The Role of Neutrinos in Nucleosynthesis + a little about the rare earth peak

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Neutrinos from Proto-Neutron Stars

Characteristics

- All flavors of neutrinos and antineutrinos
- ν_e has lowest temperature, followed by $\bar{\nu}_e$
- ν_μ, $\bar{\nu}_\mu$, ν_τ, $\bar{\nu}_\tau$
- emission surface for all types of νs is $very\ similar$
- neutrino flux slightly larger than antineutrino flux (deleptonizing)

Neutrino surfaces:

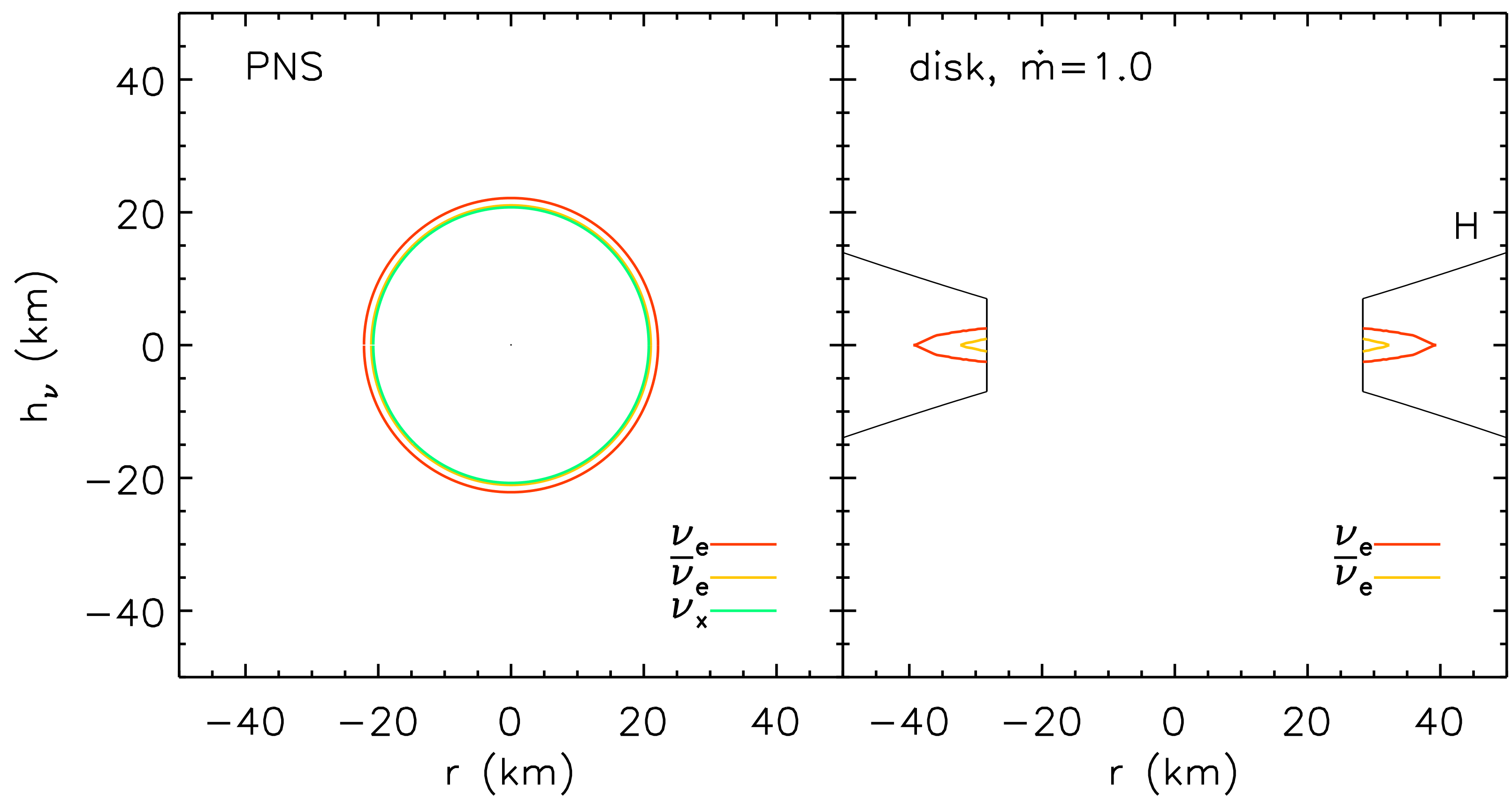


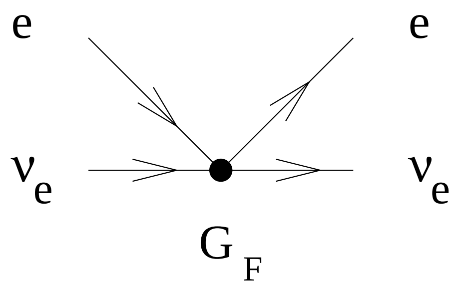
Figure from GCM and Surman 2007

Neutrino Oscillations

After neutrinos are emitted, they undergo flavor transformation.

Neutrino Oscillations

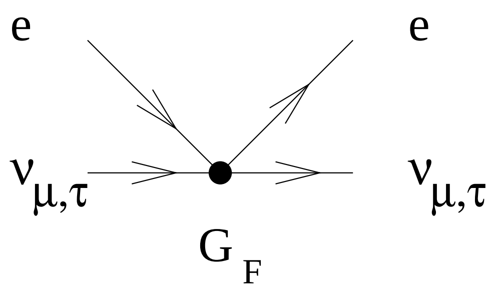
Neutrino propagation in matter: forward scattering on electrons, neutrinos leads to effective potential



CC+NC

$$V_e = \frac{V_{\nu_e,e} - V_{\nu_x,e}}{2} = 2\sqrt{2} G_F N_e(r)$$

electron density $N_e(r)$



NC

$$V_\nu = V_{\nu,\nu} - V_{\nu,\bar{\nu}}$$

similar idea for ν - νs

Modified wave equation

$$i\hbar c \frac{d}{dr}\psi_\nu = \begin{pmatrix} V_e + V_\nu^a - \frac{\delta m^2}{4E}\cos(2\theta) & V_\nu^b + \frac{\delta m^2}{4E}\sin(2\theta) \\ V_\nu^b + \frac{\delta m^2}{4E}\sin(2\theta) & -V_e - V_\nu^a + \frac{\delta m^2}{4E}\cos(2\theta) \end{pmatrix} \psi_\nu$$

Neutrino Oscillations: scales

Modified wave equation

$$i\hbar c \frac{d}{dr}\psi_\nu = \begin{pmatrix} V_e + V_\nu^a - \frac{\delta m^2}{4E}\cos(2\theta) & V_\nu^b + \frac{\delta m^2}{4E}\sin(2\theta) \\ V_\nu^b + \frac{\delta m^2}{4E}\sin(2\theta) & -V_e + -V_\nu^a + \frac{\delta m^2}{4E}\cos(2\theta) \end{pmatrix}\psi_\nu$$

Scales in the problem:

- vacuum scale $\frac{\delta m^2}{4E}$
- matter scale $V_e \propto G_F N_e(r)$
- neutrino self-interaction scale $V_\nu \propto G_F N_\nu * \text{angle} - G_F N_{\bar{\nu}} * \text{angle}$

V_ν has some subtleties. For proto-neutron star neutrinos V_ν term declines roughly as $1/r^4$

Collective neutrino oscillations

Collective neutrino oscillations are numerically more demanding than standard matter enhanced neutrino effects. Calculations see Dighe, Duan, Fuller, Kneller, Raffelt, Volpe and more

1. Non-linear effects $V_\nu \sim |\psi_\nu|^2$
2. Requires multi-group treatment: Background involves sum over neutrino momentum and angle.

