Neutrino Mass
and
Core Collapse Supernovae

The Future of Neutrino Mass Measurements
Institute for Nuclear Theory
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Neutrino mass physics is a theme common to both

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

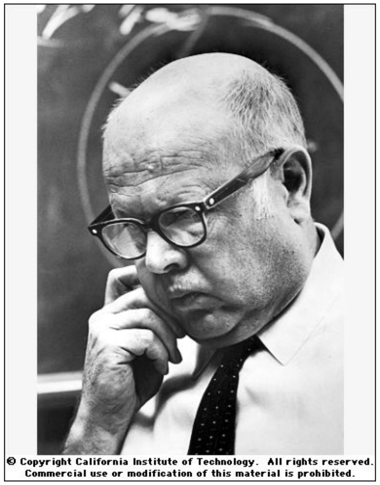
***Cosmology** (structure formation; dark matter, etc. . .)*

Synergy between laboratory/observational neutrino physics and new developments and capabilities in observational astronomy

We have an exciting situation in neutrino physics and astrophysics

Experiments are revealing the properties of neutrinos and this new data is driving interesting developments in nuclear and particle astrophysics. As I will show, these astrophysical developments may feed back on our understanding of neutrino properties.

This is *classic* particle/nuclear astrophysics, with a synergistic coupling of astrophysics and low energy laboratory measurements of physics beyond the Standard Model



Willy Fowler might appreciate this . . .

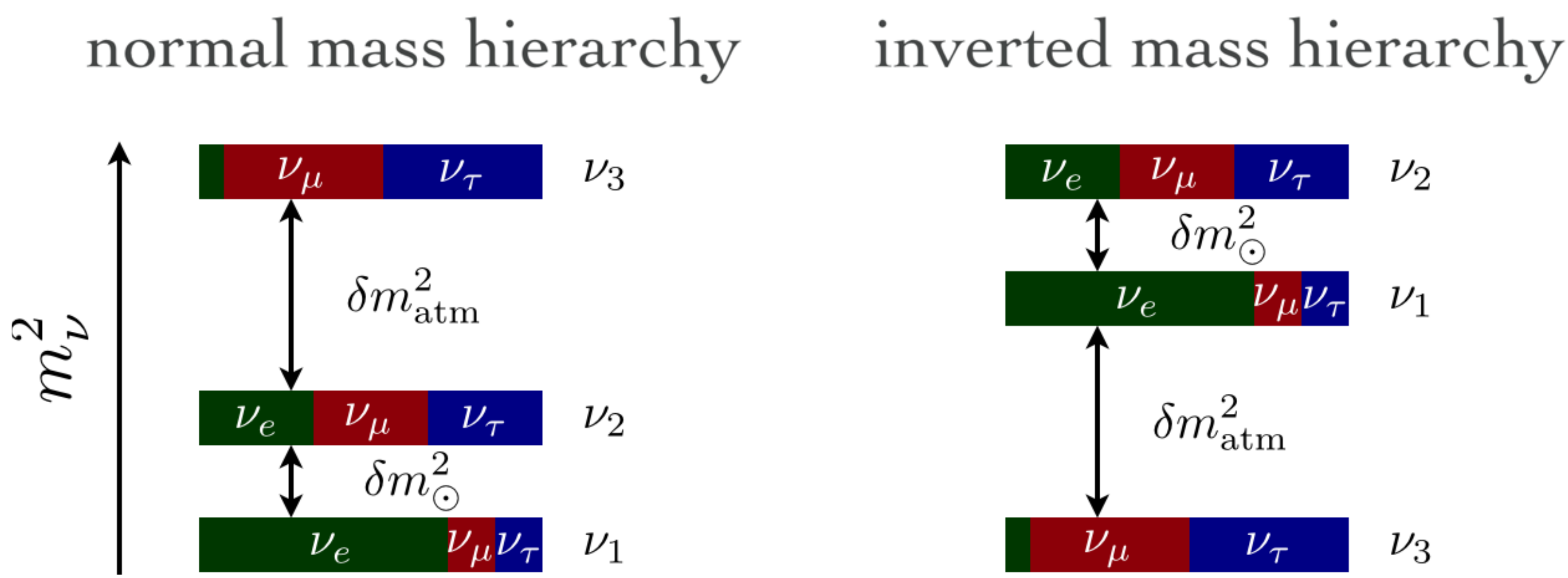
Neutrino Mass: what we know and don't know

We know the *mass-squared* differences:

$$e.g., \quad \delta m^2_{21} \equiv m^2_2 - m^2_1$$

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

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



My take on this is as follows:

(1) What we ***already know*** about neutrino mass/mixing has potentially big implications for astrophysics.

(**2**) Working out those implications may allow new insights into nucleosynthesis and unmeasured neutrino properties:
e.g., a supernova neutrino signal could help us get at θ_{13} and the *neutrino mass hierarchy*. And, *vice versa,* what we know about **neutrino flavor mixing** may give us insights into how supernovae work.
Cosmology may give *absolute masses* --- gives best limits now.

