origin of the r-process elements

Shinya Wanajo (RIKEN iTHES)

Y. Sekiguchi (YITP), N. Nishimura (Keele Univ.),
K. Kiuchi, K. Kyutoku, M. Shibata (YITP)

182nd RIKEN RIBF Nuclear Physics Seminar
July 15, 2014, RIKEN RIBF Hall

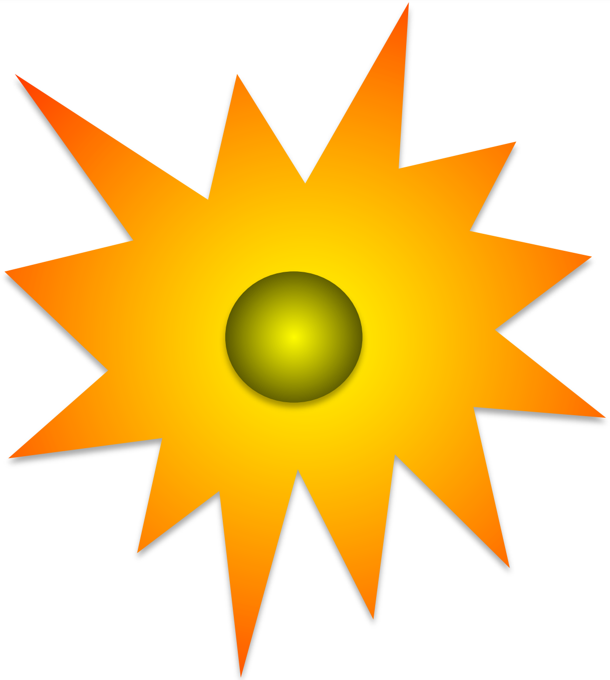
contents

1. overview
2. mergers with neutrinos
3. r-process novae (kilonovae)
4. relevant nuclear physics

1. overview

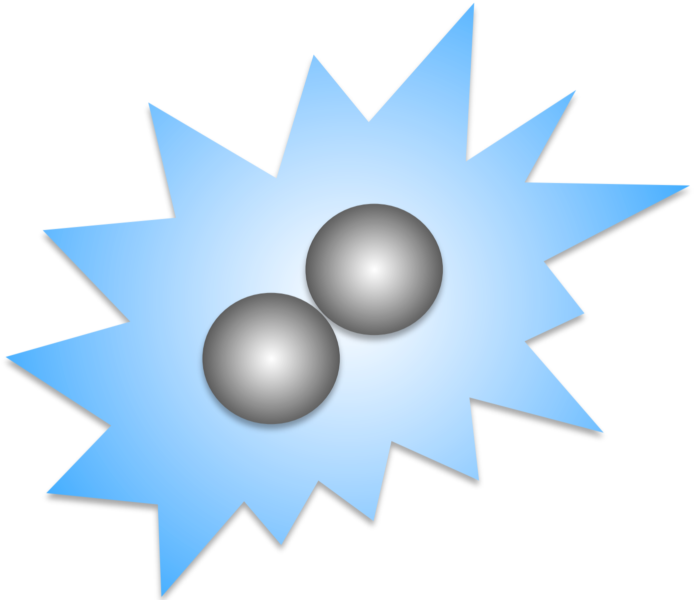
origin of gold (r-process elements) is still unknown…

popular r-process scenarios



core-collapse supernovae
(since Burbidge+1957;
Cameron 1957)

❖ n-rich ejecta nearby proto-NS
❖ not promising according to recent studies



neutron-star mergers
(since Lattimer+1974;
Symbalisty+1982)

❖ n-rich ejecta from coalescing NS-NS or BH-NS
❖ few nucleosynthesis studies

SN ejecta: not so neutron-rich…

- Y_e is determined by

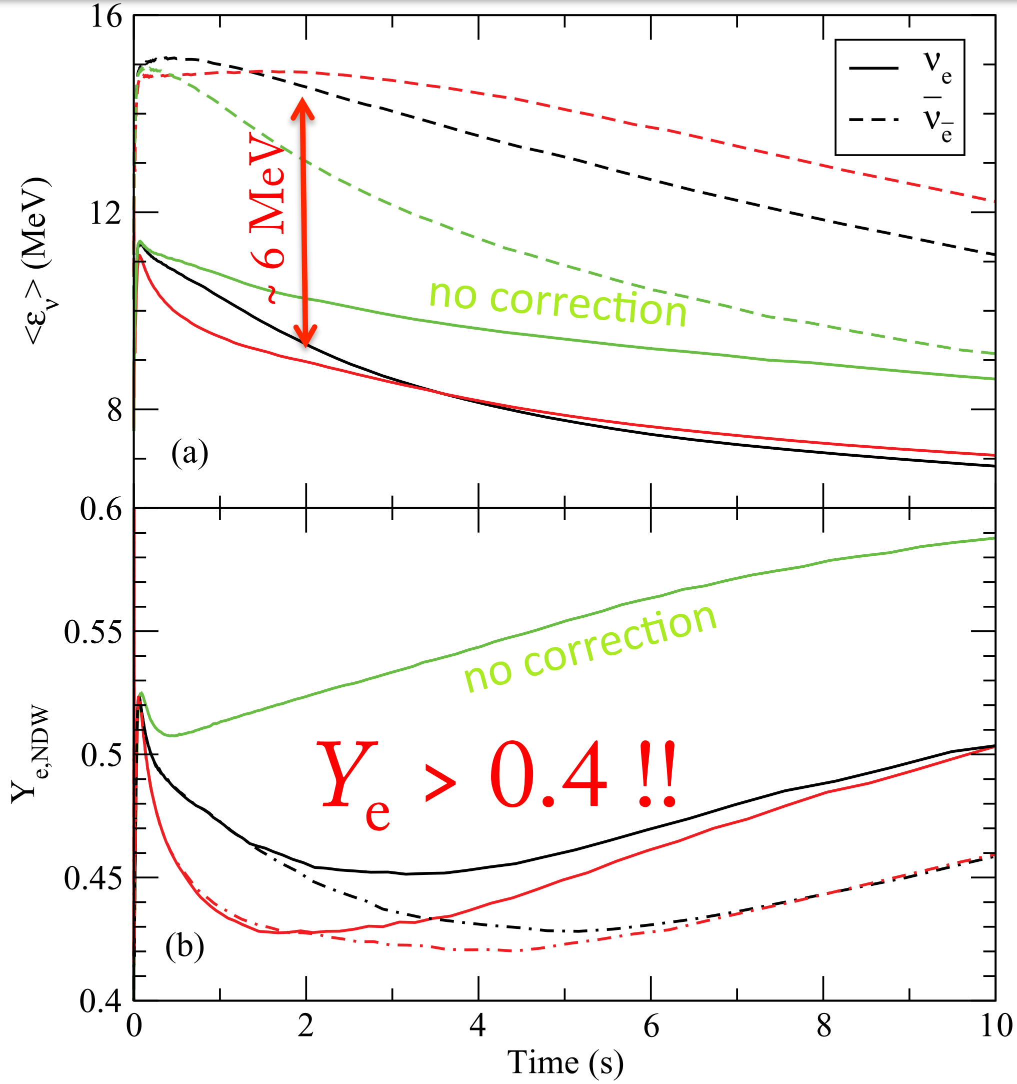
$$\nu_e + n \rightarrow p + e^-$$
$$\bar{\nu}_e + p \rightarrow n + e^+$$

- equilibrium value is

$$Y_e \sim \left[1 + \frac{L_{\bar{\nu}e}}{L_{\nu e}} \frac{\varepsilon_{\bar{\nu}e} - 2\Delta}{\varepsilon_{\nu e} + 2\Delta}\right]^{-1},$$
$$\Delta = M_n - M_p \approx 1.29 \text{ MeV}$$

- for $Y_e < 0.5$ (i.e., n-rich)

$$\varepsilon_{\bar{\nu}e} - \varepsilon_{\nu e} > 4\Delta \sim 5 \text{ MeV}$$
$$\text{if } L_{\bar{\nu}e} \approx L_{\nu e}$$

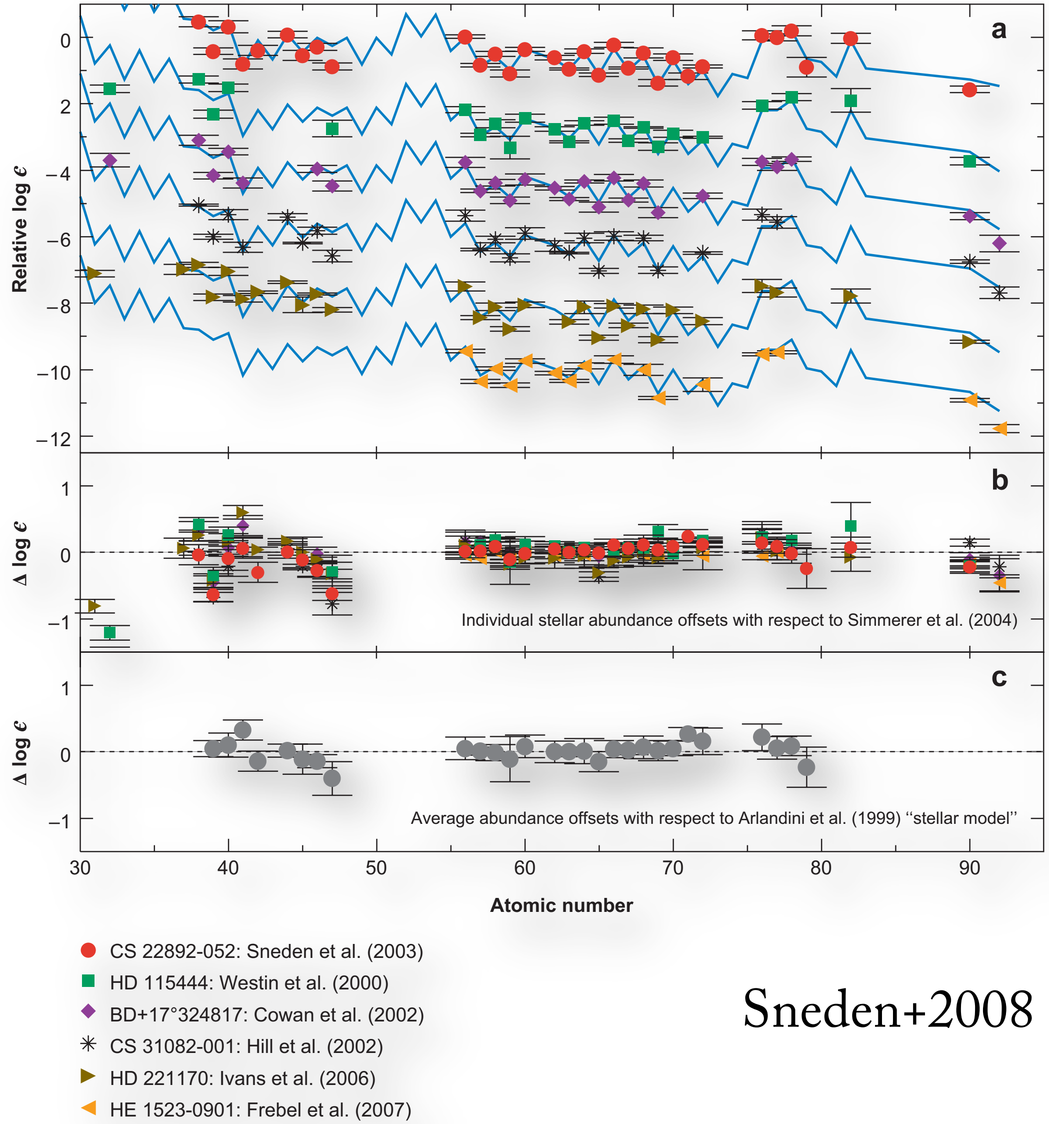


Roberts+2012

supernovae can be the origin only if …

the explosion is not due to neutrino heating (but, e.g., magneto-rotational jet; Winteler+2012) or our knowledge of neutrino physics is insufficient.

r-process in the early Galaxy



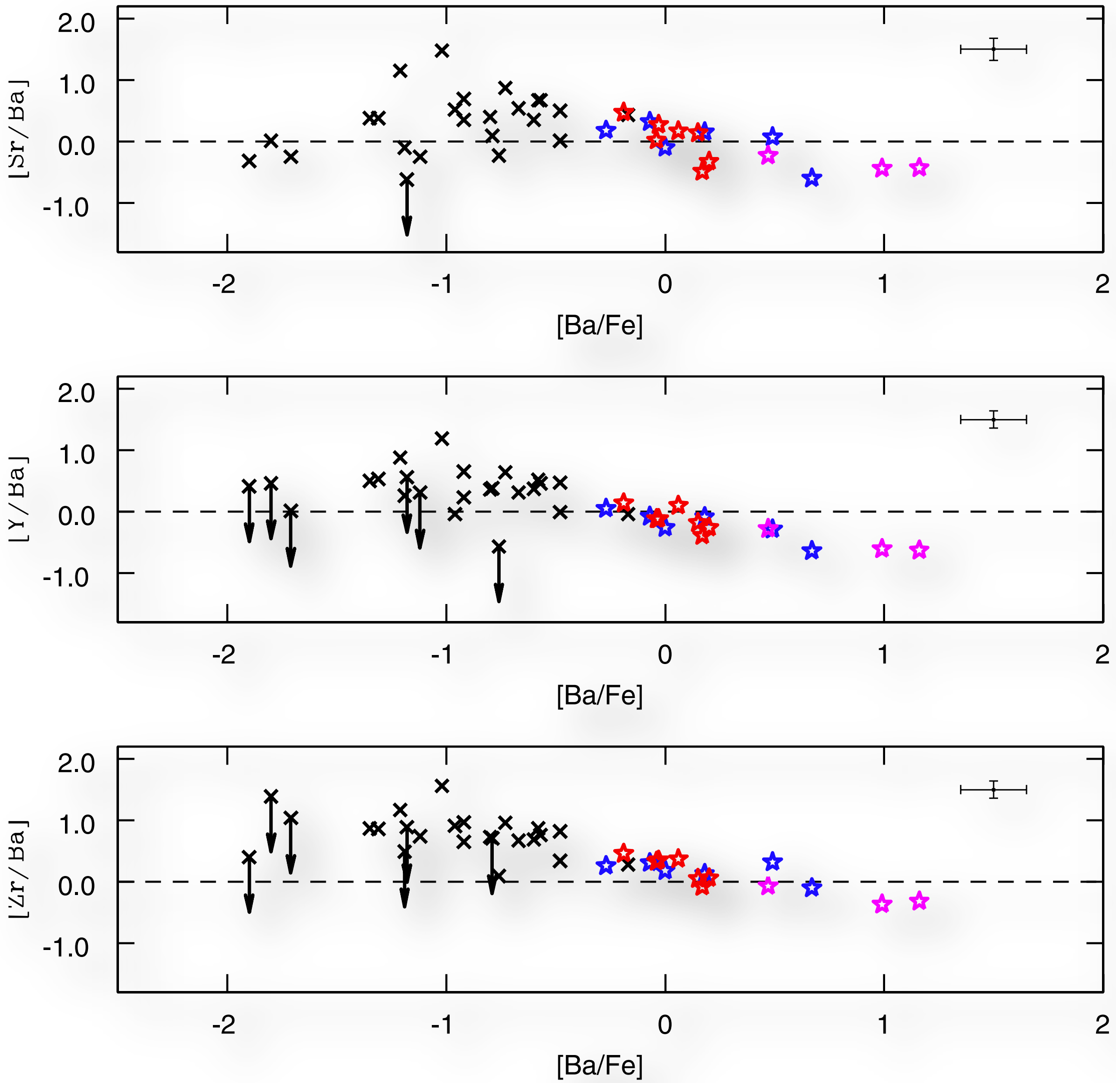
Sneden+2008

all r-rich Galactic halo stars show remarkable agreement with the solar r-pattern

