Supernova Neutrinos: High Stakes for Particle & Astrophysics

Cosmic Frontier

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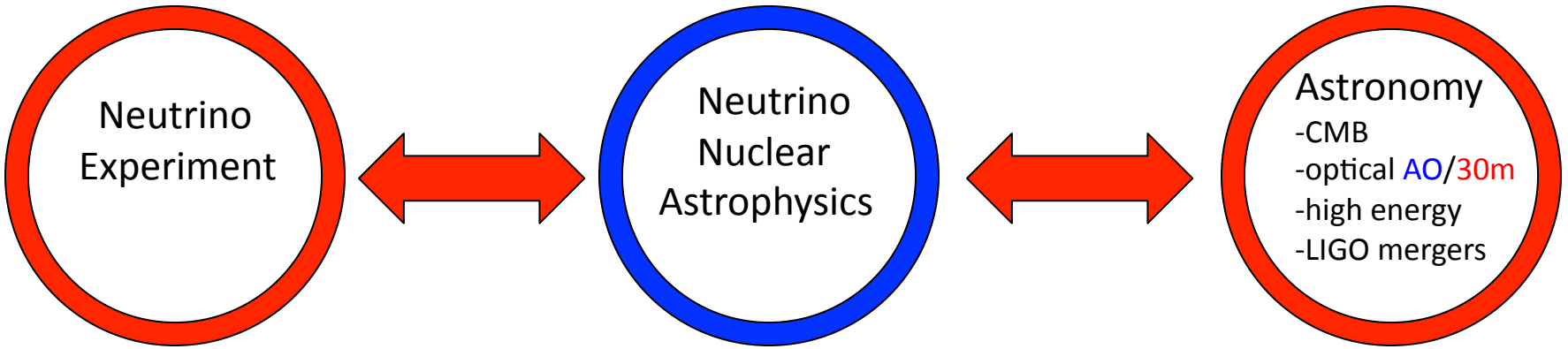
This is the golden age for both Neutrino Physics *and* Observational Astronomy

discoveries have been coming fast and thick
and, for neutrinos, this is all ***Beyond Standard Model*** physics

Neutrino/Nuclear Astrophysics is right in the middle of all this



VERY EXCITING **future** . . . because the advent of . . .

(1) comprehensive cosmic microwave background (CMB) observations
(e.g., high precision baryon number and cosmological parameter measurements, N_{eff}, ^4He, ν mass limits)

(2) 10-meter class, adaptive optics, and orbiting telescopes
(e.g., precision determinations of deuterium abundance, dark energy/matter content, structure history etc.)

(3) Laboratory neutrino mass/mixing measurements – Will LBNE be among them?

is setting up a nearly over-determined situation where new Beyond Standard Model neutrino physics likely ***must*** show itself!

At Stake . . .

Fundamental neutrino physics (mass, origin of mass)

Origin of the elements; Origin of structure

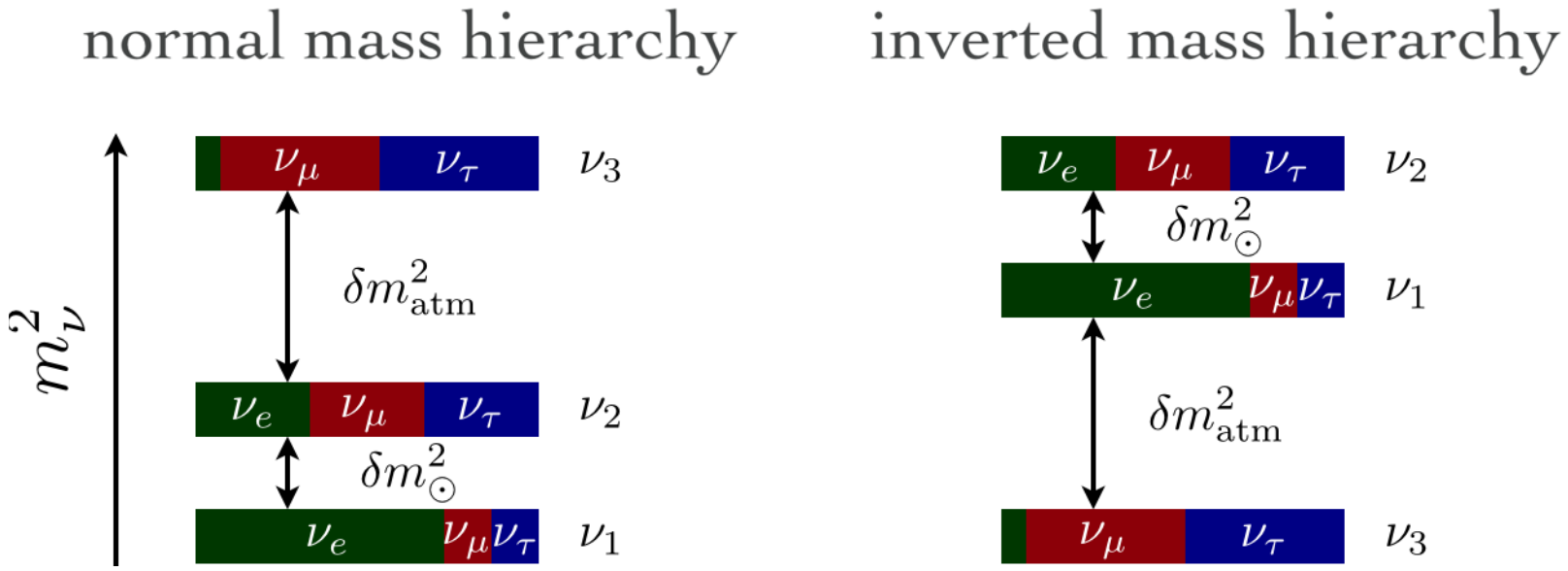
Neutrino Mass: what we know and don't know

