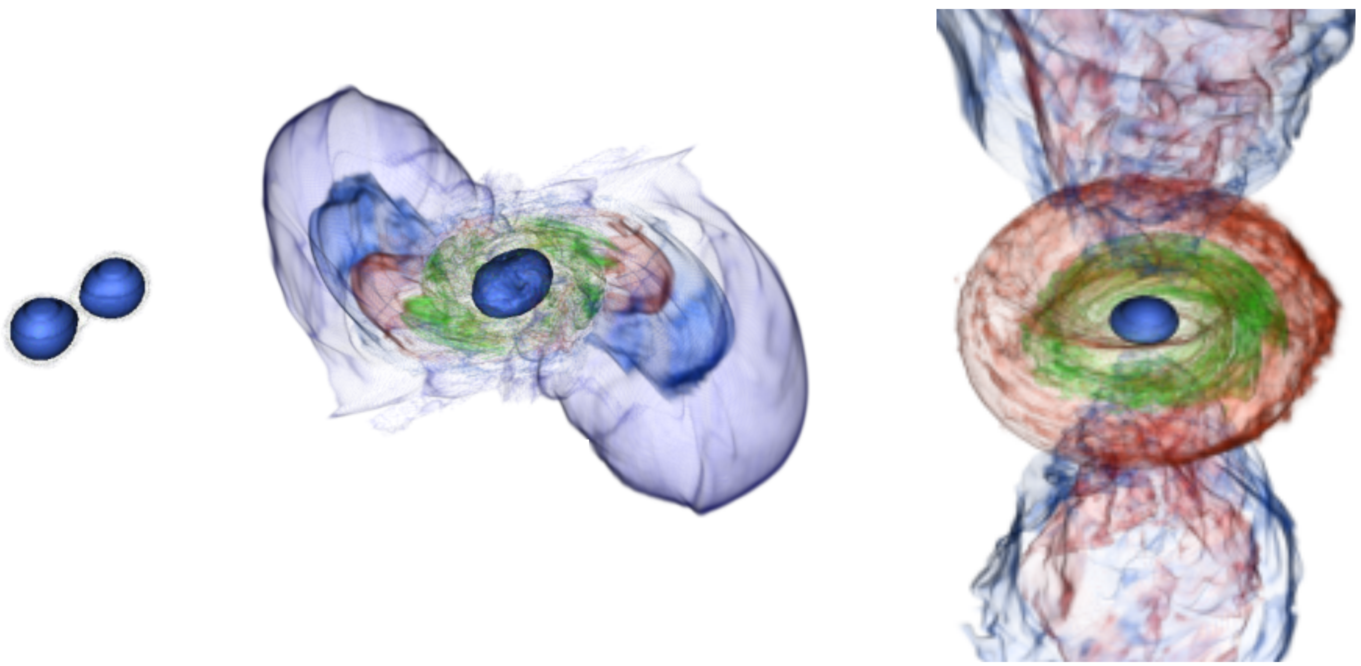
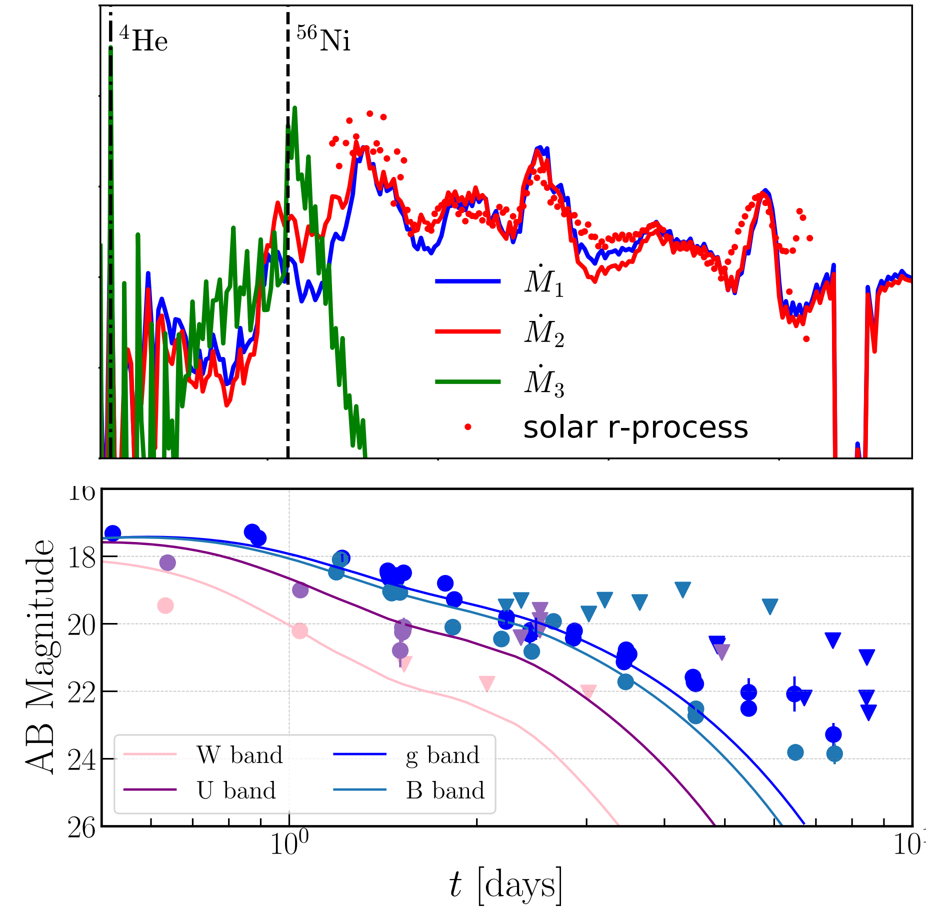
Electromagnetic signatures from GW events





Daniel Siegel

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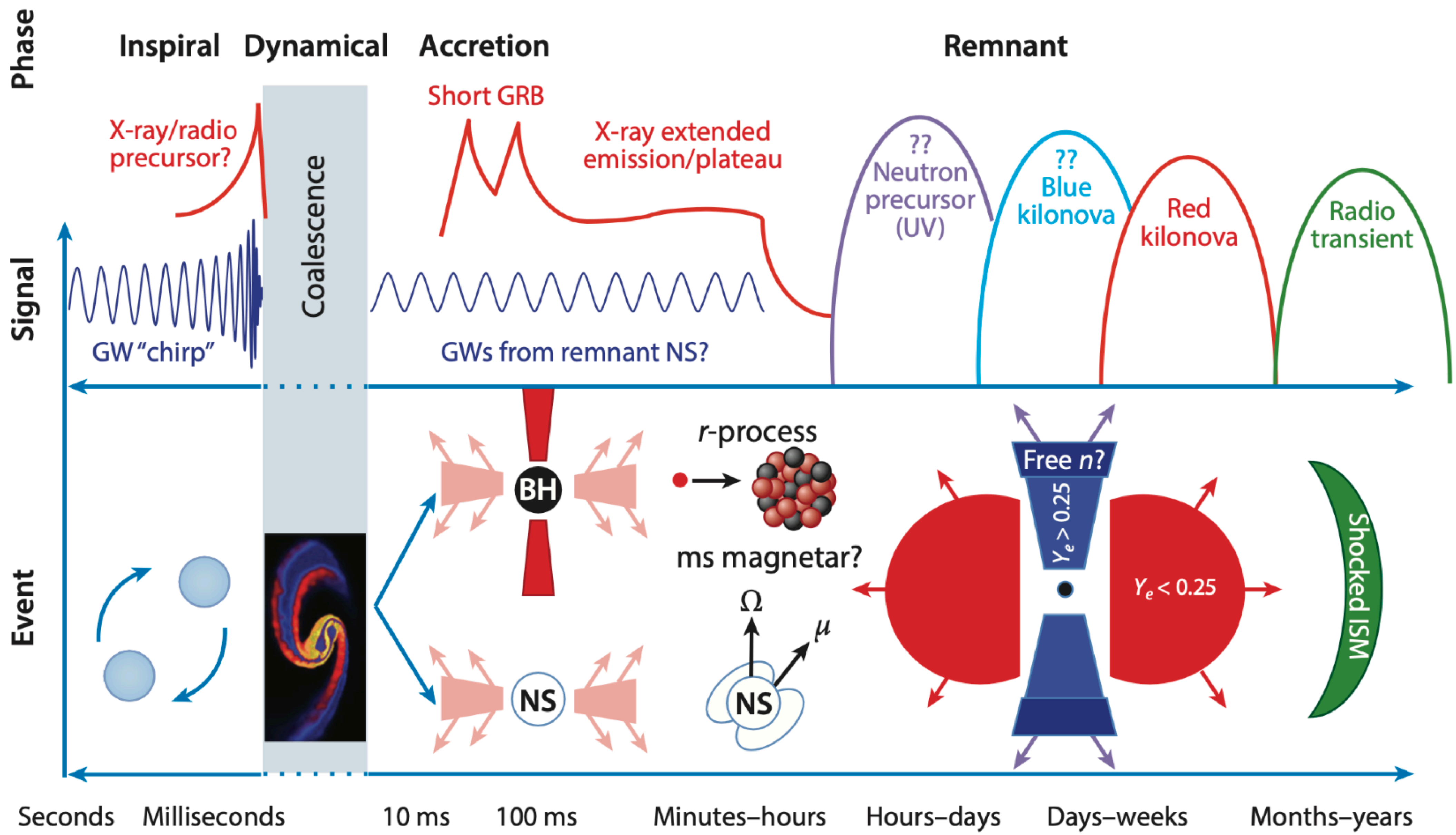
UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

1st TEONGRAV international workshop on theory of GWs, Rome, 16-20 Sept. 2024

Overview & focus of talk

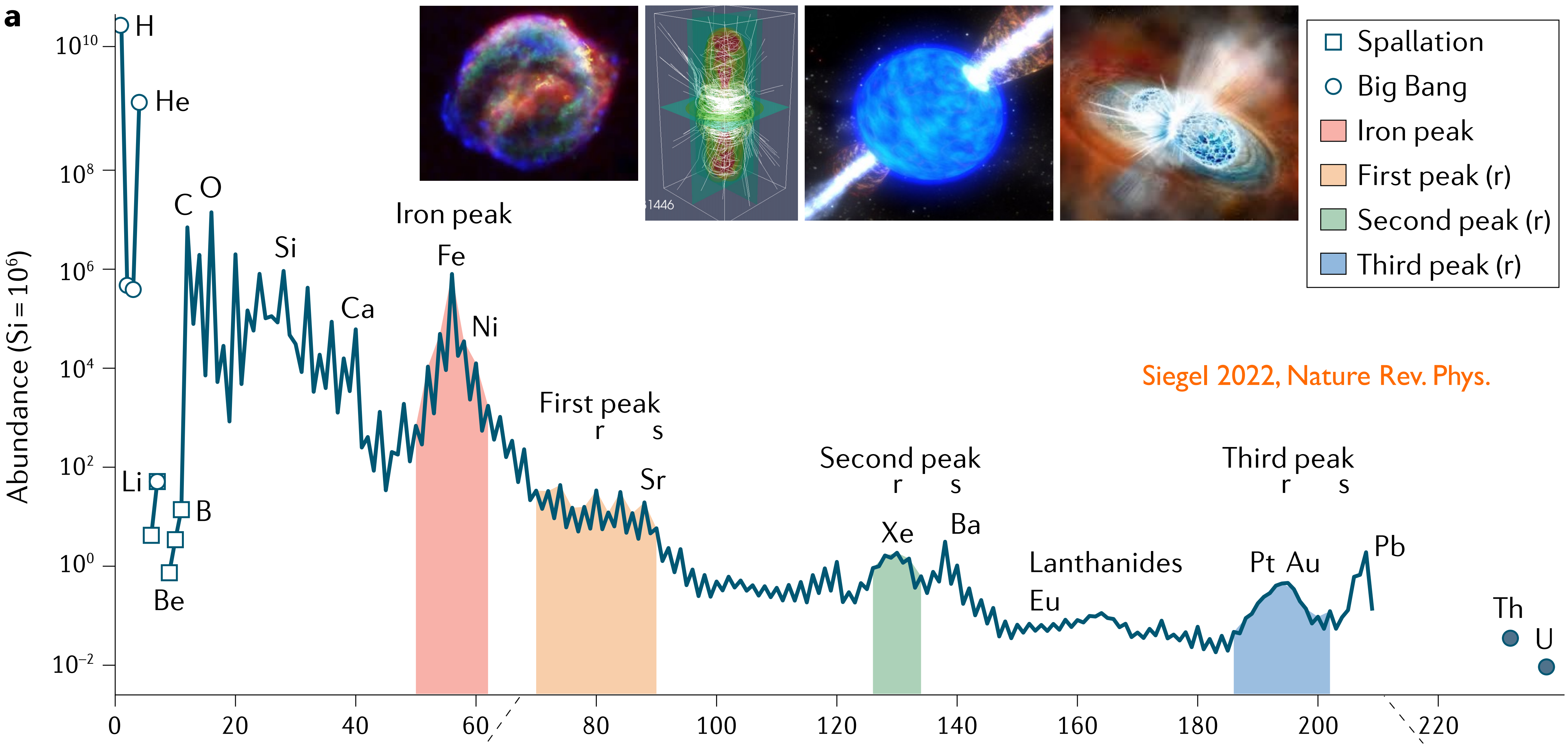


Fernandez & Metzger 2016

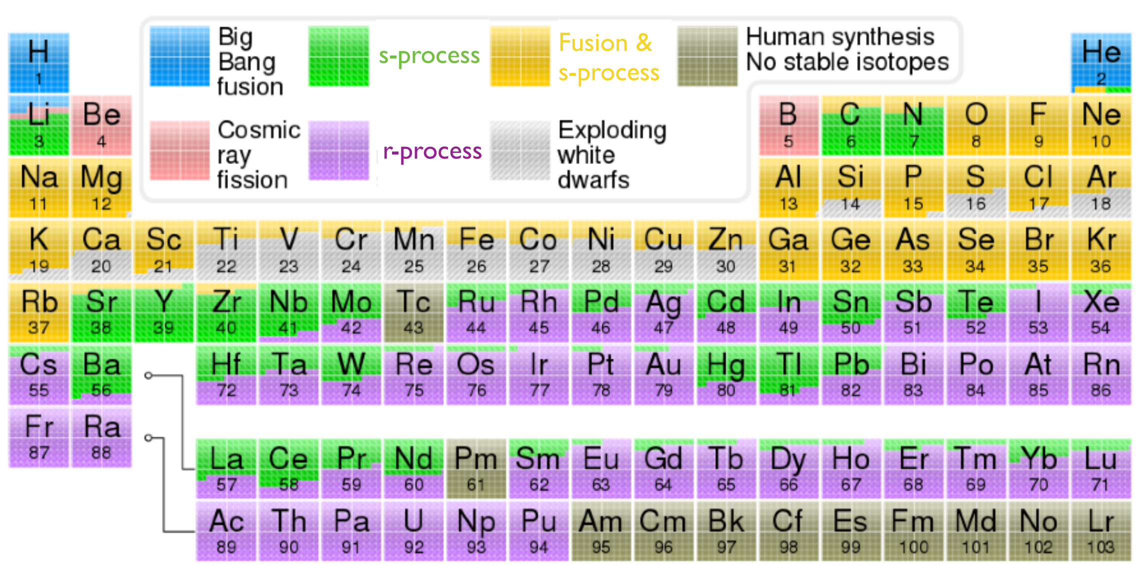
This talk:

- Theoretical (ab-initio) modelling of EM counterparts (see Eleonora Troja's talk for observational perspective)
- Focus on stellar-mass objects involving matter (BNS, NSBH, single BHs)

2nd theme: production of heavy elements

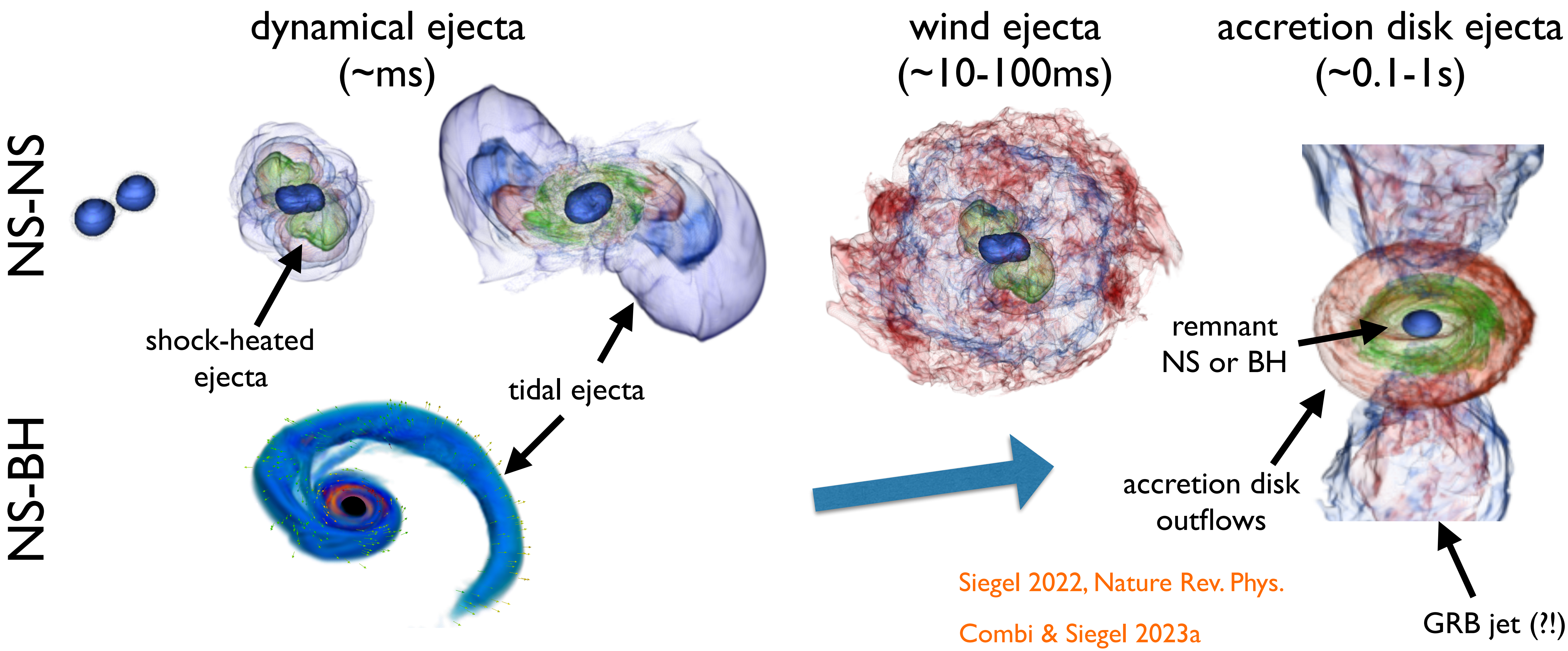


Siegel 2022, Nature Rev. Phys.



How does the universe populate the periodic table?

EM counterparts are powered by matter outflows



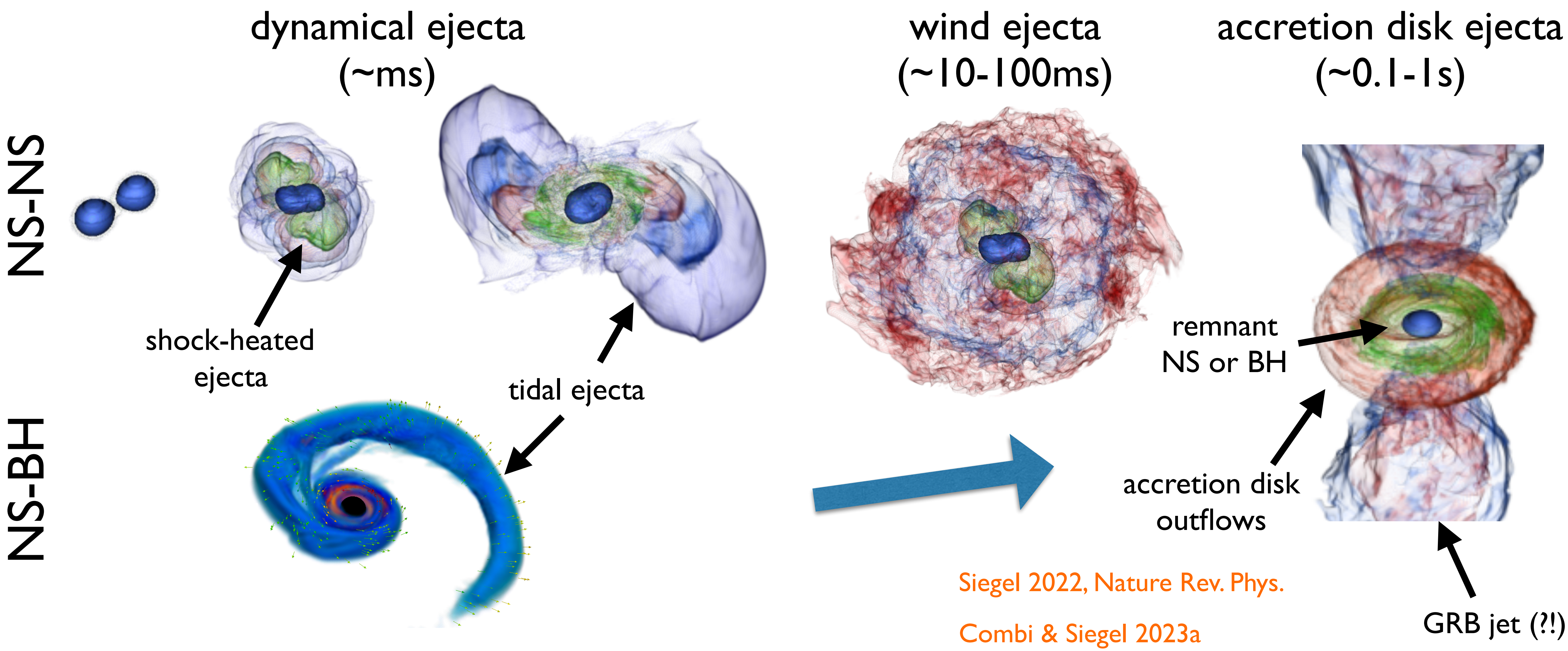
Some complications for NS-NS (complex post-merger phenomenology):

- 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.
The theoretical minimum — what it takes to model such events

Theoretical machinery: a multi-physics challenge

Fully coupled!

- General Relativity → Gravity
- Magnetohydrodynamics → Gas/plasma dynamics
- Nuclear Physics, weak interactions → Nuclear EOS (Micaela Oertel's talk) nuclear reactions, neutrino interactions
- Neutrino radiation transport → neutrino heating & cooling (leakage, M0, M1, Monte Carlo)

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$T^{\mu\nu} = T^{\mu\nu}_{\rm mat} + T^{\mu\nu}_{\rm EM} + T^{\mu\nu}_{\rm neu}$$

$$\nabla_\mu T^{\mu\nu} = \Psi^\nu$$

$$\nabla_\mu {}^\star F^{\mu\nu} = 0$$

$$\nabla_\mu (n_{\rm b} u^\mu) = 0$$

$$\nabla_\mu (n_{\rm e} u^\mu) = \mathcal{R}$$

Weak interactions (neutrinos):

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

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

$$e^+ + e^- \rightarrow \bar{\nu}_{e,\mu,\tau} + \nu_{e,\mu,\tau}$$

$$\gamma \rightarrow \bar{\nu}_{e,\mu,\tau} + \nu_{e,\mu,\tau}$$

⇒ $\Psi^\nu, \ \mathcal{R}$

Theoretical machinery: a multi-physics challenge

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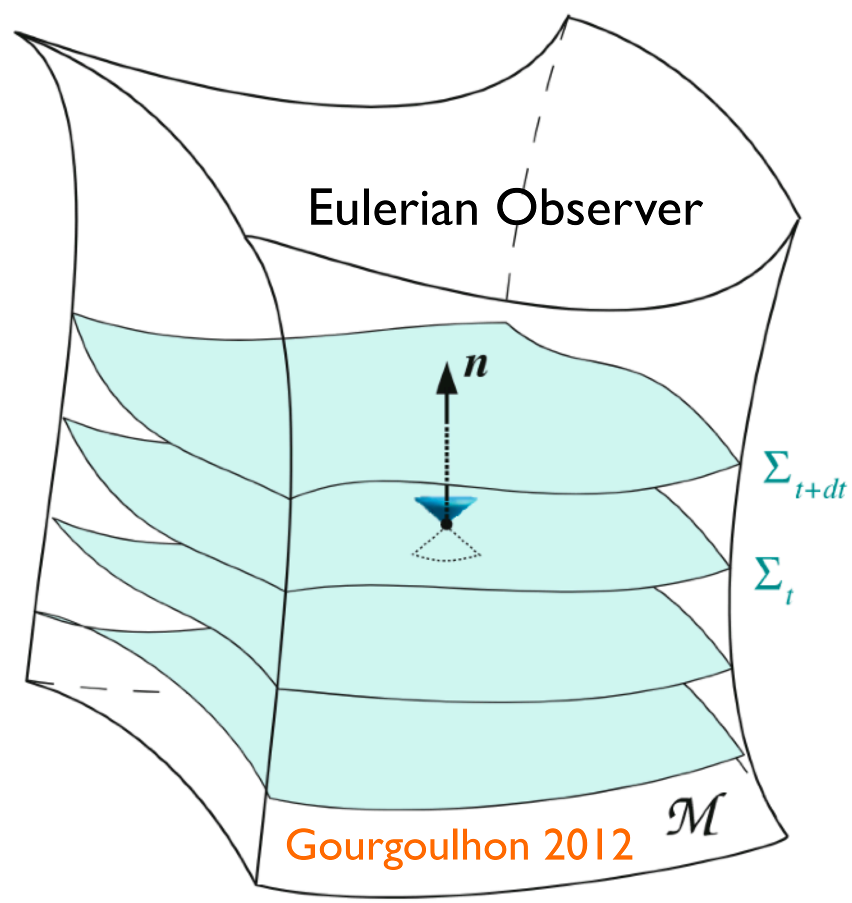
$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

↓

General Relativity in 3+1 split:
evolution and *constraint* equations
see also Helvi Witek's talk

system of first-order hyperbolic PDEs (e.g. BSSN system) + elliptical PDEs (constraints/initial data)



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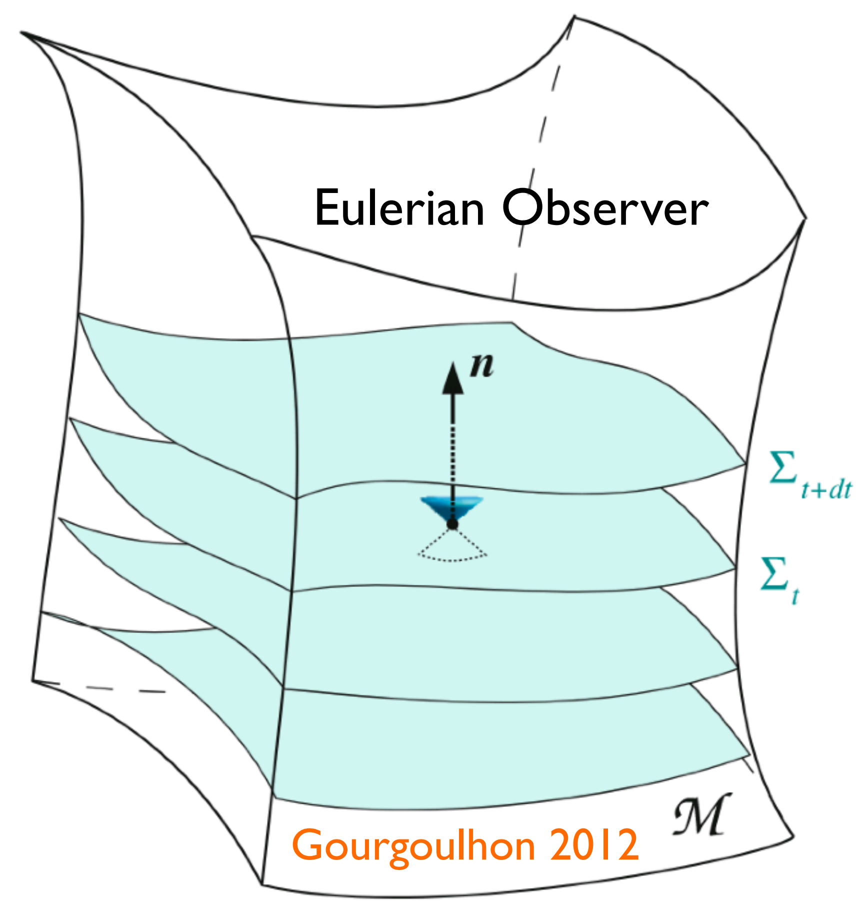
$$\nabla_\mu (n_{\rm b} u^\mu) = 0$$