We rewrite the problem as an S-matrix problem

$$i\hbar \frac{dS}{dx} = HS$$

and solve in an adiabatic basis. Kneller and McLaughlin

Supernova neutrino transition regions

Type I - Matter enhanced region

- Traditional MSW region
- vacuum interaction strength is the same size as matter potential
- neutrino self interaction strength is small
- i.e $\delta m_{ij}^2 / E_\nu \sim \sqrt{2} G_F N_e \gg V_{\nu\nu}$

Type II - nutation/bipolar

- "Traditional" nutation in NFIS picture (also called bipolar)
- $\delta m_{ij}^2 / E_\nu \sim V_{\nu\nu}$
- occurs closer to proto-neutron star than Type I regions
- occurs when matter potential is both large and small

Supernova neutrino transition regions

Type I - Matter enhanced region

- Occurs in outer layers of the star (He layer or a somewhat before)
- Straightforward to calculate (same thing that happens in the sun)
- (recall: neutrino self interaction strength is small)
- does not influence most nucleosynthesis

Type II - nutation/bipolar

- occurs closer to PNS than Type I regions $\sim 100\,\mathrm{km}$
- neutrinos in this region can moderately influence some nucleosynthesis

Consequences for wind nucleosynthesis

The earlier the oscillation starts, the more important the consequences

Electron fraction, i.e neutron to proton ratio, is set by the weak interactions:

$\nu_e + n \leftrightarrow p + e^-$, $\bar{\nu}_e + p \leftrightarrow n + e^+$

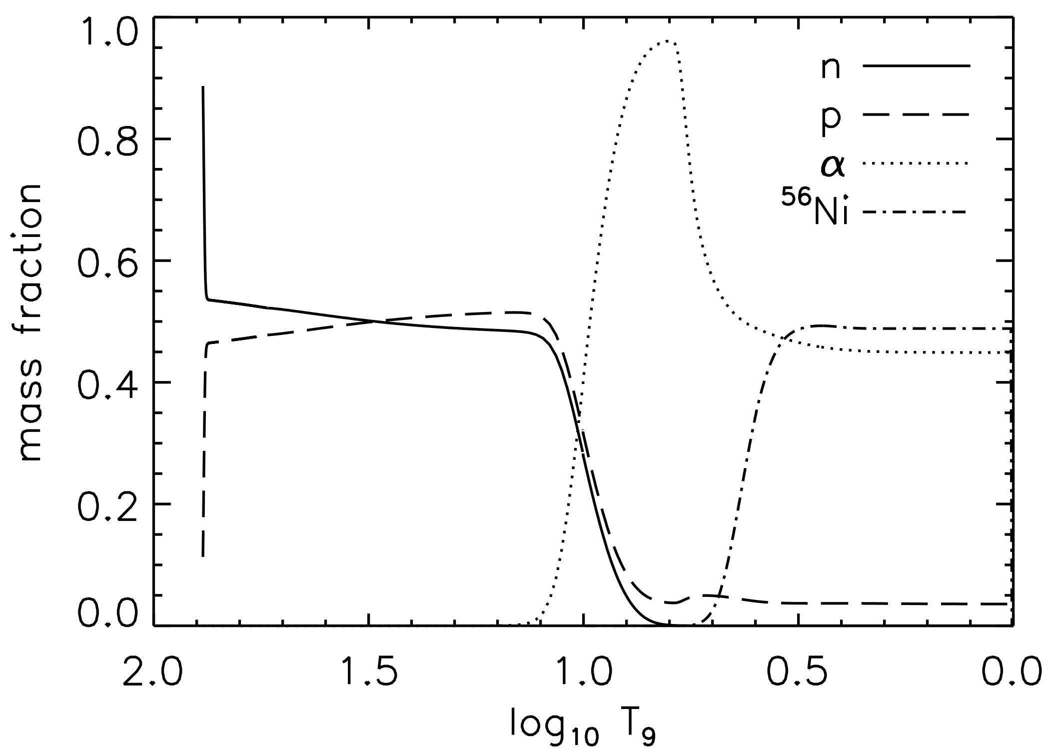
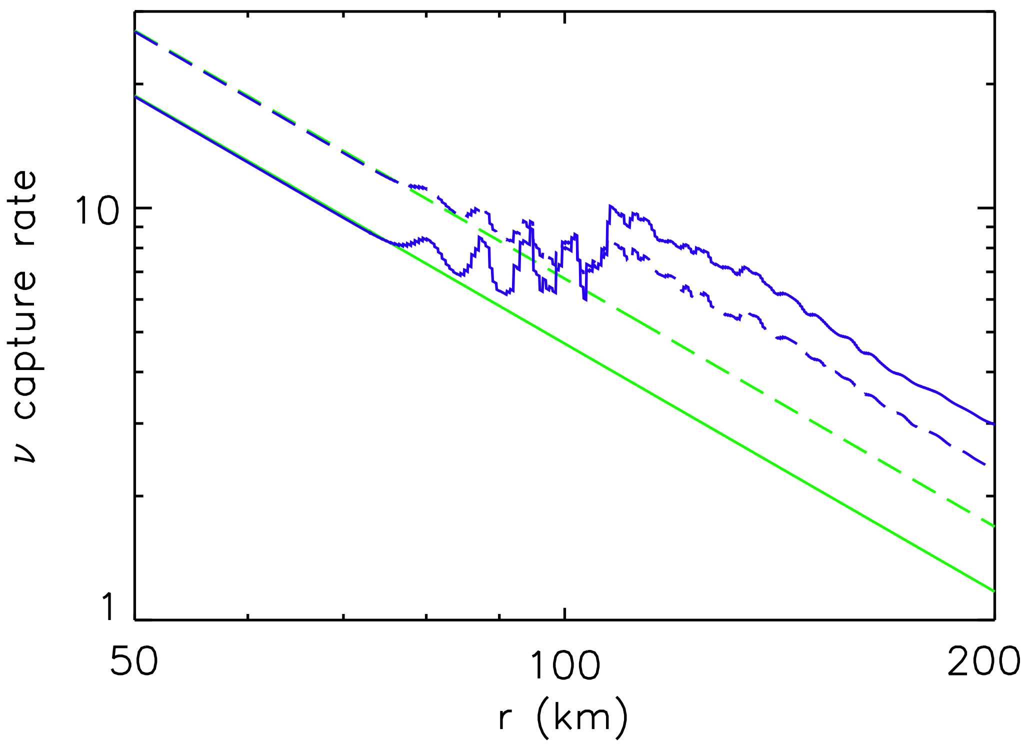


Figure from Surman, GCM and Sabbatino 2011

Electron neutrino and antineutrino capture rates



- ν_e solid line
- $\bar{\nu}_e$ dashed line
- green no oscillation
- blue oscillation

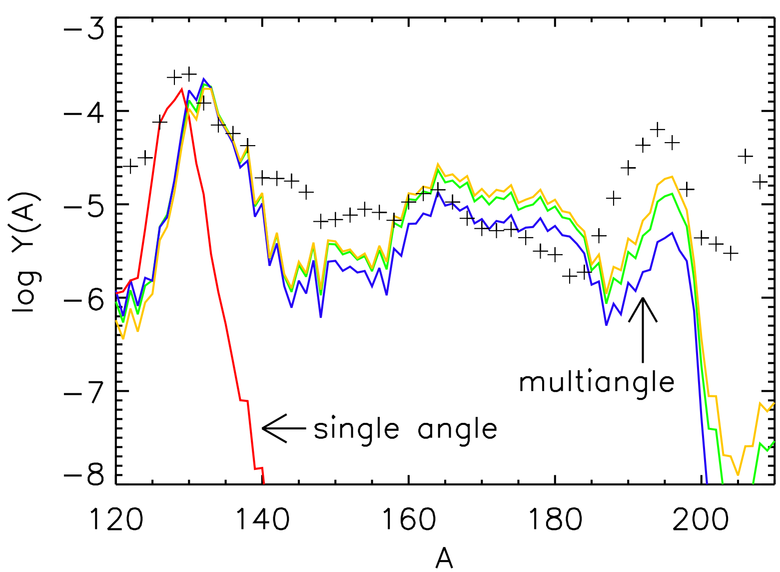
figure from Duan, Friedland, GCM and Surman 2011

