Connecting the Micro to the Macro in Dense Stars

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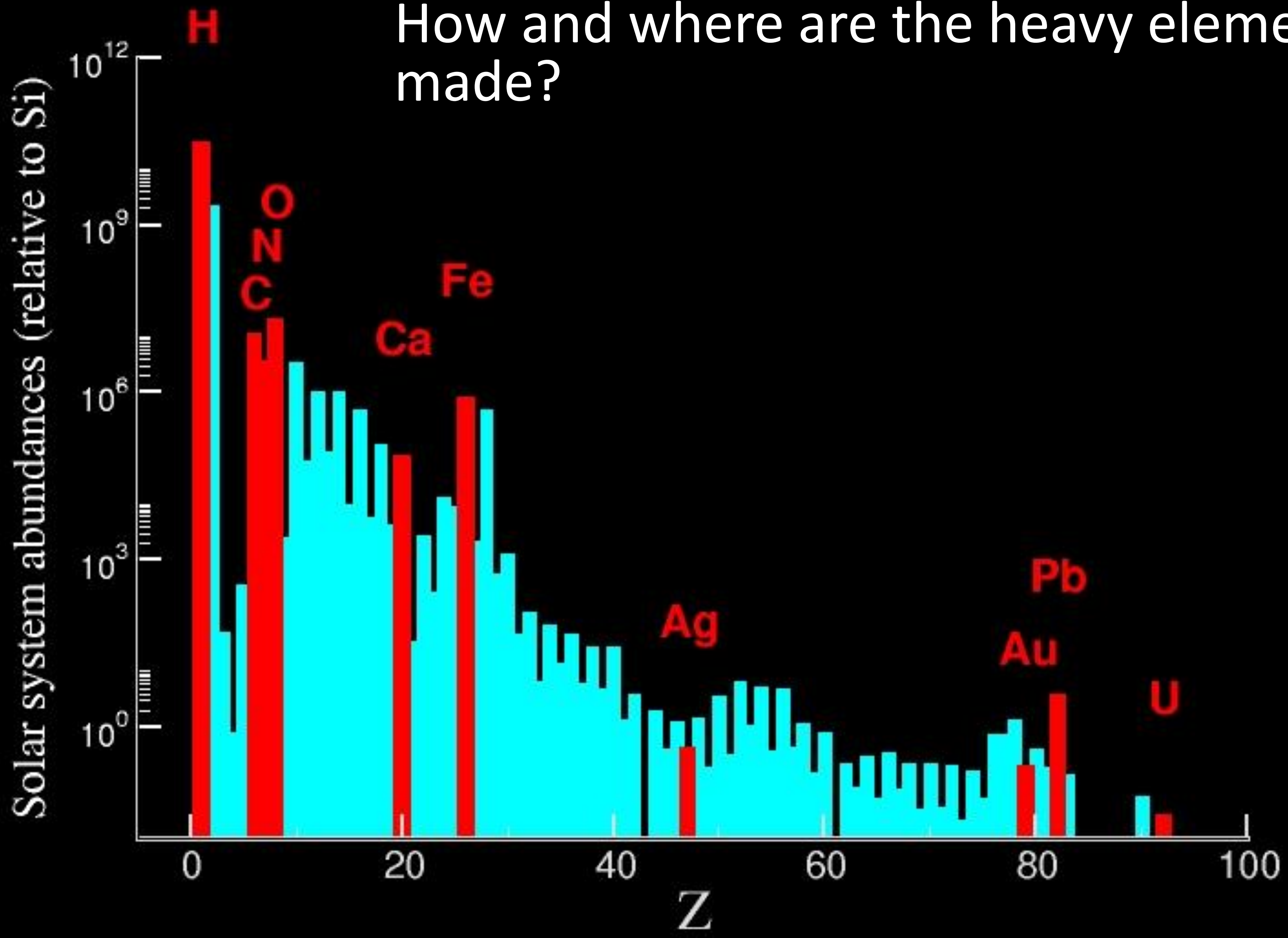
Modern Nuclear Astrophysics

How and where are the heavy elements made?

What are the mechanisms of stellar explosions?

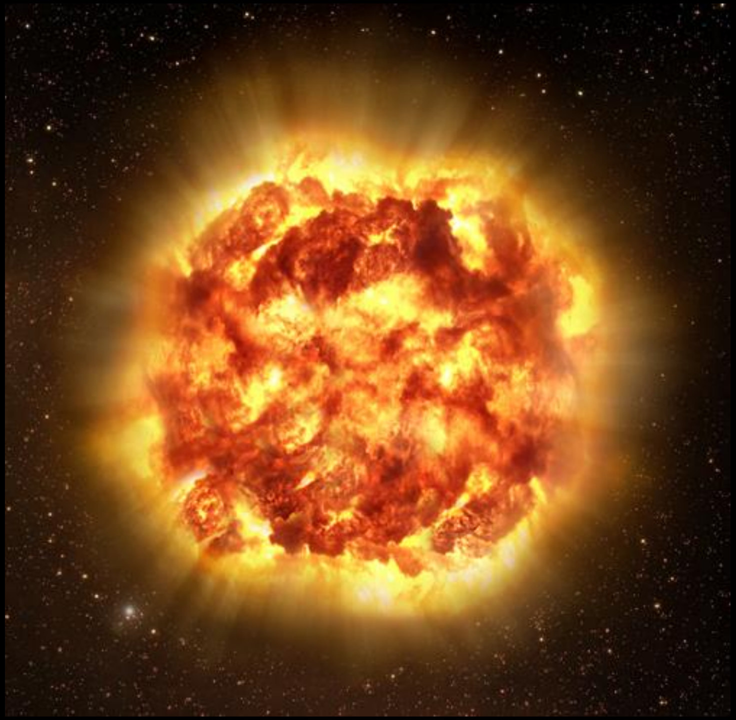
What is the nature and structure of matter under extreme conditions?

How and where are the heavy elements made?



What are the mechanisms of stellar explosions?

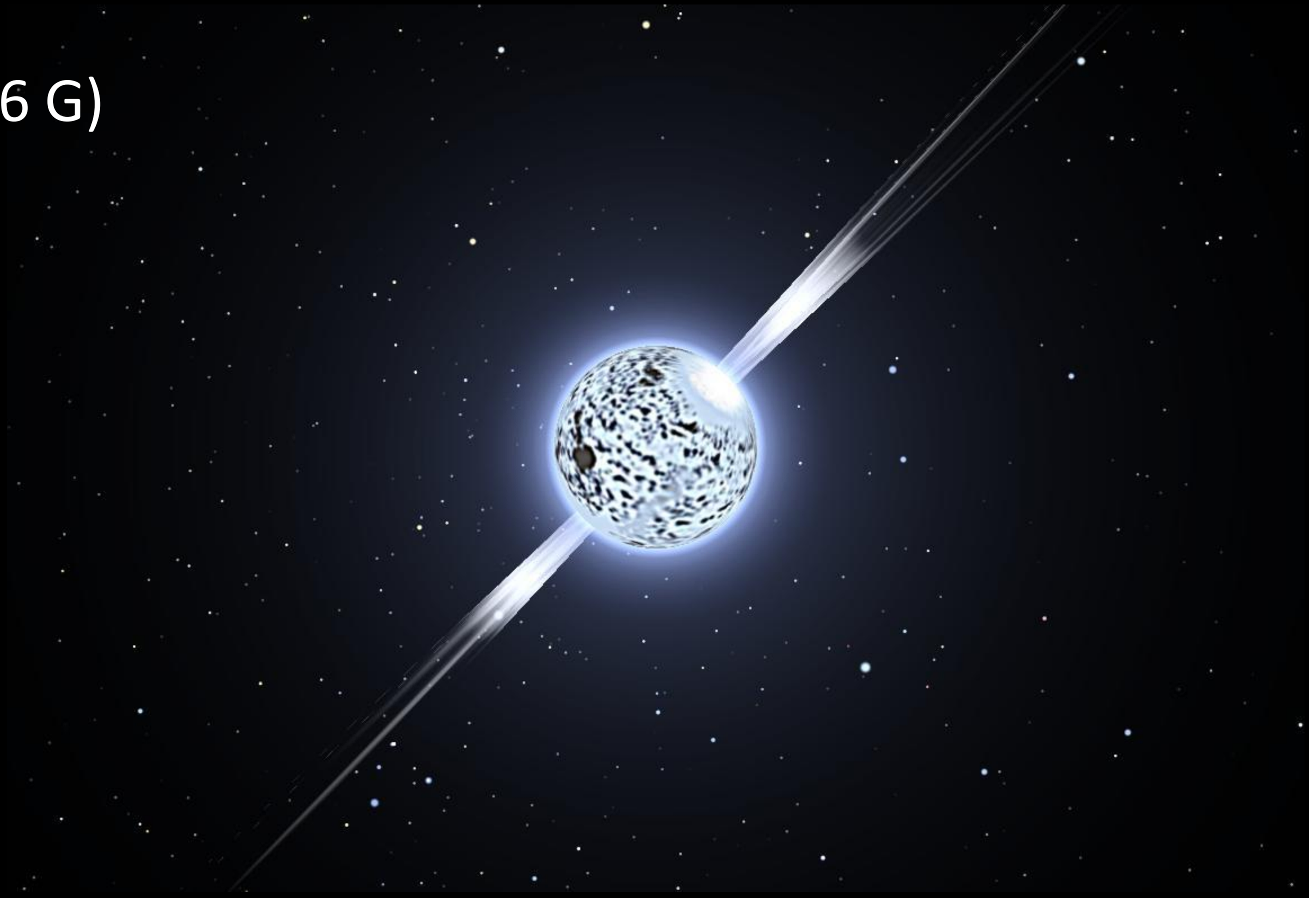
Gamma ray bursts (GRB)

