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Grant-in-Aid for Scientific Research on Innovative Areas
[Japanese] [English]
科研費
KAKENHI
重力波天体の多様な観測による宇宙物理学の新展開
New development in astrophysics through multimessenger observations of gravitational wave sources

京
K computer

Binary neutron star merger and **r-process**

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Astrophysical Journal Letters 789, L39 (2014)

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Neutron capture processes

$n + (Z,N) \Rightarrow (Z,N+1)$

$(Z,N+1) \Rightarrow (Z+1,N) + e + \bar{\nu}_e$

n-capture versus **β-decay**

$\tau_n < \tau_\beta$

rapid neutron-capture process

(r-process)

large neutron densities

- ➢ Can synthesize all heavy nuclei

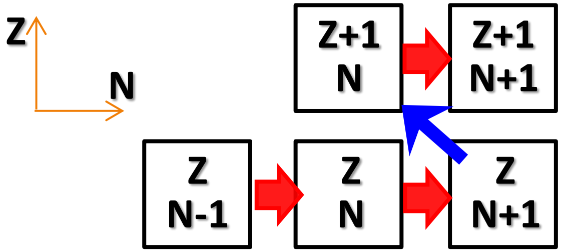
$\tau_n > \tau_\beta$

slow neutron-capture process

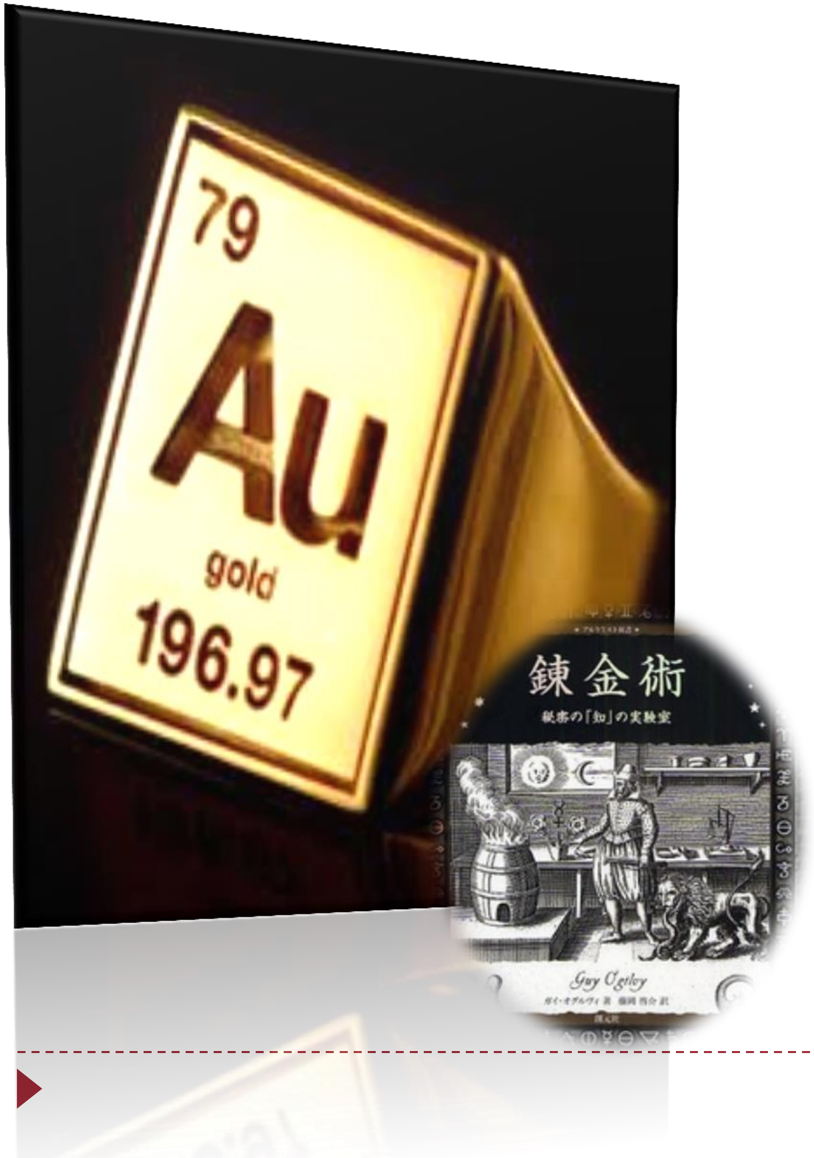
(s-process)

moderate neutron densities

- ➢ does not synthesize all heavy nuclei
- ➢ terminates at Pb, Bi



To be an alchemist : recipe to cook gold



- Neutron capture : packing neutrons into ‘seed’ nuclei $\boxed{n + (Z,N) \Rightarrow (Z,N+1)}$
  - Large #neutron/#seed ratio is required
  - A(gold) – A (seed) ~ 100
- **Low electron fraction Ye**
  - To have a large number of free neutrons
- **Higher entropy per baryon**
  - To slow the seed nuclei production
- **Short expansion timescale**
  - To freeze seed production with rapid decrease of temperature

What is the melting pot for r-process ?

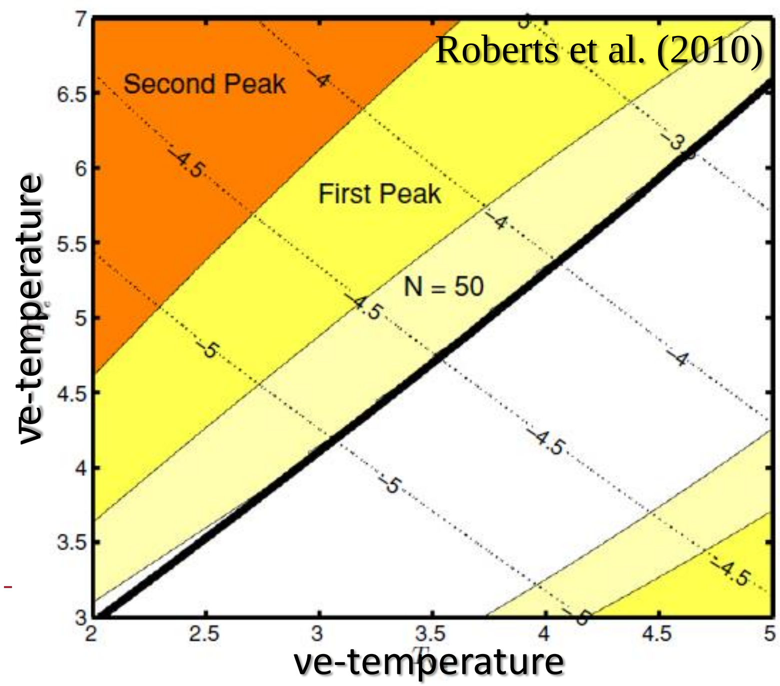
- **Supernova (SN) explosion (+ PNS v-driven wind) : (*Burbidge et al. 1957*)**
  - theoretically disfavored

- **NS-NS/BH binary merger: (*Lattimer & Schramm 1974*)**
  - Observationally disfavored ?? (Argust et al. 2004)

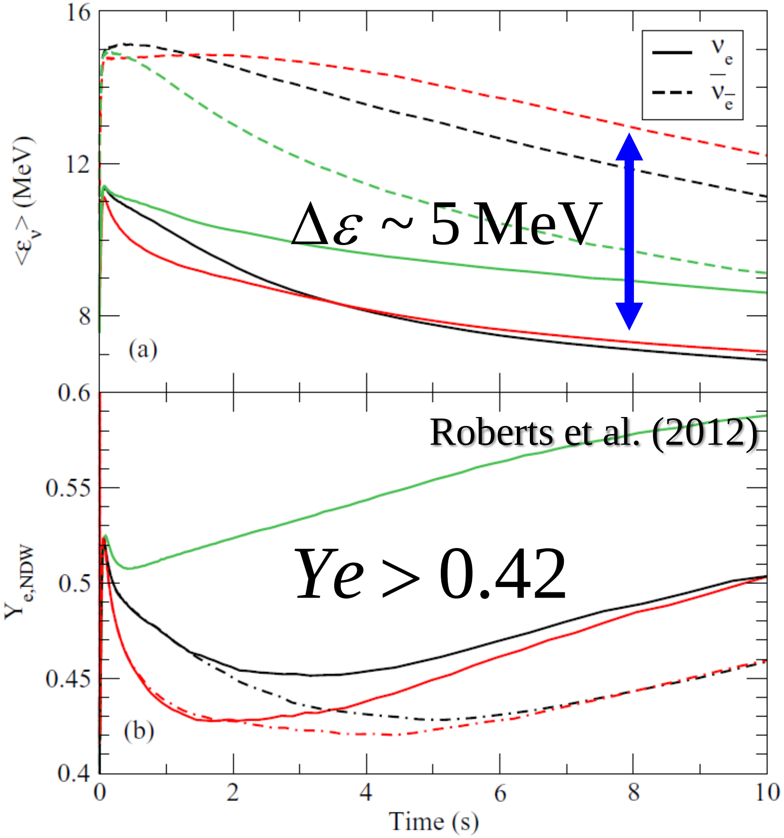
What is the melting pot for r-process ?

