Neutrino Properties
and
Supernovae

TAUP, Asilomar, CA, September 11, 2013

George M. Fuller
Department of Physics
&
Center for Astrophysics and Space Science
University of California, San Diego

Core Collapse Supernovae

Stealthy neutrinos undermine the stability of massive stars,
setting up conditions that *guarantee* their collapse,
and in so doing create the perfect engine for
generating *titanic numbers* (10^{58}) of neutrinos. These neutrinos then
bring about the explosions that seed the universe with the
elements necessary for planets and life.

But . . .

. . . though you just saw in H.T. Janka's talk that simulations
of core collapse supernovae are very sophisticated:
multi-dimensional radiation hydrodynamics;
Boltzmann neutrino transport, and *detailed microphysics/EOS* . . .

Our understanding of the effects of nonzero neutrino mass (flavor oscillations; spin flip), though numerically sophisticated, is crude, and difficult to incorporate into the SN simulations.

There are *unsettled issues* in the story of supernova neutrinos.

So what is unique about core collapse supernovae as a "lab" for studying neutrinos?

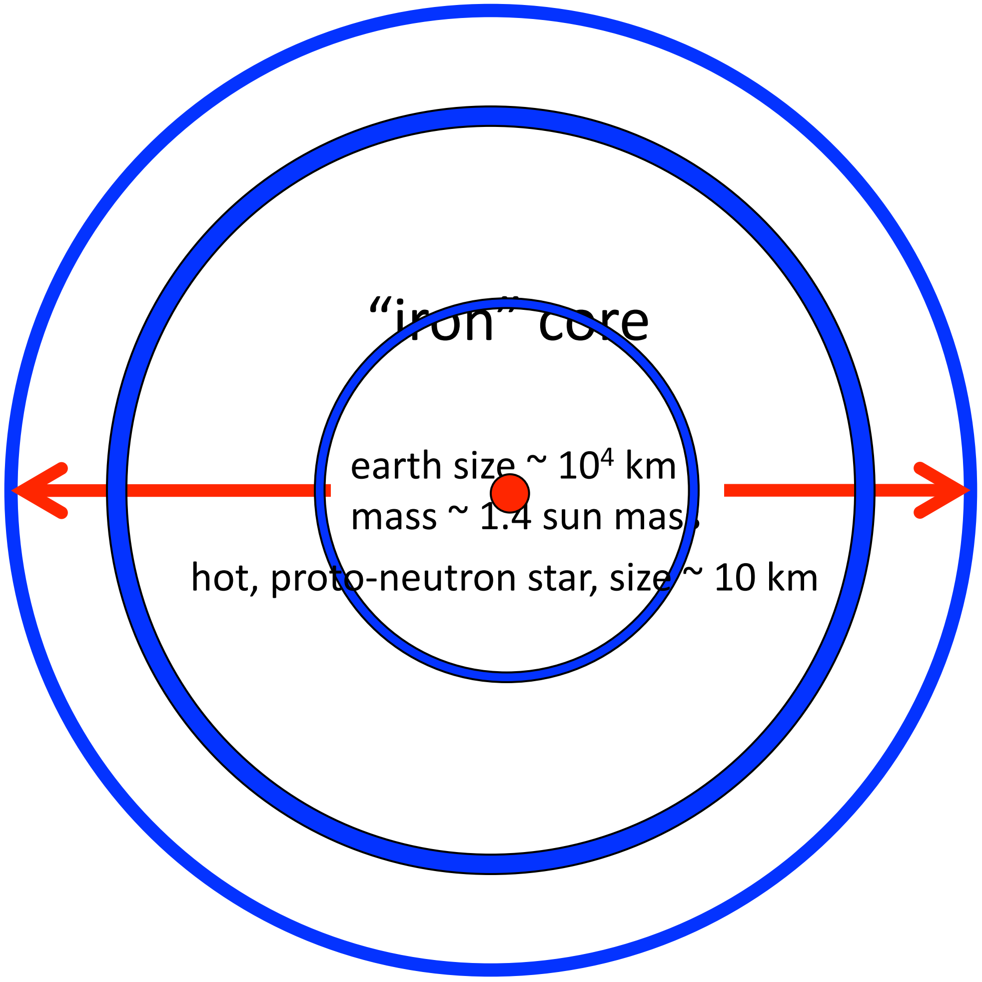
In a nutshell:

Core collapse supernovae are cold,
highly electron lepton number degenerate systems.

They are ***exquisitely sensitive*** to lepton number violating processes.

Macroscopic effects in SN physics or signal from:
flavor oscillations: very sensitive to neutrino mass hierarchy;
spin coherence: sensitive to Majorana/Dirac nature of neutrinos
& absolute neutrino masses

. . . and in about one second . . .



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**

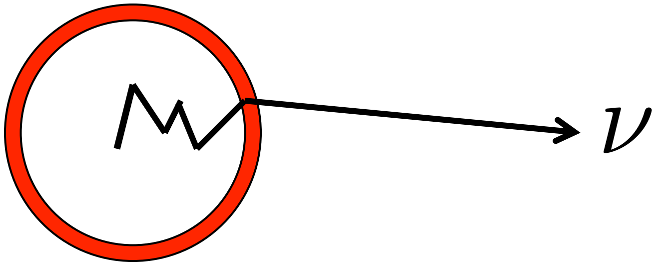
10% of star's rest mass!

$$\boxed{E_{\rm grav} \approx \frac{3}{5}\frac{{\rm G}\,M_{\rm NS}^2}{R_{\rm NS}} \approx 3\times10^{53}\,{\rm erg}\left[\frac{M_{\rm NS}}{1.4\,{\rm M}_\odot}\right]^2\left[\frac{10\,{\rm km}}{R_{\rm NS}}\right]}$$

$$\boxed{\text{neutrino diffusion time } \tau \sim 2\,{\rm s} \text{ to } 10\,{\rm s}}$$

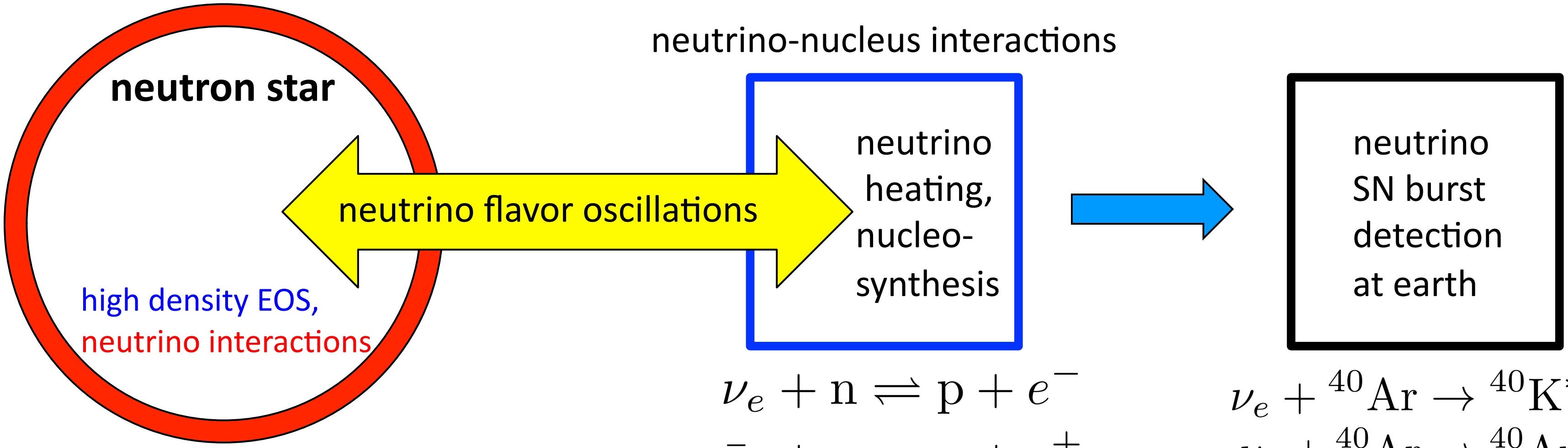
typical luminosity (energy per second)
for each of the 6 neutrino species:

$$L_\nu \approx \frac{1}{6}\cdot\frac{{\rm G}\,M_{\rm NS}^2}{R_{\rm NS}}\cdot\frac{1}{\tau} \approx 4\times10^{51}\,{\rm ergs\ s^{-1}}$$



neutrino sphere
(*i.e.*, edge of neutron star)

Calculating neutrino flavor transformation in the core collapse supernova environment is a vexing problem,
but one whose solution may lie at the heart of many aspects of the physics of stellar collapse, nucleosynthesis, and the ν signal.