- r-process should have operated in the early Galaxy; SNe 😃, mergers 😢 ?
- astrophysical models should reproduce the "universal" solar-like r-process pattern (for $Z \geq 40$; $A \geq 90$)

constraint to light-to-heavy r-ratio

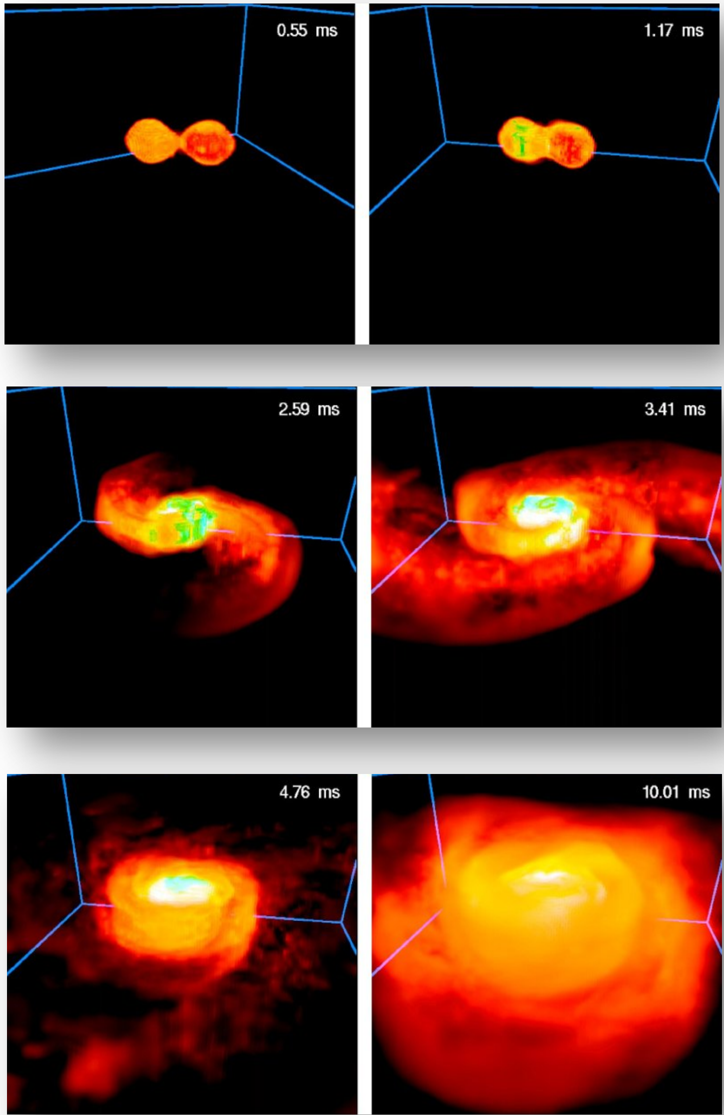
Siqueira Mello+…+ Wanajo 2014



VLT observations give tight constraint for light-to-heavy r-abundances (here [Sr, Y, Zr/Ba])

- [light-r/heavy-r] ≥ -0.3; no stars below this constraint
- “the r-process” must make lighter r-elements with similar portion

NS merger scenario: most promising?

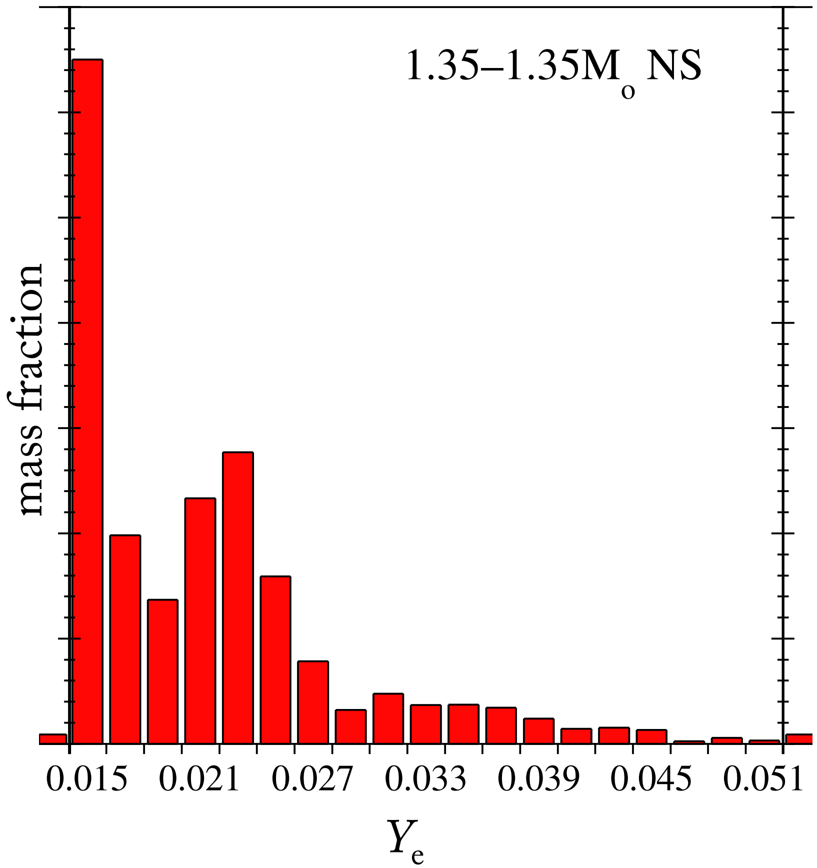


www.mpa-garching.mpg.de

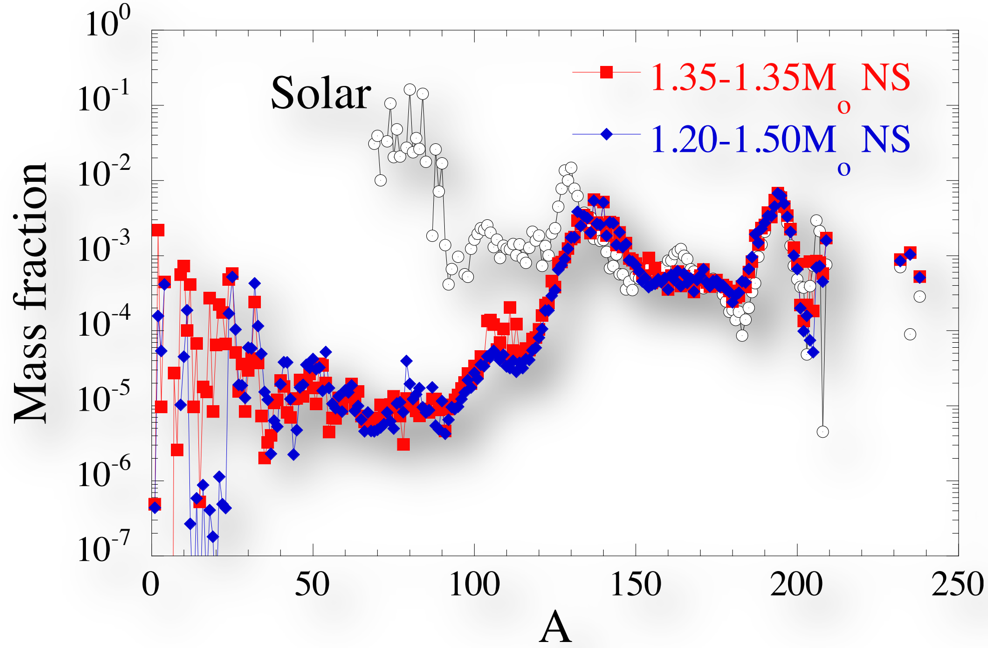
- coalescence of binary NSs expected ~ 10 – 100 per Myr in the Galaxy (also possible sources of short GRB)
- first ~ 0.1 seconds
  dynamical ejection of n-rich matter with $M_{ej} \sim 10^{-3} - 10^{-2}\, M_\odot$
- next ~ 1 second
  neutrino or viscously driven wind from the BH accretion torus with $M_{ej} \sim 10^{-3} - 10^{-2}\, M_\odot$

previous works: too neutron-rich ?

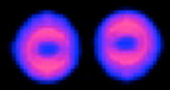
Goriely+2011 (also similar results by Korobkin+2011; Rosswog+2013)



tidal (or weakly shocked) ejection of “pure” n-matter with $Y_e < 0.1$



- strong r-process leading to fission cycling
- severe problem: only $A > 130$; another source is needed for the lighter counterpart

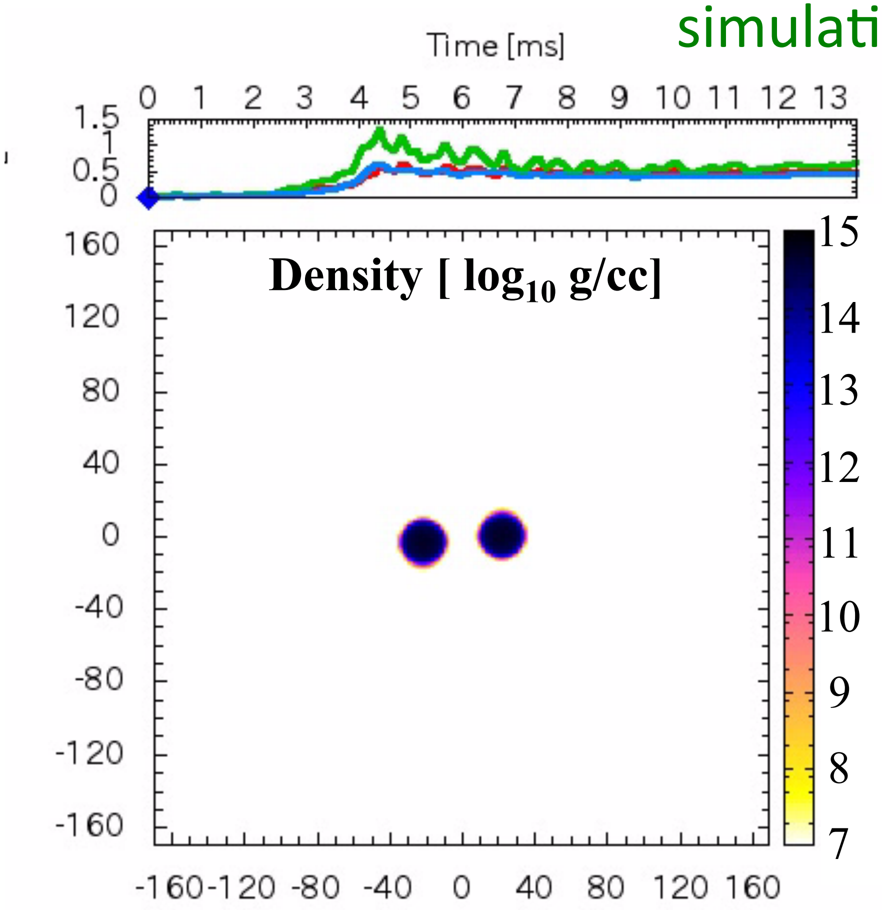


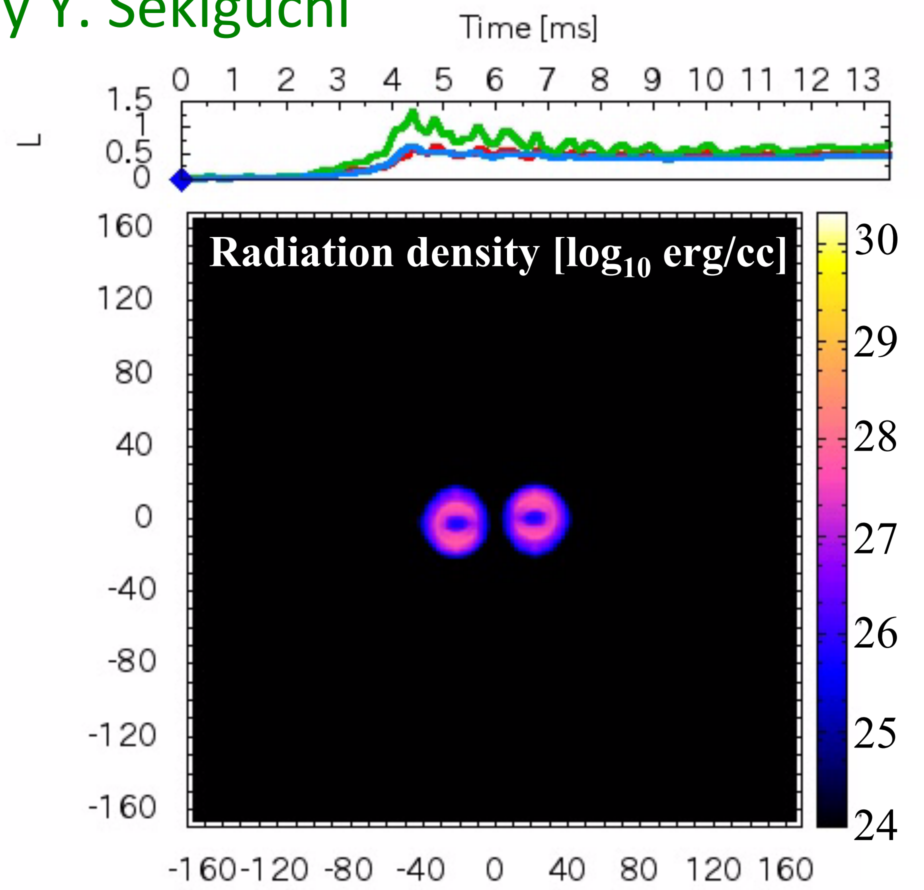
2. mergers with GR and ν

first simulation with full-GR and ν

- Approximate solution by Thorne's Moment scheme with a closure relation
- Leakage + Neutrino heating (absorption on proton/neutron) included

