Neutrino oscillations and nucleosynthesis from supernovae and black hole accretion disks

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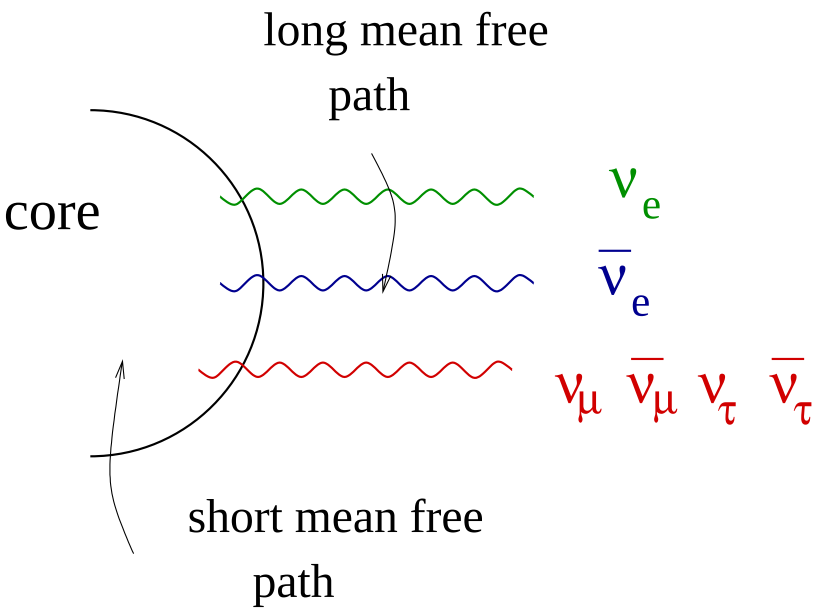
- General remarks about neutrinos from hot dense environments
- Neutrino flavor transformation
- Nucleosynthesis - winds
- The nucleosynthesis - neutrino oscillation connection

Supernova Neutrinos

All types of neutrinos emanate from the proto-neutron star core. They travel through the outer layers of the SN, then to earth.



SN neutrinos:

- may be detected
- oscillate
- nucleosynthesis
- explosion dynamics

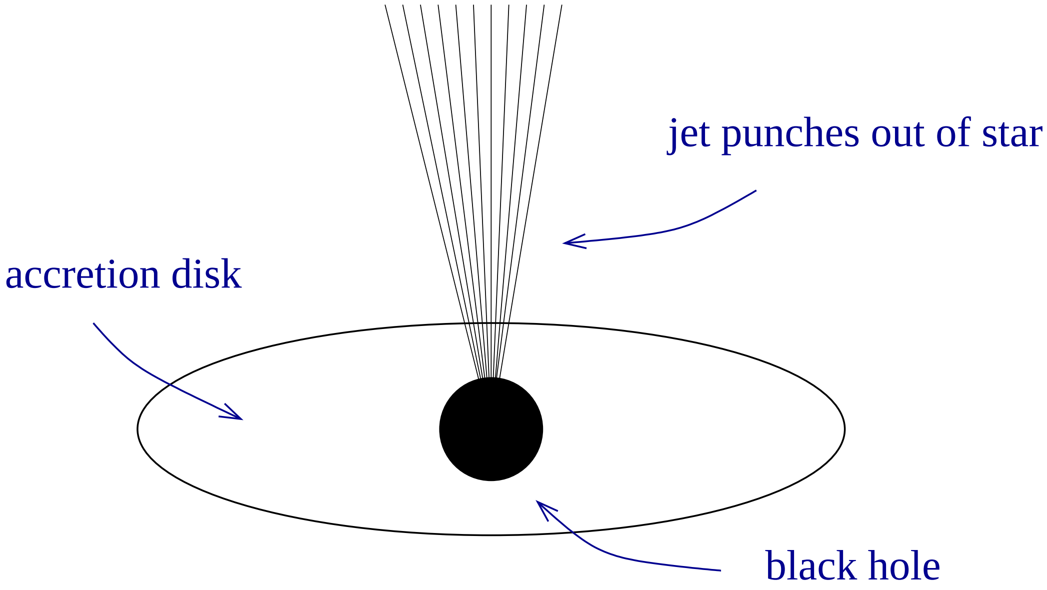
Neutrinos from Proto-Neutron Stars

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)

