The Ministry of Education, Culture, Sports, Science and Technology(MEXT)
Grant-in-Aid for Scientific Research on Innovative Areas
科研費 KAKENHI
重力波天体の多様な観測による宇宙物理学の新展開
New development in astrophysics through multimessenger observations of gravitational wave sources

K computer

Gravitational Wave Physics and Astronomy Genesis

GW170817: Observations and Theoretical modelling

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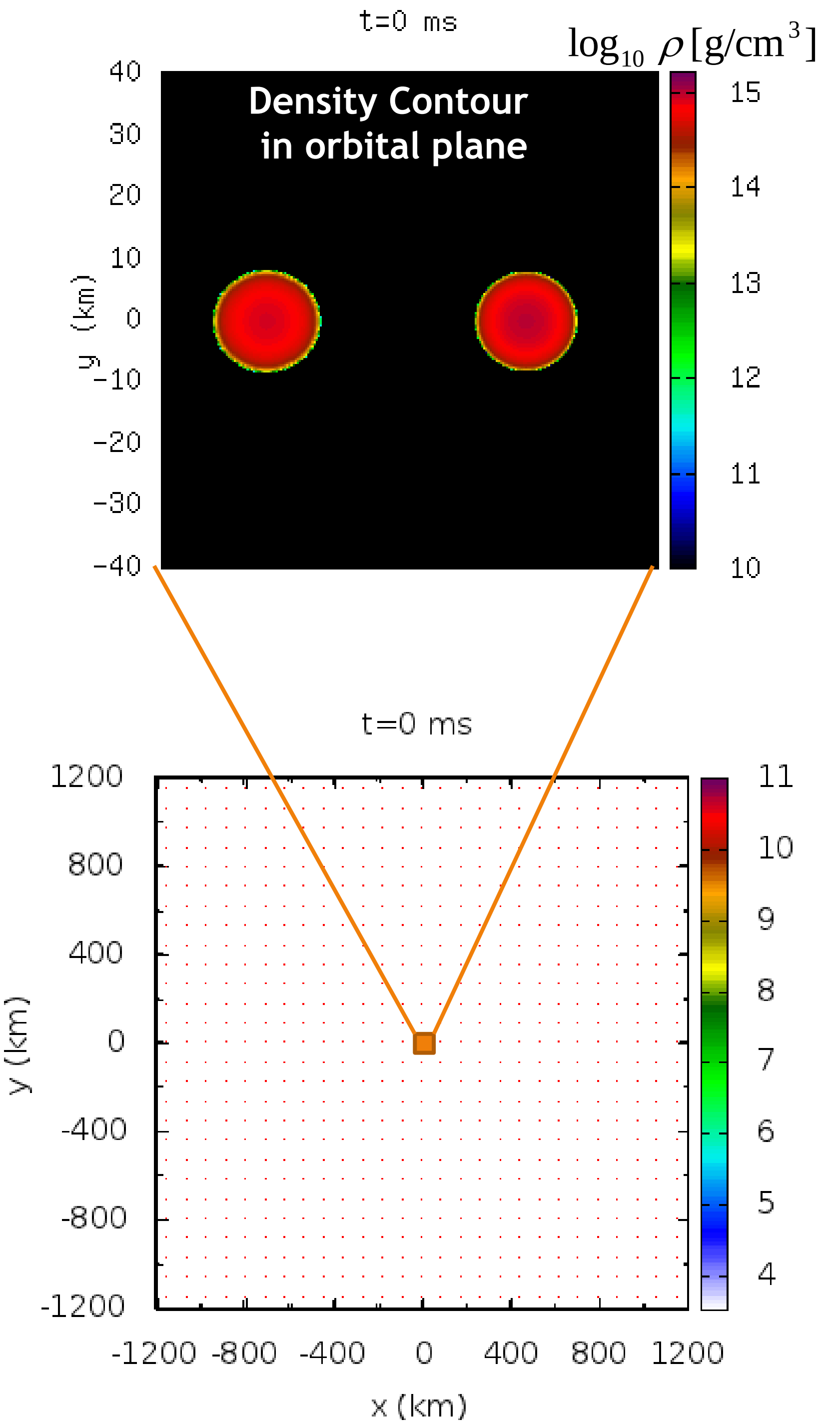
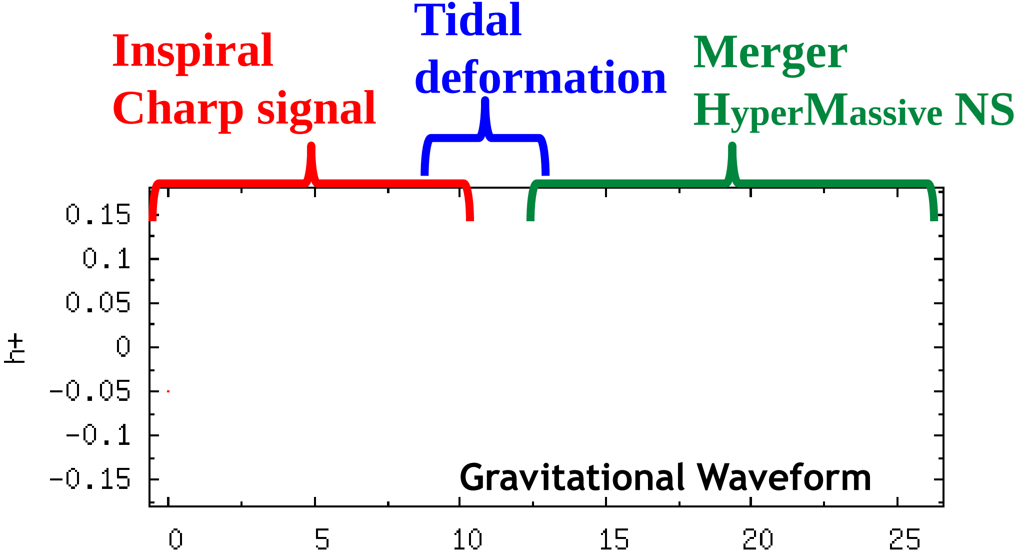
N. Nishimura (YITP), M. Shibata (YITP), M. Tanaka (NAOJ),
K. Taniguchi (Ryukyu), S. Wanajo (Sophia)

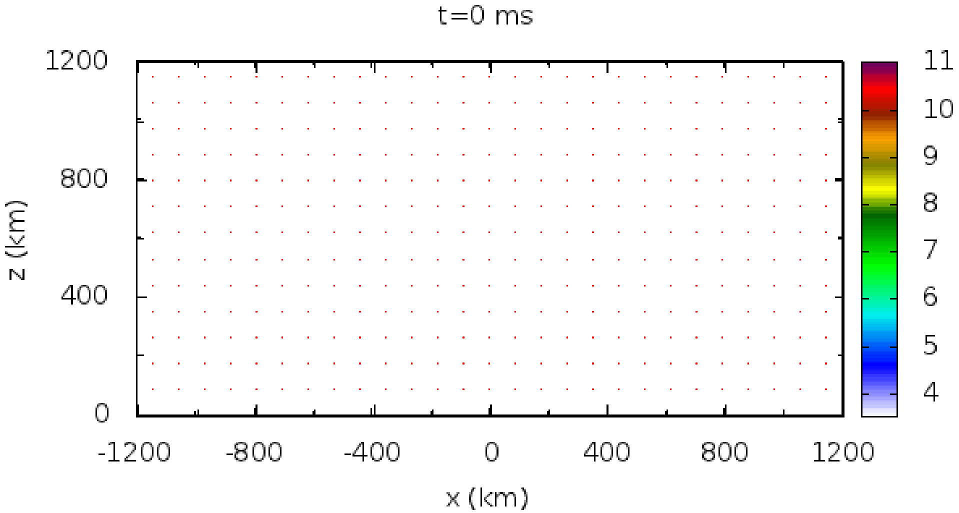
Topics

- Brief review of GW170817
  - GW observation
  - EM observation
    - Gamma-ray (GRB)
    - Radio/X-ray activity
    - Kilonova

- Kilonova modelling based on Numerical Relativity



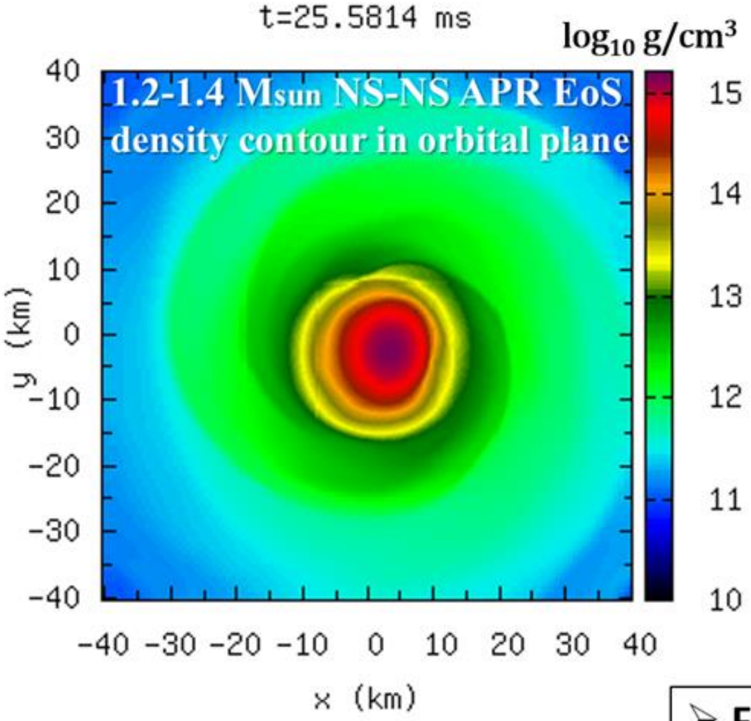


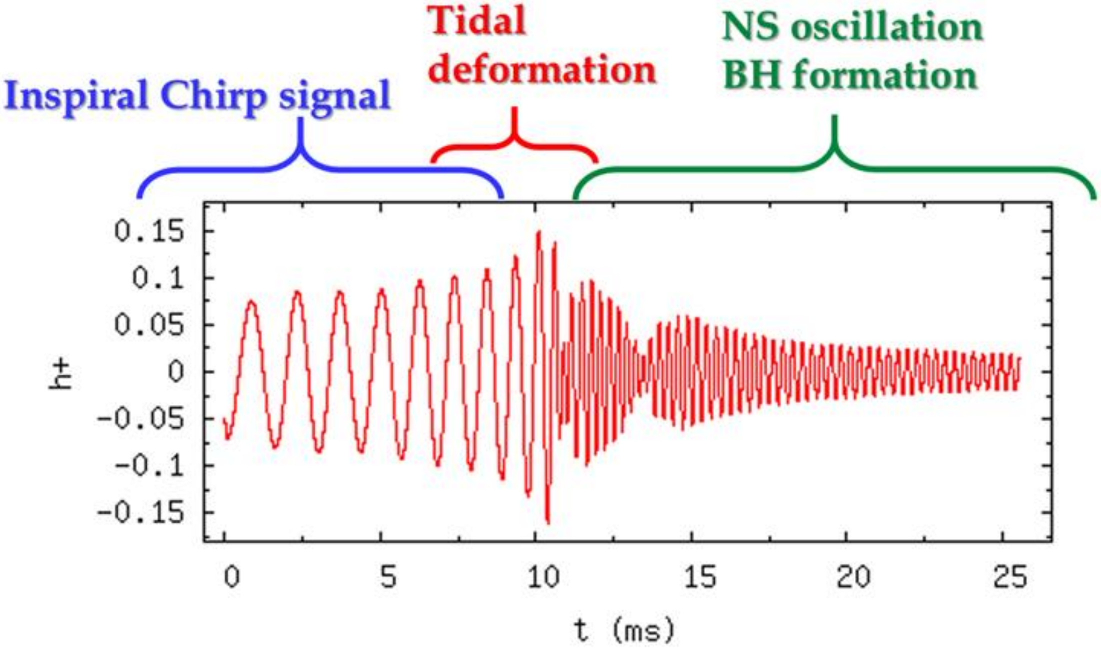


Animation by Hotokezaka

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

3 phases of GW emission





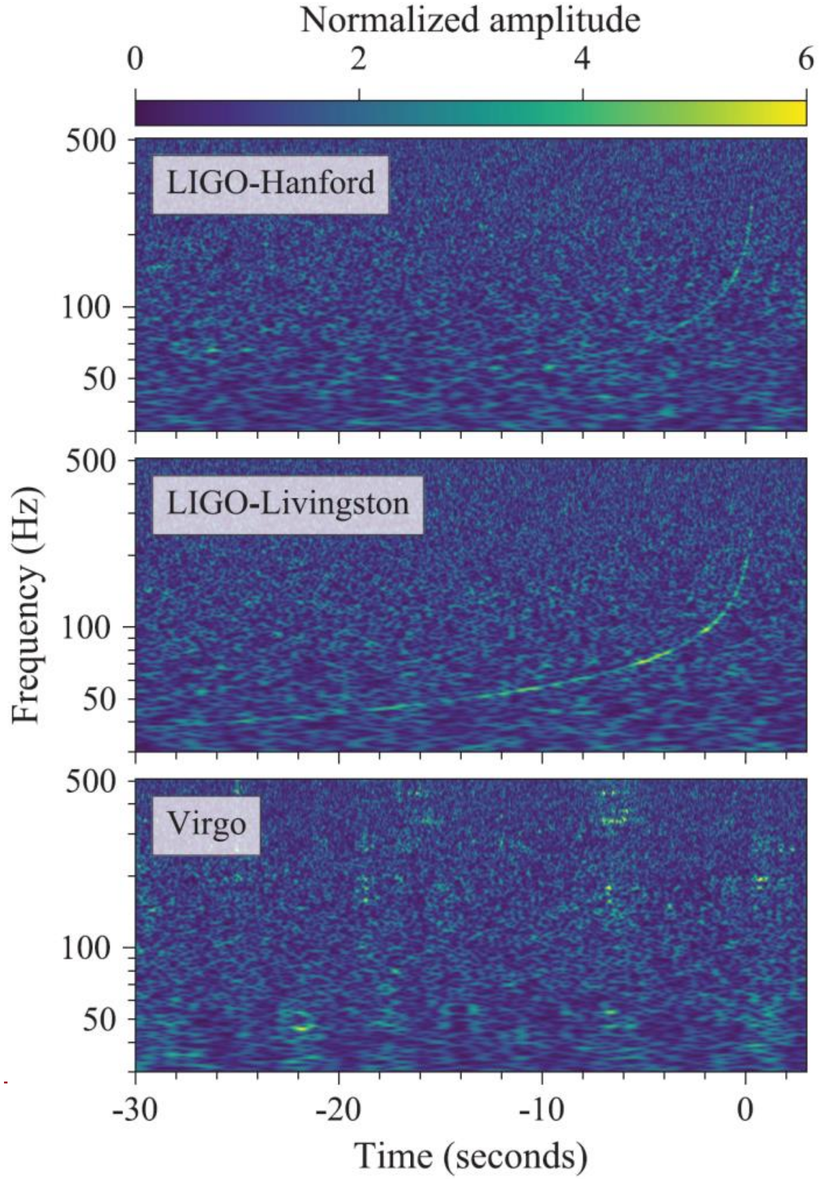
- Point particle approx.
- Information of orbits, NS mass

- Finite size effects appear
- tidal deformability
- radius

- BH or NS ⇒ maximum mass
- GWs from massive NS
  ⇒ NS radius of massive NS

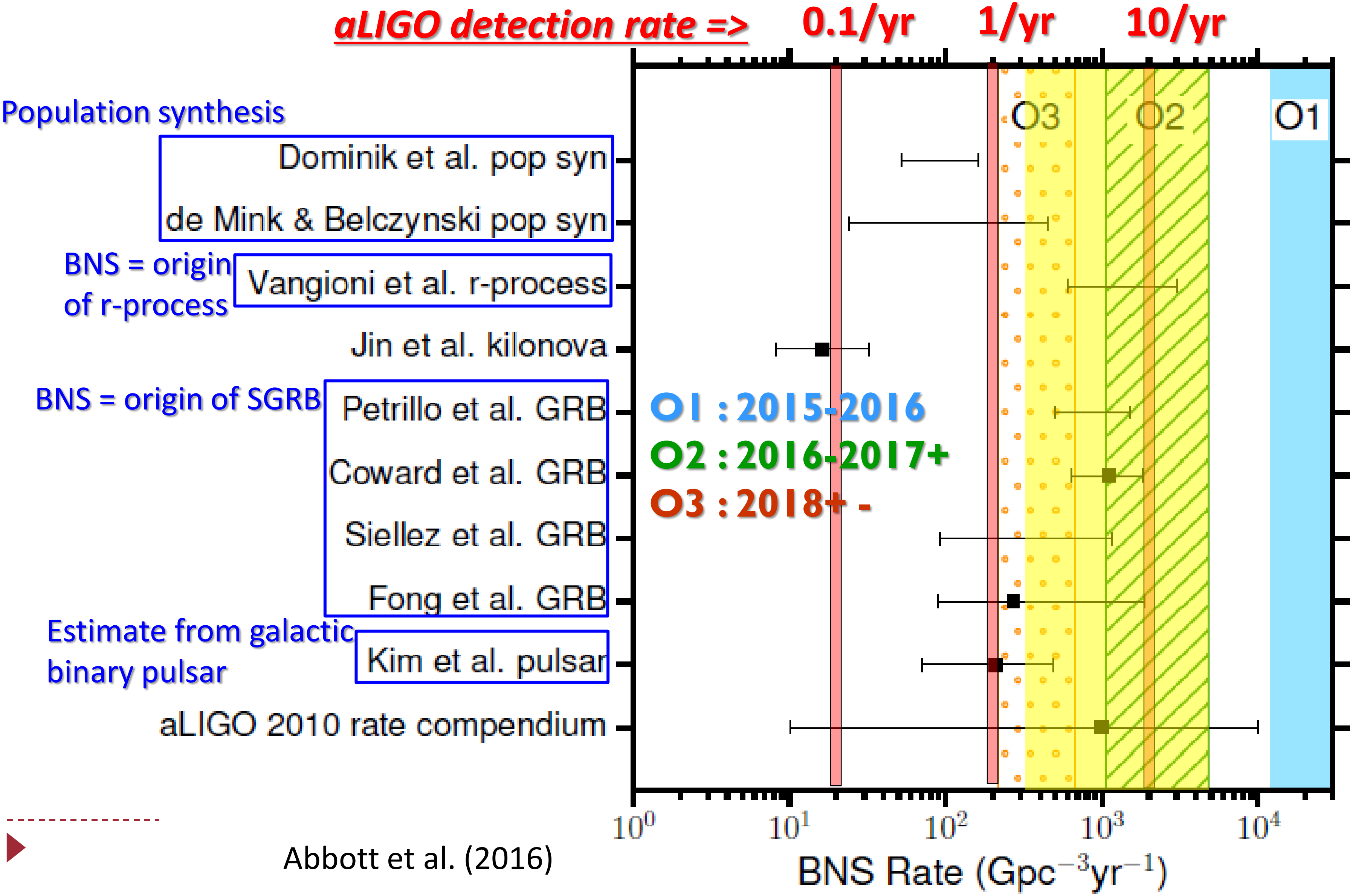
GW170817: Inspiral chirp signal provide mass and orbit parameters (90% C.L.)

- S/N = 32.4 (signal/noise)
- under a reasonable assumption that NS is not spinning rapidly like BH
- Chirp mass : $\frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = 1.188 M_\odot$ (0.1%)
  - Total mass : $2.74 M_\odot$ (1%)
  - Mass ratio : $m_1/m_2 = 0.7 - 1.0$
    - **Primary mass (m1) : 1.36-1.60 Msun**
    - **Secondary (m2) : 1.17-1.36 Msun**
- Luminosity distance : 40^{+8}_{-14} Mpc
- **Inclination angle : < 30 deg.**
  - **Consistet with EM observations ?**



Abbott et al. PRL 119, 161101 (2017)

Event rates from GW170817 : **320-4740 $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$**



aLIGO detection rate => **0.1/yr** **1/yr** **10/yr**

Population synthesis

BNS = origin of r-process

BNS = origin of SGRB

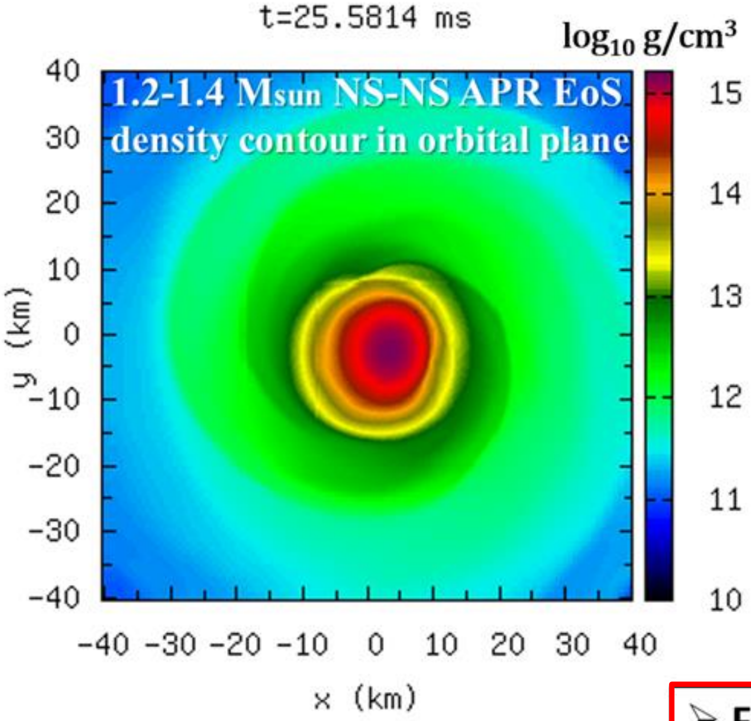
Estimate from galactic binary pulsar

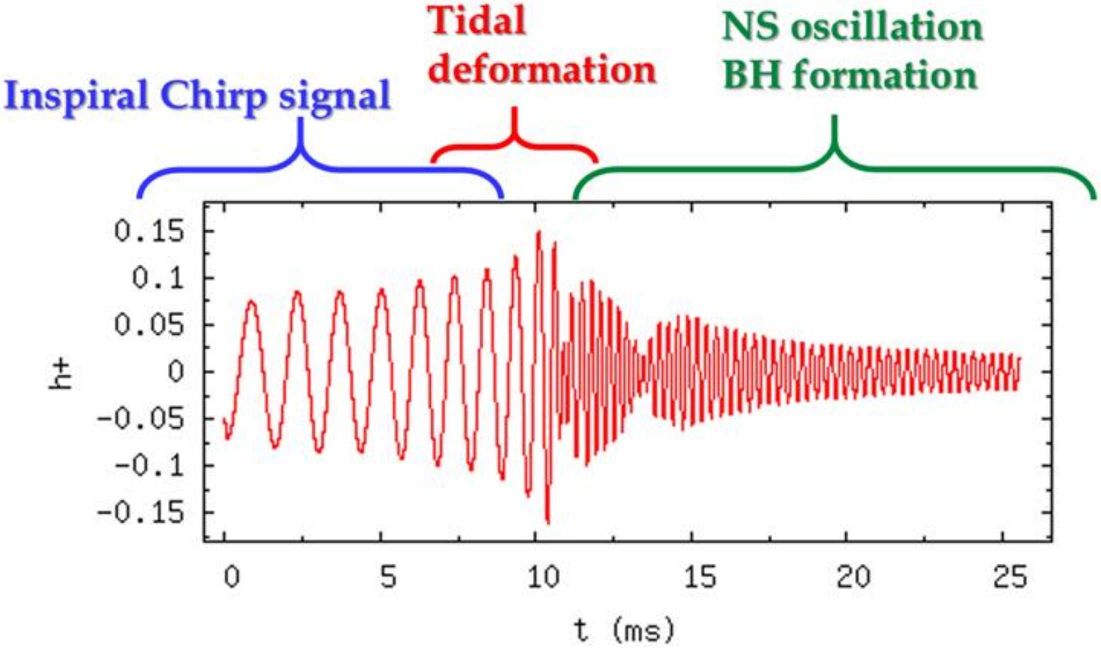
O1 : 2015-2016

O2 : 2016-2017+

O3 : 2018+ -

Abbott et al. (2016)





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Tidal deformability

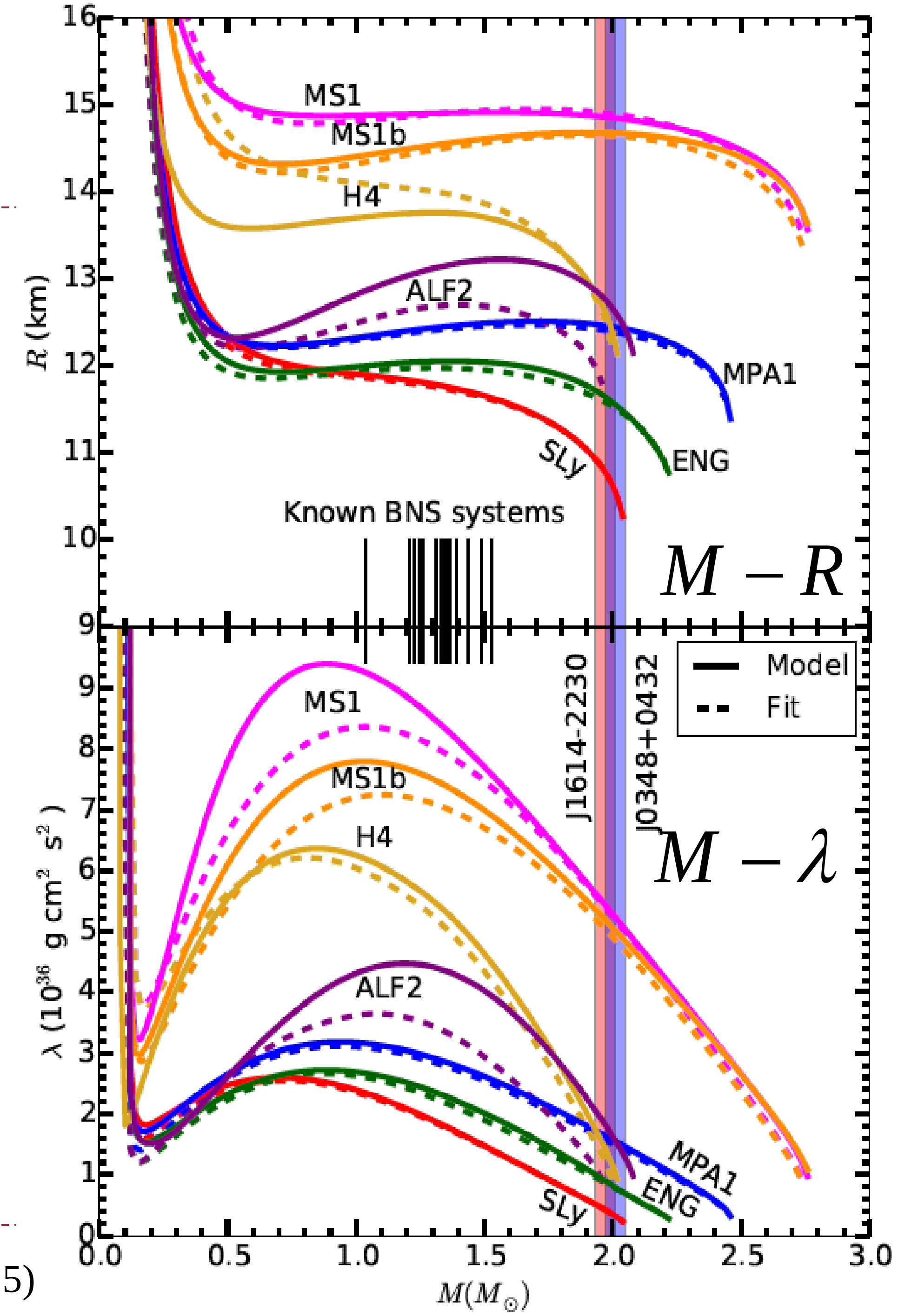
- Tidal deformability : λ
  - Response of quadrupole moment Q_{ij} to external tidal field E_{ij}

$$Q_{ij} = -\lambda E_{ij}$$

  - Stiffer NS EOS ⇒ larger NS radius ⇒ larger tidal deformability ⇒ more significant deviation of GW
  - We use non-dimensional version Λ

$$\lambda = \frac{C^5}{G}\Lambda R^5 \qquad C = \frac{GM}{c^2 R}$$

- Upper limit on tidal deformability $\Lambda \lesssim 800$ at 90% C.L. by GW170817
  - We could not distinguish between $\Lambda = 0$ and 800 GW signals

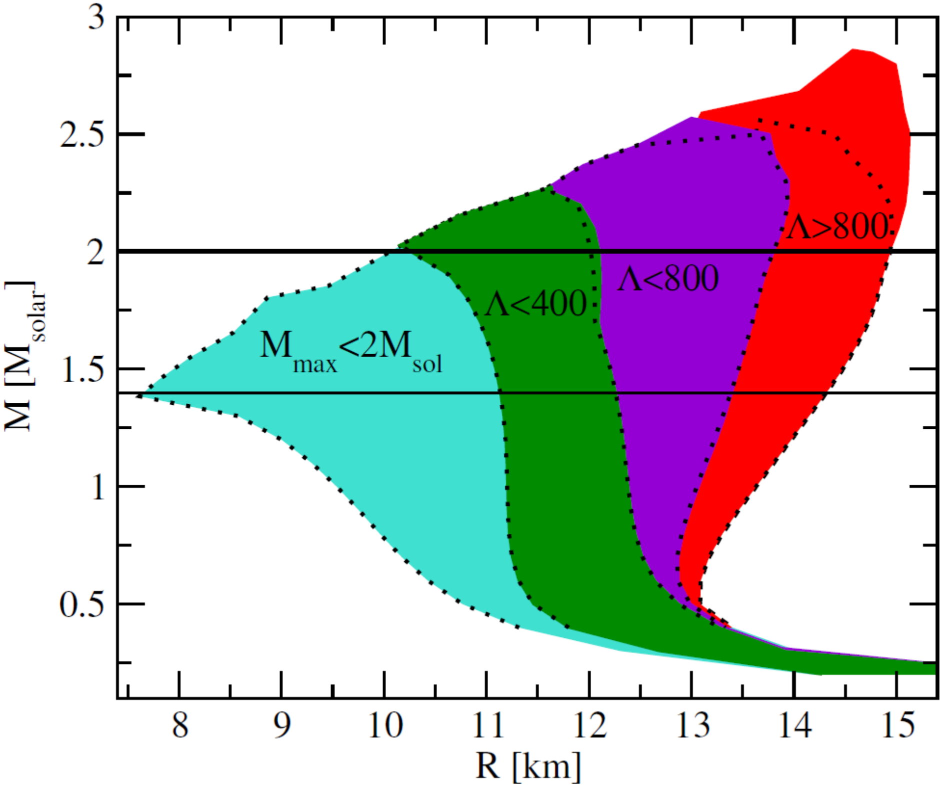


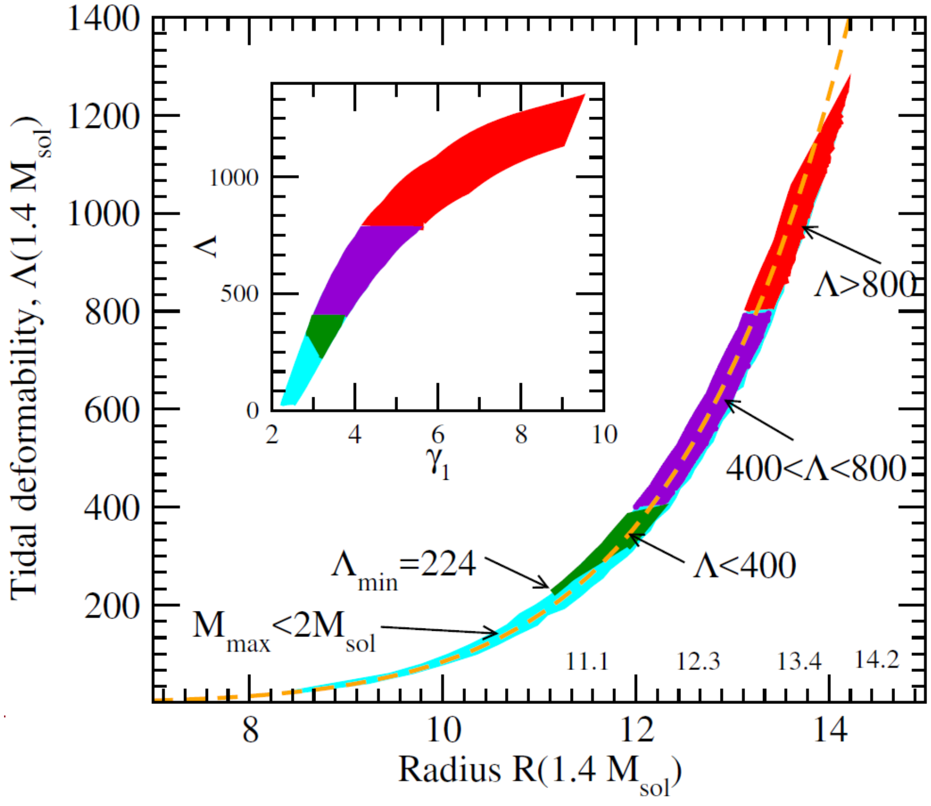
Lackey & Wade (2015)

