Supernova Neutrinos
and
a little cosmology

TAUP Summer School

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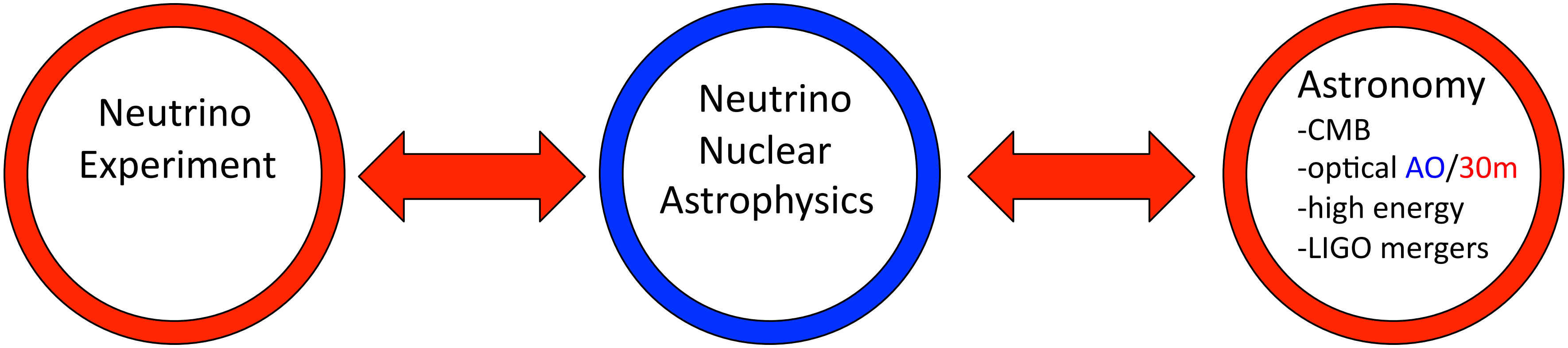
This is the golden age for both Neutrino Physics *and* Observational Astronomy

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



Neutrino Experiment

Neutrino Nuclear Astrophysics

Astronomy
- -CMB
- -optical AO/30m
- -high energy
- -LIGO mergers

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}, ^{4}He, ν mass limits)

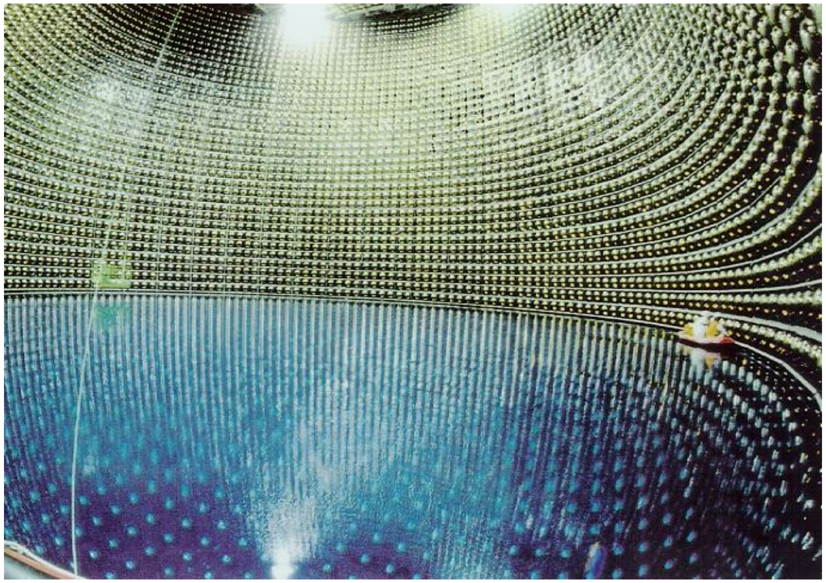
(2) 10-meter class, adaptive optics, and orbiting telescopes
(e.g., precision determinations of deuterium abundance,
dark energy/matter content, structure history etc.)

(3) Laboratory neutrino mass/mixing measurements – *e.g.,* LBNE

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

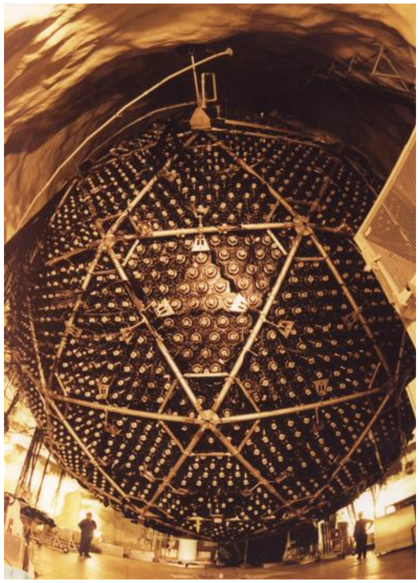
The neutrino interaction strength we typically deal with in stars and the universe is **Twenty Orders of Magnitude** (10^{-20}) ***weaker*** than the electromagnetic interaction that governs how photons (light) influence matter!

We need *really big detectors* to "see" reactor, accelerator, solar, and supernova neutrinos!



SuperK

100 KTons H_2O



Sudbury Neutrino Observatory

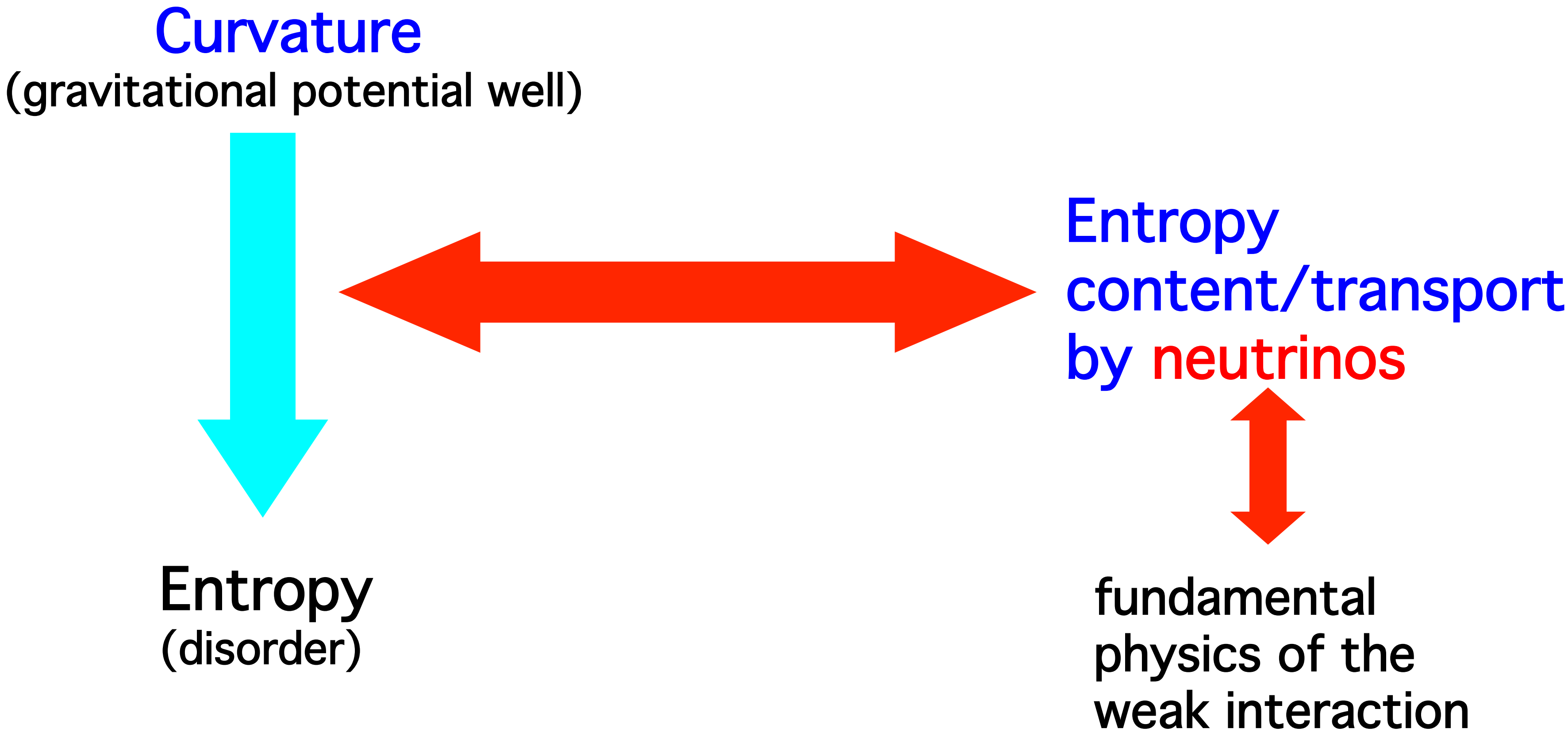
10 KTons D_2O

Neutrinos do most of the "*heavy lifting*" in exploding stars (supernovae) and in the early universe.

This is largely because they carry the bulk of the energy/entropy in these environments!

As we will see, neutrinos can more than make up for their feeble interactions with **huge** numbers!!

There is a deep connection between spacetime curvature and entropy (and neutrinos)



Curvature
(gravitational potential well)

Entropy
(disorder)

Entropy content/transport by neutrinos

fundamental physics of the weak interaction

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.

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.

Figure of Merit:

a core collapse per galaxy every 30 years

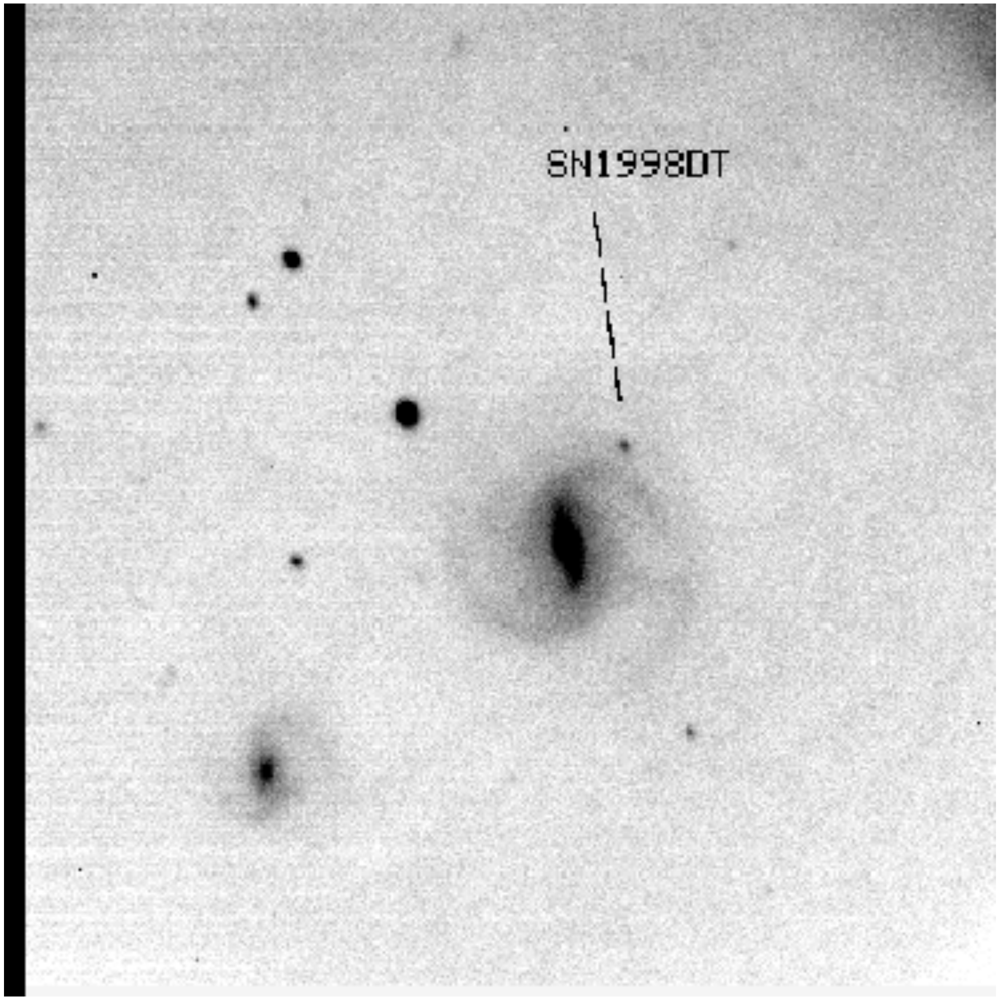
$$\text{SN rate} \quad \sim 10^{-9}\,\text{galaxy}^{-1}\,\text{s}^{-1}$$

