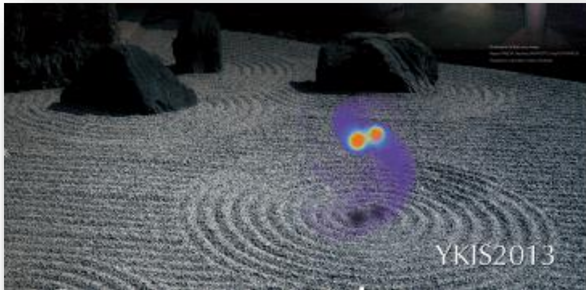
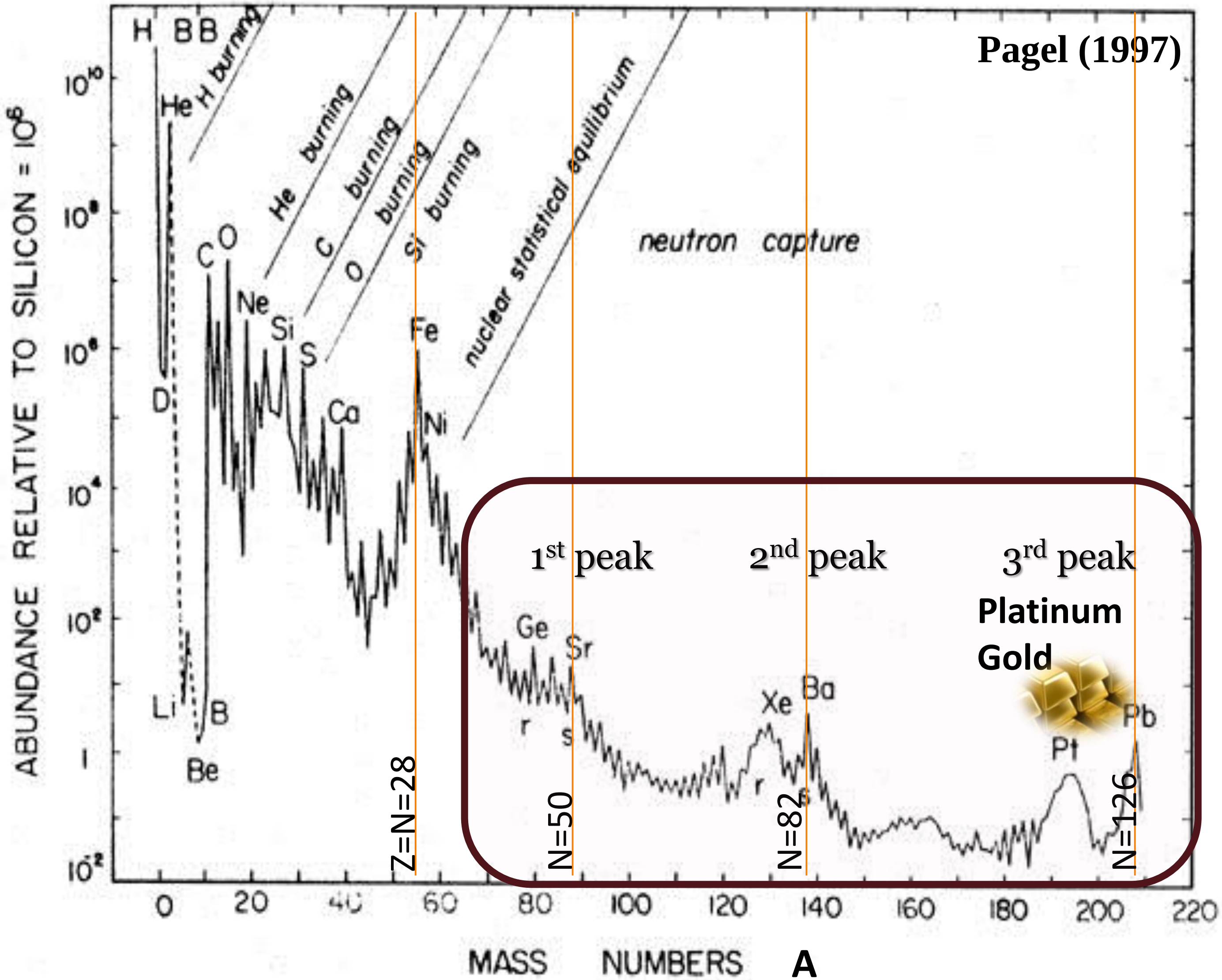


Binary neutron star merger and **r-process**

Yuichiro Sekiguchi（Toho Univ.）

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

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

n-capture versus **β-decay**

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

$\tau_n < \tau_\beta$

rapid neutron-capture process

(r-process)

large neutron densities

- Can synthesize all heavy nuclei

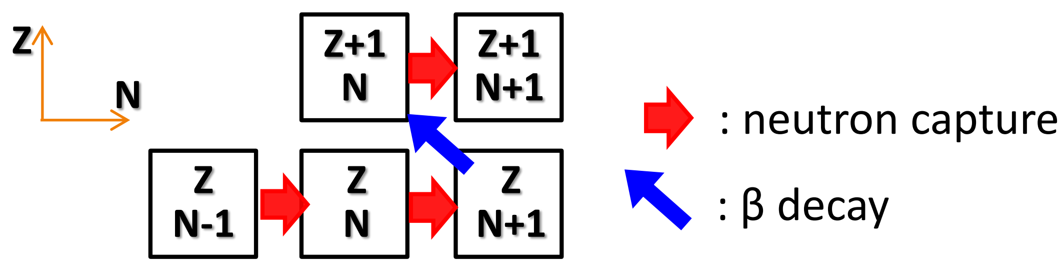
$\tau_n > \tau_\beta$

slow neutron-capture process

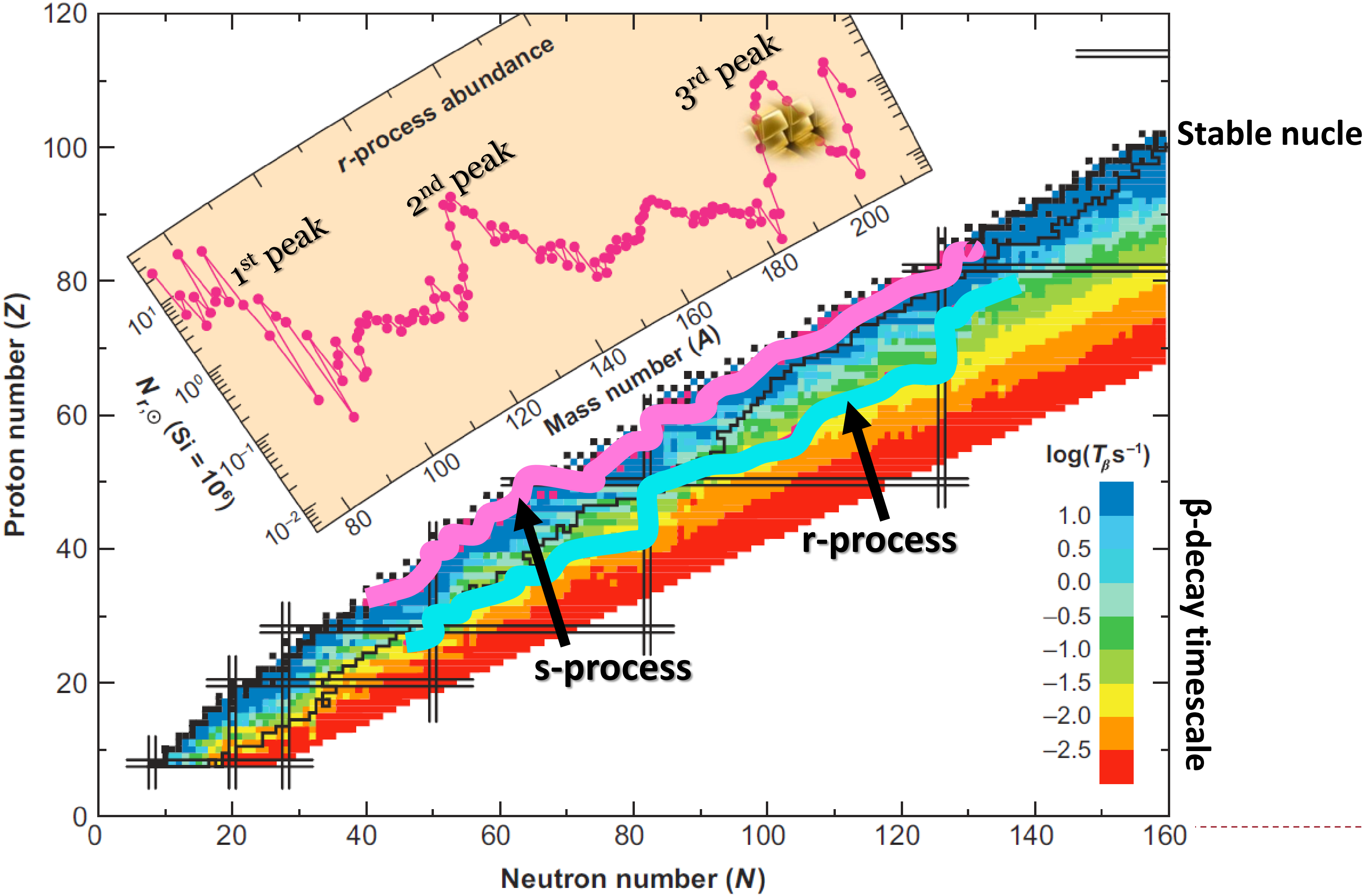
(s-process)

moderate neutron densities

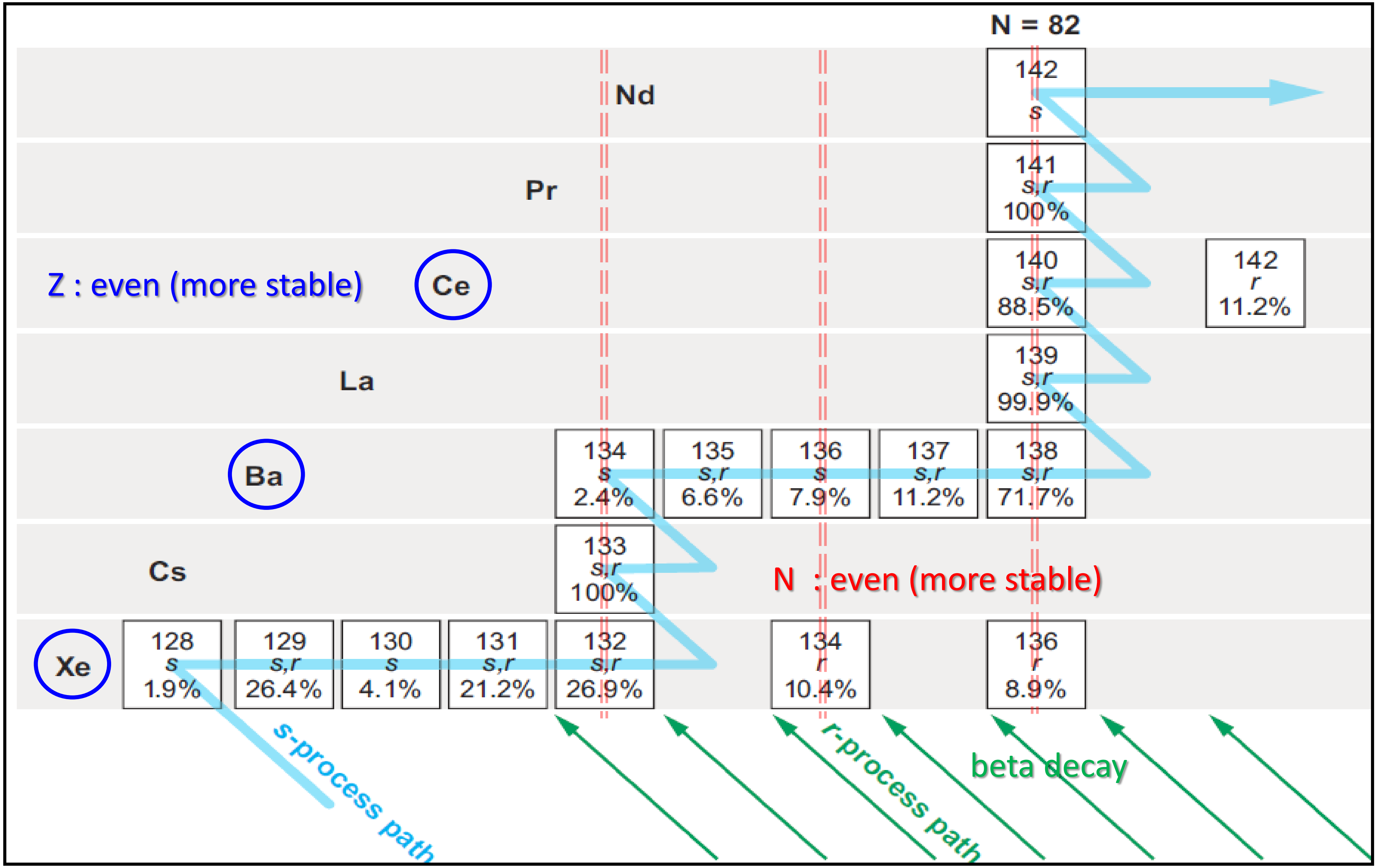
- does not synthesize all heavy nuclei
- terminates at Pb, Bi



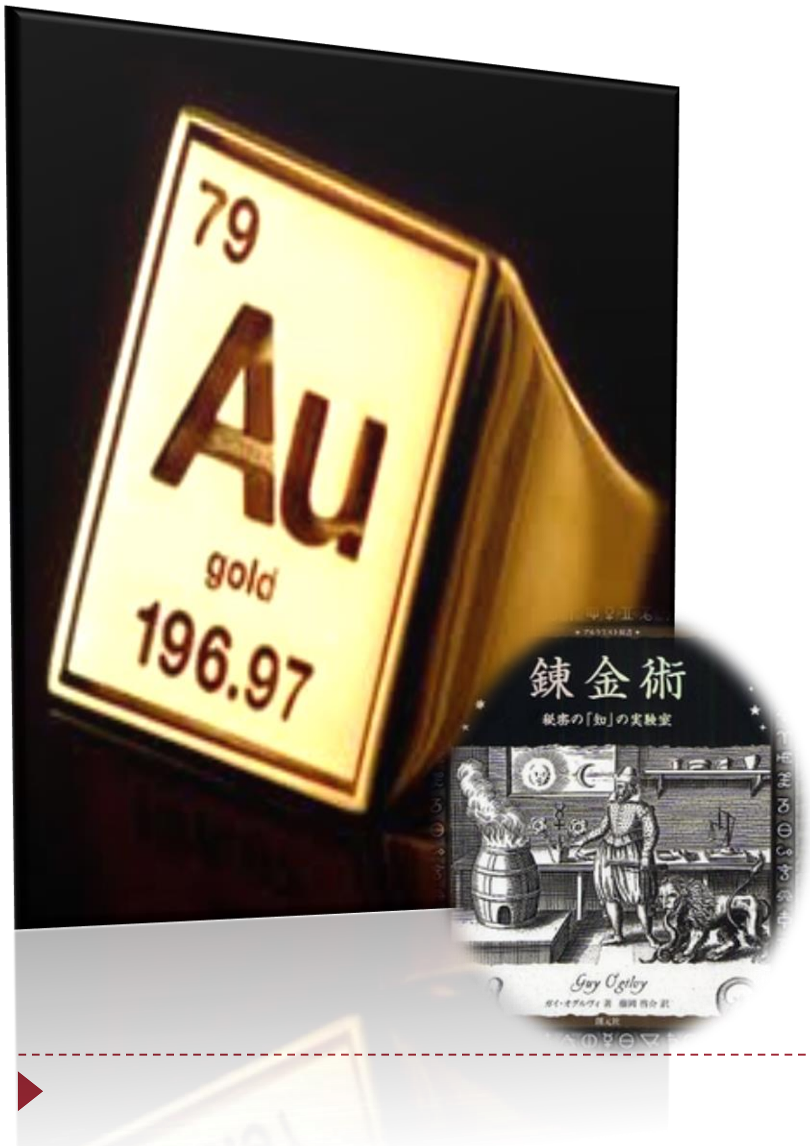
s-process / r-process path



s-process / r-process path



To be an alchemist : recipe to cook gold



- Neutron capture : packing neutrons into 'seed' nuclei

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

  - Large #neutron/#seed ratio is required
  - A(gold) – A (seed) ~ 100

- **(1) Low electron fraction Ye**
  - Ye = number of electrons per baryon ~ # of proton ~ 1 - # of neutron
  - To have a large number of free neutrons

- **(2) Higher entropy per baryon**
  - To slow the seed nuclei production

- **(3) Short expansion timescale**
  - To freeze seed production with rapid decrease of temperature

What is the melting pot for r-process ?

