Intuition and Common Sense Foiled Again:

Supercomputers Reveal Surprising Neutrino Behavior in Collapsing Stars and Supernovae

2012 UC-HIPACC Journalism Boot Camp
Computational Astronomy: From Planets to Cosmos
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I don't like computers. I don't like to use them. But I do.
I rely on physical reasoning to get at how nature works.

However, the real world is *nonlinear* and the human mind (at least mine!) seems less than adept at grappling with nonlinearity.

Linear: double some parameter in a model and, *e.g.*, some other quantity doubles.

Nonlinear: double some parameter, other quantities shoot up by, *e.g.*, huge amounts, and perhaps a whole new, **unexpected** phenomenon presents itself.

I will describe a surprising result of nonlinearity discovered in supercomputer calculations by UCSD and LANL scientists (H. Duan; G. M. Fuller UCSD; J. Carlson LANL; Y-Z. Qian U. Minn)

The elementary particles which we know about --

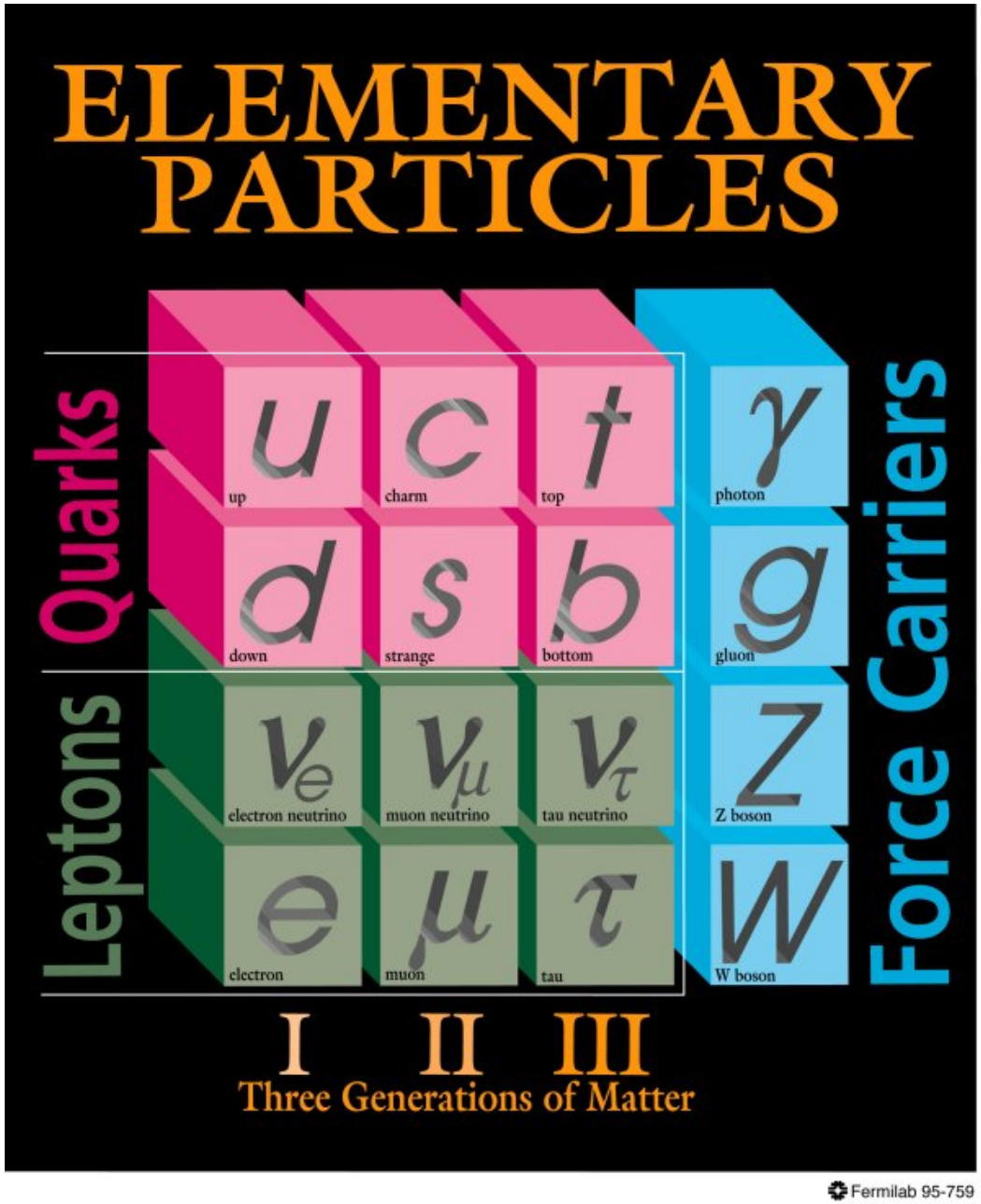
These particles are the building blocks of the *Standard Model*.

Neutrinos, like the charged leptons and quarks are spin-1/2 but, unlike those particles, neutrinos have no electric charge.

Each particle has an antiparticle, so there are six known neutrinos:

$$\underbrace{\nu_e, \bar{\nu}_e}_{\text{electron flavor}}, \underbrace{\nu_\mu, \bar{\nu}_\mu}_{\text{mu flavor}}, \underbrace{\nu_\tau, \bar{\nu}_\tau}_{\text{tau flavor}}$$

We know the rest masses of all the particles in this table ***EXCEPT*** for the neutrinos!



They don't call it the weak interaction for nothing!

Neutrinos experience only gravity and the weak interaction.

At the neutrino energies typical in stars and the early universe
the **weak** interaction is *twenty orders of magnitude* ***weaker*** (10^{-20})
than the **electromagnetic** interaction that governs how light (photons)
influences matter.

It would take a block of lead
several light years *thick*
to have a decent chance of
stopping one of these neutrinos **!**

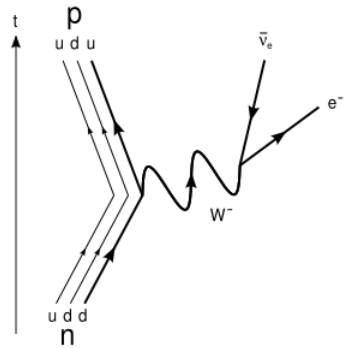
I'm never impressed by this – neutron star matter is 14 orders of magnitude denser than Pb

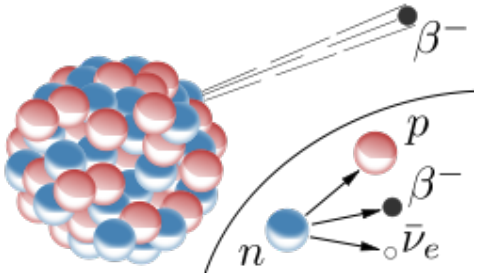
So how do we even know these particles exist?

Wolfgang Pauli's

"... *desperate remedy* ... to save the law of conservation of energy ..." 1930

In beta decay a neutron in the nucleus changes into a proton. An electron and a neutrino (an electron antineutrino actually) are emitted.





Experimenters knew the energy of the initial and final nuclei and they could measure the energy of the electron, but they *could not* detect the neutrino. To them it looked as if energy wasn't conserved. Pauli suggested that there might be an unseen neutral, chargeless particle that takes away the missing energy - he called it a "*neutron*"!

Original - Photocopie of PLC 0393

Abschrift/15.12.30 PW

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 100mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

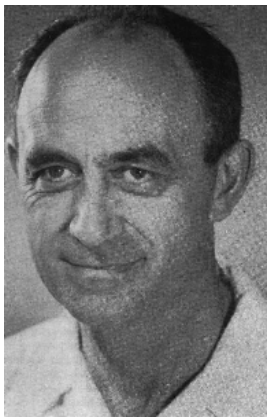
Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

from FNAL's *Symmetry* magazine

Pauli's letter to the participants of a meeting of experimental physicists which he could not attend.

In 1934 Enrico Fermi created a theory of the Weak Interaction that explains the experiments and has allowed us to calculate how neutrinos should behave and interact with matter.



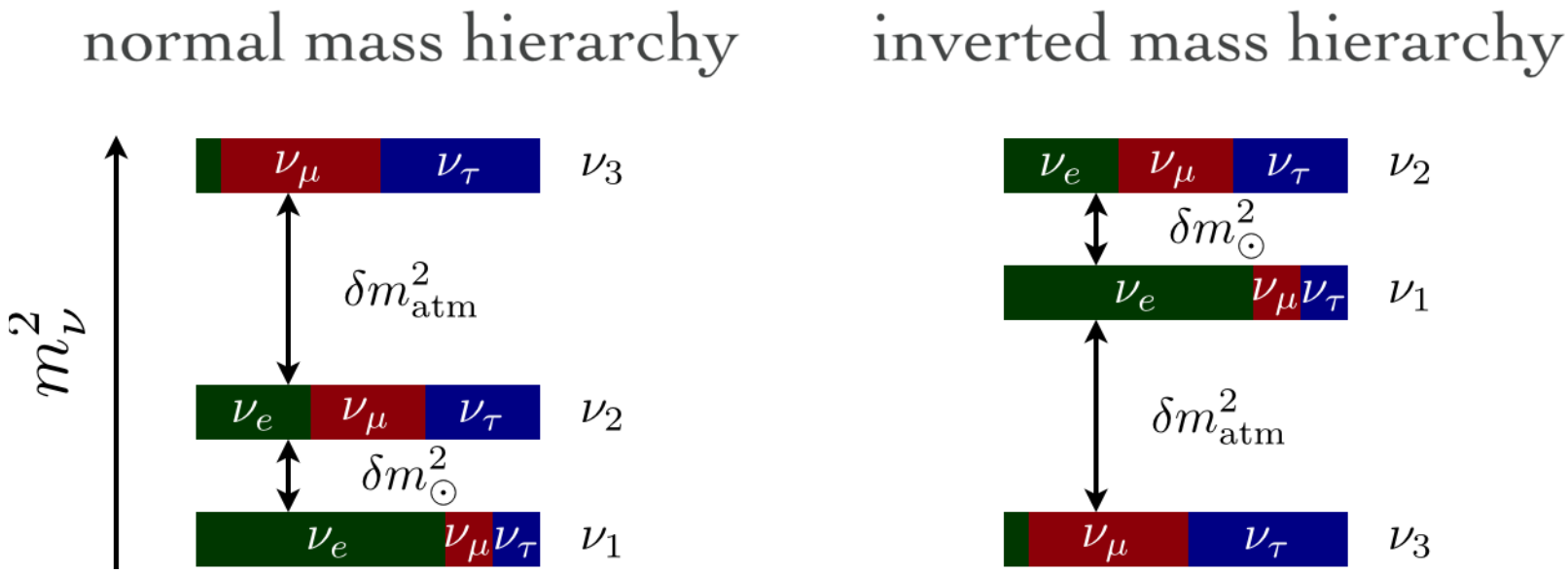
Neutrino Mass: what we know and don't know

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*:



Our Charge:

What do these neutrino properties mean
for astrophysics, *i.e.*, cosmology and supernovae??

