超新星爆発および中性子星合体における r プロセス元素合成
r-process nulceosynthesis: supernovae vs. neutron-star mergers

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素核宇融合による計算基礎物理学の進展 – ミクロとマクロのかけ橋の構築 -
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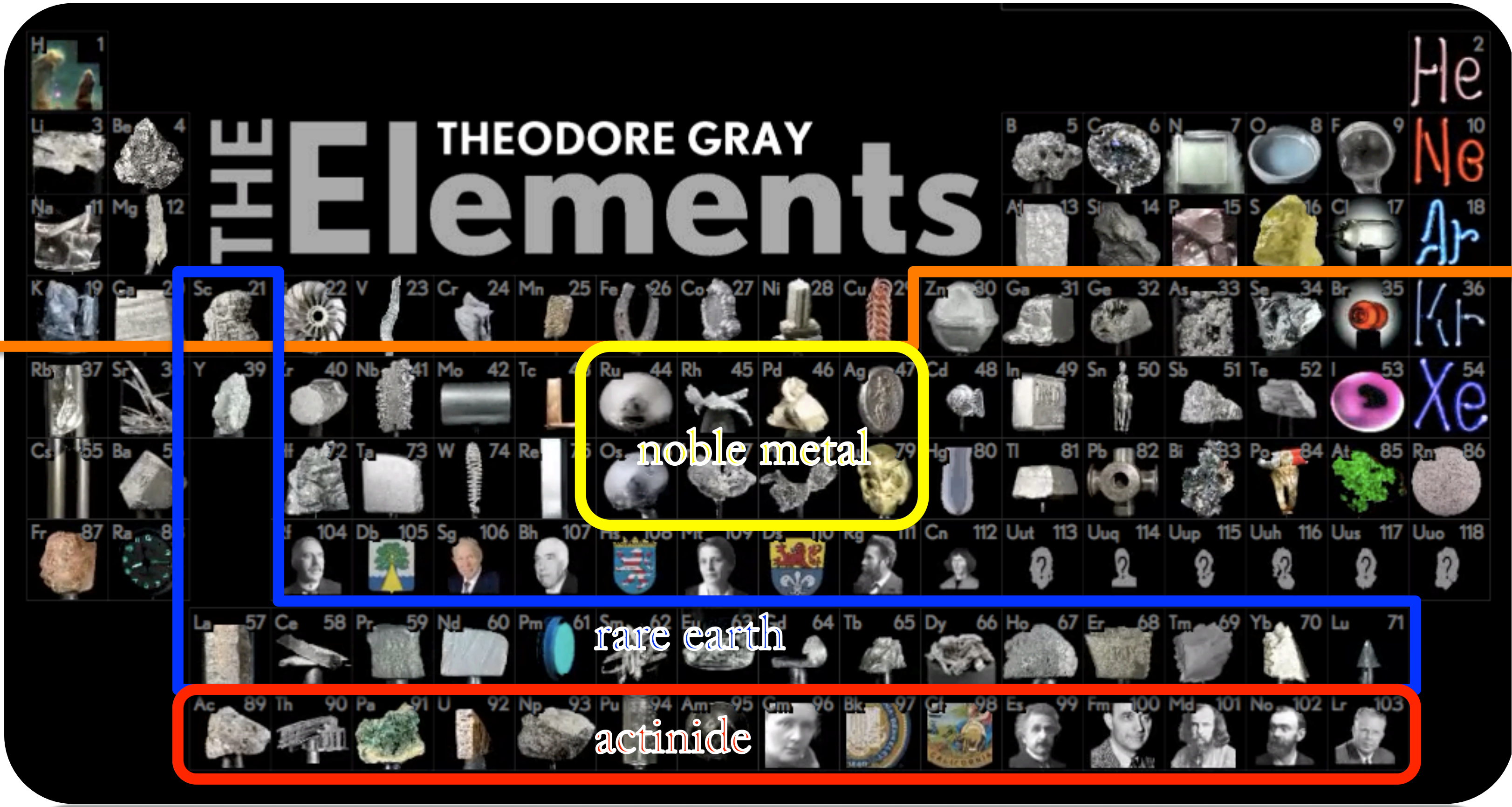
Max Planck Institute
for Astrophysics

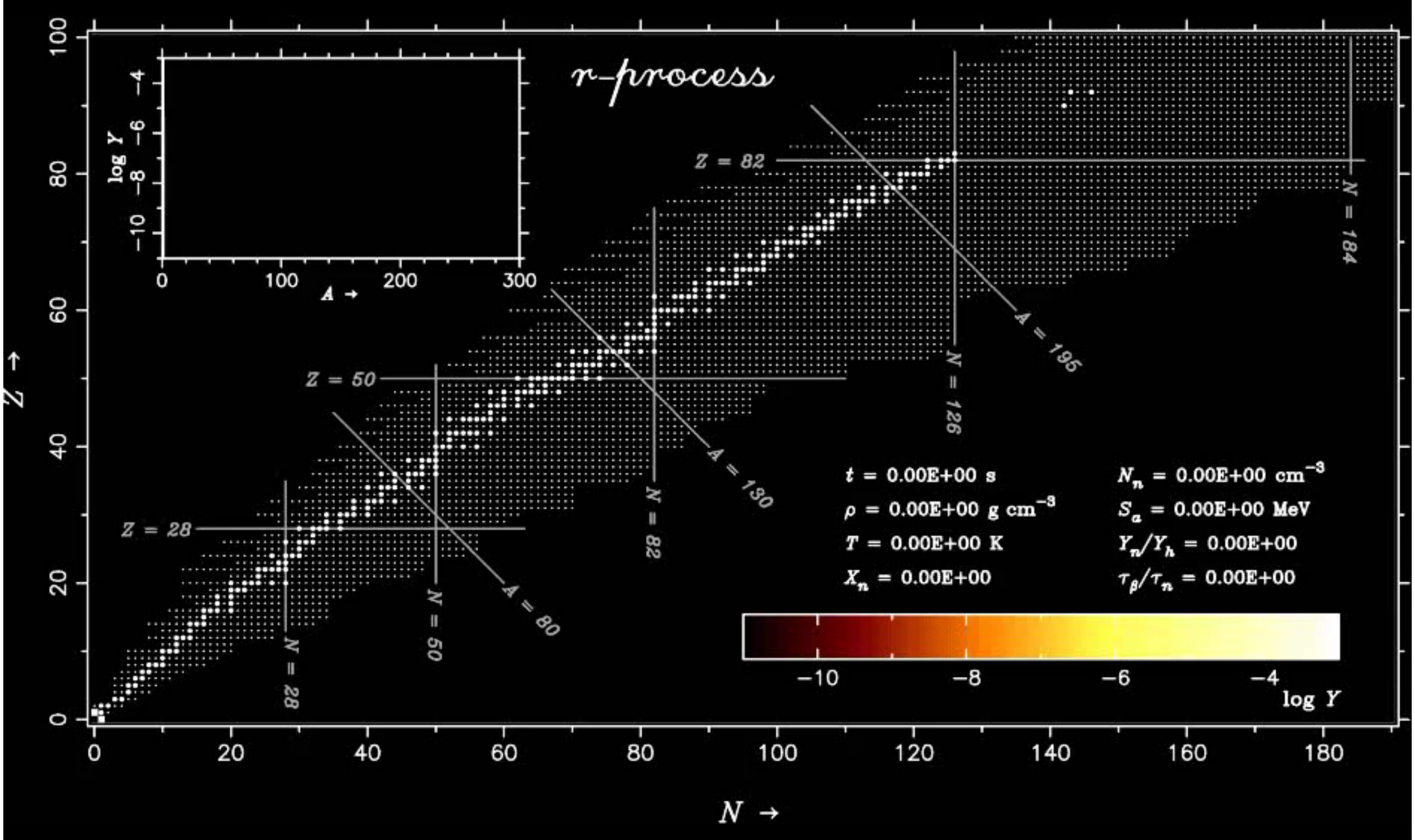
origin of elements beyond iron

understood (big bang, cosmic rays, stellar evolutions, supernovae)



