Neutrino Oscillations and Flavor Transformation in Core Collapse Supernovae

Implications of Neutrino Flavor Oscillations

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a message for the supernova modeling community

Neutrinos mass and flavor mixing is,
in some cases, laboratory-measured, settled physics,
not theoretical speculation.
Including it in models is not optional.

. . . and for the experimental particle physics community . . .

The essential issue in supernova physics
(*collapse to a neutron star with neutrinos carrying away the gravitational binding energy*) is observationally-verified fact.
Supernova neutrino burst detection can give insights complementary to those gleaned from experiment, extending the reach of those experiments.

Neutrino mass physics is a theme common to both

Compact Objects ***(supernovae; neutron stars; holes; etc. . .)***

Cosmology ***(structure formation; dark matter, etc. . .)***

Synergy between laboratory/observational neutrino physics and the continuing revolution in observational astronomy

Neutrino Flavor Transformation in Core Collapse Supernovae and Early Universe

Coherent Limit

– neutrino elastic forward scattering

(above neutrino sphere/ post decoupling)

coherent evolution + fluctuation-induced flavor de-polarization

De-Coherent Limit

-neutrino inelastic scattering dominated

-(core, high density regimes in SN/ well above BBN scale)

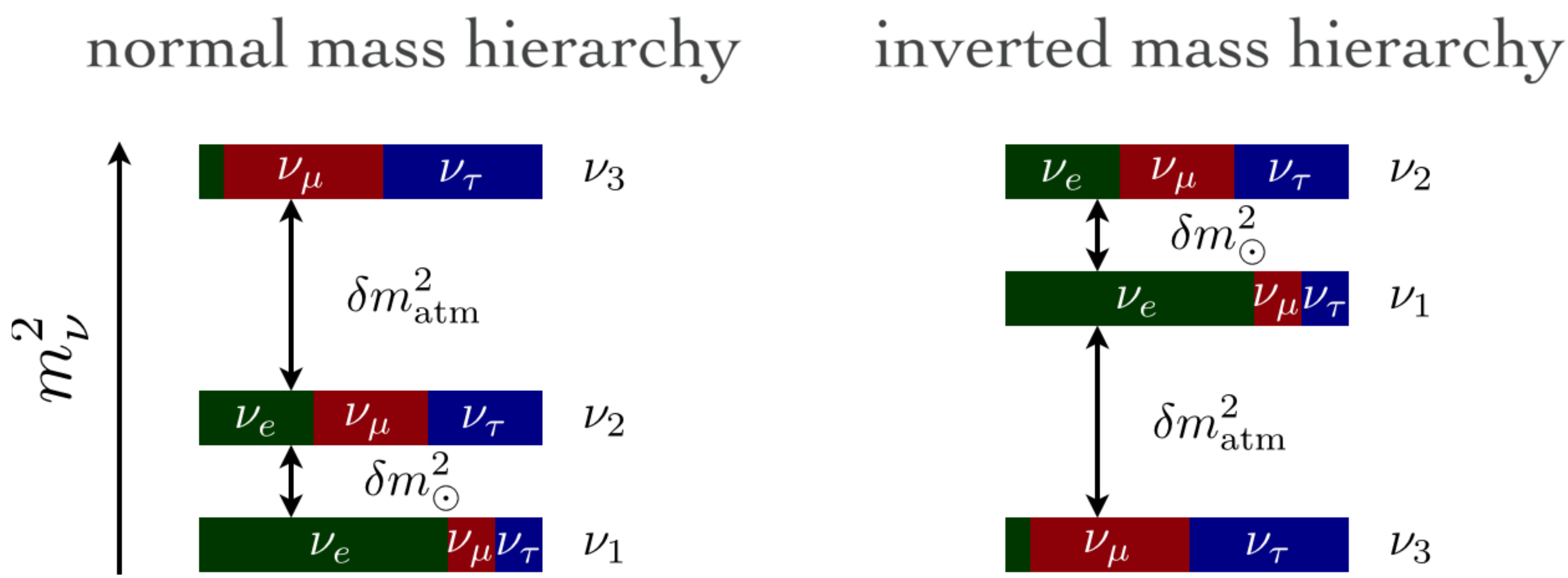
Neutrino Mass: what we know and don't know

We know the *mass-squared* differences:

$$\begin{cases} \delta m_\odot^2 \approx 8 \times 10^{-5}\,\mathrm{eV}^2 \\ \delta m_{\mathrm{atm}}^2 \approx 3 \times 10^{-3}\,\mathrm{eV}^2 \end{cases}$$

$$e.g., \quad \delta m_{21}^2 \equiv m_2^2 - m_1^2$$

We *do not* know the *absolute masses* or the *mass hierarchy*:



$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = U_m \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

Maki-Nakagawa-Sakata matrix

$$U_m = U_{23} U_{13} U_{12}$$

$$U_{23} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

$$U_{13} \equiv \begin{pmatrix} \cos\theta_{13} & 0 & e^{i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}$$

$$U_{12} \equiv \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

4 parameters

we know θ_{12} & θ_{23}

we need δ & θ_{13}

Neutrinos Dominate the Energetics of Core Collapse Supernovae

Explosion only ~1% of neutrino energy

- **Total optical + kinetic energy, 10^{51} ergs**
- **Total energy released in Neutrinos, 10^{53} ergs**

10% of star's rest mass!

$$E_{\mathrm{GRAV}} \approx \frac{3}{5}\frac{\mathrm{G}\,M_{\mathrm{NS}}^2}{R_{\mathrm{NS}}} \approx 3\times 10^{53}\mathrm{ergs}\left[\frac{M_{\mathrm{NS}}}{1.4\mathrm{M}_{\mathrm{sun}}}\right]^2\left[\frac{10\ \mathrm{km}}{R_{\mathrm{NS}}}\right]$$

Neutrino diffusion time, $\tau_\nu \approx 2\ \mathrm{s}$ **to** $10\ \mathrm{s}$

$$L_\nu \approx \frac{1}{6}\frac{GM_{\mathrm{NS}}^2}{R_{\mathrm{NS}}}\frac{1}{\tau_\nu} \approx 4\times 10^{51}\mathrm{ergs\ s}^{-1}$$

MASS in $M_\odot$	Main Seq. Entropy per baryon s/k_B	Collapse Entropy per baryon s/k_B	Iron core mass in $M_\odot$	Instability Mechanism	Fraction of rest mass radiated as neutrinos	Neutrino Trapping / Thermal equilibrium
10 to ~ 100	~ 10	~ 1	~ 1.4	Electron capture / Feynman-Chandrasekhar G.R. instab.	~ 10% Iron core mass	Yes
~ 100 to ~ 10^4	~ 100	~ 100	NONE	$e^{\pm}$ pair instability	~ 10% C/O burning core	Yes
~ 10^4 to ~ 10^8	~ 1000 no main seq.	~ 1000	NONE	Feynman-Chandrasekhar G.R. Instability	~ 5%	No

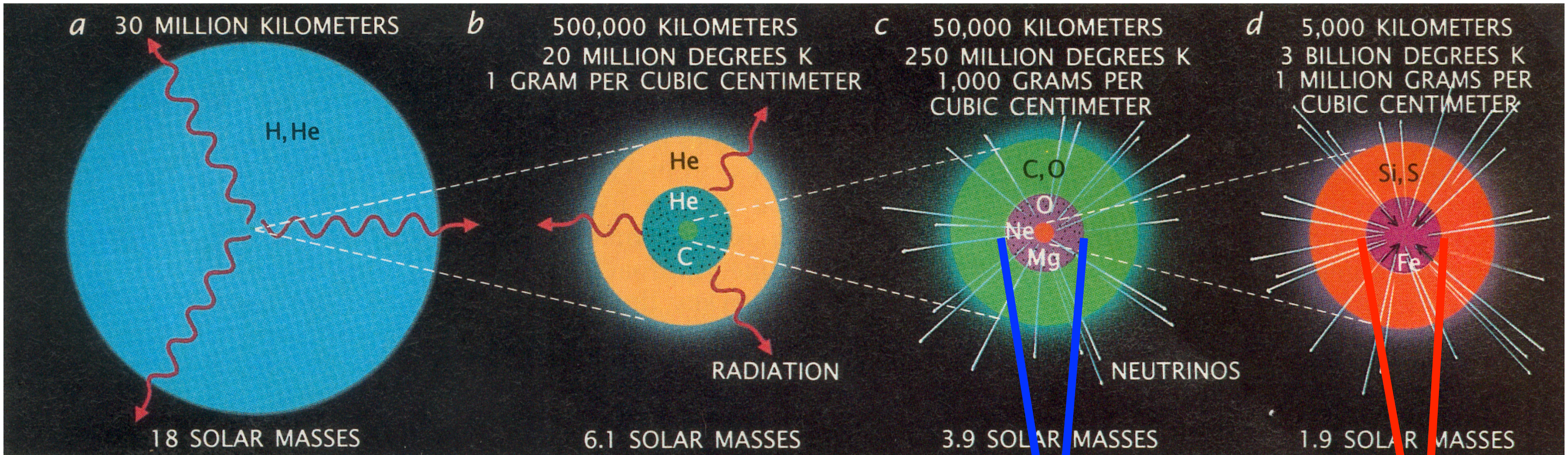
The Core Collapse Supernova Phenomenon is Exquisitely Sensitive to Flavor Changing Processes and New Neutrino Physics:

- Gravitational collapse results in high electron and ν_e Fermi Energies (representing ~ 10^{57} units of e-lepton number); μ/τ charged leptons are absent and the corresponding neutrinos are pair-produced so they carry no net lepton number.
  Any process that changes flavor $\nu_e \rightarrow \nu_{\mu/\tau/s}$ will open phase space for electron capture as well as reducing e-lepton number.

- Later, energy (10% of the core's rest mass) is in seas of active neutrinos of all flavors. Entropy and lepton number transported by neutrinos.