We know the *mass-squared* differences:

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

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

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



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

P-Maki-Nakagawa-Sakata matrix

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

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

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

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

4 parameters

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

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

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

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

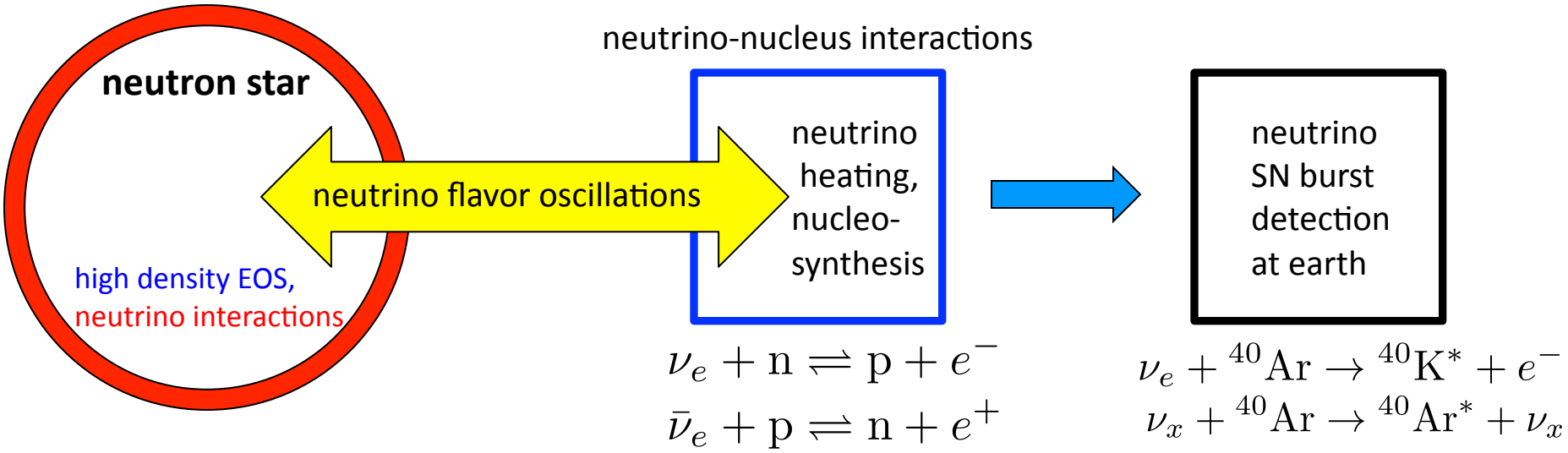
$\delta = CP$ violating phase $=?$

The basic picture of collapse of a stellar core
to a neutron star with attendant prodigious neutrino production
is absolutely settled science, confirmed by the SN1987a
observations of neutrinos. **NOT MODEL DEPENDENT**

What remains to be understood is *how* these neutrinos affect
the explosion/dynamics and nucleosynthesis.

Since neutrino flavor affects how these particles interact in matter
we have no choice but to calculate neutrino flavor histories.

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 nuclear physics of stellar collapse.



