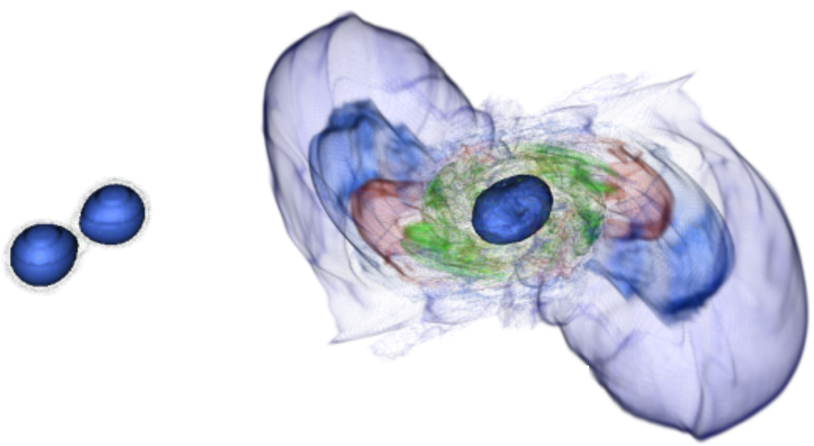
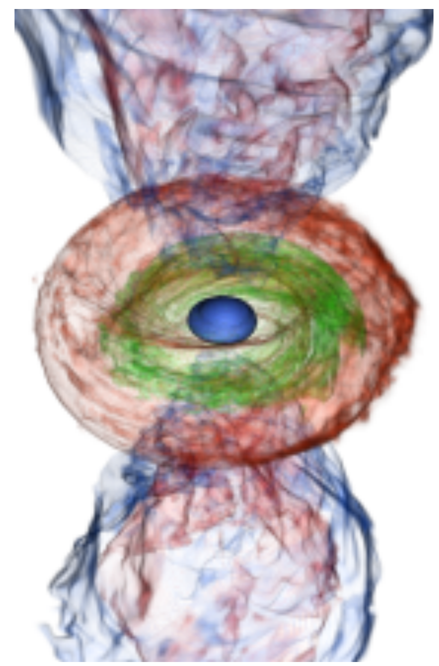
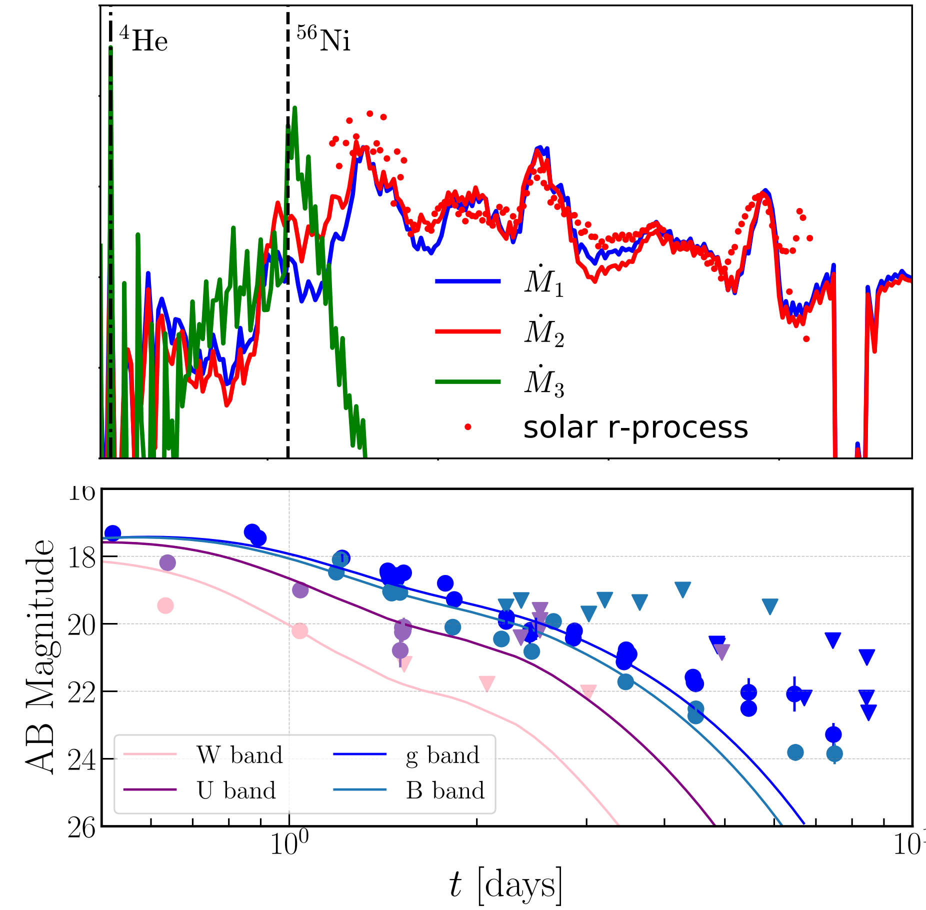
Modelling electromagnetic emission from neutron-star mergers







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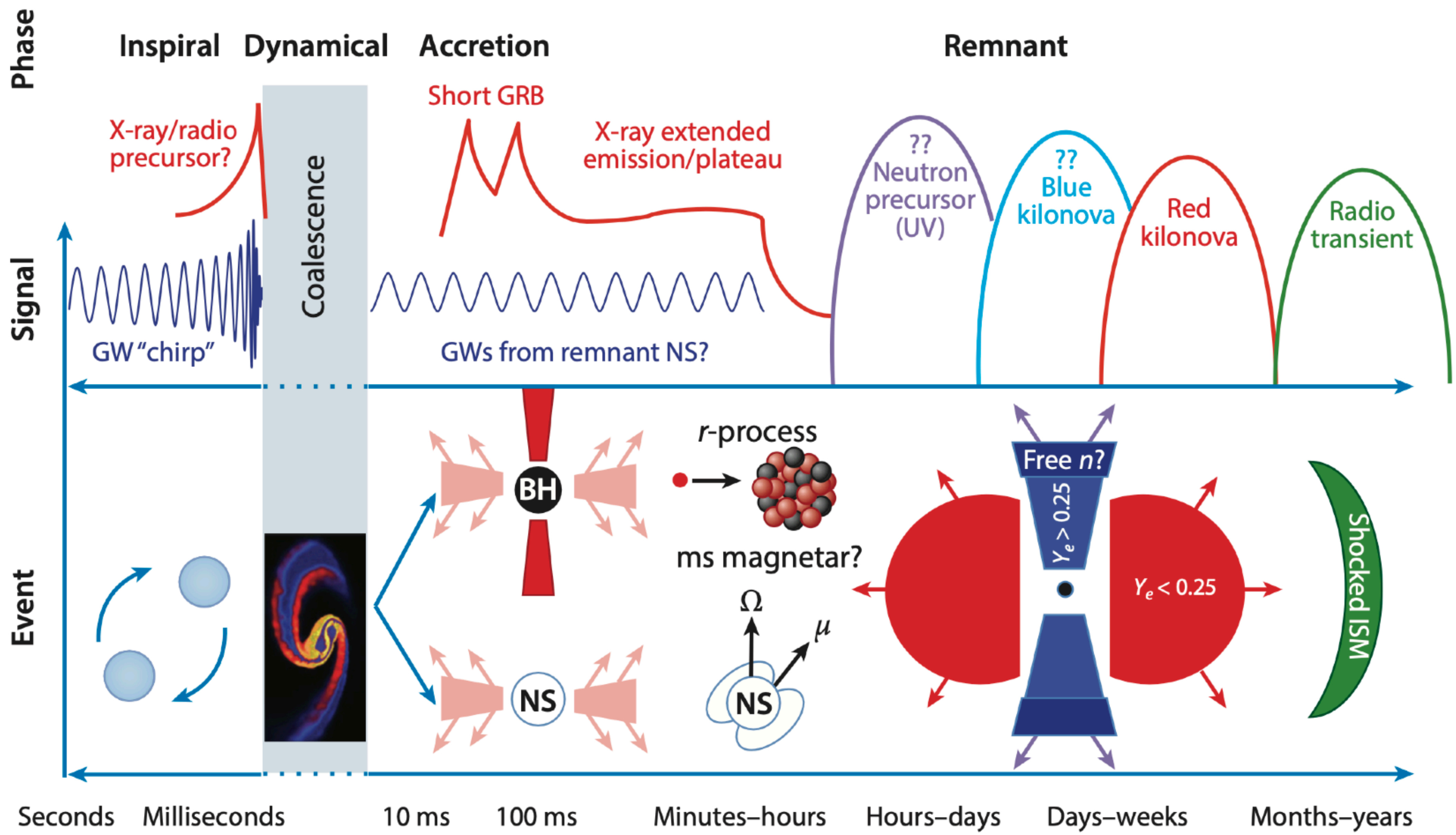
ACME workshop, Toulouse, 7-11 April 2025

Overview & focus of talk

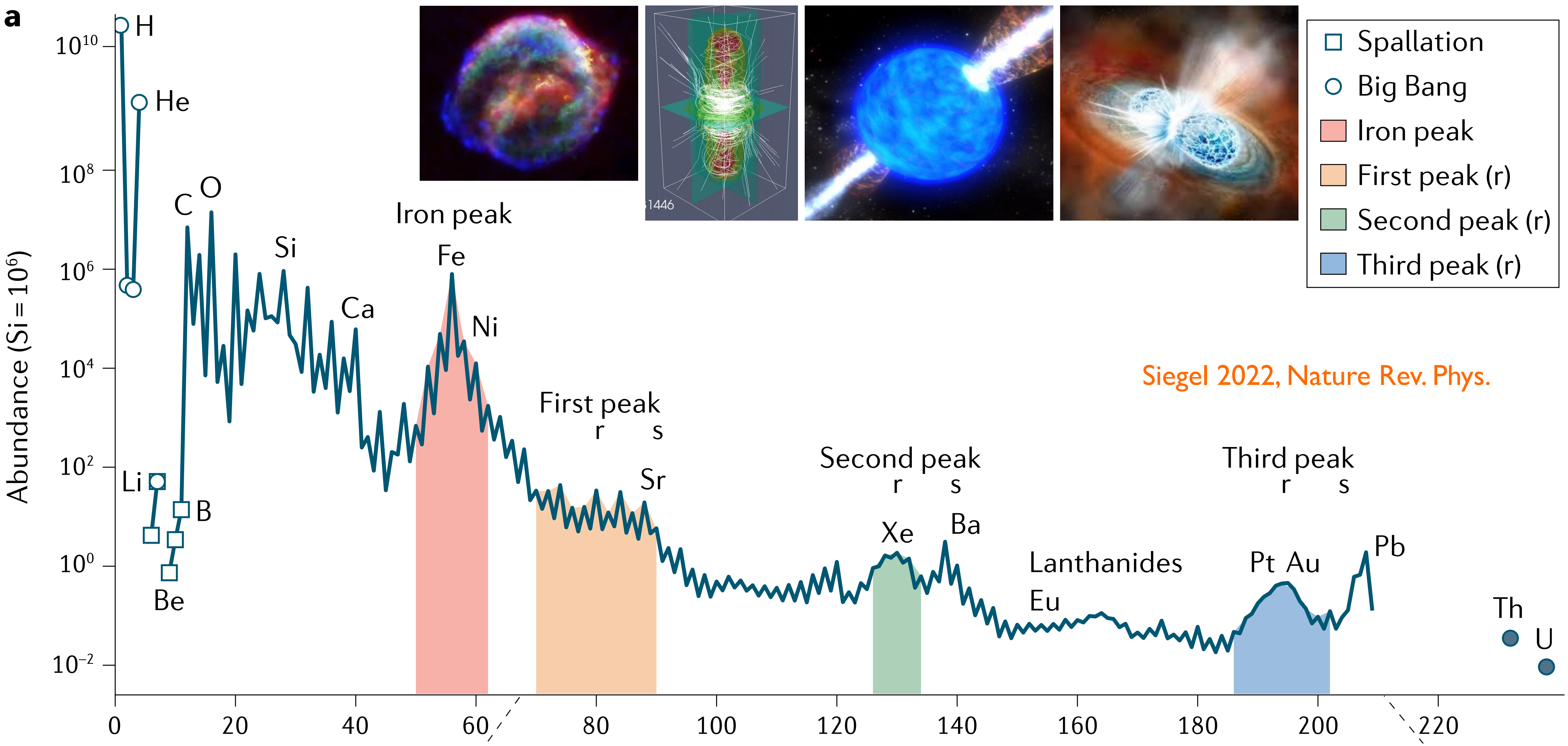


Fernandez & Metzger 2016

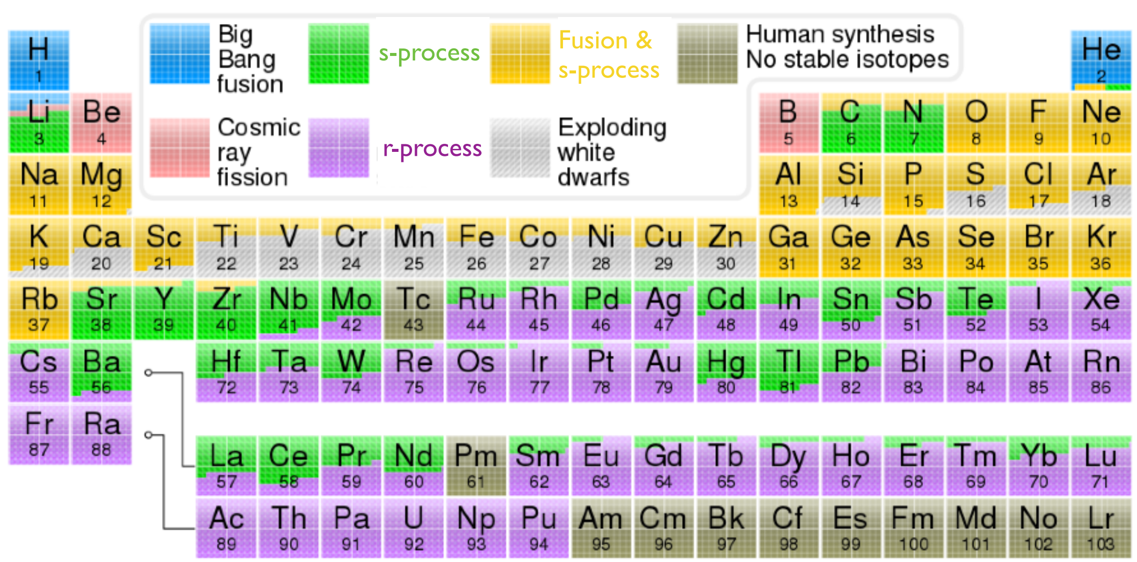
This talk:

- Theoretical (ab-initio) modelling of EM counterparts (see talks by Maria Grazia's and others for observational perspective)
- Focus on stellar-mass objects involving matter (BNS, NSBH)

2nd theme: kilonovae & production of heavy elements



Siegel 2022, Nature Rev. Phys.



How does the universe populate the periodic table?

Conjecture:

Outflows from compact accretion disks synthesize most of the Galactic heavy r-process elements

Short GRBs

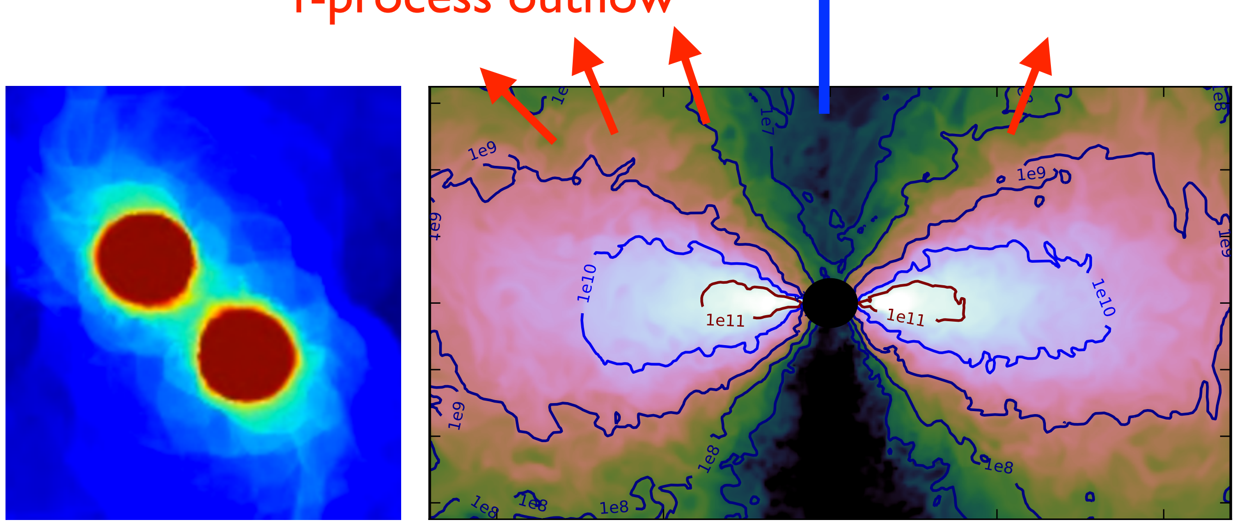
(NS mergers)

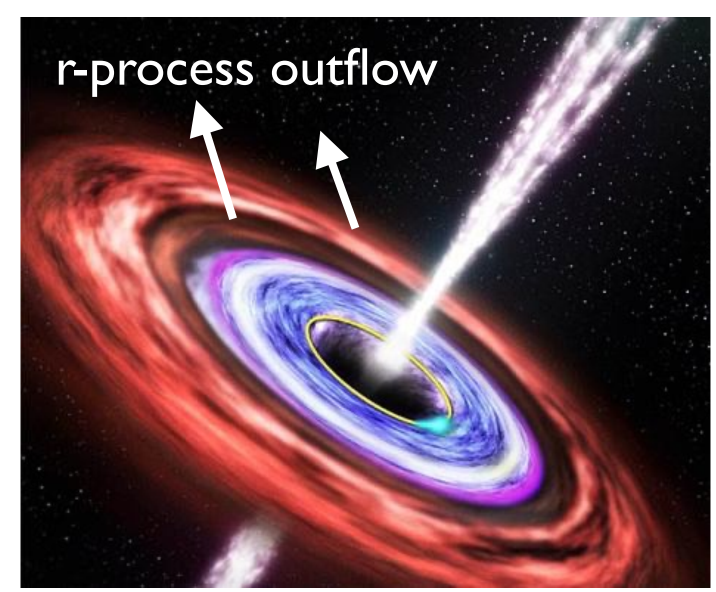
kilonovae

Long GRBs

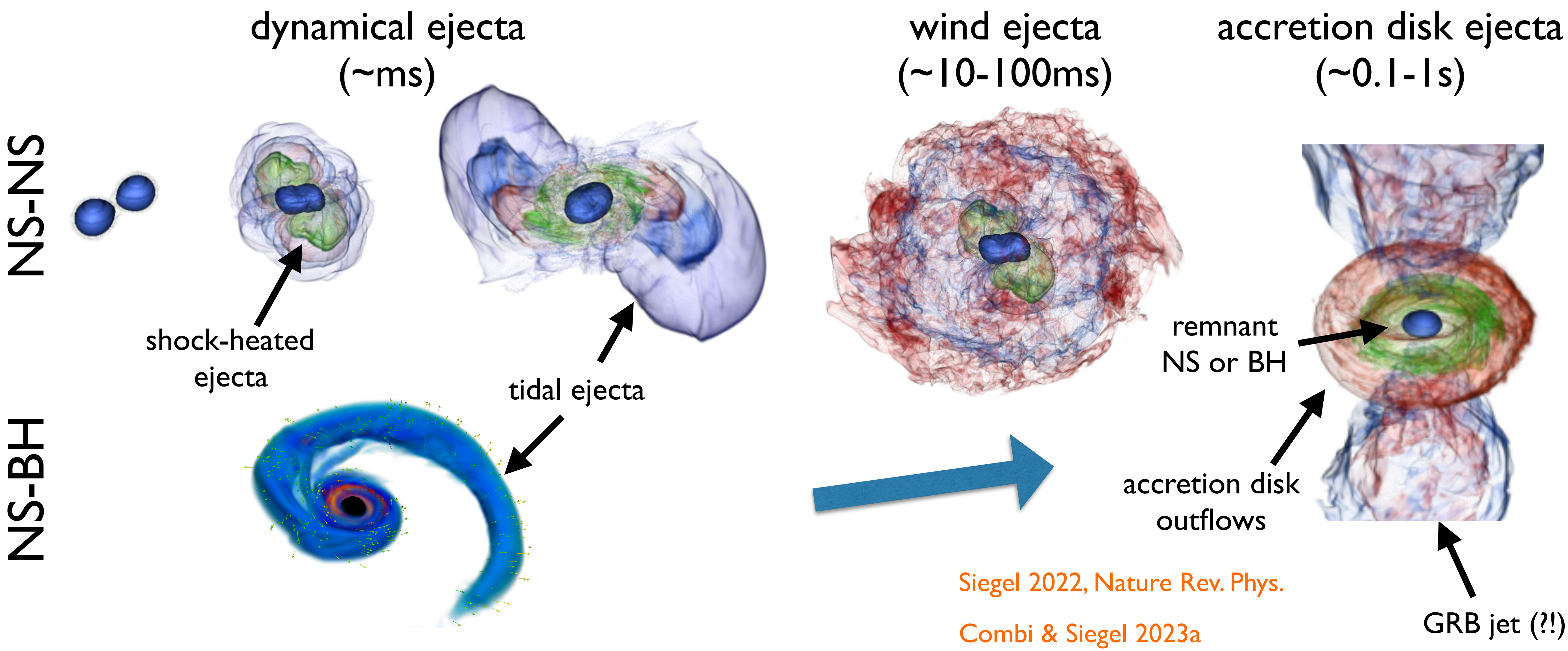
(collapsars)

SNe Ic-BL & (super-) kilonovae





EM counterparts are powered by matter outflows



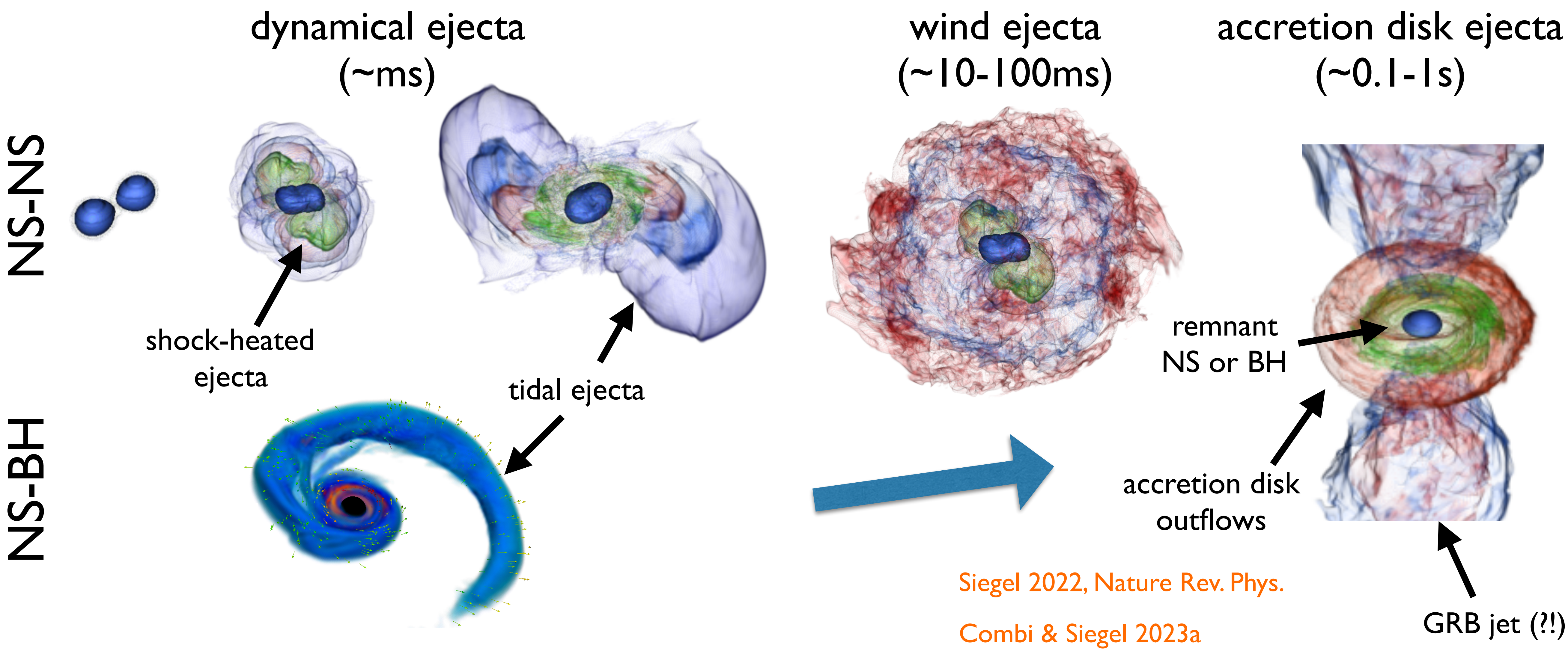
Some complications for NS-NS (complex post-merger phenomenology):

- plasma instabilities (Kelvin-Helmholtz, Rayleigh-Taylor, Magnetorotational Instability)
- MHD effects, weak interactions, neutrino quantum kinetics, equation of state effects, …
- dynamical spacetime, gravitational waves, non-linear (magneto-)hydrodynamics

Chen+ 2021

Contribution to Galactic r-process from NS-BH systems likely subdominant to irrelevant

EM counterparts are powered by matter outflows

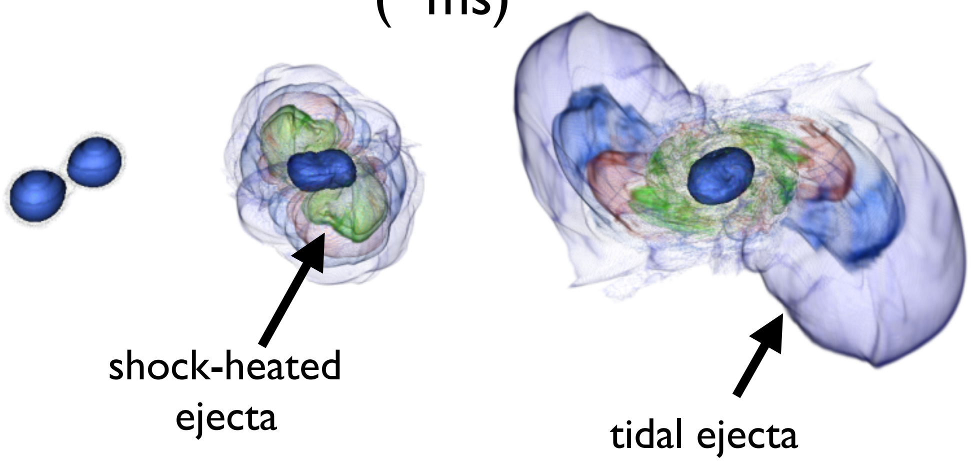


- Complex post-merger physics not well understood
- Interpretation of future observations need ab-initio modeling of non-thermal and thermal electromagnetic emission
- Key to understand central engines of gamma-ray bursts
- Key to understand synthesis of heavy elements

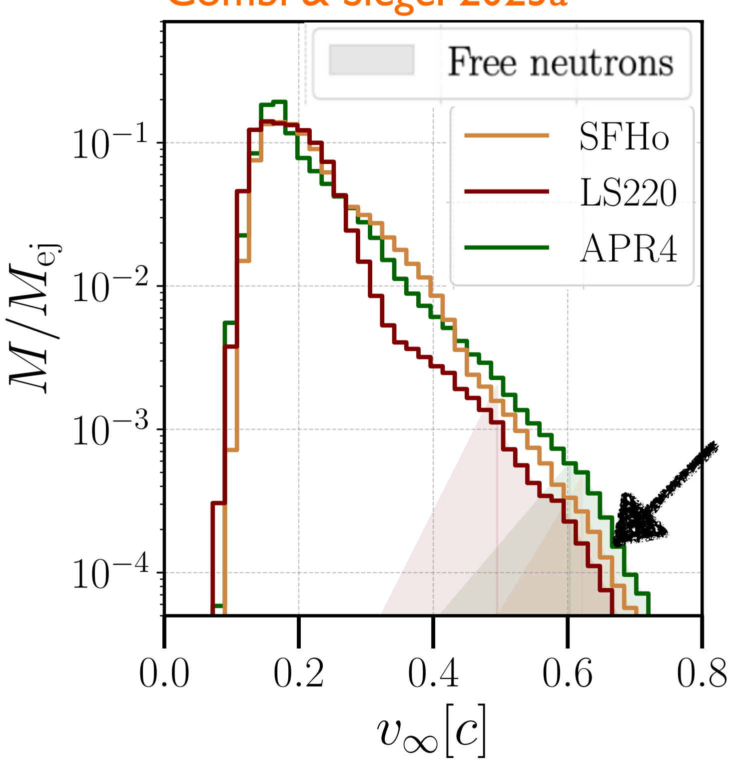
1 Electromagnetic counterparts of dynamical ejecta

