Collapsar scenario and NS-NS mergers

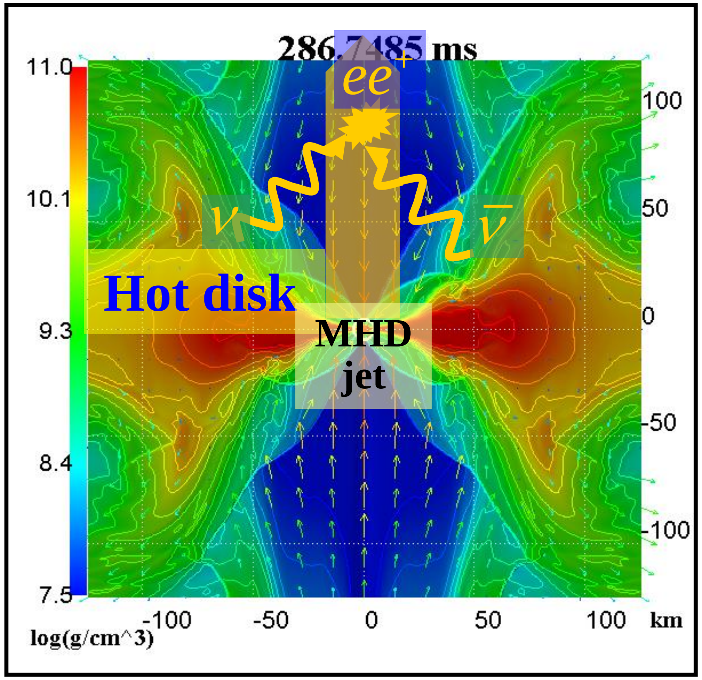
Yuichiro Sekiguchi (YITP)

A personal view on Collapsar scenario

Yuichiro Sekiguchi (YITP)

Dilemmas in Long GRB Progenitor

- **On the one hand, rapid rotation is necessary**
  - Collapsar scenario (BH + Disk)
    - □ Gravitational energy of disk ⇒ neutrinos
    - □ Rotational energy of BH⇒Poynting flux
  - Rapid rotation is crucial also in other scenario
    - E.g. magnetar scenairo: more severe due to magneitic spindown due to strong B fields
    - At least, no evidence that magnetar remnants are more energetic (not rapidly rot. NS) (Vink 2008)



Sekiguchi & Shibata 2007

- **On the other hand, association of Type-Ic HNe**
  - The progenitor star must have lost H/He envelopes
  - At the same time of mass loss, angular momentum is also lost if the envelopes are brown off by stellar wind
    - ⇒ slow rotator (e.g. Yoon et al. 2005, Woosley & Heger 2006)

- **How to make SNe component in the case of BH formation at all**

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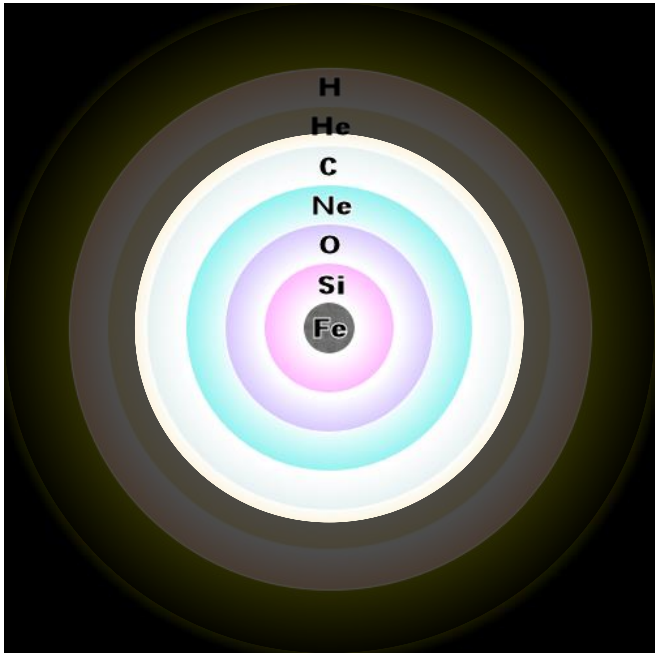

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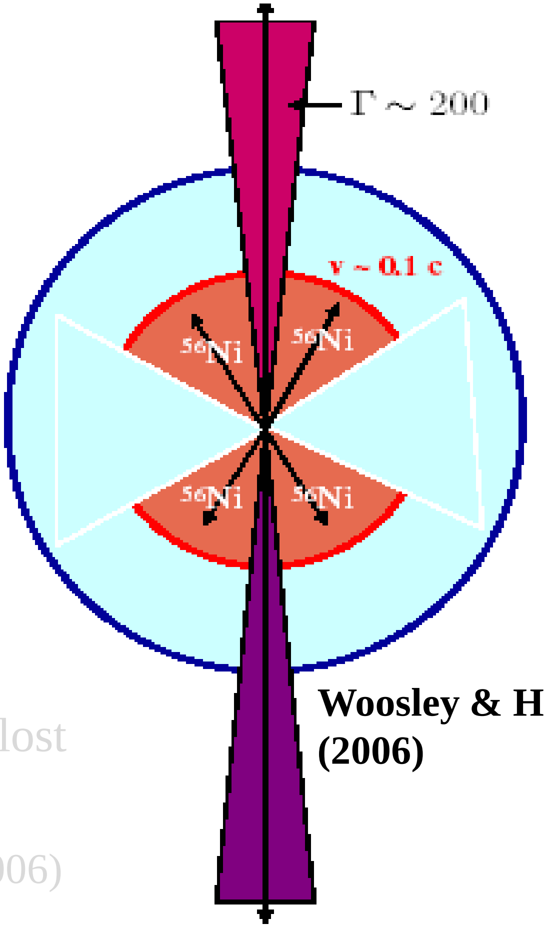
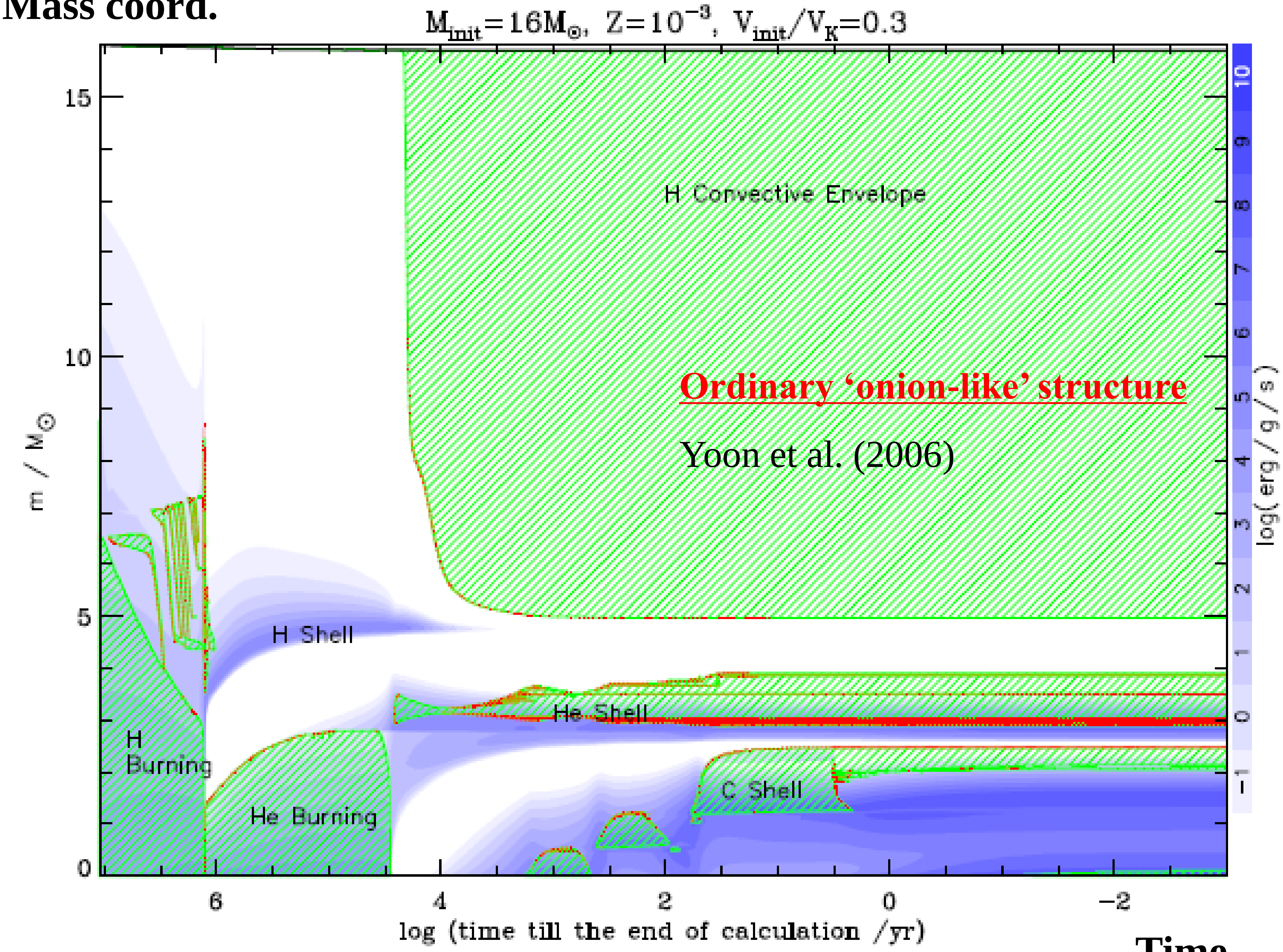


Woosley & Heger (2006)

Currently proposed models

- Peculiar progenitor models are necessary
  - LGRBs are anomalous : Progenitor cores may also be anomalous
    - He star merger model (Fryer & Heger 2005)
    - Tidal spun up star model (van den Huevel & Yoon 2007)
    - **Chemically homogeneous evolution model (Woosley & Heger 2006, Yoon et al. 2006)**
  - All of models predicts progenitor structure far different from ordinary ‘onion-structured’ SN cores
    - Strong mixing due to rapid rotation (Zahn 1983) ⇒ smaller envelope
      - ☐ Can reduce the amount of mass/angular momentum loss
    - For Ω > Ωcrit, chemically homogenous structure is achieved
      - ☐ No ‘onion-like’ structure
    - **Higher-entropy cores are predicted !!**

Mass coord.

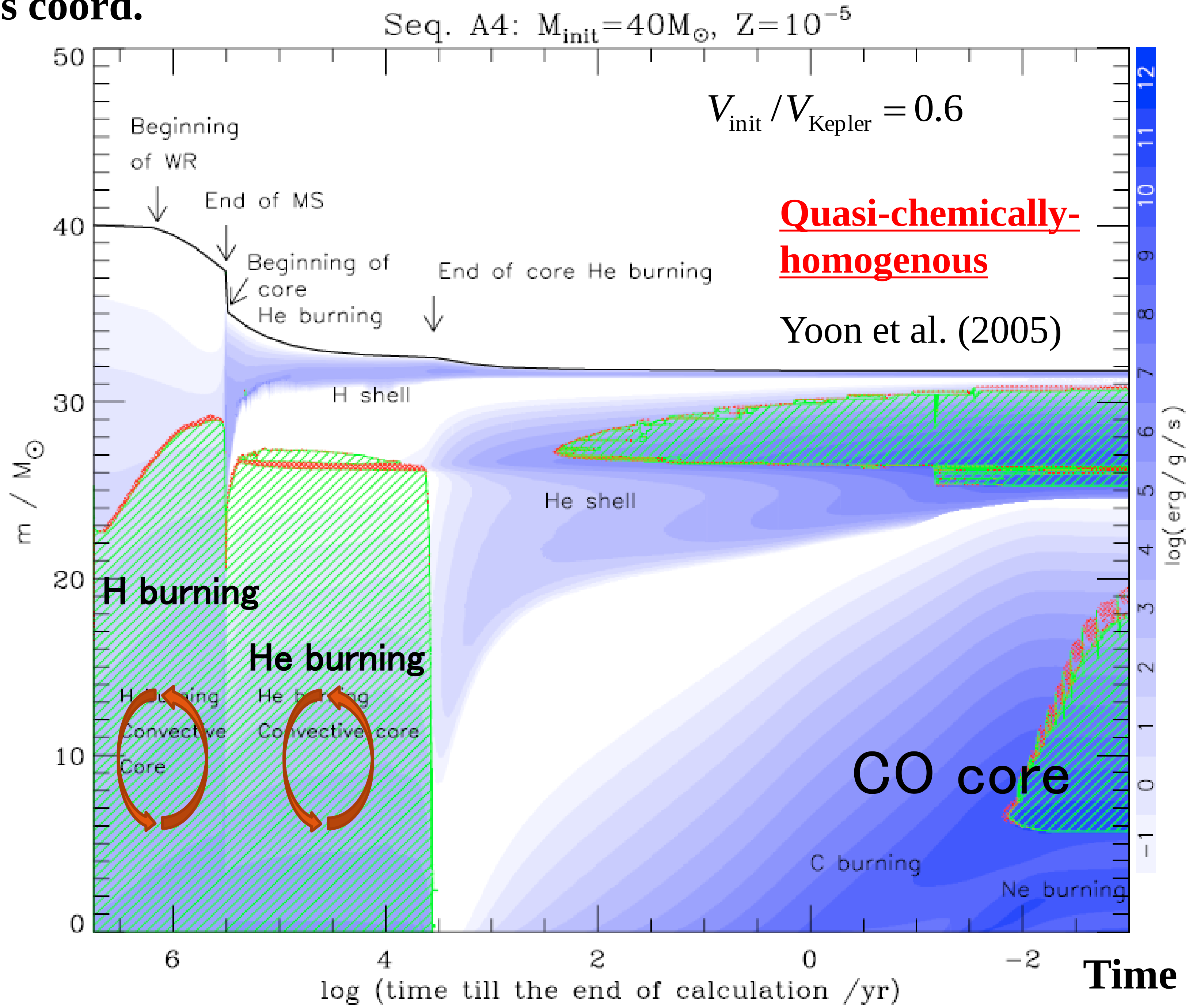


Ordinary 'onion-like' structure

Yoon et al. (2006)

Time

Mass coord.



$V_{\text{init}} / V_{\text{Kepler}} = 0.6$

Quasi-chemically-homogenous

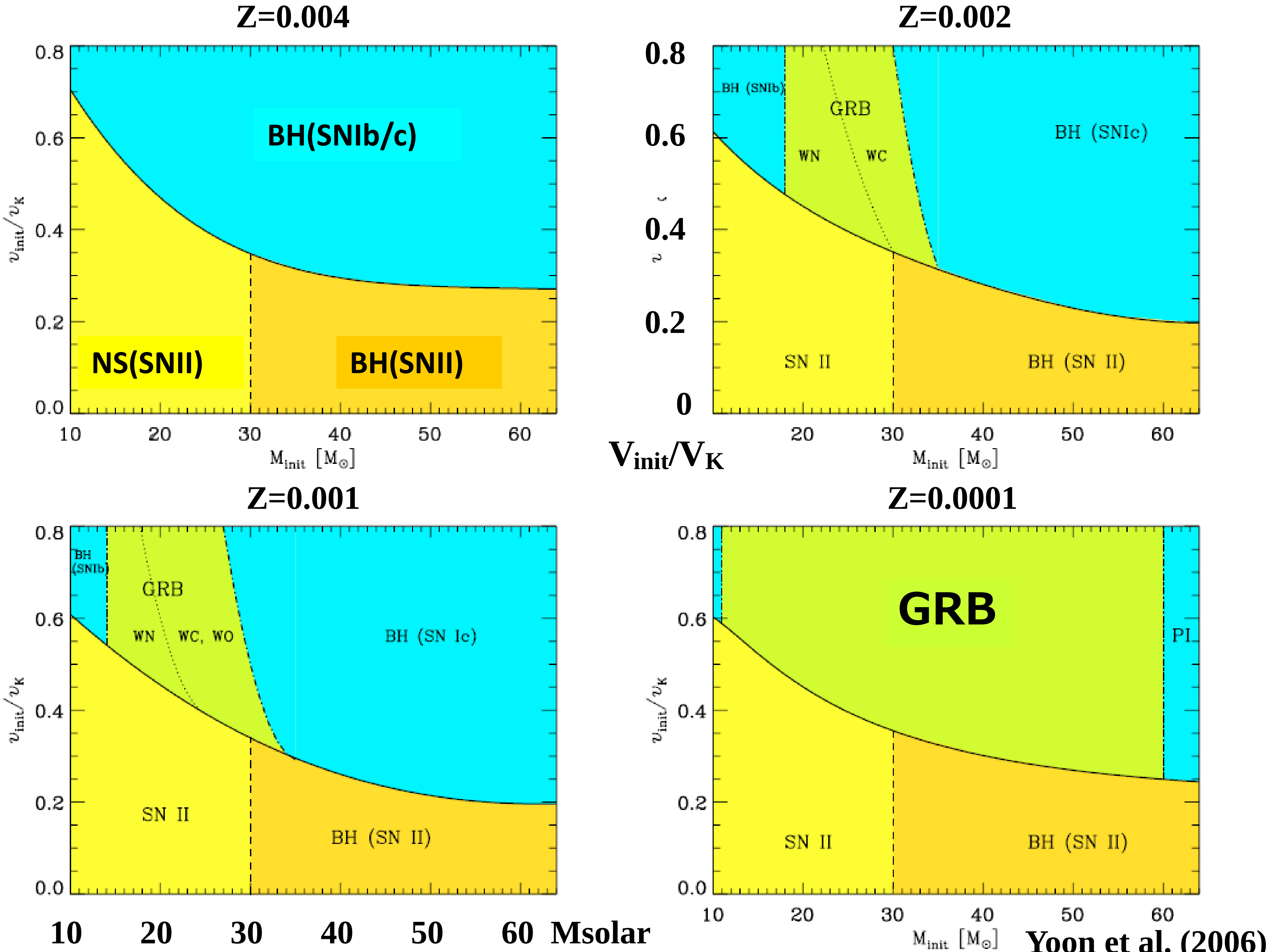
Yoon et al. (2005)

H burning

He burning

CO core

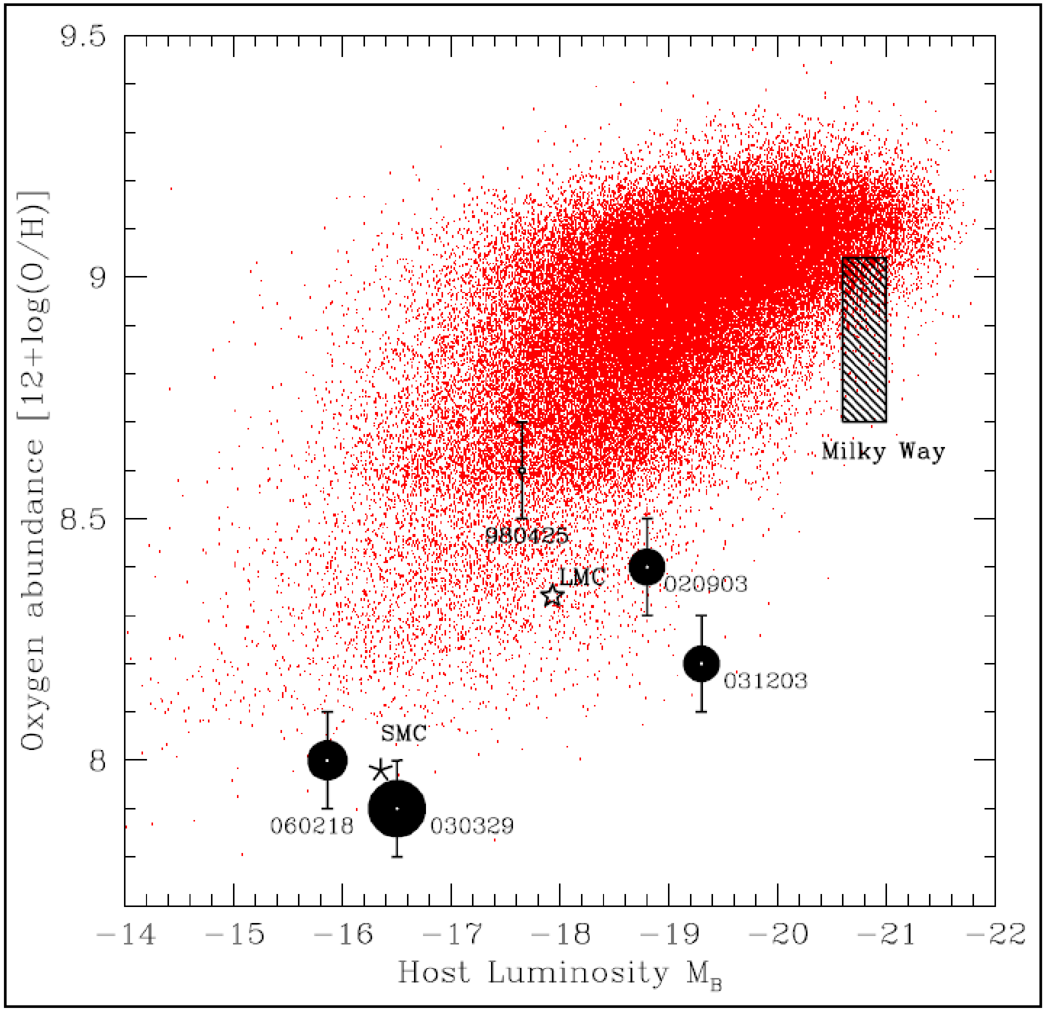
Time



Yoon et al. (2006)

A observational suggestion: GRB may prefer low metallicity

- First suggested by Stanek et al. (2006)
  - see also Modjaz et al. (2008)



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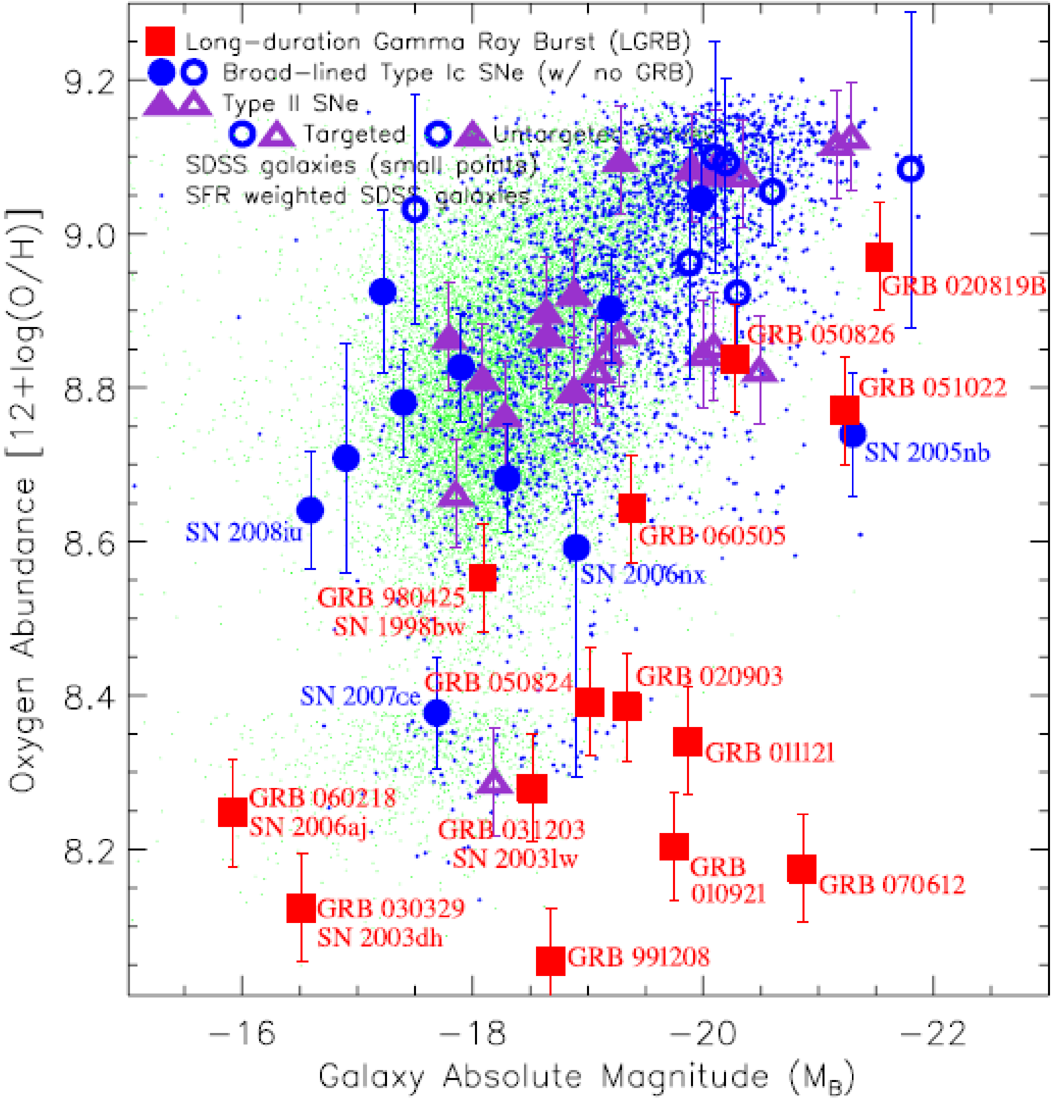
- Recent updates (Graham & Fruchter 2013)
  - **Statistical significance ↑ by # of sample ↑**
  - **Targeted type Ic SN bias ? ⇒ untargeted Ic-SN analysis**
  - Nearby SDSS event bias ? ⇒ Events in Team Keck Redshift Survey further event (z~0.8)
  - Merely due to anti-correlation between SFR and mettallicity ?⇒ No ! Something intrinsic is required



