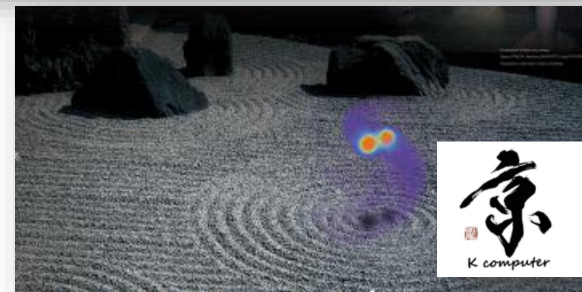


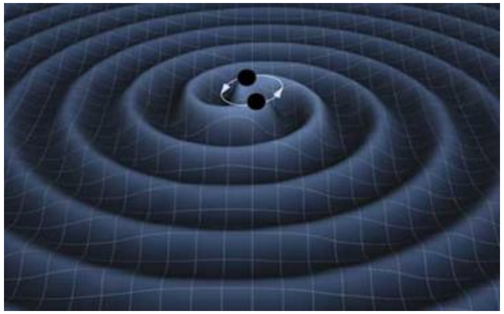
実験と観測で解き明かす中性子星の核物質 第4回ウィンタースクール

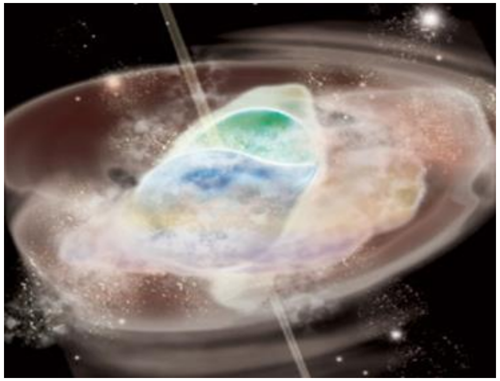
コンパクト天体連星の合体と重元素合成 I

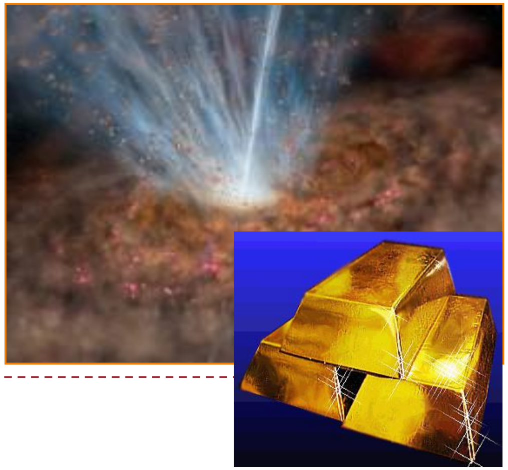
関口 雄一郎（東邦大学）

何故コンパクト天体(BH,NS)連星？

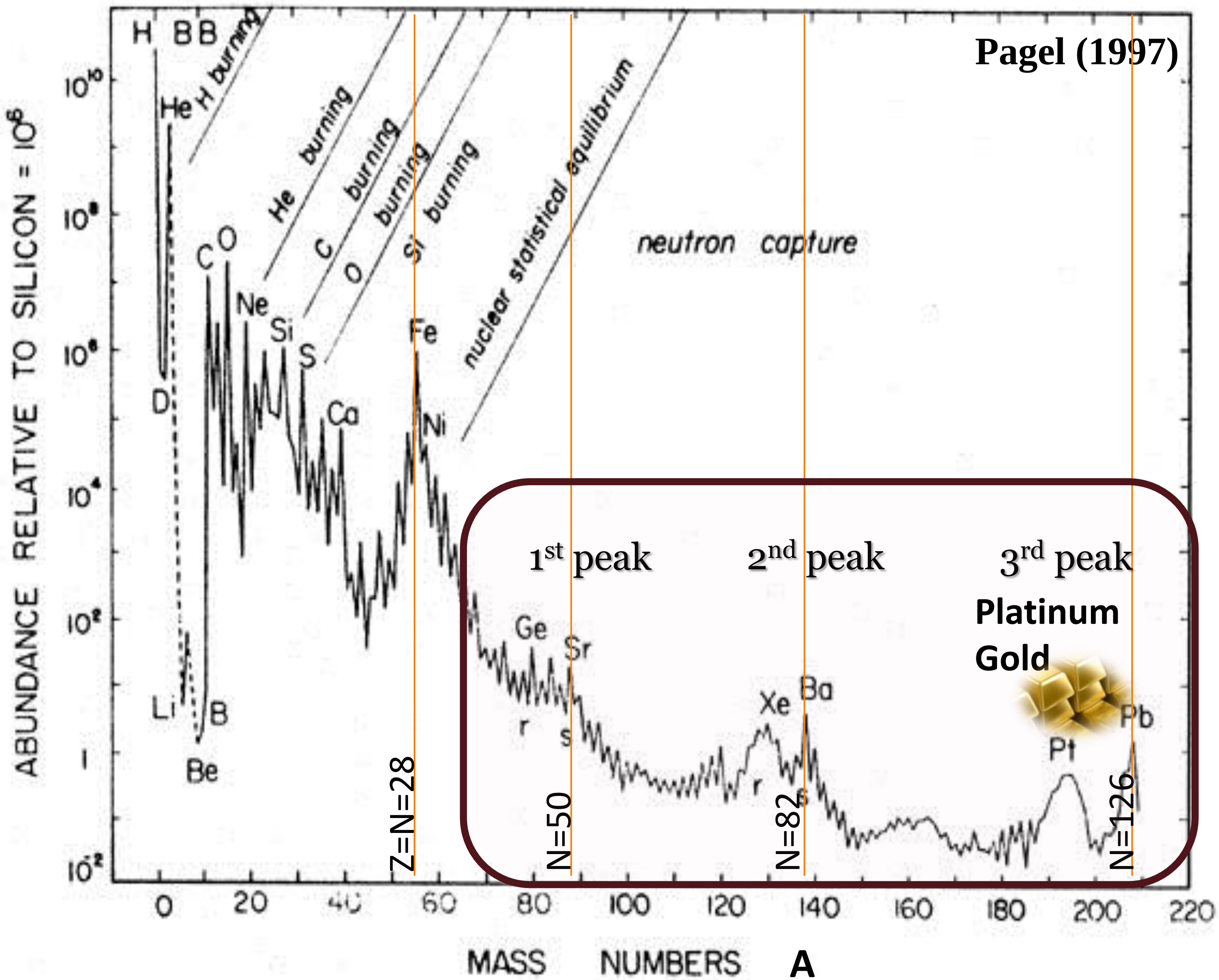
- 重力波(GW)地上干渉計の有望な波源
  - The first LIGO event GW150914 : BH-BH merger
    - ～1-100 イベント/年 ～ NS-NS event rate (population synthesis)
- 基礎物理学の実験現場として
  - 強重力場における一般相対論の検証
    - BH-BH : cleanest system
  - 極限状態における物質の物理(状態方程式)
    - GWs contain information of M, R, and internal structure of NS
- 高エネルギー天体現象の中心動力源
  - GRB中心動力源 : BH + accretion disk
- 重元素の起源(合体時の質量放出)
  - 超新星爆発におけるR過程元素合成の困難
  - 崩壊熱からの電磁放射(重力波の電磁波対応天体)







Solar abundance of nuclei



- **Basic feature :** exponential decay with mass number + constant tail
- **Characteristic features:**
- Peak in iron-group
- Deficient of D, Li, Be, and B
- Enhancement of α-nuclei (C, O, Ne, Si,..)
- **Peaks in heavier region associated with n-magic numbers,**
- **made by neutron capture processes**

Neutron capture processes:

free from Coulomb barrier

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

n-capture versus **β-decay**

$\tau_n < \tau_\beta$ $\qquad$ $\tau_n > \tau_\beta$

rapid neutron-capture process
(r-process)

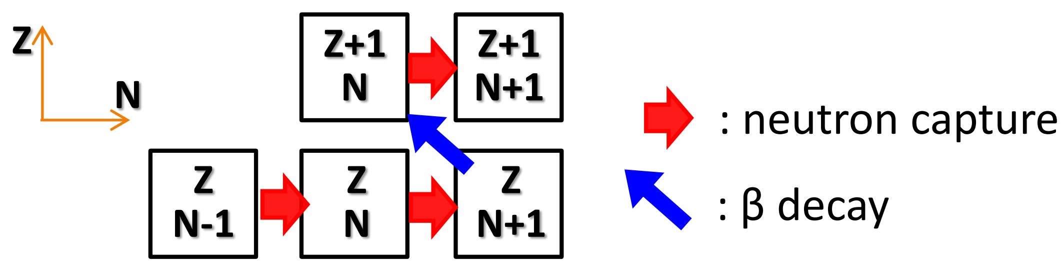
large neutron densities

- Can synthesize all heavy nuclei

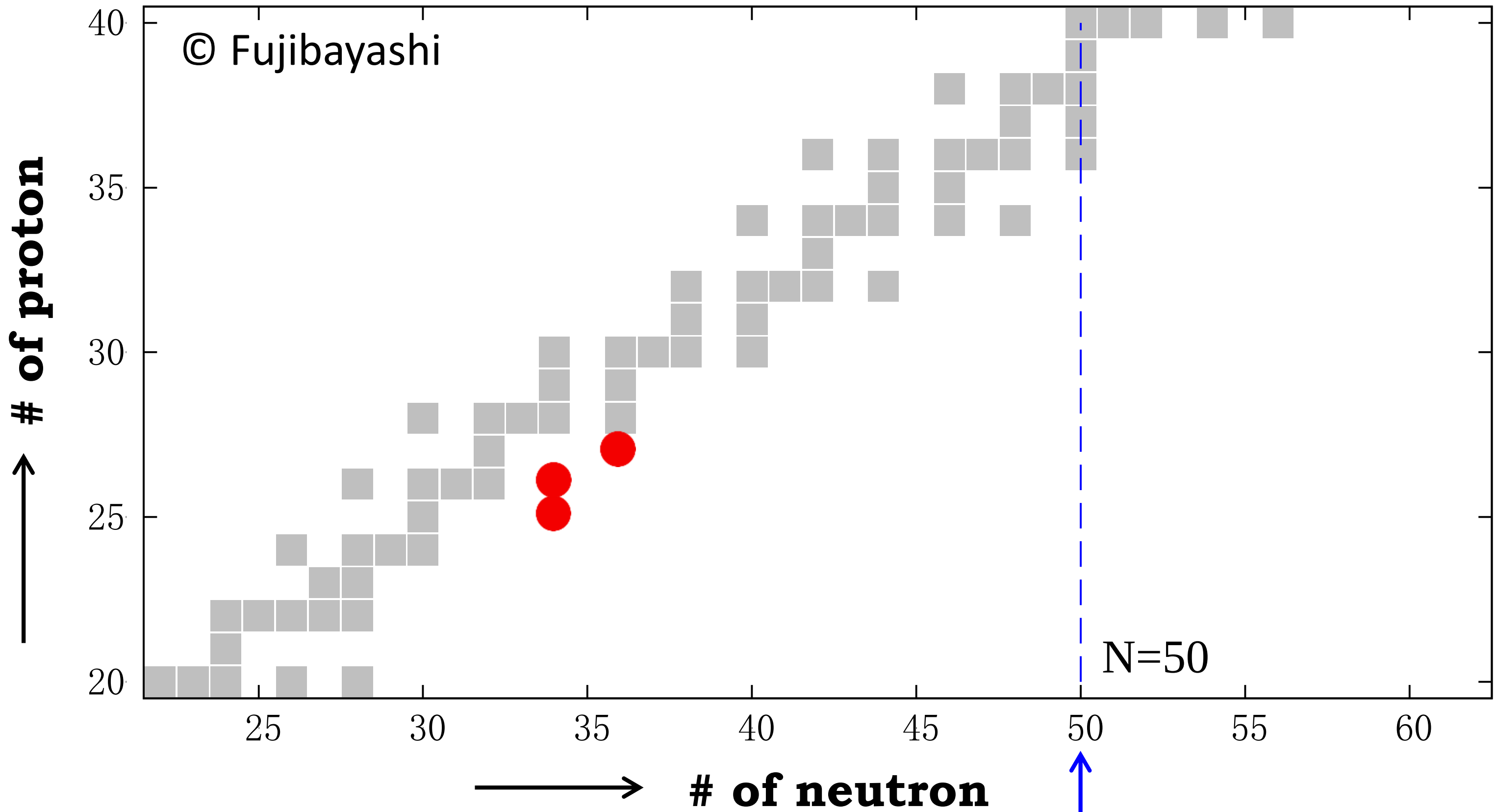
slow neutron-capture process
(s-process)

moderate neutron densities

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

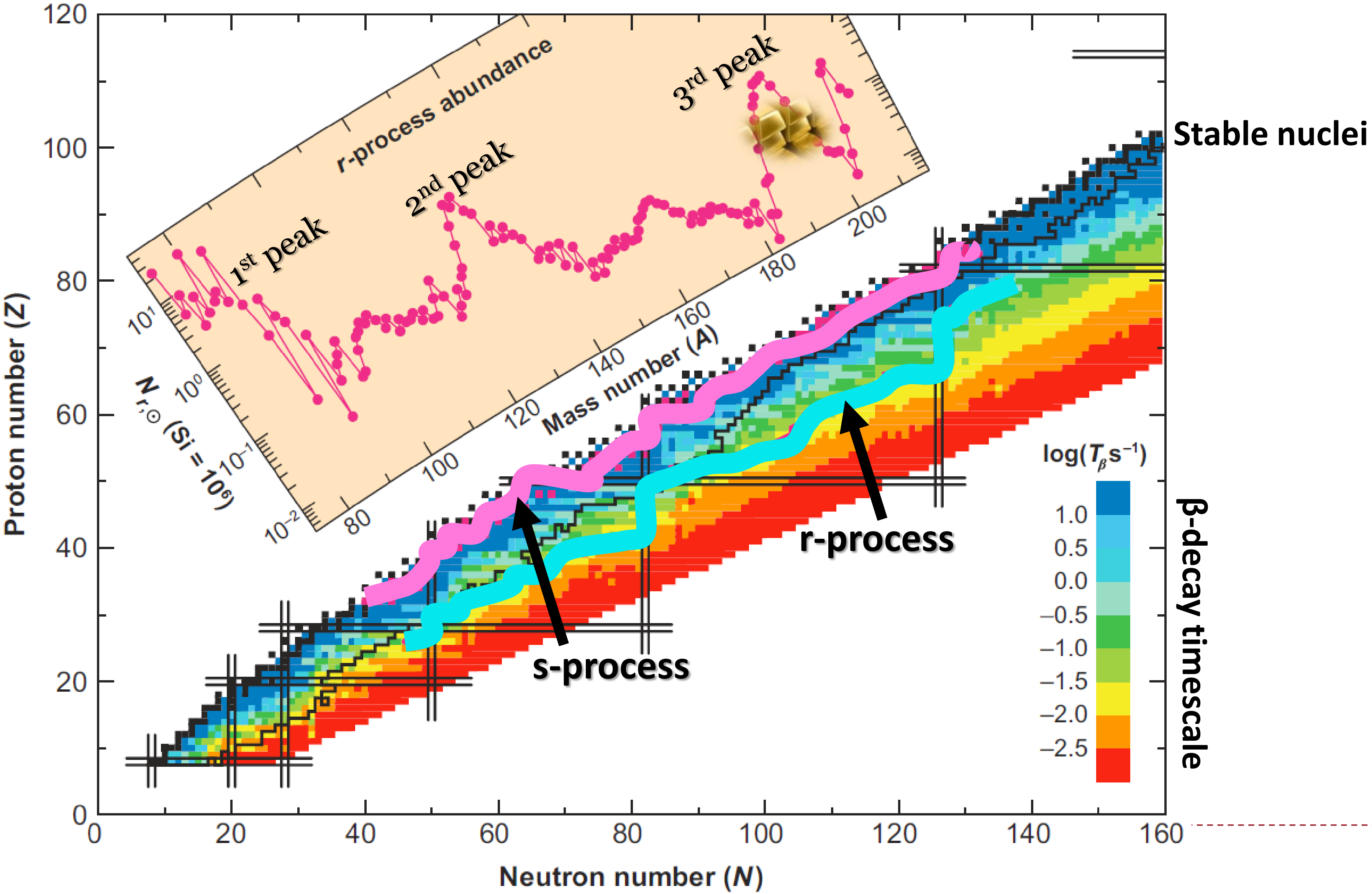


r-process (rapid neutron capture process)

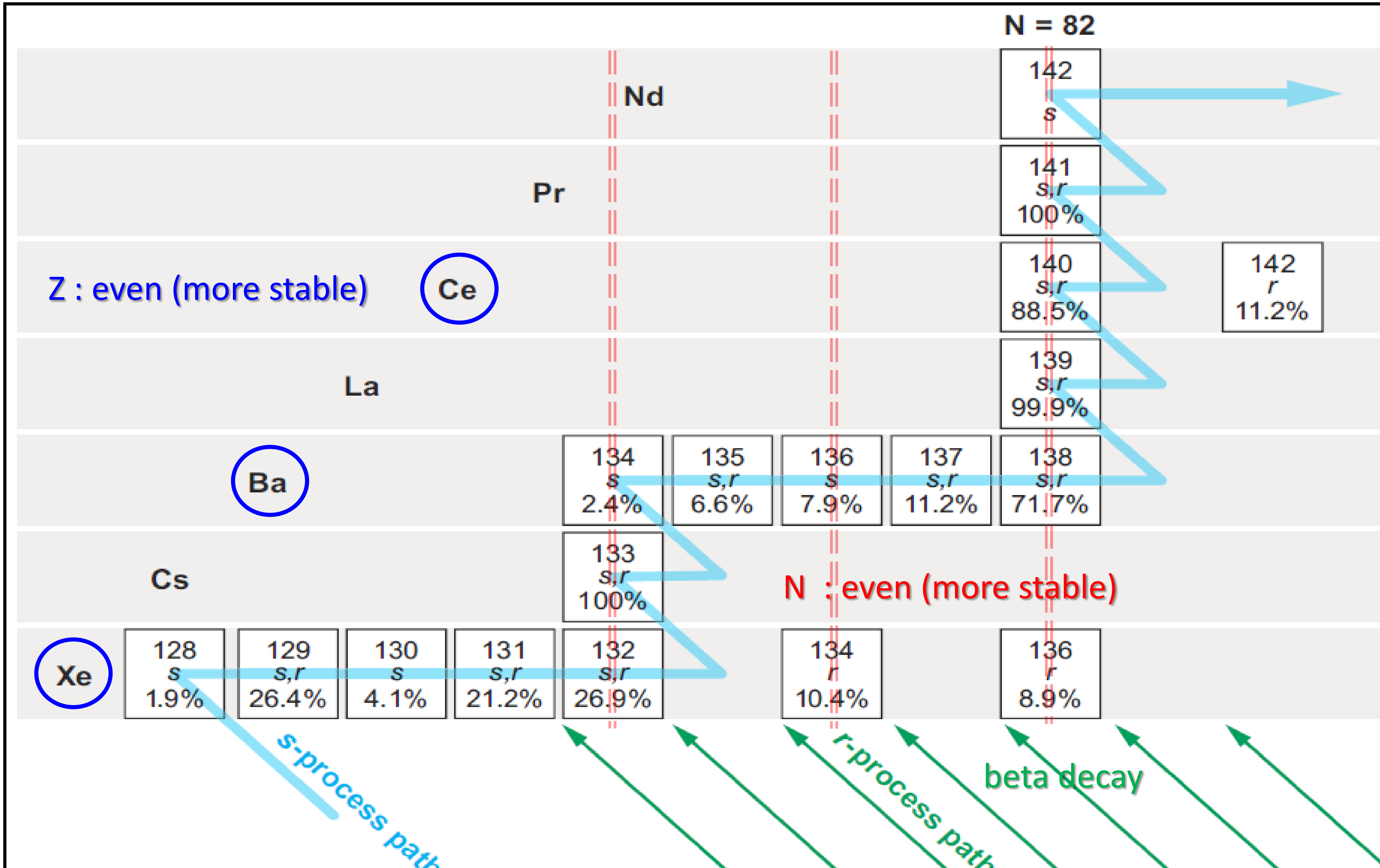


Neutron magic number: neutron capture is slower and β-decay proceeds to some extent

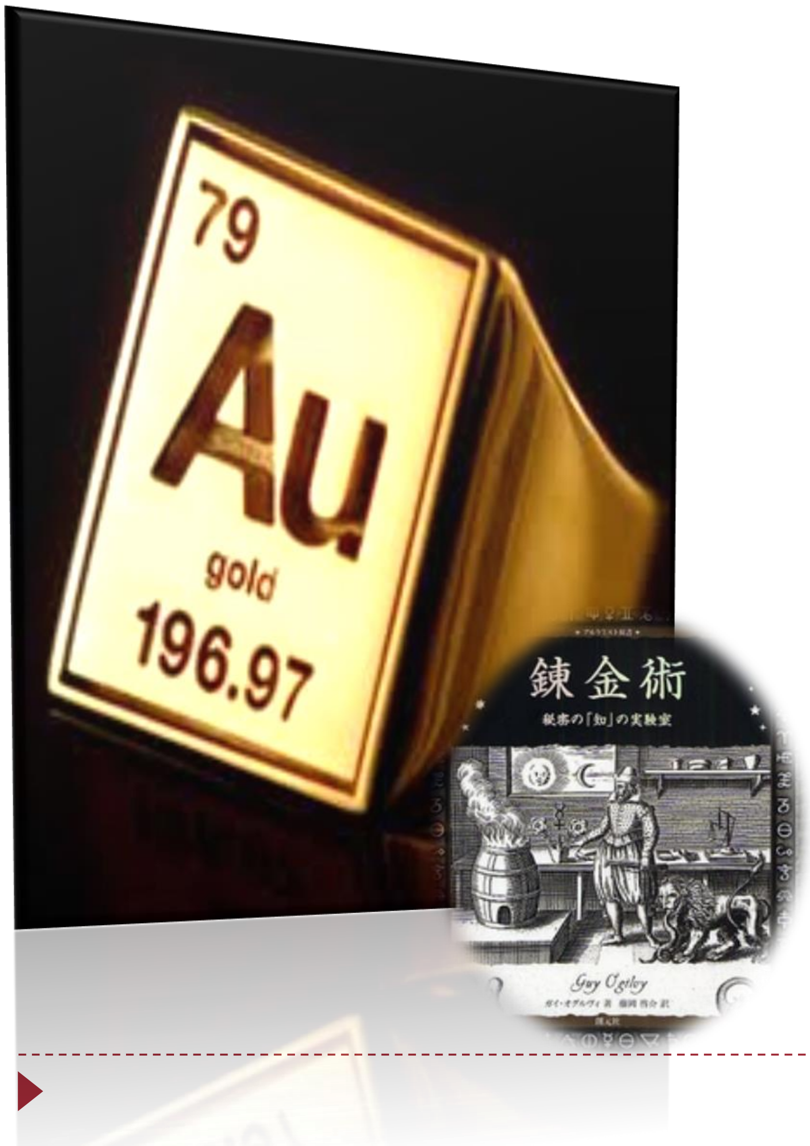
s-process / r-process path



s-process / r-process path



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
- **<u>(1) Low electron fraction Ye</u>**
  - Ye = number of electrons per baryon ~ # of proton ~ 1 - # of neutron
  - To have a large number of free neutrons
- **<u>(2) Higher entropy per baryon</u>**
  - To slow the seed nuclei production
- **<u>(3) Short expansion timescale</u>**
  - To freeze seed production with rapid decrease of temperature

What is the melting pot for r-process ?

“ $n_n \sim 10^{23}\mathrm{cm}^{-3}$ もの中性子発生過程は
星の爆発時以外にはありえないであろう.”

林 忠四郎 他「宇宙物理学」

“この過程(r過程のこと)は超新星爆発の最中に起こる.”

ポッフ 他「素粒子・原子核物理入門」

What is the melting pot for r-process ?

- **Supernova (SN) explosion (+ PNS ν-driven wind) : (*Burbidge et al. 1957*)**
  - Textbooks tell you that SNe are the origin of heavy elements, but ….
  - theoretically disfavored (Roberts et al. 2010, 2012)

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

What is the melting pot for r-process ?