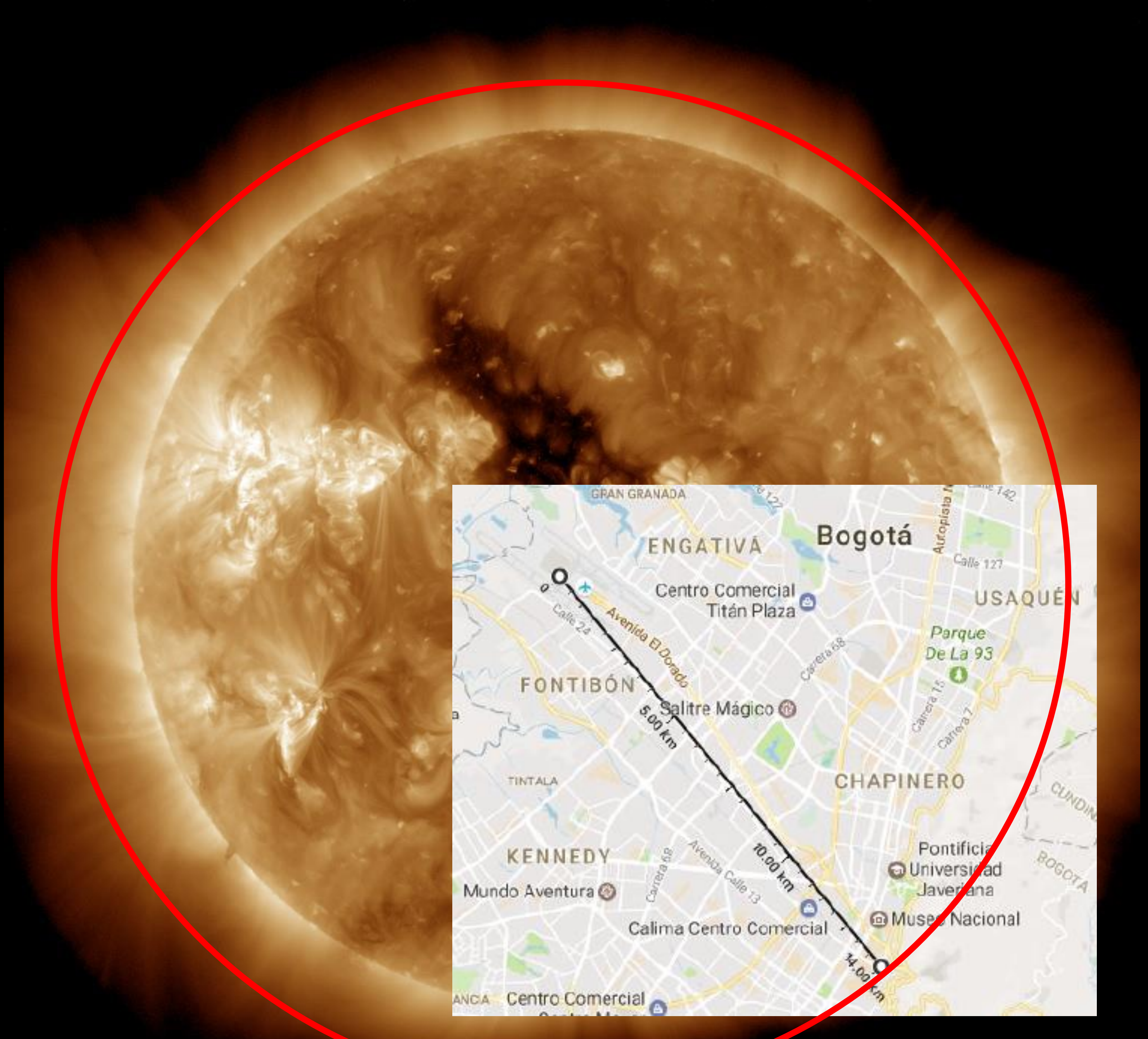


Supernovae

What is the nature and structure of matter under extreme conditions?

Magnetic Field: 10^8 -10^{15} G (Earth's ~ 0.6 G)
Mass= 1.4 Solar masses
Radius = 12 km

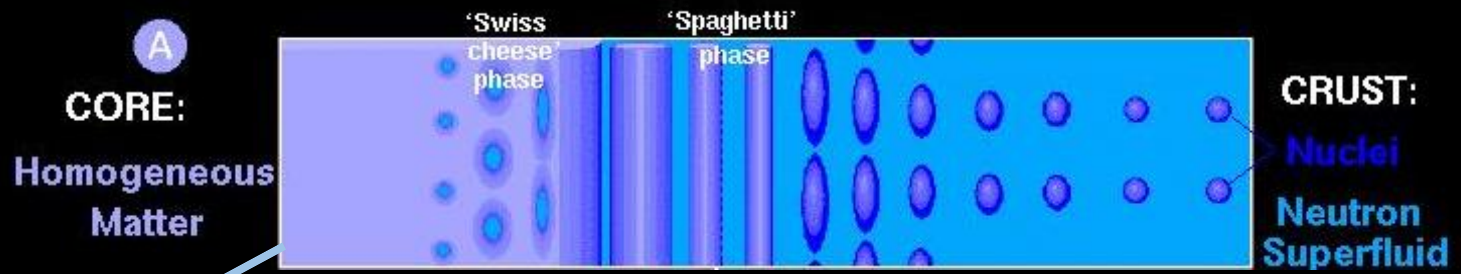


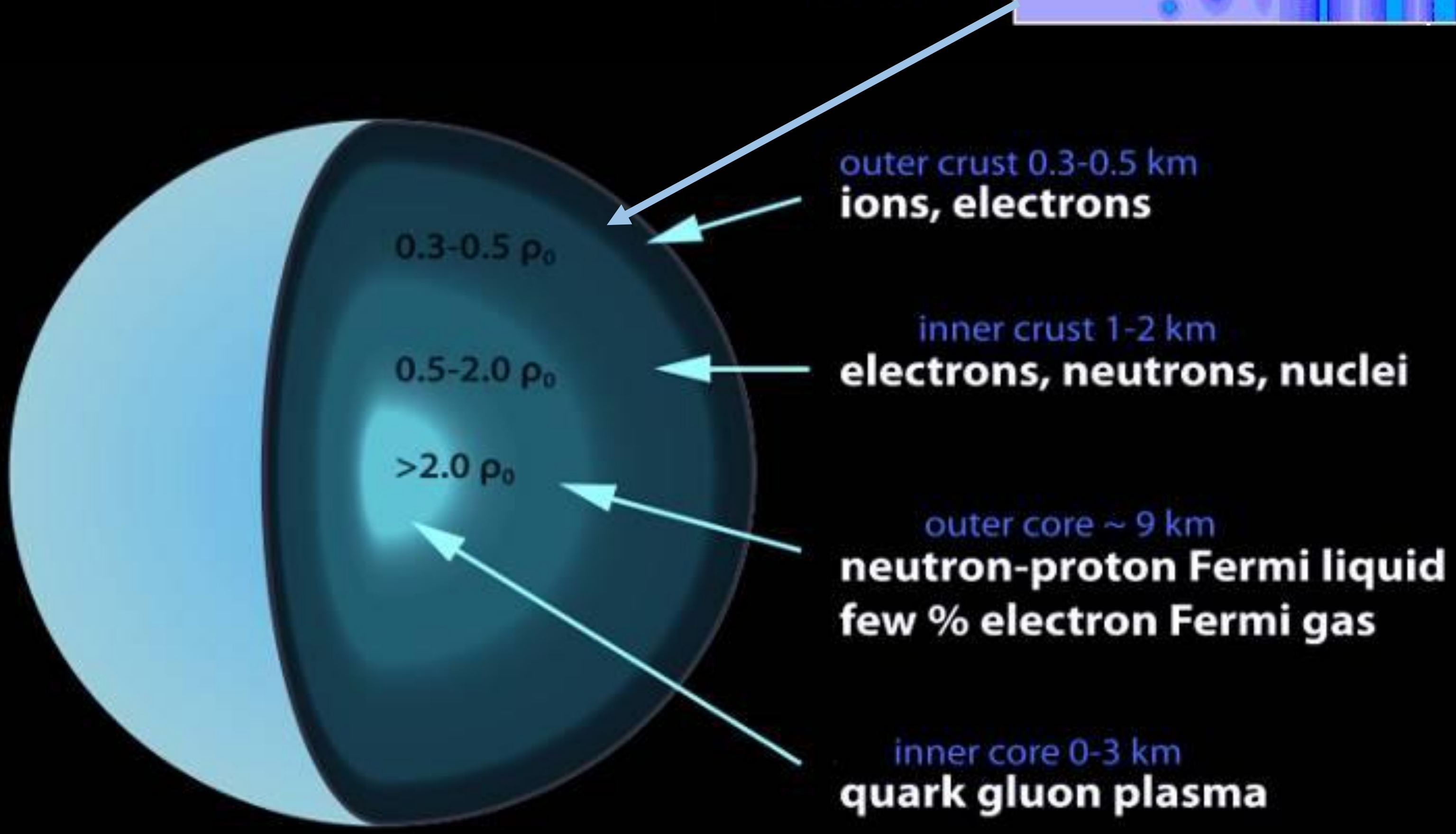


Density: 10^9 to 10^{15} g/cm^3 (lead= 11 g/cm^3, nucleus =2.3×10^{14} g/cm^3)