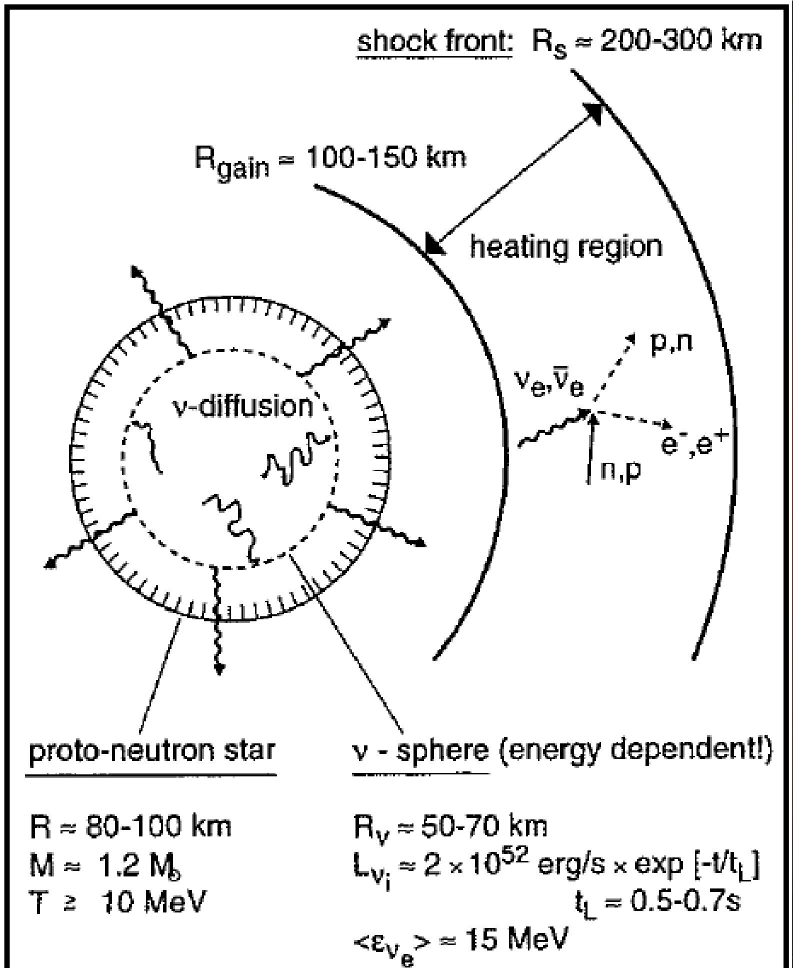
- **<u>Supernova (SN) explosion (+ PNS ν-driven wind) : (*Burbidge et al. 1957*)</u>**
  - Textbooks tell you that SNe are the origin of heavy elements, but ….
  - theoretically disfavored (Roberts et al. 2010, 2012)

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

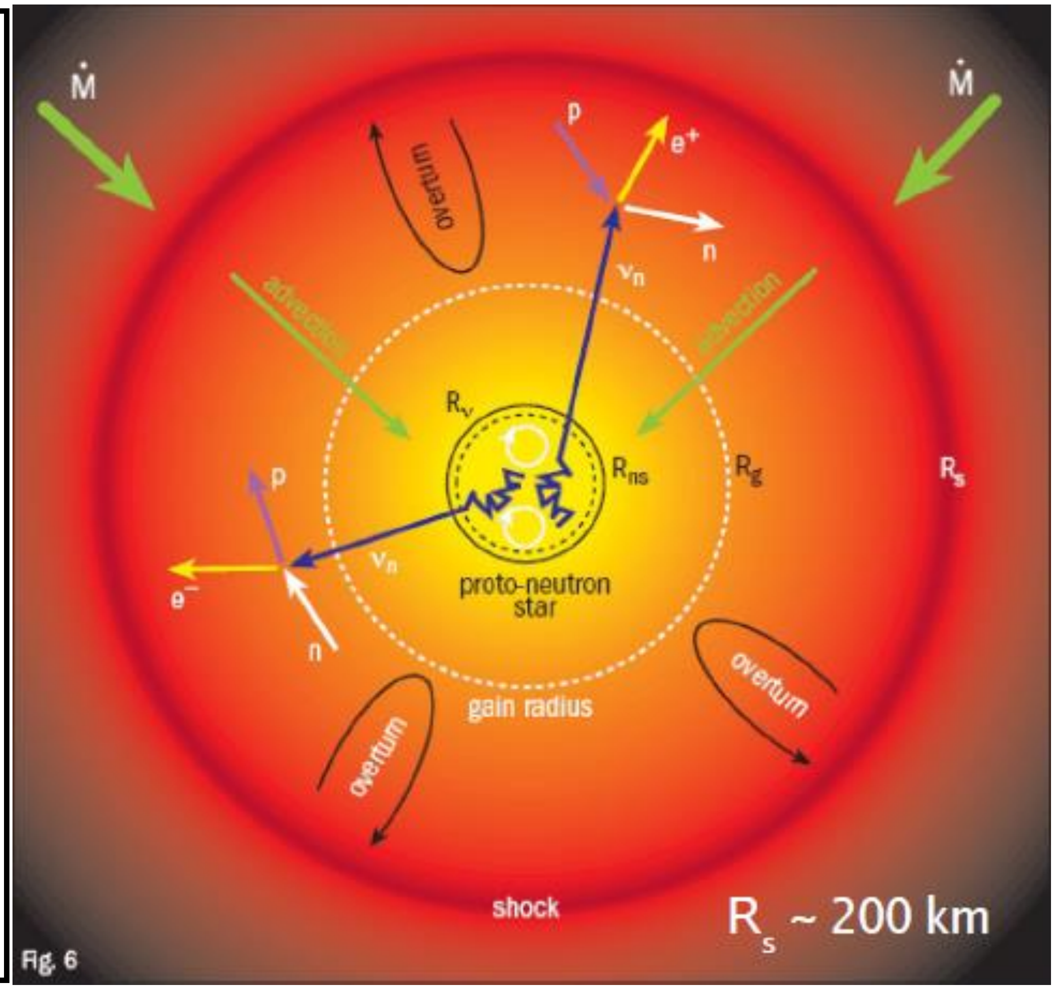
What is the melting pot for r-process ?

- **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 try to make the flow proton-rich via $n + \nu \rightarrow p + e$ and $p + \bar{\nu} \rightarrow n + e^{+}$

Overall picture of the neutrino heating mechanism



Cartoon by E. Muller (1998)



Cartoon by T. Janka

What is the melting pot for r-process ?

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  - 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)

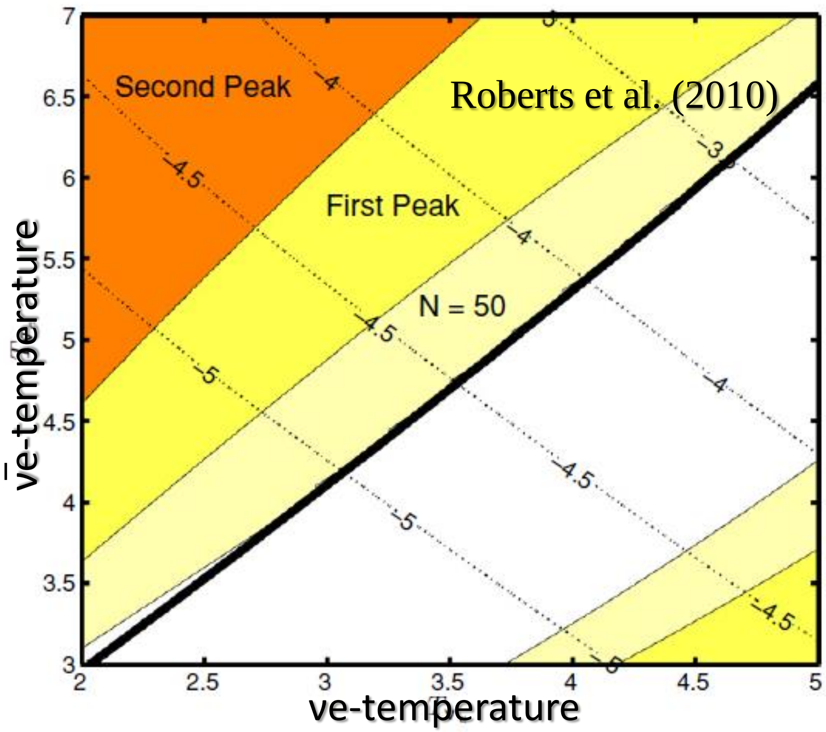
$$\Delta\varepsilon = \bar{\varepsilon}_\nu - \varepsilon_\nu \quad \text{vs.} \quad \Delta m = m_n - m_p$$

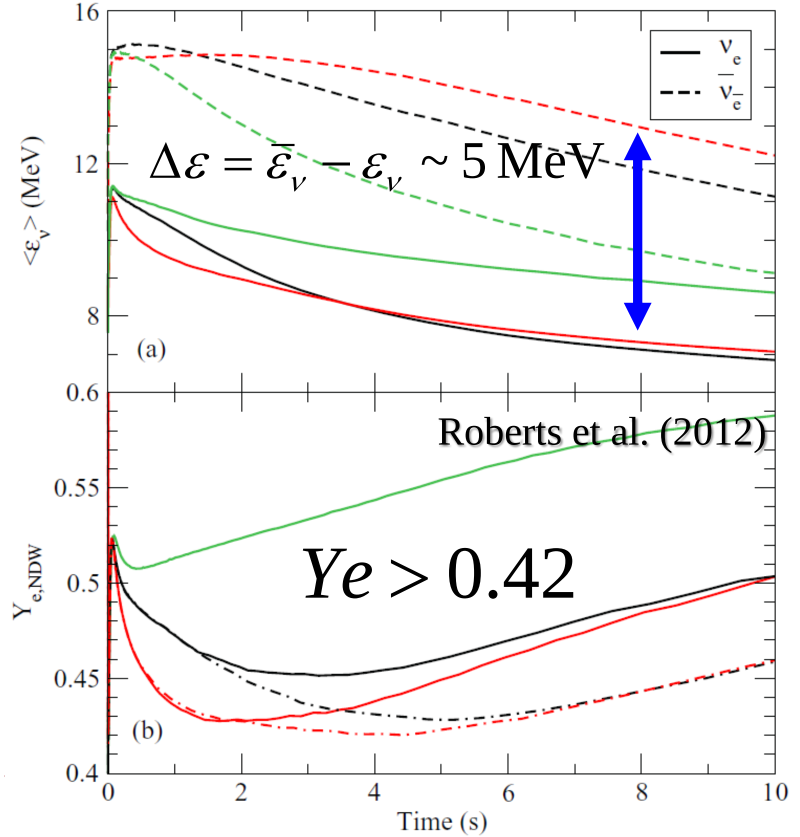
$$\Delta\varepsilon >\sim 4\Delta m \ \text{(neutron rich)} \qquad \Delta\varepsilon <\sim 4\Delta m \ \text{(proton rich)}$$

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

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 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*

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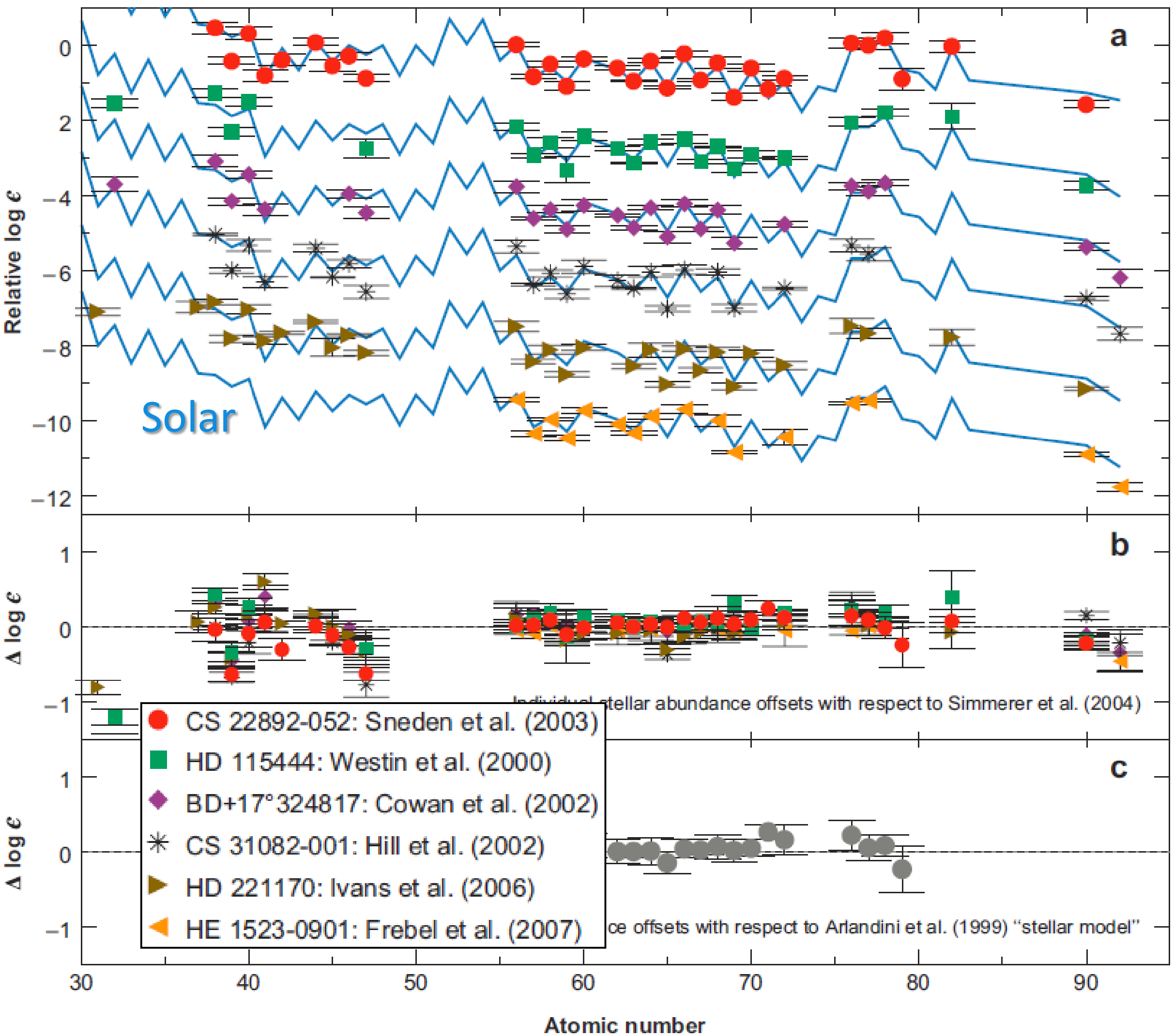
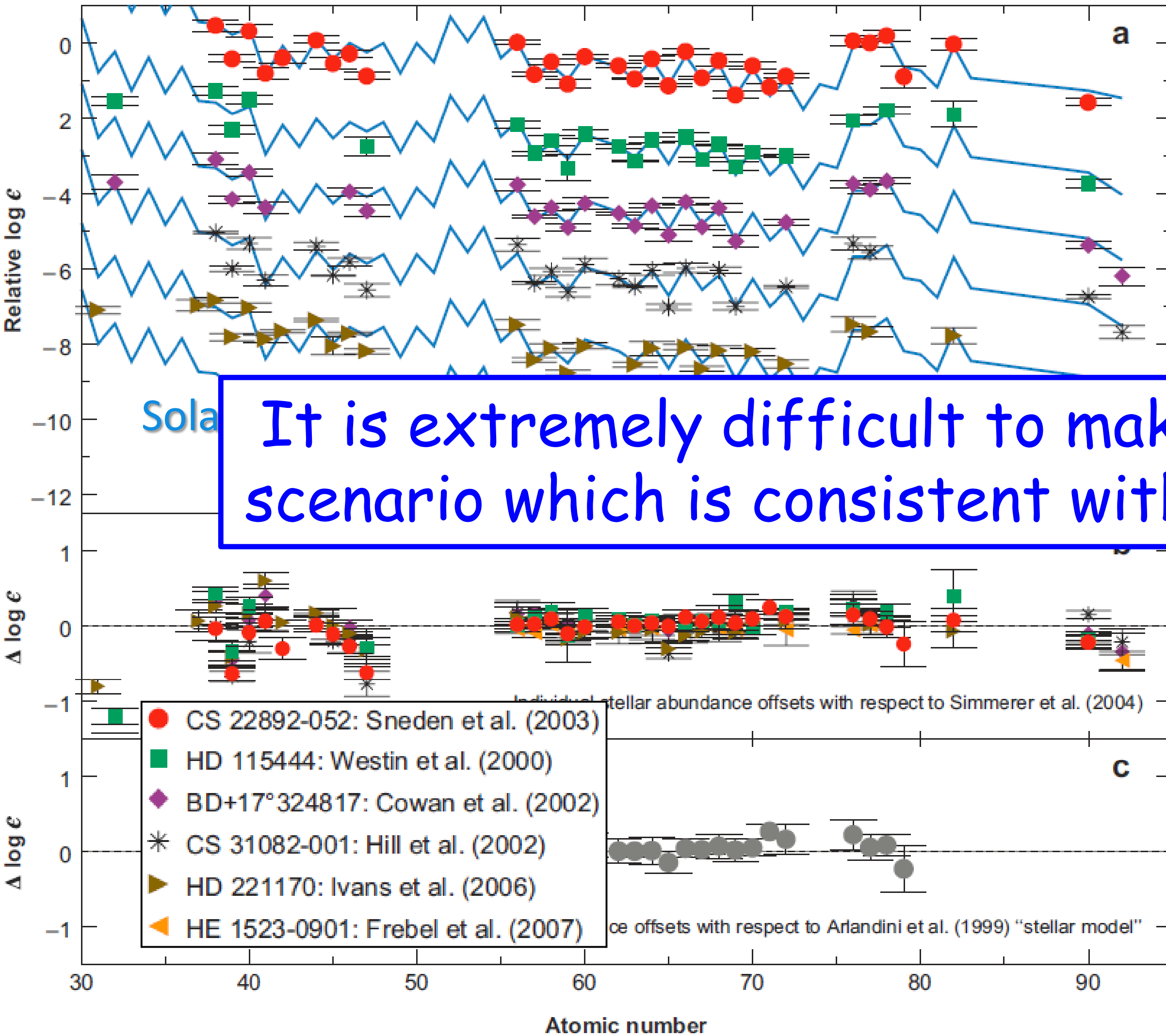
- Supernova can be the origin of r-process nuclei only if
  - The explosion mechanism is not due to the popular neutrino heating (e.g., magneto-rotational; Winteler et al. 2012)
  - or
  - Our knowledge of neutrino and nuclear physics is insufficient

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



It is extremely difficult to make a model in SNe scenario which is consistent with the universality.