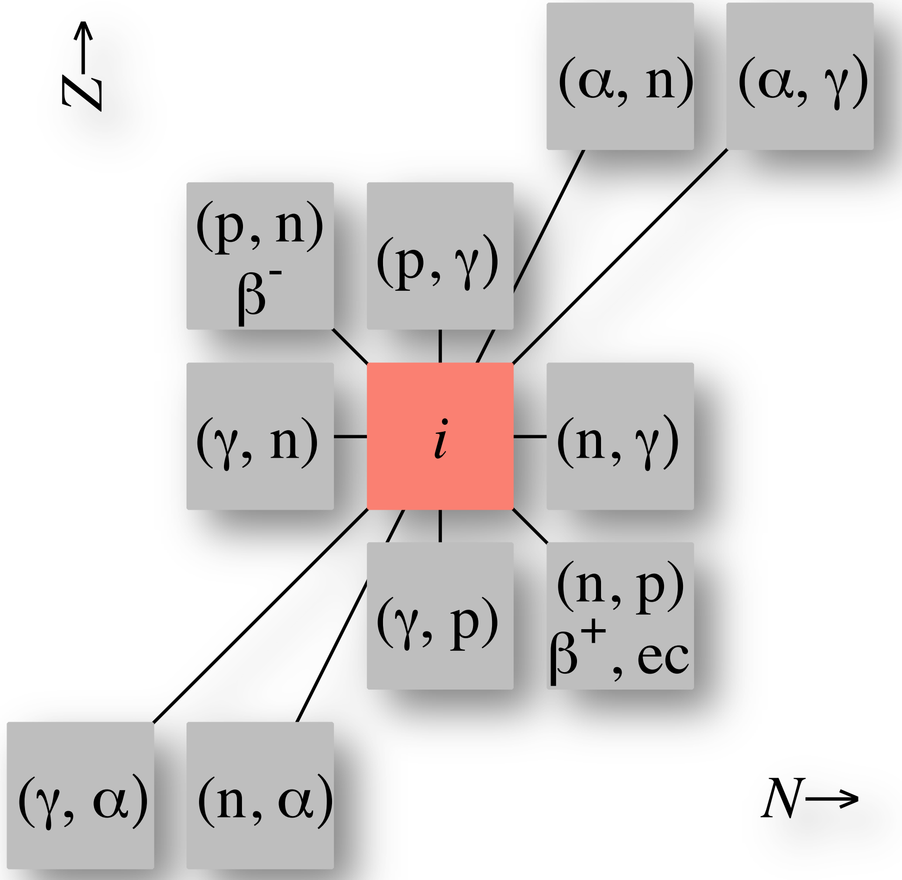
not understood

not fully understood, in particular noble metal, rare earth, actinide

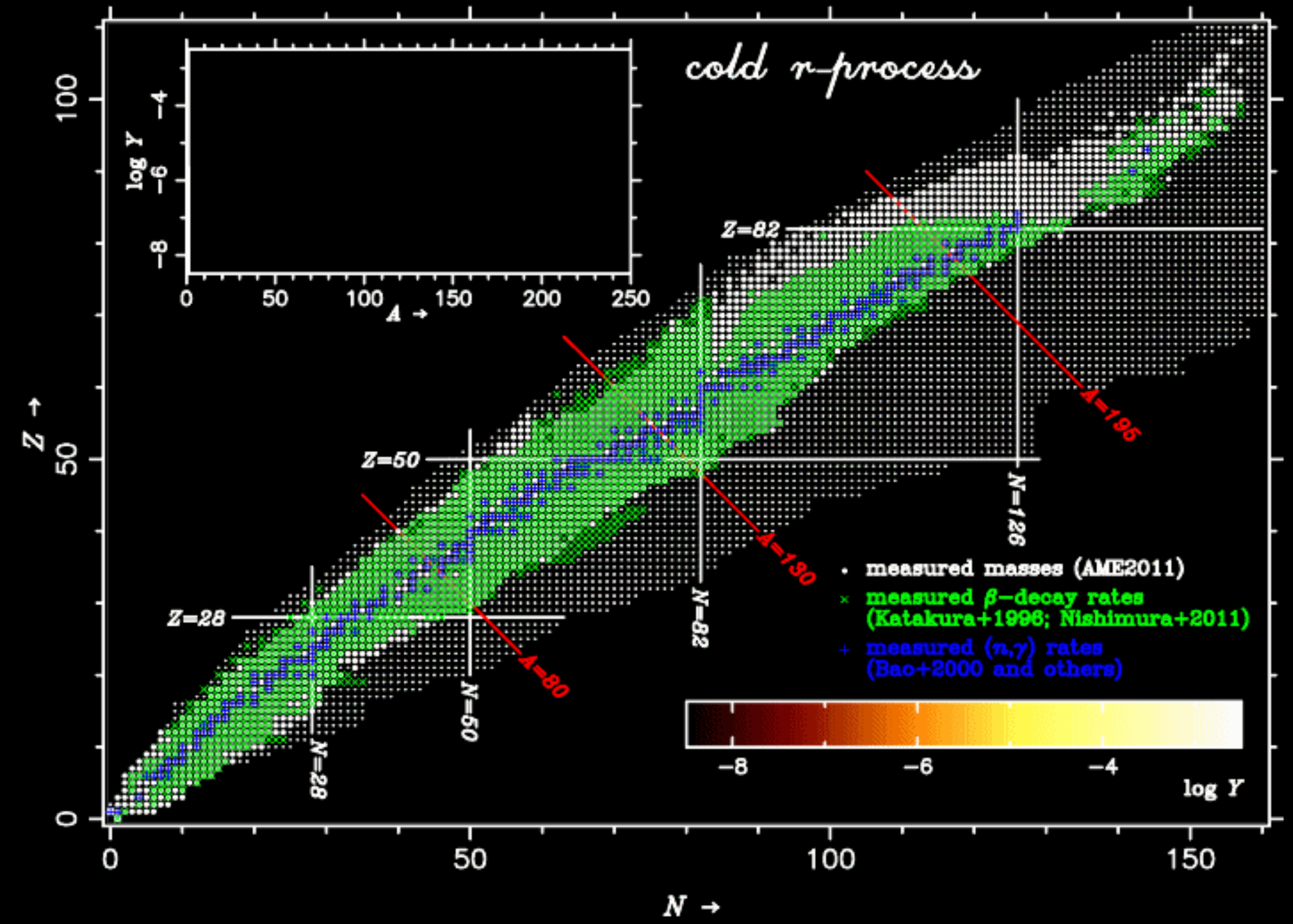

r-process
Z = 82
Z = 50
Z = 28
N = 28
N = 50
N = 82
N = 126
N = 184
A = 80
A = 130
A = 195
t = 0.00E+00 s
ρ = 0.00E+00 g cm−3
T = 0.00E+00 K
Xn = 0.00E+00
Nn = 0.00E+00 cm−3
Sa = 0.00E+00 MeV
Yn/Yh = 0.00E+00
τβ/τn = 0.00E+00
log Y
A →
Z →
N →

recipe to calculate nucleosynthesis

reaction channels for the *i*-th isotope

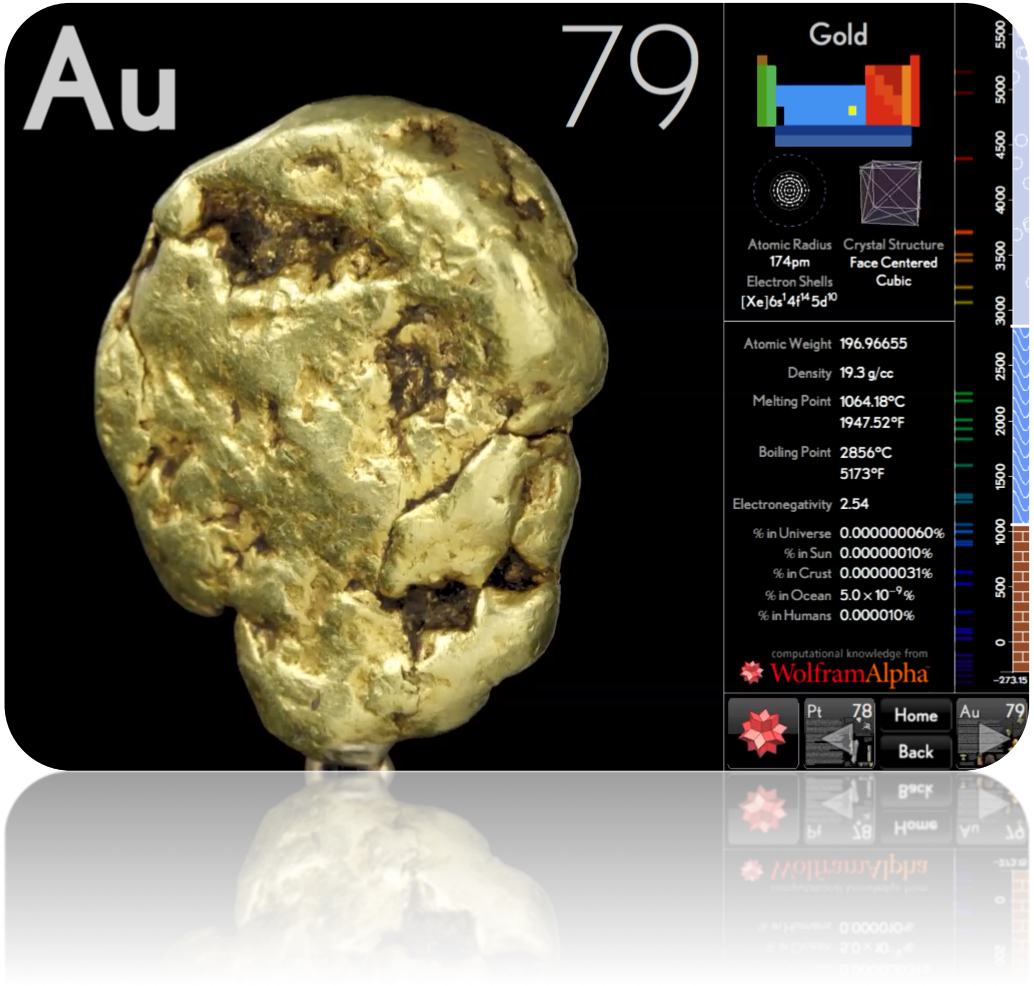


- ❖ numerical computations using a nuclear reaction network code (e.g., ~8000 isotopes and ~100,000 reactions for r-process)
- ❖ experimental (whenever available) or theoretical reaction rates (compilations available from, e.g., REACLIB, BRUSLIB)
- ❖ ρ and T temporal evolutions from astrophysical modeling (e.g., of supernova explosions or neutron-star mergers)


cold r-process
log Y
−4
−6
−8
0
50
100
150
200
250
A →
Z →
100
50
0
N →
Z=82
Z=50
Z=28
N=28
N=50
N=82
N=126
A=80
A=130
A=195
measured masses (AME2011)
measured β−decay rates
(Katakura+1996; Nishimura+2011)
measured (n,γ) rates
(Bao+2000 and others)
−8
−6
−4
log Y

