Diversity of kilonova lightcurves

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Kilonova

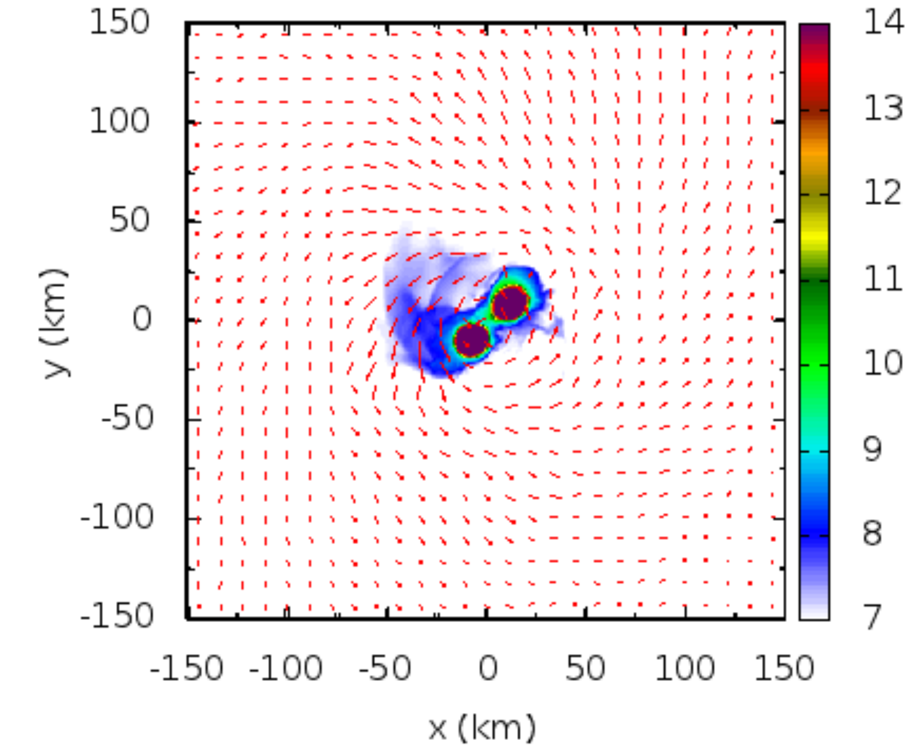
- **A kilonova (a.k.a macronova)** is a electromagnetic (EM) emission which expected to be associate with a neutron star (NS) binary merger.

- Ejected material is neutron-rich
→heavy radioactive nuclei would be synthesized in the ejecta by the so-called
r-process nucleosynthesis

→EM emission in optical and infrared wavelengths could occur by radioactive decays of heavy elements
: **kilonova**

Li & Paczyński 1998, Kulkarni 2005,
Metzger et al. 2010 …

Numerical relativity simulation for a NS-NS merger



Ref: K. Hotokezaka et al. 2013

Key quantities which characterize kilonova light curves

$M_{\rm eje}$:ejecta mass

κ :opacity

$v_{\rm eje}$:expanding velocity

f : energy conversation rate (heating rate)

$$t_{\rm peak} \approx 3.3\,{\rm days} \times \left(\frac{M}{0.03M_\odot}\right)^{1/2} \left(\frac{v}{0.2c}\right)^{-1/2} \left(\frac{\kappa}{1\,{\rm cm^2/g}}\right)^{1/2}$$

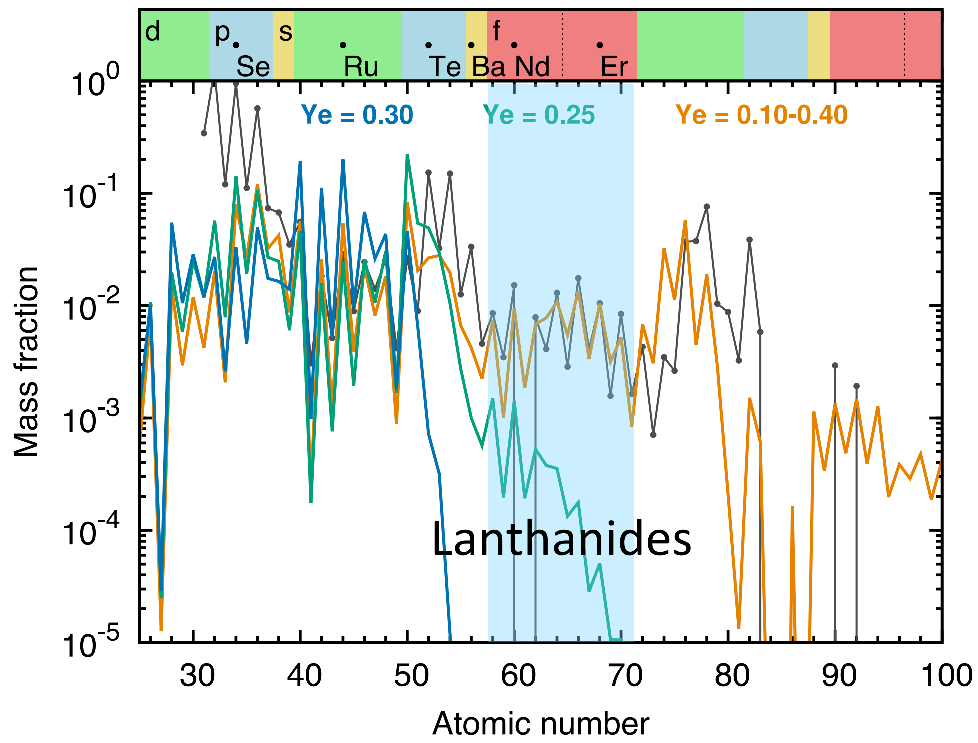
$$L_{\rm peak} \approx 2.0\times10^{41}\,{\rm ergs/s} \times \left(\frac{f}{10^{-6}}\right) \left(\frac{M}{0.03M_\odot}\right)^{1/2} \left(\frac{v}{0.2c}\right)^{1/2} \left(\frac{\kappa}{1\,{\rm cm^2/g}}\right)^{-1/2}$$

$$T_{\rm peak} \approx 3.1\times10^{3}\,{\rm K} \times \left(\frac{f}{10^{-6}}\right)^{1/4} \left(\frac{M}{0.03M_\odot}\right)^{-1/8} \left(\frac{v}{0.2c}\right)^{-1/8} \left(\frac{\kappa}{1\,{\rm cm^2/g}}\right)^{-3/8}$$

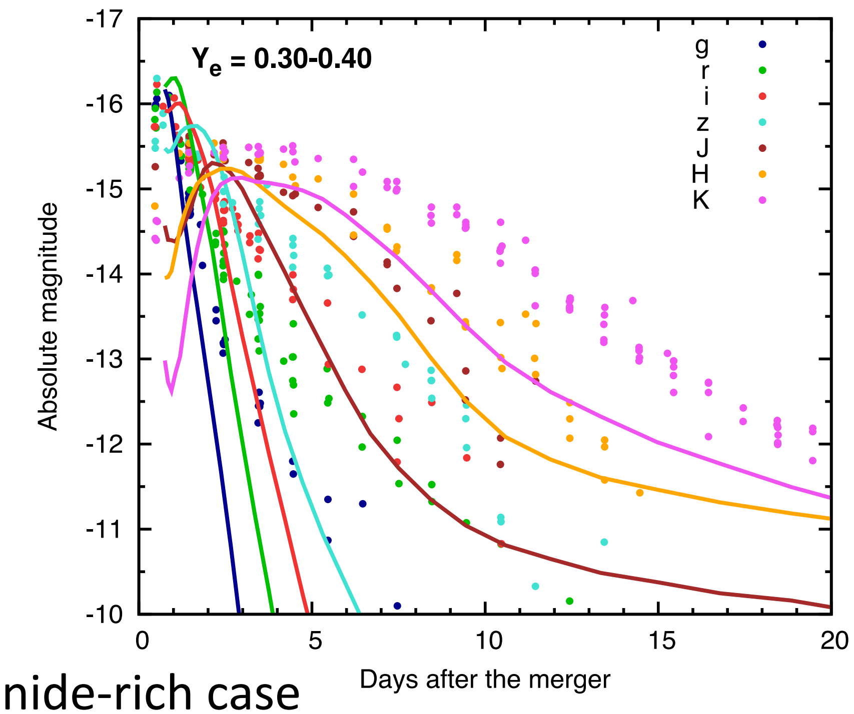
ref) Li & Paczyński 1998

Ejecta opacity

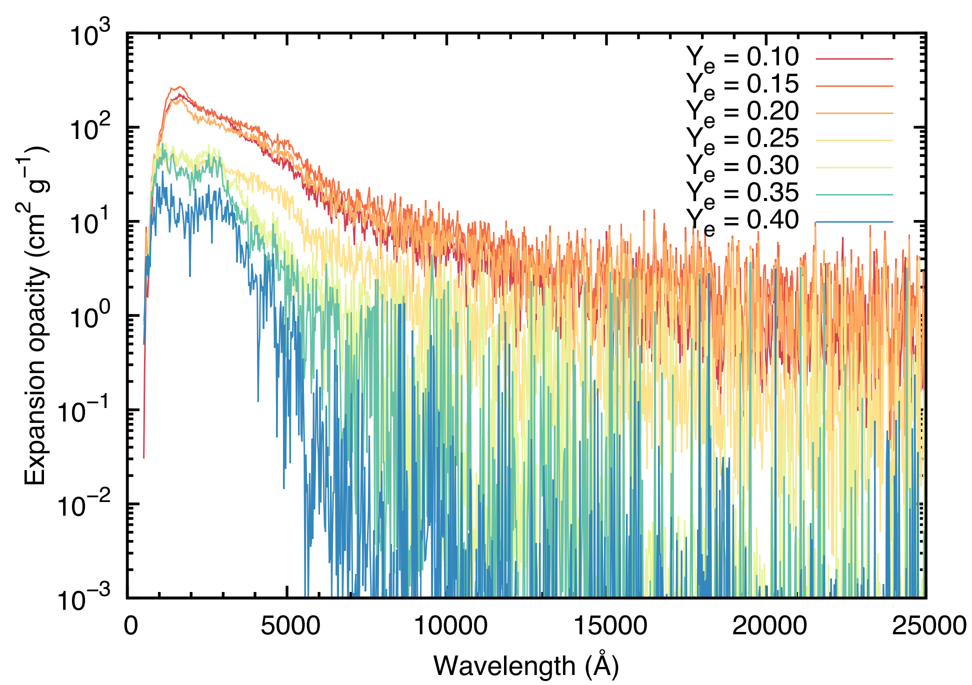
ref) Tanaka et al. 2018, 2019

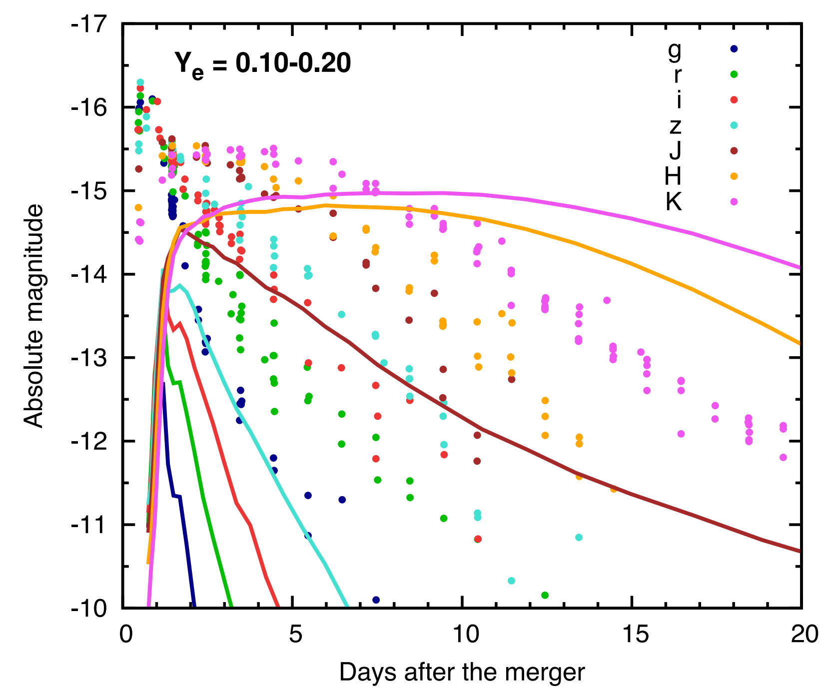


Lanthanide-poor case



Lanthanide-rich case



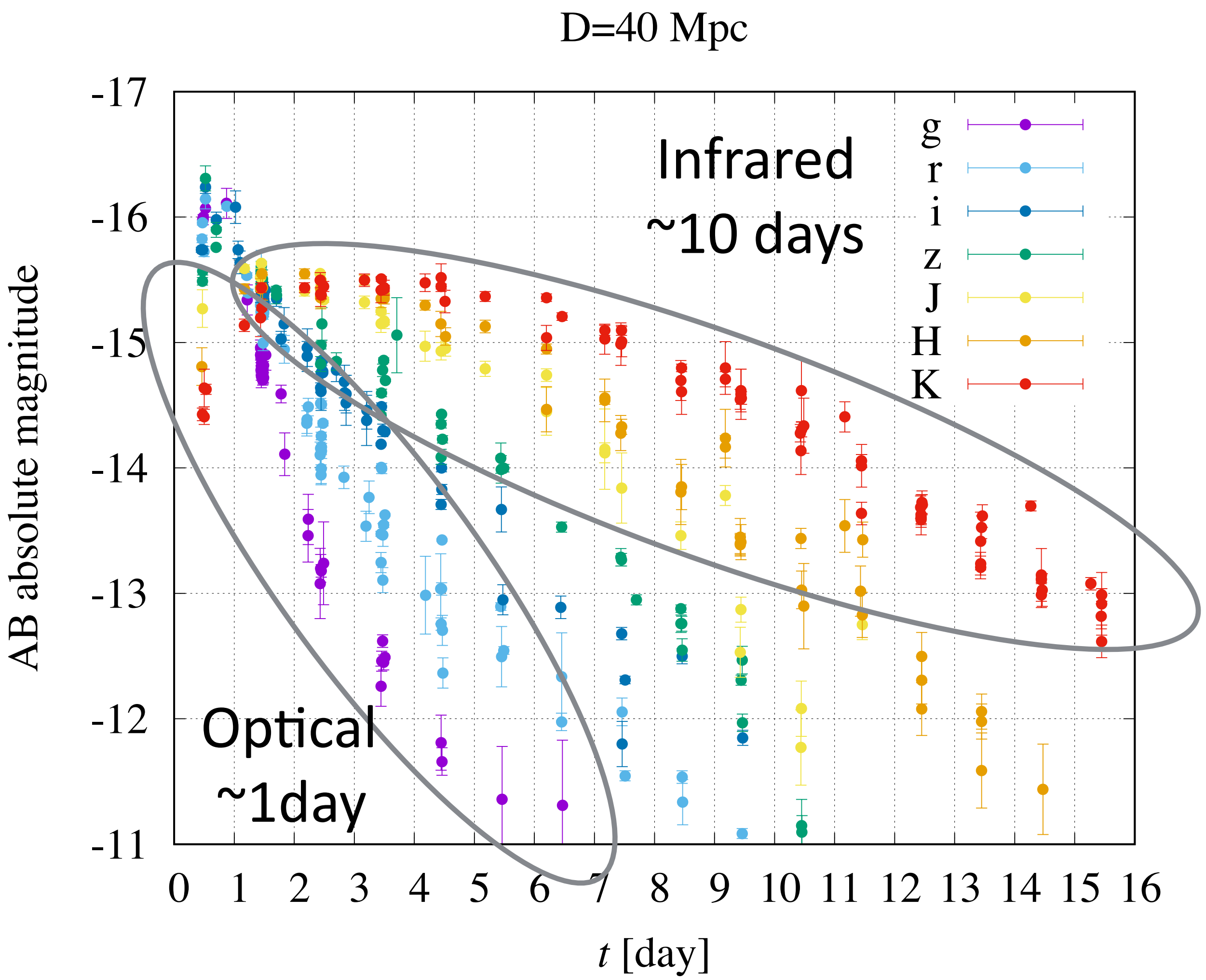


$$Y_e = \frac{[p]}{[p] + [n]}$$

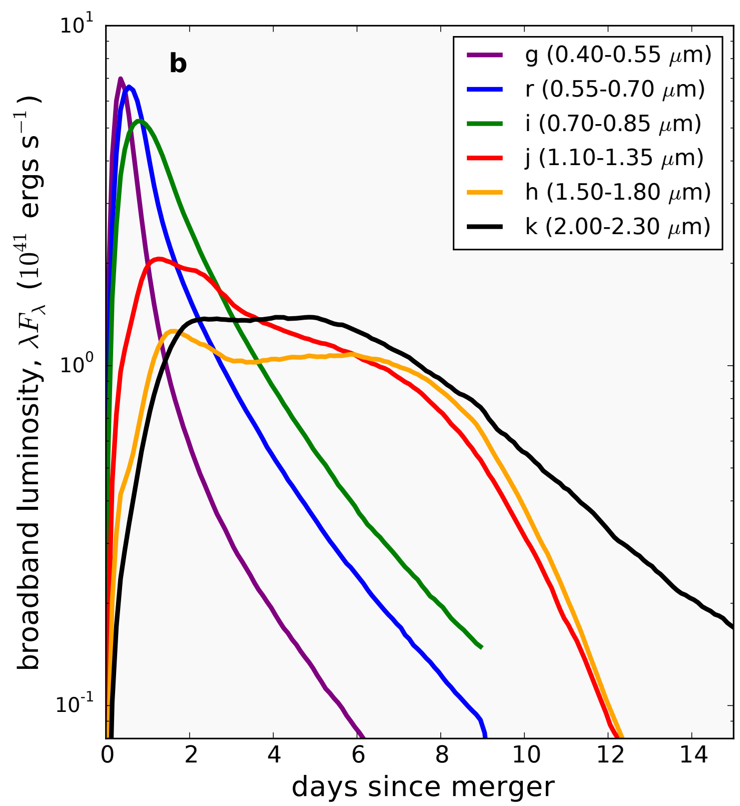
The ejecta opacity varies significantly (0.1—10 cm^2/g) depending on whether **lanthanide elements** are synthesized or not, which reflects the electron fraction, Ye, of ejecta. (Kasen et al. 2013, Barnes et al. 2013, Tanaka et al. 2013)

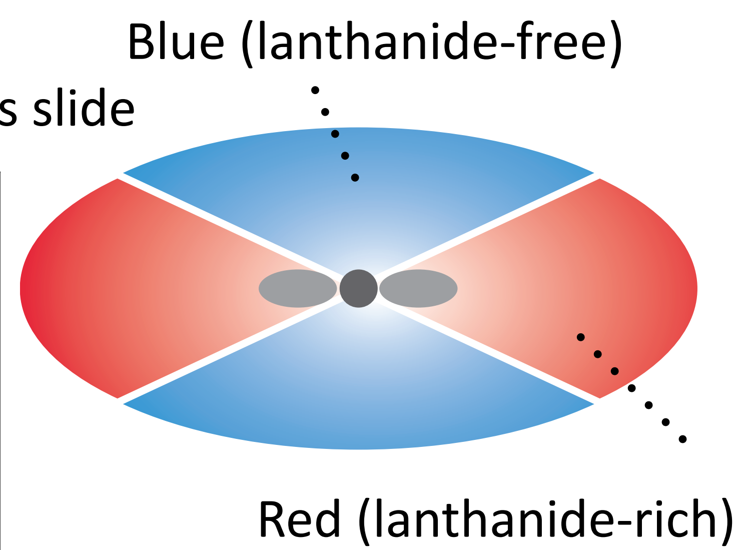
GW170817:
A Kilonova with multiple components