Image Credit: NASA/AIA

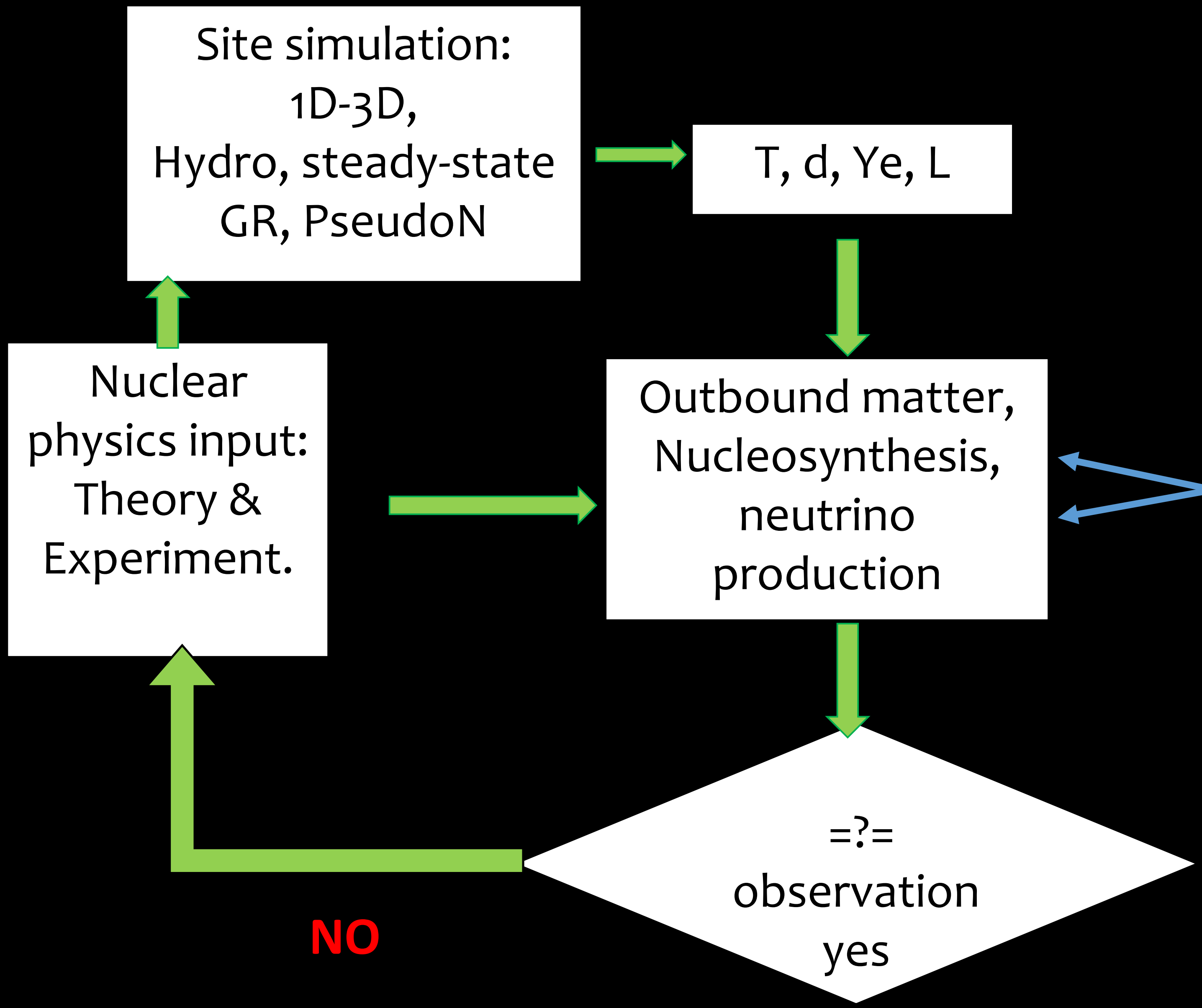
Neutron star structure



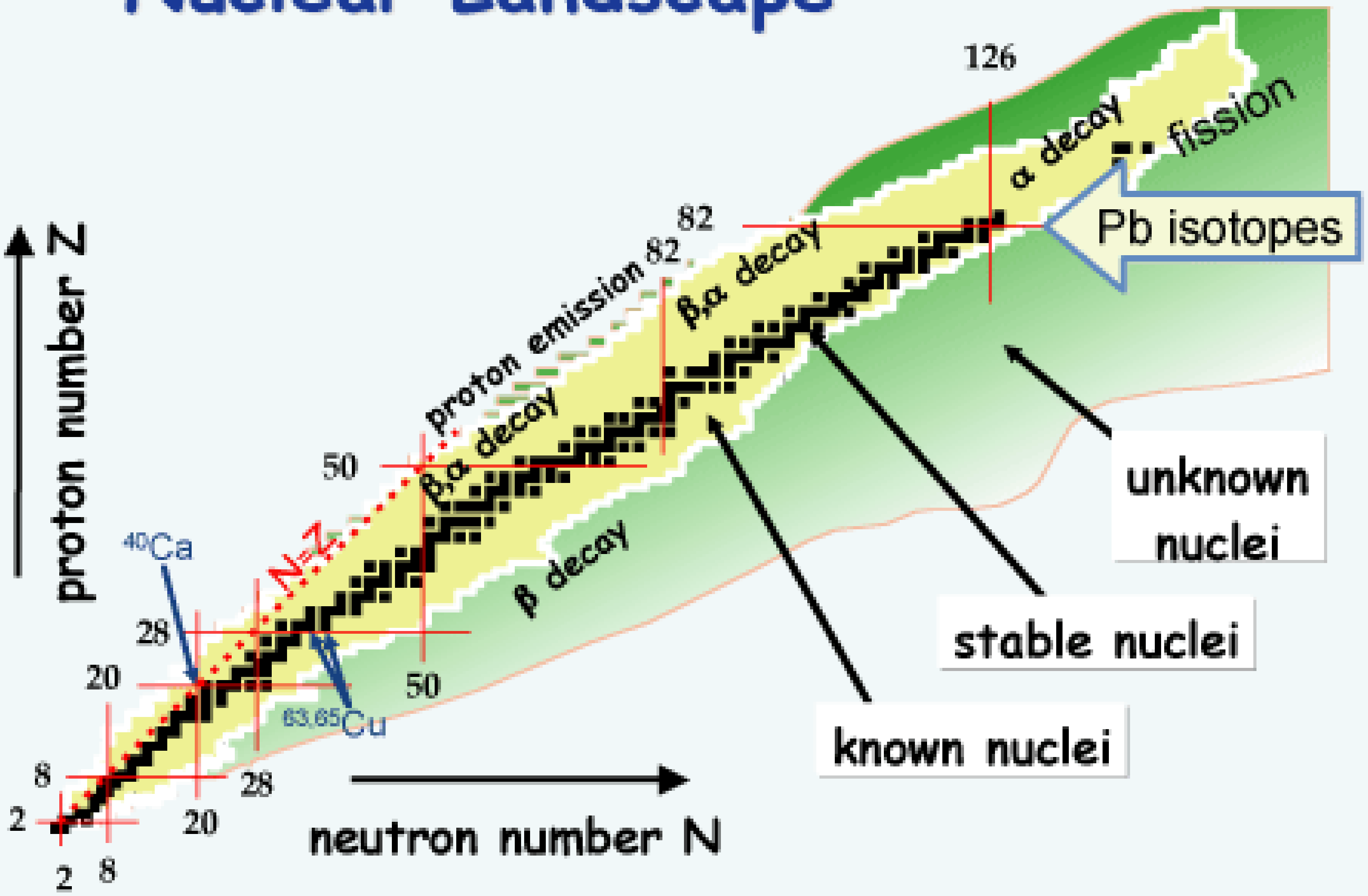


Nuclear density

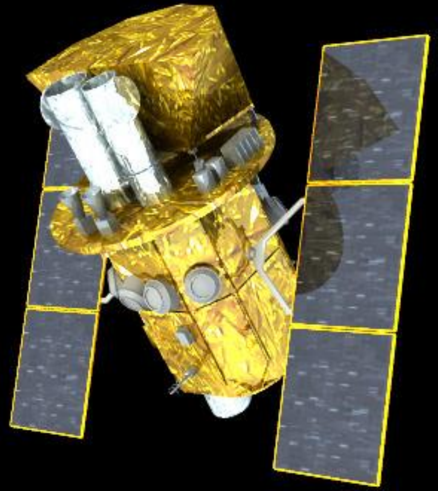
ρ_0=2.3x 10^{14} g/cm^3


Site simulation:
1D-3D,
Hydro, steady-state
GR, PseudoN
T, d, Ye, L
Nuclear
physics input:
Theory &
Experiment.
Outbound matter,
Nucleosynthesis,
neutrino
production
TODAY
=?=
observation
yes
NO

Nuclear Landscape



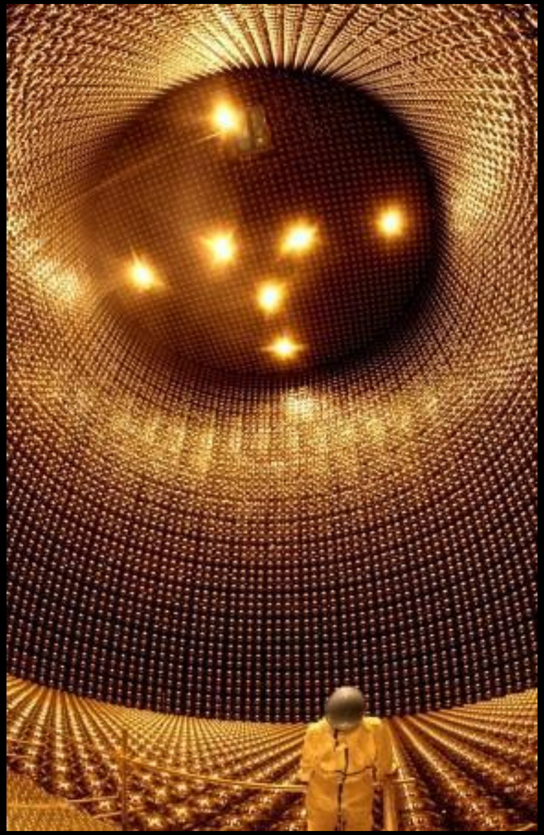
Observations



Swift: Gamma-rays

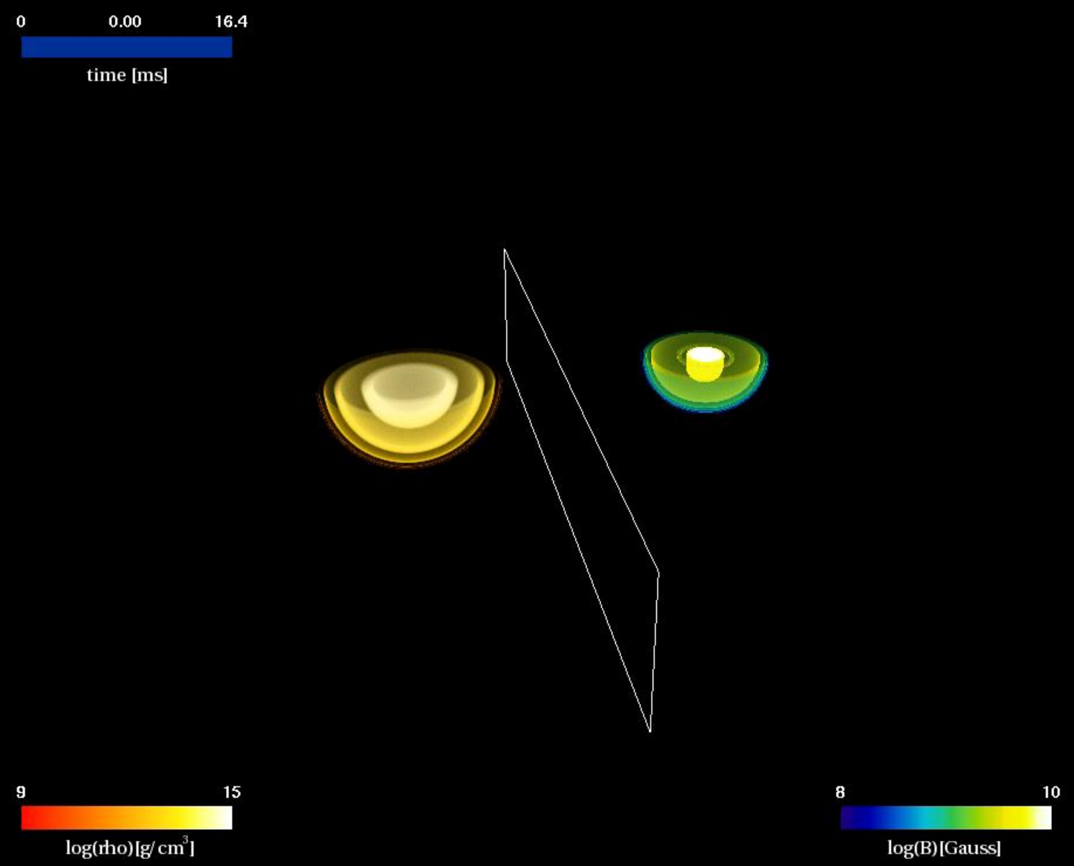
Hubble Space Telescope

LIGO: Gravitational Waves



SuperK: Neutrinos

Simulations



GR simulation, M=1.5 solar masses, initial magnetic field of 10^{12} G, ideal gas,
L. Rezzolla et al, Astrophys. J. Lett. 732, L6 (2011)

Artwork Credit: NASA, and M. Weiss (Chandra X -ray Center)

Modern Nuclear Astrophysics

- Neutrinos under extreme conditions
- Nucleosynthesis
- The nuclear matter Equation of State (EOS)

