Neutrinos and the synthesis of heavy elements

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CGS15

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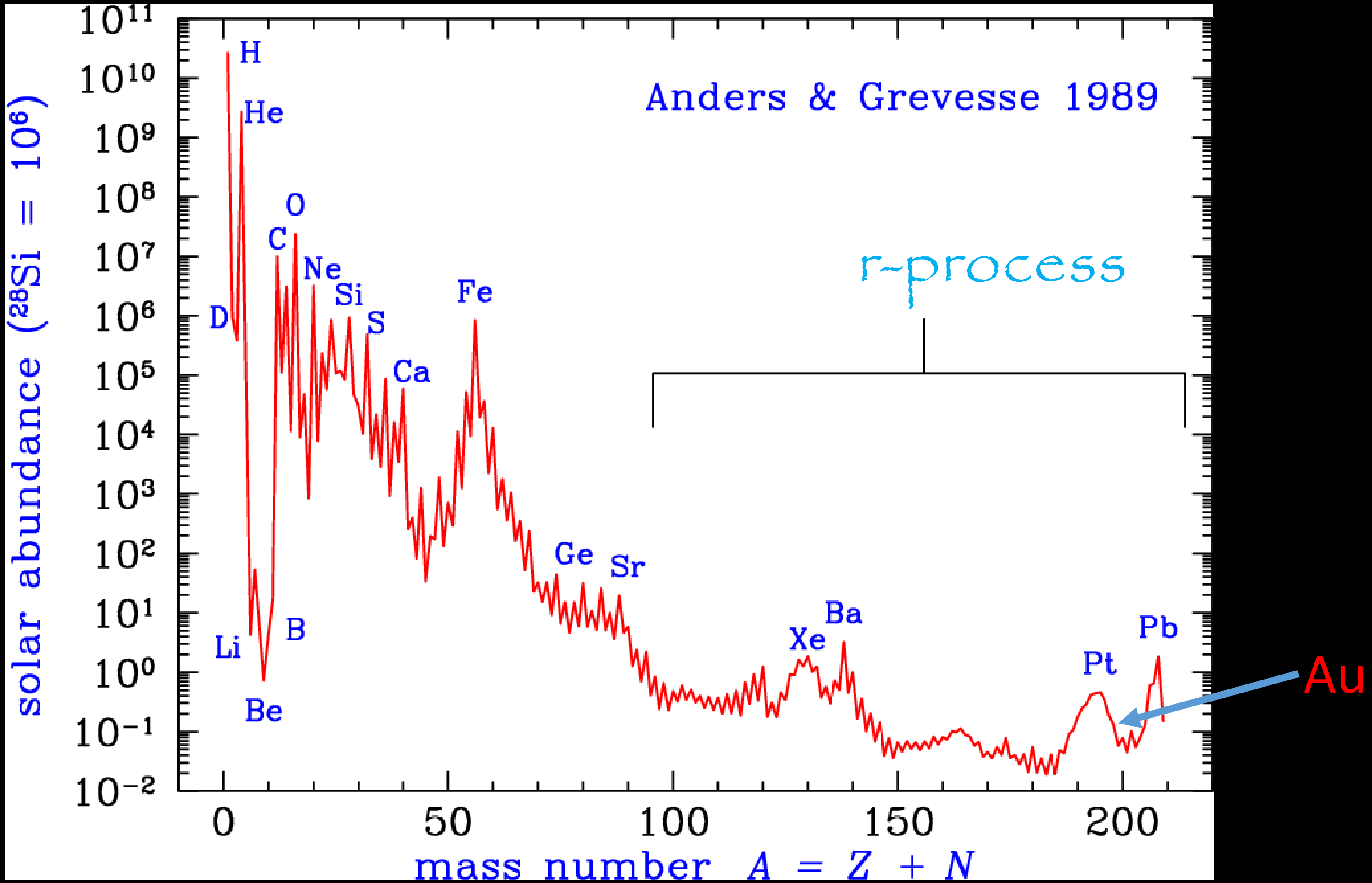
What do we need to make Gold?

Observations

Astrophysics: Sites

Nuclear Physics: Theory and Experiment

Observations

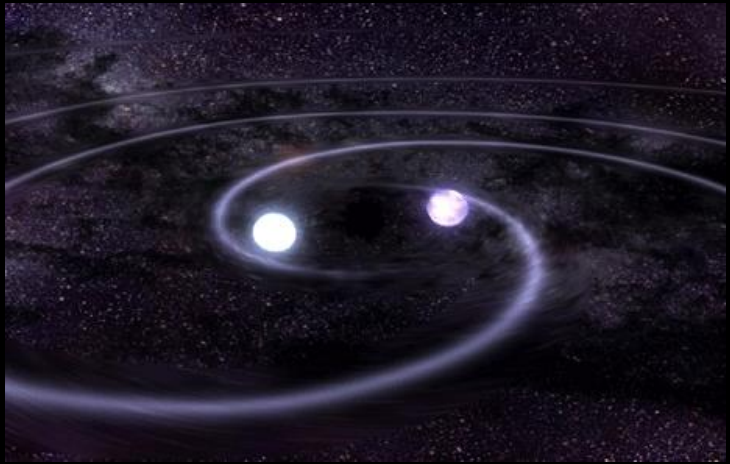


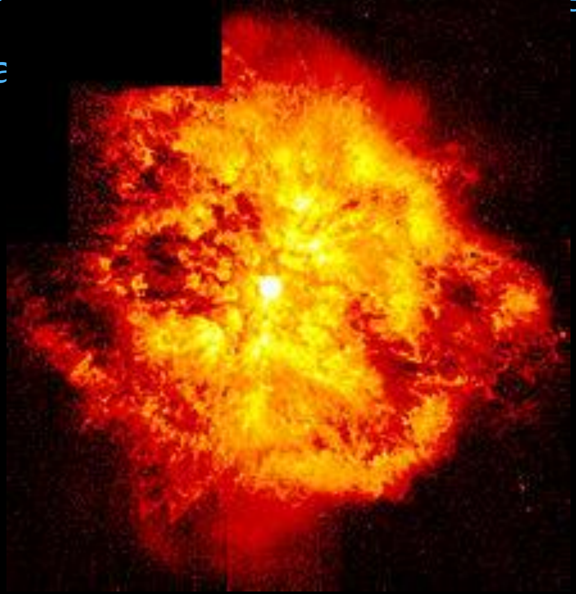
Where and how are heavy elements produced in the Universe?

Astrophysics: Sites

Mergers: Neutron star- Neutron star (NS-NS), Black Hole –Neutron Star (BH- NS)

- Decompression of cold NS matter (Lattimer et al 1974, Freiburghaus et al 1999, Metzger et al 2010)
- Hot matter ejected from accretion disk (e.g Surman et al 2008 , Wanajo & Ja





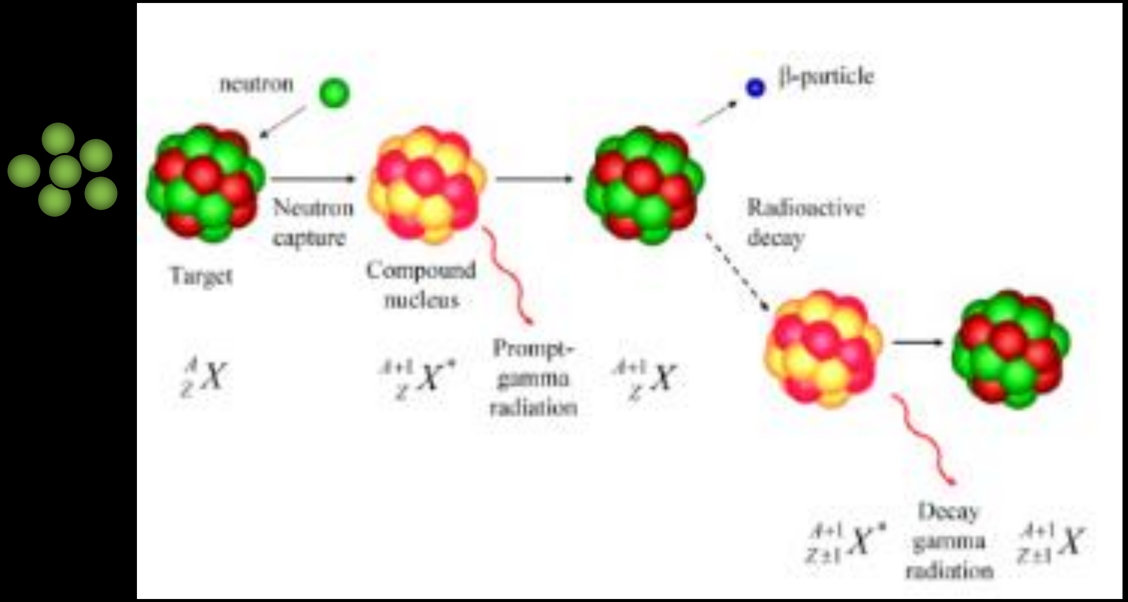
Supernovae

Neutrino-driven winds

Nuclear Physics : r-process nucleosynthesis

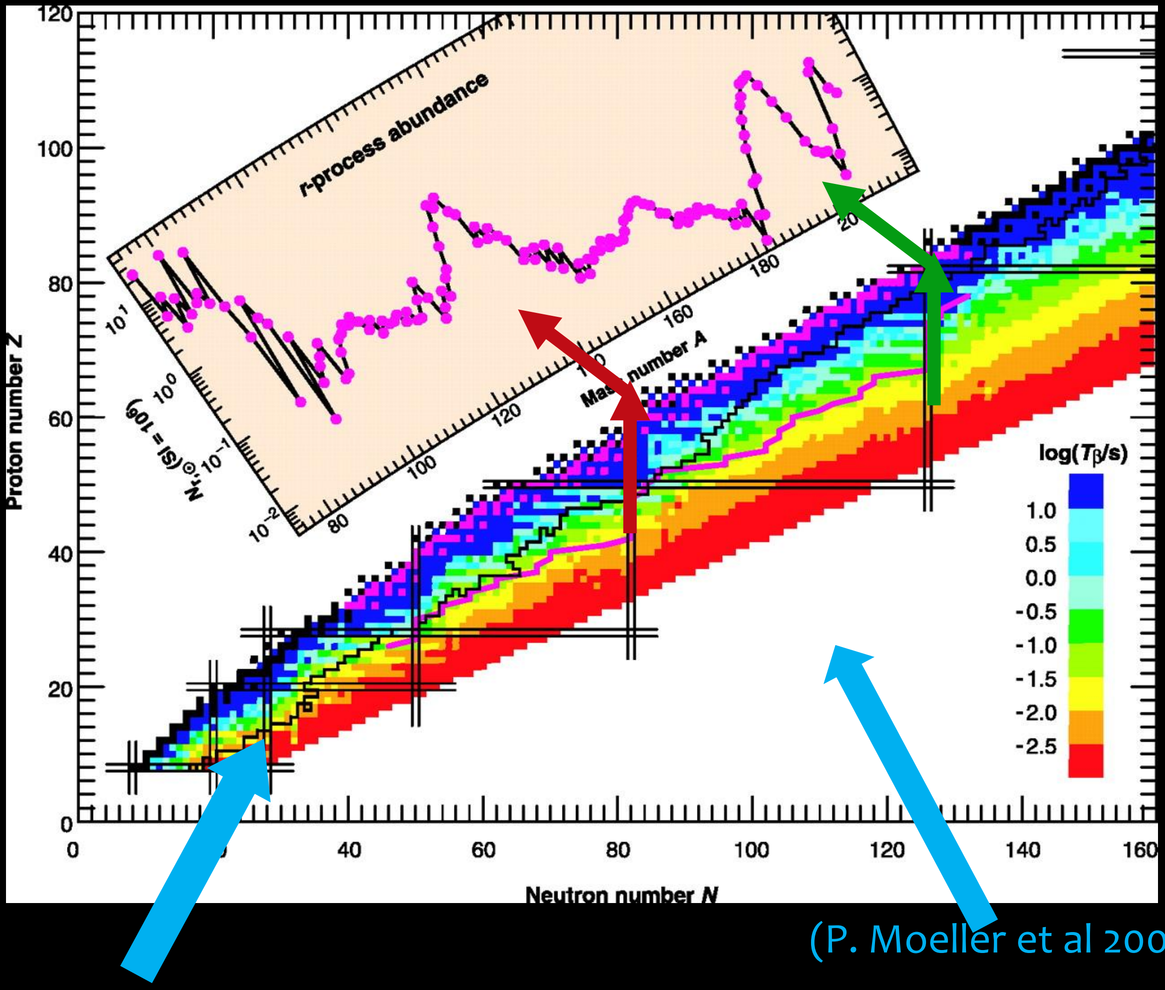
$$^{A}_{Z}X + n \leftrightarrow {}^{A+1}_{Z+1}X + \bar{\nu}_e + e + \gamma$$