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

$$\nu_e + {}^{40}\mathrm{Ar} \to {}^{40}\mathrm{K}^* + e^-$$
$$\nu_x + {}^{40}\mathrm{Ar} \to {}^{40}\mathrm{Ar}^* + \nu_x$$

We need the fluxes and energy spectra of each flavor/type of neutrino at all epochs and at all radii.

Calculating neutrino flavor evolution is *not* an optional exercise.

- *measured* neutrino flavor mixing parameters

- neutrinos carry most of the energy/entropy and the way this is transported, deposited, and (may be) detected is *flavor-dependent*

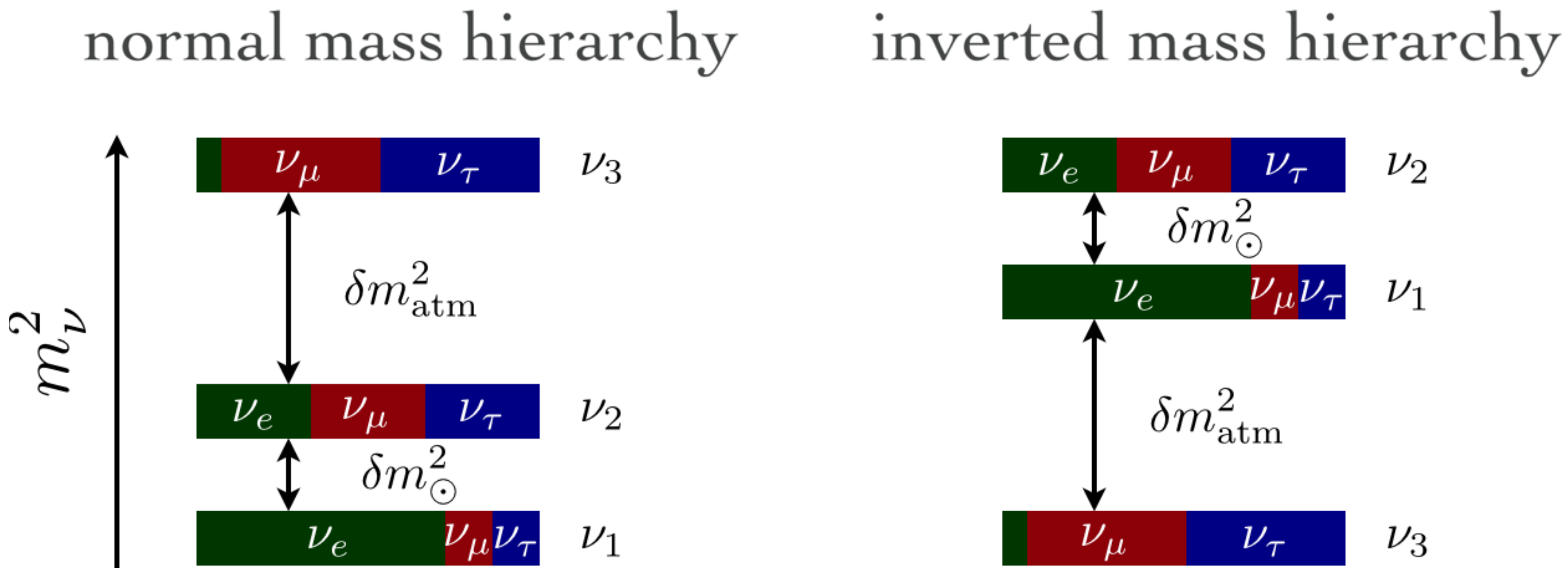
Neutrino Mass: what we know and don't know

We know the *mass-squared* differences:

$$\begin{cases} \delta m^2_\odot \approx 7.6\times 10^{-5}\,\mathrm{eV}^2 \\ \delta m^2_{\mathrm{atm}} \approx 2.4\times 10^{-3}\,\mathrm{eV}^2 \end{cases}$$

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

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



P-Maki-Nakagawa-Sakata matrix

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

$$U_m = U_{23}\, U_{13}\, U_{12}\, M$$

in VACUUM

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

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

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

4 parameters

$$\theta_{12}, \theta_{23}, \theta_{13}, \delta$$

$$\theta_{12} \approx 0.59^{+0.02}_{-0.015}$$

$$\theta_{23} \approx 0.785^{+0.124}_{-0.124} \approx \frac{\pi}{4}$$

$$\theta_{13} \approx 0.154^{+0.065}_{-0.065}$$

$$\delta = CP \text{ violating phase} = ?$$

in medium it's a different story . . .

neutrinos can scatter on *any* particles that carry weak charge, including *other neutrinos*, and this generates potentials that can make the neutrinos change flavors

like photons acquire an index of refraction when traveling through glass

But, unlike for photons . . .

Potentials that govern how a neutrino changes its flavor depend on the flavor states of neutrino: **NONLINEAR**

Quantum Kinetic Equations

$$i\,D\hat{f} - \left[\hat{\mathcal{H}}, \hat{f}\right] - \hat{U}\left[\hat{\phi}\right] = \text{collision terms}\left(\hat{f}, \hat{\bar{f}}\right)$$

where $\hat{f}$ and $\hat{\bar{f}}$ are 3×3 Hermitian density operators for neutrinos and antineutrinos, respectively, and $\hat{\phi}$ is a 3×3 complex matrix encoding spin coherence.

and where $\hat{\mathcal{H}}$ & $\hat{U}$ give neutrino interactions with matter and other neutrinos

separation of scales ??

Schroedinger-like:

$$i\frac{\partial|\psi\rangle}{\partial t} = \hat{H}|\psi\rangle \text{ with } |\psi\rangle = (\psi_{\mathrm{e}}, \psi_{\mu}, \psi_{\tau})$$