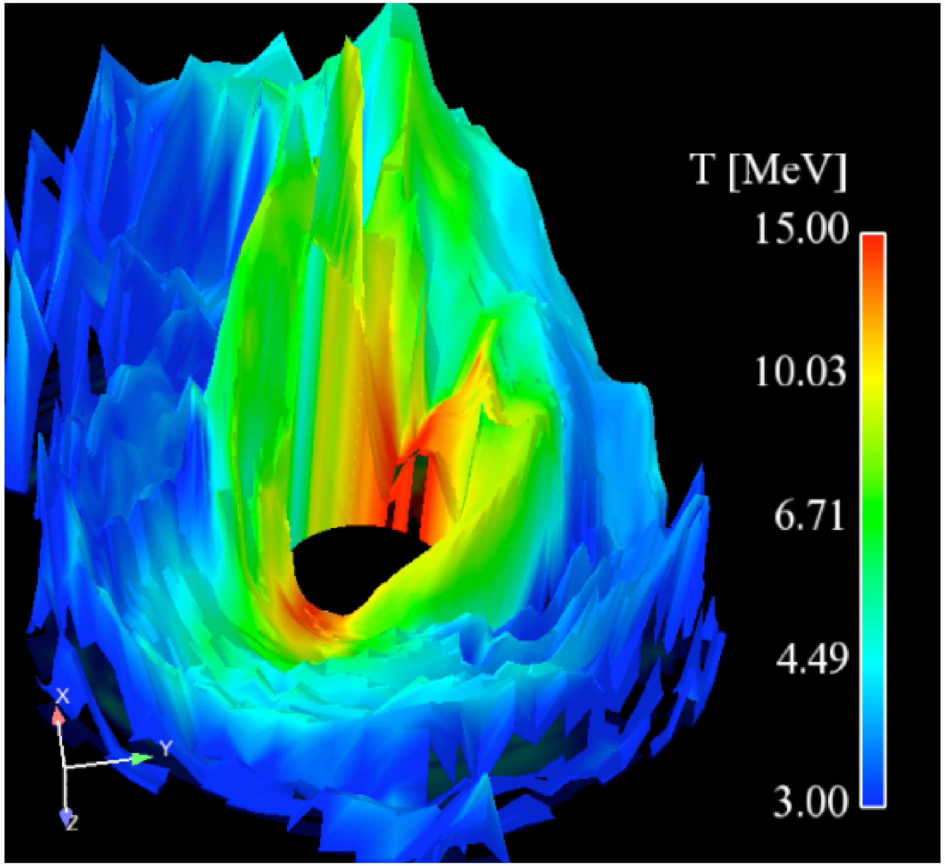
Collapsar/Hypernovae Model of Long Duration Gamma Ray Bursts

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

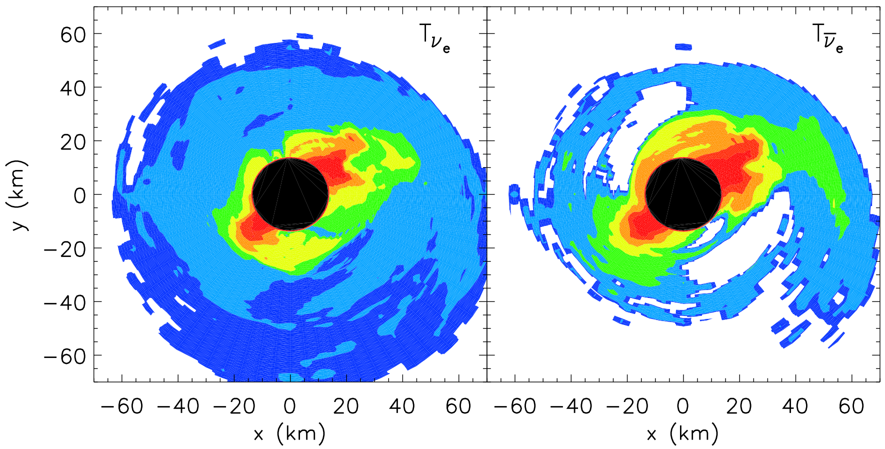


Neutrinos from the disk may provide some of the energy required to power the jet.

Accretion Disk ν_e temperatures

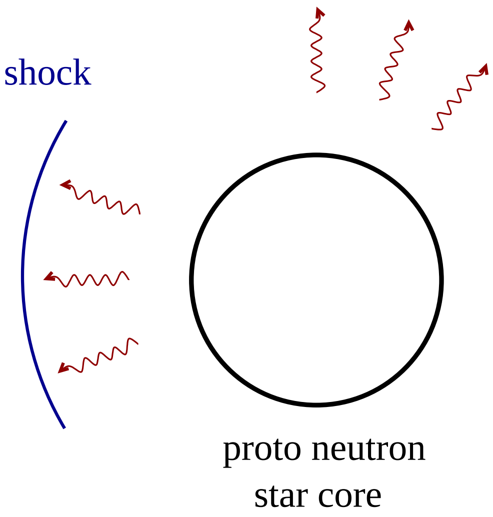


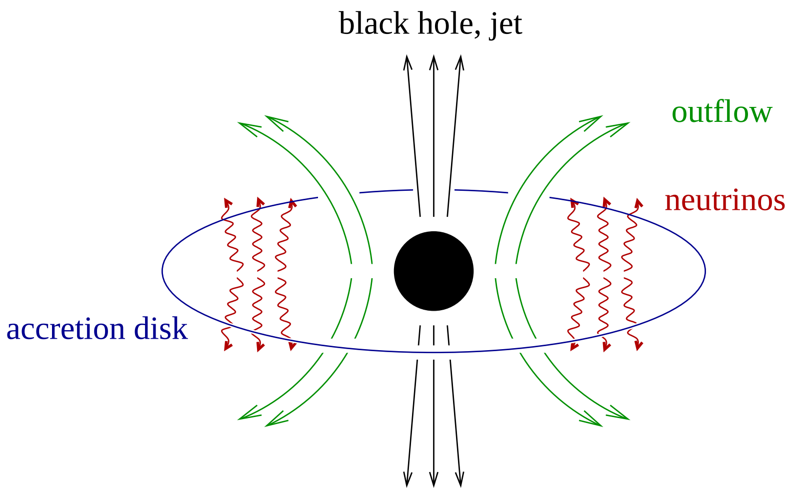
Caballero et al



Surman et al

Explosions of Massive Stars: What's happening at the Center?