neutron capture rate is larger than beta emission rate



The r-process path

$$Y_e = \frac{1}{1+{}^{n}/_{p}}$$



(P. Moeller et al 2003)

Neutrinos set the electron fraction Y_e

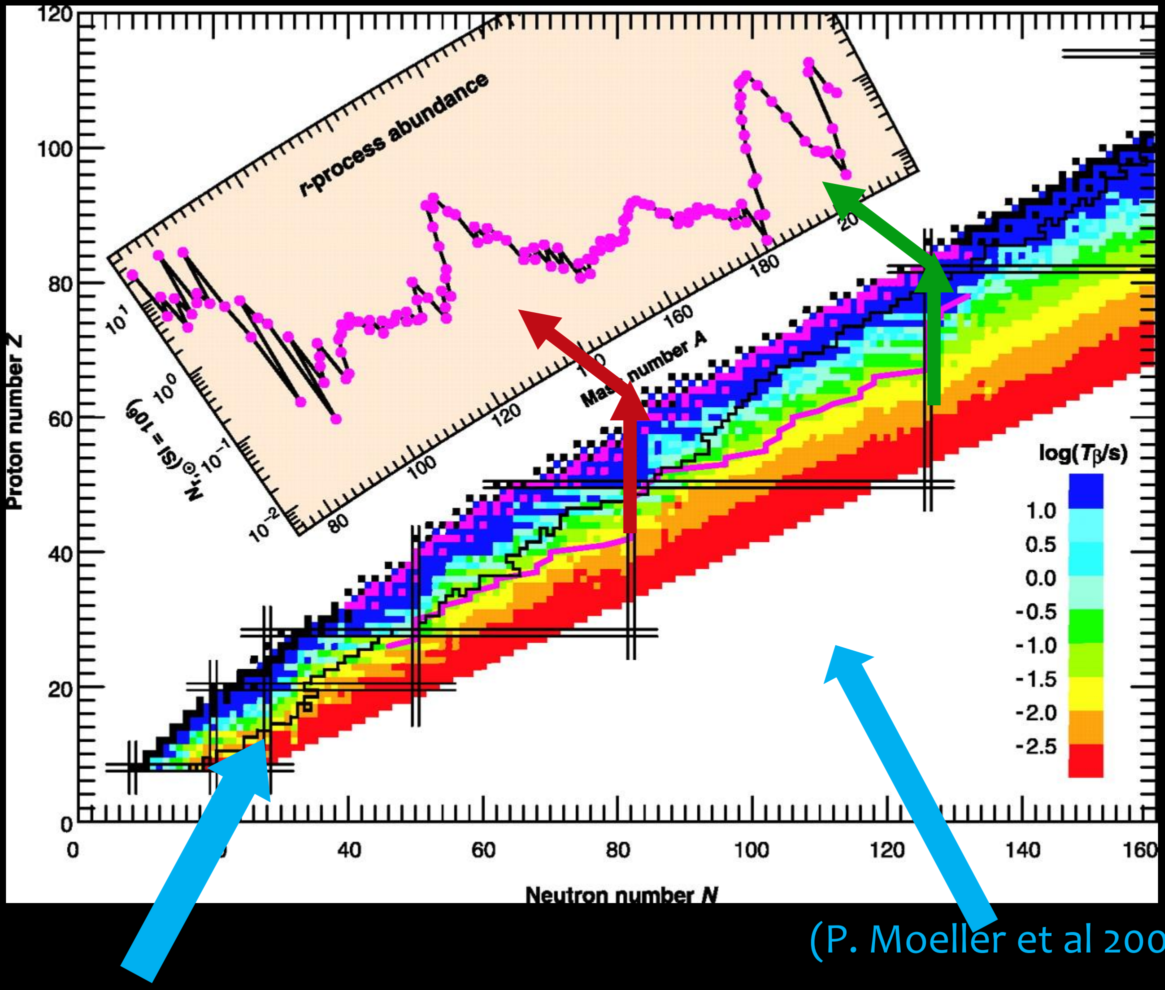
Neutron captures and beta decays determine the flow of matter

The r-process path

Proton rich

$Y_e = 0.5$

Neutron rich



(P. Moeller et al 2003)

Neutrinos set the electron fraction Y_e

Neutron captures and beta decays determine the flow of matter

Nuclear Physics Input

- Neutrino interactions ⬅
- Mass model
- Charge particle reactions
- Neutron captures
- Photodissociation
- Beta decay
- Alpha decay
- Fission
- Beta-delayed neutron emission

Neutrino Spectra

Neutrinos set the electron fraction

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

$$\nu_e + n \leftrightarrow e + p$$

Rates depend on effective fluxes ϕ^{eff}

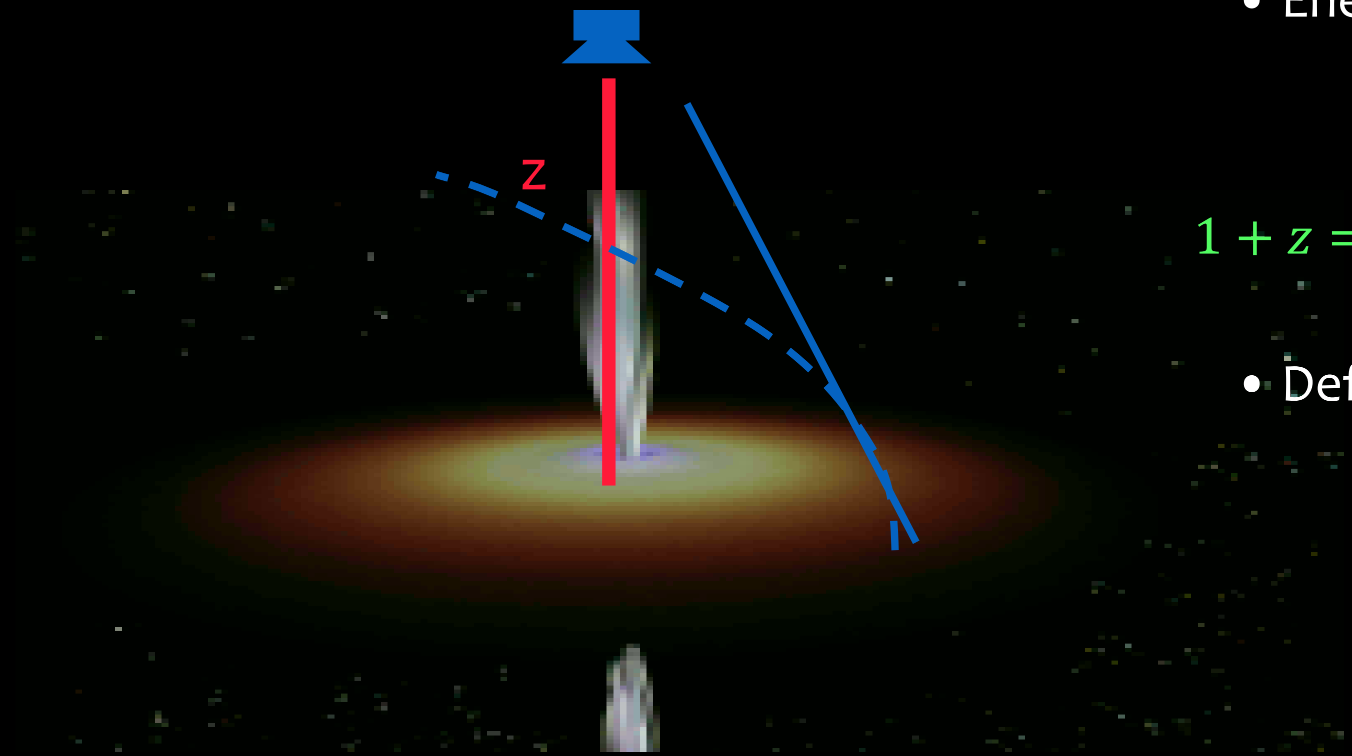
During mergers and supernovae, neutrinos are copiously produced. Spectra can be modified by e.g.

