Lecture II: Neutrinos in Multi-Messenger Astrophysics

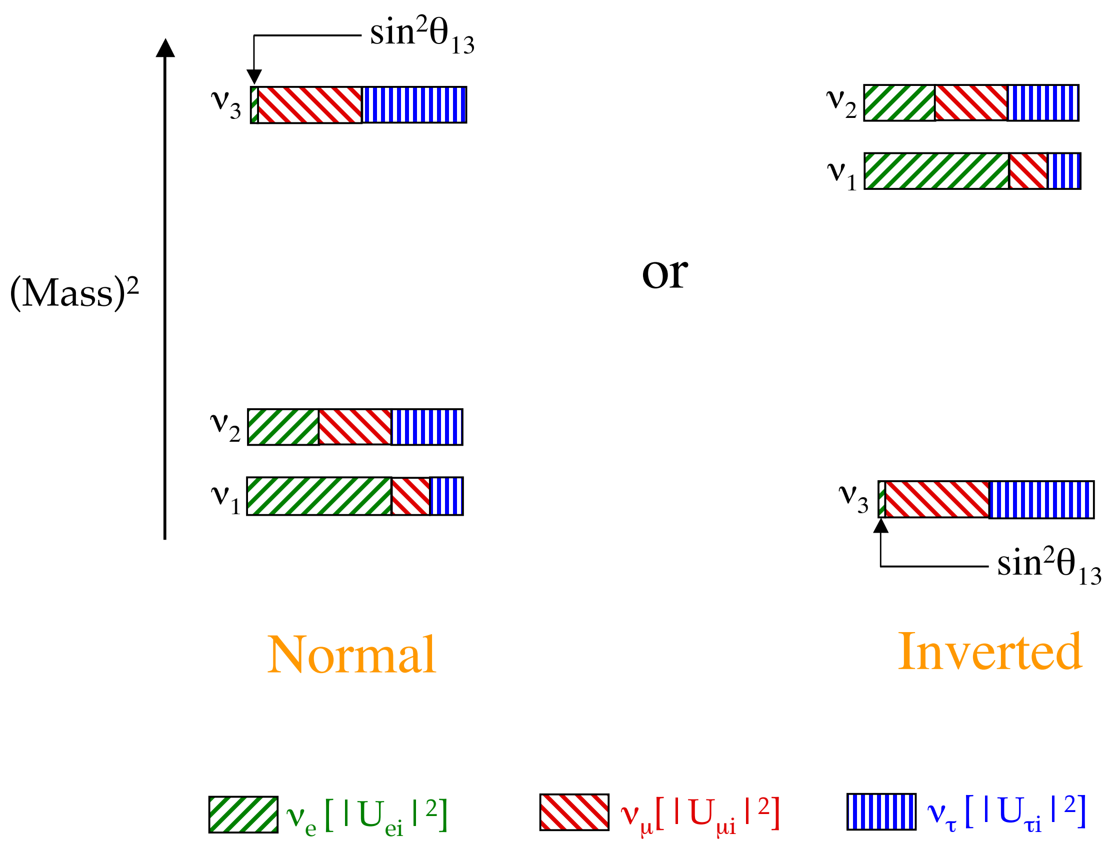
- Neutrinos in multi-messenger astrophysics
- Core collapse supernovae
- Nucleosynthesis

Wick Haxton Niels Bohr Institute July 2-6, 2018

Multi-Messengers from Compact Sources

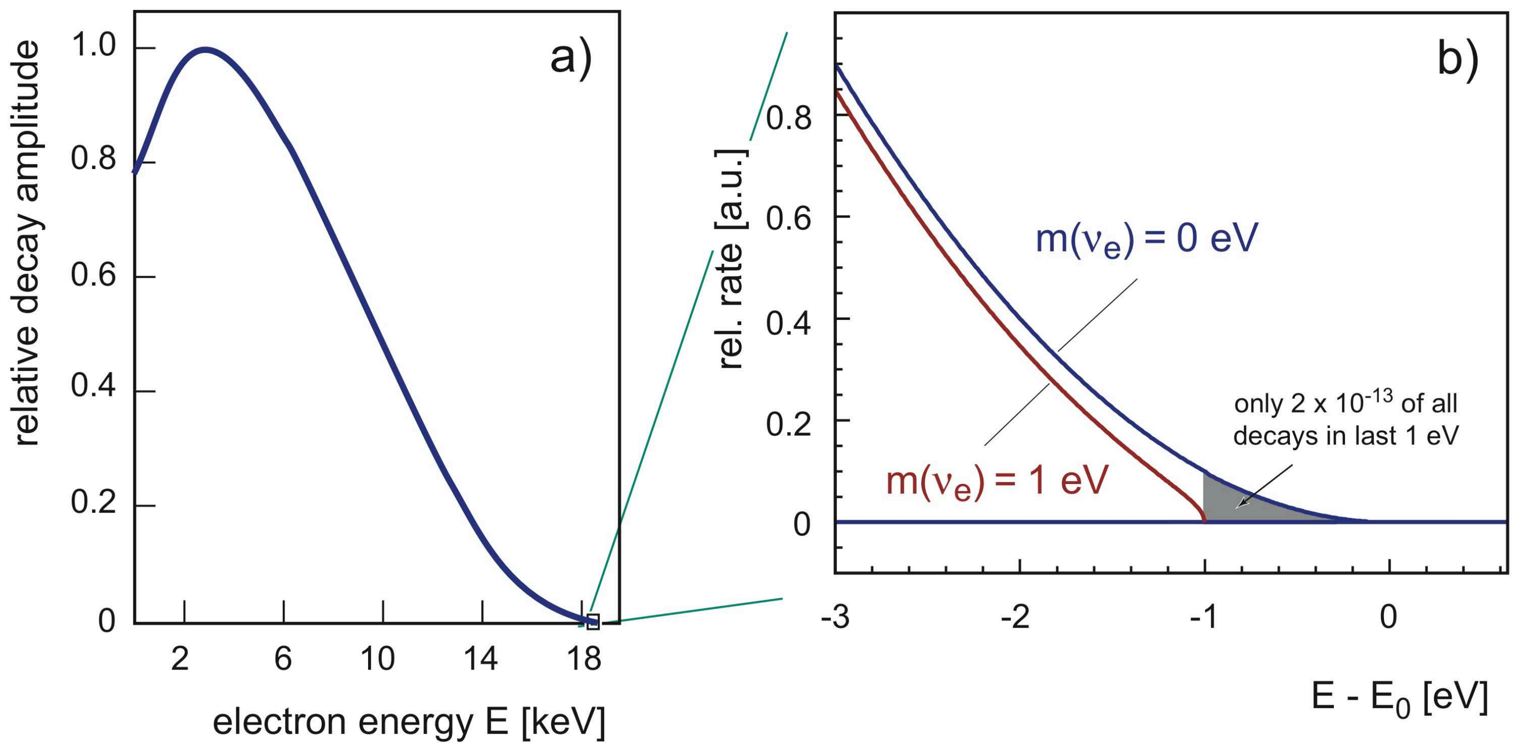
Inner space/Outer space Connections: Open Questions

1. *Hierarchy:* Matter can be used to probe eigenstate orderings!
Sun is not dense enough to cause the 3rd neutrino to cross



So we need to find another way: NOvA, T2K, LBNE, ….
(Evidence is mounting it is normal)

2. <u>Absolute mass</u>: Oscillations probe mass differences
There can be an offset — the mass of the lightest neutrino



$$\langle m_\nu \rangle_{\text{tritium}} = \sum_i |U_{ei}|^2 m_\nu^2(i)$$

KATRIN just starting: pushing the technology to the limits

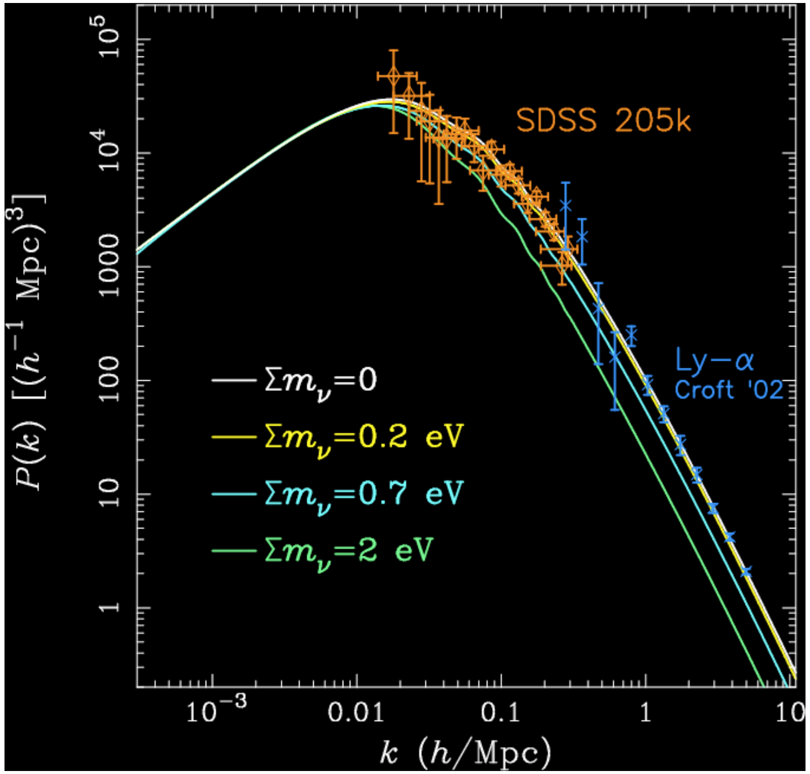
2.2 MeV → 0.25 MeV = 250 meV

A potentially more powerful alternative: the influence of BBN neutrinos (the cosmological neutrino component of DM) on large-scale structure:

$$n_\nu = N_\nu \left(\frac{3}{11}\right) n_\gamma \sim 340\ \mathrm{cm}^3$$

Relativistic species suppress the growth of LSS: relativistic particles travel further, helping to equilibrate on large scales

Neutrinos can start off relativistic, become non relativistic: the effects are both scale and red shift dependent



leverage: at 0.1% density of neutrinos has a 1% impact on the power at large wave numbers

e.g., CMB measurements at large k are still far below the statistical limit: much improvement to come

from Kev Abazajian

<u>The mixing:</u> knowns $\theta_{12}, \theta_{23}, \theta_{13}$

3. known unknowns $\delta,\ \phi_1,\ \phi_2$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ e^{i\phi_1}\nu_2 \\ e^{i\phi_2}\nu_3 \end{pmatrix}$$

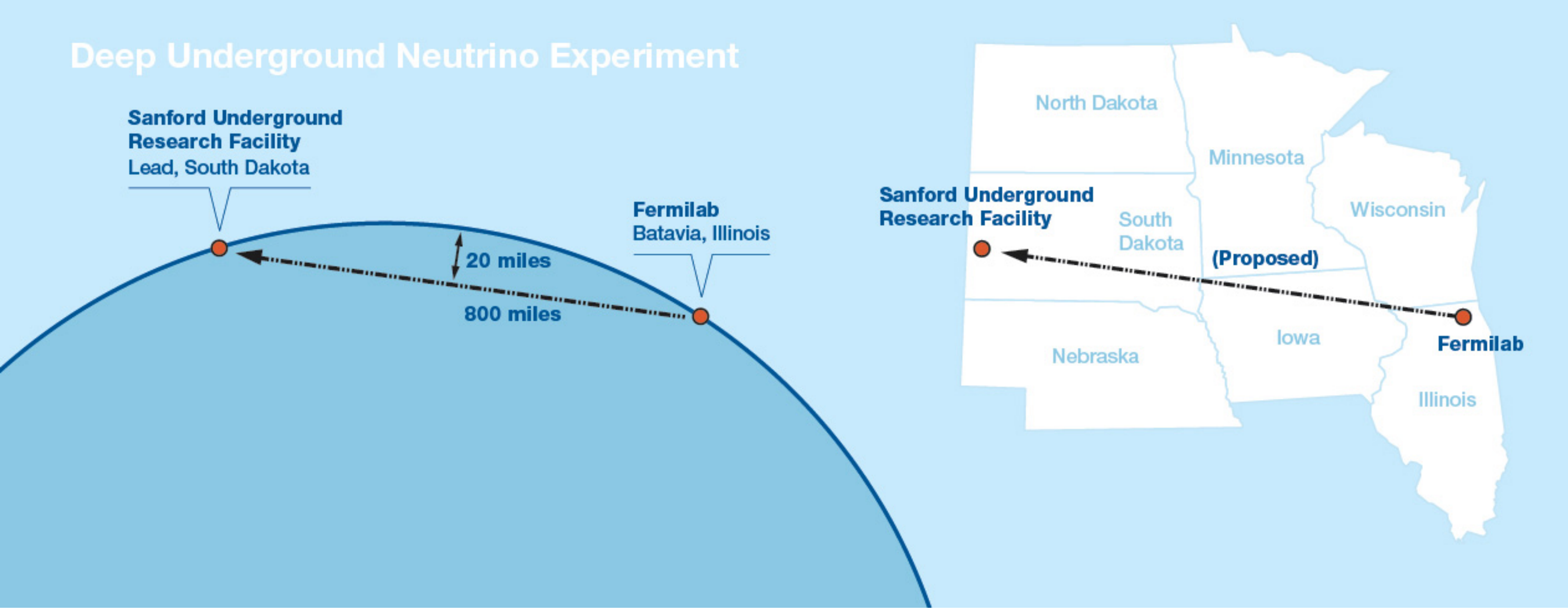
$$= \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-\boxed{i\delta}} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \boxed{e^{i\phi_1}}\nu_2 \\ \boxed{e^{i\phi_2}}\nu_3 \end{pmatrix}$$

atmospheric | ν_e disappearance | solar

results: $\theta_{23} \sim 45^\circ$ | $\theta_{13} \sim 8.3^o$ | $\theta_{12} \sim 34^o$

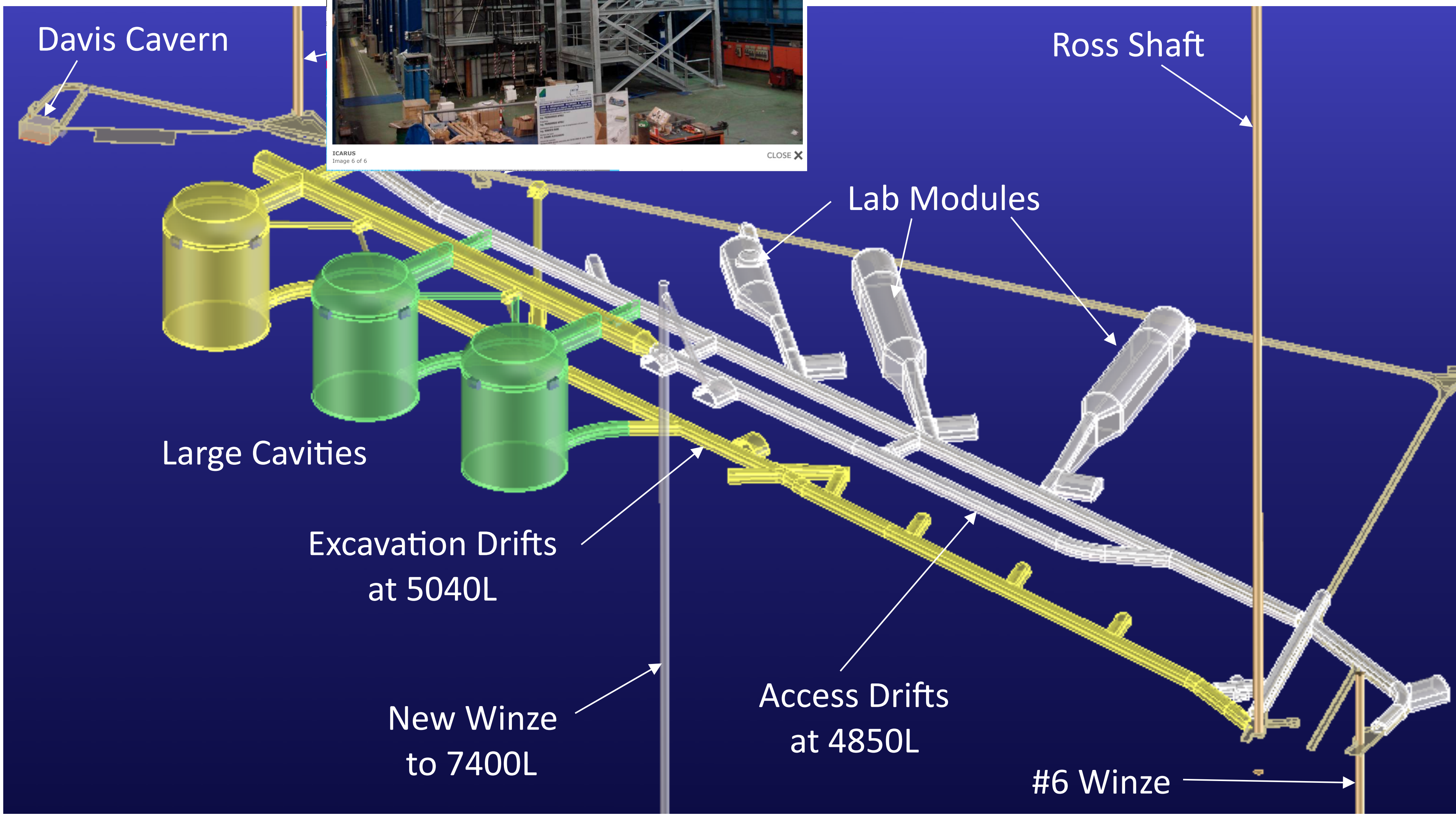
is one of the goals of LBNE, T2K, NOvA, etc

DUNE (Fermilab to Sanford Lab)
T2KII (upgraded T2K beam to HyperKamiokande):
hierarchy and CP phase

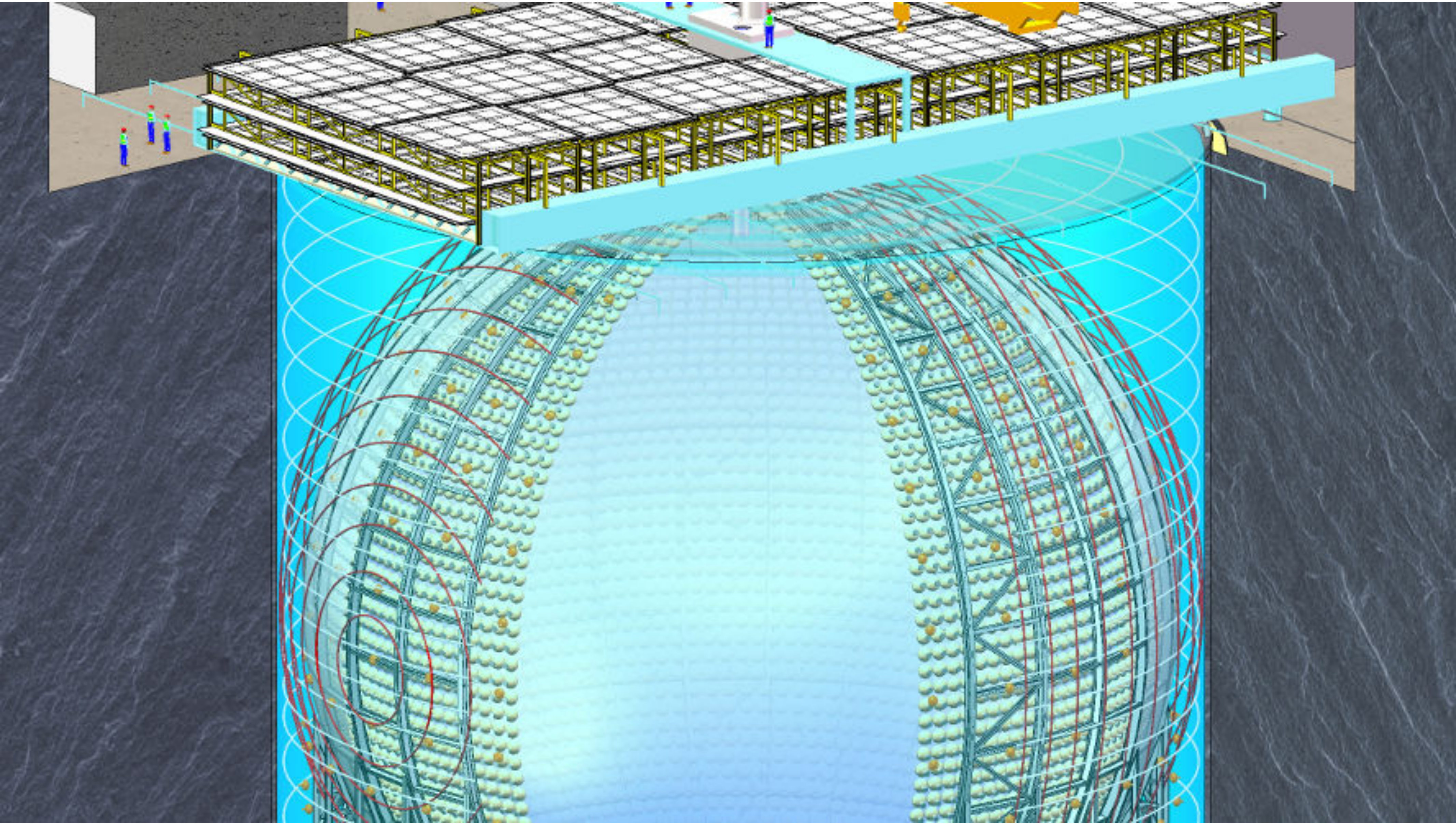


Icarus-like LiAr detector

goals: hierarch, CP phase



JUNO: 20 kton liquid scintillator under construction
hierarchy, precision measurements of mixing angles,
supernova, solar, and geoneutrinos



Two <u>inner space/outer space</u> mass questions are bigger than others

1. Why are we here? Might have expected the Big Bang to have produced equal amounts of matter and antimatter — which would have annihilated as the universe expanded and cooled, leaving just a bath of radiation. Did not happen.

