On the nuclear astrophysics from astrophysics perspective

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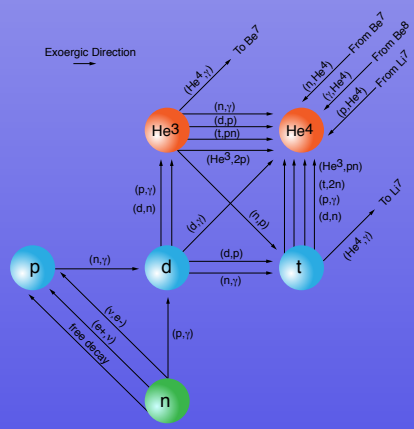
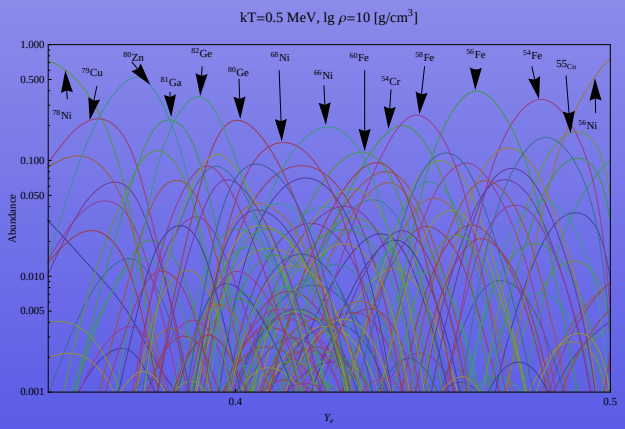
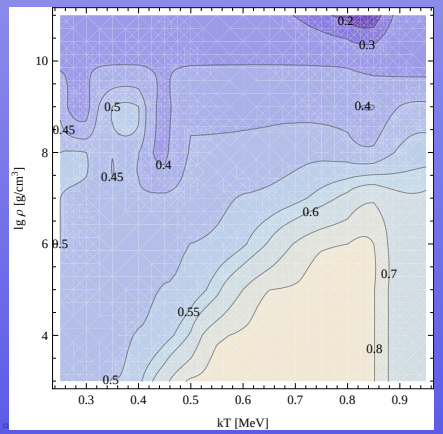
22 May 2018



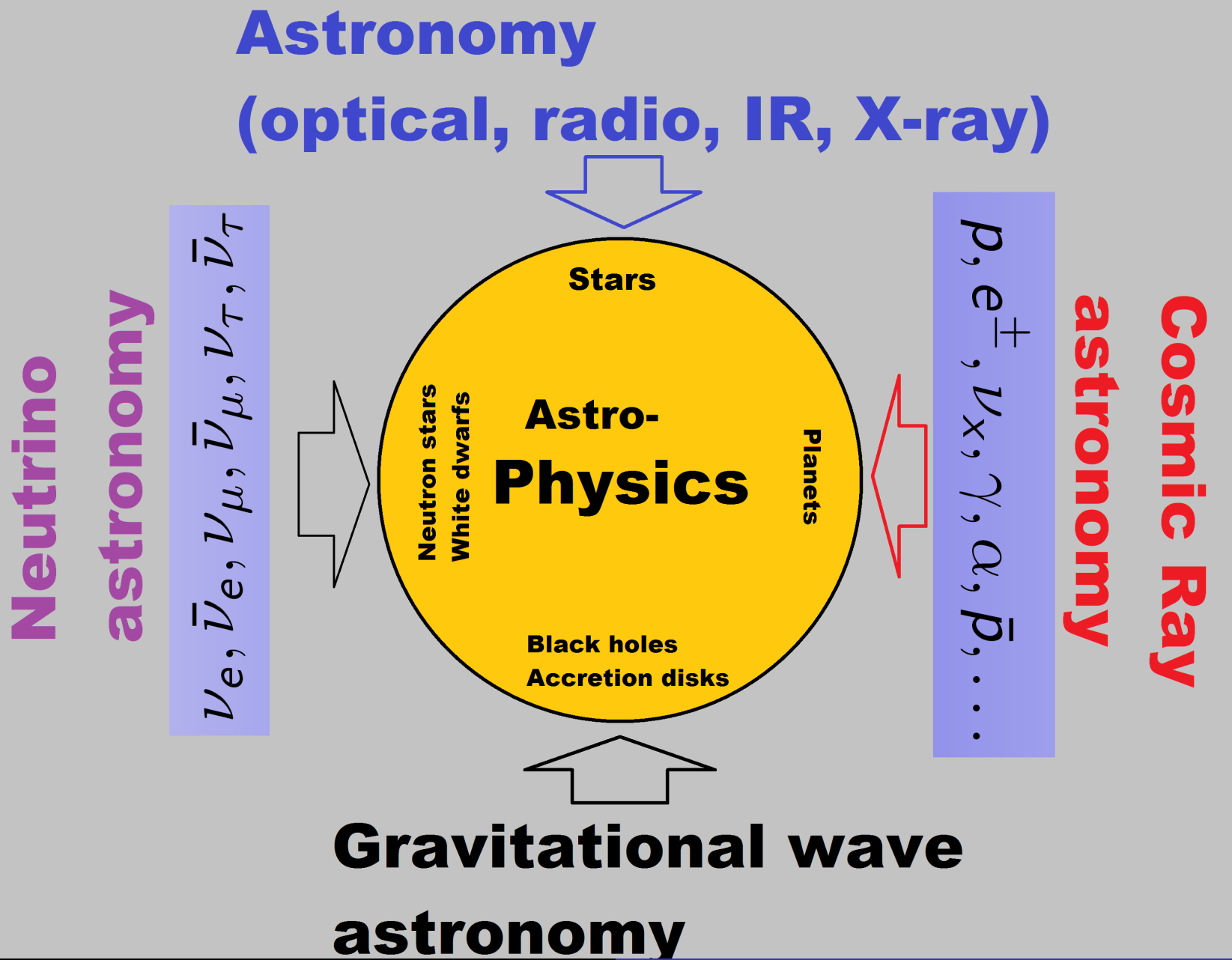




Why Nuclear Astrophysics?

1. Big Bang Nucleosynthesis
2. Nuclear Evolution of the Universe (production of elements)
3. Stellar Amnesia (thermodynamic equlibrium)
4. Supernovae, Novae, Kilonovae
5. Neutrino emission, evolution of neutron excess
6. Neutron stars: interiors, pasta phases, EOS
7. Pyconuclear reactions, explosive hydrogen burning
8. Rotating liquid drop models *vs* rotating stars/disks
9. Extrasolar planet composition: super-Earths, blue ocean, etc.

Astronomy *vs* Astrophysics



Big Bang Nucleosynthesis

Three stages

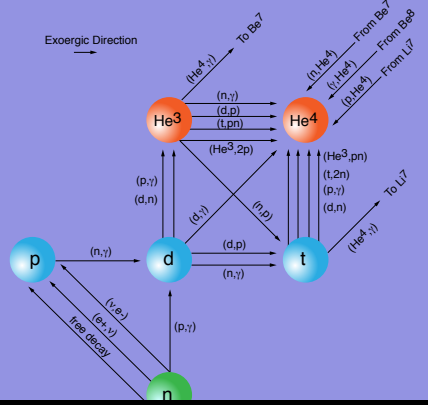
1. p, n in thermodynamic equilibrium ($\Delta = 1.2933$ MeV)

$$\frac{N_n}{N_p} = \frac{e^{-m_n c^2/kT}}{e^{-m_p c^2/kT}} = e^{-\Delta/kT}$$

2. weak freezeout ($kT \simeq 0.7$ MeV), neutron decay/ $d, t, {}^3\mathrm{He}$ photodisintegration ($20kT > 2.2MeV$)

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

3. full nuclear reaction network in expanding matter



Weak freezeout

Proton/neutron mixture kinetics

$$\frac{dn_n(t)}{dt} + 3H(t)n_n = -\lambda_{n\nu_e} n_n + \lambda_{p\bar{\nu}_e} n_p - \lambda_{\beta-} n_n + \lambda_{pe^-\bar{\nu}_e} n_p - \lambda_{ne^+} n_n + \lambda_{pe^-} n_p$$

$$\frac{dn_p(t)}{dt} + 3H(t)n_p = +\lambda_{n\nu_e} n_n - \lambda_{p\bar{\nu}_e} n_p + \lambda_{\beta-} n_n - \lambda_{pe^-\bar{\nu}_e} n_p + \lambda_{ne^+} n_n - \lambda_{pe^-} n_p$$

$H(t)$ - Hubble „constant”; $n_n(t), n_p(t)$ - number density of neutrons and protons; λ_i - reaction rate.

All reaction rates are remarkably similar, e.g:

$$\lambda_{n\nu_e} = \frac{\ln 2}{\langle ft \rangle m_e^5} \int_\Delta^\infty \frac{(E_e + \Delta)^2 E_e \sqrt{E_e^2 - m_e^2}}{1 + e^{(E_e - \Delta)/kT}} \left(1 - \frac{1}{1 + e^{E_e/kT}}\right) \mathrm{d}E_e$$

and except for phase-space/blocking factors can be tracked down do **free neutron lifetime**!

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Importance of neutron lifetime

BBN uncertainties

BBN now (could) become zero-parameter (?) model:

1. traditional BBN free parameter, baryon-to-photon ratio PDG2015, [PDG2018, 95% CL (2σ)]:

$$\eta \equiv \frac{n_B}{n_\gamma} \simeq 6.05 \pm 0.07 \times 10^{-10},\ 6.2 \pm 0.4 \times 10^{-10}$$

   which determine initial conditions for BBN reaction network, now known from **C**osmic **M**icrowave **B**ackground/Planck satellite.

2. number of neutrino families:

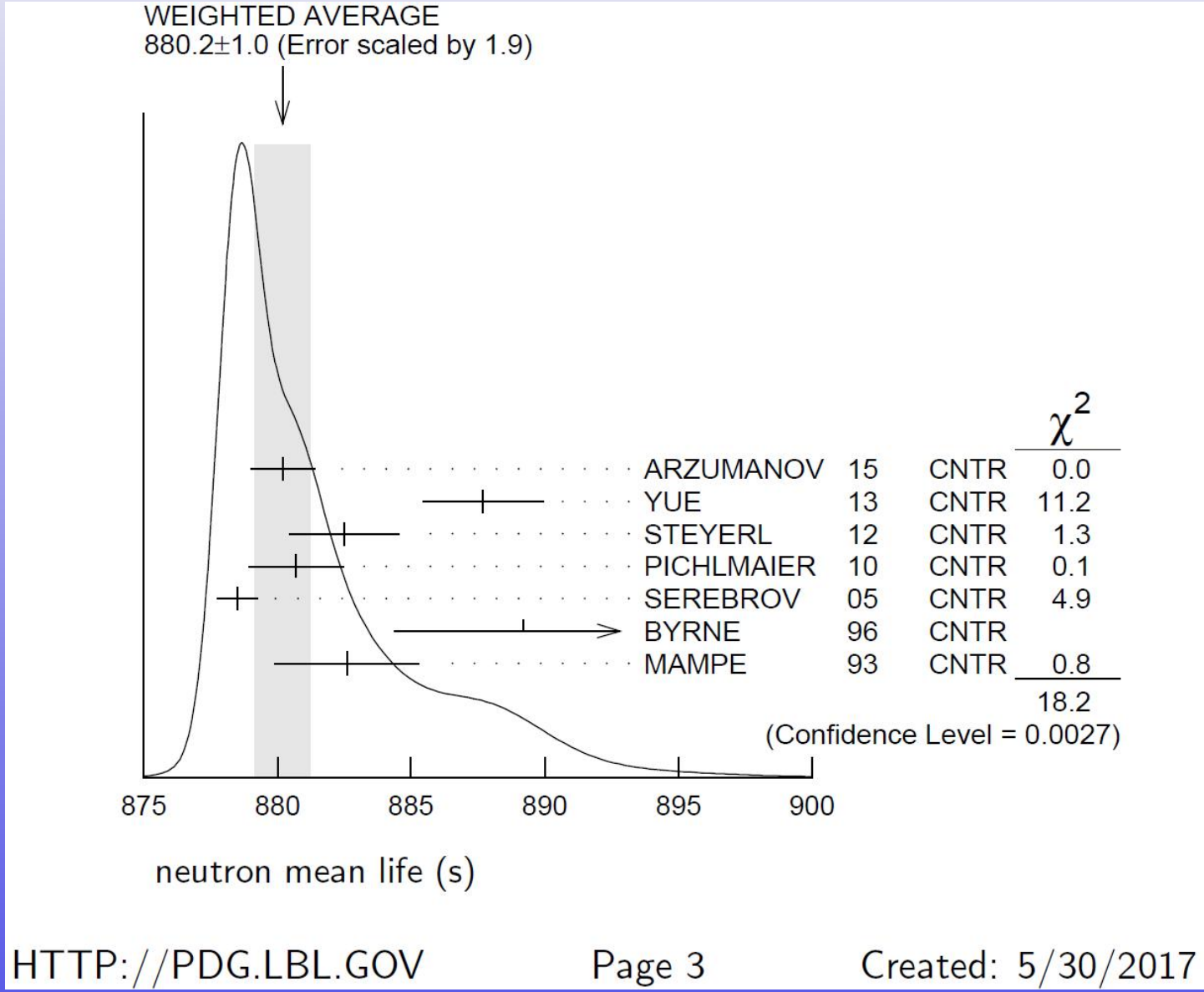
$$N_\nu = 2.984 \pm 0.008$$

   known from CERN LEP.