- Reactions with the medium
- Neutrino oscillations
- General relativistic effects

Neutrino flux under the influence of strong gravitational fields

$$\phi^{eff} = \frac{1}{4\pi}\int d\Omega_{ob}\phi_{ob}(E_{ob})$$

$$\phi_{ob}(E_{ob}) = \frac{g_\nu c}{2\pi^2(\hbar c)^3}\frac{E_{ob}^2}{\exp\left({}^{E_{ob}}/_{T_{ob}}\right)+1}$$



- Energy is red-shifted Eob

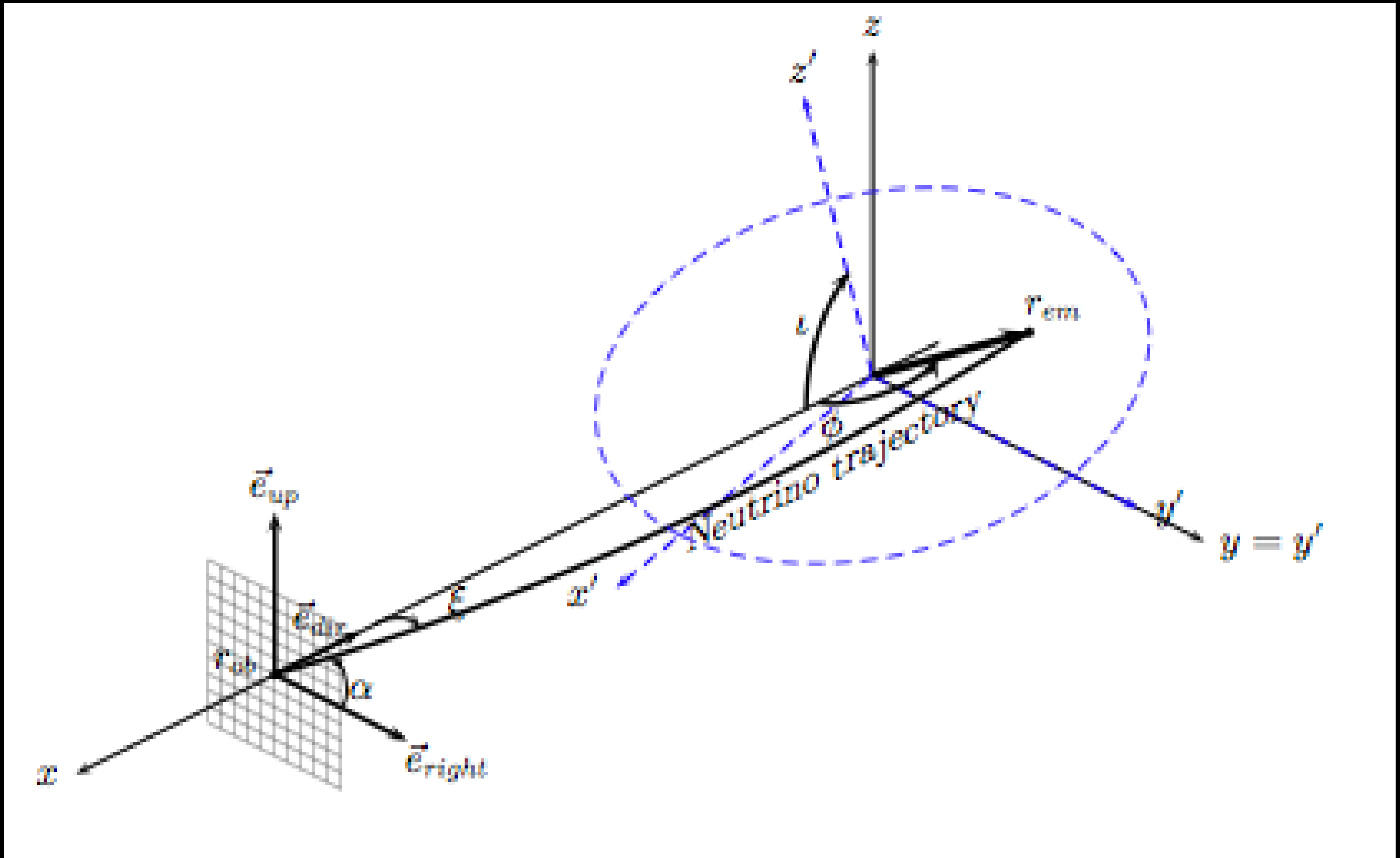
$$E_{em} = (1+z)E_{ob}$$

$$1+z = \frac{(p_t u^t + p_r u^r + p_\theta u^\theta + p_\varphi u^\varphi)_{em}}{(p_t u^t + p_r u^r + p_\theta u^\theta + p_\varphi u^\varphi)_{ob}}$$

- Deflection of trajectories

$$d\Omega_{ob} = \sin\xi\, d\xi d\alpha$$

General Relativistic effects: Null Geodesics



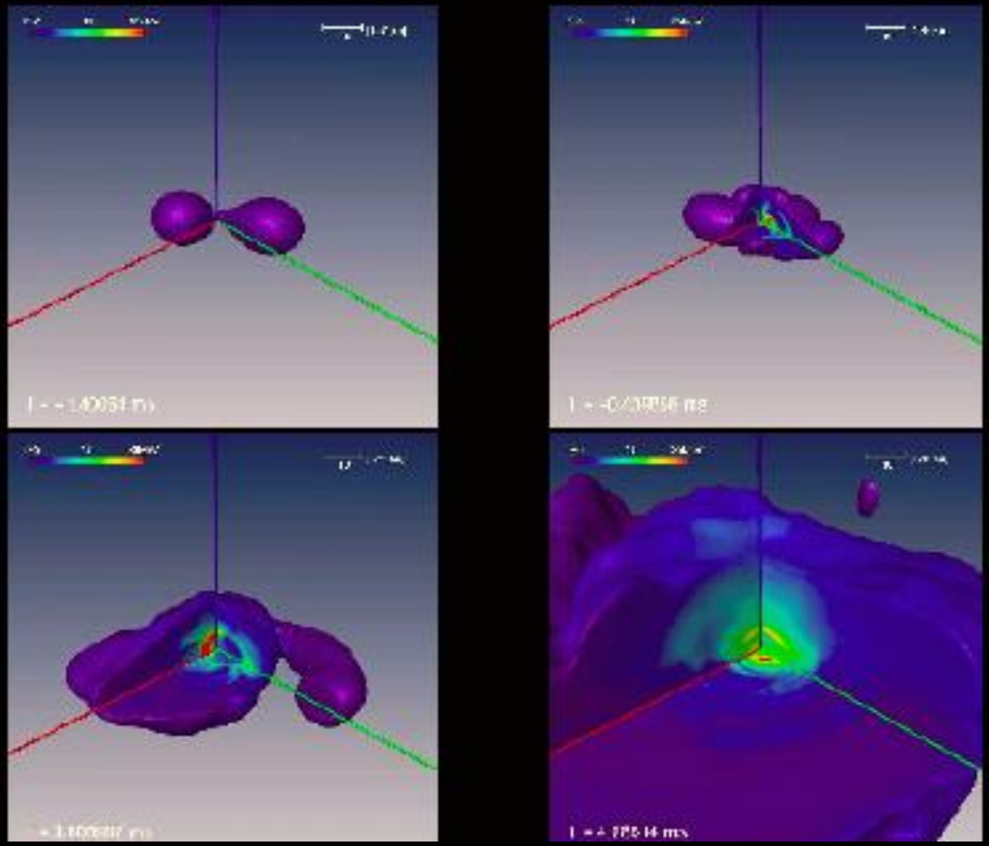
Schwarzschild metric

$$b = \frac{r \sin \xi}{\sqrt{1 - {r_s}/{r}}} \qquad \int_{\varphi_{em}}^{\varphi_{ob}} d\varphi = \pm \int_{r_{em}}^{r_{ob}} \frac{dr}{r\sqrt{\frac{r^2}{b^2} - \left(1 - \frac{r_s}{r}\right)}}$$

Accretion disk neutrinos

Mergers: Accretion Disk (AD) Model

BH=2.5 solar masses, NS= 1.6 solar masses
Hydrodynamics including GW & neutrino emission, M. Ruffert, H. Janka (2001)



Neutrino Surface

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

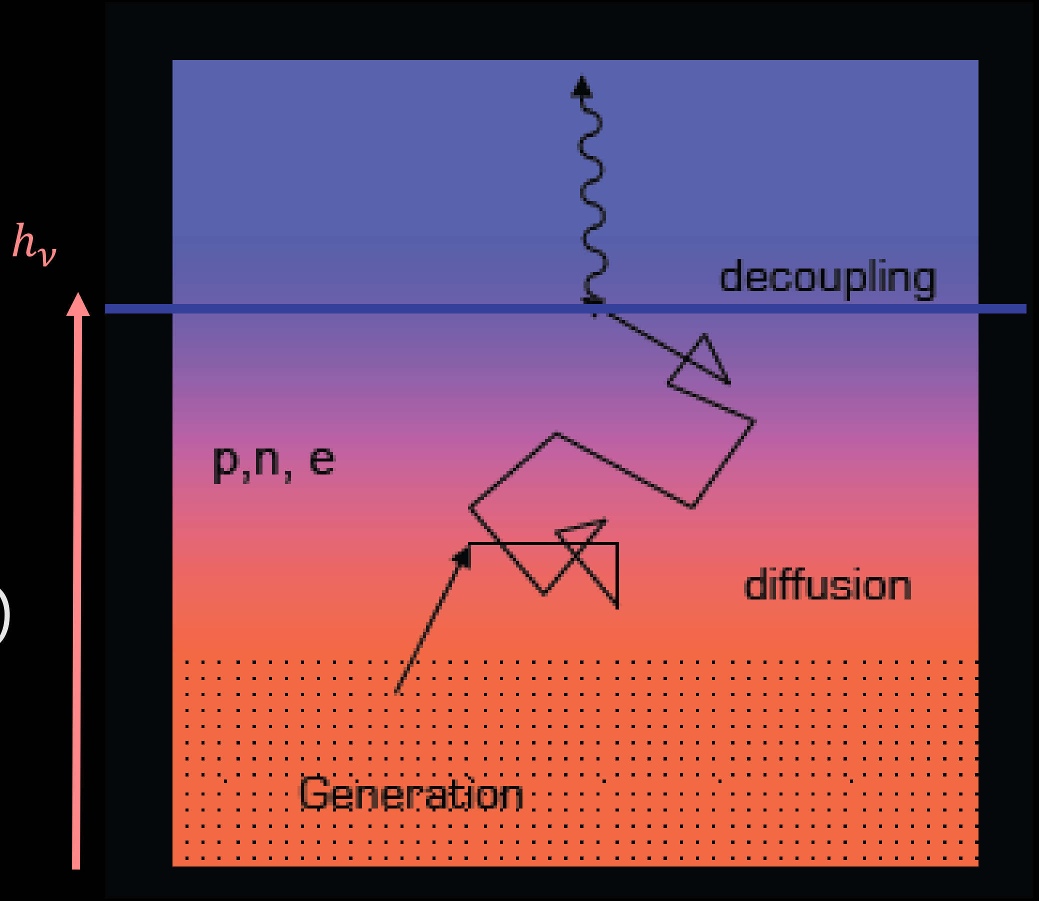
Charged Current

$$\nu + \bar{\nu} \rightarrow e + e^+$$

$$\nu + n \rightarrow \nu + n$$
$$\nu + p \rightarrow \nu + p$$
$$\nu + e \rightarrow \nu + e$$