Shows the influence of Type II (nutation/bipolar) oscillations

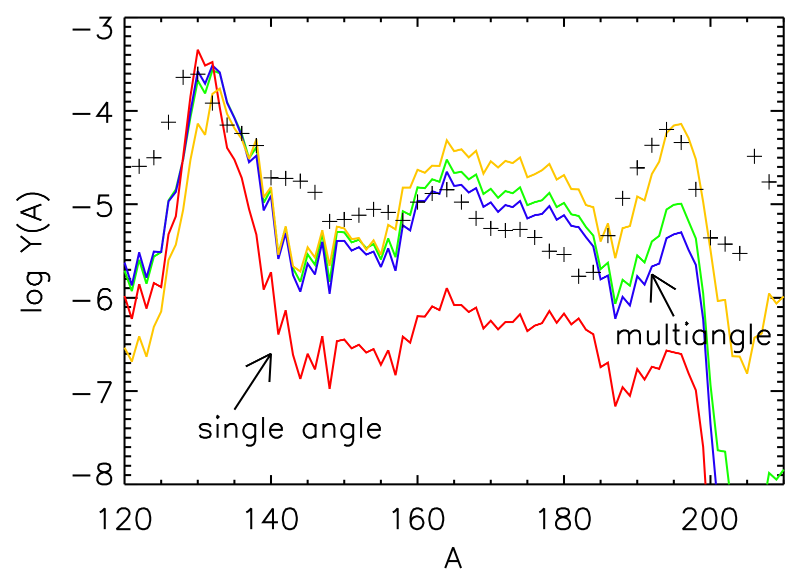
ν_es are exchanging with ν_μs, ν_τs $\bar{\nu}_e$s are exchanging with $\bar{\nu}_\mu$s, $\bar{\nu}_\tau$s

Neutrino Flavor Transformation

In SN winds, the oscillation often starts after nuclei begin to form



Early time density profile, $s/k = 200$, $\tau = 15\text{ms}$



Late time density profile, $s/k = 200$, $\tau = 18\text{ms}$

wind conditions tweaked to create r-process favorable conditions

For recent discussion of PNS winds, see Arcones and Thielemann 2012

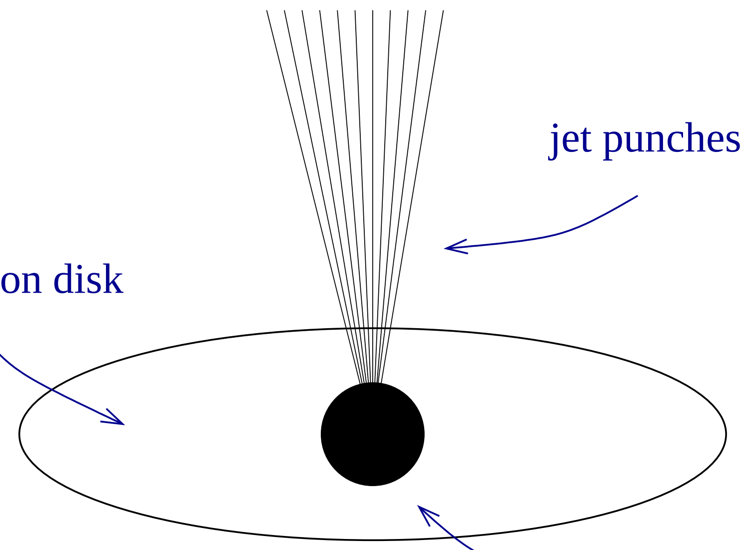
Accretion Disks

Black hole accretion disks are an outcome for a small portion of core collapse supernovae and most neutron star - neutron star mergers and black hole neutron star mergers.

Let's consider the core collapse kind of accretion disk...

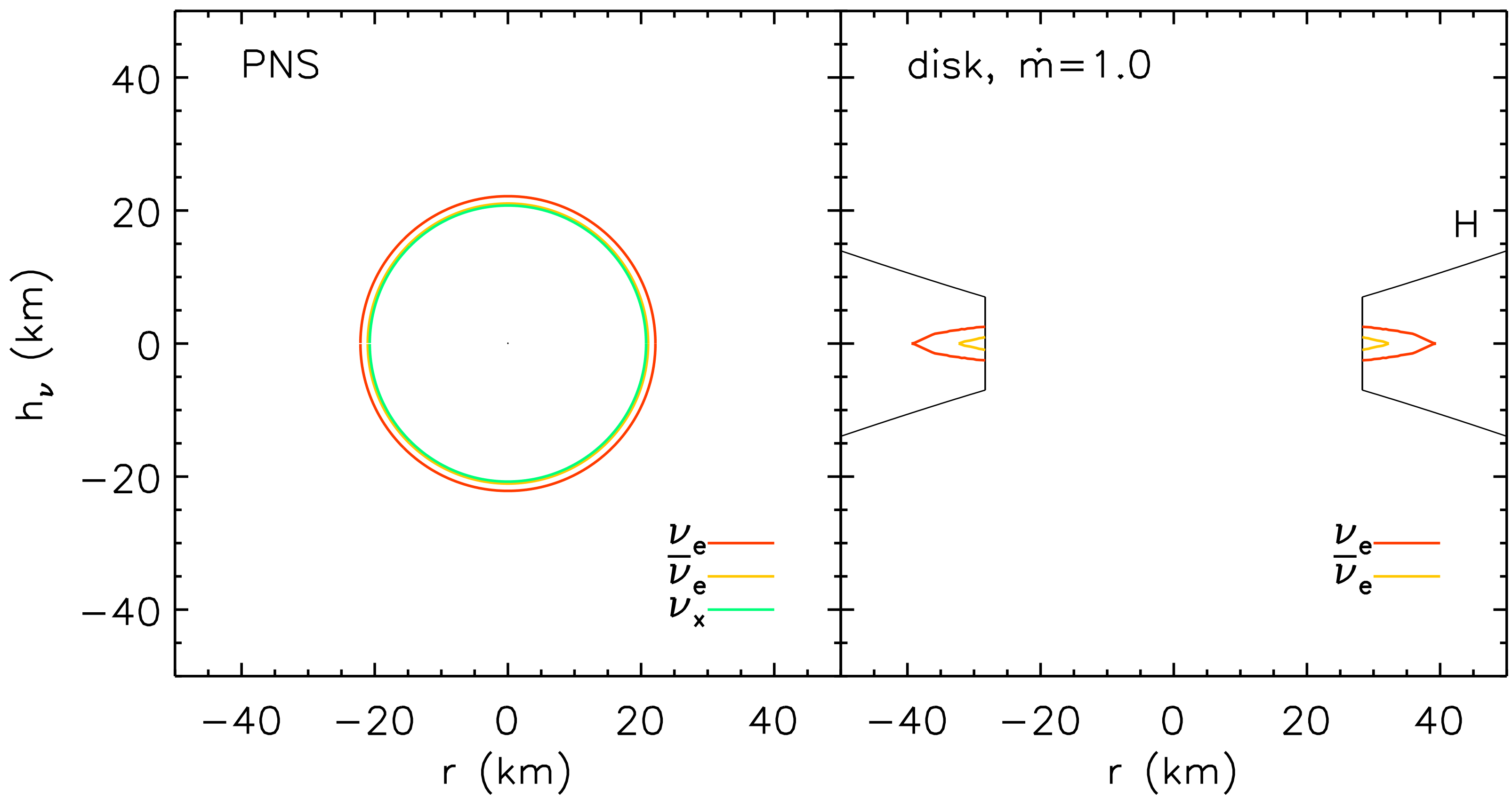
Collapsar/Hypernovae instead of Traditional core-collapse supernova