Data: Summarized in Villar et al. 2017



ref) Tanaka-san's slide





Ref: D. Kasen et al. 2017

Electromagnetic (EM) counterparts to GW170817 were observed simultaneously over the entire wavelength range (from radio to gamma wavelengths)

A Kilonova model with multiple components well interprets the optical-Infrared observation (see e.g., Kasliwal et al. 2017, Cowperthwaite et al. 2017, Kasen et al. 2017, Tanaka et al. 2017, Villar et al. 2017)

- early-blue component (~1day) from **lanthanide-free ejecta (~0.01 M_sun, opacity ~0.1-1 cm²/g)** + long-lasting red component (~10days) from **lanthanide-rich ejecta (~0.04 M_sun, opacity ~10 cm²/g)**

※radiation transfer effect among the multiple ejecta components would change the ejecta mass estimation

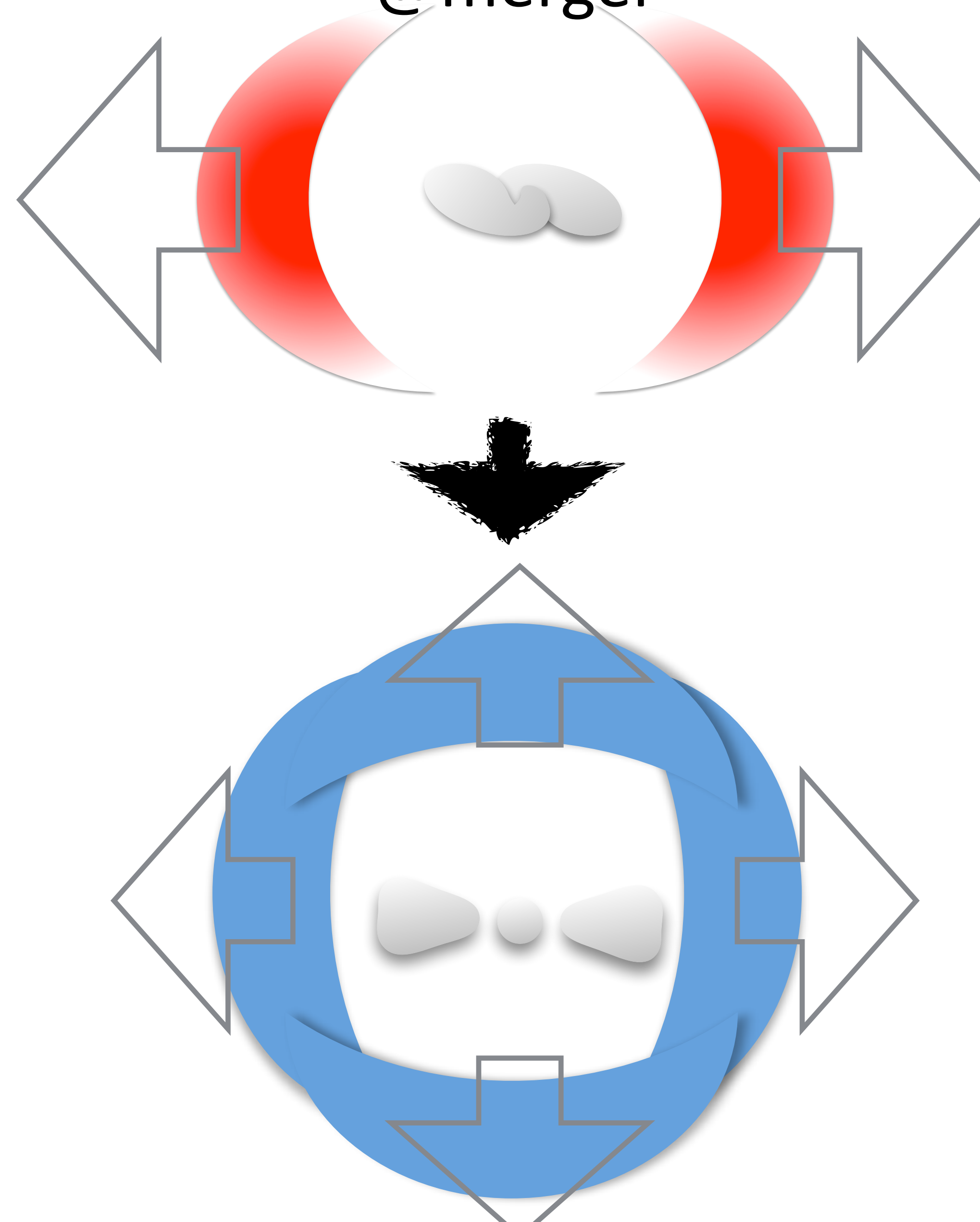
Mass Ejection Mechanisms

- In the last decades, many efforts have been made to study the mass ejection process and evolution of the merger remnant performing numerical-relativity simulations

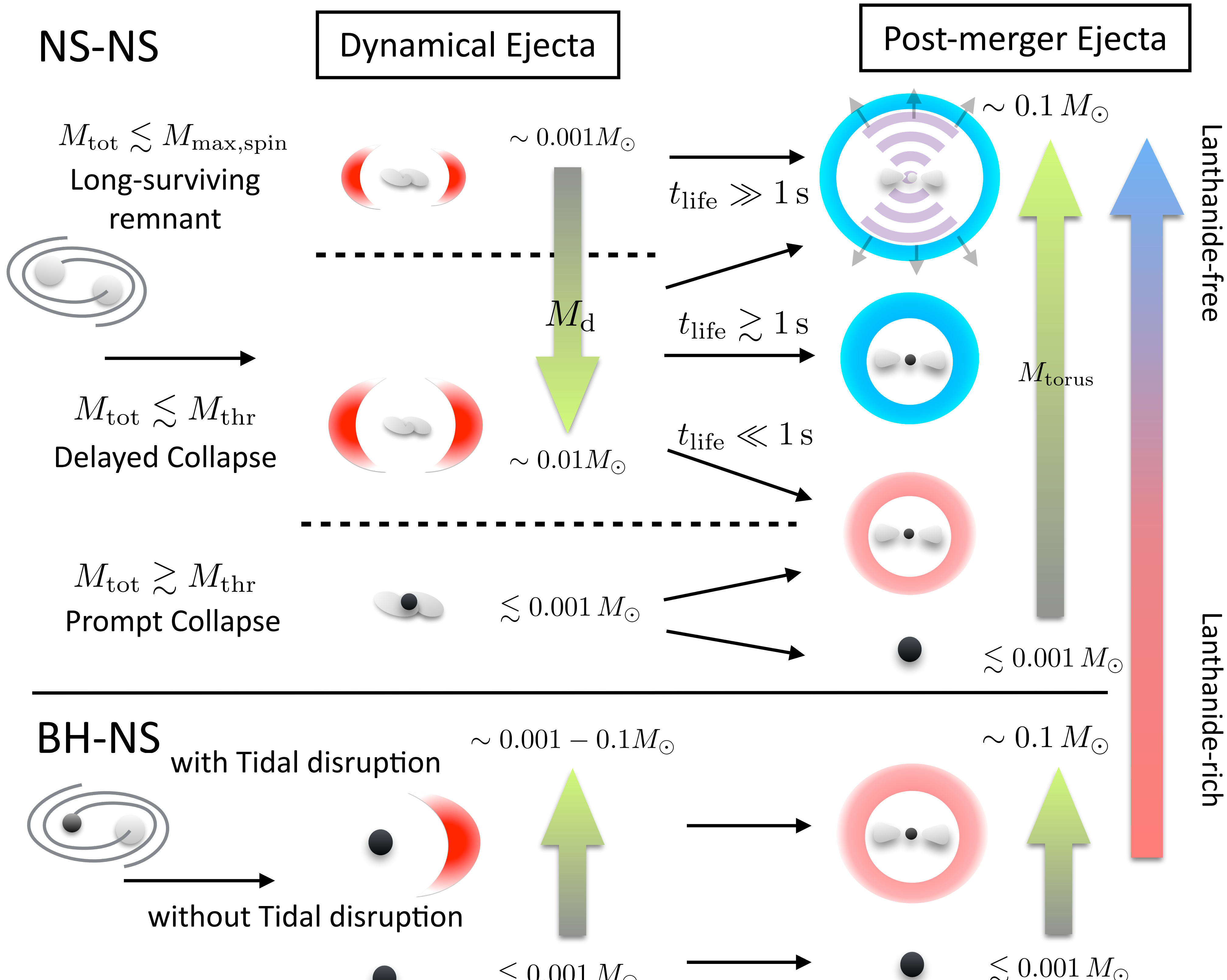
- **Dynamical mass ejection**
  mass ejection driven by tidal interaction
  or
  shock heating during the collision
  (e.g., Hotokezaka et al. 2013; Bauswein et al. 2013; Sekiguchi et al. 2016; Radice et al. 2016; Dietrich et al. 2017; Bovard et al. 2017)

- **Post-merger mass ejection**
  mass ejection from the merger remnant driven by effective viscosity and/or neutrino heating
  (e.g., Dessart et al. 2009; Metzger & Fernández 2014; Perego et al. 2014; Just et al. 2015; Shibata et al. 2017; Lippuner et al. 2017; Fujibayashi et al. 2018, Siegel et al. 2018, Fernandez et al.2018)

Dynamical mass ejection
@merger



Post-merger mass ejection
@after merger

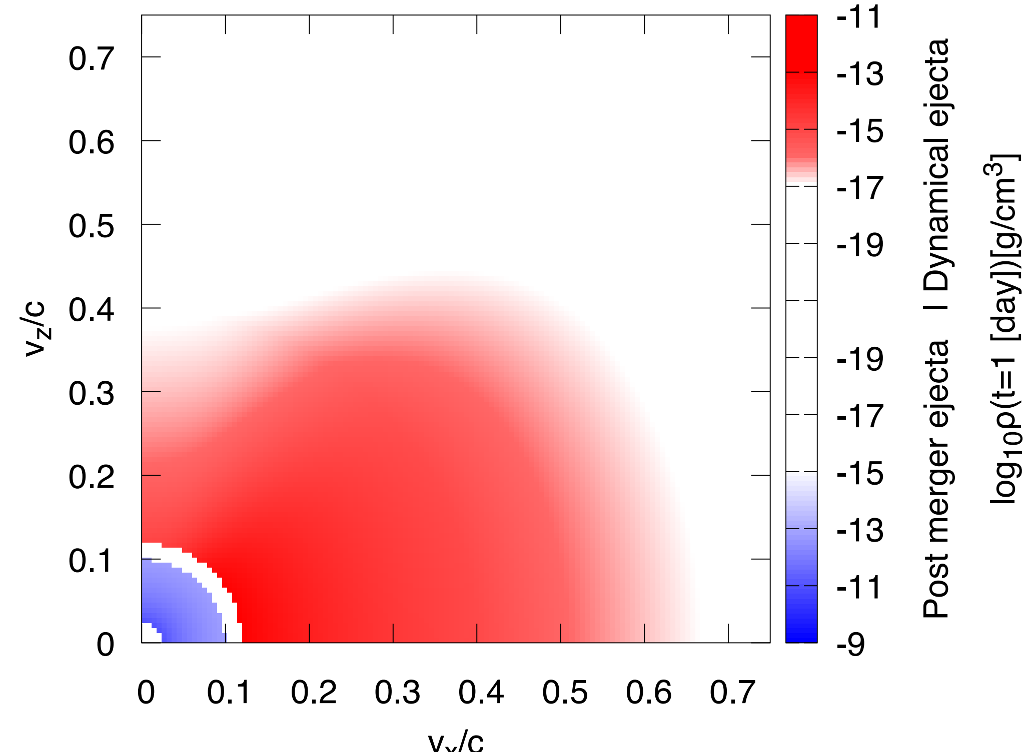


Kilonova lightcurves could show large diversity reflecting the variety in the binary parameters or the binary composition (see also e.g. Gompertz et al. 2018, Rossi et al. 2019)

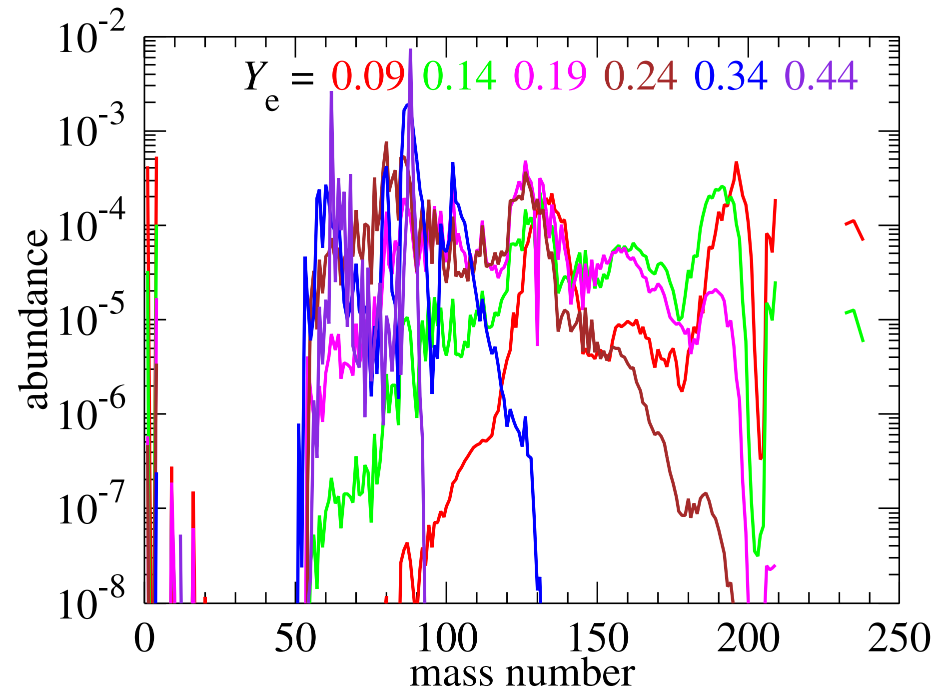
Radiative transfer simulation

- A wavelength-dependent Monte-Carlo radiative transfer simulation code (Tanaka et al. 2013, 2014, 2017, Kawaguchi et al. 2018, 2019)
- The density, velocity, and Ye profiles of ejecta based on predictions of numerical-relativity simulations. (e.g., Dietrich et al. 2016, Hotokezaka et al. 2018, Metzger&Fernandez et al. 2014, Fujibayashi et al. 2018)
- Axisymmetric & homologous expanding ejecta
- The abundance pattern and nuclear heating rate based on nucleosynthesis calculations (Wanajo et al. 2014)
- New line list derived by systematic atomic structure calculations for all the r-process elements from Z=26 to 92 (Tanaka et al. 2019)

Ejecta density profile for a NS-NS merger

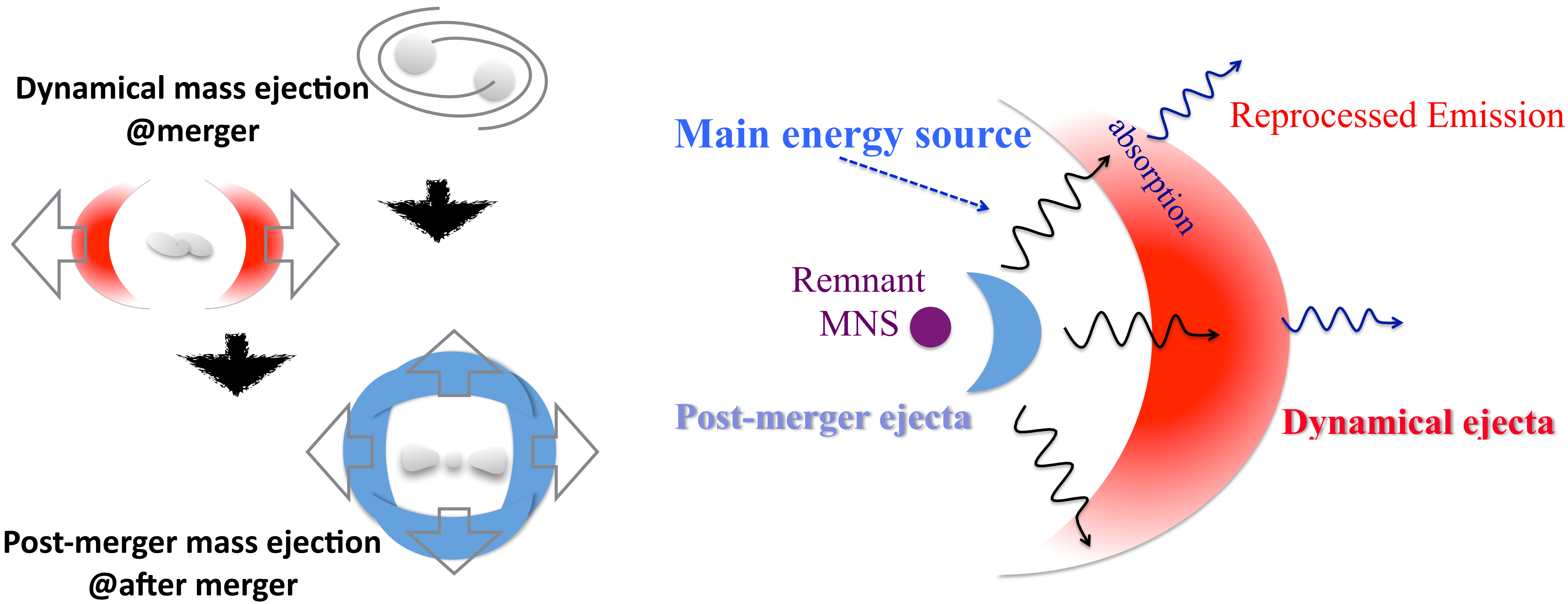


Elements abundance



Ref: Wanajo et al. 2014

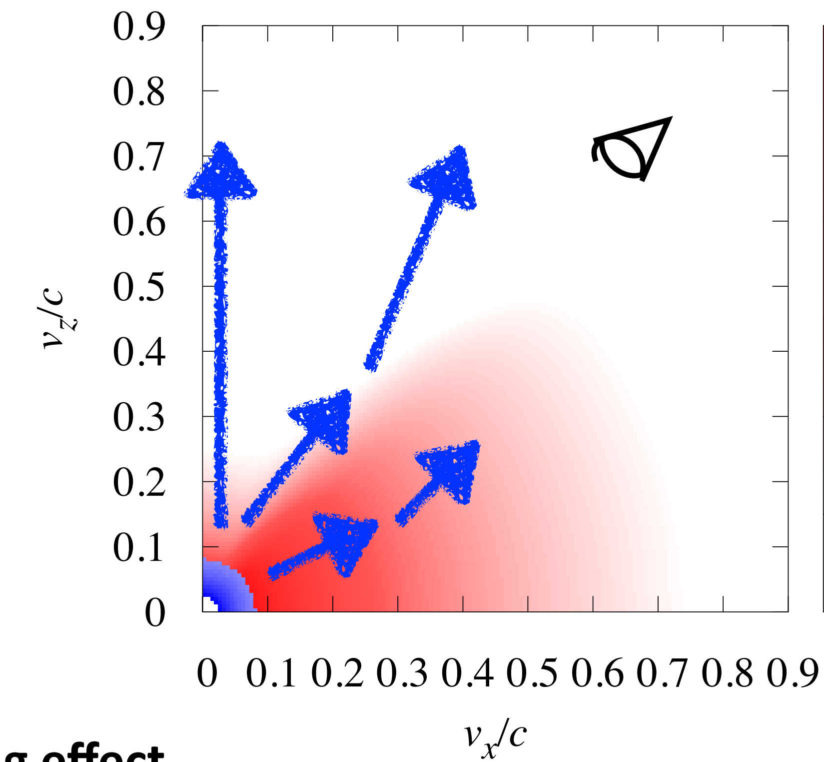
Photon interaction among different ejecta components