3. lifetime of neutron measured:

$$\tau_n = 880.2 \pm 1.0 \text{ seconds.}$$

Neutron lifetime



Notable BBN software

- Kawano, PArthENoPE - original Wagoner/Hoyle code and clones, http://parthenope.na.infn.it/
- Alter BBN, https://alterbbn.hepforge.org/
- PRIMAT - Mathematica code, https://arxiv.org/abs/1801.08023
- F.X.Timmes BBN code, http://cococubed.asu.edu/code_pages/net_bigbang.shtml

Experiments devoted to improve low-energy cross-sections, e.g:

$$d\,(p,\gamma)^3\,\mathrm{He}$$

1. LUNA (Laboratory for Underground Nuclear Astrophysics), Laboratori Nazionali del Gran Sasso (LNGS), Italy

Hydrogen burning: *ppI* cycle

$$
\begin{array}{rcll}
p + p & \rightarrow & d + e^+ + \nu_e & \text{reaction rate } \lambda_{pp} \\
p + d & \rightarrow & {}^3\mathrm{He} + \gamma & \text{reaction rate } \lambda_{pd} \\
{}^3\mathrm{He} + {}^3\mathrm{He} & \rightarrow & \alpha + 2p & \text{reaction rate } \lambda_{33}
\end{array}
$$

Kinetic equations:

$$
\begin{aligned}
\dot{n}_p &= -2\lambda_{pp} n_p^2 - \lambda_{pd} n_p n_d + 2\lambda_{33} n_3^2 \\
\dot{n}_d &= +\lambda_{pp} n_p^2 - \lambda_{pd} n_p n_d \\
\dot{n}_3 &= +\lambda_{pd} n_p n_d - 2\lambda_{33} n_3^2 \\
\dot{n}_\alpha &= \lambda_{33} n_3^2
\end{aligned}
$$

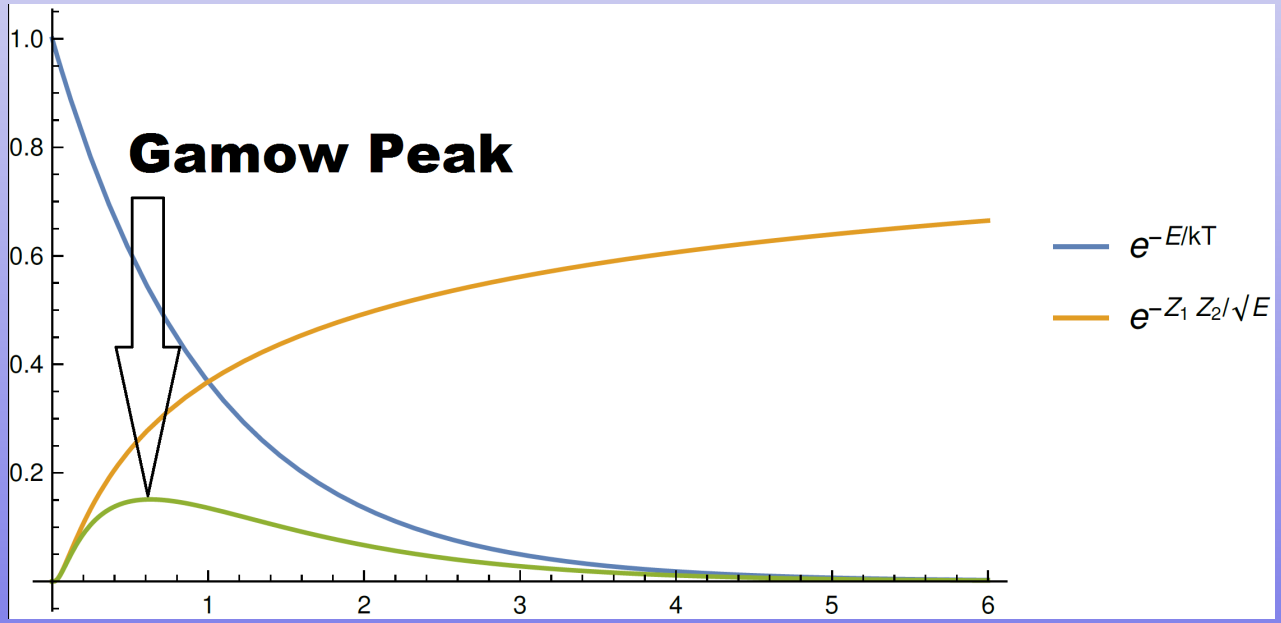
Baryon number conservation:

$$
\sum_{i=1}^{4} A_i n_i = n_p + 2n_d + 3n_3 + 4n_\alpha = const,
$$

$$
\dot{n}_p + 2\dot{n}_d + 3\dot{n}_3 + 4\dot{n}_\alpha = 0.
$$

From cross-section/S-factor to reaction rate

$$\lambda \propto \int_0^\infty e^{-\frac{E}{kT}} \sigma(E) E \, \mathrm{d}E = \int_0^\infty e^{-\frac{E}{kT}} \frac{S(E)}{E} e^{-2\pi\eta} E \, \mathrm{d}E$$

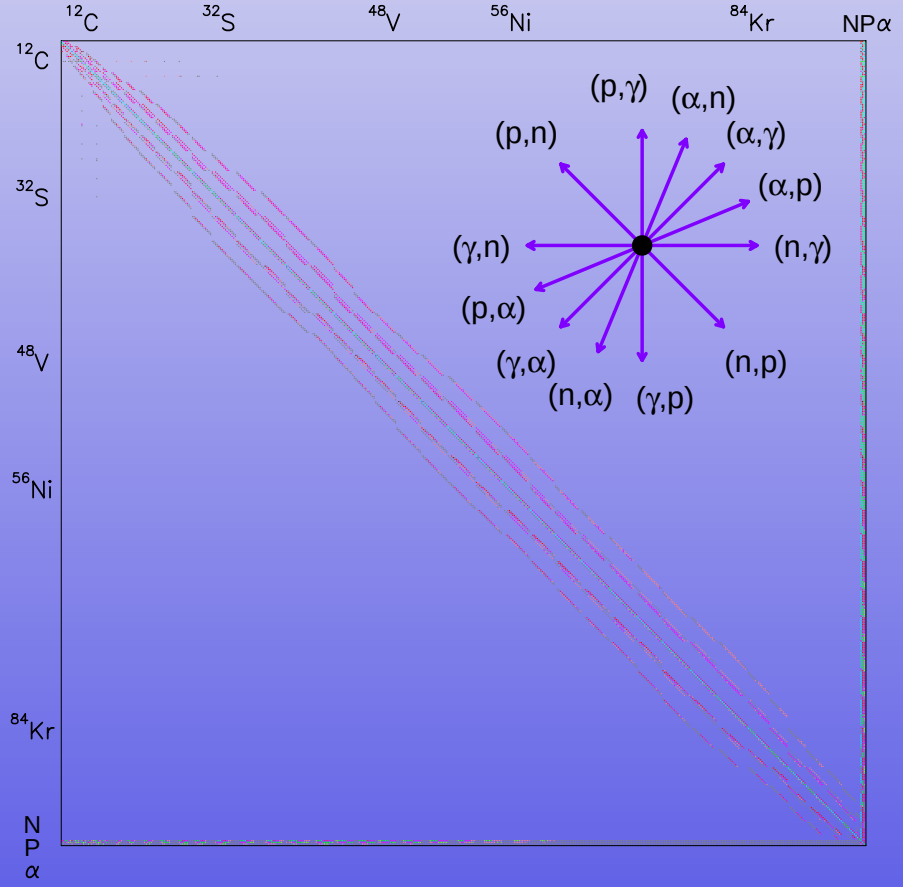


- Boltzmann distribution $e^{-\frac{E}{kT}}$ (thermal energy tail)
- Sommerfeld parameter ($v = \sqrt{2E/m}$ - relative velocity): (quantum electrostatic barrier tunneling)

$$\eta = \alpha \frac{Z_1 Z_2}{v/c} = \frac{Z_1 Z_2}{2\epsilon_0 \, v}$$

General nuclear burning: hardwired vs soft-wired

With increased amount of measured/computed nuclei and cross-sections reaction networks become prohibitively complicated and poorly understood. **Statistical methods can help!**



See e.g. http://cococubed.asu.edu/code_pages/net_torch.shtml

Nuclear Statistical Equilibrium

- idea dates back to F. Hoyle, „nuclear statistical mechanics"

  „The synthesis of the elements from hydrogen", MNRAS, **106** (1946) 343.
- Hoyle proposed two pathways to nucleosynthesis theory:
  1. find equilibrium for **known** objects `[in 1946 just stars]`
  2. analyze whole $T - \rho$ plane, select interesting regions **then** look for appropriate phenomena in cosmos `[now: stars, thermonuclear & core-collapse supernovae, novae, X-ray bursts, NS-NS mergers, Big Bang, cosmic-ray, ...?]`
- P. Holfich coined „stellar amnesia" idea - regardless of complicated history matter finish in equilibrium state
- in famous B^2FH article *Synthesis of the Elements in Stars*, E. Burbridge, G. Burbridge, W. Fowler, F. Hoyle, Rev. Mod. Phys. 29 (1957) 547 NSE is referred to as **e-Process**.
- above article established **Nuclear Astrophysics** as separate branch of physics; many nuclear physicists retrained as astrophysicists, incl. H. Bethe and many our colleagues here in Cracov e.g. K. Grotowski

NSE: assumptions

1. Full equilibrium determined by 2 parameters T and ρ only (baryon number B and electric charge Q conservation) is very rare, because of properties of *neutrinos*.
2. additional parameter is required, related to [electron] lepton number L_e conservation
3. usually it is either **neutron excess** η or lepton-to-baryon number ratio Y_e:

$$\eta = \frac{N_n - N_p}{N_B}, \qquad Y_e = \frac{N_e}{N_B} \equiv \frac{N_p}{N_B}, \qquad \eta = 1 - 2Y_e$$

4. Y_e is assumed constant because:
   1. slow weak interactions compared to strong interactions
   2. kinetic β equilibrium: identical ν_e and $\bar{\nu}_e$ emission

NSE: equations

$$\sum_{k=0}^{N_{iso}} X_k = 1 \tag{1a}$$

$$\sum_{k=0}^{N_{iso}} \frac{Z_k}{A_k} X_k = Y_e \tag{1b}$$

Abundance X_k k-th nuclide of atomic number Z_k and mass number A_k:

$$X_k = \frac{1}{2} G_k(T) \left(\frac{1}{2}\rho N_A \lambda^3\right)^{A_k - 1} {A_k}^{5/2} X_n^{A_k - Z_k} X_p^{Z_k} e^{\frac{Q_k}{kT}}. \tag{2}$$