$$\hat{H} = \frac{m^2}{2E} + \hat{H}_{\mathrm{e}\nu} + \hat{H}_{\nu\nu}$$

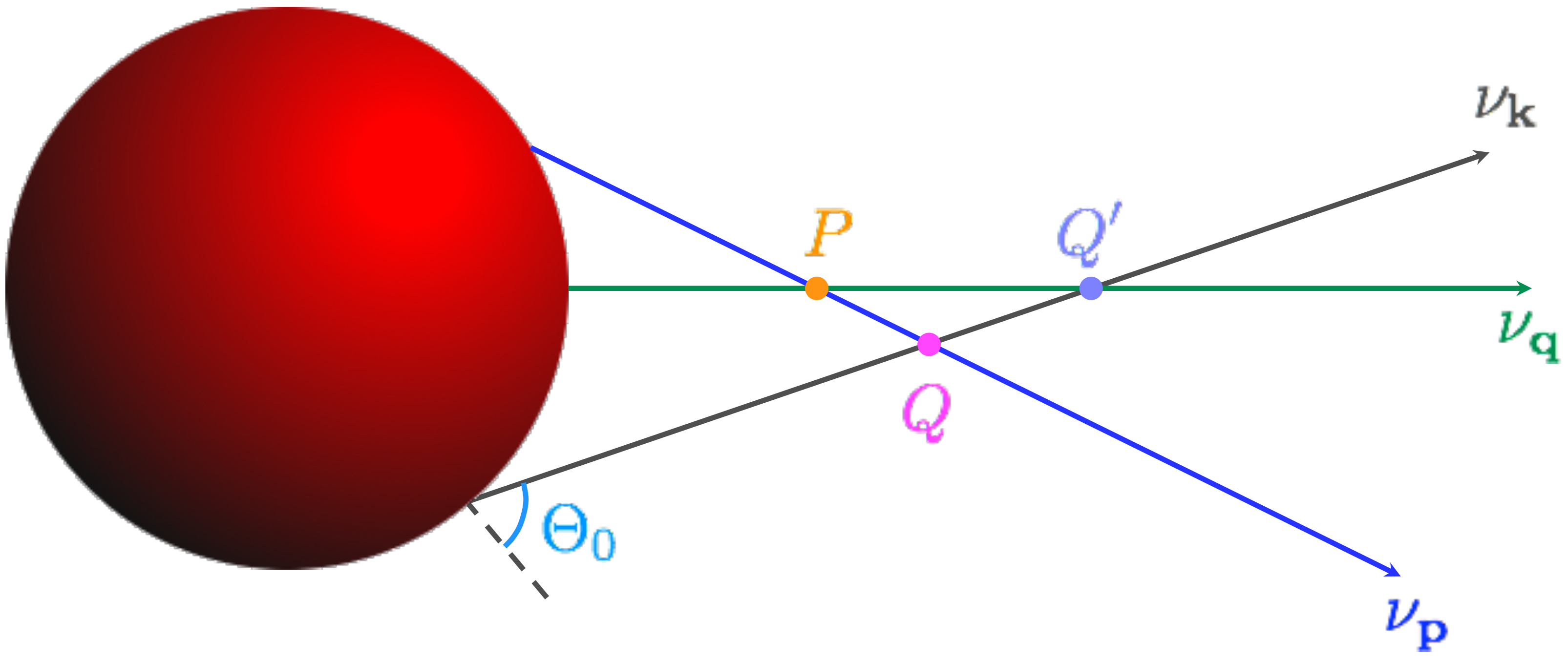
@ "low" density where
neutrinos propagate coherently

Boltzmann equation

@ "high" density where
inelastic scattering dominates

A. Vlasenko, G.M.F., V. Cirigliano (2013), arXiv:1309.2628

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

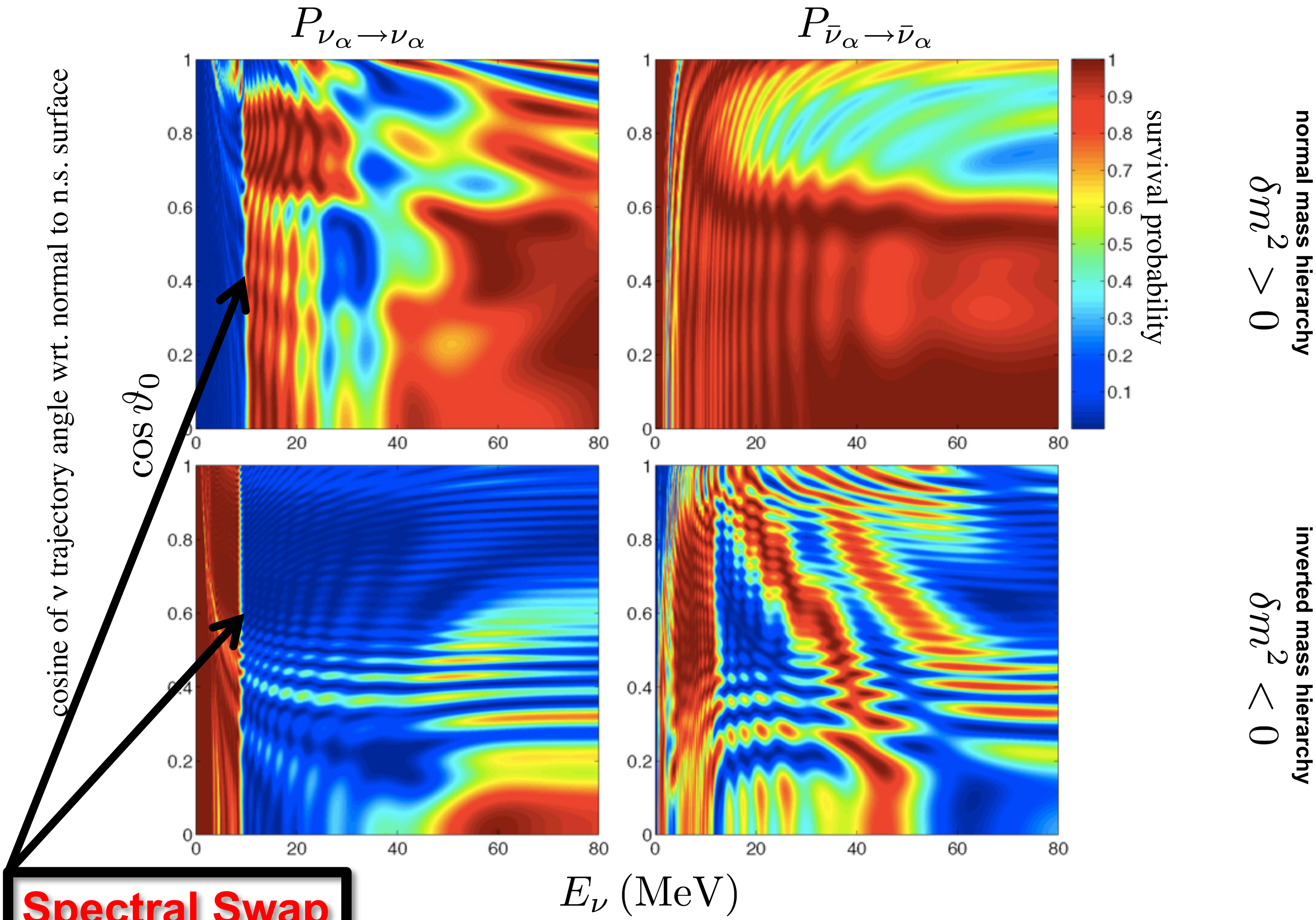


Must solve many *millions* of coupled, nonlinear partial differential equations!!