simulation by Y. Sekiguchi





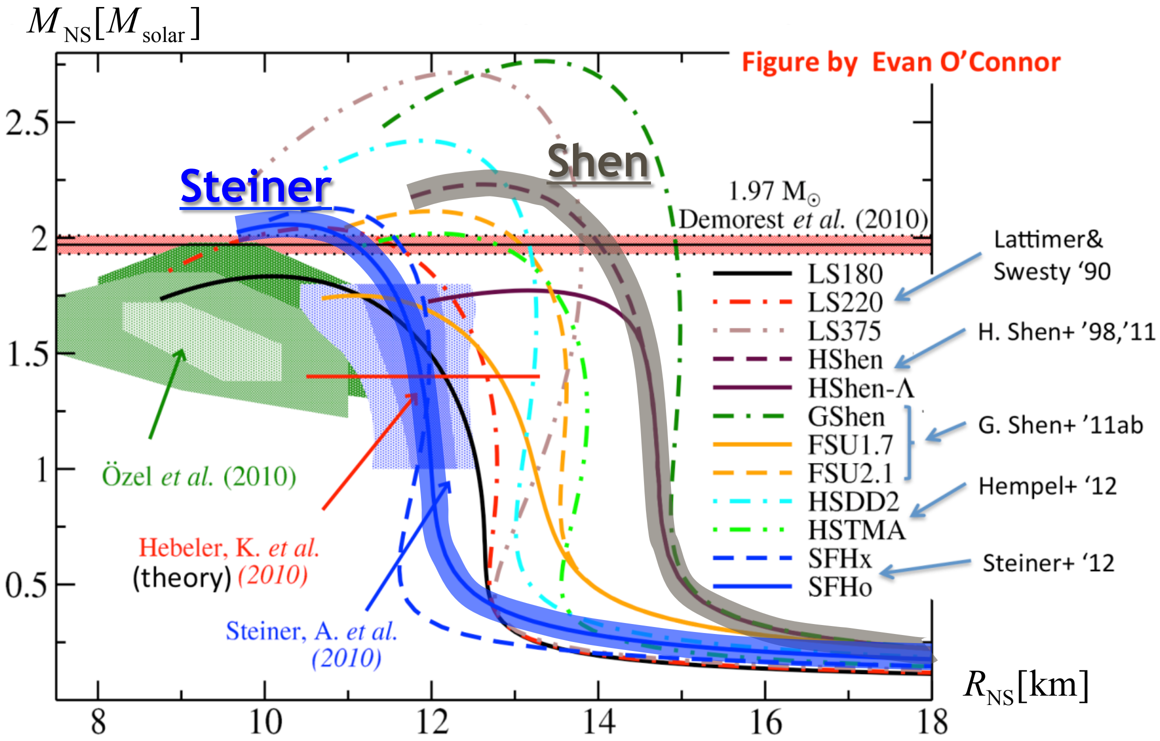
slide by Y. Sekiguchi

'Robustness' of r-process in NS-NS merger ?

- **Korobkin et al. 2012 :** Ye of the ejecta depends only weakly on the binary parameters so that r-process in the NS-NS is 'robust',
  - They adopted only one EoS (**Shen EoS**) : dependence on EoS is not explored
- **In This Study :** Comparison between **Steiner EoS** and **Shen EoS**

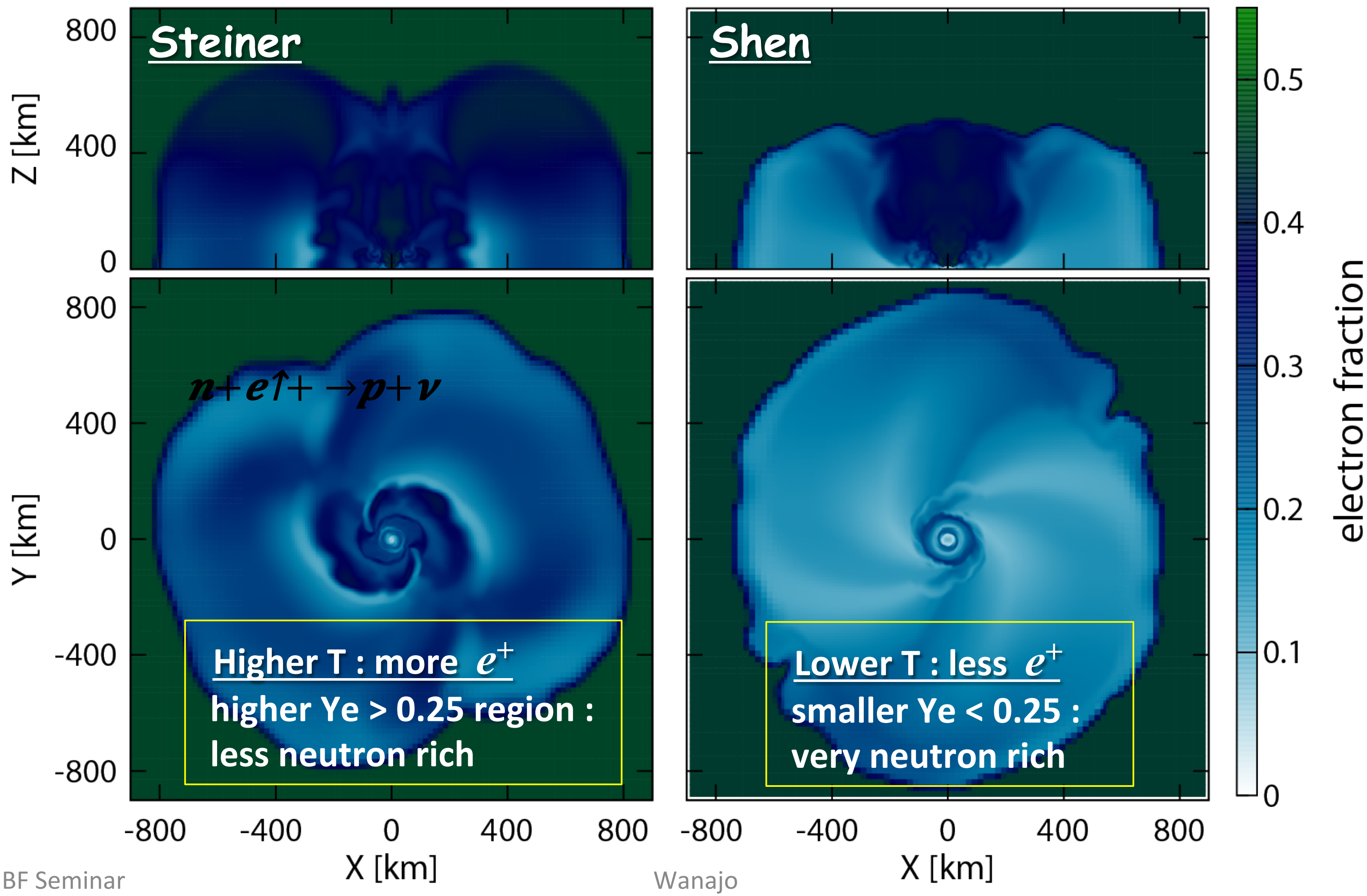
- **Shen EOS: 'Stiffer'**
  - Larger NS radius
  - Mass ejection is driven mainly by Tidal force
- **Steiner EOS: 'Softer'**
  - Smaller NS radius
  - Tidal effects are less important in mass ejection
  - Stronger bounce

$$F \sim k_{\rm EOS}\Delta x \sim M_{\rm NS},$$
$$E \sim k_{\rm EOS}(\Delta x)^2 \sim M_{\rm NS}^2 k_{\rm EOS}^{-1}$$

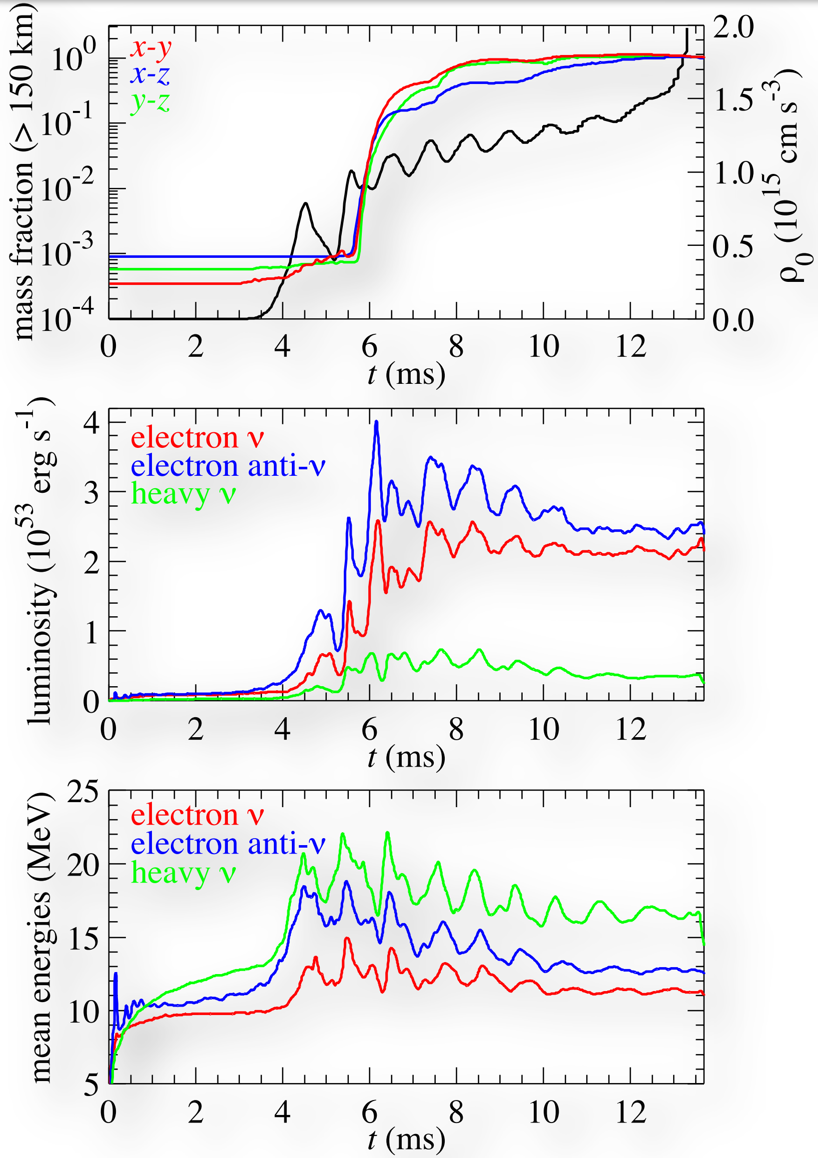


slide by Y. Sekiguchi

Composition depends on EOS

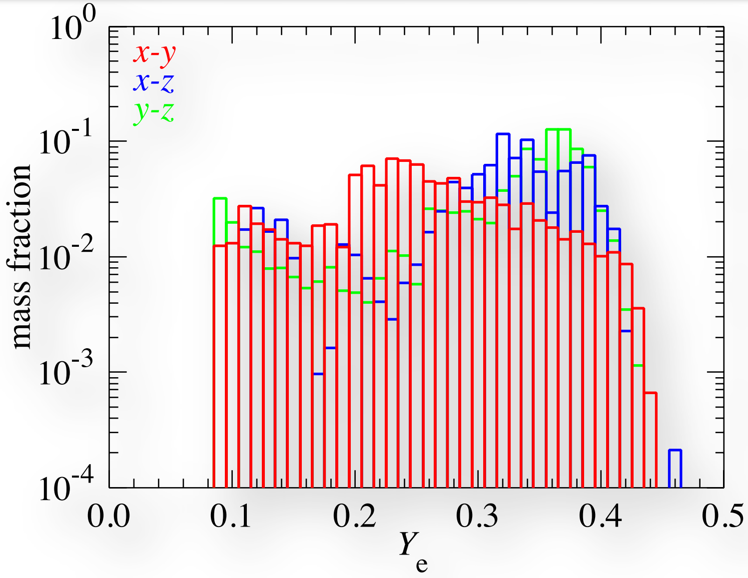


neutrino properties (Steiner's EOS)

