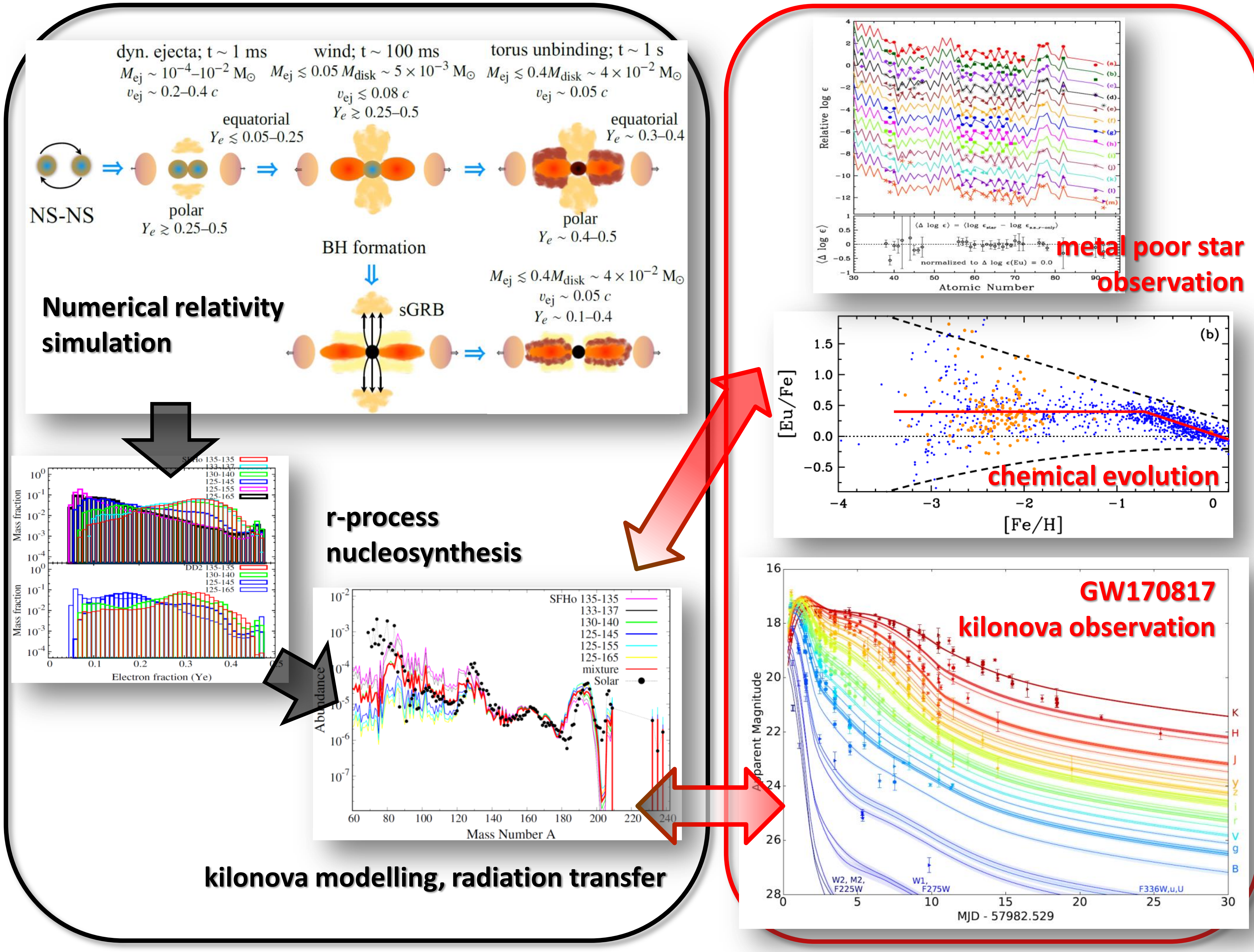
基研研究会「原子核物理でつむぐrプロセス」

中性子星合体とrプロセス元素合成

関口 雄一郎（東邦大学）



dyn. ejecta; t ~ 1 ms
$M_{ej} \sim 10^{-4}$–10^{-2} $M_\odot$
$v_{ej} \sim 0.2$–$0.4\,c$
wind; t ~ 100 ms
$M_{ej} \lesssim 0.05\,M_{disk} \sim 5 \times 10^{-3}$ $M_\odot$
$v_{ej} \lesssim 0.08\,c$
$Y_e \gtrsim 0.25$–0.5
torus unbinding; t ~ 1 s
$M_{ej} \lesssim 0.4 M_{disk} \sim 4 \times 10^{-2}$ $M_\odot$
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$Y_e \lesssim 0.05$–0.25
equatorial
$Y_e \sim 0.3$–0.4
NS-NS
polar
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BH formation
sGRB
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SFHo 135-135
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125-145
125-155
125-165
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mixture
Solar
Abundance
Mass Number A
kilonova modelling, radiation transfer
Relative log ε
⟨Δ log ε⟩
normalized to Δ log ε(Eu) = 0.0
Atomic Number
metal poor star observation
(b)
[Eu/Fe]
[Fe/H]
chemical evolution
GW170817 kilonova observation
Apparent Magnitude
MJD - 57982.529
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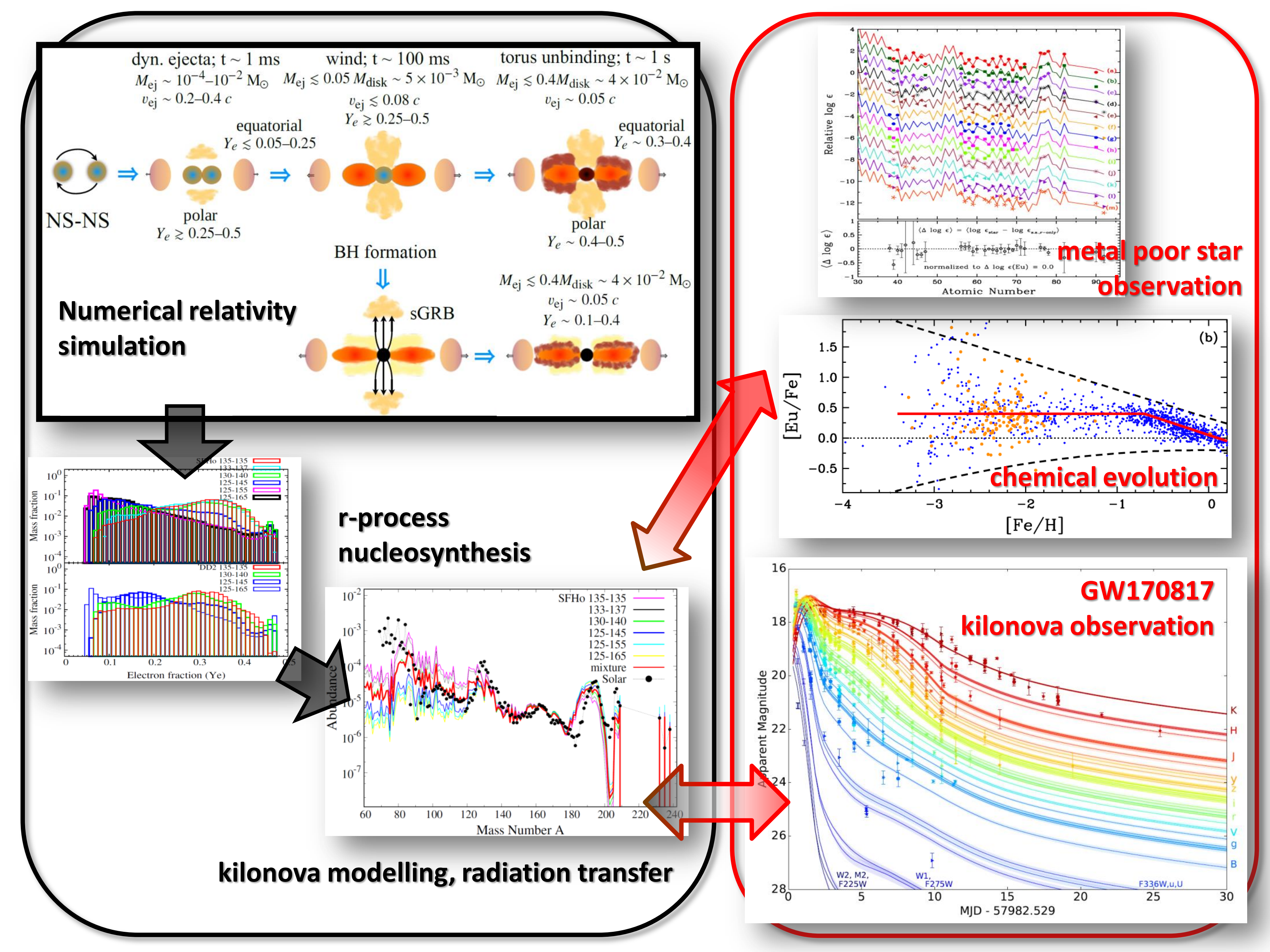
W2, M2, F225W
W1, F275W
F336W,u,U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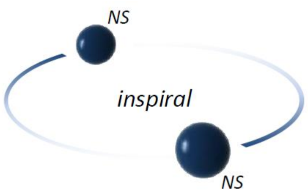
Shibata et al. 2005,2006
Hotokezaka et al. 2013

連星中性子星の進化



インスパイラル
f ~ 0.1mHz to several 100 Hz

重力波放射により進化

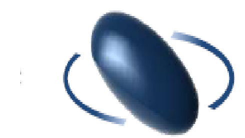
↓

軌道半径 ~ 中性子星半径
潮汐変形
f ~ several 100 Hz to 1 kHz

↓

合体
f ~ a few kHz

→



大質量中性子星
f ~ a few kHz

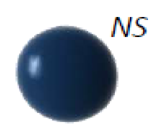
質量が大きい場合
$M \gtrsim 3.2 M_{\mathrm{sun}}$
状態方程式が柔らかい

↓

BH + Torus

質量が小さい場合
$M \lesssim 2.5 M_{\mathrm{sun}}$
状態方程式が硬い場合

↓



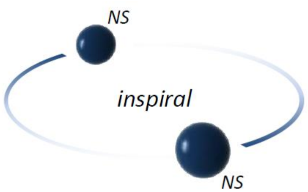
高速回転パルサー

Typical scenario for NS-NS merger

- Kinematical (using General Relativistic effect of Shapiro time delay) measurement of massive neutron star mass
  - PSR J1614-2230 : $\mathbf{1.97 \pm 0.04}M_\odot$ (Demorest et al. 2010), updated to $\mathbf{1.908 \pm 0.016}M_\odot$ (Arzoumanian et al. 2018)
  - PSR J0740+6620: $\mathbf{2.17^{+0.11}_{-0.10}}M_\odot$ 68.3% C.L. (Cromartie et al. 2019)
- Typical total mass of (compact) NS-NS : $\mathbf{2.7 - 2.75}M_\odot$
- Numerical relativity simulations have shown that the typical remnant soon after the merger is a **massive NS, not BH**
  e.g, Shibata et al. 2006; Hotokezaka et al. 2013
- GW170817 : **total mass 2.74Msun**
  - Massive NS formation, maybe followed by later collapse to a BH ?
  - No well-established activity from long-lived massive NS

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

連星中性子星の進化



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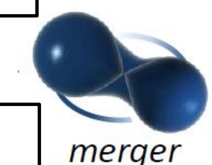
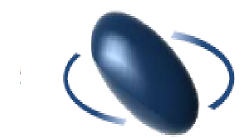
GW170817 の場合



合体
f ~ a few kHz



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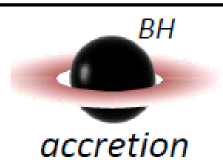
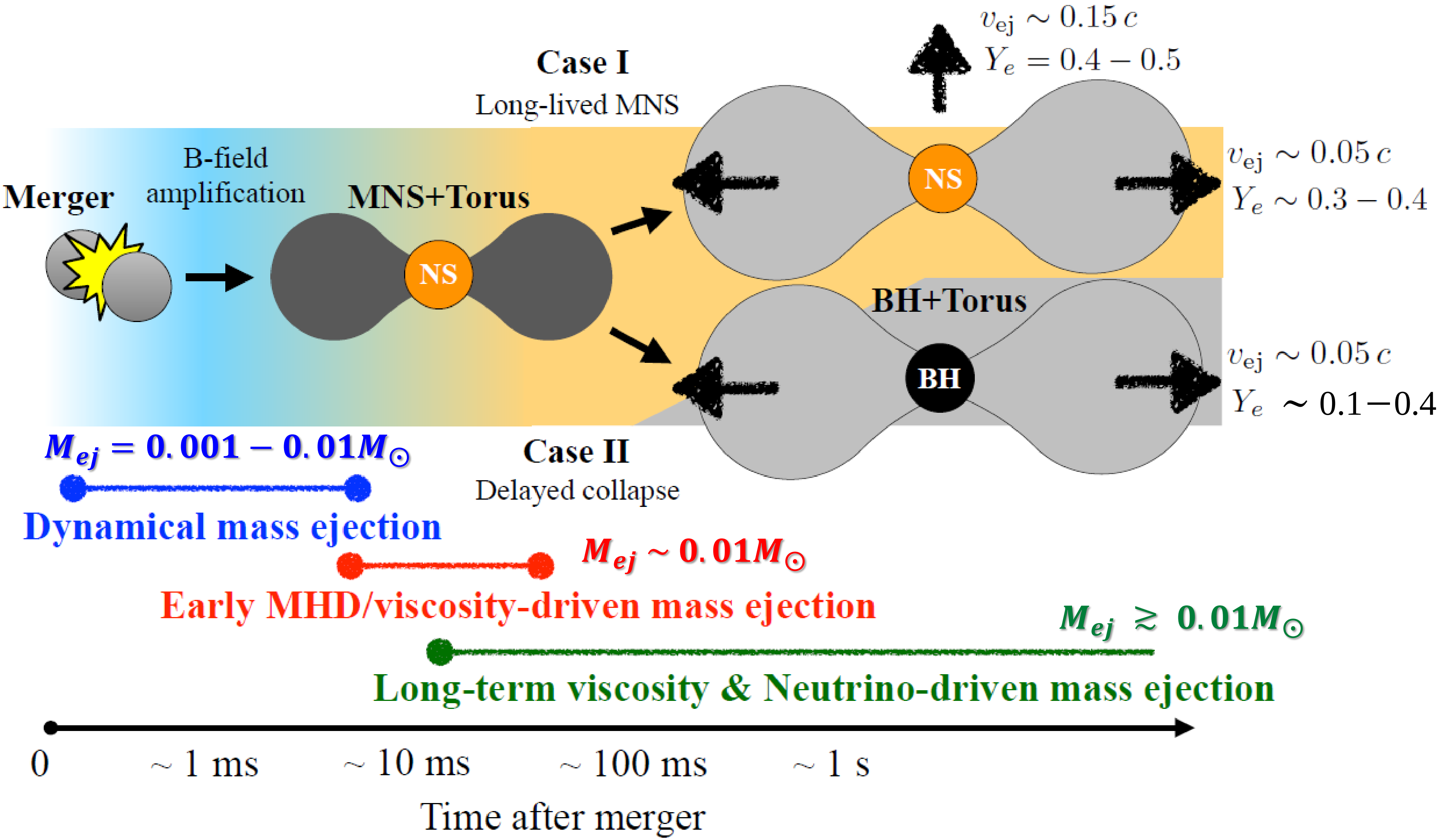