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

a new kind of quantum transport problem



Spectral Swap

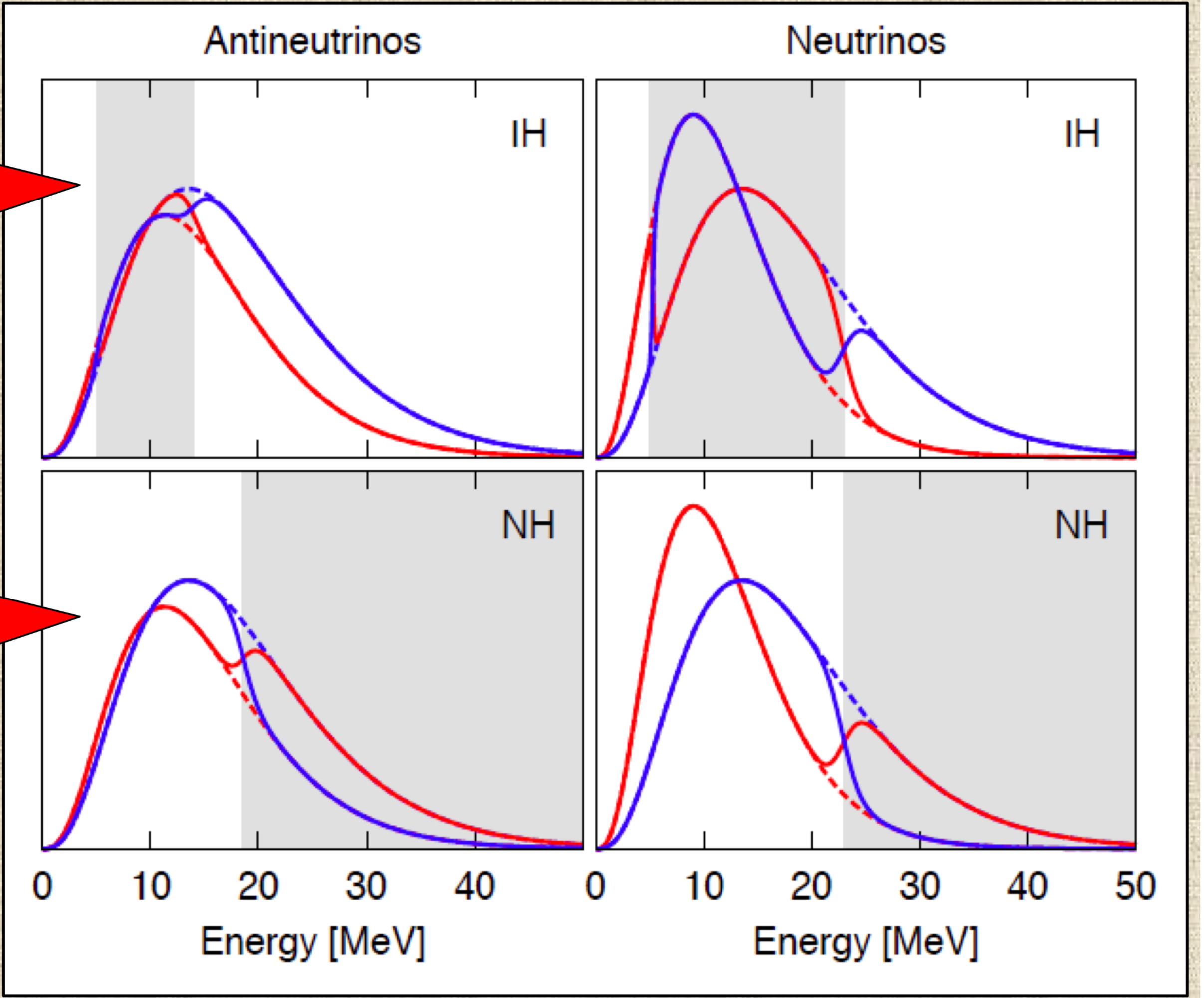
consequences of neutrino mass and quantum coherence in supernovae

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

Multiple Spectral Splits

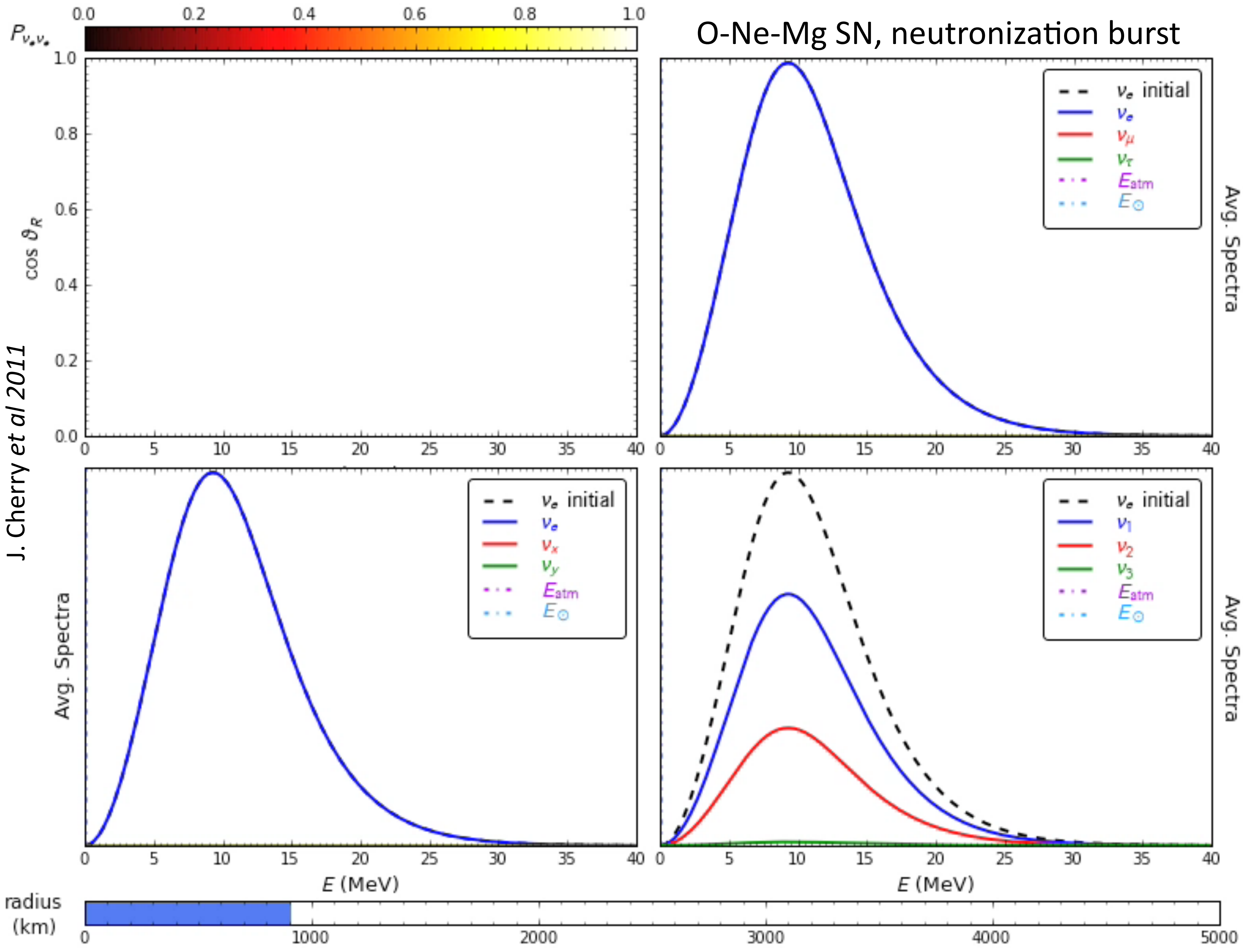
Spectral Splits in
Inverted
Hierarchy

Spectral Splits in
Normal
Hierarchy



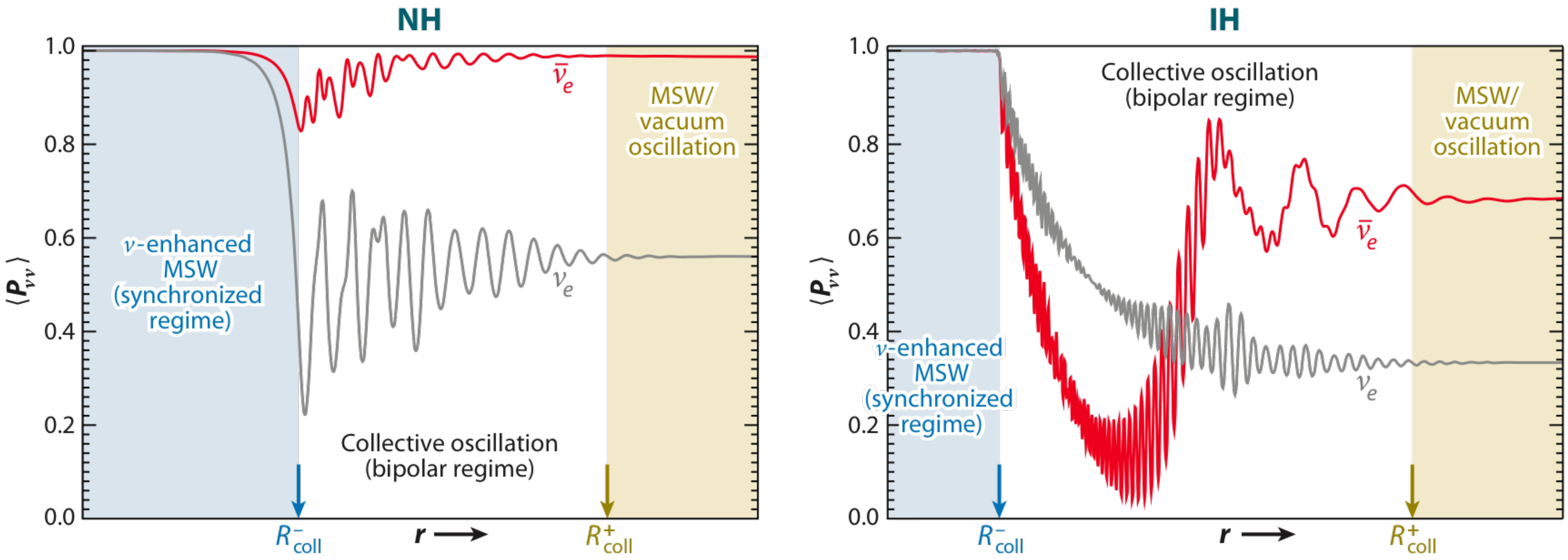
Dasgupta, Dighe, Raffelt and Smirnov, arXiv: 0904.3542 (PRL)