$$\sim \; 1 \text{ galaxy per Mpc}^3$$

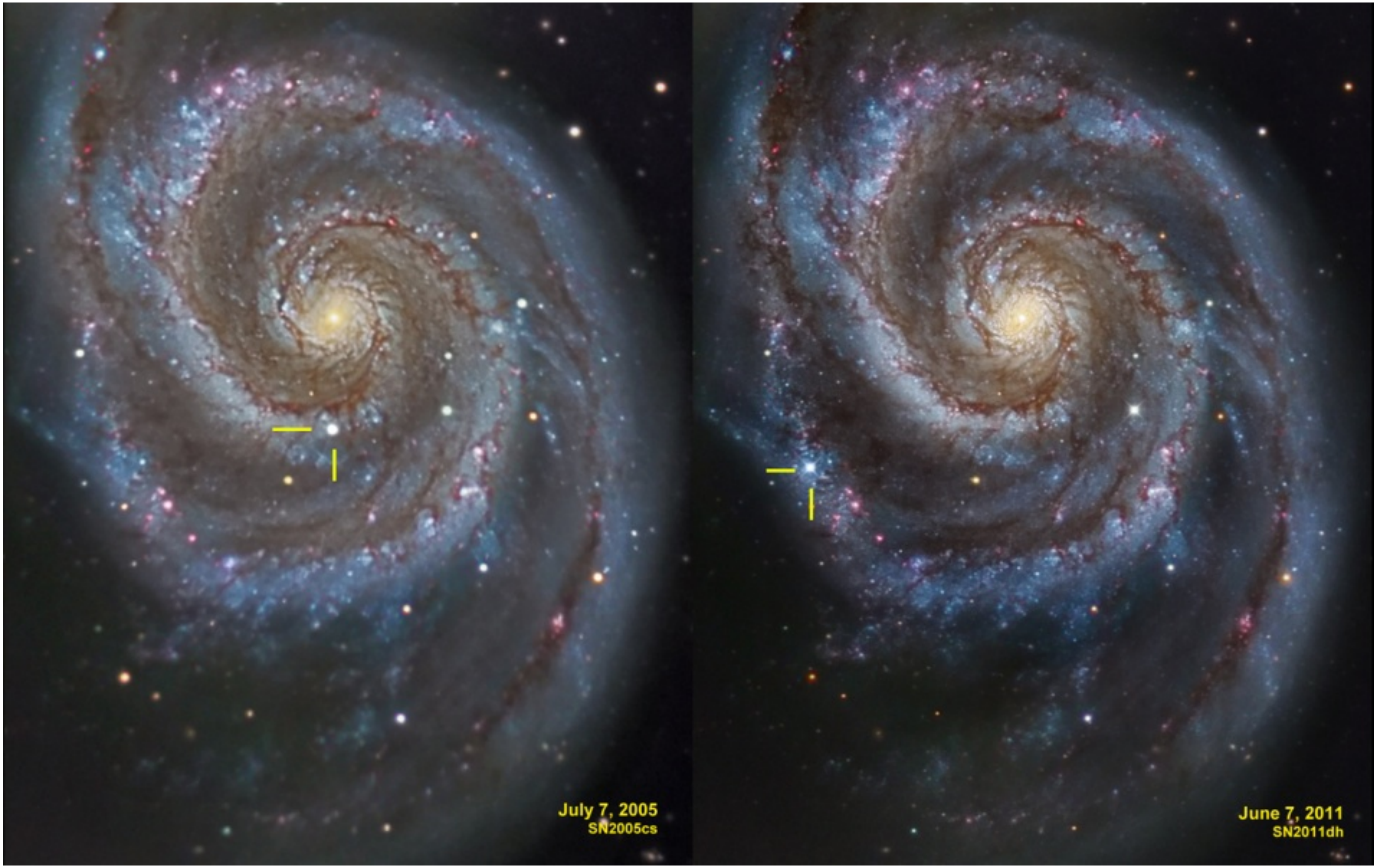
$$\text{causal horizon size} \;\; \sim 3000\,\text{Mpc}$$

$$\boxed{\Rightarrow \quad 10 \text{ core collapses per second in universe}}$$

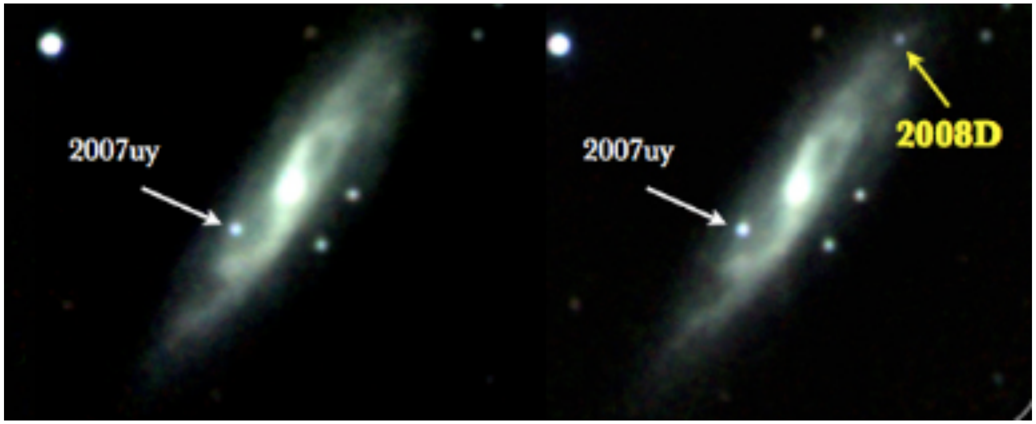
Type II supernova



cse.ssl.berkeley.edu

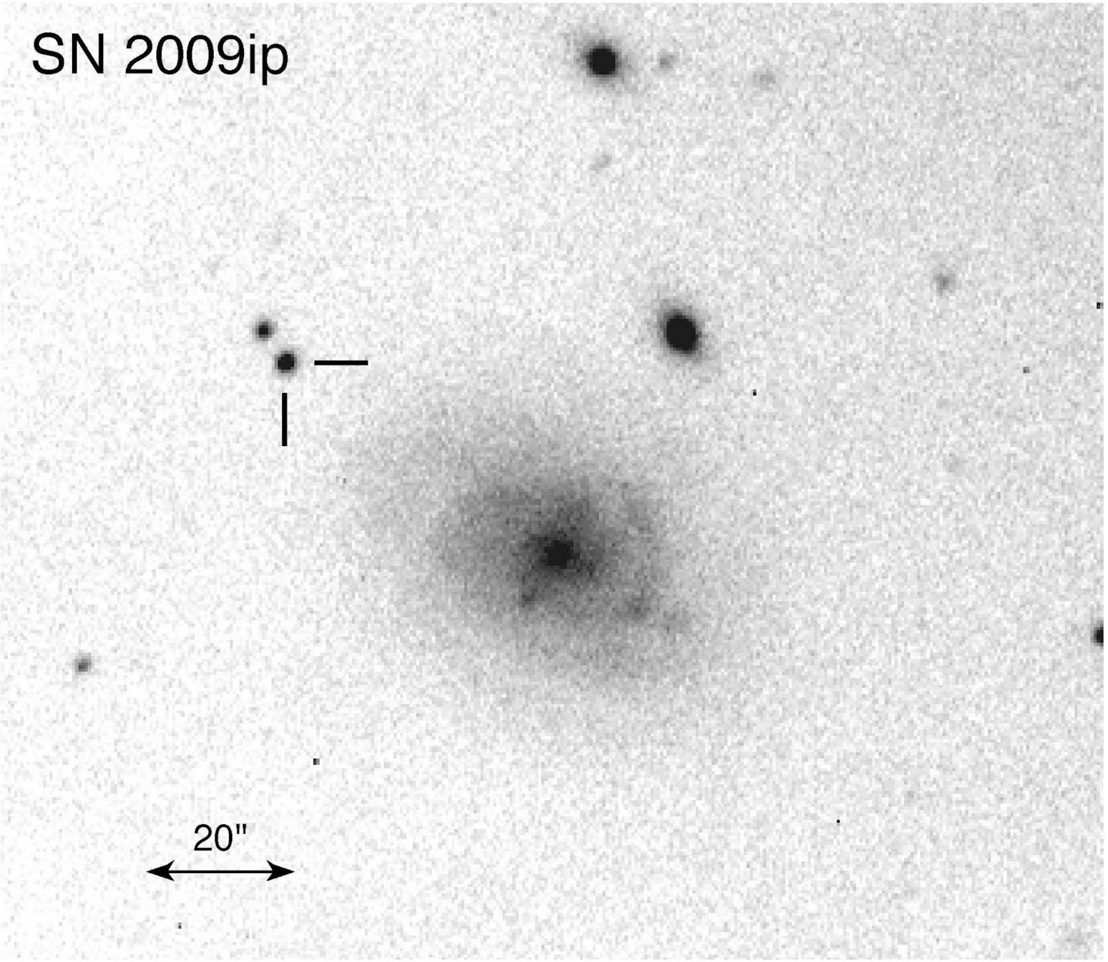


Lucky neutrino physicists in M51 - Two core collapse (Type II) supernovae in 6 years!



NGC 2770: a Type II (2007uy) and a Type Ib (2008D). Two in a year!!

http://berkeley.edu/news/media/releases/2008/05/21_supernova.shtml

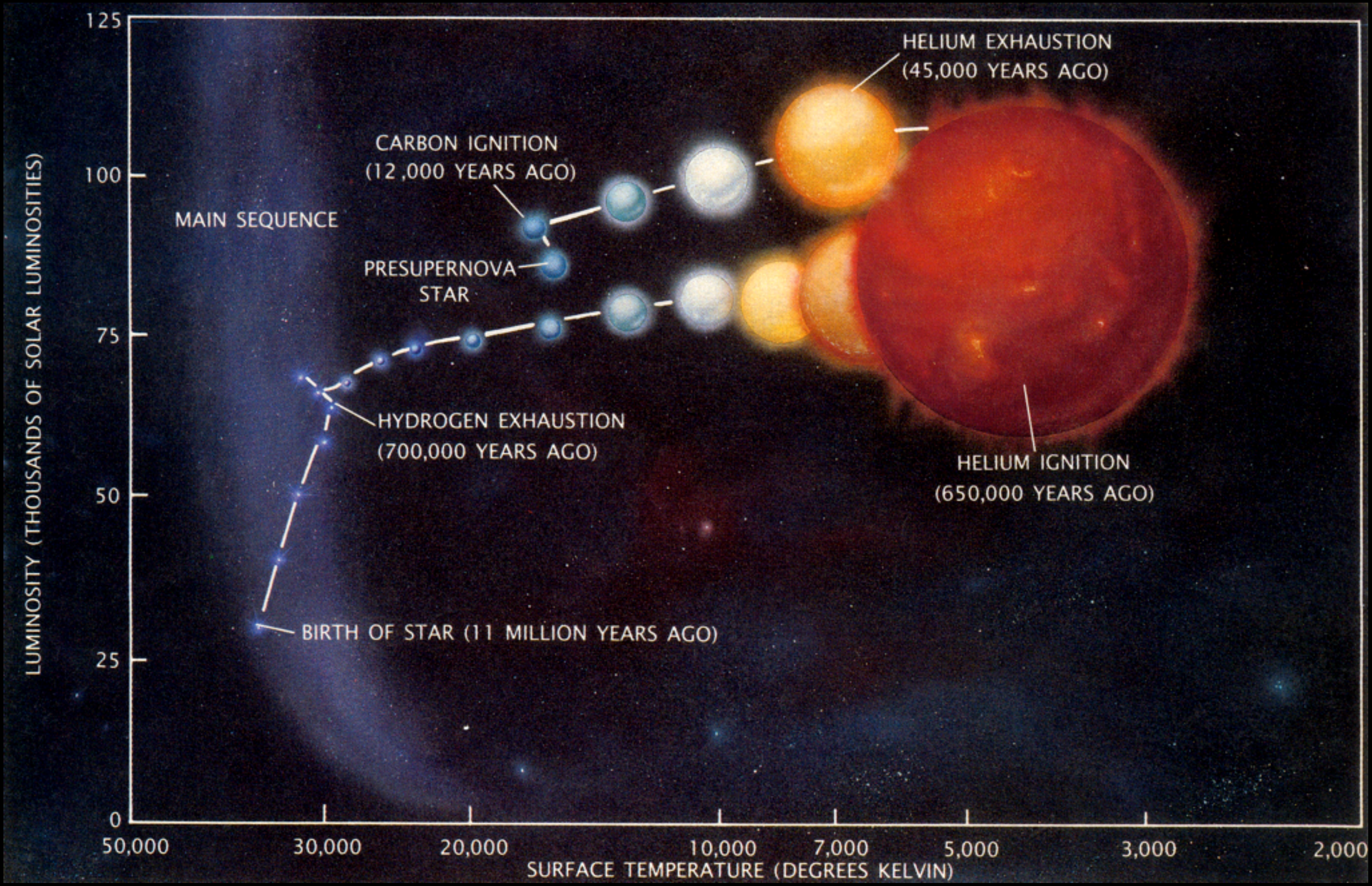


Supernova 2009ip in NGC 7559, July 24, 2012,

A pair-instability core collapse/explosion ??
or a *merger* of a 60-100 M_{sun} star and a ~ 50 M_{sun} star ??