- **Supernova (SN) explosion: (*Burbidge et al. 1957*)**
  - Smaller entropy/per baryon than previously expected (e.g., ***Janka et al. 1997***)
  - Neutrinos from PNS make the flow proton-rich via $n+\nu \rightarrow p+e$
  - ⇒ only weak r-process (up to 2nd peak, no gold (3rd peak)!) (***Roverts et al. 2011***)
    - Electron capture SN : *Hoffman et al. 2008; Wanajo et al. 2009*
    - (Iron) core collapse SN : *Fisher et al. 2010;*

      Hudepohl et al. 2010; *Wanajo et al. 2011; Roberts et al. 2012*



Roberts et al. (2010)



$\Delta\varepsilon \sim 5$ MeV

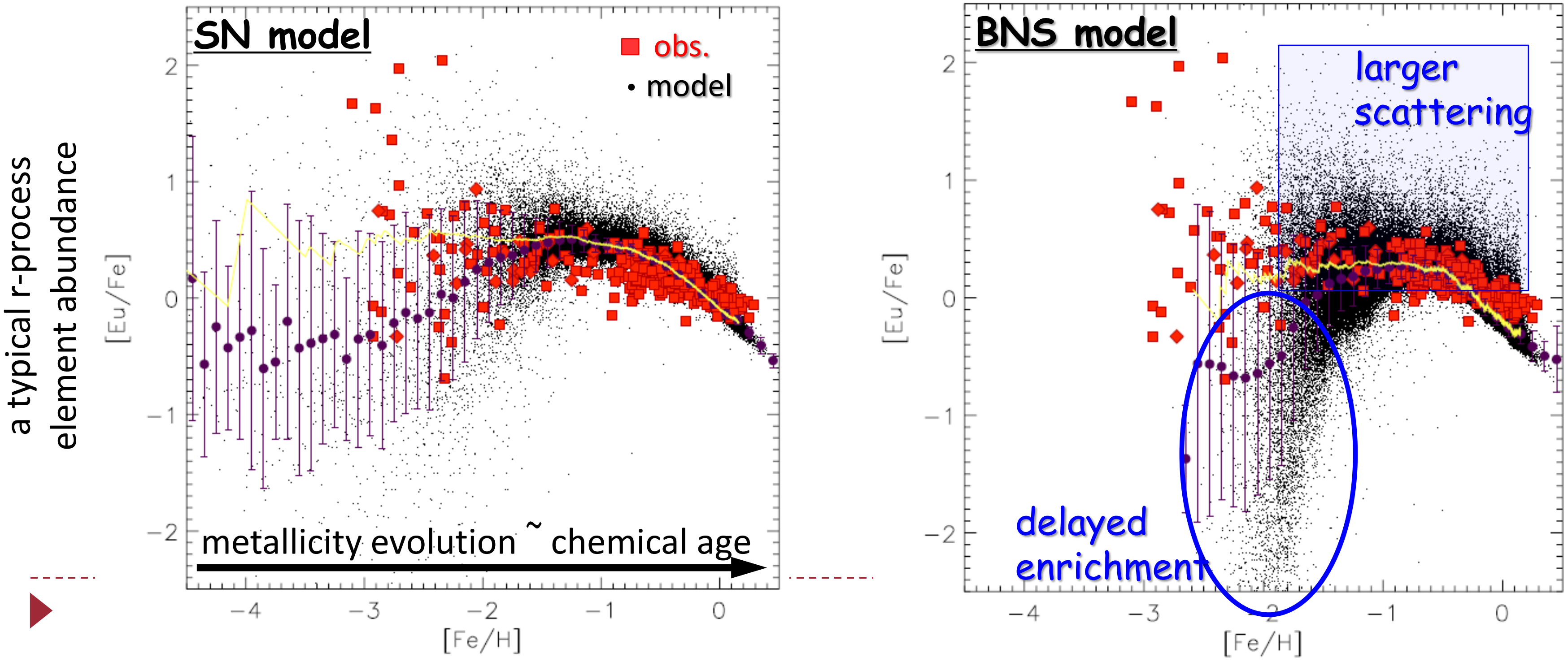
Roberts et al. (2012)

$Ye > 0.42$

What is the melting pot for r-process ?

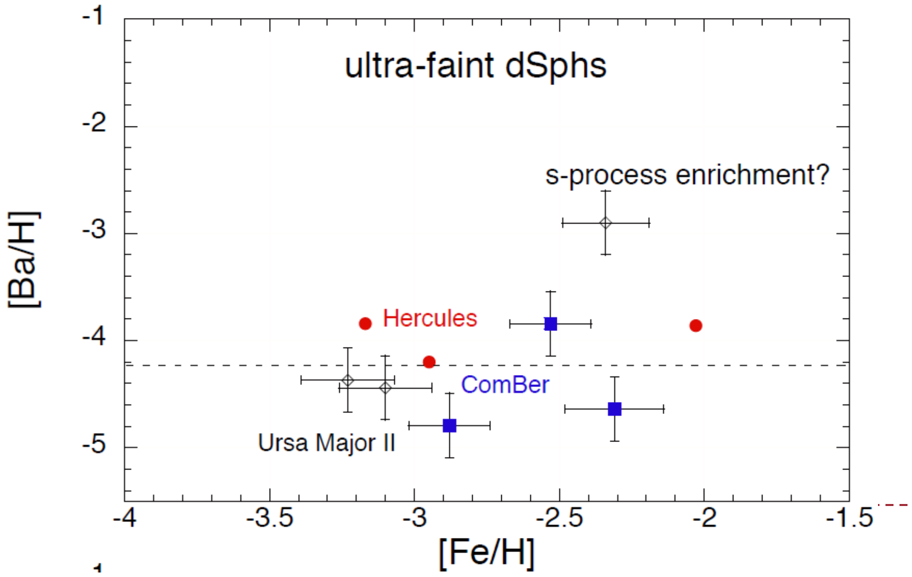
- **NS-NS/BH binary merger: (*Lattimer & Schramm 1974*)**
  - **Observationally disfavored ?? (*Argast et al. 2004*)**
    - delayed appearance of r-process element (long lifetime to merge)
    - large star-to-star scattering (low event rate (~ 10^{-5}/yr/gal) : rock sugar vs. table sugar)

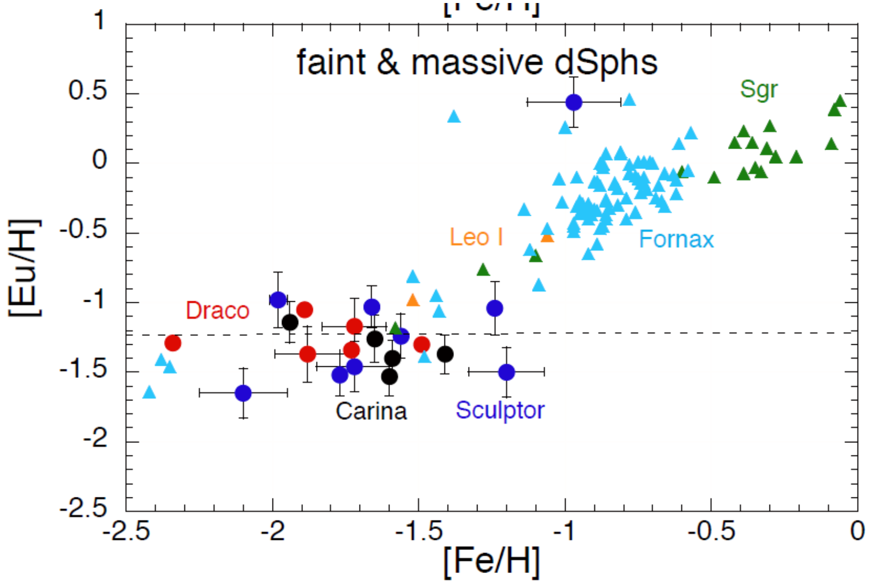
Argast et al. (2004)



What is the melting pot for r-process ?