   Efforts to create the needed baryon number and CP violation in the context of the SM have been unsuccessful: parameters too small

   In GUT theories that preserve B-L, a very attractive alternative is that large lepton number and CP violation lives among neutrinos, then communicated to the baryons. The large mixing angles and possibly large CP of neutrinos greatly eases this

2. What generates neutrino mass? Why are neutrinos so much lighter than other SM fermions?

Lepton number revisited

$$p_{\text{bound}} \to n + e^+ + \nu_e \quad \text{then} \quad \nu_e + n \to p + e^-$$

$$\text{but} \quad \nu_e + p \not\to n + e^+$$

$$n \to p + e^- + \bar{\nu}_e \quad \text{then} \quad \bar{\nu}_e + p \to n + e^+$$

$$\text{but} \quad \bar{\nu}_e + n \not\to p + e^-$$

so operationally distinct, requiring a quantum number (lepton number) to distinguish the two types of neutrinos; reactions above then correspond to the additive conservation of lepton number

but this is wrong, post 1957

Lepton number revisited

$$p_{\text{bound}} \rightarrow n + e^+ + \nu_e^{\text{LH}} \text{ then } \nu_e^{\text{LH}} + n \rightarrow p + e^-$$

$$\text{but } \nu_e^{\text{LH}} + p \not\rightarrow n + e^+$$

$$n \rightarrow p + e^- + \nu_e^{\text{RH}} \text{ then } \nu_e^{\text{RH}} + p \rightarrow n + e^+$$

$$\text{but } \nu_e^{\text{RH}} + n \not\rightarrow p + e^-$$

helicity alone can explain experiment
so this means the neutrino does not need another q. no.

the possibility of Majorana vs. Dirac is then completely open (good)

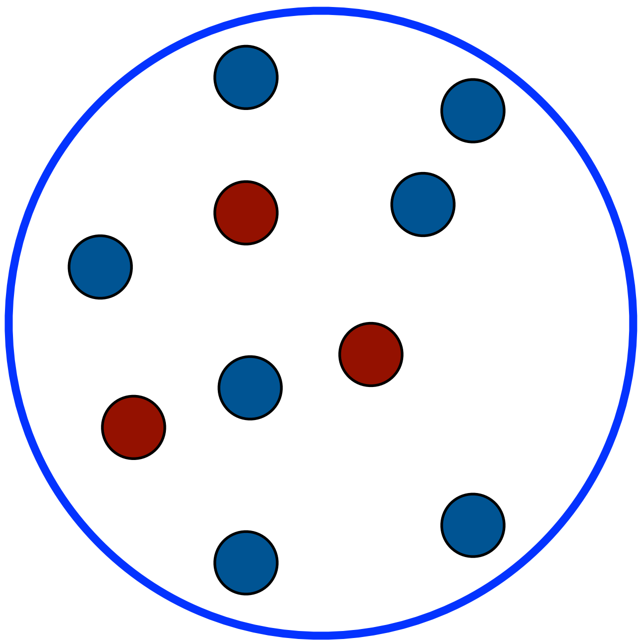
but the experiments above then do not tell us about
neutrino types, as they could just reflect neutrino helicity (bad)

These experiments can be done inside one nucleus, in the process of
neutrinoless double beta decay

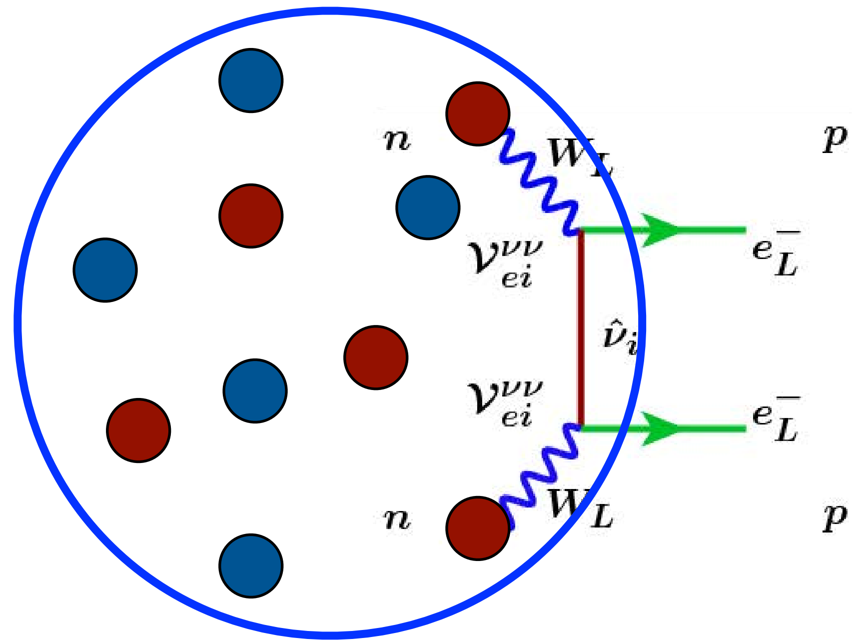
$$n_{\mathrm{bound}} + n_{\mathrm{bound}} \rightarrow n_{\mathrm{bound}} + p_{\mathrm{bound}} + e^- + \bar{\nu}_e \not\rightarrow p_{\mathrm{bound}} + p_{\mathrm{bound}} + e^- + e^-$$

Forbidden by lepton number
Forbidden by helicity

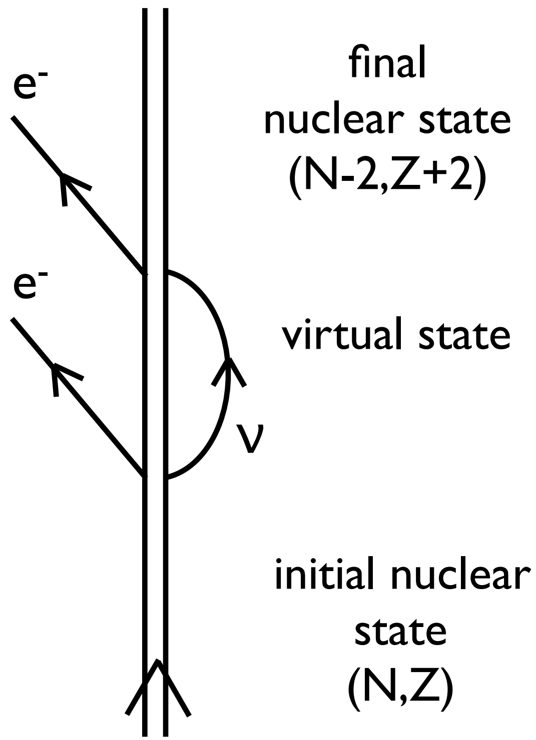
(N,Z)



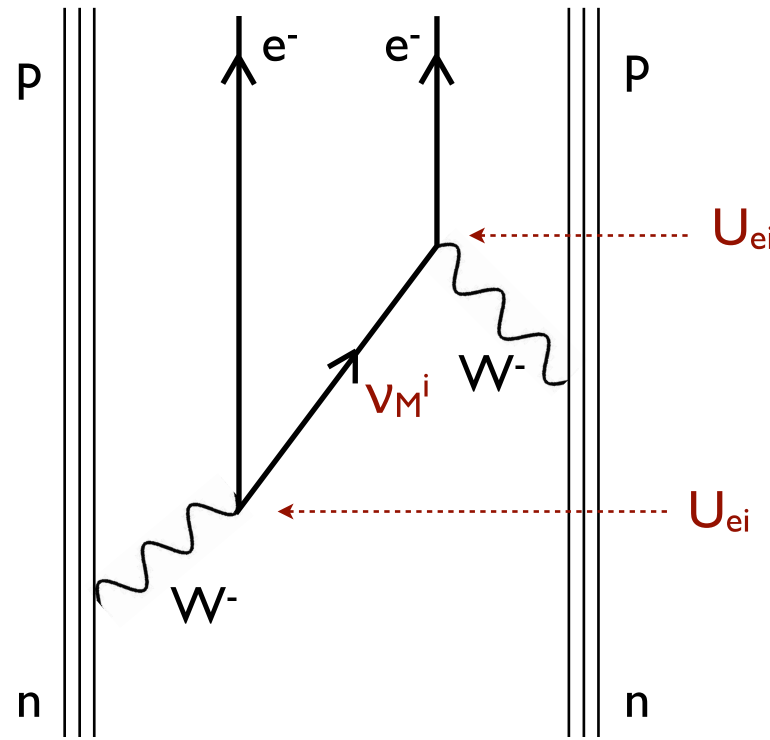
$\not\rightarrow$



Nature has made it easy to do this (apparently null) experiment

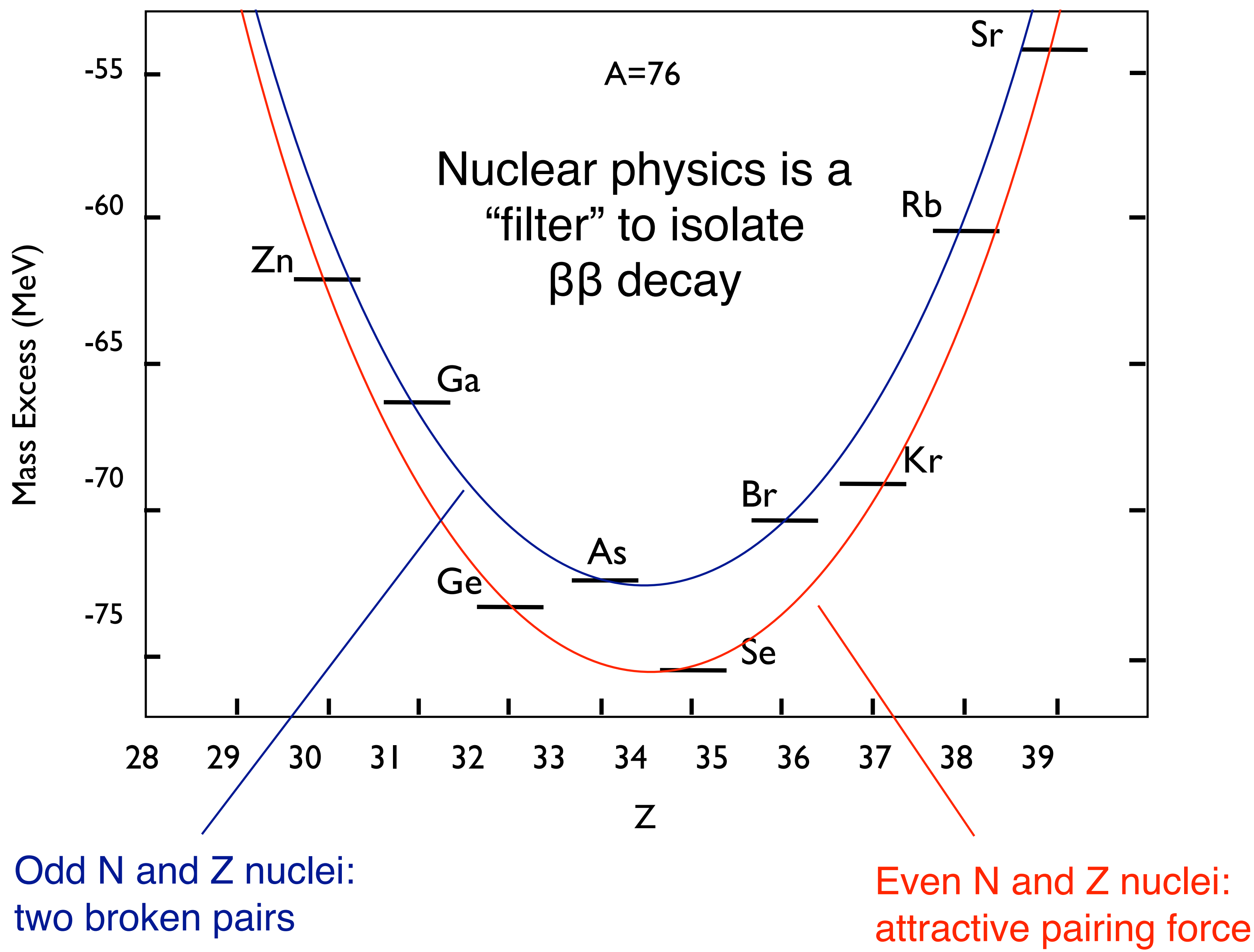


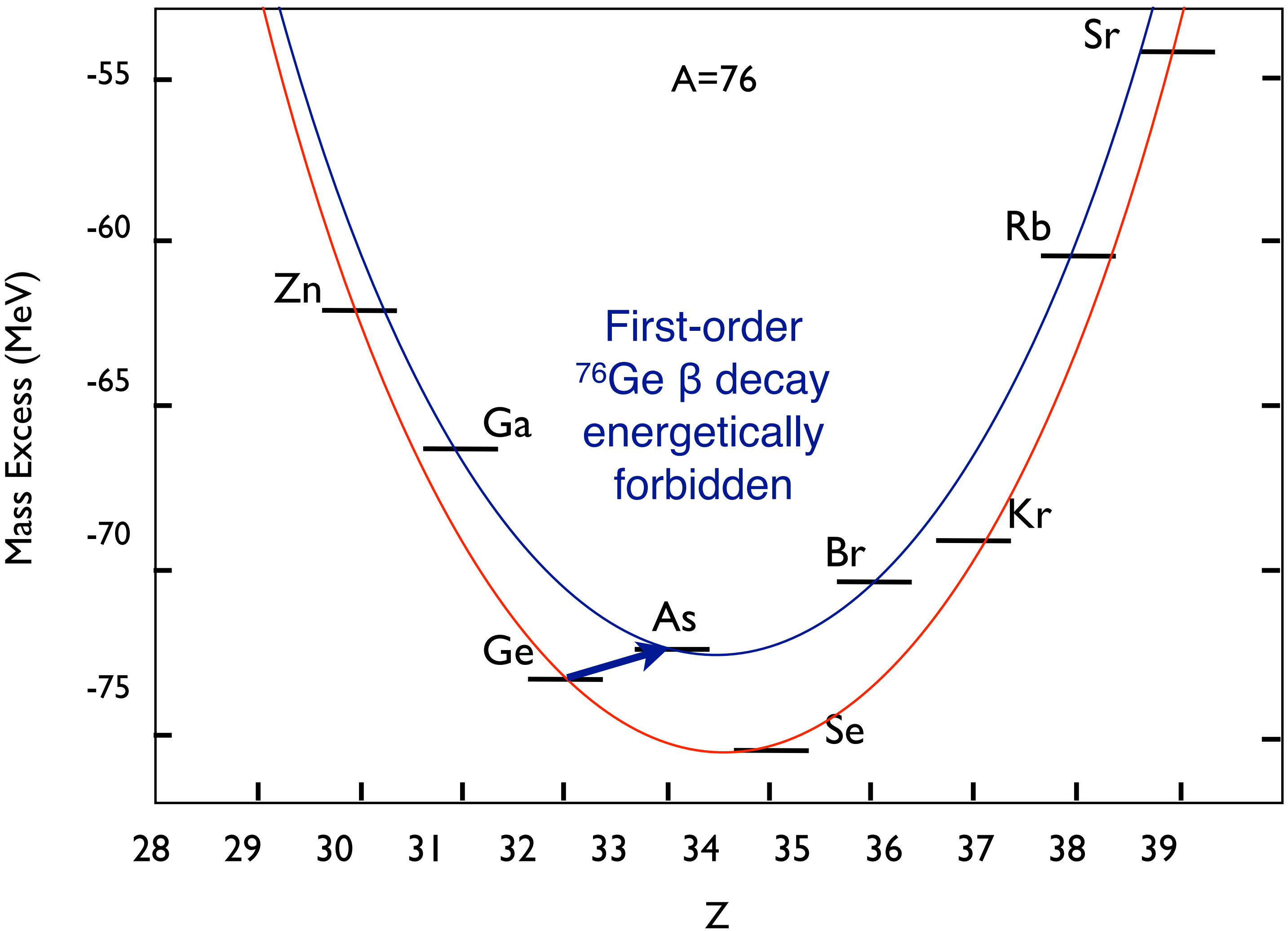
e-
e-
final
nuclear state
(N-2,Z+2)
virtual state
ν
initial nuclear
state
(N,Z)