N. Stoker & A. Kashi, Astrophys. J. Lett. **764**, L6 (2013)

J. Mauerhan, N. Smith, A. Filipenko, K. Blanchard, P. Blanchard, C. Casper, S. B. Cenko,
K. Clubb, D. Cohen, K. Fuller, G. Li, J. J. Silverman, MNRAS **430**, 1801 (2013)



Weaver & Woosley, ***Sci Am***, **1987**

Nuclear Burning Stages of a 25 M_{sun} Star

Burning Stage	Temperature	Density	Time Scale
Hydrogen	5 keV	5 g cm^{-3}	7 X 10^6 years
Helium	20 keV	700 g cm^{-3}	5 X 10^5 years
Carbon	80 keV	2 X 10^5 g cm^{-3}	600 years
Neon	150 keV	4 X 10^6 g cm^{-3}	1 year
Oxygen	200 keV	10^7 g cm^{-3}	6 months
Silicon	350 keV	3 X 10^7 g cm^{-3}	1 day
Core Collapse	700 keV at instability point $\mu_e \sim 10\,\mathrm{MeV}$ neutronization : $e^- + \mathrm{p} \rightarrow \mathrm{n} + \nu_e$	4 X 10^9 g cm^{-3}	~ seconds of order the free fall time
“Bounce”	~ 2 MeV	~10^{15} g cm^{-3}	~ milli-seconds
Neutron Star	< 70 MeV initial ~ keV “cold”	~10^{15} g cm^{-3}	initial cooling ~ 15-20 seconds ~ thousands of years

Massive Stars are Giant Refrigerators

From core carbon/oxygen burning onward
the neutrino luminosity exceeds the photon luminosity.

Neutrinos carry energy/entropy away from the core!

Core goes from S/k~10 on the Main Sequence (hydrogen burning)
to a thermodynamically cold S/k ~1 at the onset of collapse!

e.g., the collapsing core of a supernova can be a
frozen (Coulomb) crystalline solid with a
temperature ~1 MeV!

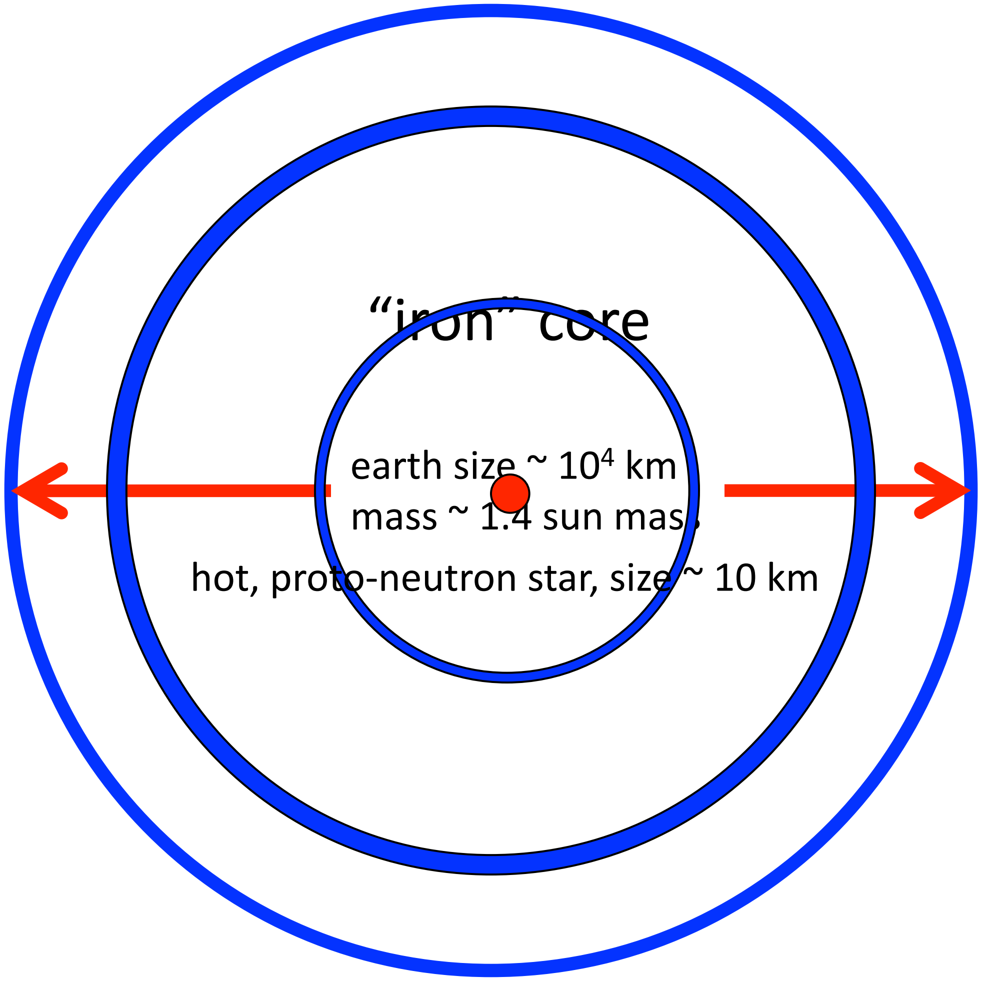
General Relativistic Instability

Star's support pressure coming from particles with relativistic kinematics
(e.g., photons or relativistically-degenerate electrons)

Newtonian Gravitation: Zero total (gravitational + thermal) energy = *neutrally stable,*

General Relativity: nonlinear, so a little more curvature makes even more curvature
= *non-restoring forces*; **unstable**

. . . 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!

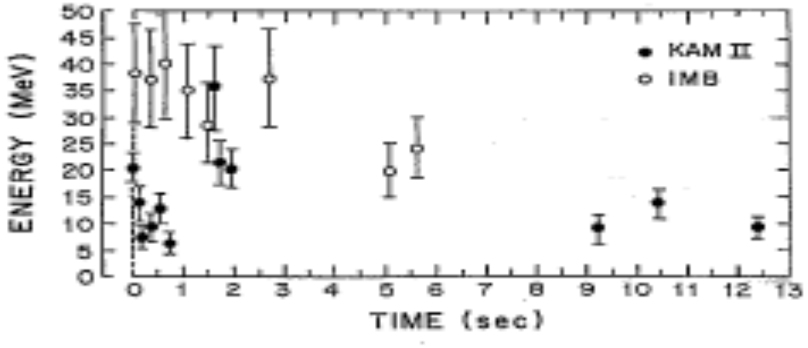
$$\boxed{E_{\mathrm{GRAV}} \approx \frac{3}{5}\frac{\mathrm{G}\,M_{\mathrm{NS}}^2}{R_{\mathrm{NS}}} \approx 3\times10^{53}\,\mathrm{ergs}\left[\frac{M_{\mathrm{NS}}}{1.4\mathrm{M}_{\mathrm{sun}}}\right]^2\left[\frac{10\ \mathrm{km}}{R_{\mathrm{NS}}}\right]}$$

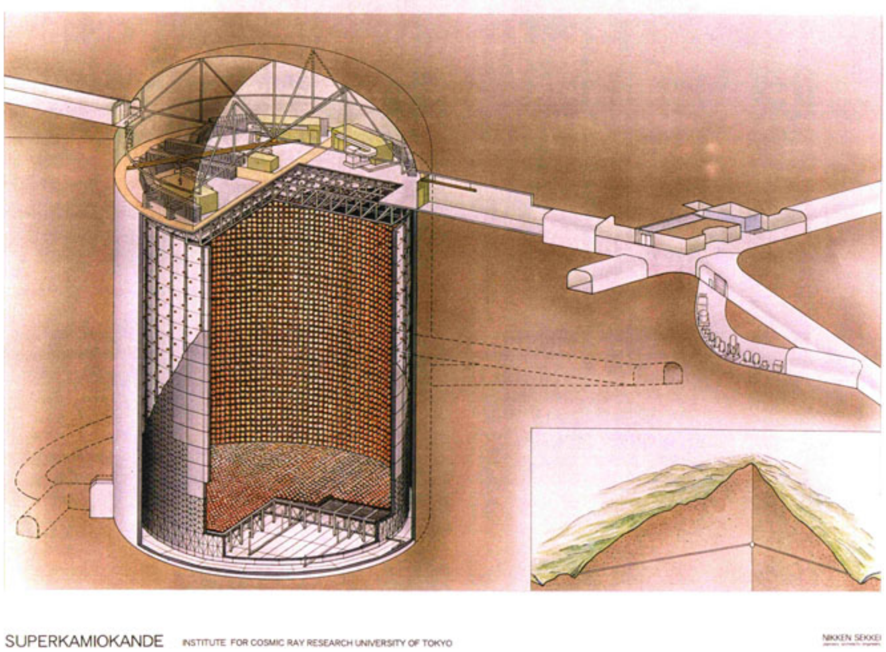
Neutrino diffusion time, $\tau_\nu \approx 2$ s to 10 s

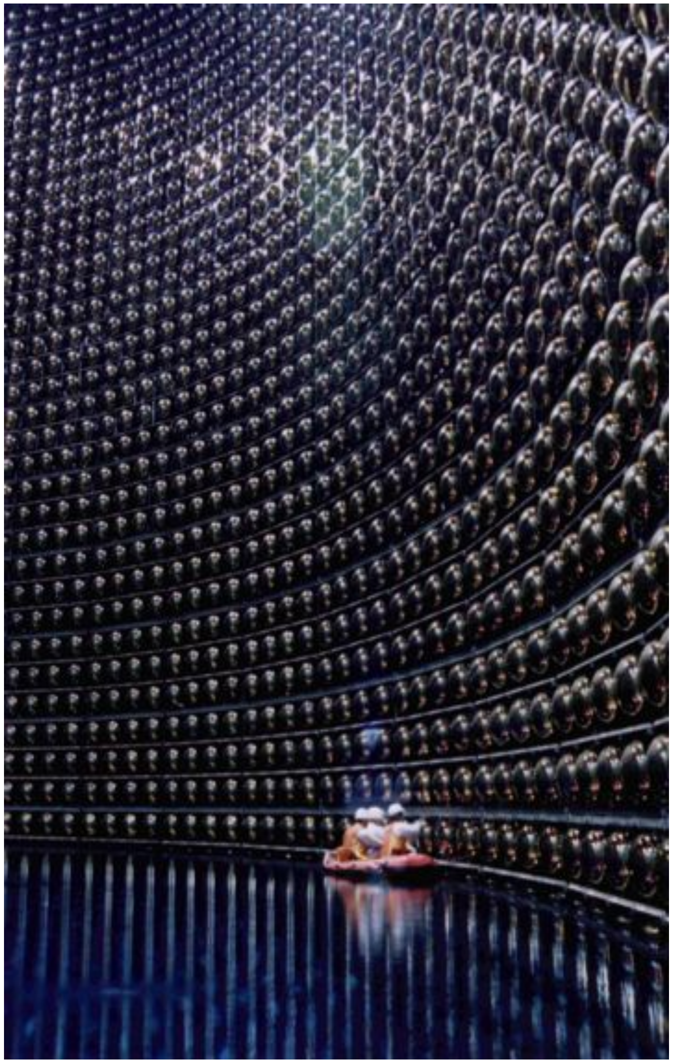
$$\boxed{L_\nu \approx \frac{1}{6}\frac{GM_{\mathrm{NS}}^2}{R_{\mathrm{NS}}}\frac{1}{\tau_\nu} \approx 4\times10^{51}\,\mathrm{ergs\ s^{-1}}}$$

