Towards realistic modeling of the electromagnetic counterparts of neutron star mergers

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“The Radiative Transfer and Atomic Physics of Kilonovae”
@ Stockholm 4-7th Sep./2023

Max-Planck-Institut für Gravitationsphysik
ALBERT-EINSTEIN-INSTITUT

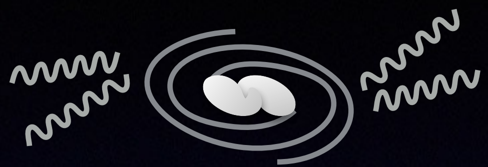
ICRR
Institute for Cosmic Ray Research
University of Tokyo

CGPQI
京都大学基礎物理学研究所
重力量子情報研究センター

Kilonova: Overview

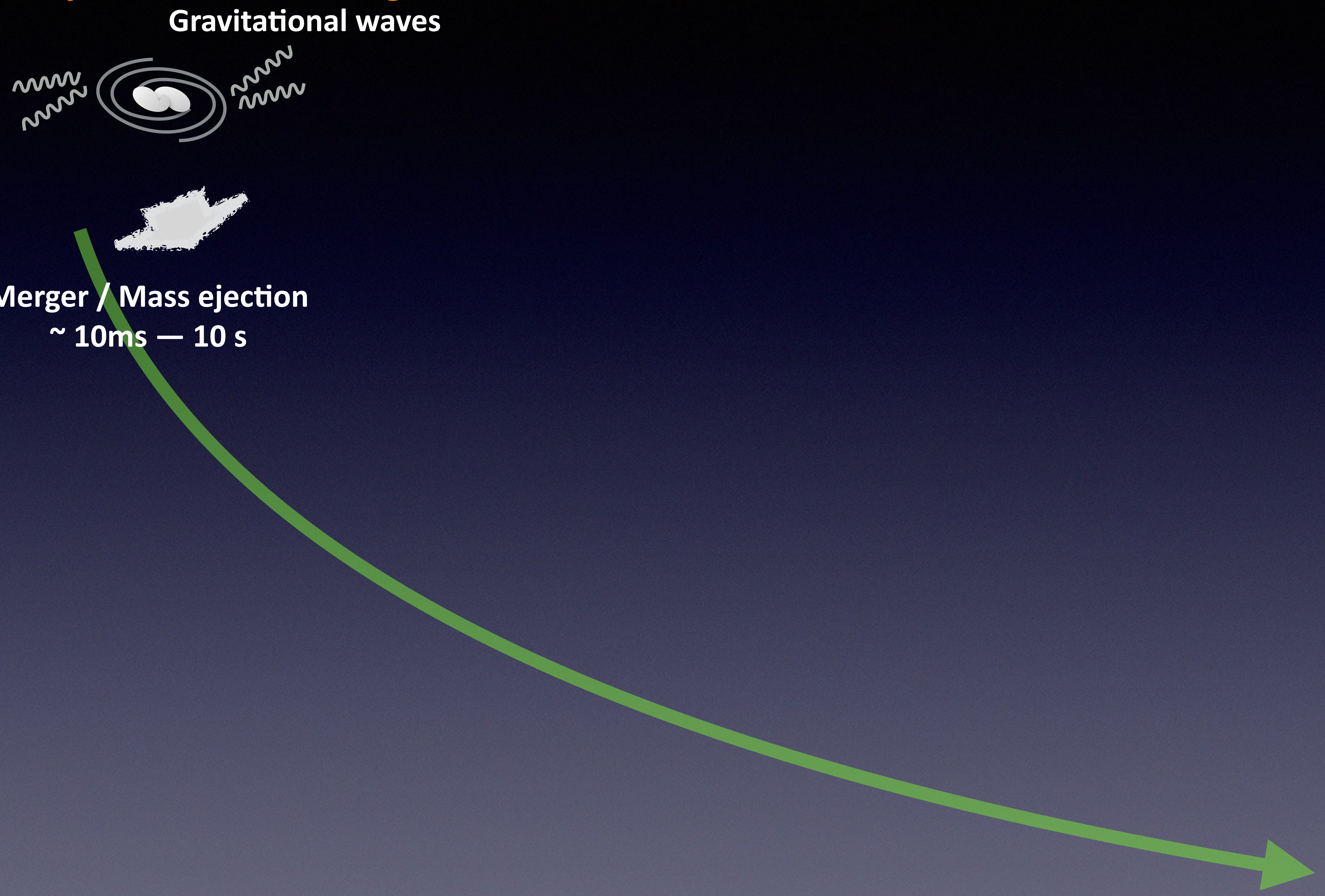
Binary neutron star merger

Gravitational waves

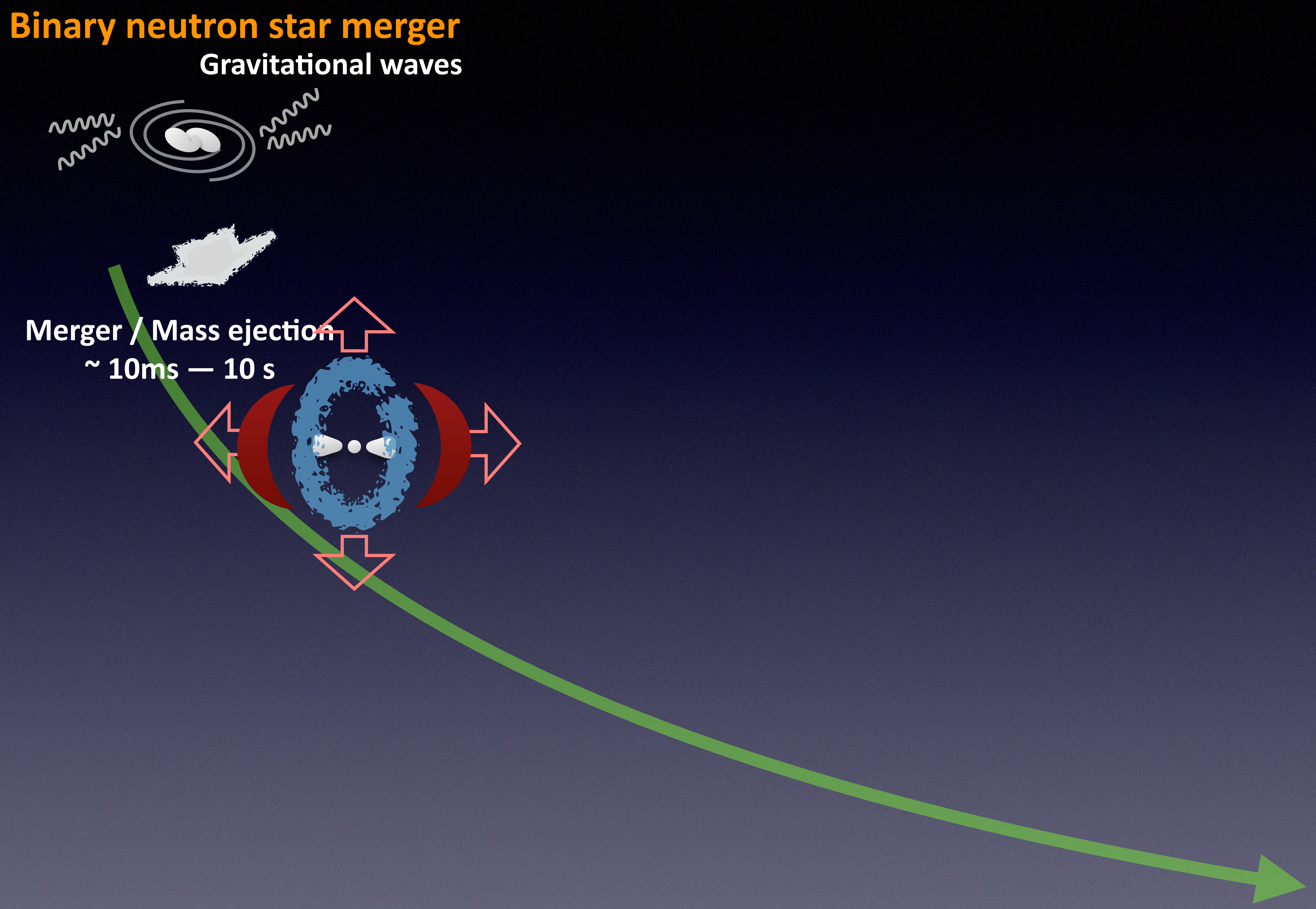


Kilonova: Overview

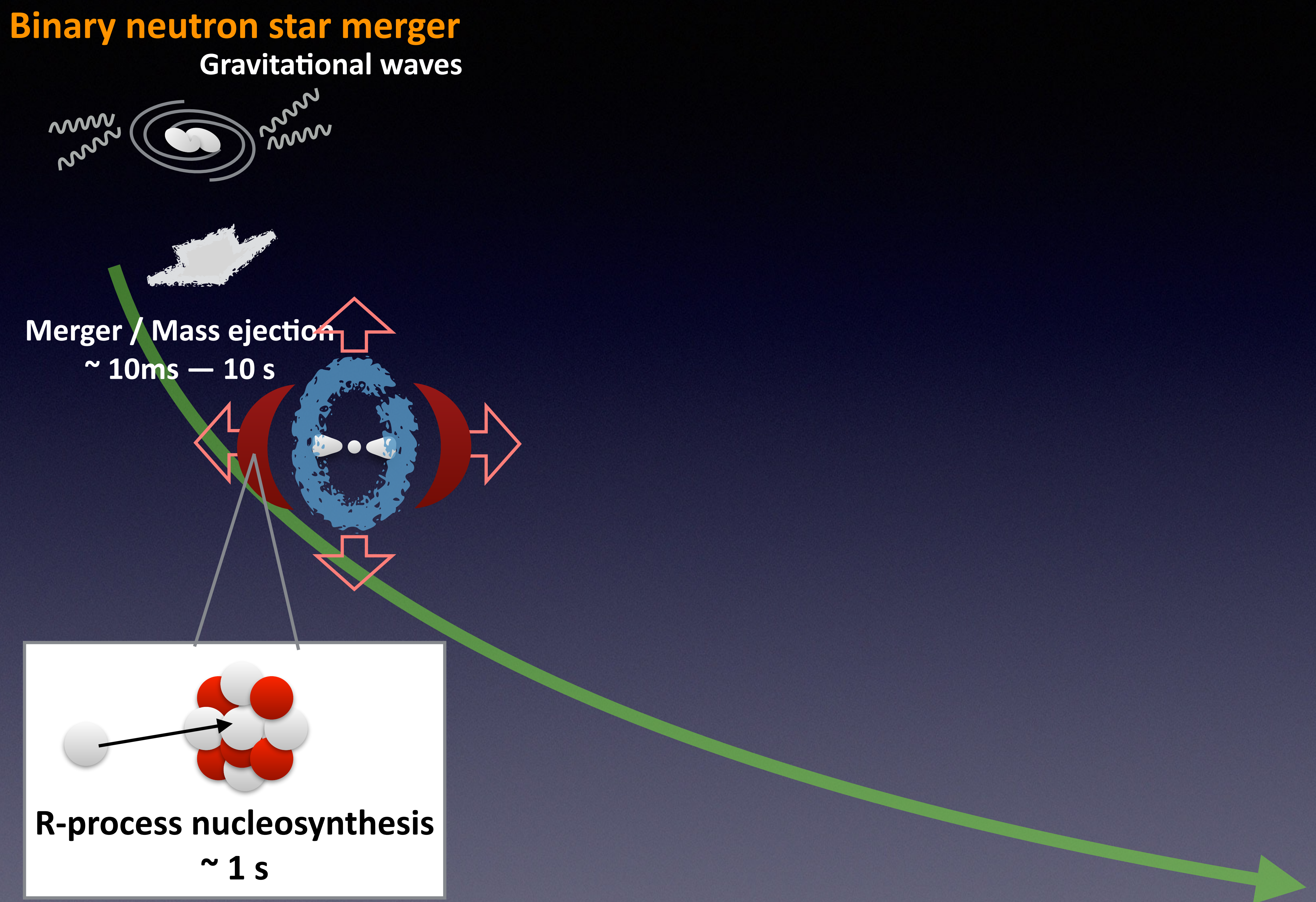
Binary neutron star merger



Kilonova: Overview



Kilonova: Overview



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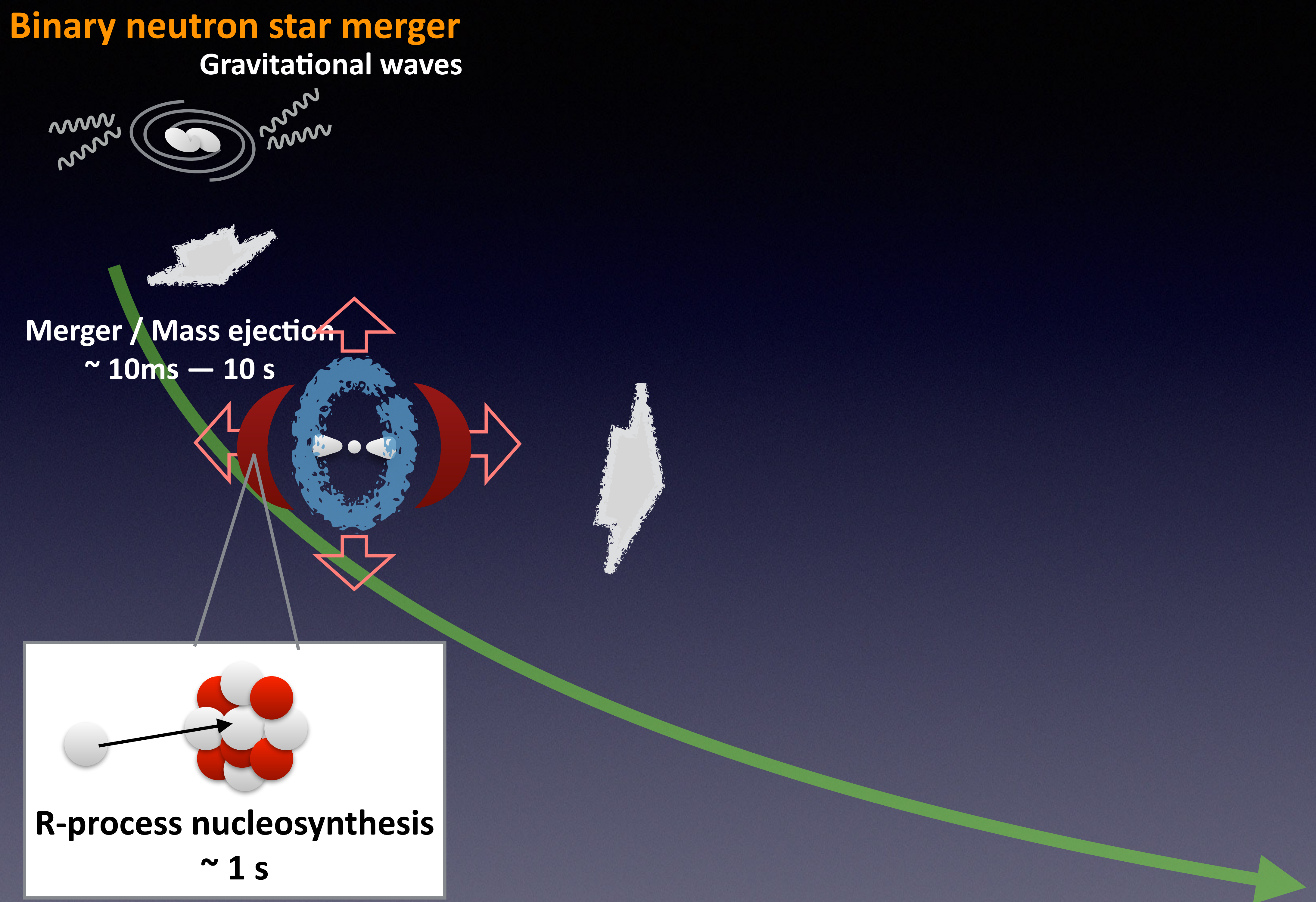

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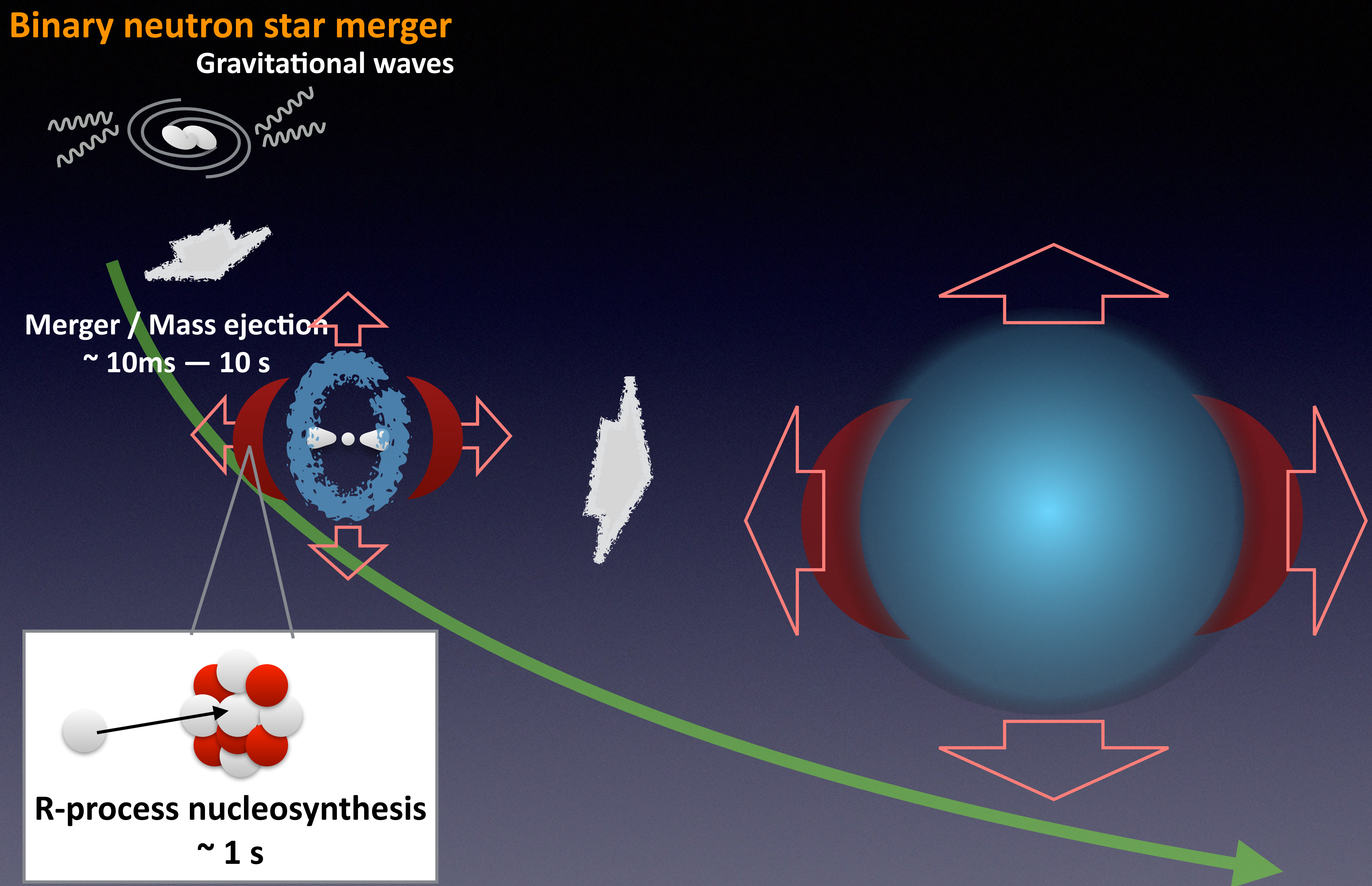

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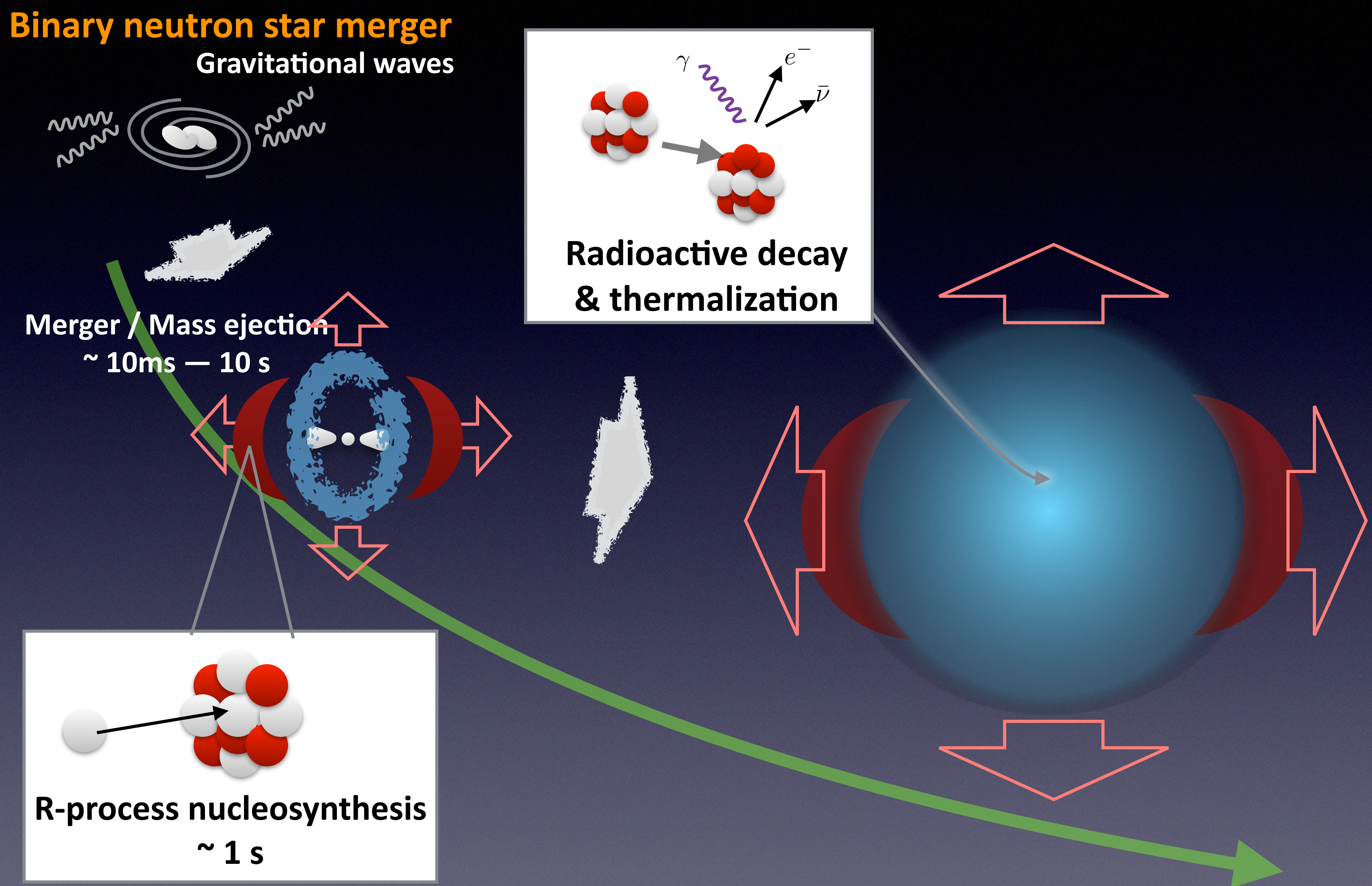
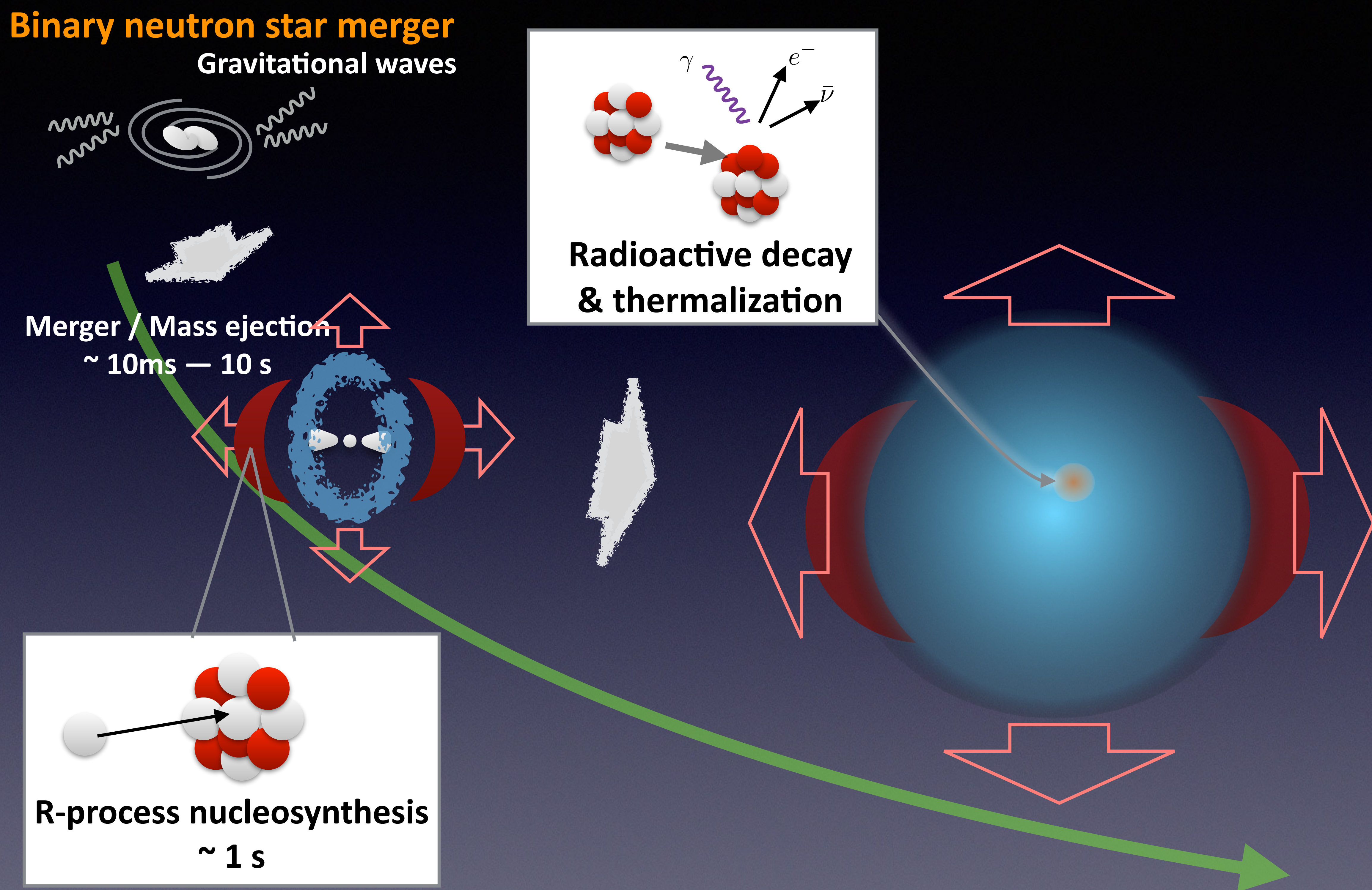
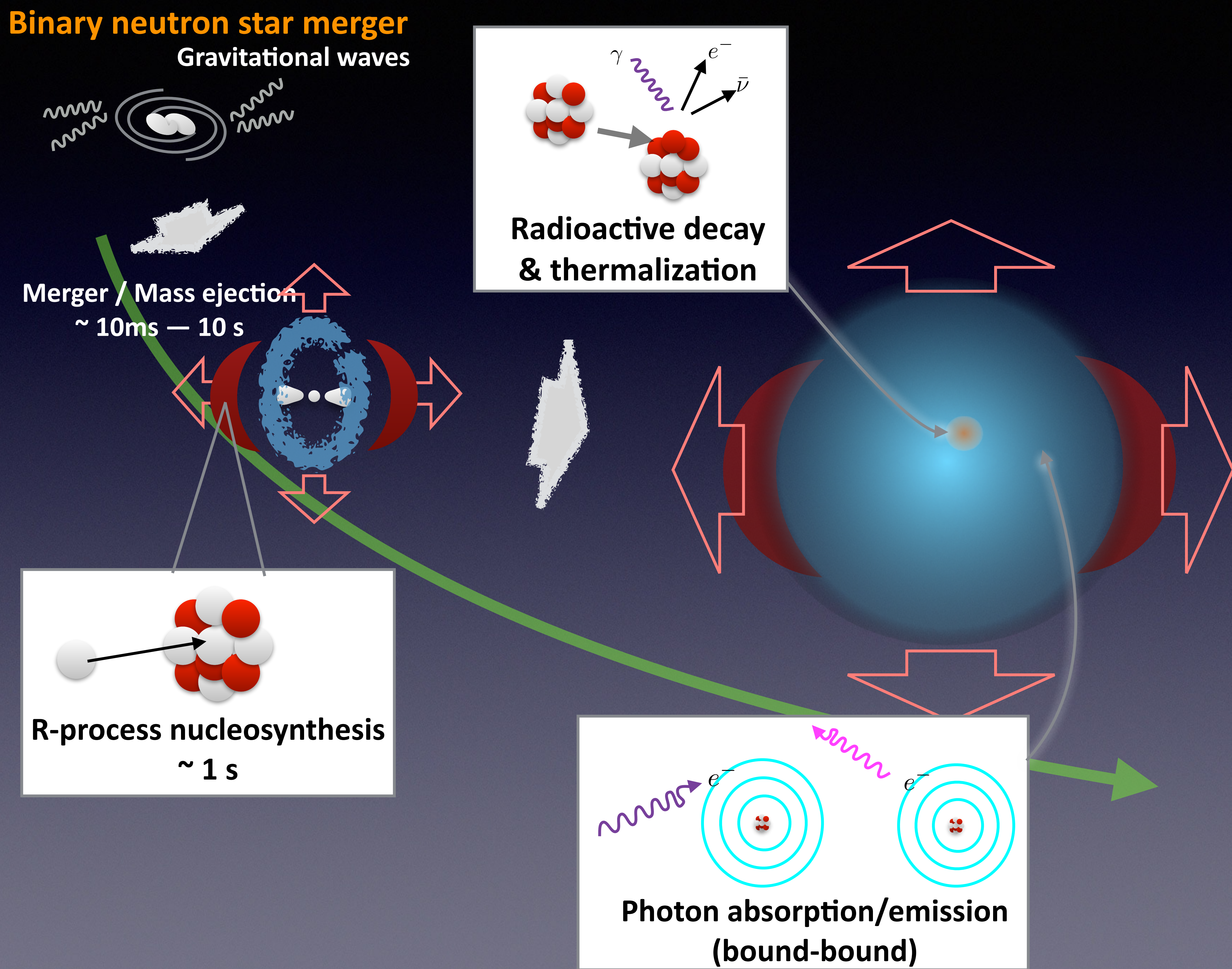


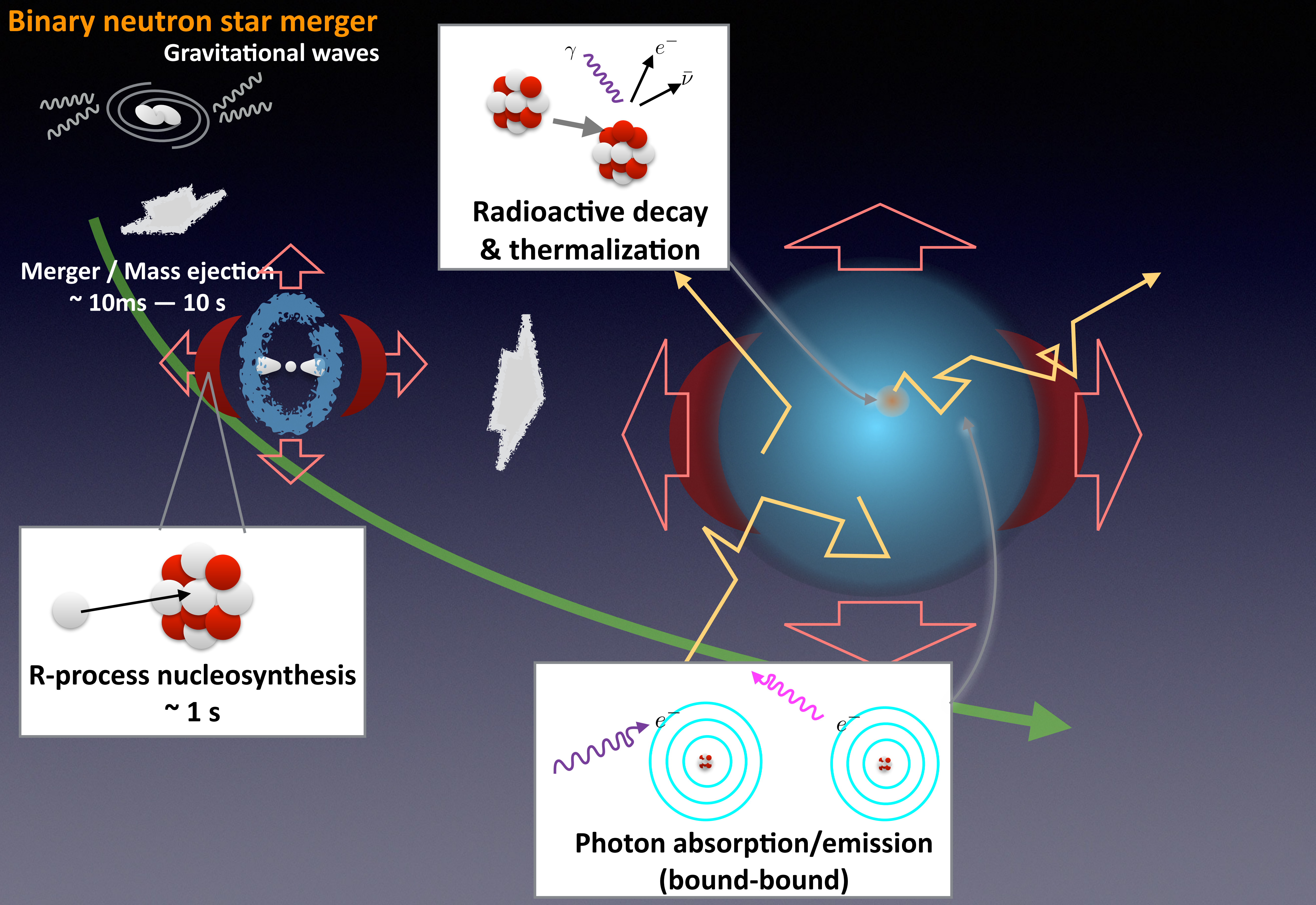
Kilonova: Overview



Kilonova: Overview



Kilonova: Overview



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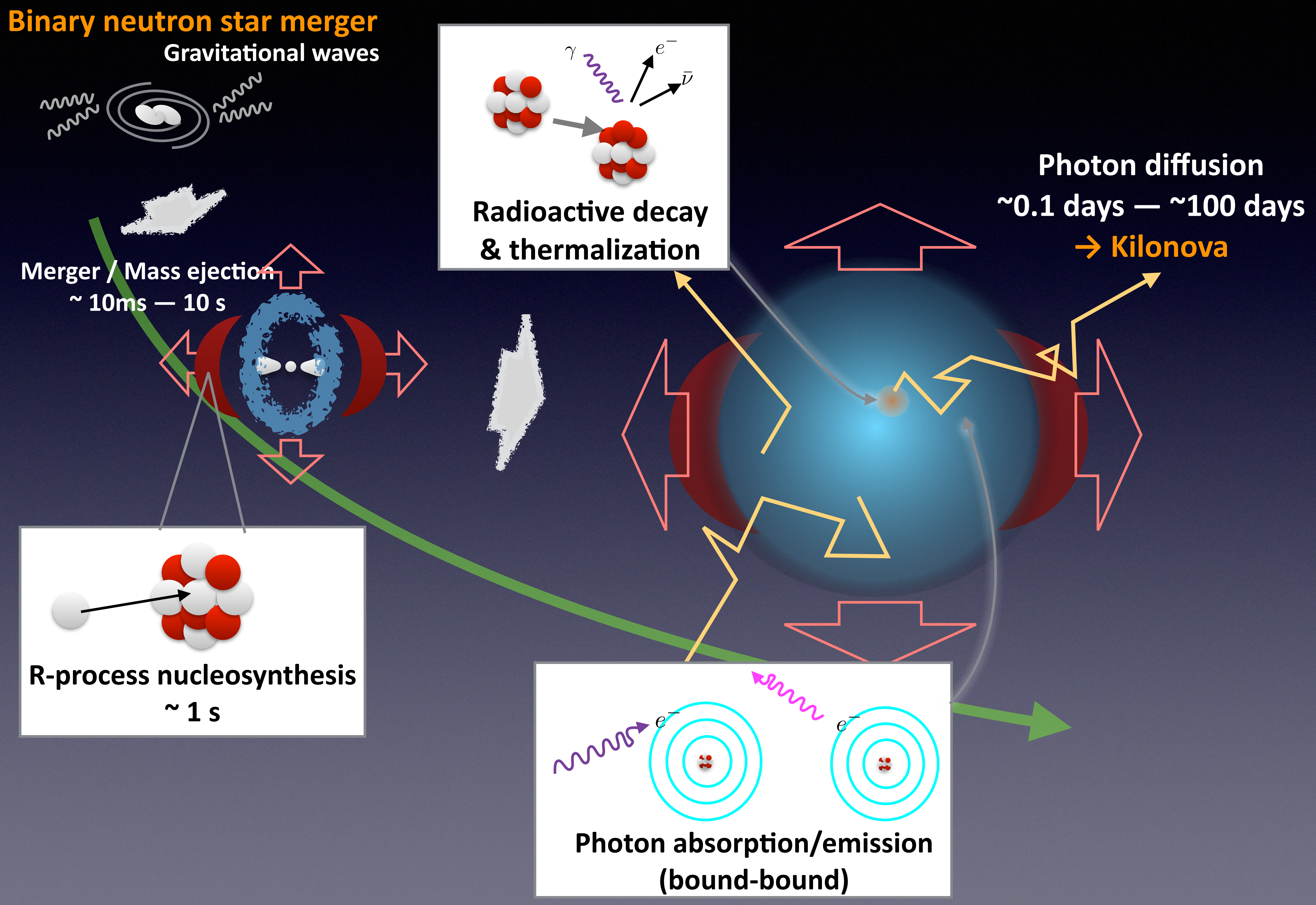
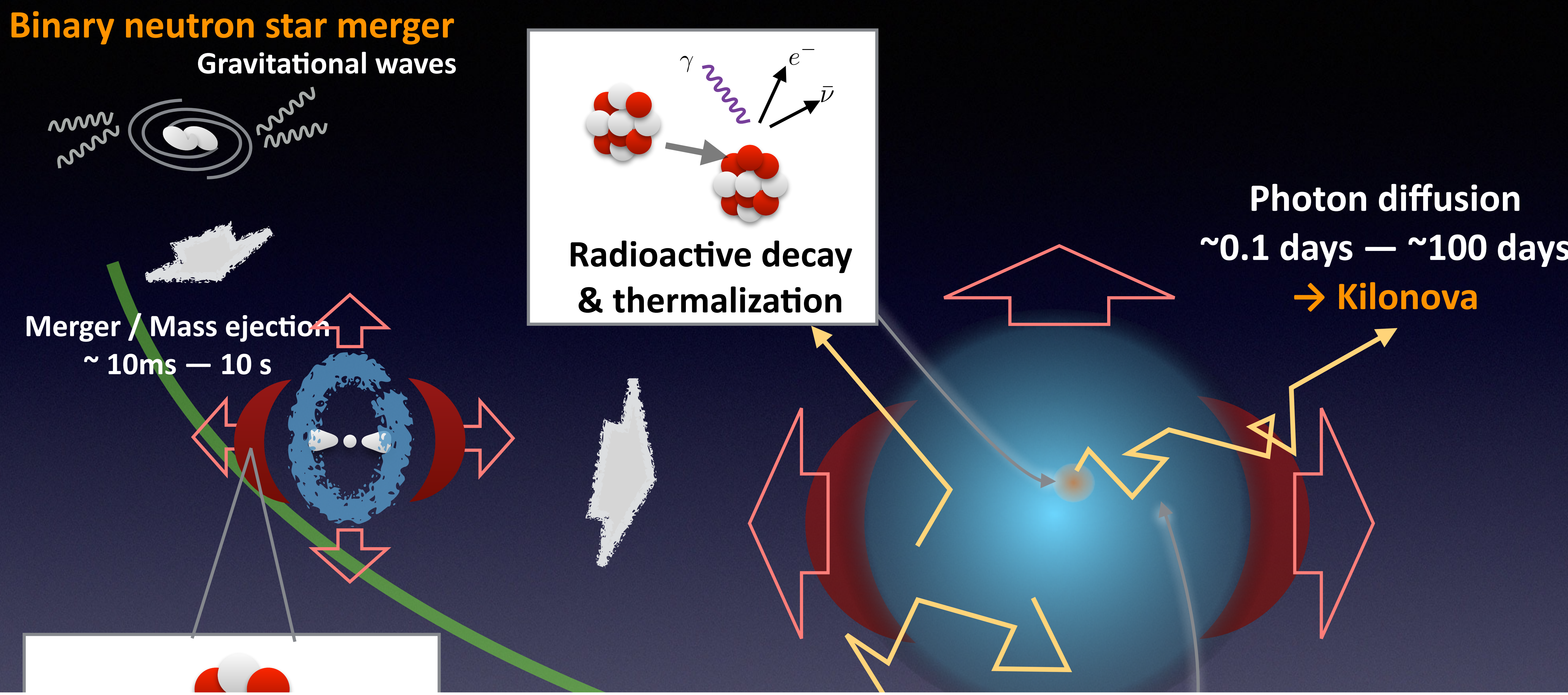