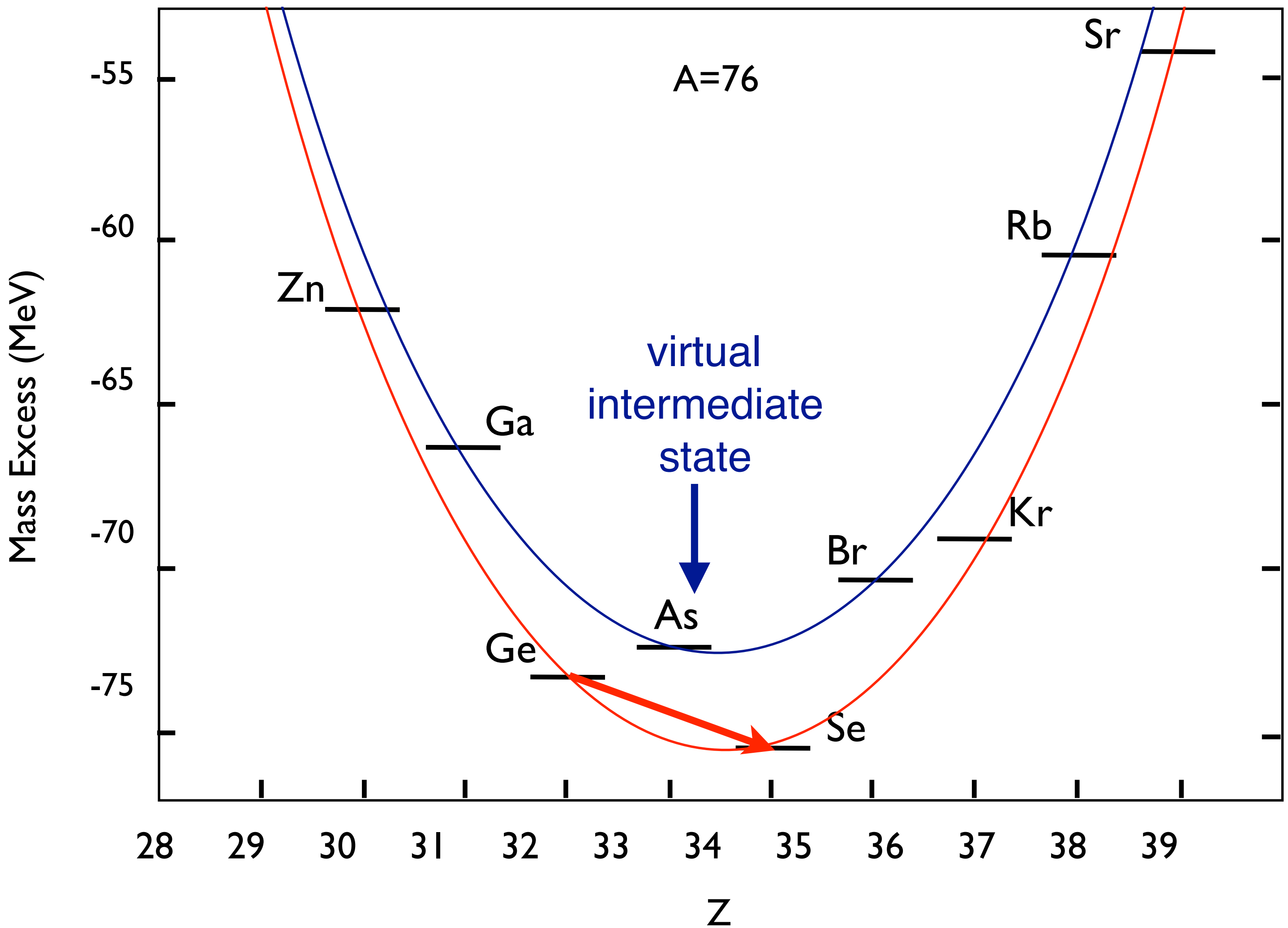
p
e-
e-
p
Uei
νMi
W-
Uei
W-
n
n

nucleons in nuclei of the same type find it energetically favorable to pair





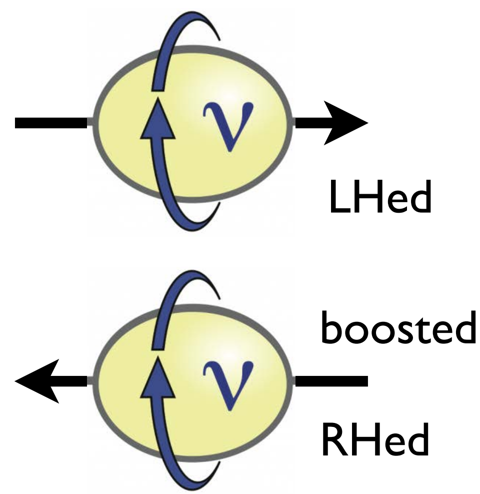
A=76
Sr
Rb
Zn
First-order
^{76}Ge β decay
energetically
forbidden
Ga
Kr
Br
As
Ge
Se
-55
-60
-65
-70
-75
Mass Excess (MeV)
28
29
30
31
32
33
34
35
36
37
38
39
Z



About 50 cases where nuclear physics isolates very rare, second-order weak interactions

And now we see why the small neutrino mass is so important

If neutrinos have a mass, helicity is no longer a particle label



as the label would then be frame dependent, violating Lorentz invariance

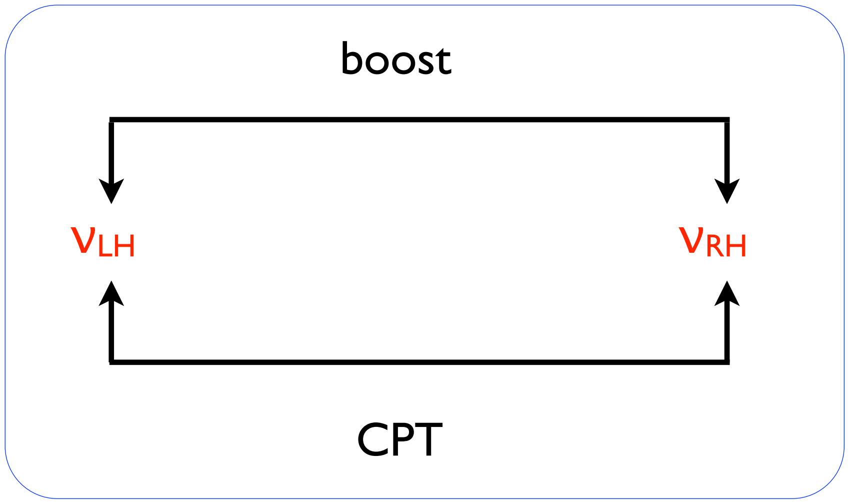
Helicity suppresses previously forbidden amplitudes by m_ν/E_ν
Rates then suppressed by $(m_\nu/E_\nu)^2$

If the neutrino has a Majorana mass that simultaneous avoids the helicity and lepton number selection rules. Neutrinoless $\beta\beta$ decay measures

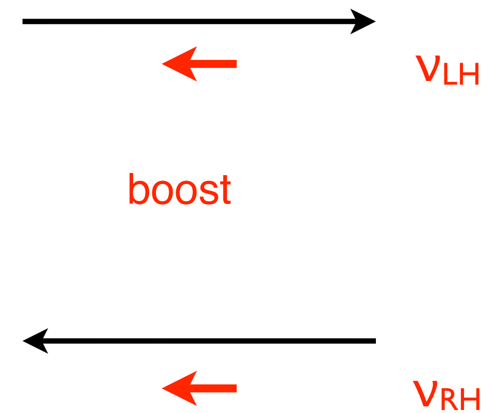
$$\langle m_\nu^2 \rangle_{\mathrm{Majorana}}$$

We have been discussing two limits for describing massive neutrinos

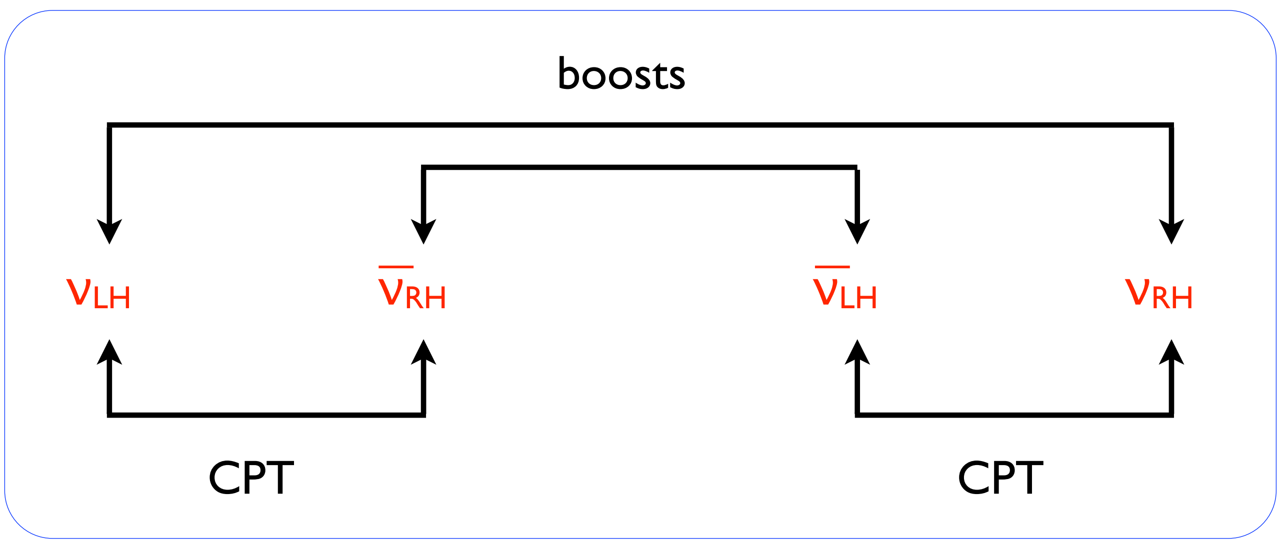
Majorana:



Lorentz invariance



Dirac:



Let's see the mass consequences: start with the Dirac eq. $m_D \bar{\Psi}\Psi$

$$\psi_{R/L} = \frac{1}{2}(1 \pm \gamma_5)\psi]$$

$$C\ \psi_{R/L}\ C^{-1} = \psi^c_{R/L}$$

Allow for multiple flavors and flavor mixing

$$L_m(x) \sim m_D \bar{\psi}(x)\psi(x) \Rightarrow M_D \bar{\Psi}(x)\Psi(x)$$

$$\Psi_L \equiv \begin{pmatrix} \Psi^e_L \\ \Psi^\mu_L \\ \Psi^\tau_L \end{pmatrix}$$

Gives a 4n by 4n matrix, n the number of generations

$$(\bar{\Psi}^c_L, \bar{\Psi}_R, \bar{\Psi}_L, \bar{\Psi}^c_R) \begin{pmatrix} 0 & 0 & & M^T_D \\ 0 & 0 & M_D & \\ & M^\dagger_D & 0 & 0 \\ M^*_D & & 0 & 0 \end{pmatrix} \begin{pmatrix} \Psi^c_L \\ \Psi_R \\ \Psi_L \\ \Psi^c_R \end{pmatrix}$$

The Majorana mass terms complete this matrix

$$L_M = \left[\bar{\Psi}_R M_D \Psi_L + \bar{\Psi}^c_L M_D^T \Psi^c_R + \bar{\Psi}^c_L M_L \Psi_L + \bar{\Psi}^c_R M_R \Psi_R\right] + h.c.$$

$$= \left(\bar{\Psi}^c_L, \bar{\Psi}_R, \bar{\Psi}_L, \bar{\Psi}^c_R\right) \begin{pmatrix} 0 & 0 & M_L & M_D^T \\ 0 & 0 & M_D & M_R^\dagger \\ M_L^\dagger & M_D^\dagger & 0 & 0 \\ M_D^* & M_R & 0 & 0 \end{pmatrix} \begin{pmatrix} \Psi^c_L \\ \Psi_R \\ \Psi_L \\ \Psi^c_R \end{pmatrix}$$

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The SM: 1) has no RHed ν fields $\Rightarrow$ no Dirac masses

2) renormalizable $\Rightarrow$ no Majorana masses

so massless SM neutrinos

The Majorana mass terms complete this matrix

$$L_M = \left[\bar{\Psi}_R M_D \Psi_L + \bar{\Psi}^c_L M^T_D \Psi^c_R + \bar{\Psi}^c_L M_L \Psi_L + \bar{\Psi}^c_R M_R \Psi_R\right] + h.c.$$

$$= \left(\bar{\Psi}^c_L, \bar{\Psi}_R, \bar{\Psi}_L, \bar{\Psi}^c_R\right) \begin{pmatrix} 0 & 0 & M_L & M^T_D \\ 0 & 0 & M_D & M^\dagger_R \\ M^\dagger_L & M^\dagger_D & 0 & 0 \\ M^*_D & M_R & 0 & 0 \end{pmatrix} \begin{pmatrix} \Psi^c_L \\ \Psi_R \\ \Psi_L \\ \Psi^c_R \end{pmatrix}$$

But 1) might anticipate M_D ~ other SM Dirac masses

2) know $M_L << M_D$ (no ββ decay), reasonably $M_R >> M_D$

so with these assumptions can diagonalize this matrix

The Majorana mass terms complete this matrix

$$L_M = \left[\bar{\Psi}_R M_D \Psi_L + \bar{\Psi}^c_L M_D^T \Psi^c_R + \bar{\Psi}^c_L M_L \Psi_L + \bar{\Psi}^c_R M_R \Psi_R\right] + h.c.$$

$$= \left(\bar{\Psi}^c_L, \bar{\Psi}_R, \bar{\Psi}_L, \bar{\Psi}^c_R\right) \begin{pmatrix} 0 & 0 & M_L & M_D^T \\ 0 & 0 & M_D & M_R^\dagger \\ M_L^\dagger & M_D^\dagger & 0 & 0 \\ M_D^* & M_R & 0 & 0 \end{pmatrix} \begin{pmatrix} \Psi^c_L \\ \Psi_R \\ \Psi_L \\ \Psi^c_R \end{pmatrix}$$

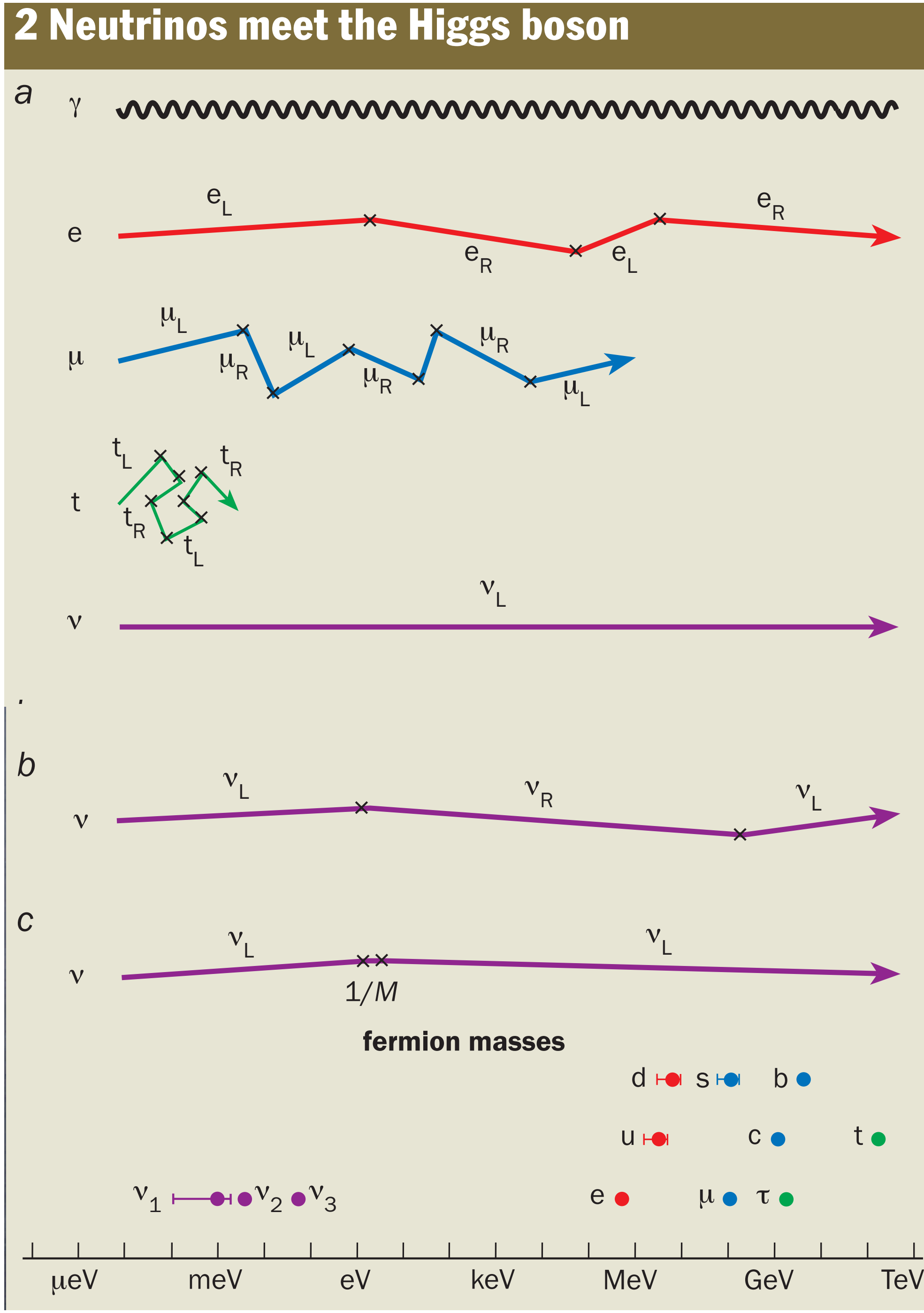
$$m_\nu^{\text{light}} = M_D \left(\frac{M_D}{M_R}\right)$$