Fast dynamical ejecta

dynamical ejecta
(~ms)

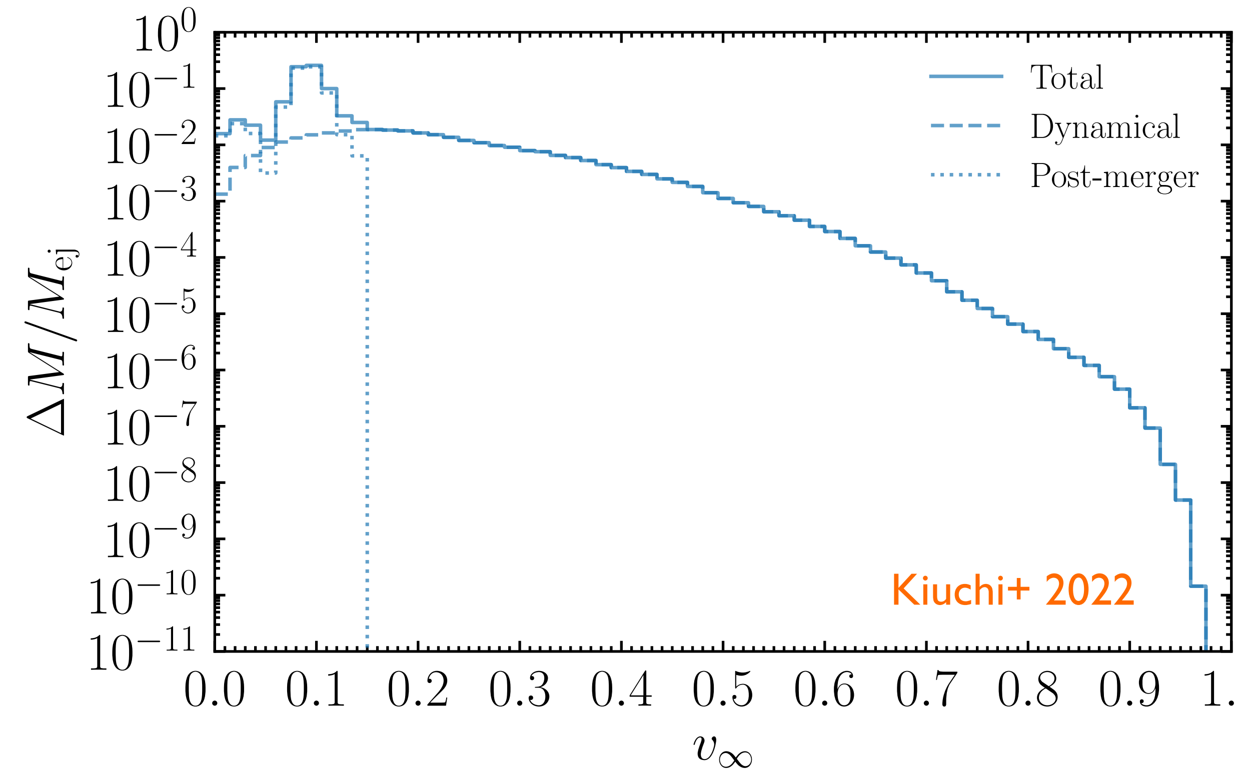


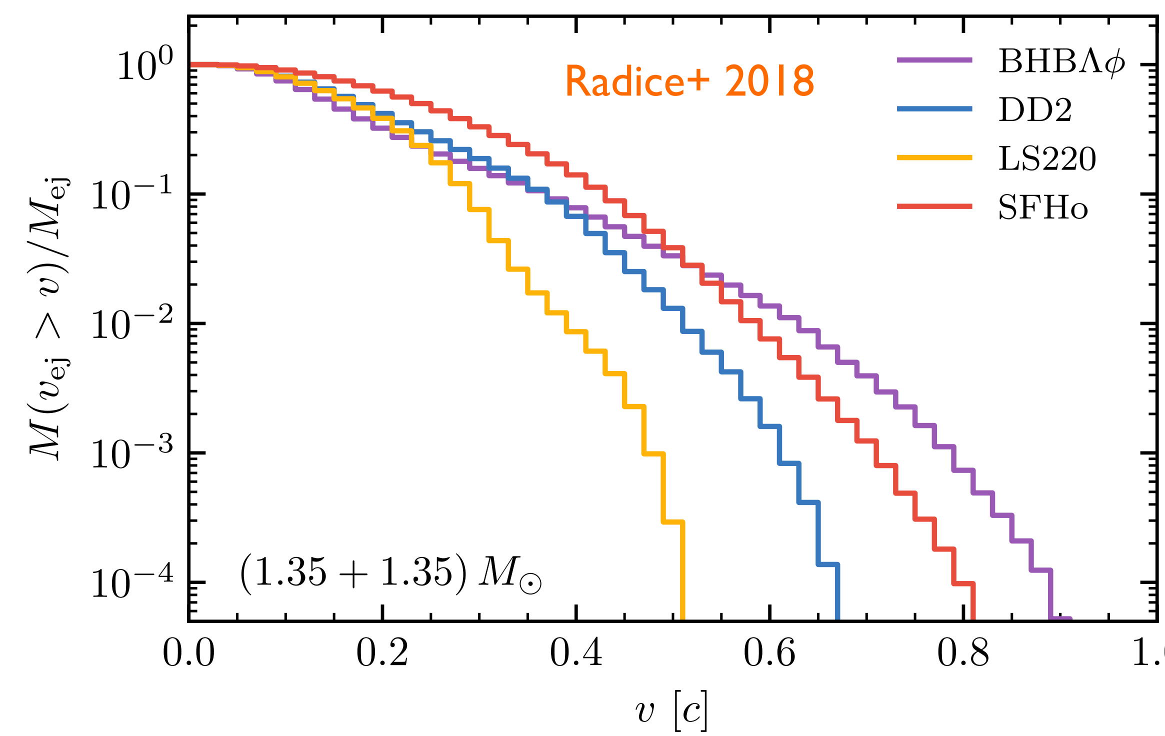
Combi & Siegel 2023a



~5x10^{-6} M_{sun}
>0.6c ejecta

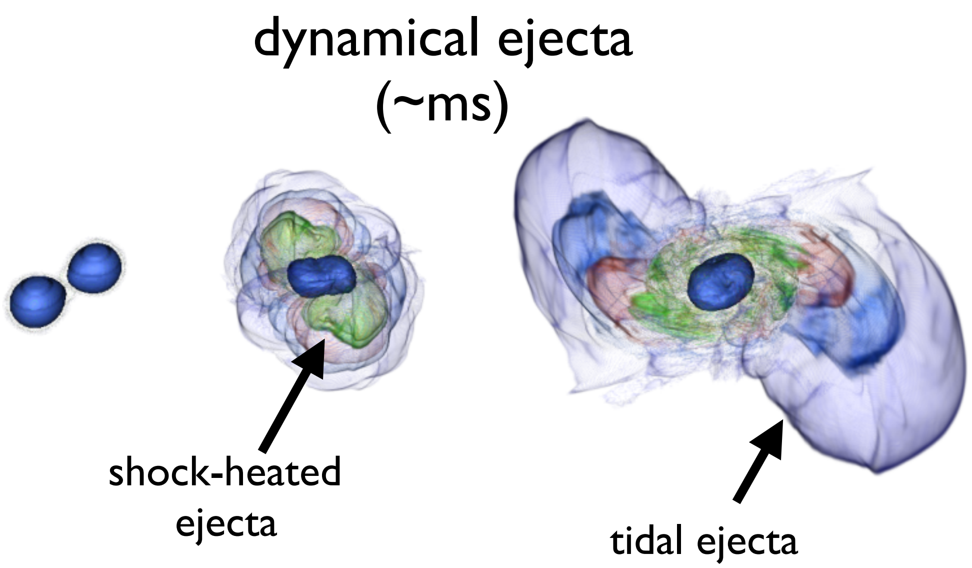
fast, high-Y_e (>0.25), shock-heated ejecta drives shock wave into the ISM



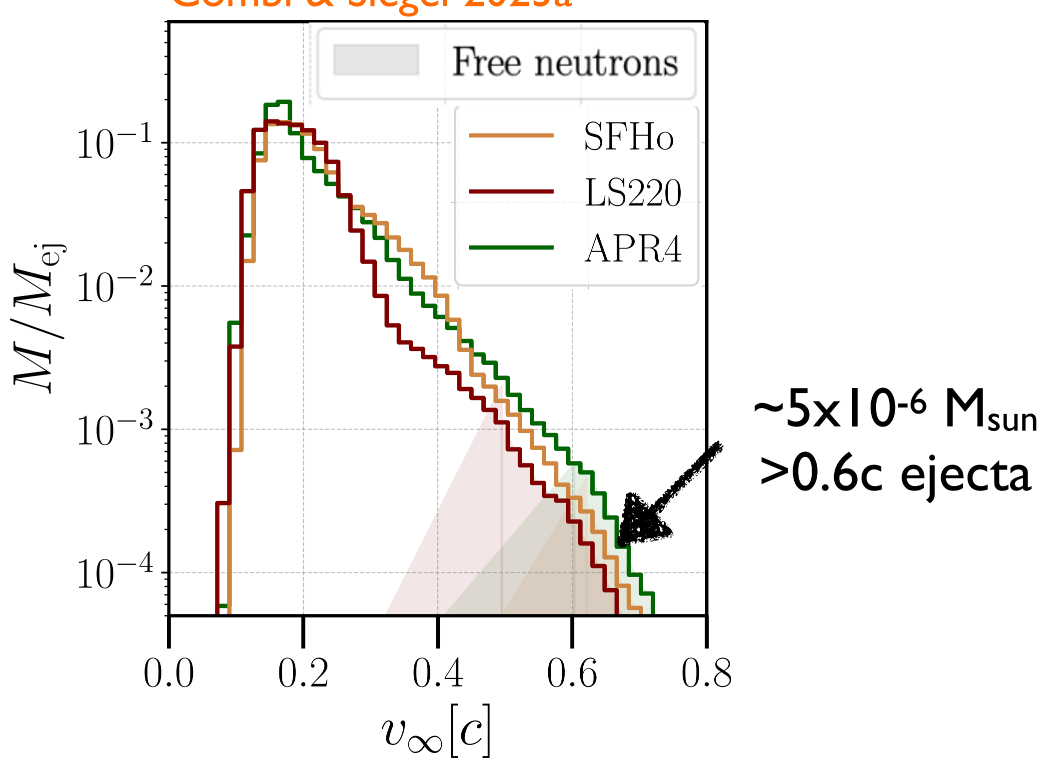


See also: Hotokezaka+ 2018, Dean+ 2021

Fast dynamical ejecta: X-ray to radio afterglow

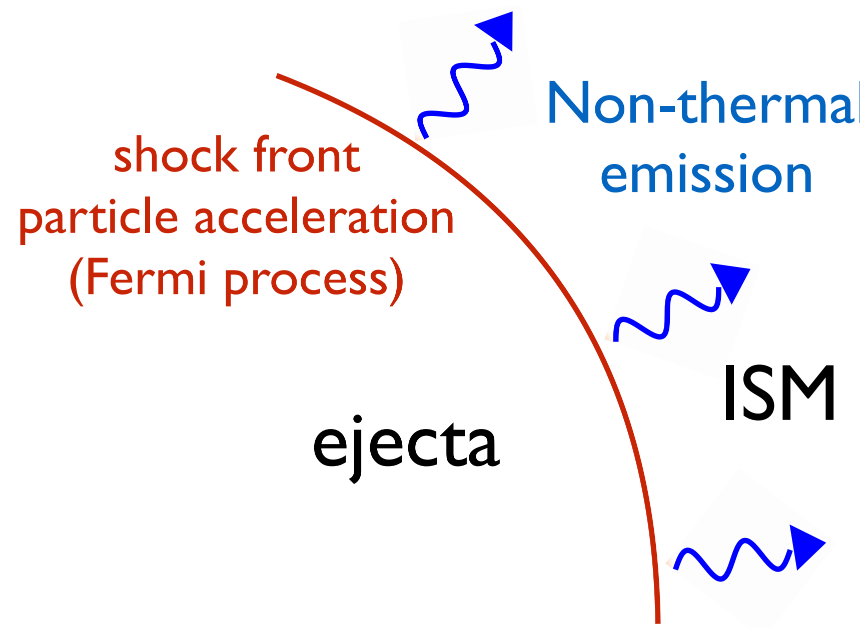


Combi & Siegel 2023a



- fast, high-Y_e (>0.25), shock-heated ejecta
- GW170817: source of X-ray-radio afterglow, timescale of years

→ Helps distinguish BNS vs. NS-BH nature of event

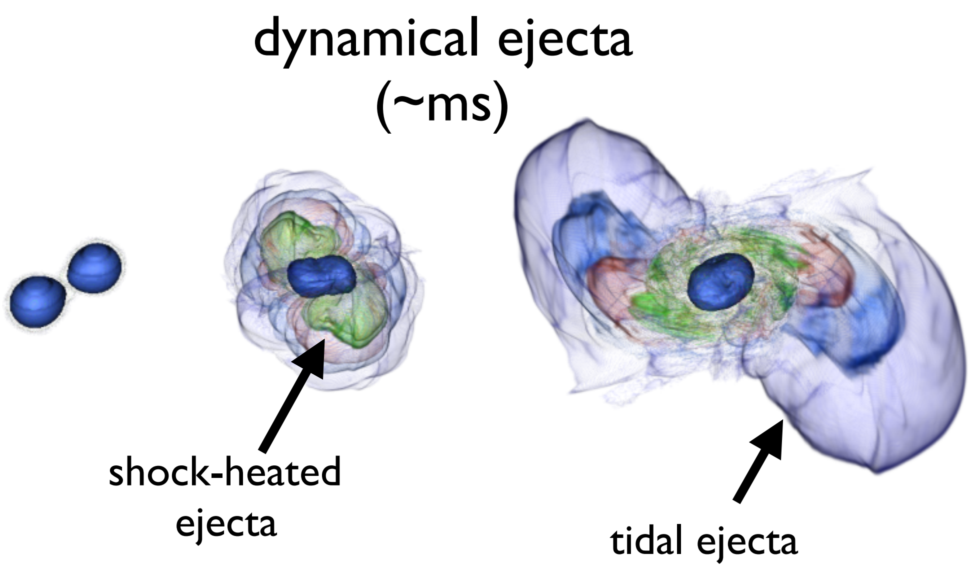


$$\frac{\partial n_e(\gamma_e, t)}{\partial t} = -\frac{\partial}{\partial \gamma_e}[\dot{\gamma}_e(\gamma_e, t) n_e(\gamma_e, t)] + Q(\gamma_e, t) - \frac{n_e(\gamma_e, t)}{t_{\rm esc}}.$$

- Full numerical solution of Fokker-Planck equation

  (Syn+IC cooling, Syn self-Compton, self-absorption)
- angle dependent
- relativistic effects

Fast dynamical ejecta: X-ray to radio afterglow



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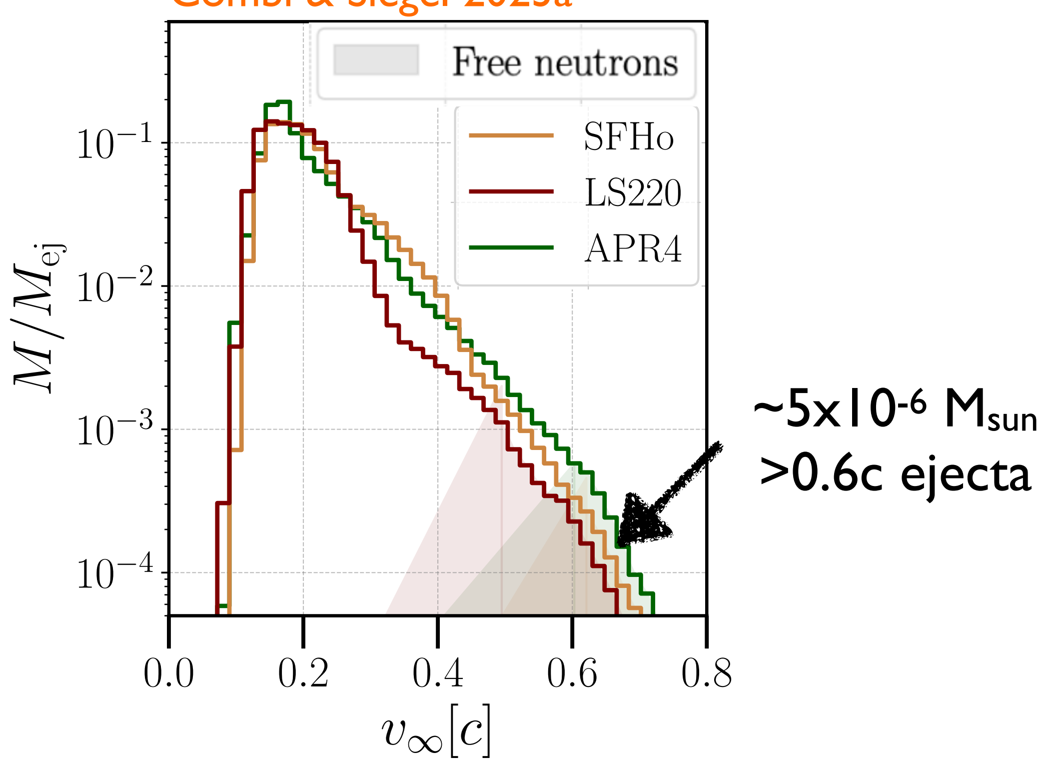

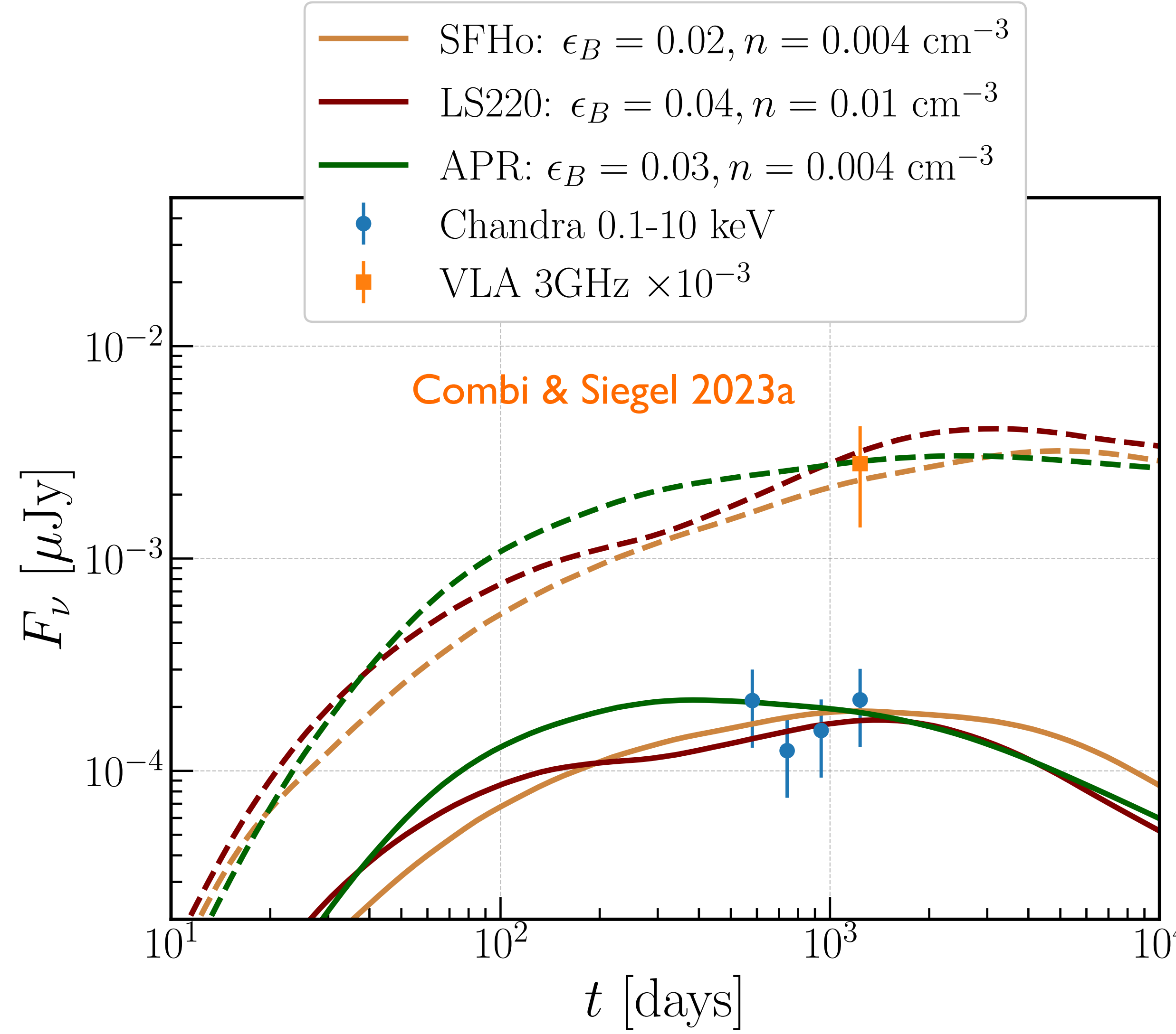

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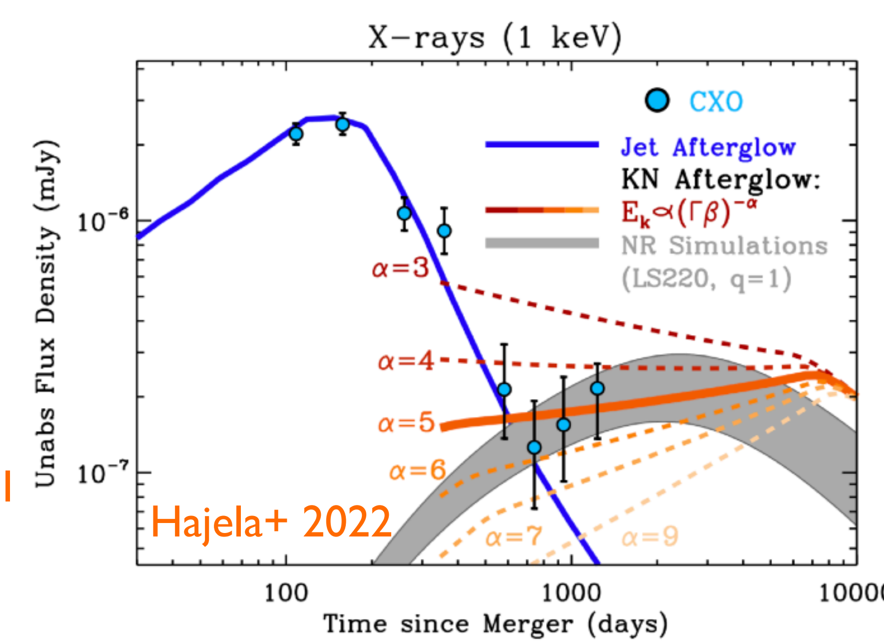
Hajela+ 2022
Troja+ 2022
Ryan+ 2024
Balasubramanian+ 2021
Nedora+ 2021



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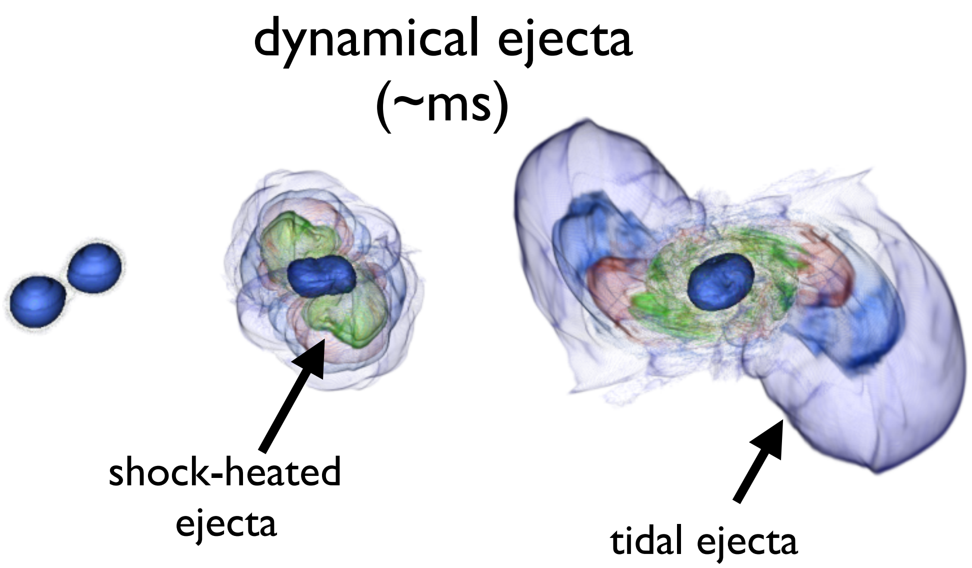
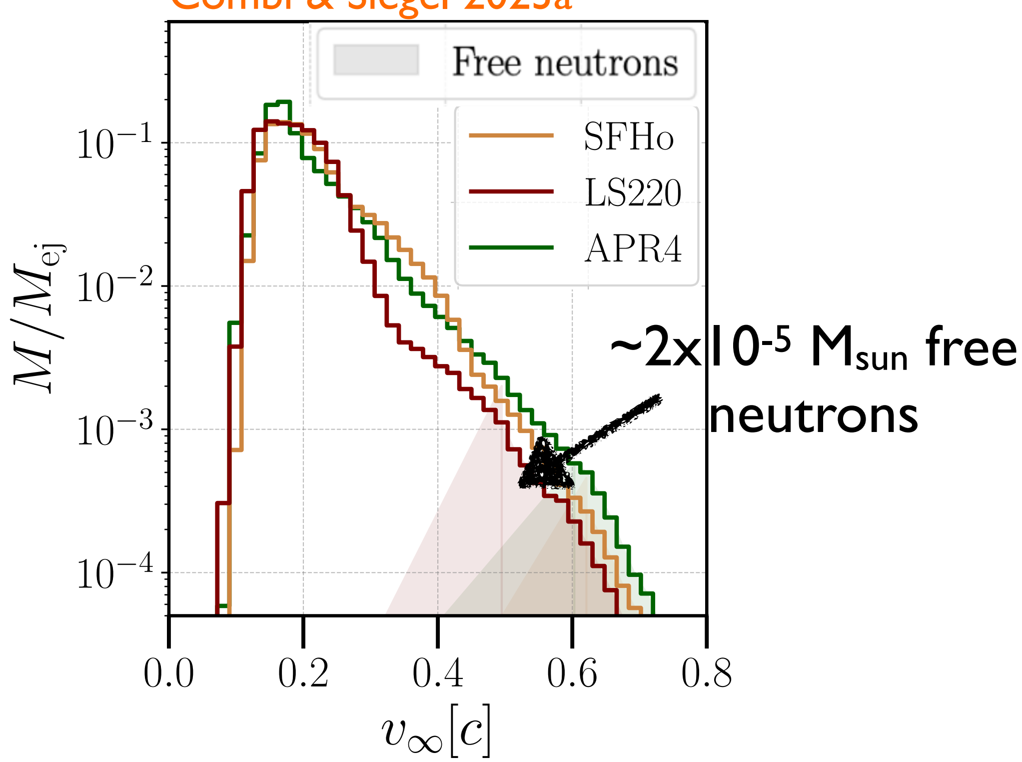
Fast dynamical ejecta: neutron precursor