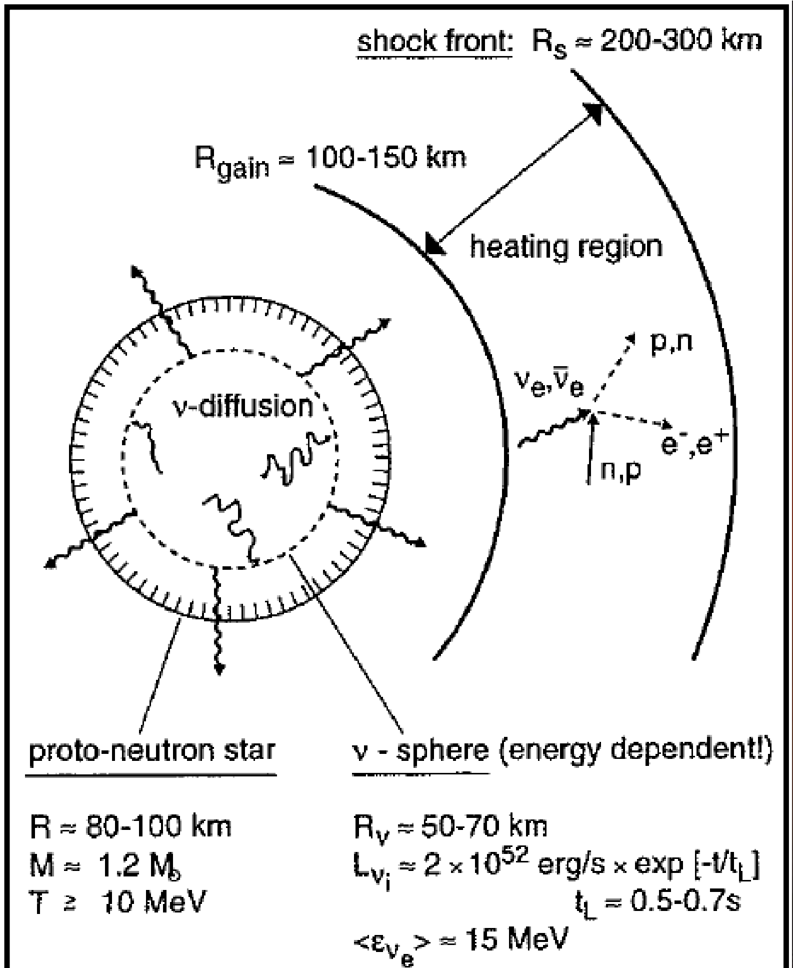
- **Supernova (SN) explosion: (***Burbidge et al. 1957***)**
  - Smaller entropy/per baryon than previously expected (e.g., ***Janka et al. 1997***)
    - Previous expectation (s/kB > 200) => recent update s/kB ~ 100-150
  - Neutrino heating mechanism of SNe explosion:
  - Neutrinos from PNS may make the flow proton-rich v ia $n+\nu \rightarrow p+e$ and $p+\bar{\nu} \rightarrow n+e^{+}$
    - Note : neutrons are heavier than proton => tendency of being proton rich.
    - Whether the flow becomes proton rich or not depends on mean neutrino energy
    - Mass difference vs. neutrino energy difference (and luminosities)

$$\Delta\varepsilon = \bar{\varepsilon}_{\nu} - \varepsilon_{\nu} \quad \text{vs.} \quad \Delta m = m_n - m_p$$

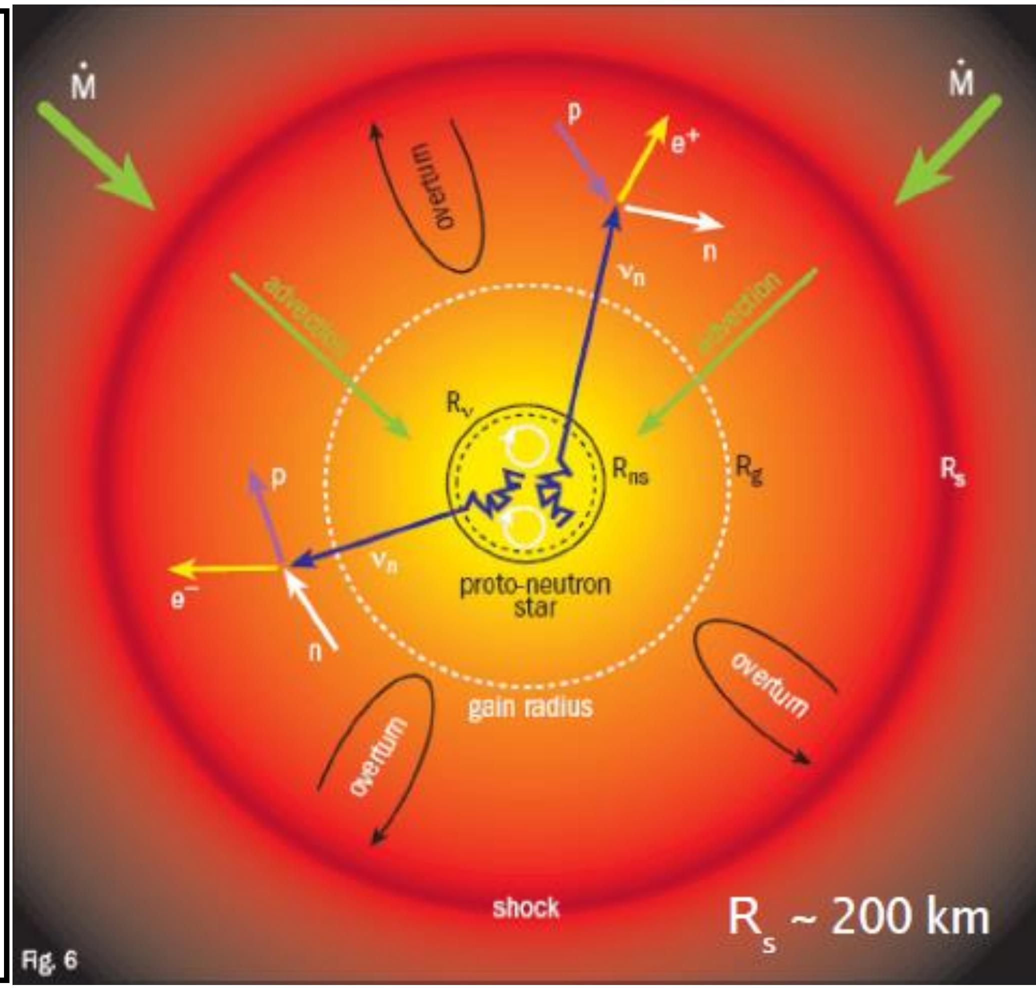
$$\Delta\varepsilon >\sim 4\Delta m \ \ \text{(neutron rich)} \qquad \Delta\varepsilon <\sim 4\Delta m \ \ \text{(proton rich)}$$

    - Higher electron anti-neutrino energy => effectively larger proton mass

Overall picture of the neutrino heating mechanism



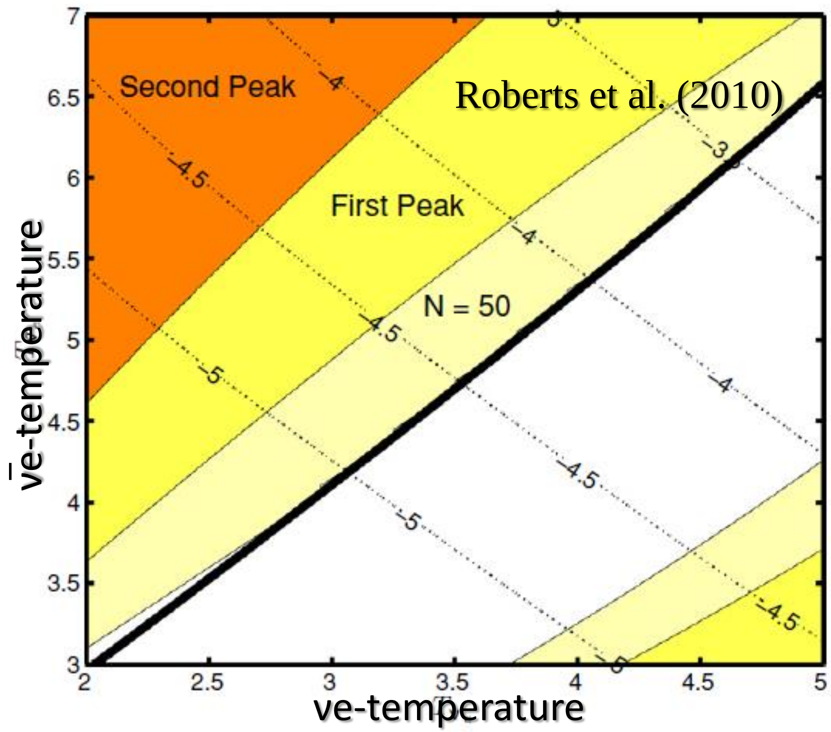
Cartoon by E. Muller (1998)

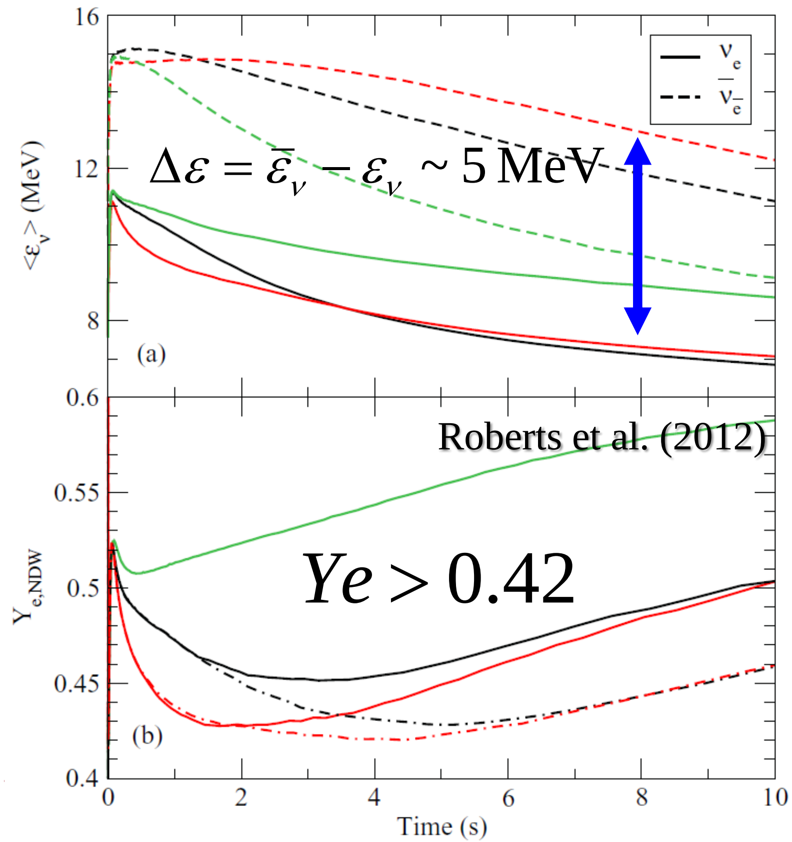


Cartoon by T. Janka

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 weak interactions
  - ⇒ only weak r-process (up to 2nd peak, no gold (3rd peak)!) (***Roberts et al. 2010, 2012;*** *Wajajo et al, 2013 etc.*)





What is the melting pot for r-process ?

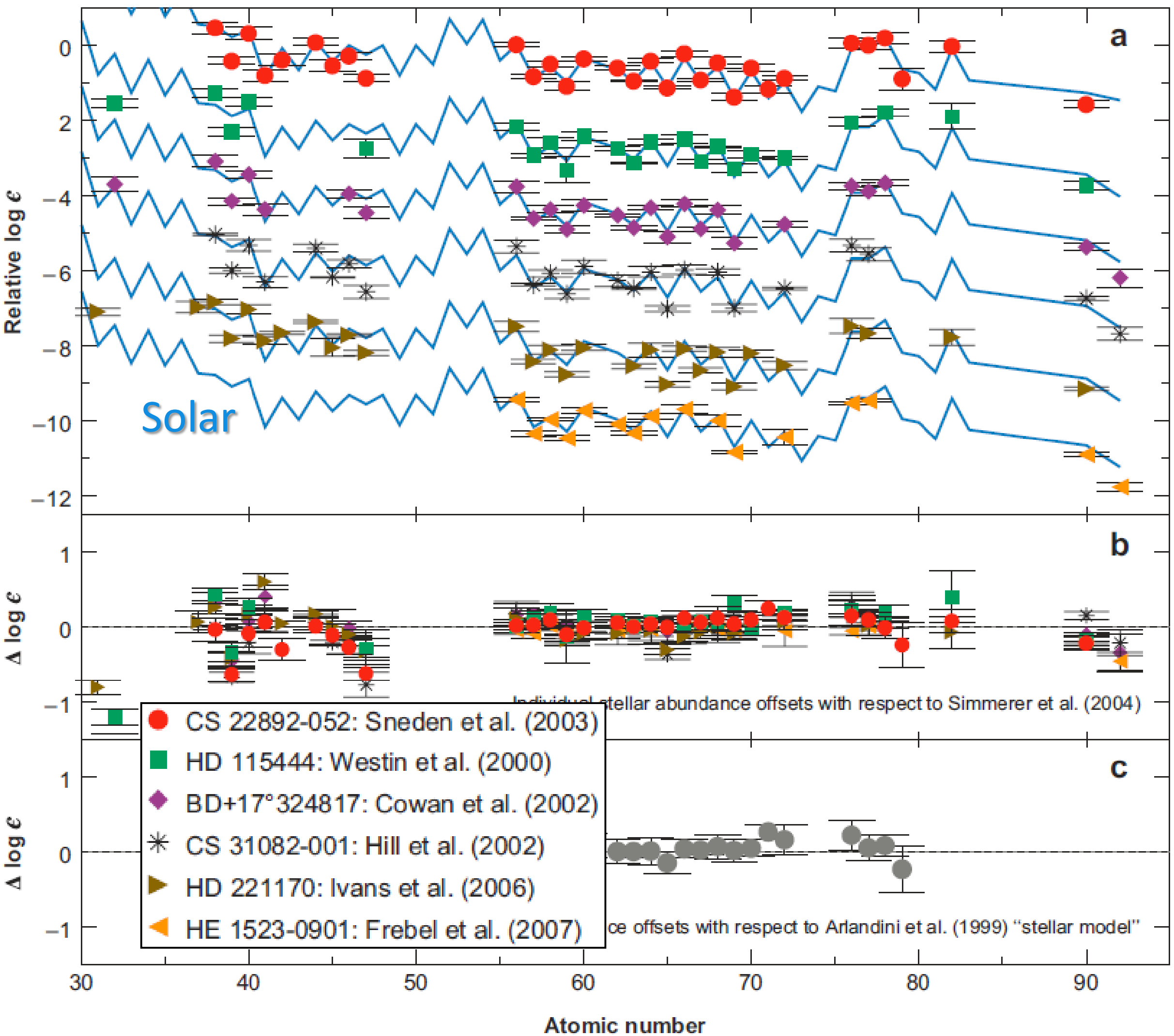
- **Supernova (SN) explosion: (*Burbidge et al. 1957*)**
  - Smaller entropy/per baryon than previously expected (e.g., ***Janka et al. 1997***)
    - Previous expectation (s/kB > 200) => recent update s/kB ~ 100-150
  - Neutrinos from PNS try to make the flow proton-rich via $n+\nu \rightarrow p+e$ and $p+\bar{\nu} \rightarrow n+e^{+}$
    - Note : neutrons are heavier than proton
    - Whether the flow becomes proton rich or not depends on neutrino energy
  - According to the recent studies, only weak r-process occurs (up to 2[nd] peak, no gold (3[rd] peak)!) (***Roberts et al. 2010, 2012***)
    - *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*

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)!) (***Roberts et al. 2010, 2012***)
    - 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*

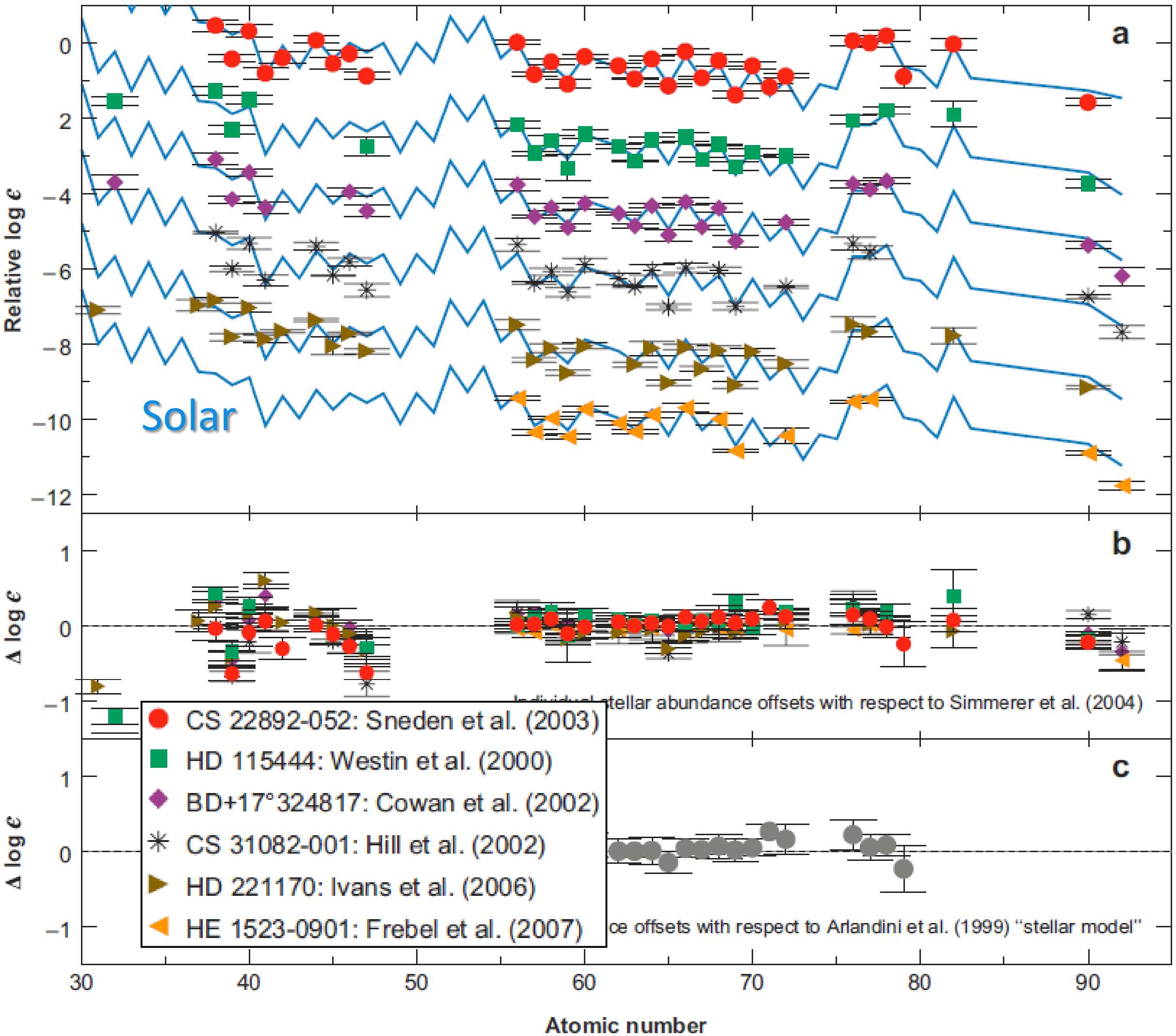
- Supernova can be the origin of r-process nuclei only if
  - The explosion mechanism is not due to the popular neutrino heating (e.g., magneto-rotational; Winteler et al. 2012)
  - or
  - Our knowledge of neutrino (and nuclear) physics is insufficient

A key observation to resolve the problem: Universality of the r-process cite



- Abundance pattern comparison :
  - r-rich low metallicity stars
  - Solar neighborhood
- Low metallicity means
  - Such stars experience only one/two r-process events
  - Such stars preserve the original pattern of the r-process events (chemical fossil)

A key observation to resolve the problem: Universality of the r-process cite



- Abundance pattern comparison :
- The solar and chemical fossil pattern agree well
  - for Z > 35-40 (A > 85-90)
- Recall that the low metallicity stars record the original pattern
- => these observations strongly suggest that the (main) <u>r-process event synthesize the elements with a pattern similar to solar (Univsersality)</u>

What is the melting pot for r-process ?

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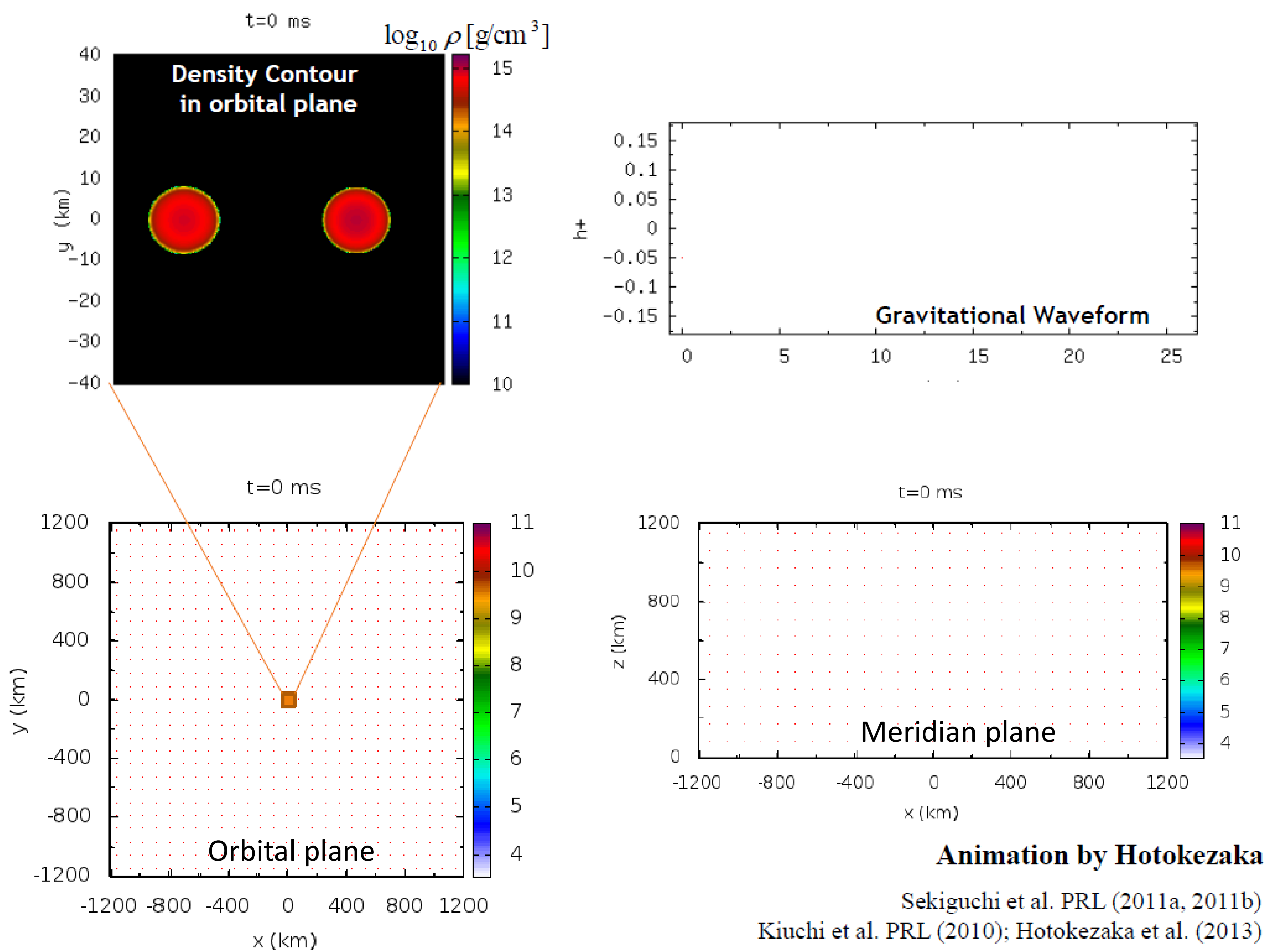
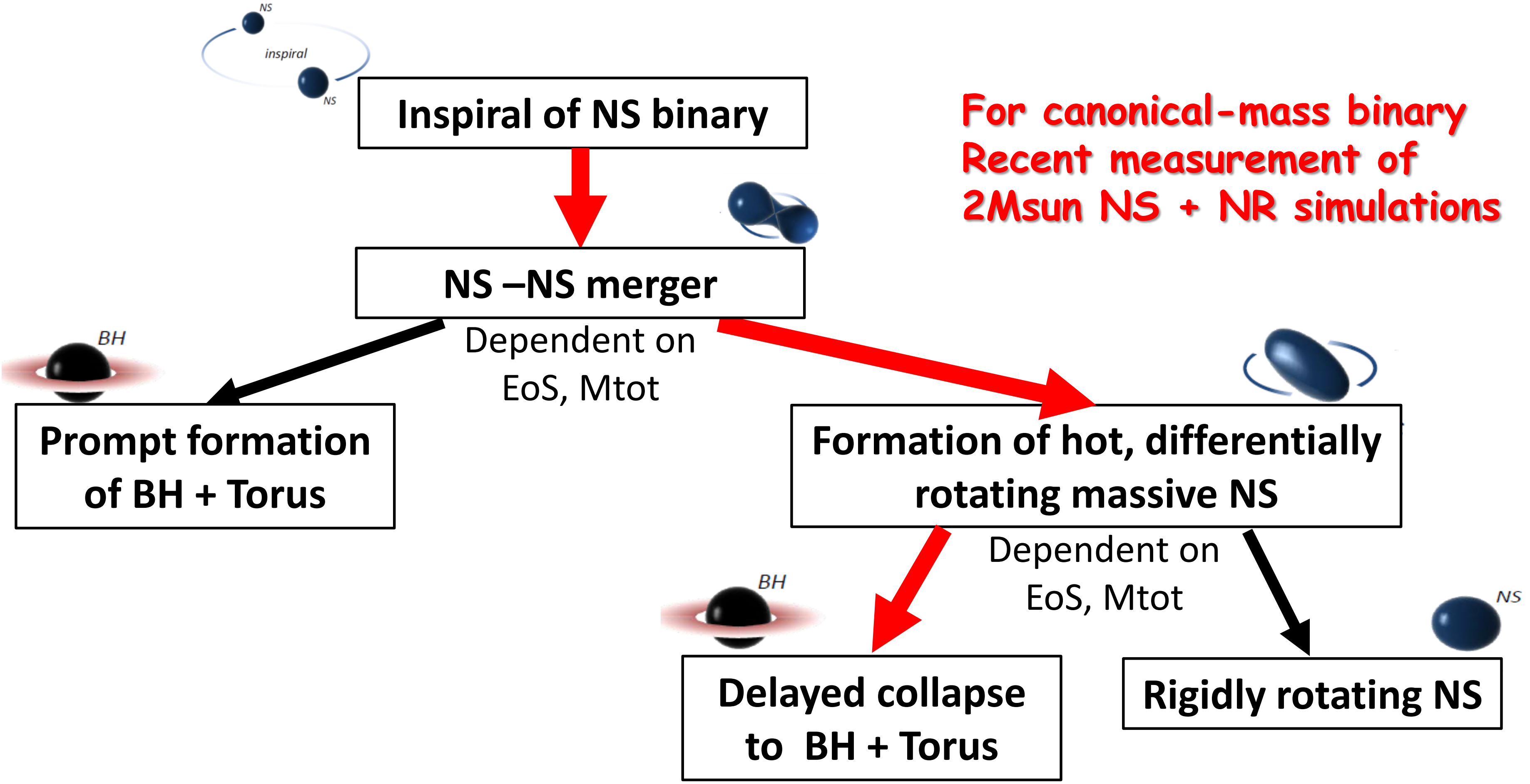

t=0 ms
$\log_{10}\rho\,[\mathrm{g/cm^3}]$
Density Contour
in orbital plane
Gravitational Waveform
h+
t=0 ms
Orbital plane
y (km)
x (km)
t=0 ms
Meridian plane
z (km)
x (km)
Animation by Hotokezaka
Sekiguchi et al. PRL (2011a, 2011b)
Kiuchi et al. PRL (2010); Hotokezaka et al. (2013)