Neutral Current

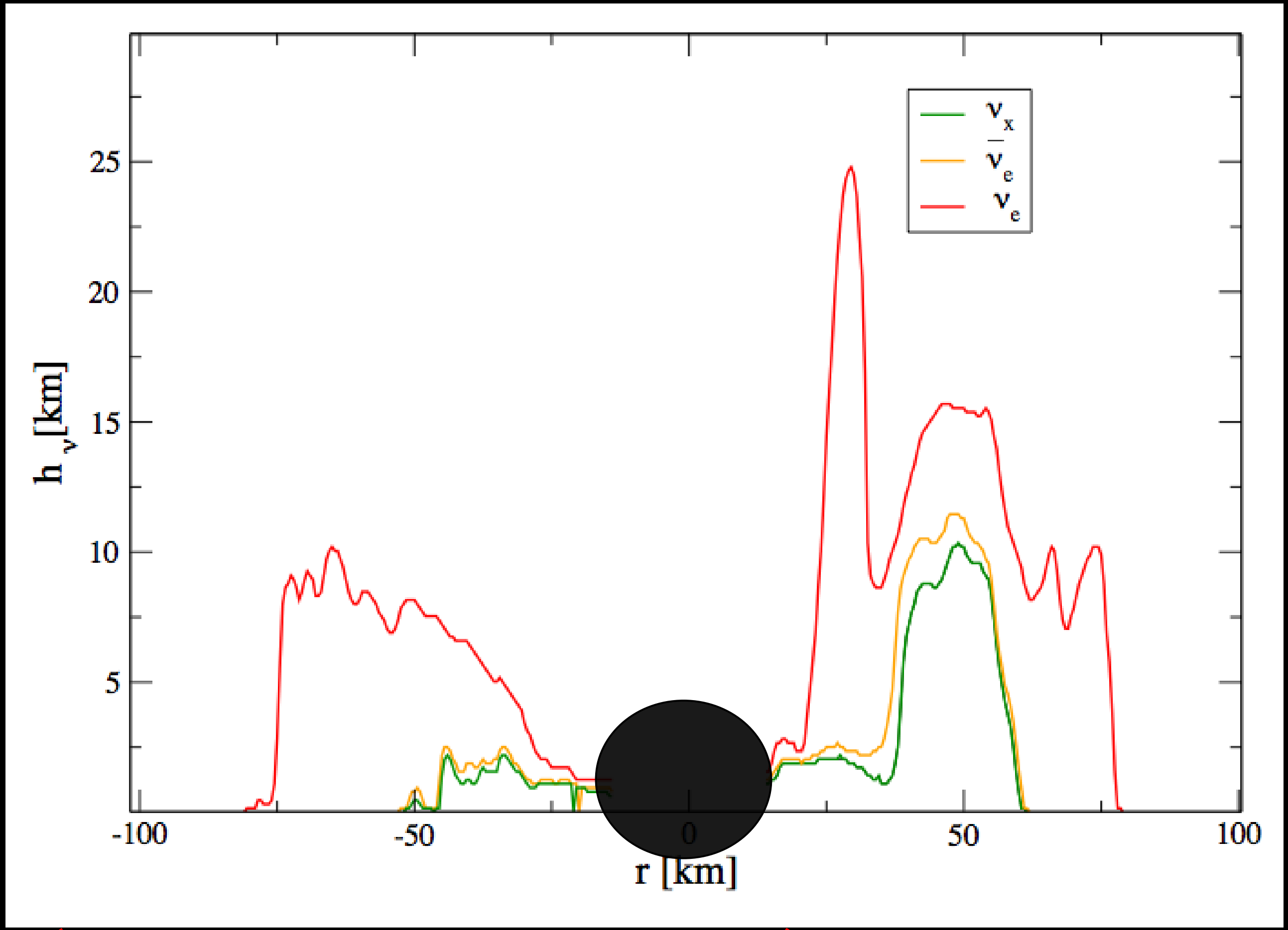
(All flavors)



Accretion Disk Neutrino Surface

BH=2.5 solar masses, NS= 1.6 solar masses
BH-NS merger: 3D hydrodynamical simulation, M. Ruffert, H. –Th. Janka (2001)

Electron neutrinos decouple later at smaller temperatures and densities



(Caballero, McLaughlin and Surman 2009)

Neutrino surface defines the neutrino decoupling Temperature T_ν

Accretion Disk Neutrino Surface

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BH-NS merger: 3D hydrodynamical simulation, M. Ruffert, H. –Th. Janka (2001)

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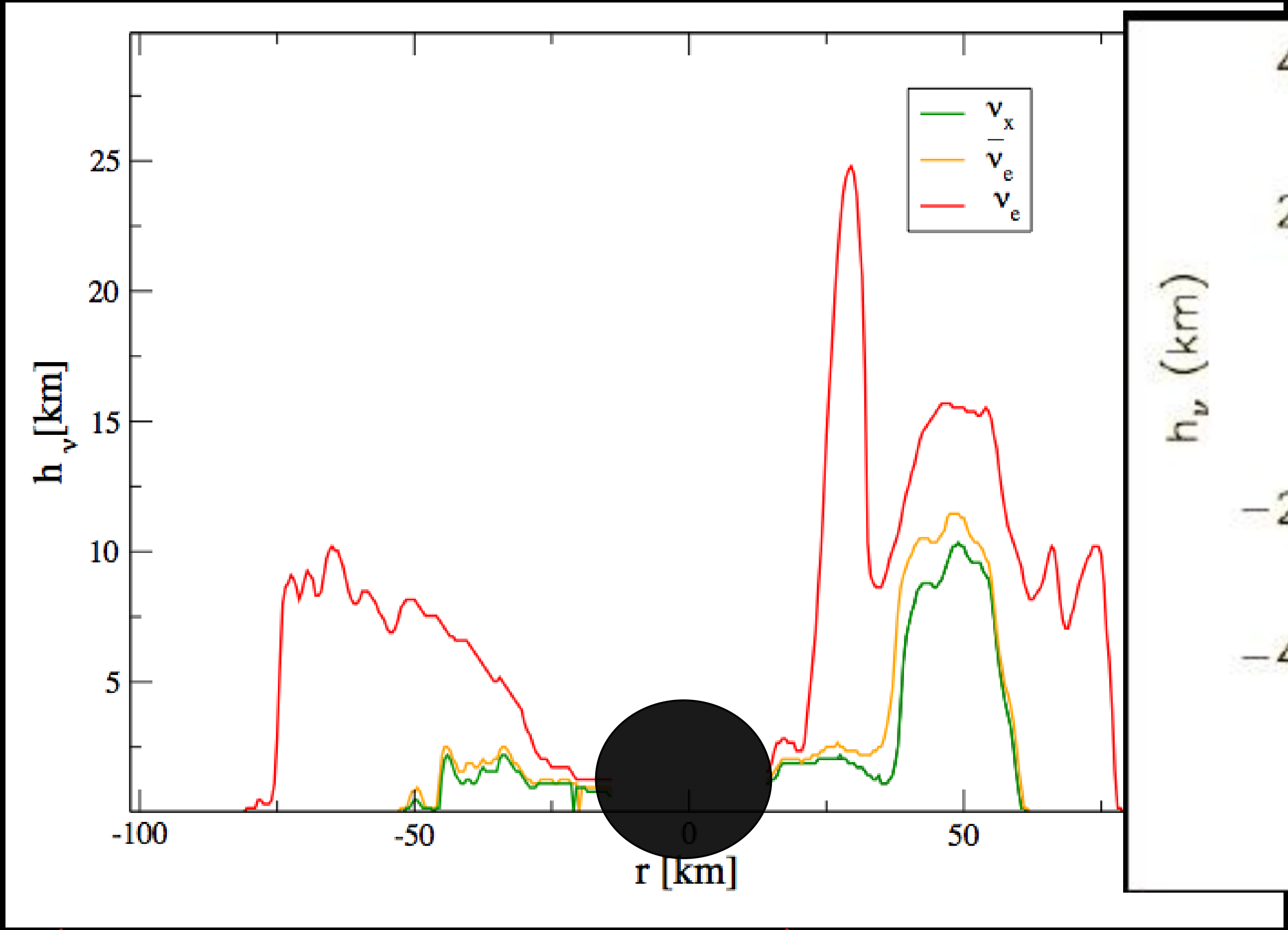
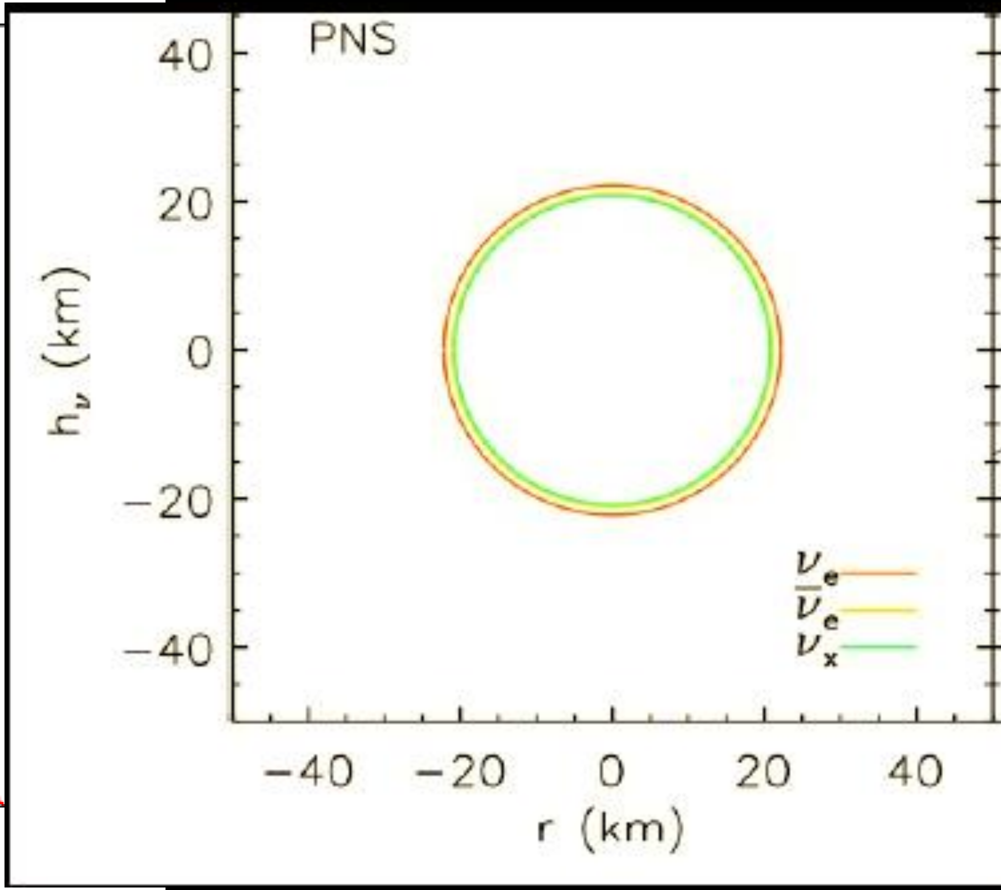


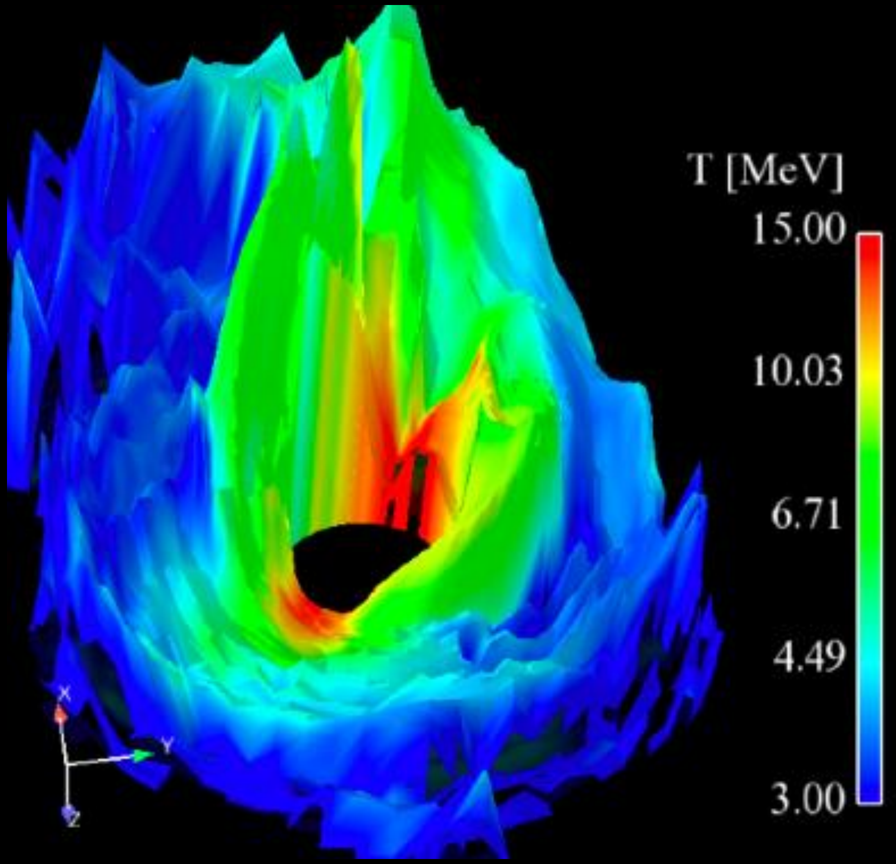
(Caballero, McLaughlin and Surman 2009)