- **Observationally favored ?? (*Tsujimoto and Shigeyama. 2014*)**
  - No enrichment of Eu in ultra dwarf galaxies but Fe increases
    - No r-process events but a number of SNe (Fe↑)
  - Enrichment of Eu in massive dwarfs
    - event rate is estimate as 1/1000 of SNe : suggests BNS merger
  - Higher velocities : ejecta spreads 1000 times farther than SNe
    - No over-enrichment as in Argast et al. 2004





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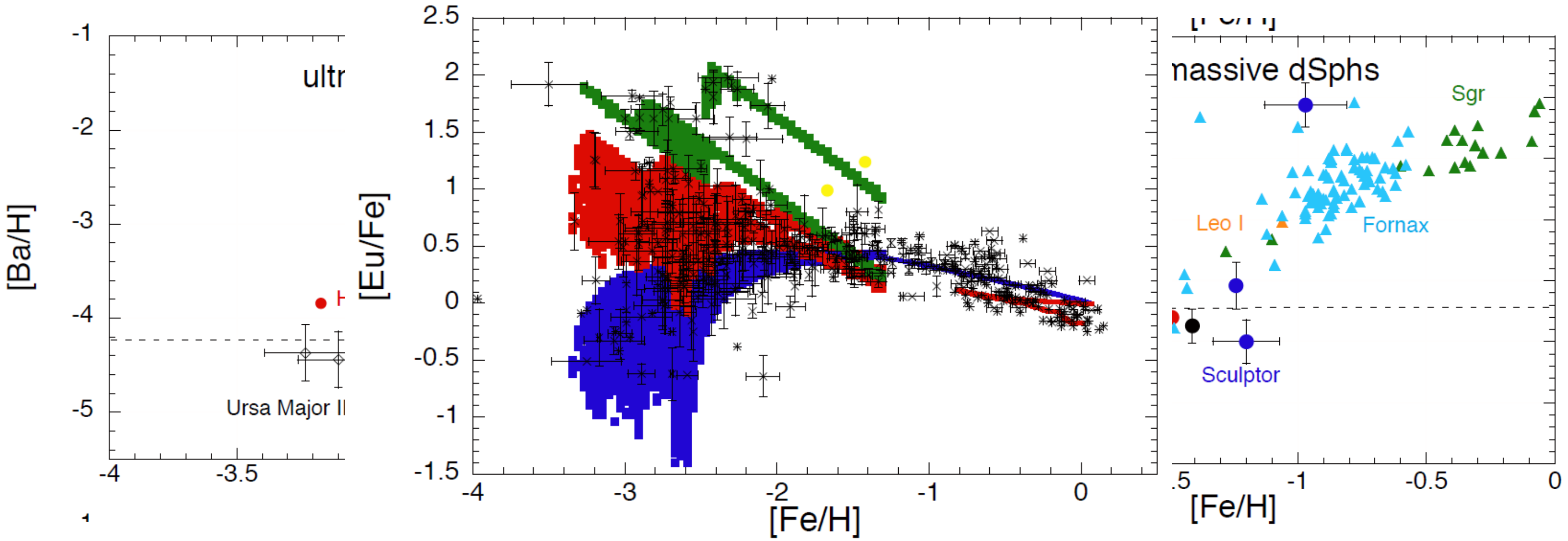
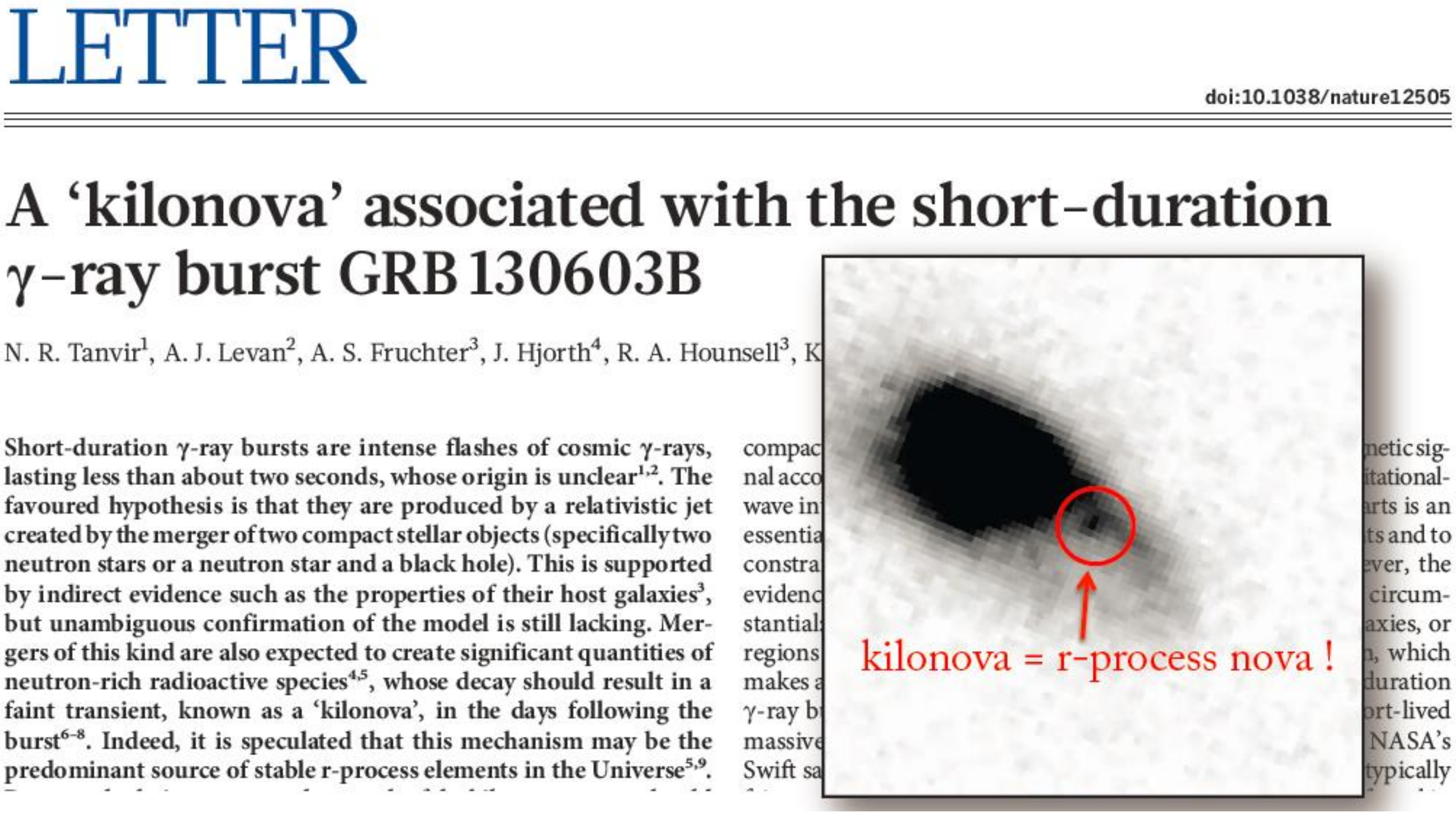


Further evidence ?
Kilo-nova/Macro-nova/r-process-nova

- **EM transients powered by radioactivity of the r-process elements are expected (Li & Paczynski 1998) (⇒ important EM counterpart of GW)**



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].