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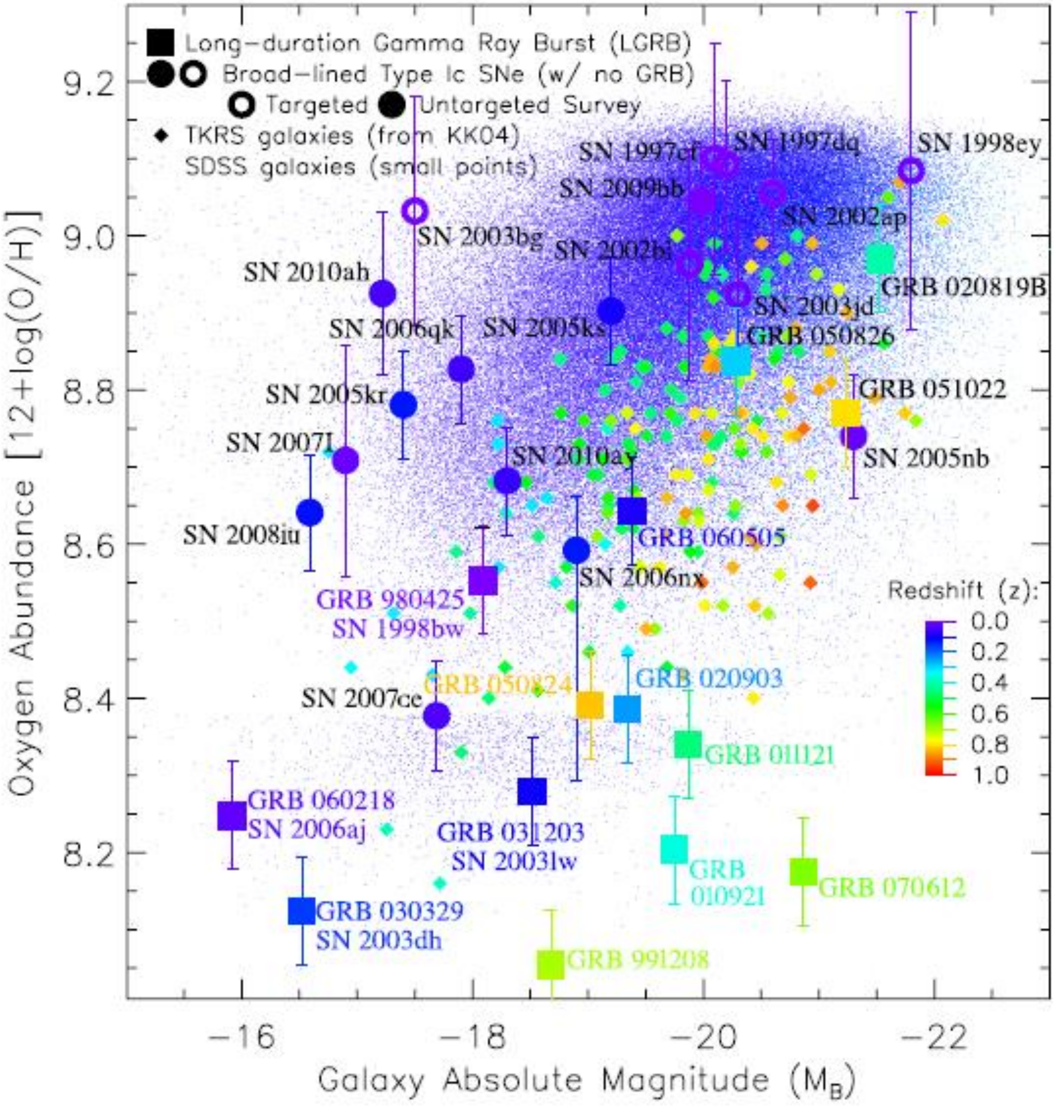
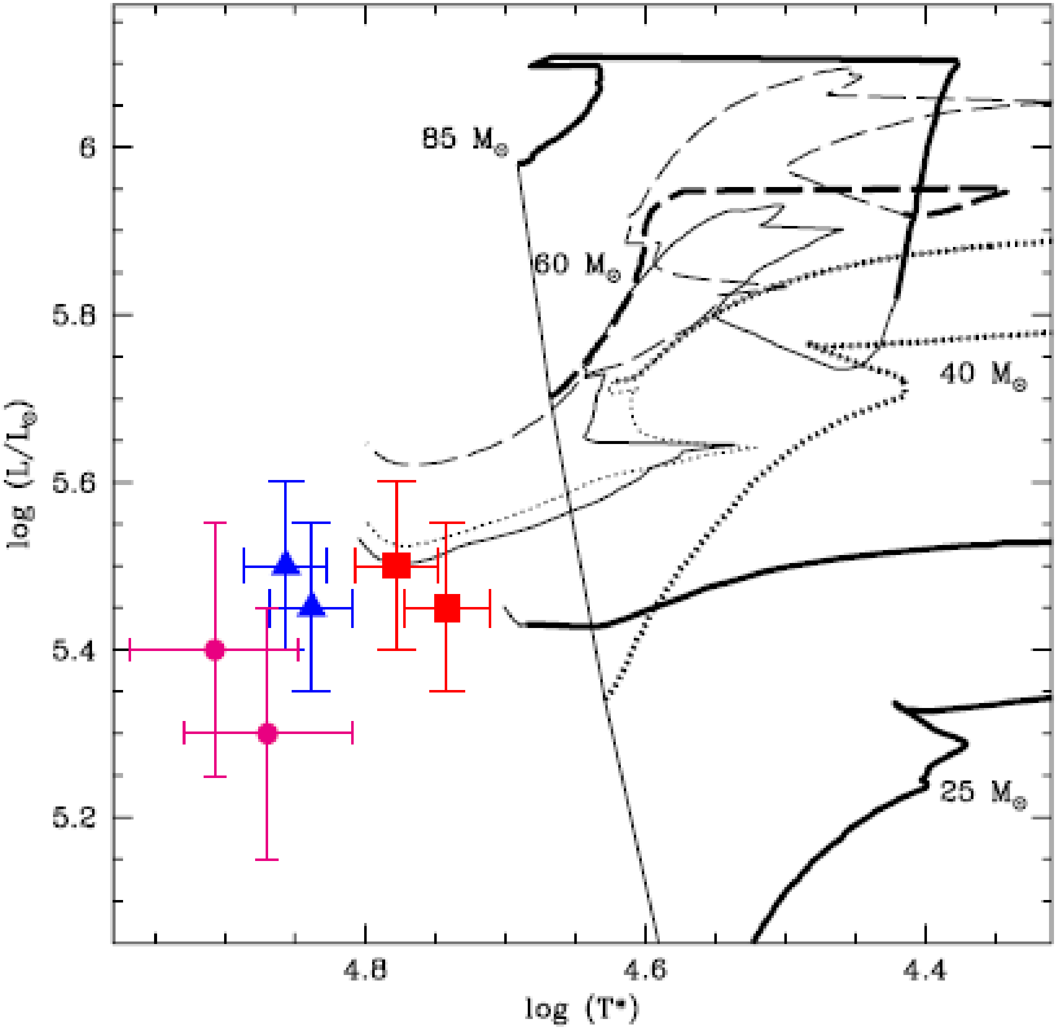


Chemically homogeneous star candidates

- Hydrogen-rich (X(H) > 0.1) blue stars in LMC, SMC
- Ordinary evolution (Meynet & Maeder 2005 + 2 other groups) cannot explain these stars: Wolf-Rayet star with almost no H will be the outcome
  - Black thick curves in the figure denote X(H)>0.1
- But consistent with Chemically Homogeneous evolution models



Martins et al. 2009, 2013

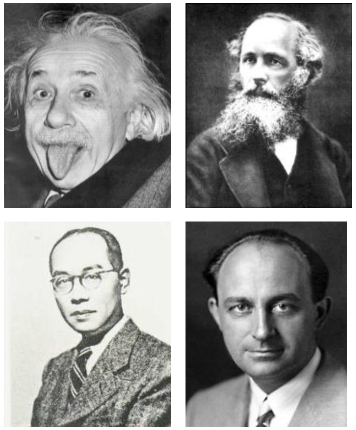
What is Numerical Relativity ?

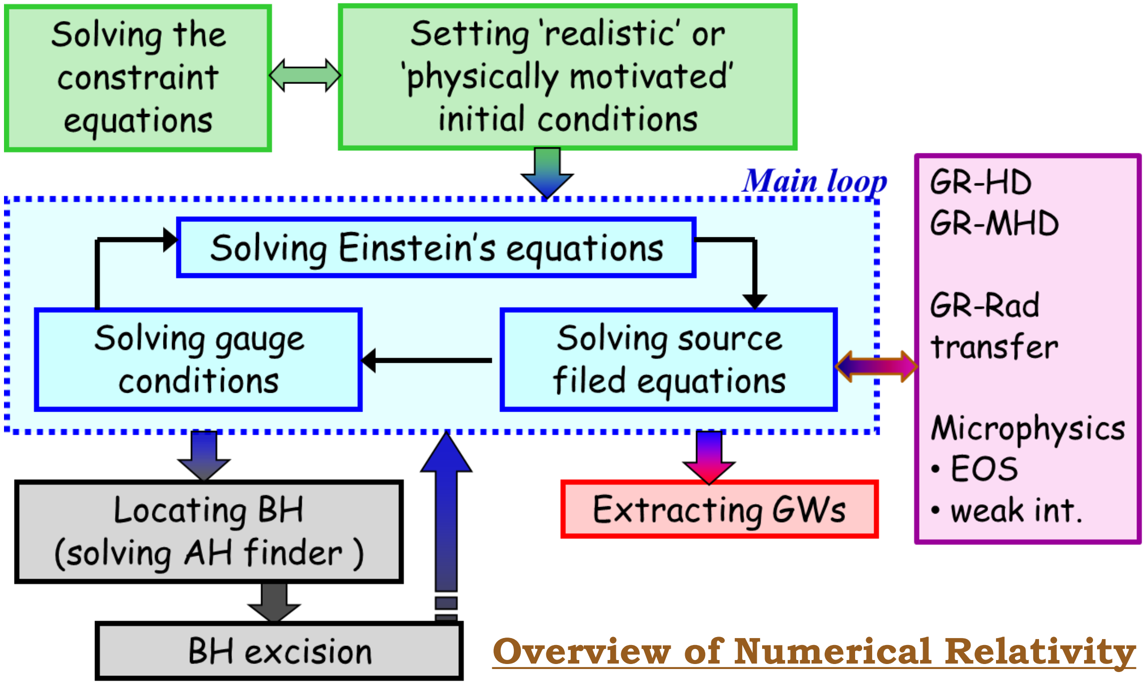
- Solving Einstein eq. and source field eqs. to clarify dynamical phenomena in the universe where strong gravity plays a role

$$G_{ab} = \frac{8\pi G}{c^4} T_{ab}$$

$$\nabla_a T^{ab} = 0 \quad (T^{ab} = (T_{\text{Fluid}} + T_{\text{EM}} + T_\nu + \dots)^{ab})$$
$$\nabla_a J^a = 0 \quad (J^a \sim (n_{\text{baryon}},\ n_{\text{lepton}}(n_e, n_\nu, \dots),\ \dots) u^a)$$

- All four known interactions play important roles
  - **Gravity** : BH/NS formation
  - **Strong** : EOS (Equation of State)
  - **EM** : MHD phenomena
  - **Weak** : Neutrino





Solving the constraint equations

Setting 'realistic' or 'physically motivated' initial conditions

Main loop

Solving Einstein's equations

Solving gauge conditions

Solving source filed equations

GR-HD
GR-MHD

GR-Rad transfer

Microphysics
- EOS
- weak int.

Locating BH (solving AH finder)

BH excision

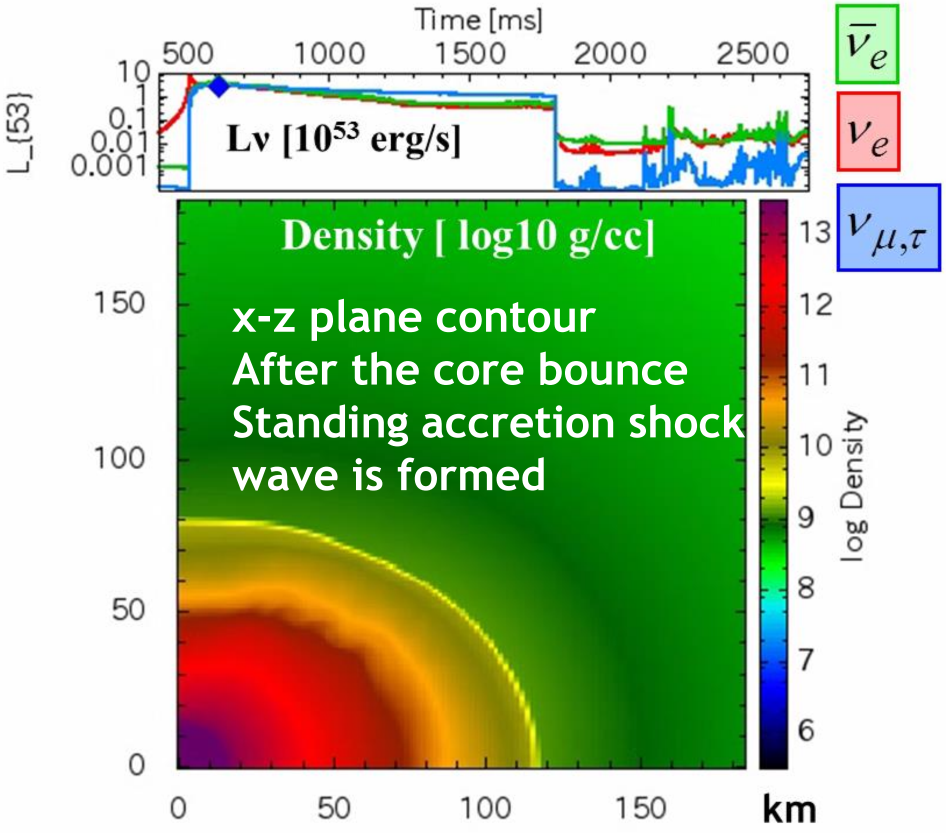
Extracting GWs

Overview of Numerical Relativity

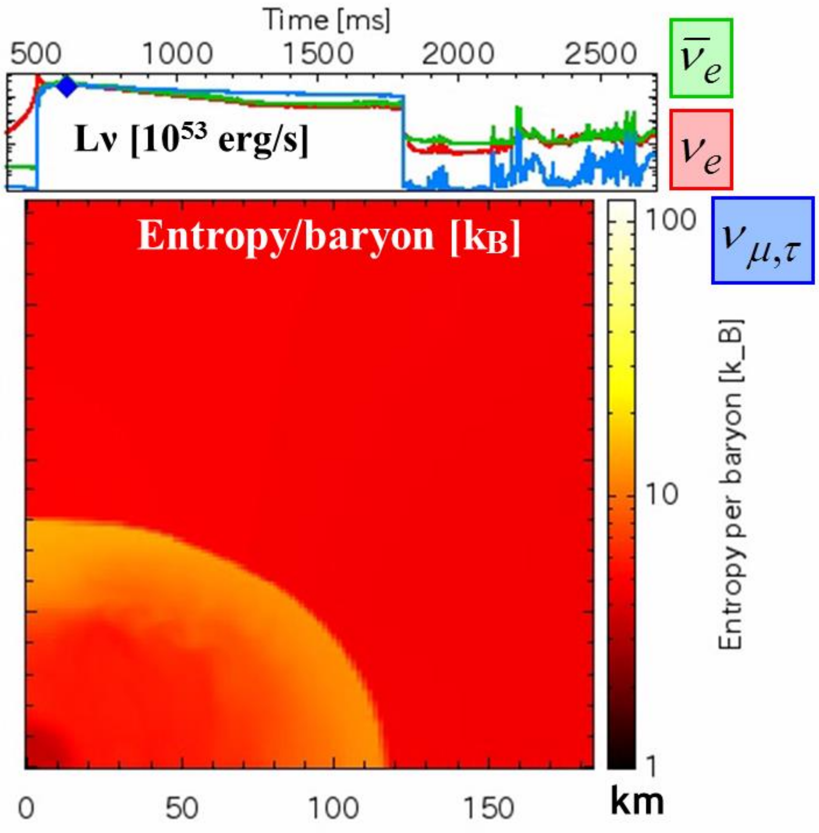
Sekiguchi et al. (2012) Progress of Theoretical & Experimental Physics
Sekiguchi & Shibata ApJ (2011)

Collapsar as High-entropy core collapse

- Full GR simulations with neutrino cooling of collapse of 100Msun very metal poor progenitor model by Umeda & Nomoto (2008)
  - Entropy per baryon ~ 4kB >> ordinary SN core ~ 0.5kB
  - Rotational profile is superimposed so that accretion torus is formed



x-z plane contour
After the core bounce
Standing accretion shock wave is formed



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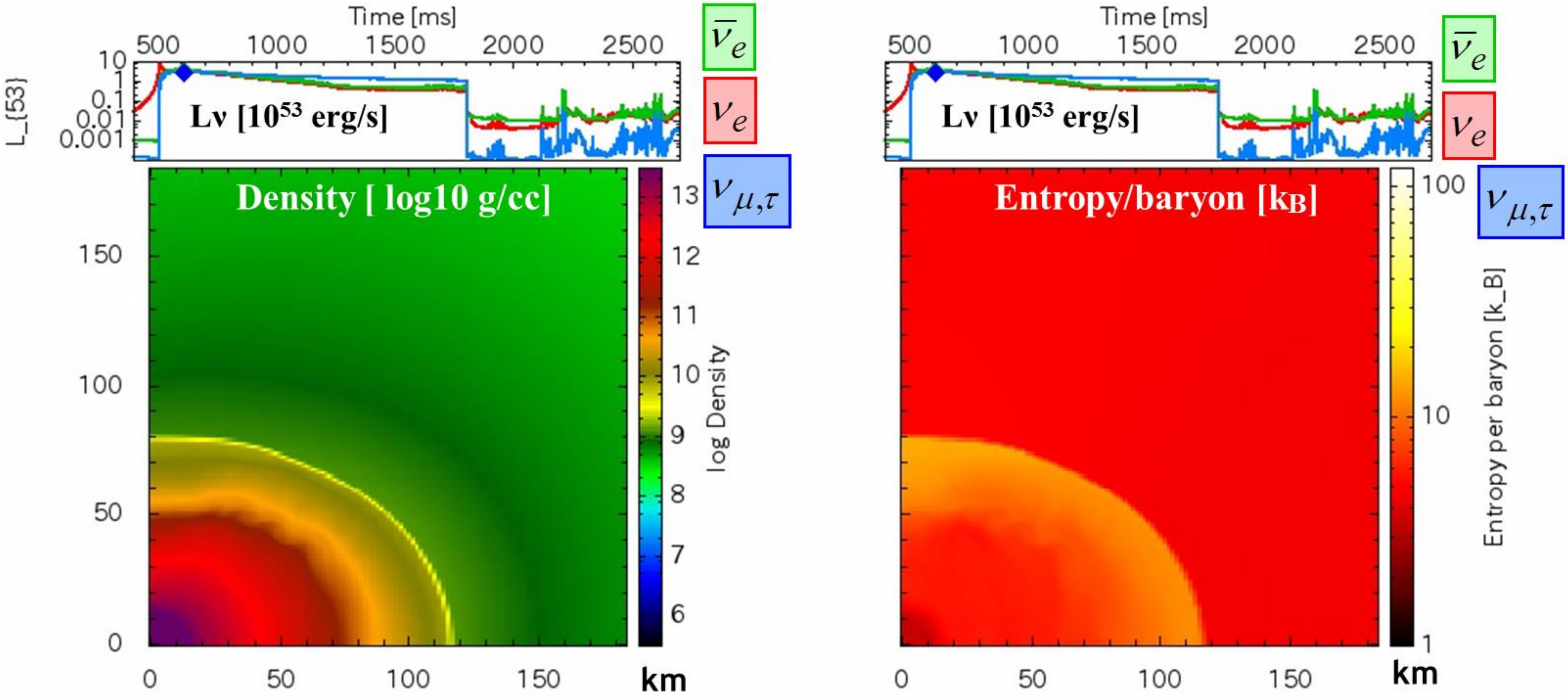
  - Torus and PNS are overheated (explained later) ⇒ convection



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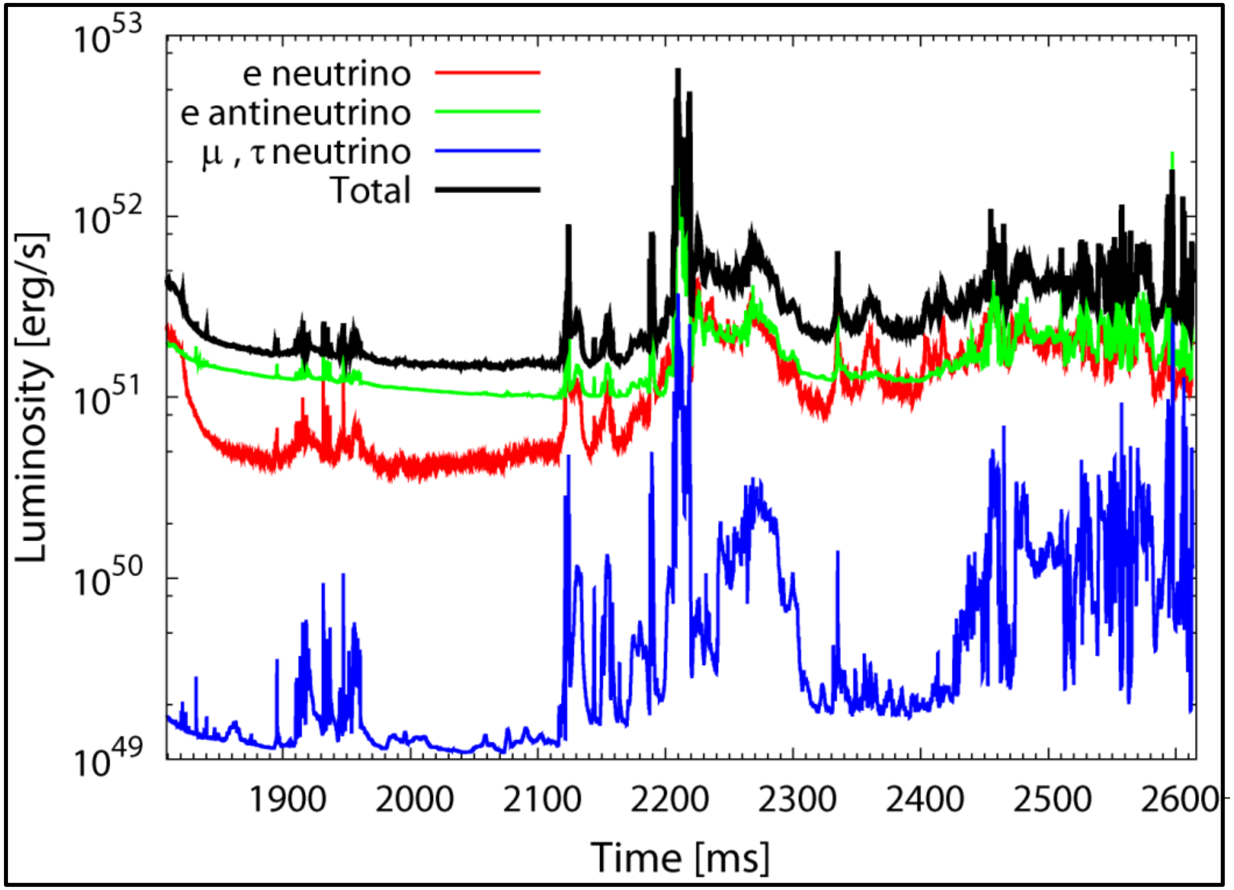

Collapsar as high-entropy core collapse and long GRB

- dM/dt (larger in higher entropy) is crucial in collapsar scenario
  - ν-pair annihilation efficiency (increases as Lν increases)

$$(\mathrm{eff})_{\nu\bar{\nu}} \sim 0.01 \left(\frac{\dot{M}}{M_{\mathrm{sun}}/s}\right)^{5/4} \left(\frac{M_{\mathrm{BH}}}{10M_{\mathrm{sun}}}\right)^{-3/2} \quad \text{(Zalamea \& Belborodov 2011)}$$

$$\sim 0.01 \frac{L_\nu}{10^{53}\,\mathrm{erg/s}} \frac{\langle \varepsilon_\nu \rangle}{10\mathrm{MeV}} \quad \text{(Setiawan et al. 2005)}$$

  - Blandford-Znajek power (McKinney 2005)
    - B-fields quickly decay due to the horizon diffusivity unless the accretion supply B

$$(B_H^{\perp})^2 \sim 3\times10^{31} f_\Omega \left(\frac{\dot{M}}{M_{\mathrm{sun}}/s}\right)\left(\frac{M_{\mathrm{BH}}}{10M_{\mathrm{sun}}}\right)^{-2}$$

$$\dot{E}_{\mathrm{BZ,\,jet}} \sim 0.1\dot{E}_{\mathrm{BZ,\,total}} \sim 10^{51} f_\Omega q_{\mathrm{BH}}^2 \left(\frac{\dot{M}}{M_{\mathrm{sun}}/s}\right) \mathrm{erg/s}$$

    - Optimistic case ($\Omega_B=\Omega_H/2$), f_Ω=5 for q_{BH}~0.75 (very rapidly rotating case)
- Disk/Torus Topology will be changed
  - Geometrically thick torus (pair annihilation will be enhanced: Liu et al. 2010)
  - Convection may produce poloidal B-field otherwise toroidal field dominant due to rapid rotation (B-field topology crucial for BZ power; Beckwith et al. 2008)

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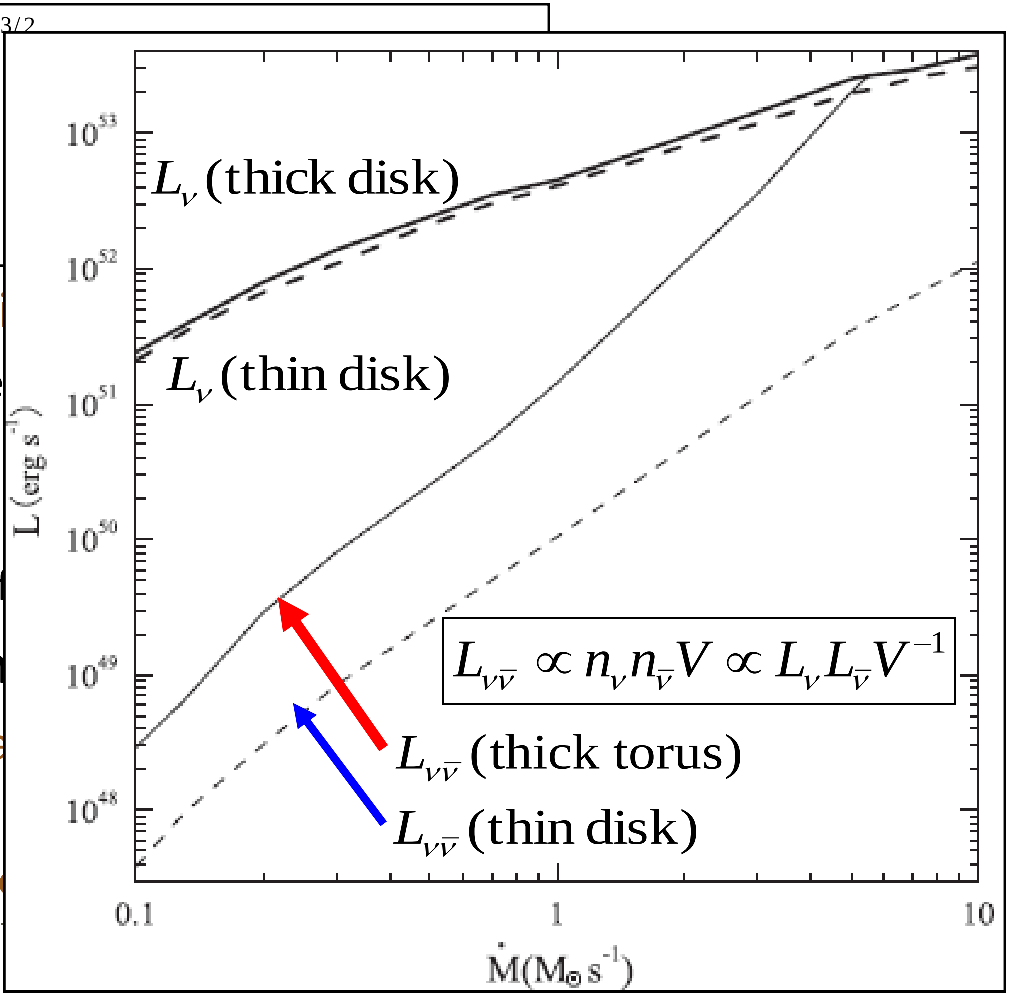

