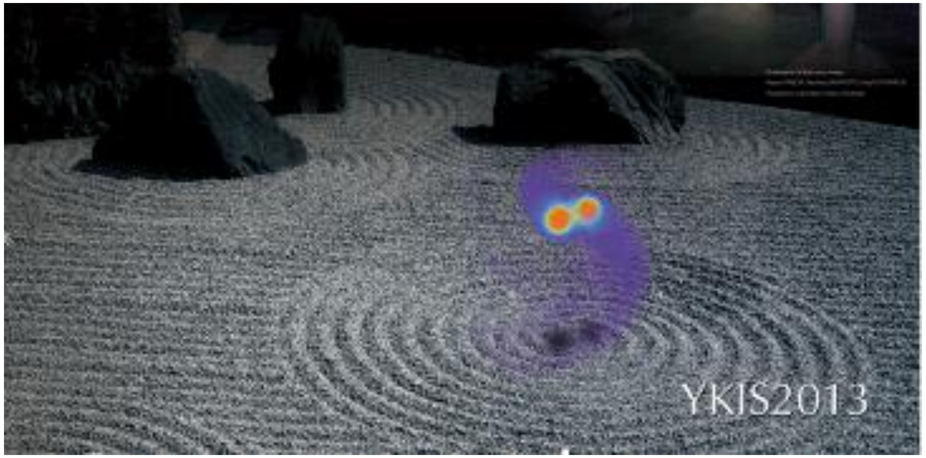


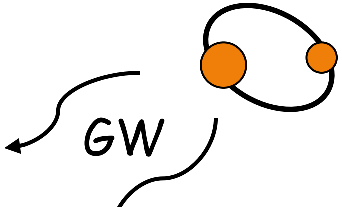
連星中性子星合体

NR simulations, mass ejection, and EM counterparts

Yuichiro Sekiguchi (YITP)

重力波天文学に向けて...

Advanced LIGO



KAGRA

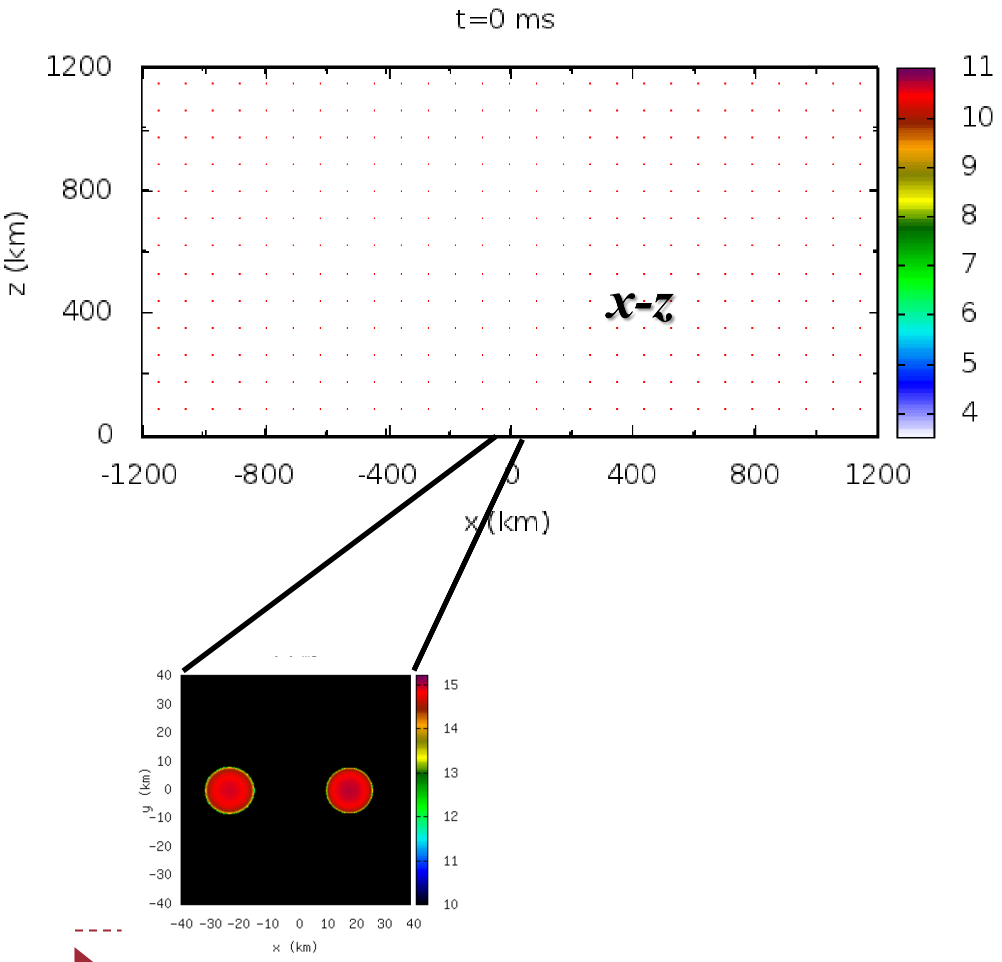
Advanced Virgo

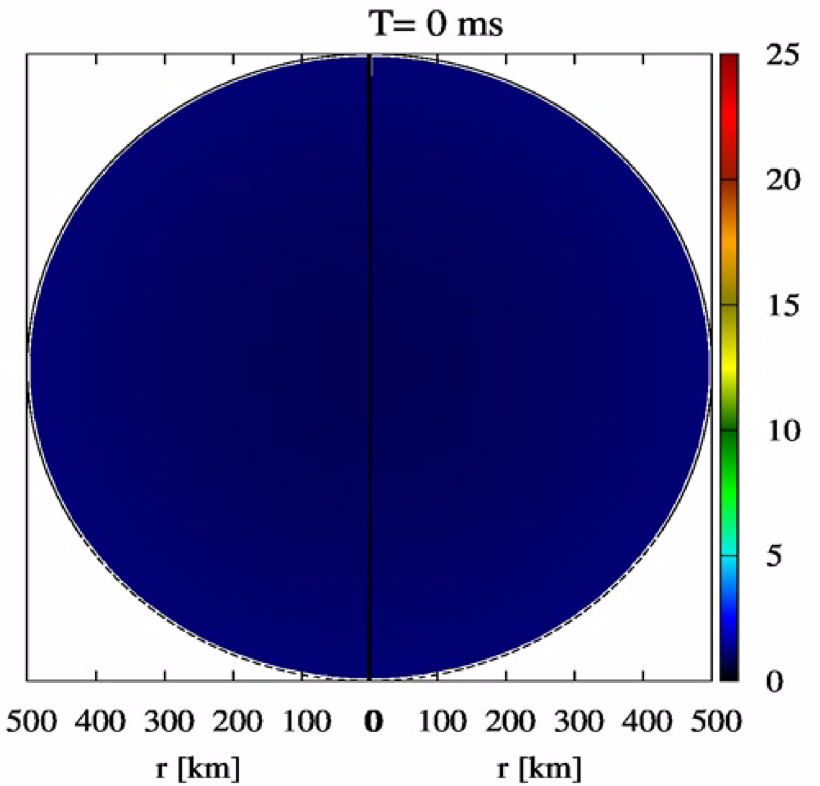
有望な波源
コンパクト天体連星の合体

- Expected event rate ~ a few ~ 10 / yr
- 理論波形との matched filtering 解析
  - 膨大なパラメータ空間
- 電磁波対応天体の観測
  - パラメータ空間の縮減(実効的にS/N向上)
    - **発生時刻・位置(母銀河)決定**
  - **電磁波観測を trigger とした解析**
  - Multi-messenger confirmation
- 連星合体の観測がもたしうる情報
  - **高エネルギー天体現象との関連**
  - **元素の起源、銀河の化学進化**
  - 中性子星内部状態
  - 強重力場におけるGRテスト, …etc

連星中性子星合体 & 超新星爆発

Density contour
Animation by Hotokezaka





Entropy contour
Animation by Suwa

Possible EM counterparts : Similarities to SNe

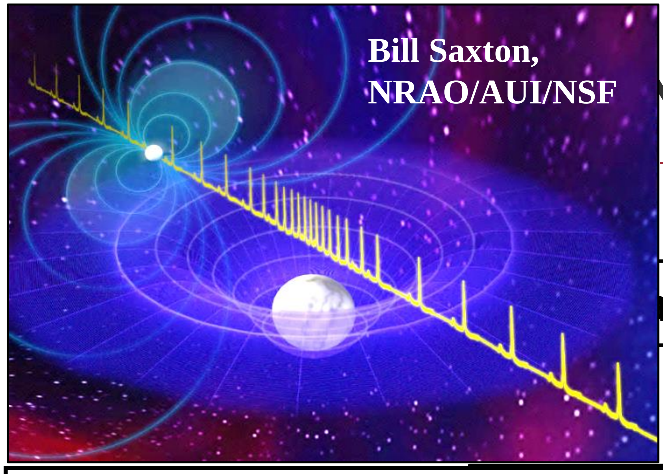
- **Supernovae**
  - Long GRBs
    - Prompt (γ), afterglow (X to Radio)
  - Supernova remnants
    - Synchrotron: Ejecta-ISM interaction
    - Activities Powered by Pulsar
  - Radioactive decay of ^{56}Ni
    - produced in the explosive ejecta
    - Optical
  - Classification by spectra
  - Shock breakout
    - UV ~ X. (e.g. Tominaga+ 2009)

- **Merger of NS-NS, BH-NS**
  - Short GRBs
    - Prompt (γ), afterglow (X to radio)
  - Merger remnants
    - Radio Flare: Ejecta-ISM interaction
    - Powered by Massive NS ? (Zhang 2013)
  - Decay of r-process elements
    - Proceeds in the n-rich ejecta
    - Macronova / Kilonova / r-process nova
  - Classification by spectra ???
  - Merger Shock breakout
    - X-ray : Kyutoku et al. (2012)

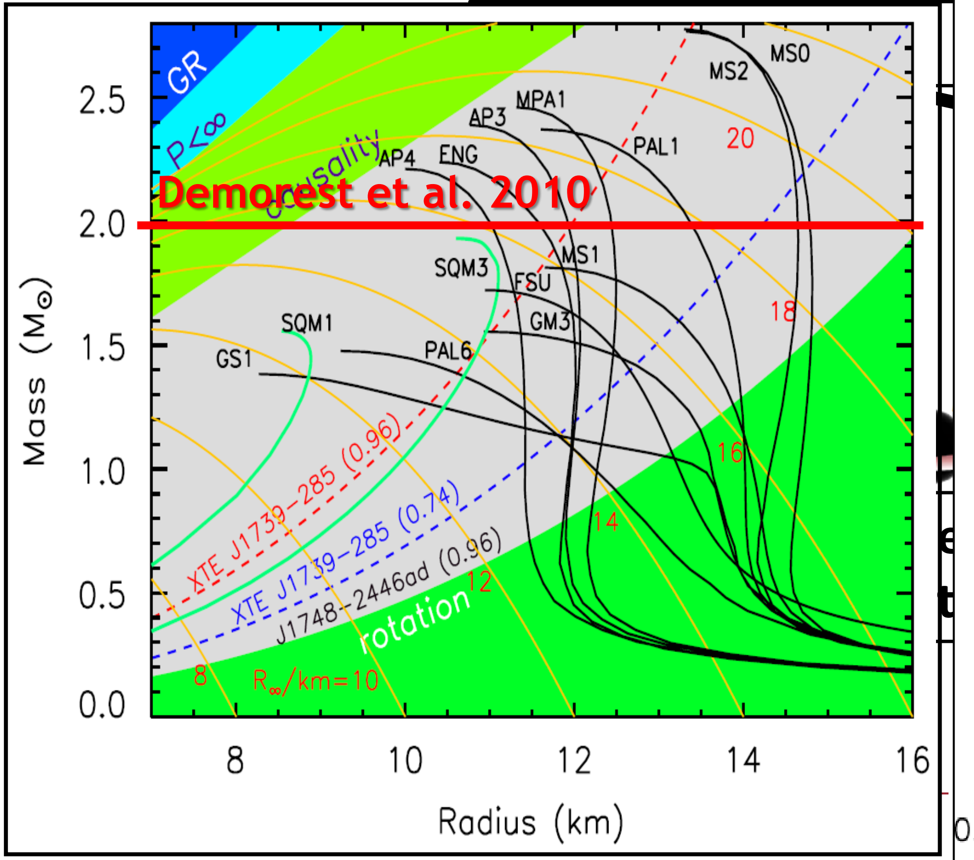
See also Metzger & Berger (2012)

NS-NS r

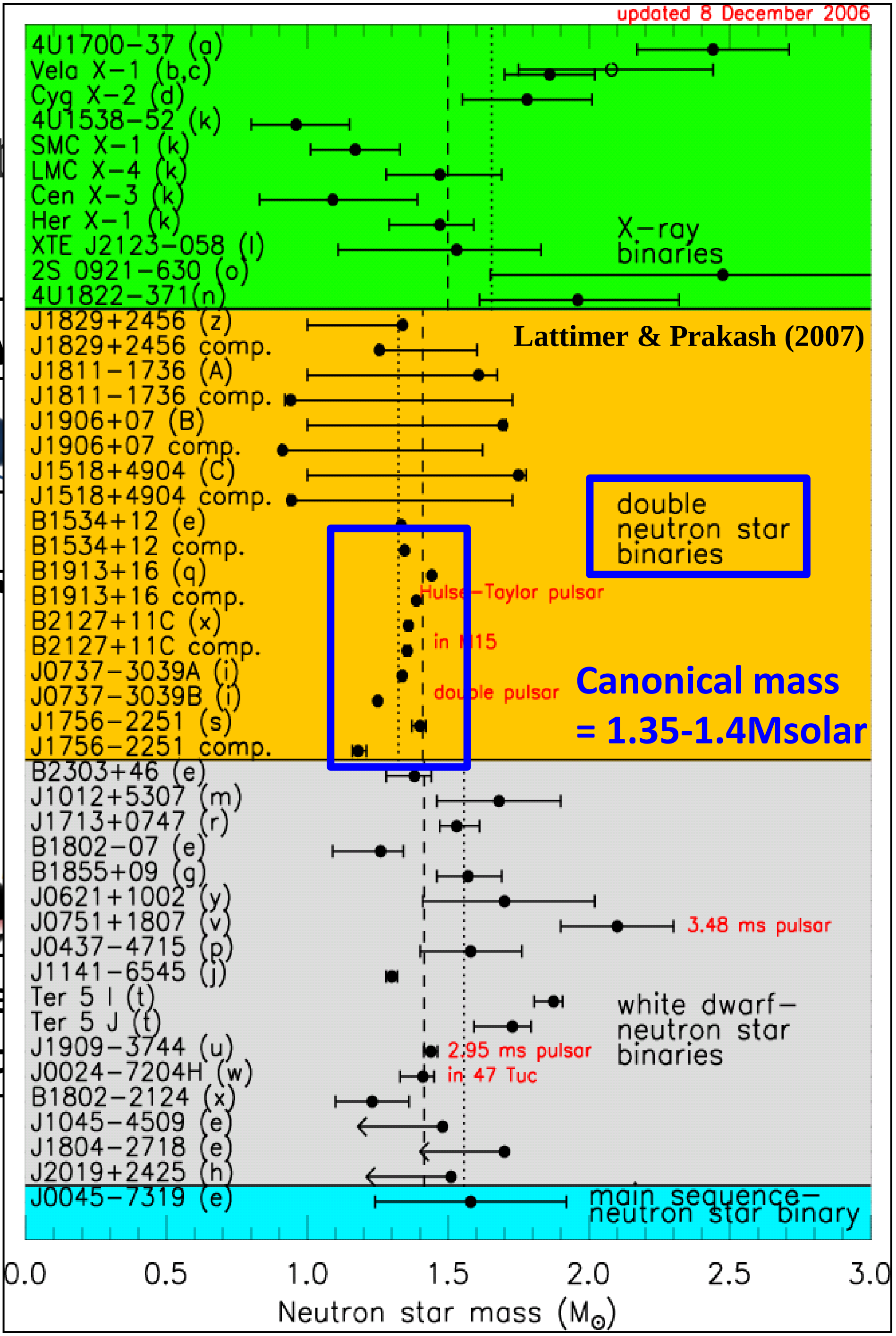
l of NS binary



Bill Saxton, NRAO/AUI/NSF



Demorest et al. 2010

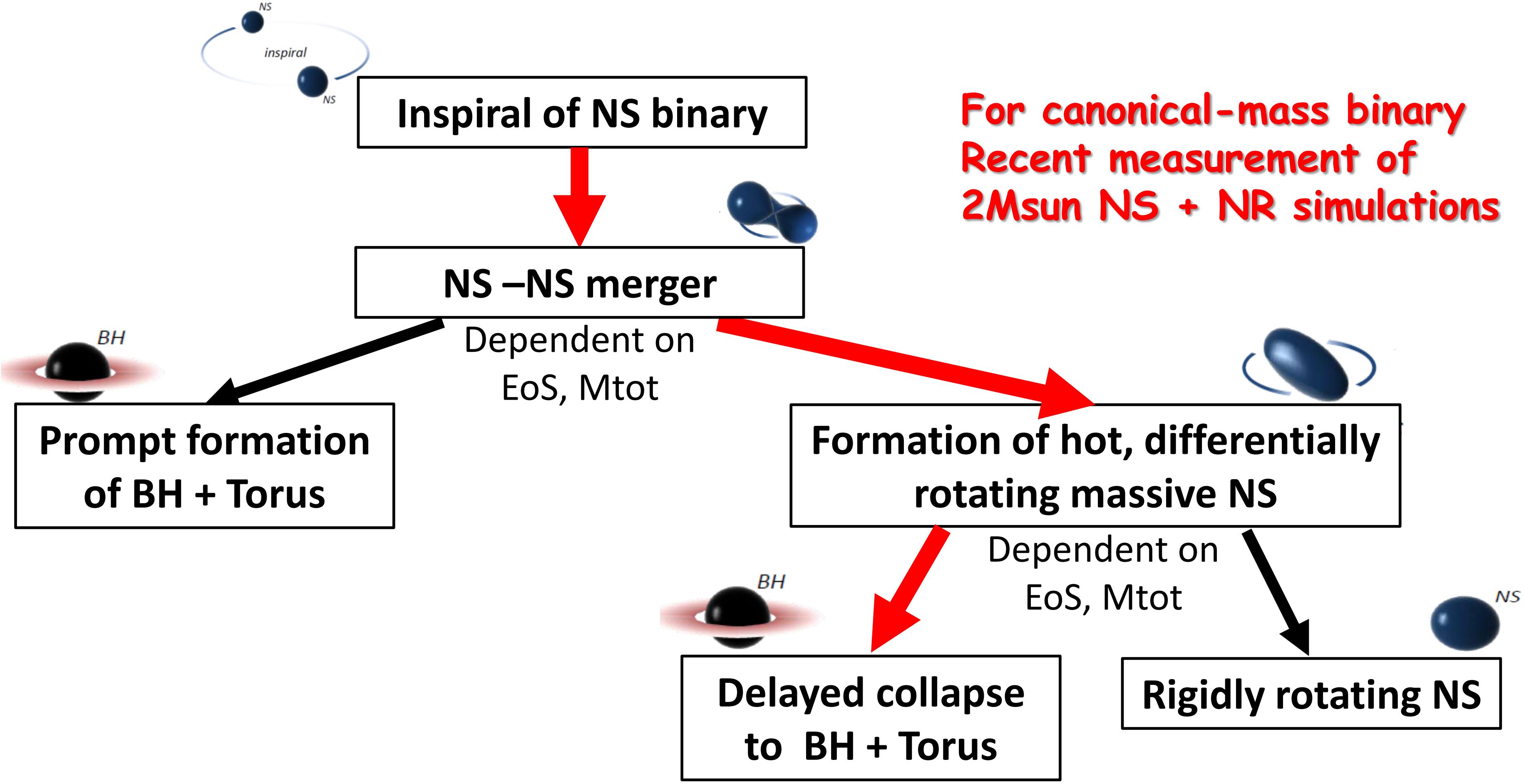


Lattimer & Prakash (2007)

Canonical mass = 1.35-1.4Msolar

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

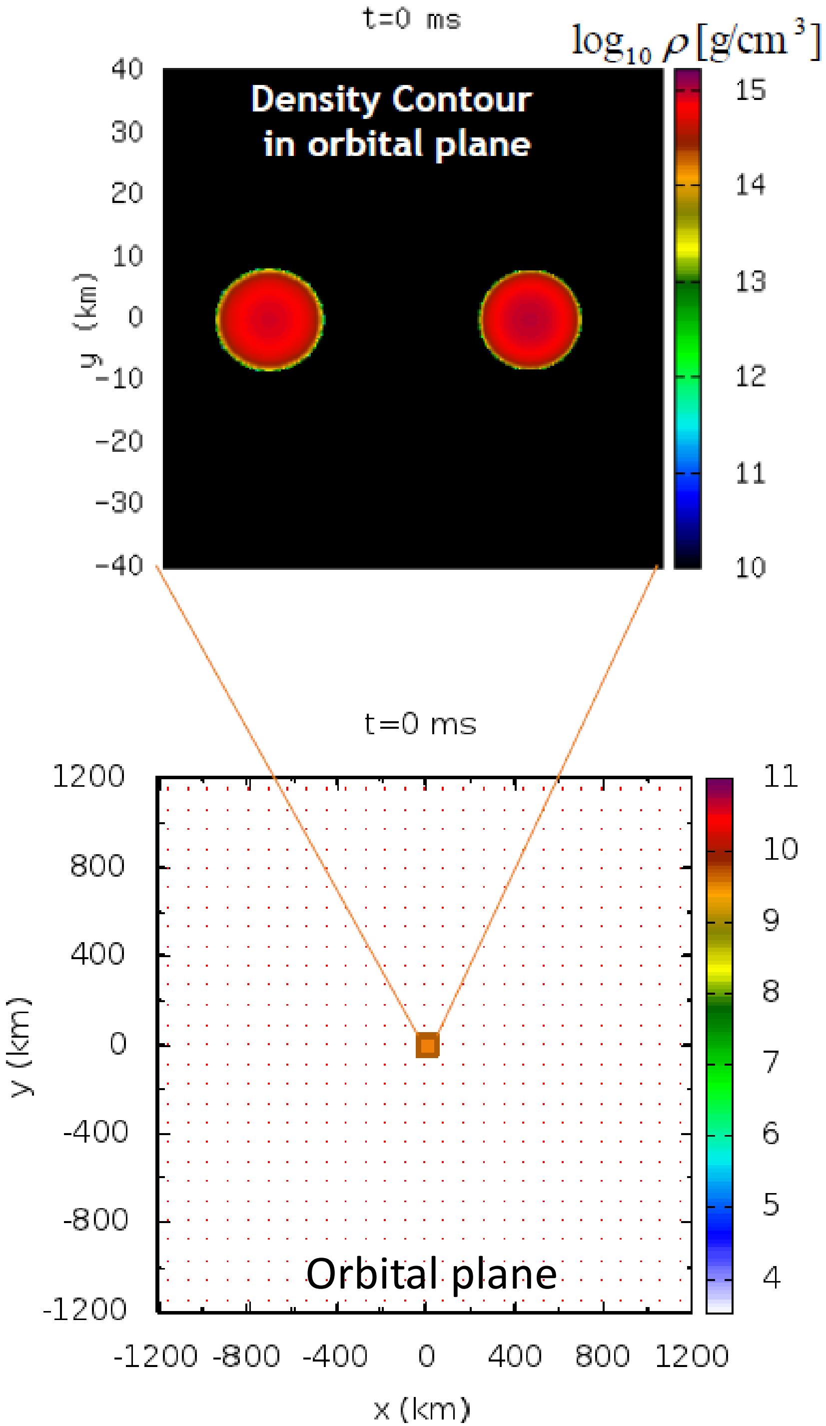
Formation of hot, differentially rotating massive NS

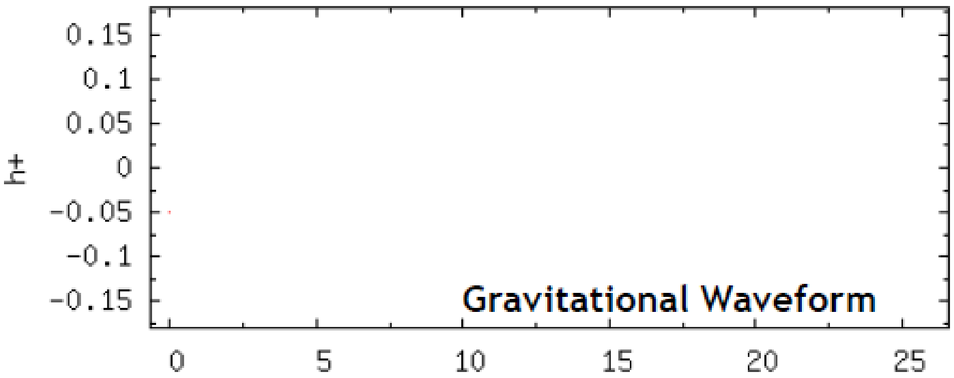
Dependent on EoS, Mtot

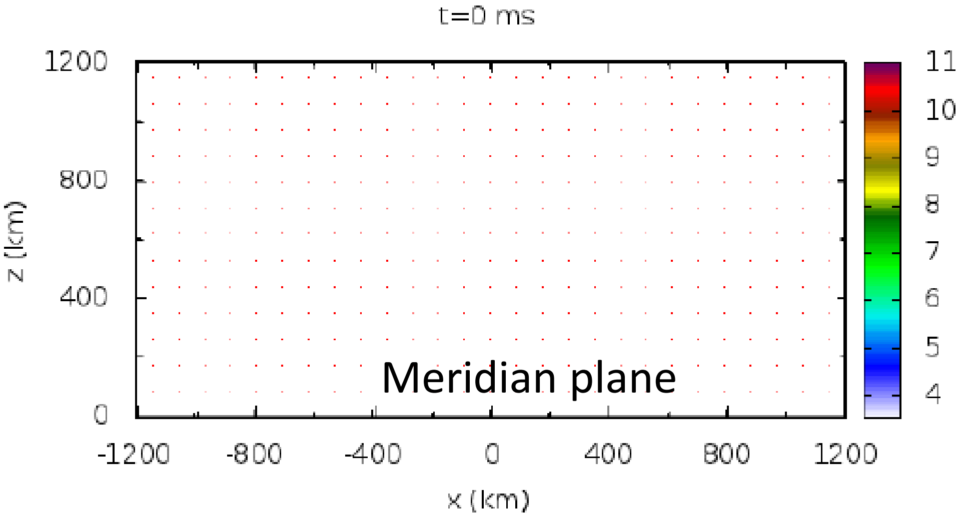
Delayed collapse to BH + Torus

Rigidly rotating NS

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



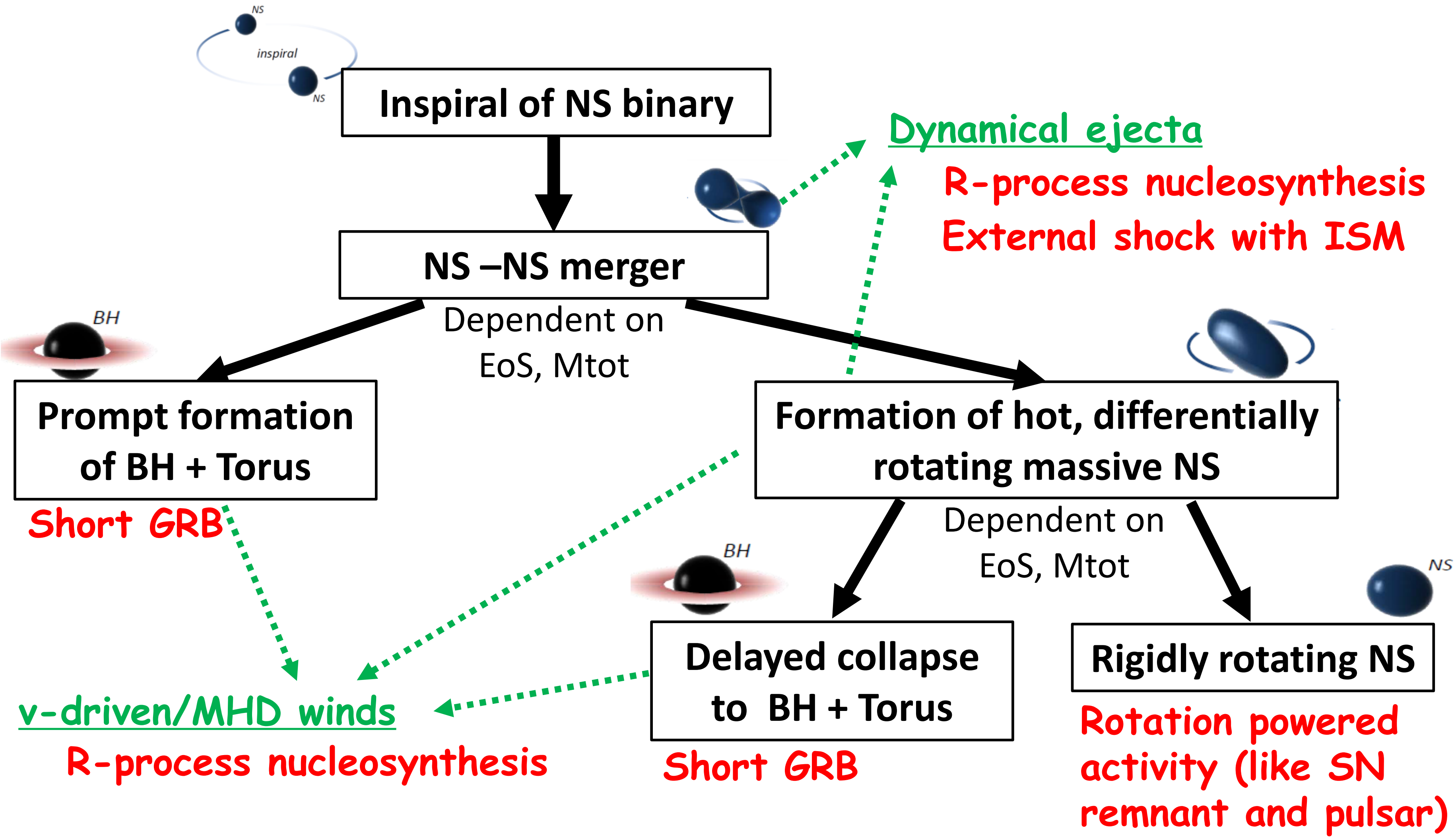




Animation by Hotokezaka

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

Messengers of NS-NS mergers



Inspiral of NS binary

NS –NS merger

Dependent on
EoS, Mtot

Dynamical ejecta

R-process nucleosynthesis

External shock with ISM

Prompt formation of BH + Torus

Short GRB

Formation of hot, differentially rotating massive NS

Dependent on
EoS, Mtot

v-driven/MHD winds

R-process nucleosynthesis

Delayed collapse to BH + Torus

Short GRB

Rigidly rotating NS

Rotation powered activity (like SN remnant and pulsar)

Possible EM counterparts : Similarities to SNe

- **Supernovae**
  - Long GRBs
    - Prompt (γ), afterglow (X to Radio)
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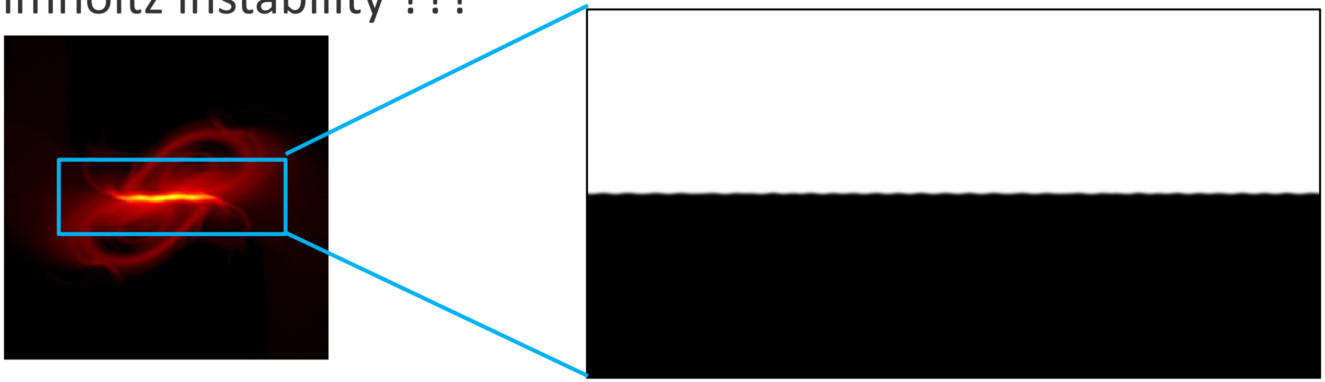
  - Classification by spectra ???
  - Merger Shock breakout
    - X-ray : Kyutoku et al. (2012)

See also Metzger & Berger (2012)

Importance of magnetic fields

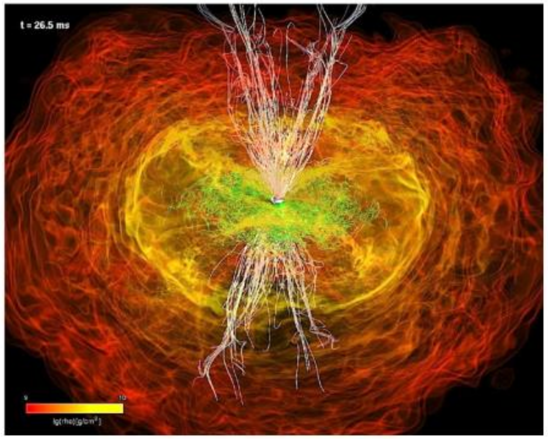
- Inspiral phase : dynamically not important
- After the merger : play a role if large (~ $10^{14\text{-}15}$G) B-fields exist
- Amplification mechanism of B-field
  - Kelvin-Helmholtz instability ???