- Abundance pattern comparison :
- The solar and chemical fossil pattern agree well
  - for Z > 35-40 (A > 85-90)
- ...rd 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>

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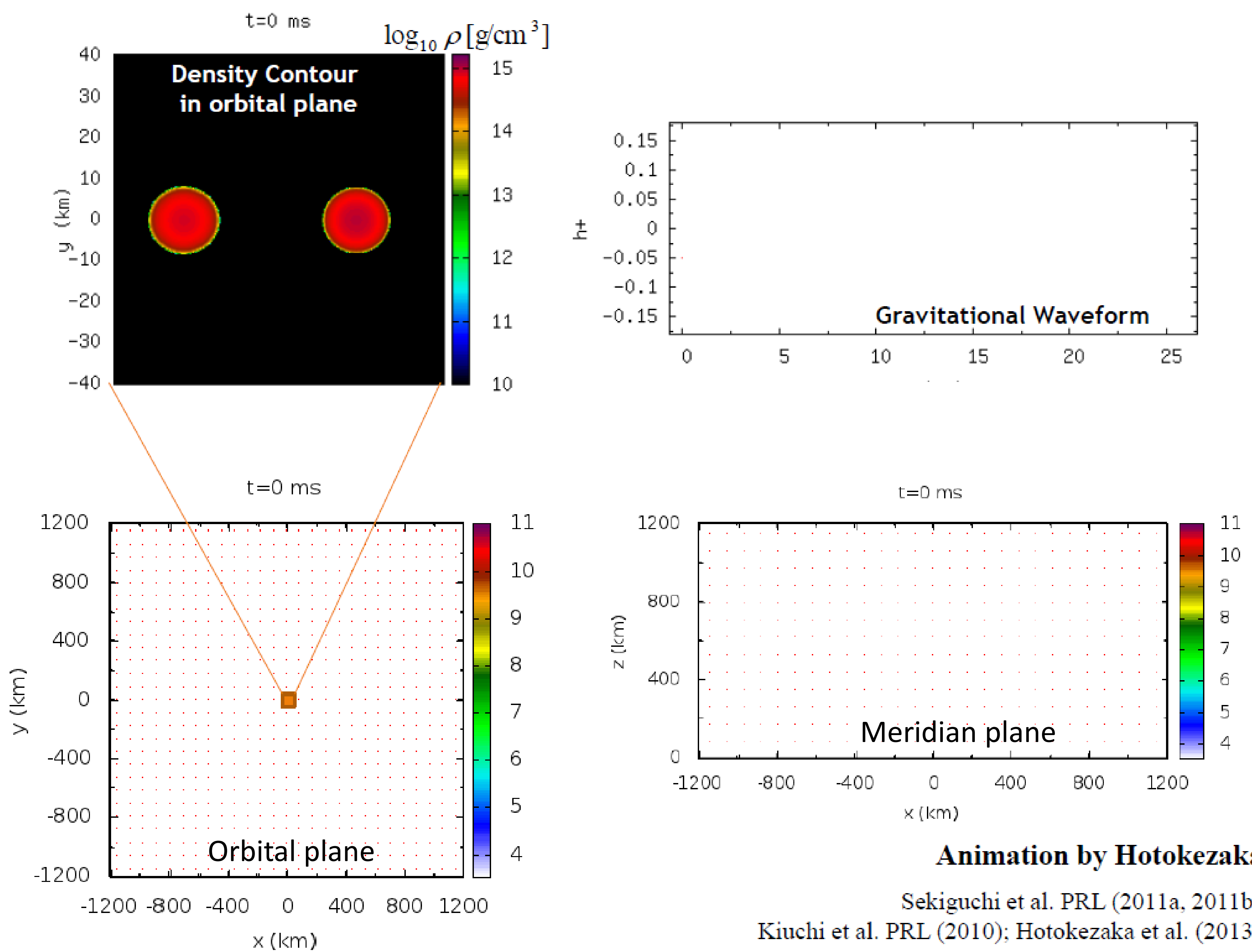
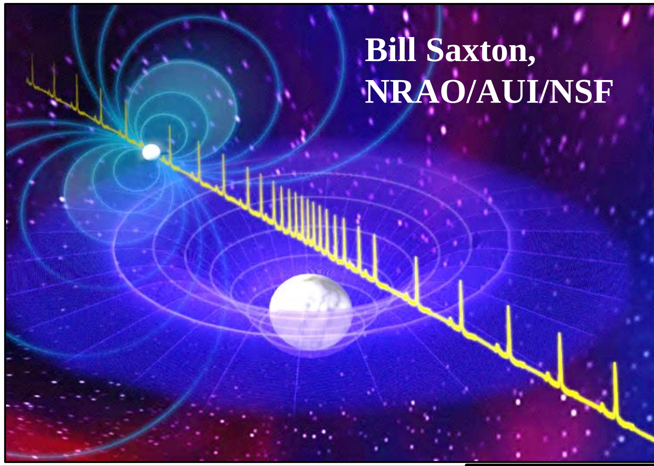


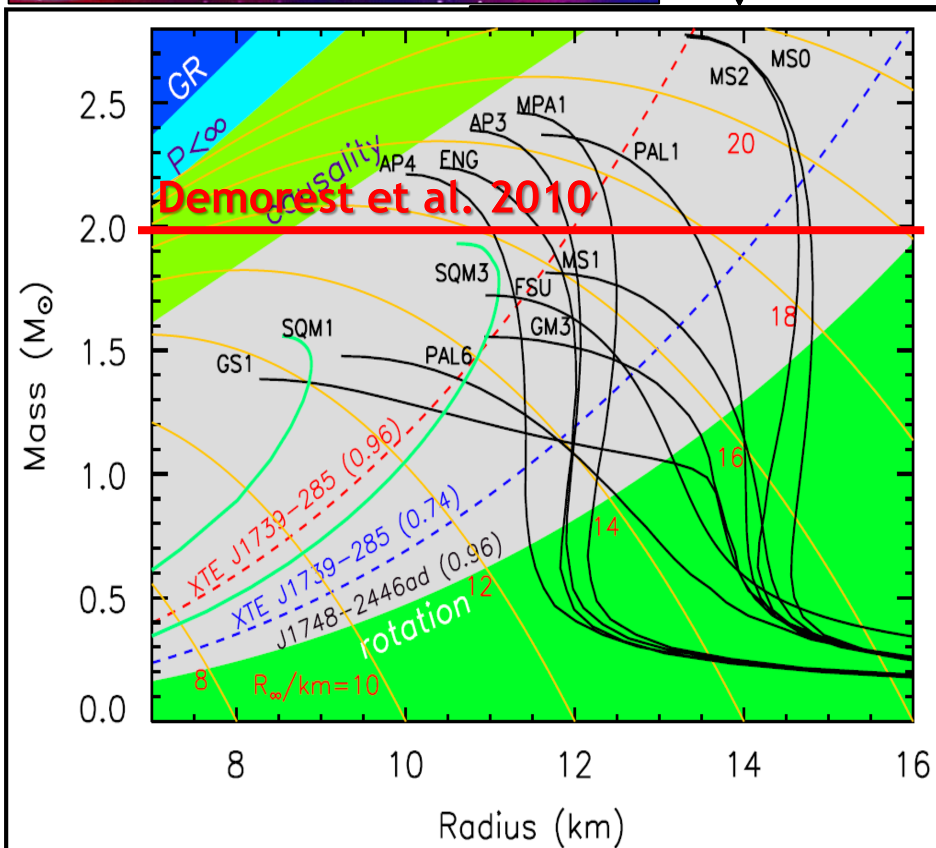
Animation by Hotokezaka

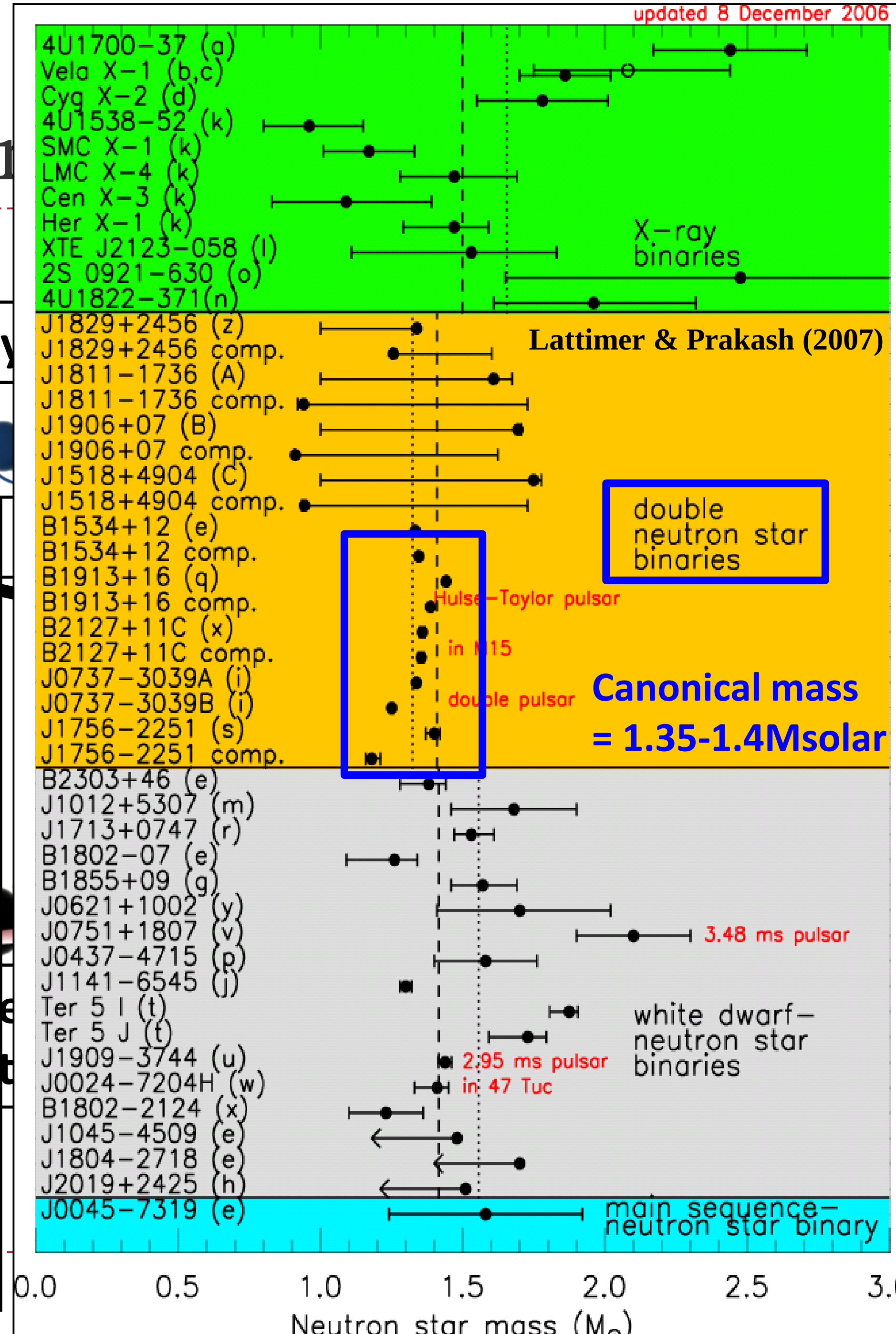
Sekiguchi et al. PRL (2011a, 2011b)
Kiuchi et al. PRL (2010); Hotokezaka et al. (2013)

NS-NS r

al of NS binary



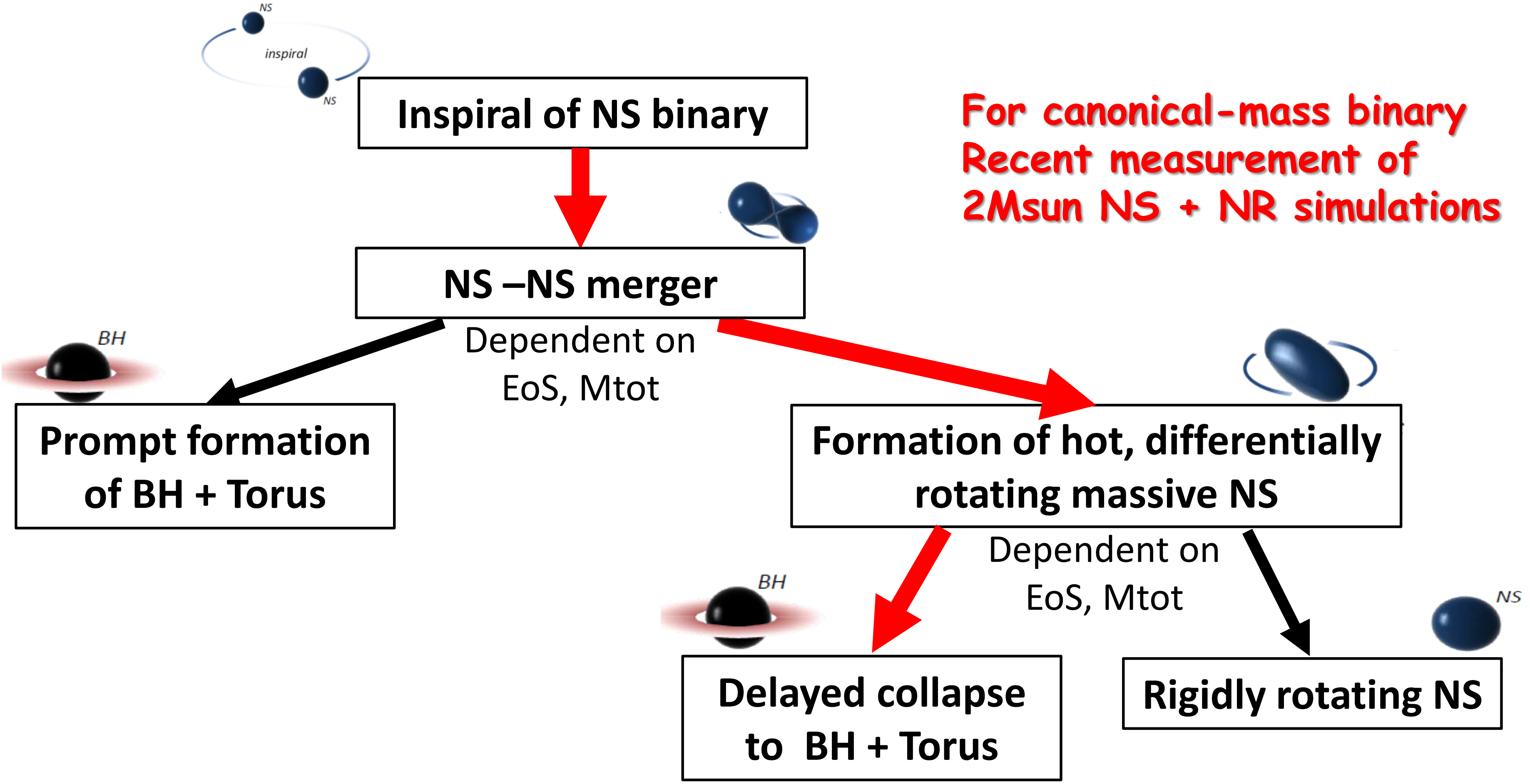




Evolution of NS-NS mergers

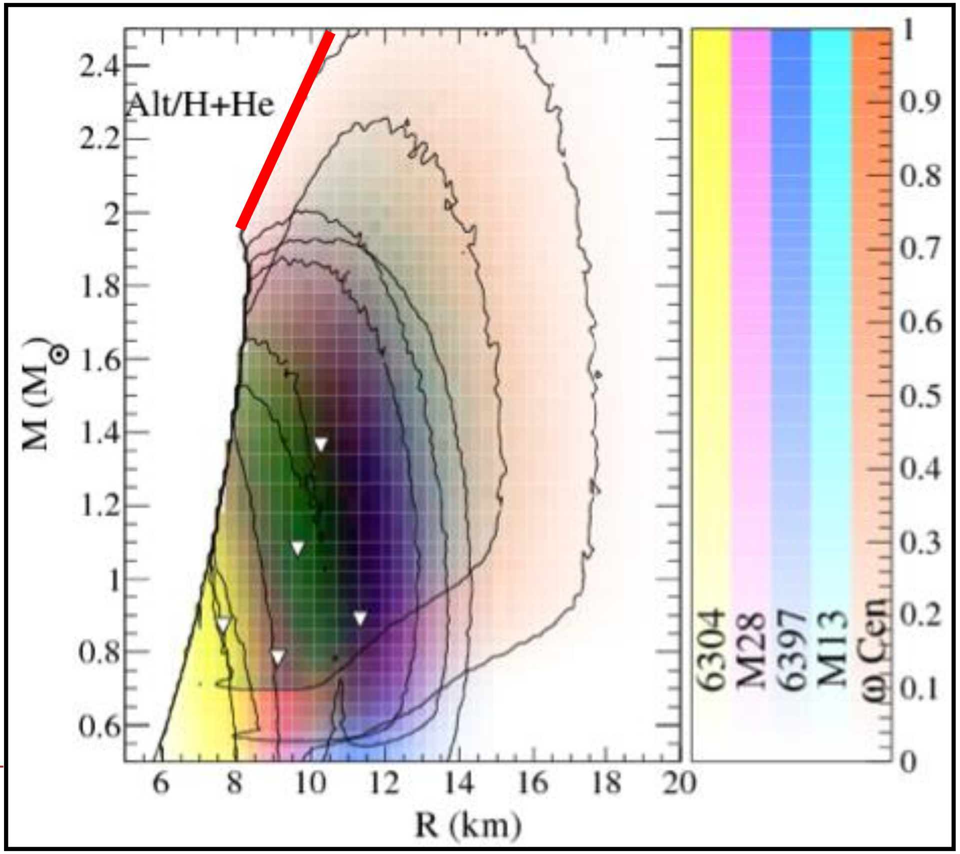
Shibata et al. 2005,2006
Sekiguchi et al, 2011
Hotokezaka et al. 2013

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



Causality limit : NS radius estimation

- The measurement of flux and temperature yields an apparent angular size (pseudo-BB) $\frac{R_\infty}{D} = \frac{R}{D}\frac{1}{\sqrt{1-GM/Rc^2}}$ $F \propto T_{\rm eff}^4 \frac{R_\infty^2}{D^2}$
  - Many uncertainties : redshift, distance, interstellar absorption, atmospheric composition
- Good Targets:
  - Quiescent X-ray binaries in globular clusters (D, composition)
  - Bursting sources with peak flux close to Eddington limit (M)
- Imply rather small radius
  - **If true, maximum mass may not be much greater than 2Msun**

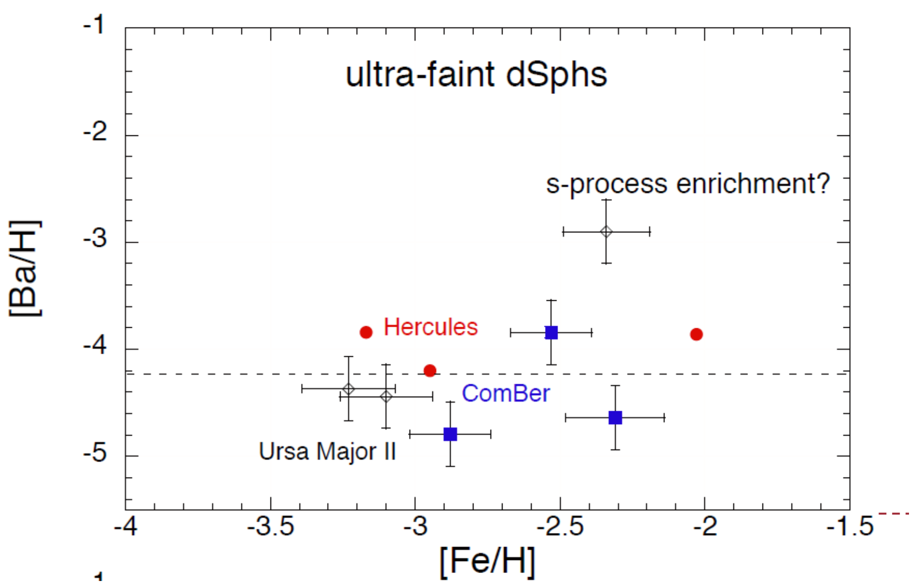


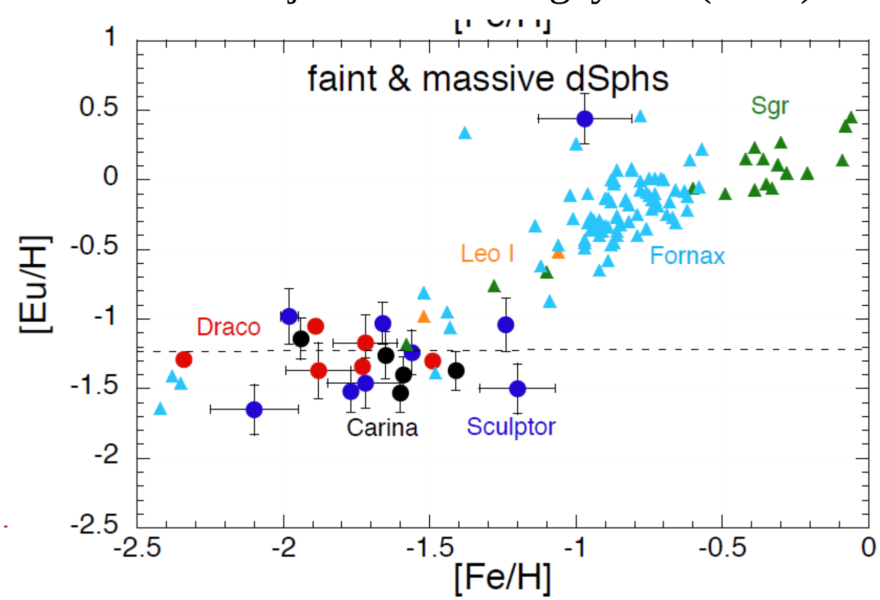
- Lattimer & Steiner 2014 for quiescent LMXBs

What is the melting pot for r-process ?