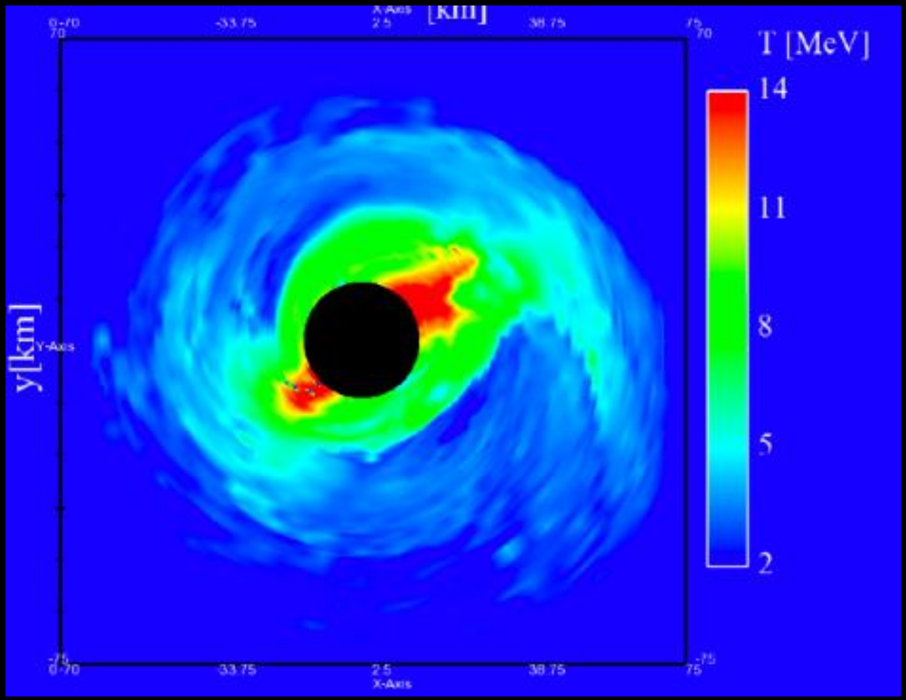


McLaughlin, Surman (2007)

Neutrino surface defines the neutrino decoupling Temperature T_ν

Electron antineutrino surface

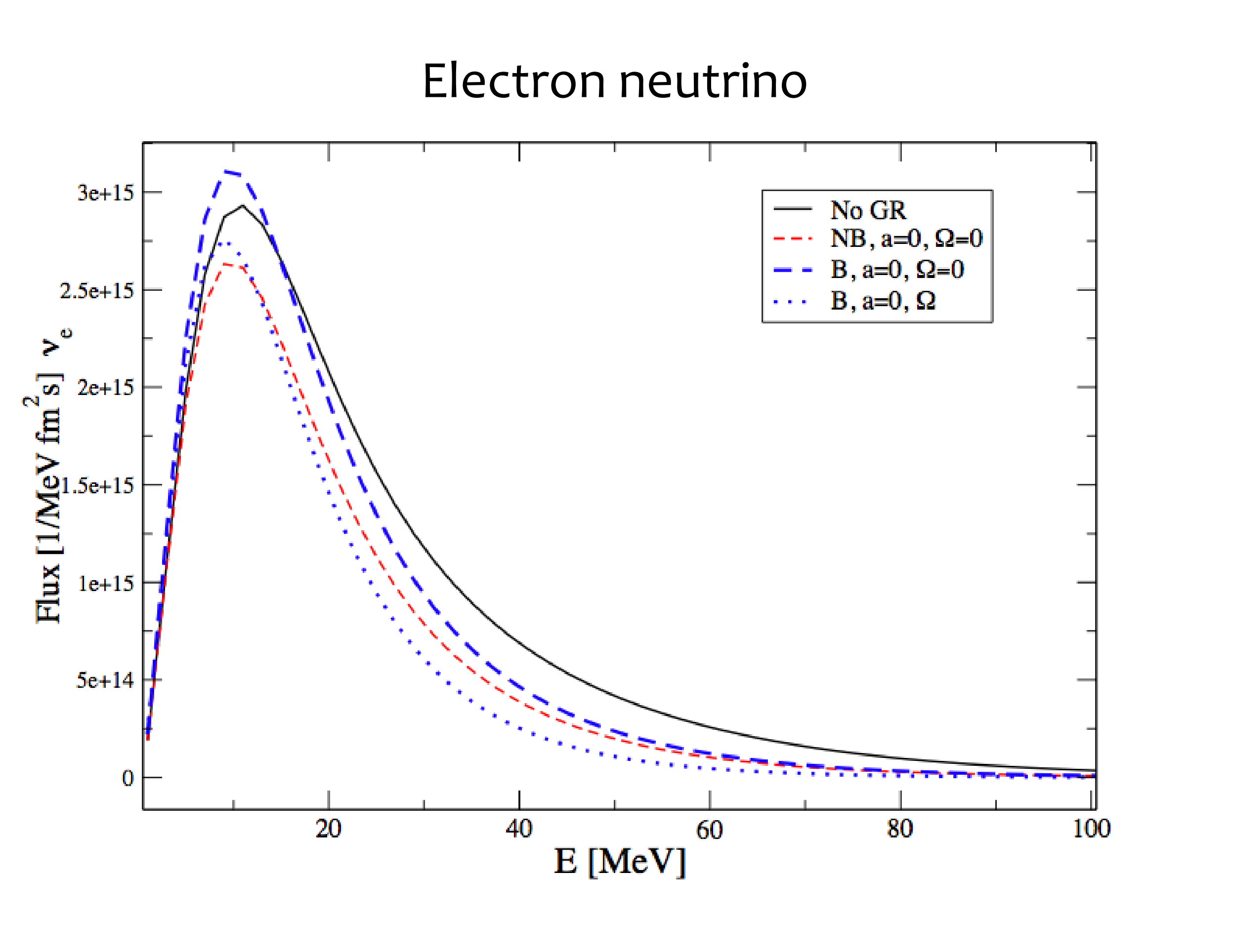




3D hydrodynamical merger simulation

General relativistic effects: Neutrino Flux

Observer at r = 64 km, φ=0, θ=52



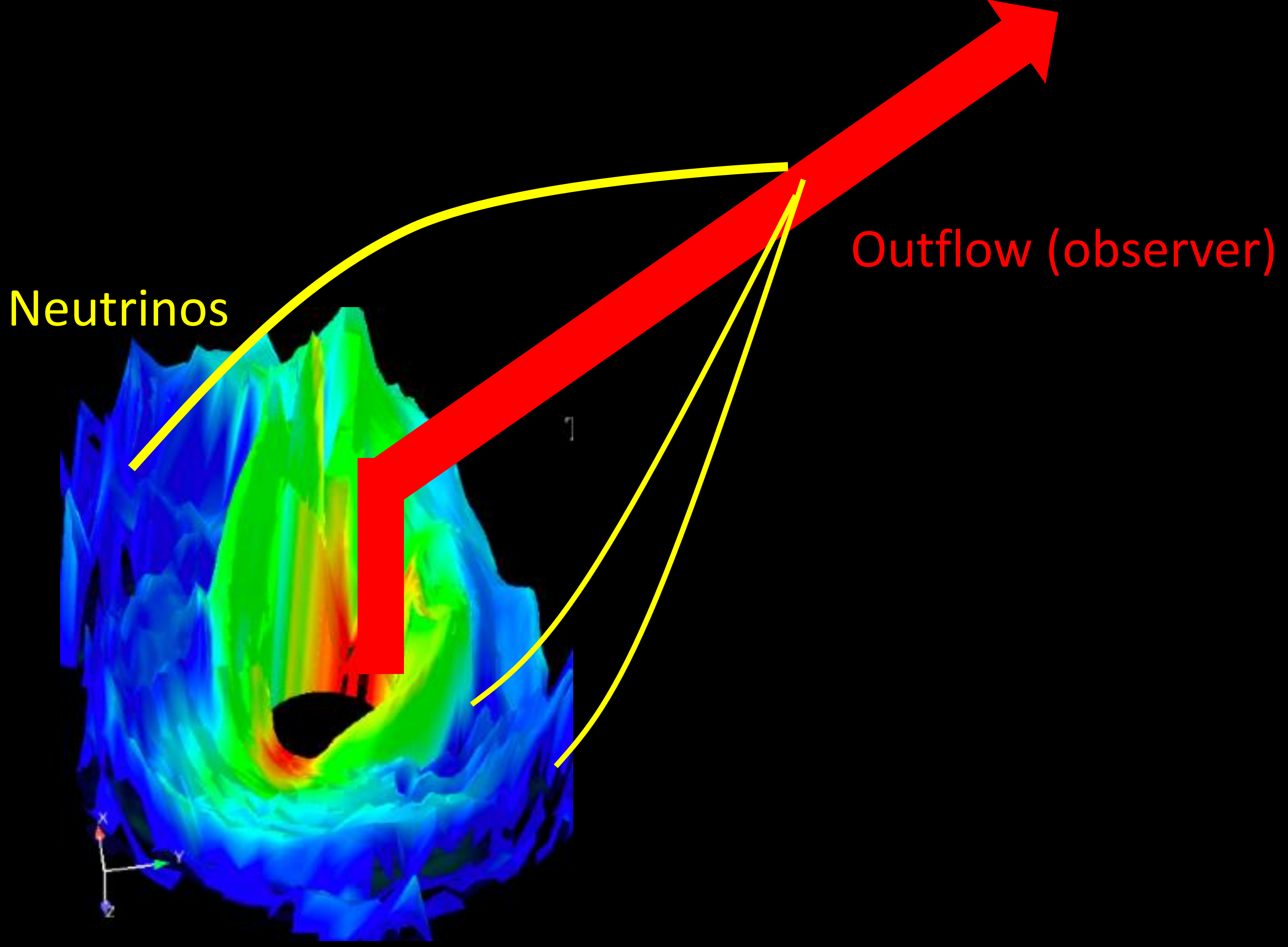
High energy tail of the flux is reduced

Black hole accretion disk (BH-AD) nucleosynthesis

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

$$\nu_e + n \leftrightarrow e + p$$

If antineutrinos are more energetic than neutrinos then they will drive the material neutron rich



