XXVIII International Conference on Neutrino Physics and Astrophysics
9 June 2018, Heidelberg

Supernova Neutrinos

Challenges & Opportunities

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TIFR Mumbai

Outline

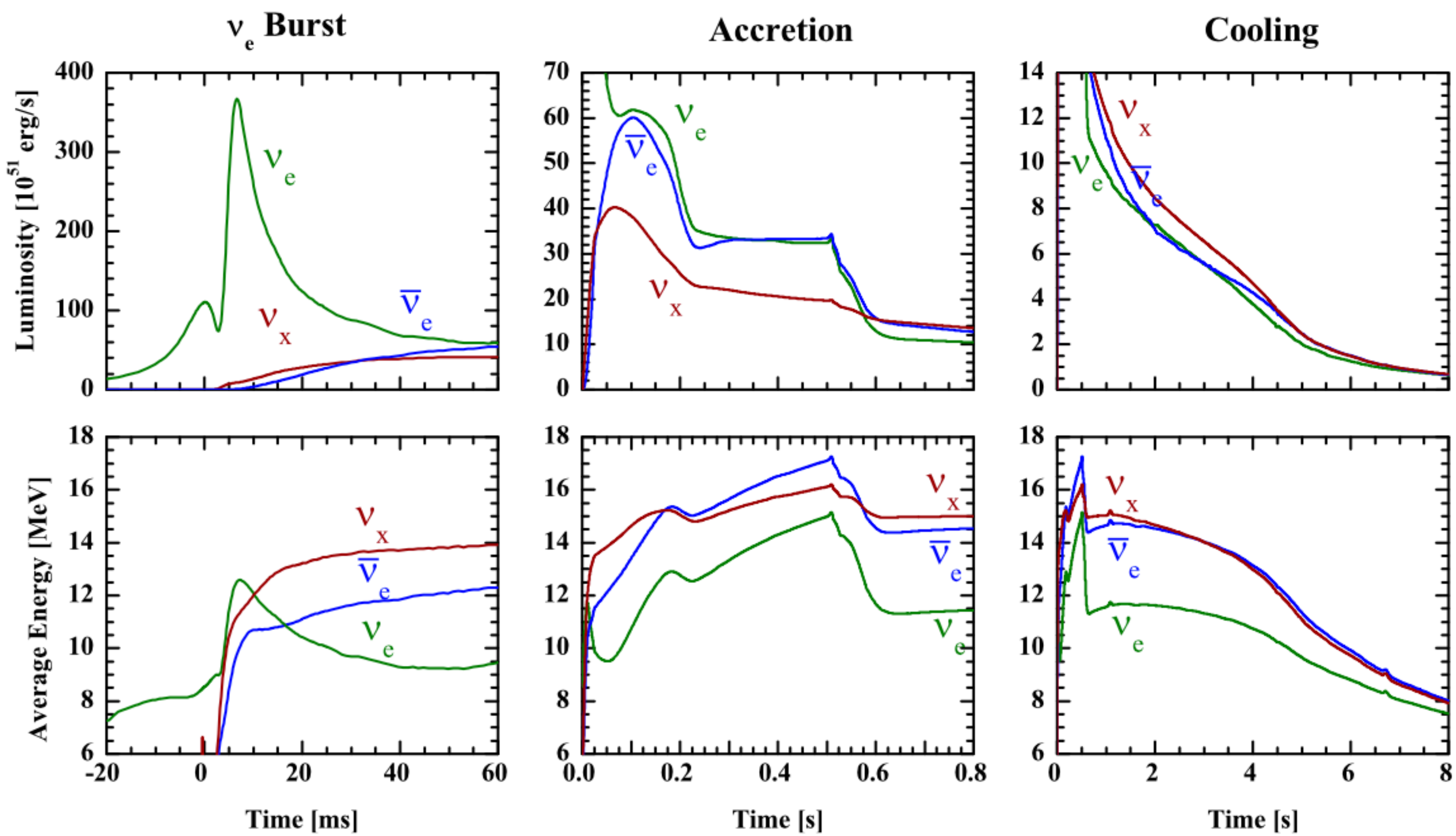
Prologue

Theory of SN neutrino oscillations

Phenomenology with SN neutrinos

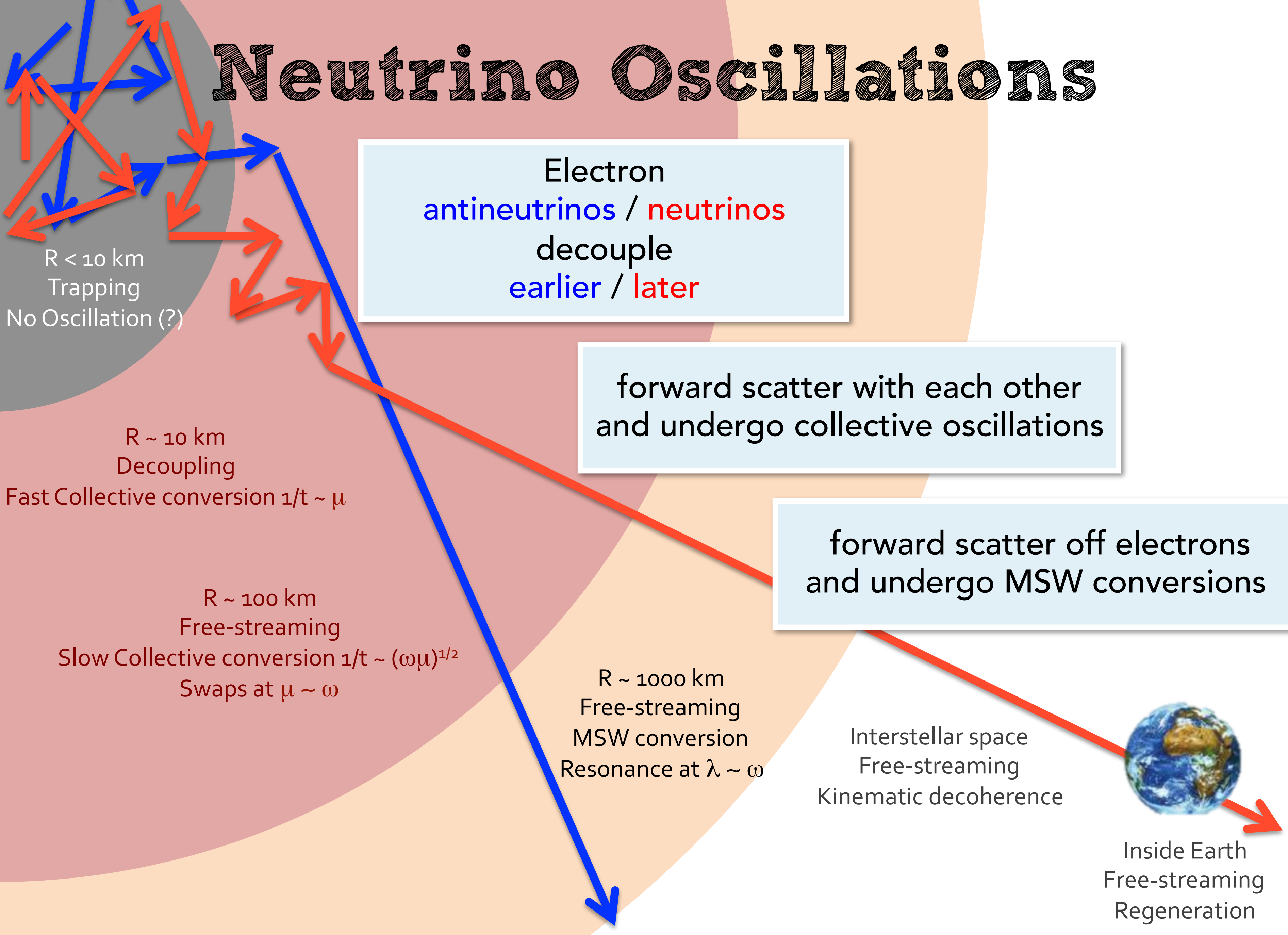
Concluding remarks

Neutrinos from a SN



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

Neutrino Oscillations

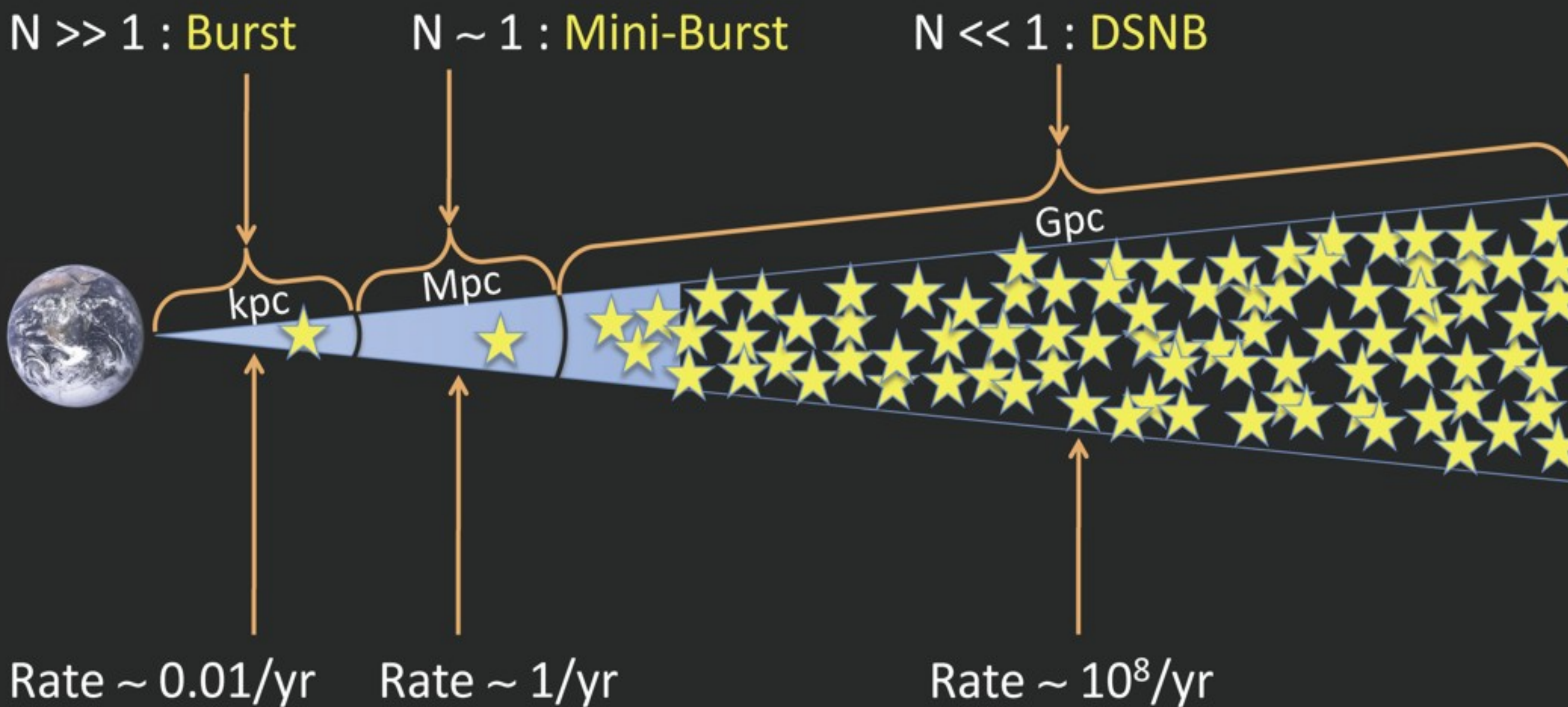


SN Neutrino Detectors

	Detector	Type	Mass (kt)	Location	Events	Flavors
Running	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	$\bar{\nu}_e$
Future	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)

Distance, Strategy, Science!

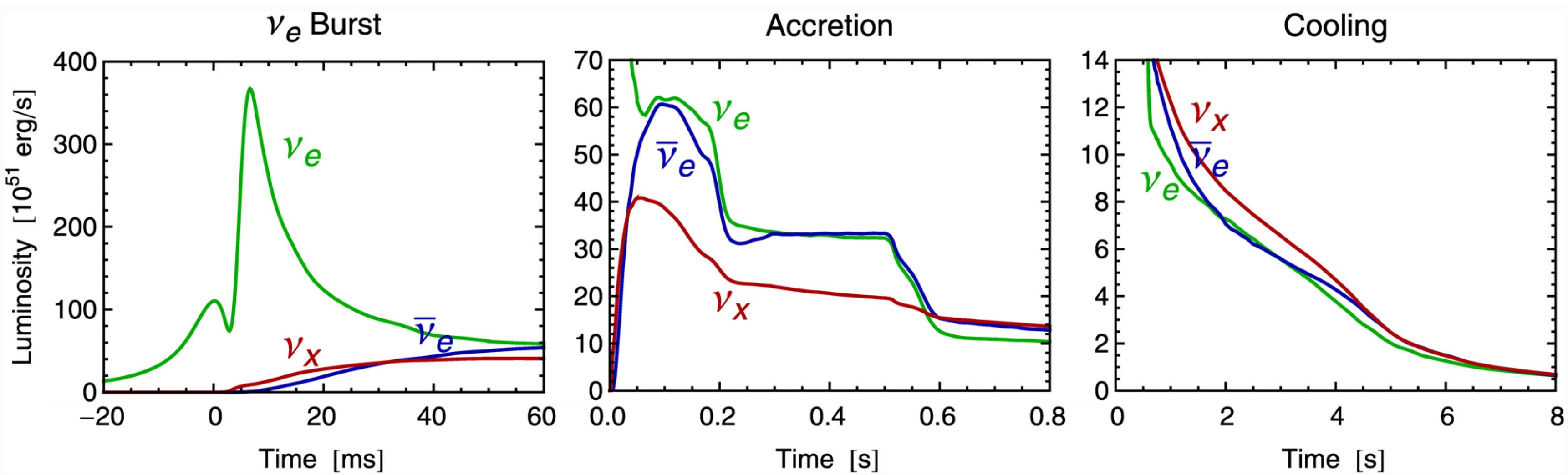


high statistics,
all flavors

object identity,
burst variety

cosmic rate,
average emission

Highlights



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

The Takeaway

- Introduction
  - Different phases of SN explosion and different oscillation physics
- Oscillation theory
  - MSW : Adiabatic and Non-adiabatic
  - Collective : Slow/Fast both need spectral crossings
- Non-oscillation observables
  - timing, pointing, mass, lifetime, E-loss, SASI, failed SN, exotica
- Oscillation-sensitive observables
  - Mass ordering, Earth effects, SN properties, equilibration, …
- Upshot
  - Neutrinozation burst : MSW-like
  - Accretion : If crossing exists then fast, else MSW-like
  - Cooling : Spectra are very similar

What's so special about SN neutrino oscillations?