- **Observationally NOT disfavored ?? (*Tsujimoto and Shigeyama. 2014*)**
  - 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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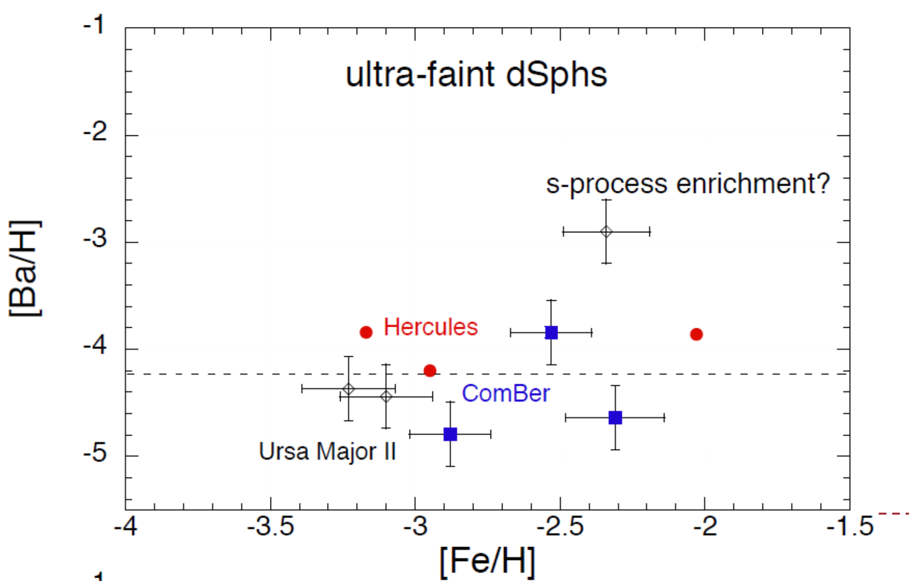
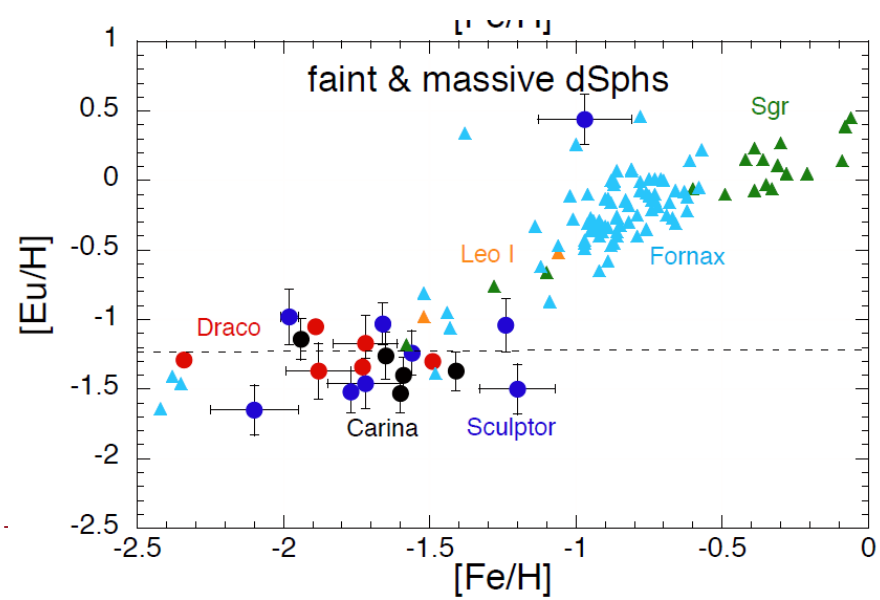
    - No r-process events (No Eu) but a number of SNe (Fe↑)
    - If SNe are the r-process cite, both Eu and Fe should increase
    - Suggest different origin for Fe and Eu
  - Enrichment of Eu in massive dwarfs
    - event rate is estimate as 1/1000 of SNe : consistent with BNS merger





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

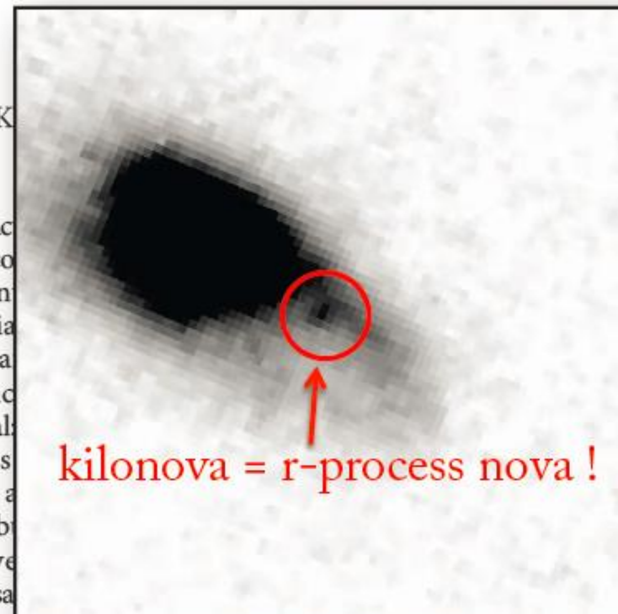
- **EM transients possibly powered by radioactivity of the r-process elements were expected (Li & Paczynski 1998) and found (important GW counterpart)**

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].

Short summary

- 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
      - Ye profile of merger ejecta

From the 'Universality' point of view :

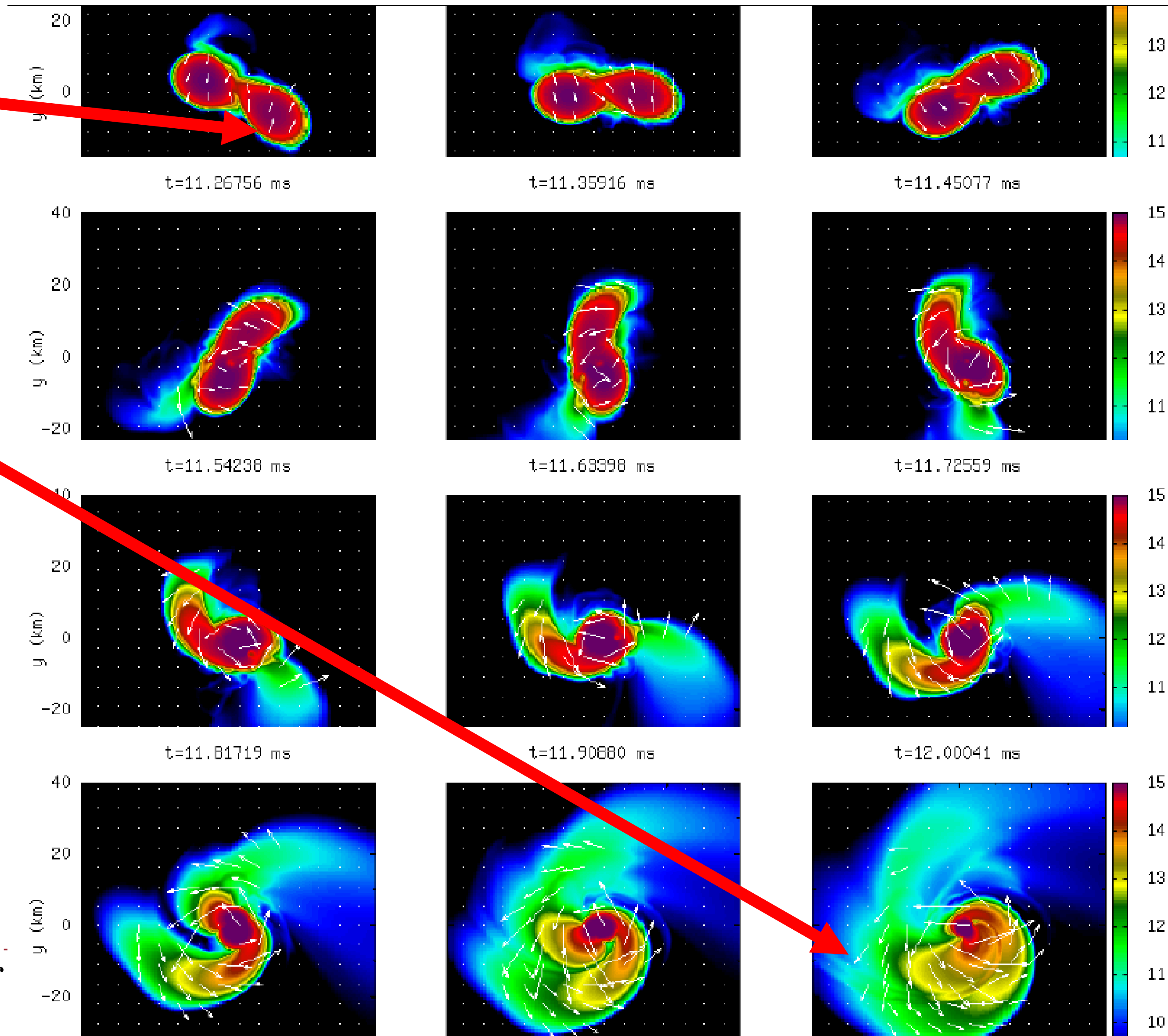
NS-NS merger ejecta: too neutron-rich ?

- Goriely et al. 2011; Bauswein et al. 2013
  - Approx. GR SPH sim. **without** weak interactions
  - No way to change Ye => ejecta remains n-rich (initial low Ye)
  - See also post-process calculation of weak interactions
- Korobkin et al. 2012; Rosswog et al. 2013
  - Newtonian SPH sim. with neutrino
  - **tidal mass ejection (explained in the next slide)** 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)

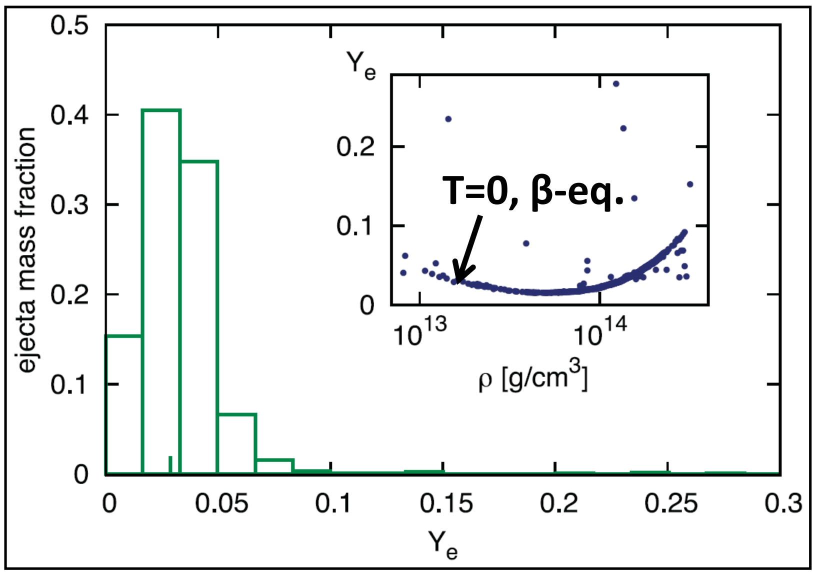
- Less massive NS is tidally deformed
- Angular momentum transfer by spiral arm and swing-by
- A part of matter is ejected along the orbital plane
- **reflects low Ye of cold NS** (β-eq. at T~0), no shock heating, rapid expansion (fast T drop), no time to change Ye by weak interactions



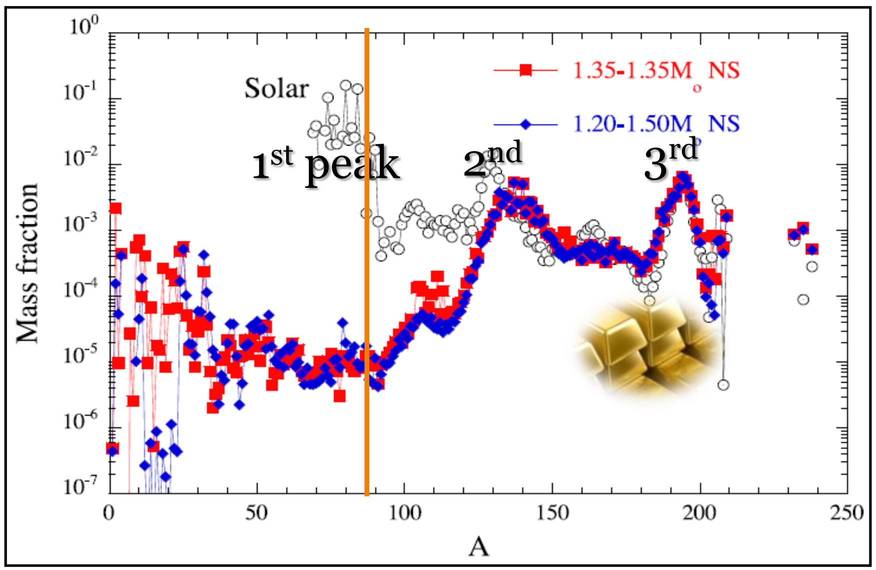
Density contour
[log (g/cm^3)]

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



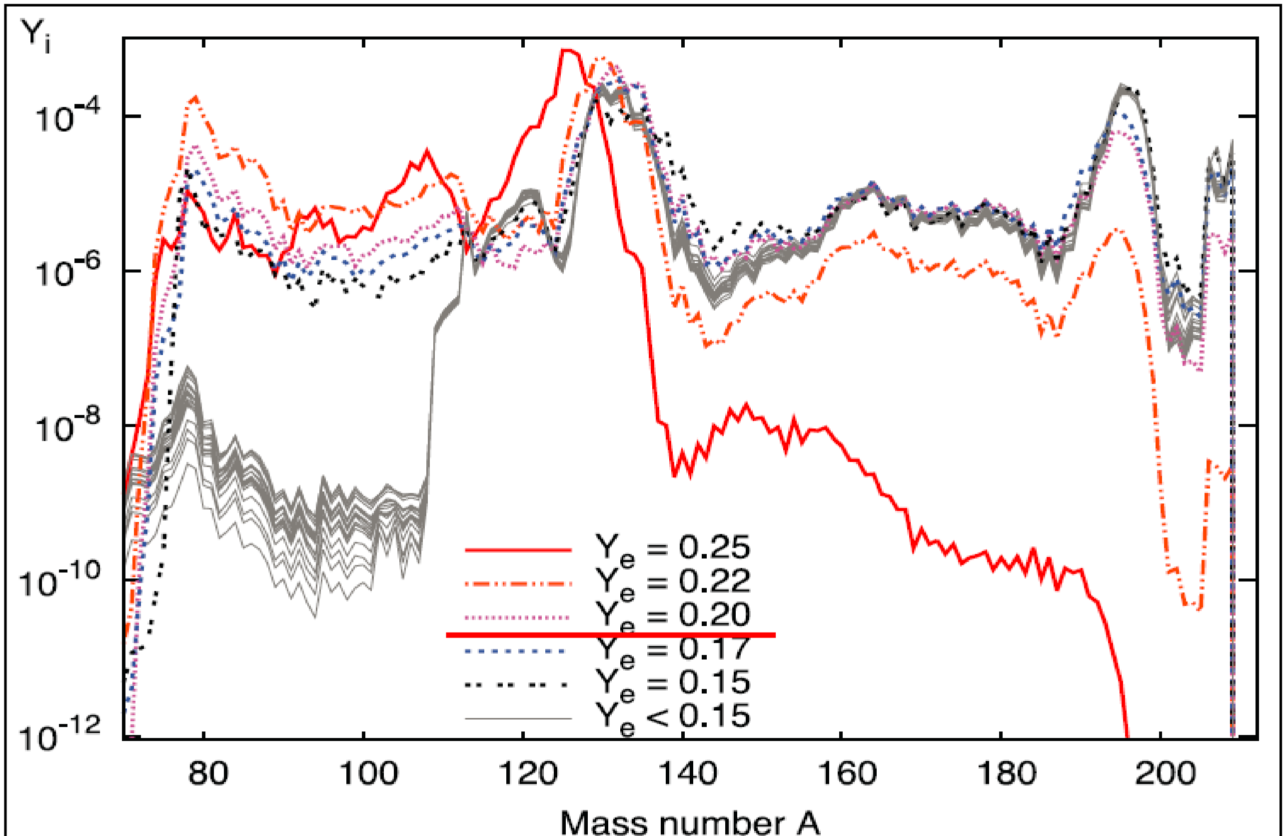
Korobkin et al. (2012) MNRAS 426 1940



Goriely et al. (2011) ApJL 738 32

How to satisfy the universality

- **Electron fraction (Ye) is a key parameter : Ye ~ 0.2 is critical threshold**
  - Ye < 0.2 : strong r-process ⇒ nuclei with A>130 (the pattern is robust)
  - Ye > 0.2 : weak r-process ⇒ nuclei with A< 130 (for larger Ye, nuclei with smaller A)