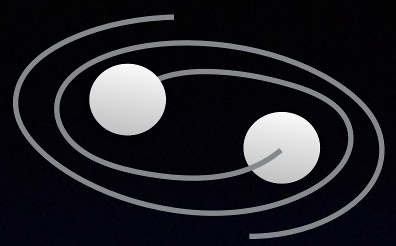
Kilonova: Overview



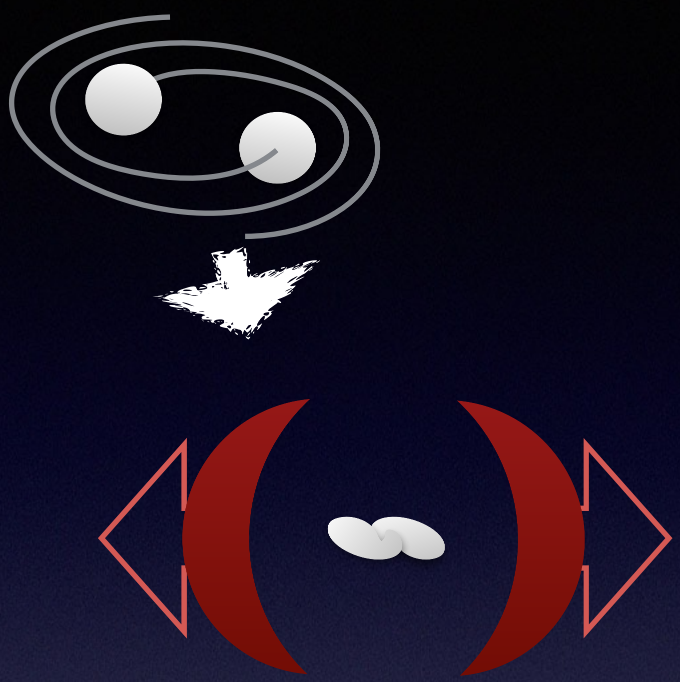
Li & Paczynski 1998, and e.g., Kulkarni 2005, Metzger et al. 2010, Hotokezaka et al. 2014, Tanaka et al. 2013, 2014, Kasen et al. 2013, 2015, Barnes et al. 2016, Wollaeger et al. 2018, Tanaka et al. 2018, Wu et al. 2019, Kawaguchi et al. 2018, Hotokezaka & Nakar 2019, Kawaguchi et al. 2019, Bulla 2019, Zhu et al. 2020, Darbha & Kasen 2020, Korobkin et al. 2020, Bulla et al. 2021, Zhu et al. 2021, Barnes et al. 2021, Nativi et al. 2020, Kawaguchi et al. 2021, Wu et al. 2021, Just et al. 2021b, Curtis et al. 2021, Wollaeger et al. 2021, Just et al. 2022, Bulla et al. 2020, Hotokezaka et al. 2022, Pognan et al. 2021, 2022, Banerjee et al. 2022, Neuweiler et al. 2022, Collins et al. 2022, Fontes et al. 2022, Just et al. 2023…

Photon absorption/emission
(bound-bound)

Long-term hydrodynamics evolution of ejecta

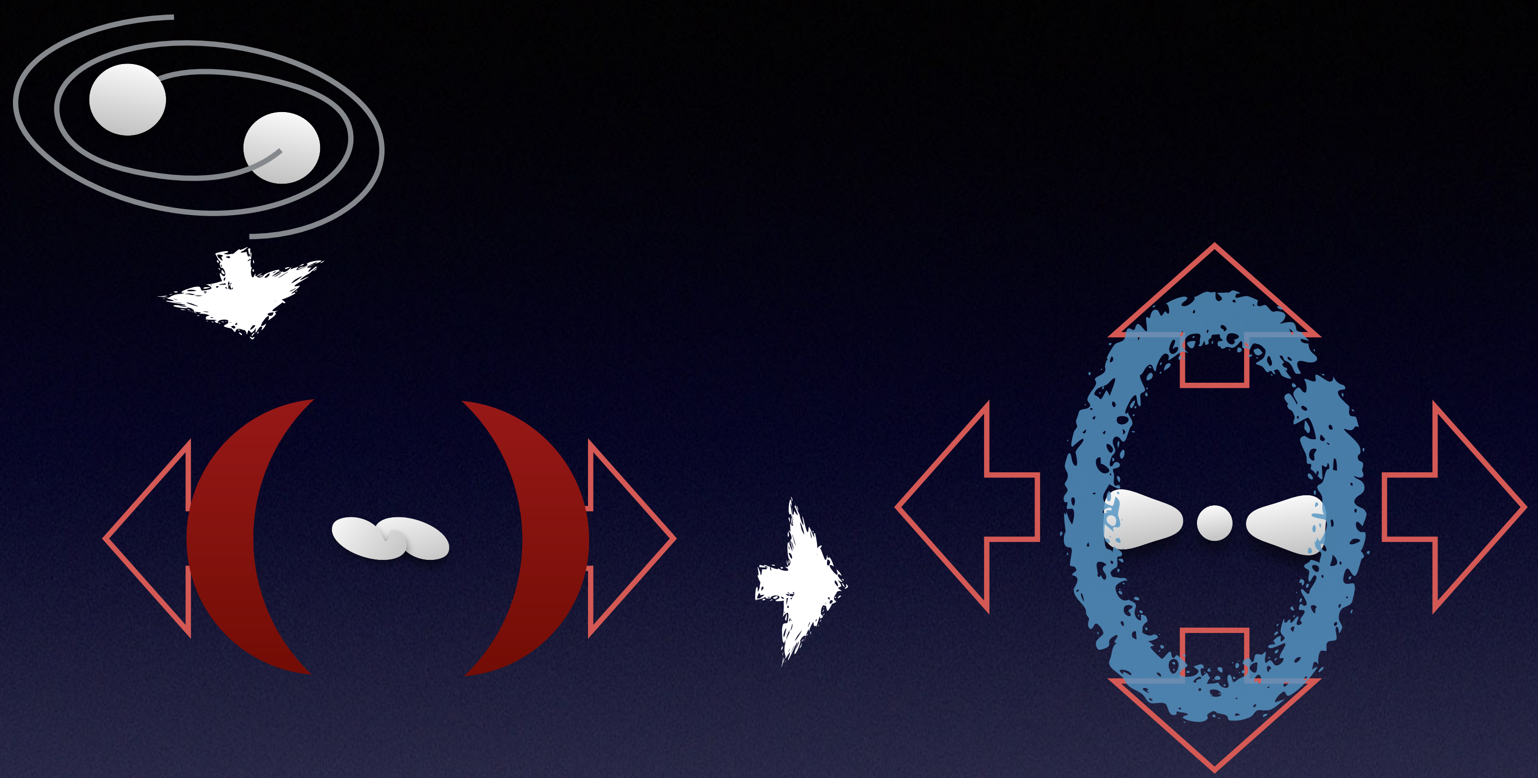


Long-term hydrodynamics evolution of ejecta



Dynamical mass ejection @merger

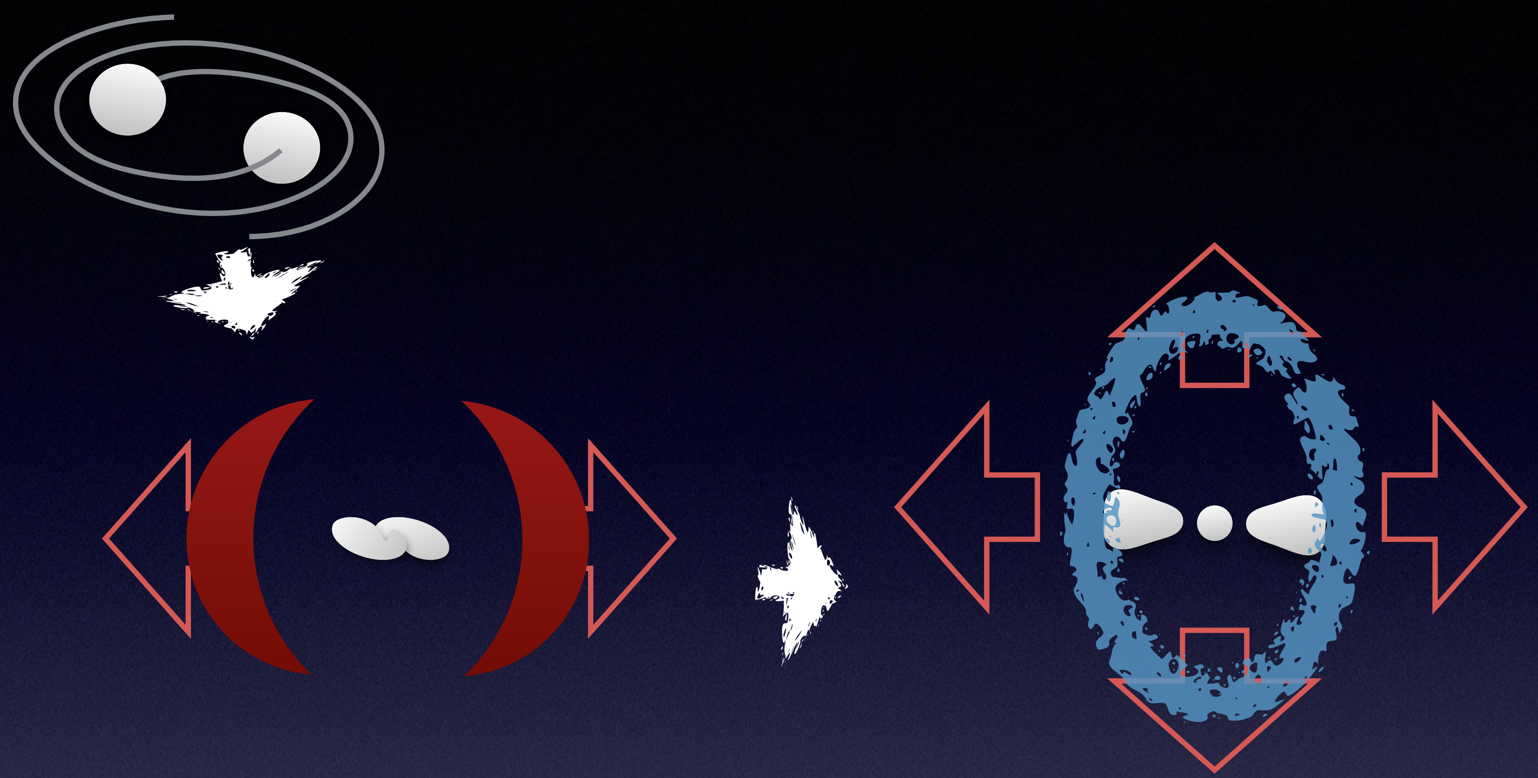
Long-term hydrodynamics evolution of ejecta



Dynamical mass ejection
@merger

Post-merger mass ejection
@after merger

Long-term hydrodynamics evolution of ejecta

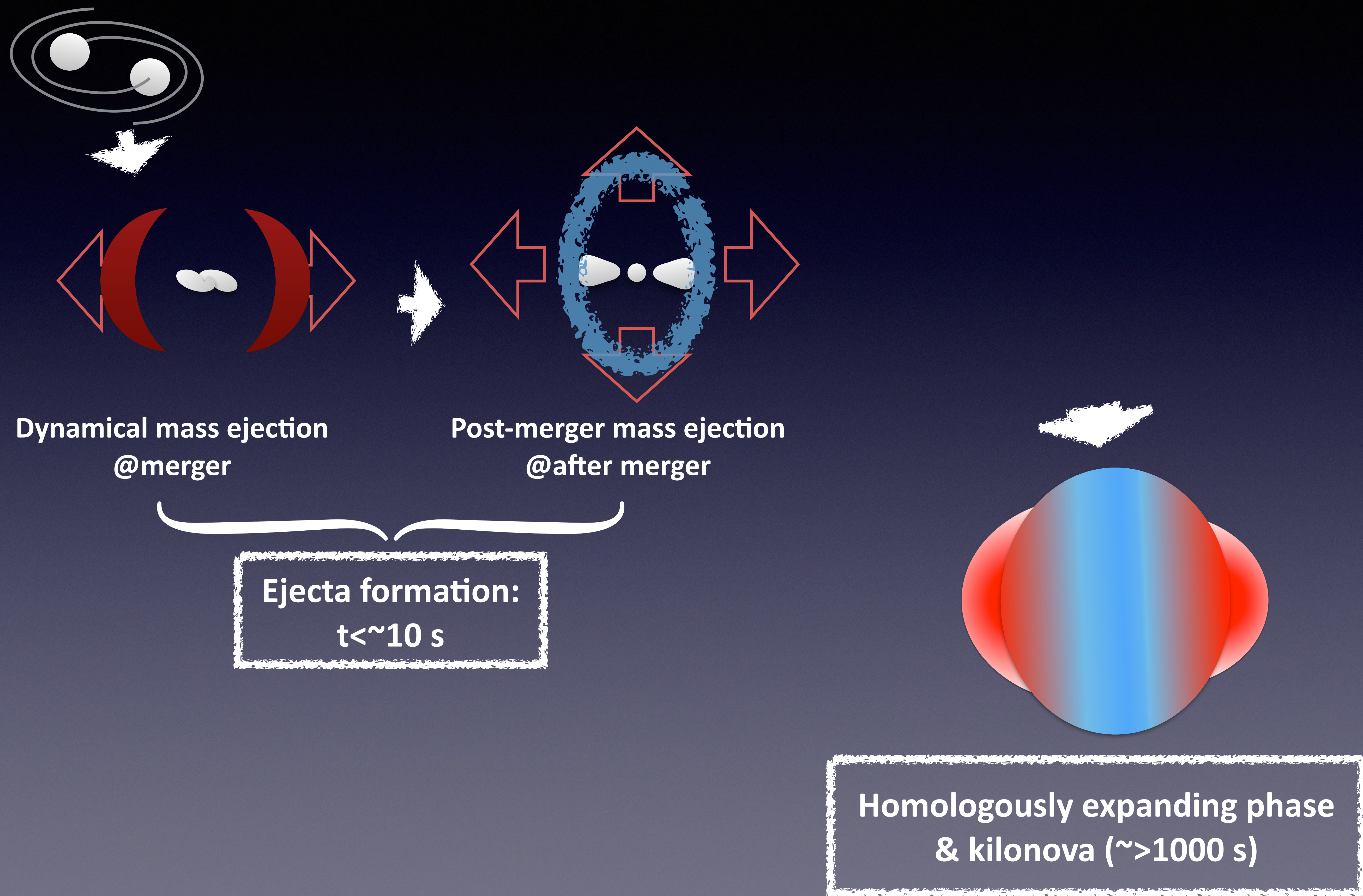


Dynamical mass ejection
@merger

Post-merger mass ejection
@after merger

Ejecta formation:
t<~10 s

Long-term hydrodynamics evolution of ejecta



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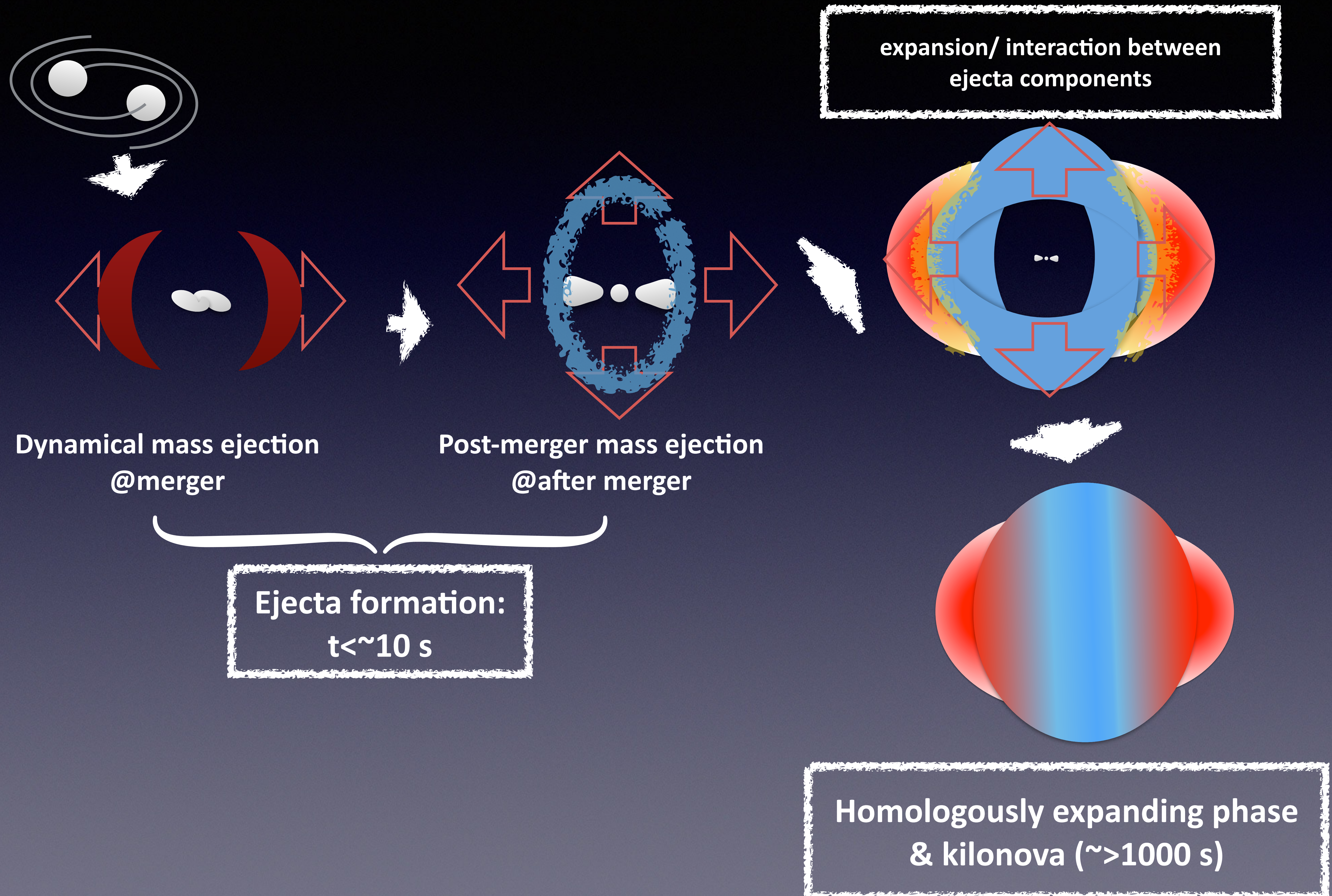

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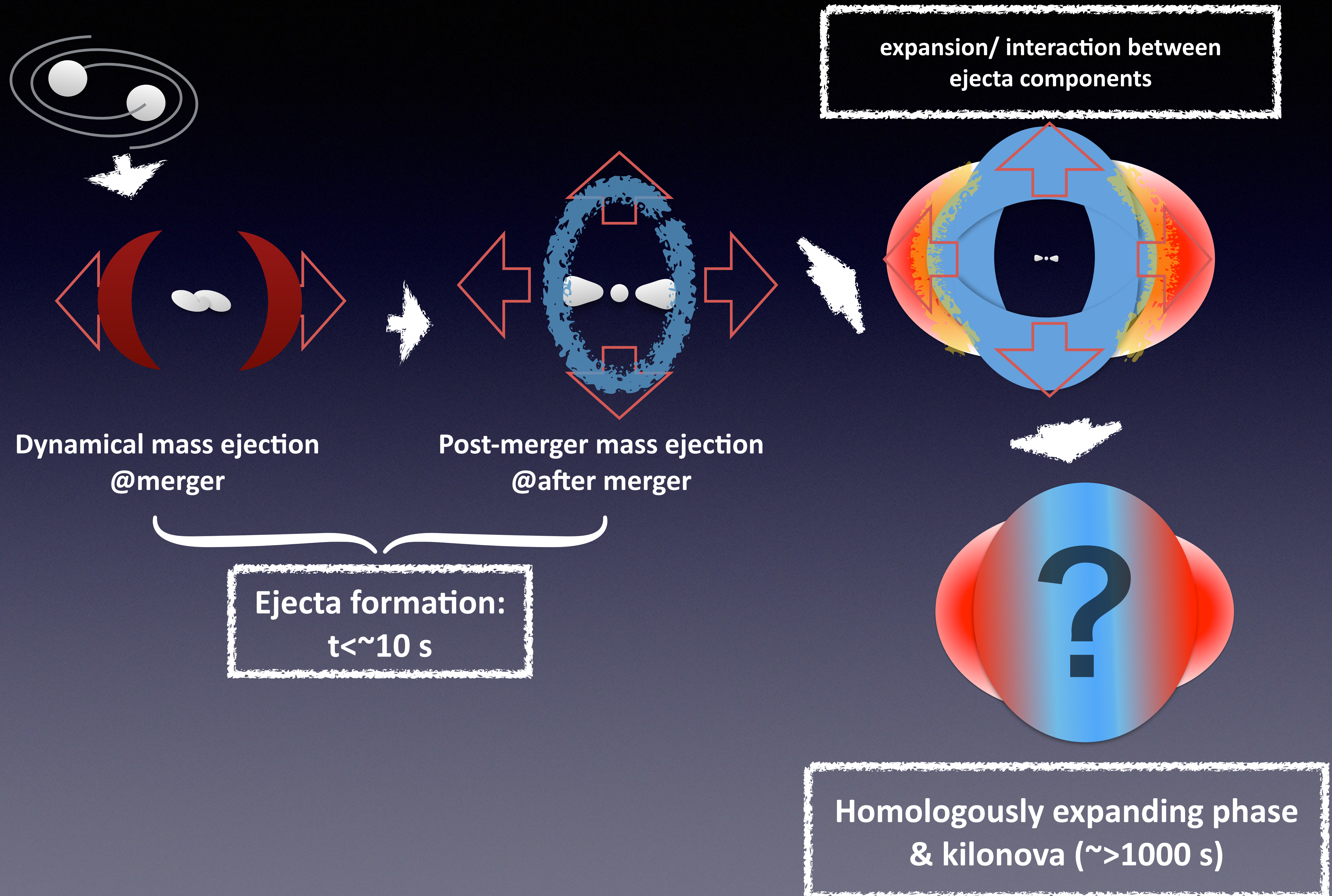

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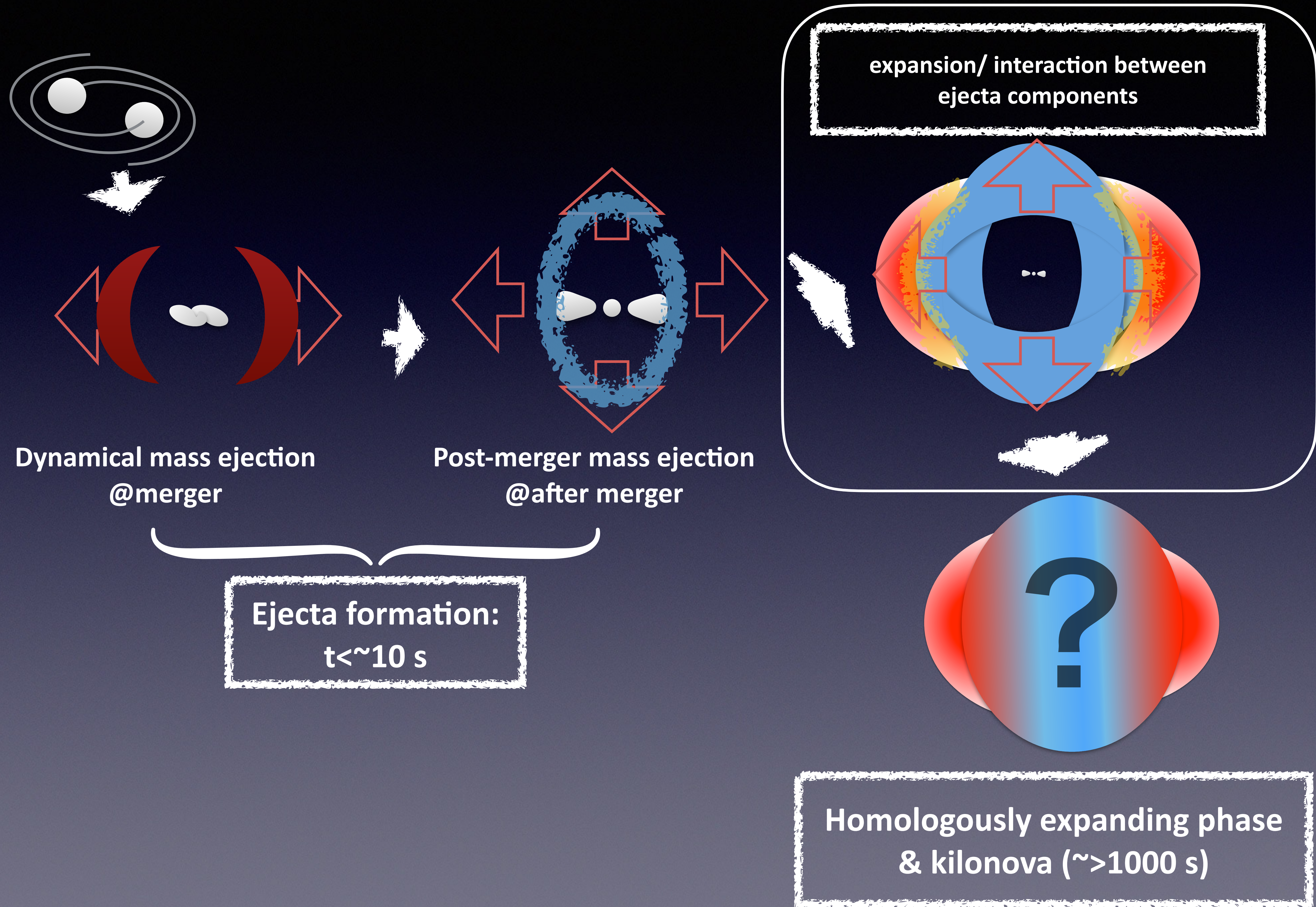

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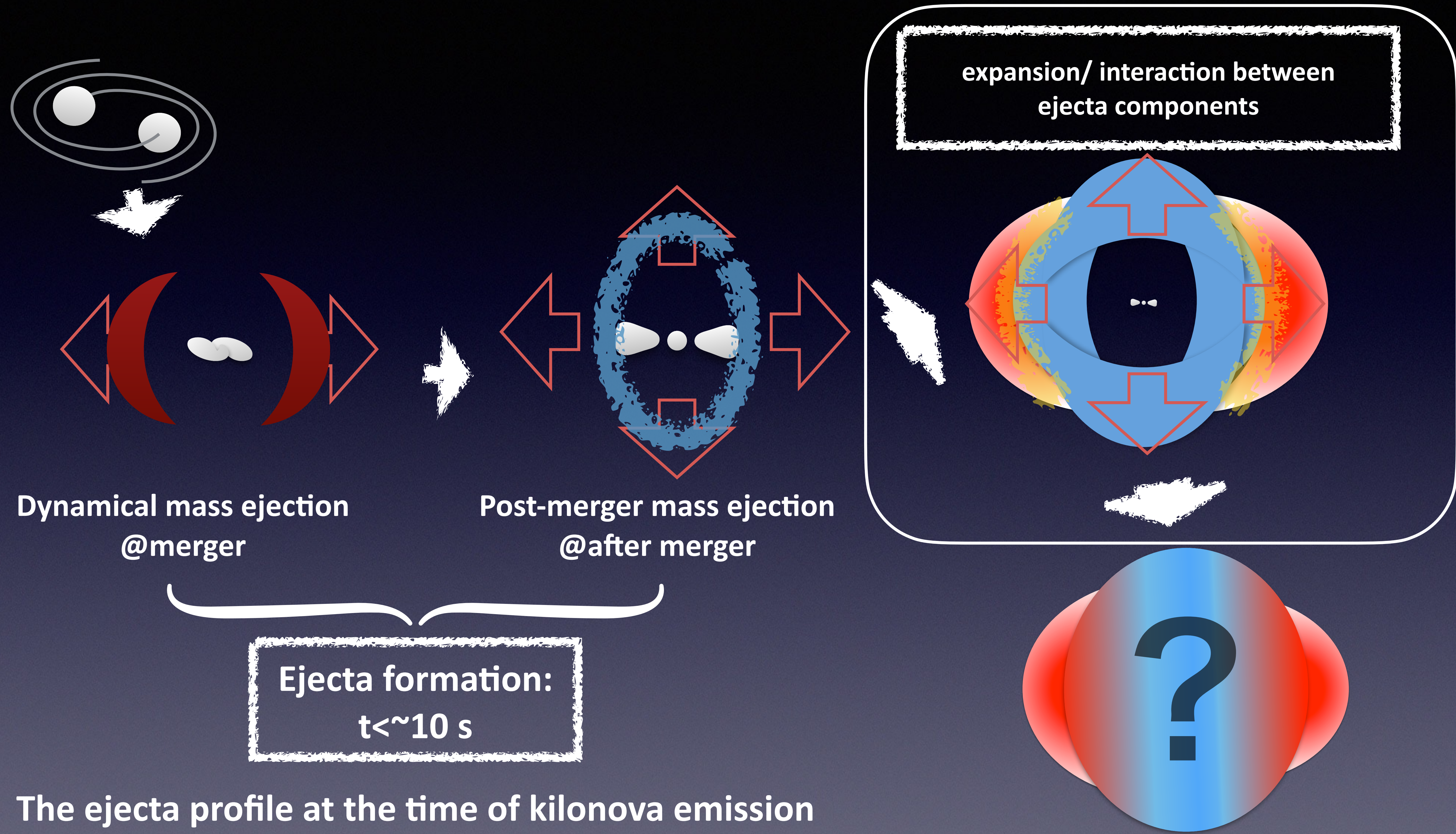


The ejecta profile at the time of kilonova emission is not trivial only from the simulations in the ejecta formation time scale
(see also Rosswog et al. 2014, Grossman et al. 2014, Fernandez et al. 2015, 2017, Foucart et al. 2021, Wu et al. 2021, Collins et al. 2022, Neuweiler et al. 2022, Just et al. 2023)

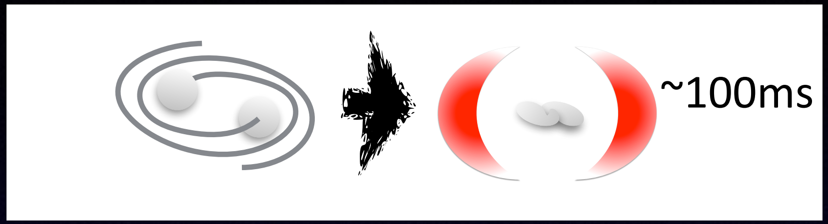
Homologously expanding phase & kilonova (~>1000 s)

Comprehensive EM prediction from merger simulations

KK. et al. 2021, 2022, 2023

Comprehensive EM prediction from merger simulations

3D GR-R-HD BNS merger simulation



Fujibayashi et al. 2020, 2022
Shibata et al. 2021

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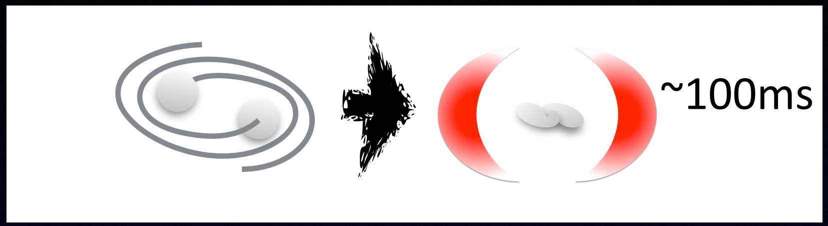

Fujibayashi et al. 2020, 2022
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Axisymmetrize

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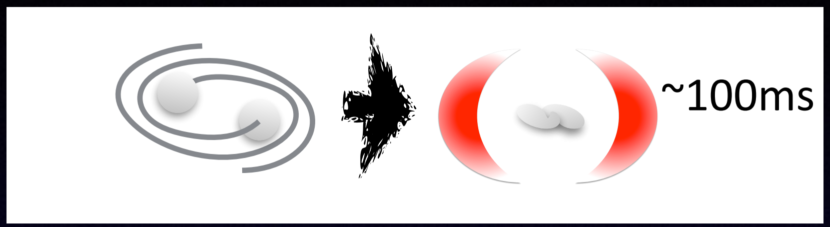
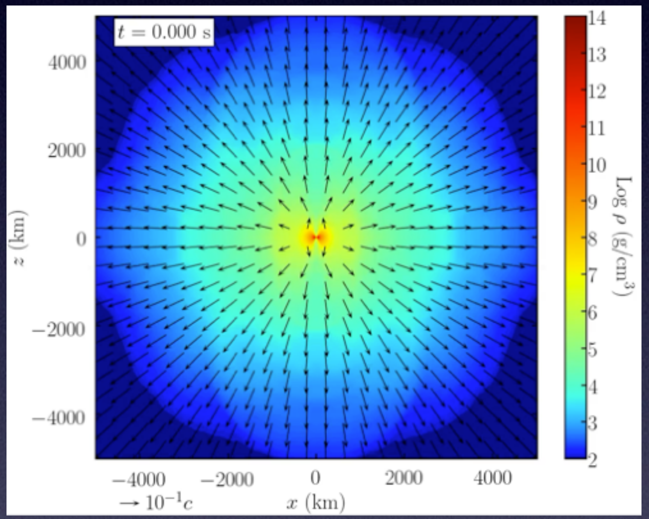
3D GR-R-HD BNS merger simulation



Fujibayashi et al. 2020, 2022
Shibata et al. 2021

Long-term axisymmetric
GR-R-viscous/MHD simulation ***(~1 s-10 s)***

Axisymmetrize



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3D GR-R-HD BNS merger simulation

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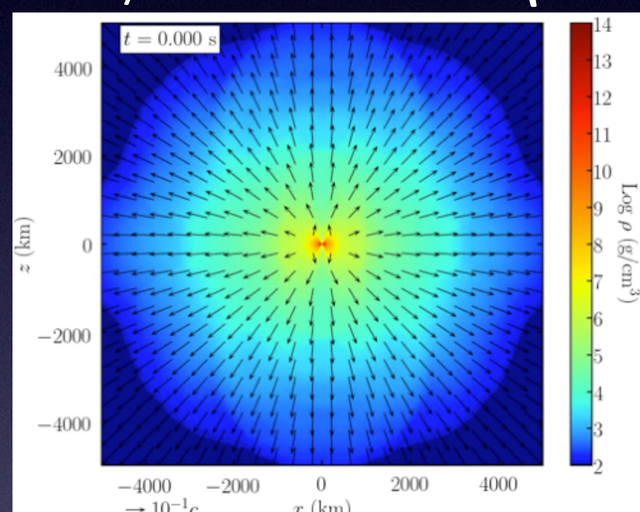

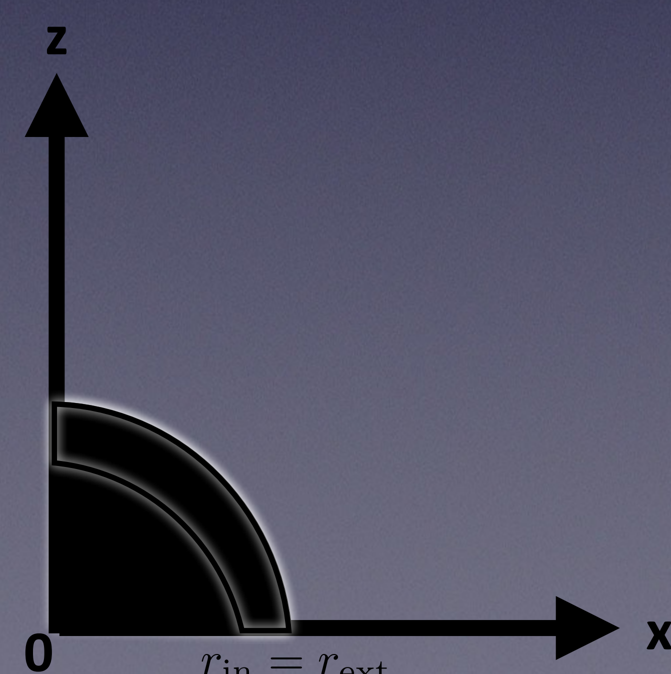

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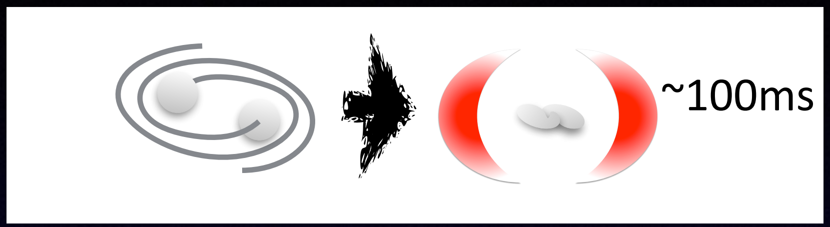