seesaw

SM fermion mass scale

needed “small parameter” specific to νs

Gell-Mann, Ramond, and Slansky 80; Yanagida

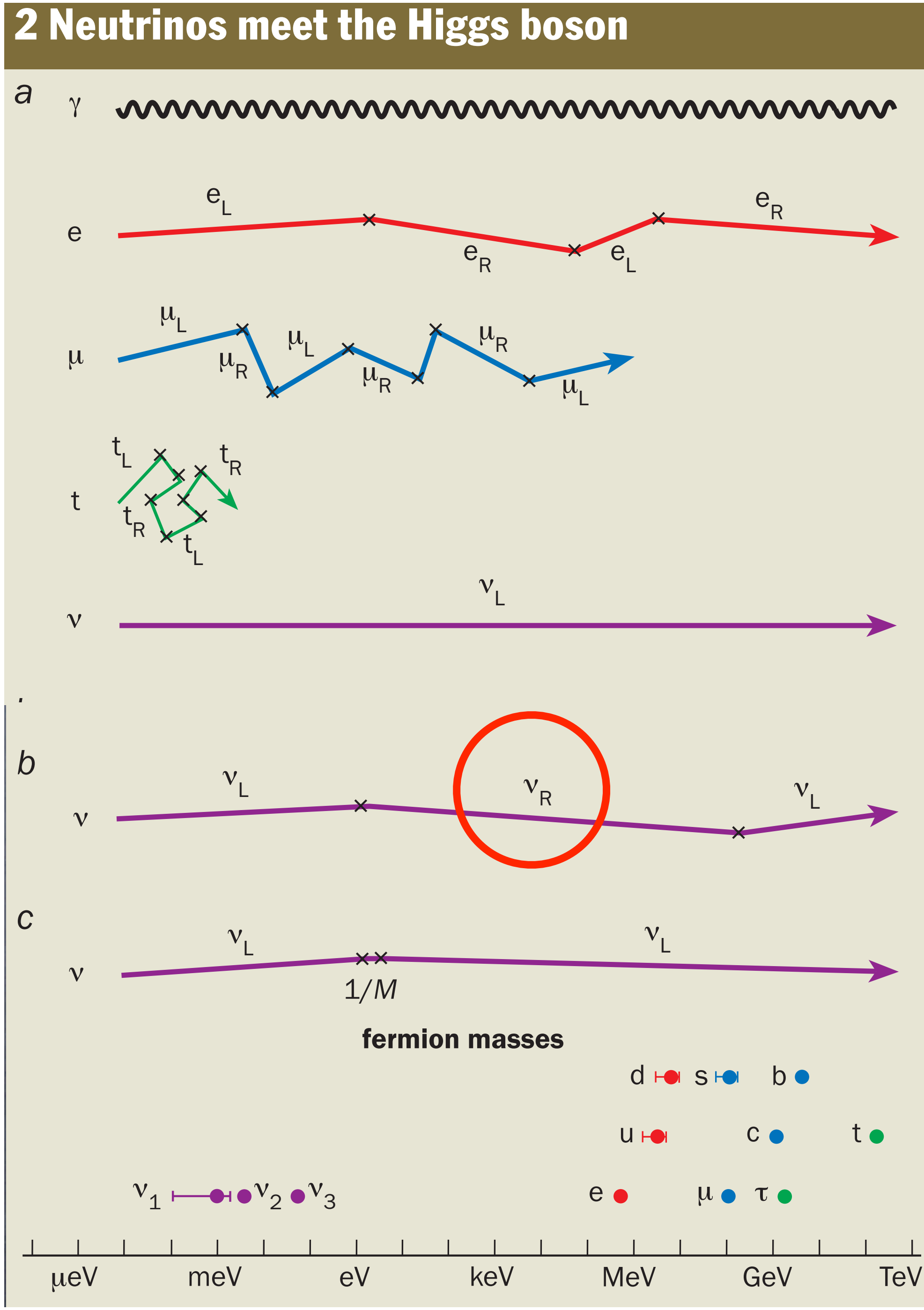


Murayama's ν mass cartoon

standard model fermion masses

standard model ν and mass=0

Murayama's ν mass cartoon

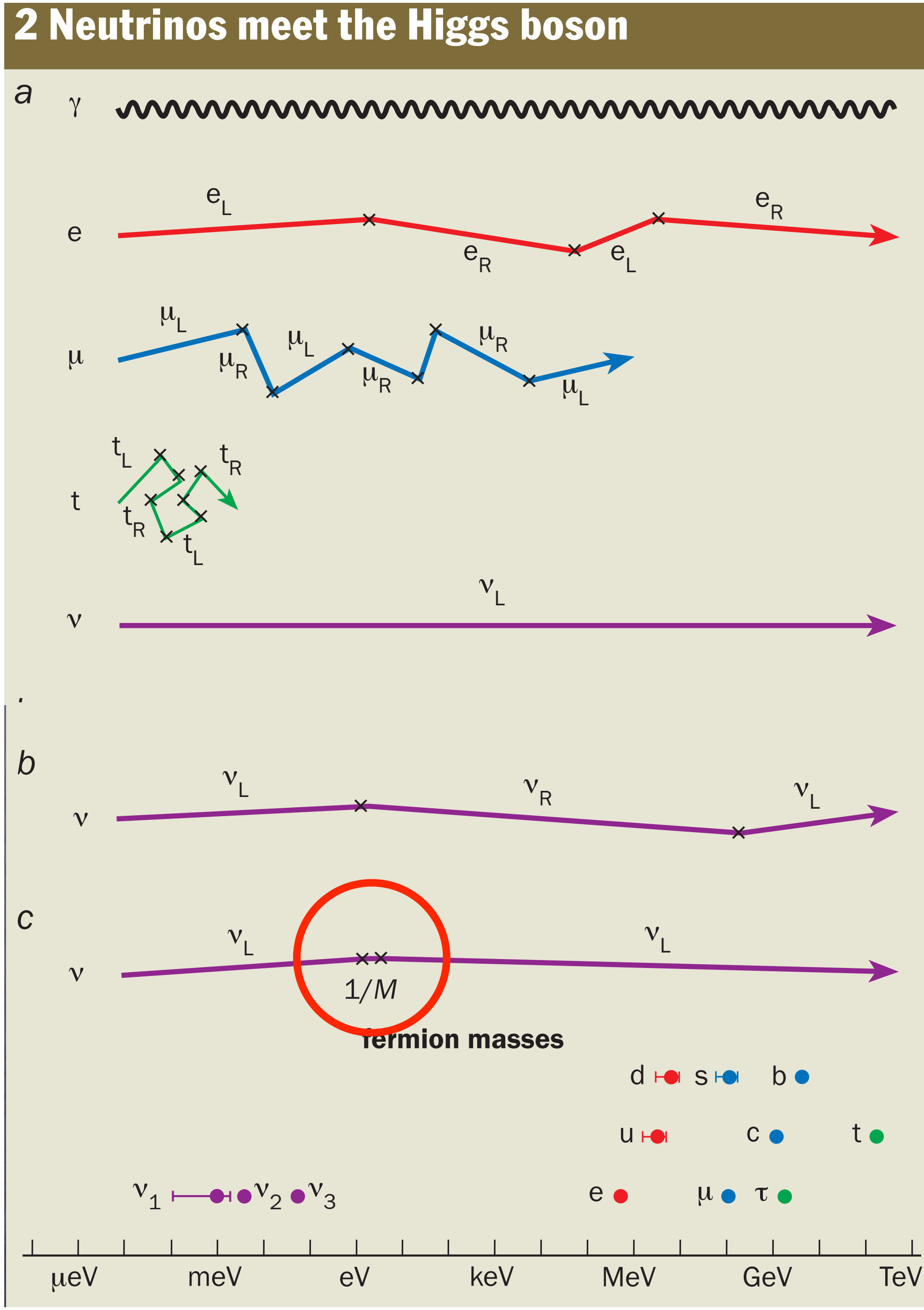


standard model fermion masses

standard model ν and mass=0

light Dirac neutrino mass

Murayama's ν mass cartoon



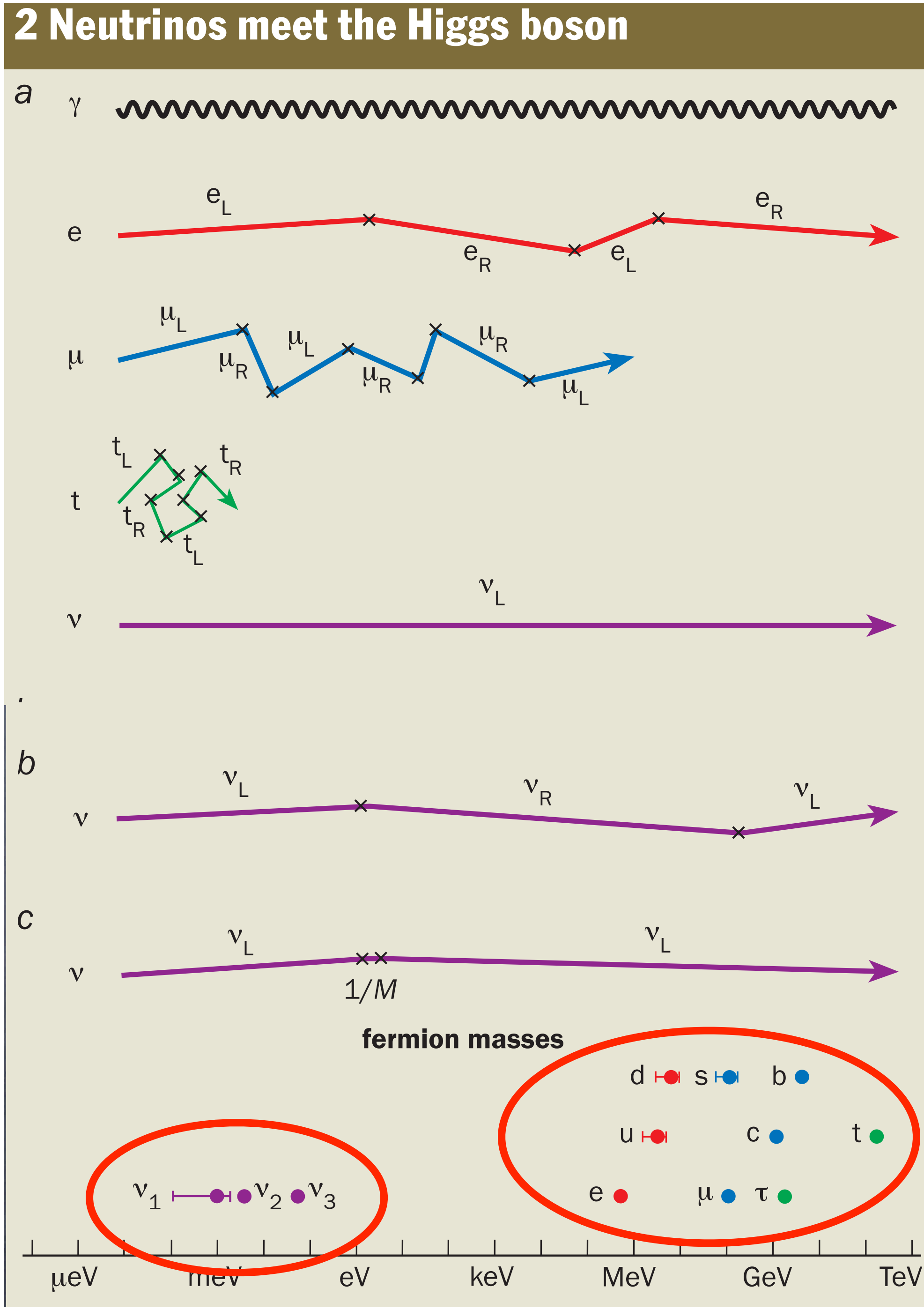
standard model fermion masses

standard model ν and mass=0

light Dirac neutrino mass

light LHed Majorana neutrino mass

Murayama's ν mass cartoon



standard model fermion masses

standard model ν and mass=0

light Dirac neutrino mass

light LHed Majorana neutrino mass

← the anomalous ν mass scale, connected with the seesaw?

So we come to the “bottom lines”

Neutrinos are special because they are unique among the SM fermions: they carry no charges, and thus can be their own antiparticles. Other fermions must be Dirac

What is not forbidden must be allowed: we expect neutrinos to carry both masses. This provides an understanding of their lightness

$$m_\nu^{\text{light}} = M_D \left(\frac{M_D}{M_R} \right)$$

Simplest extension of the SM

These same Majorana masses (or their HE cousins) could transmit this lepton number violation into the baryon sector, explaining why the Big Bang generated an excess of matter over antimatter

The discovery that mixing angles — and it appears CP violation — among the neutrinos are large makes this very plausible

These neutrino properties determine what neutrinos do in astrophysics

Neutrinos in Multimessenger Astrophysics

Solar neutrinos might have been the first robust example of multi-messenger astrophysics

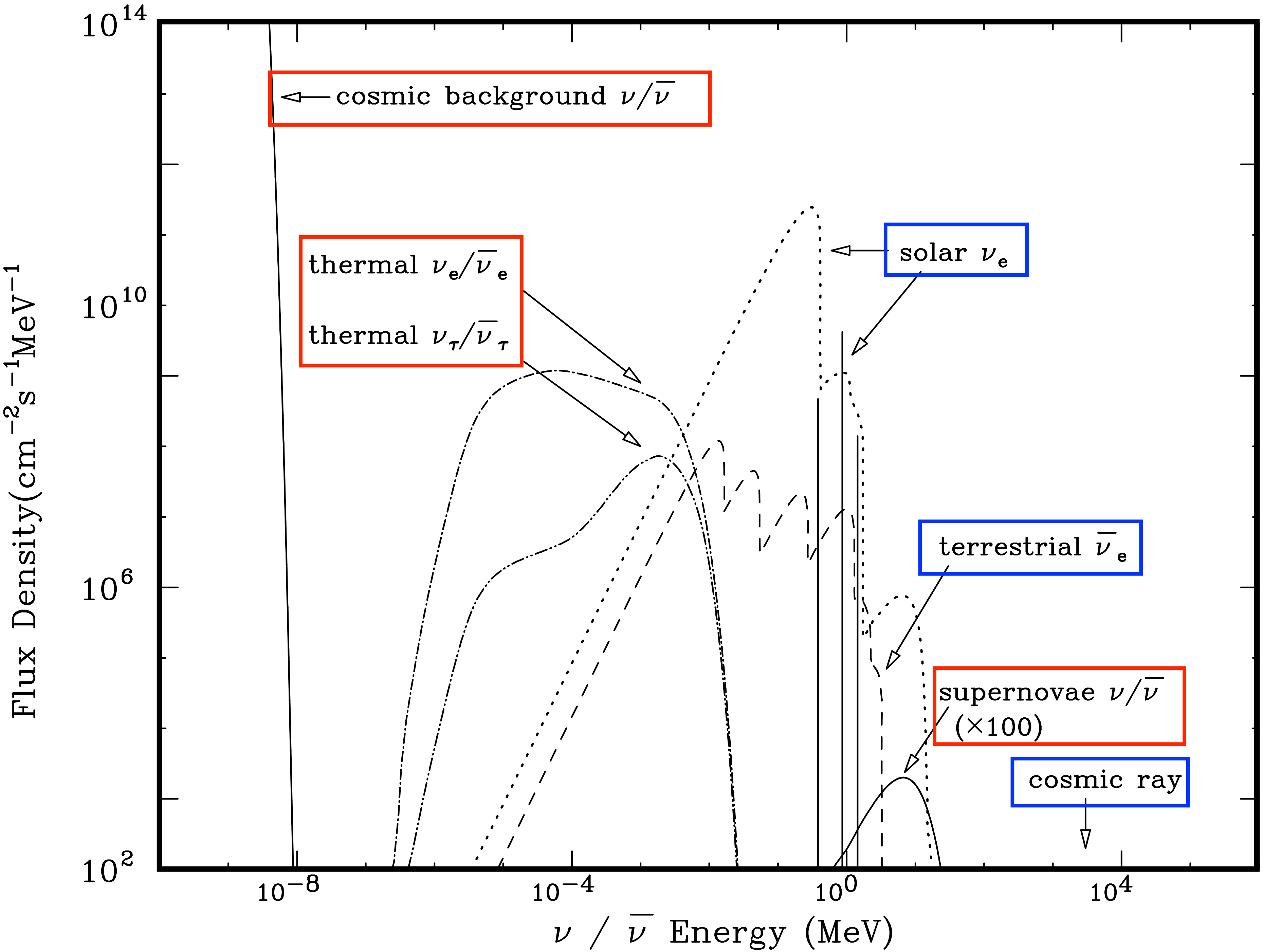
- solar mass, radius, age, composition, luminosity (model constraints)
- helioseismology (model validation)
- neutrinos

Another important example was provided by SN 1987a

- observed in the optical and in neutrinos
- the neutrino observations supported basic modeling ideas about the energy release and core cooling time accompanying collapse
- optical constraints provided a distance, from which mildly interesting limits on the neutrino lifetime and mass were obtained

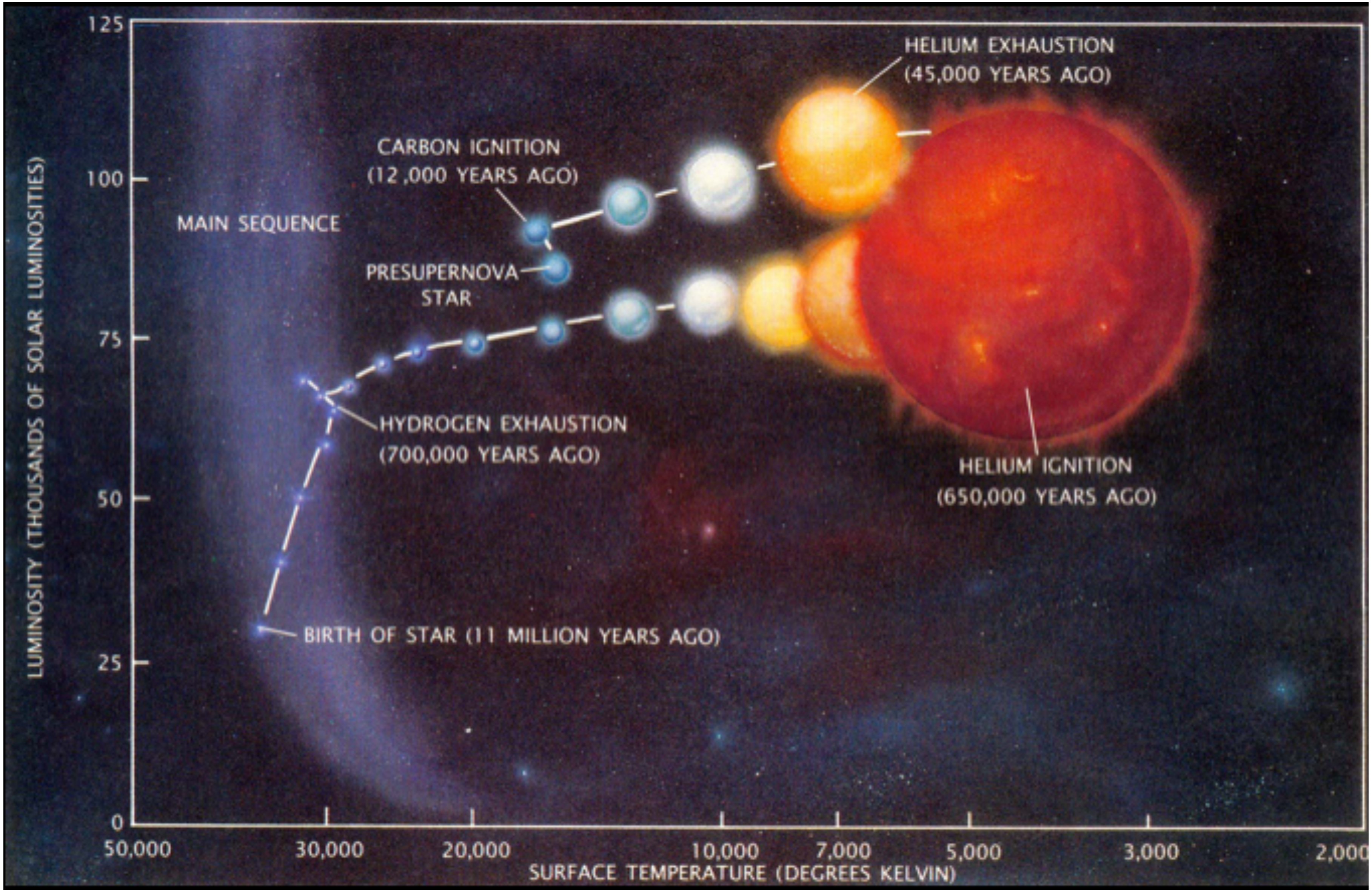
Low energy sources:

Sources



cosmic background $\nu/\bar{\nu}$
thermal $\nu_e/\bar{\nu}_e$
thermal $\nu_\tau/\bar{\nu}_\tau$
solar ν_e
terrestrial $\bar{\nu}_e$
supernovae $\nu/\bar{\nu}$ (×100)
cosmic ray
Flux Density(cm^{-2}s^{-1}MeV^{-1})
10^{14}
10^{10}
10^{6}
10^{2}
10^{-8}
10^{-4}
10^{0}
10^{4}
ν / $\bar{\nu}$ Energy (MeV)

Pre-Supernova Evolution



Woosley and Weaver

Progenitor evolution

- The standard solar model just discussed is in fact the general model of stellar evolution for main-sequence stars: the smaller, more slowly evolving hydrogen burning stars

- The guiding principle is hydrostatic equilibrium: the balancing of the gas pressure gradient and the gravitational force

- The higher gravitational potentials of more massive stars accelerates the evolution: we are interested in progenitors of 8-25 M_{solar}

- Burning proceeds through a series of cycles: when the core hydrogen has been exhausted, after a brief period of hydrogen shell burning, core contraction leads to temperatures densities are reached where core He can be ignited through the 3α process

- Process repeats through subsequent phases of C, O, Ne, .. burning: fuel exhaustion, core contraction, ignition of the ashes from the previous cycle, followed by a period of hydrostatic evolution

- Burning becomes increasingly rapid, explosive in later stages The underlying physics is nuclear energetics (binding energy/nucleon)

$$\begin{array}{ll}
{}^{12}\mathrm{C} & \delta/\mathrm{nucleon} = 0.000\ \mathrm{MeV} \\
{}^{16}\mathrm{O} & \delta/\mathrm{nucleon} = \text{-}0.296\ \mathrm{MeV} \\
{}^{28}\mathrm{Si} & \delta/\mathrm{nucleon} = \text{-}0.768\ \mathrm{MeV} \\
{}^{40}\mathrm{Ca} & \delta/\mathrm{nucleon} = \text{-}0.871\ \mathrm{MeV} \\
{}^{56}\mathrm{Fe} & \delta/\mathrm{nucleon} = \text{-}1.082\ \mathrm{MeV} \\
{}^{72}\mathrm{Ge} & \delta/\mathrm{nucleon} = \text{-}1.008\ \mathrm{MeV} \\
{}^{98}\mathrm{Mo} & \delta/\mathrm{nucleon} = \text{-}0.899\ \mathrm{Mev}
\end{array}$$