Based on Bartos (2013)

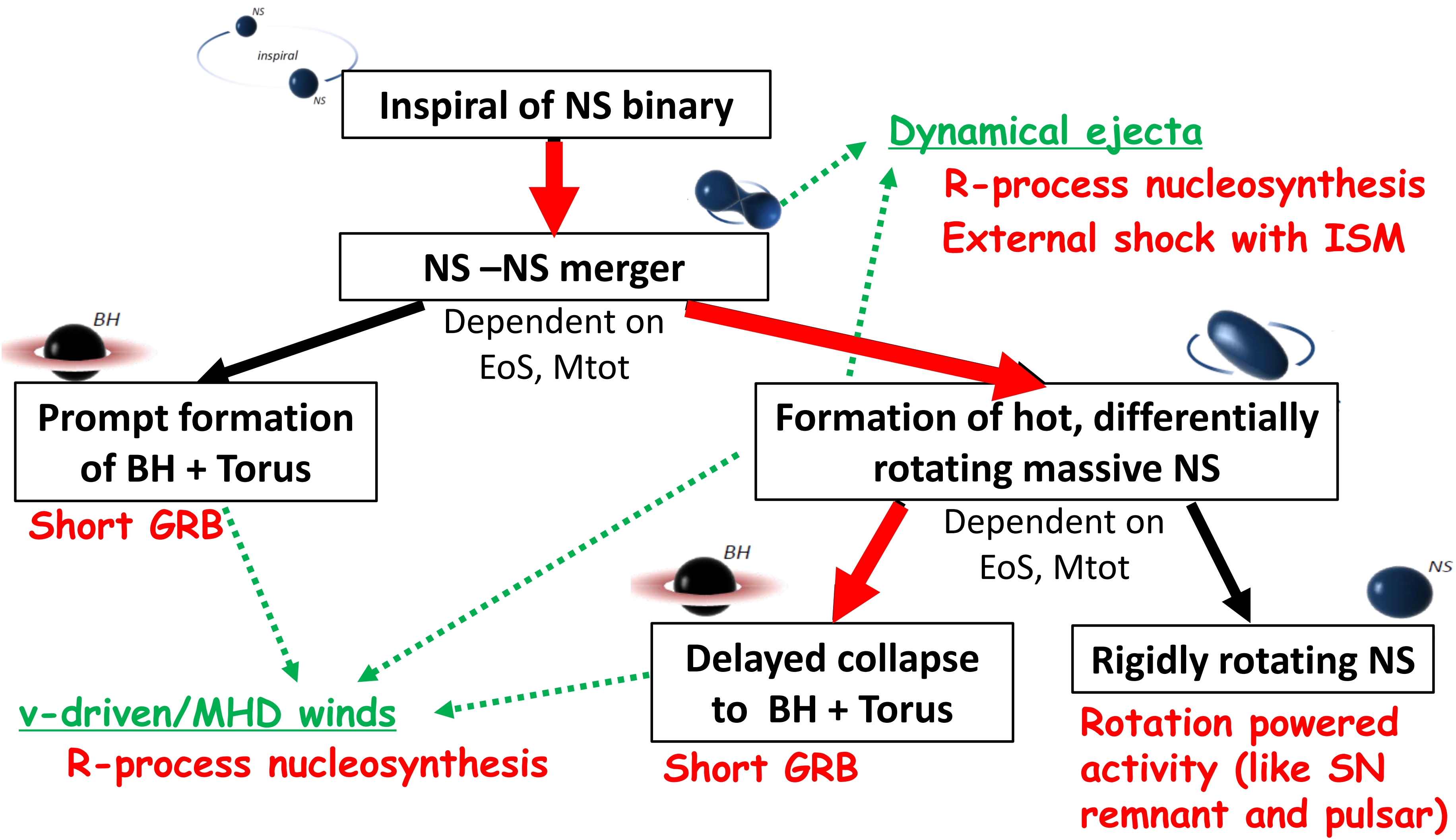
Evolution of NS-NS mergers



For canonical-mass binary
Recent measurement of
2Msun NS + NR simulations

Based on Bartos (2013)

Multi Messengers and GW counterpart

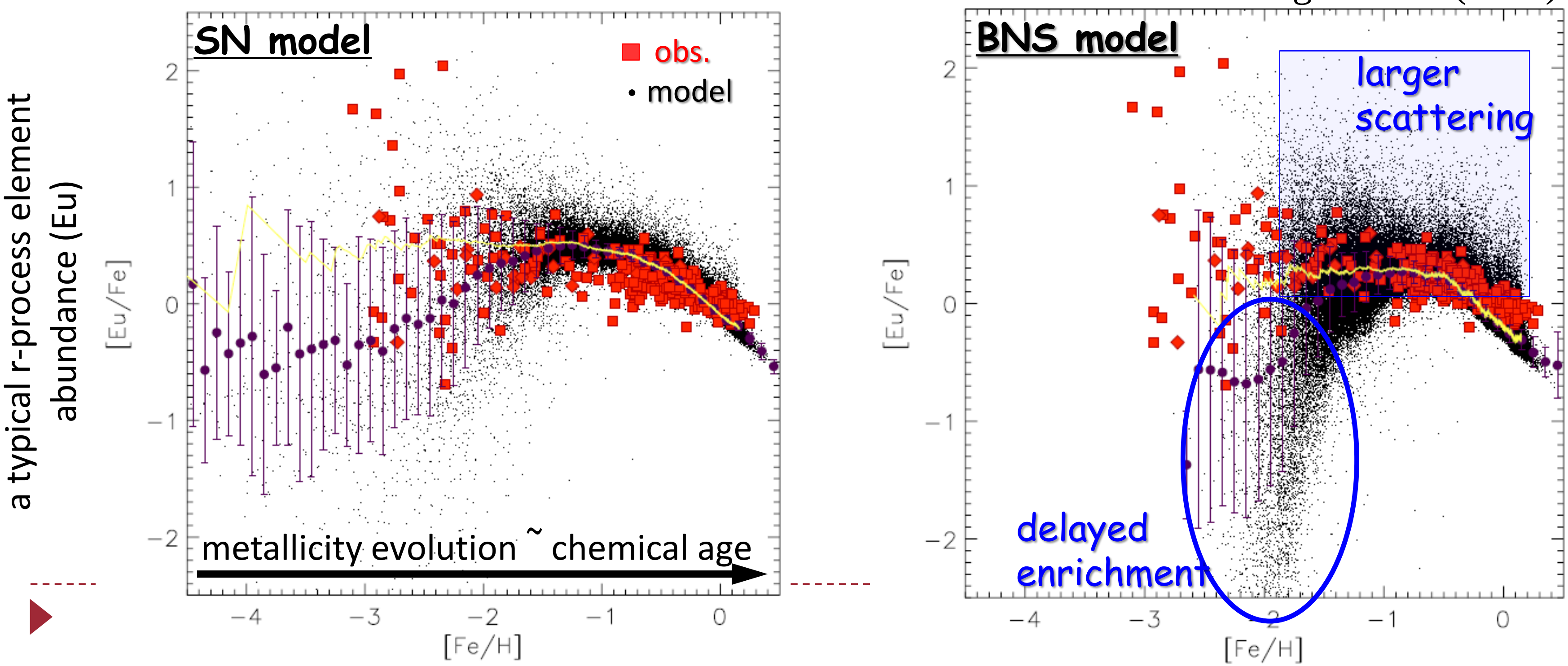


e.g., Matteucci et al. 2014, MNRAS, 438, 2177; Komiya et al. 2014, ApJ, 783, 132, Tsujimoto & Shigeyama, A&A, 565, L5

What is the melting pot for r-process ?

- **NS-NS/BH binary merger: (*Lattimer & Schramm 1974*)**
  - **was observationally disfavored ?? (*Argast et al. 2004*)**
    - delayed appearance of r-process element (long merger time ~ 100Myr)
    - large star-to-star scattering (low event rate (~ 10^{-5}/yr/gal) : rock sugar vs. table sugar)

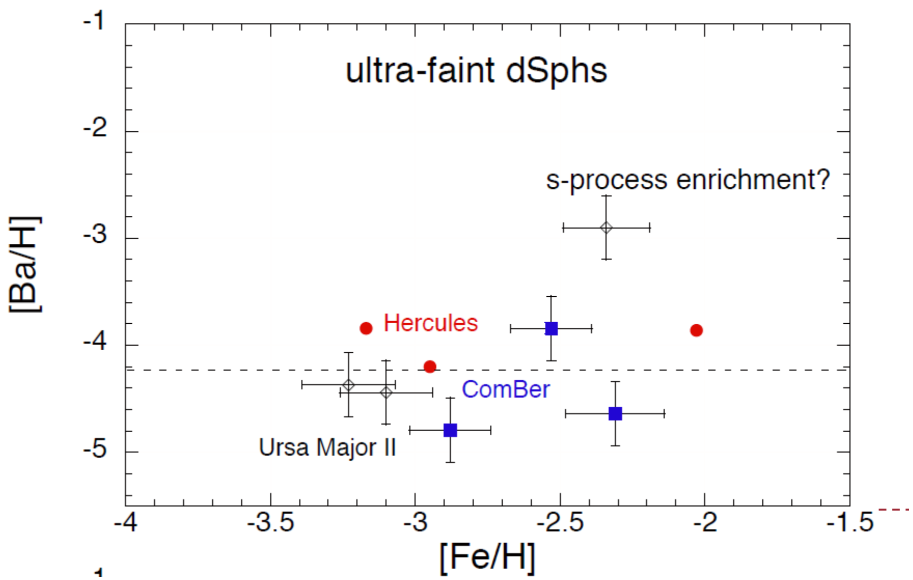
Argast et al. (2004)

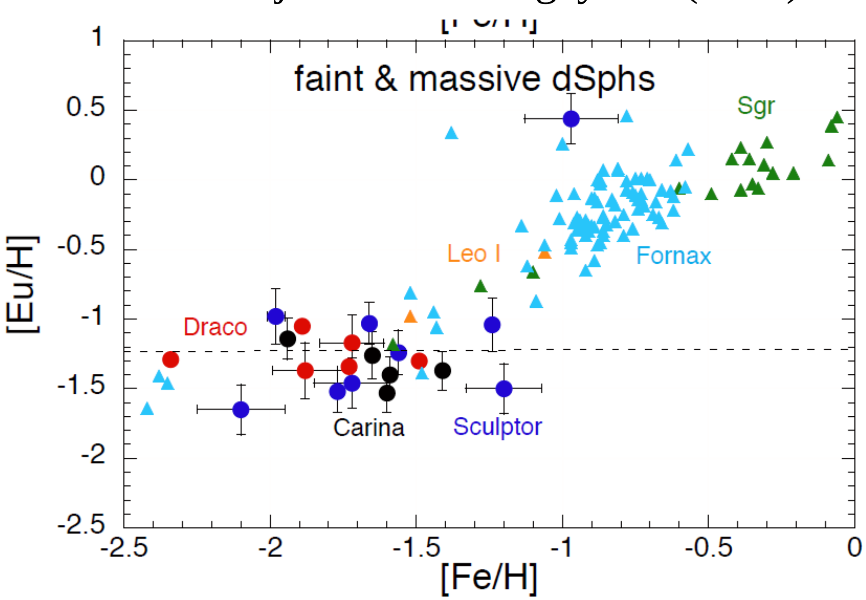


What is the melting pot for r-process ?

- **<u>Observationally NOT disfavored ?? (*Tsujimoto and Shigeyama. 2014*)</u>**
  - No enrichment of Eu in ultra dwarf galaxies but Fe increases
    - No r-process events (No Eu) but a number of SNe (Fe↑)
    - If SNe are the r-process cite, both Eu and Fe should increase
    - Suggest different origin for Fe and Eu

Tsujimoto and Shigeyama (2014)





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    - If SNe are the r-process cite, both Eu and Fe should increase
    - Suggest different origin for Fe and Eu
  - Enrichment of Eu in massive dwarfs
    - event rate is estimate as 1/1000 of SNe : consistent with BNS merger
  - Delay time problem due to merger time of ~ 100 Myr:
    - In the dwarf galaxies, chemical enrichment is different from that in the ordinary galaxies due to less deep gravitational potential.
    - Fe produced in SNe can escape from the dwarf galaxies efficiently
    - => it takes more time for the dwarf galaxies to be Fe rich than in the normal galaxies
    - Studies taken into account this indicate that merger time of 100 Myr is consistent with the observations (Ishimaru et al. 2015; Hirai et al. in prep.)

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

- **EM transients possibly powered by radioactivity of the r-process elements were expected (Li & Paczynski 1998) and found (important GW counterpart)**

- Recent critical update : Opacities are dominated by lanthanoids : orders of magnitude (~100) larger (Kasen e al. 2013; Tanaka & Hotokezaka 2013)

$$t_{\rm peak} \sim 10\,{\rm days} \left(\frac{v}{0.3c}\right)^{-1/2} \left(\frac{M}{0.01 M{\rm solar}}\right)^{1/2} \left(\boxed{\frac{\kappa}{10\,{\rm cm}^2/g}}\right)^{1/2}$$

1 day ⇒ 10 days

$$L_{\rm peak} \sim 10^{41}{\rm erg/s} \left(\frac{f}{10^{-6}}\right)\left(\frac{v}{0.3c}\right)^{1/2} \left(\frac{M}{0.01 M{\rm solar}}\right)^{1/2} \left(\boxed{\frac{\kappa}{10\,{\rm cm}^2/g}}\right)^{-1/2}$$

1/10 dimmer

$$T^{\rm eff}_{\rm peak} \sim 2\times 10^3{\rm K} \left(\frac{f}{10^{-6}}\right)^{1/4}\left(\frac{v}{0.3c}\right)^{-1/8} \left(\frac{M}{0.01 M{\rm solar}}\right)^{-1/8} \left(\boxed{\frac{\kappa}{10\,{\rm cm}^2/g}}\right)^{-3/8}$$

Opt-UV ⇒ NIR

- Although it gets difficult to observe, they are still among the promising EM counterparts ⇒ needs more studies to clarify the ejecta properties

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

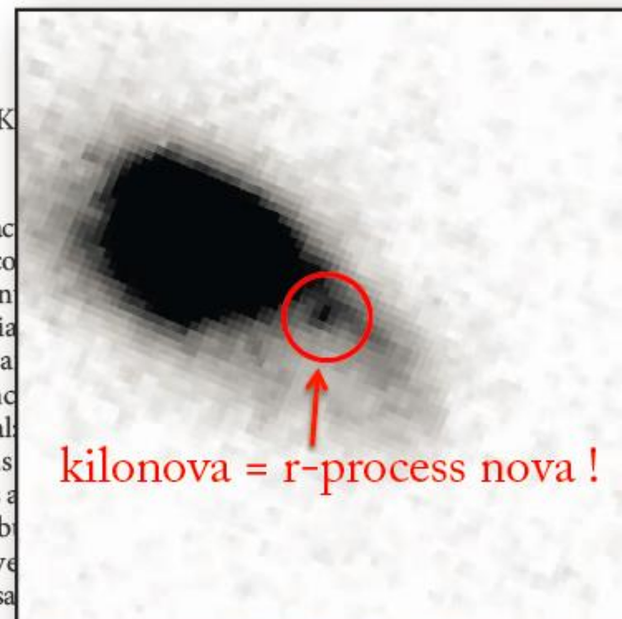
- **EM transients possibly powered by radioactivity of the r-process elements were expected (Li & Paczynski 1998) and found (important GW counterpart)**

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].

From the 'Universality' point of view :

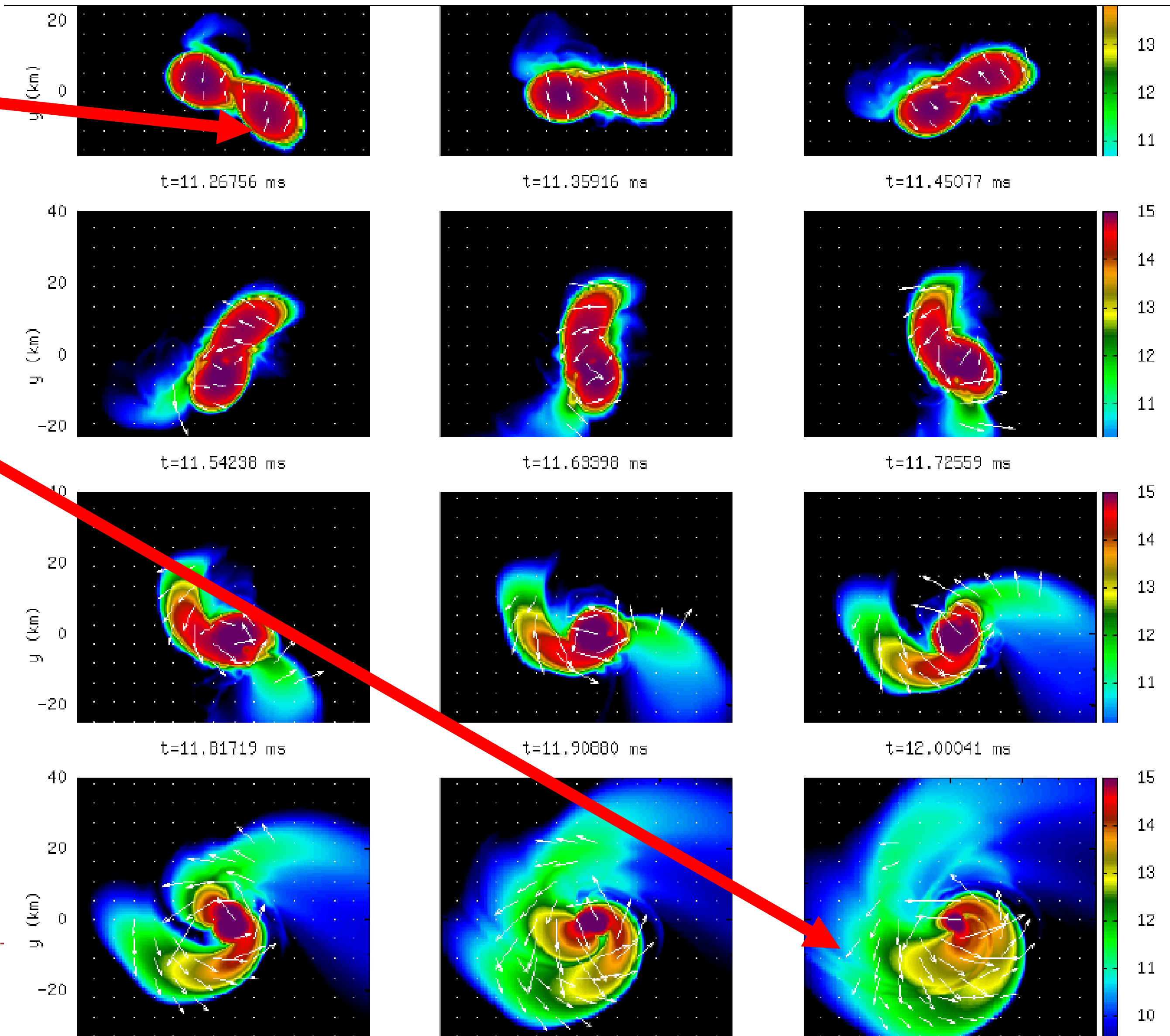
NS-NS merger ejecta: too neutron-rich ?

- Korobkin et al. 2012; Rosswog et al. 2013 (Newtonian sim. with neutrino); see also Goriely et al. 2011 (Approx. GR sim. **without** weak interactions)
  - Approx. GR simulation: no way to change Ye (ejecta remains n-rich (initial low Ye))
  - **Newtonian SPH simulations: tidal mass ejection** of 'pure' neutron star matter
  - Ejecta is very n-rich with Ye < 0.1

Mass ejection from BNS merger (1) : Tidal torque + centrifugal force

Hotokezaka et al. (2013)

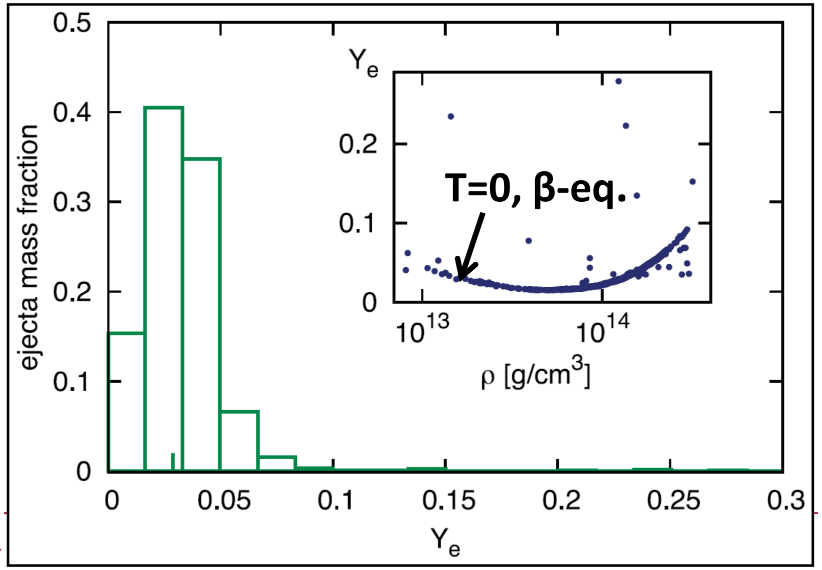
- Less massive NS is tidally deformed
- Angular momentum transfer by spiral arm and swing-by
- A part of matter is ejected along the orbital plane
- **reflects low Ye of cold NS** (β-eq. at T~0), no shock heating, rapid expansion (fast T drop), no time to change Ye by weak interactions



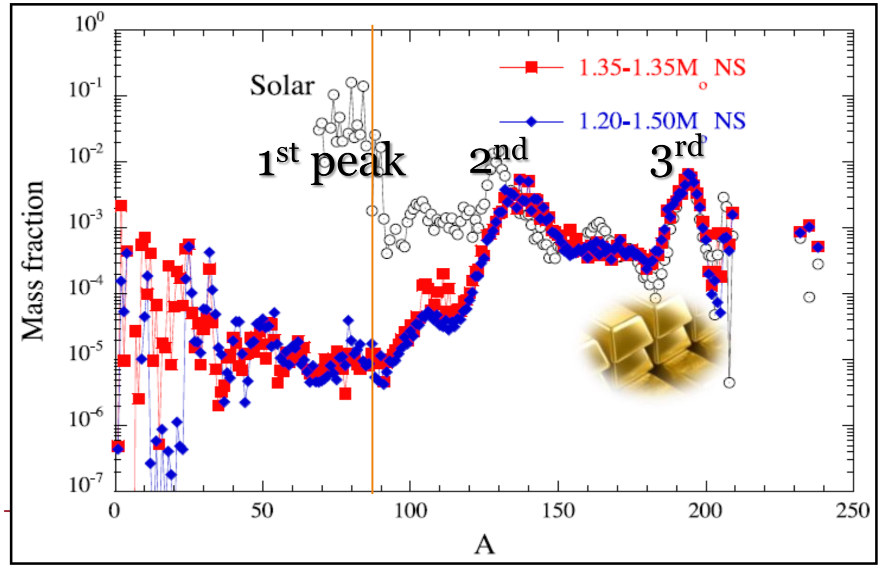
Density contour
[log (g/cm^3)]

From the 'Universality' point of view :
NS-NS merger ejecta: too neutron-rich ?