O-Ne-Mg SN, neutronization burst



J. Cherry *et al 2011*

Neutrino Oscillation Regimes in Core Collapse Supernovae



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

Azimuthal asymmetry develops in neutrino flavor field above neutron star

enhanced instability
in the neutrino flavor field
– not easily matter-suppressed

nonlinearity:
neutrino flavor field may not retain the symmetry of the neutrino sphere initial conditions

G. Raffelt, S. Sarikas, and D. de Sousa; ArXiv:1308.1

A. Mirrizi; ArXiv:1308.5255

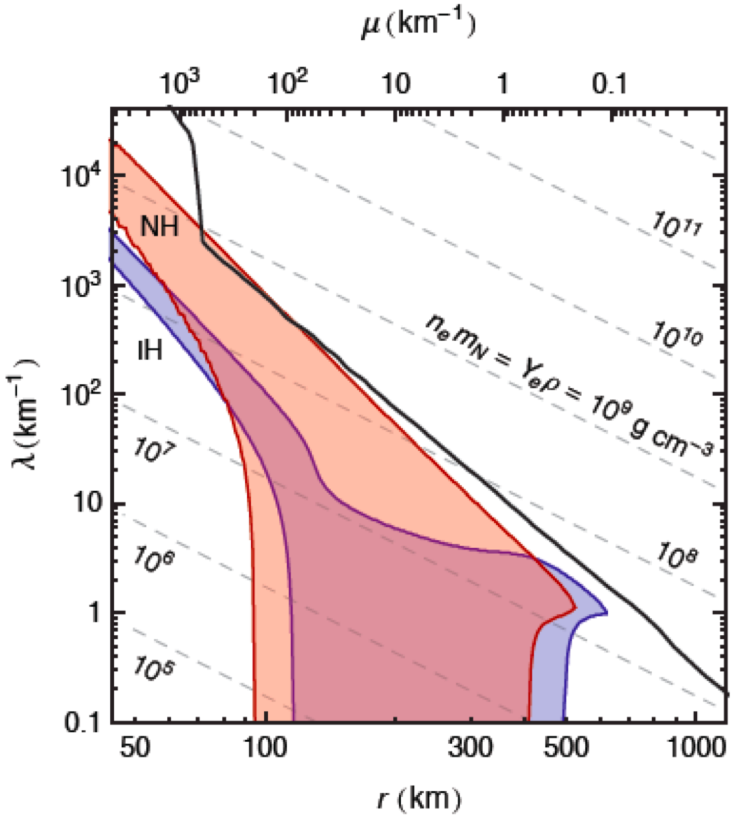
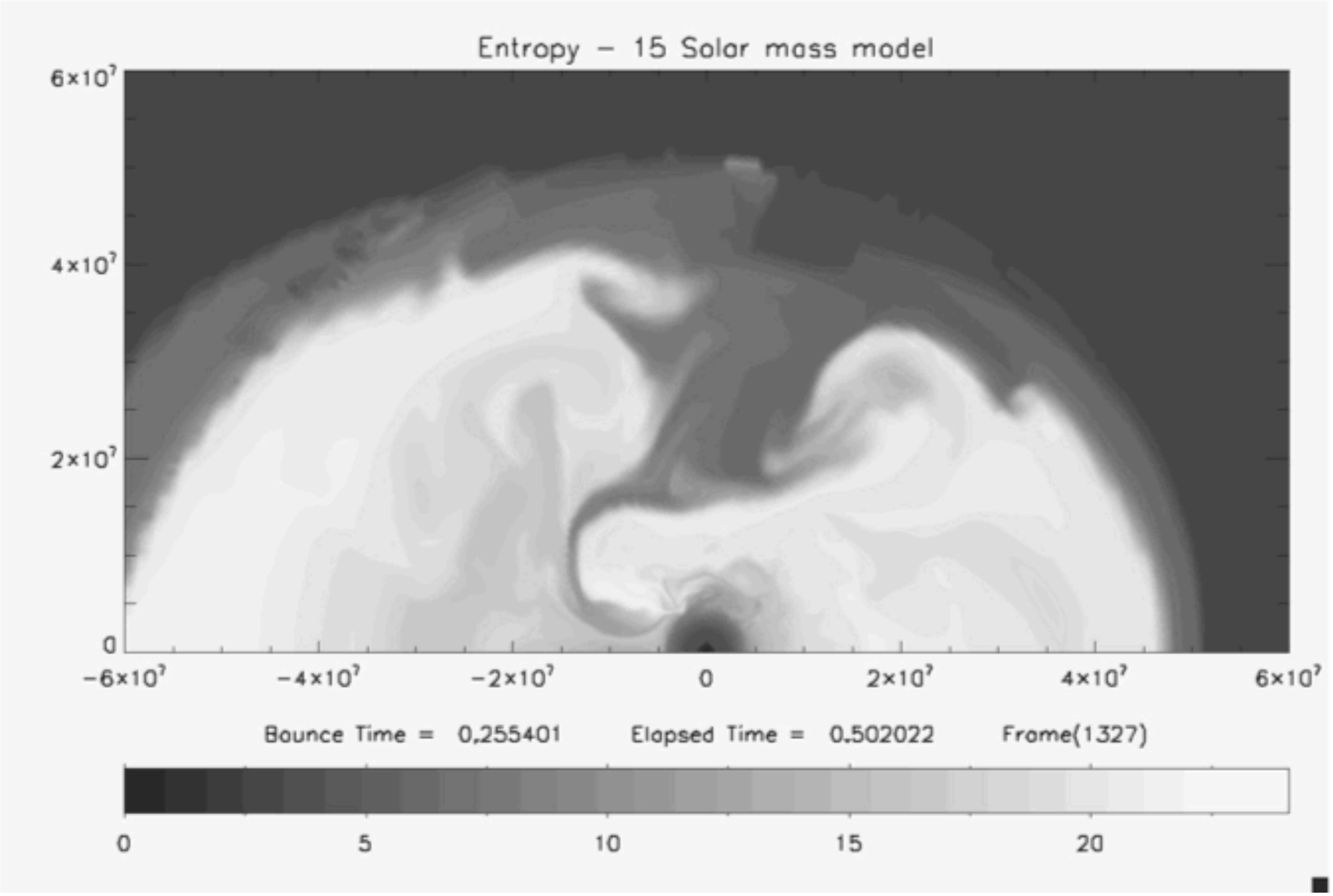


FIG. 2: Region where $\kappa r > 1$ for IH (blue) and NH (red), depending on radius r and multi-angle matter potential λ for our simplified SN model. *Thick black line:* SN density profile. *Thin dashed lines:* Contours of constant electron density, where Y_e is the electron abundance per baryon. (The IH case corresponds to Fig. 4 of Ref. [18], except for the simplified spectrum used here.)