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Neutrino Surface

At high temperatures (~ 10 MeV) matter is dissociated

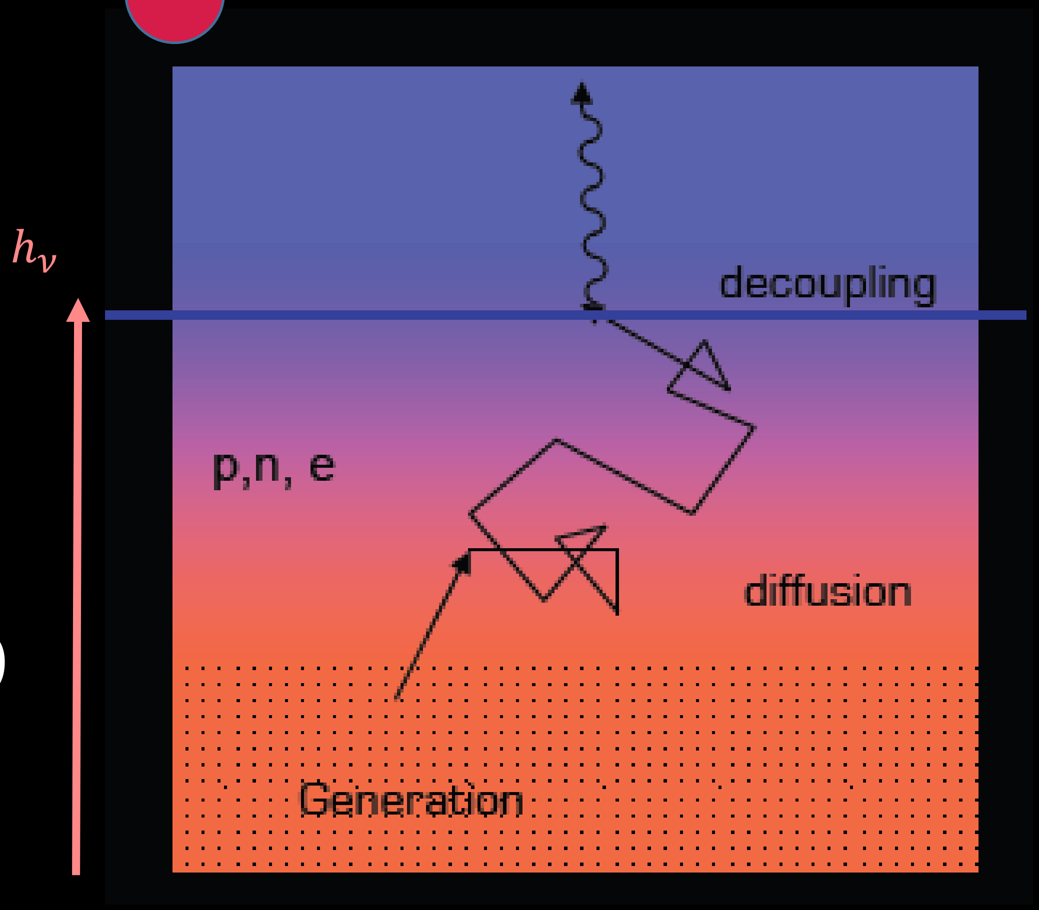
ν

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

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

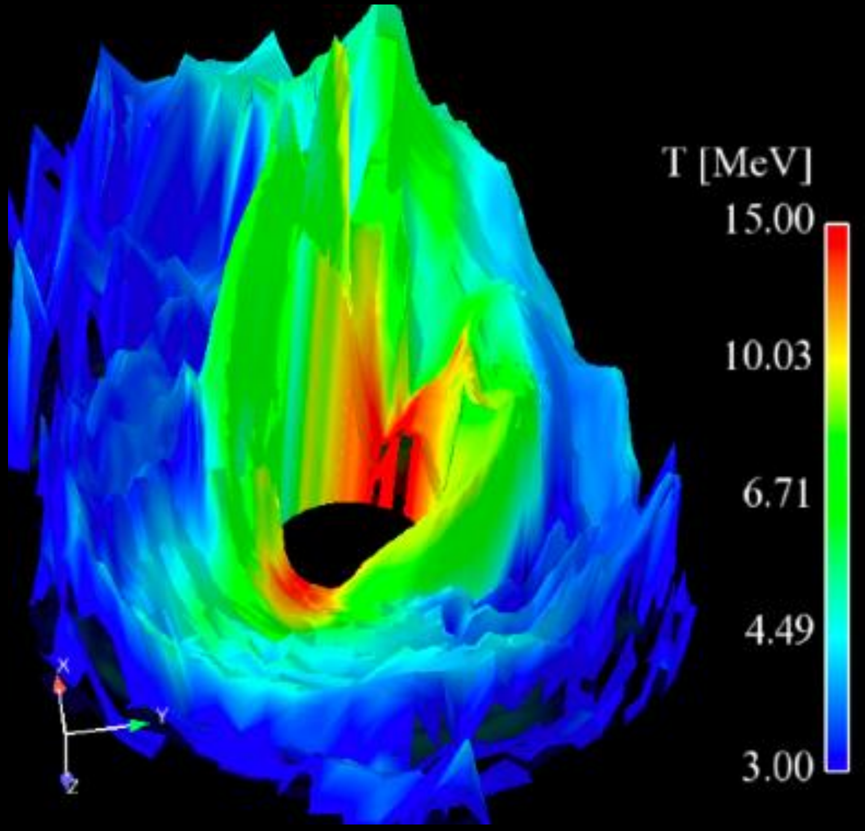
$\nu + n \rightarrow \nu + n$ Neutral Current
$\nu + p \rightarrow \nu + p$
$\nu + e \rightarrow \nu + e$ (All flavors)

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



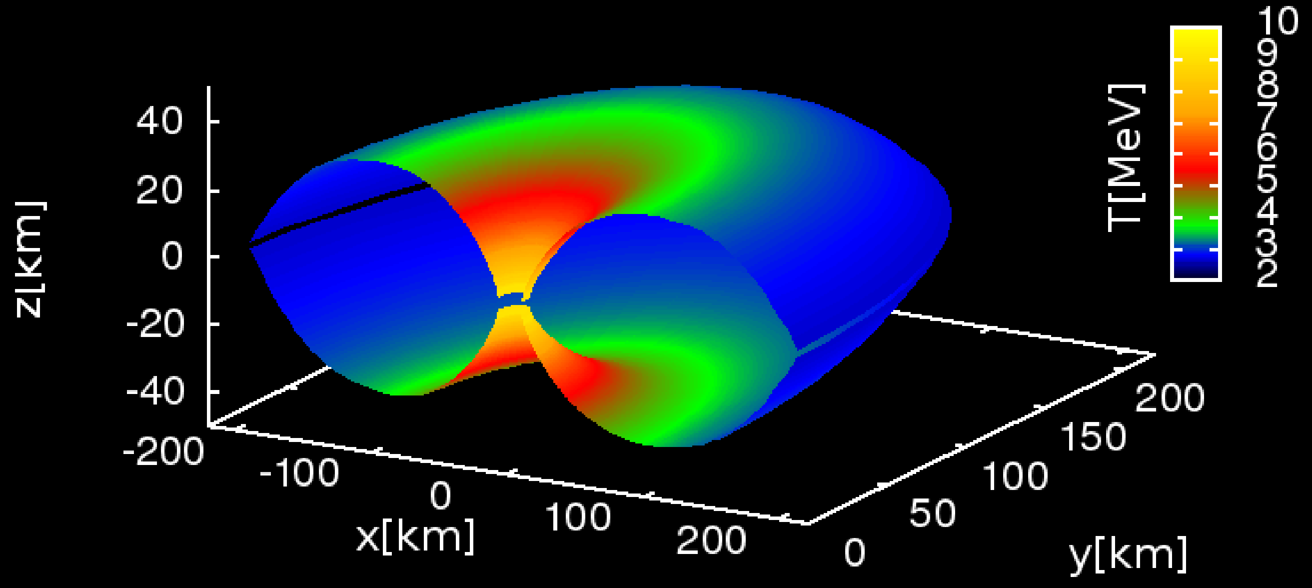
Electron antineutrino surface

BH=2.5 solar masses, NS= 1.6 solar masses
3D hydrodynamical simulation, Ruffert, Janka (2001)



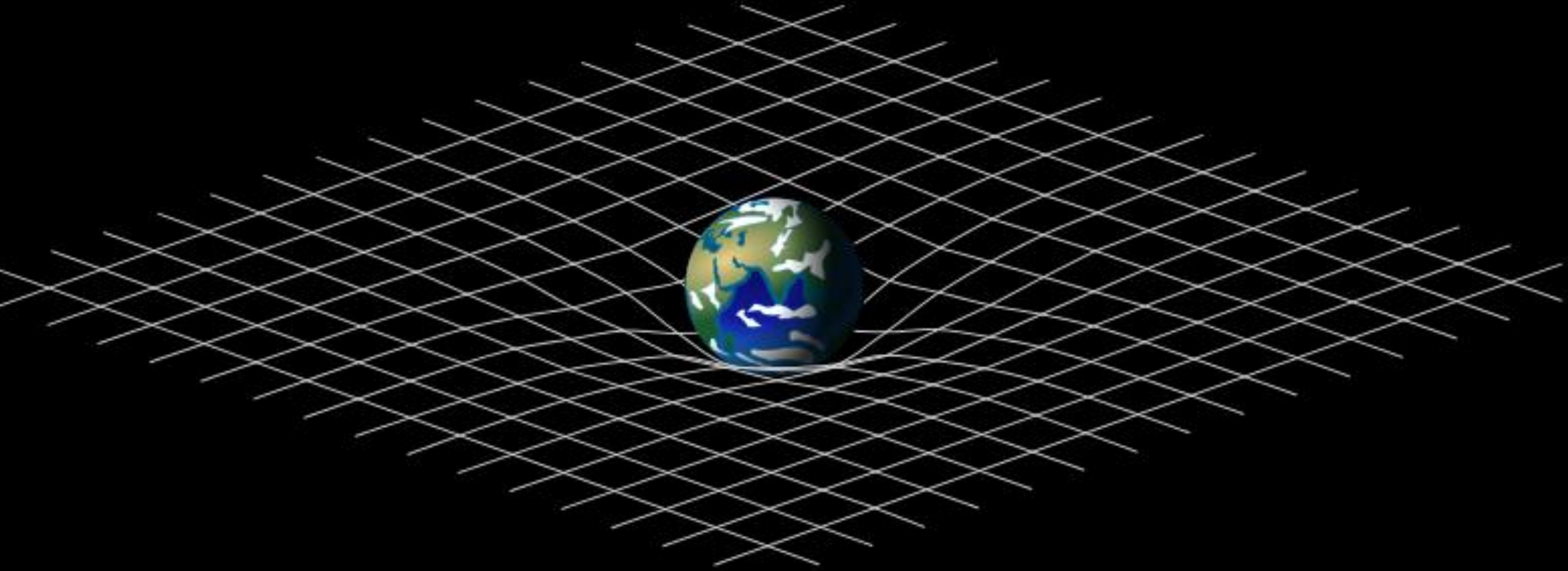
Caballero, McLaughlin, Surman. PRD 2009

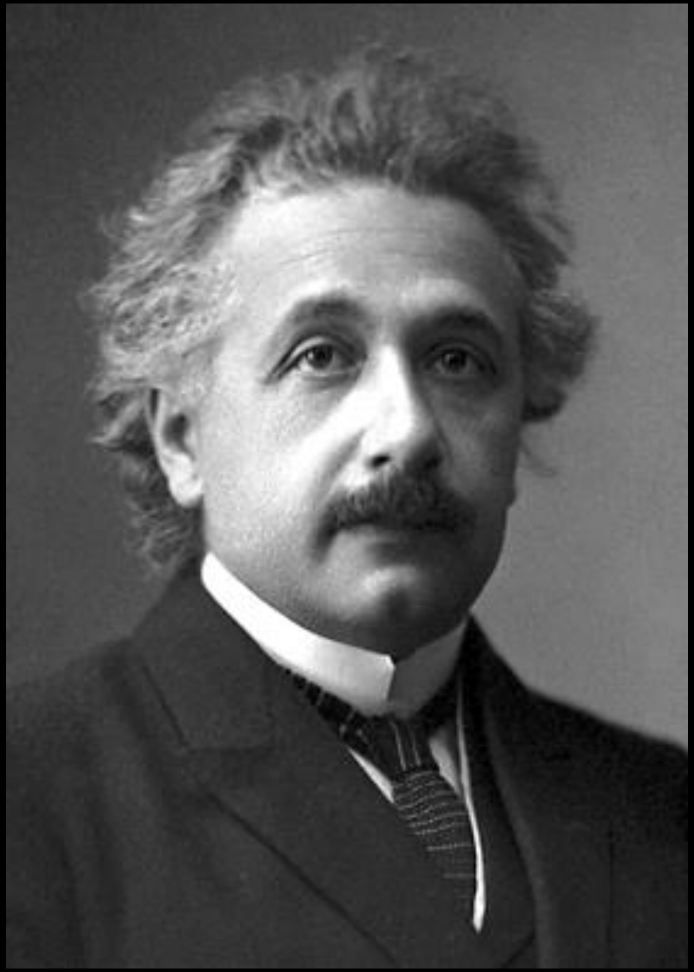
BH=3 solar masses, accretion rate of 5 solar mass/s.
GR steady-state simulation , Chen and Belobodorov APJ (2007)