- **Korobkin et al. 2012; Rosswog et al. 2013; see also Goriely et al. 2011**
  - tidal mass ejection of 'pure' neutron star matter (very n-rich) with Ye < 0.1
    - Ye is that of T=0, β-equilibrium
  - strong r-process with fission recycling only 2nd (A~130; N=82) and 3rd (A~195; N=126) peaks are produced (few nuclei in A=90-120)
  - the resulting abundance pattern does not satisfy universality in A=90-120
- Is it impossible to satisfy the universality in BNS merger scenario ?
  - No ! If you take into account both neutrino and GR



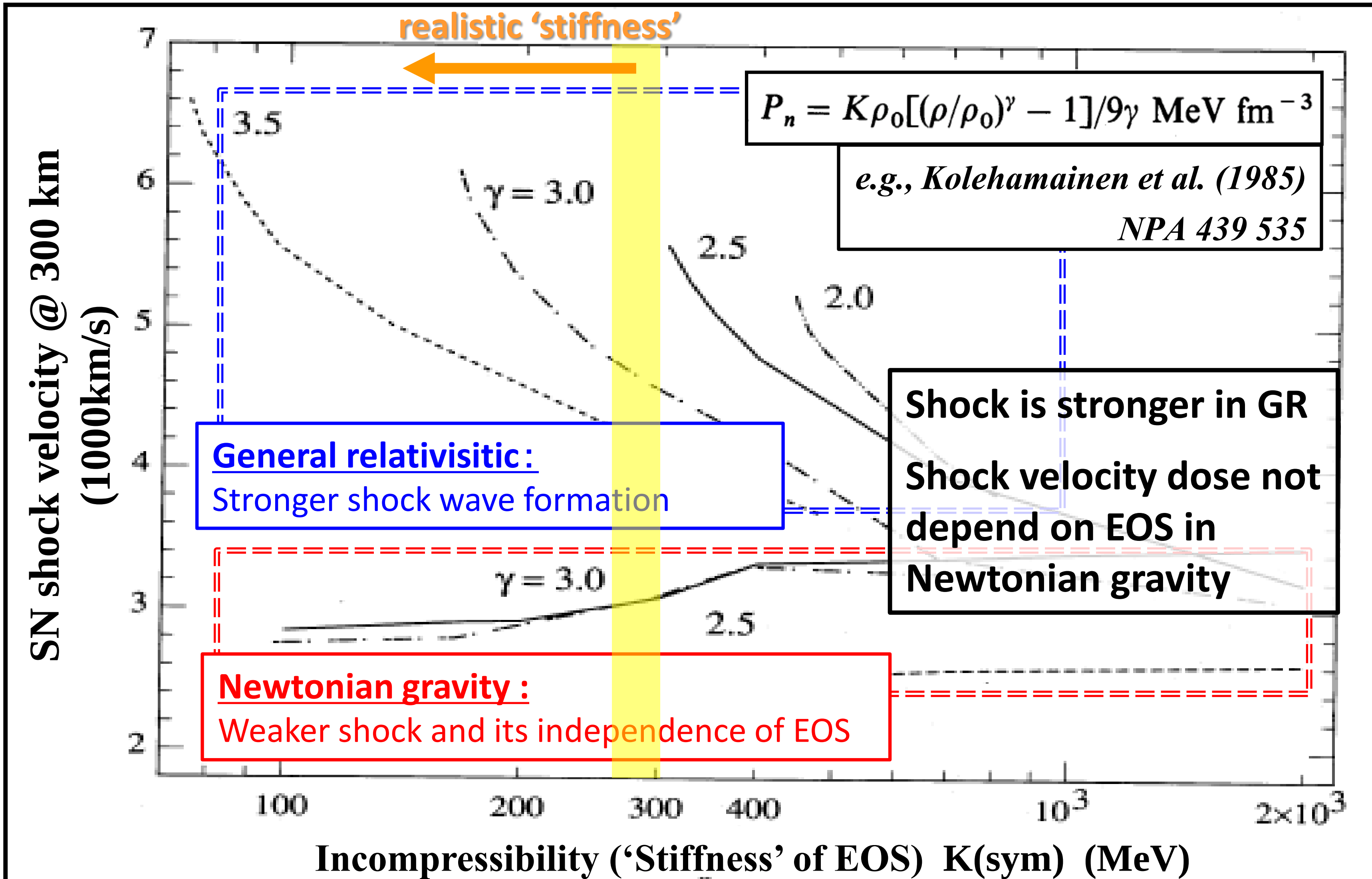
Korobkin et al. (2012) MNRAS 426 1940



Goriely et al. (2011) ApJL 738 32

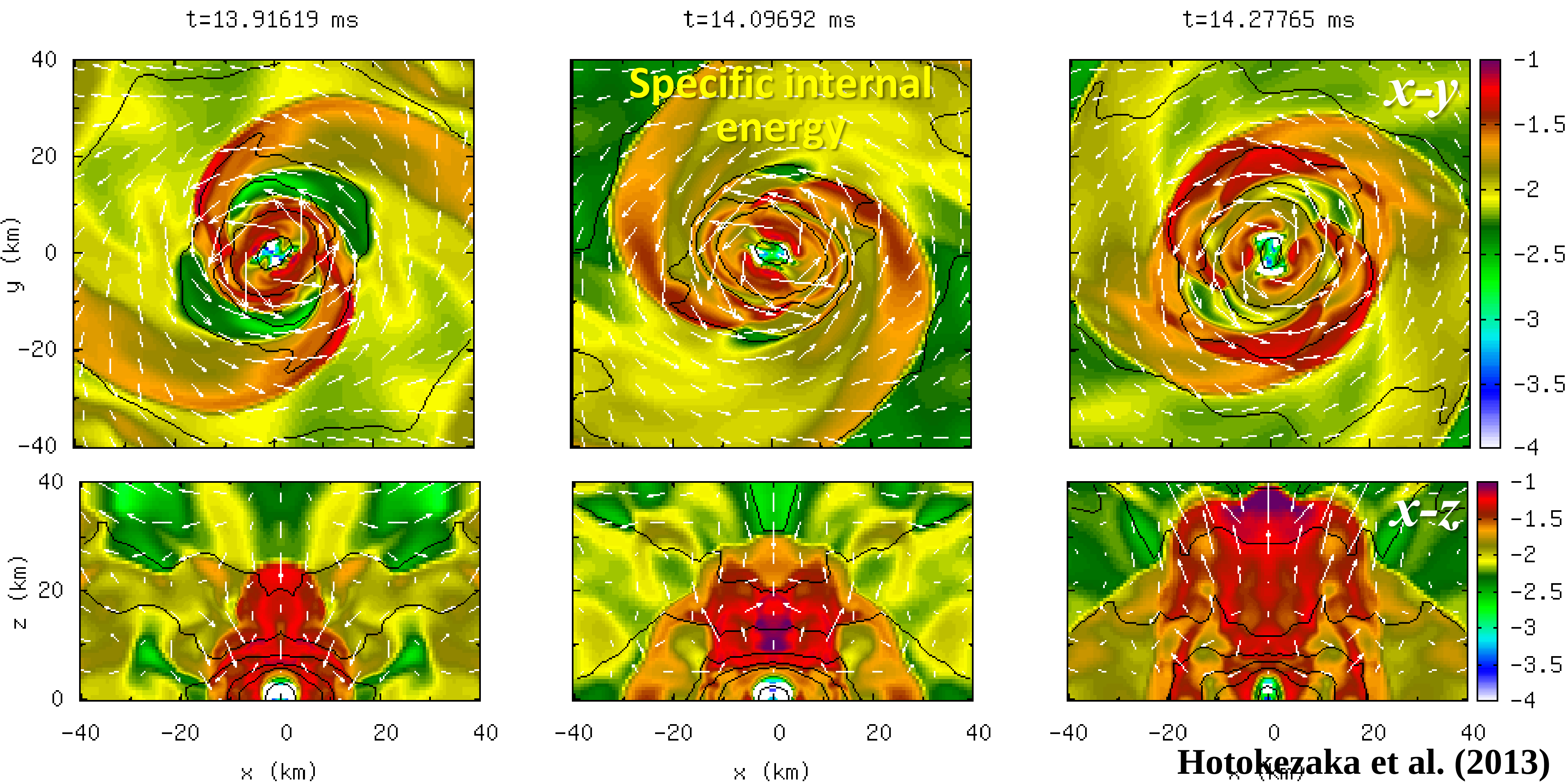
What will change if you include GR and microphysics (1) : Stronger shock in GR

van Riper (1988) ApJ 326 235



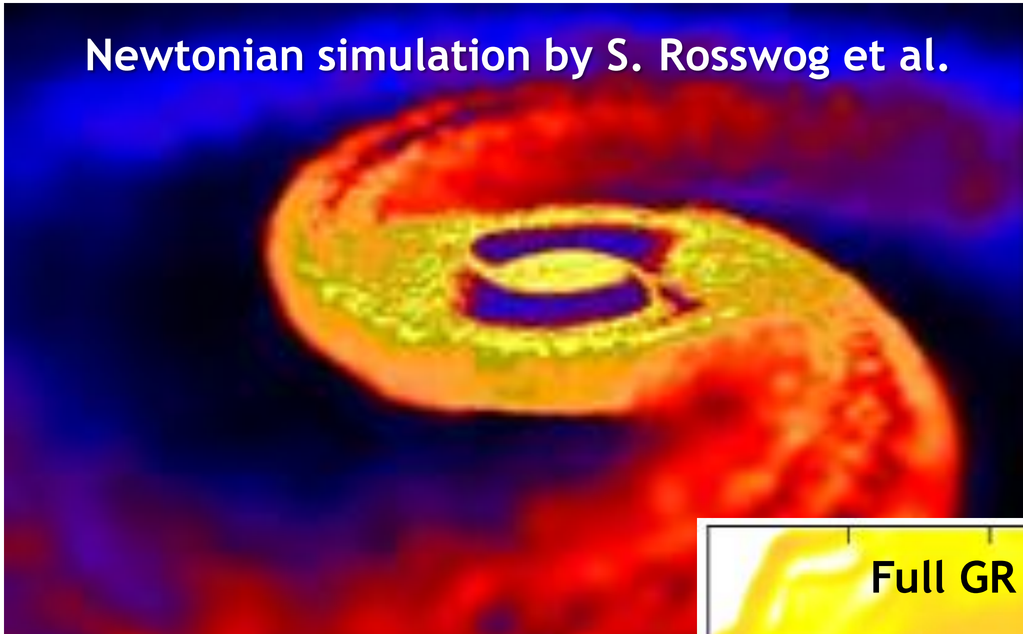
Mass ejection from BNS merger (2): Shock driven components

- Shocks occur due to oscillations of massive NS and collisions of spiral arms
- Isotropic mass ejection, higher temperature (weak interactions set in)



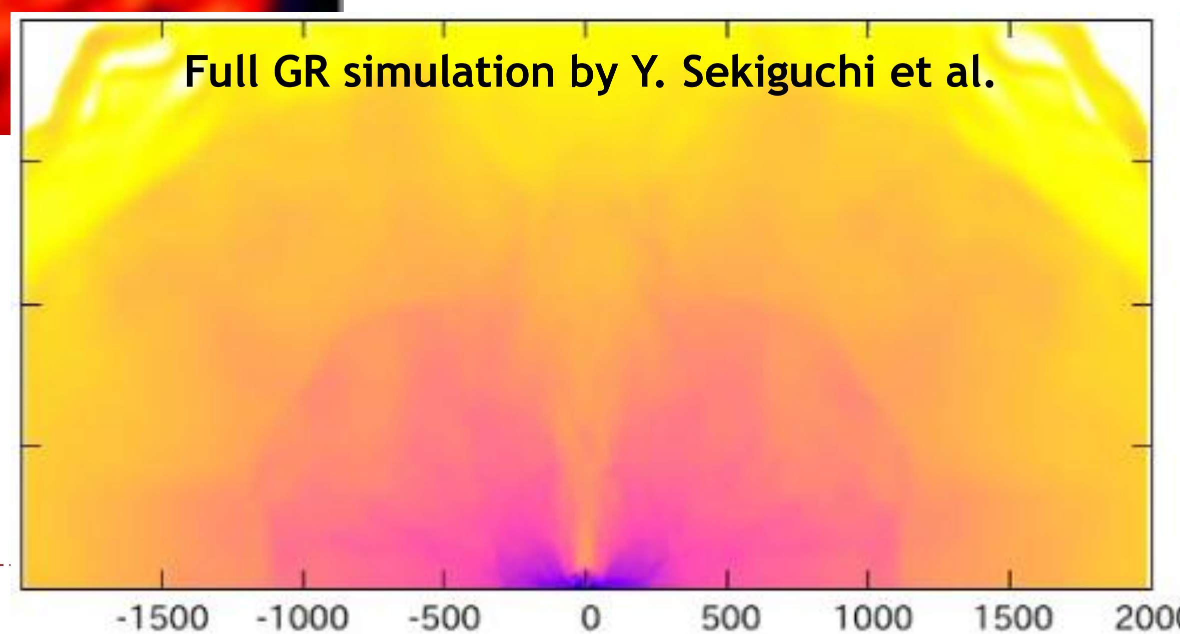
Hotokezaka et al. (2013)

What will change if you include GR and microphysics (1) : Stronger shock in GR



Almost no isotropic component (shock-driven) in Newtonian simulation

Only the tidal component



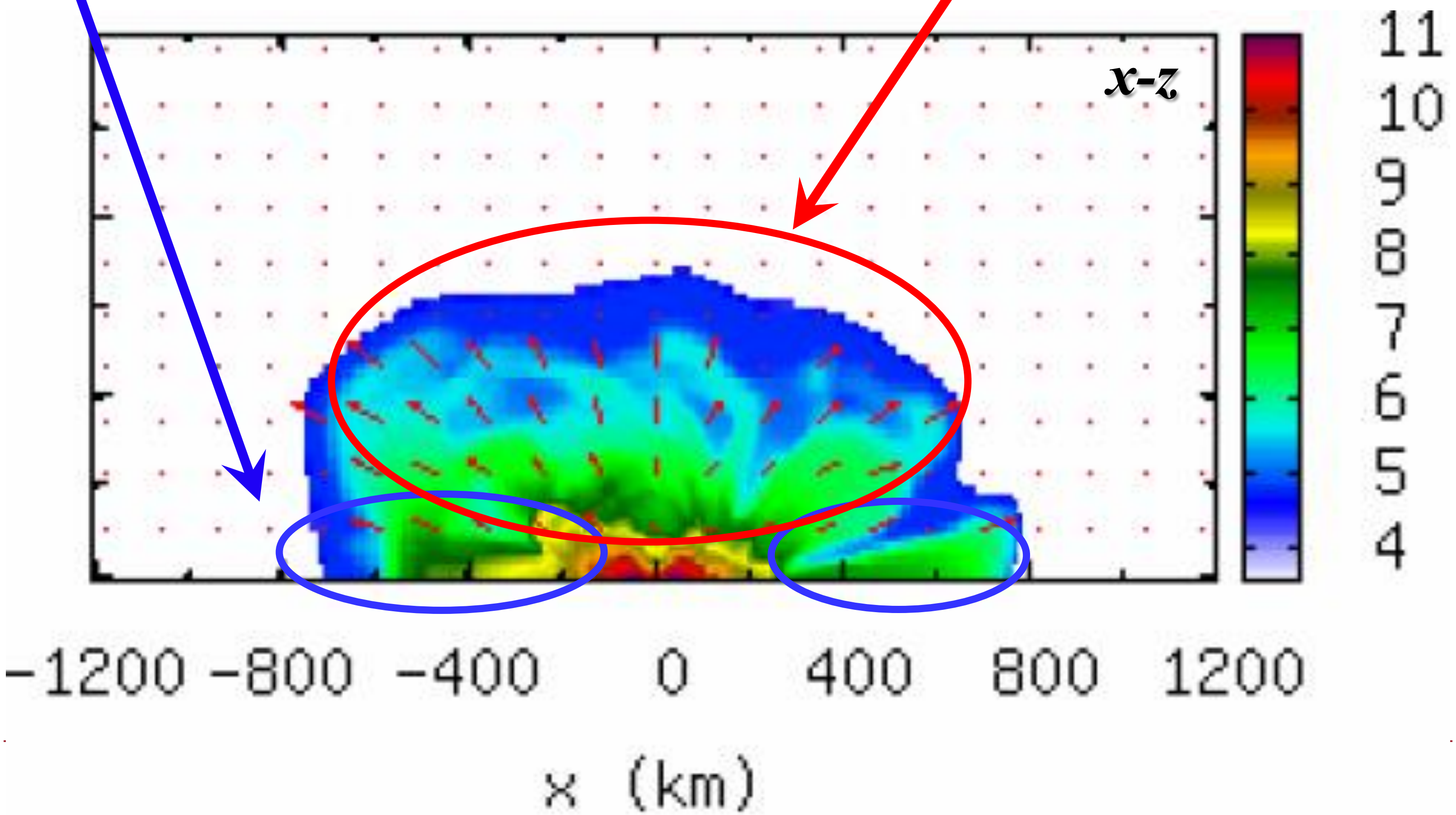
What will change if you include GR and microphysics (2) : Ye can change via weak interaction

- **Driven by tidal interactions**

  Consists of cold NS matter in β-equilibrium ⇒ **low Ye and T**

- **Driven by shocks**

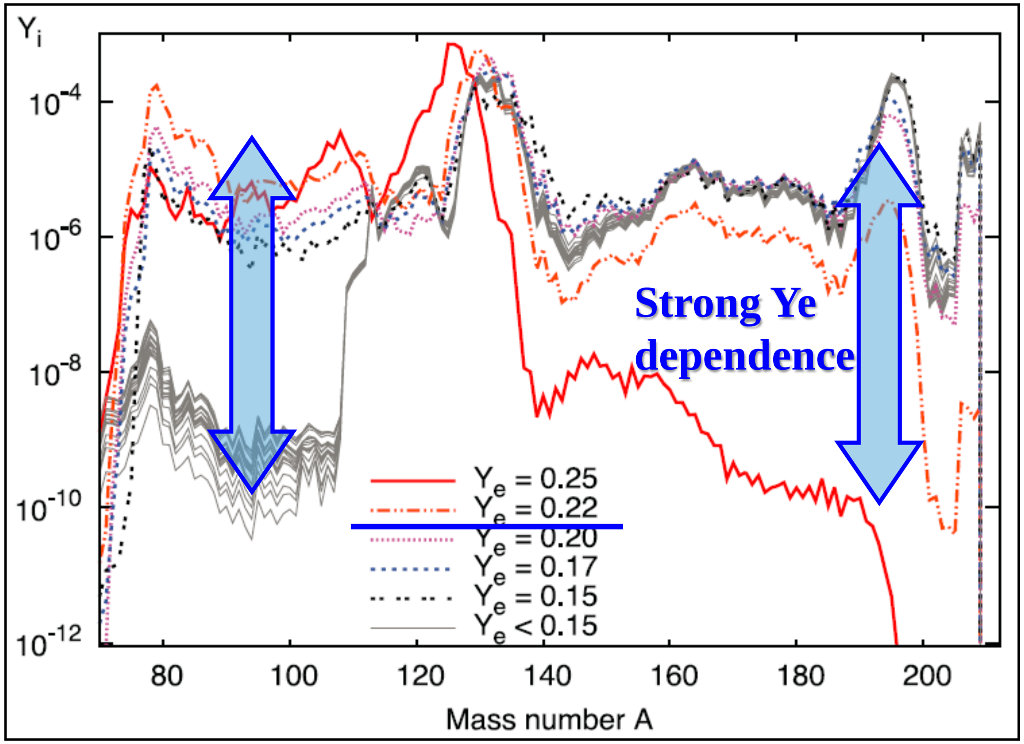
  Consists of shock heated matter higher temperature =>
  Weak interaction can change Ye



Importance of Ye in the r-process

- **Electron fraction (Ye) is the key parameter : <u>Ye ~ 0.2 is critical threshold</u>**
  - Ye < 0.2 : strong r-process ⇒ nuclei with A>130
  - Ye > 0.2 : 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**
  - **<u>Ye can be changed</u>**
  - Two reactions which increase Ye
  - Positron capture : $\boxed{n + e^{+} \rightarrow p + \bar{\nu}_e}$
    - **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

Short summary of lecture I (1)

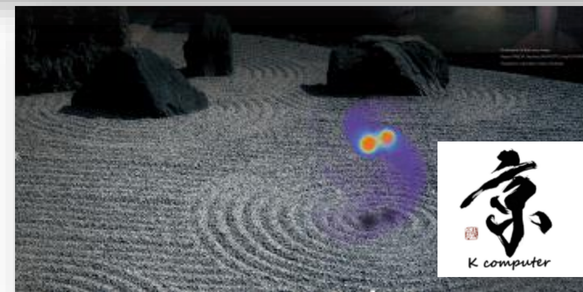
- The origin of r-process nuclei : SNe vs. BNS merger
  - Key words
    - low Ye required, universality of the pattern
    - Nice lecture by Evan for nucleosynthesis
  - SNe
    - Difficult to preserve n-rich condition necessary for the r-process
    - Extremely difficult to satisfy the universality
  - BNS
    - Recent theoretical and observational studies indicate BNS mergers are a promising candidate
    - **Kilonova-like signal : important as EM counterpart to GW**
    - How about from the universality point of view

Short summary of lecture I (2)

- BNS merger as the origin of r-process nuclei

  - Requirement : should satisfy the 'universality'
    - Both low (< 0.2) and moderate (> 0.2) Ye are necessary
    - Difficulty in previous studies

  - How to satisfy the 'universality' ?
    - (1) add new mass ejection mechanism
      - may need some fine 'tuning ' to satisfy the 'universality'
    - (2) include both GR and neutrino processes
      - Our strategy
      - GR => stronger shock => higher temperature => neutrino processes can change ejecta Ye



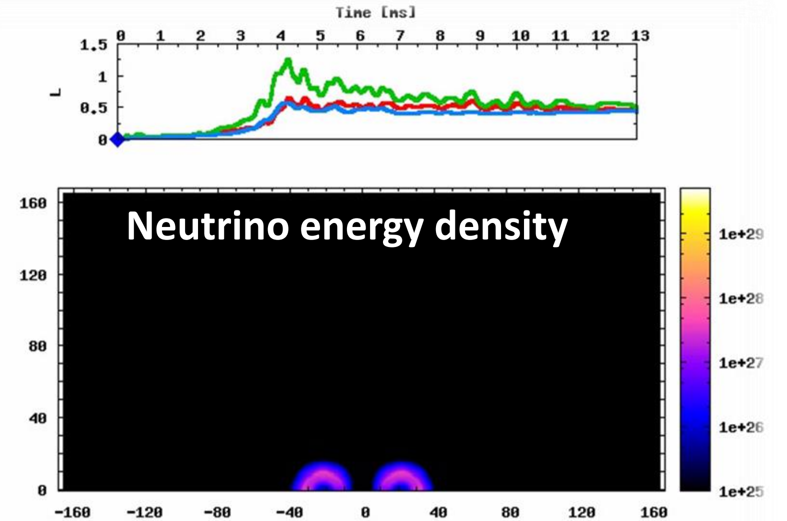
実験と観測で解き明かす中性子星の核物質 第4回ウィンタースクール

コンパクト天体連星の合体と重元素合成 I

関口 雄一郎（東邦大学）

Previous studies and our study

- **Korobkin et al. 2012 :** Newtonian SPH simulations with neutrinos
- **Bauswein et al. 2013:** Relativistic SPH simulations with many EOS but without neutronos
- **This Study :** Full GR, approximate gray radiation hydrodynamics simulation with multiple EOS and neutrinos (brief summary of code is in appendix of lecture note)
  - Einstein's equations: Puncture-BSSN/Z4c formalism
  - GR radiation-hydrodynamics (*neutrino heating can be approximately treated*)
    - Advection terms : Truncated Moment scheme (*Shibata et al. 2011*)
      - EOS : any tabulated EOS with 3D smooth connection to Timmes EOS
      - gray or multi-energy but advection in energy is not included
      - Fully covariant and relativistic M-1 closure
    - Source terms : two options
      - Implicit treatment : Bruenn's prescription
      - Explicit treatment : trapped/streaming ν's
        - e-captures: thermal unblocking/weak magnetism; NSE rate
        - Iso-energy scattering : recoil, Coulomb, finite size
        - e±annihilation, plasmon decay, bremsstrahlung
        - diffusion rate (Rosswog & Liebendoerfer 2004)
        - two (beta- and non-beta) EOS method
    - Lepton conservation equations