Gravitational Collapse of Massive Stars

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) determined by electron degeneracy or by charged current neutrino capture:

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

Neutrinos Dominate the Energetics of Core Collapse Supernovae

Explosion
only ~1% of neutrino energy

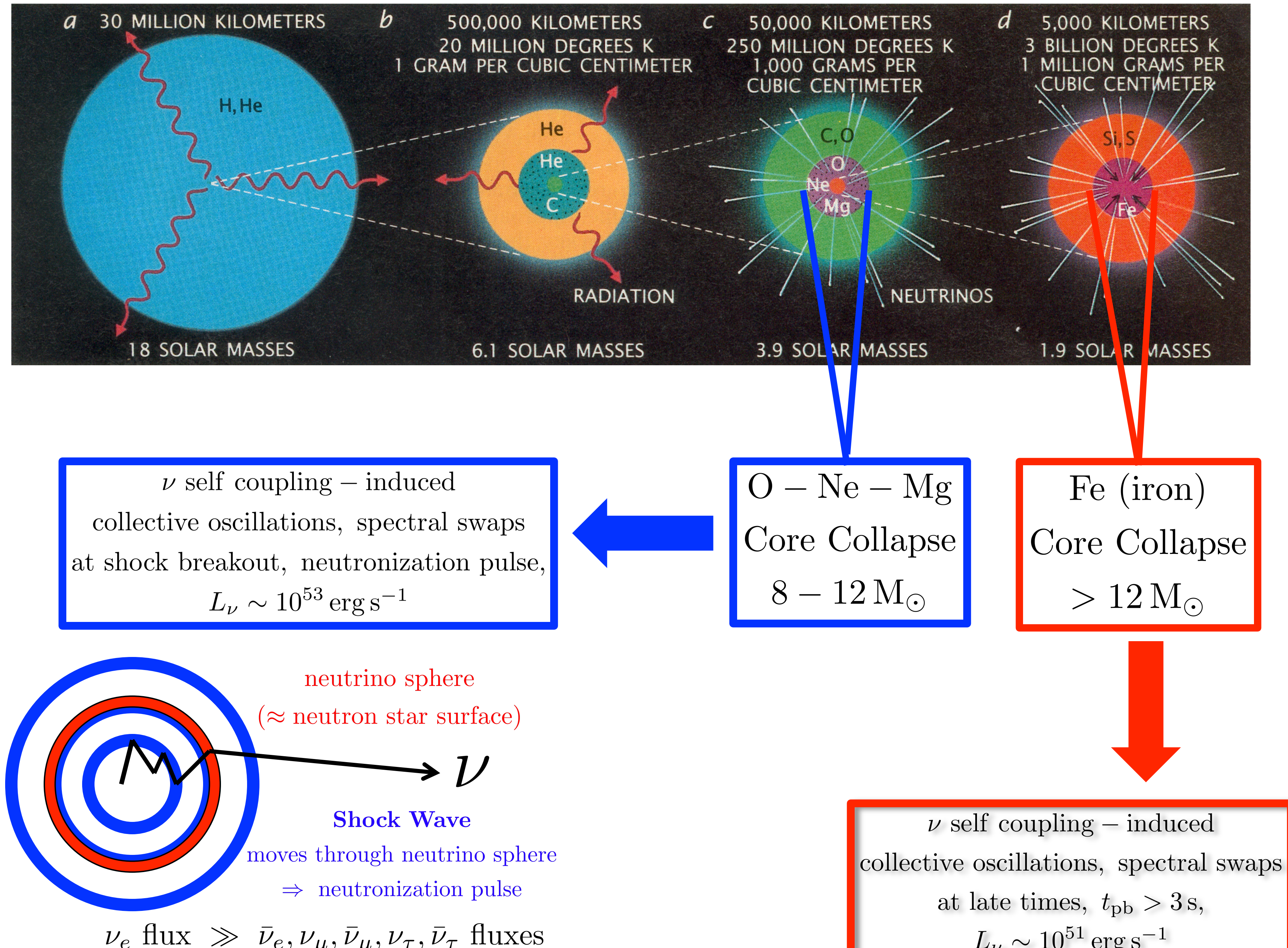
- Total optical + kinetic energy, 10^{51} ergs
- Total energy released in Neutrinos, 10^{53} ergs

10% of star's rest mass!

$$E_{\mathrm{GRAV}} \approx \frac{3}{5}\frac{\mathrm{G}\,M_{\mathrm{NS}}^{2}}{R_{\mathrm{NS}}} \approx 3\times10^{53}\mathrm{ergs}\left[\frac{M_{\mathrm{NS}}}{1.4\mathrm{M}_{\mathrm{sun}}}\right]^{2}\left[\frac{10\ \mathrm{km}}{R_{\mathrm{NS}}}\right]$$

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

$$L_{\nu} \approx \frac{1}{6}\frac{GM_{\mathrm{NS}}^{2}}{R_{\mathrm{NS}}}\frac{1}{\tau_{\nu}} \approx 4\times10^{51}\mathrm{ergs\ s}^{-1}$$