- Neutron/proton ratio (crucial for nucleosynthesis) and energy deposition determined by:

$$\nu_e + n \rightleftharpoons p + e^- \qquad \bar{\nu}_e + p \rightleftharpoons n + e^+$$

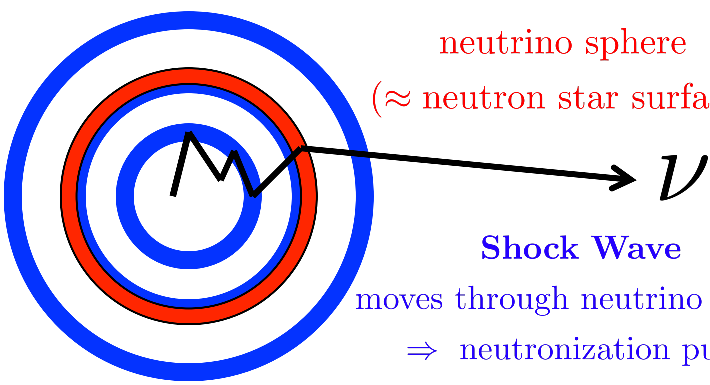


O – Ne – Mg
Core Collapse
$8 - 12\,\mathrm{M}_\odot$

ν self coupling – induced
collective oscillations, spectral swaps
at shock breakout, neutronization pulse,
$L_\nu \sim 10^{53}\,\mathrm{erg\,s^{-1}}$

Fe (iron)
Core Collapse
$> 12\,\mathrm{M}_\odot$

ν self coupling – induced
collective oscillations, spectral swaps
at late times, $t_{\mathrm{pb}} > 3\,\mathrm{s}$,
$L_\nu \sim 10^{51}\,\mathrm{erg\,s^{-1}}$



neutrino sphere
($\approx$ neutron star surface)

Shock Wave
moves through neutrino sphere
$\Rightarrow$ neutronization pulse

ν_e flux $\gg$ $\bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$ fluxes

The advent of supercomputers has allowed us in the last few years to follow neutrino flavor transformation in core collapse supernovae, including the first self-consistent treatment of **nonlinearity** stemming from neutrino-neutrino forward scattering.

The results are startling. Despite the small measured neutrino mass-squared differences, **collective** neutrino flavor transformation can take place deep in the supernova envelope;

~~MSW~~ does not work in some important regimes in supernovae.

Instead we discovered something very different . . .
H. Duan, G. Fuller, J. Carlson, Y.-Z. Qian, PRD D74, 105014 (2006)

A phenomenon which can occur in many different environments in the different varieties of core collapse supernova :

The neutrino spectral swap/split.

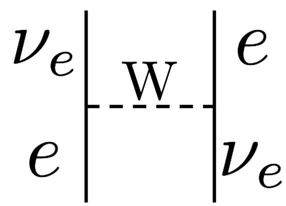
This phenomenon produces a distinctive signature in a supernova neutrino burst signal which, if detected, is usually a dead give away for the neutrino mass hierarchy.

Coherent Flavor Evolution for Neutrino i

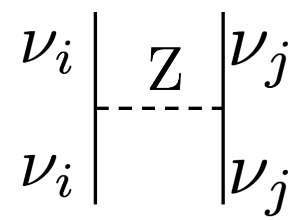
$$\psi_{\nu,i} = \begin{bmatrix} \text{amplitude to be } \nu_{\mathrm{e}} \\ \text{amplitude to be } \nu_{\mu,\tau} \end{bmatrix}$$

$$i\,\frac{\partial}{\partial t}\,\psi_{\nu,i} \;=\; \left(\mathcal{H}_{\mathrm{vac},i} + \mathcal{H}_{\mathrm{e},i} + \mathcal{H}_{\nu\nu,i}\right)\psi_{\nu,i}$$

neutrino-electron charged current forward exchange scattering



neutrino-neutrino neutral current forward scattering



Neutrino Self Coupling - the source of nonlinearity

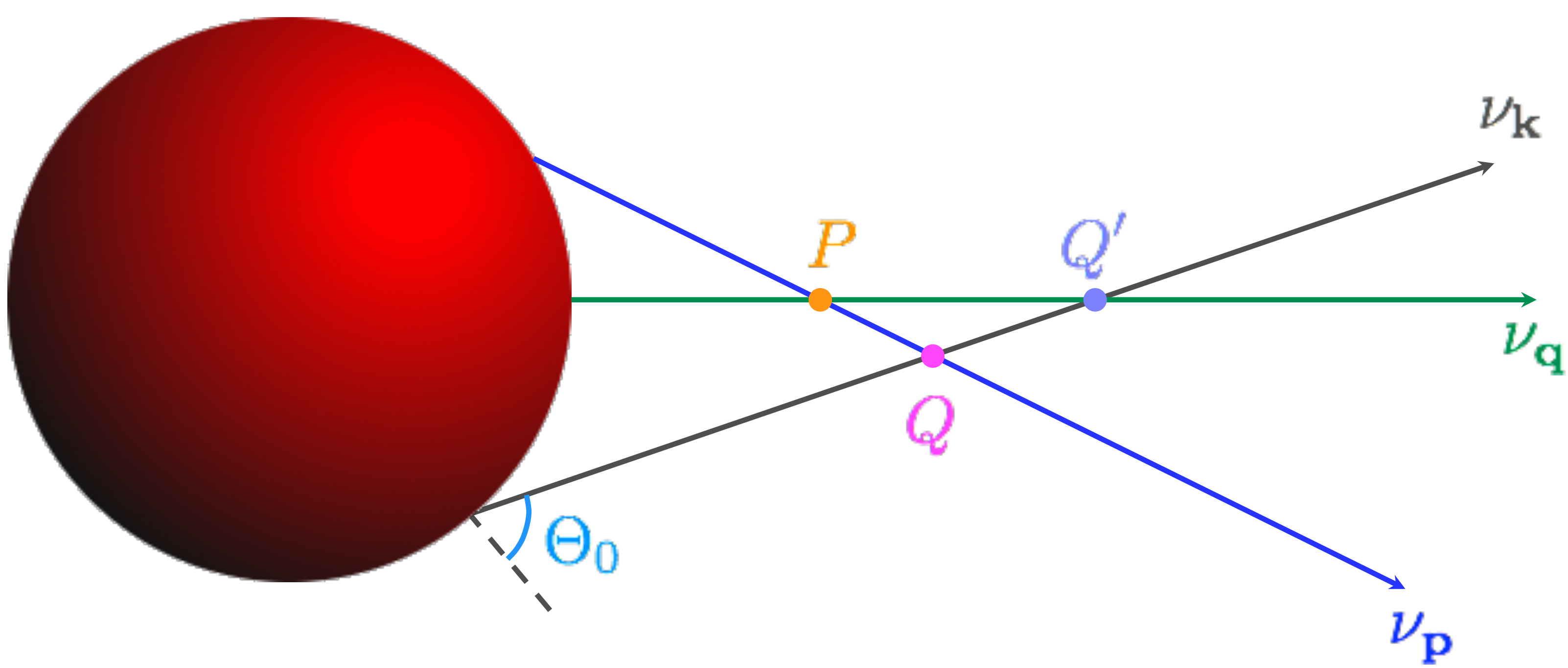
$$\mathcal{H}_{\nu\nu,i} \equiv \sqrt{2}G_{\mathrm{F}} \sum_j \left(1 - \hat{\mathbf{k}}_i \cdot \hat{\mathbf{k}}_j\right) n_{\nu,j}\psi_{\nu,j}\psi^{\dagger}_{\nu,j}$$

$$-\sqrt{2}G_{\mathrm{F}} \sum_j \left(1 - \hat{\mathbf{k}}_i \cdot \hat{\mathbf{k}}_j\right) n_{\bar{\nu},j}\psi_{\bar{\nu},j}\psi^{\dagger}_{\bar{\nu},j}$$

now self-consistently couple flavor evolution

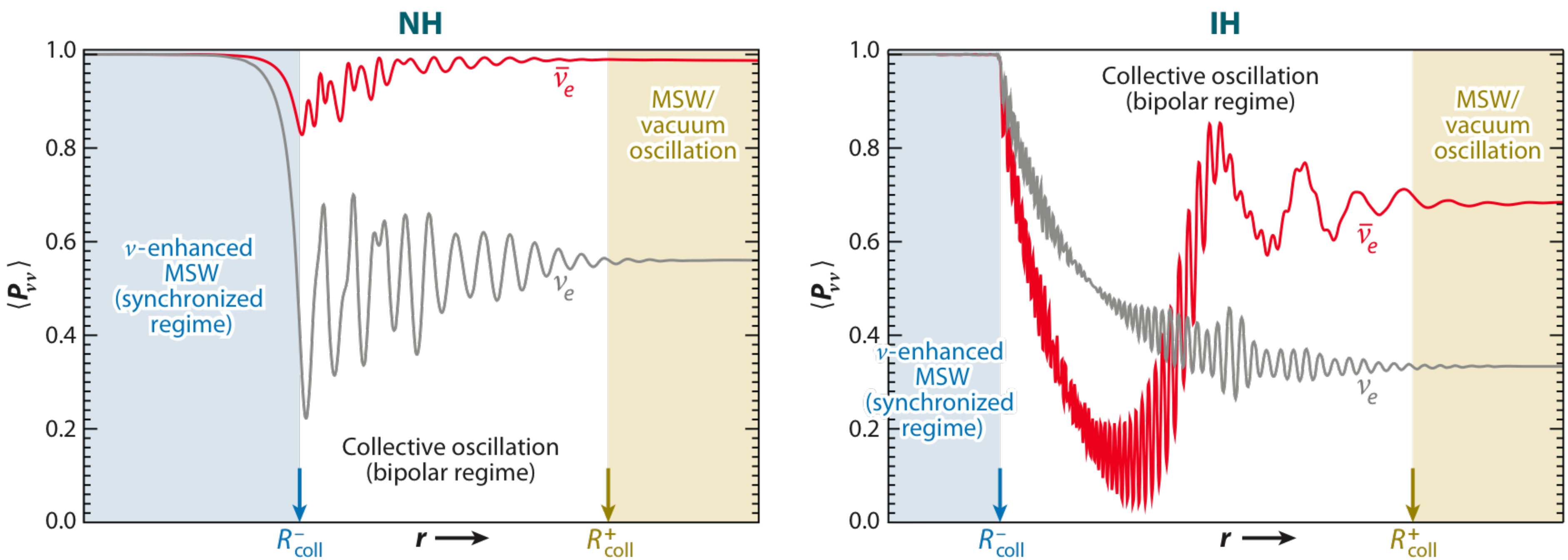
on all neutrino trajectories . . .