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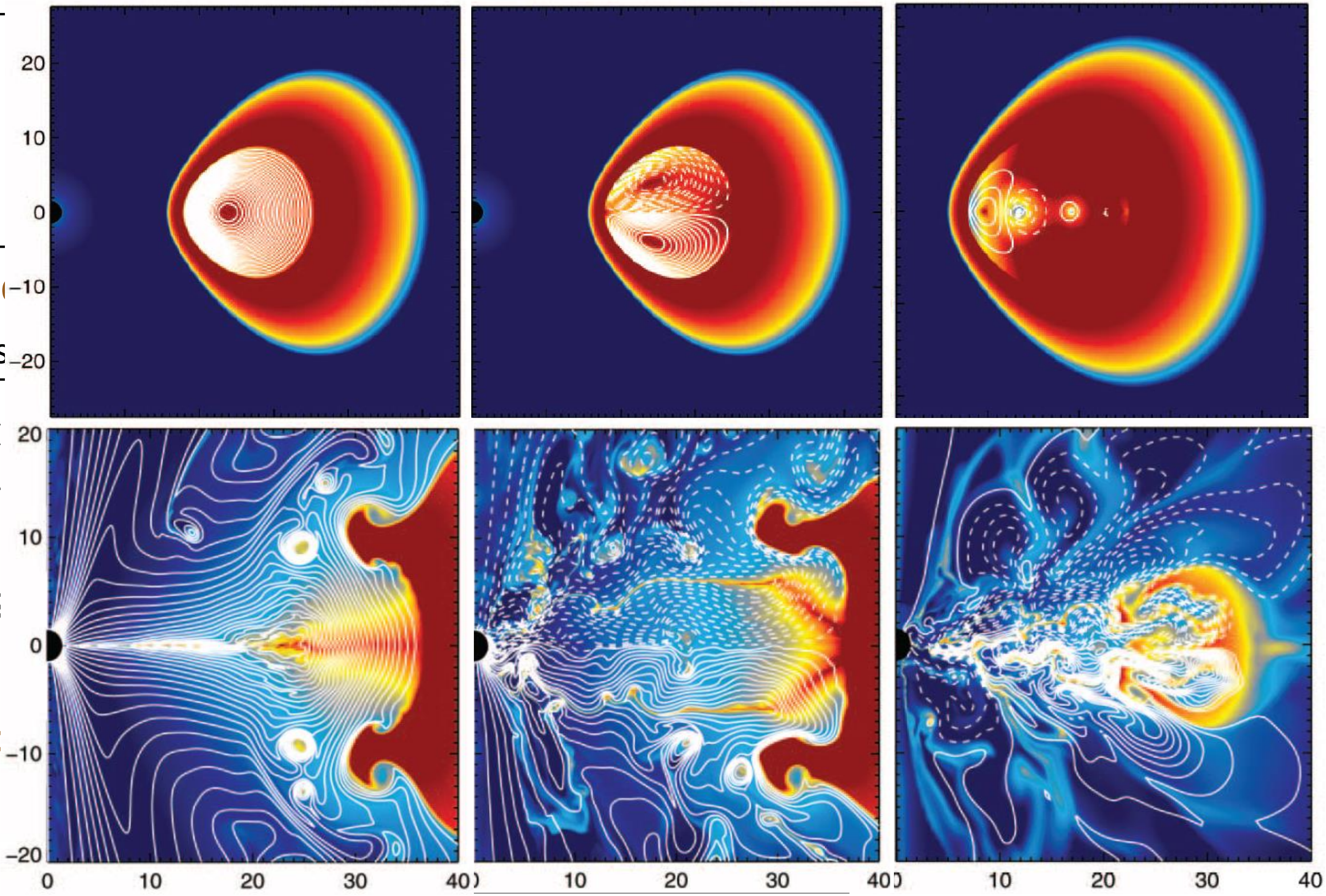
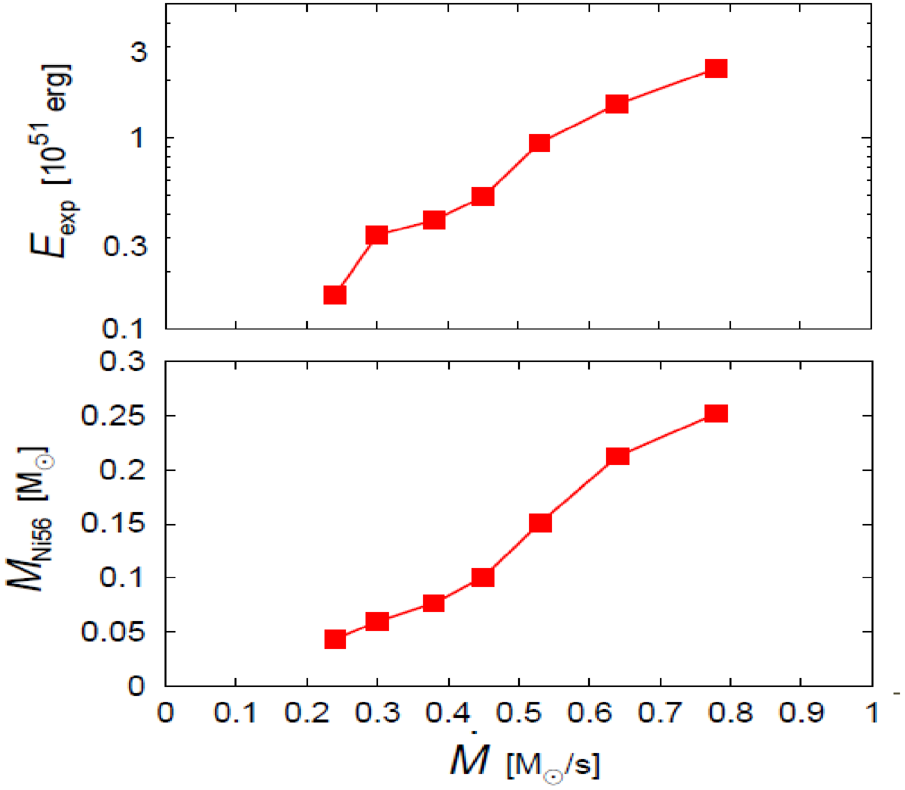
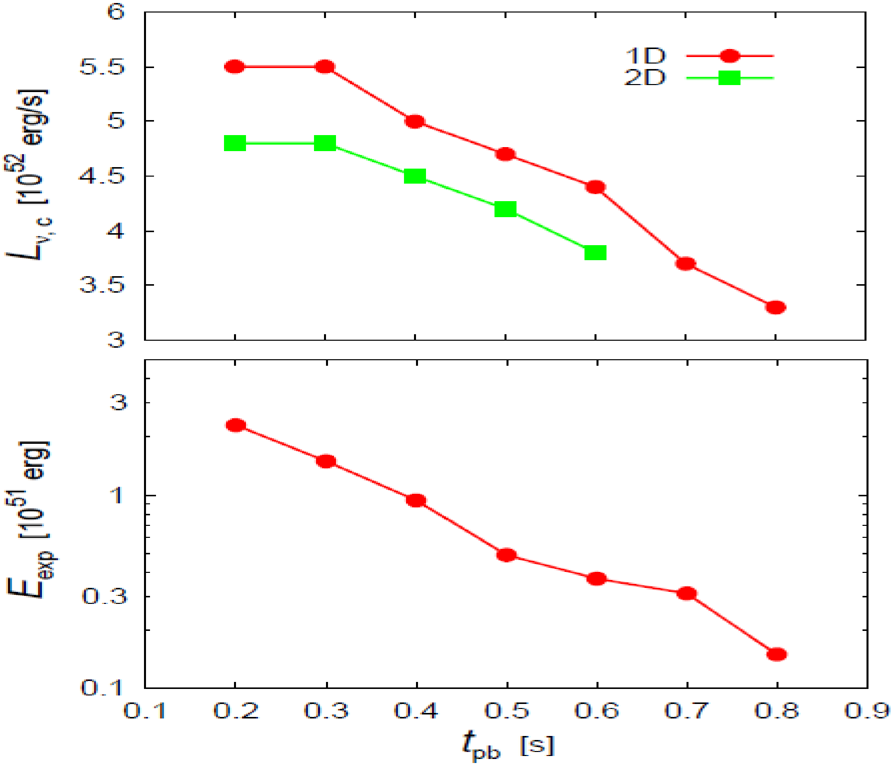


Collapse of high-entropy core and hypernovae (1)

- Consequences of higher entropy
  - higher dM/dt⇒ larger explosion energy ？(Yamamoto et al. 2013)
    - dM/dt, Lnu shows interesting values (compared with Sekiguchi et al. 2011, 2012)
  - Lower X_H in infall ⇒ more energetic SNe ? (photodissociation ~ 10^{51} erg/0.1Msun Fe)
  - Less Pauli blocking in neutrino pair annihilation





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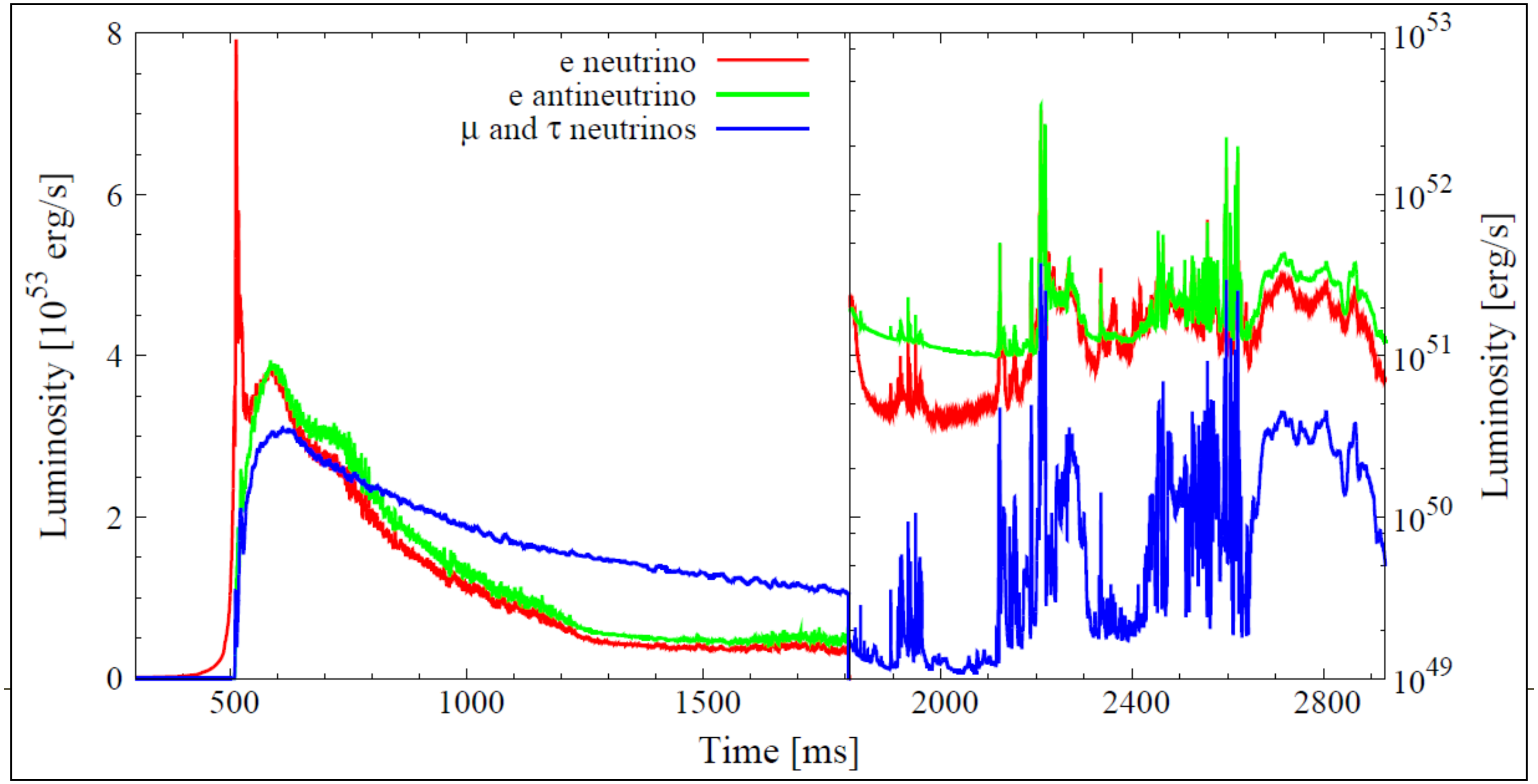

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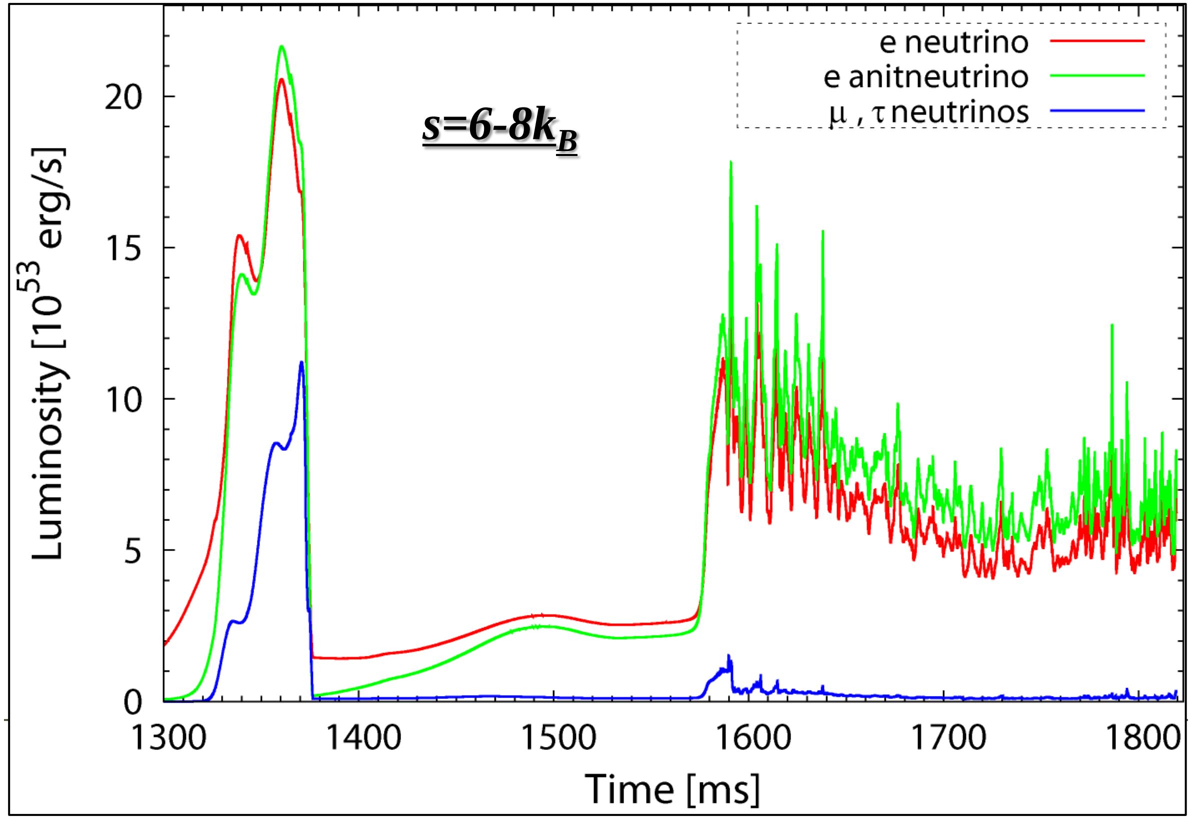

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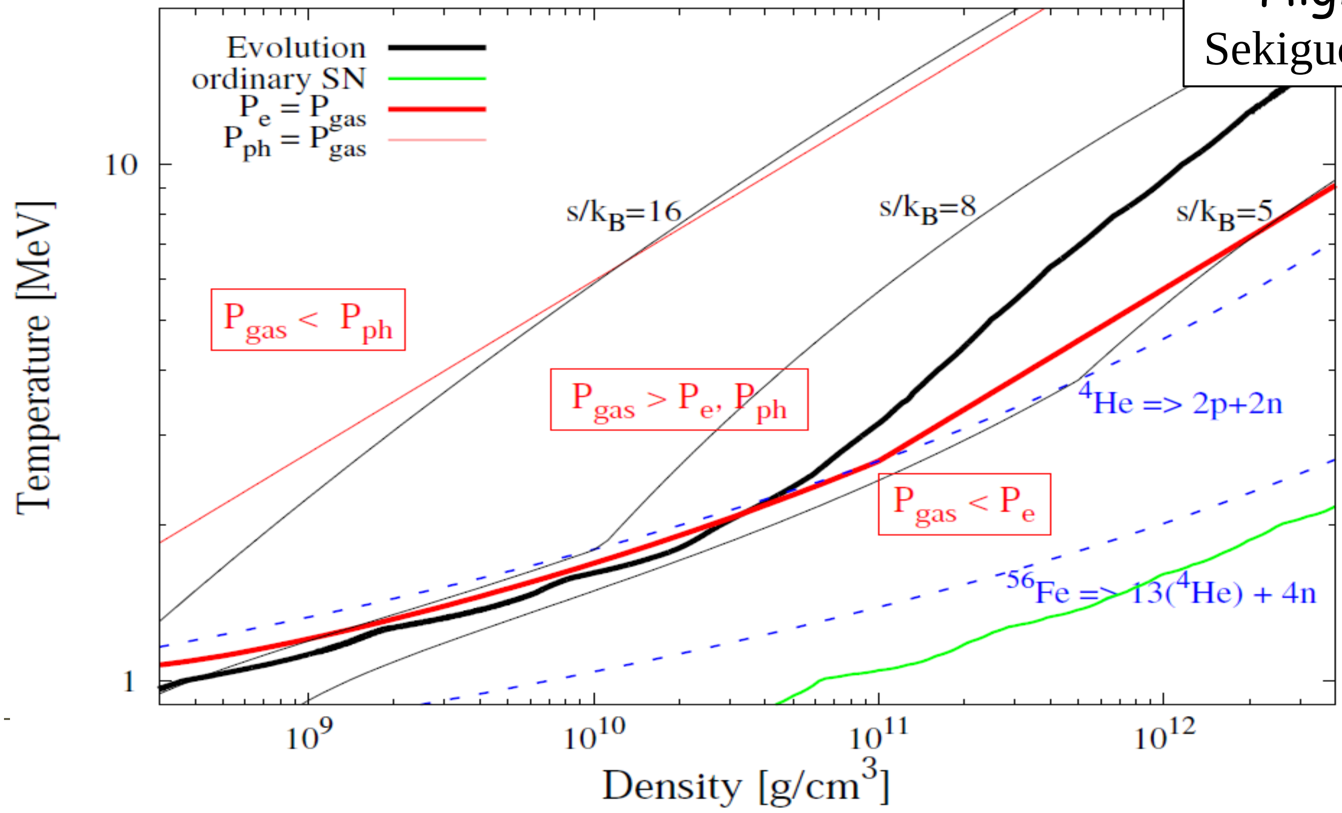

High entropy core
Sekiguchi & Shibata (2011)

$P_{gas}=P_{deg}$

Ordinary SN
Sekiguchi (2010)

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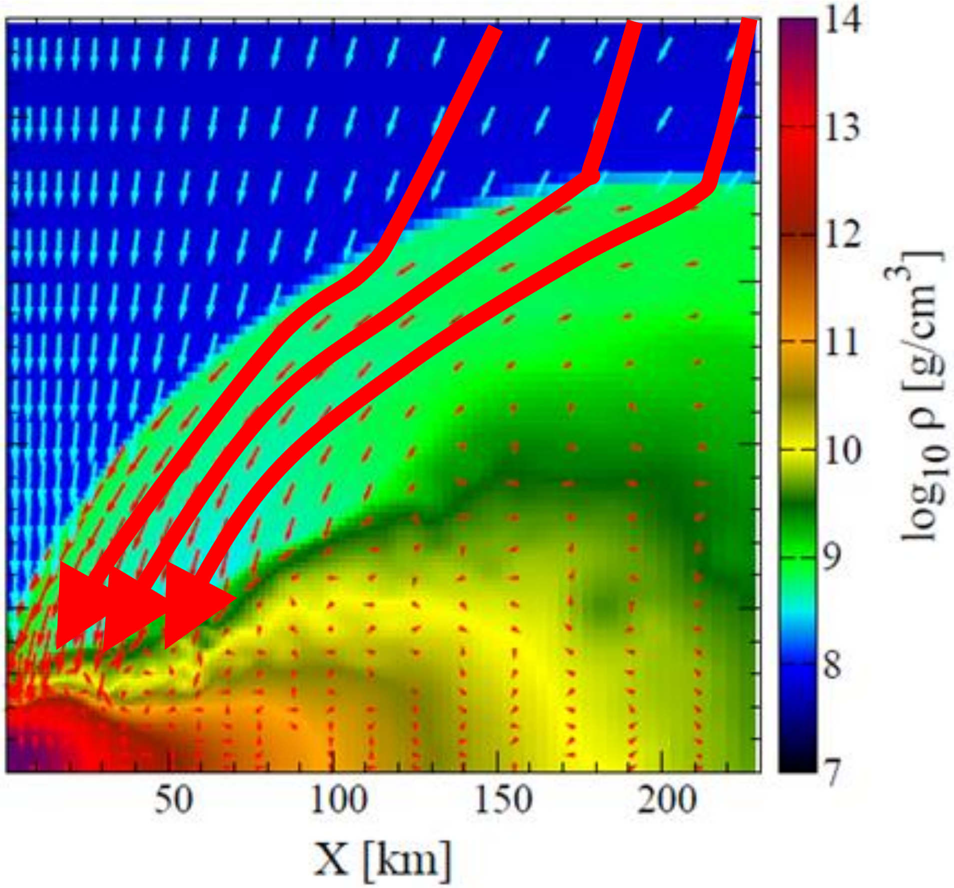
- **Consequences of rapid rotation**
  - Torus-structured shock ⇒ oblique shock accumulate infall matter into central region (**dM/dt enhancement**)
  - Different topology but same ingredients
    - Stalled shock
    - Neutrino 'torus'
    - Gain region
- How will this system evolve in presence of ν-heating ?