SN Neutrino Oscillations

$$iD\rho_{\vec{p}} = +\left[\frac{M^2}{2p}, \rho_{\vec{p}}\right] + \sqrt{2}G_F[L, \rho_{\vec{p}}] + \sqrt{2}G_F \int \frac{d^3\vec{q}}{(2\pi)^3}(1-\cos\theta_{\vec{p}\vec{q}})[(\rho_{\vec{q}} - \bar{\rho}_{\vec{q}}), \rho_{\vec{p}}]$$

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

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

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

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

Collective effects depends on the neutrino density

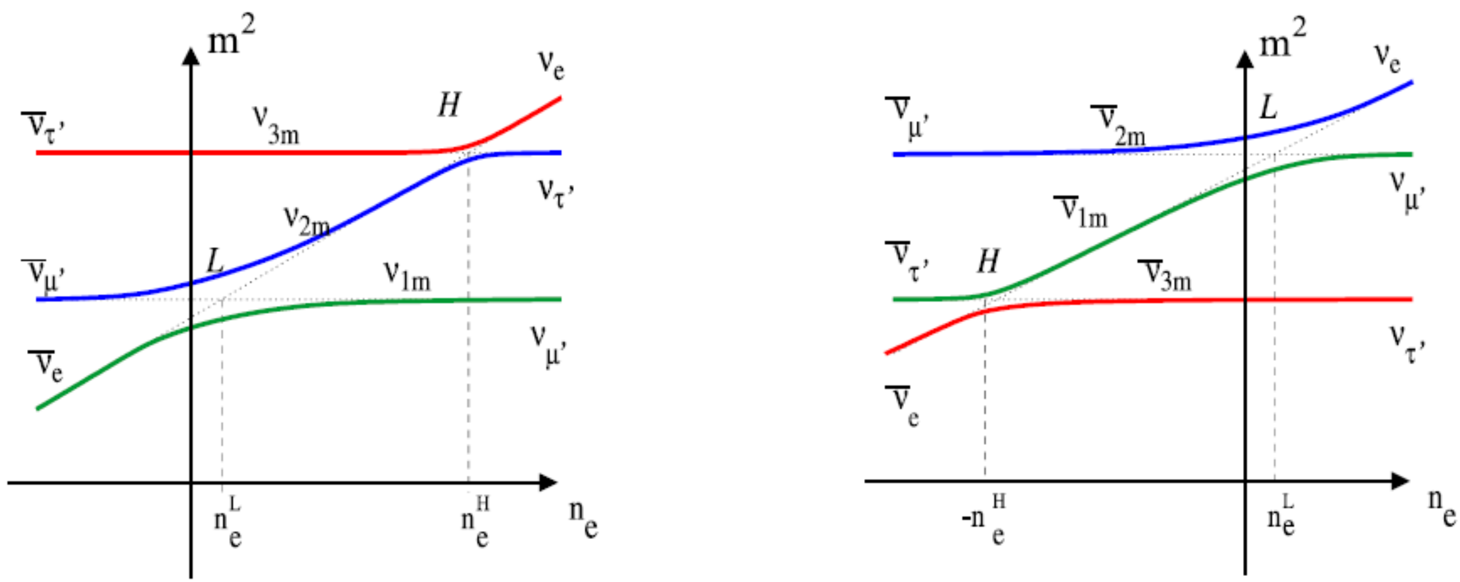
$$\mu = \sqrt{2}G_F\, n_\nu$$

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 $n_p + n_x + n_t$

MSW Effect in SN

Neutrino oscillations in a variable-density medium and $\nu-$ bursts due to the gravitational collapse of stars

S. P. Mikheev and A. Yu. Smirnov
Institute of Nuclear Research, Academy of Sciences of the USSR
(Submitted 24 December 1985)
Zh. Eksp. Teor. Fiz. **91**, *7-13 (July 1986)*



Dighe and Smirnov (1999)

Can compute energy spectra of each flavor at Earth in terms of pre-MSW spectra

Collective Effect

Fermi National Accelerator Laboratory

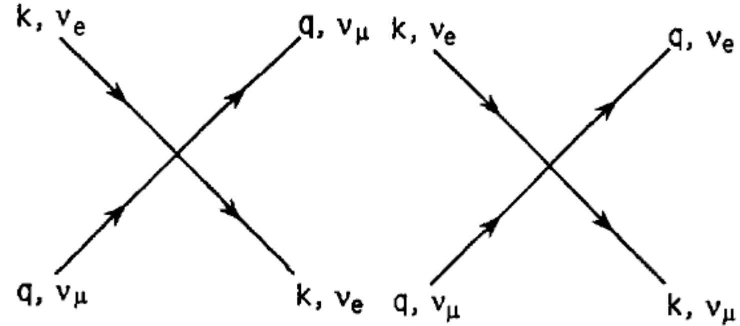
UCRHEP-T84
FERMILAB-PUB-92/18-T
January 1992

DIRAC NEUTRINOS IN DENSE MATTER

James Pantaleone

Fermi National Accelerator Lab
Batavia, IL 60510
and
Department of Physics
University of California
Riverside, CA 92521

In this formulation, it is apparent that basis rotations of the "propagating" neutrino cancel with those of the "background" neutrinos. Thus the U(2) flavor symmetry is maintained. *To neglect the off diagonal terms in every basis is obviously incorrect since it breaks this symmetry and then the result of the flavor evolution of a given state would be different in each basis.* The U(2) symmetry maintains the net flavor content.



Pantaleone (1992)

Forward scattering neutrinos exchange flavor

$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}t}\begin{vmatrix} |\nu_e(\boldsymbol{k})\nu_e(\boldsymbol{q})\rangle \\ |\nu_e(\boldsymbol{k})\nu_\mu(\boldsymbol{q})\rangle \\ |\nu_\mu(\boldsymbol{k})\nu_e(\boldsymbol{q})\rangle \\ |\nu_\mu(\boldsymbol{k})\nu_\mu(\boldsymbol{q})\rangle \end{vmatrix} = V_2 \begin{vmatrix} |\nu_e(\boldsymbol{k})\nu_e(\boldsymbol{q})\rangle \\ |\nu_e(\boldsymbol{k})\nu_\mu(\boldsymbol{q})\rangle \\ |\nu_\mu(\boldsymbol{k})\nu_e(\boldsymbol{q})\rangle \\ |\nu_\mu(\boldsymbol{k})\nu_\mu(\boldsymbol{q})\rangle \end{vmatrix}$$

where $$V_{2\nu} = \sqrt{2}G_F\xi\frac{1}{V}\begin{vmatrix} 2 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 2 \end{vmatrix}$$

Collective Effects

When neutrino density is high

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

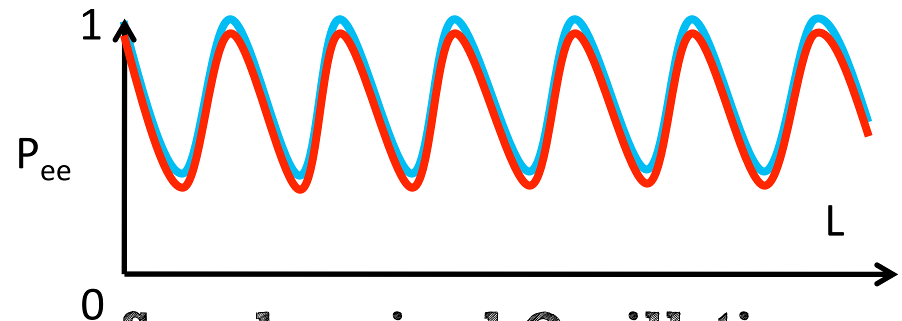
the system is synchronized

As neutrino density gets lower

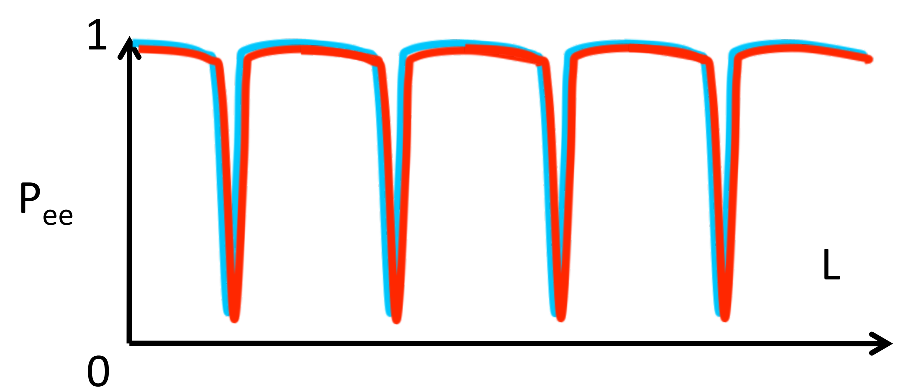
$$G_F\, n_\nu \gtrsim \frac{\Delta m^2}{2E}$$

the system starts wobbling

Instability grows at rate proportional to geometric mean of ω and μ



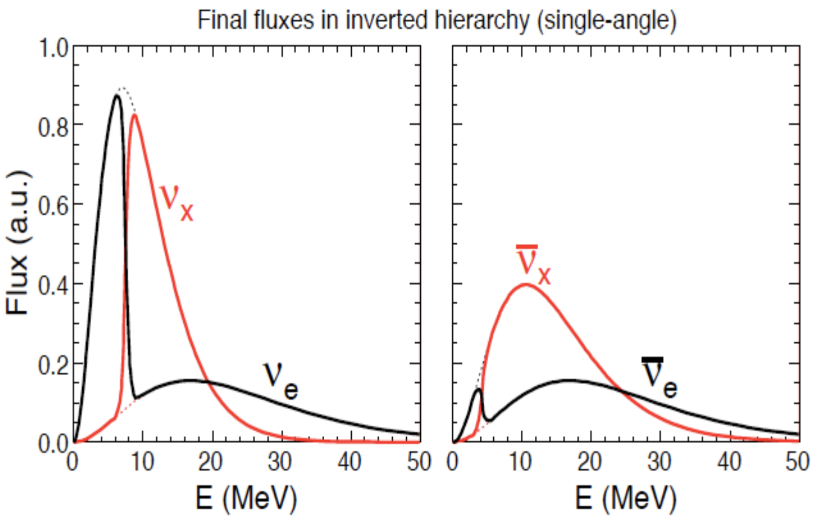
Synchronized Oscillations

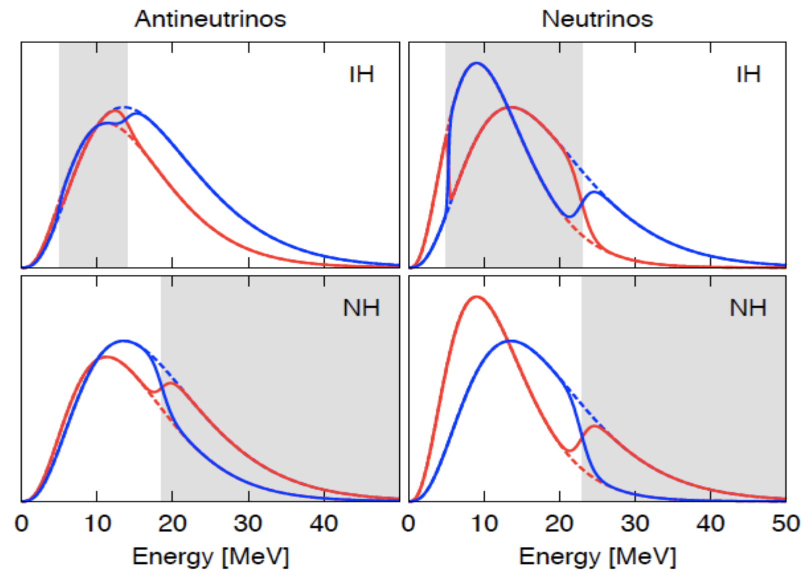


Bipolar Oscillations

Pioneering work by Pantaleone, Kostelecky, Samuel in the 1990s

Spectral Swaps





Portions of the energy spectra get exchanged

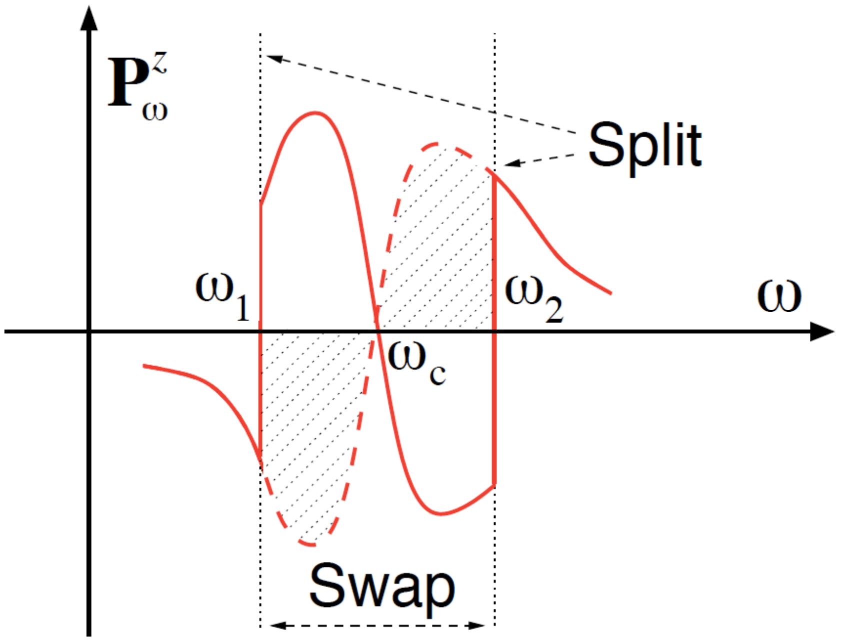
Initially thought to occur for Inverted ordering

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)

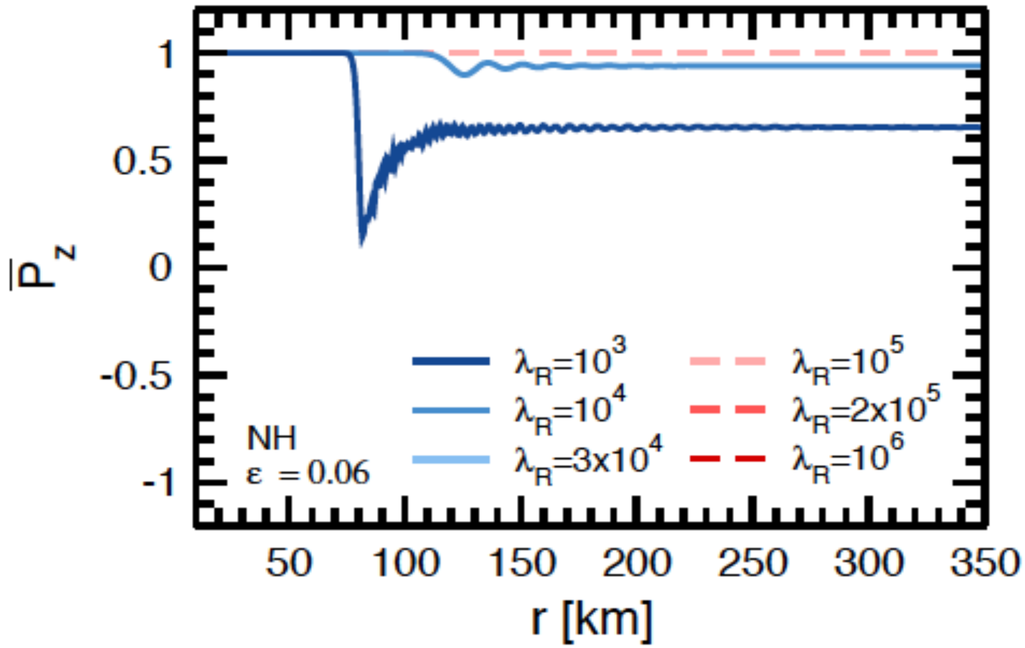
Crossing of Spectra

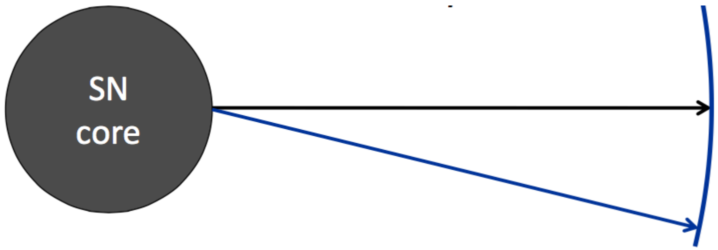


The main dynamical quantity turns out to be $F_e - F_x$
This is often what we refer to as the "spectrum" as a function of energy, or emission angle, etc. If this spectrum has a "crossing" the system tends to become unstable and there is flavor conversion.