O. L. Caballero et al PRD (2016)

Neutrinos will be deflected and their energies will be redshifted

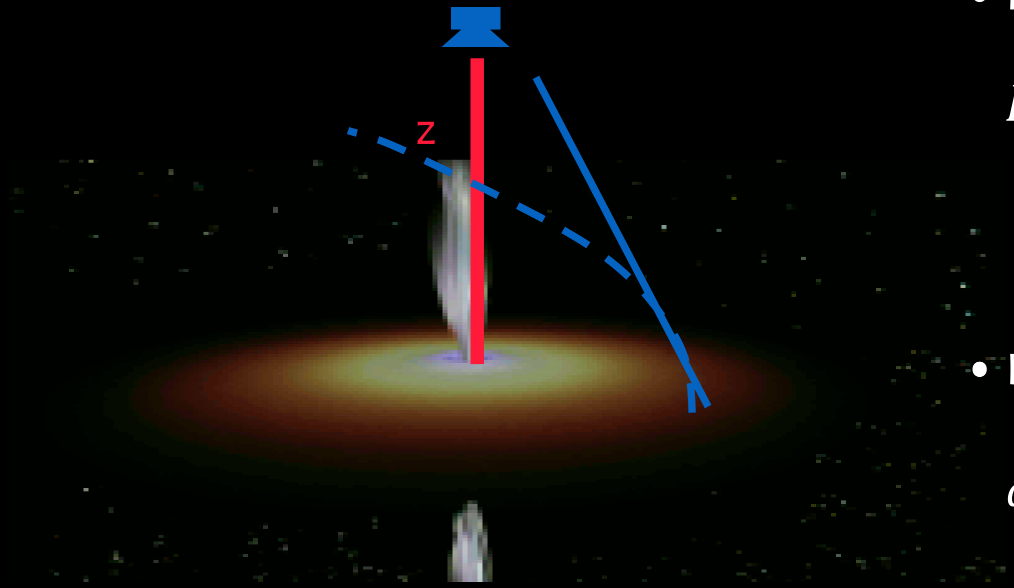




Neutrino flux under the influence of strong gravitational fields

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

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



- Energy is red-shifted

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

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

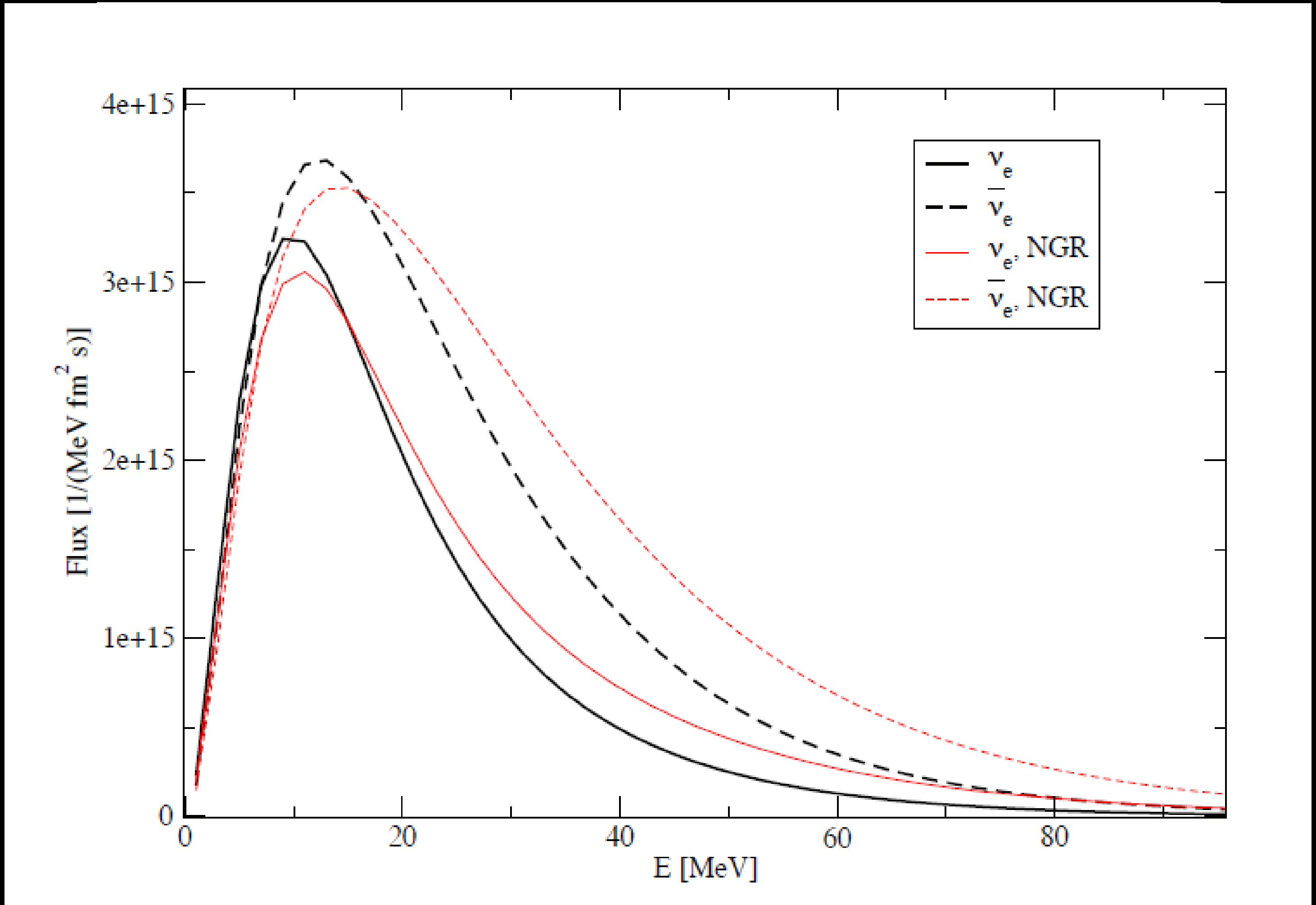
- Deflection of trajectories

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

Neutrinos follow null geodesics in the metric imposed by the mass distribution

Neutrinos under strong gravity

Observer at (x,z)=(40,48) km

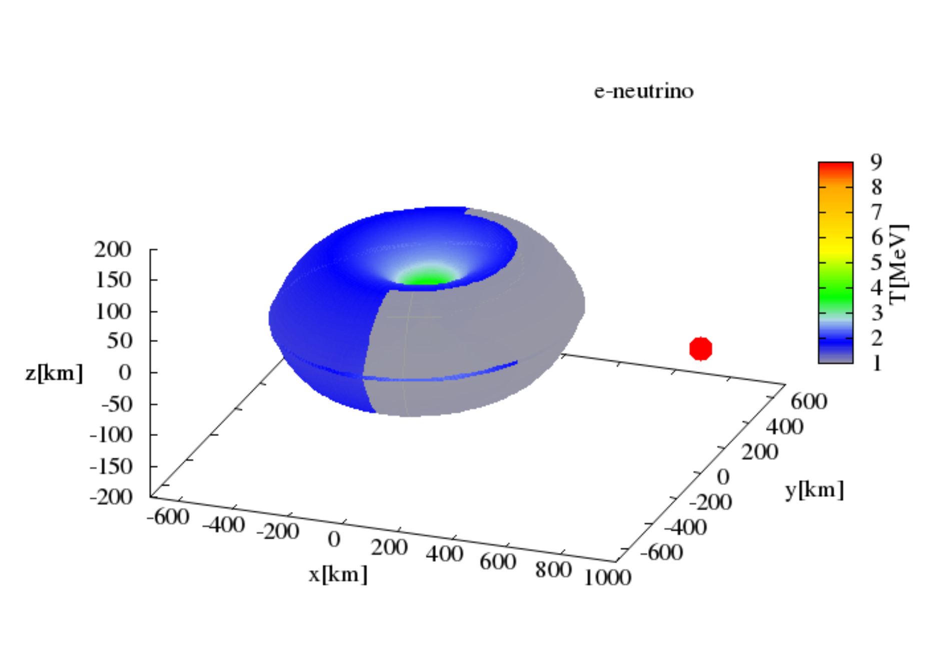


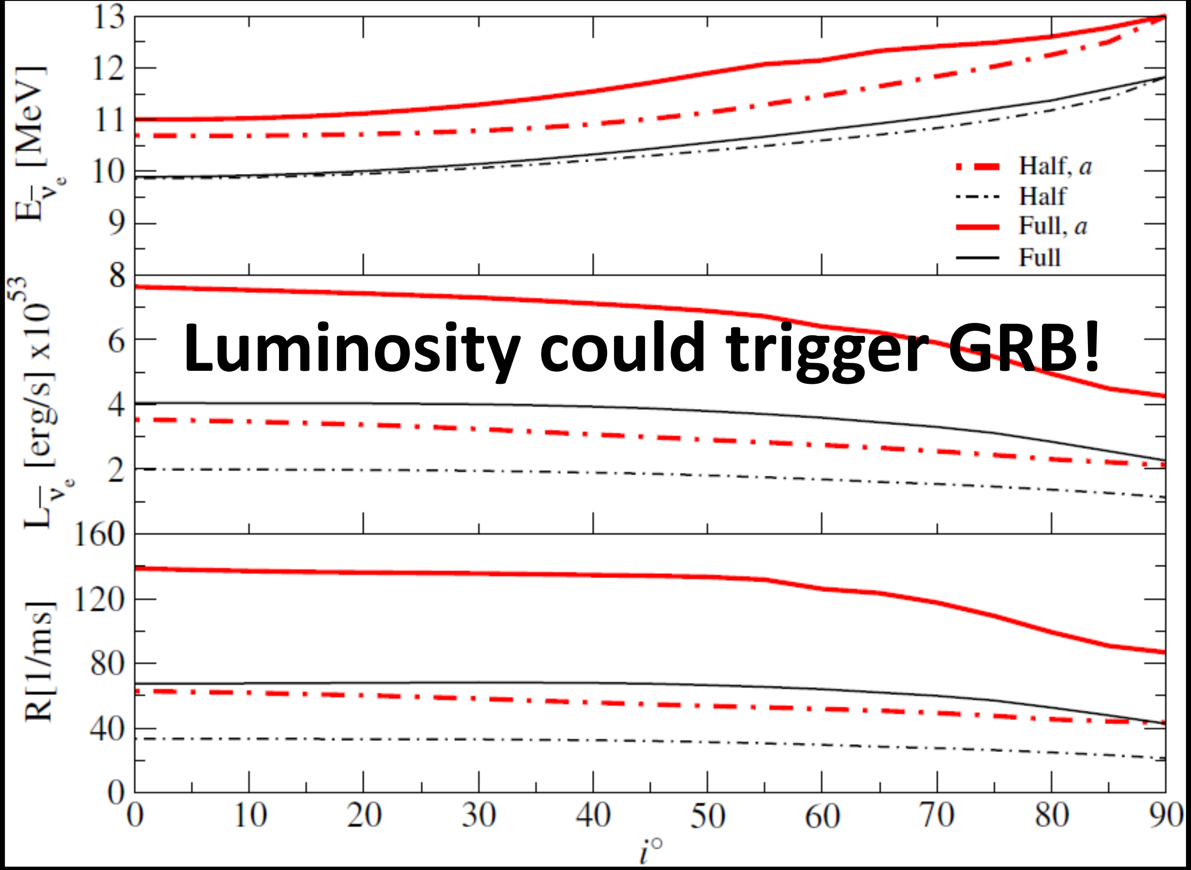
O. L. Caballero J. Phys. Conf. Ser. (2013)

High energy tail of the flux is reduced

Neutrinos under strong gravity

Fluxes depend on observer's direction and BH spin





O. L. Caballero , T. Zielinski et al PRD (2016)

Supernova: R= 1/ms, L=10^{52} erg/s, E~ 11 MeV, t=10 sec

- Strong gravity impacts observable neutrino quantities: detection rates, spectra, oscillations…
- Neutrinos from mergers will not be mistaken for Supernova neutrinos
- We could detect neutrinos from:
    - Milky way and satellite galaxies in SuperK
    - Andromeda (780 kpc) in HyperK