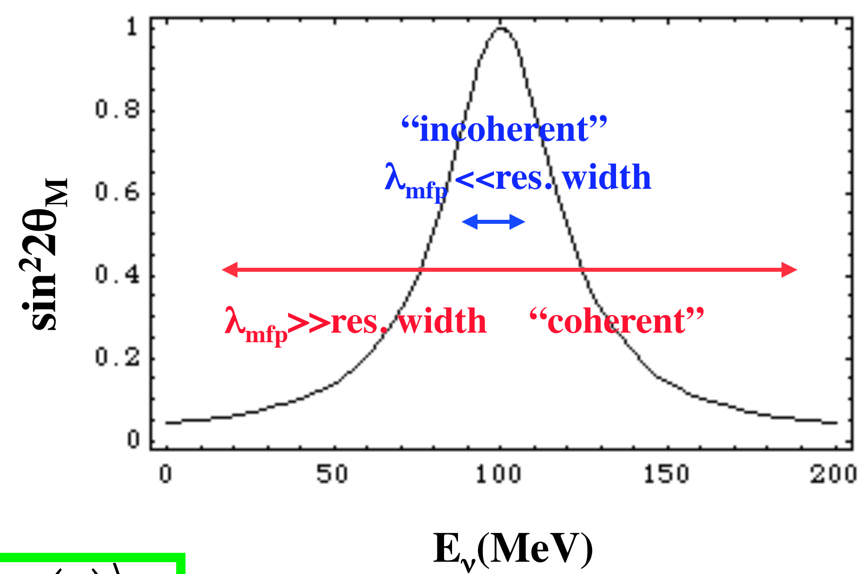

a 30 MILLION KILOMETERS
H, He
18 SOLAR MASSES
b 500,000 KILOMETERS
20 MILLION DEGREES K
1 GRAM PER CUBIC CENTIMETER
He
He
C
RADIATION
6.1 SOLAR MASSES
c 50,000 KILOMETERS
250 MILLION DEGREES K
1,000 GRAMS PER
CUBIC CENTIMETER
C, O
O
Ne
Mg
NEUTRINOS
3.9 SOLAR MASSES
d 5,000 KILOMETERS
3 BILLION DEGREES K
1 MILLION GRAMS PER
CUBIC CENTIMETER
Si, S
Fe
1.9 SOLAR MASSES
ν self coupling – induced
collective oscillations, spectral swaps
at shock breakout, neutronization pulse,
$L_\nu \sim 10^{53}\,\mathrm{erg\,s^{-1}}$
O – Ne – Mg
Core Collapse
$8 - 12\,\mathrm{M_\odot}$
Fe (iron)
Core Collapse
$> 12\,\mathrm{M_\odot}$
neutrino sphere
($\approx$ neutron star surface)
ν
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
ν self coupling – induced
collective oscillations, spectral swaps
at late times, $t_{\mathrm{pb}} > 3\,\mathrm{s}$,
$L_\nu \sim 10^{51}\,\mathrm{erg\,s^{-1}}$

ordinary MSW evolution of neutrino flavors

MSW resonance at neutrino energy

$$E_\nu = \frac{\delta m^2 \cos 2\theta}{2(A+B)} \approx (0.02 \text{ MeV})\left(\frac{\delta m^2 \cos 2\theta}{3\times 10^{-3} \text{ eV}^2}\right)\left(\frac{10^6 \text{ g cm}^{-3}}{\rho(\mathrm{Y_e}+\mathrm{Y}_\nu)}\right)$$

At a given location expect only neutrinos in a narrow energy range to experience large flavor mixing while anti-neutrino mixing is suppressed. With the small measured neutrino mass-squared differences we expect significant flavor conversion only at low densities.



time/position - dependent mixing angle and mass-states

$$|\nu_e\rangle = \cos\theta_M(t)|\nu_1(t)\rangle + \sin\theta_M(t)|\nu_2(t)\rangle$$

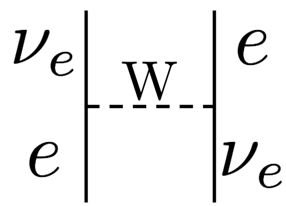
$$|\nu_\tau\rangle = -\sin\theta_M(t)|\nu_1(t)\rangle + \cos\theta_M(t)|\nu_2(t)\rangle$$

Coherent Flavor Evolution for Neutrino i

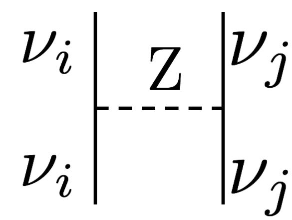
$$\psi_{\nu,i} = \begin{bmatrix} \text{amplitude to be } \nu_{\rm e} \\ \text{amplitude to be } \nu_{\mu,\tau} \end{bmatrix}$$