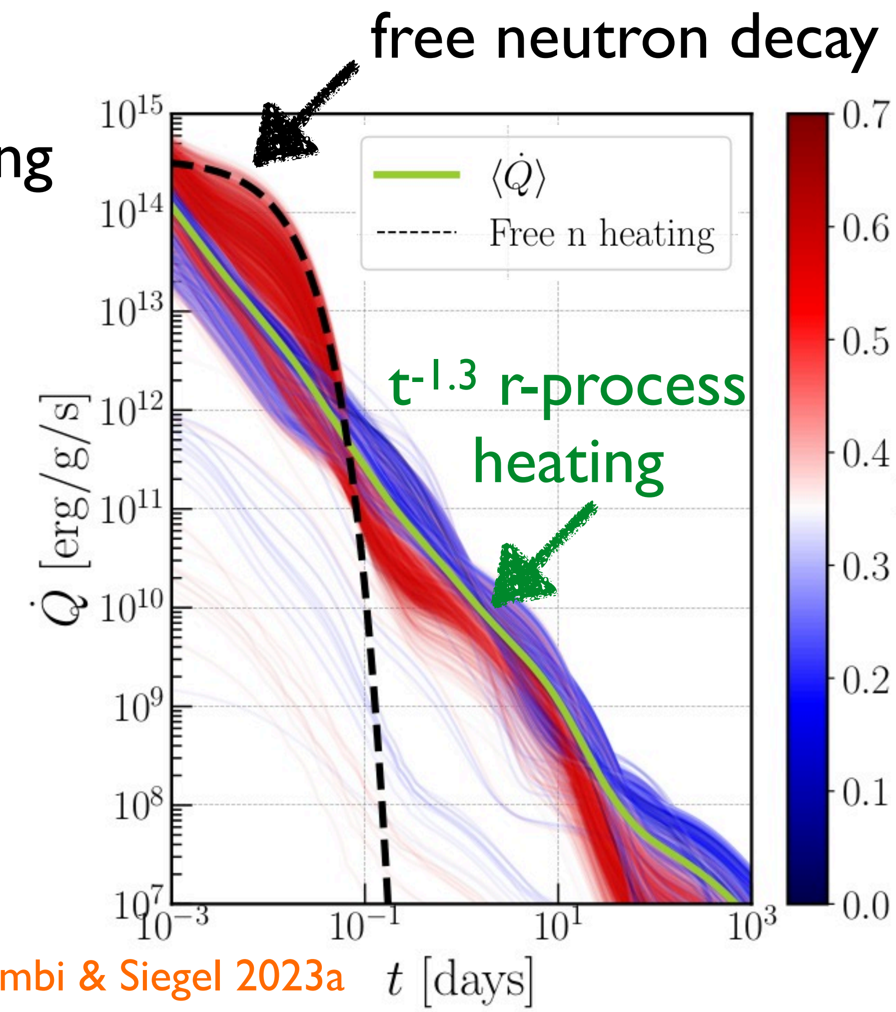
Combi & Siegel 2023a



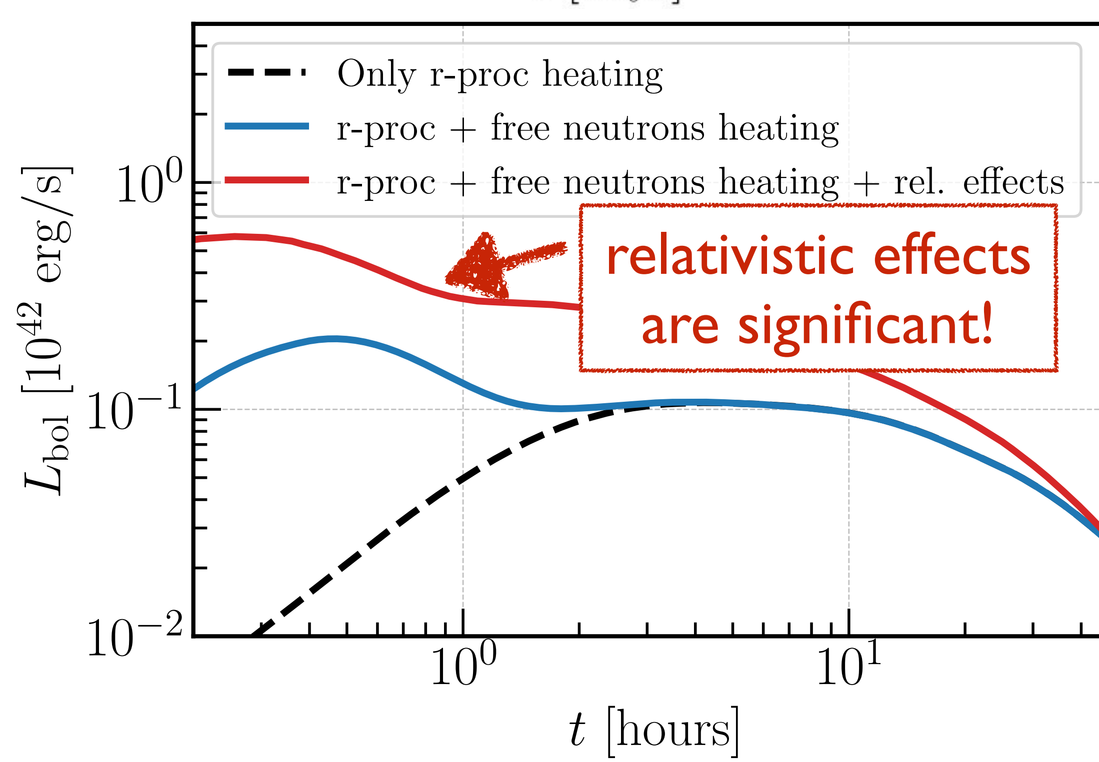
fast, high-Y_e (>0.25), shock-heated ejecta leads to free neutrons

⟶ early UV emission ≲hours ('neutron precursor') Metzger+ 2015

Nuclear heating in ejecta



Combi & Siegel 2023a



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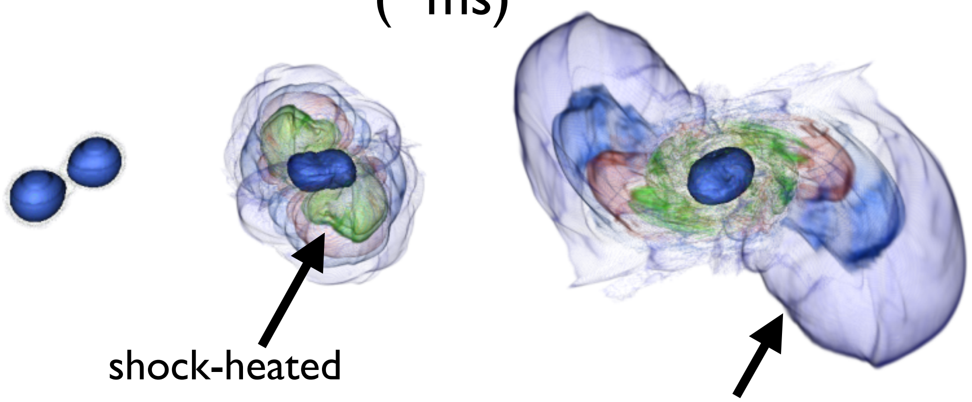
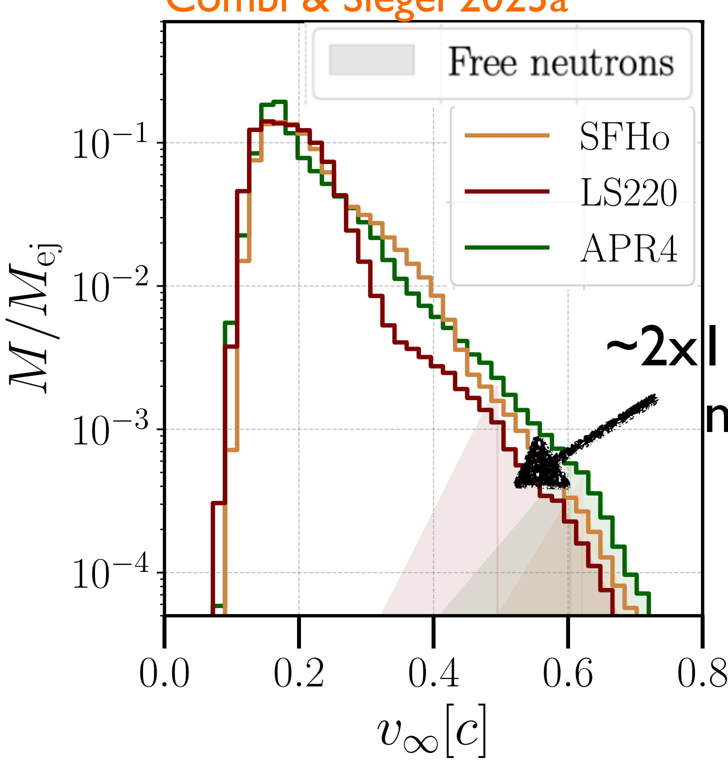
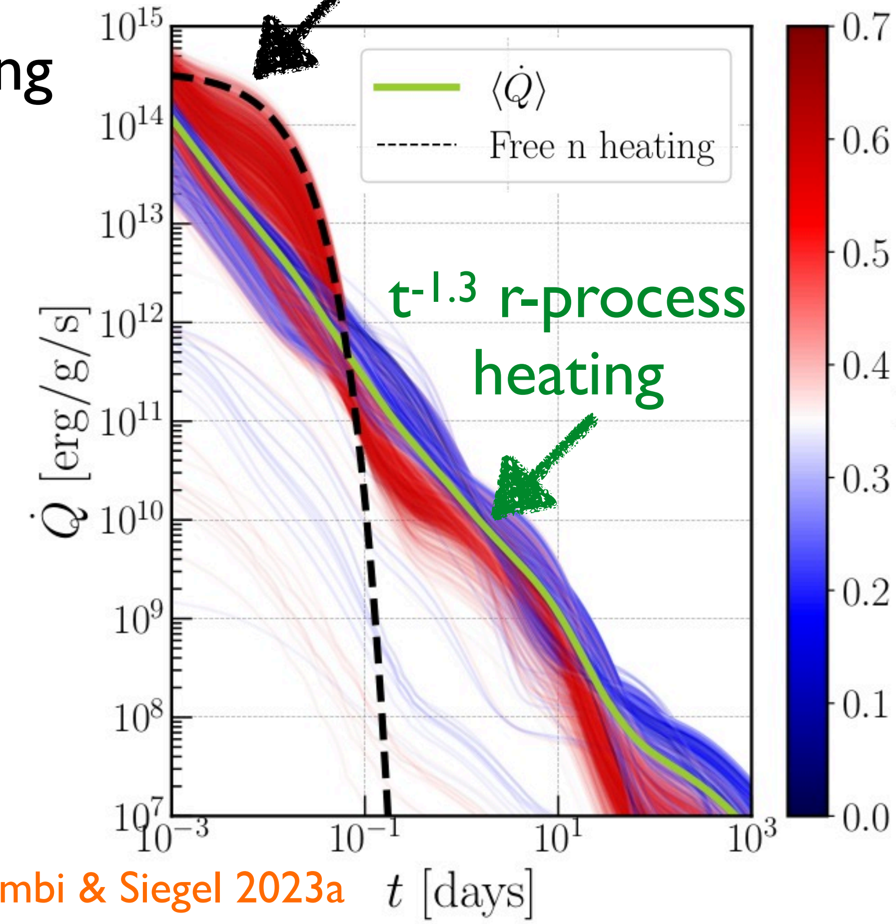


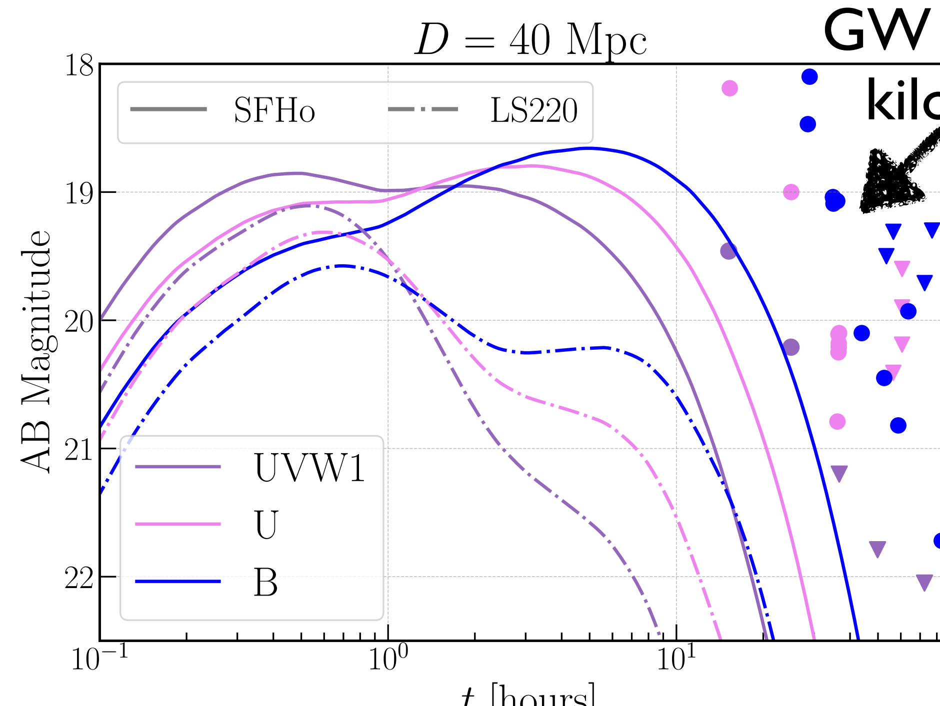
Combi & Siegel 2023a



Nuclear heating in ejecta



Combi & Siegel 2023a



fast, high-Y_e (>0.25), shock-heated ejecta leads to free neutrons

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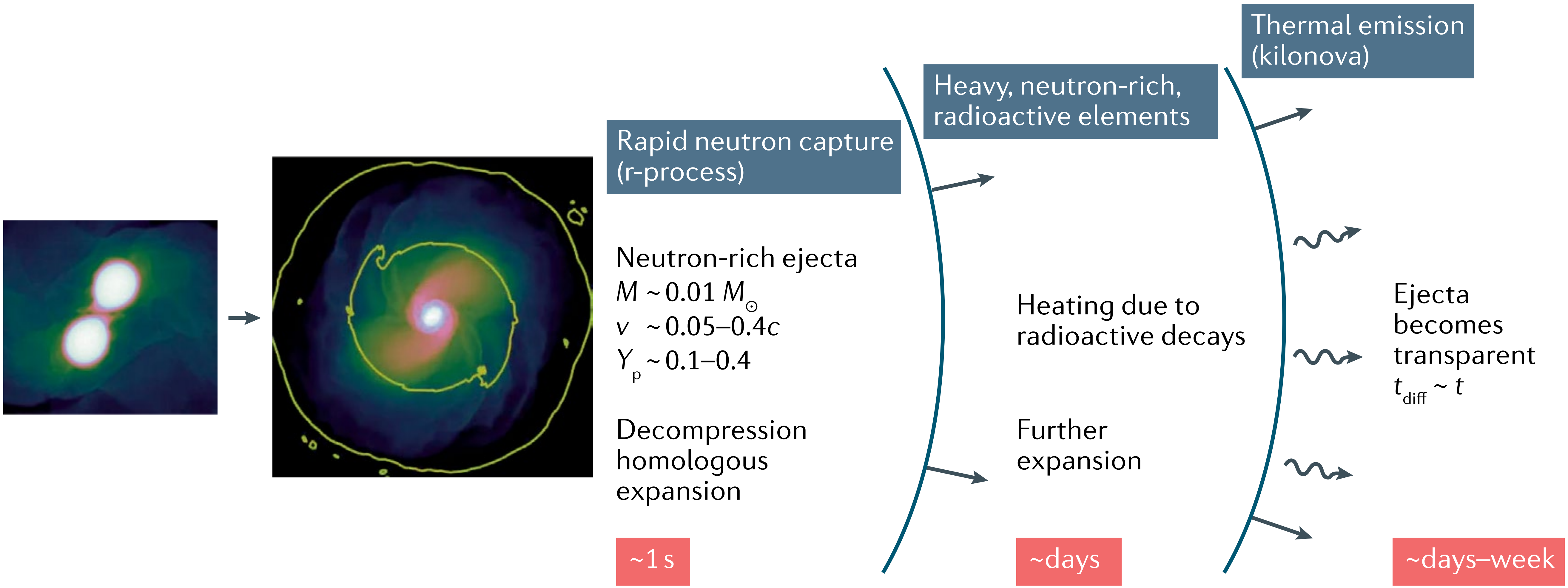
II Post-merger physics:
Jets & kilonovae

Kilonovae—illuminating merger ejecta

Metzger+ 2010



Siegel 2022, Nature Rev. Phys.

- Ejecta parameters: mass, velocity, composition (Y_e)
- Kilonova emission (color: 'red' vs. 'blue') very sensitive to composition/weak interactions (high opacities of lanthanides)

$$e^+ + n \rightleftharpoons p + \bar{\nu}_e, \quad e^- + p \rightleftharpoons n + \nu_e$$

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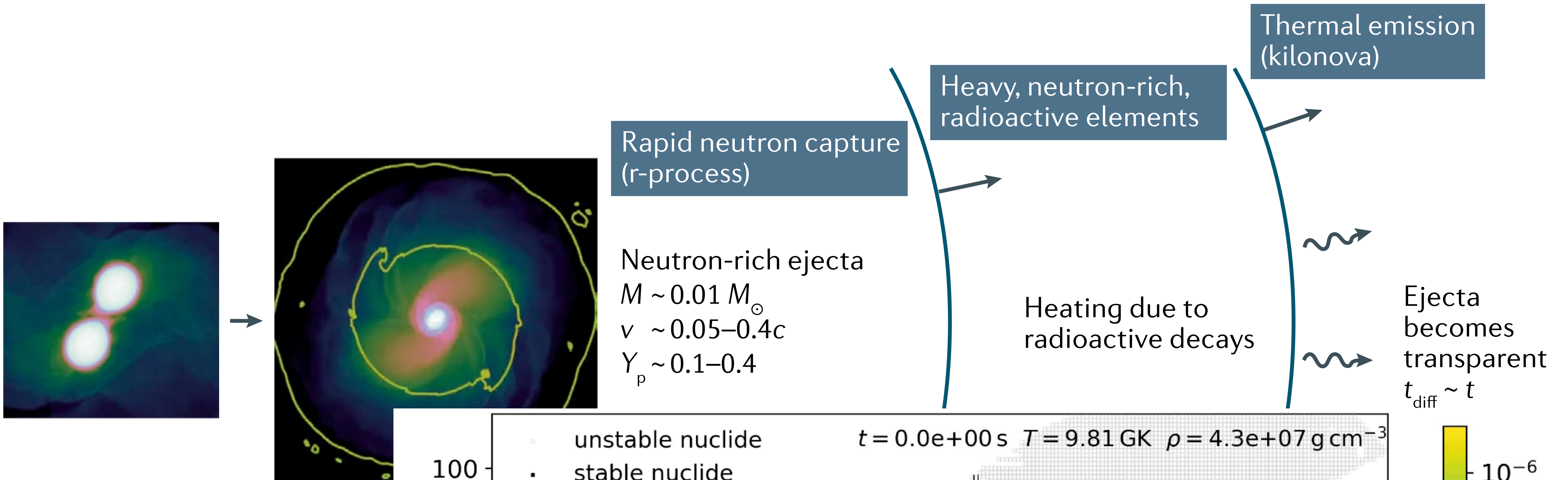
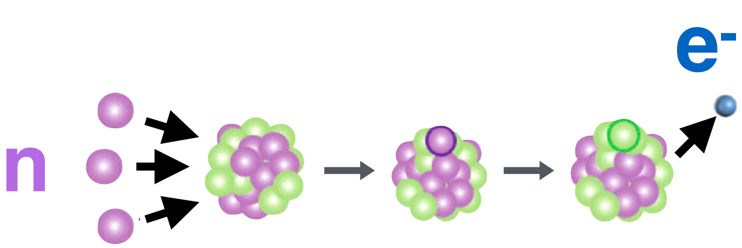
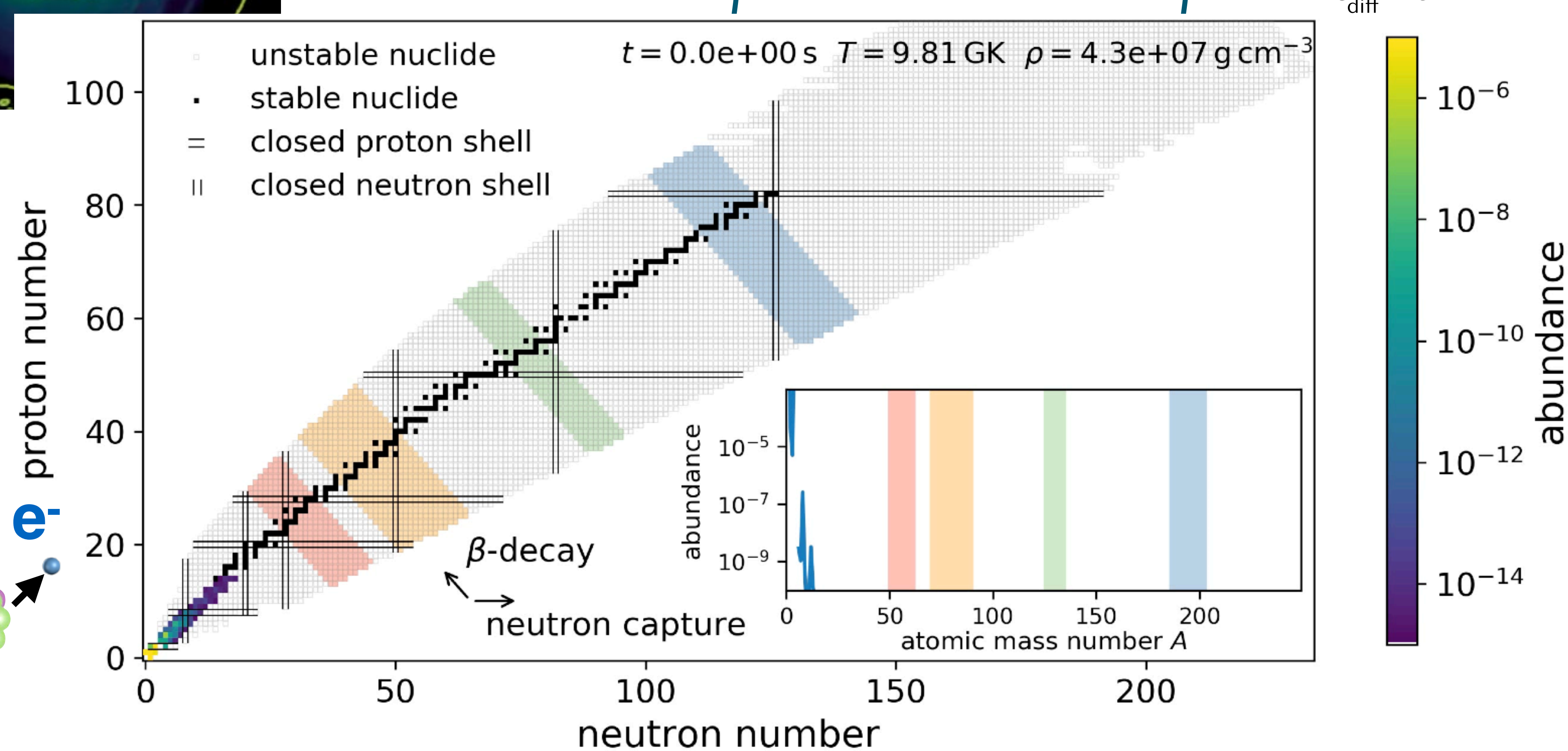


Rapid neutron capture

r-process: timescale for neutron capture shorter than for β-decay





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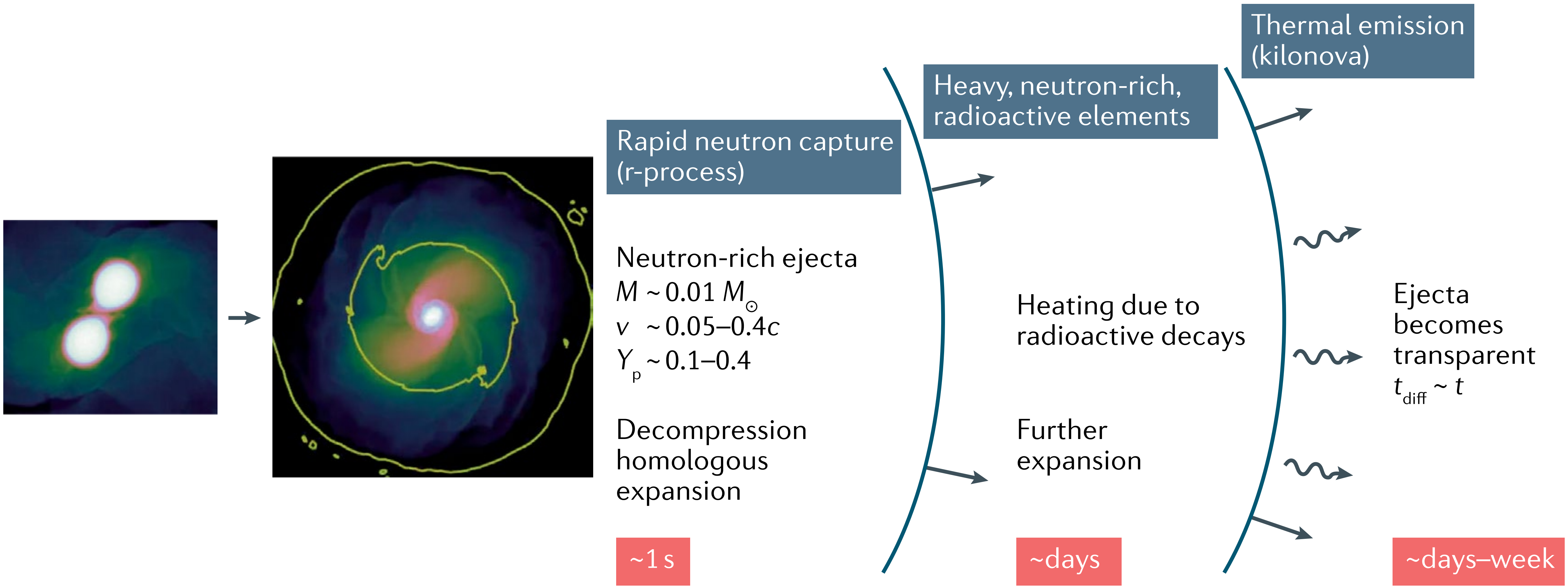

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High opacities of the Lanthanides