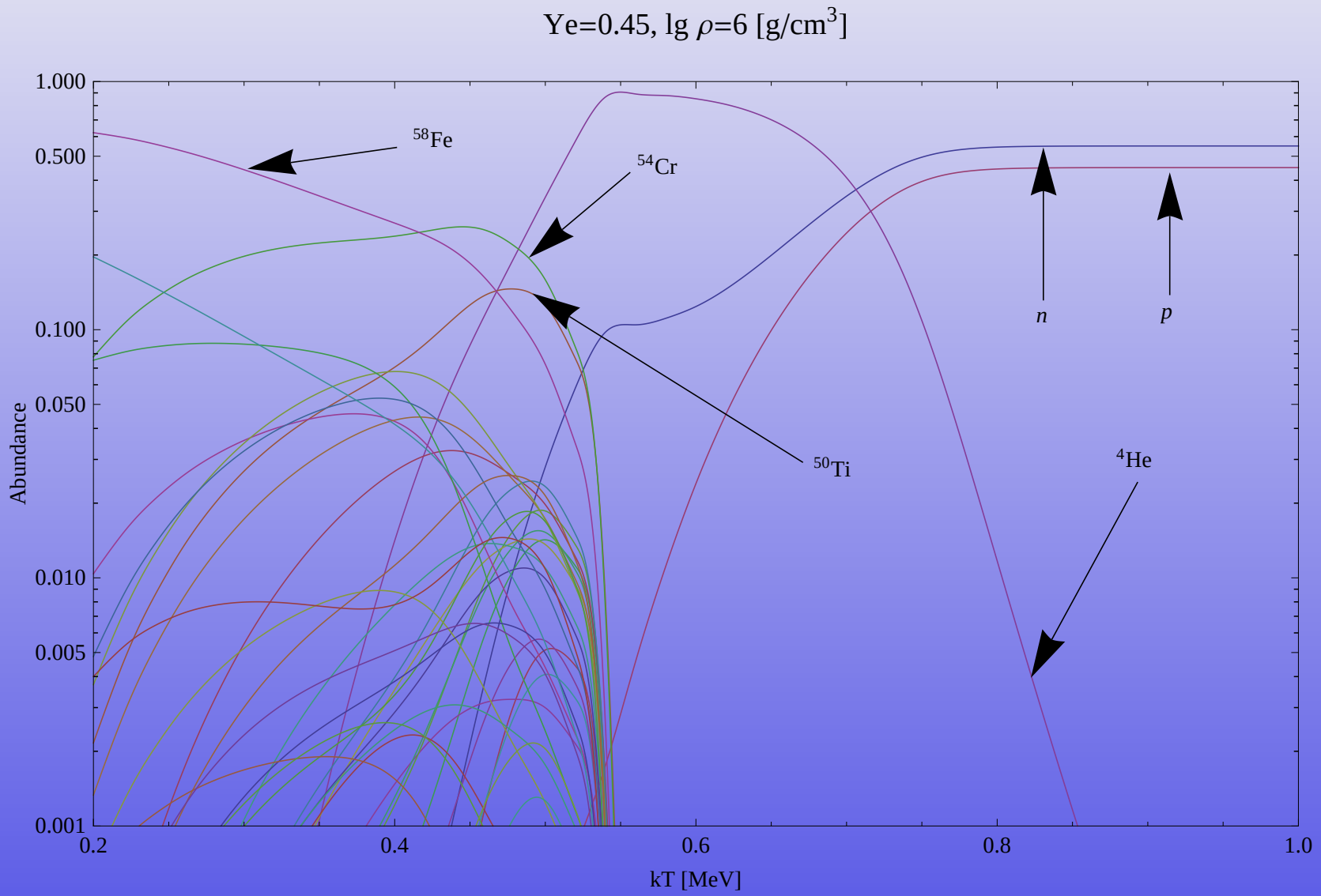
Temperature-dependent partition function:

$$G_k(T) = \sum_{i=0}^{i_{max}} (2J_{ik} + 1) e^{-\frac{E_{ik}}{kT}} \tag{3}$$

NSE: solution

1. two unknowns: proton and neutron abundance X_p and X_n
2. very high order polynomial system (up to X^A, e.g. ^{238}U)
3. basic nuclear structure enough:
   - nuclear mass or binding energy
   - ground state spin
   - excited energy levels and spins
4. input variables: $T - \rho - Y_e$ triad

NSE: viewgraphs



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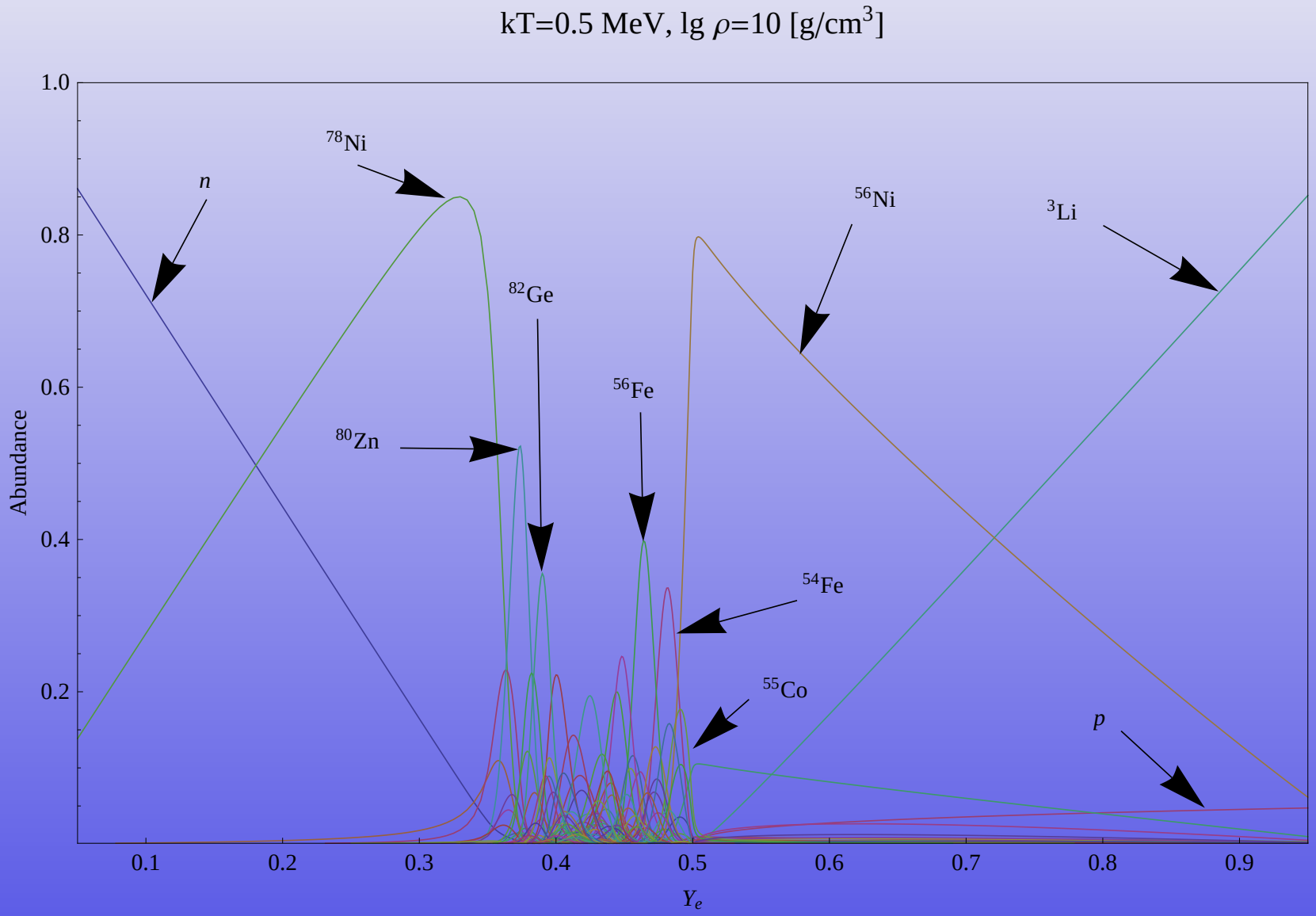

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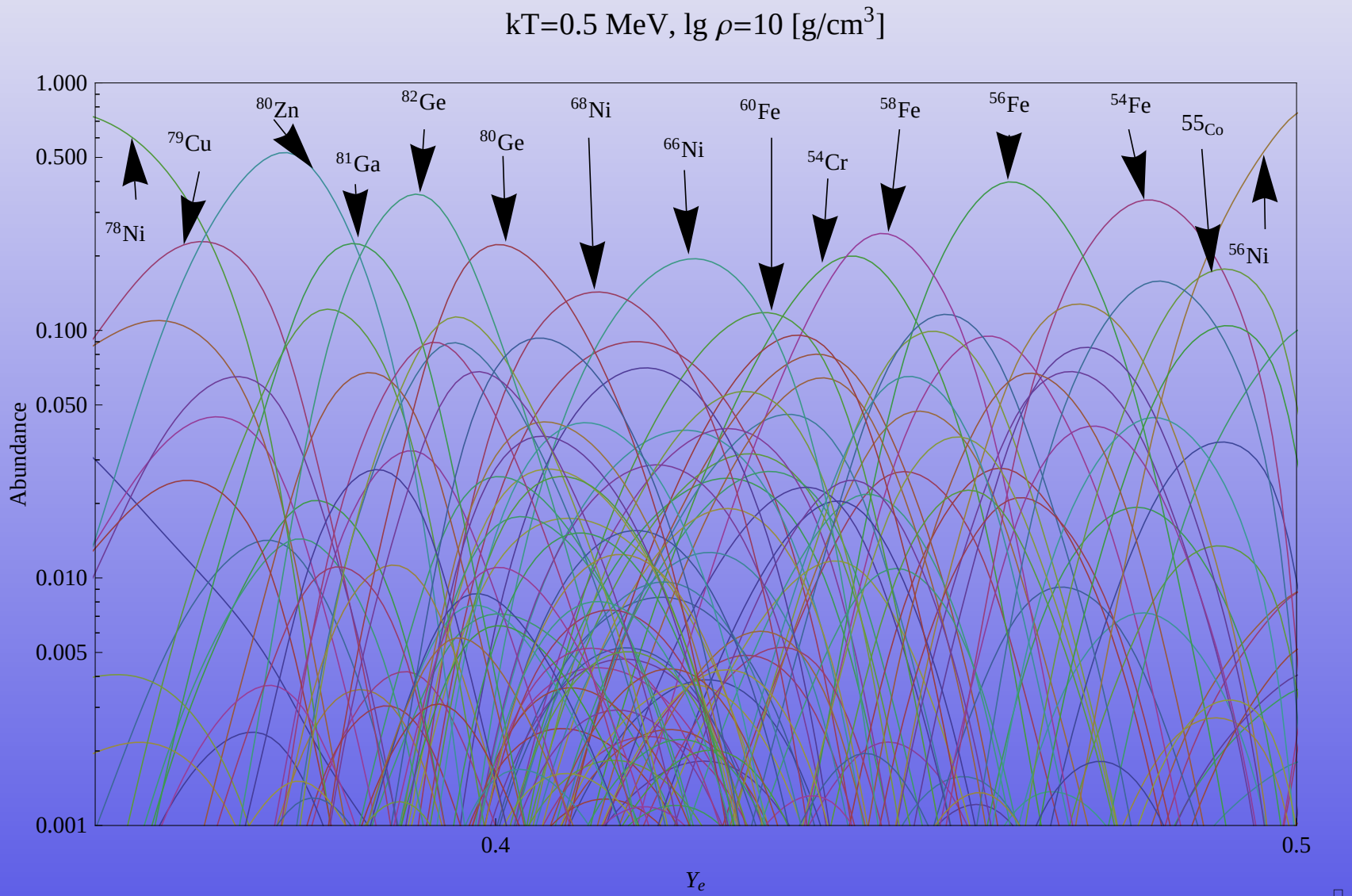


Explosive phenomena in the Universe

1. either by kinetic equations or equilibrium methods we are able to find conditions responsible for a subset of produced nuclei
2. most sites are now established
3. it is not enough to produce elements — they must be ejected/spread into the Galaxy
4. we must enter formidable area of numerical simulations of **supernovae**, **novae** , compact object (black holes, neutron stars, white dwarfs) **mergers** and accretion disks
5. nuclear physics provides essential input data in form of:
   - nuclear cross-sections / reaction rates
   - binding energies and structure of nuclei
   - weak interaction rates (β decays, $e^{\pm}$ captures)
   - last but not least: **E**quation **O**f **S**tate for nuclear matter

Supernovae

Two physical types of supernova

Given two known primary sources of energy in the Universe:

1. **Thermonuclear** supernova - nuclear explosion or even detonation of the whole star `[Type Ia, PISN?]`
2. **Core-Collapse** supernova - gravitational collapse of the central region of the star `[Type Ib/c, II, long-GRB]`