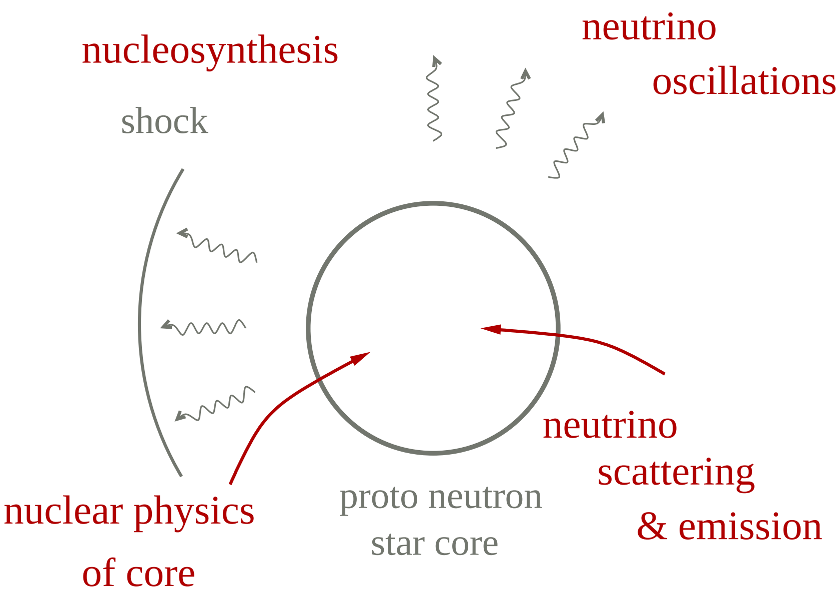


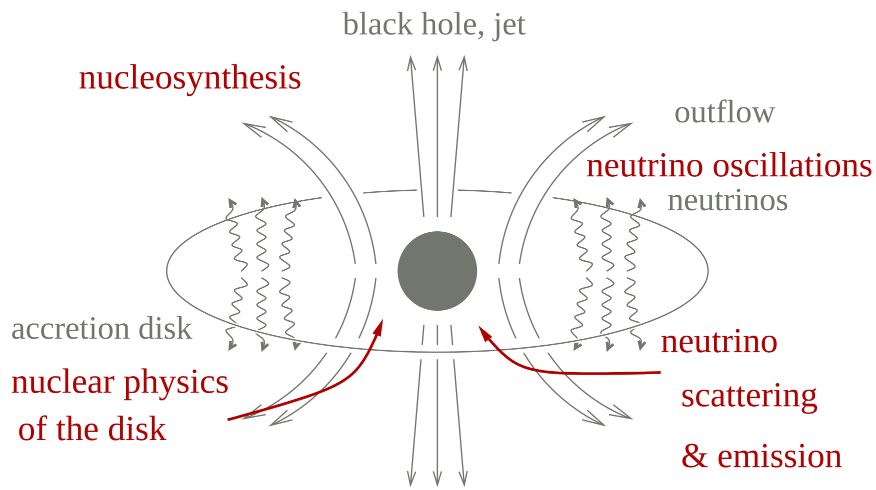


Standard core core collapse SN

accretion disk - black hole

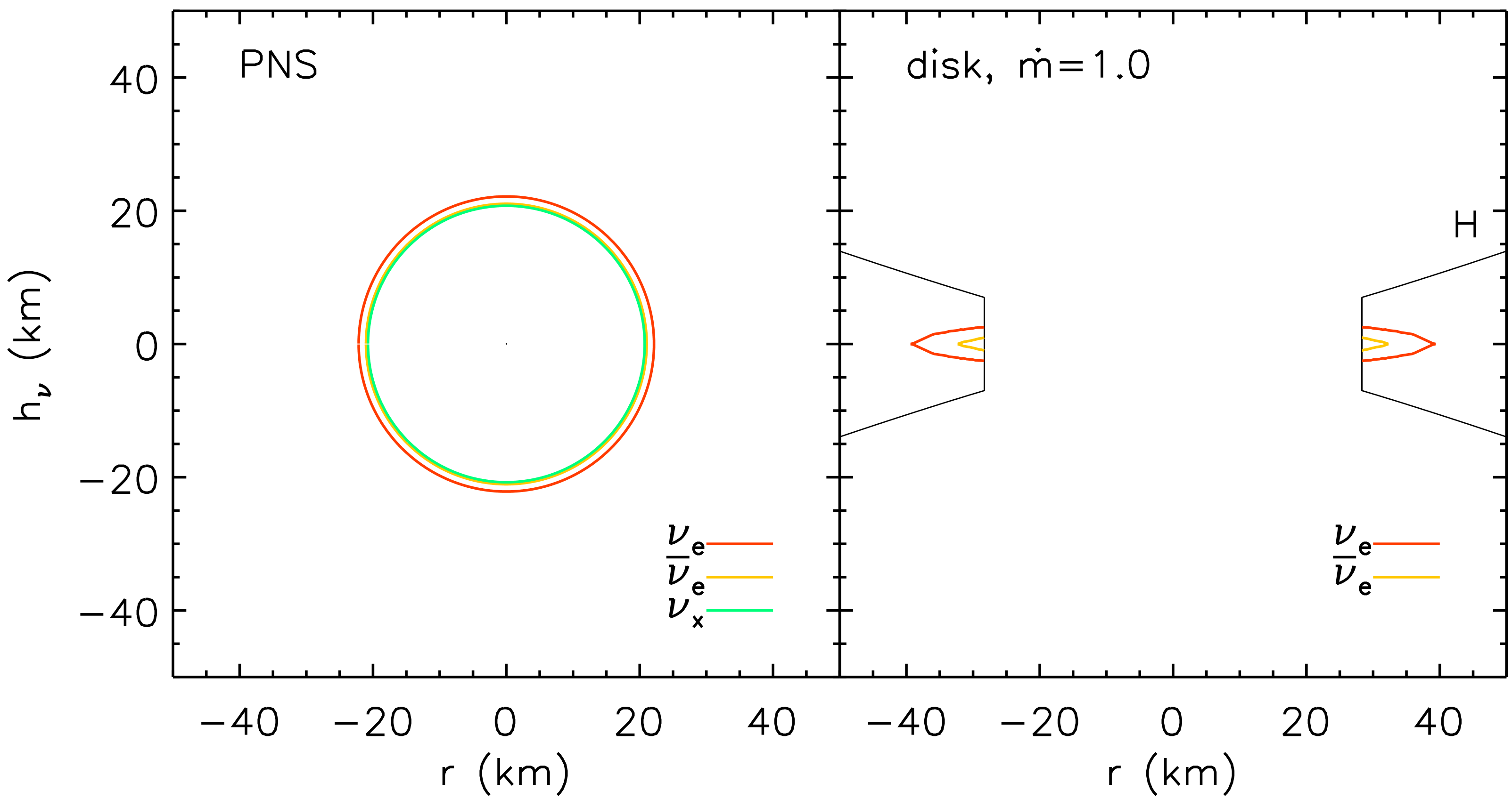
Explosions of Massive Stars:
Where is the nuclear-neutrino physics?





Standard core core collapse SN   accretion disk - black hole

Neutrino surfaces:

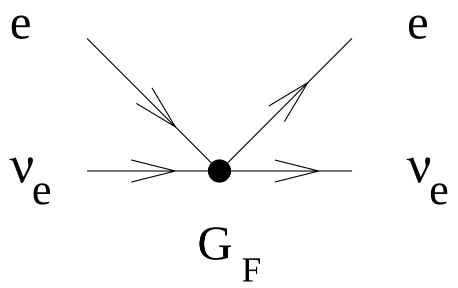


Neutrino Oscillations

After neutrinos are emitted, they undergo flavor transformation.

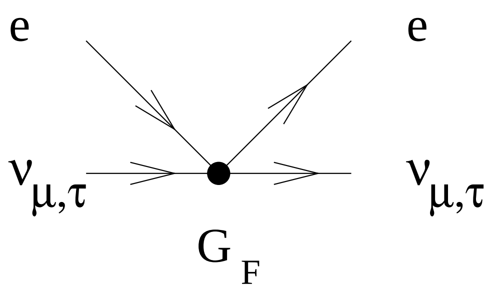
Neutrino Oscillations

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



CC+NC

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



NC

electron density $N_e(r)$

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

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 $V_\nu \propto G_F N_\nu * \mathrm{angle} - G_F N_{\bar{\nu}} * \mathrm{angle}$

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

PNS 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 $\delta m^2_{ij}/E_\nu \sim \sqrt{2} G_F N_e << V_{\nu\nu}$