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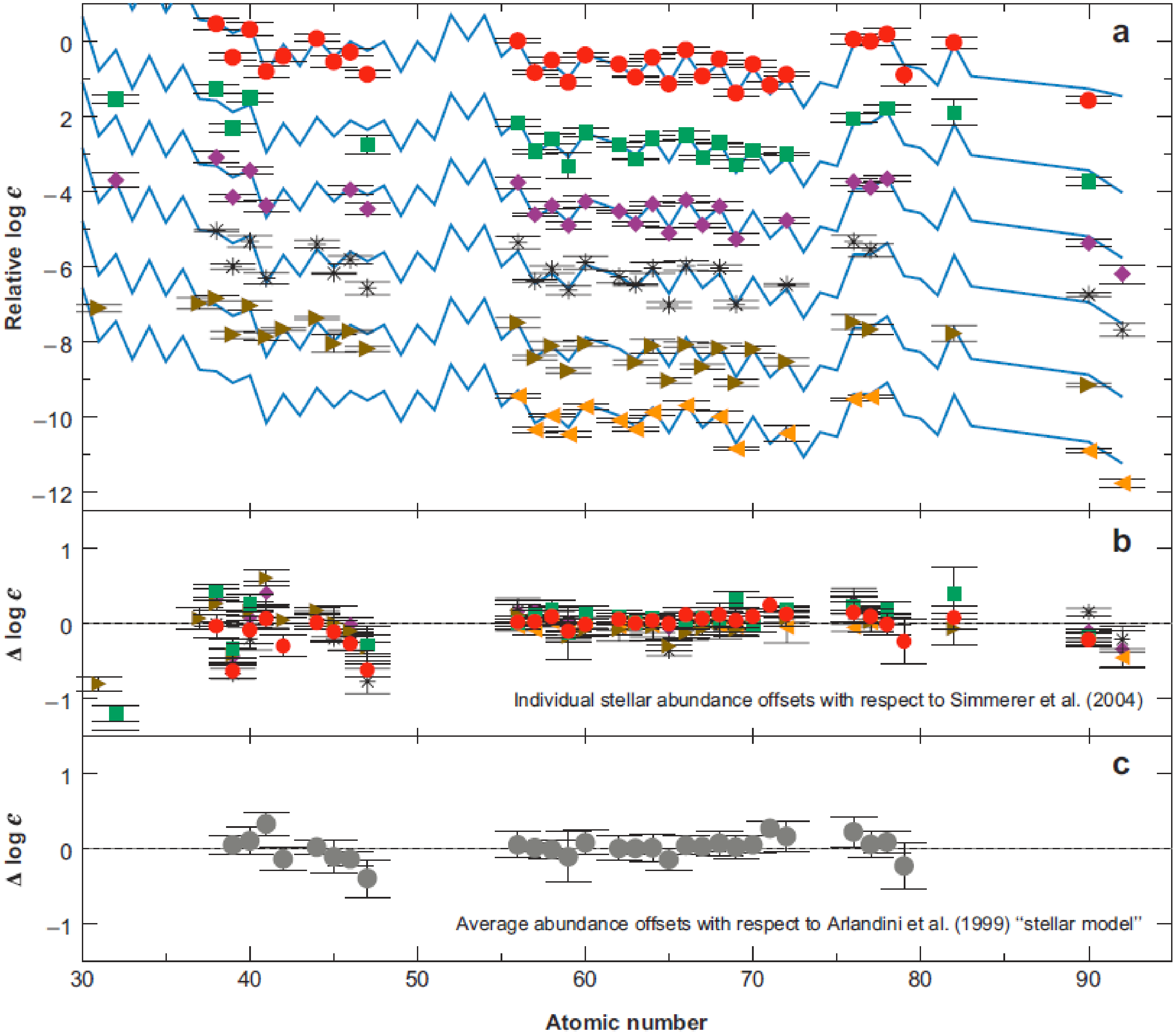
kilonova = r-process nova !

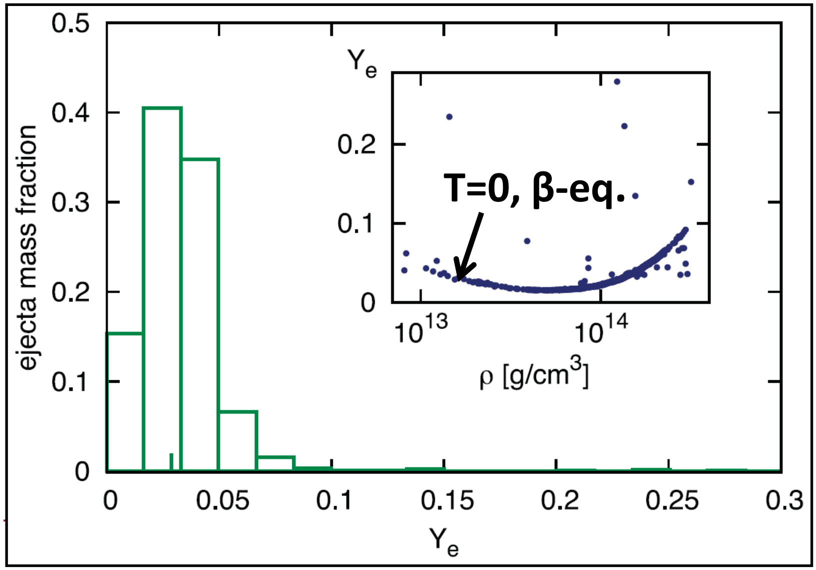
A Issue to be resolved:
Universality of the r-process cite



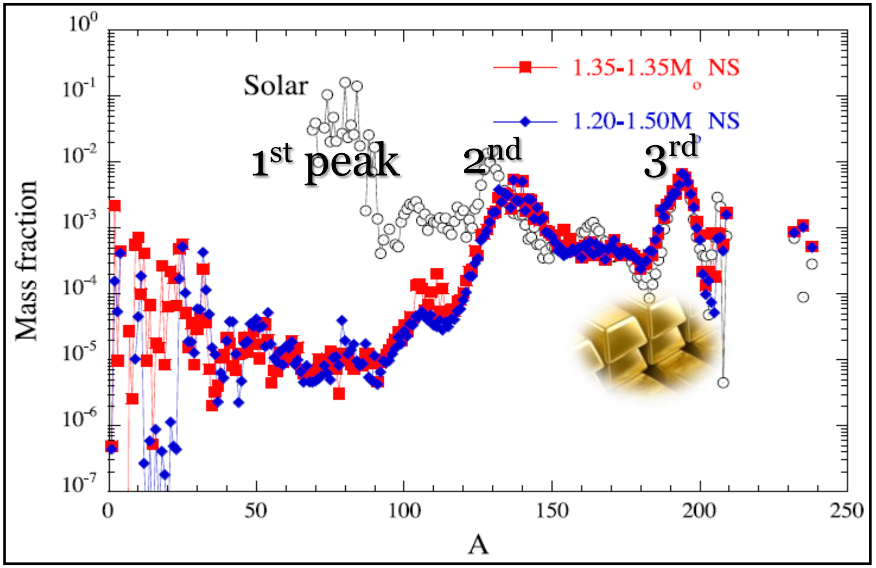
- Obs. of abundances of r-process element enhanced metal poor stars
- All stars show a remarkable agreement with solar r-pattern (blue curve)
- **The melting-pot should reproduce universal solar pattern**

‘Robustness’ of r-process in NS-NS merger ?