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*

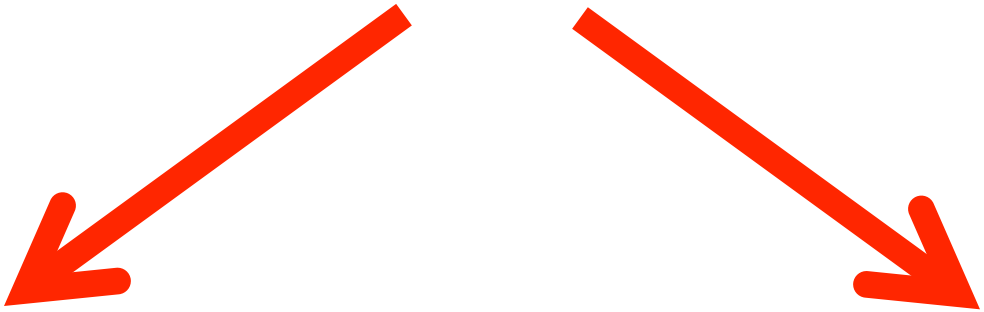
Neutrino Flavor Oscillations

in Medium

Quantum Kinetic Equations

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

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



Schroedinger-like

@ low density where
neutrinos propagate coherently

Boltzmann equation

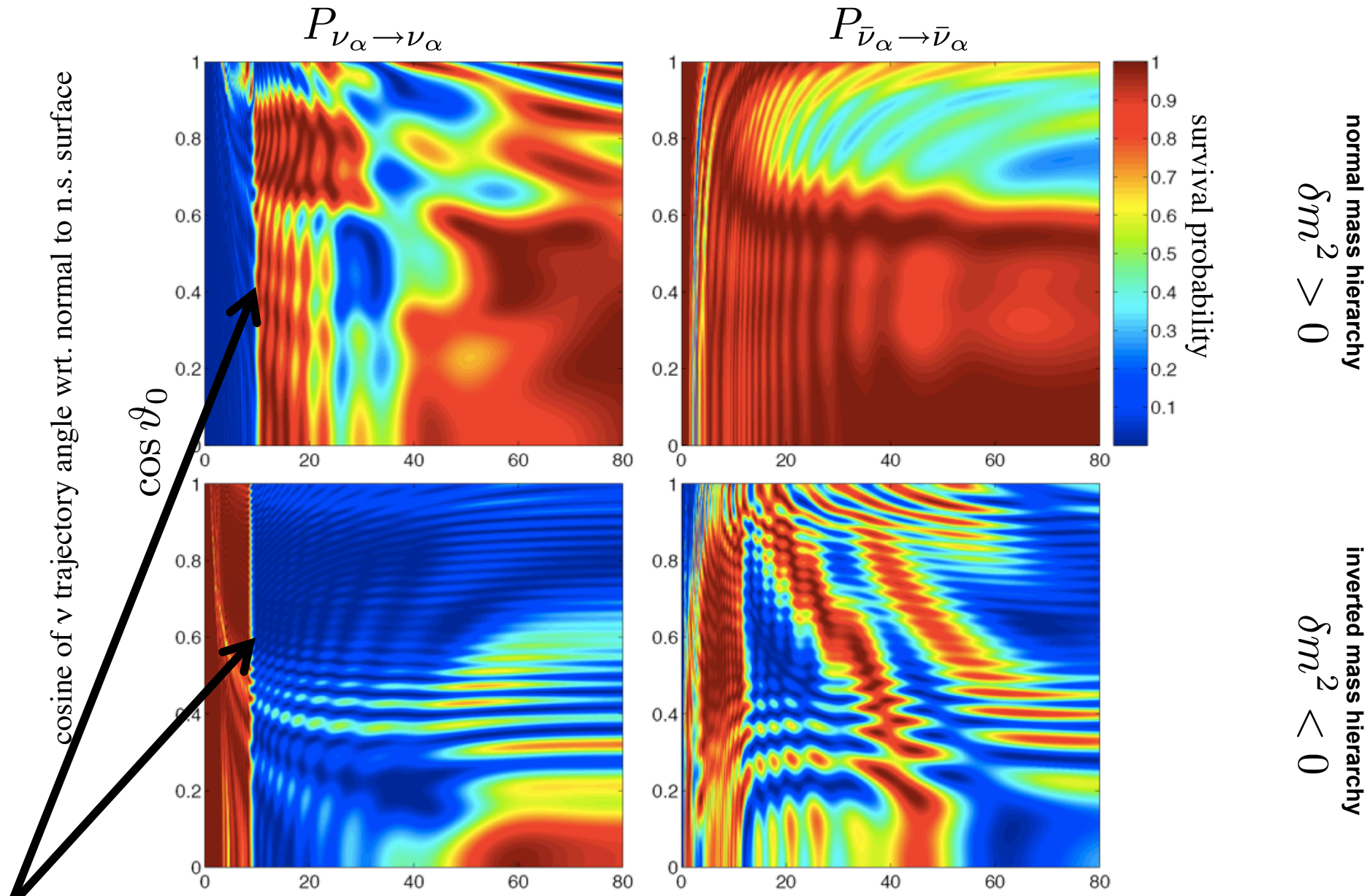
@ high density where
inelastic scattering dominates

A. Vlasenko, V. Cirigliano, G. Fuller 2012

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

Pushing the frontier of high performance computing with a unique new kind of transport problem