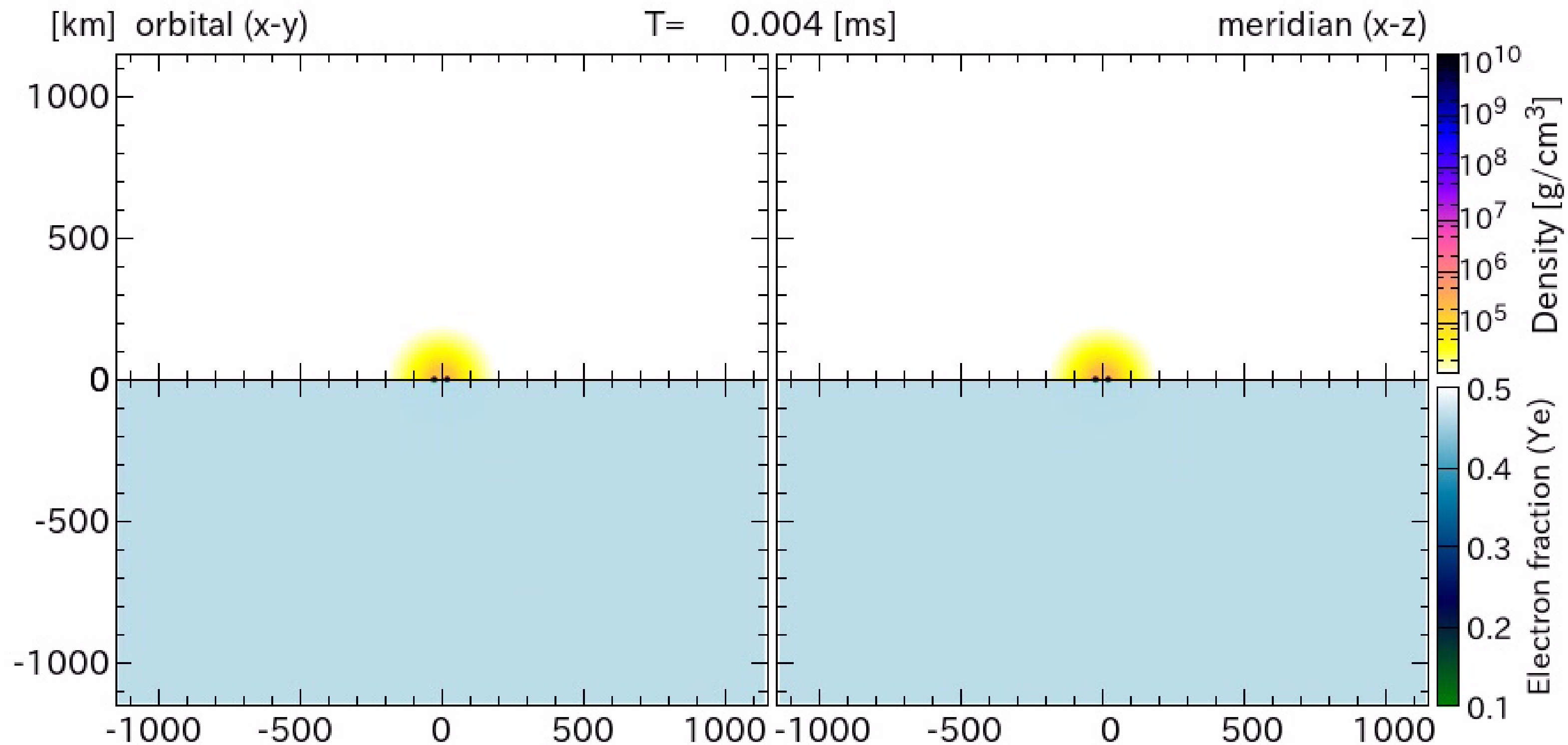
高速回転パルサー

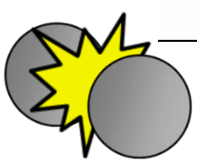
Mass ejection from NS-NS merger



Fujibayashi et al. (2018)

Mass ejection mechanisms : Dynamical





Merger

- Due to tidal force and shock heating
- Relatively well studied (e.g., EOS dependence)

Dynamical-ejection

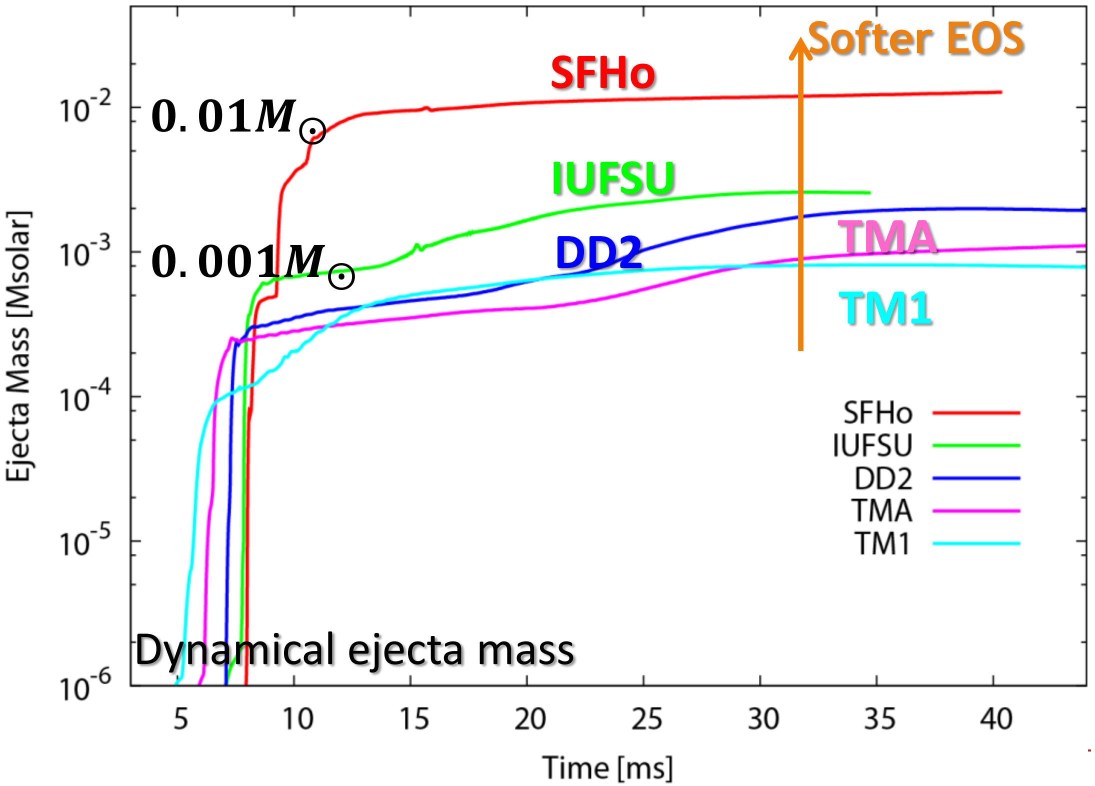
0 ~ 1 ms ~ 10 ms ~ 100 ms ~ 1 s ~ 10 s

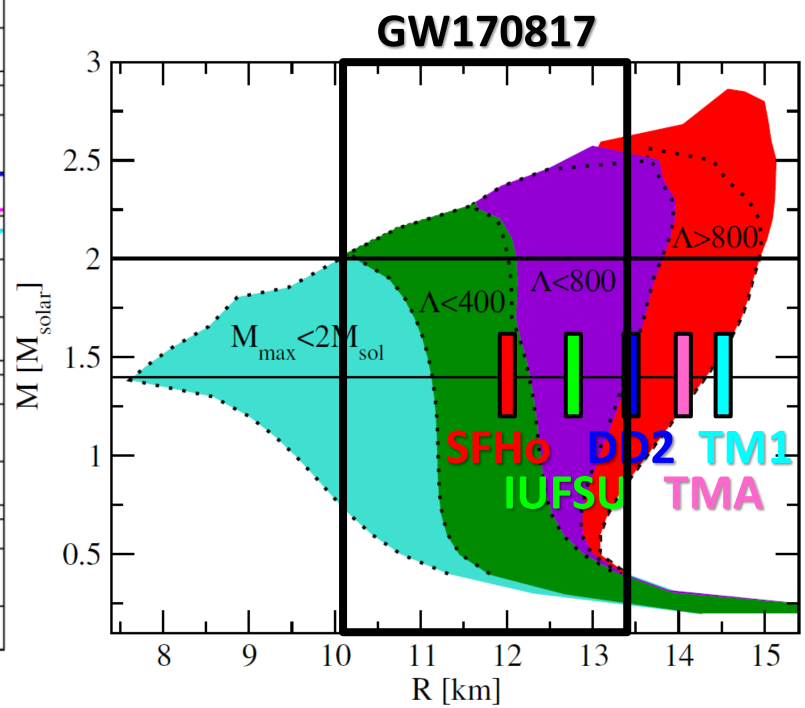
Sekiguchi et al. (2016) : DD2 125-145 model

See also Rosswog et al. 2004; Bauswein et al. 2013; Lehner et al. 2016; Foucart et al. 2017; Radice et al. 2018

Properties of **Dynamical** ejecta : mass

- Dynamical ejecta mass depends strongly on NS equation of state (EOS)
  - $M_{\rm ej,dyn} \sim 0.001 - 0.01 M_\odot$: larger for softer EOS
    - But $M_{\rm ej,dyn}$ is very small if BH is directly formed after the merger
  - **$M_{\rm ej,dyn} \sim 0.01 M_\odot$ only for Soft EOS like SFHo ($R_{1.4} \approx 12$km, $\Lambda < 400$)**



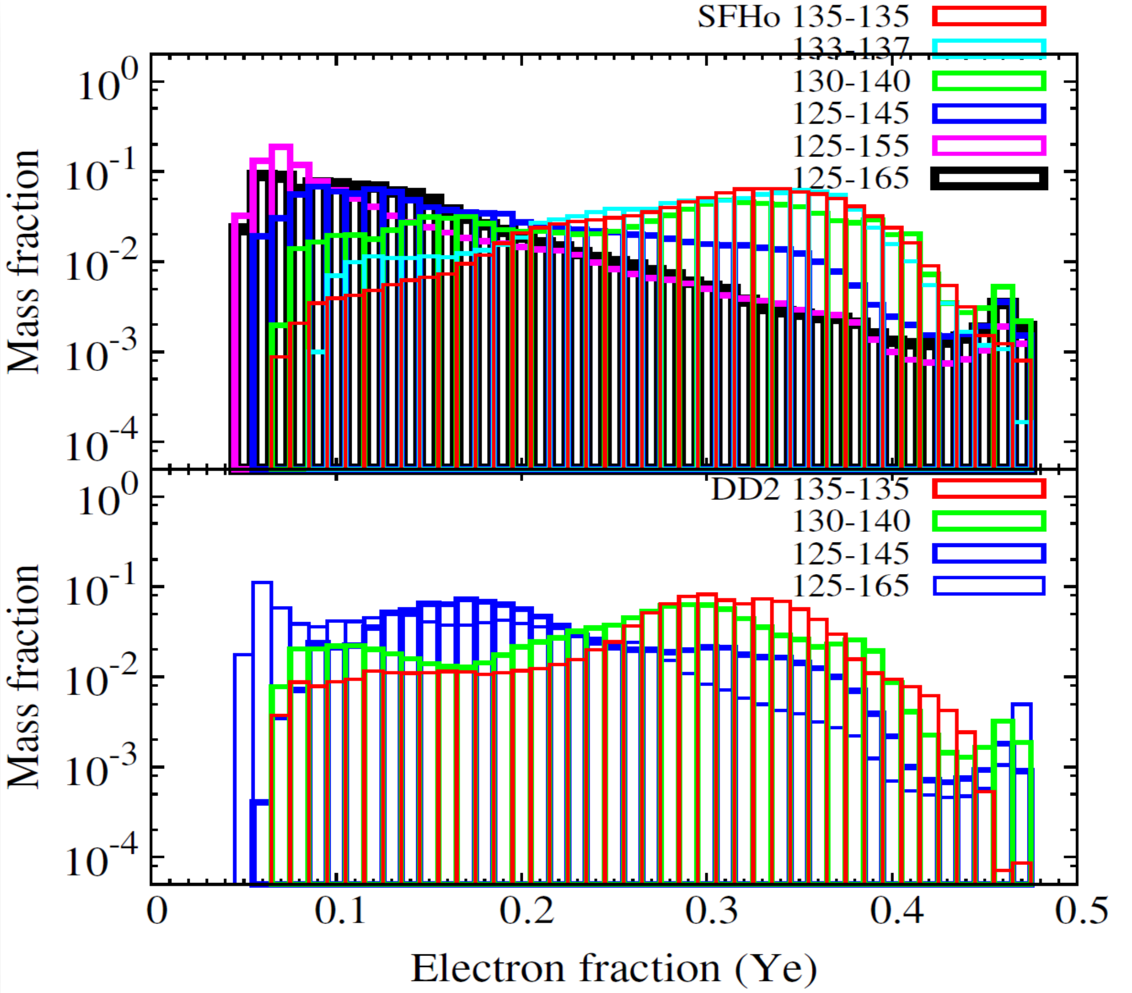


Annala et al. (2018)