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!

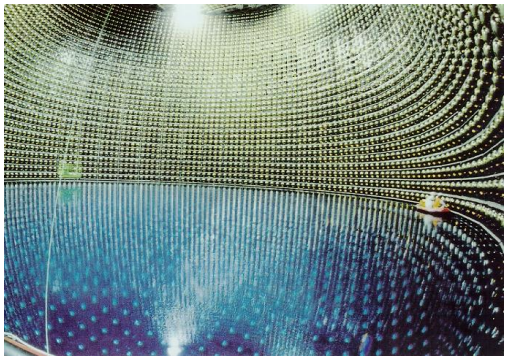
As we will see, neutrinos can more than make up for their feeble interactions with **huge** numbers!!

This might seem like an outrageously absurd statement given how feebly neutrinos interact with matter.

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!

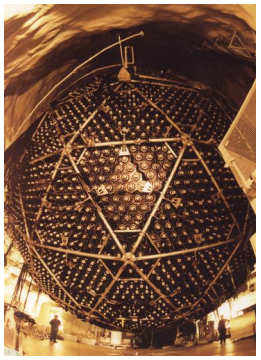
However, as we shall see, with HUGE NUMBERS, neutrinos can easily make up for their weak interactions.

Nevertheless, 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

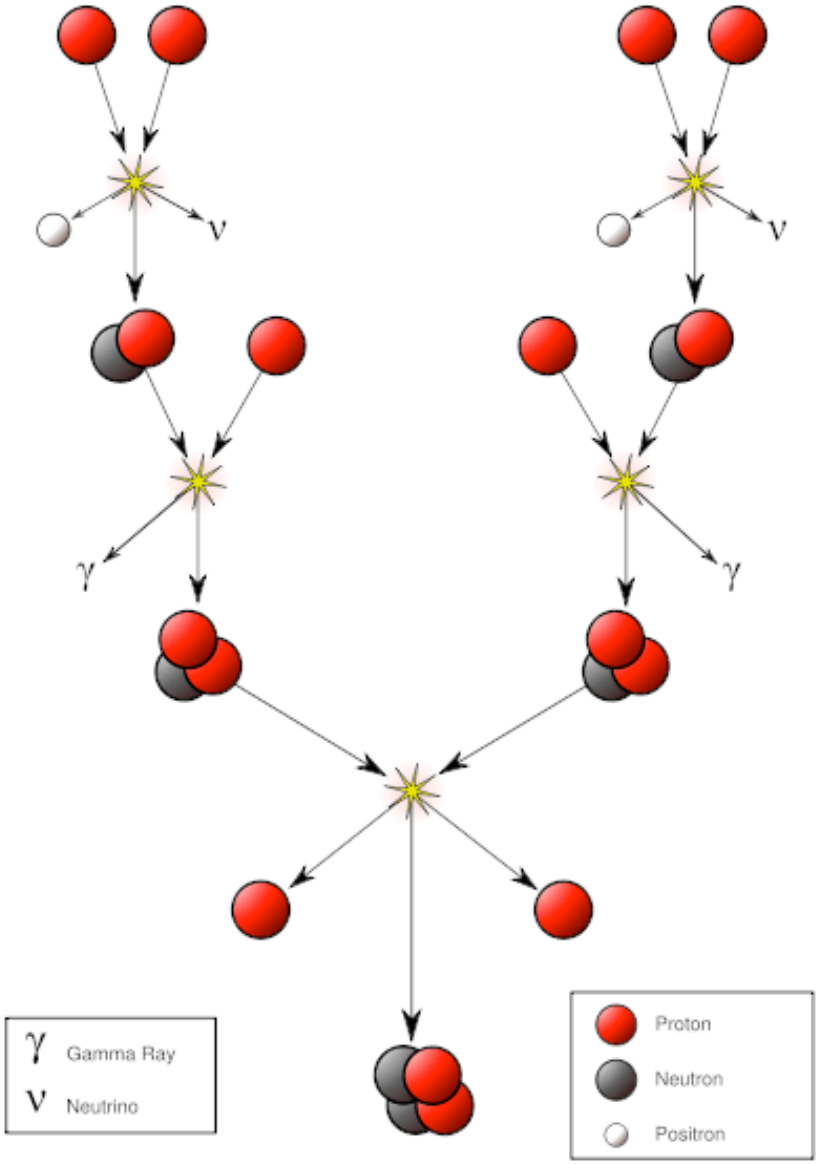
The Weak Interaction may be feeble, but . . .

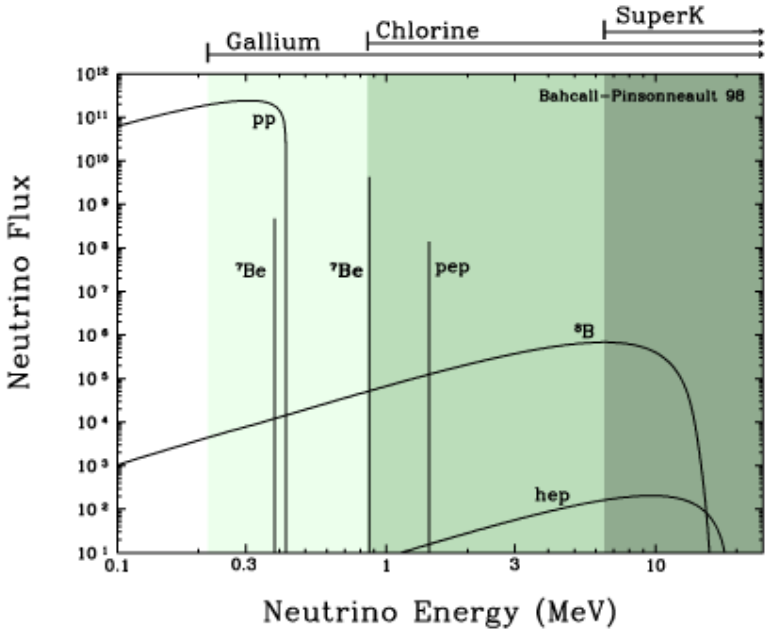
The weak interaction is the only means for
converting neutrons into protons and *vice versa*.

If it were not for the weak interaction:
-stars would not shine (for very long anyway)
-there would be very few of the elements required for life (no CC SN)

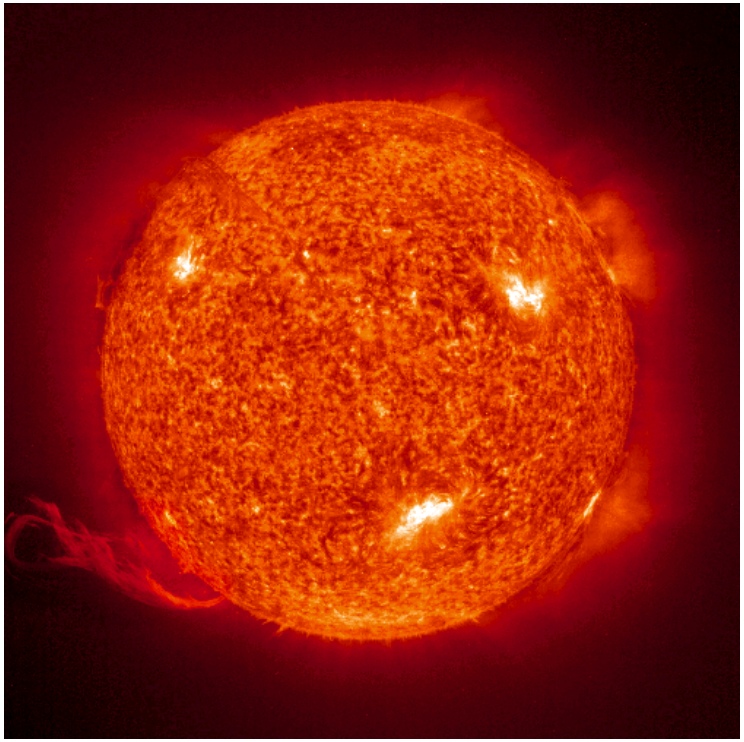
Fusion reactions power the sun

-they make, ultimately, photons and neutrinos



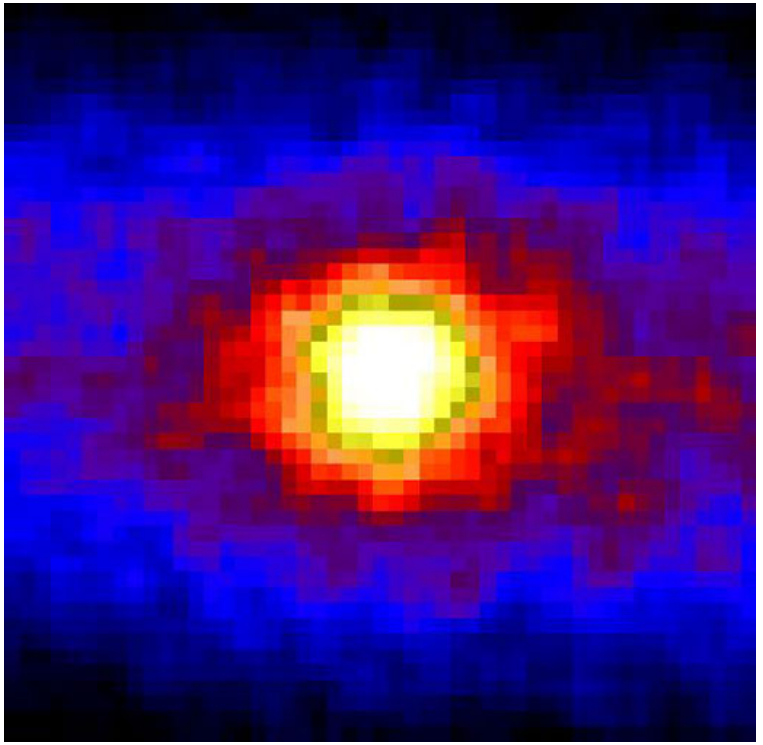


John Bahcall - solar neutrino problem



The sun in x-rays (photons)