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

neutrino-electron
charged current
forward exchange
scattering



neutrino-neutrino
neutral current
forward scattering



Neutrino Self Coupling - the source of nonlinearity

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

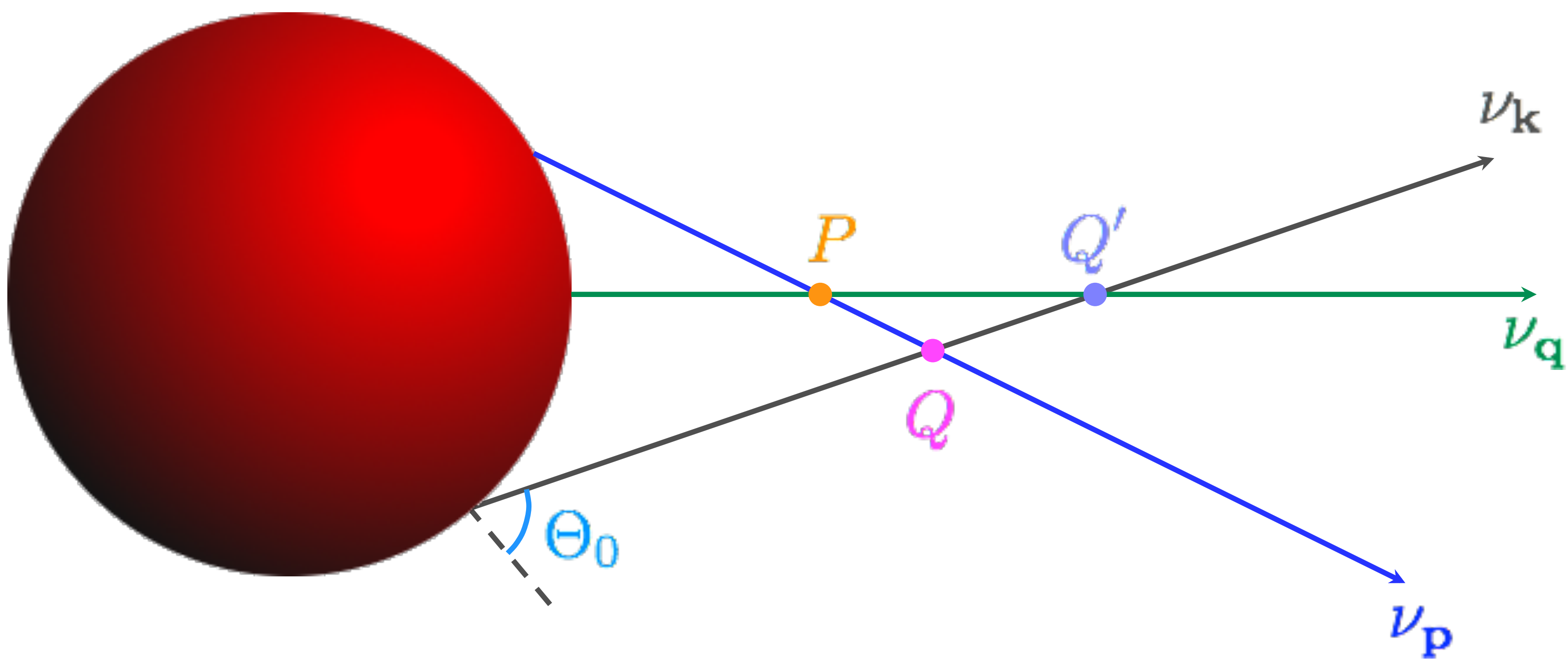
$$-\sqrt{2}G_{\rm F}\sum_j \left(1-\hat{\mathbf{k}}_i\cdot\hat{\mathbf{k}}_j\right) n_{\bar\nu,j}\,\psi_{\bar\nu,j}\psi^\dagger_{\bar\nu,j}$$

Effects beyond the mean field?
Balantekin & Pehlivan (2007)
Friedland & Lunardini (2003)

now self-consistently couple flavor evolution

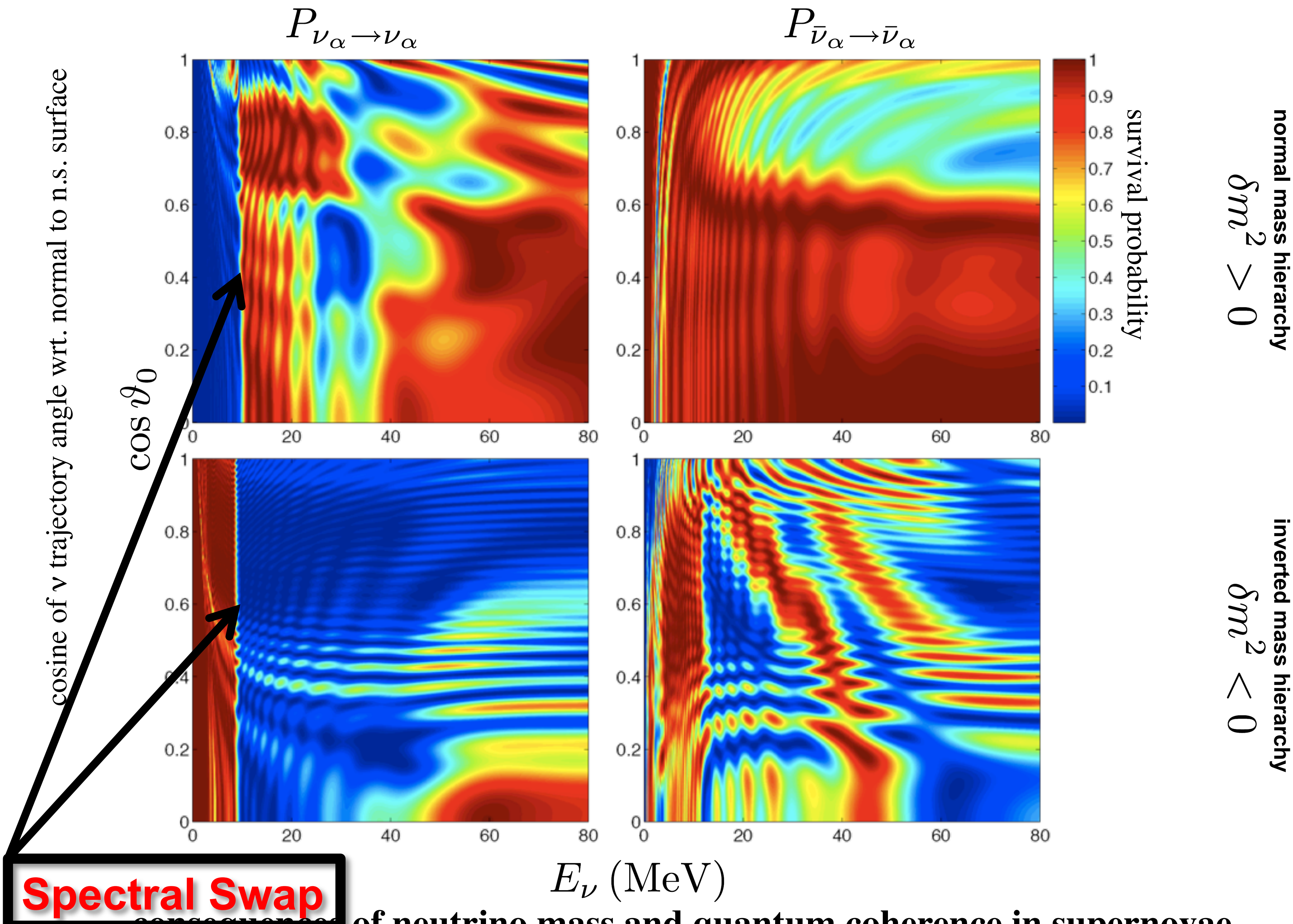
on all neutrino trajectories . . .