consequences of neutrino mass and quantum coherence in supernovae

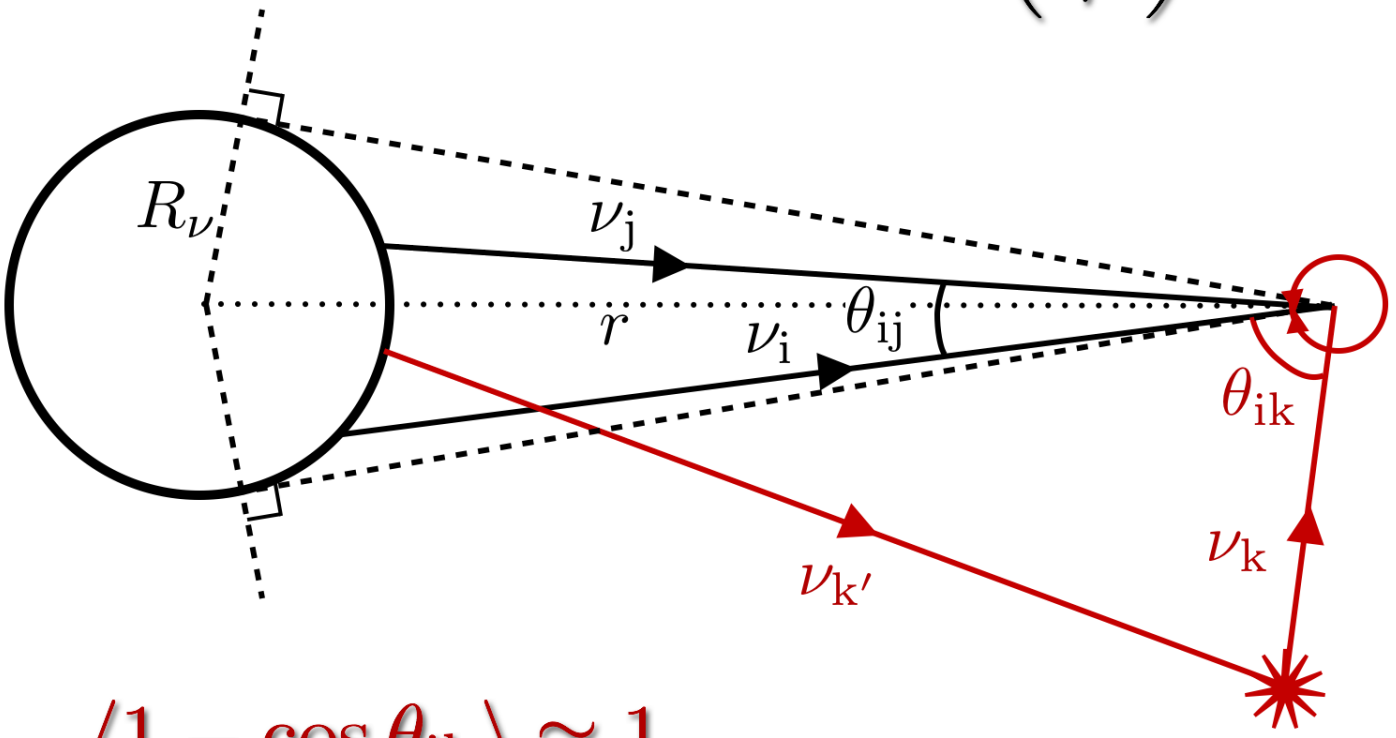
H. Duan, G. M. Fuller, J. Carlson, Y.-Z. Qian, Phys. Rev. Lett. **97**, 241101 (2006) **astro-ph/0606616**

Toward Quantum Kinetics

i.e., what effect does direction-changing scattering have on the neutrino flavor transformation