- Anisotropic, nonlinear quantum coupling of all neutrino flavor evolution histories

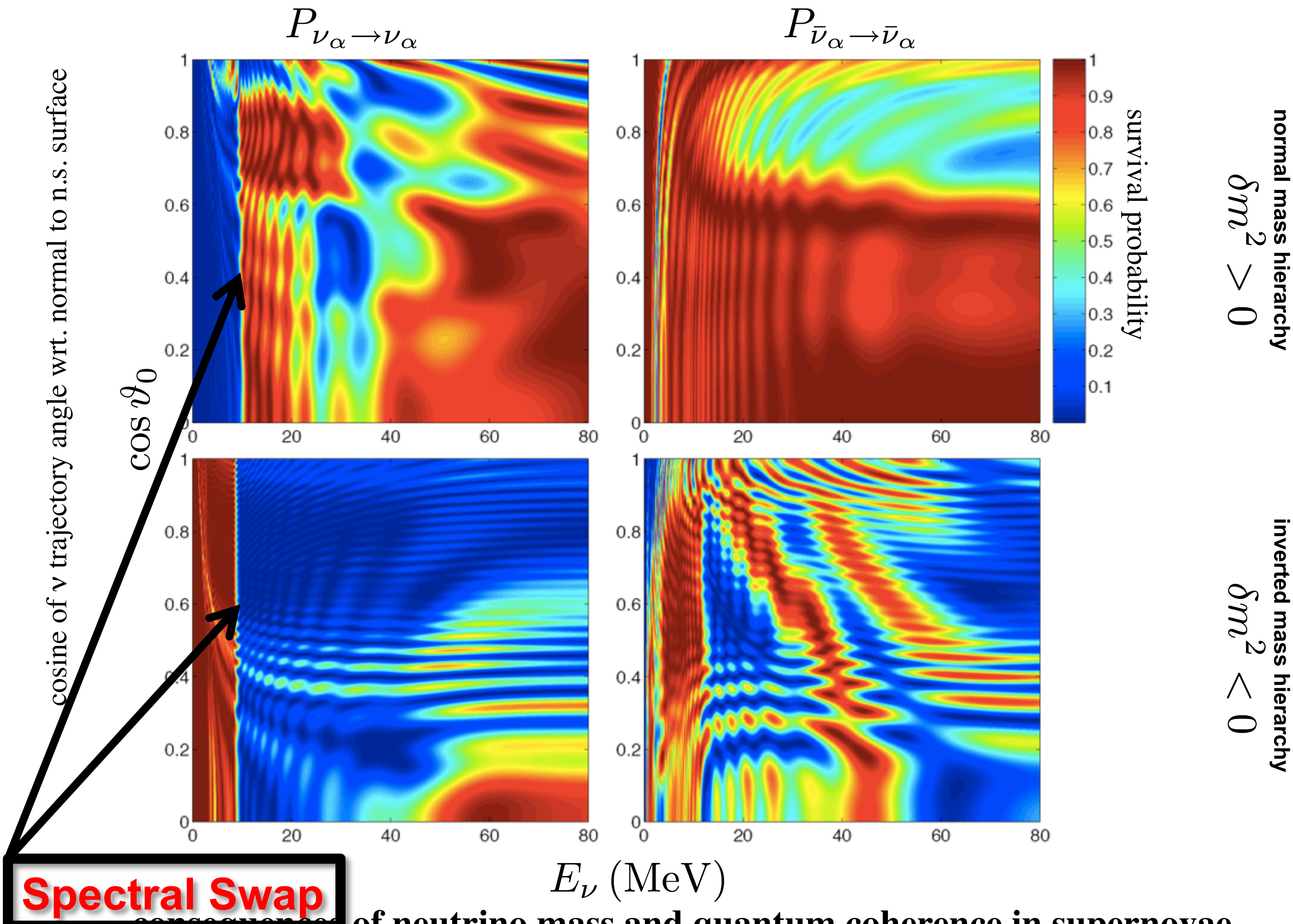


Must solve many *millions* of coupled, nonlinear partial differential equations!!

Neutrino Oscillation Regimes in Core Collapse Supernovae



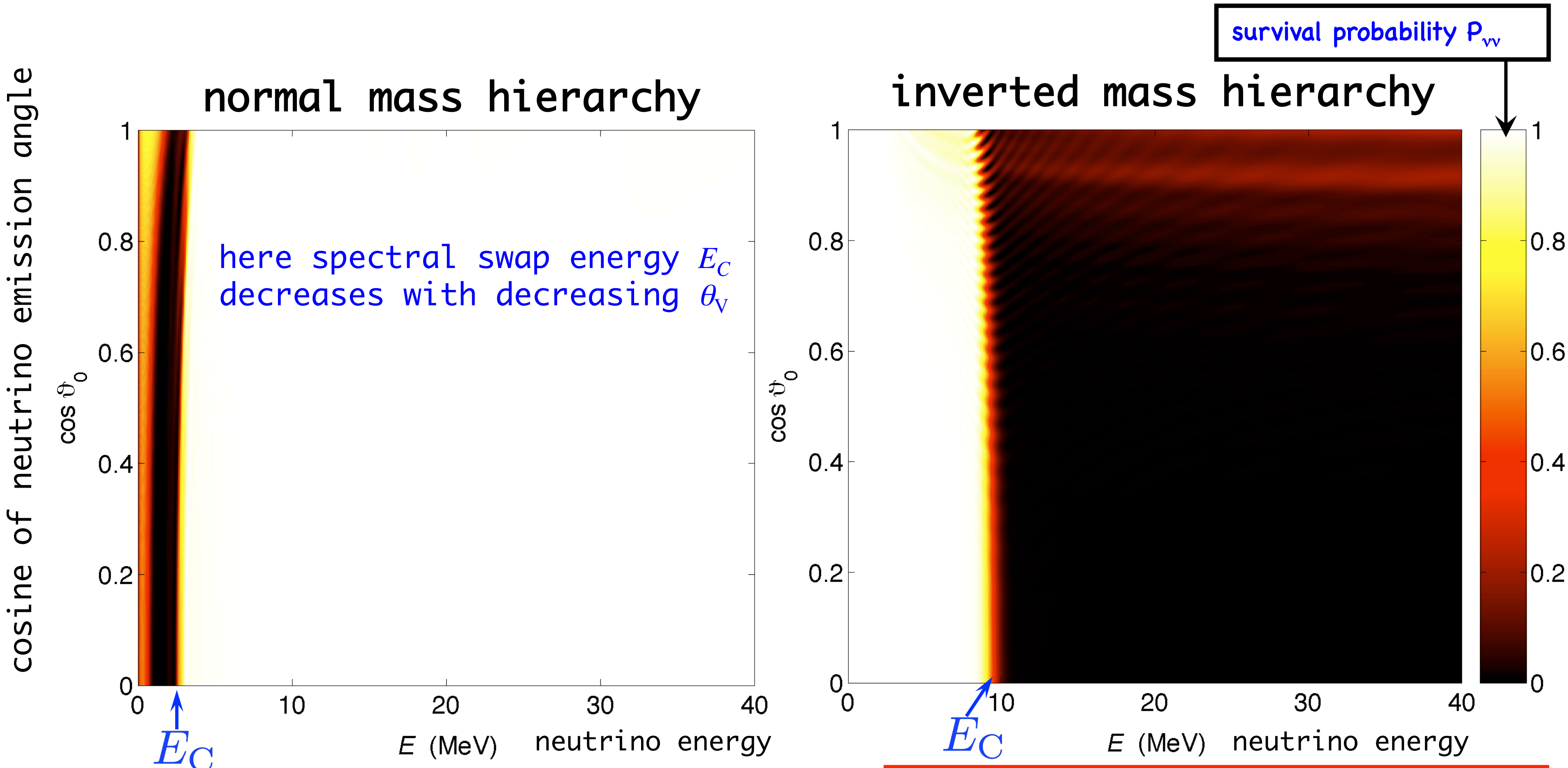
Duan, Huaiyu, et al. 2010.
Annu. Rev. Nucl. Part. Sci 60:569–594.