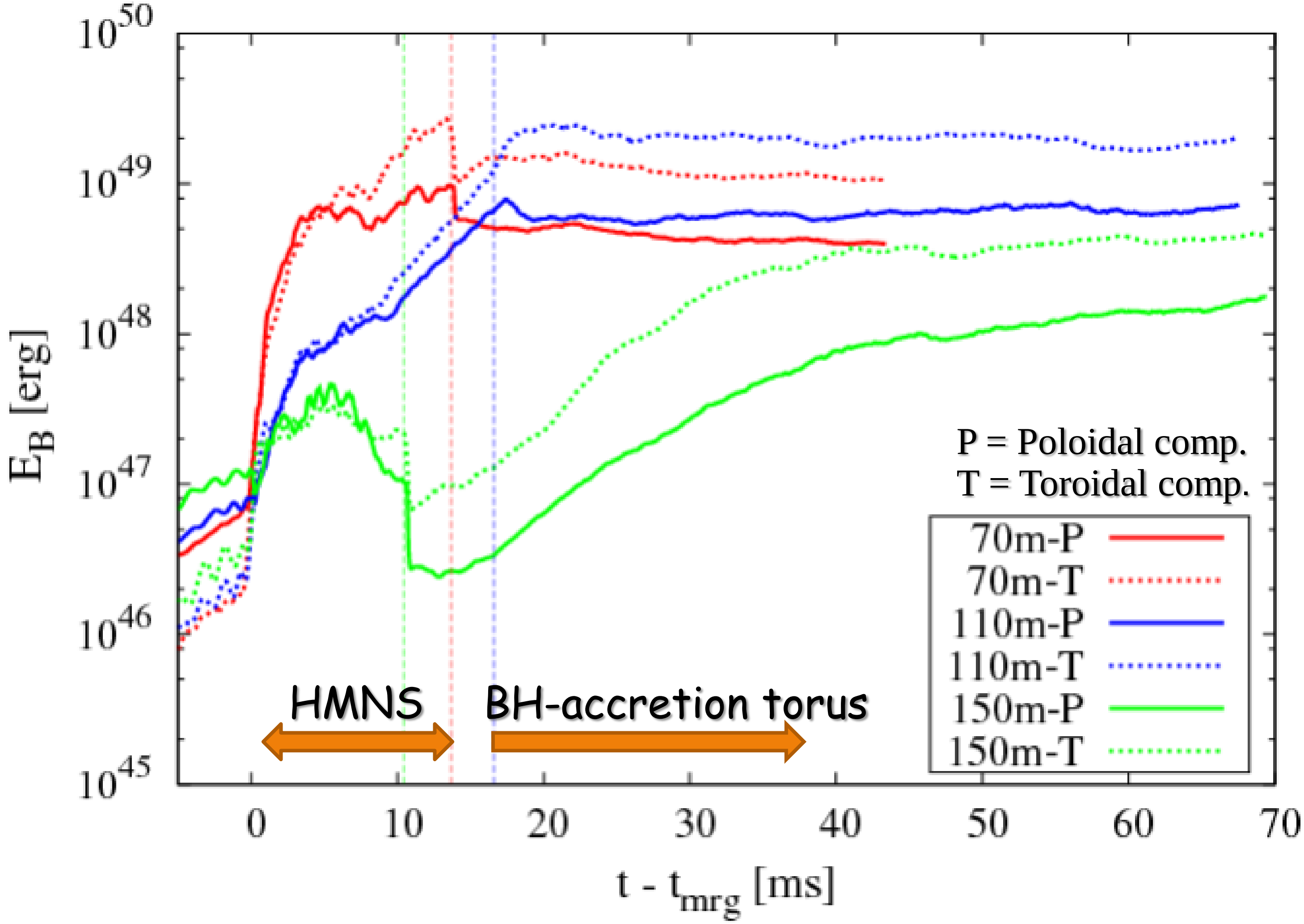
  - Magneto-rotational instability ?
    - Balbus & Howley 1998

$$\boxed{\lambda_{\mathrm{MRI}}^{\max} \sim 1.6\,\mathrm{km}\left(\frac{\rho}{10^{12}\,g/\mathrm{cm}^3}\right)^{-1/2}\left(\frac{B}{10^{15}G}\right)\left(\frac{\Omega}{10^4\,\mathrm{rad/s}}\right)^{-1}}$$

  - Needs high-resolution studies

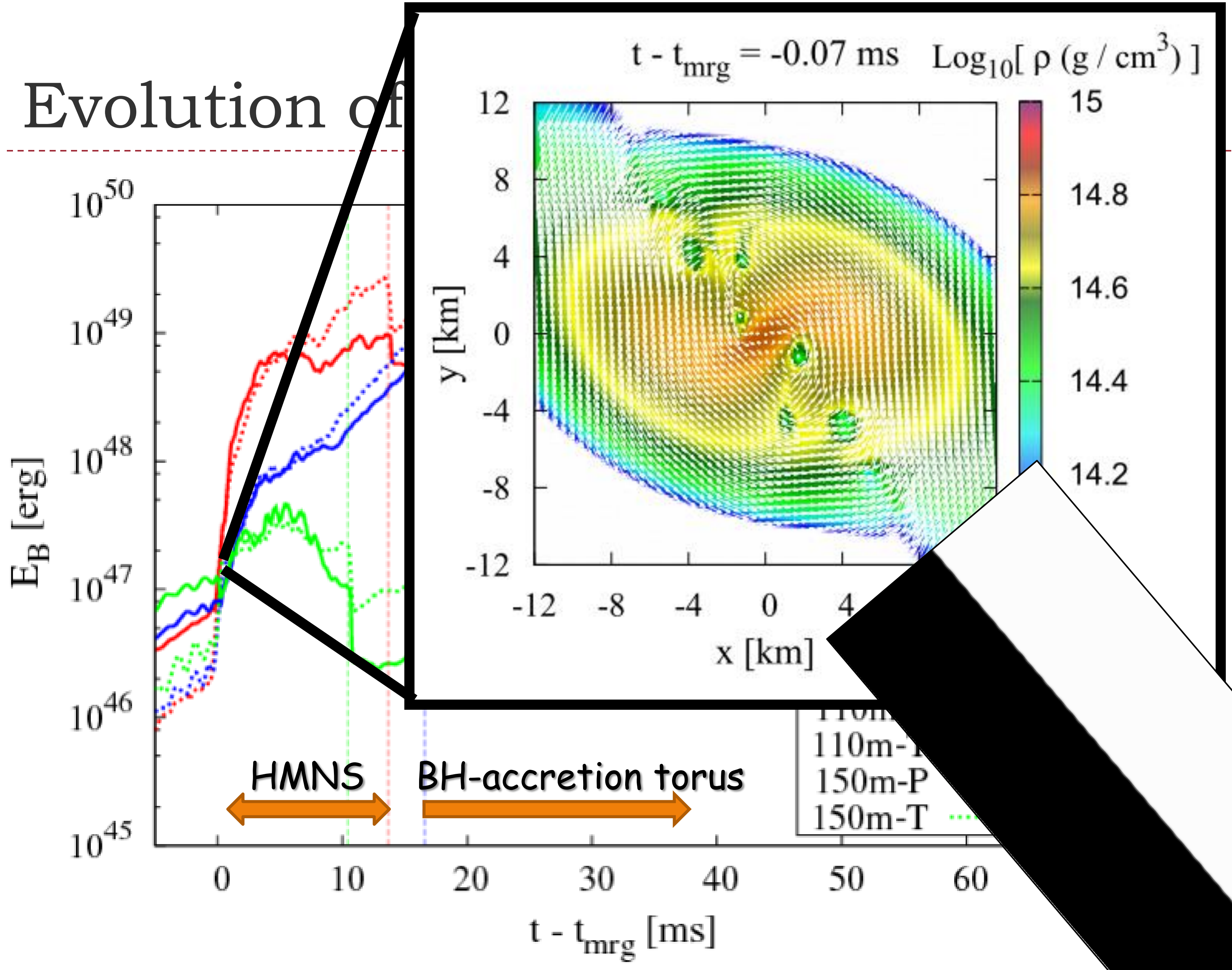


Evolution of B-field energies



- **Kiuchi et al. (2014)**

Evolution of

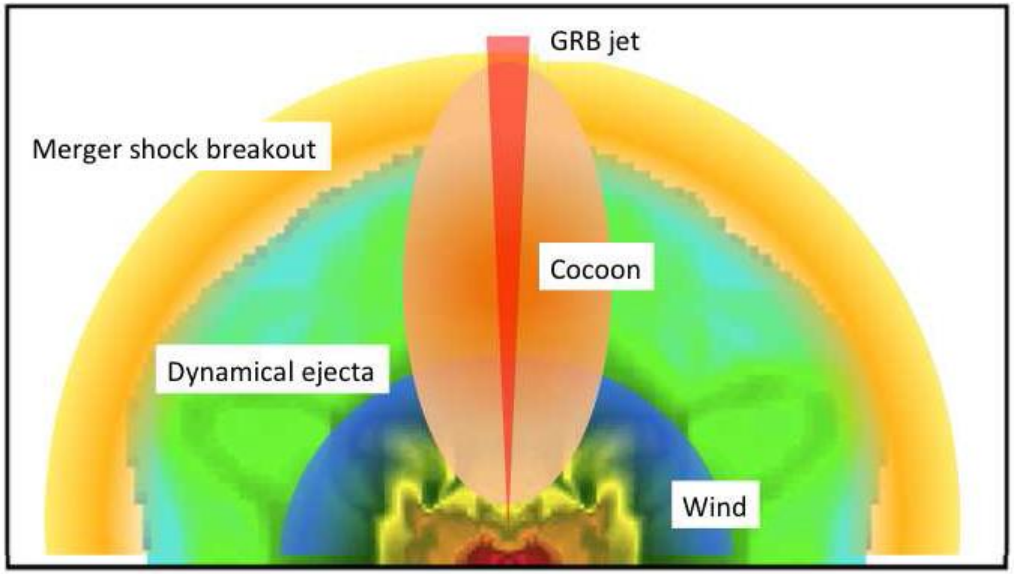


- **Kiuchi et al. (2014)**

Multi Messengers ad GW counterpart

- Jets of short GRBs might be collimated in general
    - SGRB111020A : $\theta_j \sim$ 3-8° (Fong et al. 2012)
    - SGRB051121A : $\theta_j \sim$ 7° (Burrows et al. 2006)
  - Most of GRB Jets are expected to be Off-Axis ⇒ **very faint**
  - Emission from cocoon ??

Hotokezaka & Piran (2015)



- We need 4π emission events
  - Associated with 4π ejecta
    - **Merger shock breakout**
    - **Dynamical ejecta**
    - **neutrino-driven/MHD winds**
    - **Late-time disk dissolution**
      - □ Fernandez & Metzger 2013
  - Quests for 4π EM counterparts

Radio flare from Ejecta-ISM interaction

- External shock with inter stellar matter (ISM) : a 4π emission
- Synchrotron radiation becomes most luminous when ejecta mass = swept-up ISM mass: for typical values (Nakar & Piran 2011)

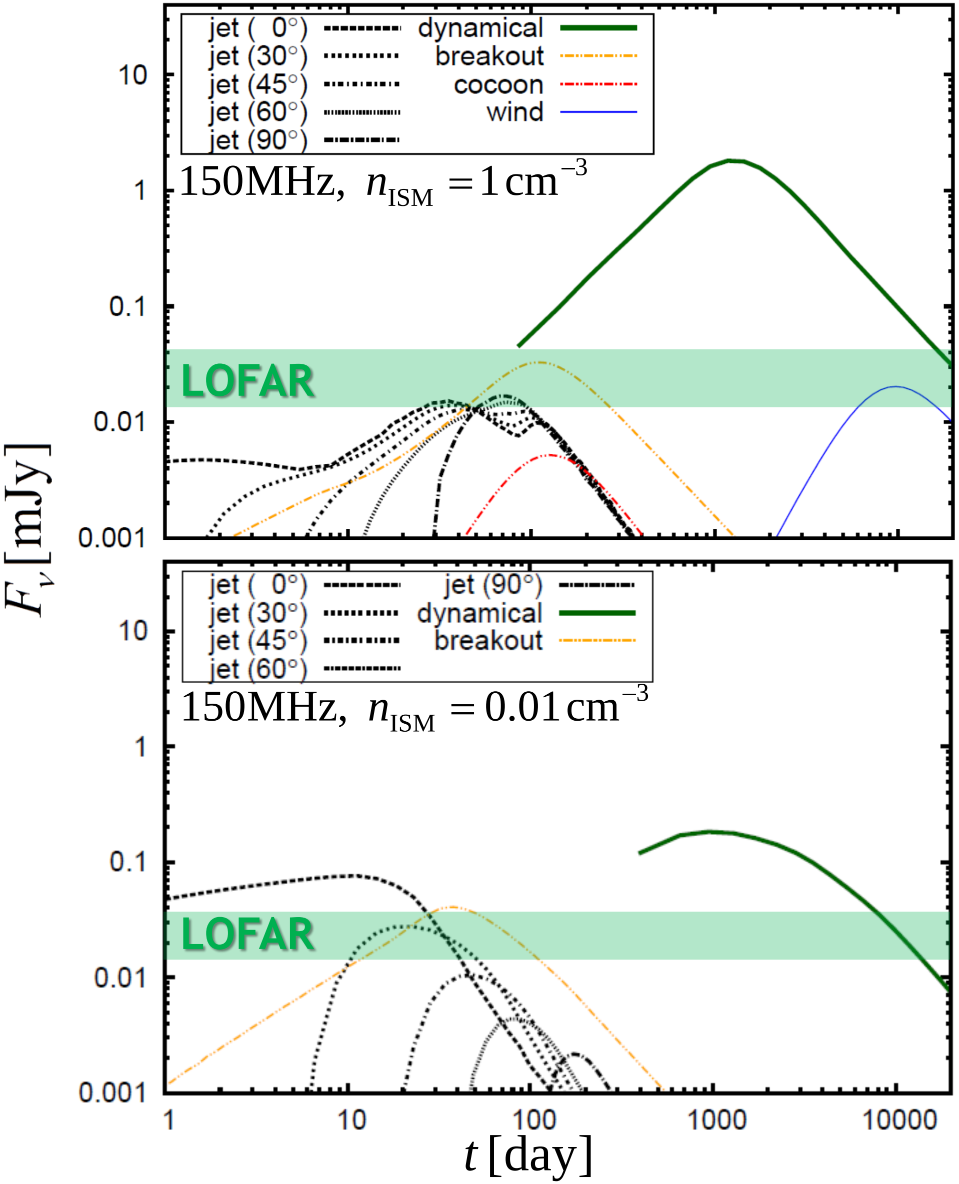
$$t_{\mathrm{peak}} \sim \boxed{4\ \mathrm{yrs}} \left(\frac{E_{\mathrm{ejecta}}}{10^{50}\,\mathrm{ergs}}\right)^{1/3} \left(\frac{n_{\mathrm{ISM}}}{1\,\mathrm{cm}^{-3}}\right)^{-1/3} \left(\frac{v_{\mathrm{ejecta}}}{0.2c}\right)^{-5/3}$$

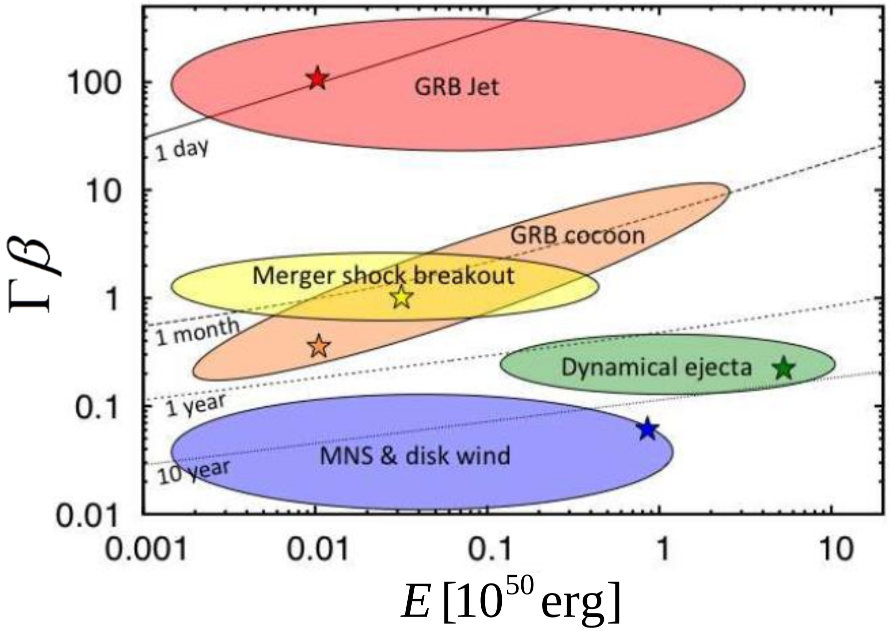
$$F_{\nu} \sim 0.1\,\mathrm{mJy} \left(\frac{E_{\mathrm{ejecta}}}{10^{50}\,\mathrm{ergs}}\right) \left(\frac{n_{\mathrm{ISM}}}{1\,\mathrm{cm}^{-3}}\right)^{0.9} \left(\frac{v_{\mathrm{ejecta}}}{0.2c}\right)^{2.8} \left(\frac{D}{200\,\mathrm{Mpc}}\right)^{-2} \left(\frac{\nu_{\mathrm{obs}}}{1.4\,\mathrm{GHz}}\right)^{-0.75}$$

- ISM density may be much smaller : according to recent SGRB obs.
  - $\mathbf{n_{ISM} \sim 0.01\text{-}0.1\ cm^{-3}}$ for SGRB 111020A (Fong et al. 2012)
  - $\mathbf{n_{IMS} \sim 0.0001\text{-}1\ cm^{-3}}$ for SGRB 111117A (Margutti et al. 2012)
- Radio flare may be less bright and shine in a very late time : Not very suited as EM counterparts of GWs

Hotokezaka & Piran (2015)

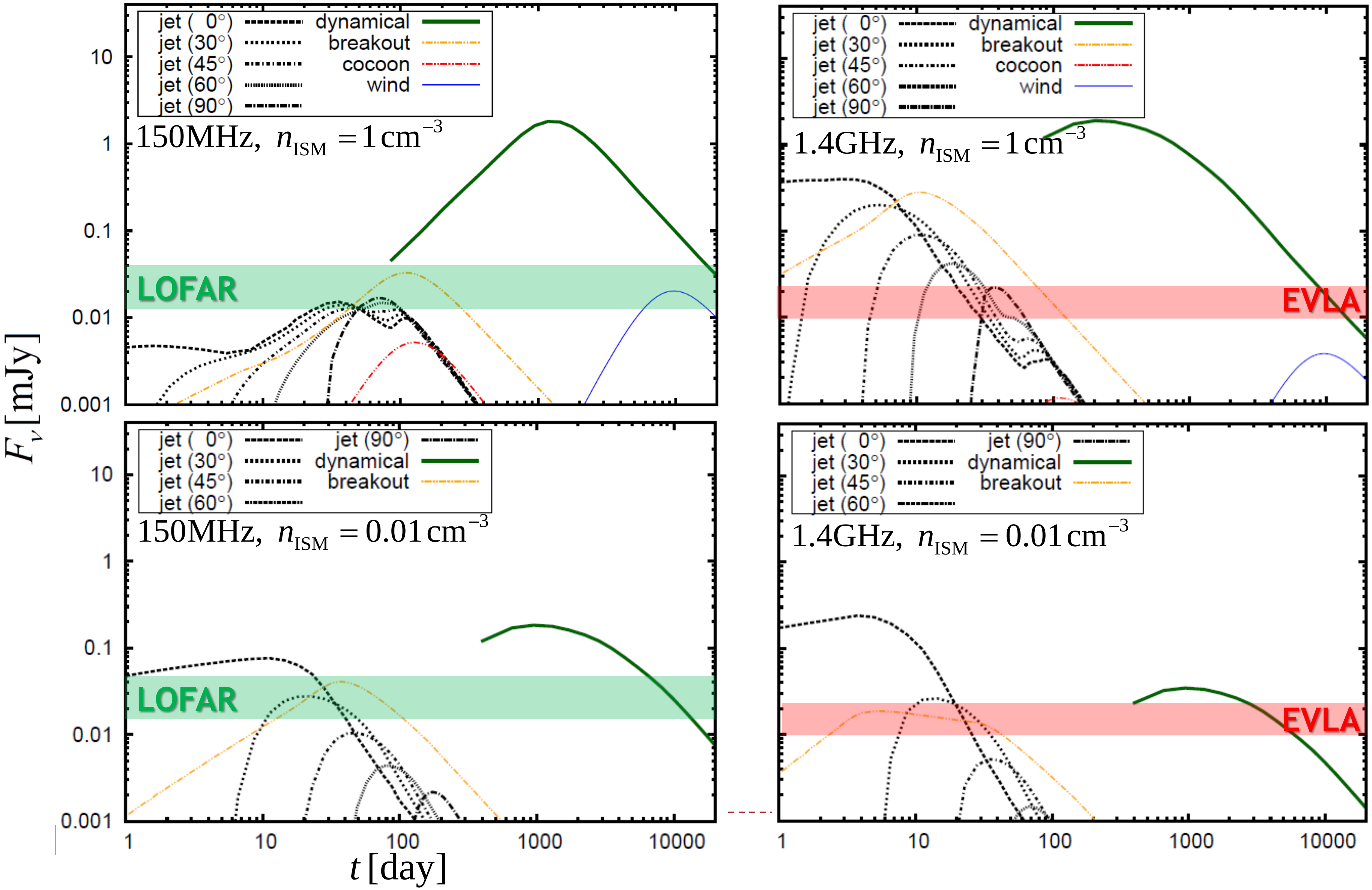
Radio emissions : 150MHz @200Mpc





Hotokezaka & Piran (2015)

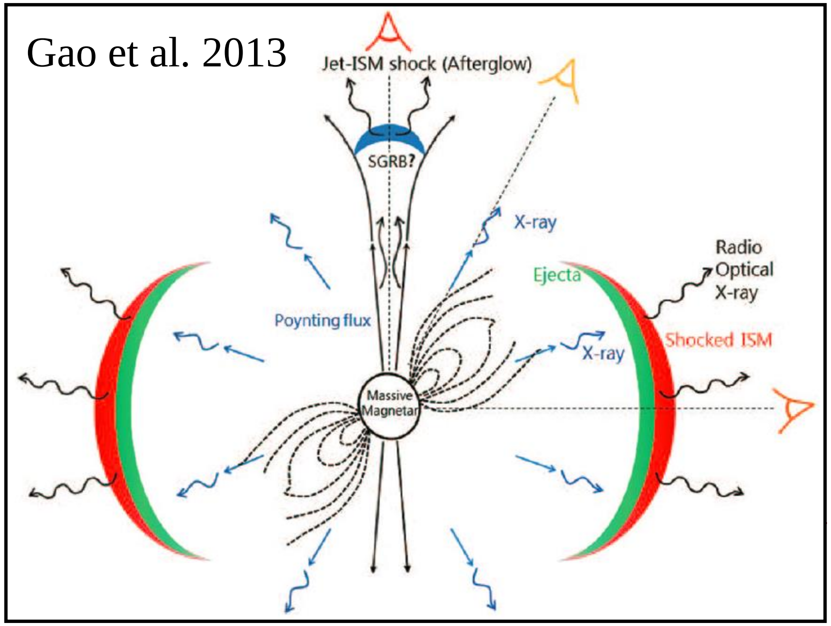
Radio emissions : 1.4GHz @200Mpc



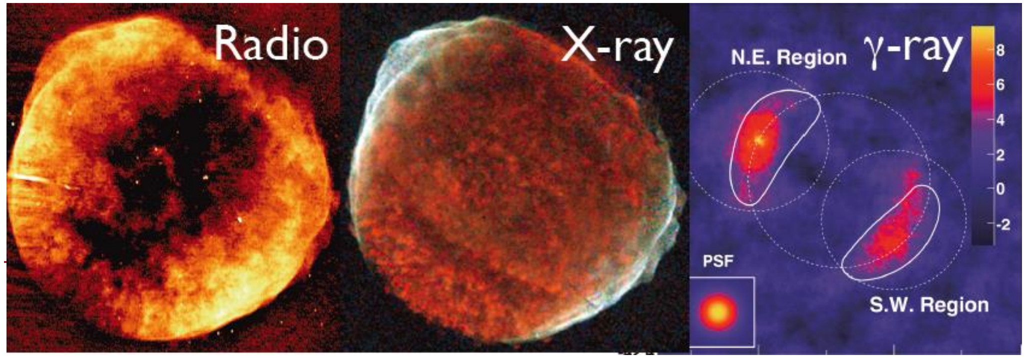
Rotation powered activities ?

might be promising for low-mass binary

- If a **stable massive NS** is survived, additional EM emissions powered by NS-rotation may be expected (Metzger et al. 2011; Zhang 2013; Gao et al. 2013)
  - Compared to normal pulsars, rapid rotation (P~ms), strong B-fields (B~10^{15} G)
- **However, such additional emissions may not be very frequent :**
  - Nuclear theory : might hard to make such a very stiff EoS with Mmax > 2.4Msolar
    - For canonical mass binary : otherwise need low mass binary
  - SGRB : if central engine of SGRB be BH + Disk, frequent formation of the massive NS means that there are much more mergers

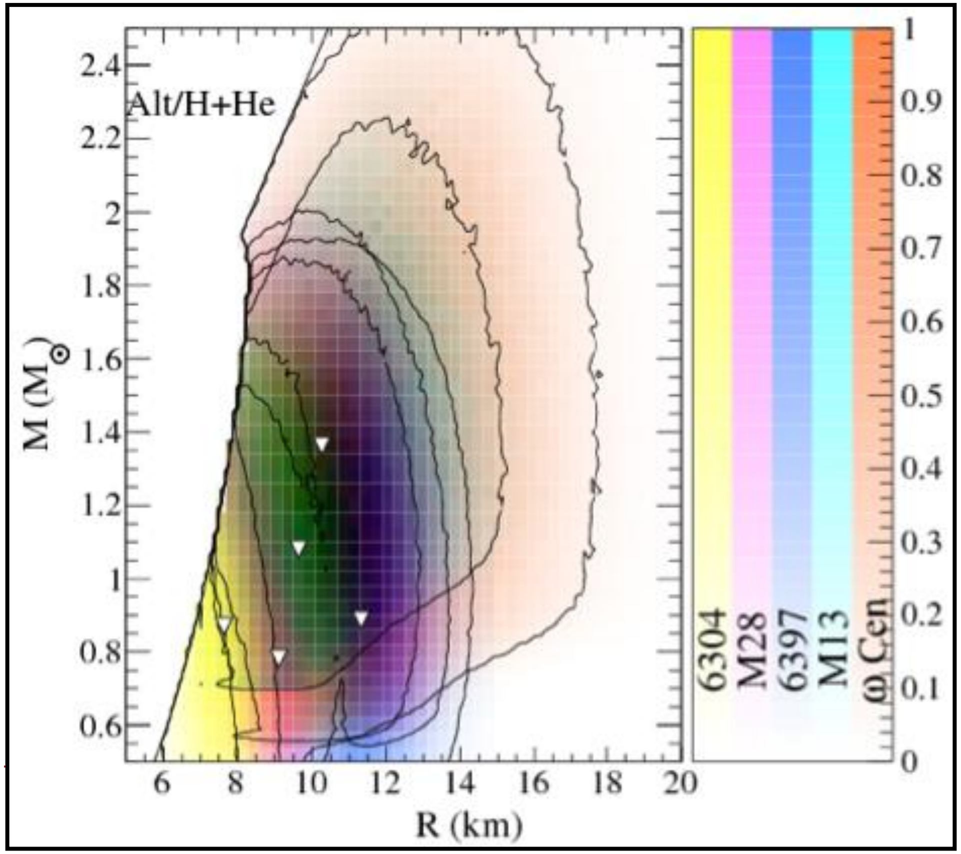

Gao et al. 2013

- ~1/3 of SGBRs may have late-time activity
  - which could be originated in the massive SN
- Most of them are short duration < O(100s)
  - Collapse to a BH ?
  - shorter than the spin down timescale > 1000s



NS mass/radius measurements

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



- Lattimer & Steiner 2014 for quiescent LMXBs

Kilonova/Macronova/r-process nova/巨新星

- Merger ejecta will be very 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 *were*** expected (Li & Paczynski 1998)

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

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

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

Kilonova/Macronova/r-process nova/巨新星

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- Competition with the β-decay : $(Z,N+1) \Rightarrow (Z+1,N) + e + \bar{\nu}_e$
  - **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 !**
- **Recent critical update :** Opacities are dominated by lanthanoids : orders of magnitude (~100) larger (Kasen e al. 2013; Tanaka & Hotokezaka 2013)

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

1 day ⇒ 10 days

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

1/10 dimmer

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

Opt-UV ⇒ NIR

Kilonova/Macronova/r-process nova/巨新星

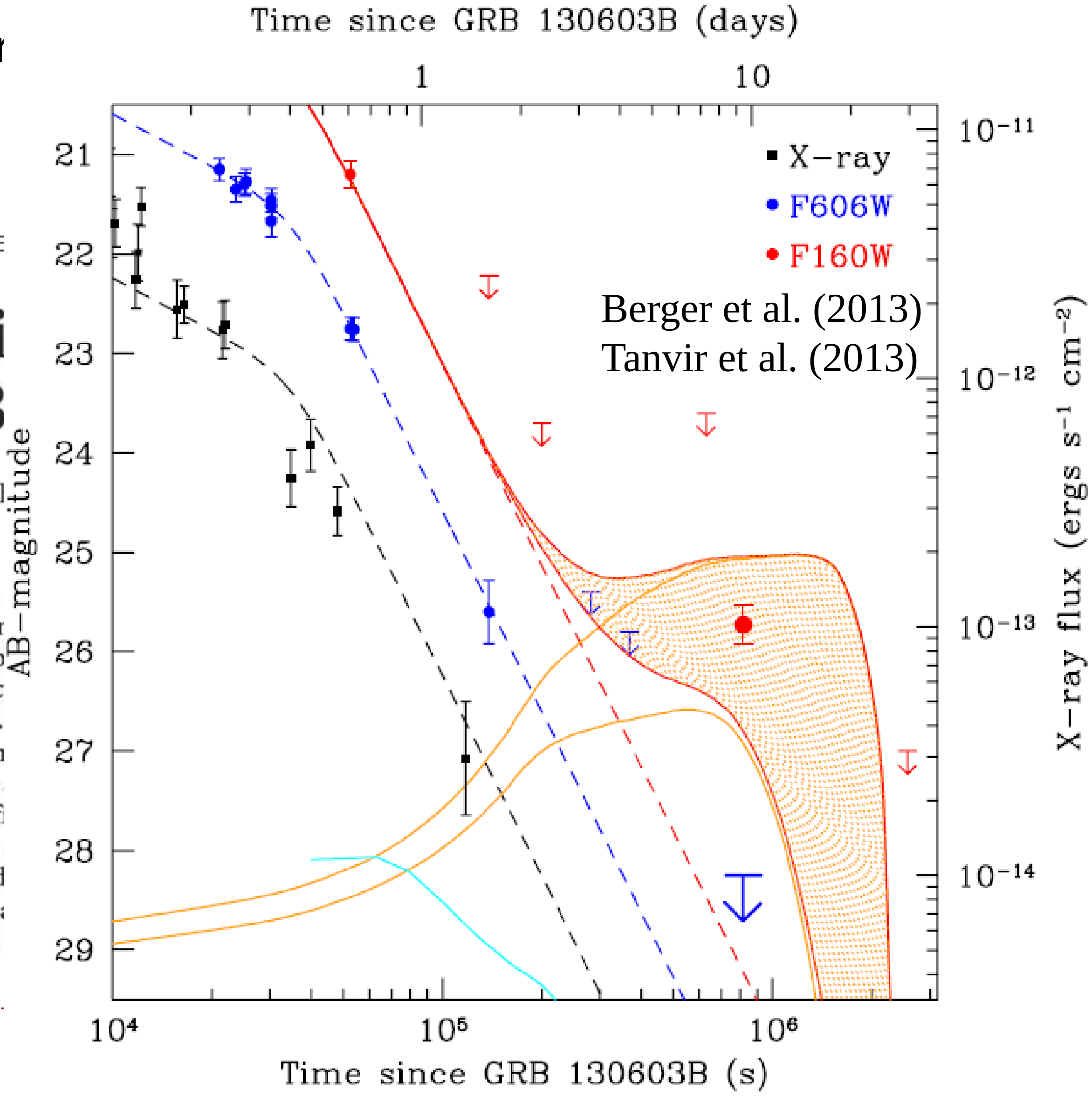
- Merger ejecta will be ver

LETTER

A ‘kilonova’ associ γ-ray burst GRB 13

N. R. Tanvir[1], A. J. Levan[2], A. S. Fruchter[3], J. l

Short-duration γ-ray bursts are intense flashes lasting less than about two seconds, whose origir favoured hypothesis is that they are produced b created by the merger of two compact stellar objec neutron stars or a neutron star and a black hole). by indirect evidence such as the properties of th but unambiguous confirmation of the model is gers of this kind are also expected to create signifi neutron-rich radioactive species[4,5], whose decay faint transient, known as a ‘kilonova’, in the d burst[6–8]. Indeed, it is speculated that this mecha predominant source of stable r-process elements



Berger et al. (2013)
Tanvir et al. (2013)