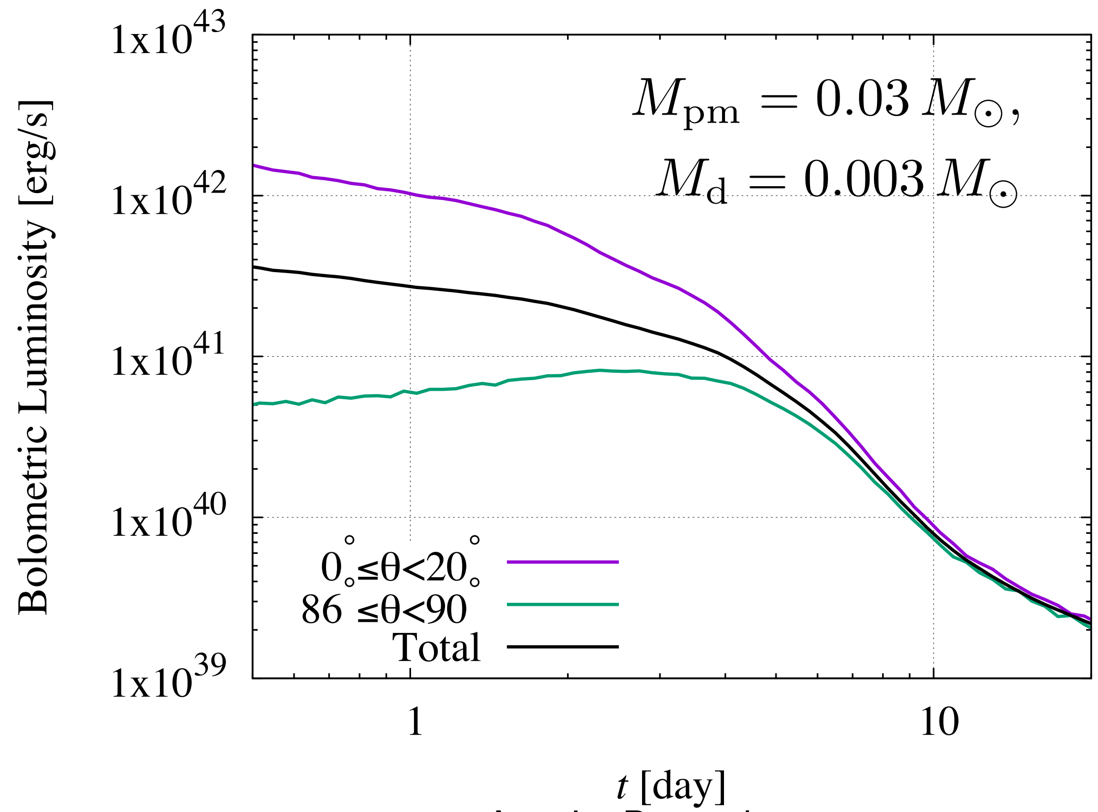


Radiative transfer of photons among the multiple ejecta components
has a large impact on the lightcurve predictions
(see Perego et al. 2017, Wollaeger et al. 2017 for studies with similar setups
and also Matsumoto et al. 2018 for reprocessing models in different context)

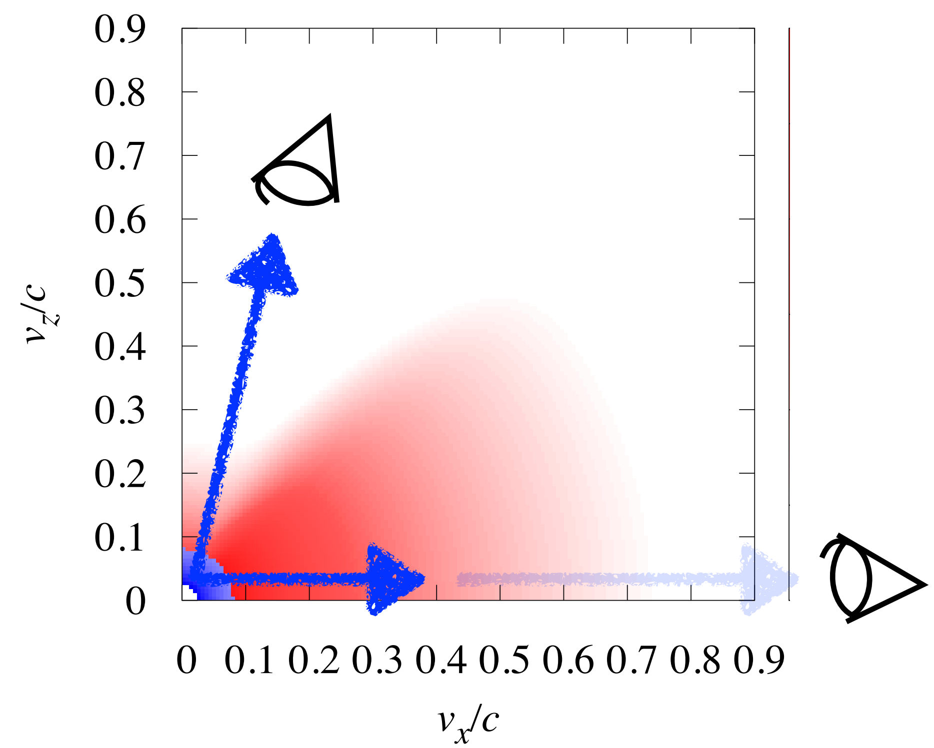
Effect of radiative transfer of photons in multiple ejecta components

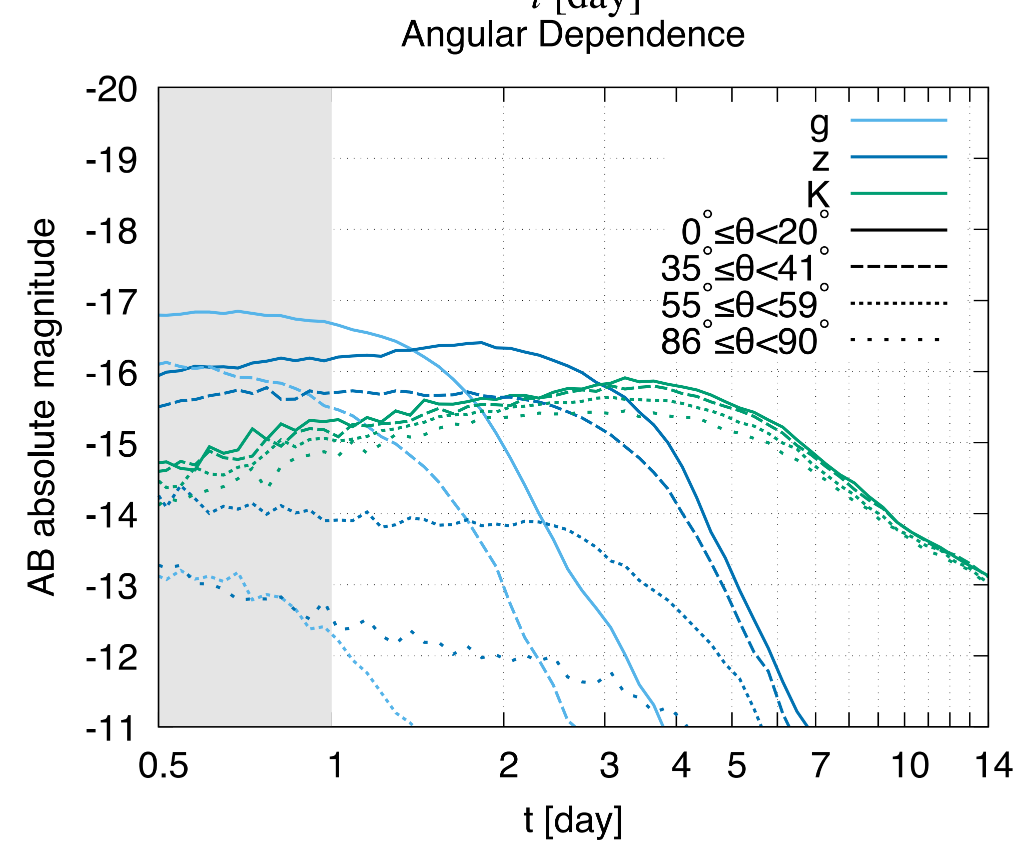
- **Enhancement of luminosity in polar direction**





- **Blocking effect**

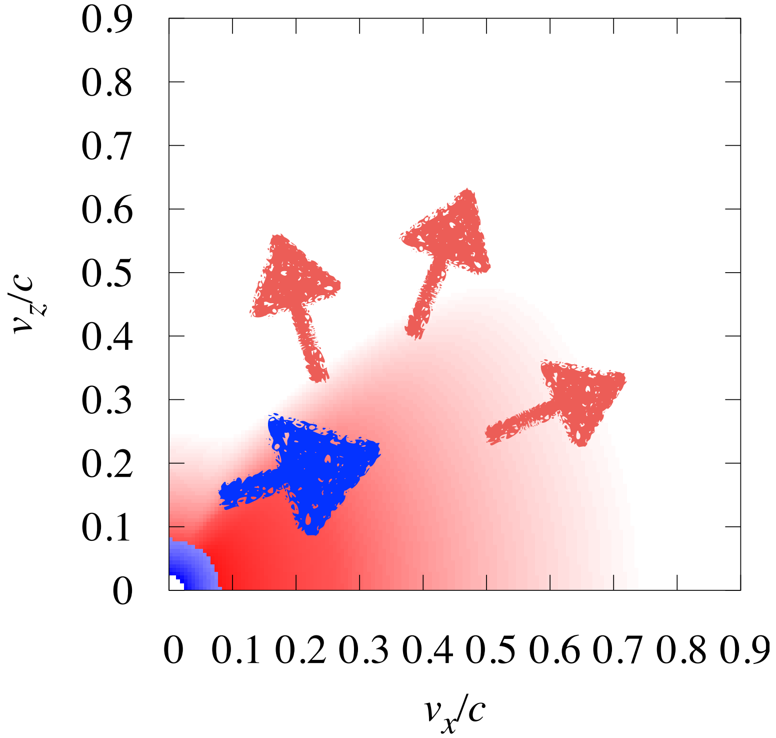




Effect of radiative transfer of photons in multiple ejecta components

- **Heating up of the dynamical ejecta**

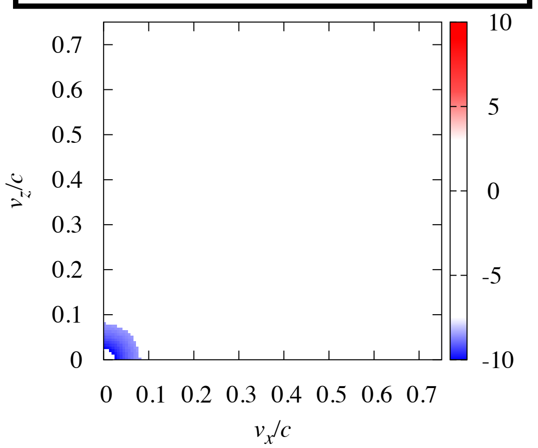
Solid: the full calculation



$$M_{\rm pm} = 0.03\,M_{\odot},$$
$$M_{\rm d} = 0.003\,M_{\odot}$$

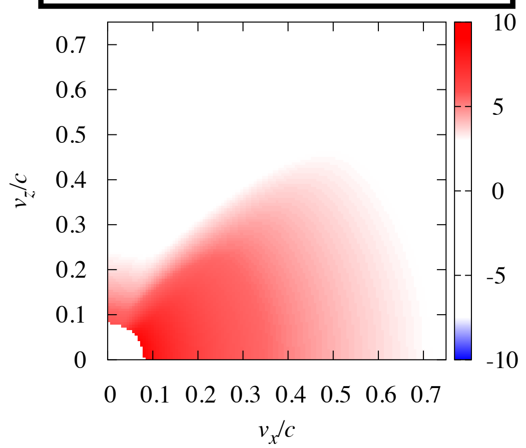
Dashed: Separately calculated and combined