- The final explosive Si-burning phase of a 25 M_{solar} star is $\sim$ week

- The growing Fe core has no way to tap further energy: when it becomes sufficiently massive, $\sim$1.4 M_{solar}, the electron gas EoS is no longer able to support the star: the implosion begins

Qualitative aspects of the collapse

- The iron core collapses at $\sim$0.6 of the free-fall velocity
  - infall does work on the matter: temperatures increase
  - rising density and temperature drive $p + e^- \to n + \nu_e$
  - this is part of the initial neutronization caused by the rising electron chemical potential
  - some energy also gets removed from the electron gas by nuclear excitations
  - both effects reduce the capacity of the gas to support the star

- The physics of this period determines the initial conditions of the core at maximum density, and thus of the explosion
  - energy is being removed from the star by neutrino emission

$$\mathrm{rate} \sim G_F^2 T^5$$

  - but this process shuts off mid-way through the collapse: trapping

- “Trapping” means conditions are reached where the time required for a neutrino to random walk out of the star is long compared to the time to core bounce

- The dominant cross section responsible for trapping is neutral current scattering off nuclei

$$\sigma_{\rm coherent} \sim E_\nu^2 Z_{\rm weak}^2 \qquad Z_{\rm weak} \sim N$$

- As Bethe emphasized, entropy is a critical parameter: if the infalling nuclear material can be kept cold until one reaches trapping, less *electron capture will occur* and thus *less lepton number will be radiated*. This leads to a larger core that is easier to explode

- The neutrino physics is complex, interconnected. Low-energy νs escape more readily. The low-energy states basically empty at the speed of light, then refill as rapidly as possible due to other neutrinos “downscattering” of electrons or nuclei

So: pre-collapse

$$\text{core electrons/baryon} \equiv Y_L^{\text{core}}(0) = Y_e^{\text{core}}(0) \sim 0.42$$

An infalling volume element that will become core material looses lepton number by electron capture and neutrino emission

This process is halted at $\rho \sim 10^{12}\ \text{g/cm}^3$ by NC neutrino trapping

The final value of Y_L^{core} is the most important parameter determining the strength of the subsequent hydrodynamical shock and thus the prospect of a successful collapse

After trapping, the initial conditions for core bounce are fixed. As every volume element in the star is gravitational bound at this point, most of the rest of the physics is about transport of the gravitational energy released in the collapse:

giving the ejected mantle of the star more than its fair share

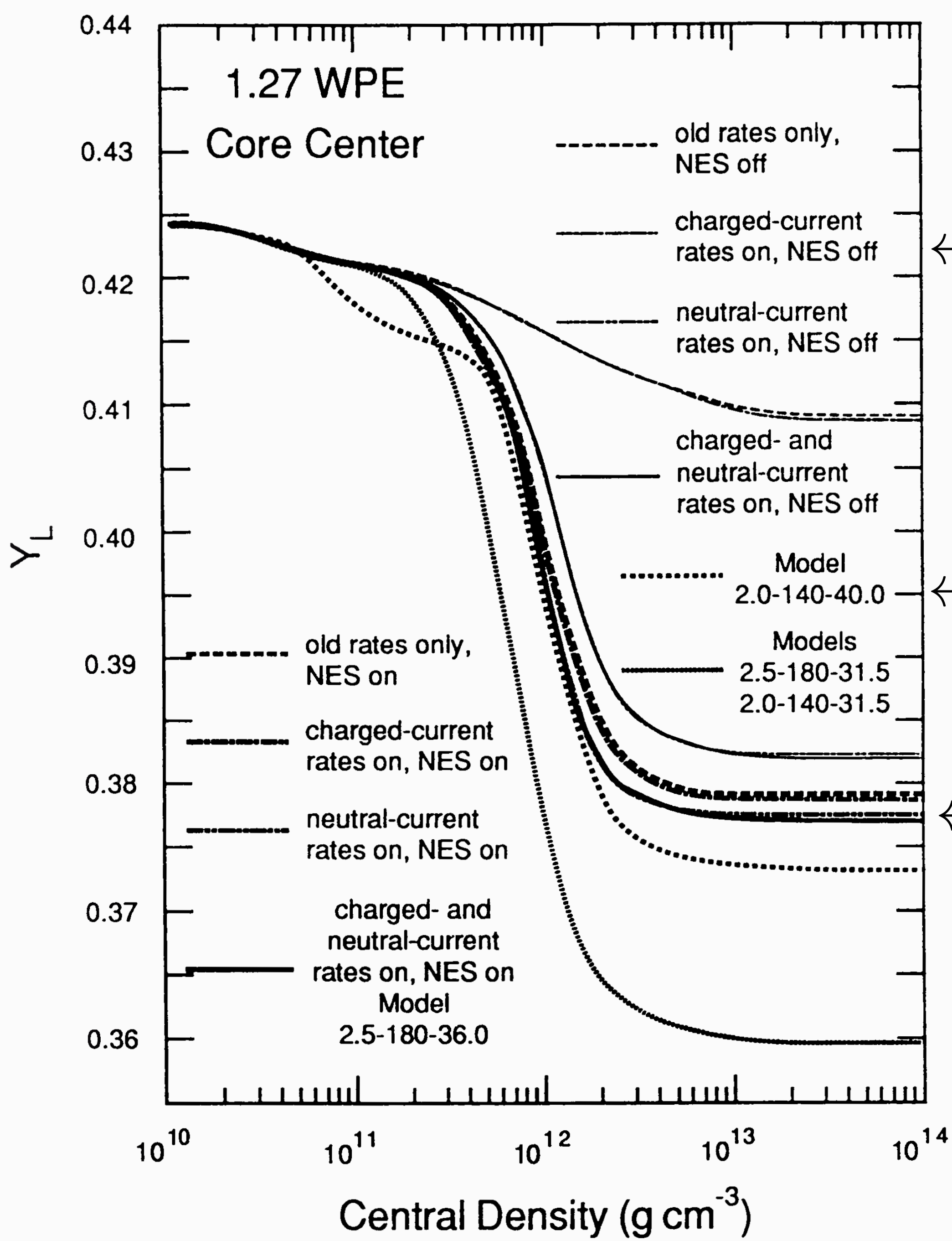


FIG. 3.—Lepton fraction Y_L as a function of the density of a comoving mass element near the core center during infall for the various indicated models.

$\leftarrow$ *precollapse*

$\leftarrow$ *pretrapping* : T^5 *emission*

$\leftarrow$ *trapping* : *no more evolution*

- *homologous core:* $v_{sound} > v_{infall}$ at high nuclear density
  - defines homologous core
  - inner core retains its density profile as collapse proceeds
  - would collapse to a point except for nuclear EOS

- *formation of the shock wave:*
  - relativistic electron gas ineffective at supporting star
  - at few 10^{14} g/cm^3 inner ring of material exceeds nuclear density, where is experiences the extremely repulsive short-range NN potential
  - a trampoline-like rebound produces a pressure wave travels out ($v_{sound} > v_{infall}$) toward the edge of homologous core (v_{sound} v_{infall})
  - next ring repeats process, pressure wave chases first
  - waves concentrate at edge of homologous core
  - shock wave breaks out when that point reaches nuclear density, propagates through the outer iron core

- *Shock energy losses, stalling:*
  - boils iron to nucleon soup at the cost of 8 MeV/nucleon
  - sudden reduction in opacity ($\sigma \sim Z^2_{\mathrm{weak}}$), trapped ν_es released: deleptonization flux lasting a few milliseconds
  - losses overcome shock, *stalls* at a radius of 250-300 km
  - energy delivered across shock front by infalling matter, and lost by the shocking of that material: a standoff
  - about .1 sec post bounce

- *Neutrino reheating of shock:*
  - strong CC neutrino reactions off nucleons left in wake of the shock heat gas, acts for ~ 0.5 s
  - increasing pressure pushes shock outward, drives convection
  - convection can make neutrino heating more effective, overcoming "gain-radius" limitations
  - shock wave regenerates, moves outward, ejecting the mantle

Modeling challenges

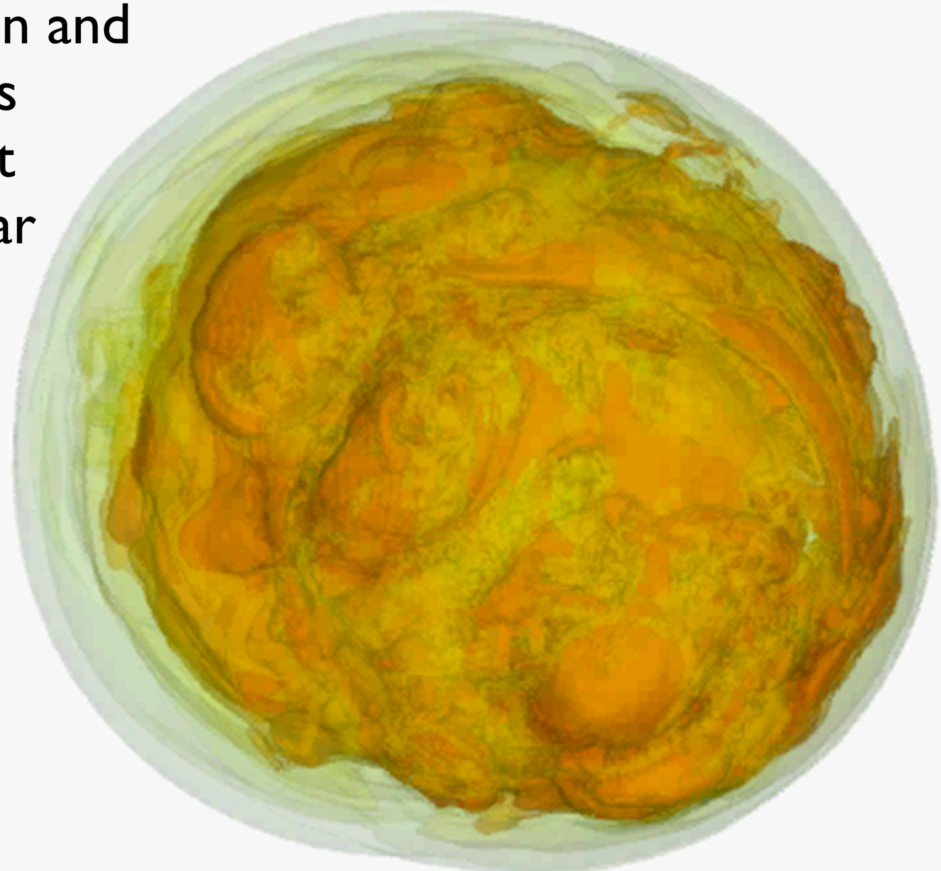
- shock wave
- multi-D nature
- lepton/energy transport by six neutrino types: must follow position and energy distributions
- need nuclear EoS at several times nuclear density

…..

and then there is the new neutrino physics

e.g., spherical acccretion shock instability

Blondin and Mezzacappa
Blondin and Shaw
Ohnishi et al.

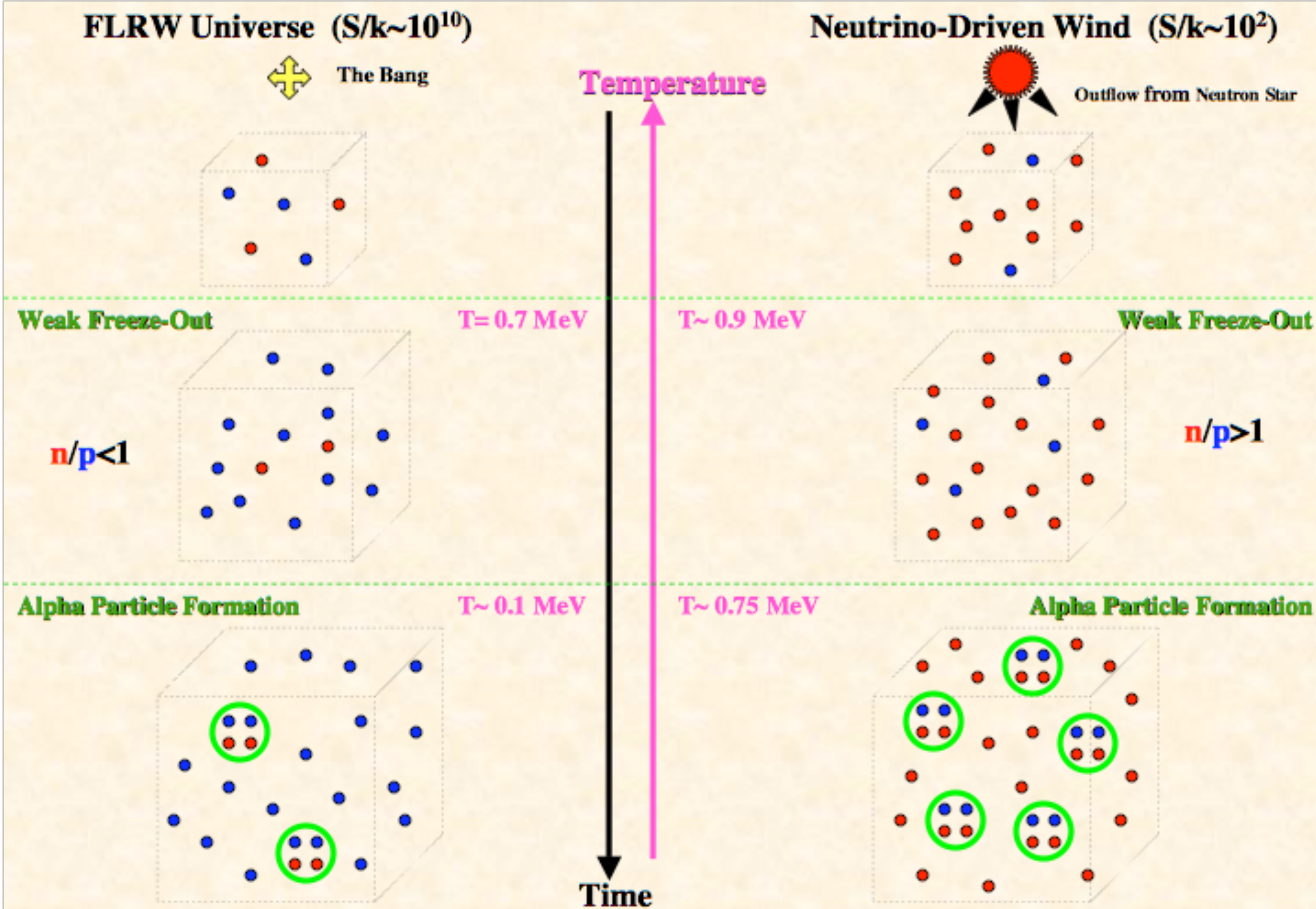


In nature Type II supernovae succeed for a wide variety of progenitors

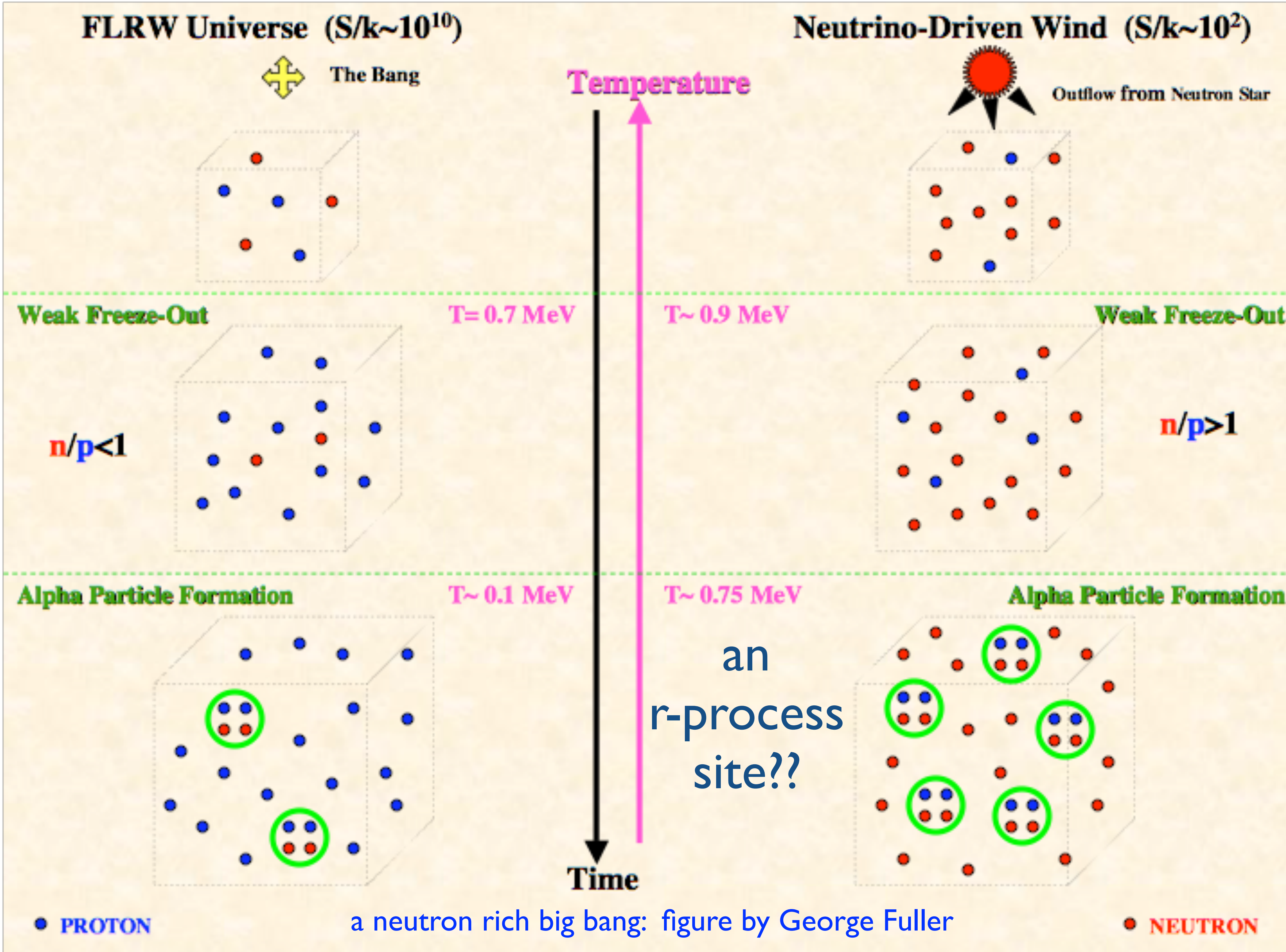
- *Pro-neutron star cooling*
  - hot, puffy neutron cools with a time constant $\sim$ 3 sec, with a long exponential tail
  - mantle ejected: last such material is a neutron-rich high-entropy nucleon gas, blown off the star by the neutrino wind
  - cooling mechanism is neutrino emission: cooling timescale is governed by diffusion of neutrinos from the core to the neutrino sphere (decoupling radius) at $\rho \sim 10^{12}\ \mathrm{g/cm^2}$
  - approximate equipartition of energy in flavors: $\nu_e + \bar{\nu}_e \leftrightarrow \nu_\mu + \bar{\nu}_\mu$
  - neutrino decoupling is somewhat flavor dependent

$$T_{\nu_e} \lesssim T_{\bar{\nu}_e} \lesssim T_{\nu_{\mathrm{heavy}}} \qquad\qquad n(E_\nu) \sim \frac{0.55}{T_\nu^3} \frac{E_\nu^2}{e^{E_\nu/T_\nu}+1}$$

  - neutrinos basically free-stream beyond the neutrino sphere
  - but they control the p/n chemistry of the nearest material, and drive or alter nucleosynthesis throughout much of the mantle



a neutron rich big bang: figure by George Fuller



an r-process site??

a neutron rich big bang: figure by George Fuller

- *Neutrinos dominate SN energetics:*

$$E_{\text{grav}} \sim \frac{GM_{\text{NS}}^2}{R_{\text{NS}}} \sim 3 \times 10^{53} \text{ergs}$$

  - optical + explosion accounts for $\sim 10^{51}$ ergs (1 "Bethe")
  - 99% of the energy emitted over 10-20 seconds in neutrinos
  - a galactic SN at 10 kpsec would produce about 10^4 events in our largest current detector, SuperKamiokande (mostly $\bar{\nu}_e$ s)
  - search strategies for identifying extra-galactic SNe in neutrinos from nearby starburst galaxies have ben discussed: requires detectors at or beyond 10 megatons

- *Multi-messenger opportunity: Shock breakout*
  - the optical signals accompanying SBO can provide a great deal of information about the nature of the progenitor
  - one would like to see the SBO … neutrino or GW early warnings?