Impact of the constraint on Λ

- $\Lambda < 800$ corresponds to NS radius of $R_{1.4} < 12.5$-13.5 km for a very wide class of EOS (Hebeler et al. 2013)
  - Together with the 2Msun NS constraint, $200 \lesssim \Lambda \lesssim 800$
  - *Luka's talk for more detail*

Annala et al. arXiv:1711.02644





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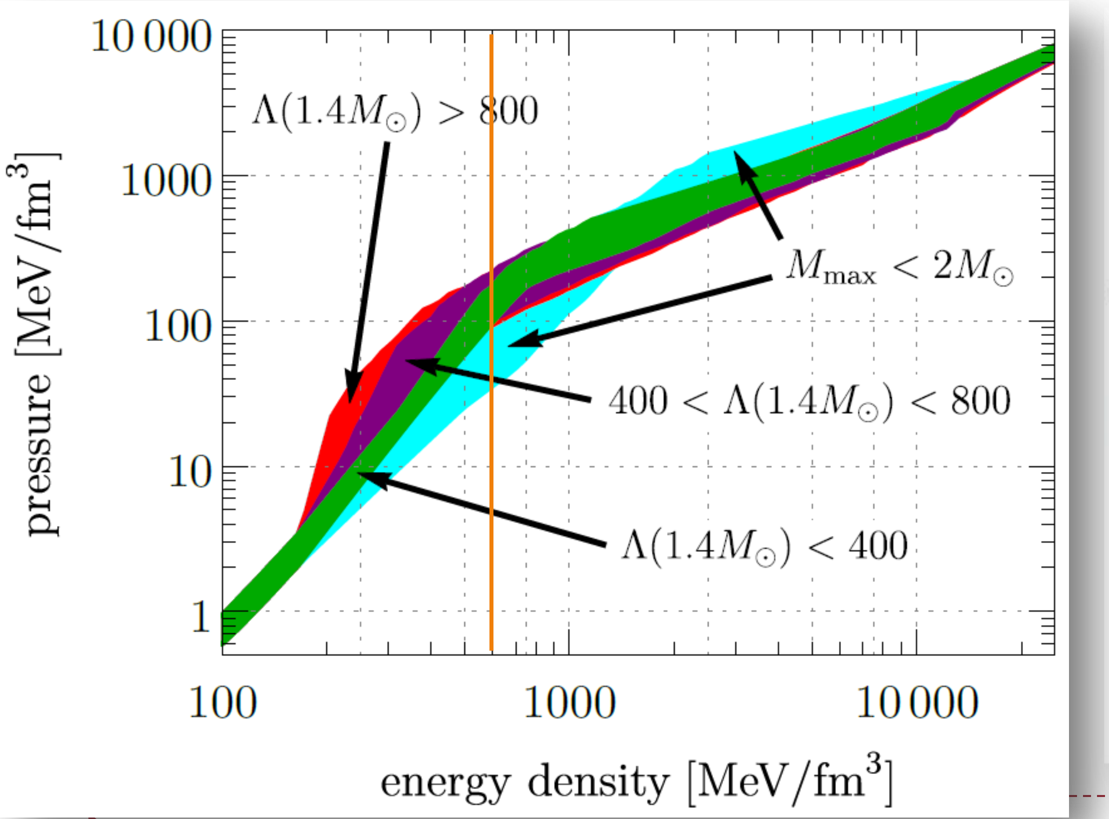
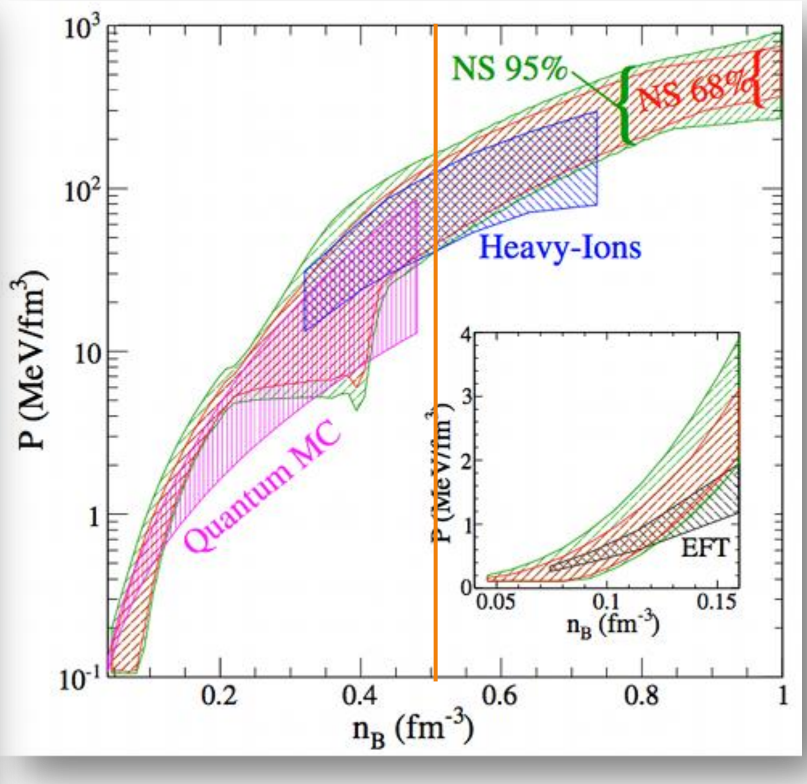
  - $P = 100 - 200\,\mathrm{MeV/fm}^3$ at $n_B \sim 3n_0$?





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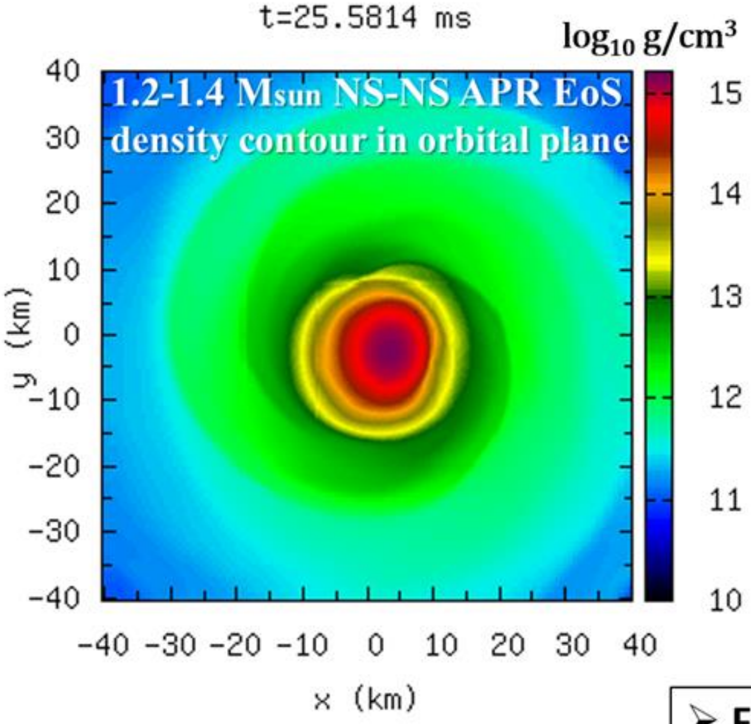

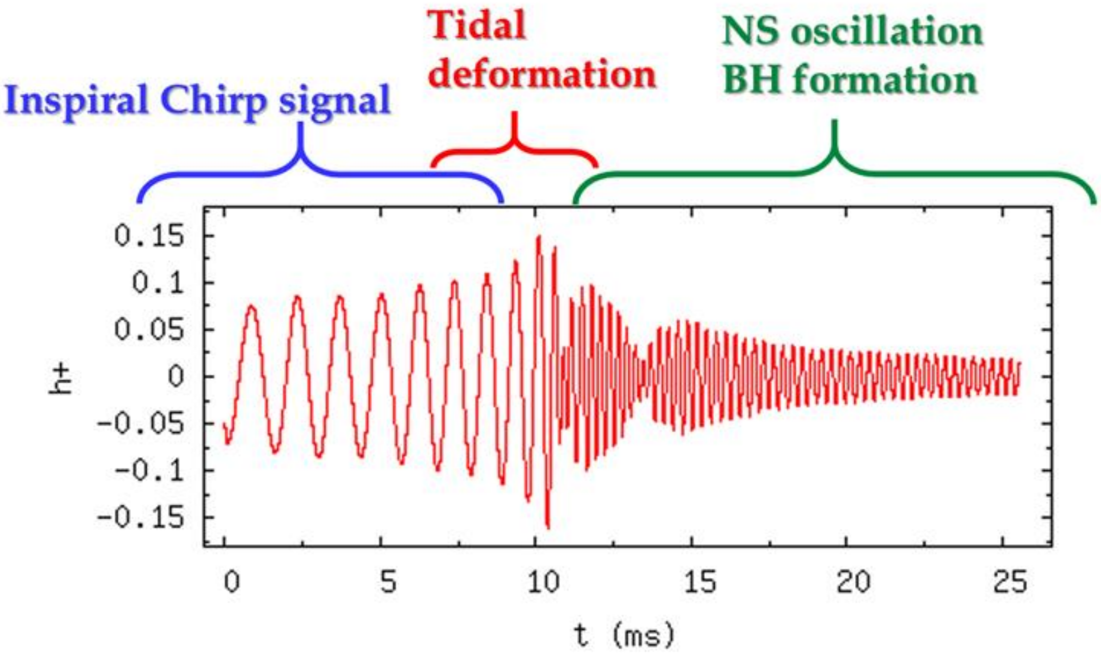

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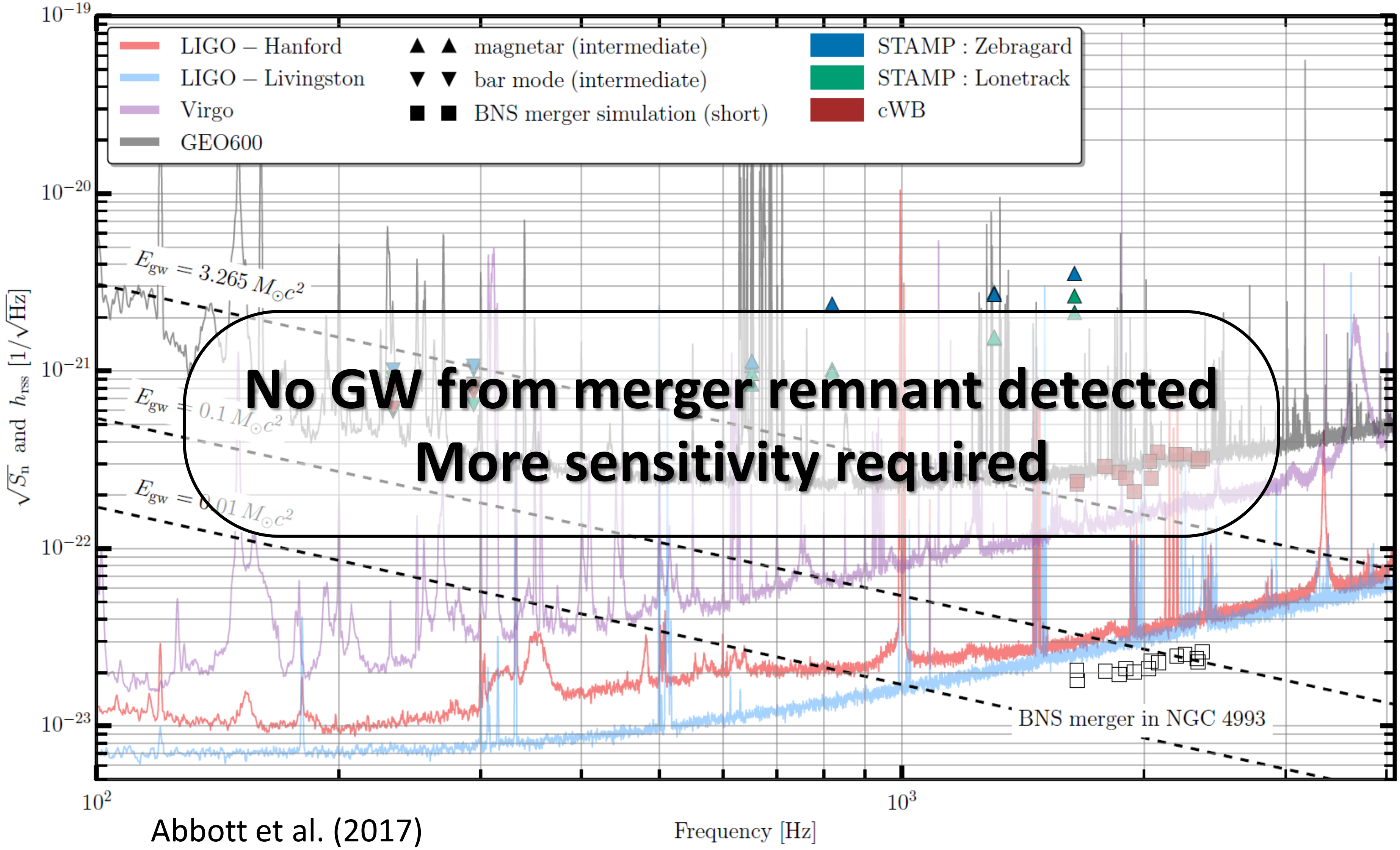
GW from merger remnant detected



No GW from merger remnant detected
More sensitivity required

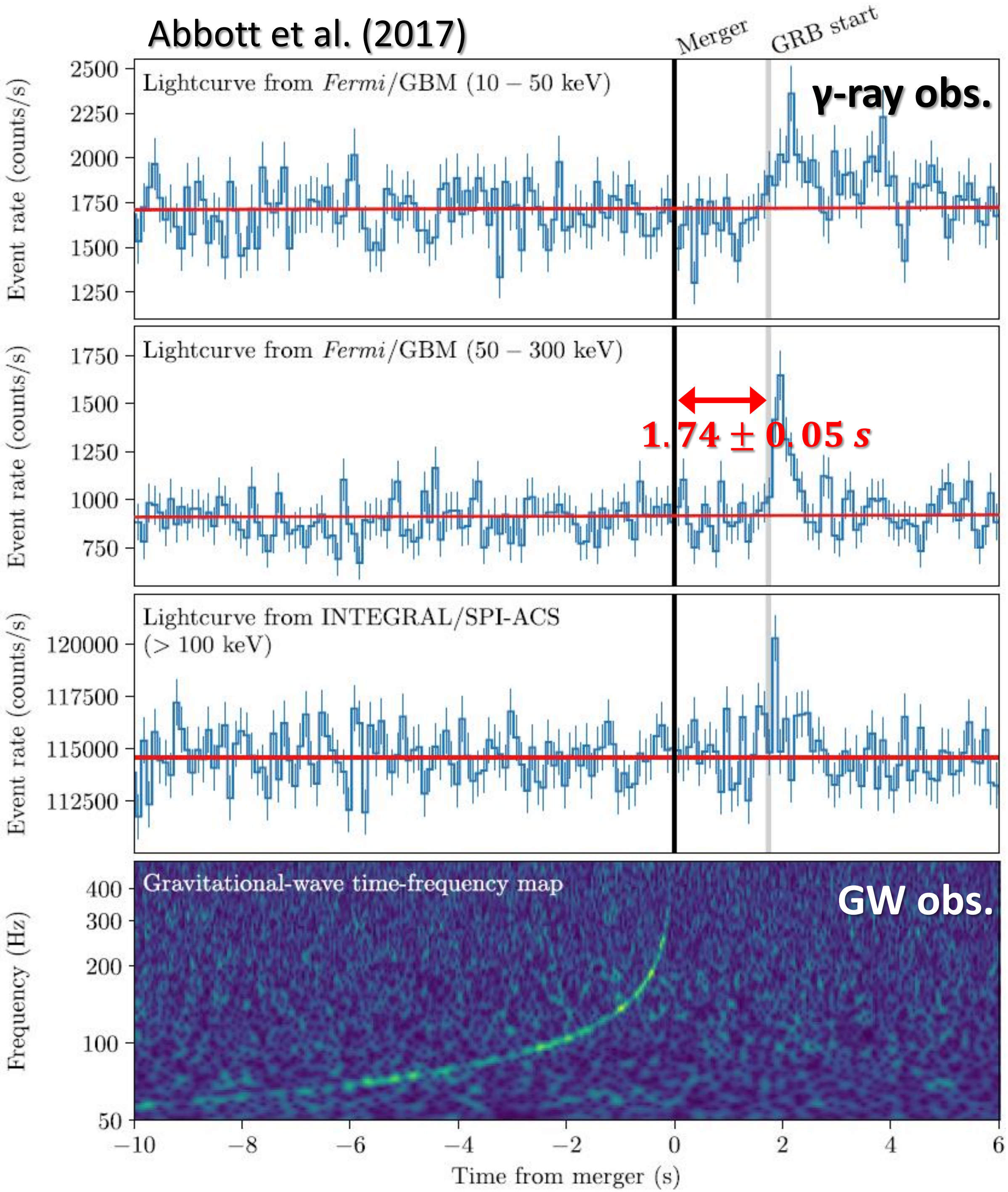
Abbott et al. (2017)

EM follow-up observations of GW170817

gamma-ray, X-ray, and Radio observations and their implication to SGRB modelling

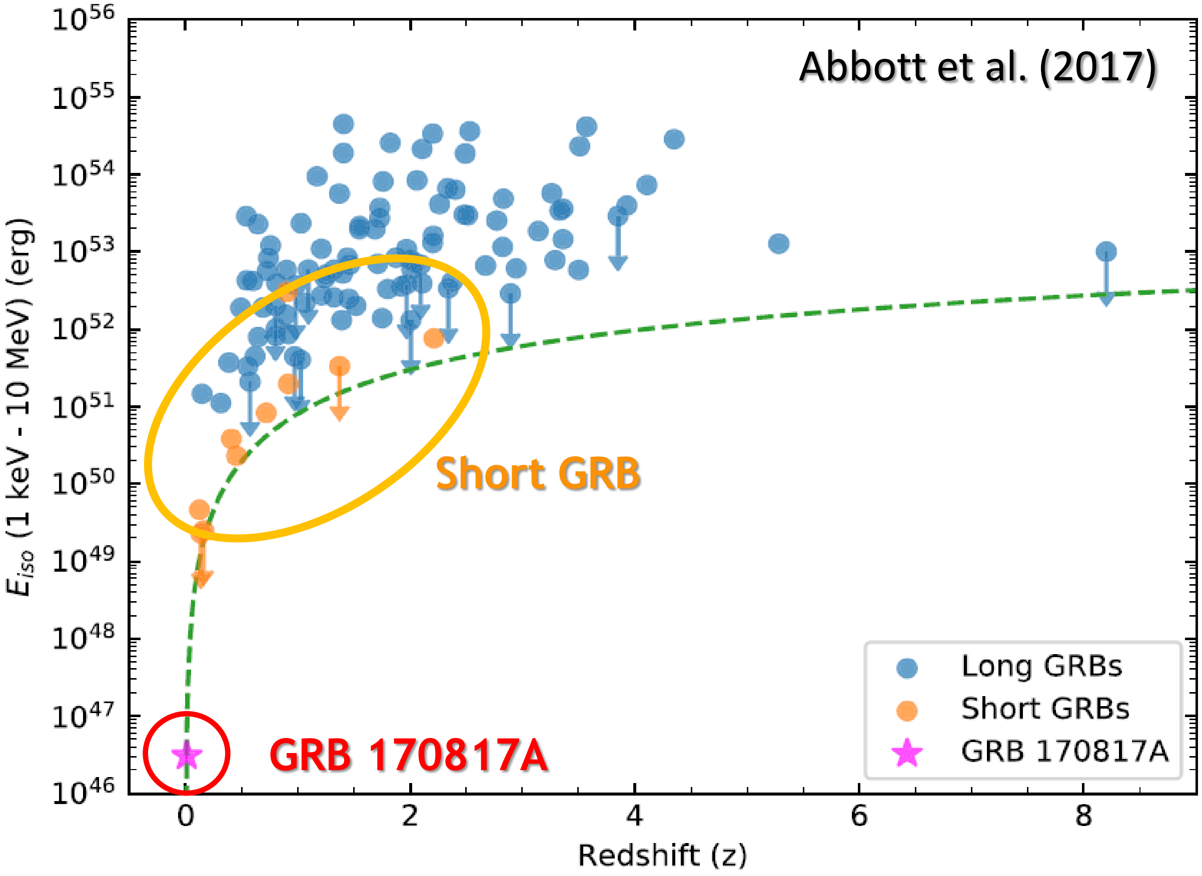
GRB170817A

- Observed by Fermi/GBM and INTEGRAL
    - $\sim 1.74 \pm 0.05\ s$ after GW170817
        - Abbott et al. (2017) ApJL 848, L13;
        - Goldstein et al. (2017) ApJL 848, L14



GRB170817A

- Observed by Fermi/GBM and INTEGRAL
  - ~ 2 (1.74±0.05) sec after the GW170817
  - **Very faint : $E_{iso} \sim 5 \times 10^{46}$ erg (fainter by 4 orders than typical SGRBs)**



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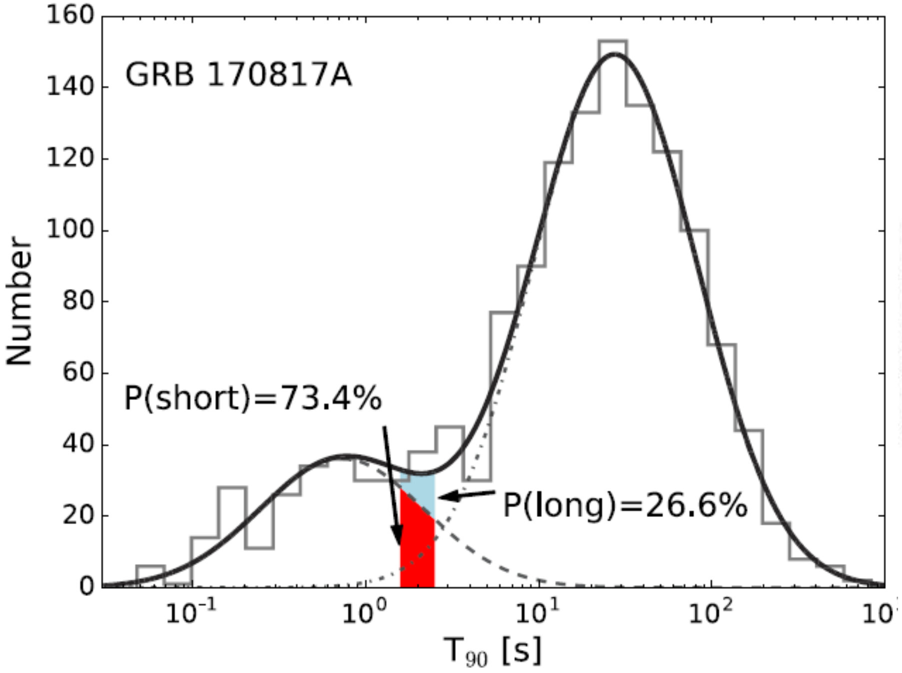
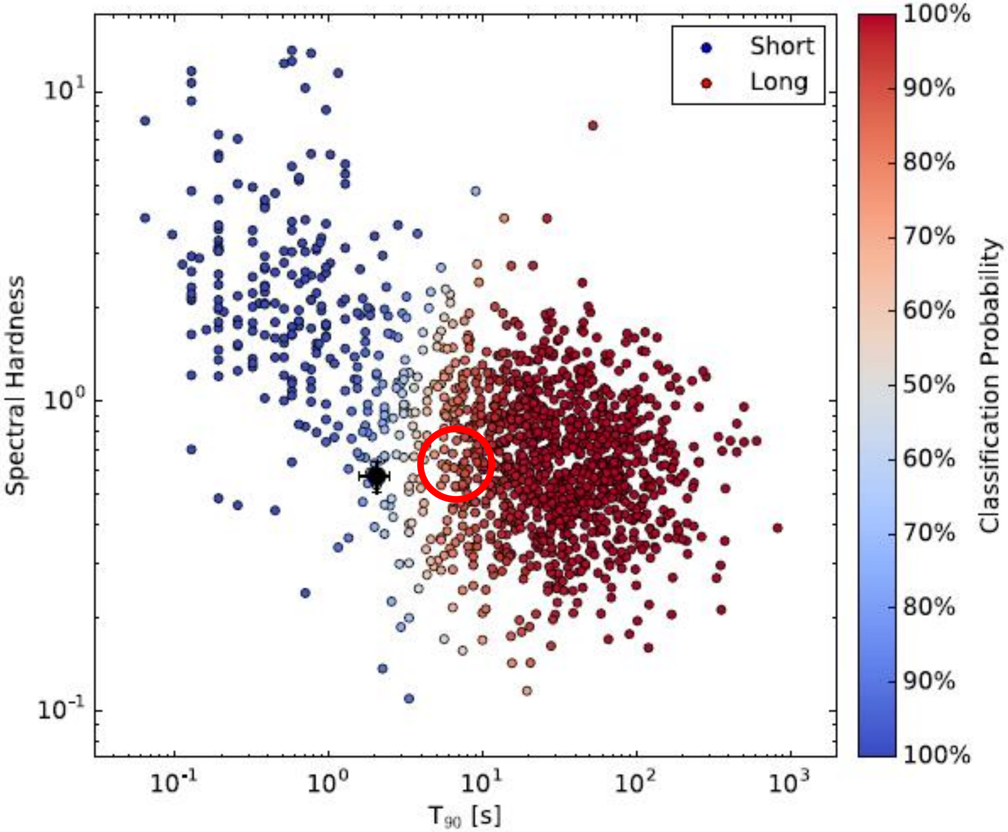
  - **Duration and hardness are consistent with typical SGRBs**





Goldstein et al. (2017)

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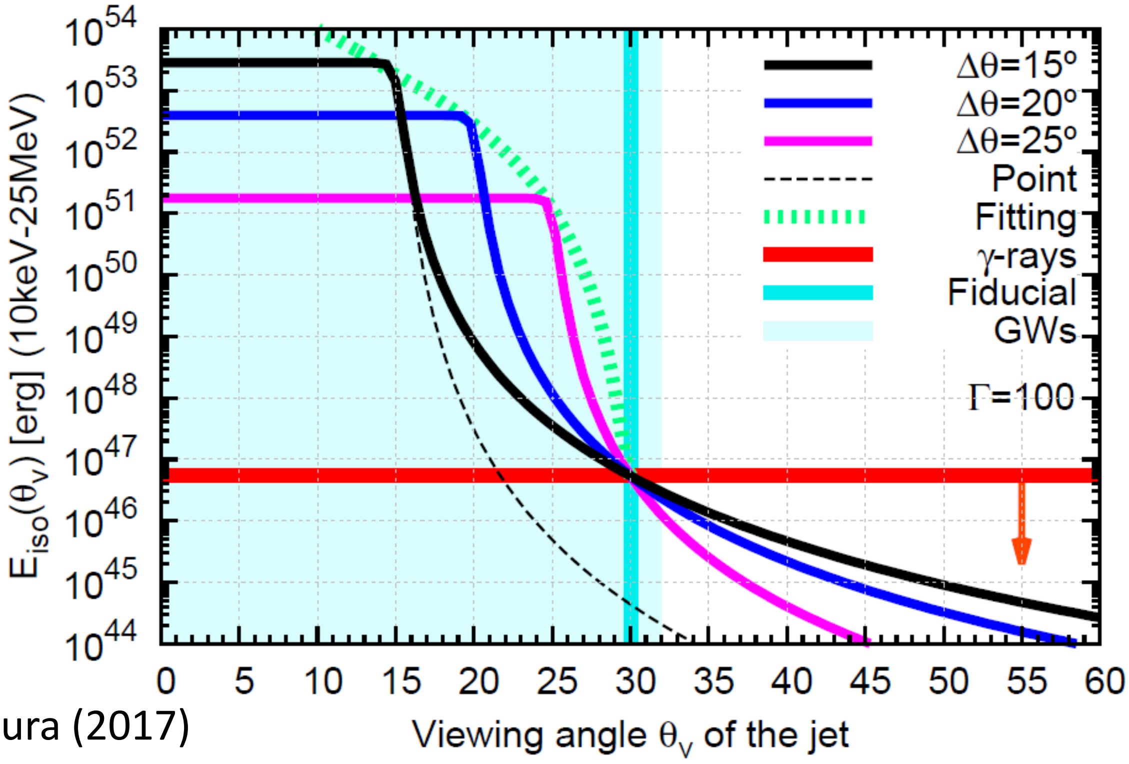
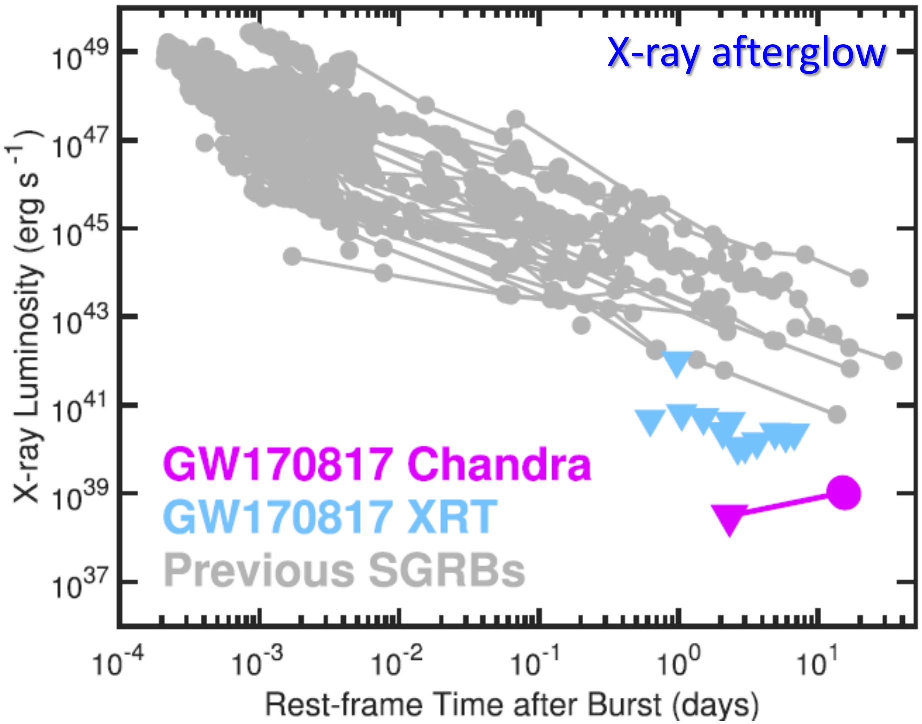
  - Very faint : Eiso ~ 5 × 10^{46} erg (fainter by 4 orders than typical SGRBs)
  - Duration and hardness are consistent with typical SGRBs
  - **Suggest off-axis nature of this GRB (e.g., Ioka & Nakamura, 2017)**
    - But need some fine tuning
    - **Consistent with GW observation !**
      - ☐ **Θ < 30 deg.**