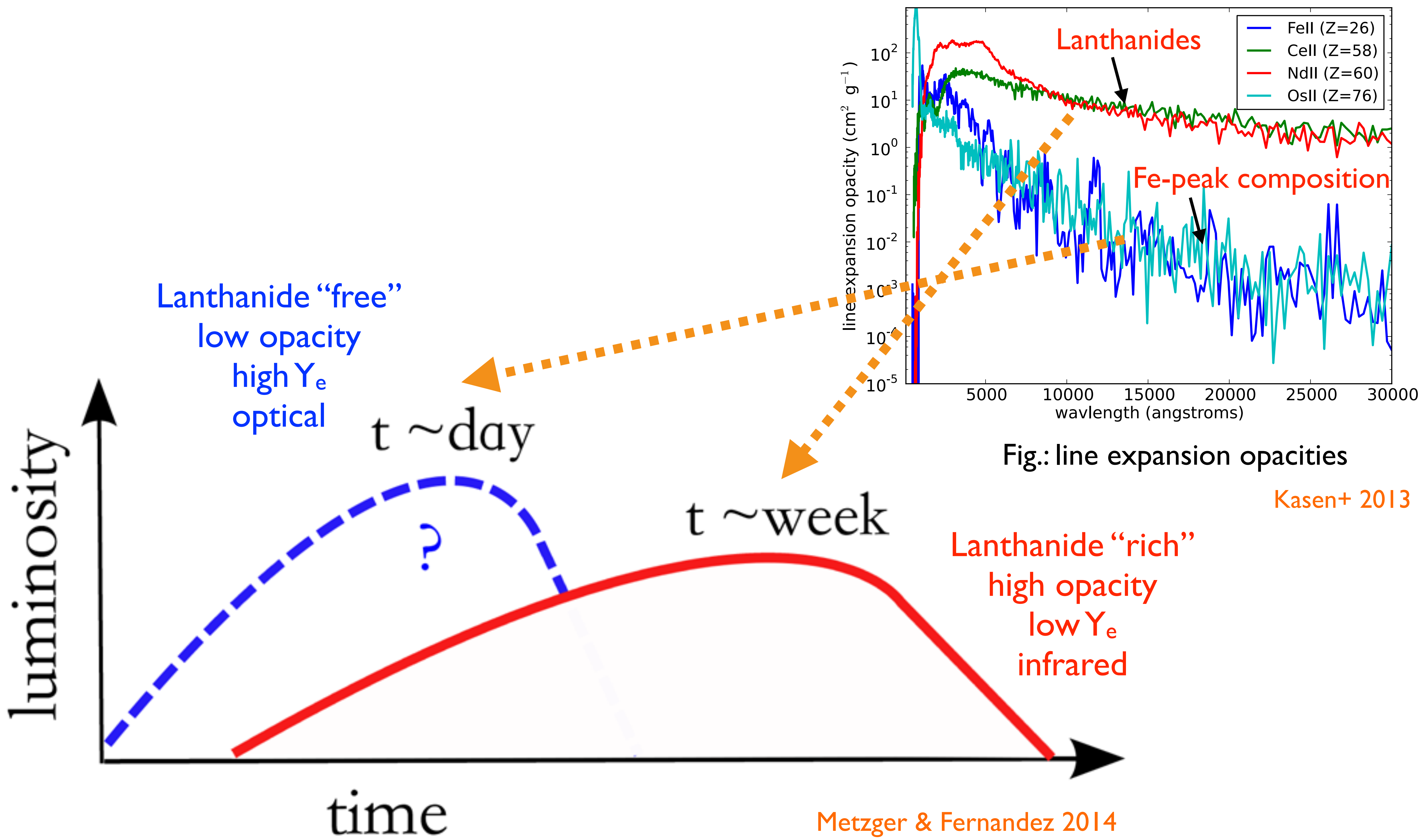


Fig.: line expansion opacities

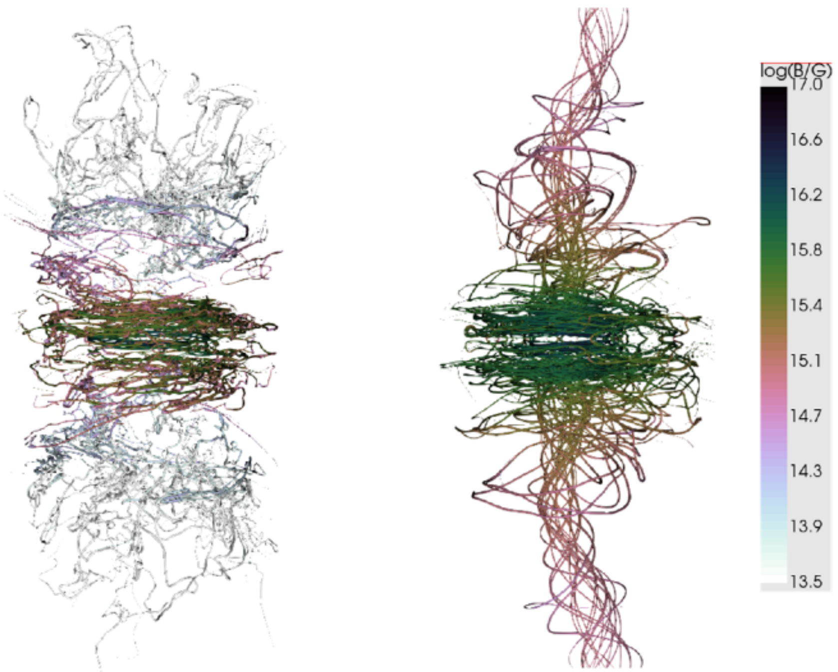
Kasen+ 2013

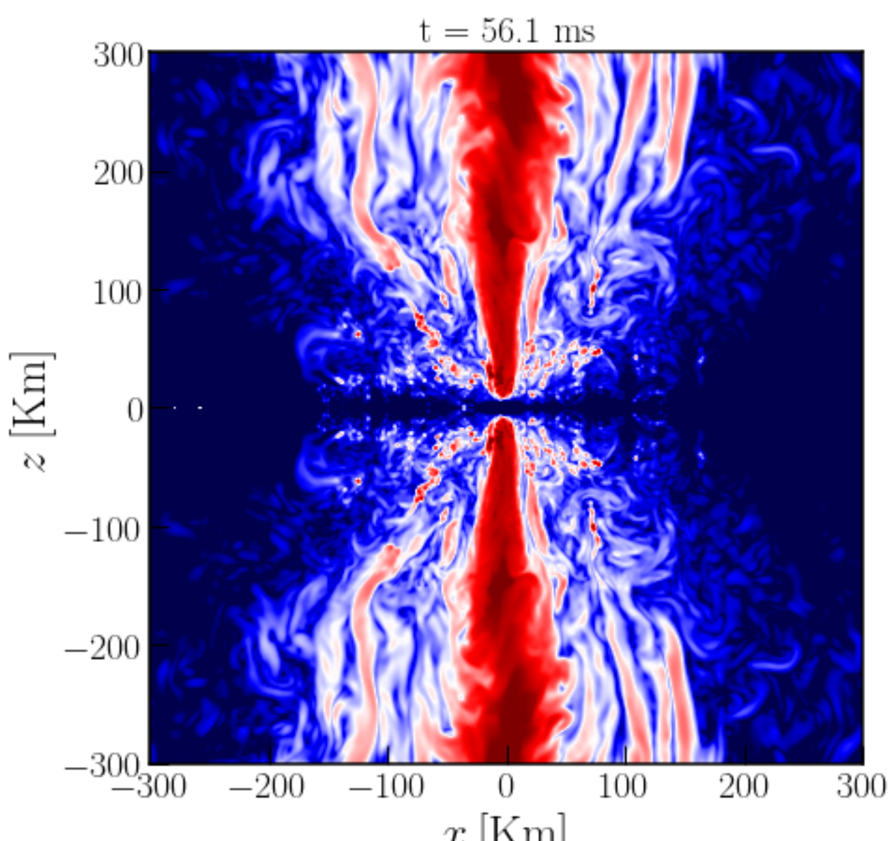
Metzger & Fernandez 2014

Fig.: kilonova lightcurves probe composition (Lanthanide mass fraction).

Post-merger physics: GRB jets & kilonovae

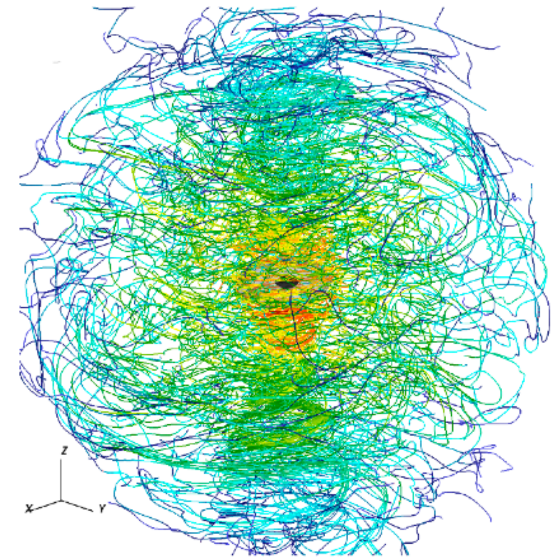
Combi & Siegel 2023b, PRL





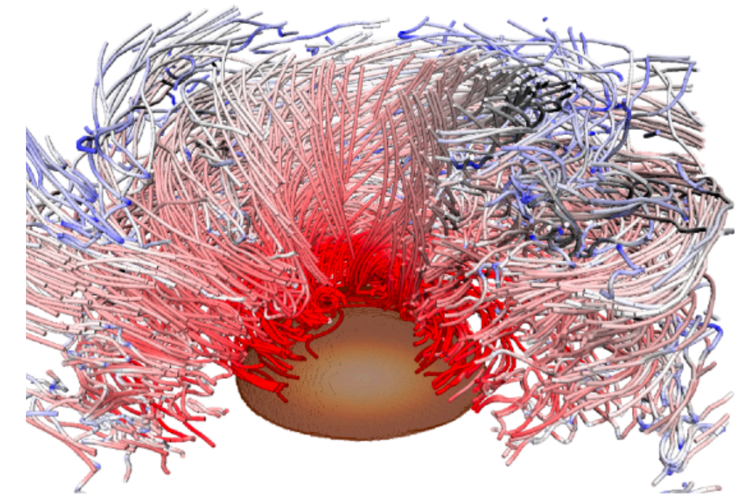
Aguilera-Miret+ 2023

(GRMHD+LES, no weak interactions; late-time structures)



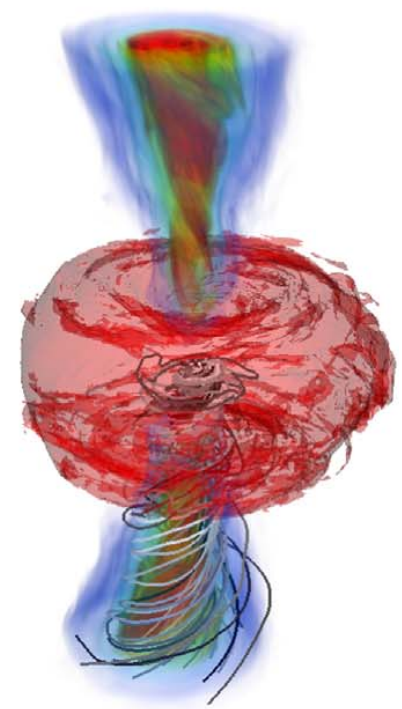
Kiuchi+ 2024

(high-res GRMHD, structure attributed to MRI in remnant envelope/disk)



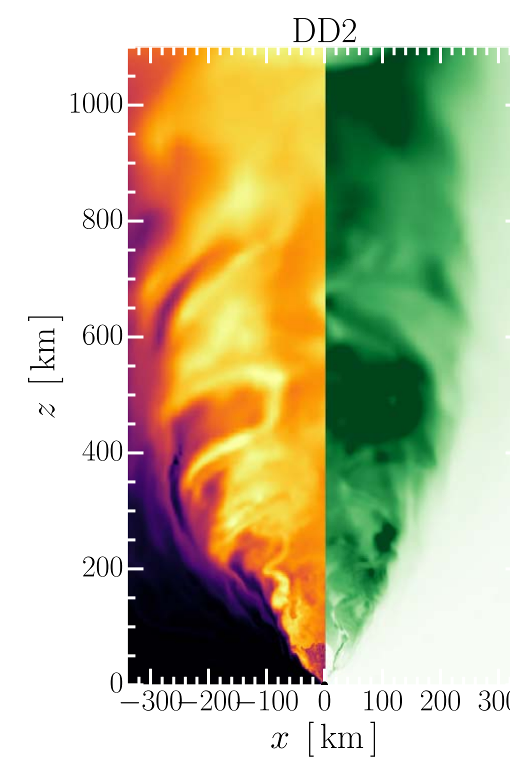
Mösta+ 2020, Curtis+ 2023

(starting with large-scale poloidal field post-merger)

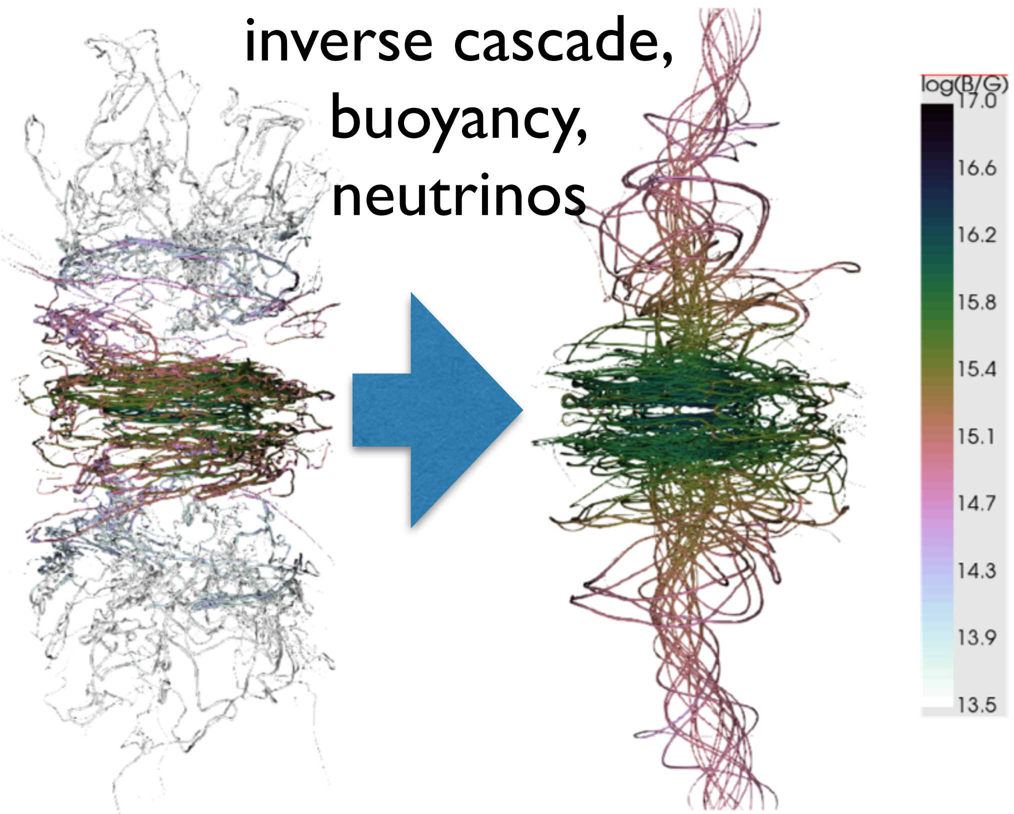


Most & Quataert 2023

(using α-dynamo)



Post-merger: B-field amplification

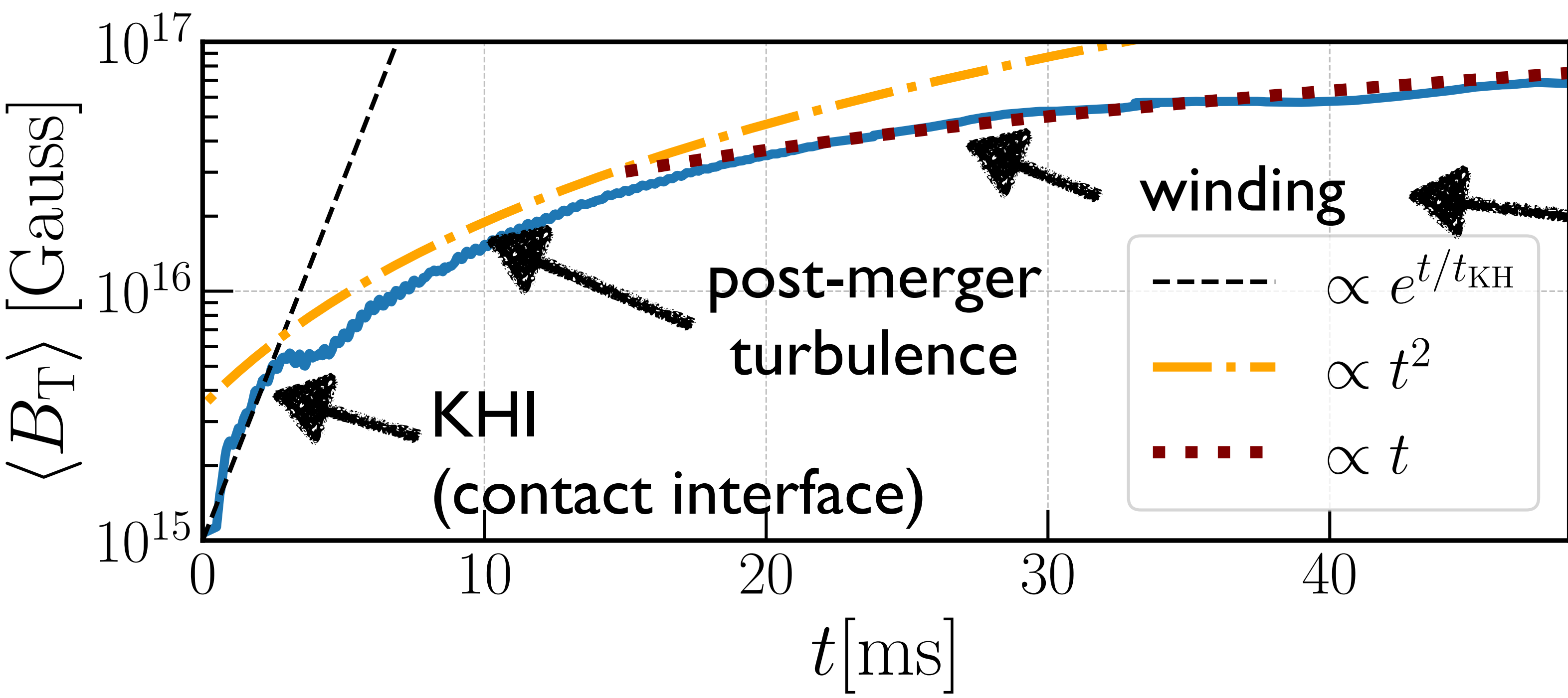


Combi & Siegel 2023b, PRL

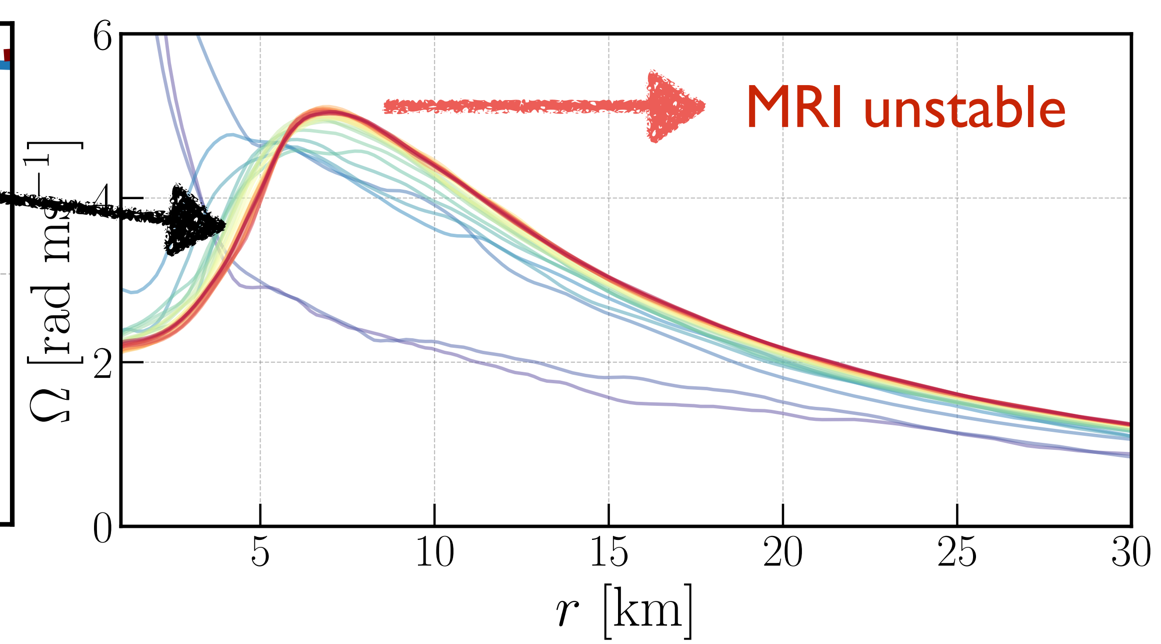
Magnetic field amplification during merger & within remnant:

- Kelvin-Helmholtz instability (KHI)
- Turbulence stirred by double-core bounces
- Magnetorotational Instability (MRI; envelope + disk)
- magnetic winding

toroidal magnetic field amplification

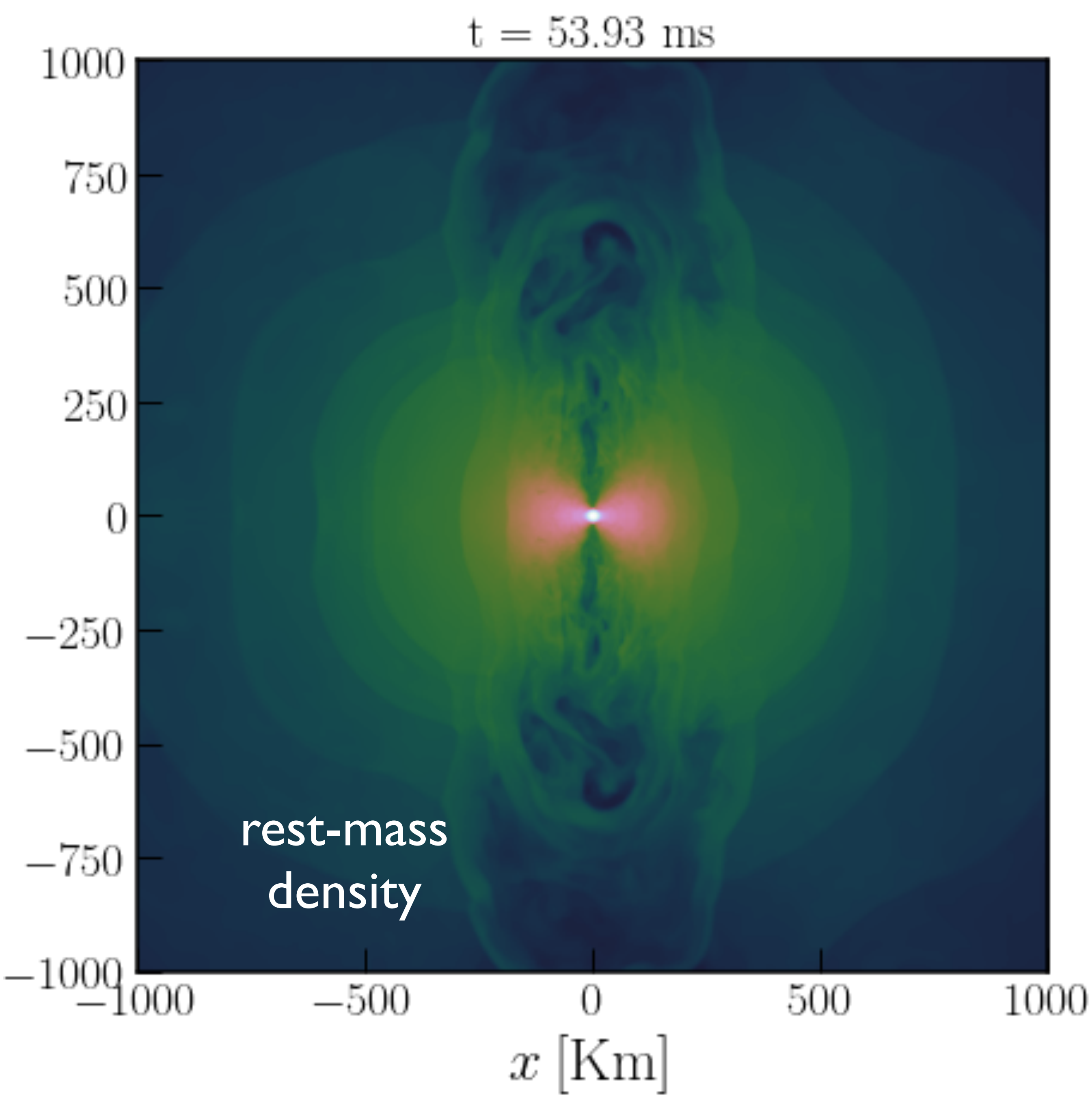


angular rotation profile



GRB central engines: Jet from NS remnant

Combi & Siegel 2023b, PRL



- Neutrino absorption in polar regions helps generating magnetic tower and 'stabilizing' jet structure

- Self-consistent formation of a 'jet' from a remnant NS
  $\sigma = L_{\rm EM}/\dot{M} \sim 5 - 10$

- Maximum terminal Lorentz factor
  $\Gamma \lesssim -u_0(h/h_\infty + b^2/\rho) \approx 5 - 10$

- Jet head propagates with v ~ 0.6c through dynamical ejecta and breaks out by ~50ms

- Jet luminosity: $L_{\rm EM} \sim 10^{52}$ erg/s

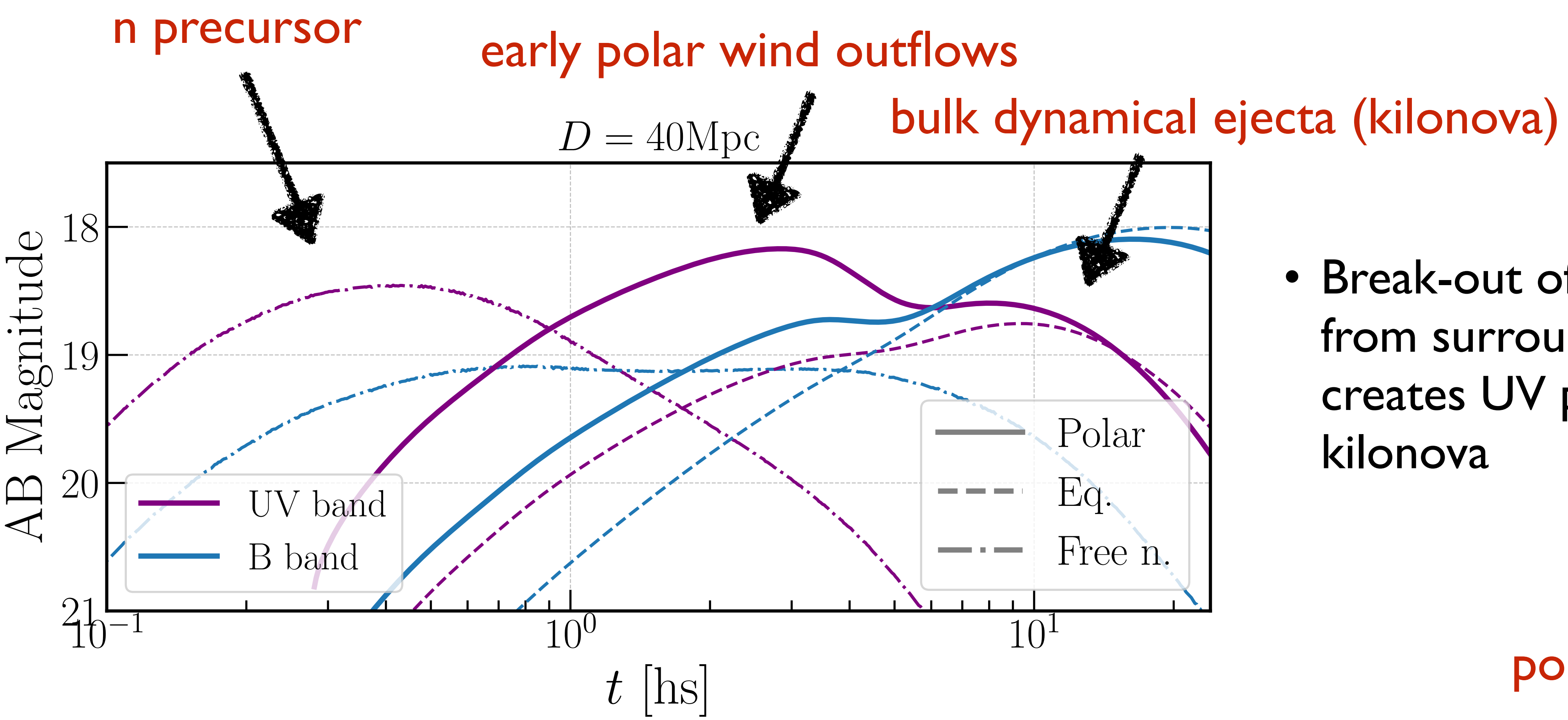
→ NS able to power short GRBs ?!

→ Short GRB precursors?