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



A great deal of work has now been done on this problem by many groups around the world. There is now a huge literature on this topic. See review on *Collective Neutrino Oscillations*:

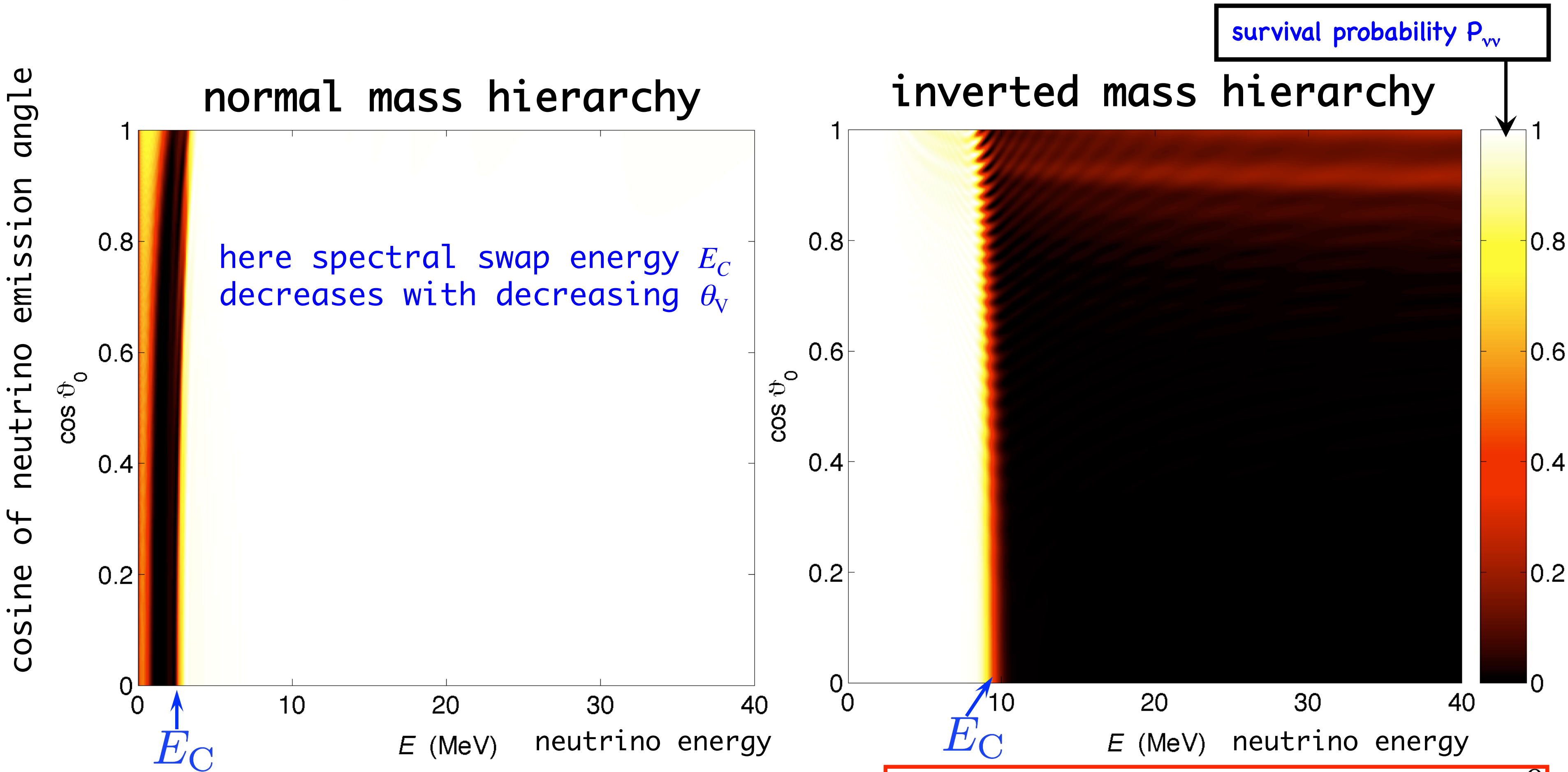
H. Duan, G. M. Fuller, & Y.-Z. Qian, hep-ph/1001.2799



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

H. Duan, G.M. Fuller, J. Carlson, Y.-Z. Qian, Phys. Rev. Lett. **99**, 241802 (2007)

O-Ne-Mg Core Collapse Supernovae

The progenitors of these events are stars in the mass range

$$8\,\mathrm{M}_\odot - 12\,\mathrm{M}_\odot$$

K. Nomoto, *Astrophys. J.*, **277**, 791 (1984); **322**, 206 (1987)

Post-collapse, these objects have a very steep matter density profile above the neutron star and behind the (viable) shock.