Adopted finite-temperature EOS

- Multi-EOS study (Thanks to ***M. Hempel***)

See also, Bauswein et al. (2013);
Just et al. (2014)

- Adopted EOS

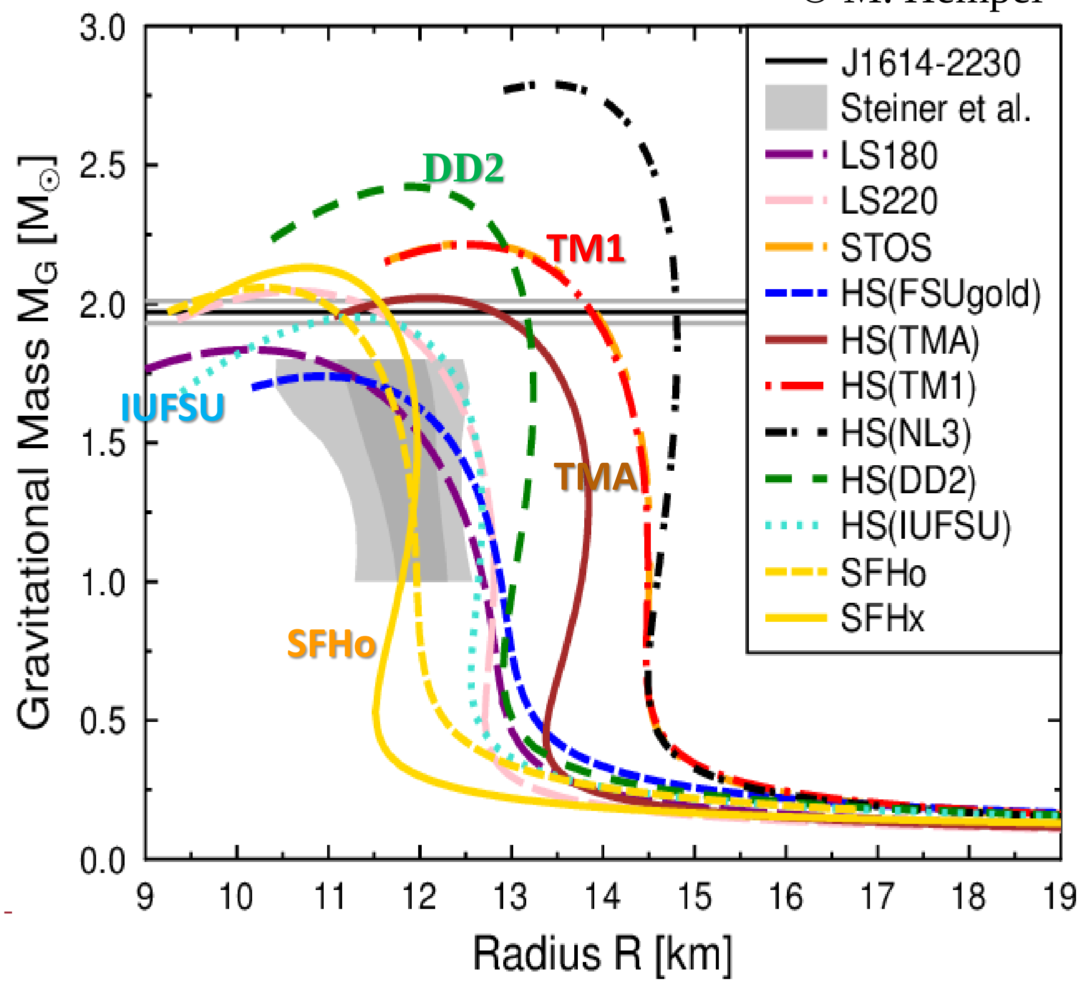
14.5km
- TM1 (Shen EOS)
  - TMA

13.2km
- DD2
  - IUFSU

11.8km
- SFHo

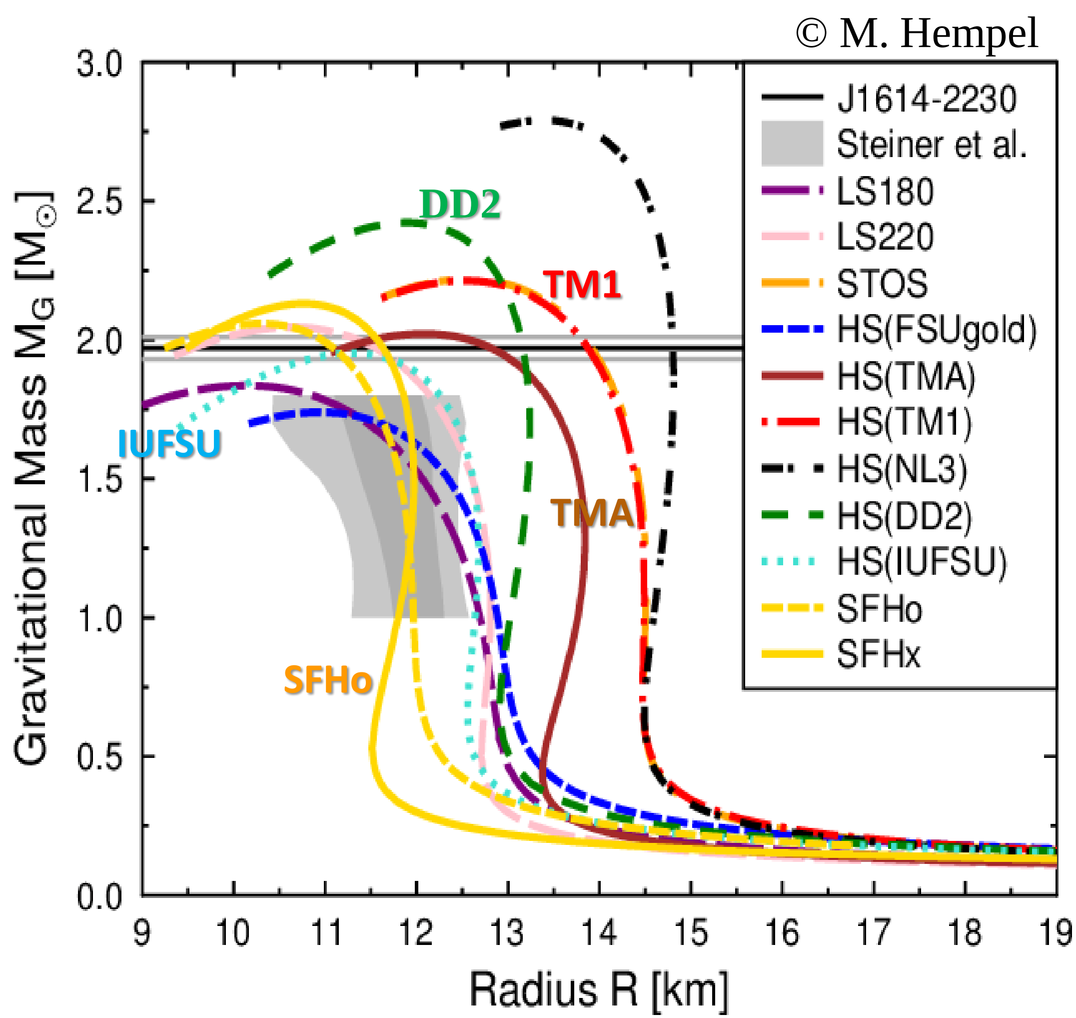
Consistent with
  - NS radius estimation
  - Chiral effective theory

© M. Hempel



(Expected) Mass ejection mechanism & EOS

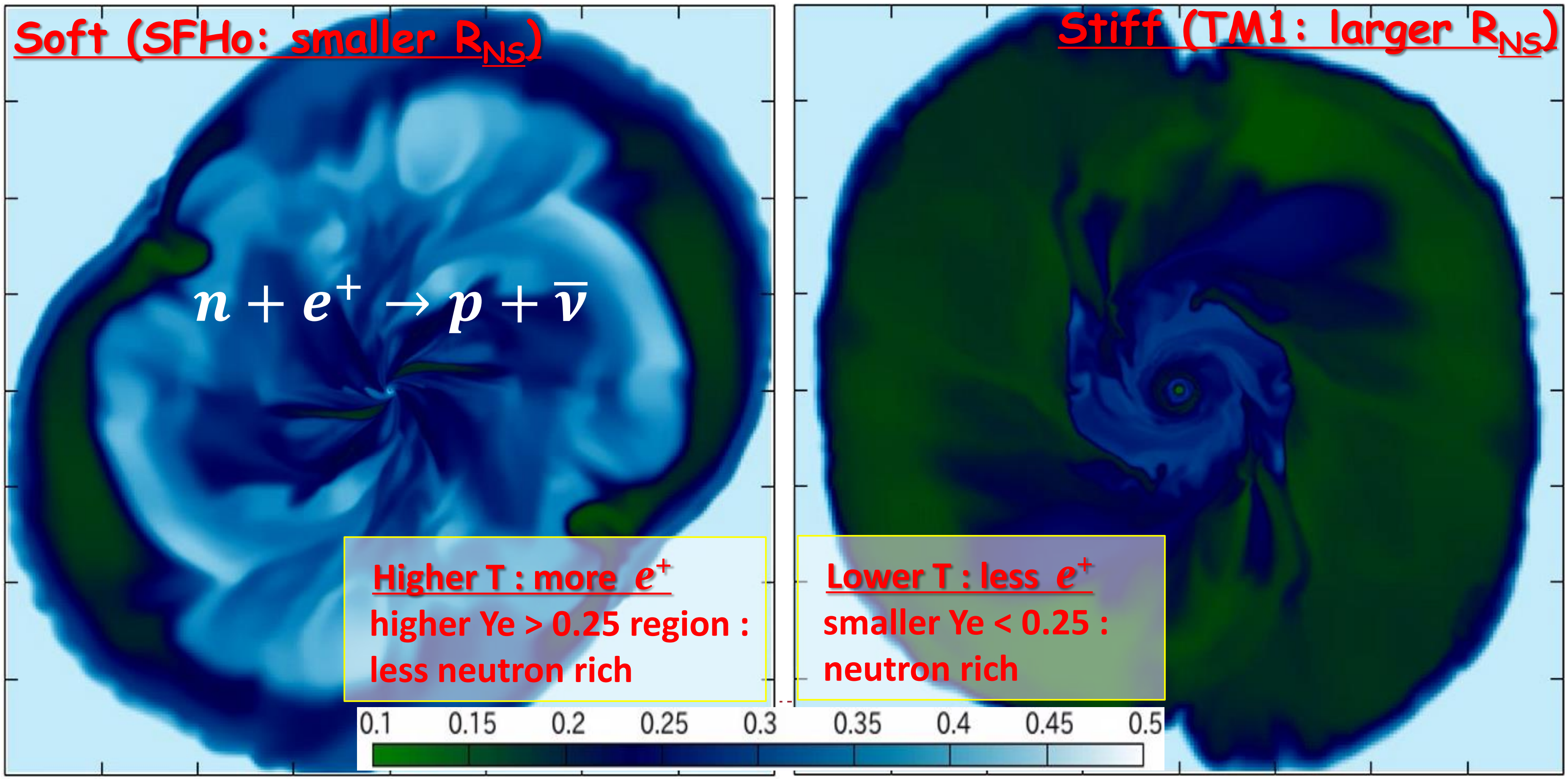
- 'Stiffer EOS'
  - ⇔ R_{NS} : larger
  - **TM1, TMA**
  - Tidal-driven dominant
  - **Ejecta consist of low T & Ye NS matter**
- 'Intermediate EOS'
  - **DD2**
- 'Softer EOS'
  - ⇔ R_{NS} : smaller
  - **SFHo, IUFSU**
  - Tidal-driven less dominant
  - Shock-driven dominant
  - **Ye can change via weak processes**



See also, Bauswein et al. (2013); Just et al. (2014)

Soft(SFHo) vs. Stiff(TM1): Ejecta Ye = 1- Yn

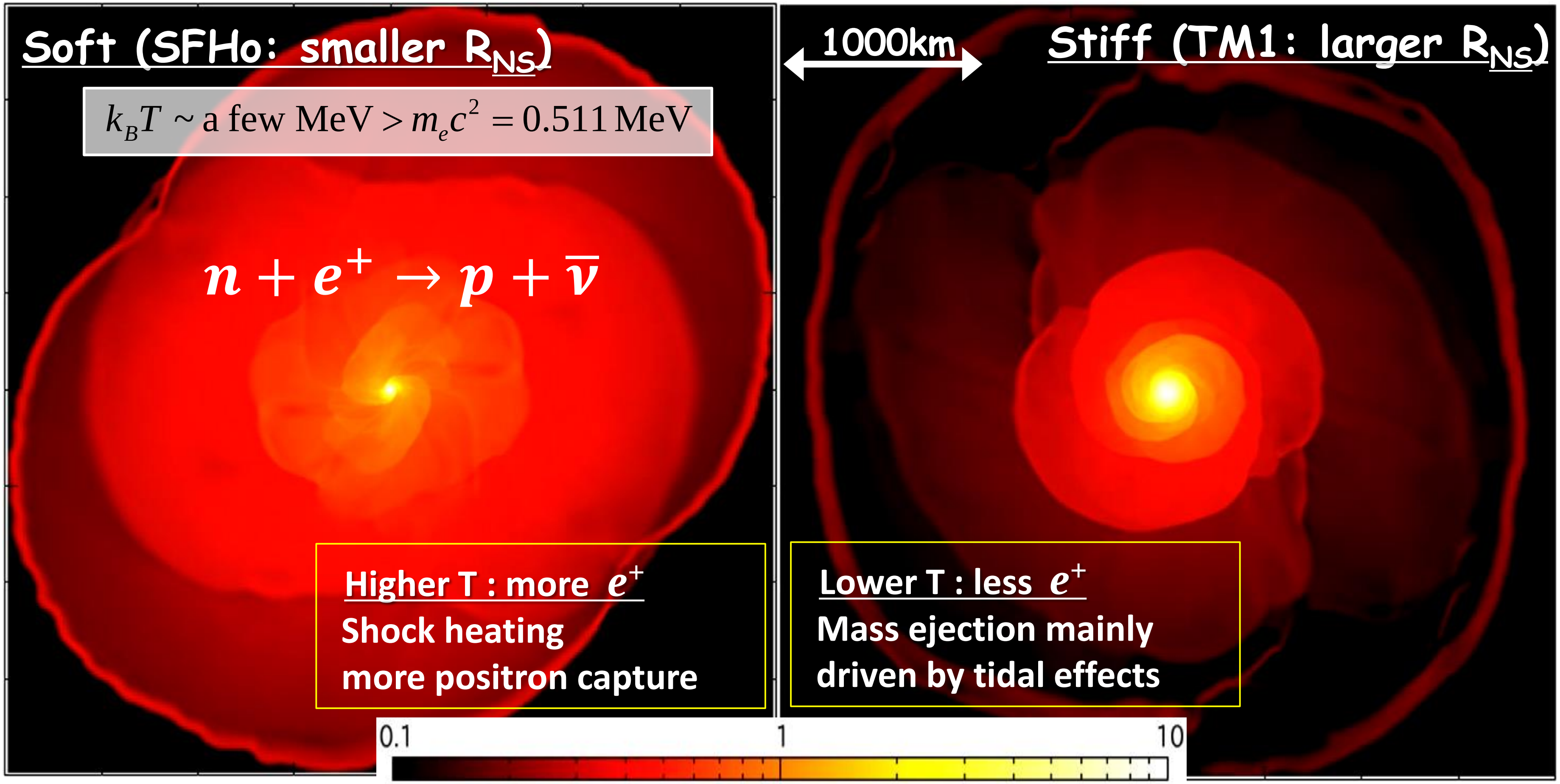
- Soft (SFHo): In the shocked regions, Ye >> 0.2 by weak processes
- Stiff (TM1): Ye is low as < 0.2 (only strong r-process expected)



Sekiguchi et al PRD (2015)

Soft(SFHo) vs. Stiff(TM1): Ejecta temperature

- Soft (SFHo): temperature of unbound ejecta is higher (as 1MeV) due to the shock heating, and produce copious positrons
- Stiff (TM1): temperature is much lower



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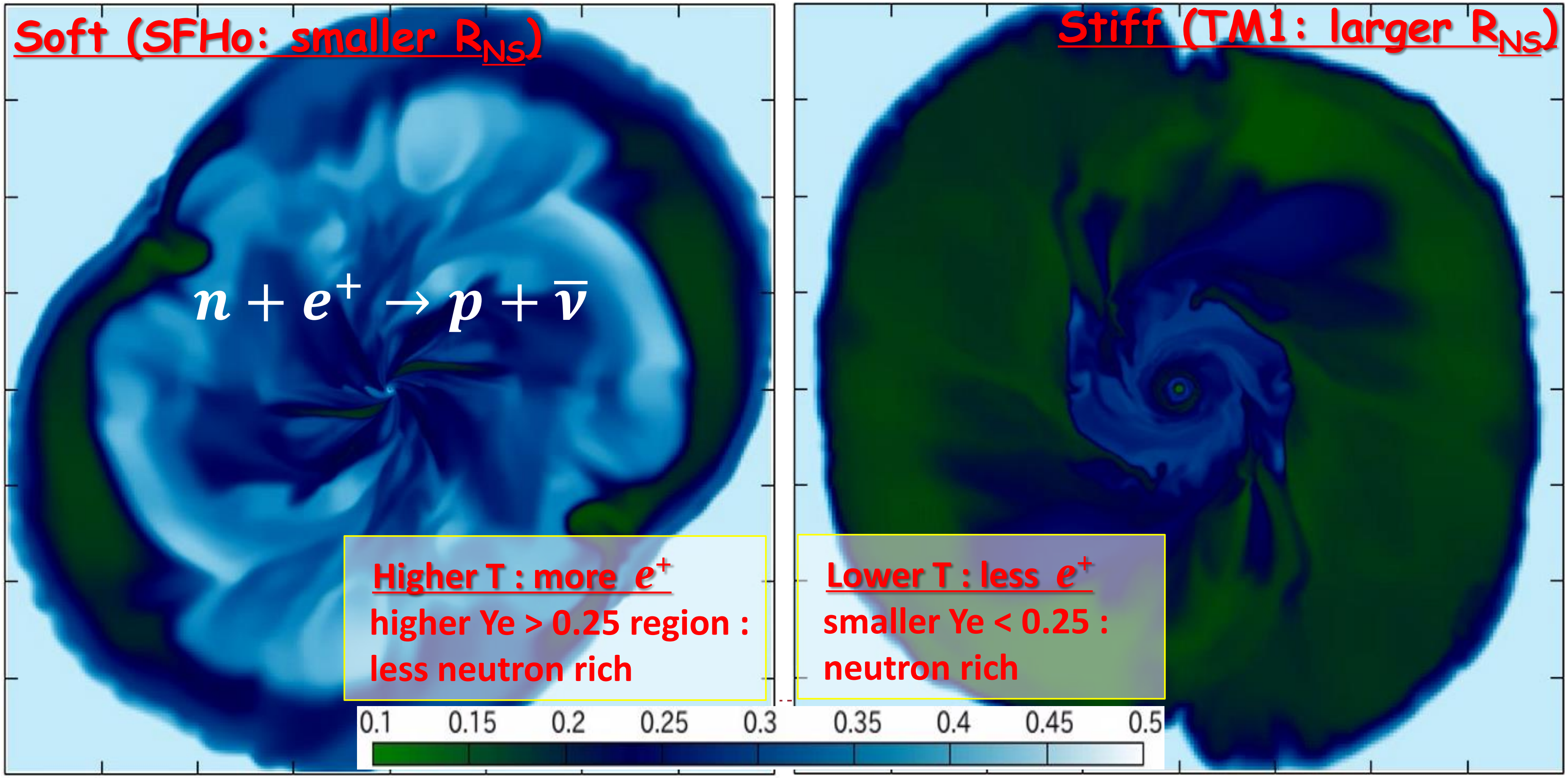
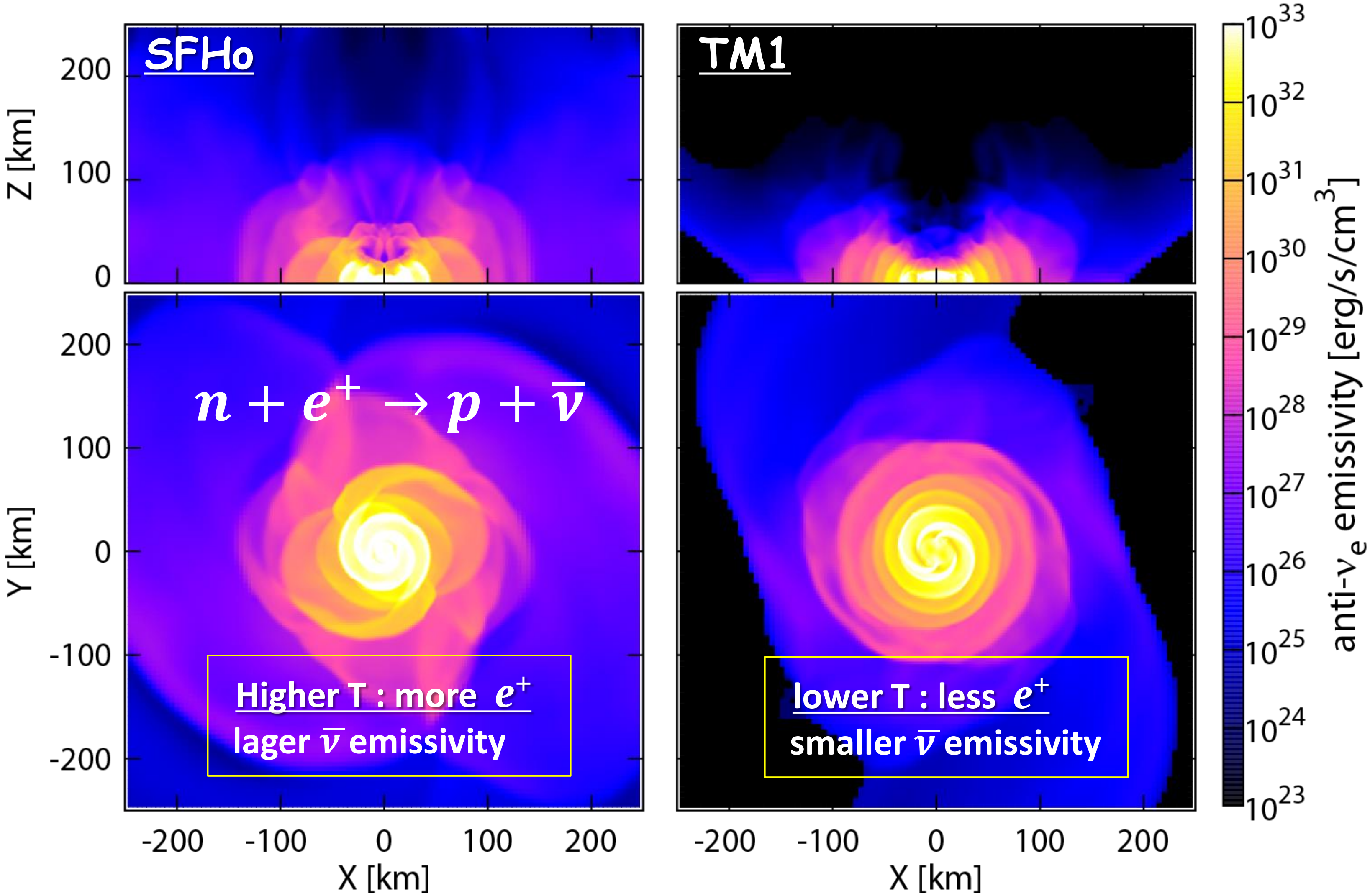
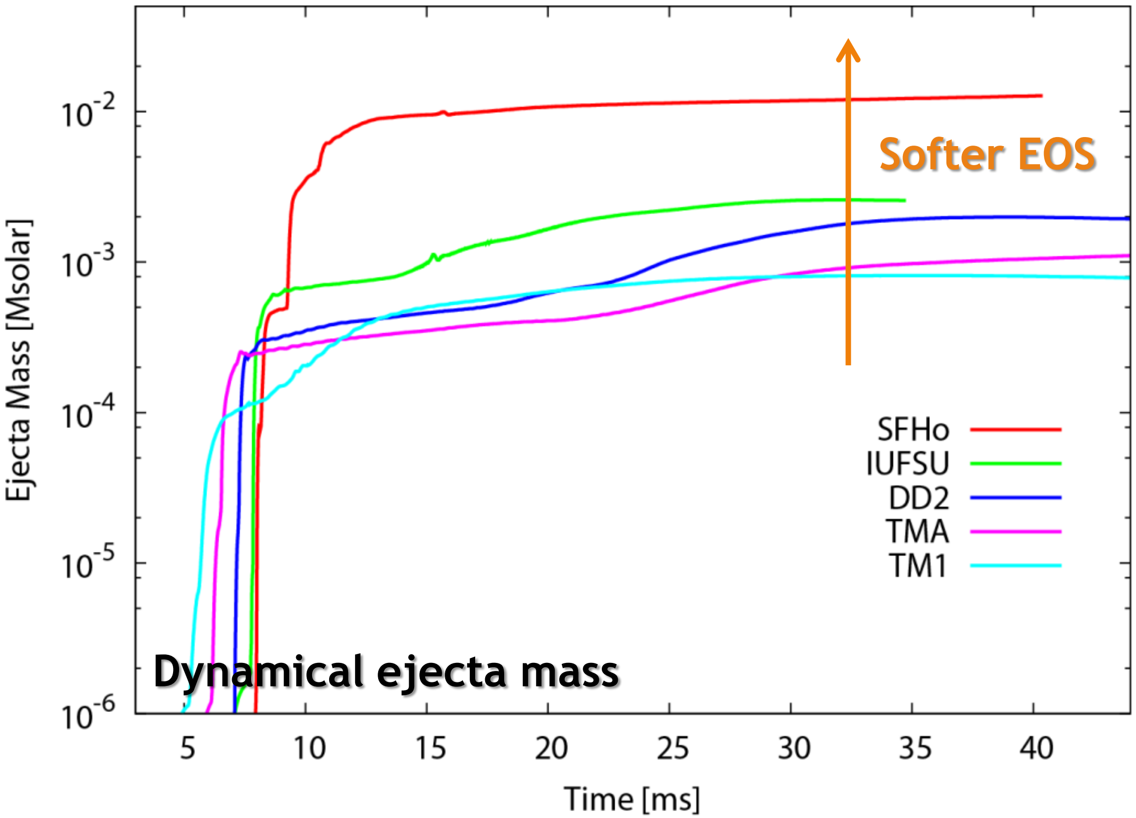