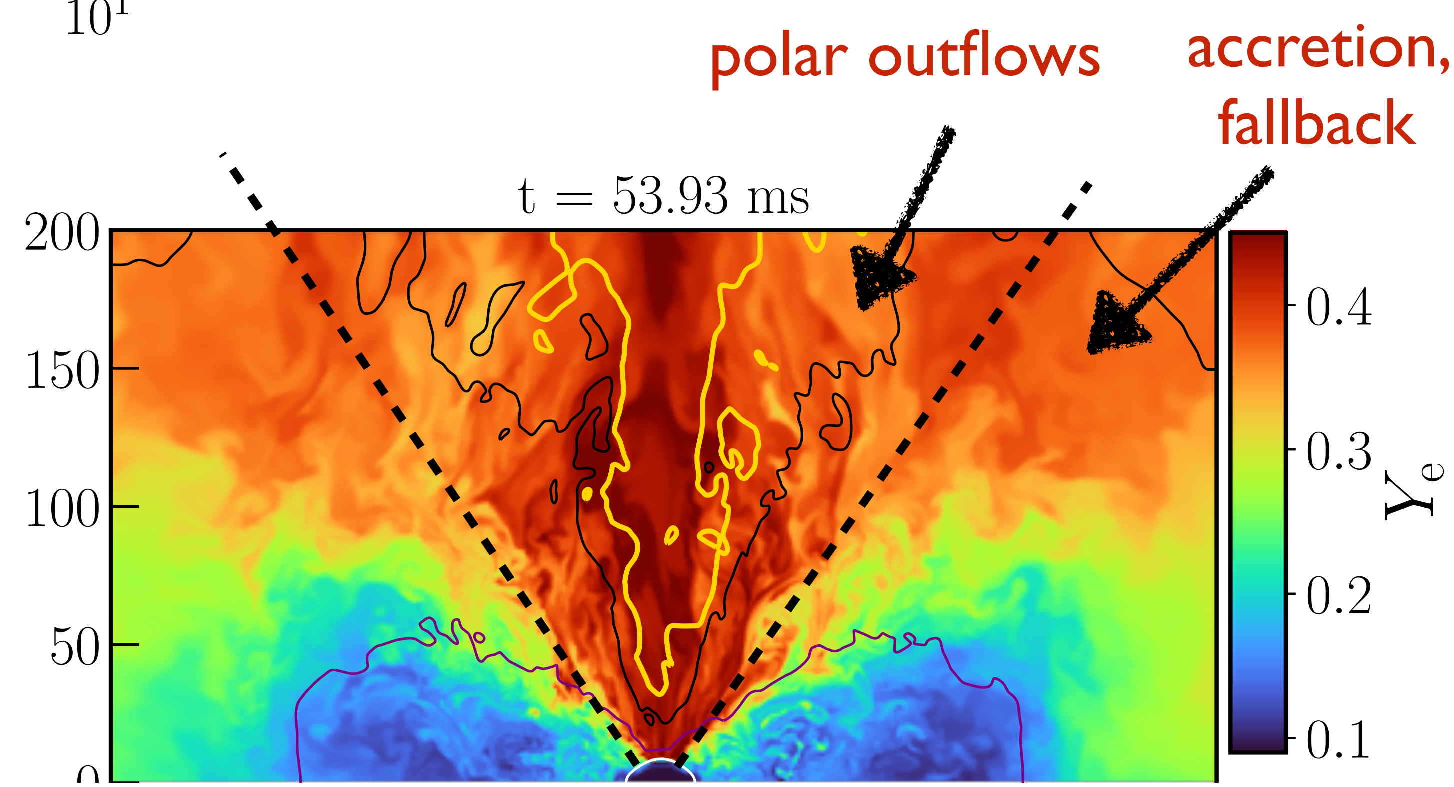
→ *Novel BH GRB jet formation mechanism:* NS jet 'seeds' BH jet

Polar MHD outflows: UV/blue precursor

Combi & Siegel 2023b, PRL

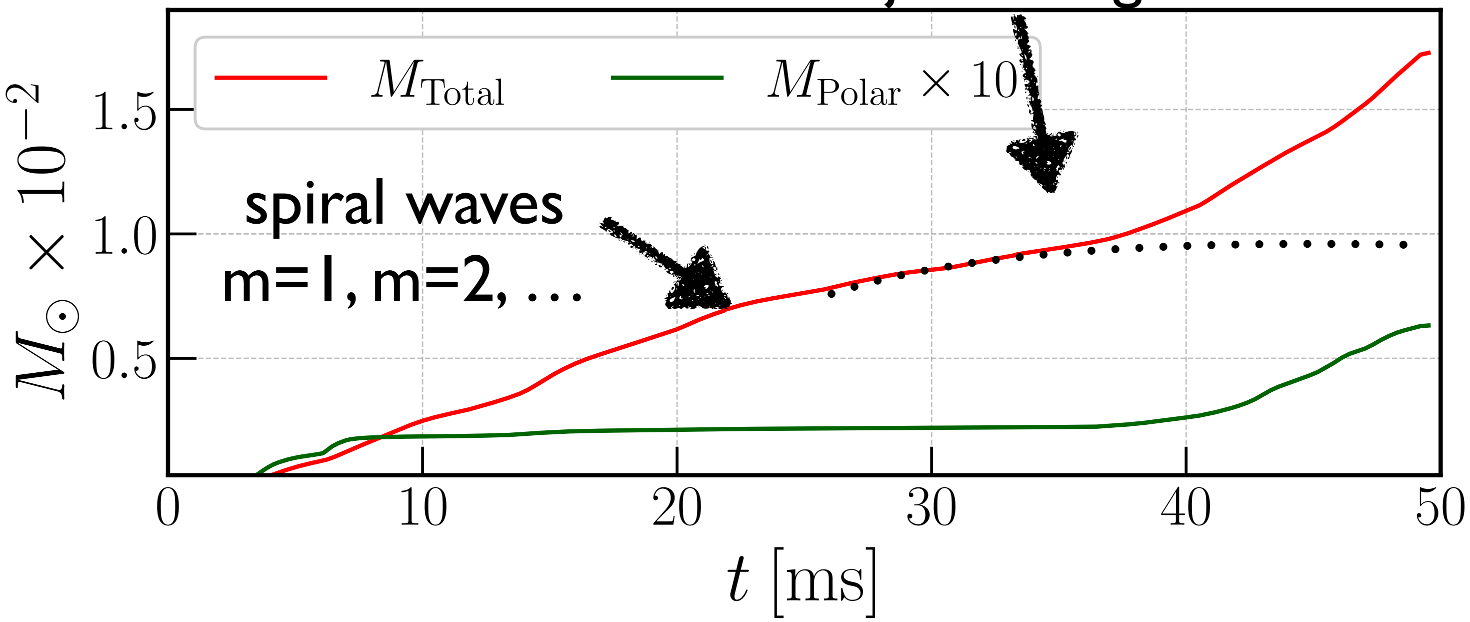


- Break-out of fast polar wind material from surrounding dynamical ejecta creates UV precursor signal to the kilonova



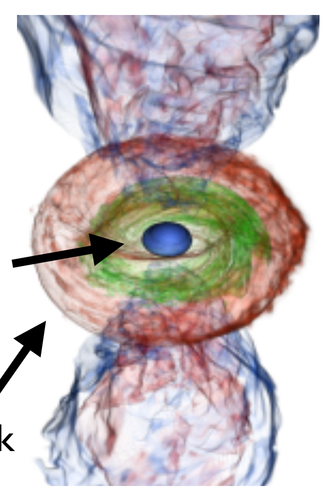
Post-merger disk evolution & outflows

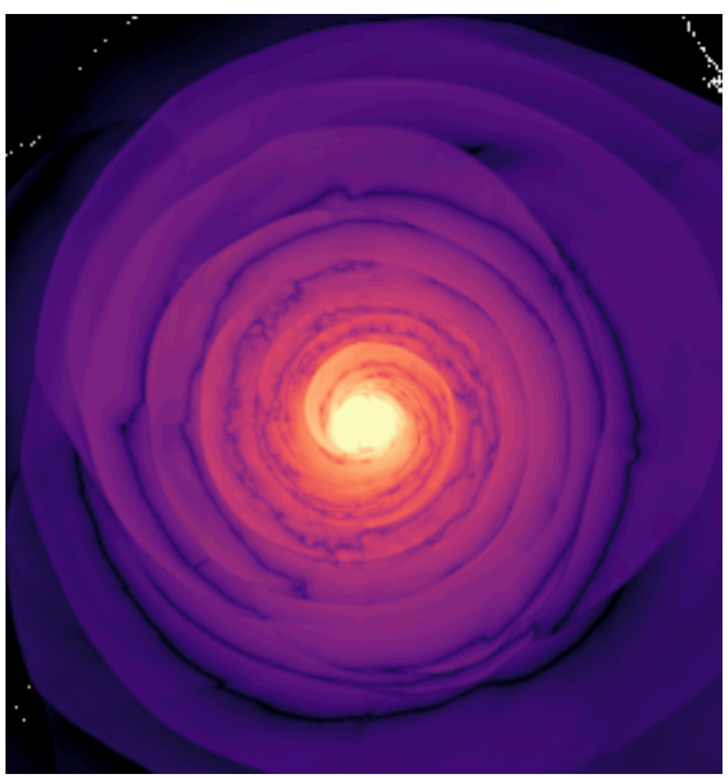
Combi & Siegel 2023b, PRL

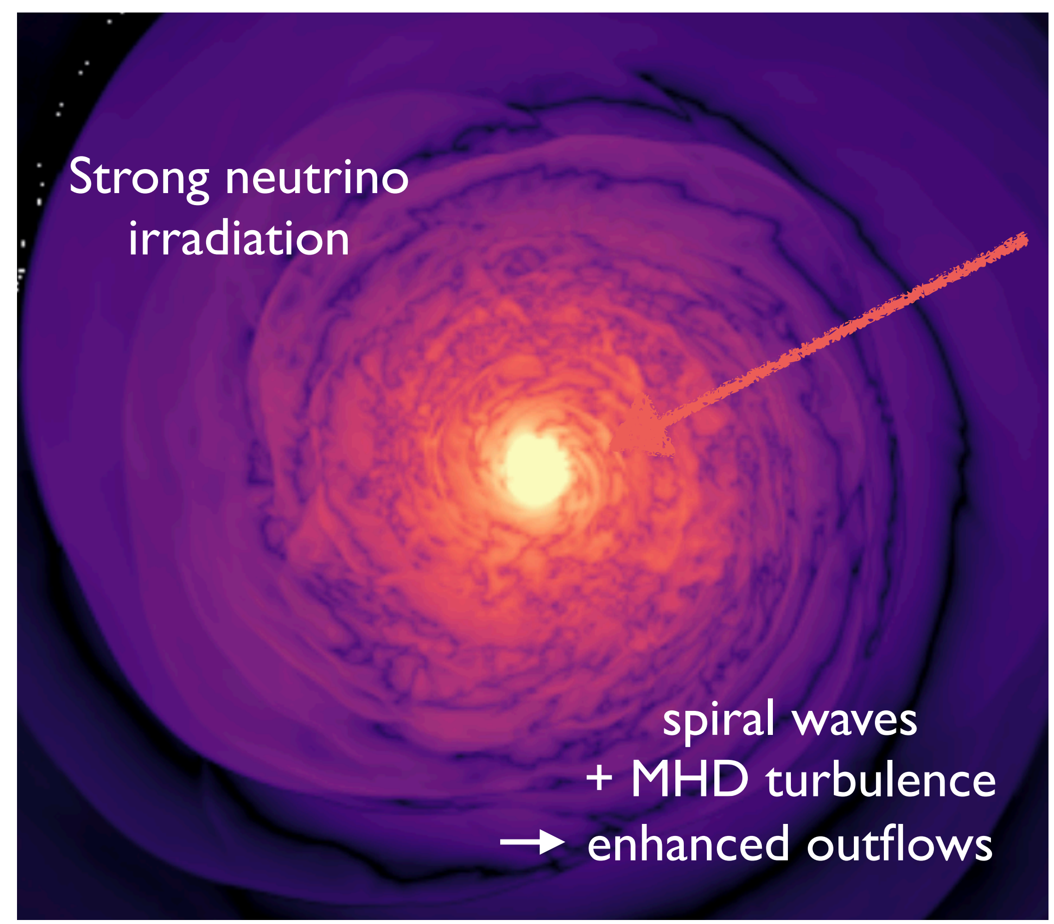


- t < 35ms mass ejection dominated by non-axisymmetric modes
  Nedora+ 2019, 2021
- Strong boost once MHD turbulence sets in (t > 40ms), reaching 2×10^{-2} M_{sun} within 50ms post-merger
- Accretion disk rapidly spreads radially due to enhanced angular momentum transport

accretion disk ejecta (~0.1-1s)

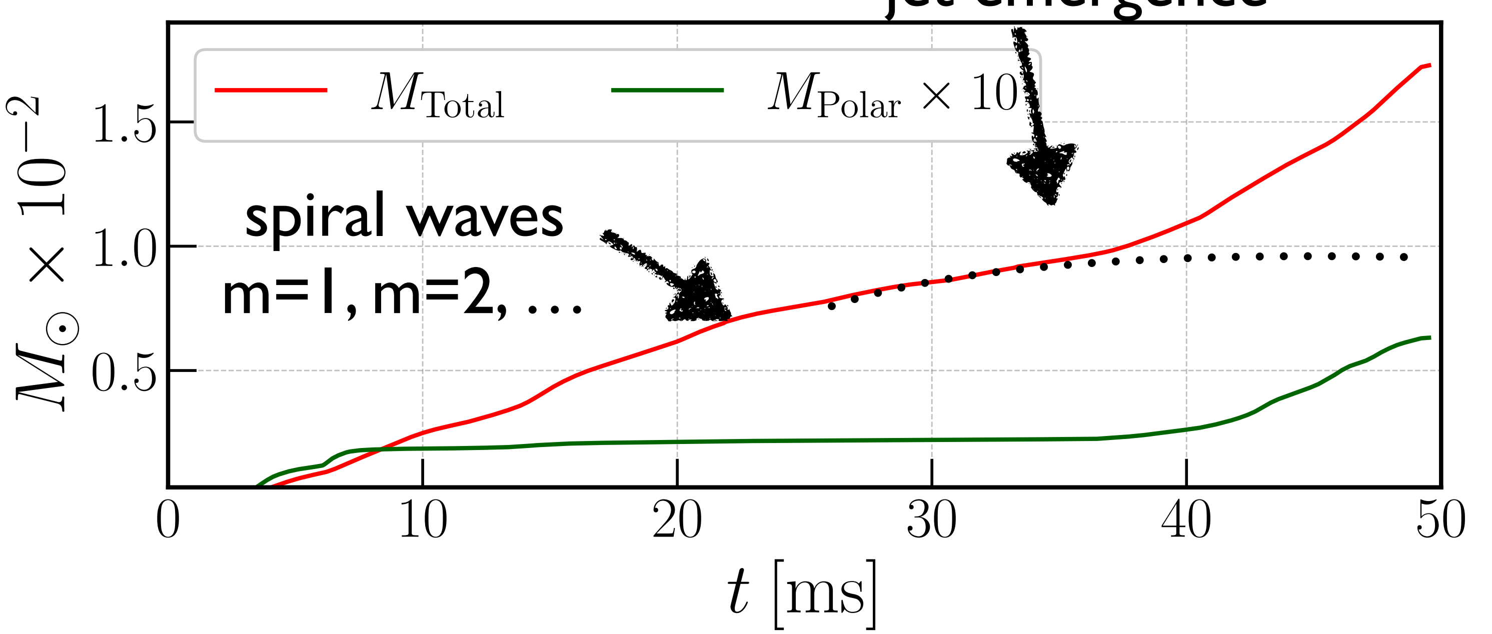






Post-merger disk evolution & outflows

Combi & Siegel 2023b, PRL



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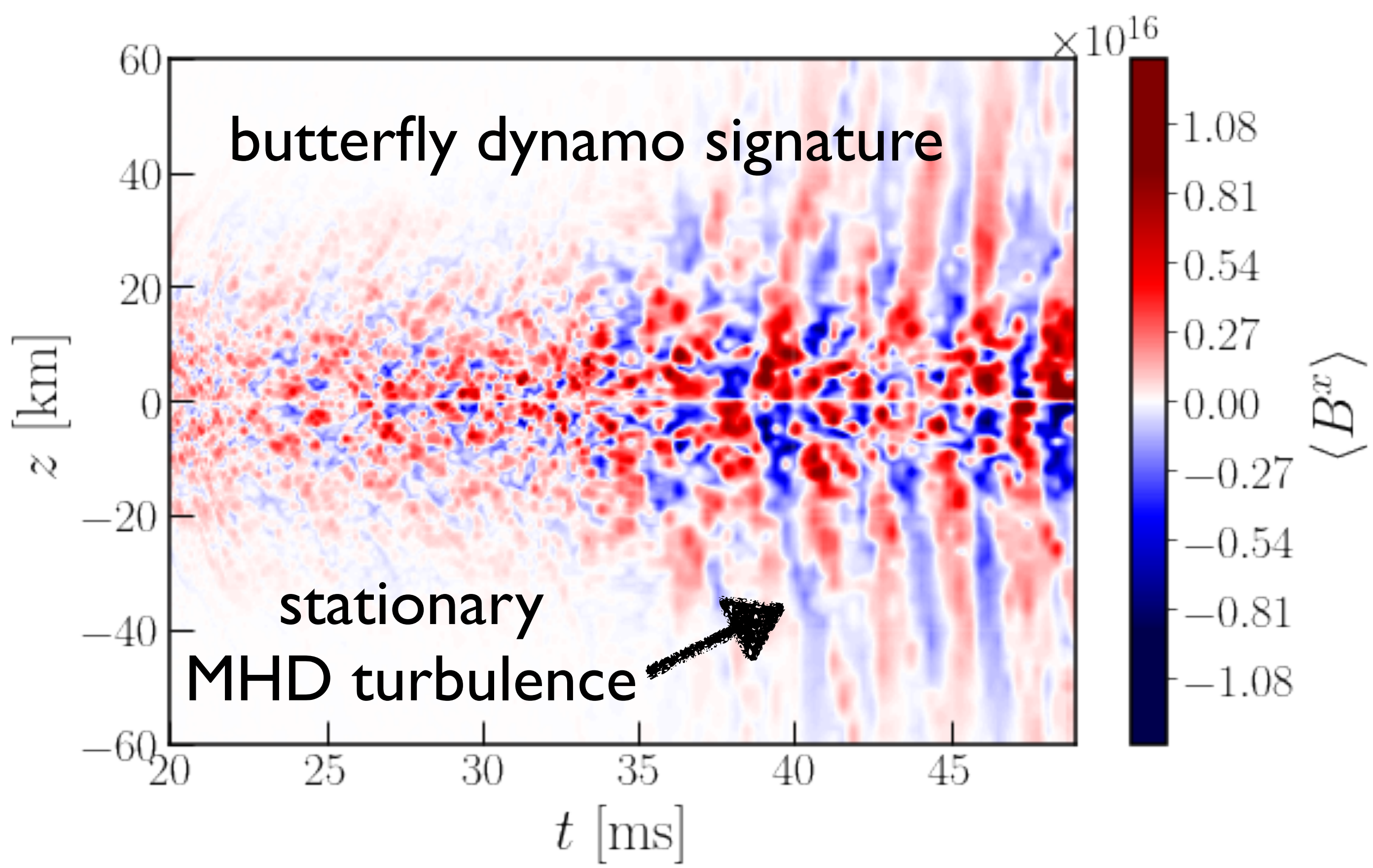
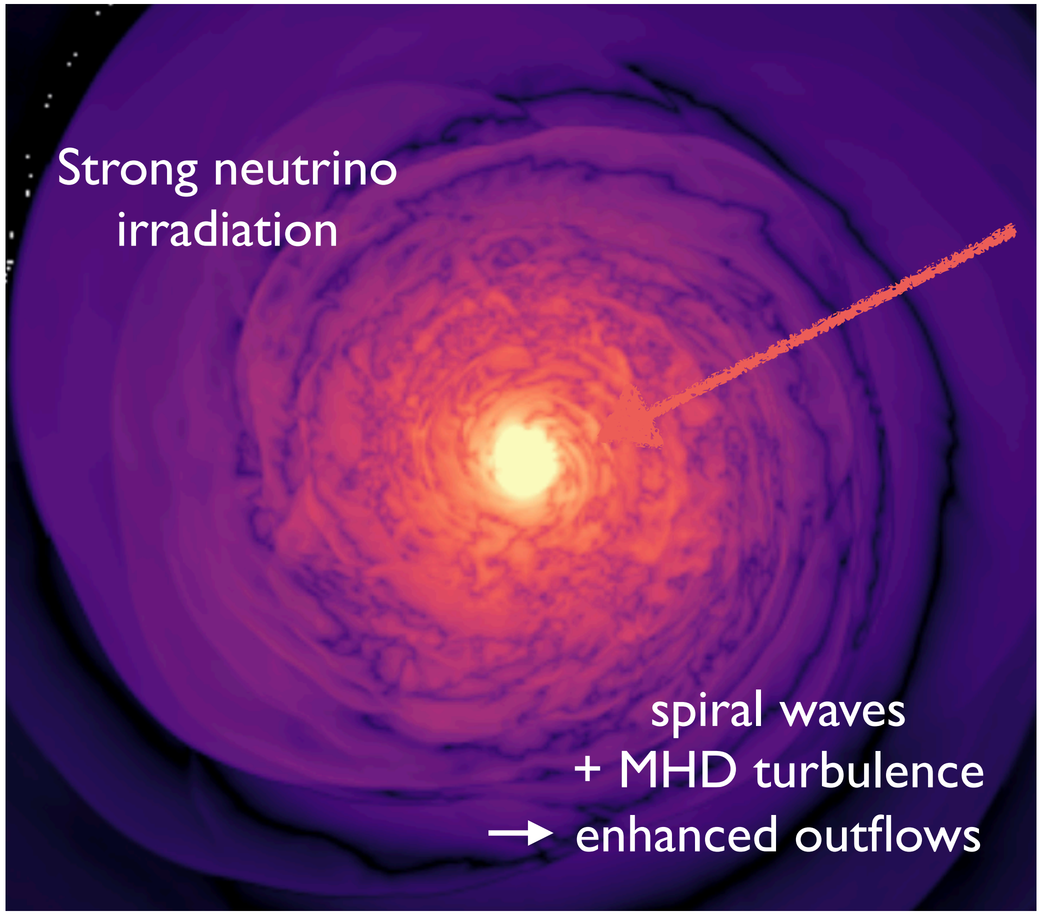
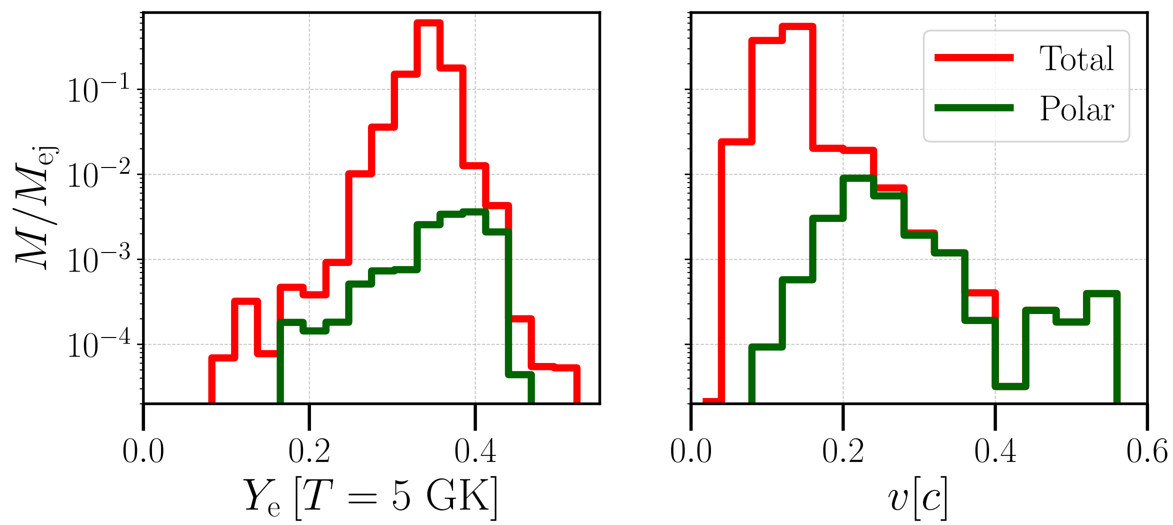


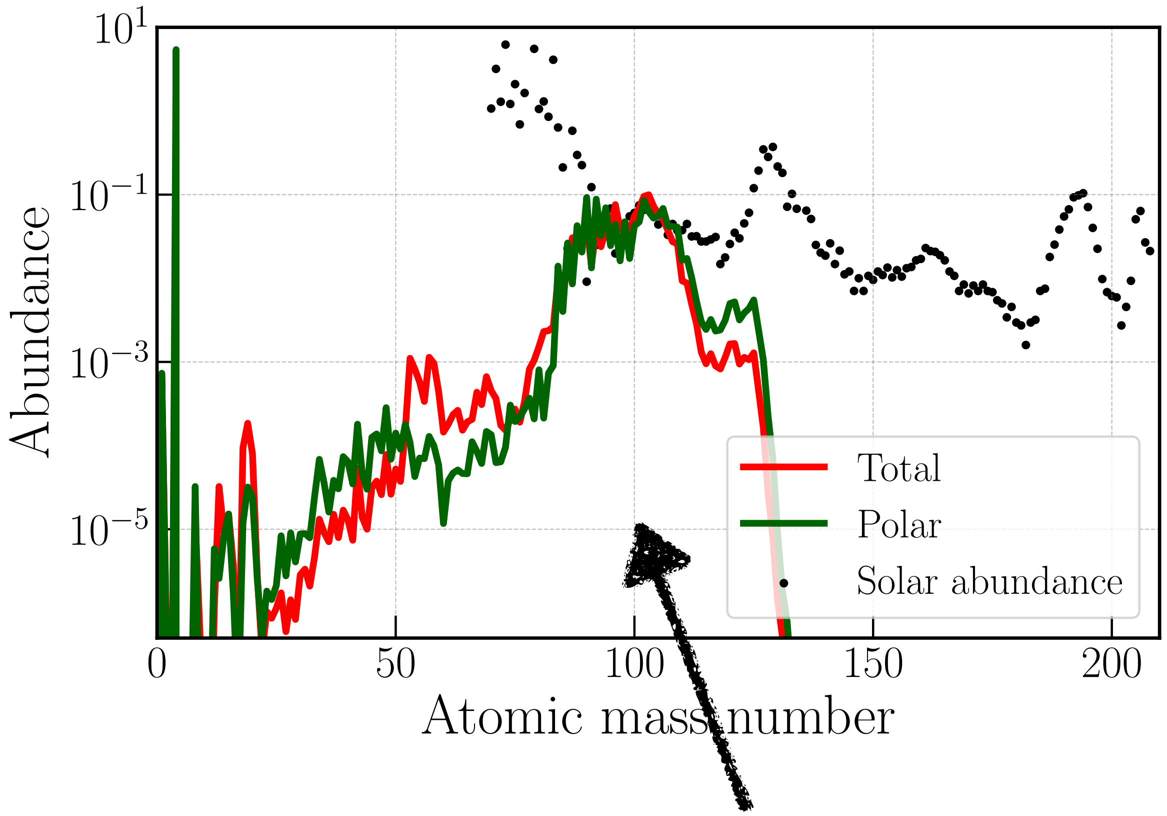


Nucleosynthesis & kilonova

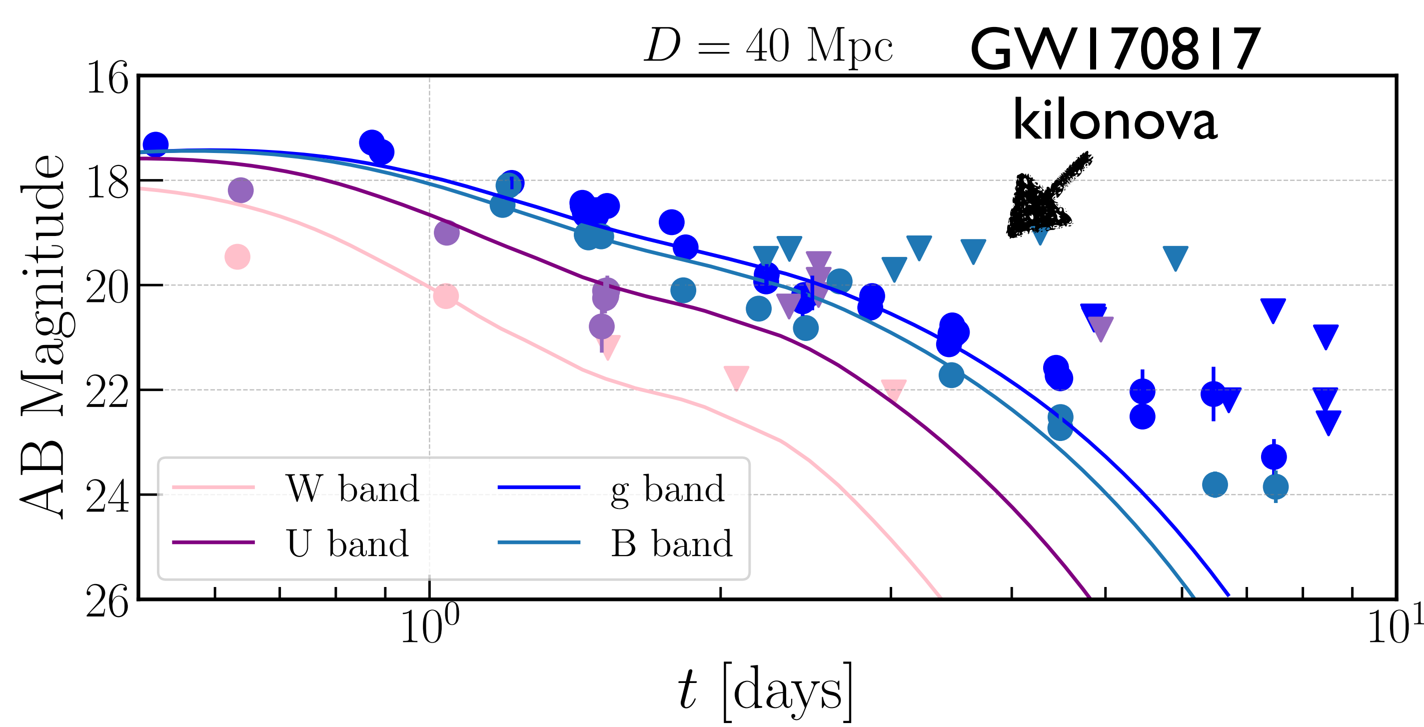
Combi & Siegel 2023b, PRL



- Outflows are protonized to Y_e~0.35 by strong neutrino irradiation
- Fast ejecta dominated by polar outflows up to v ~ 0.6c
- Disk outflows mostly v ~ 0.1-0.2 c
- Outflows of first 50ms in good agreement with blue GW170817 kilonova (2×10^{-2} M_{sun})