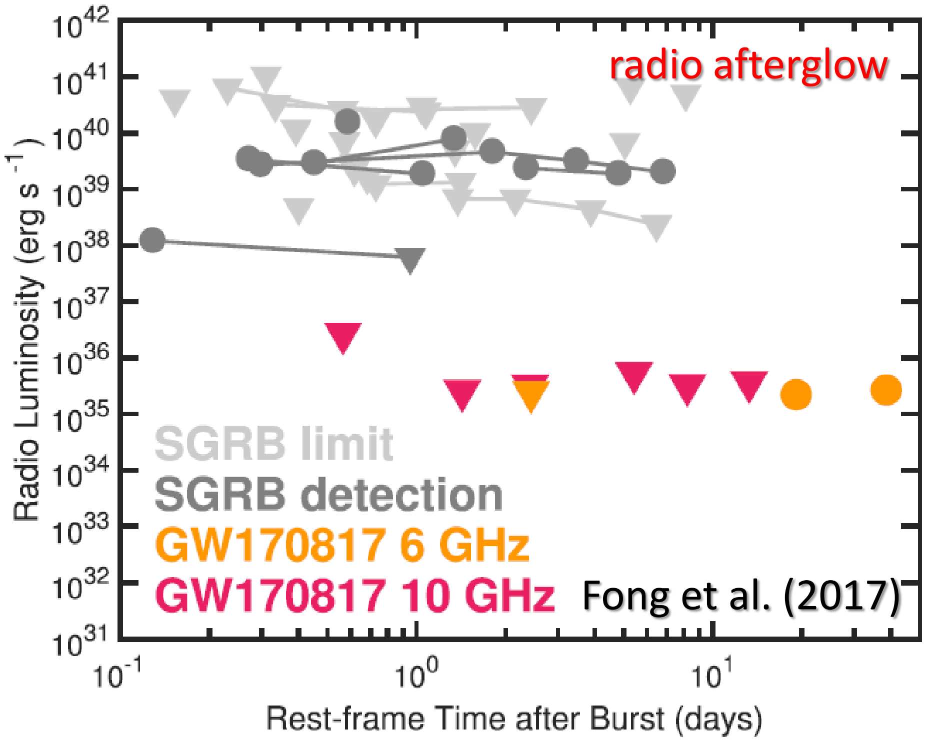


Ioka & Nakamura (2017)

X-ray and radio afterglow

- X-ray : 3000/50 times fainter than the median/faintest
  - Margutti et al. (2017) ApJL 848, L20; Fong et al. (2017) ApJL 848, L23, and more
- Radio : 10^4/500 times less luminous than median/faintest
  - Alexander et al. (2017) ApJL 848, L21; Fong et al. (2017) ApJL 848, L23, and more





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- X-ray : 3000/50 times fainter than the median/faintest
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- **X-ray and radio afterglows rise up at ~ 15 days after**
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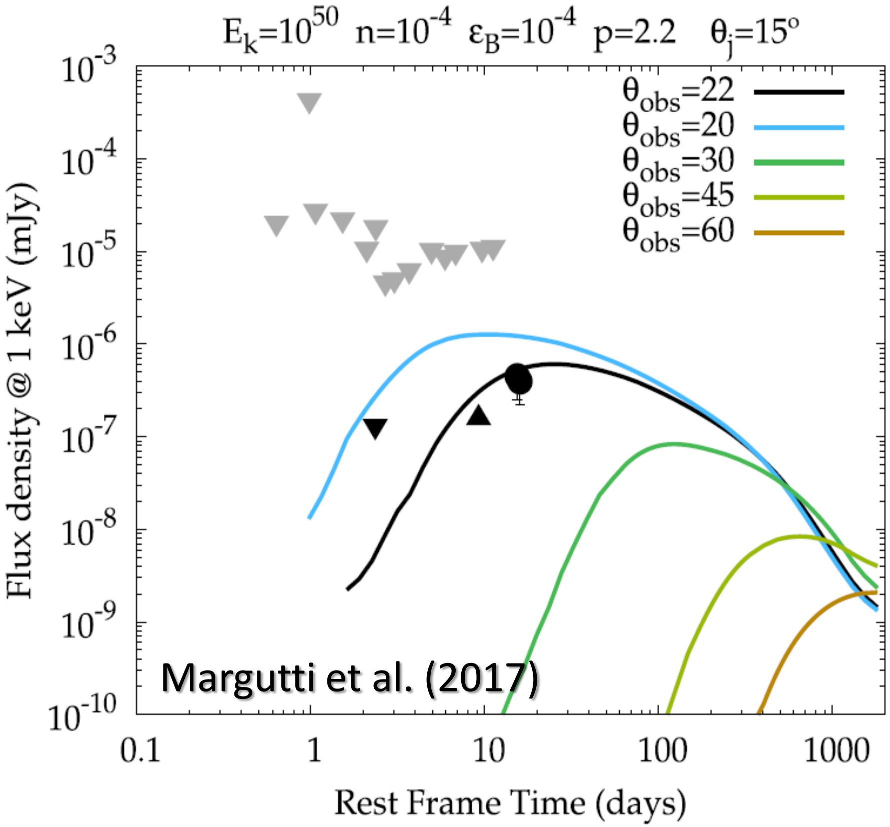

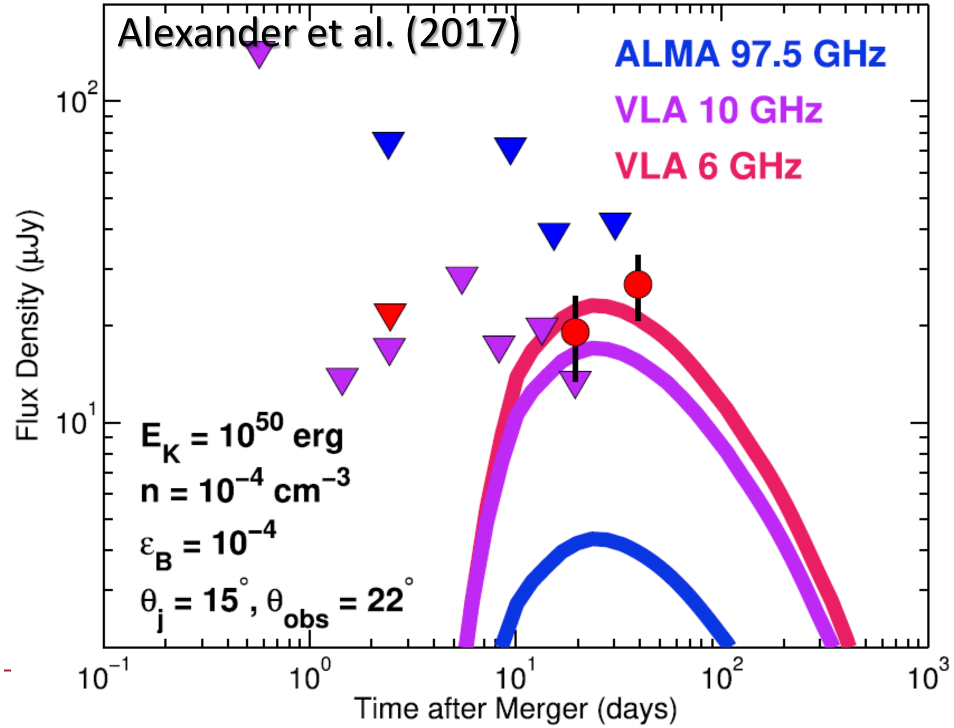

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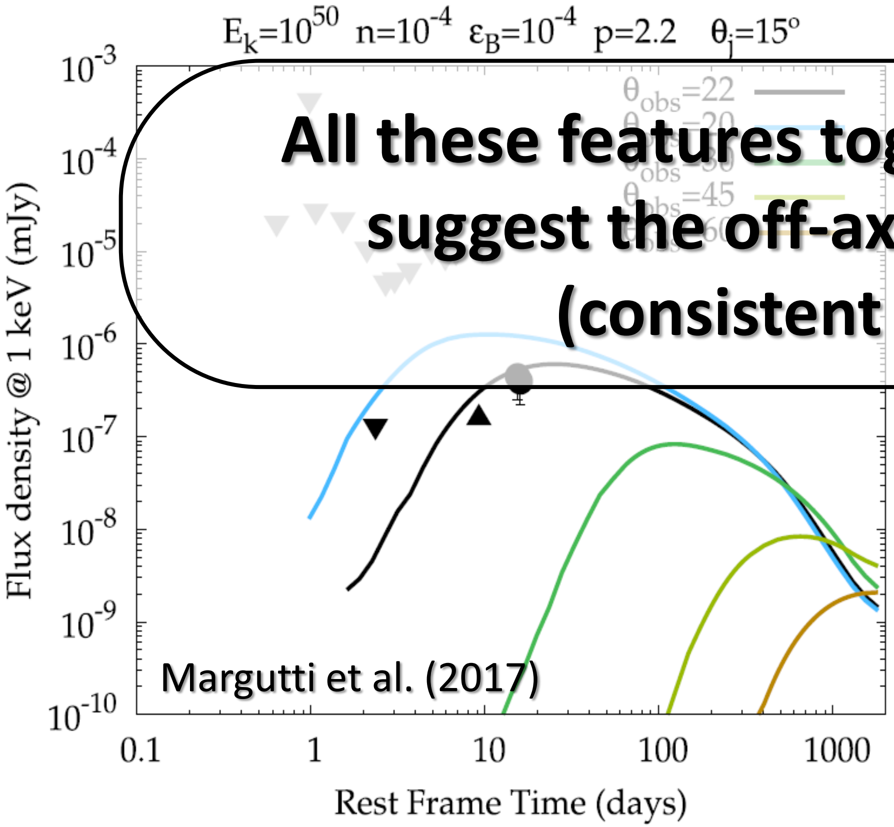
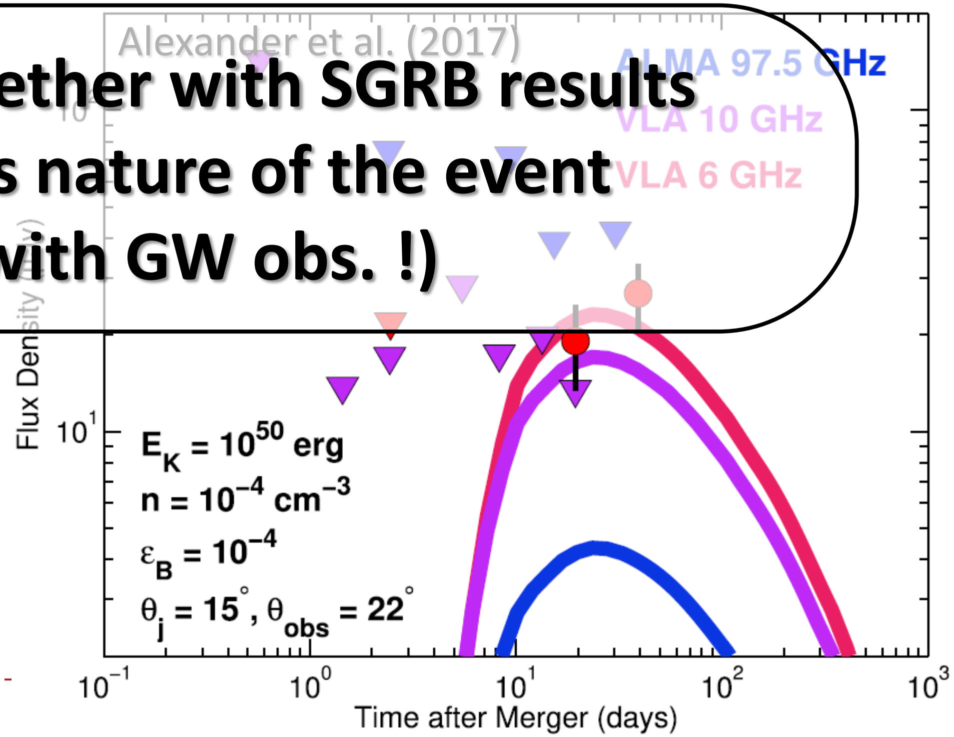


Margutti et al. (2017)

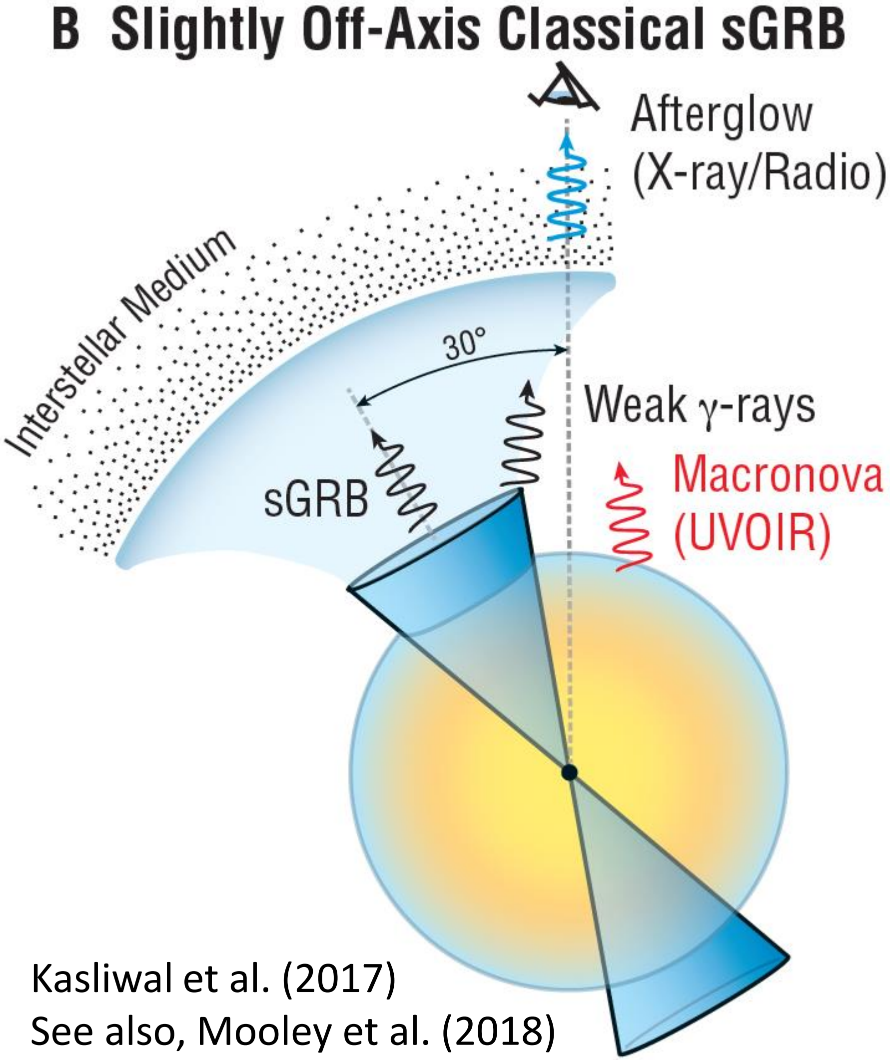


Alexander et al. (2017)

All these features together with SGRB results suggest the off-axis nature of the event (consistent with GW obs. !)

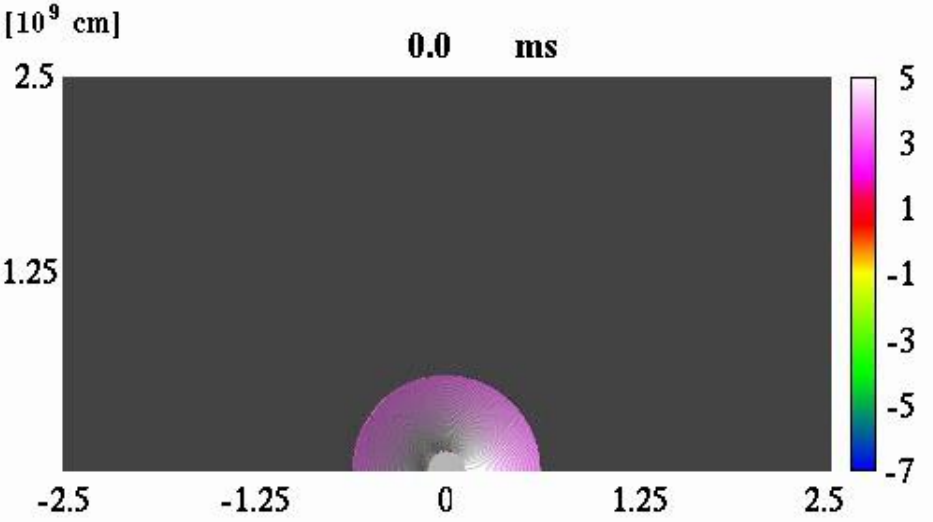
Kasliwal et al., arXiv:1710.05436
Ioka & Nakamura, arXiv:1710.05905
Murguia-Berthier et al. (2017) ApJL 848, L34

Suggested models



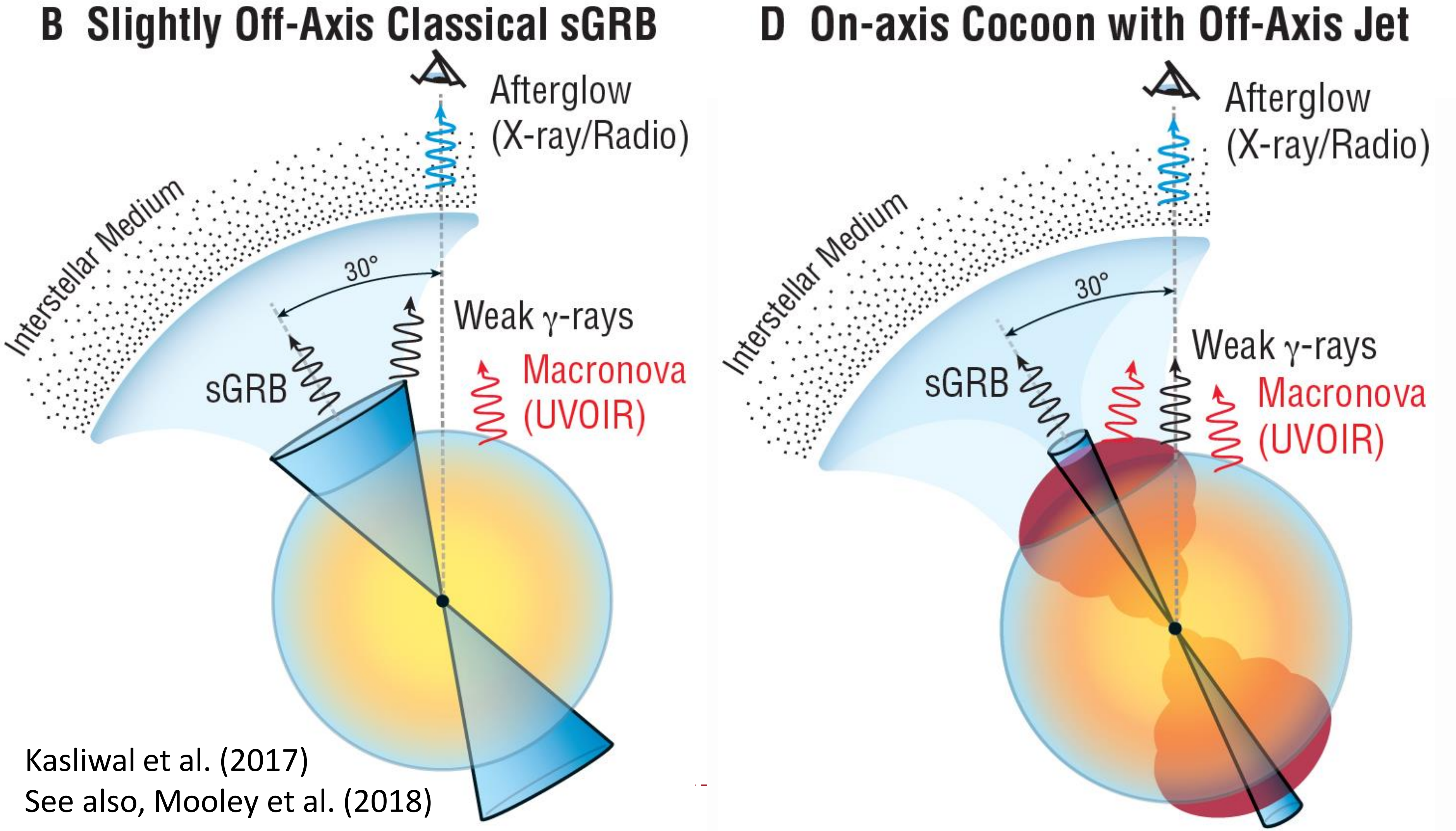
Kasliwal et al. (2017)
See also, Mooley et al. (2018)

Jet propagation in the merger ejecta will be accompanied by cocoon formation



Nagakura, Hotokezaka, YS et al. (2014)
Gottlieb et al. (2018)
Bromberg et al. (2018）

Suggested models



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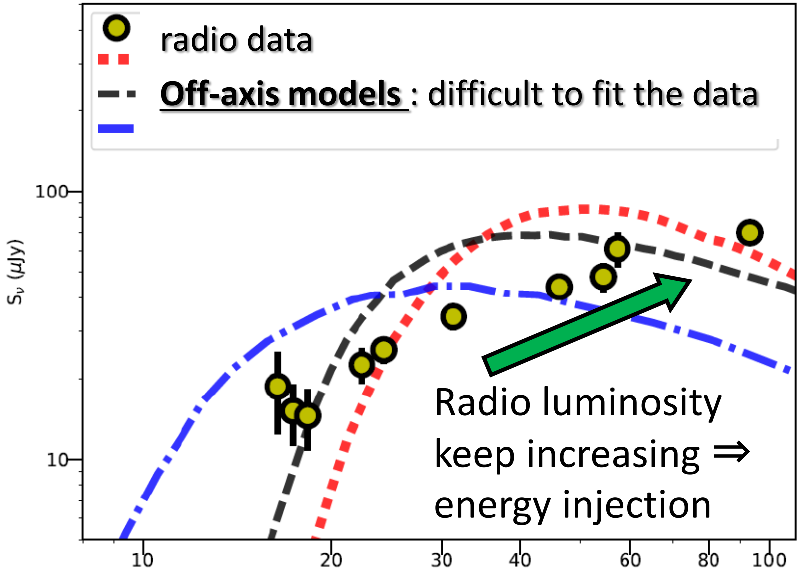
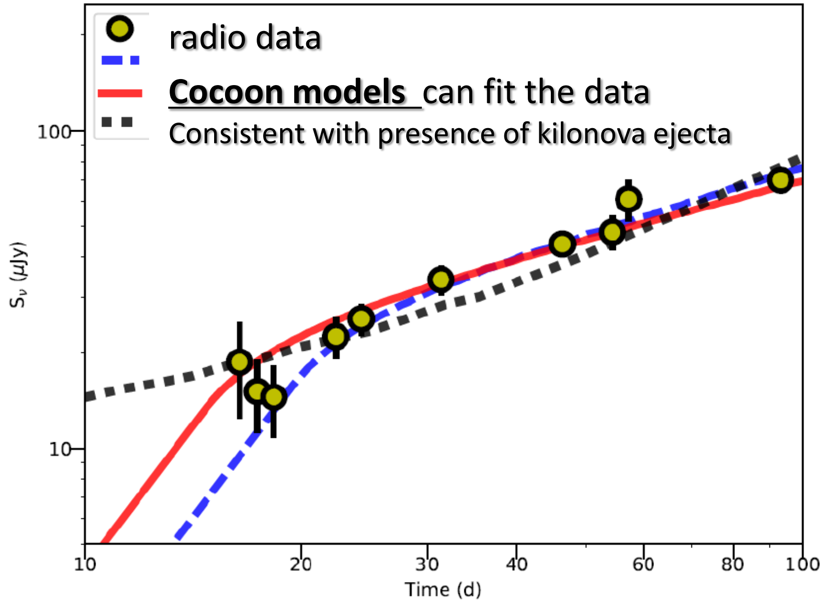
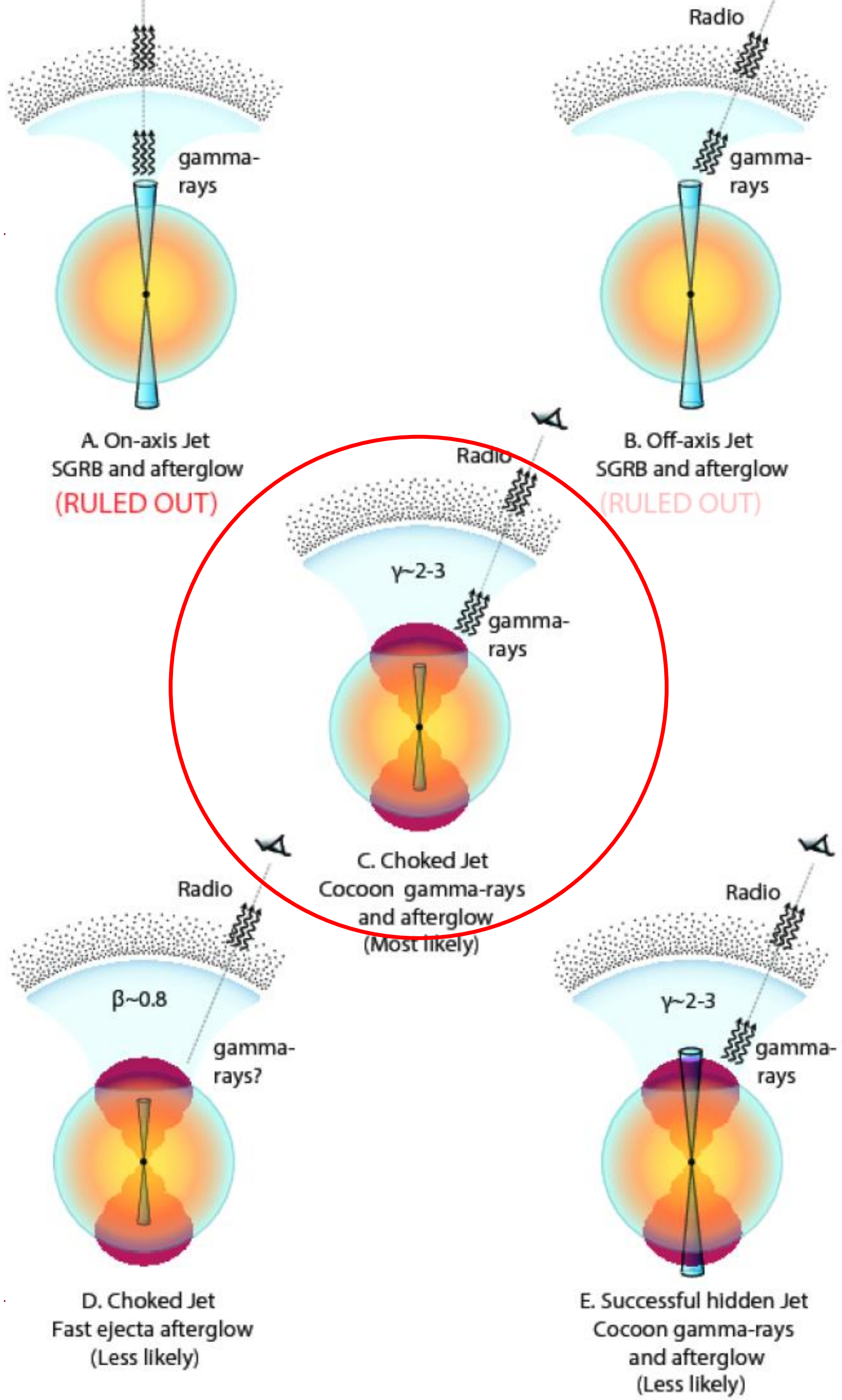
Mooley et al. (2018)

100 days later …

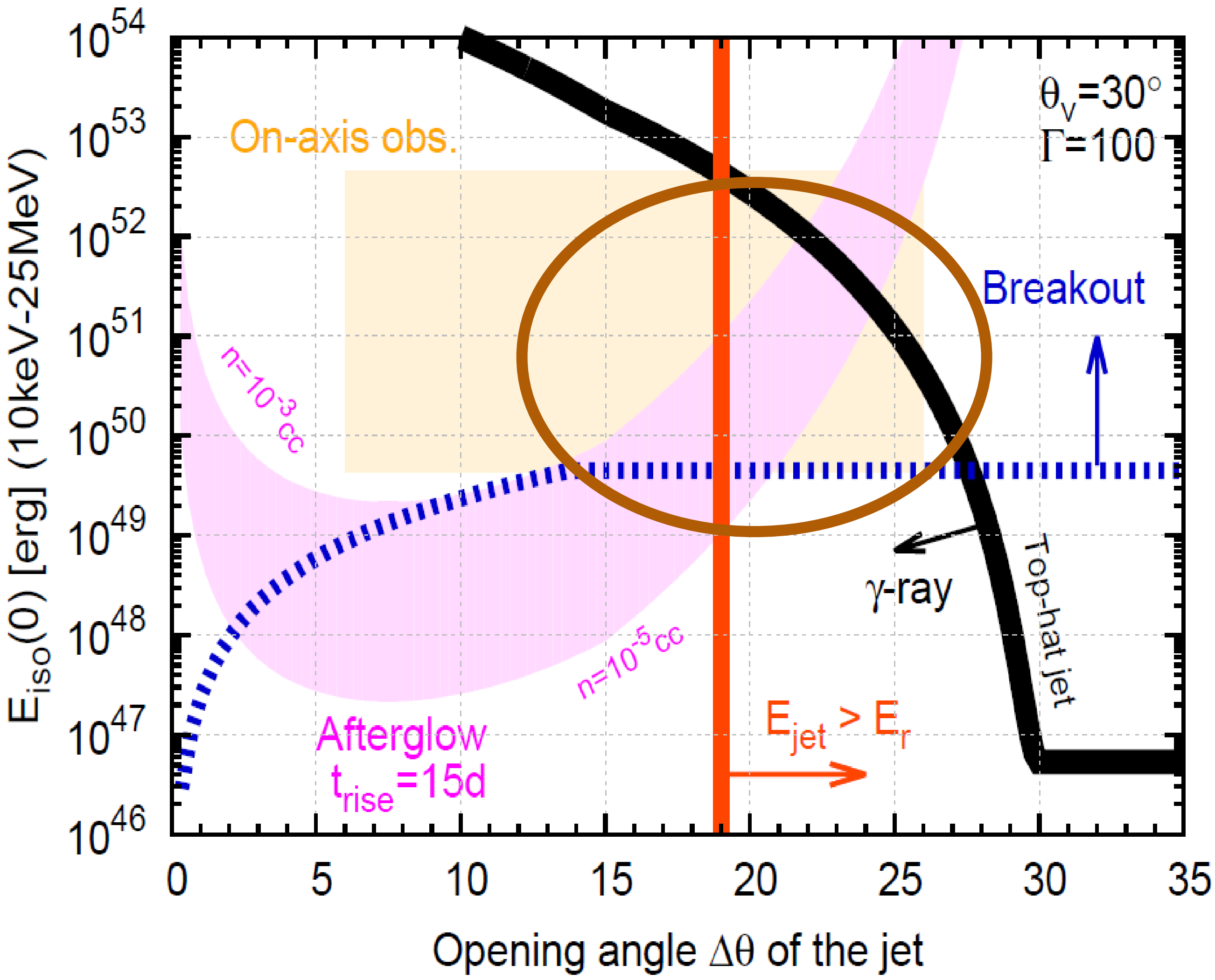






Ioka & Nakamura, arXiv:1710.05905

A systematic modelling



- **Parameters**
  - Viewing angle
    - < 32° (GW)
  - Lorentz factor
    - Γ ~ 100 (GRB)
  - ISM density
    - Host galaxy
  - jet opening angle
  - Eiso at on-axis
- **Constraints**
  - **γ-ray emission**
  - **Jet breakout**
  - **Afterglow 15d after**
  - **Cocoon domination in blue kilonova**