- **Sekiguchi et al. 2011, 2012**

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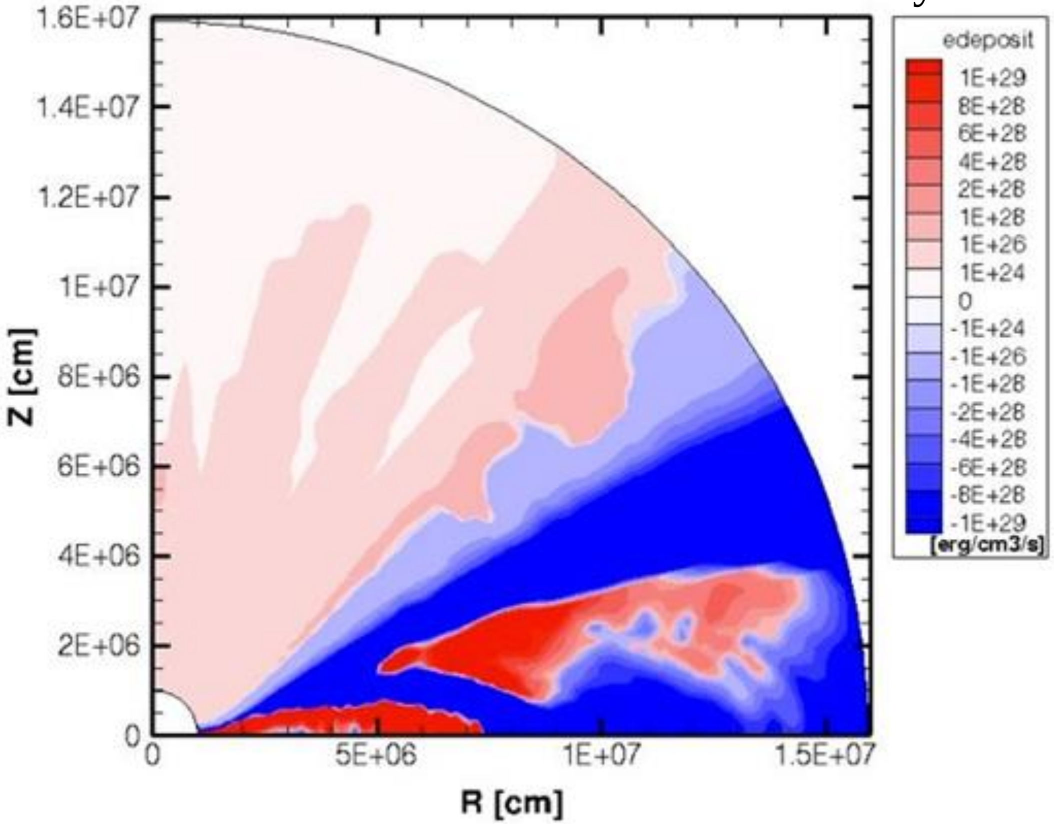

Thanks to K. Sumiyoshi

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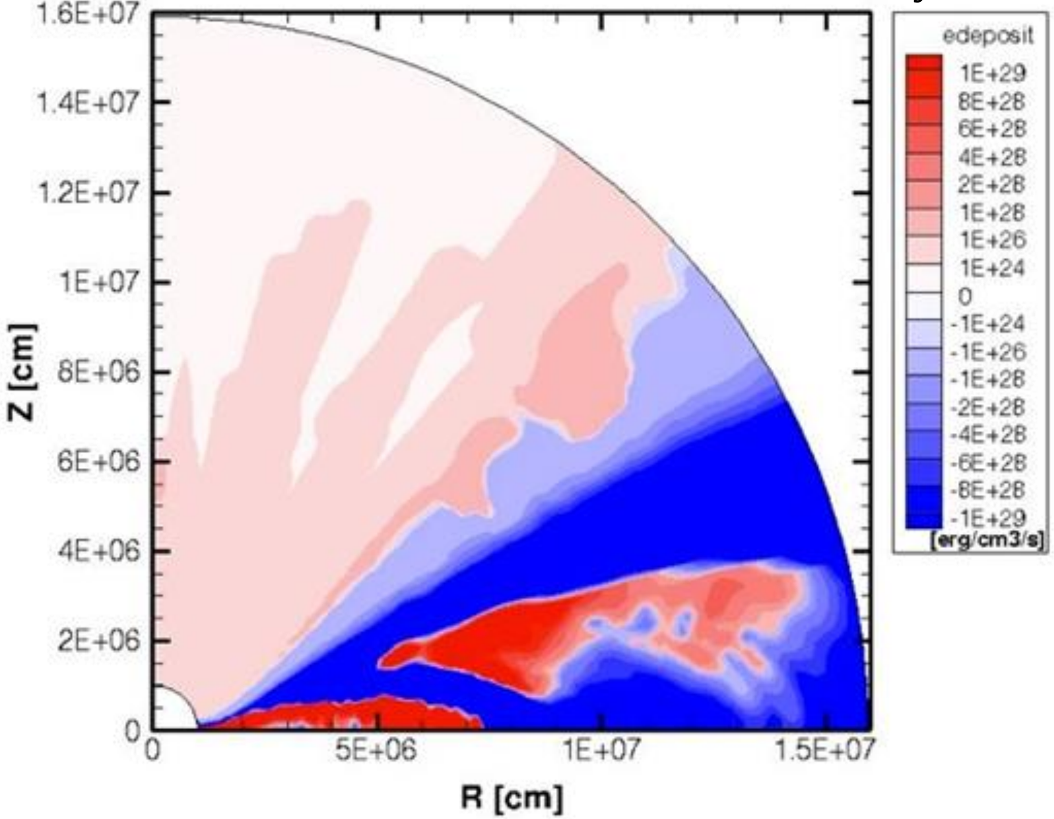
    - **Gain regions**
- **How will this system evolve ?**
  - Simulations ongoing with ν-heating and simple ν-pair annihilation

Thanks to K. Sumiyoshi



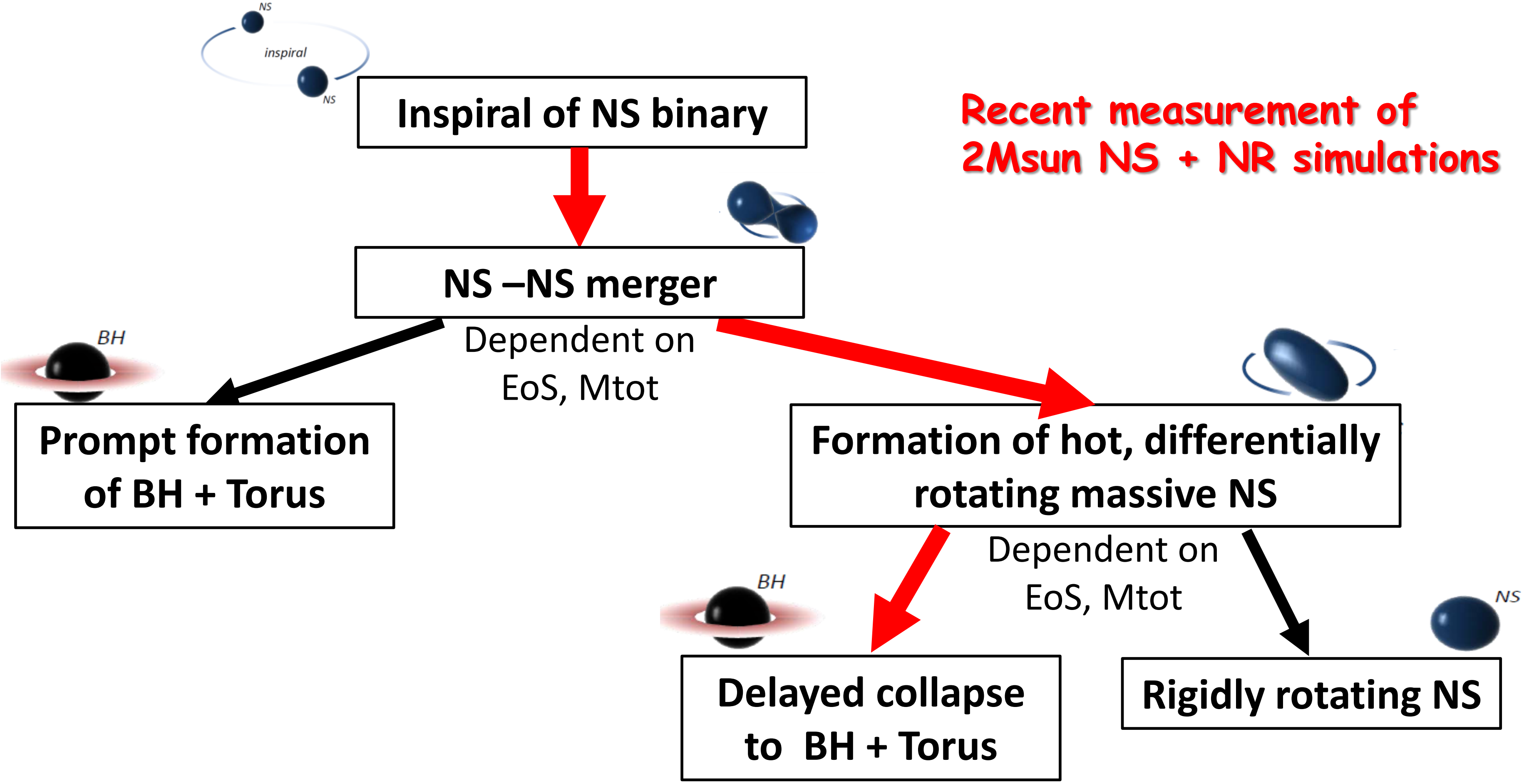
On Compact binary mergers, Short GRBs, and r-process nucleosynthesis

Yuichiro Sekiguchi （YITP)

S.Wanajo (RIKEN), N. Nishimura (Keele Univ.)
K. Kyutoku (UMW), K. Kiuchi, H.Nagakura, M. Shibata (YITP)
M. Tanaka (NAOJ), K. Hotokazaka

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

Evolution of NS-NS mergers



Inspiral of NS binary

NS –NS merger

Dependent on
EoS, Mtot

Prompt formation of BH + Torus

Formation of hot, differentially rotating massive NS

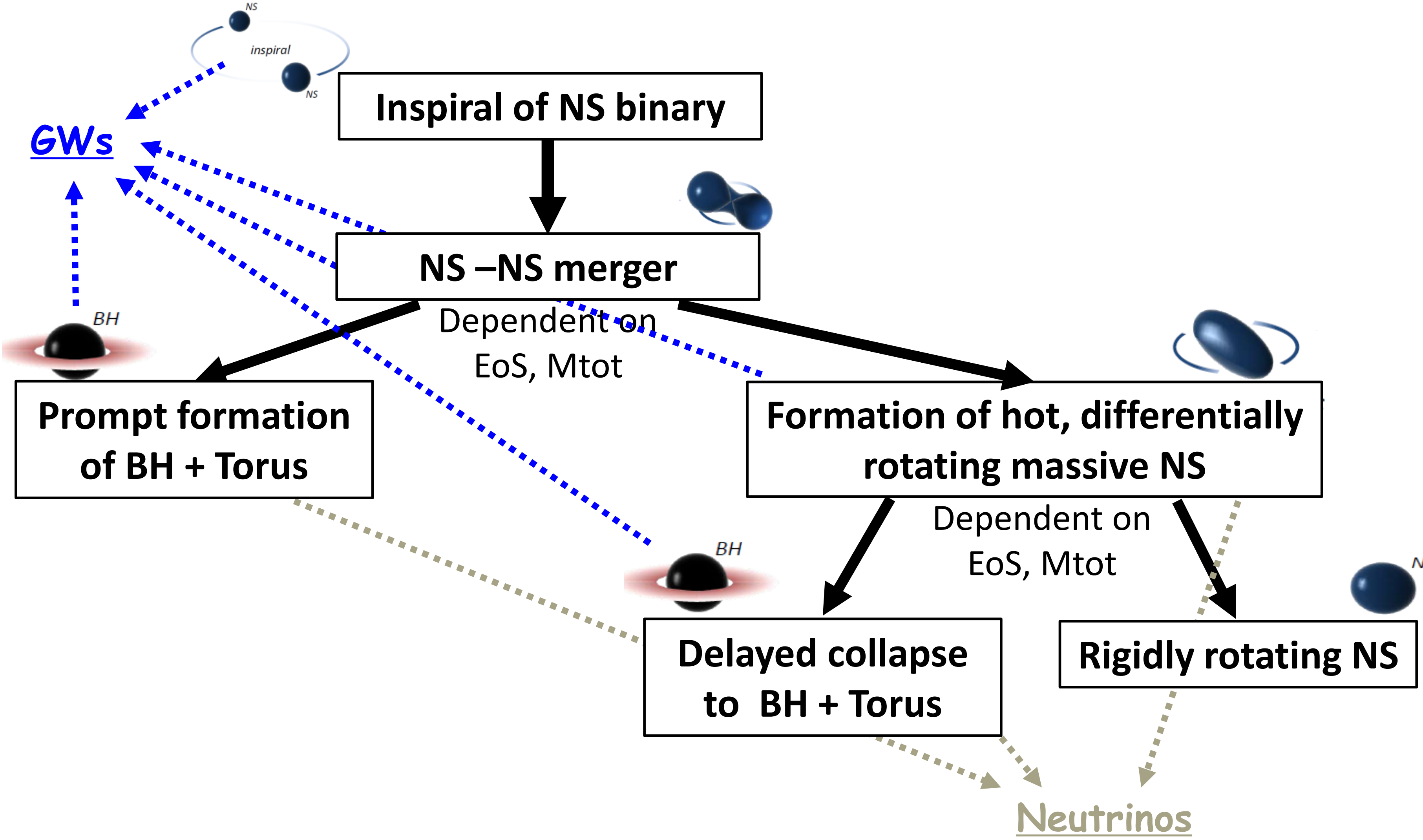
Dependent on
EoS, Mtot

Delayed collapse to BH + Torus

Rigidly rotating NS

Recent measurement of 2Msun NS + NR simulations

Messengers of NS-NS mergers



GWs

Inspiral of NS binary

NS –NS merger

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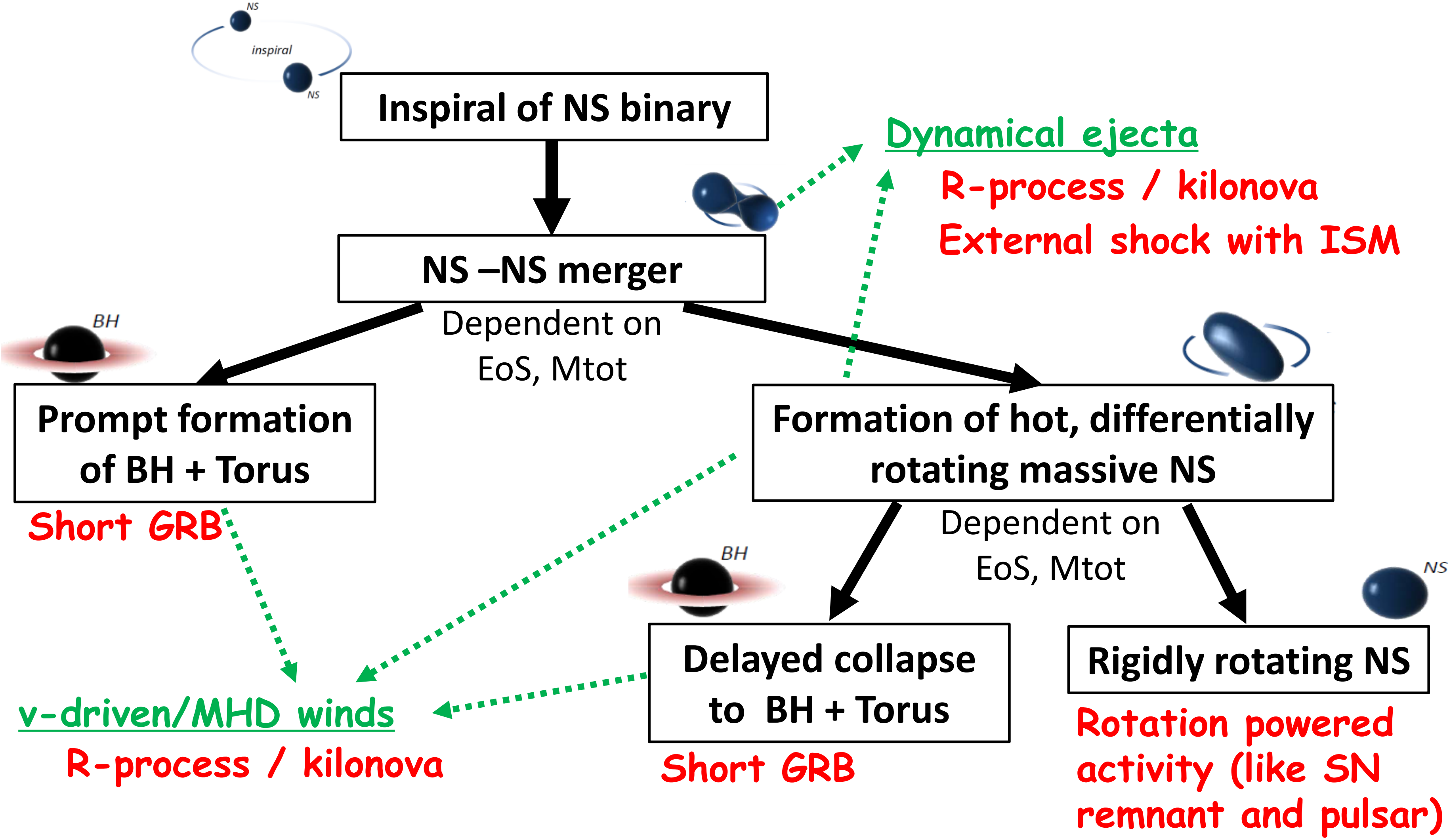
Neutrinos

Messengers of NS-NS mergers



Inspiral of NS binary

NS –NS merger

Dependent on EoS, Mtot

Prompt formation of BH + Torus

Short GRB

Formation of hot, differentially rotating massive NS

Dependent on EoS, Mtot

Delayed collapse to BH + Torus

Short GRB

Rigidly rotating NS

Rotation powered activity (like SN remnant and pulsar)

Dynamical ejecta

R-process / kilonova

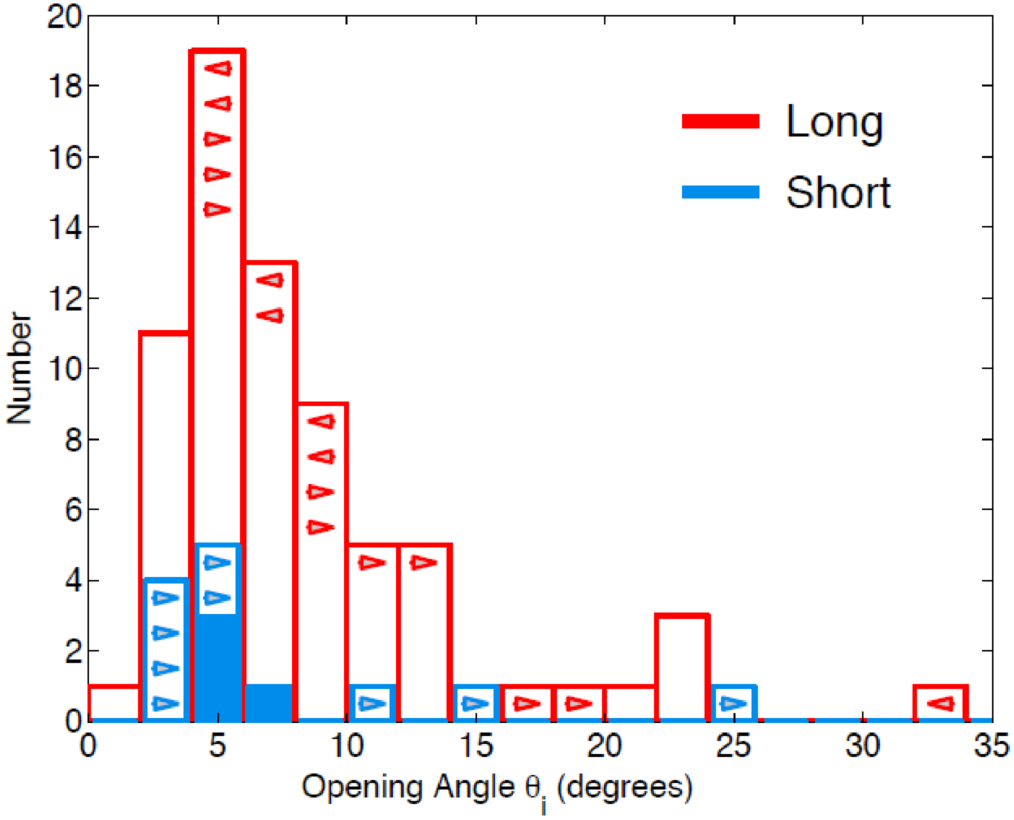
External shock with ISM

ν-driven/MHD winds

R-process / kilonova

Three assumptions and issues in this talk

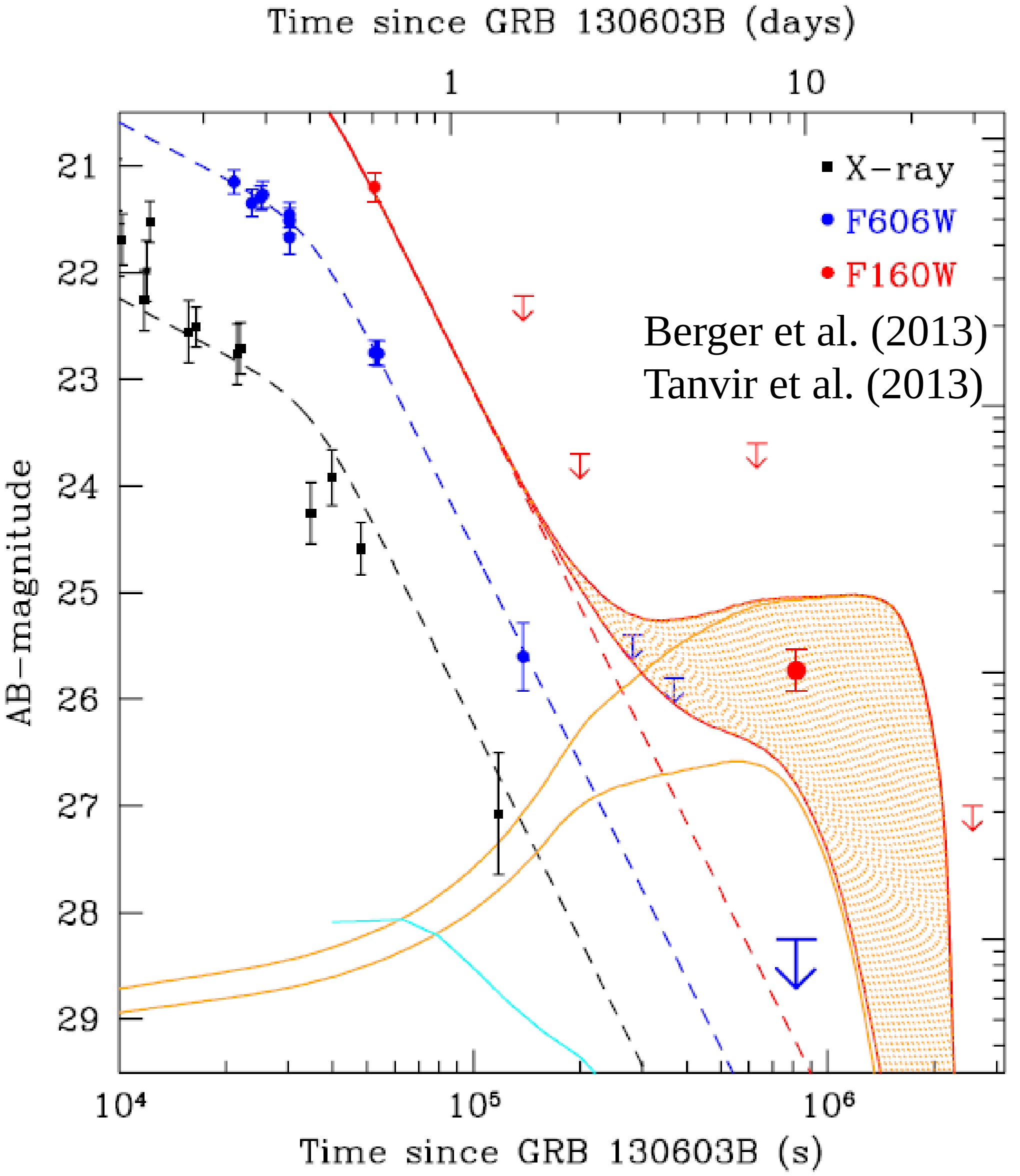
- The central engine of SGRB is NS-NS or BH-NS mergers
  - Θjet ~< 10 degree ?



Berger (2013)
Fong et al. (2013)

Three assumptions and issues in this talk

- The central engine of SGRB is NS-NS or BH-NS mergers
  - Θjet ~< 10 degree ?
- EM transient associated with GRB130603B is powered by radioactive decay of r-process elements in *dynamical* ejecta
  - Mej ~ 0.01 Msun ?



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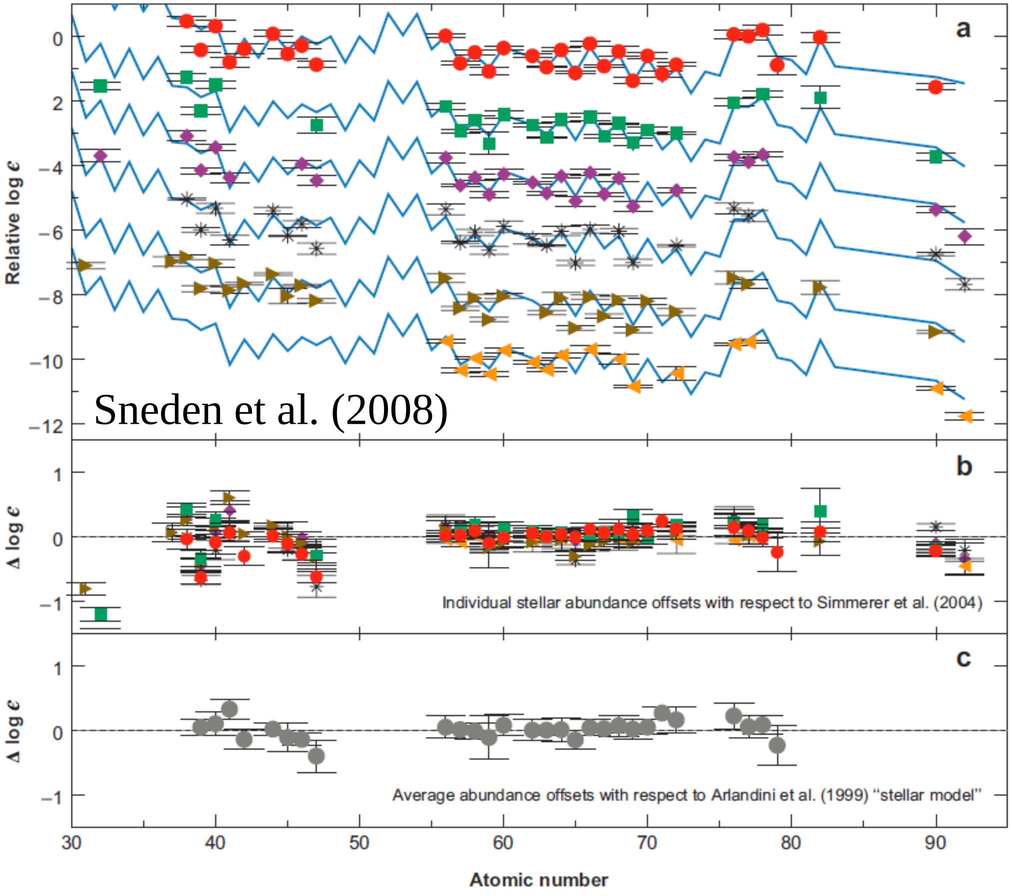
  - Universality of abundance ?