Properties of **Dynamical** ejecta : Ye

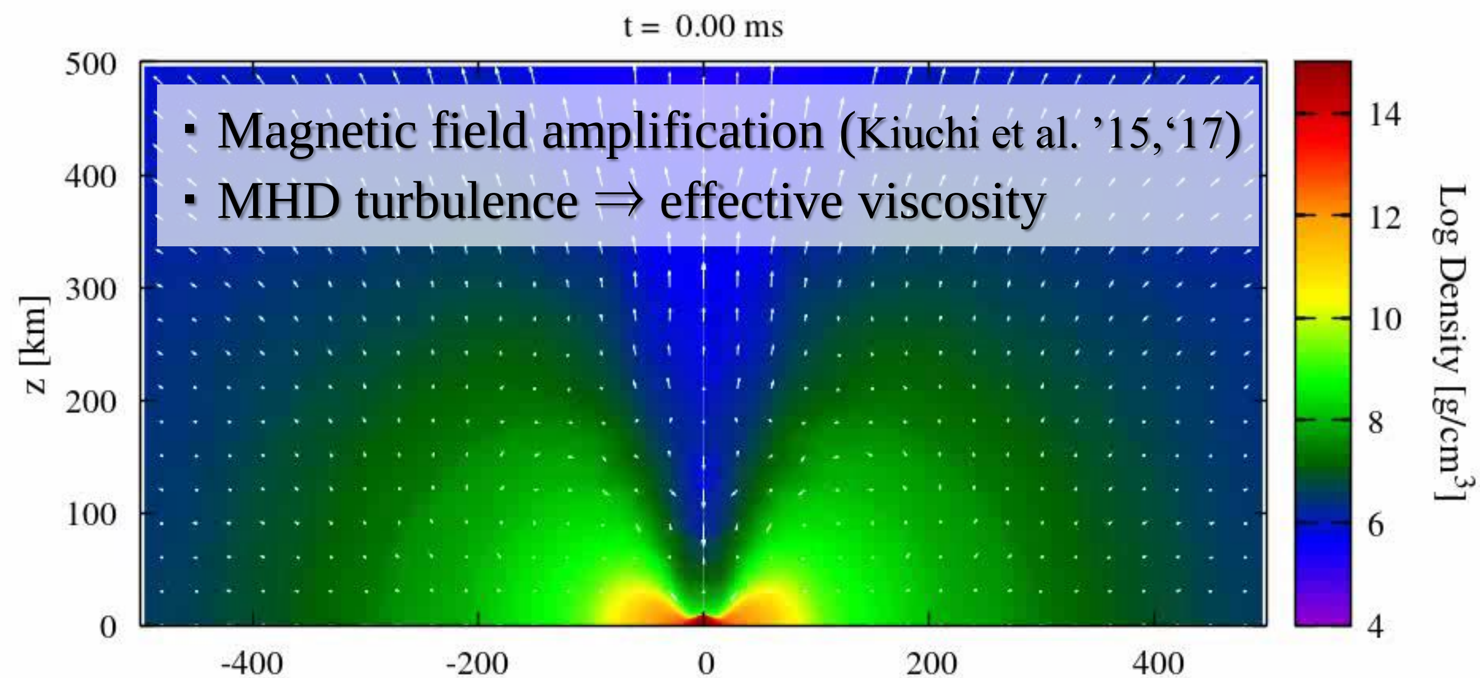
- For EOS consistent with GW170817 ($\Lambda < 800$) : SFHo (soft) , DD2 (stiff)
  - $\mathrm{Ye}_{\mathrm{ej,dyn}} = 0.05 - 0.5$, irrespective of mass ratio for $q = 0.8 - 1.0$

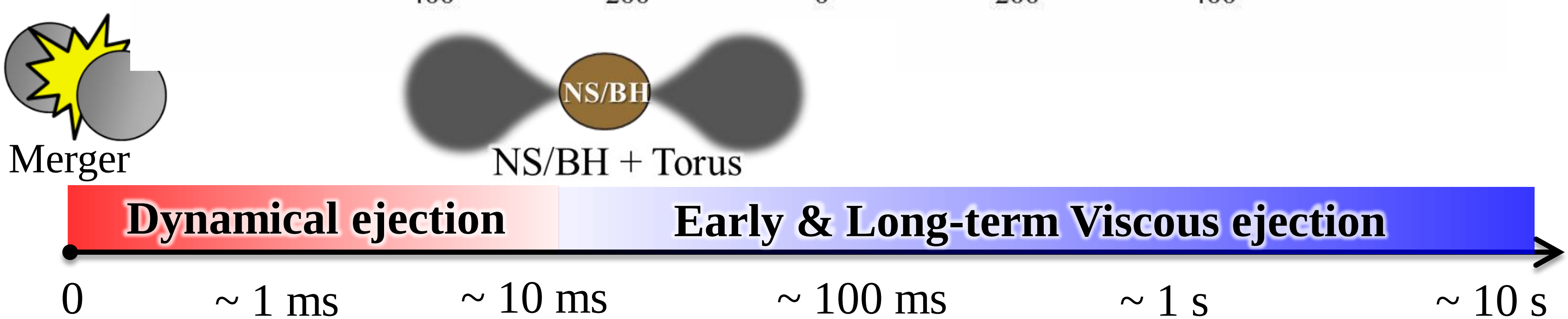
- ***Equatorial direction***
  - Tidally driven (low T)
    - Ye < 0.20
    - Lanthanide rich, red
    - **Dominates for q < 0.9**
- ***Polar direction***
  - Neutrino irradiated
    - Ye > 0.4
    - Lanthanide free, blue
    - Mass is small
- ***Intermediate***
  - Thermal driven (hight T)
    - Moderate Lanthanide



Mass ejection mechanisms : Viscosity

- Magnetic field amplification (Kiuchi et al. ’15,‘17)
- MHD turbulence ⇒ effective viscosity





Fujibayashi et al. (2018) : α=0.04 model

See also Metzger & Fernandez 2014; Pregp et al. 2017; Lippuner et al. 2017; Radice et al. 2019

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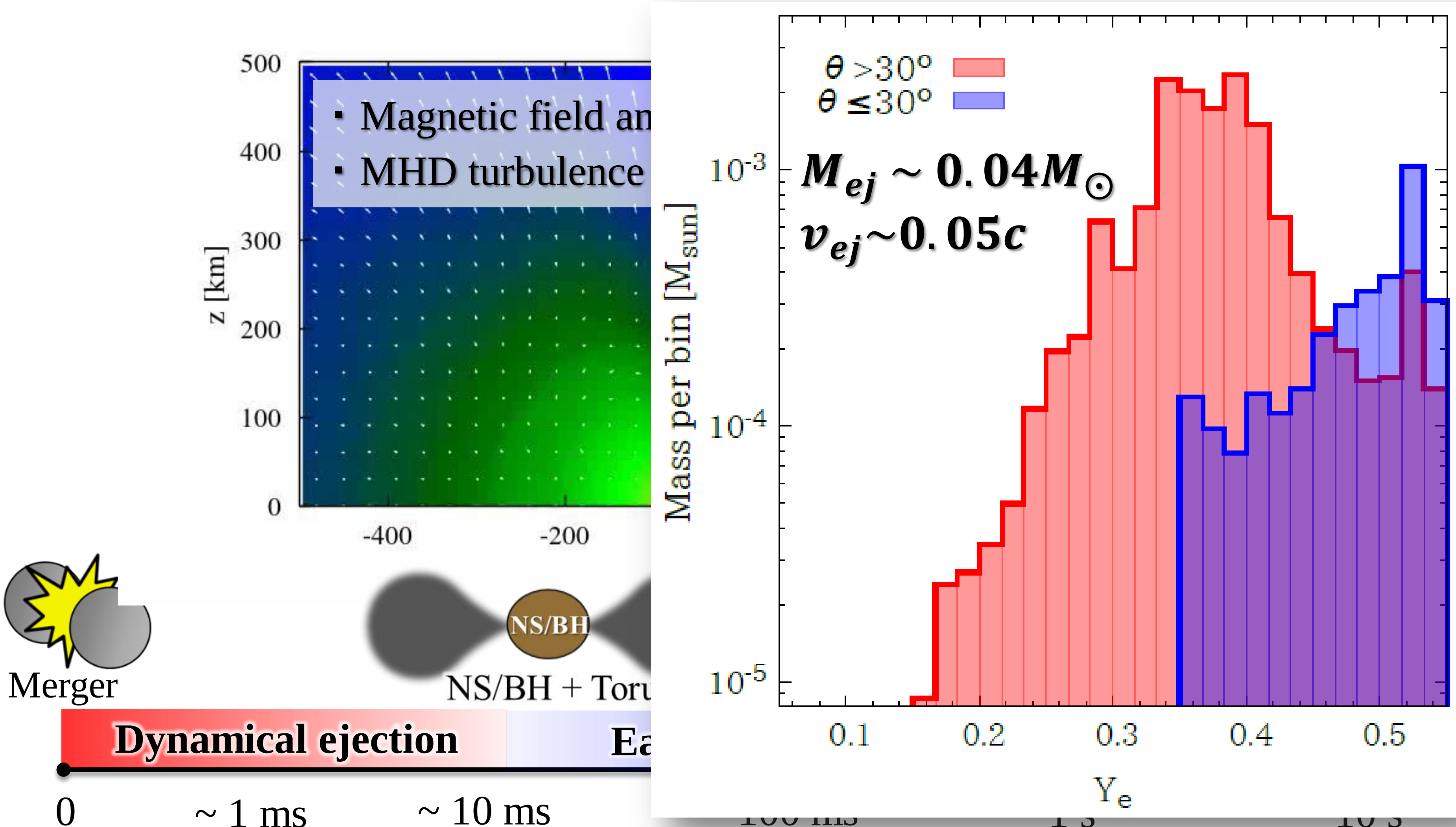

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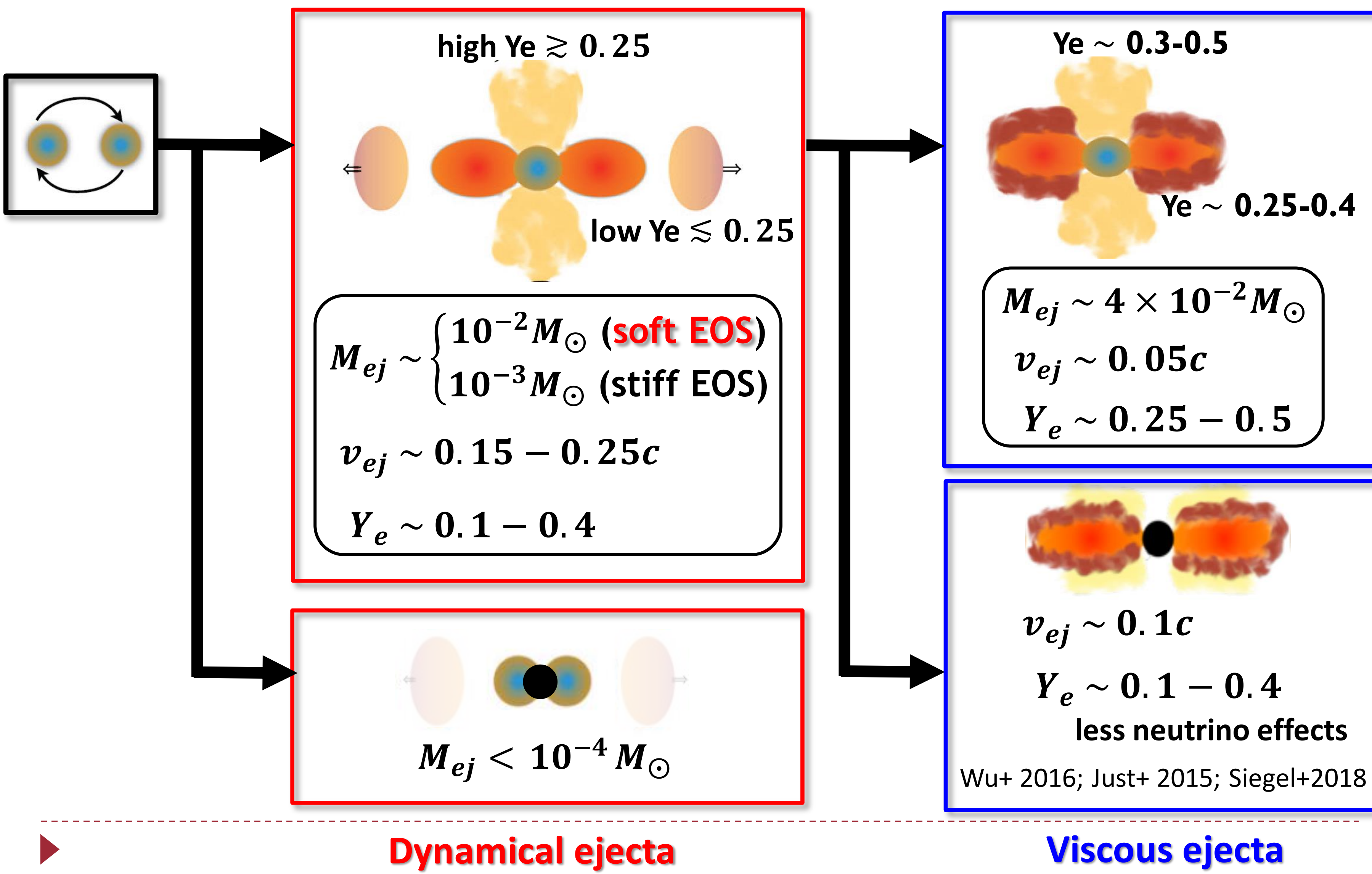
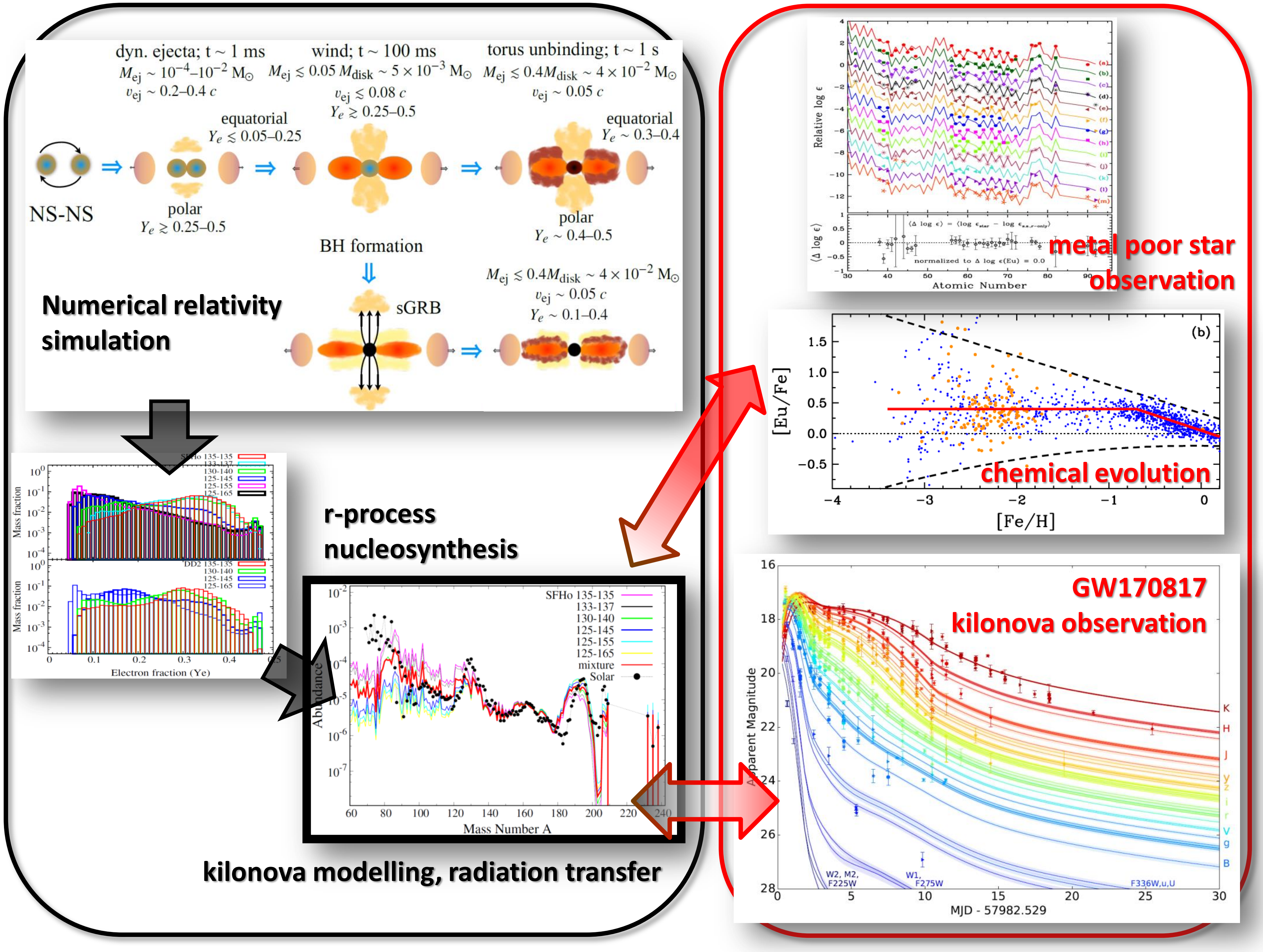
Mass ejection in NS-NS : Summary