Dasgupta, Dighe, Raffelt, Smirnov (2009)

Dense Matter Effect





longer path =
more matter

The electron background is different for the different trajectories, and while most of it drops out as a common phase, the differences are large enough to "block" collective effects.

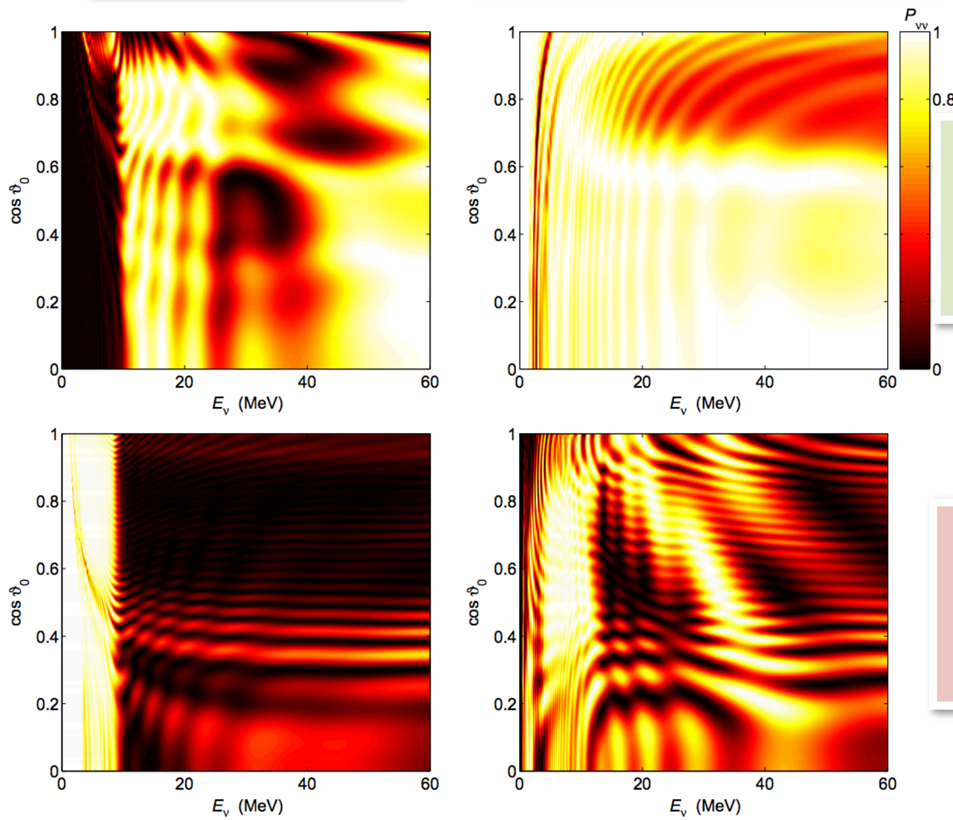
Esteban-Pretel, Mirizzi, Pastor, Tomas, Raffelt, Serpico, Sigl (2008)

Numerically challenging …

Neutrinos

Anti-Neutrinos

Emission Angle



Normal Mass Ordering

Inverted Mass Ordering

Energy

State-of-the-art
(1+1)+1+0 dims
or
(0+2)+1+0 dims

Duan, Fuller, Carlson, Qian (2006)
Mirizzi and Tomas (2010)

Linear Stability Analysis

$$\varrho_{\omega,v_z,\varphi} = \frac{1}{2}\mathrm{Tr}(\varrho_{\omega,v_z,\varphi})\,\mathbb{I} + \Phi_\nu \frac{g_{\omega,v_z,\varphi}}{2}\begin{pmatrix} s_{\omega,v_z,\varphi} & S_{\omega,v_z,\varphi} \\ S^*_{\omega,v_z,\varphi} & -s_{\omega,v_z,\varphi}\end{pmatrix}$$

Off-diagonal element of density matrix measures departure from initial pure-flavor-state.

Linearize equation in S see if there are exponentially growing solutions

Bannerjee, Dighe, Raffelt (2010)

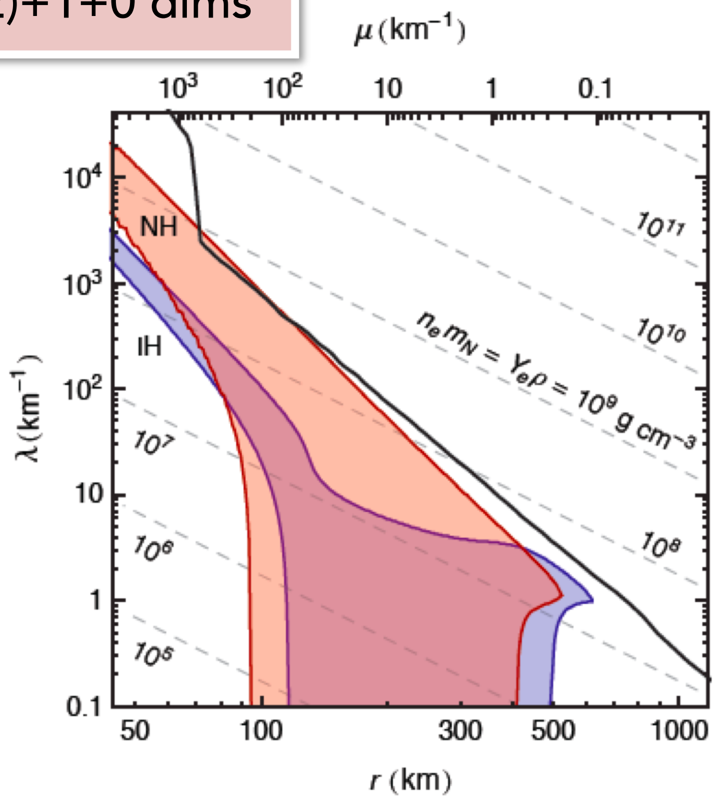
Turns out to be equivalent to demanding that there be a crossing in the spectrum

Abbar and Duan (2017)

Spontaneous Symmetry Breaking

Solutions do not preserve the approximate symmetries of initial conditions and the equations of motion

(1+2)+1+0 dims



In the red/blue shaded region, flavor composition changes exponentially fast

The red region (for NMO) breaks azimuthal symmetry

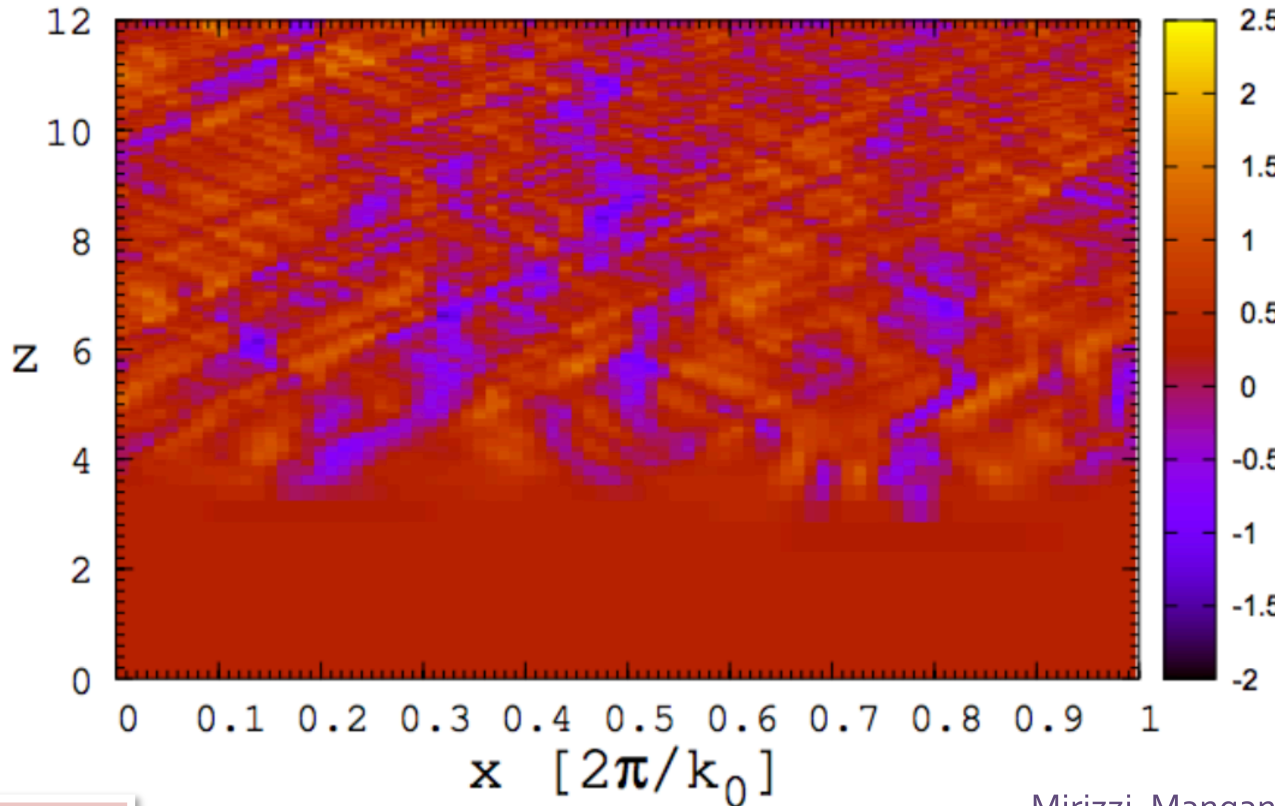
Raffelt, Sarikas, Seixas (2013)

But suppressed by matter

Chakraborty, Mirizzi, Saviano, Seixas (2014)

Neutrinos emitted with aziuthally-symmetric fluxes but their flavor evolution depends on the azimuthal angle

SSB of Spatial Translation



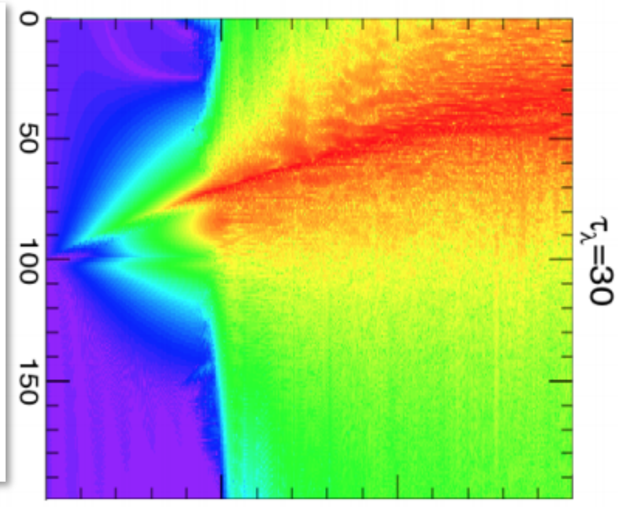
In 1+2+0 dims

Mirizzi, Mangano, Saviano (2015)
Duan and Shalgar (2014)
Mangano, Mirizzi, Saviano (2014)

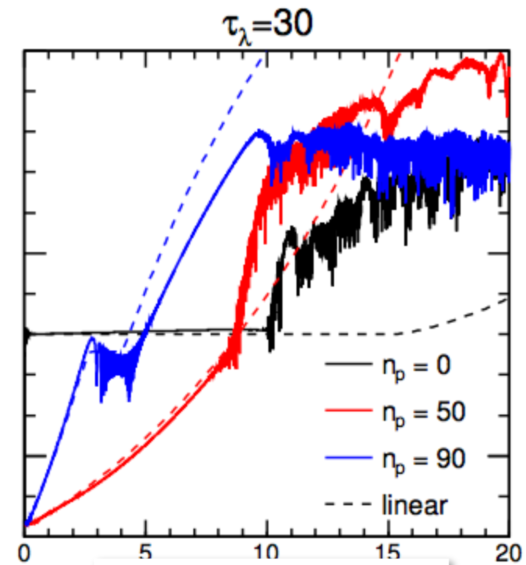
Initial conditions are homogeneous, but evolution breaks homogeneity

SSB of Time Translation

Frequency Mode



Space



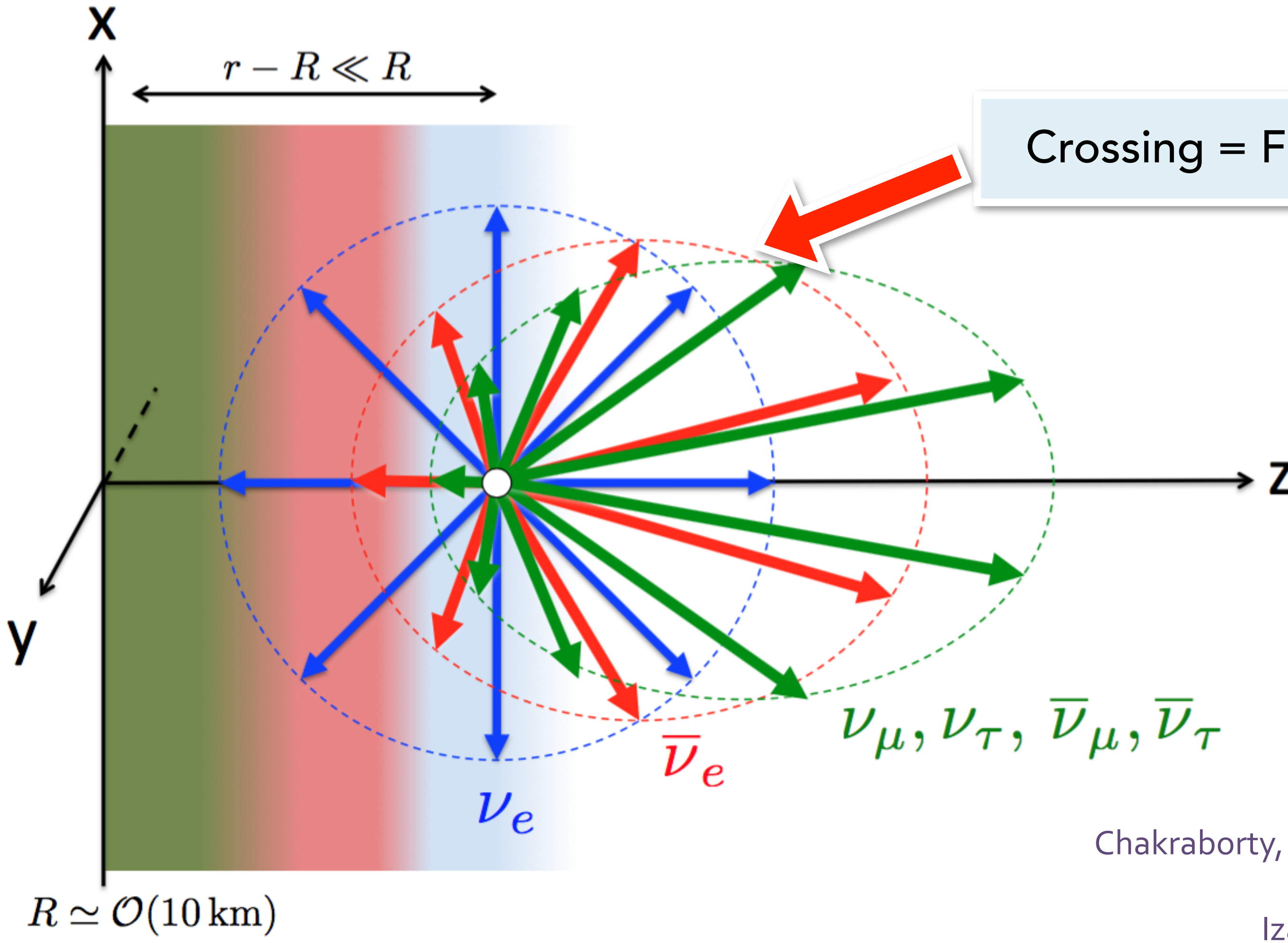
Space

In 1+1+1 dims

Dasgupta and Mirizzi (2015)
Capozzi, Dasgupta, Mirizzi (2016)
See also linearized study by Abbar and Duan (2015)