Modeling flavor transformation in the *neutronization* burst requires a full 3X3 mixing treatment with neutrino self-coupling.

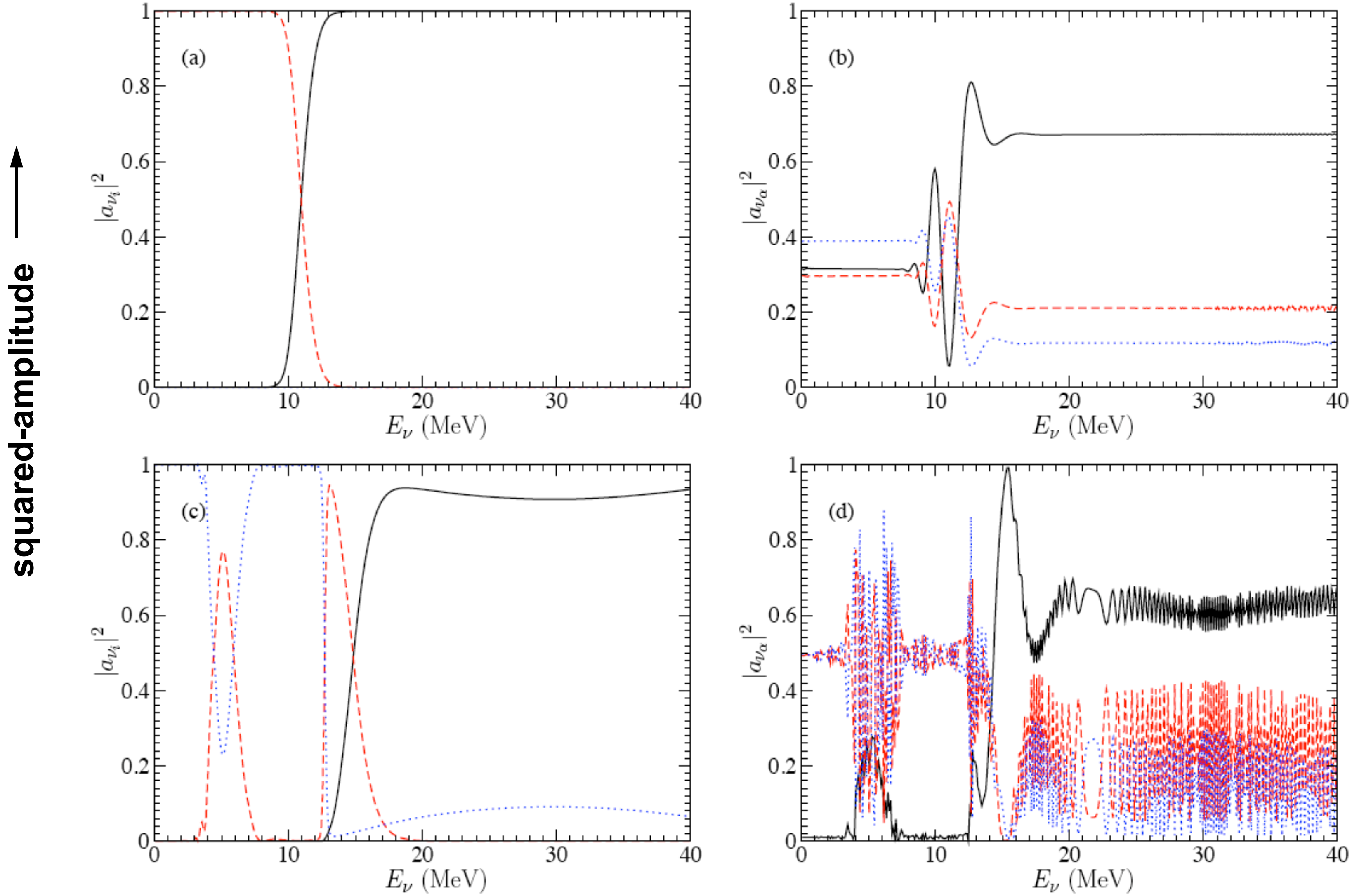
We find a sequence of neutrino spectral swaps which, if detected, could identify the neutrino burst as originating in an O-Ne-Mg event instead of an ordinary Fe-core-collapse!