But if both fluxes are weak the nucleosynthesis will strongly depend on the outflow conditions

BH-AD Nucleosynthesis

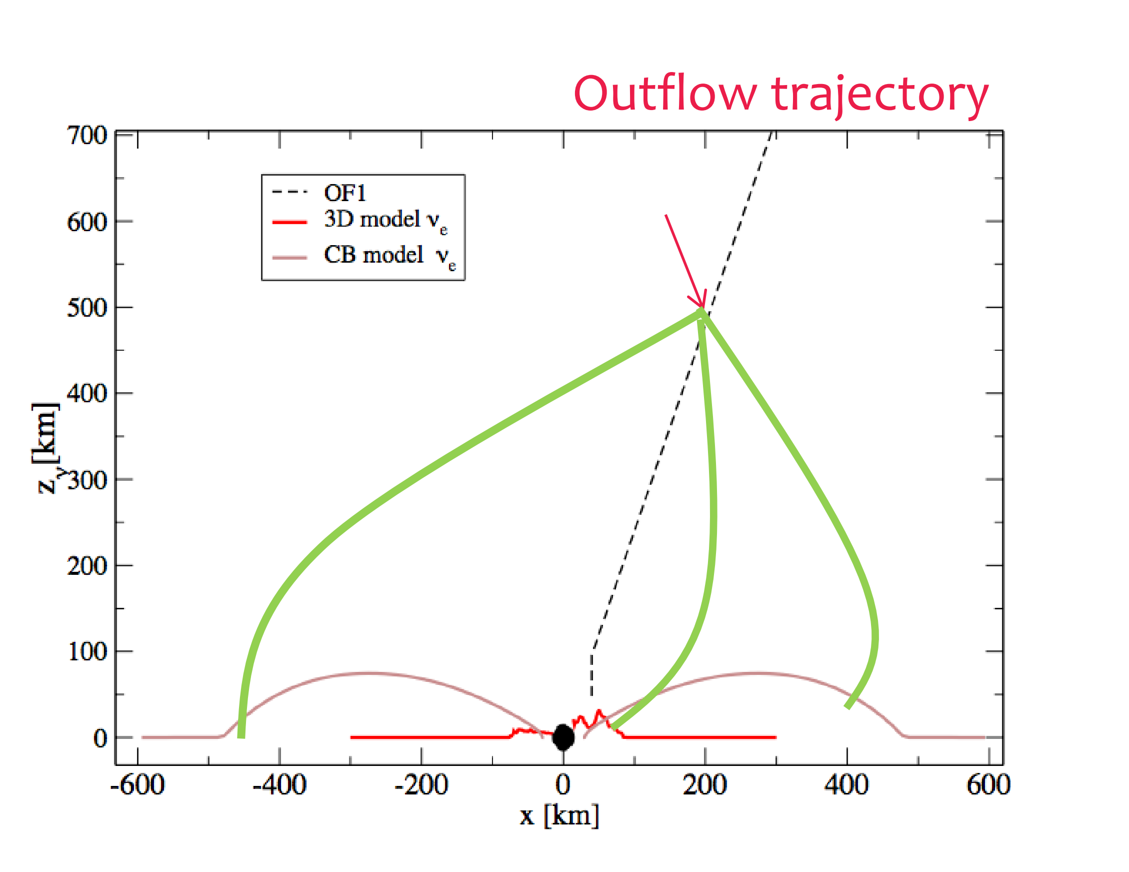
$$\bar{\nu}_e + p \leftrightarrow e^+ + n$$

$$\nu_e + n \leftrightarrow e + p$$

Neutrinos set the proton fraction

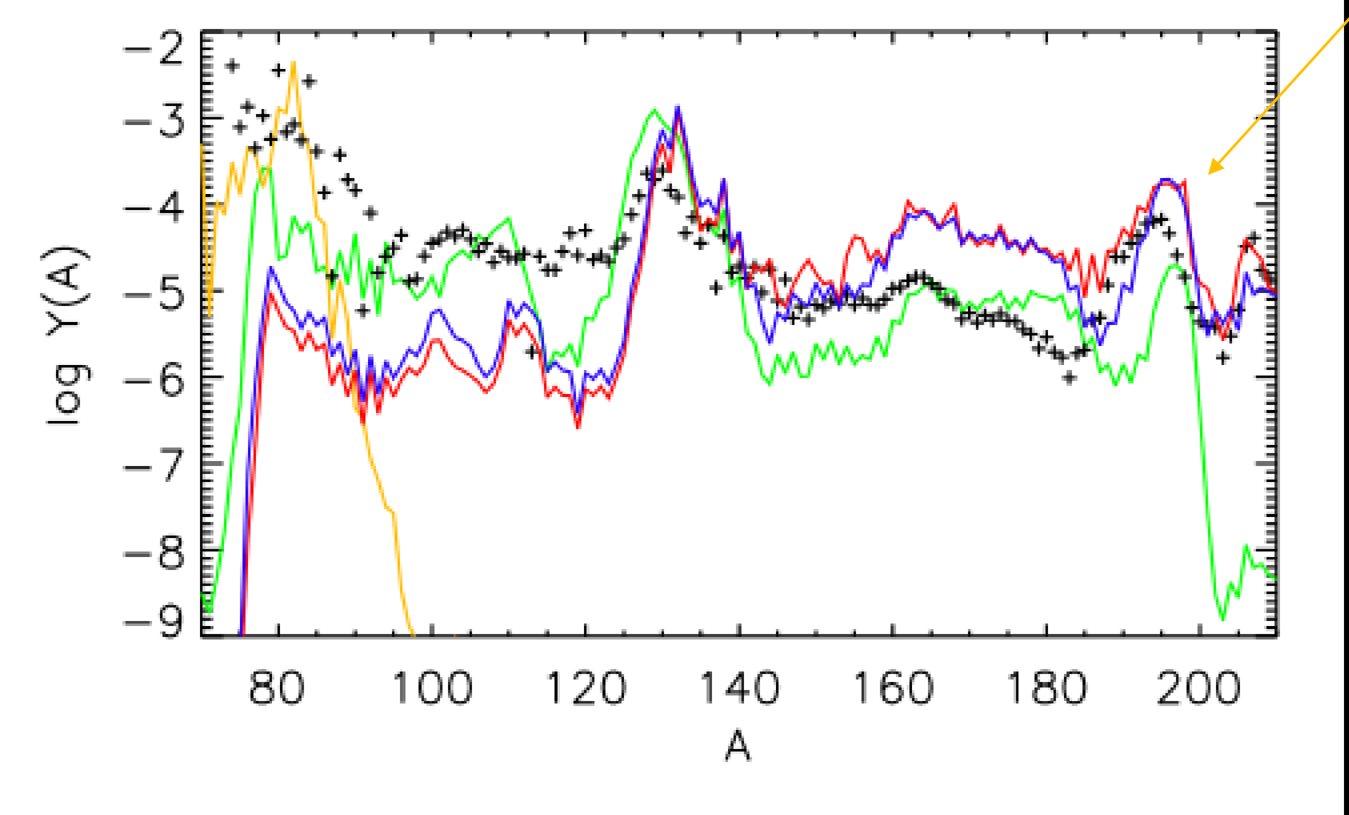
$$\phi^{eff} = \frac{1}{4\pi}\int d\Omega_{ob}\phi_{ob}(E_{ob})$$

Neutrino surface



Nucleosynthesis

No GR: only first peak achieved.