Initial conditions are approximately static, but flavor composition spontaneously picks up a pulsation that grows and breaks stationarity

Fast Conversions



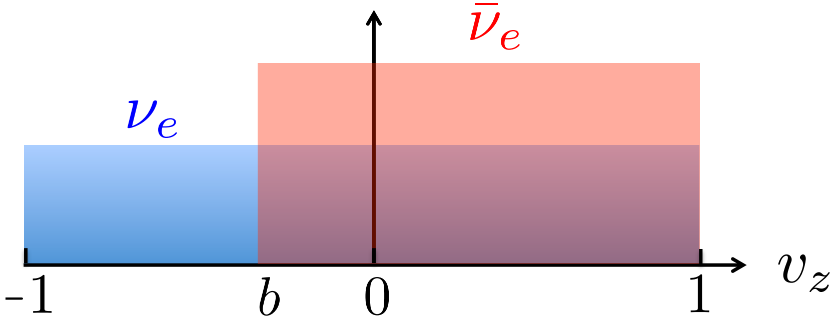
Crossing = Fast Instability

Instability grows at rate proportional to neutrino density

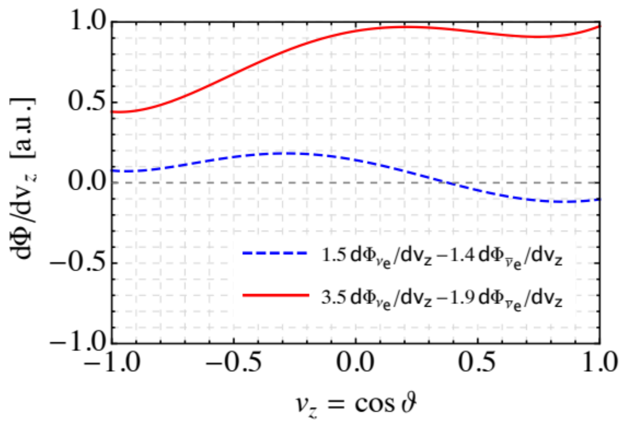
Sawyer (2005, 2015)
Chakraborty, Hansen, Izaguirre, Raffelt (2016)
Dasgupta, Mirizzi, Sen (2016)
Izaguirre, Raffelt, Tamborra (2016)
Capozzi, Dasgupta, Lisi, Marrone, Mirizzi (2017)
Dasgupta and Sen (2017)

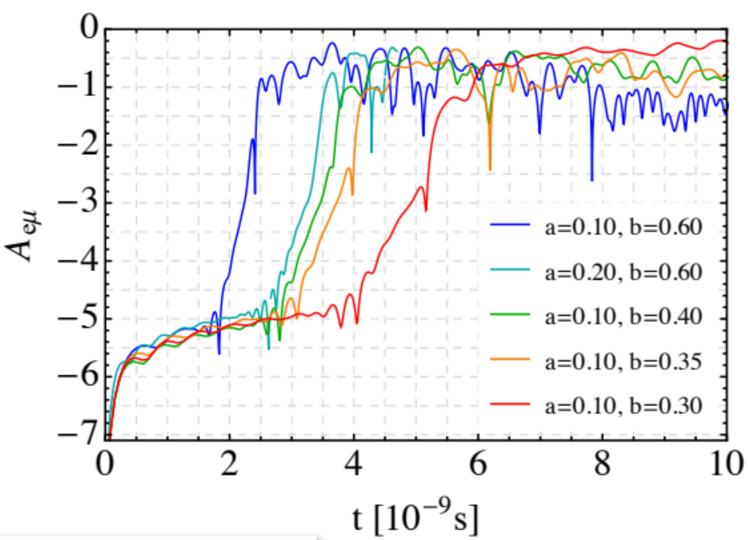
Crossing and Back-flux

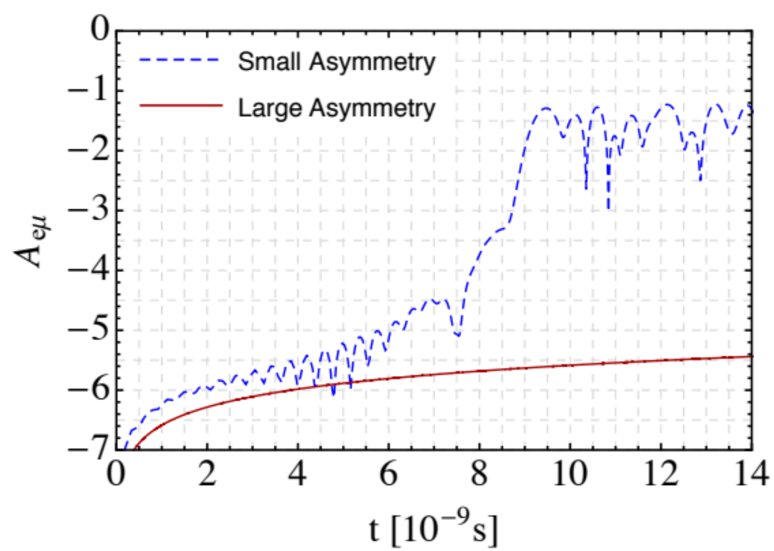
Toy Model



SN Inspired Models







1+0+1 dims

Dasgupta, Mirizzi, Sen (2016)

Challenges

- **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**

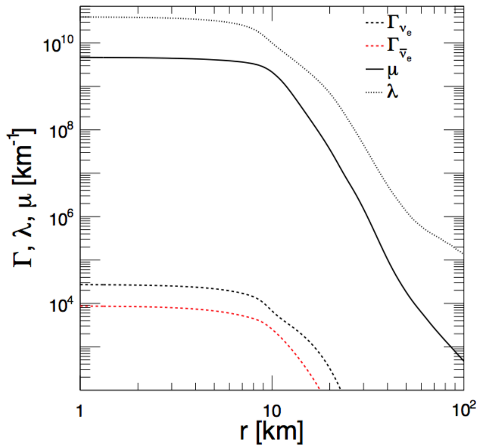
Akhmedov, Kopp, Lindner (2017)
Hansen, Smirnov (2016)

- **Sterile nus, NSI, ...** Skipping non-standard physics for lack of space and time
- **Interpretation of collective effects**

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

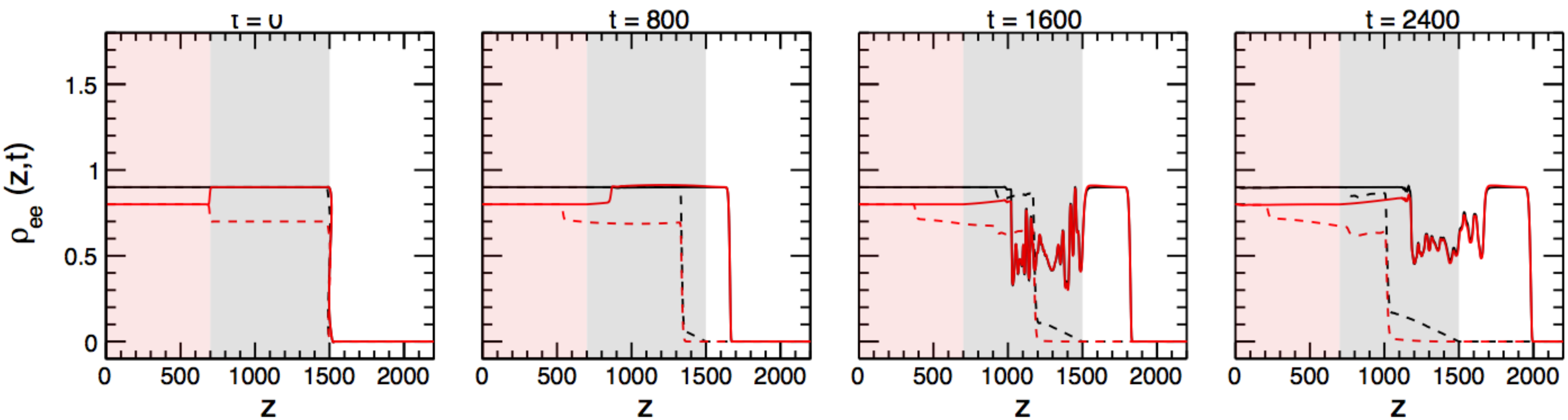
- **Dynamical decoherence**

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, to appear)



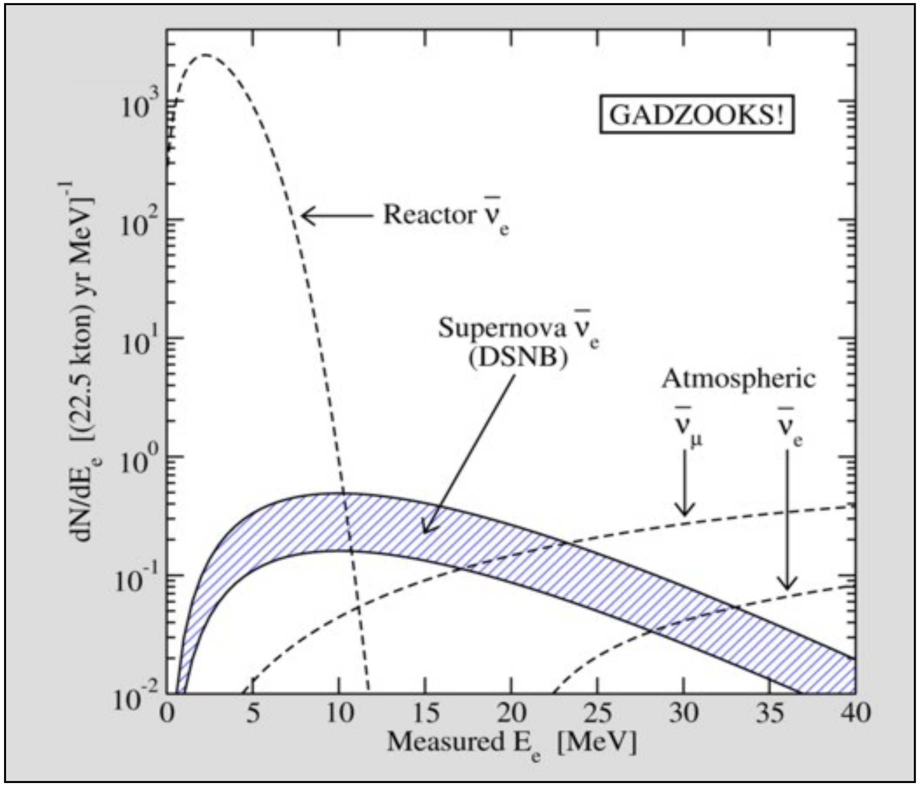
Do fast conversions, once generated, penetrate the SN core?

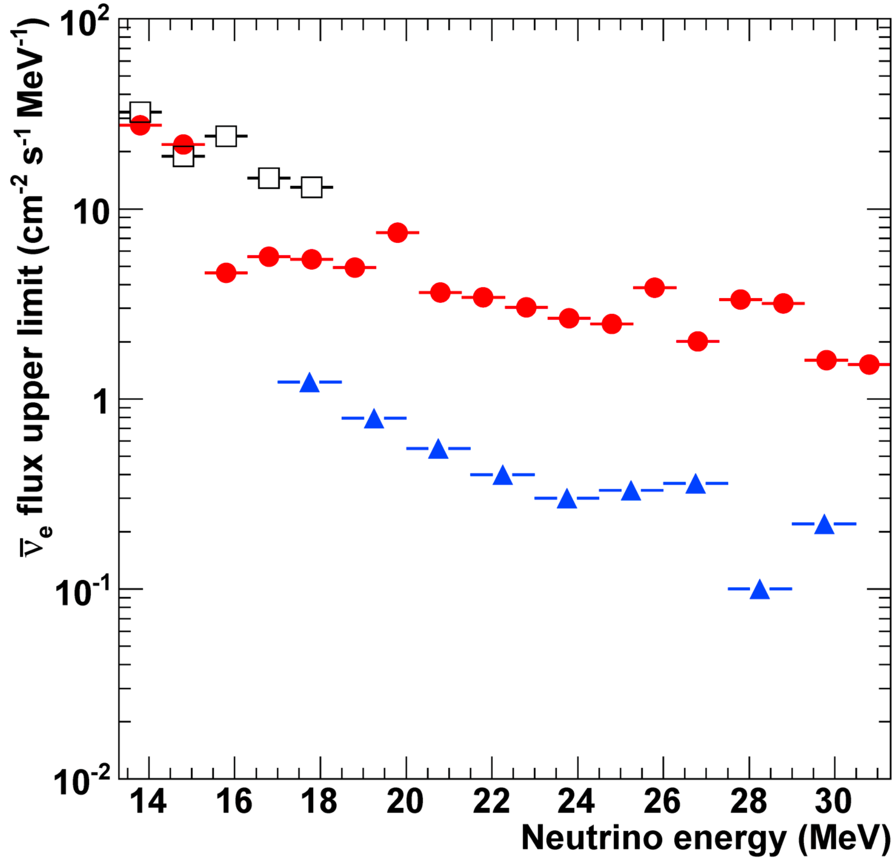
Main Results

- Neutrino-Neutrino interactions can lead to large flavor changes
- Can find “when” and “how fast” using stability analysis
- Solutions are space-time dependent and can spontaneously break symmetries
- The spatial growth of slow collective effects typically blocked by the dispersion in dense ordinary matter
- Crossing in the ELN distribution leads to fast conversion that can make all flavors almost equally populated in situ

What can we learn?