Observing Supernova Neutrinos

SN 1987A







supernovae and neutron star mergers

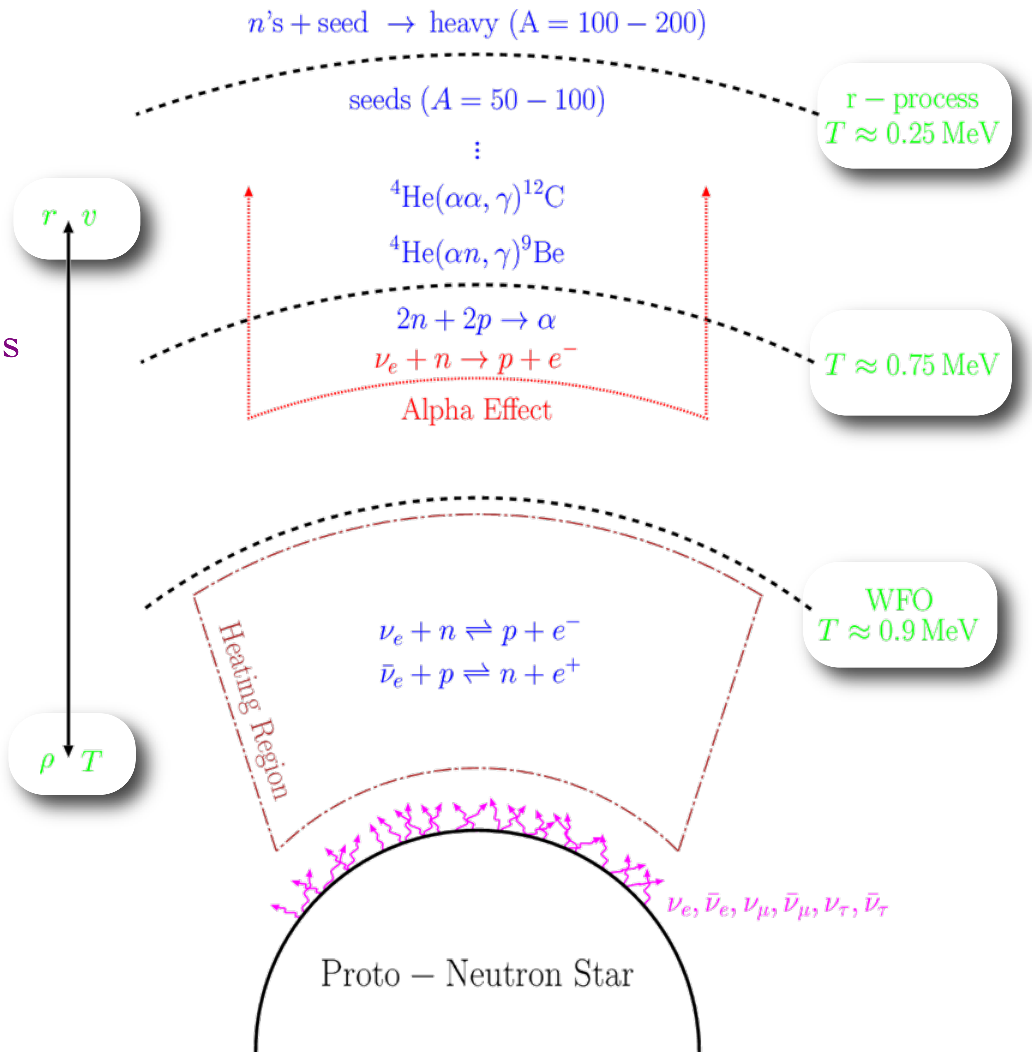
the environment in broad brush

Supernova neutrino signals are sensitive to neutrino mixing parameters.

Neutrino flavor transformation in the “right” regions can help or hinder r-process nucleosynthesis and the explosion.

Charge current neutrino interactions set the composition (n/p ratio) and can be instrumental in energetics.

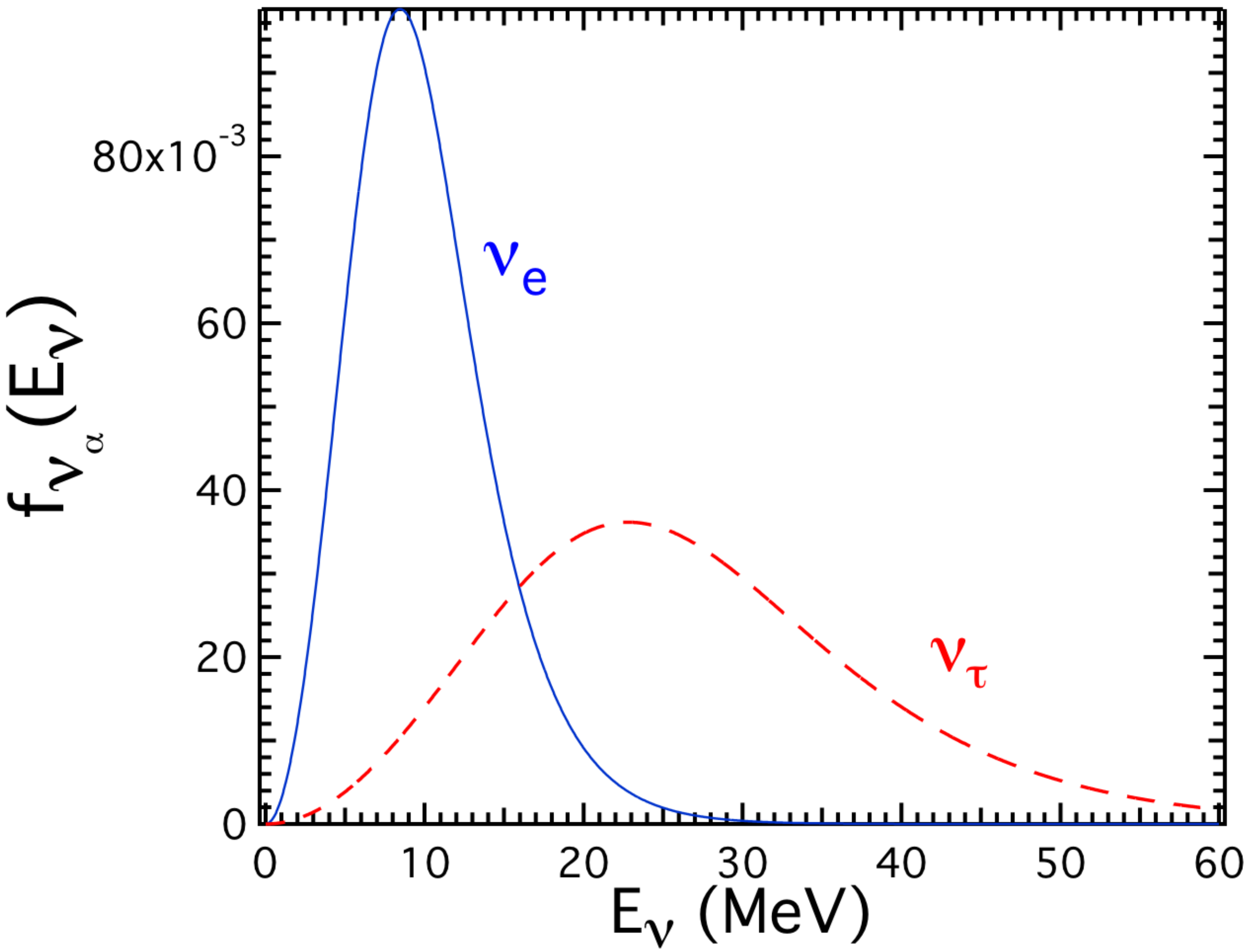
- Most of the gravitational binding energy (99%) is released in the form of neutrinos of all kinds.



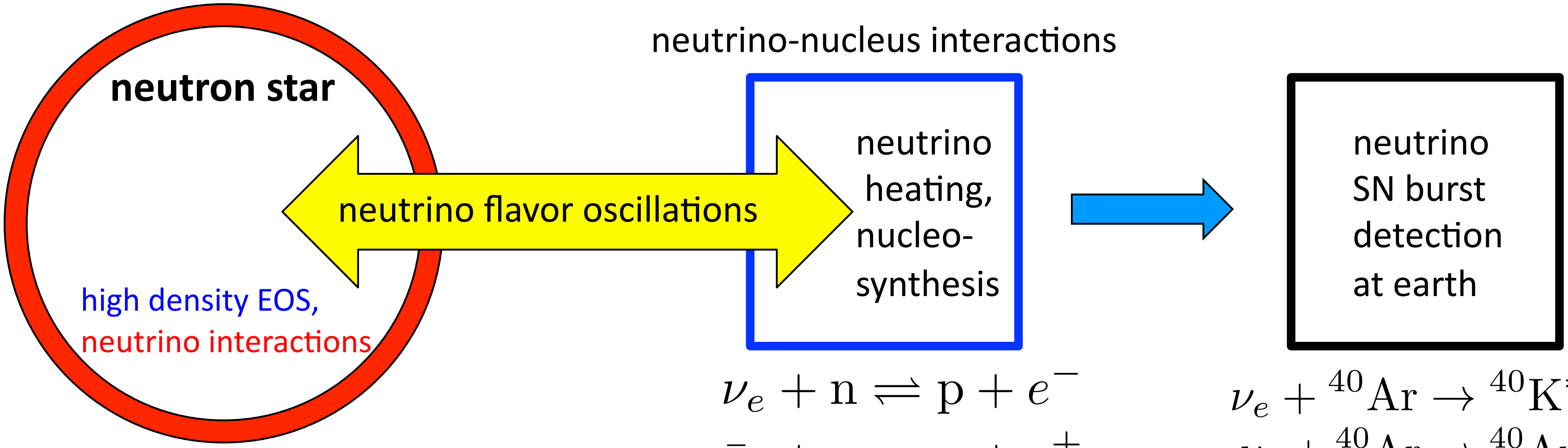
Neutrino Distribution Functions f_ν

At late times ($t_{pb} > 10$ s) we expect an average energy hierarchy:

$$\langle E_{\nu_{\mu,\tau}} \rangle > \langle E_{\bar{\nu}_e} \rangle > \langle E_{\nu_e} \rangle$$



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.



neutron star

high density EOS,

neutrino interactions

neutrino flavor oscillations

neutrino-nucleus interactions

neutrino heating, nucleo-synthesis

neutrino SN burst detection at earth

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

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

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

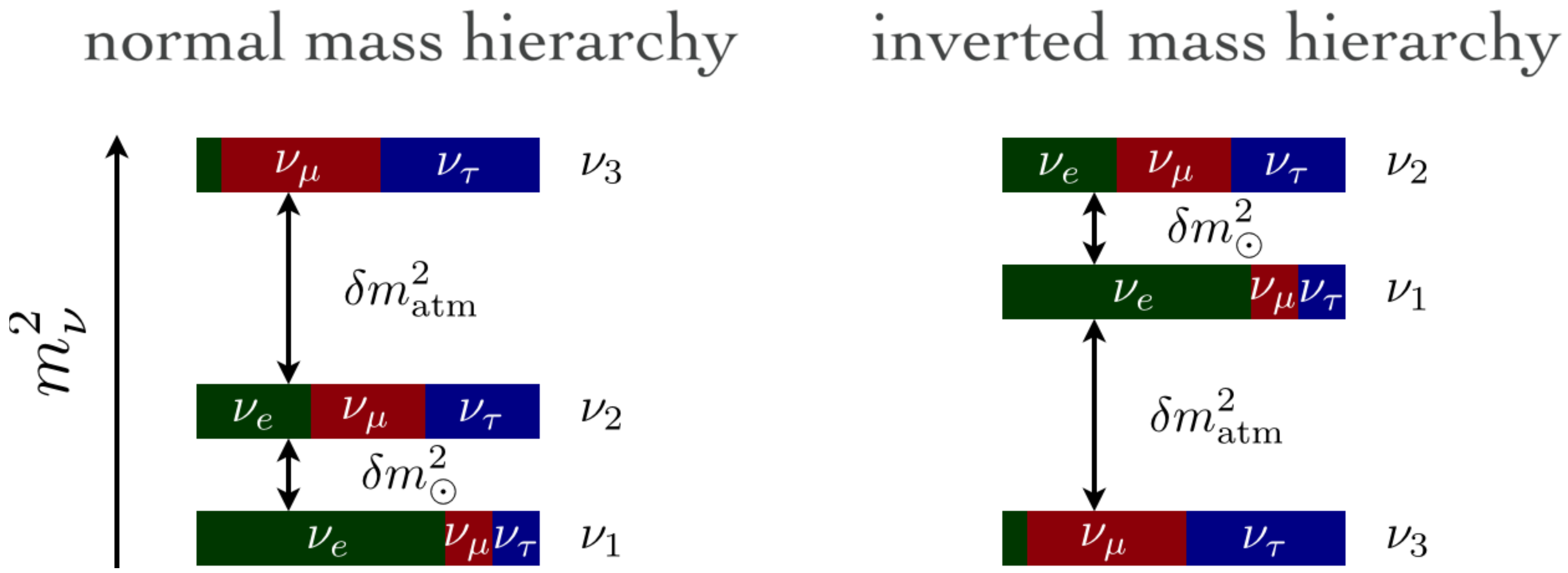
Neutrino Mass: what we know and don't know

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 can 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**

As we saw, each Neutrino is a Quantum System

In quantum mechanics a system can be in two or more
seemingly mutually exclusive states at the same time!
(*e.g.*, Schroedinger's Cat is both alive *and* dead)

As it propagates along a neutrino can be in a superposition of different flavors, and the *medium* around it can influence the relative mix of these flavors.