(Cornell)



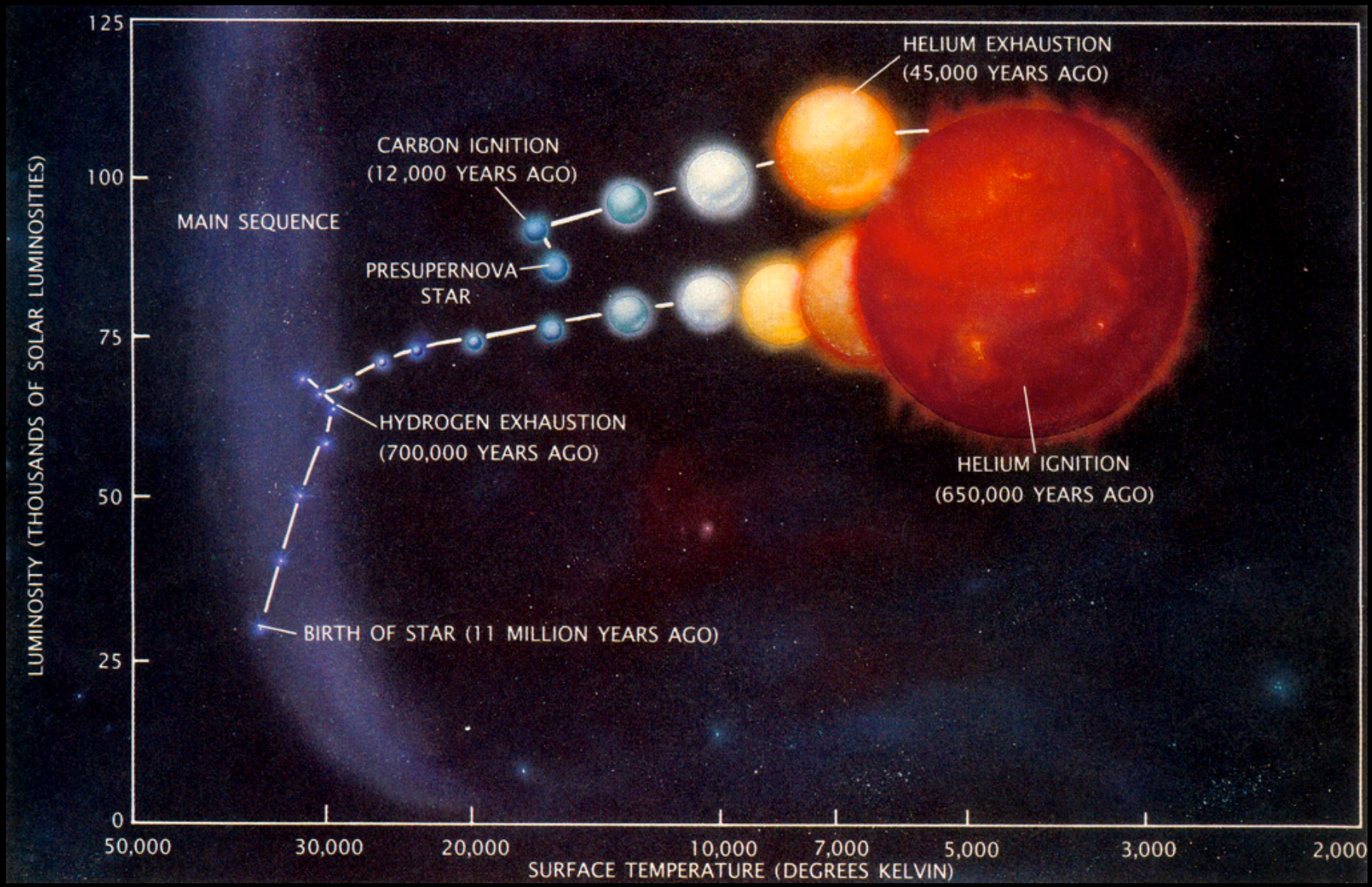
the sun in neutrinos
-composite from SuperK

(R. Svoboda, LBNL, now UCD)

But whereas neutrinos are innocent bystanders in the sun,
they are the criminal masterminds in core collapse supernovae!

Core Collapse Supernovae

Stealthy neutrinos undermine the financial (*energy deposits*) stability of massive stars, set up the 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.



Weaver & Woosley, *Sci Am*, 1987

Nuclear Burning Stages of a 25 M_{sun} Star

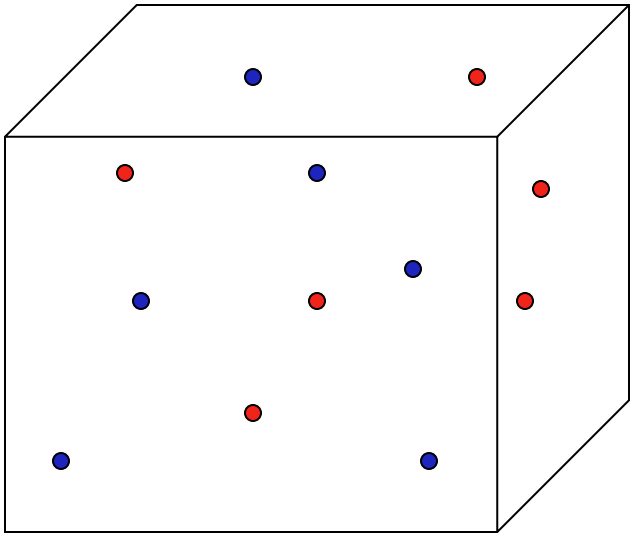
Burning Stage	Temperature	Density	Time Scale
Hydrogen	5 keV	5 g cm^{-3}	7 X 10^6 years
Helium	20 keV	700 g cm^{-3}	5 X 10^5 years
Carbon	80 keV	2 X 10^5 g cm^{-3}	600 years
Neon	150 keV	4 X 10^6 g cm^{-3}	1 year
Oxygen	200 keV	10^7 g cm^{-3}	6 months
Silicon	350 keV	3 X 10^7 g cm^{-3}	1 day
Core Collapse	700 keV ↓	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