EM follow-up observations of GW170817

UV, optical, and IR observations
and their implication to kilonova modelling

UV-Optical to NIR light curves/spectra

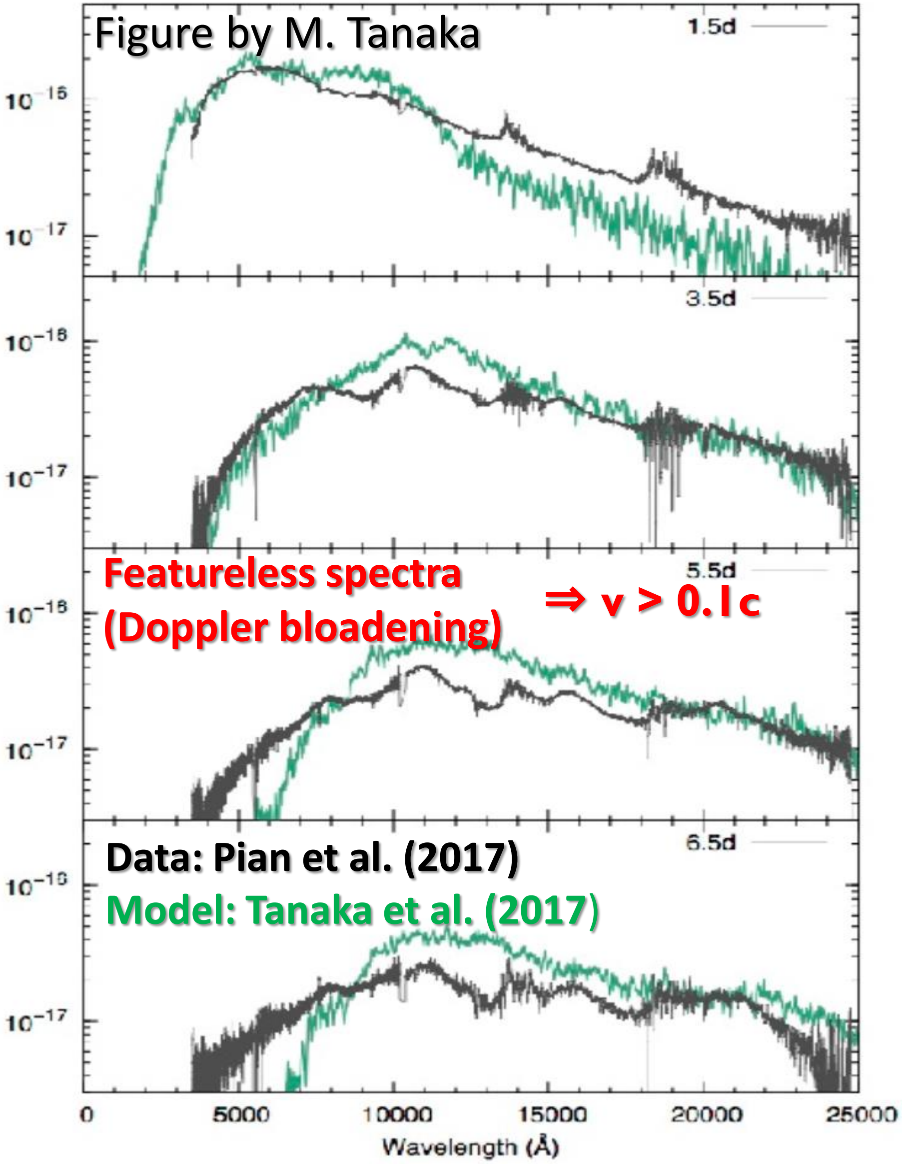


Figure by M. Tanaka

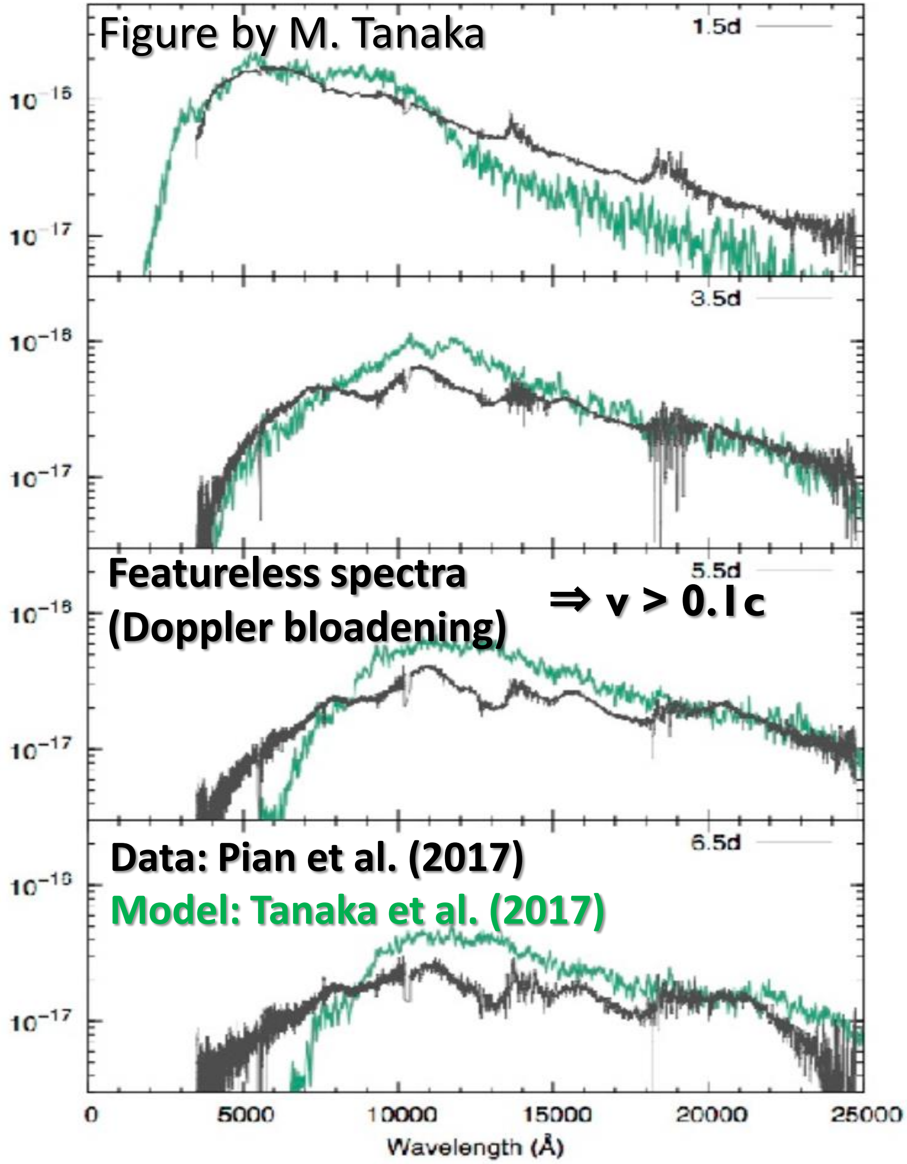
Featureless spectra (Doppler bloadening)

⇒ v > 0.1c

Data: Pian et al. (2017)

Model: Tanaka et al. (2017)

UV-Optical to NIR light curves/spectra



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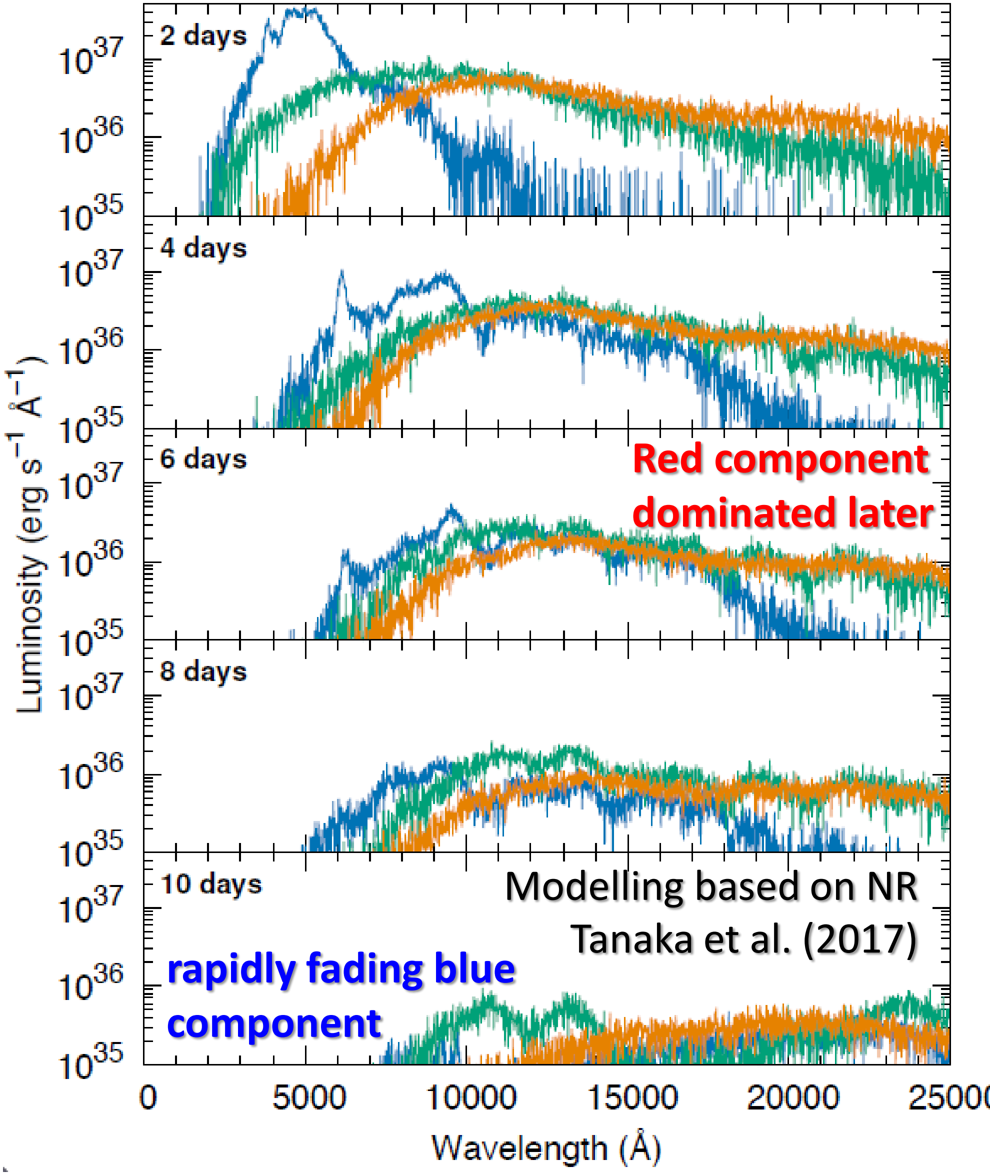


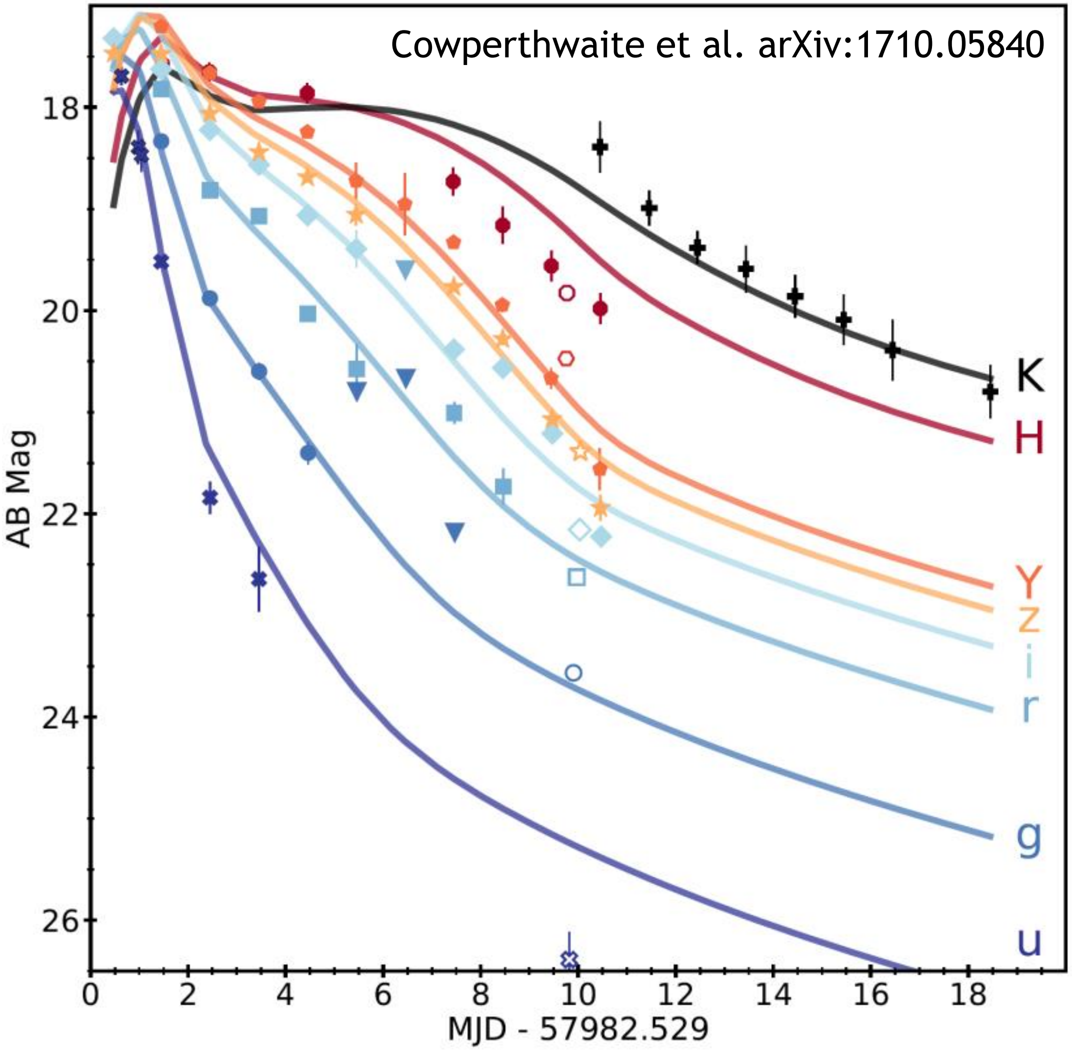
Red component dominated later

Modelling based on NR Tanaka et al. (2017)

rapidly fading blue component

UV-Optical to NIR light curves/spectra

- UV-Optical-NIR signals are characterized by
  - Rapid fading in UV and blue optical bands
  - Significant reddening of the optical/NIR colors in a later phase
  - Linear polarization of 0.5%
    - Covino et al. Nature Astronomy (2017)
  - **Largely consistent with kilonova/macronova model**
    - Jonas's and Luke's talks for more on r-process


Cowperthwaite et al. arXiv:1710.05840

Utsumi et al. arXiv:1710.05848, Tanvir et al. arXiv:1710.05455, Nicholl et al. ariXiv:1710.05456, Chronock et al. arXiv:1710.05454, Smartt et al. arXiv:1710.05841, etc

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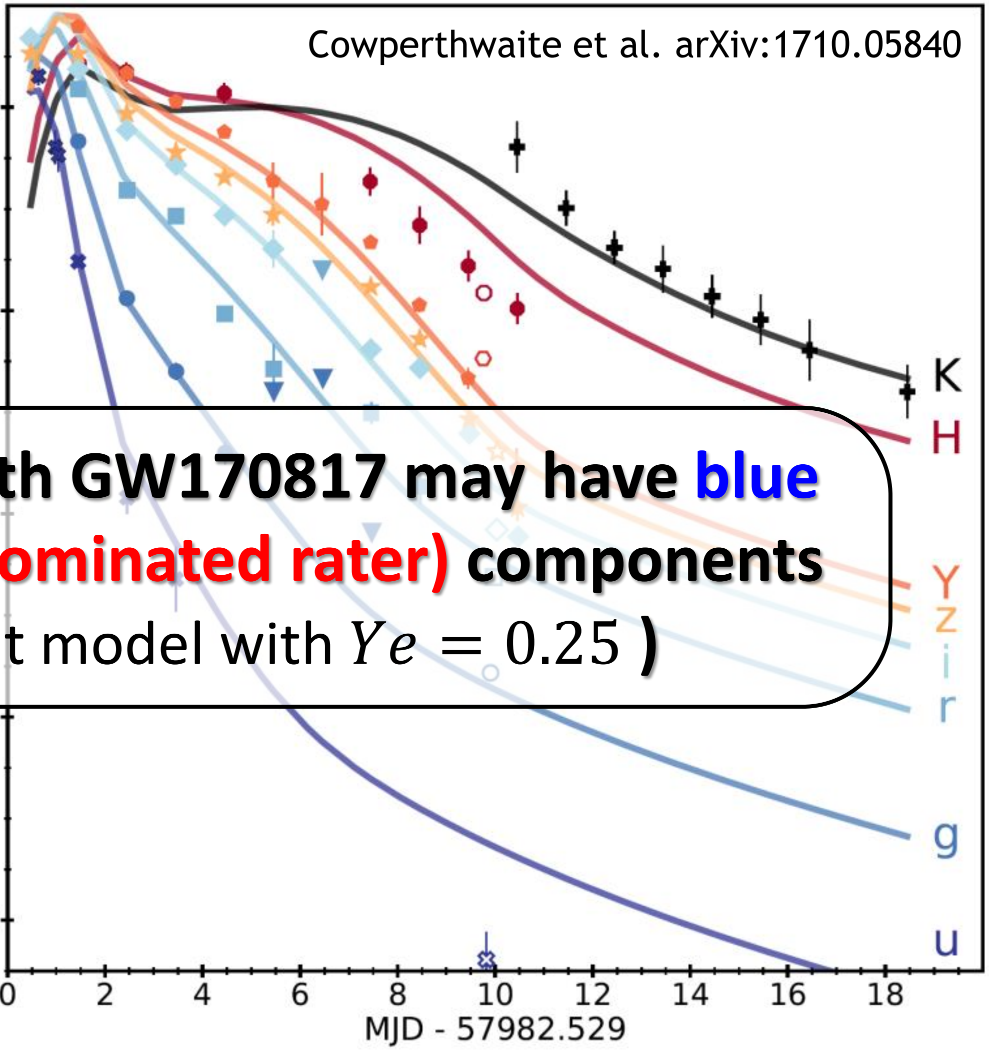


Cowperthwaite et al. arXiv:1710.05840

kilonova associated with GW170817 may have blue (rapid fading) & red (dominated rater) components

(or one component model with $Ye = 0.25$)

Utsumi et al. arXiv:1710.05848, Tanvir et al. arXiv:1710.05455, Nicholl et al. ariXiv:1710.05456, Chronock et al. arXiv:1710.05454, Smartt et al. arXiv:1710.05841, etc

Modelling based on Kilonovae

- Peak time, L_{peak}, and color depend of M_{ej}, V_{ej}, and opacity as

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

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

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

Li & Paczynski (1998)
Kasen et al. (2013)
Barnes & Kasen (2013)
Tanaka & Hotokezaka (2013)

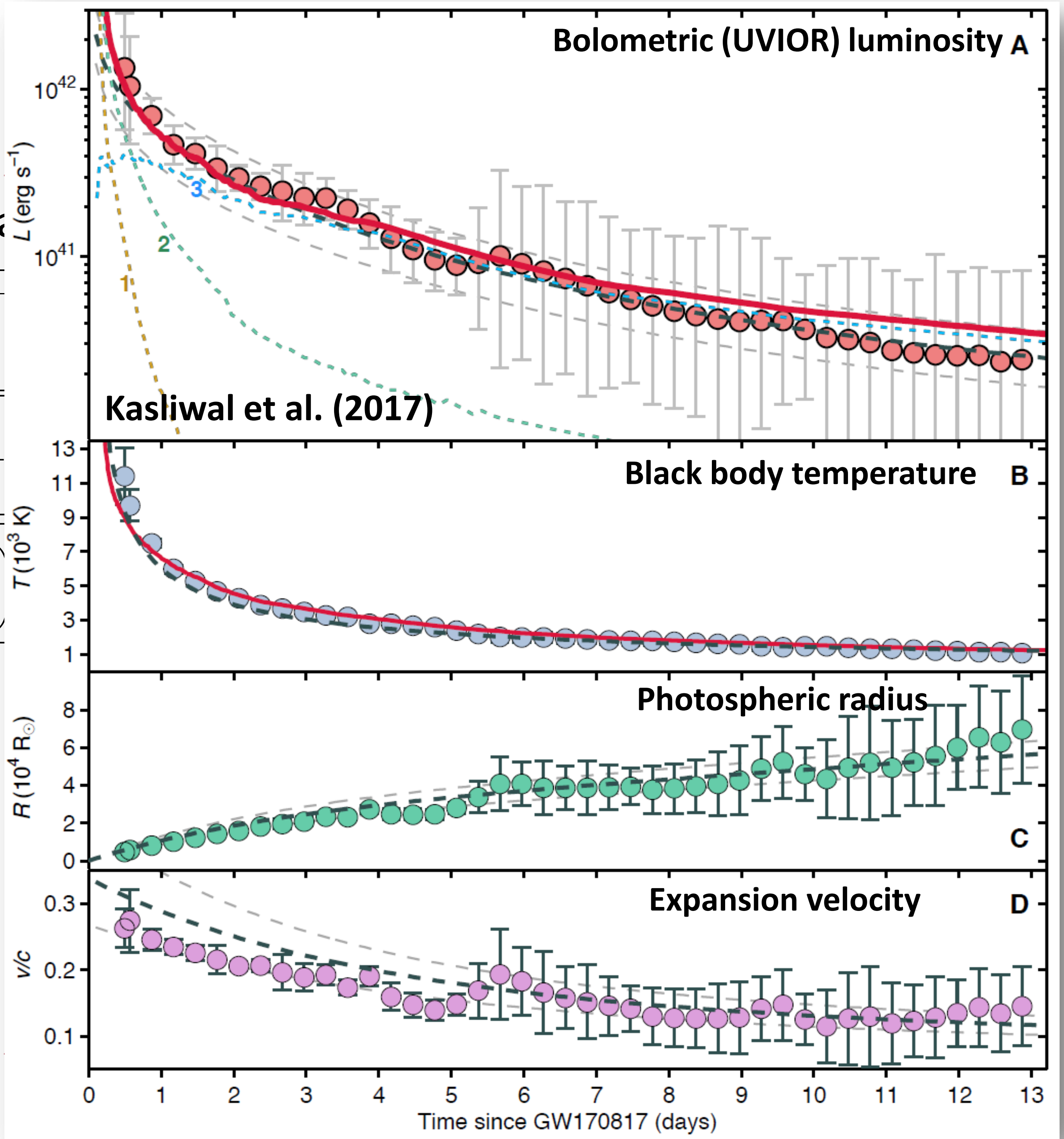
Modelling b

- Peak time, Lpeak, a

$$t_{peak} \sim 10\,\text{days}\left(\frac{v}{0.3c}\right)$$

$$L_{peak} \sim 10^{41}\,\text{erg/s}\left(\frac{f}{10^{-6}}\right.$$

$$T^{eff}_{peak} \sim 2\times10^{3}\,\text{K}\left(\frac{f}{10^{-6}}\right)$$



Kasliwal et al. (2017)

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- Peak time, Lpeak, and color depend of Mej, Vej, and opacity as

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

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

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

Li & Paczynski (1998)
Kasen et al. (2013)
Barnes & Kasen (2013)
Tanaka & Hotokezaka (2013)

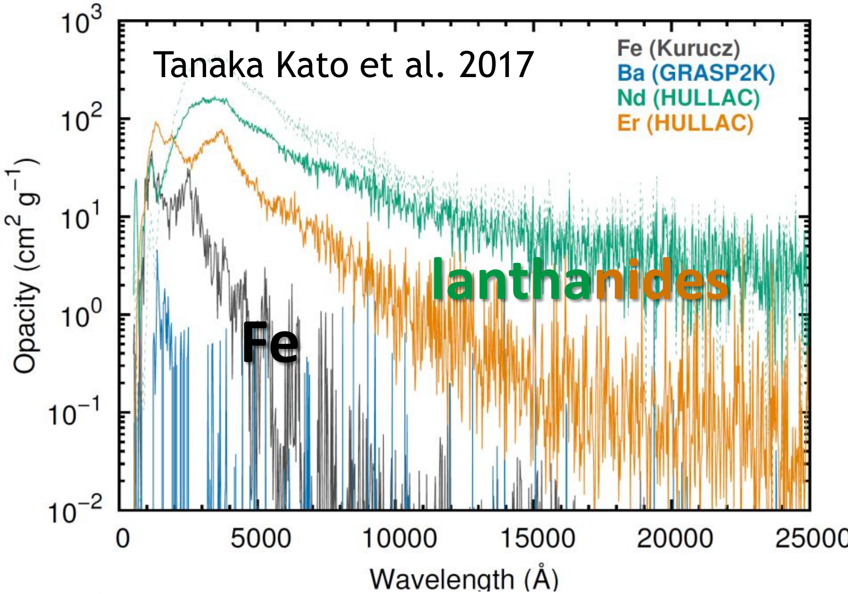
- **For the blue component, ejecta with**
  - **low opacity (κ < 1cm^2/g)**
  - high velocity (v > 0.2c)
  - mass >~ **0.01 Msun**
- **For the red component, ejecta with**
  - **high opacity (κ > 1 cm^2/g) ,** mass >~ **0.01 Msun**

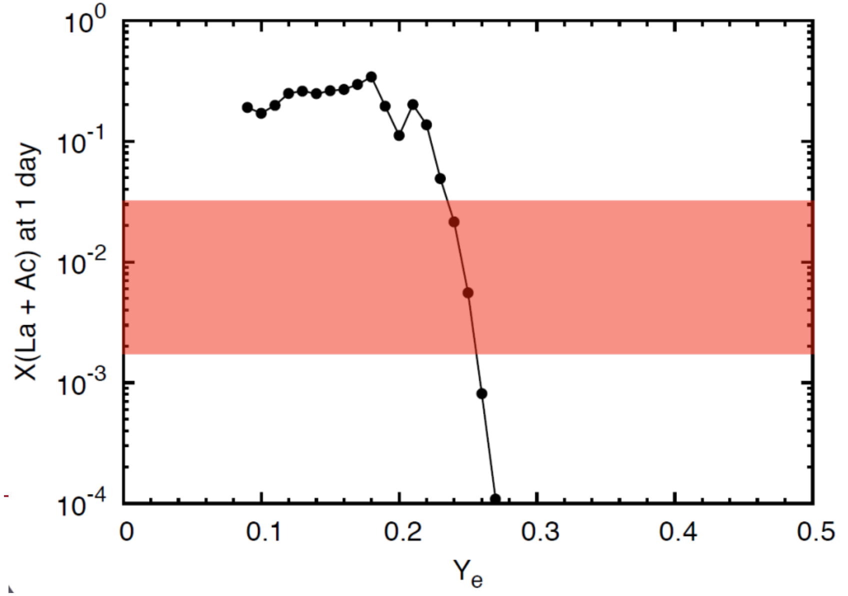
Opacity is determined by ejecta composition

- 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, $\kappa < 1\ \mathrm{cm^2/g}$ ⇒ blue component**
  - **lanthanide rich ejecta, $\kappa \sim 10\ \mathrm{cm^2/g}$ ⇒ red component**
- Criterion for Lanthanide production
  - $Ye < 0.25$ (e.g, Korobkin+. 2012; Wanajo+ 2014)

Important to know ejecta Ye

$Ye \lesssim 0.25$

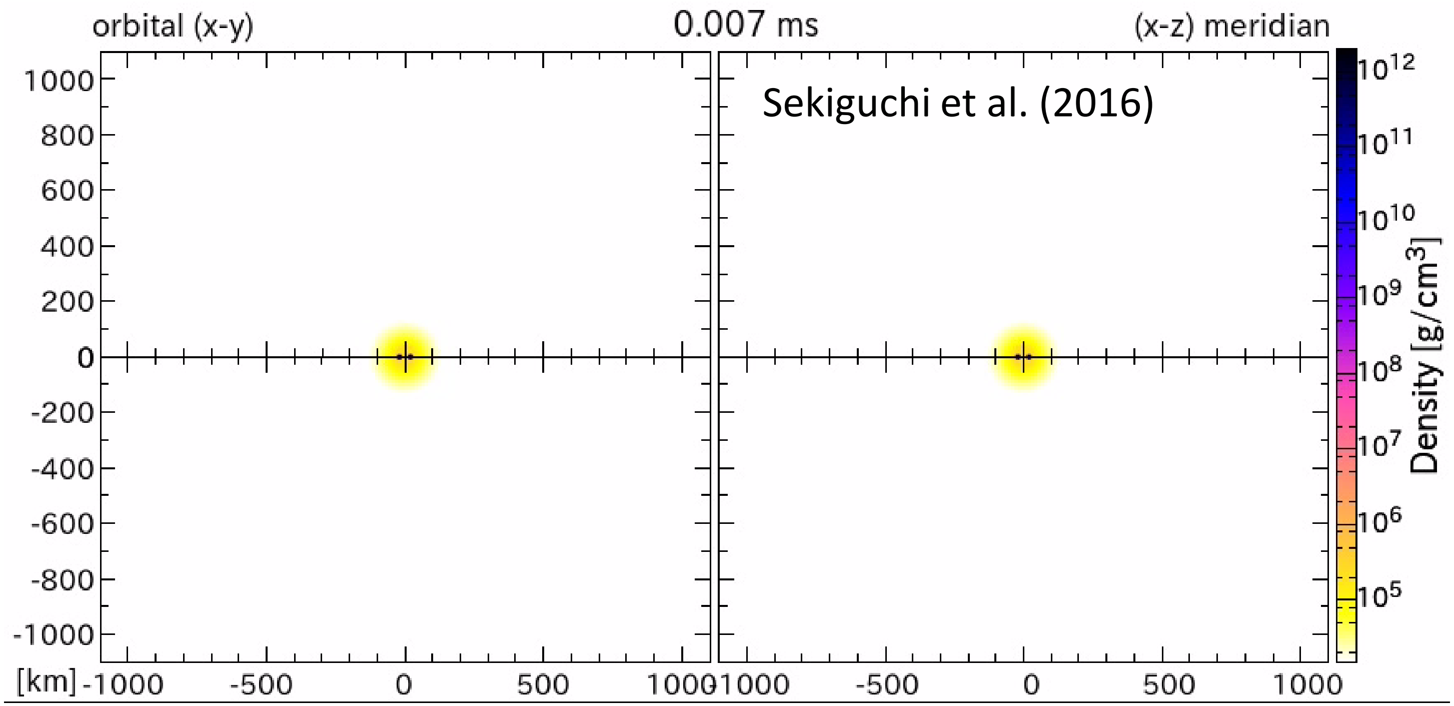




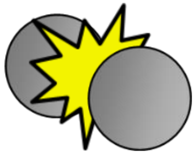
GW170817: kilonova modelling based on numerical relativity

With
S. Fujibayashi (YITP), K. Kiuchi (YITP), K. Kyutoku (YITP),
N. Nishimura (YITP), M. Shibata (YITP), M. Tanaka (NAOJ),
K. Taniguchi (Ryukyu), S. Wanajo (Sophia)

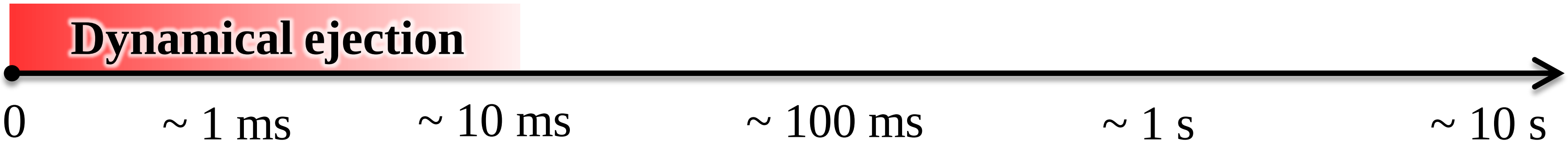
Mass ejection mechanisms : Dynamical



Sekiguchi et al. (2016)