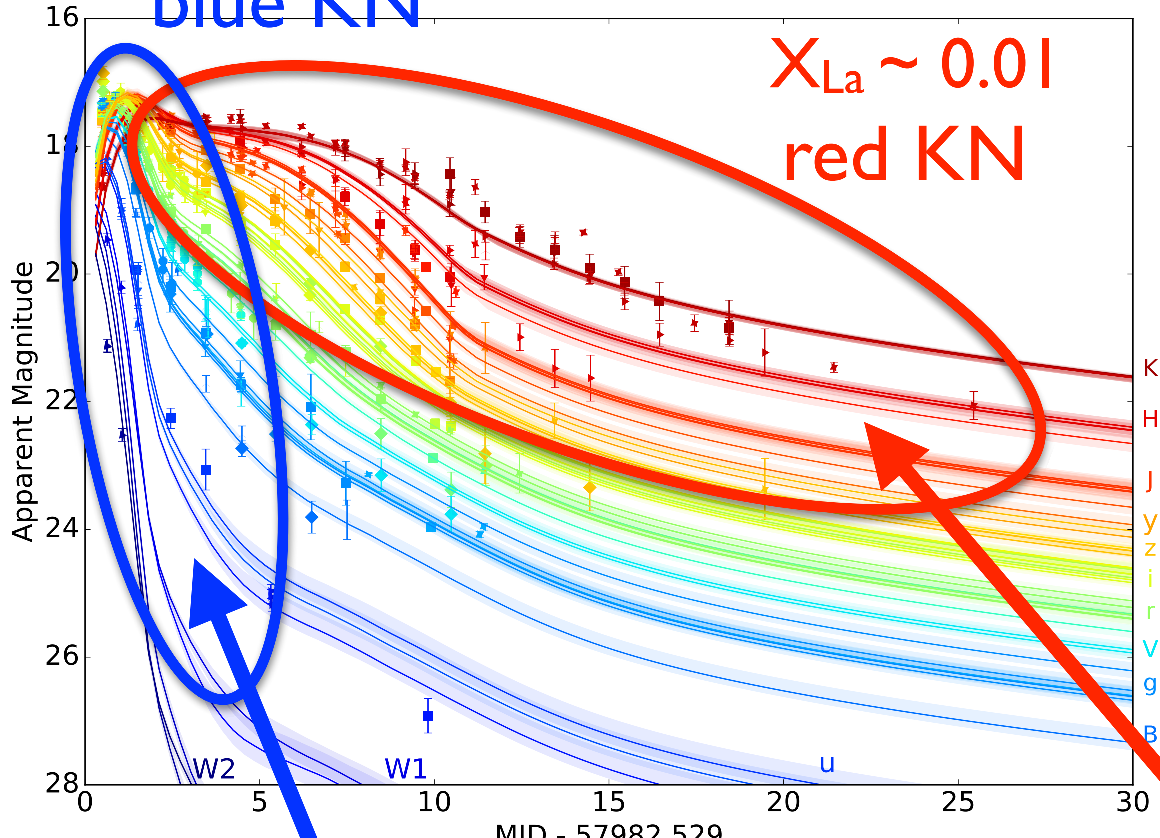
lanthanide-free disk ejecta



The GW170817 kilonova

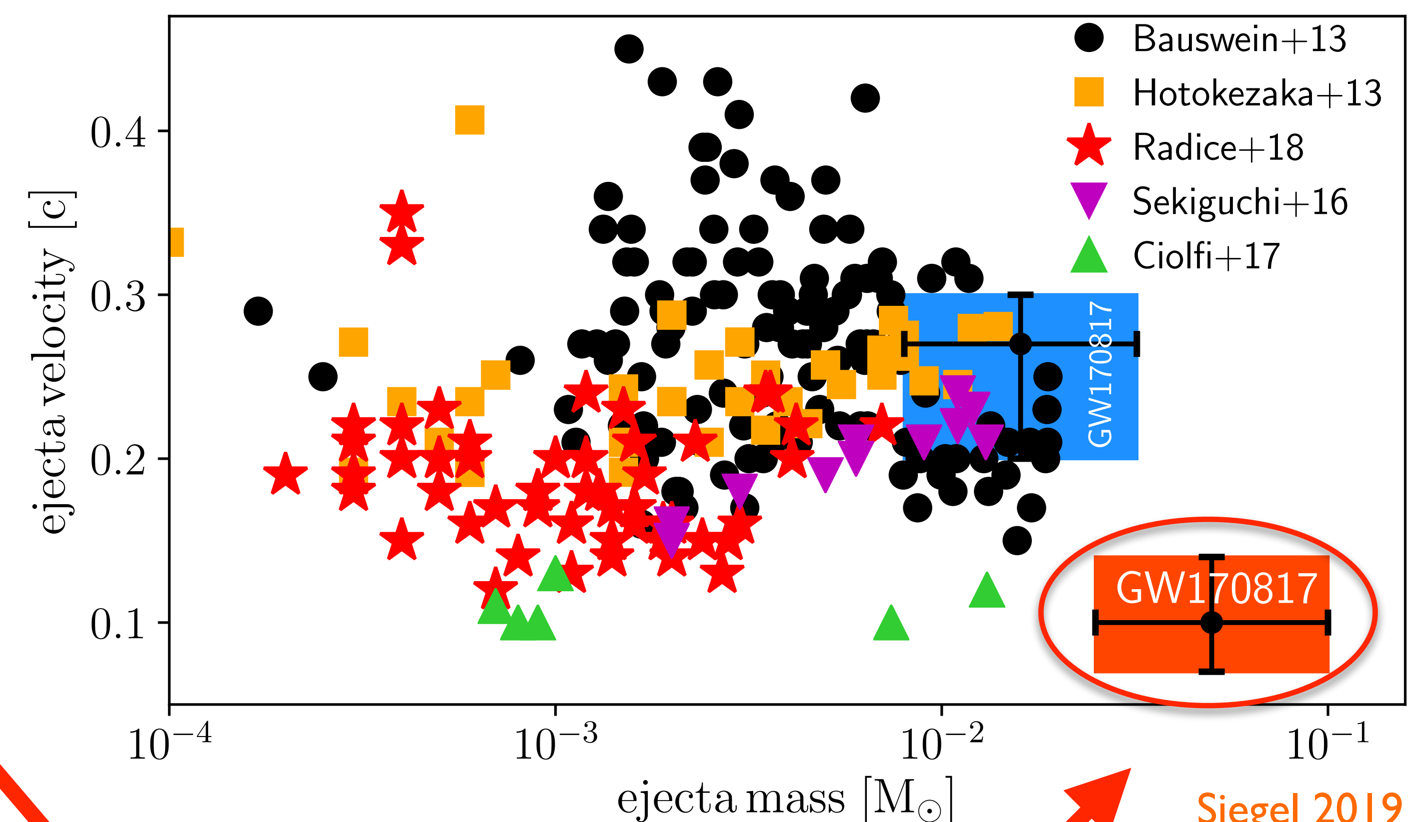
X_{La} < 10^{-4}
blue KN

X_{La} ~ 0.01
red KN



Villar+ 2017

BNS merger simulations: dynamical ejecta



Siegel 2019

likely post-merger
NS-disk ejecta !

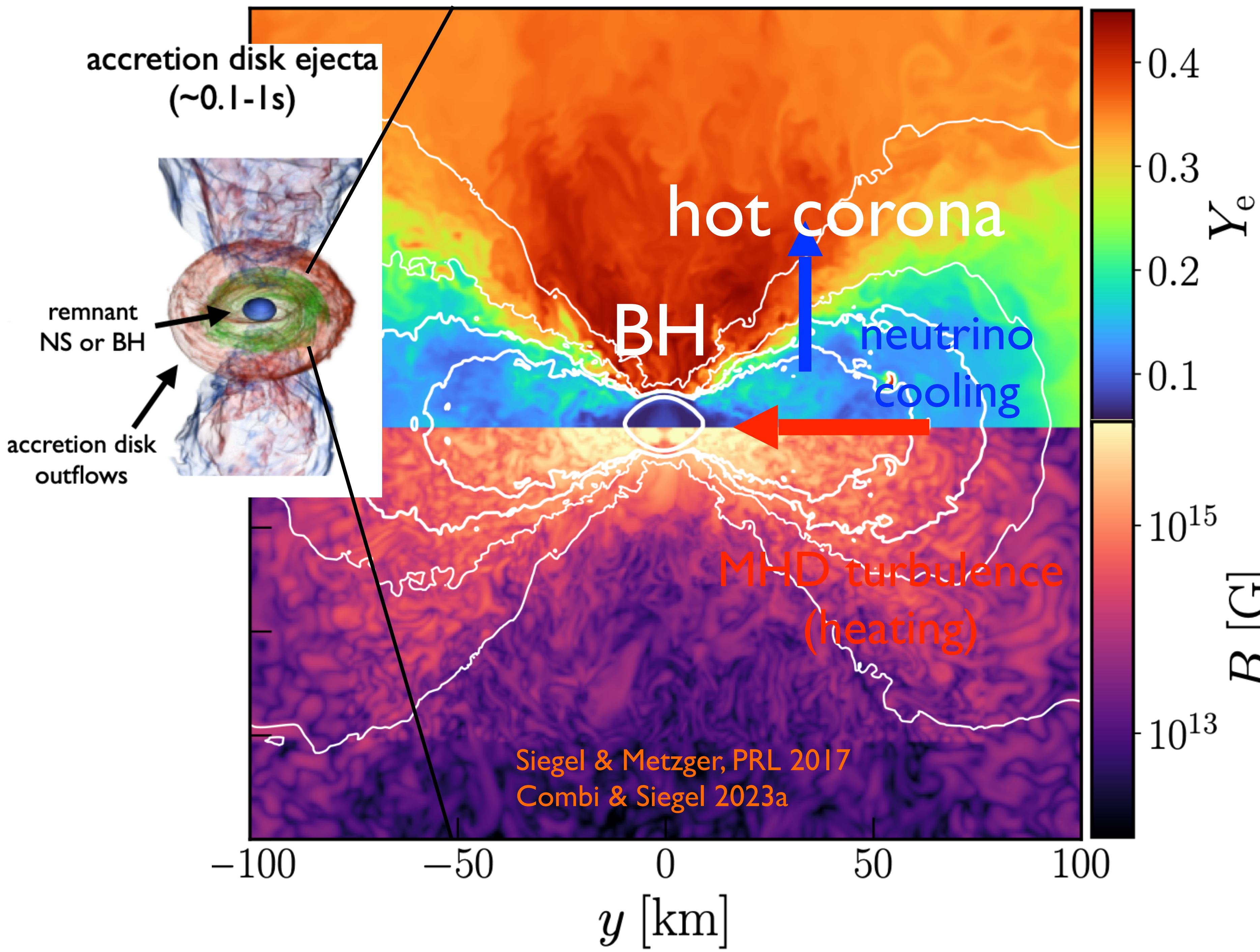
Combi & Siegel 2023b, PRL

likely post-merger
BH-disk ejecta

Kasen+ 2017

Siegel & Metzger, PRL 2017

Long-term post-merger disk ejecta



heating-cooling imbalance in corona &
nuclear recombination launches disk outflow

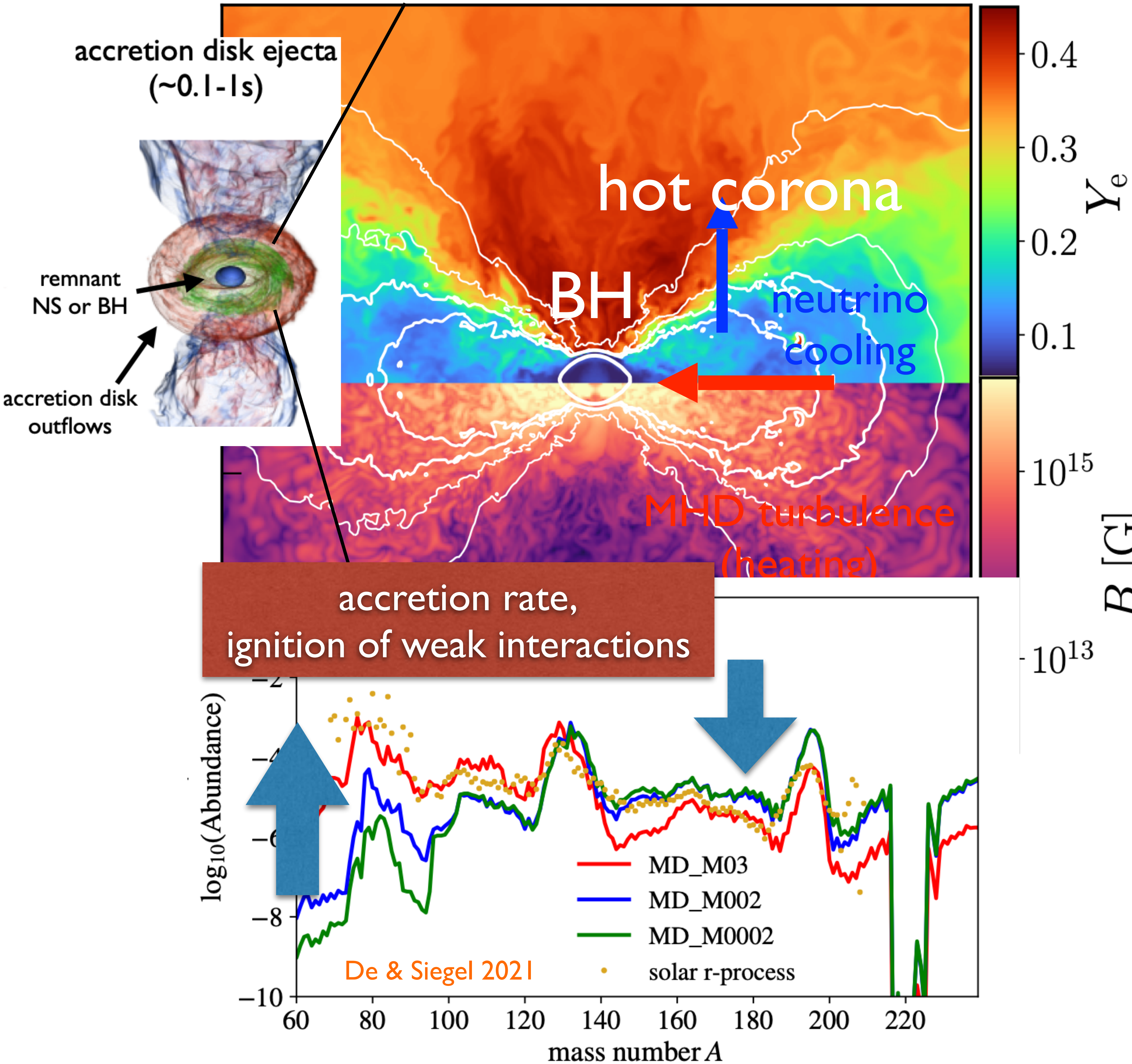
- Weak interactions are key for composition, nucleosynthesis, kilonova
- Self-regulation keeps disk neutron-rich: *light* & *heavy* r-process

  Siegel & Metzger, PRL 2017
  Chen & Beloborodov 2007
- Long-term (~s) outflows generated by self-sustained MRI dynamo
- Detailed nucleosynthesis varies across parameter space

  De & Siegel 2021
  Fernandez+ 2020
  Just+ 2021
  Fahlman & Fernandez 2022
- Total ejecta can dominate all other channels

  Siegel & Metzger 2018
  Fernandez+ 2019
  Kiuchi+ 2022

Long-term post-merger disk ejecta



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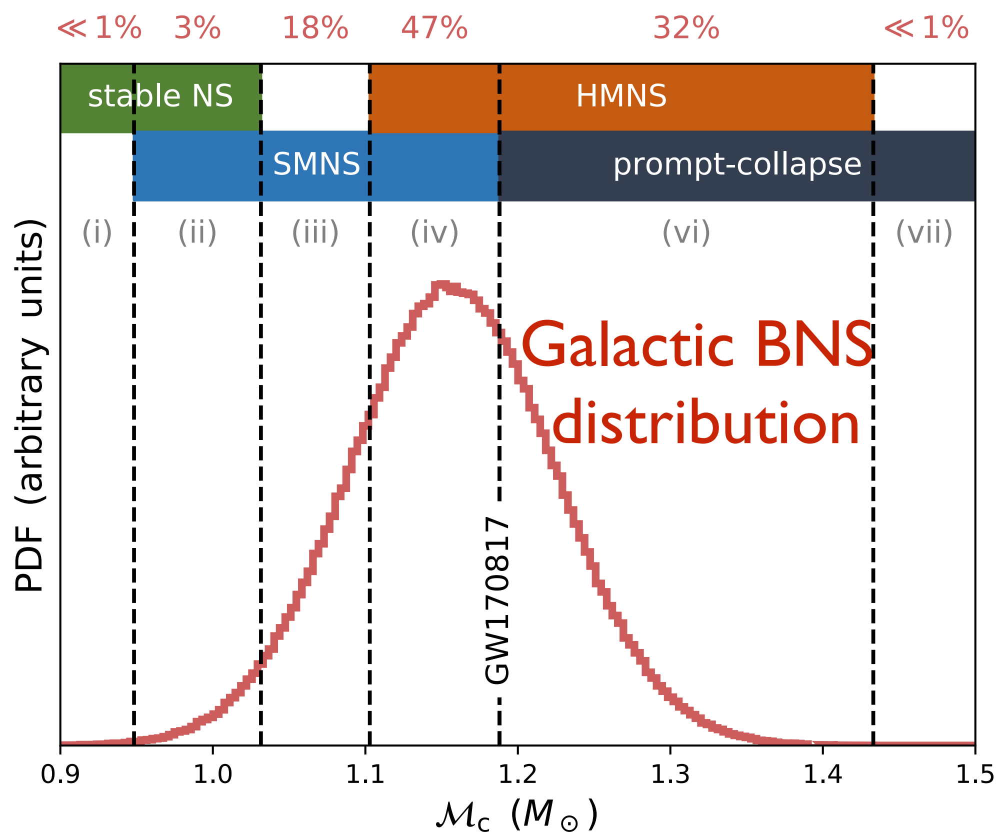
III.
Long-lived remnants: magnetar-powered kilonovae

Remnant diversity & distribution



Margalit & Metzger 2019

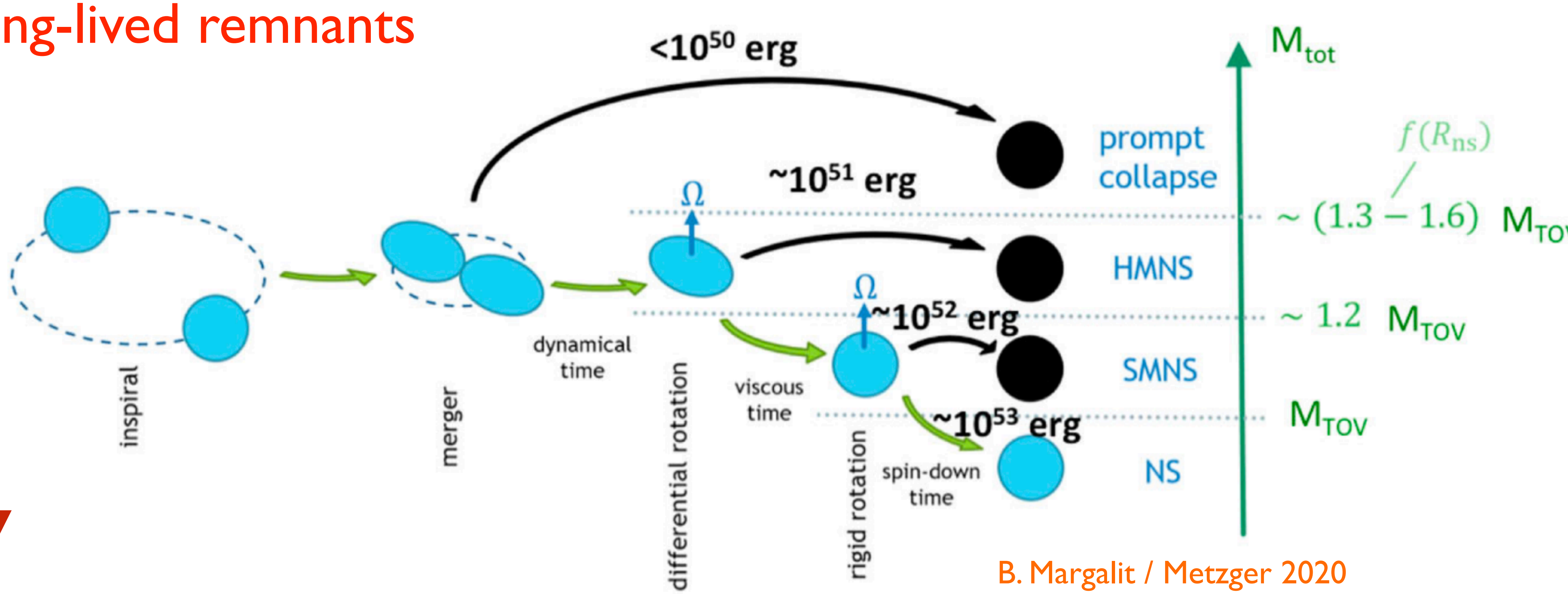
long-lived remnants

Delayed BH formation leads to NS lifetimes of seconds to infinity in

$\gtrsim$ 15-20 % of BNS mergers (?)

E_{rot}

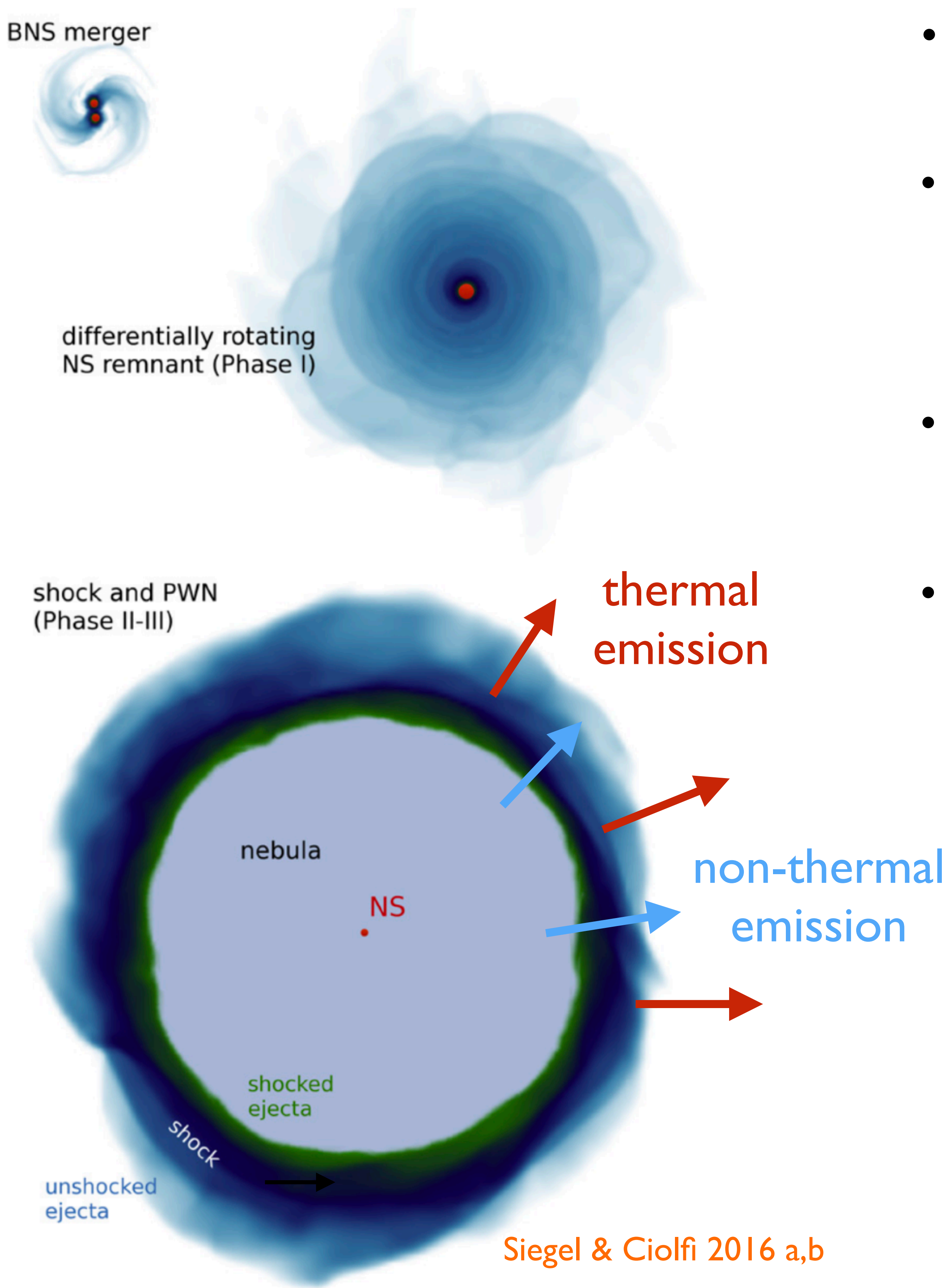
EM emission



B. Margalit / Metzger 2020

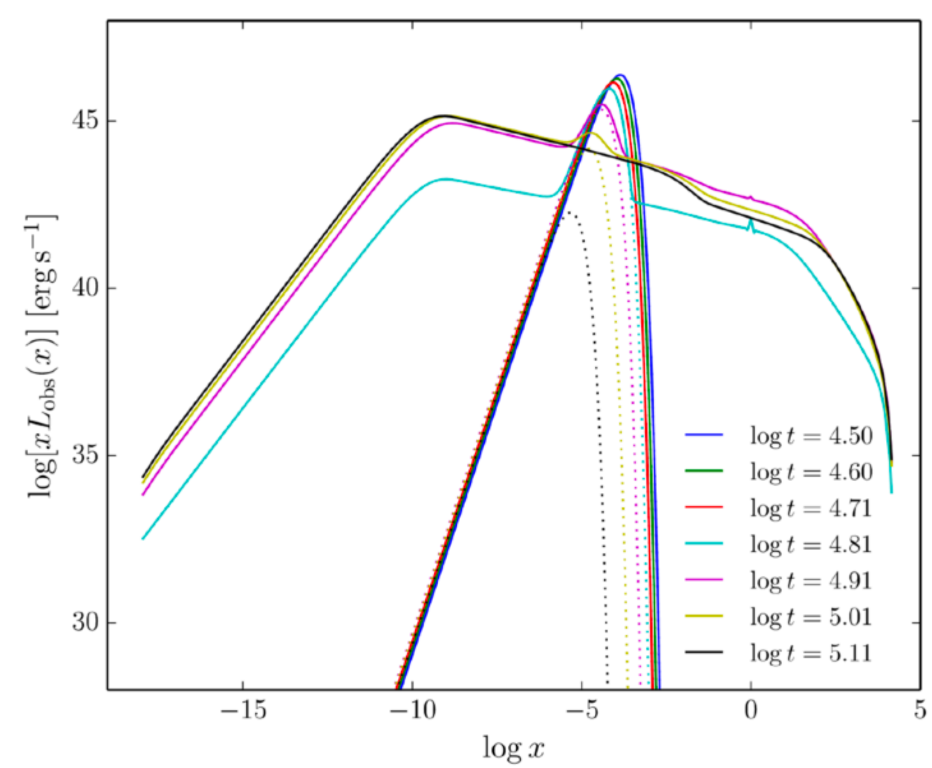
Long-lived remnants

EM emission from systems with long-lived remnants



Siegel & Ciolfi 2016 a,b

- $E_{rot} \sim 10^{52}$-10^{53}erg rotational energy powers non-thermal and thermal emission
- Pulsar wind nebulae similar to SN remnants, but with differing radiative processes due to high compactness Metzger+ 2014 Siegel & Ciolfi 2016 a,b
- non-thermal nebula emission across the EM band, once ejecta optically thin to nebula radiation
- 'magnetar-supported' kilonovae Li+ 2018 Metzger+ 2018 Sarin+ 2022



IV The bigger picture:

Collapsars, long & short GRBs,

super-kilonovae

Collapsars

- BH-accretion disk from collapse of *rapidly* rotating massive stars ($M > 20\ M_{sun}$)

  ⟶ "failed explosion" (direct collapse to a BH)

  ⟶ "weak explosion" (proto-NS collapses due to fallback material)

- Angular momentum of infalling stellar material leads to circularization and formation of accretion disk around the BH