Neutron capture processes

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

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

n-capture versus **β-decay**

$\tau_n < \tau_\beta$

rapid neutron-capture process

(r-process)

large neutron densities

- Can synthesize all heavy nuclei

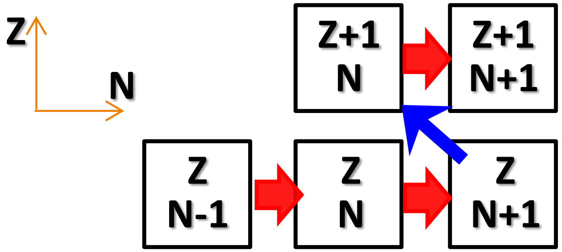
$\tau_n > \tau_\beta$

slow neutron-capture process

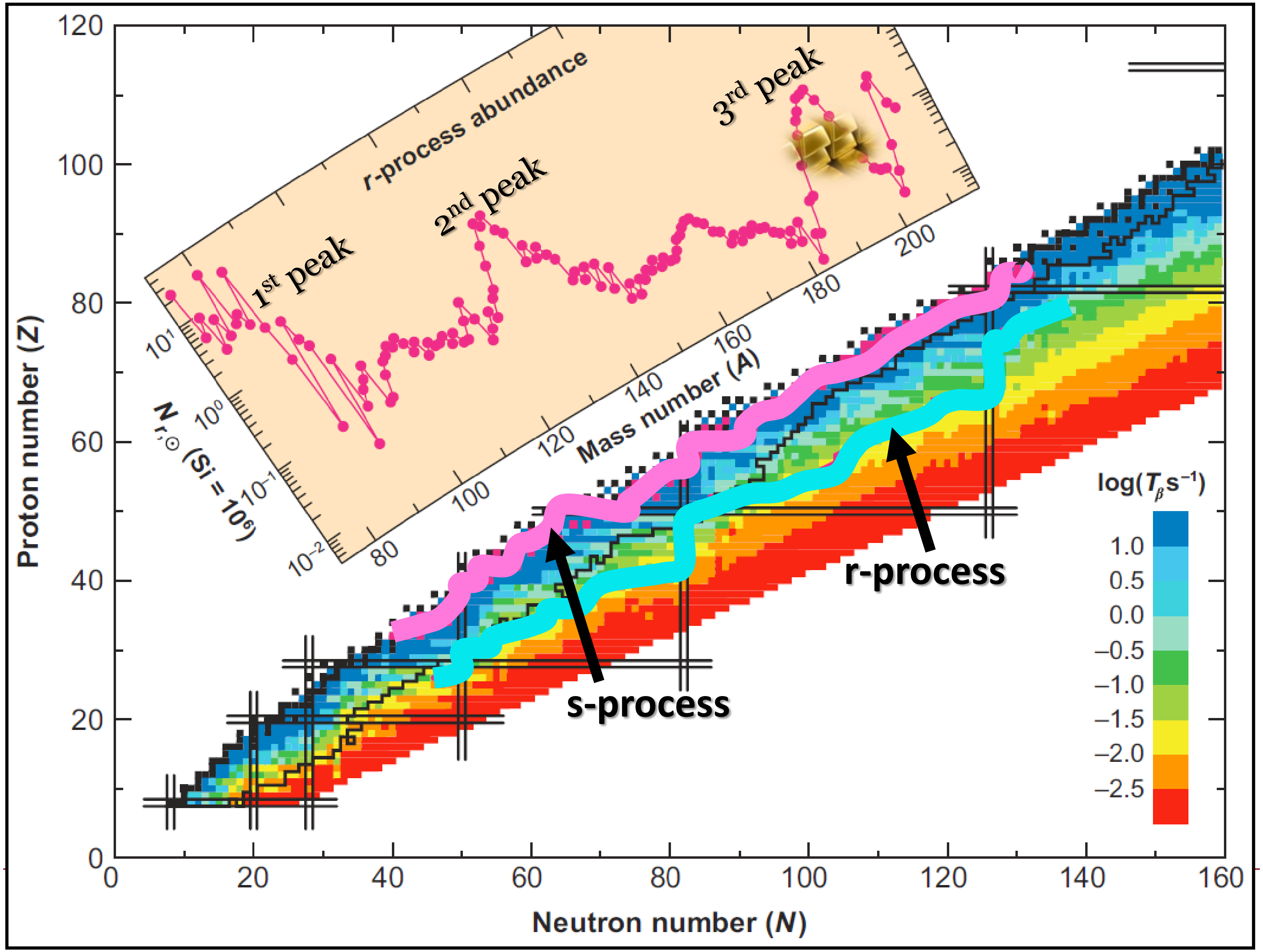
(s-process)

moderate neutron densities

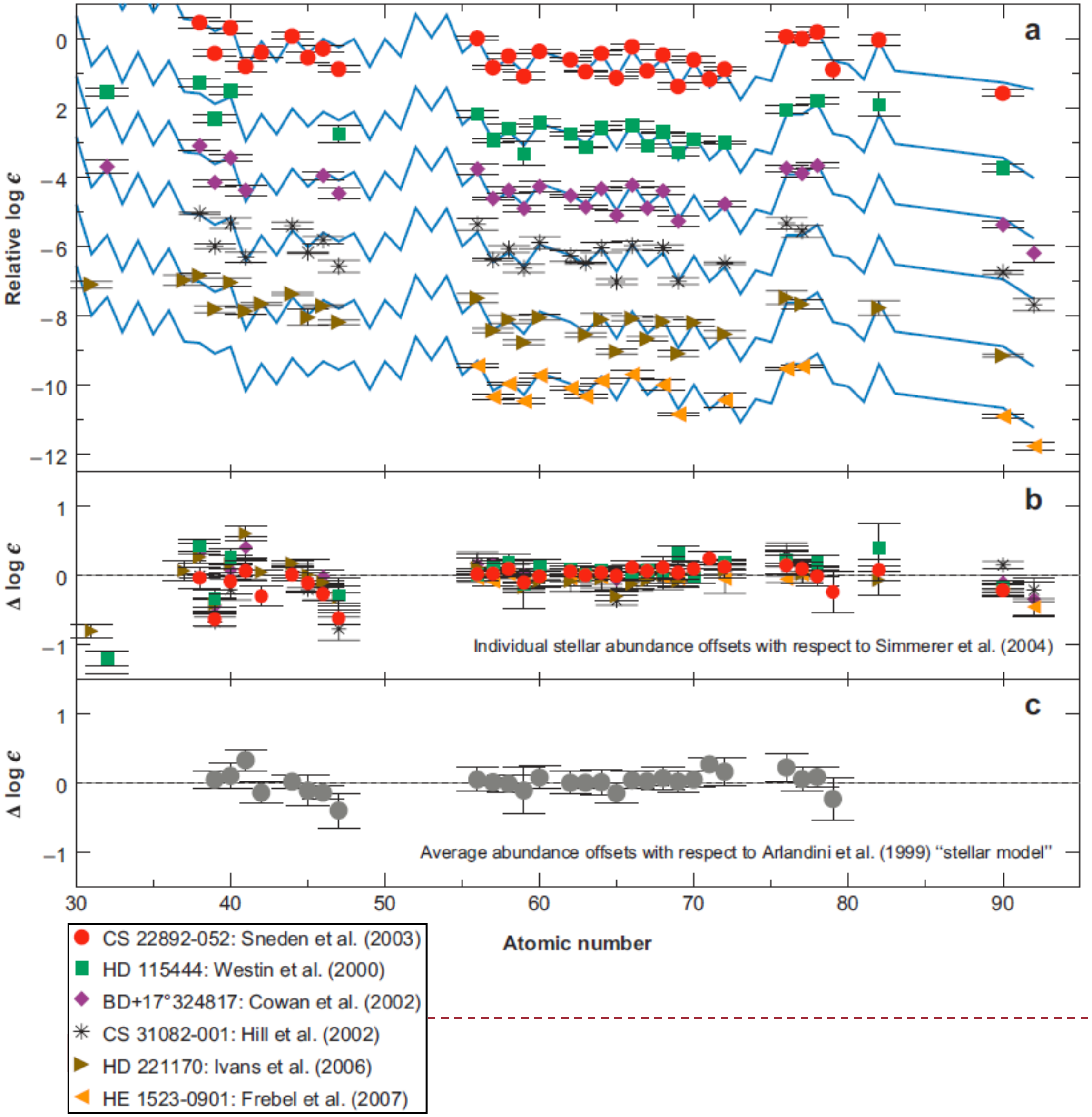
- does not synthesize all heavy nuclei
- terminates at Pb, Bi



s-process / r-process path

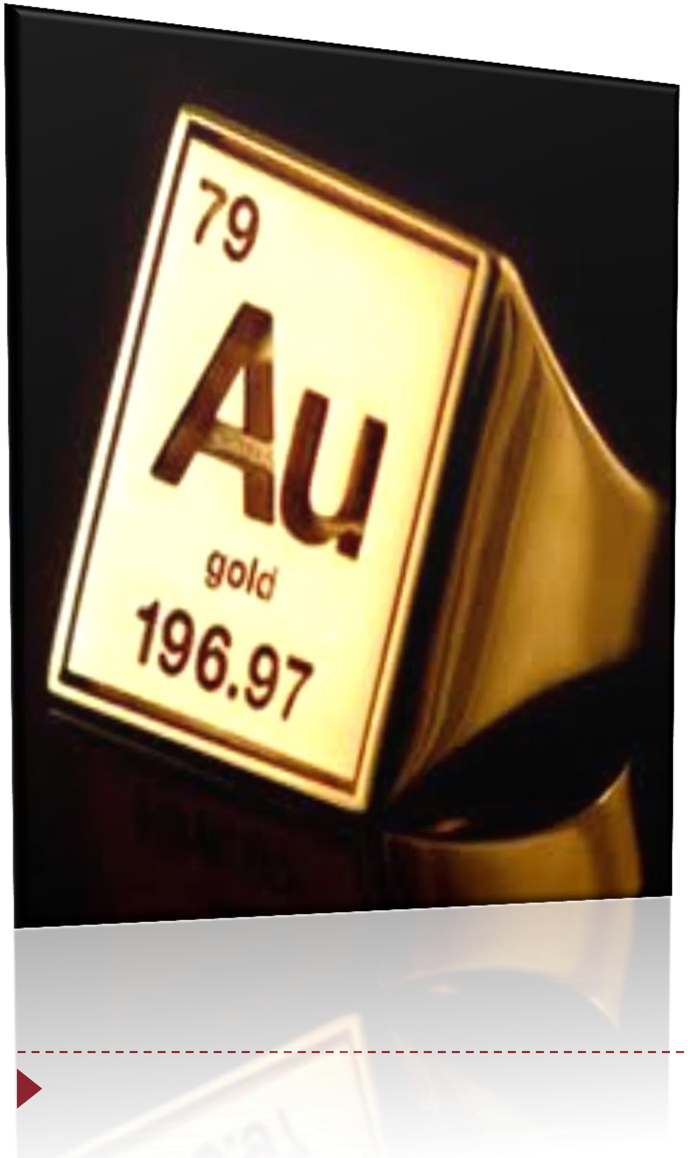


The r-process: a observational request



- Many r-rich, low metallicity halo stars show remarkable agreement with solar pattern
  - R-process must occur in the early Galaxies
  - Astrophysical events must reproduce this common pattern (Z>40, A>90)
- suggests existence of "main" r-process sites producing the solar-like common pattern

Conditions for 'main' r-process nucleosynthesis



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

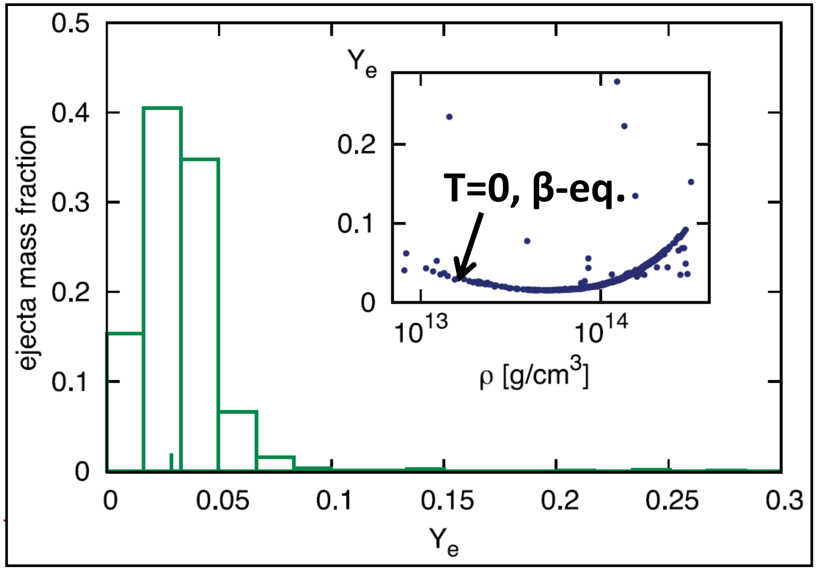
What is the ‘main’ r-process cite ?

- **Supernova (SN) explosion (+ PNS ν-driven wind) :**
  (*Burbidge et al. 1957; Cameron 1957***)**
  - n-rich ejecta nearby proto-NS
  - Not promising according to recent studies (e.g. Roverts et al. (2012); Wanajo (2013))
  - 和南城さん’s talk

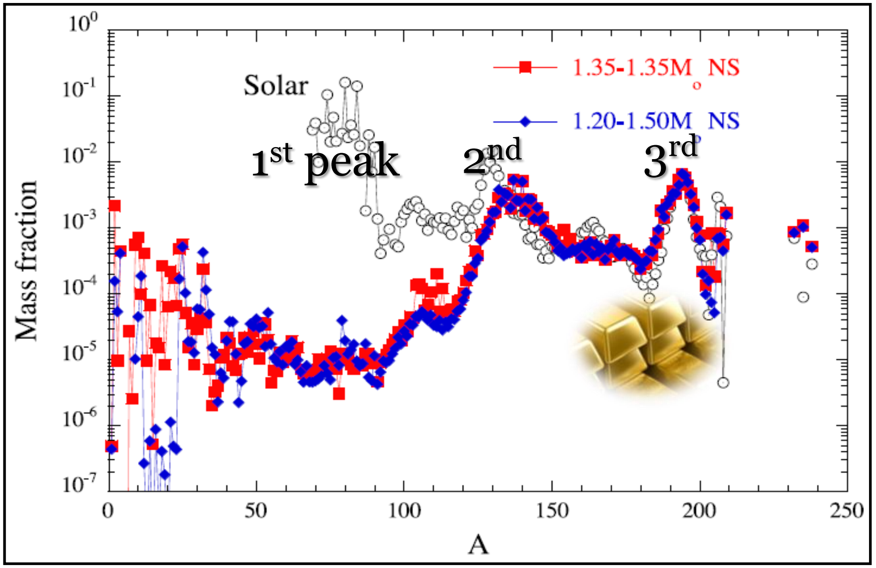
- **NS-NS/BH binary merger: (***Lattimer & Schramm 1974; Symbalisty 1982***)**
  - n-rich ejecta from coalescence of NS-NS/BH
  - Not studied in detail
  - Chemical evolution ? (青木さん、石丸さん, 辻本さん、平居さん、etc)

NS-NS merger ejecta: too neutron-rich ?

- **Goriely et al. 2011; Korobkin et al. 2012; Rosswog et al. 2013**
  - tidal mass ejection of ‘pure’ neutron star matter (very n-rich) with Ye < 0.1
  - strong r-process with fission recycling only 2nd (A~130; N=82) and 3rd (A~195; N=126) peaks are produced
  - the resulting abundance pattern is far from the common solar-like pattern
  - **They adopted only one ‘stiff’ EoS (Shen EoS) : dependence on EoS is not explored**
  - **Newtonian SPH simulation or no neutrino heating: GR and weak-interaction effects are not included**



Korobkin et al. (2012) MNRAS 426 1940



Goriely et al. (2011) ApJL 738 32

Dynamical mass ejection from BNS merger

- Two components

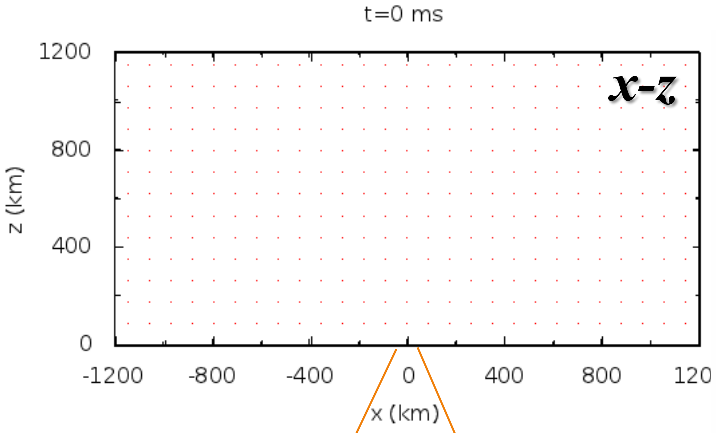
  + (neutrino-heated component (Perego et al. (2014); Just et al. (2014))

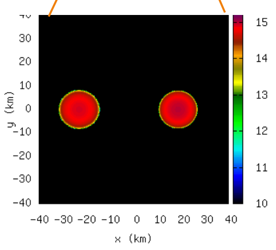
- **Driven by tidal interactions**

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

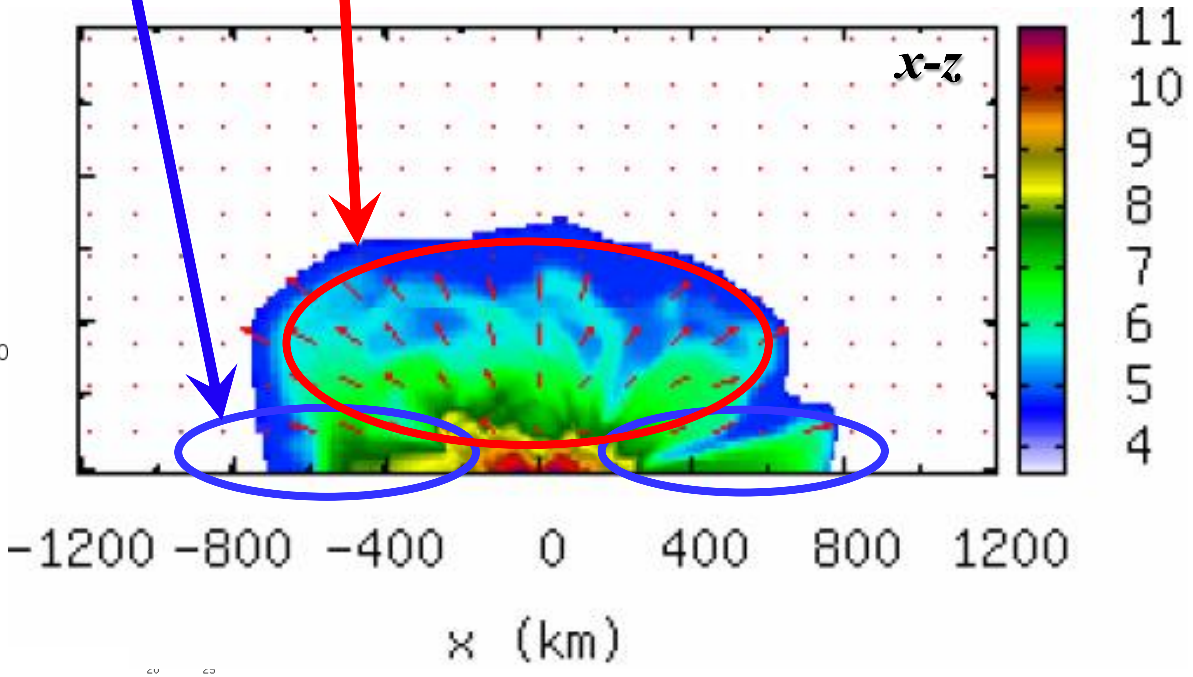
- **Driven by shocks**

  Consists of hot shock heated matter
  Weak interaction can change Ye



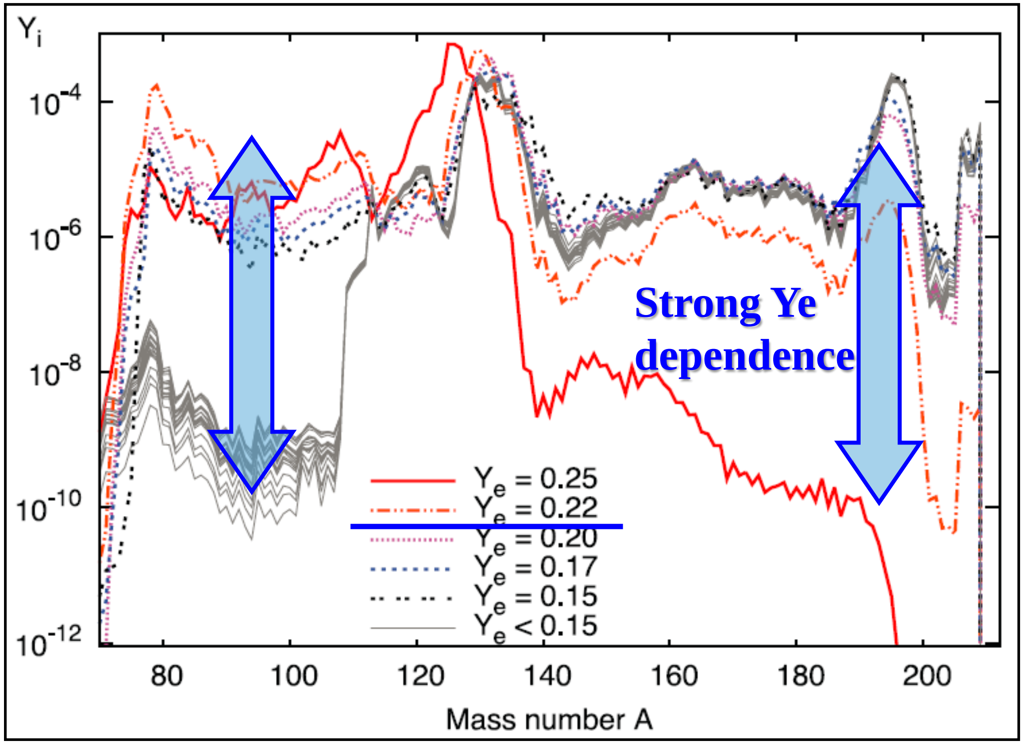


animation by
Hotokezaka



Importance of Ye in the r-process

- **Electron fraction (Ye) is the key parameter : Ye ~ 0.25 is critical threshold**
  - Ye < 0.25 : strong r-process ⇒ nuclei with A>130
  - Ye > 0.25 : weak r-process ⇒ nuclei with A< 130 (for larger Ye, nuclei with smaller A)
  - Different nuclei : different opacity (Smaller opacity for smllaer A? Grossman et al. 2013)
- **Neutrino-matter interaction**
  - **Ye can be changed**
  - Two reactions which increase Ye
  - Positron capture : $\boxed{n + e^{+} \rightarrow p + \overline{\nu}_e}$
    - **Important for higher temperature**
      ∵ there are more positrons
  - Neutrino capture : $\boxed{n + \nu_e \rightarrow p + e^{-}}$
    - Copious neutrinos are emitted
    - NS matter is neutron rich
    - Not considered in the previous studies (need neutrino transfer)



Strong Ye dependence

Korobkin et al. 2012

Recent result with finite-temperature EOS

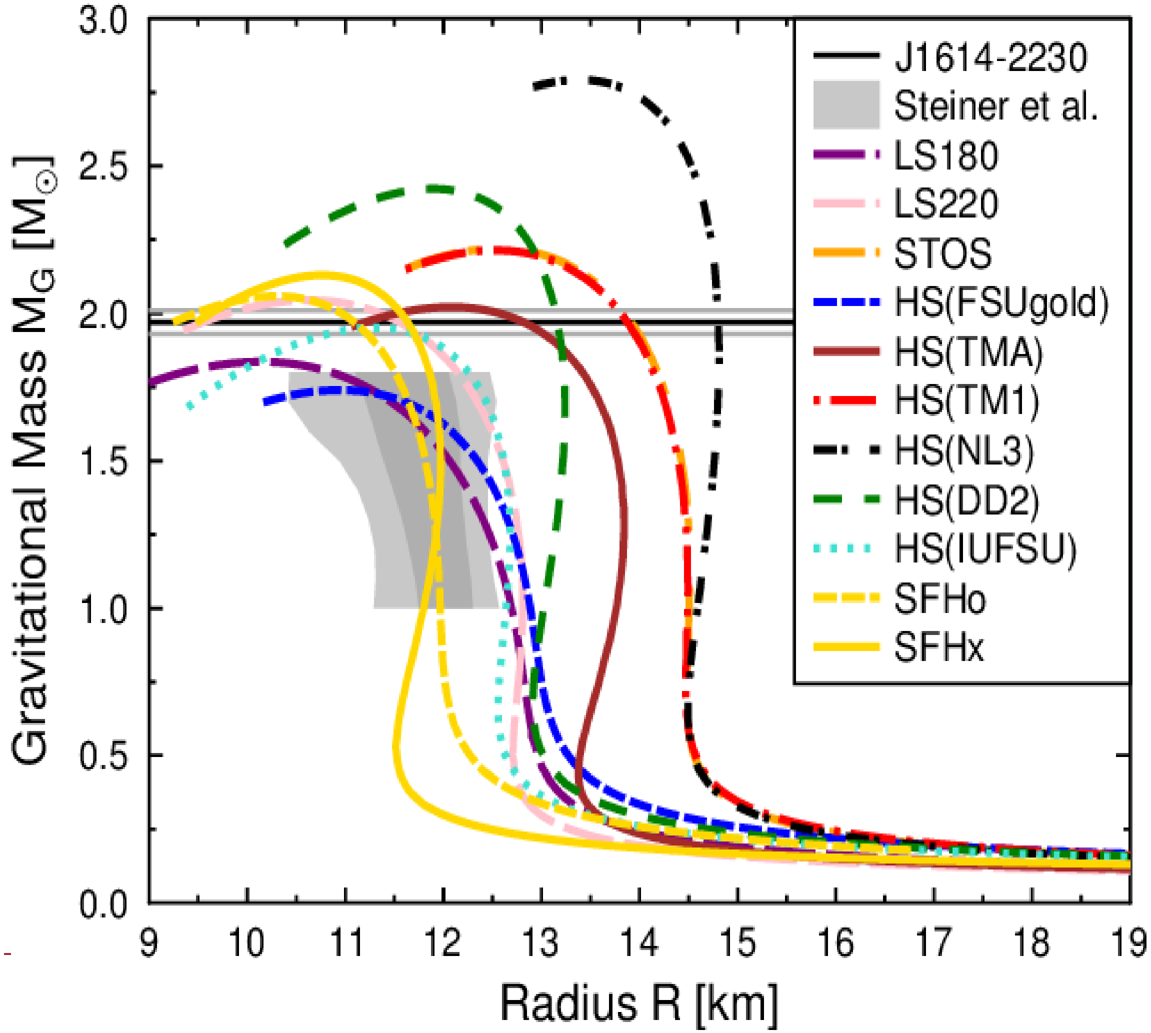
- Multi-EOS study (Thanks to ***M. Hempel***)
- GR approximate ν-rad hydro simulation
- Adopted EOS

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

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

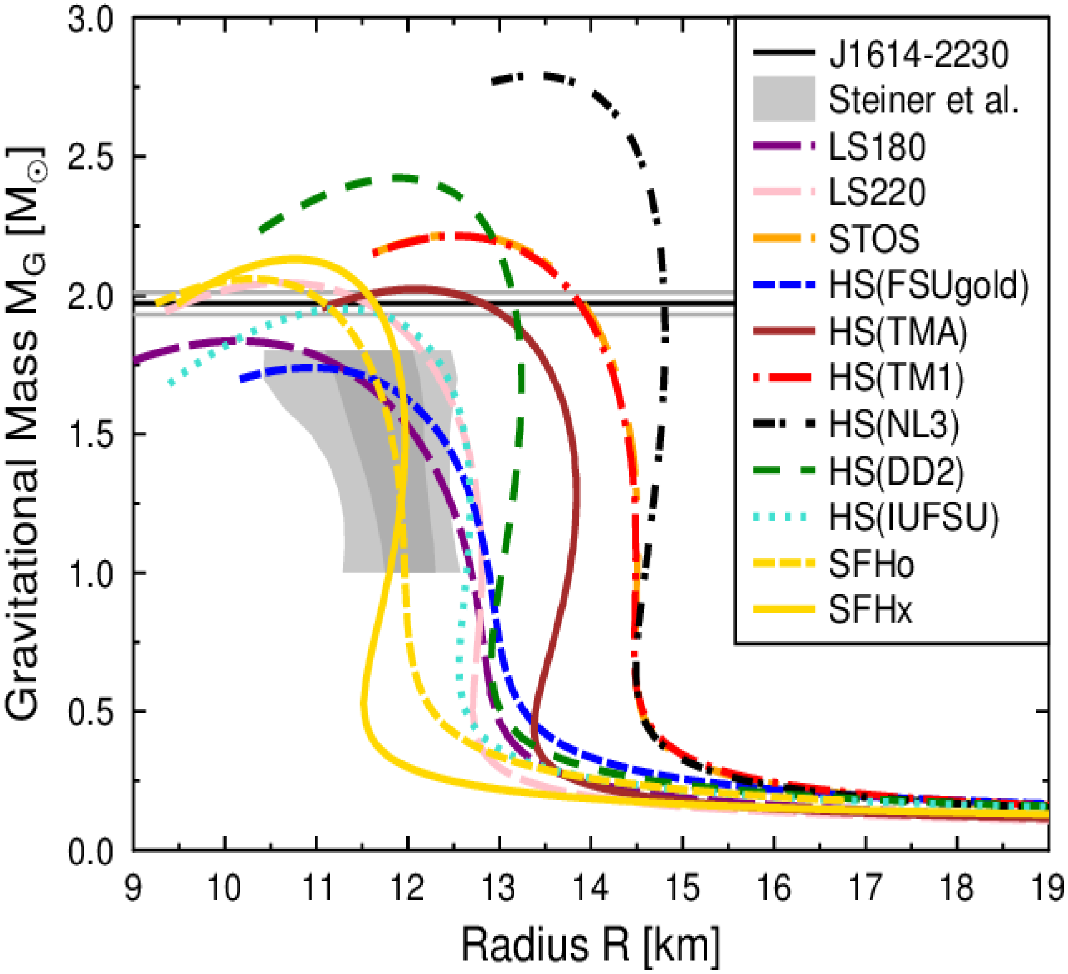
11.8km
- **SFHo**

Consistent with
  - NS radius estimation
  - Chiral effective theory



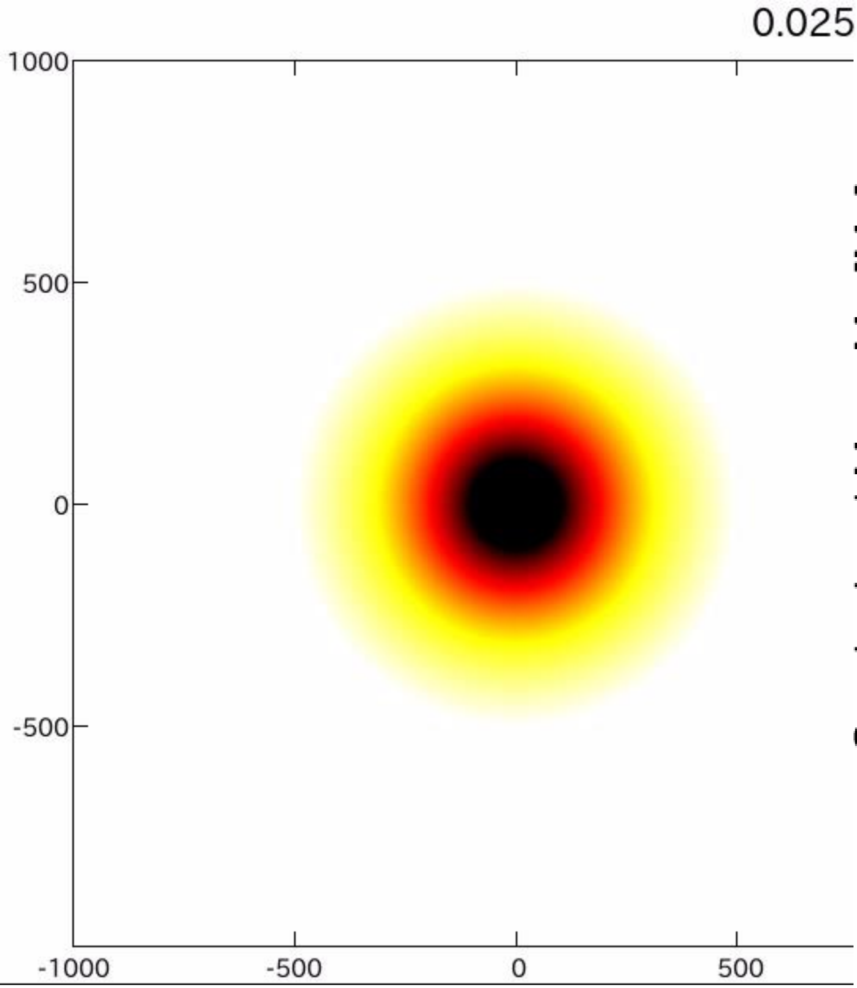
Dynamical mass ejection mechanism & EOS

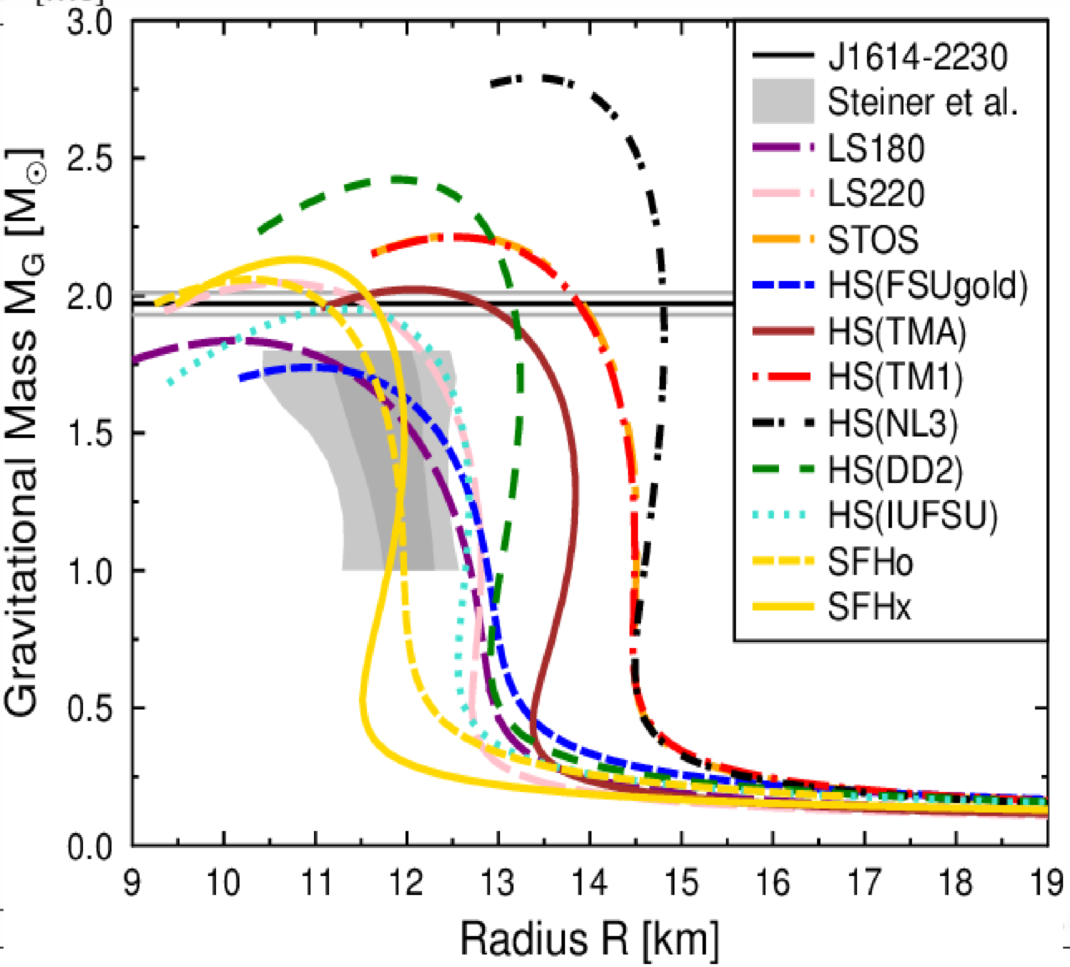
- ‘Stiffer EOS’
  - **TM1, TMA**
  - R_{NS} : lager
  - Tidal-driven dominant
  - **Ejecta consist of low T & Ye NS matter**
- ‘Intermediate EOS’
  - **DD2**
- ‘Softer EOS’
  - **SFHo, IUFSU**
  - R_{NS} : smaller
  - Tidal-driven less dominant
  - Shock-driven dominant
  - **Ye can change via weak processes**



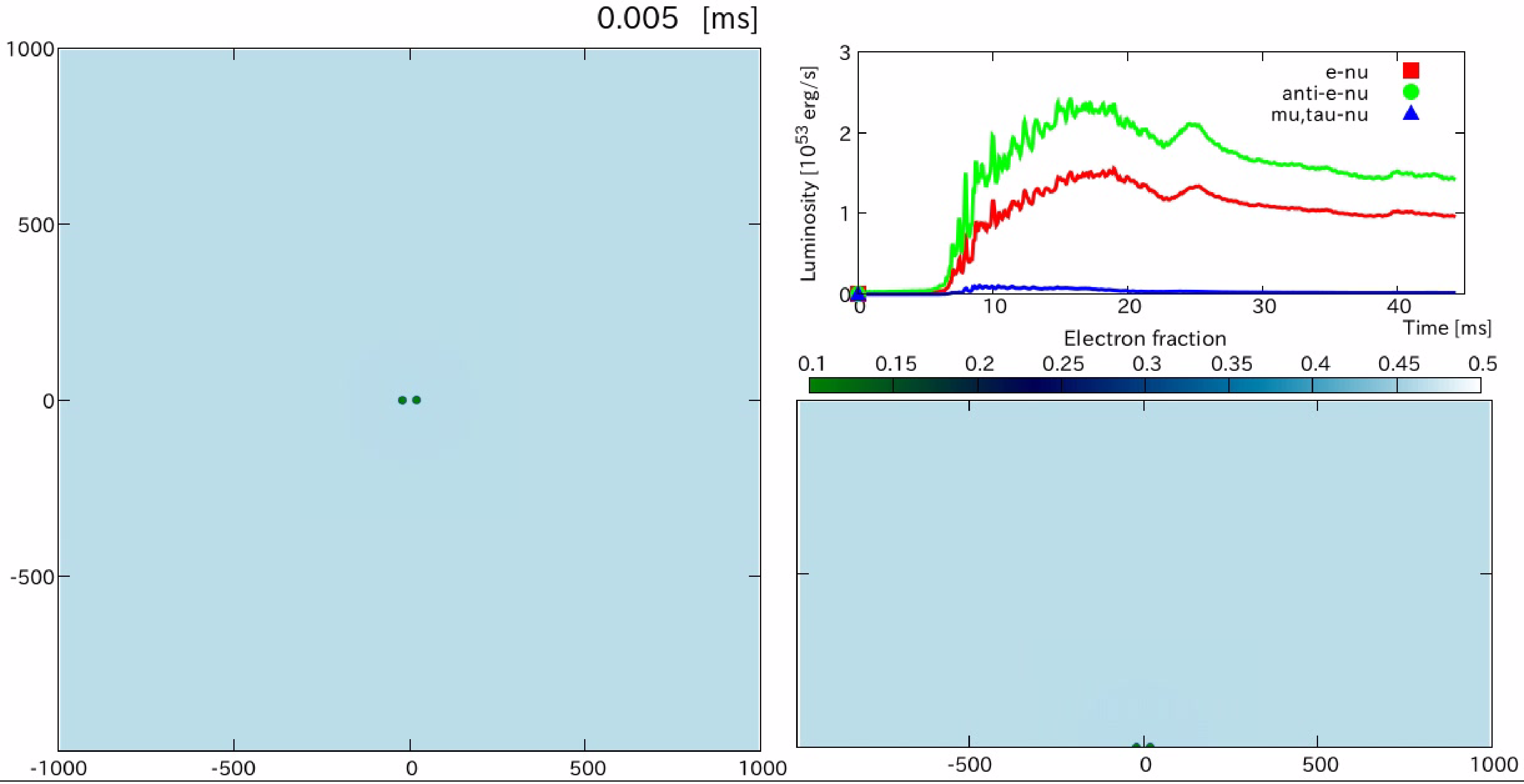
See also, Bauswein et al. (2013); Just et al. (2014)