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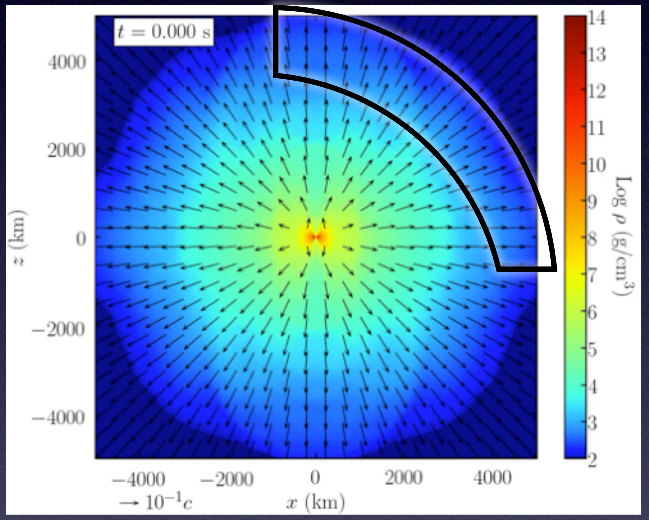

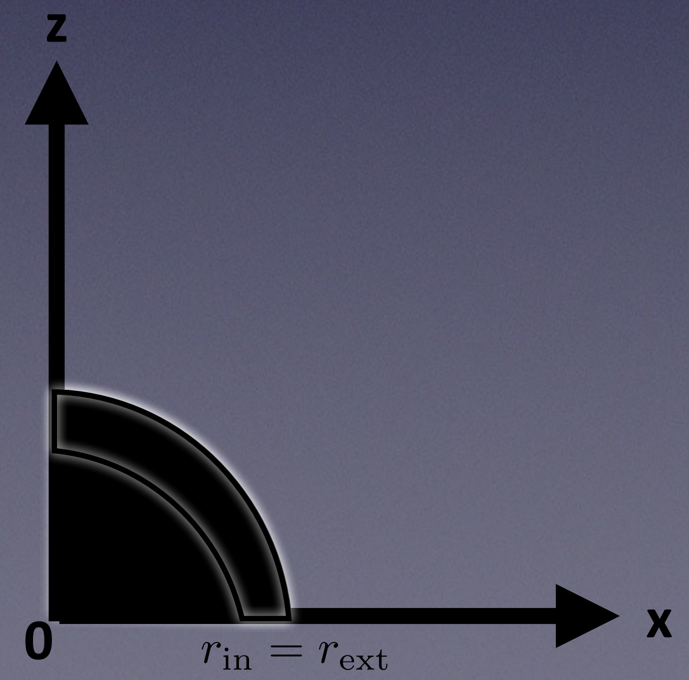

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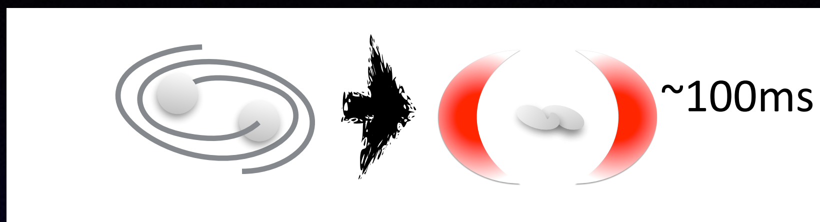

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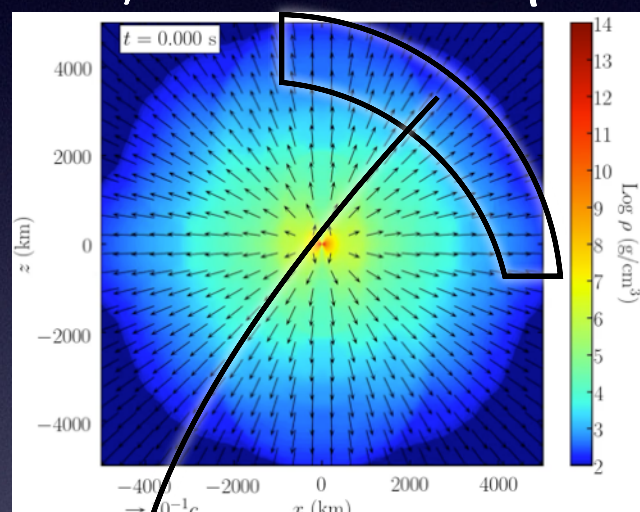
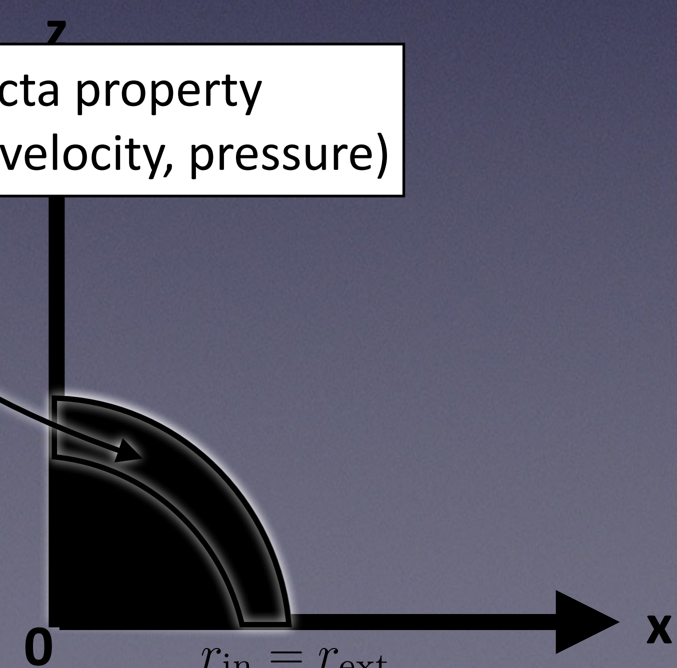
Axisymmetrize



Ejecta property
(density, velocity, pressure)



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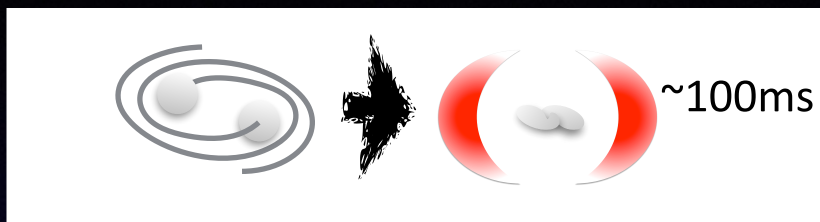
3D GR-R-HD BNS merger simulation



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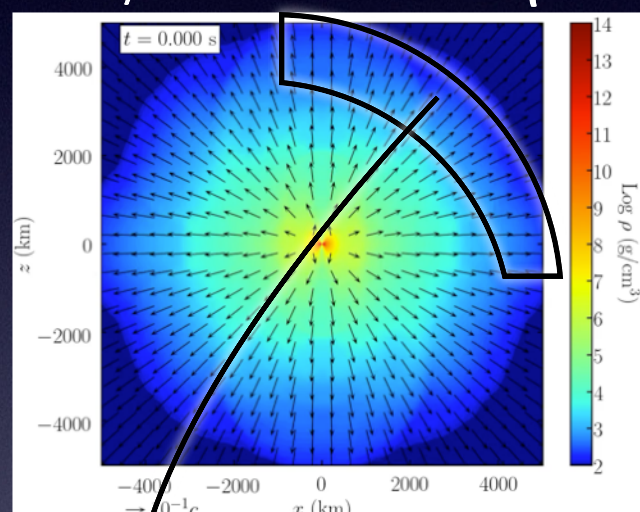
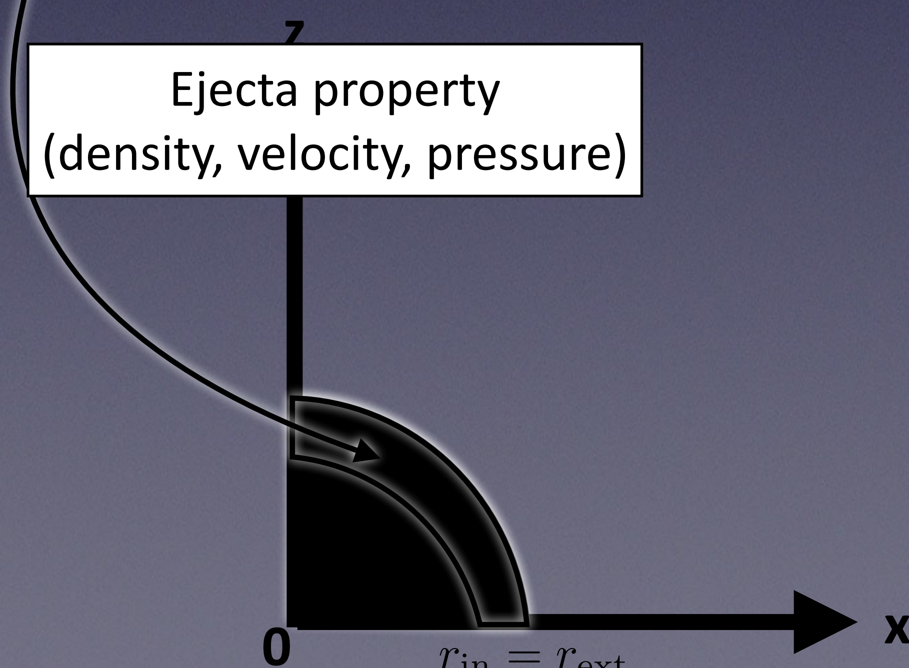


Extract ejecta component



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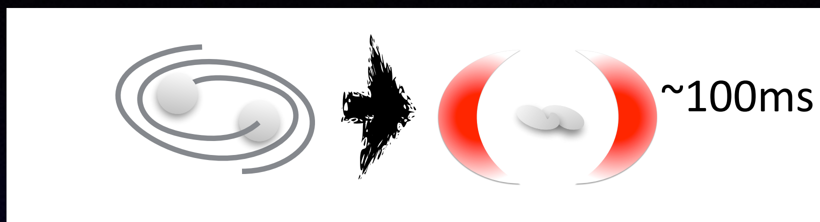
3D GR-R-HD BNS merger simulation



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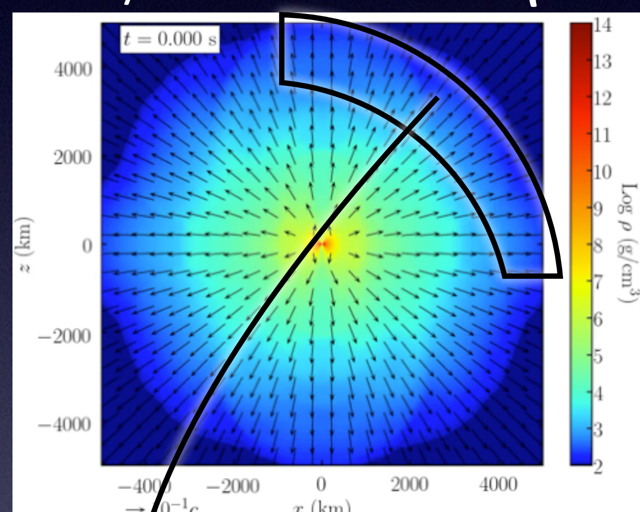

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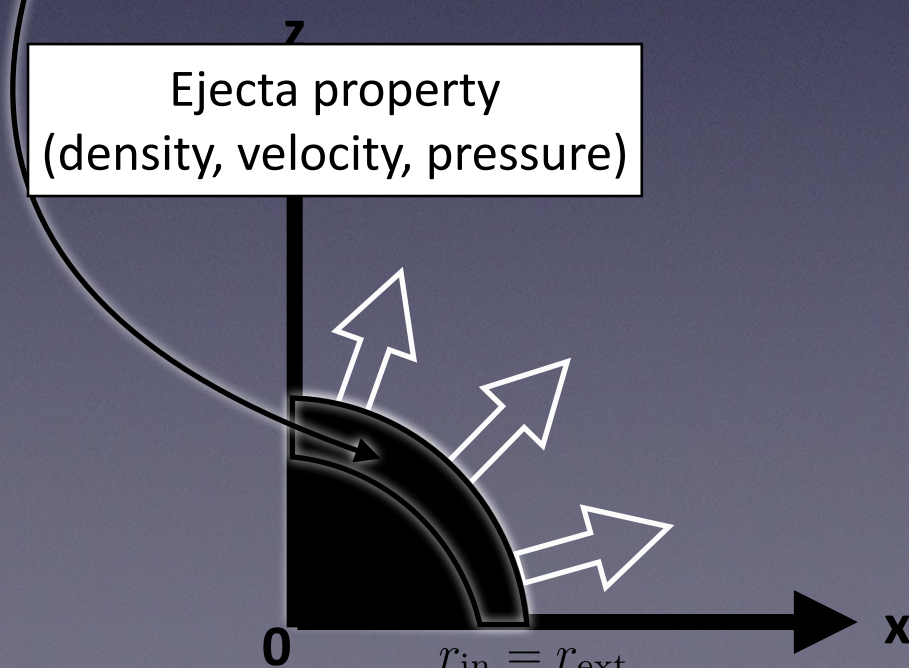

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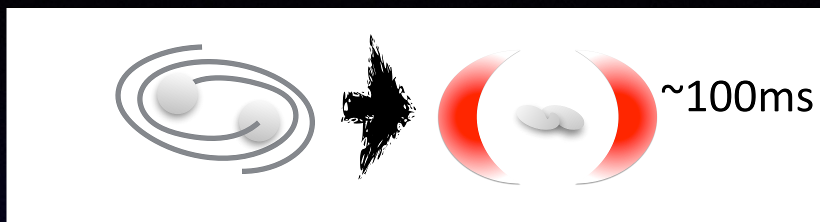

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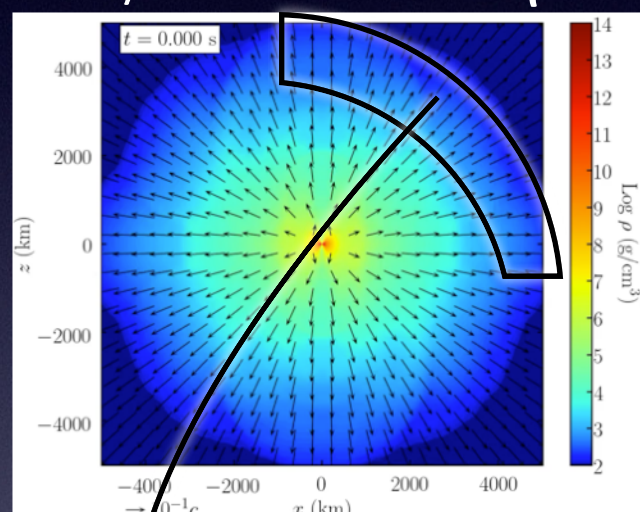

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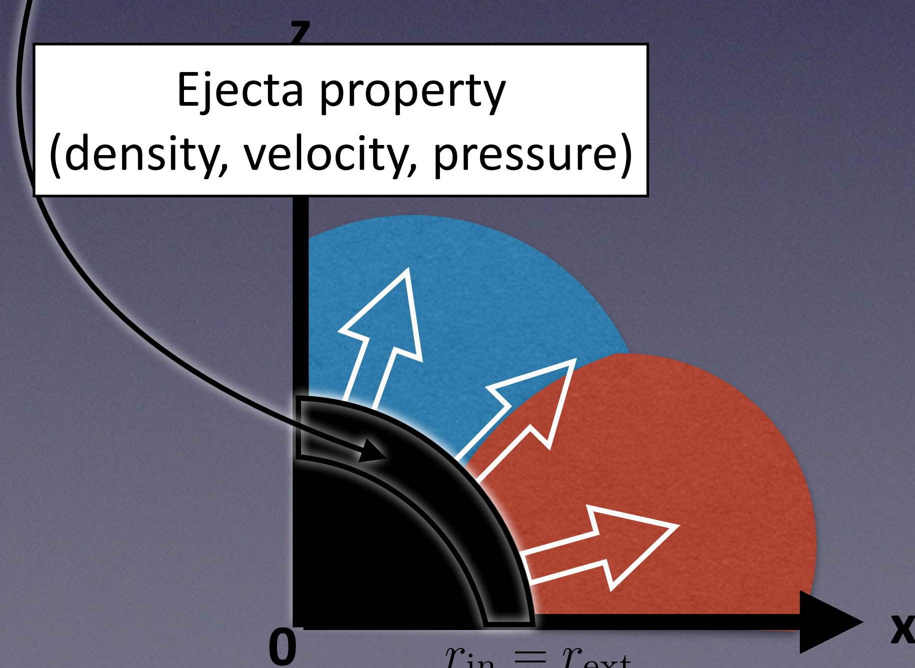

Comprehensive EM prediction from merger simulations

3D GR-R-HD BNS merger simulation

Fujibayashi et al. 2020, 2022
Shibata et al. 2021

Long-term axisymmetric
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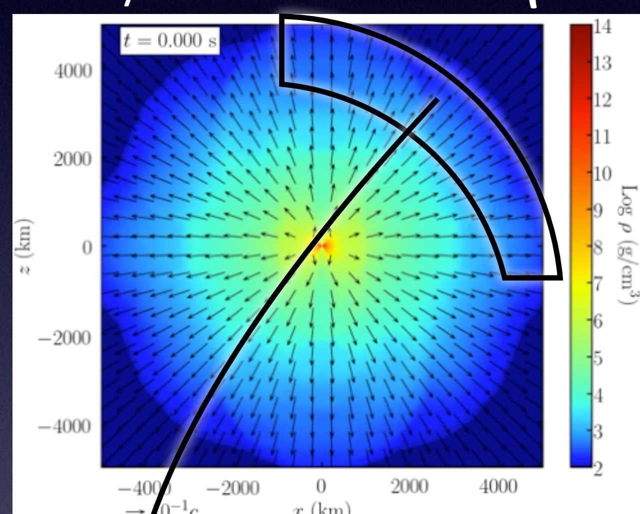
Axisymmetrize



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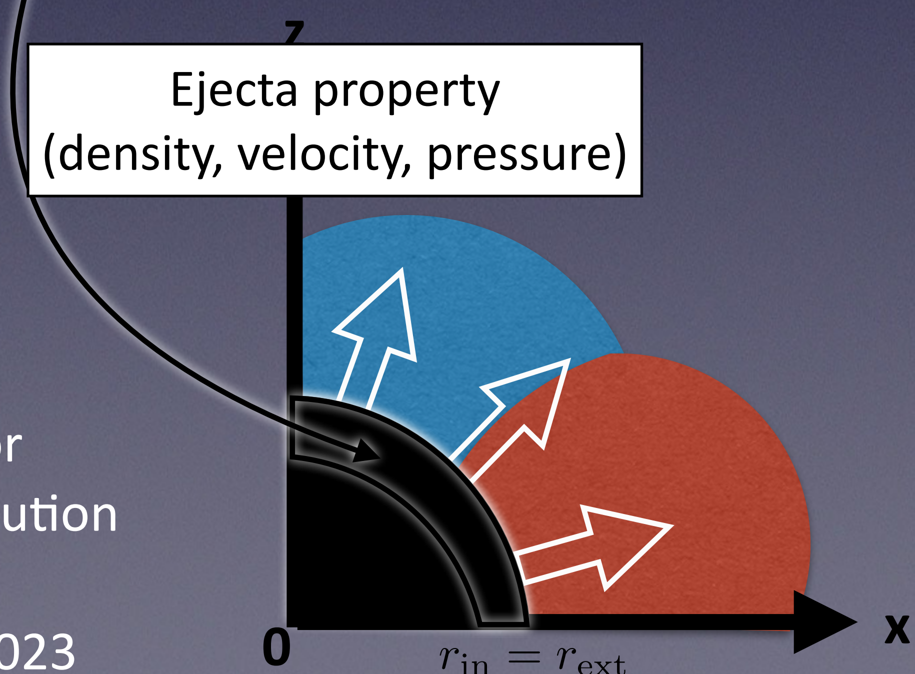
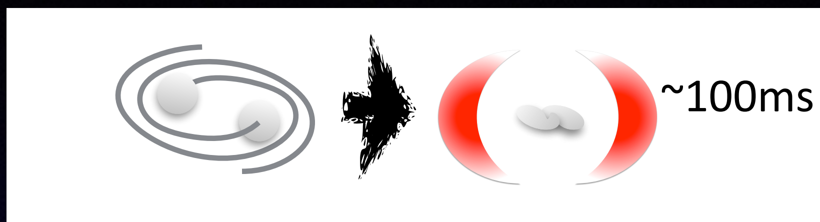


GR-HD simulation for
the longterm ejecta evolution
(~0.1 d)
KK et al. 2021, 2022, 2023

Comprehensive EM prediction from merger simulations

3D GR-R-HD BNS merger simulation



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Shibata et al. 2021

Long-term axisymmetric
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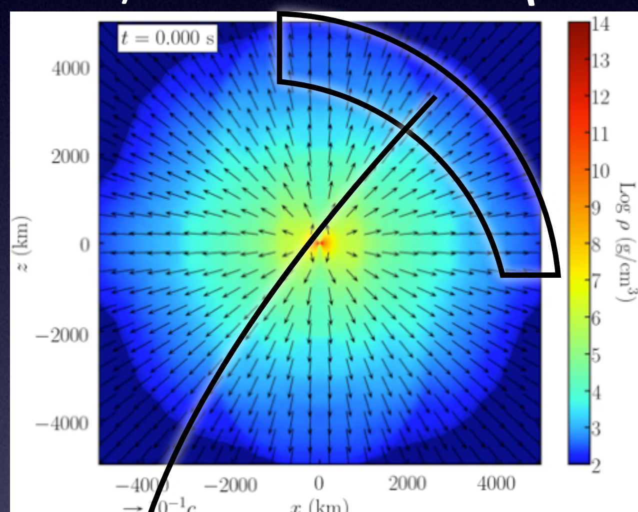
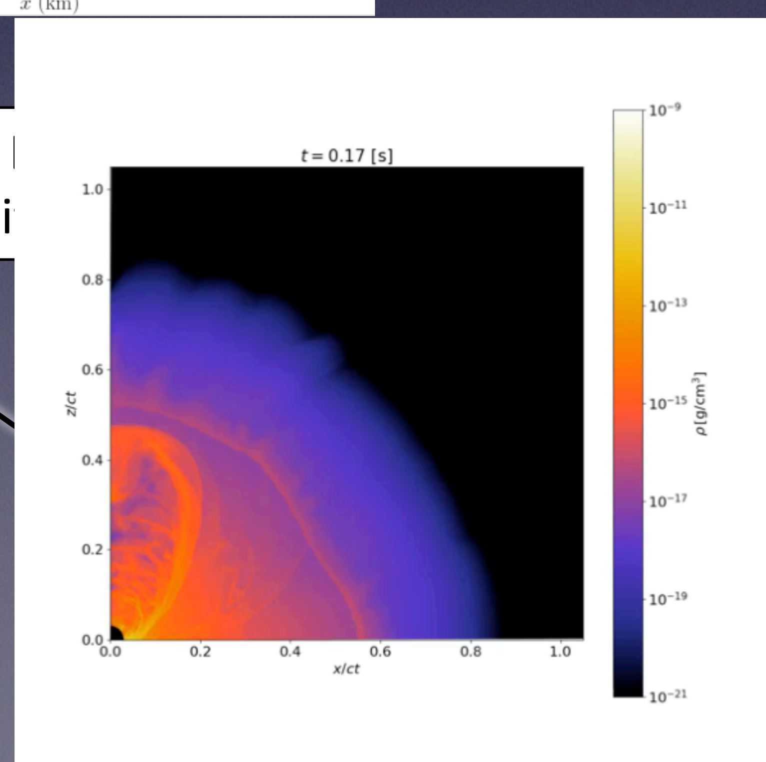
Axisymmetrize



Extract ejecta component

(densi



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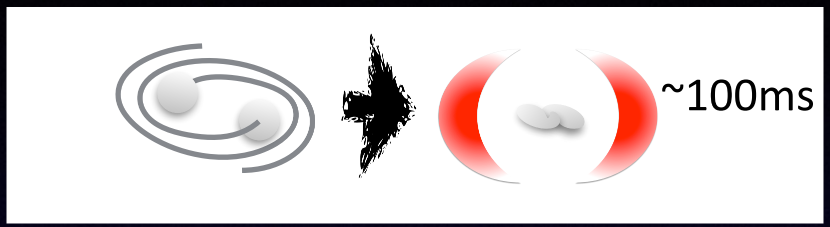

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Long-term axisymmetric
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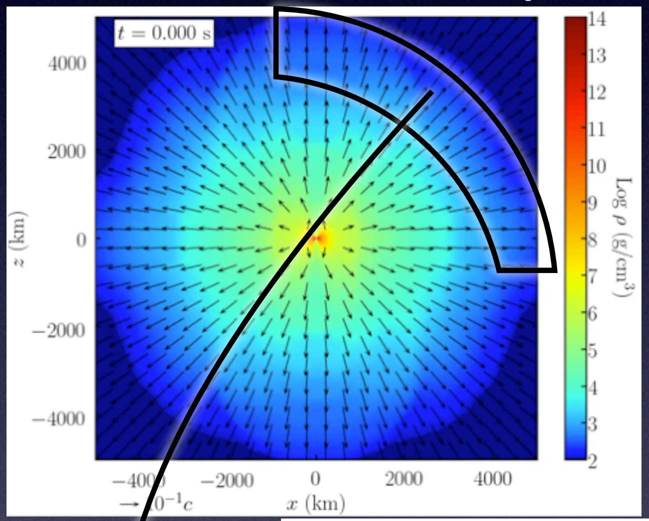
Axisymmetrize



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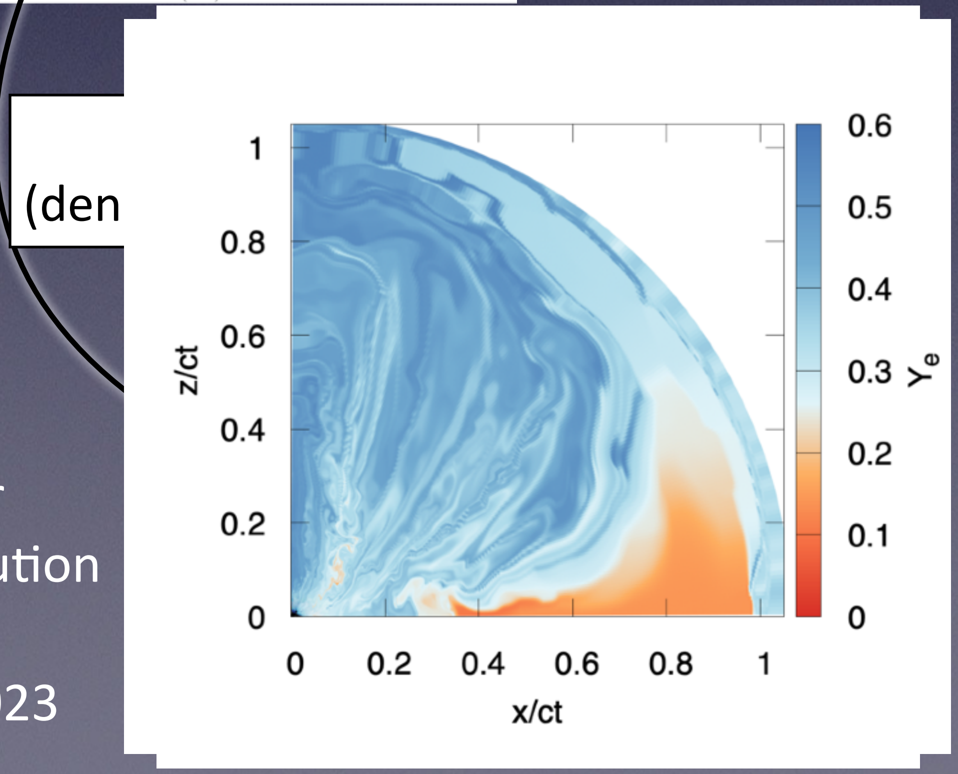

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Comprehensive EM prediction from merger simulations

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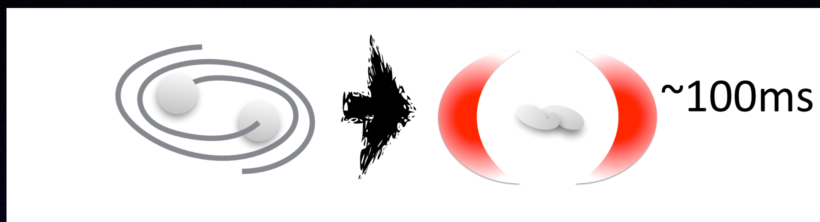
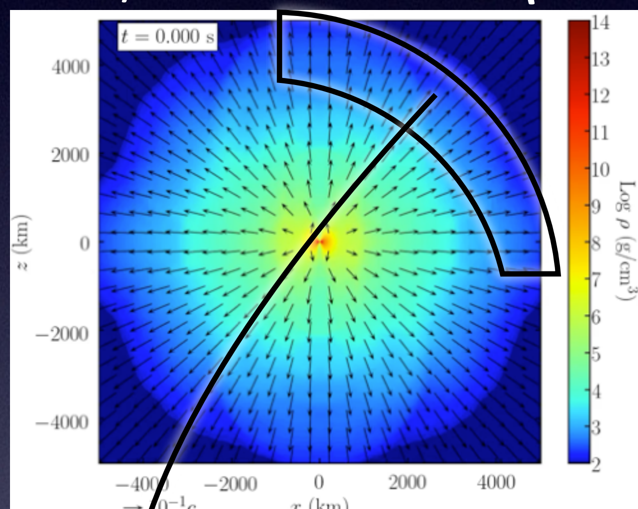


Fujibayashi et al. 2020, 2022
Shibata et al. 2021

Axisymmetrize

Long-term axisymmetric
GR-R-viscous/MHD simulation ***(~1 s-10 s)***



Extract ejecta component

GR-HD simulation for
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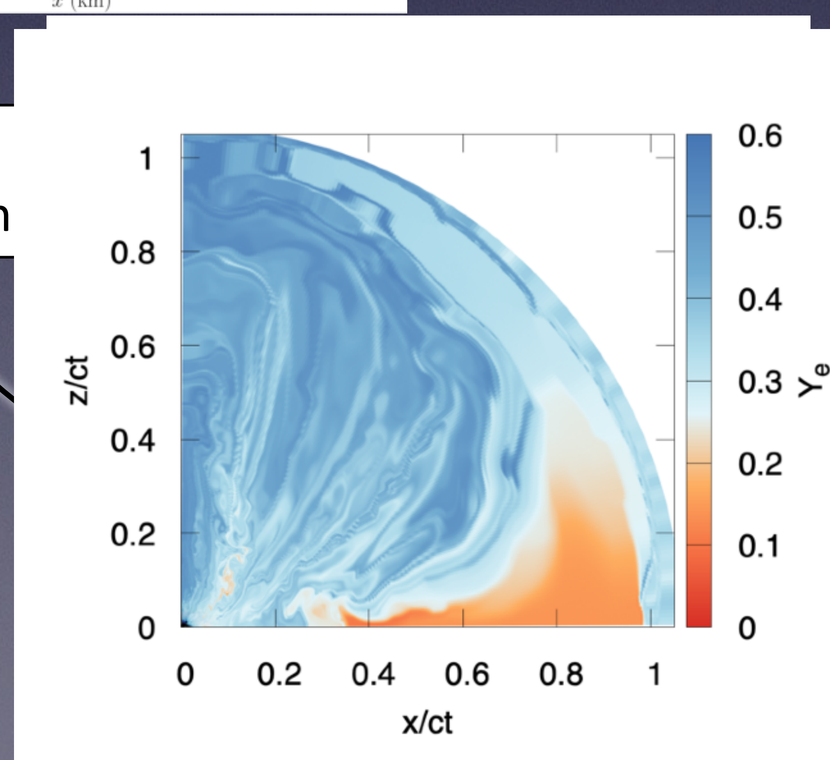
KK et al. 2021, 2022, 2023



EM counterpart prediction

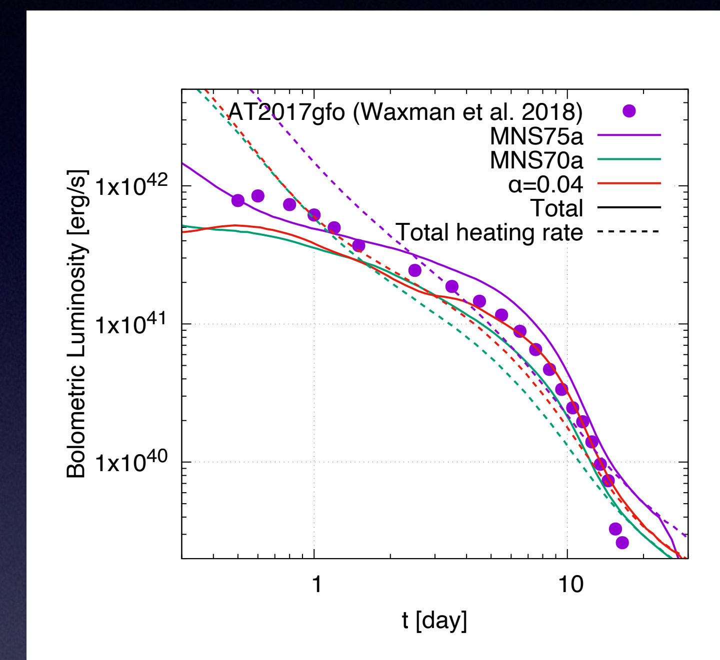
Multi-color RT code:
Tanaka et al, 2013,2014, KK. et. al. 2018, 2021
Opacity Table:
Tanaka et al. 2020, Domoto et al. 2021, 2022
Synchrotron calculation:
Hotokezaka et al. 2018

Comprehensive EM prediction from merger simulations

3D GR-R-HD BNS merger simulation

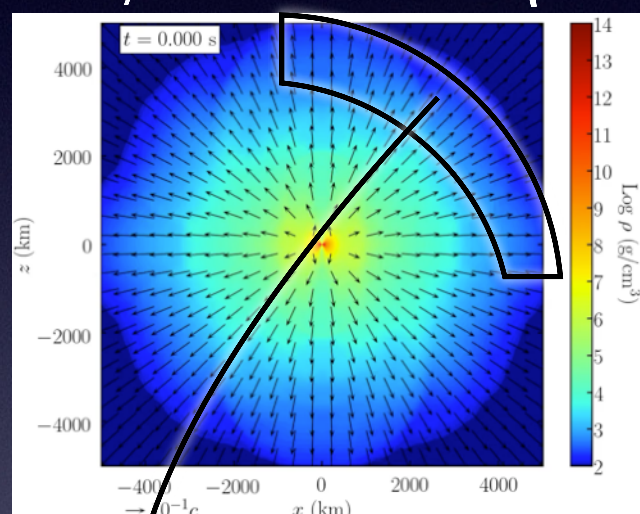
Fujibayashi et al. 2020, 2022
Shibata et al. 2021

Radiative transfer simulation/
Synchrotron emission calculation



Long-term axisymmetric
GR-R-viscous/MHD simulation ***(~1 s-10 s)***

Axisymmetrize



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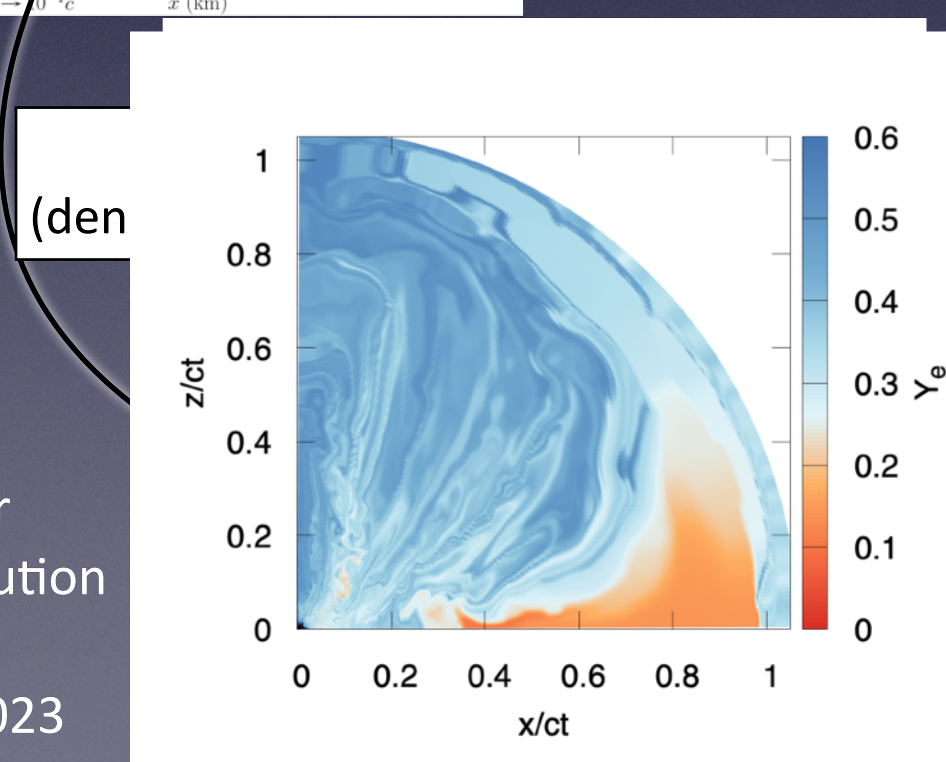

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KK et al. 2021, 2022, 2023

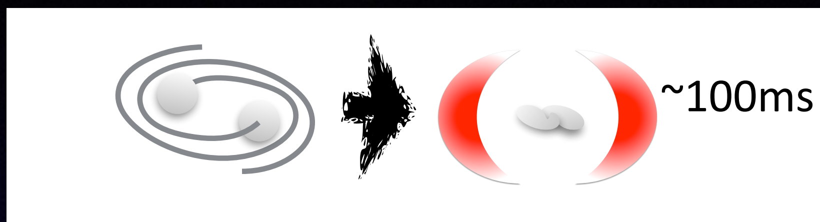
KK et al. 2021, 2022, 2023

EM counterpart prediction

Multi-color RT code:
Tanaka et al, 2013,2014, KK. et. al. 2018, 2021
Opacity Table:
Tanaka et al. 2020, Domoto et al. 2021, 2022
Synchrotron calculation:
Hotokezaka et al. 2018

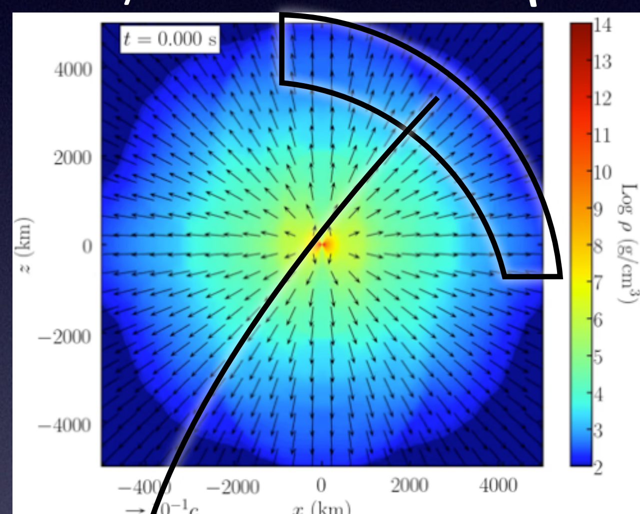
Comprehensive EM prediction from merger simulations