We need ejecta with higher Ye

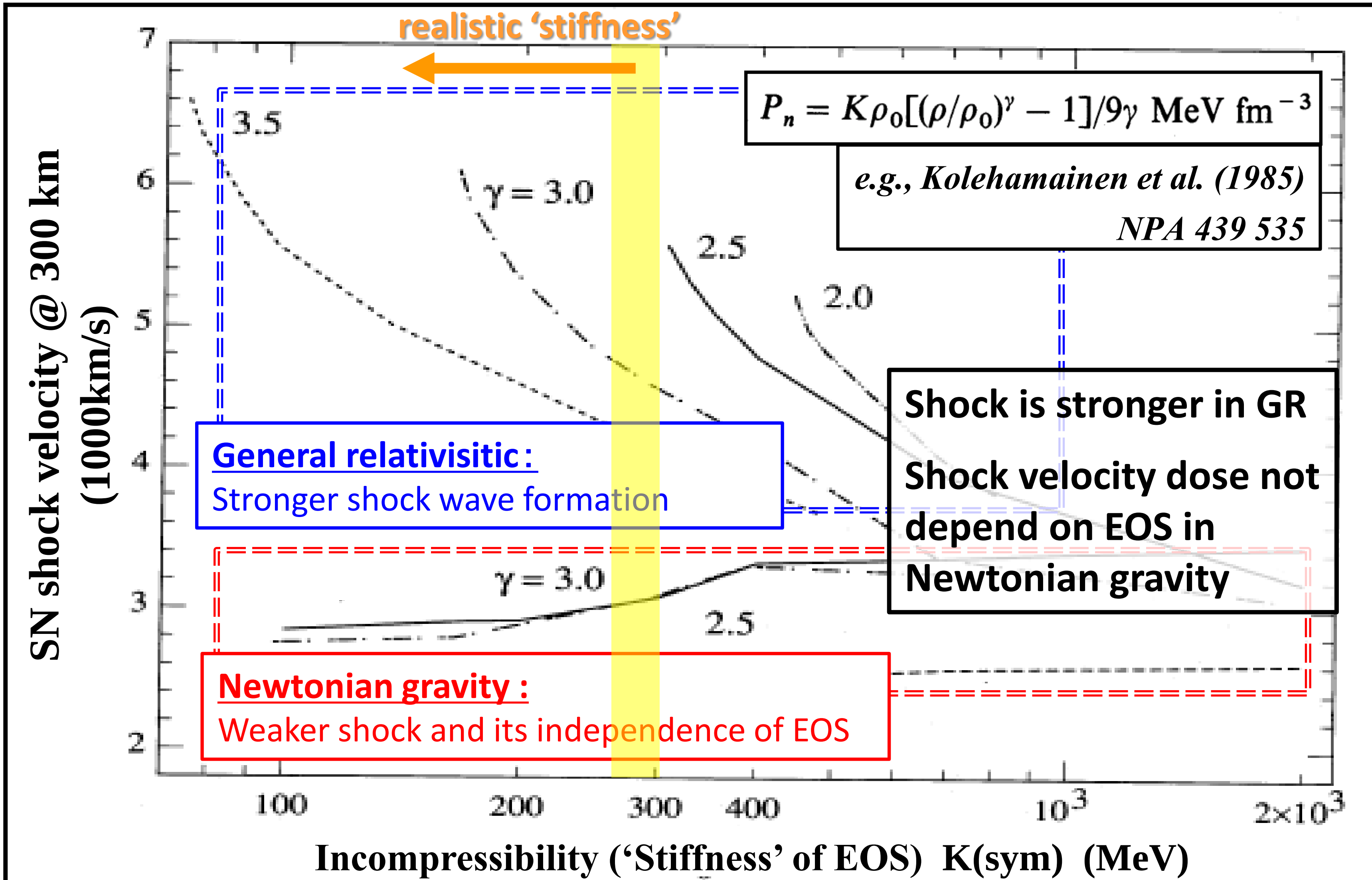
- Korobkin et al. 2012

How to satisfy the universality

- Introduce new ejecta components
  - Neutrino driven winds from the remnant system
    - Dessart et al. (2009); Grossman et al. (2014); Perego et al. (2014); Just et al. (2015)
  - late time disk/torus disintegration
    - Fernandez & Metzger (2013)
- Take into account effects of both GR and weak interaction in the dynamical ejecta (this talk)

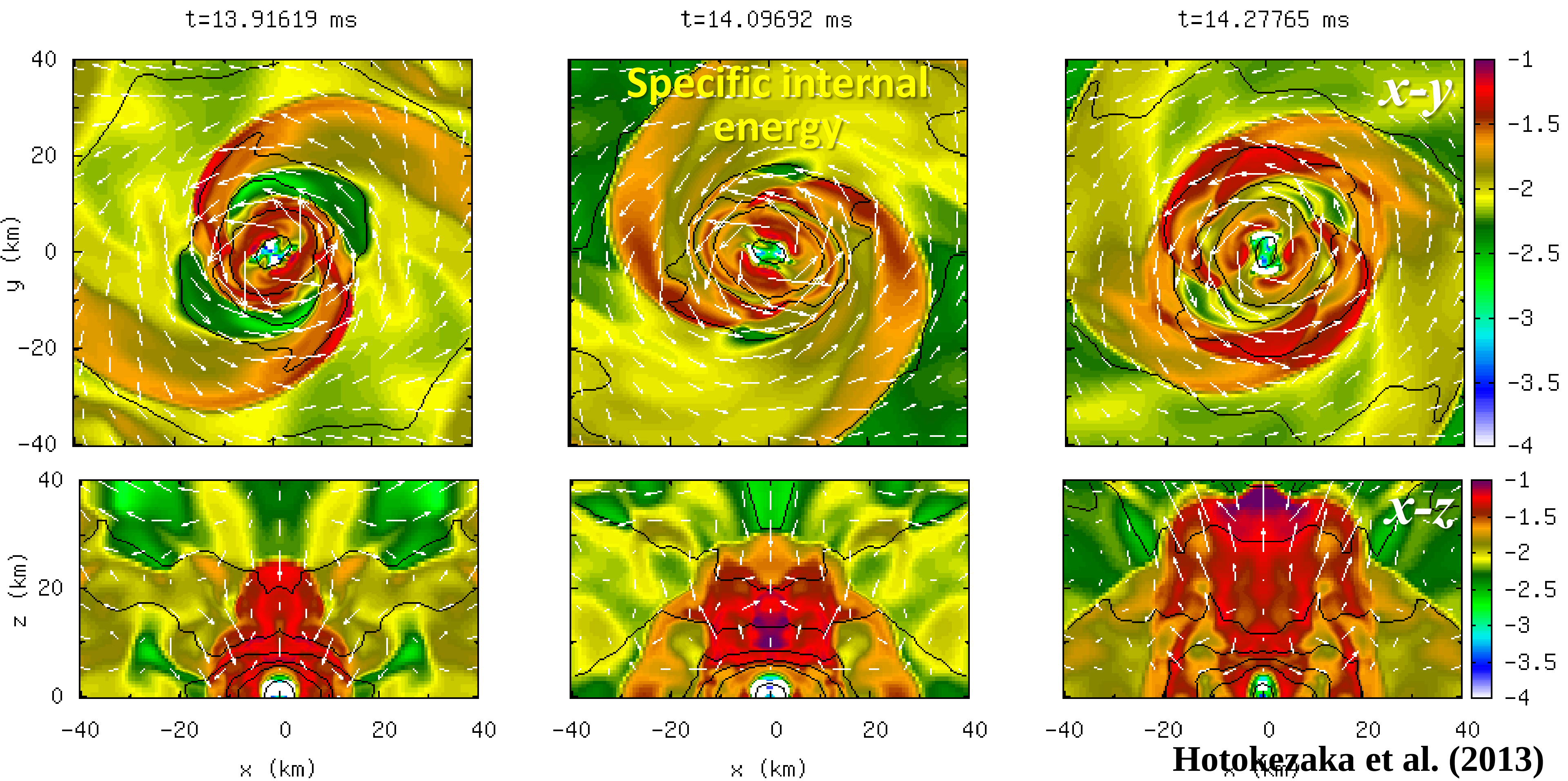
What will change if you include GR and microphysics (1) : Stronger shock in GR

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)

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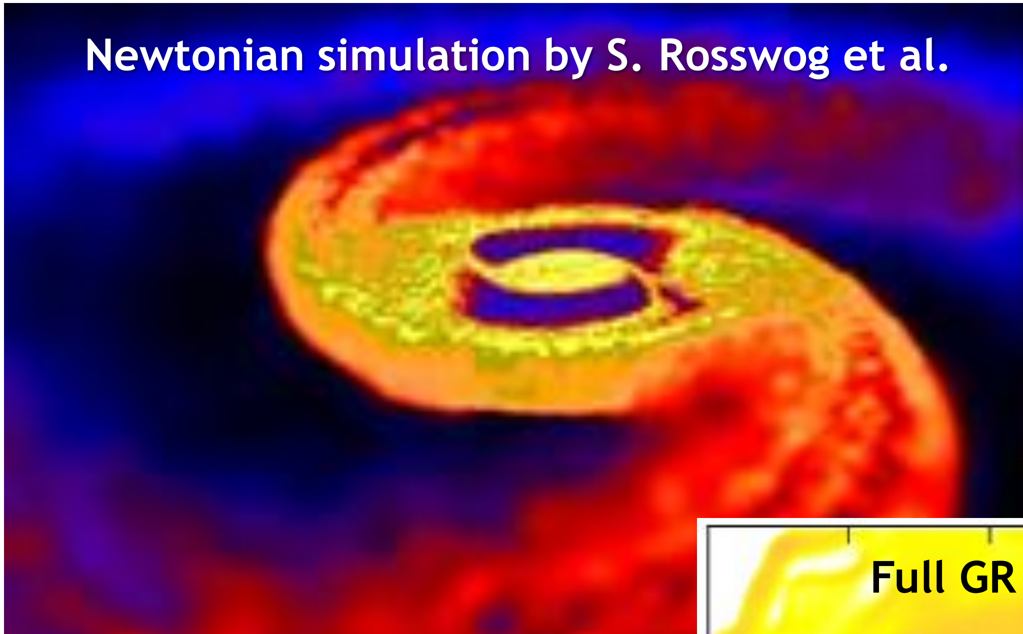
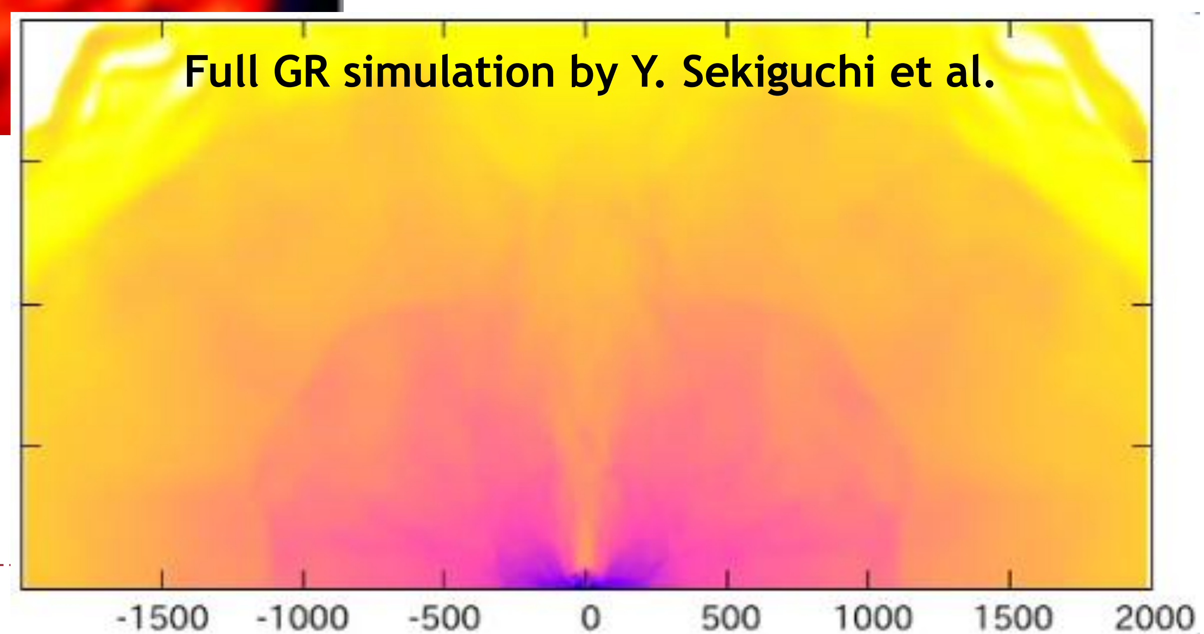


Isotropic component less dominant (shock-driven) in Newtonian simulation
Only the tidal component



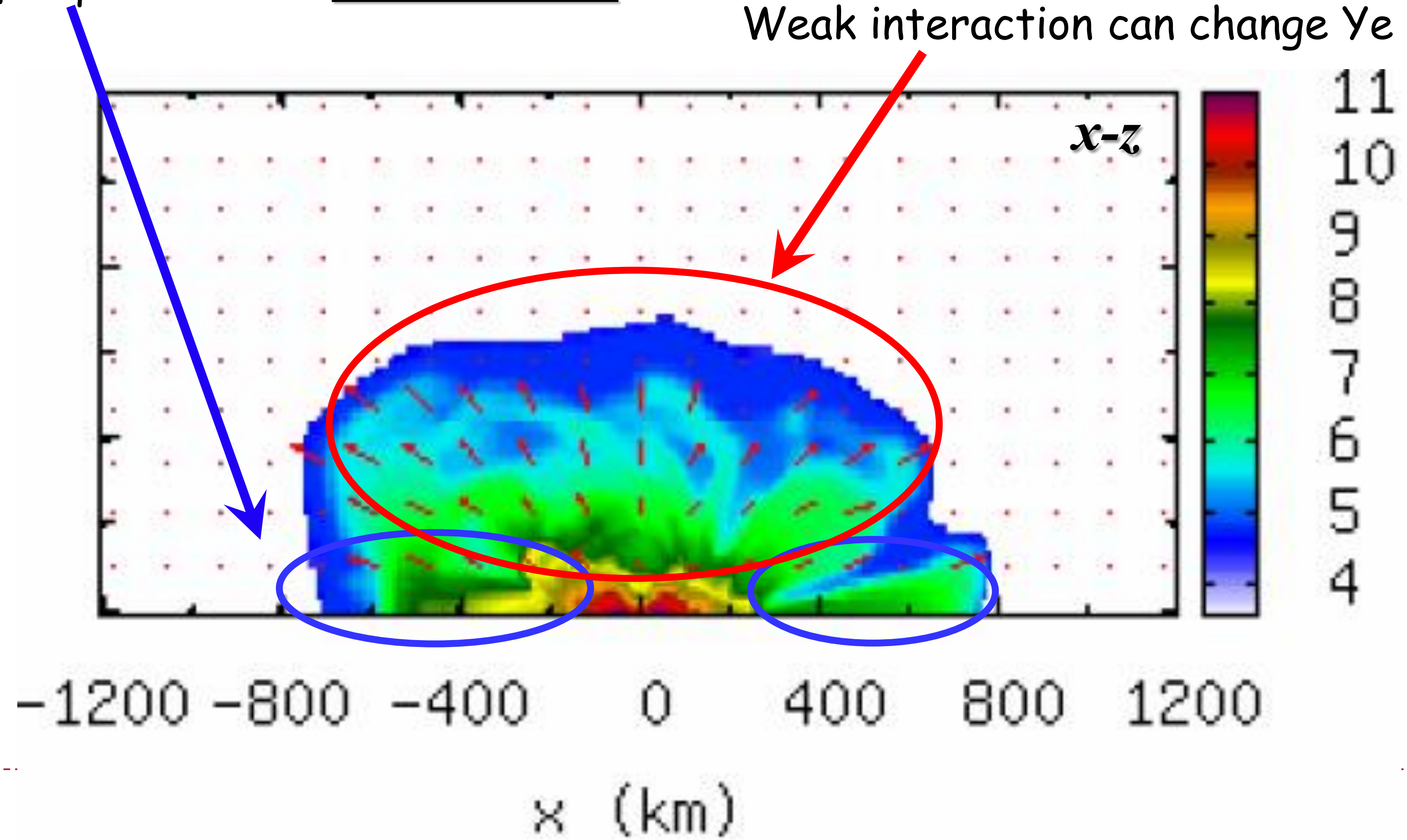
What will change if you include GR and microphysics (2) : Ye can change via weak interaction