Merger

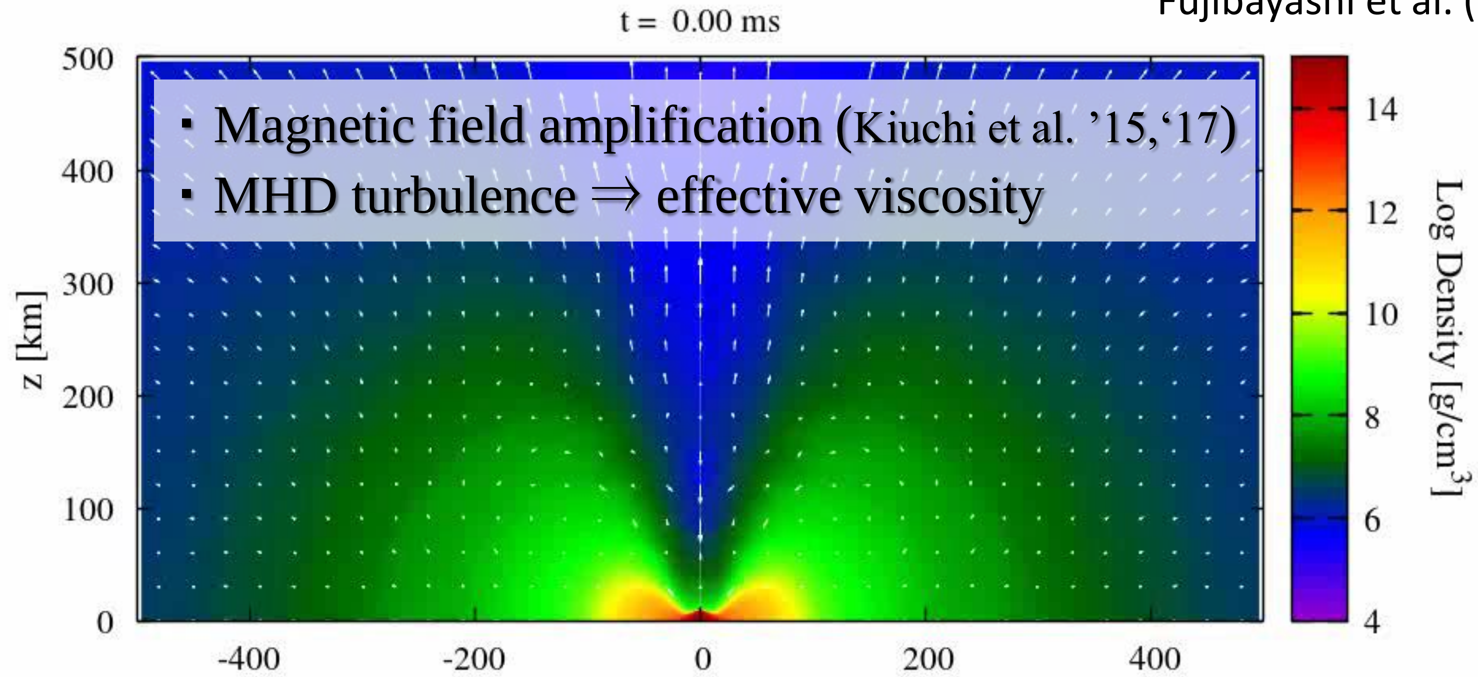
- Due to tidal force and shock heating
- Relatively well studied (e.g., EOS dependence)


Dynamical ejection

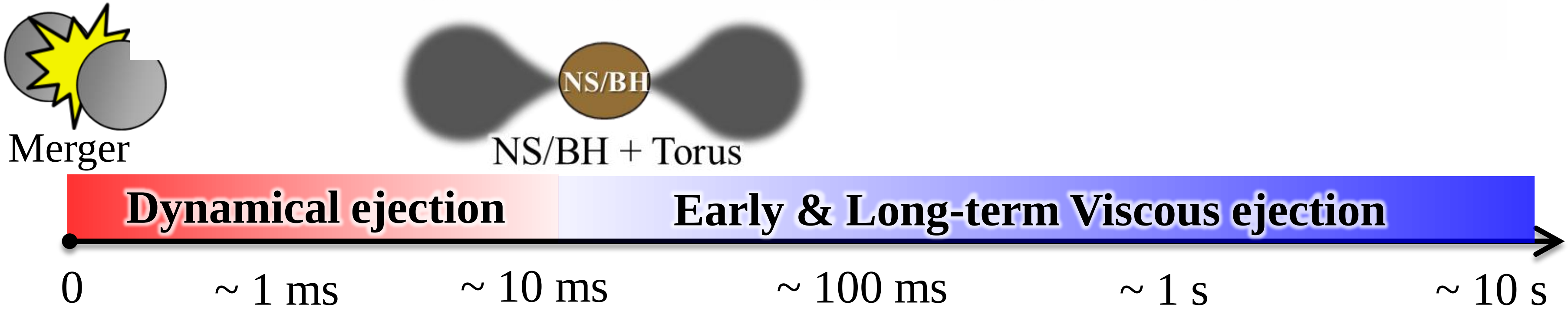
0 ~ 1 ms ~ 10 ms ~ 100 ms ~ 1 s ~ 10 s

Mass ejection mechanisms : Viscosity

Fujibayashi et al. (2018)



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



Merger

NS/BH + Torus

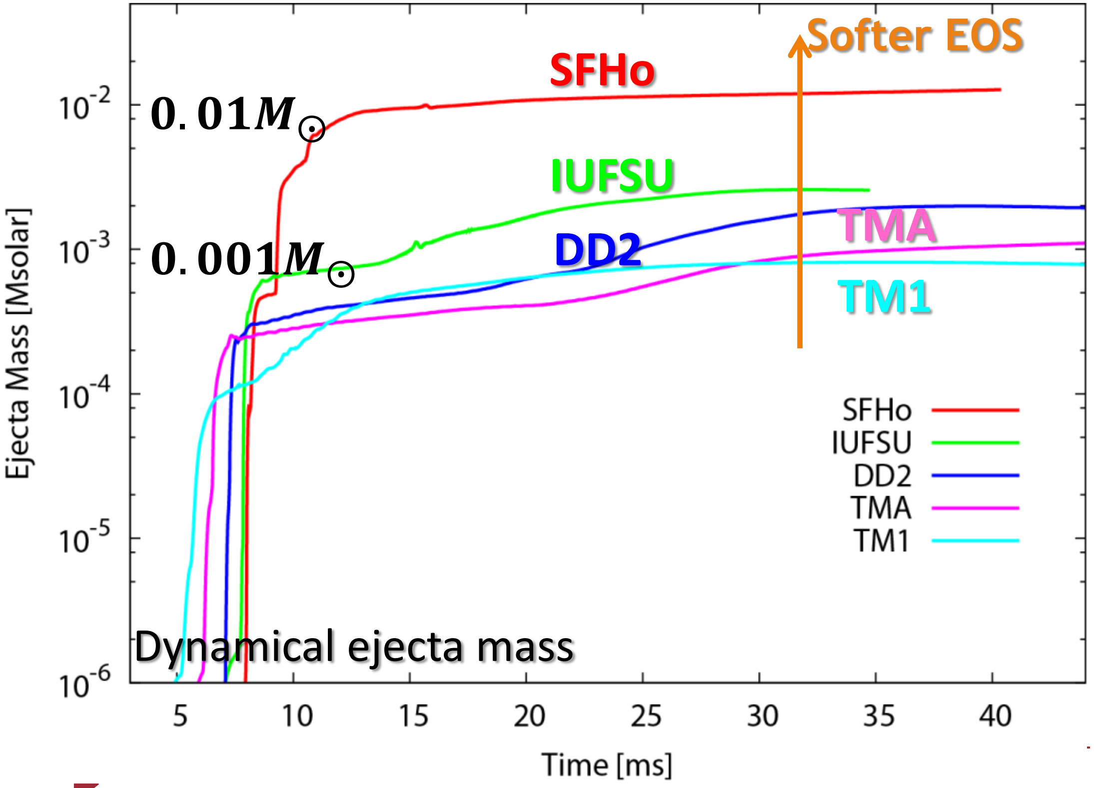
Dynamical ejection

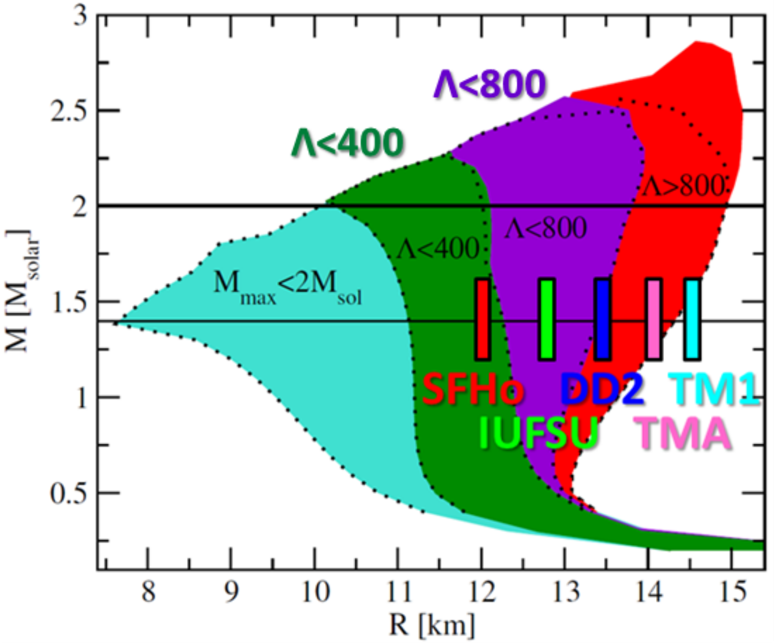
Early & Long-term Viscous ejection

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

Properties of **Dynamical** ejecta : mass

- Dynamical ejecta mass depends strongly on NS equation of state (EOS)
  - $M_{\mathrm{ej,dyn}} \sim 0.001 - 0.01 M_\odot$: larger for softer EOS (Sekiguchi et al. 2015, 2016)
    - But $M_{\mathrm{ej,dyn}}$ is very small if BH is directly formed after the merger (Hotokezaka+ 2013)
  - **$M_{\mathrm{ej,dyn}} \sim 0.01 M_\odot$ only for Soft EOS like SFHo ($R_{1.4} \approx 12\mathrm{km},\ \Lambda < 400$)**

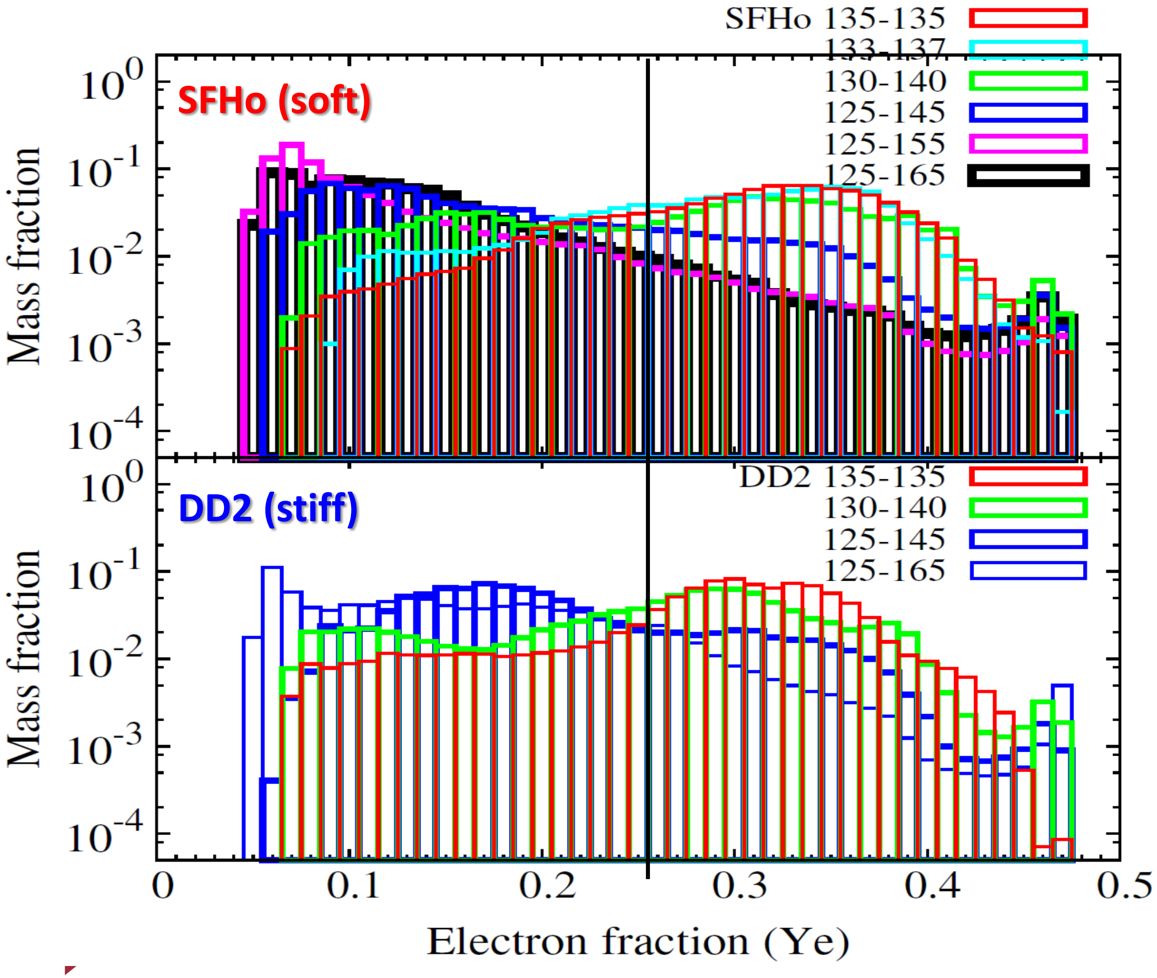




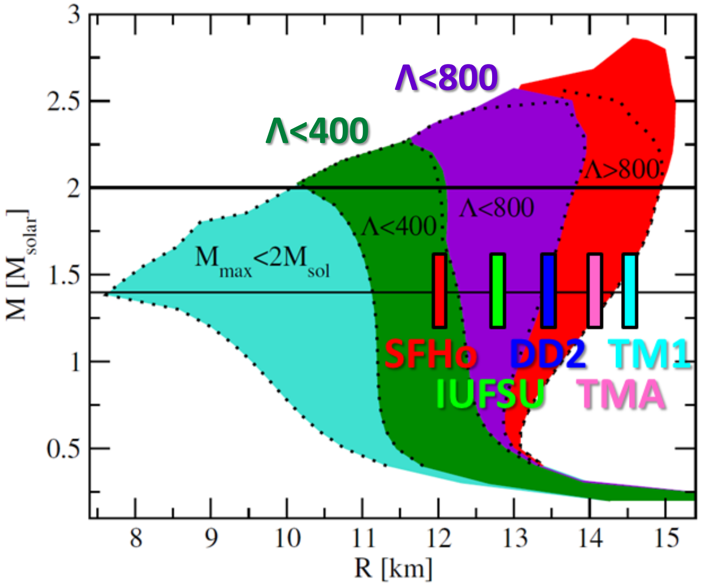
Annala et al. arXiv:1711.02644

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 $q = 0.8 - 1.0$



Weak interactions are important in changing Ye of originally neutron-rich matter



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Properties of **Dynamical** ejecta : Ye

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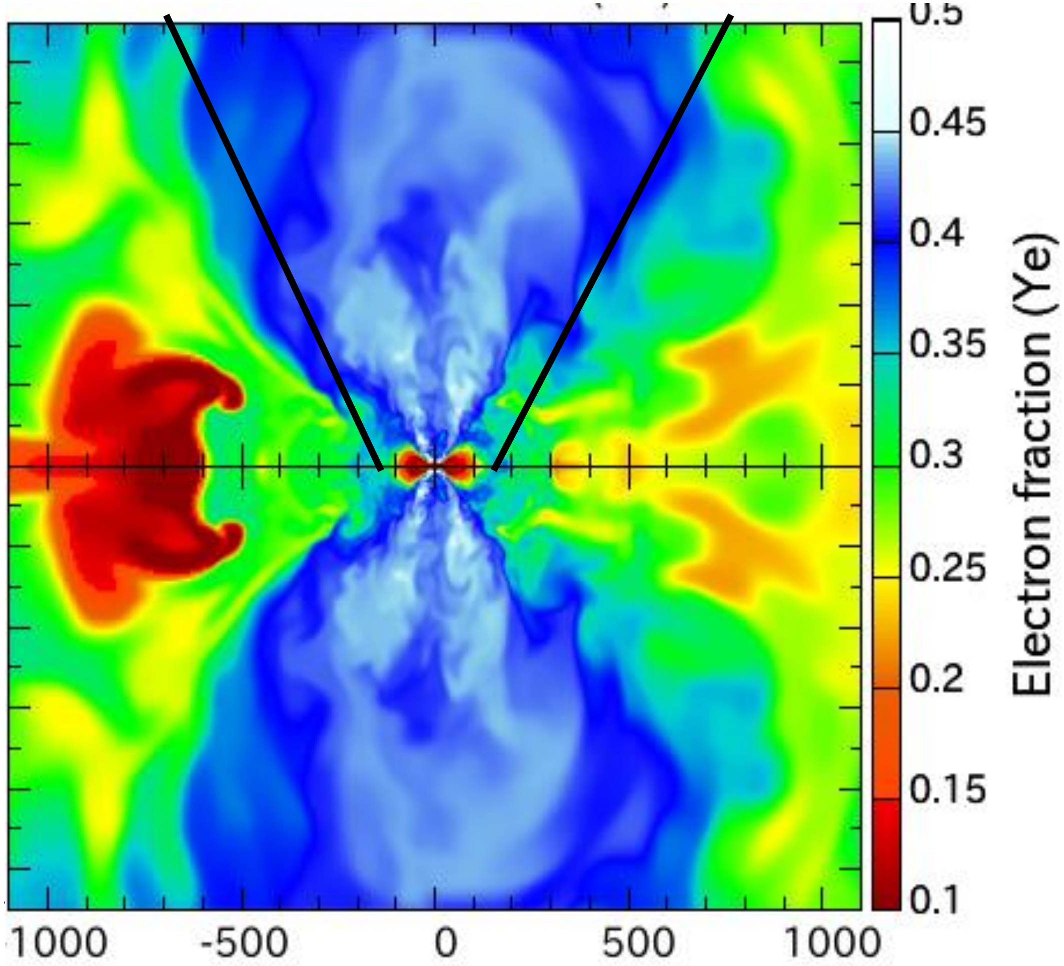
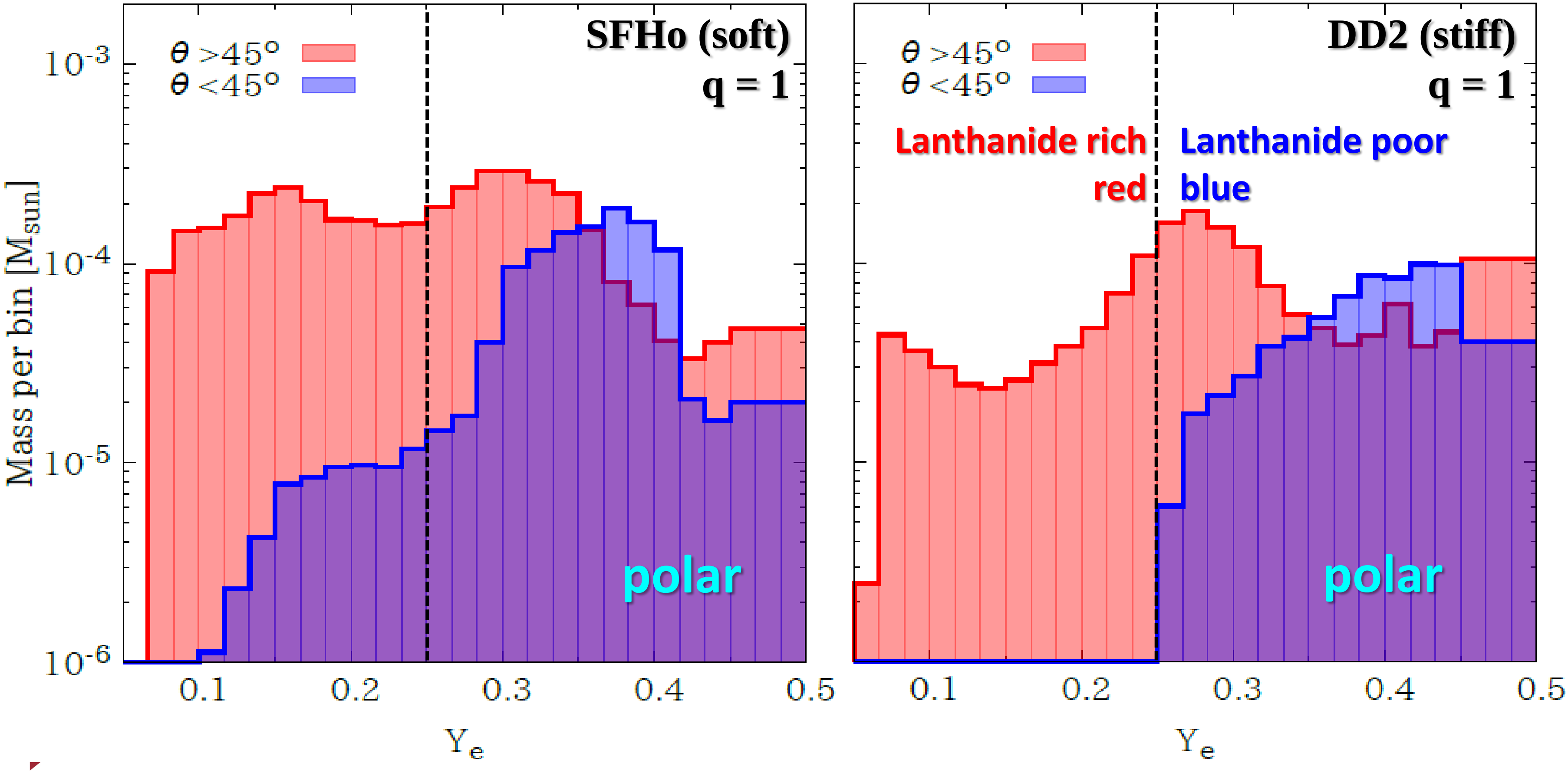
  - $\mathrm{Ye}_{\mathrm{ej,dyn}} = 0.05 - 0.5$, irrespective of mass ratio for $q = 0.8 - 1.0$

- ***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



Properties of **Dynamical** ejecta

- For EOS consistent with GW170817 ($\Lambda < 800$) : SFHo (soft) , DD2 (stiff)
  - **The red component may be explained by the dynamical ejecta for soft EOS**
  - **Ejecta mass in polar direction is insufficient to explain the blue comp.**

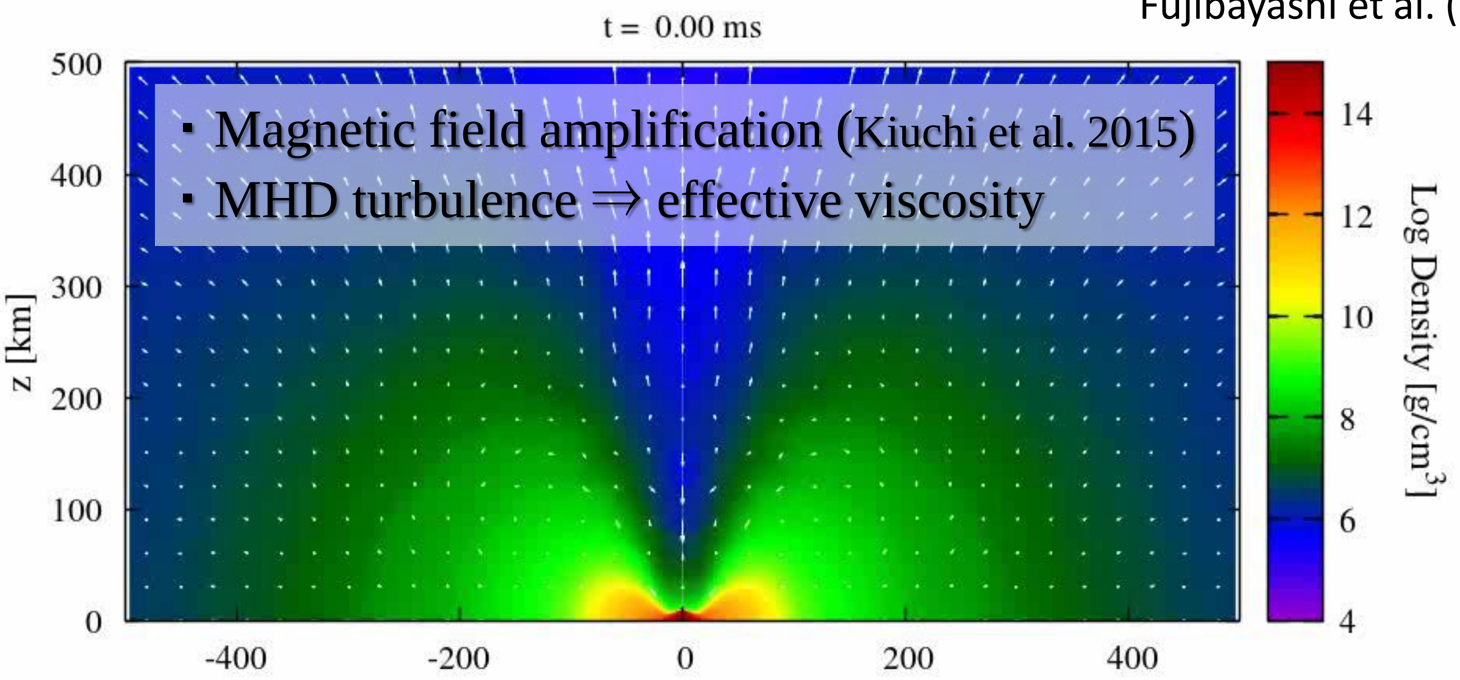


Dynamical ejecta : summary

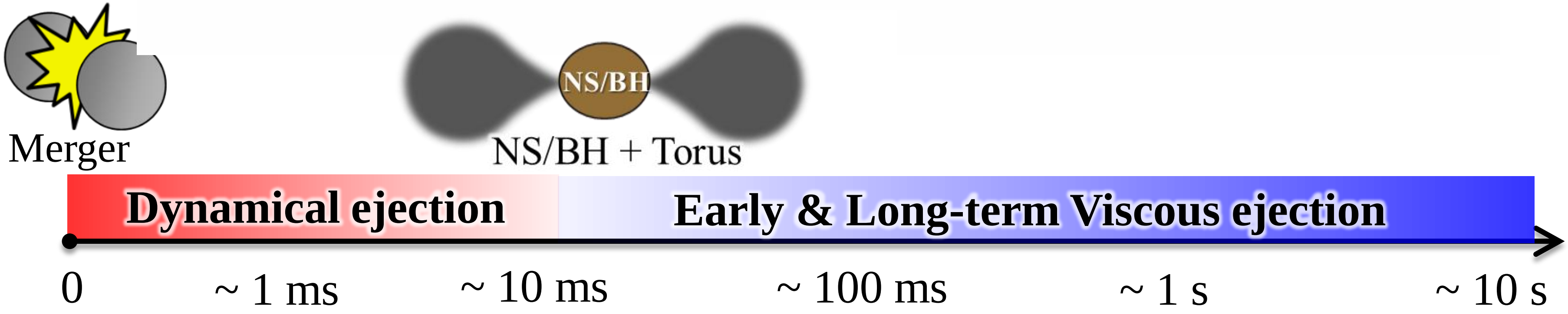
- **$\boldsymbol{Ye_{\mathrm{ej,dyn}} = 0.05 - 0.5}$, typical velocity is $\boldsymbol{v = 0.1 - 0.5c}$**
  - for EOS consistent with GW170817 ($\Lambda < 800$) irrespective of mass ratio in $q = 0.8 - 1.0$
- **$\boldsymbol{M_{\mathrm{ej,dyn}} = 0.001 - 0.01 M_\odot}$**
  - larger for softer EOS (Hotokezaka+ 2013; Sekiguchi et al. 2015, 2016)
  - $M_{\mathrm{ej,dyn}} \sim 0.01 M_\odot$ only for soft EOS like SFHo ($\Lambda_{1.4} \lesssim 400, R_{1.4} \approx 12\mathrm{km}$)
  - For q < 0.9 (GW170817 ?) , red component ($Ye < 0.25$) dominates
- **Red component**
  - may be explained by dynamical ejecta for soft EOS
    - Extra contribution from other (viscosity-driven) ejecta is helpful/necessary (stiff)
- **Blue component**
  - Amount of lanthanide-poor ejecta ($Ye \gtrsim 0.25$) is not sufficient, other mass ejection mechanisms are essential
  - Early high velocity component may be explained

Mass ejection mechanisms : Viscous

Fujibayashi et al. (2018)



- Magnetic field amplification (Kiuchi et al. 2015)
- MHD turbulence ⇒ effective viscosity



Merger

NS/BH + Torus

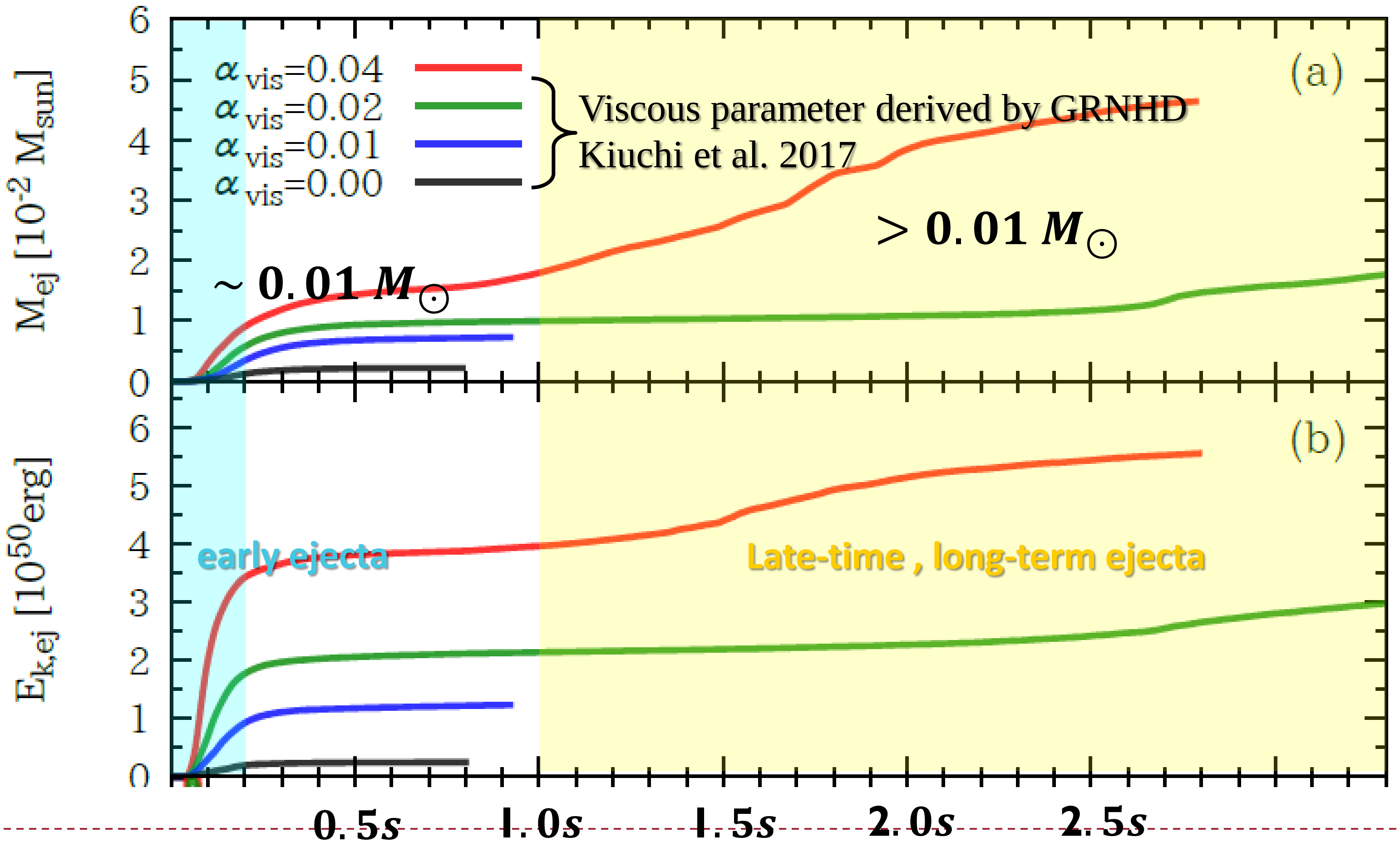
Dynamical ejection

Early & Long-term Viscous ejection

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

Viscosity-driven ejecta : two types

- There are **early** and **late-time long-term** **viscosity-driven ejecta**
  - **For EOS in which massive NS (MNS) survives in ≫ 100 ms :** not only for DD2