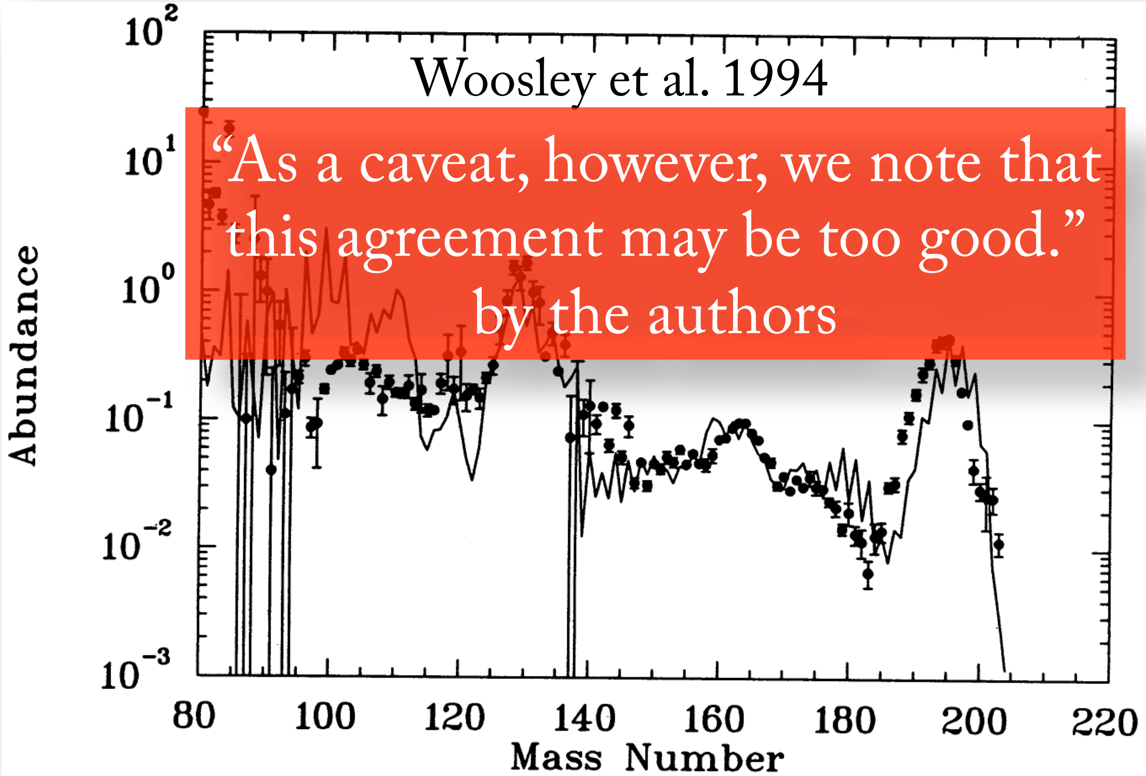
SUPERNOVAE

how to cook gold and heavier



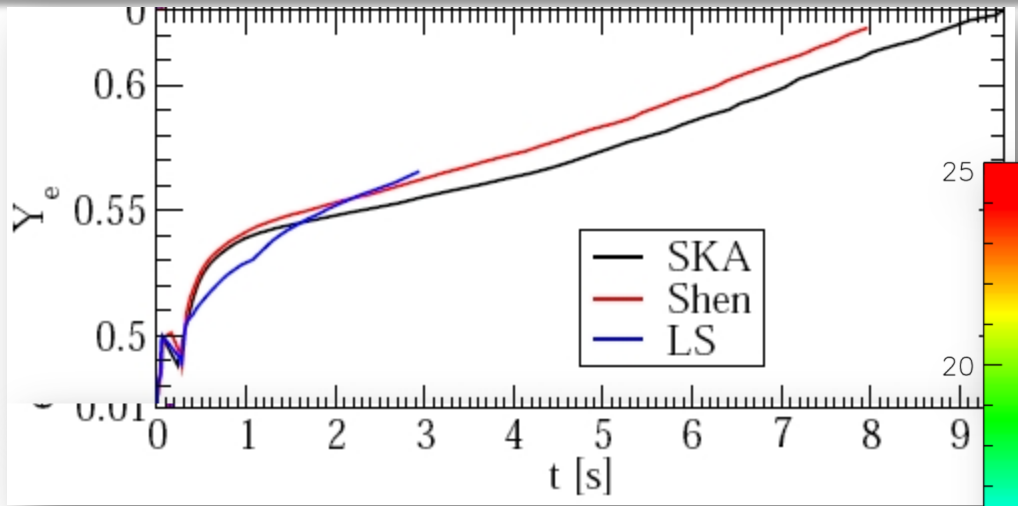
- either of the following is needed to obtain n/seed > A(3rd) – A(seed) ~ 100
- high entropy $S_{\rm rad}$ ($\propto T^3/\rho$) > 200 $k_{\rm B}$/nuc to slow the $\alpha\alpha$n rate
- short expansion timescale $\tau_{\rm exp}$ < 10 ms to slow the $\alpha\alpha$n rate
- low electron fraction (protons per nucleon) $Y_{\rm e}$ < 0.2 to leave free neutrons

SN neutrino-driven wind



- ❖ successful r-process in the neutrino-driven winds of S_{rad}~400 k_B/nuc (1D hydro, 20 $M_\odot$ star; Meyer+1992; Woosley+1994)
- ❖ but such high entropy is unlikely (~100 k_B/nuc; Takahashi+1994; Qian+1996; Otsuki+2000)

neutrino-driven wind is "proton-rich"