The Neutrino Halo

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

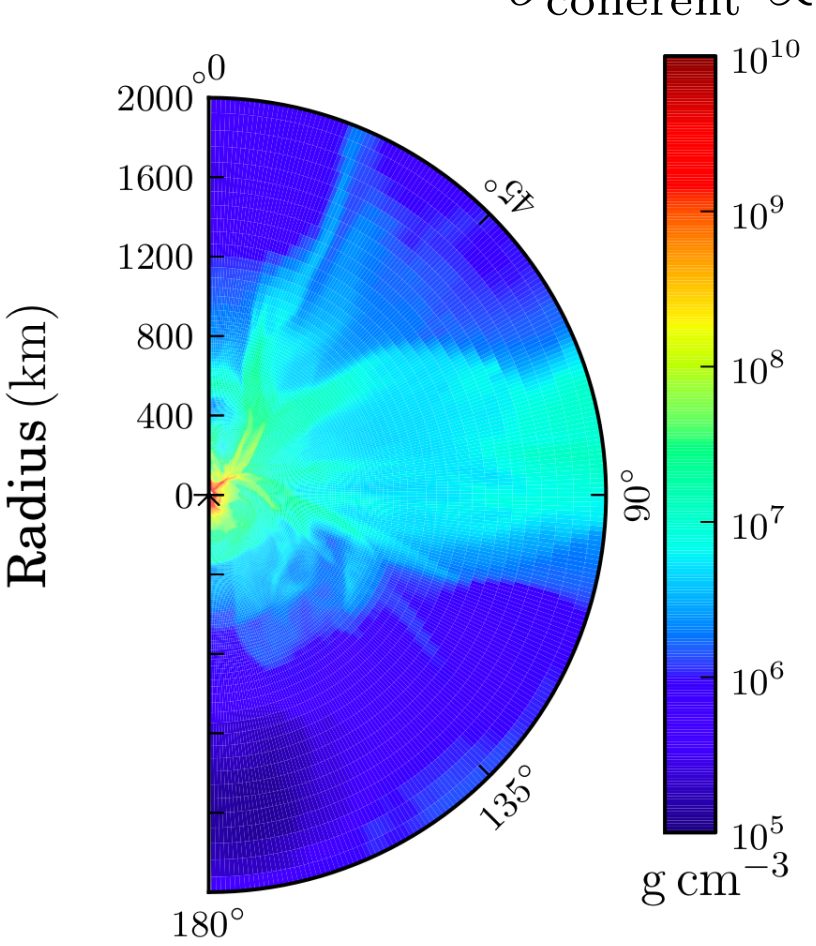


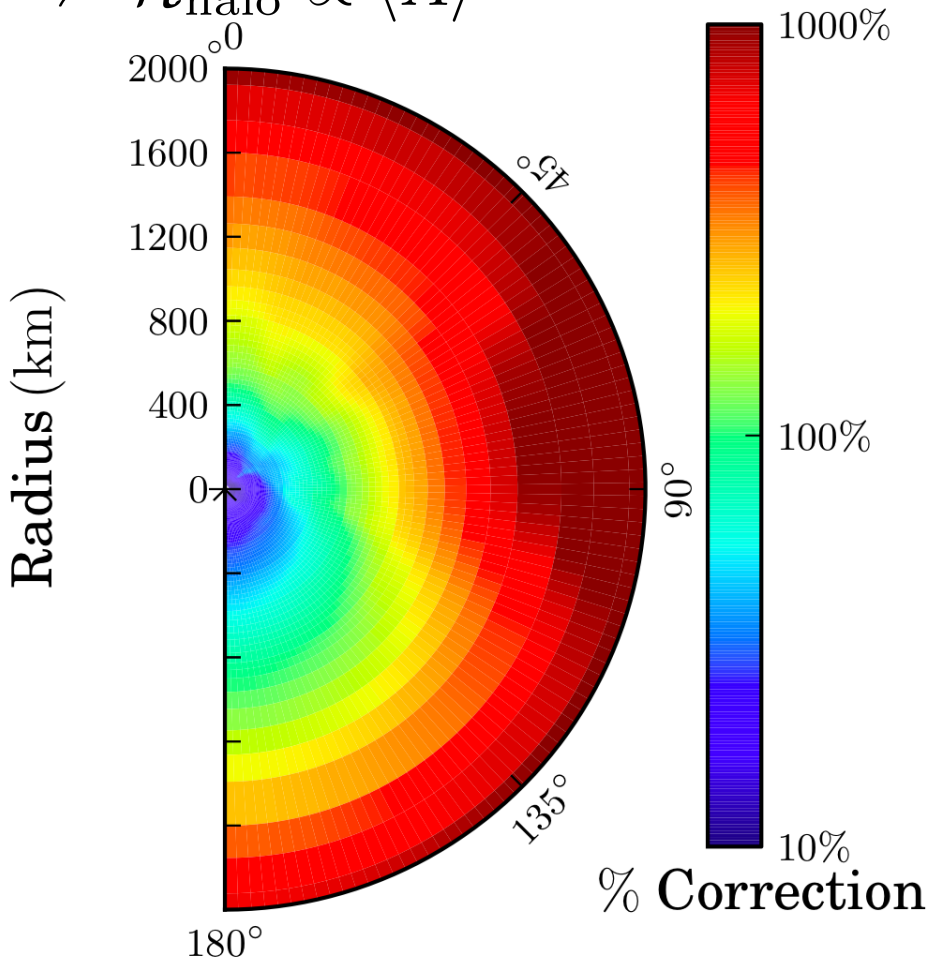
$$\langle 1 - \cos\theta_{ik} \rangle \approx 1$$

$\sim 10^{-3}$ of all ν's

How large is the Halo effect for free nucleons?