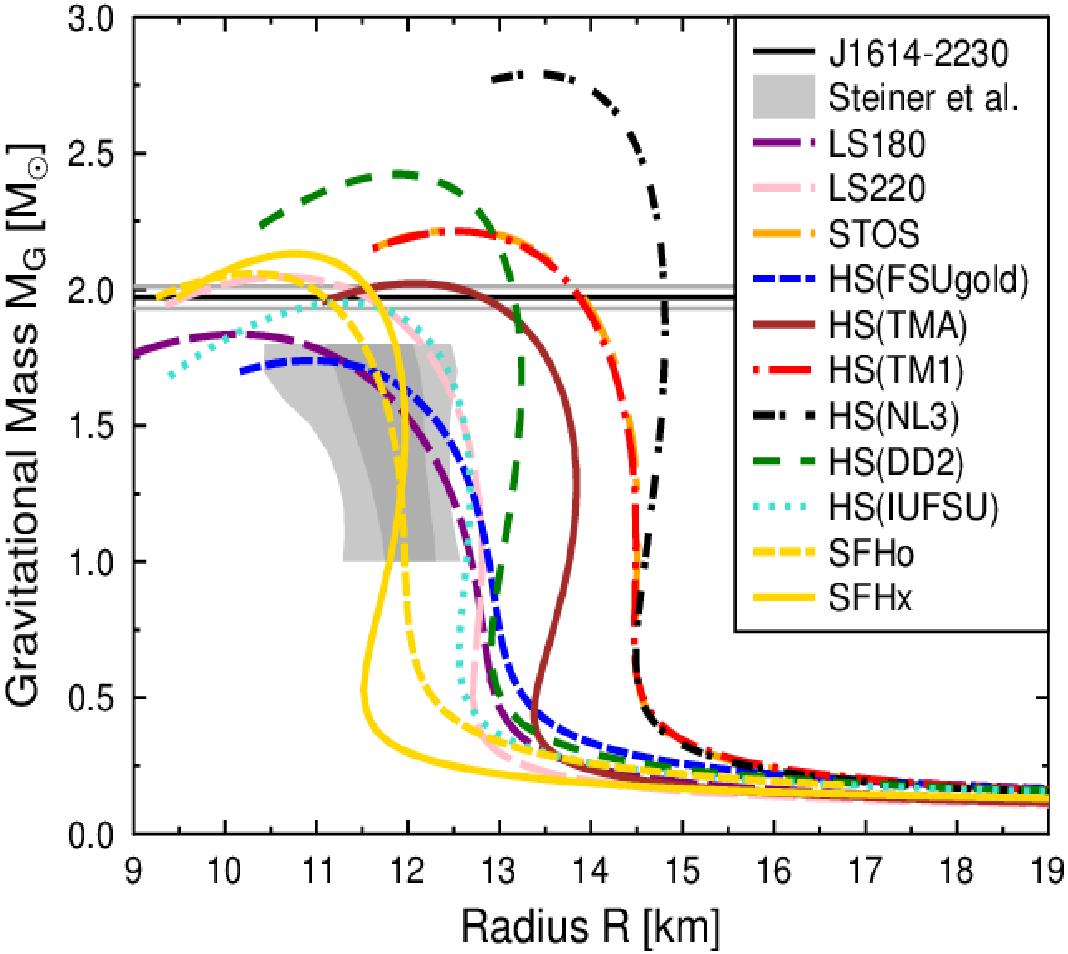
Sneden et al. (2008)

Individual stellar abundance offsets with respect to Simmerer et al. (2004)

Average abundance offsets with respect to Arlandini et al. (1999) "stellar model"

What we want to say in this talk

- All these issues may be resolved if NS EOS is soft like SFHo

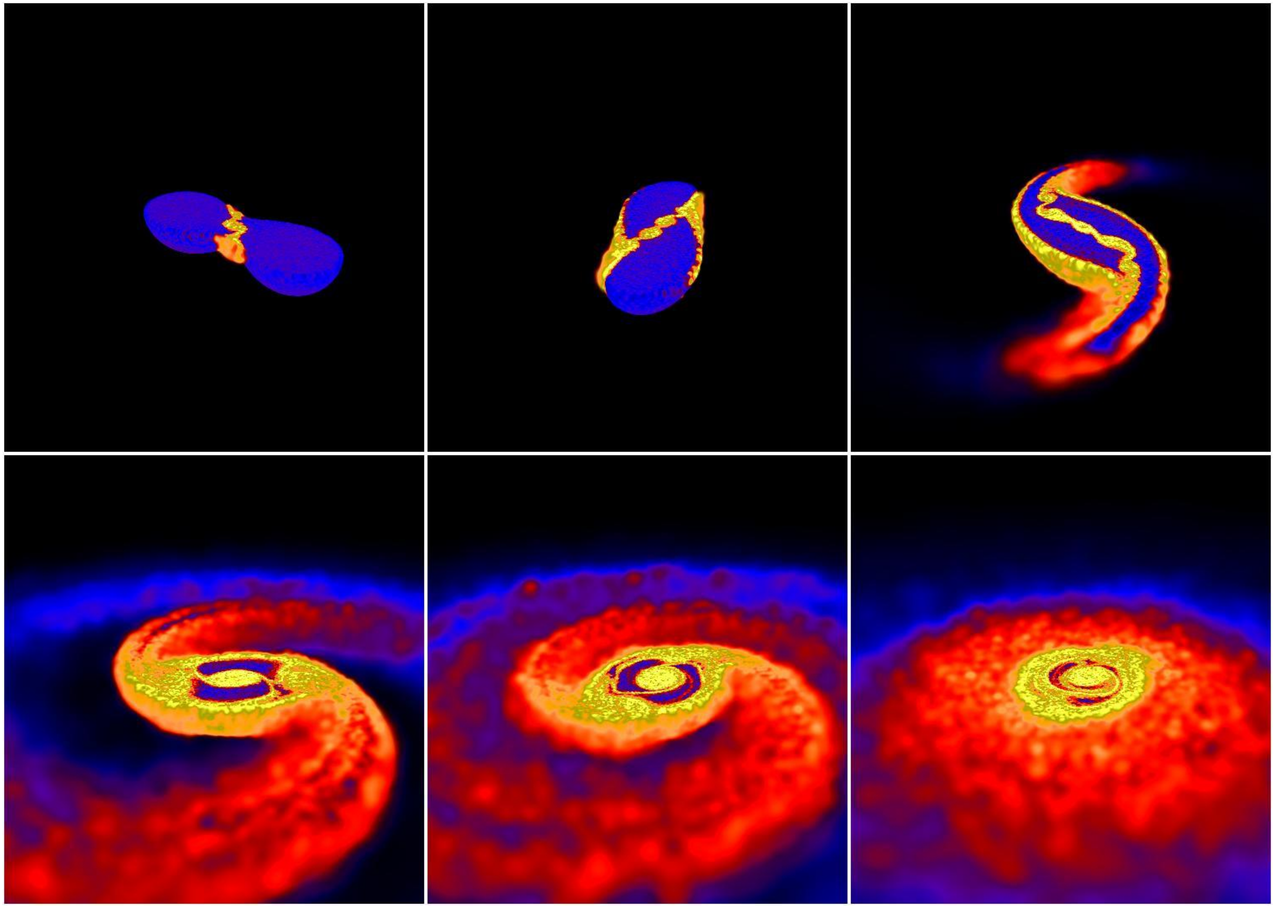


Jet Collimation

Nakakura et al. (2014)

Jet collimation problem

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



Simulation by Rosswog

Nakakura et al. (2014)

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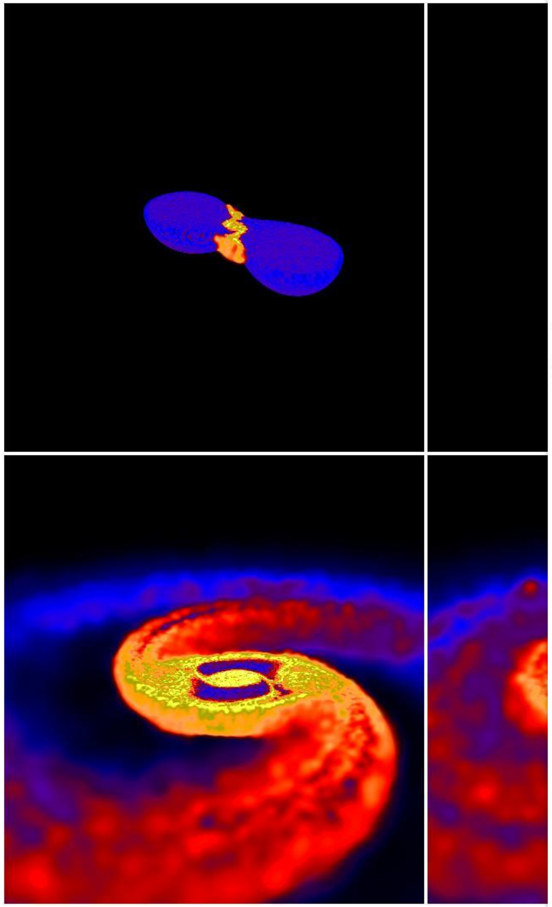

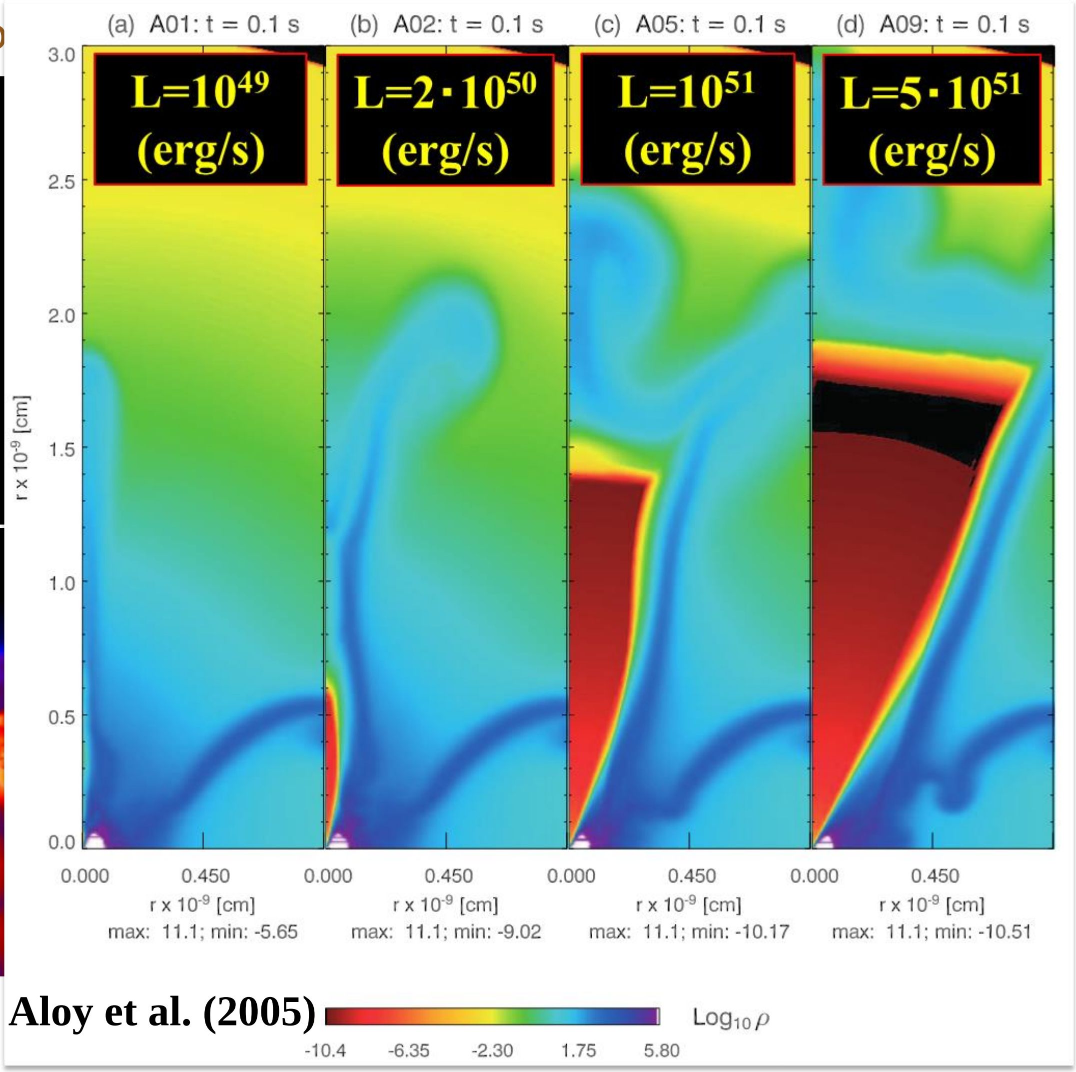

Aloy et al. (2005)

Jet collimation problem

- Jet collimation in SGRBs has been a long-standing problem
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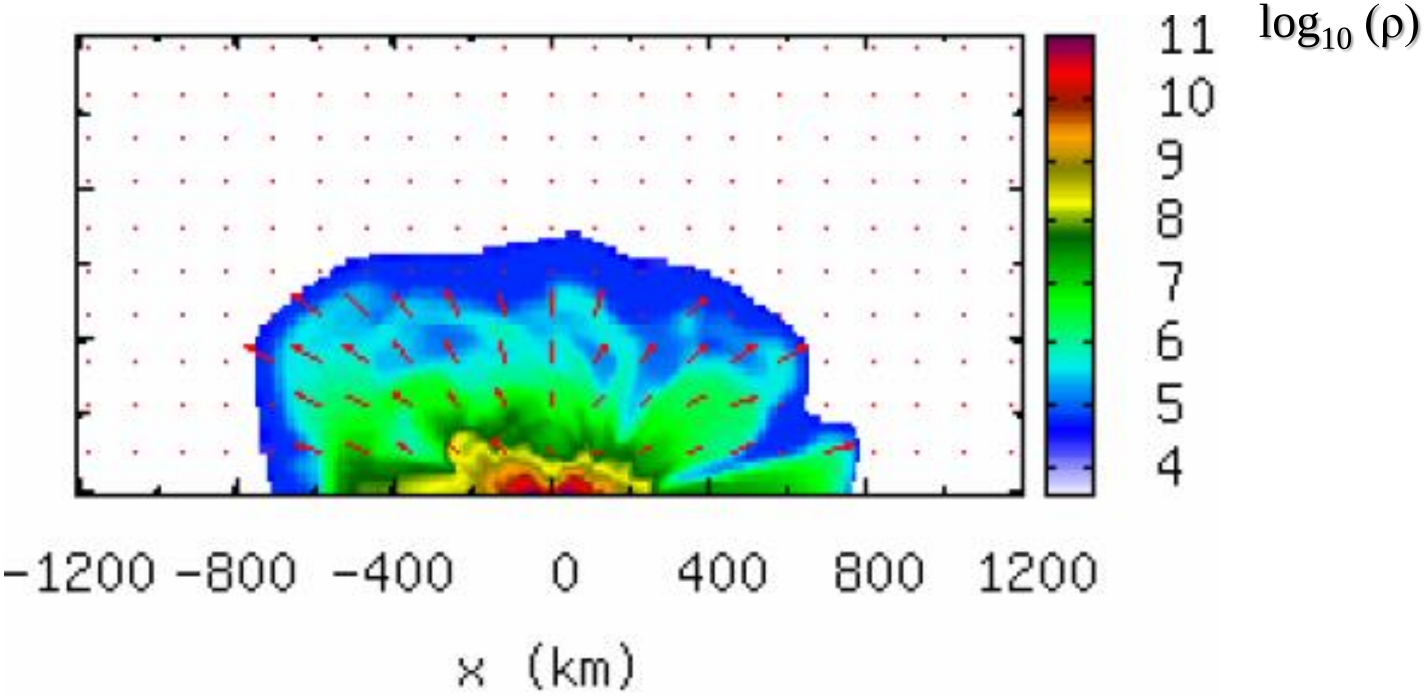
- Latest NR simulations of NS-NS clarified that there is quasi-isotropic mass ejection driven by shocks (e.g., Hotokezaka et al. 2013)
  - Jet collimation may be achieved



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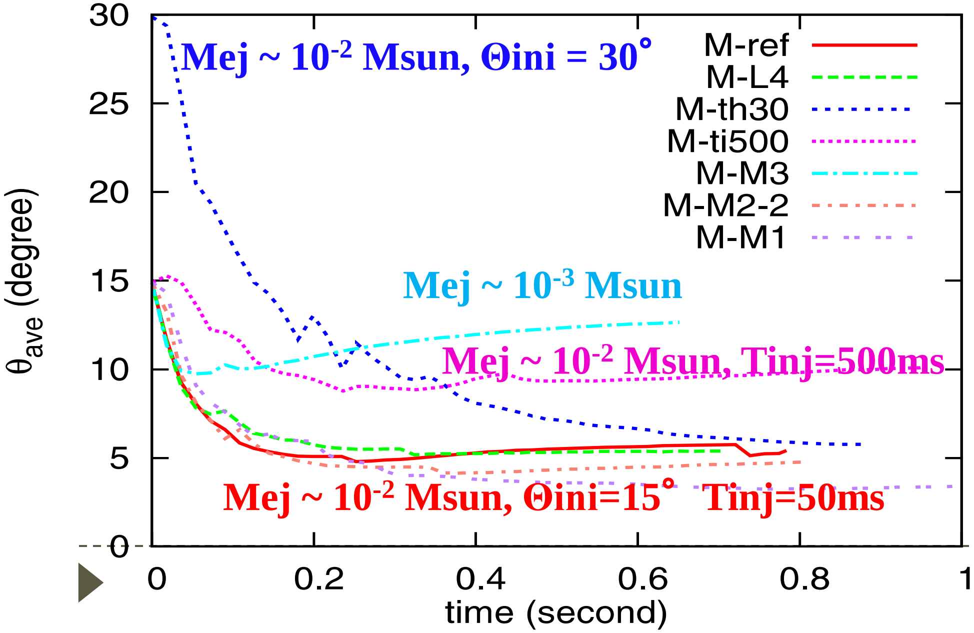
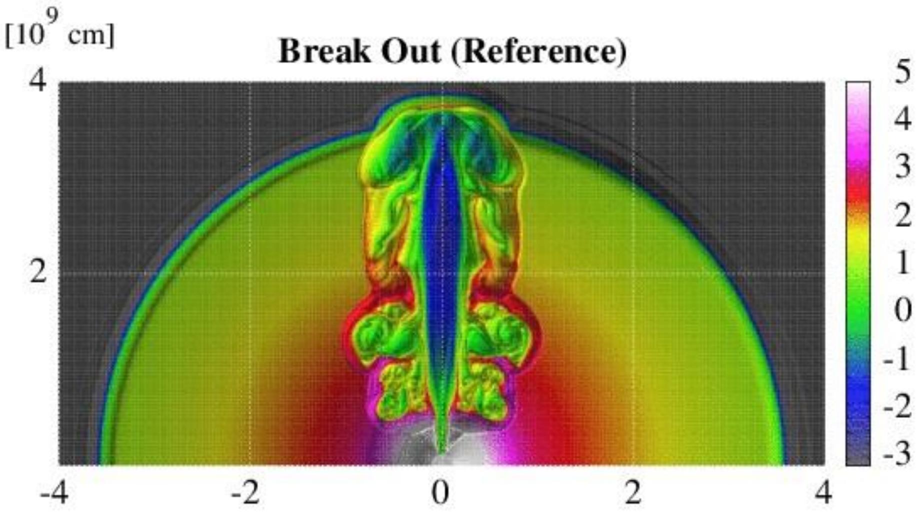
- How much mass is necessary ? Jet simulation by Nagakura et al. (2014)
  - **~ 0.01 Msun is necessary to explain GRB130603B (a kilonova candidate)**





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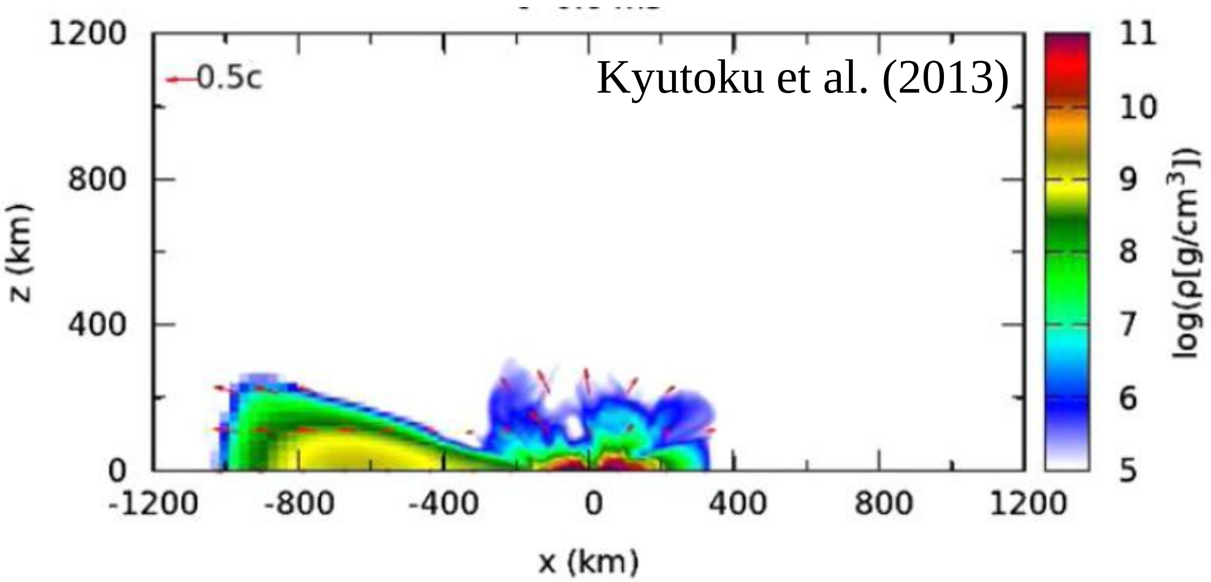
- **BH-NS:**

no *dynamical* mass ejection into the pole

'Wind' components will be necessary



Jet Collimation

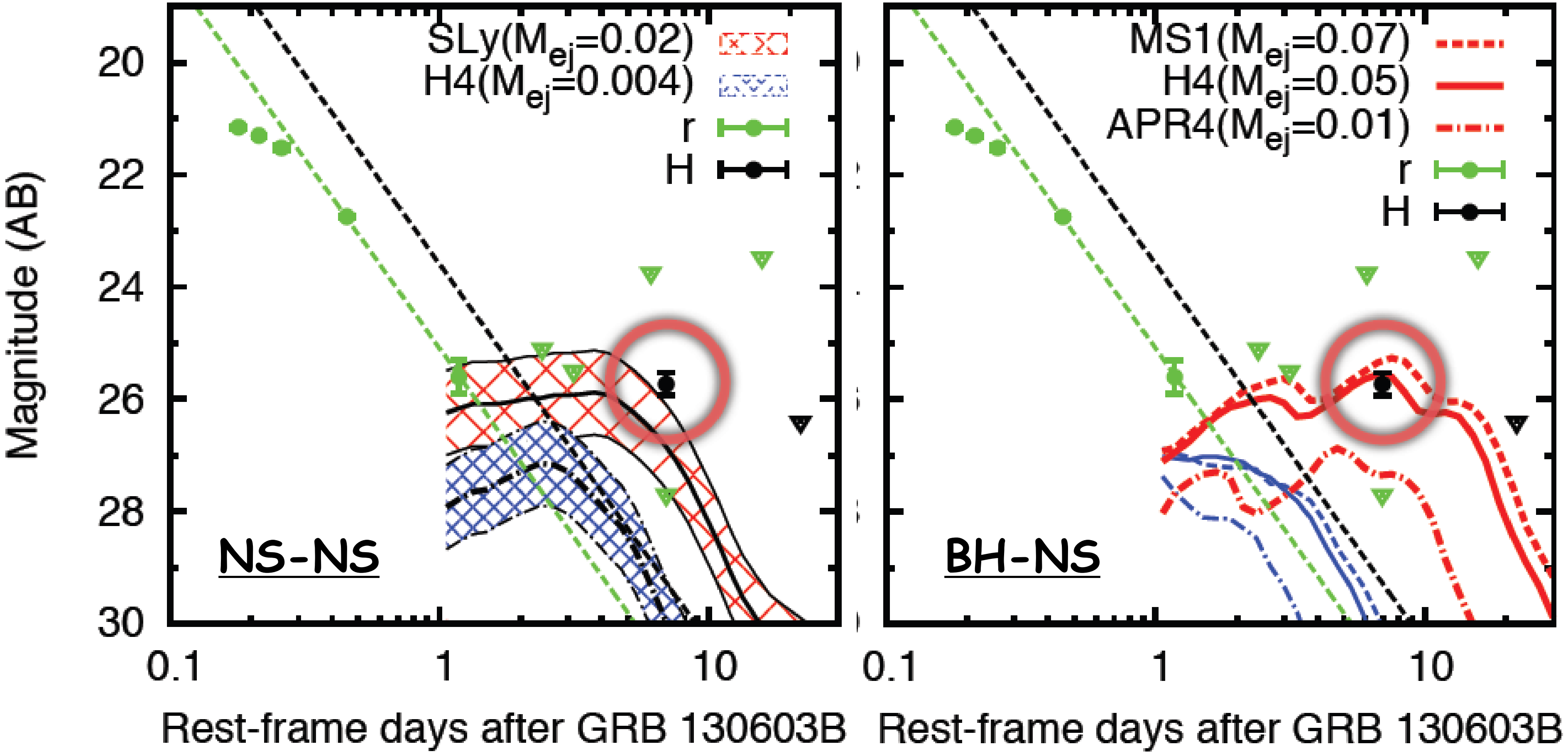
- We need ~0.01Msun ejecta for the jet collimation
- Interestingly, ejecta mass of this value is necessary to explain kilonova

Kilonova modelling and mass ejection

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

Kilonova modeling : NS-NS vs. BH-NS

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



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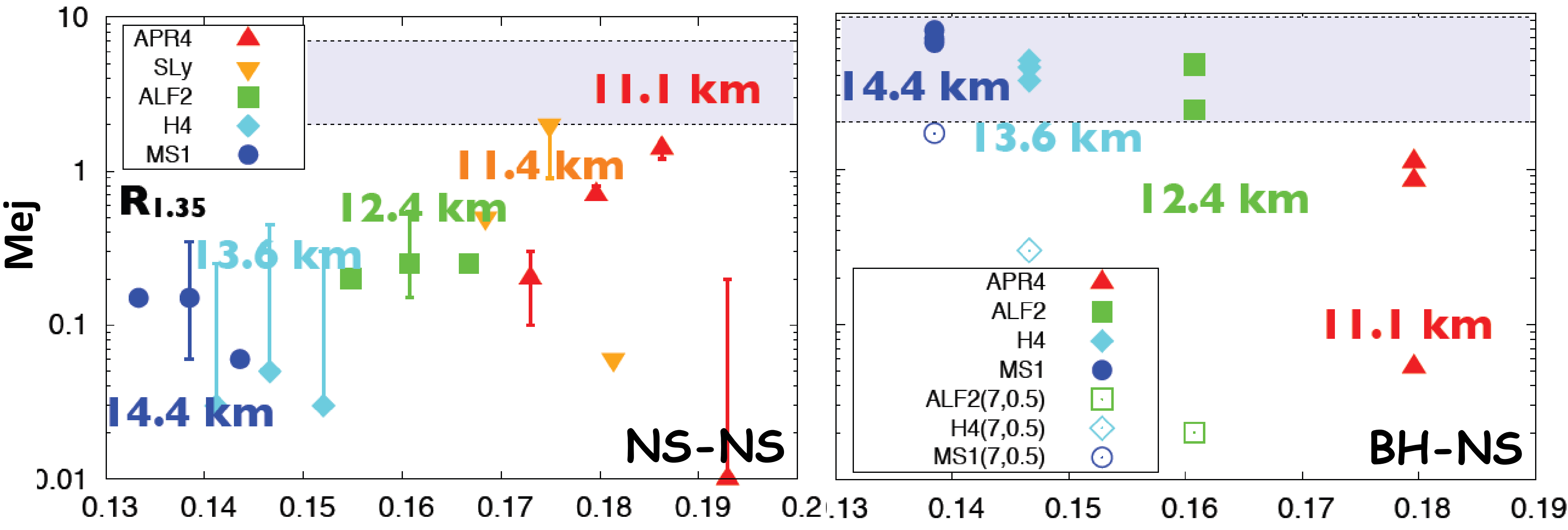
Kilonova modeling : NS-NS vs. BH-NS

- Requirement based on Li & Paczynski (1998) : **Mej > 0.01 Msun**
- **NS-NS :** **Soft EOS is necessary** (shocks play a role)
  - Small diversity in conditions before merger, Mej ~ 0.01 Msun may be universal within the typical mass range of NS-NS
- **BH-NS :** **Stiffer EOS is preferable** (tidal component is dominant)
  - large diversity is expected, because mass ejection (mostly tidal-driven) depends further on ***mass and spin of BH*** (need more observations !)