DSNB



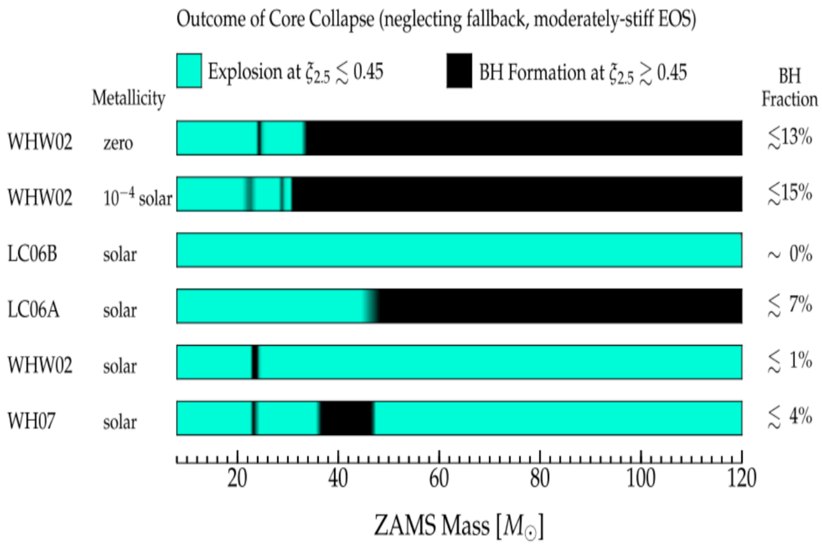


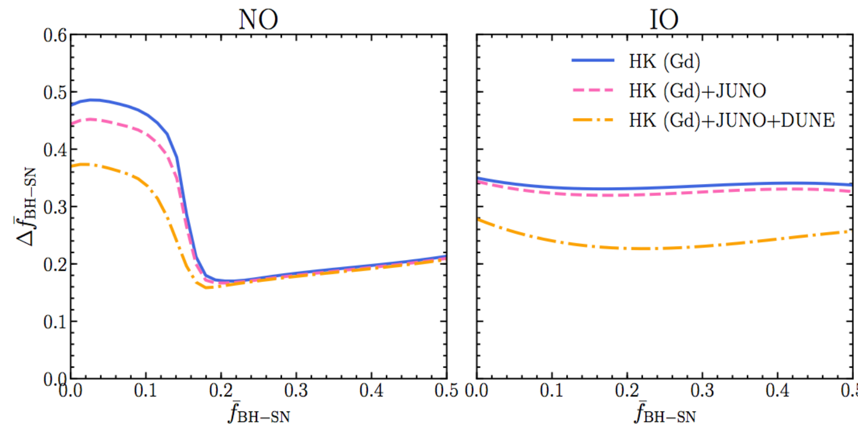
Zeldovic (1964), Bisnovatyi-Kogan and Seidov (1982)
Plot from Beacom and Vagins (2003)
See reviews by Lunardini (2010) and Beacom (2010)

Super-Kamiokande Collaboration (2013)

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

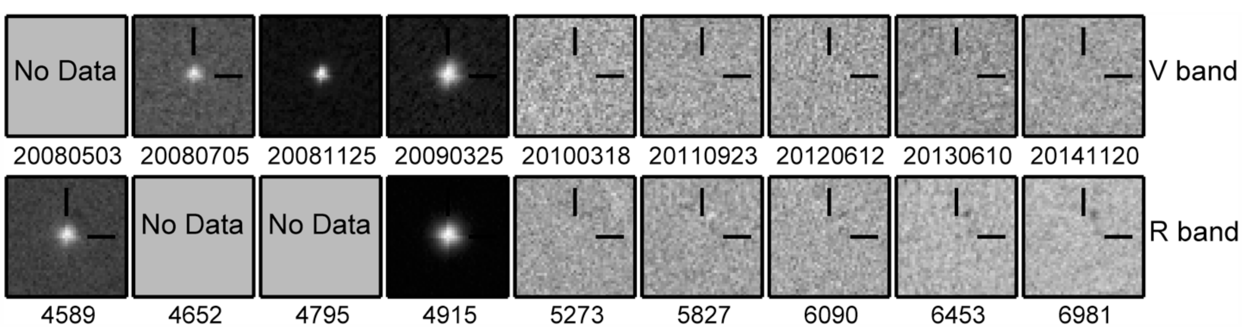
Are there failed SN?





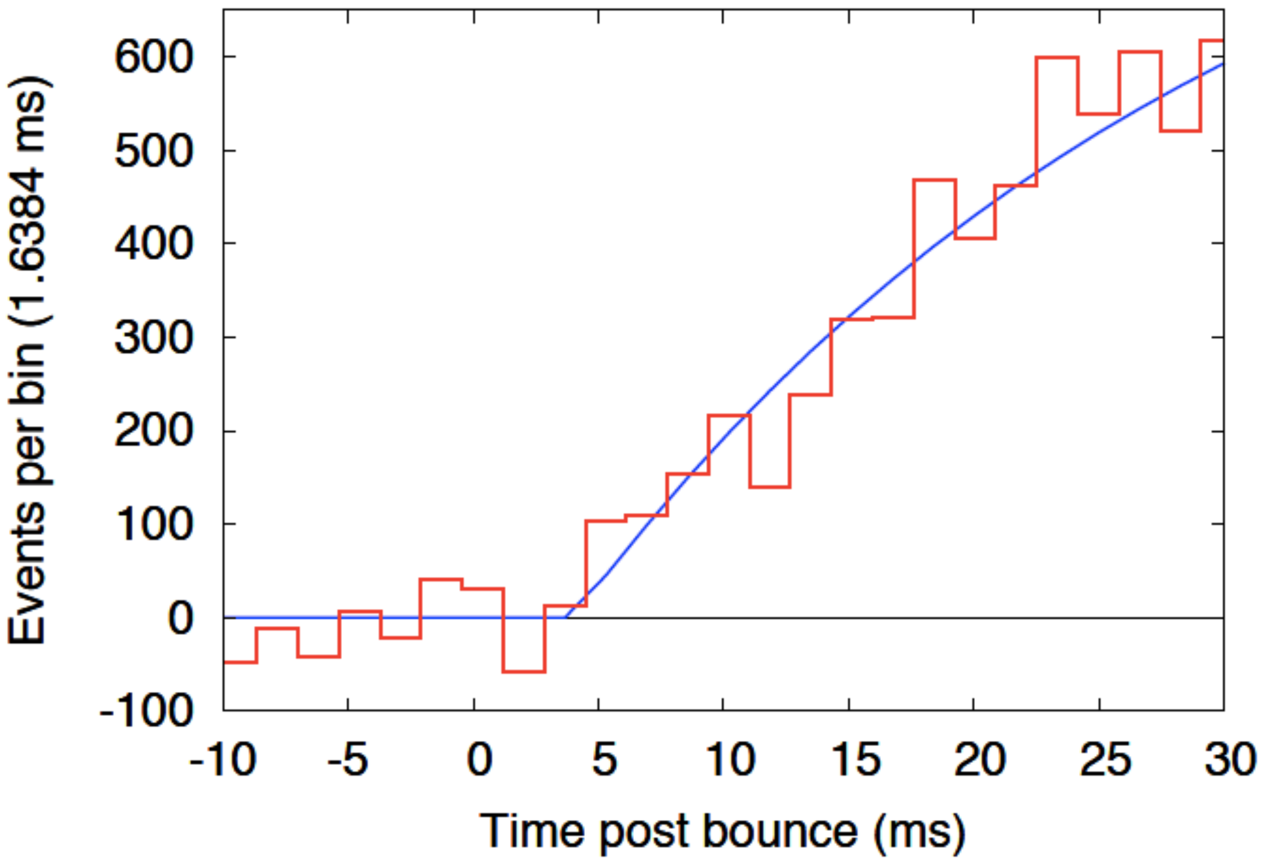
Some supernovae are not expected to explode
O'Connor and Ott (2013)
Ertl, Janka, Woosley, Sukhbold, Ugliano (2016)

DSNB is sensitive to the failed SN fraction
Lunardini (2009)
Moller, Suliga, Tamborra, Denton (2018)

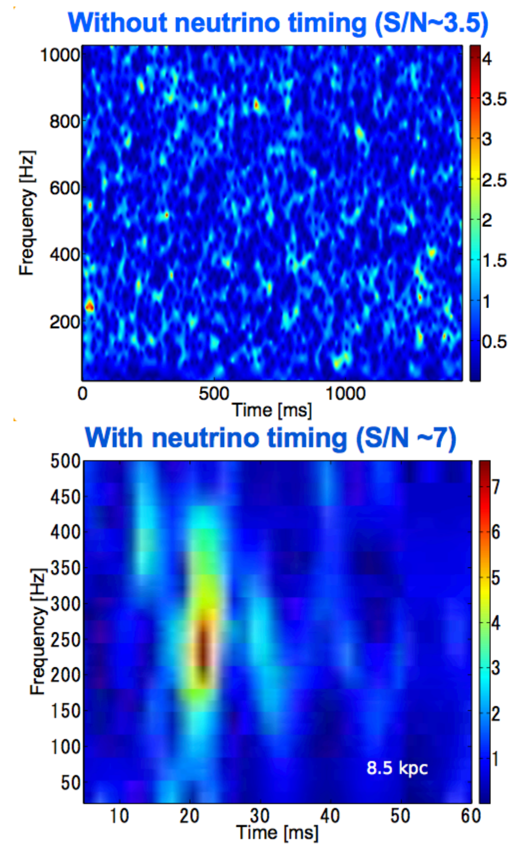


SN without a bang
Gerke, Kochanek, Stanek (2014)
Reynolds, Fraser, Gilmore (2015)

Timing



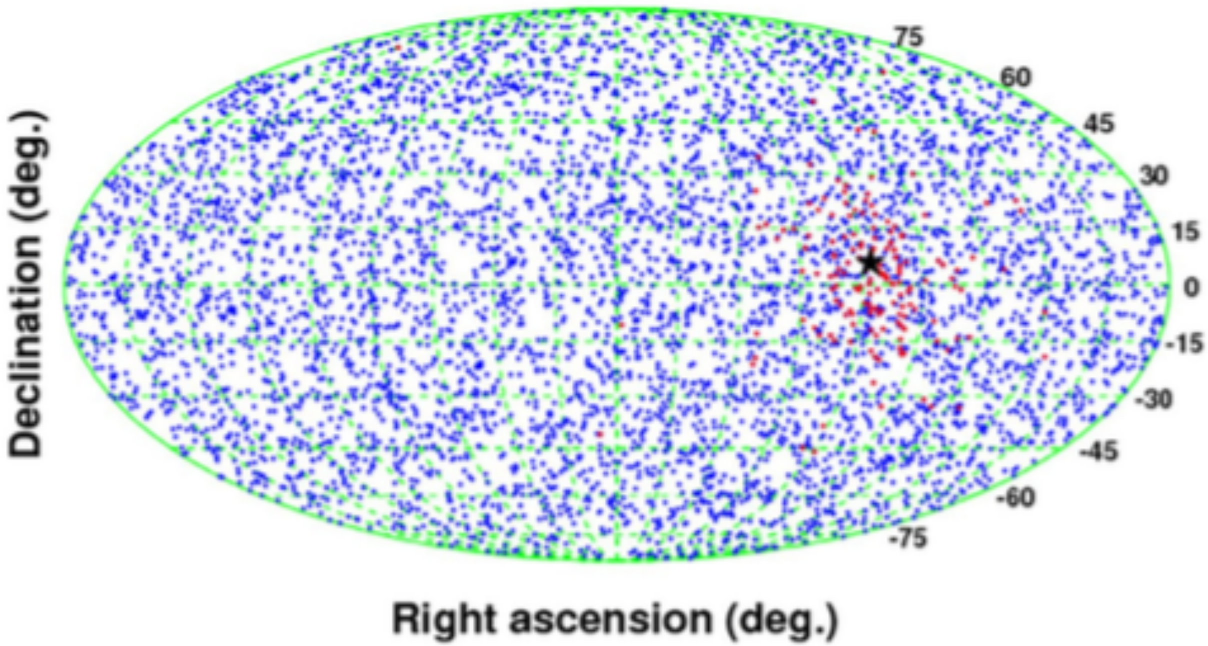
Pagliaroni, Vissani, Coccia, Fulgione (2009)
Plot from Halzen and Raffelt (2009)



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)

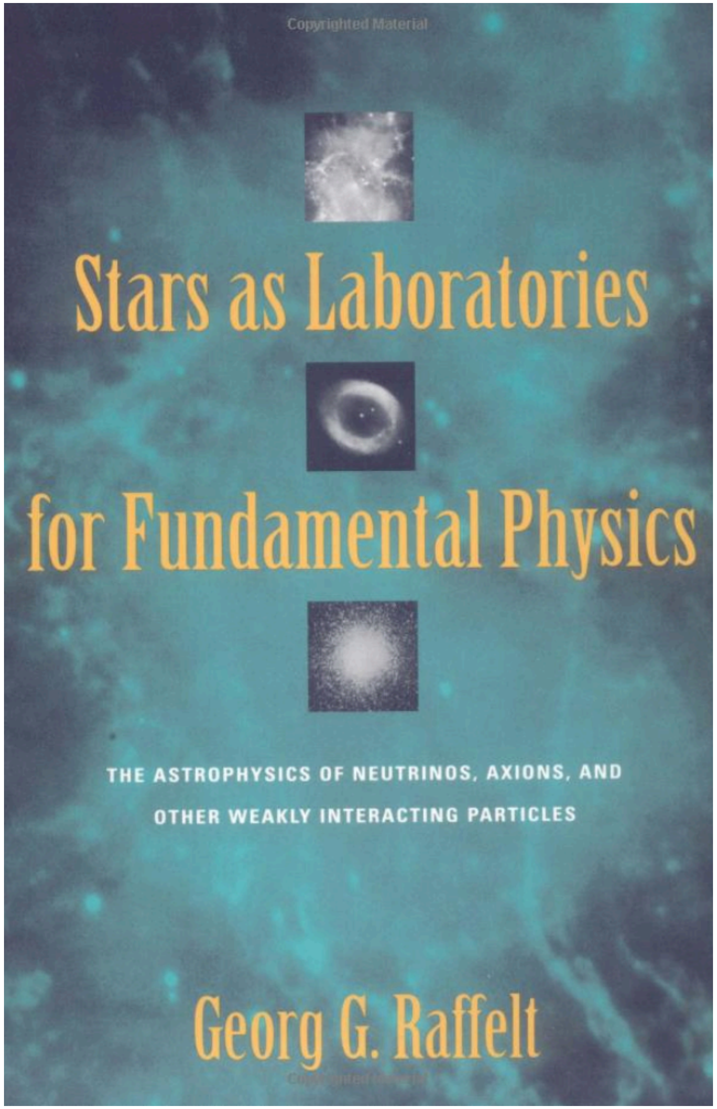
Tomas, Semikox, Raffelt, Kachelriess, Dighe (2003)