Entropy

$$S = k \log \Gamma$$

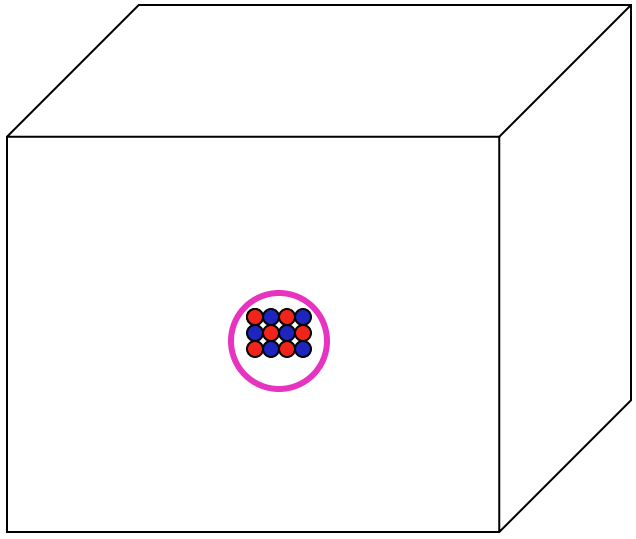
a measure of a system's disorder/order

High Entropy



12 free nucleons

Low Entropy



^{12}C nucleus

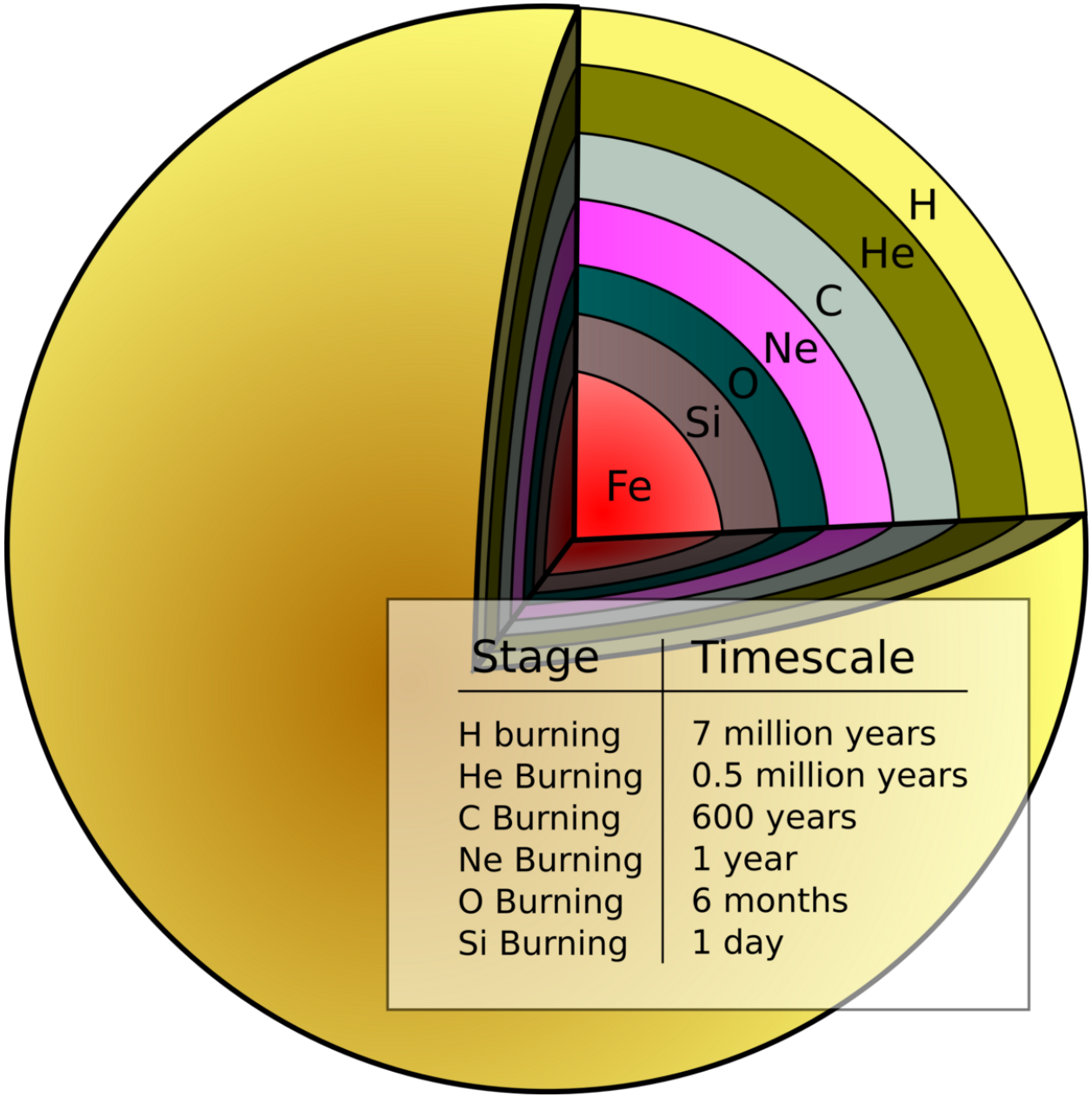
Massive Stars are Giant Refrigerators

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!

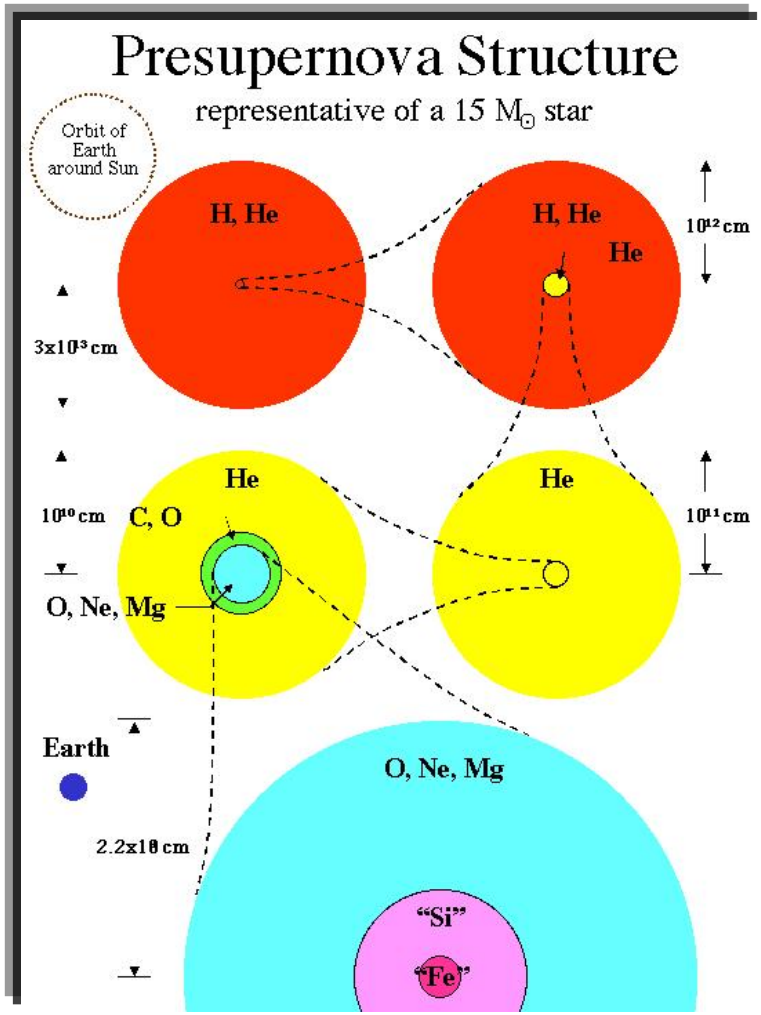
e.g., the collapsing core of a supernova can be a
frozen (Coulomb) crystalline solid with a
temperature ~1 MeV!



Stage	Timescale
H burning	7 million years
He Burning	0.5 million years
C Burning	600 years
Ne Burning	1 year
O Burning	6 months
Si Burning	1 day

http://large.stanford.edu/courses/2008/ph204/deaconu1/

Structure of an Evolved Massive Star



Relevant Time Scales:

- ⇨ **Massive stars evolve for millions of years.**
- ⇨ **Die in a few hours in a supernova.**
- ⇨ **Explosion initiated in < 1 second.**

Relevant Spatial Scales:

- ⇨ **Iron core is roughly of Earth's size.**
- ⇨ **Outer stellar radius is larger than the orbit of the Earth around the Sun.**

Neutrinos Dominate the Energetics of Core Collapse Supernovae

Total optical + kinetic energy, 10^{51} ergs

Total energy released in Neutrinos, 10^{53} ergs

10% of star's rest mass!

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

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

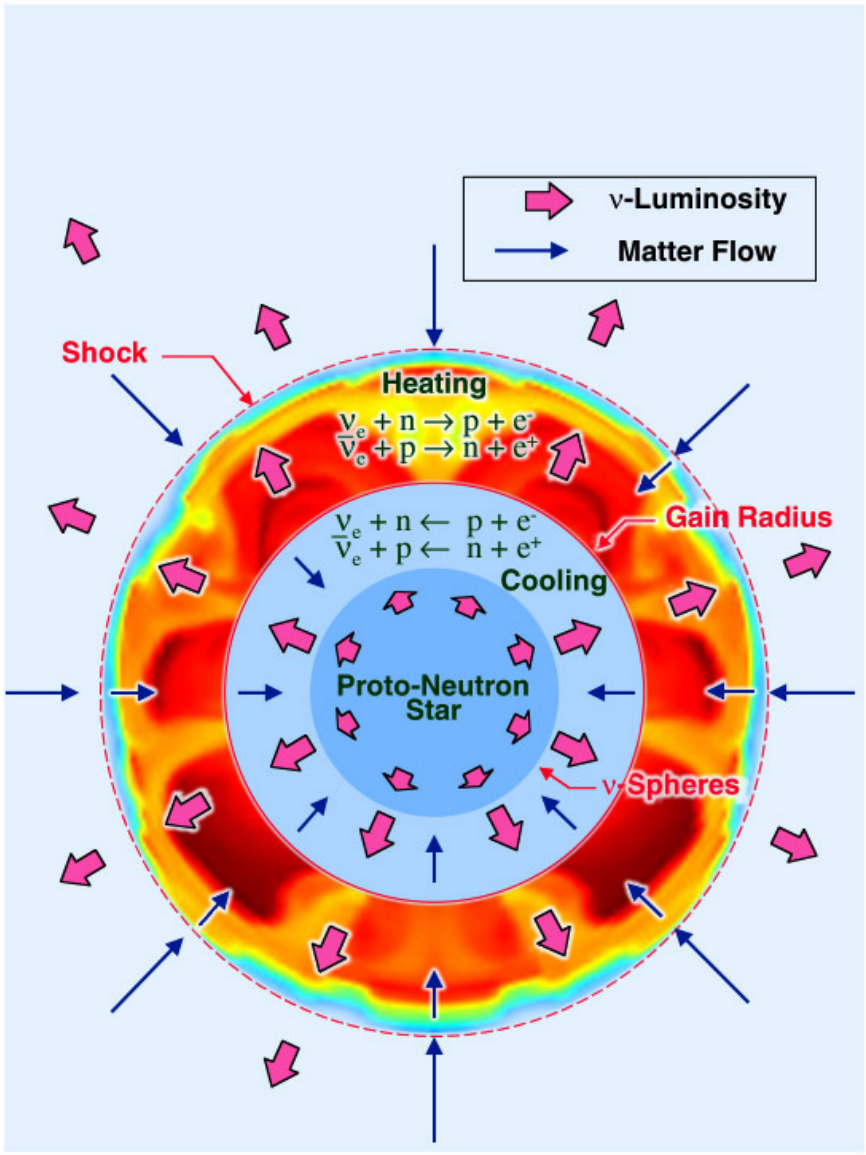
$$L_\nu \approx \frac{1}{6}\frac{GM_{NS}^2}{R_{NS}}\frac{1}{\tau_\nu} \approx 4\times10^{51}\,\text{ergs s}^{-1}$$

Neutron-to-proton ratio and energy deposition largely determined by these processes:

$$\nu_e + n \longrightarrow p + e^-$$

$$\bar{\nu}_e + p \longrightarrow n + e^+$$

The Role of Core Fluid Instabilities



Possible Instabilities:

⇨ **Convection (e.g., Ledoux)**

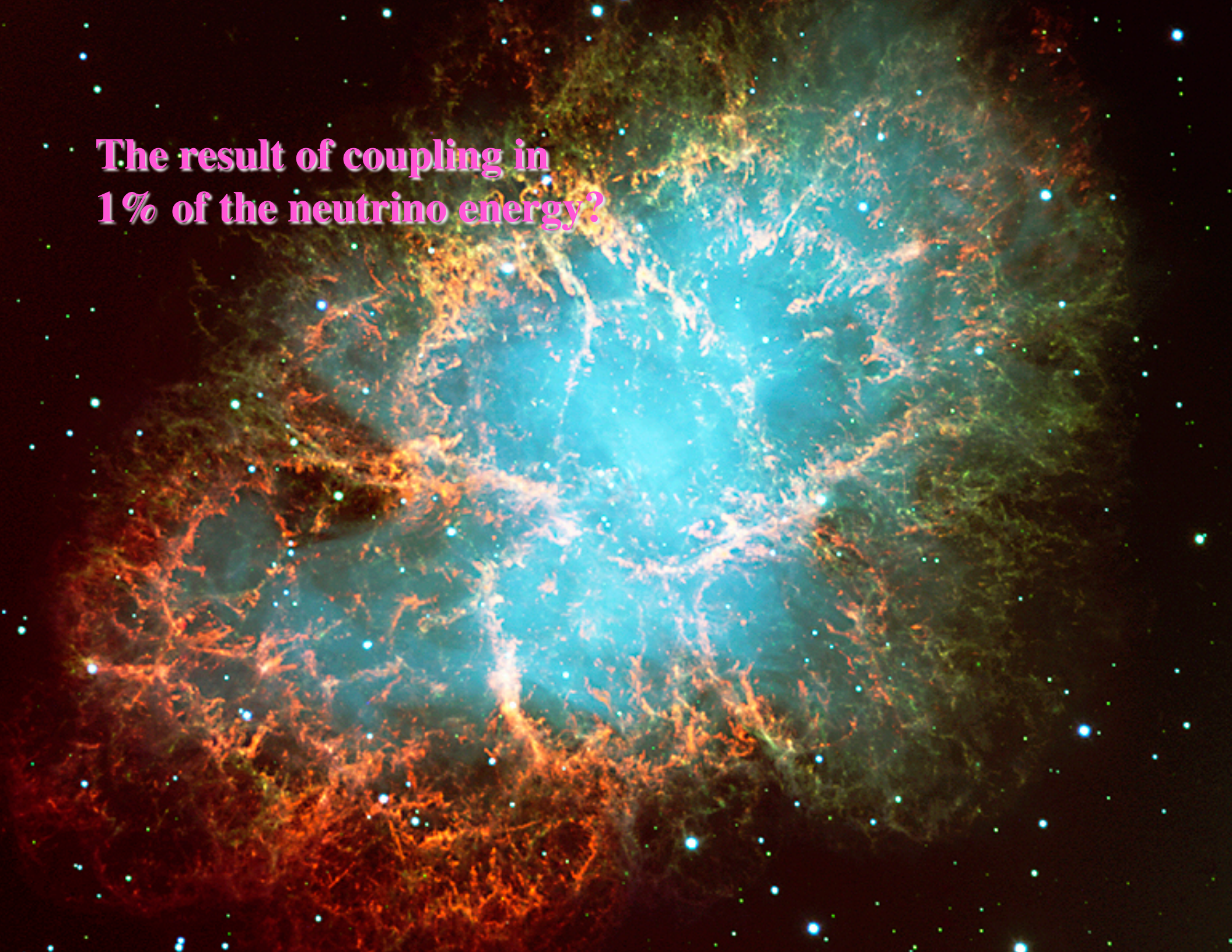
Negative gradients in entropy, lepton fraction, or both.

⇨ **Doubly Diffusive Instabilities (e.g., Neutron Fingers, LEF)**

Crossed gradients in entropy and lepton fraction.

⇨ **Shock Wave Instability**

Something completely different.

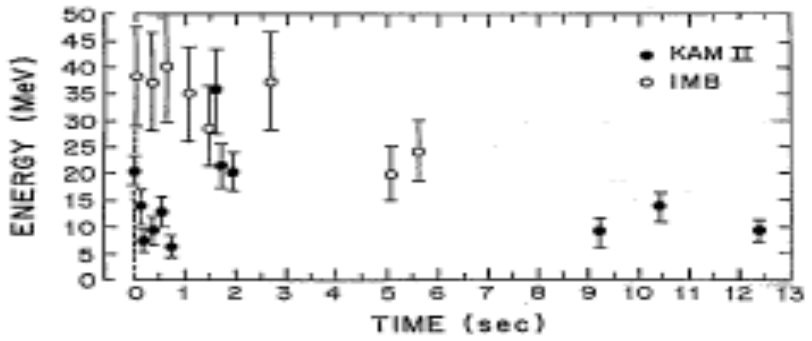

The result of coupling in
1% of the neutrino energy?

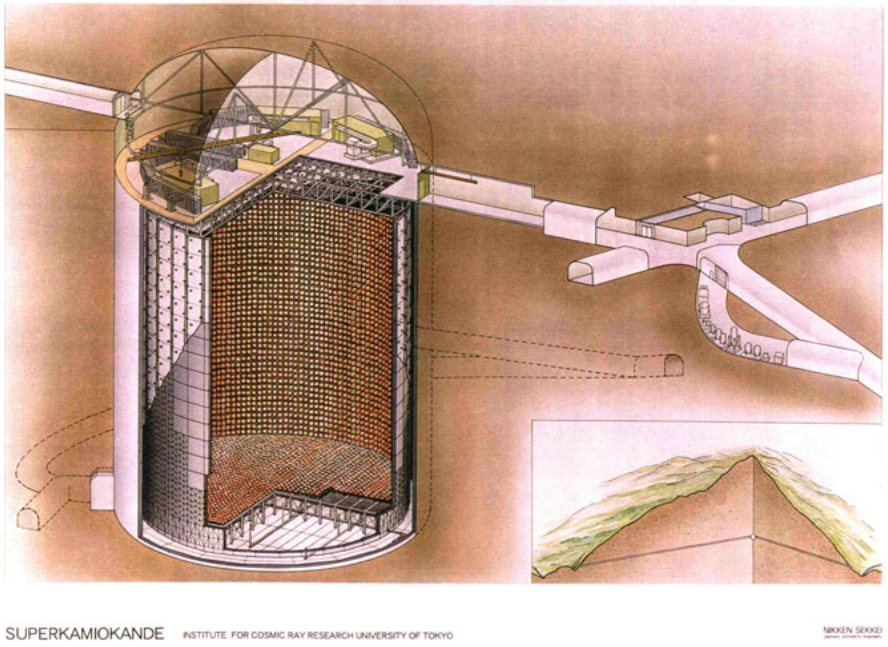
SN1987A

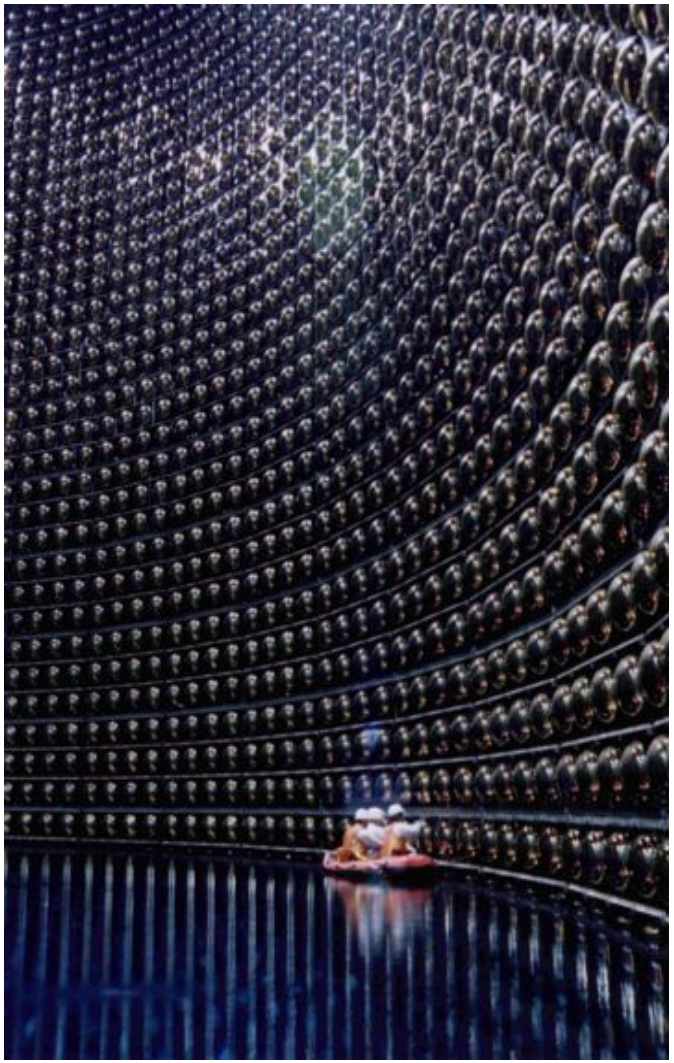
Tarantula Nebula in the Large Magellanic Cloud (50 kpc)

Observing Supernova Neutrinos

SN 1987A







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)