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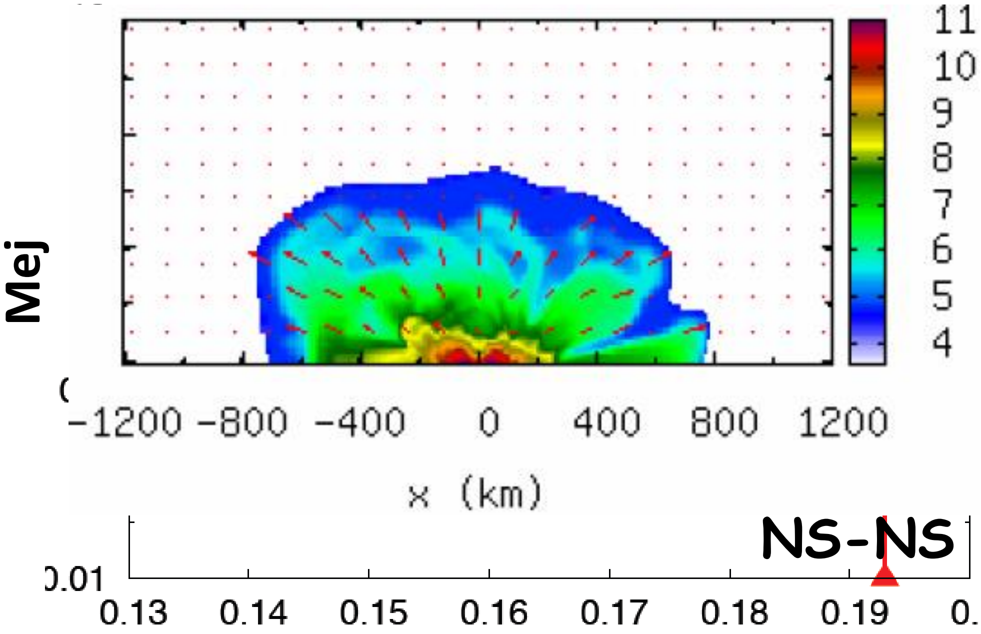
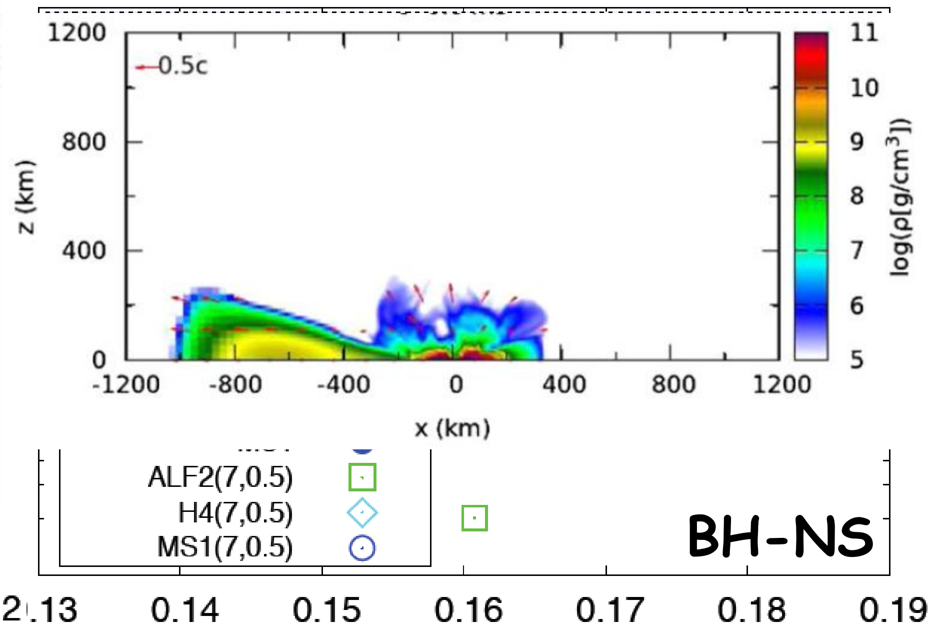




Kilonova modelling and mass ejection

- We need ~0.01Msun ejecta to explain EM transient associated with GRB130603B in Kilonova model
  - NS-NS : soft EOS is necessary
  - BH-NS : stiff EOS is preferable
- Interestingly, ejecta mass of this value is required to achieve the jet collimation

NS-NS merger as origin of r-process and universality

Dynamical mass ejection from BNS merger

- Two components

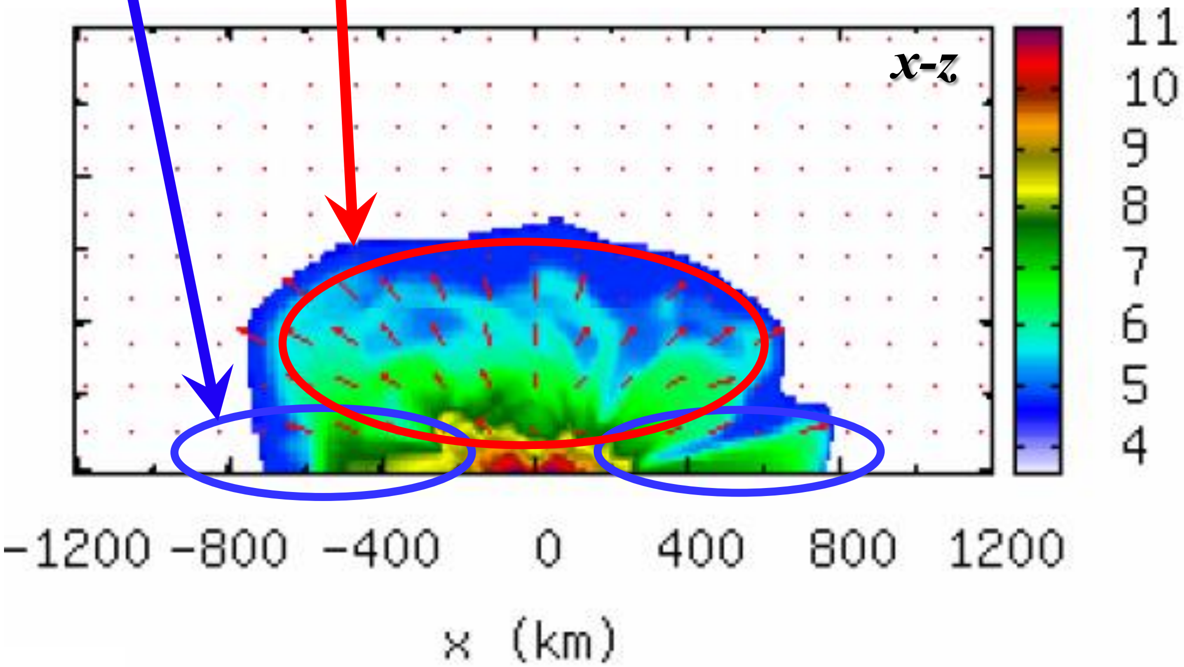
  \+ (neutrino-heated component (Perego et al. (2014); Just et al. (2014))

- **Driven by tidal interactions**

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

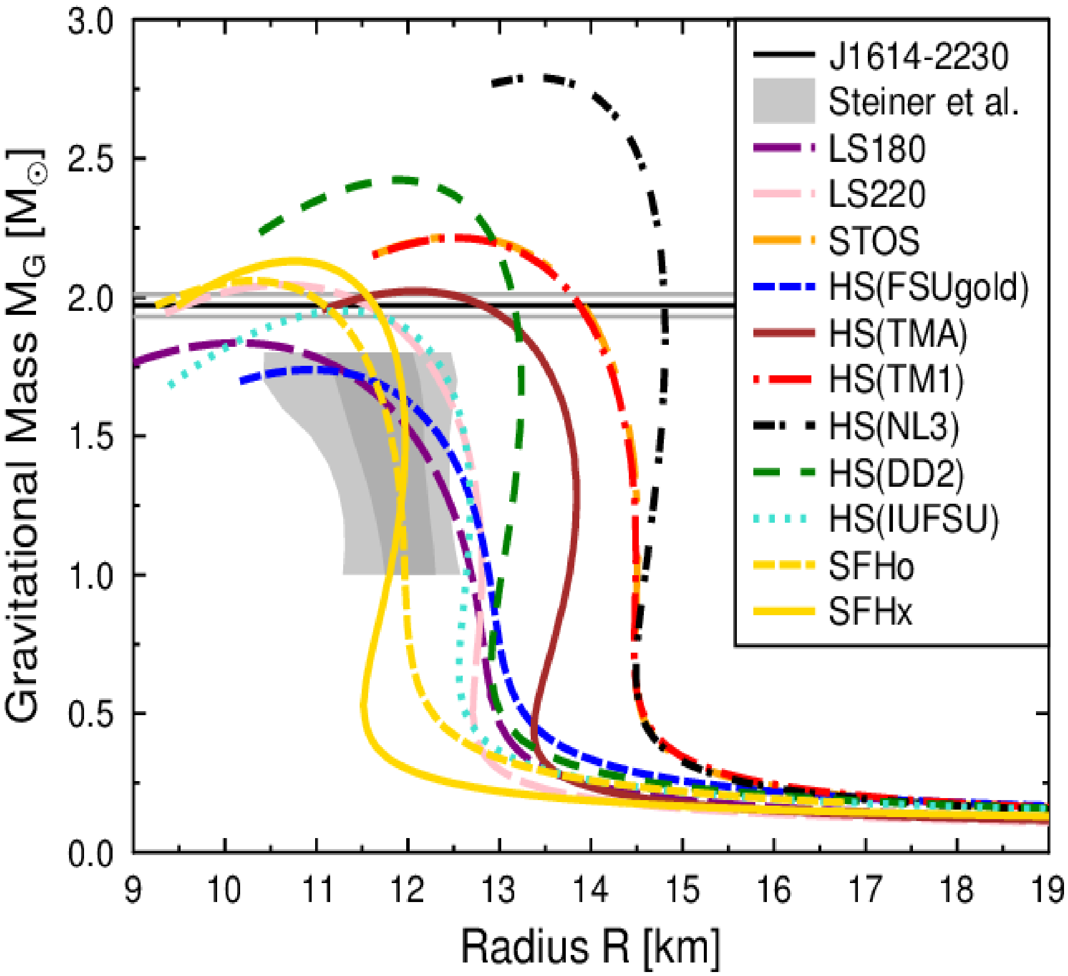
- **Driven by shocks**

  Consists of hot shock heated matter
  Weak interaction can change Ye



Dynamical mass ejection mechanism & EOS

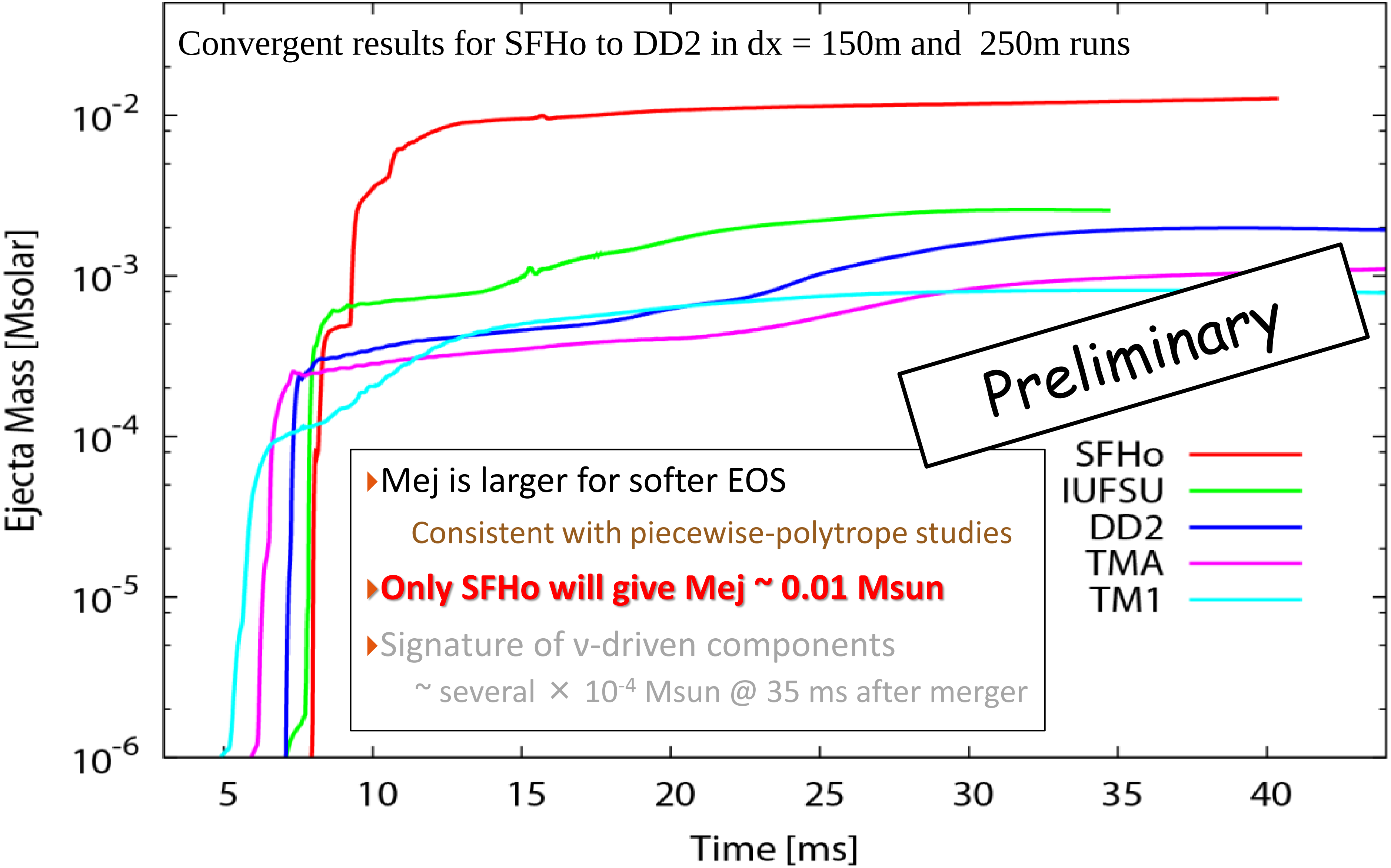
- ‘Stiffer EOS’
  - **TM1, TMA**
  - R_{NS} : lager
  - Tidal-driven dominant
  - **Ejecta consist of low T & Ye NS matter**
- ‘Intermediate EOS’
  - **DD2**
- ‘Softer EOS’
  - **SFHo, IUFSU**
  - R_{NS} : smaller
  - Tidal-driven less dominant
  - Shock-driven dominant
  - **Ye can change via weak processes**



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

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

Dynamical Mej depends strongly on EOS



Convergent results for SFHo to DD2 in dx = 150m and 250m runs

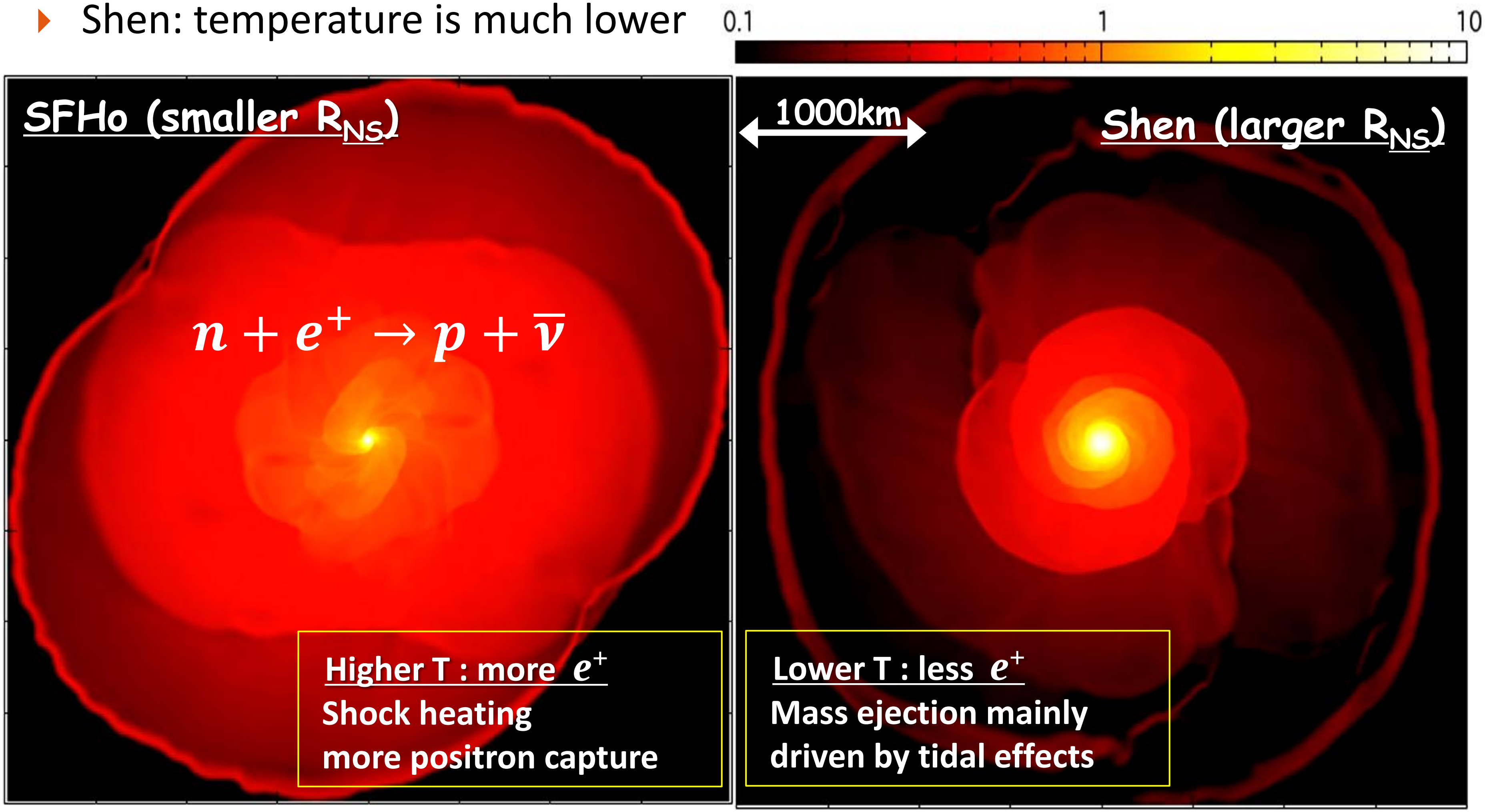
- Mej is larger for softer EOS

  Consistent with piecewise-polytrope studies
- **Only SFHo will give Mej ~ 0.01 Msun**
- Signature of ν-driven components

  ~ several × 10^{-4} Msun @ 35 ms after merger

SFHo vs. Shen: Ejecta temperature

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



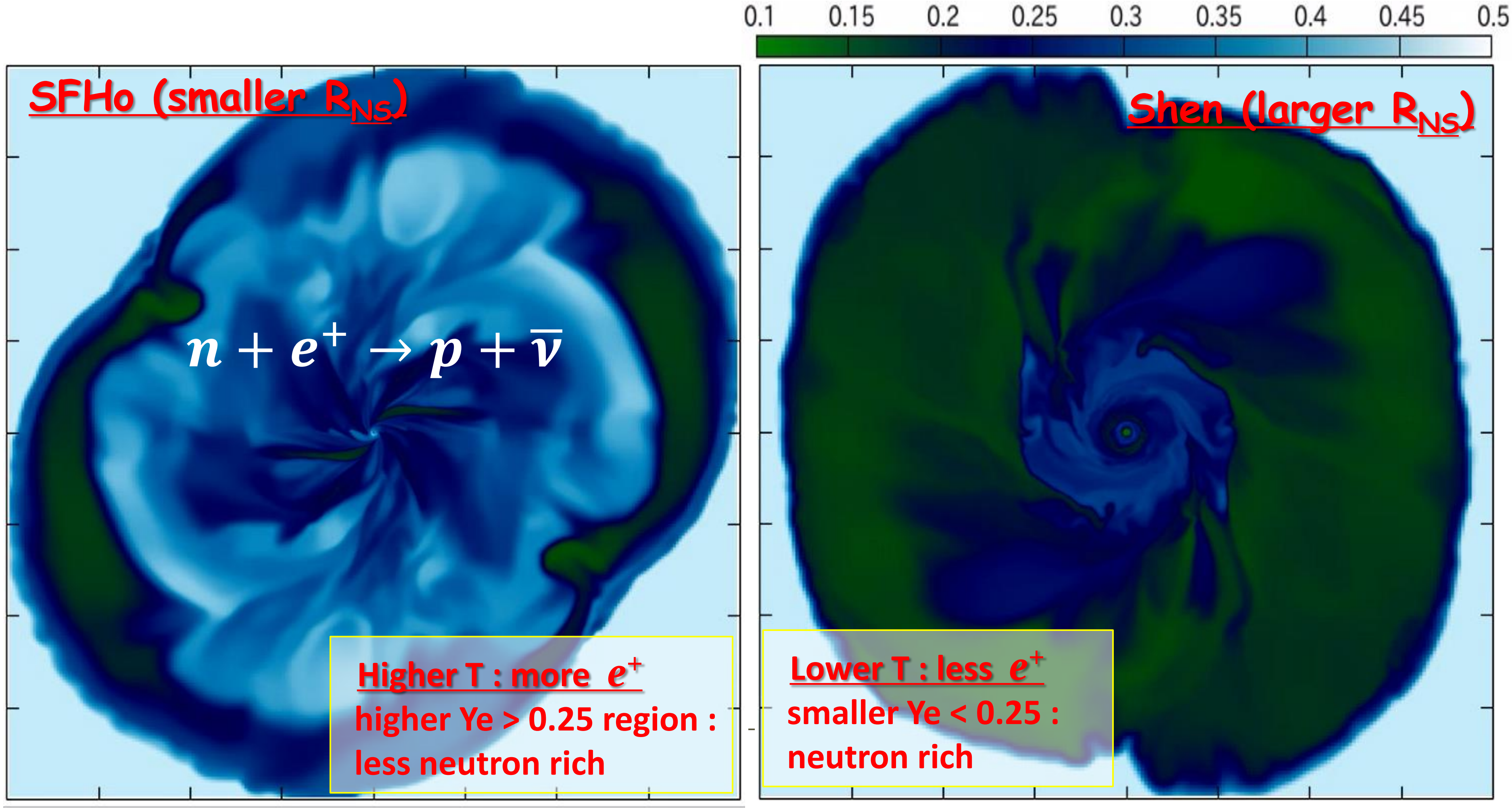
$$n + e^{+} \rightarrow p + \overline{\nu}$$

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

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

SFHo vs. Shen: 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})

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

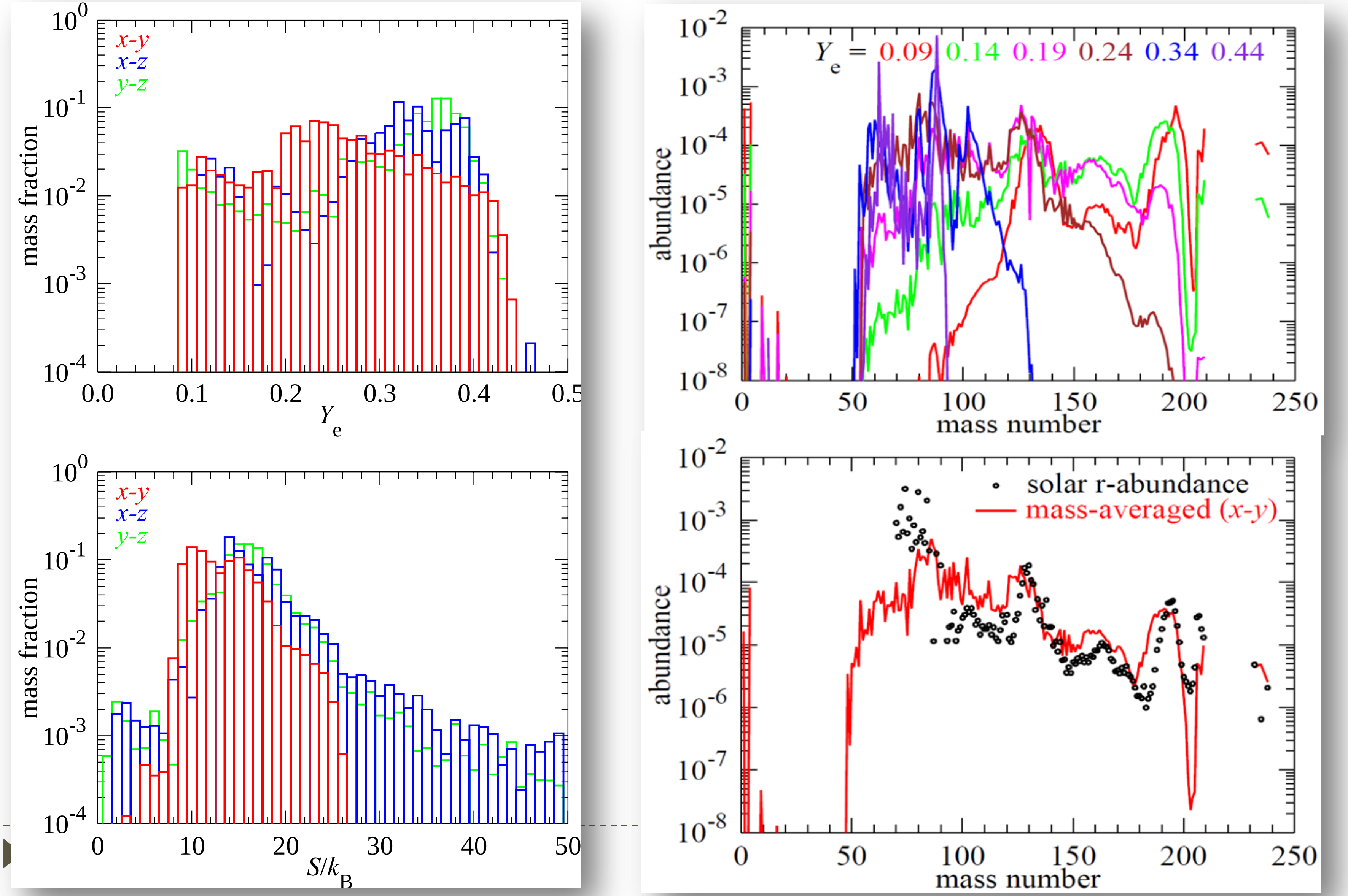
Higher T : more e^{+}
higher Ye > 0.25 region :
less neutron rich