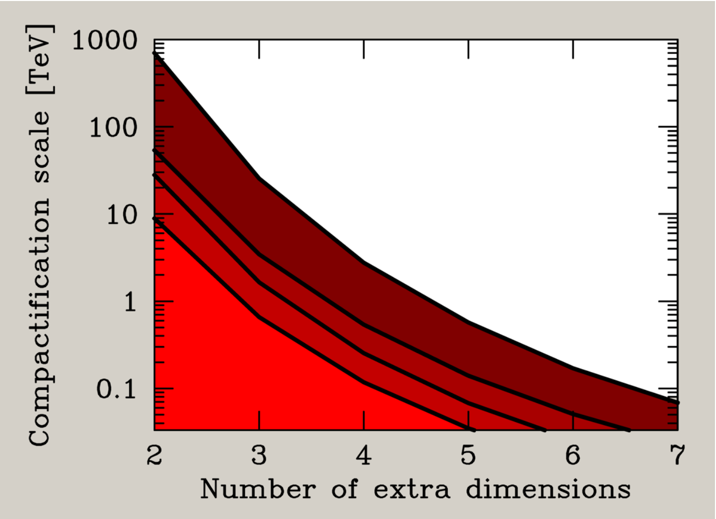
Plot from Abe at al. for Super-K (2016)

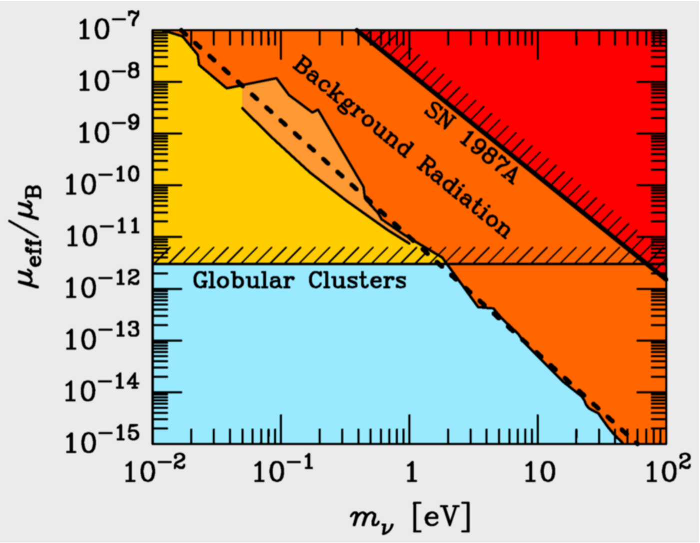
For triangulation: see Beacom and Vogel (1998)
Muhlbeier, Nunokawa, and Zukanovich Funchal (2013)
Brdar, Lindner, Xu (2018)

Pointing accuracy of a few degrees for SN at 10 kpc

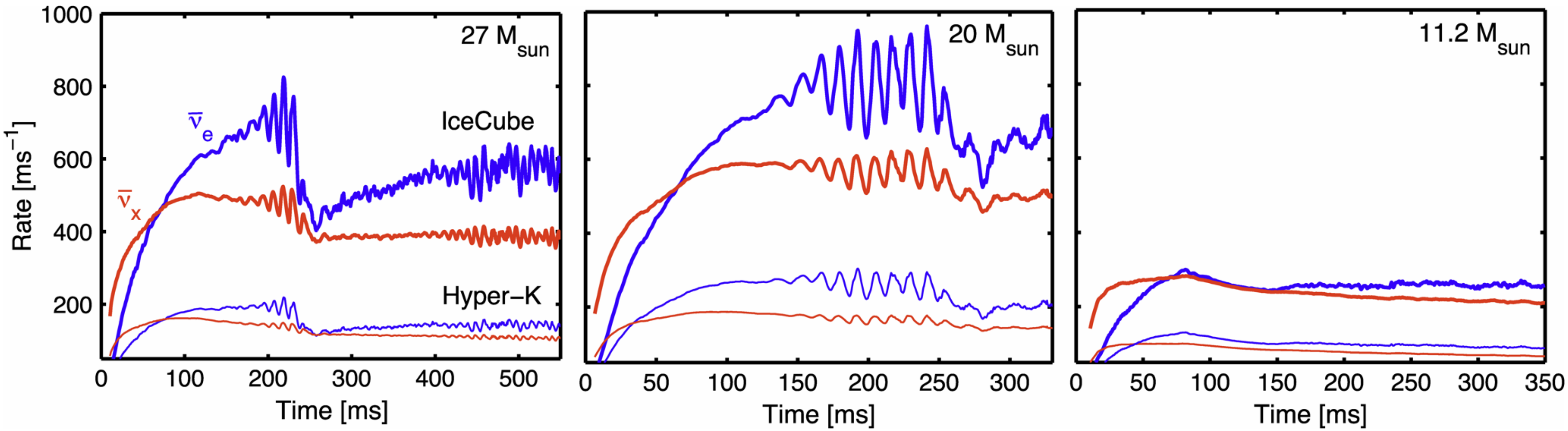
Fundamental Physics with Stars







SASI Signatures



27 M_{sun} star
Multiple SASI episodes and convection

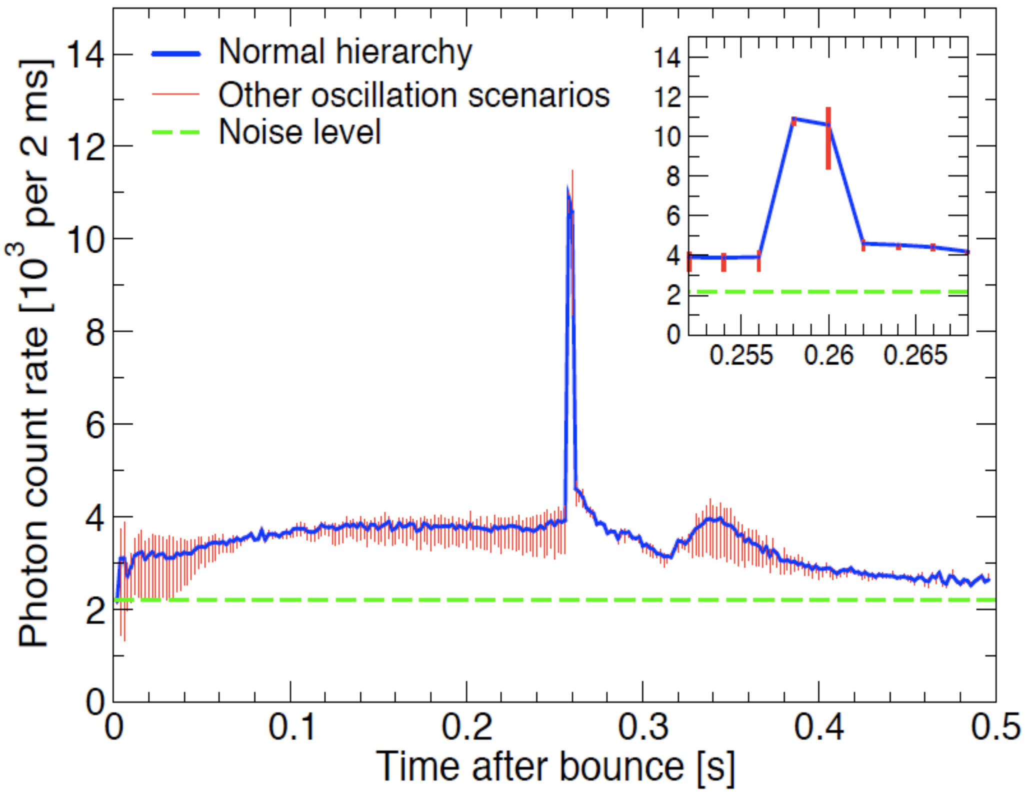
20 M_{sun} star
Single SASI episode and convection

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

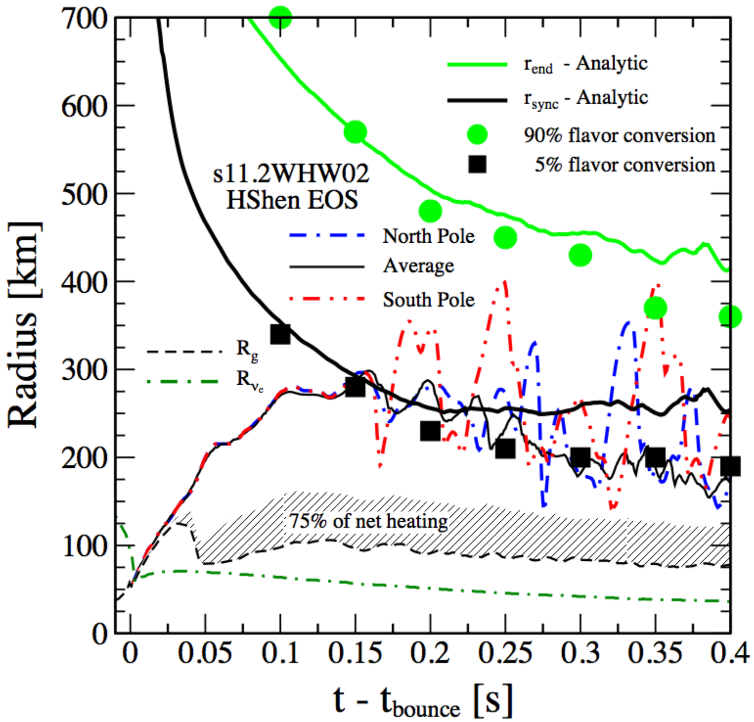
QCD transition in SN

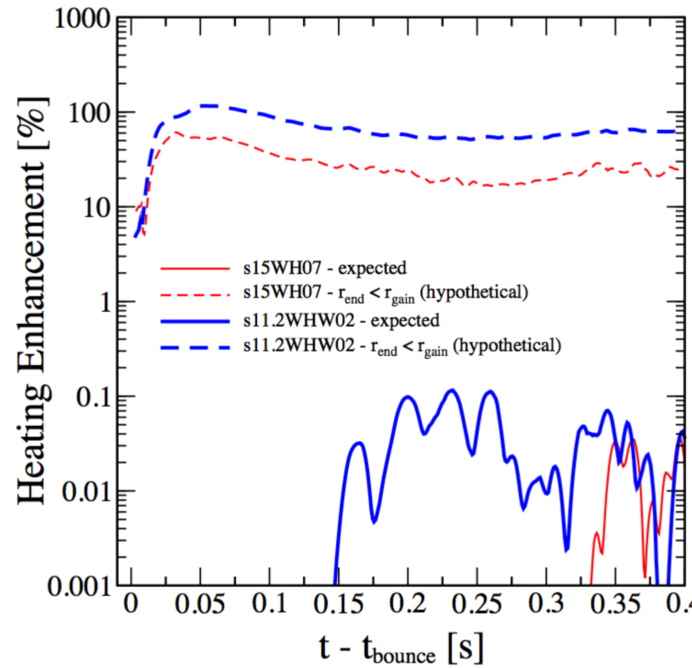


Dasgupta, Fischer, Horiuchi, Liebendoerfer, Mirizzi, Sagert, Schaffner-Bielich (2009)
Simulation by Sagert, Fischer, Hempel, Pagliara, Schaffner-Bielich, Mezzacappa, Thielemann, Liebendoerfer (2008)

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

Fast Conversions = Heating?



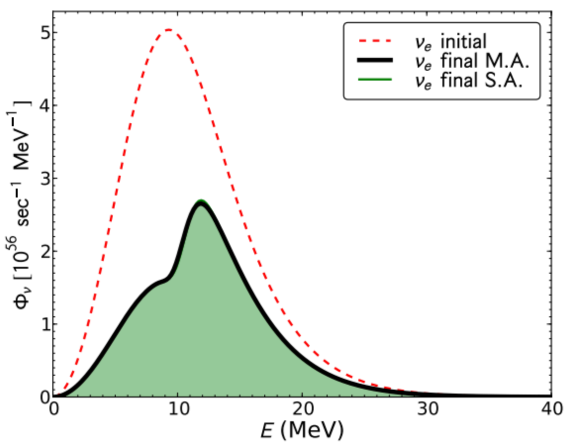


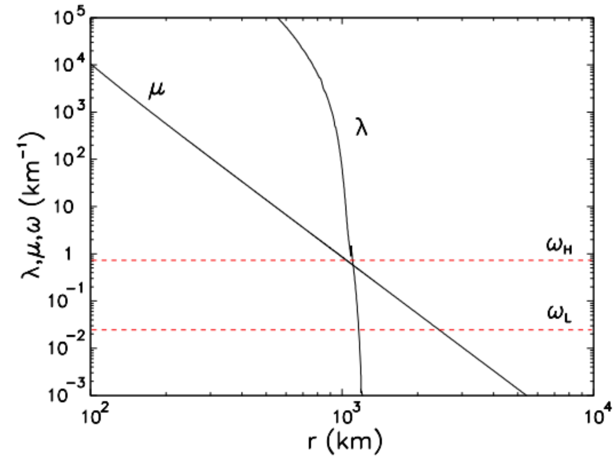
Not possible with slow conversions that occur above r_gain

May be possible if fast conversions that occur below r_gain!

Dasgupta, O'Connor, Ott (2011)

O-Mg-Ne Supernovae

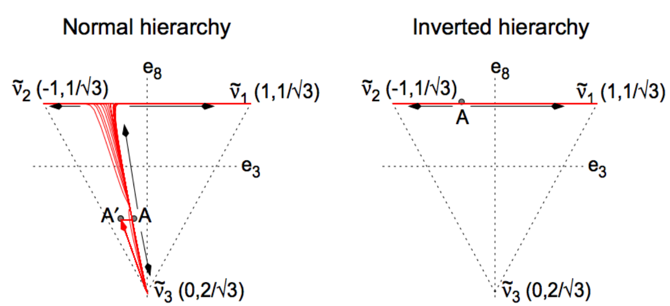




Duan, Fuller, Carlson, Qian (2007)
Duan, Fuller, Carlson, Qian (2008)
Dasgupta, Dighe, Mirizzi, Raffelt (2008)
Cherry, Fuller, Carlson, Duan, Qian (2010)

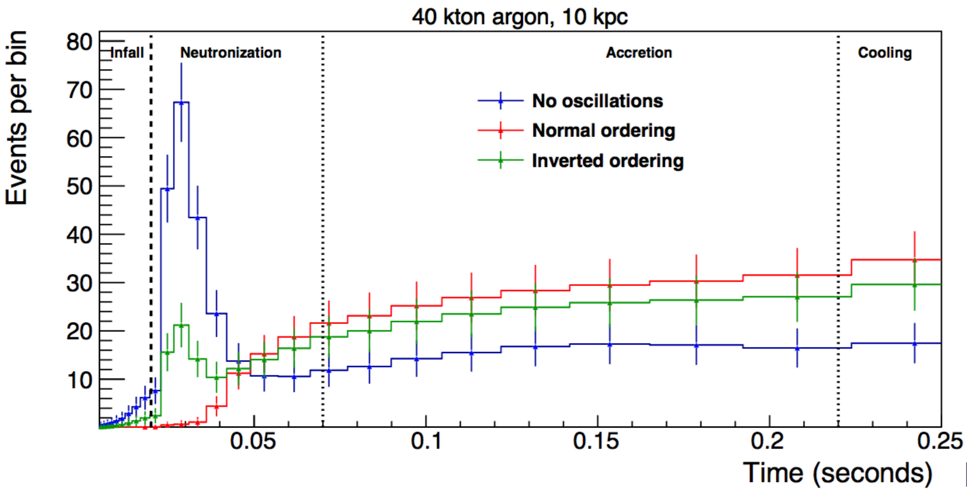
Star has sharply falling matter density, so MSW resonance occurs before (slow) collective effects.