- Failed Supernova
- Too much rotation for real collapse & bounce

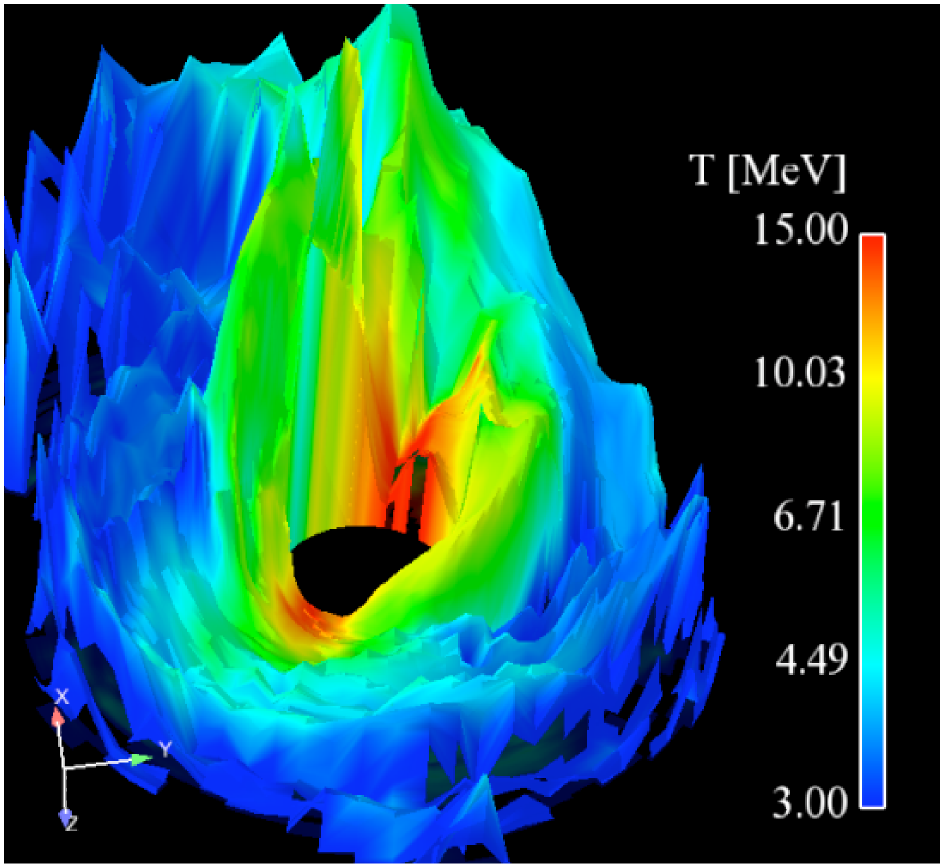


Neutrinos from the disk may provide some of the energy required to power a GRB jet.

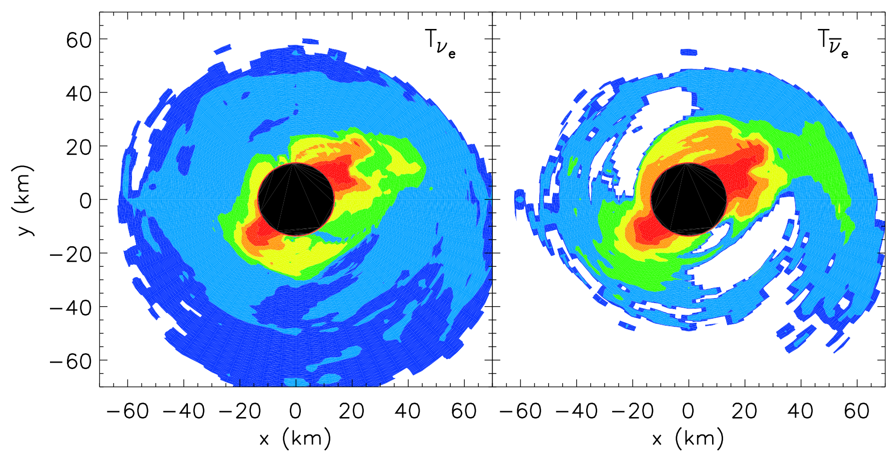
Neutrino surfaces:



Accretion Disk ν_e temperatures



Caballero, GCM and Surman 2009



Surman, GCM, Ruffert and Janka 2008

Neutrinos from ν_e and $\bar{\nu}_e$ emitting disks

Characteristics

- primarily ν_e and $\bar{\nu}_e$ (PNS has all flavors: ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$)
- similar spectra
- emitted from a fairly different geometry
- emission surface for neutrinos is much larger than for antineutrinos
- antineutrinos have higher temperature than neutrinos

Vanilla Model

- flat disk approximation
- antineutrino flux dominates over neutrino flux close to the emission point, but neutrino flux dominates over antineutrino flux farther out (new!, doesn't happen in PNS)

Accretion disk neutrino transition regions

Type I - Matter enhanced region

- Traditional MSW region
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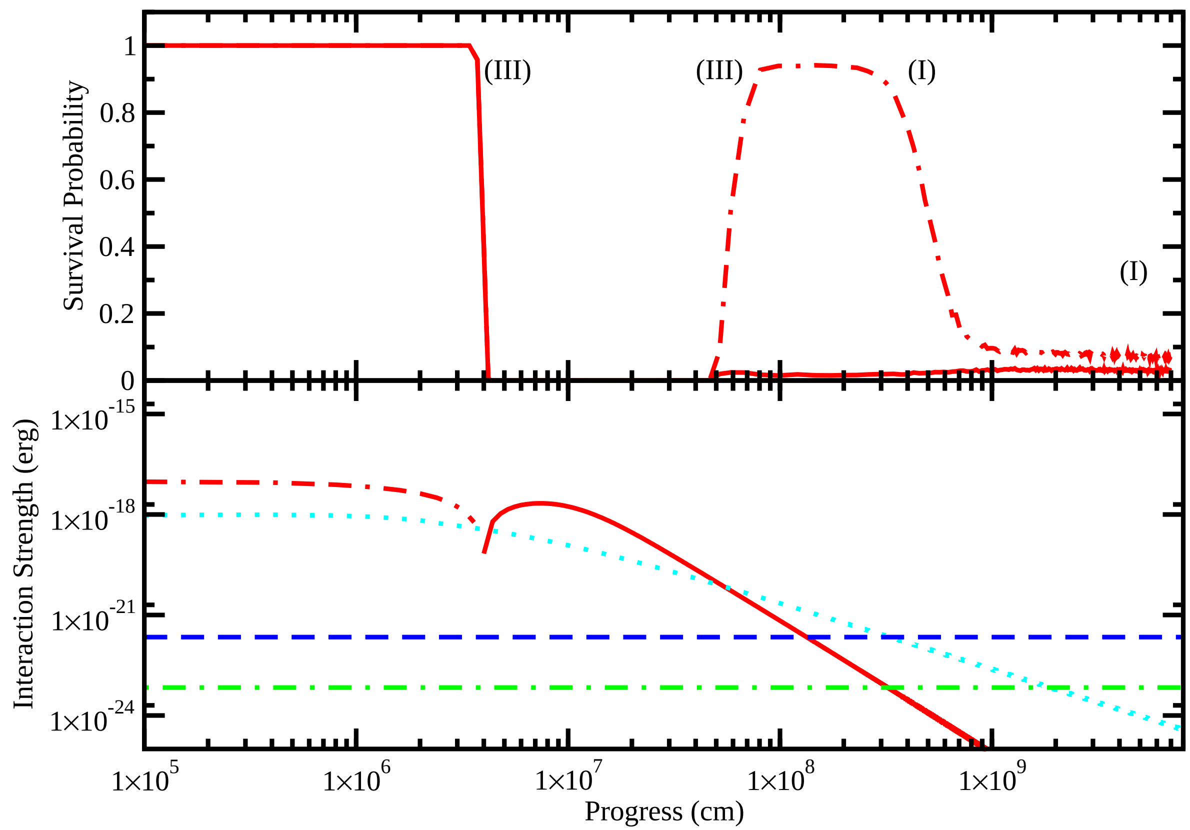
Accretion disk transition regions

Type III "Neutrino - Matter enhanced" New!