consequences of neutrino mass and quantum coherence in supernovae

H. Duan, G. M. Fuller, J. Carlson, Y.-Z. Qian, Phys. Rev. Lett. **97**, 241101 (2006) **astro-ph/0606616**

The ν_e - $\nu_{\mu/\tau}$ Spectral Swap - *a mass hierarchy signal ?*



vacuum mixing angle $\theta_V = 0.01$

vacuum mixing angle $\theta_V = 10^{-9}$

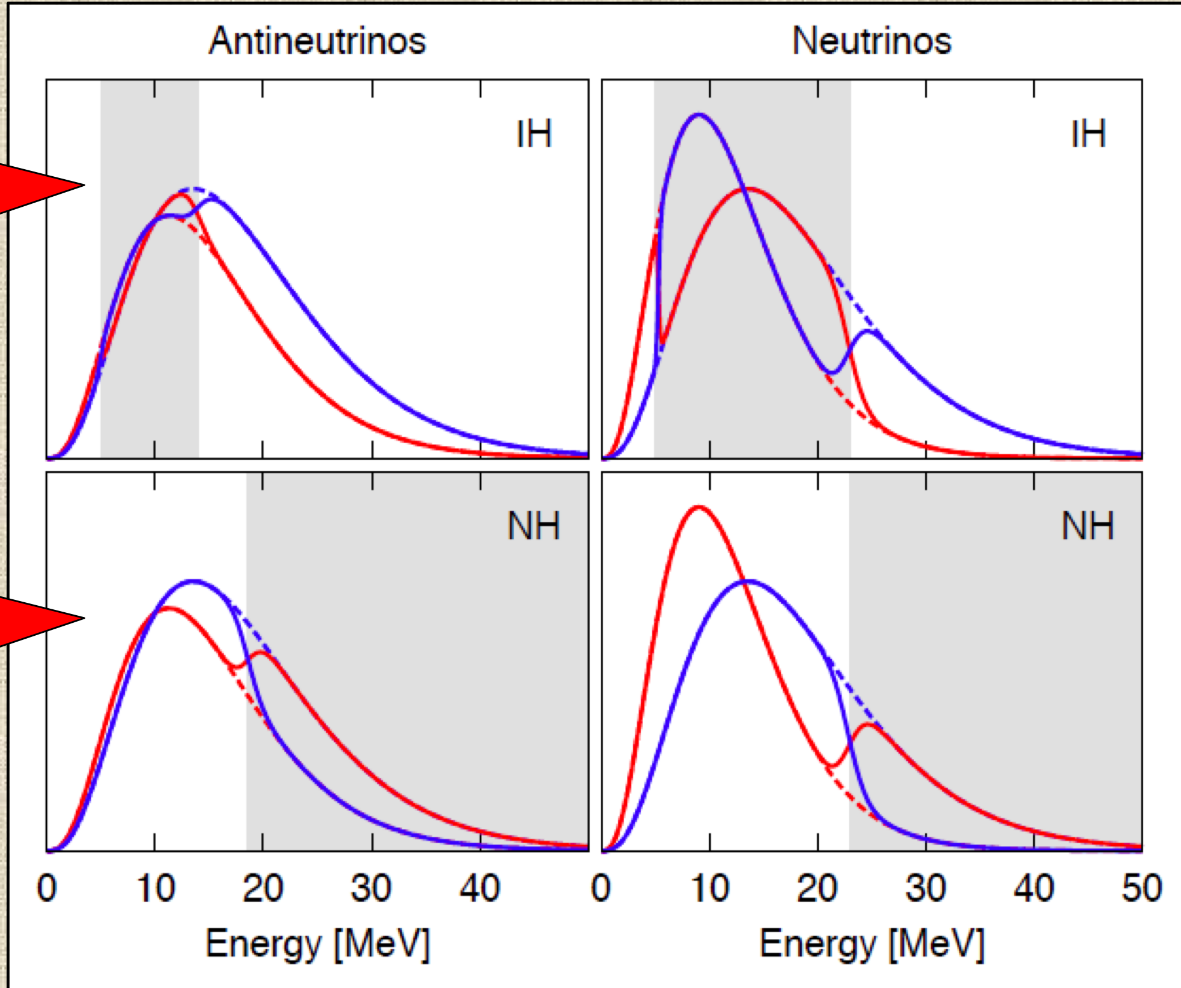
$$\theta_V \approx \theta_{13}$$

swap has its origin in nonlinear neutrino self-coupling

Multiple Spectral Splits

Spectral Splits in Inverted Hierarchy

Spectral Splits in Normal Hierarchy



Dasgupta, Dighe, Raffelt and Smirnov, arXiv: 0904.3542 (PRL)

Though core collapse supernovae are very complicated and have various epochs/environments with vastly different values of neutrino energy spectra/fluxes and matter densities/distributions, we find this swap phenomenon in many of them.

Think of the earth's atmosphere: very complicated, with water vapor and solar heating, and radiation transport, and the ocean, all played out on the surface of a rotating sphere. Nevertheless, there are phenomena like thunderstorms which occur and which have a life and characteristics of their own, independent of the model for the atmosphere . . .

The neutrino spectral swap may be like this.

	Neutronization Burst Epoch ~ 10ms	Shock Reheating Epoch ~ 100ms - 4s	Late Explosion Epoch ~ 4s - 10s (Shock reaches MSW resonance regions)	Neutrino Driven Wind Epoch > 4s
O-Ne-Mg Normal Mass Hierarchy	Multiple flavor swaps formed by Synchronous MSW and the Regular Precession Mode ?	? ?	? ?	? ?
O-Ne-Mg Inverted Mass Hierarchy	Single flavor swap formed by the Synchronous MSW and the Regular Precession Mode ?	? ?	? ?	? ?
Iron Core Collapse Normal Mass Hierarchy	? ?	MSW Effect in outer Envelope? MSW Effect in outer Envelope?	? Shock and turbulence MSW modification. Flavor depolarization of ν's .	Regular Precession Mode produces multiple flavor swaps. Swap energies sensitive to θ_{13} . ?
Iron Core Collapse Inverted Mass Hierarchy	? ?	Flavor Evolution leads to Swaps Bipolar Flavor Evolution and turbulence leads to a combination of Swaps and decoherence..	? Shock and turbulence MSW modification. Flavor depolarization of $\bar{\nu}$'s .	IMH flavor instability and the Regular Precession Mode produce multiple flavor swaps. ?
Pair Instability Collapse Normal Mass Hierarchy	? ?	? ?	? ?	? ?
Pair Instability Collapse Inverted Mass Hierarchy	? ?	? ?	? ?	? ?
Direct Black Hole/ Accretion Disk Normal Mass Hierarchy	? ?	? ?	? ?	? ?
Direct Black Hole/ Accretion Disk Inverted Mass Hierarchy	? ?	? ?	? ?	? ?

J. J. Cherry

But . . .

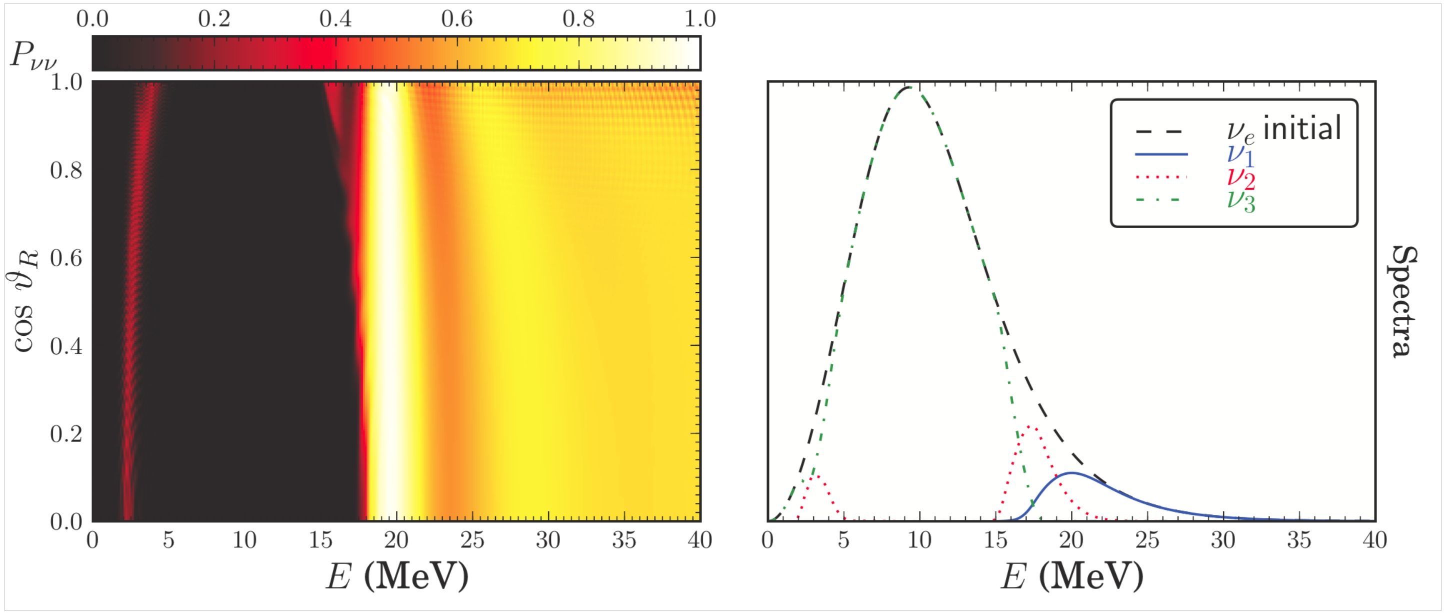
there are three neutrinos, not two,
and the world of neutrinos is fundamentally
3X3 !!

First multi-angle 3X3 Simulation

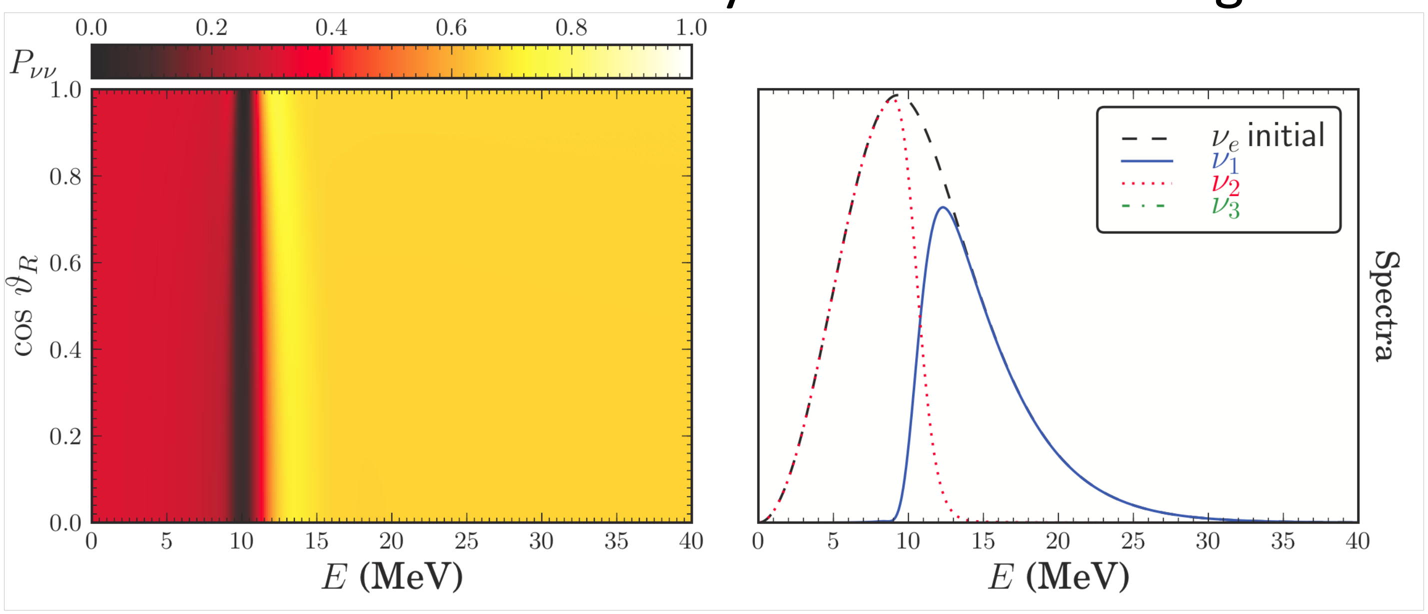
J. Cherry, G. Fuller, J. Carlson, H. Duan, Y.-Z. Qian arXiv:1006.2175 [astro-ph.HE]
Phys. Rev. D **82**, 085025 (2010)