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





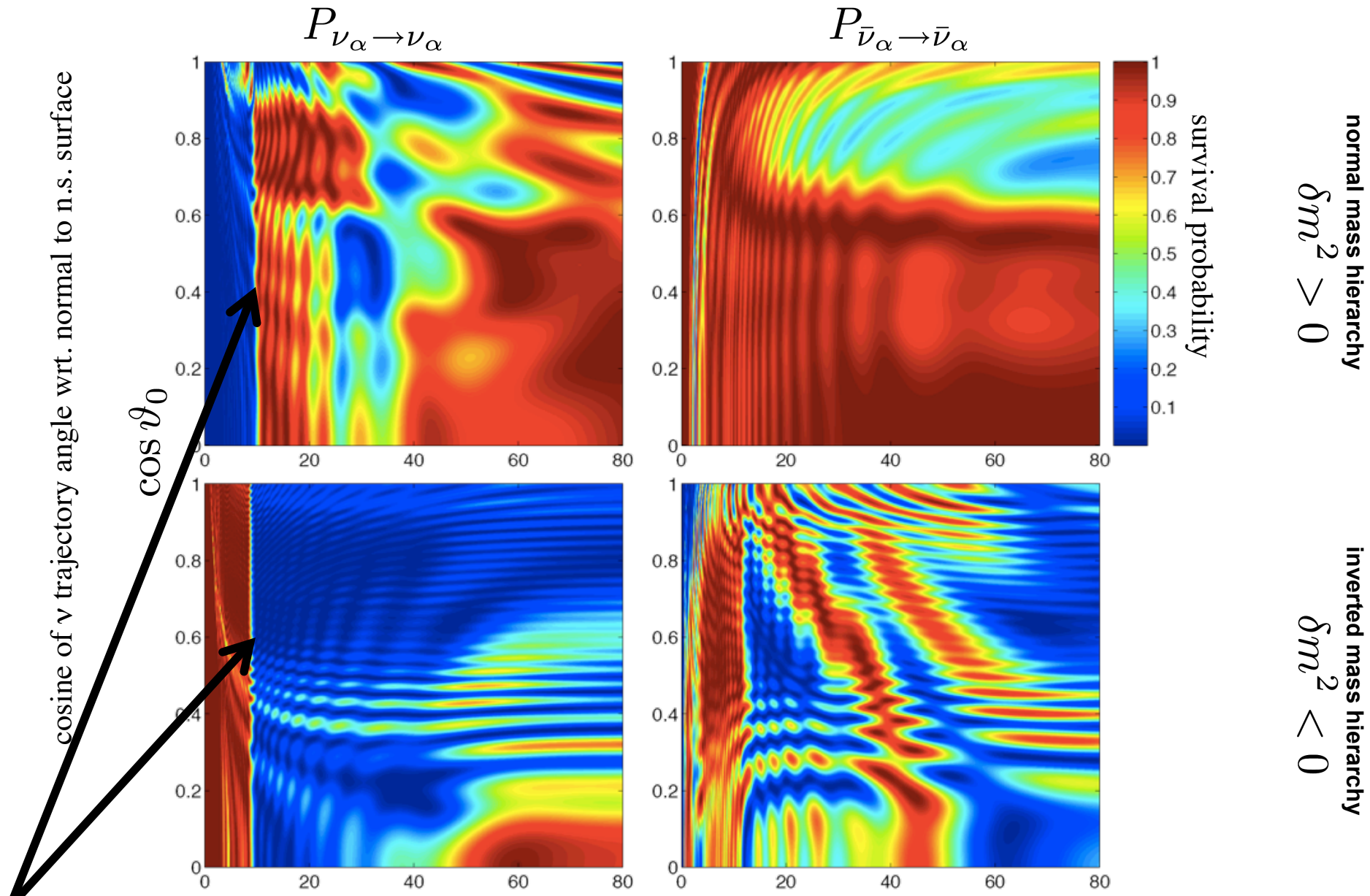
J. F. Cherry, A. Friedland, G. M. Fuller, J. Carlson, and A. Vlasenko, Phys. Rev. Lett. **108**, 261104 (2012), 1203.1607.

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

(quantum flavor information coming down from above)

and moreover couples in nuclear composition
in a completely new way

Detecting a Classic Swap



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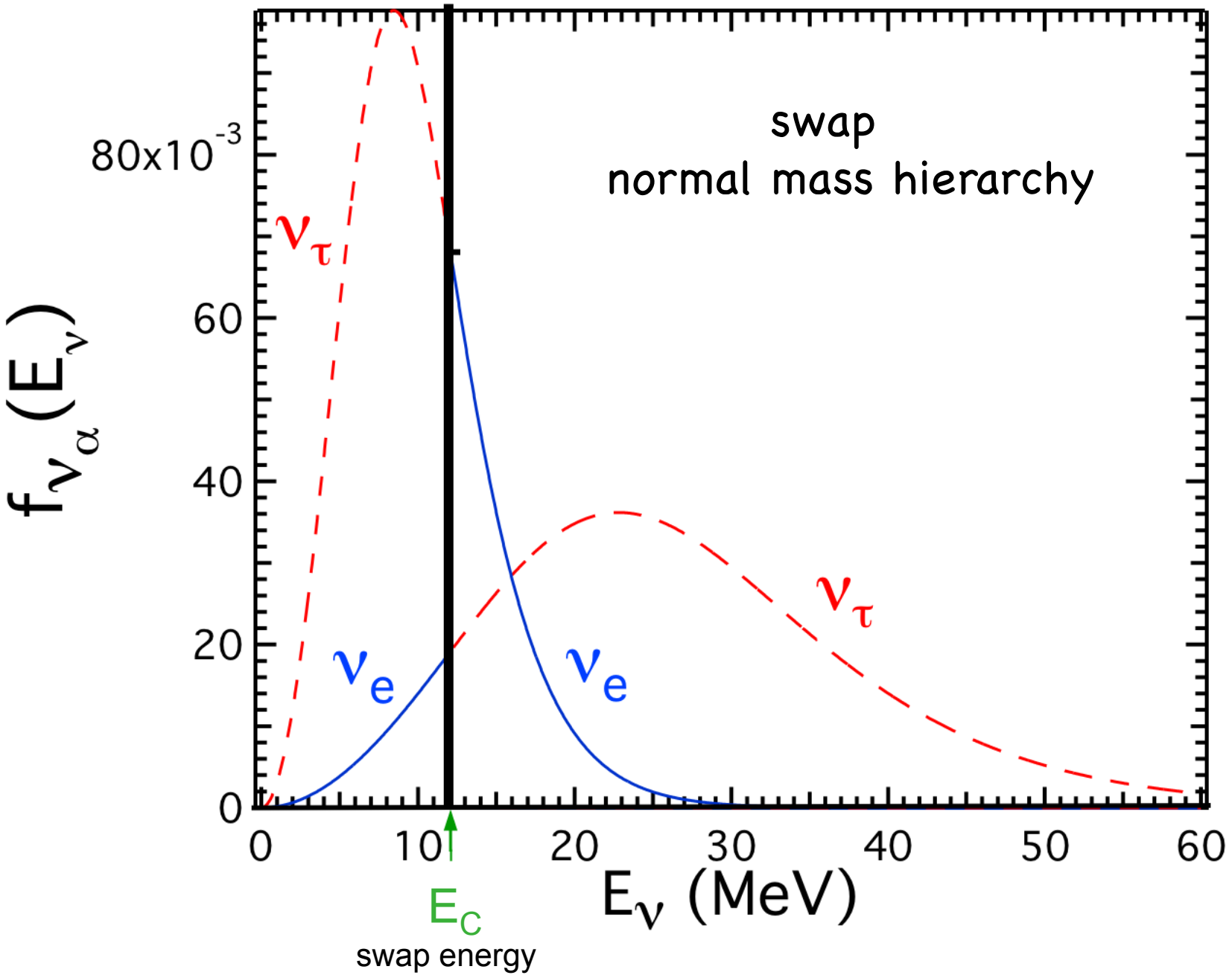
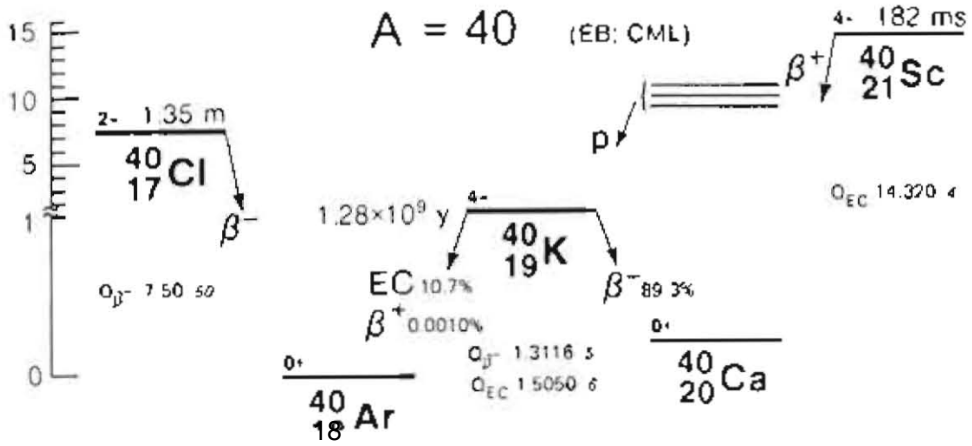