- Self-interaction potential $\sim$ matter potential
- vaccuum interaction strength is small
- i.e. $\delta m_{ij}^2/E_\nu << \sqrt{2}G_F N_e \sim V_{\nu\nu}$
- potentials have opposite signs! cancellation!
- occurs in both hierarchies
- not a usual situation in supernovae

Inverted hierarchy, $\bar{\nu}$ dominated first, ν later

Model Vanilla figure from Malkus, Kneller and GCM 2012



Upper panel: solid red - electron neutrino survival probability

Upper panel: dashed red - electron antineutrino survival probability

Neutrino Flavor Transformation + Nucleosynthesis

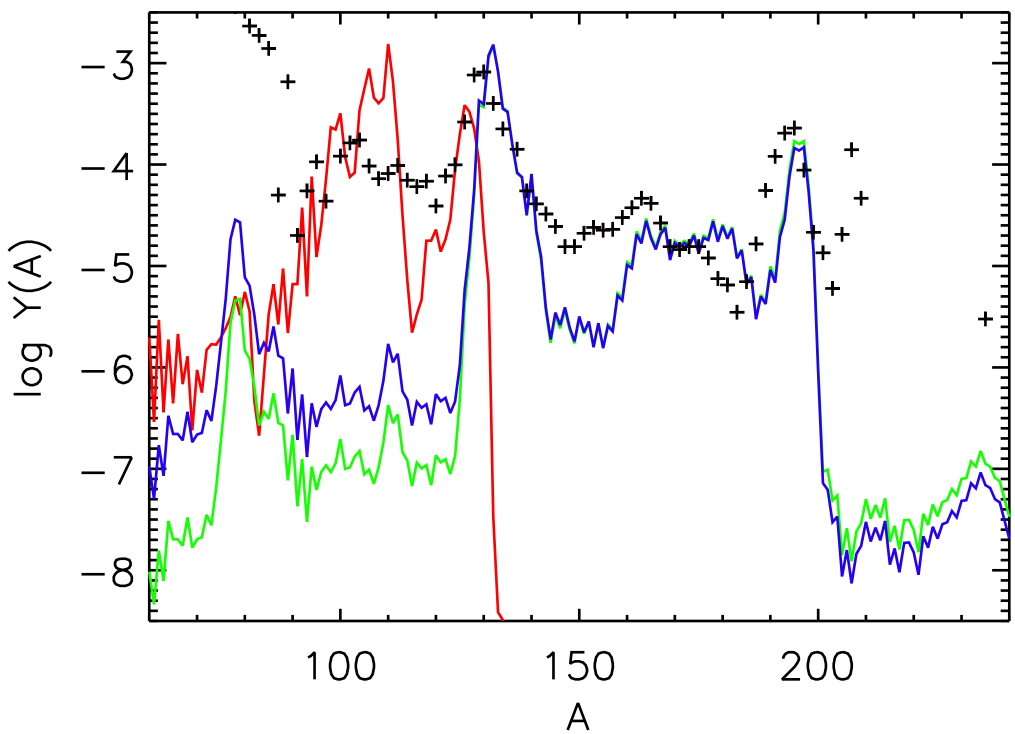
Supernovae Neutrinos

- In the SN, oscillations tend to occur after the most important point for wind nucleosynthesis
- In the SN, oscillations increase ν_e, $\bar{\nu}_e$ capture rates
- There is some re-arrangement of the abundance pattern

Accretion disk neutrinos

- In the accretion disk, they occur earlier, because of the Type III transition
- In the accretion disk, oscillations decrease ν_e, $\bar{\nu}_e$ capture rates
- One expects significant changes the abundance pattern

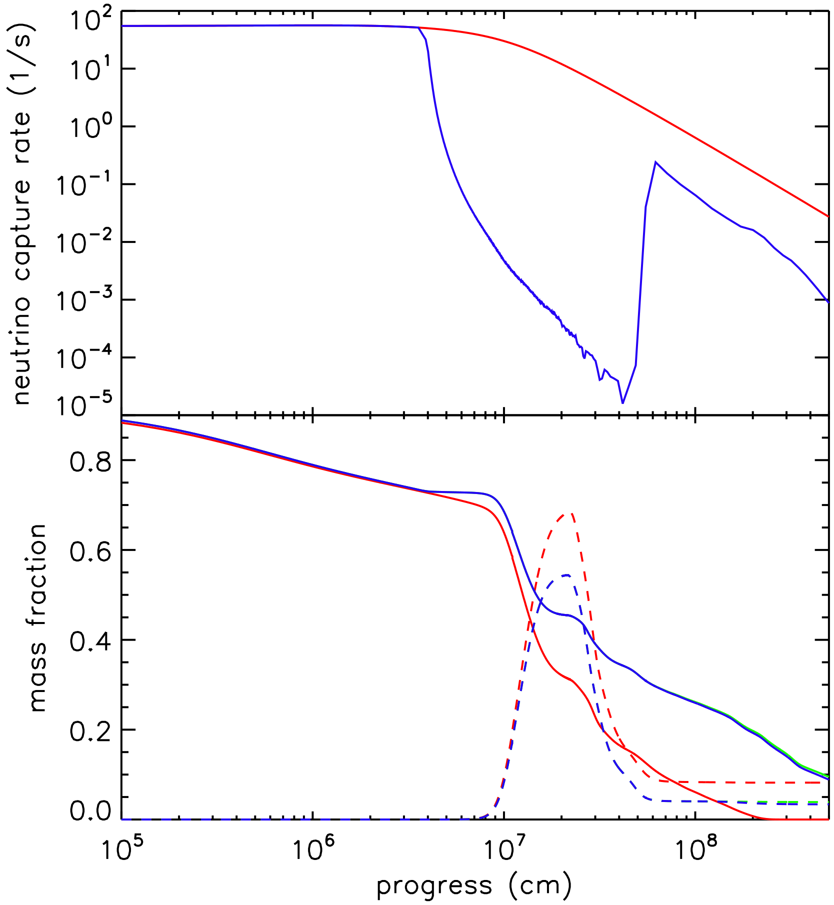
Accretion Disk Nucleosynthesis



red - no oscillations, blue - oscillations

s/k $= 50$, $\beta = 1.4$ (moderate acceleration) figure from Malkus, Kneller and GCM 2012

Accretion disk neutrino capture rate, mass fractions



red - without oscillations

blue - with oscillations

upper panel: ν_e capture

lower panel: fract. of n, α

figure from Malkus, Kneller and GCM 2012

Outlook for accretion disk neutrino transformation

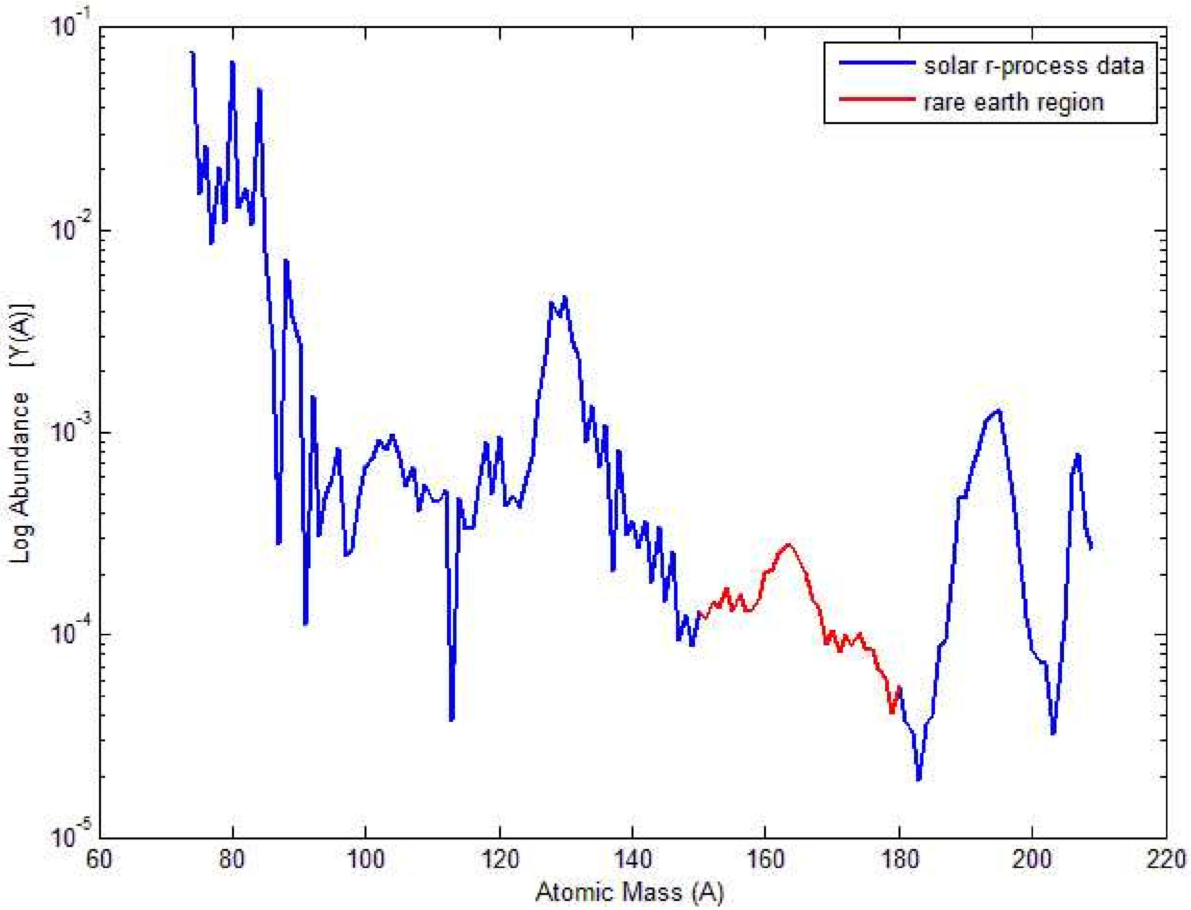
- SN disks are in many ways qualitatively similar to SN
- One difference is that many disks emit primarily ν_e and $\bar{\nu}_e$
- Another is that close to the emission surface the neutrino potential can be $\bar{\nu}$ dominated
- Disks which begin $\bar{\nu}$ dominated exhibit a (new type of) flavor transition at the crossover point
- This transition can change the result of wind nucleosynthesis dramatically
- More to be considered, e.g. multi-angle effects, 3-D disk emission surfaces