Magnetohydrodynamics in 3+1 split: system of conservation equations

$$\partial_t(\sqrt{\gamma}\boldsymbol{q}) + \partial_i[\alpha\sqrt{\gamma}\boldsymbol{f}^{(i)}(\boldsymbol{p},\boldsymbol{q})] = \alpha\sqrt{\gamma}\boldsymbol{s}(\boldsymbol{p}),$$

conserved variables — fluxes — source terms



Theoretical machinery: a multi-physics challenge

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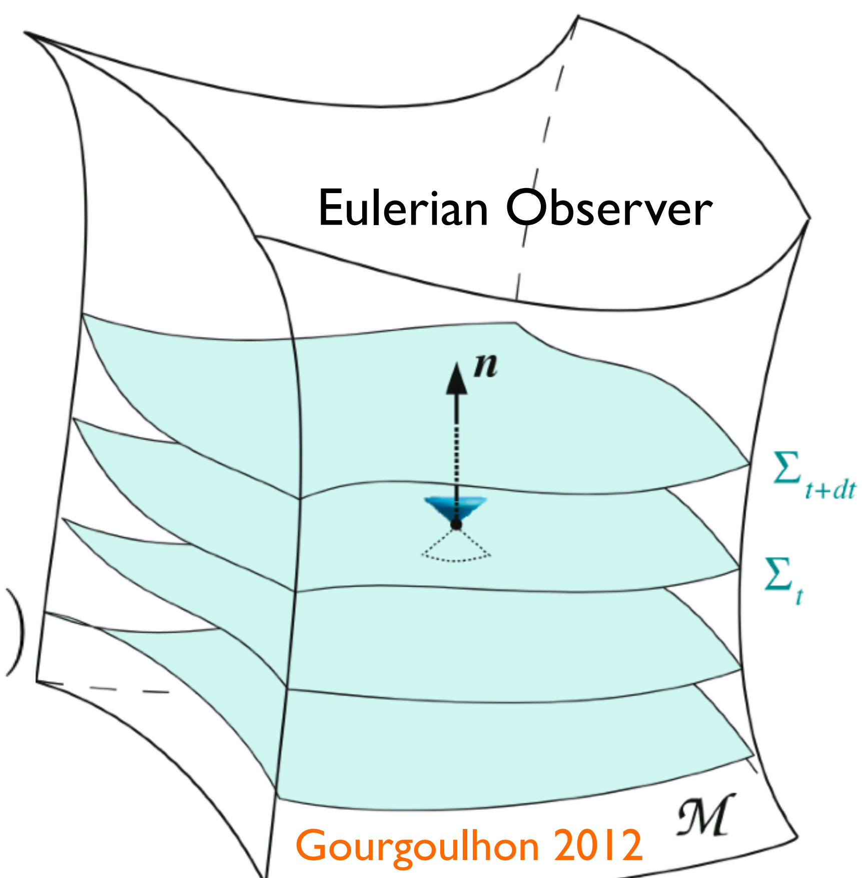
$$\frac{dx^\alpha}{d\tau}\frac{\partial f}{\partial x^\alpha} + \frac{dp^i}{d\tau}\frac{\partial f}{\partial p^i} = (-p^\alpha u_\alpha) S(p^\mu, x^\mu, f)$$

Boltzmann equation in 3+1 split with truncated moments:
system of conservation equations

$$\partial_t(\sqrt{\gamma}E) + \partial_j\left[\sqrt{\gamma}\left(\alpha F^j - \beta^j E\right)\right] = \alpha\sqrt{\gamma}\left(P^{ij}K_{ij} - F^j\partial_j \ln\alpha - S^\alpha n_\alpha\right),$$

$$\partial_t(\sqrt{\gamma}F_i) + \partial_j\left[\sqrt{\gamma}\left(\alpha P_i^j - \beta^j F_i\right)\right] = \sqrt{\gamma}\left(-E\partial_i\alpha + F_k\partial_j\beta^k + \frac{\alpha}{2}P^{jk}\partial_i\gamma_{jk} + \alpha S^\alpha\gamma_{i\alpha}\right)$$

conserved variables | fluxes | source terms



BNS post-merger: multi-physics, multi-scales challenge

Magnetohydrodynamics

- role of turbulence in the remnant

  angular momentum transport, dynamo,
  magnetic fields across various scales, …

  MHD subgrid models, LES, viscous hydrodynamics
- magnetic topology across scales, jet formation, short GRBs
- beyond MHD: resistive MHD

Nuclear Physics, weak interactions

- EOS and finite-temperature effects, phase transitions
- nucleosynthesis across ejecta components, param. space
- weak interactions neglected, neutrino fast flavour conversions

Neutrino radiation transport

- ray-by-ray (M0), two-moment (M1), Monte-Carlo transport

Other microphysics: bulk viscosity, non-ideal hydrodynamics, …

Recent developments:

Radice 2017, 2022
Nedora+ 2021
Palenzuela+ 2022
Combi & Siegel 2023a,b
Kiuchi+ 2024
Aguilera-Miret+ 2024
Ciolfi+ 2020
Ruiz+ 2016

Andersson+ 2022
Shibata+ 2021

Raithel+ 2022
Most+ 2020
Bauswein+ 2019

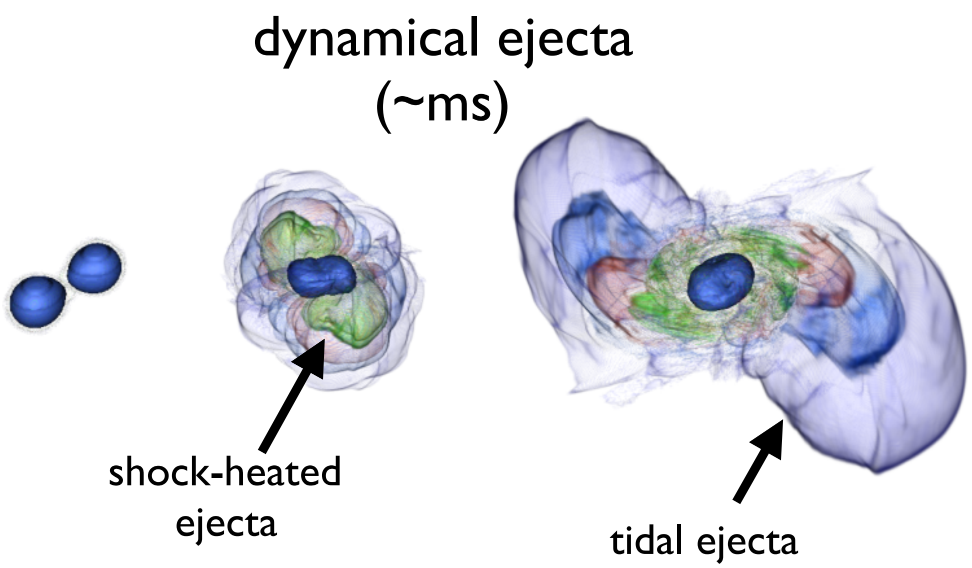
Fujibayashi+ 2020
Shibata+ 2021
Kawaguchi+ 2021
Li & Siegel 2021
Fernandez+ 2022
Just+ 2022

Foucart+ 2018, 2020
Li & Siegel 2021
Radice+ 2022

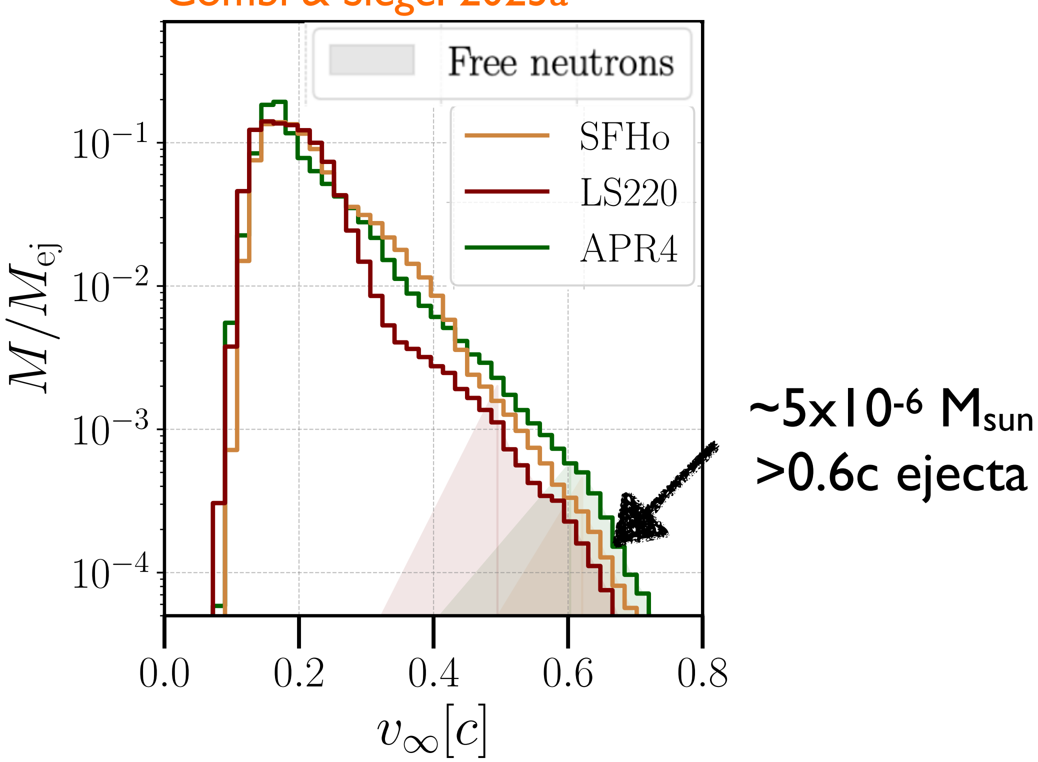
Most+ 2022

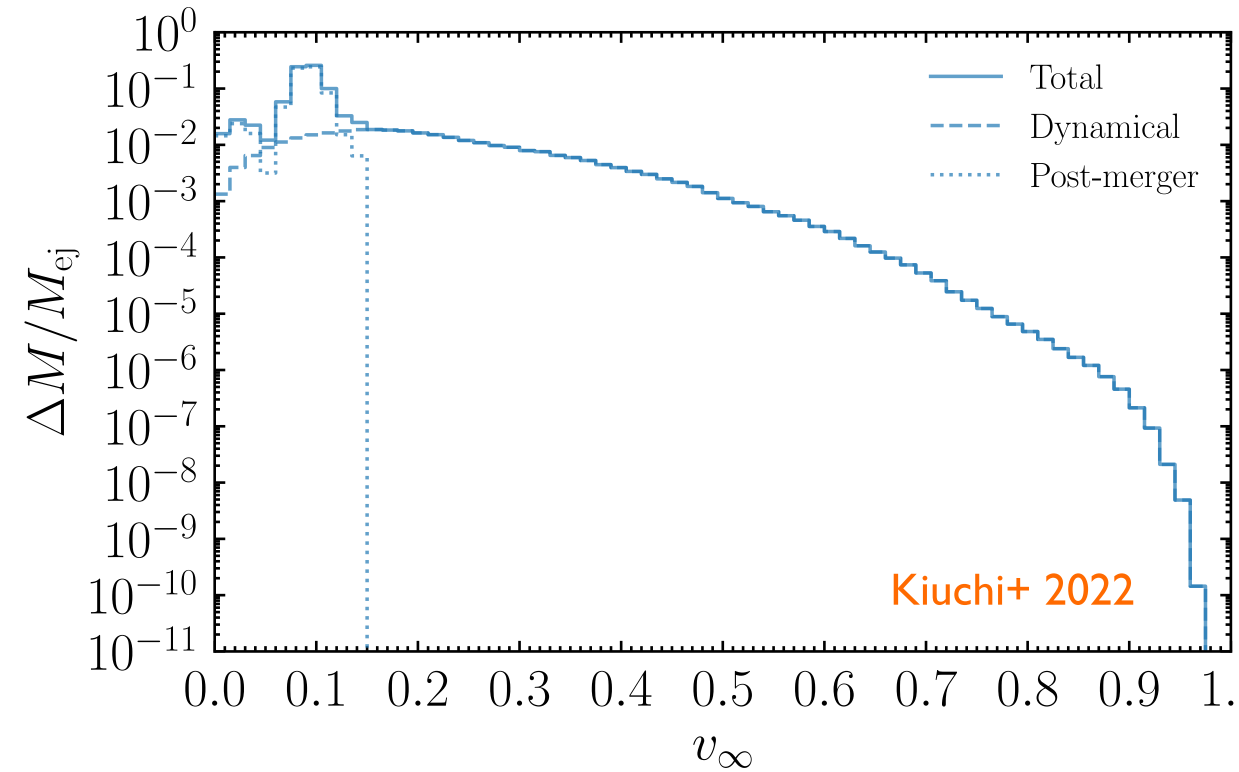
II Electromagnetic counterparts of dynamical ejecta

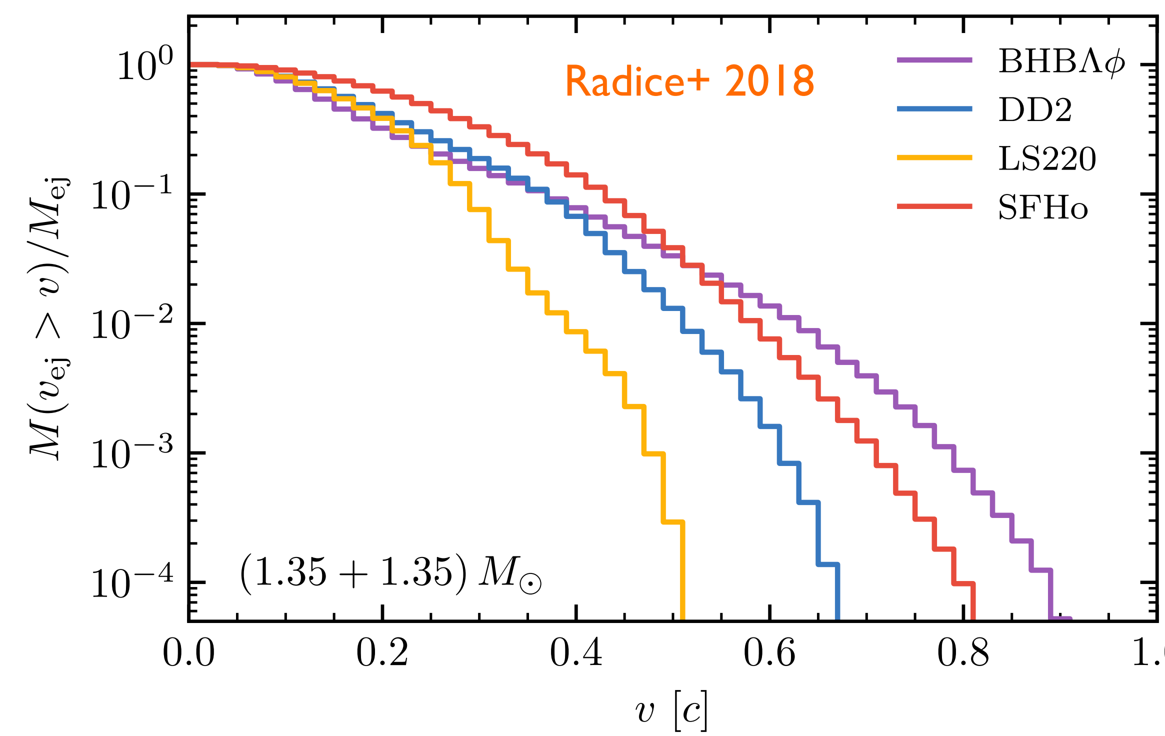
Fast dynamical ejecta



Combi & Siegel 2023a





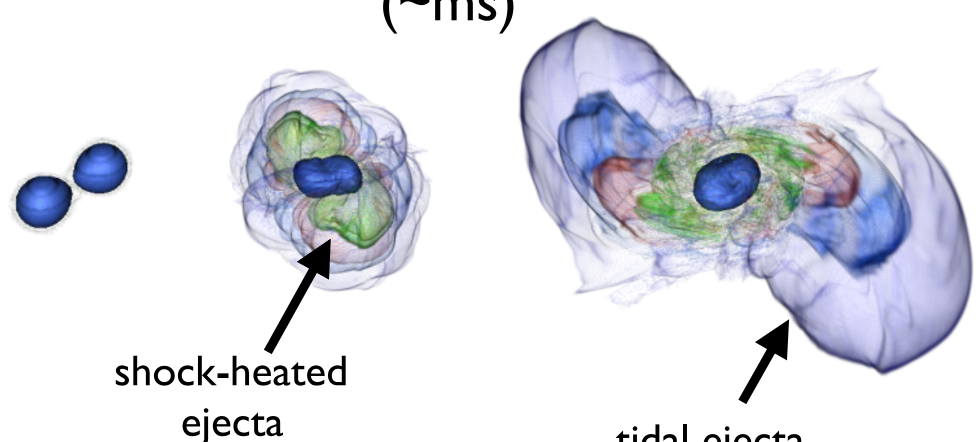


fast, high-Y_e (>0.25), shock-heated ejecta drives shock wave into the ISM

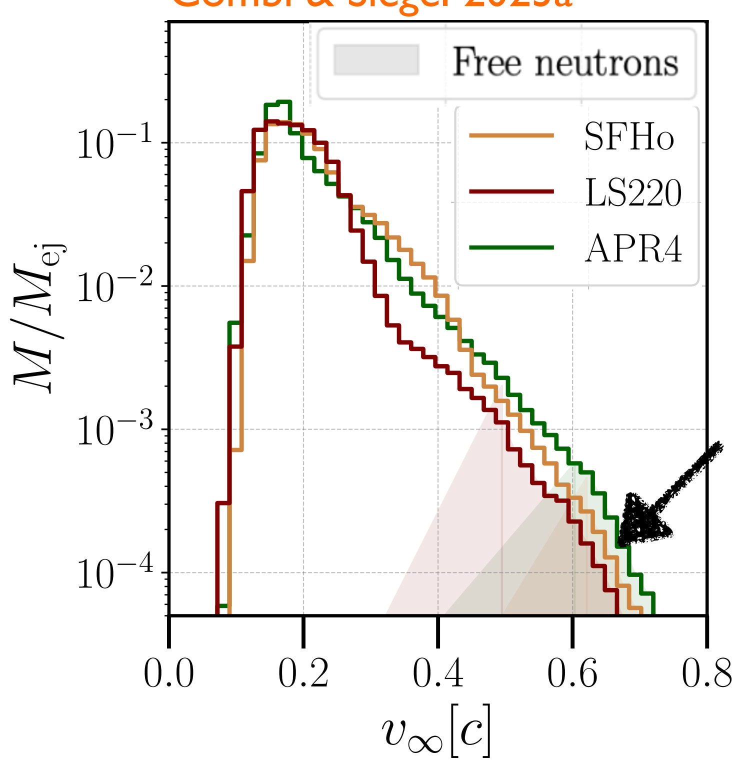
See also: Hotokezaka+ 2018, Dean+ 2021

Fast dynamical ejecta: X-ray to radio afterglow

dynamical ejecta
(~ms)



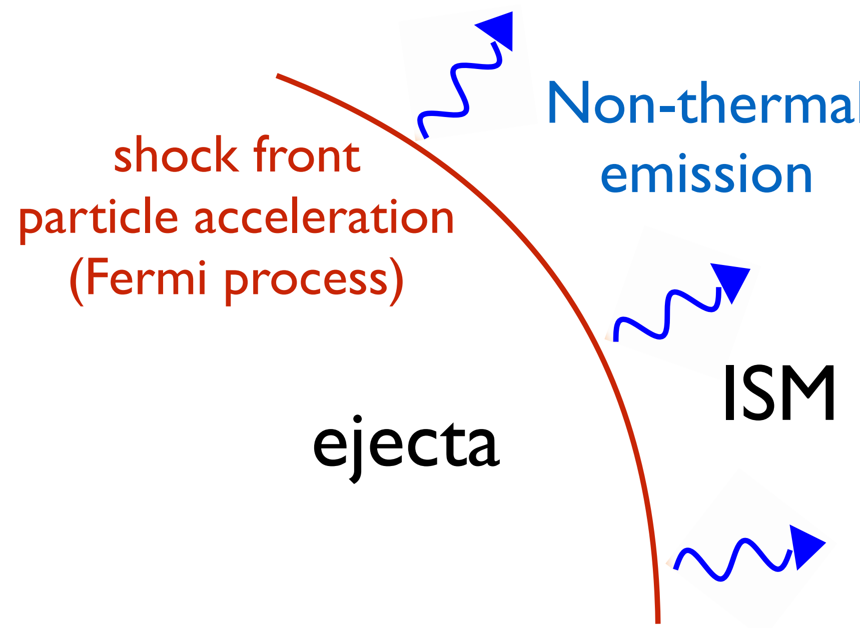
Combi & Siegel 2023a



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

- 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

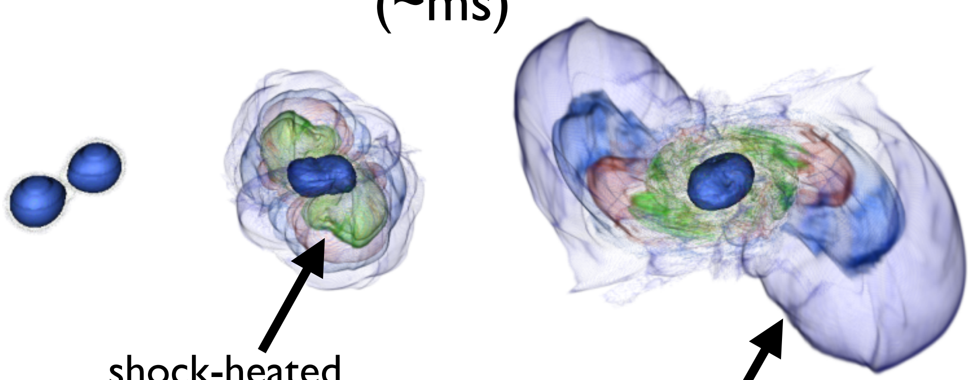


$$\frac{\partial n_e(\gamma_e, t)}{\partial t} = -\frac{\partial}{\partial \gamma_e}[\dot{\gamma_e}(\gamma_e, t) n_e(\gamma_e, t)] + Q(\gamma_e, t) - \frac{n_e(\gamma_e, t)}{t_{esc}}.$$

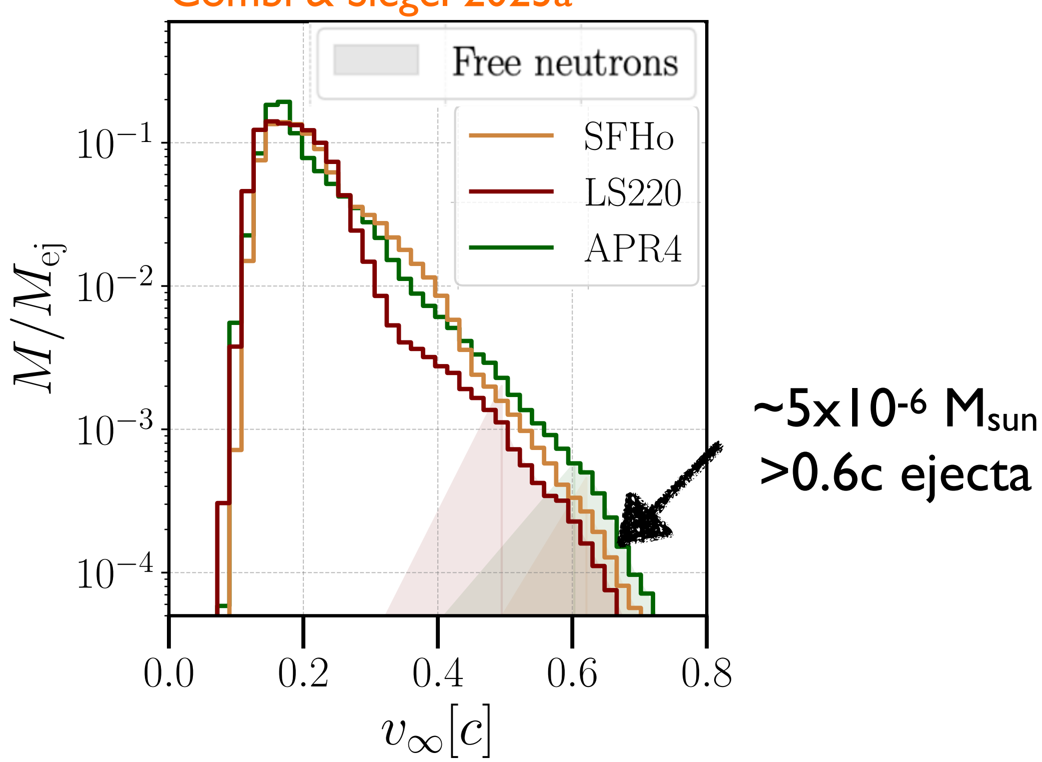
- Full numerical solution of Fokker-Planck equation

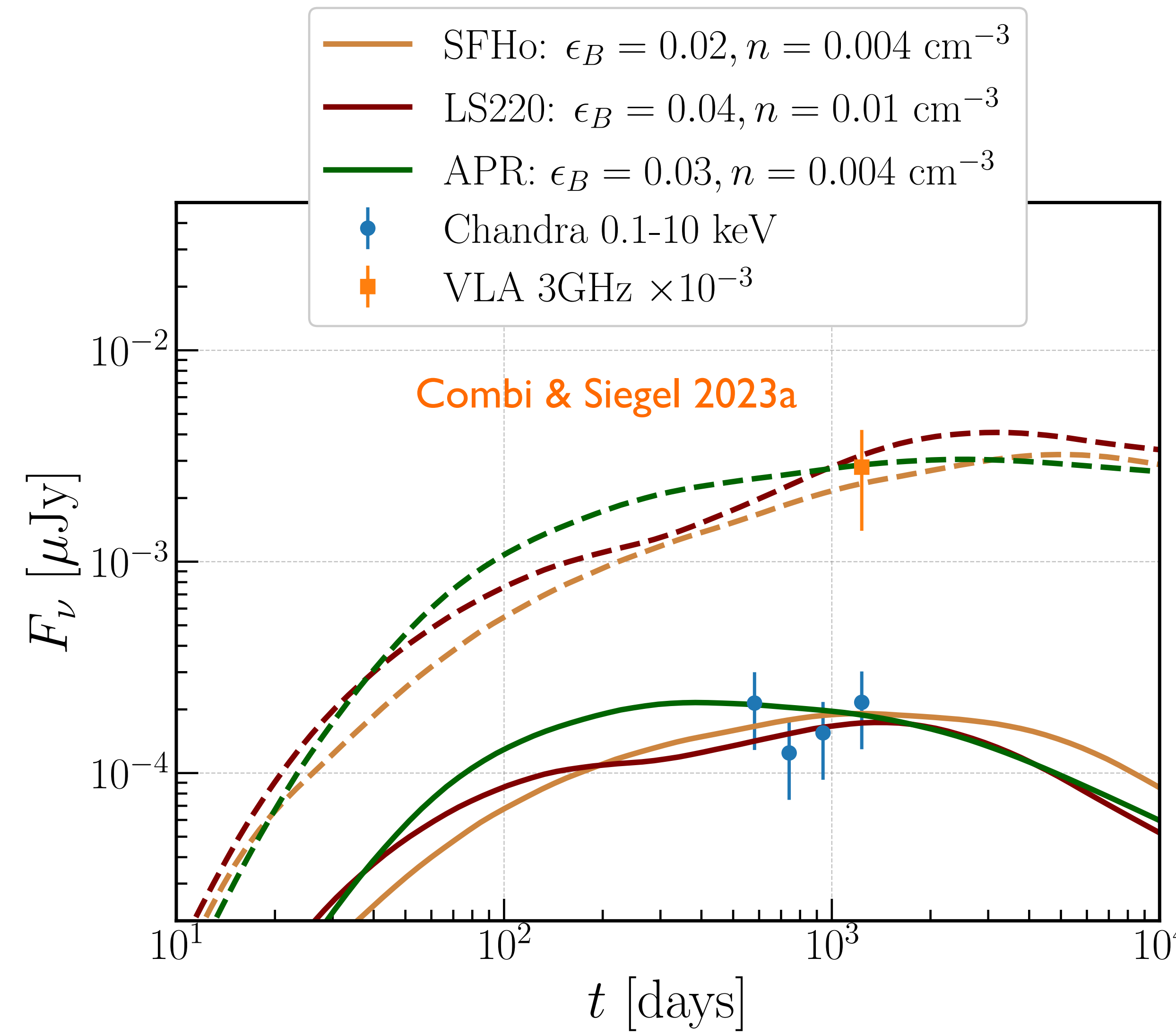
  (Syn+IC cooling, Syn self-Compton, self-absorption)
- angle dependent
- relativistic effects