The region above the neutron star can be quite inhomogeneous



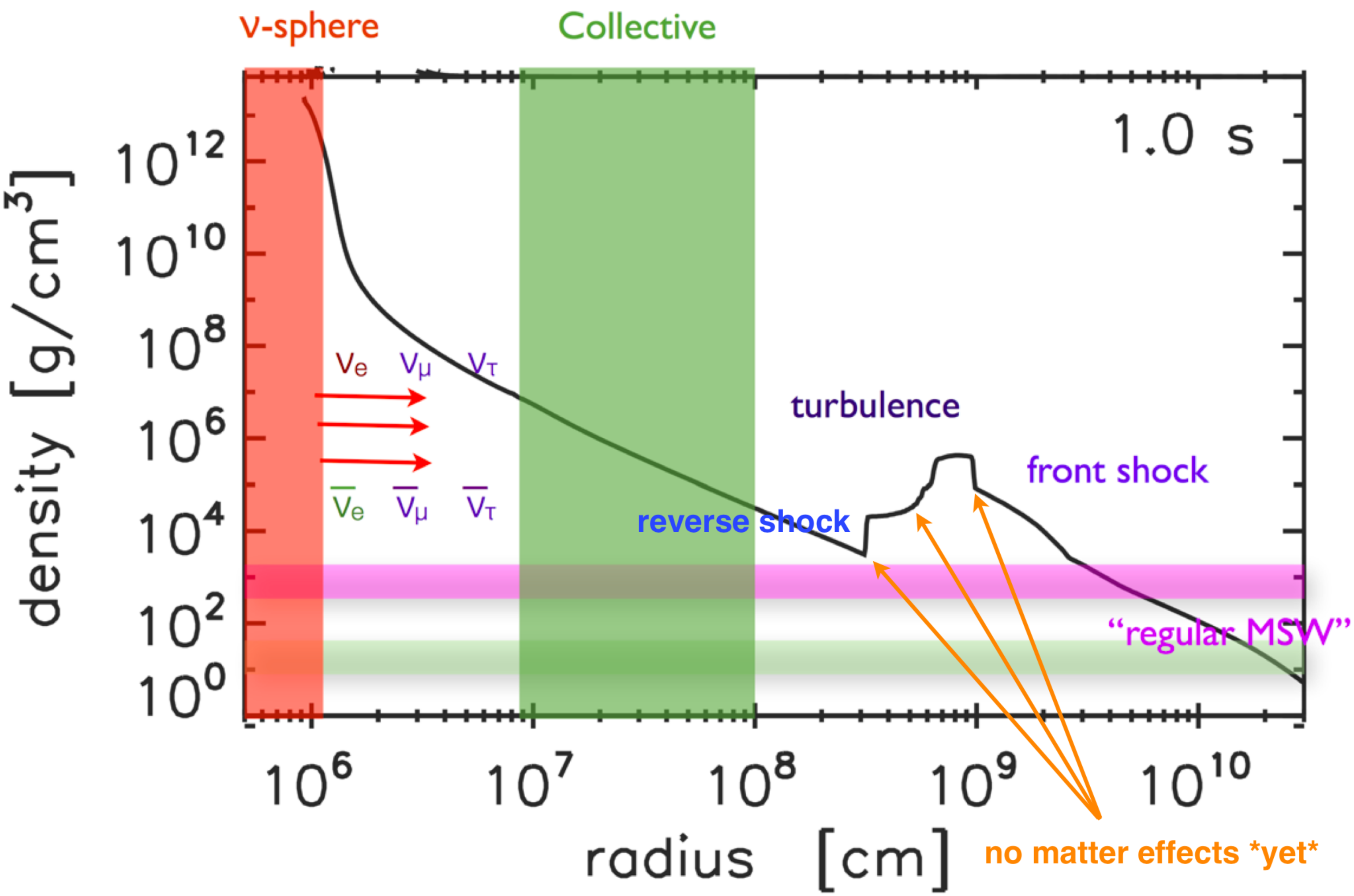
turbulence: (see, e.g., Friedland; Volpe & Kneller 2011)

Effects that can modify or even wash-out the swap signal

-the supernova shock

-turbulence & density fluctuations

-neutrino direction-changing scattering
(quantum kinetic effects)



J. Cherry, H. Duan, A. Friedland, G. Fuller 2013

Toward Quantum Kinetics

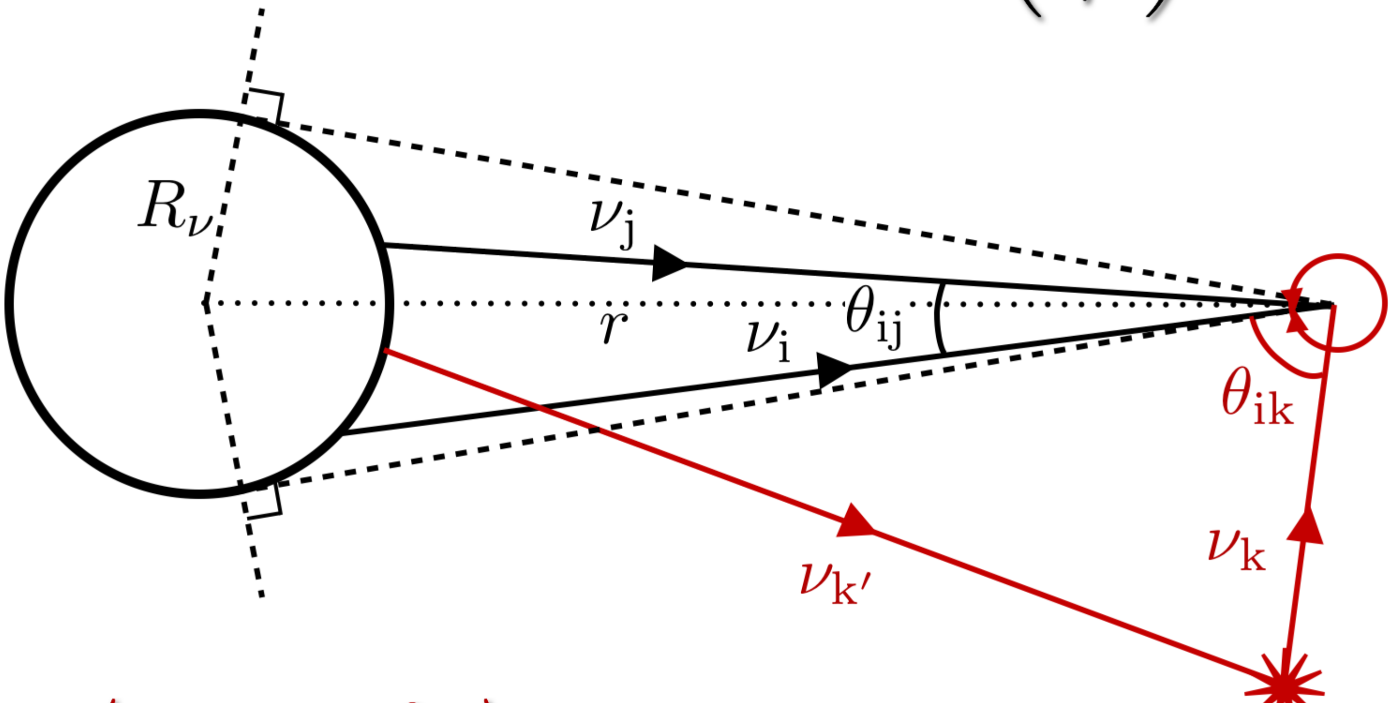
(a) Effects of a small amount of direction-changing scattering on the neutrino flavor transformation? – The Halo

(b) *Spin Coherence*: neutrino-antineutrino inter-conversion

J. Cherry, A. Friedland, G. Fuller, J. Carlson, A. Vlasenko, Phys. Rev. Lett. **108**, 261104 (2012) 1203.1607

The Neutrino Halo

$$r \gg R_\nu \Rightarrow \langle 1 - \cos\theta_{\mathrm{ij}} \rangle \propto \left(\frac{R_\nu}{r}\right)^2$$