Gold

More redshifted

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

$$\nu_e + n \leftrightarrow e + p$$

GR neutrinos are less energetic.
Material remains neutron rich

Caballero, McLaughlin, Surman. ApJ 2012

Yellow = Newtonian neutrinos

Green = Static disk and a=0

Red = Rotating disk and a=0

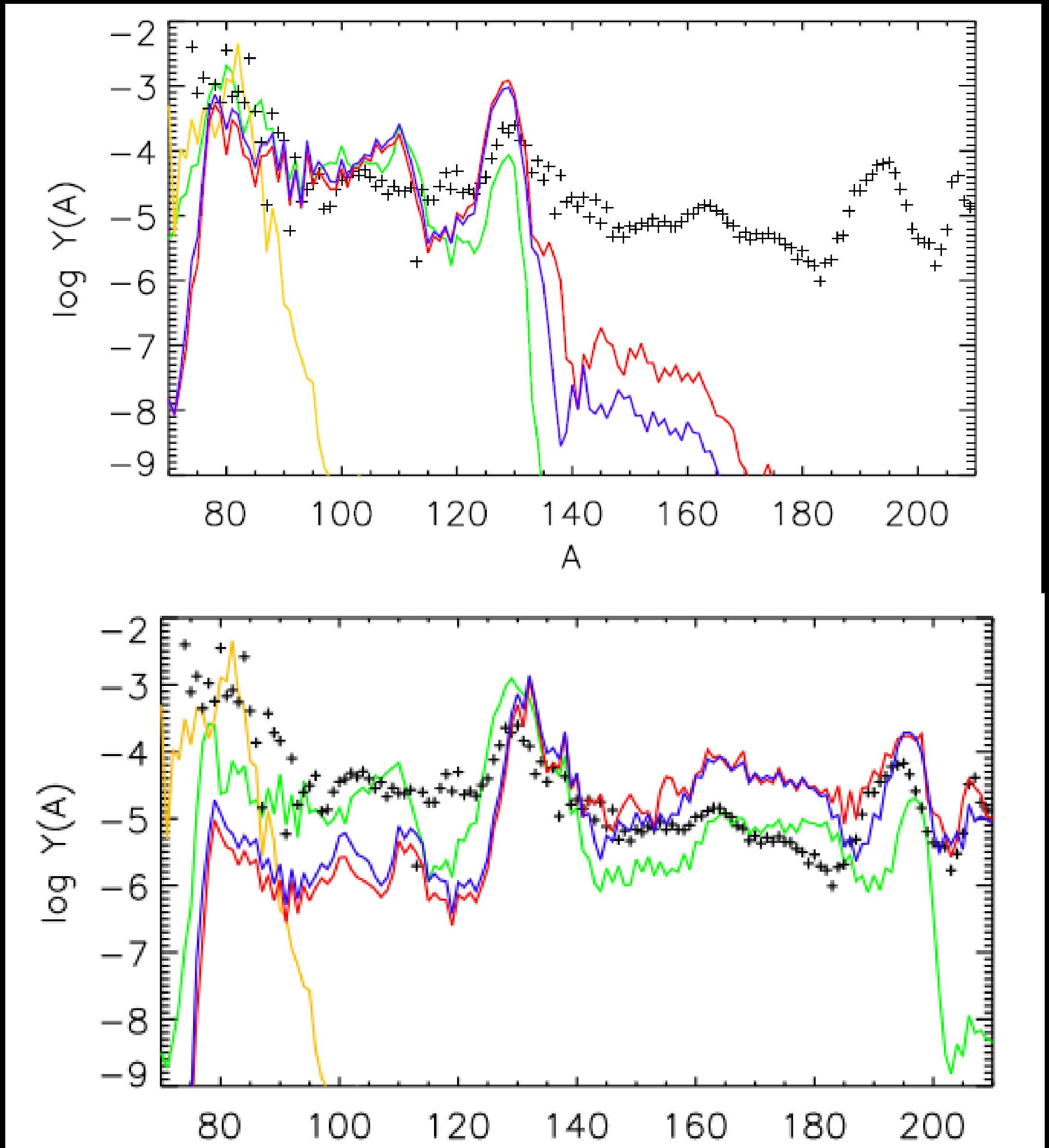
Blue = Rotating disk and a=0.6

Outflow model

- Low entropy S/k=20
- Fast outflow t=5 ms

Trend depends on the geometry of the neutrino surfaces

Flat



Low entropy S/k=20

Fast outflow t=5 ms

Puffy

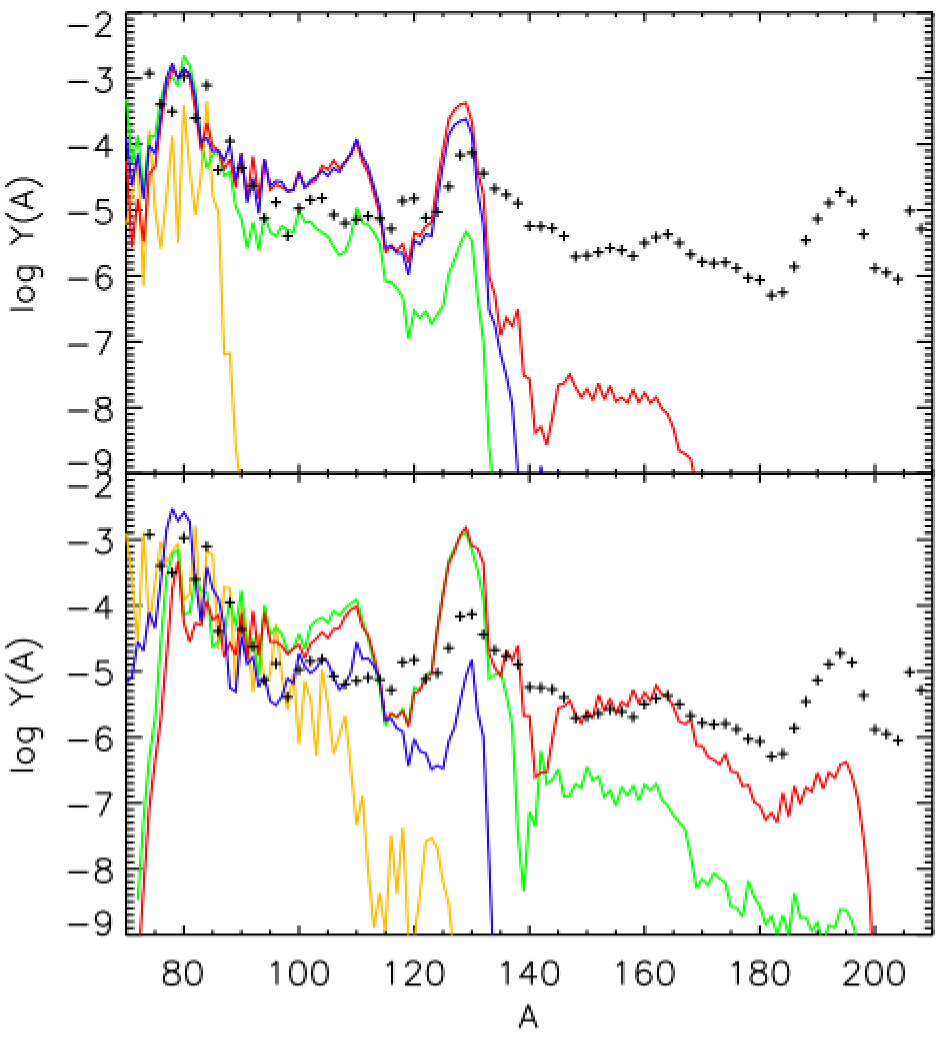
Trend does not depend on the on the disk model

Outflow model s/k =10, β=0.2

3D Hydrodynamical Model
(Ruffert & Janka)

1D steady state disk

(Chen & Belobodorov)