Type II - nutation/bipolar

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

PNS neutrino transition regions

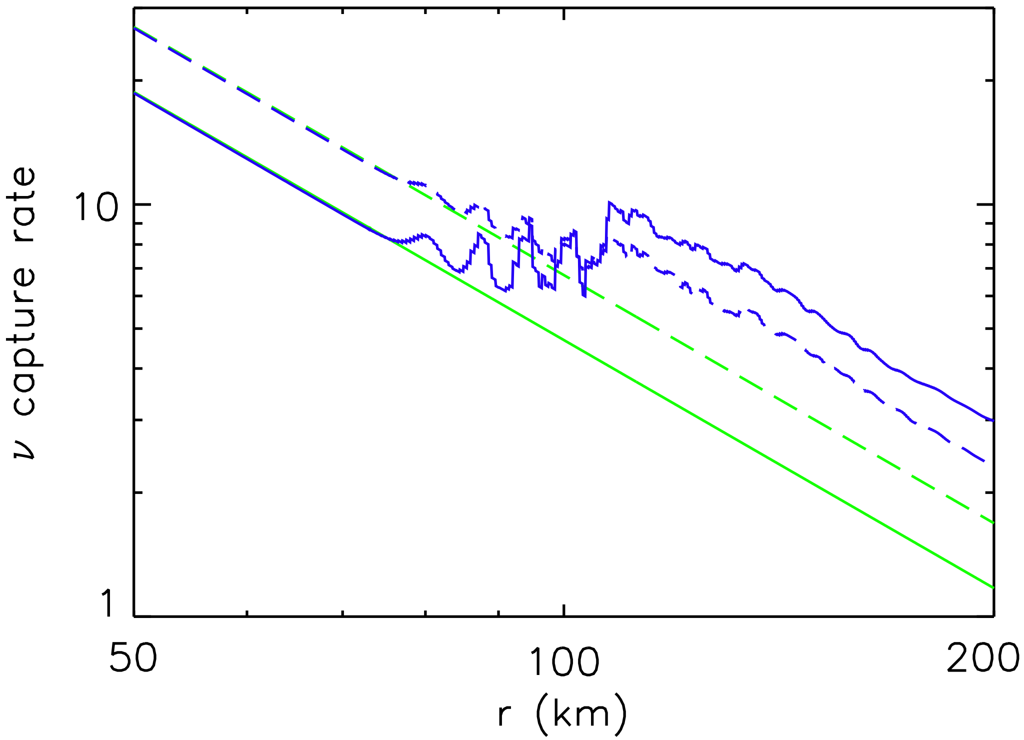
Type I - Matter enhanced region

- 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

Electron Neutrino and antineutrino capture rates



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

figure from Duan et al

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

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

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- occurs when matter potential is both large and small

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

Disks that emit ν_es and $\bar{\nu}_e$s

Vanilla Model

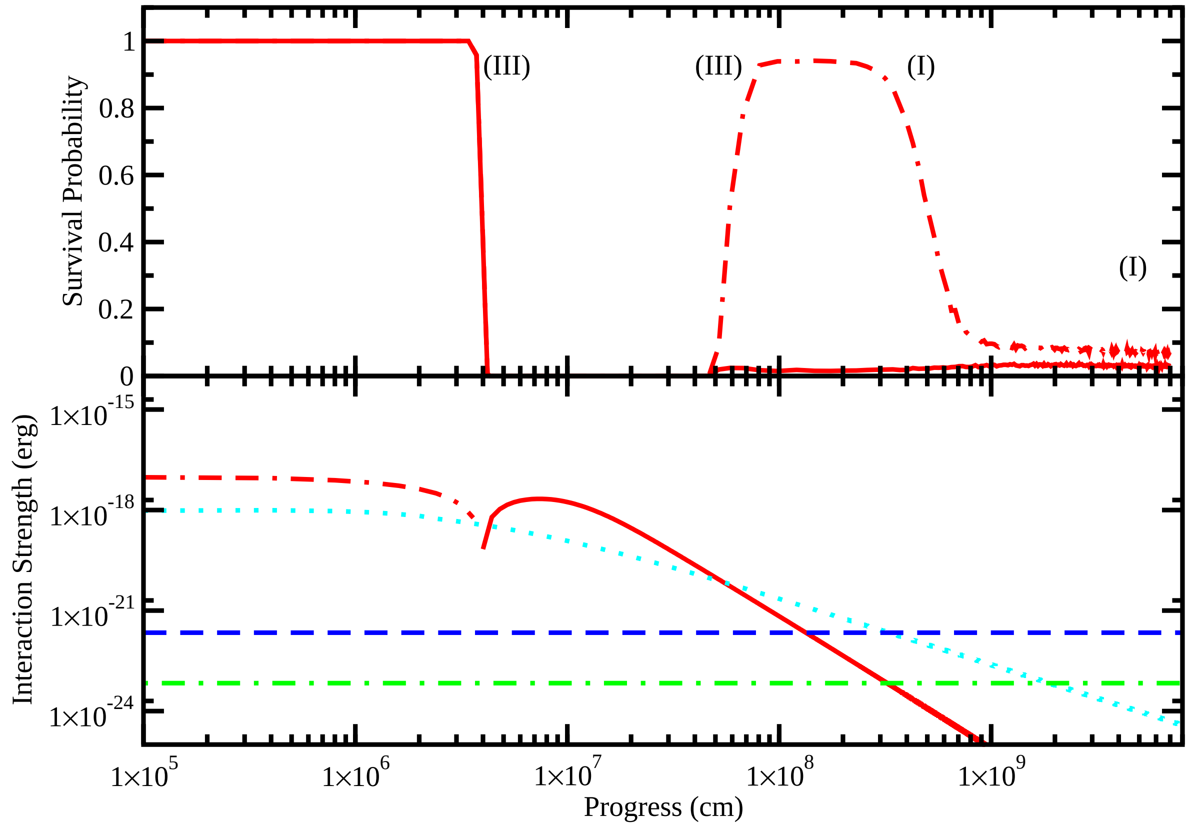
- Antineutrino flux dominates over neutrino flux near disks
- Farther away, neutrino flux dominates over antineutrino flux
- $T_{\nu_e} = 3.2$ MeV, $T_{\bar{\nu}_e} = 4.1$ Mev
- $R_{\nu_e} = 150$ km, $R_{\bar{\nu}_e} = 100$ km
- Black hole is 3 $\mathrm{M}_\odot$