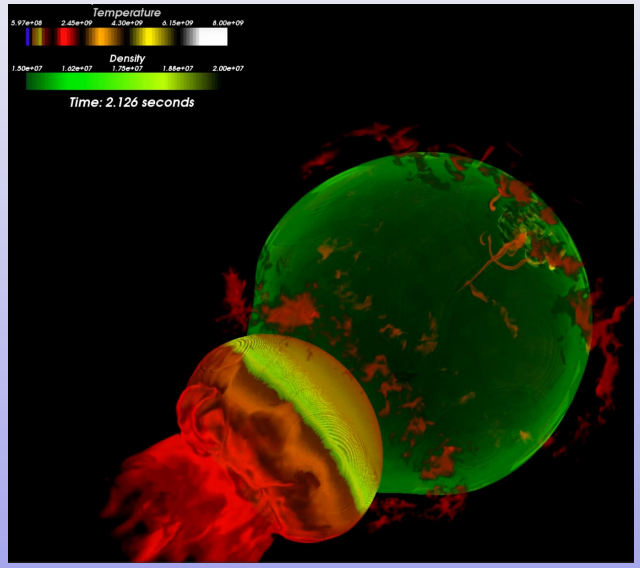
Crash-course in stellar evolution:

- burn H $\rightarrow$ He $\rightarrow$ C/O $\rightarrow$ „iron" as far as initial mass goes UP
- if $M < M_\odot$ He white dwarf forms with $M < M_\odot$
- if $1M_\odot < M < 8M_\odot$ C/O white dwarf forms with $M \simeq M_\odot$
- if $M > 8M_\odot$ iron white dwarf forms at the center with $M_\odot < M_{\mathrm{Fe}} < 2M_\odot$ and subsequently collapse to **neutron star**
- if $M \gg 25M_\odot$ quiet collapse to a black of a whole star [or possibly thermonuclear explosion of massive C/O core]

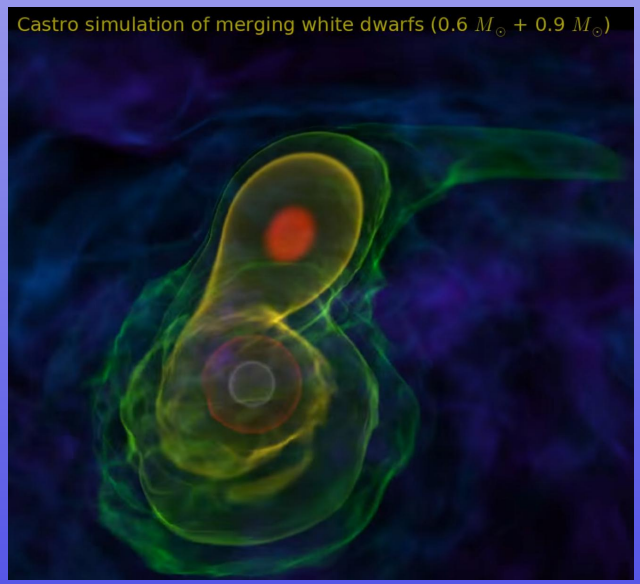
Type Ia (thermonuclear) supernova

1. every white dwarf is a ticking unexploded bomb waiting for $\sim 10^9$ years for explosion
2. slow-match fuse is either accretion from companion star in binary system, or emission of gravitational waves
3. after ignition mass threshold, explosive thermonuclear burning front incinerate whole star in few seconds

Deflagration-Detonation Transition: click:[D-D-T]

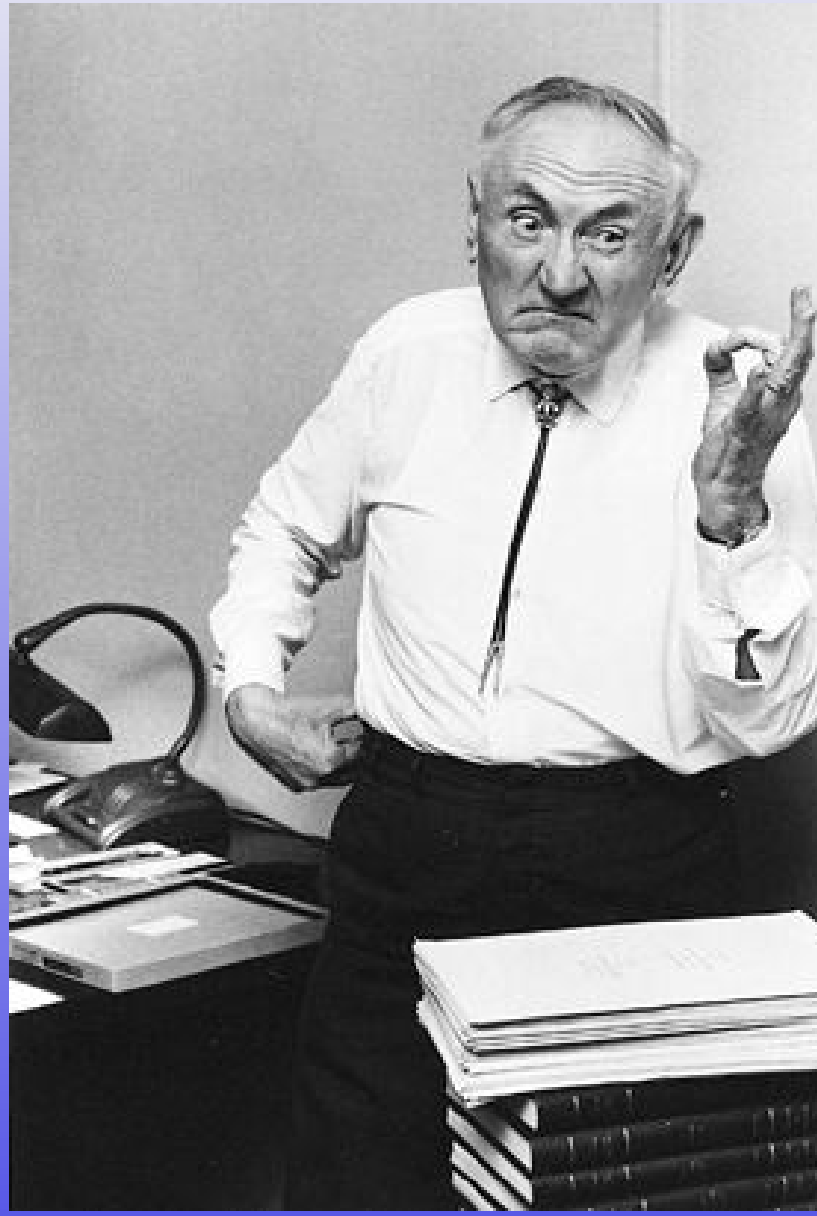


White dwarf merger: click:[WD Merger]



[Core-Collapse] Super-Nova

- Baade&Zwicky (1930-40) find and name several supernovae
- final distinction between classical novae [Galactic] and super-novae [extragalactic]
- they correctly (!) guess physical explosion mechanism: collapse to pure neutron object (neutron discovery: 1932)
- finally super-nova becomes supernova
- true Zwicky's motivation for name still mystery



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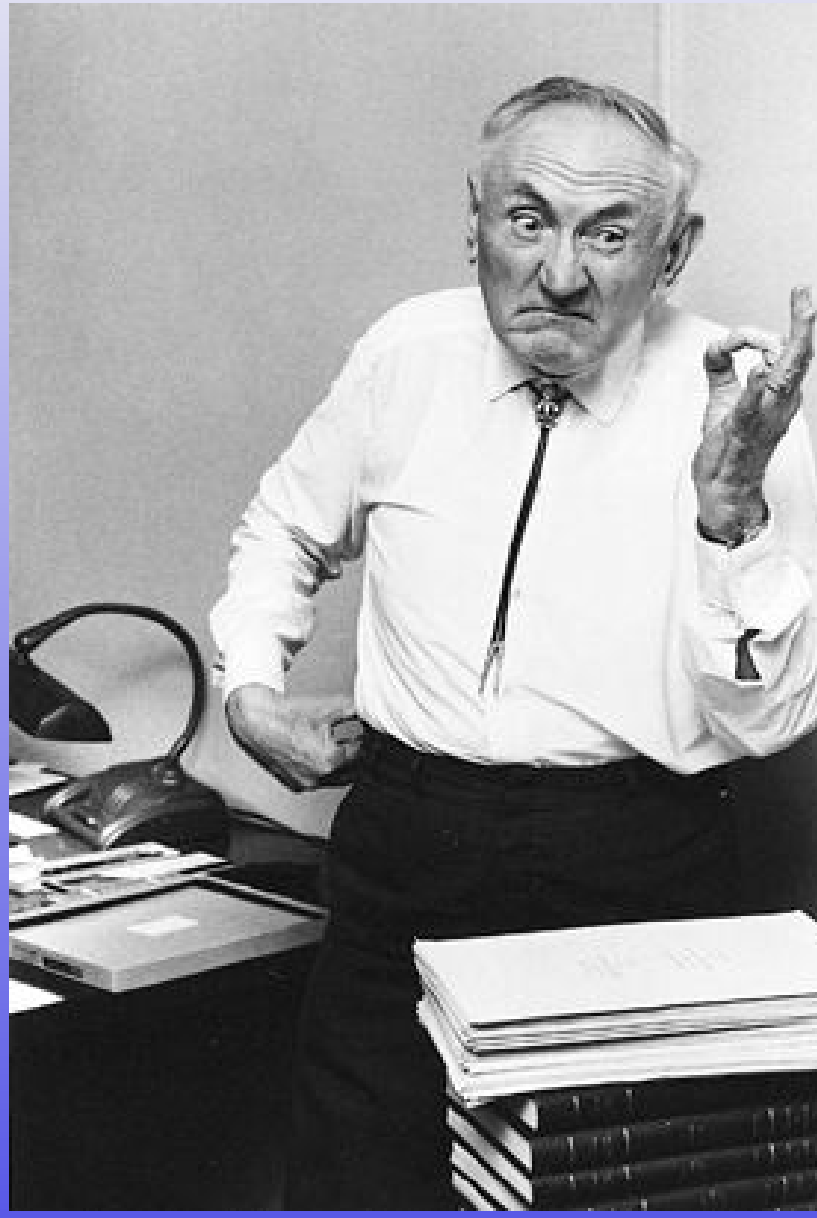

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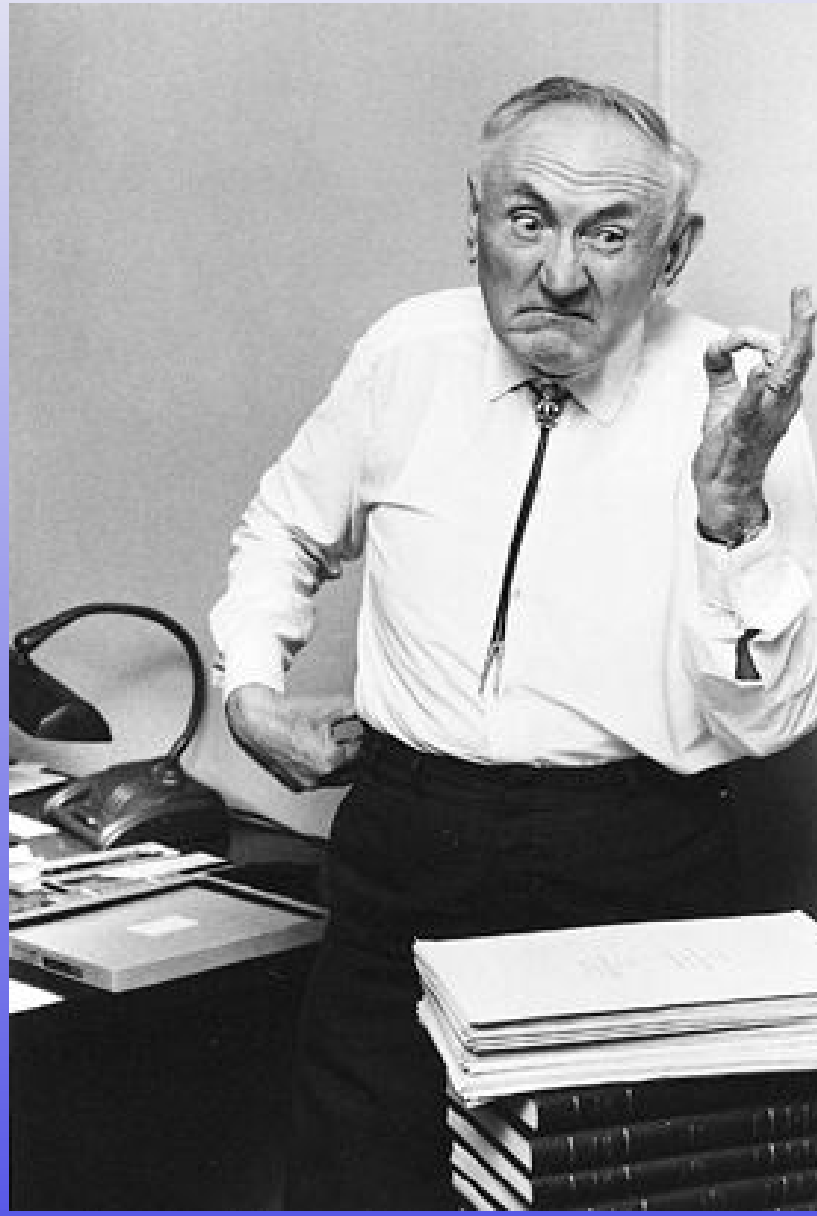