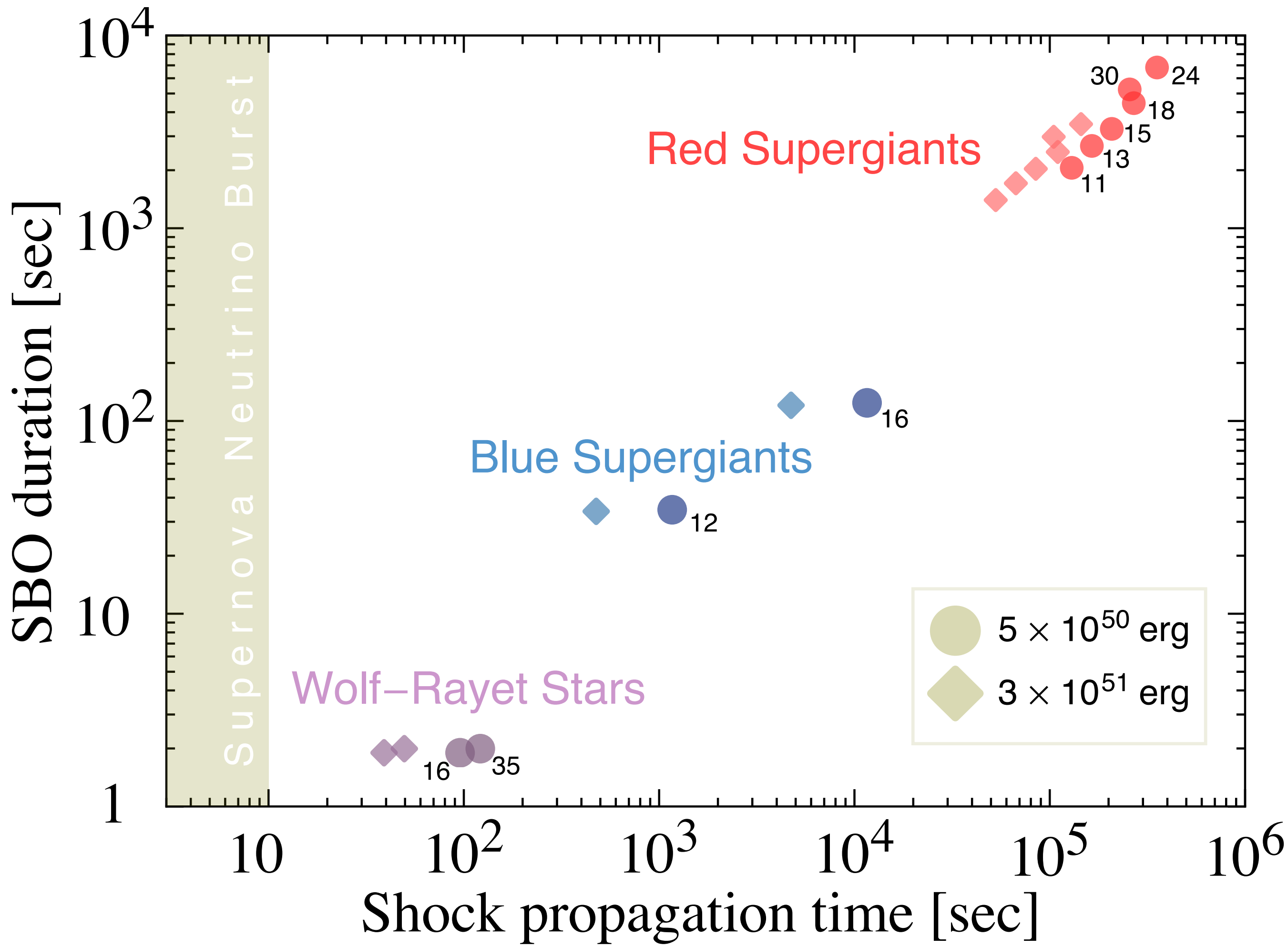


FIG. 3.— A comparison of shock breakout (SBO) durations versus shock propagation times in the envelopes of SN progenitor models, as calculated for a variety of initial masses from $11 - 35\ M_{\odot}$ (as labeled), using density profiles from Woosley et al. (56) for RSG and Woosley & Heger (55) for BSG and Wolf-Rayet stars, with shock energies of 0.5 and 3×10^{51} erg.

Supernova neutrinos and nucleosynthesis

- The elements synthesized in both quiescent and explosive sites are an important component of multi-messenger astrophysics

- Neutrinos drive nucleosynthesis indirectly through their charge-current control of the p/n chemistry, and directly through their CC transmutation of nuclei (neutrino process)

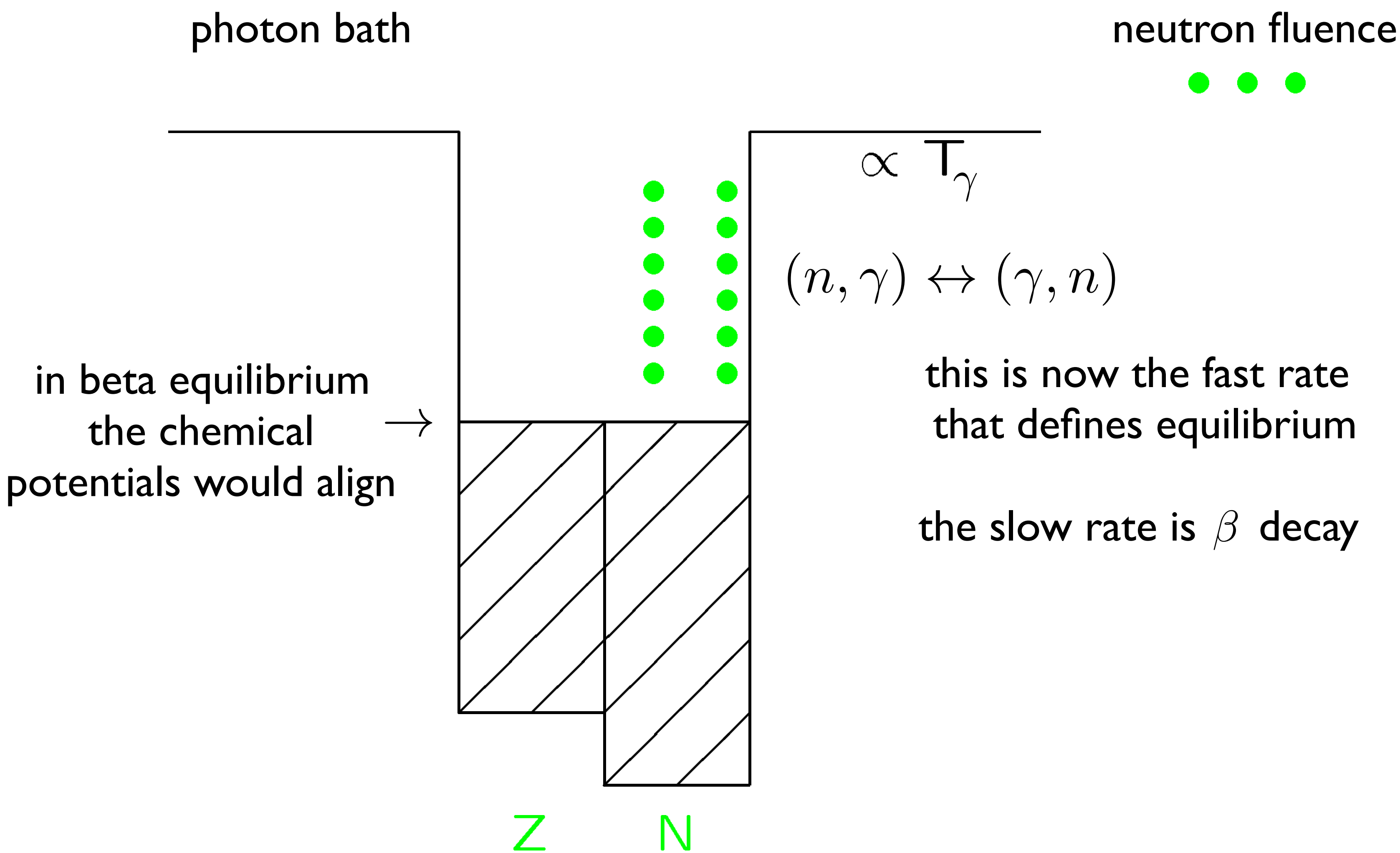
- An example of the former is the r-process

Basics of the r-process

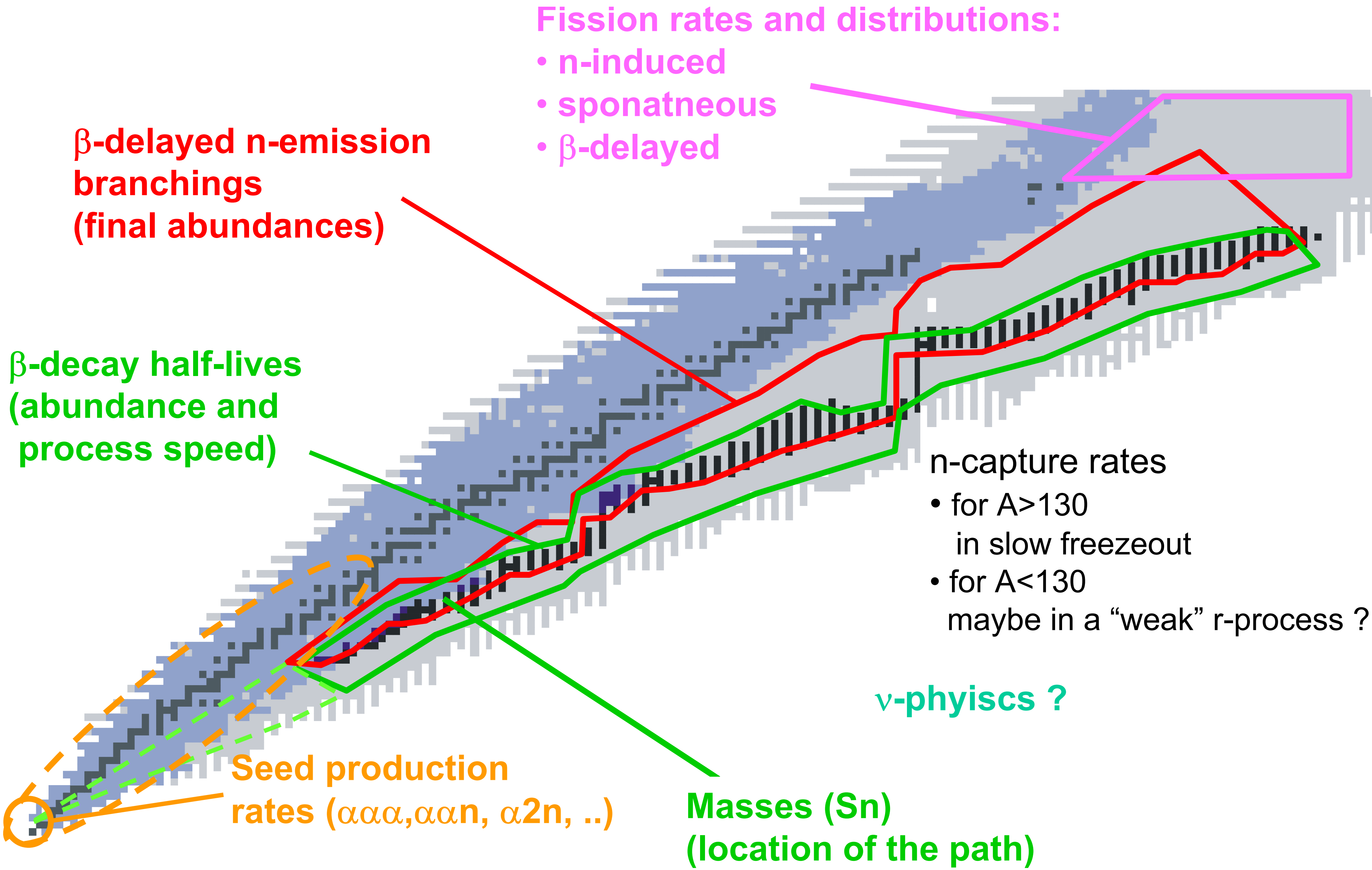
- Cold nuclei (temperatures much less than an MeV) reside in β equilibrium: a nucleus of fixed A decays by weak interactions until it reaches the state (N,Z) of minimum energy. This defines the "valley of stability"

- Most nucleosynthesis is "slow/cold" - the relevant time for reactions is long compared to β decay. Reactions occur that may change A, but after each such reaction the system β equilibrates: the neutron capture that occurs in normal stars follows the valley of stability

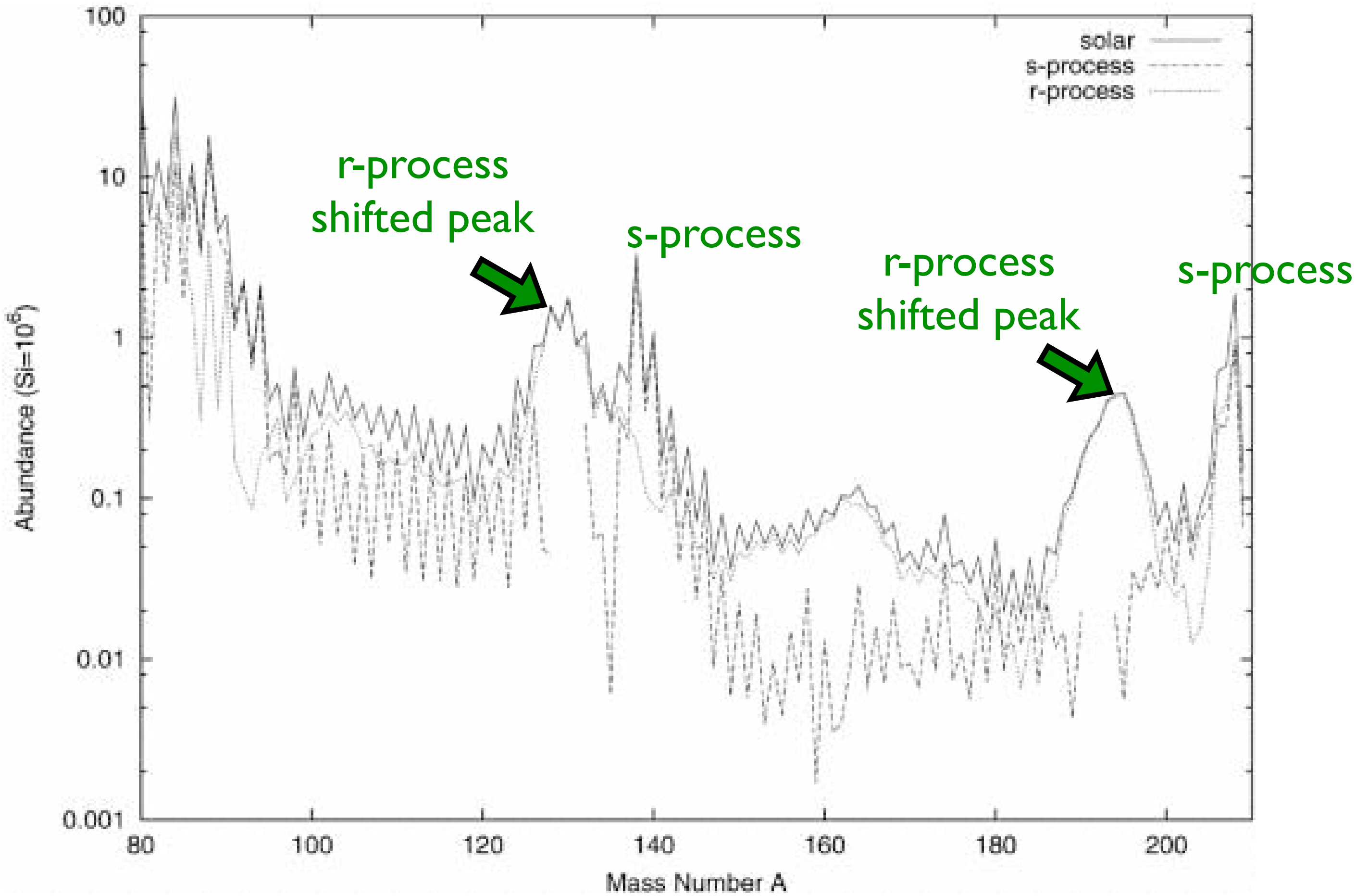
- In the r-process temperatures are on the order of an MeV, the synthesis by neutron capture is fast, and β decay is too slow to maintain β equilibrium


photon bath
neutron fluence
$\propto T_\gamma$
$(n,\gamma) \leftrightarrow (\gamma,n)$
in beta equilibrium the chemical potentials would align $\rightarrow$
this is now the fast rate that defines equilibrium
the slow rate is β decay
Z
N

From Schatz



Fission rates and distributions:
• n-induced
• sponatneous
• β-delayed
β-delayed n-emission branchings (final abundances)
β-decay half-lives (abundance and process speed)
n-capture rates
• for A>130 in slow freezeout
• for A<130 maybe in a “weak” r-process ?
ν-phyiscs ?
Seed production rates (ααα,ααn, α2n, ..)
Masses (Sn) (location of the path)



- Explosive conditions required: $\rho_n \sim 10^{20}/\mathrm{cm}^3, \quad T \gtrsim 300\ \mathrm{keV}, \quad t \sim \mathrm{sec}$

- Rate of nucleosynthesis is controlled by β decay: opens up a neutron hole for capturing n from gas. Mass flow from light to heavy

- Mass piles up at shell gaps, where multiple weak decays must occur: when explosion ends, β decays back to stability, generating the shift