Shen (larger R_{NS})

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

Wanajo, Sekiguchi et a. (2014)

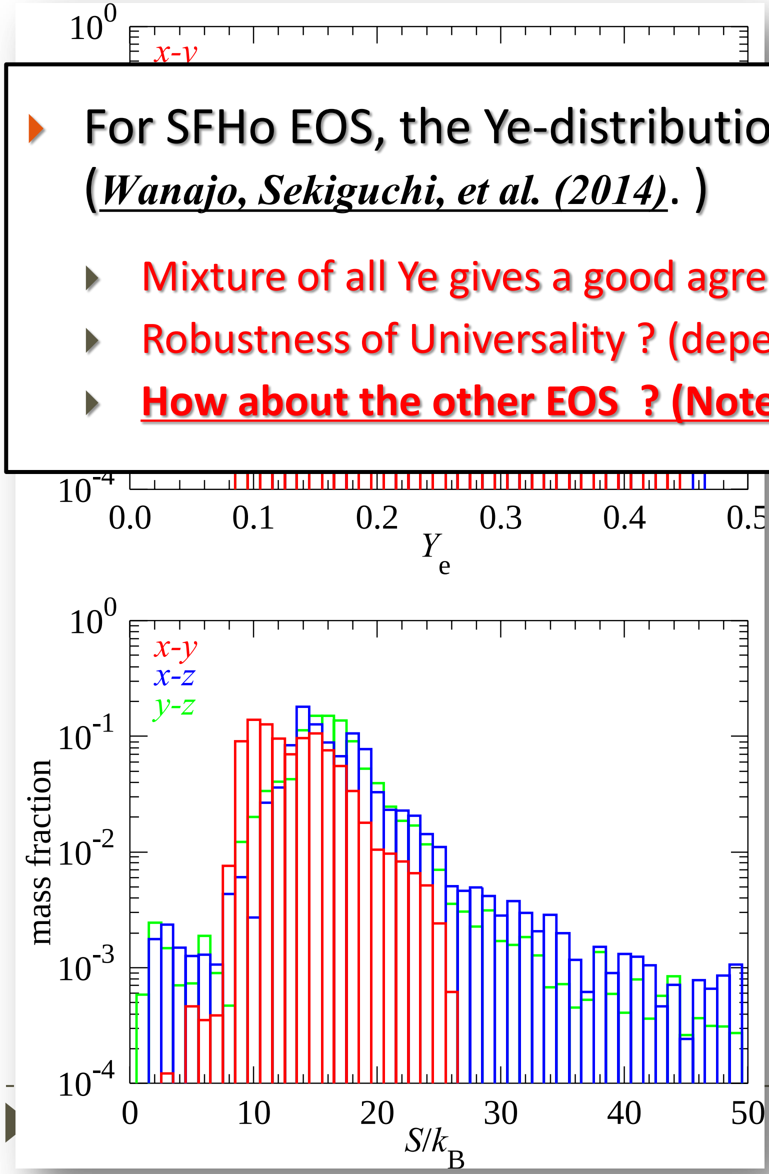
SFHo: Universality may be achieved

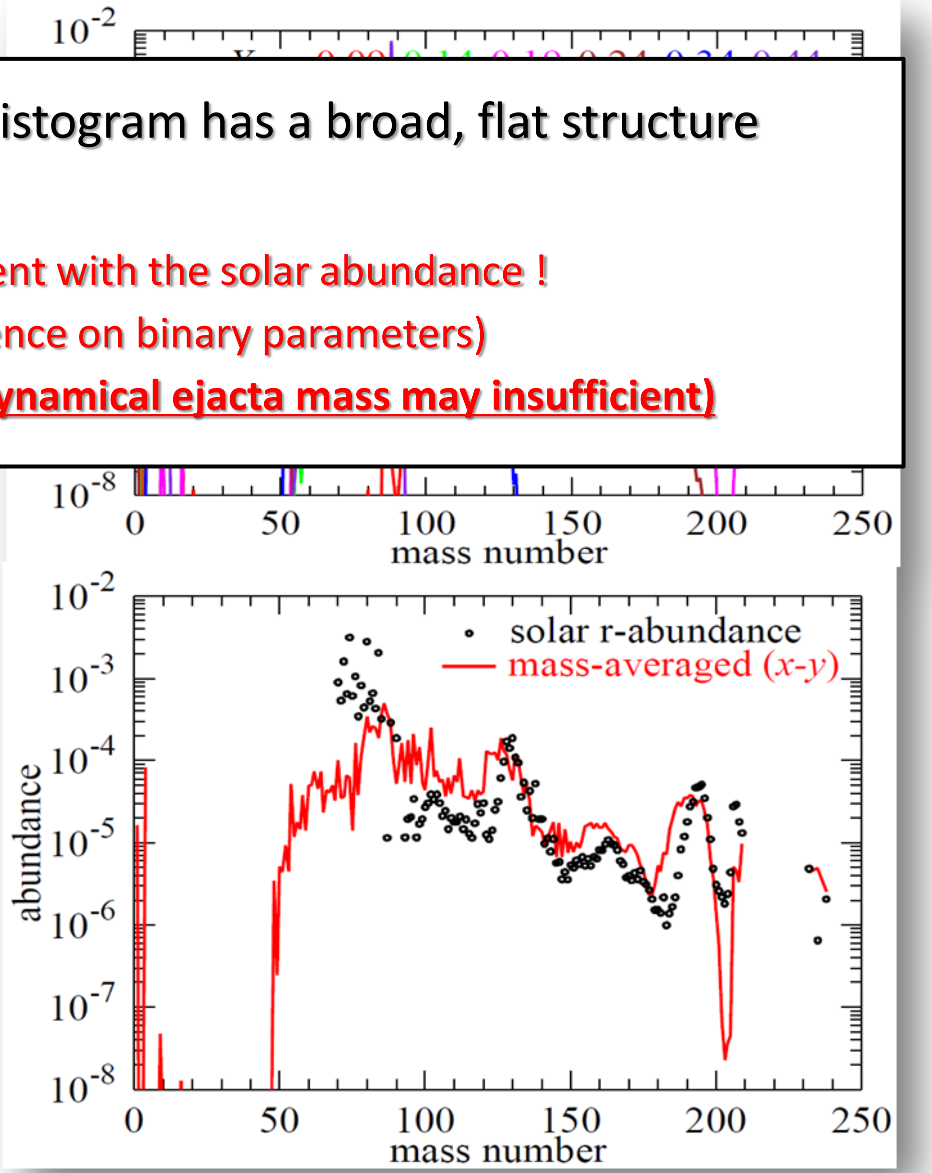


Wanajo, Sekiguchi et a. (2014)

SFHo: Universality may be achieved

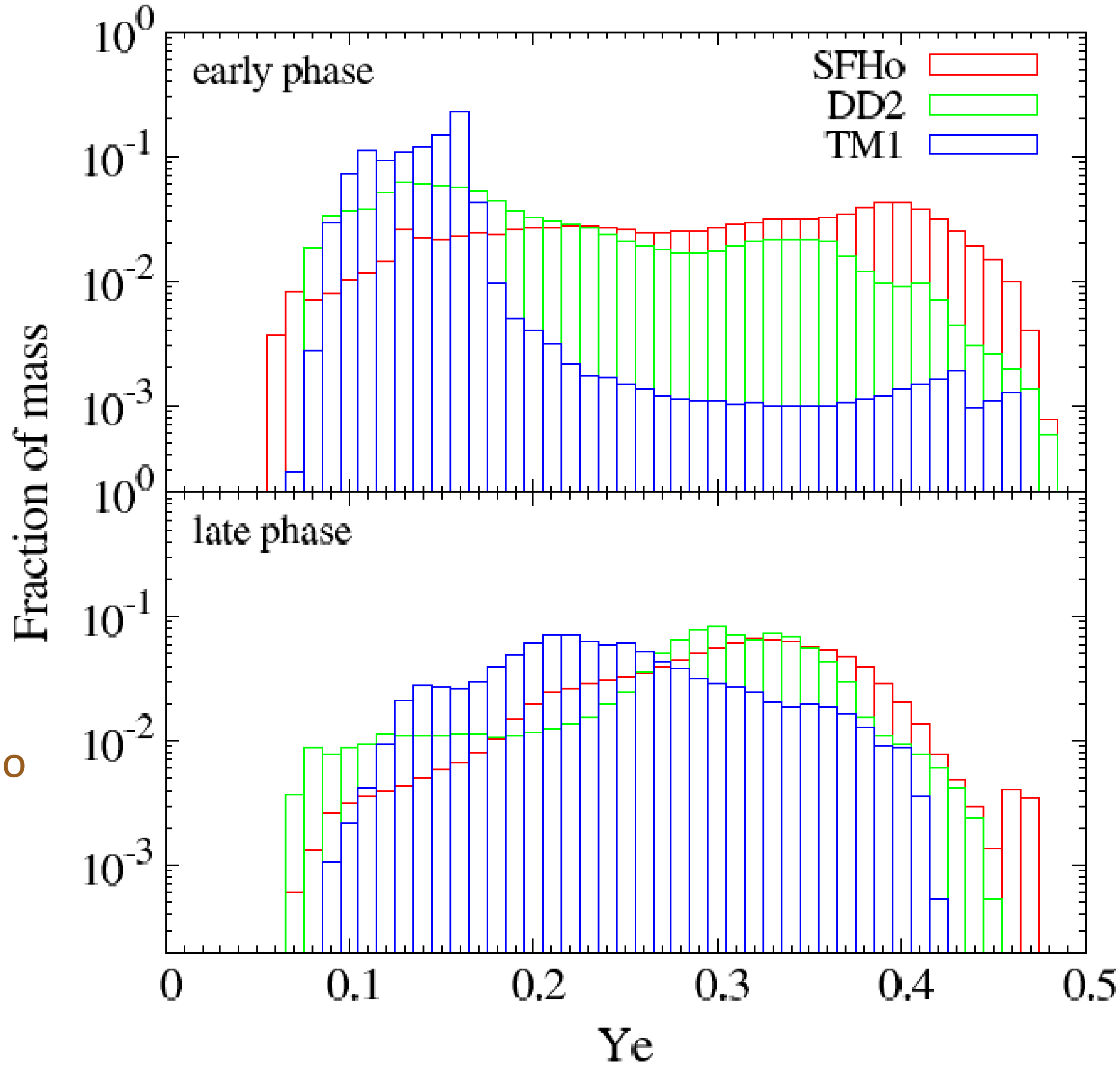
- For SFHo EOS, the Ye-distribution histogram has a broad, flat structure (*Wanajo, Sekiguchi, et al. (2014)*.)
  - Mixture of all Ye gives a good agreement with the solar abundance !
  - Robustness of Universality ? (dependence on binary parameters)
  - **How about the other EOS ? (Note : dynamical ejecta mass may insufficient)**





EOS dependences

- All of EOS models show wide Ye(m) distribution in later phase
- The peak shifts higher Ye for softer EOS
- Time evolution of the distribution due to weak interactions
  - e+ (and ν) capture in SFHo
  - e+/ν captures in DD2
  - ν capture in TM1



Summary

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  - Θjet ~< 10 degree ?
- EM transient associate with GRB130603B is powered by radioactive decay of r-process elements in <u>*dynamical*</u> ejecta
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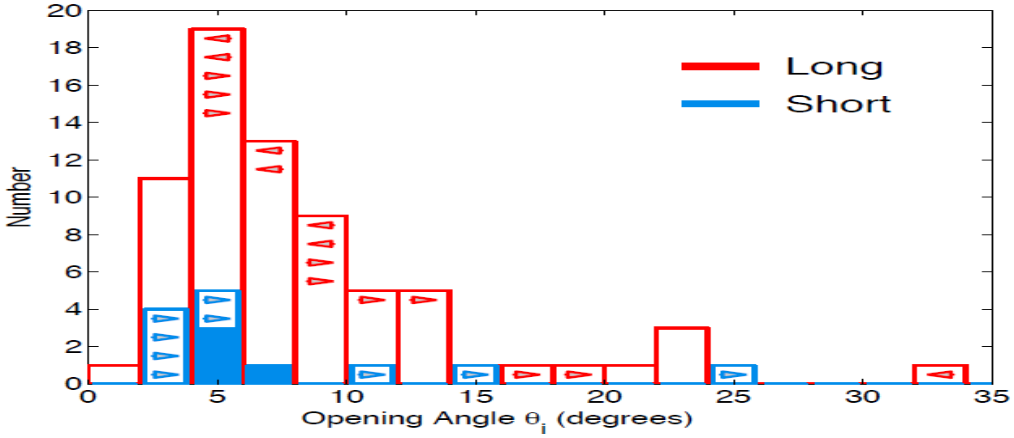

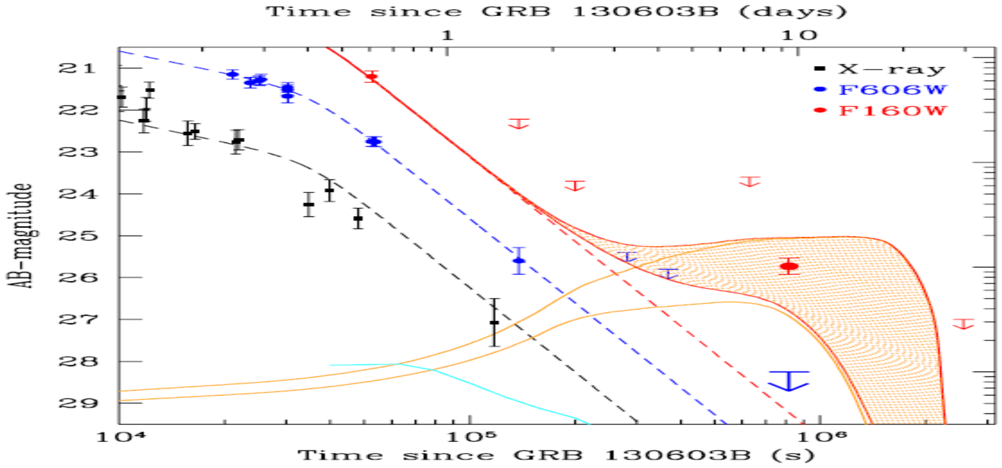

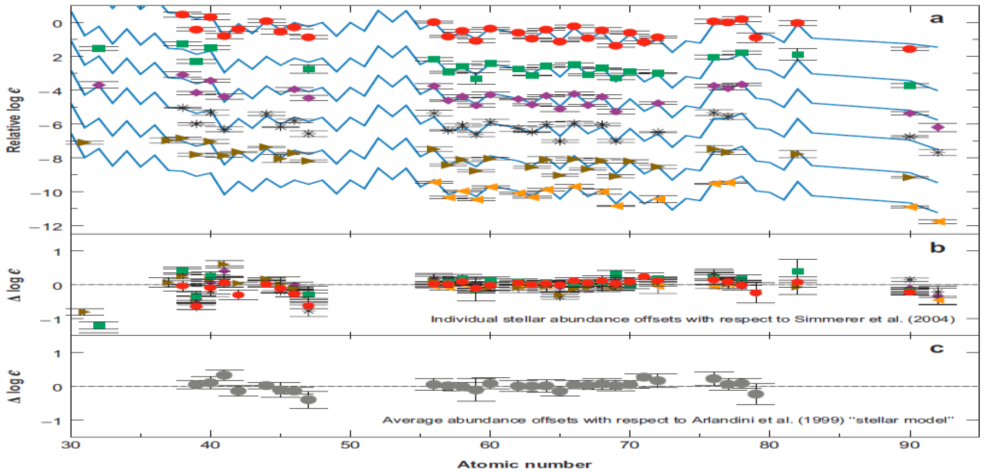

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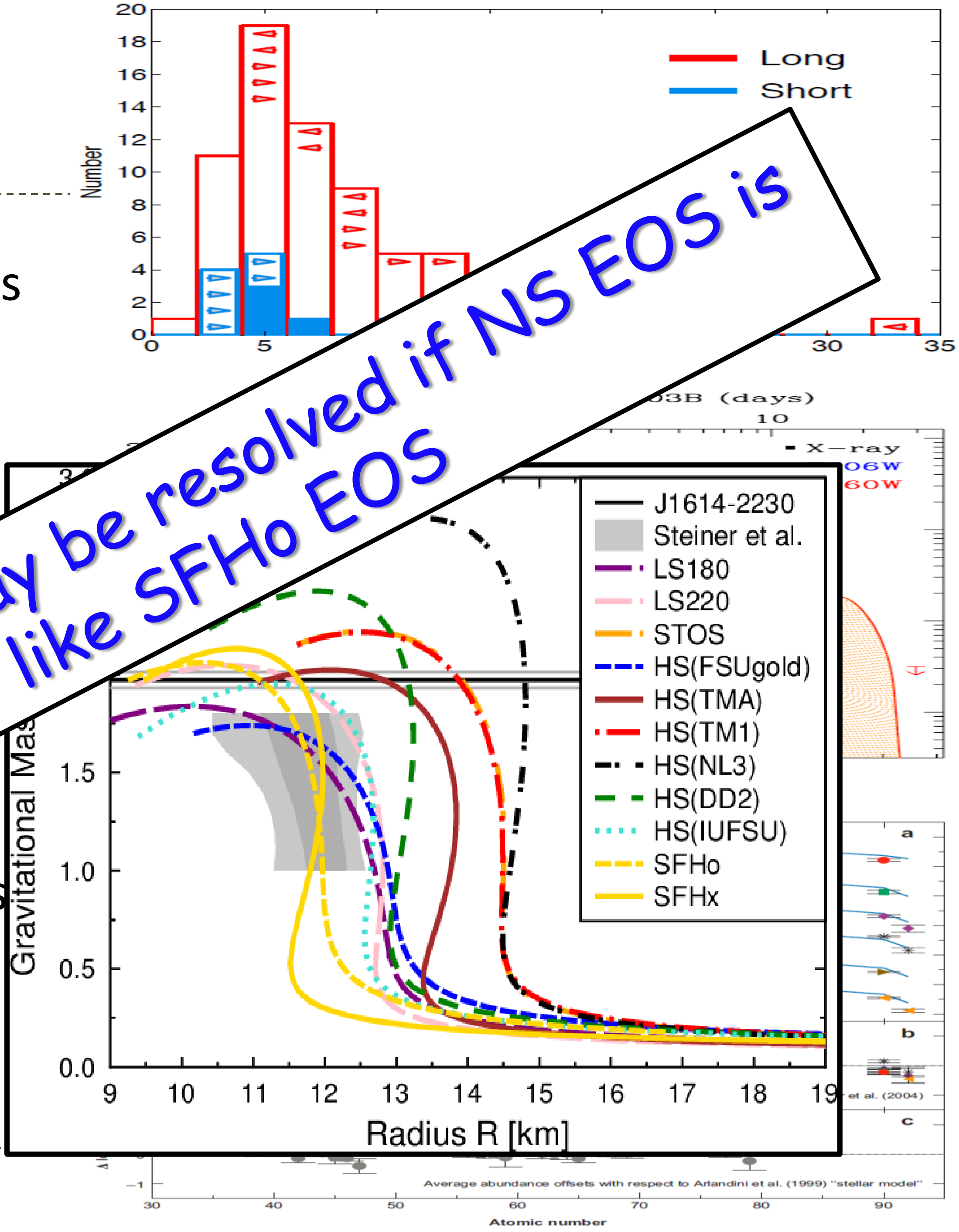
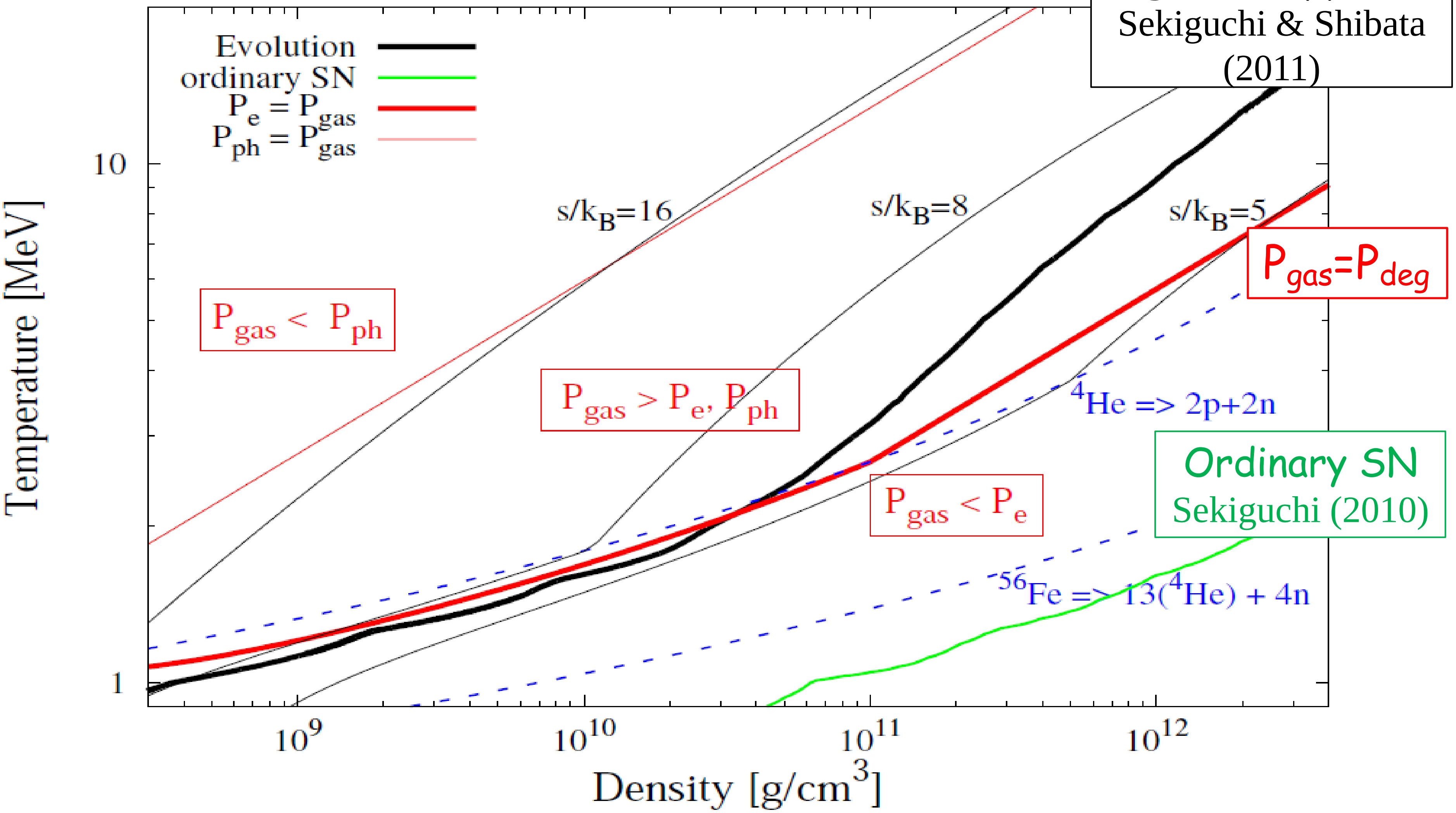


A Comment on magnetar scenario

- Lack of observational evidence that magnetars are formed as rapidly rotating NS (Vink & Kuiper 2006; Vink 2008)
  - Magnetar remnants Kes 73, CTB109, N49 do not show enhancement of explosion energy

Evolution paths of high-entropy cores



High entropy core
Sekiguchi & Shibata
(2011)

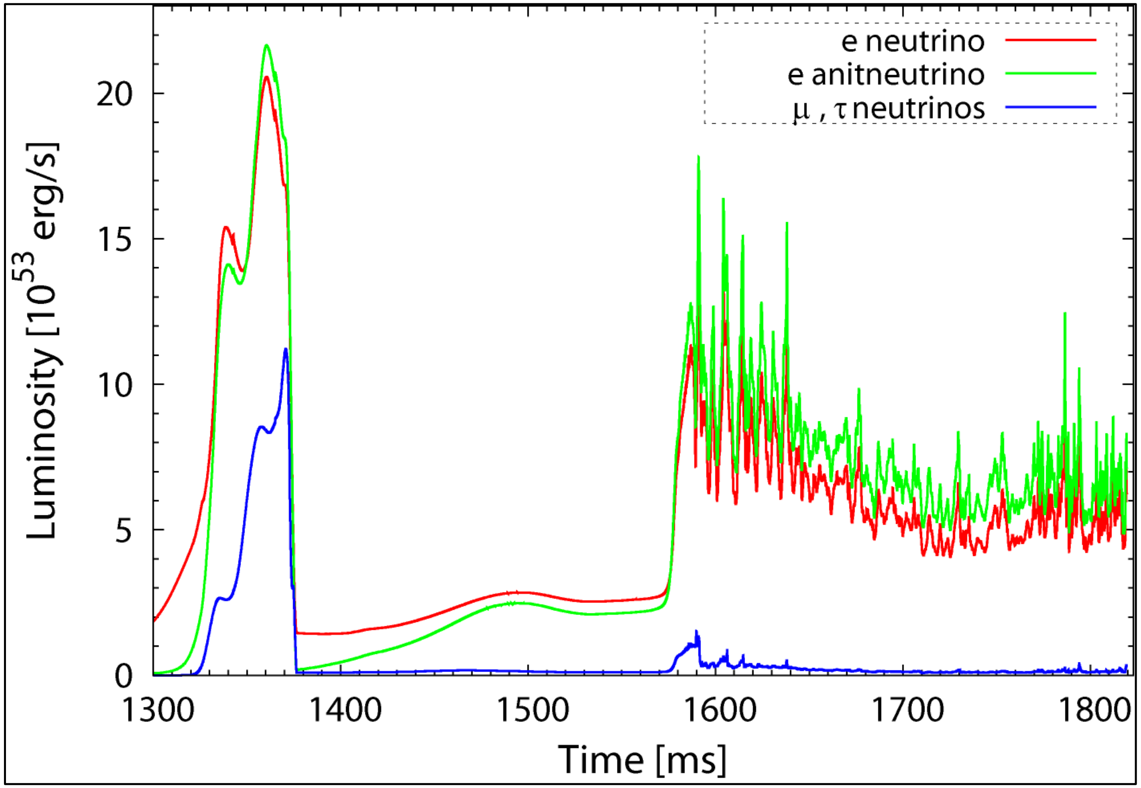
$P_{gas}=P_{deg}$

Ordinary SN
Sekiguchi (2010)