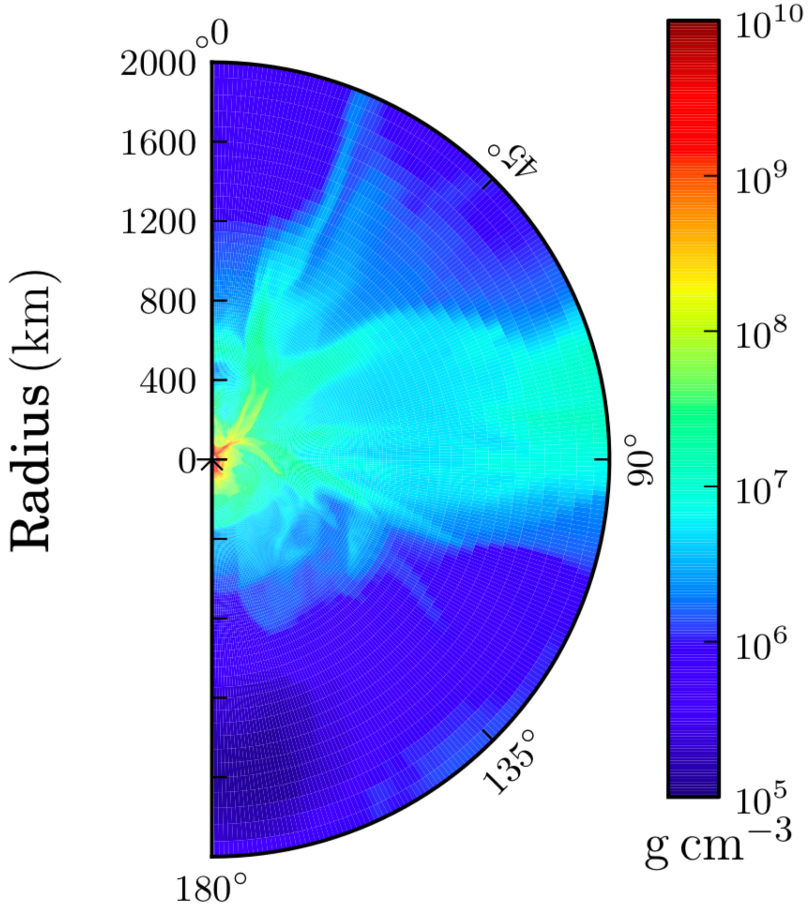


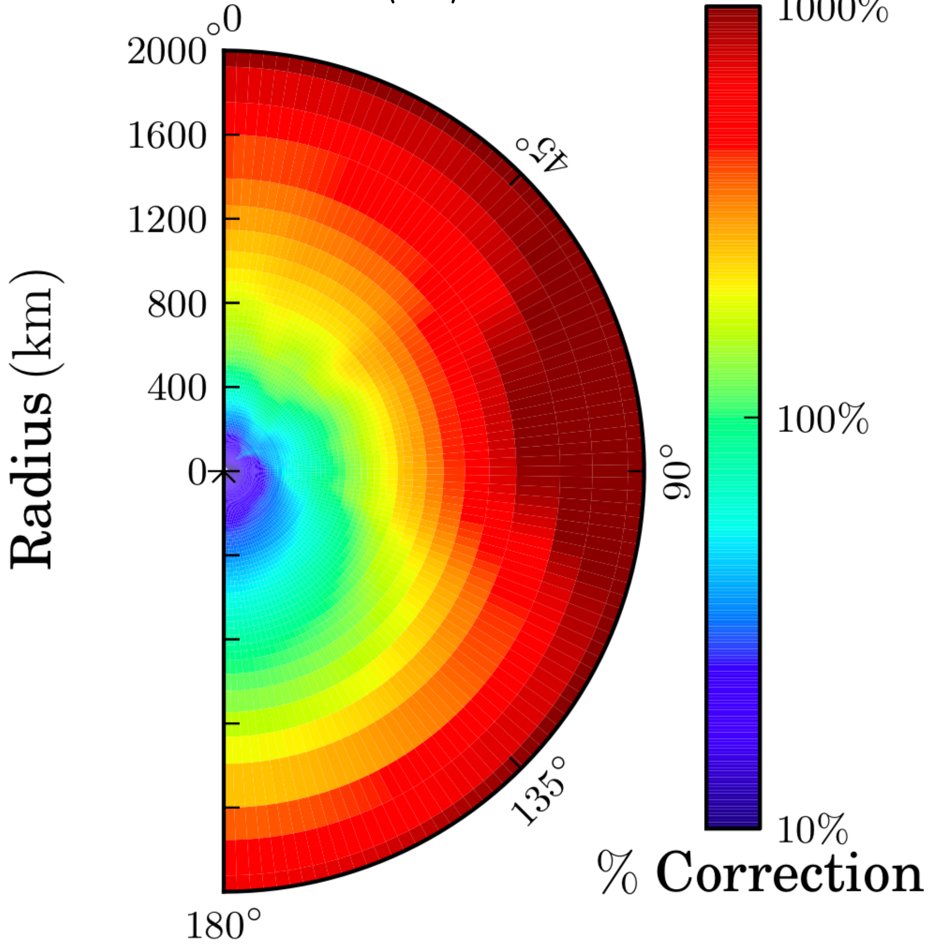
$$\langle 1 - \cos\theta_{\mathrm{ik}} \rangle \approx 1$$

$\sim 10^{-3}$ of all ν's

How large is the Halo effect for free nucleons?

$$\sigma_{\text{coherent}} \propto A^2 \;\Rightarrow\; \mathcal{H}_{\text{halo}} \propto \langle A \rangle$$





J. F. Cherry, A. Friedland, G. M. Fuller, J. Carlson, and A. Vlasenko, Phys. Rev. Lett. **108**, 261104 (2012), 1203.1607.

the Halo converts the neutrino flavor evolution problem from an *initial value problem* into a *boundary value problem*

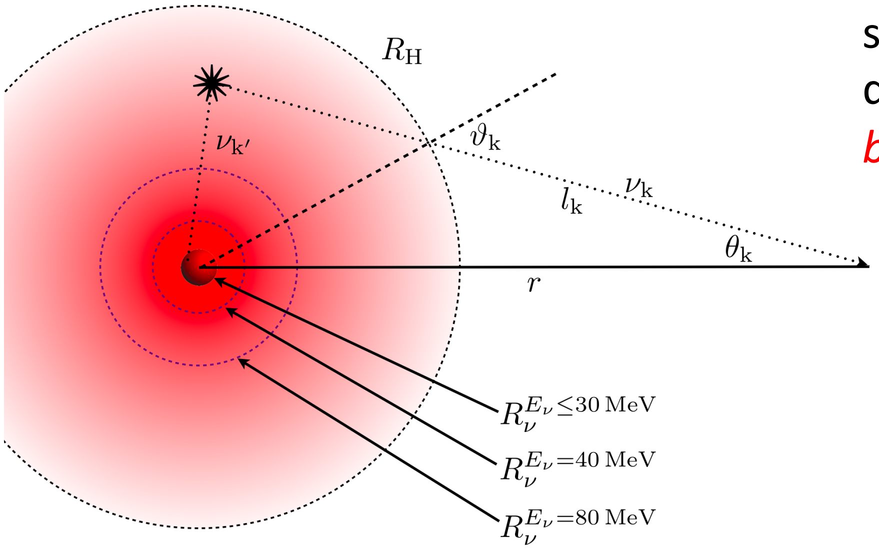
(quantum flavor information *coming down* from outer regions of star)

and moreover couples in nuclear composition in a completely new way

stability analyses suggest little effect from Halo during shock re-heating/accretion phase

(S. Sarikas, I. Tamborra, G. Raffelt, L. Hudepohl, H.T. Janka PRD **85**, 113007 (2012) 1204.0971;