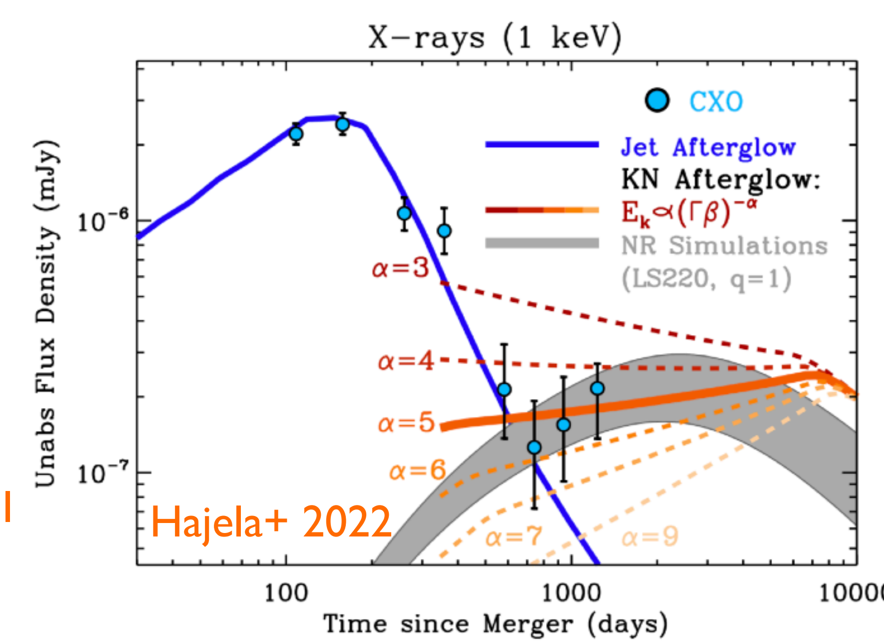
Fast dynamical ejecta: X-ray to radio afterglow



Combi & Siegel 2023a







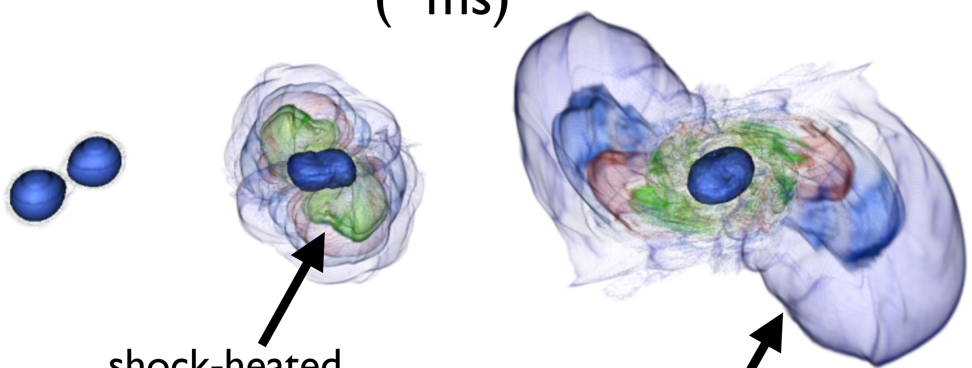
- fast, high-Y_e (>0.25), shock-heated ejecta
- GW170817: source of X-ray-radio afterglow, timescale of years

→ Helps distinguish BNS vs. NS-BH

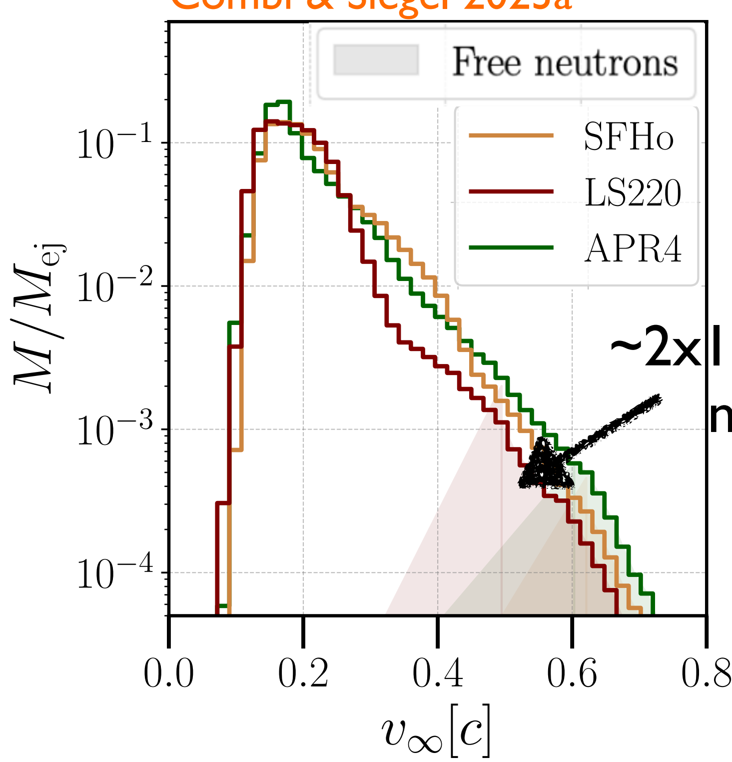
Hajela+ 2022
Troja+ 2022
Ryan+ 2024
Balasubramanian+ 2021
Nedora+ 2021

Fast dynamical ejecta: neutron precursor

dynamical ejecta (~ms)



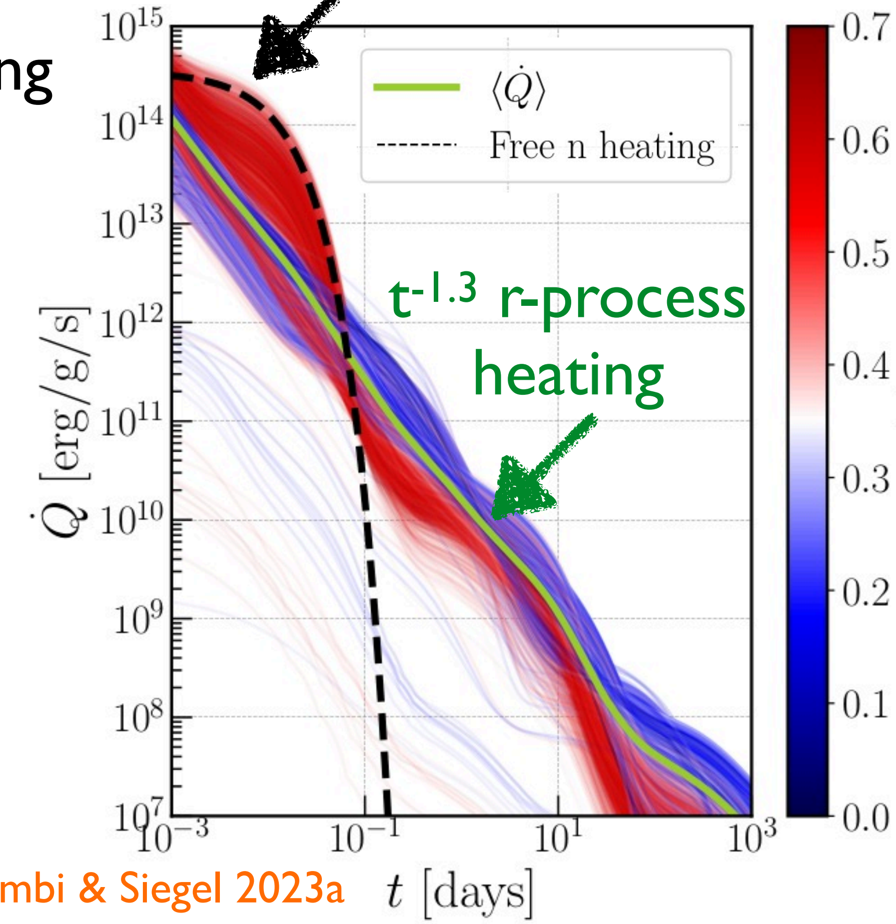
Combi & Siegel 2023a



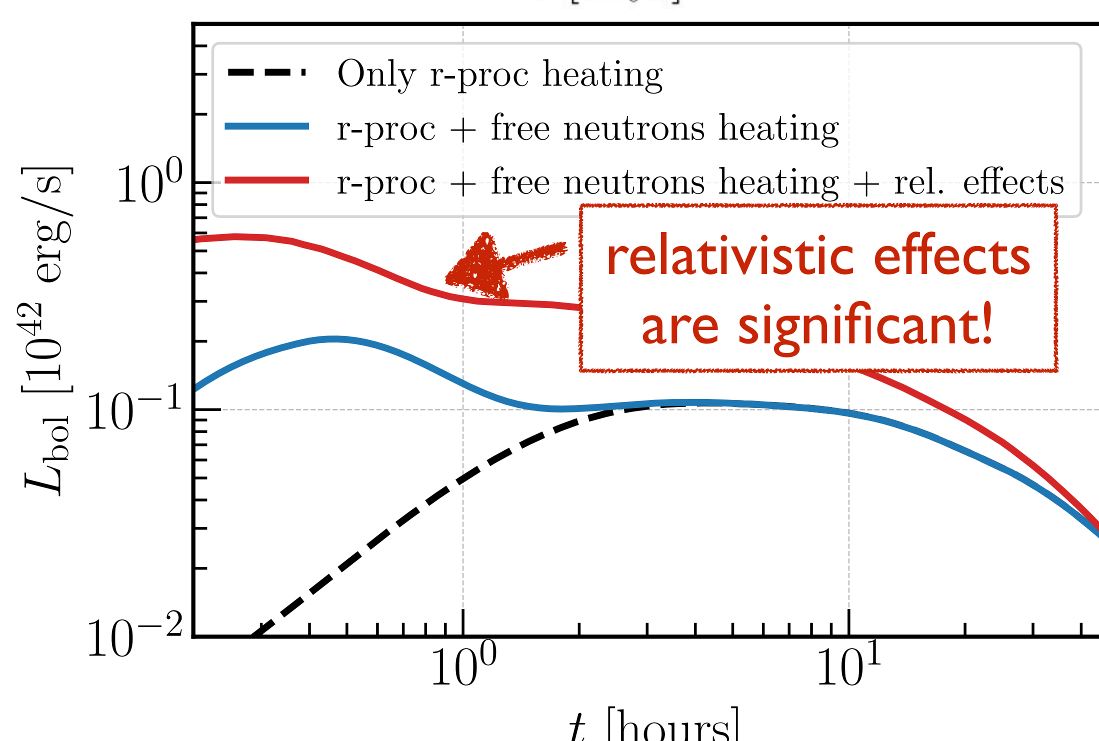
~2x10^{-5} M$_{\rm sun}$ free neutrons

Nuclear heating in ejecta

free neutron decay



Combi & Siegel 2023a

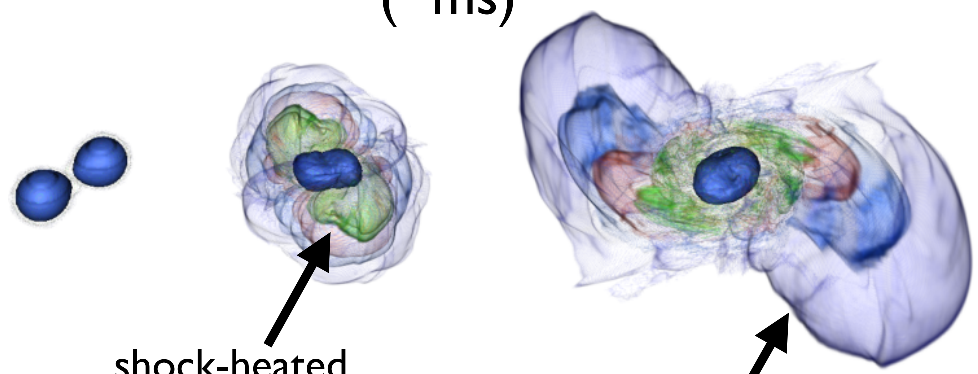


fast, high-Y_e (>0.25), shock-heated ejecta leads to free neutrons

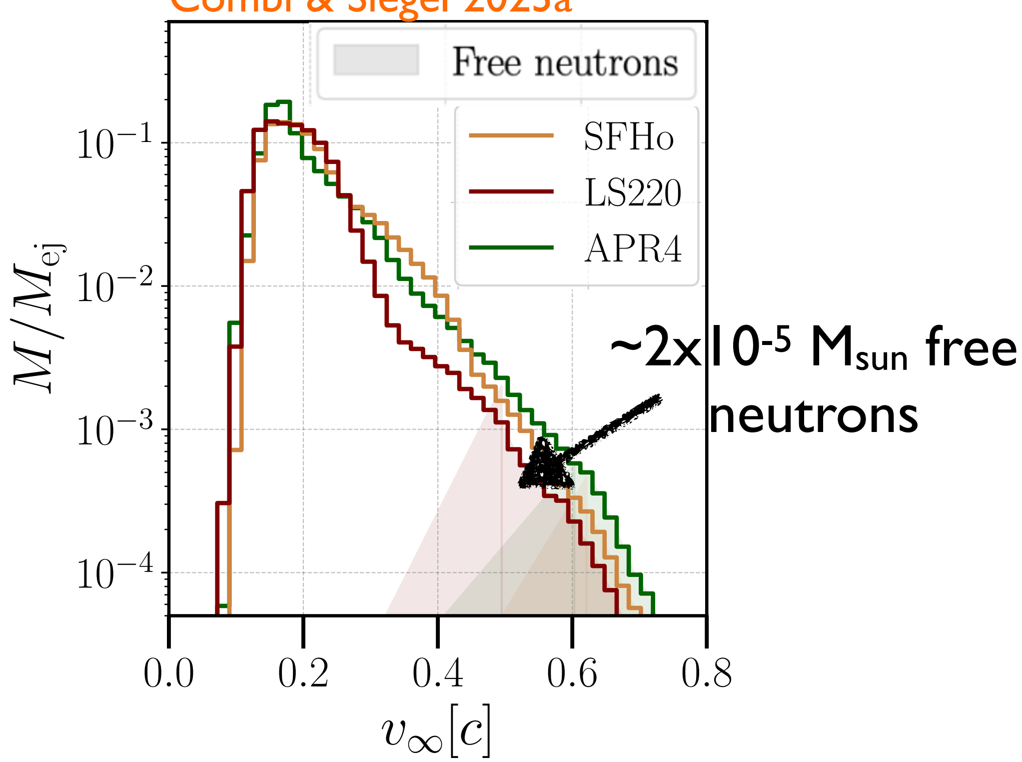
⟶ early UV emission ≲hours ('neutron precursor') Metzger+ 2015

Fast dynamical ejecta: neutron precursor

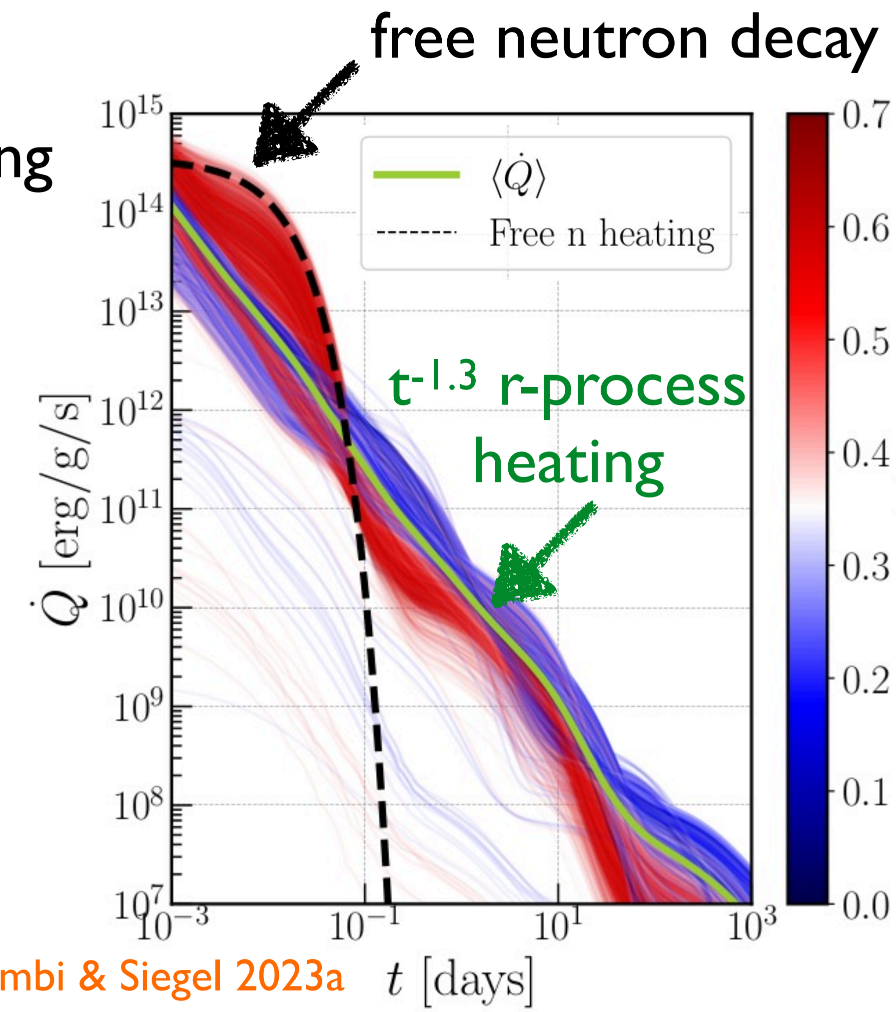
dynamical ejecta (~ms)



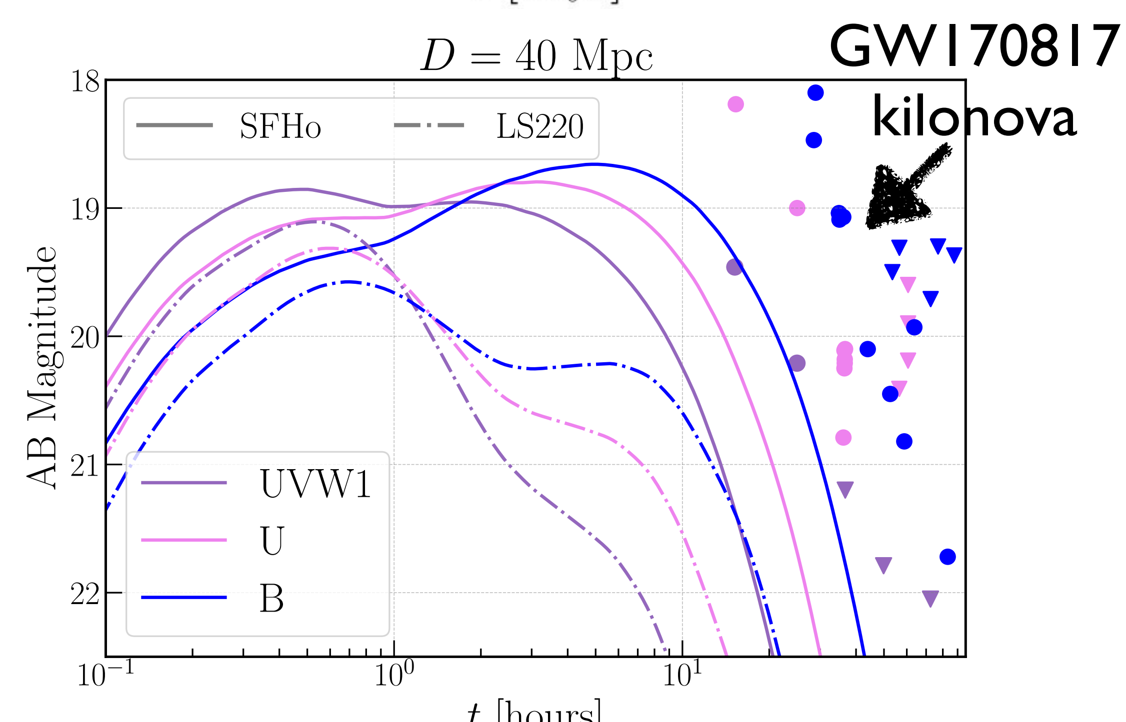
Combi & Siegel 2023a



Nuclear heating in ejecta



Combi & Siegel 2023a

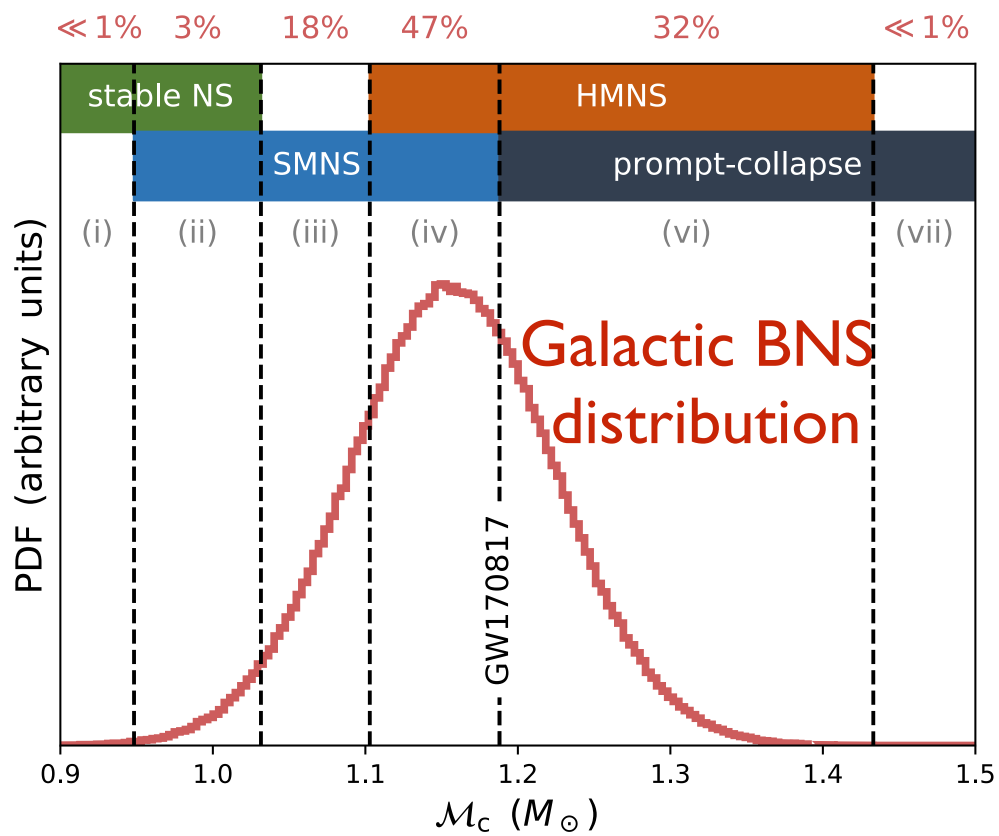


fast, high-Y_e (>0.25), shock-heated ejecta leads to free neutrons

→ distinguish BNS vs. NS-BH

III.
Non-thermal EM from long-lived remnant NSs

Remnant diversity & distribution



Margalit & Metzger 2019

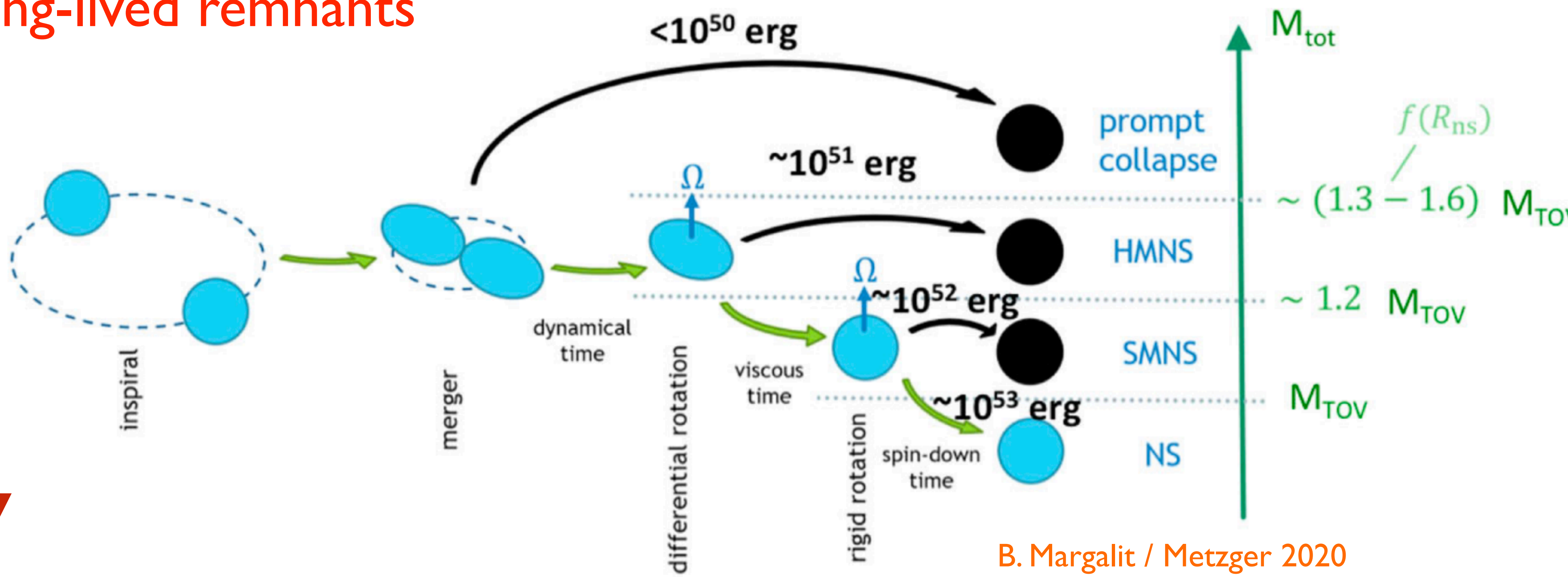
long-lived remnants

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

≳ 15-20 % of BNS mergers (?)