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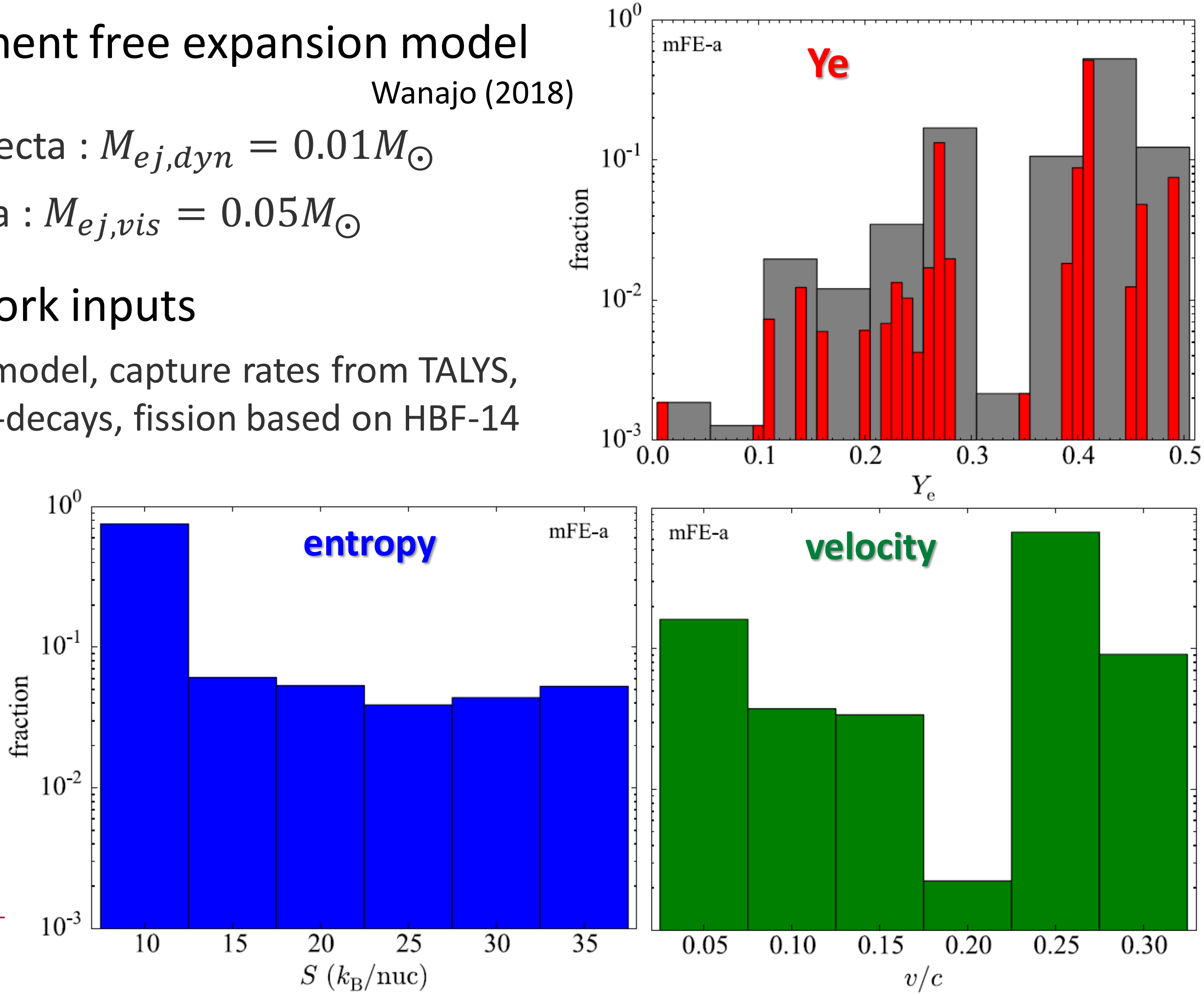
r-process nucleosynthesis calculation

- Multi-component free expansion model

  Wanajo (2018)

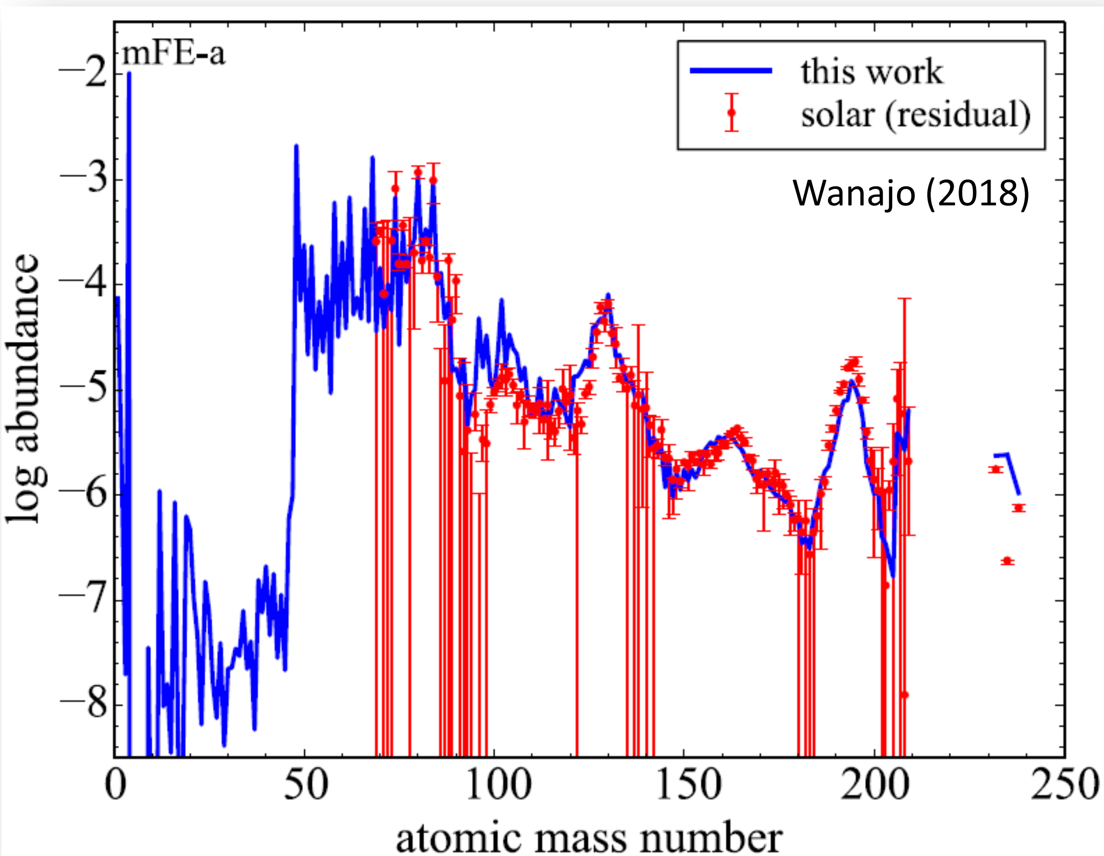
  - Dynamical ejecta : $M_{ej,dyn} = 0.01M_{\odot}$
  - viscous ejecta : $M_{ej,vis} = 0.05M_{\odot}$

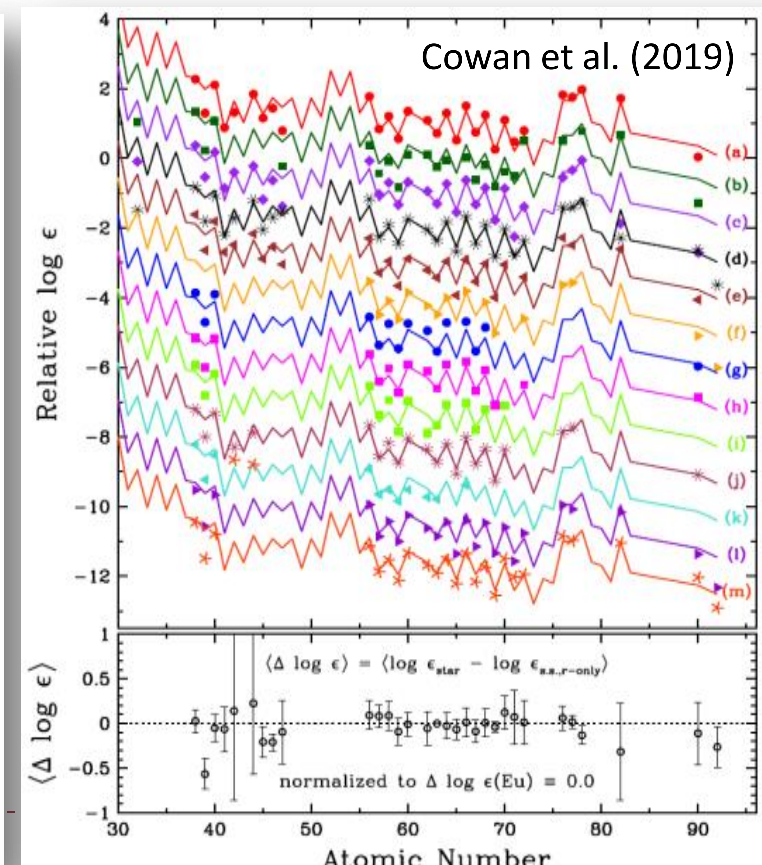
- Nuclear network inputs
  - HBF-21 mass model, capture rates from TALYS, GT2 rate for β-decays, fission based on HBF-14



r-process abundance pattern

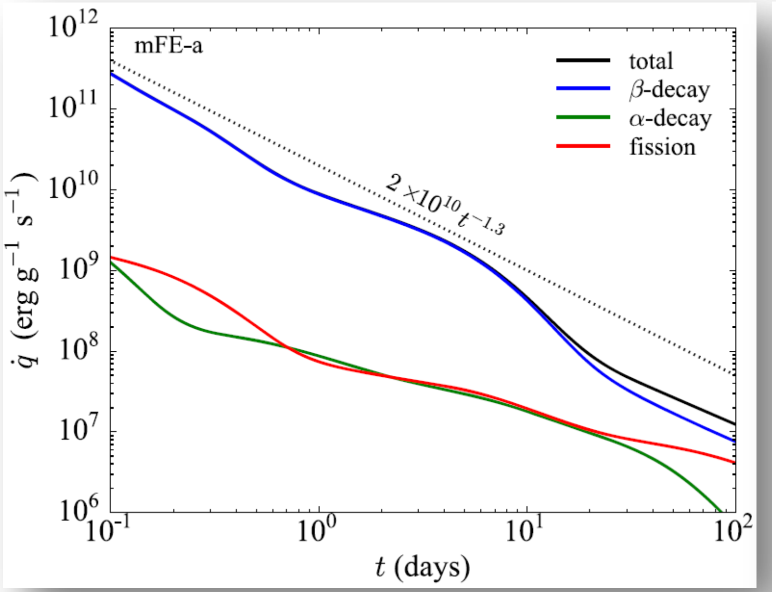
- Nicely reproduce the solar r-process pattern
  - approximated model calculation, some tuning done
- Consistent with r-rich, metal-poor stars (r-II stars)

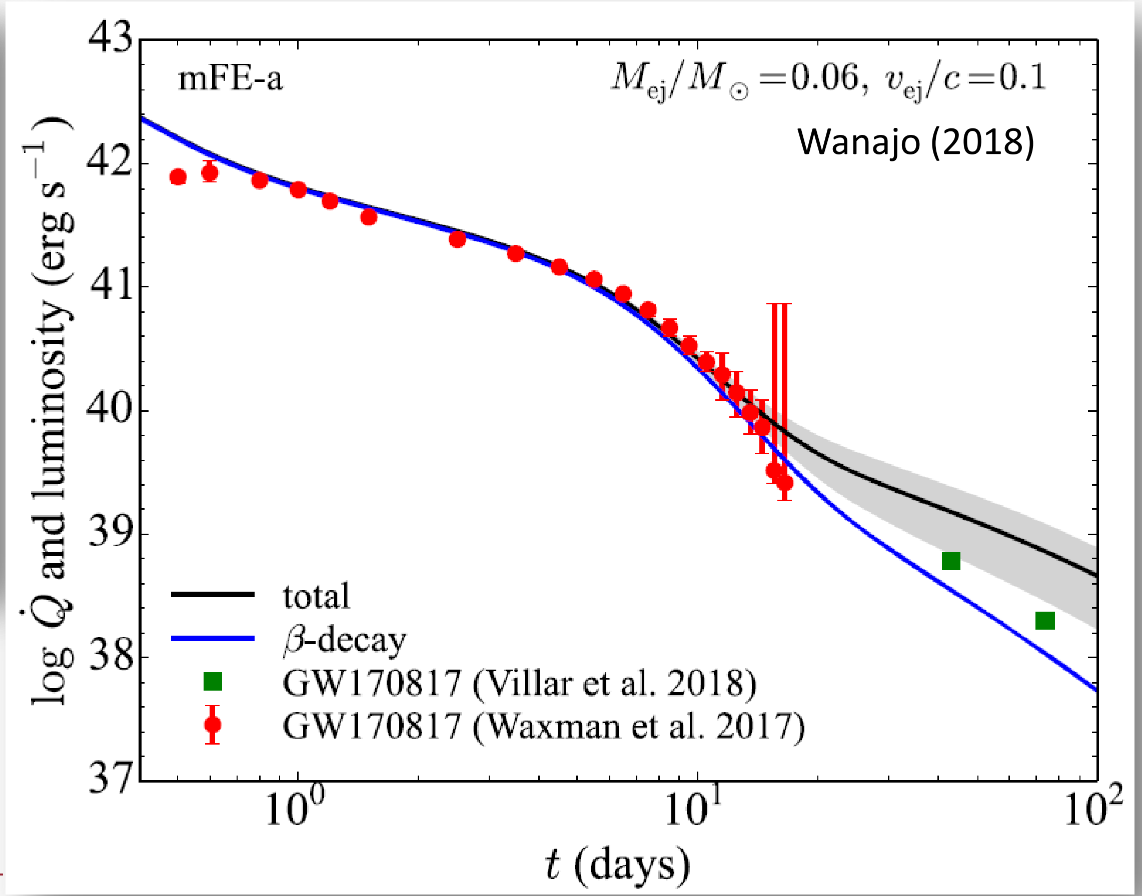




Nuclear heating rate

- Total heating rate $\dot{Q}$ vs. Bolometric luminosity L_{bol} of kilonova
  - L_{bol} in later optically-thin phase ($\gtrsim$ 7 days) should agree with $\dot{Q}$