Modern Nuclear Astrophysics

- Neutrinos under extreme conditions
- Nucleosynthesis
- The nuclear matter Equation of State (EOS)

Nucleosynthesis

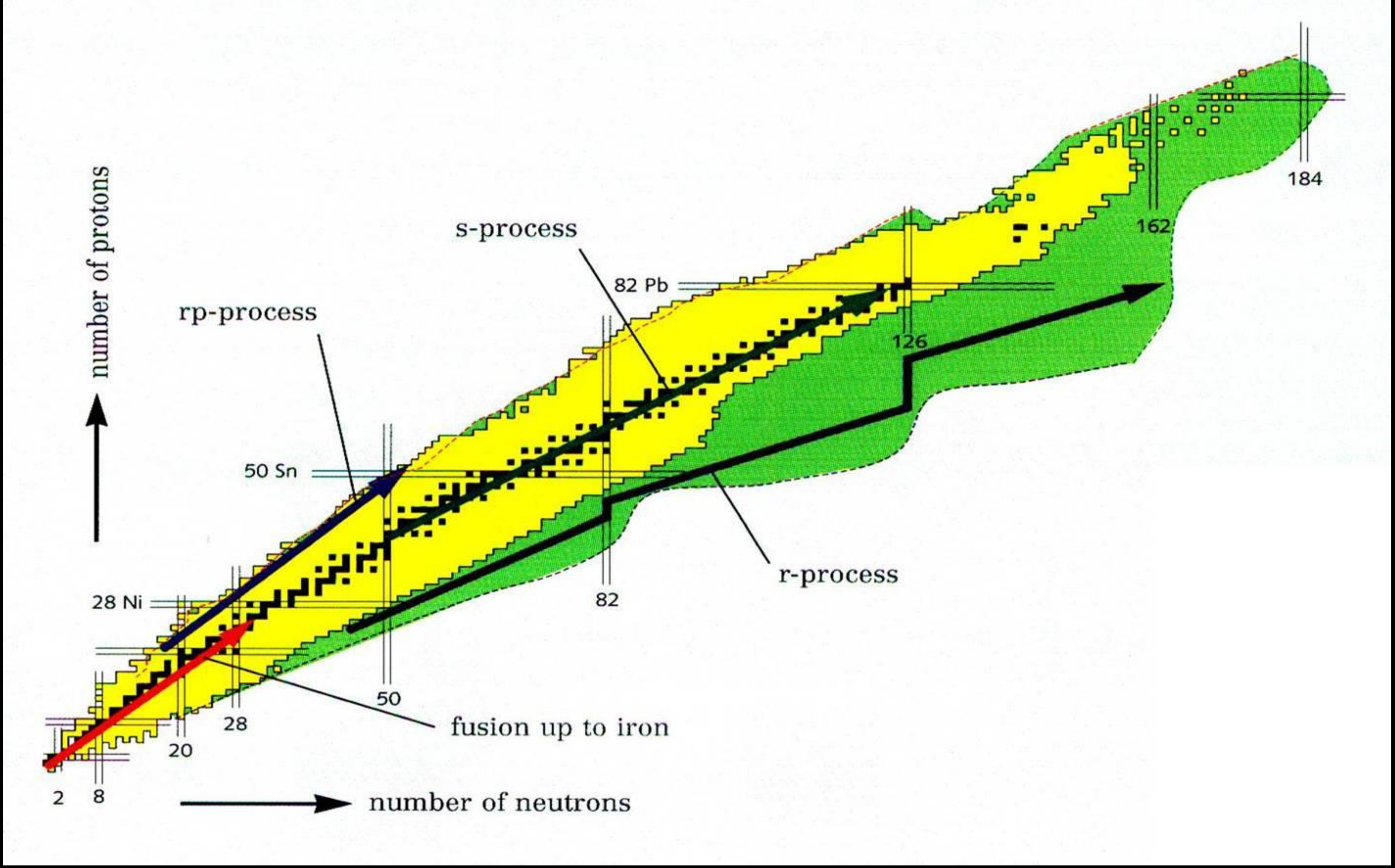
Electron fraction

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

Proton rich

$Y_e = 0.5$

Neutron rich



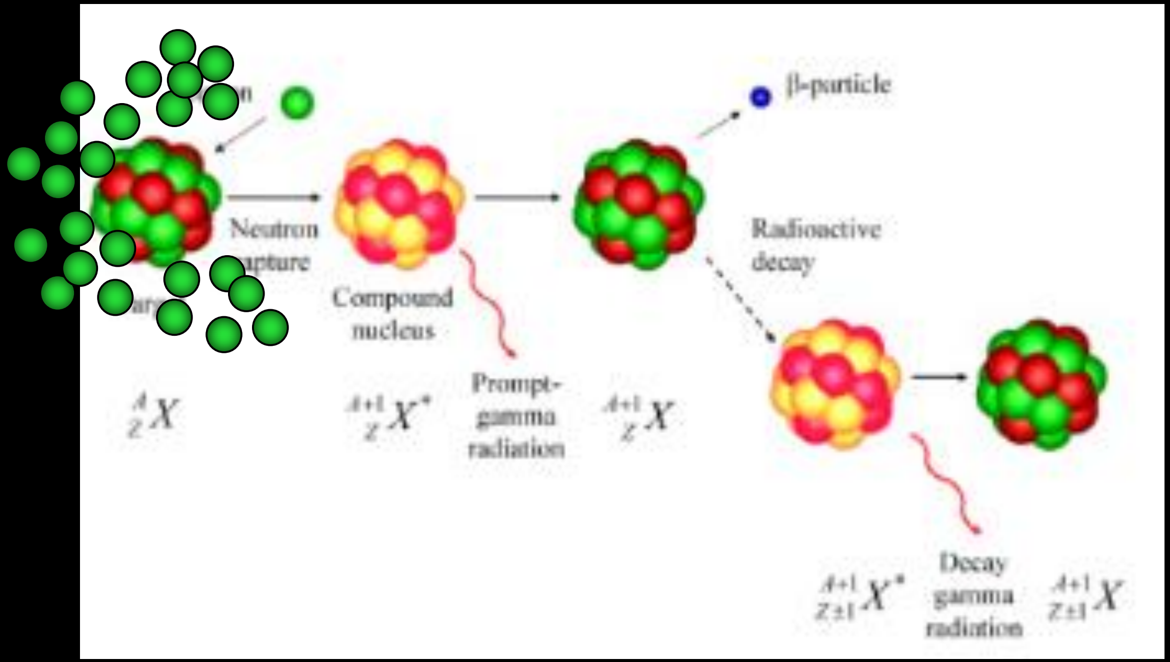
r-process = heavy element synthesis

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

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

rapid neutron capture: neutron capture rate is larger than beta emission rate

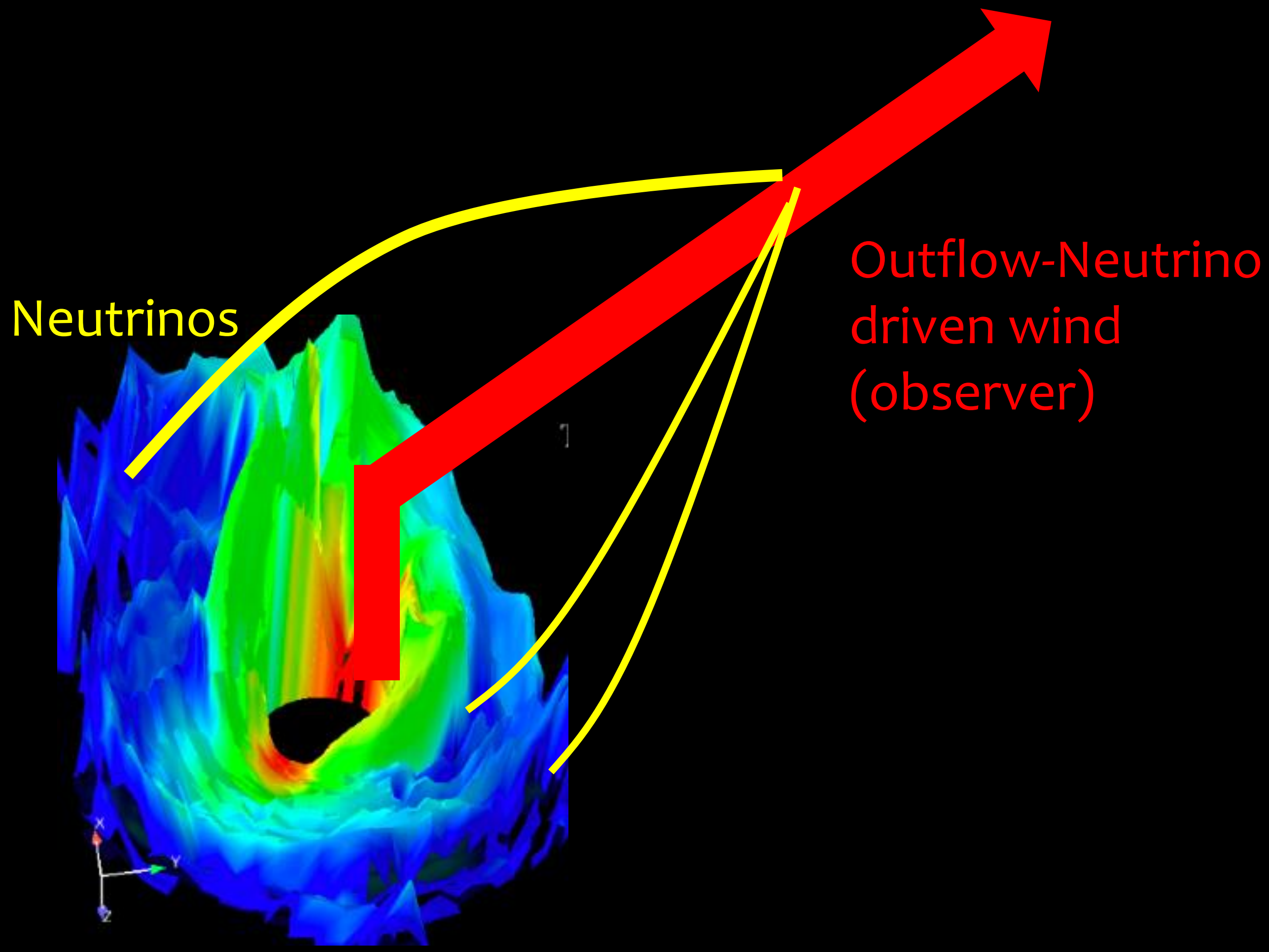
Nuclear structure
Nuclear reactions
Mass models