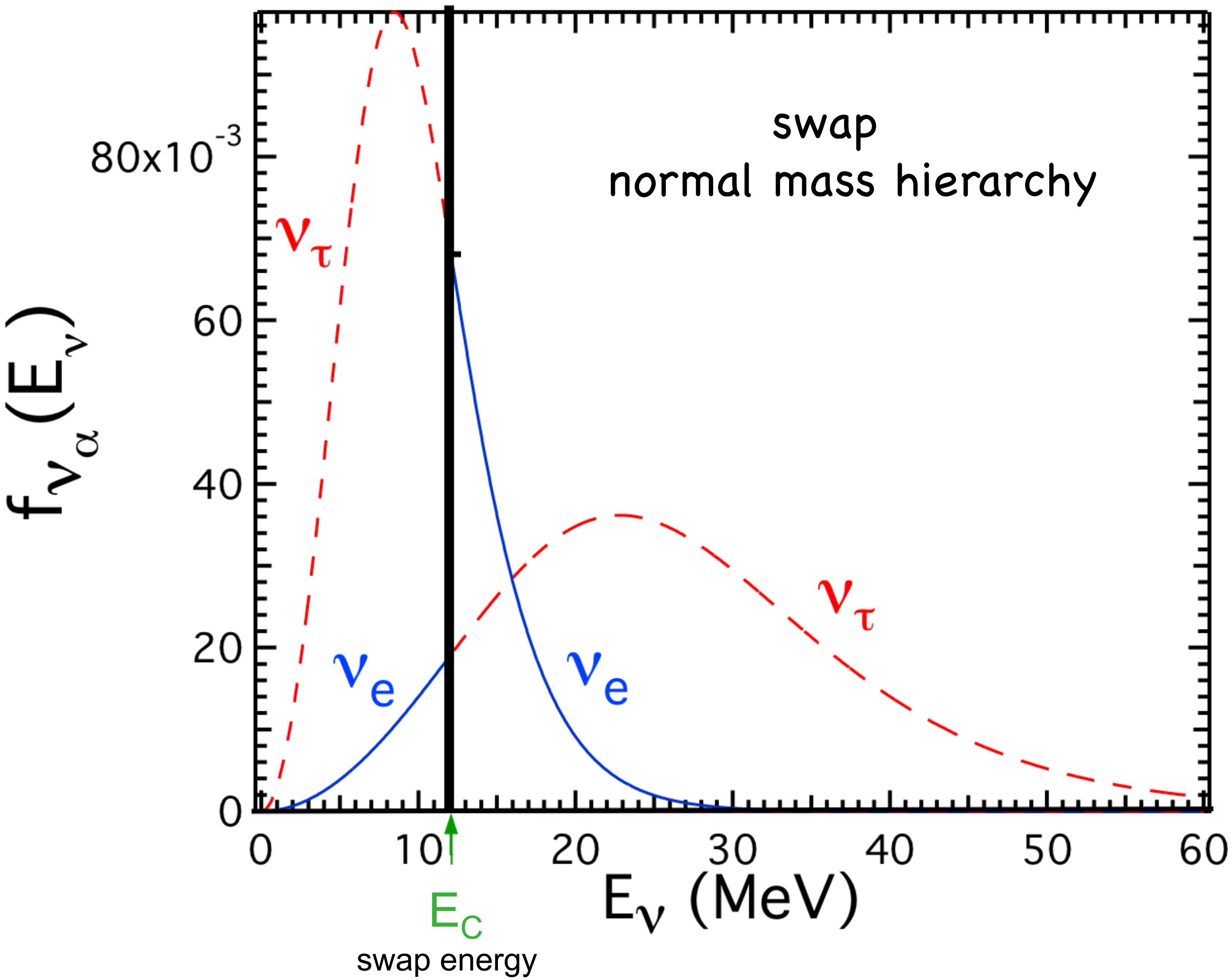
H. Duan, G.M. Fuller, J. Carlson, Y.-Z. Qian, Phys. Rev. Lett. **100**, 021101 (2008)
C. Lunardini, B. Mueller, H.-Th. Janka, Phys. Rev. D **78**, 023016 (2008)

Full 3X3 treatment (with both atmospheric and solar mass-squared differences) of the neutronization burst from an O-Ne-Mg core collapse: succession of spectral swaps

Distinctive pattern could tell us whether SN is an Fe-core or an O-Ne-Mg core collapse:

H. Duan, G.M. Fuller, J. Carlson, Y.-Z. Qian, Phys. Rev. Lett. **100**, 021101 (2008)





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

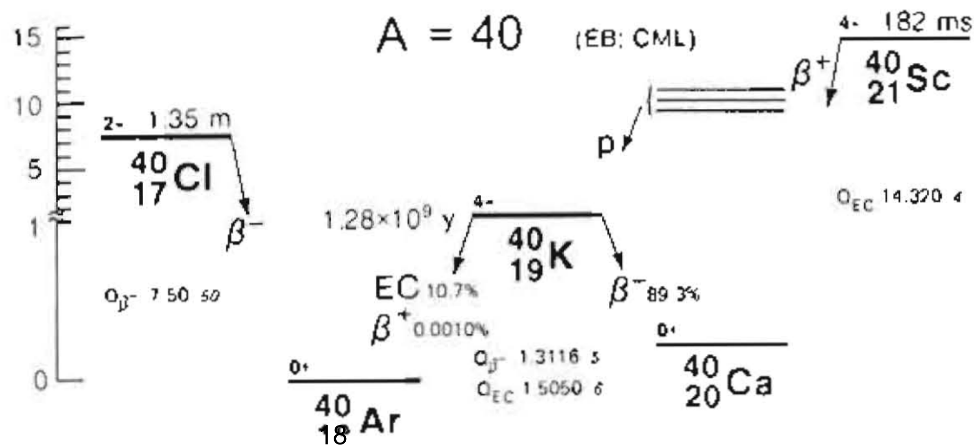
- Perhaps consider liquid scintillator and liquid noble gas detectors for **DUSEL**.