Entropy/baryon : DD2

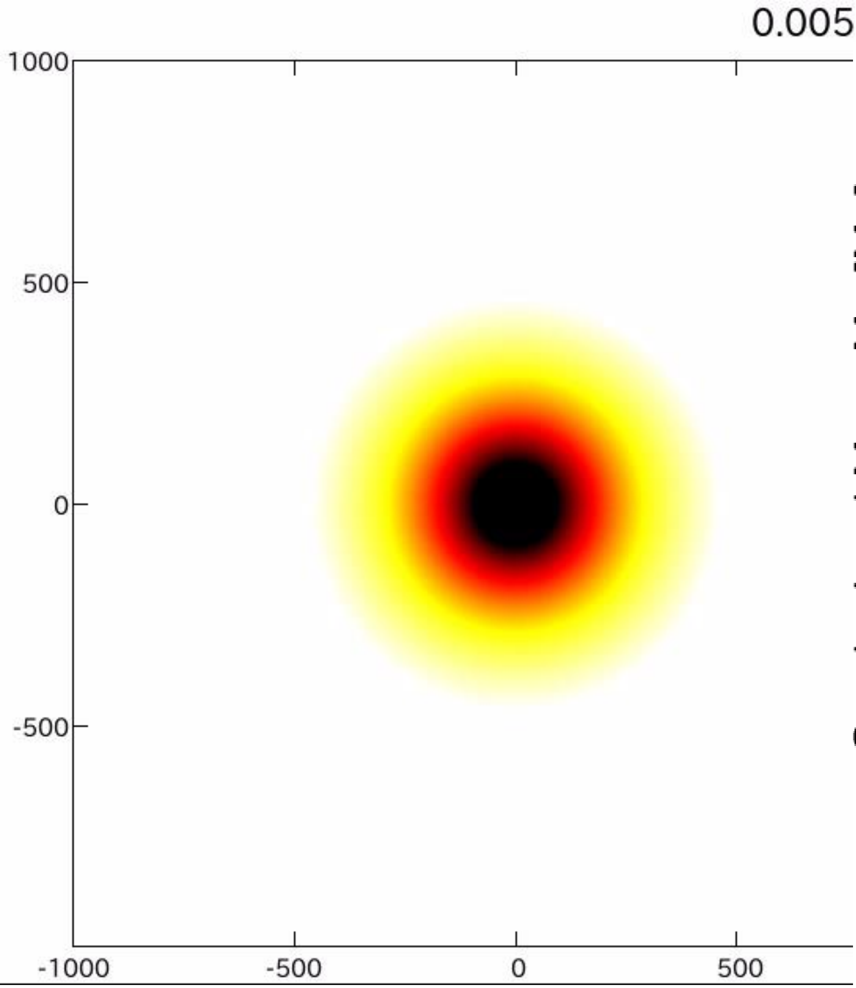


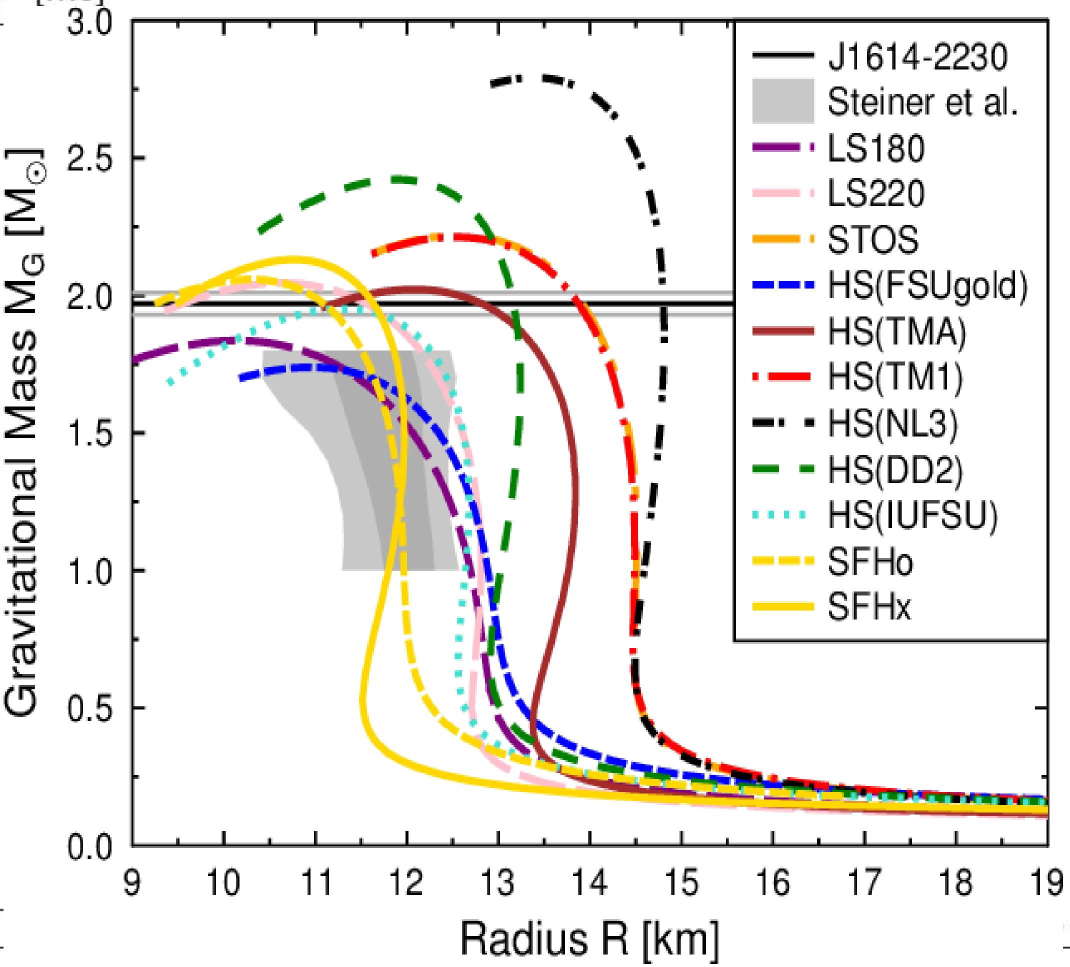


Ye : DD2

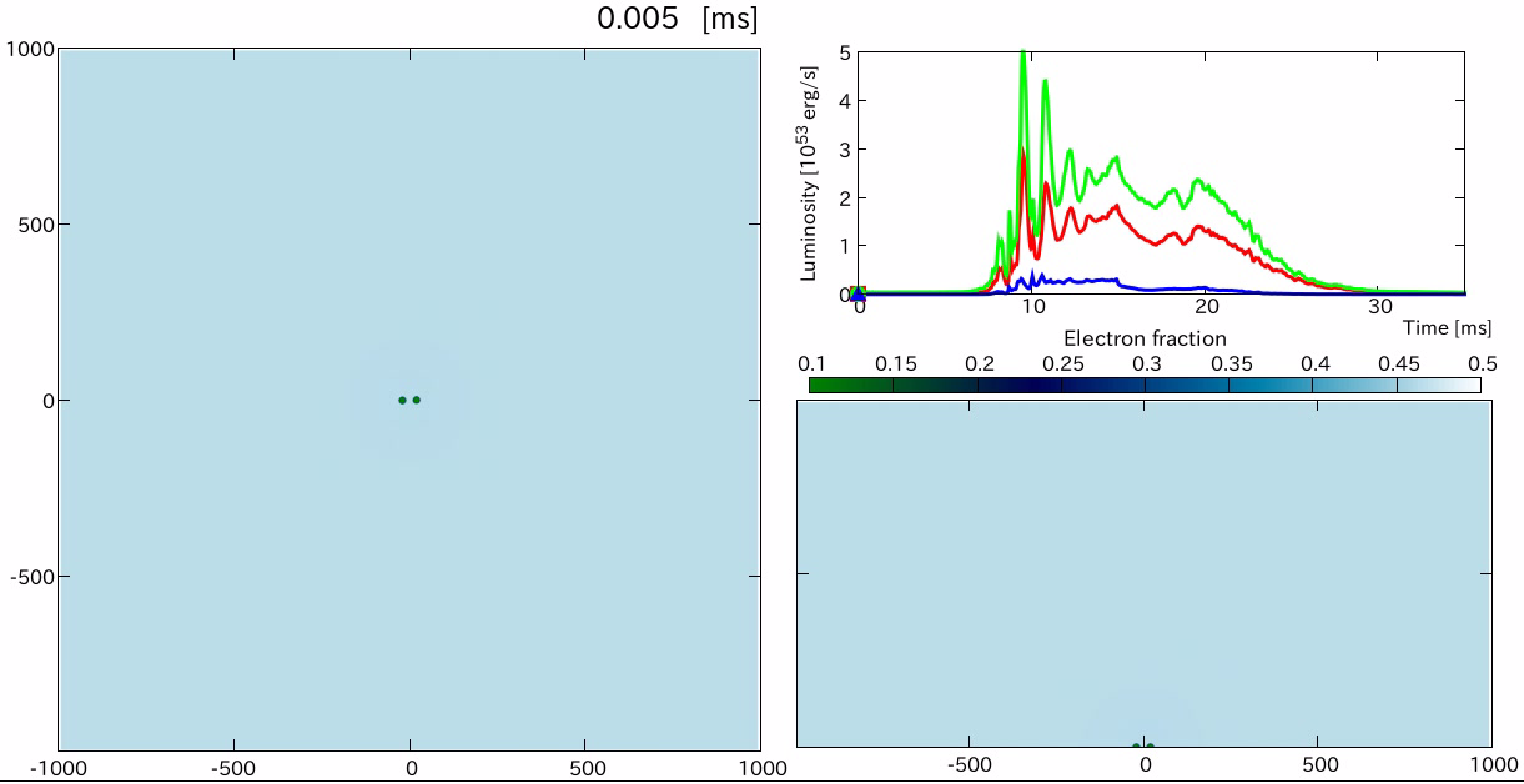

0.005 [ms]
1000
500
0
-500
-1000
-500
0
500
1000
Luminosity [10^{53} erg/s]
3
2
1
0
0
10
20
30
40
Time [ms]
e-nu 🟥
anti-e-nu ●
mu,tau-nu ▲
Electron fraction
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
-500
0
500
1000

Entropy/baryon : SFHo



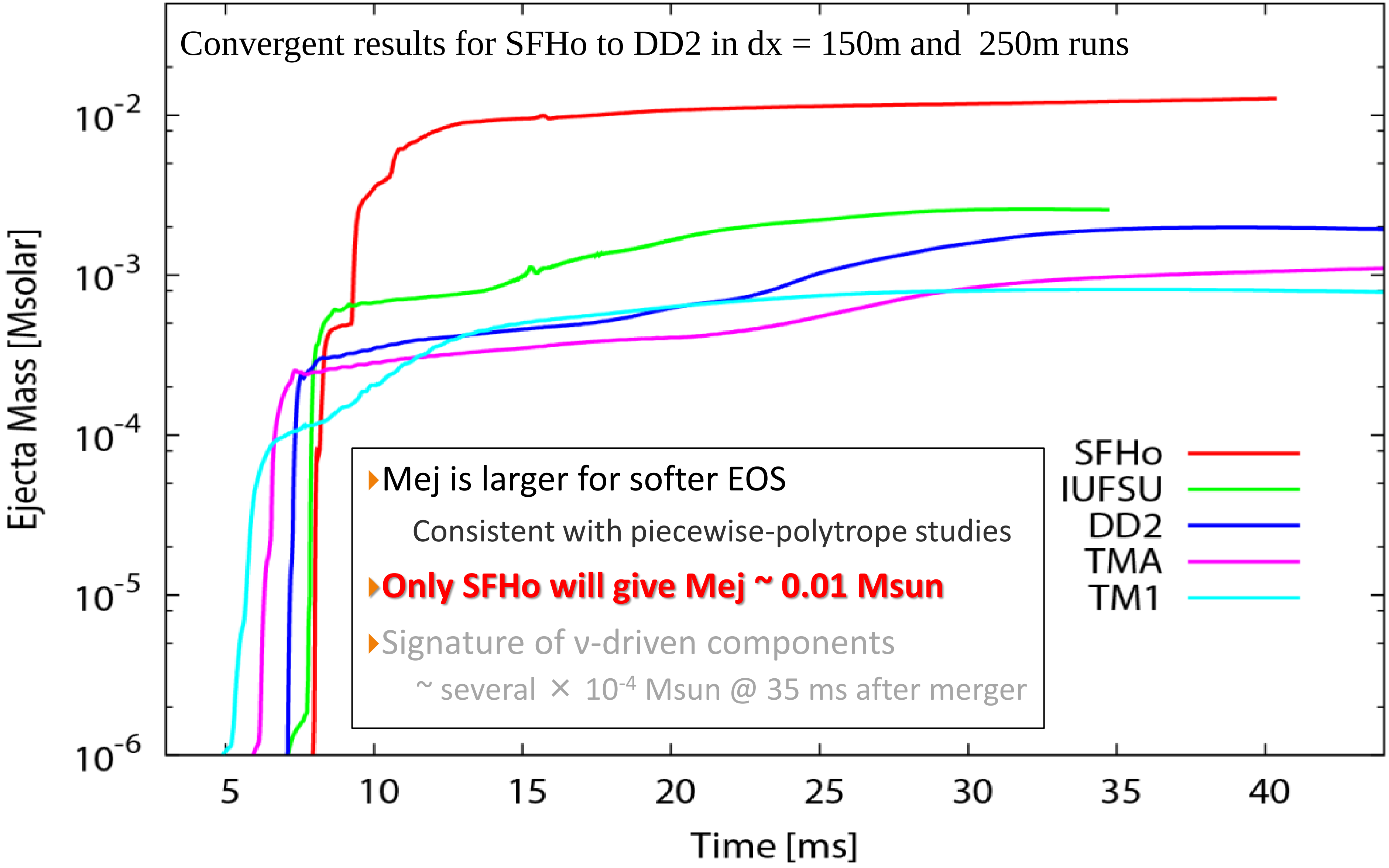


Ye : SFHo (Softer)



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

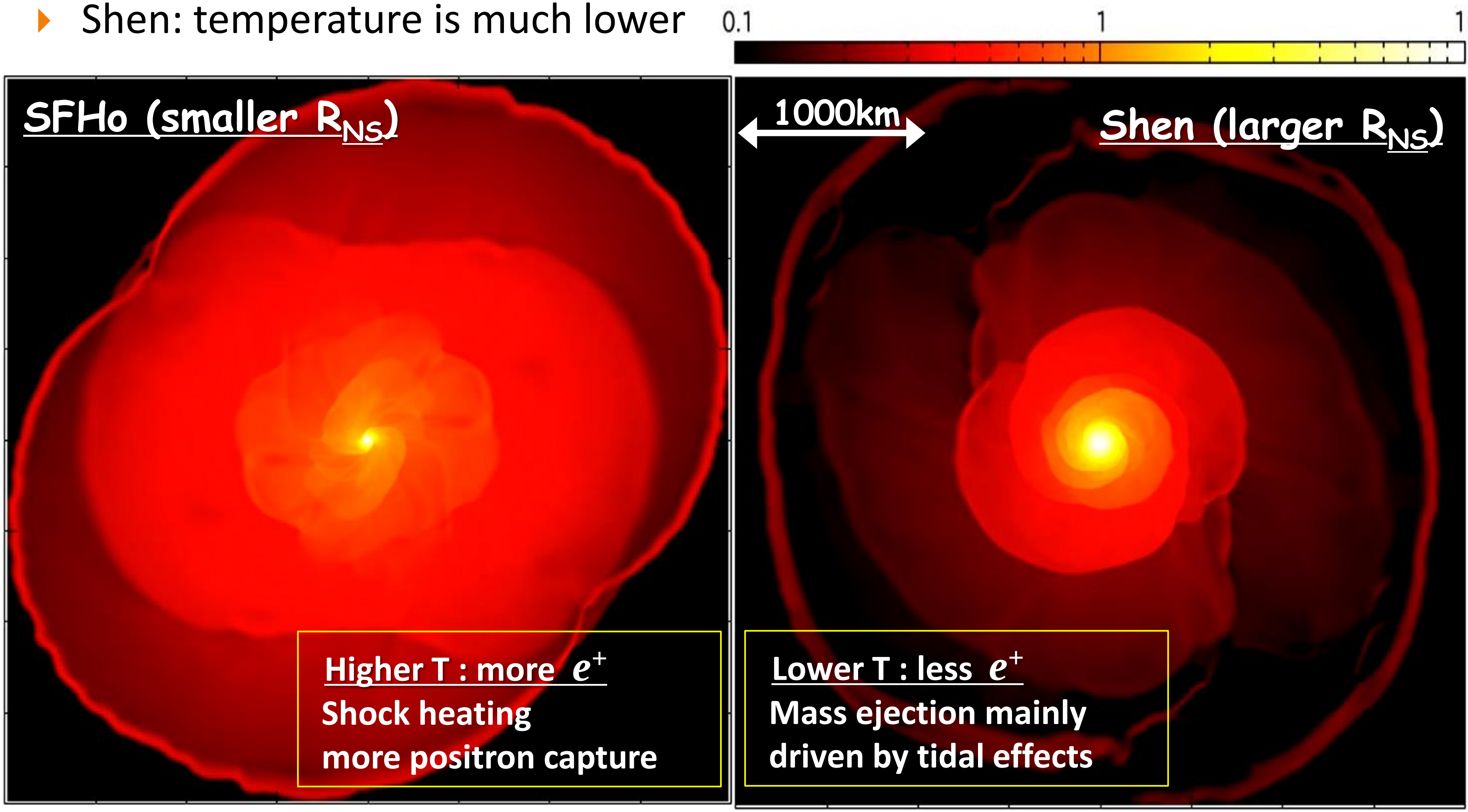
- **Only SFHo will give Mej ~ 0.01 Msun**

- 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

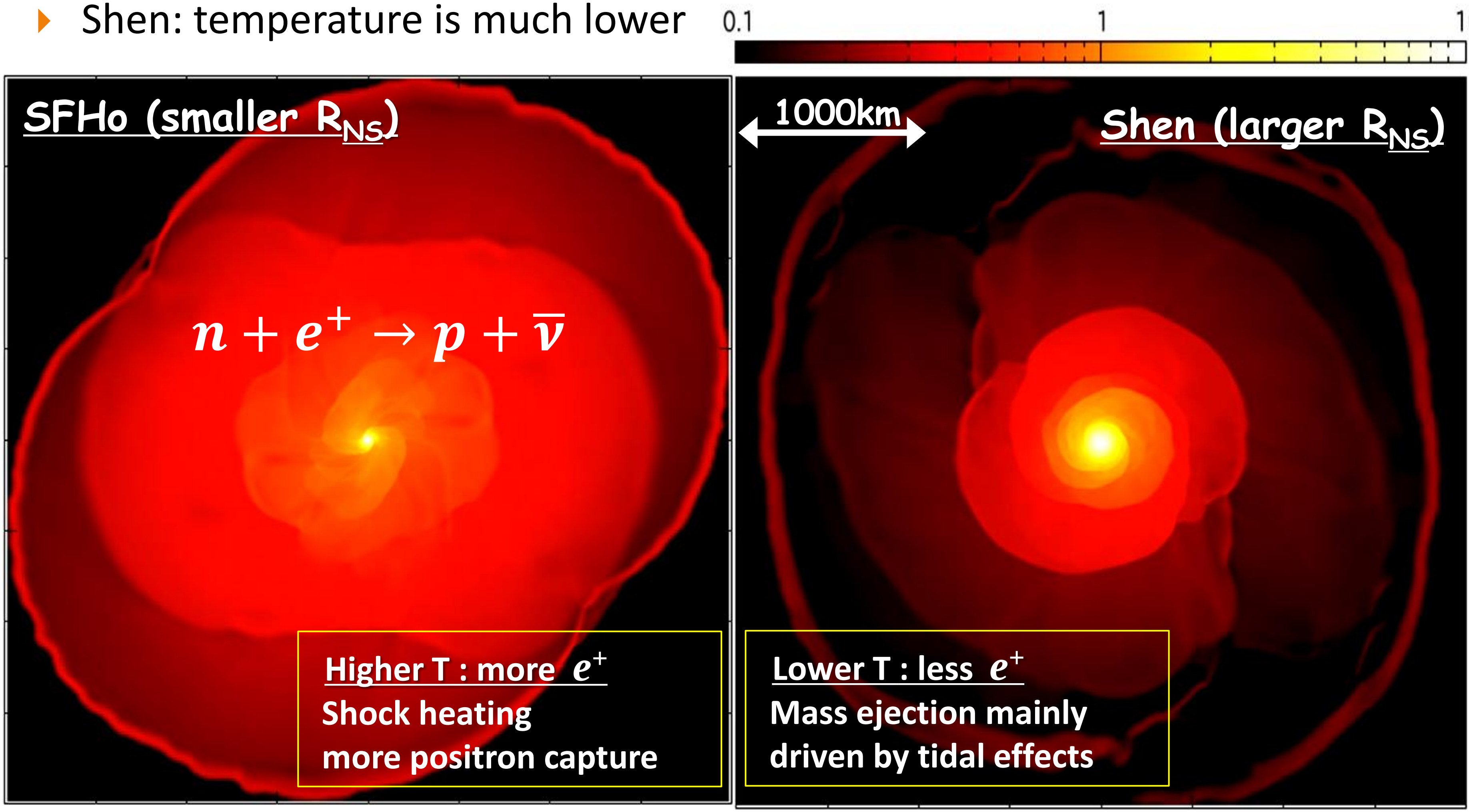


Higher T : more e^+
Shock heating
more positron capture

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

SFHo vs. Shen: Ejecta temperature

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

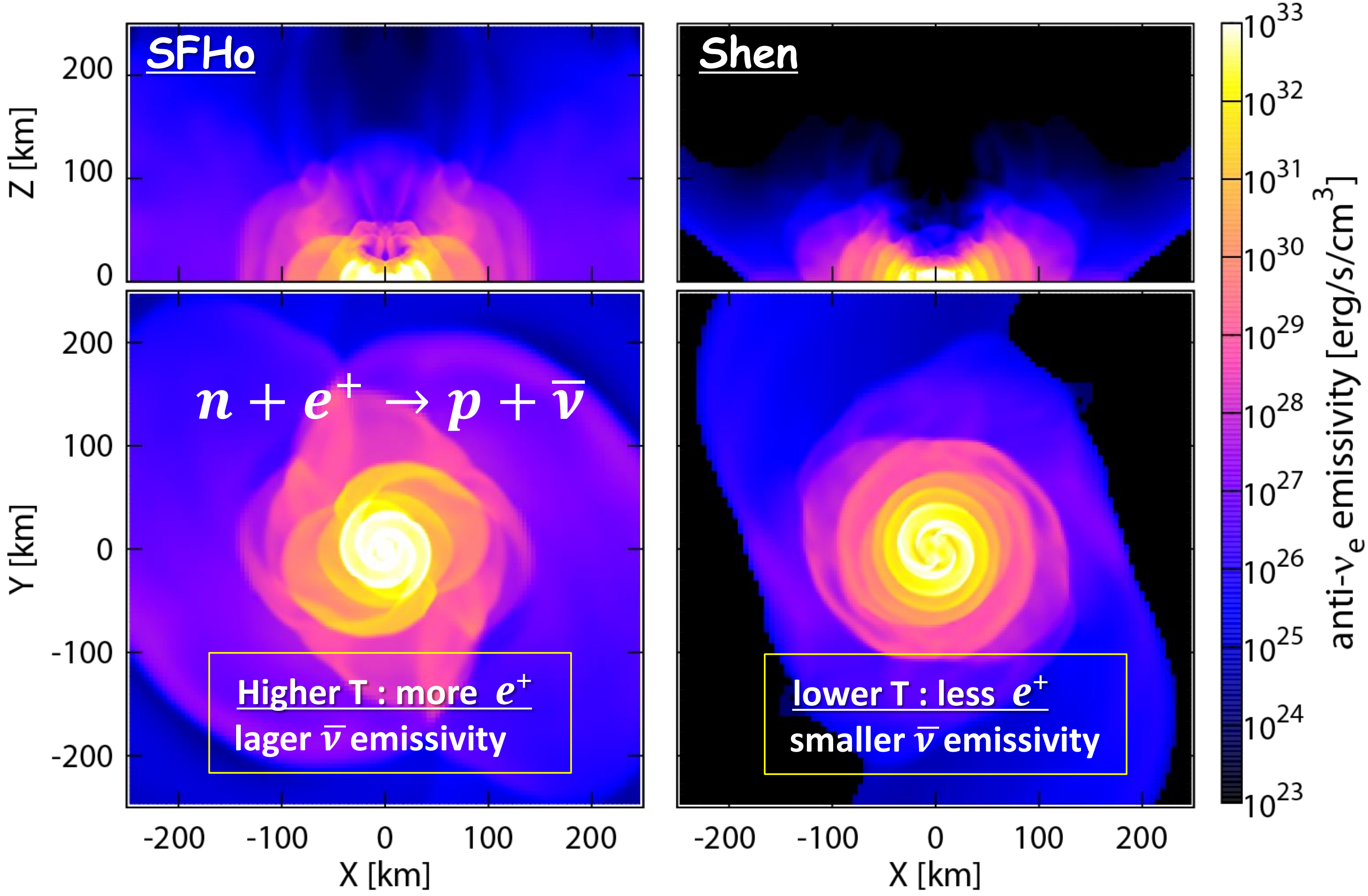


$$n + e^{+} \rightarrow p + \overline{\nu}$$

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

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

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



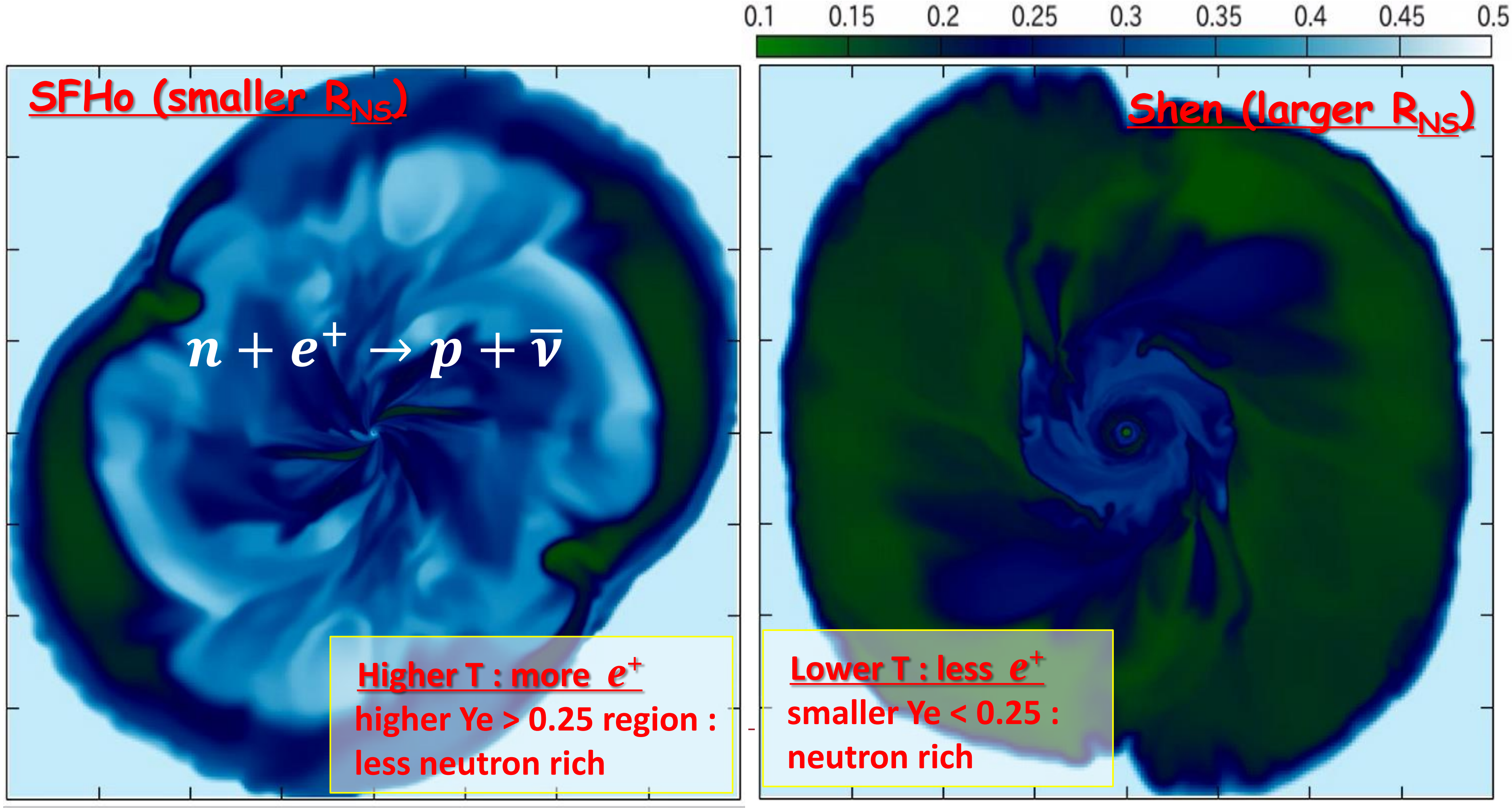
$$n + e^{+} \rightarrow p + \bar{\nu}$$

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

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

SFHo vs. Shen: Ejecta Ye

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



SFHo (smaller R_{NS})

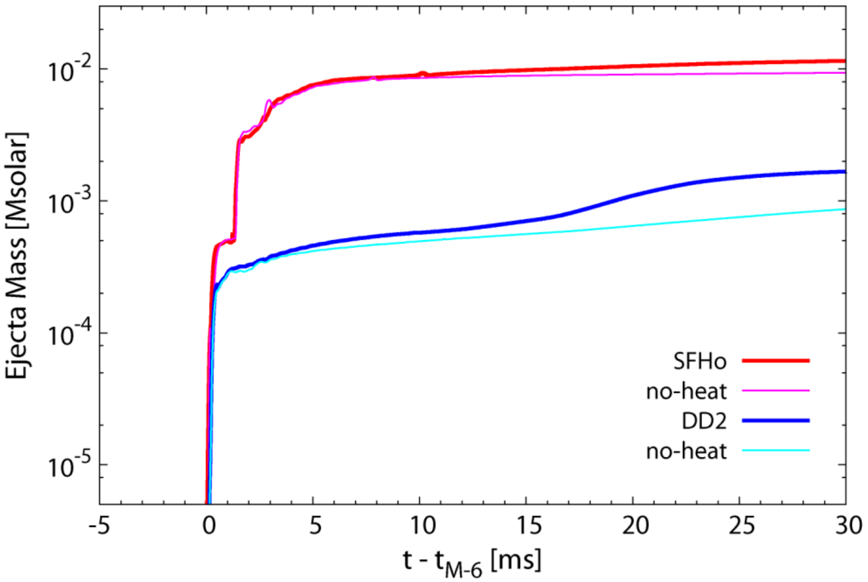
$$n + e^{+} \rightarrow p + \overline{\nu}$$

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

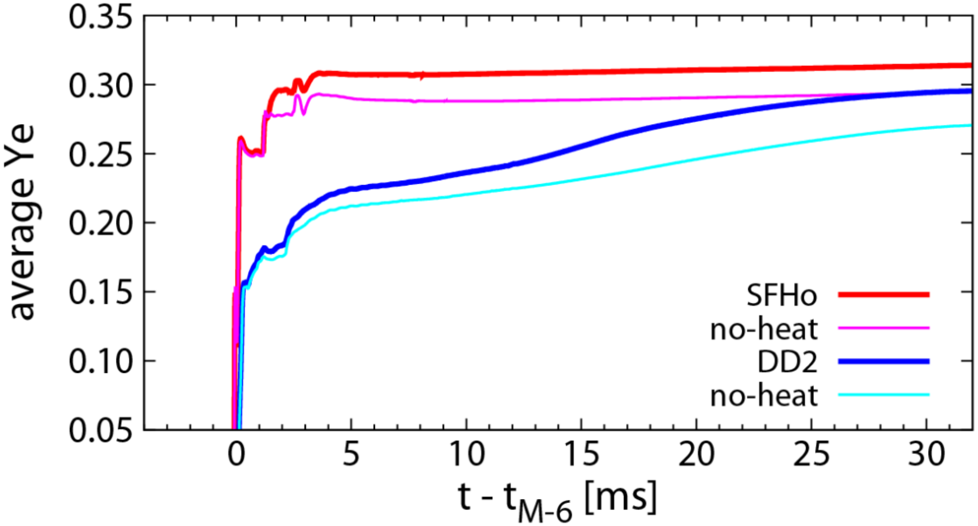
Shen (larger R_{NS})

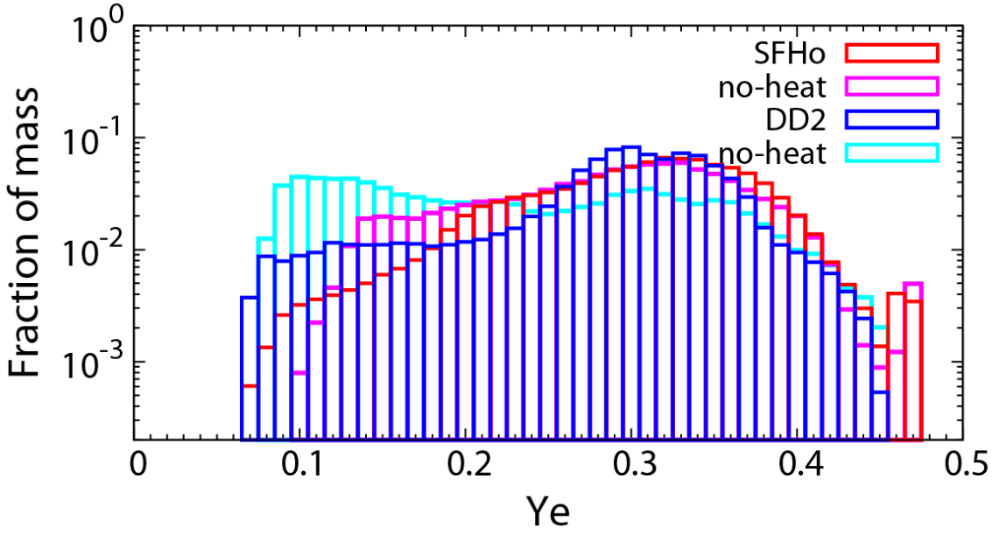
Lower T : less e^{+}
smaller Ye < 0.25 : neutron rich

Effects of neutrino heating



- Amount of ejecta mass can be increased ~ 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