E_{rot}

EM emission

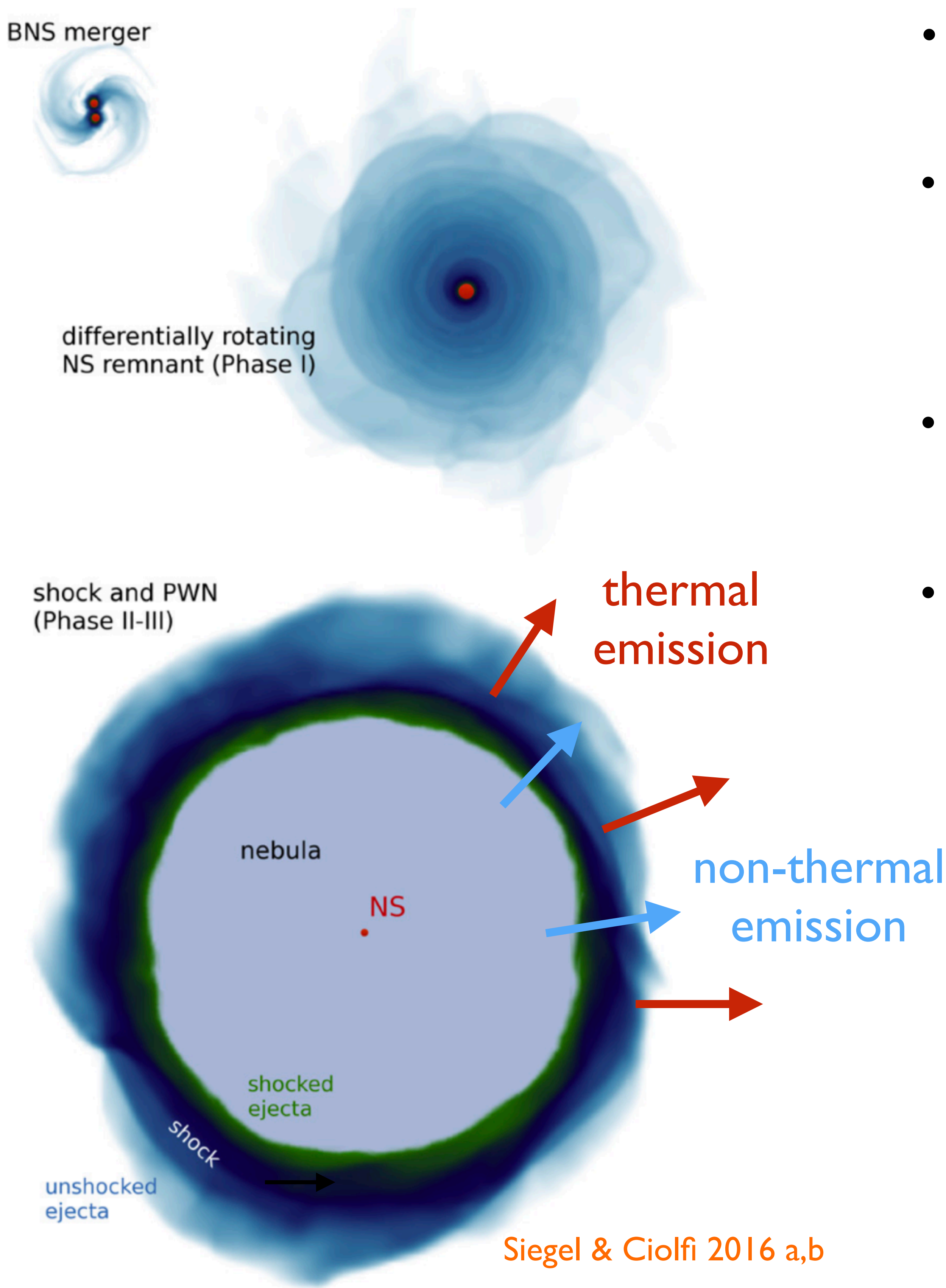


B. Margalit / Metzger 2020

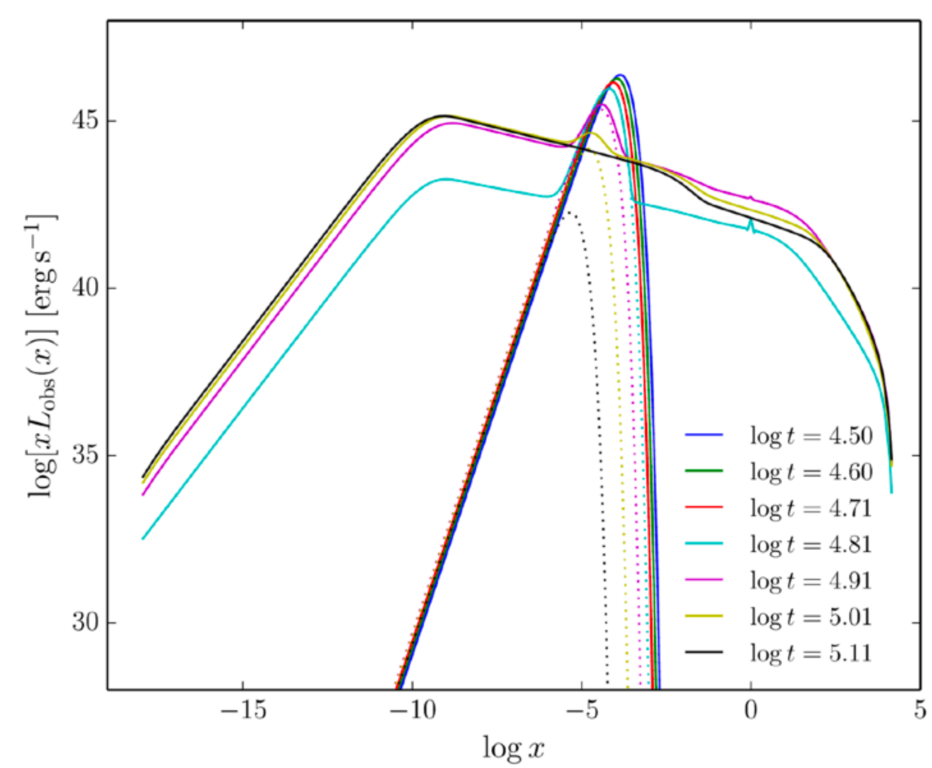
Long-lived remnants

EM emission from systems with long-lived remnants

- E_{rot} ~ 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



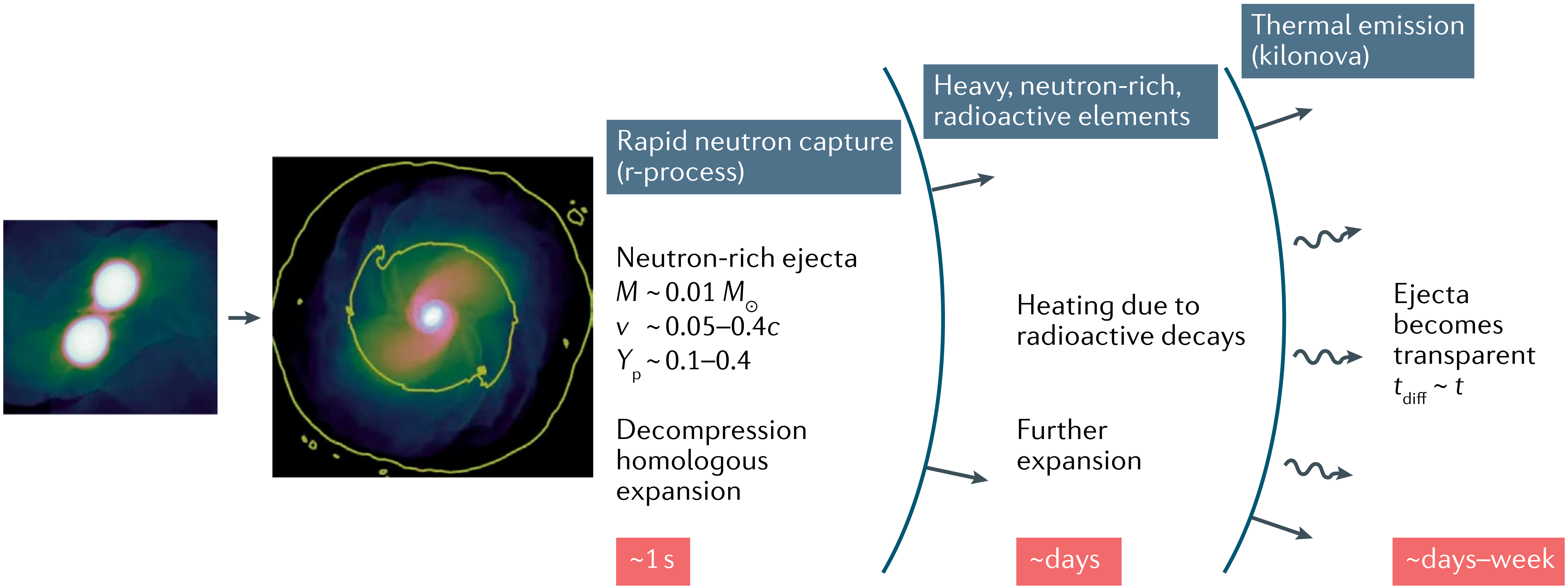
Siegel & Ciolfi 2016 a,b



IV Post-merger physics:
Jets & massive blue kilonovae

Kilonovae—illuminating merger ejecta

Metzger+ 2010



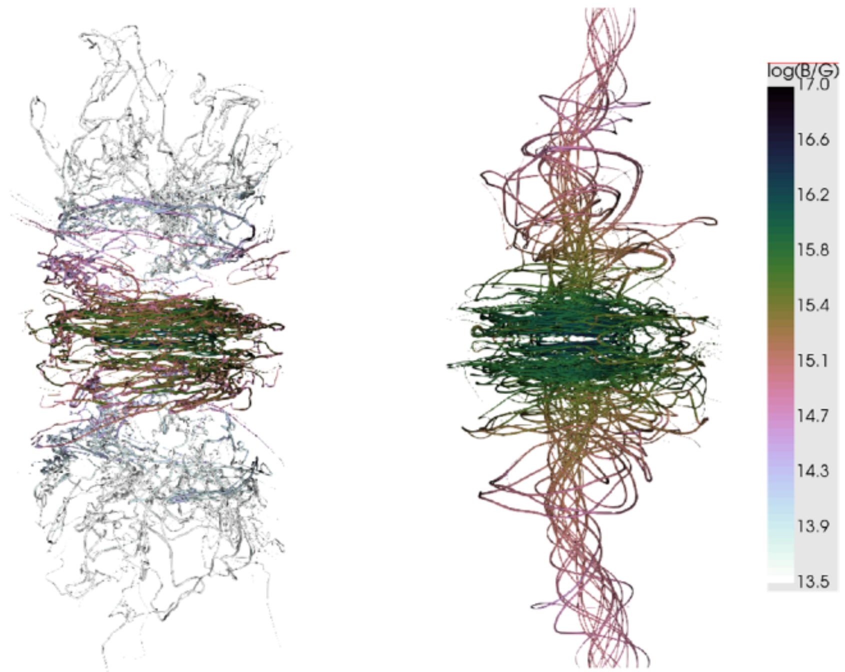
Siegel 2022, Nature Rev. Phys.

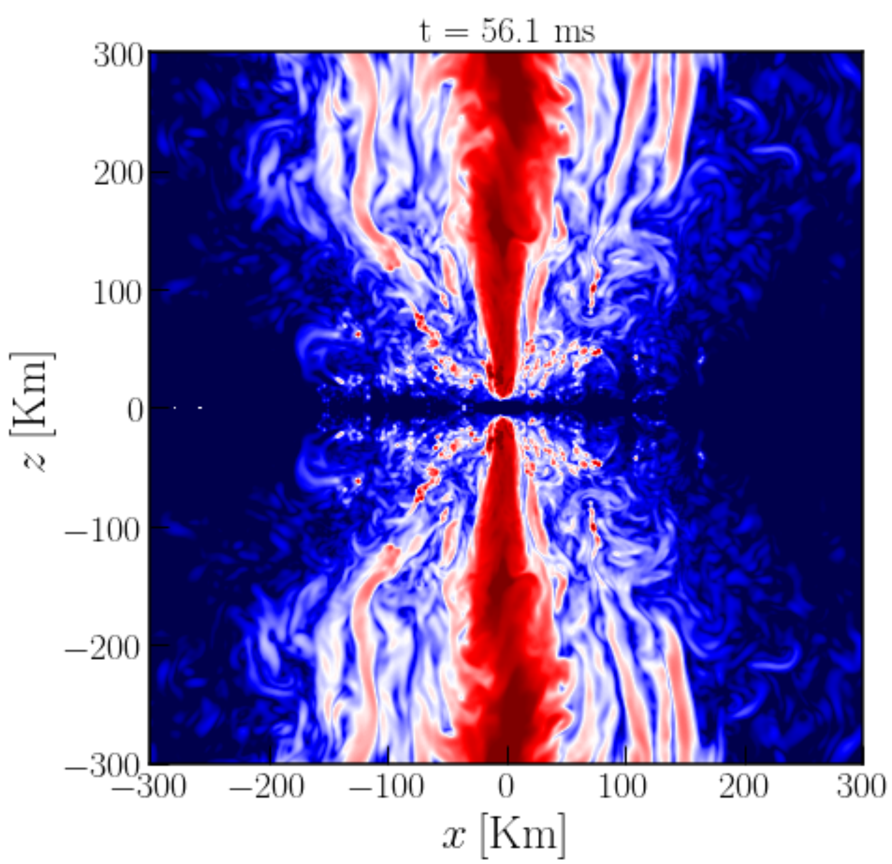
- Ejecta parameters: mass, velocity, composition (Y_e)
- Kilonova emission (color: 'red' vs. 'blue') very sensitive to composition/weak interactions (high opacities of lanthanides)

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

Post-merger physics: MHD phenomena & r-process

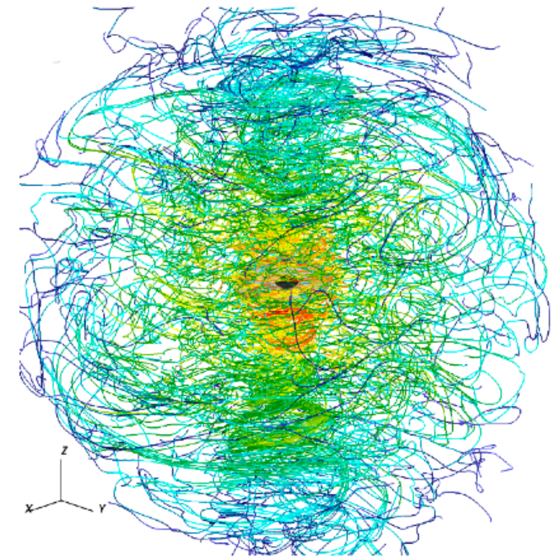
Combi & Siegel 2023b, PRL





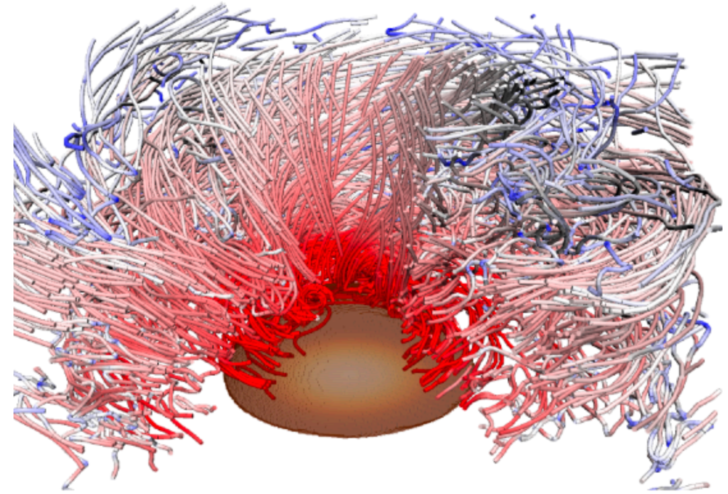
Aguilera-Miret+ 2023

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



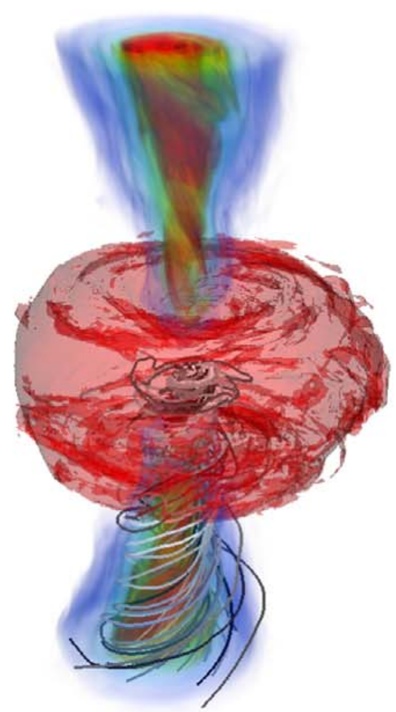
Kiuchi+ 2024

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



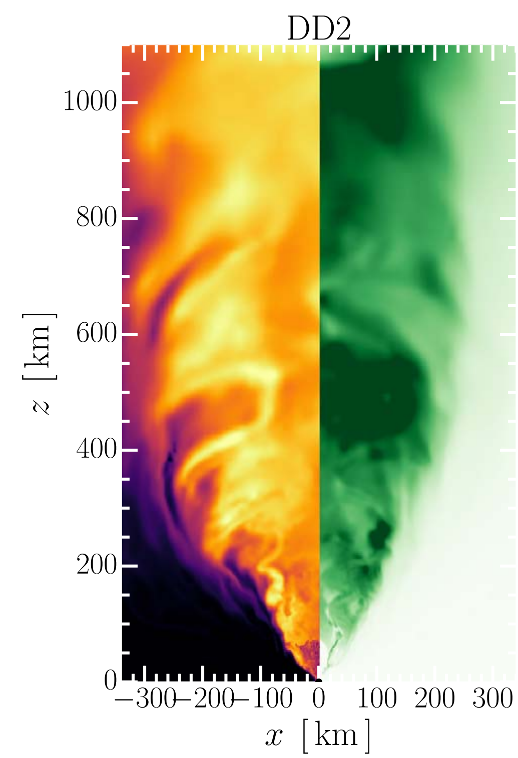
Mösta+ 2020, Curtis+ 2023

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

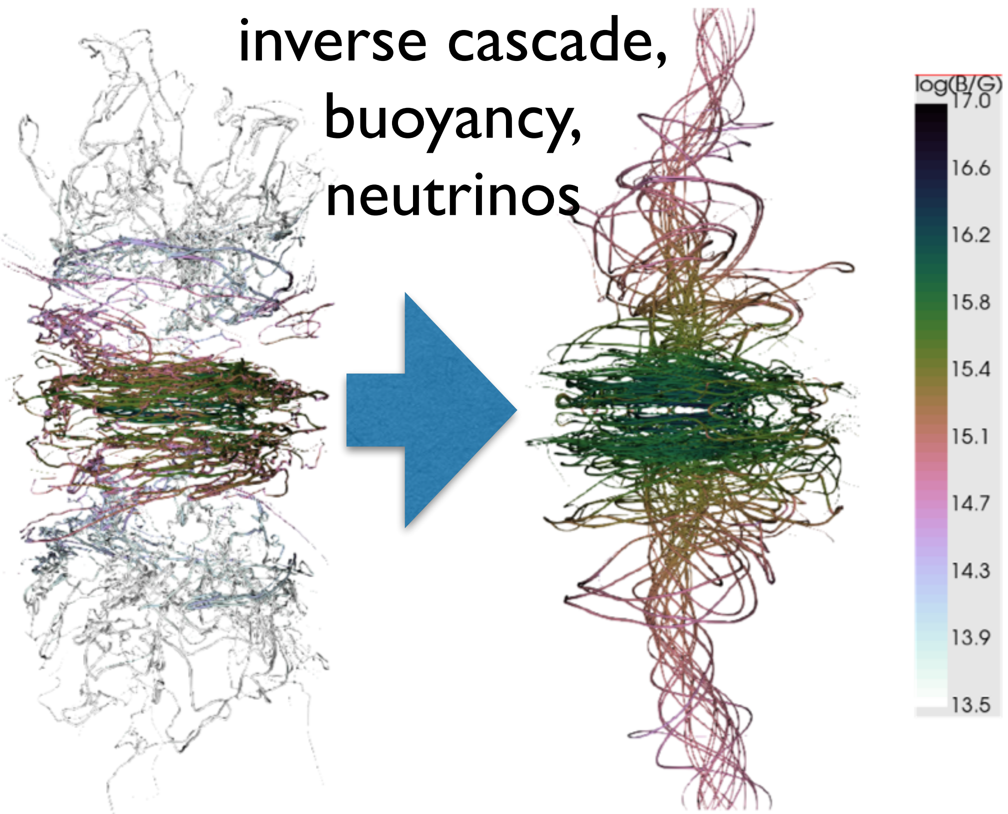


Most & Quataert 2023

(using α-dynamo)



Post-merger: B-field amplification

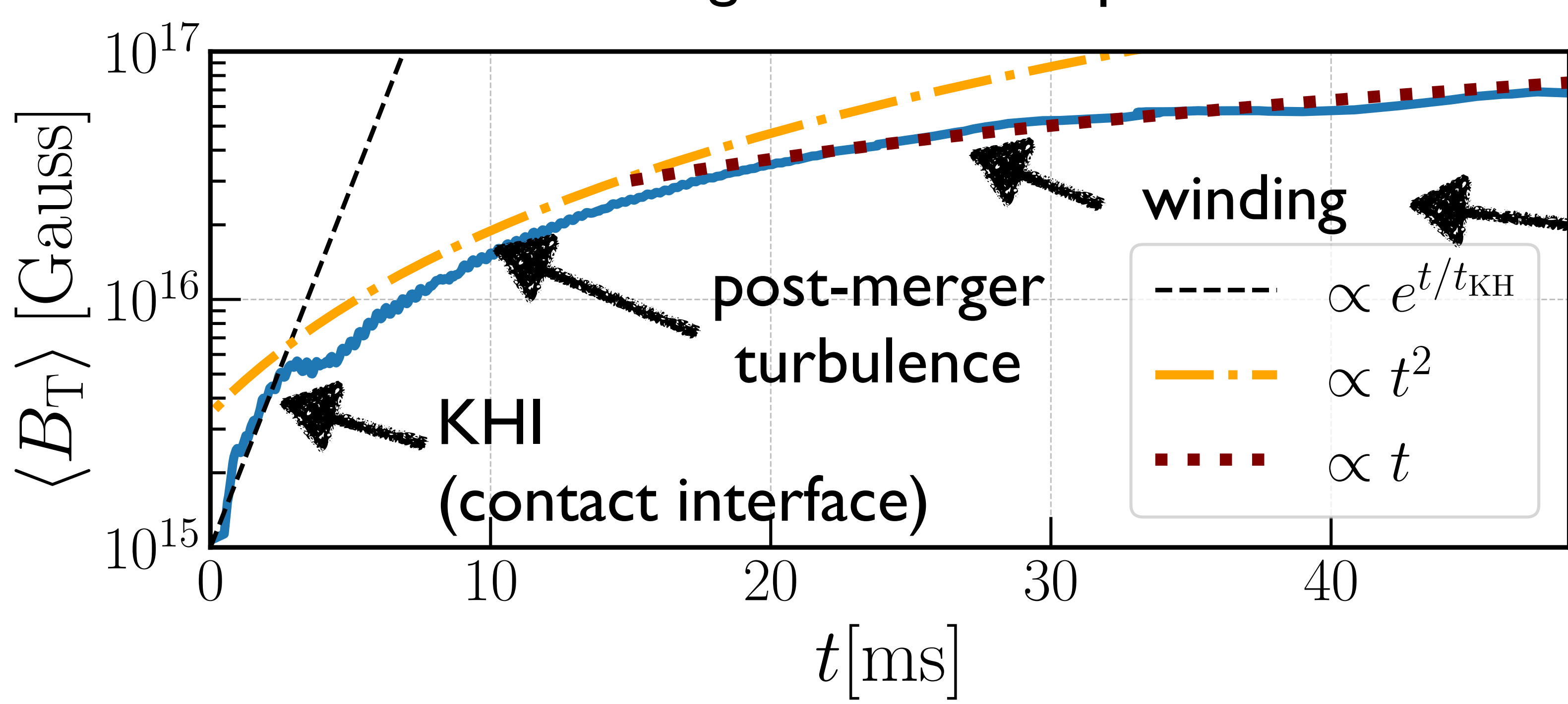


Combi & Siegel 2023b, PRL

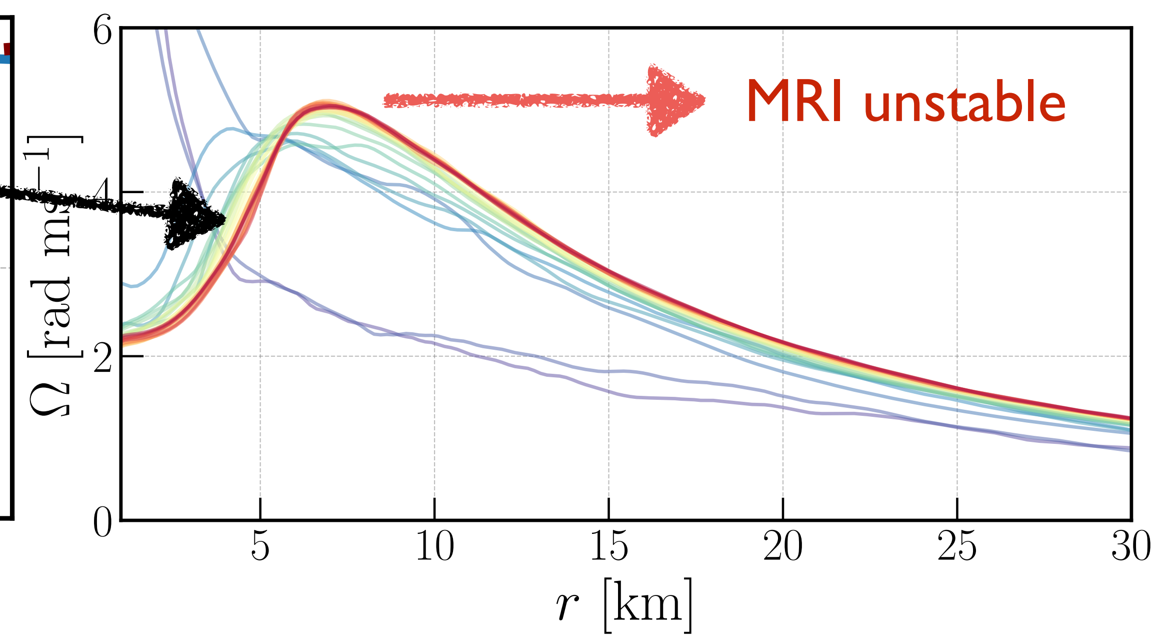
Magnetic field amplification during merger & within remnant:

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

toroidal magnetic field amplification

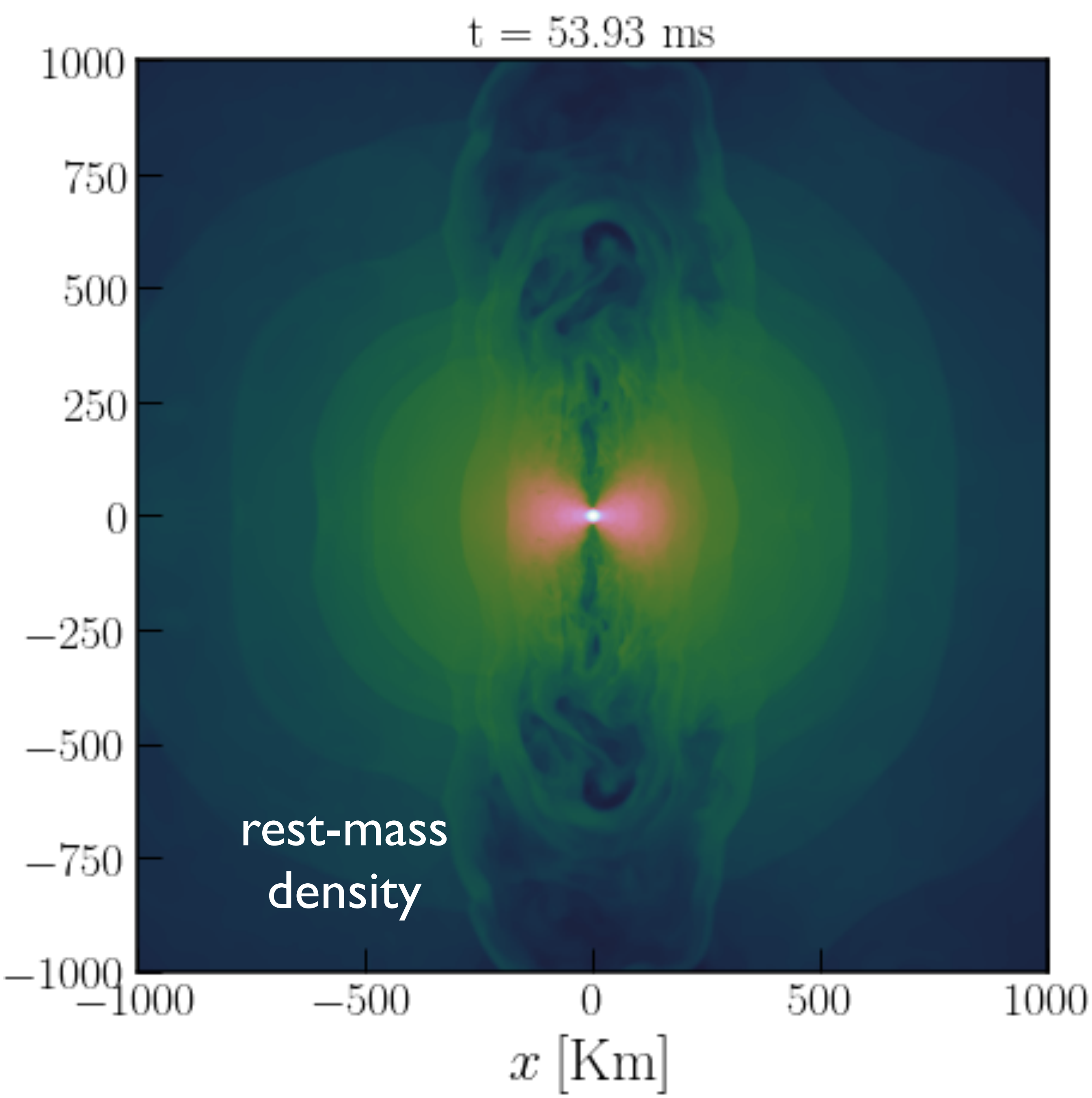


angular rotation profile



Magnetic tower with neutrinos—a 'jet' emerges

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

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

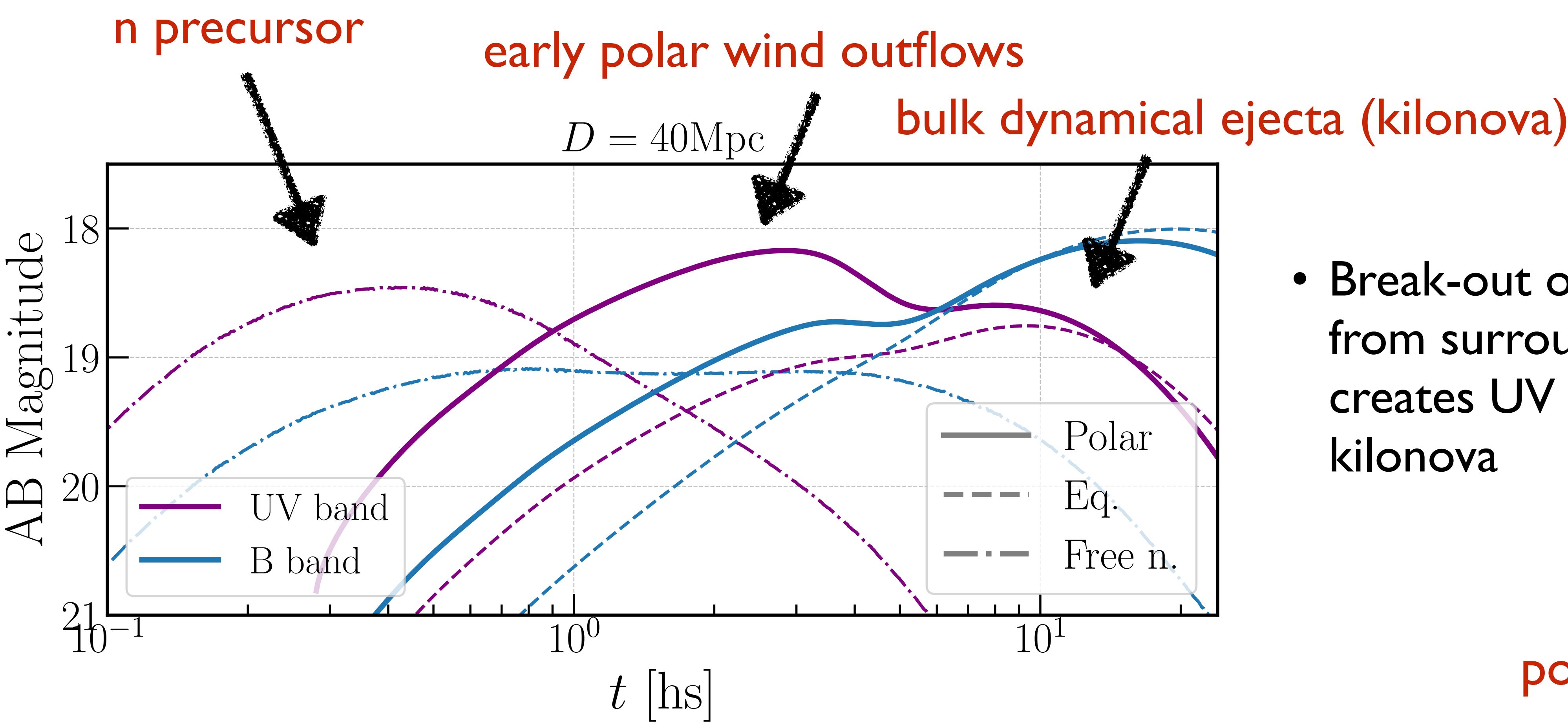
- Jet head propagates with v ~ 0.6c through dynamical ejecta and breaks out by ~50ms

⟶ NS able to power short GRBs ?!

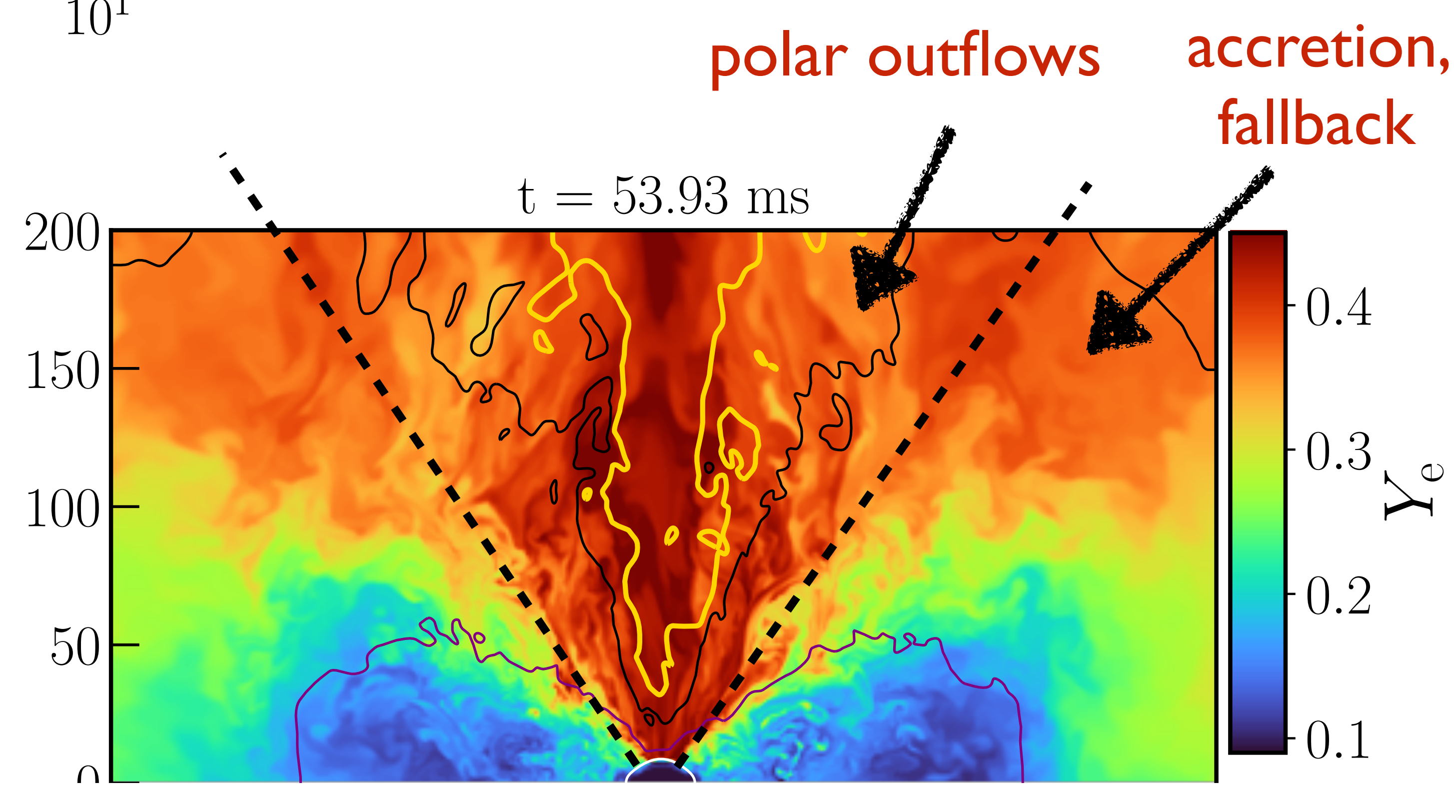
⟶ *Novel BH GRB jet formation mechanism:* NS jet 'seeds' BH jet

Polar MHD outflows: UV/blue precursor

Combi & Siegel 2023b, PRL

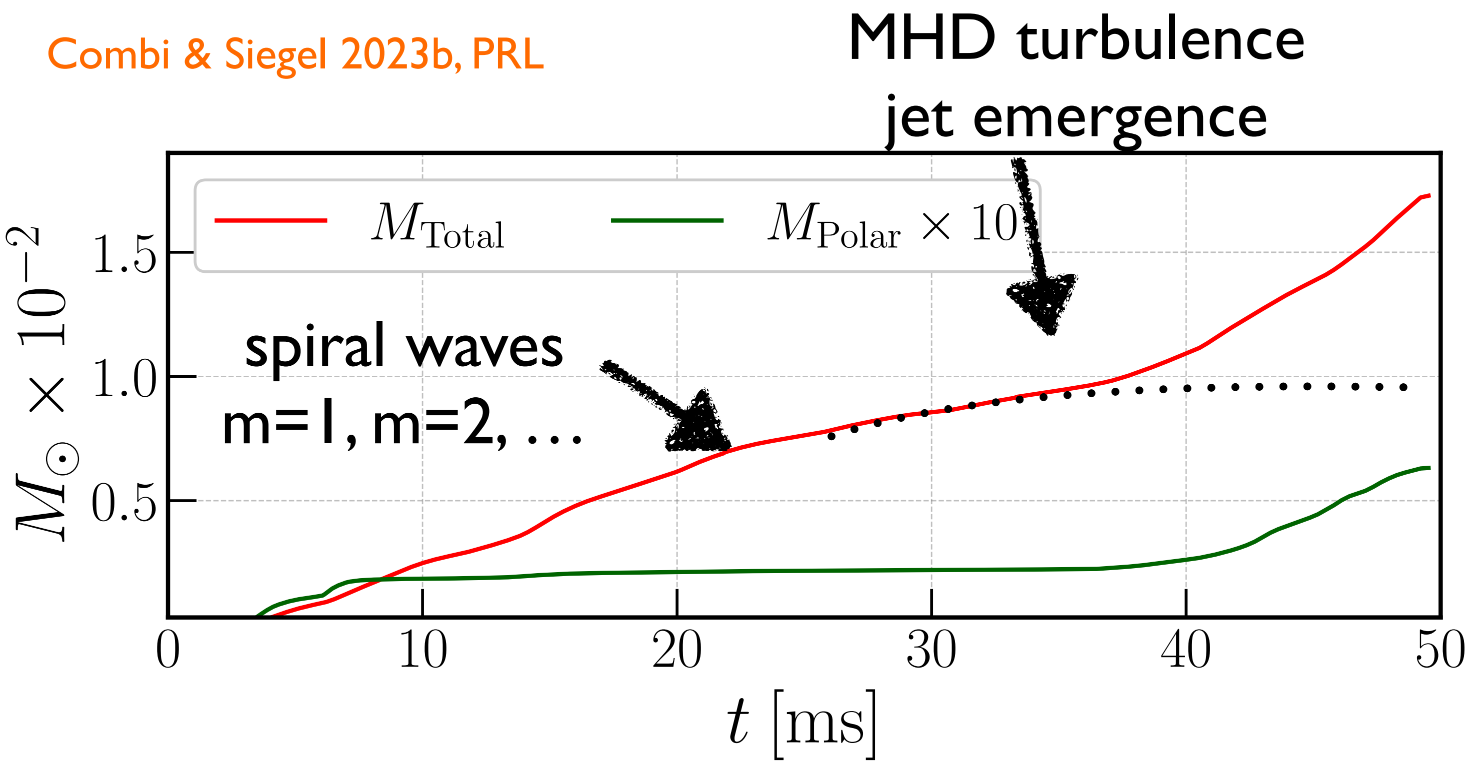


- Break-out of fast polar wind material from surrounding dynamical ejecta creates UV precursor signal to the kilonova



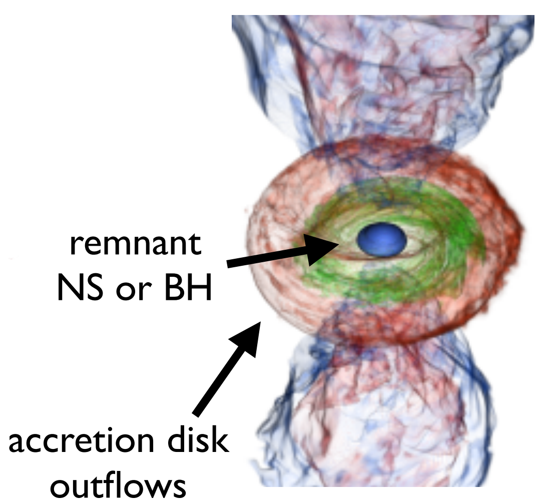
Post-merger disk evolution & outflows

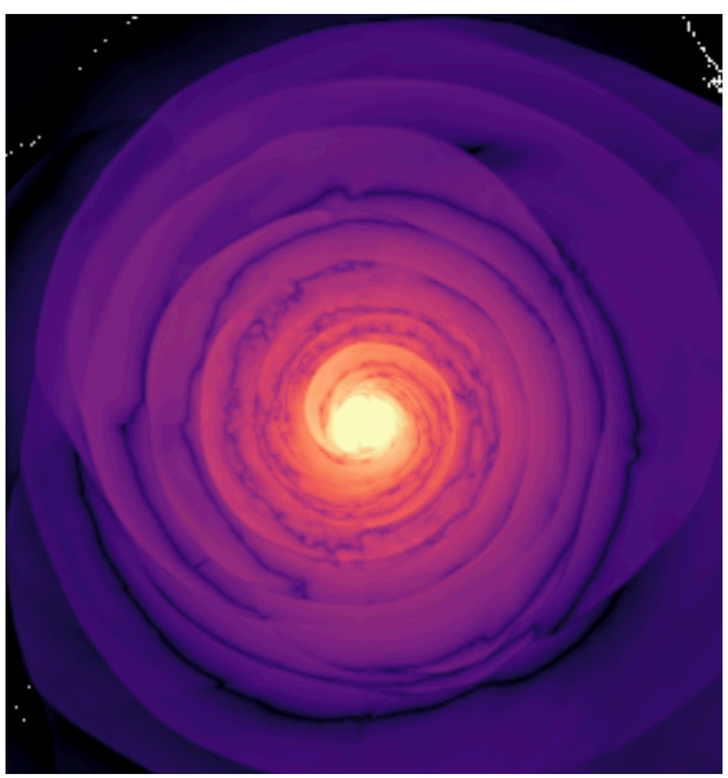
Combi & Siegel 2023b, PRL

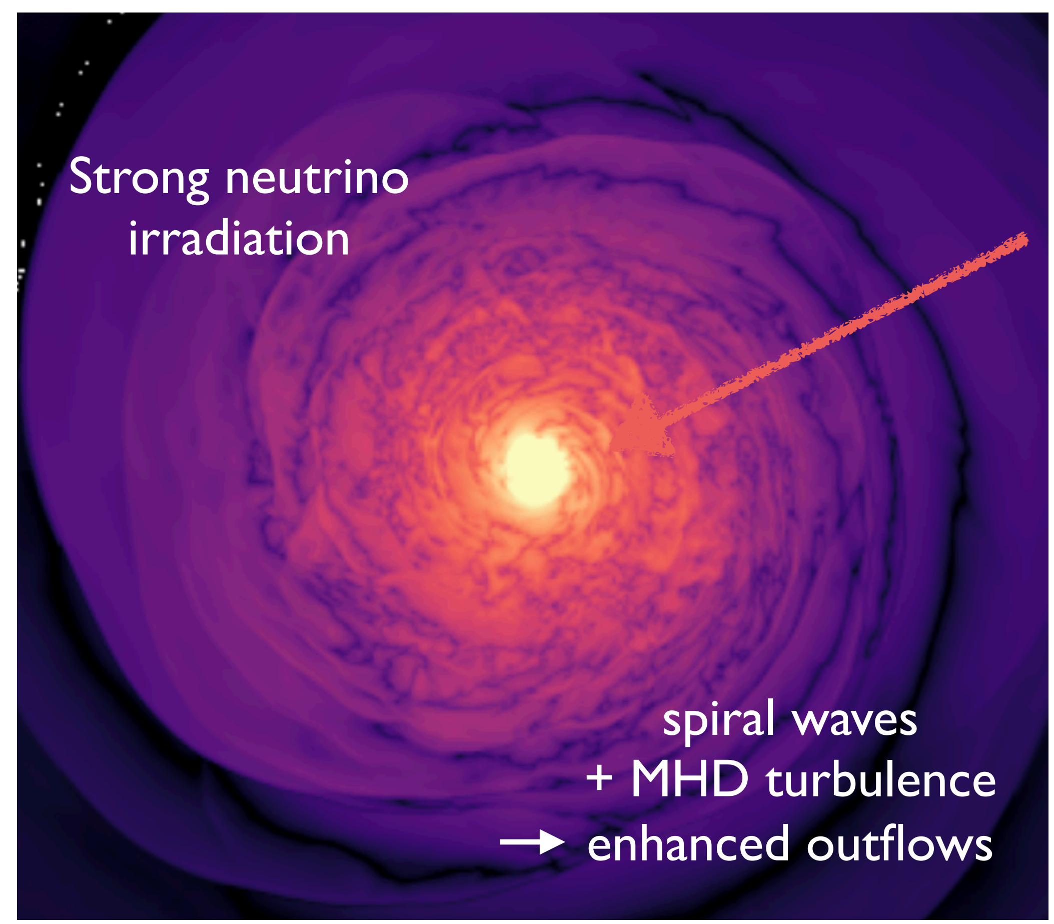


- t < 35ms mass ejection dominated by non-axisymmetric modes
  Nedora+ 2019, 2021
- Strong boost once MHD turbulence sets in (t > 40ms), reaching 2×10^{-2} M_{sun} within 50ms post-merger
- Accretion disk rapidly spreads radially due to enhanced angular momentum transport

accretion disk ejecta (~0.1-1s)