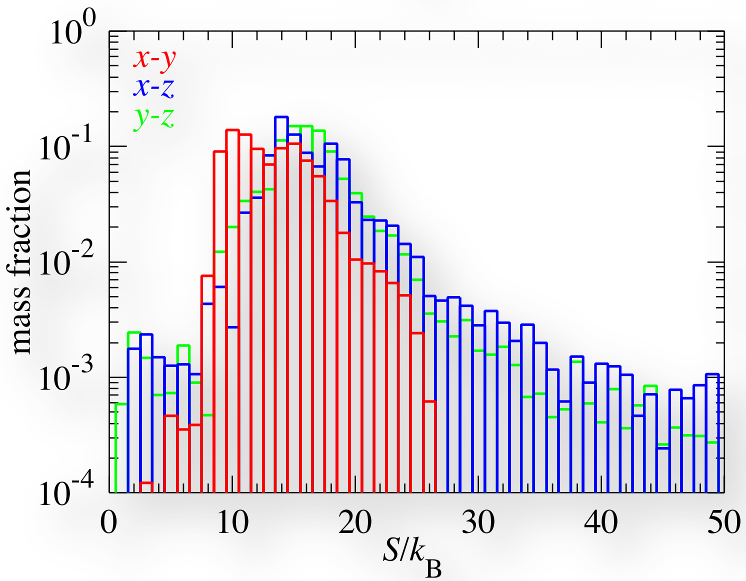


- ❖ mass ejection before (40%) and after (60%) HMNS formation; 70% ejecta reside near orbital
- ❖ neutrino luminosities similar between ν_e and anti-ν_e
- ❖ neutrino mean energies similar between ν_e and anti-ν_e

nucleosynthesis in the NS ejecta

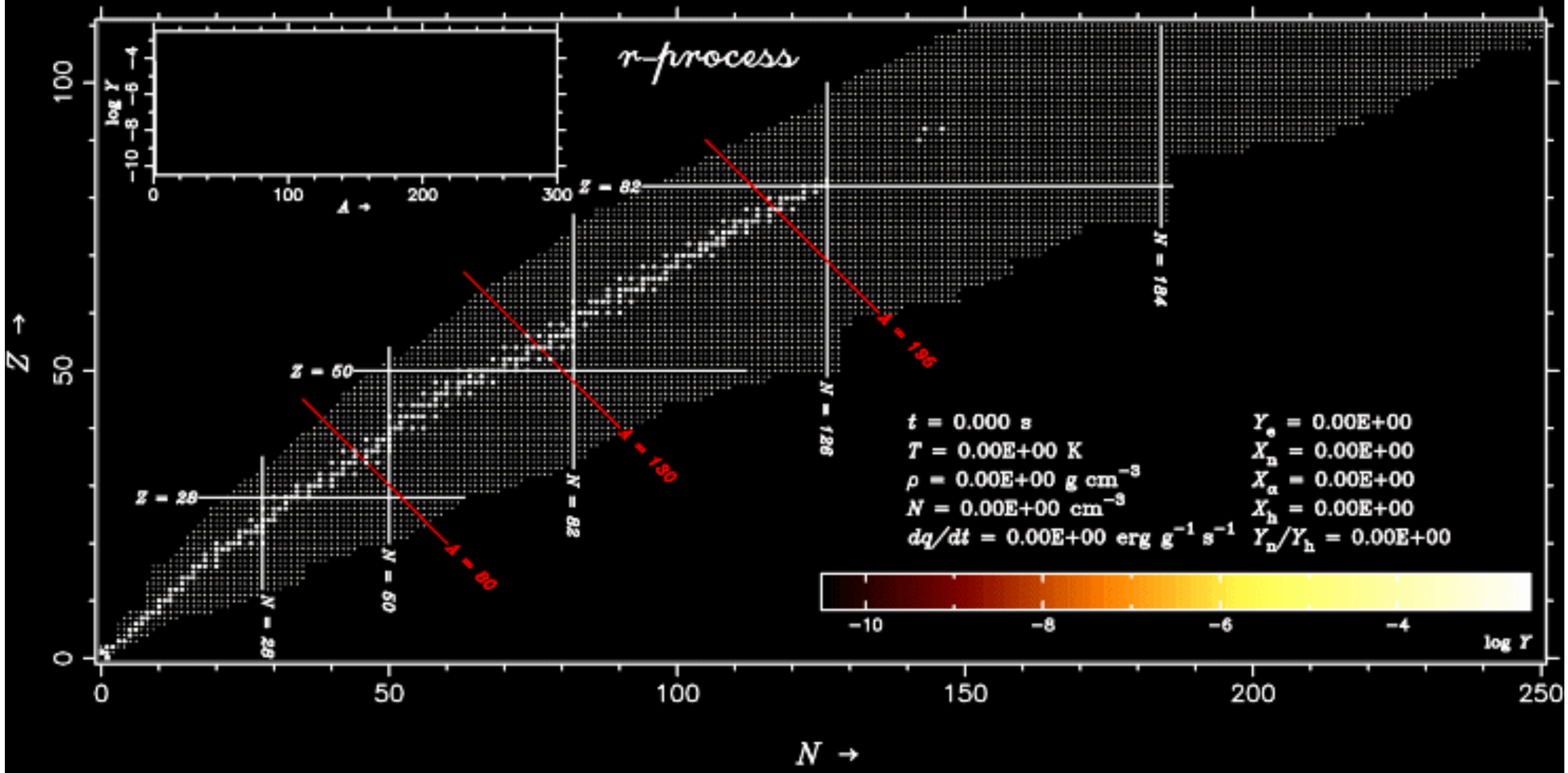


❖ higher and wider range of Y_e (= 0.09-0.45) in contrast to previous cases Y_e (= 0.01-0.05)



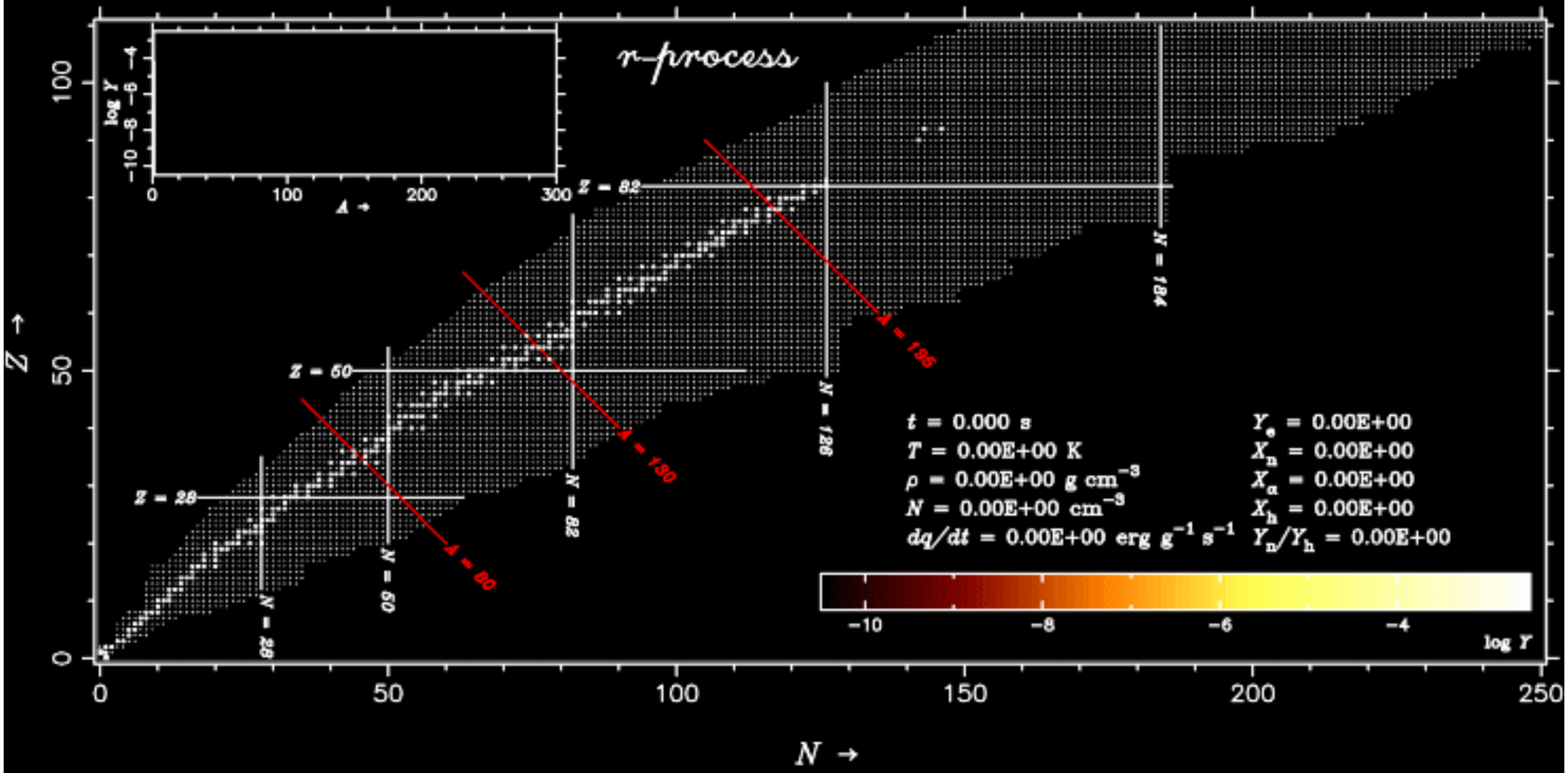
❖ higher and weder range of entropy per baryon (= 0-50) in contrast to previous cases (= 0-3)

Y_e = 0.1



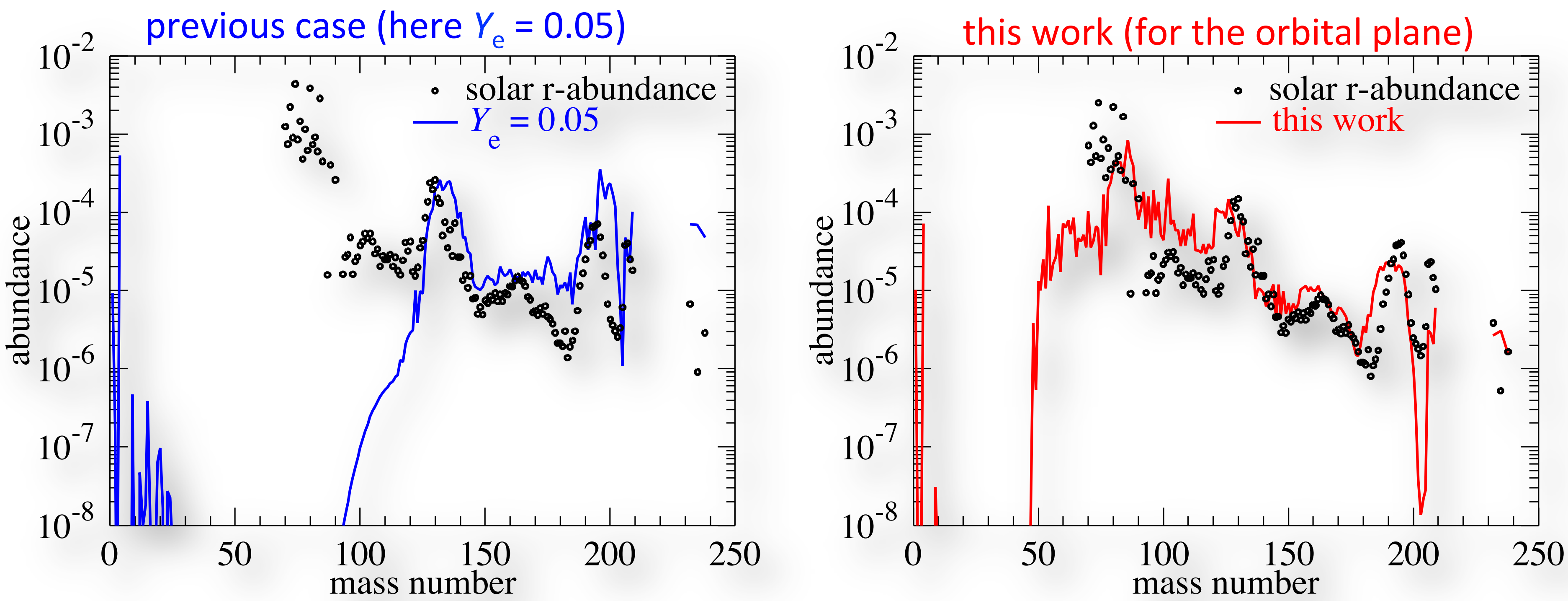
r-process
log Y
100
200
300
A →
Z = 28
Z = 50
Z = 82
N = 28
N = 50
N = 82
N = 126
N = 184
A = 80
A = 130
A = 195
t = 0.000 s
T = 0.00E+00 K
ρ = 0.00E+00 g cm⁻³
N = 0.00E+00 cm⁻³
dq/dt = 0.00E+00 erg g⁻¹ s⁻¹
Ye = 0.00E+00
Xn = 0.00E+00
Xα = 0.00E+00
Xh = 0.00E+00
Yn/Yh = 0.00E+00
−10
−8
−6
−4
log Y
Z →
N →
0
50
100
150
200
250

Y_e = 0.2



r-process
log Y
−10 −8 −6 −4
0 100 200 300
A →
Z = 82
Z = 50
Z = 28
N = 28
N = 50
N = 82
N = 126
N = 184
A = 80
A = 130
A = 195
t = 0.000 s
T = 0.00E+00 K
ρ = 0.00E+00 g cm−3
N = 0.00E+00 cm−3
dq/dt = 0.00E+00 erg g−1 s−1
Ye = 0.00E+00
Xn = 0.00E+00
Xα = 0.00E+00
Xh = 0.00E+00
Yn/Yh = 0.00E+00
−10 −8 −6 −4
log Y
Z →
0 50 100
0 50 100 150 200 250
N →

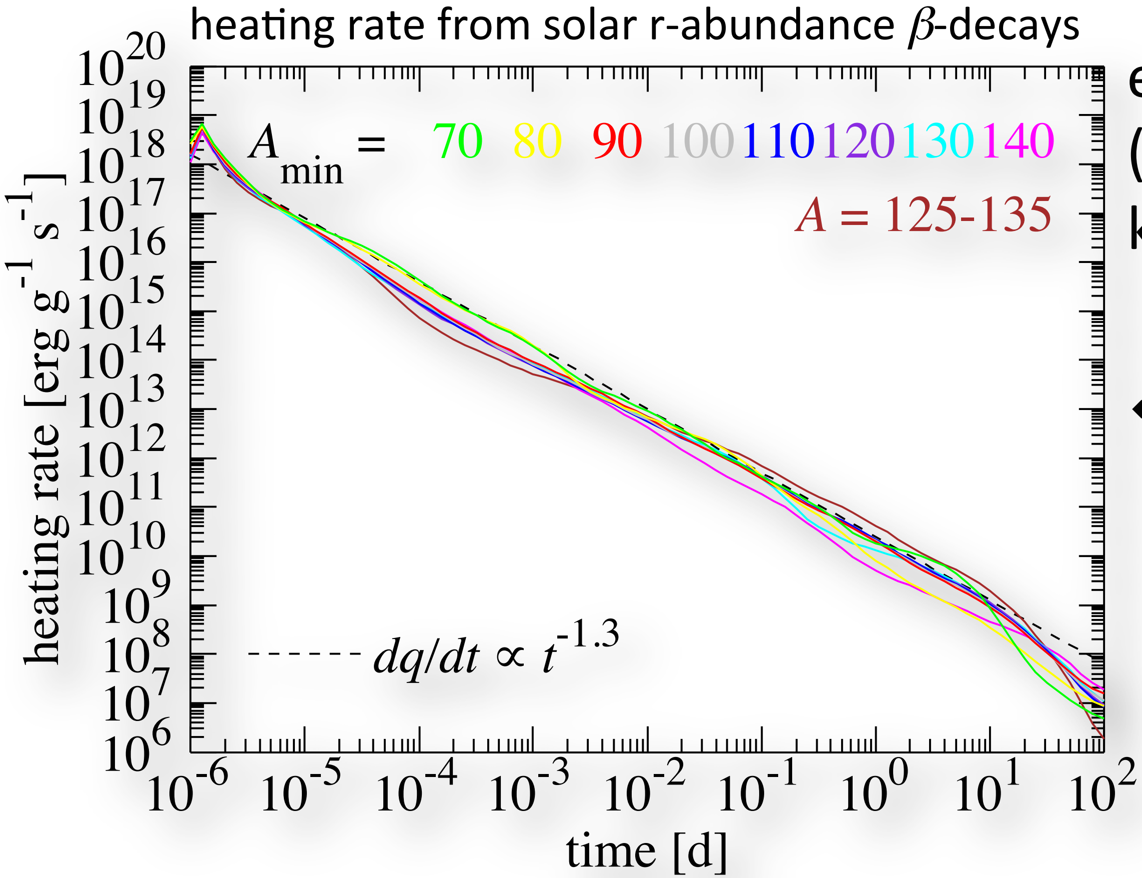
mass-integrated abundances



- ❖ previous case: not in agreement with solar r-pattern (e.g., for A < 130)
  → also the case for NS-NSs with stiff EOSs and BH-NSs
- ❖ this work: good agreement with solar r-pattern for A = 90-240
  → no need of additional (e.g., BH-torus) sources for light r-elements