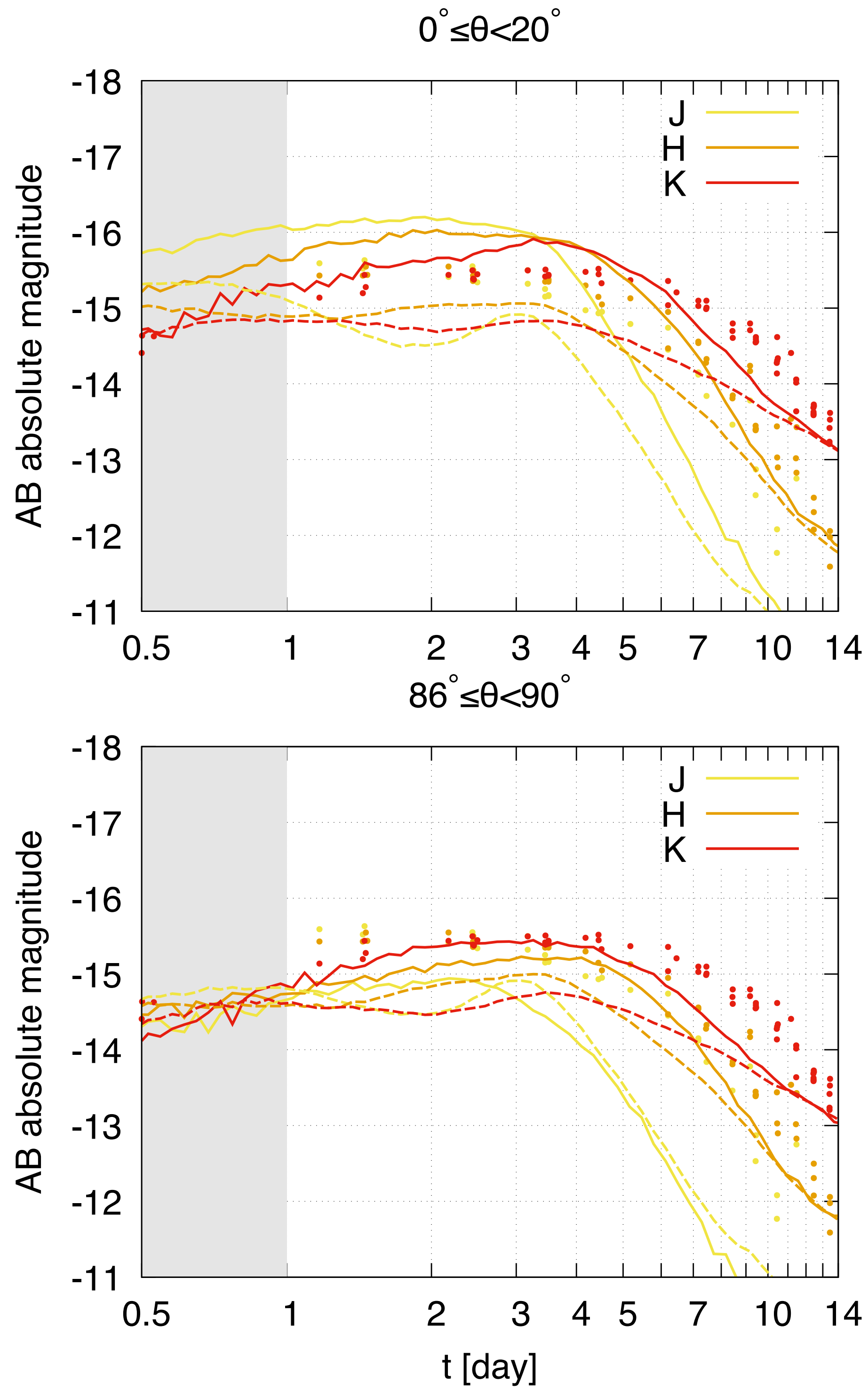
Only post-merger ejecta



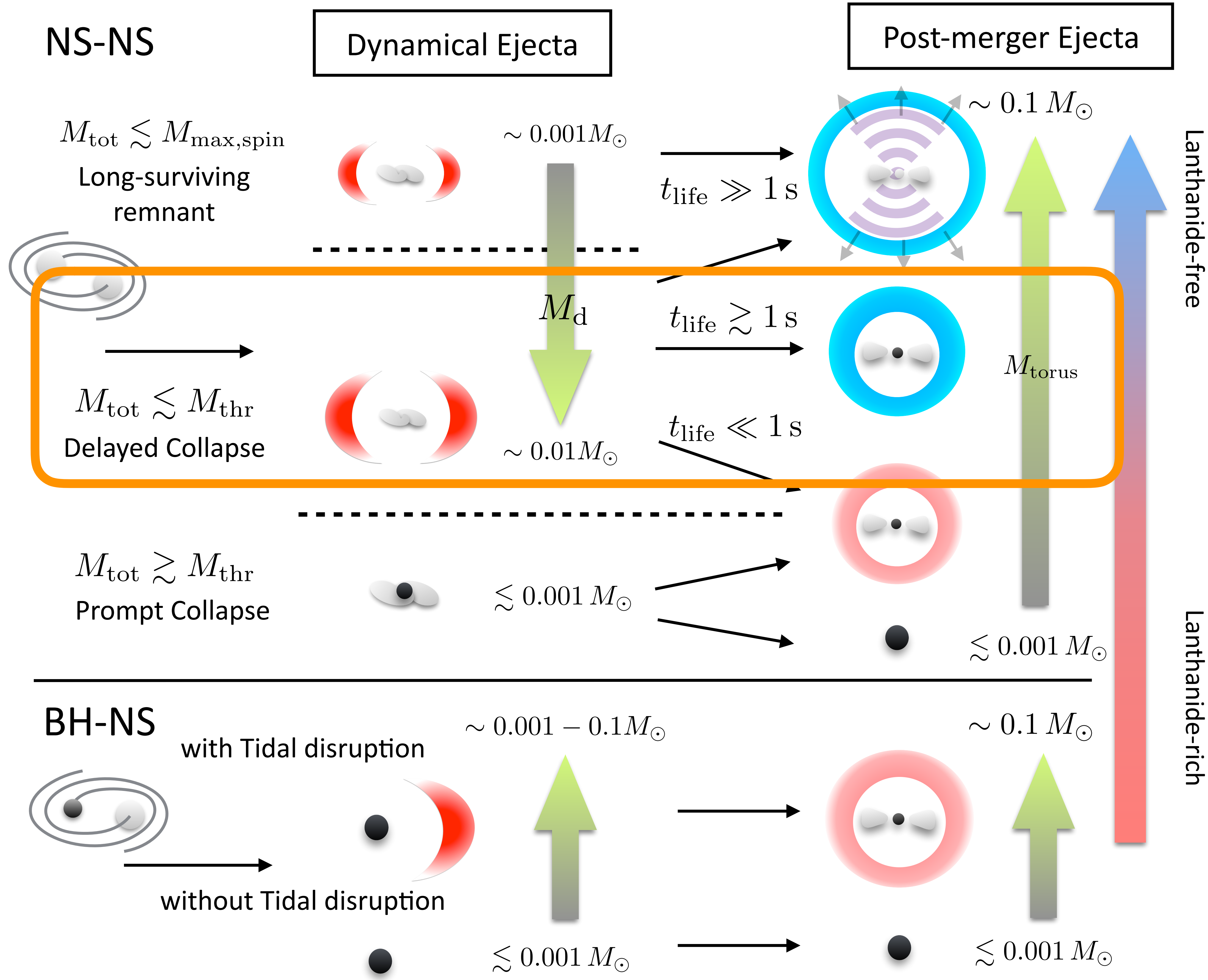
+

Only dynamical ejecta

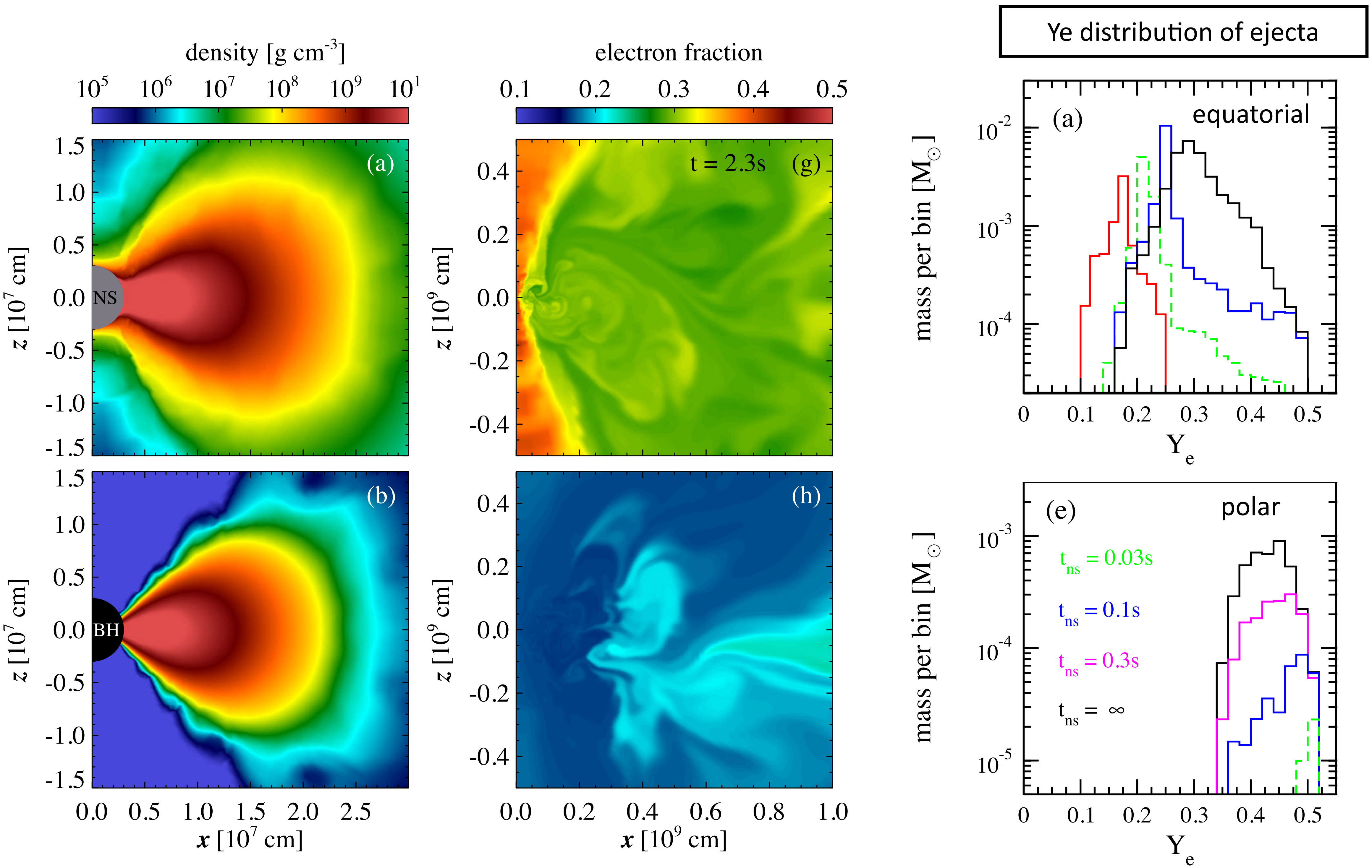




Taking the radiative transfer effect of photons in the multiple ejecta components of non-spherical morphology into account is crucial for the lightcurve prediction


NS-NS
Dynamical Ejecta
Post-merger Ejecta
$M_{tot} \lesssim M_{max,spin}$
Long-surviving remnant
$\sim 0.001 M_\odot$
$t_{life} \gg 1\,s$
$\sim 0.1\, M_\odot$
M_d
$t_{life} \gtrsim 1\,s$
M_{torus}
$M_{tot} \lesssim M_{thr}$
Delayed Collapse
$\sim 0.01 M_\odot$
$t_{life} \ll 1\,s$
$M_{tot} \gtrsim M_{thr}$
Prompt Collapse
$\lesssim 0.001\, M_\odot$
$\lesssim 0.001\, M_\odot$
Lanthanide-free
Lanthanide-rich
BH-NS
with Tidal disruption
$\sim 0.001 - 0.1 M_\odot$
$\sim 0.1\, M_\odot$
without Tidal disruption
$\lesssim 0.001\, M_\odot$
$\lesssim 0.001\, M_\odot$

Remnant NS Lifetime



Ref: Metzger & Fernández et al. 2014

- Life time of the remnant NS has a large impact on the Ye distribution of the post merger ejecta: low (high) Ye → large (small) lanthanide fraction (See also Lippuner et al. 2017)

Ye dependence

Optical/infrared EM data points observed in GW170817 summarized by Villar et al. 2017 (D=40Mpc)

$$M_{\rm pm} = 0.03\,M_\odot,$$
$$M_{\rm d} = 0.01\,M_\odot$$

Solid:

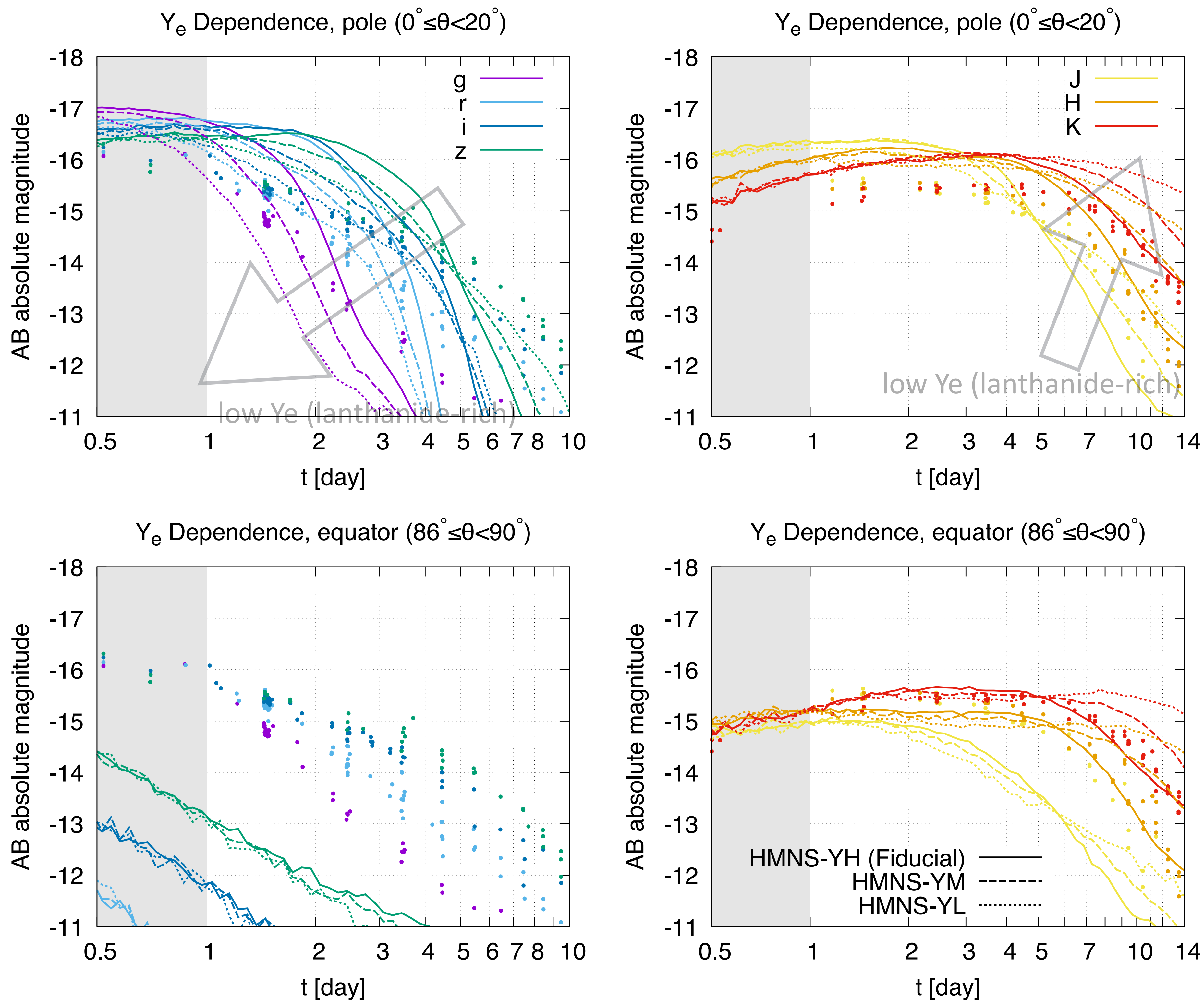
$Y_{e,\rm pm} : 0.3 - 0.4 (X_{\rm lan} \ll 1)$

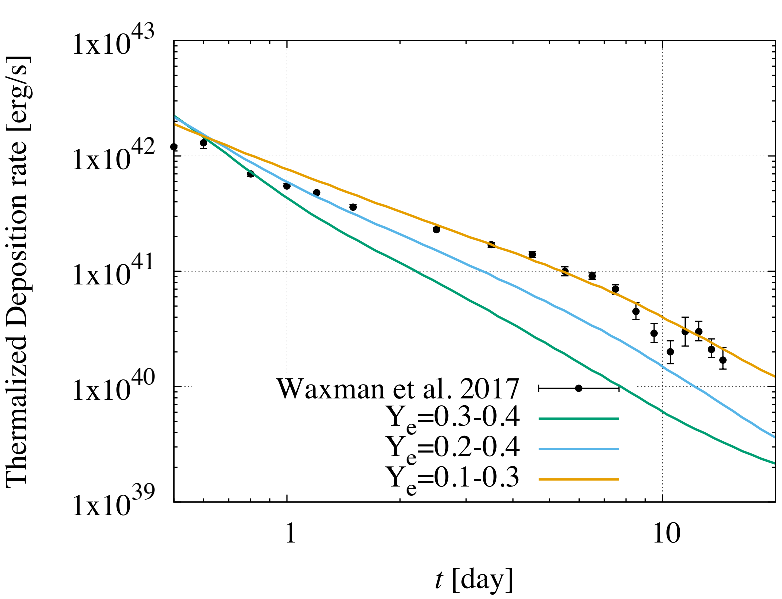
Dashed:

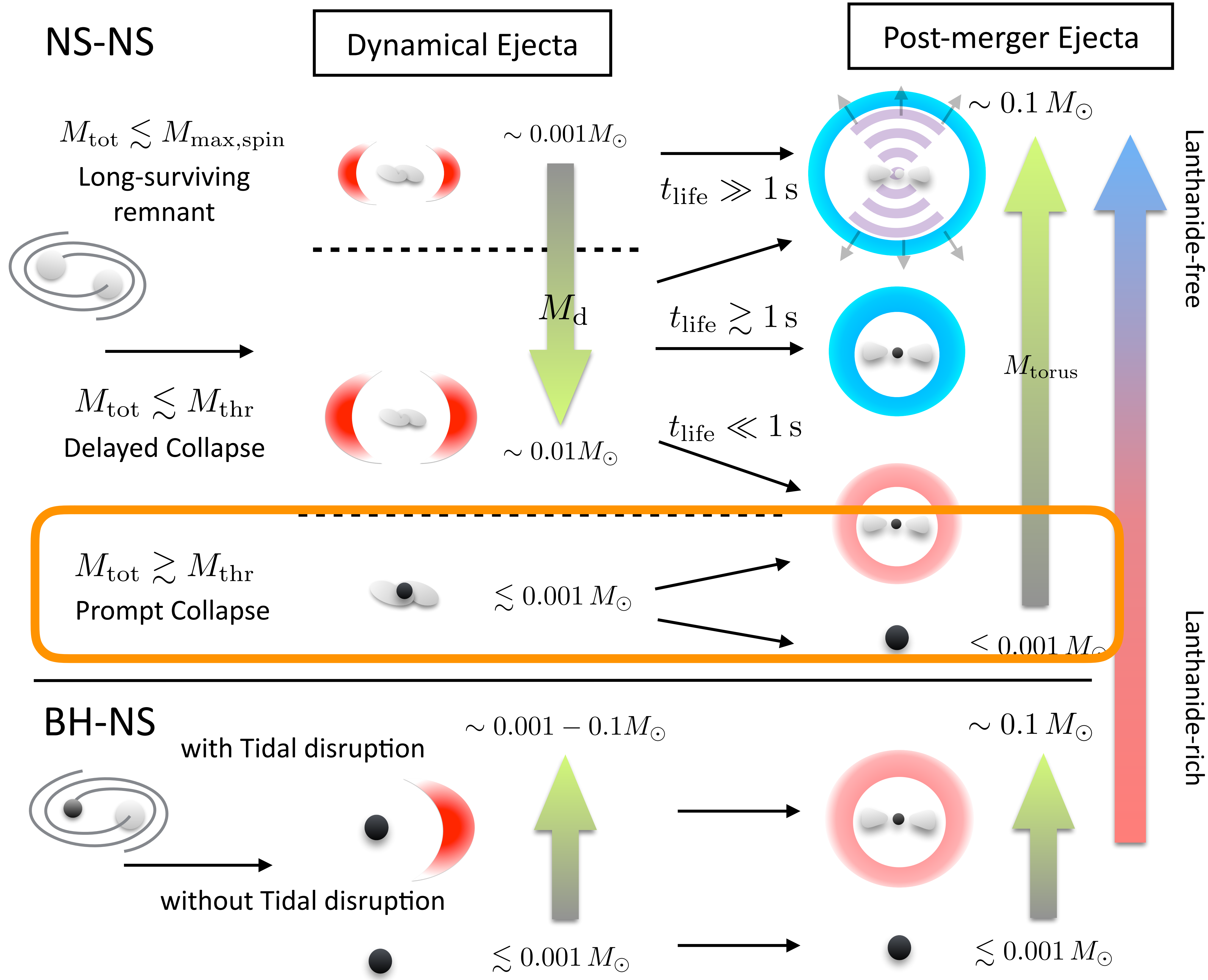
$Y_{e,\rm pm} : 0.2 - 0.4 (X_{\rm lan} \approx 0.025)$

Dotted:

$Y_{e,\rm pm} : 0.1 - 0.3 (X_{\rm lan} \approx 0.15)$







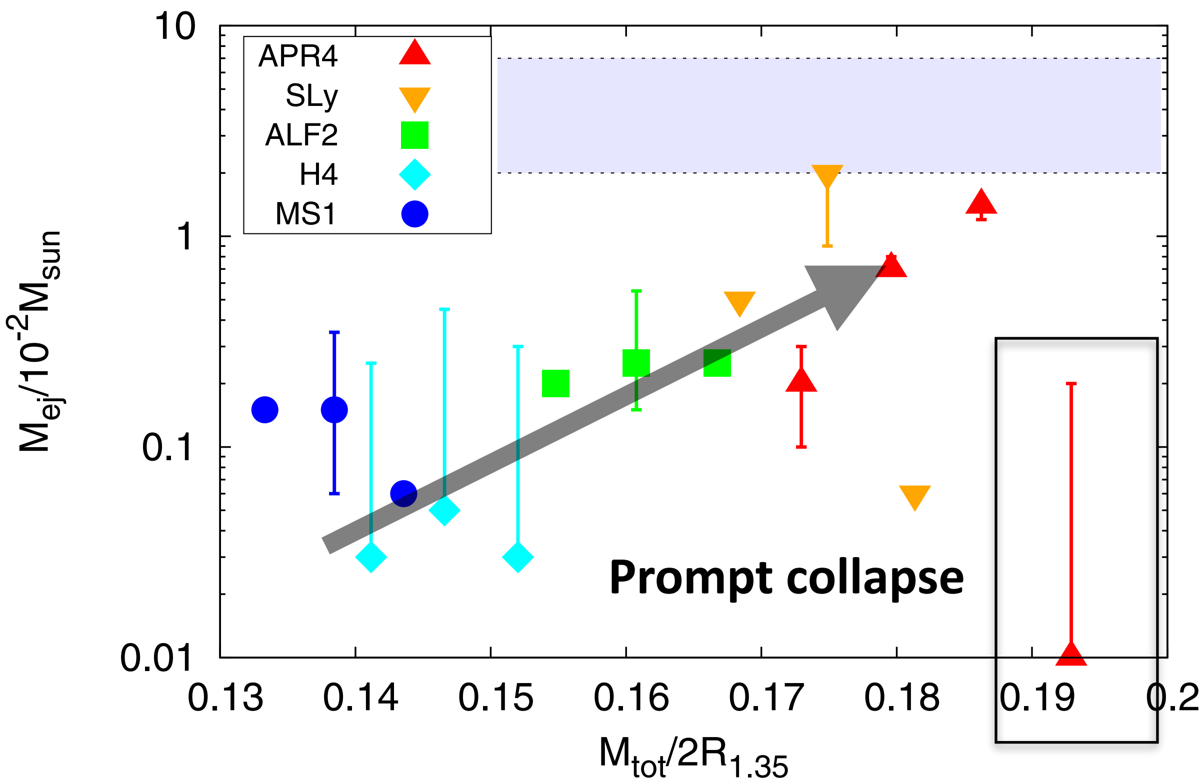
NS-NS
Dynamical Ejecta
Post-merger Ejecta
$M_{\rm tot} \lesssim M_{\rm max,spin}$
Long-surviving remnant
$\sim 0.001 M_\odot$
$t_{\rm life} \gg 1\,{\rm s}$
$\sim 0.1\ M_\odot$
$M_{\rm d}$
$t_{\rm life} \gtrsim 1\,{\rm s}$
$M_{\rm torus}$
$M_{\rm tot} \lesssim M_{\rm thr}$
Delayed Collapse
$\sim 0.01 M_\odot$
$t_{\rm life} \ll 1\,{\rm s}$
$M_{\rm tot} \gtrsim M_{\rm thr}$
Prompt Collapse
$\lesssim 0.001\ M_\odot$
$< 0.001\ M_\odot$
Lanthanide-free
Lanthanide-rich
BH-NS
with Tidal disruption
$\sim 0.001 - 0.1 M_\odot$
$\sim 0.1\ M_\odot$
without Tidal disruption
$\lesssim 0.001\ M_\odot$
$\lesssim 0.001\ M_\odot$