- **Korobkin et al. 2012 :**
  - *Ye of the ejecta is low as < 0.1 and depends weakly on the binary parameters so that r-process in the NS-NS is ‘robust’*
    - Main mass ejection mechanism : tidal effects
    - Very low Ye, too effective neutron capture and r-process only 2nd (A~130; N=82) and 3rd (A~195; N=126) peaks are produced : almost no production of 1st peak
  - **They adopted only one ‘stiff’ EoS (Shen EoS) : dependence on EoS is not explored**
  - **Newtonian SPH simulation: GR effects are not included**



Korobkin et al. (2012) MNRAS 426 1940



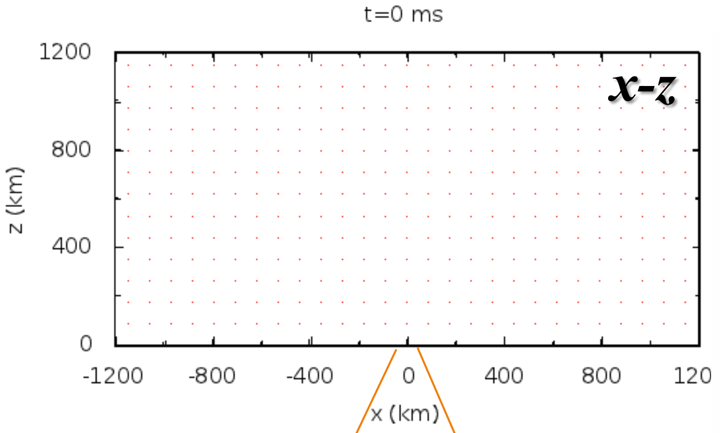
Goriely et al. (2011) ApJL 738 32

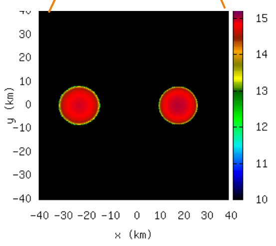
Dynamical mass ejection from BNS merger

- Two components
  + (neutrino-heated component (Perego et al. (2014); Just et al. (2014))

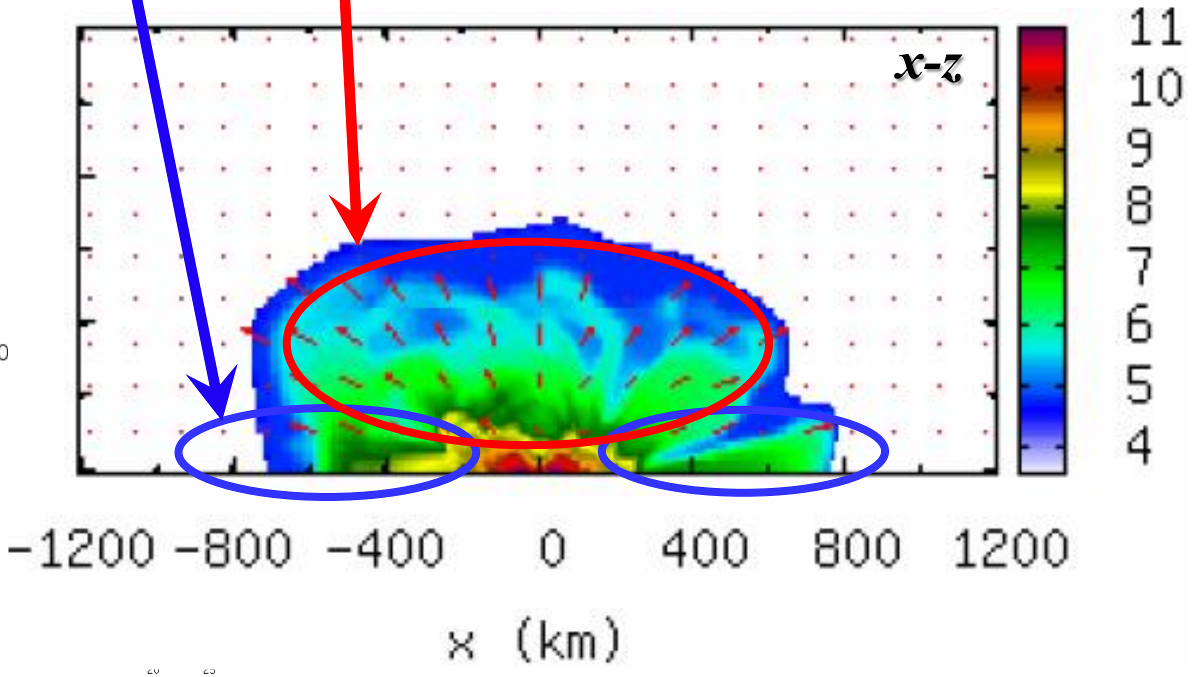
- **Driven by tidal interactions**
  Consists of cold NS matter in β-equilibrium ⇒ **low Ye and T**

- **Driven by shocks**
  Consists of hot shock heated matter
  Weak interaction can change Ye





animation by
Hotokezaka

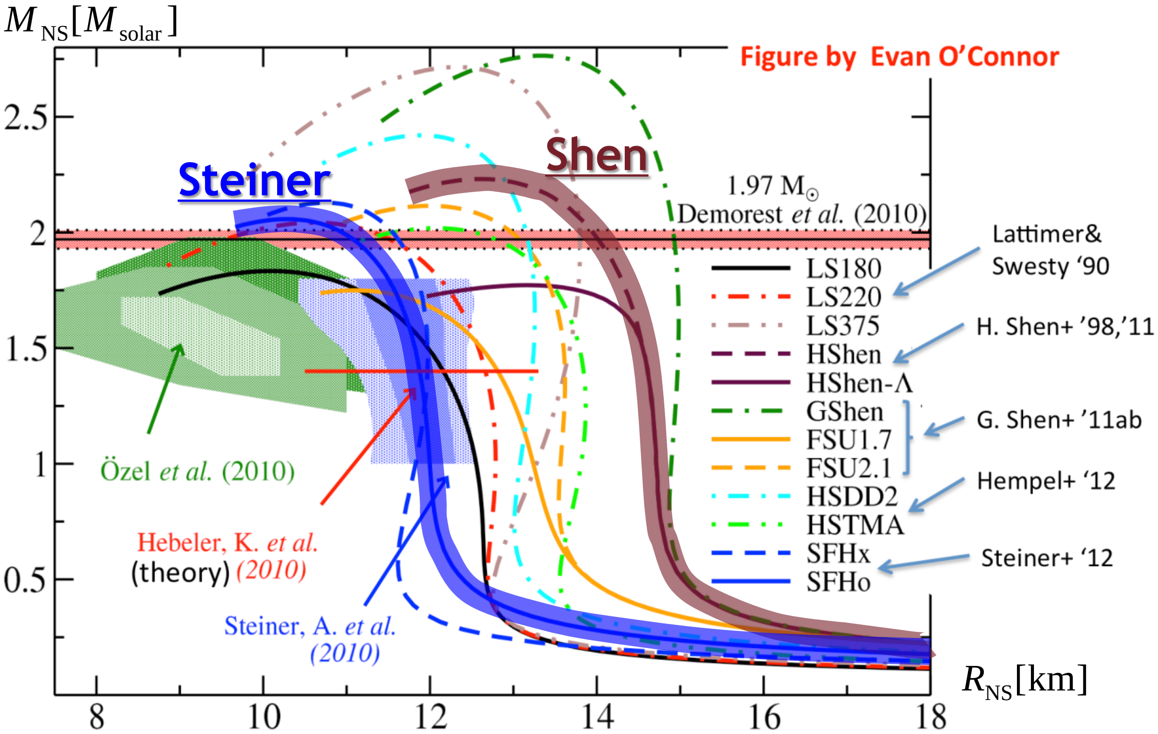


‘Robustness’ of r-process in NS-NS merger ?