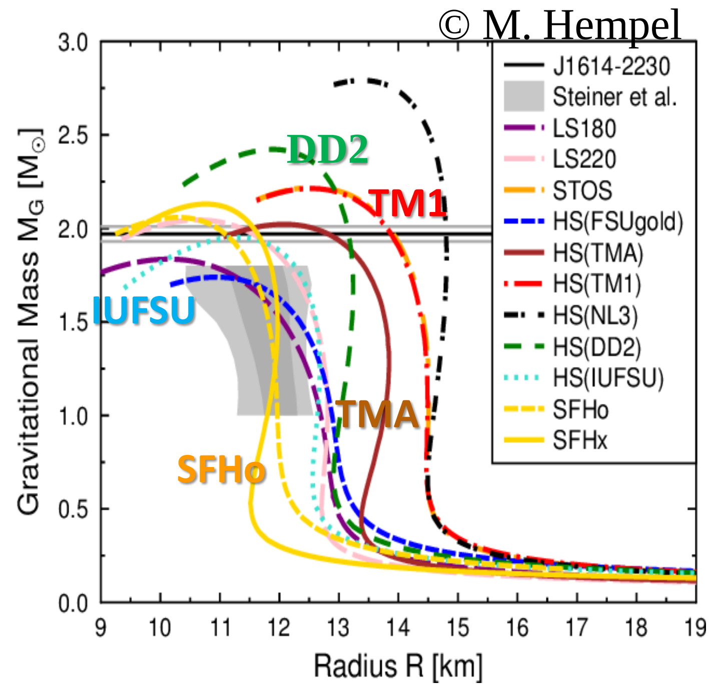
SFHo vs. TM1: $\bar{\nu}_e$ emissivity



Sekiguchi et al PRD (2015)

EOS dependence : 1.35-1.35 NS-NS





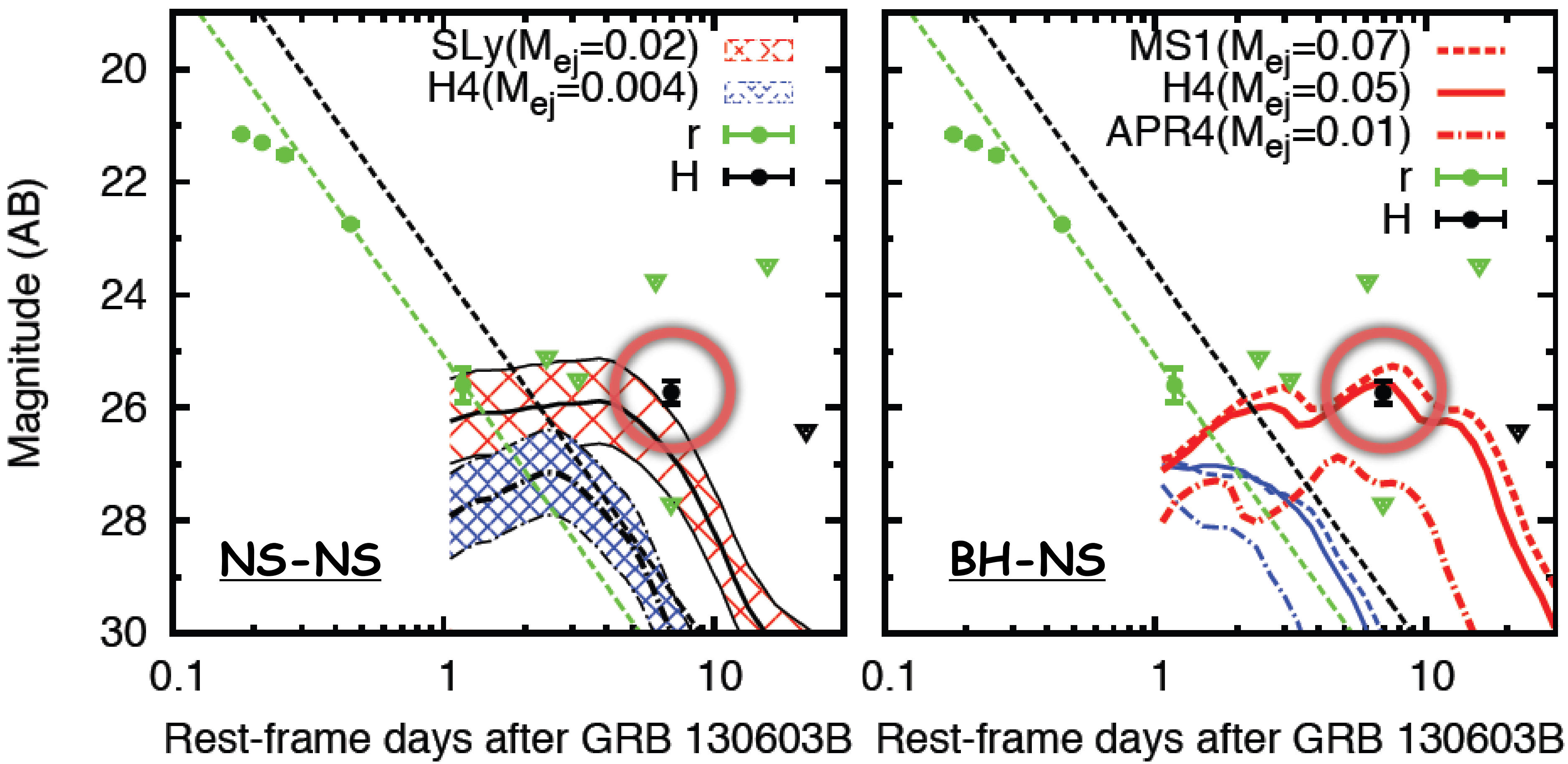
- Mej is larger for softer EOS : importance of shock heating and GR
- **Only SFHo achieves Mej ~ 0.01 Msun :** required by the total amount of r-process elements and flux of the 'kilonova' event (GRB 130603B)

Hotokezaka et al. (2013)
Tanaka et al. (2014)

'Macronova' modeling : NS-NS vs. BH-NS

- Requirement based on Li & Paczynski (1998) : **Mej > 0.01 Msun**

$$L_{\rm peak} \sim 10^{41}\,{\rm erg/s}\left(\frac{f}{10^{-6}}\right)\left(\frac{v}{0.3c}\right)^{1/2}\left(\frac{M}{0.01M_{\rm solar}}\right)^{1/2}\left(\frac{\kappa}{10\,{\rm cm}^2/g}\right)^{-1/2}$$



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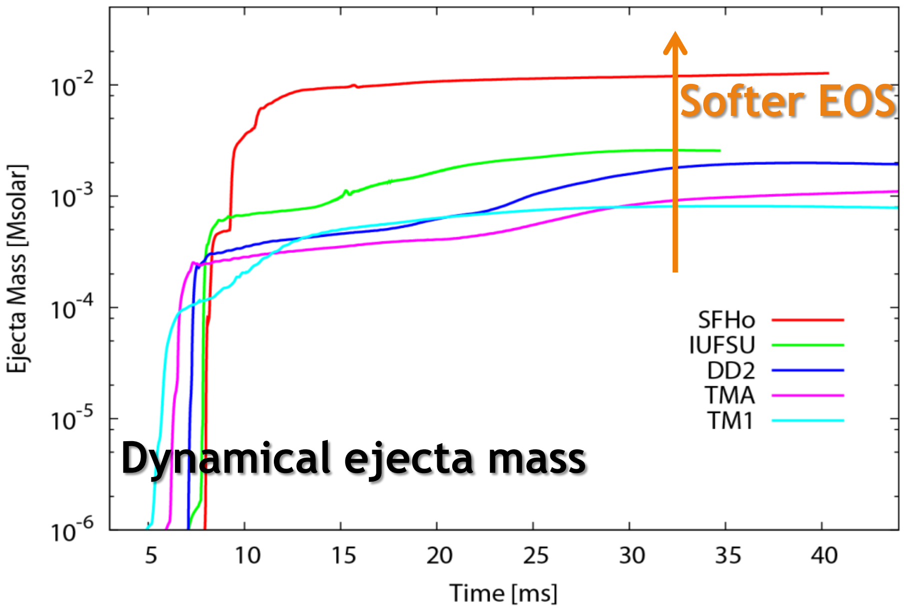
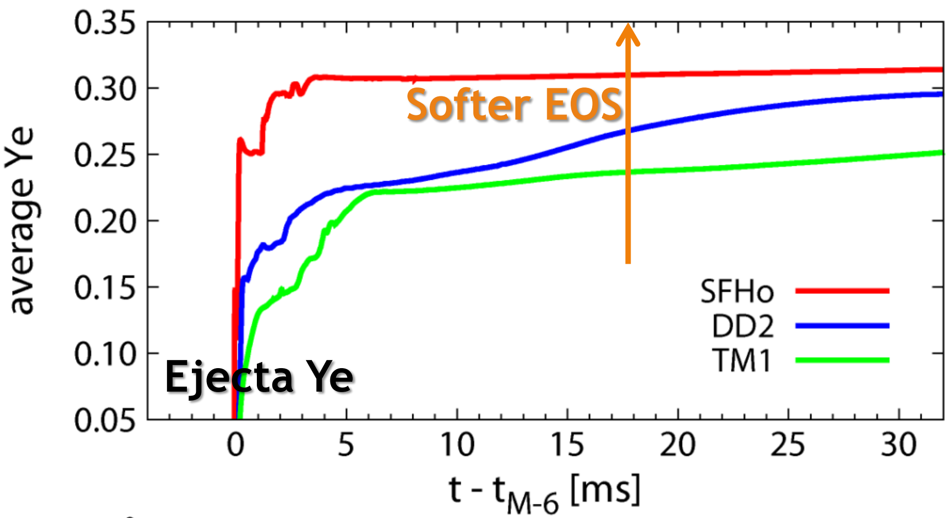
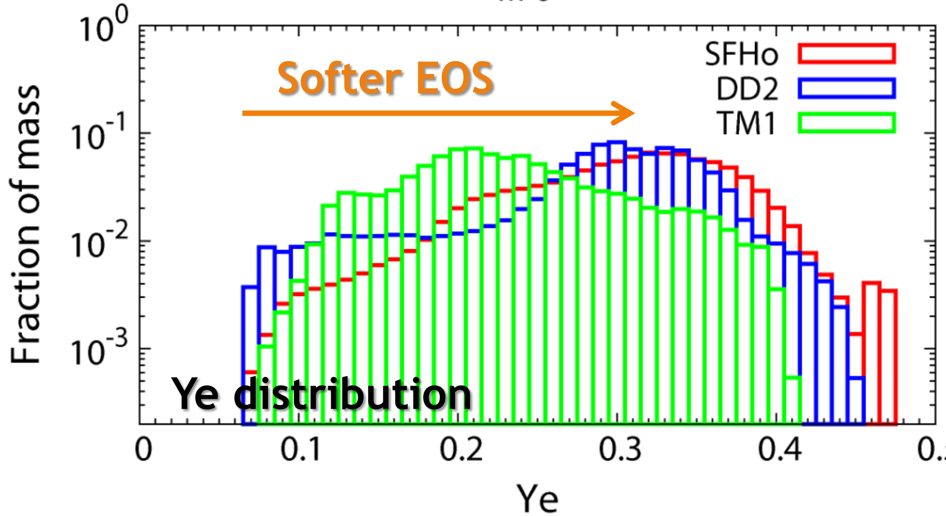




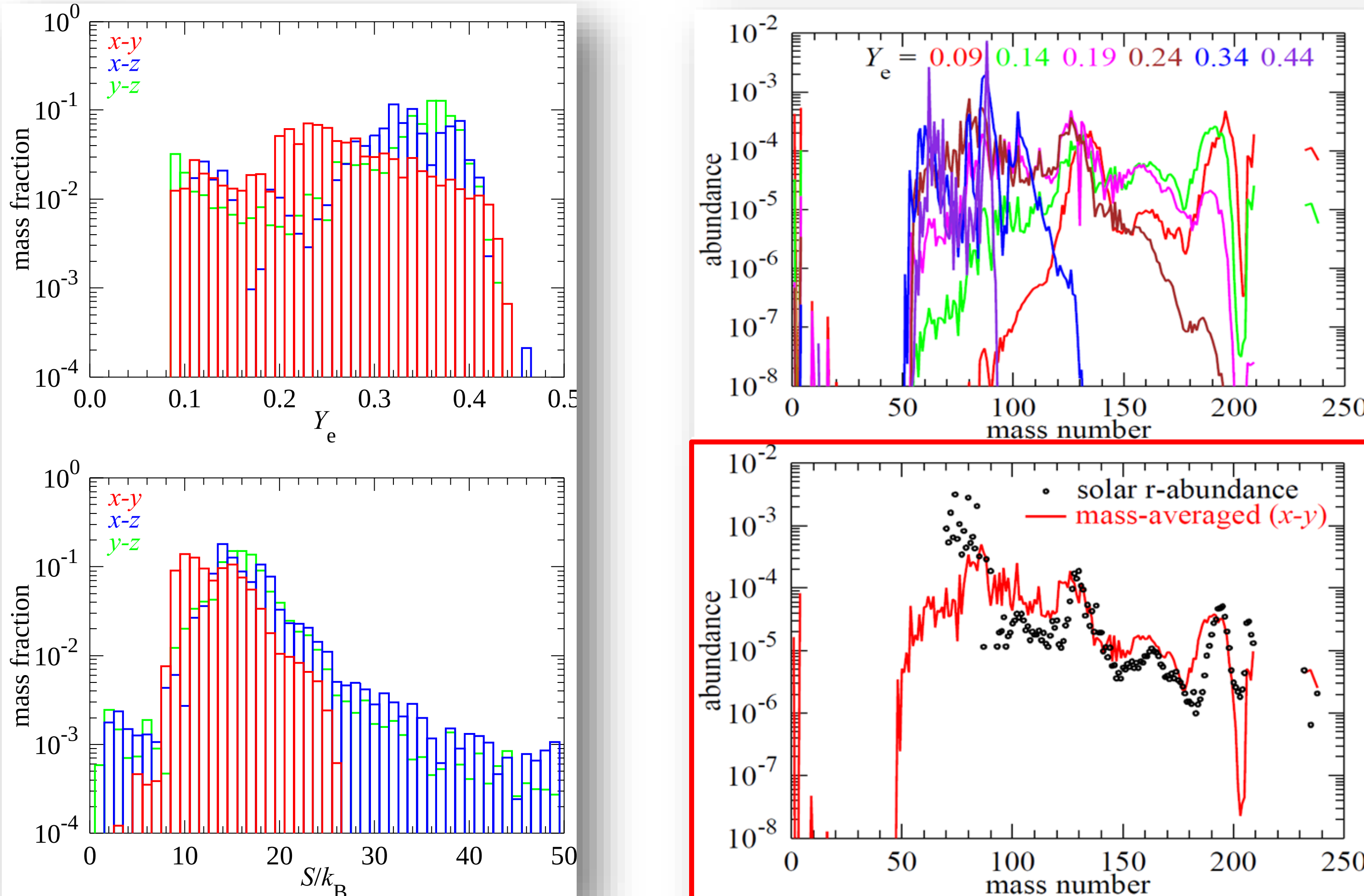


- Mej is larger for softer EOS

  Consistent with piecewise-polytrope studies
- **Only SFHo will give Mej ~ 0.01 Msun**
- a value required by the total amount of r-process elements and flux of the 'kilonova' event (GRB 130603B)

Wanajo, Sekiguchi et al. ApJL (2014)

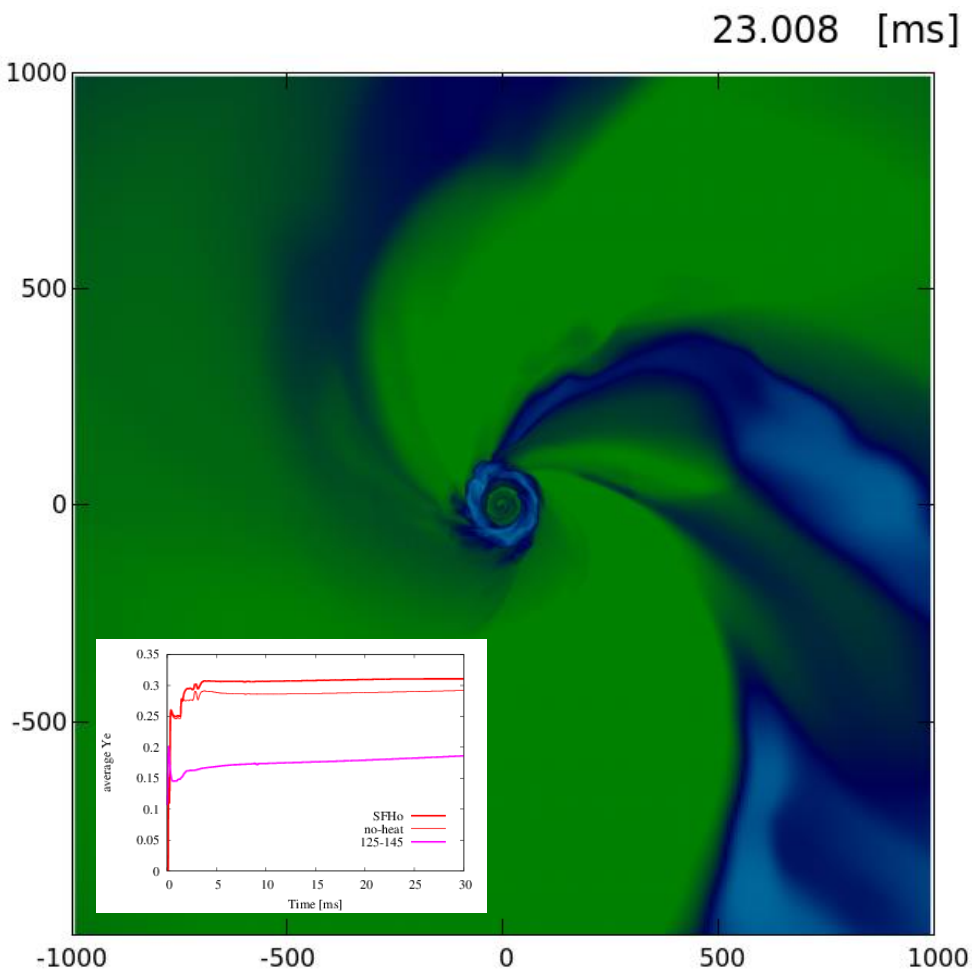
Achievement of the universality
(soft EOS (SFHo), equal mass (1.35-1.35))

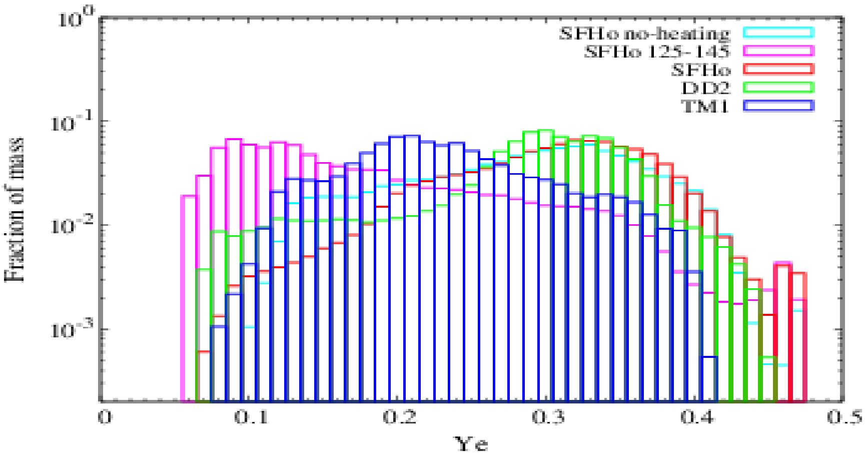


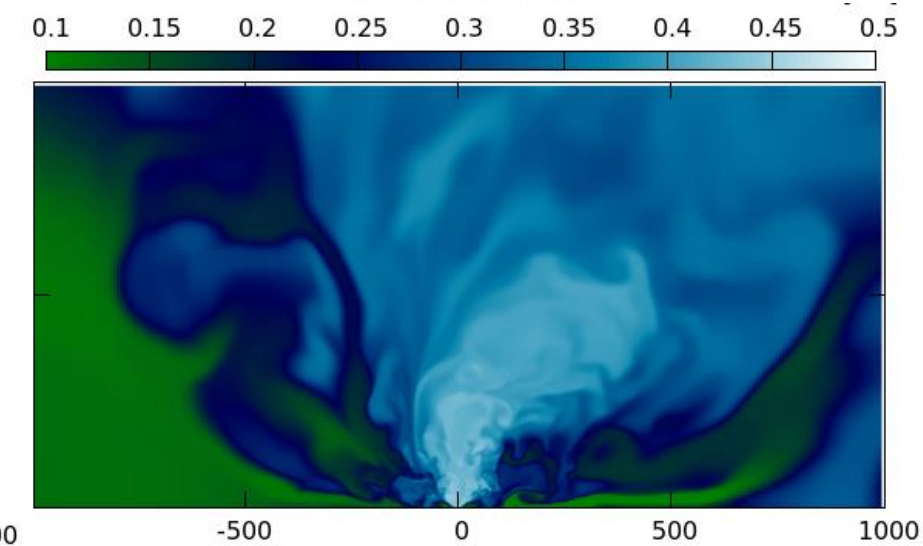
- The Ye-distribution histogram has a broad, flat structure (*Wanajo, Sekiguchi, et al. (2014)*.)
  - Mixture of all Ye gives a good agreement with the solar abundance !
  - Robustness of Universality (dependence on binary parameters)