Prompt collapse case

Dynamical ejecta mass

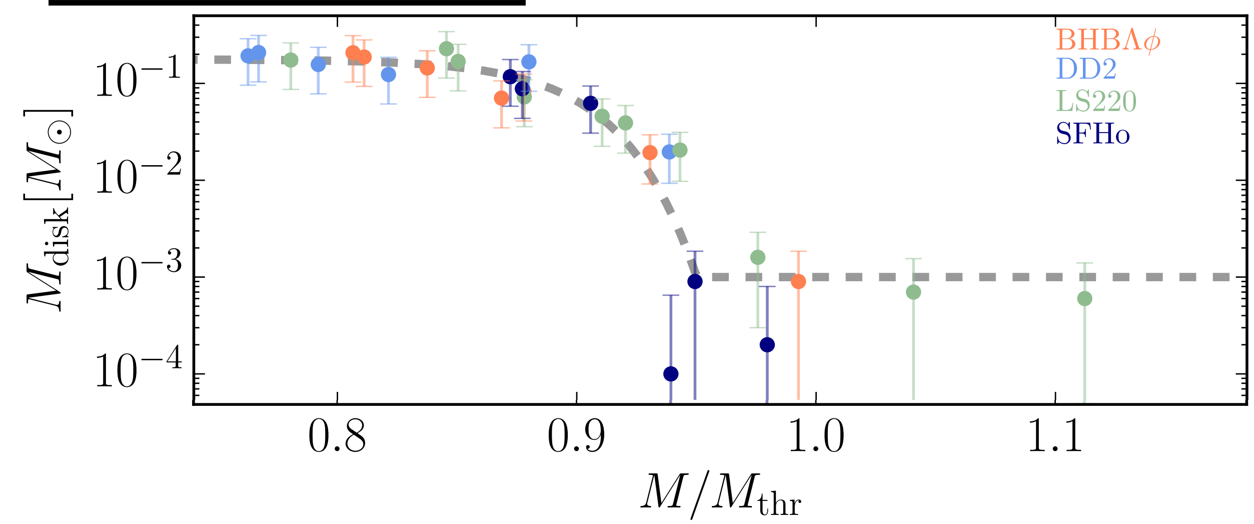
Ref: K. Hotokezaka et al. 2013

NS-NS models



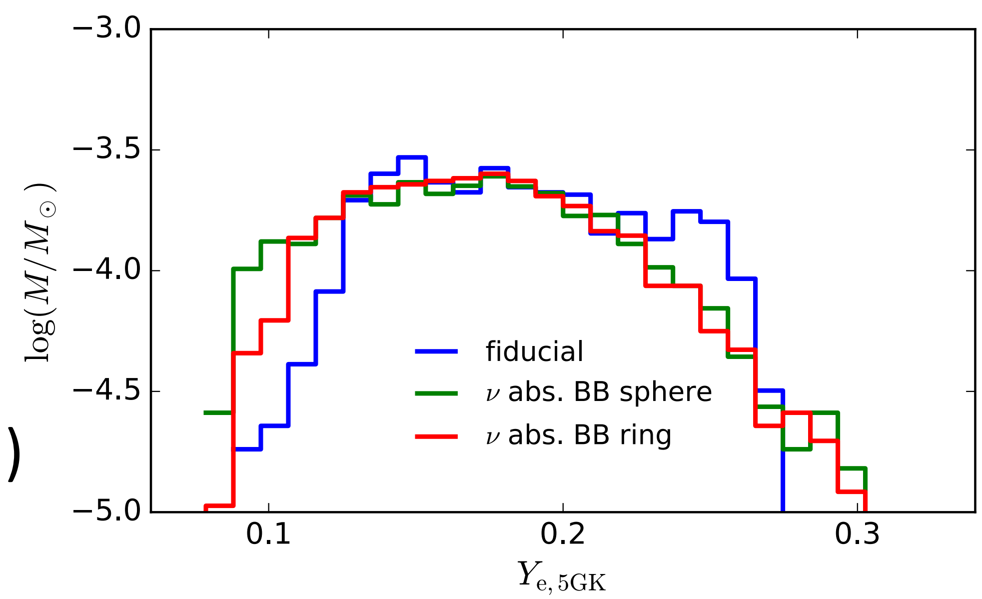
Remnant torus mass

Ref: Radice et al. 2018, Coughlin et al. 2019



Ye distribution of post merger ejecta in the absence of remnant NS

Ref: Siegel et al. 2018



- Both dynamical ejecta and remnant torus mass are significantly suppressed for most of the prompt collapse cases. (*however, it depends on the mass ratio; see Kiuchi et al. 2019a)
- In addition, post-merger ejecta would be lanthanide-rich in the absence of ν irradiation from the remnant NS (see e.g., Just et al. 2015, Wu et al. 2016, Siegel et al. 2018, Fernandez et al. 2018)

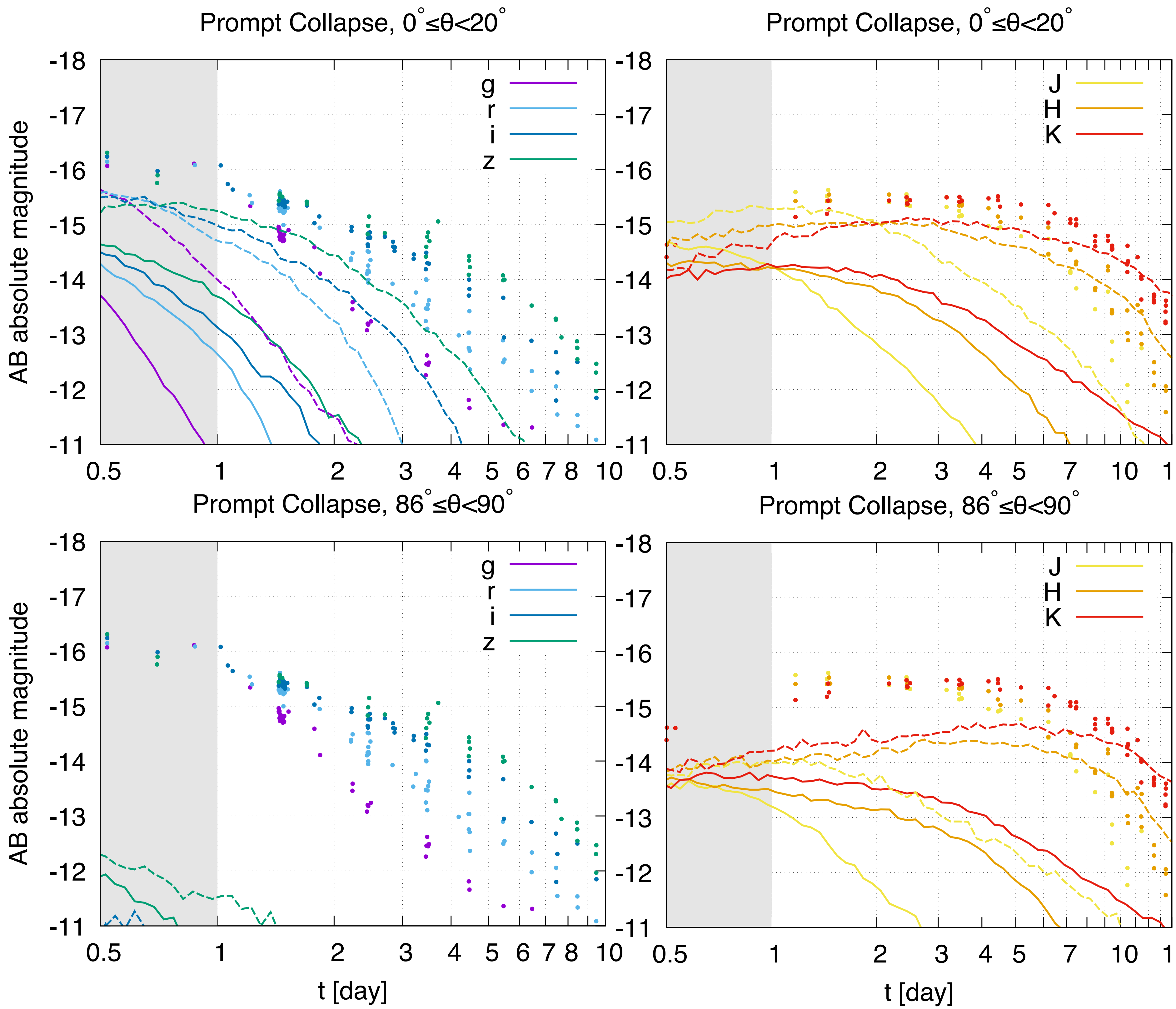
Prompt collapse

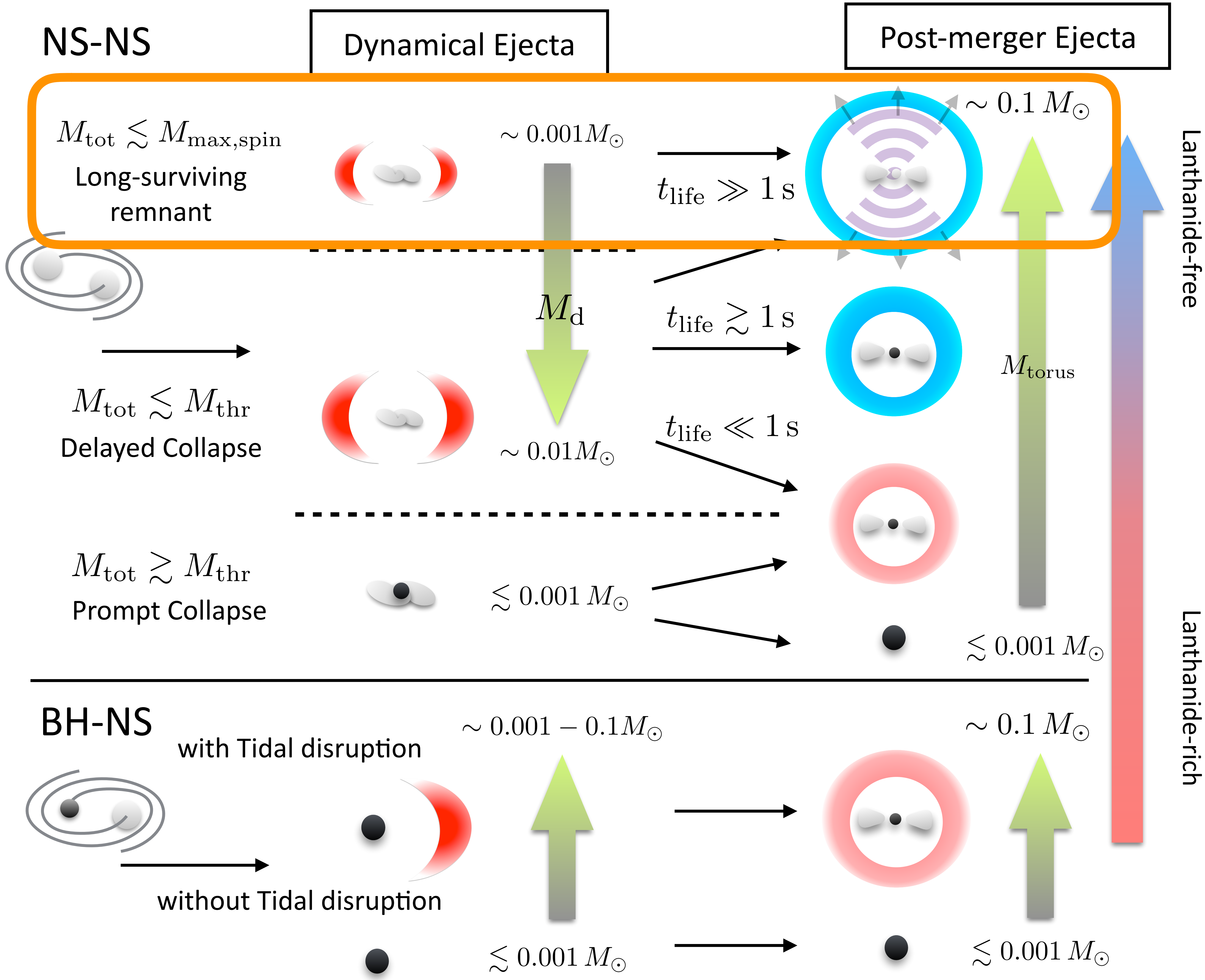
$$M_{\rm d} = 0.001\, M_\odot$$

Solid: $M_{\rm pm} = 0.001\, M_\odot$

Dashed: $M_{\rm pm} = 0.01\, M_\odot$

$$Y_{e,{\rm pm}} = 0.1 - 0.3$$





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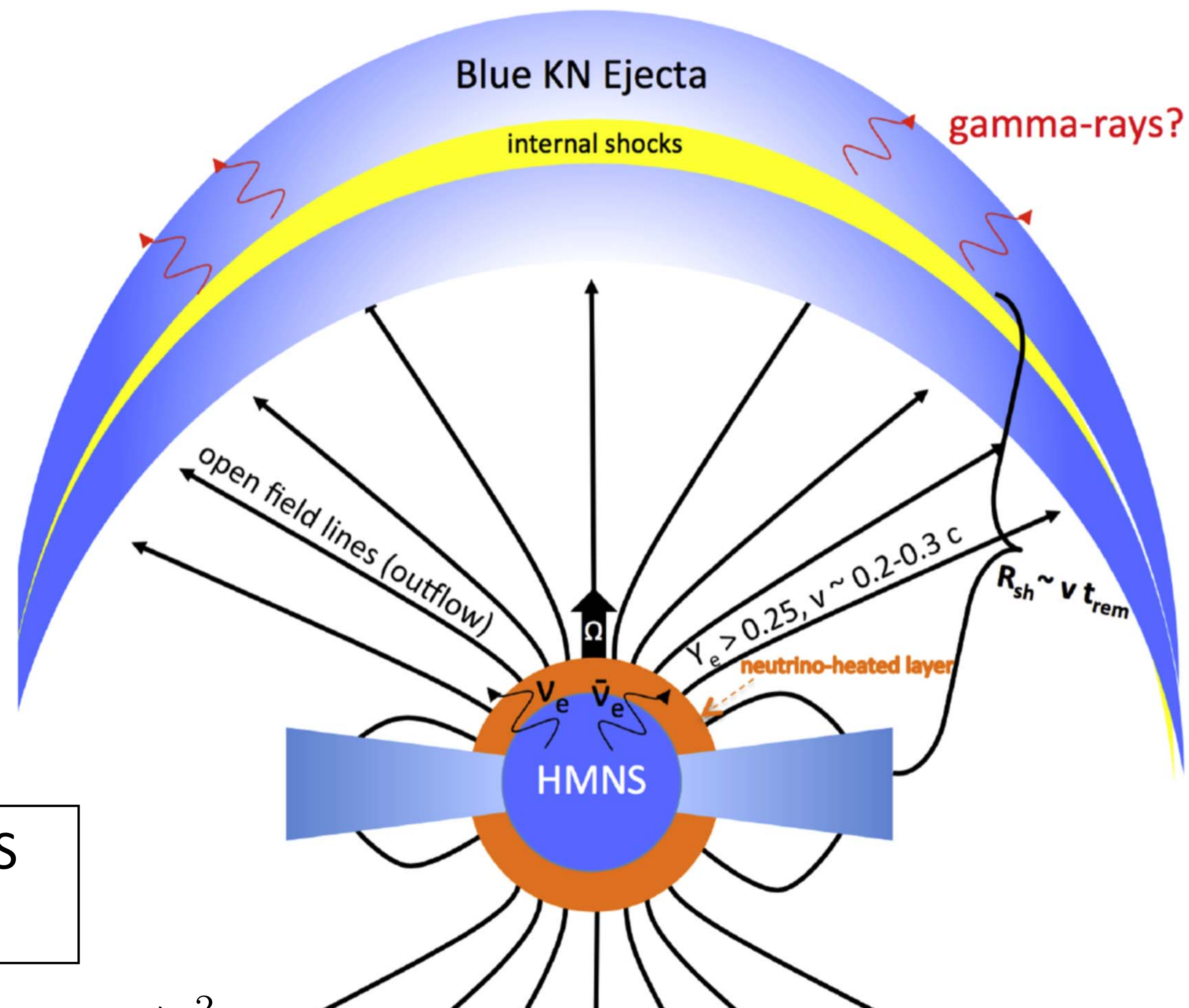
$\lesssim 0.001\, M_\odot$

Long-surviving NS/Magnetor

Ref: Martínez-Pinedo et al 2012,
Metzger et al. 2018

- If the remnant NS survives for sufficiently long time, the rotational energy of the remnant NS could be an additional energy source to the ejecta
  by releasing it via magnetic fields

- Even if the energy injected into the ejecta is lost due to adiabatic cooling and does not directly reflected to the lightcurves, the velocity profile of the ejecta would be modified



Rotational kinetic energy of a rigidly rotating NS at maximum mass (ref: Shibata et al. 2019)

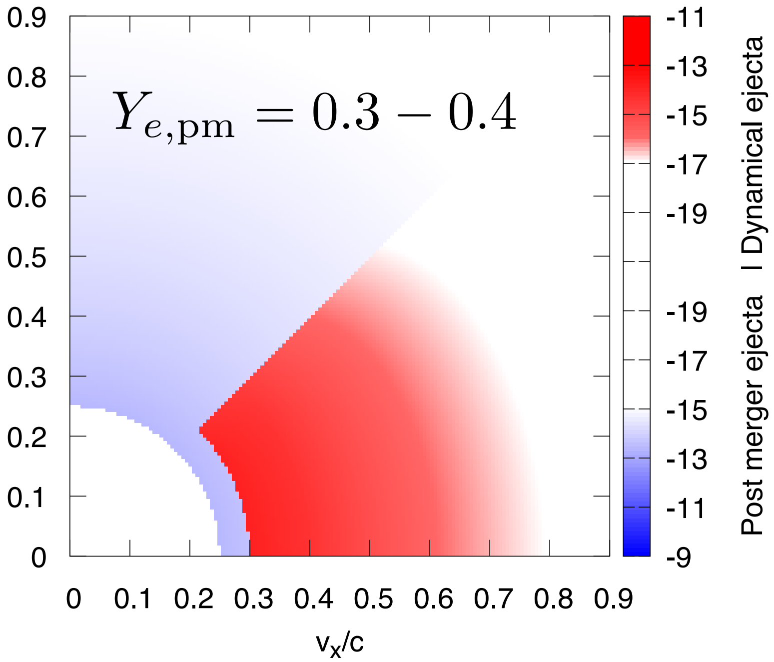
$$E_{\rm rot} \approx 2 \times 10^{53}\,{\rm erg} \left(\frac{M_{\rm MNS}}{2.6\,M_\odot}\right) \left(\frac{R_{\rm MNS}}{15\,{\rm km}}\right)^2 \left(\frac{\Omega}{10^4 {\rm rad/s}}\right)^2$$