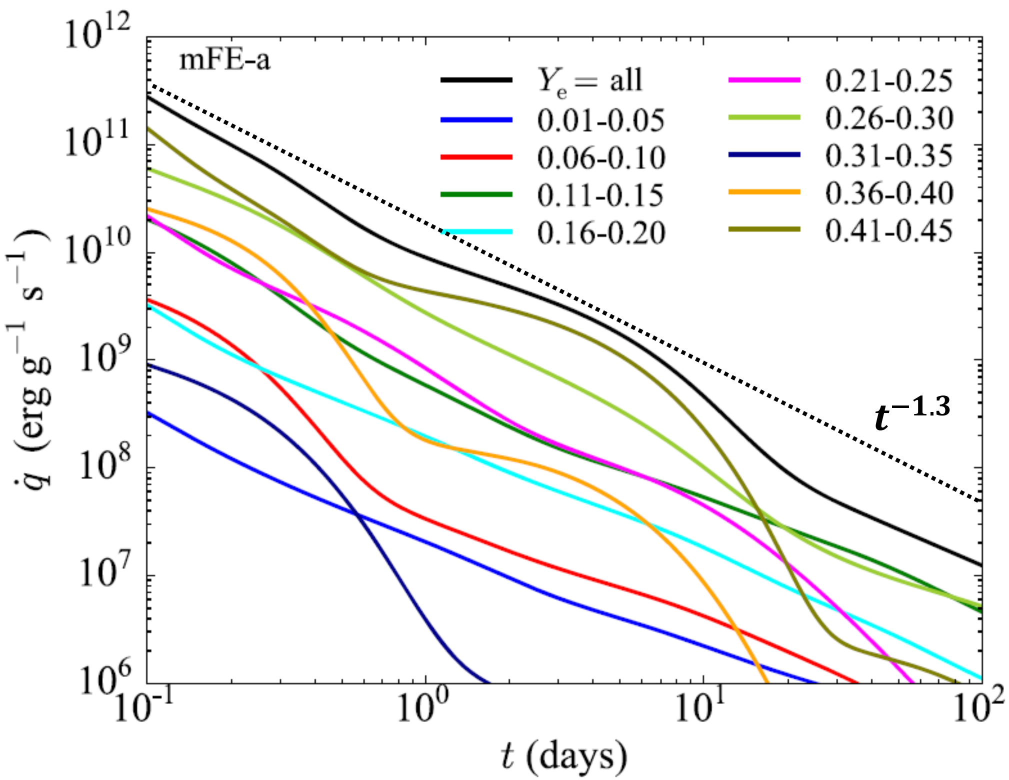
Nuclear heating rate

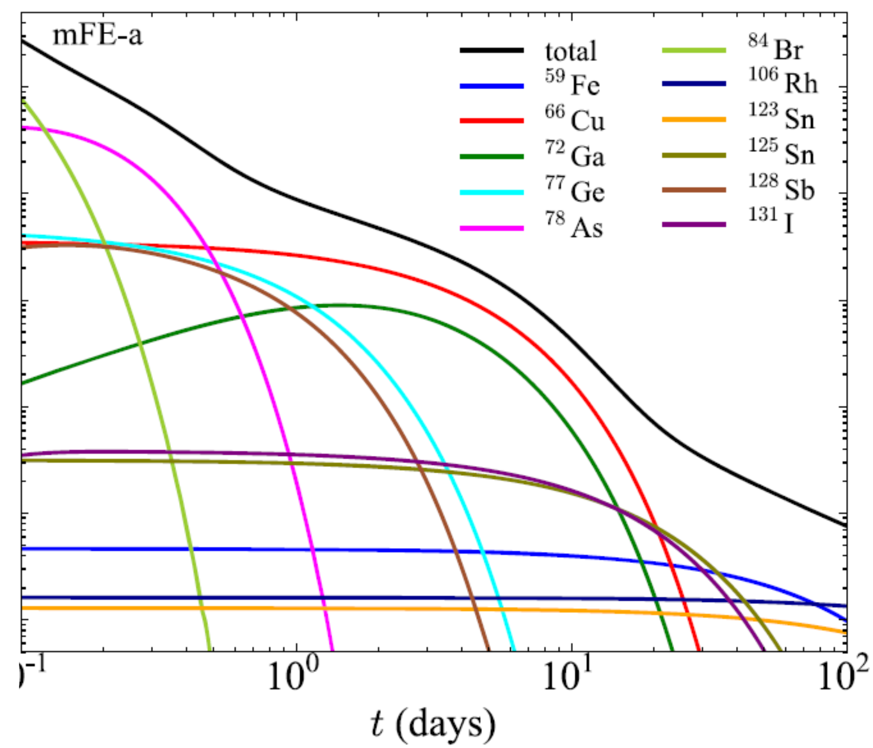
- The humpy feature at 5-10 days comes from β-decays of ^{66}Cu and ^{72}Ga in high Ye > 0.4 ejecta

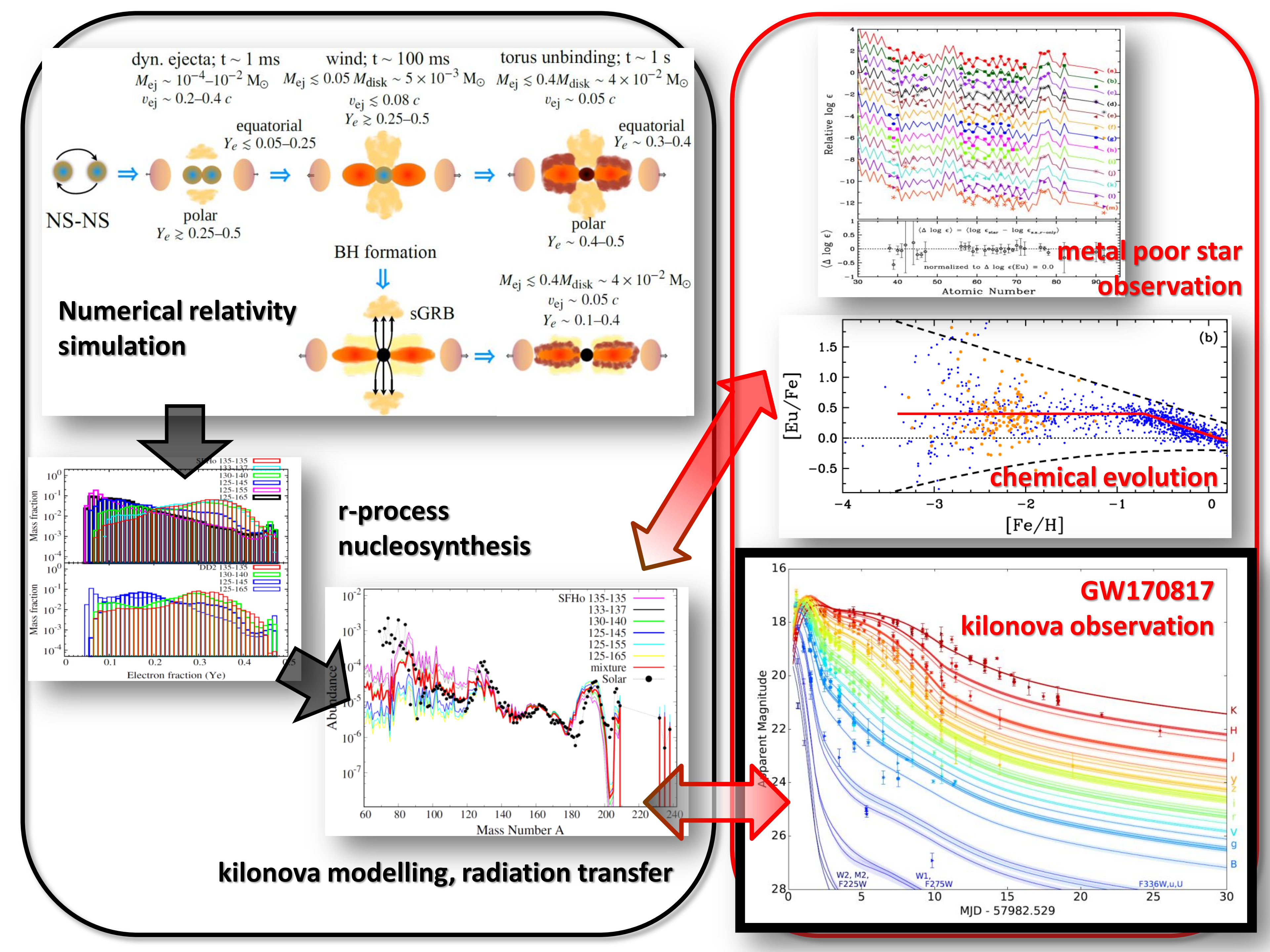
$$^{66}\mathrm{Ni}\ (2.28\ \mathrm{day}) \rightarrow ^{66}\mathrm{Cu}\ (5.12\ \mathrm{m}) \rightarrow ^{66}\mathrm{Zn}$$

$$^{72}\mathrm{Zn}\ (1.94\ \mathrm{day}) \rightarrow ^{72}\mathrm{Ga}\ (14.1\ \mathrm{hr}) \rightarrow ^{72}\mathrm{Ge}$$

  - See Wu et al. (2018) and Kasliwal et al. (2019) for alternative explanation by α-decays of actinides (heavy nuclei)



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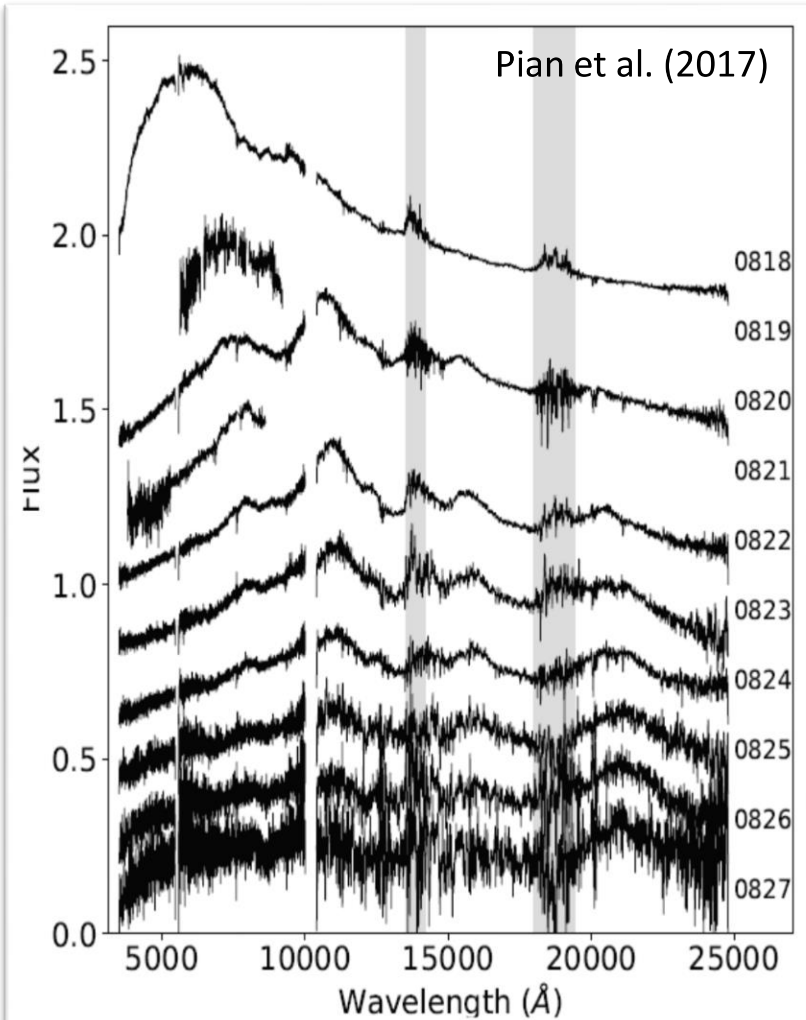
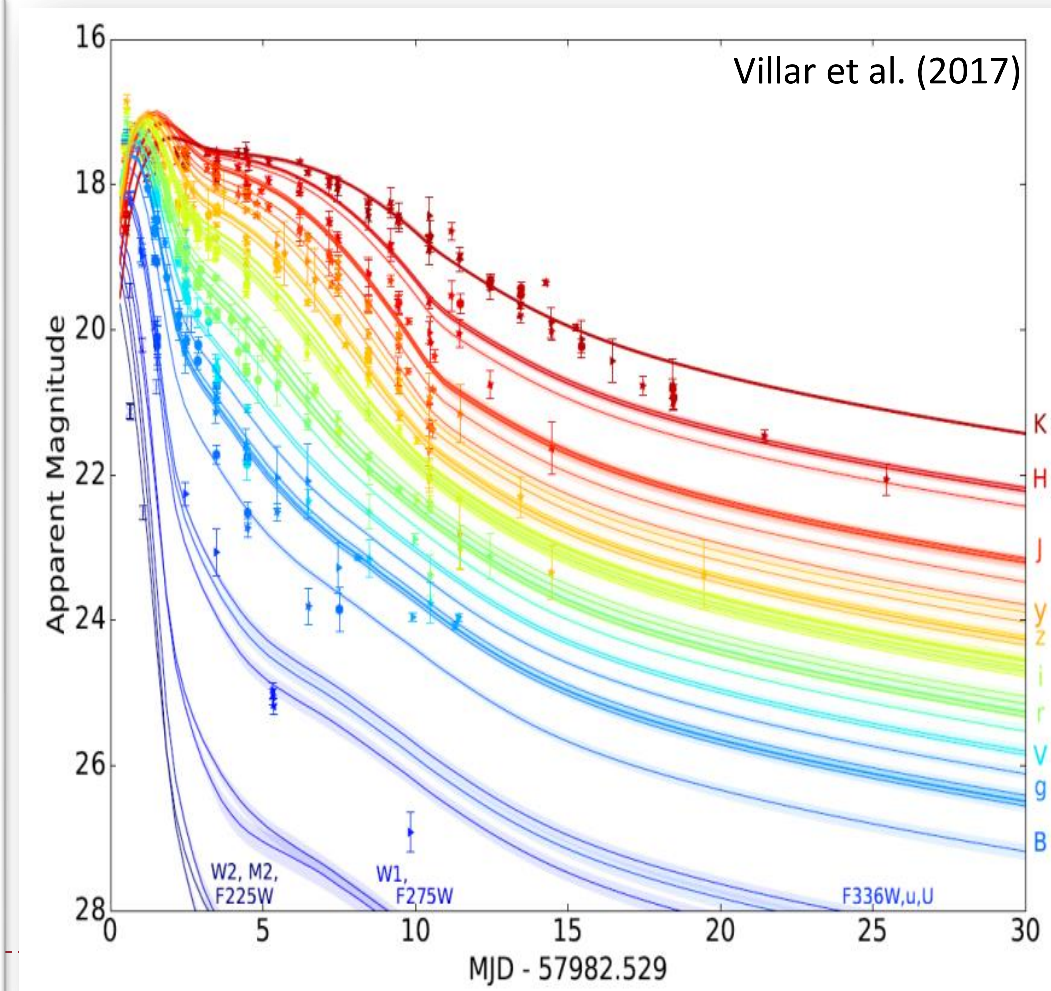
Kilonova modelling