H. Duan, A. Friedland, arXiv:1006.2359 [hep-ph],
Phys.Rev.Lett. **106**, 091101 (2011).

Normal Mass Hierarchy - 3X3 multi-angle



Inverted Mass Hierarchy - 3X3 multi-angle



$$\theta_{13} = 0.1$$

N.H. =
Pair of flavor swaps
corresponding to solar & atmospheric mass splitting scales

I.H. =
Single swap
corresponding to solar mass splitting scale

$$\theta_{13} = 10^{-3}$$

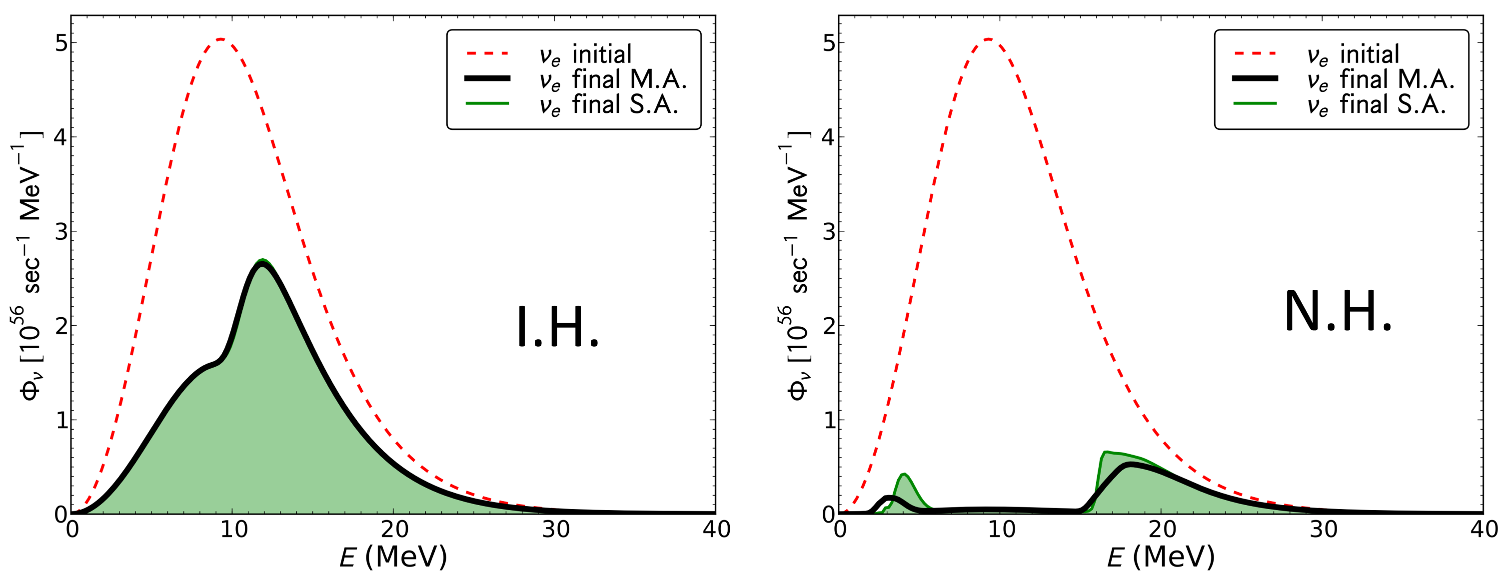
N.H. =
Single swap
at solar scale; identical to I.H.

Observing this swap won't distinguish between hierarchies

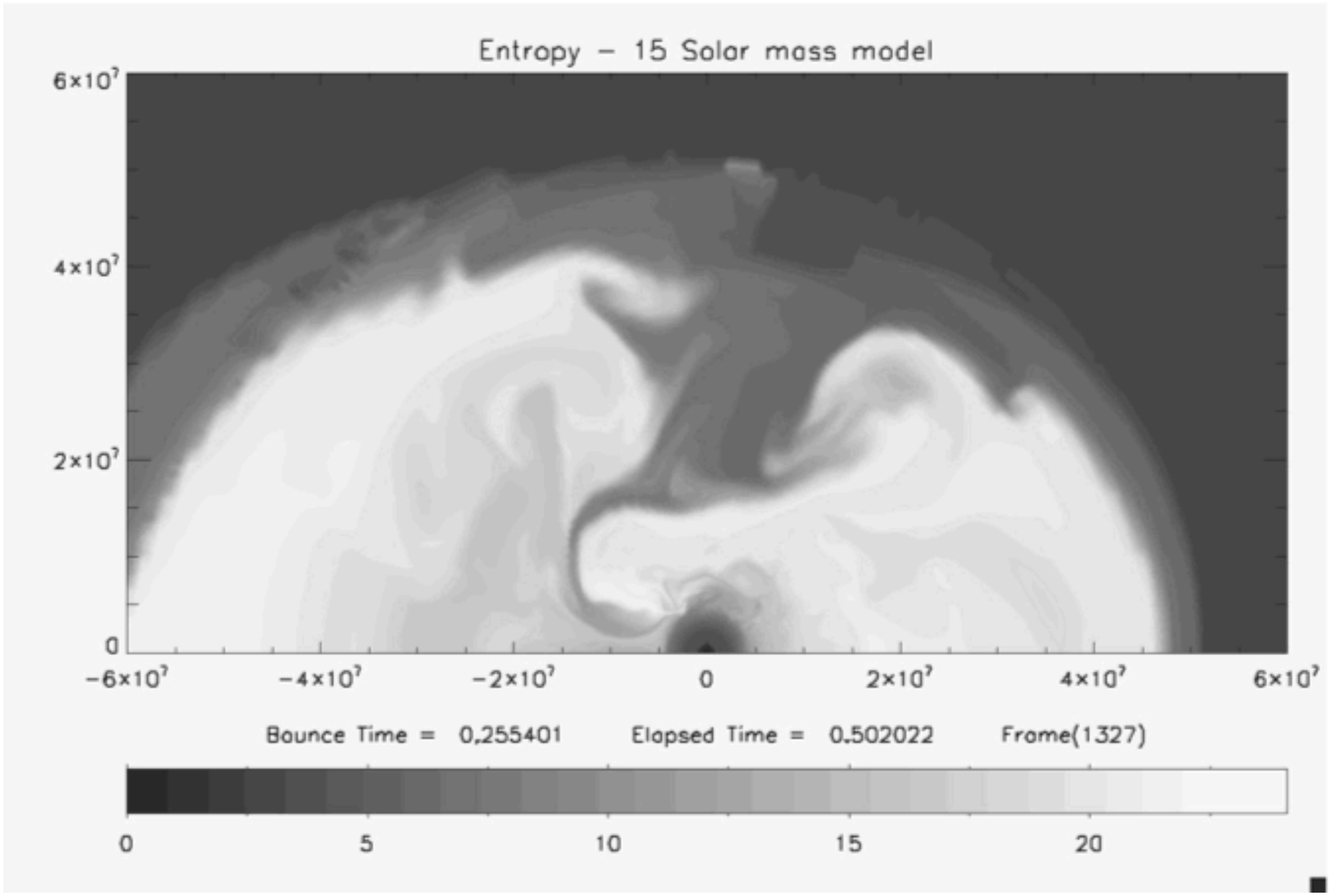
Single-angle (S.A.) reproduces the full multi-angle (M.A.) results well for the I.H.
- Not so for the N.H., where swap energies decrease significantly with M.A.

$$\nu_3/\nu_2 \text{ swap } E_\nu = 12.5\,\mathrm{MeV} \text{ in S.A.}, \; = 10\,\mathrm{MeV} \text{ in M.A.}$$

$$\nu_2/\nu_1 \text{ swap } E_\nu = 15\,\mathrm{MeV} \text{ in S.A.}, \; = 13.5\,\mathrm{MeV} \text{ in M.A.}$$