Toward the use of the rare earth peak earth peak as a diagnostic of r-process conditions

Collaborators: Matt Mumpower and Rebecca Surman

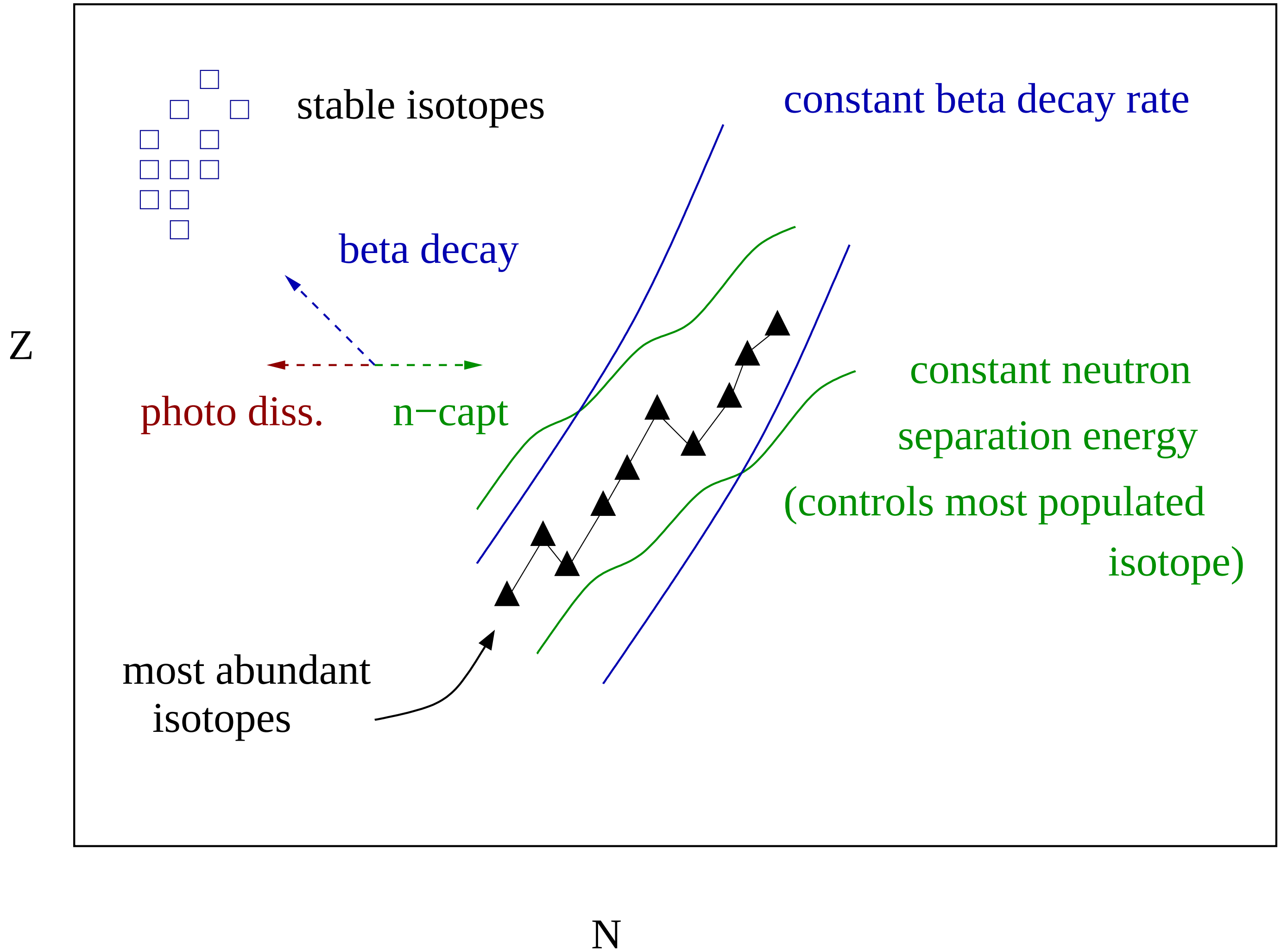
- Determine how the rare earth peak forms
- Consider the nuclear physics uncertainties
- Determine the range of thermodynamic conditions that are successful