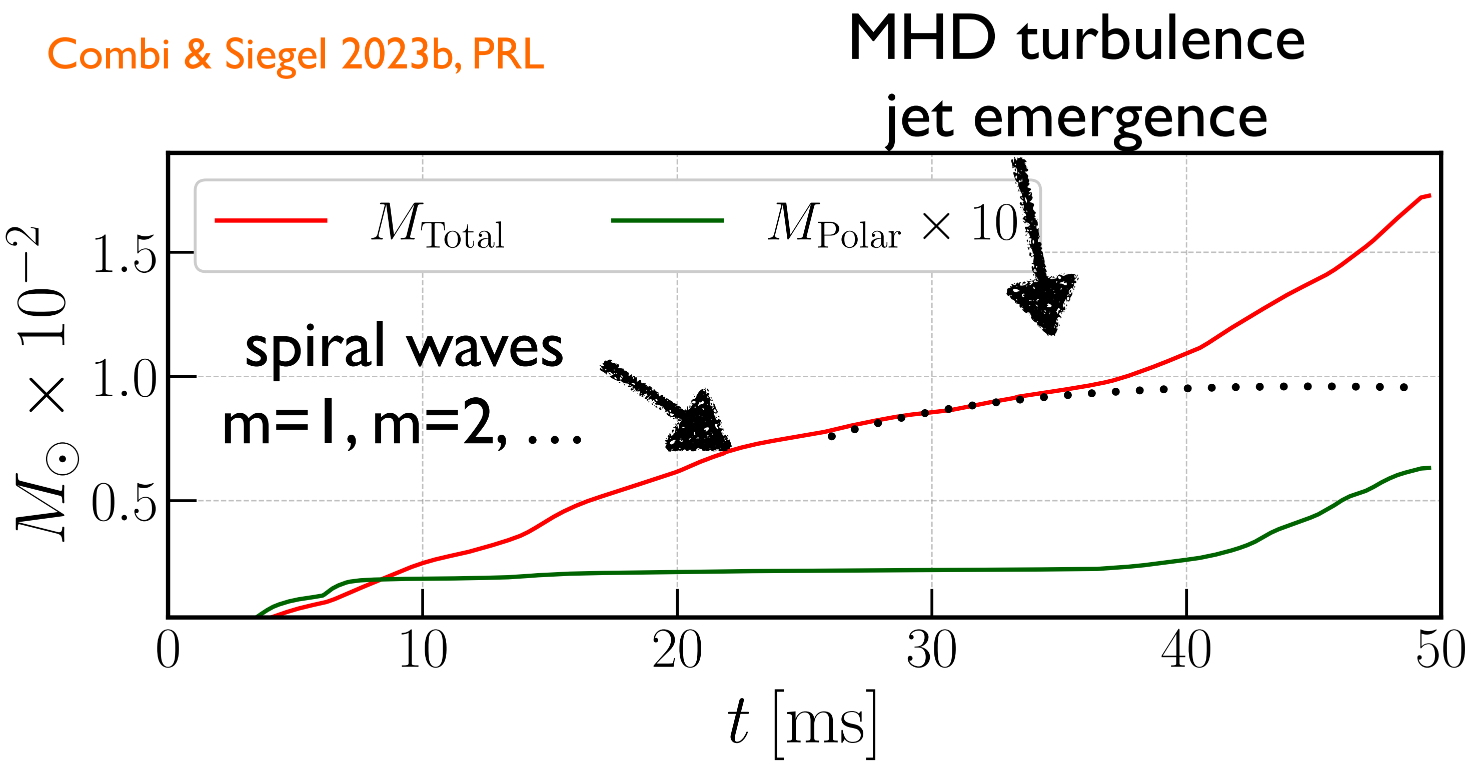




Neutron star

Post-merger disk evolution & outflows

Combi & Siegel 2023b, PRL



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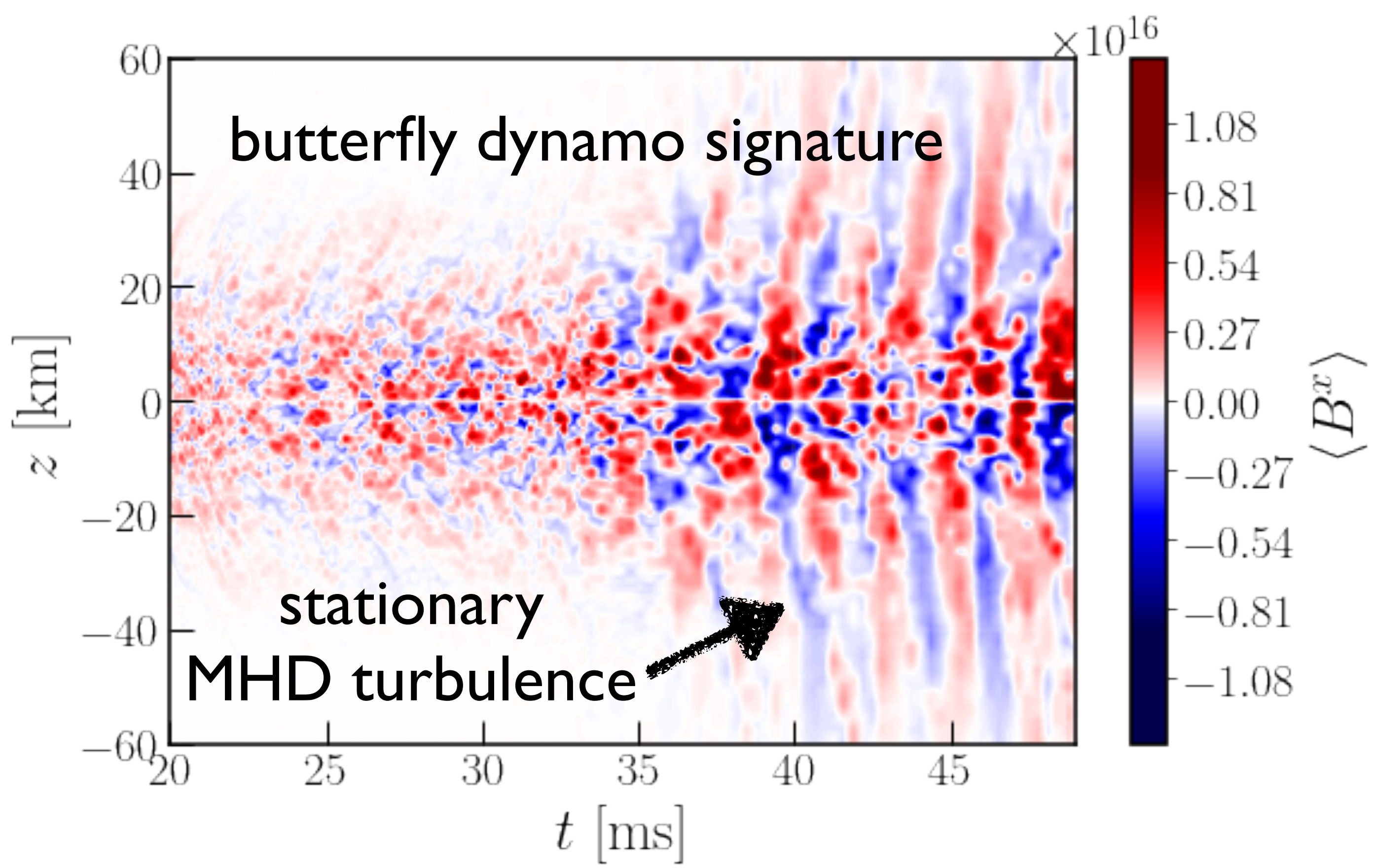
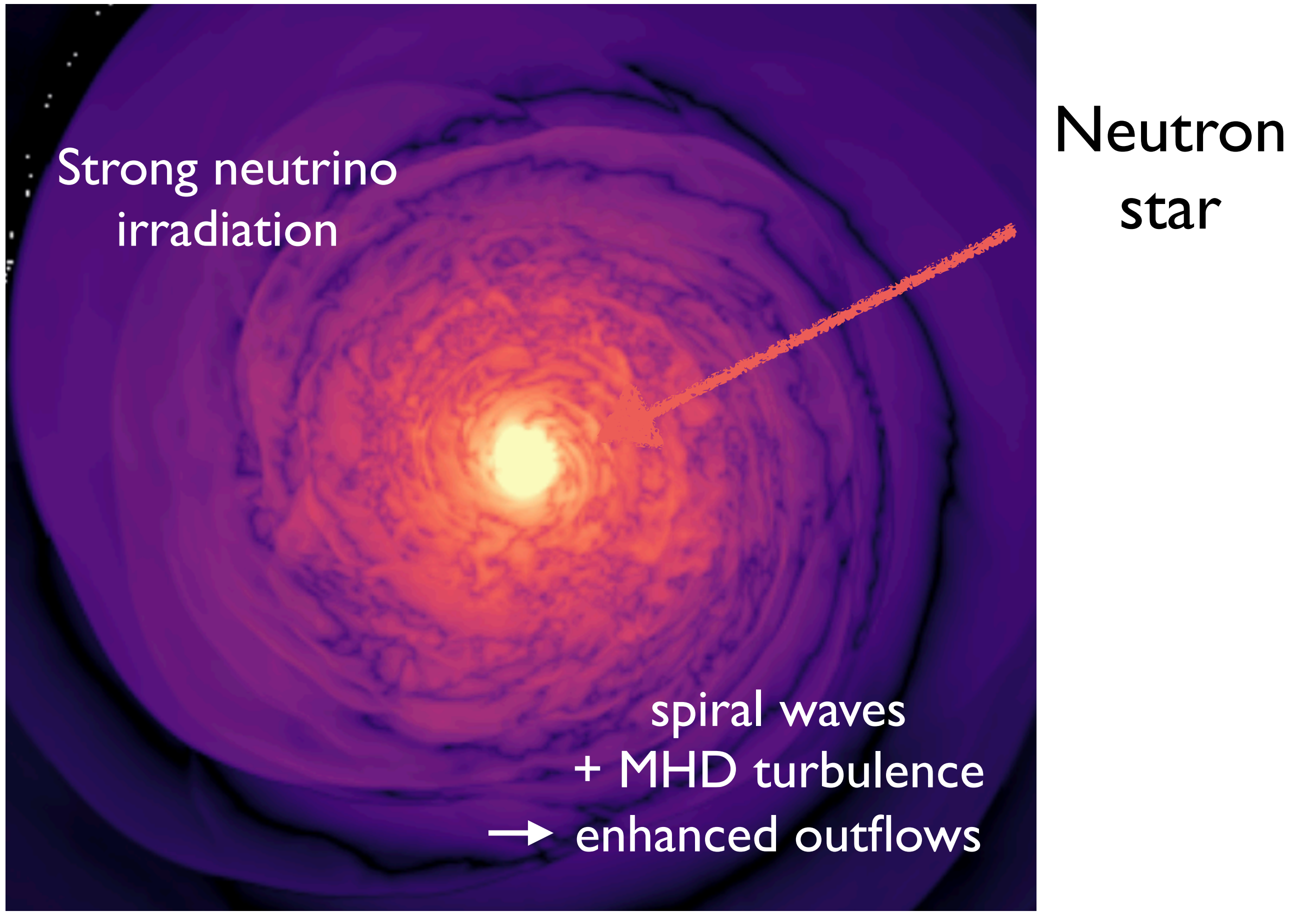
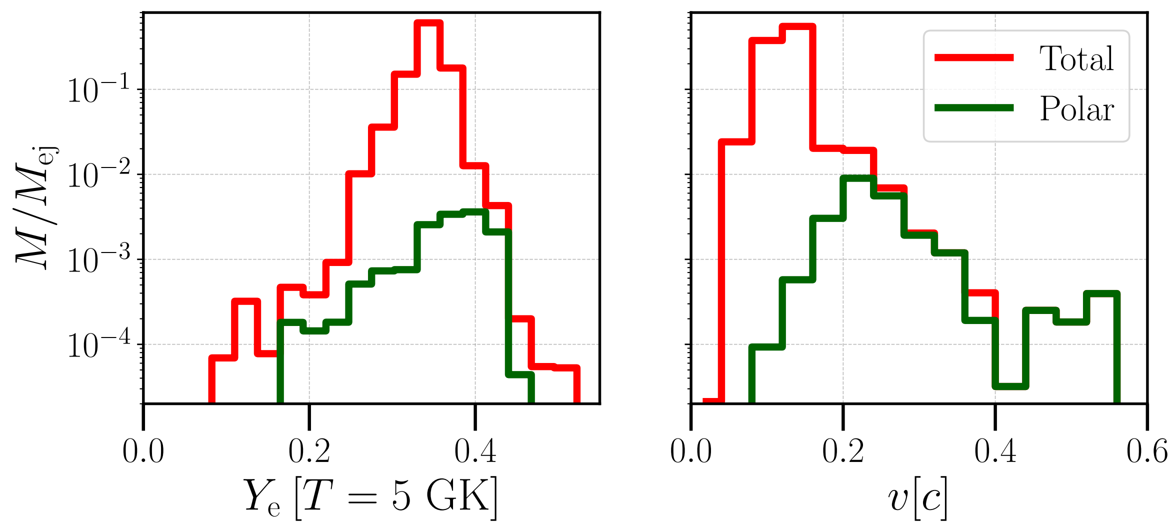
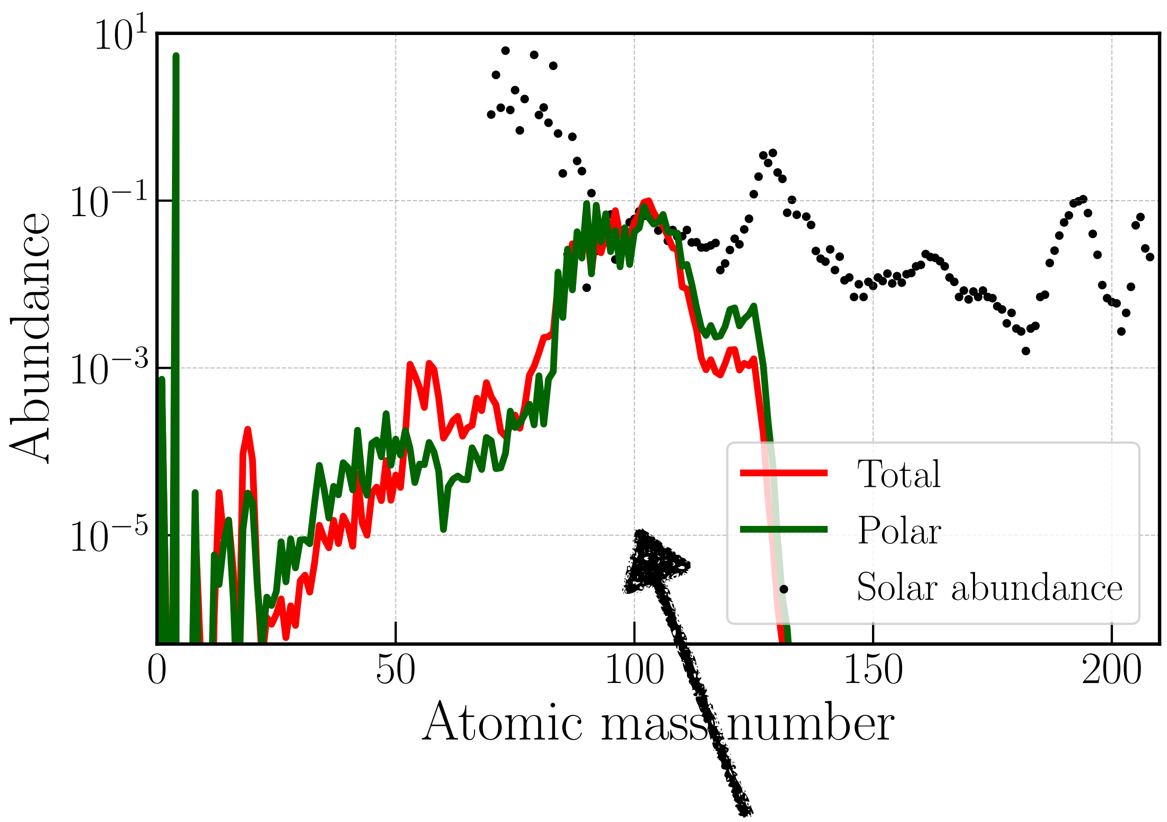




Nucleosynthesis & kilonova

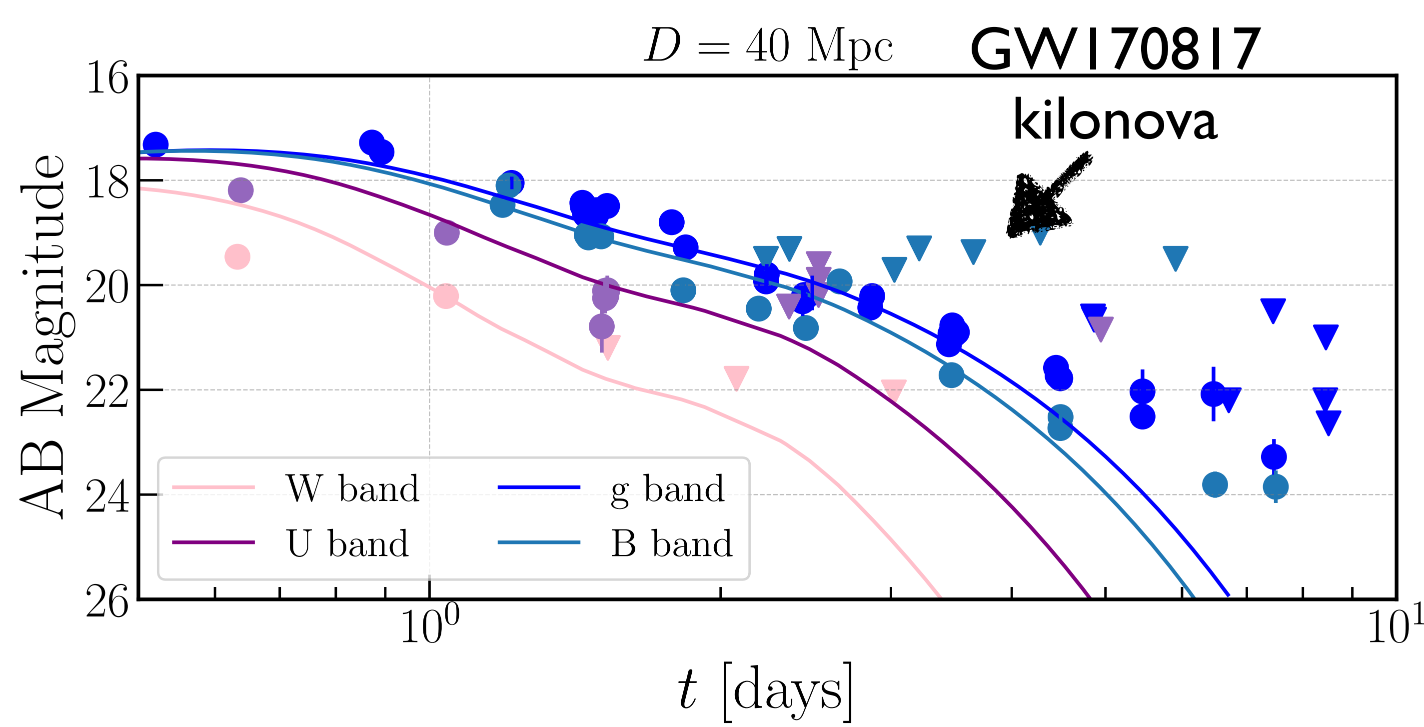
Combi & Siegel 2023b, PRL





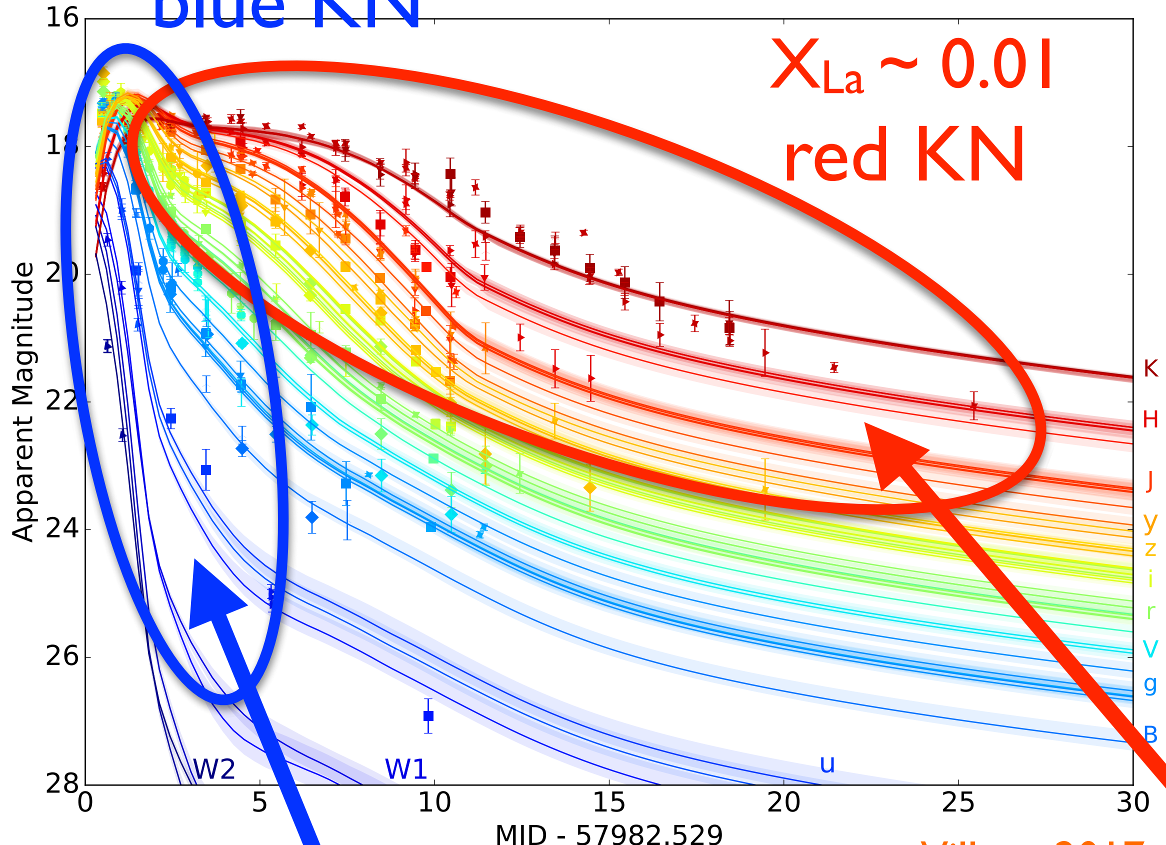
lanthanide-free disk ejecta

- 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 ($2x10^{-2}$ M_{sun})



The GW170817 kilonova

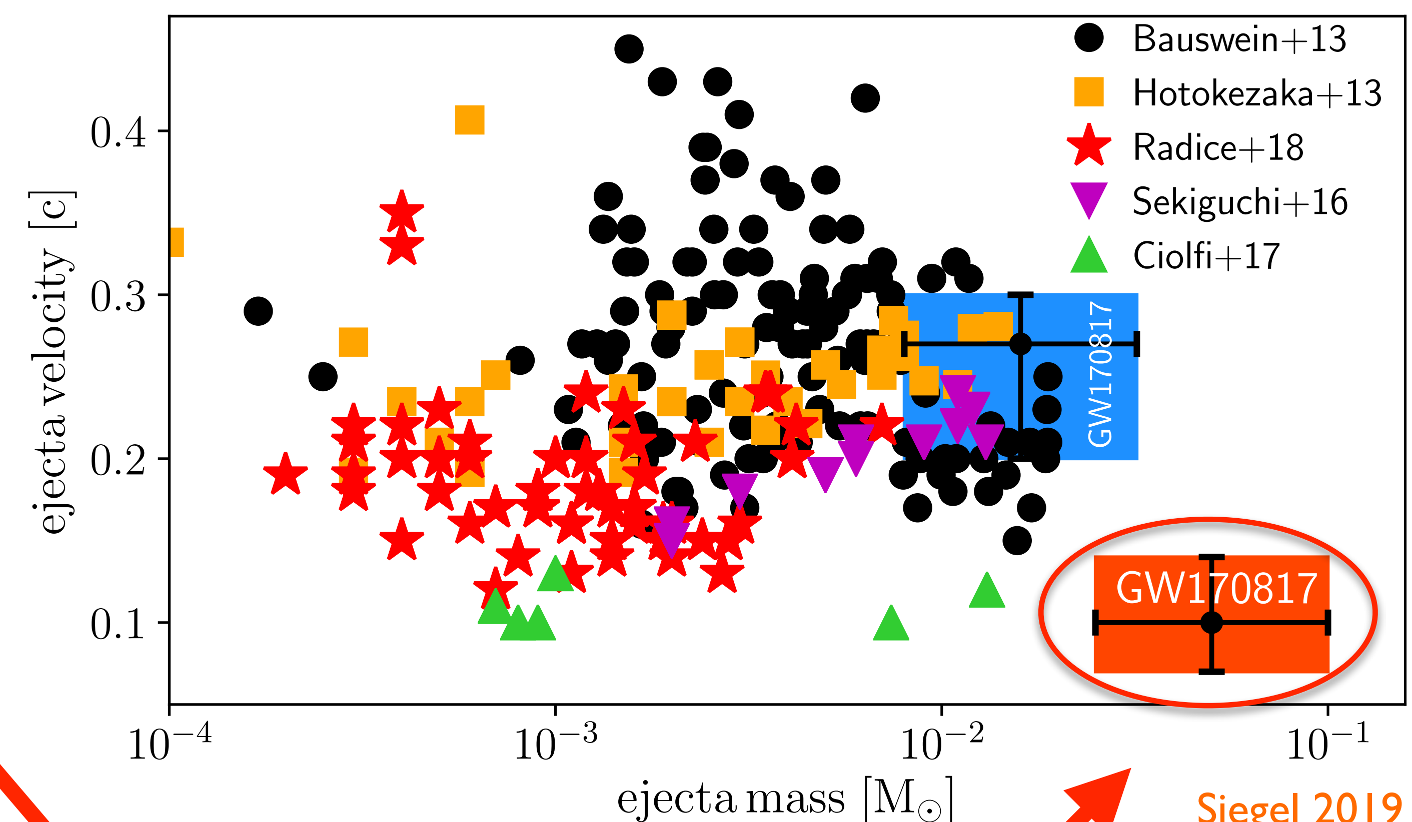
$X_{La} < 10^{-4}$
blue KN



$X_{La} \sim 0.01$
red KN

Villar+ 2017

BNS merger simulations: dynamical ejecta



Siegel 2019

likely post-merger
NS-disk ejecta !

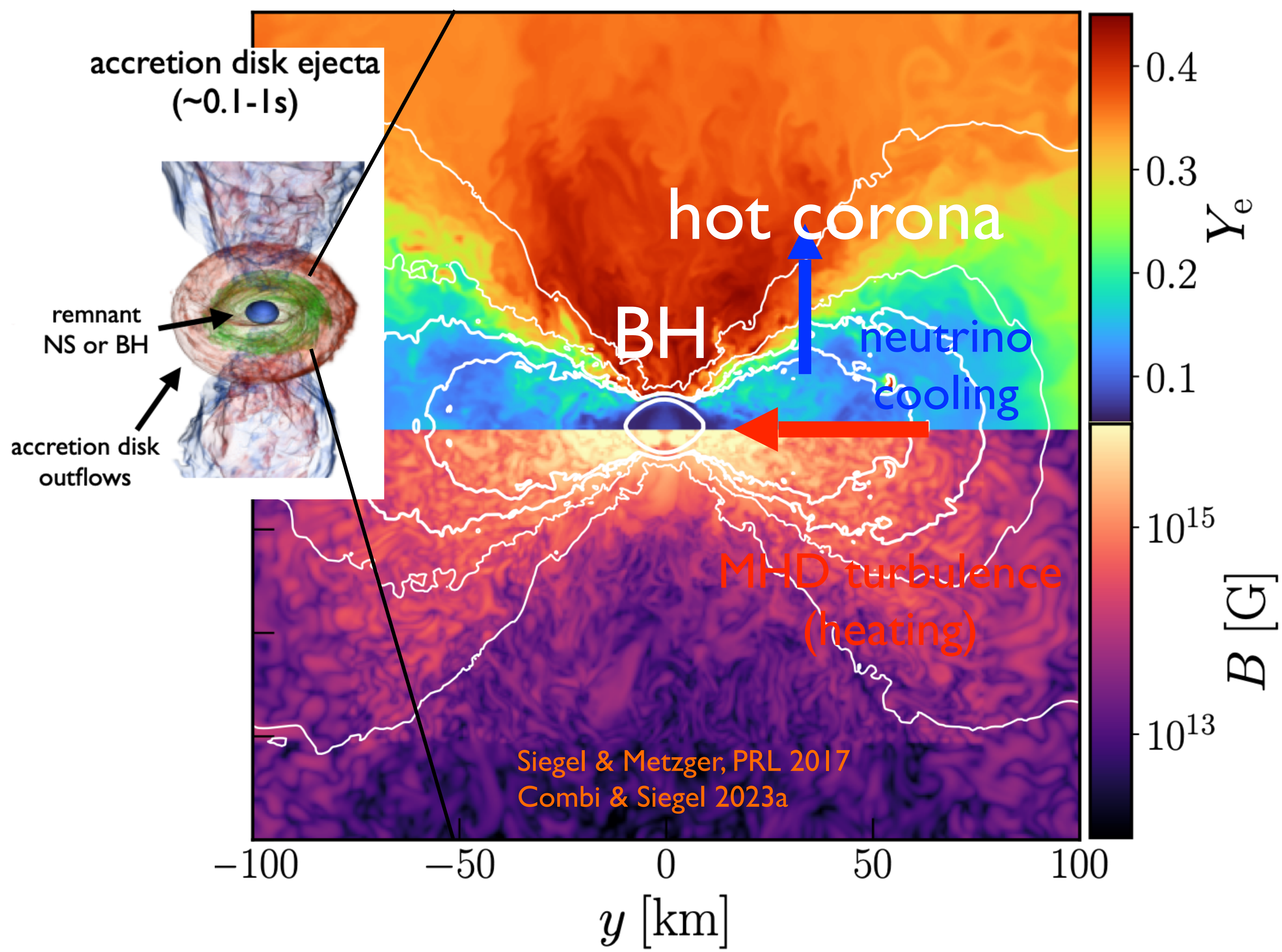
Combi & Siegel 2023b, PRL

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

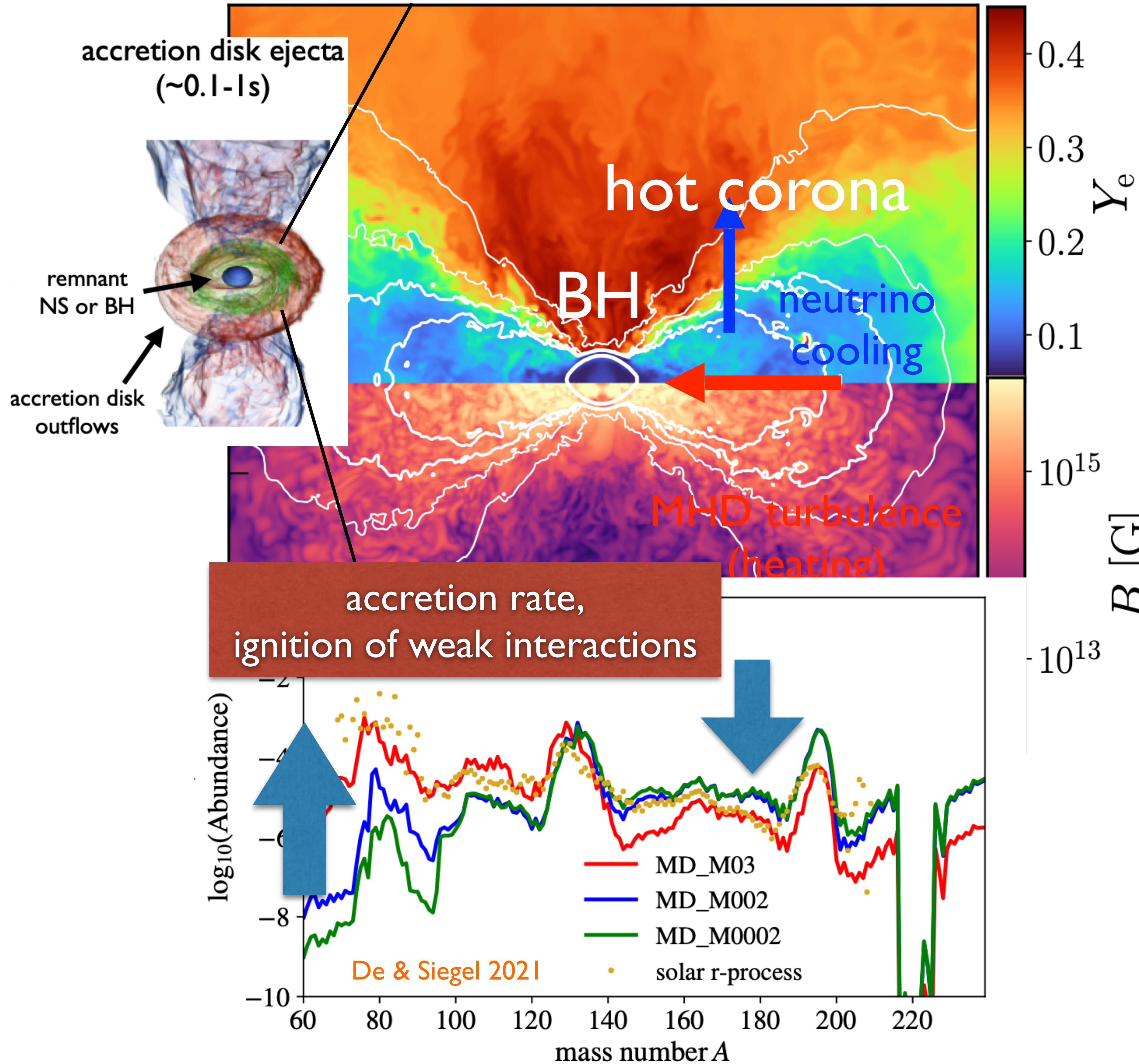
- Weak interactions are key for composition, nucleosynthesis, kilonova
- Self-regulation keeps disk neutron-rich: *light* & *heavy* r-process

  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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Chen & Beloborodov 2007

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De & Siegel 2021
Fernandez+ 2020
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Fahlman & Fernandez 2022

- Total ejecta can dominate all other channels

Siegel & Metzger 2018
Fernandez+ 2019
Kiuchi+ 2022

V Other multi-messenger sources:

Collapsars, long GRBs, super-kilonovae

Collapsars

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

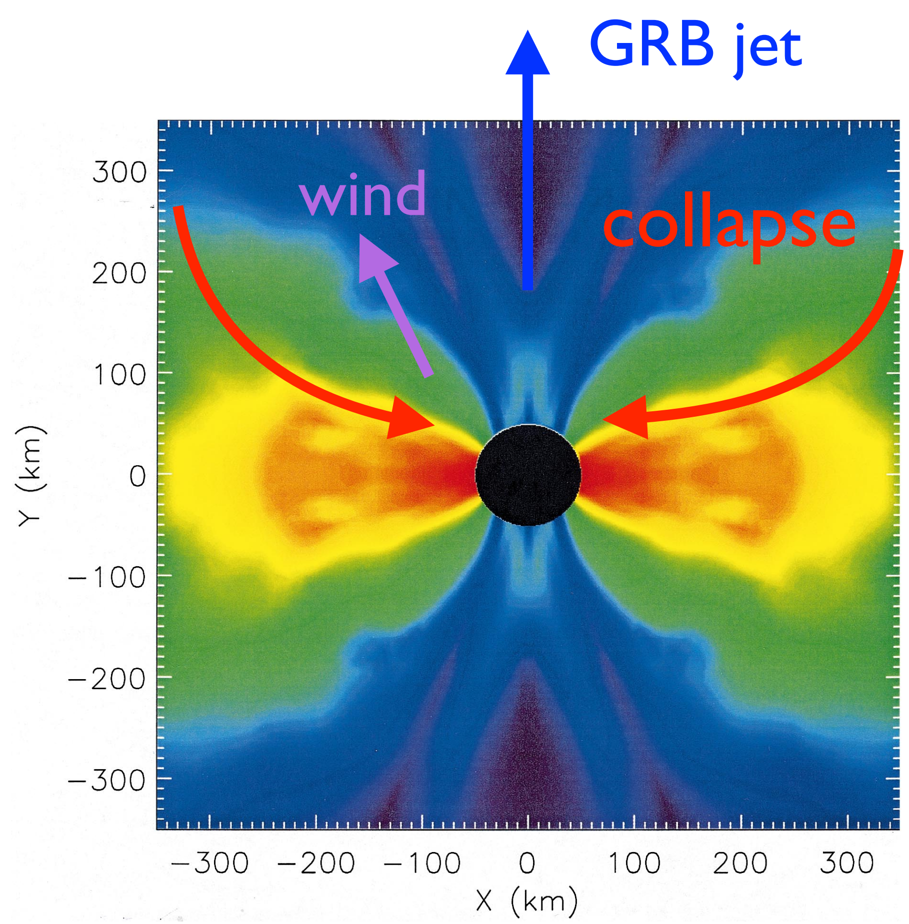
  ⟶ "failed explosion" (direct collapse to a BH)