3D GR-R-HD BNS merger simulation



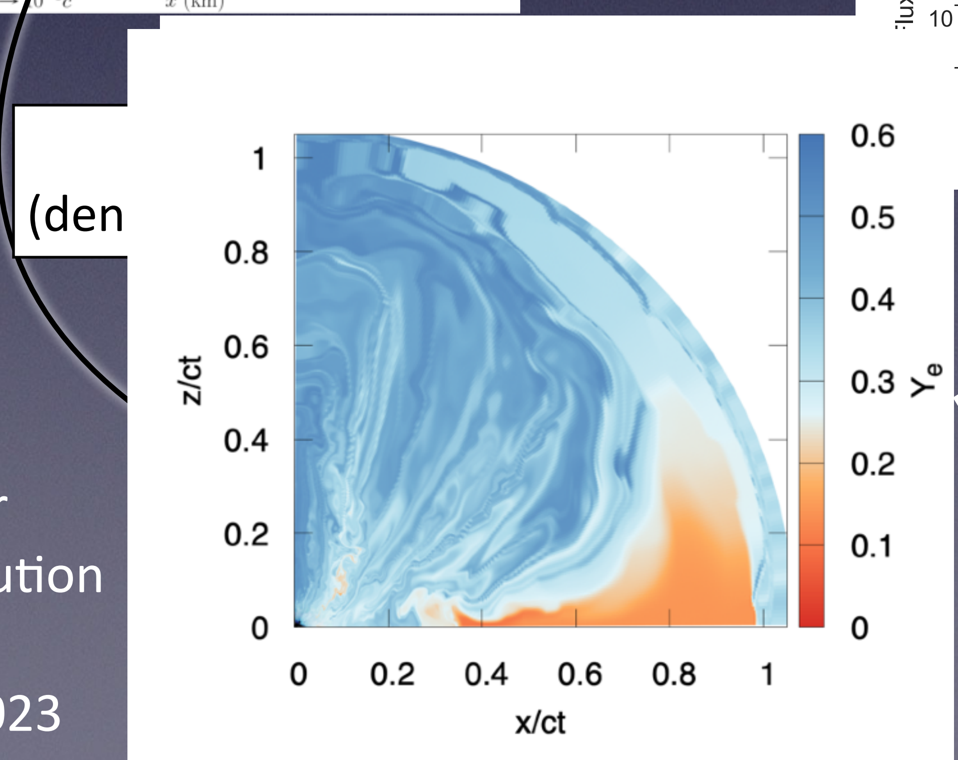
Fujibayashi et al. 2020, 2022
Shibata et al. 2021

Long-term axisymmetric
GR-R-viscous/MHD simulation ***(~1 s-10 s)***



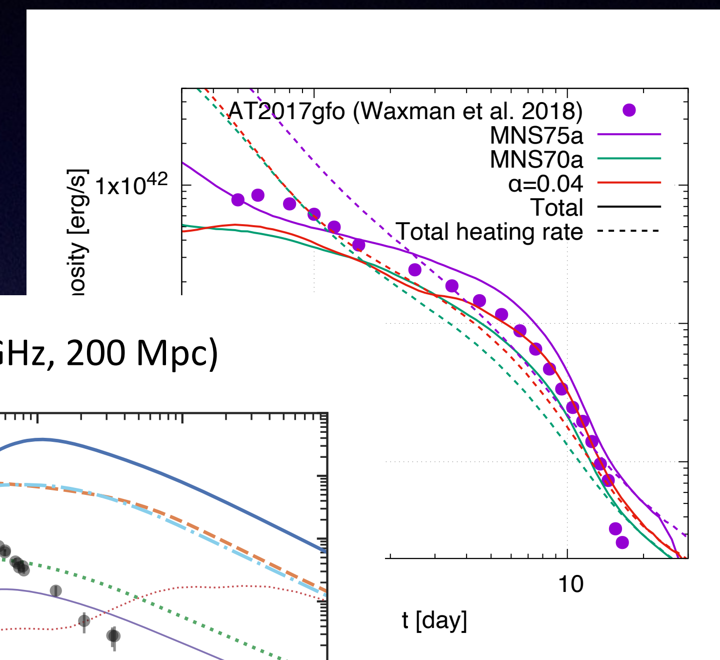
Axisymmetrize

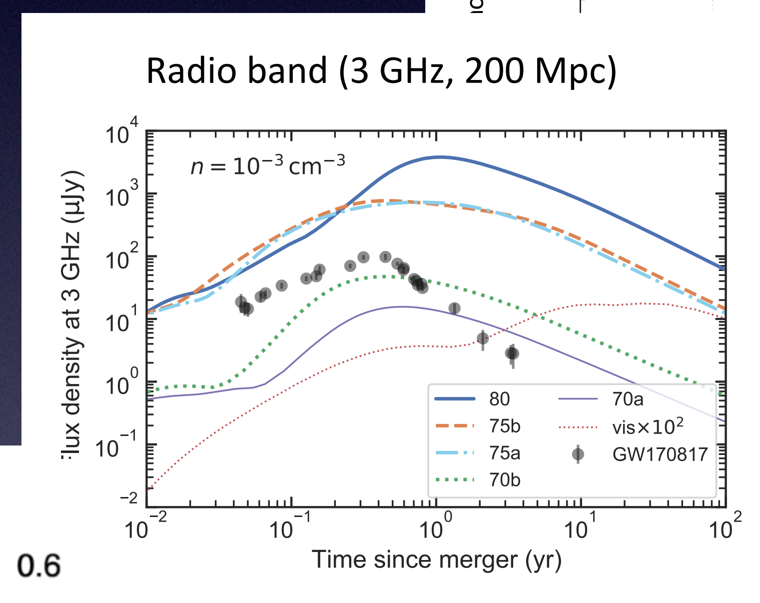
Extract ejecta component



GR-HD simulation for
the longterm ejecta evolution
(~0.1 d)
KK et al. 2021, 2022, 2023

Radiative transfer simulation/
Synchrotron emission calculation





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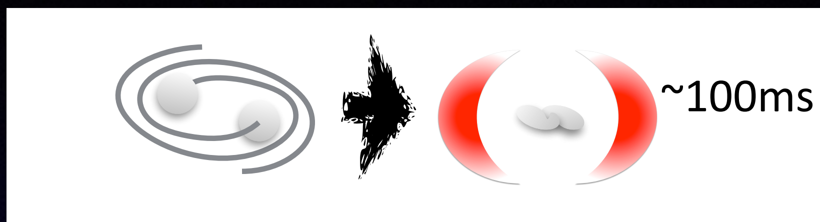

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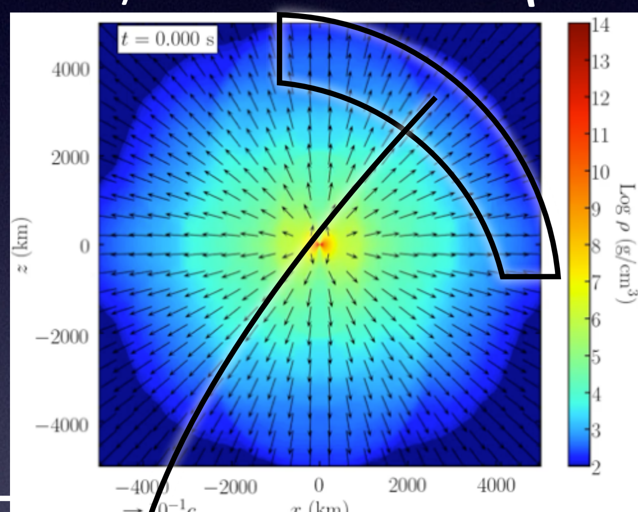
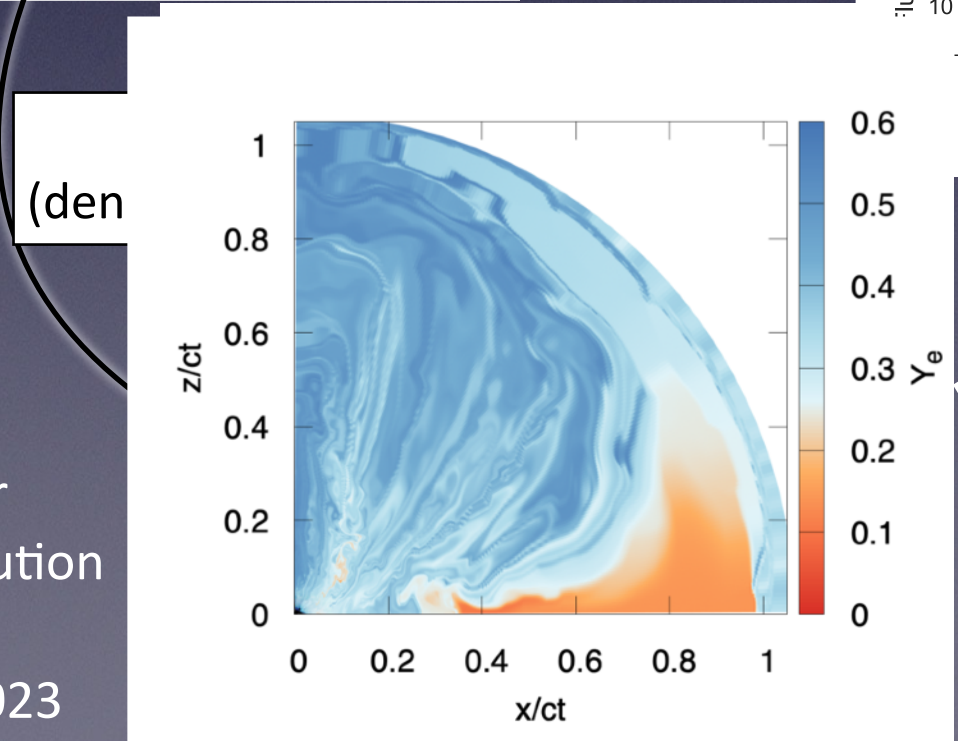


Extract ejecta component



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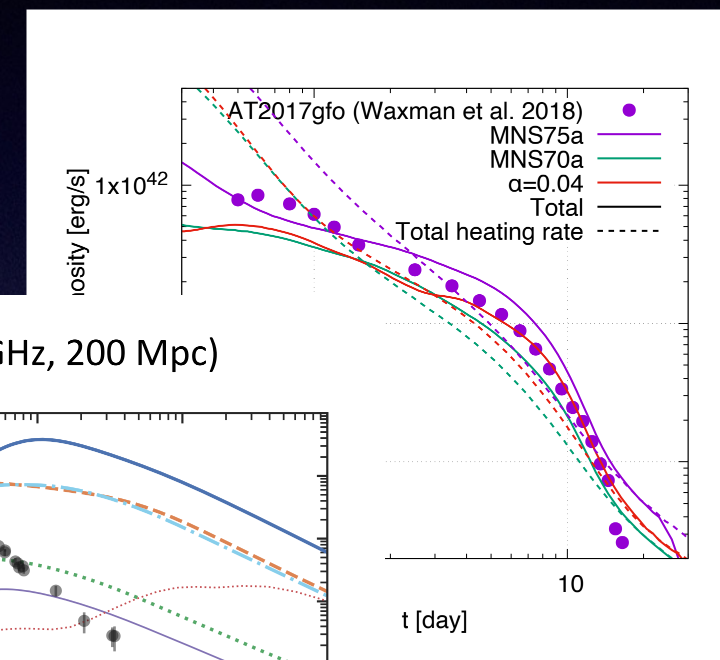

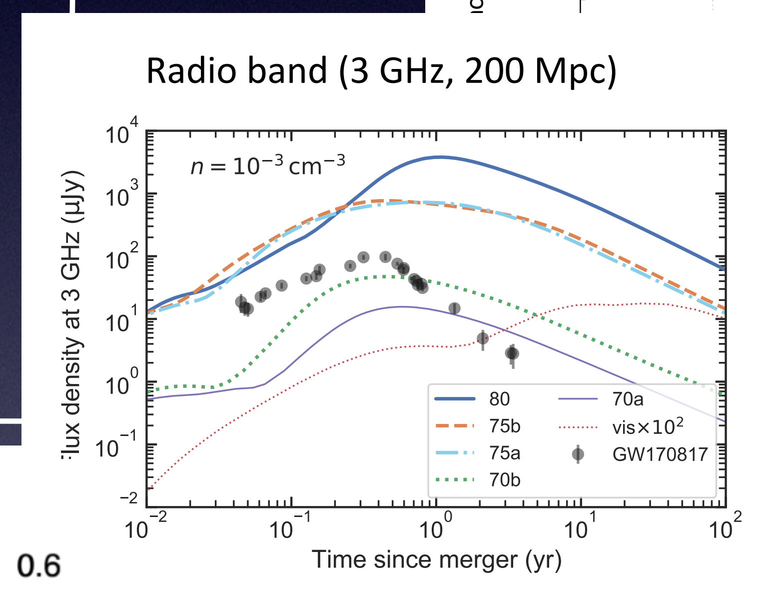

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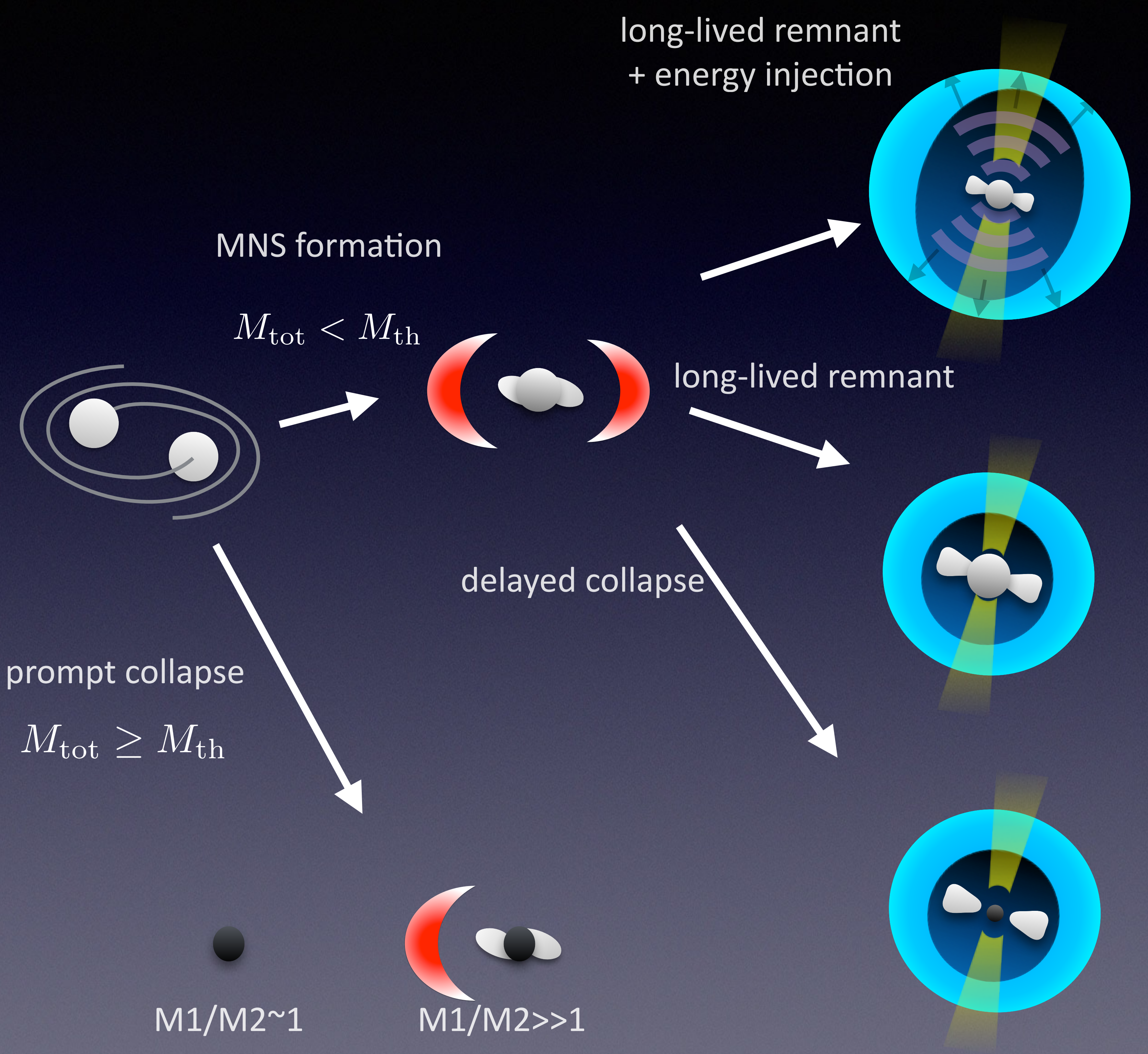
Models: Various BNS cases with different fates



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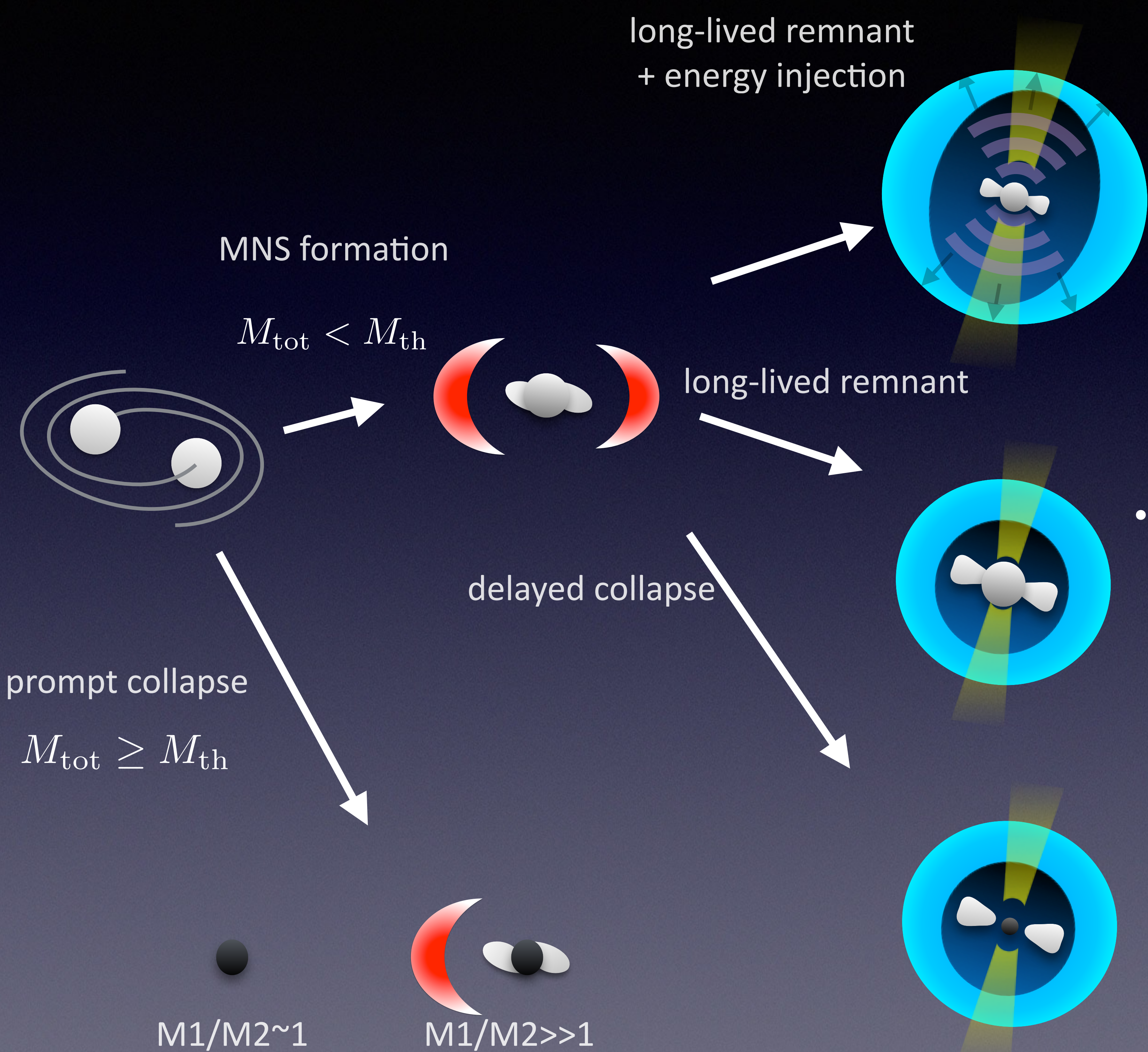

- **Long-lived remnant (>>1s) cases**

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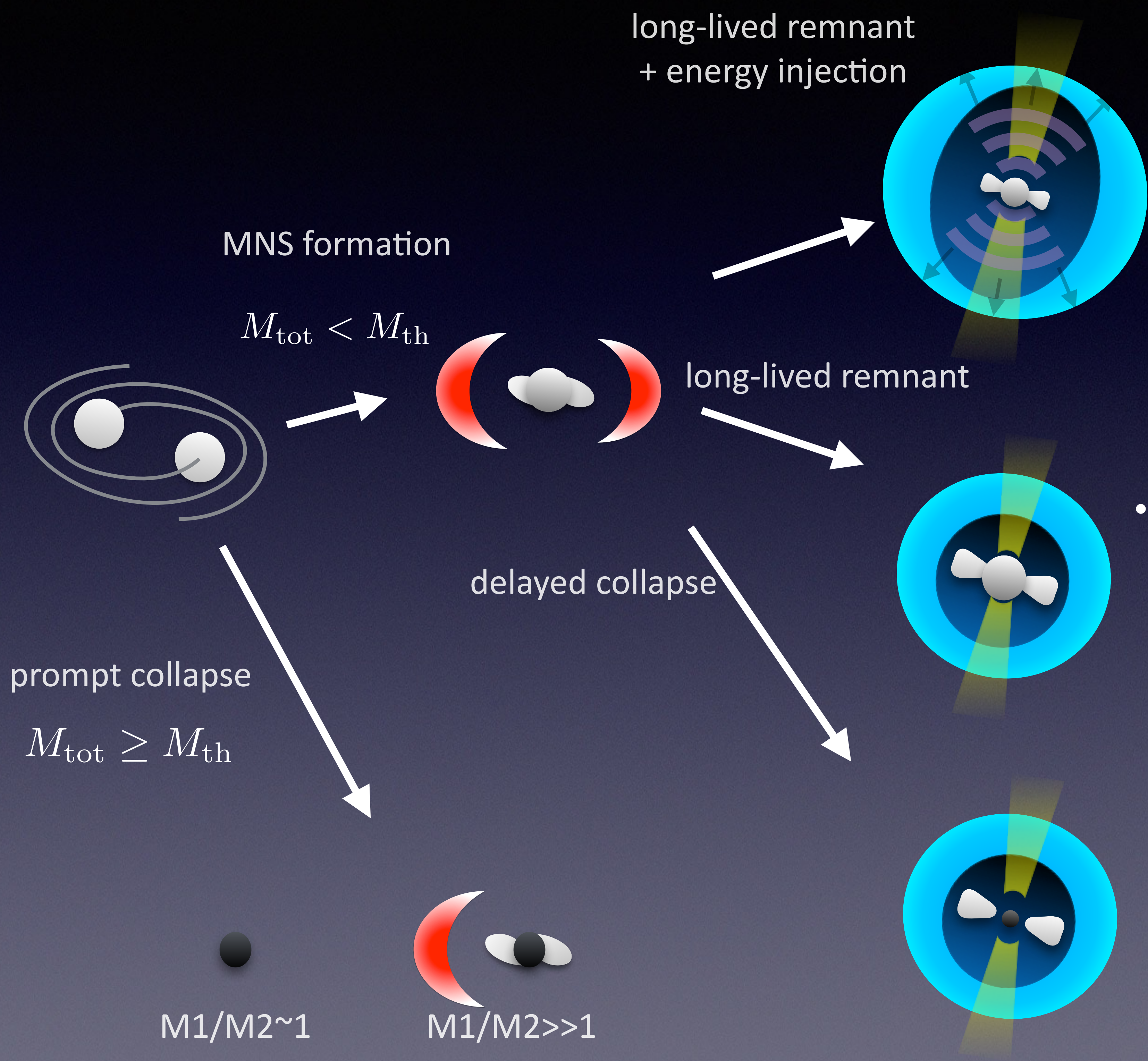

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  (S. Fujibayashi et al. 2020, KK. et al. 2021)
  1.25 Msun-1.25 Msun,
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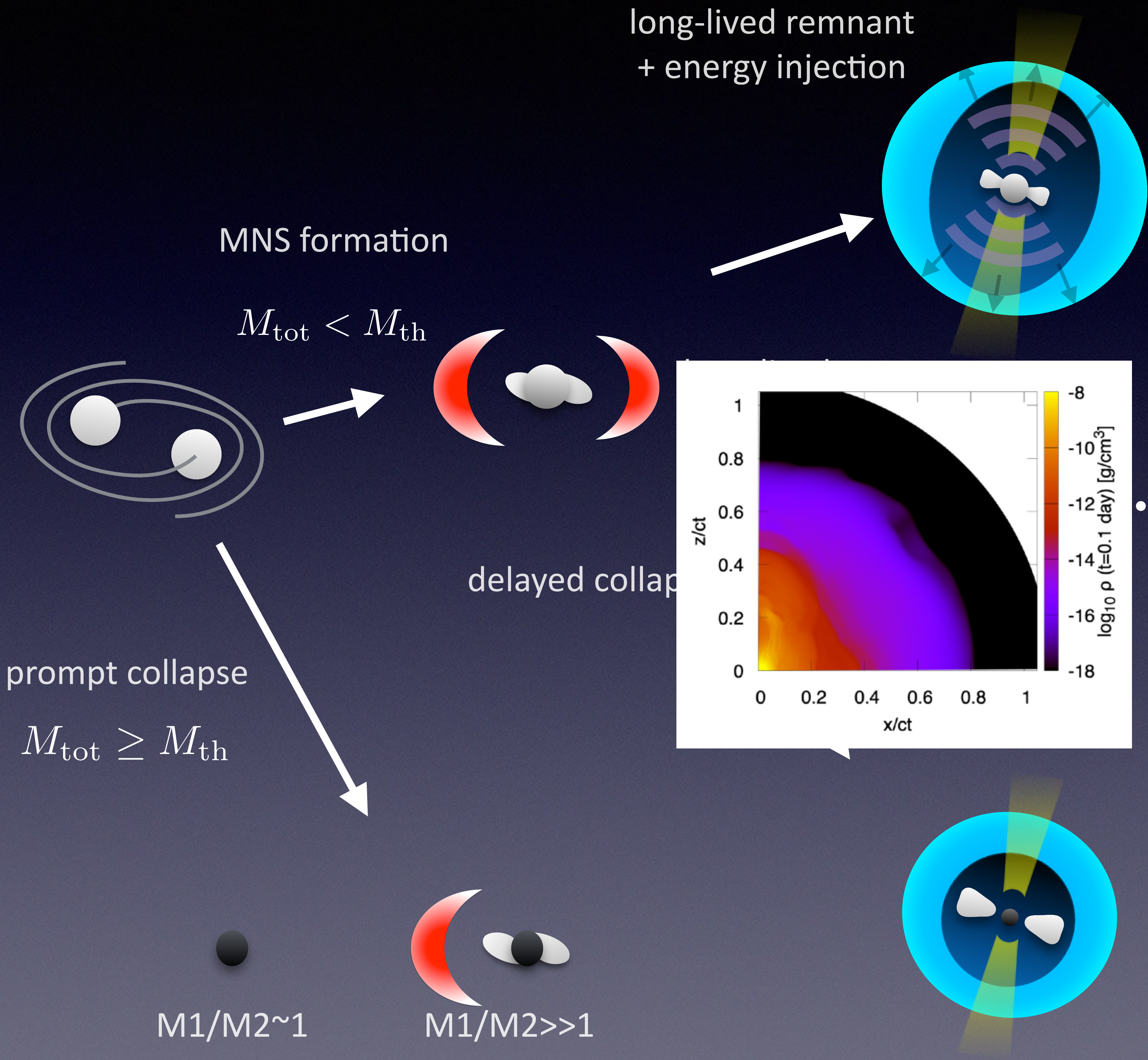

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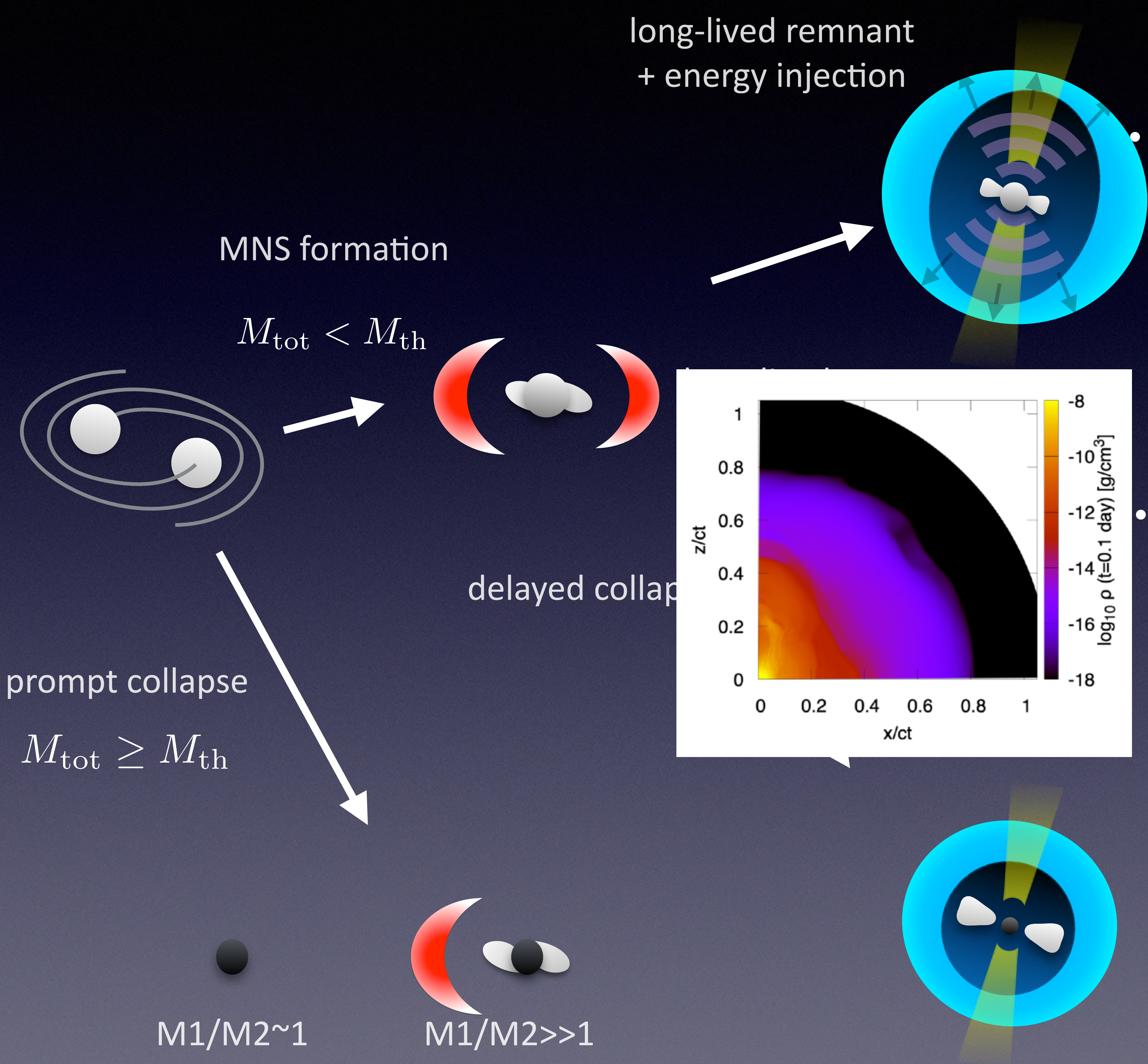

- **Long-lived remnant (>>1s) cases with strong magnetic dynamo effects**

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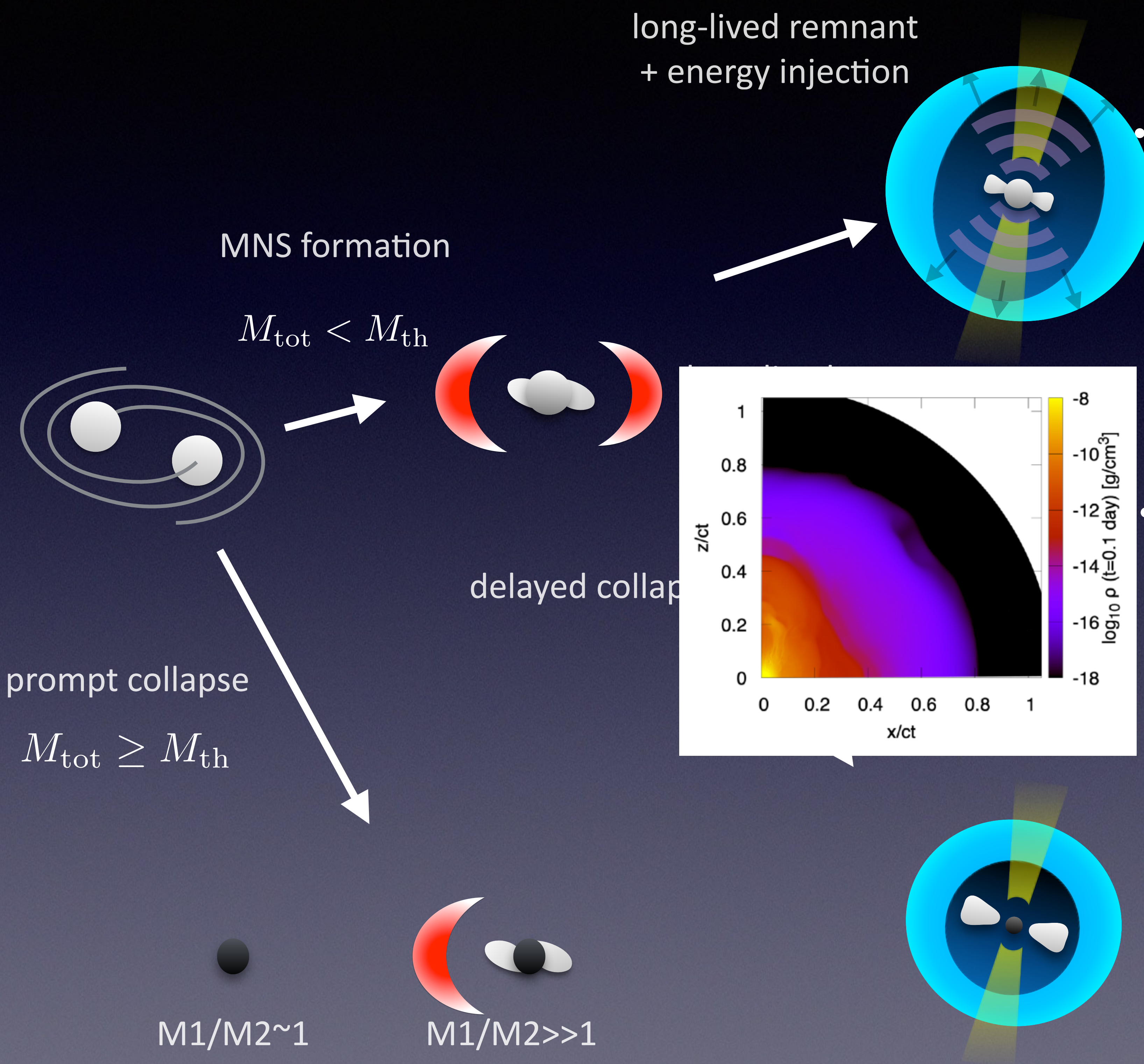

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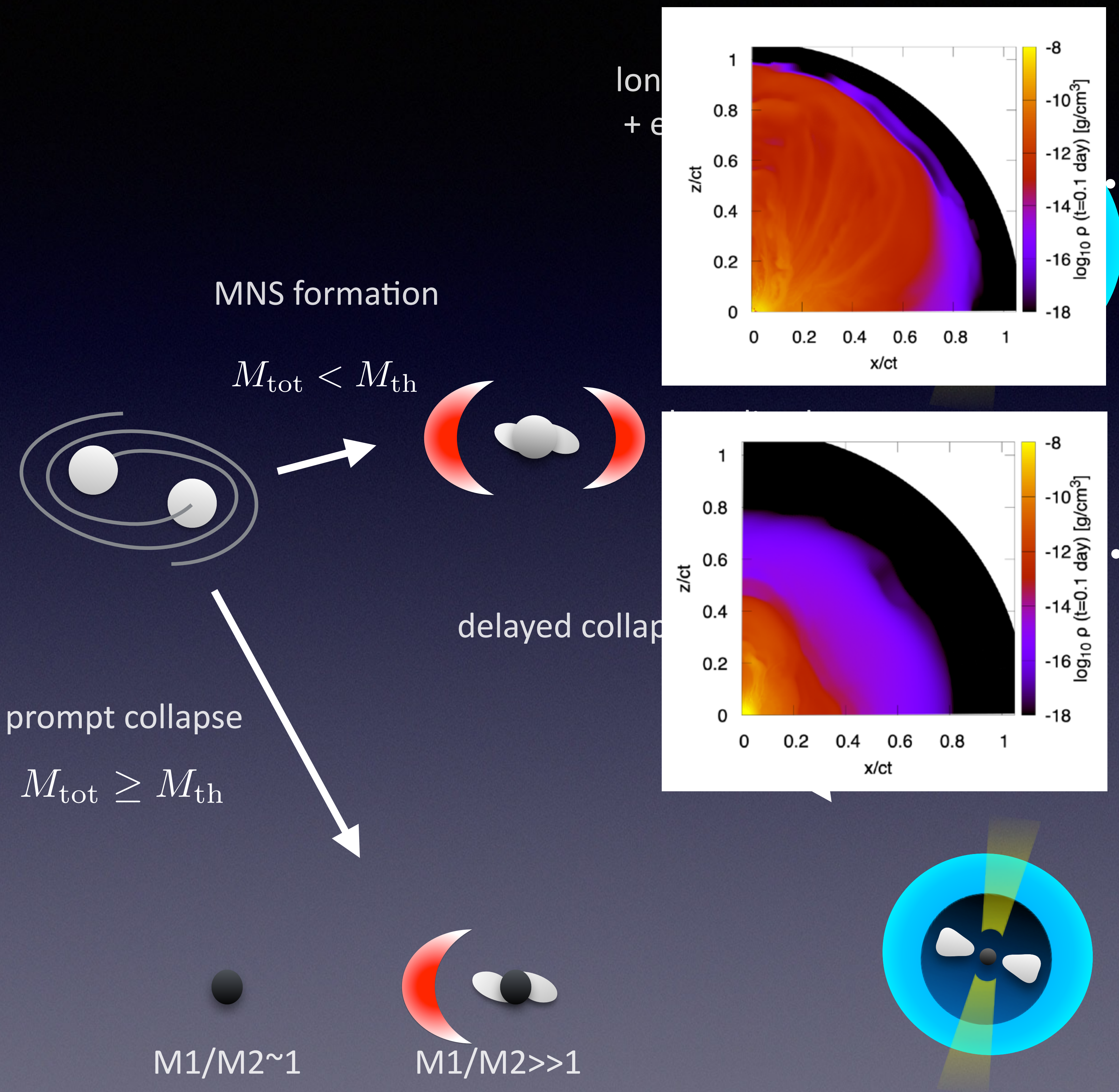