The Figure of Merit

one core collapse supernova
in the Galaxy every 30 years . . .

but what about the relic core collapse
neutrino background (*see C. Lunardini*)

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

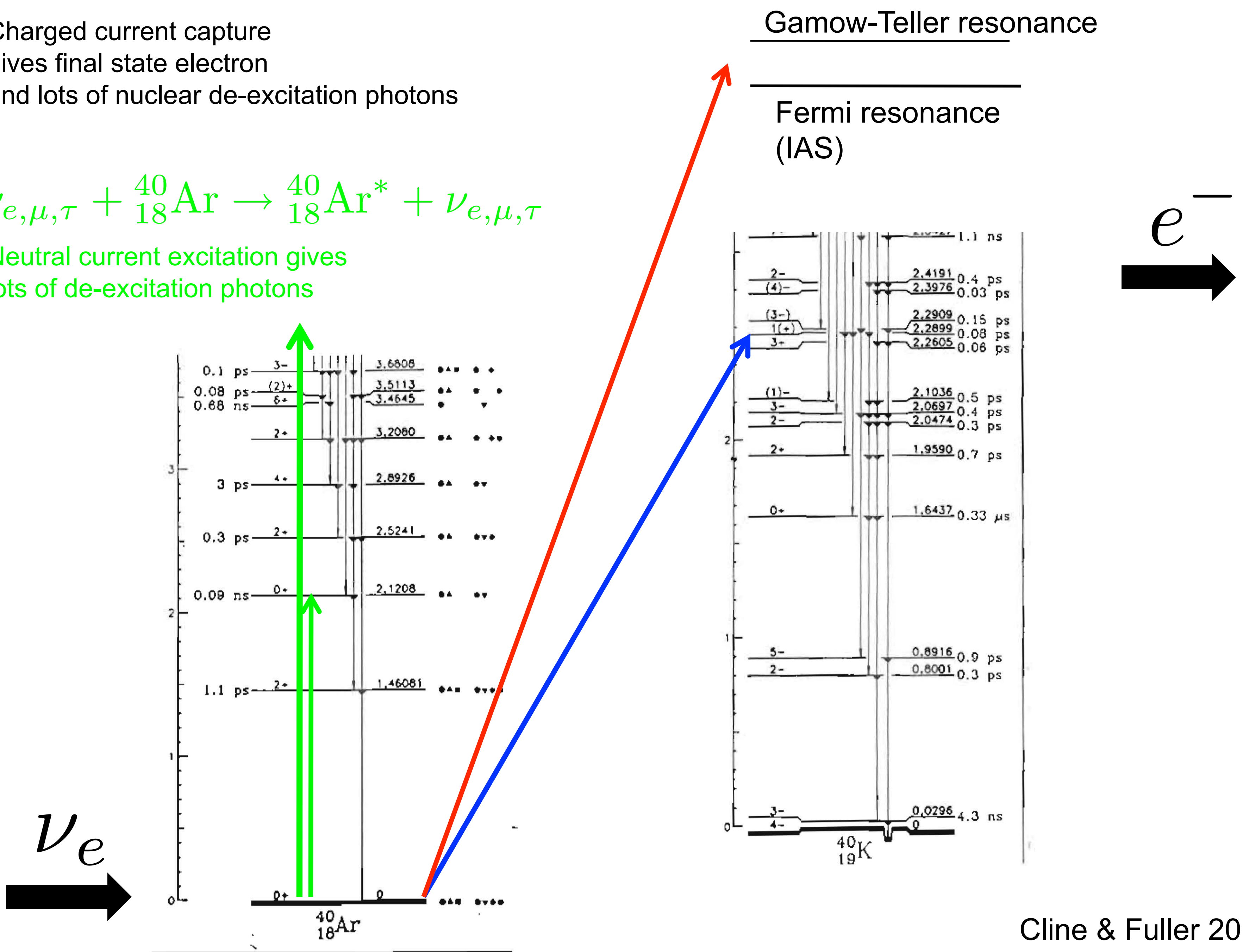
Minimum allowed weak threshold: to first 0^+ excited state at 2.12 MeV

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

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



Cline & Fuller 2010

model dependence ?

If you can see the sense of a swap (i.e., most transformation above or below some energy) then you can get the hierarchy . . . .

But how robust are these swaps
in realistic (messy) supernova environments ?

to this end . . . open issues

- Non-Spherical geometries . . . 3-D hydro
  e.g., the SASI and late re-heating Blondin & Mezzacappa *Nature* **445**, 58 (2007)

- Inhomogeneous matter/neutrino environments,
  e.g., what are the effects of inhomogeneities like turbulence or the shock on the neutrino signal,
  anisotropic neutrino emission? Friedland & Gruzinov (2006); Gava et al. (2009)
  Galais, Kneller, Volpe, & Gava (2009); review by H. Duan & J. Kneller (2009)

- Full 3X3 flavor transformation in realistic environments, "multi-angle", phase averaging - *necessary*
  e.g., A. Friedland hep-ph/1001.0996 (2010)

- Extension to regime where scattering-induced de-coherence is significant: the full Quantum Kinetic Equations.
  Abazajian, Fuller, Patel (2001); Strack & Burrows (2005)
  Cardall (2007, 2009); Kishimoto & Fuller (2008)

CONCLUSIONS

- The experimental revolution in neutrino physics has given us some of the mass/mixing properties of the neutrinos.
  Modelers should 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.