3. r-process novae (or goldnovae)

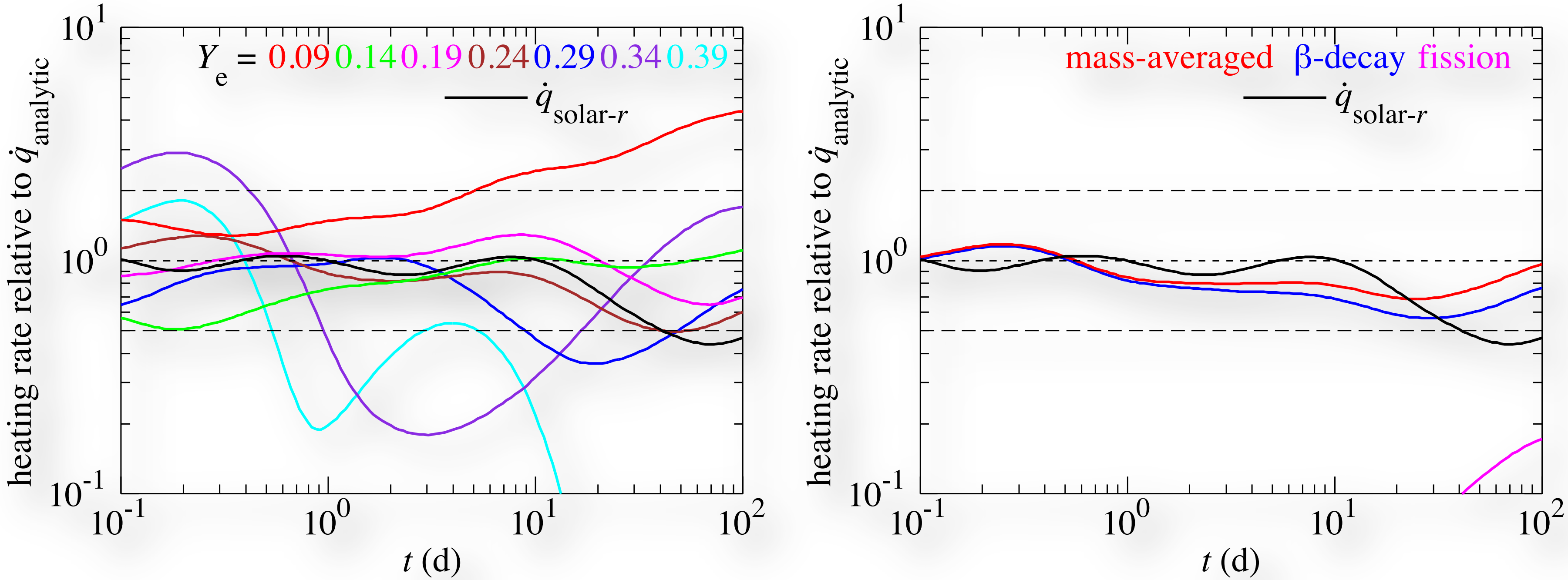
r-process novae (kilonovae)



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

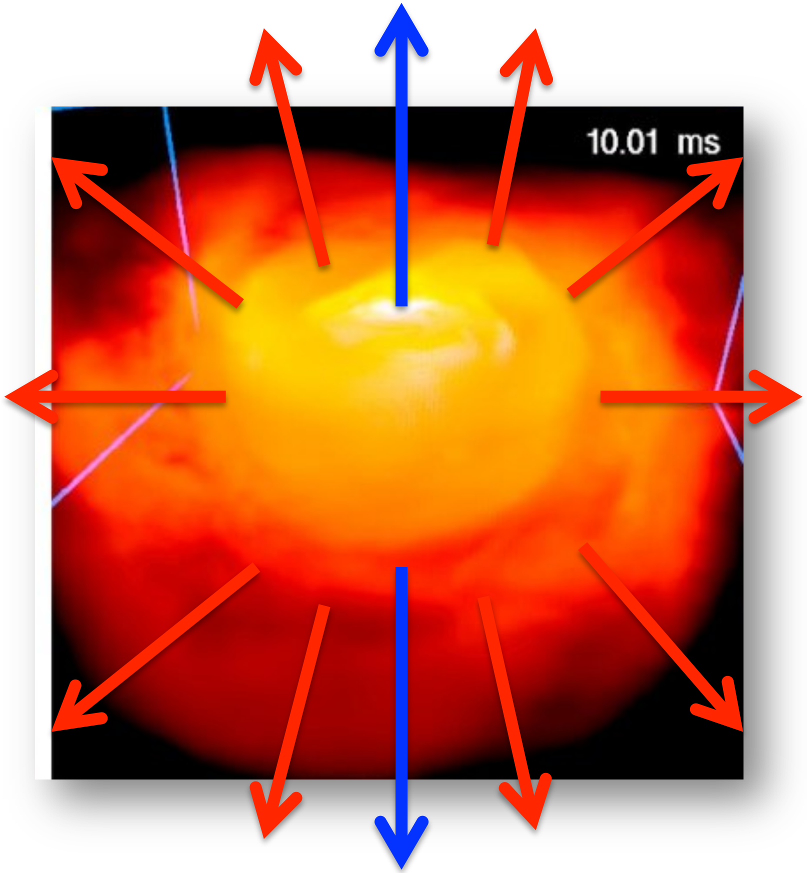
- heating from decays of radionuclides well scaled as $dq/dt \sim t^{-1.3}$

heating rate for the NS-NS ejecta



- heating rate for the mass-averaged abundances well fitted by the scaling law $dq/dt \sim t^{-1.3}$ (as well as by the solar r-pattern case)
- but dependent on Y_e; there might be directional (polar to equatorial) differences

EM counterparts of GW signals



GW signal can be spatially resolved only ~ 100 deg^2 by KAGRA/a.LIGO/a.Virgo (from 2017)
→ EM counterparts are needed

- SGRBs
  events should be restricted due to narrow beaming

- r-process novae
  detectable (by, e.g., Subaru/HSC) from all directions!

already found?

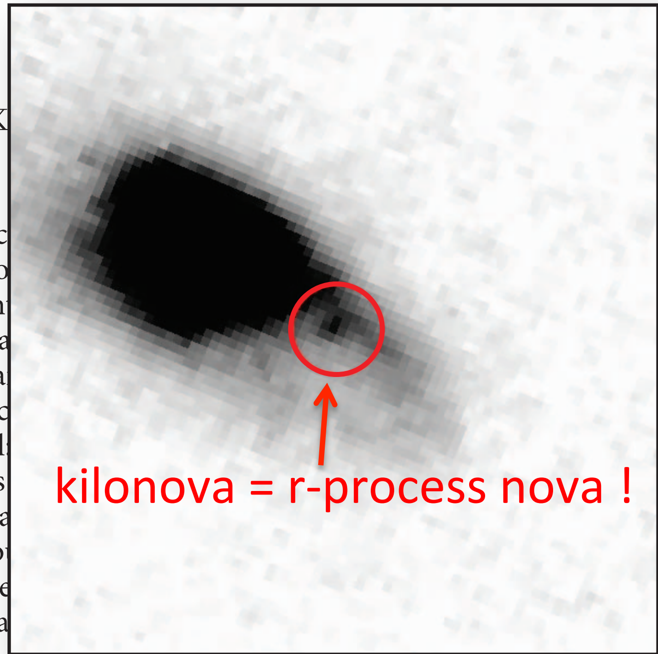
LETTER

doi:10.1038/nature12505

A 'kilonova' associated with the short-duration γ-ray burst GRB 130603B

N. R. Tanvir[1], A. J. Levan[2], A. S. Fruchter[3], J. Hjorth[4], R. A. Hounsell[3], K

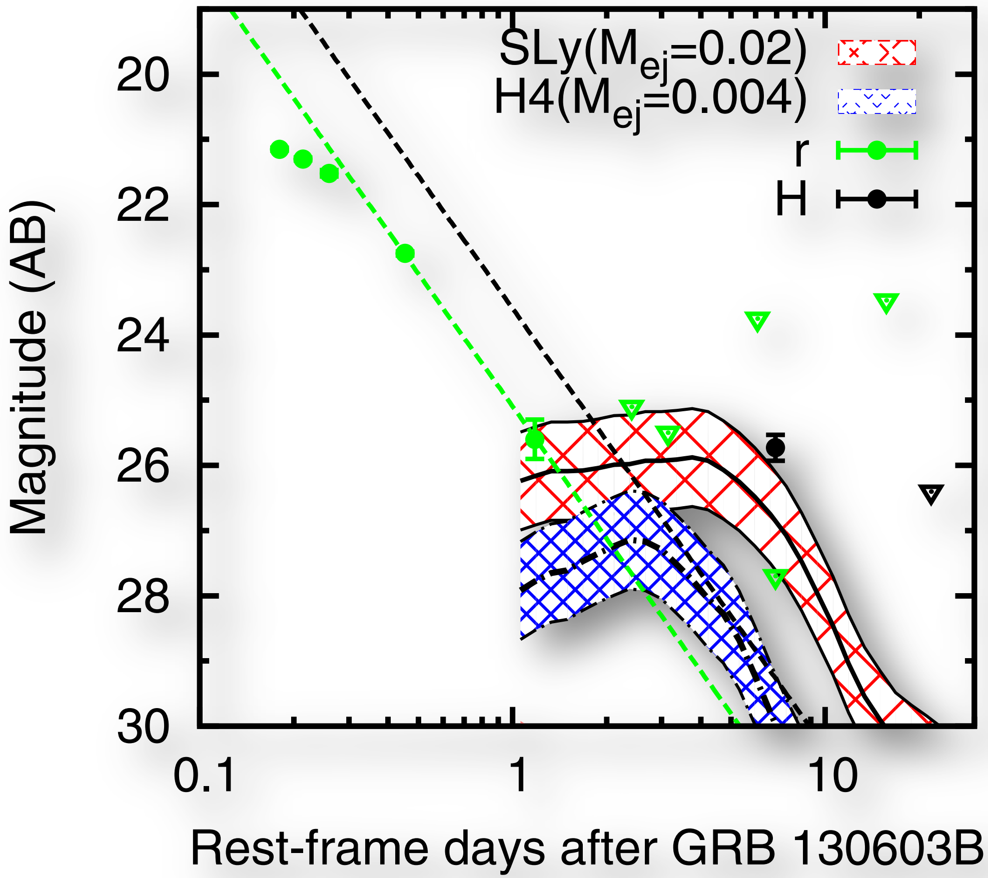
Short-duration γ-ray bursts are intense flashes of cosmic γ-rays, lasting less than about two seconds, whose origin is unclear[1,2]. The favoured hypothesis is that they are produced by a relativistic jet created by the merger of two compact stellar objects (specifically two neutron stars or a neutron star and a black hole). This is supported by indirect evidence such as the properties of their host galaxies[3], but unambiguous confirmation of the model is still lacking. Mergers of this kind are also expected to create significant quantities of neutron-rich radioactive species[4,5], whose decay should result in a faint transient, known as a 'kilonova', in the days following the burst[6–8]. Indeed, it is speculated that this mechanism may be the predominant source of stable r-process elements in the Universe[5,9].



Tanvir+2013, Nature, Aug. 29

r-process nova in the SGRB afterglow?

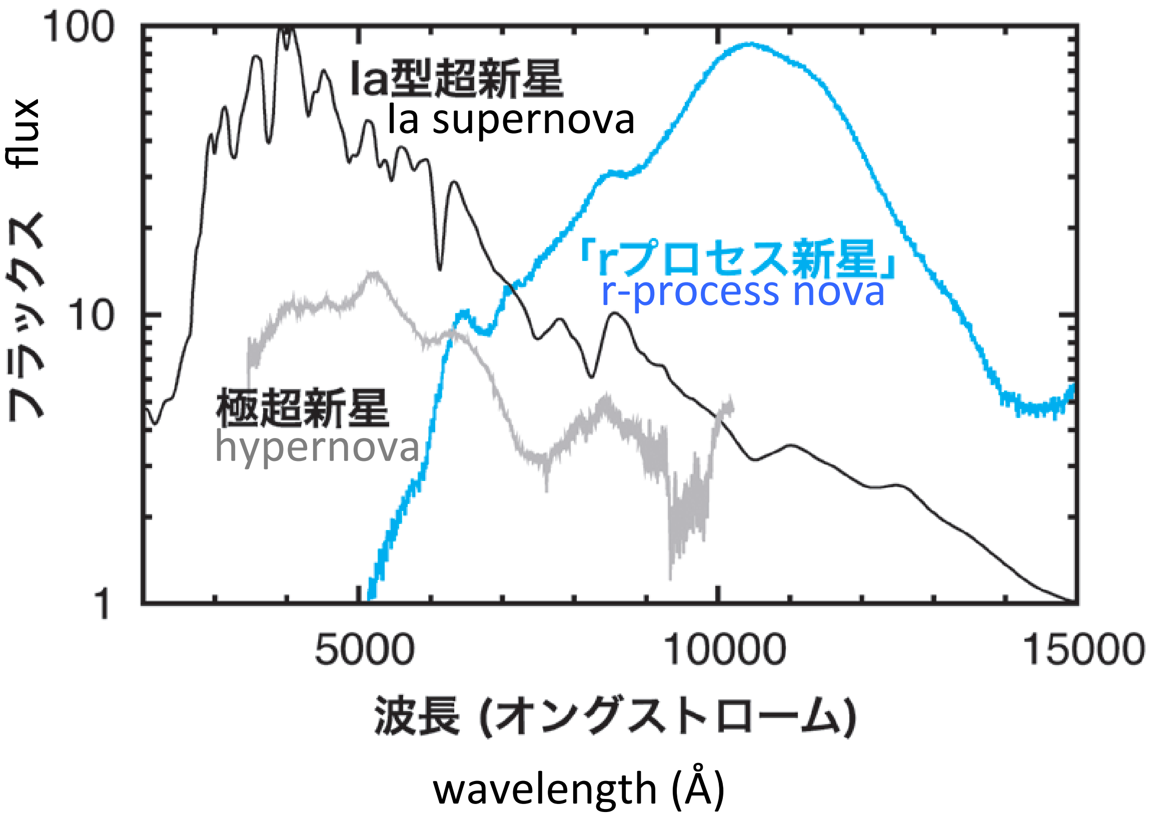
Hotokezaka+Tanaka…+Wanajo 2013;
NS+NS models



- late-time excess NIR flux requires an additional component (most likely an r-process nova)
- the excess NIR indicates the NS-NS ejecta with M_{ej} ~ 0.02 $M_\odot$
- additional late-time red transients in SGRBs should be observed

what is a smoking gun of the r-process?