- The color/spectra evolution observed in GW170817





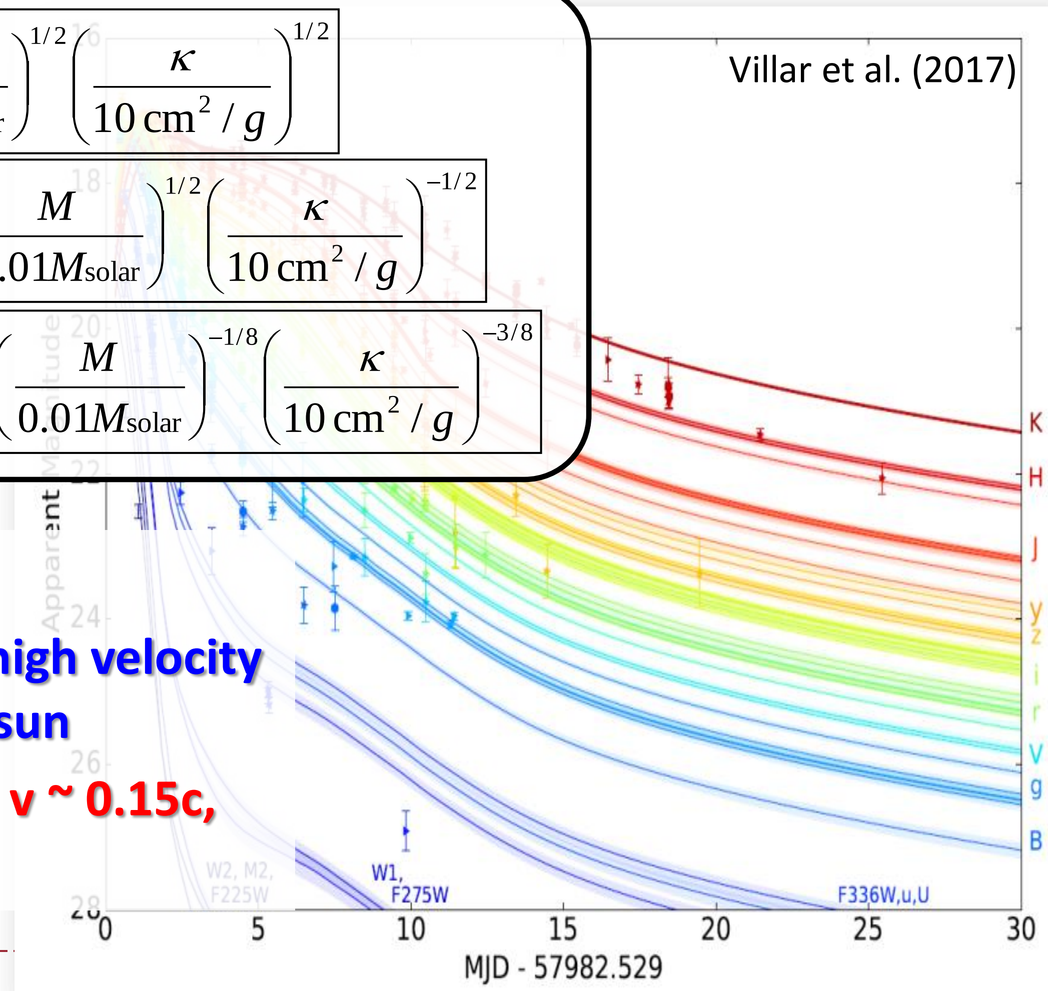
Kilonova modelling

- The color/spectra evolution observed in GW170817

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

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

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

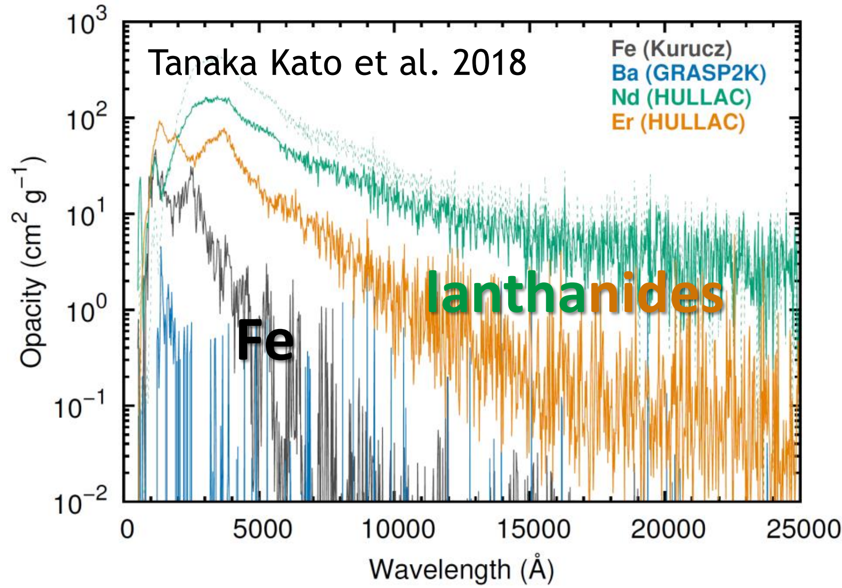


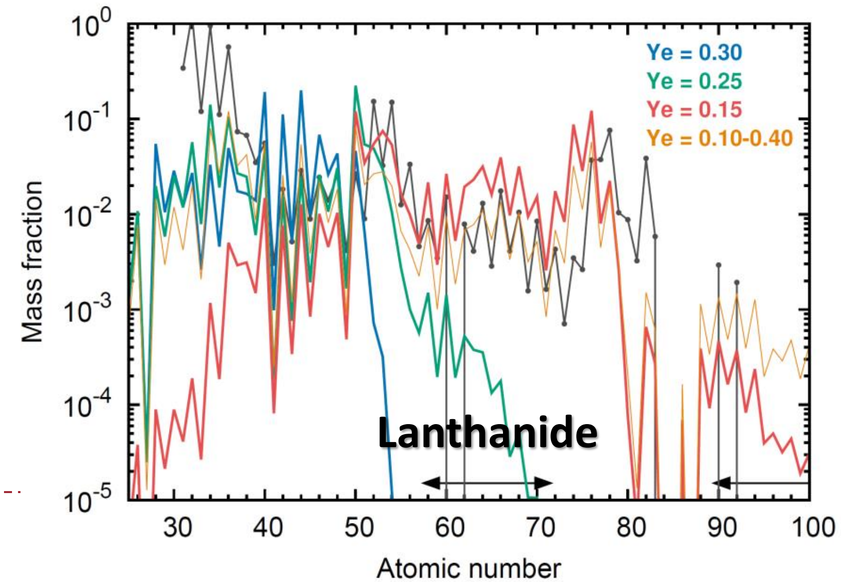
- Simple modelling requires
  - **low opacity (κ < 1cm²/g), high velocity (v > 0.25c), mass ~ 0.02 Msun**
  - **high opacity (κ > 3 cm²/g), v ~ 0.15c, massive ~ 0.05 Msun**

Opacity is determined by ejecta composition

- Lanthanides are key elements
  - Lanthanide opacities are large due to their dense atomic line structure
    - Kasen+ 2013; Tanaka & Hotokezaka 2013; Tanaka, Kato et al. 2017
  - **lanthanide free ejecta, κ < 1 cm²/g ⇒ blue component**
  - **lanthanide rich ejecta, κ ~ 10 cm²/g ⇒ red component**
- Criterion for Lanthanide production
  - $Ye < 0.25$ (e.g, Korobkin+. 2012; Wanajo, YS+ 2014)

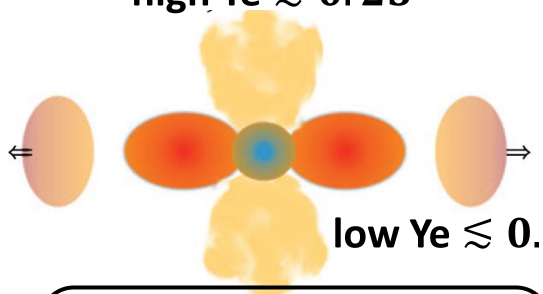
Important to know ejecta Ye
$Ye \lesssim 0.25$