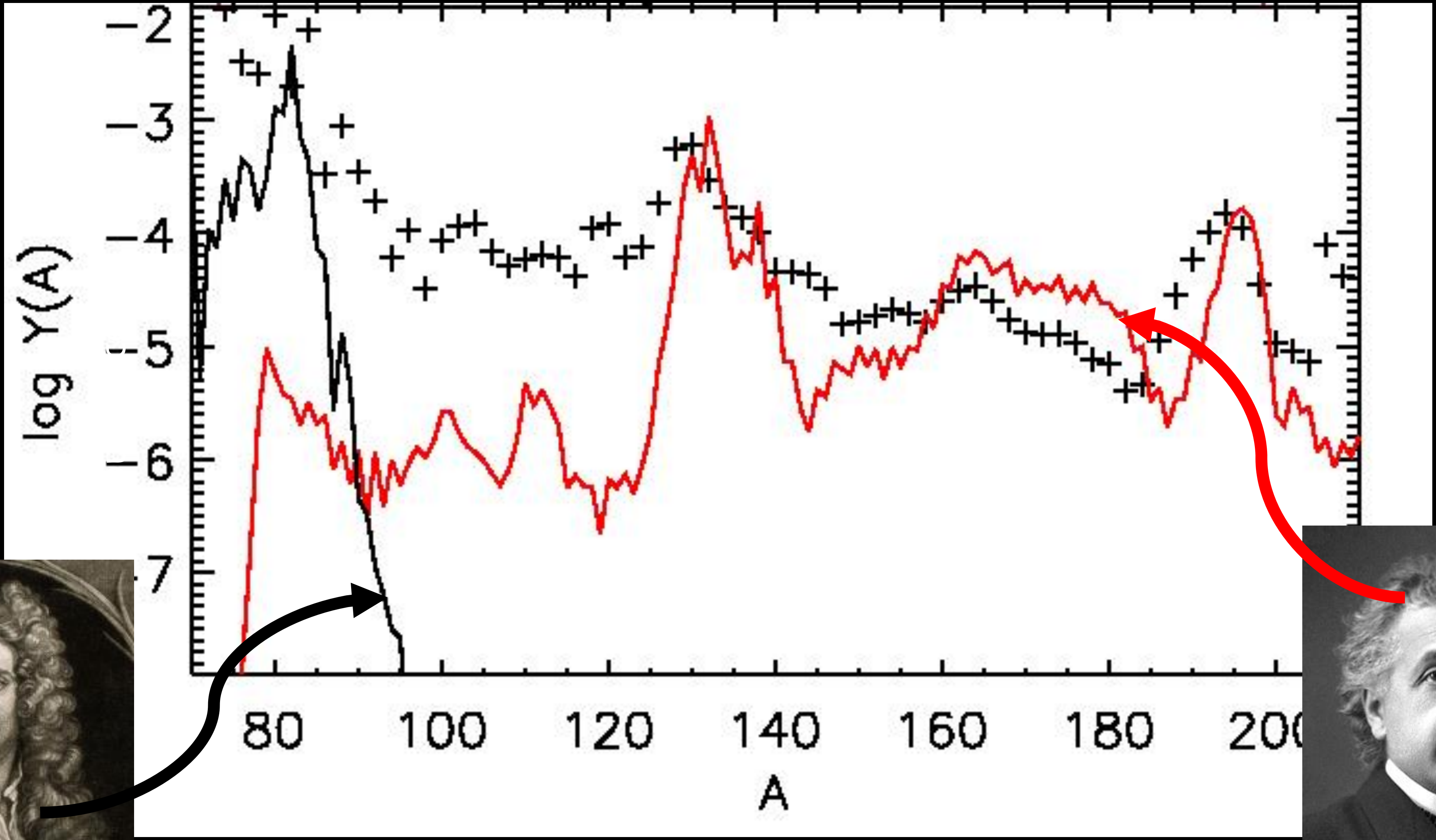
Nucleosynthesis depends on neutrinos and outflow conditions

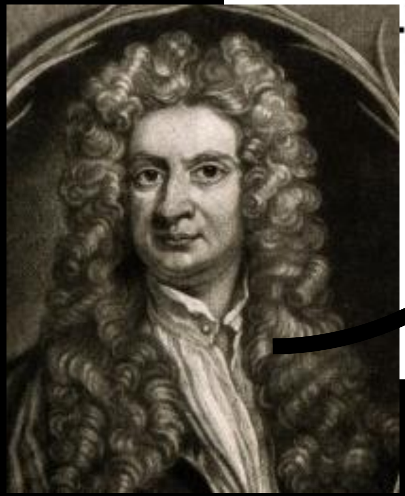
$$\bar{\nu}_e + p \leftrightarrow e^+ + n$$

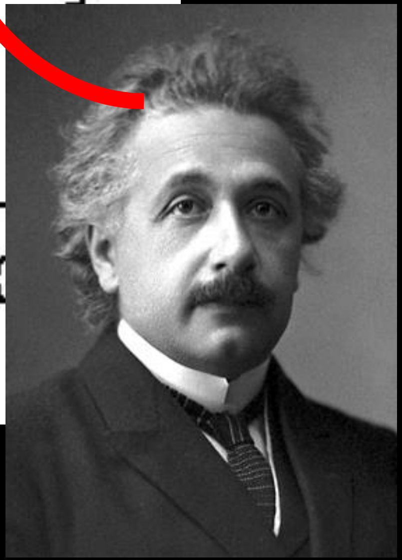
$$\nu_e + n \leftrightarrow e + p$$



If both neutrino and antineutrino fluxes are weak, the nucleosynthesis will strongly depend on the outflow conditions



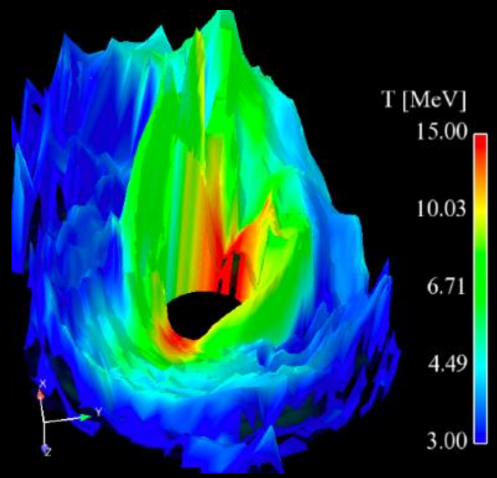




Caballero, McLaughlin, Surman. ApJ 2012

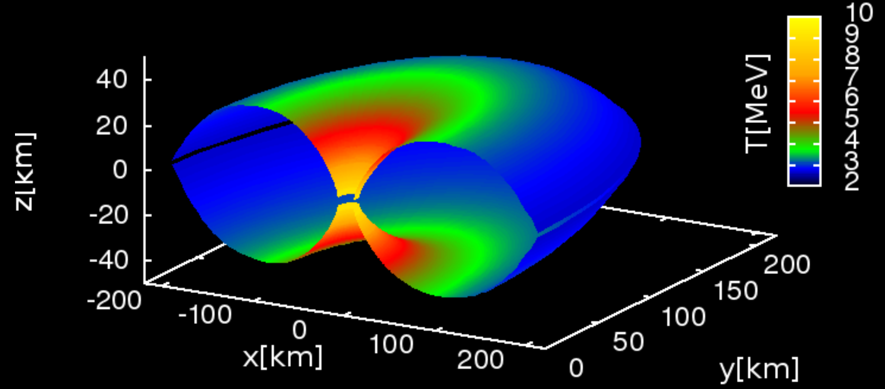
GR: Does not depend on the on the disk model

3D Hydrodynamical Model
(Ruffert & Janka)

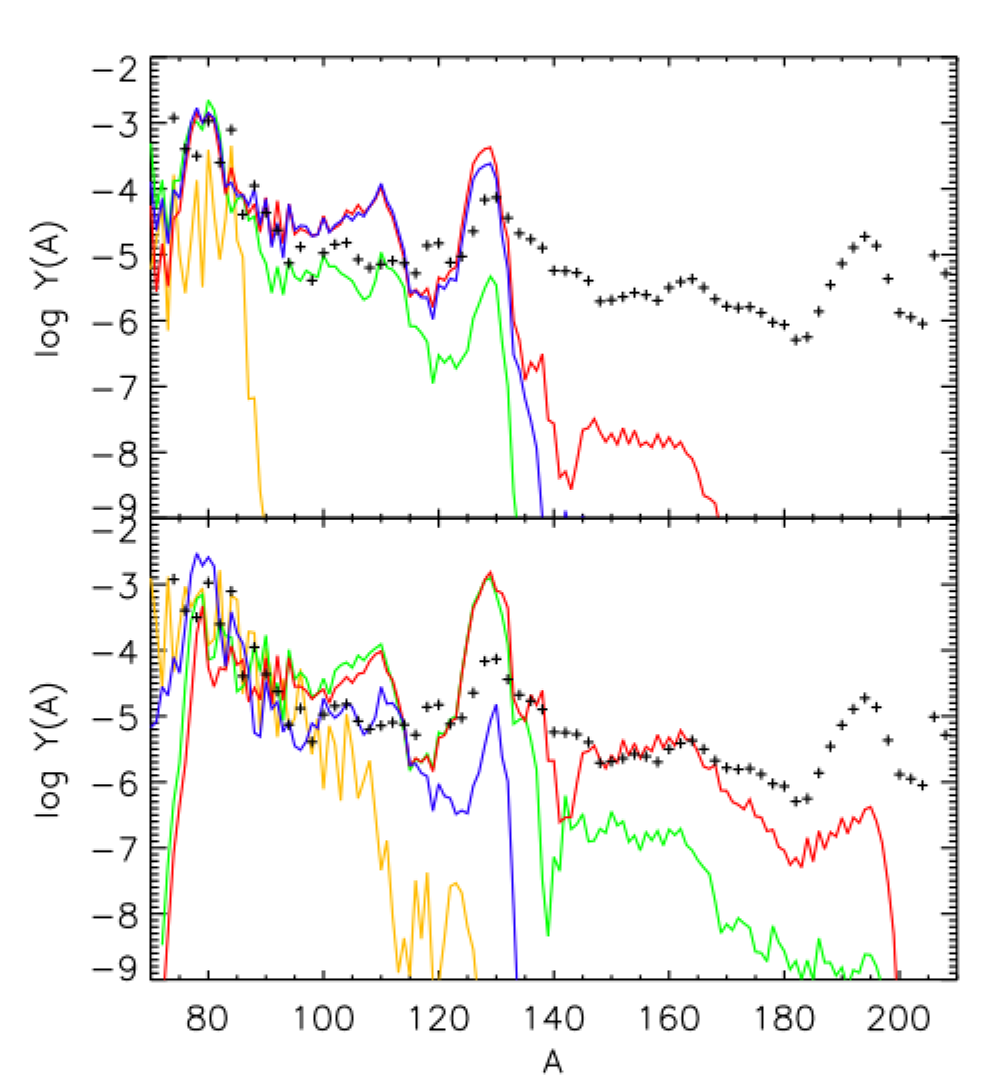


1D steady state disk

(Chen & Belobodorov)



s/k =10, β=0.2



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

- GR effects reduce the neutrino fluxes at high energies (strong for antineutrinos)
- Neutrinos lose some of the influence in setting the neutron to proton ratio
- Abundances (r-process) depend on the conditions of the outflow, the geometry of the disk, and on neutrino fluxes.