- **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 **SFHo (Steiner)EoS** and **Shen EoS**

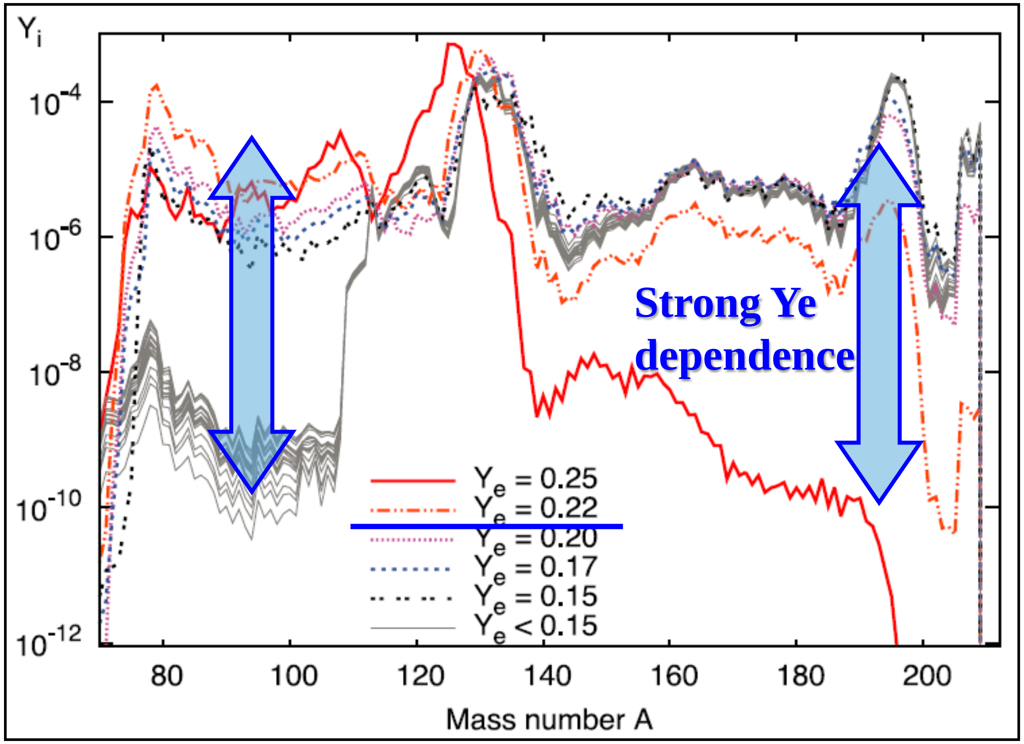
- **Shen EOS: ‘Stiffer’**
  - **Larger NS radius**
  - **Mass ejection is driven mainly by Tidal force**
- **SFHo (Steiner) EOS: ‘Softer’**
  - **Smaller NS radius**
  - **Tidal effects are less important in mass ejection**
  - **Stronger bounce**

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



Importance of Ye in the r-process

- **Electron fraction (Ye) is the key parameter : Ye ~ 0.2 is a critical threshold**
  - Ye < 0.22 : strong r-process ⇒ nuclei with A>130
  - Ye > 0.22 : weak r-process ⇒ nuclei with A< 130 (for larger Ye, nuclei with smaller A)
  - Different nuclei : different opacity (Smaller opacity for smllaer A? Grossman et al. 2013)
- **Neutrino-matter interaction**
  - **Ye can be changed**
  - Two reactions which increase Ye
  - Positron capture : $\boxed{n + e^{+} \rightarrow p + \overline{\nu}_e}$
    - **Important for higher temperature**
      ∵ there are more positrons
  - Neutrino capture : $\boxed{n + \nu_e \rightarrow p + e^{-}}$
    - Copious neutrinos are emitted
    - NS matter is neutron rich
    - Not considered in the previous studies (need neutrino transfer)



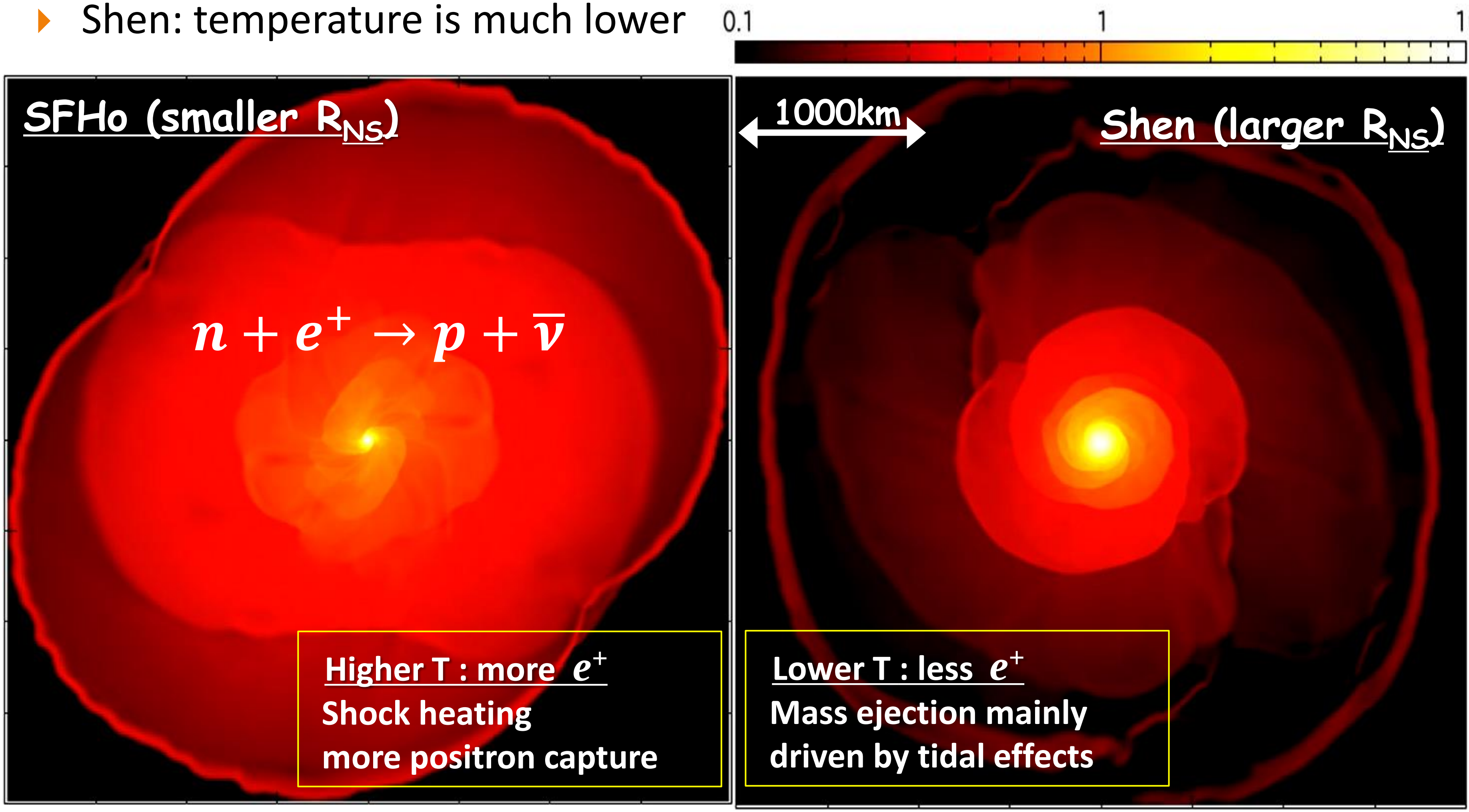
Korobkin et al. 2012

Summary of Code

- Einstein's equations: Puncture-BSSN formalism
  - 4th order finite difference in space, 4th order Runge-Kutta time evolution
  - Gauge conditions : 1+log slicing, dynamical shift
- GR ν-Radiation-Hydrodynamics with ***ν-Heating***
  - **The first study with neutrino heating (neutrino transfer + simple heating)**
  - EOM of Neutrinos (Truncated moment formalism : Shibata et al. 2011)
  - Lepton Conservations (GR leakage: Sekiguchi 2010)
  - Nuclear-theory-based EOSs
  - Weak Interactions (similar to considered in SN simulations)
    - $e^{\pm}$ captures (Fuller et al 1985), $e^{\pm}$ pair annihilation (Cooperstein et al. 1986)
    - plasmon decay (Ruffert et al. 1996), Bremsstrahlung (Burrows et al. 2006)
  - Neutrino opacities (Burrows et al. 2006)
    - (n,p,A)-scattering and absorption
    - Ion-ion screening, nucleon recoil
  - **BH excision technique**
  - **Fixed mesh refinement technique**

SFHo vs. Shen: Ejecta temperature

- SFHo: temperature is higher (as 1MeV) due to the shock heating, and produce copious positrons
- Shen: temperature is much lower