The rare earth peak

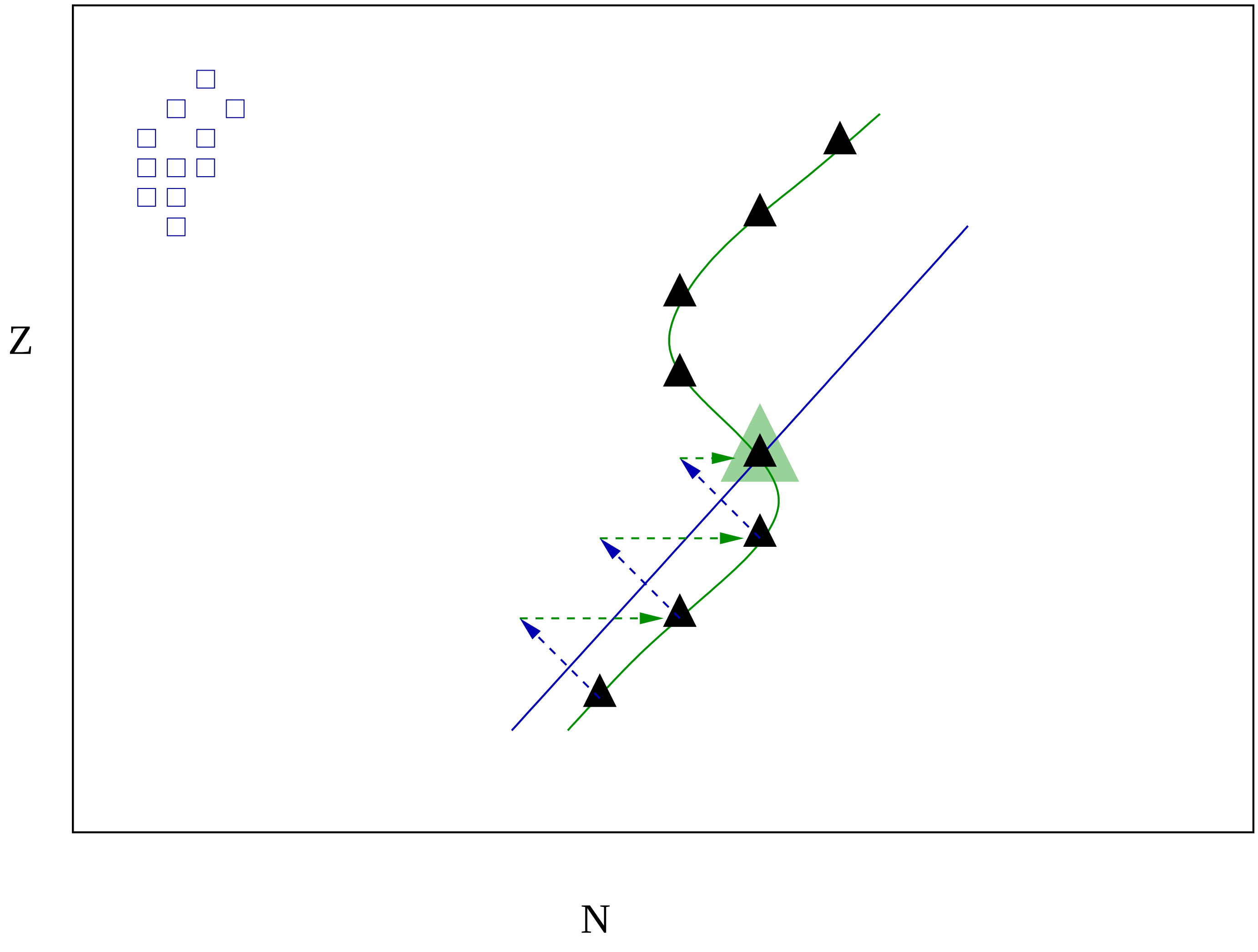


Solar abundance data with the rare earth peak in red

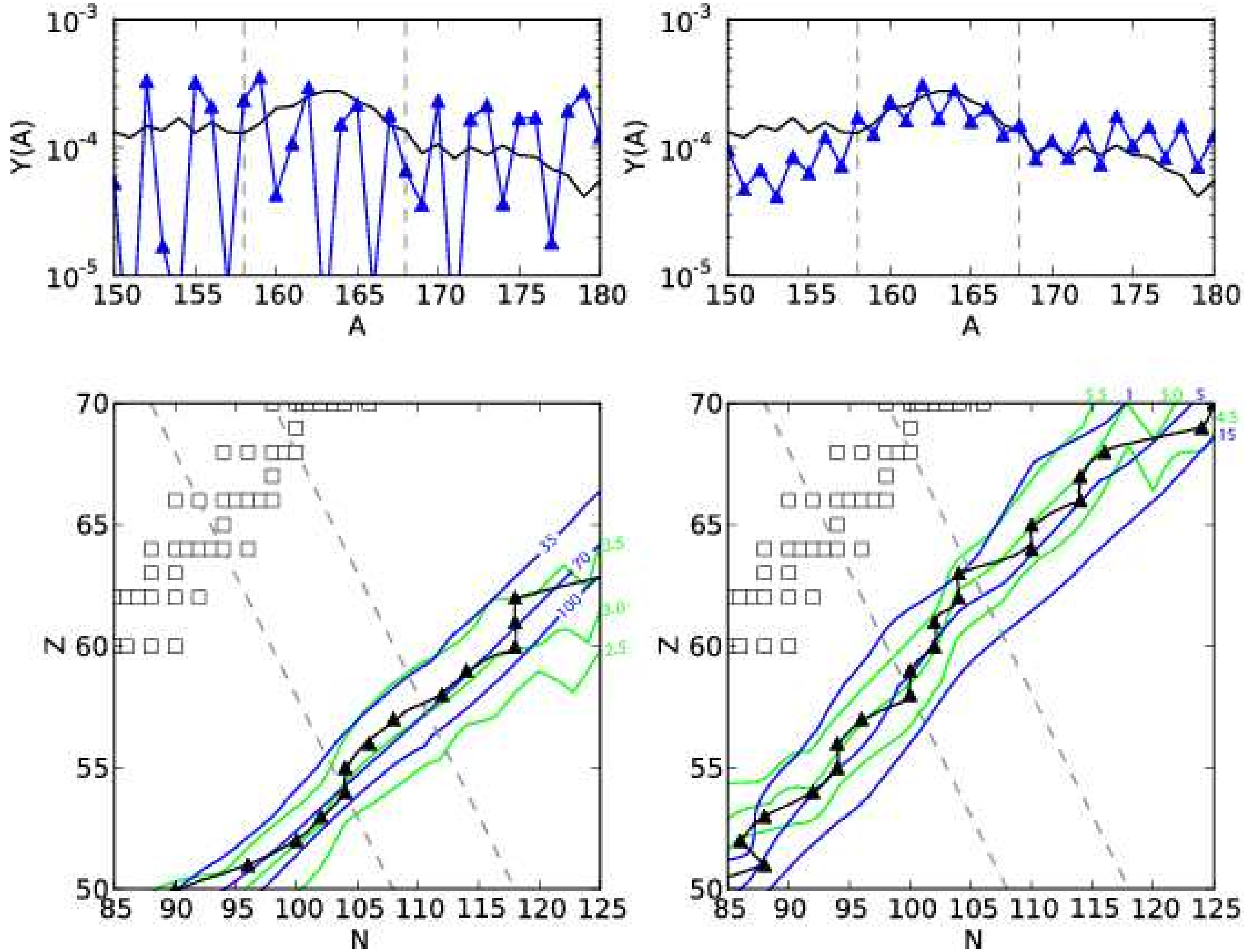
How to read r-process flow plots



How to form structures

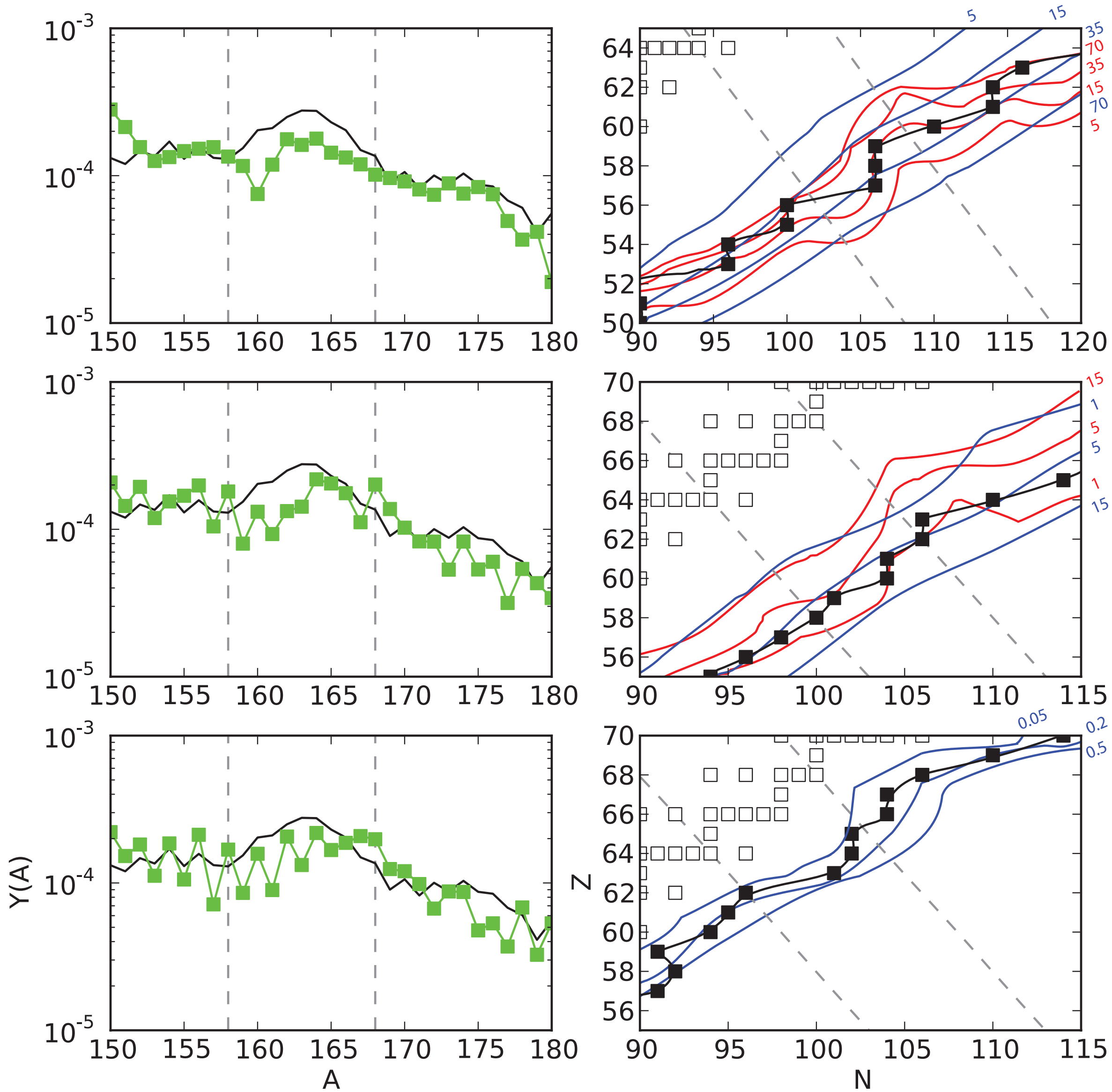


Hot rare earth peak formation
Mumpower, GCM, Surman 2012, see also Surman and Engel 1997