But (some of) this medium the neutrino moves through consists of *other neutrinos*.

The upshot is that how neutrinos *change their flavor*
depends on the *flavor states* of the neutrinos in the "medium".

NONLINEAR !!!

How Quantum Mechanical Systems Evolve – The Rules

- when you make a measurement you have to get an eigenvalue and system is "collapsed" into the corresponding eigenstate

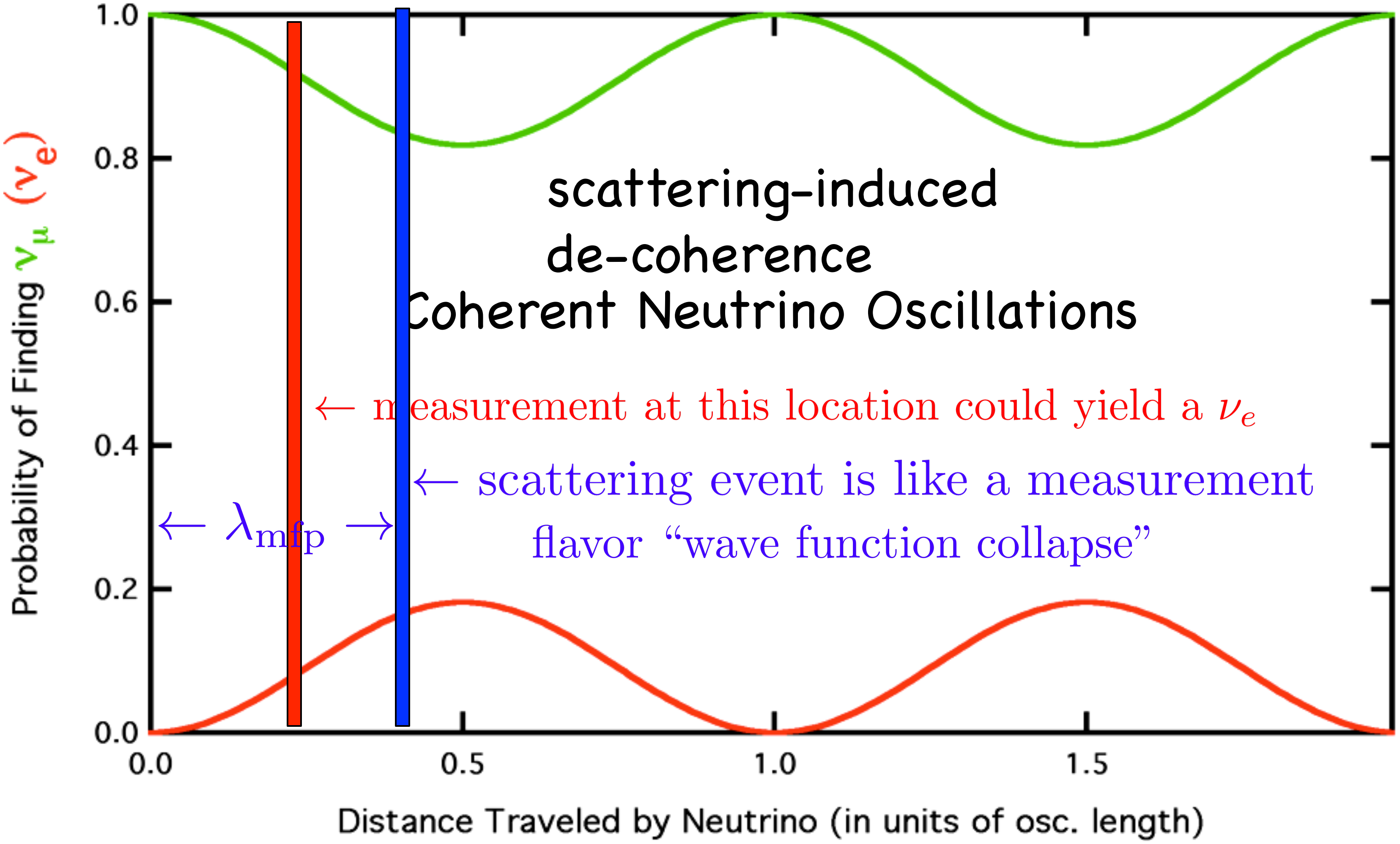
- two ways system can evolve in time:

  Schroedinger-like evolution

  state reduction ("wave function collapse") because of a "measurement"

Simple Example: two-by-two vacuum neutrino oscillations

$$|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$
$$|\nu_\mu\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$



scattering-induced de-coherence

Coherent Neutrino Oscillations

$\leftarrow$ measurement at this location could yield a ν_e

$\leftarrow$ scattering event is like a measurement flavor "wave function collapse"

$$|\Psi(t=0)\rangle = |\nu_\mu\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

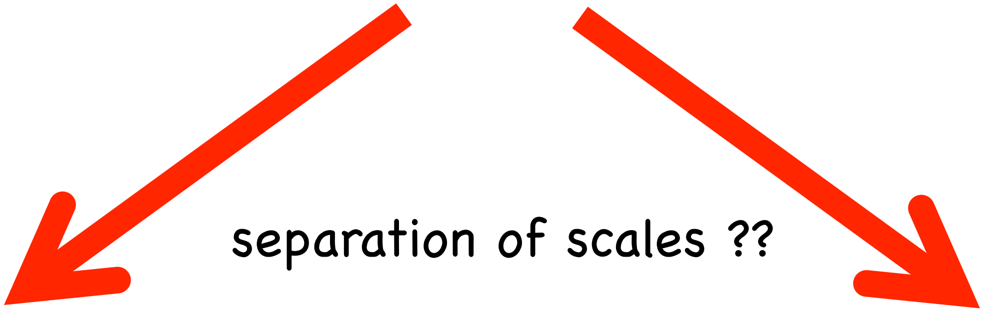
$$|\Psi(t)\rangle = -\sin\theta\, e^{-iE_1 t}\,|\nu_1\rangle + \cos\theta\, e^{-iE_2 t}\,|\nu_2\rangle$$

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:

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

@ low density where
neutrinos propagate coherently

Boltzmann equation

@ high density where
inelastic scattering dominates

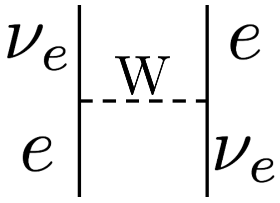
A. Vlasenko, G.M.F., V. Cirigliano 2013

Coherent Flavor Evolution for Neutrino i

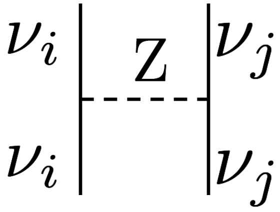
$$\psi_{\nu,i} = \begin{pmatrix} \text{amplitude to be } \nu_e \\ \text{amplitude to be } \nu_\mu \\ \text{amplitude to be } \nu_\tau \end{pmatrix}$$

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

neutrino-electron
charged current
forward exchange
scattering



neutrino-neutrino
neutral current
forward scattering

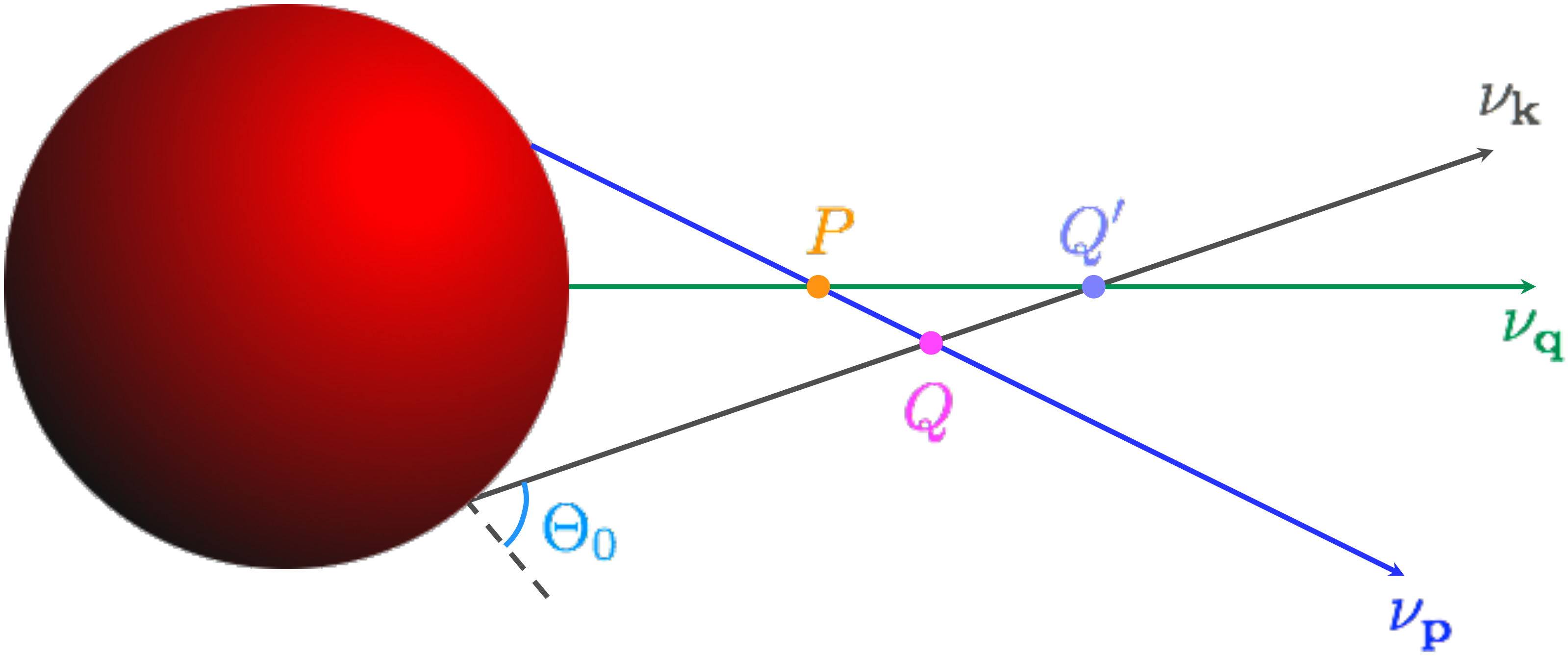


Neutrino Self Coupling - the source of nonlinearity

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

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

- 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.