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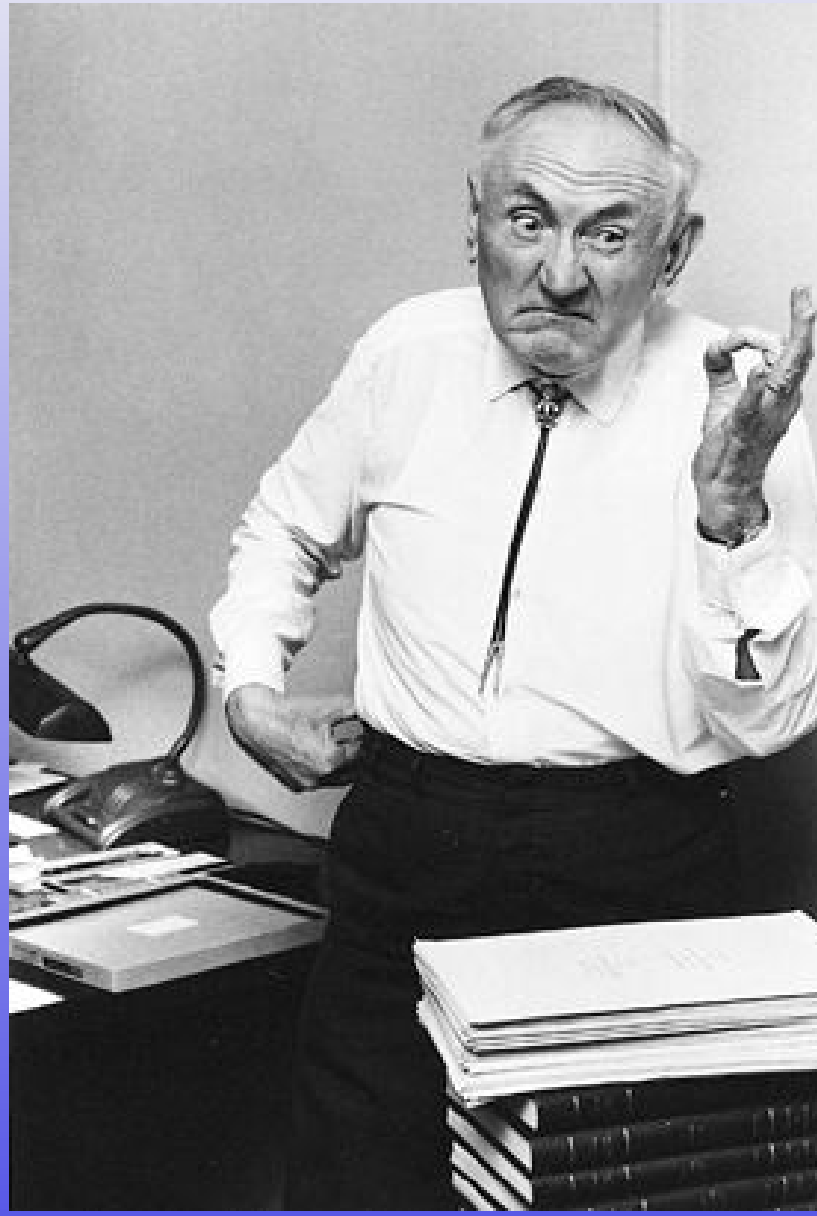

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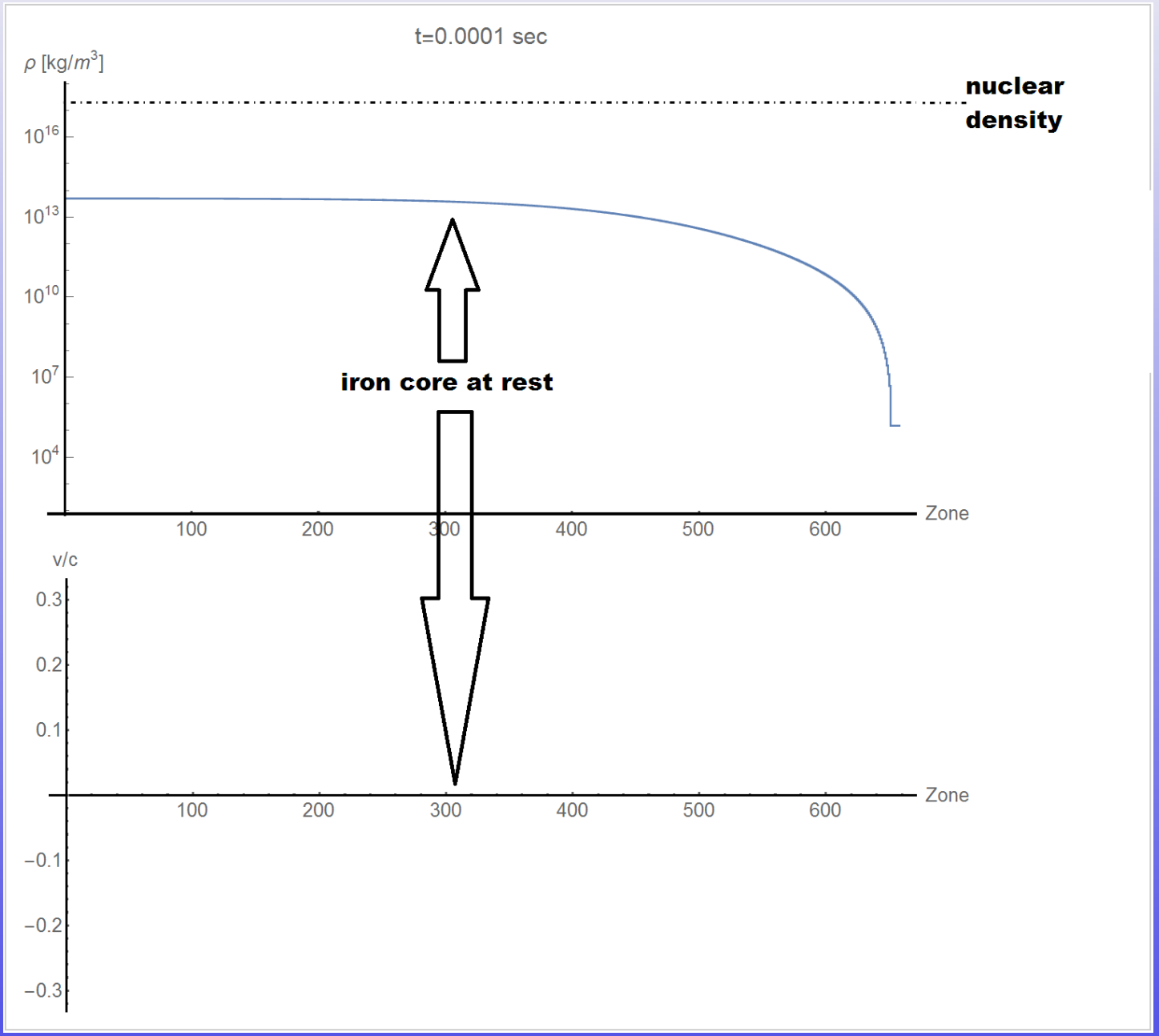
Core-collapse with GR1D



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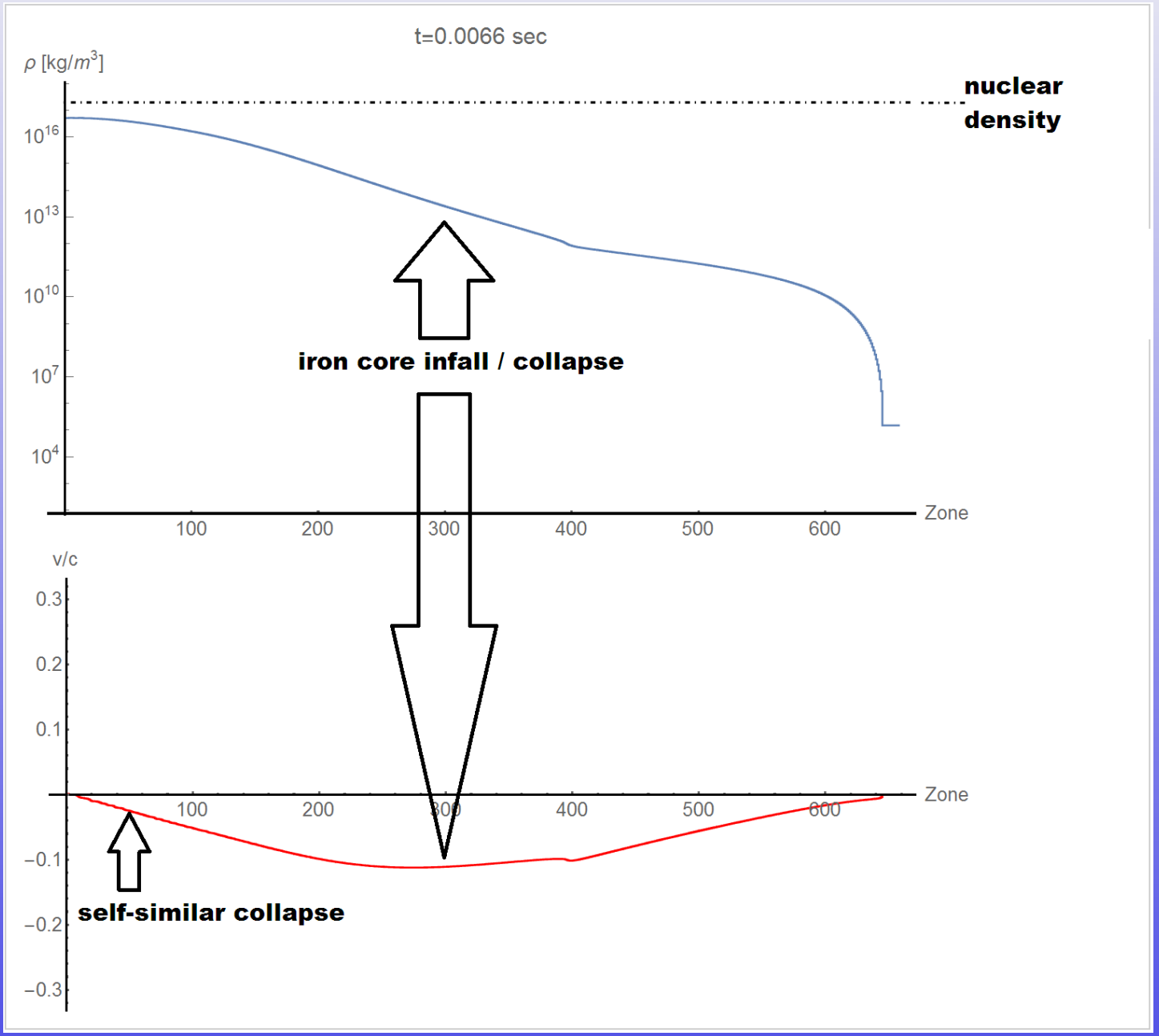