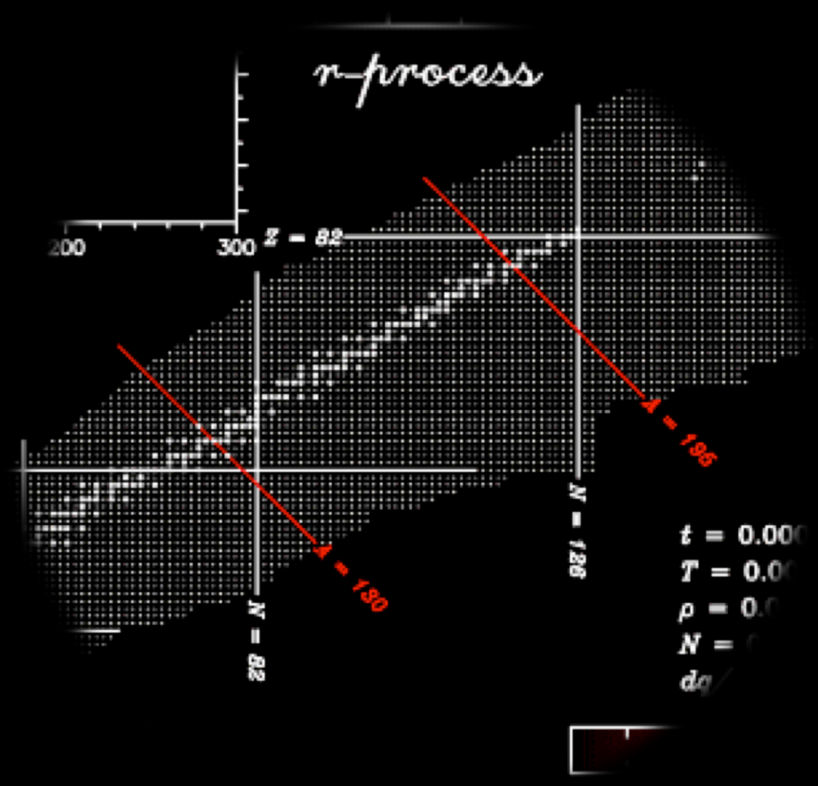
田中，天文月報2014年1月



can we see r-abundances in the spectra?

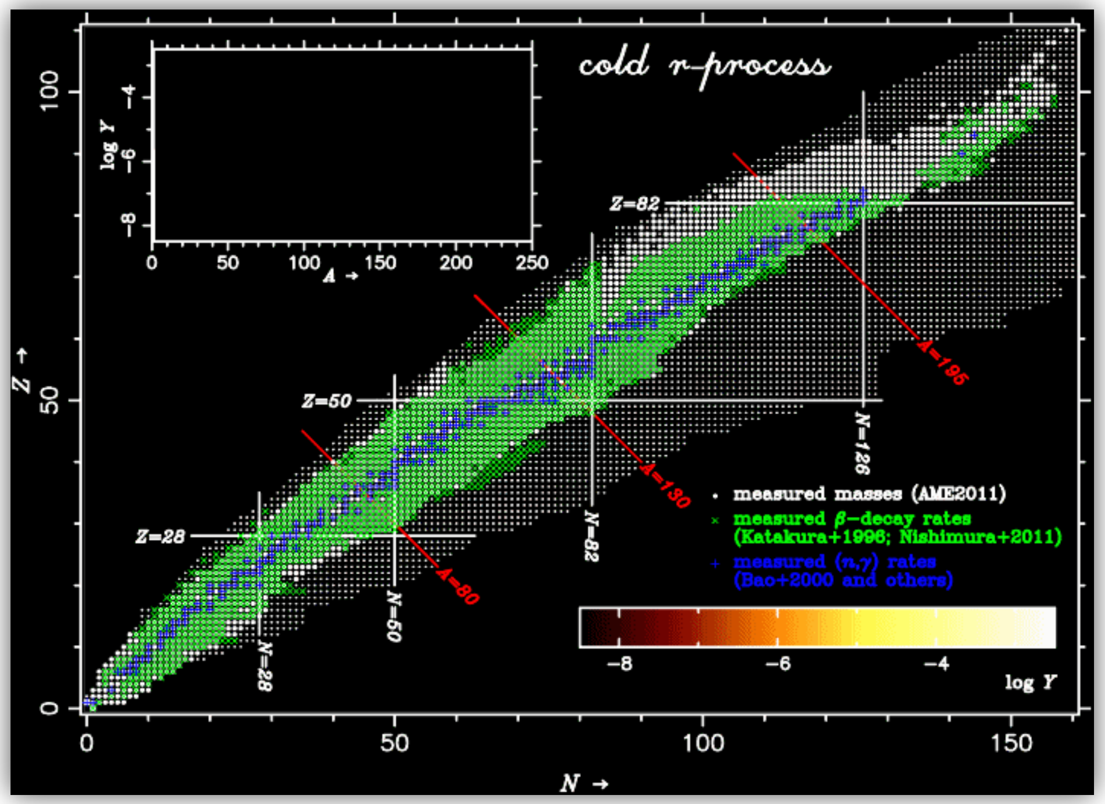
- almost featureless because of too many bound-bound lines and Doppler shifts (v/c ~ 0.1-0.3)

- identification of red, featureless spectral shape can be an unambiguous evidence of an r-process



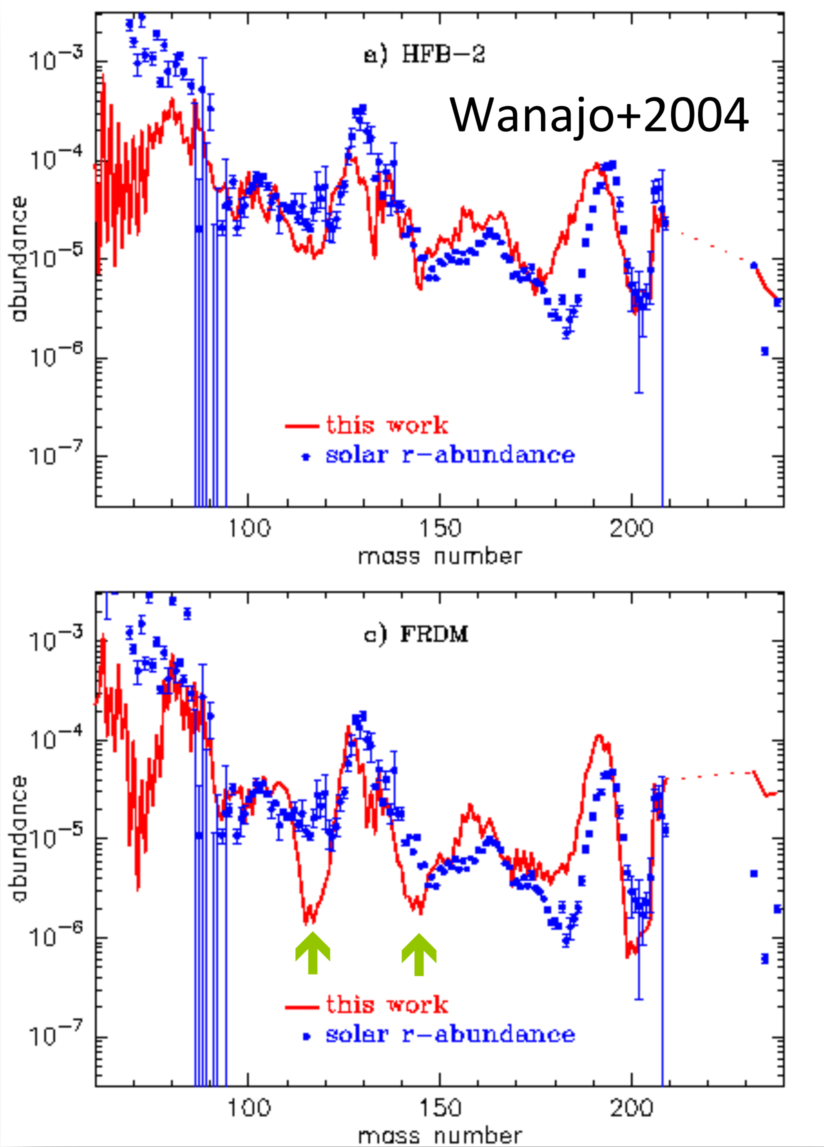
4. relevant nuclear physics

needs of theoretical data



- r-process goes through the n-rich region where experiments are out of reach
- abundances approach the experimentally accessible region of A < 140 only during freezeout
- theoretical rates are needed for (n, γ), (γ, n), β-decay, and fission

problems of abundance “troughs”

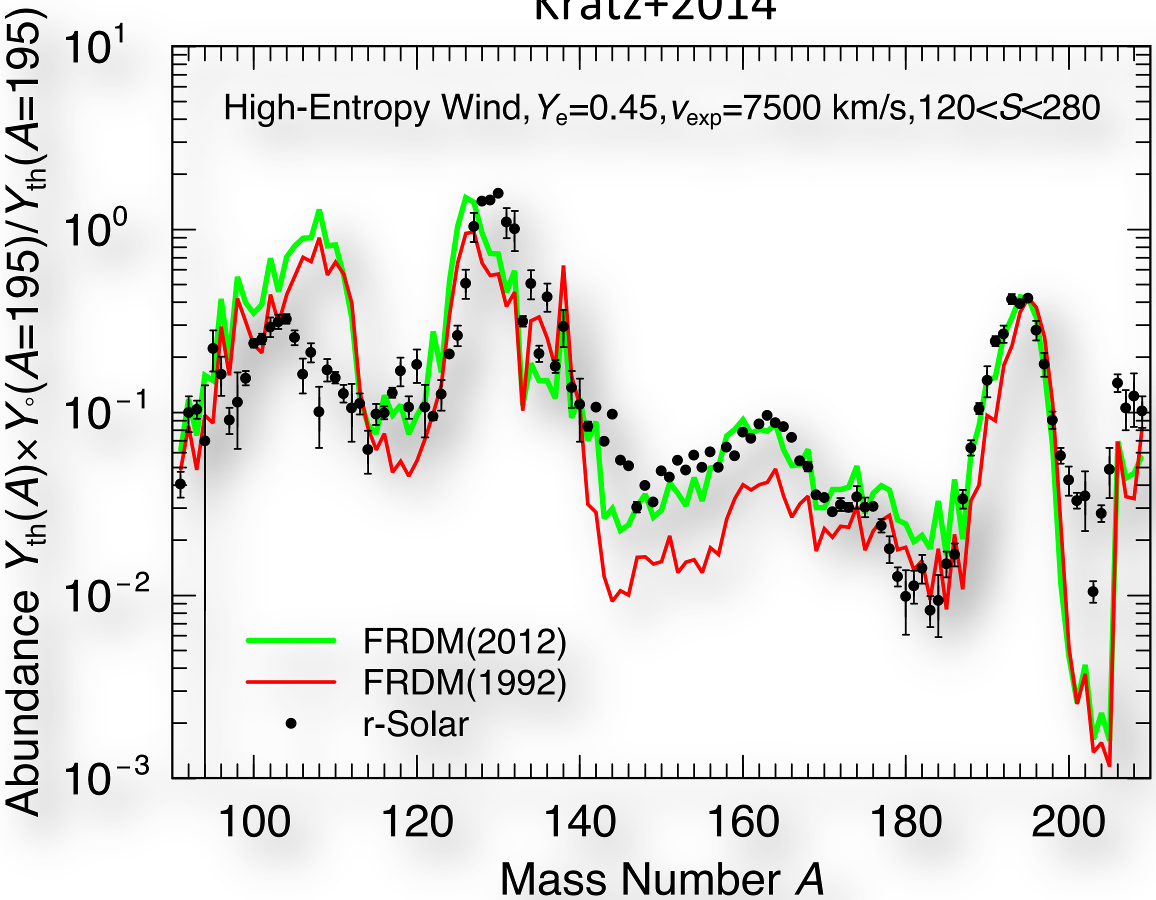


calculated r-abundace “troughs”