A. Mirizzi & P.D. Serpico, PRD **86**, 085010 (2012) 1208.0157) – But these studies leave out much of the halo and do not capture the composition/inhomogeneous effects

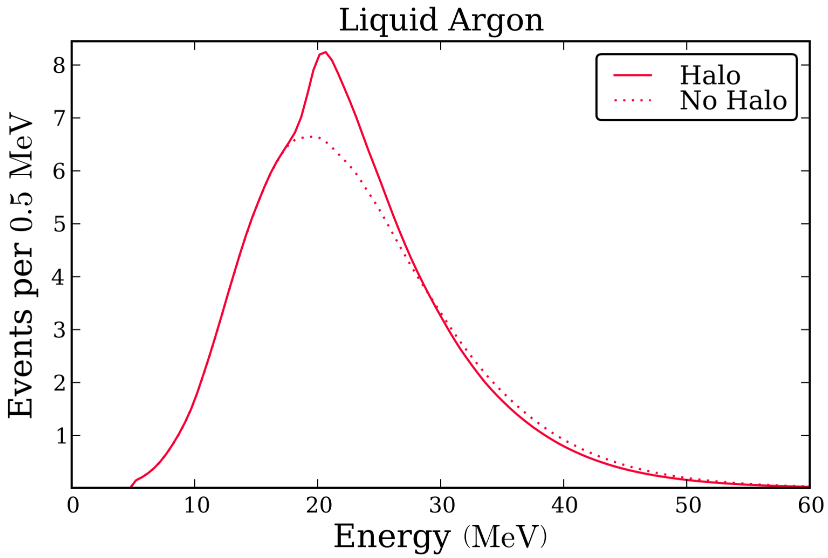


O-Ne-Mg Core Collapse – *very centrally-condensed*, so we *can* model the Halo with our initial value code: quantum mechanical information all coming from *below* region of collective oscillations!

Dispersion/de-coherence in Halo causes neutrino trajectory-dependent swap energy, which could have consequences for a detected neutrino signal

With Halo fewer high energy ν_e's are transformed

$\Rightarrow$ more ν_e-induced events in detector



J. Cherry, J. Carlson, A. Friedland, G.M.F, A. Vlasenko, PRD **87**, 085037 (2013). arXiv:1302.1159

Quantum Kinetic Equations

A. Vlasenko, G.M.F., V. Cirigliano (2013), arXiv:1309.2628

$$i\,\mathcal{D}\,[\mathcal{F}] - [\mathcal{H},\ \mathcal{F}] - \left(\Delta\mathcal{H}\,\mathcal{F}_\phi - \mathcal{F}_\phi\,\Delta\mathcal{H}^\dagger\right) = i\,\mathcal{C}\,[\mathcal{F}]$$

$$i\,\mathcal{D}\,[\mathcal{F}] - [\mathcal{H},\ \mathcal{F}] \approx i\,\mathcal{C}\,[\mathcal{F}]$$ a 6X6 matrix formulation

$\mathcal{F} = \begin{bmatrix} f & \phi \\ \phi^\dagger & \bar{f}^{\mathrm{T}} \end{bmatrix}$ $f(x,p)$ and $\bar{f}(x,p)$ are neutrino/antineutrino density operators, so they are 3×3 matrices $\Rightarrow$ $\begin{bmatrix} f_{11} & f_{12} & f_{13} \\ f_{21} & f_{22} & f_{23} \\ f_{31} & f_{32} & f_{33} \end{bmatrix}$

$$\Downarrow$$

Boltzmann limit $\Rightarrow$ $\begin{bmatrix} f_{11} & 0 & 0 \\ 0 & f_{22} & 0 \\ 0 & 0 & f_{33} \end{bmatrix}$

neutrino-antineutrino transformation

Here ϕ is a new dynamical quantity encoding neutrino spin/helicity

Collision terms $\Rightarrow$ $\mathcal{C} = \begin{bmatrix} C & C_\phi \\ C_\phi^\dagger & \bar{C}^{\mathrm{T}} \end{bmatrix}$

and the Hamiltonian is $\mathcal{H} = \begin{bmatrix} H & H_{\nu\bar{\nu}} \\ H_{\nu\bar{\nu}}^\dagger & -\bar{H}^{\mathrm{T}} \end{bmatrix}$

with $H_{\nu\bar{\nu}} = \dfrac{-1}{|\vec{p}|}\left(\Sigma^+\,m^* + m^*\,\Sigma^{+\,\mathrm{T}}\right)$

with Σ^+ spacelike potentials orthogonal to neutrino trajectory

Coherent Limit

low densities $\Rightarrow$ potentials small, $\Sigma \ll m$, collision term smaller still, so drop Σ^2 and maybe $m\Sigma$ terms. Then ϕ decouples and we have

$$i\,\frac{p^\mu}{E}\partial_\mu f - [H, f] = 0 \quad \text{with} \quad H = \Sigma^\kappa + \frac{m^\dagger\,m}{2E}$$

$$i\,\frac{p^\mu}{E}\partial_\mu \bar{f} - [\bar{H}, \bar{f}] = 0 \quad \text{with} \quad \bar{H} = \Sigma^\kappa - \frac{m^\dagger\,m}{2E}$$

This is the Schrödinger Equation for the wave functions $|\psi\rangle$ given earlier.

$\Rightarrow$ collision terms mix different energy & flavor states, averaging out the off-diagonal terms, so f diagonal

$\Rightarrow$ no coherence $[f, H] = 0$

$\Rightarrow$ mass terms small enough to discard, but must be careful because of nonlinearity

$H_{\nu\bar{\nu}} \propto \dfrac{m}{E}$ (weak magnetic vector potential)

$\Rightarrow$ particles must have mass

$\Rightarrow$ need anisotropic matter/neutrino potentials, with components $\perp$ to neutrino momentum

$\Rightarrow$ spin coherence density ϕ must be present

$$\Rightarrow \quad \frac{p^\mu}{E}\partial_\mu f_\alpha = \Pi^+_\alpha\,(1 - f_\alpha) - \Pi^-_\alpha\,f_\alpha \quad \text{with} \quad \alpha = e, \mu, \tau$$

Π functions $\Rightarrow$ usual Boltzmann gain-loss terms (depend on matter and ν densities)

Neutrino-Antineutrino inter-conversion

interesting analogy to Majorana neutrino spin precession in a ***real magnetic field***

A. de Gouvea & S. Shalgar arXiv:1301.5637 showed that
standard model neutrino transition magnetic moment (~ 10^{-22} Bohr magnetons)
could engender *collective* neutrino-antineutrino oscillations – require ~ 10^{12} Gauss fields

similar process with QKE spin coherence, but no magnetic field required
--- sensitive to Majorana/Dirac nature of neutrinos, absolute mass

neutrino-antineutrino conversion
potentially very important for nucleosynthesis
because the relative mix of neutrinos and antineutrinos
determines neutron-to-proton ratio

CONCLUSIONS

- Experimental neutrino physics has given us *some* of the mass/mixing properties of the neutrinos.
  Neutrino flavor evolution is sensitive to these, but may be sensitive to other issues, e.g., *hierarchy*, *magnetic moments*, *absolute mass*, *Majorana/Dirac* nature.

- Neutrino self coupling-induced ***nonlinearity*** has led to surprises and may lead to more
  --very difficult to incorporate into existing SN simulations
  -- our existing neutrino flavor simulations in SN are crude –hard to conclude anything

- Despite uncertainties in calculations, it is imperative that we build and maintain an underground detector to capture a Galactic core collapse event

  – swaps/splits are generic and will likely form at *late times (where neutrino fluxes are low!)*

  -- will learn a great deal about supernovae, *e.g., if experiment gives us the hierarchy*

  -- heavy element nucleosynthesis, *e.g., r-Process models can be sensitive to*
  neutrino/antineutrino ratio,
  which can influence the neutron/proton ratio