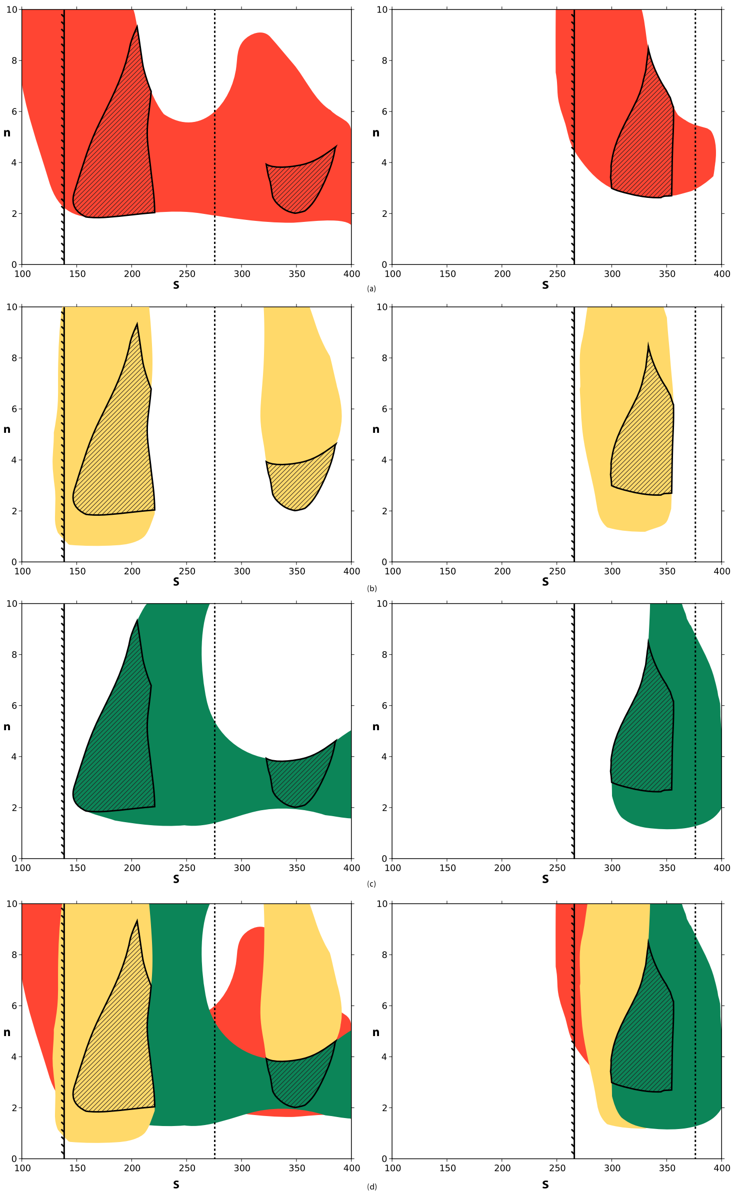
Neutron capture just below the peak and photo-dissociation above FRDM

Correct structure must persist until neutrons are exhausted



Calculation with different mass model ETFSI

Constraints on the rare earth peak from solar data



Red: comparison to data with $G^{REP} < 0.15$

Yellow: rare earth to A=195 ratio to within a factor of 2

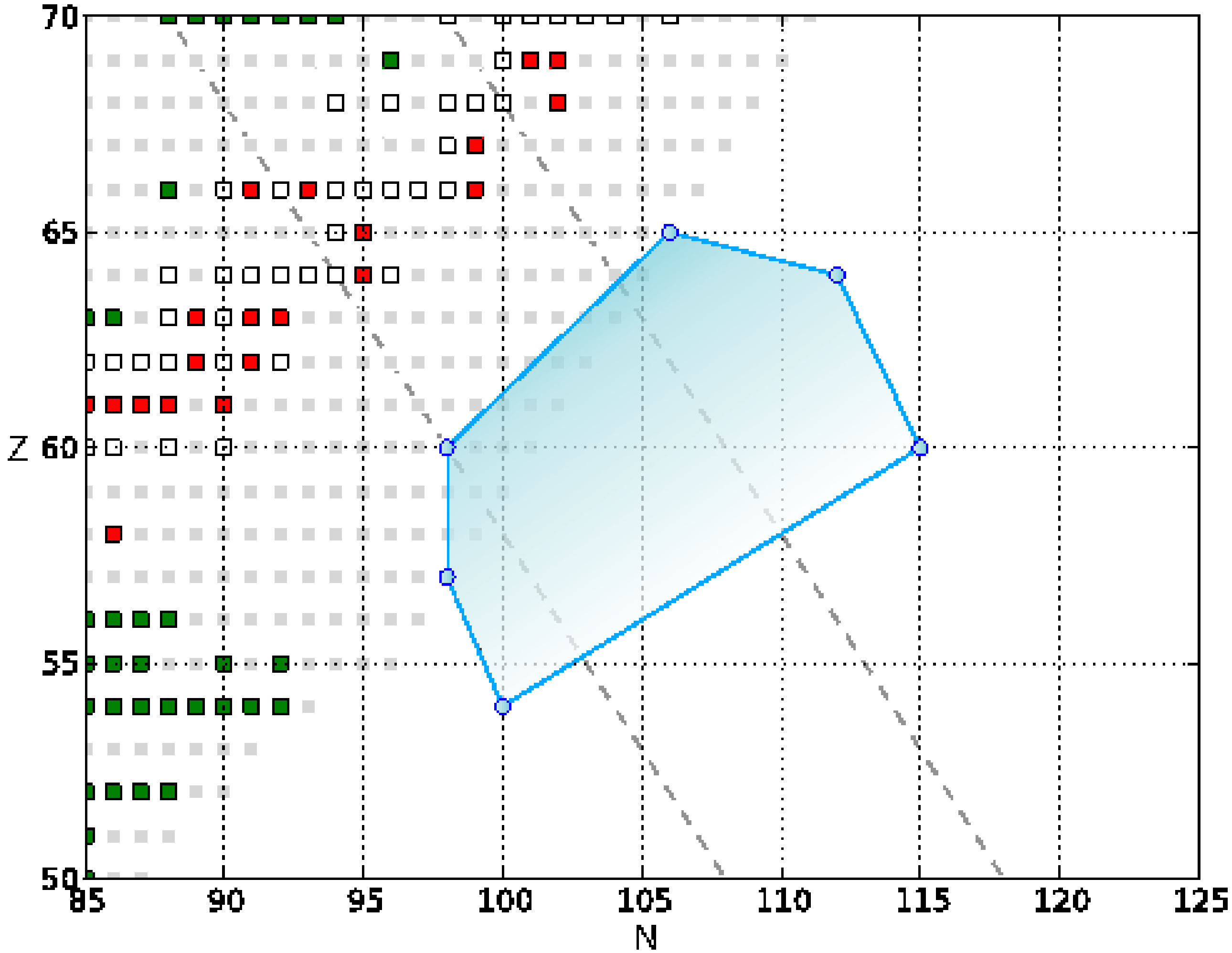
Green: measures late time neutron capture on the sides of the peak $\Delta G_{final/min}^{A=150-180} < 1$ see also Arcones and Martinez-Pinedo 2011

Constrain cooling time scale $T \sim t^{-n}$ and entropy/baryon s

Calculation with the FRDM (finite range droplet model) using $Y_e = 0.3$, $Y_e = 0.4$

Reduce nuclear physics uncertainties: Most important nuclei for the formation of the rare earth peak

Mumpower, GCM, Surman 2012



Outlook for the rare earth peak

- The rare earth peak formation is associated with stucture in the mass or capture rates
- There are large uncertainties associated with the nuclear physics inputs
- We should test our understanding of how the rare earth peak forms with measurements
- Not all astrophysical conditions produce rare earth peaks
- Tentative conclusion is that "hot" conditions are more favorable
- Need more data to make firm conclusions