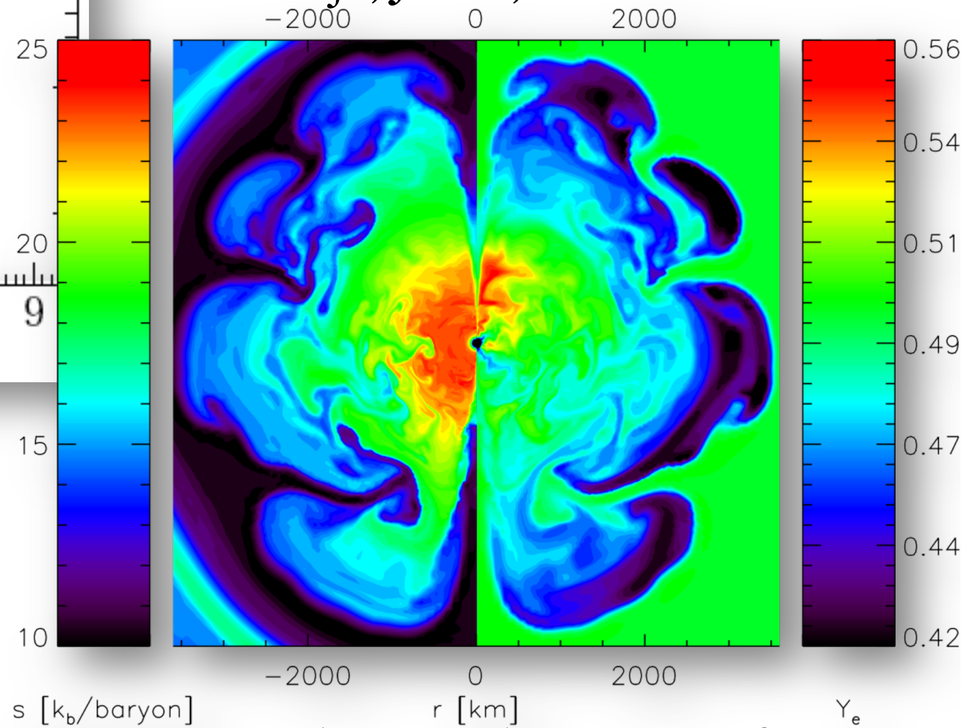


self-consistent explosion of a 9 $M_\odot$ star
Hüdepohl+2009

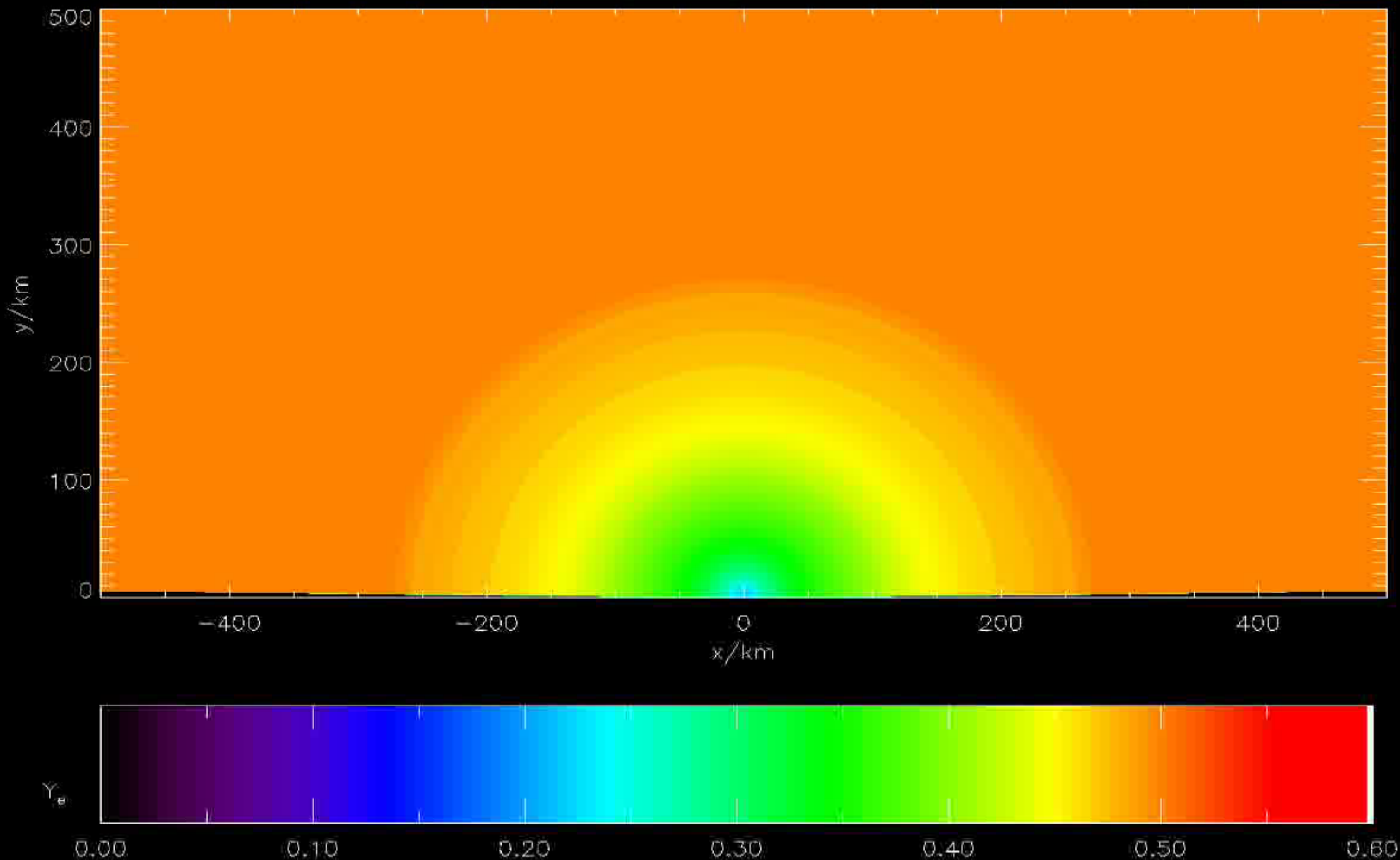
$$\nu_e + n \rightarrow p + e^-$$

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

2D supernova simulation
Wanajo, Janka, Müller 2011

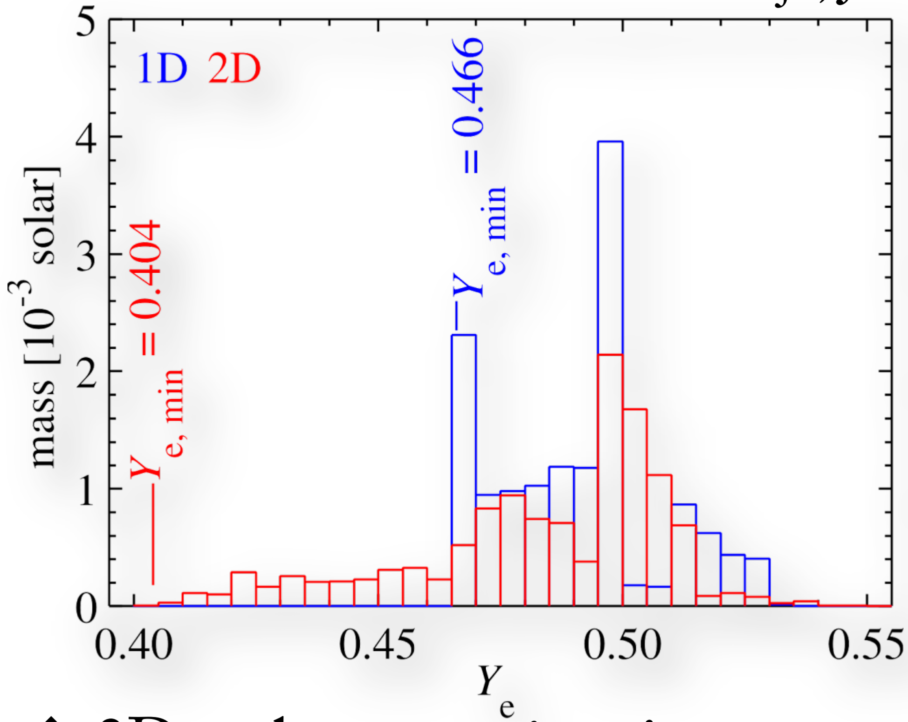


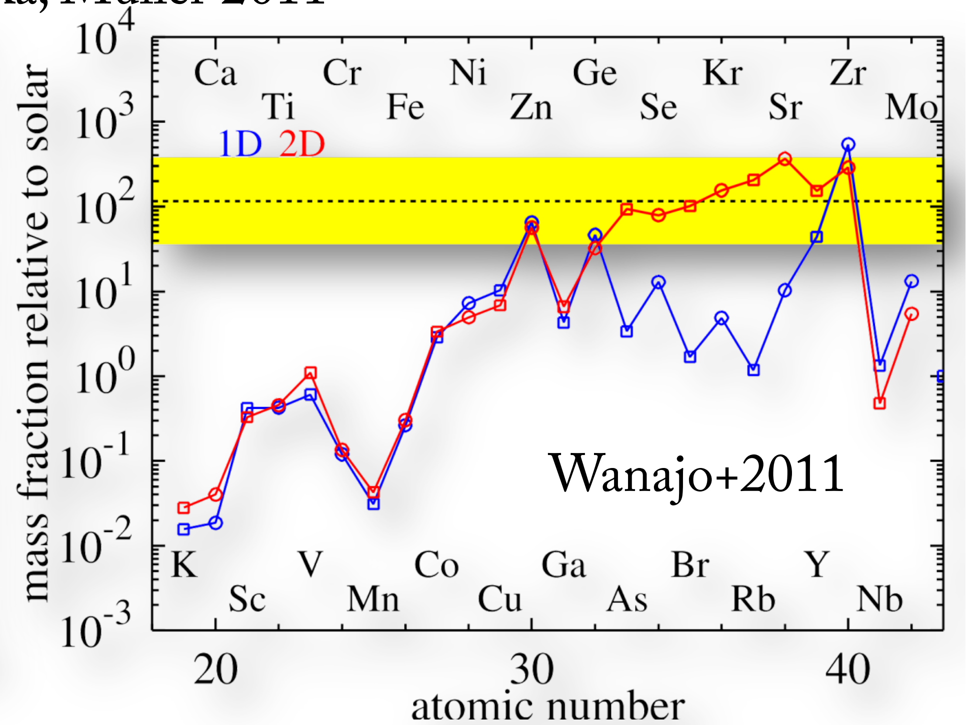
- ❖ Y_e > 0.5 in all recent neutrino-transport simulations because of similar neutrino energies and luminosities for all flavors (i.e., protons are favored due to the p-n-mass difference)
- ❖ but, early convective blobs have some n-rich pockets (< 10 $M_\odot$ only)


y/km
500
400
300
200
100
0
−400
−200
0
200
400
x/km
Ye
0.00
0.10
0.20
0.30
0.40
0.50
0.60

supernovae at the low-mass end

Wanajo, Janka, Müller 2011

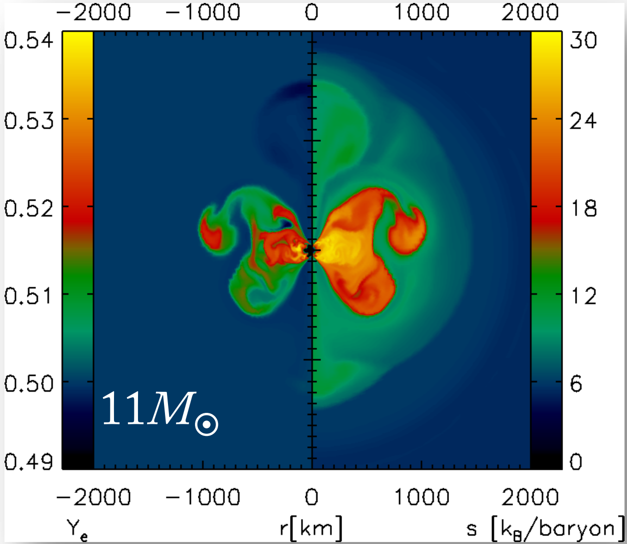


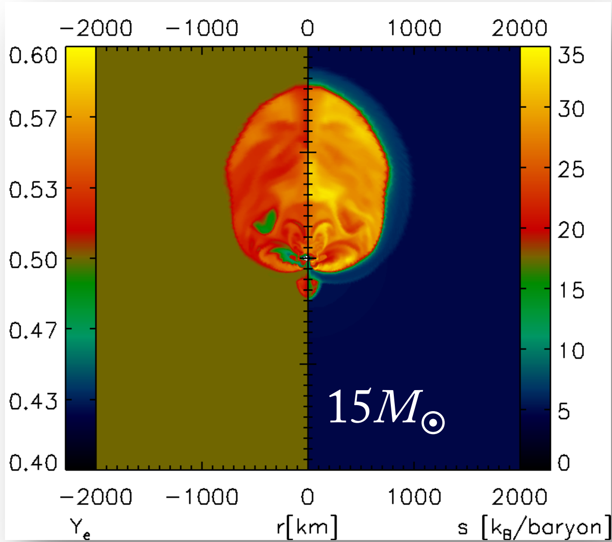


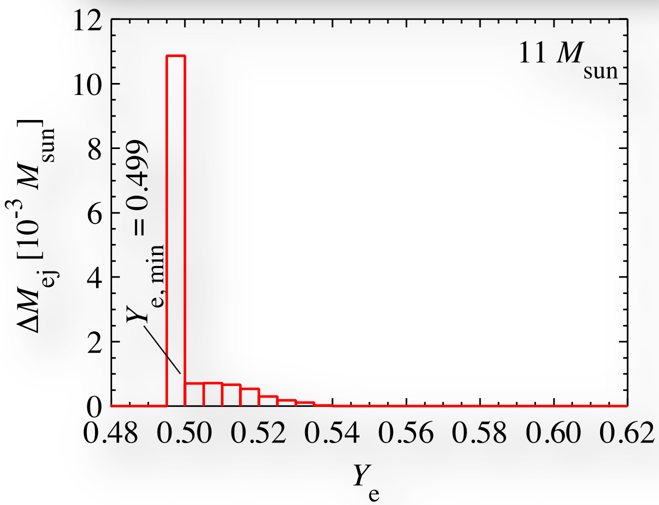
- 2D early convective ejecta: $Y_{e,\,min} \approx 0.40$ with $S_{rad} \approx 13\ k_B$/nuc
- 1D ejecta: $Y_{e,\,min} \approx 0.47$ with $S_{rad} \approx 20\ k_B$/nuc