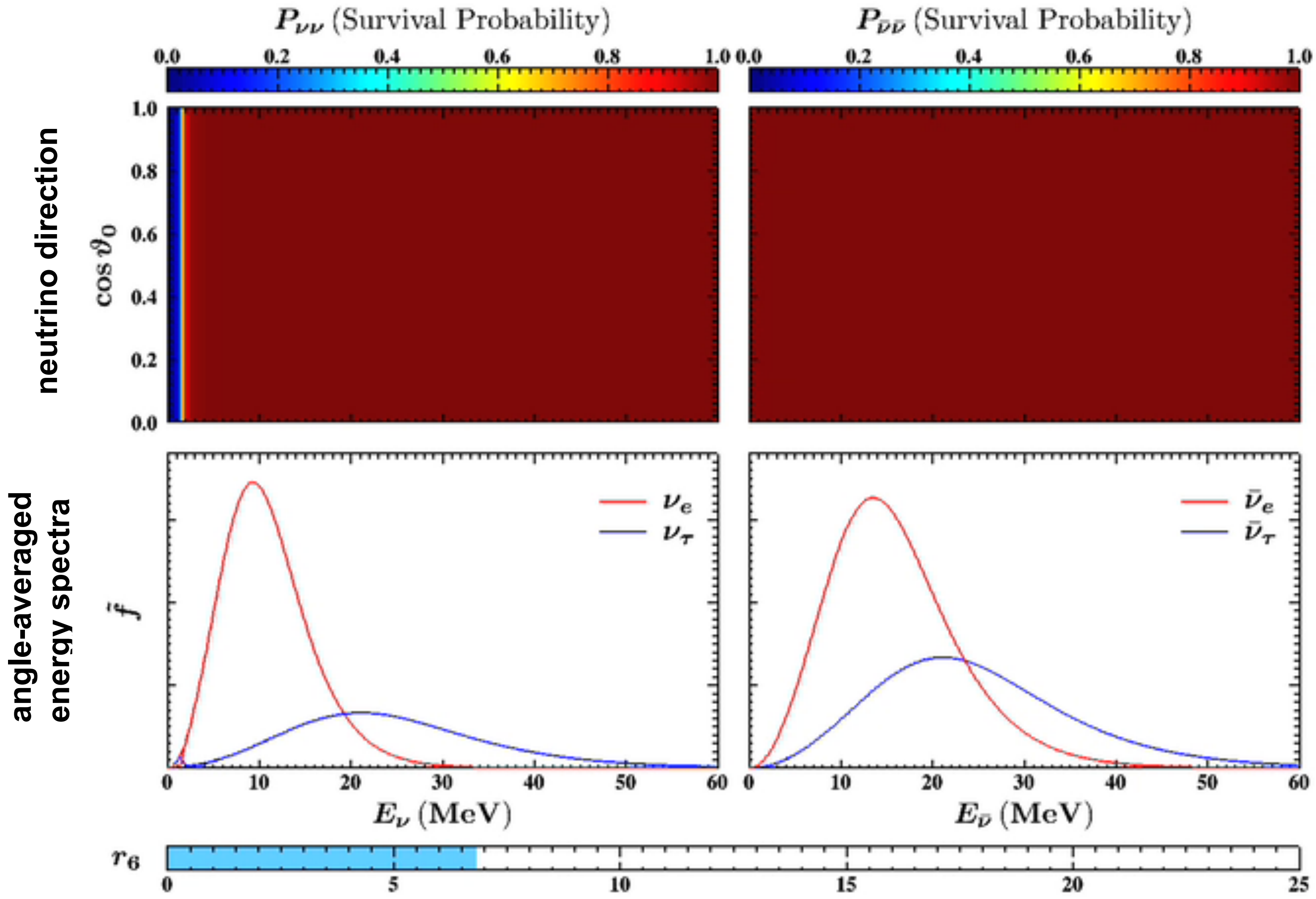
The results are startling. Despite the small measured neutrino mass-squared differences, **collective** neutrino flavor transformation can take place deep in the supernova envelope

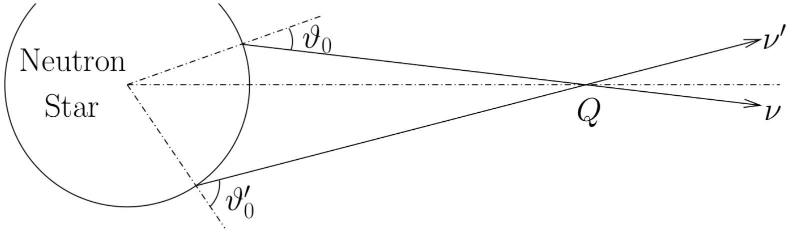
Pushing the frontier of high performance computing with a unique new kind of transport problem

neutrinos $\nu_e \rightleftharpoons \nu_\tau$ **antineutrinos** $\bar{\nu}_e \rightleftharpoons \bar{\nu}_\tau$

NORMAL MASS HIERARCHY

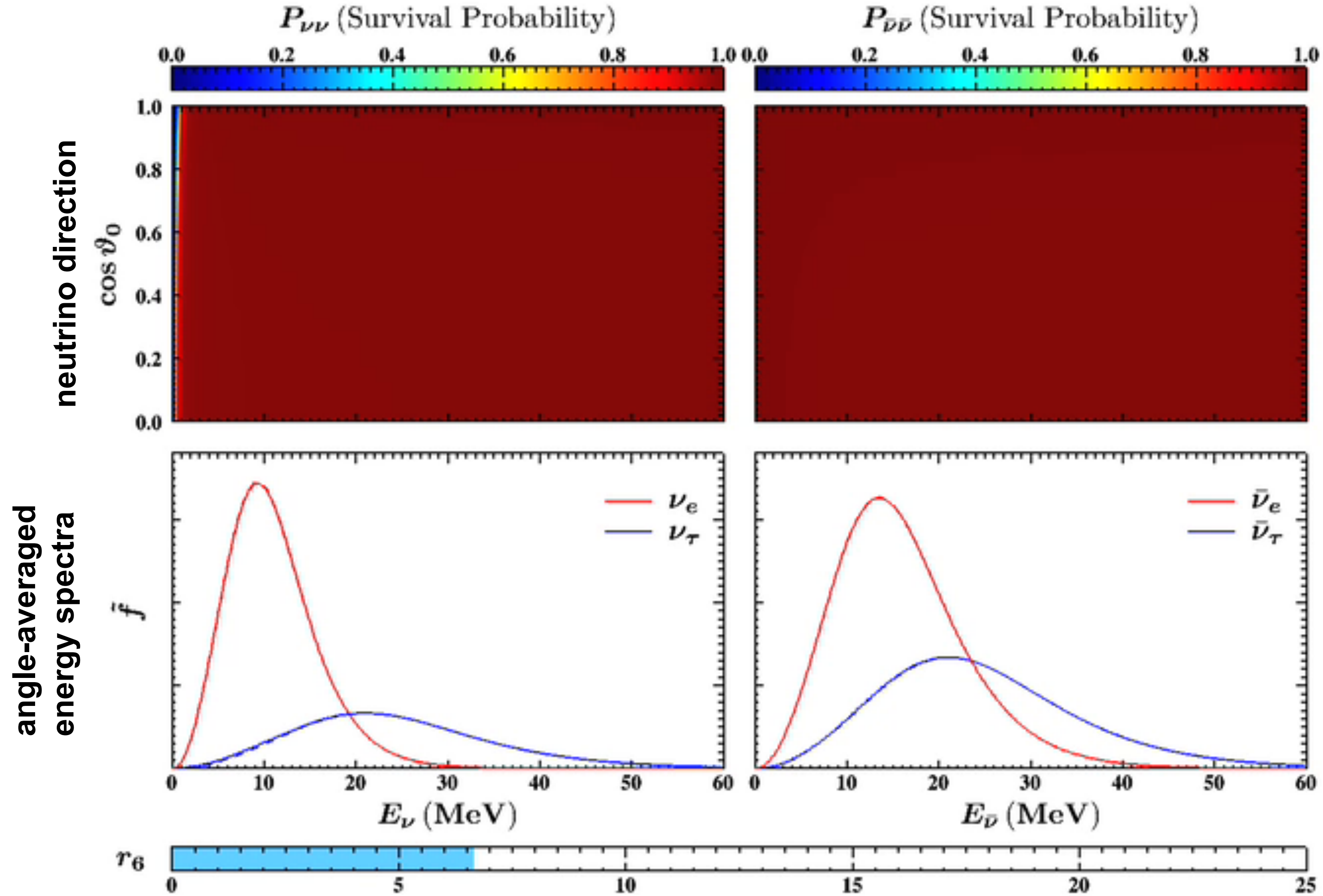
$$L_\nu = 0$$





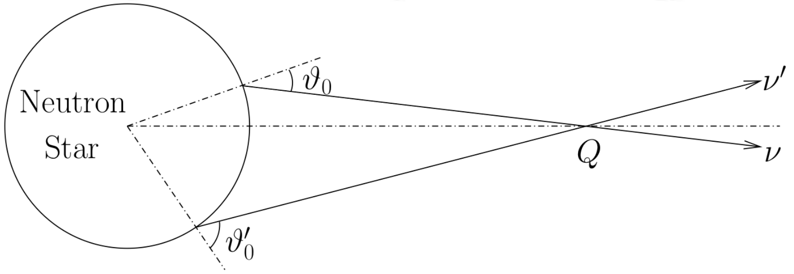
r_6 **radius in units of 10^6 cm**

neutrinos $\nu_e \rightleftharpoons \nu_\tau$ **antineutrinos** $\bar{\nu}_e \rightleftharpoons \bar{\nu}_\tau$



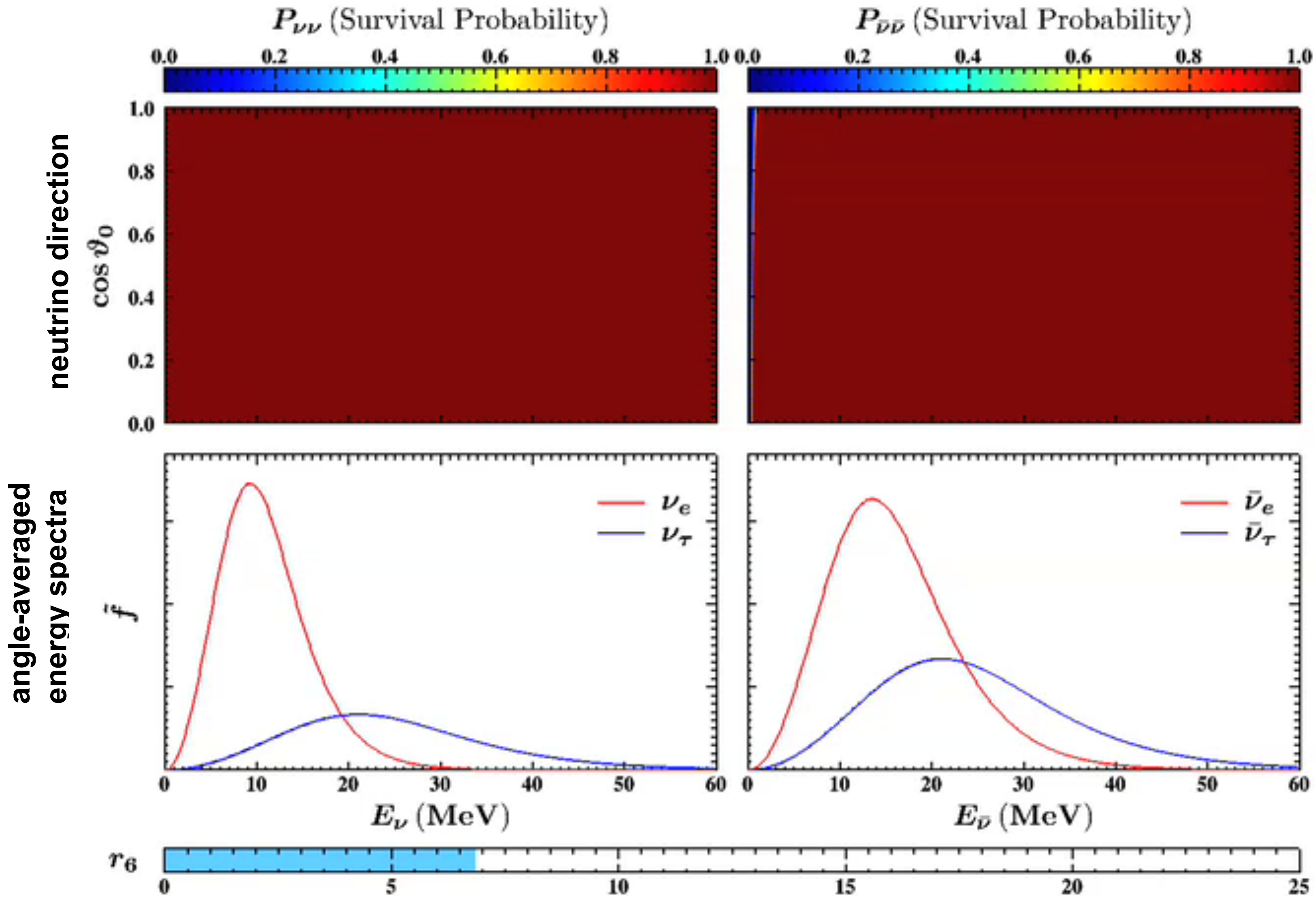
NORMAL MASS HIERARCHY

$L_\nu = 10^{51}\ \mathrm{erg\ s^{-1}}$



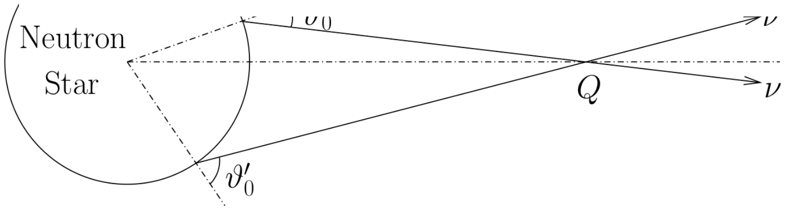
r_6 radius in units of 10^6 cm

neutrinos $\nu_e \rightleftharpoons \nu_\tau$ **antineutrinos** $\bar{\nu}_e \rightleftharpoons \bar{\nu}_\tau$