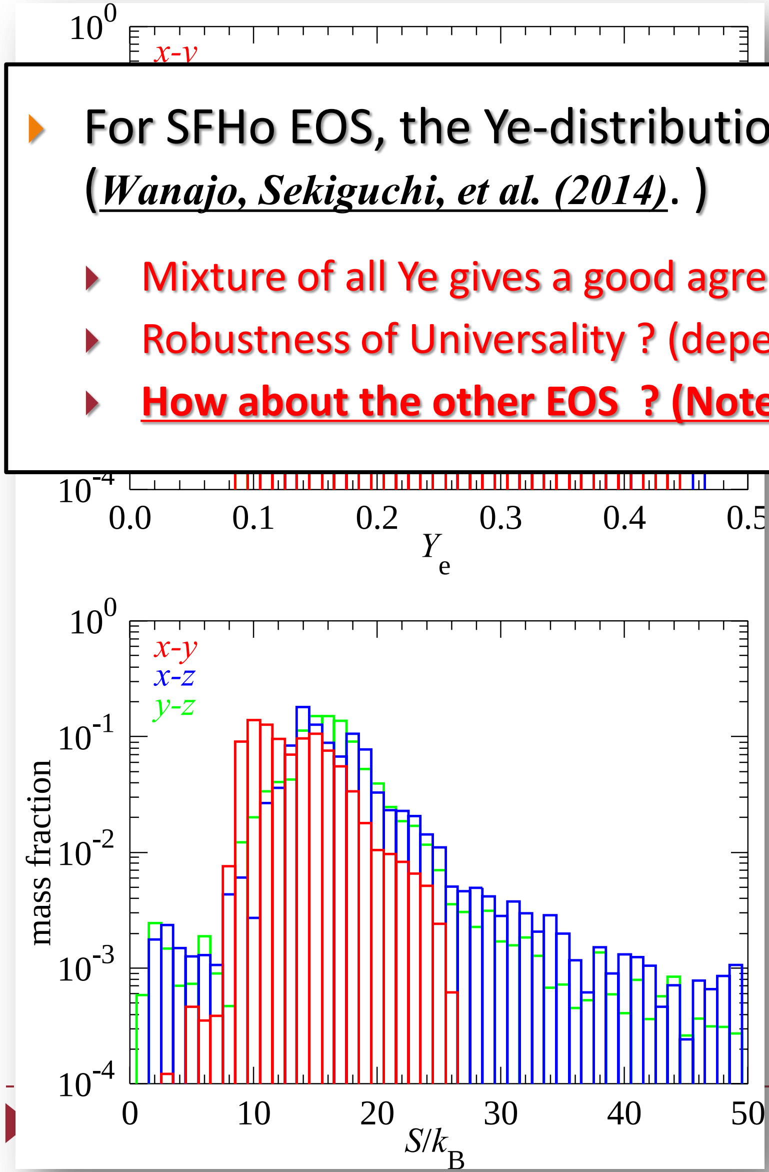


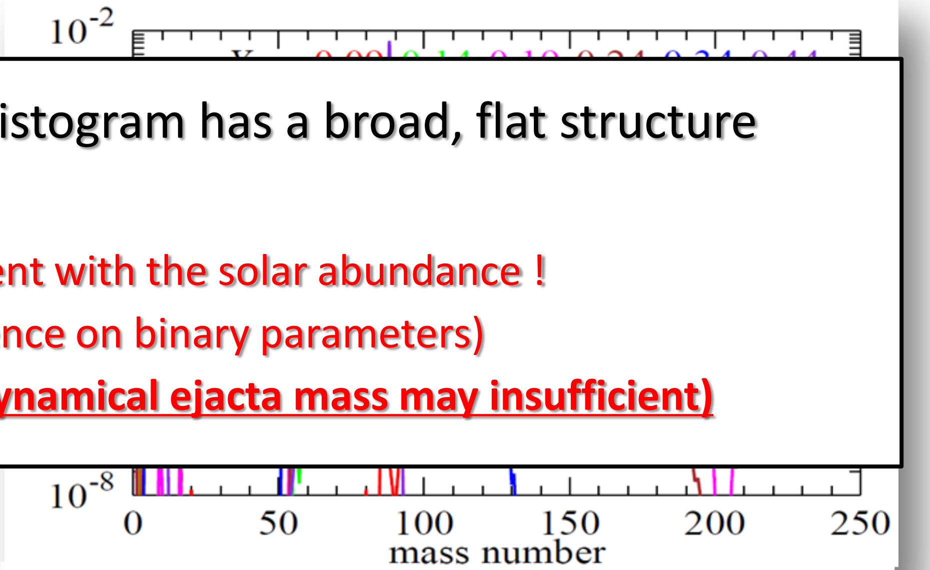


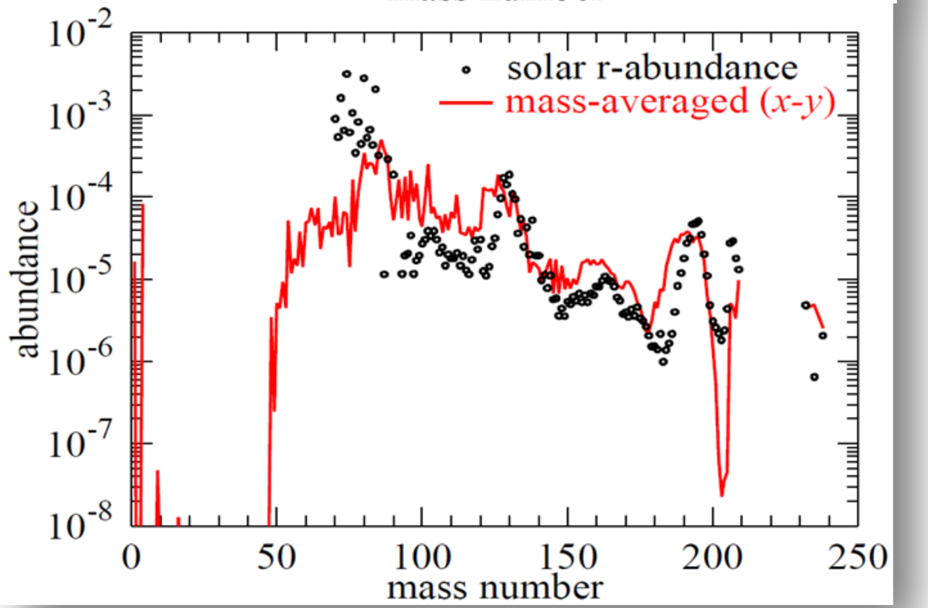
Wanajo, Sekiguchi et a. (2014)

SFHo: the common pattern 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 ejacta mass may insufficient)**

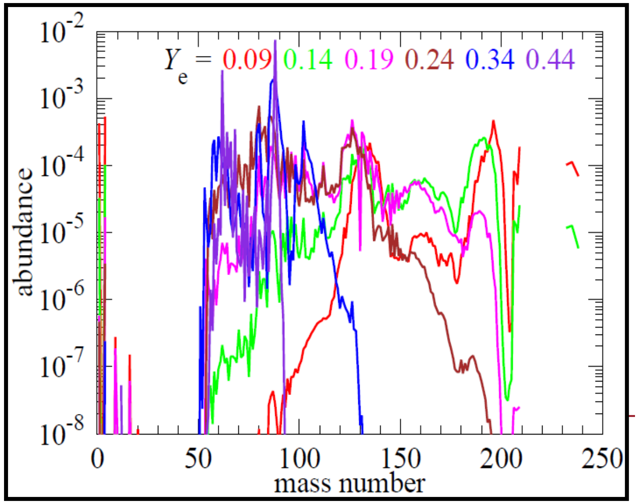


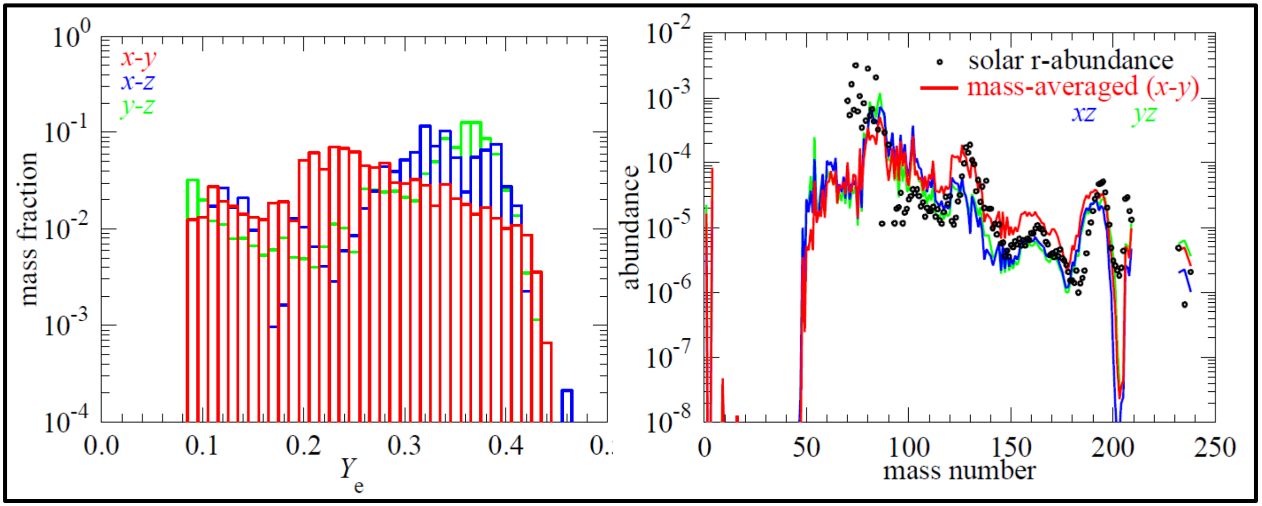




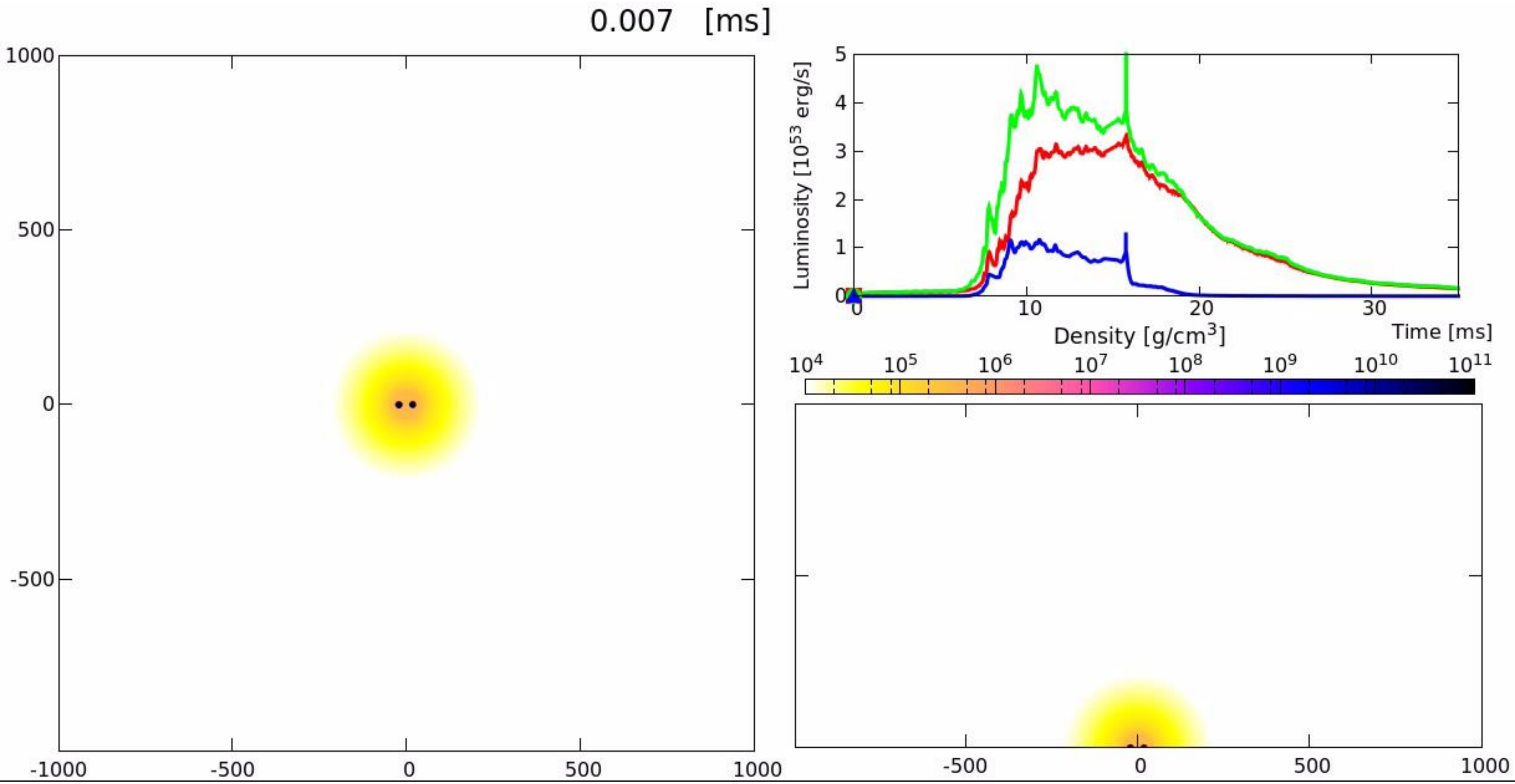
On robustness of common pattern

- 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

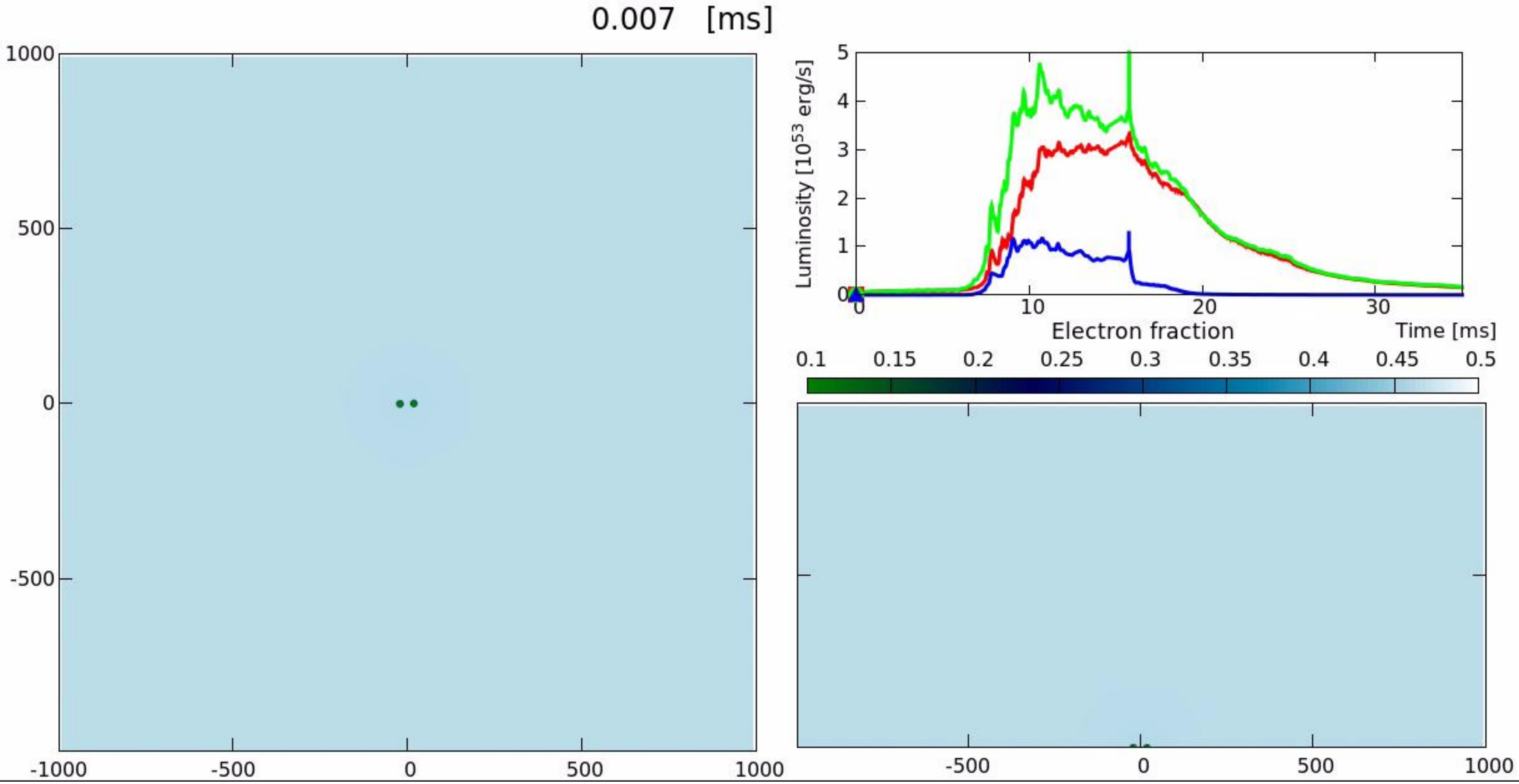




Unequal mass NS-NS system: SFHo1.25-1.45

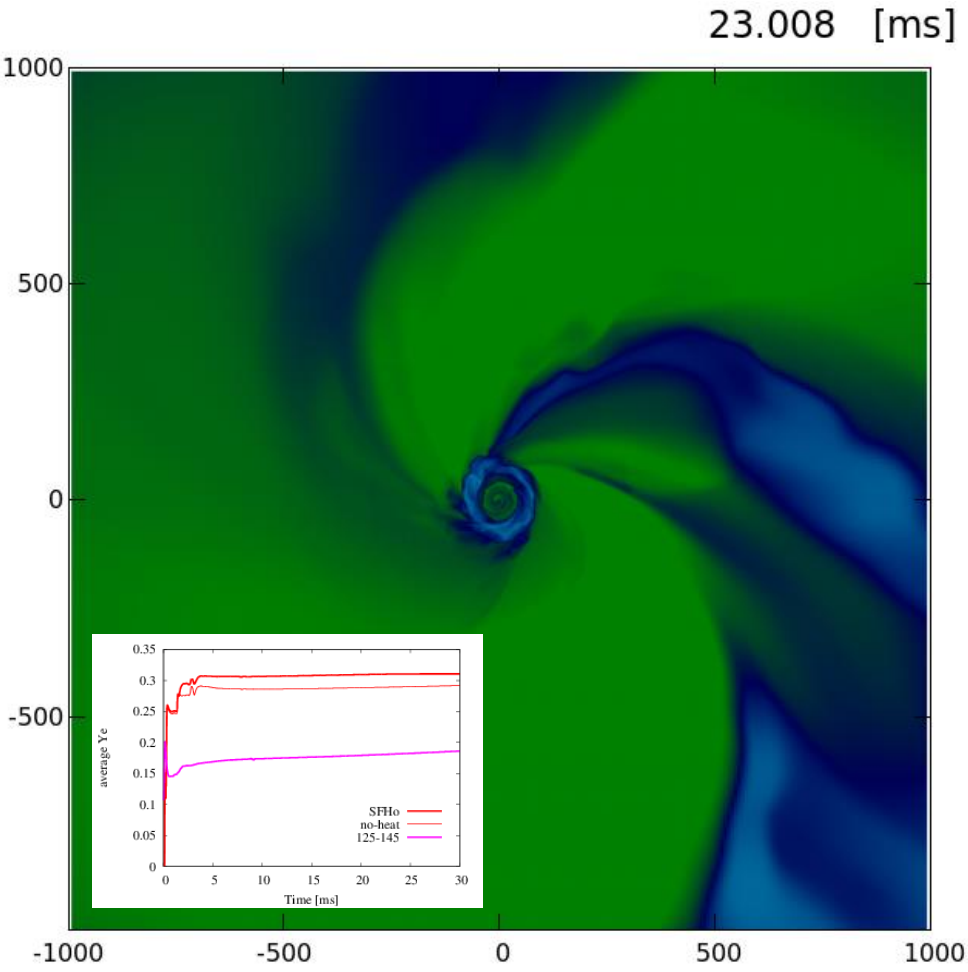


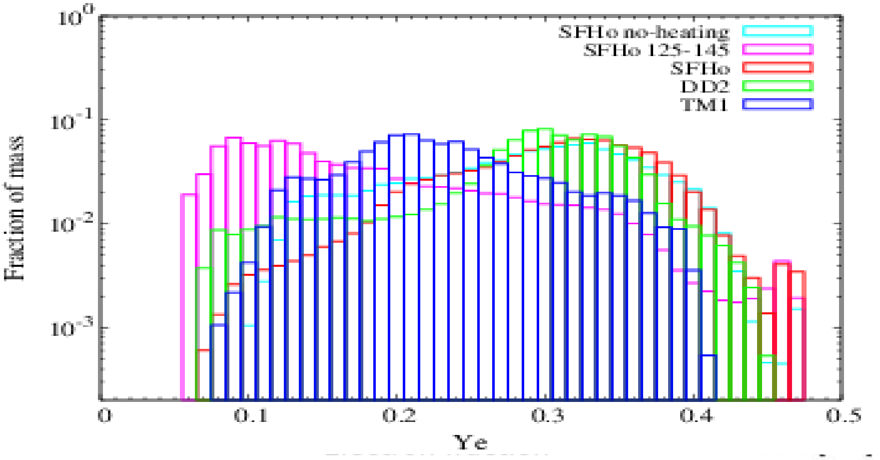
Unequal mass NS-NS system: SFHo1.25-1.45

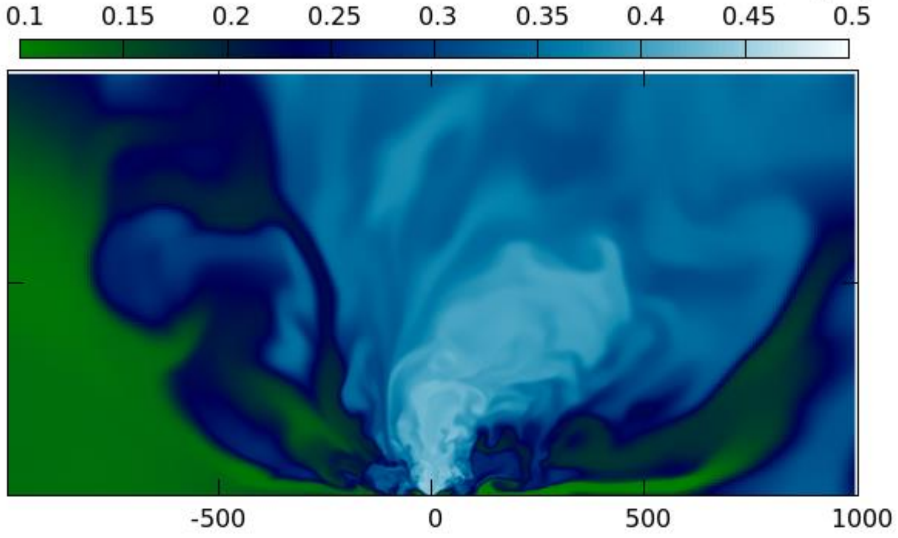


Unequal mass NS-NS system: SFHo1.25-1.45

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

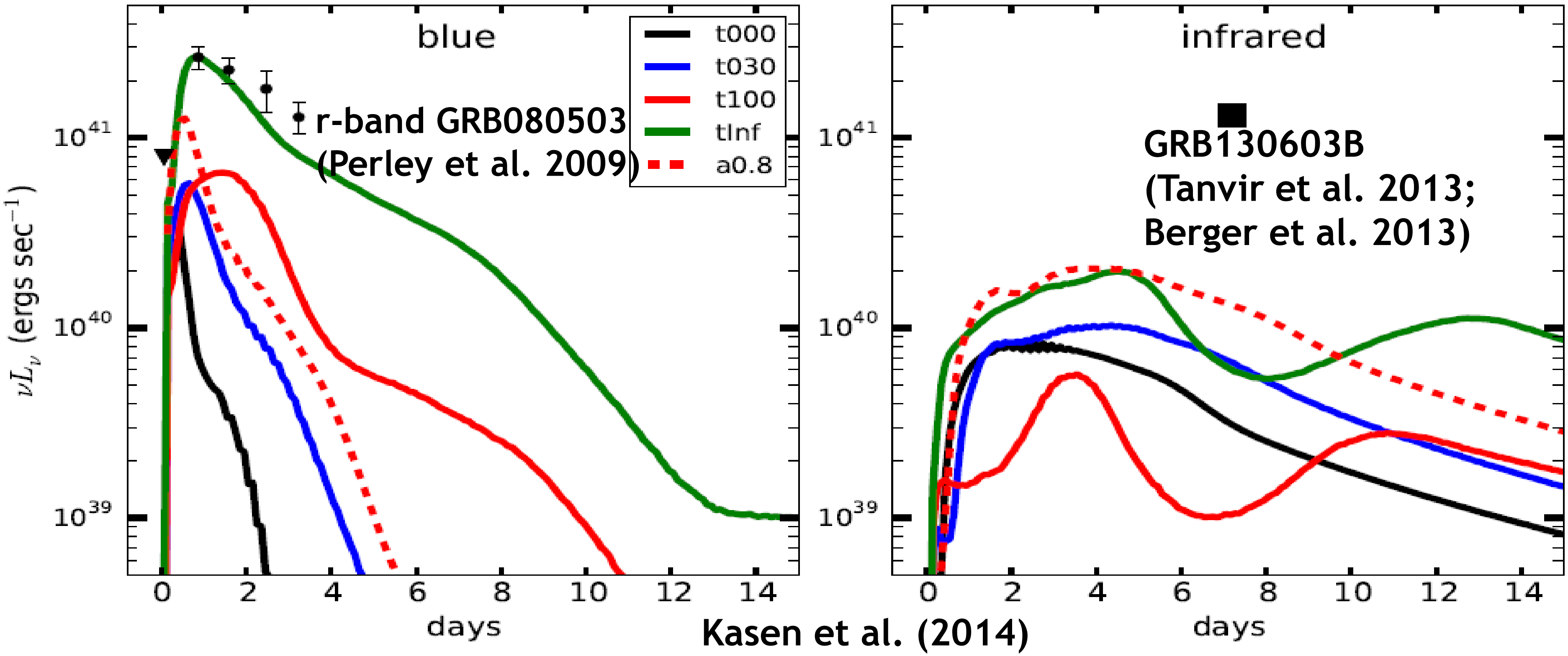






EM counterparts associated with winds

- Extrapolation from an estimate for ν-driven ejecta (Ye ~ 0.3; Mej ~ 0.01Msun)
  - Higher Ye : Distribution of r-process nuclei will be different
  - Opacity may be smaller (Grossman et al. 2013, Kasen et al. 2014 : $\kappa = 1\ \mathrm{cm}^2/\mathrm{g}$)
  - More bright EM counterpart in Opt. band ??? ⇒ **need self-consistent studies**
    - EM counterpart may be more than 10 times brighter than the previous estimate
    - Direction dependence (Kasen et al 2014) ? : face on (higher Ye) vs. edge on (lower Ye)



Kasen et al. (2014)

Summary

- EM Counterparts to GWs (安東さん) from NS-NS mergers (BH-NS: 木内さん)
  - Many channels
    - 河合さん、木阪さん、岩崎さん
  - Similarities to SNe
    - 前田さん、藤本さん、藤林さん
  - Kilonova seems to be still one of the most promising EM counterpart
    - 田中さん、本原さん
  - Also interesting in terms of the origin of heavy elements
    - 和南城さん、石丸さん、青木さん、辻本さん、平居さん etc.

- **Importance of GR, EoS and neutrinos in r-process and kilonova**
  - A wide Ye distribution due to weak processes
  - Only soft EOS like SFHo can achieve $M_{ej} \sim 0.01 M_{sun}$
  - Dependence on binary parameter (mass ratio) :
    - Tidal (low Ye) component increases for unequal mass binary

Shibata et al. 2006; Sekiguchi et al, 2011;
Hotokezaka et al. 2013; Kepran et al 2014

Maximum mass of HMNS

- $$\boxed{M_{\mathrm{crit}} \approx M_{\mathrm{max,sph.cold.NS}} + \Delta M_{\mathrm{rot}}^{\mathrm{rigid}} + \Delta M_{\mathrm{rot}}^{\mathrm{diff}} + \Delta M_{\mathrm{thermal}}}$$
  - $M_{\mathrm{max,sph.cold.NS}}$: maximum mass of spherical NS at T = 0, depends on EOS
    - Most massive NS accurately observed : 1.97 Msolar (Demorest et al. 2010)
  - $\Delta M_{\mathrm{rot}}^{\mathrm{rigid}}$: effects of rigid rotation $\sim O(10\%)$
  - $\Delta M_{\mathrm{rot}}^{\mathrm{diff}}$: effects of differential rotation typically $\sim O(10\%)$
  - $\Delta M_{\mathrm{thermal}}$: effects of finite temperature $\sim O(10\%)$
    - HMNS formed after the merger is very hot as T ~ O(10MeV)
- The enhancement parameter : k $\boxed{M_{\mathrm{crit}} \approx k\ M_{\mathrm{max,sph.cold.NS}}}$
  - 1.4 < k < 1.7 (depend strongly on EOS and weakly on mass ratio)

Importance of *T* and microphysics

- High density (>10^{12} g/cc) and T (> 1-10 MeV) regions
  - $\lambda_\nu >> \lambda_\gamma, \lambda_e$ ⇒ neutrinos drive the thermal / chemical evolution
    - 99% of energy released *in stellar core collapse* is carried away by neutrinos
    - **Neutrino : Weak interactions** should be taken into account
    - Strong dependences of weak rates on T ⇒ **Finite temperature EOS**
- NS-NS, BH-NS mergers (*T* can be > 50 MeV)
  - Inspiral : NS is cold ($k_BT/E_F << 1$) ⇒ **zero T EOS**
  - Meger : Compression, shock heating ($k_BT/E_F \sim O(0.1)$) ⇒ **finite T EOS**
  - **Prompt BH formation ⇒ hot region quickly swallowed by BH**
    - **Effects of finite temperature would be miner**
  - **HMNS, late time BH, and massive disk formation (more likely)**
    - **Shock heating, neutrino cooling, etc. are important**

Importance of *T* and microphysics

- High density (>10^{12} g/cc) and T (> 1-10 MeV) regions
  - $\lambda_\nu >> \lambda_\gamma, \lambda_e$ ⇒ neutrinos drive the thermal / chemical evolution
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    - **Neutrino : Weak interactio**
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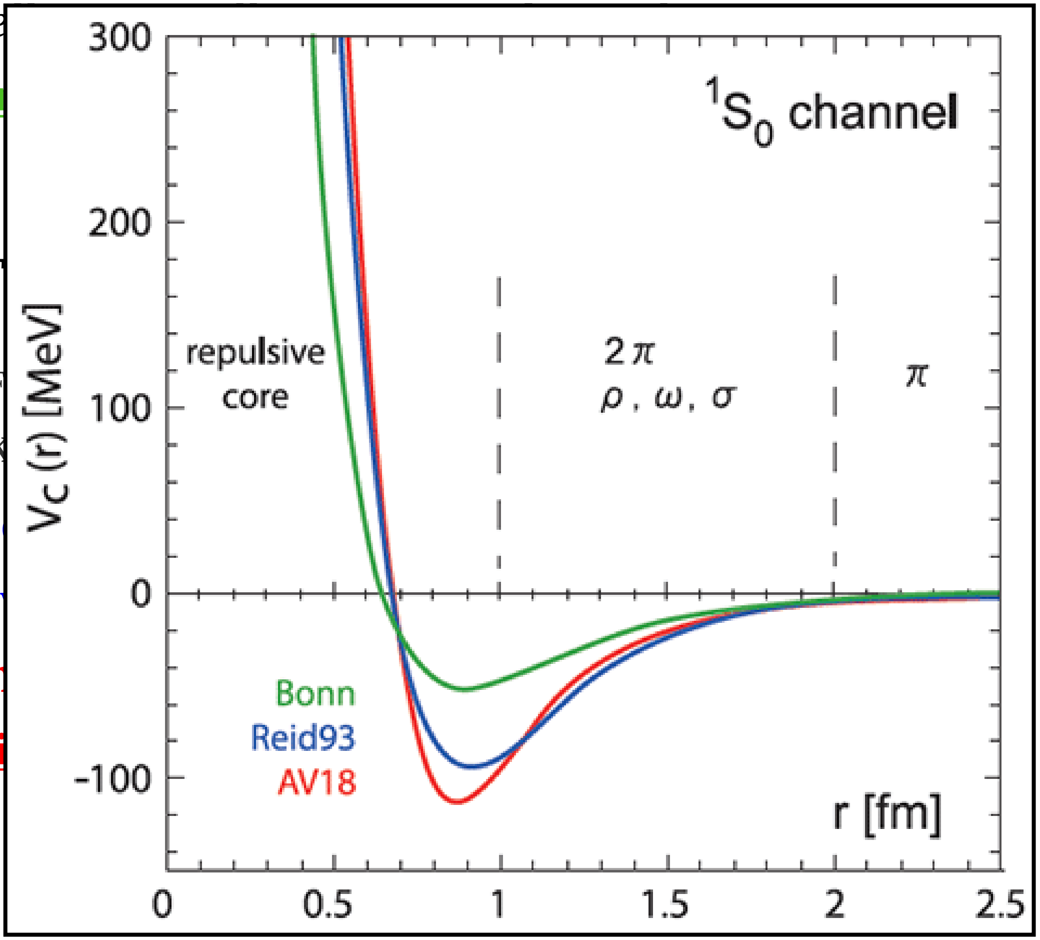
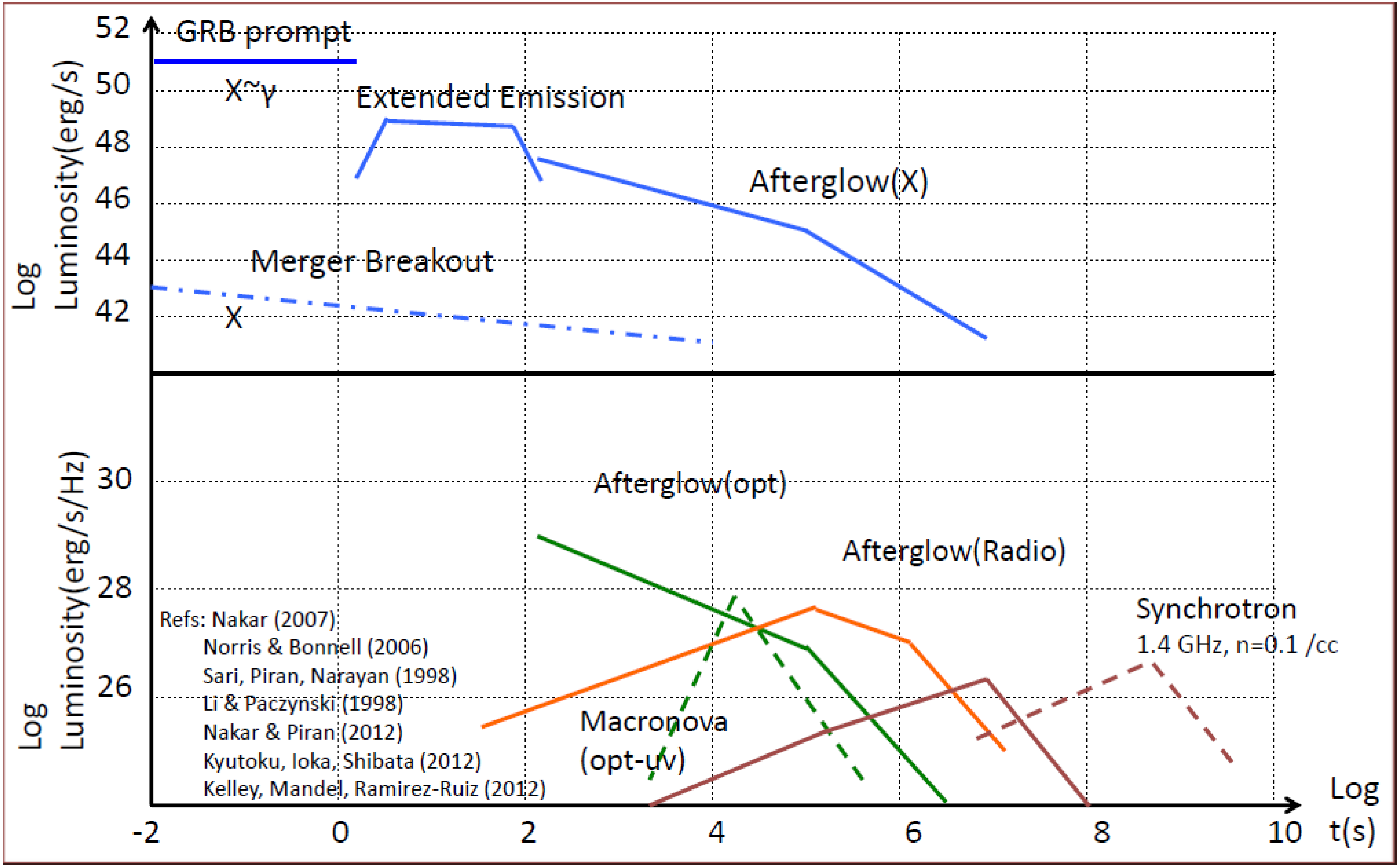
- NS-NS, BH-NS mergers (*T*
  - Inspiral : NS is cold ($k_B T/ E_F$
  - Meger : Compression, shock
  - **Prompt BH formation ⇒ h**
    - **Effects of finite temperature**
  - **HMNS, late time BH, and r**
    - **Shock heating, neutrino cooli**