Details of calculation

- "single angle" calculation
- three neutrino calculation
- disks have holes in the center
- radial trajectory

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

Model Vanilla figure from Malkus et al, in prep



Upper panel: solid red - electron neutrino survival probability

Upper panel: dashed red - electron antineutrino survival probability

Consequences for wind nucleosynthesis

The early the oscillation starts, the more important the consequences

Nucleosynthesis in Winds

Three types of environments

- proto-neutron star supernovae
- accretion disk supernovae
- compact object mergers

Three types of nucleosynthesis

- r-process
- p-process
- $^{56}\mathrm{Ni}$ - an ingredient in light curves

Nucleosynthesis in Hot Outflows

n,p $\rightarrow {}^4\mathrm{He} \rightarrow$ iron peak nuclei $\rightarrow$ heavier nuclei

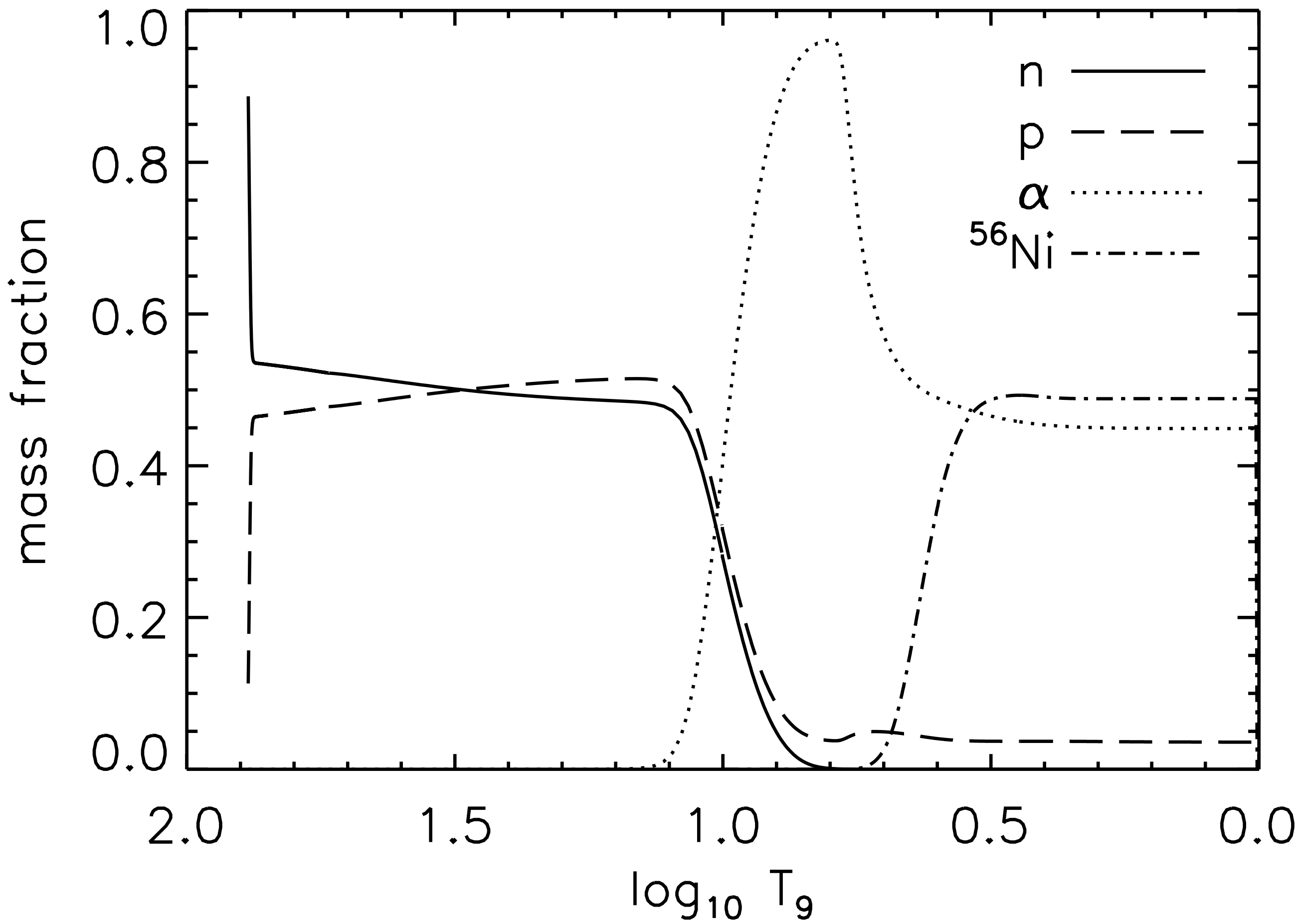


Figure from Surman et al

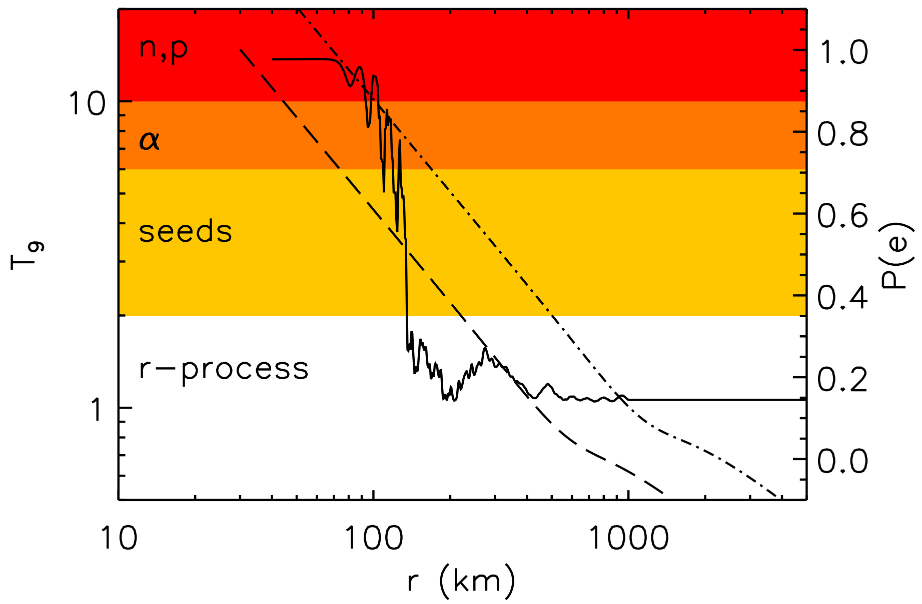
Nucleosynthesis in hot outflows

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

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

Neutrino Flavor Transformation in Winds

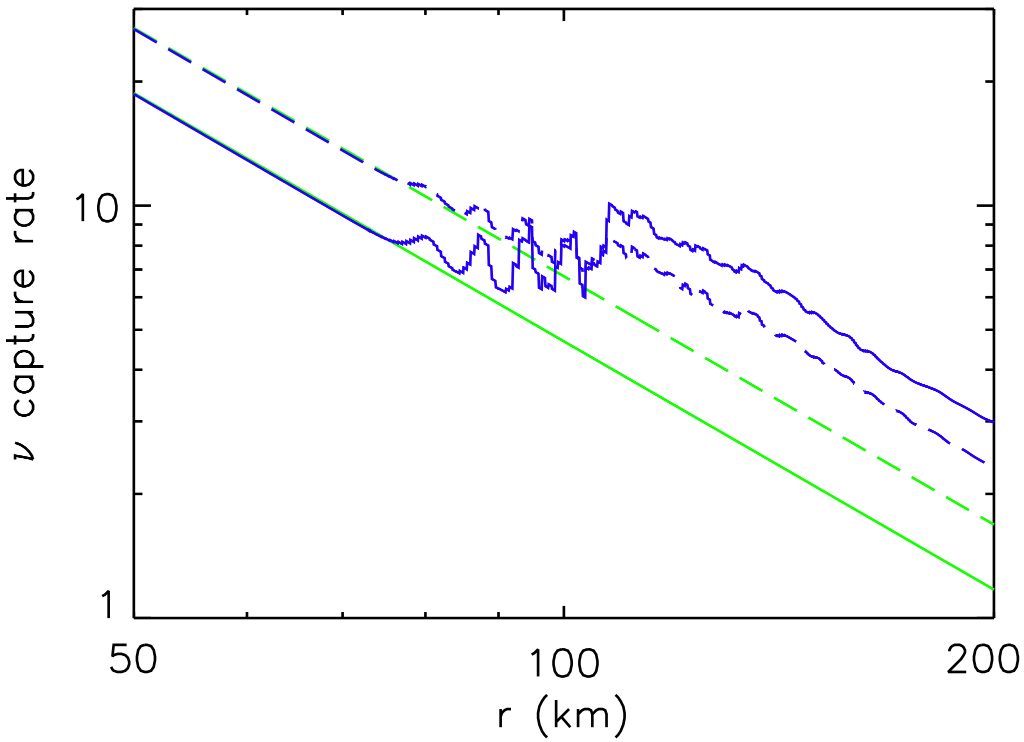
Where does the oscillation start? Figure from Duan et al



- stages of nucleosynthesis are shown
- $\mathrm{E}_{\nu_e} < \mathrm{E}_{\nu_x}$
- oscillation often moves material toward $Y_e = 0.5$

Electron neutrino and antineutrino capture rates

Recall the effect of oscillations on SN-like neutrinos Duan et al



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

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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