Viscous parameter derived by GRNHD Kiuchi et al. 2017

$\sim 0.01\,M_\odot$

$> 0.01\,M_\odot$

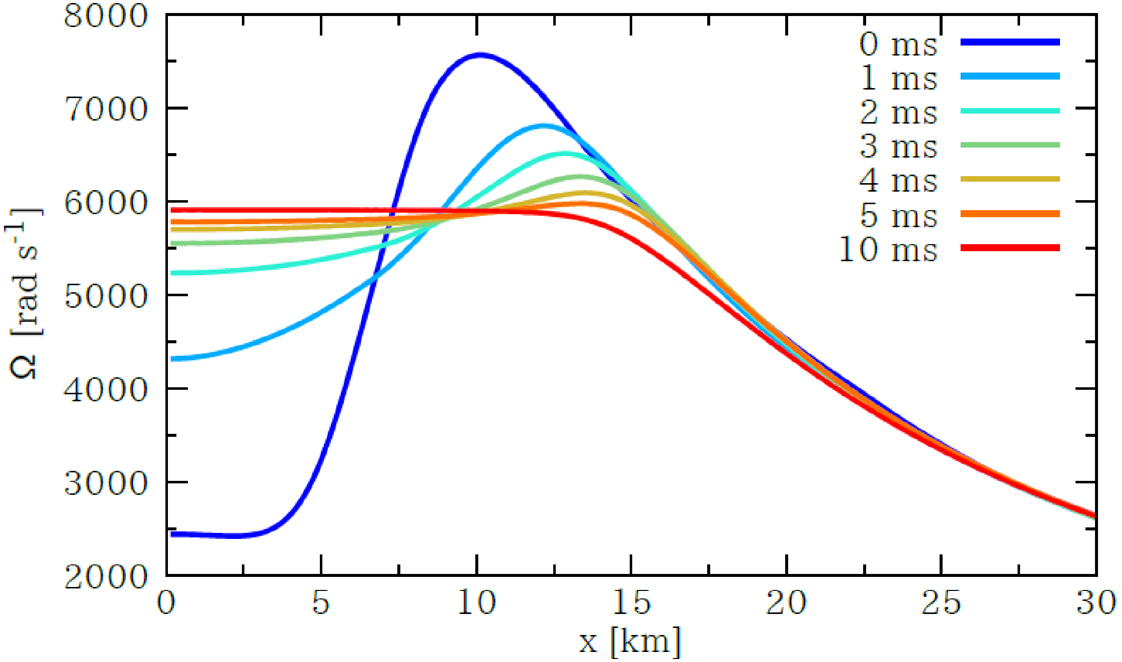
early ejecta

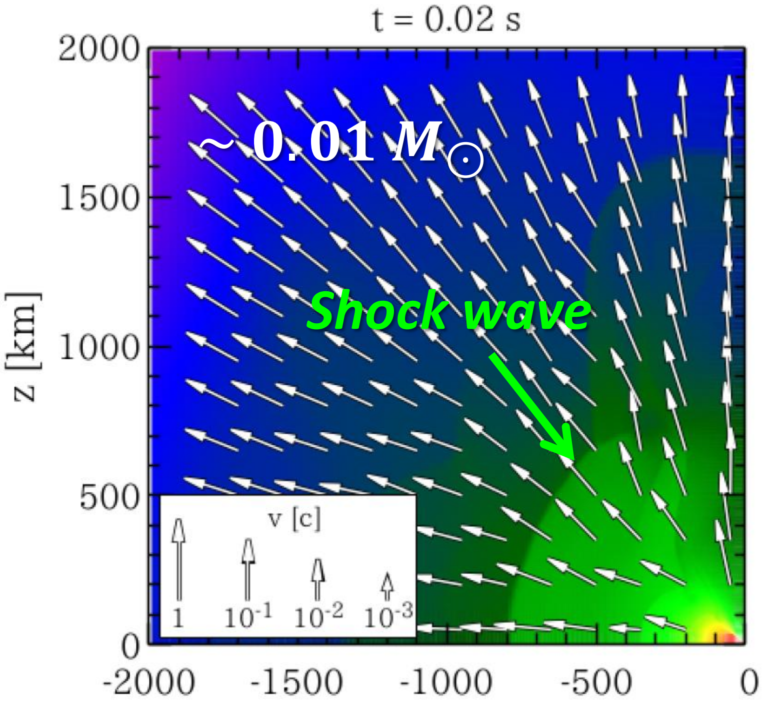
Late-time , long-term ejecta

Early Viscosity-driven ejecta

- Early viscosity-driven mass ejection first appears in $\lesssim 100$ ms
  - Energy source : (redistribution of) the MNS rotational energy

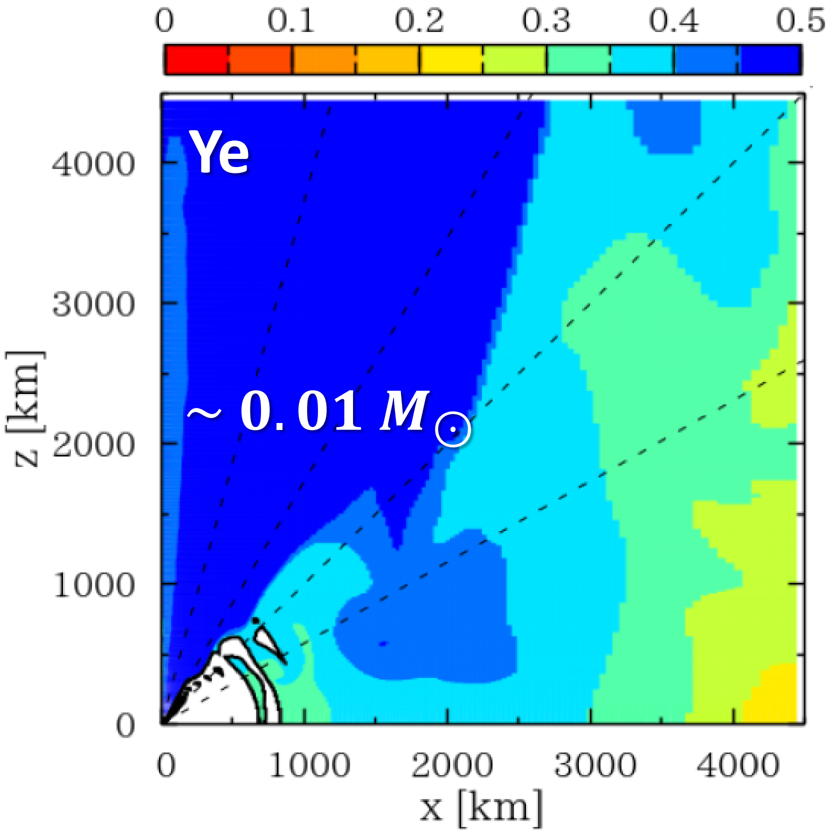
$$E_{\mathrm{rot}} \sim \frac{1}{2} M \Delta(R^2\Omega^2) \sim 2.5 \times 10^{52}\mathrm{erg}\left(\frac{\Delta(\Omega^2)}{10^7(\mathrm{rad}/s)^2}\right)\left(\frac{R}{10\,\mathrm{km}}\right)^2\left(\frac{M}{2.5\,M_\odot}\right)$$

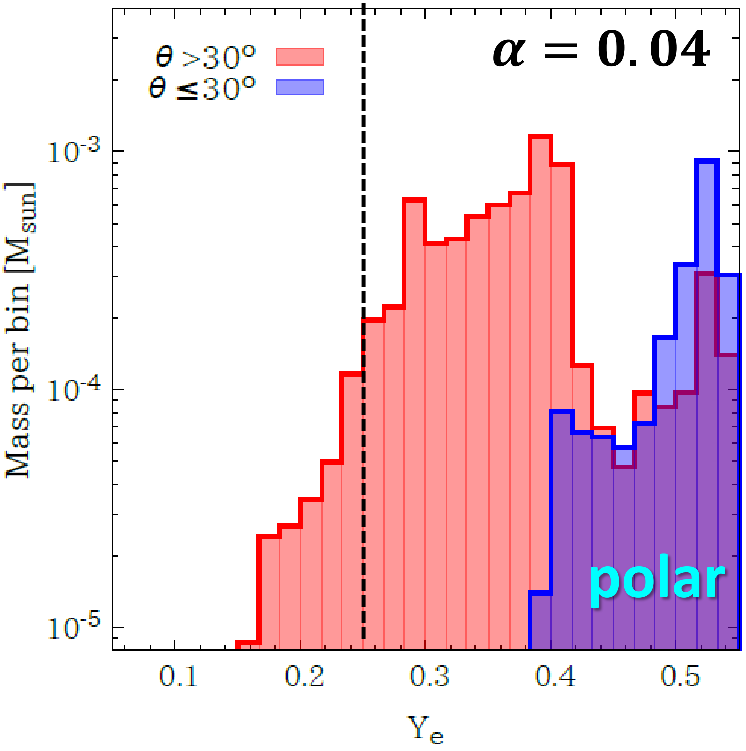




Early Viscosity-driven ejecta : **Ye**

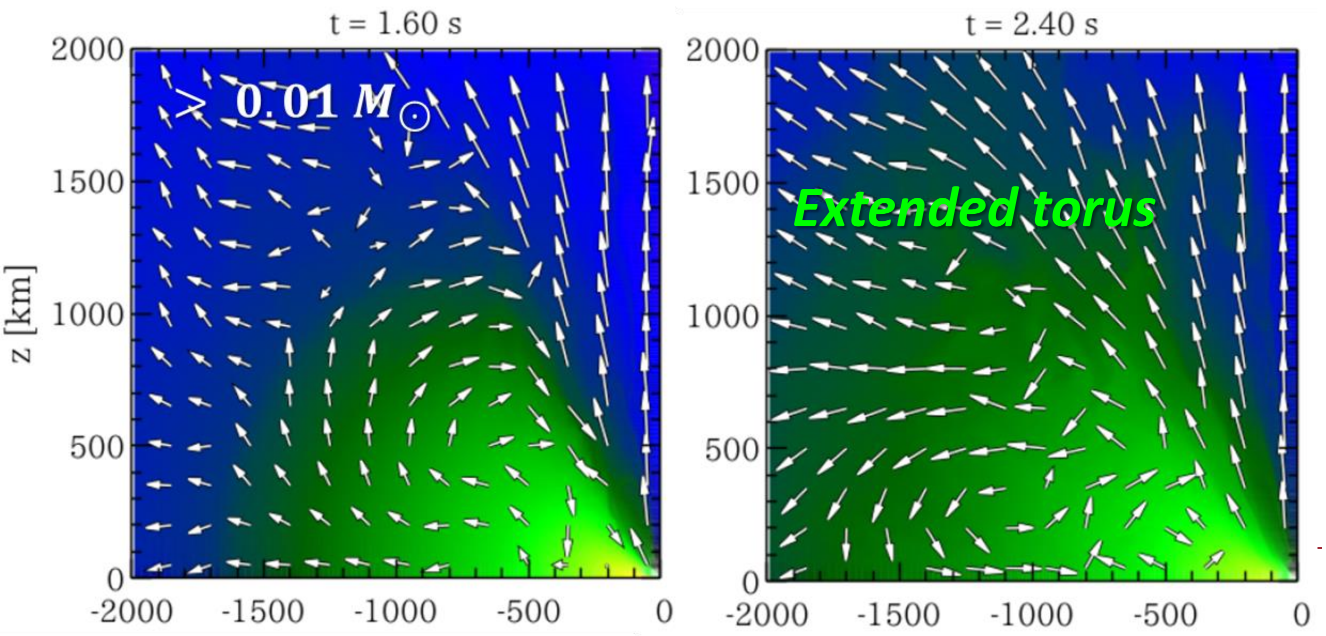
- Lanthanide-poor but marginal amount of mass ($\sim 0.01 M_\odot$) to explain the blue component ⇒ additional component required
  - $Ye = 0.2 - 0.4$ for $\theta < 30°$ ($Ye > 0.25$ for most of the ejecta)
  - $Ye > 0.4$ for $\theta > 30°$ (polar direction)



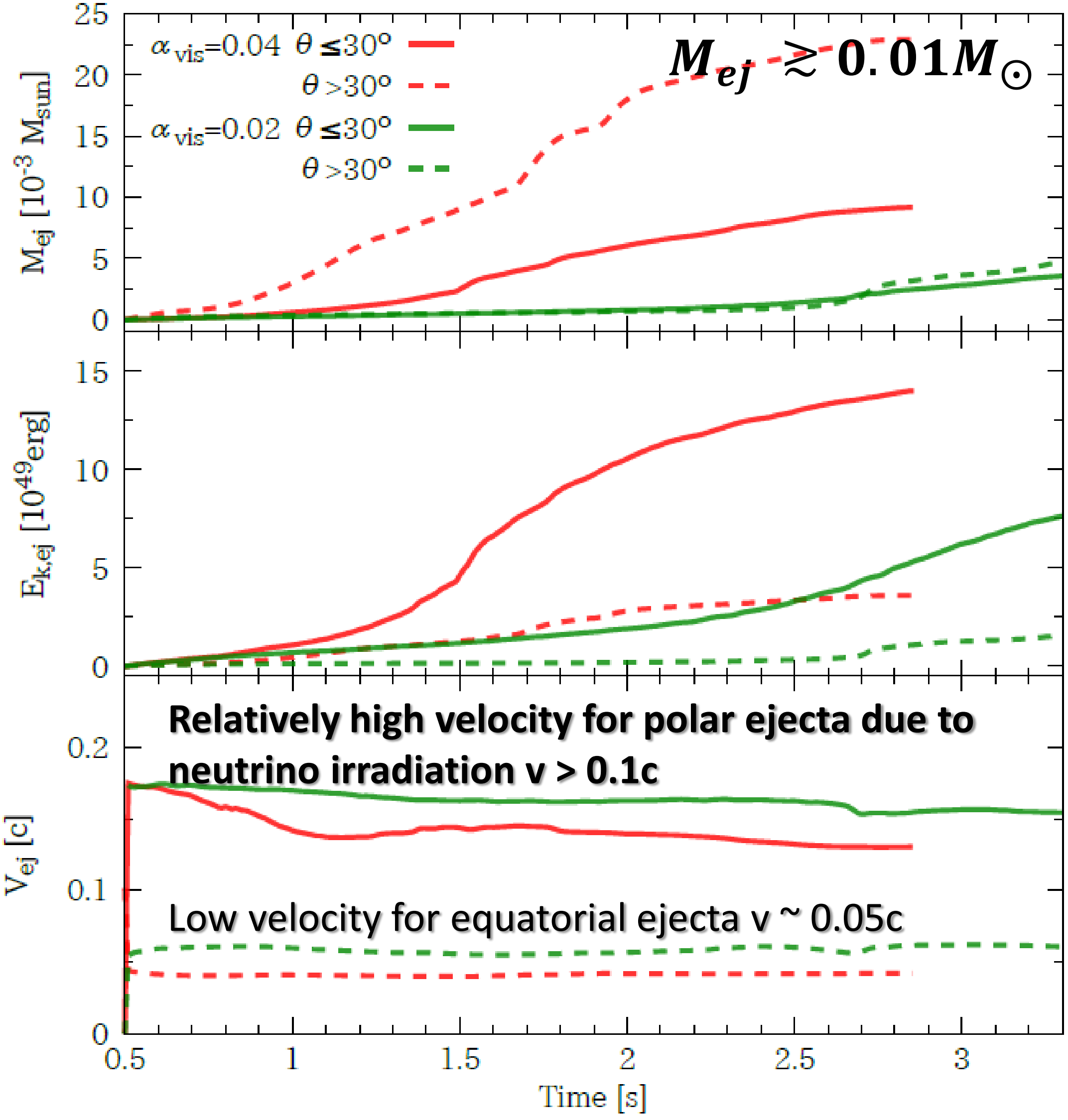


Late-time long-term viscosity-driven ejecta

- **For stiff EOS with which MNS survives in $\gtrsim$ 1 sec :** e.g., DD2
  - For soft EOS with which BH is formed via delayed collapse : BH + torus system
  - No full GR self-consistent study (will be comment on later)
- **Mass ejection from expanded torus**
  - Viscous heating can unbound material ⇒ **long-term** viscosity-driven ejecta
  - gravitational binding energy is small ⇒ escape (ejecta) velocity is low $\sim 0.05c$
  - It takes a long time for the torus to expand sufficiently ⇒ late-time



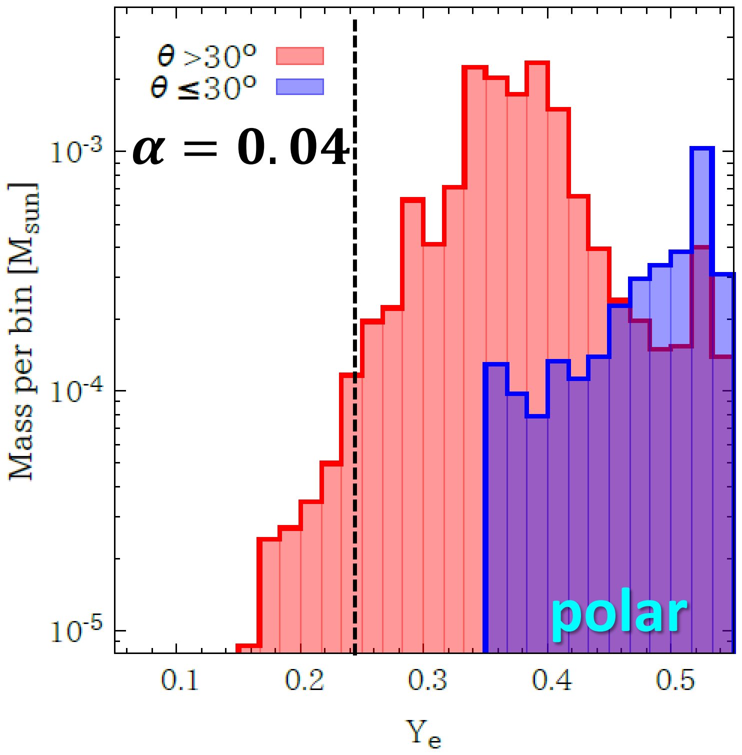
Late-time long-term ejecta : properties



$M_{ej} \gtrsim 0.01 M_\odot$

Relatively high velocity for polar ejecta due to neutrino irradiation v > 0.1c

Low velocity for equatorial ejecta v ~ 0.05c



$\alpha = 0.04$

- ***high velocity*** ejecta in polar direction with Ye > 0.35
- ***Low velocity*** ejecta in other direction with Ye = 0.2-0.5

Viscosity-driven wind from **BH+torus**

- ***For soft EOS, (H)MNS may collapse to a BH ⇒ BH + torus***

- **Major difference between MNS + torus and BH + torus :**
  - neutrino irradiation from the MNS is absent
- **Consequence :**
  - absence of the ***high velocity*** ejecta in polar direction with Ye > 0.4
  - Quasi-equatorial components do exist but Ye may be relatively lower ⇒ *lanthanide rich ?* ⇒ blue component may not be explained
    - Fernandez & Metzger (2013); Fernandez et al. (2015); Just et al. (2015); Siegel & Metzger (2017)
- **Need of more studies**
  - No detailed simulations both incorporating GR and neutrino heating
  - Code has been developed : studies are on going

Viscosity-driven ejecta : summary

- **Early viscosity-driven mass ejection first appears in $\lesssim 100$ ms**
  - Energy source : redistribution of the MNS rotational profile
  - Lanthanide-poor but amount of mass is marginal ($\sim 0.01 M_{\odot}$) to explain the blue component
- **For a 'stiff' EOS with which MNS survives in $\sim$ 1 sec, there will be long-term viscosity driven winds from NS + torus system**
  - Mass ejection is from expanded torus where gravitational binding energy is small ⇒ escape (ejecta) velocity is basically low as $\sim 0.05c$
  - **For polar region, winds come from inner region with the help of neutrino irradiation ⇒ velocity is as high as $\sim \mathbf{0.15}c$**
  - Lanthanide-poor and ejecta mass is sufficient to explain the blue component
- For a softer EOS : delayed collapse to a BH ⇒ BH + torus system
  - Neutrino irradiation effects will be smaller ⇒ lower Ye ⇒ lanthanide rich ???
  - No detailed study ⇒ need more study

Remarks on NS matter EOS

- **Critical mass of BH formation**

$$M_{\mathrm{crit}} = M_{\mathrm{max,sph}} + \Delta M_{\mathrm{rot,rig}} + \Delta M_{\mathrm{rot,diff}} + \Delta M_{\mathrm{therm}}$$

  - $M_{\mathrm{max,sph}}$: maximum mass of cold spherical NS
  - $\Delta M_{\mathrm{rot,rig}}$: effect of rigid rotation
  - $\Delta M_{\mathrm{rot,diff}}$: effect of differential rotation
  - $\Delta M_{\mathrm{therm}}$: thermal contribution

- **Condition 1 : BH should not be directly formed :**

$$M_{\mathrm{crit}} \gtrsim 2.74 M_{\odot}$$

  - Constraint on NS compactness (radius) (Bauswein et al. 2017)

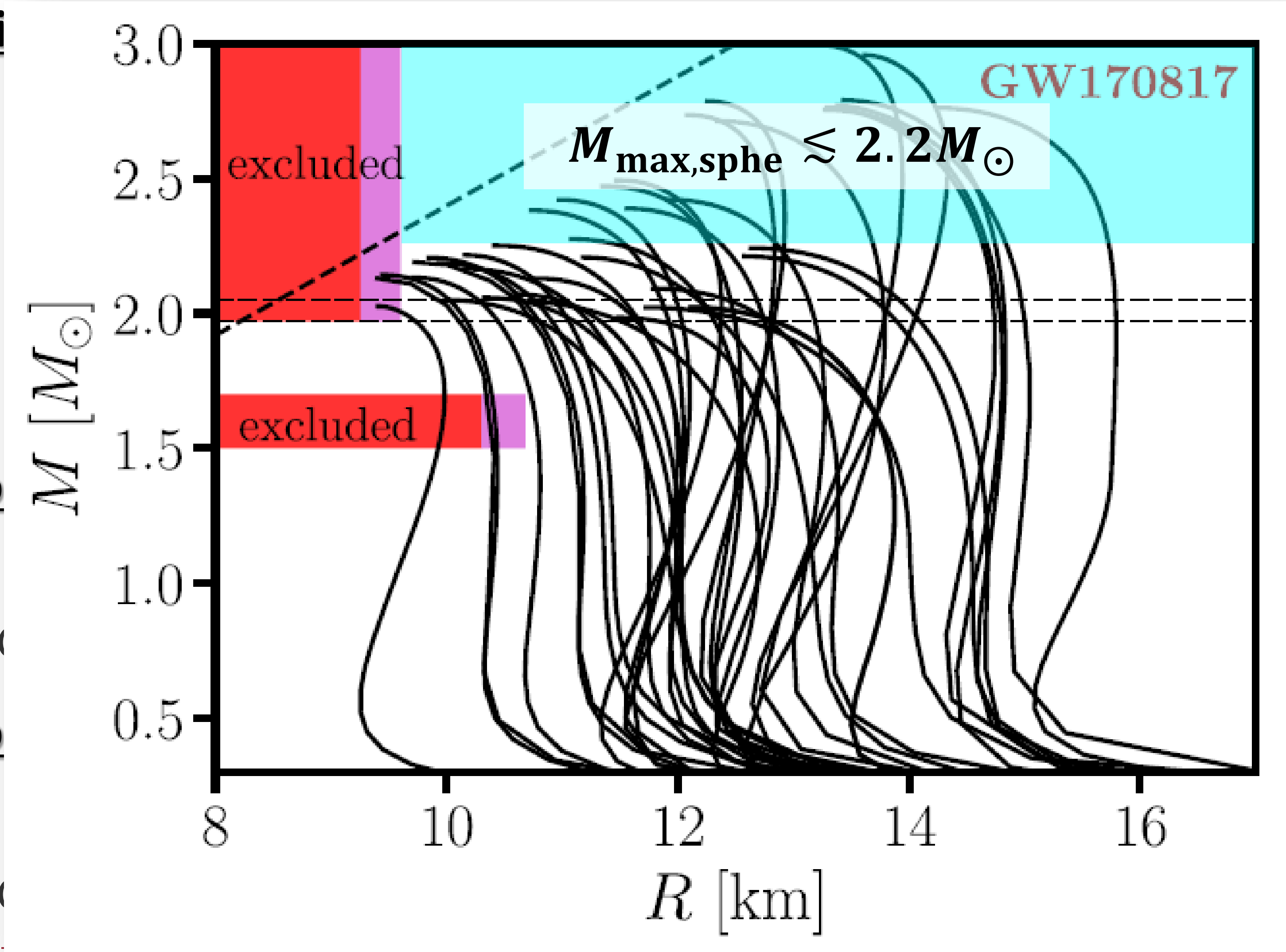
- **Condition 2 : MNS should not be too long-lived :**

$$M_{\mathrm{max,sph}} + \Delta M_{\mathrm{rot,rig}} \lesssim 2.74 M_{\odot}$$

  - Constraint on $M_{\mathrm{max,sph}}$ (Margalit & Metzger 2017; Rezzolla et al. 2018 see also Shibata et al. 2017)

Remarks on NS matter EOS

- **Cri**

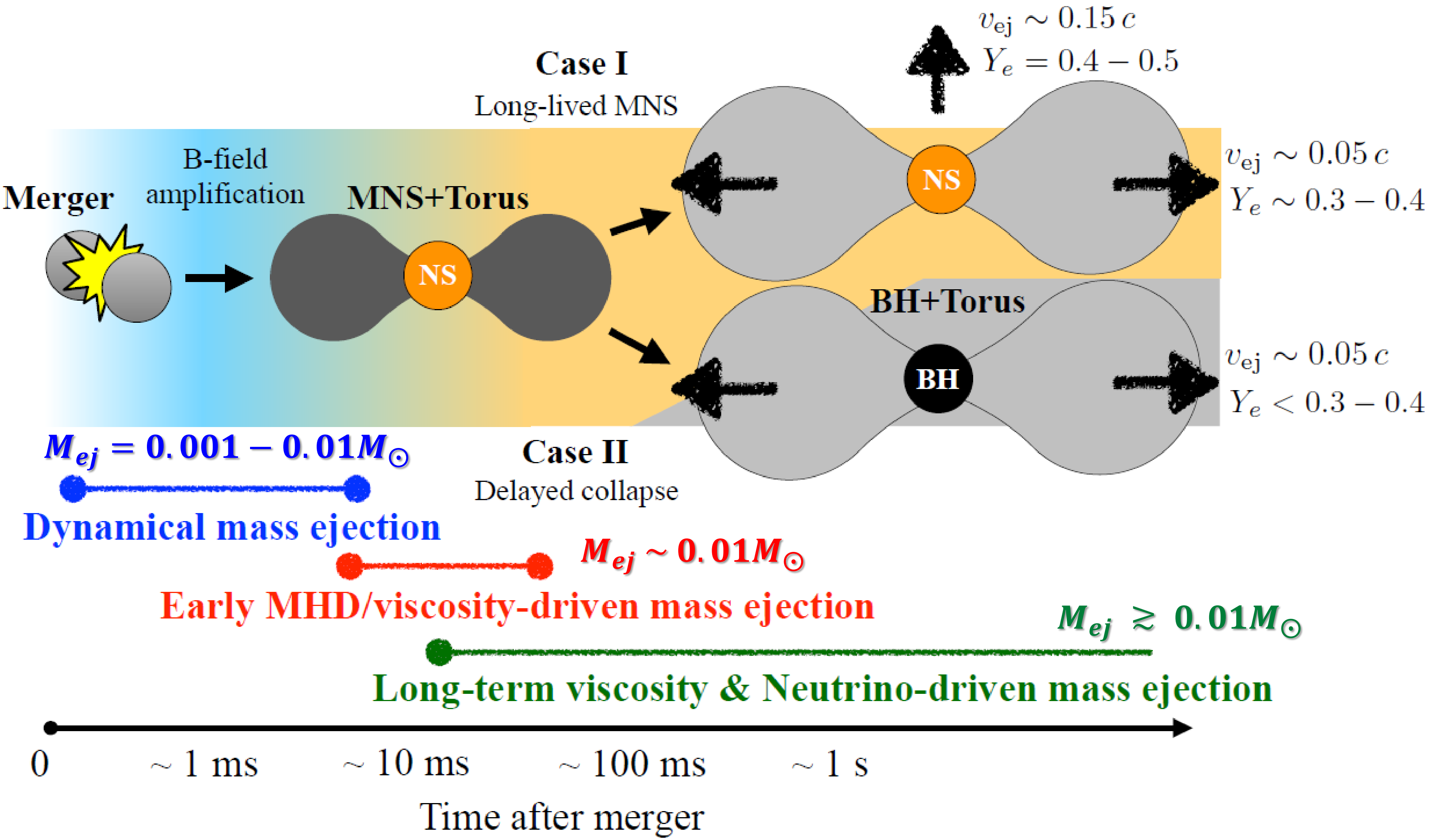


$M_{\text{max,sphe}} \lesssim 2.2 M_\odot$

- **Co**
  - (
- **Co**
  - (

see also Shibata et al. 2017)