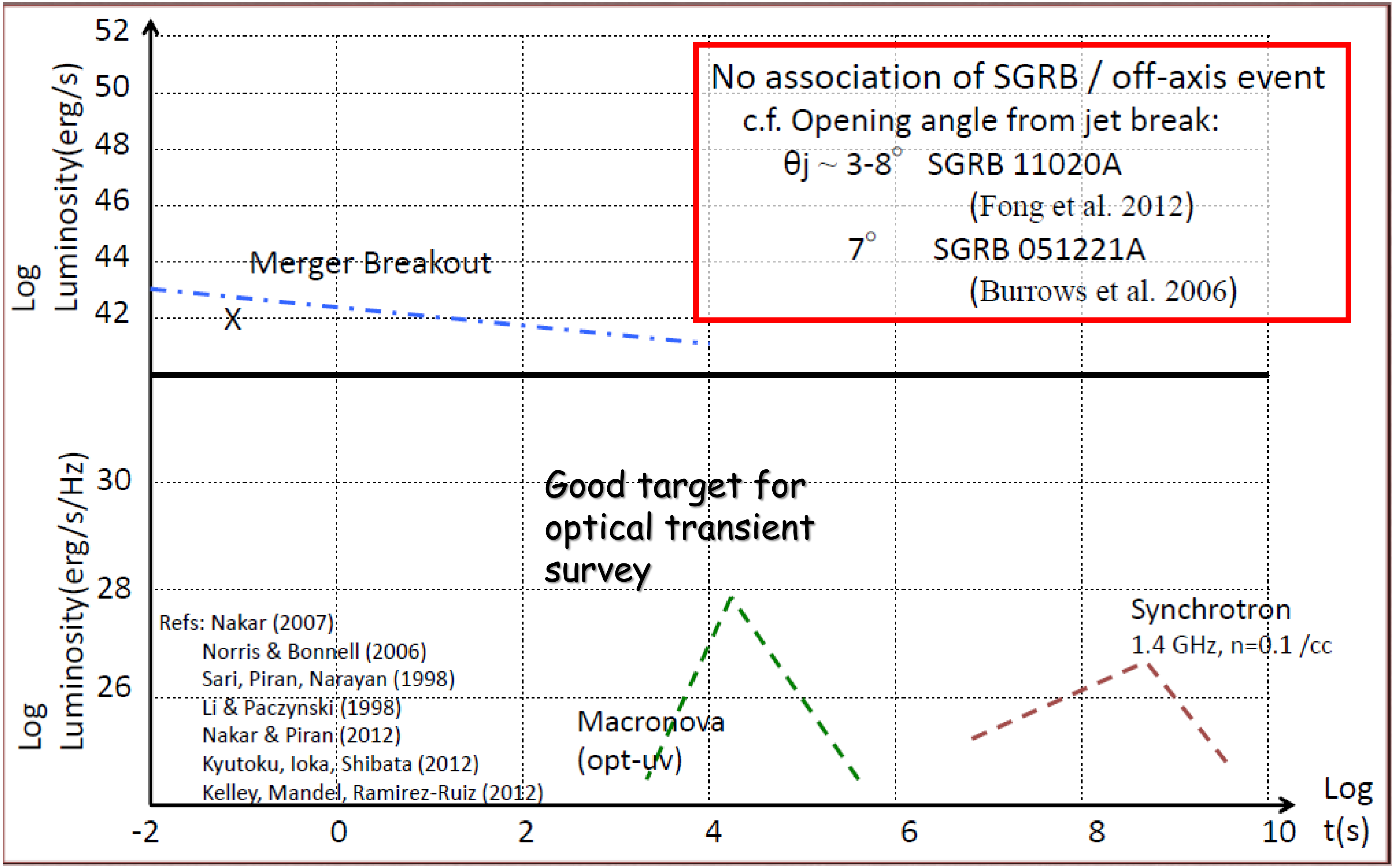


Expected Light curves



Refs: Nakar (2007)
Norris & Bonnell (2006)
Sari, Piran, Narayan (1998)
Li & Paczynski (1998)
Nakar & Piran (2012)
Kyutoku, Ioka, Shibata (2012)
Kelley, Mandel, Ramirez-Ruiz (2012)

Expected Light curves (off-axis)



No association of SGRB / off-axis event
c.f. Opening angle from jet break:
θj ~ 3-8° SGRB 11020A
(Fong et al. 2012)
7° SGRB 051221A
(Burrows et al. 2006)

Good target for optical transient survey

Refs: Nakar (2007)
Norris & Bonnell (2006)
Sari, Piran, Narayan (1998)
Li & Paczynski (1998)
Nakar & Piran (2012)
Kyutoku, Ioka, Shibata (2012)
Kelley, Mandel, Ramirez-Ruiz (2012)

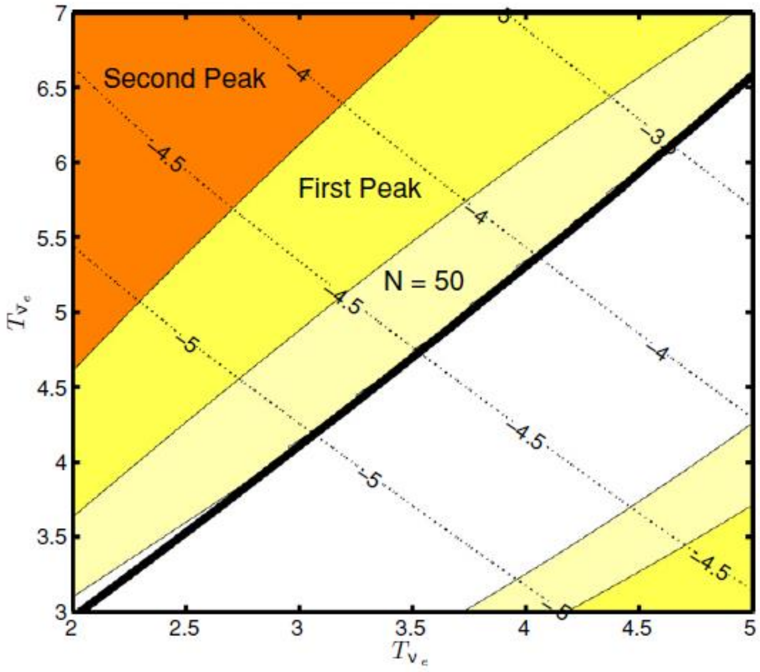
SN ejecta: not so neutron-rich

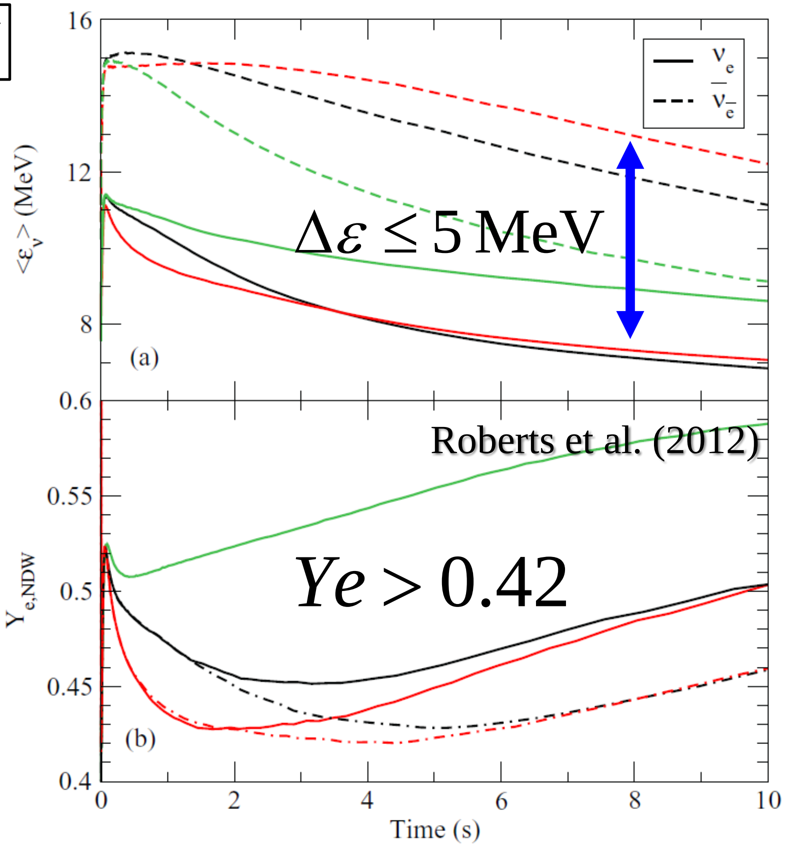
- *Ye* is determined by $\boxed{\bar{\nu}_e + p \leftrightarrow n + e^+}$ $\boxed{\nu_e + n \leftrightarrow p + e^-}$
- equilibrium value is $\boxed{Y_e \sim \left[1+\frac{L_{\bar{\nu}e}}{L_{\nu e}}\frac{\varepsilon_{\bar{\nu}e}-2\Delta}{\varepsilon_{\nu e}+2\Delta}\right]^{-1}}$

$\Delta = m_n - m_p \approx 1.293\mathrm{MeV}$

$L_{\nu e} \approx L_{\bar{\nu}e}$

- For *Ye* < 0.5 (n-rich) $\boxed{\varepsilon_{\bar{\nu}e} - \varepsilon_{\nu e} > 4\Delta \sim 5\mathrm{MeV}}$





$\Delta\varepsilon \leq 5\,\mathrm{MeV}$

Roberts et al. (2012)

$Ye > 0.42$

SN ejecta: not so neutron-rich

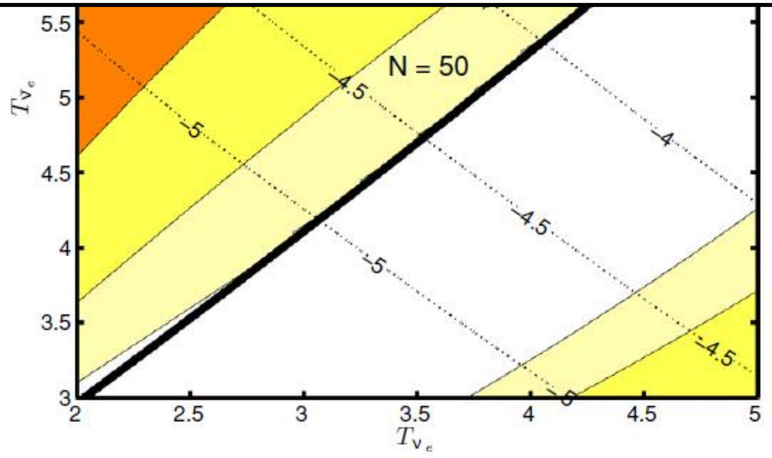
- *Ye* is determined by $\boxed{\bar{\nu}_e + p \leftrightarrow n + e^+}$ $\boxed{\nu_e + n \leftrightarrow p + e^-}$
- equilibrium value is $\boxed{Y_e \sim \left[1 + \frac{L_{\bar{\nu}e}}{L_{\nu e}} \frac{\varepsilon_{\bar{\nu}e} - 2\Delta}{\varepsilon_{\nu e} + 2\Delta}\right]^{-1}}$

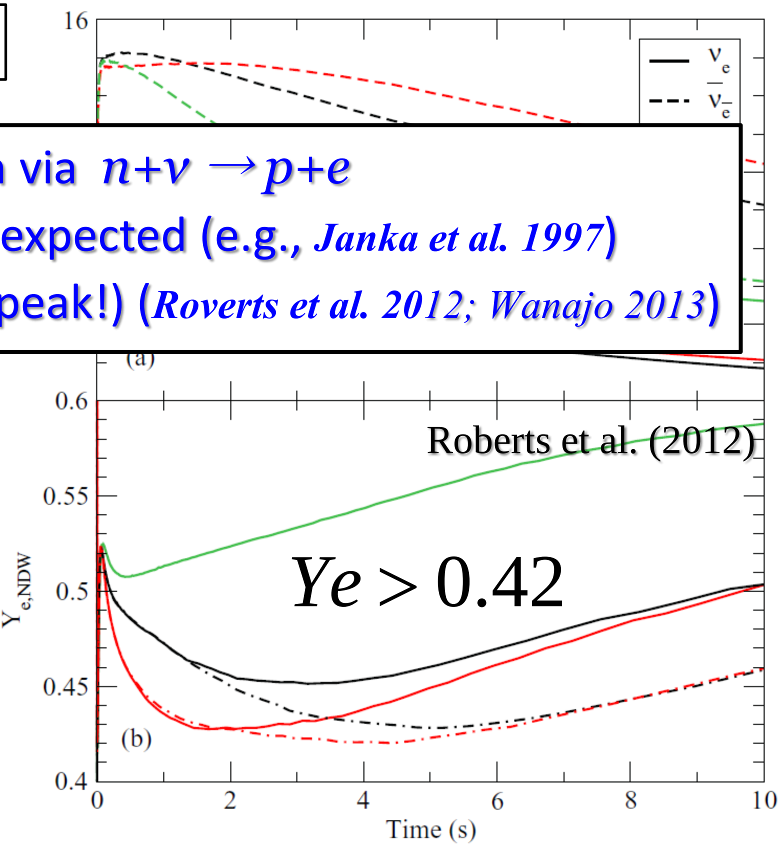
$\Delta = m_n - m_p \approx 1.293\text{MeV}$

$L_{\nu e} \approx L_{\bar{\nu}e}$

- For *Ye* < 0.5 (n-rich) $\boxed{\varepsilon_{\bar{\nu}e} - \varepsilon_{\nu e} > 4\Delta \sim 5\text{MeV}}$

- Neutrinos from PNS make the flow proton-rich via $n + \nu \rightarrow p + e$
- + Smaller entropy/per baryon than previously expected (e.g., *Janka et al. 1997*)
- ⇒ only weak r-process (up to 2nd peak, no 3rd peak!) (*Roverts et al. 2012; Wanajo 2013*)





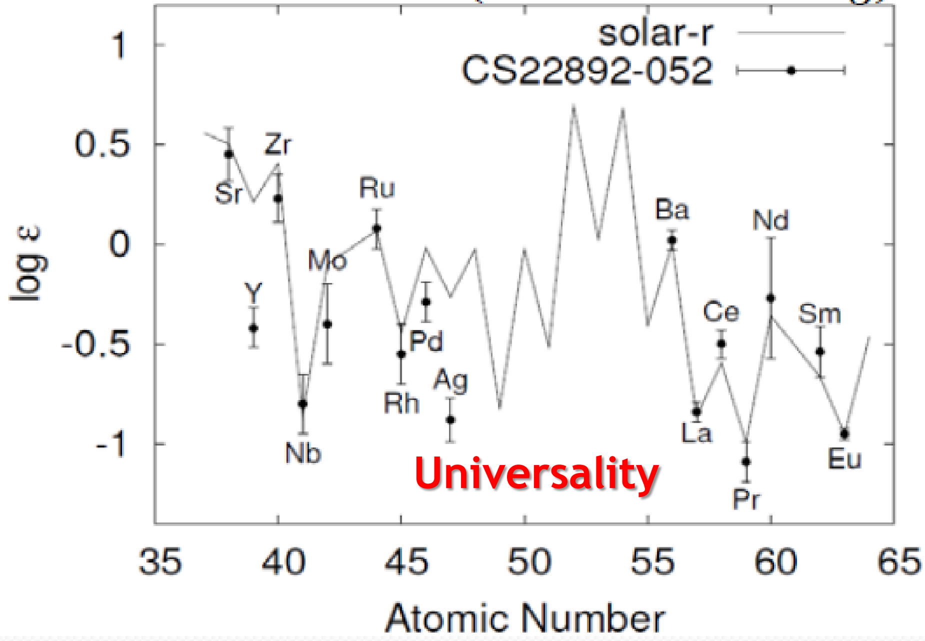
Roberts et al. (2012)

$Ye > 0.42$

More on r-process cite: main and weak

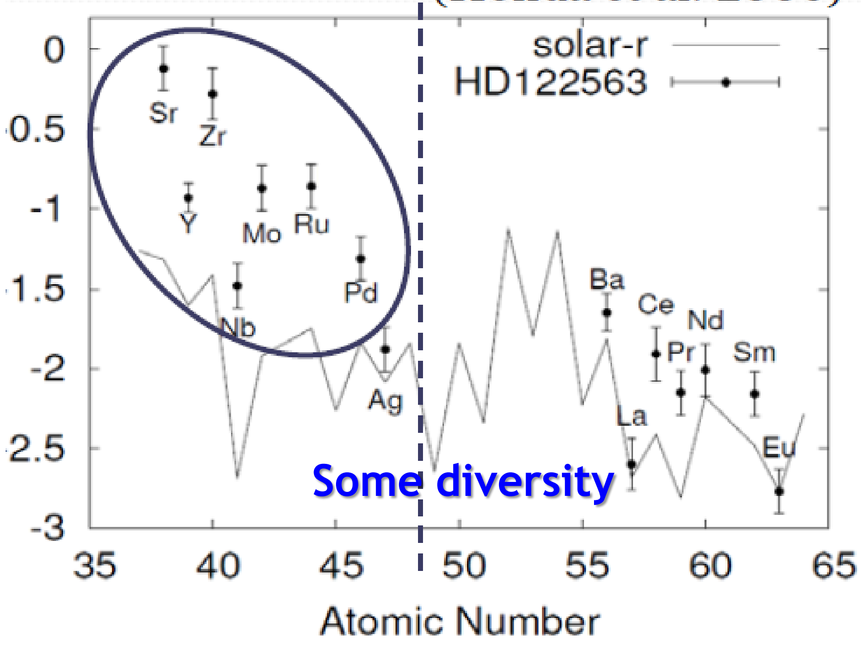
CS22892-052 ([Fe/H]=-3.10)

Main r-star (Sneden et al. 2003)



HD122563 ([Fe/H]=-2.65)

Weak r-star (Honda et al. 2006)



Main r-process:

Process which creates neutron-capture elements including heavier elements (eg. Ba, Eu etc.)

Weak r-process:

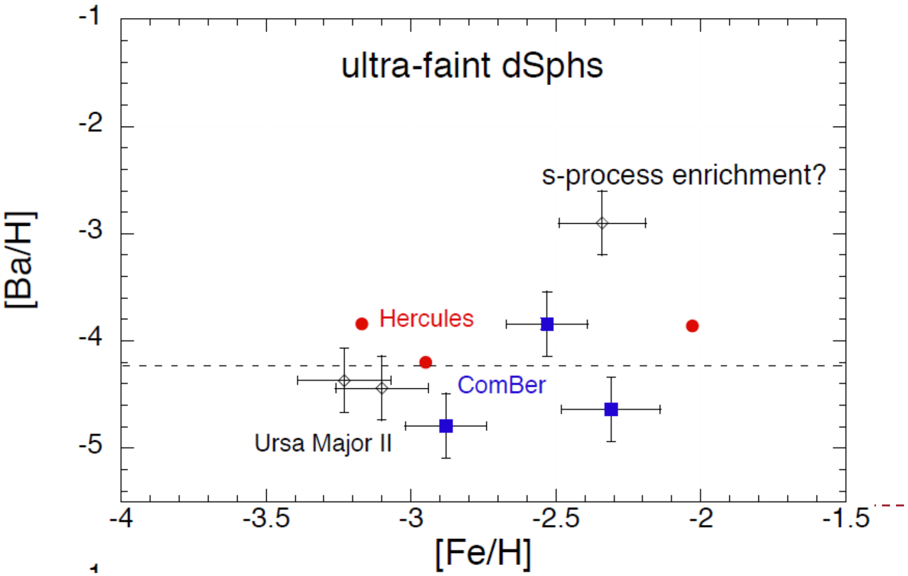
Process responsible for lighter neutron-capture elements (eg. Sr, Y, Zr etc.)

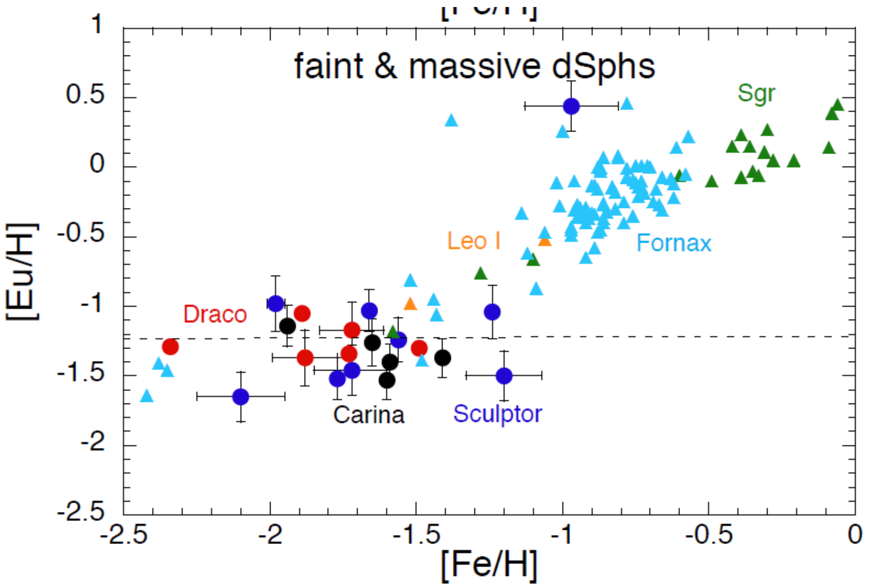
- $\log \varepsilon_X = \log(N_X / N_H) + 12$

From W. Aoki @ INT workshop

Further evidence ???

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

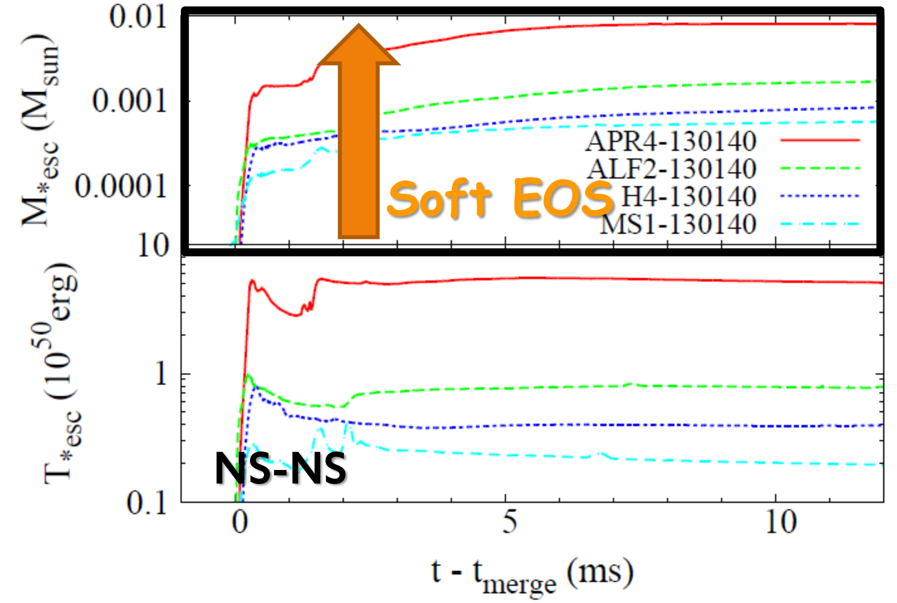


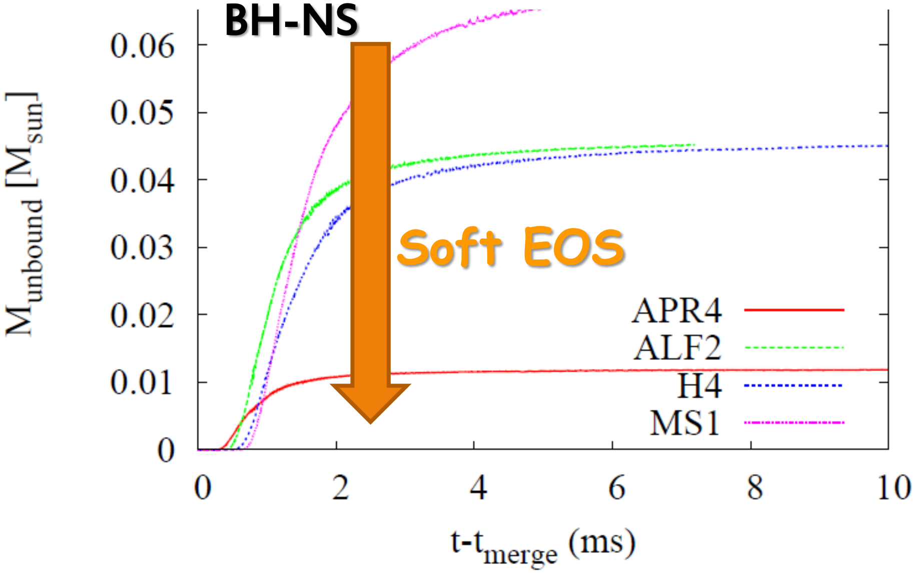


Hotokezaka et al. (2013); Kyutoku et al. in prep.

Ejecta property depends on NS EOS

- Stiff EOS ⇒ large NS radius
  ⇒ tidal-driven
  - **Cold, low Ye, along orbital plane**
- Soft EOS ⇒ shock-driven
  - **Hot, higher Ye, more isotropic**
- **Can we distinguish by Obs.?**
  - Constraint on NS-EOS by Opt-UV Obs. ?
- **BH-NS vs. NS-NS**
    - BH-NS : (tidal) orbital plane
    - NS-NS : (shock + tidal) isotropic
  - NS EOS dependence is different
    - BH-NS prefers stiff EOS
    - NS-NS prefers soft EOS

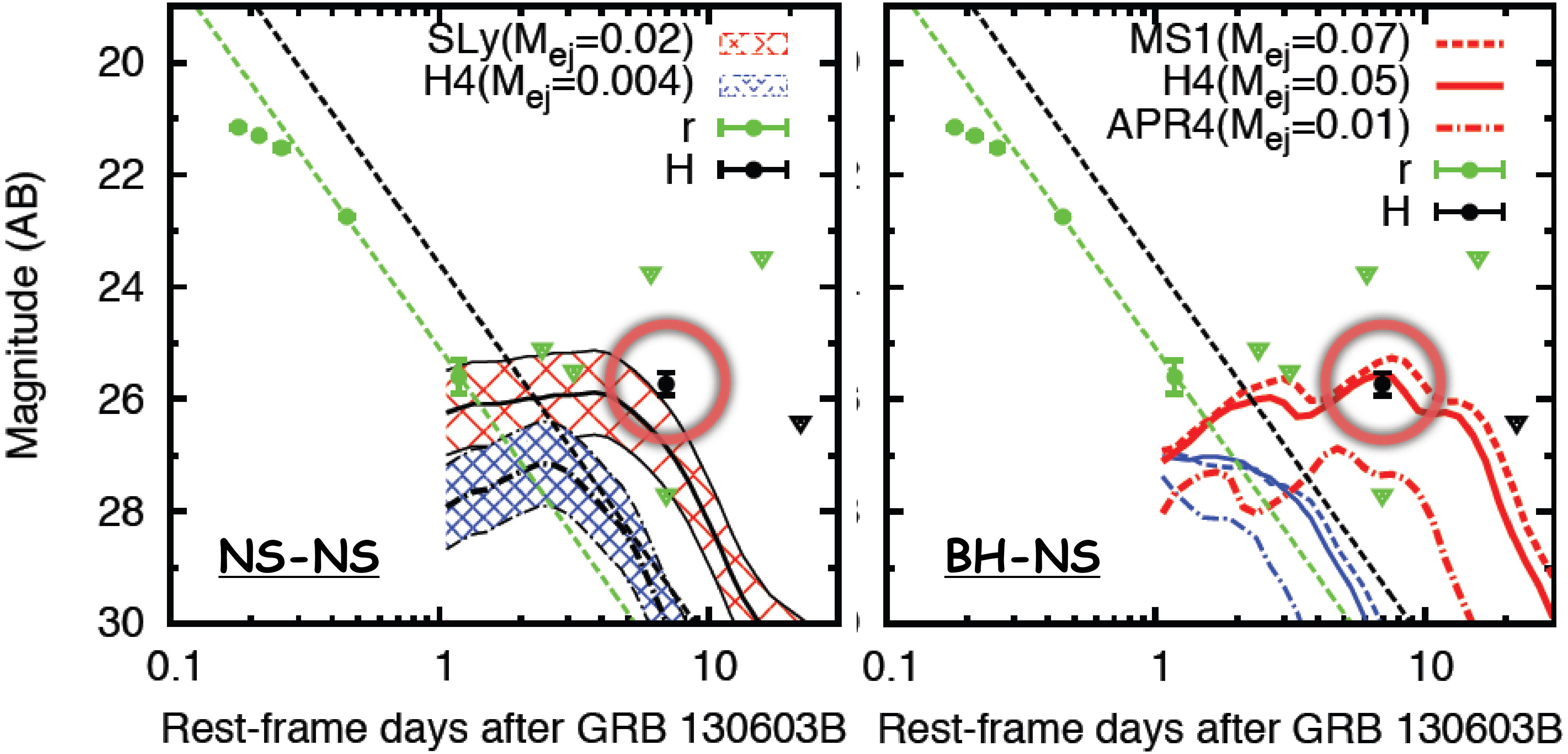




Hotokezaka et al. (2013)
Tanaka et al. (2014)

Kilonova modeling : NS-NS vs. BH-NS

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



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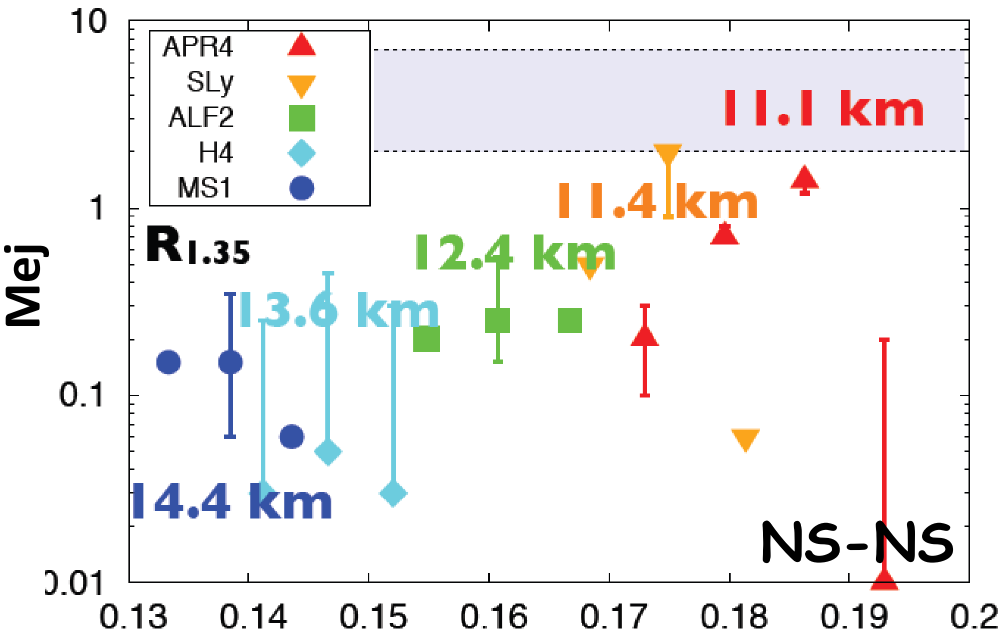
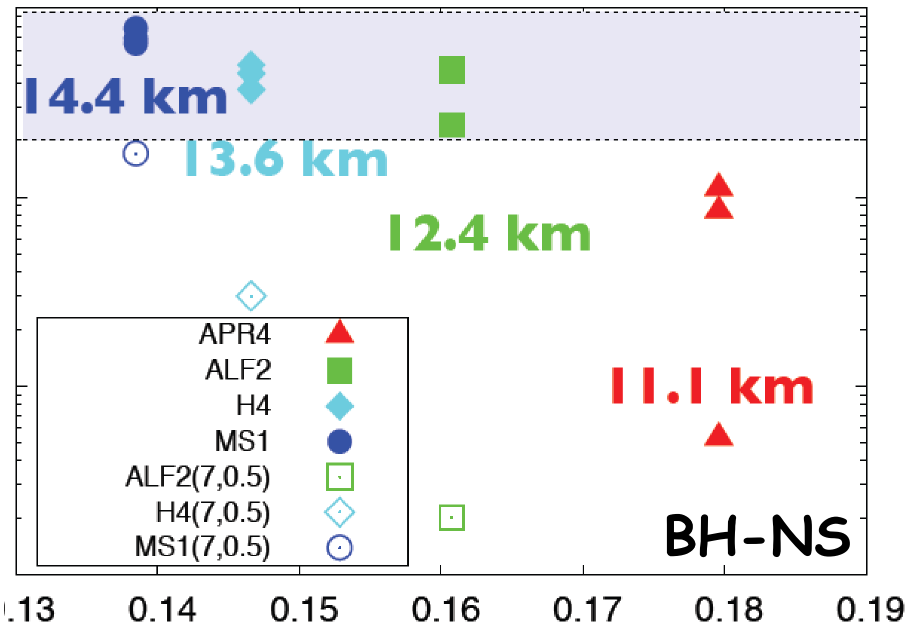
- **NS-NS :** **Soft EOS is necessary** (shocks play a role)
  - Small diversity in conditions before merger, Mej ~ 0.01 Msun may be universal within the typical mass range of NS-NS
- **BH-NS :** **Stiffer EOS is preferable** (tidal component is dominant)
  - large diversity is expected, because mass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





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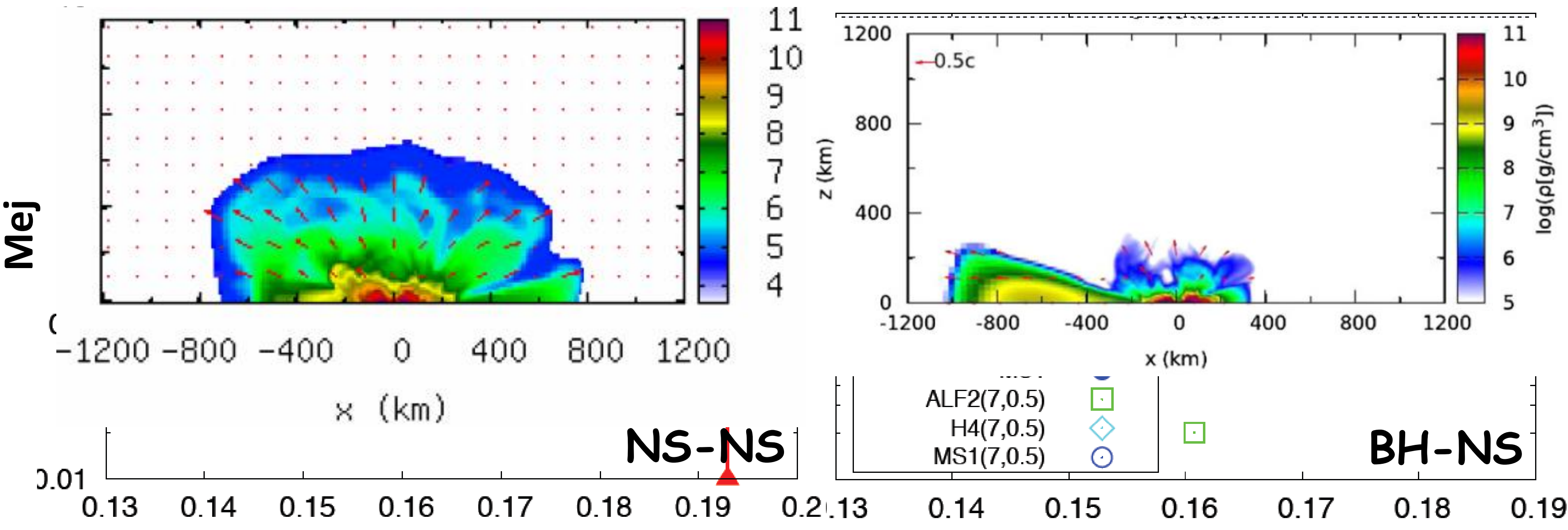
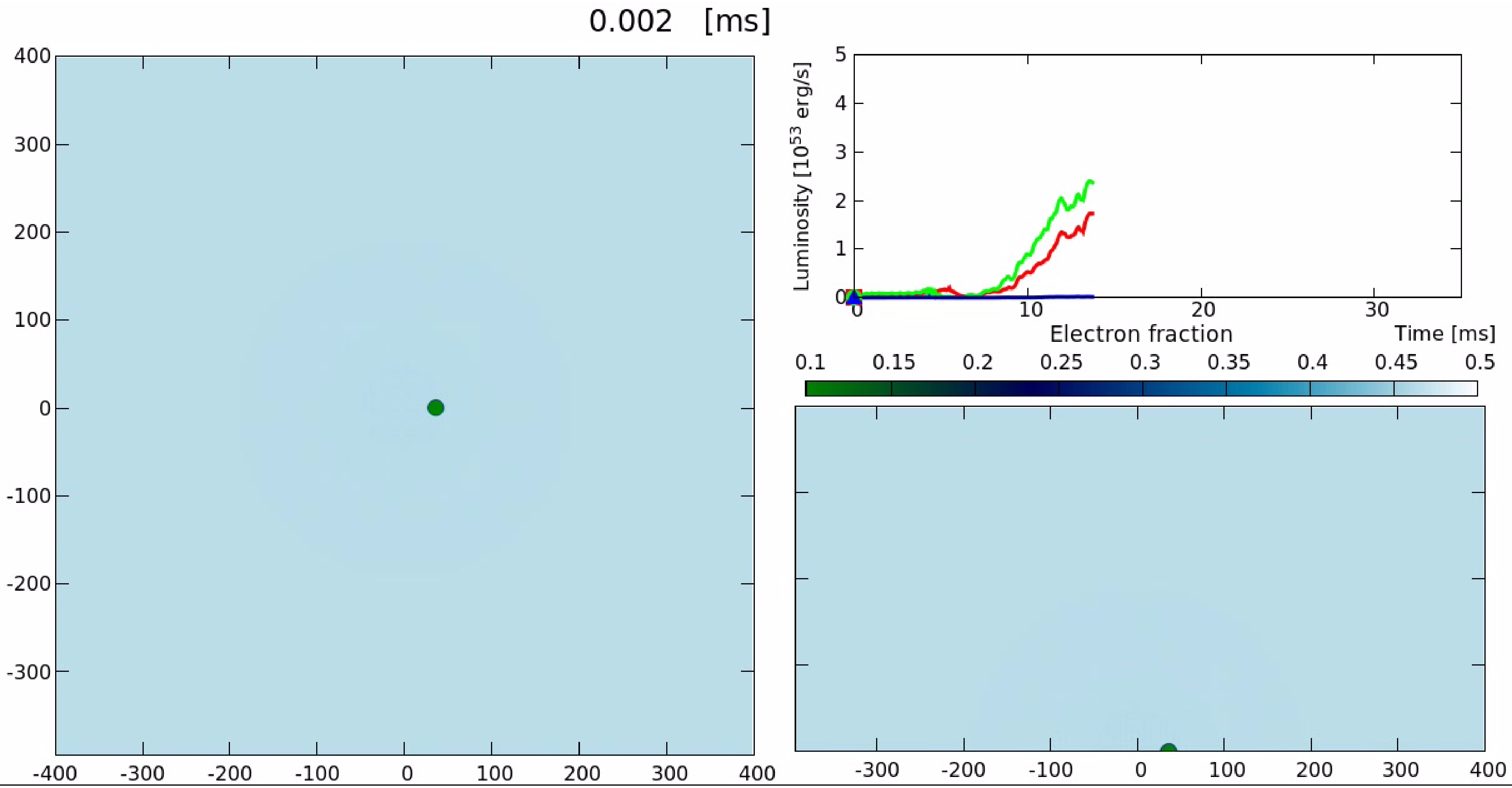