swap
normal mass hierarchy
80x10^-3
60
40
20
0
$f_{\nu_\alpha}(E_\nu)$
ν_τ
ν_e
ν_e
ν_τ
0
10
20
30
40
50
60
E_ν (MeV)
E_C
swap energy

Re-think strategy for detecting the neutrino signal from a future Galactic supernova:

- Swap features that could tell us the neutrino mass hierarchy are at relatively low energy, like solar neutrinos, at least for Fe-core collapse supernovae.
- Swap features *could* occur at late times post-core-bounce, when neutrino fluxes are low.
- liquid scintillator and liquid noble gas (LAr) detectors are IDEAL.

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 MeV - A. Hayes

Gamow-Teller resonance

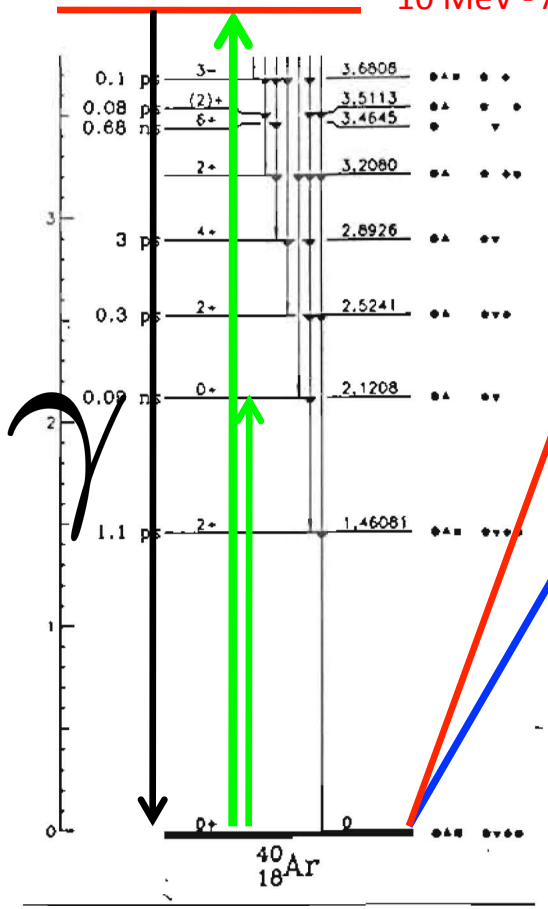
Fermi resonance
(IAS)