Numerical relativity vs. Simple modelling

Dynamical ejecta

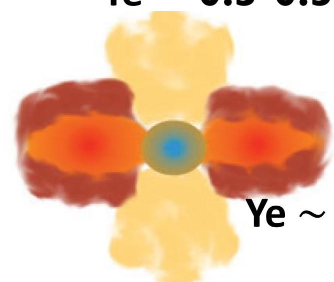


$M_{ej} \sim 10^{-2} M_{\odot}$

$v_{ej} \sim 0.15 - 0.25c$

$Y_e \sim 0.1 - 0.4$

Viscous ejecta



$M_{ej} \sim 4 \times 10^{-2} M_{\odot}$

$v_{ej} \sim 0.05c$

$Y_e \sim 0.25 - 0.5$

red component

- high opacity (κ > 3cm^2/g)
- velocity (v ~ 0.15c)
- **massive ~ 0.05 Msun**

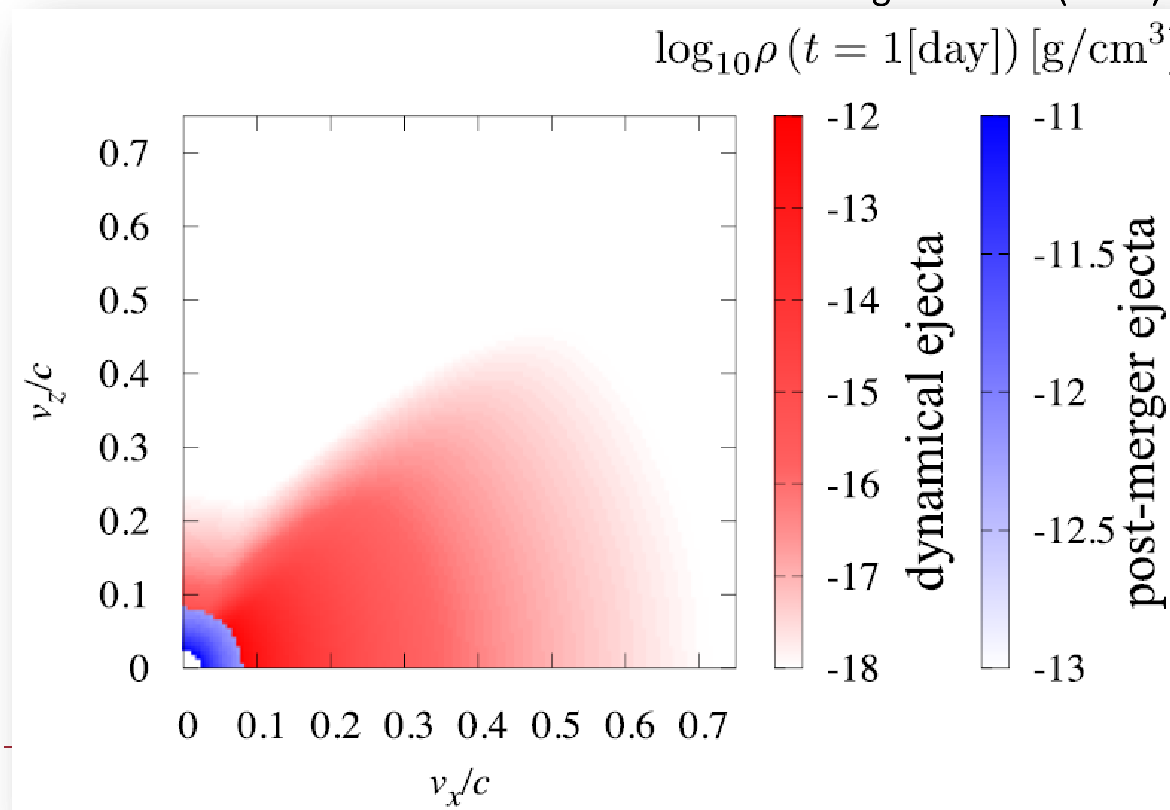
blue component

- low opacity (κ < 1cm^2/g)
- **high velocity (v > 0.25c)**
- mass ~ 0.02 Msun

Modelling based on Numerical Relativity

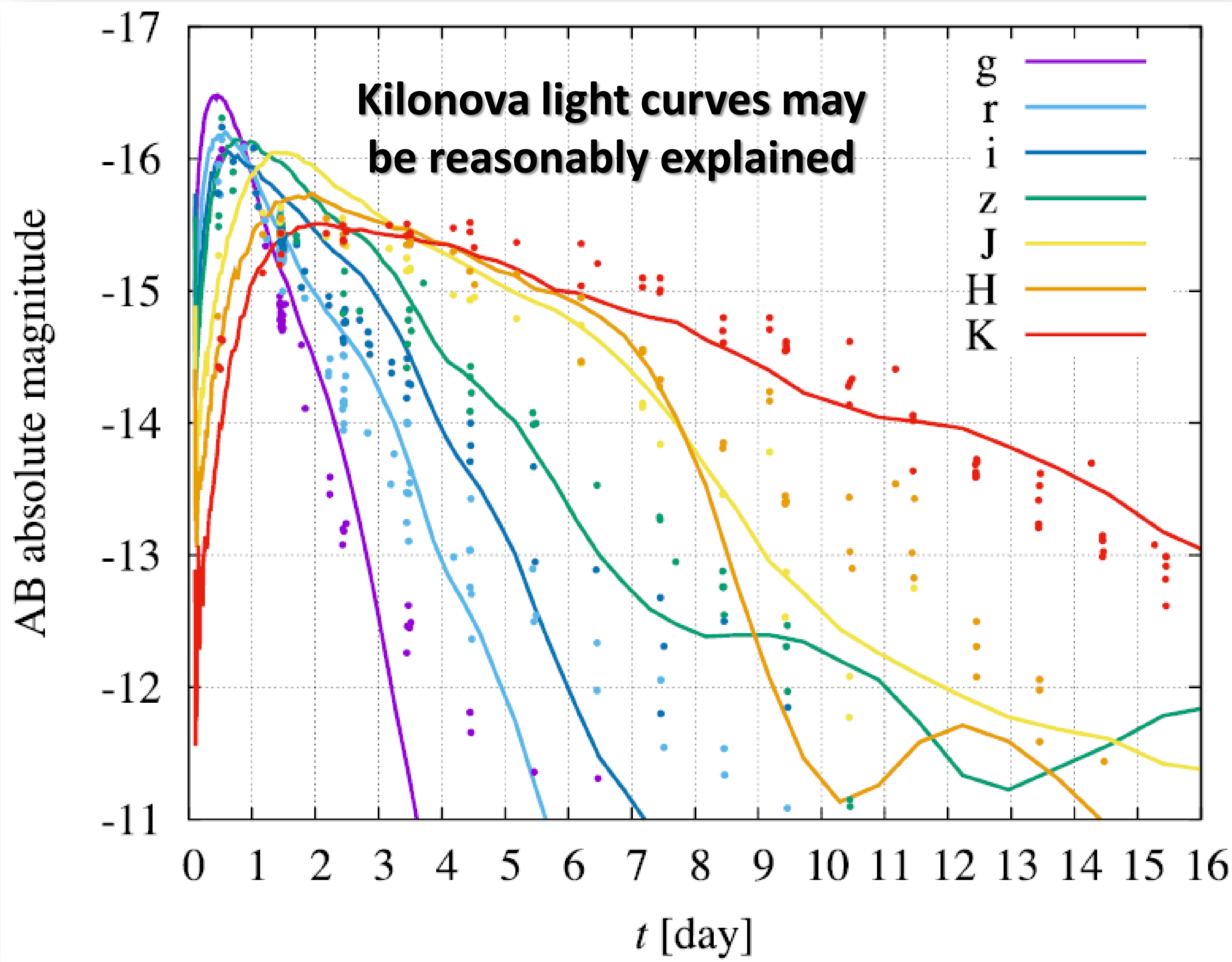
- Radiation transfer based on the Numerical-Relativity result
- Viscous (post-merger) ejecta are surrounded by dynamical ejecta
  - photons from viscous ejecta may be absorbed in outer region
  - dimensionality will play role

Kawaguchi et al. (2018)



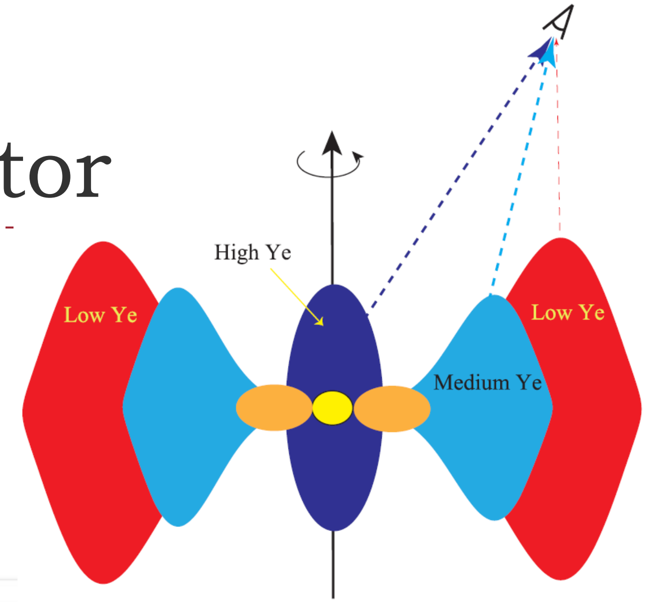
Modelling based on Numerical Relativity

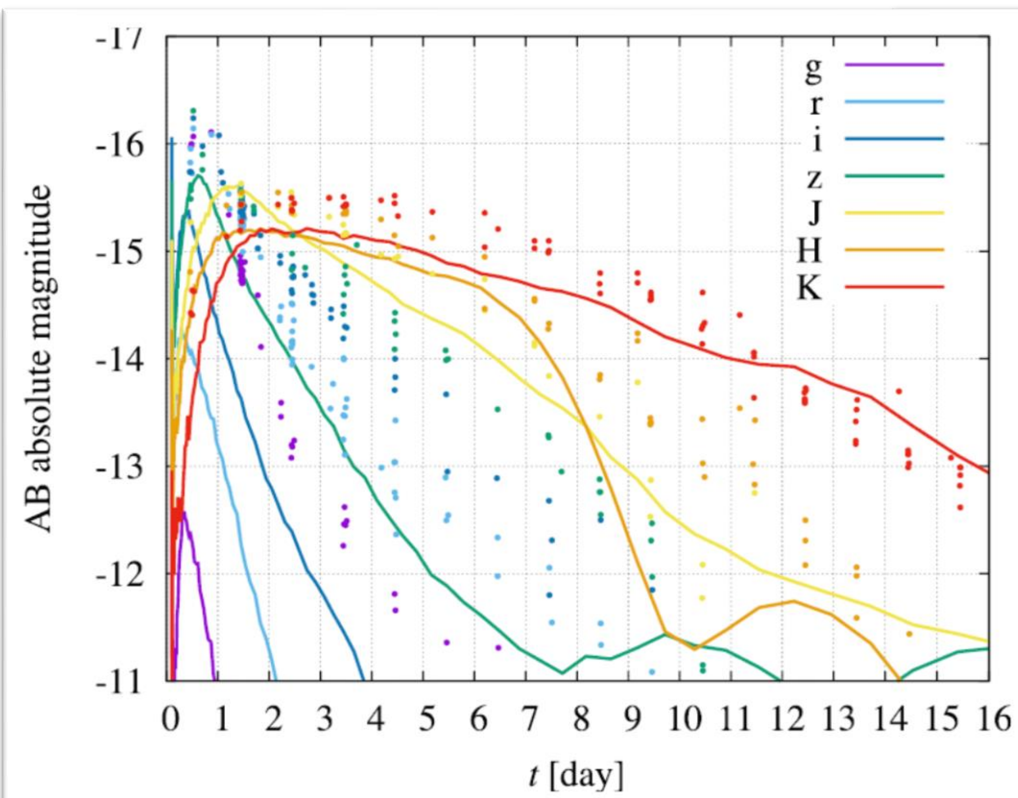
- R
- V

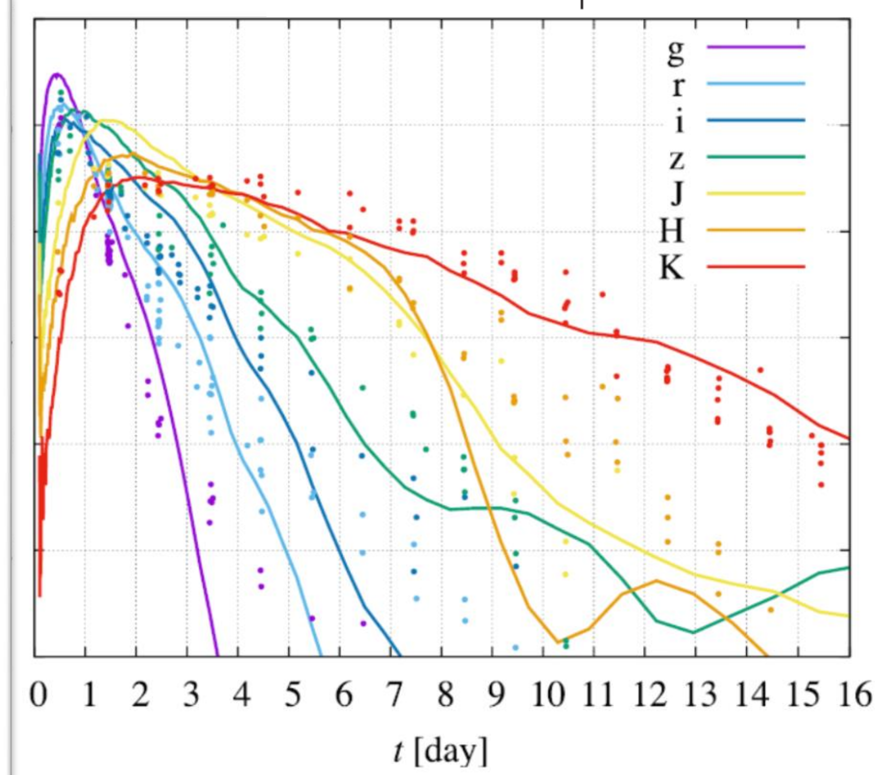


Same event seen from equator

- GW170817 : viewing angle ~ 30 deg
- Blue emissions will be decreased when seen from equator
  - Simple modelling : different composition





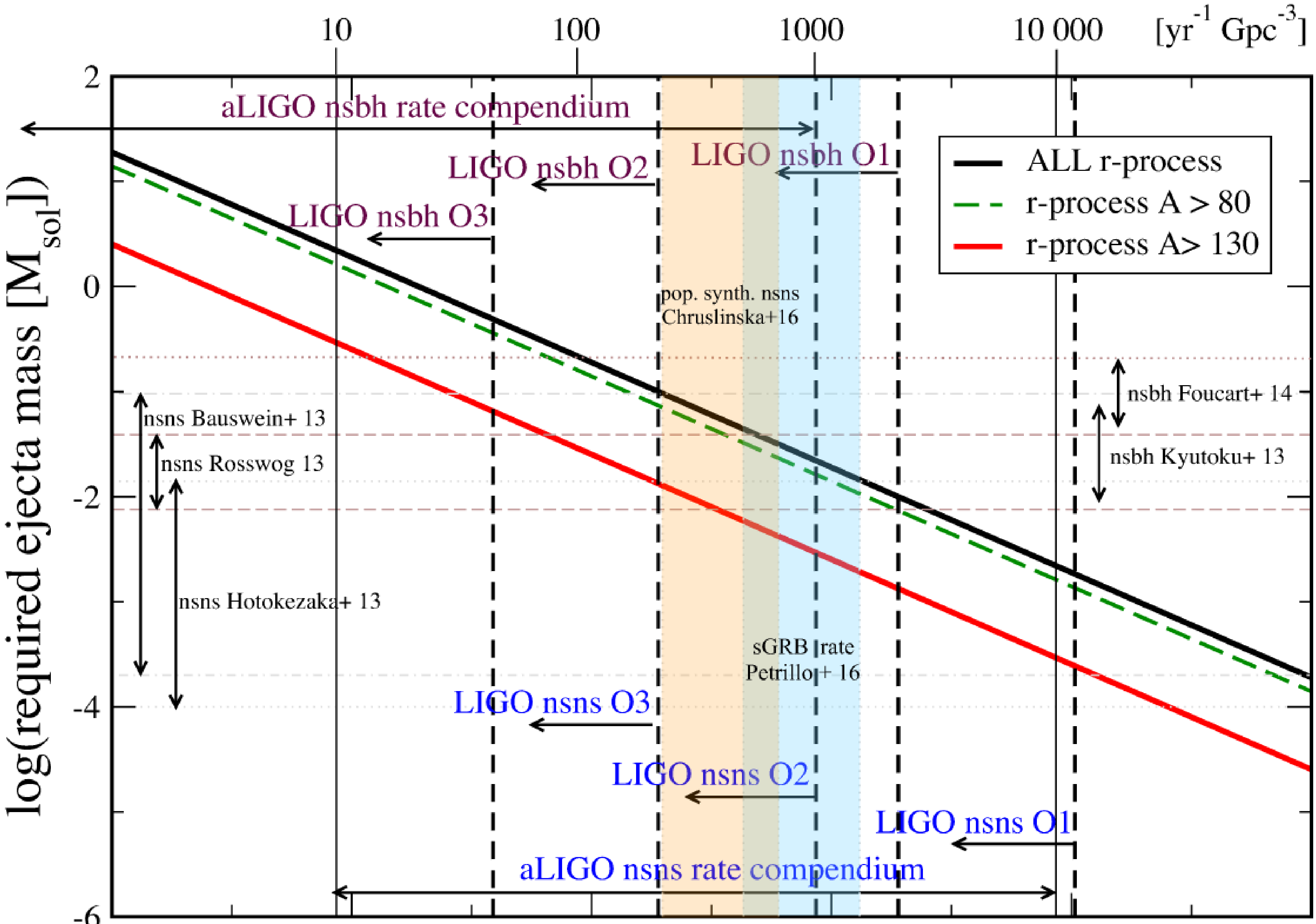


NS-NS(BH) candidates : S190425a and S190426c

- NS-NS merger event rate from GW170817 : 110-3840 /Gpc^3/yr
- We have two additional candidates in 1 month
  - S190425a
    - probability (from mass estimation) being NS-NS : 0.999
    - $D \approx 160^{+40}_{-40}$ Mpc
  - S190426c
    - probability being NS-NS : 0.493, NS-BH($> 5M_{\odot}$) : 0.129, NS-(NS or low mass BH) : 0.237 , unknown terrestrial : 0.140
    - $D \approx 420^{+130}_{-130}$ Mpc