- discrepancies seen in macroscopic models (FRDM, etc.) diminish by making use of microscopic models (HFB-2, etc.)
- likely problems in nuclear physics, not in astrophysical modelling

shell-quenching saves the problem

Kratz+2014



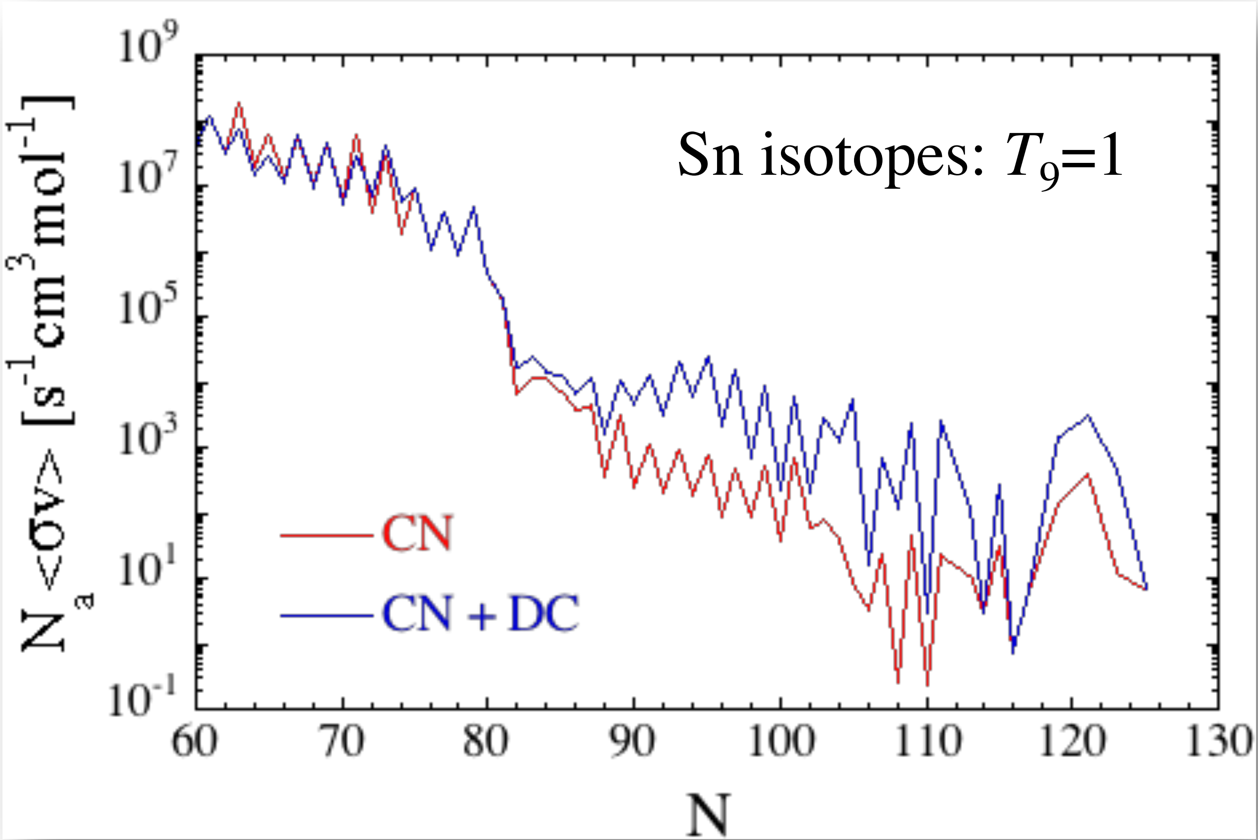
❖ troughs at A ~ 120 and 140 with the older FRDM (1992) disappear in those with the latest FRDM (2012), but still evident at A ~ 200 ?

hot, cold, or both?

- hot r-process (T ~ 10^9 K)
  (n, γ)-(γ, n) eq. holds; only nuclear masses (and in part b-decay but n-cap rates) determine the r-pattern (Mathews & Cowan 1990; Kratz+1993; etc.)
- cold r-process ($T < 5\times10^8$ K)
  (n, γ)-β competition (γn plays no role) both n-cap and β-decay rates determine the r-pattern (Wanajo 2007; Farouqi+2010; etc. cf. Blake & Schramm 1976)
- which is “the” r-process, or both?

role of the direct capture

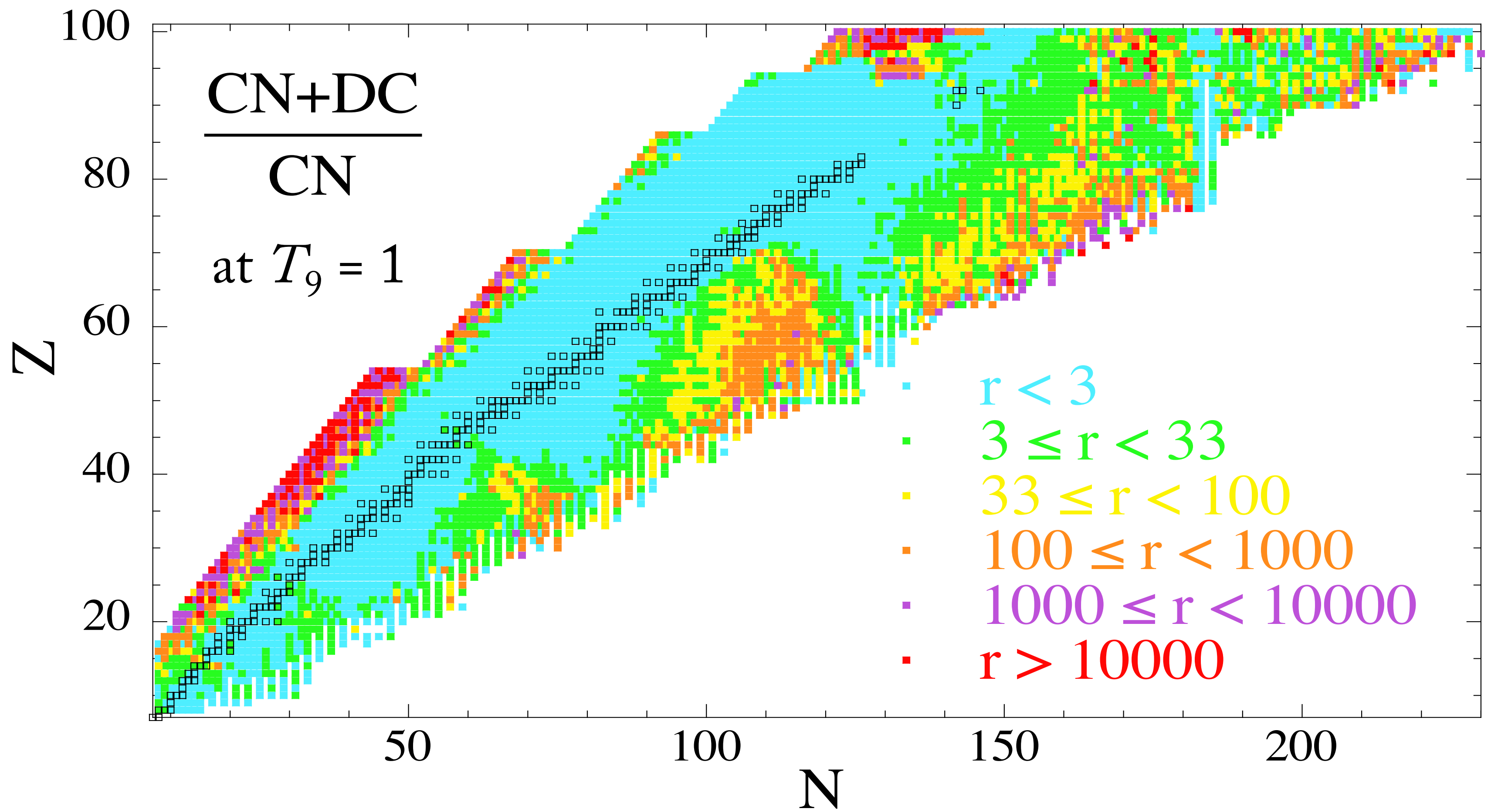
courtesy of S. Goriely



❖ direct capture on the prediction of (n, γ) rates becomes significant when going far away from stability