BH-NS merger: wind components may be important

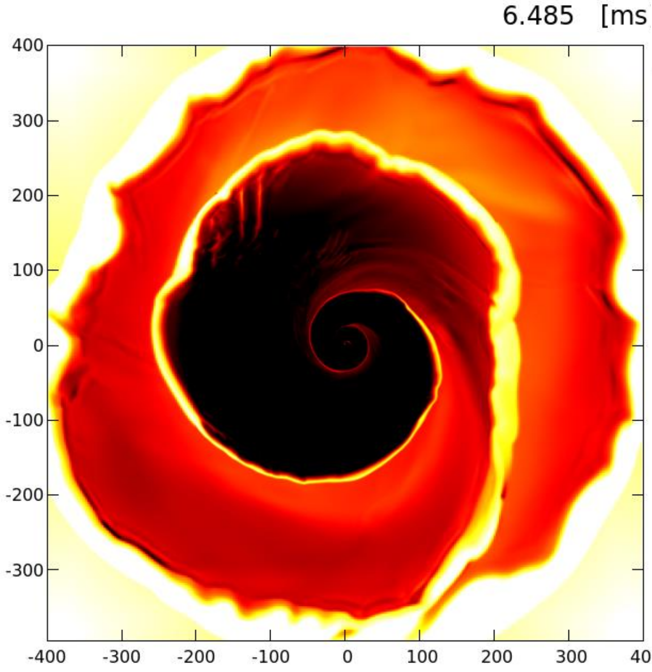


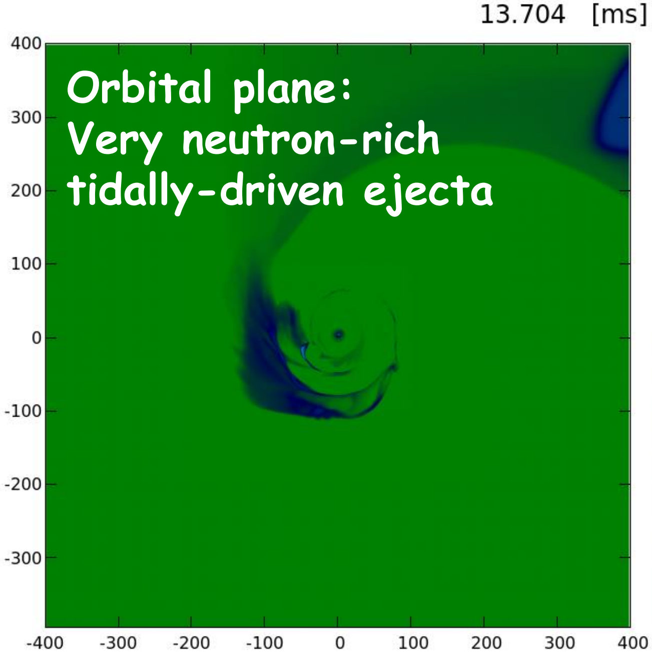
BH-NS merger : test simulation (mass ratio 3:1, spin 0.75)

NS is tidally disrupted

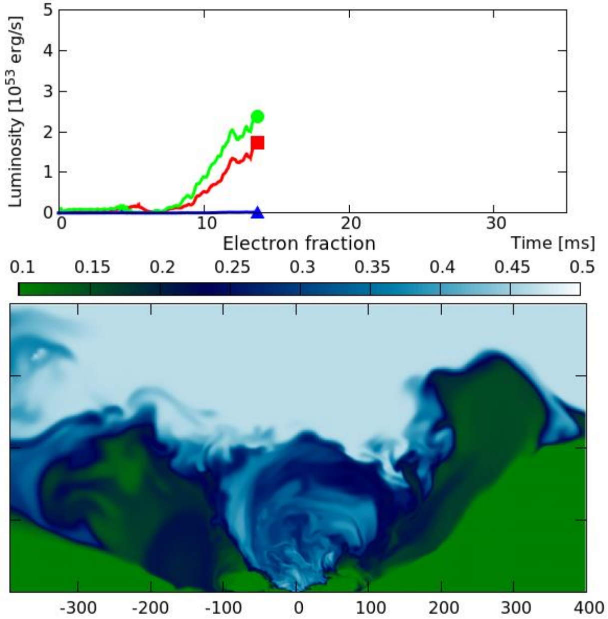
Shocks are generated when spiral arms interacts

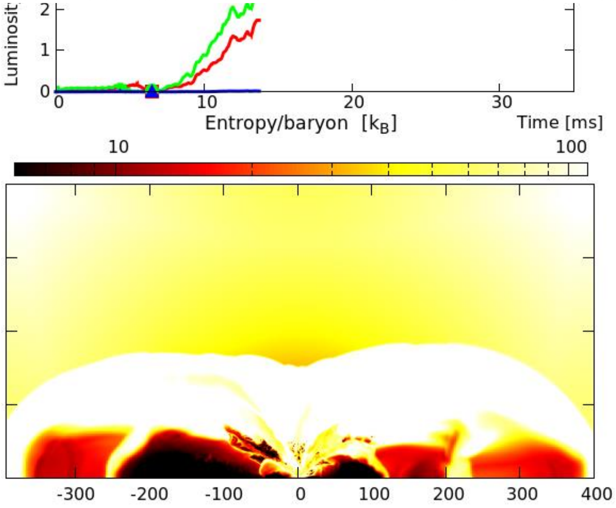
Entropy of tidally disrupted NS remains low





Orbital plane:
Very neutron-rich tidally-driven ejecta





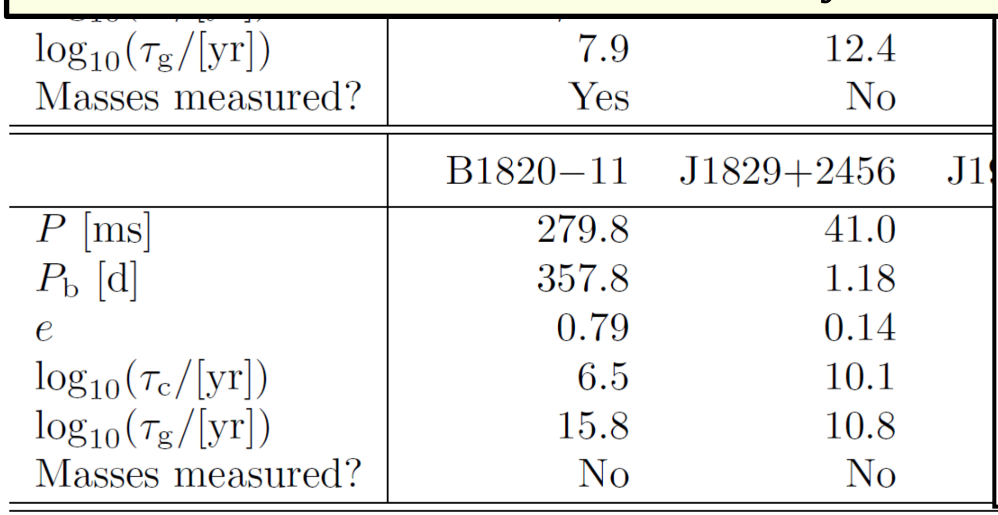
Pole region: Neutrino-driven winds with less neutron rich materials

New discovery !
(GR+neutrinos essential)

Expected Merger Rate

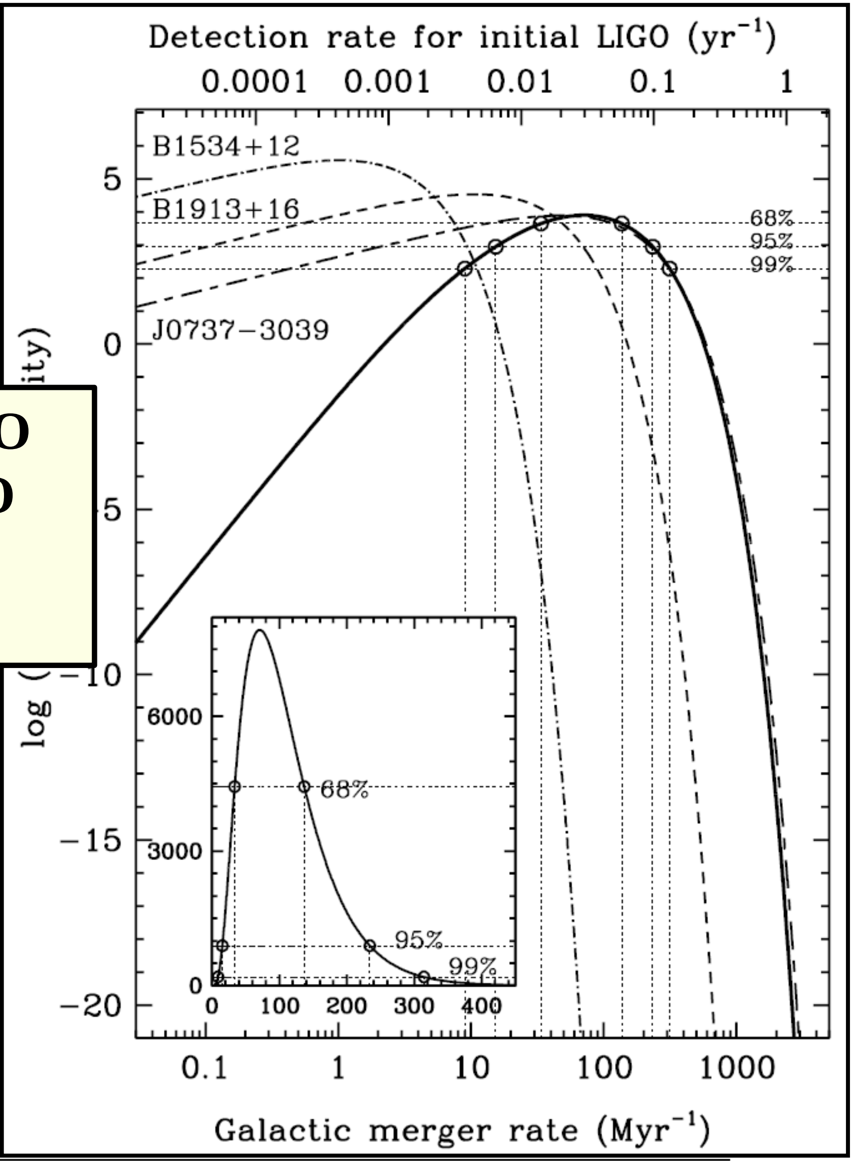
- Binary Neutron Star (BNS, NS-NS) and candi
  - 6 Binaries with pulsar are expected to merge wit
  - Empirical NS-NS merger rate: 3-190 Myr^{-1} /galax
- Merger rate from population synthesis
  - NS-NS : 10-200 Myr^{-1}/gal. (**Kalogera et al. 2004**)
  - BH-NS : 0.1-5 Myr^{-1}/gal. (**Belczynski 2007**)

NS-NS : ~10 - 100 events/yr for advLIGO
BH-NS : ~ 1 - 30 events/yr for advLIGO
Not so rare events !
We can do GW astronomy



$\log_{10}(\tau_g/[\mathrm{yr}])$	7.9	12.4
Masses measured?	Yes	No

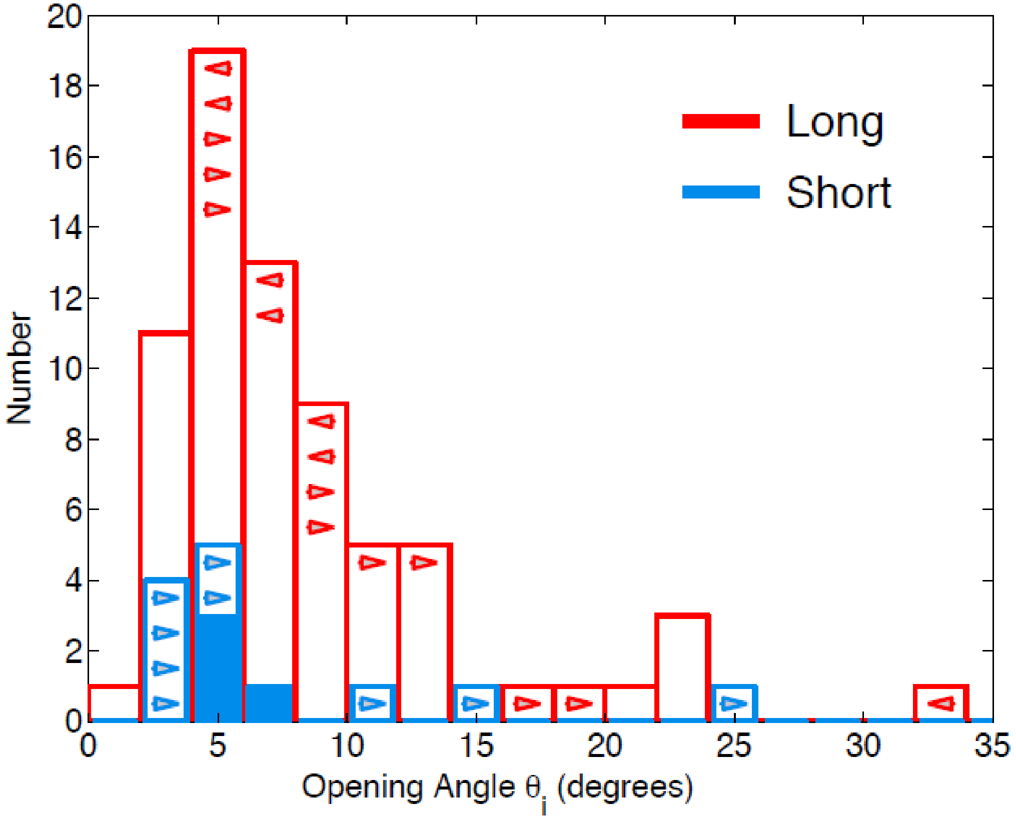
	B1820−11	J1829+2456
P [ms]	279.8	41.0
P_b [d]	357.8	1.18
e	0.79	0.14
$\log_{10}(\tau_c/[\mathrm{yr}])$	6.5	10.1
$\log_{10}(\tau_g/[\mathrm{yr}])$	15.8	10.8
Masses measured?	No	No



Author	NS-NS		BH-NS		Method
	LIGO	AdLIGO	LIGO	AdLIGO	
Kim et al. [143]	5e-3	27			Empirical
Nakar et al. [198]		~ 2		~ 20.0	SGRBs
Guetta & Stella [128]	7.0e-3	22	7.0e-2	220	SGRBs
Voss & Tauris [323]	6.0e-4	2.0	1.2e-3	4.0	Pop. Synth. – SFR
de Freitas Pacheco et al. [79]	8.0e-4	6.0			Pop. Synth. – SFR
Kalogera et al. [140]	1.0e-2	35	4.0e-3	20	Pop. Synth. – NS-NS
O'Shaughnessy et al. [218]	1.0e-2	10	1.0e-2	10	Pop. Synth. – NS-NS

Further good news ?

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

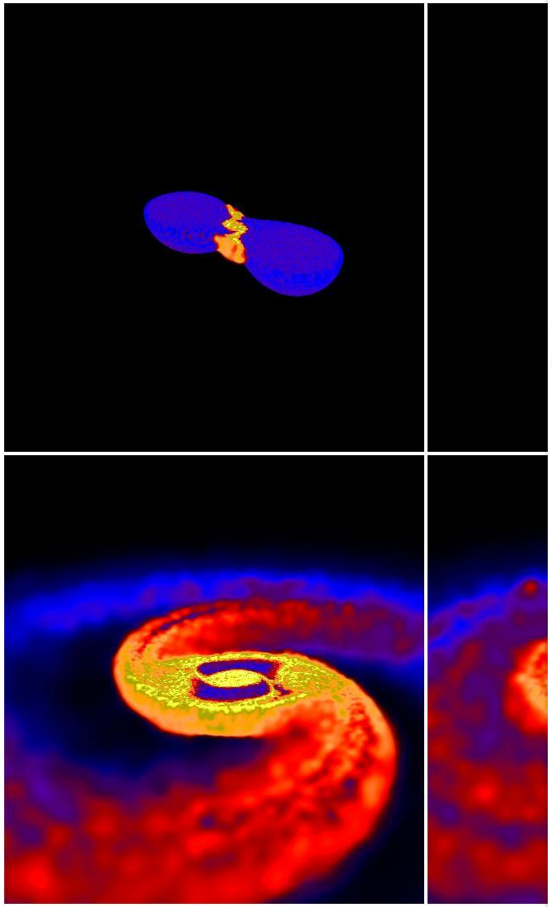


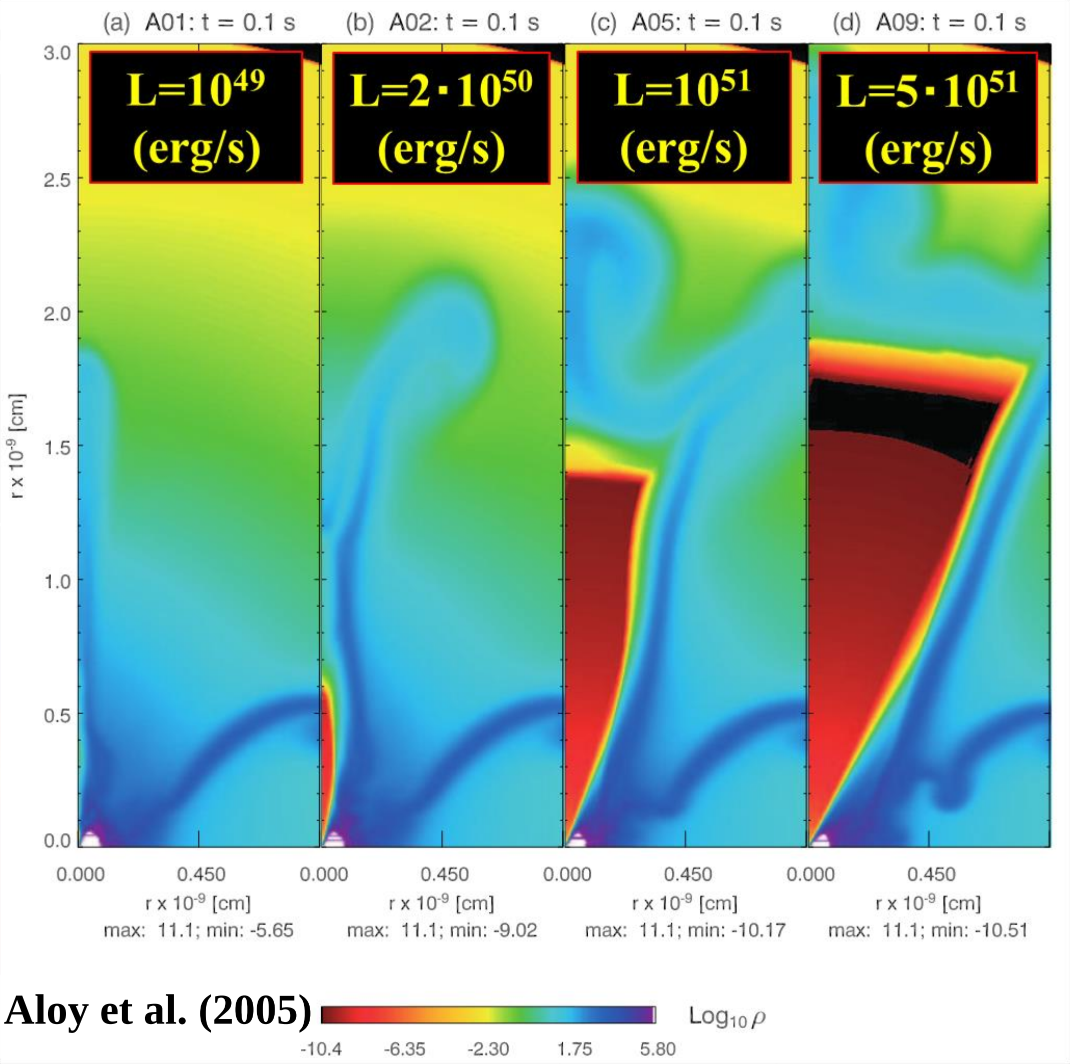
Berger (2013)
Fong et al. (2013)

Nakakura et al. (2014)

Jet collimation problem

- Jet collimation in SGRBs has been a long-standing problem
  - No matter above the pole regio

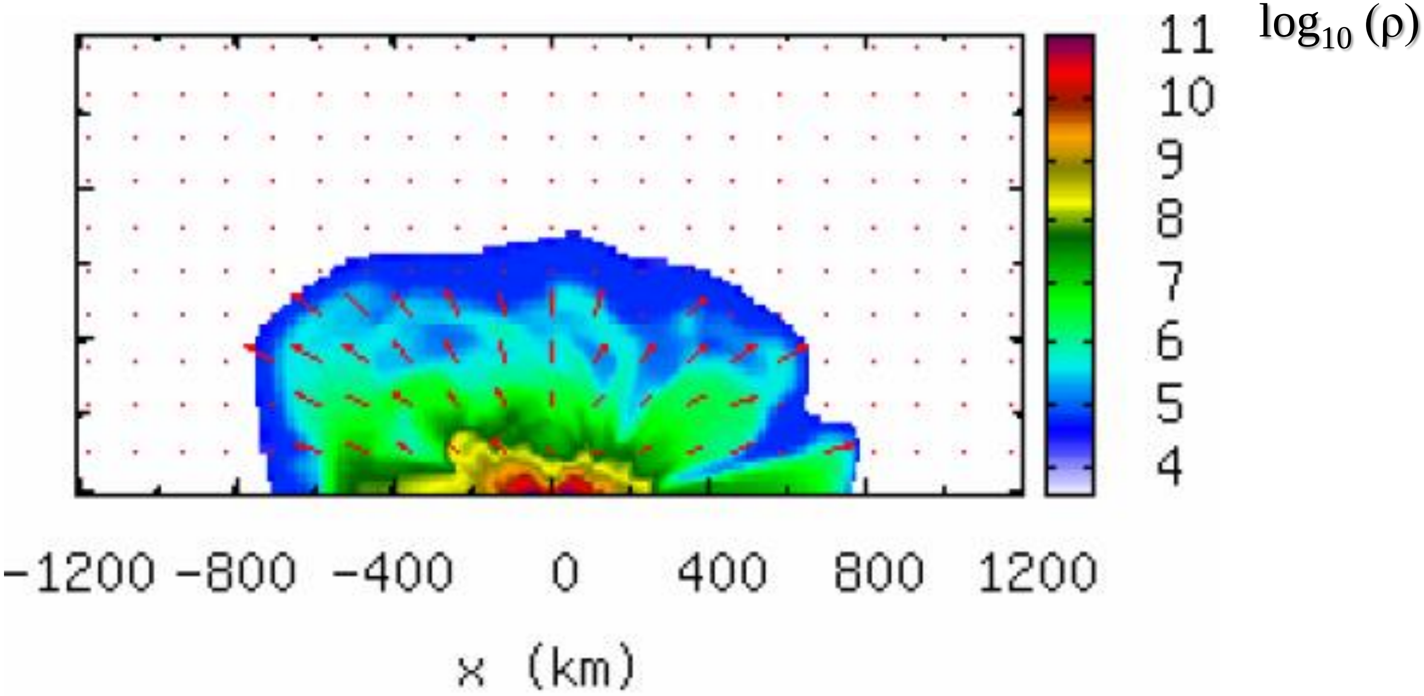




Aloy et al. (2005)

Jet collimation problem

- Jet collimation in SGRBs has been a long-standing problem
  - No mass 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)
  - Jet collimation may be achieved



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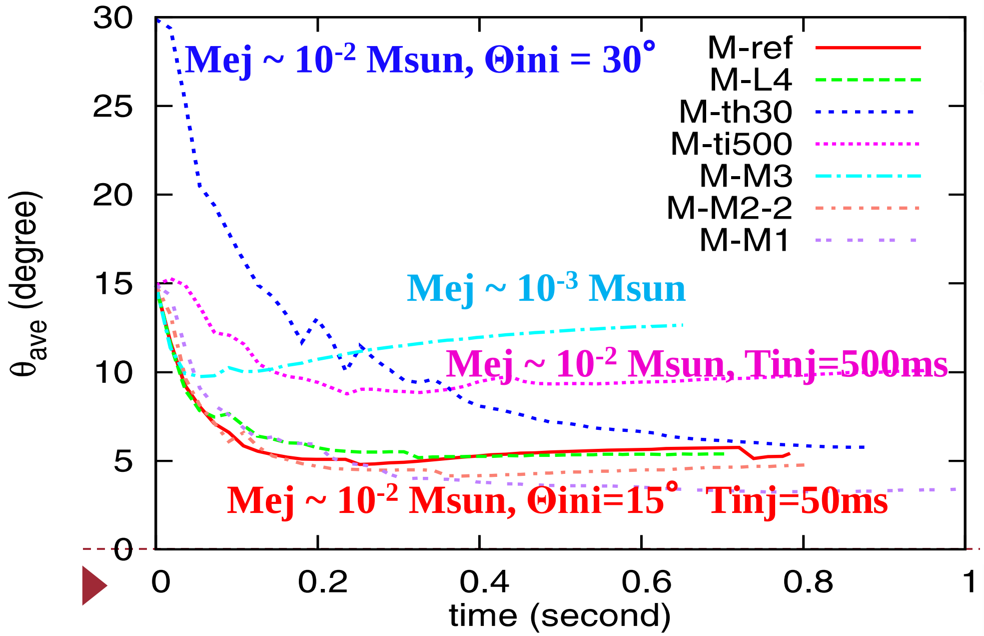
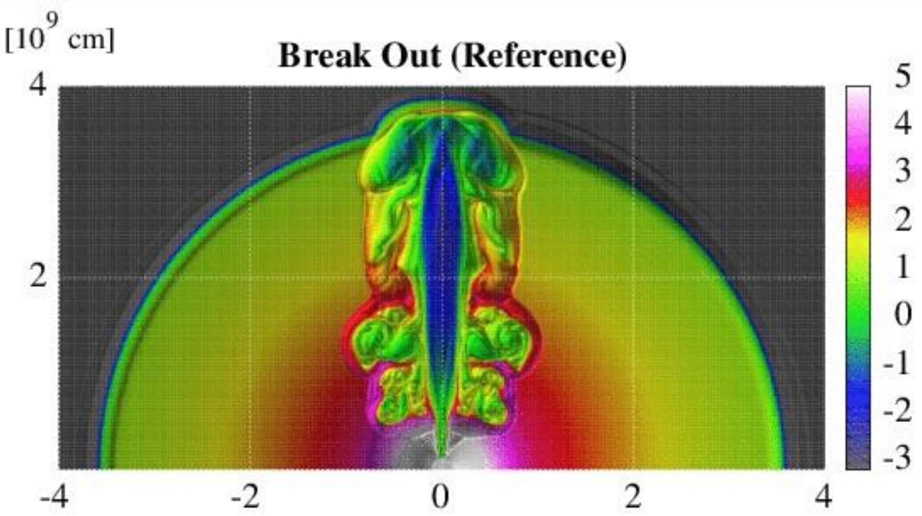
  - Jet collimation may be achieved
- How much mass is necessary ? Jet simulation by Nagakura et al. (2014)
  - **~ 0.01 Msun is necessary to explain GRB130603B (a kilonova candidate)**





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- How much mass is necessary ? Jet simulation by Nagakura et al. (2014)
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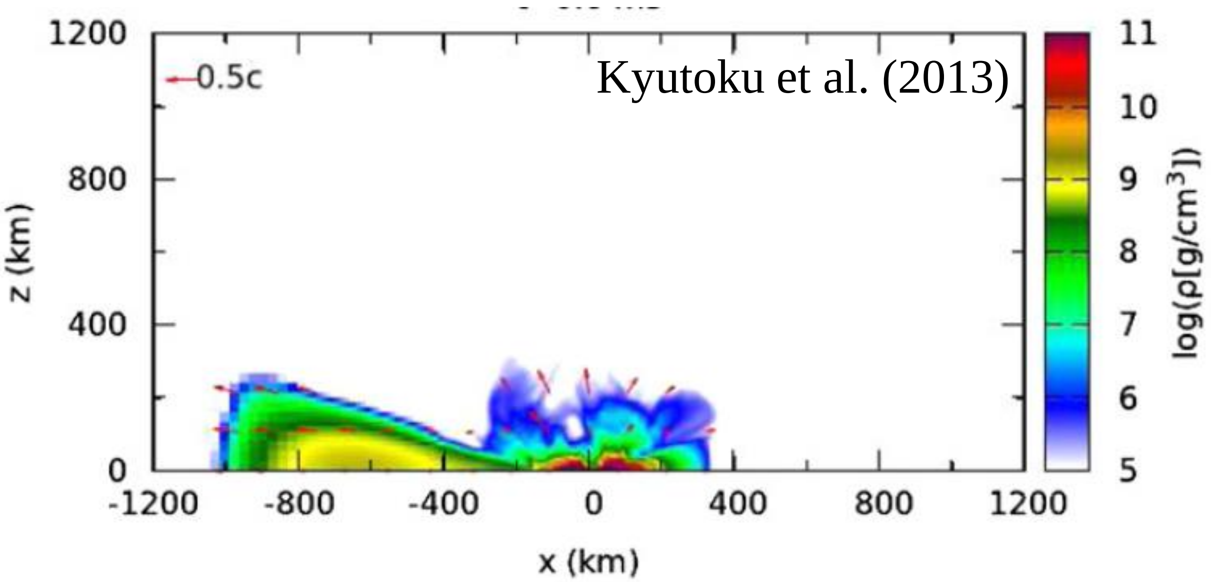
- **BH-NS:**

no *dynamical* mass ejection into the pole

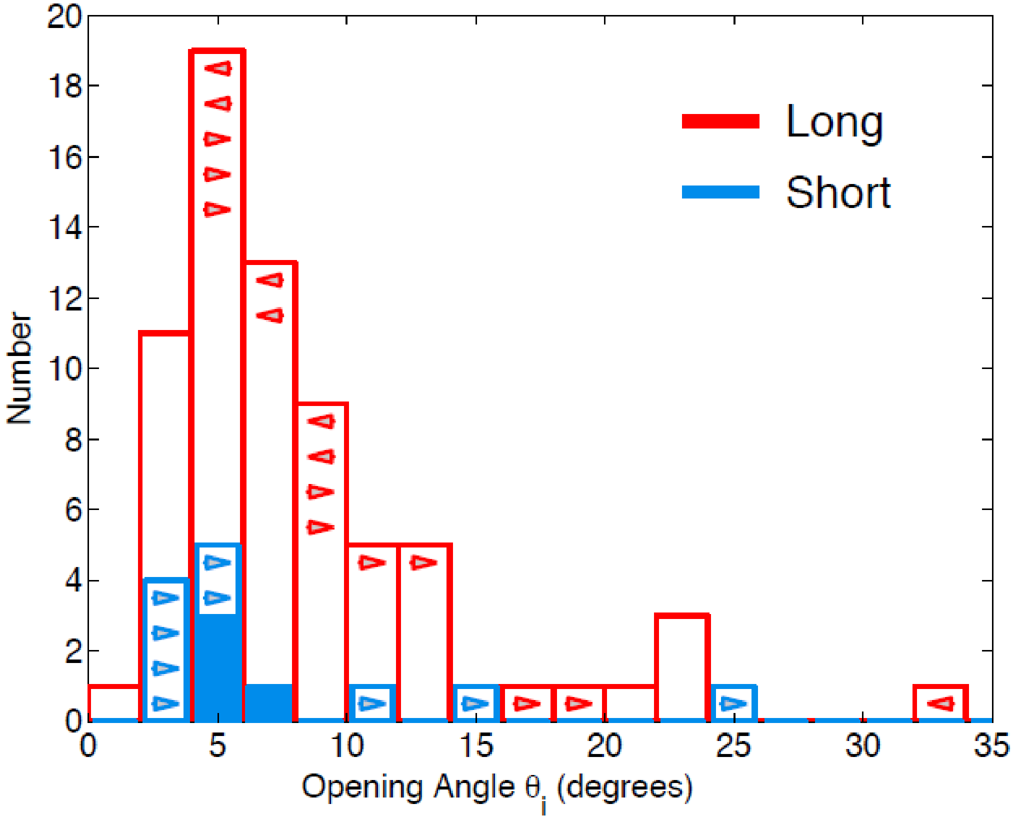
'Wind' components will be necessary



Kyutoku et al. (2013)

Further good news ?

- 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 ?