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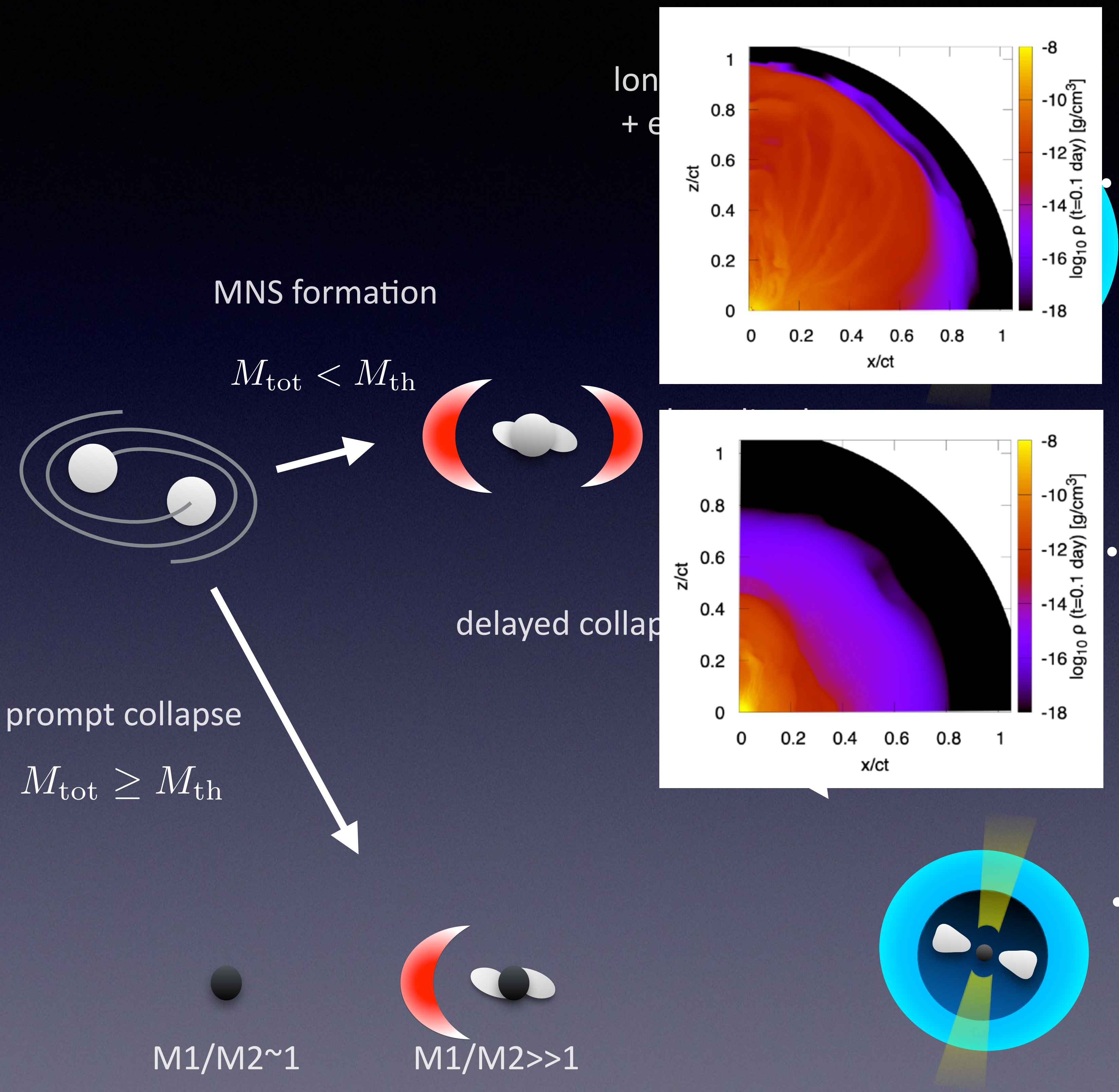

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- **Short-lived remnant (<20 ms) cases**

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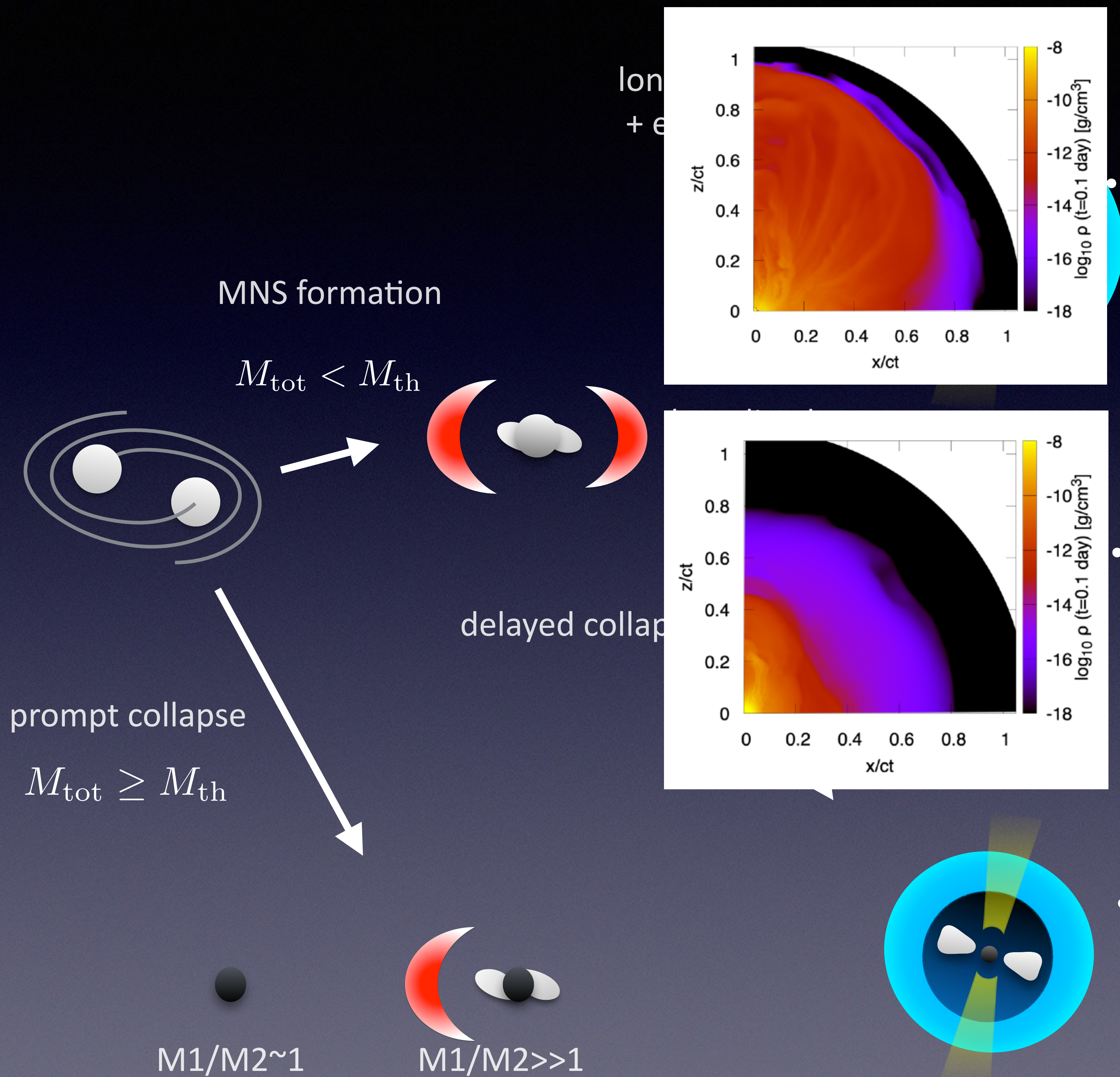

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  Mtot = 2.7 Msun, 2.8 Msun,
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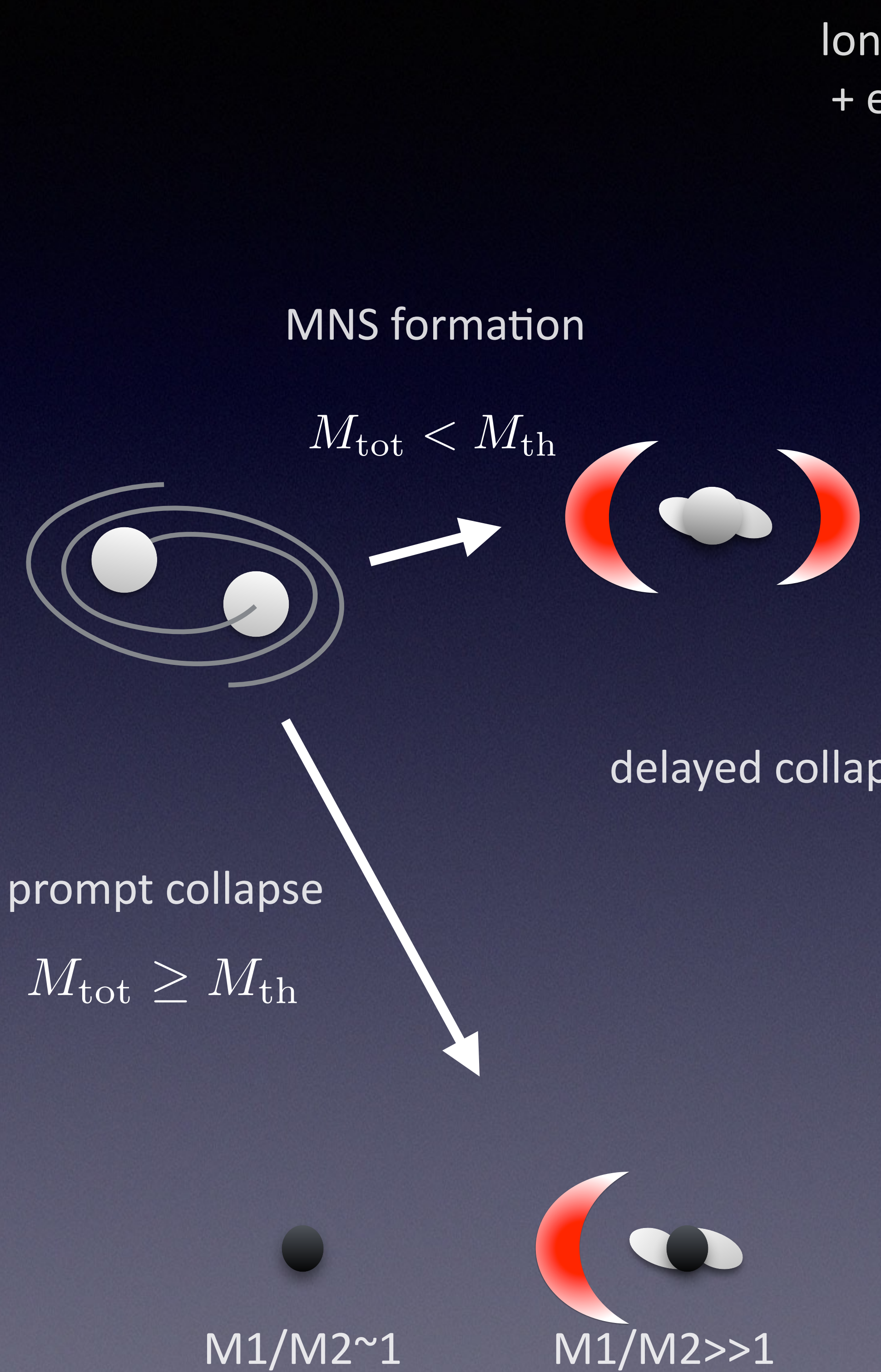
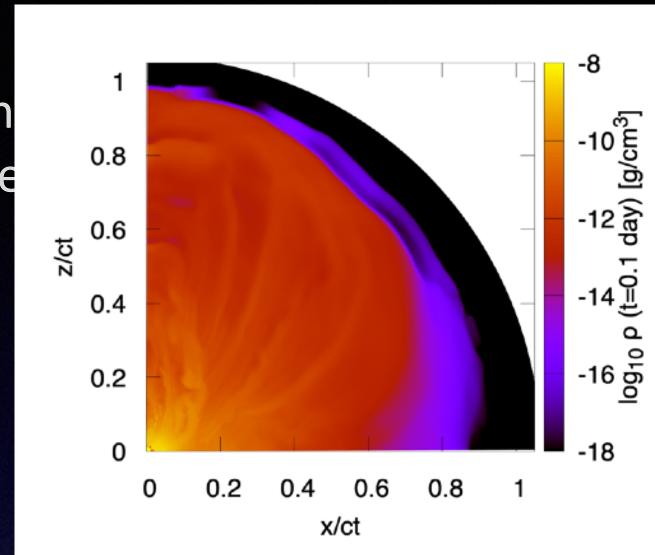
  SFHo EOS (11.9 km@1.35 Msun)

Models: Various BNS cases with different fates





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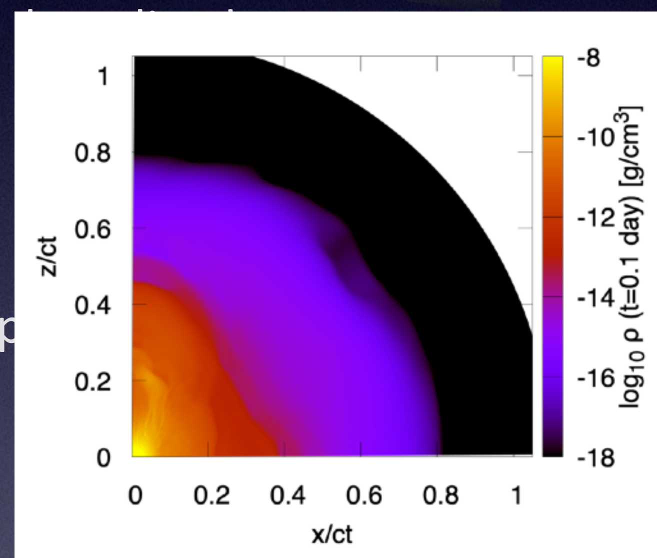

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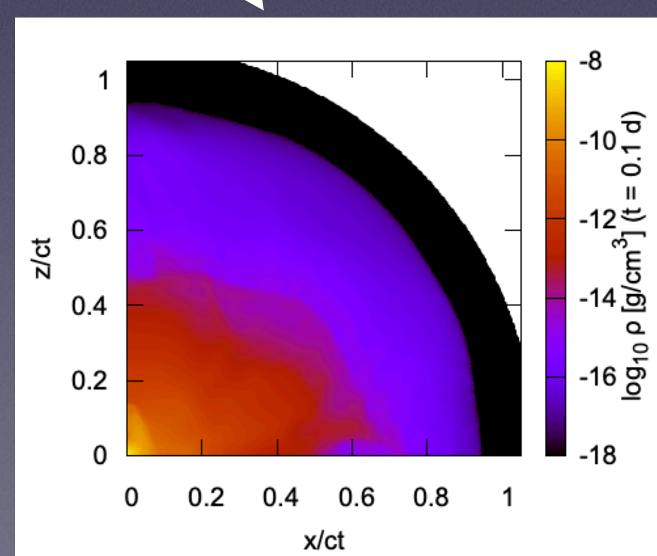

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AT2017gfo (GW170817)

Solid: Long-lived (>>1s) MNS

$$M_{\rm eje,tot} = 0.08 M_{\odot}$$

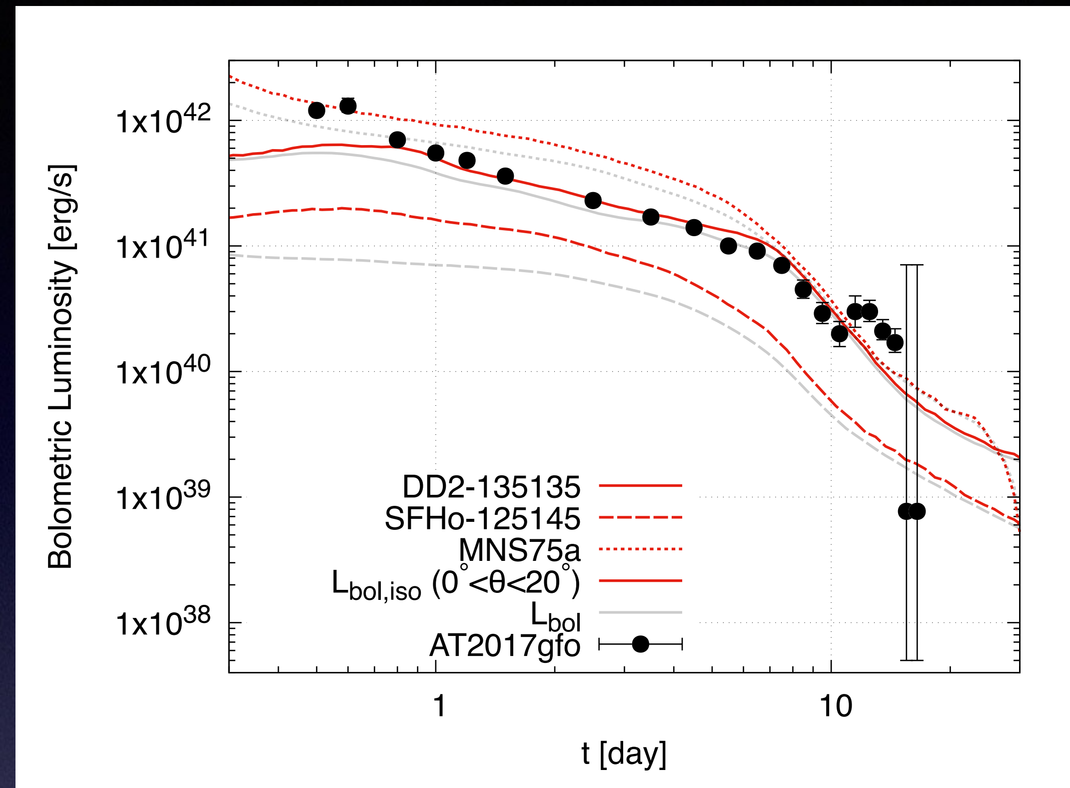
Dashed: Short-lived (<20ms) MNS

$$M_{\rm eje,tot} = 0.01 M_{\odot}$$

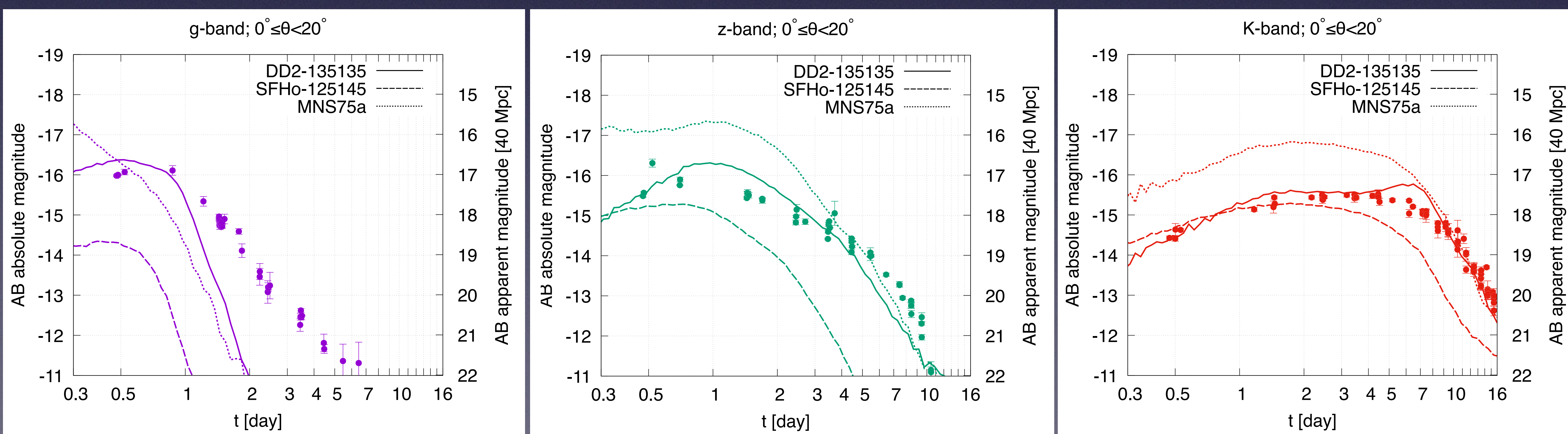
Dotted: Long-lived MNS
with significant magnetic dynamo

$$M_{\rm eje,tot} = 0.09 M_{\odot}$$

Data: Waxman et al. 2018



Data: Villar et al. 2017



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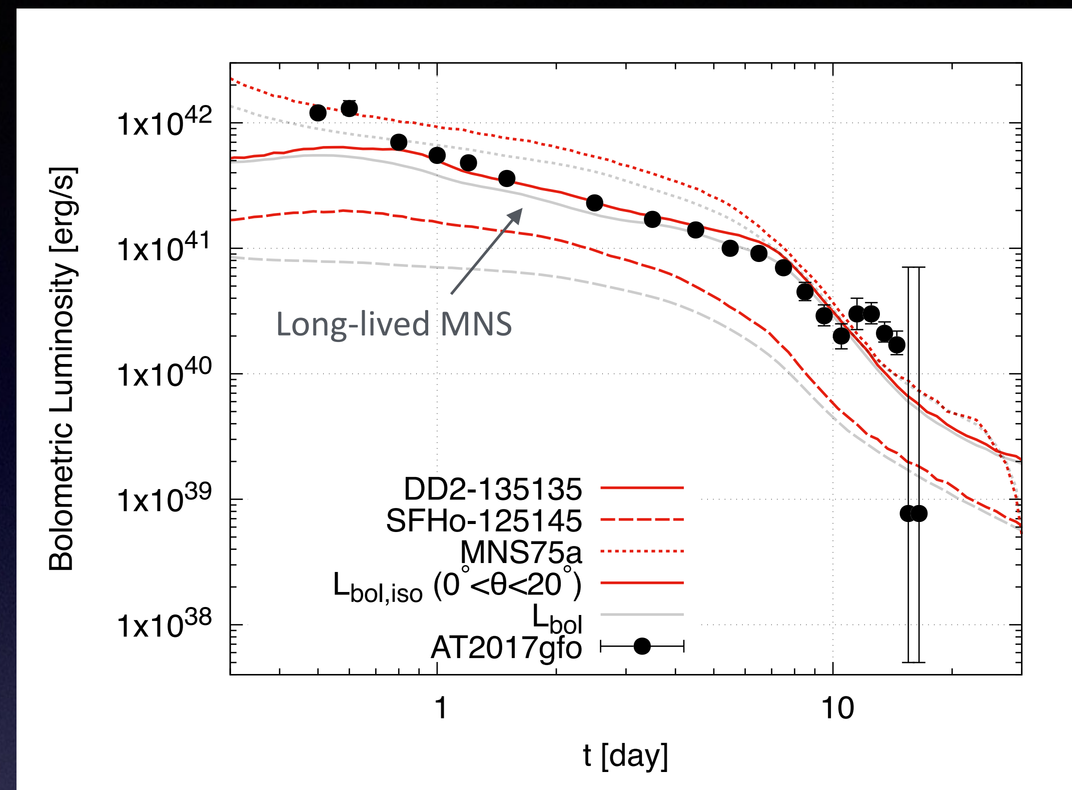

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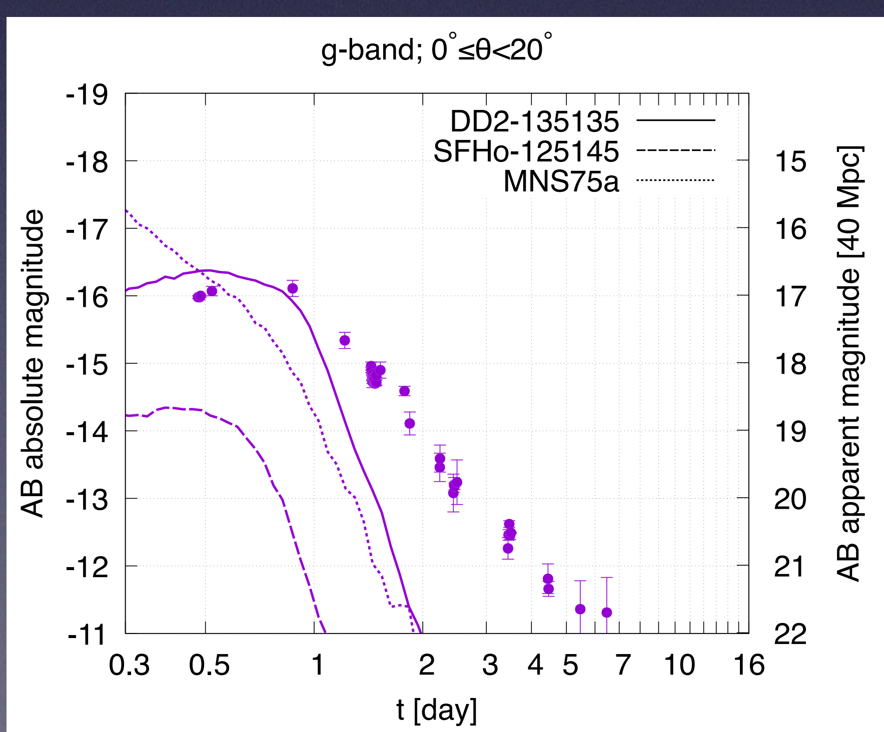

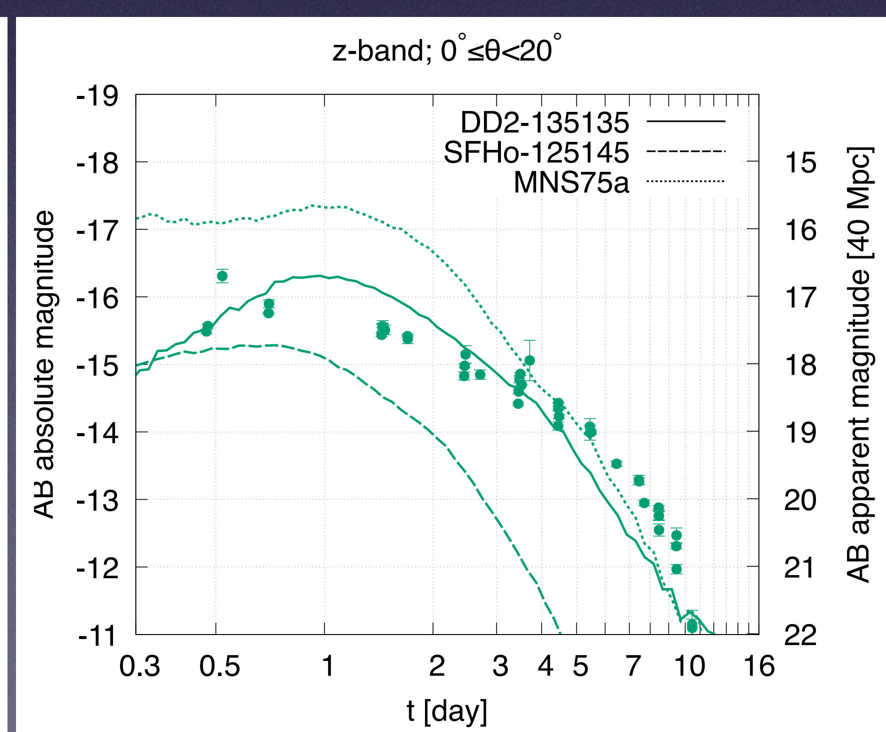

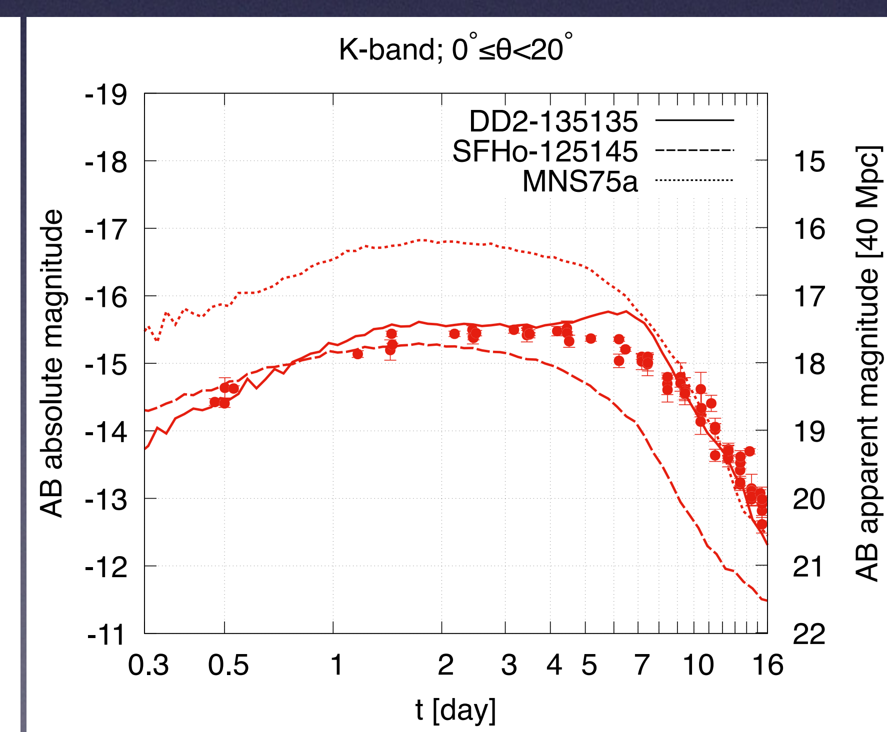

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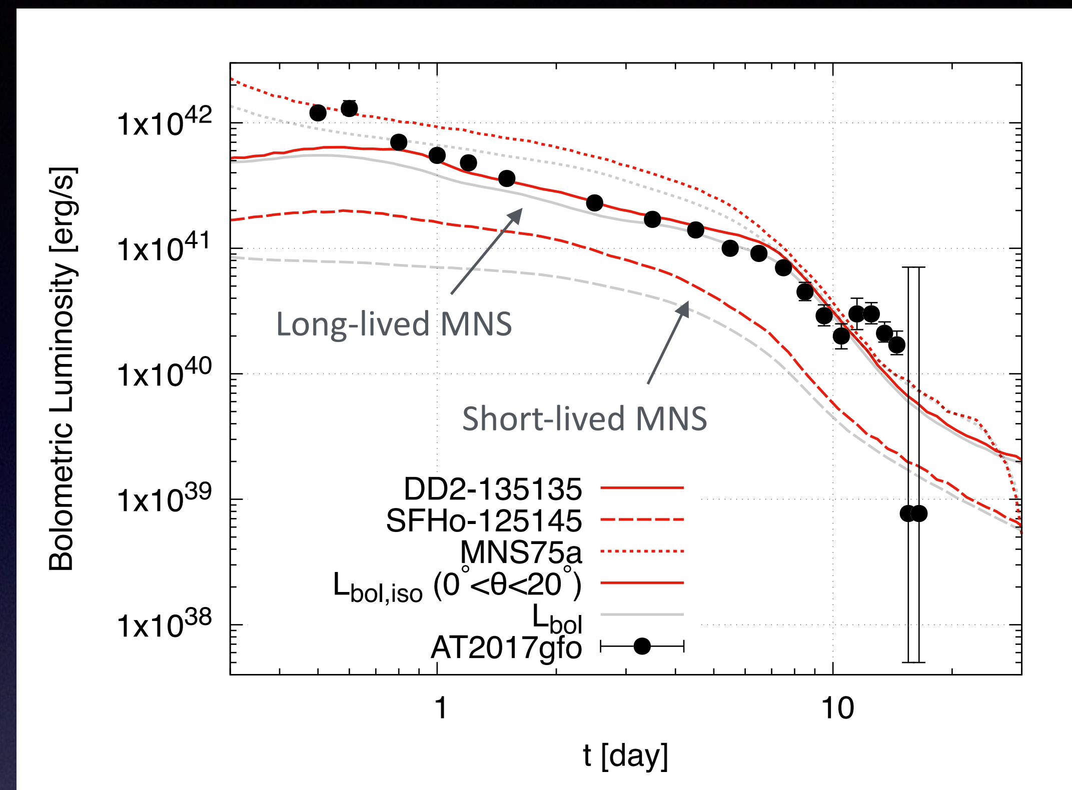

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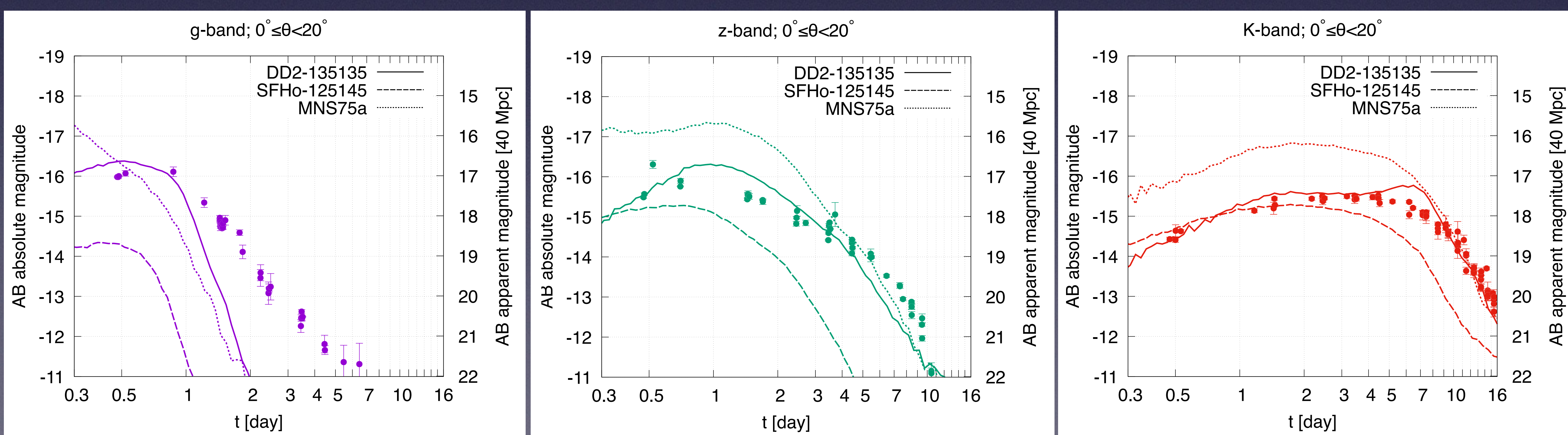

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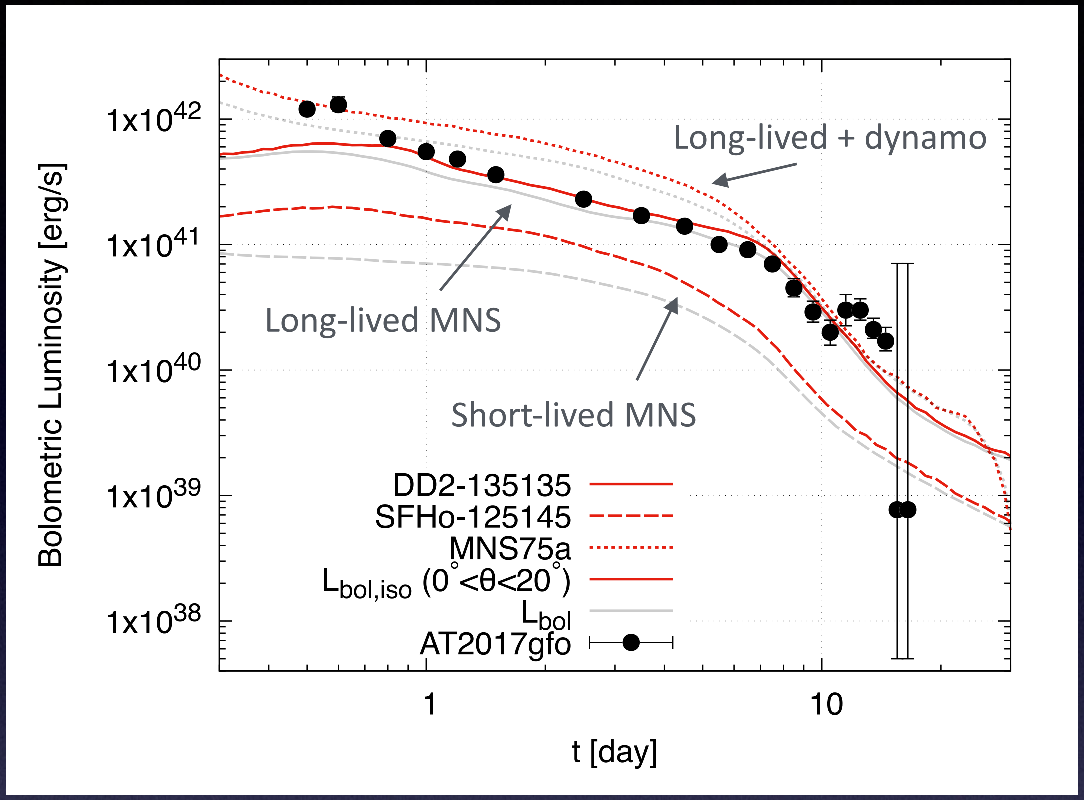

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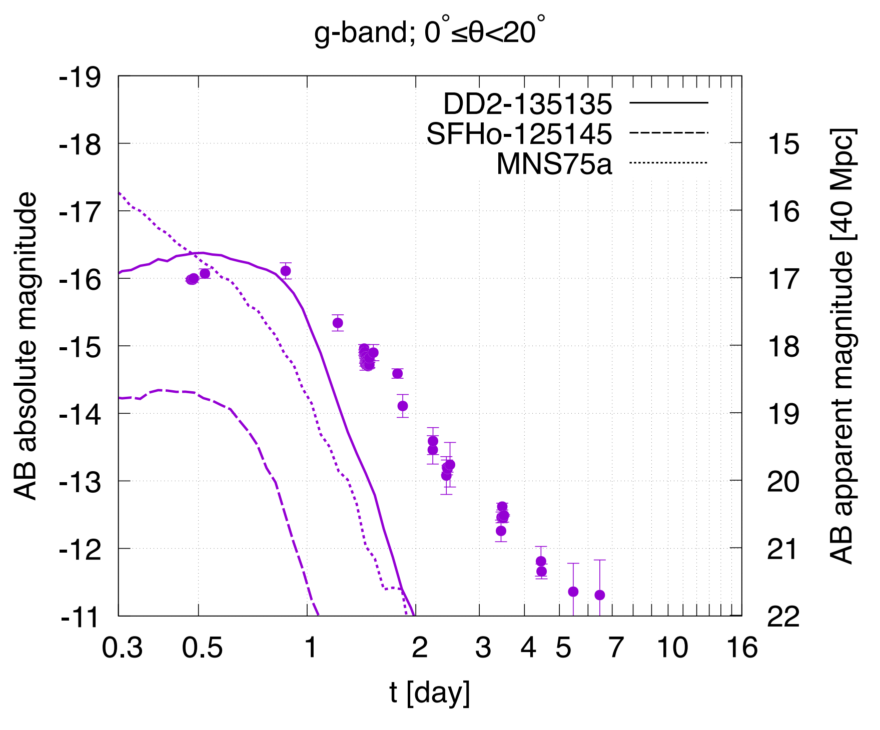