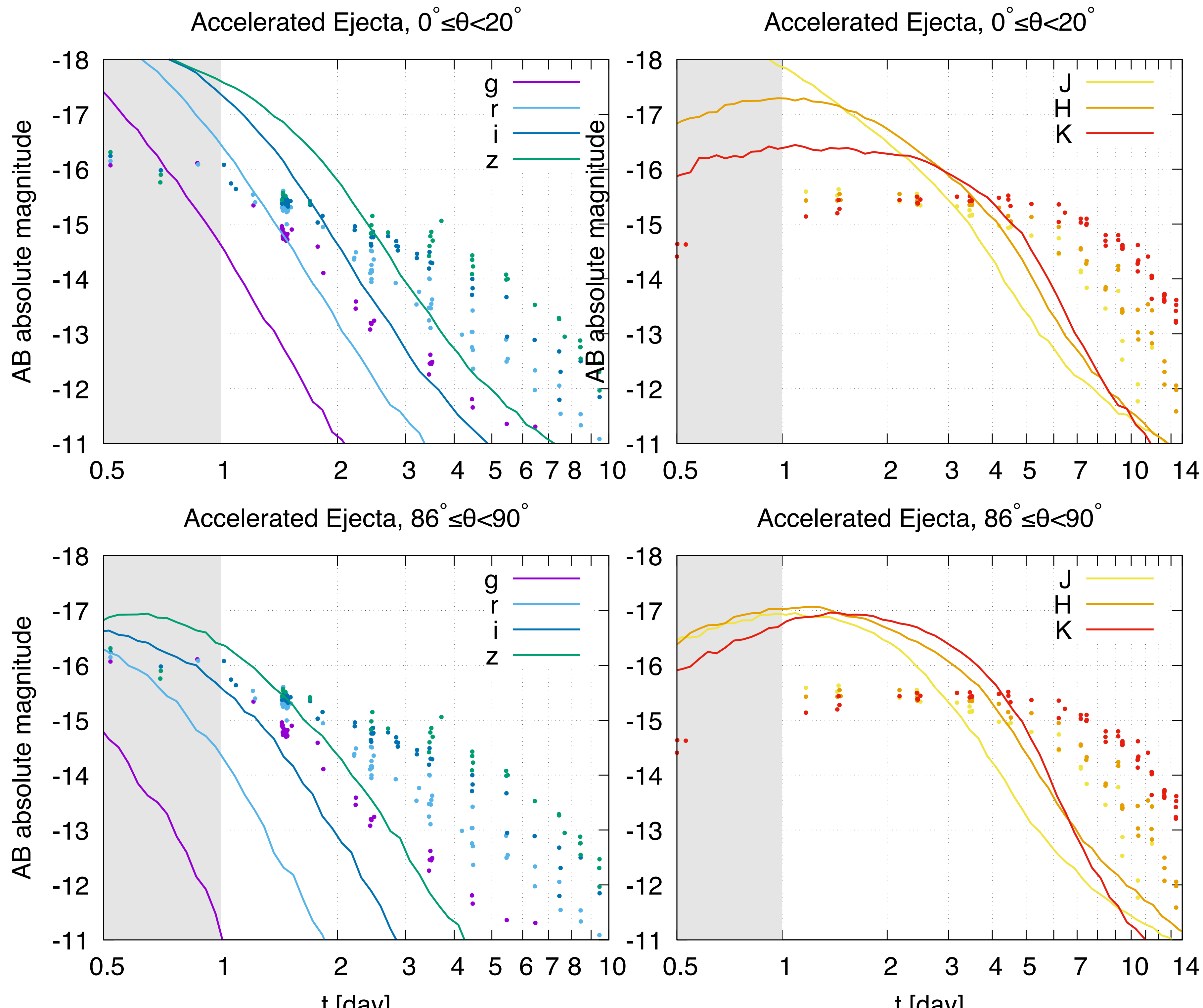
c.f. typical total kinetic energy of ejecta

$$E_{\rm k,eje} \sim 10^{49} - 10^{51}\,{\rm erg}$$

*relativistic jets would also be the cause of energy injection/ejecta acceleration (e.g. Gottlieb et al. 2017)

Accelerated ejecta





Post-merger ejecta:

$$v = 0.25\,c - 0.9\,c$$

$$< v > \approx 0.5\,c$$

Dynamical ejecta:

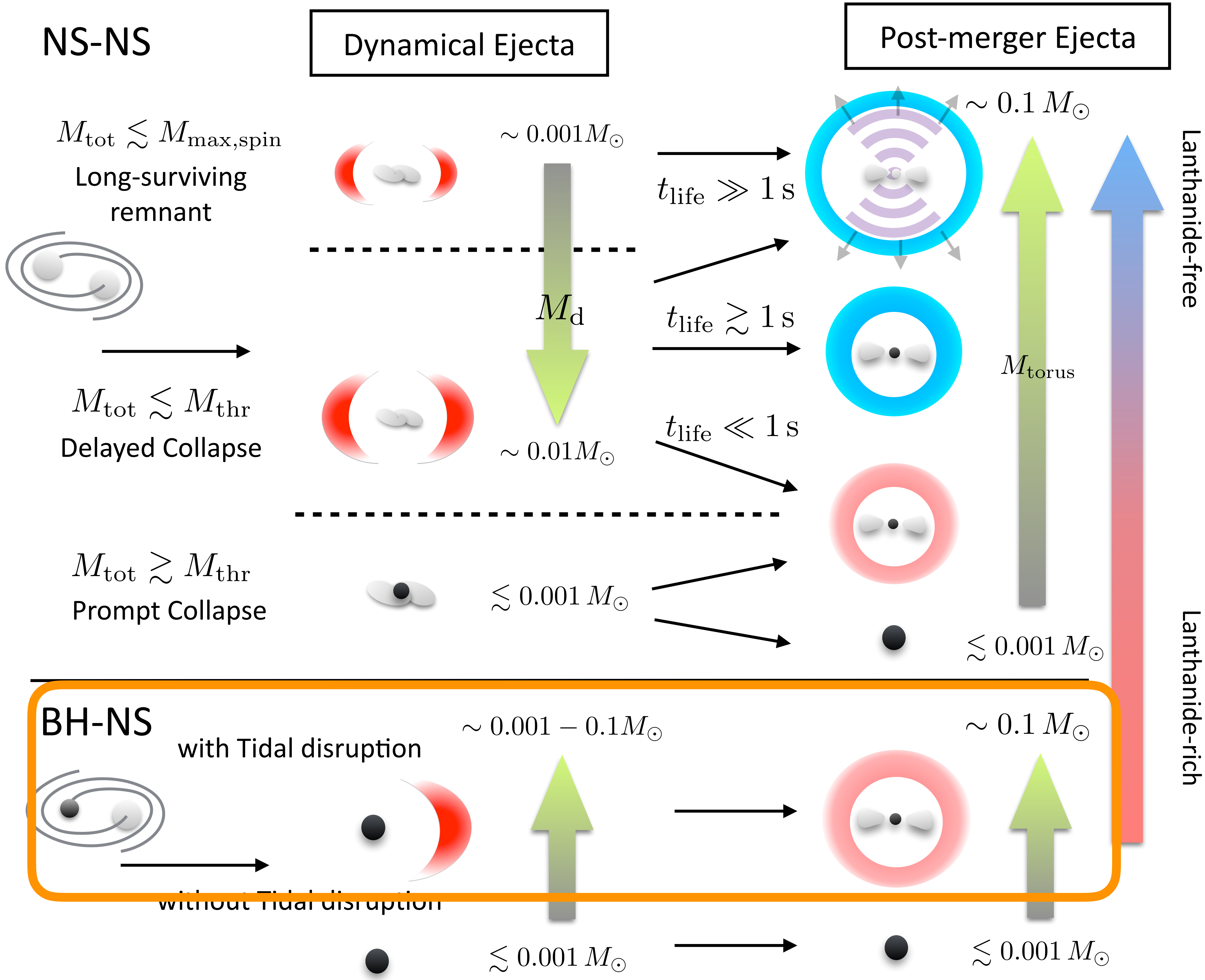
$$v = 0.3\,c - 0.9\,c$$

$$< v > \approx 0.4\,c$$

$$M_{\mathrm{pm}} = 0.05\,M_{\odot},$$

$$M_{\mathrm{d}} = 0.003\,M_{\odot}$$

*correspond to the case for which ~10% of the rotational kinetic energy of remnant NS, ~10^{52} erg, is converted to the ejecta kinetic energy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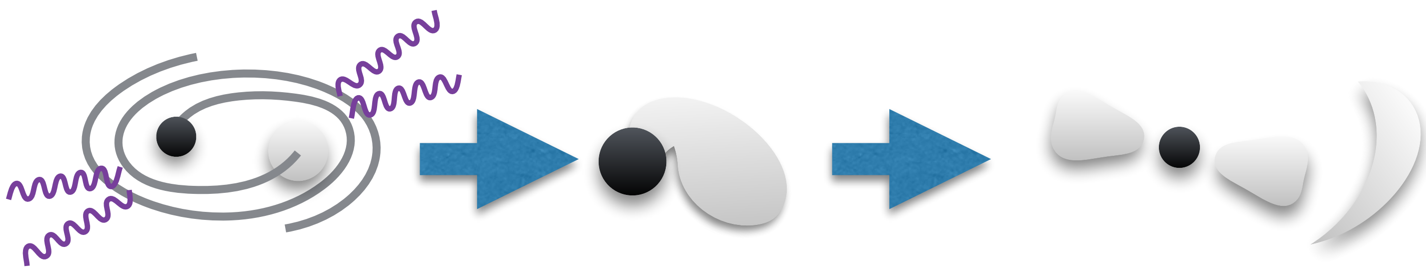
$\sim 0.1\, M_\odot$
$\lesssim 0.001\, M_\odot$
$\lesssim 0.001\, M_\odot$

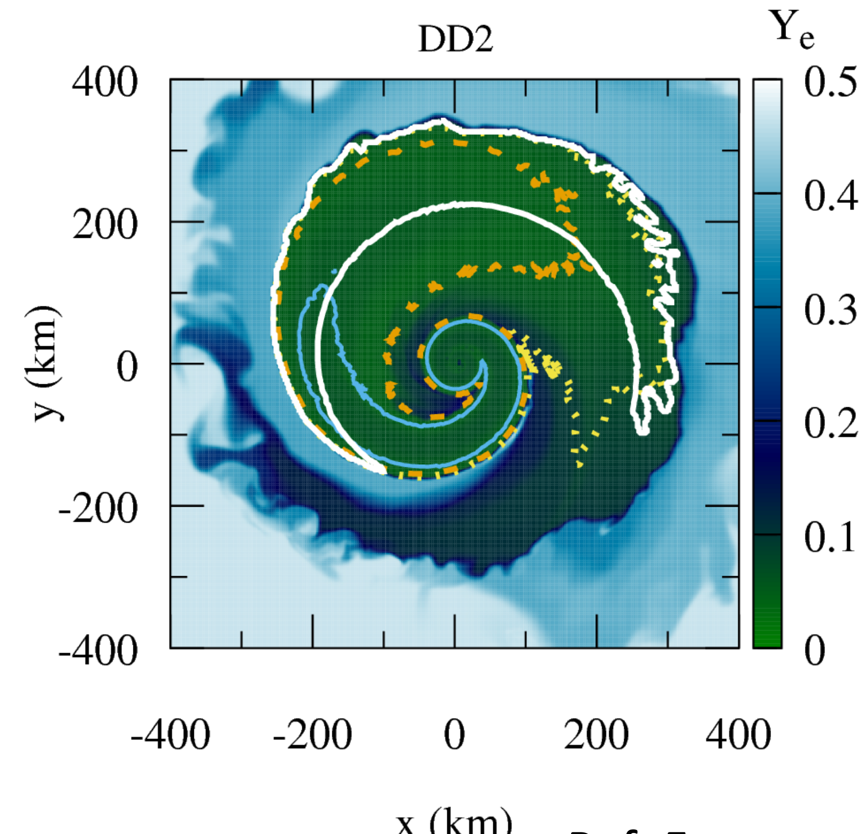
Black hole-Neutron star (BH-NS) merger

Ref: Kyutoku et al. 2018

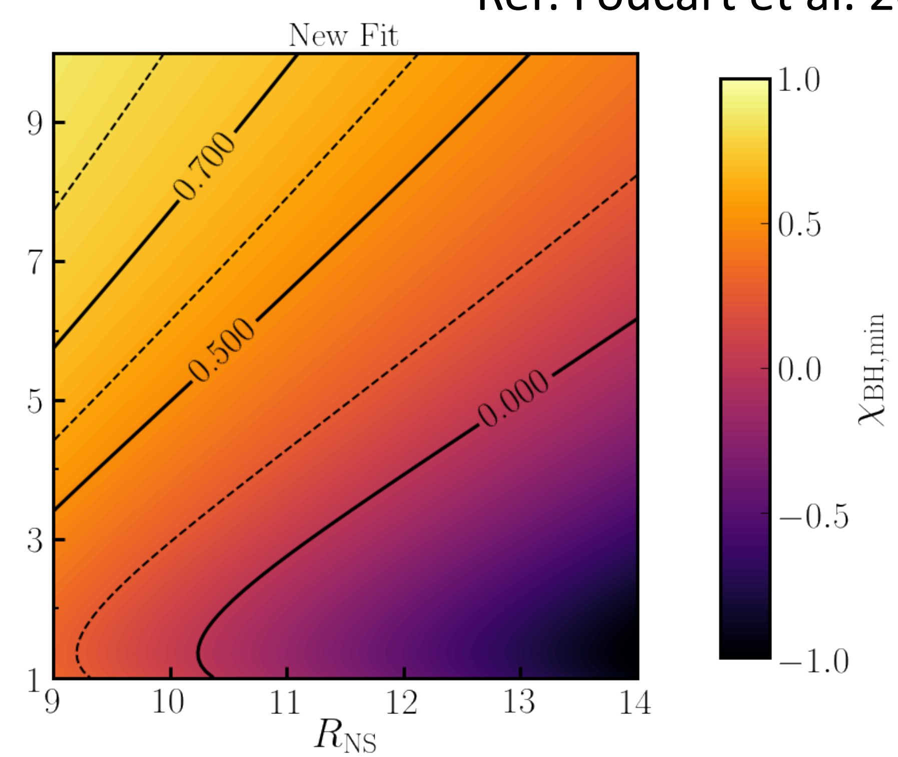
- If the NS is **tidally disrupted** substantial amount of material would remain/ejected after the merger



For BHNS merger, lanthanide fraction of the ejecta would be higher in the absent of shock heating and neutrino irradiation
(e.g. Just et al. 2015, Foucart et al. 2017,Kyutoku et al. 2018)

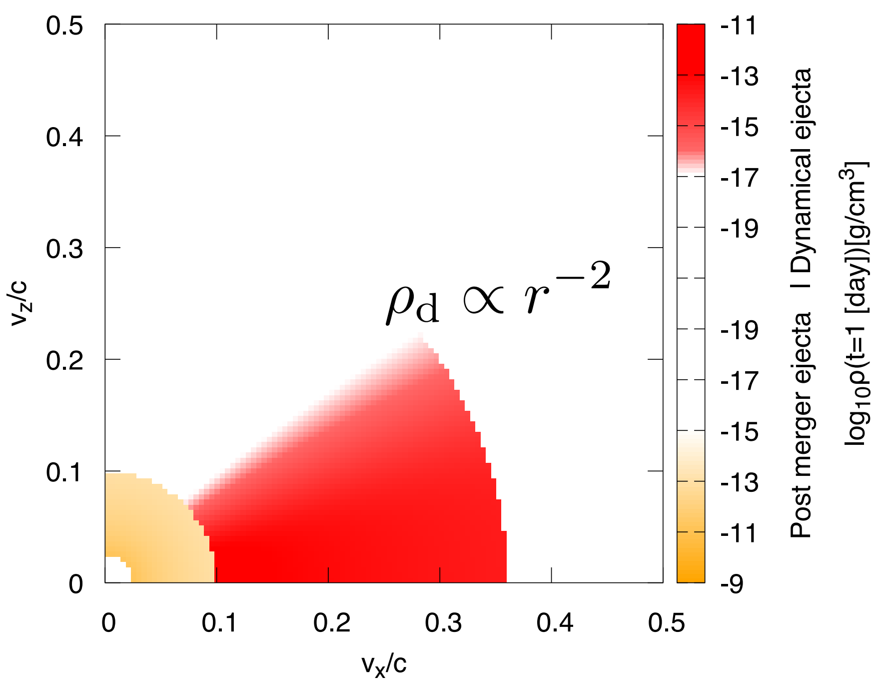


Ref: Foucart et al. 2018



- Kilonova emission would also be different due to difference in the ejecta morphology and composition
- Whether NS is tidally disrupted or not, and the remnant disk/ejecta mass depends strongly on the binary parameters.