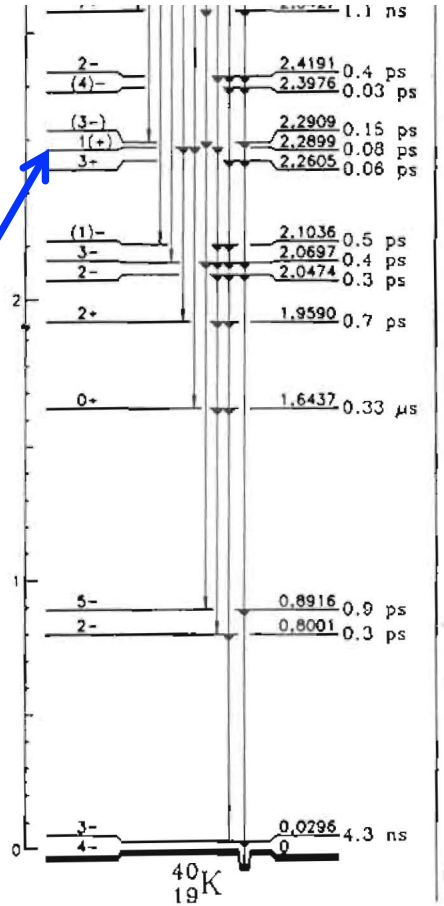
Carlson
group at LANL

ν_e

γ

e^-





10 kT Liquid Argon Detector

Supernova at 10 kpc

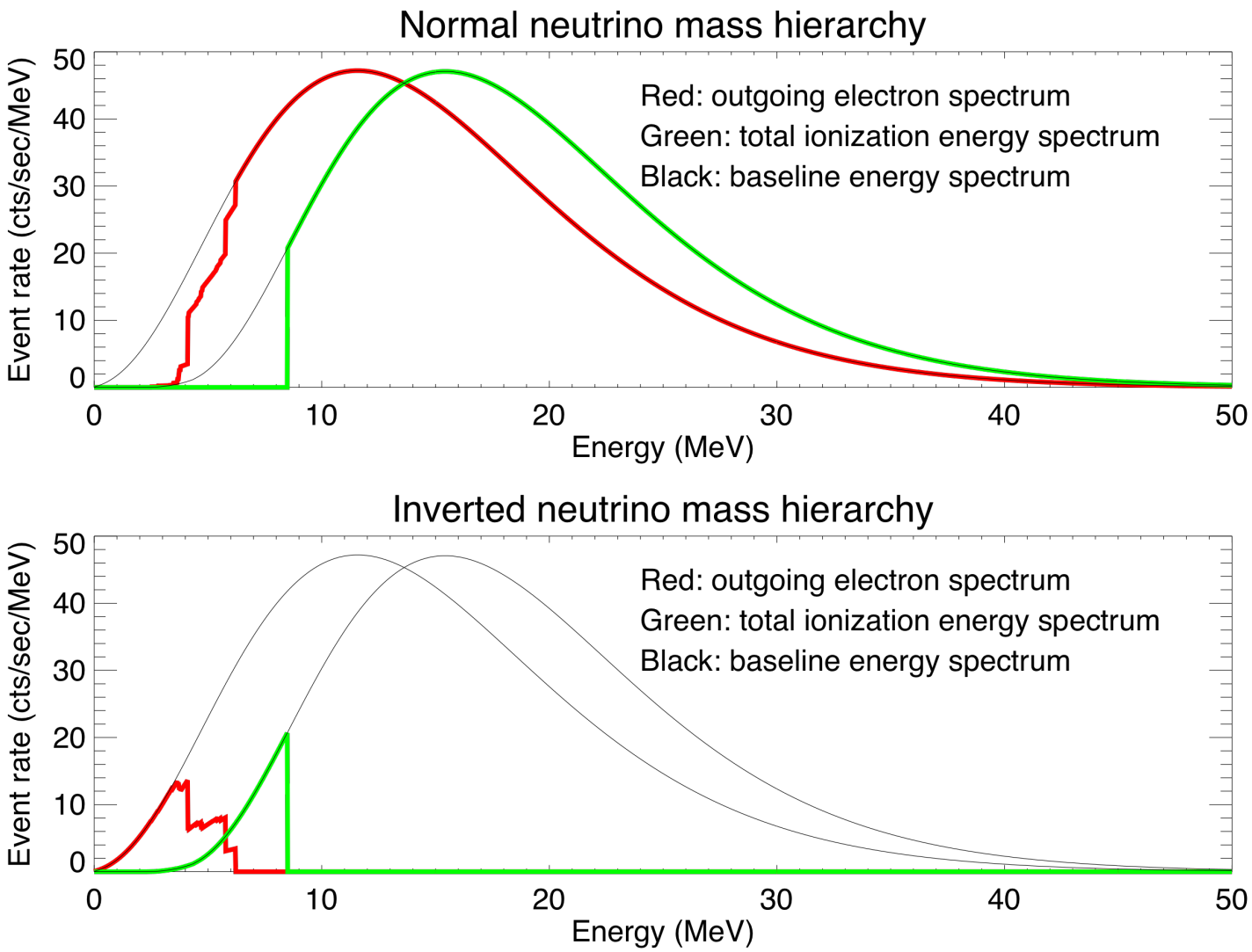
Total number of electron events = 233

8 in first 10 ms

150 between 10 ms and 2 s

75 after 2 s

David Cline, G.M.F., Kevin Lee, Tom Skelton (2012)


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)