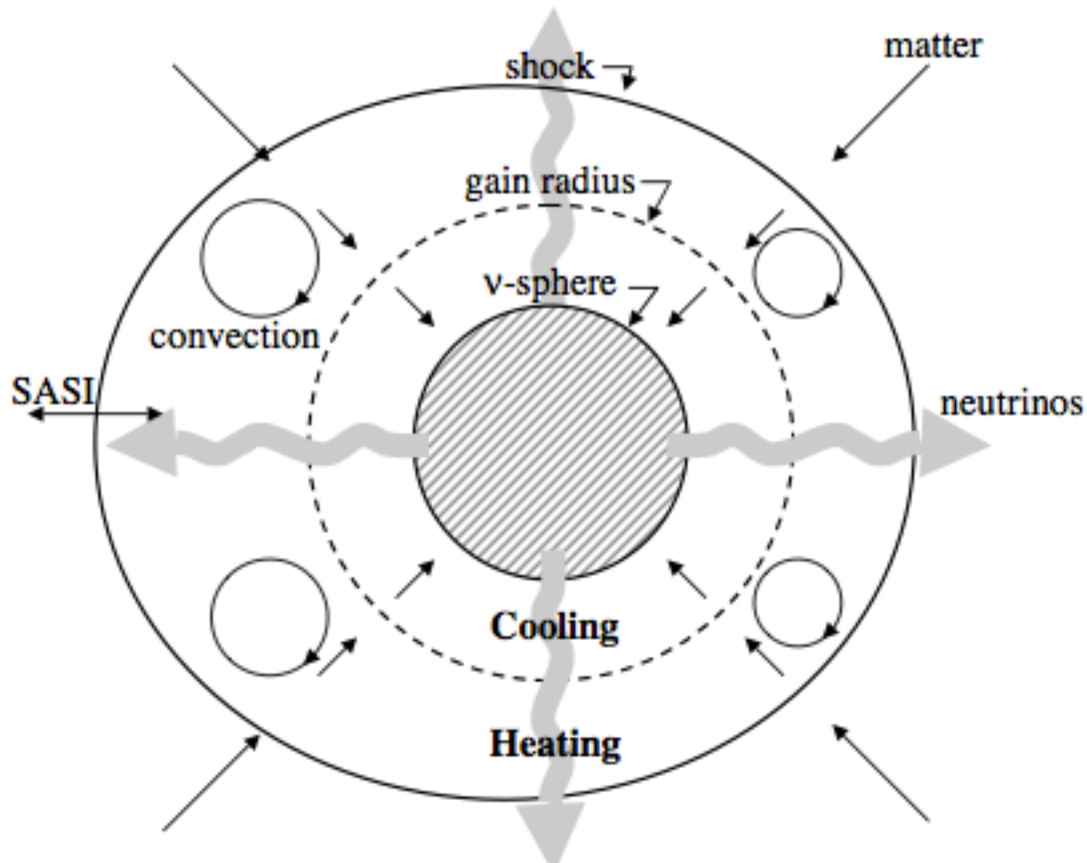


The region above the neutron star can be quite inhomogeneous

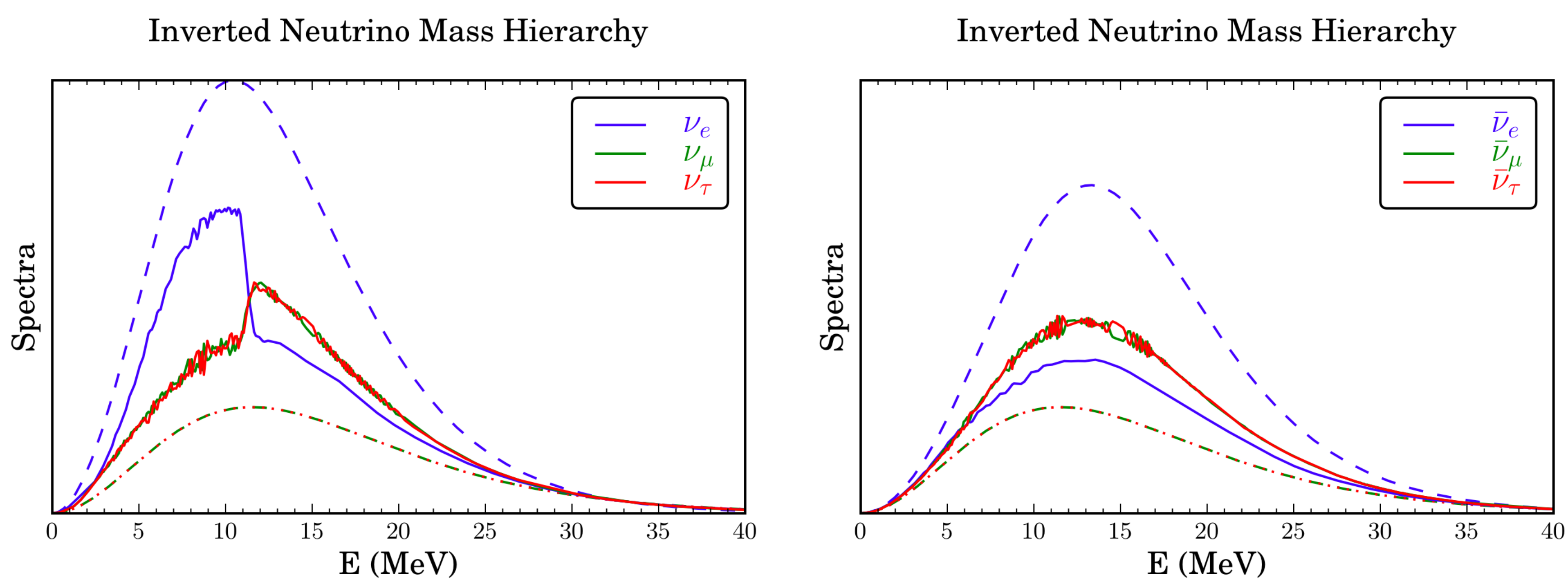


turbulence: (see, e.g., Friedland; Volpe & Kneller 2011)

The Standing Accretion Shock Instability model for the supernova explosion (Mezzacappa, Blondin)

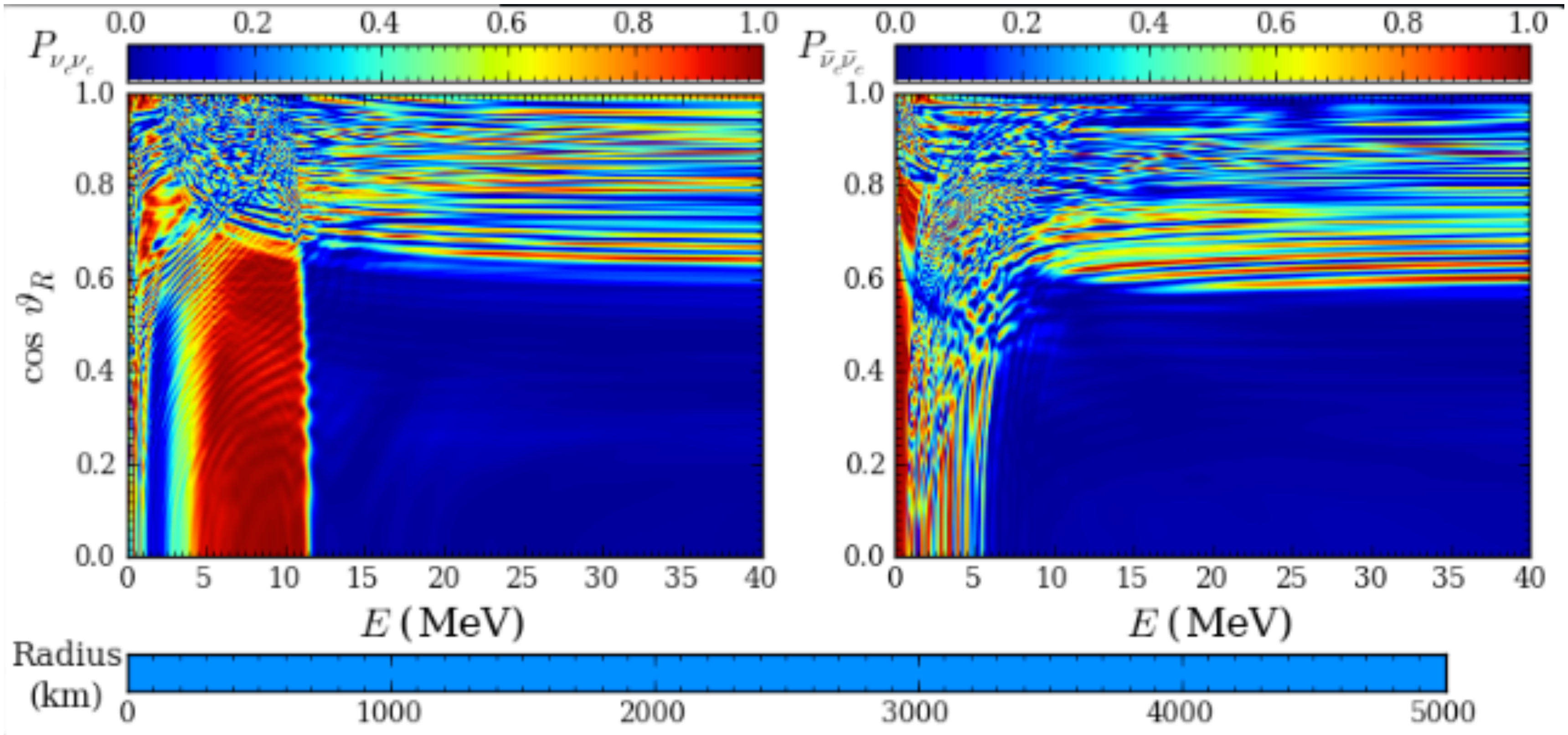


We find spectral swaps even in some regimes in these complicated inhomogeneous environments



Emission angle averaged spectra exhibiting a swap (the swap emerges at ~ 1500 km and persists out to the end of the simulation at 5000km). The swap is in the neutrino sector (left panel). The anti-neutrinos are affected by bi-polar collective oscillation.

J. J. Cherry, G.M.F., J. Carlson, H. Duan, Y.-Z. Qian, preliminary 2011



Cherry et al. 2011: swap along outflow line of sight

So, do we know what neutrino flavor transformation does?