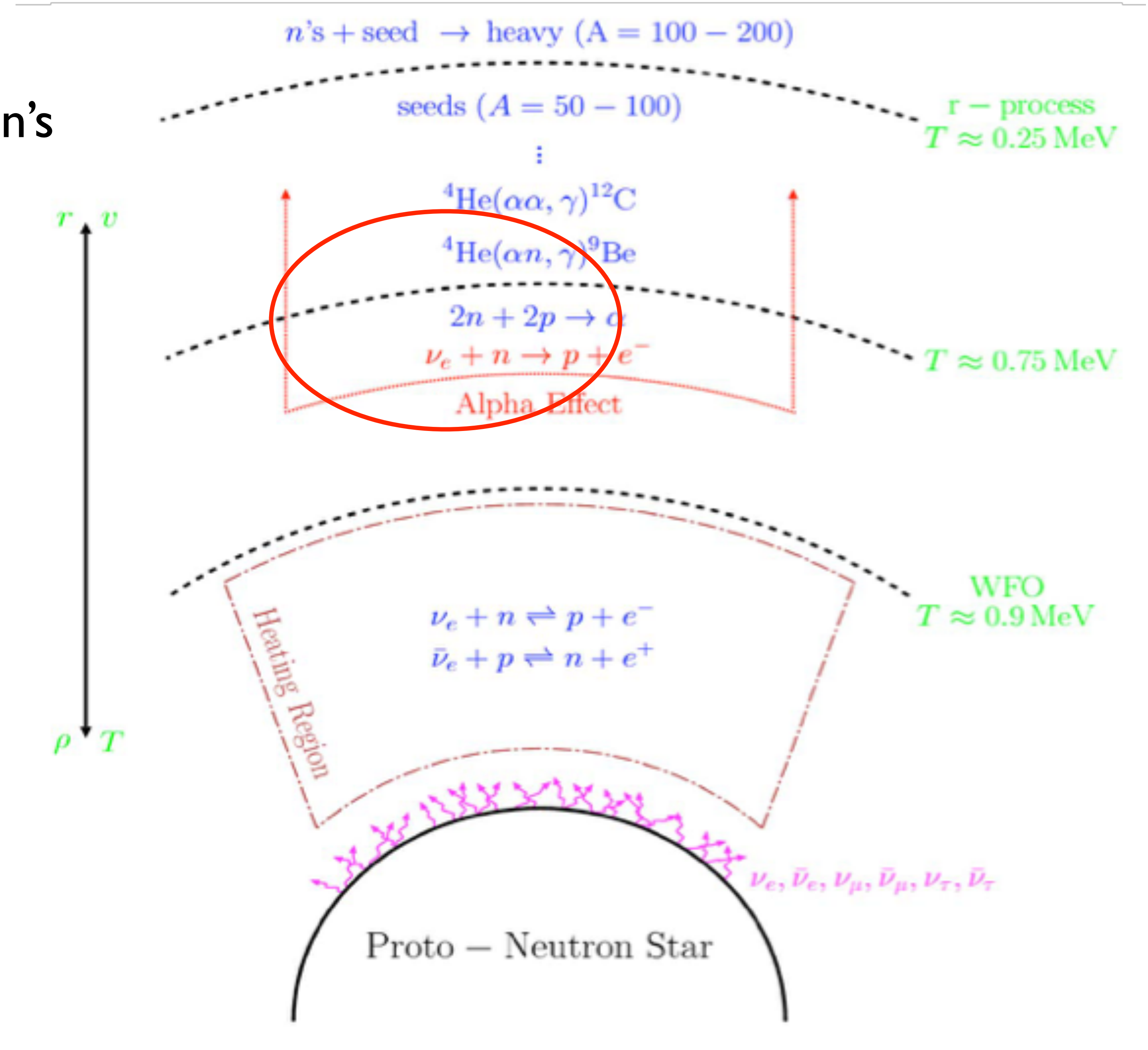
- r-process is responsible for synthesizing about half the heavy elements

- the process can be primary - all of the synthesis occurring in one site - or secondary, requiring pre-existing metals as neutron capture targets

- core-collapse SNe long thought to be a candidate site: with a galactic frequency of 1/100 y, the production/event needed is $\sim 10^{-5} - 10^{-6}\ \mathrm{M}_{\odot}$

- specifically, neutron-rich neutrino-driven wind (Woosley, Hoffman; Meyer; Fuller)

- hot bubble conditions provide α's and excess n's
- α's combine to form heavier N=Z nuclei
- neutrons capture on these heavy seeds
- generically one needs ~ 100 neutrons/seed
- neutrino pressure "lifts" the matter off star



From Fuller

After extensive study, a consensus has grown that the site is not viable

- The neutron richness is typically modest: $Y_e \sim 0.48$

- The same neutrino reactions needed to drive the wind work to destroy the neutrons

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

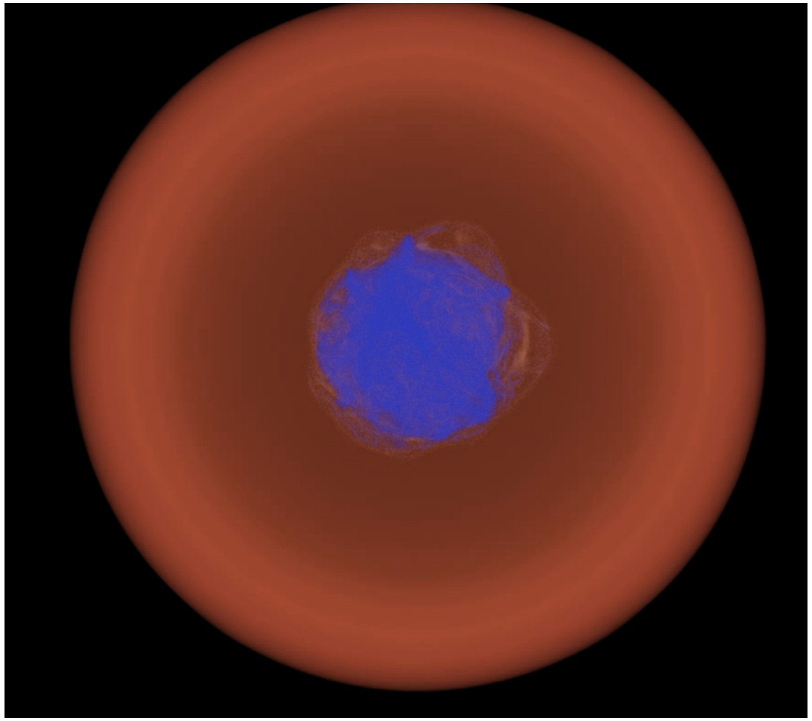
and the protons then capture other neutrons

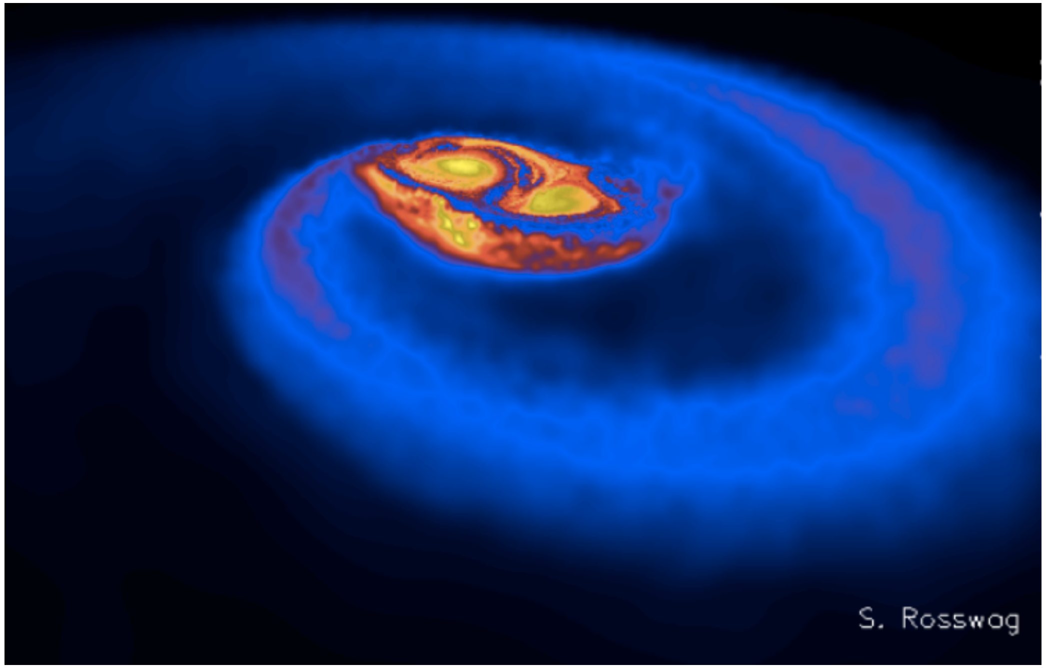
- The thermodynamics conditions cause seeds to proliferate

$$\alpha + \alpha + \mathrm{n} \to {}^9\mathrm{Be} \qquad \alpha + \alpha + \alpha \to {}^{12}\mathrm{C}$$

- The net result is an insufficient n/seed ratio: the neutron-capture process produces some medium-mass nuclei, then is exhausted core-collapse supernovae

neutron star merger





neutrino driven wind from
a proto-neutron star

$$Y_e \sim 0.5$$

$$\text{frequency} \ \sim 10^{-2}/y$$

$$\text{production} \ \sim 10^{-5} - 10^{-6} \ \mathrm{M}_{\odot}/\text{event}$$

dynamical ejecta
or post-merger disk winds

$$Y_e << 0.5$$

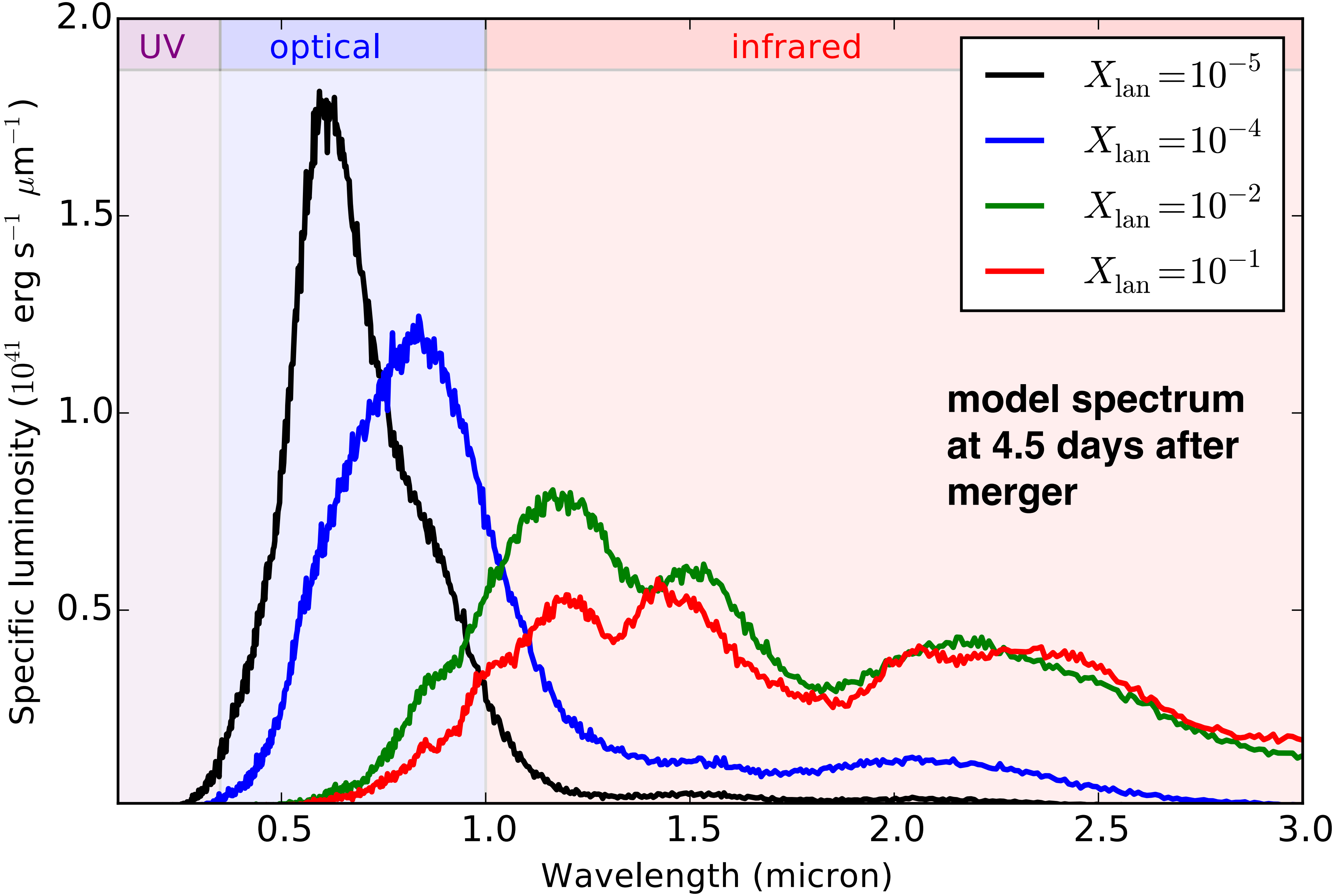
$$\text{frequency} \ \sim 10^{-5}/y$$

$$\text{production} \ \sim 10^{-2} \ \mathrm{M}_{\odot}/\text{event}$$

Leaves a substantial cloud of radioactive ejecta: Kilonova

Model kilonova spectra
dependence on lanthanide fraction

kasen, badnell and barnes 2013, barnes & kasen 2013, Tanaka&Hotokezka 2013, kasen+2017



Slide: Dan Kasen

(others will show in more detail)

- The optical counterpart of the NS merger GW 170817 provides a test
- Excellent fit to the evolving light curve with

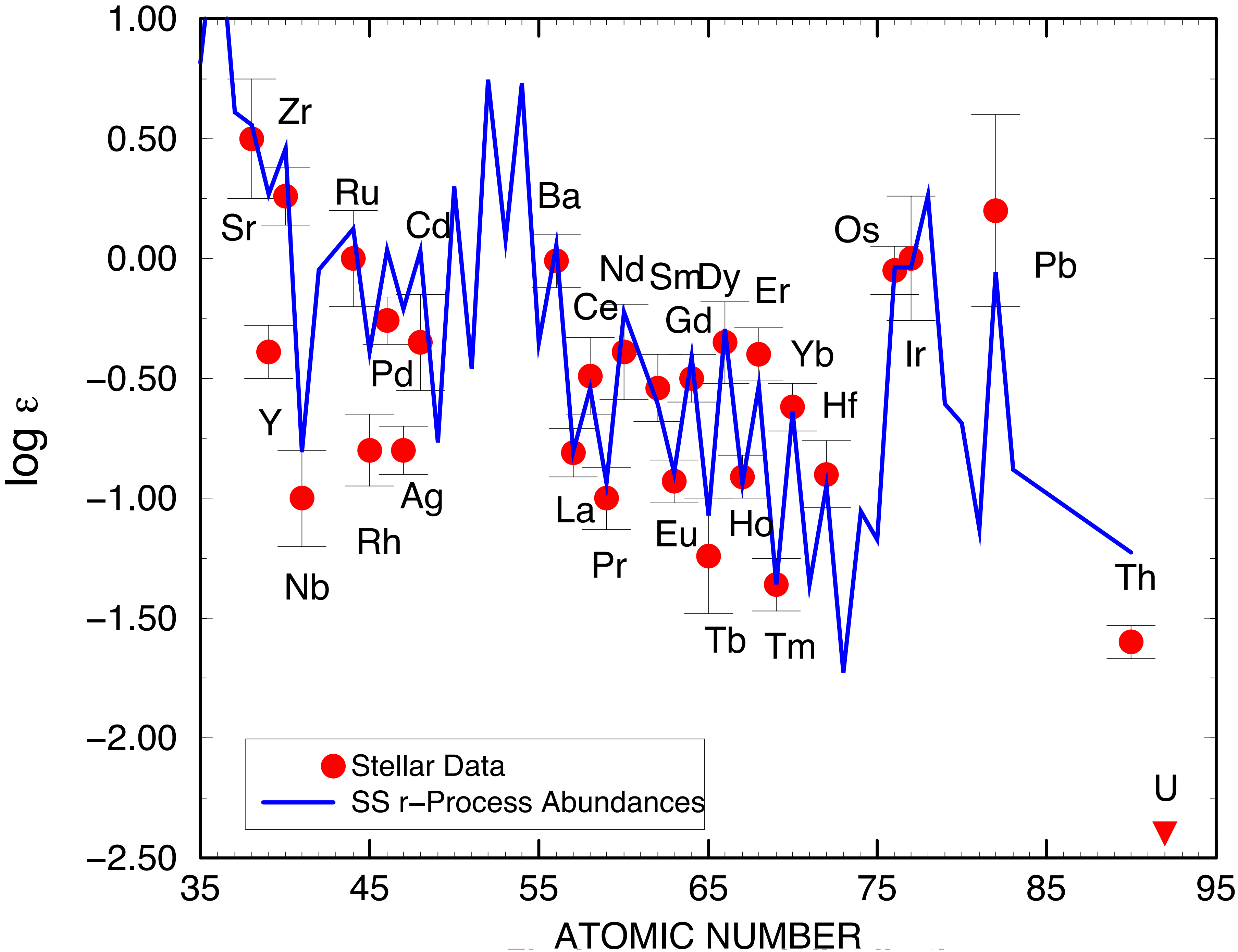
$$\text{heavy rprocess } (A > 130) \;\sim 0.04 M_\odot \qquad \text{light rprocess } (A < 130) \;\sim 0.02 M_\odot$$

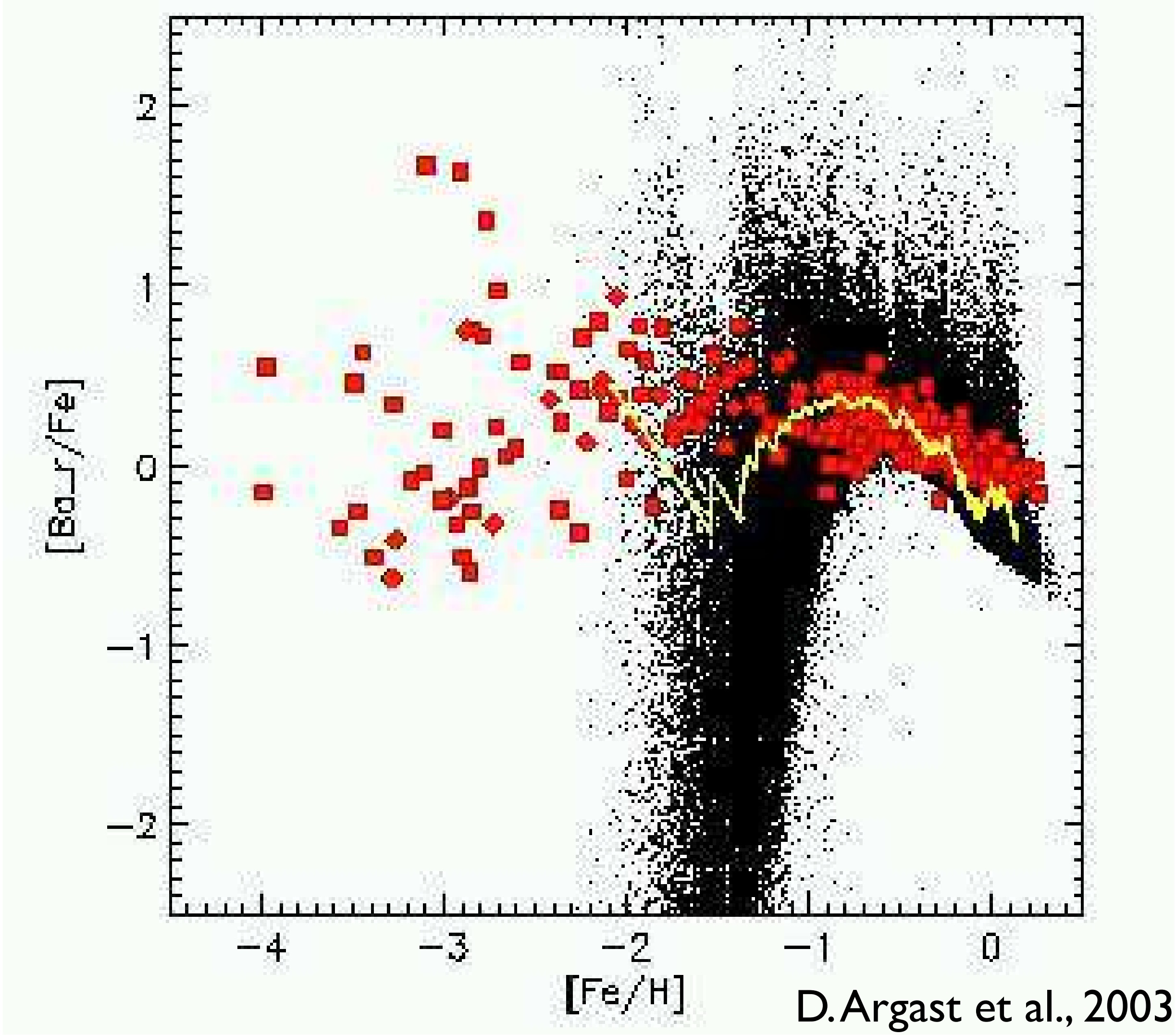
While the neutrino/nuclear microphysics of NS mergers is not yet treated in the detail used in supernova physics, the large neutron excess likely makes this scenario more robust

The yield is compatible with NS mergers being the source of the galaxy's inventory of r-process material

Are things settled?