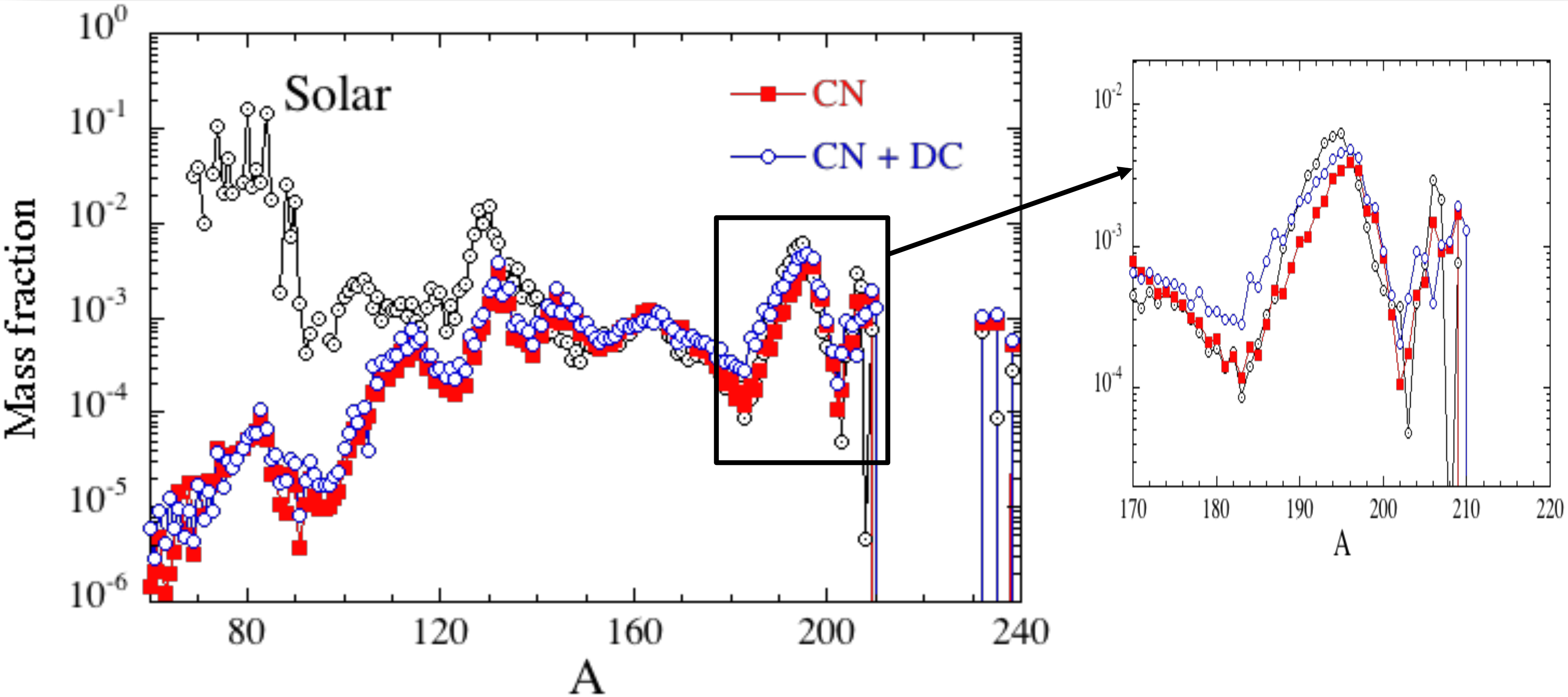
role of the direct capture

courtesy of S. Goriely



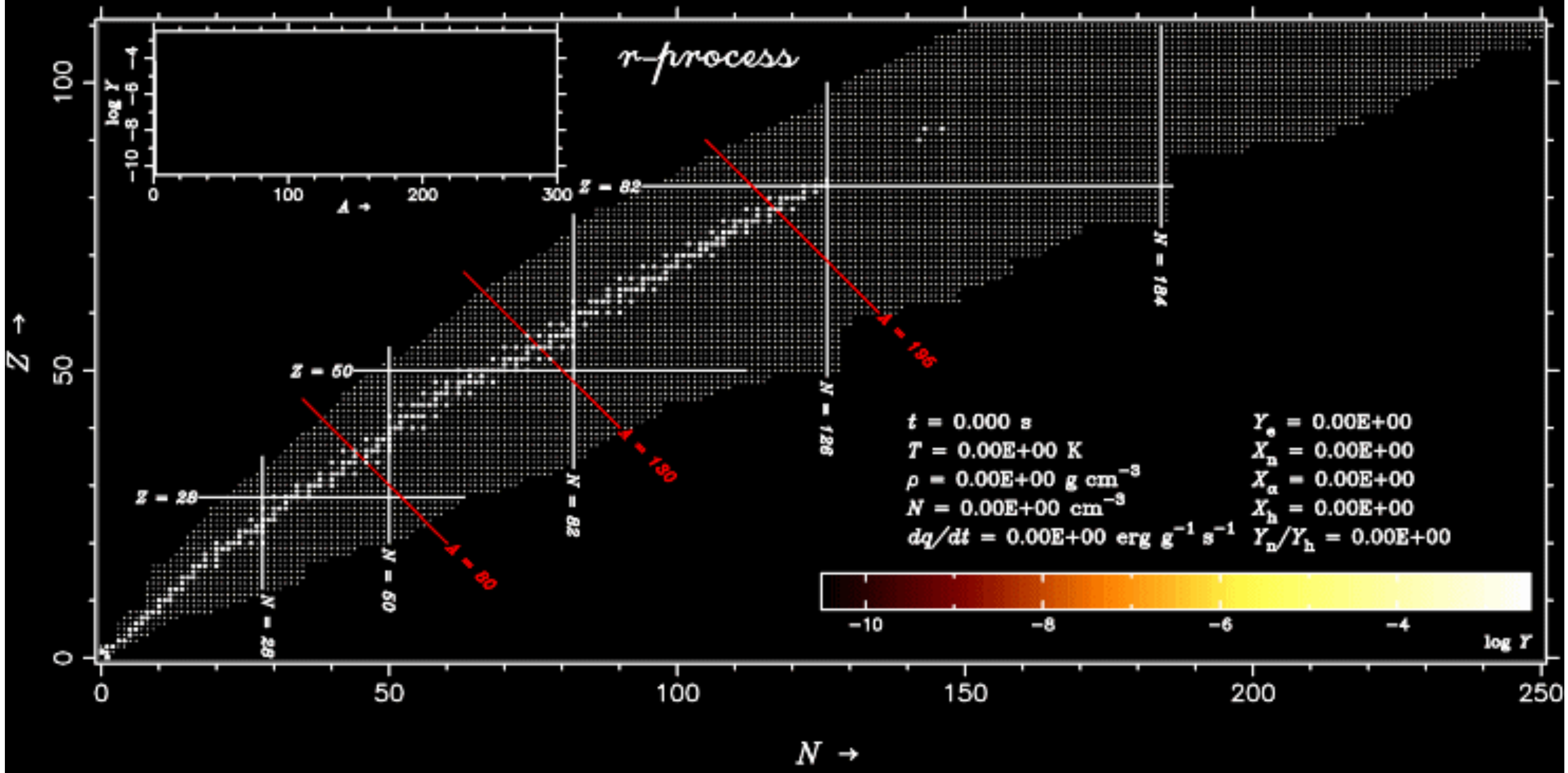
role of the direct capture

courtesy of S. Goriely



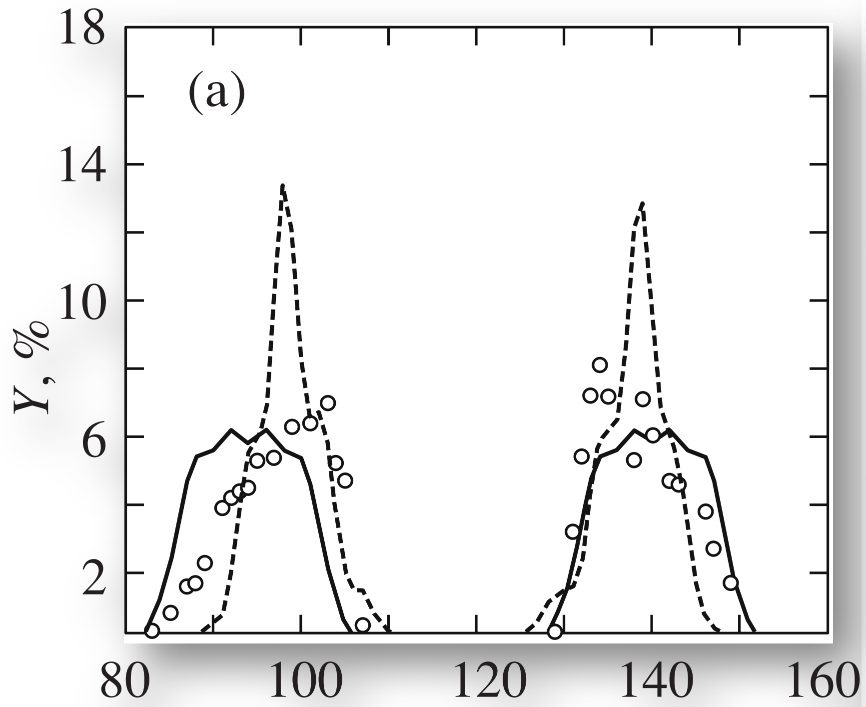
- ❖ visible local differences (even with fission recycling with Y_e ~ 0.02)
- ❖ impact could be more dramatic for high Y_e cases (as in our result)

fission fragments are dominated by *A* ~ 280 nuclei

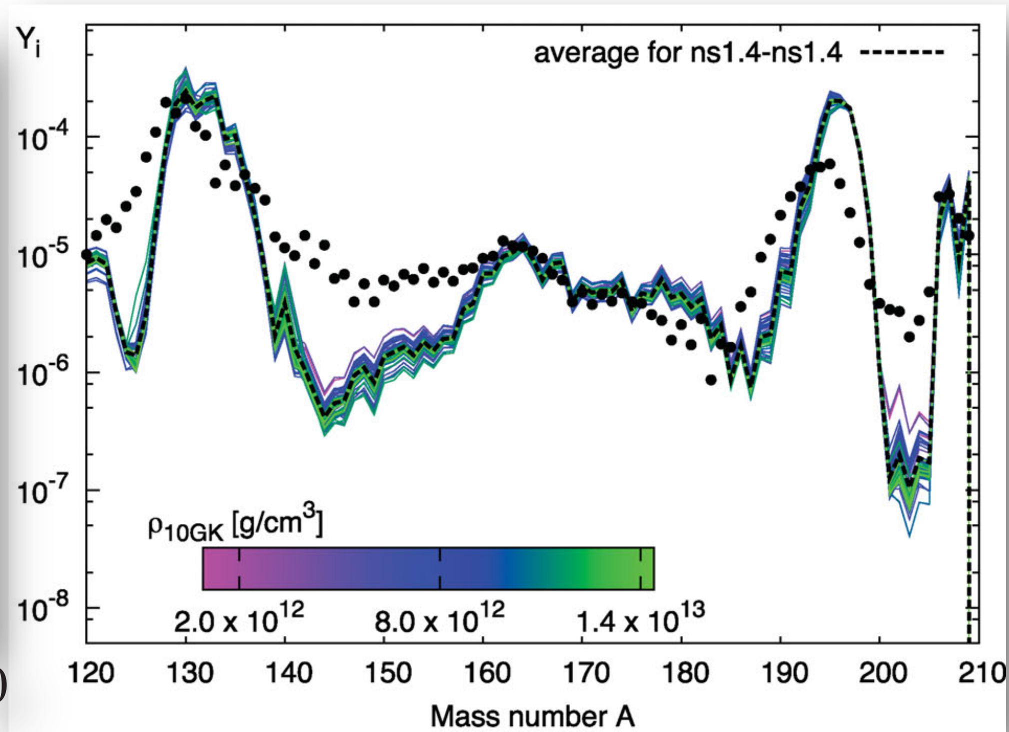


role of fission: 2nd peak ?

Panov+2008



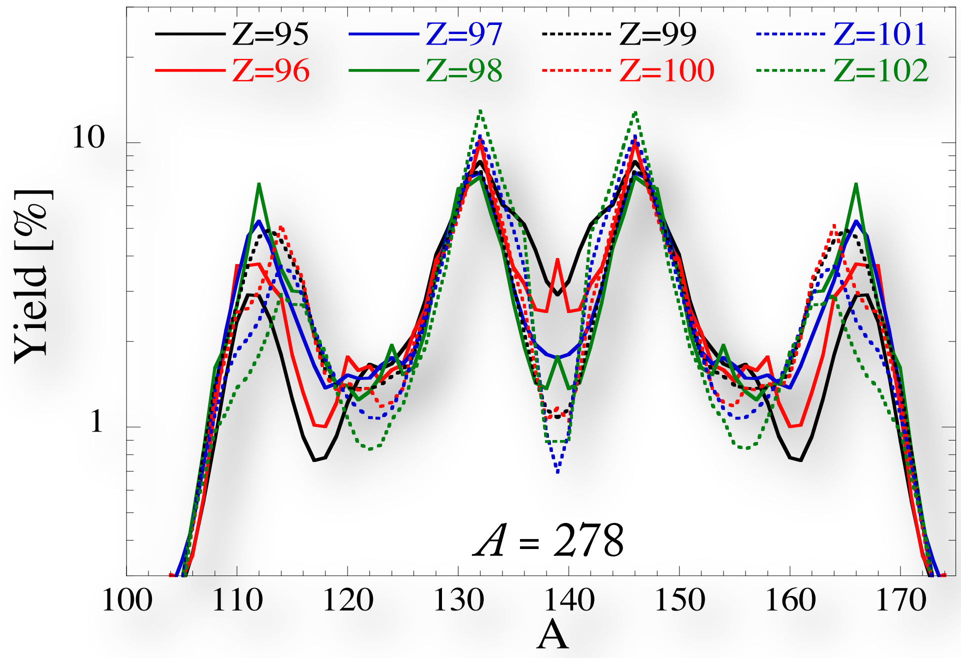
Korobkin+2012

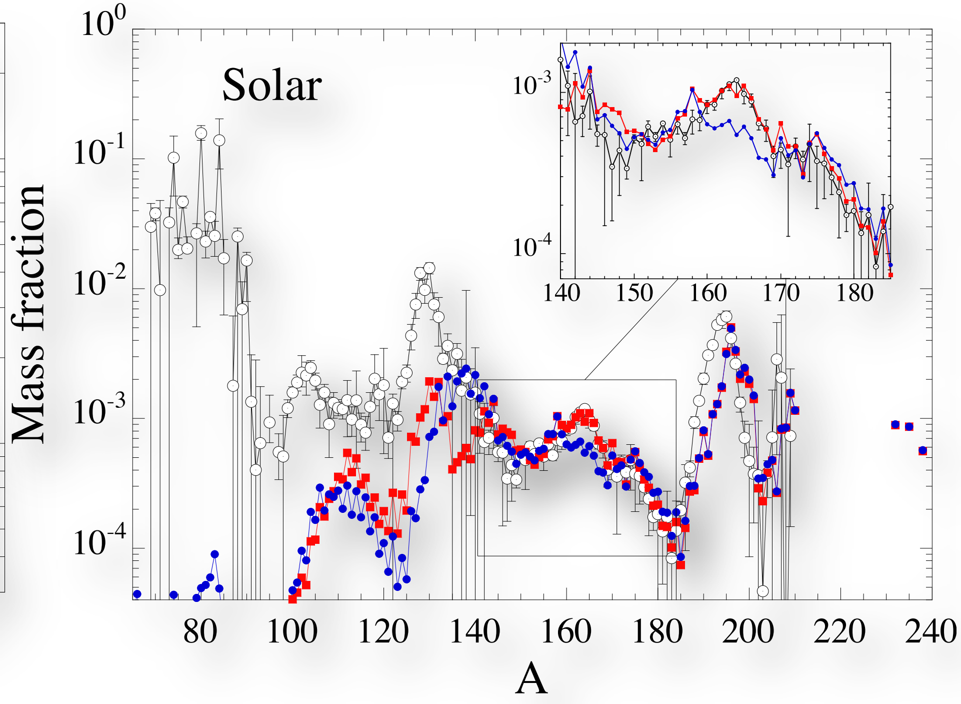


- 2 hump or single peak with one at *A* ~ 140
- origin of the 2nd peak with ~ 20 prompt neutrons ?
- difficult to build the 2nd peak 3 times higher than the 3rd peak ?

role of fission: rare-earth peak ?

Goriely+2013

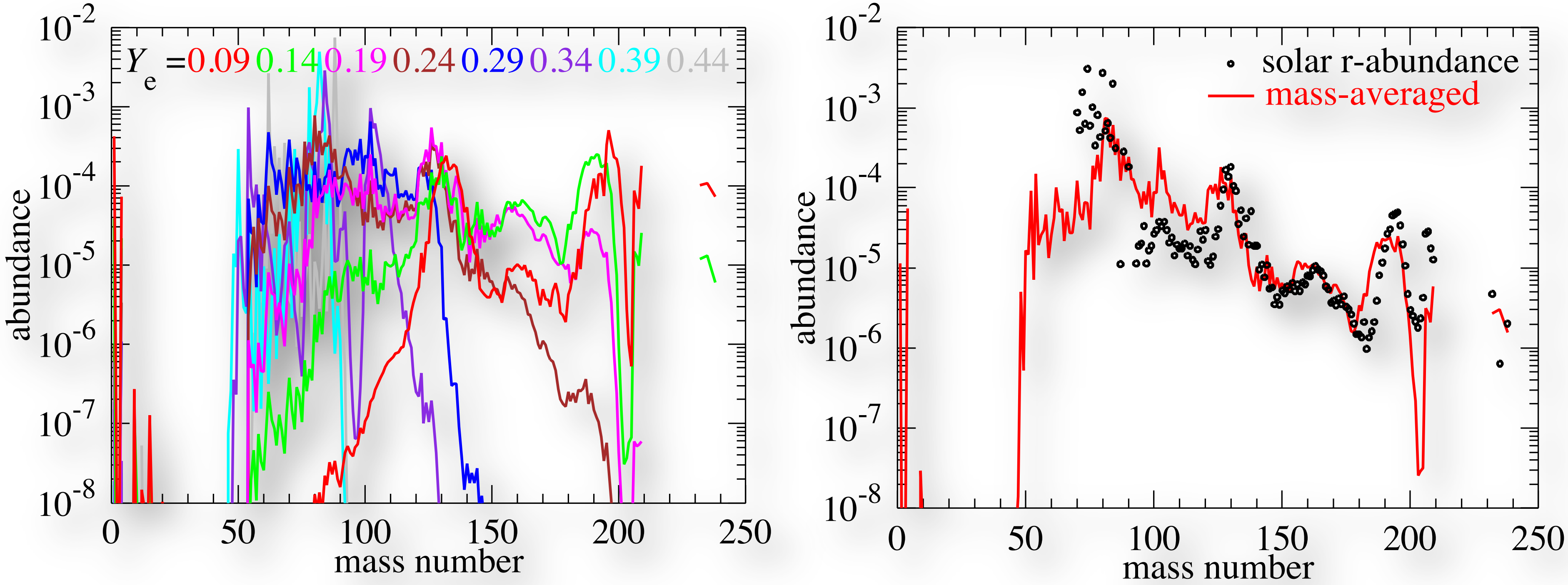




- ❖ new scission-point model predicts 4 hump peaks !? and ~ 4 prompt neutrons for *A* ~ 280 (Goriely+2013)
- ❖ 2nd peak cannot be explained, but the rare-earth peak can be formed by the fission fragments

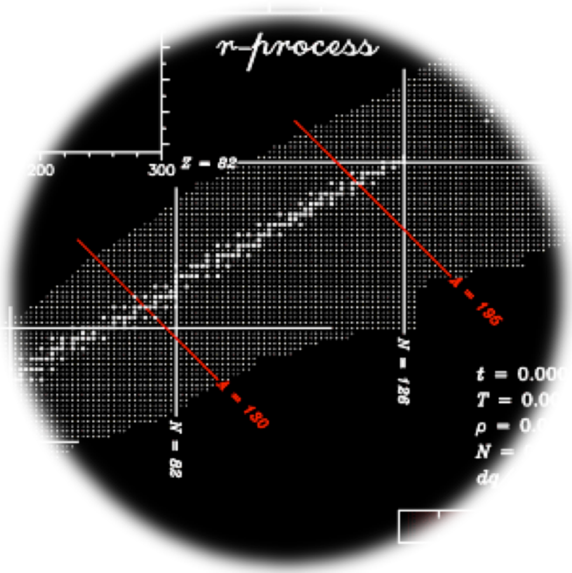
role of fission: sub-dominant ?

Wanajo, Sekiguchi, Nishimura+2014



- ❖ both 2nd and rare-earth peaks can be directly fomed in the Y_e ~ 0.2 ejecta (cf., Surman+1998; Mumpower+2012)
- ❖ fission plays only a sub-dominant role for r-pattern?

summary



- NS mergers: very promising site of r-process
  - neutrinos play a crucial role (in particular for a soft EOS)
- r-process novae can be "smoking guns"
  - connection with GW/HE astronomy will be inportant
- nuclear data needs for r-process calculations
  - (n, γ) rates with direct capture, β-rates, fission fragments …