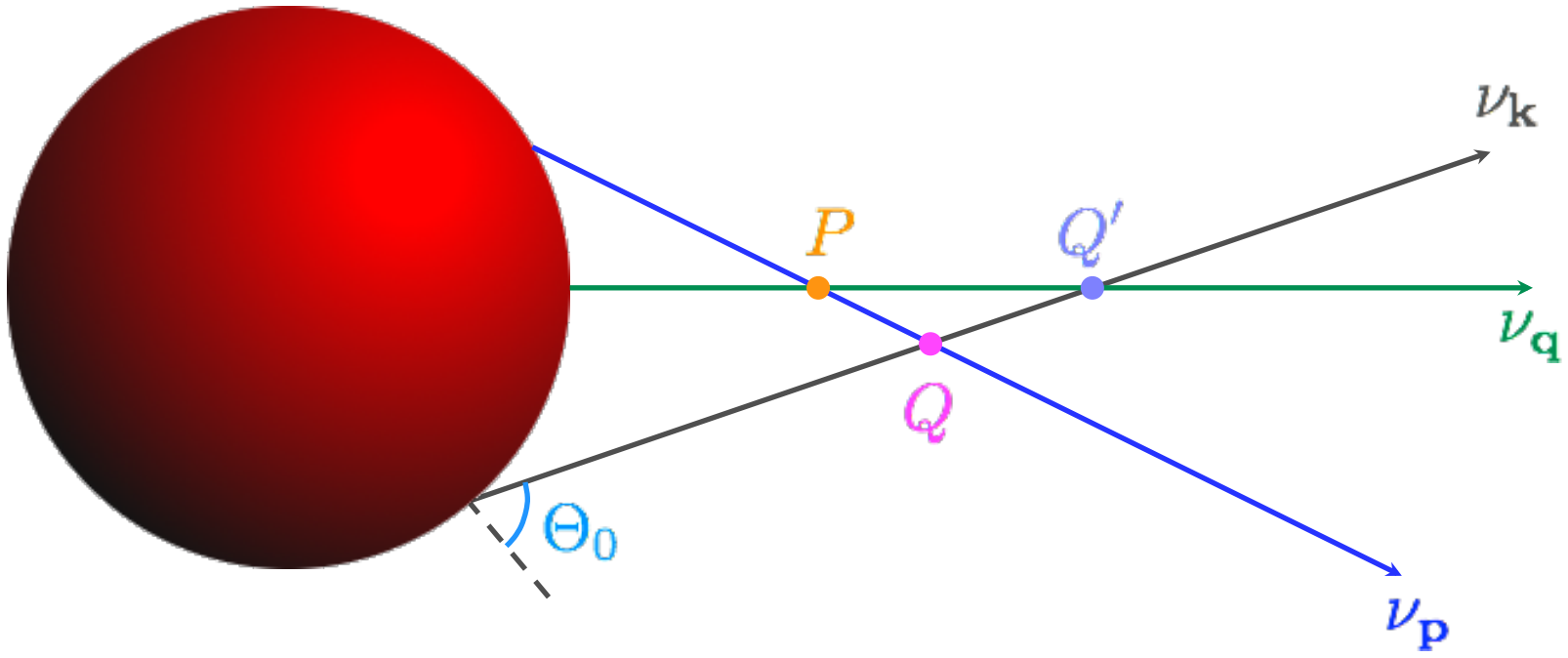
As it propagates along a neutrino can be in a superposition of different flavors, and the *medium* around it can influence the relative mix of these flavors.

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".

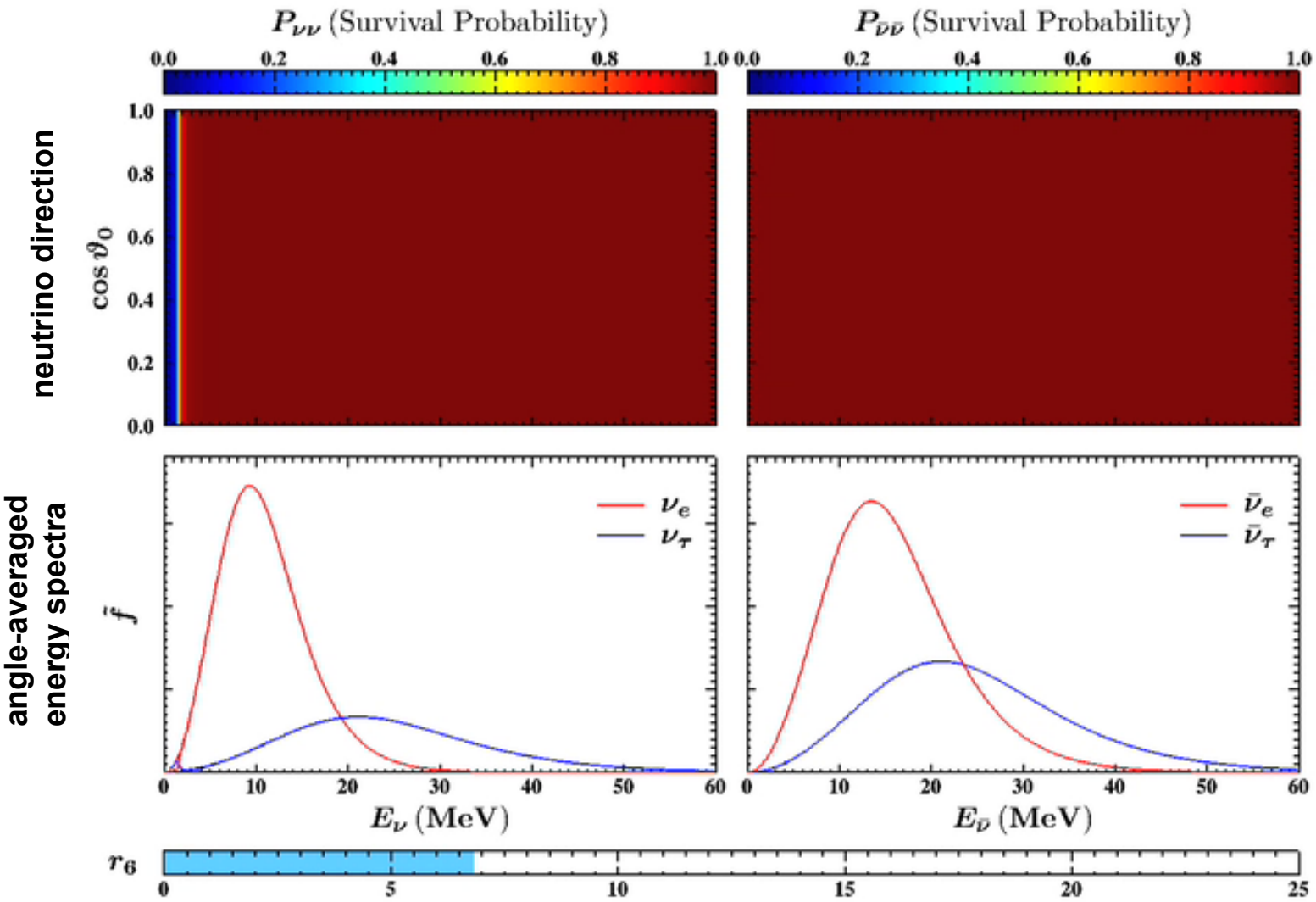
NONLINEAR !!!

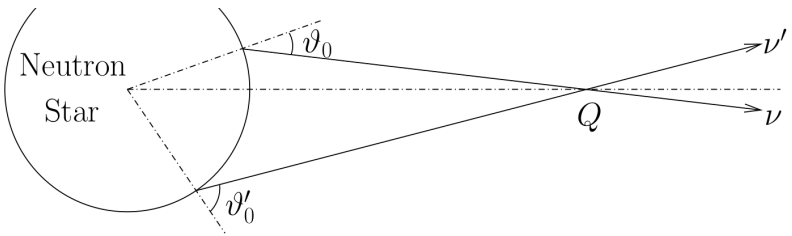
- Anisotropic, nonlinear quantum coupling of all neutrino flavor evolution histories