Modern Nuclear Astrophysics

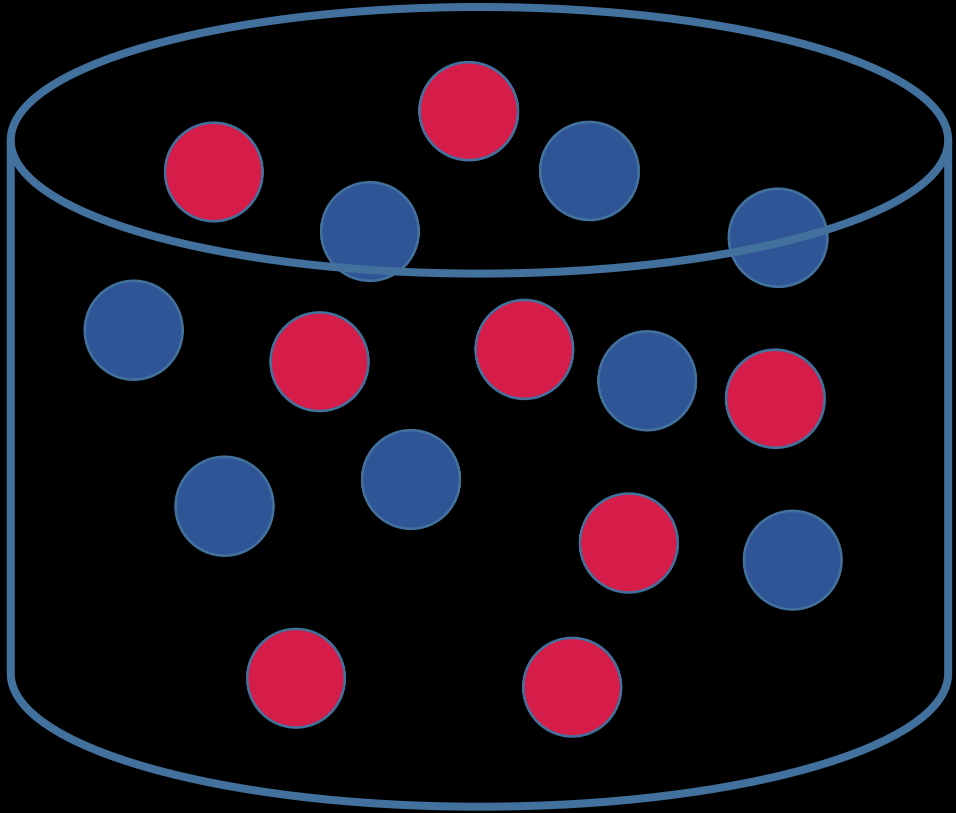
- Neutrinos in dense matter
- Nucleosynthesis
- The nuclear matter Equation of State (EOS)

Equation of State (EOS)

PV=nRT   Ideal Gas

$P = K\rho^n$ Polytrope

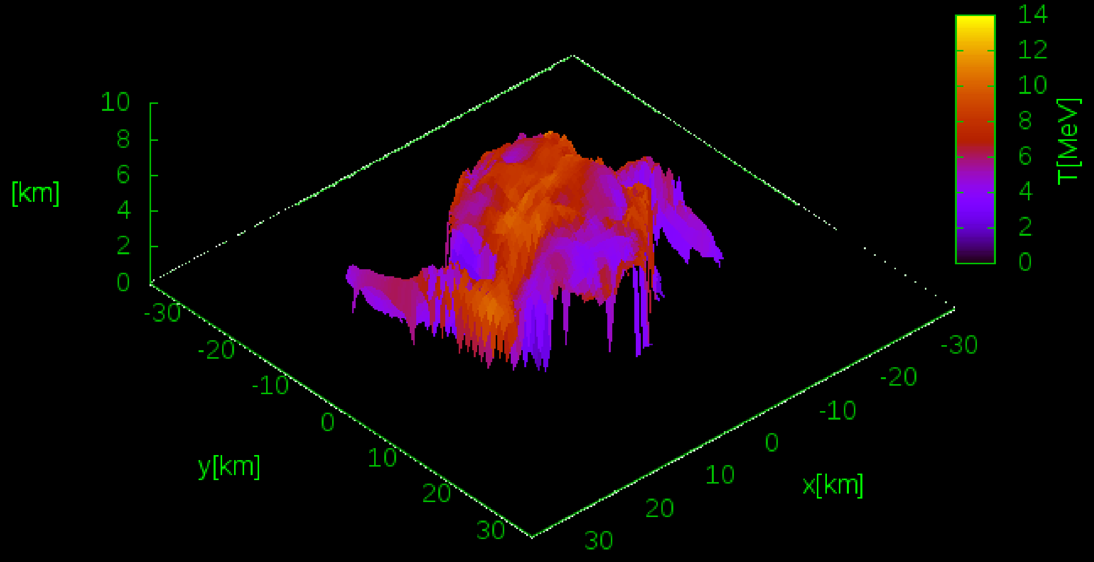
Modern EOSs depend on nuclear interactions



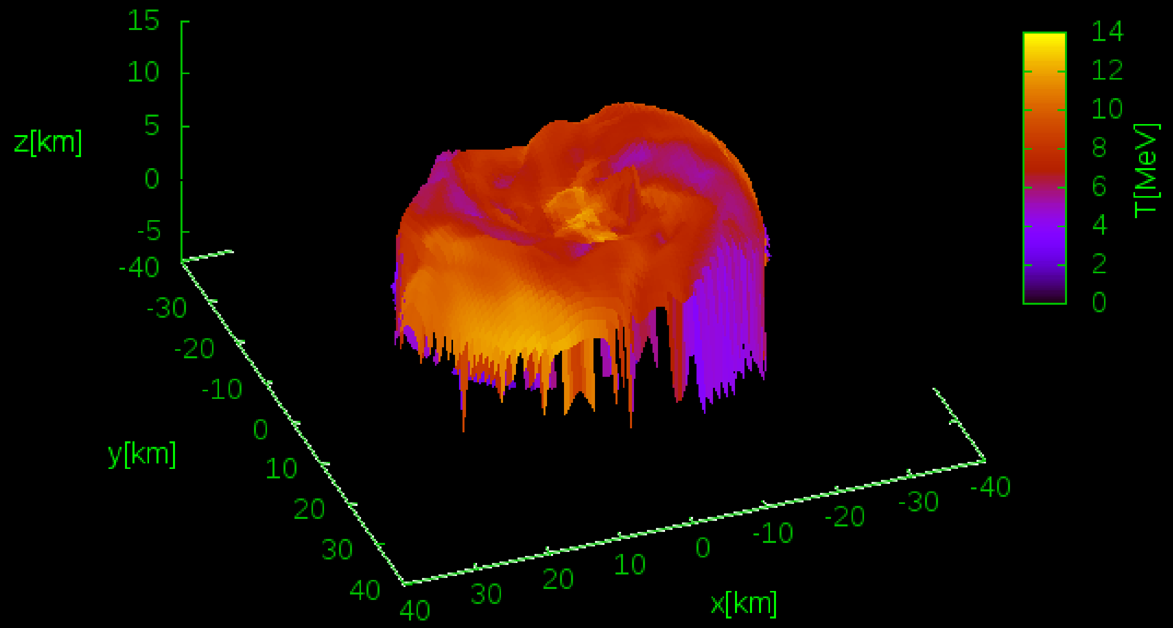
Electron antineutrino surfaces

Fully relativistic 3D merger simulation with neutrino cooling, C. Palenzuela et al PRD 2015

O. L. Caballero (2016)



NL3



SFHo

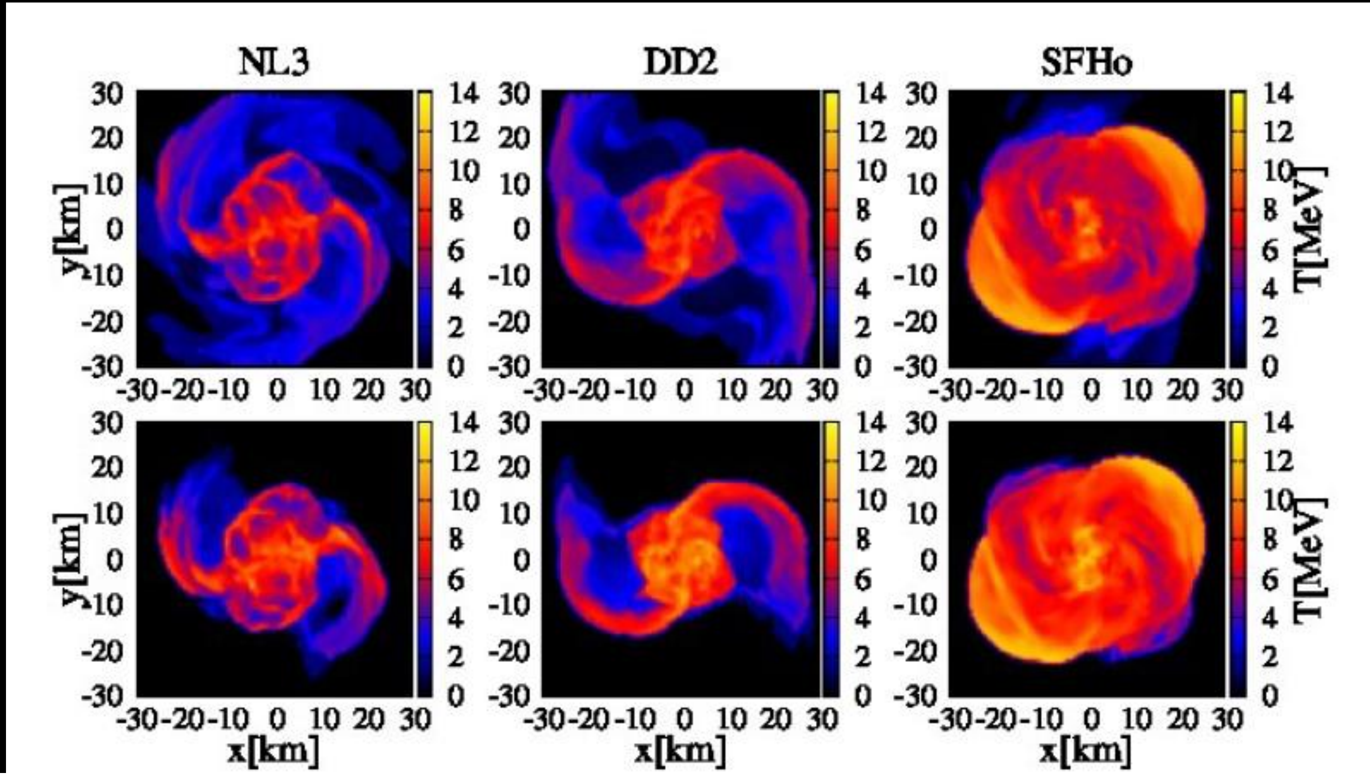
Nuclear interaction
NL3: Lalazissis et al (2008) , stiff
SFHo: Steiner et al (2012) , soft

Could we infer the EoS from the neutrino detection?

Fully relativistic 3D merger simulation with neutrino cooling, C. Palenzuela et al PRD 2015

e-neutrino

e-antineutrino



Time [ms]	$\langle E_{\bar{\nu}_e} \rangle$ [MeV]	$\langle E_{\nu_e} \rangle$ [MeV]	$L_{\bar{\nu}_e}$ [10^{53} erg/s]	R_ν [#/ms]
2.5 (NL3)	18.5 (22.4)	15.2 (18.3)	0.71	18.1
3.0 (DD2)	18.3 (22.1)	14.6 (17.4)	1.1	28.2
3.2 (SFHo)	24.6 (29.7)	23.5 (28.3)	3.5	120.8

Supernova: R= 1/ms, $L=10^{52}$ erg/s, E~ 11 MeV, t=10 sec

- Soft EOS would produce a stronger (more energetic and more counts) neutrino signal compared to a stiff EOS.
- It could be possible to infer the nuclear matter EOS from neutrino and gravitational wave signals.

Conclusions

- Nuclear astrophysics is entering an era of unprecedented developments. Contributions from nuclear physics together with multi-messenger observations will unravel new mysteries.
- Matter at extreme conditions, e.g black hole accretion disks, neutron stars, supernovae provide information to understand the nucleus and vice-versa.
- Neutrinos play a crucial role in the synthesis of elements, and supernovae. Their effect depends of the matter conditions and the space-time geometry.

What is next?....

- How does the EOS affect the synthesis of heavy elements in neutron star mergers?
- How does the black hole spin affect the matter electron fraction in neutrino driven winds from accretion disks?
- How the elemental abundances?
- How does neutron degeneracy influence the neutron capture rates?
- How do nucleon-nucleon correlations change the neutrino surface and related quantities such as electron fraction?

Collaborators

- G. McLaughlin (North Carolina State University), R. Surman (University of Notre Dame), T. Zielinski*(University of Guelph)

- Luis Lehner (Perimeter Institute), Carlos Palenzuela (University of the Balearic Islands), David Neilsen (Bringham Young U.), Steve Liebling (Long Island U.), Evan O’Connor (North Carolina State University)