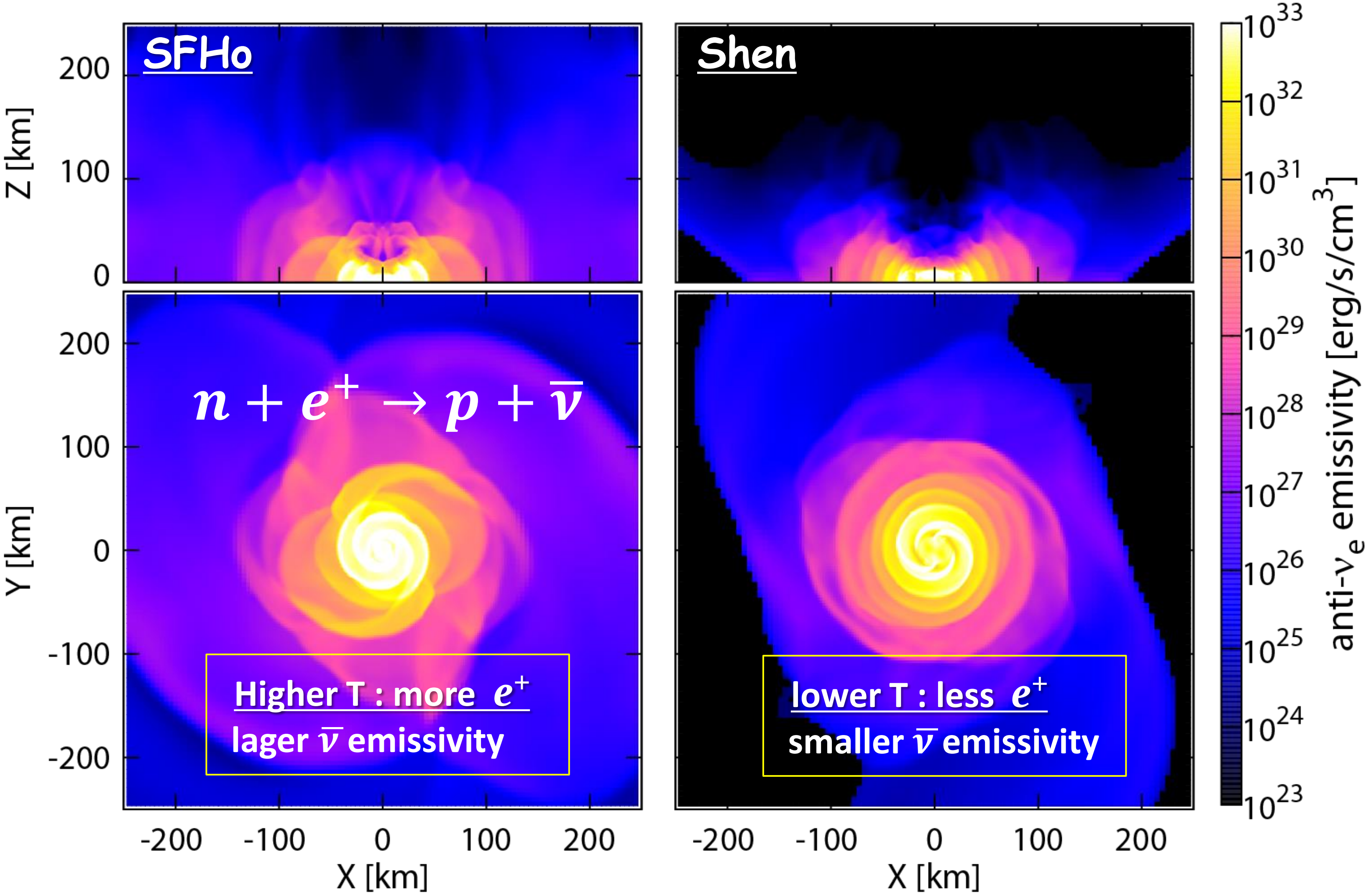


$$n + e^{+} \rightarrow p + \overline{\nu}$$

Higher T : more e^{+}
Shock heating
more positron capture

Lower T : less e^{+}
Mass ejection mainly
driven by tidal effects

SFHo vs. Shen: $\bar{\nu}_e$ emissivity



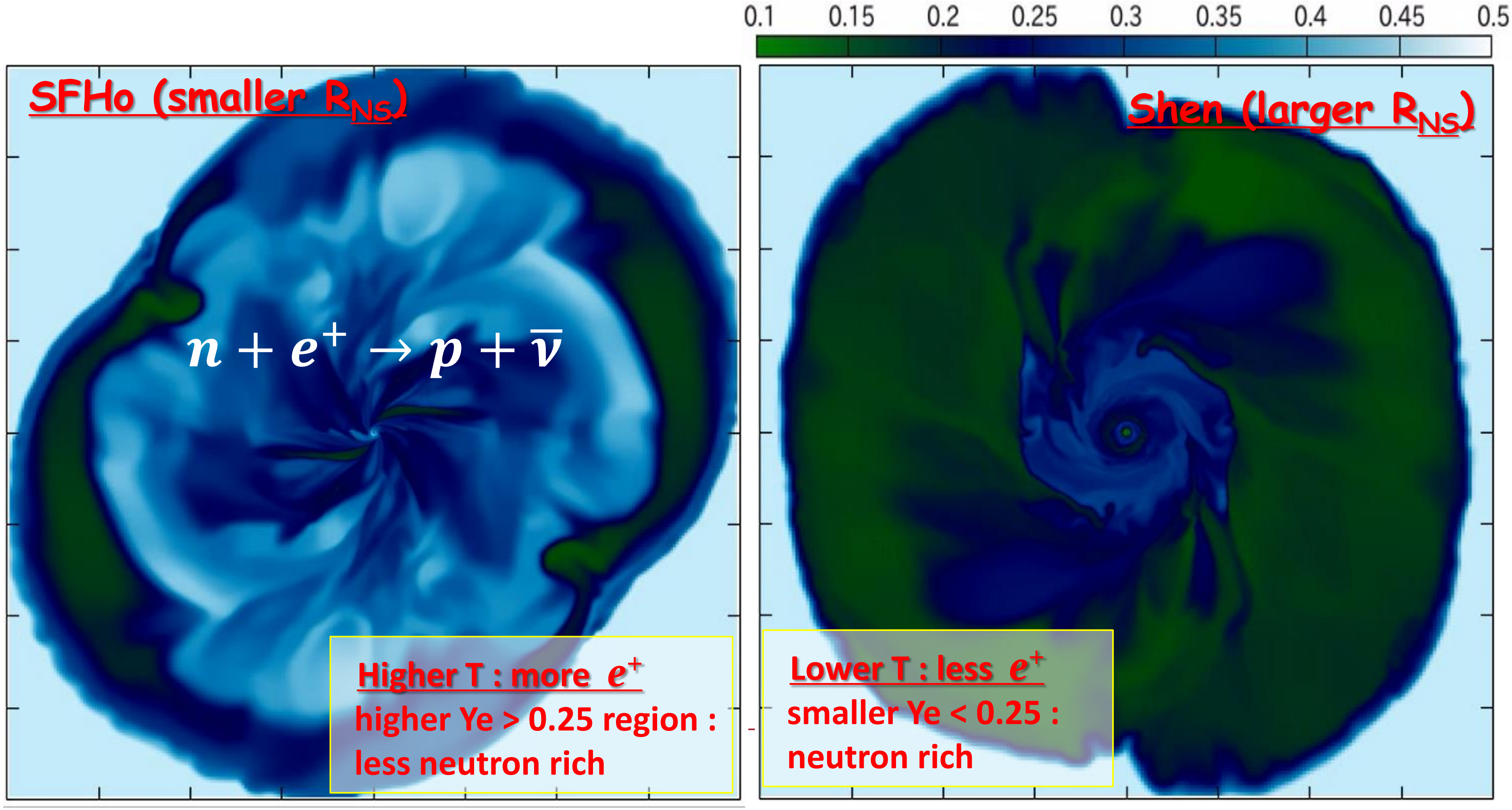
$$n + e^{+} \rightarrow p + \bar{\nu}$$

Higher T : more e^{+}
lager $\bar{\nu}$ emissivity

lower T : less e^{+}
smaller $\bar{\nu}$ emissivity

SFHo vs. Shen: Ejecta Ye

- SFHo: In the shocked regions, Ye increases to be >> 0.2 by weak processes
- Shen: Ye is low as < 0.2 (only strong r-process expected)