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

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





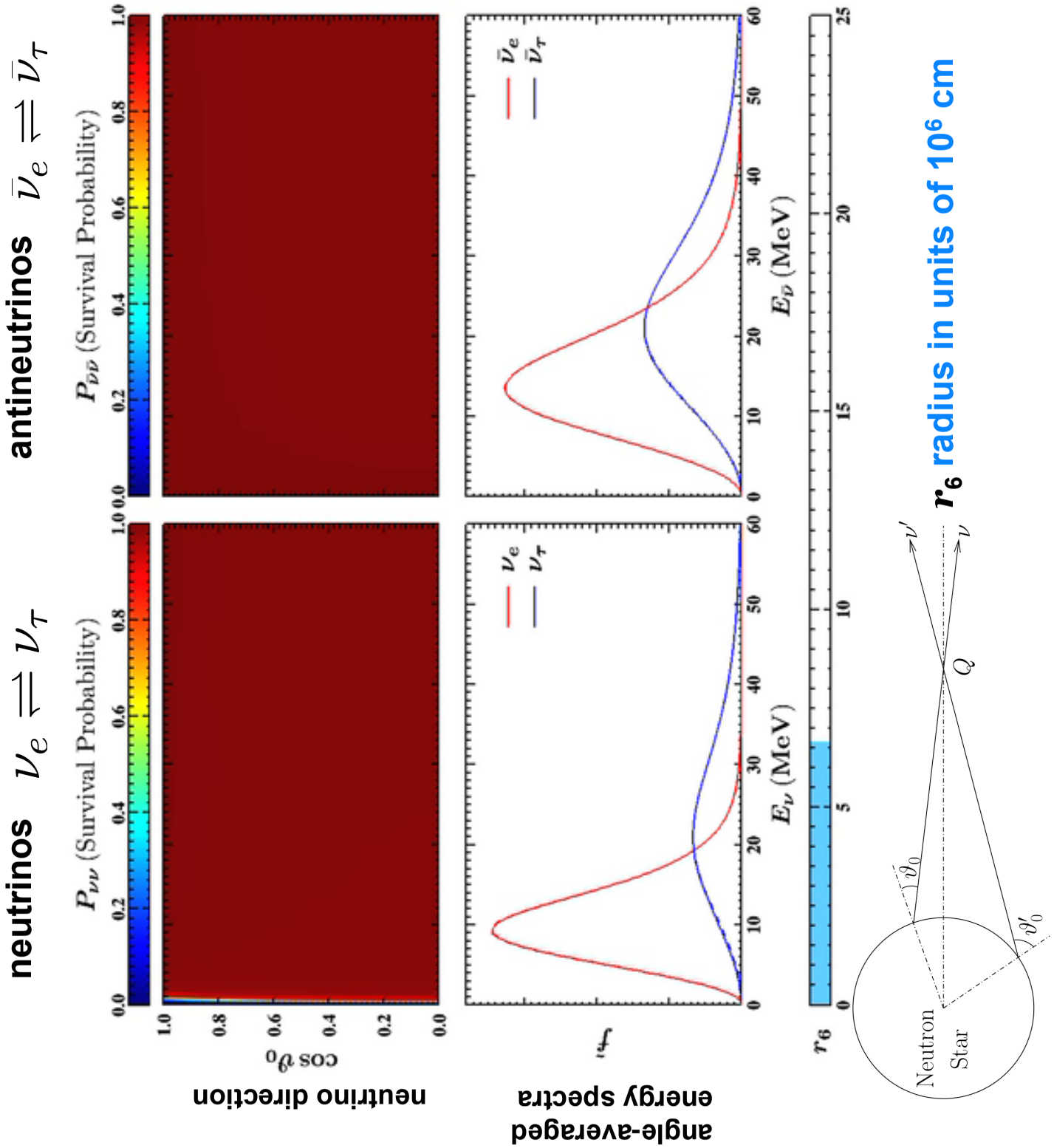
r_6 radius in units of 10^6 cm

$L_\nu = 0$

NORMAL MASS HIERARCHY

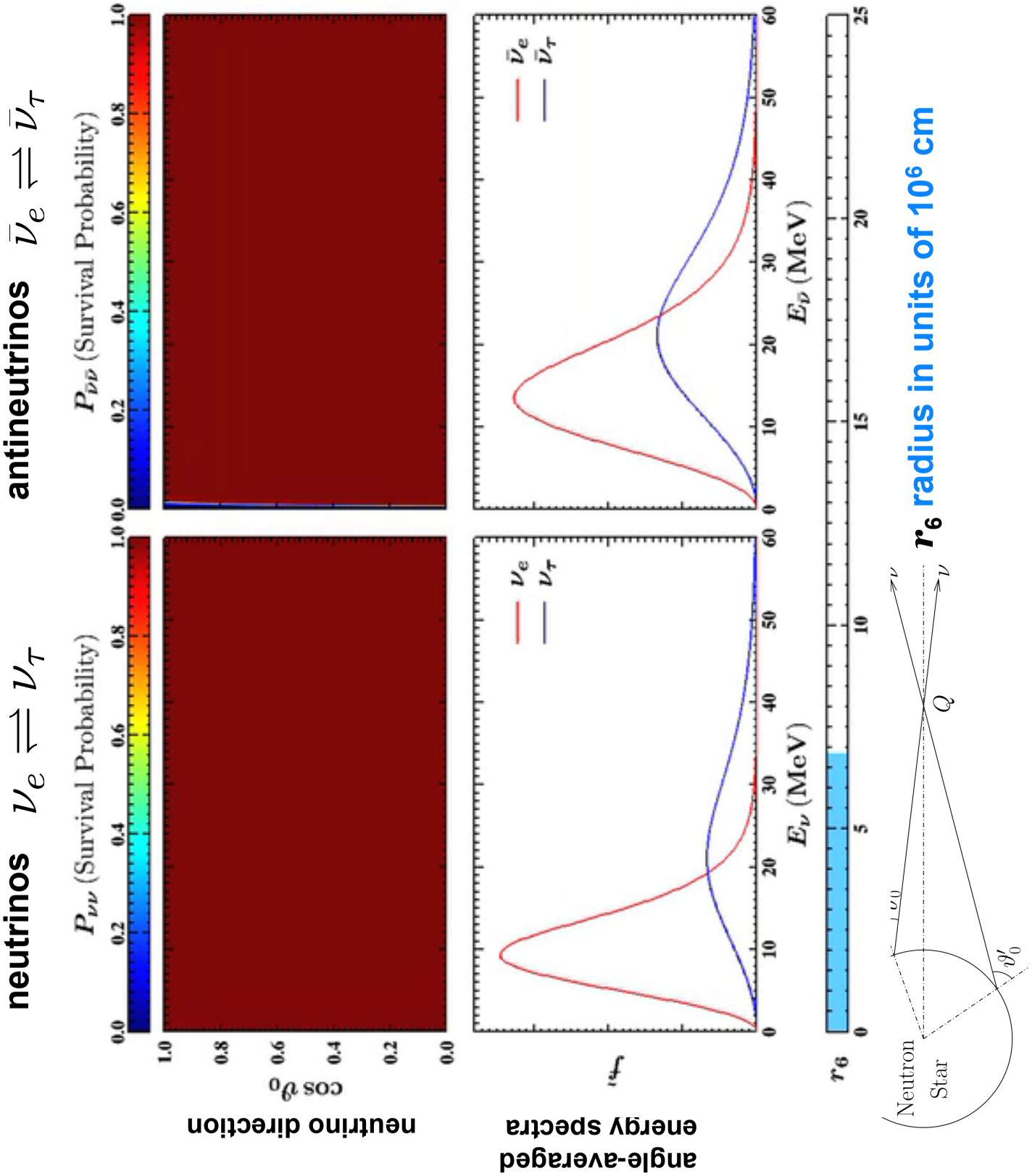
$$L_\nu = 10^{51}\,\mathrm{erg\,s^{-1}}$$