Neutrino Flavor Transformation + Nucleosynthesis

Supernovae Neutrinos

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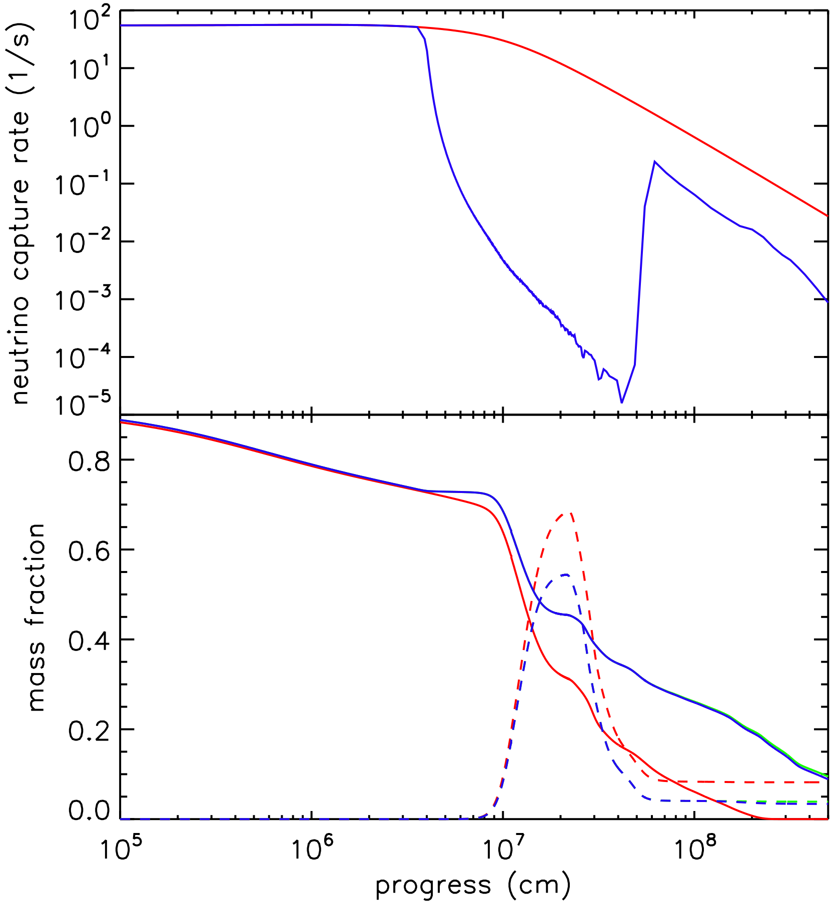
Accretion disk neutrinos

- 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 neutrino capture rate, mass fractions



red - without oscillations

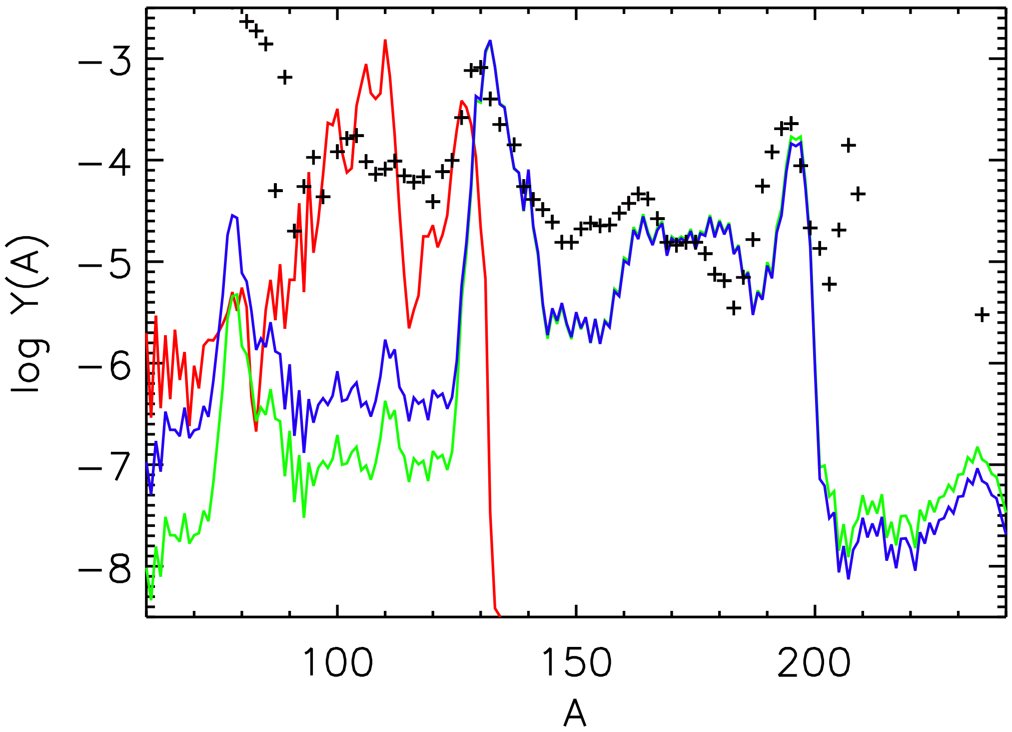
blue - with oscillations

upper panel: ν_e capture

lower panel: fract. of n, α

figure from Malkus et al, in prep

Accretion Disk Nucleosynthesis



red - no oscillations, blue - oscillations

s/k = 50, $\beta = 1.4$ (moderate acceleration) figure from Malkus et al, in prep

Conclusions

- Disks which are always ν_e dominated 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