Explained using synchronized MSW



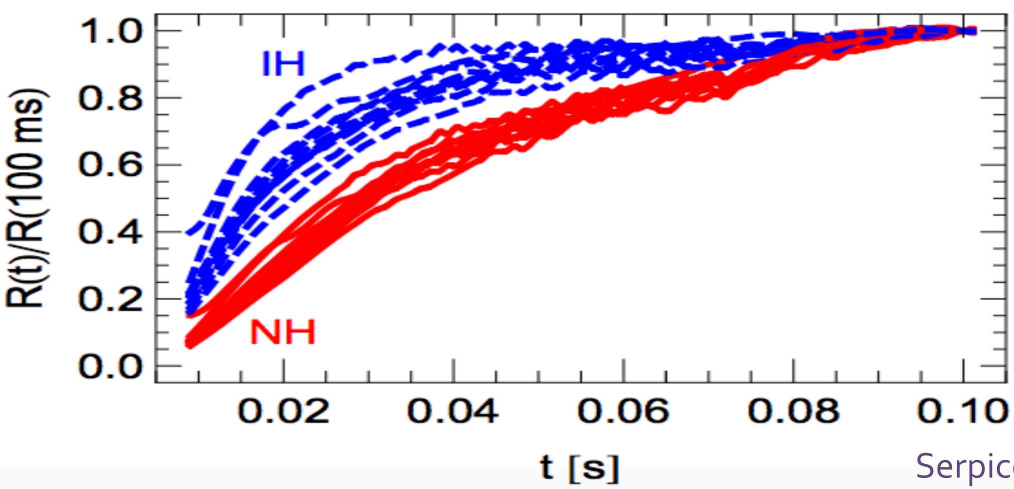
Application of 3 flavor formalism by Dasgupta and Dighe (2007)

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)



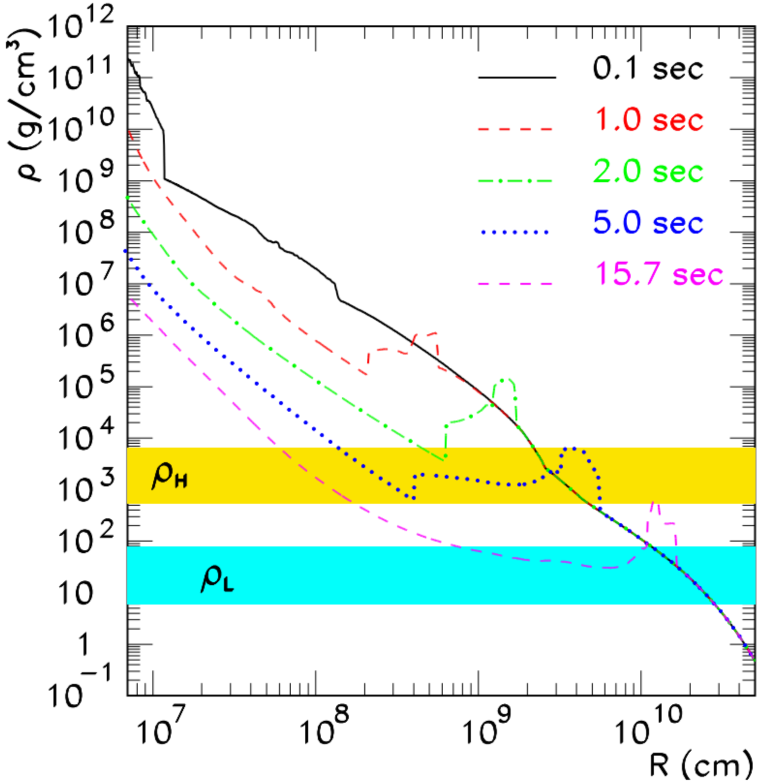
Electron antineutrino signal rises faster for inverted ordering

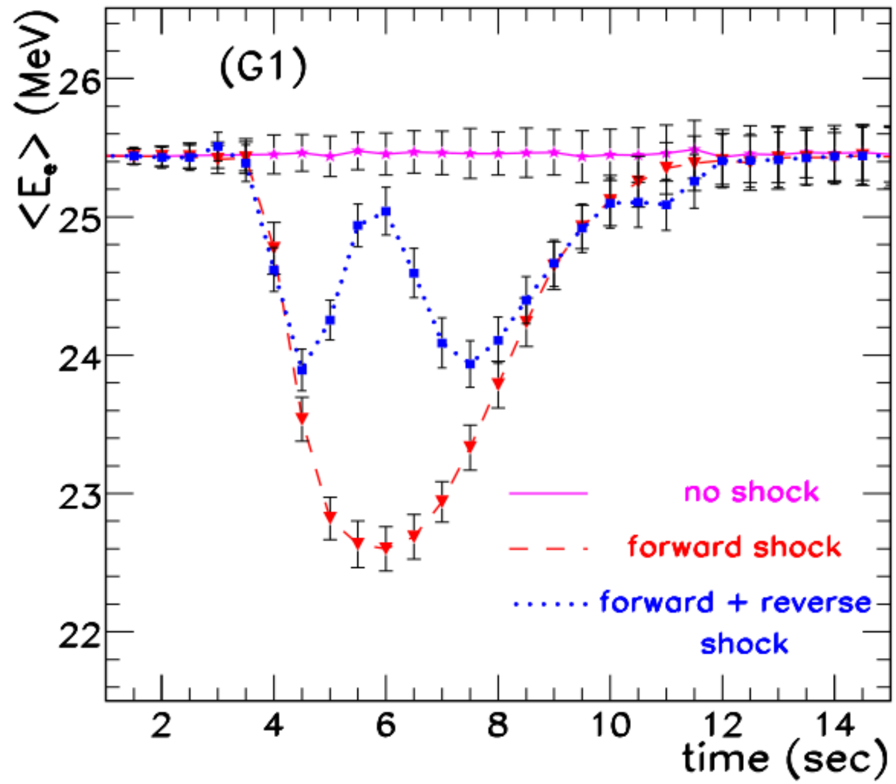
Note: This can change if fast conversions occurs in the accretion phase

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

Neutronization burst can reveal the neutrino mass ordering

Shock Wave

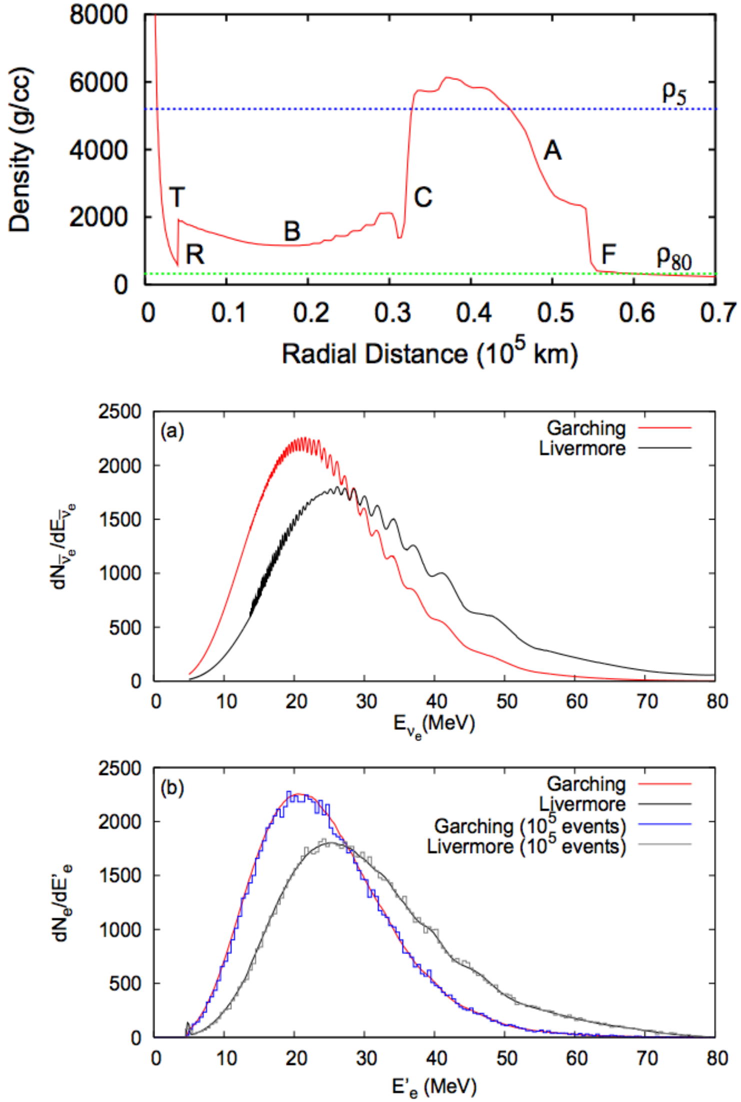




Schirato and Fuller (2002)
Tomas, Kachelriess, Raffelt, Dighe, Janka, Scheck (2004)

Shockwave propagation leads to dips/bumps in observed average E

Phase Effects

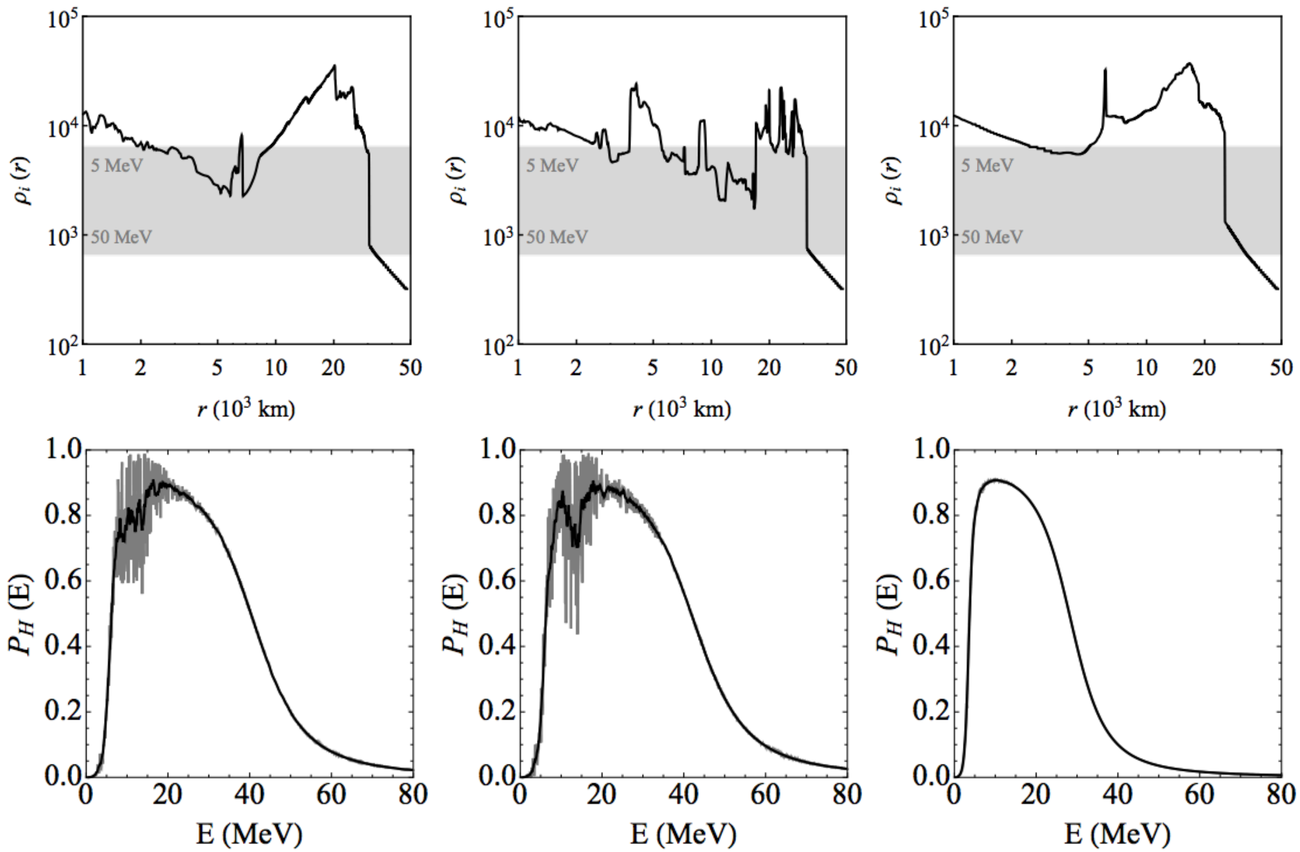


Density profile is not monotonic. There are multiple resonances. Some of them are close enough and lead to interference features with large wavelength in 1/E

Typically gets averaged out due to finite energy resolution

Dasgupta and Dighe (2005)

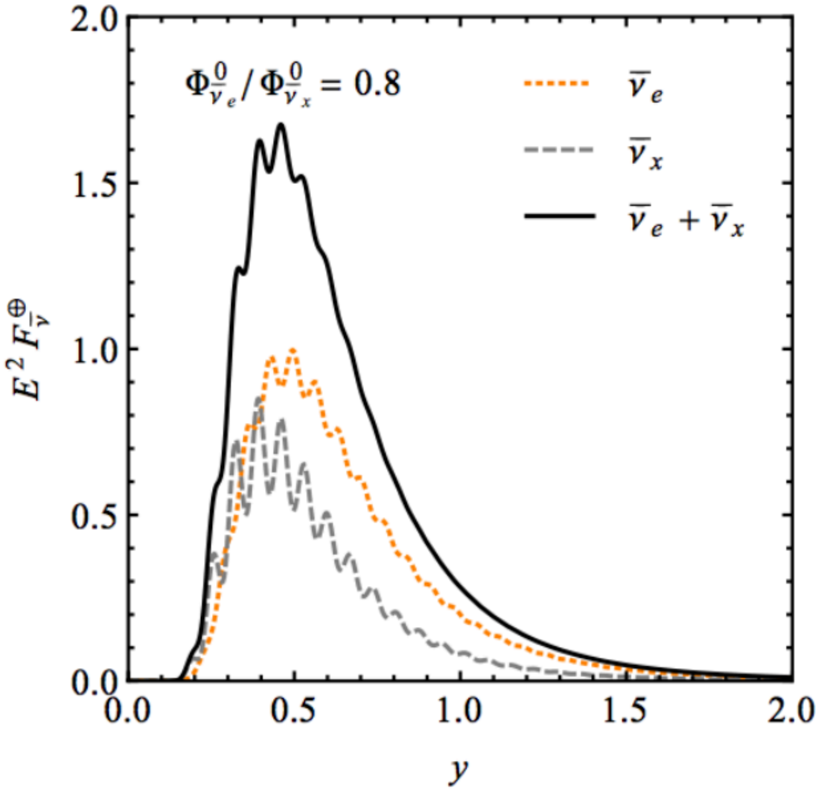
Turbulence

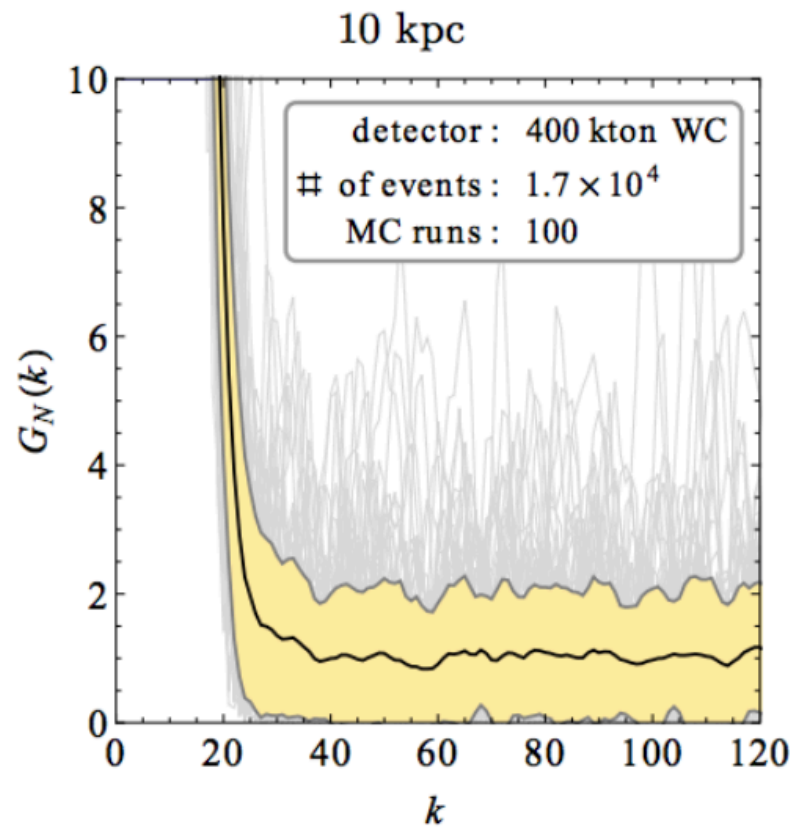


Plot from Borriello, Chakraborty, Janka, Lisi, Mirizzi (2013)
Fogli, Lisi, Mirizzi, Montanino (2006)
Friedland and Gruzinov (2006)