From Cowan et al.





D. Argast et al., 2003

neutron stars take time to form and then to merge:
expected Ba/Fe chemical evolution for NS mergers (black) vs. observation (red)

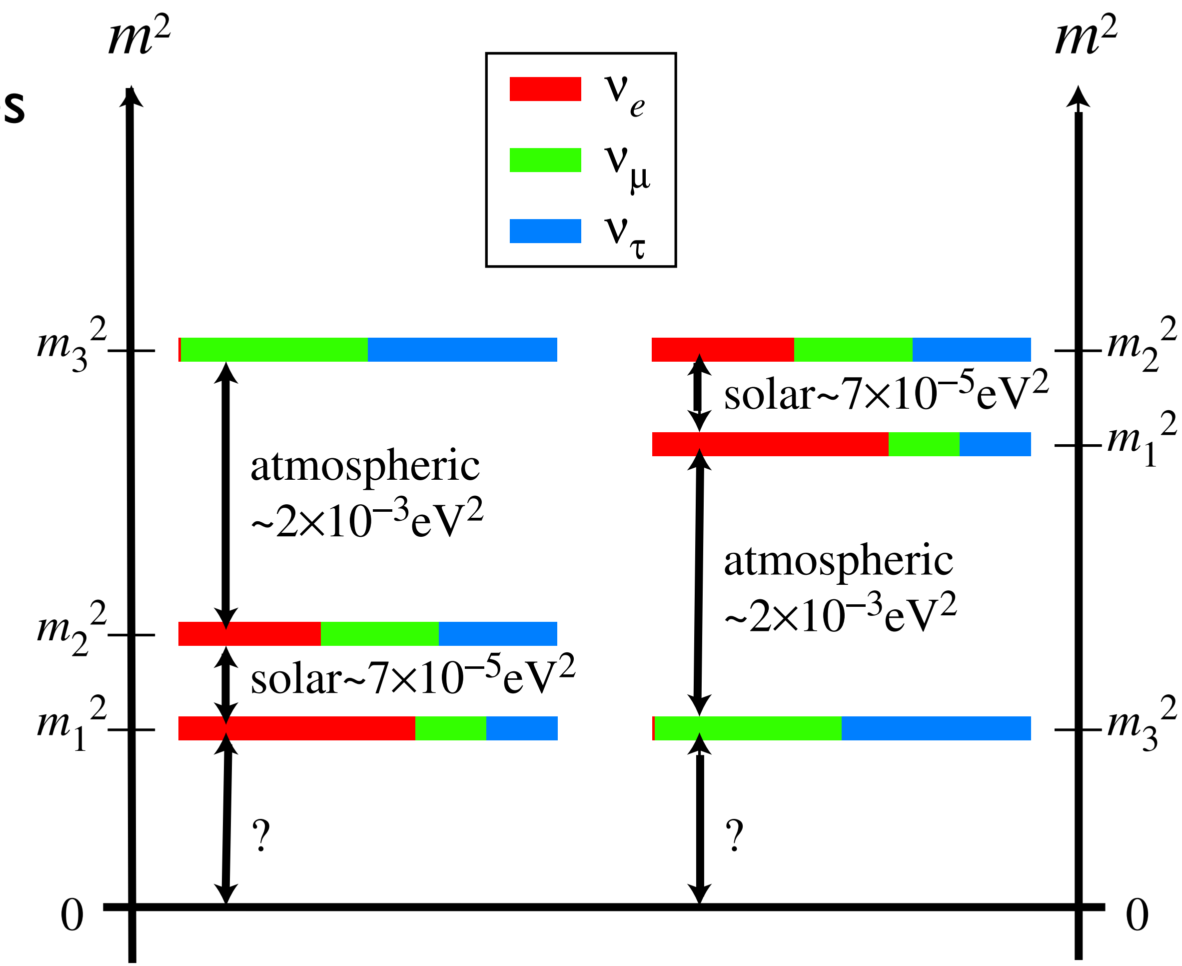
some of us believe there is still need for an r-process mechanism that operates at very early times in the galaxy:
some variations of a SN r-process may work under such conditions

New neutrino physics: what is the impact on what we discussed?

Recall the solar level crossing: matter allows us to measure the ordering of mass eigenstates

Matter effects in the sun decrease $\delta m_{21} = m_2^2 - m_1^2$, altering the oscillation pattern

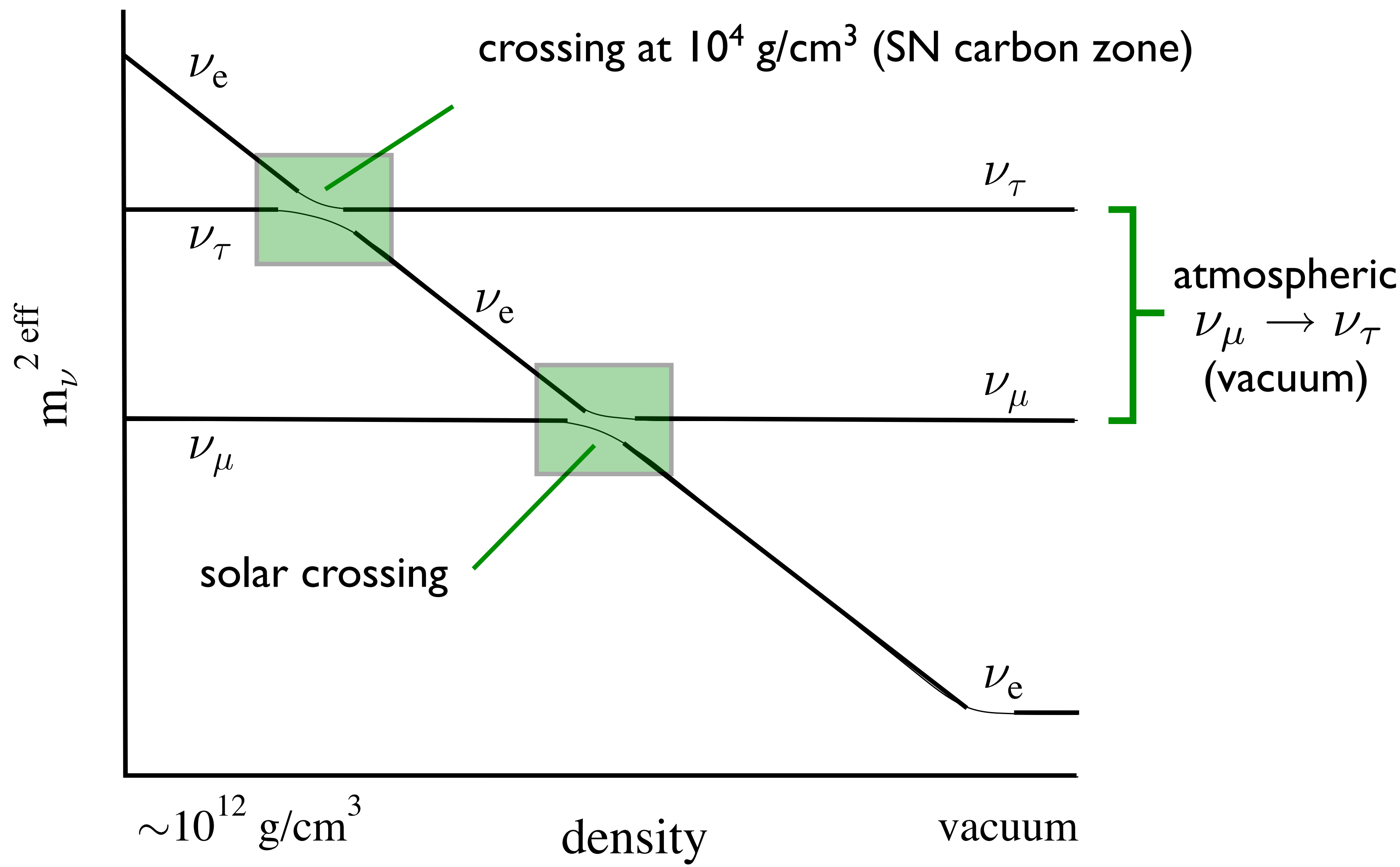
The hierarchy uncertainty exists because we have no such MSW probe of δm_{32}



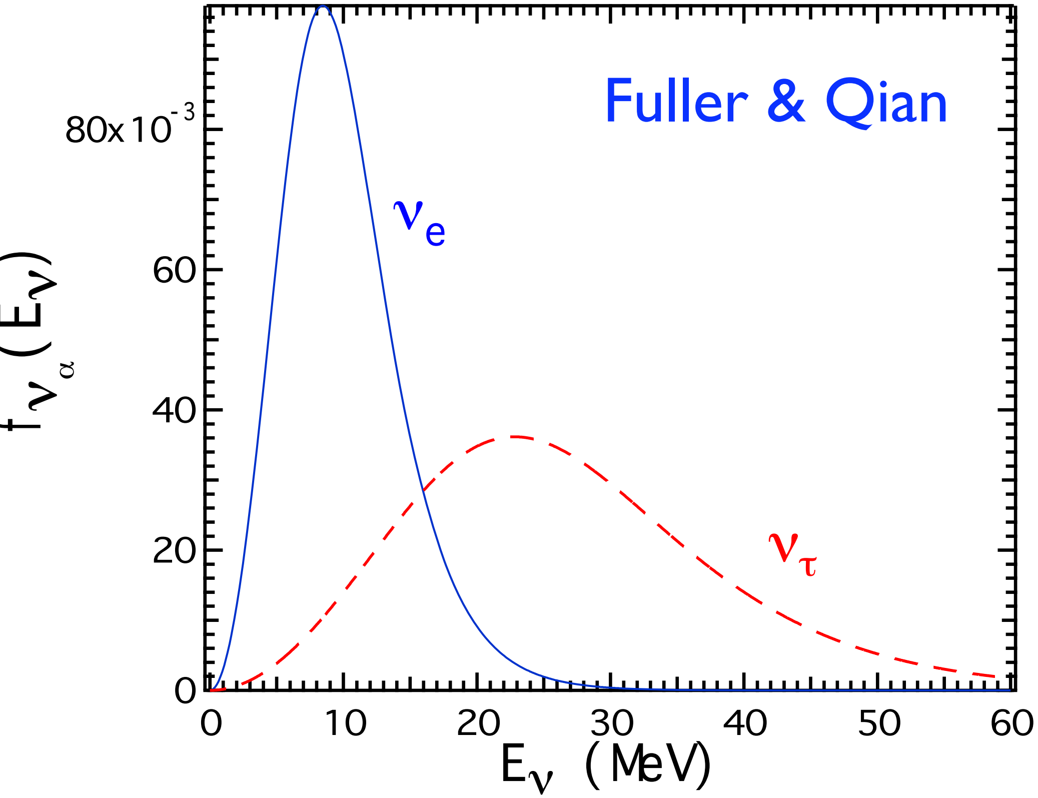
Mohapatra et al., APS study

SNe probe this crossing outside the neutrino sphere: $\nu_e, \bar{\nu}_e$

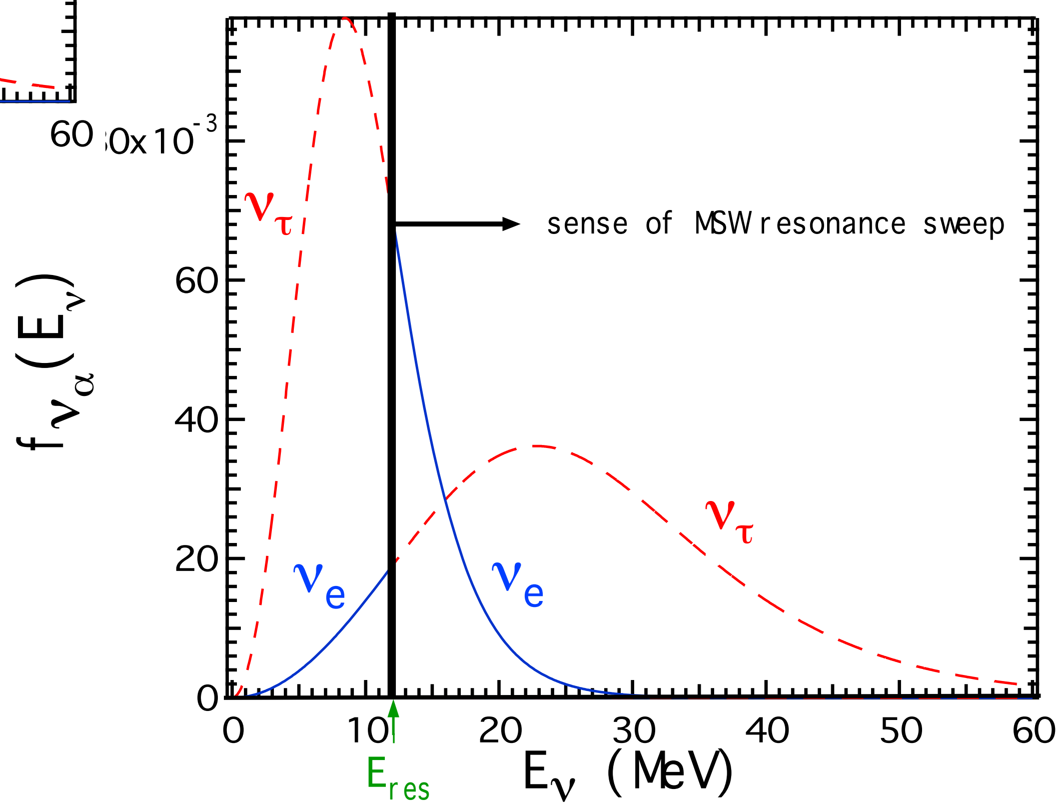
For the normal hierarchy



For the inverted hierarchy, the $\bar{\nu}_e$ experiences the crossing



The shock wave reaches the crossing density quickly - a second or so - while the neutrino flux is strong. The C shell then expands. The resonance sweeps



Sweep by the 1-3 resonance: most of the spectrum now heavy flavor -- and soon to have hot ν_e's

While the neutrino spectrum difference is exaggerated in this picture, this illustrates we can change the new number of neutrinos of a given flavor, at a given point

This effects the neutrino opacity and energy deposition

But an even more exotic effect is found in supernova, one that pulls oscillation physics much deeper into the core of the star, where it can affect dynamics: new contribution arise from the potential generated by ν-ν scattering

$$\hat{H} = \begin{pmatrix} -\delta m_{12} \cos 2\theta_{12} + 2\sqrt{2} E G_F \rho(t) + M_{11}^2(t) & \delta m_{12}^2 \sin 2\theta_{12} + M_{12}^2(t) \\ \delta m_{12}^2 \sin 2\theta_{12} + M_{21}^{2}{}^*(t) & -\delta m_{12} \cos 2\theta_{12} + 2\sqrt{2} E G_F \rho(t) + M_{22}^2(t) \end{pmatrix}$$

Ordinary MSW is due to effective potential exerted by CC reactions

$$\frac{G_F}{\sqrt{2}} \rho_\nu \rho_e$$

But in the supernova core there is huge local lepton number carried by trapped neutrinos, producing ν−ν *charge and current interactions*

$$\frac{G_F}{\sqrt{2}} \left[\rho_\nu \rho_{\nu'} - \vec{j}_\nu \cdot \vec{j}_{\nu'} \right]$$

that dominates when neutrino densities are high

Treatment of oscillations within a SN becomes difficult computationally

- nonlinear
- flavor dependent, with six flavors to track
- angle dependent

Integrating the physics into an explosion is challenging: we are far short of the goal in both SN and merger physics, despite 25 years of work

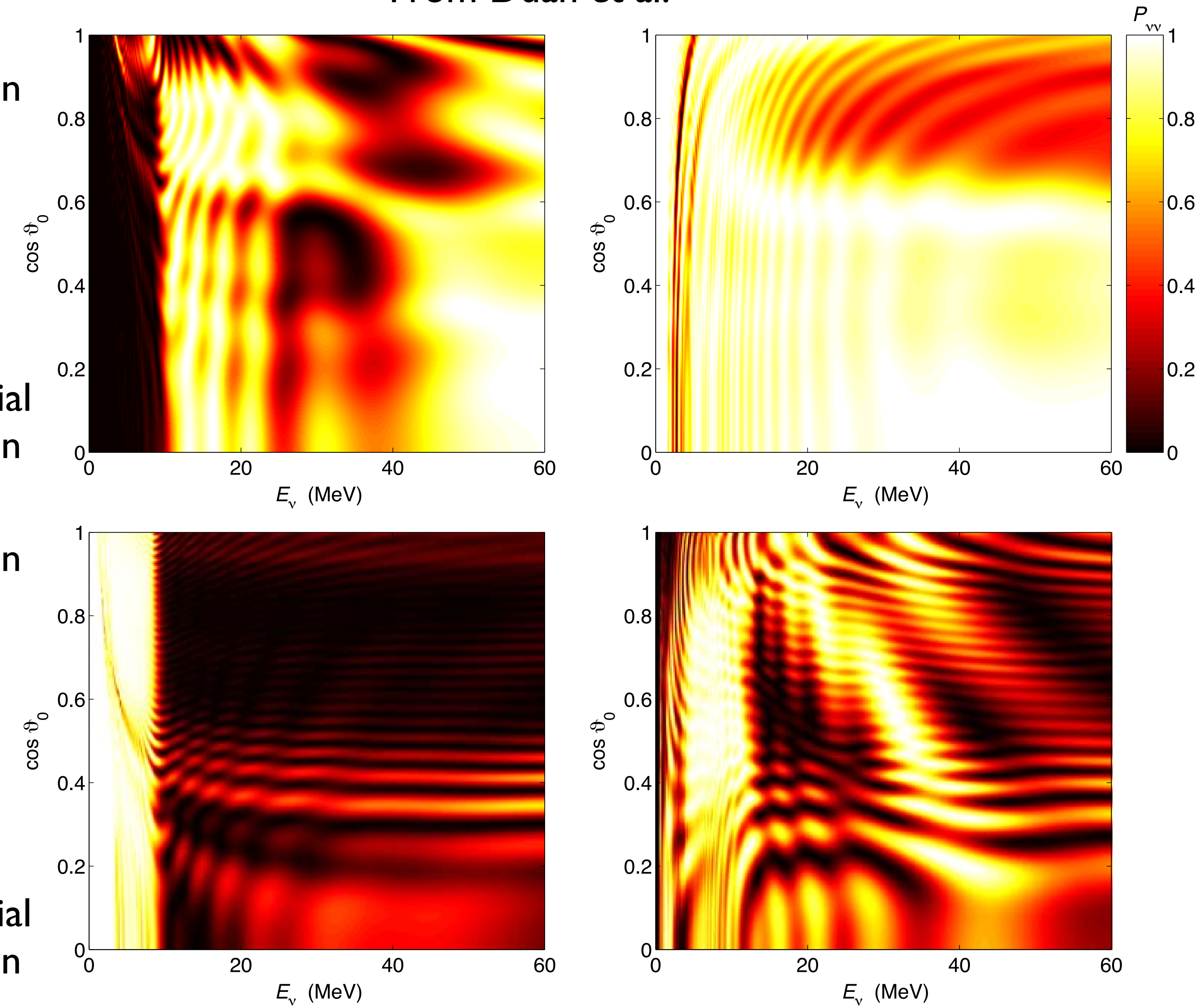
From Duan et al.

Radial emission

Tangential emission

Radial emission

Tangential emission



Normal

Inverted

Neutrinos

Antineutrinos

r ~ 225 km!

Closing Remarks

I will make some remarks about how rewarding I have found work in this inner space/outer space juncture.