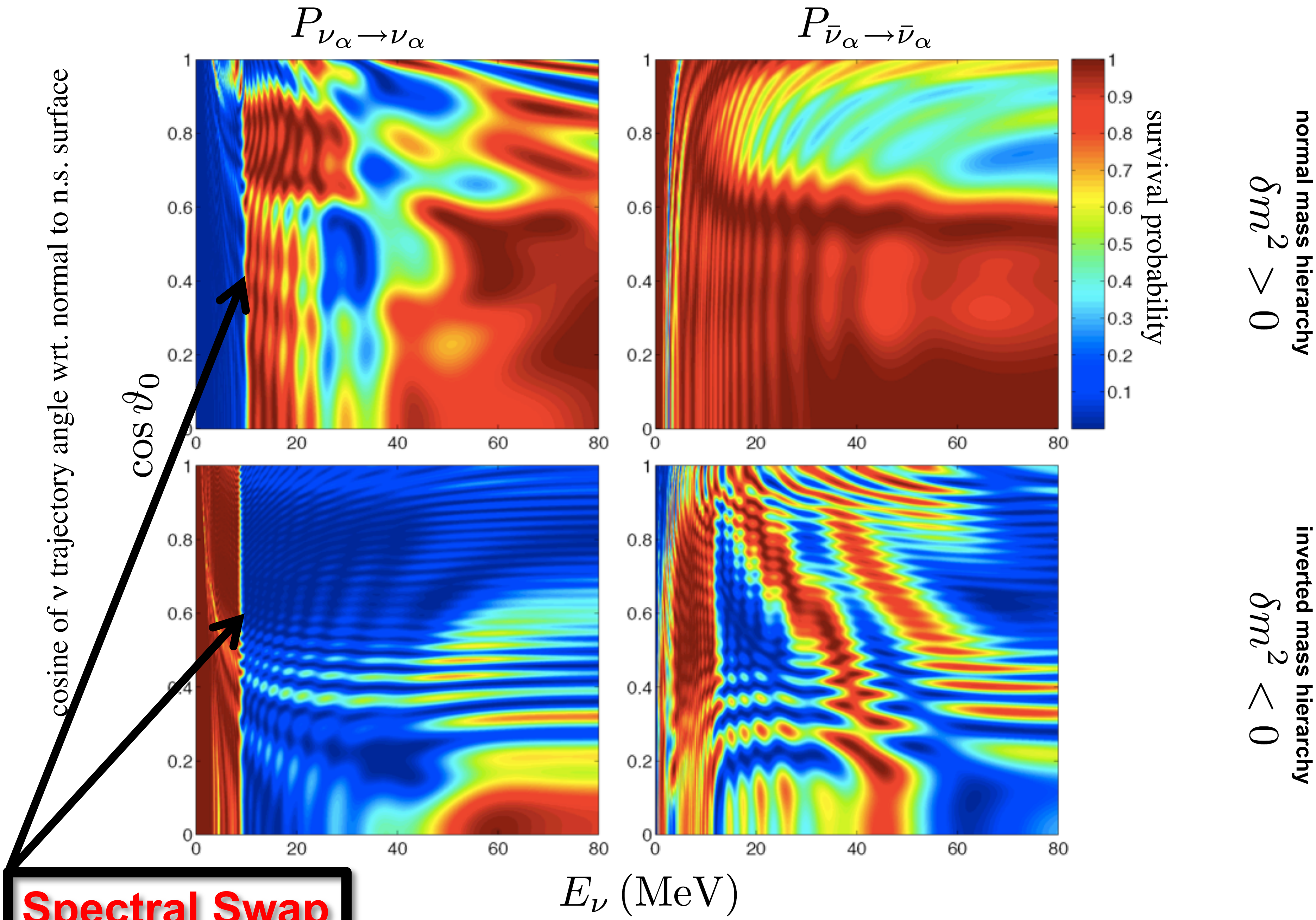


INVERTED MASS HIERARCHY

$L_\nu = 10^{51}\,\mathrm{erg\,s^{-1}}$



r_6 **radius in units of 10^6 cm**

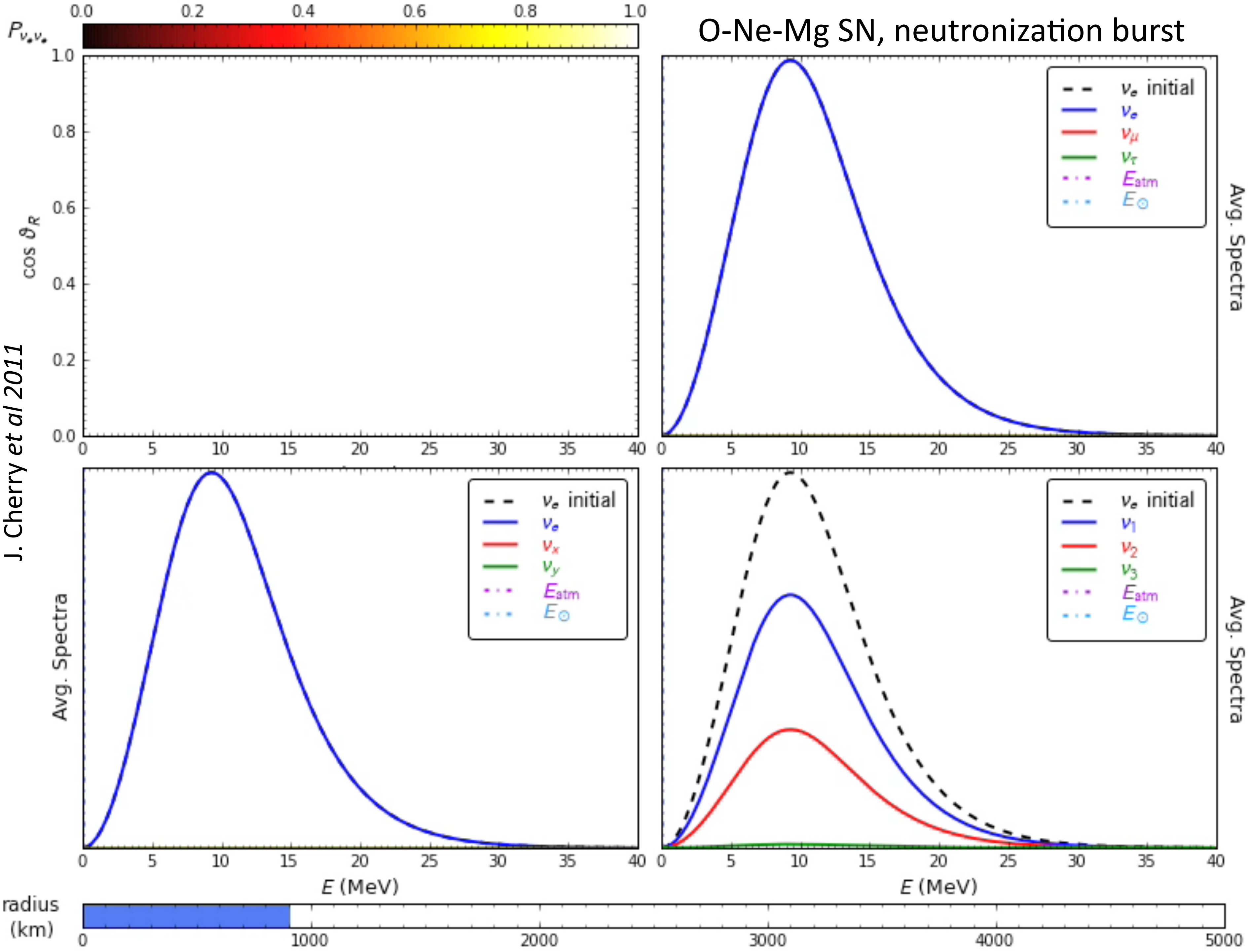


Spectral Swap

consequences of neutrino mass and quantum coherence in supernovae

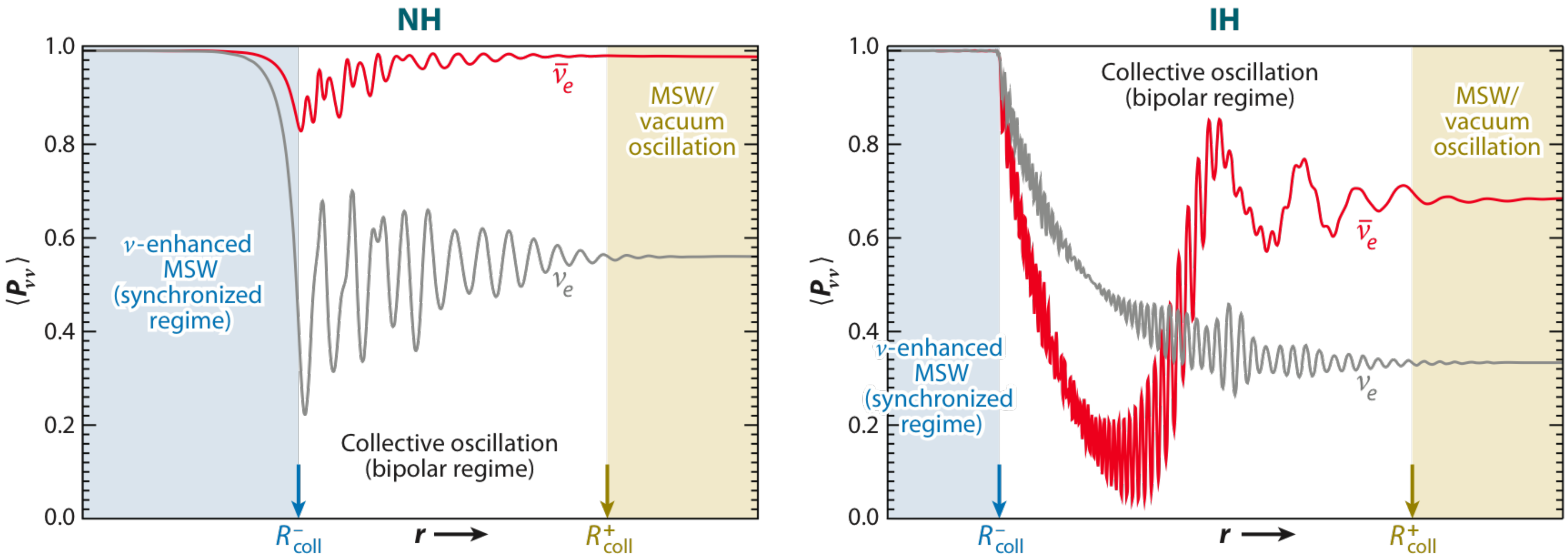
H. Duan, G. M. Fuller, J. Carlson, Y.-Z. Qian, Phys. Rev. Lett. **97**, 241101 (2006) astro-ph/0606616

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.