Survival probabilities are highly stochastic quantities

Earth Matter Effects

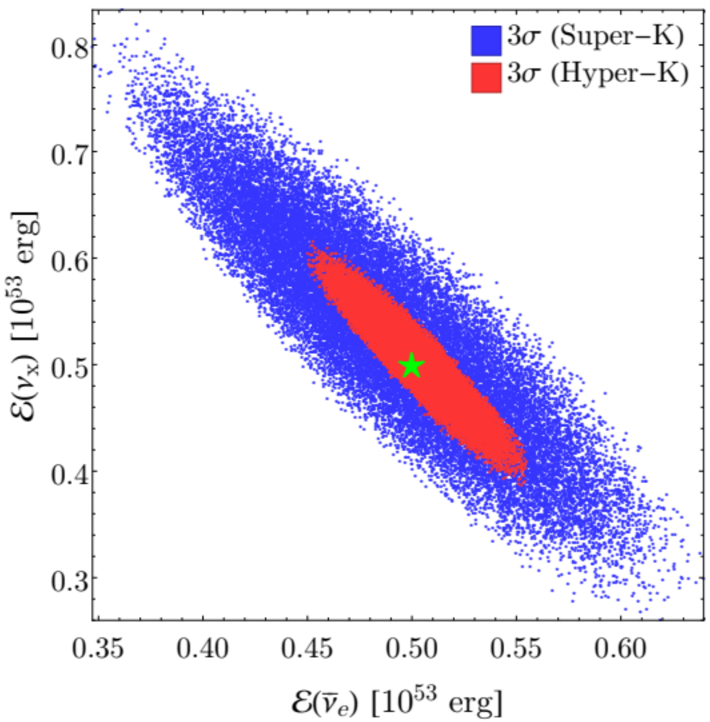




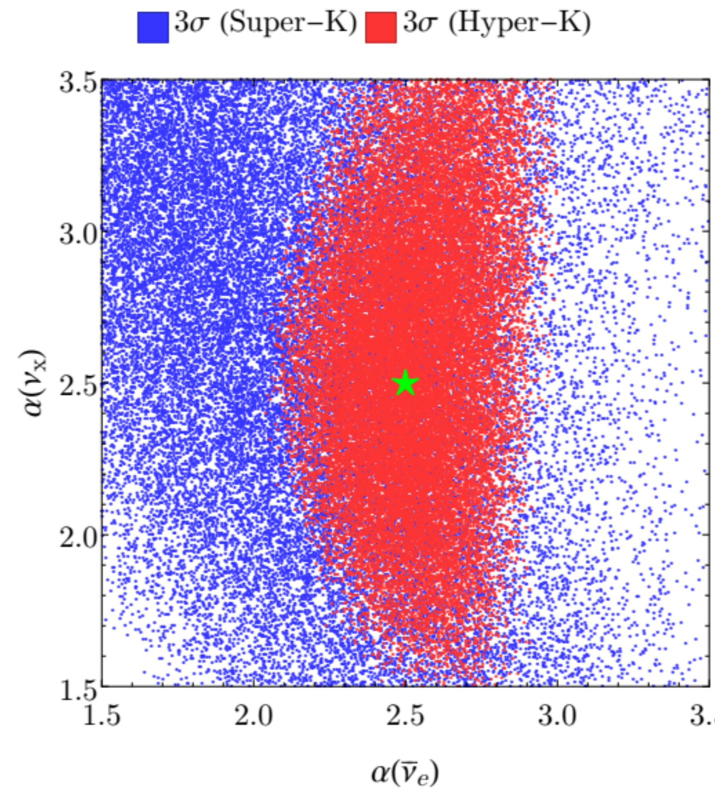
Energy-dependent regeneration in Earth depends on spectral differences between flavors and encodes neutrino mass ordering. May be hard to see.

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

SN Flux Reconstruction



(a) IBD+ES+NCR

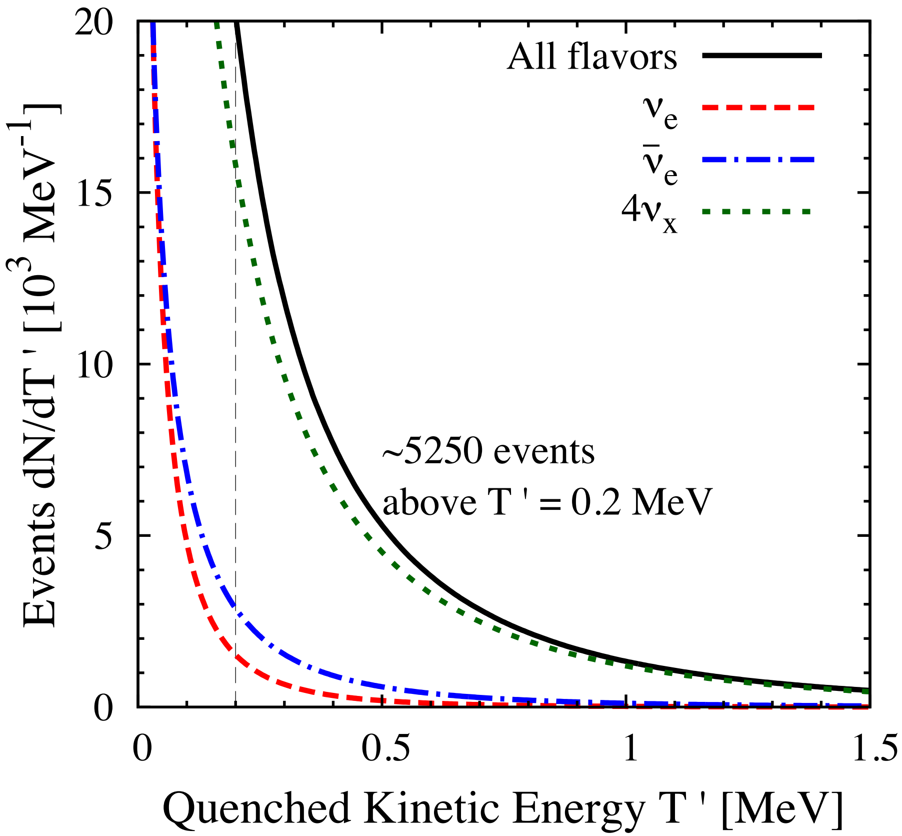


(b) IBD+ES+NCR

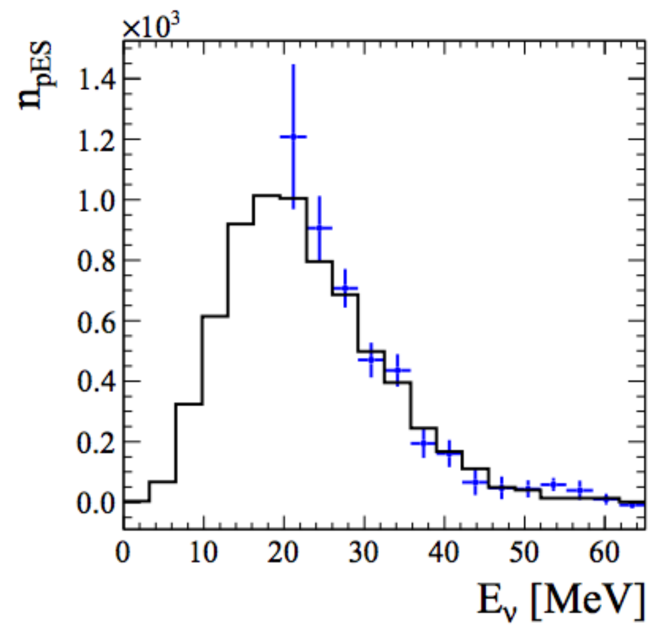
May be possible to reconstruct fluxes with unknown pinching

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 Key



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



Beacom, Farr, Vogel (2003)
Dasgupta and Beacom (2011)

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

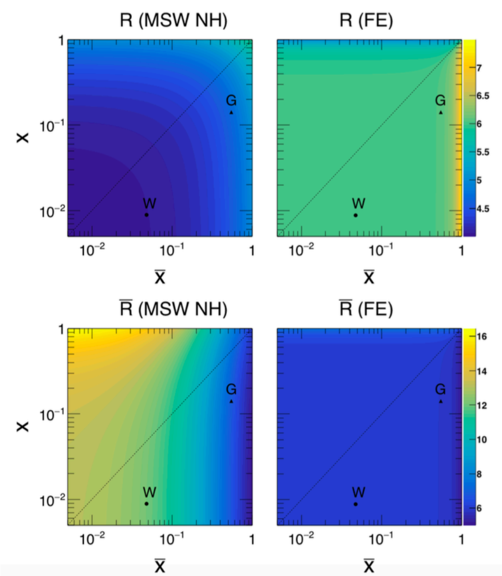
MSW or Collective

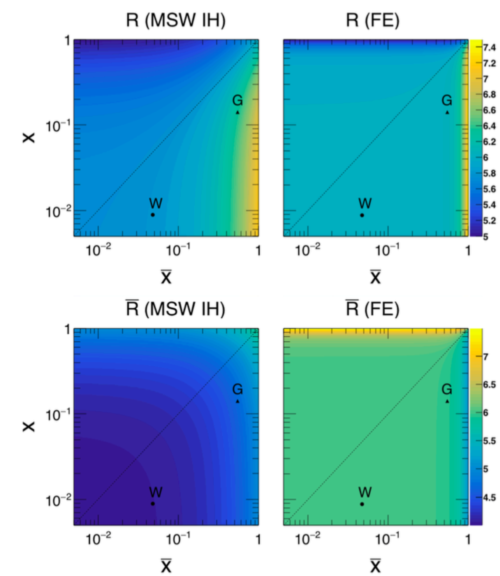
Normal Ordering

Inverted Ordering

$$R = \frac{F_{\mathrm{pES}}}{F_{\mathrm{IB}}}$$

$$\bar{R} = \frac{F_{\mathrm{pES}}}{F_{\mathrm{LAr}}}$$





It may be possible to reject "only MSW" or "full flavor equilibrium" using a combination of JUNO, Hyper-K, and DUNE

… without assuming any details of the SN neutrino spectra

Capozzi, Dasgupta, Mirizzi (2018, to appear)

More Reading

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

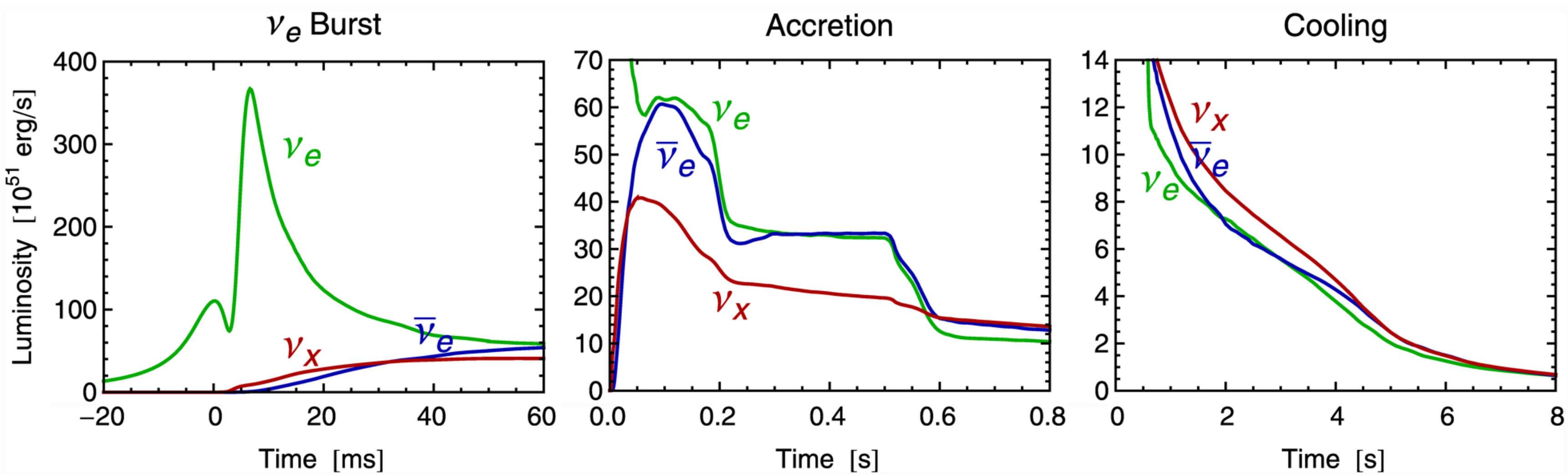
Horiuchi and Kneller
J.Phys. G45 (2018)
Interpretative

Dasgupta
PoS ICHEP2010 (2010)
Short review for the impatient. Oscillation section needs update

Duan, Fuller, Qian
Ann.Rev.Nucl.Part.Sci. 60 (2010)
Covers the "slow" collective effects

Chakraborty, Hansen, Izaguirre, Raffelt
Nucl.Phys. B908 (2016)
Covers SSB effects in detail

Highlights



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

The Takeaway

- Introduction
  - Different phases of SN explosion and different oscillation physics
- Oscillation theory
  - MSW : Adiabatic and Non-adiabatic
  - Collective : Slow/Fast both need spectral crossings
- Non-oscillation observables
  - timing, pointing, mass, lifetime, E-loss, SASI, failed SN, exotica
- Oscillation-sensitive observables
  - Mass ordering, Earth effects, SN properties, equilibration, …
- Upshot
  - Neutrinozation burst : MSW-like
  - Accretion : If crossing exists then fast, else MSW-like
  - Cooling : Spectra are very similar