Black hole-Neutron star



$$Y_{e,\rm pm} = 0.1 - 0.3$$

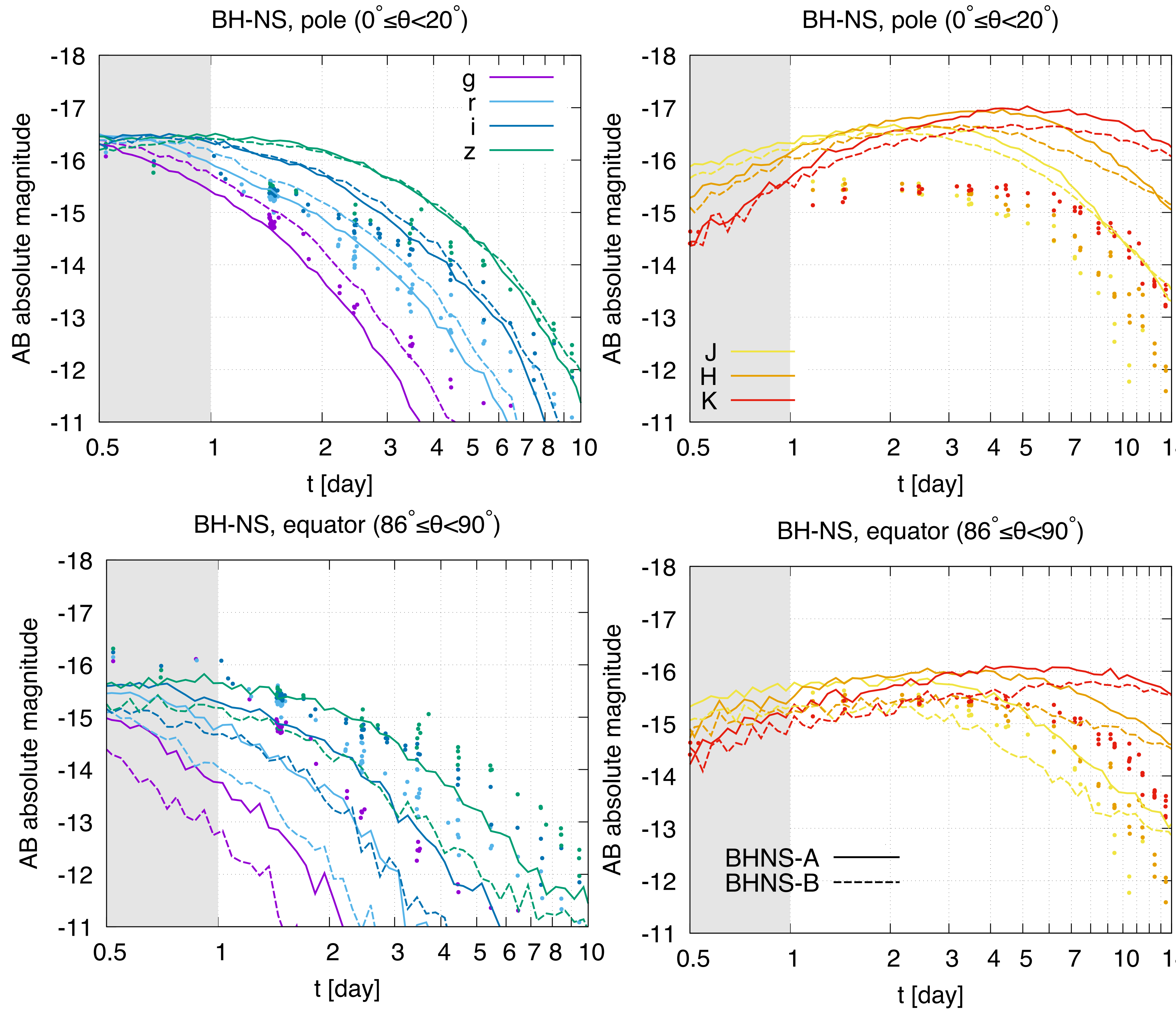
$$Y_{e,\rm d} \approx 0.1$$

Solid: (BHNS-A)

$$M_{\rm pm} = 0.02\,M_\odot,$$
$$M_{\rm d} = 0.02\,M_\odot$$

Dashed: (BHNS-B)

$$M_{\rm pm} = 0.04\,M_\odot,$$
$$M_{\rm d} = 0.01\,M_\odot$$

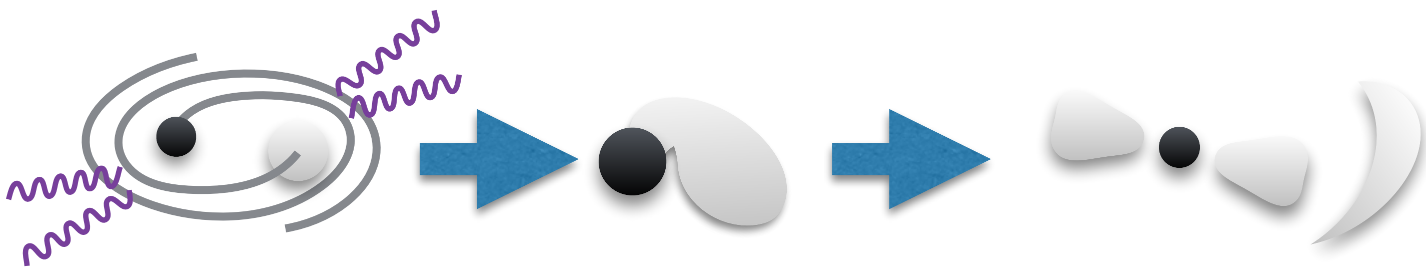


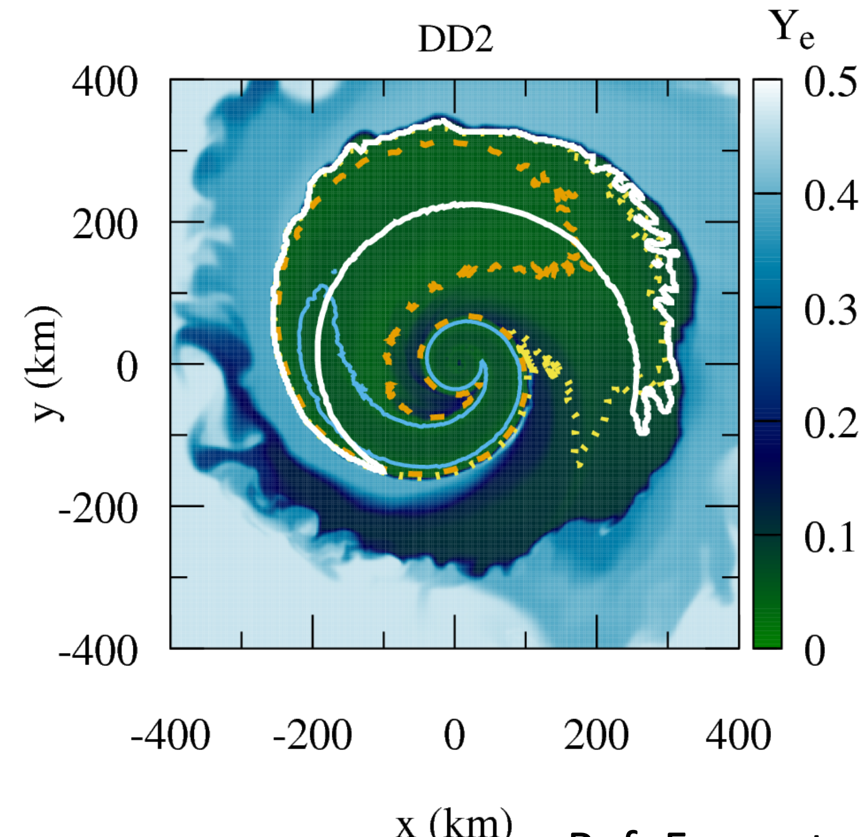
*note that the ejecta mass from BH-NS merger could have a large variety depending on the binary parameters

Black hole-Neutron star (BH-NS) merger

Ref: Kyutoku et al. 2018

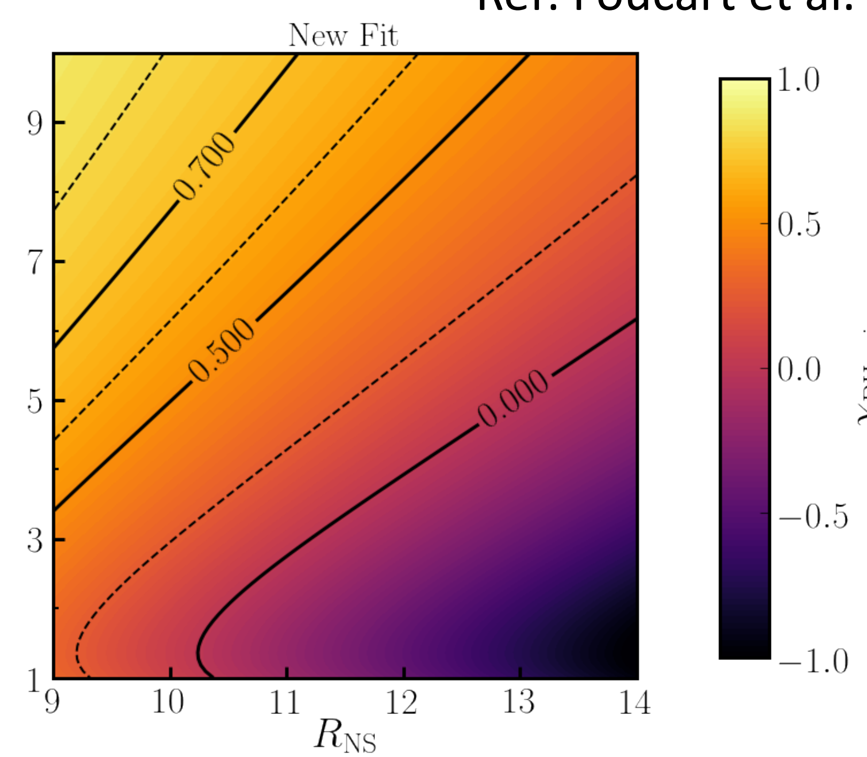
- If the NS is **tidally disrupted** substantial amount of material would remain/ejected after the merger





For BHNS merger, lanthanide fraction of the ejecta would be higher in the absent of shock heating and neutrino irradiation (e.g. Just et al. 2015, Foucart et al. 2017,Kyutoku et al. 2018)

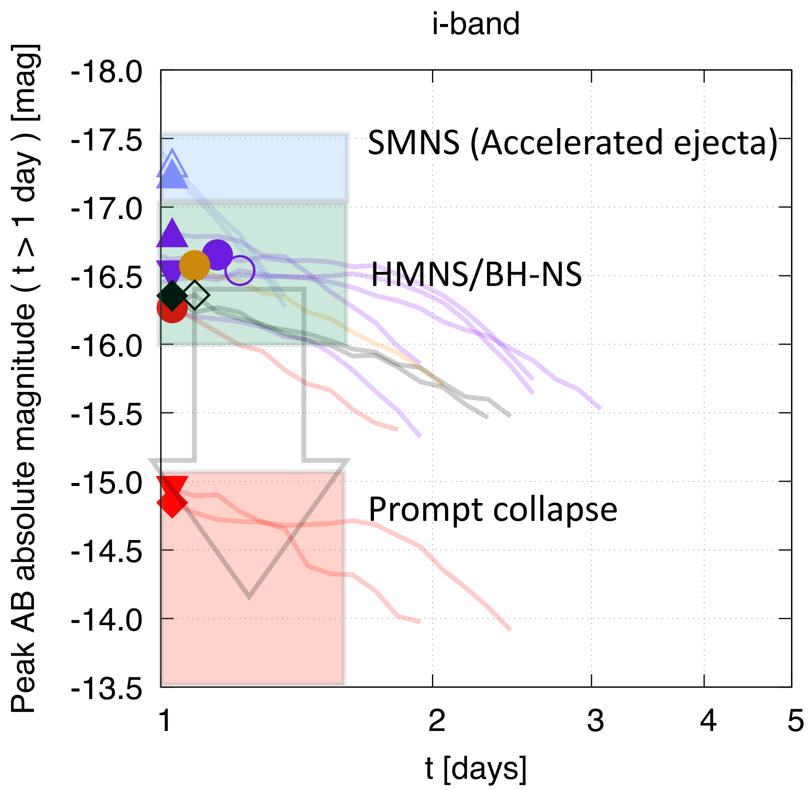
Ref: Foucart et al. 2018

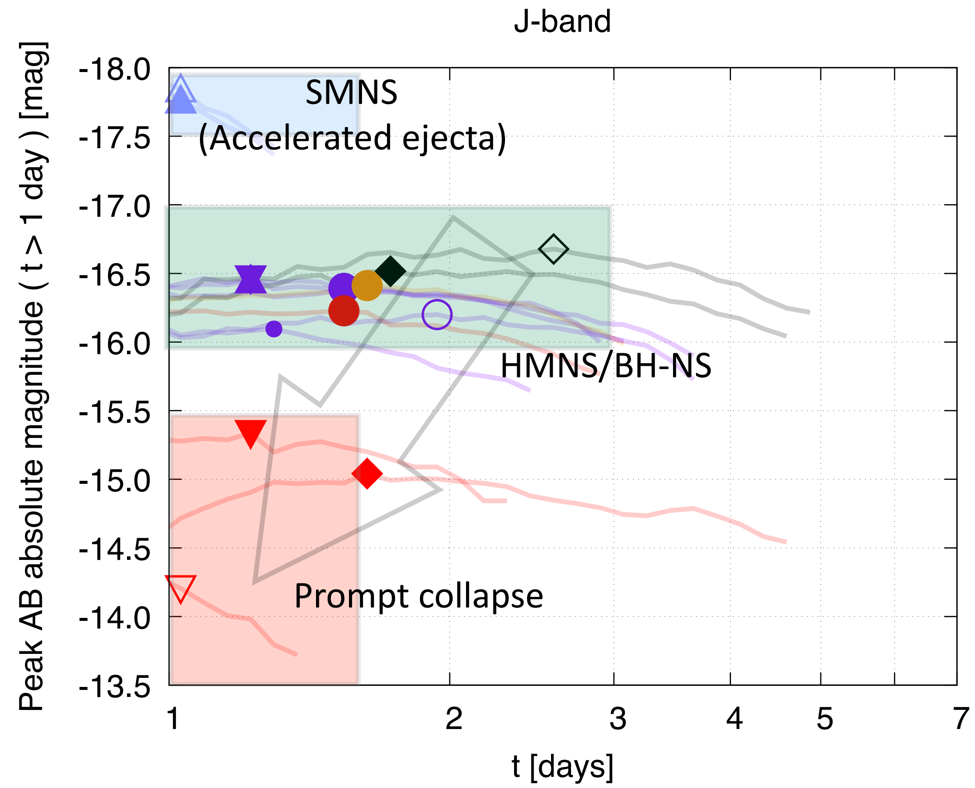


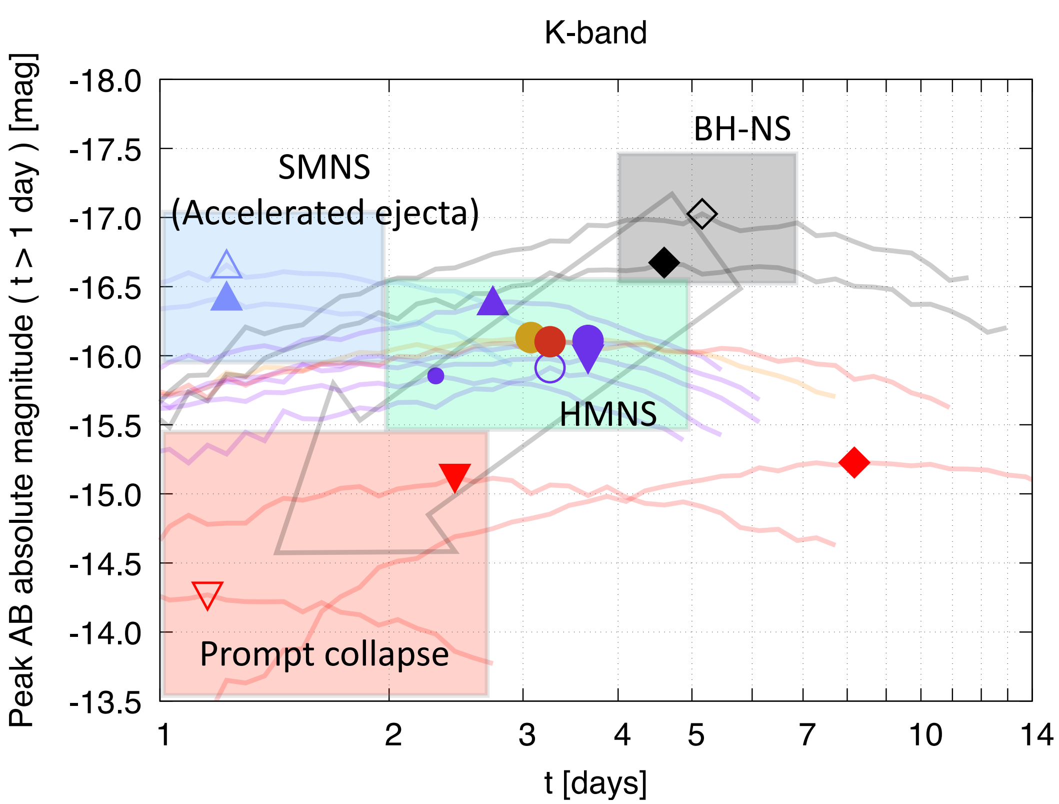
- Kilonova emission would also be different due to difference in the ejecta morphology and composition

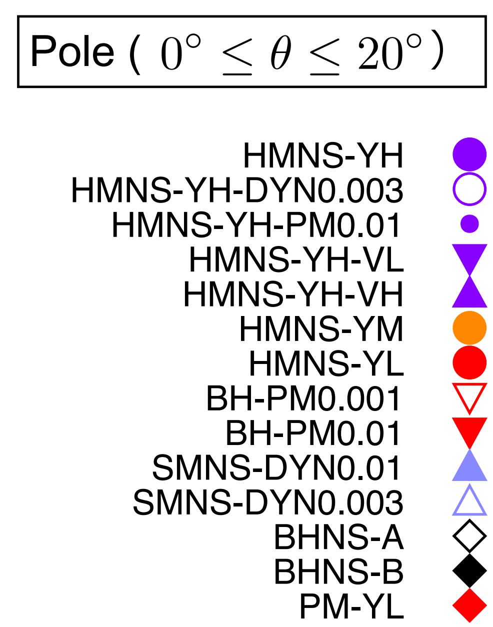
- Whether NS is tidally disrupted or not, and the remnant disk/ejecta mass depends strongly on the binary parameters.

Comparison among various models (polar)









SMNS:
cases that the remnant NS survives for a long time scale (>>1 s)

HMNS:
cases that the remnant NS survives temporarily and eventually collapses to a BH

Prompt collapse:
cases that the NSs collapses to a BH immediately after the merger

- Comparison of peak time vs. peak magnitude* among various models

*since the lightcurves for t<1day are not reliable for our calculation, we define the peak magnitude as the brightest point after t=1day.