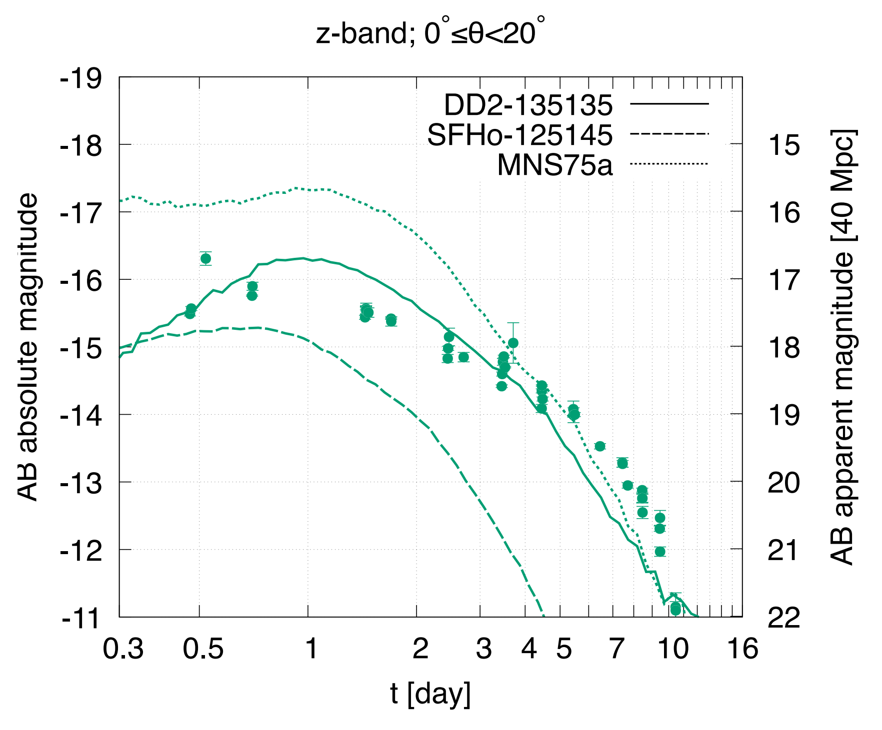

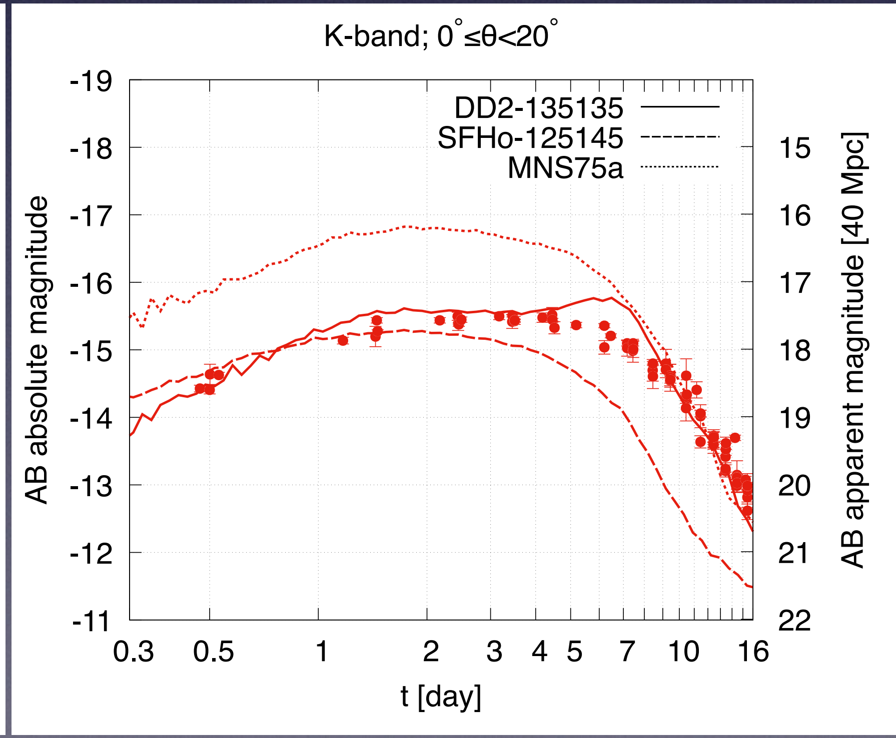

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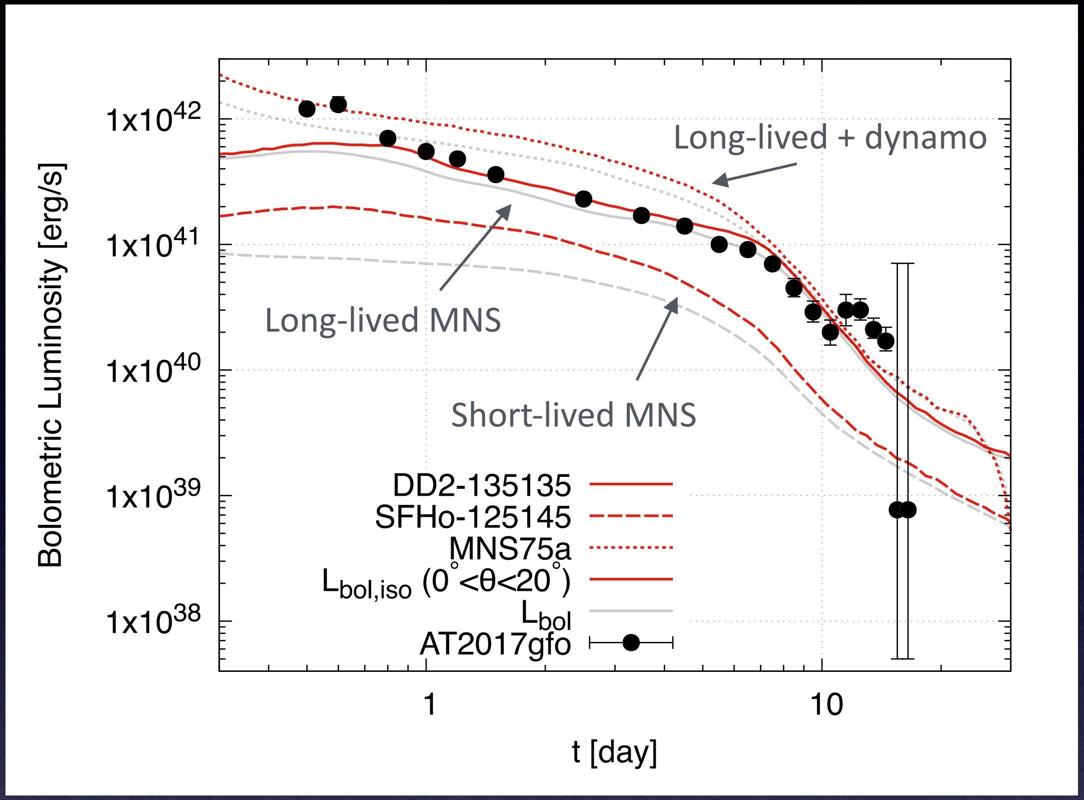

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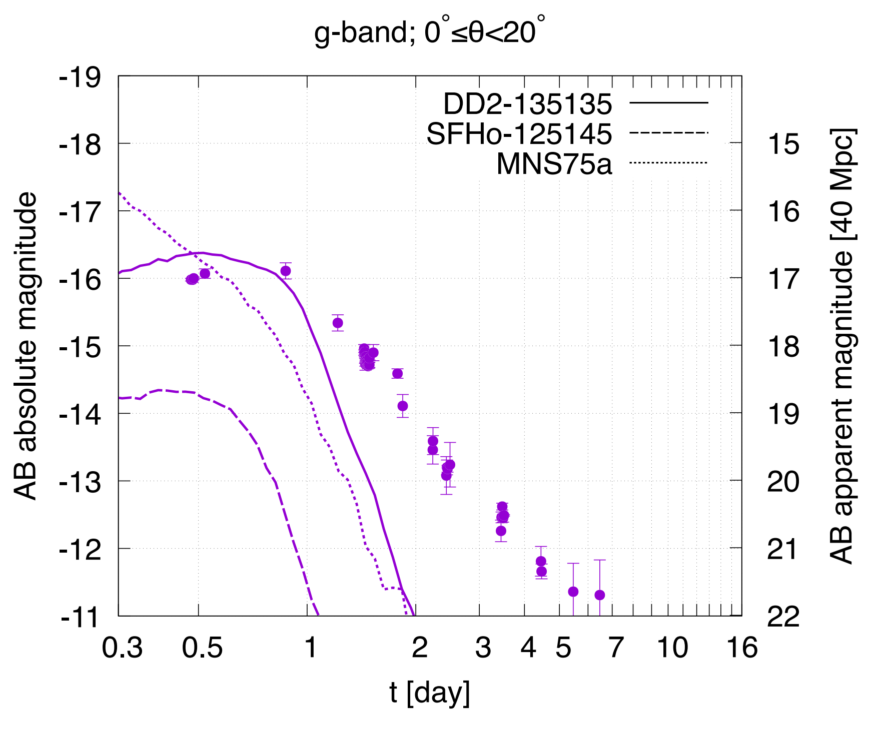
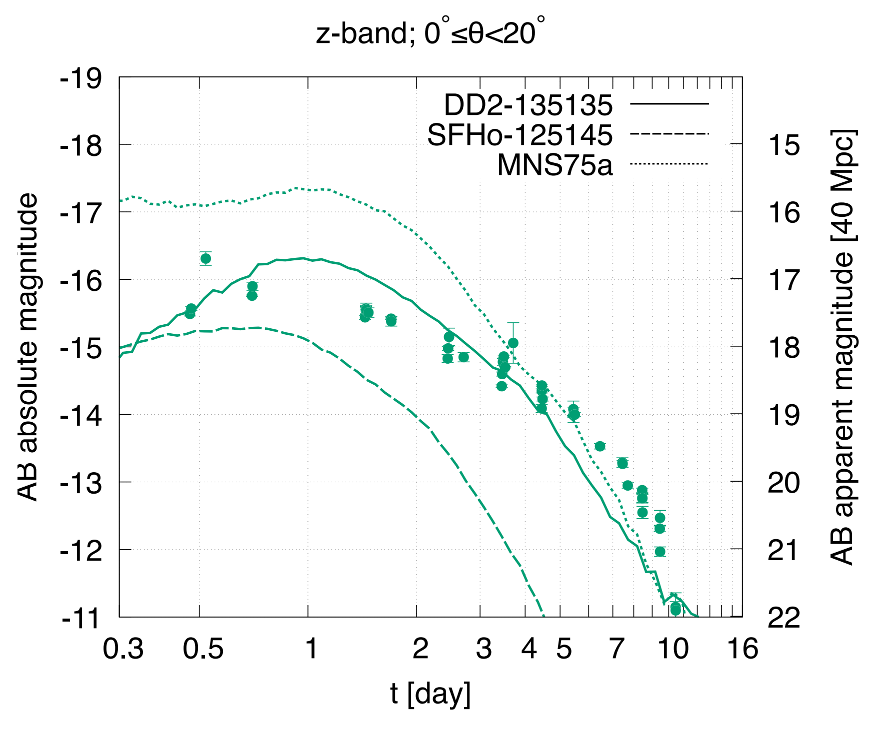
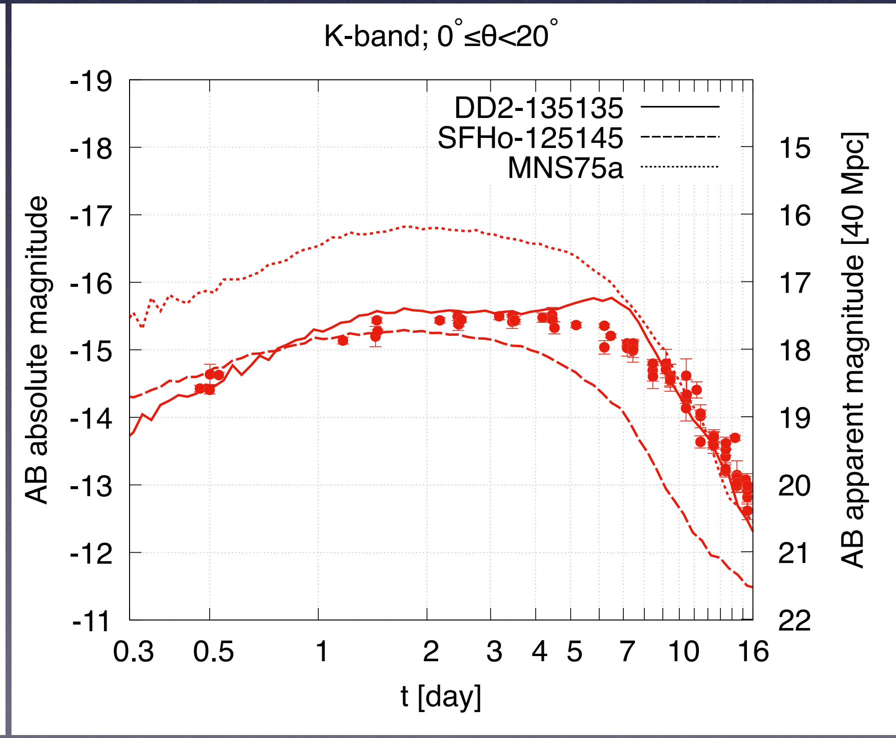
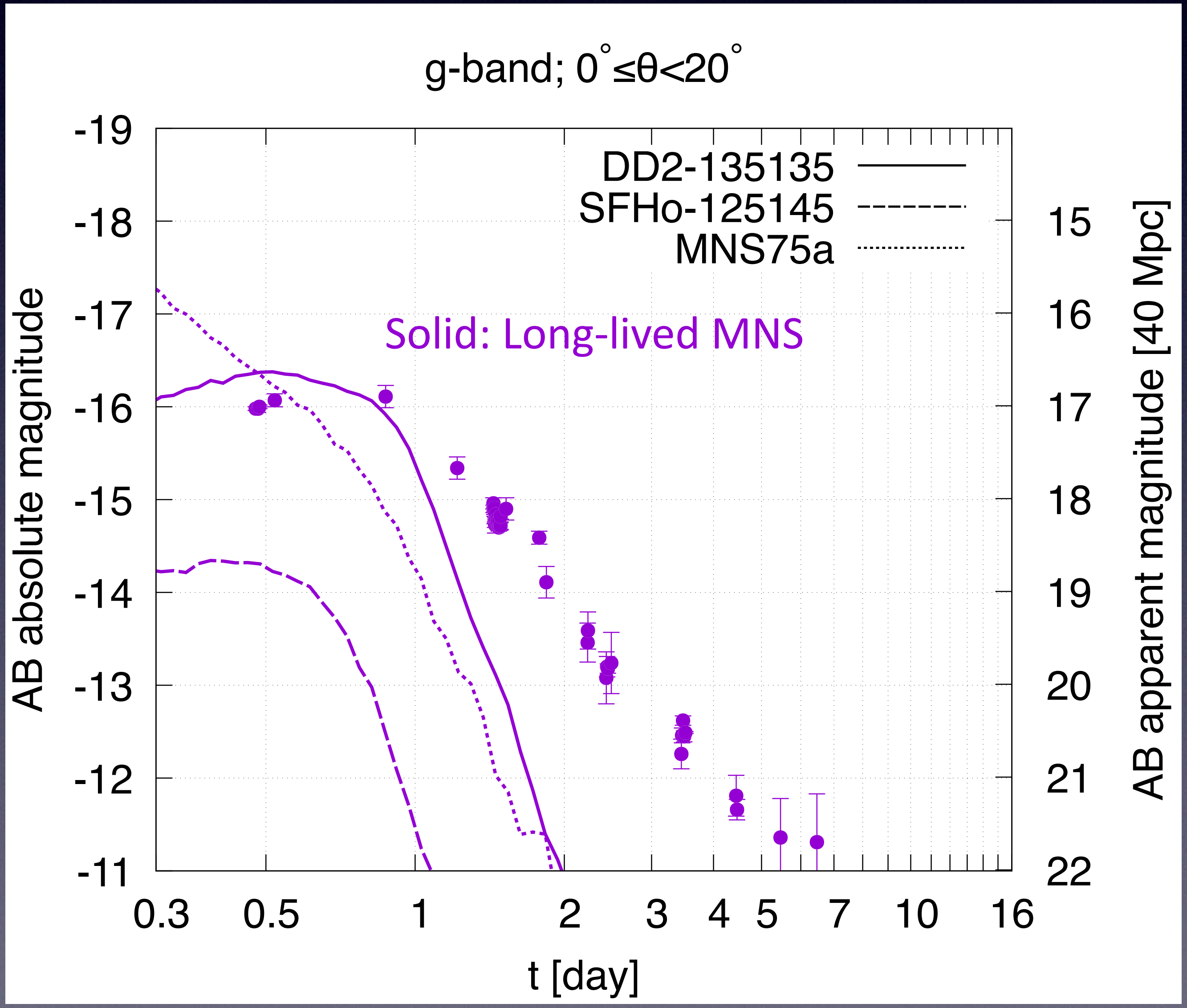






A BNS with a formation of a MNS survives for >0.1 s is likely to be consistent as the progenitor of AT2017gfo (but may be not too long if significant magnetic dynamo effects)

Late optical emission: non-LTE effect?



KK et al. 2021,2022

see Hotokezaka et al. 2020, Pognan et al. 2021,2022 for the study of non-LTE property and J. Barnes et al. 2021 for the impact of heating rate uncertainty to the ionization structure

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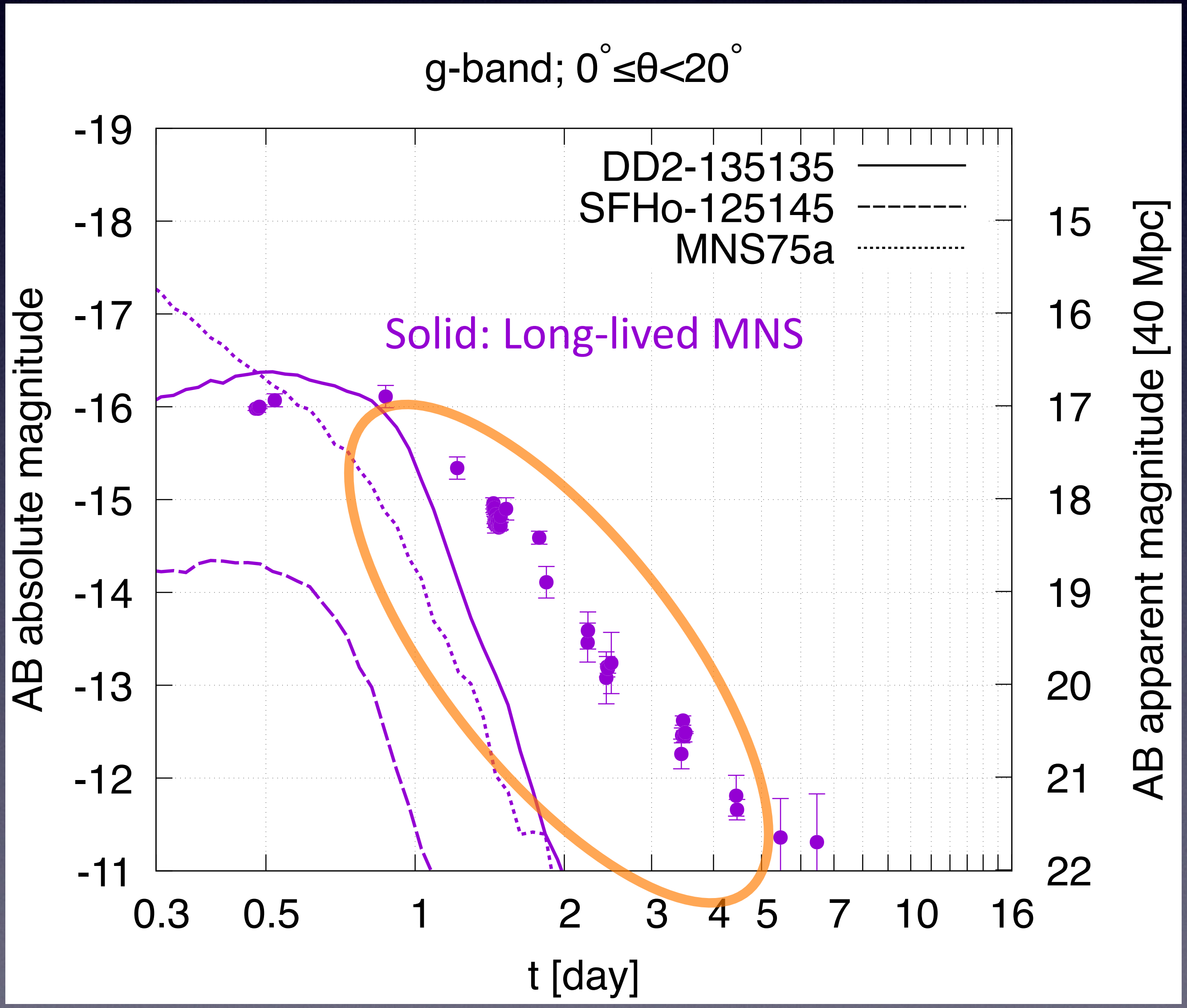

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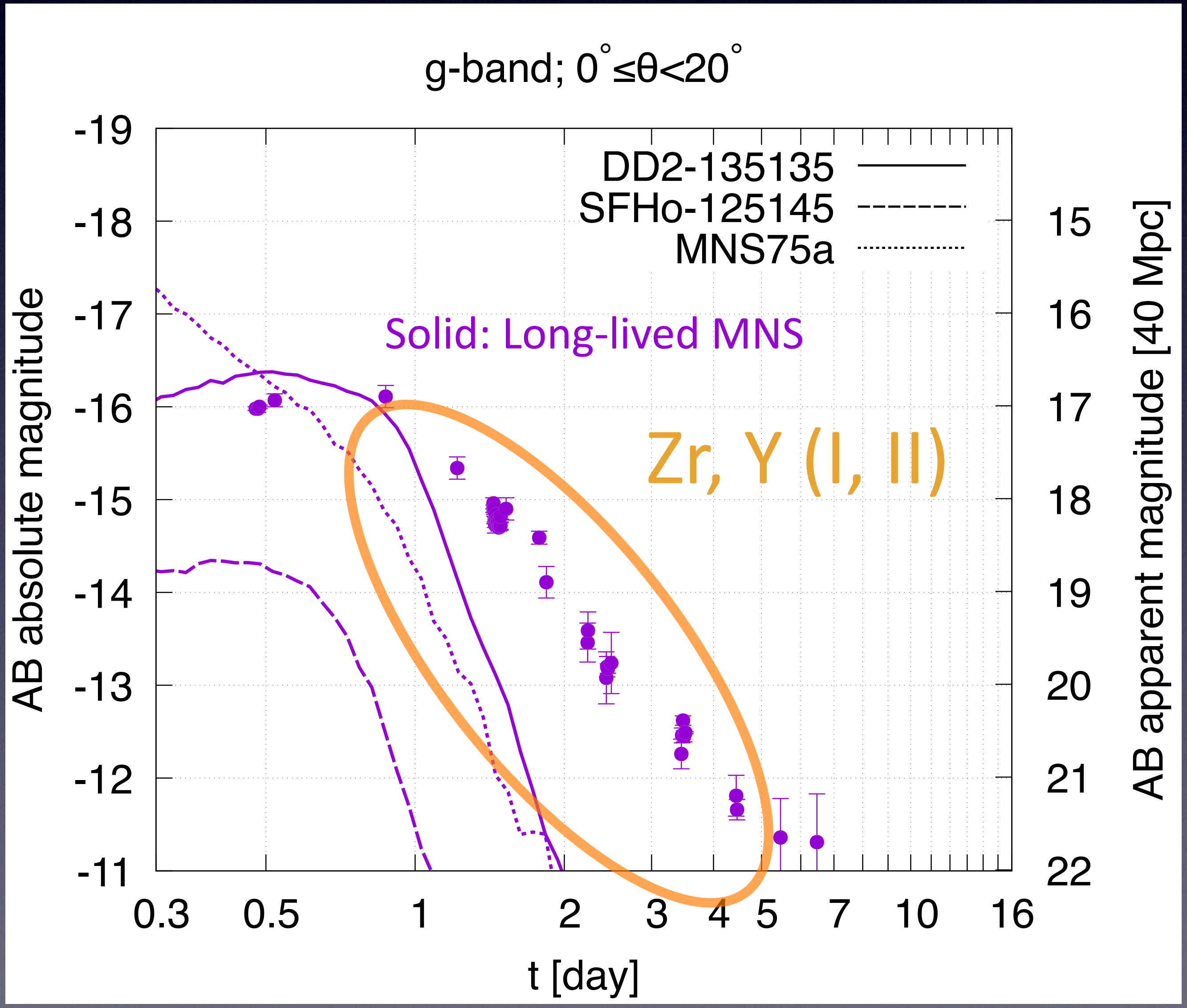

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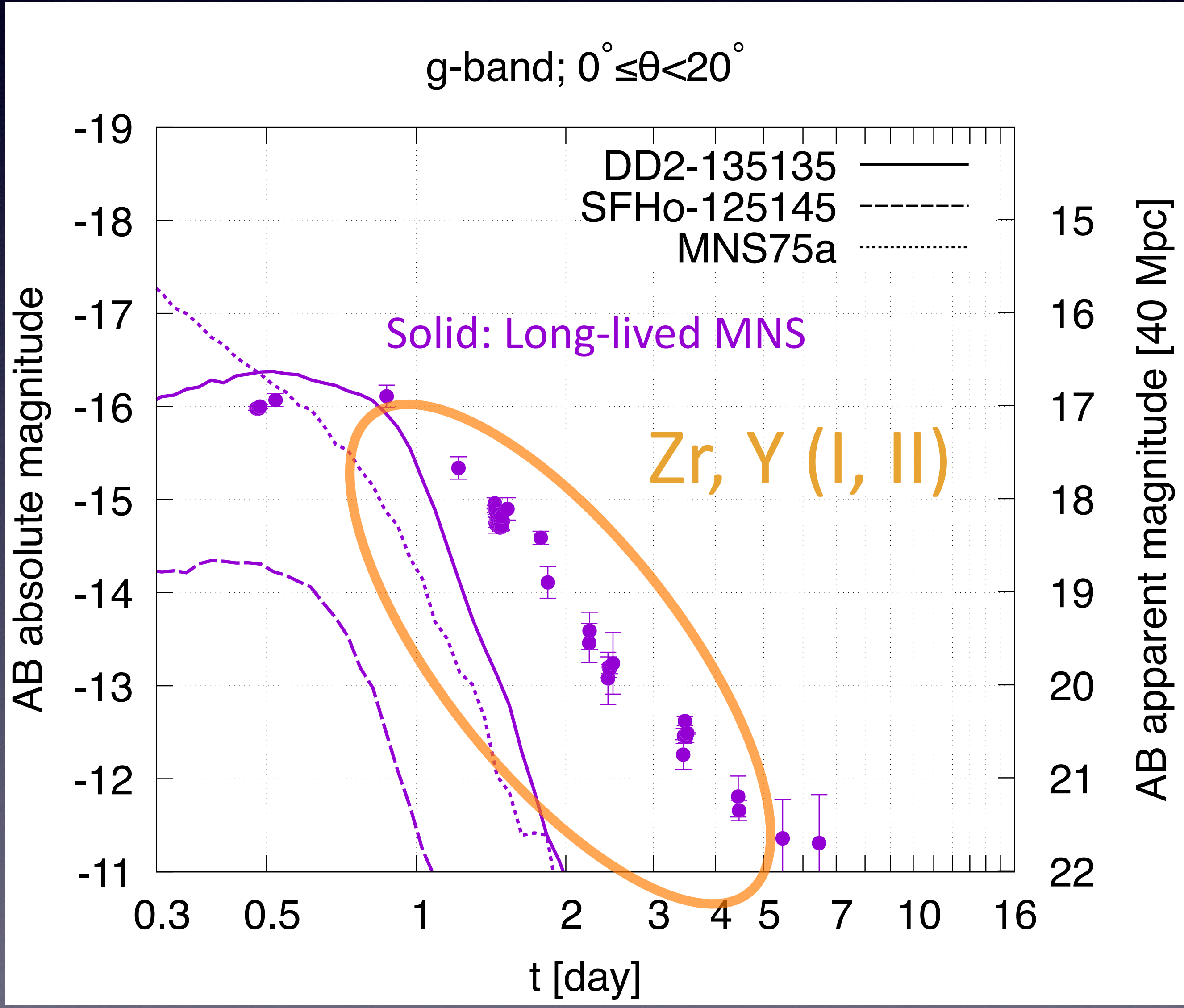

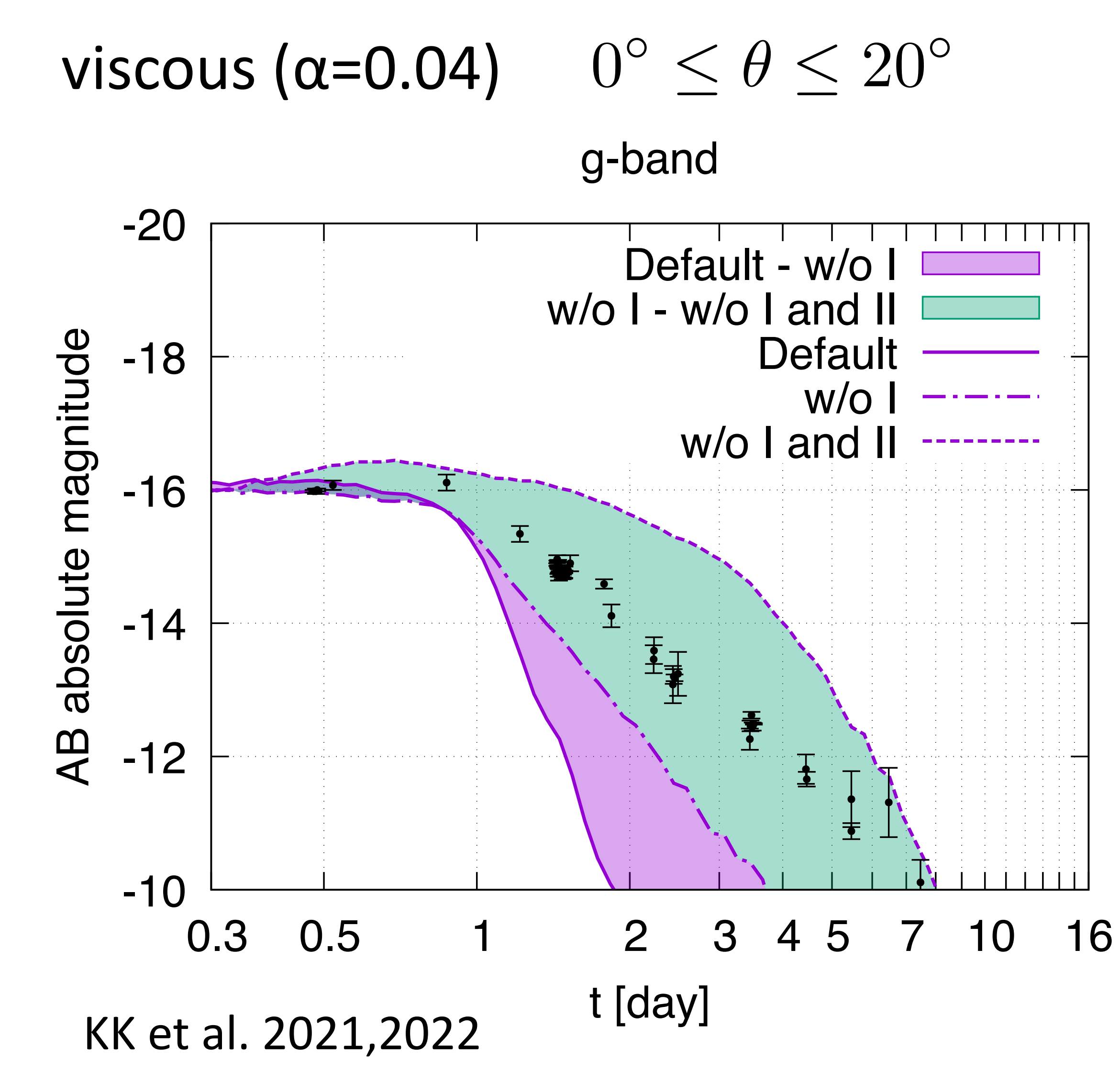

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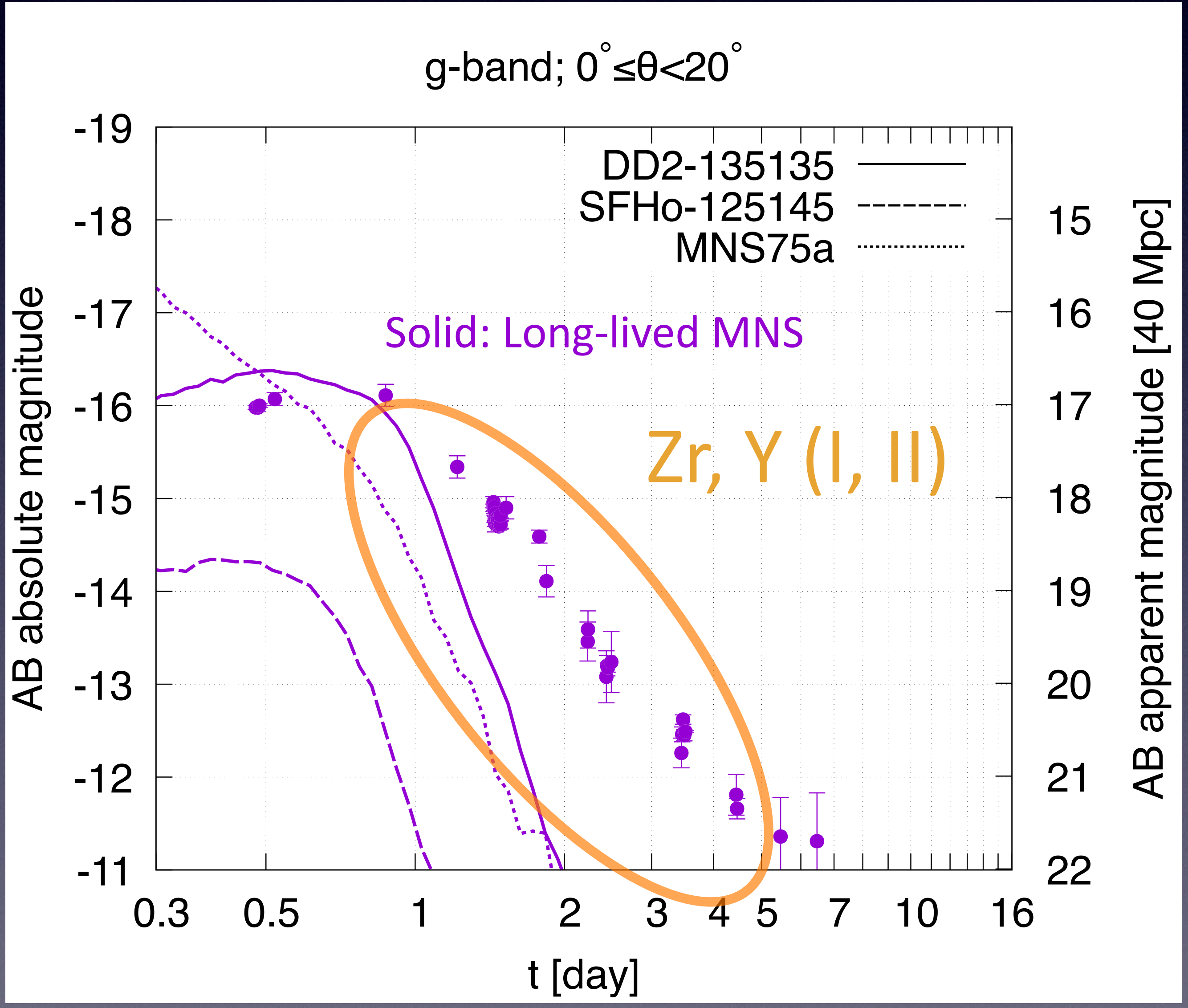
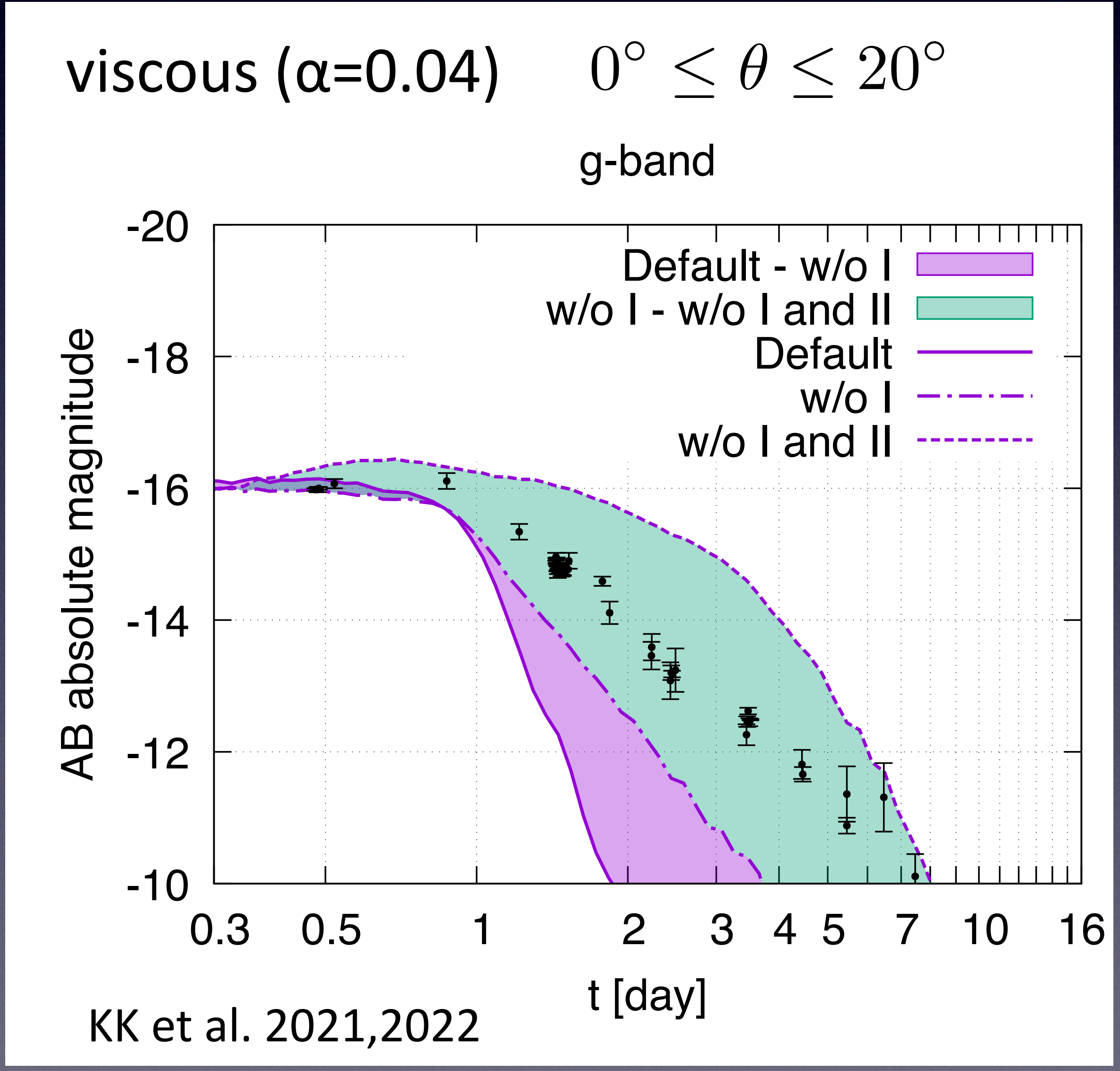
Late optical emission: non-LTE effect?

non-LTE effect on the ionization population in the low-density polar region
may modify the optical emission in the late phase:





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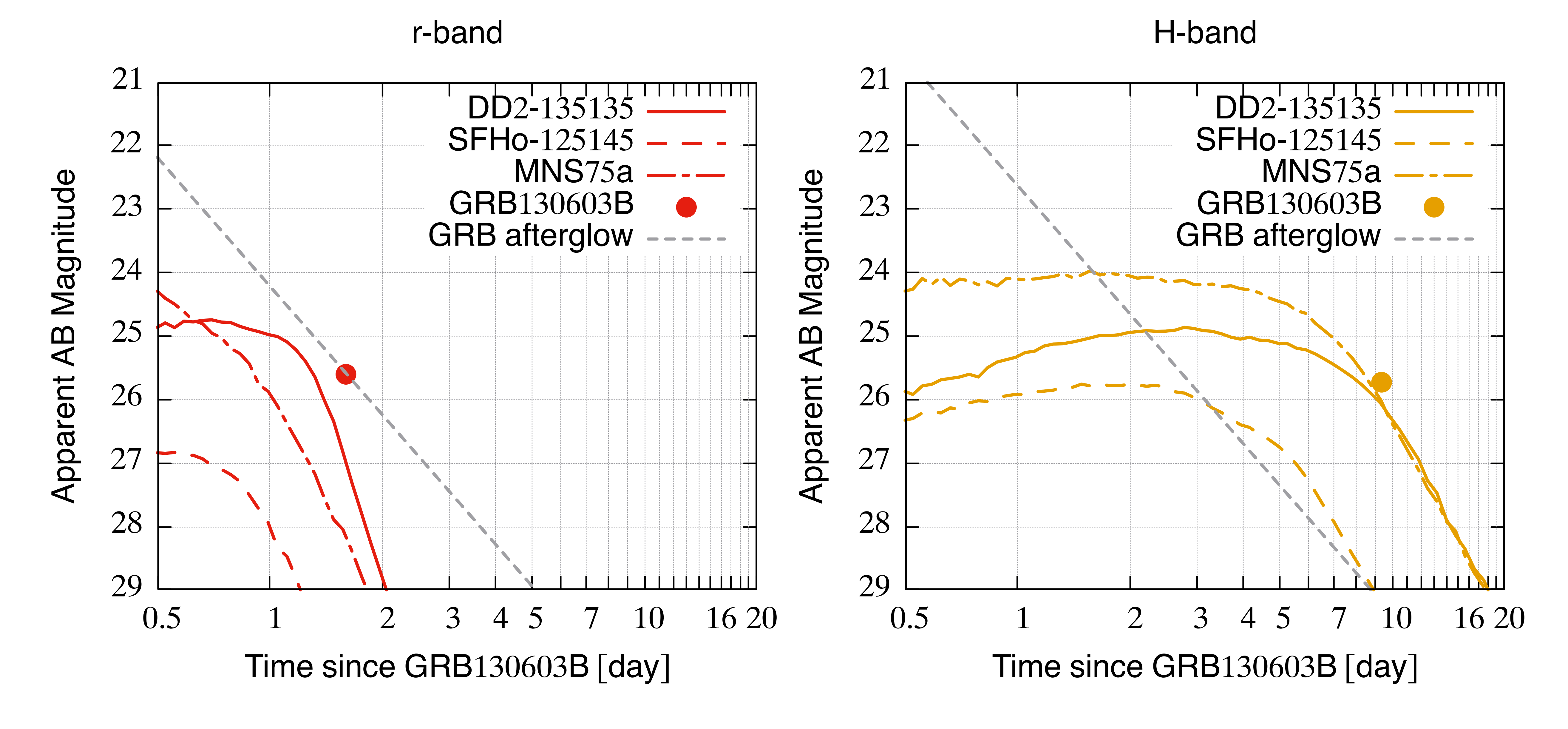
and J. Barnes et al. 2021 for the impact of heating rate uncertainty to the ionization structure

GRB130603B

Solid: Long-lived MNS ***Dashed:*** Short-lived MNS
Dot-dashed: Long-lived MNS with significant magnetic dynamo

Data: Tanvir et al. 2013



GRB130603B

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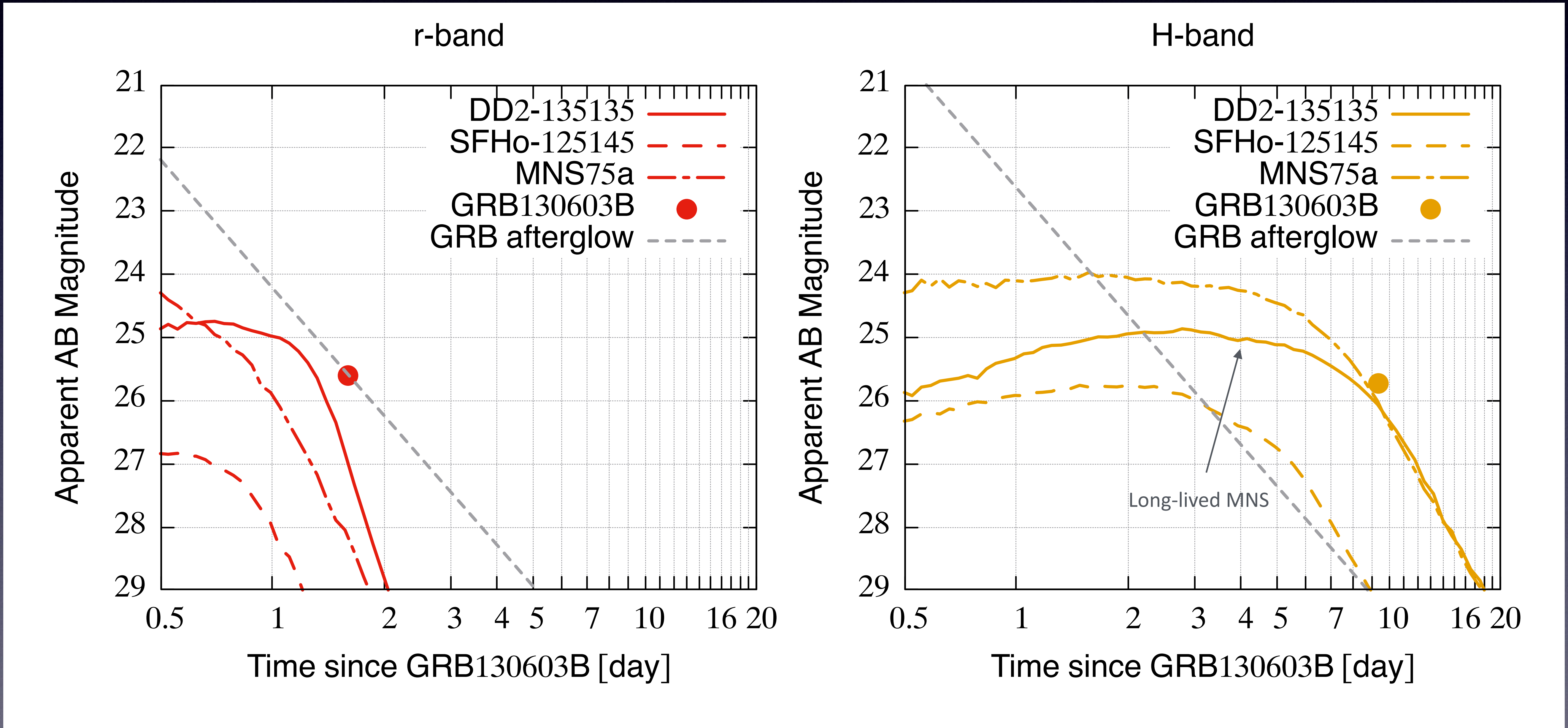

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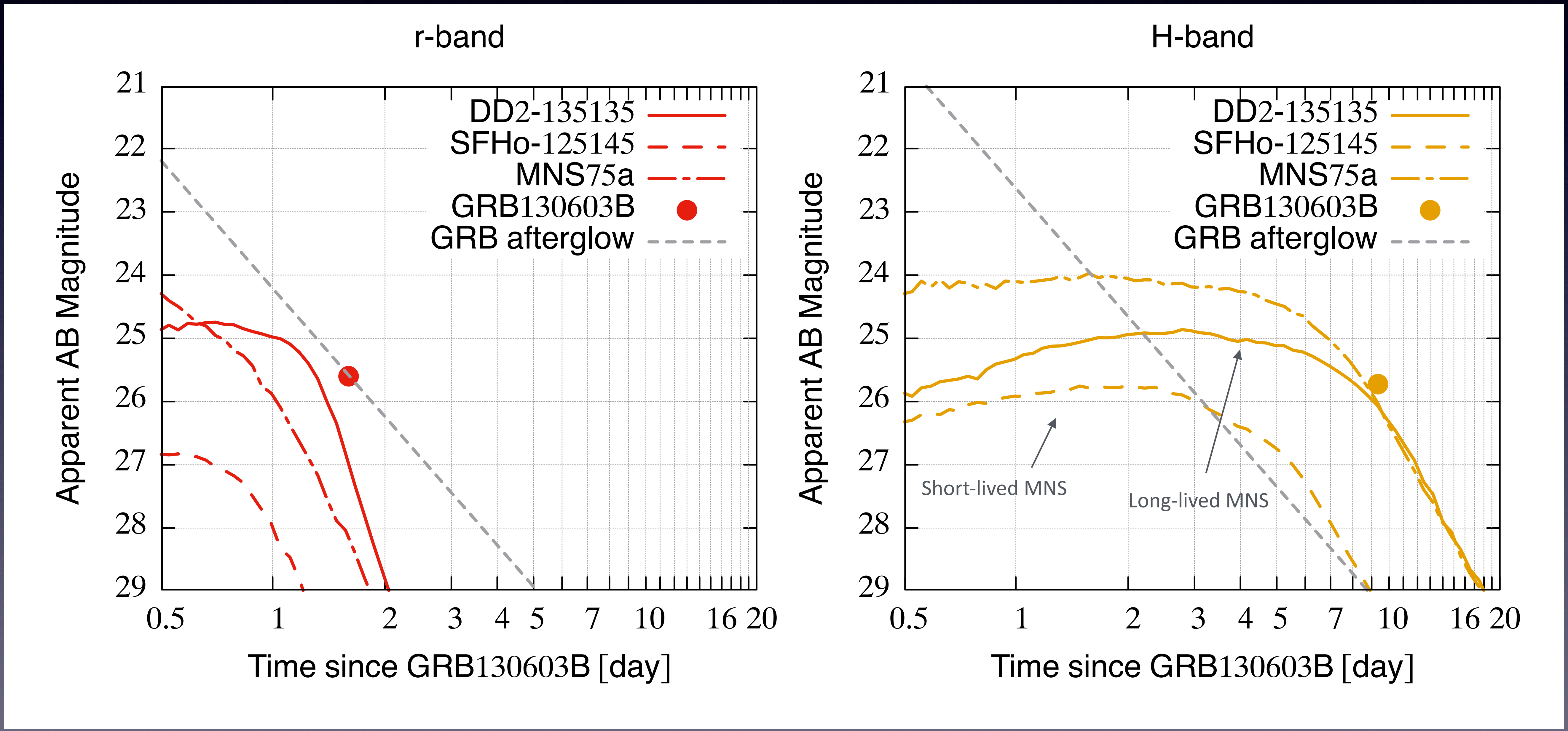
Dot-dashed: Long-lived MNS with significant magnetic dynamo

Data: Tanvir et al. 2013



GRB130603B

Solid: Long-lived MNS ***Dashed:*** Short-lived MNS
Dot-dashed: Long-lived MNS with significant magnetic dynamo

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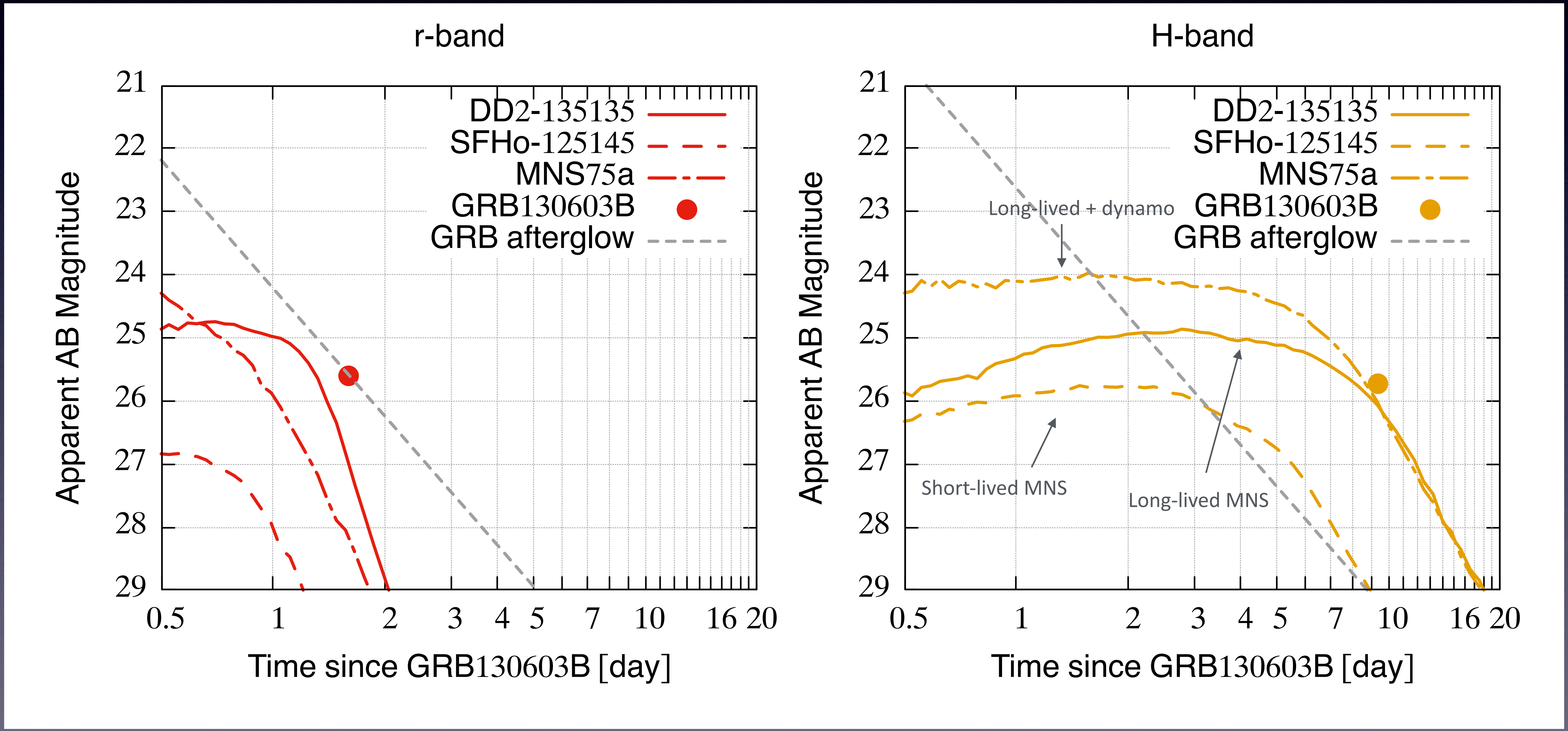

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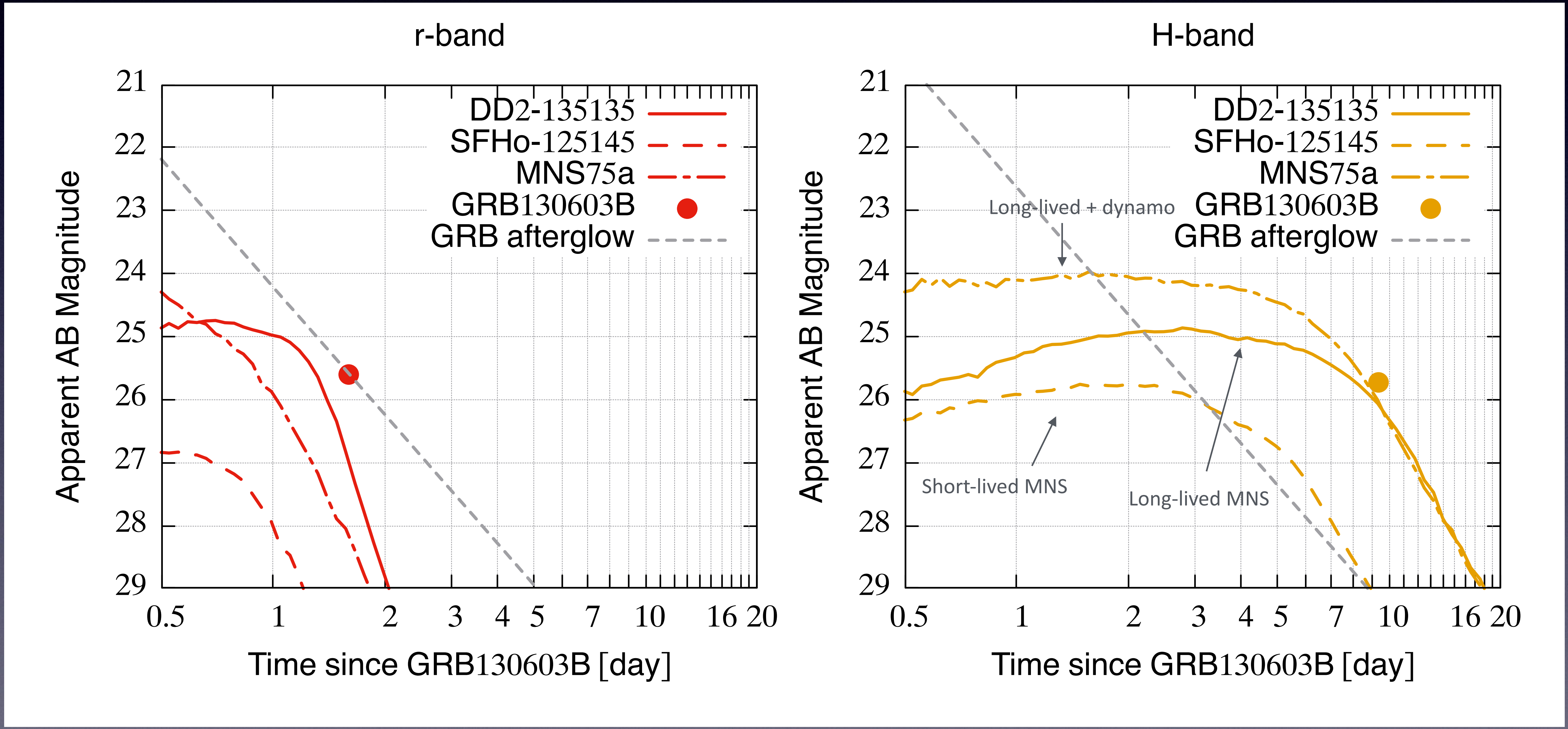


A BNS with a formation of a MNS survives for >0.1 s
is consitent with the observation of GRB130603B

Elemental abundance

Fujibayashi et al. 2020,2022, Shibata et al. 2021

Long-lived (>> 1 s) MNS

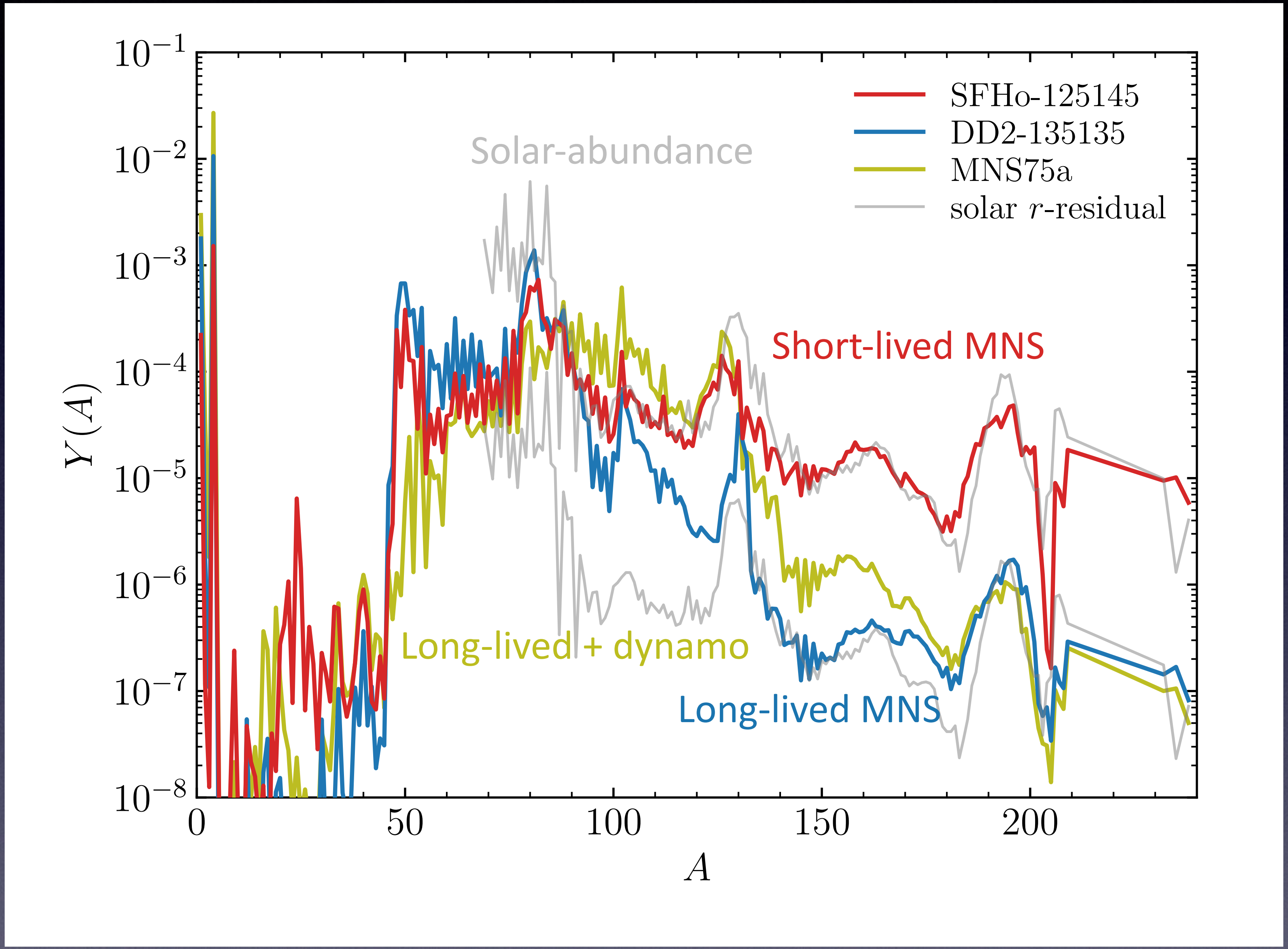
$$(M_{\rm pm}, M_{\rm dyn}) = (0.08, 0.002)M_\odot$$

Short-lived (<20ms)MNS

$$(M_{\rm pm}, M_{\rm dyn}) = (0.006, 0.006)M_\odot$$

Long-lived + dynamo

$$(M_{\rm pm}, M_{\rm dyn}) = (0.09, 0.002)M_\odot$$

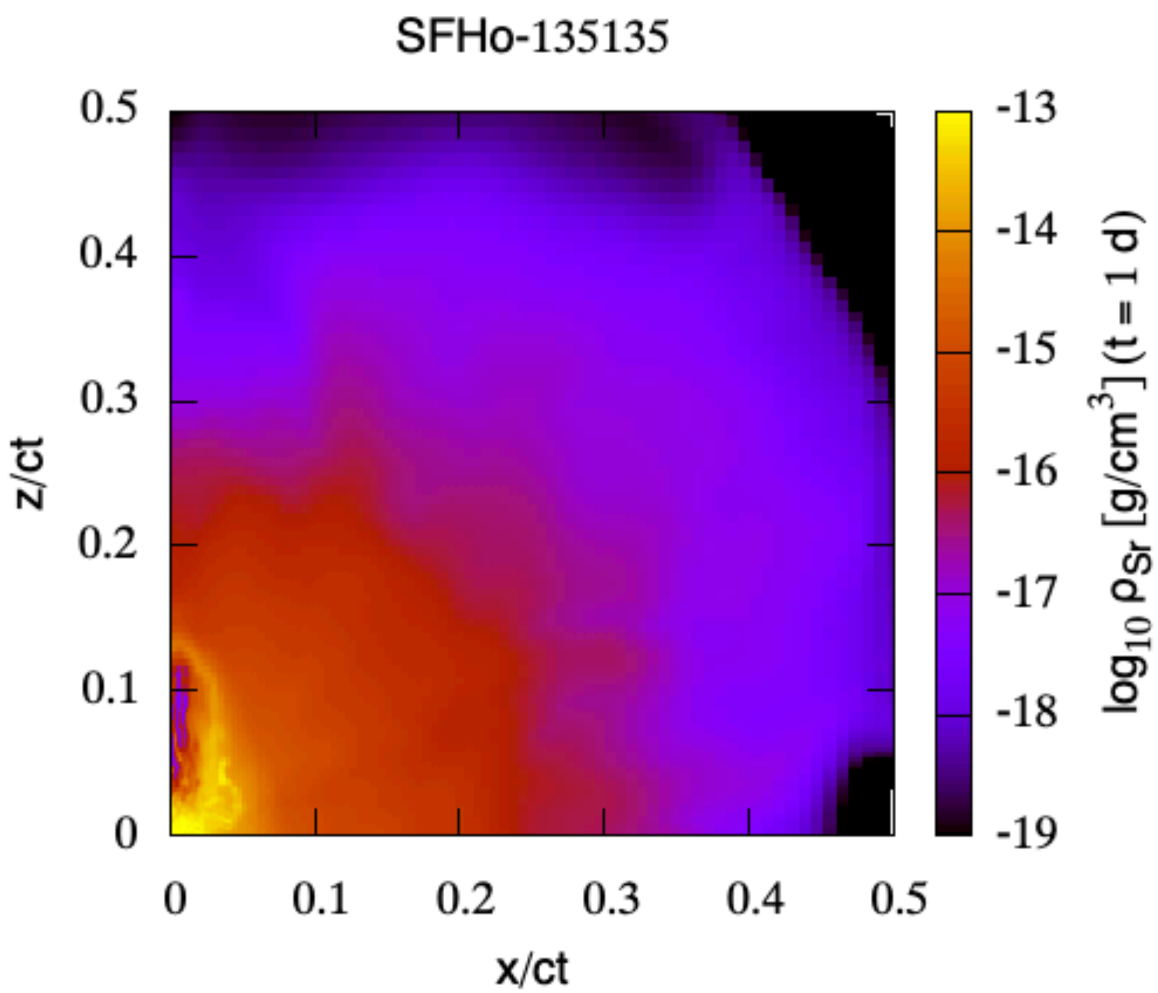


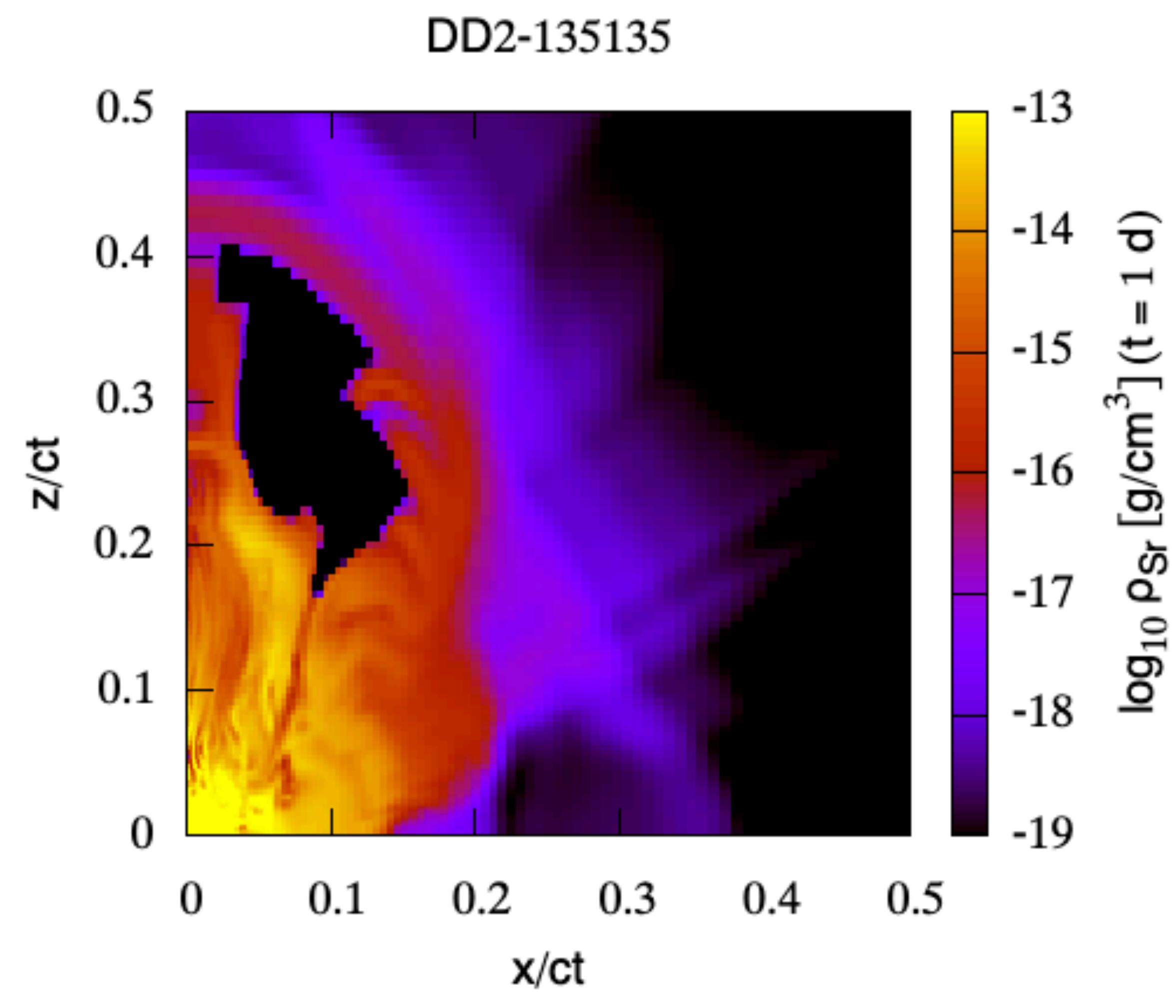
long-lived MNS models should not be the major outcomes of BNSs that merge in a Hubble time if the dominant sources of r-process elements are BNS mergers.

(However, more self-consistent magnetohydrodynamics treatment might change the results)

Sr distribution

Short-lived MNS case **Long-lived MNS case**



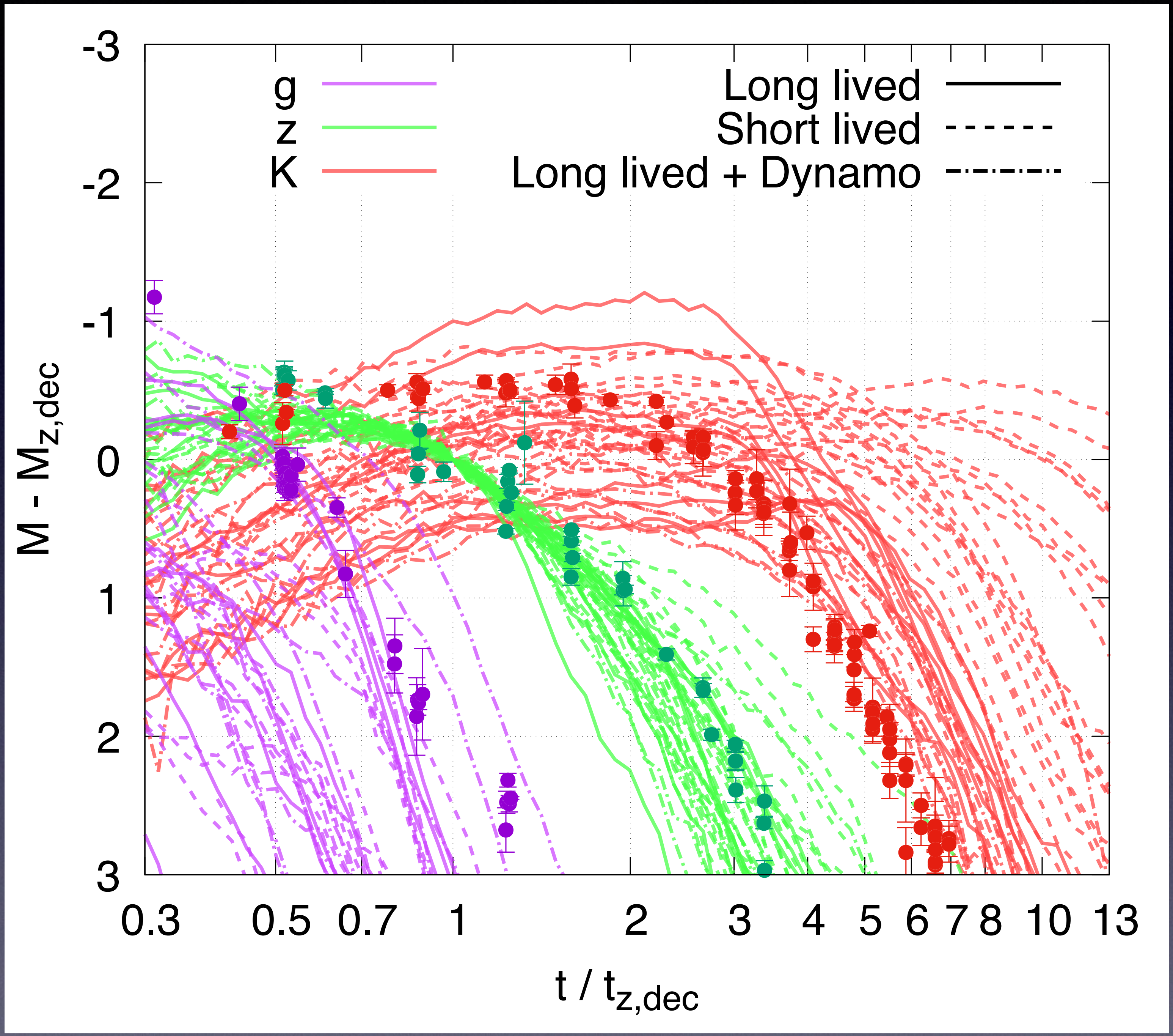


Spectral analysis of Sneppen et al. 2023 suggestes that
the Sr distribution of the ejecta should have nearly spherical morphology:
Ejecta models for both long-lived MNS cases and short-lived MNS cases (low velocity part)
have non-spherical Sr distributions (see also Just et al. 2023).

Summary

- Accurately determine the ejecta profile for the rest-mass density and compositions at the time of kilonova emission is important for the kilonova modeling.
- For this purpose, conducting a study based on numerical simulations consistently starting from the merger up to the phase of EM emission is a useful approach to link the various observables.
- Lightcurve comparisons suggests…
    - Our kilonova models indicate that the remnant MNS in GW170817 is less likely to have collapsed within a short time (<20 ms) but survived for a longer time (~>0.1s).
    - At the same time, it is likely that the remnant MNS should have collapsed to a BH within the dynamo time scale of the magnetic-field growth, unless the dynamo effect in the post-merger phase was subdominant.
    - Kilonova models with long-lived MNS formation are also consistent with the observation of GRB130603B.
    - Study for a BNS with an Intermediate MNS lifetime (0.1-1 s) should be interesting to be checked (see also Just et al. 2013).
- Calculated nucleosynthesis yields suggets…
    - Long-lived MNS models should not be the major outcomes of BNSs that merge in a Hubble time if the dominant sources of r-process elements are BNS mergers. On the other hand, calculated nucleosynthesis yields of short-lived MNS models are consistent with the solar r-process residual.
    - The aspherical features in Sr distribution for both long-lived/short live MNS models are inconsistent with the implication of Sneppen et al. 2023.