- **Driven by tidal interactions**

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

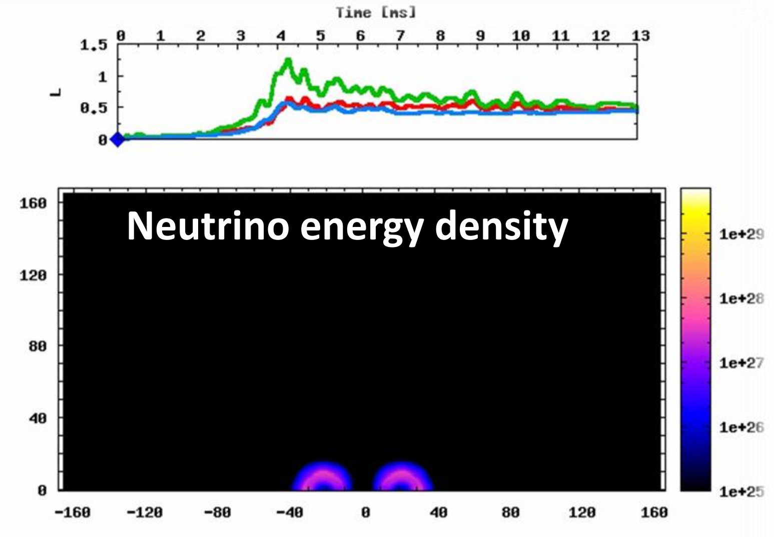
- **Driven by shocks**

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



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

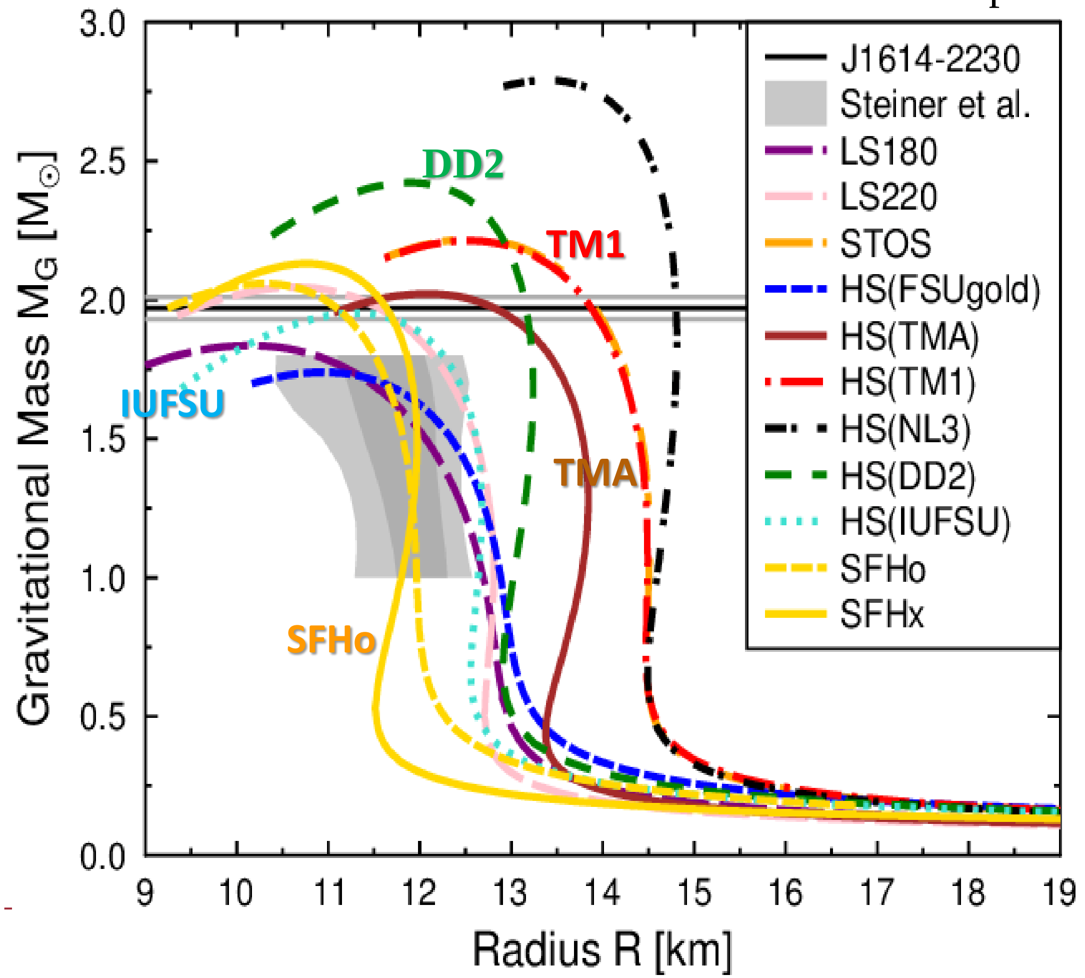
14.5km
- TM1 (Shen EOS)
  - TMA

13.2km
- DD2
  - IUFSU

11.8km
- SFHo

Consistent with
  - NS radius estimation
  - Chiral effective theory

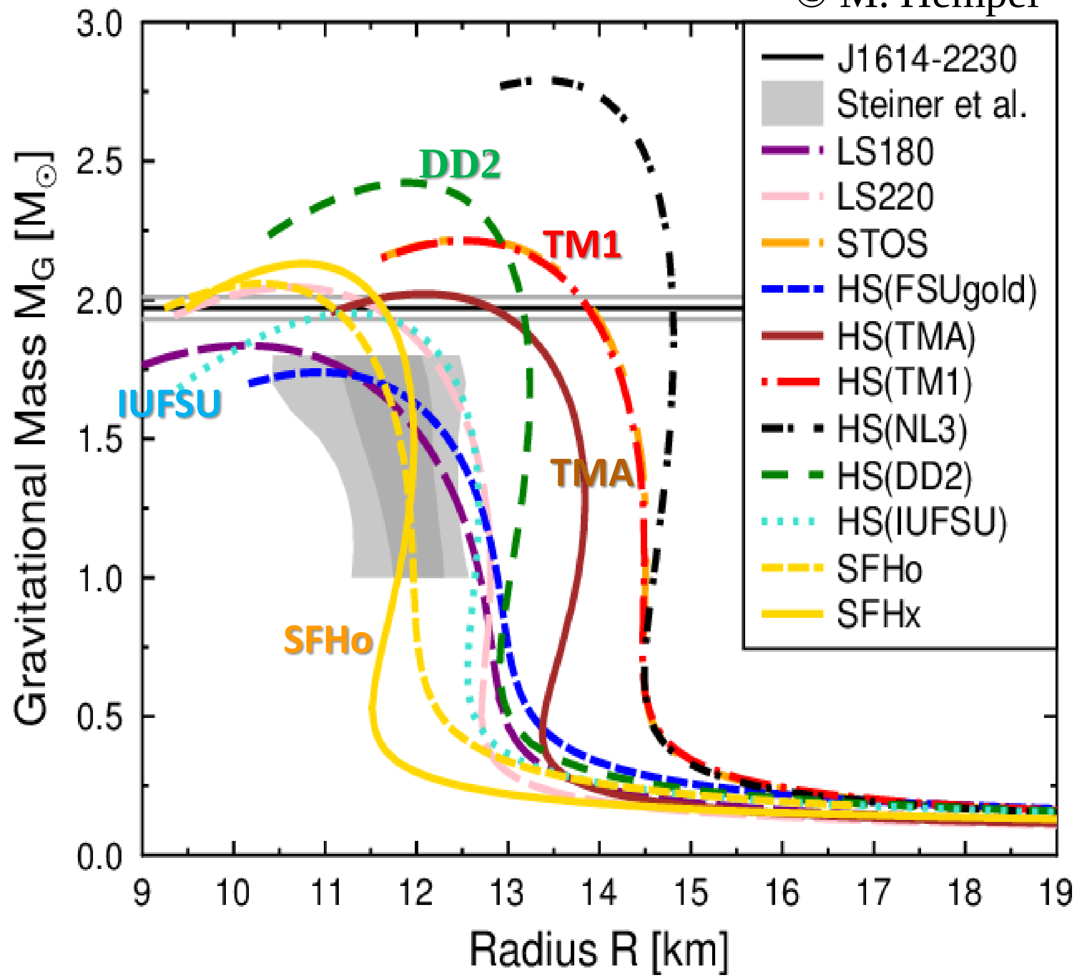
© M. Hempel



(Expected) Mass ejection mechanism & EOS

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

© M. Hempel

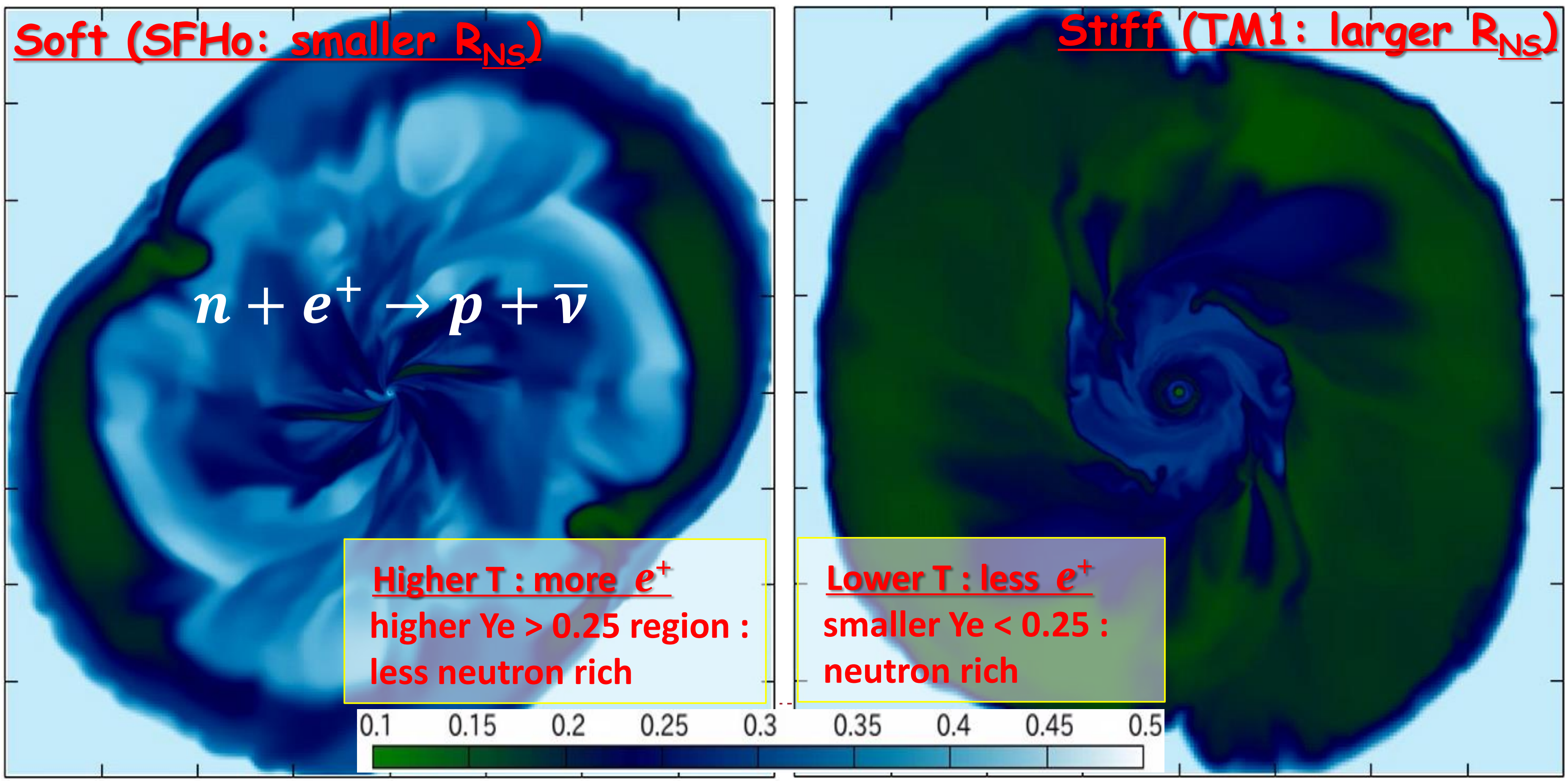


See also, Bauswein et al. (2013); Just et al. (2014)

Sekiguchi et al PRD (2015)

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

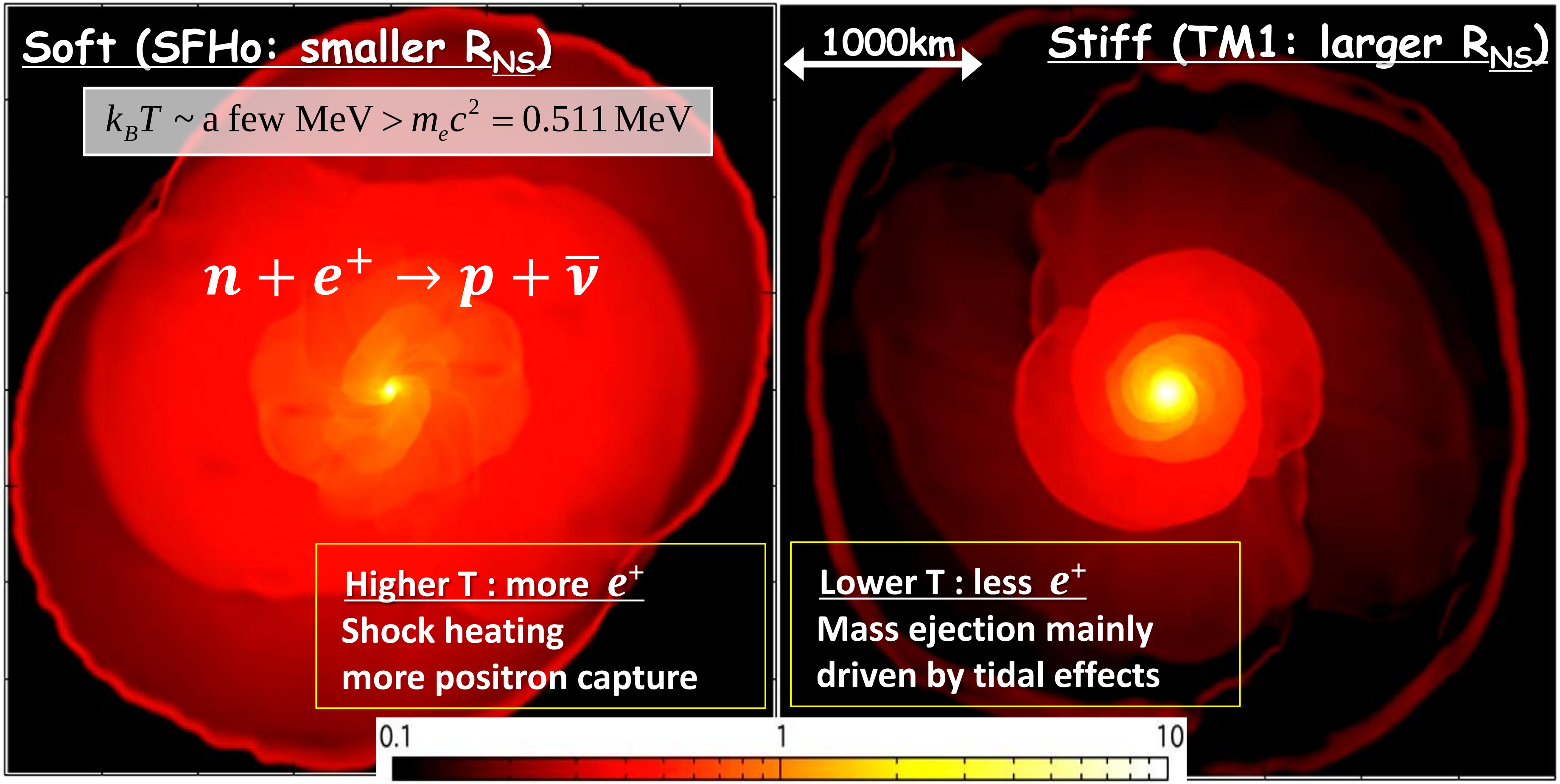
- Soft (SFHo): In the shocked regions, Ye >> 0.2 by weak processes
- Stiff (TM1): Ye is low as < 0.2 (only strong r-process expected)



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



Sekiguchi et al PRD (2015)

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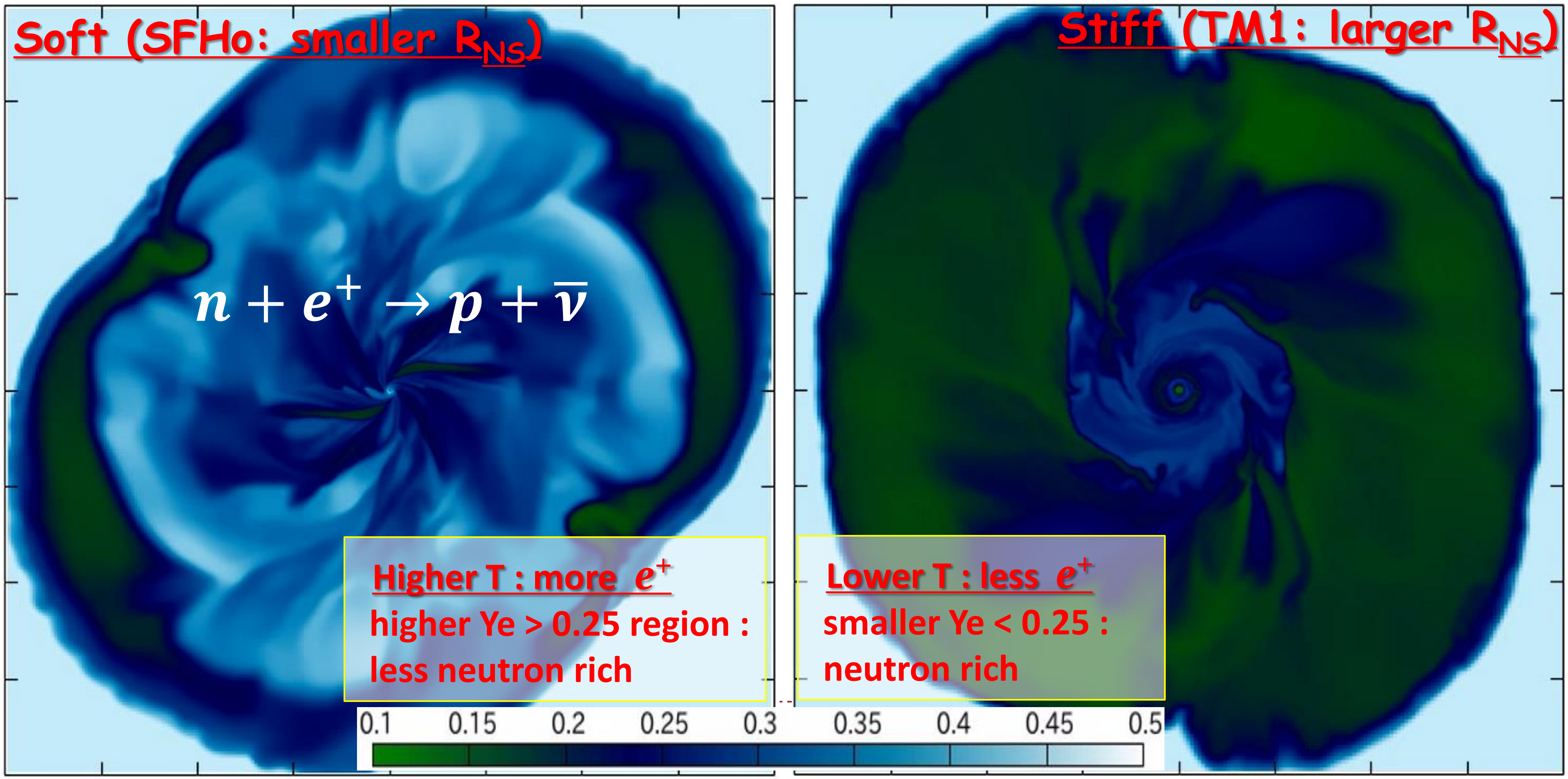
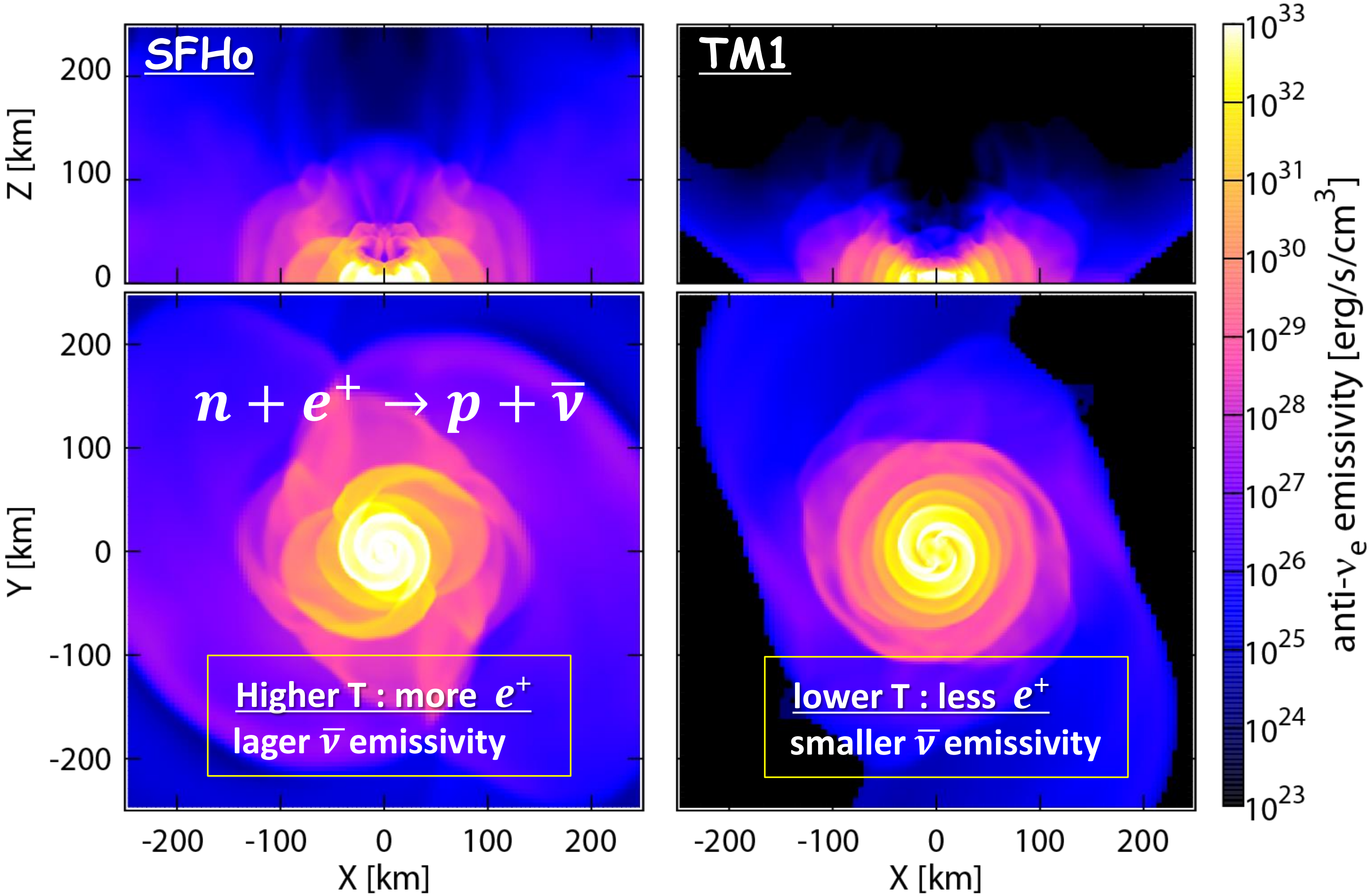
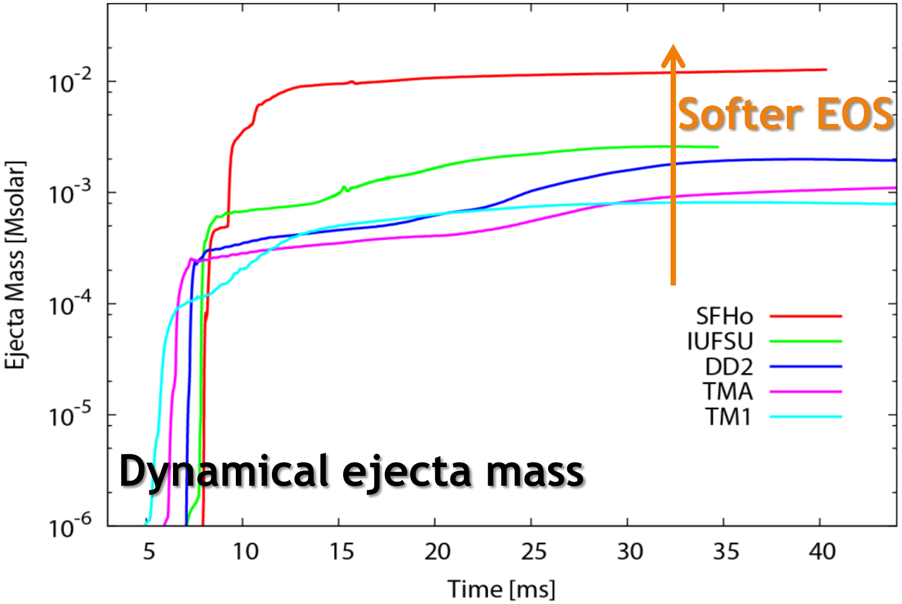