Shock re-heating

B. Dasgupta, W. O'Connor, C.D. Ott astro-ph/1106:1167
J. Cherry et al. 2011

neutrino-affected nucleosynthesis (e.g., *r*-Process)

P. Banerjee, W. C. Haxton, Y.-Z. Qian, astro-ph/1103.1193

Quantum Kinetic Equations

A. Vlasenko, G.M.F., V. Cirigliano (2011)

$$i p_\mu \partial^\mu f\,(x,\vec{p}) - [m^2, f\,(x,\vec{p})] - p_\mu [\Sigma_V^\mu(x), f\,(x,\vec{p})] = I_{\rm col}(f,\bar{f})$$

$$i p_\mu \partial^\mu \bar{f}\,(x,\vec{p}) - [m^2, \bar{f}\,(x,\vec{p})] - p_\mu [\Sigma_V^\mu(x), \bar{f}\,(x,\vec{p})] = \bar{I}_{\rm col}(f,\bar{f})$$

Schroedinger-like

@ low density where
neutrinos propagate coherently

Boltzmann equation

@ high density where
inelastic scattering dominates

Poor Man's QKE's

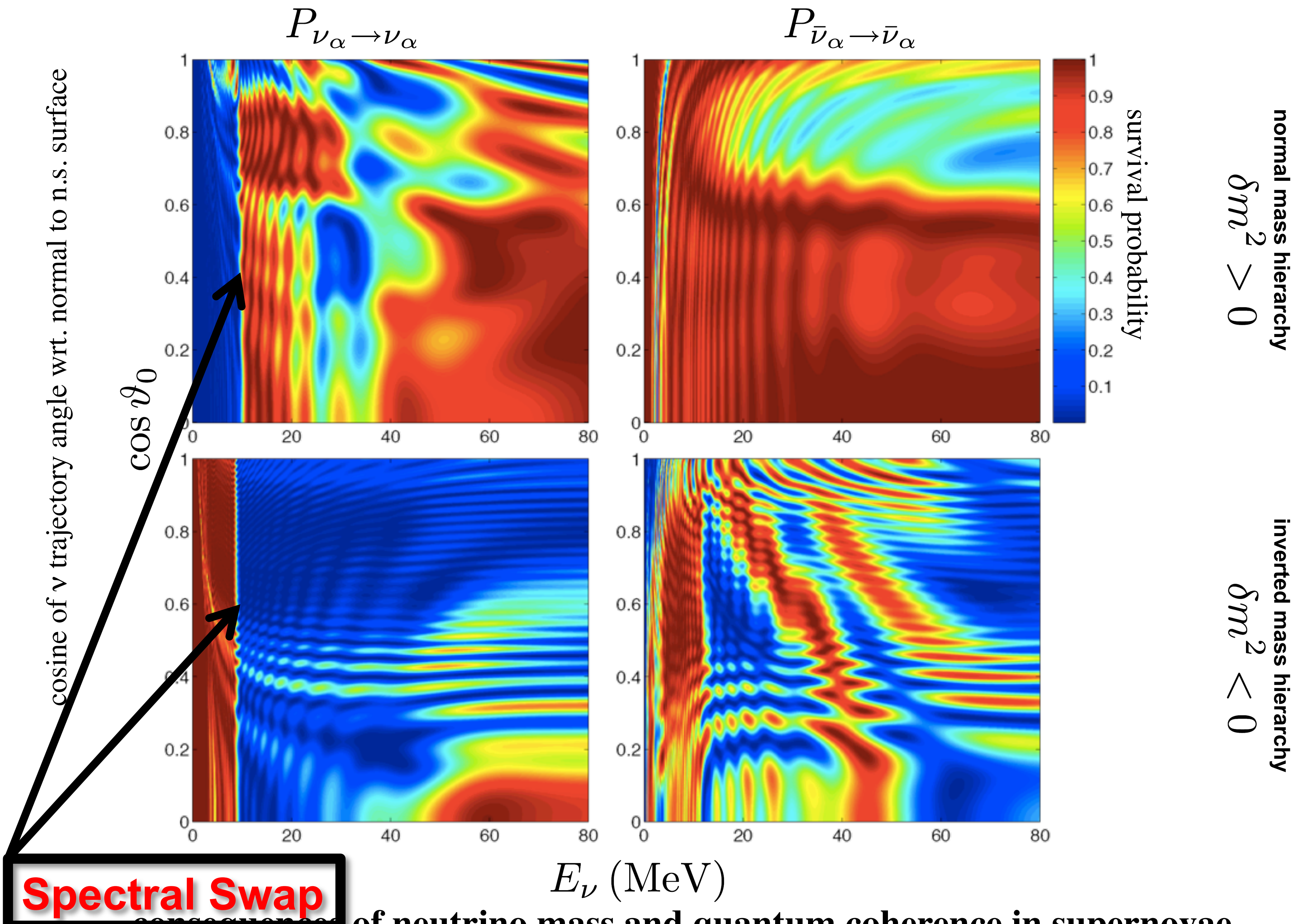
At a scattering event the neutrino's flavor is "measured"

Subsequently, as the neutrino propagates freely toward the next scattering event, it accumulates phase in neutrino flavor oscillation

By the time it gets to the next scattering event it will be in a coherent superposition of flavor states

The inelastic scattering event, mediated by the weak interaction, "asks" the question "what flavor are you?"
– wave function reduction/collapse

Detecting a Classic Swap



consequences of neutrino mass and quantum coherence in supernovae

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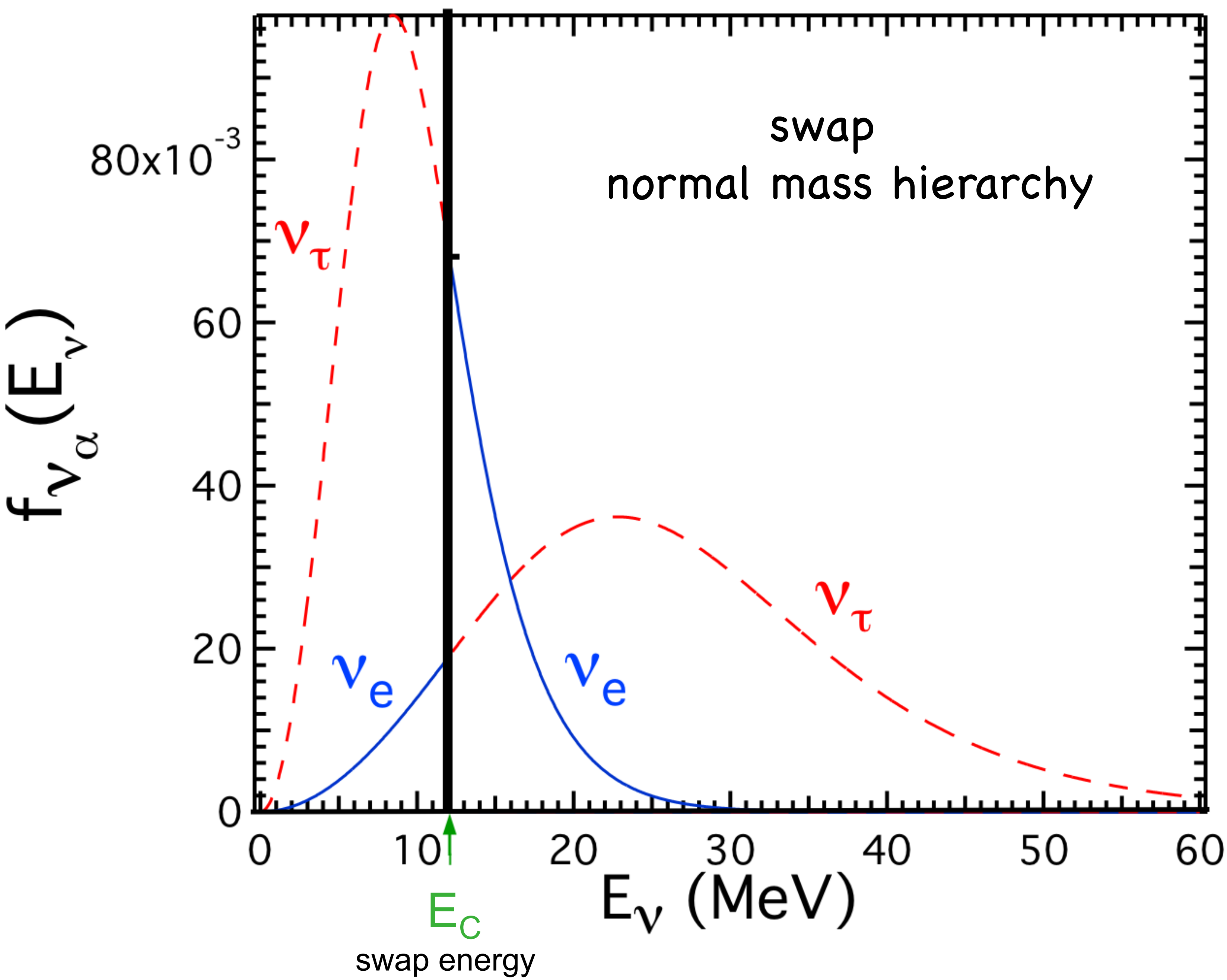
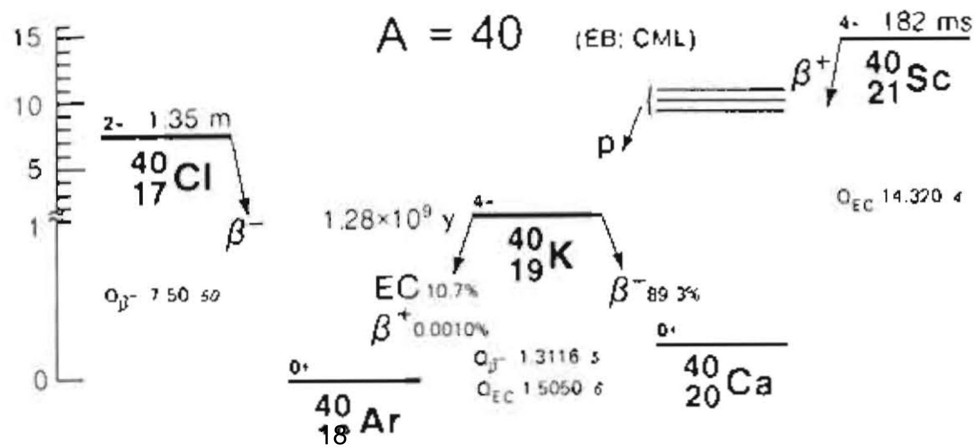


swap
normal mass hierarchy
80x10^{-3}
60
40
20
0
10
20
30
40
50
60
$f_{\nu_\alpha}(E_\nu)$
E_ν (MeV)
ν_τ
ν_τ
ν_e
ν_e
E_C
swap energy

Probably now need to re-think strategy for detecting the neutrino signal from a future Galactic supernova.

- Swap features that could tell us the neutrino mass hierarchy and θ_{13} are at relatively low energy, like solar neutrinos, at least for Fe-core collapse supernovae.
- Swap features *might* occur at late times post-core-bounce, when neutrino fluxes are low.
- Perhaps consider liquid scintillator and liquid noble gas detectors for **DUSEL**.