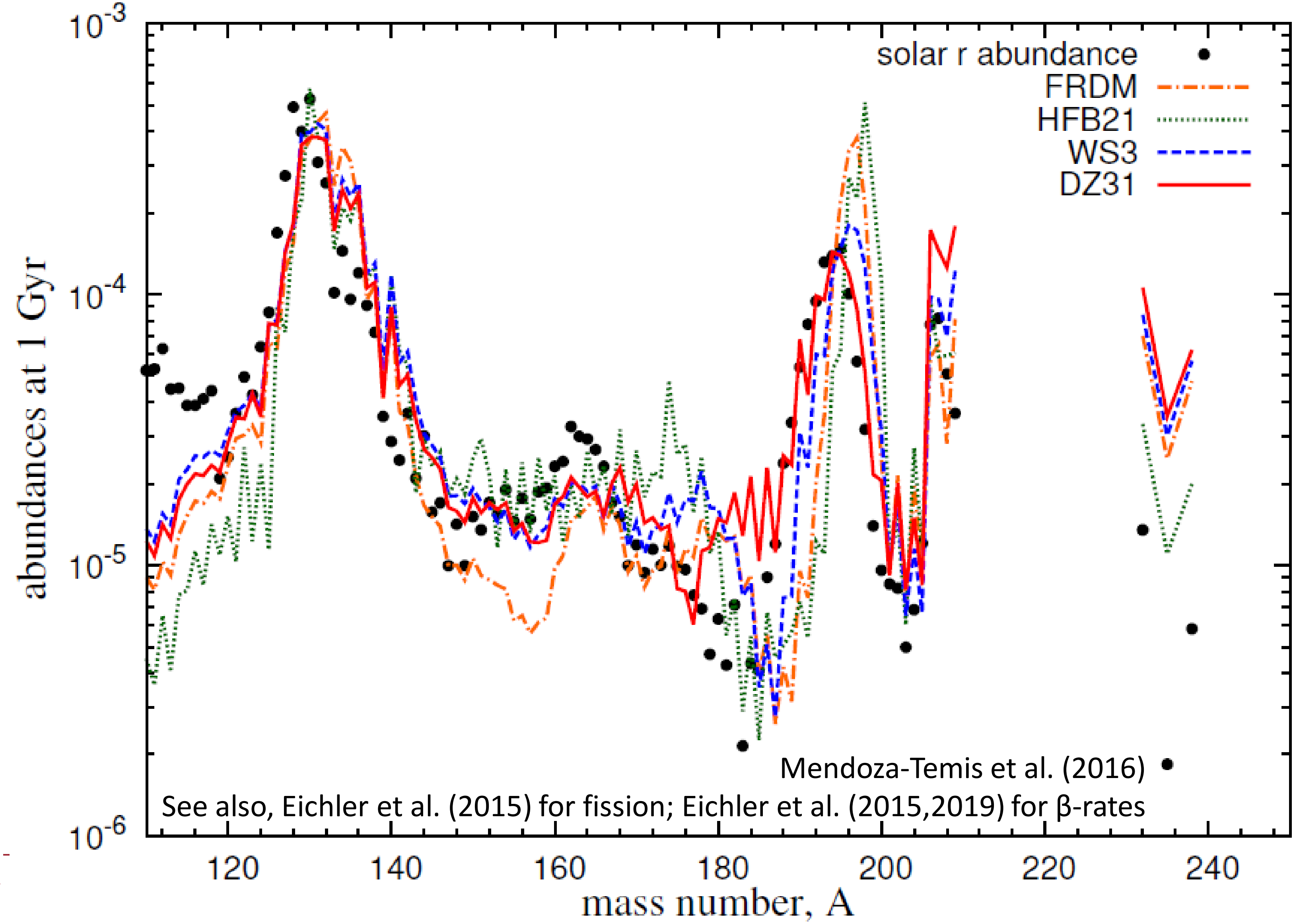
⇒ suggest that the event rate may be relatively high as ~ 10/yr

⇒ **~ 1000 /Gpc^3 /yr**

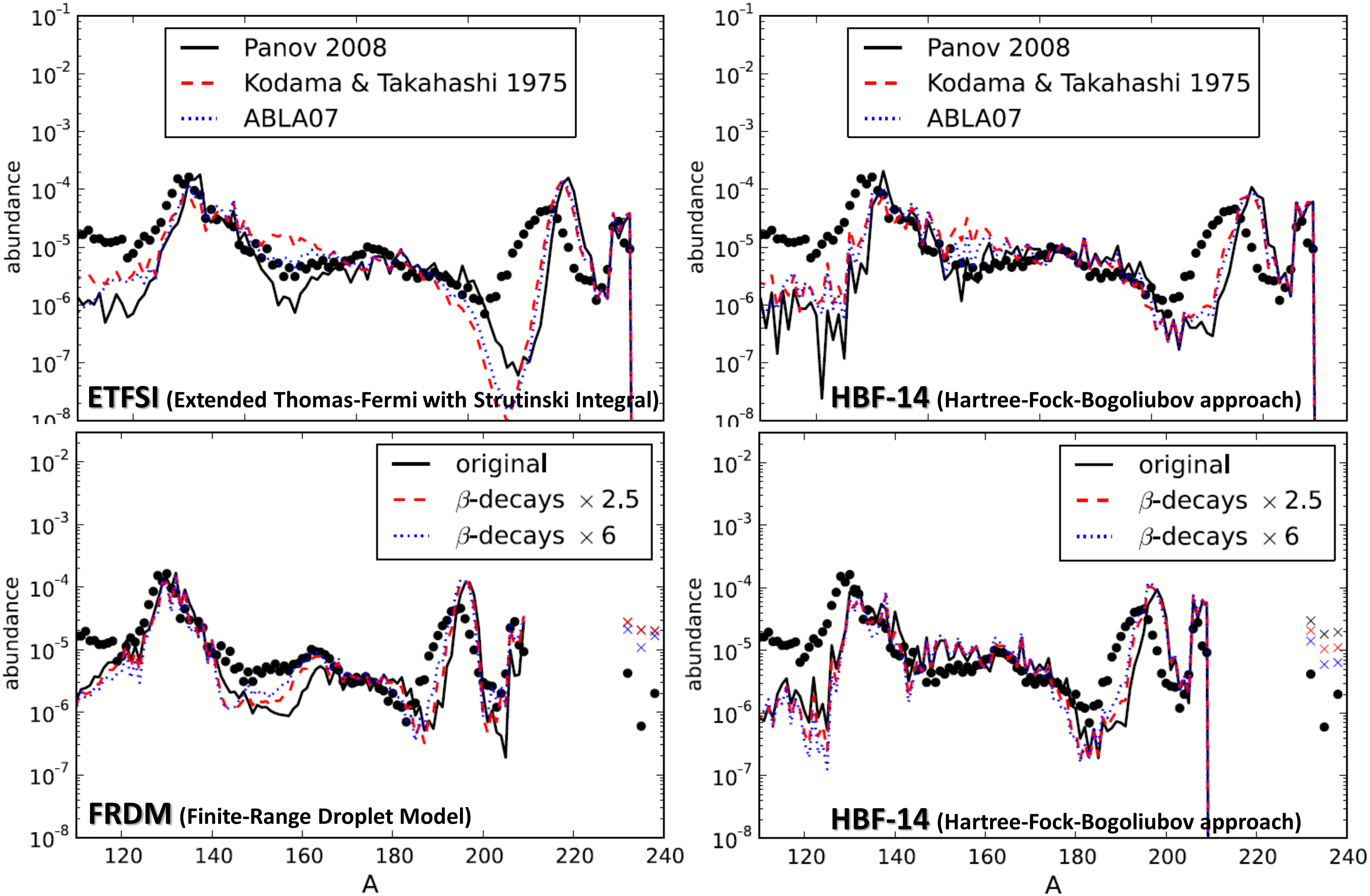


Rosswog et al. (2017)

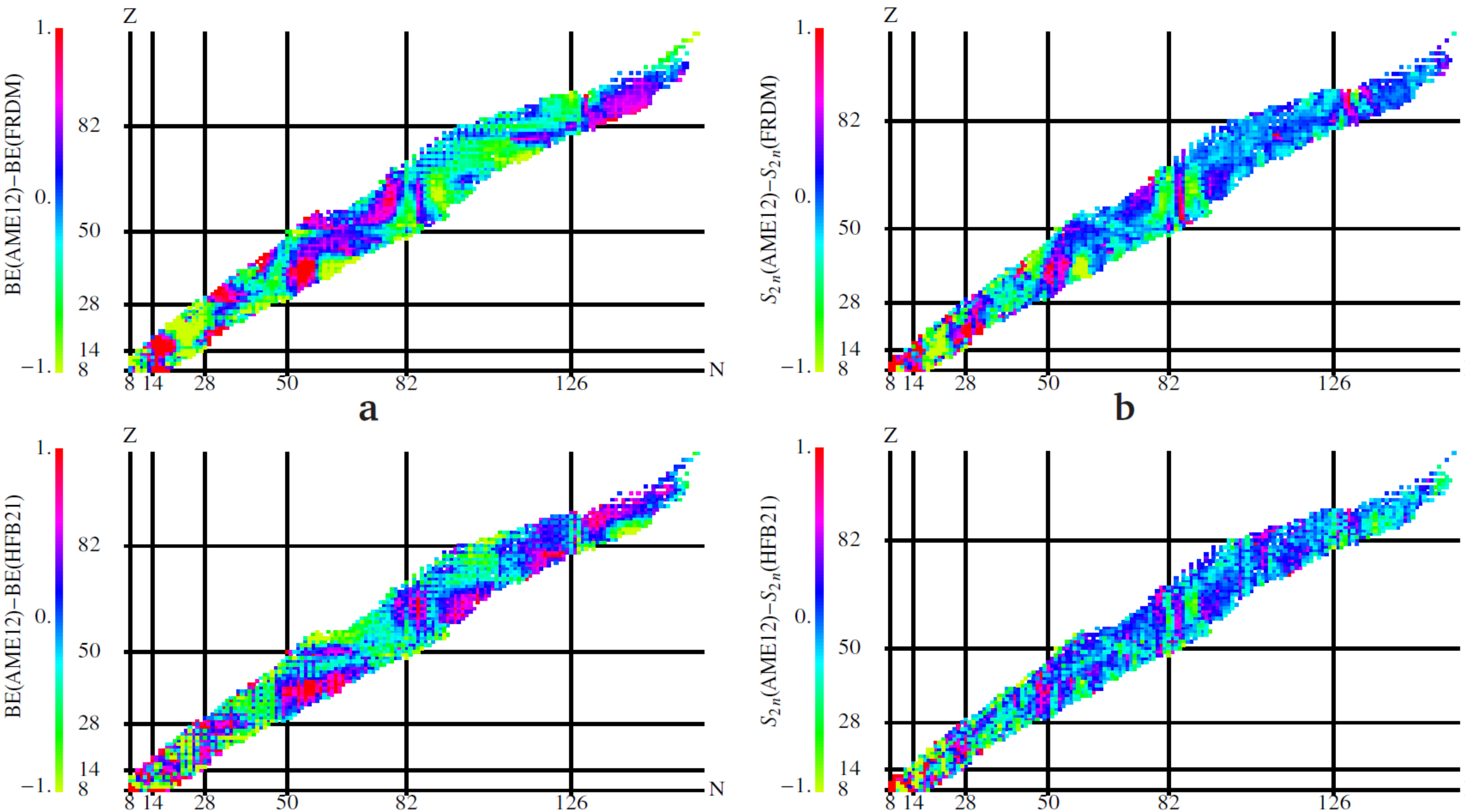
Dependence on nuclear-input models



Dependence on fission fragments/β-rates

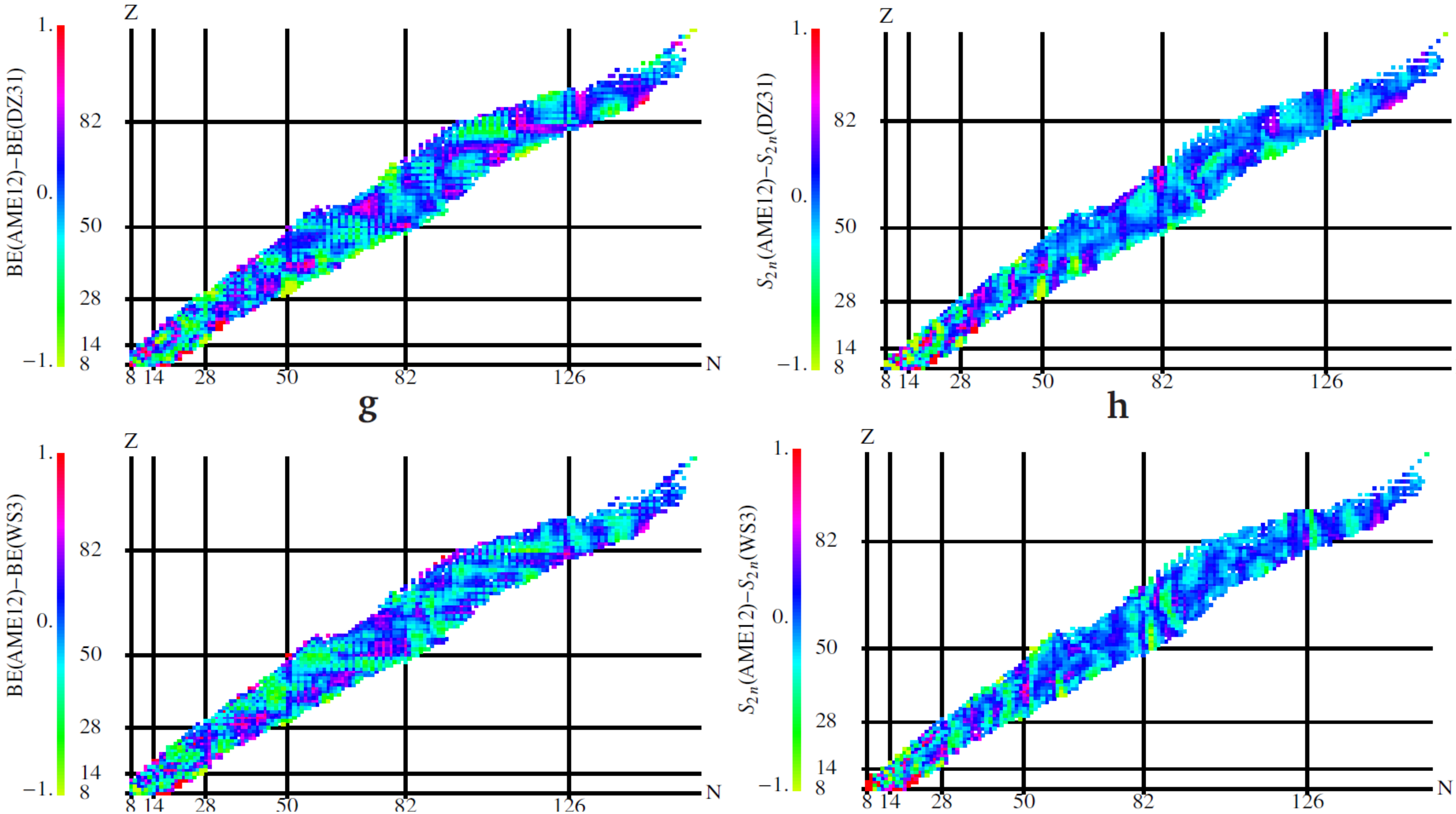


Experiments vs. nuclear models (1)



Mendoza-Temis et al. (2017)

Experiments vs. nuclear models (2)



Mendoza-Temis et al. (2017)

On extrapolation to n-rich region

- Comparison of r.m.s deviation for mass in keV

Model	AME-2003 (full)	AME-2012 (new) (new)	AME-2012 (full)
FRDM-1992	655	765	666
HFB-21	576	646	584
WS3	336	424	345
DZ10	551	880	588
DZ31	363	665	400

Cowan et al. (2019)

- Inclusion of 219 new (n-rich) experimental masses (AME-2012) does not make worse the deviation significantly

Summary

- Modelling based on recent Numerical Relativity simulations is consistent with observational results from GW170817
  - Dynamical ejecta : Ye = 0.1-0.4, Mej = 0.001-0.01Msun, Vej ~ 0.2c
  - Viscous (post-merger) ejecta : Ye > 0.25, Mej ~ 0.04Msun, Vej < 0.1c
  - Total amount of solar r-process elements
  - Solar and r-II star abundance patterns
  - Bolometric luminosity and color evolution of the kilonova