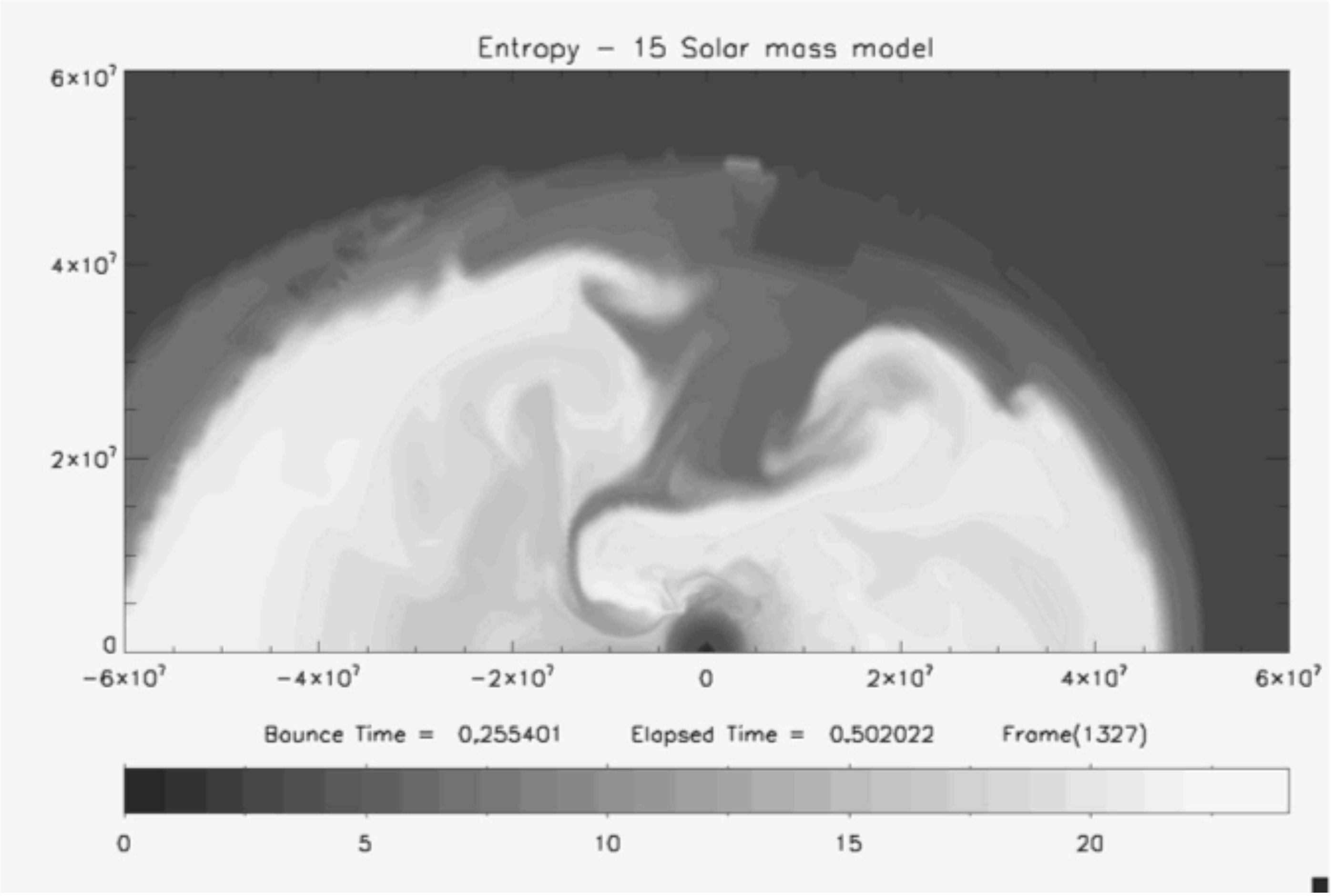
Effects that can modify or even wash-out the swap signal

-the supernova shock

-turbulence & density fluctuations

-neutrino direction-changing scattering
(quantum kinetic effects)

The region above the neutron star can be quite inhomogeneous



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

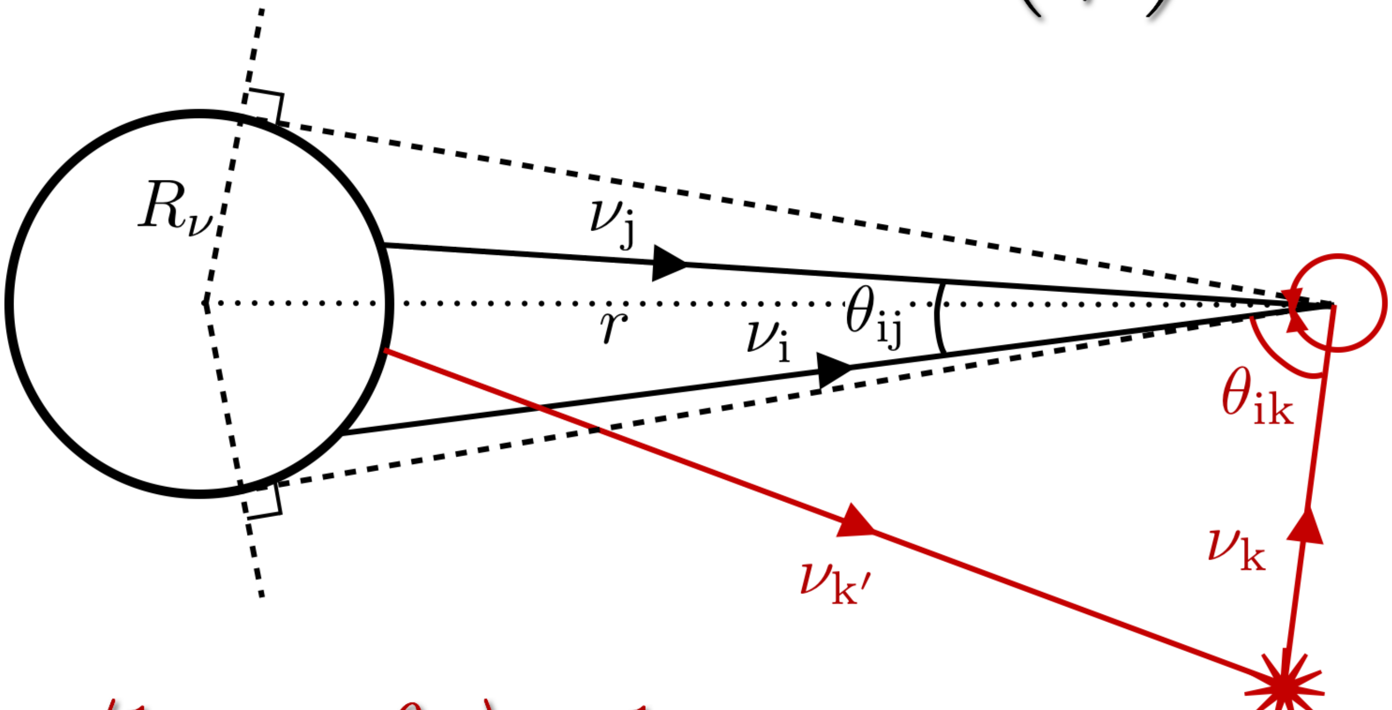
Toward Quantum Kinetics

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

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

The Neutrino Halo

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

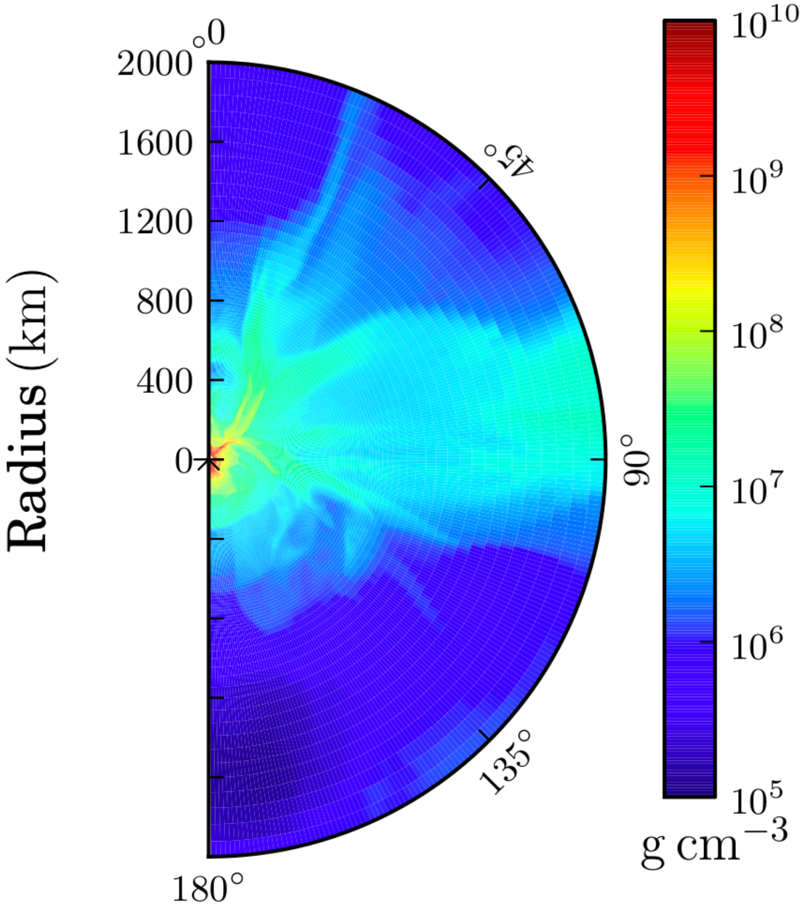


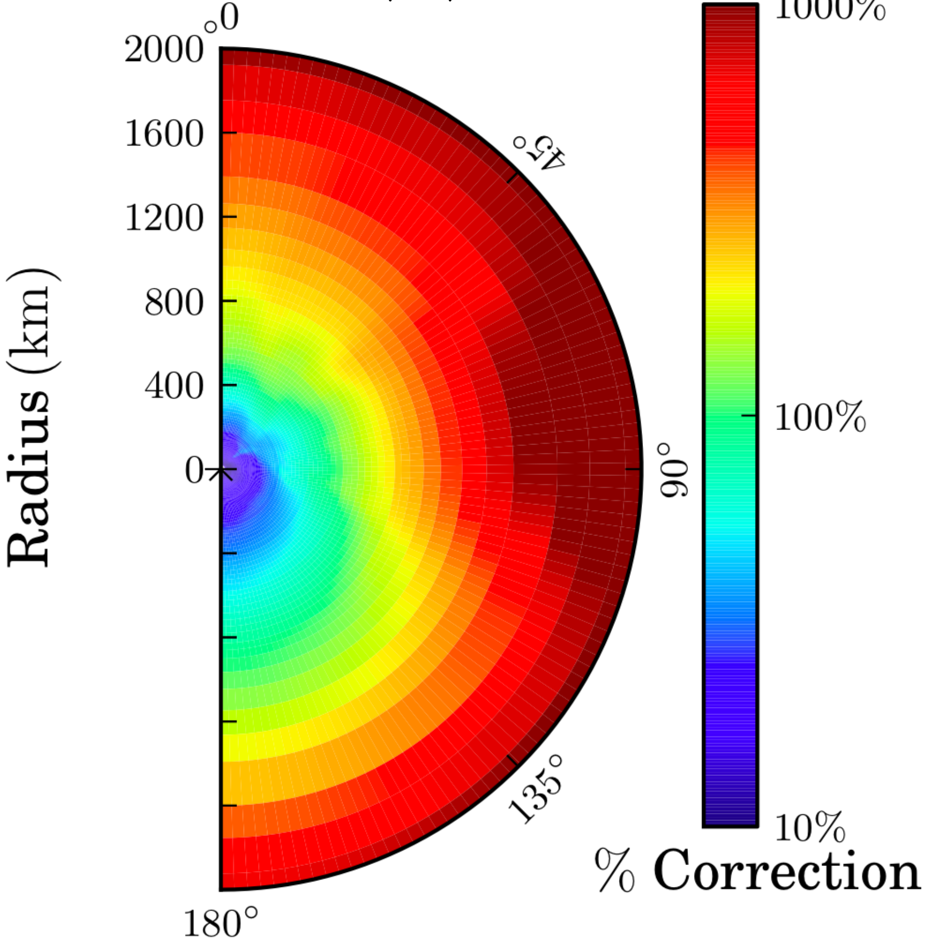
$$\langle 1 - \cos\theta_{\mathrm{ik}} \rangle \approx 1$$

$\sim 10^{-3}$ 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