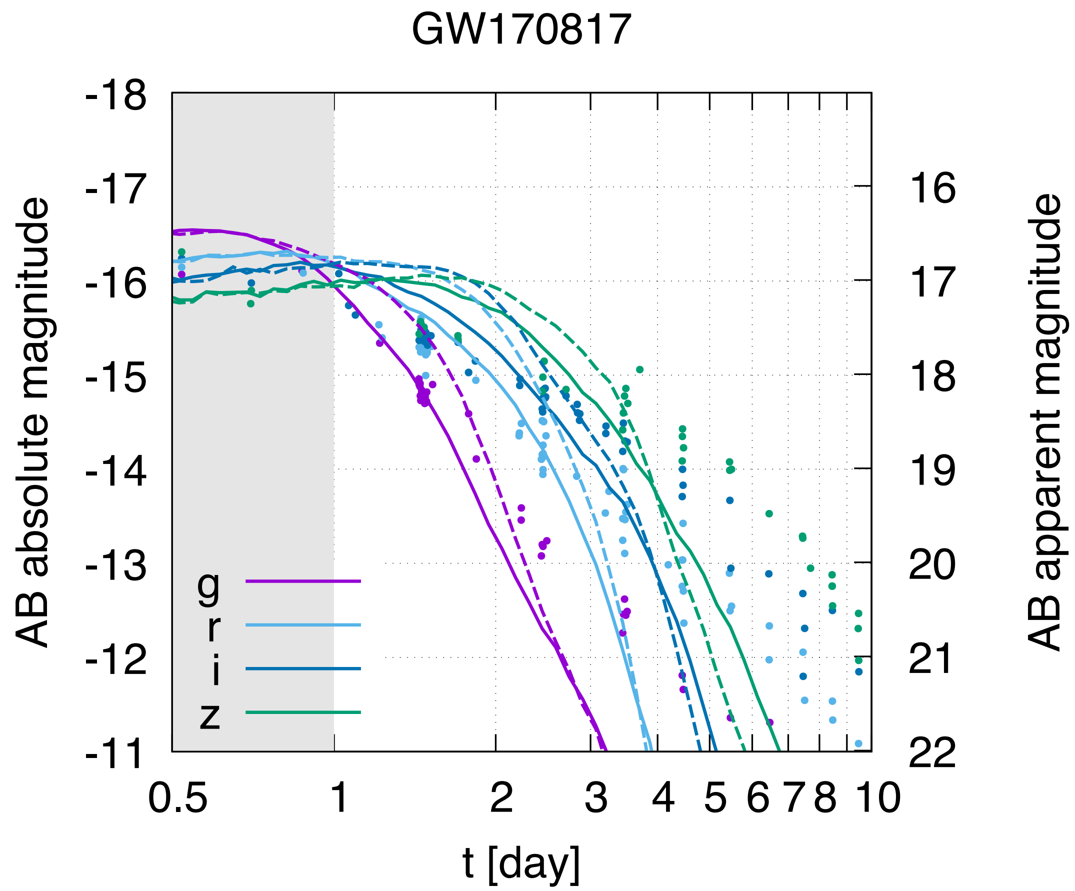
Summary

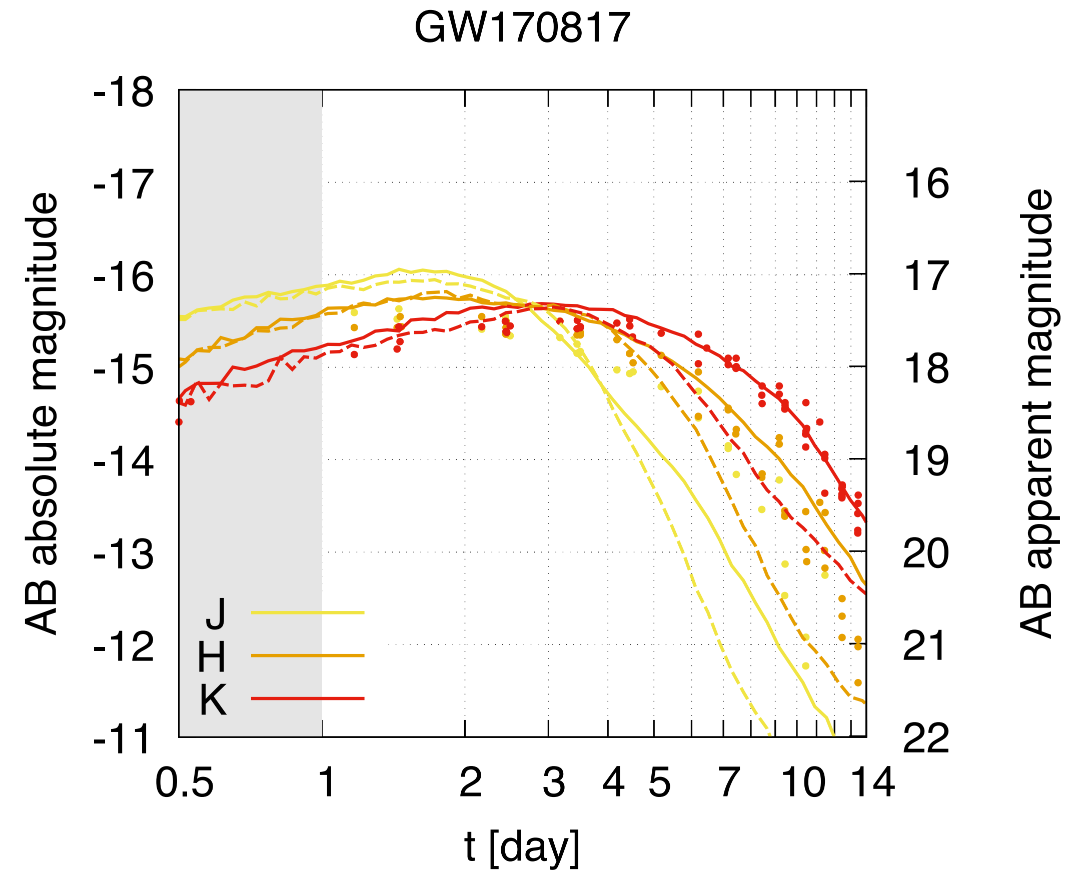
- We perform radiative transfer simulations for kilonova lightcurves in various situations employing ejecta profiles predicted by numerical-relativity simulations.

- We demonstrate that **kilonova lightcurves could show large diversity** reflecting the variety in the binary parameters or the binary composition.

  - The difference in the ejecta properties would be imprinted in the differences
    in **the peak brightness and time of peak**, and this indicates that
    we may be able to infer the type of the central engine for kilonovae
    by observation of the peak in the multiple band lightcurves.

GW170817





$$M_{\rm pm} = 0.02\, M_\odot,$$

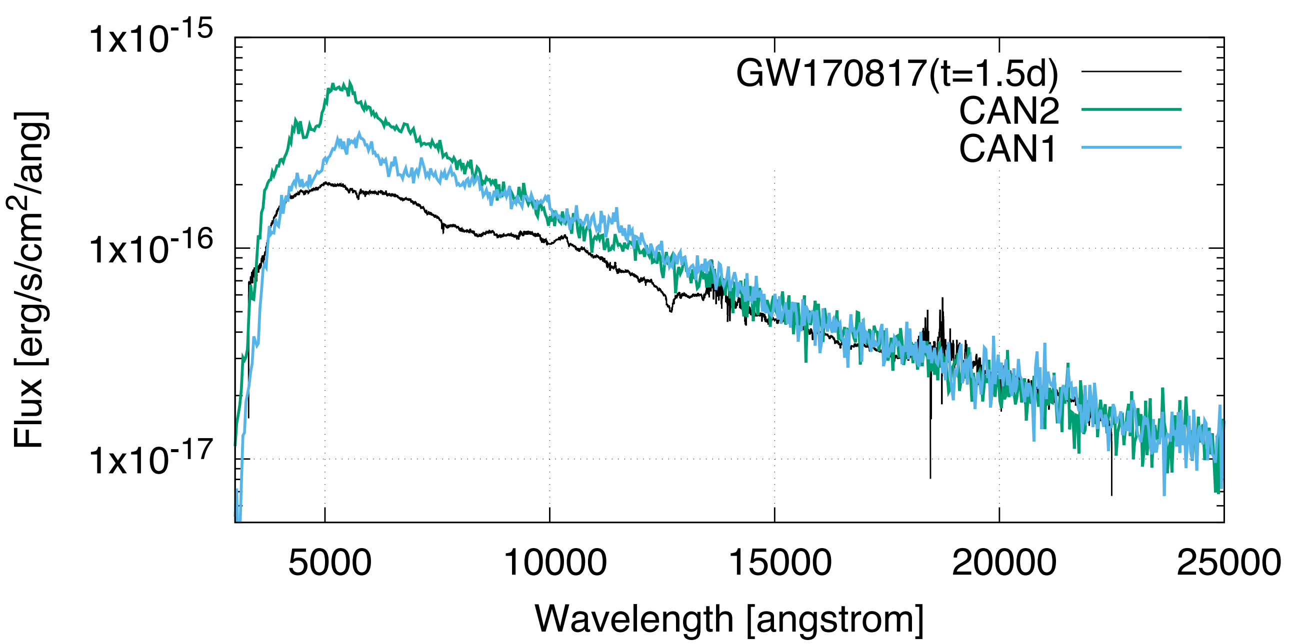
$$M_{\rm d} = 0.003\, M_\odot$$

Solid:

$$Y_{e,\rm pm}: 0.2 - 0.4(X_{\rm lan} \approx 0.025),\ \ 0^\circ \leq \theta \leq 20^\circ$$

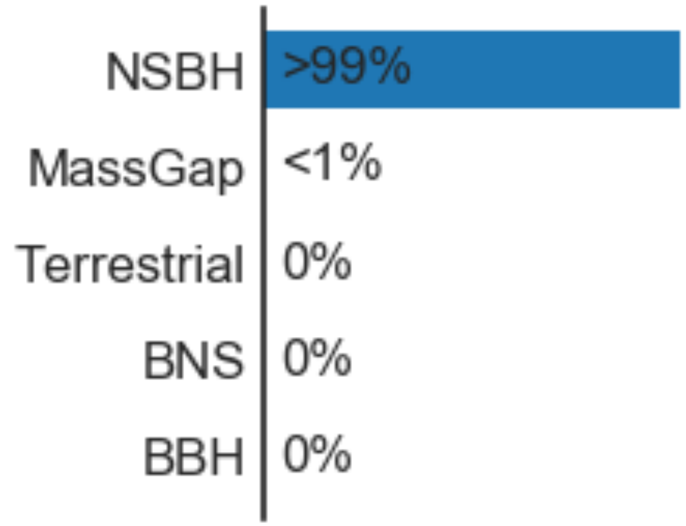
Dashed:

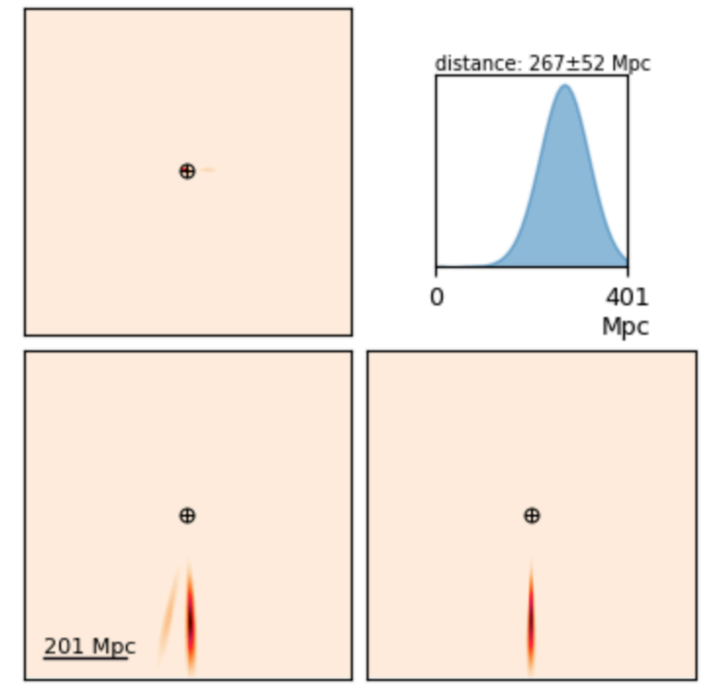
$$Y_{e,\rm pm}: 0.3 - 0.4(X_{\rm lan} \ll 1)\ ,\ \ 20^\circ \leq \theta \leq 28^\circ$$

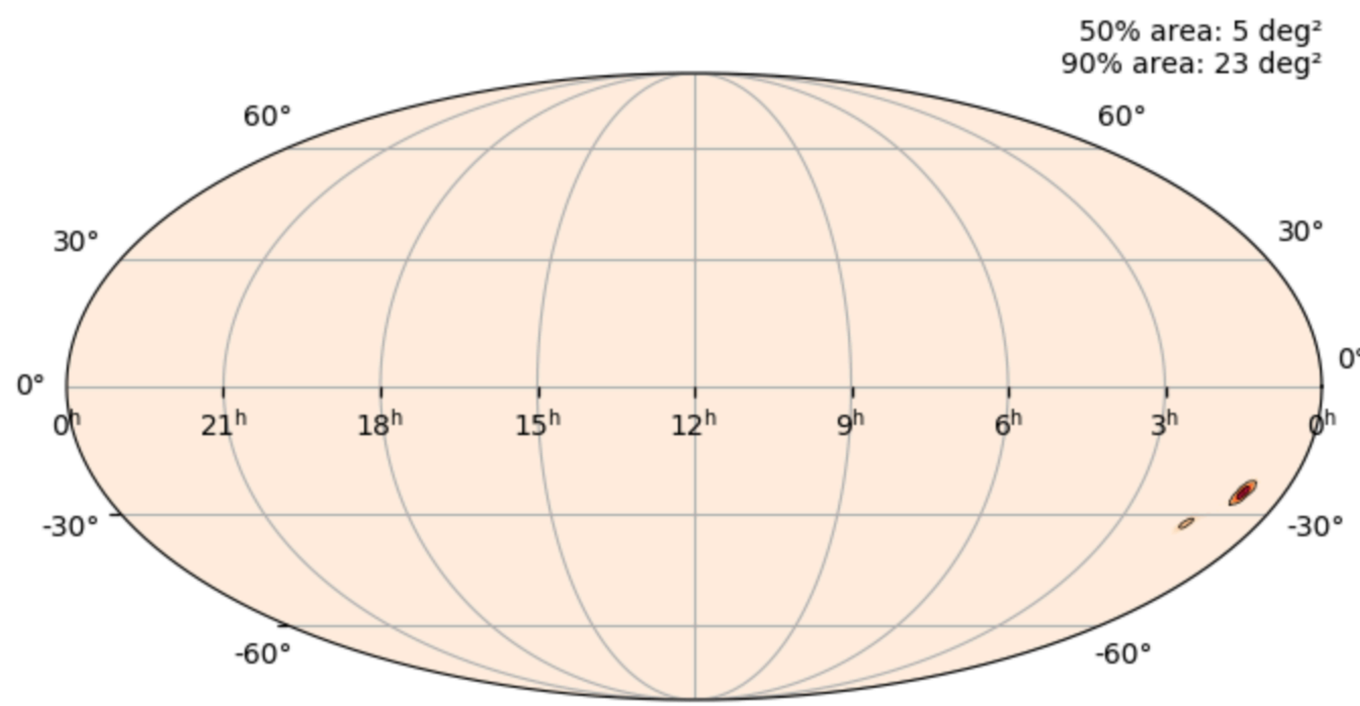


S190814bv: a BH-NS merger candidate

- Aug. 14, 2019 21:10:39 UTC, detection of a BH-NS merger candidates has been reported
- False alarm rate:~ 1 / 10^{25} yrs.
- Distance: ~267±52 Mpc (c.f. GW170817: ~40 Mpc)
- Sky localization: 23 deg^2(90%)
- **No electromagnetic counterpart has been found**







Ref) https://gracedb.ligo.org/superevents/S190814bv/view/

Can we constrain the binary parameters from EM upper limits?

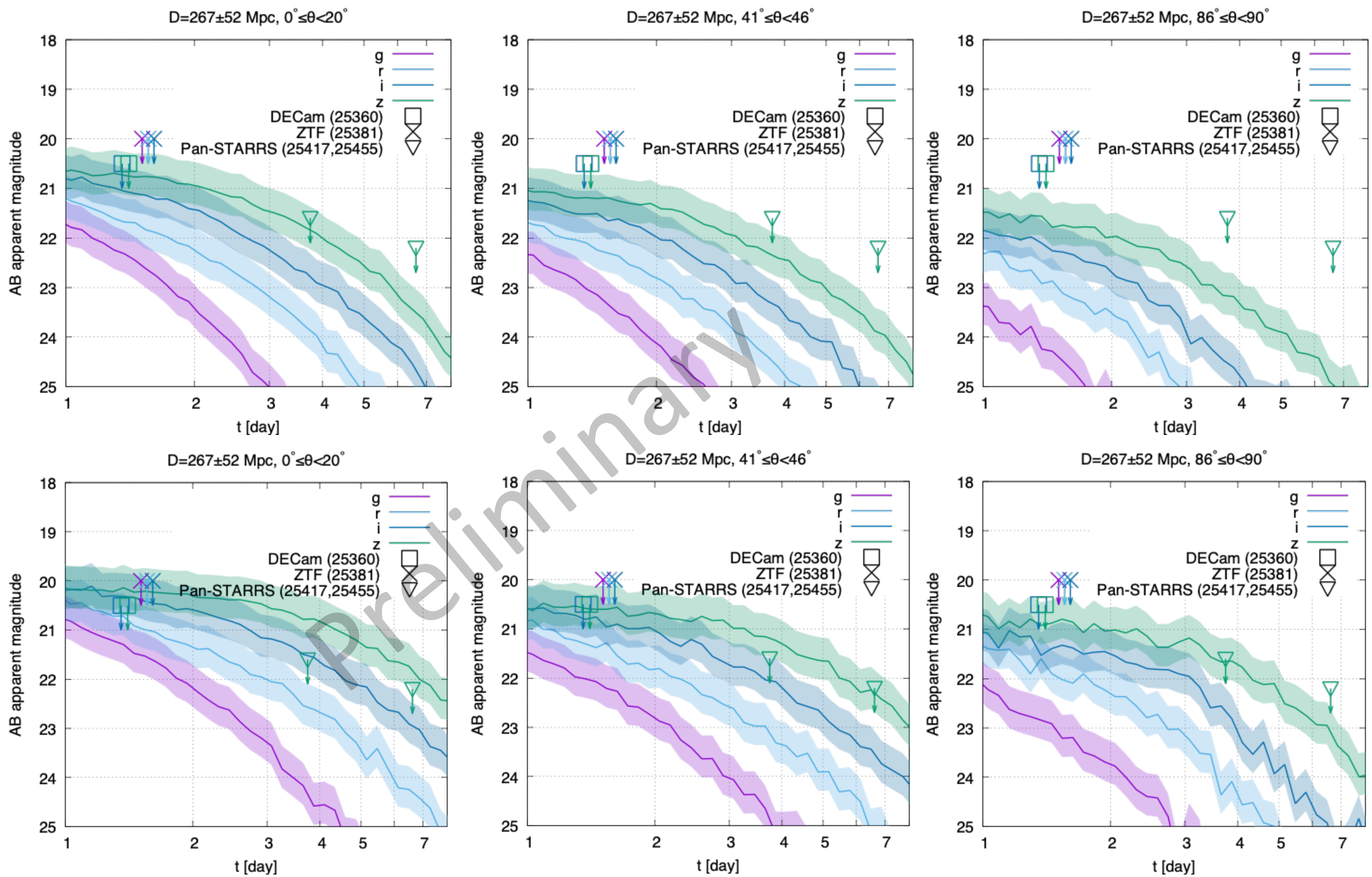
Constraint on the ejecta mass

$m_{\rm d} = 0.02\,M_\odot$
$m_{\rm pm} = 0.02\,M_\odot$

$m_{\rm d} = 0.05\,M_\odot$
$m_{\rm pm} = 0.05\,M_\odot$

$M_d \leqq M_{pm}$ is assumed since the remnant torus mass is typically much larger than the dynamical ejecta mass (see e.g., Kyutoku et al. 2015)

Shaded regions denote the uncertainty due to the error bar in the distance measurement



- Employing optical/near infrared upper limits for the 50% probable sky region (GCN 25360,25381,25417,25455),

$$m_{\rm d} \lesssim 0.02\,M_\odot(\theta_{\rm obs} < 20^\circ), 0.03\,M_\odot(\theta_{\rm obs} < 45^\circ), 0.05\,M_\odot(\theta_{\rm obs} < 90^\circ)$$

Summary

- We perform radiative transfer simulations for kilonova lightcurves in various situations employing ejecta profiles predicted by numerical-relativity simulations.

- We demonstrate that **kilonova lightcurves could show large diversity** reflecting the variety in the binary parameters or the binary composition.

  - The optical lightcurves **become dim and show shallow decline** as **the lanthanide fraction** of the post-merger ejecta **increases**, while much brighter infrared lightcurves are seen in the model with large value of lanthanide fraction.

  - The optical lightcurves from **a BH-NS merger ejecta** could be as bright as those observed in GW170817 for the case that sufficiently large amount of matter is ejected (say >0.02 M_{sun}) while the infrared lightcurves would be much brighter at the same time.

  - The difference in the ejecta properties would be imprinted in the differences in **the peak brightness and time of peak**, and this indicates that **we may be able to infer the type of the central engine for kilonovae** by observation of the peak in the multiple band lightcurves.