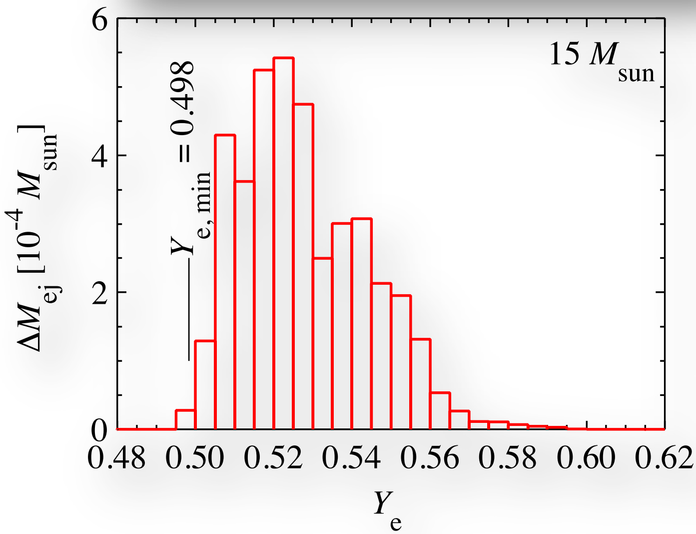
- 2D: production of the 1st peak ^{80}Se and up to ^{90}Zr
- but of nuclei beyond $N = 50$
- production factor of ~100 → ~ 4% of all SNe

no n-rich ejecta from massive SNe !





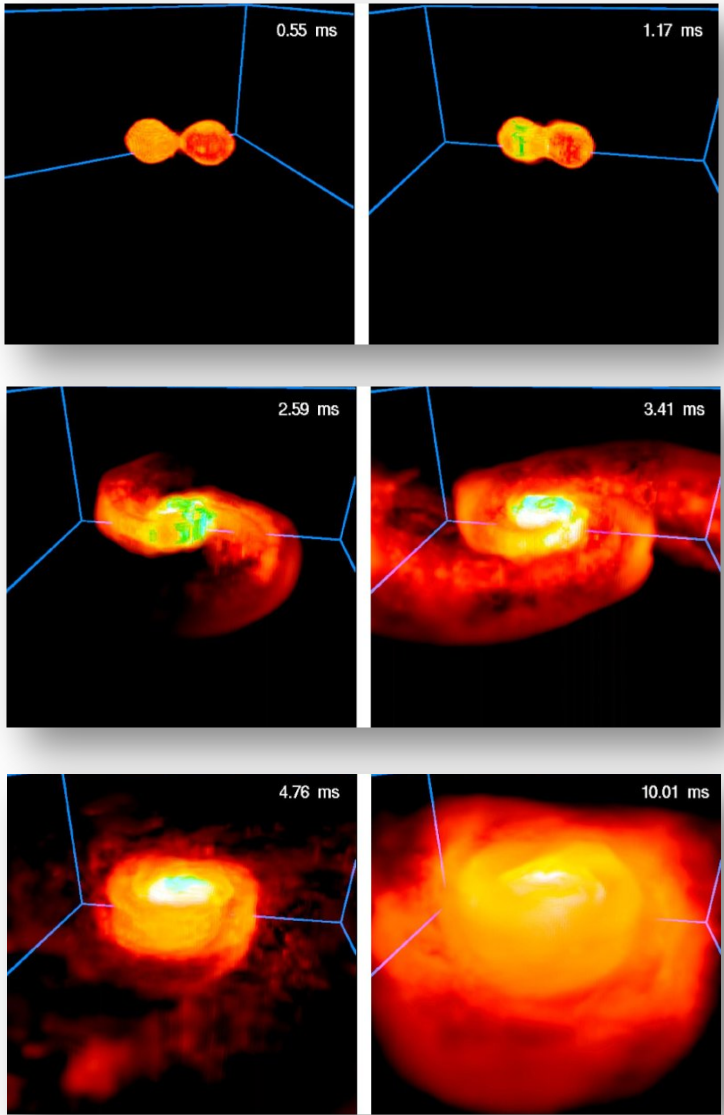




❖ $Y_{e,\,min} \approx 0.5$ for self-consistent 2D SNe of 11, 15 $M_\odot$ (Müller+in prep)