Unequal mass NS-NS system: SFHo1.25-1.45

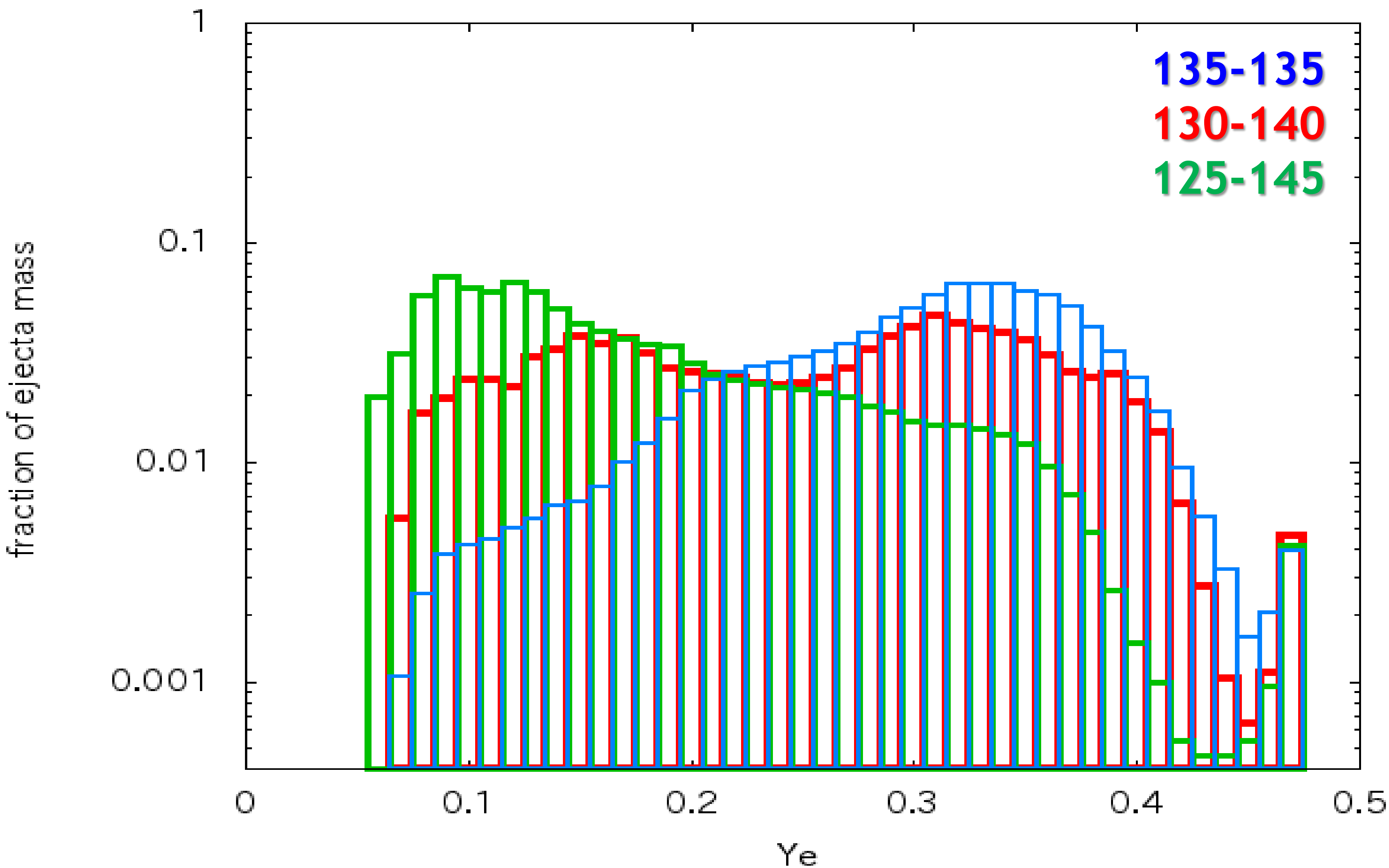
- Orbital plane : Tidal effects play a role, ejecta is neutron rich
- Meridian plane : shock + neutrinos play roles, ejecta less neutron rich



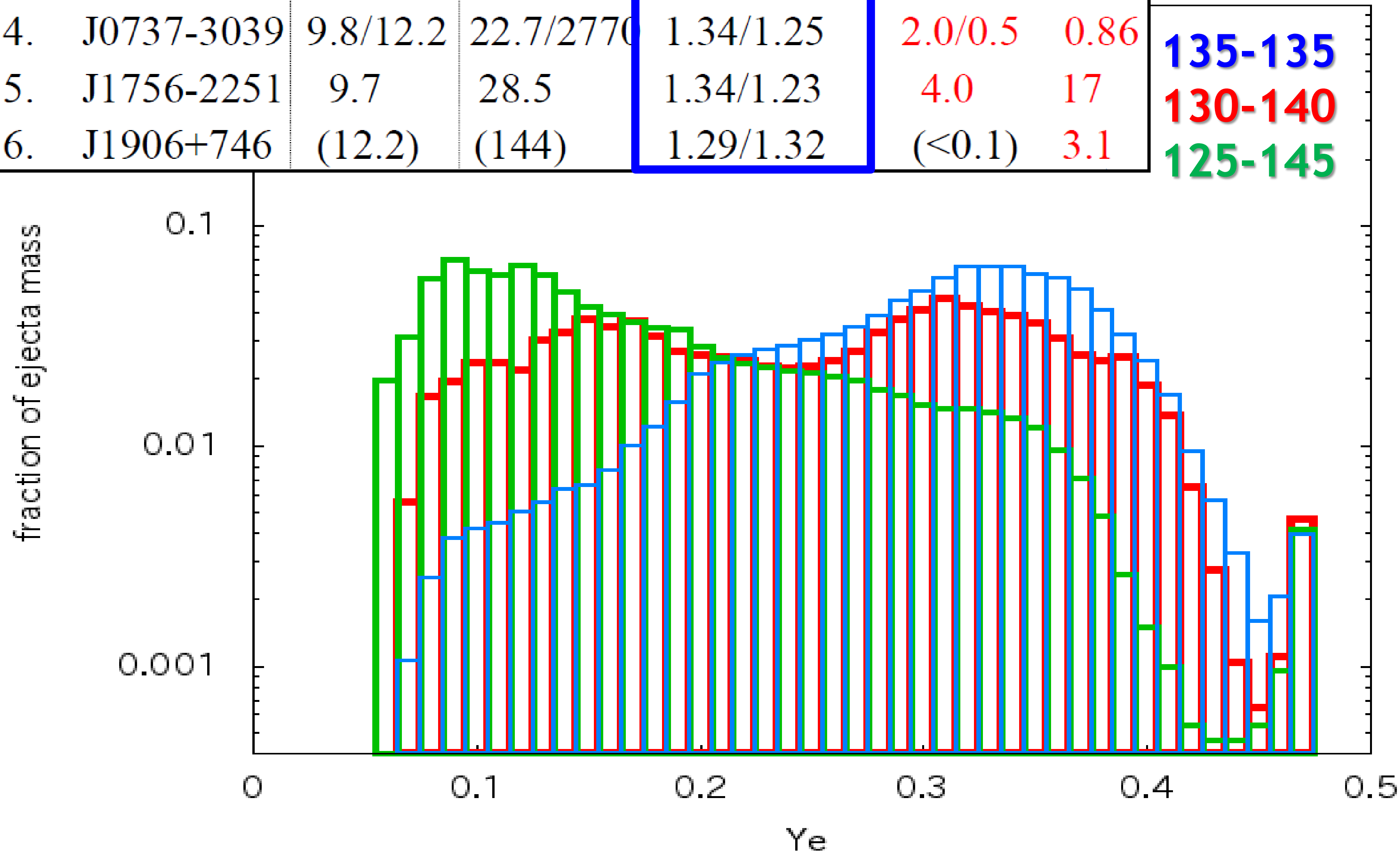




Dependence on binary parameter
for soft EOS (SFHo)

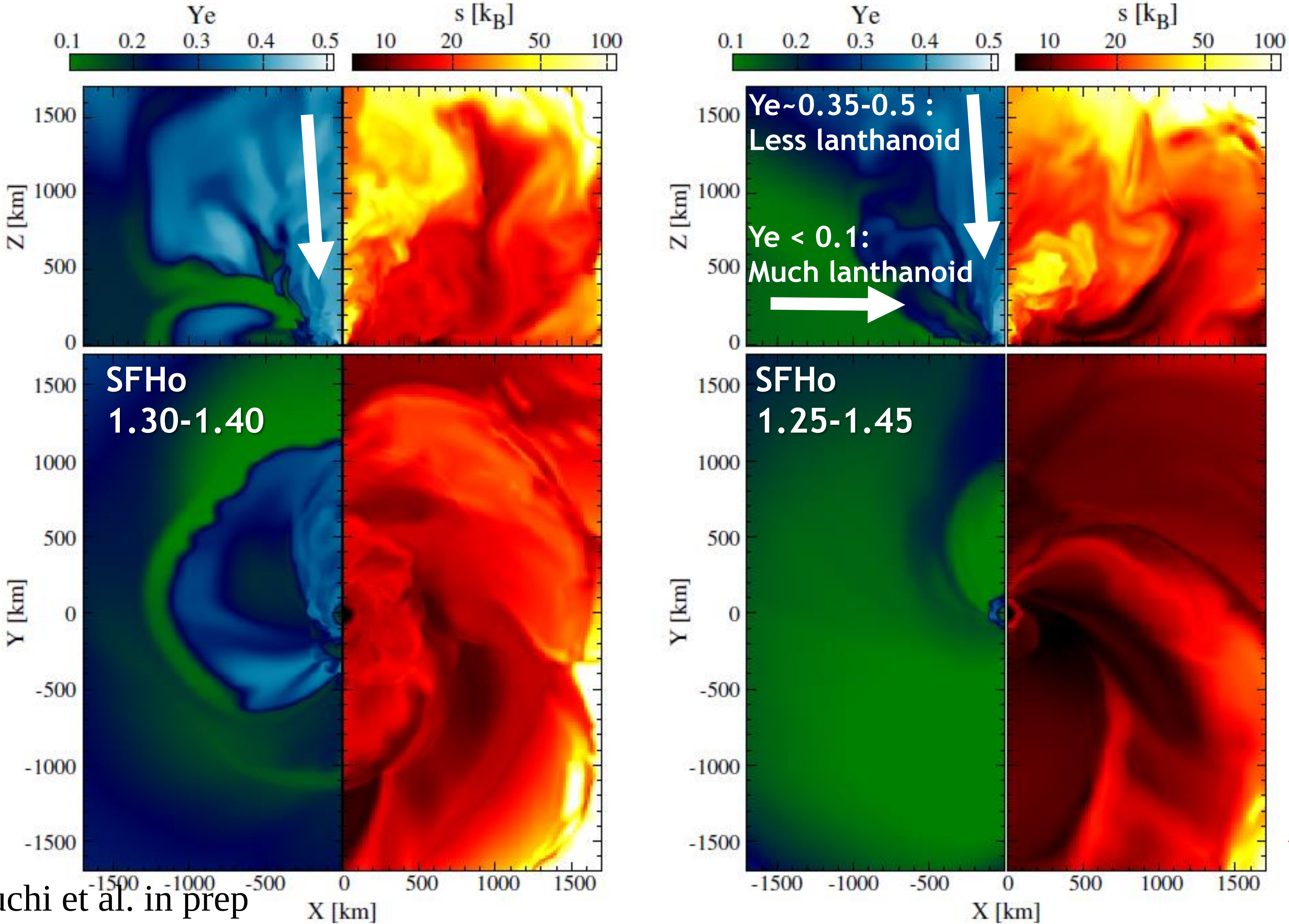


	PSR	log B(G)	$P_{\rm rot}$ (ms)	$M(M_{\rm sun})$	$T_{\rm Mag}$	$T_{\rm GW}$
1.	B1913+16	10.4	59.0	1.441/1.387	1.0	3.0
2.	B1534+12	10.0	37.9	1.333/1.345	2.5	27
3.	B2127+11C	10.7	30.5	1.36/1.35	1.0	2.2
4.	J0737-3039	9.8/12.2	22.7/2770	1.34/1.25	2.0/0.5	0.86
5.	J1756-2251	9.7	28.5	1.34/1.23	4.0	17
6.	J1906+746	(12.2)	(144)	1.29/1.32	(<0.1)	3.1



c.f. Kasen et al. 2014

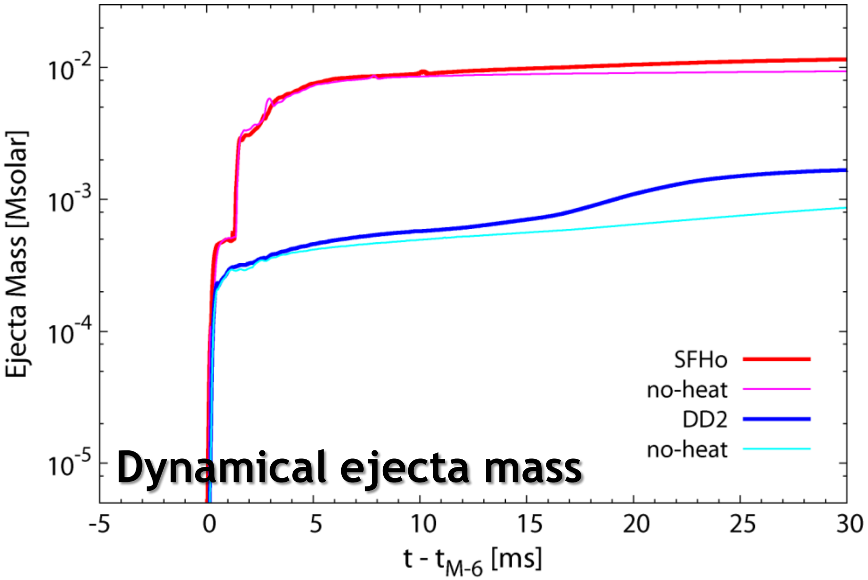
Direction dependence ?

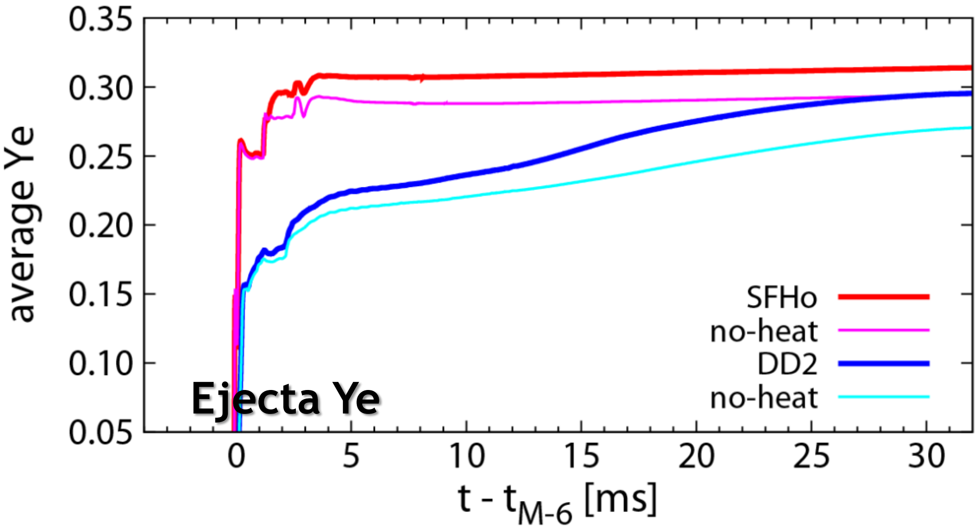


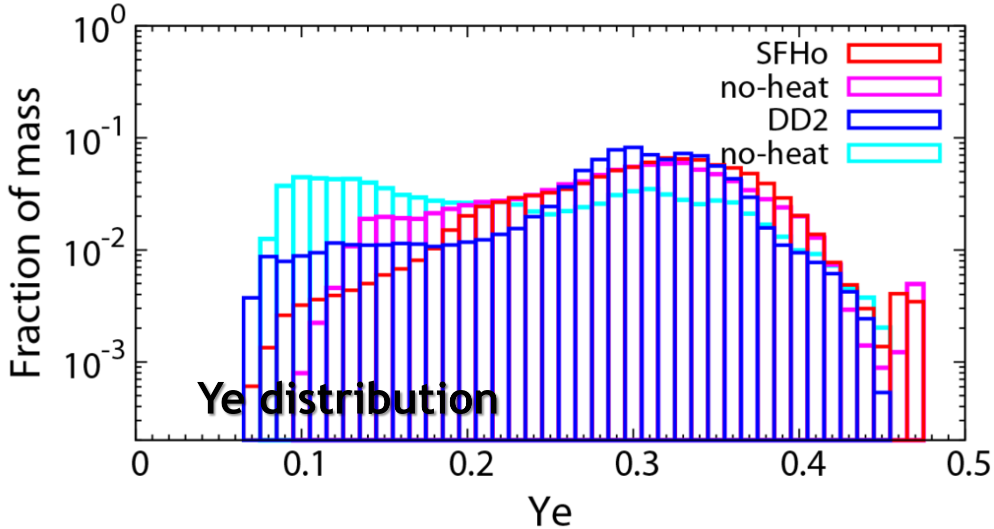
Sekiguchi et al. in prep

Sekiguchi et al PRD (2015); Prego et al. (2014); Just et al. (2014); Goriely et al. (2015); Martin et al. (2015)

Importance of neutrino heating (absorption)

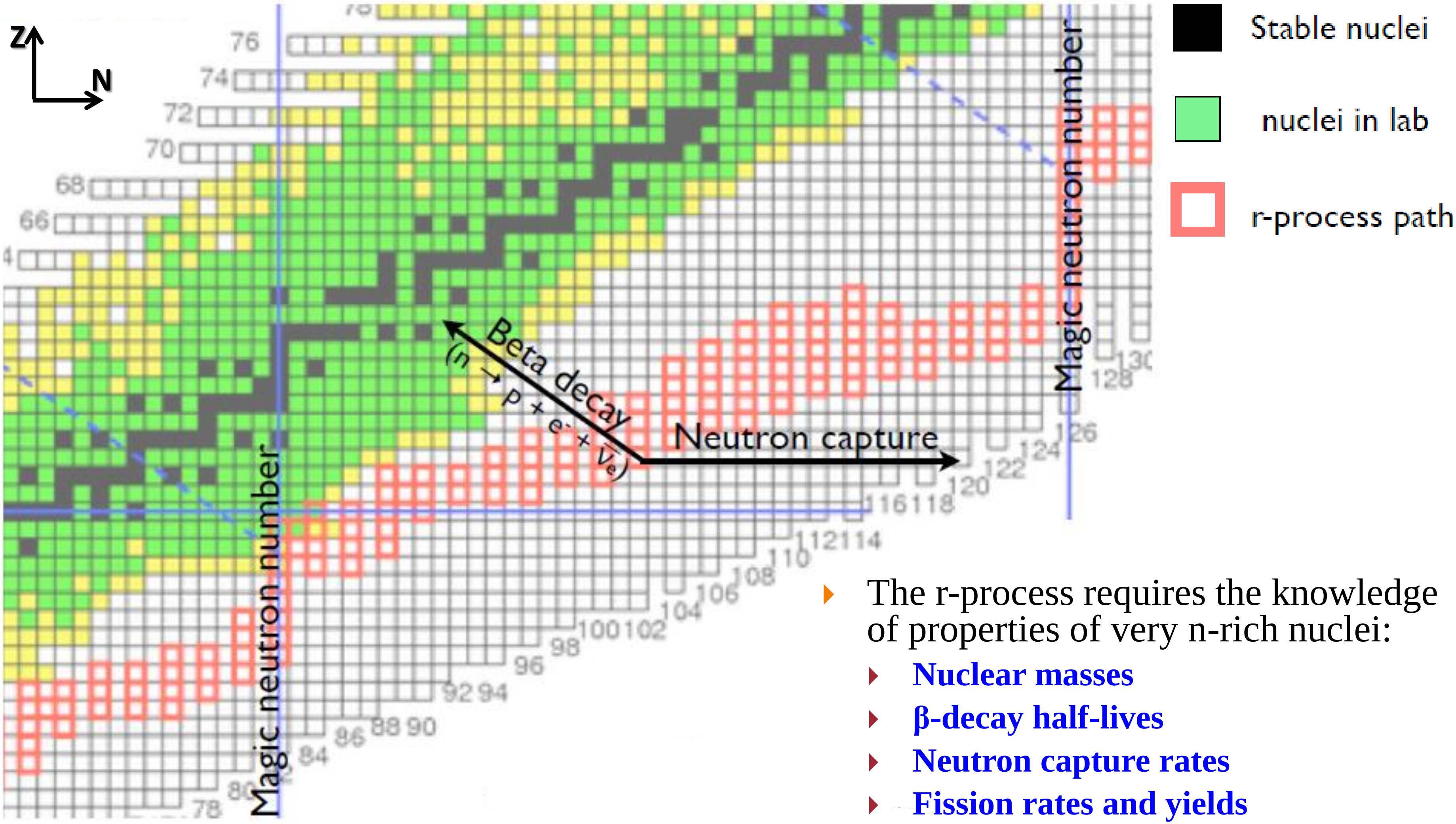






- Amount of ejecta mass can be increased order of 10^{-3} Msun
- Average Ye can change 0.02~0.03 depending on EOS : effect is stronger for stiffer EOS where HMNS survive in a longer time

r-process nucleosynthesis: nuclear physics inputs



- The r-process requires the knowledge of properties of very n-rich nuclei:
  - **Nuclear masses**
  - **β-decay half-lives**
  - **Neutron capture rates**
  - **Fission rates and yields**

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Global mass models vs. Experiments

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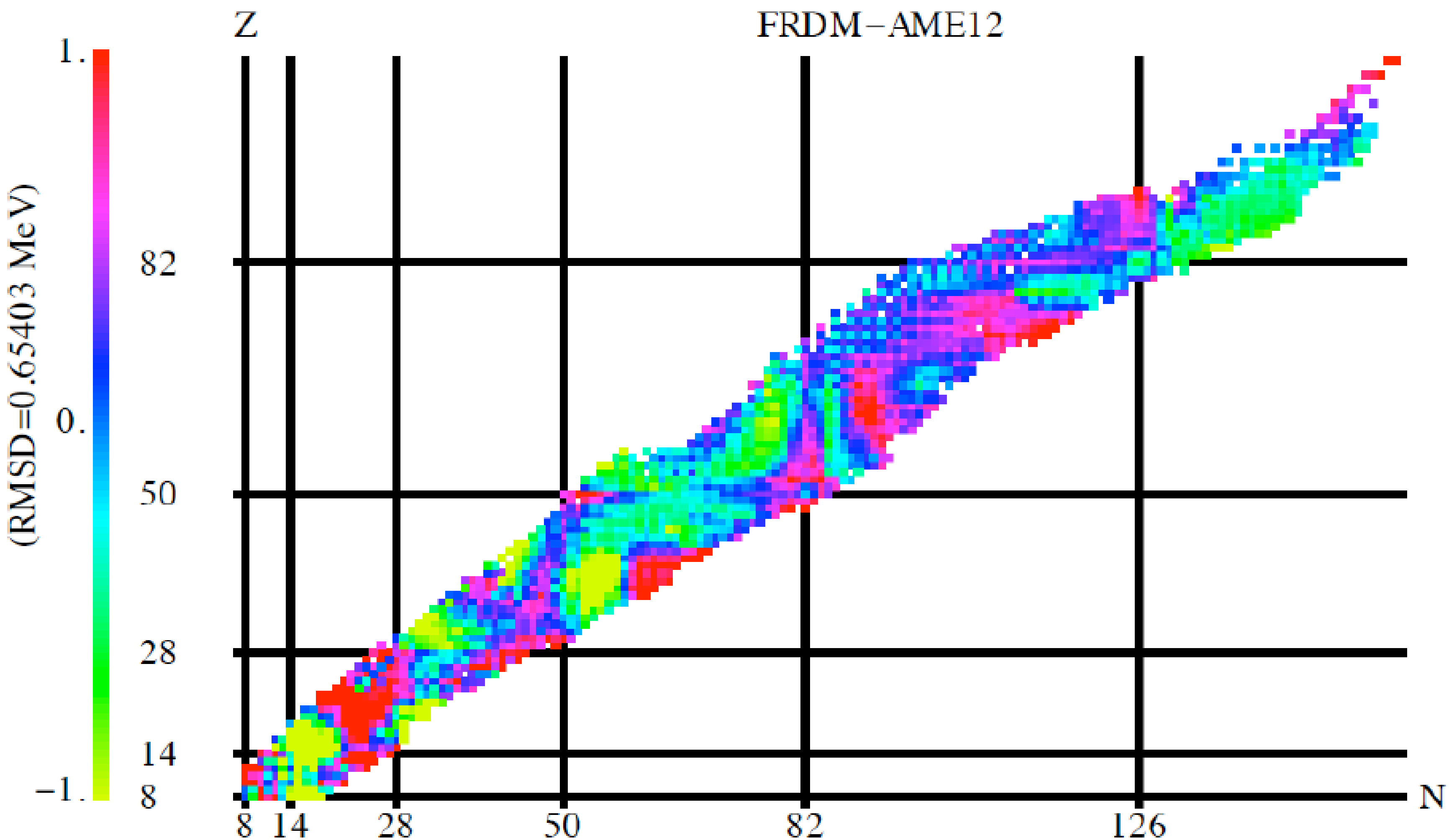