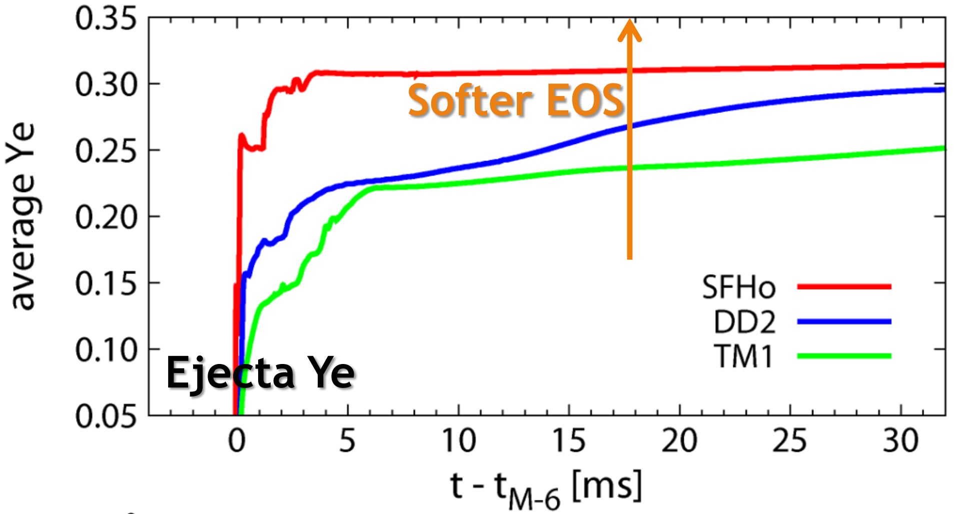
SFHo vs. TM1: $\bar{\nu}_e$ emissivity

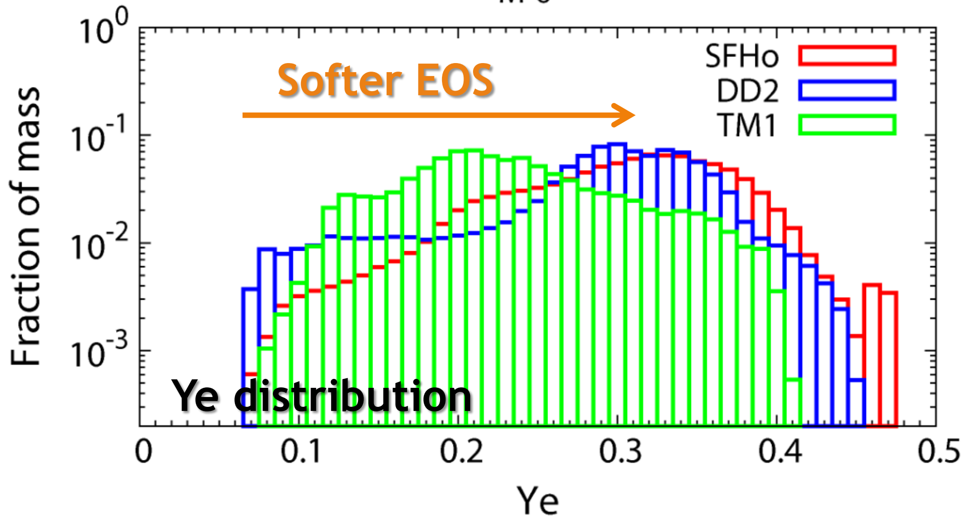


Sekiguchi et al PRD (2015)

EOS dependence : 1.35-1.35 NS-NS





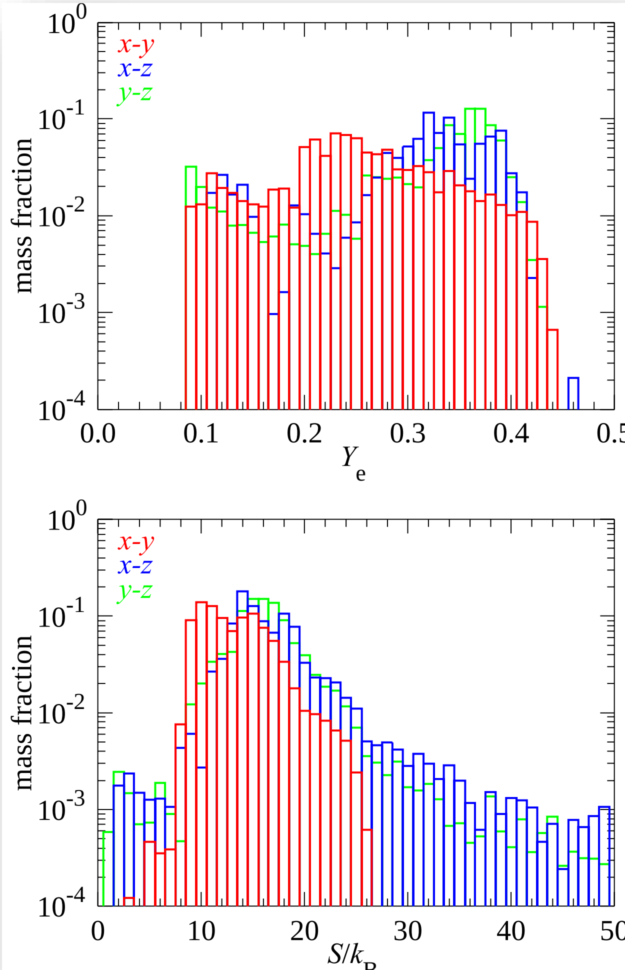


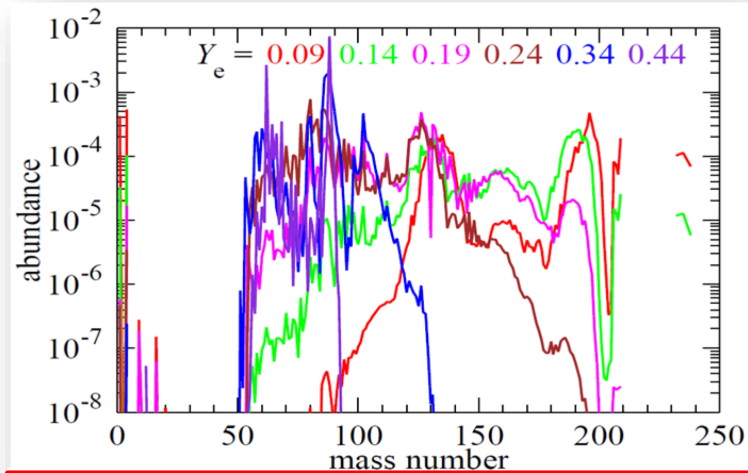
- Mej is larger for softer EOS

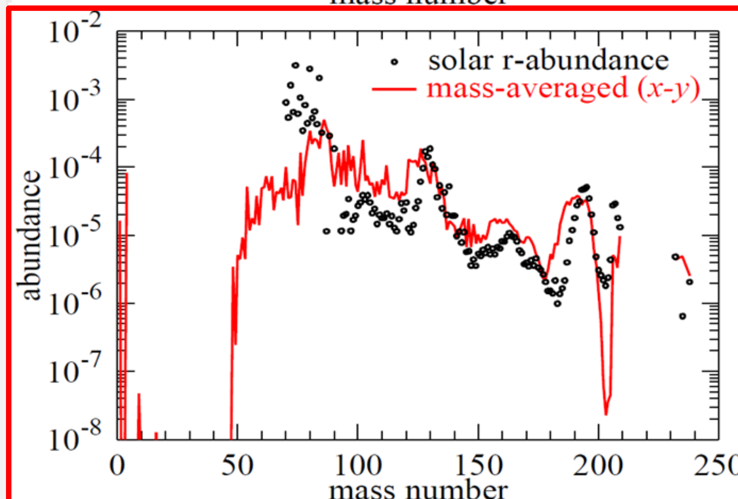
  Consistent with piecewise-polytrope studies
- **Only SFHo will give Mej ~ 0.01 Msun**
  - a value required by the total amount of r-process elements and flux of the 'kilonova' event (GRB 130603B)
- If BNS is the origin, EOS should be soft

Wanajo, Sekiguchi et al. ApJL (2014)

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



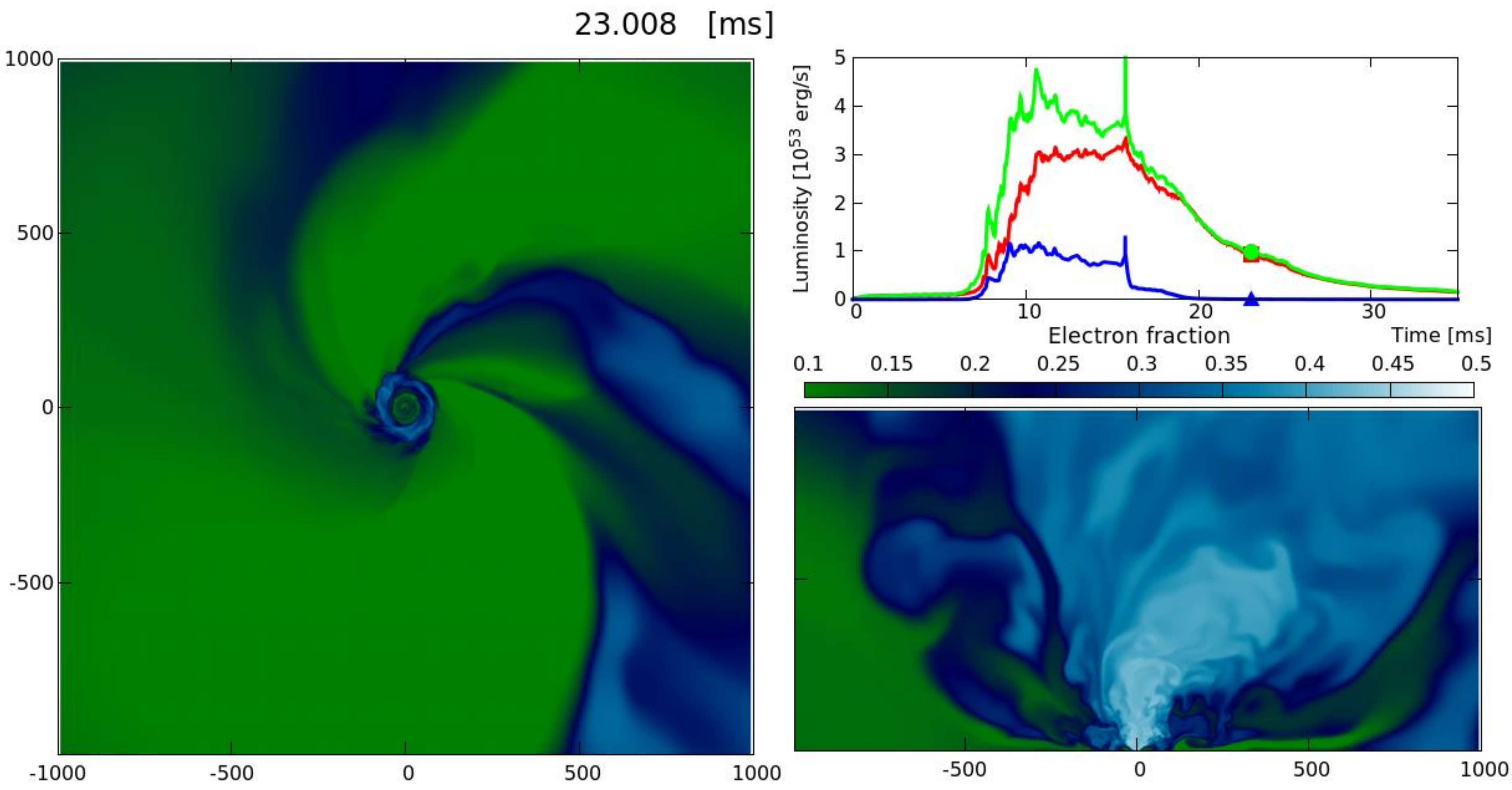




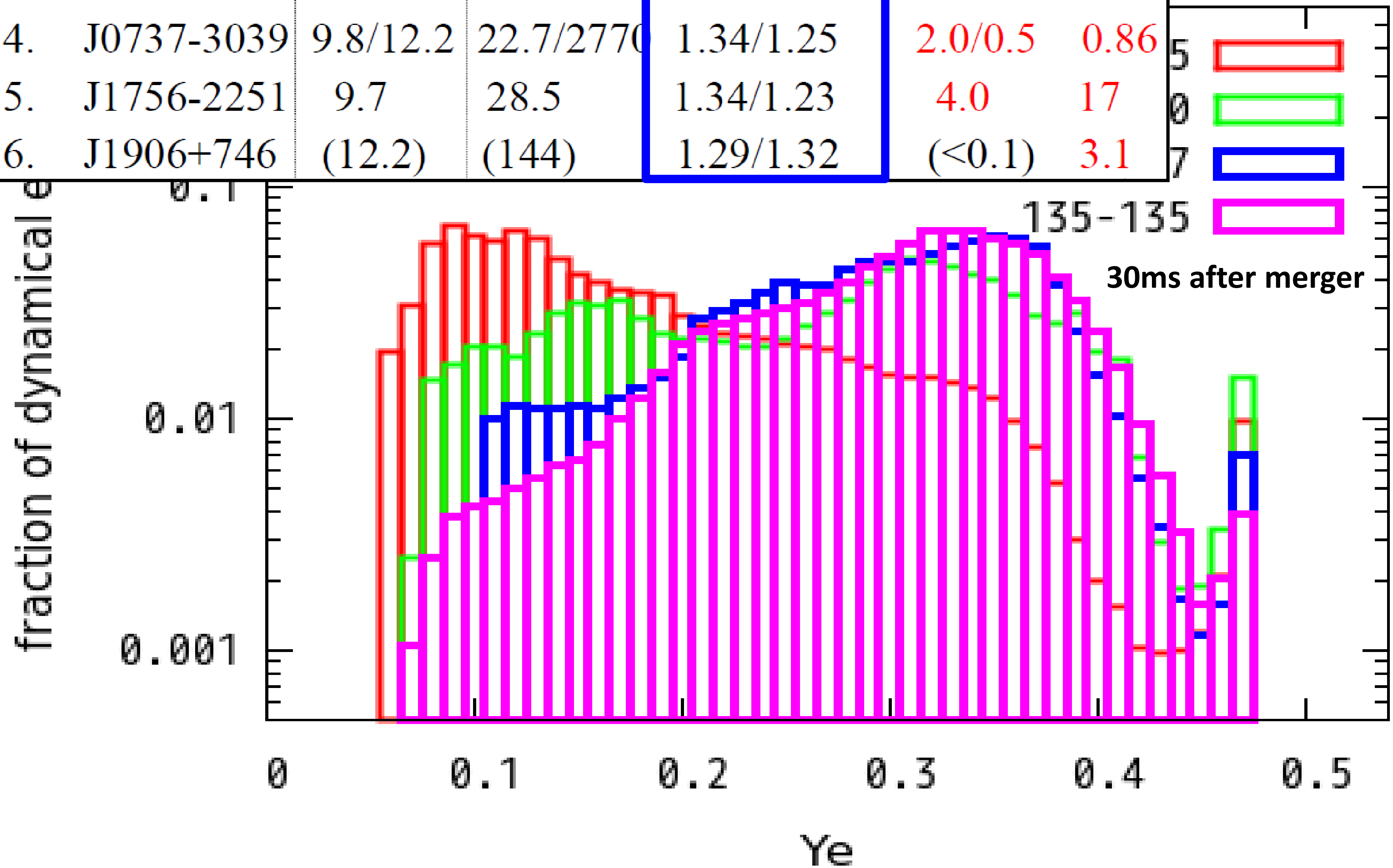
- The Ye-distribution histogram has a broad, flat structure (*Wanajo, Sekiguchi, et al. (2014)*.)
  - Mixture of all Ye gives a good agreement with the solar abundance !
  - Robustness of Universality (dependence on binary parameters)