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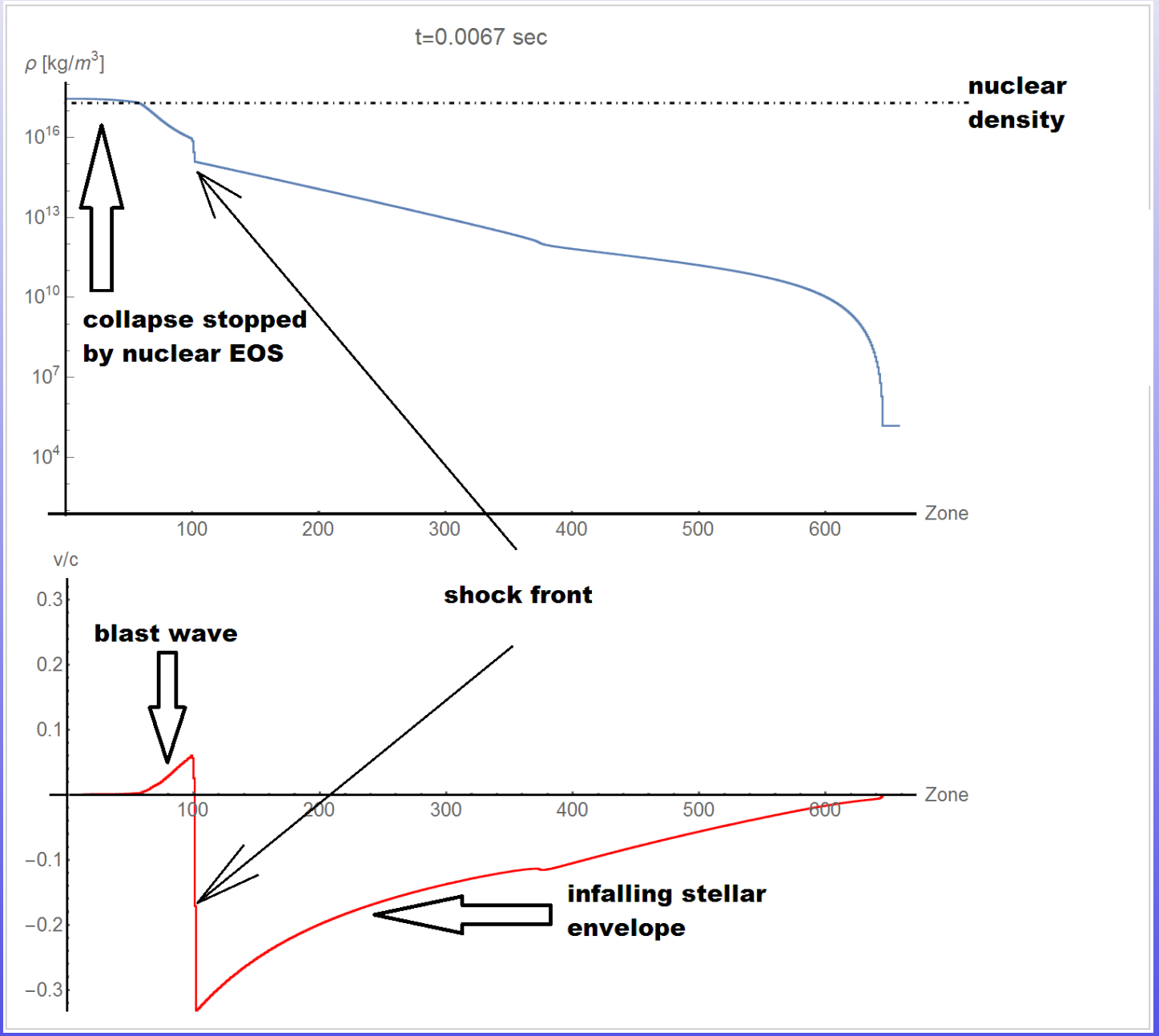

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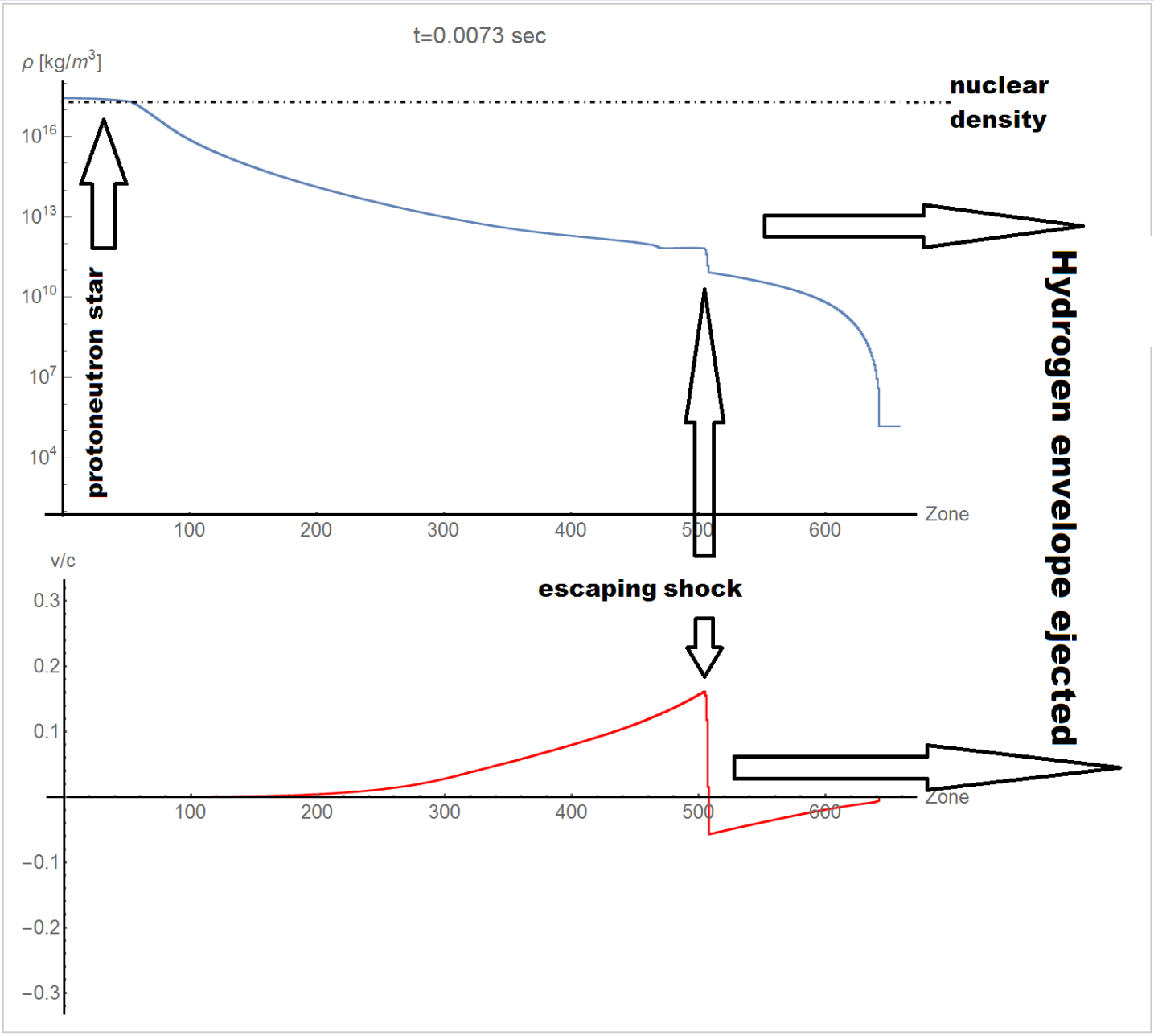

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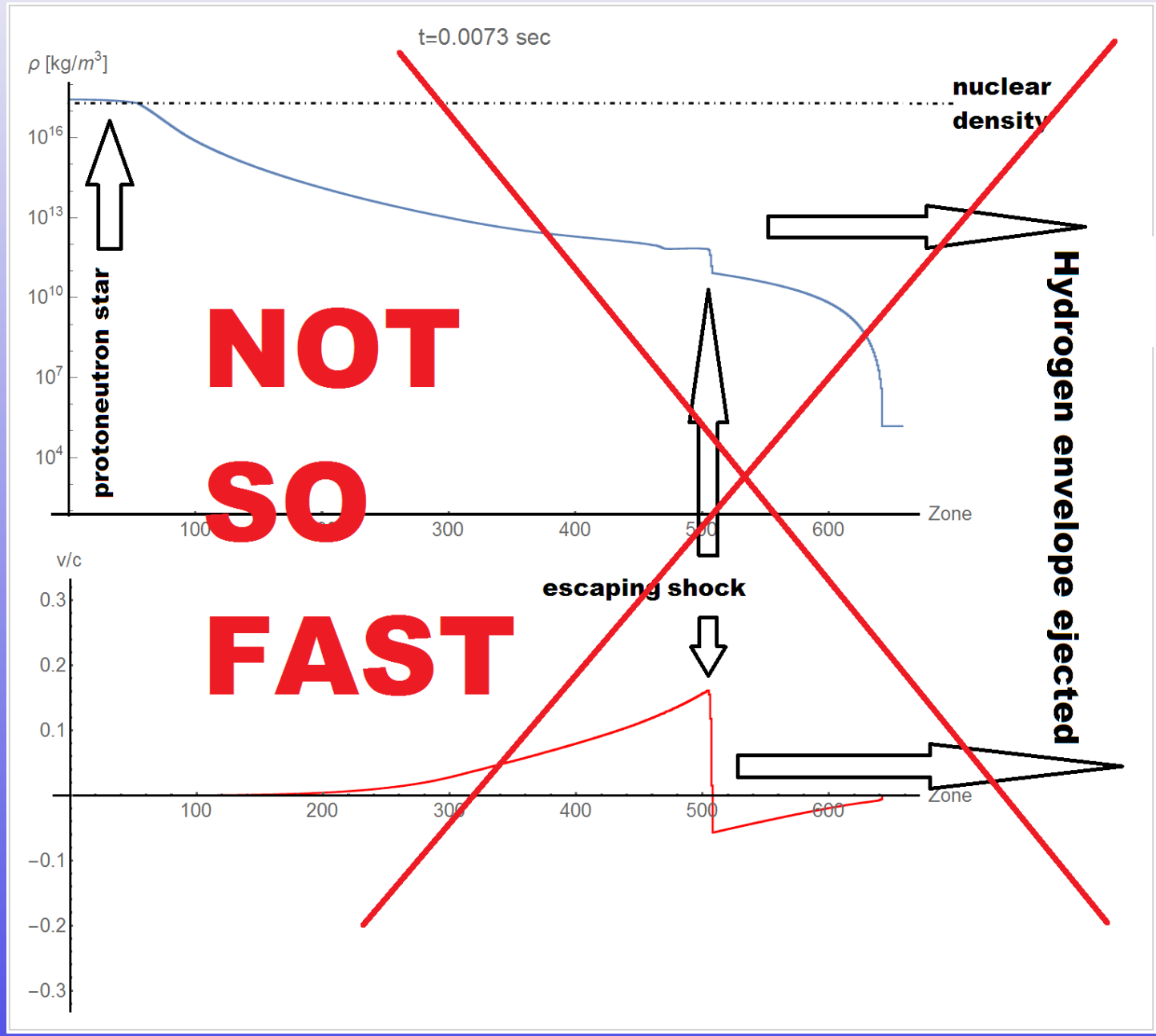


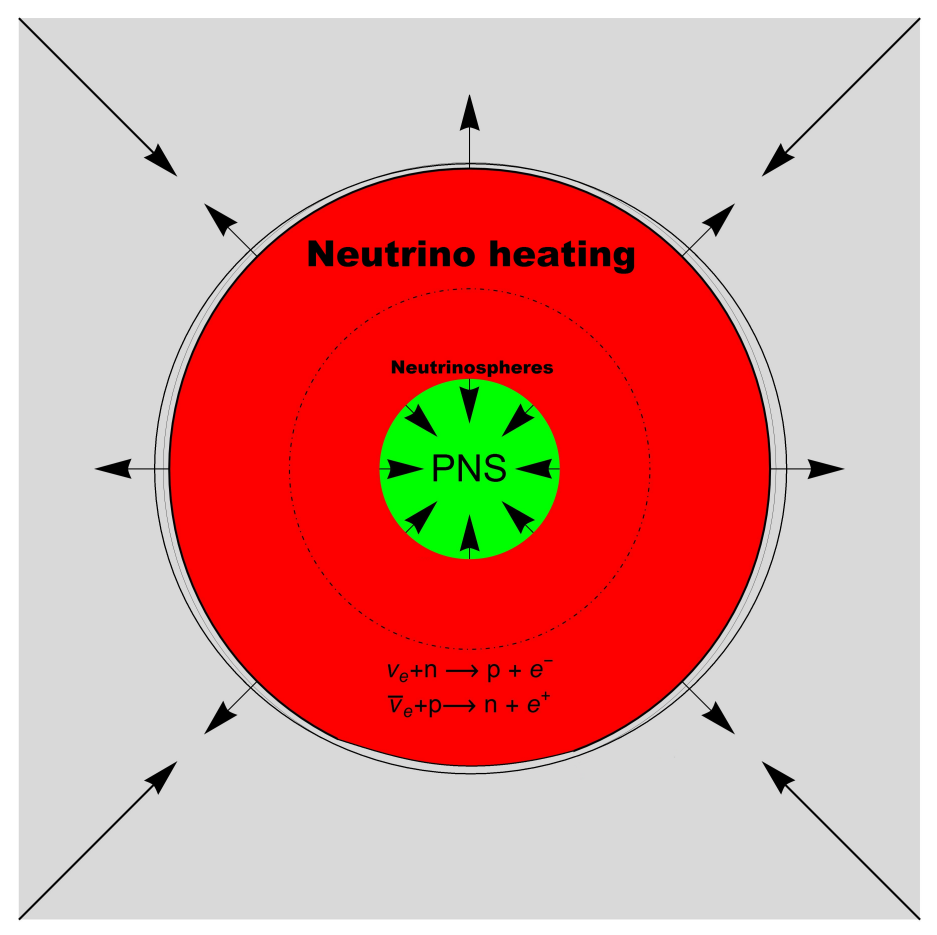
Core-collapse supernova problem

Supernova problem

1. so-called prompt supernova mechanism generally **do not work**, except for very soft EOS ($K \ll 200$ MeV) and low-end stellar mass ($8M_\odot < M < 11M_\odot$ with O-Ne-Mg core)
2. in typical situation shock retreat with infalling envelope with no explosion at all `[quiet collapse]`
3. above is in contradiction to hundreds of observed supernova events every year