Dependence on mass model

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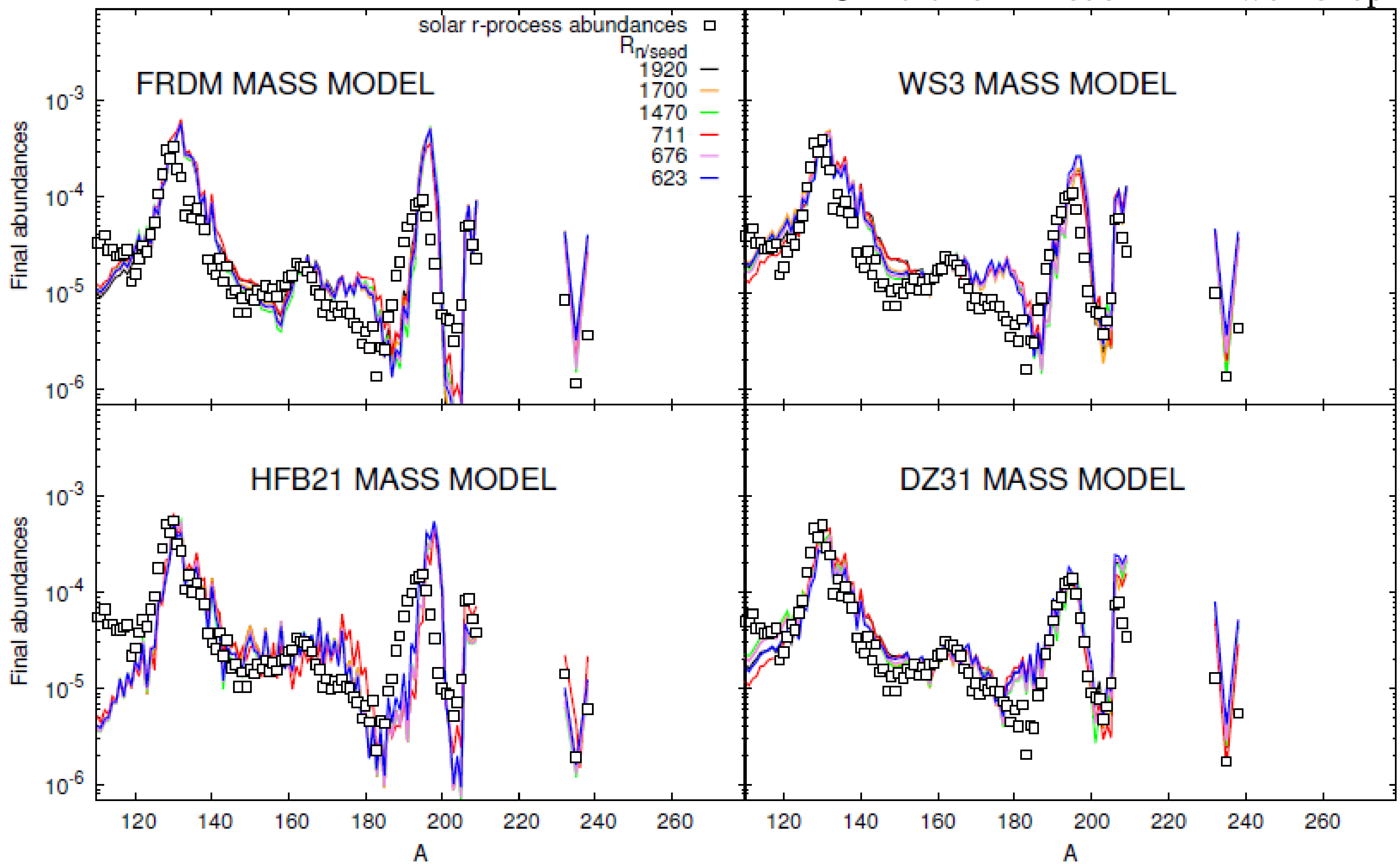

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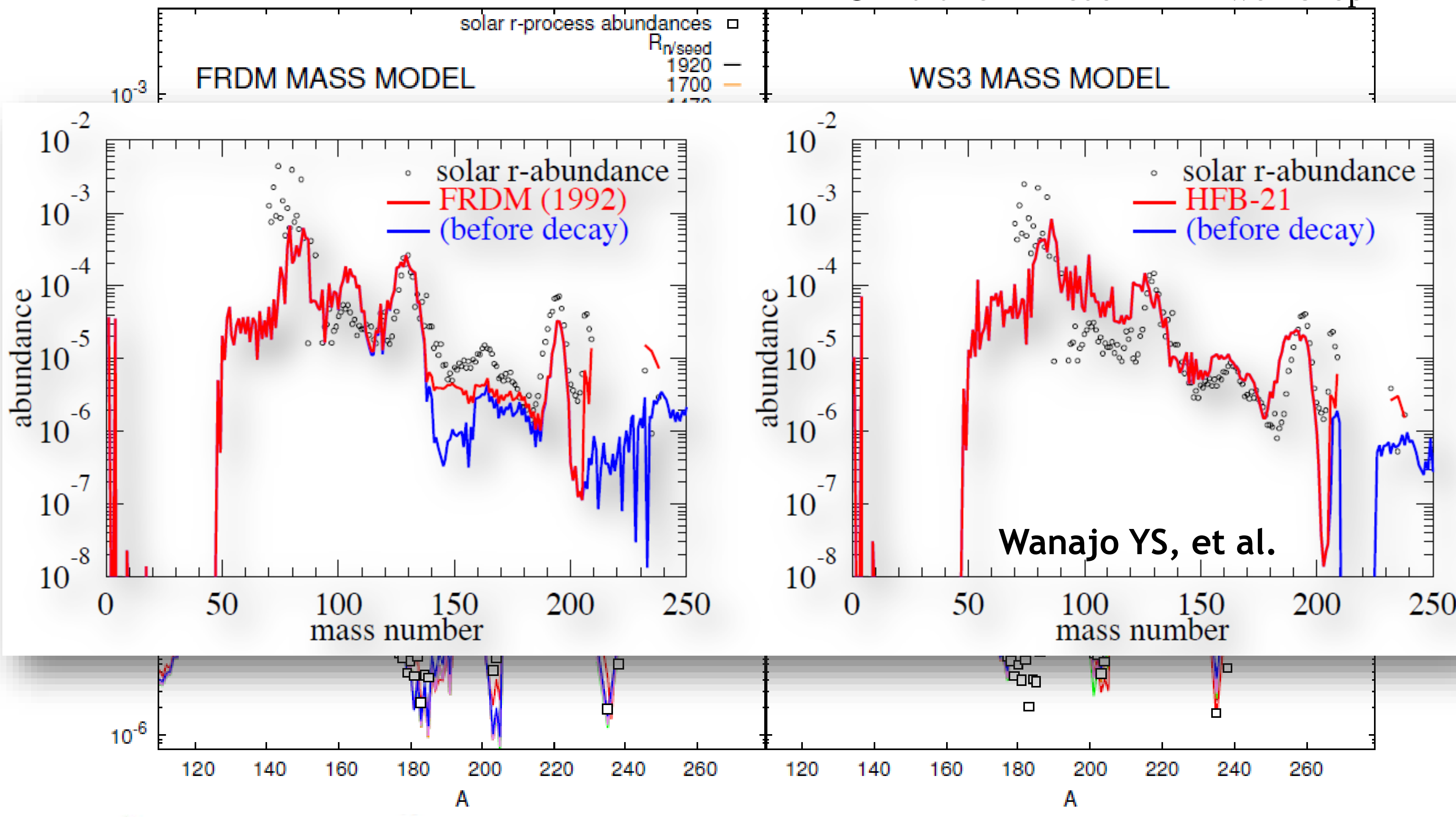
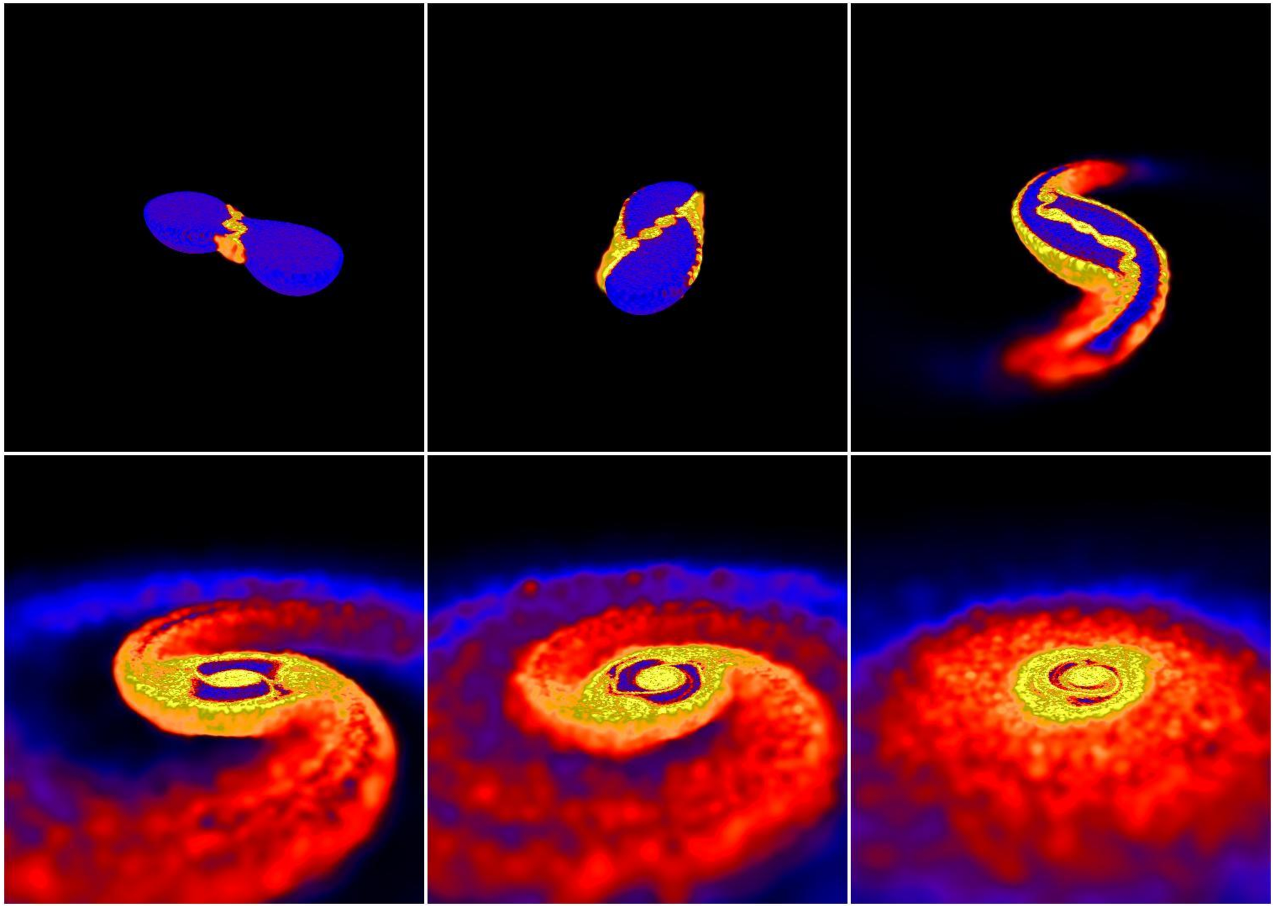


Short summary of lecture II

- BNS merger as the origin of r-process nuclei
  - Requirement : should satisfy the 'universality'
    - Due to stronger shock in GR, temperature increases and weak interactions set in => neutron richness modified
    - Wide distribution of ejecta Ye => universality can be satisfied
    - How large are the effects of nuclear inputs uncertainty ?
  - To explain total amount of solar r-process elements
    - Mej ~ O(0.01) is necessary
    - Only 'soft' EOS (Rns ~< 12km) like SFHo (APR, SLy) satisfy this requirement
      - Interestingly, Mej > 0.01 is also required by the 'kilonova' event
      - could be interpreted as a suggestion that NS EOS is relatively soft ?

Further evidence ?
Jet collimation problem in Short GRB

- Jet collimation in SGRBs has been a long-standing problem
  - No matter above the pole region in previous Newtonian simulations



Simulation by Rosswog

Further evidence ?
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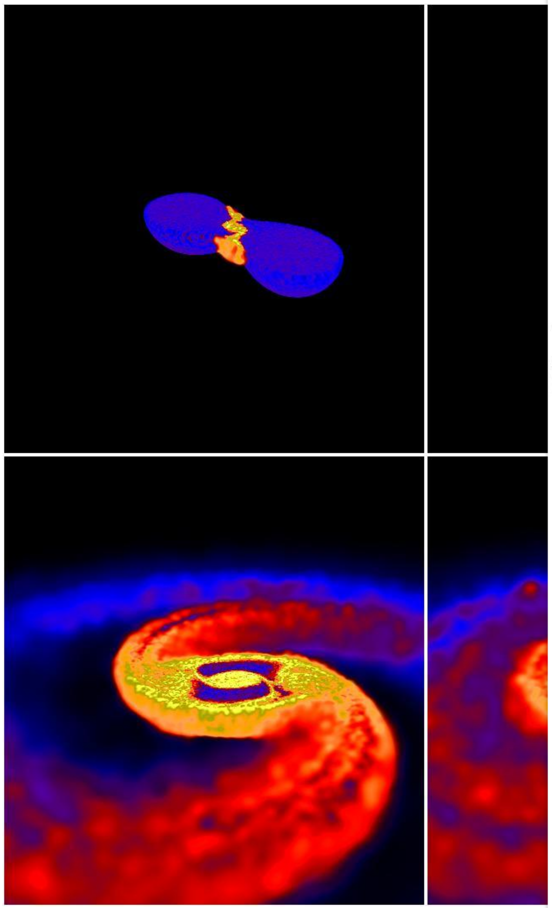
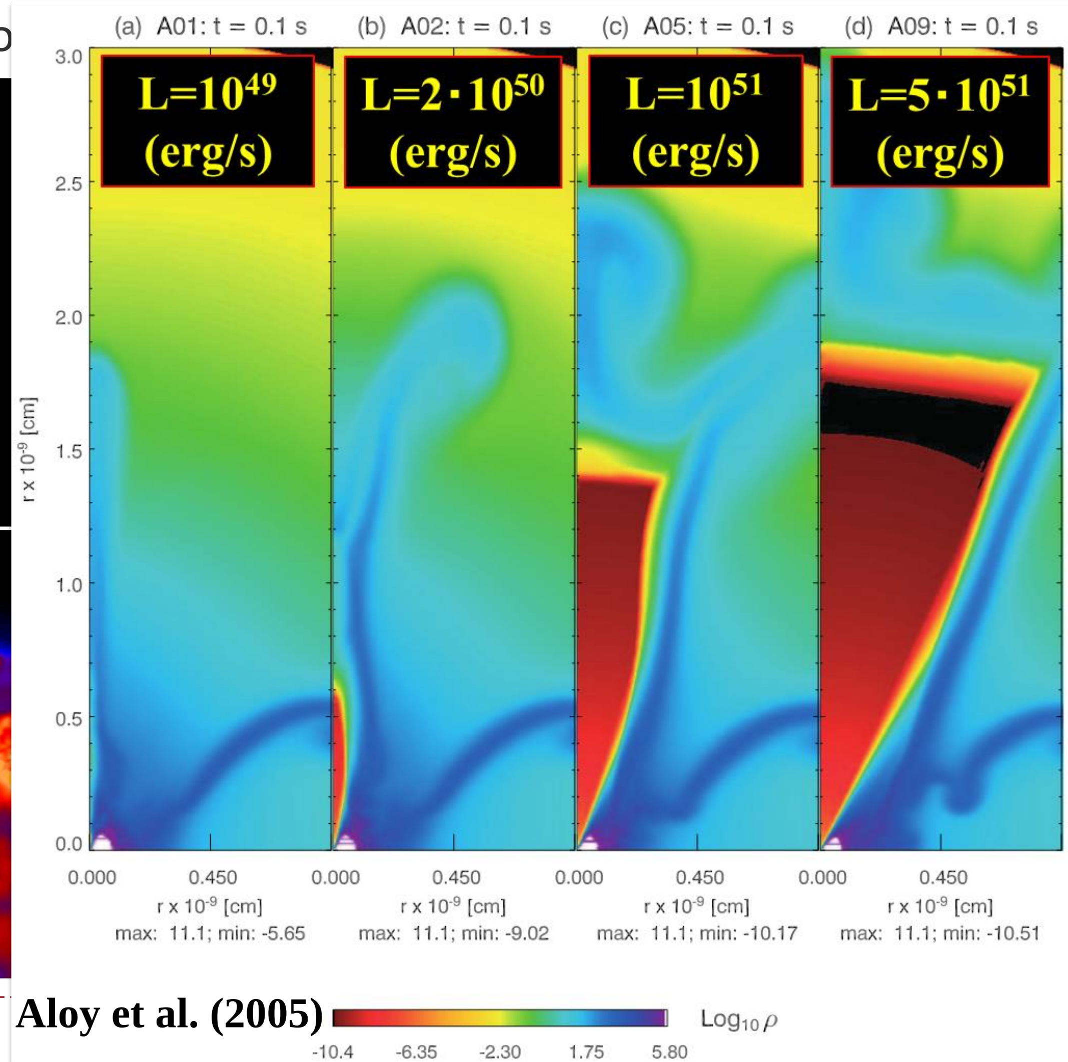
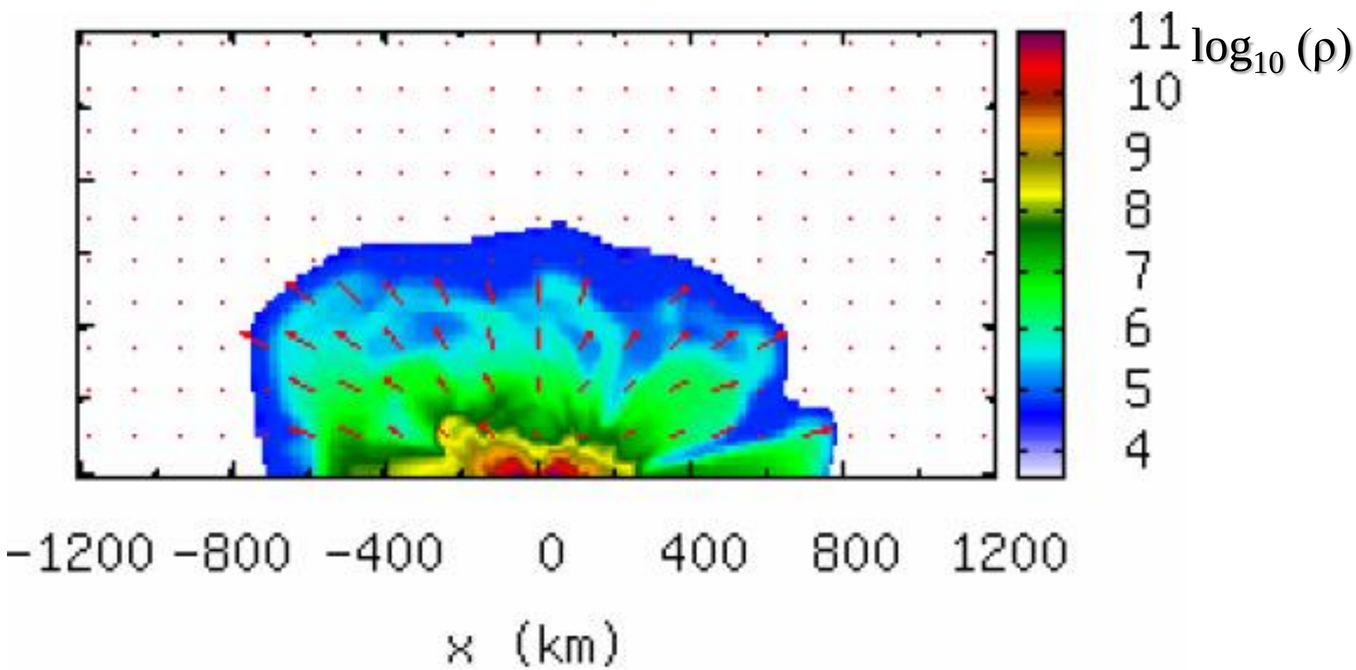




Further evidence ?
Jet collimation problem in Short GRB

- Jet collimation in SGRBs has been a long-standing problem
  - No matter above the pole region in previous Newtonian simulations
- Latest NR simulations of NS-NS clarified that there is quasi-isotropic mass ejection driven by shocks (e.g., Hotokezaka et al. 2013; Bauswein et al. 2013)
  - Jet collimation may be achieved



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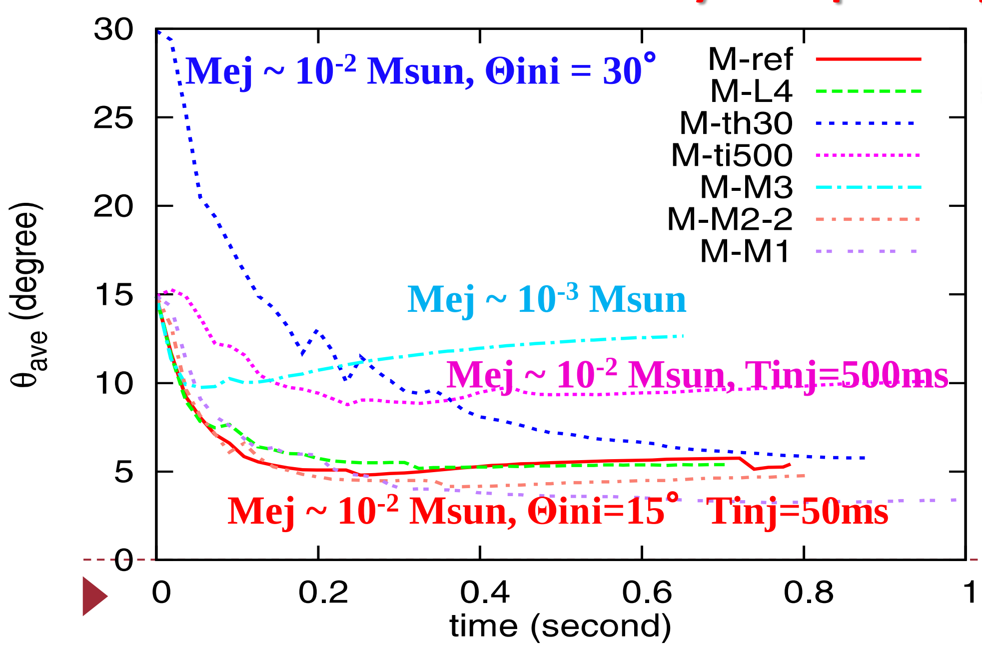
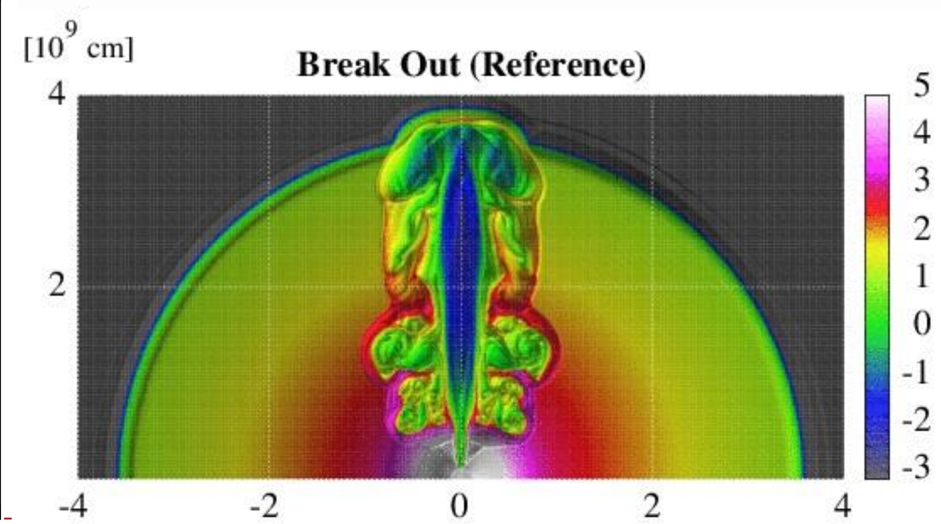
- Jet collimation in SGRBs has been a long-standing problem
  - No matter above the pole region in previous Newtonian simulations
- Latest NR simulations of NS-NS clarified that there is quasi-isotropic mass ejection driven by shocks ⇒ Jet collimation may be achieved
- How much mass is necessary ? Jet simulation with parameters of observed energetics and duration of GRB130603B (Nagakura et al. (2014))
  - **~ 0.01 Msun is necessary to explain Θjet of GRB130603B (macronova candidate)**





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      - Interestingly, Mej > 0.01 is also required by the 'kilonova' event
      - could be interpreted as a suggestion that NS EOS is relatively soft ?
  - <u>Additional support from jet collimation problem in SGRB</u>