Nuclear Physics of Mass 40



Charged current capture on ^{40}Ar : $\nu_e + {}^{40}_{18}\mathrm{Ar} \rightarrow {}^{40}_{19}\mathrm{K} + e^-$

sensitive to neutrino energy
- electron flavor only

Minimum Gamow-Teller Threshold: 3.8 MeV to first 1^+ state

Gamow-Teller resonance: excitation energy E_{GT} ~ 4.46 to 6 MeV
GT-Res Threshold: ~ 6 to 8 MeV

Neutral current excitation of ^{40}Ar : $\nu_{e,\mu,\tau} + {}^{40}_{18}\mathrm{Ar} \rightarrow {}^{40}_{18}\mathrm{Ar}^* + \nu_{e,\mu,\tau}$

from all flavors-
normalizes flux

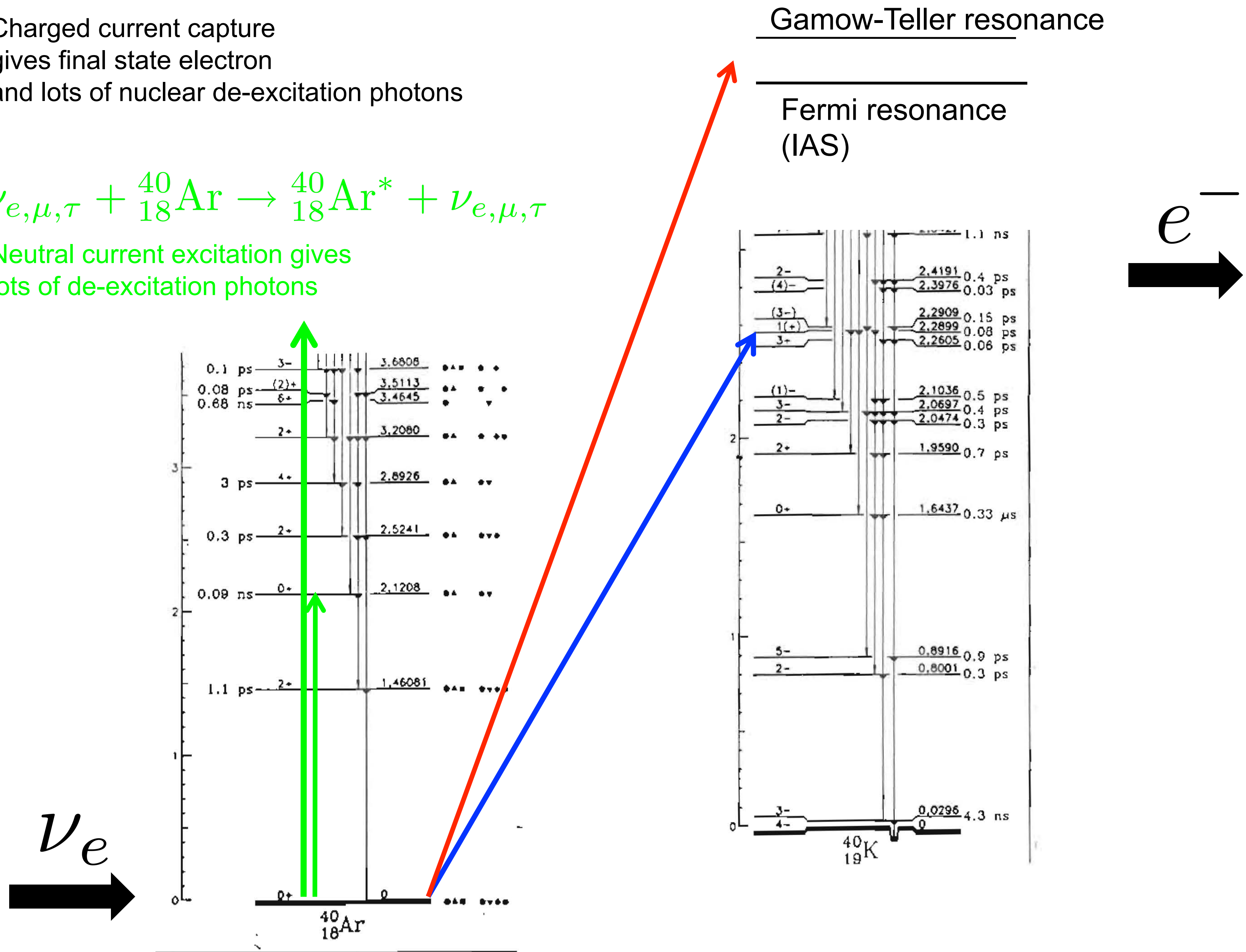
Minimum allowed weak threshold: to first 0^+ excited state at 2.12 MeV

$$\nu_e + {}^{40}_{18}\mathrm{Ar} \rightarrow {}^{40}_{19}\mathrm{K}^* + e^-$$

Charged current capture
gives final state electron
and lots of nuclear de-excitation photons

$$\nu_{e,\mu,\tau} + {}^{40}_{18}\mathrm{Ar} \rightarrow {}^{40}_{18}\mathrm{Ar}^* + \nu_{e,\mu,\tau}$$

Neutral current excitation gives
lots of de-excitation photons



10 kT Liquid Argon Detector

Supernova at 10 kpc

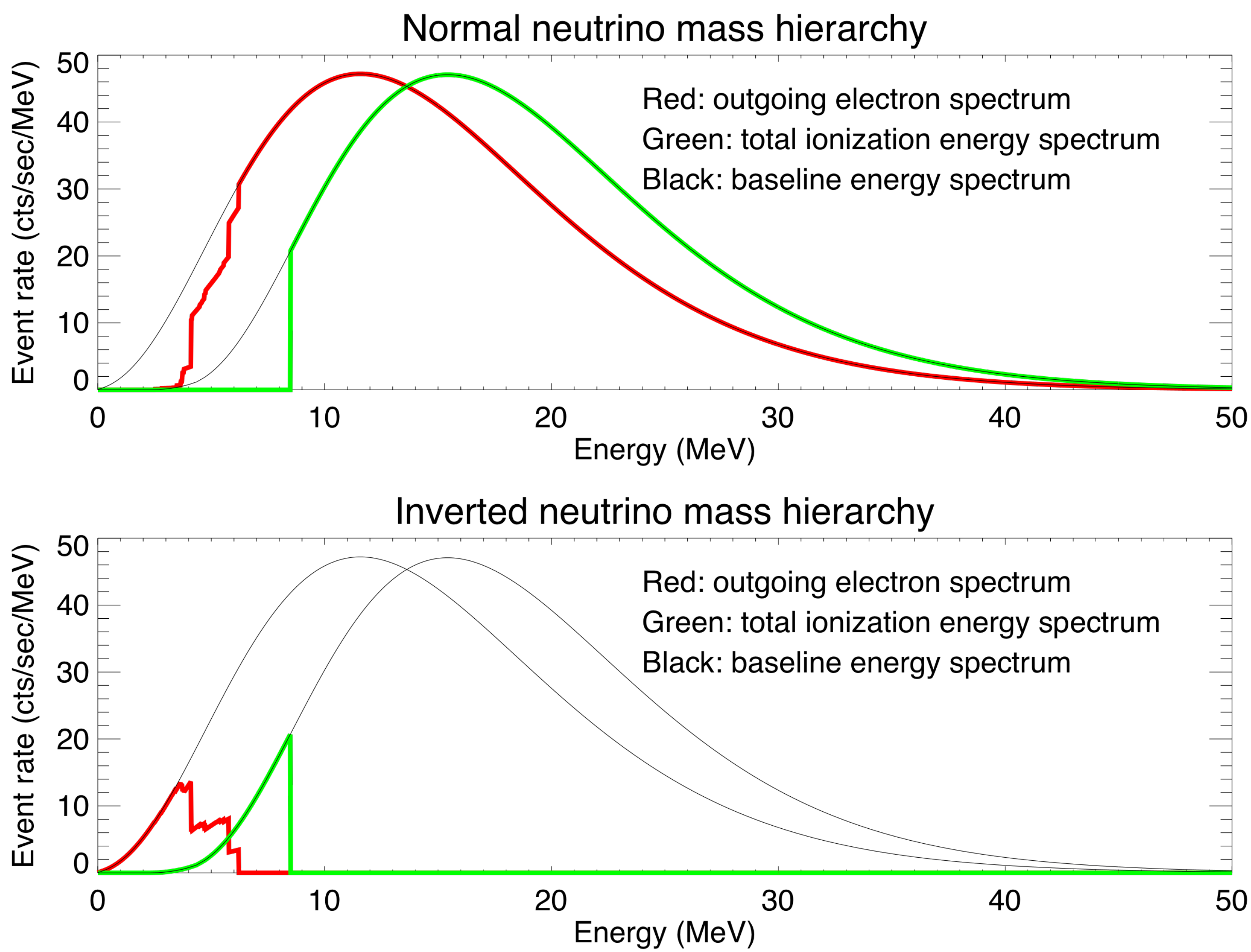
Total number of electron events = 233

8 in first 10 ms

150 between 10 ms and 2 s

75 after 2 s

D. Cline, G.M.F., K. Lee, T. Skelton (2011)



Normal neutrino mass hierarchy
Red: outgoing electron spectrum
Green: total ionization energy spectrum
Black: baseline energy spectrum
Event rate (cts/sec/MeV)
Energy (MeV)
0
10
20
30
40
50
Inverted neutrino mass hierarchy
Red: outgoing electron spectrum
Green: total ionization energy spectrum
Black: baseline energy spectrum
Event rate (cts/sec/MeV)
Energy (MeV)

CONCLUSIONS

- The experimental neutrino physics has given us *some* of the mass/mixing properties of the neutrinos.
  We must include this physics in models of core collapse supernovae and in the early universe.

- Neutrino self coupling can alter neutrino flavor evolution in SN, ultimately causing large-scale flavor conversion deep in the supernova envelope, despite the small measured neutrino mass-squared differences.
  MSW-based analyses are inadequate.
  This could affect neutrino-heated nucleosynthesis and the neutrino signal.

- Neutrino self coupling-induced flavor collective modes
  may produce distinctive signatures
  which could allow a supernova neutrino signal to give us the
  neutrino mass hierarchy and θ_{13}
  as well as give us an observational window on the deep interior of the core
  and distinguish between Fe-core collapse and O-Ne-Mg core collapse.