SFHo (smaller R_{NS})

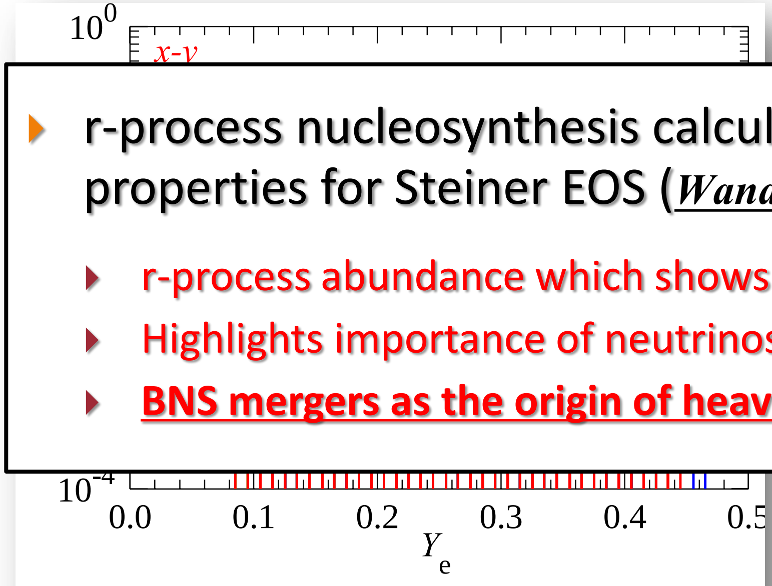
$$n + e^{+} \rightarrow p + \overline{\nu}$$

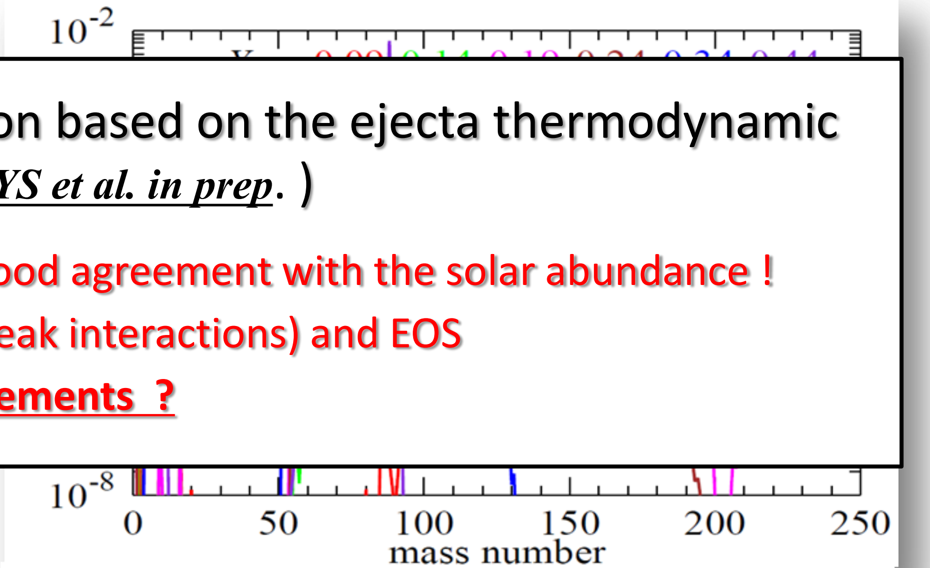
Higher T : more e^{+}
higher Ye > 0.25 region :
less neutron rich

Shen (larger R_{NS})

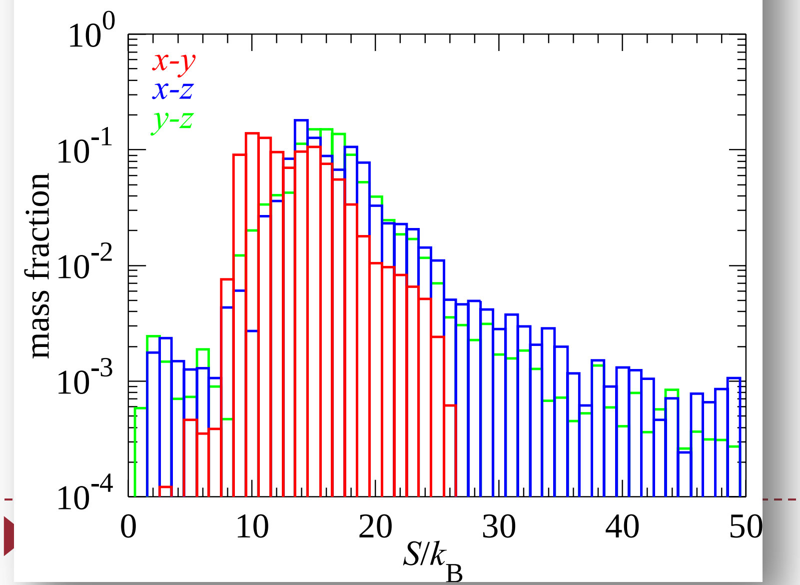
Lower T : less e^{+}
smaller Ye < 0.25 :
neutron rich

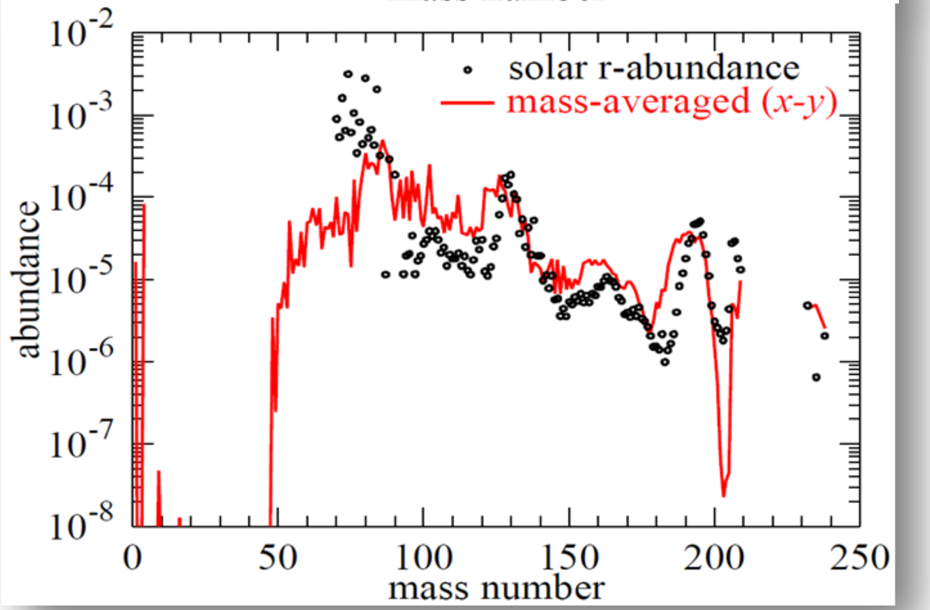
SFHo: Ye distribution and r-process yields





- r-process nucleosynthesis calculation based on the ejecta thermodynamic properties for Steiner EOS (***Wanajo, YS et al. in prep***.)
  - r-process abundance which shows a good agreement with the solar abundance !
  - Highlights importance of neutrinos (weak interactions) and EOS
  - **BNS mergers as the origin of heavy elements ?**





Summary

- Neutrino-Radiation-Hydrodynamics in numerical relativity is now feasible !
  - based on truncated moment formalism with M-1 closure
  - both implicit and explicit schemes can be adopted
- **Importance of neutrinos and EOS for r-process in BNS merger**
  - strong EOS dependence
  - For a softer EOS **shock heating** is more important and **ejecta *T* increases**
  - As a result, **positron capture** proceeds more and **ejecta Ye increases**
  - **Resulting r-process yield agrees well with the solar abundance**
  - BNS merger as origin of heavy elements ?
- Future studies
  - Further investigation of EOS dependence
  - Long-term simulations to see neutrino heating effects
  - EM counterpart study based on r-process nucleosynthesis calculation
  - BH-NS, Collapsar, etc.