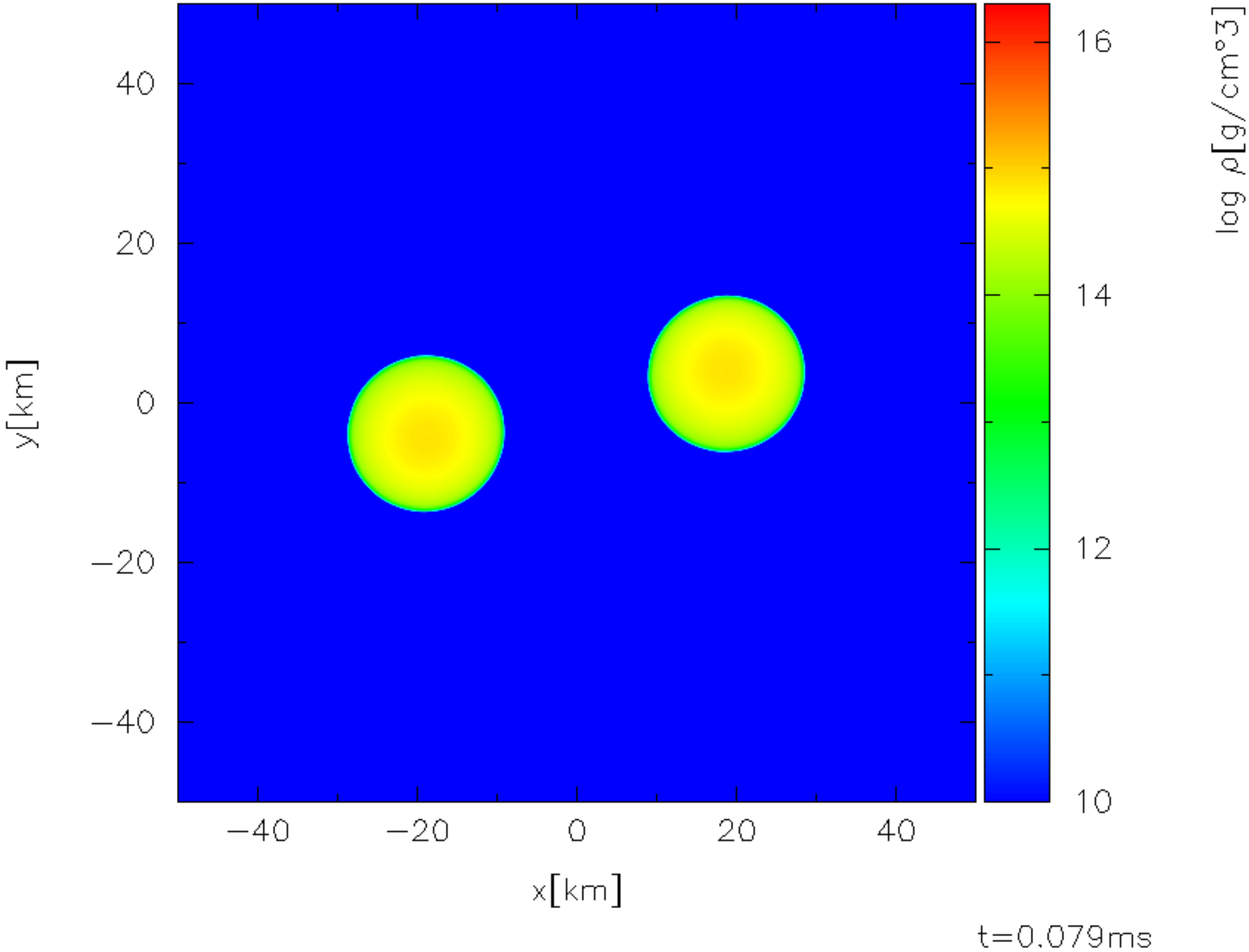
NEUTRON-STAR MERGERS

NS mergers as another posibility



www.mpa-garching.mpg.de

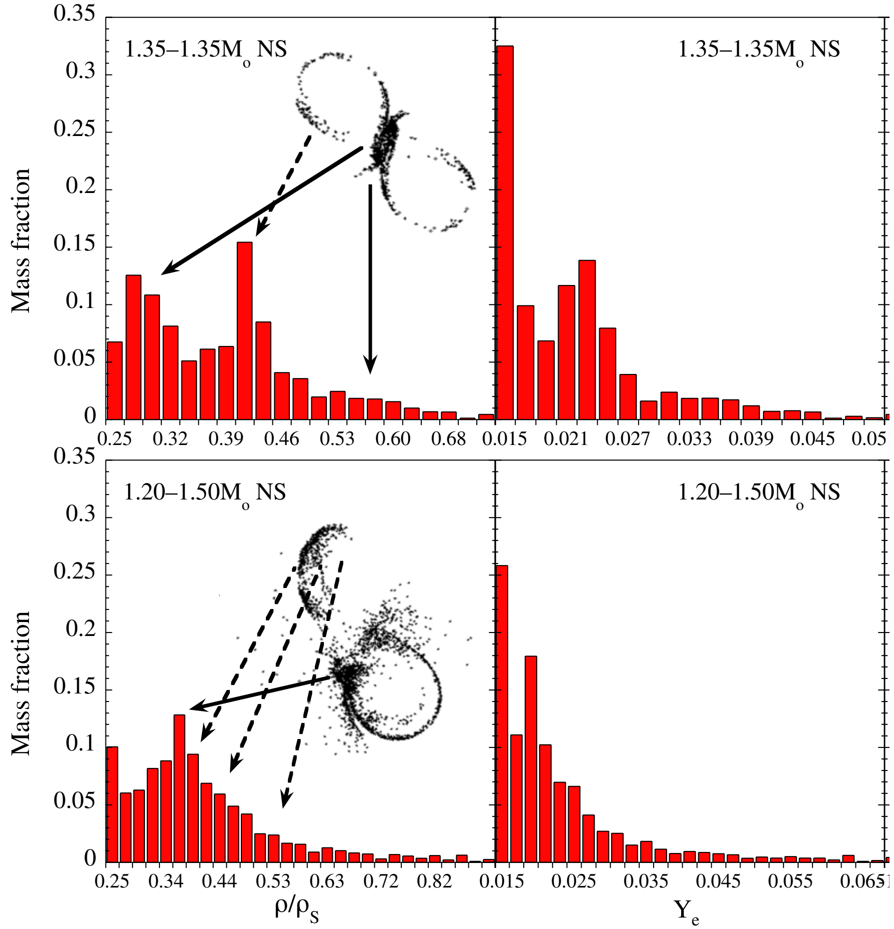
- coalescence of binary NSs expected ~ 10 – 100 per Myr in the Galaxy (also possible sources of short GRB)
- tidal ejection of n-rich matter with $Y_e < 0.1$ (Goriely+2011)
- neutrino- (or viscous, MHD) winds from the BH accretion torus with $Y_e \sim 0.2 - 0.4$ (Wanajo & Janka 2011)

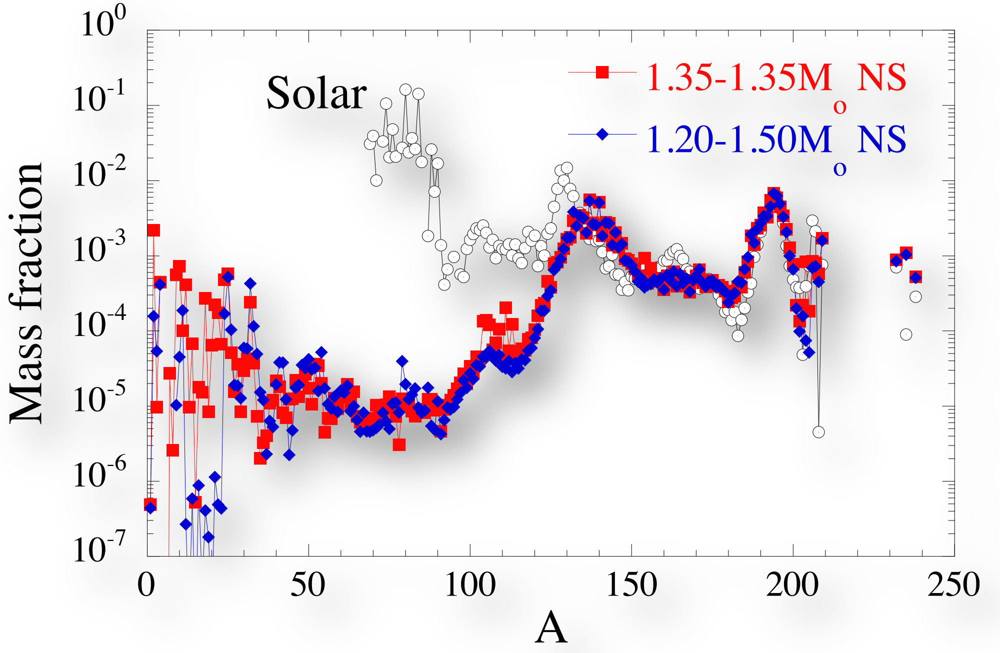


log ρ[g/cm^3]
16
14
12
10
40
20
0
−20
−40
y[km]
−40
−20
0
20
40
x[km]
t=0.079ms

NS mergers: dynamical components

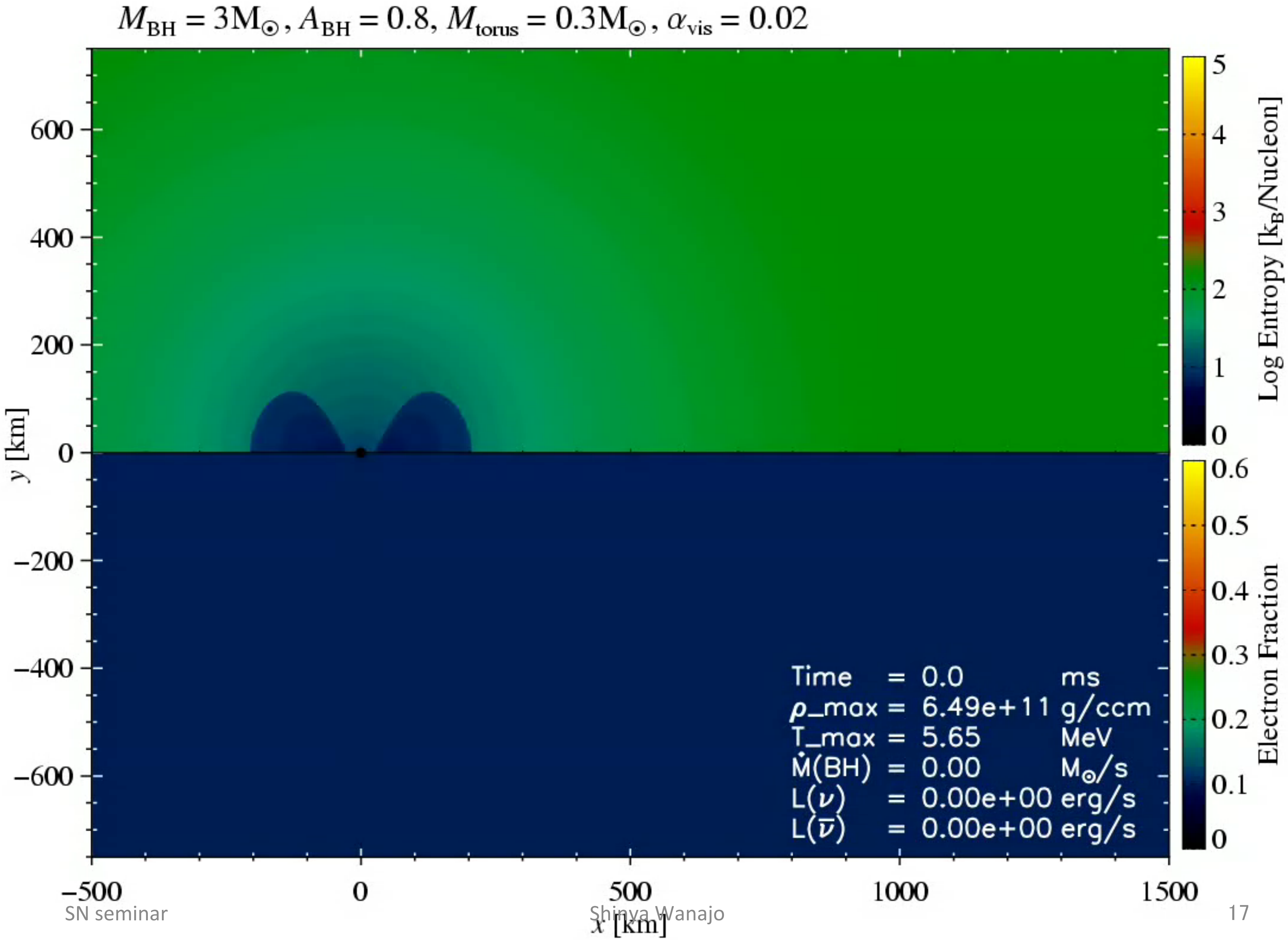
Goriely, Bauswein, Janka 2011





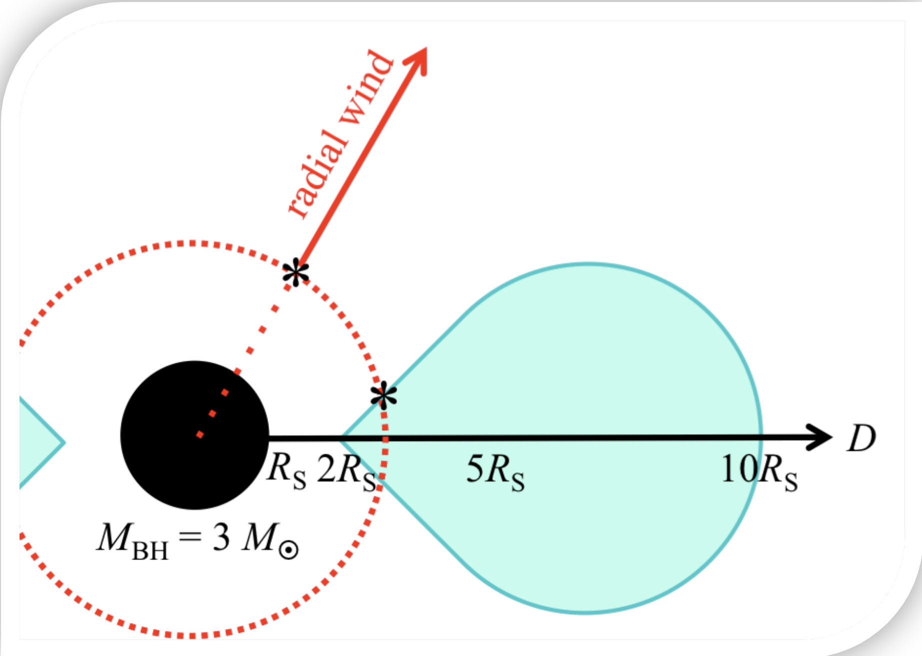
ejection of "pure" n-matter; $Y_e << 0.1$

