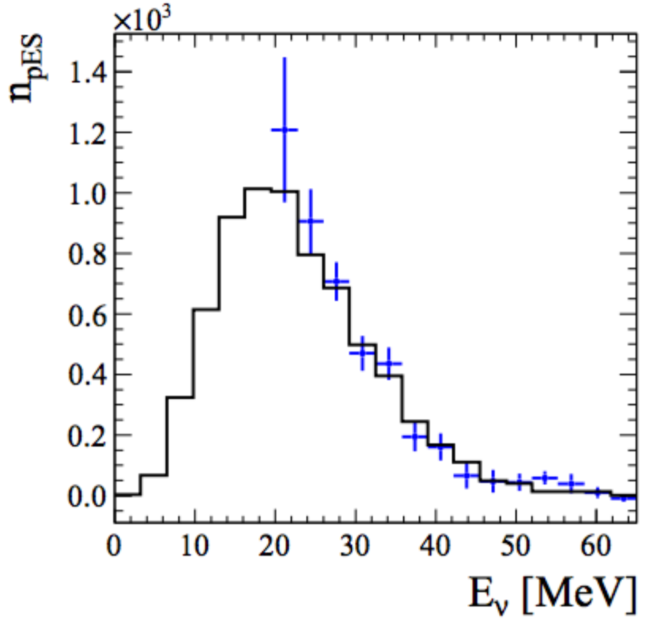
Rosso, Vissani, Volpe (2017)
For nue: Laha, Beacom (2014), Laha, Beacom, Agarwalla (2014), Nikrant, Laha, Horiuchi (2017)
Previously: Minakata, Nunokawa, Tomas, Valle (2008)

Neutral Current is Important



Beacom, Farr, Vogel (2003)
Dasgupta and Beacom (2011)
See also Chauhan, Dasgupta, Datar (2021) for a new idea using Deuterium

Neutrino – Proton elastic scattering can give the unoscillated fluxes if measured with enough statistics and reconstructed with precision



Detailed analysis for JUNO by Li, Li, Wang, Wen, Zhou (2017)

If you want to know more …

Mirizzi, Tamborra, Janka, Saviano, Scholberg, Bollig, Huedepohl, Chakraborty
Riv. Nuovo Cimento 39 (2016)
Detailed SN Neutrino Review

Horiuchi and Kneller
J.Phys. G45 (2018)
Interpretative

Duan, Fuller, Qian
Ann.Rev.Nucl.Part.Sci. 60 (2010)

Chakraborty, Hansen, Izaguirre, Raffelt
Nucl.Phys. B908 (2016)

Shalgar and Tamborra - Annual Rev. (2021)
Capozzi, Saviano - Universe 8 (2022)
Richers and Sen - (2022)
Focussed on collective effects

Dasgupta
PoS ICHEP2010 (2010), and PoS NOW 2022 (2023)
Short reviews for the impatient

Takeaway

www.bdasgupta.com
bdasgupta@theory.tifr.res.in

- SN theory
  - Different phases of SN explosion and different oscillation physics
- Oscillation theory
  - Adiabatic and Non-adiabatic (at Shock) MSW
  - Slow/Fast Collective Mixing due to “Crossings”
- Detection Prospects, Bounds
  - Neutrinos of all Flavors, Energies, Times, Directions …
  - Multi-messenger helps
- Upshot
  - Neutronization burst : Physics is MSW-like
  - Accretion : If “Crossing” exists then Collective -> Mixing, else MSW-like
  - Cooling : Spectra are very similar; New and Improved BSM Bounds