Application to GW170817



Merger

B-field amplification

MNS+Torus

NS

Case I

Long-lived MNS

$v_{\rm ej} \sim 0.15\,c$

$Y_e = 0.4 - 0.5$

NS

$v_{\rm ej} \sim 0.05\,c$

$Y_e \sim 0.3 - 0.4$

BH+Torus

BH

$v_{\rm ej} \sim 0.05\,c$

$Y_e < 0.3 - 0.4$

Case II

Delayed collapse

$M_{ej} = 0.001 - 0.01 M_\odot$

Dynamical mass ejection

$M_{ej} \sim 0.01 M_\odot$

Early MHD/viscosity-driven mass ejection

$M_{ej} \gtrsim 0.01 M_\odot$

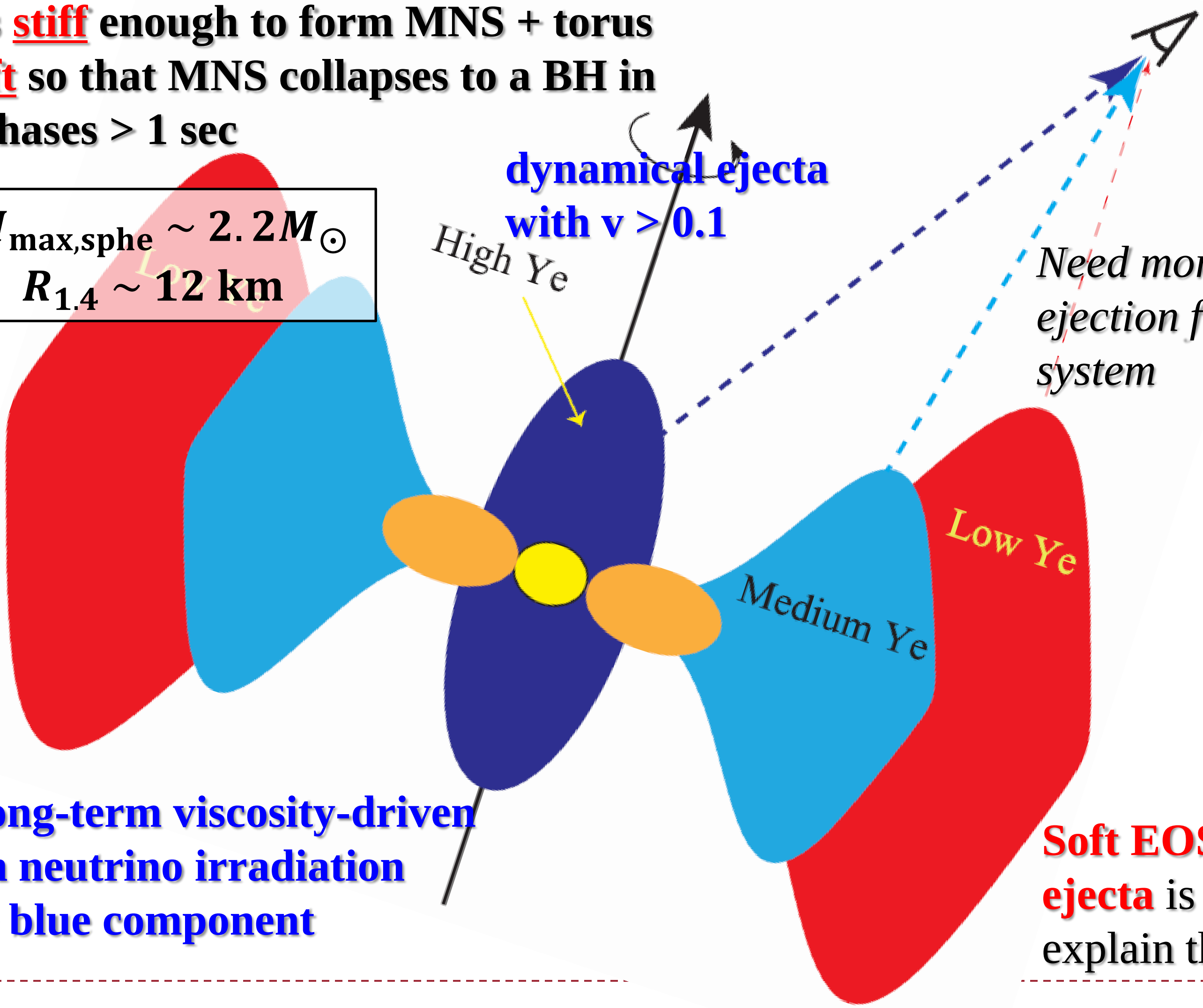
Long-term viscosity & Neutrino-driven mass ejection

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

Time after merger

Best model : Soft EOS with MNS + torus

EOS is stiff enough to form MNS + torus but soft so that MNS collapses to a BH in later phases > 1 sec



$M_{\max,\mathrm{sphe}} \sim 2.2 M_{\odot}$
$R_{1.4} \sim 12$ km

dynamical ejecta with v > 0.1

Need more study for mass ejection from BH + torus system

Early + Long-term viscosity-driven ejecta with neutrino irradiation explain the **blue component**

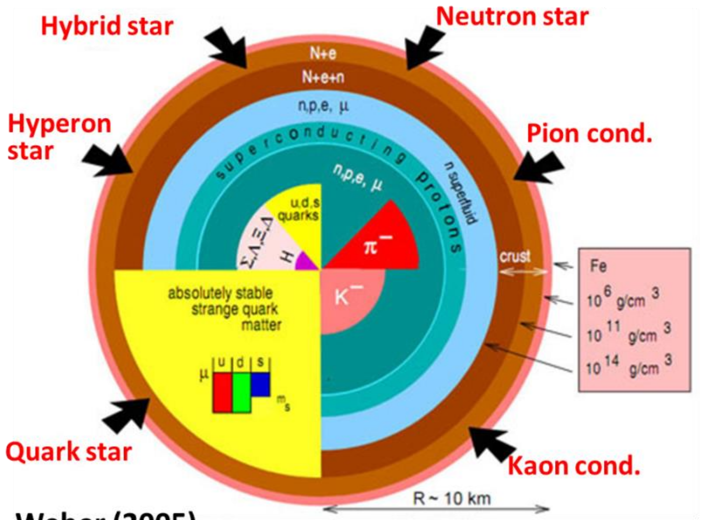
Soft EOS : dynamical ejecta is sufficient to explain the **red component**

Major scientific achievements: GW170817 provided us clues to

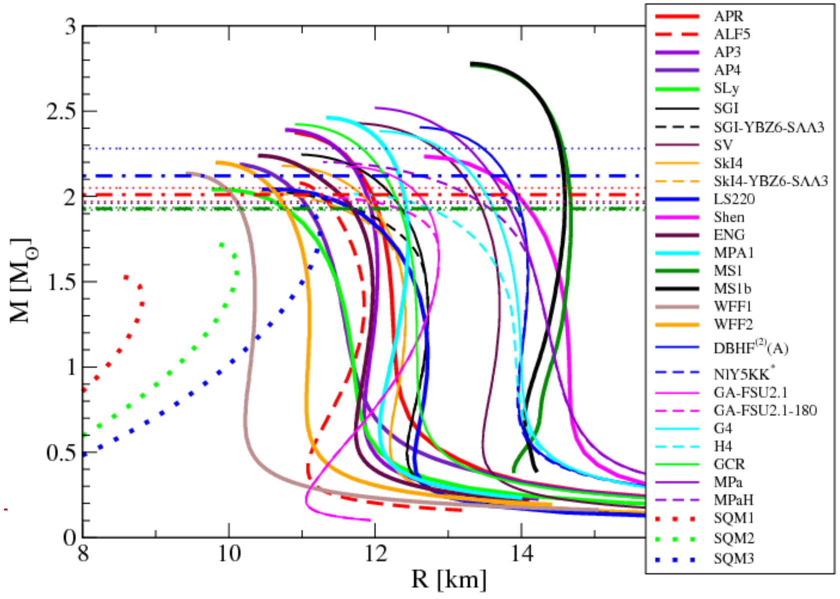
- **NS matter EOS**

  Luka's talk

  - **Tidal deformability extraction**
- Short gamma-ray bursts (SGRB) central engine
- Origin of heavy elements
  - r-process nucleosynthesis
  - kilonova/macronova from decay energy of the synthesized elements
- GW as standard siren
  - Hubble constant



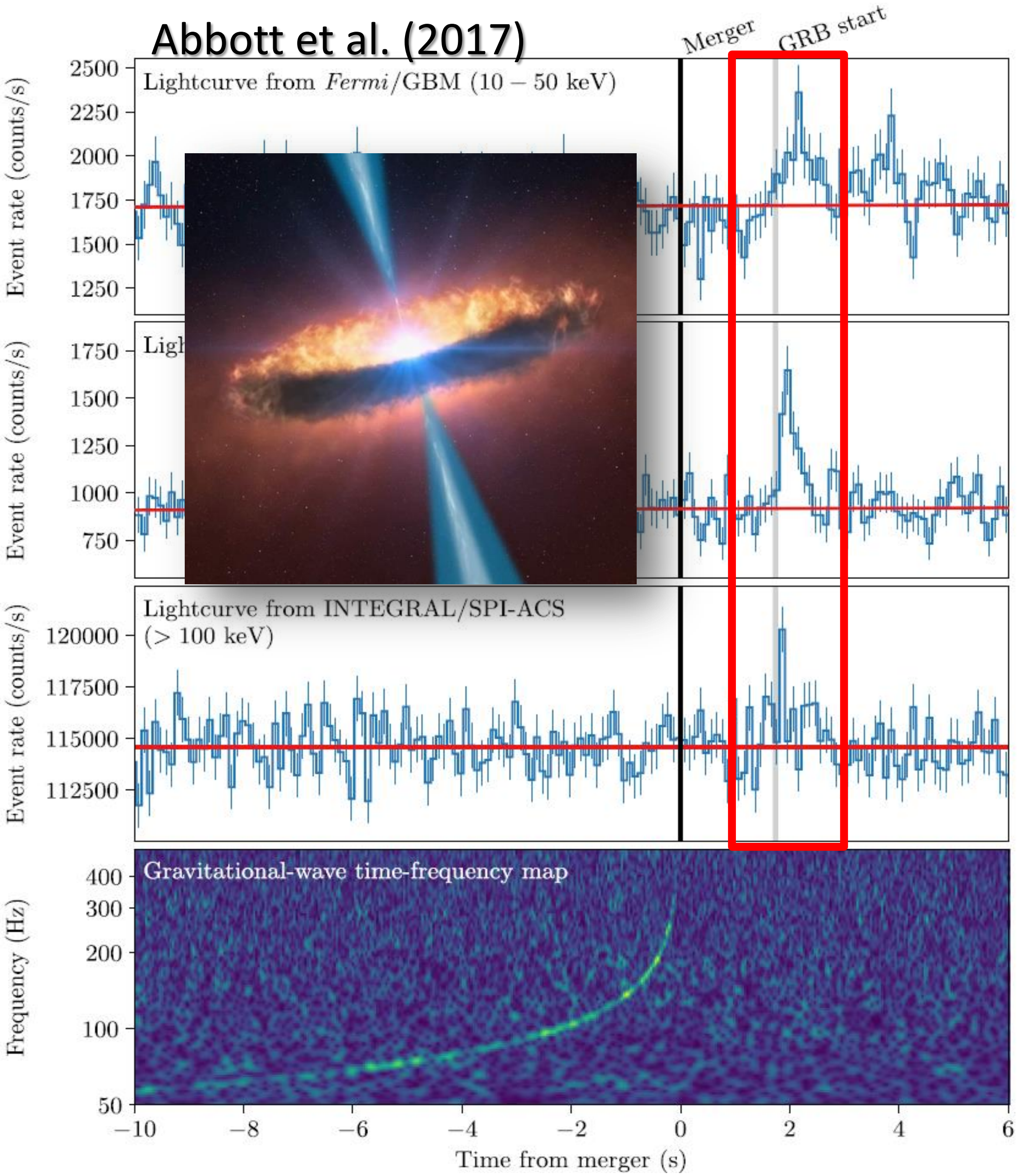
Weber (2005)



Major scientific achievements: GW170817 provided us clues to

- NS matter EOS
  - Tidal deformability extraction
- **Short gamma-ray bursts (SGRB) central engine**

  But not normal
- Origin of heavy elements
  - r-process nucleosynthesis
  - kilonova/macronova from decay energy of the synthesized elements
- GW as standard siren
  - Hubble constant



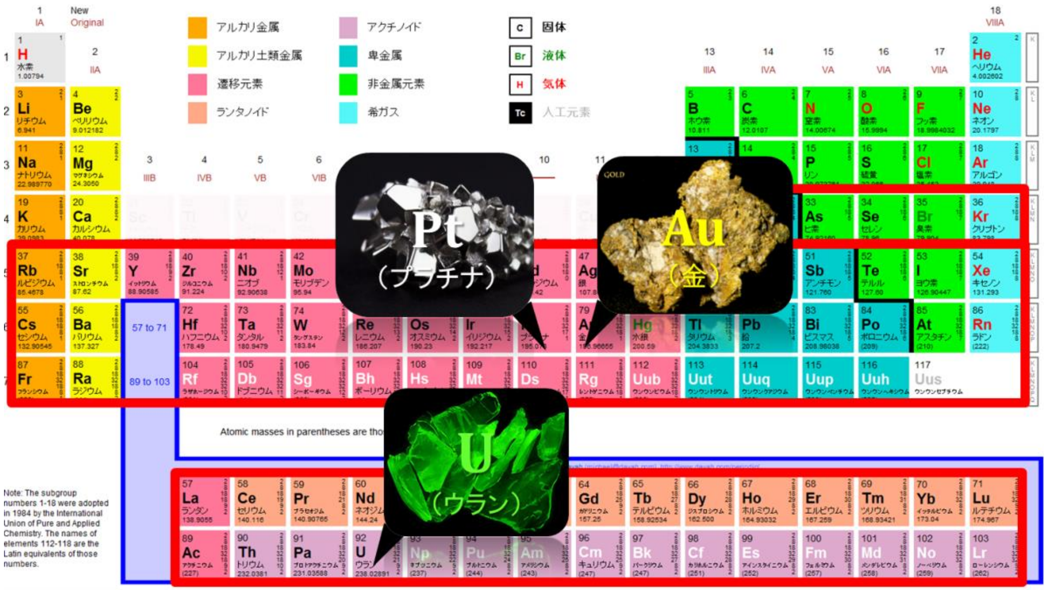
Abbott et al. (2017)

Major scientific achievements: GW170817 provided us clues to

- NS matter EOS
  - Tidal deformability extraction
- Short gamma-ray bursts (SGRB) central engine
- **Origin of heavy elements**
  - **r-process nucleosynthesis**
  - **kilonova/macronova from decay energy of the synthesized elements**

Jonas's, Luke's, Nobuya's, and Takashi's talks

- GW as standard siren
  - Hubble constant



Major scientific achievements: GW170817 provided us clues to

- NS matter EOS
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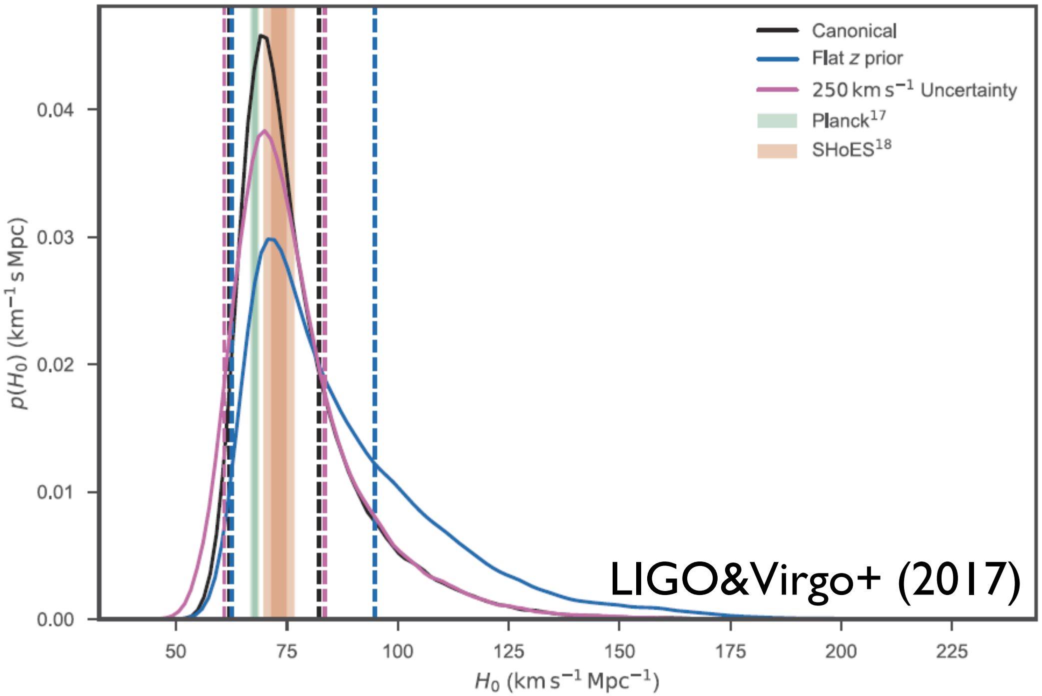
- Short gamma-ray bursts (SGRB) central engine
- Origin of heavy elements
    - r-process nucleosynthesis
    - kilonova/macronova from decay energy of the synthesized elements
- **GW as standard siren**
    - **Hubble constant**

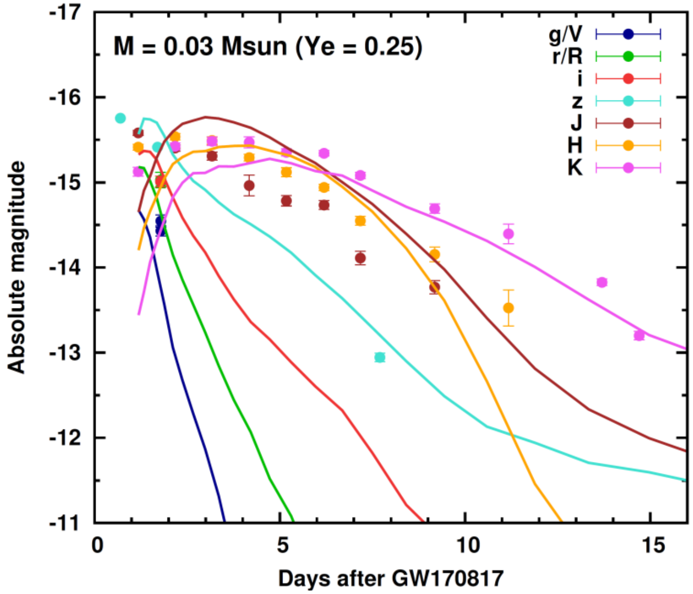


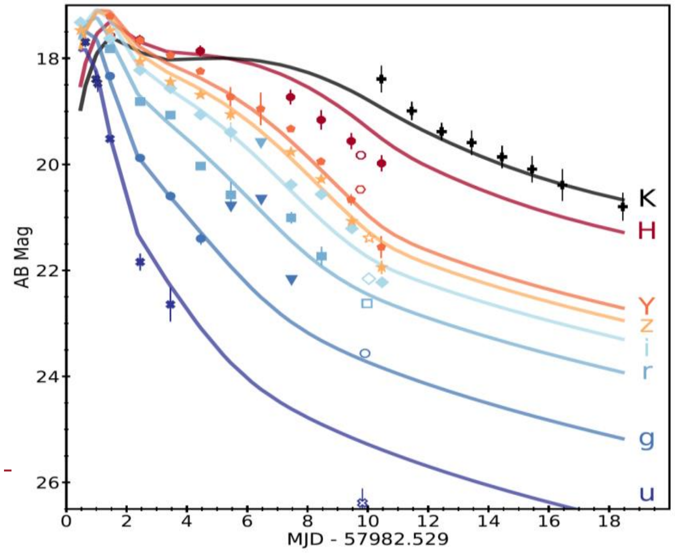
LIGO&Virgo+ (2017)

Appendix

Light curve modelling by Kilonova/Macronova

- Tanaka+ 2017 showed Mej = 0.03 Msun with Ye = 0.25 (moderately lanthanide rich ejecta) reasonably reproduce the observed multi-color light curves
- Cowperthwaite+ 2017 suggested a three component model in which $M_{ej,r\text{-}process}$ ~ 0.01Msun and M_{ej} = 0.03 Msun with κ = 3 cm^2/g
- Both model requires additional moderately lanthanide-rich ~ 0.03 Msun ejecta
- Asymmetric models suggest lower Mej
    - Tanvir et al. (2017); Villar et al. (2017)





Light curve modelling by Kilonova/Macronova

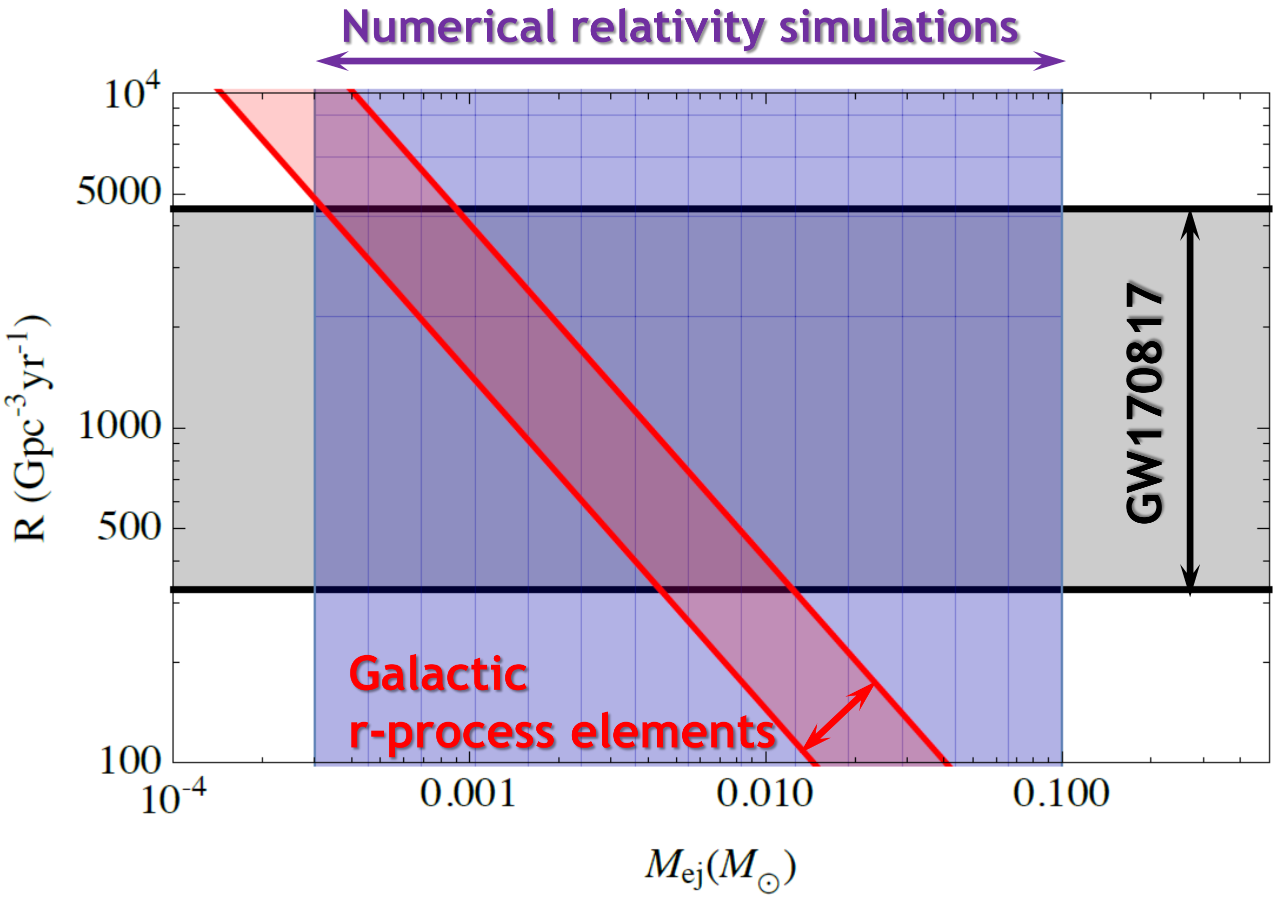
- Many modellings suggest 'red' ejecta of ~ 0.03-0.04 Msun (Vej ~ 0.1c) as well as 'blue' ejecta of ~ 0.01 Msun (Vej ~ (0.2-0.3)c)
  - Kasen+ 2017; Cowperthwaite+ 2017 see also Tanaka, Utsumi+ 2017; Nicholl+ 2017; Chornock+ 2017
  - Optical-NIR counterpart to GW170817 is consistent with kilonova
- But …
  - If the red ejecta is all of Ye < 0.2, it is extremely difficult (or almost impossible) to make it according to latest Numerical Relativity simulations
  - In this case, the red ejecta will synthesize huge amount of 'heavy' r-process elements. it conflicts with the GW observation (too much r-elements ??)
    - NS-NS merger rate from GW170817 : $R_{GW} = 1540^{+3200}_{-1220}\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
    - NS-NS rate necessary to explain the amount of r-elements :

$$R_{\text{r-process}} = 600\left(\frac{M_{ej,\text{r-process}}}{0.01M_{\text{sun}}}\right)^{-1}\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

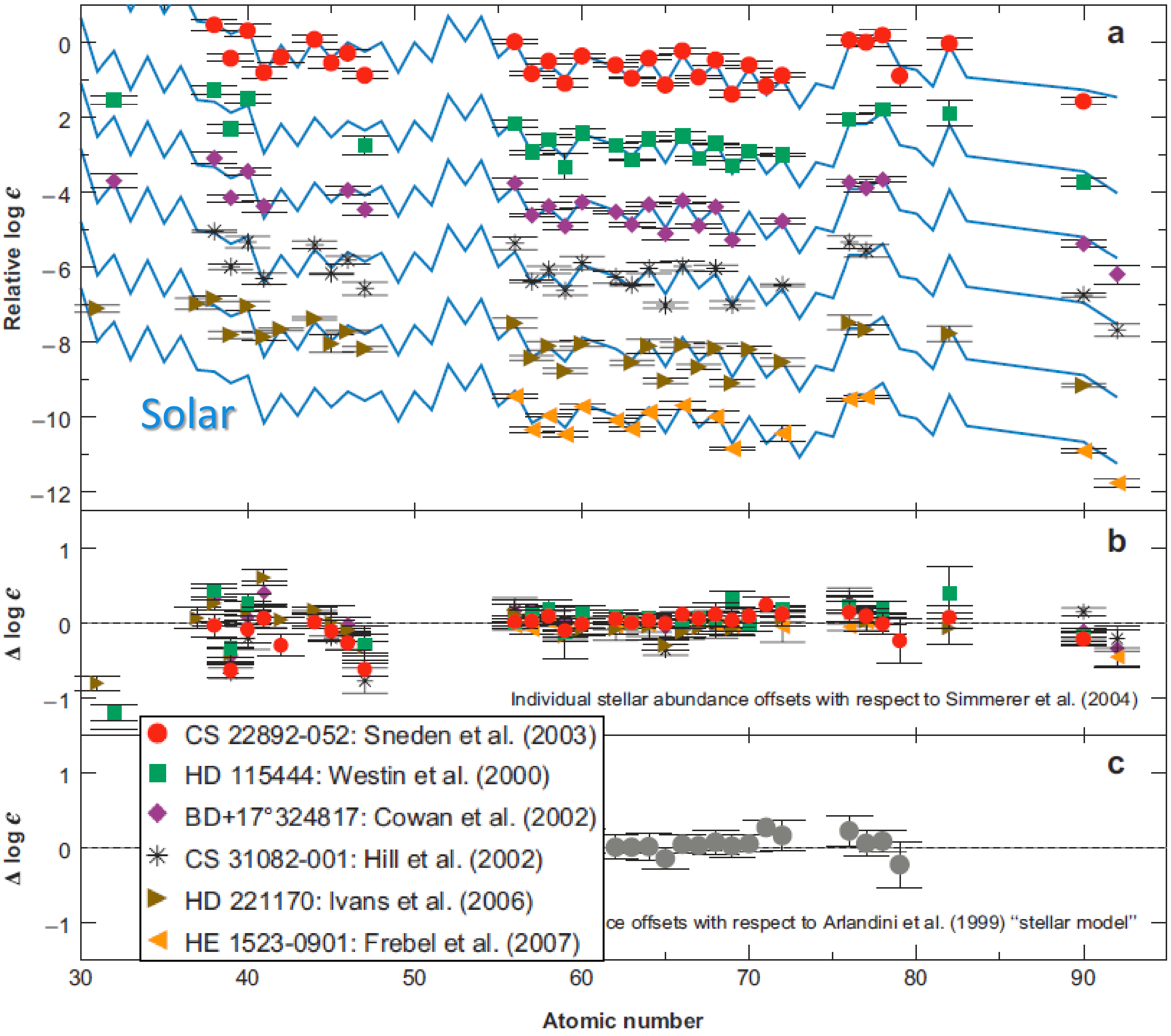
    - For Mej, r-process = 0.04Msun, the two rates differ by factor 10

r-process nucleosynthesis

- NS-NS rate from GW170817 : 320-4740 $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
  - Mej ~ 0.01 Msun is sufficient for NS-NS merger to be the origin of r-process elements ! (Abbott et al. 2017)



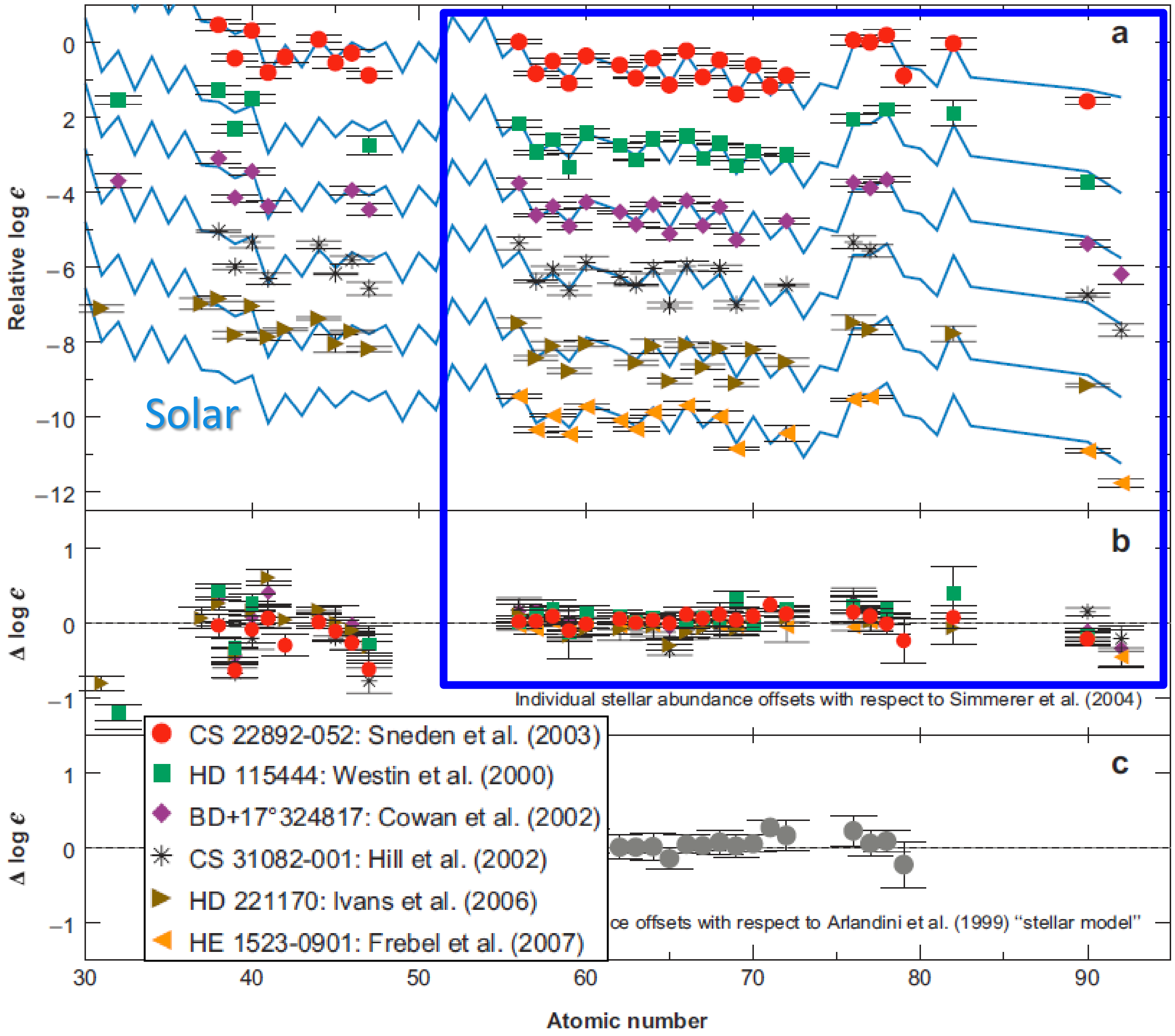
Key observations : Universality



- **Abundance pattern comparison :**
  - r-rich low metallicity stars
  - Solar neighborhood
- **Low metallicity suggests**
  - Such stars experience a few r-process events
  - preserve the pattern of the r-process events (chemical fossil)
    - Not the mixture of many events

- Sneden et al. (2008)

Key observations : Universality



- **The abundance patterns agree well for Z >~ 55**
- suggests that r-process event synthesize heavy elements with a pattern similar to solar pattern (Univsersality)

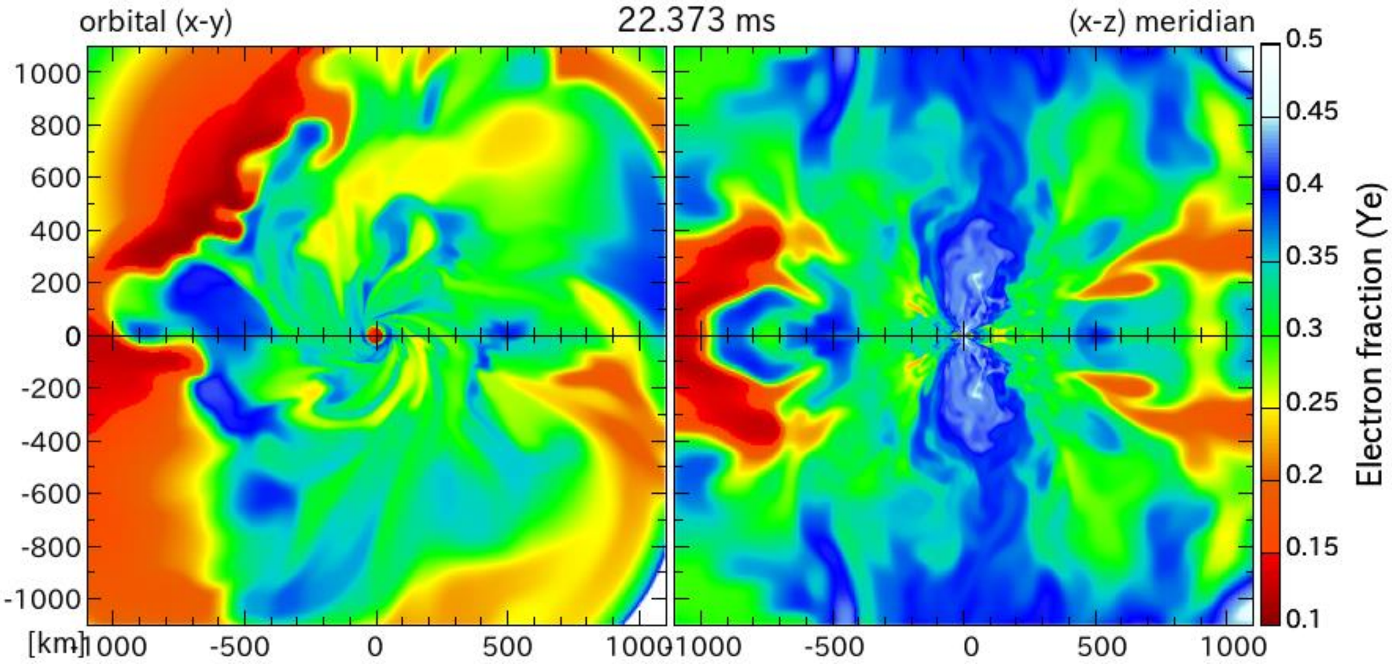
- Sneden et al. (2008)

Wanajo, Sekiguchi et al. ApJL (2014)

Achievement of the universality

(soft EOS (SFHo), equal mass (1.35-1.35))

- Wanajo YS et al. (2014) showed that at least for a specific model, the Universality is satisfied.
- NS-NS mergers are the astrophysical cite of r-process nucleosynthesis !?