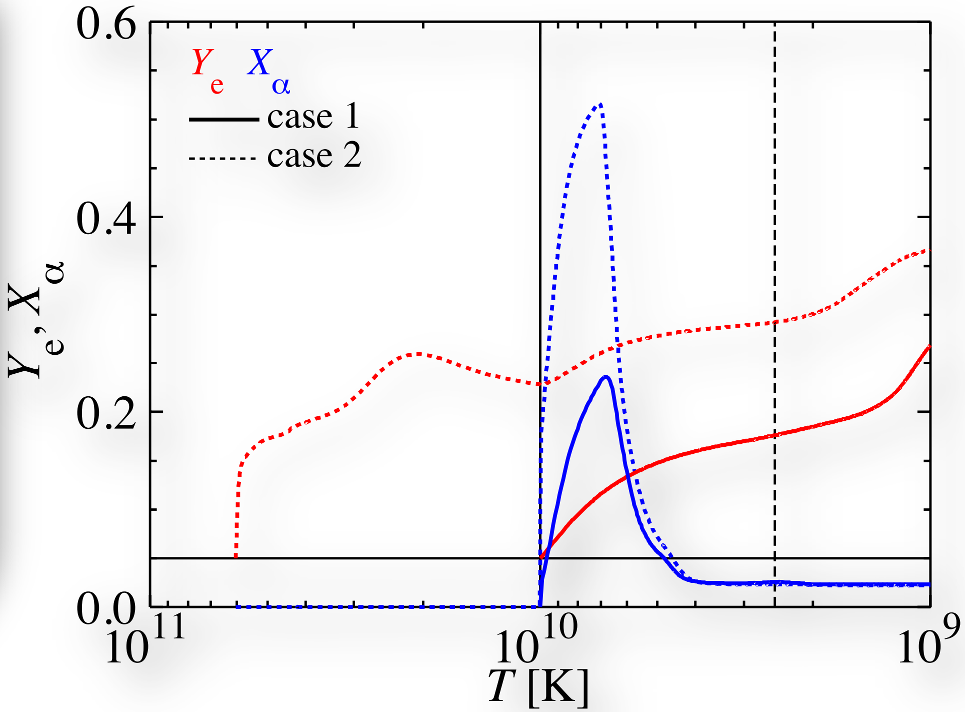
- r-process with fission cyclyng: origin of the "universality"?
- but only $A > 130$; another source is needed for $A < 130$


$M_{BH} = 3M_\odot, A_{BH} = 0.8, M_{torus} = 0.3M_\odot, \alpha_{vis} = 0.02$
Log Entropy [k_B/Nucleon]
Electron Fraction
y [km]
x [km]
Time = 0.0 ms
ρ_max = 6.49e+11 g/ccm
T_max = 5.65 MeV
$\dot{M}$(BH) = 0.00 $M_\odot$/s
L(ν) = 0.00e+00 erg/s
L($\bar{\nu}$) = 0.00e+00 erg/s

NS mergers: wind components

Wanajo & Janka 2011





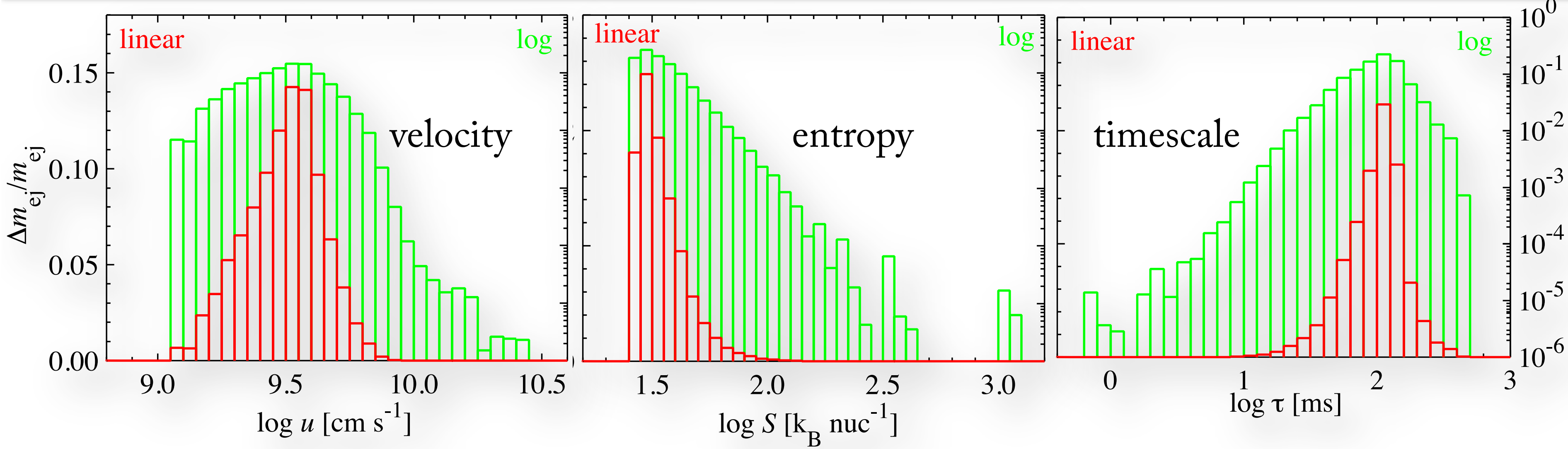
semi-analytic wind model

- ❖ neutrino-driven wind from the BH-accretion torus
- ❖ spherical PNS wind model is applied with modifications

weak interactions on n and p

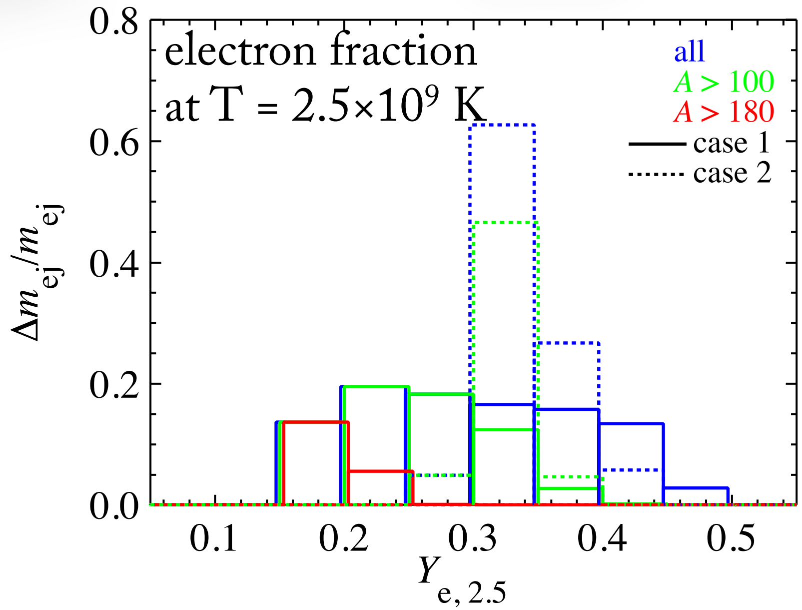
- ❖ case 1: from $T = 1 \times 10^{10}$ K
- ❖ case 2: from $T \approx 6 \times 10^{10}$ K (at the inner boundary)

NS mergers: wind components

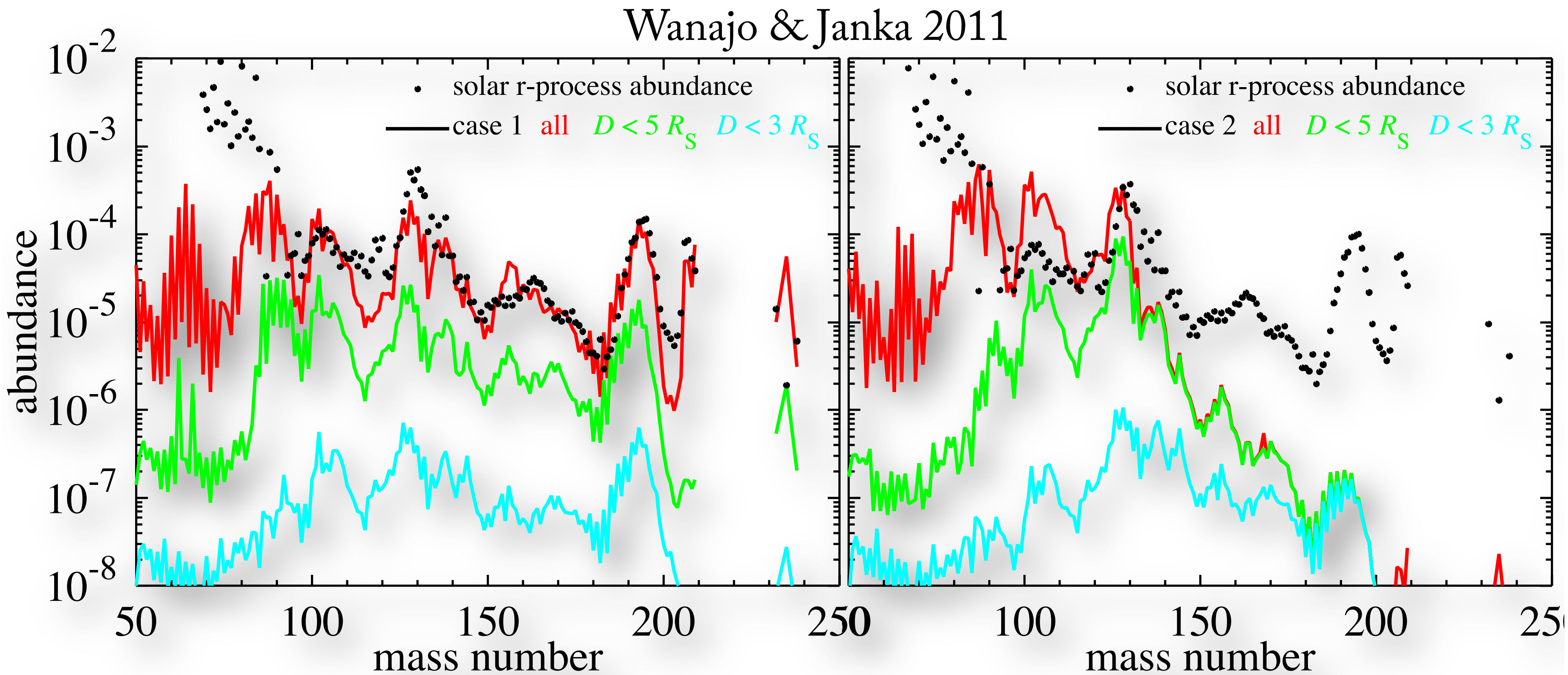


bulk of the wind ejecta has moderate

- v ~ 0.1 c
- S ~ 30 k_B/nuc
- τ ~ 100 ms, and
- Y_e ~ 0.3 (case 2; but 0.2 in case 1)



NS mergers: wind components



case 1 (extreme?)