Possible solutions include:

- neutrino mechanism
- 2D/3D turbulence/ SASI
- neutron star rocket effect
- magnetic/rotation/jet [supernova remnants with ears]



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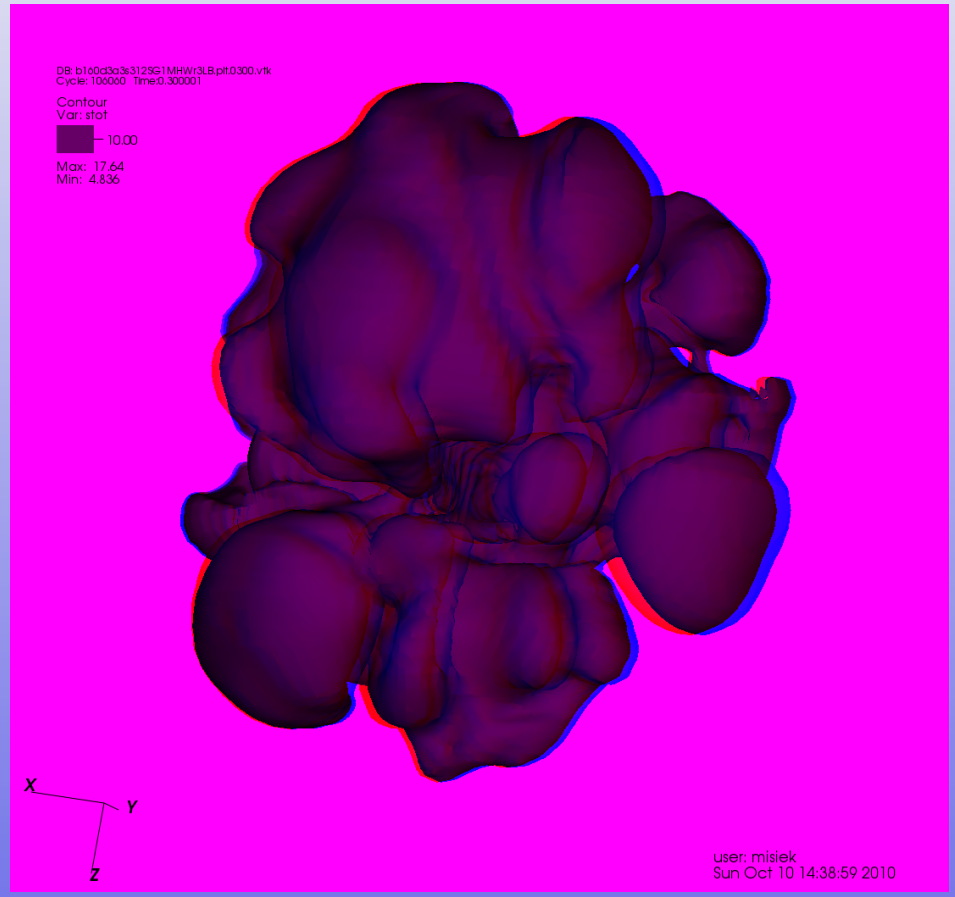

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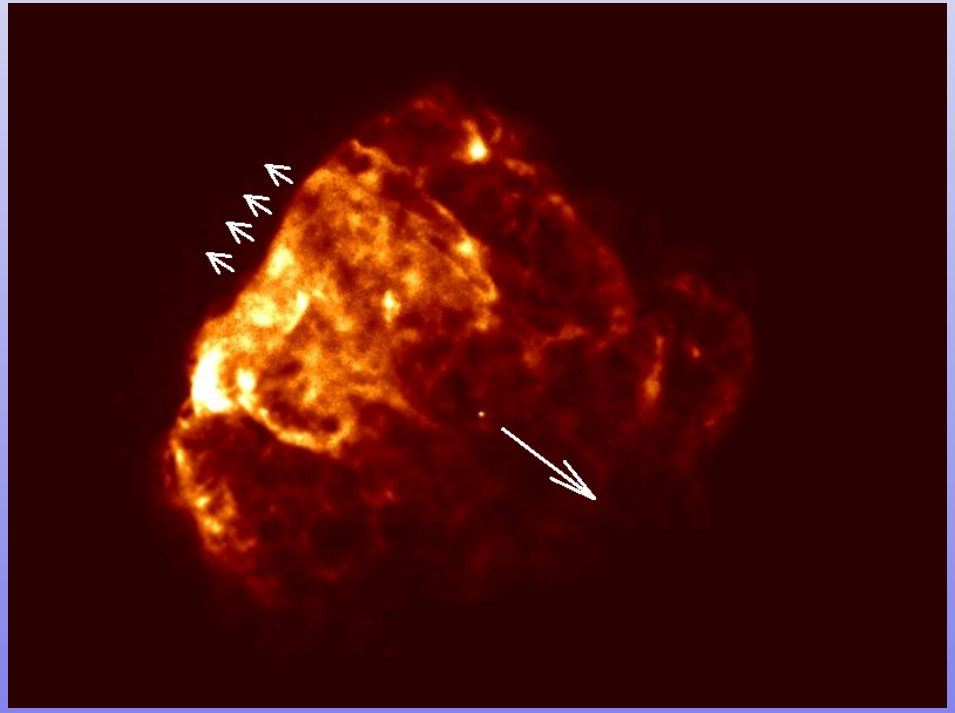

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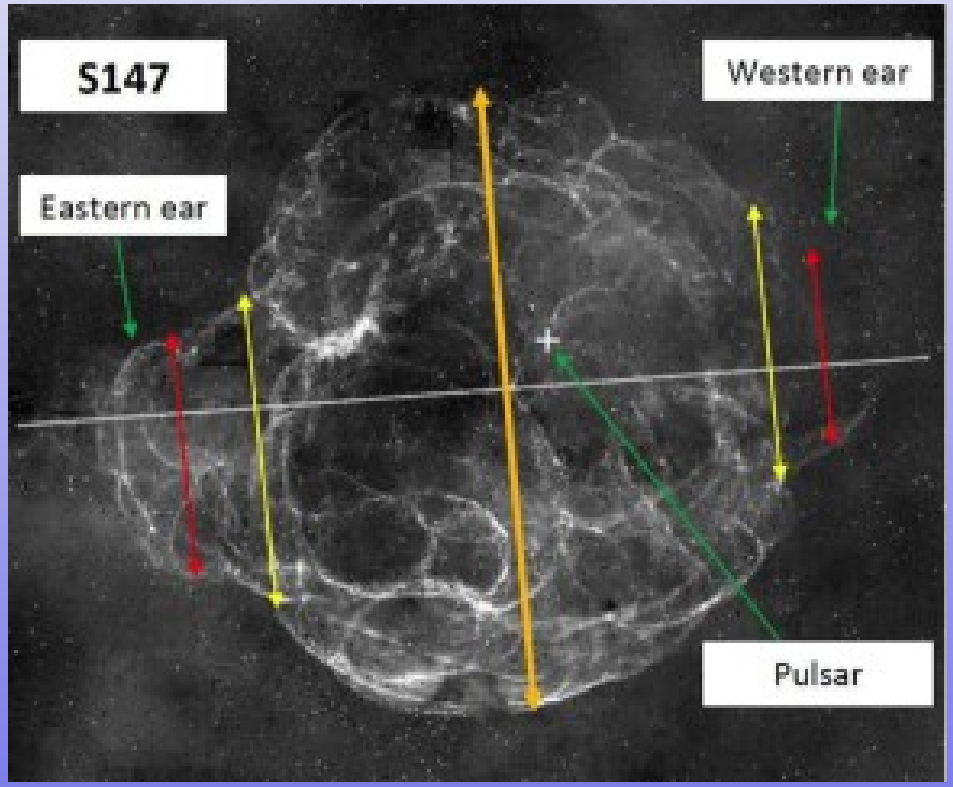
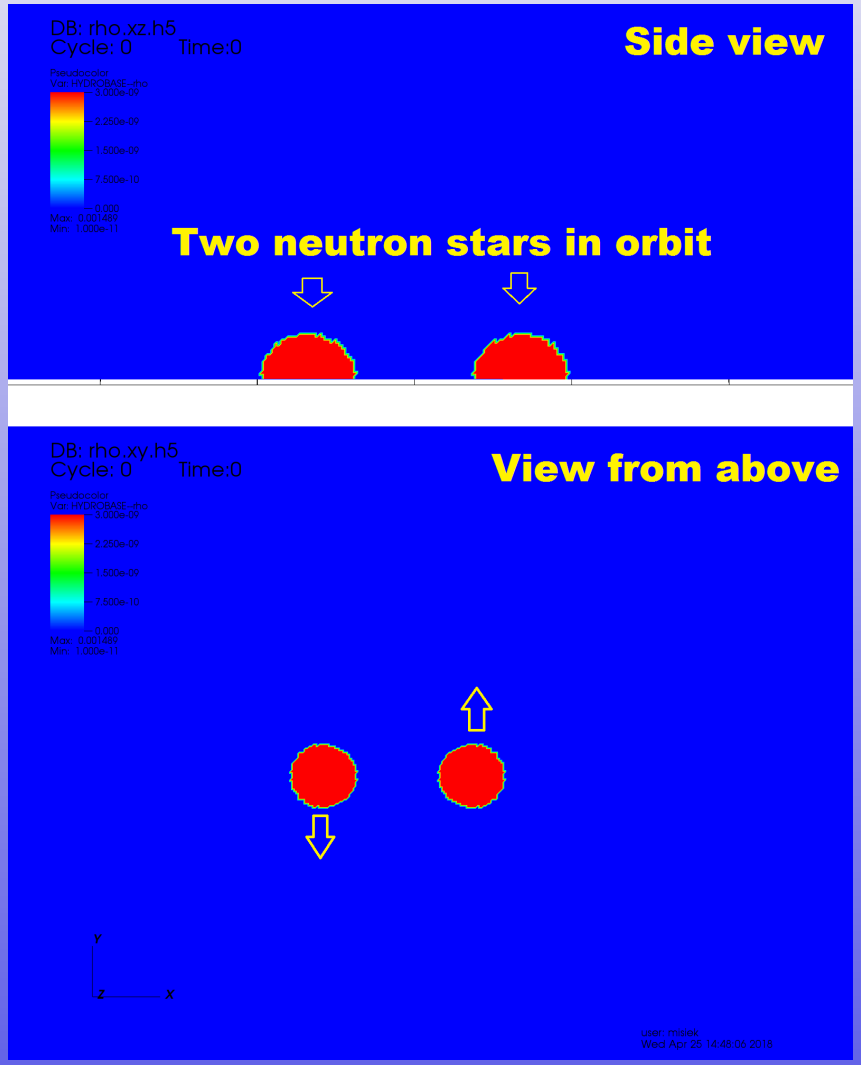
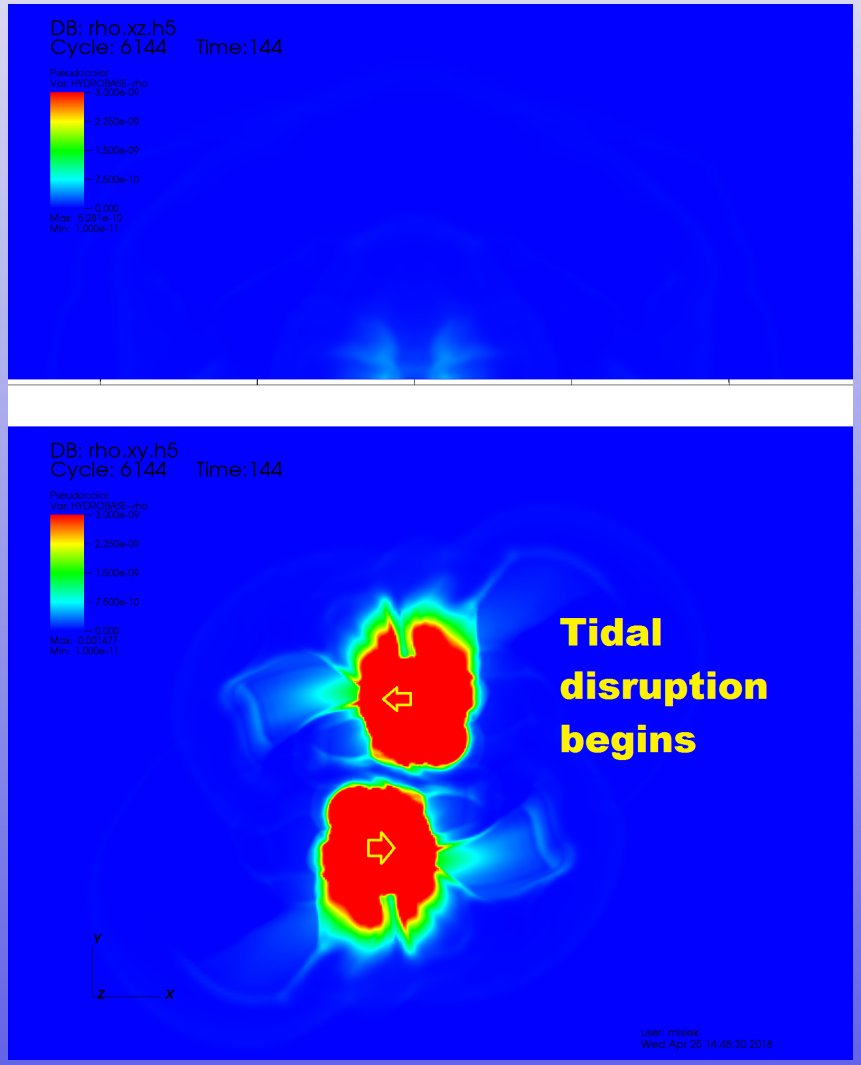