Approx. scaling law for NIR LCs



$$\frac{d\ln F_z}{d\ln t} = -1 \iff \frac{dM_z}{d\log_{10} t} = 2.5 @ t = t_{z,\mathrm{dec}} \qquad M_{z,\mathrm{dec}} = M_z(t_{\mathrm{dec}})$$

$$M_{H,K} = M_{z,\mathrm{dec}} \pm 1\,\mathrm{mag}\ \mathrm{for}\ t/t_{\mathrm{dec}} = 0.6 - 4$$

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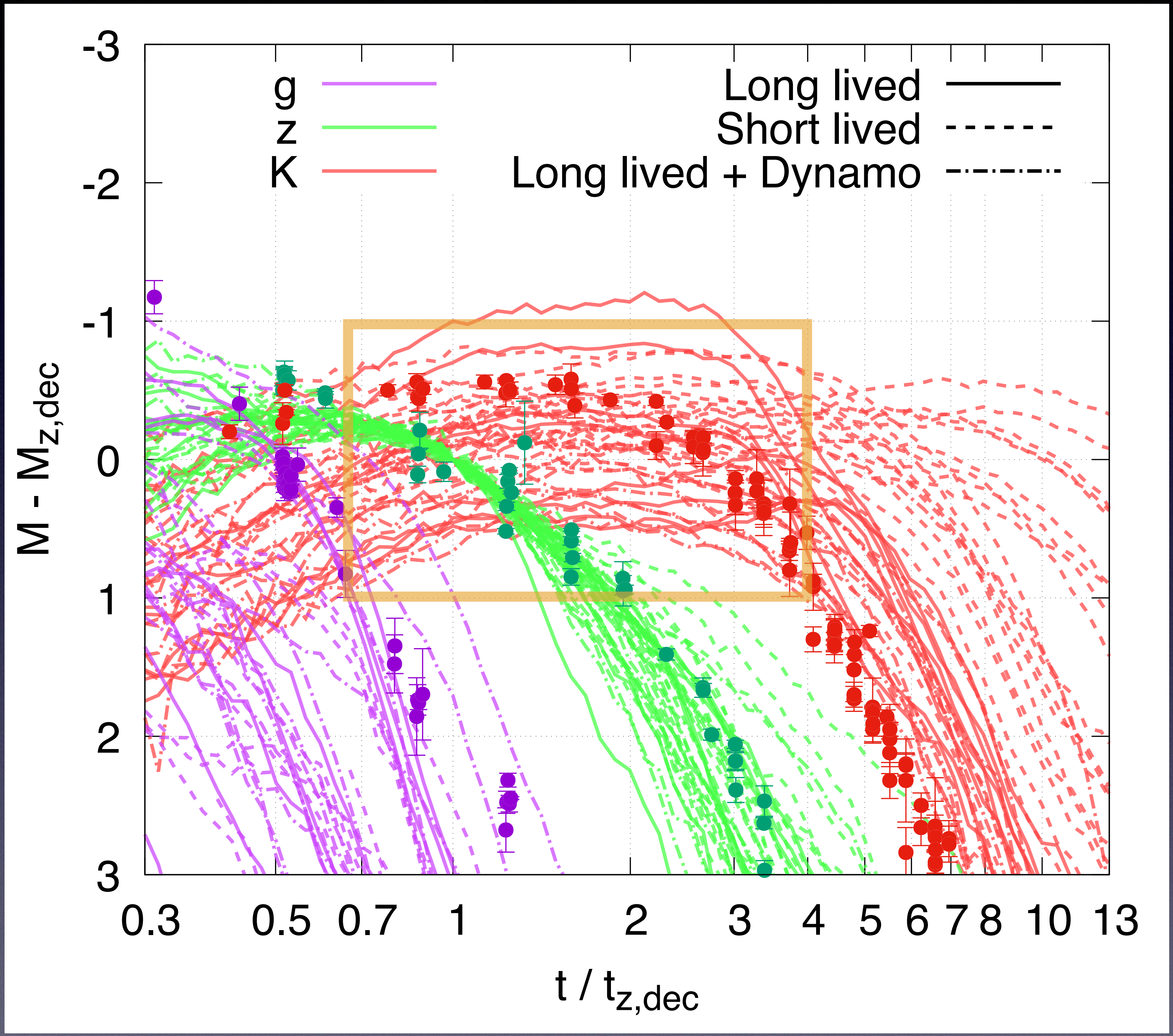

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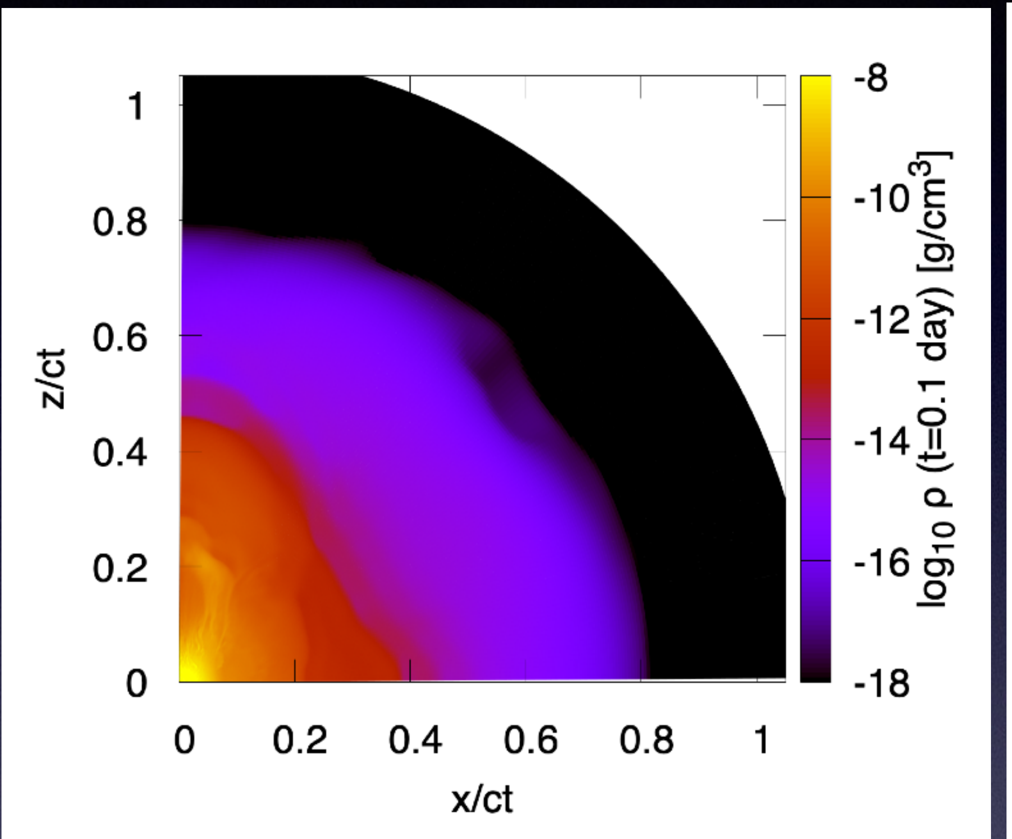
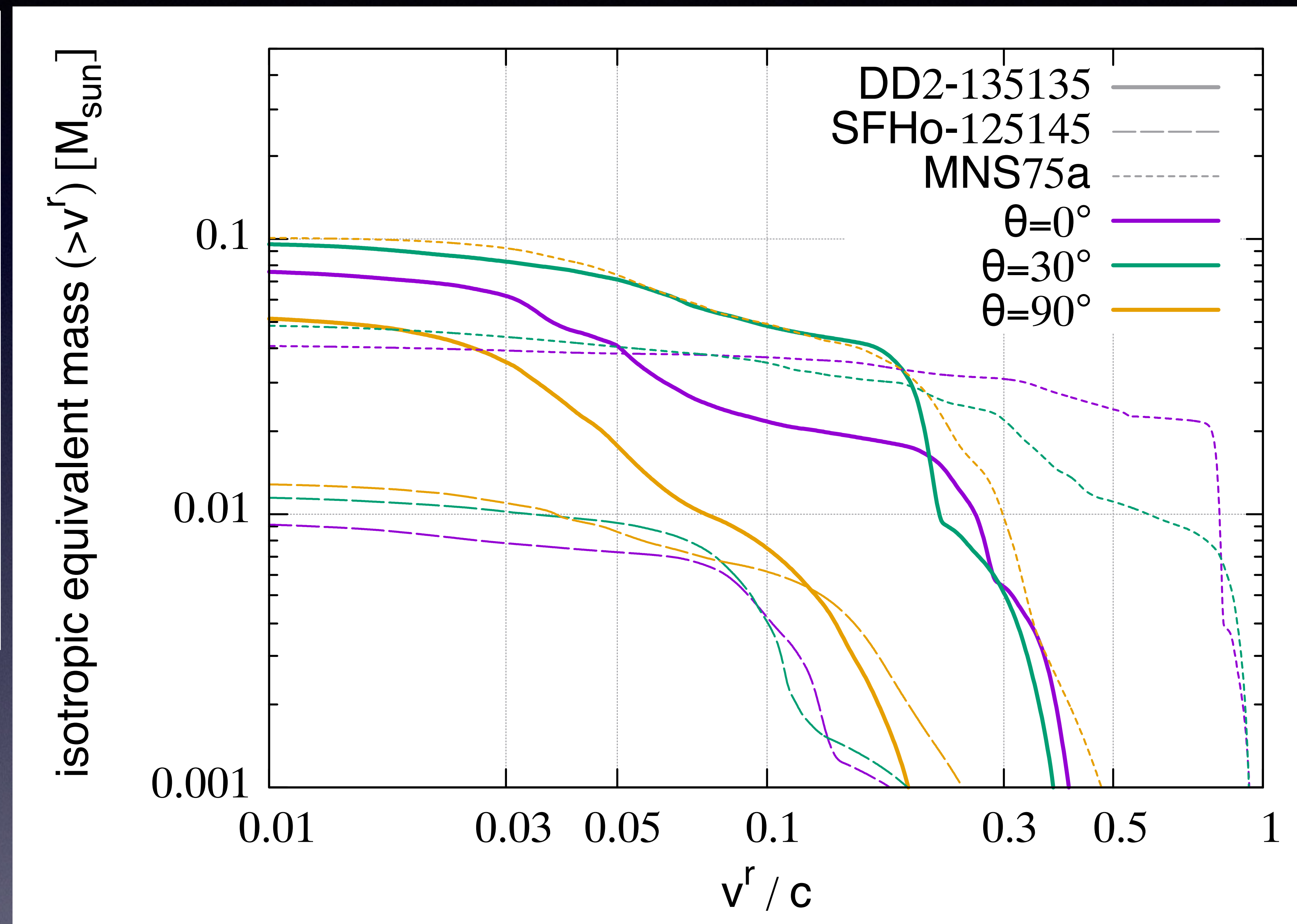
Fast blue components?
Isotropic equivalent mass distribution





$$\langle v_{\rm eje,pm} \rangle \approx 0.05 - 0.1\,c$$

$$M^{\rm iso}_{\rm eje}(v^r,\theta) = 4\pi \int_{>v^r} \rho(r,\theta) r^2 dr$$

The isotropic equivalent mass in the polar directions is larger than 0.01 M_sun
for v > 0.2 c for long-lived MNS models:
Matches to the requirement of the AT2017gfo blue components
(e.g., Kasliwal et al. 2017. Cowperthwaite et al. 2017, Kasen et al. 2017, Villar et al. 2017)
See also Just et al. 2023 for similar findings.

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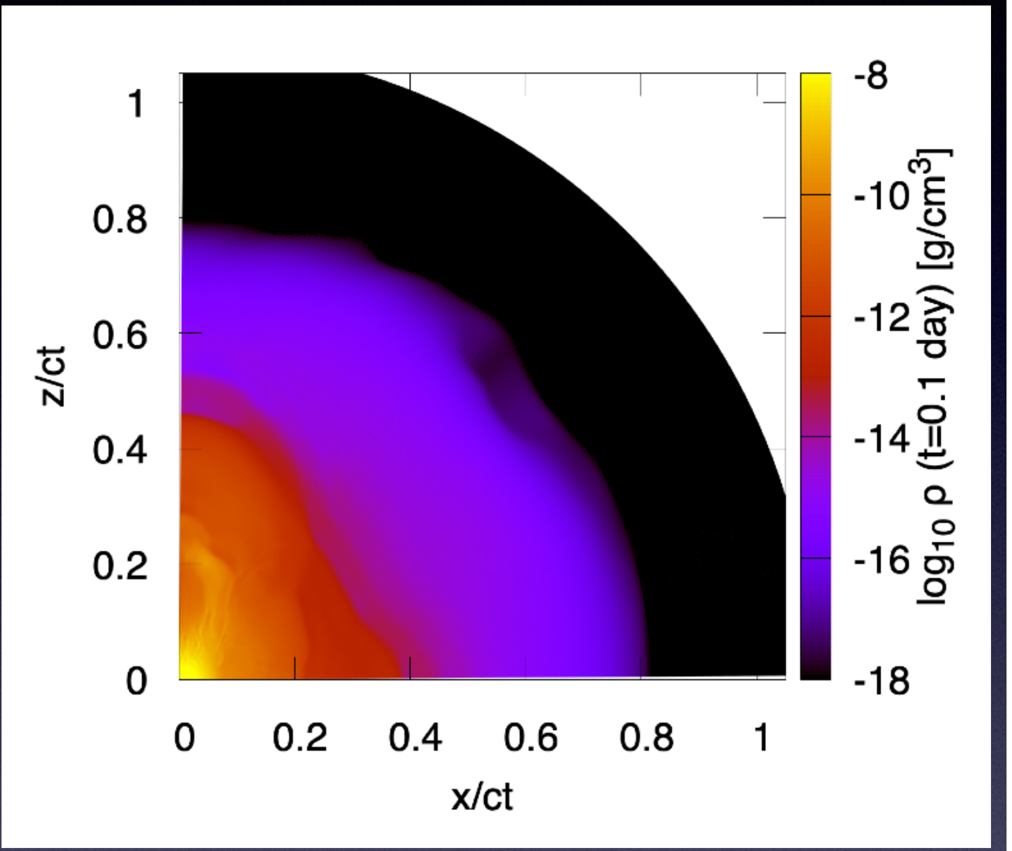

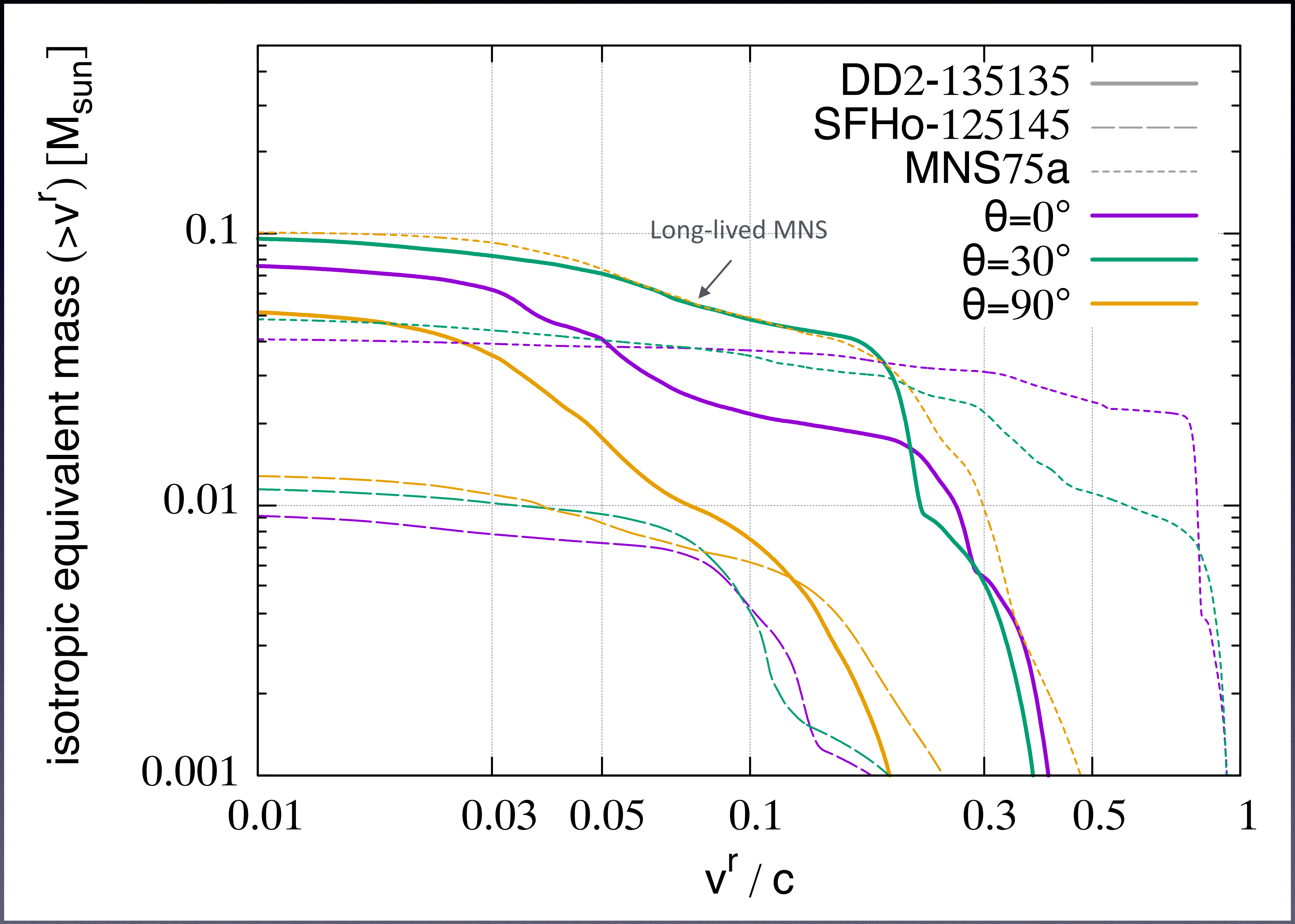

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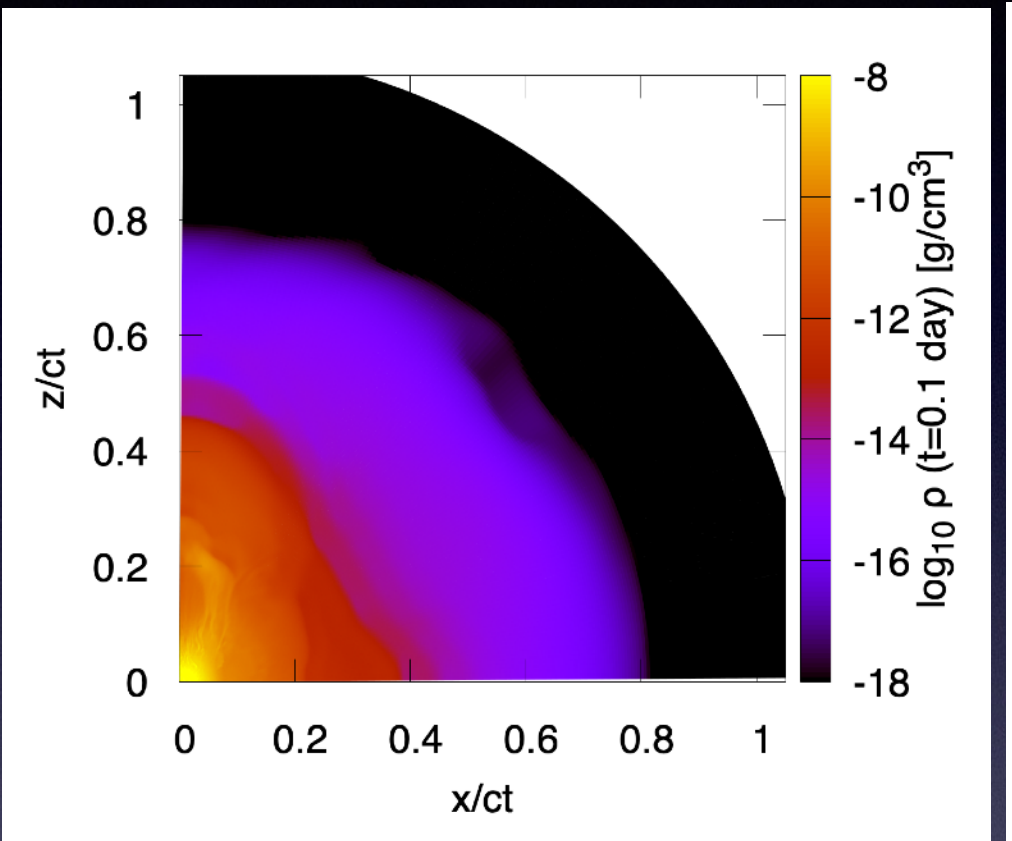

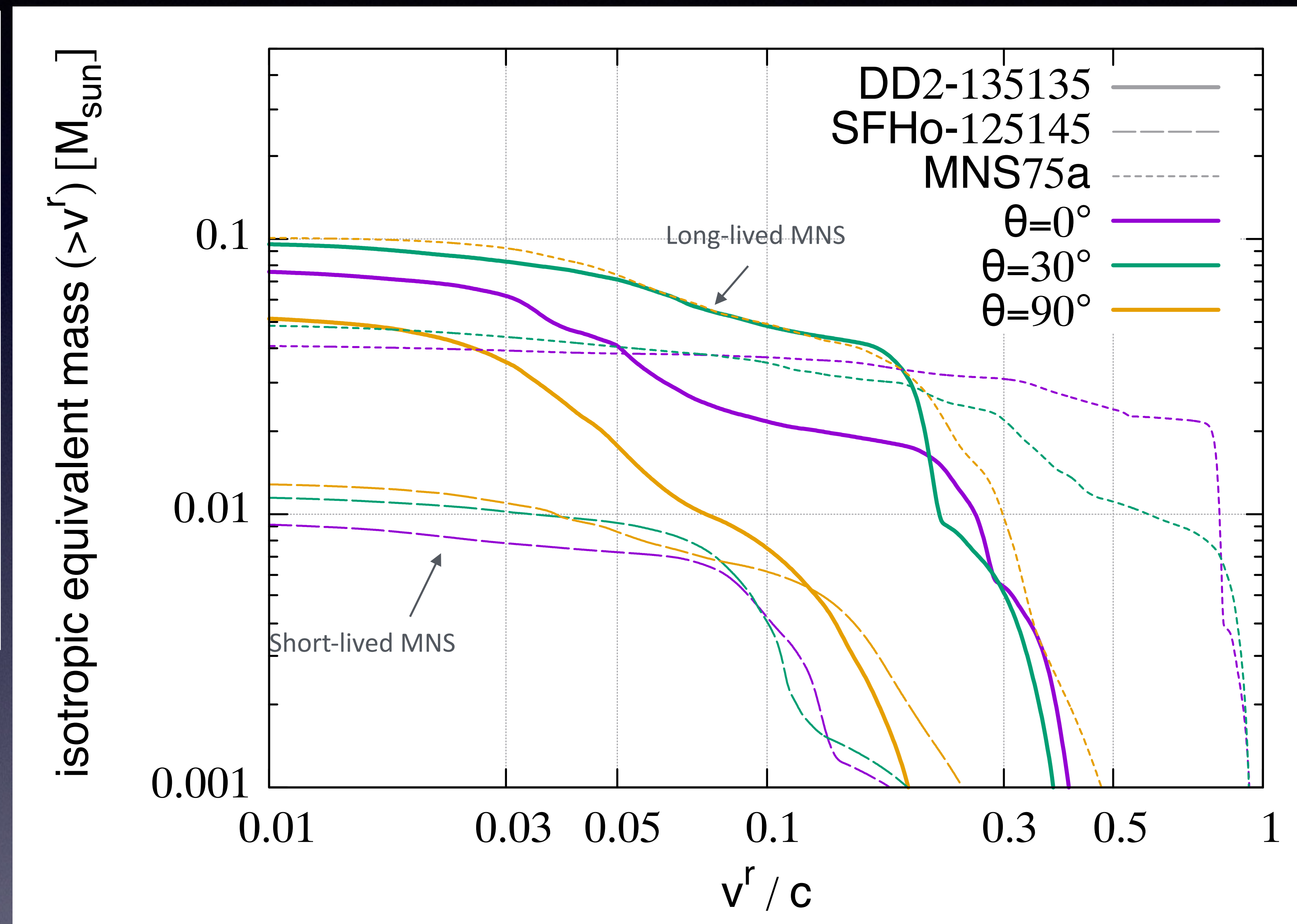

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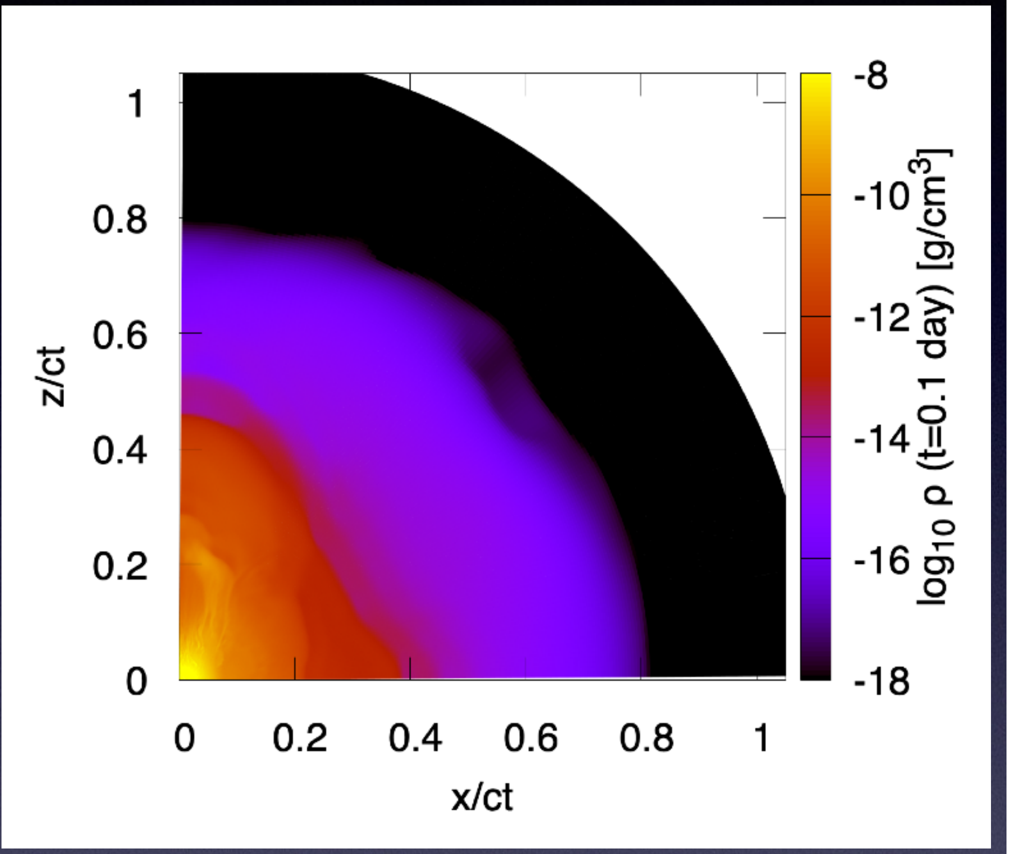

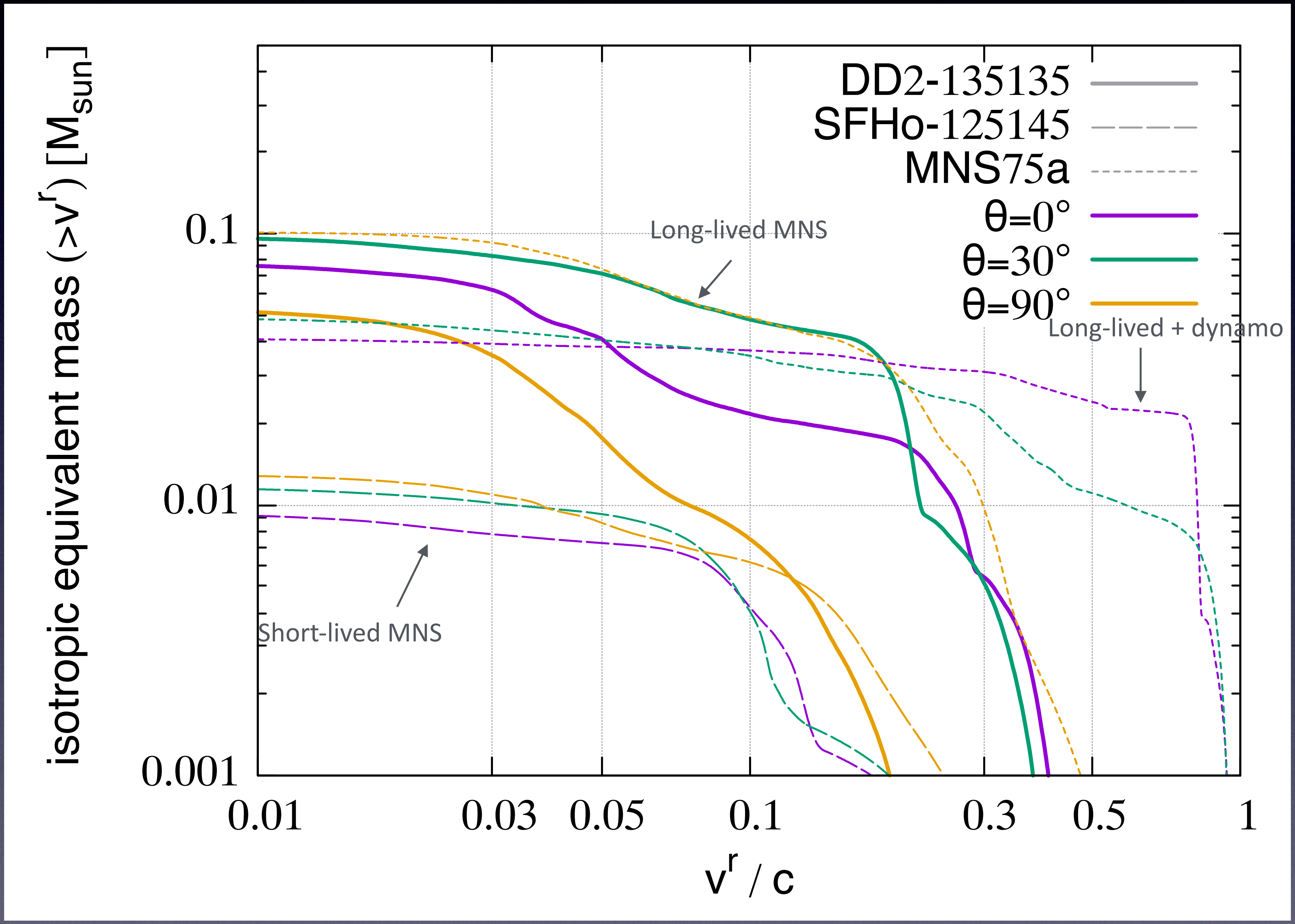

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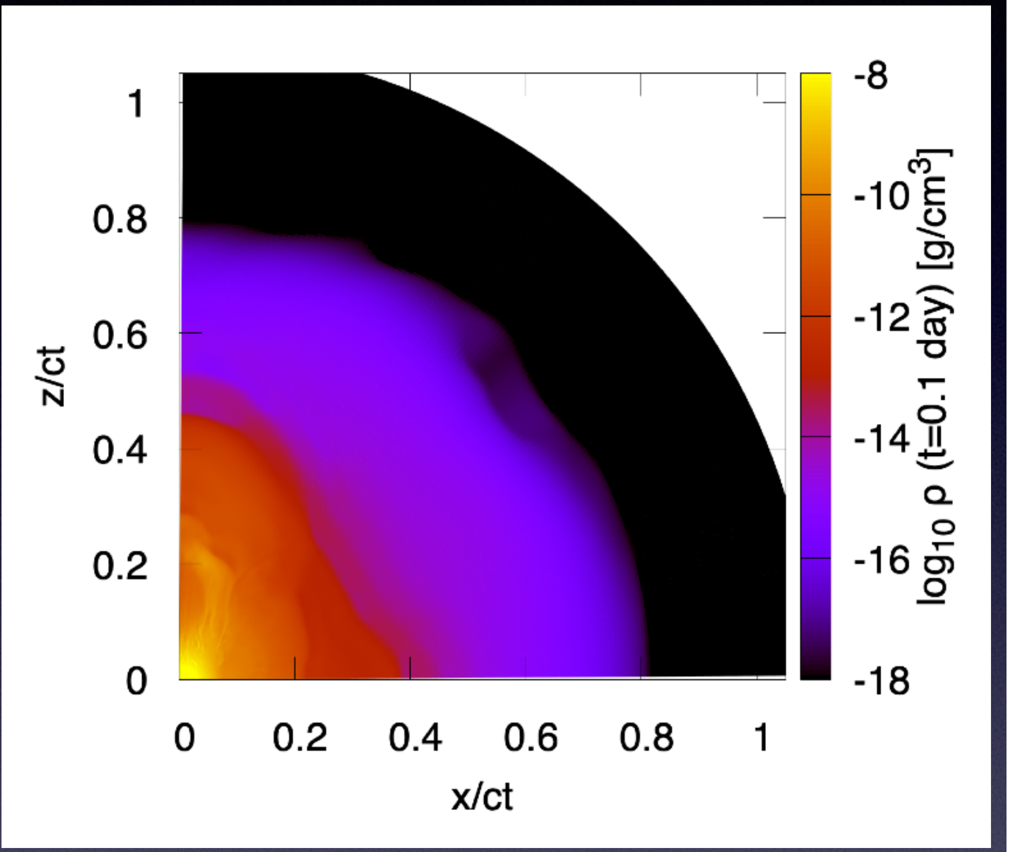

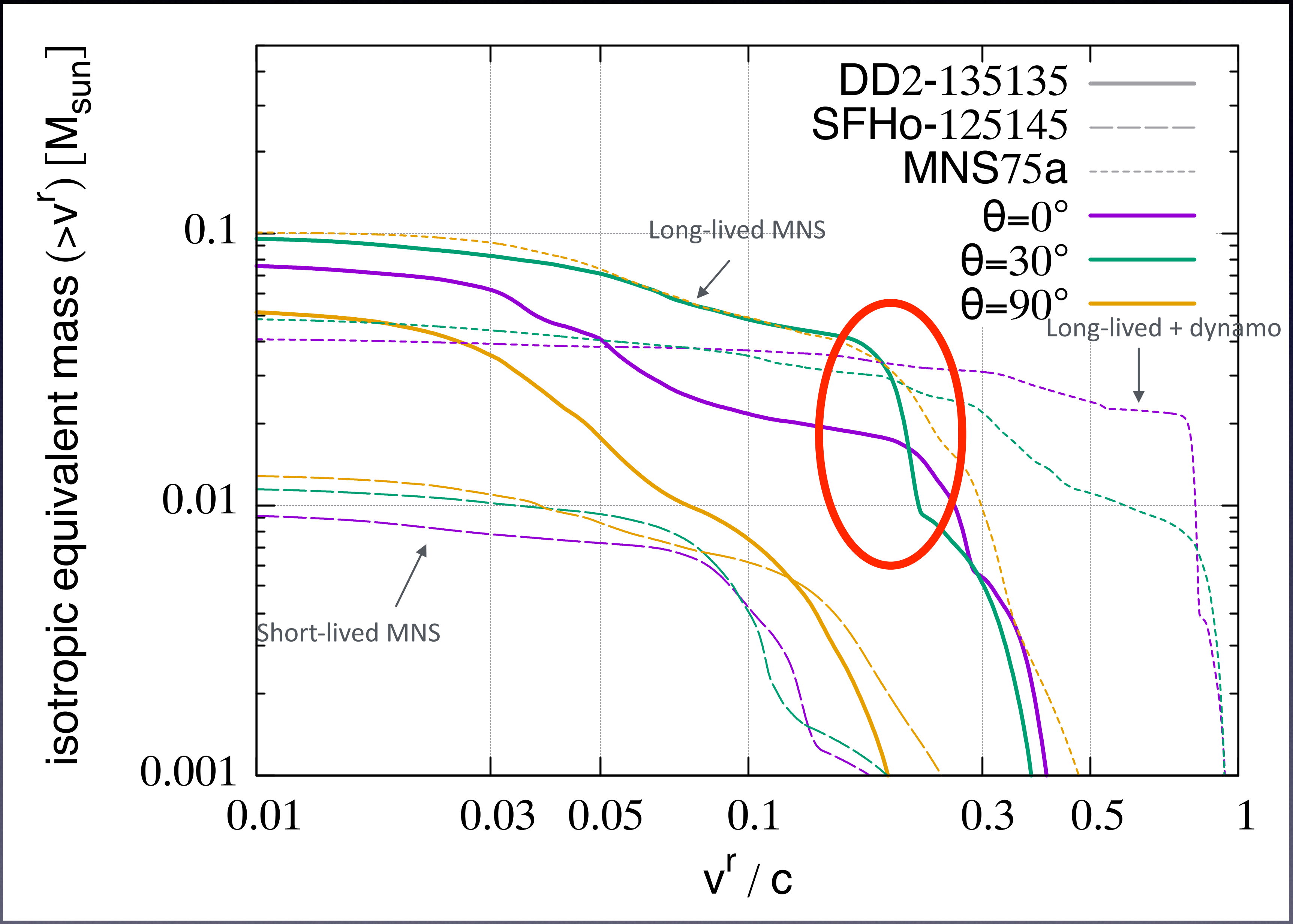

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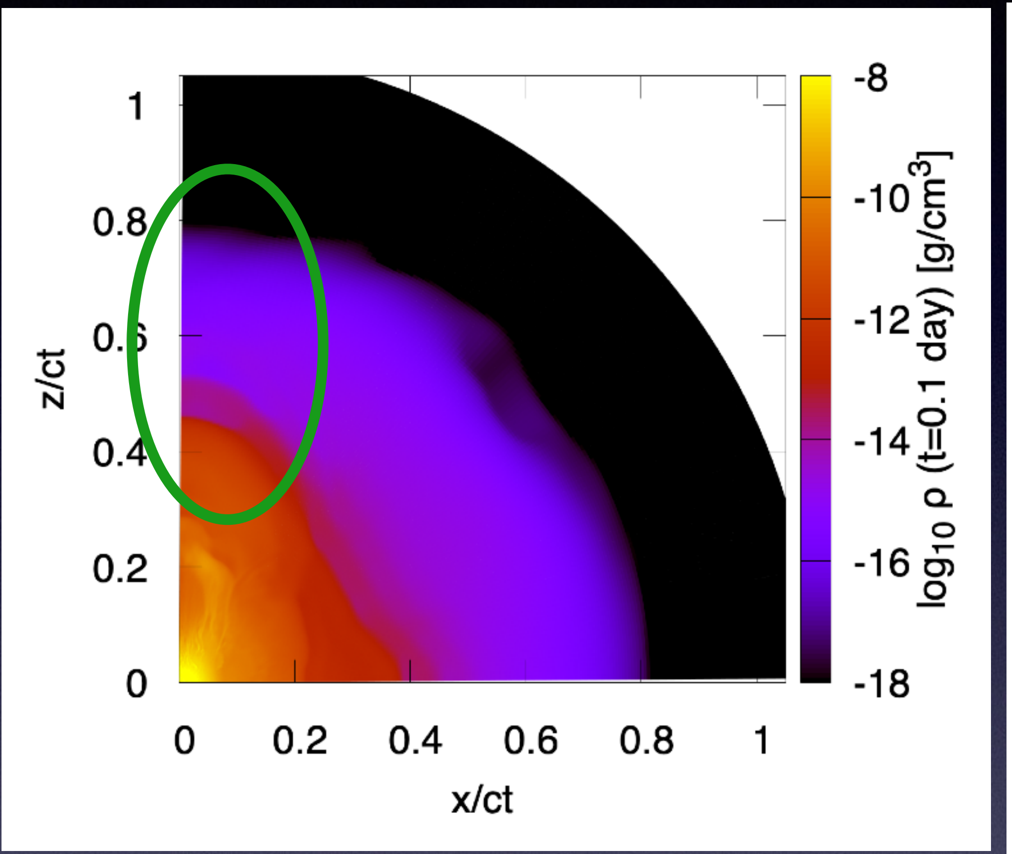

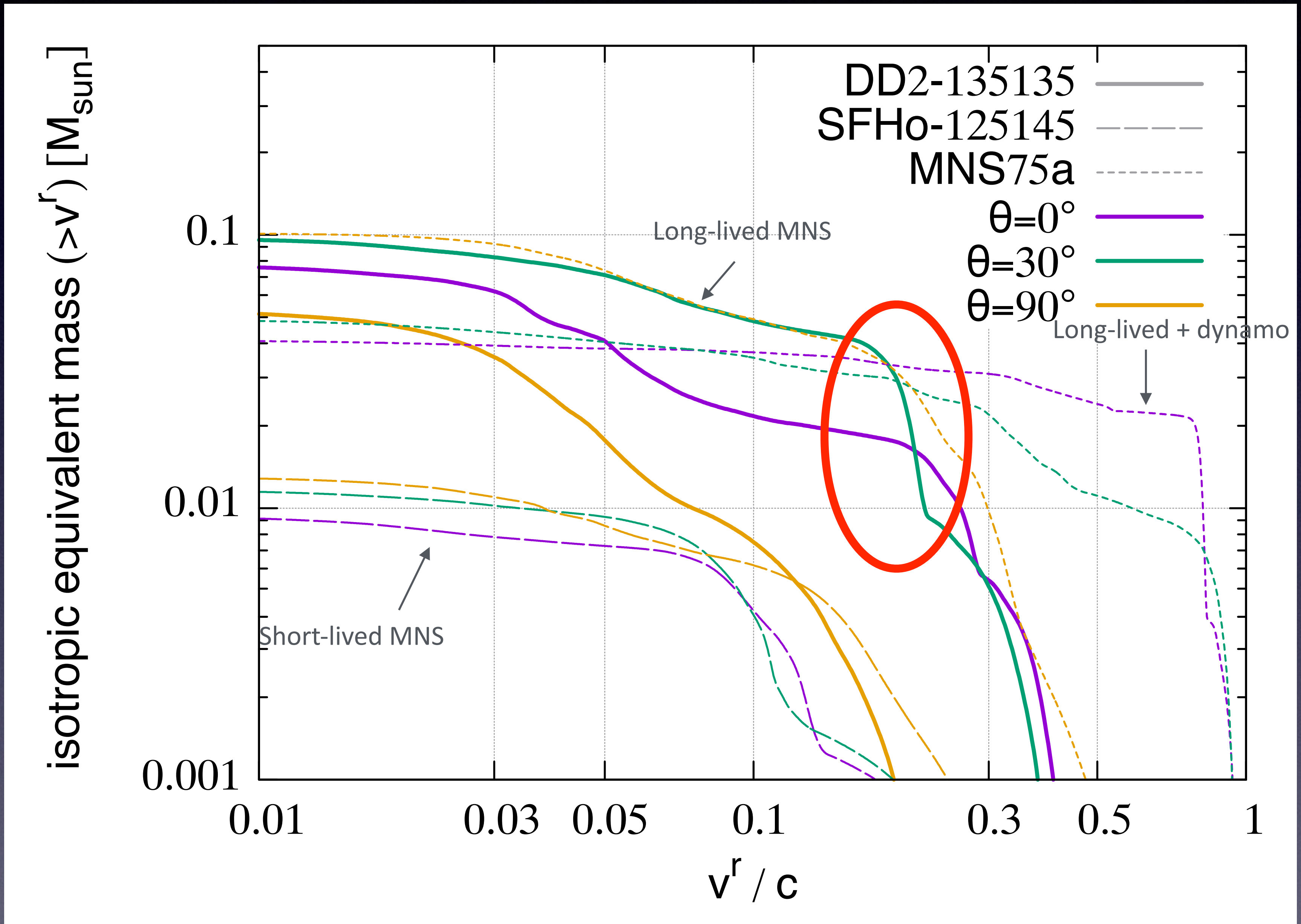

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