Caballero, McLaughlin, Surman. ApJ 2012

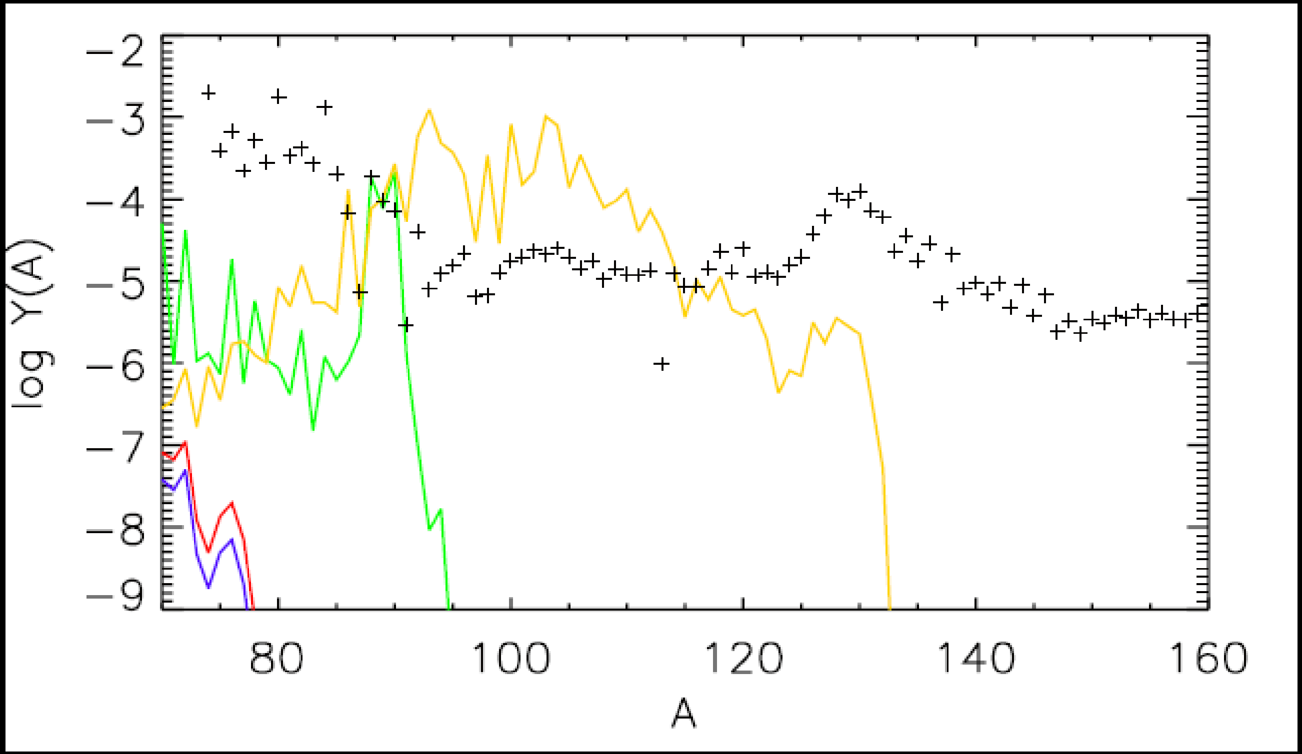
Yellow = Newtonian neutrinos

Green = Static disk and a=0

Red = Rotating disk and a=0

Blue = Rotating disk a=0.6 top , a=0.95 bottom

R-process depends on the outflow conditions



3D hydro model

More redshifted

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

$$\nu_e + n \leftrightarrow e + p$$

Material becomes proton rich

Yellow = Newtonian neutrinos

Green = Static disk and a=0

Red = Rotating disk and a=0

Blue = Rotating disk and a=0.6

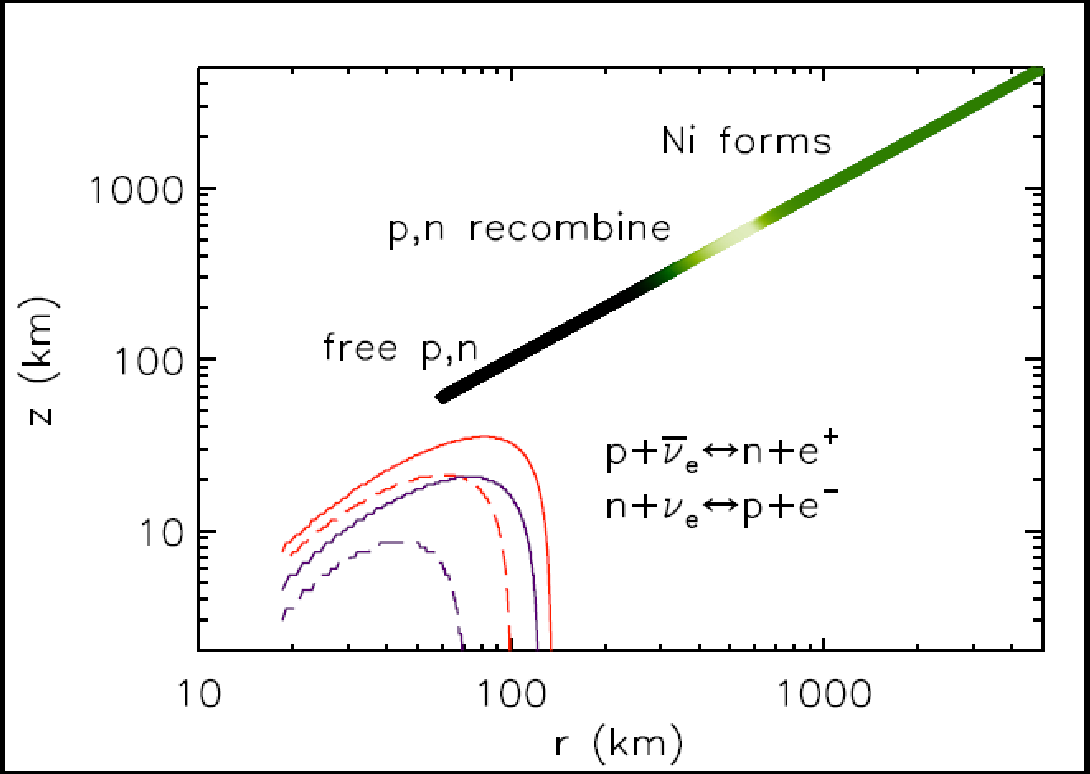
Outflow model

- High entropy S/k=75
- slow outflow t=50 ms

Time dependence

BH-AD 3D hydro, BH mass: 3 solar masses, a=0.8

Neutrino surfaces and outflow

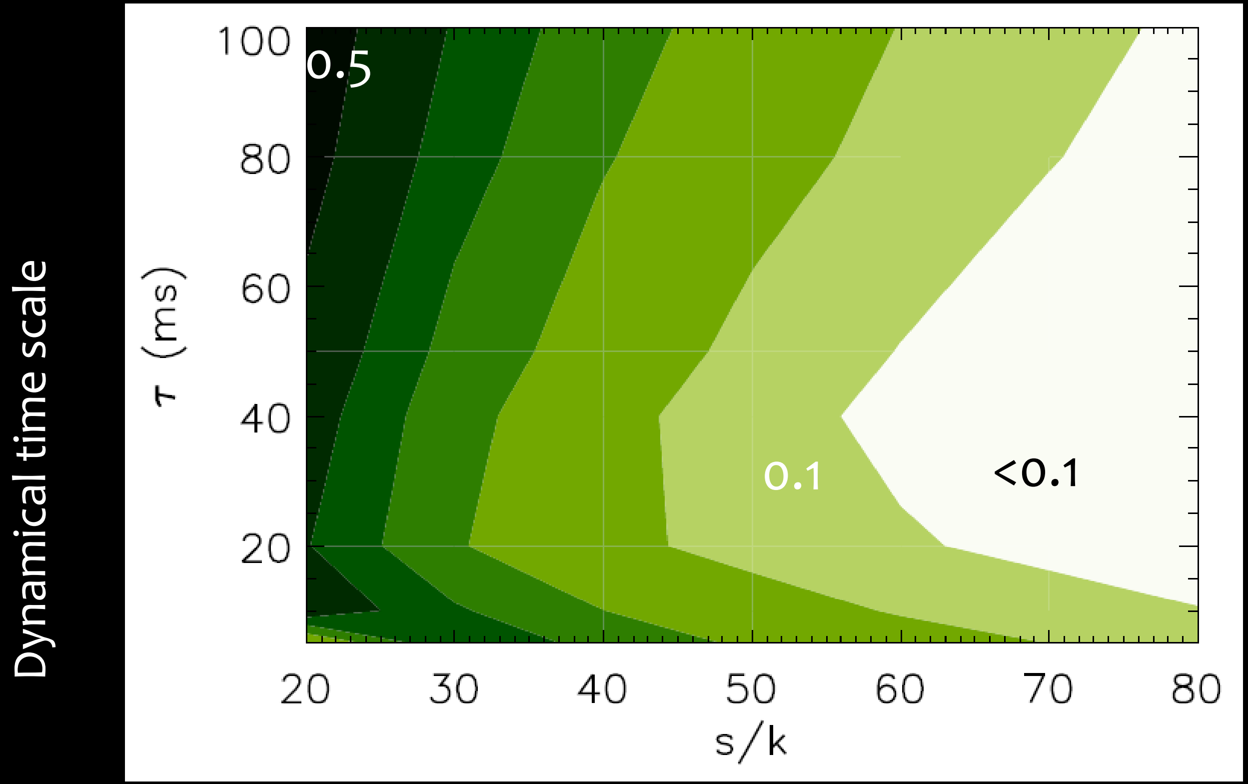


Surman, Caballero, McLaughlin, Just, Janka 2014

Snapshots
Red: 20 ms, disk is formed & outflow is ejected
Purple: 60 ms
Solid: e-neutrinos
Dashed: e-antineutrinos

- Neutrino surfaces shrink.
- At later times the outflow will see more neutrinos than antineutrinos

56-Nickel production



Surman, Caballero, McLaughlin, Just, Janka 2014

Outflow parameter space

- ^{56}Ni is the (A>4) most abundant element.
- For mildly heated outflows over half of the outflow material is ejected as ^{56}Ni
- Decay of Ni could generate a optical counterpart

BH-AD nucleosynthesis

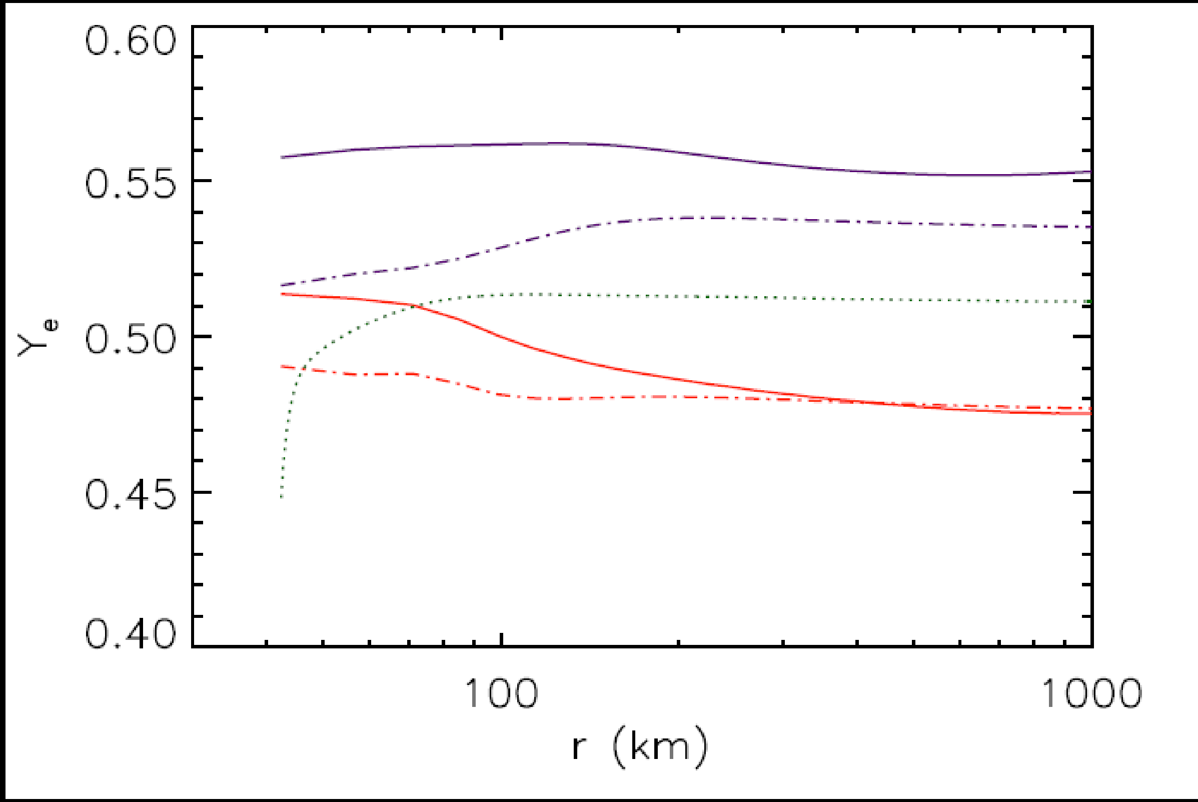
- Abundances (r-process) depend on the conditions of the outflow, the geometry of the disk and on neutrino fluxes
- General relativistic effects influence observable quantities: abundances, neutrino detection, and cannot be ingnored!
- GR: Neutrinos less decisive in setting the neutron to proton ratio.
- Dynamical studies show a high 56-Nickel production
- The combination of GR effects and the rapid evolution of neutrino surfaces makes an initially neutron-rich outflow proton-rich.

Outlook

- GR effects should be (consistently) included in nucleosynthesis studies
- Consider merger ejecta and other possible outflow trajectories.
- There will be also changes due to neutrino oscillations (and they will be also affected by GR)
- The influence of magnetic fields on neutrino emissions needs to be studied

Collaborators

- G. McLaughlin (North Carolina State University)
- R. Surman (University of Notre Dame)
- O. Just (Max-Plank-Institute fur Astrophysik/Princeton Center for Plasma Physics)
- H. –Th. Janka (Max-Plank-Institute fur Astrophysik)



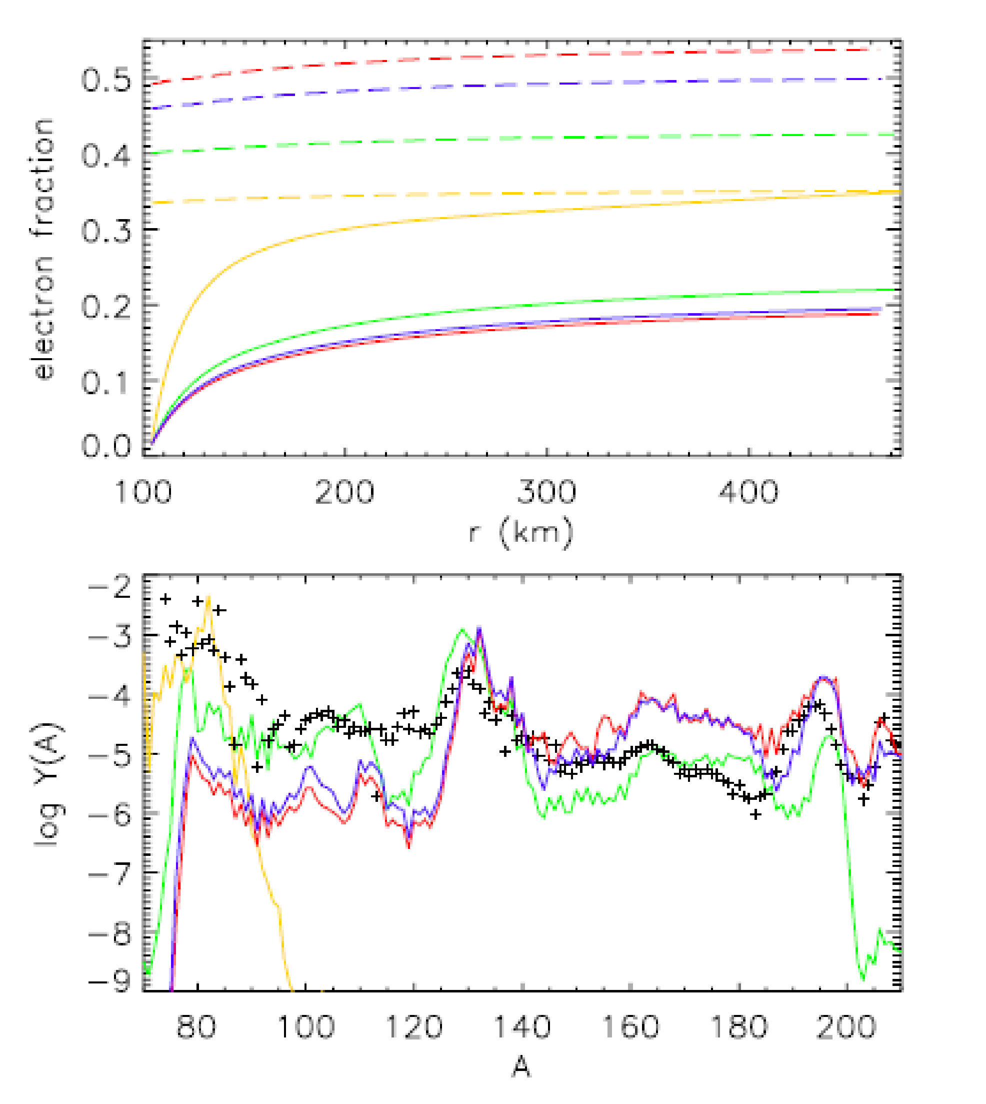
Surman, Caballero, McLaughlin, Just, Janka 2013

Snapshots
Red: 20 ms,
Purple: 60 ms
Solid: GR
Dashed: Newtonian

56Ni: Most produced element
For mildly heated outflows
over half is ejected as 56-Nickel

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

$$\nu_e + n \leftrightarrow e + p$$



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