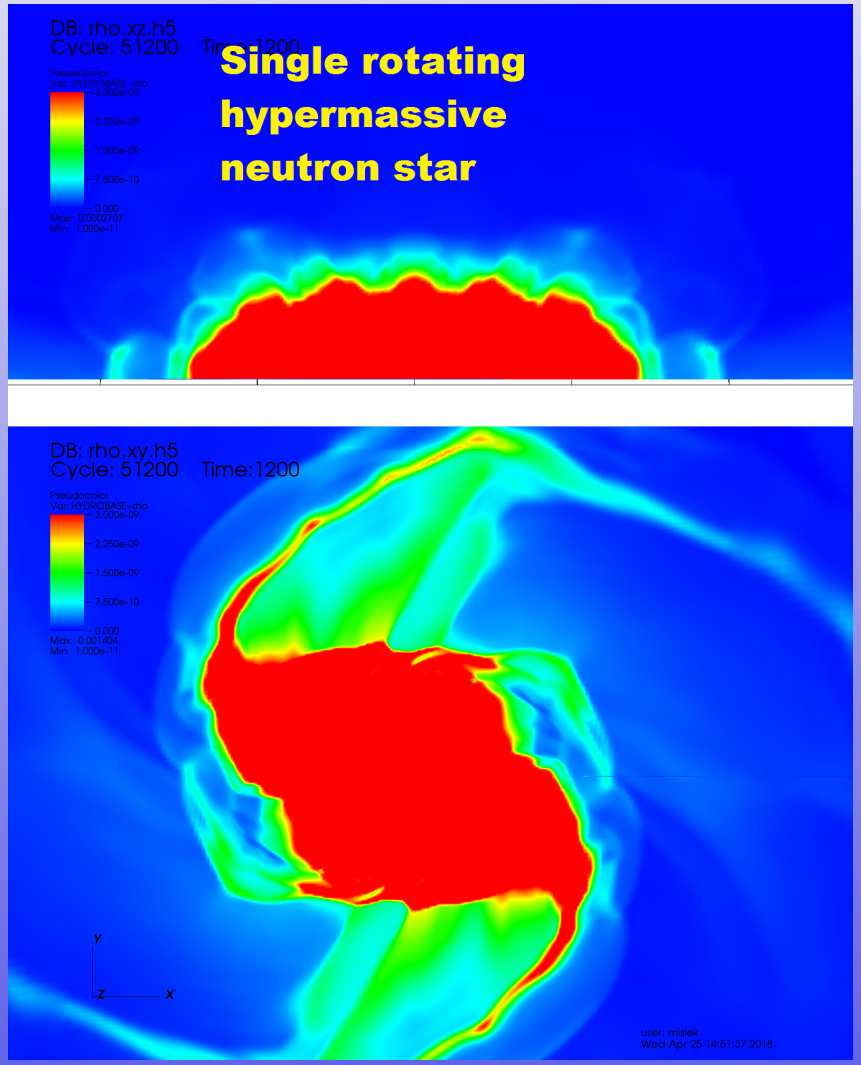
Neutron star mergers (kilonova)



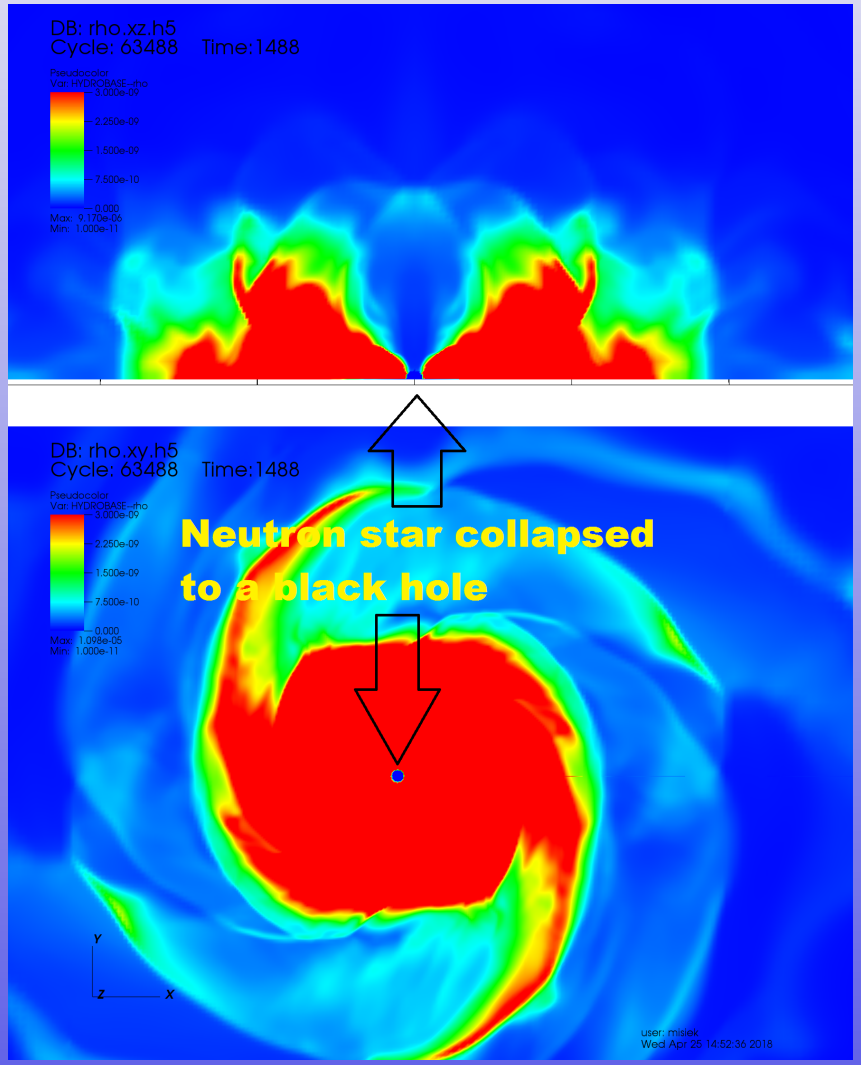
Neutron star mergers (kilonova)



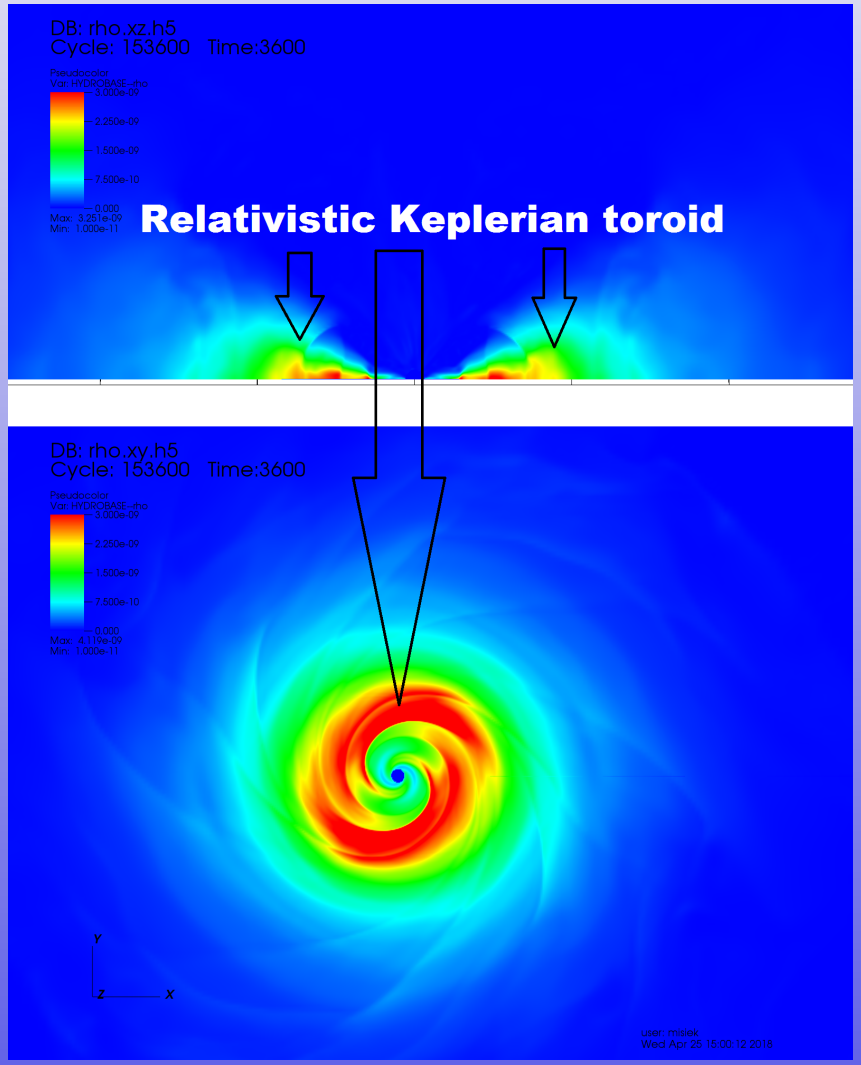
Neutron star mergers (kilonova)



Neutron star mergers (kilonova)



Neutron star mergers (kilonova)



Conclusions

1. connection and influence from/to nuclear physics $\leftrightarrow$ astrophysics still strong
2. active research area related to *r*-process (**N**eutron **S**tar *mergers*) and *rp*-process (explosive H burning)
3. huge amount of cross-sections, weak rates, masses measured and computed (incl. radioactive) ...
4. ... but a lot of effort required to use them, including purely technical/IT problems
5. significant lag between experimental knowledge (e.g. nuclear EOS, neutrino oscillations) and full astrophysical implementation still persists due to historical reasons and legacy codes

Thank you!

Beyond simple H burning

- H-burn in the Sun (pp-cycles) is well understood and experimentally confirmed (cf. our Borexino team)
- CNO-cycle (catalyzed) is well understood, but CNO-neutrinos still not confirmed
- standard CNO powers stars more massive than 2 $M_\odot$
- hot-CNO (explosive H burning) powers classical novae and X-ray bursts
- explosion is a result of H accumulation on surface of compact degenerate object: **white dwarf** or **neutron star**
- *rp*-process (rapid proton capture) operates at $T > 10^9$ K
- reaction networks become complicated and might involved *short-lived* α-**unstable nuclei**
- another intriguing case is H-burning in first stars after Big Bang
- yet another unexplored idea is antineutrino-accelerated hot H-burning:

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