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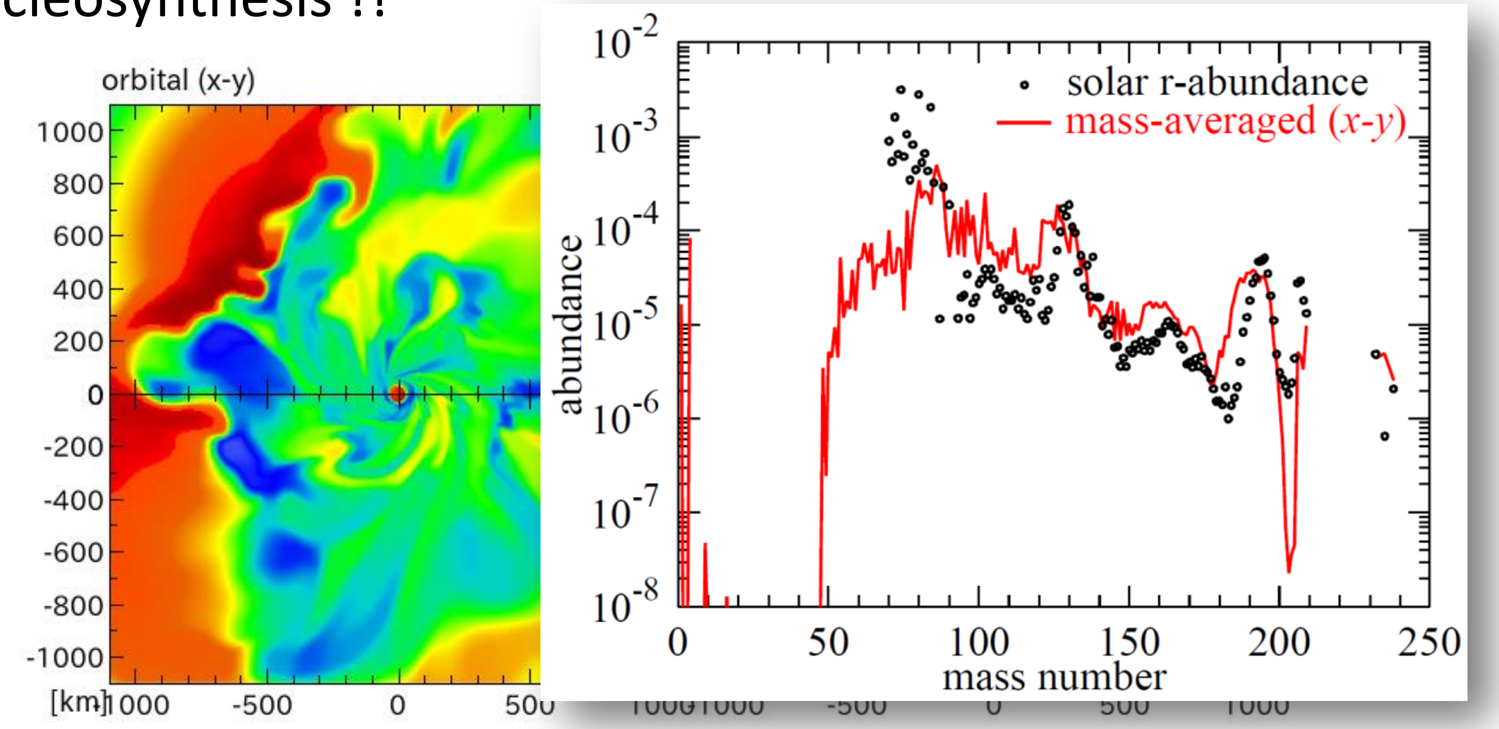


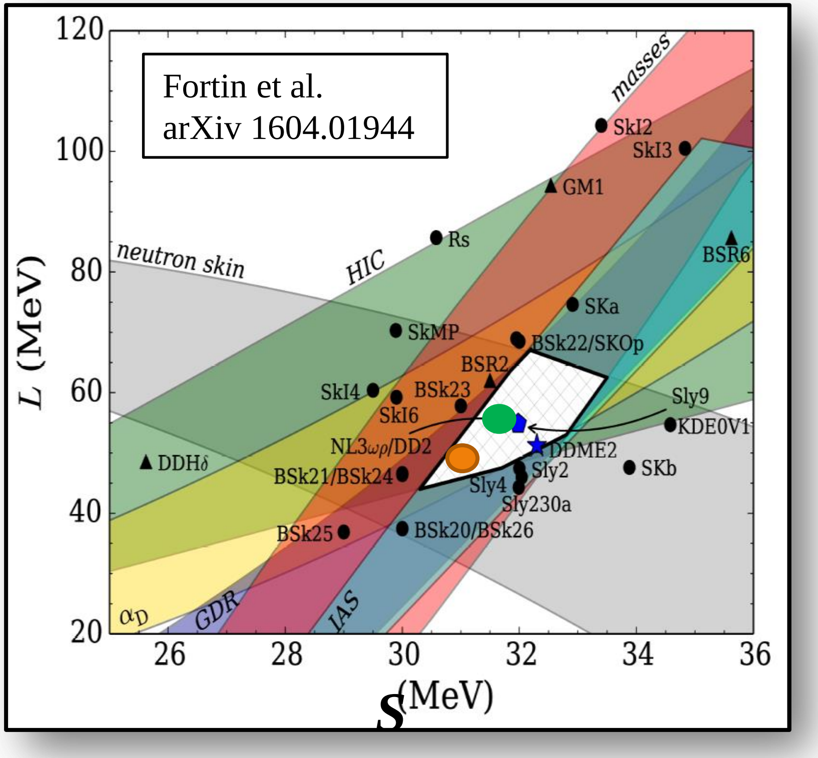
A question :

- The abundance pattern should depends on NS EOS, mass ratio of binary etc. (the previous one is a special case ?)
- Mass ratio may be estimated by galactic binary pulsars

- With the constraint on NS EOS from GW170817 (Λ<800), the abundance pattern of r-process elements, ***mixed according to the mass-ratio distribution of galactic binary pulsars***, satisfies the Universality ?

The adopted EOS

- **SFHo（R=12km, Λ=420）**, **DD2（R=13km, Λ=850 marginal）**
  - Both EOS satisfy (DD2 marginal) the constraint by GW170817
  - Also satisfy the symmetry energy constraint



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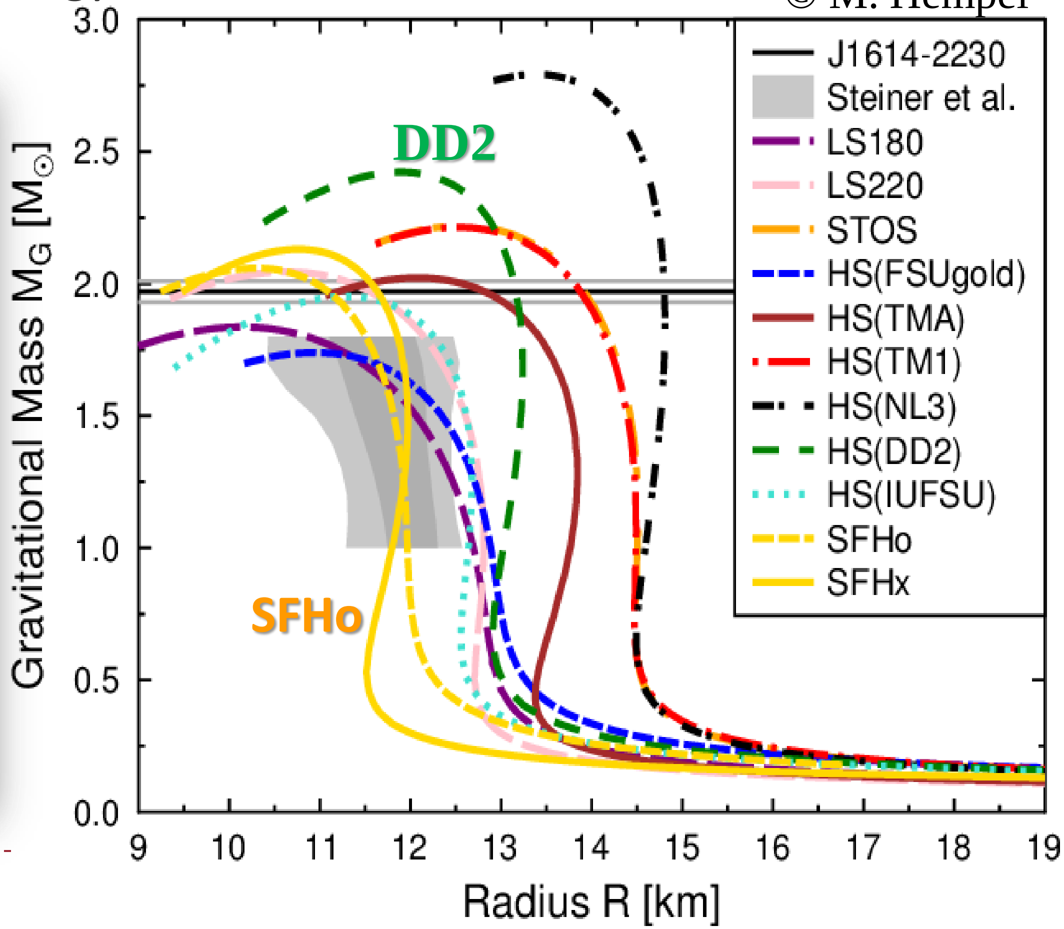
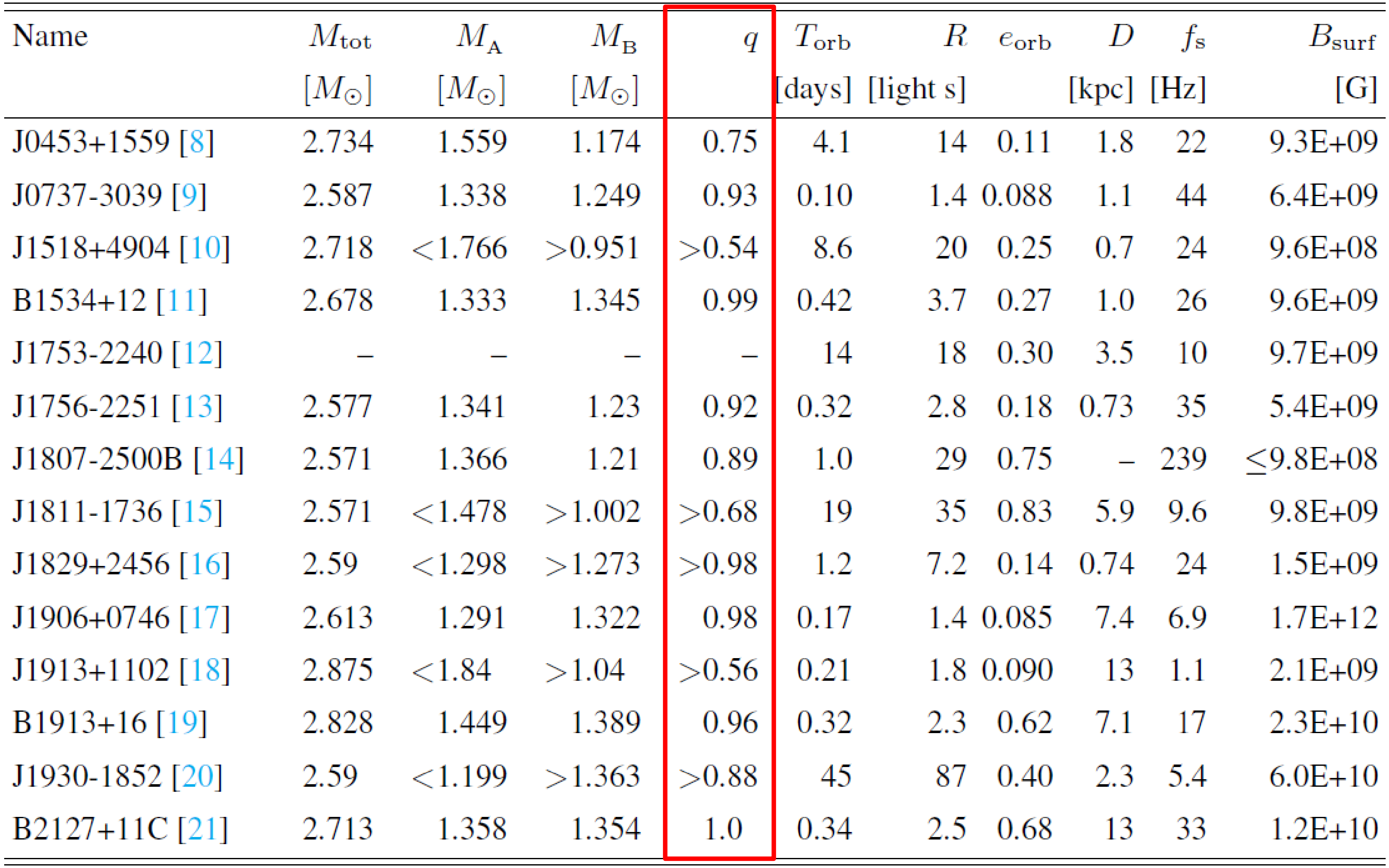


Mass ratio based on galactic binary pulsars (including candidates) **note. q=0.7-1.0 from GW170817**

- The mass ratios adopted are 1.0, 0.97, 0.93, 0.86, 0.81, 0.76



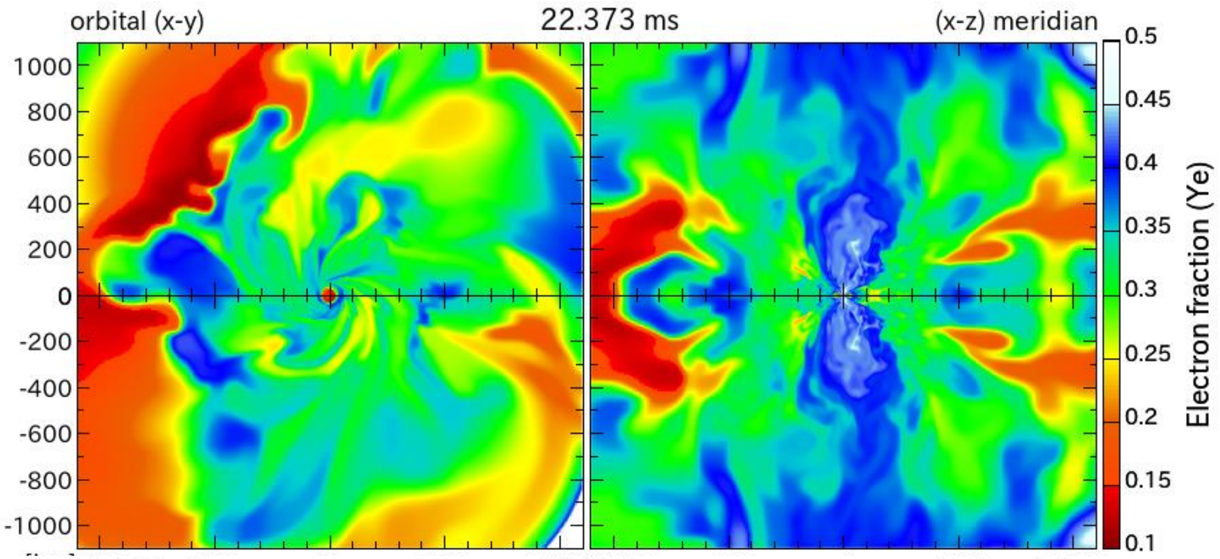
Name	$M_{\rm tot}$ $[M_\odot]$	$M_{\rm A}$ $[M_\odot]$	$M_{\rm B}$ $[M_\odot]$	q	$T_{\rm orb}$ [days]	R [light s]	$e_{\rm orb}$	D [kpc]	$f_{\rm s}$ [Hz]	$B_{\rm surf}$ [G]
J0453+1559 [8]	2.734	1.559	1.174	0.75	4.1	14	0.11	1.8	22	9.3E+09
J0737-3039 [9]	2.587	1.338	1.249	0.93	0.10	1.4	0.088	1.1	44	6.4E+09
J1518+4904 [10]	2.718	<1.766	>0.951	>0.54	8.6	20	0.25	0.7	24	9.6E+08
B1534+12 [11]	2.678	1.333	1.345	0.99	0.42	3.7	0.27	1.0	26	9.6E+09
J1753-2240 [12]	–	–	–	–	14	18	0.30	3.5	10	9.7E+09
J1756-2251 [13]	2.577	1.341	1.23	0.92	0.32	2.8	0.18	0.73	35	5.4E+09
J1807-2500B [14]	2.571	1.366	1.21	0.89	1.0	29	0.75	–	239	$\leq$9.8E+08
J1811-1736 [15]	2.571	<1.478	>1.002	>0.68	19	35	0.83	5.9	9.6	9.8E+09
J1829+2456 [16]	2.59	<1.298	>1.273	>0.98	1.2	7.2	0.14	0.74	24	1.5E+09
J1906+0746 [17]	2.613	1.291	1.322	0.98	0.17	1.4	0.085	7.4	6.9	1.7E+12
J1913+1102 [18]	2.875	<1.84	>1.04	>0.56	0.21	1.8	0.090	13	1.1	2.1E+09
B1913+16 [19]	2.828	1.449	1.389	0.96	0.32	2.3	0.62	7.1	17	2.3E+10
J1930-1852 [20]	2.59	<1.199	>1.363	>0.88	45	87	0.40	2.3	5.4	6.0E+10
B2127+11C [21]	2.713	1.358	1.354	1.0	0.34	2.5	0.68	13	33	1.2E+10

Mass ratio dependence :

SFHo EOS, 1.33-1.37 Msun vs. 1.25-1.55 Msun

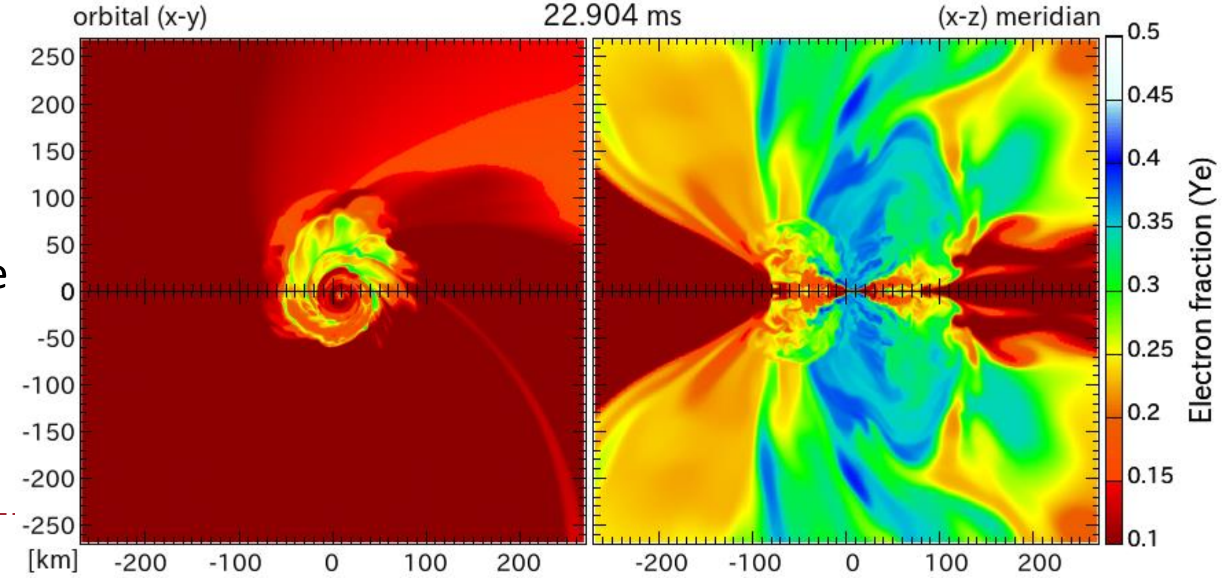
1.33-1.37 Msun

- Low Ye tidal ejecta (red) is less prominent
- Substantial amount of high Ye thermal and neutrino irradiated ejecta (green to blue)



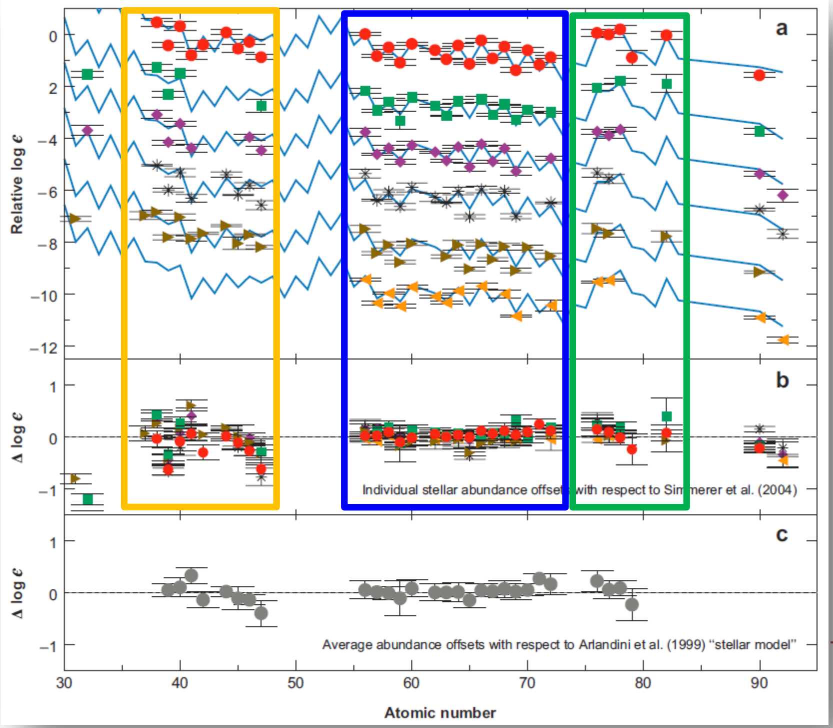
1.25-1.55 Msun

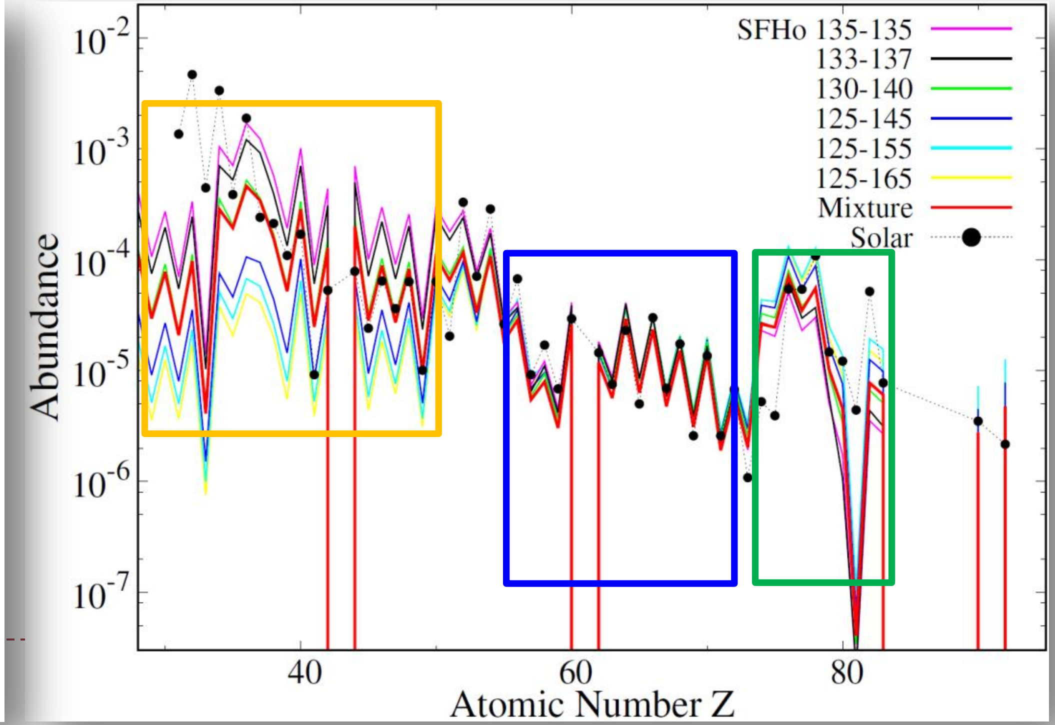
- Low Ye tidal ejecta is dominated in particular around the orbital plane



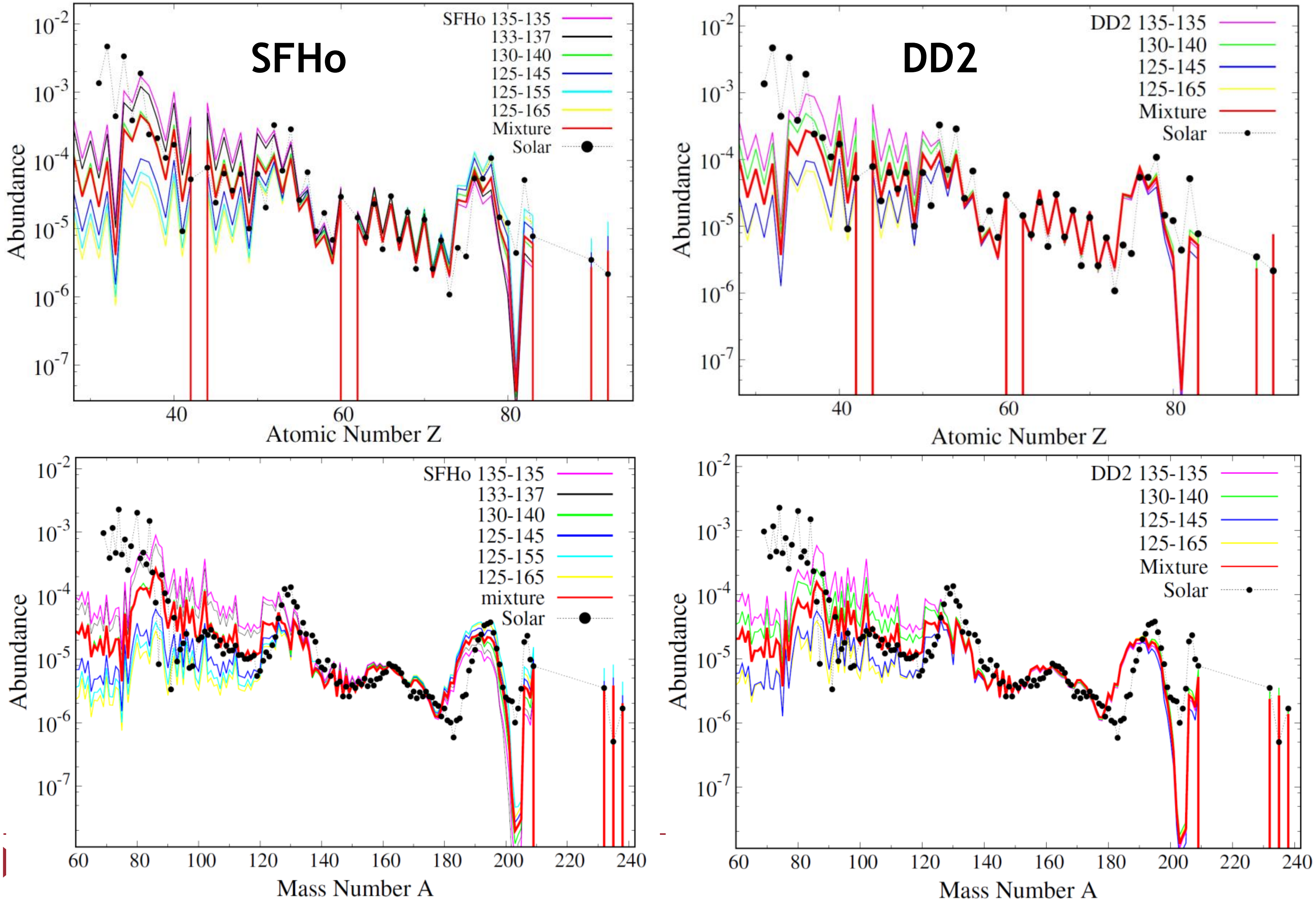
Mixed abundance pattern : SFHo

- We use results of Wanajo YS et al. (2014) to calculate r-process yield for simplicity (not self-consistent calculations)
- Even with a wide distribution of mass ratio, Universality is satisfied
  - very small diversity for rare earth elements (Z～60-70)
  - small diversity in 3rd peak elements
  - large diversity in Z < 50 elements





Similar results for DD2 EOS



Constraints on NS radius

- No direct BH formation means $M_{\mathrm{crit}} > M_{\mathrm{GW170817}} \approx 2.74 M_\odot$
- The critical mass depends on EOS : it may be written as

$$M_{\mathrm{crit}} = \left(-3.61 \frac{G M_{\mathrm{max}}}{c^2 R_{1.6}} + 2.38\right) M_{\mathrm{max}} = \left(-3.38 \frac{G M_{\mathrm{max}}}{c^2 R_{\mathrm{max}}} + 2.43\right) M_{\mathrm{max}}$$

  - Bauswein et al. ApJL 850, L34 (2017) : empirical relations from simulation results
- We may set lower limits on $R_{1.6}$ and R_{max}
- $R_{1.6} \gtrsim 11\mathrm{km}$
- $R_{\mathrm{max}} \gtrsim 10$ km
  - Constraints for a very compact configuration
  - May not be reliable, because Bauswein et al. performed approximate GR simulations