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

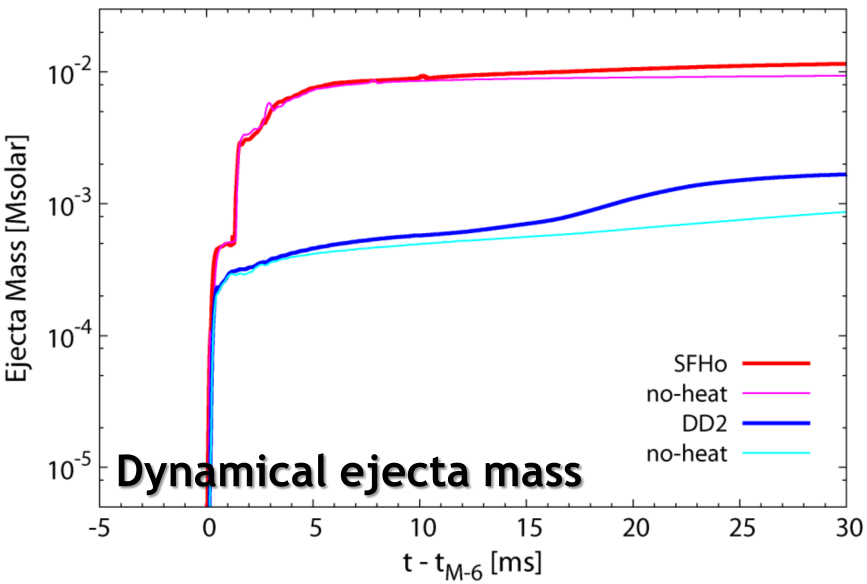


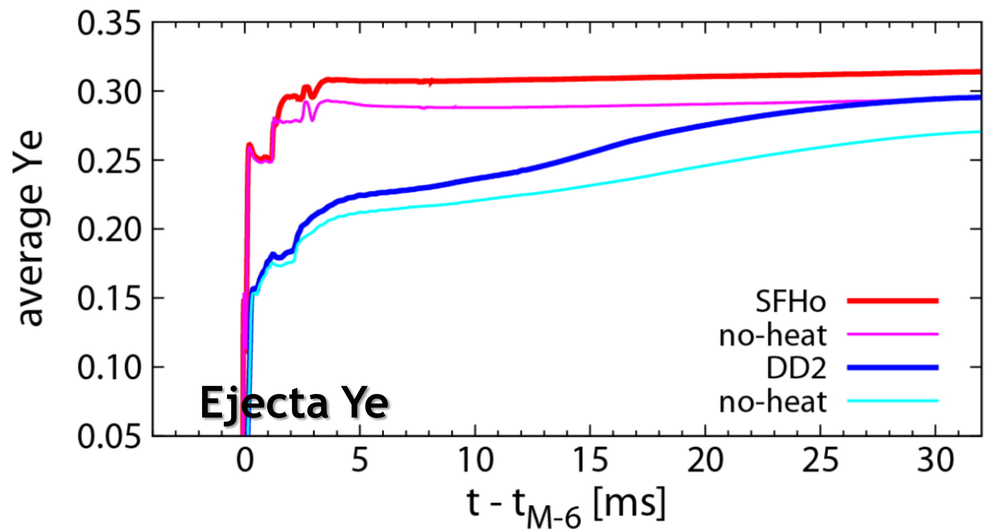
	PSR	log B(G)	P_{rot} (ms)	$M(M_{sun})$	T_{Mag}	T_{GW}
1.	B1913+16	10.4	59.0	1.441/1.387	1.0	3.0
2.	B1534+12	10.0	37.9	1.333/1.345	2.5	27
3.	B2127+11C	10.7	30.5	1.36/1.35	1.0	2.2
4.	J0737-3039	9.8/12.2	22.7/2770	1.34/1.25	2.0/0.5	0.86
5.	J1756-2251	9.7	28.5	1.34/1.23	4.0	17
6.	J1906+746	(12.2)	(144)	1.29/1.32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



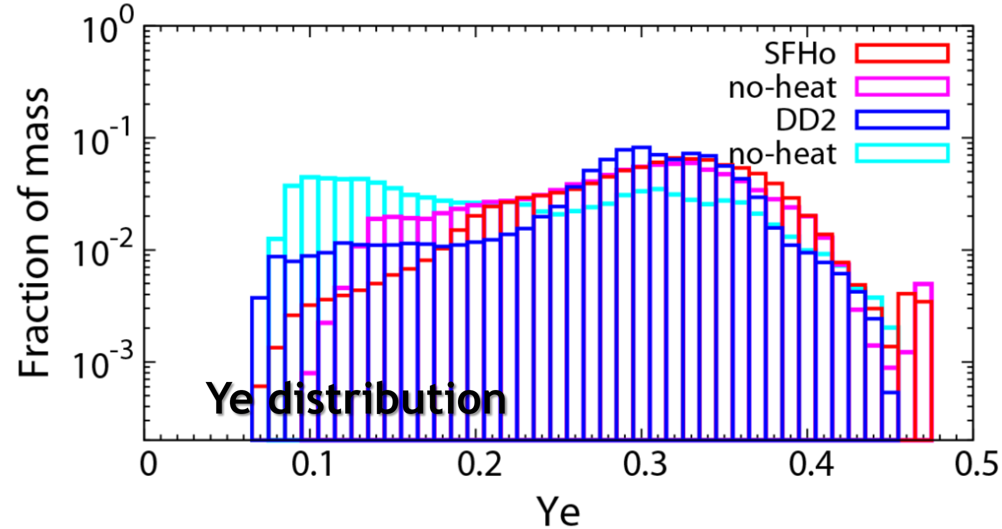
Sekiguchi et al PRD (2015); Prego et al. (2014); Just et al. (2014); Goriely et al. (2015); Martin et al. (2015)

Importance of neutrino heating (absorption)

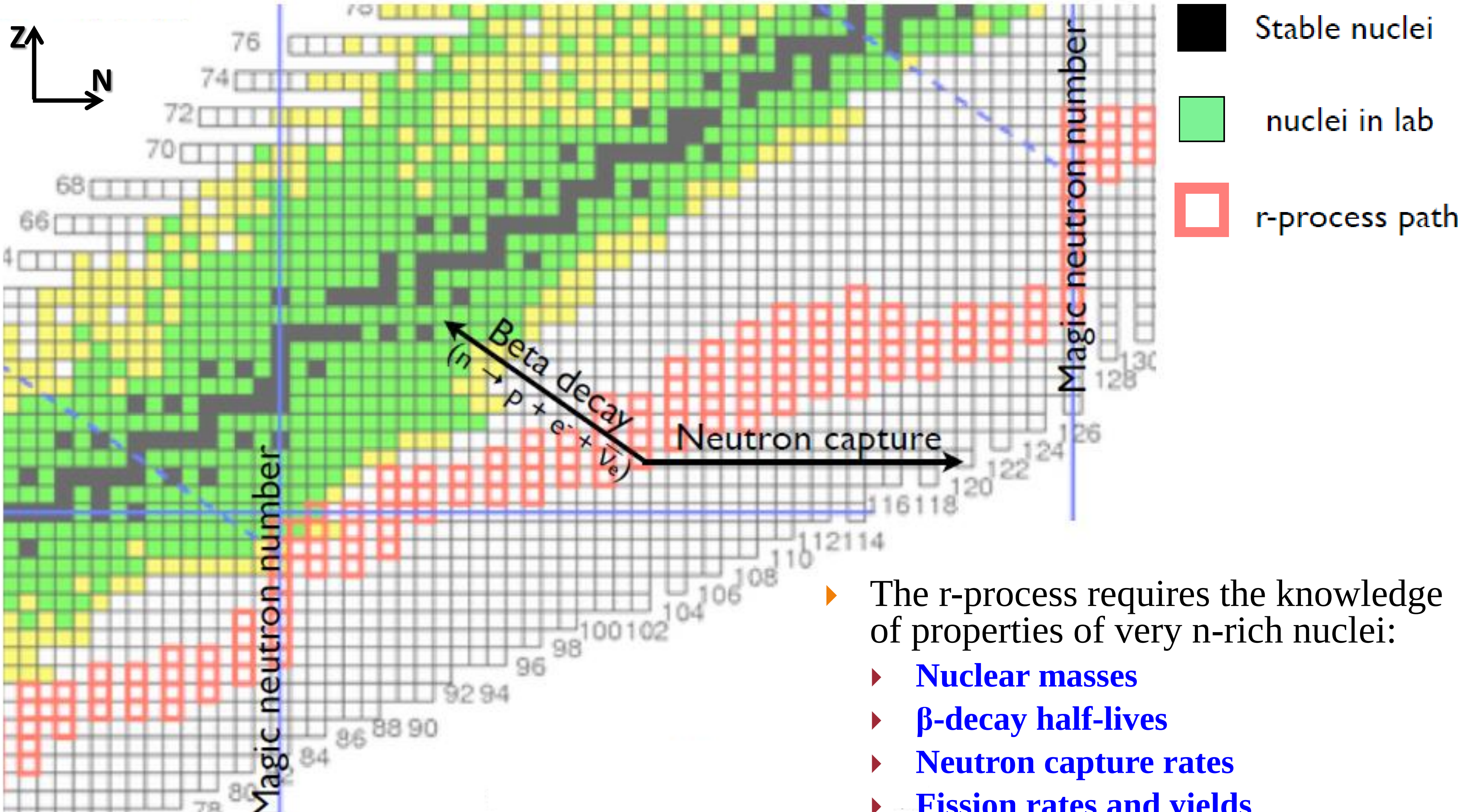




- Amount of ejecta mass can be increased order of 10^{-3} Msun
- Average Ye can change 0.02~0.03 depending on EOS : effect is stronger for stiffer EOS where HMNS survive in a longer time



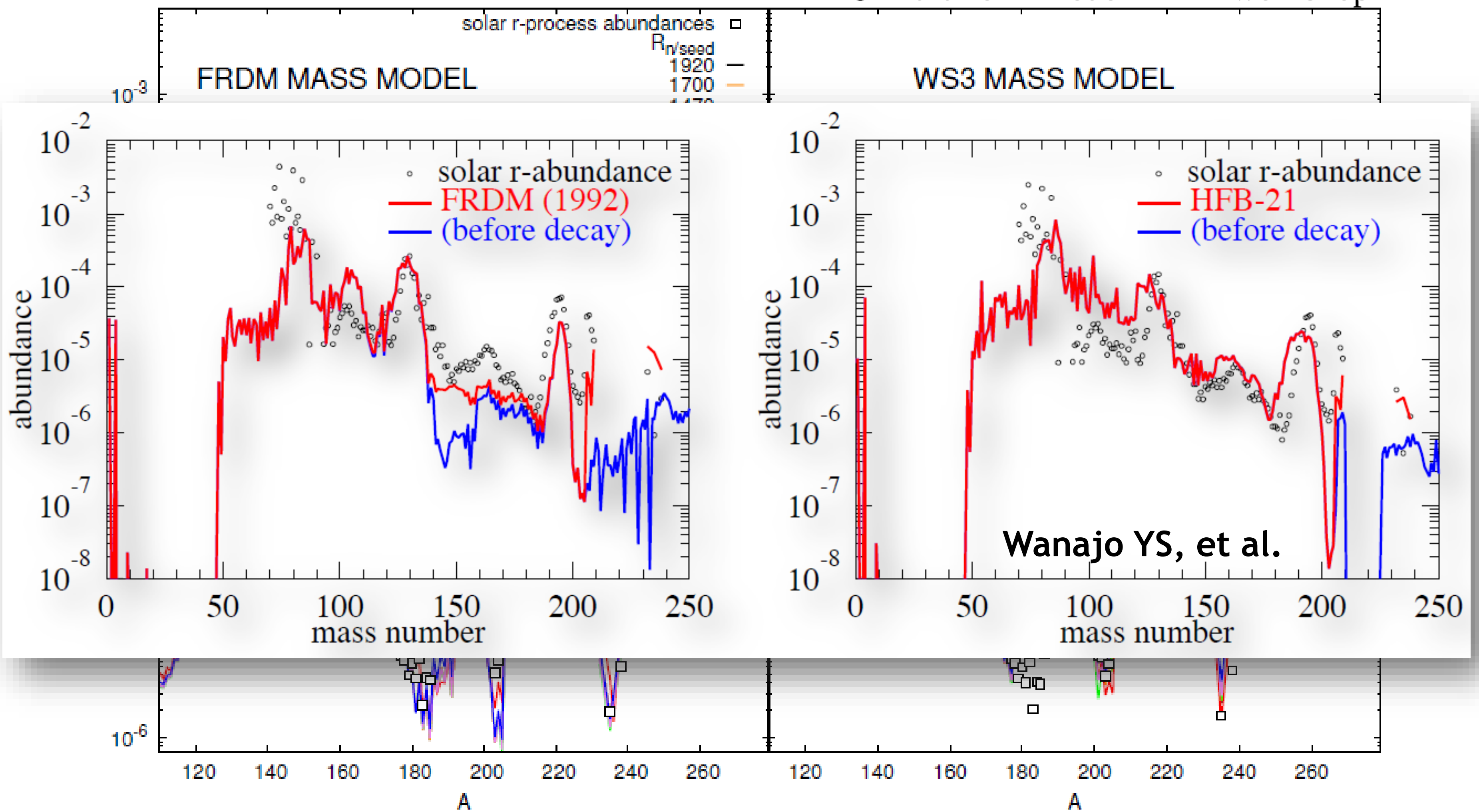
r-process nucleosynthesis: nuclear physics inputs



- 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**

Dependence on mass model

© Martinez-Pinedo in INT workshop



Summary

- A long history about the origin of heavy elements
- Supernovae vs. Neutron star mergers
  - Supernova scenario is now theoretically and observationally disfavored
- Key observation: Universality
  - r-process cite synthesize elements with pattern which is similar to the observed solar pattern
  - Less diverse ‘Initial condition’ or some physical attracter (fission yields)
- General relativity and weak/strong interactions are key to resolve the problem
    - If EOS of NS is soft (like APR or SFHo), then it is strongly suggested that the origin of heavy elements are BNS mergers.

Final words:
Towards the first direct detection of GW

- The first detection of neutrinos
  - Simultaneous observation of SN 1987A (EM counterpart to neutrino) was very important
  - Similarly, EM counterpart to GW could play a role
- Possible EM counterpart to GW
  - Short GRBs : likely to be collimated => Most of them are off axis and faint
    - SGRB111020A : $\theta_j \sim 3\text{-}8^\circ$ (Fong et al. 2012)
    - SGRB051121A : $\theta_j \sim 7^\circ$ (Burrows et al. 2006)
  - We need 4π counterparts
  - 'kilonova' like event from radioactive decay of r-process nuclei is one of promising candidates
  - Many studies : Rosswog, Goriely, Bauswein, Metzger, Kasen, YS, Wanajo, Hotokezaka, Tanaka
  - Studies based on full GR simulations on going in collaboration with Wanajo, Tanaka (Subaru group), …

Kilonova/Macronova/r-process nova

- Merger ejecta will be neutron rich: rapid neutron capture (r-process) proceeds (Lattimer & Schramm 1974) : **n + (Z,N) ⇒ (Z,N+1)**
- Competition with the β-decay : **(Z,N+1) ⇒ (Z+1,N) + e + $\bar{\nu}_e$**
  - The r-process is very sensitive to how much neutrons are there, that is, to the electron fraction Ye (= Yp = 1 – Yn) : we need michrophysics !
- Then, **EM transients powered by radioactivity of the r-process elements** are expected (Li & Paczynski 1998; Kulkarni 2005; Metzger et al. 2010)

$$t_{\rm peak} \sim 1\,{\rm days}\left(\frac{v}{0.3c}\right)^{-1/2}\left(\frac{M}{0.01M{\rm solar}}\right)^{1/2}\left(\frac{\kappa}{0.1\,{\rm cm}^2/g}\right)^{1/2}$$

$$L_{\rm peak} \sim 10^{42}\,{\rm erg/s}\left(\frac{f}{10^{-6}}\right)\left(\frac{v}{0.3c}\right)^{1/2}\left(\frac{M}{0.01M{\rm solar}}\right)^{1/2}\left(\frac{\kappa}{0.1\,{\rm cm}^2/g}\right)^{-1/2}$$

$$T^{\rm eff}_{\rm peak} \sim 10^{4}\,{\rm K}\left(\frac{f}{10^{-6}}\right)^{1/4}\left(\frac{v}{0.3c}\right)^{-1/8}\left(\frac{M}{0.01M{\rm solar}}\right)^{-1/8}\left(\frac{\kappa}{0.1\,{\rm cm}^2/g}\right)^{-3/8}$$

Kilonova/Macronova/r-process nova

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  - The r-process is very sensitive to how much neutrons are there, that is, to the electron fraction Ye (= Yp = 1 – Yn) : we need michrophysics !
- Recent critical update : Opacities are dominated by lanthanoids : orders of magnitude (~100) larger (Kasen e al. 2013; Tanaka & Hotokezaka 2013)

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

1 day ⇒ 10 days

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

1/10 dimmer

$$T^{\rm eff}_{\rm peak} \sim 2\times10^{3}\,{\rm K}\left(\frac{f}{10^{-6}}\right)^{1/4}\left(\frac{v}{0.3c}\right)^{-1/8}\left(\frac{M}{0.01M{\rm solar}}\right)^{-1/8}\left(\frac{\kappa}{10\,{\rm cm}^2/g}\right)^{-3/8}$$

Opt-UV ⇒ NIR

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

NS-NS vs. BH-NS

- kilonova and total mass of r-process element => **Mej > 0.01 Msun**
- **NS-NS :** **Soft EOS is necessary** (shocks play a role)
  - **Small diversity** in conditions before merger, Mej ~ 0.01 Msun will be universal within the typical mass range of NS-NS for soft EOS
- **BH-NS :** **Stiffer EOS is preferable** (tidal component is dominant)
  - **some diversity** is expected, because mass ejection (mostly tidal-driven) depends further on ***mass and spin of BH*** in addition to EOS

Hotokezaka et al. (2013)