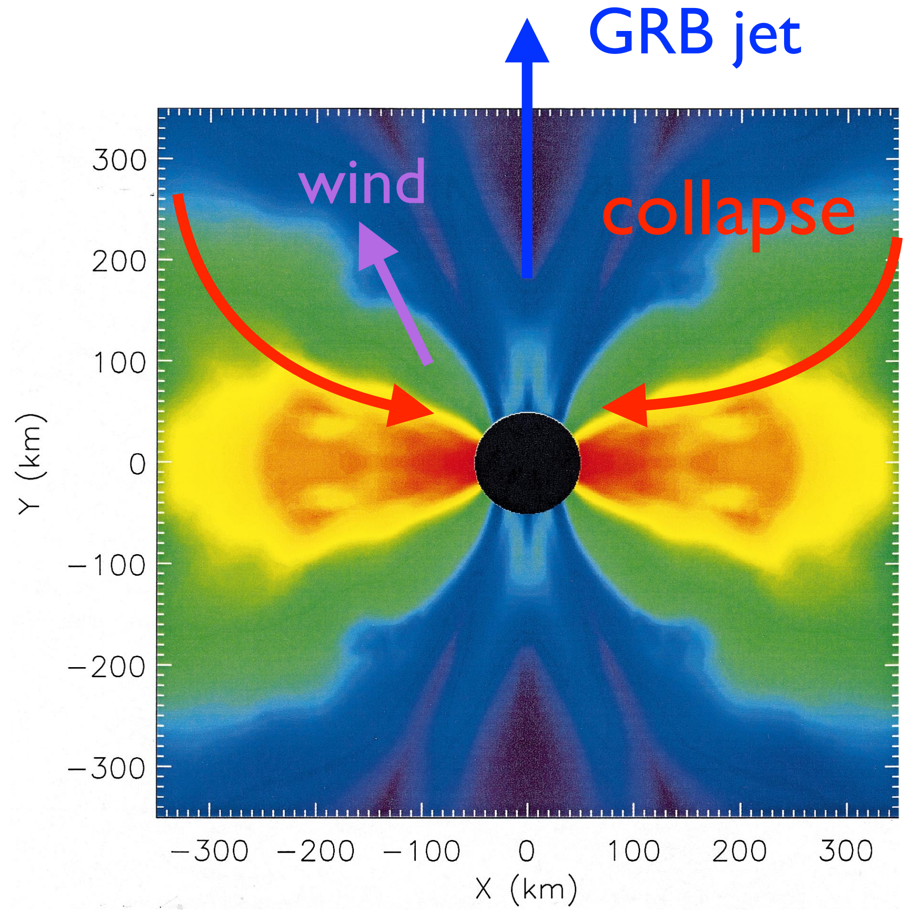
- Main model to generate long GRBs and their accompanying SNe Ic-BL ('hypernovae')

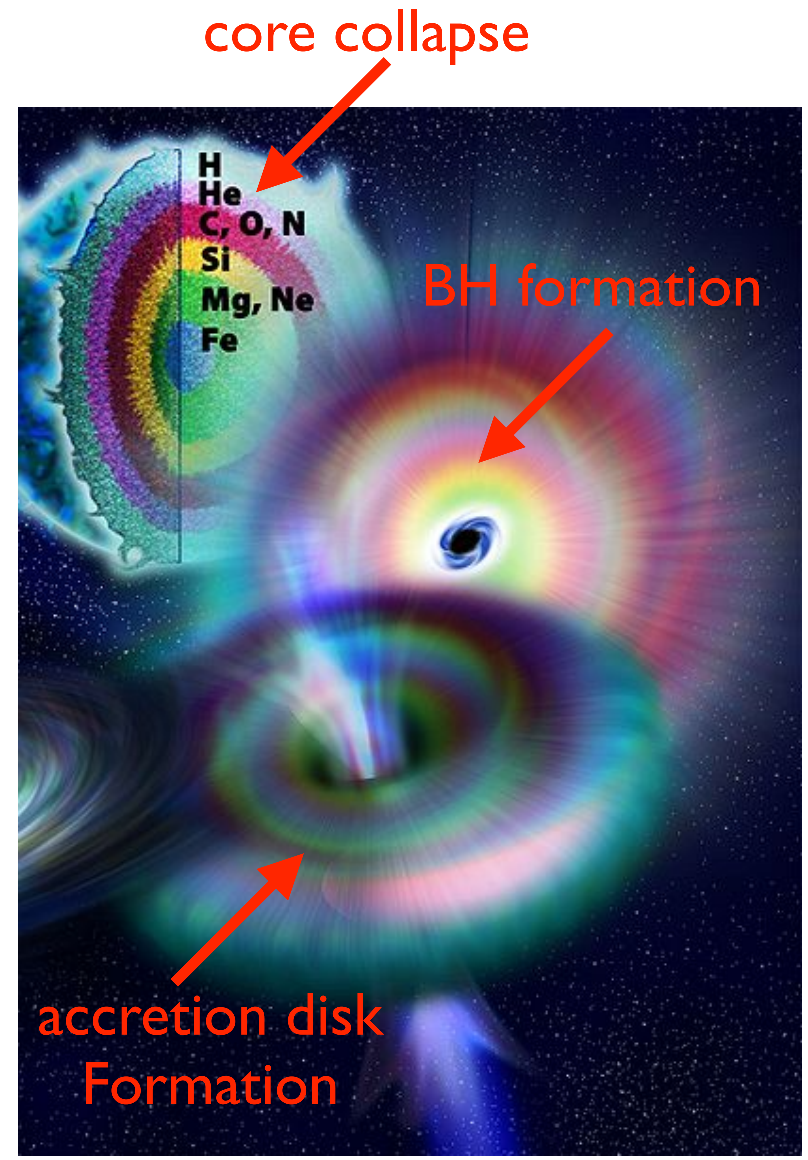
  MacFadyen & Woosley 1999

- Accretion powered jet and disk winds 'explode' the star

  ⟶ in fact, disk winds are sufficient in most cases

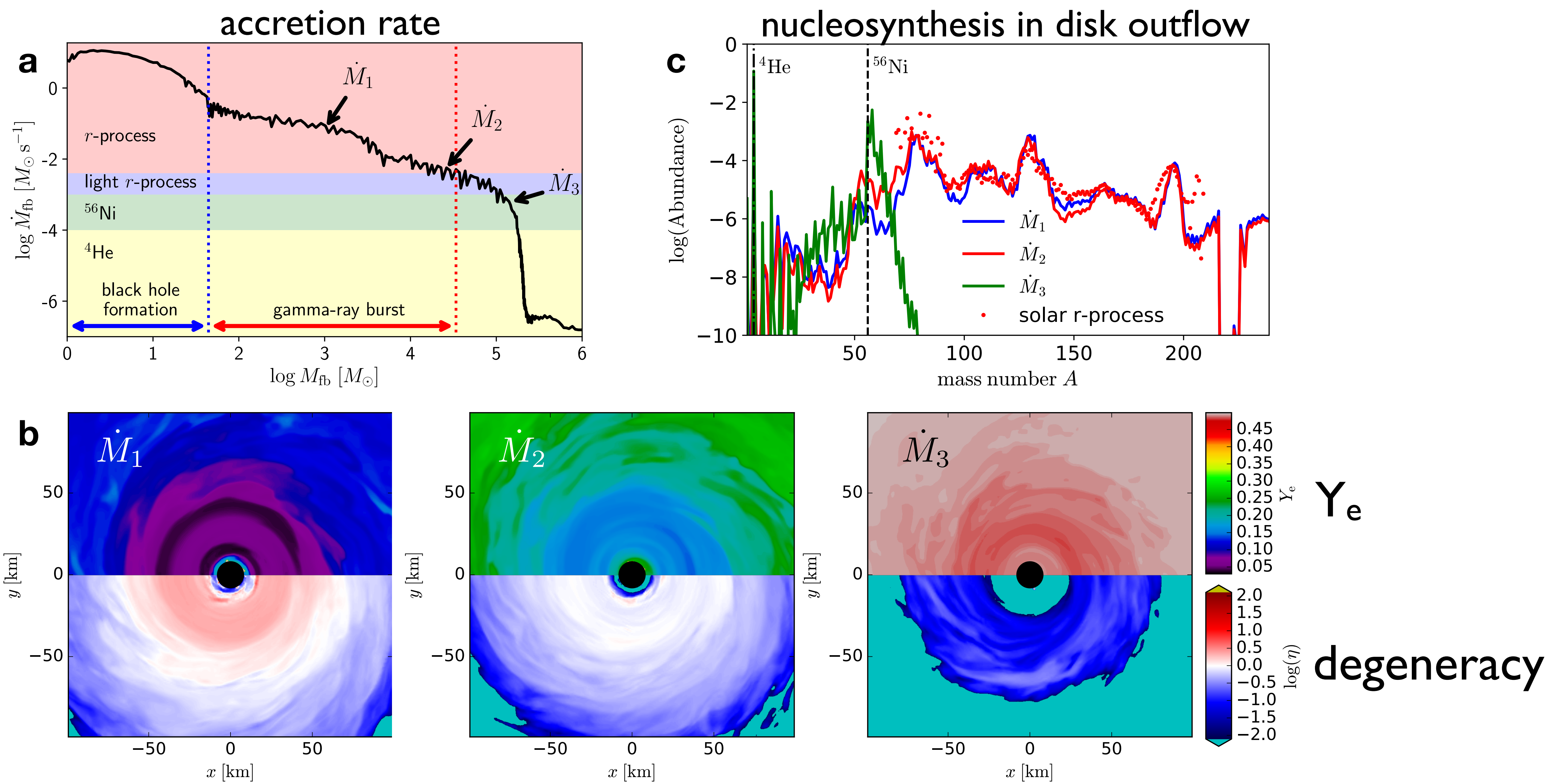
  MacFadyen & Woosley 1999
  Siegel+ 2019, Siegel+ 2022





Post-merger physics in other systems: *collapsars*

Siegel, Barnes, Metzger 2019, Nature



$$e^- + p \rightarrow n + \nu_e$$

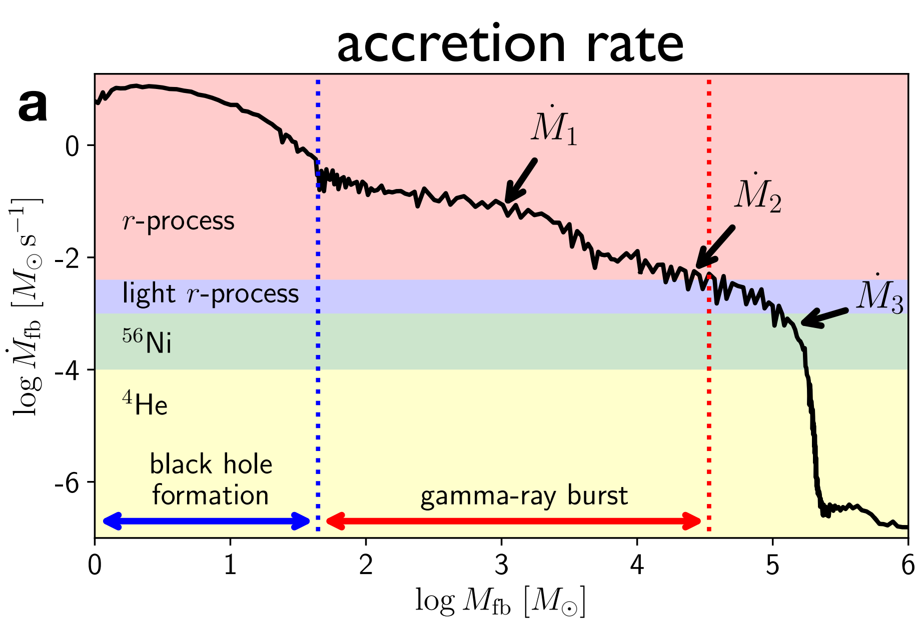
$$e^+ + n \rightarrow p + \bar{\nu}_e$$

Post-merger physics in other systems: *collapsars*

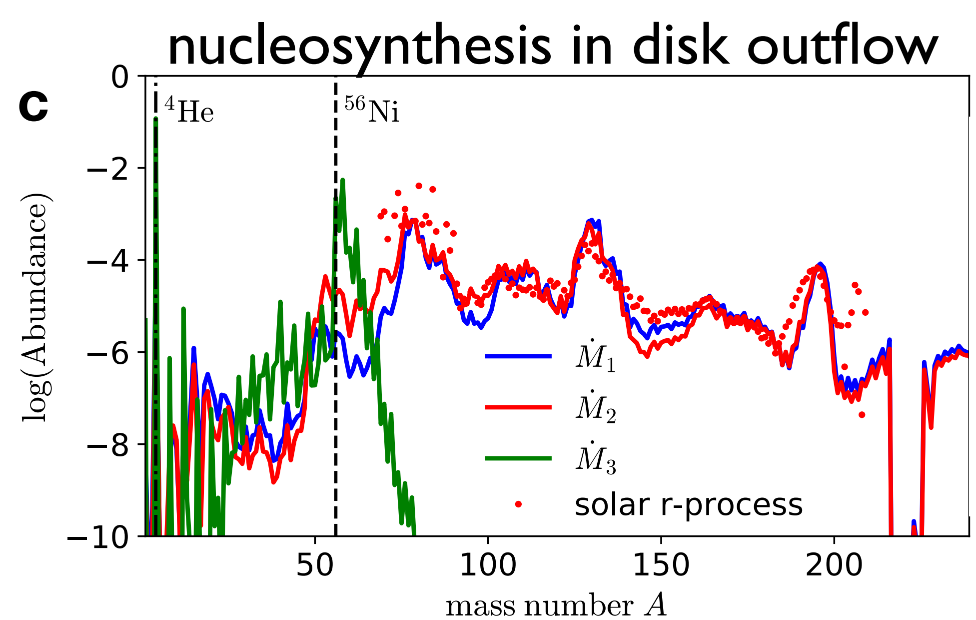
Siegel, Barnes, Metzger 2019, Nature

Siegel+ 2022

accretion rate

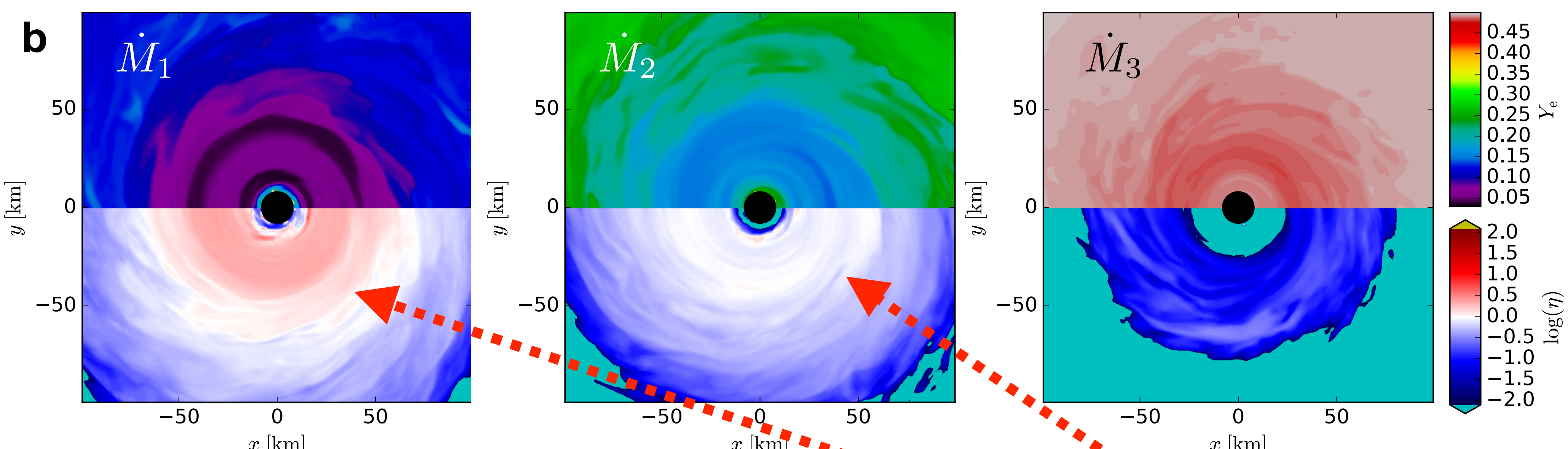


nucleosynthesis in disk outflow



nucleosynthesis bands:

$$\frac{M_{\rm disk}}{t_{\rm visc}} = \begin{cases} > \dot{M}_{\nu,{\rm r-p}} & \text{limited } r\text{-process, } (69 \le A \le 136) \\ \in [2\dot{M}_{\rm ign}, \dot{M}_{\nu,{\rm r-p}}] & \text{main } r\text{-process, } (69 \le A) \\ \in [\dot{M}_{\rm ign}, 2\dot{M}_{\rm ign}] & \text{limited } r\text{-process, } (69 \le A \le 136) \\ < \dot{M}_{\rm ign} & \text{no } r\text{-process, } ^{56}\text{Ni production.} \end{cases}$$



Y_e

degeneracy

Neutron-richness:

$$e^- + p \rightarrow n + \nu_e$$

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

High disk densities ($\dot{M} > \dot{M}_{\rm ign}$):

→ degenerate electrons

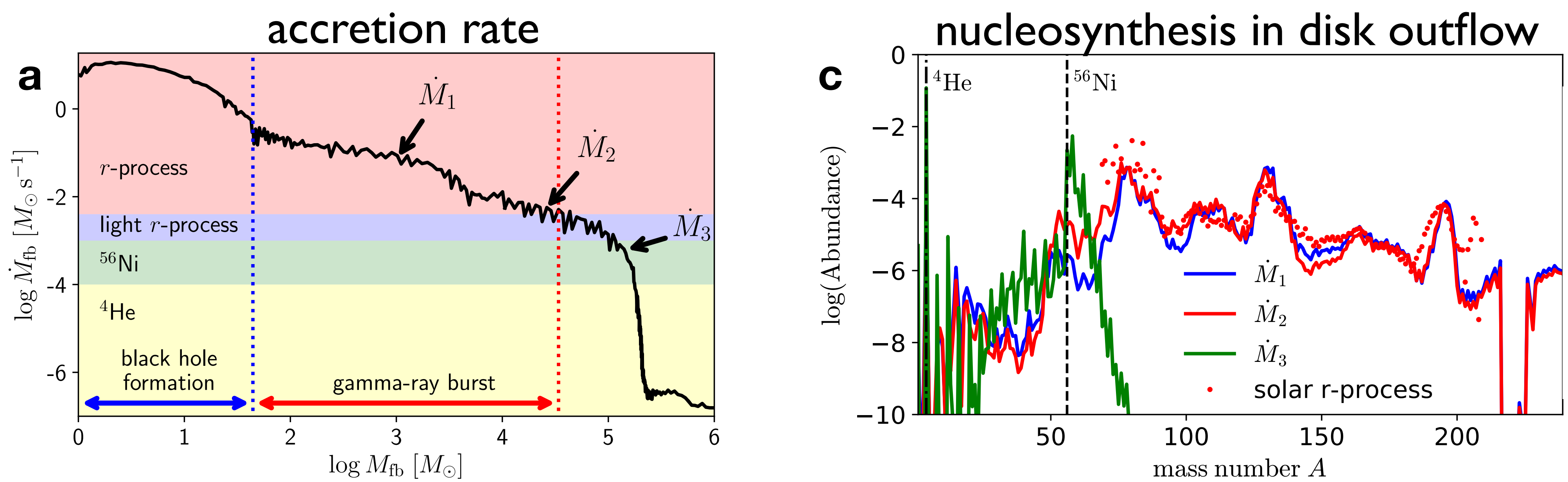
$Y_e \sim 0.1$

outflows produce r-process nuclei

Post-merger physics in other systems: *collapsars*

Siegel, Barnes, Metzger 2019, Nature

Siegel+ 2022



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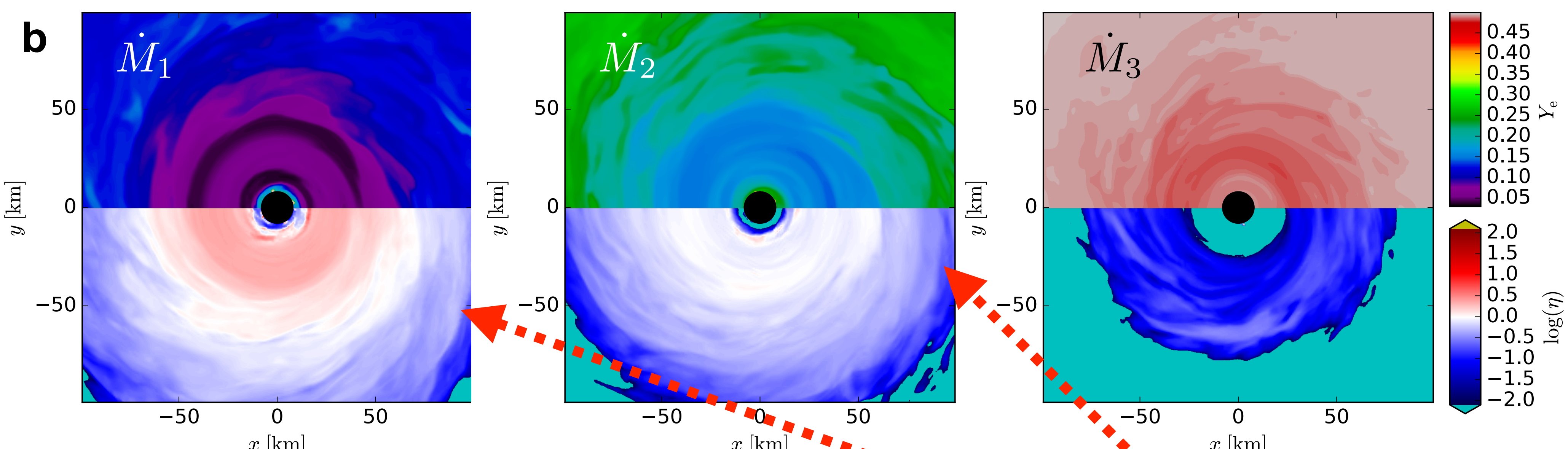

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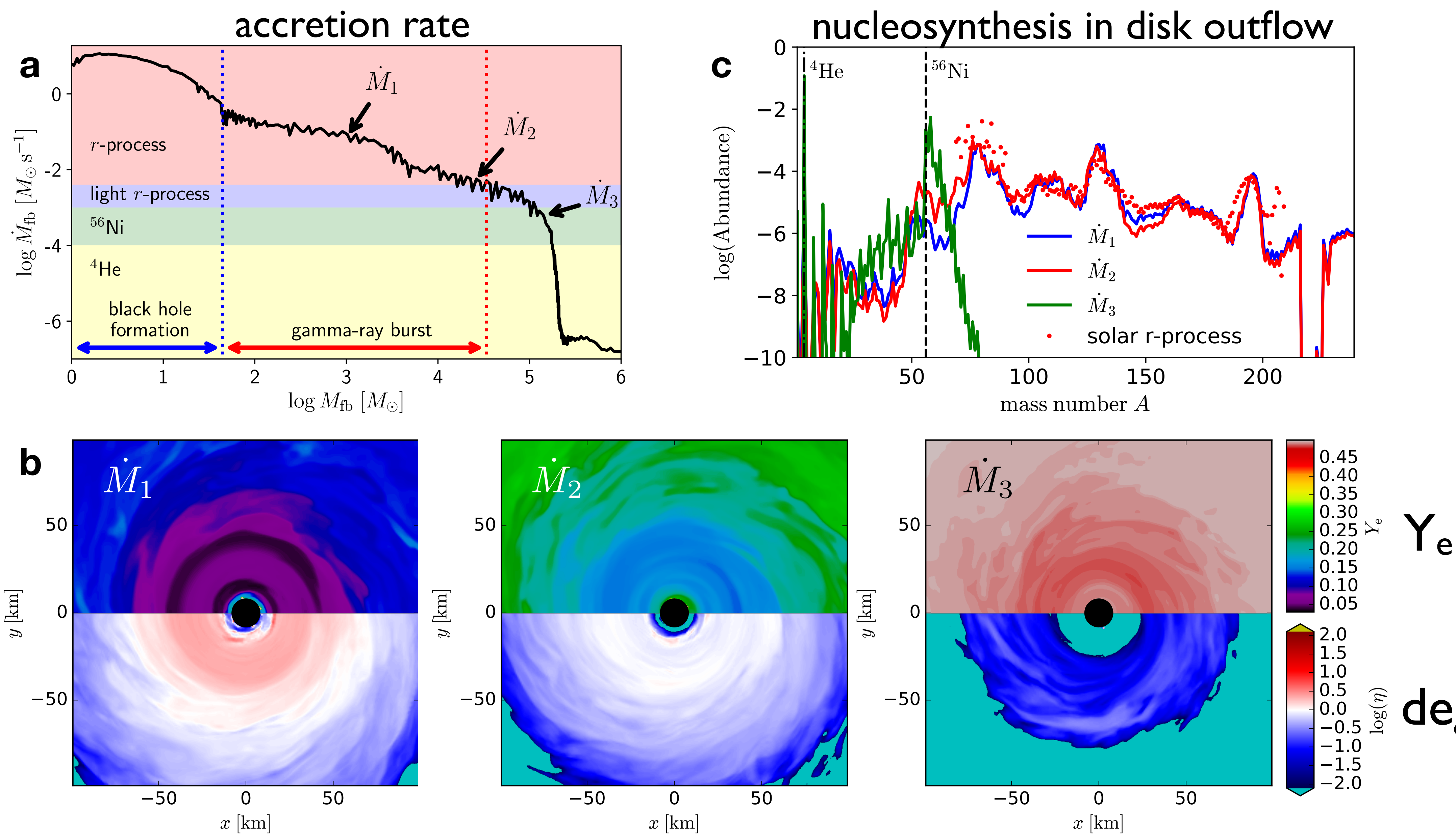
Siegel, Barnes, Metzger 2019, Nature



Ye

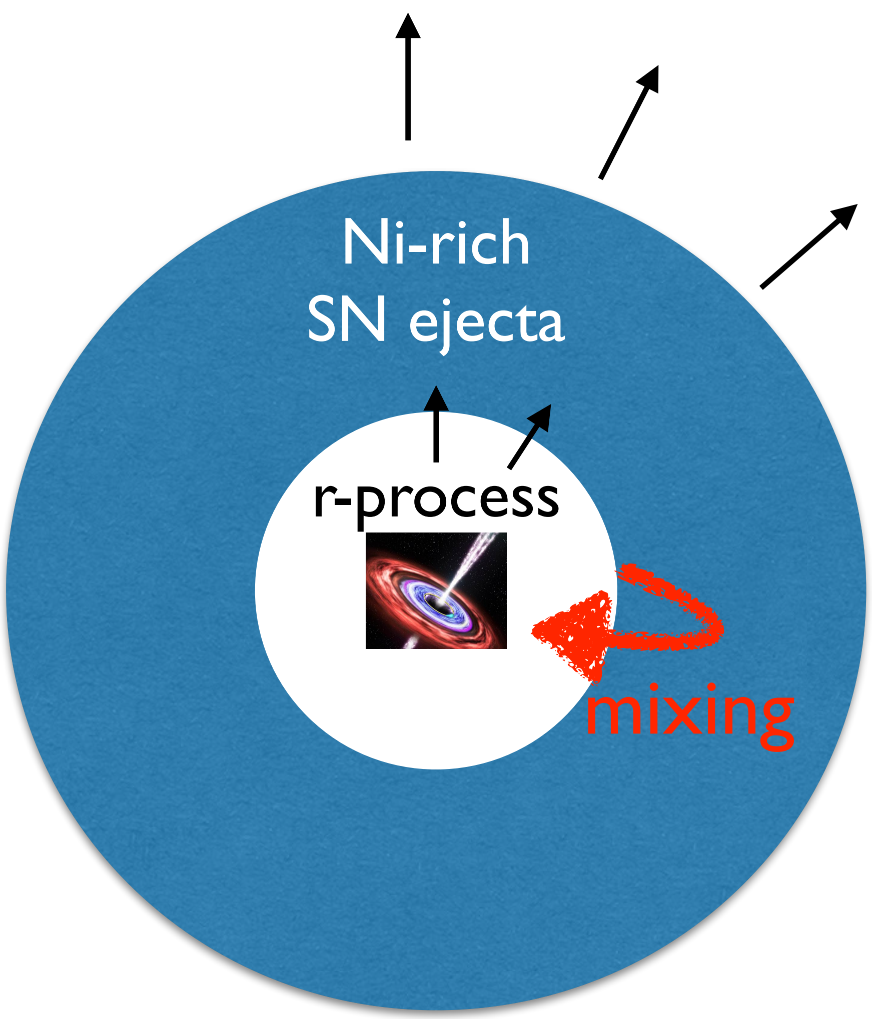
degeneracy

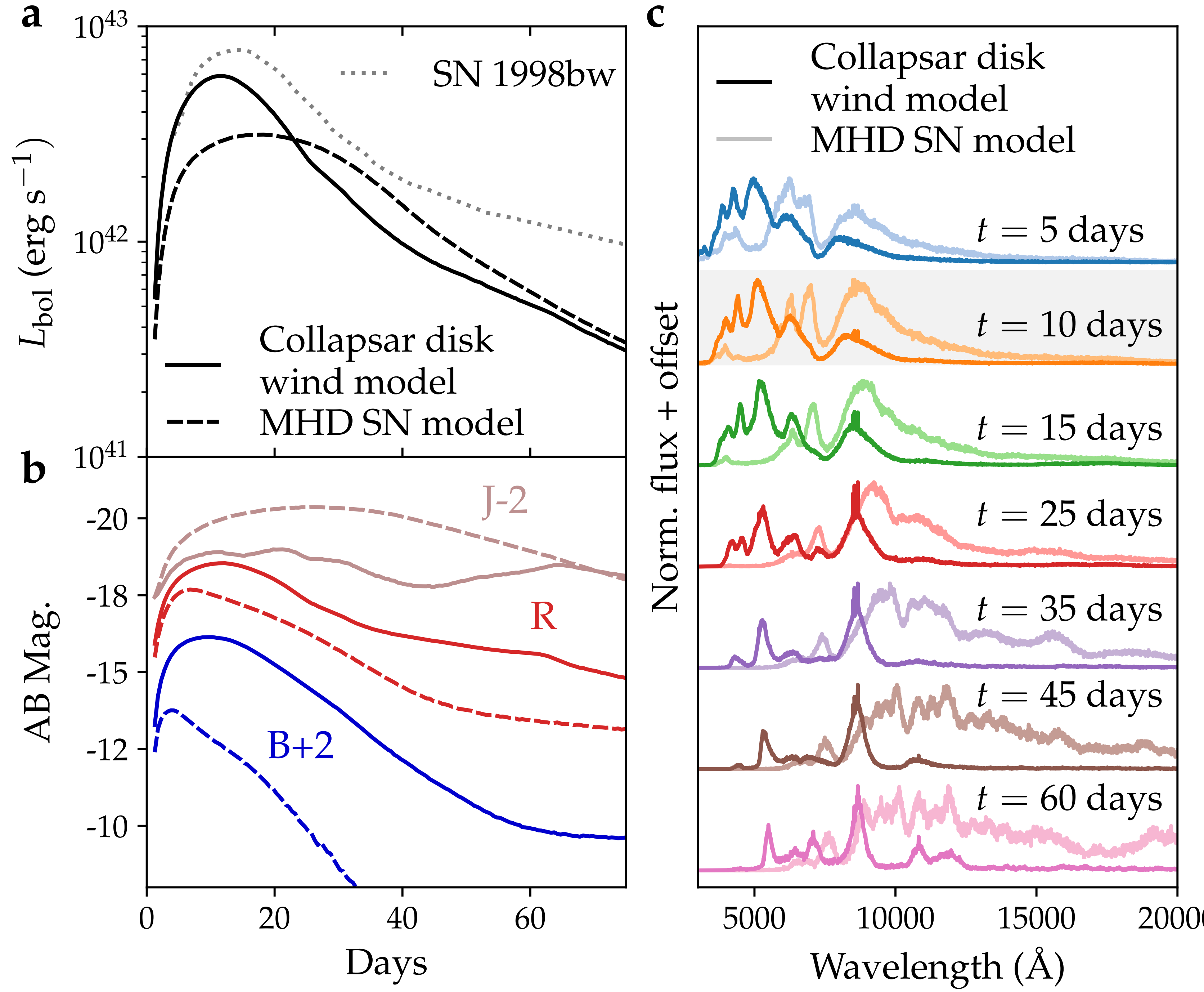
- 0.05–1 M_{sun} of r-process material per event over-compensates lower rates relative to mergers
- self-regulation over wide range of accretion rates produced well-defined nucleosynthesis pattern similar to solar
- may dominate r-process production by mergers