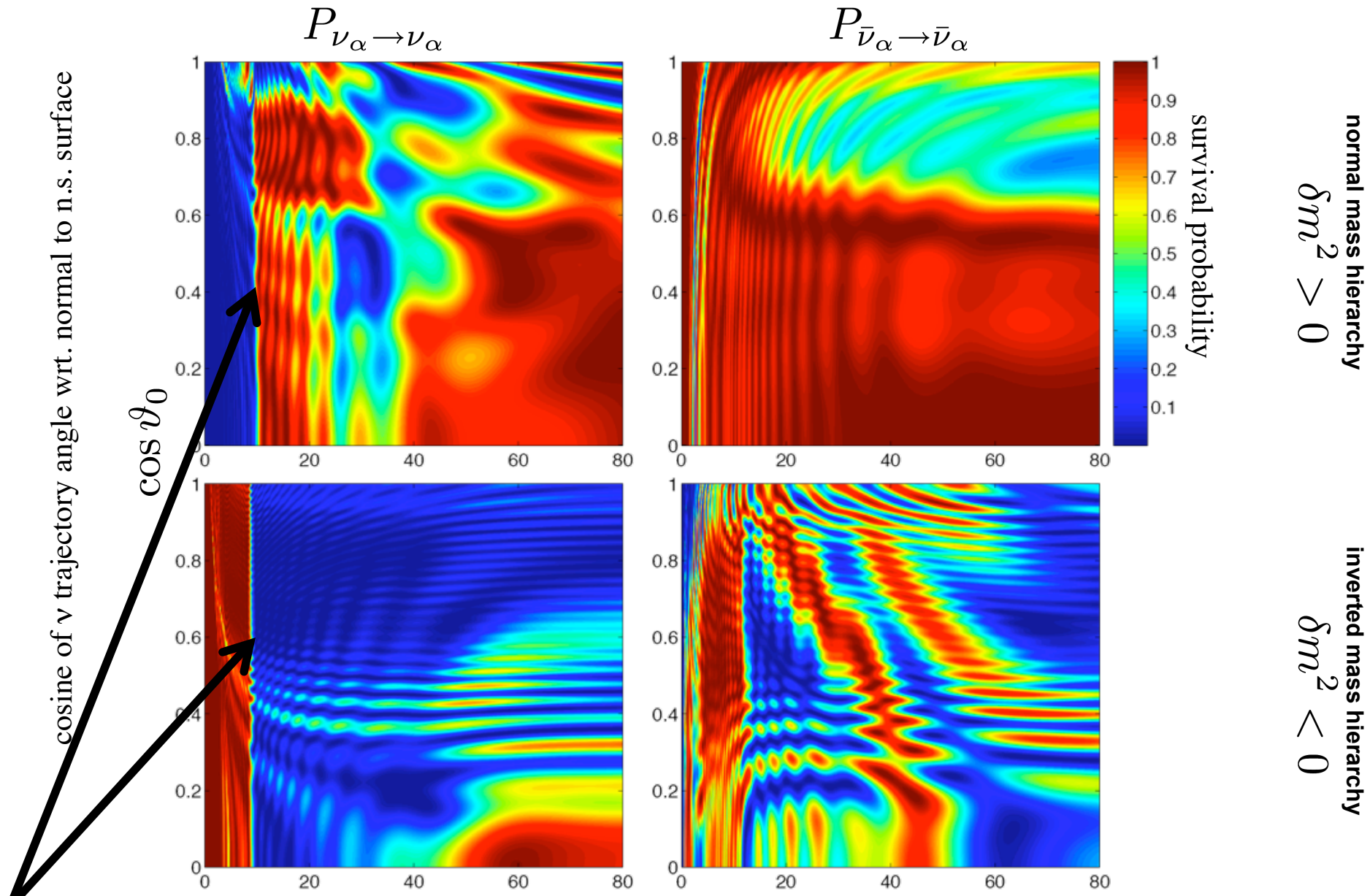
NORMAL MASS HIERARCHY



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

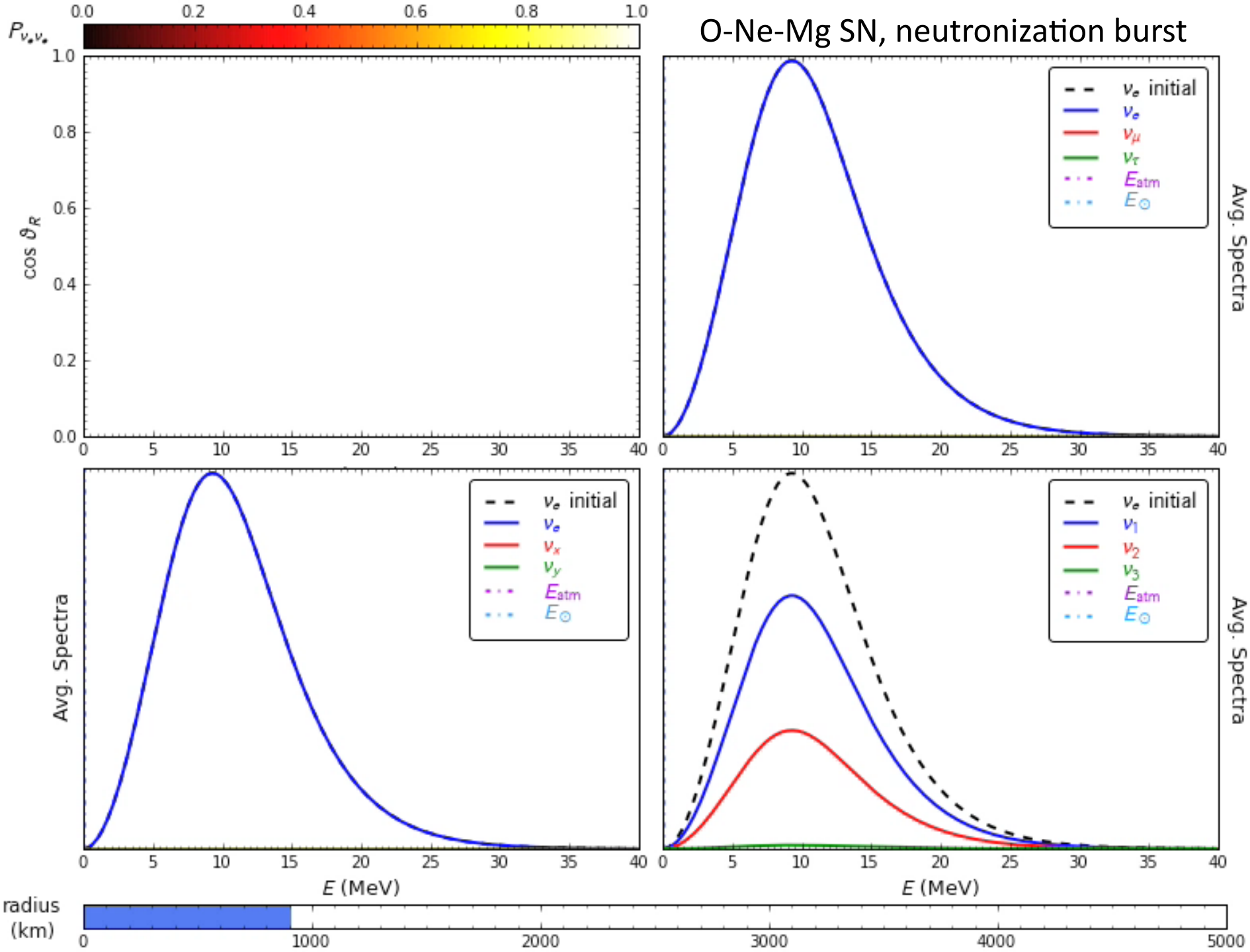
INVERTED MASS HIERARCHY





consequences of neutrino mass and quantum coherence in supernovae

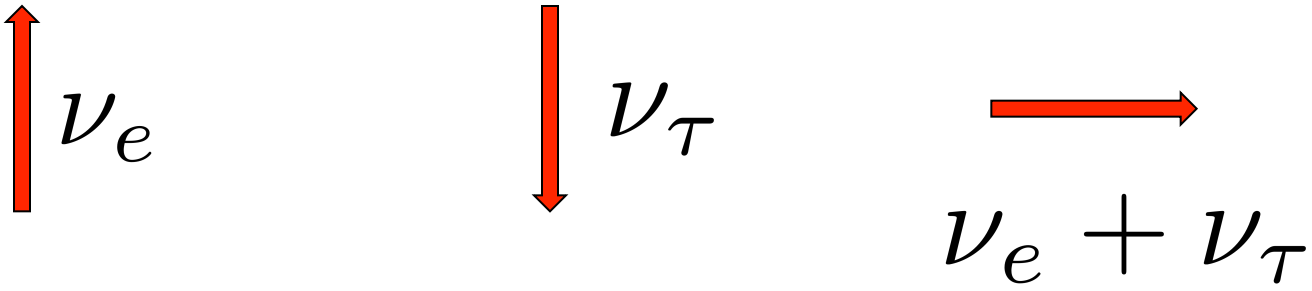
H. Duan, G. M. Fuller, J. Carlson, Y.-Z. Qian, Phys. Rev. Lett. **97**, 241101 (2006) **astro-ph/0606616**


O-Ne-Mg SN, neutronization burst
$P_{\nu_e\nu_e}$
0.0
0.2
0.4
0.6
0.8
1.0
cos ϑ_R
ν_e initial
ν_e
ν_μ
ν_τ
E_{atm}
$E_\odot$
Avg. Spectra
ν_e initial
ν_e
ν_x
ν_y
E_{atm}
$E_\odot$
Avg. Spectra
ν_e initial
ν_1
ν_2
ν_3
E_{atm}
$E_\odot$
Avg. Spectra
E (MeV)
E (MeV)
radius
(km)
0
1000
2000
3000
4000
5000

Swap Phenomenon seems to be ubiquitous

Can understand this if we associate a "spin" with the neutrino's flavor:

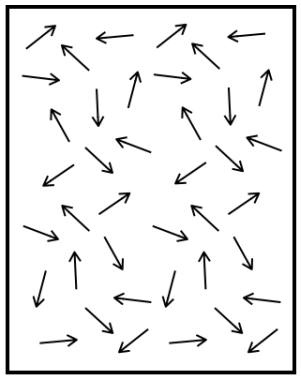
The direction of this "spin" gives the flavor, *e.g.,*



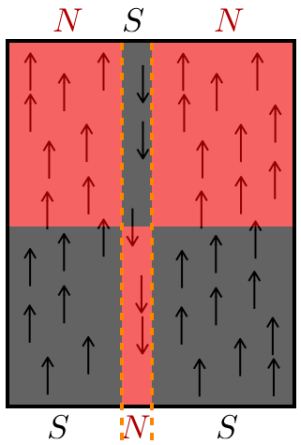
analogy: magnetic (moment) spins of atoms

Magnetic Analogy

$T > T_C$

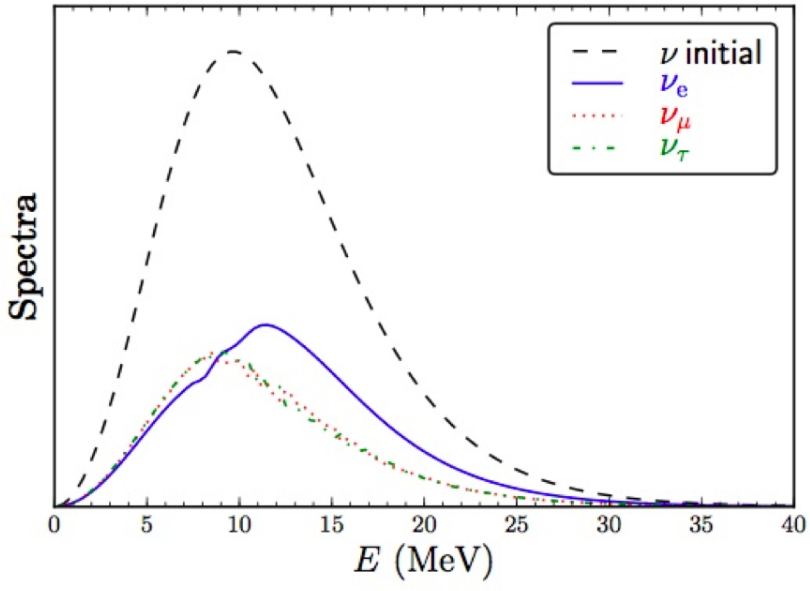


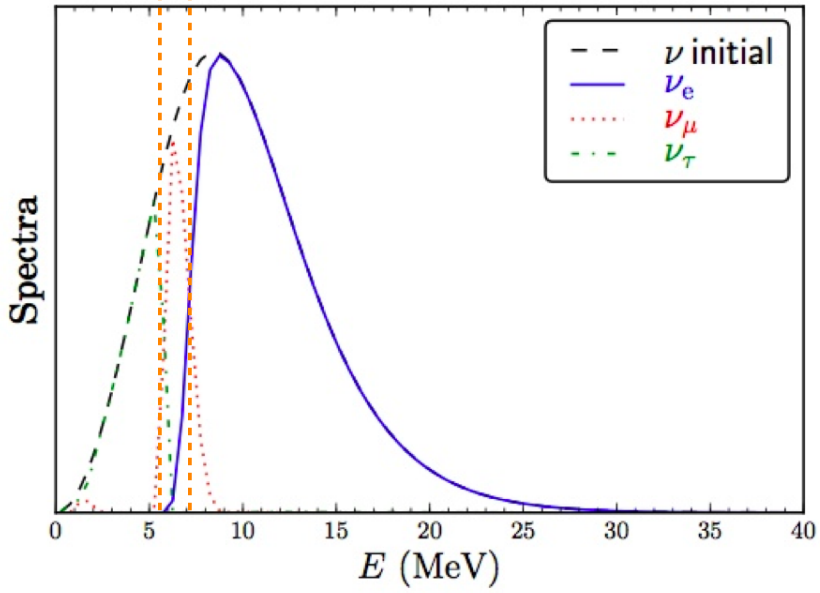
$T < T_C$



Cooling causes the magnetic spins to line up in domains in space.

"Cooling" (moving away from the neutron star) causes the neutrino spins to line up in domains in energy space.





Detecting a supernova neutrino burst in the Galaxy
would give us insights into both fundamental particle physics
and the workings of core collapse supernovae.