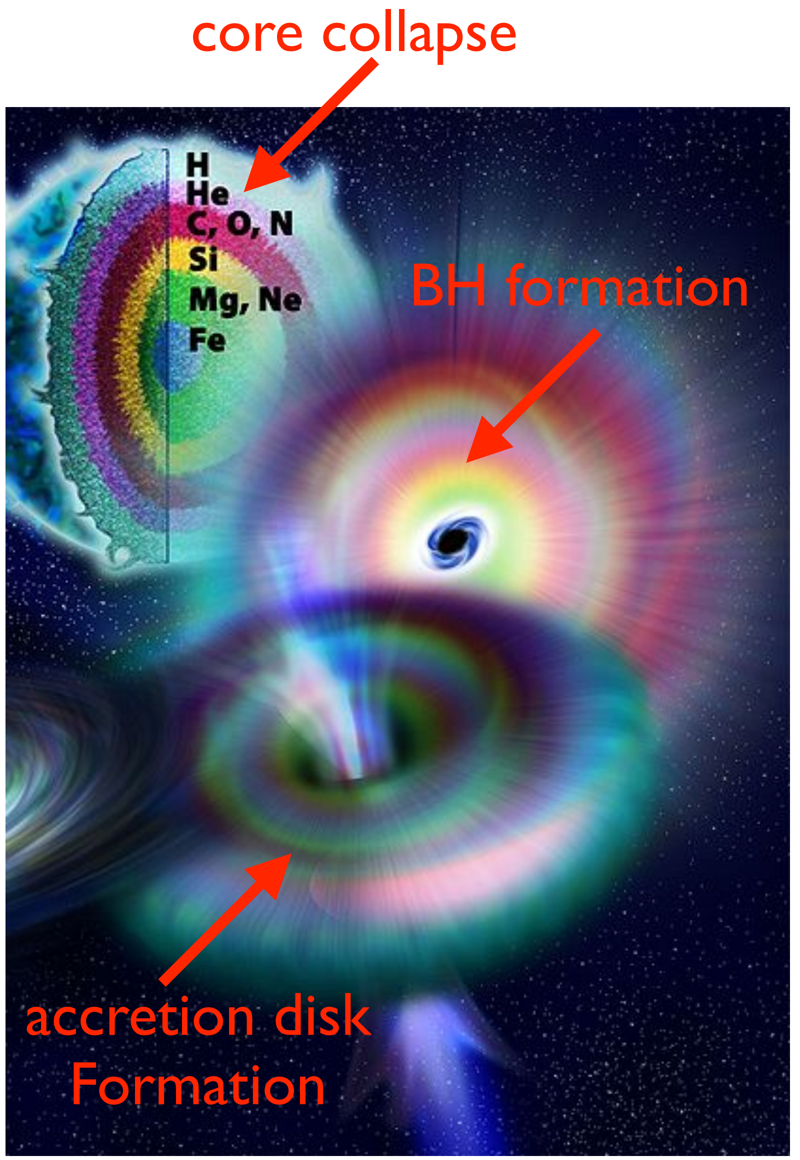
  ⟶ "weak explosion" (proto-NS collapses due to fallback material)

- 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 (hypernovae, broad-lined Type Ic)

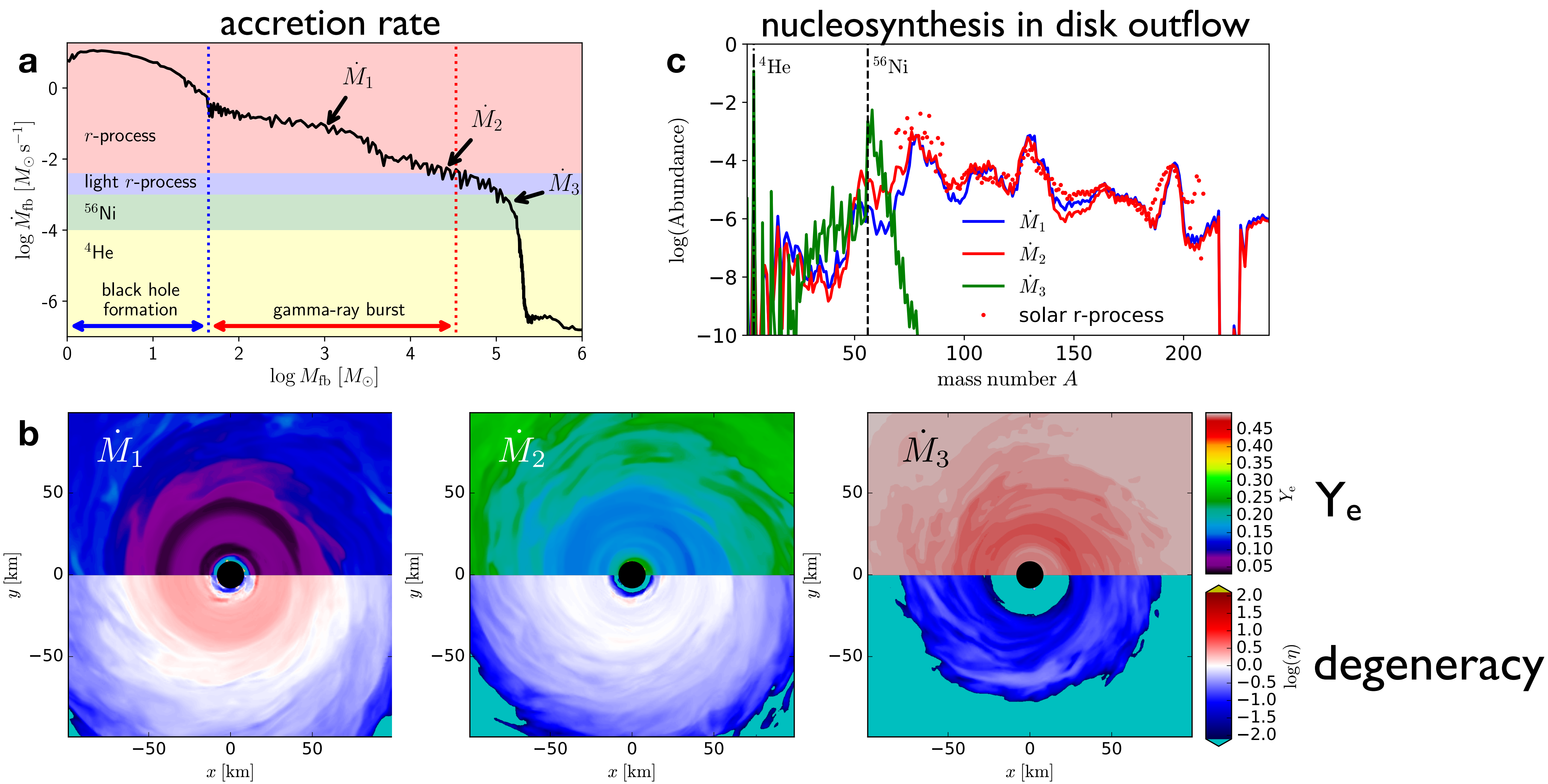
MacFadyen & Woosley 1999





Post-merger physics in other systems: *collapsars*

Siegel, Barnes, Metzger 2019, Nature



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

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

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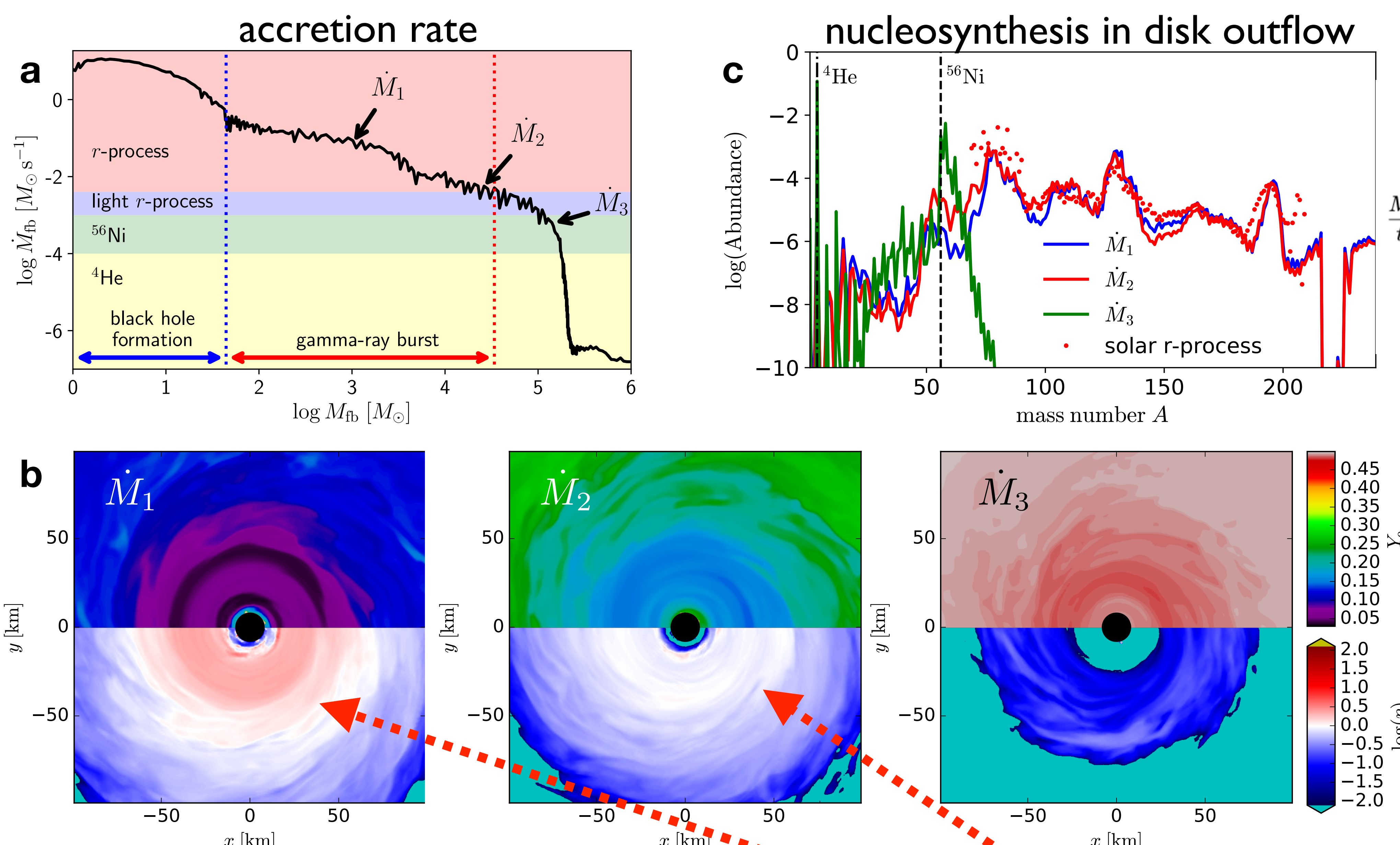
Siegel, Barnes, Metzger 2019, Nature

Siegel+ 2022



Ye

degeneracy

nucleosynthesis bands:

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

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

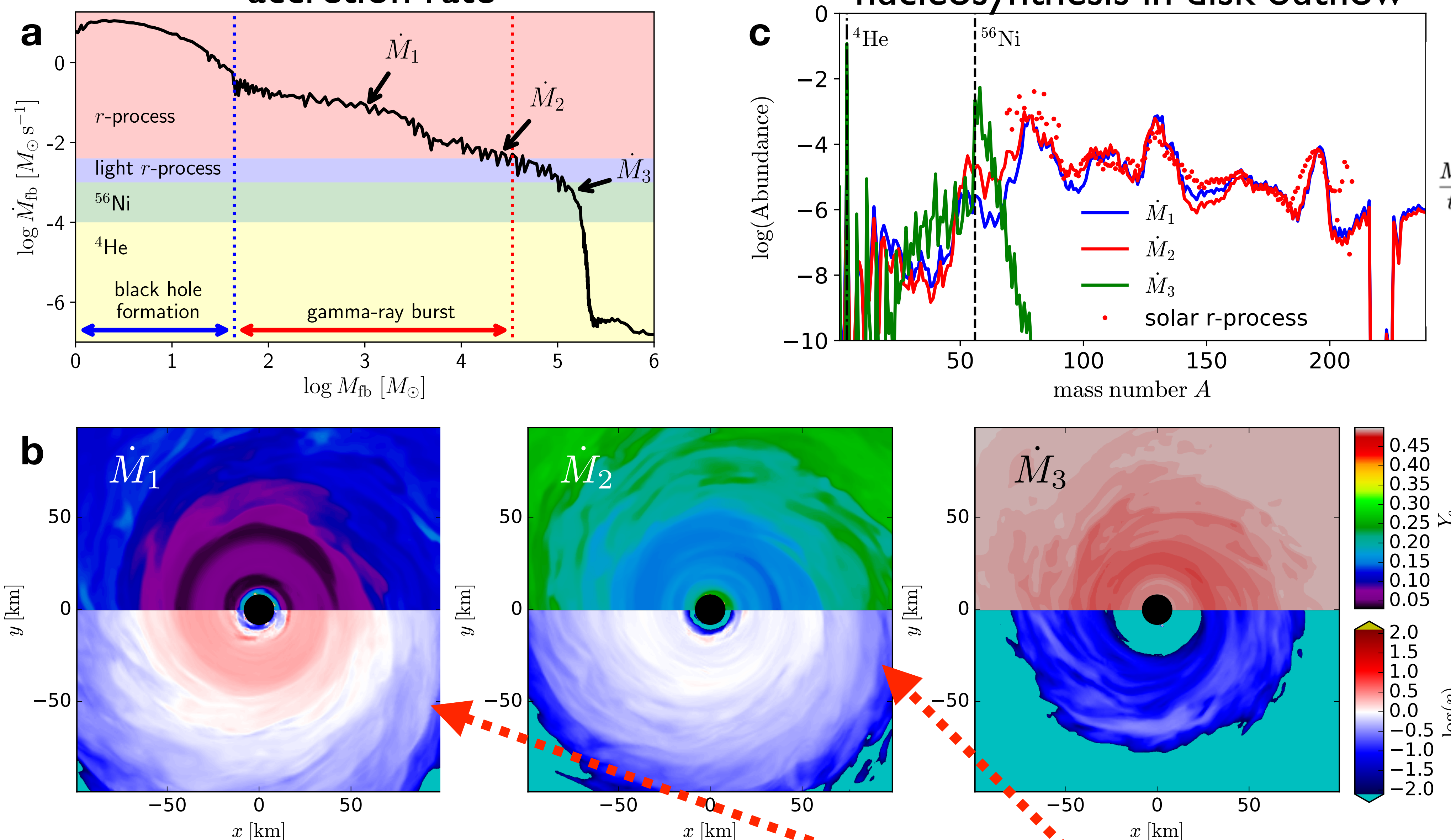
Post-merger physics in other systems: *collapsars*

Siegel, Barnes, Metzger 2019, Nature

Siegel+ 2022

accretion rate

nucleosynthesis in disk outflow



Y_e

degeneracy

nucleosynthesis bands:

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

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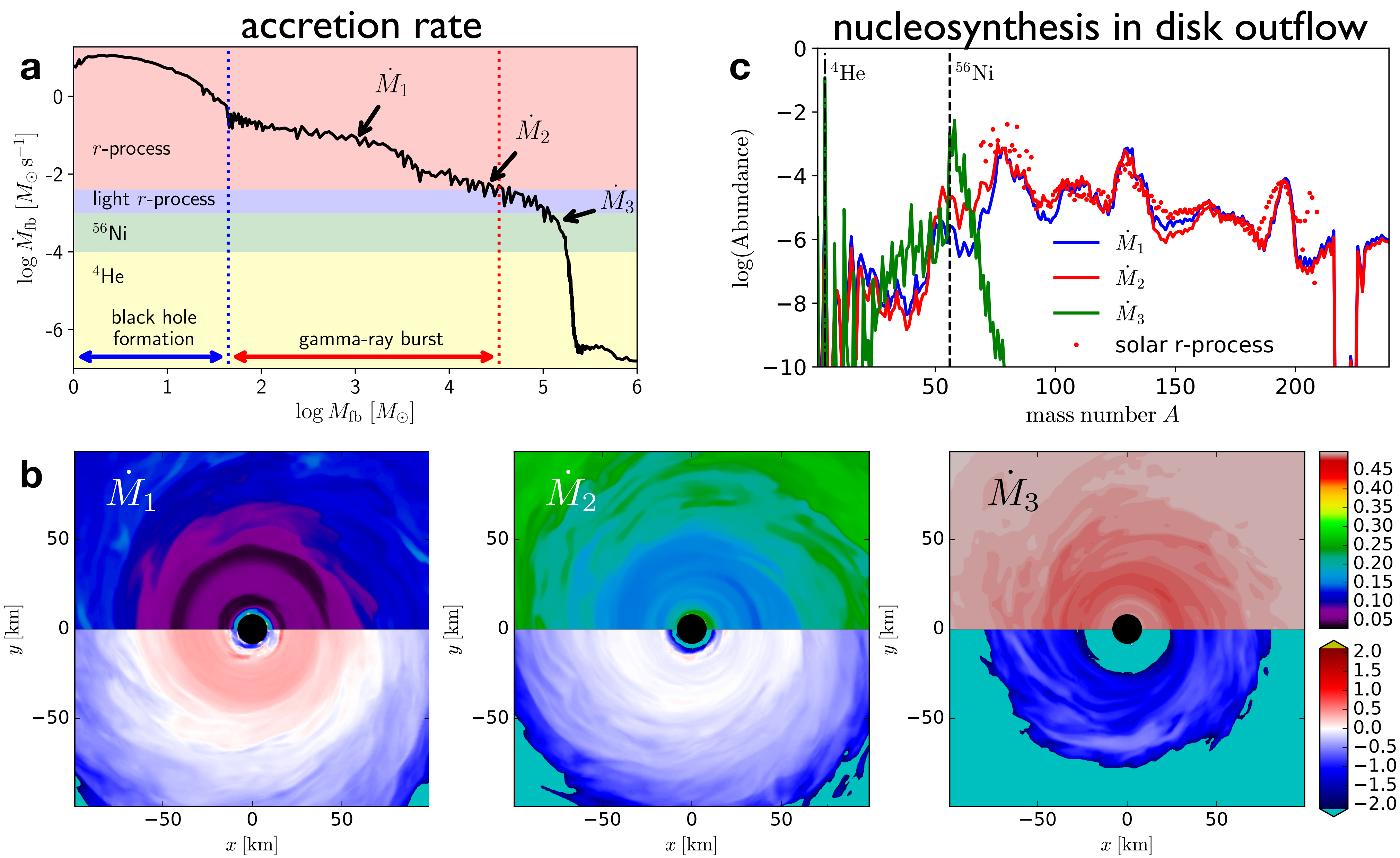


Ye

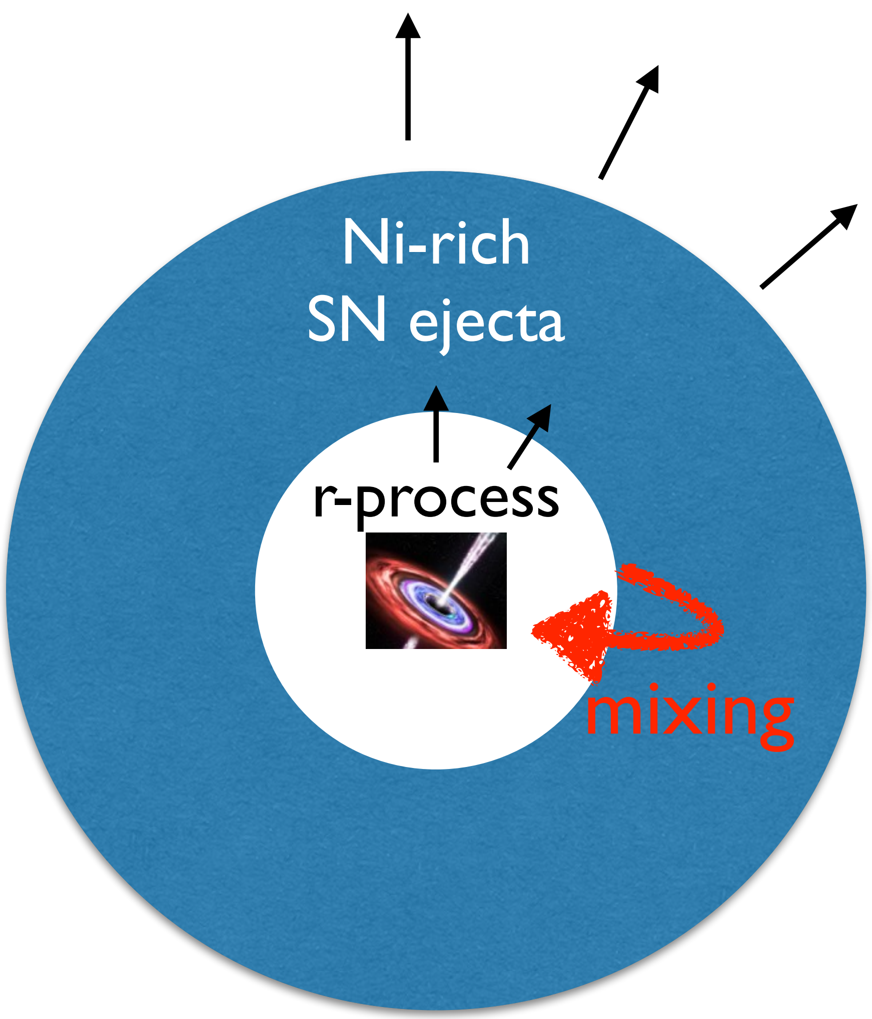
degeneracy

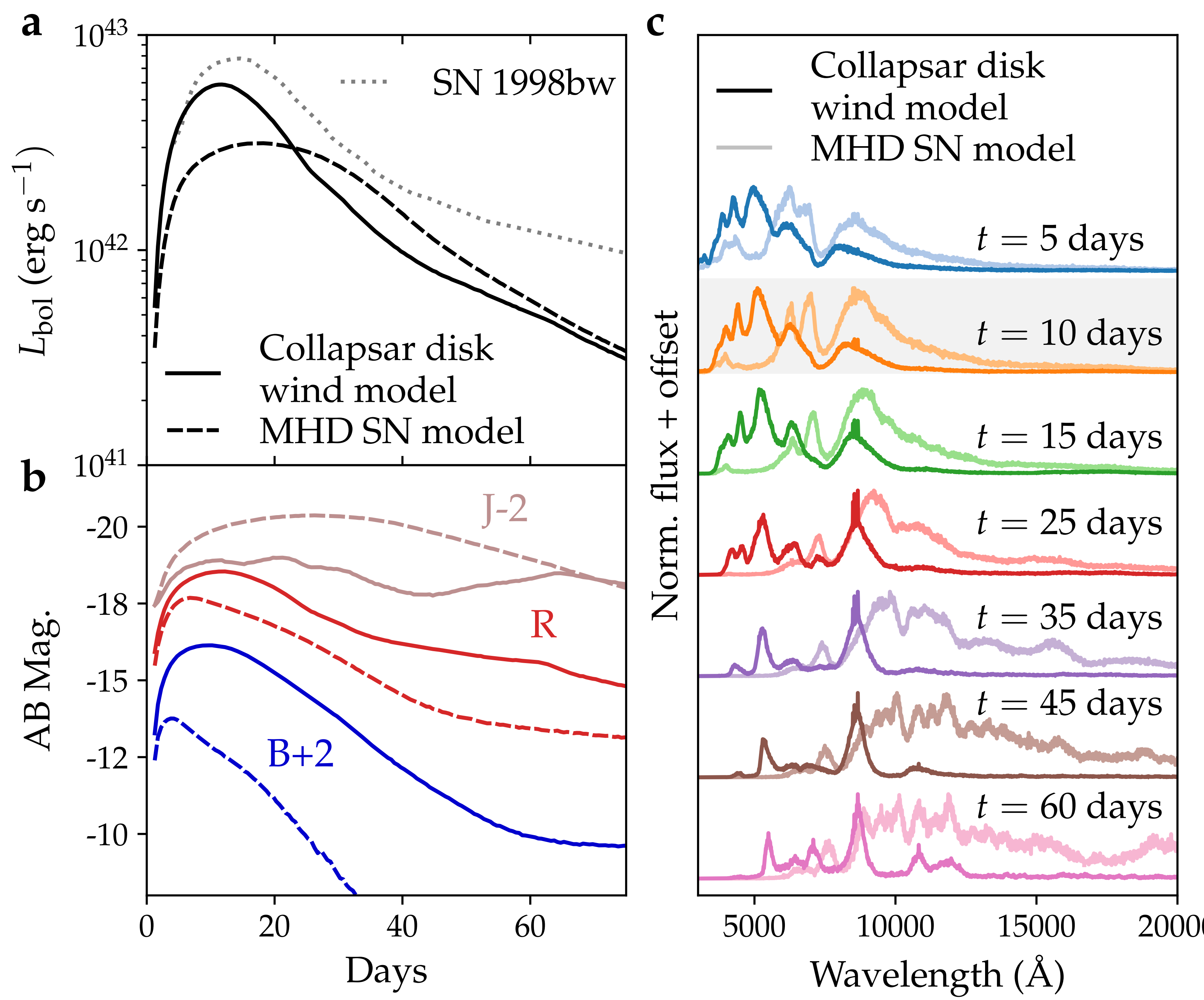
- 0.05–1 M_{sun} of r-process material per event over-compensates lower rates relative to mergers
- self-regulation over wide range of accretion rates produced well-defined nucleosynthesis pattern similar to solar
- may dominate r-process production by mergers

See also:

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

How to observe?