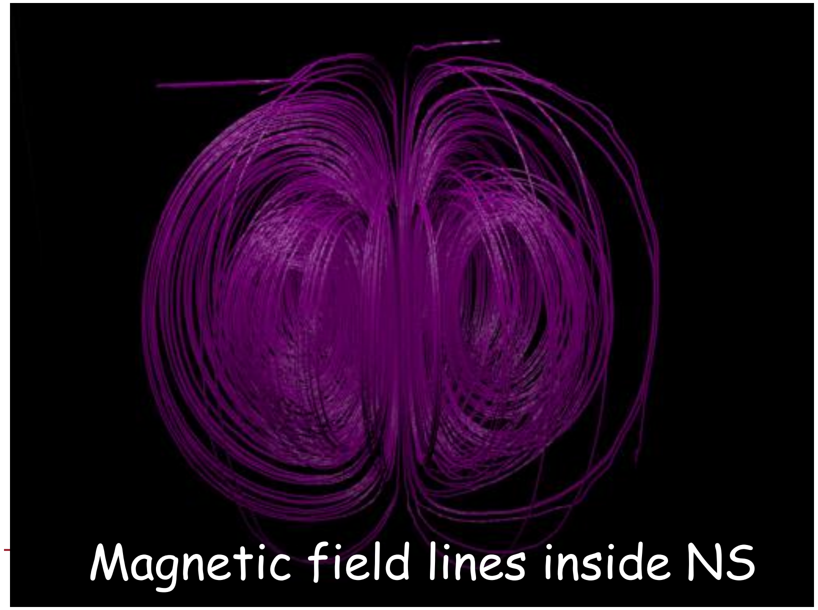


Berger (2013)
Fong et al. (2013)

Numerical Relativity simulation of magnetized BNS mergers (led by Kiuchi)

- High resolution Δx =70m （16,384 cores on K)
- Medium resolution Δx =110m（10,976 cores on K)
- Low resolution Δx =150m（XC30, FX10 etc.)
  - c.f. Radii of NS～10km, the highest resolution of the previous work is $\Delta x \approx 180$m (Liu et al. 08, Giacomazzo et al. 11, Anderson et al. 08)

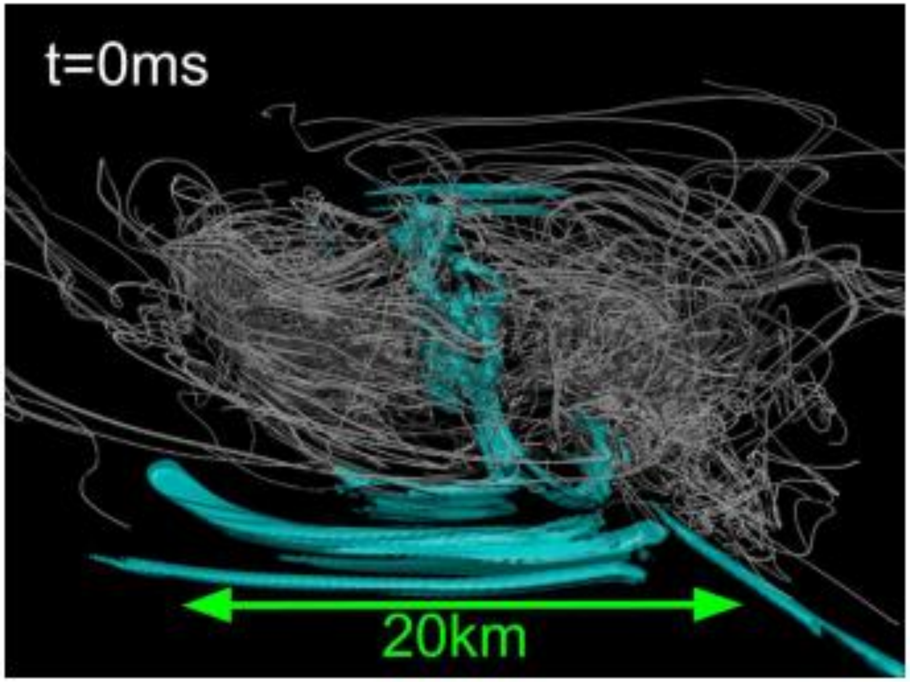
- <u>Fiducial model</u>
  - EOS : H4
    - Gledenning and Moszkoski 1991) $M_{max} \approx 2.03 M_\odot$
  - Mass : 1.4-1.4 $M_\odot$
  - B-field : 10^{15}G

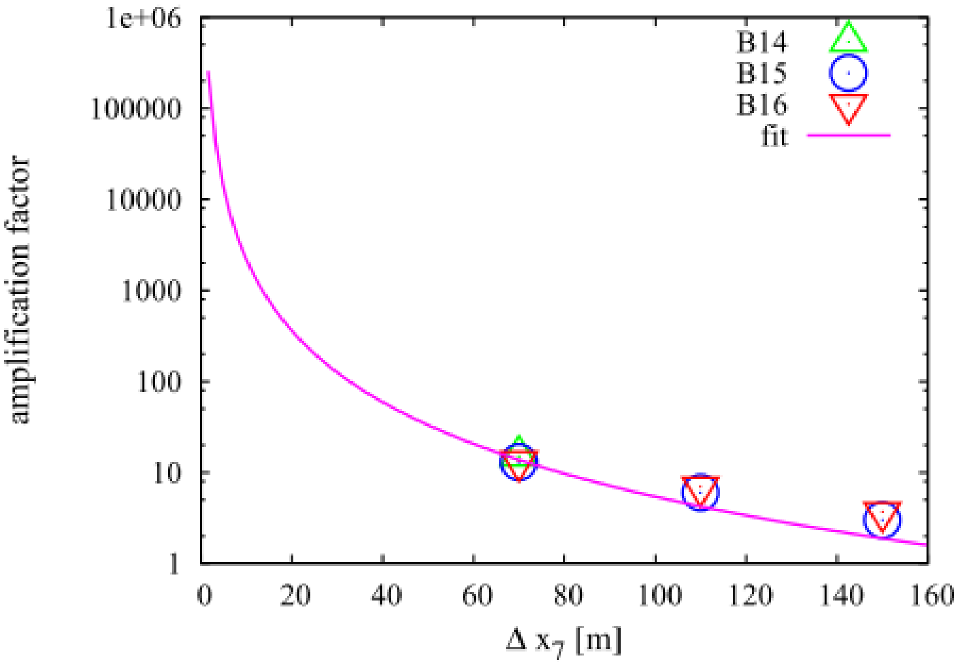


Magnetic field lines inside NS

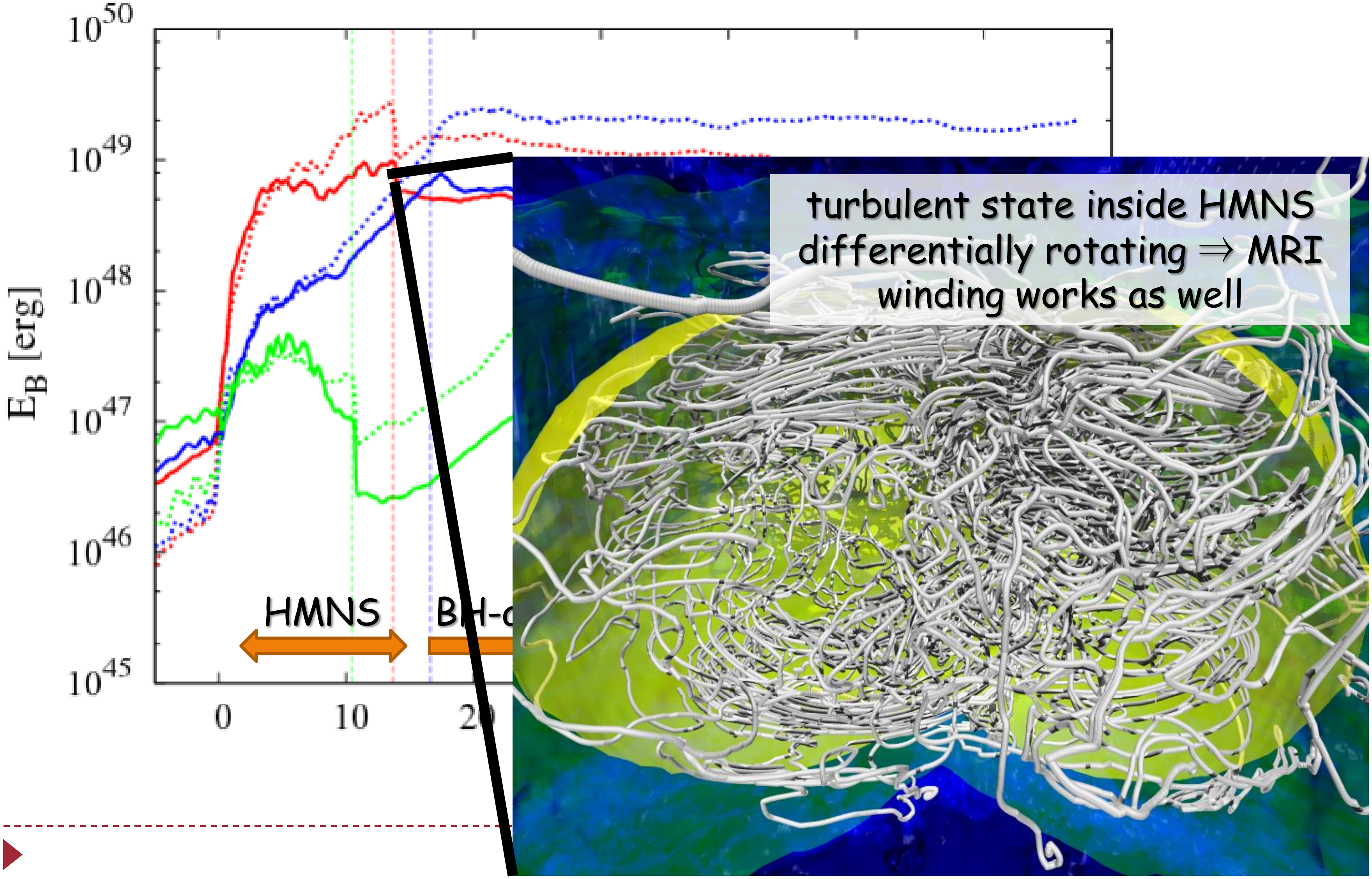
B-field amplification by KH-instability

- The smaller Δx is, the higher growth rate is.
- The amplification factor does not depend on the initial field strength
- It is consistent with the amplification mechanism due to the KH instability. (Obergaulinger et al. 10, Zrake and MacFadyen 13)





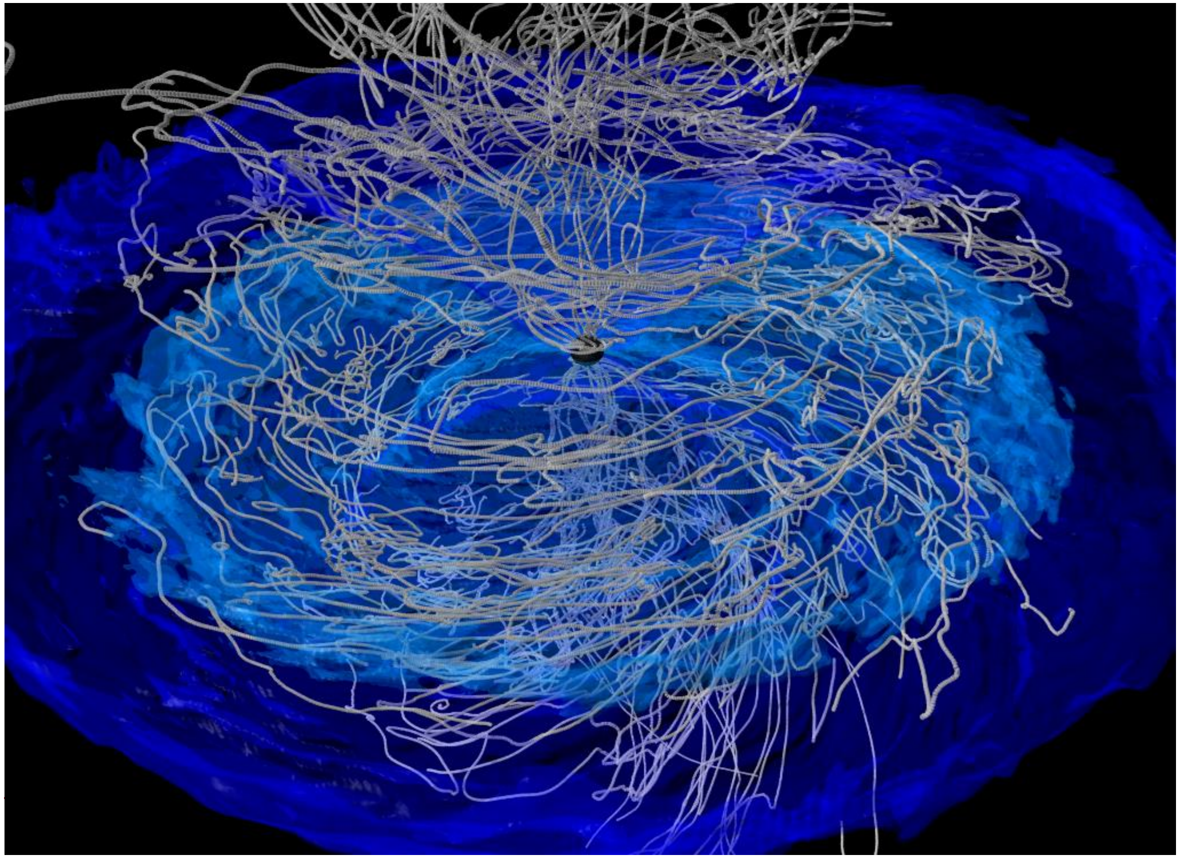
Evolution of B-field energies



turbulent state inside HMNS
differentially rotating ⇒ MRI
winding works as well

We do not observe Jet

- Ram pressure due to the fall back motion $\sim 10^{28}$ dyn/cm^2
  - Need $10^{14\text{-}15}$G in the vicinity of the torus surface
- Weak poloidal motion to build global poloidal fields



Moment formalism

Definition of Moment

$$\boxed{M_{(\nu)}{}^{a_1\cdots a_k}(x^b)=\int\frac{f(x^b,p^b)\delta(\nu'-\nu)}{\nu'^{k-2}}p^{a_1}\cdots p^{a_k}dV_p}$$

$\nu=-u^a p_a$: energy seen by an arbitrary observer u^a

$p^a=\nu(u^a+l^a)$: decomposition of momentum

$l_a u^a=0,\quad l_a l^a=1$

$$\boxed{M_{(\nu)}{}^{a_1\cdots a_k}(x^b)=\nu^3\int f(\nu,\Omega)(u^{a_1}+l^{a_1})\cdots(u^{a_k}+l^{a_k})d\Omega}$$

Boltzmann equation ⇔

$$\boxed{\begin{aligned}&\nabla_b M_{(\nu)}^{a_1\cdots a_k b}-\frac{\partial}{\partial\nu}\left(\nu M_{(\nu)}^{a_1\cdots a_k bc}\nabla_c u_b\right)\\&\quad-(k-1)M_{(\nu)}^{a_1\cdots a_k bc}\nabla_c u_b\;=\;S_{(\nu)}^{a_1\cdots a_k}\end{aligned}}$$

- **Infinite hierarchy series**
  ⇒ need Truncation
- **Source terms given in the fluid rest frame**

Truncation at 1st order Moment

$$\boxed{\nabla_b M_{(\nu)}^{ab}-\frac{\partial}{\partial\nu}\left(\nu M_{(\nu)}^{abc}\nabla_c u_b\right)=S_{(\nu)}^{a}}$$

$$\boxed{\begin{aligned}&M_{(\nu)}^{ab}=J_{(\nu)}u^a u^b+H_{(\nu)}^{(a}u^{b)}+L_{(\nu)}^{ab}\\&M_{(\nu)}^{abc}=J_{(\nu)}u^a u^b u^c+H_{(\nu)}^{(a}u^b u^{c)}+L_{(\nu)}^{(ab}u^{c)}+N_{(\nu)}^{abc}\\&J\equiv\int\nu^3 f(\nu,\Omega)d\nu\,d\Omega\qquad H^a\equiv\int\nu^3 f(\nu,\Omega)\;l^a d\nu\,d\Omega\\&L^{ab}\equiv\int\nu^3 f(\nu,\Omega)\;l^a l^b d\nu\,d\Omega\qquad N^{abc}\equiv\int\nu^3 f(\nu,\Omega)\;l^a l^b l^c d\nu\,d\Omega\end{aligned}}$$

Energy Integration

$$\boxed{\nabla_b M^{ab}=S^a}$$

$$\boxed{\begin{aligned}T_{ab}^{\nu}=M_{ab}&=Ju_a u_b+H_a u_b+H_b u_a+L_{ab}\\&=En_a n_b+F_a n_b+F_b n_a+P_{ab}\end{aligned}}$$

- **Only *0th and 1st order moments* evolved**
- **Introduce *closure relation for 2nd (and 3rd) order moment***

Closure relation

- **Optically Thick**
  - assume small 'anisotropy' of *f*(x,t)

$$\boxed{f(\nu,\Omega,x^c) = f_0(\nu,x^c) + f_1^{\,a}(\nu,x^c)l_a + f_2^{\,ab}(\nu,x^c)l_a l_b}$$

$$\begin{aligned} J_{(\nu)} &= 4\pi\nu^3 f_0 \\ H^a_{(\nu)} &= 4\pi\nu^3 f_1^{\,a} \\ L^{ab}_{(\nu)} &= \frac{1}{3}J_{(\nu)}h^{ab} + \frac{8\pi}{15}\nu^3 f_2^{\,ab} \\ N^{abc}_{(\nu)} &= \frac{1}{5}H^{(a}_{(\nu)}h^{bc)} \end{aligned}$$

$$\boxed{L^{ab} = \frac{1}{3}J\ h^{ab}}$$

Eddington Closure

$$h_{ab} = g_{ab} + u_a u_b$$

- **Optically Thin** *(Thanks to 村主)*
  - assume 'definite direction' of *f*(x,t)

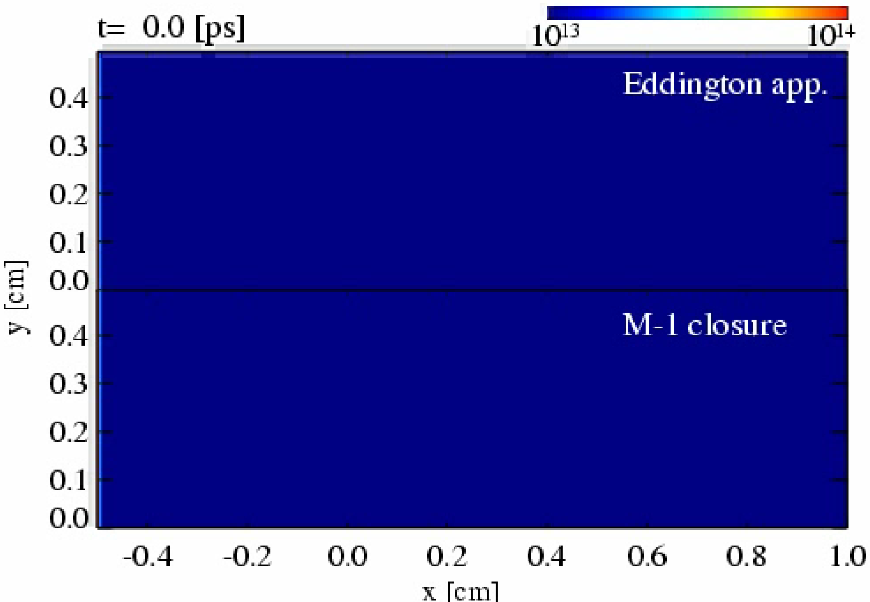
$$\boxed{f(\nu,\Omega,x^c) = 4\pi\ f_{\mathrm{f}}(\nu,x^c)\delta(\Omega-\Omega_{\mathrm{f}})}$$

$$\begin{aligned} J_{(\nu)} &= 4\pi\nu^3 f_{\mathrm{f}} \\ H^a_{(\nu)} &= 4\pi\nu^3 f_{\mathrm{f}} l^a_{\mathrm{f}} \\ L^{ab}_{(\nu)} &= 4\pi\nu^3 f_{\mathrm{f}} l^a_{\mathrm{f}} l^b_{\mathrm{f}} \\ N^{abc}_{(\nu)} &= 4\pi\nu^3 f_{\mathrm{f}} l^a_{\mathrm{f}} l^b_{\mathrm{f}} l^c_{\mathrm{f}} \end{aligned}$$

$$\boxed{L^{ab}_{(\nu)} = J_{(\nu)}\frac{H^a_{(\nu)}H^b_{(\nu)}}{|H^c_{(\nu)}|^2}}$$

- Optically thick and thin regions are smoothly connected using variable Eddington factor (*Livermore (1984)*)

$$\boxed{P_{ab} = \gamma^c_a\gamma^d_b T^{(\nu)}_{cd} = \gamma^c_a\gamma^d_b\left(Ju_c u_d + H_{(c}u_{d)} + L_{cd}\right)}$$



Takahashi, Ohsuga, Sekiguchi, Inoue, & Tomida

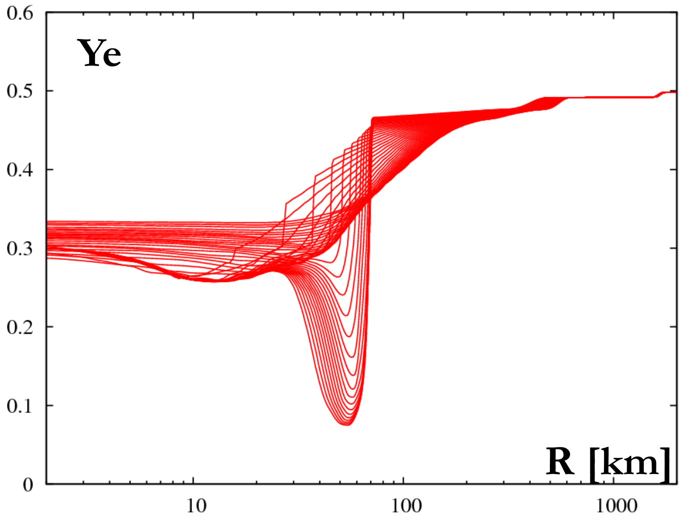
Source terms

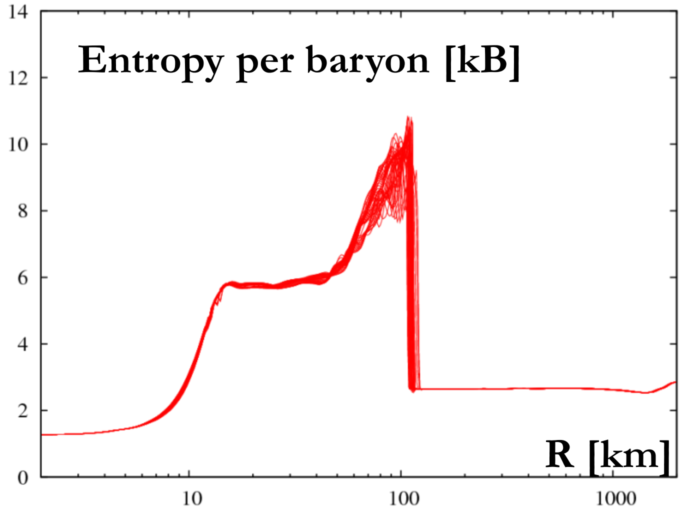
$$\boxed{S = \dot{Q} \sim \frac{Q}{t_{\mathrm{diff}}}, \quad t_{\mathrm{diff}} \sim \frac{L\tau}{c}}$$

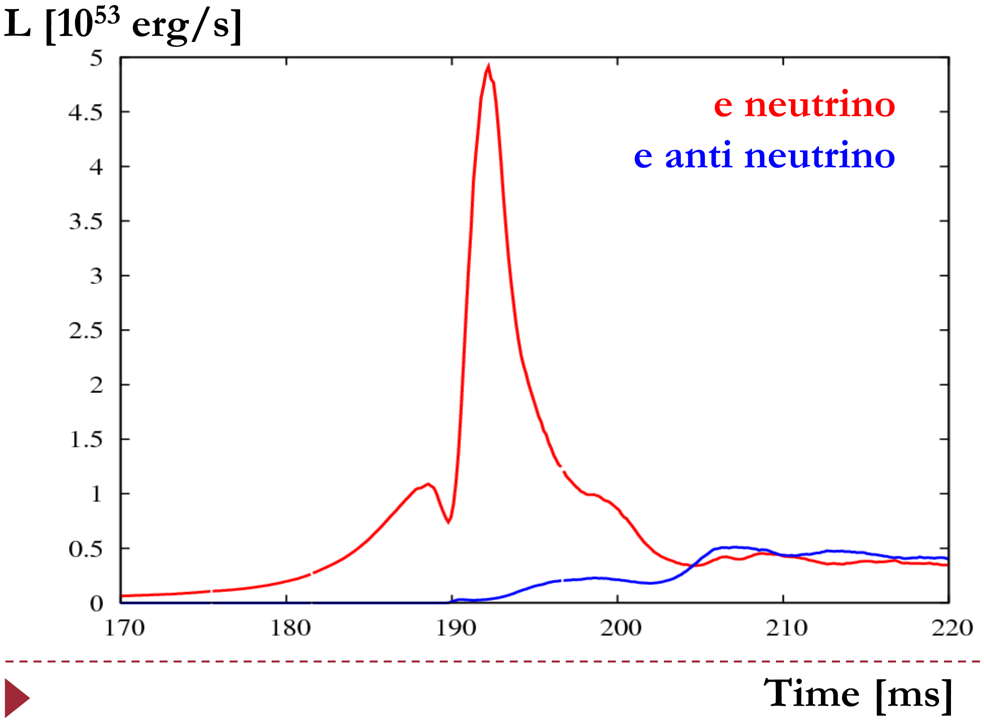
- Leakage scheme (Sekiguchi 2010)
  - Source terms is given using diffusion time in optically thick region
    - Appropriate connection between diffusion and streaming limits
- Leakage scheme + absorption (Kuroda et al. 2012)
  - Neutrinos leak out from the core are absorbed in outer region (ν-heating)
  - $S^{a}_{(\nu\text{-heating})} = \kappa_{(\nu)} \left[(J^{\beta\text{-eq}} - J) u^{a} - H^{a} \right]$
- Implicit transfer

Leakage + Neutrino heating

- Neutrino burst emission can be followed
  - Lν calculated from neutrino radiation field
- Neutrino heating does occur (at least qualitatively)
  - Entropy increases in the gain region



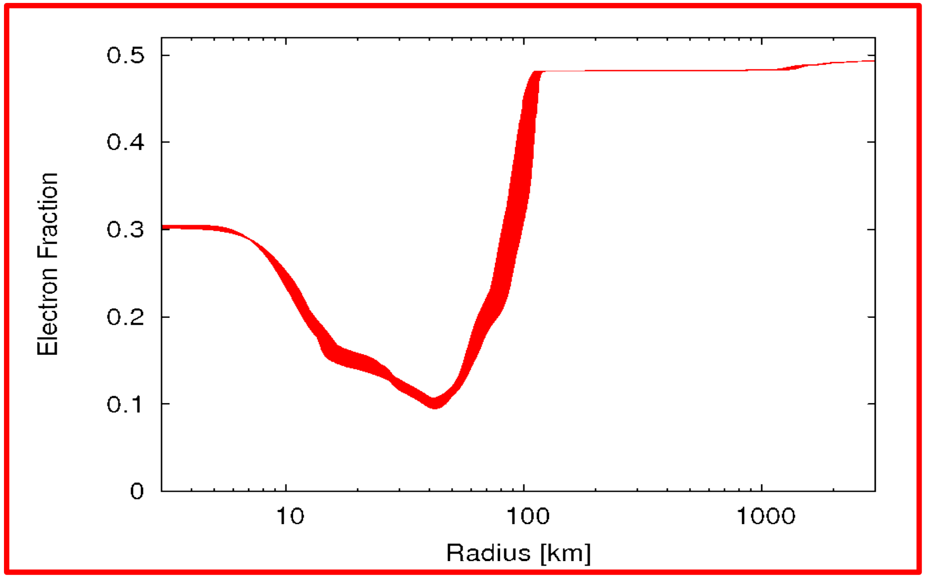


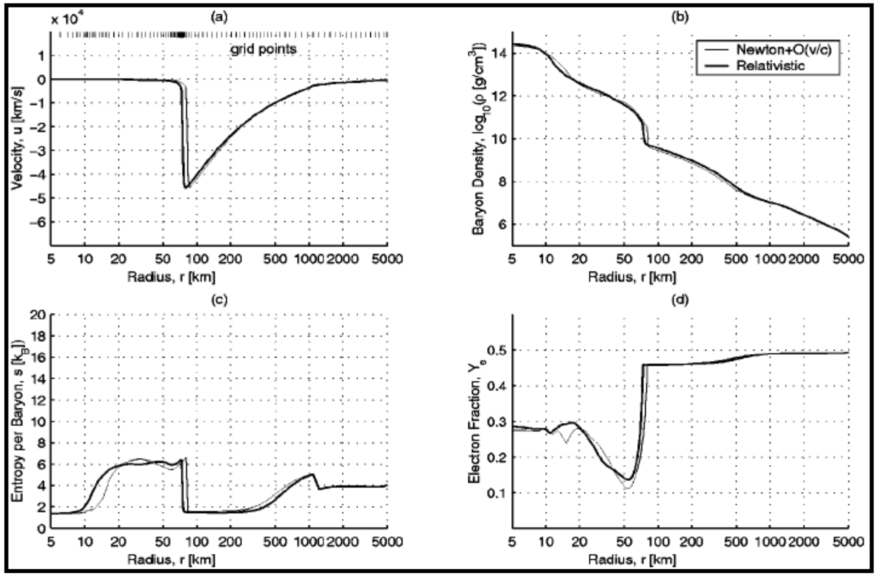


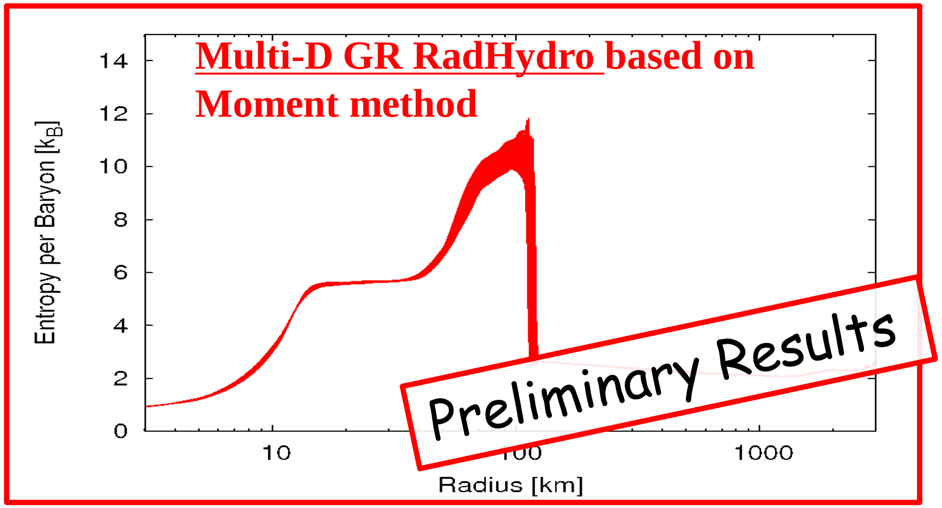
Numerical Issues

- Recovery of diffusion limit
  - Godunov scheme may not provide correct diffusion flux (Sekora & Stone 2010)
  - ***Numerical fluxes are modified (Audit et al. 2002)***
    - Adopted in MPA group (Obergalinger 2011), Caltech group (O'Connor & Ott 2012),..
    - Some group adopt flux-limited-diffusion-approximation-like procedure
- Coupling radiation with hydrodynamics
  - Hydro and radiation must be 'tuned' to achieve (beta-)equilibrium
    - Hydro ⇔ radiation interation may be required
  - ***Implicit-Explicit Runge-Kutta scheme is adopted (Pareschi & Russo 2005)***
    - which may not provide exact equilibrium but is rather stable
      - Solving Einstein equation in spherical coordinate (MPA group)
      - GR Resistive MHD (Bucciantini & Del Zanna 2012; Dionysopoulou et al. 2012)
      - GR force-free (Alic et al. 2012)
      - GR RadiationHydro (Roedig et al. 2012)

Implicit transfer : Stellar core collapse

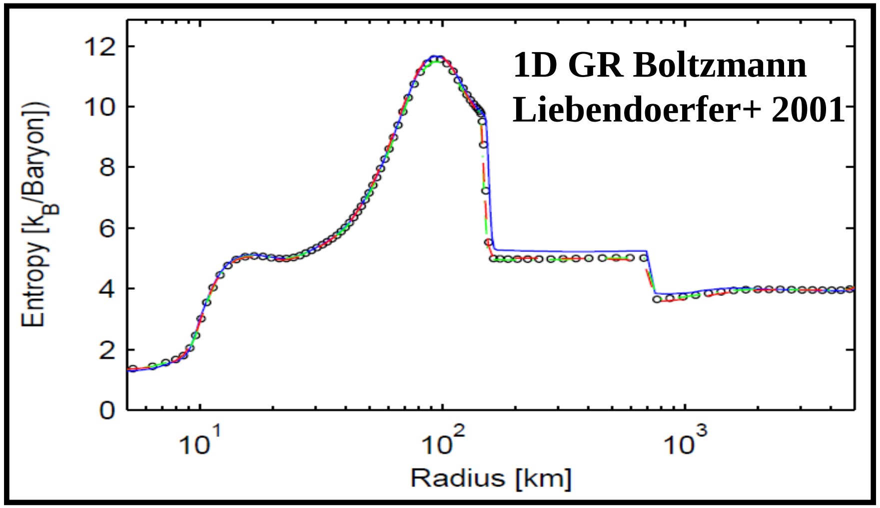






Multi-D GR RadHydro based on Moment method

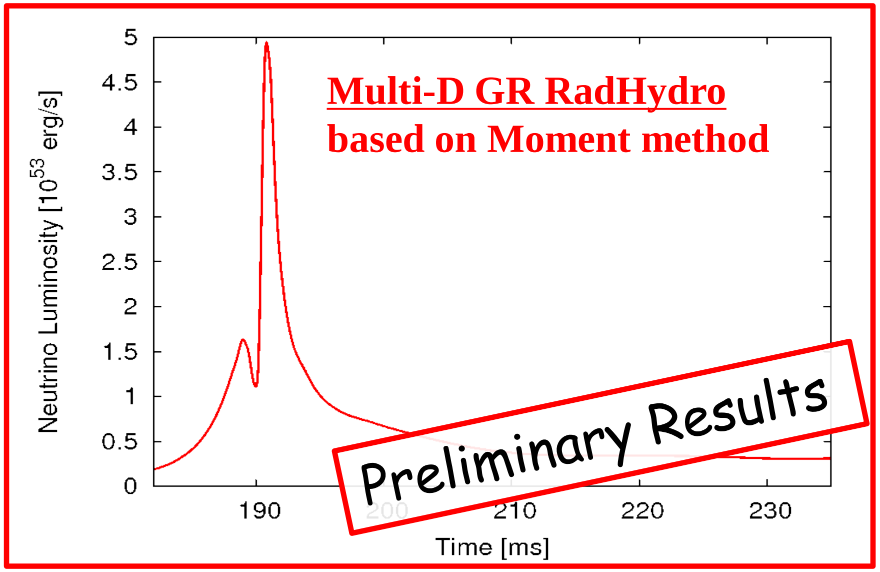
Preliminary Results



1D GR Boltzmann Liebendoerfer+ 2001

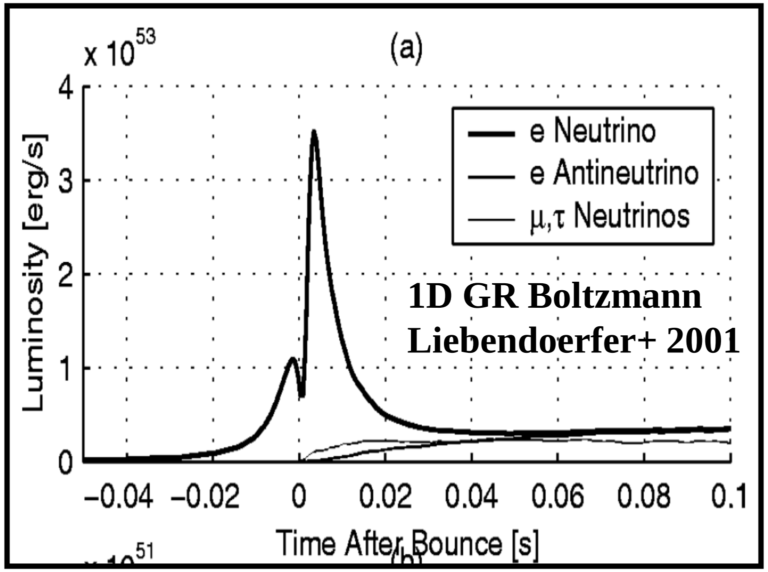
Implicit transfer : Stellar core collapse

- Qualitatively (or semi-quantitatively) reproduce results in 1D GR Boltzmann.
- Evolution scheme : implicit-explicit (IMEX) Runge-Kutta
  - Pareschi & Russo J. Sci. Comp. 25, 129 (2005)



Multi-D GR RadHydro based on Moment method

Preliminary Results



1D GR Boltzmann Liebendoerfer+ 2001