See also:

Miller+ 2020, Just+ 2021, Li & Siegel 2021

How to observe?





r-process elements lead to near-infrared excess at late times:

'kilonova within a supernova'

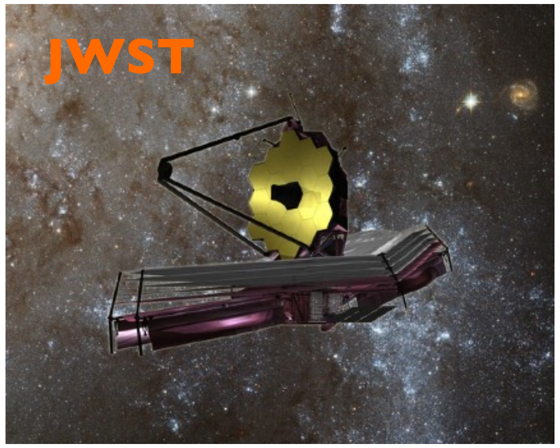
Siegel, Barnes, Metzger 2019, Nature

Barnes & Metzger 2022

First observational searches: Arnand+ 2024, Rastinejad+ 2024, Blanchard+ 2024

Extraordinary GRB 221009A

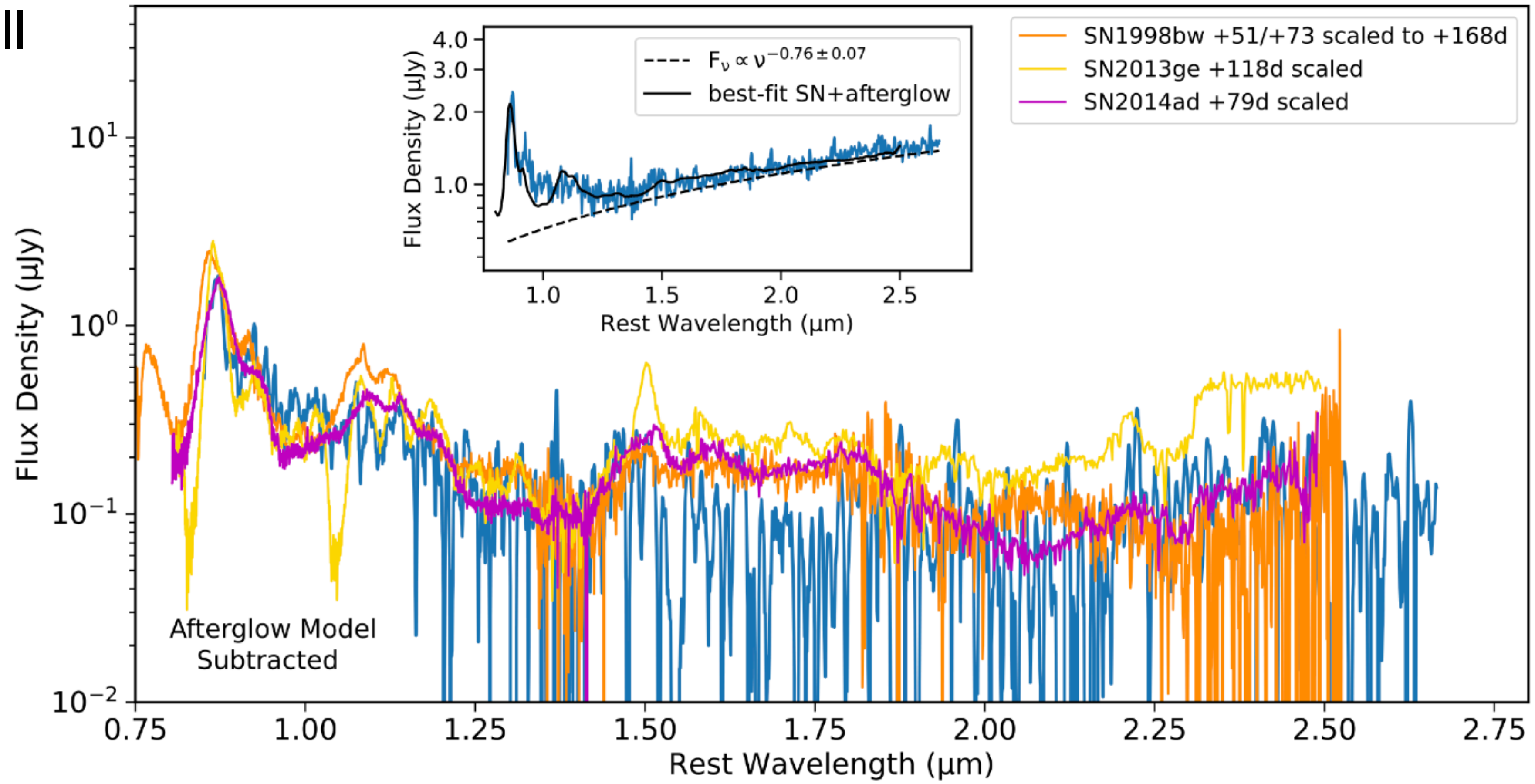
Blanchard+, Siegel 2024, Nature Astronomy



- Brightest gamma-ray burst of all time ($L_{\gamma, iso}$ ~ 1e54 erg/s)
- JWST +168d & +170d observations reveal ordinary GRB SN Ic-BL

  M_{Ni} ~ 0.09 Msun, comparable brightness to SN 1998bw at similar epoch

- No evidence of r-process



If GRB γ-ray luminosity tracks accretion rate, absence of r-process expected here, due to neutrino irradiation killing neutron-richness

→ *exceptionally* luminous GRBs may produce limited r-process

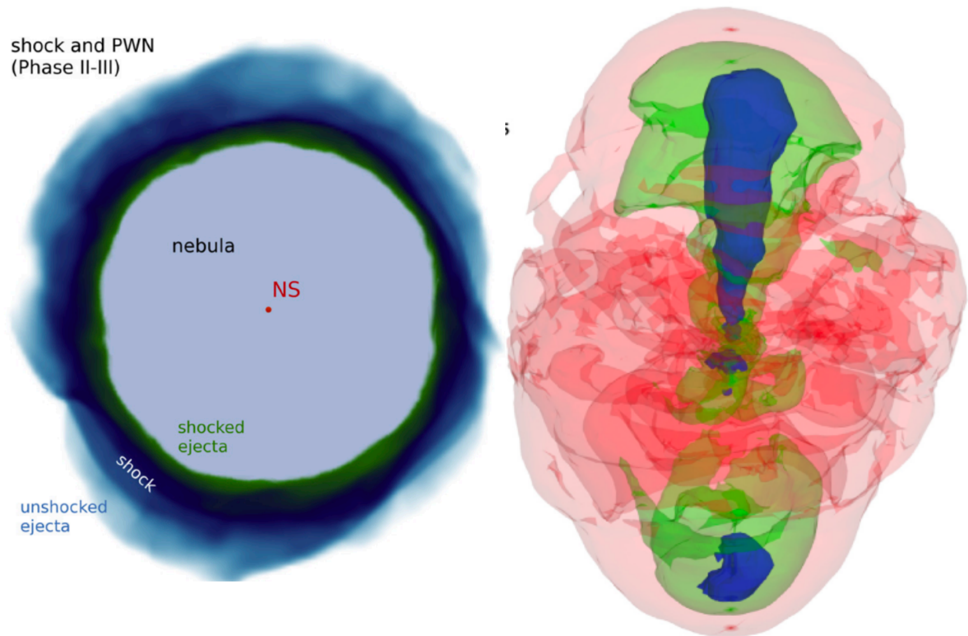
A range of multi-messenger central engines

binaries

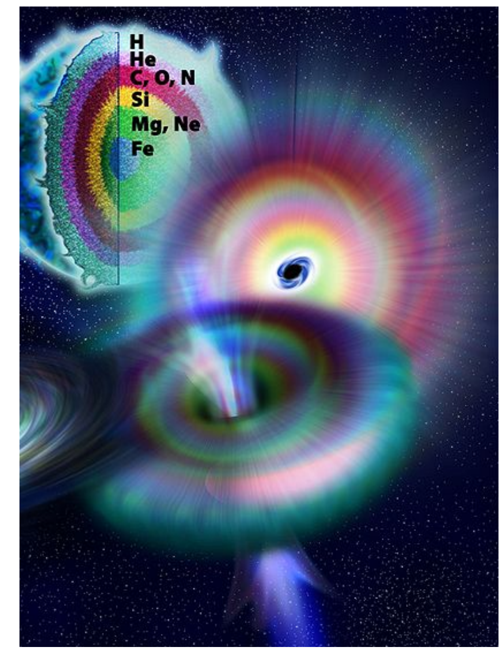
massive star collapse

NS mergers

Magnetars



Collapsars



Super-
Collapsars

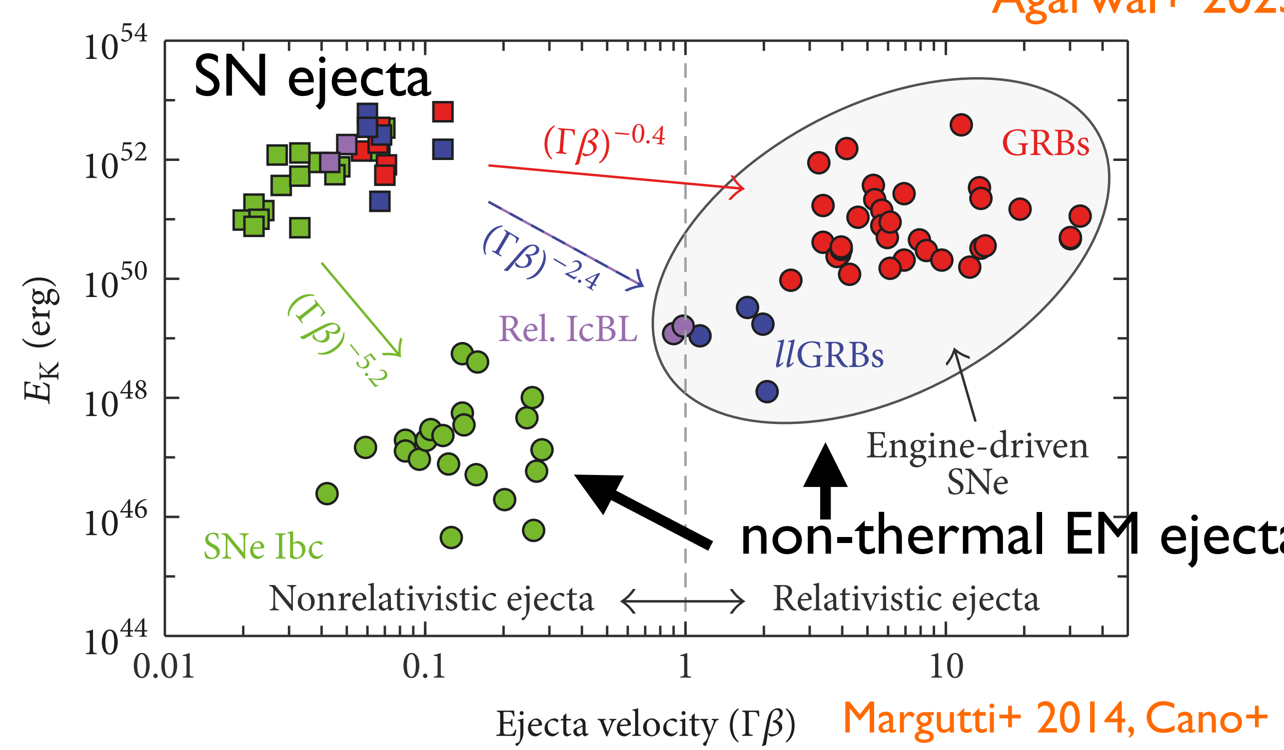
130 - 10^5 M_{sun}

Siegel+ 2022
Agarwal+ 2025

kilonovae

short GRBs

extended
emission?



Margutti+ 2014, Cano+ 2017

A range of multi-messenger central engines

binaries

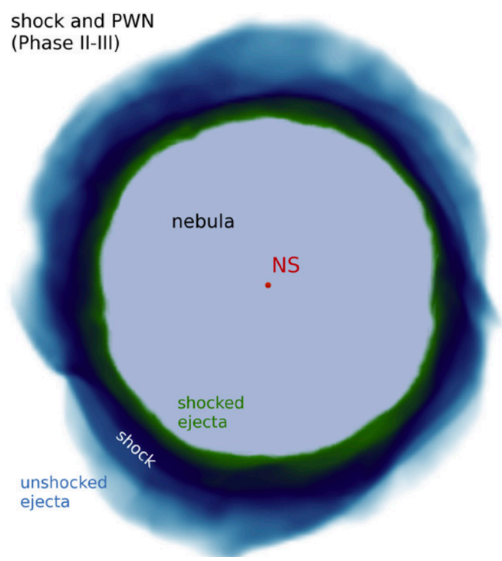
massive star collapse

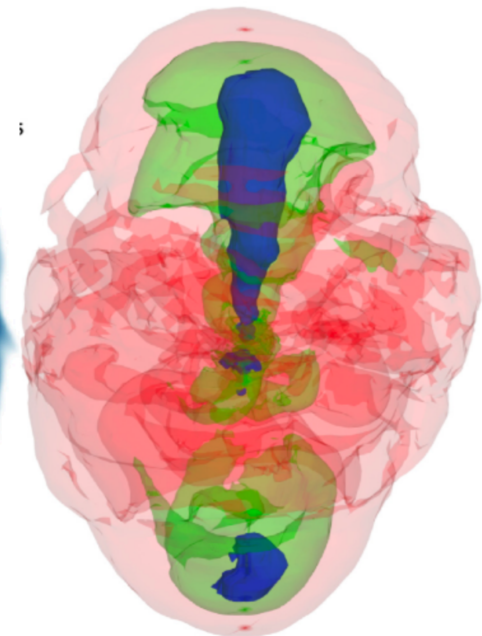
NS mergers

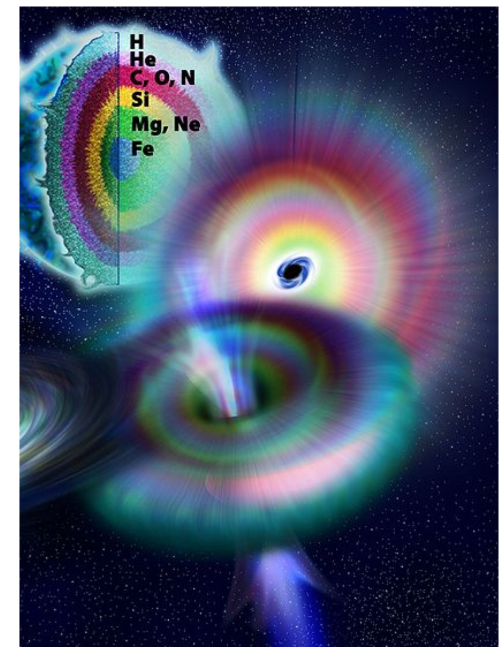
Magnetars

Collapsars

Super-Collapsars







130 - 10^5 M_{sun}

Siegel+ 2022

Agarwal+ 2025

SNe Ic-BL

kilonovae

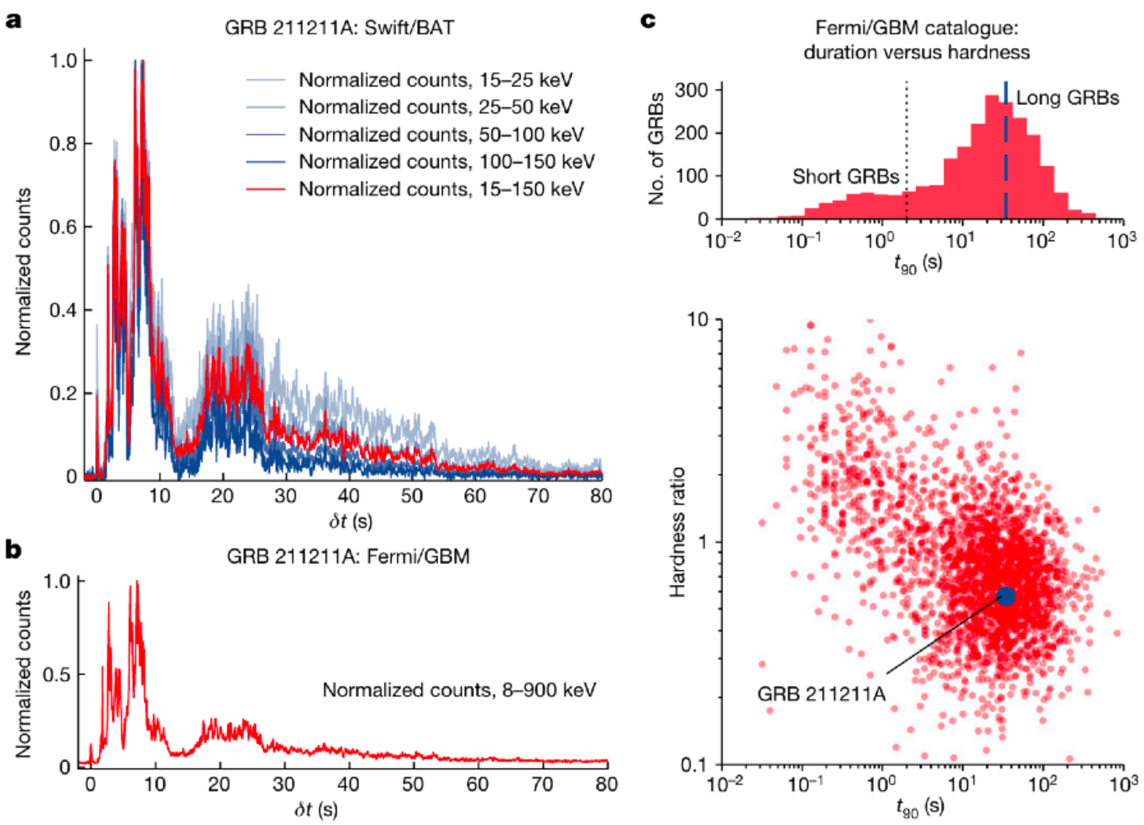
(super)kilonovae

extended emission?

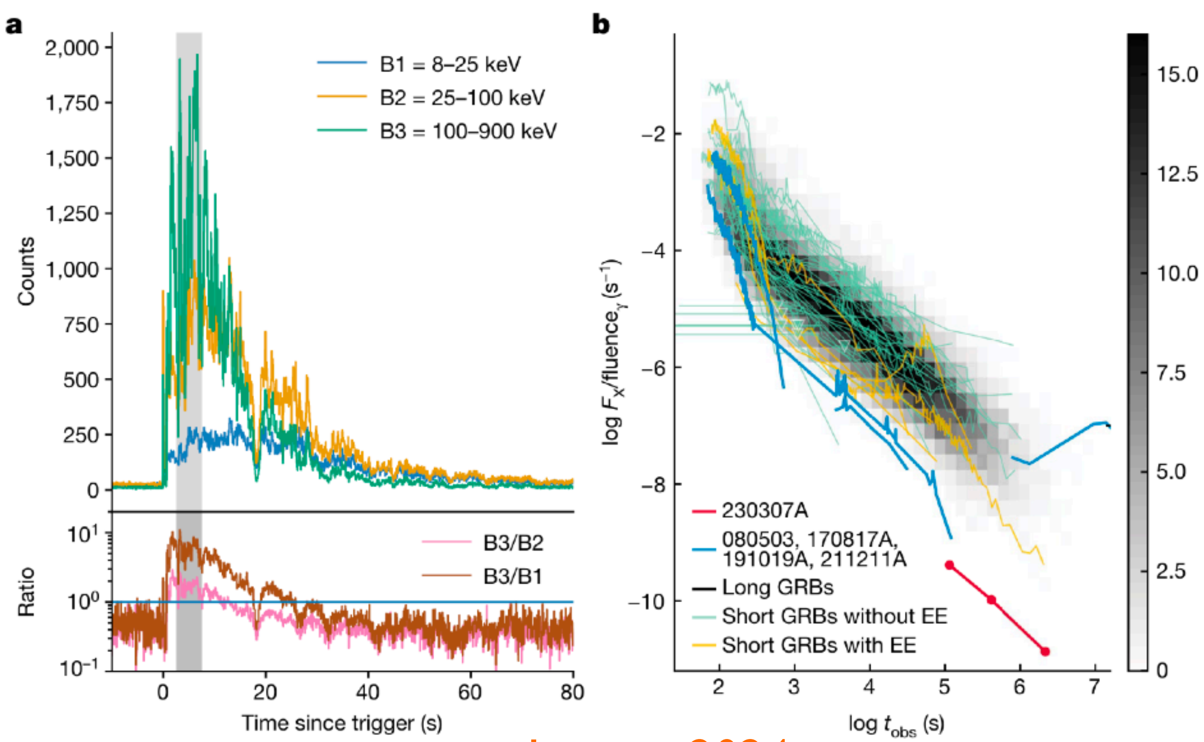
short GRBs

long GRBs

‘Cross-over’ events?

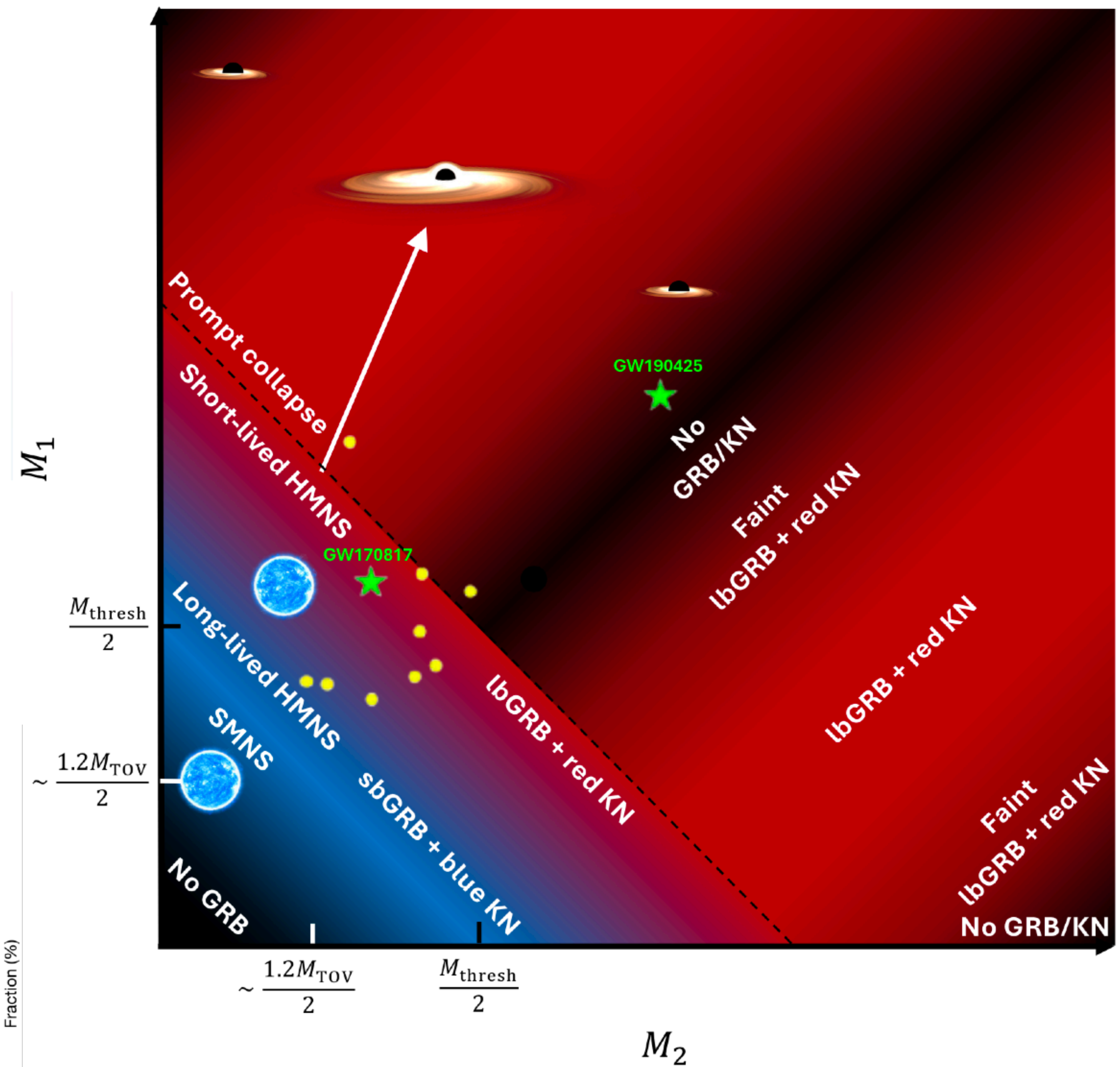


Rastinejad+ 2022



Levan+ 2024

Gottlieb & Metzger 2025



Kilonova and environmental information (incl. afterglow) key in identifying nature of progenitor

Summary & conclusions

- NS mergers give rise to various ejecta components with a broad range of properties
- First self-consistent ab initio modelling of multiple EM counterparts from NR simulations with relativistic effects underway, key to interpret future observations
- Non-thermal + magnetar enhanced kilonovae from mergers with long-lived remnant NS are key to identify long-lived remnant
- First self-consistent generation of twin polar jets σ ~ 5-10 and Γ ~ few-10

⟶ NS central engine for short GRBs ?! GRB precursors?

⟶ *Novel BH-disk GRB jet formation mechanism*

- jet/polar outflows create ~hr kilonova precursor (UV)
- NS+disk winds consistent with blue kilonova of GW170817
- Late winds from black hole+disk consistent with red kilonova of GW170817
- Collapsars (BHs M~20-50 Msun) and super-kilonovae (BHs M > 50 Msun): multi-messenger sources for 3rd generation GW detectors, GRB and supernova-kilonova EM counterparts, prolific sources of r-process elements
- Wide range (continuous?) range of central engines with GRB and kilonova phenomena