Sekiguchi et al. (2012) Progress of Theoretical & Experimental Physics
Sekiguchi & Shibata ApJ (2011)

Collapsar as High-entropy core collapse (2)

- Full GR simulations with neutrino cooling of collapse of a very high entropy core : **s ~ 8kB**
  - Direct BH formation : long GRB with no SNe ??
  - Huge neutrino luminosity due to very high mass accretion rate > Msun/sec



Importance of High Entropy/Rotation : **Energy balance**

- **Compact core / Oblique shock ⇒ high mass accretion rate**
- Energy balance may not be satisfied ……
  - **Rotation decreases |Qadv| & |Qν| (dense disk)**
  - **Additional 'cooling' sources required**

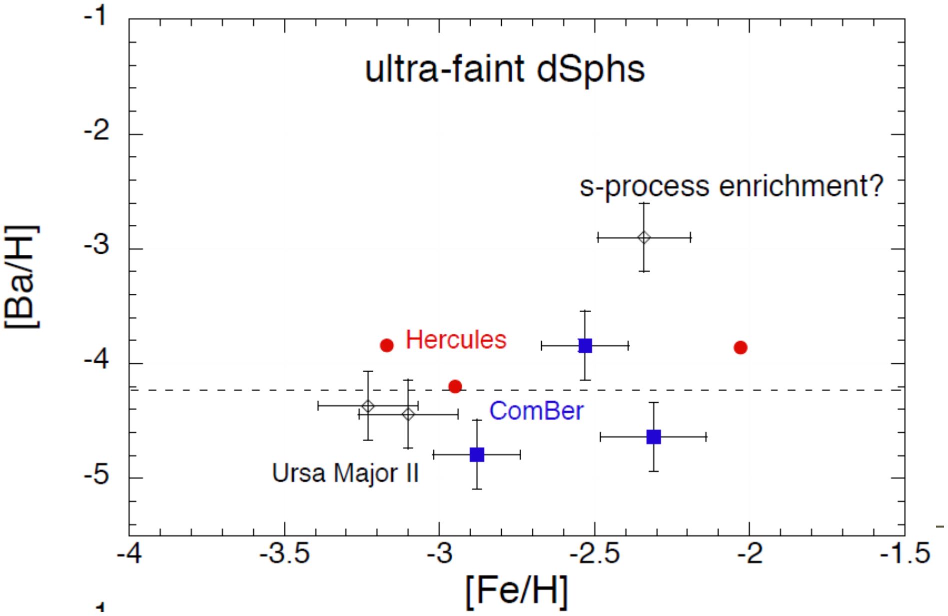
$$\dot{Q}^{+}_{\rm acc} = \dot{Q}^{-}_{\rm adv} + \dot{Q}^{-}_{\nu}$$

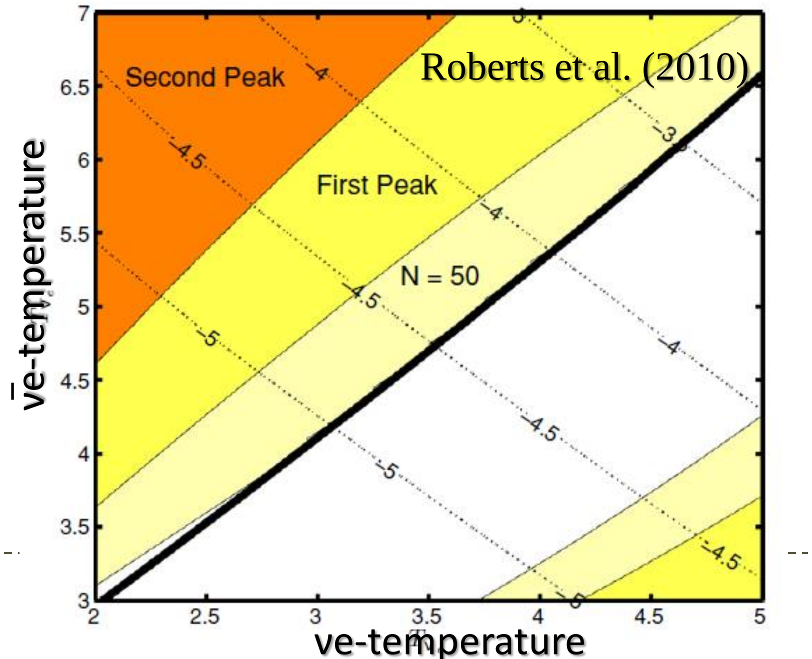
$$\Rightarrow \dot{Q}^{+}_{\rm acc} = \dot{Q}^{-}_{\rm adv} + \dot{Q}^{-}_{\nu} + \dot{Q}^{-}_{\rm outflow/expansion} + \dot{Q}^{-}_{\rm convection}$$

  - Strong dependence of Qν (ν-cooling) on T (and ρ)
    ⇒ slight change of configuration leads to dynamically large change
    - Torus is partially supported by the (thermal) pressure gradient
- **Smaller amount of heavy nuclei ⇒ more energetic SNe ?**
  - **Dissociation of 0.1 Msolar Fe costs ~ 10^{51} erg**
- Higher temperature : Less Pauli blocking in neutrino pair annihilation

R-process nucleosynthesis : difficulty in SNe

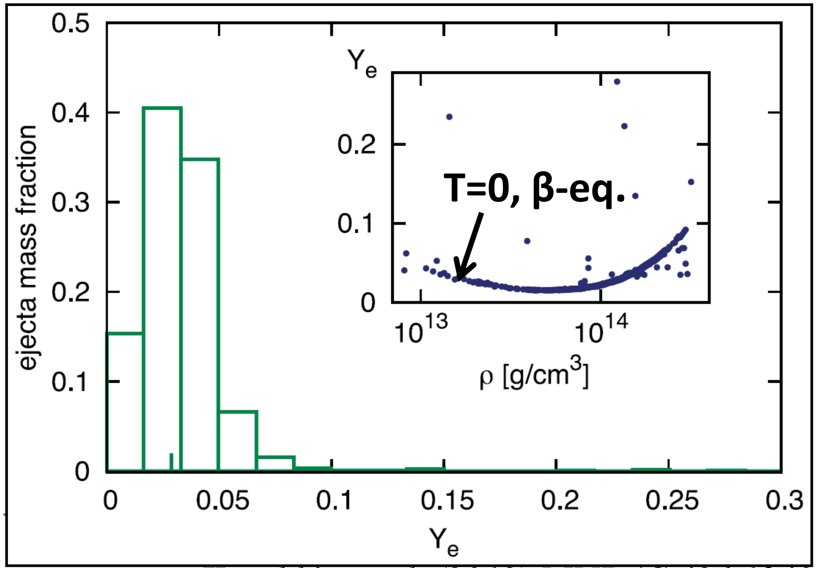
- **Theoretically**
  - Neutrinos from PNS make the flow proton-rich via $n+\nu \rightarrow p+e$
  - ⇒ only weak r-process (up to 2nd peak) (*Roverts et al. 2010, 2012*)
    - *Electron capture SN* : *Hoffman et al. 2008; Wanajo et al. 2009*
    - *(Iron) core collapse SN* : *Fisher et al. 2010; Hudepohl et al. 2010*; *Wanajo et al. 2011*
- **Observationally (*Tsujimoto and Shigeyama. 2014*)**
  - No enrichment of Eu in ultra dwarf galaxies but Fe increases
    - There should be no r-process events but a number of SNe (Fe↑)



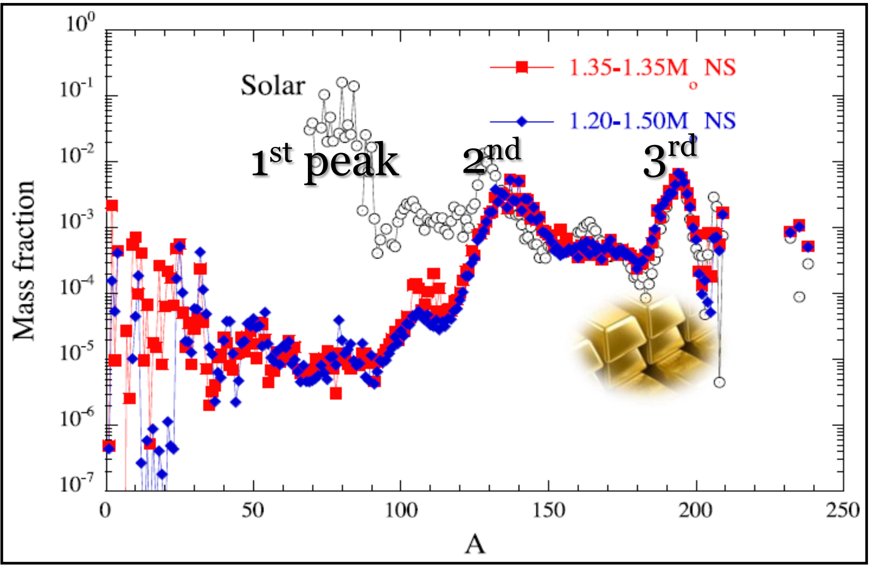

Roberts et al. (2010)

R-process nucleosynthesis: NS-NS

- **Previous NS-NS merger simulations**
  - Main mass ejection mechanism : tidal effects (or weak interactions are not included)
  - Ejecta composed of NS matter in β-eq. at low T, very low Ye
  - only 2nd (A~130; N=82) and 3rd (A~195; N=126) peaks are produced
  - ⇔ Universality
- **Our new study**
  - Full GR simulations with several EOS , weak interactions and approx. ν-transport
  - Universality may be satisfied if the NS EOS is soft (requirement from collimation, kilonova)



Korobkin et al. (2012) MNRAS 426 1940



Goriely et al. (2011) ApJL 738 32

Recent result with finite-temperature EOS

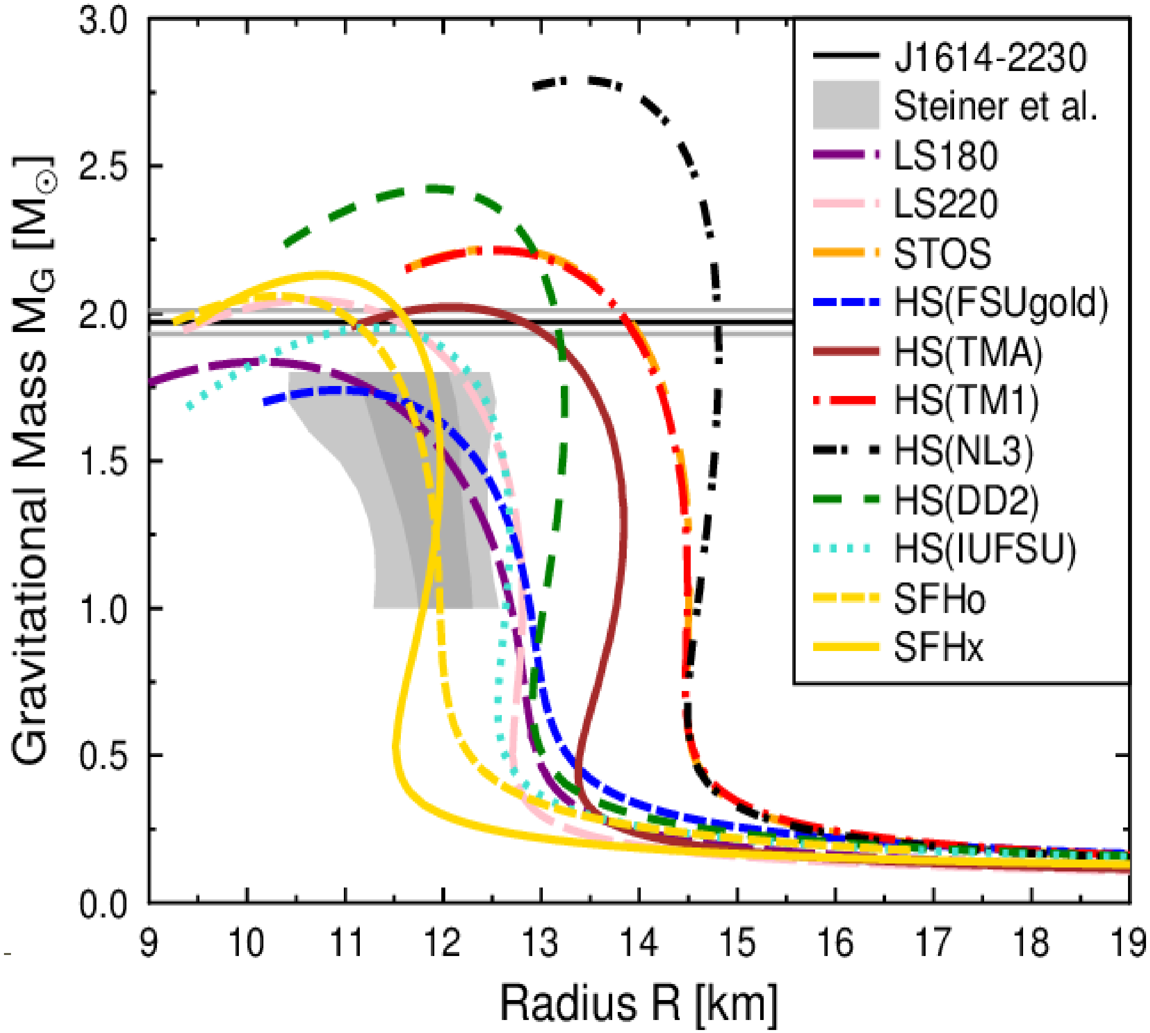
- Multi-EOS study (Thanks to ***M. Hempel***)
- GR approximate v-rad hydro simulation
- Adopted EOS

14.5km
- **TM1 (Shen EOS)**
  - **TMA**

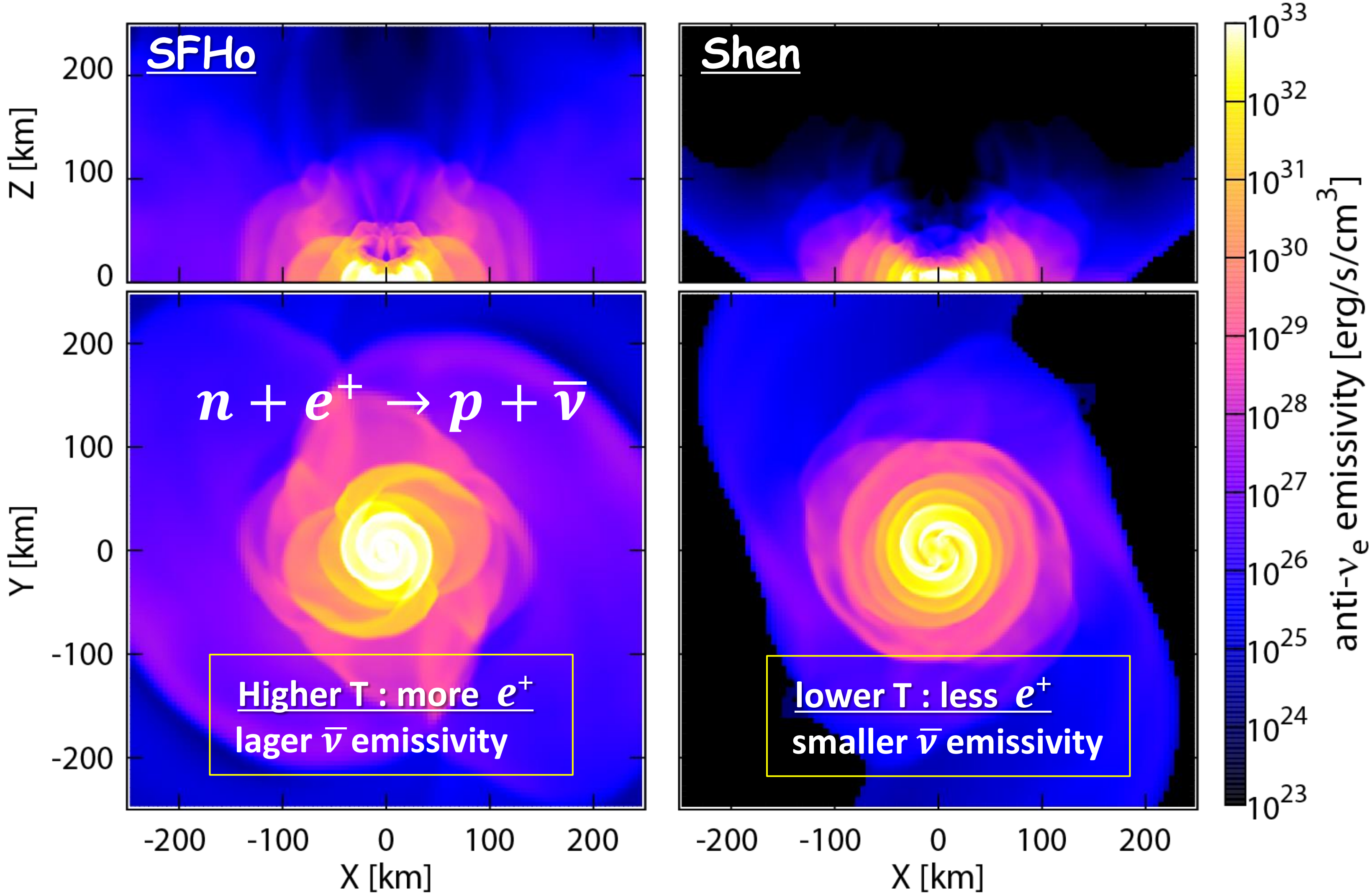
13.2km
- **DD2**
  - **IUFSU**

11.8km
- **SFHo**

Consistent with
  - NS radius estimation
  - Chiral effective theory



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



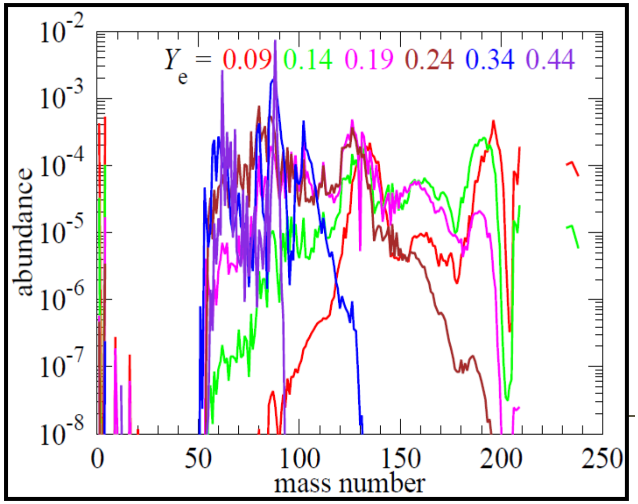
$$n + e^+ \rightarrow p + \bar{\nu}$$

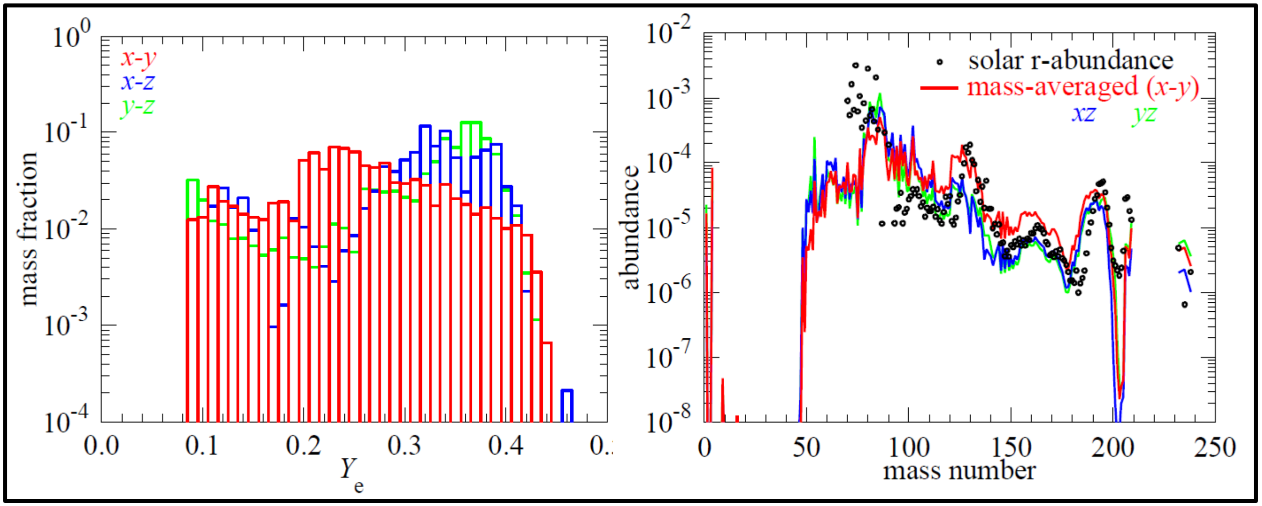
Higher T : more e^+
lager $\bar{\nu}$ emissivity

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

On robustness of universality

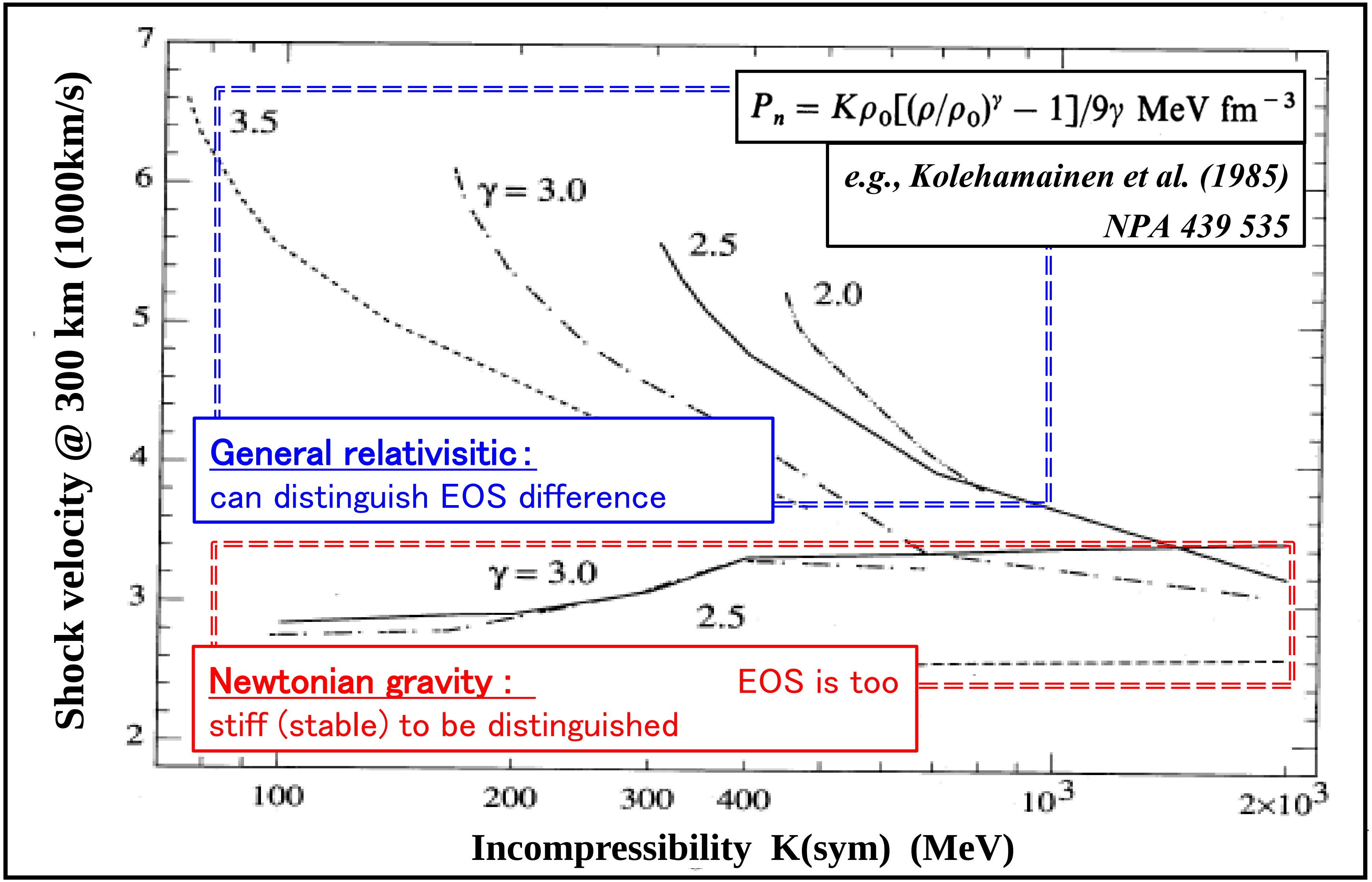
- Rough expectation based on limited information currently available
  - Ye < 0.2 is responsible to the 3rd peak
  - Ye ~ 0.2—0.25 is responsible to the 2nd peak
  - Ye > 0.3 is responsible to the 1st peak
- For fixed mass fraction in Ye ~ 0.1 (fixed 3rd peak)
  - Factor of ~ 5 difference in Ye > 0.3 does not change 1st peak very much ⇒ enhancement (from flat distribution) in Ye > 0.3 would not be serious
  - Factor of ~ 10 difference in Ye ~ 0.2 reduces 2nd peak considerably ⇒ mass ratio between Ye ~ 0.1 and 0.2 may be important for 2nd and 3rd peaks





Importance of GR

van Riper (1988) ApJ 326 235



$$P_n = K\rho_0[(\rho/\rho_0)^\gamma - 1]/9\gamma \text{ MeV fm}^{-3}$$

e.g., Kolehamainen et al. (1985) NPA 439 535

General relativisitic :
can distinguish EOS difference

Newtonian gravity : EOS is too stiff (stable) to be distinguished