- $Y_{e,\,min} \sim 0.2$
- full (main) r-process

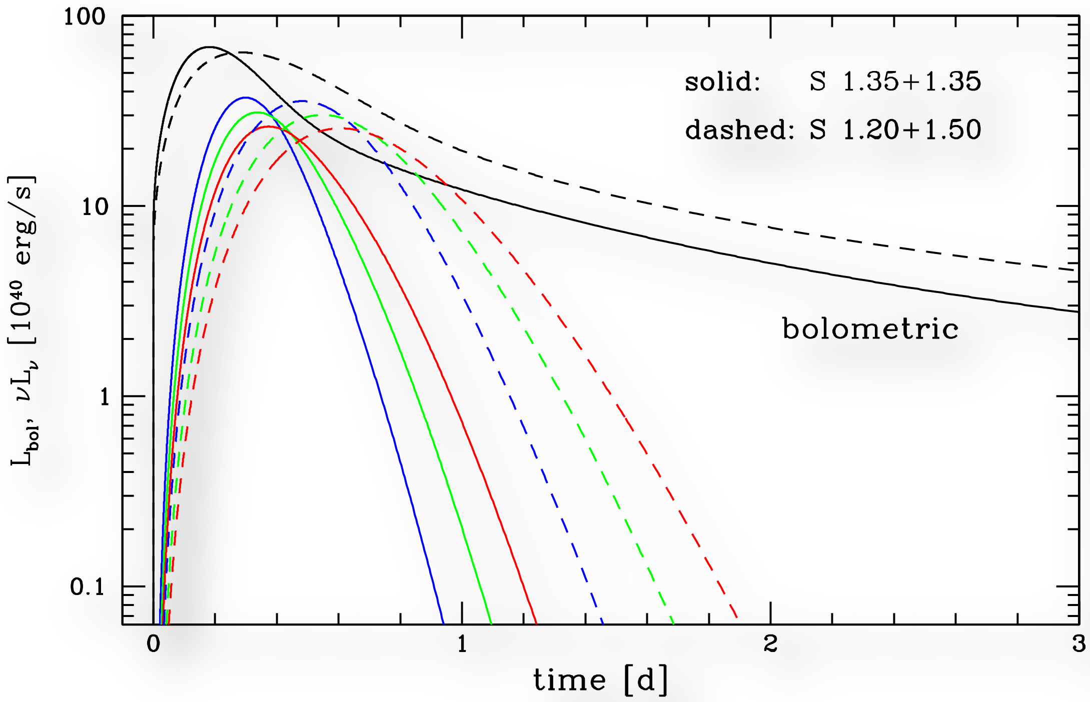
case 2 (reasonable?)

- $Y_{e,\,min} \sim 0.3$
- weak r-process

SMOKING GUN

kilonova?

Goriely+2011

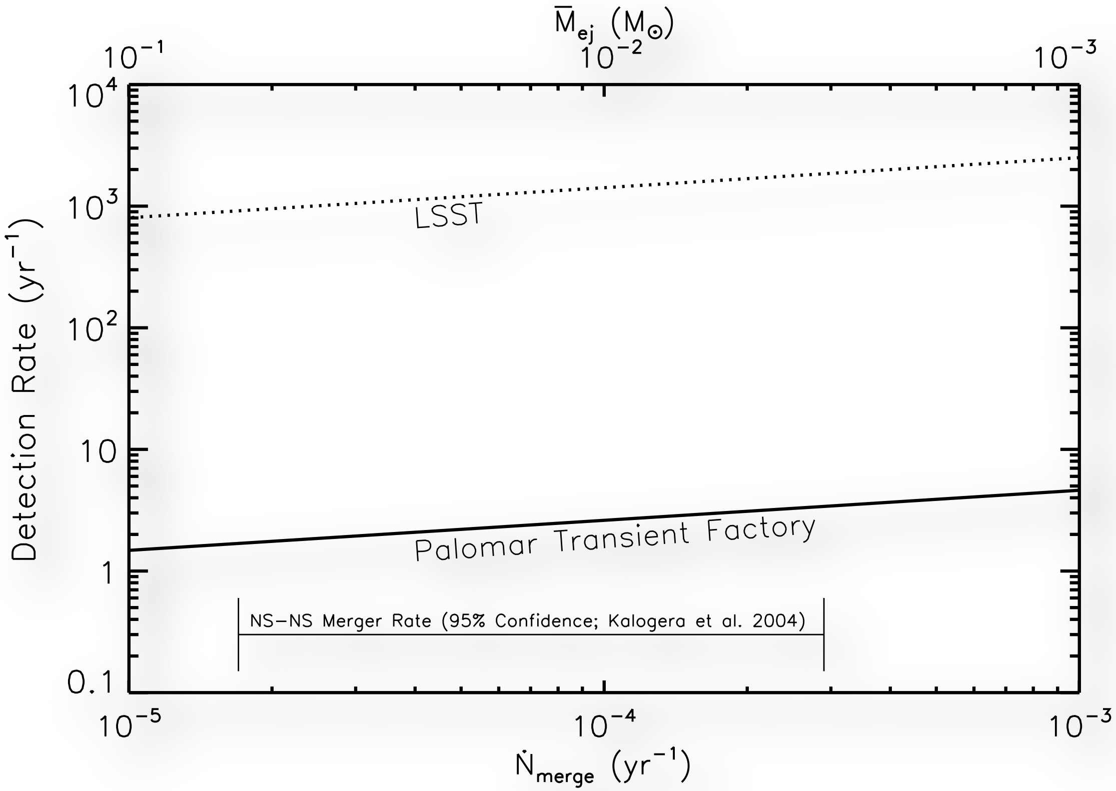


electro-magnetic transients (macronova, Kulkarni 2005; kilonova, Metzger+2010)

- heating from β-decay and fission of r-products
- $L_{peak} \sim v_{exp}^{1/2} M_{ej}^{1/2}$
  $\sim 10^{41} - 10^{42}$ erg s^{-1}
- $t_{peak} \sim v_{exp}^{-1/2} M_{ej}^{1/2}$
  ~ hours
- absorption lines of r-elements to be a "smoking gun"?

kilonova?

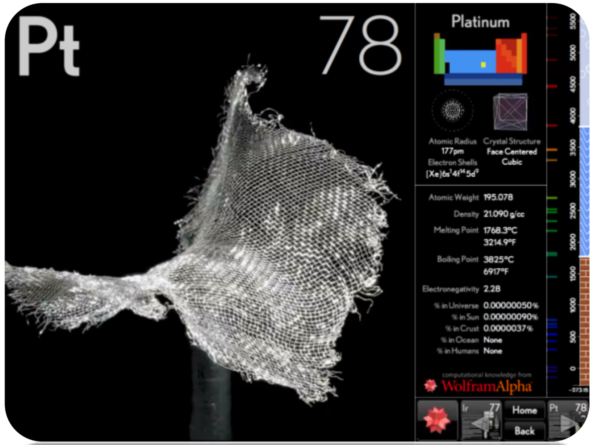
Metzger+2010

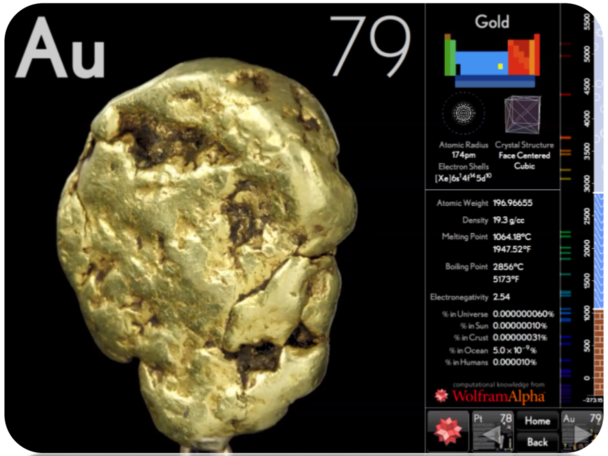


how can we find kilonovae?

- ❖ follow-up of GW surveys by advanced LIGO/Virgo; ~ 6 – 89 events yr^{-1} (Kim+2005)
- ❖ follow-up of short GRBs given the association with NS-NS/BH-NS mergers; GRB080503, Perley+2009
- ❖ blind optical/NIR surveys by LSST/SASIR; most promising?

summary





- ❖ SNe are not very promising; NS mergers show some promise but astrophysical models are still premature
- ❖ survey of kilonovae to be a smoking gun (with GWs, sGRBs)?
- ❖ key roles of computational physics include those of
  nuclear physics (masses, n-capture, β-decay, fission, EOS, …)
  astrophysical modeling (SNe and in particular NS mergers)
  nucleosynthesis calculations of r-process including fission