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

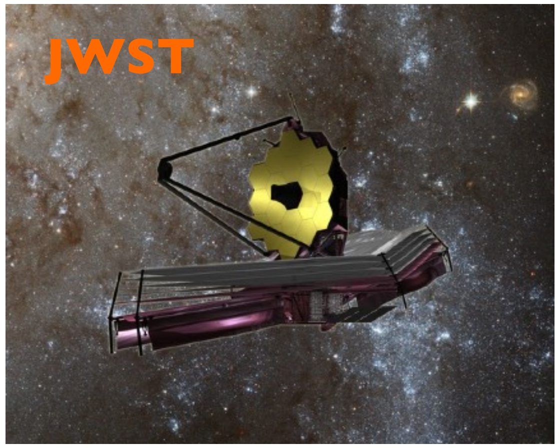
'kilonova within a supernova'

Siegel, Barnes, Metzger 2019, Nature

Barnes & Metzger 2022

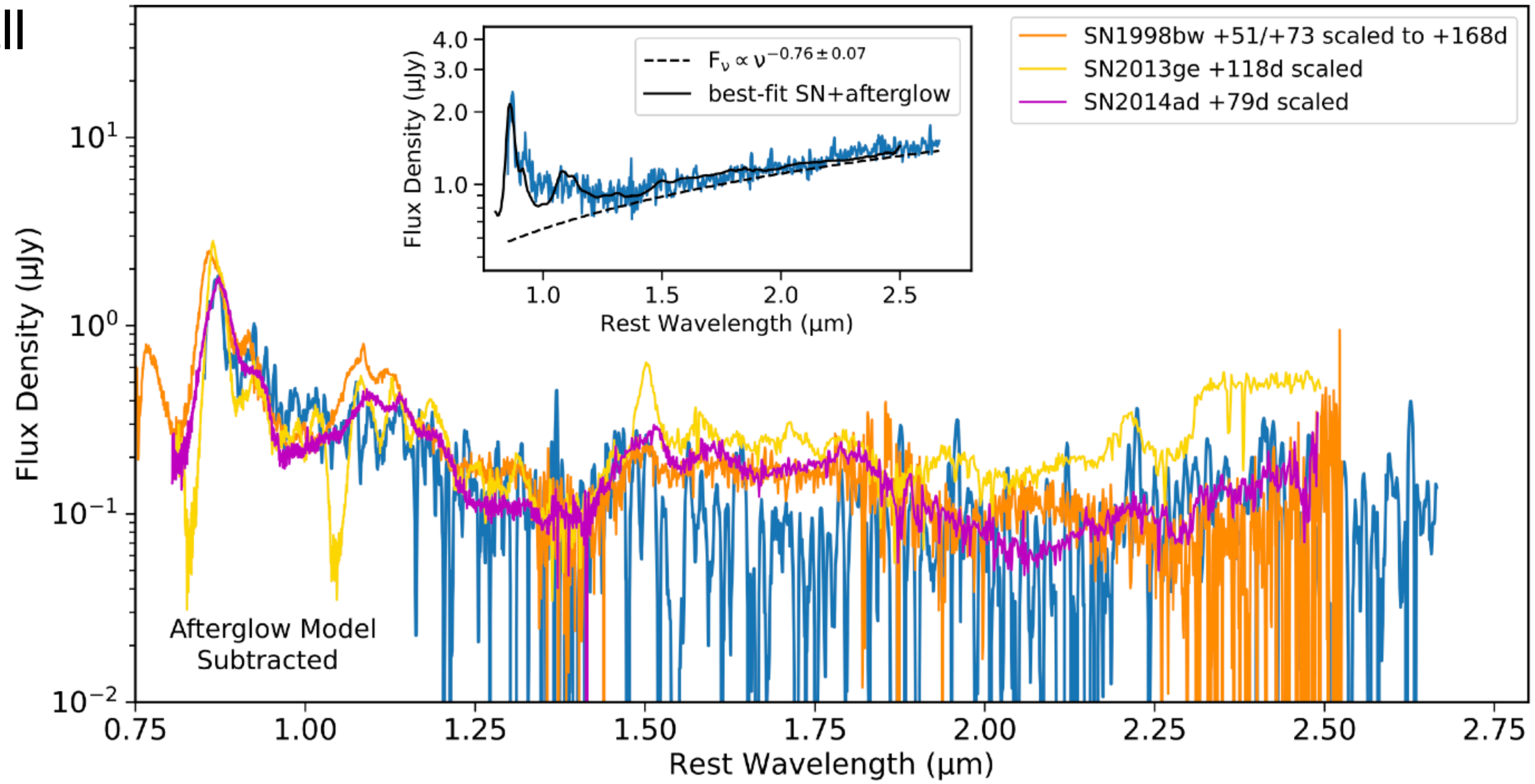
Extraordinary GRB 221009A

Blanchard+, Siegel 2024, Nature Astronomy



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

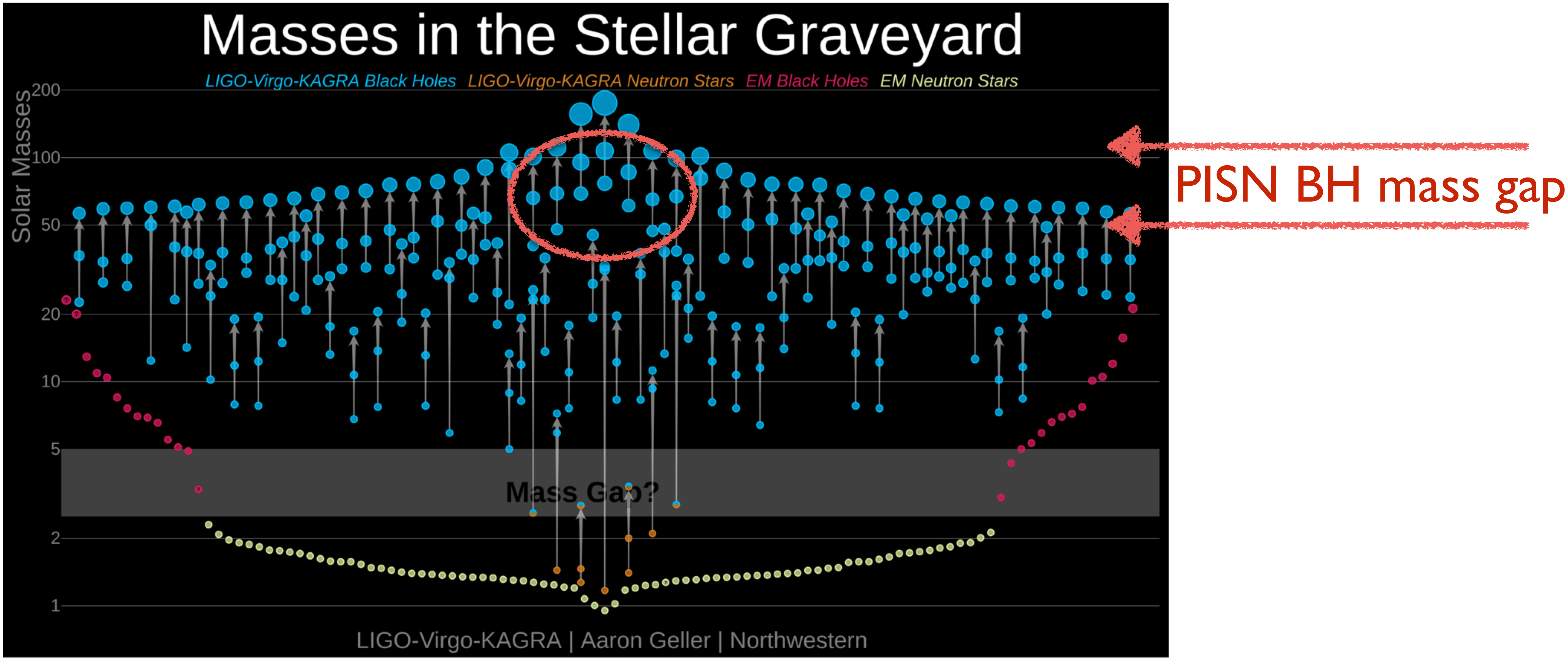
  M_{Ni} ~ 0.09 Msun, comparable brightness to SN 1998bw at similar epoch
- No evidence of r-process



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

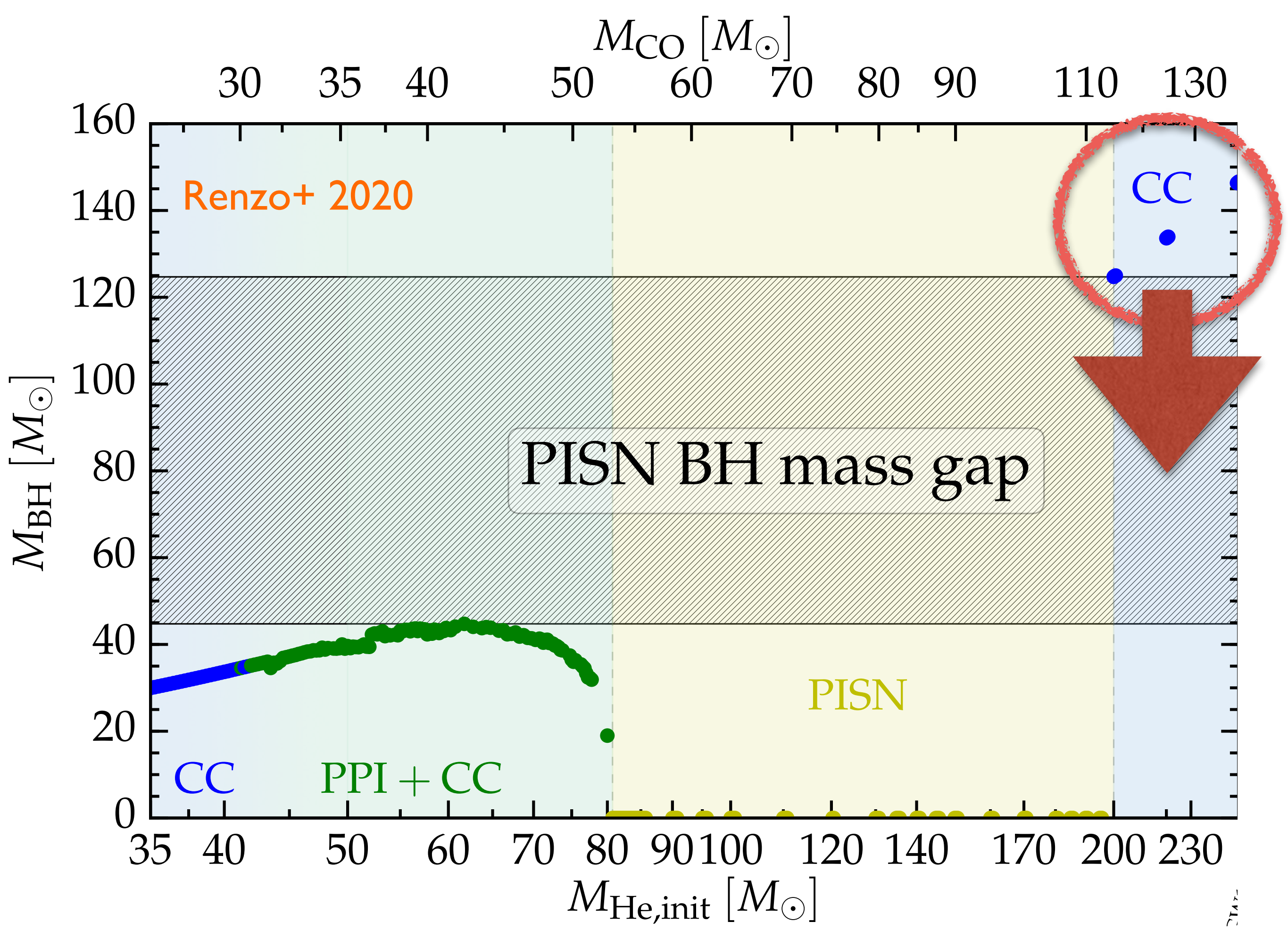
Black holes in the pair-instability mass gap



How to populate the PISN BH mass gap?

- Stellar mergers DiCarlo+ 2019, Renzo+ 2020b
- Hierarchical BBH mergers Antonini & Rasio 2016, …
- Modifying stellar physics at low metallicity Farell+ 21, Vink+ 21
- Gas accretion onto PopIII remnant BHs Safarzadeh & Haiman 20
- To some extent: nuclear reaction rates & rotation Woosley & Heger 21, …

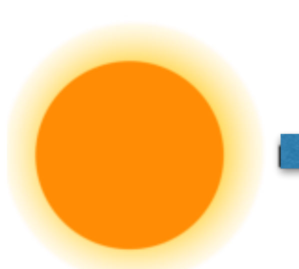
More massive collapsars populate the PISN mass gap

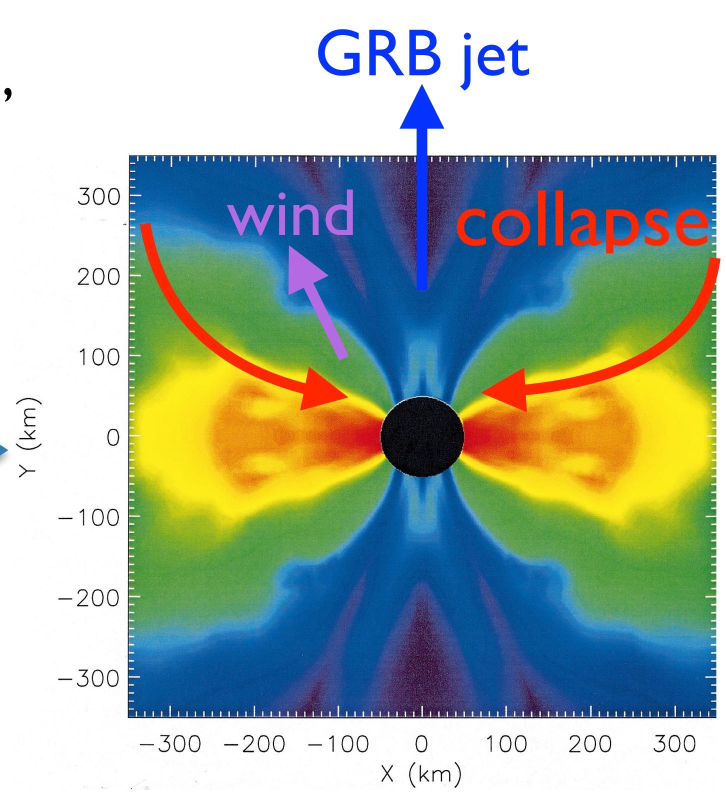


Siegel+ 2022

- populate the PISN mass gap 'from above'
- compact massive progenitors >130 M_{sun}
- endowed with parametrized rotation profile (f_K, r_b)

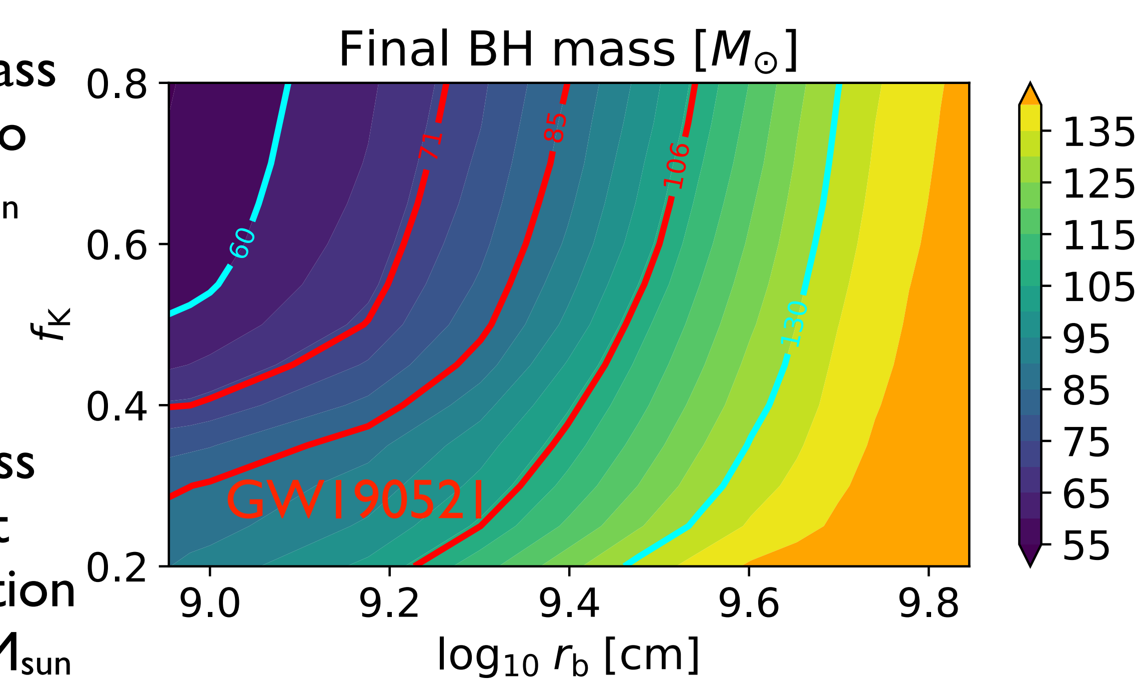
Collapse of massive, rapidly rotating progenitors > 130 M_{sun}



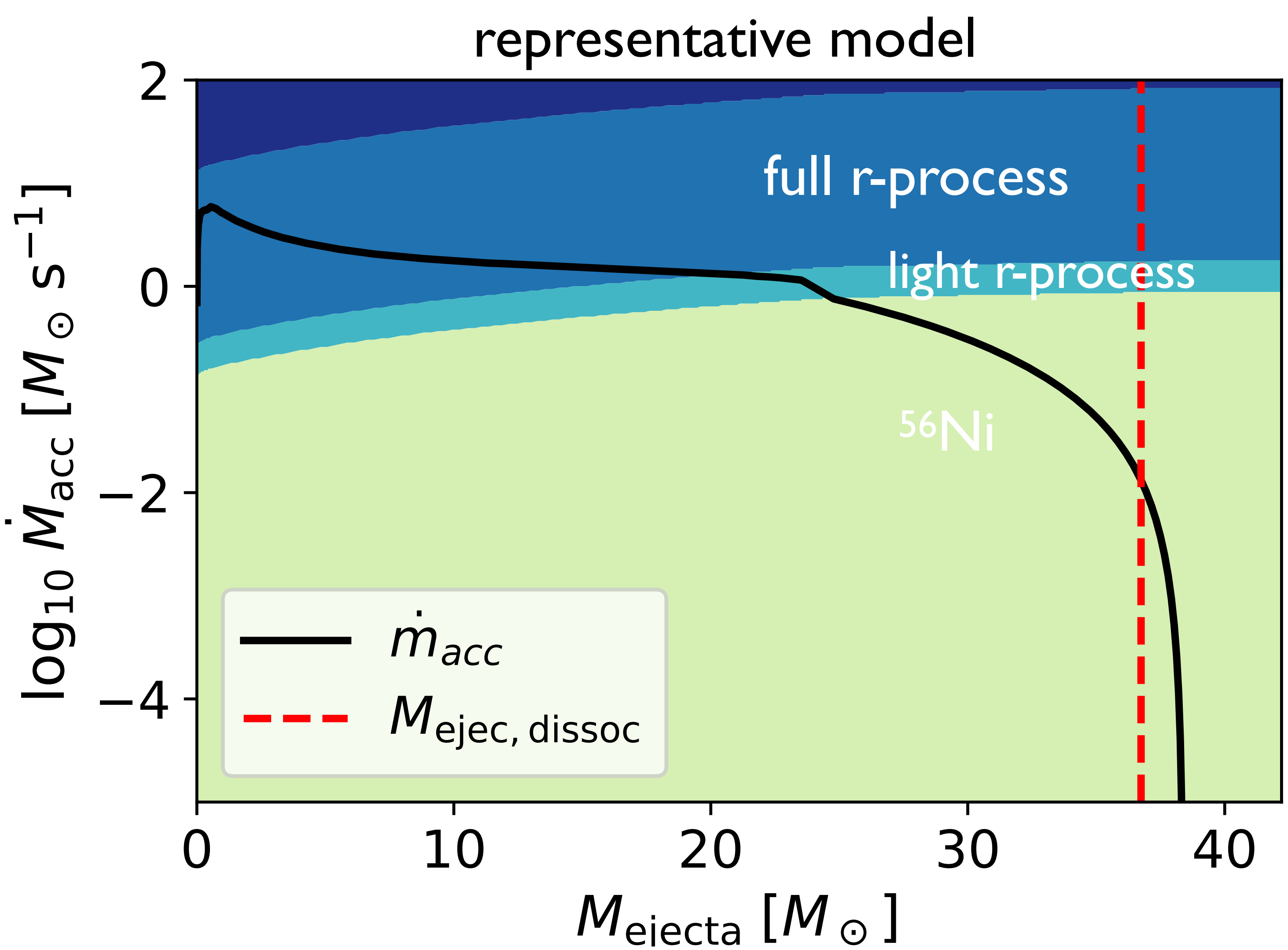


Wind mass loss up to > 50 M_{sun}

r-process element production ~1-10 M_{sun}



Ejecta composition reflects accretion process



- At high accretion rates, flow neutronizes
  Beloborodov 2003, Siegel & Metzger 2017, Siegel+ 2019
- Various nucleosynthesis regimes, see also
  Siegel, Barnes, Metzger 2019, Nature
- Ejecta contains high-opacity, lanthanide-rich material, $X_{La} \sim 10^{-4}$–10^{-2}
- parameter space scan

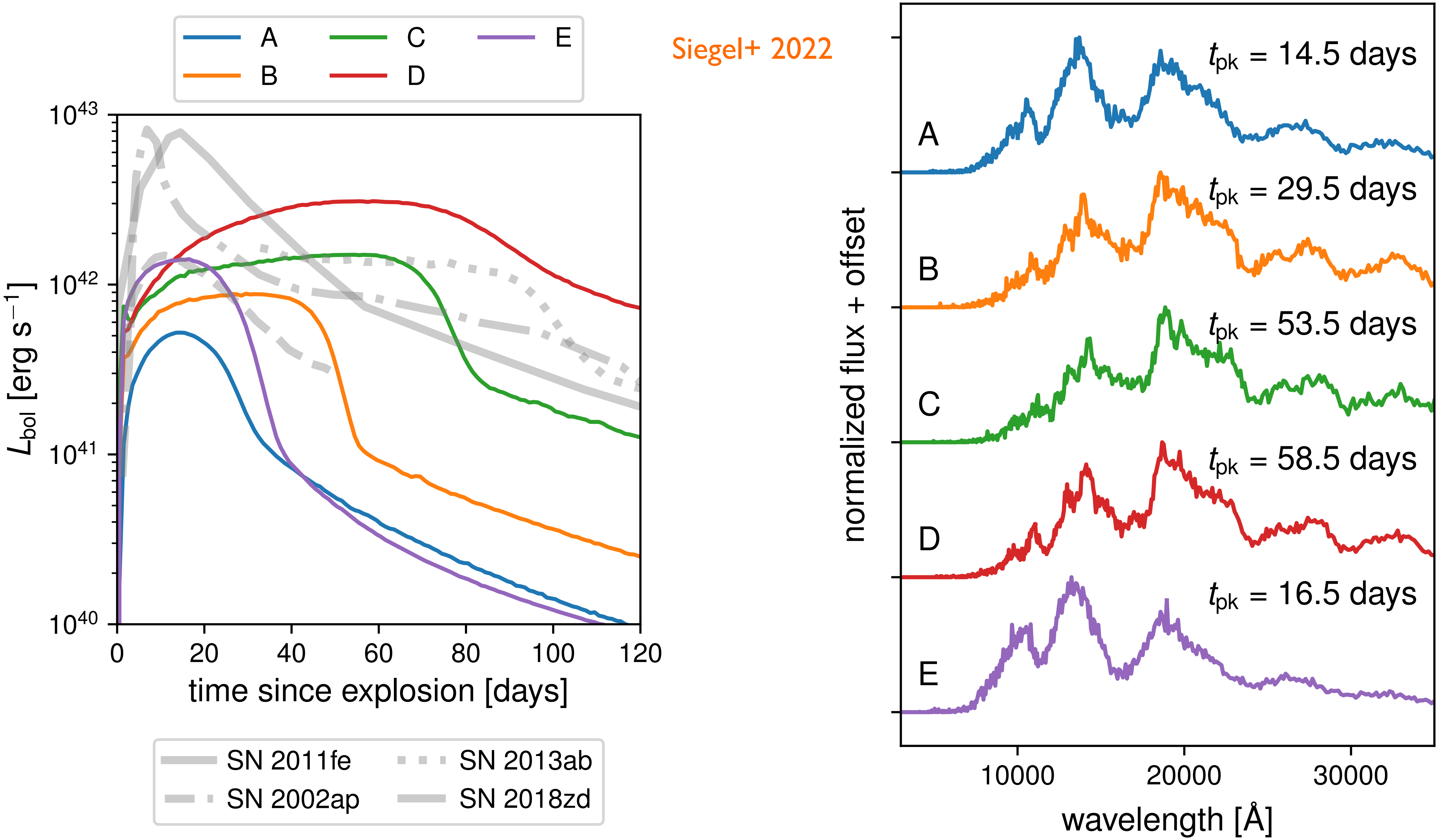
  $M_{ej} \sim$ 10–60 M_{sun}

  $M_{ej,\,r\text{-}p} \sim$ 1–20 M_{sun}

  $M_{ej,\,Ni56} \sim$ 0.05–1 M_{sun}

  $M_{BH} \sim$ 60–130 M_{sun}

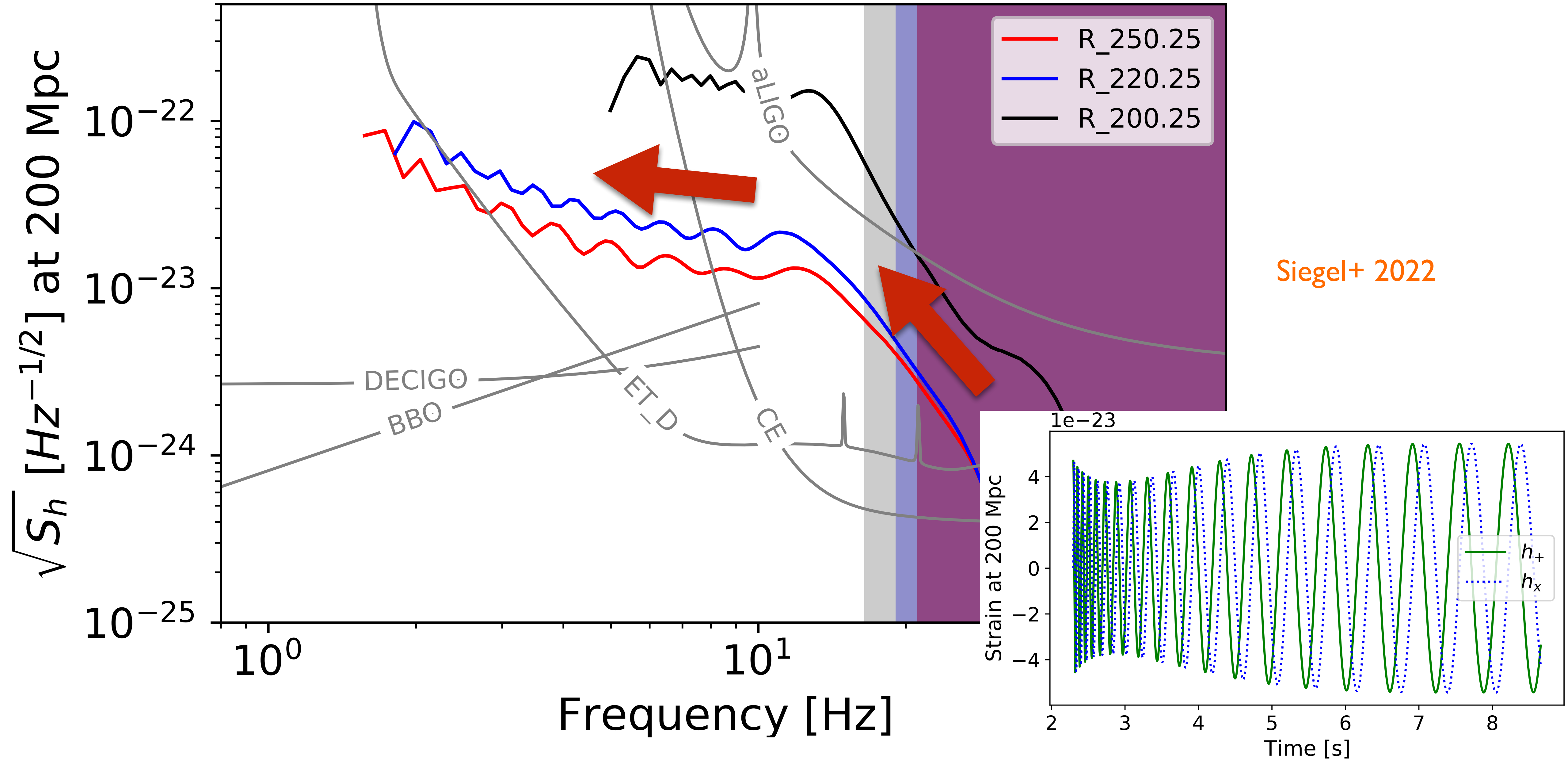
EM transients: *Super-Kilonovae*



Siegel+ 2022

- representative models span a range of light curve morphologies
- r-process + ^{56}Ni powered transients on timescales ~tens of days (‘scaled-up NS merger’)
- red colors and distinctive spectra with and broad lines (v ~ 0.1c)
- up to ~few per year detectable with wide field surveys (Roman Space Telescope)

Super-Kilonovae are multimessenger events



Siegel+ 2022

- Gravitational instabilities in the accretion disk give rise to gravitational-wave emission observable with 3rd generation GW observatories (Cosmic Explorer, Einstein Telescope)
- GW frequency decreases as disk expands: distinctive "sad-trombone" GW signal

see Gottlieb+ 2024 for different GW mechanism in collapsar disks

Summary & conclusions

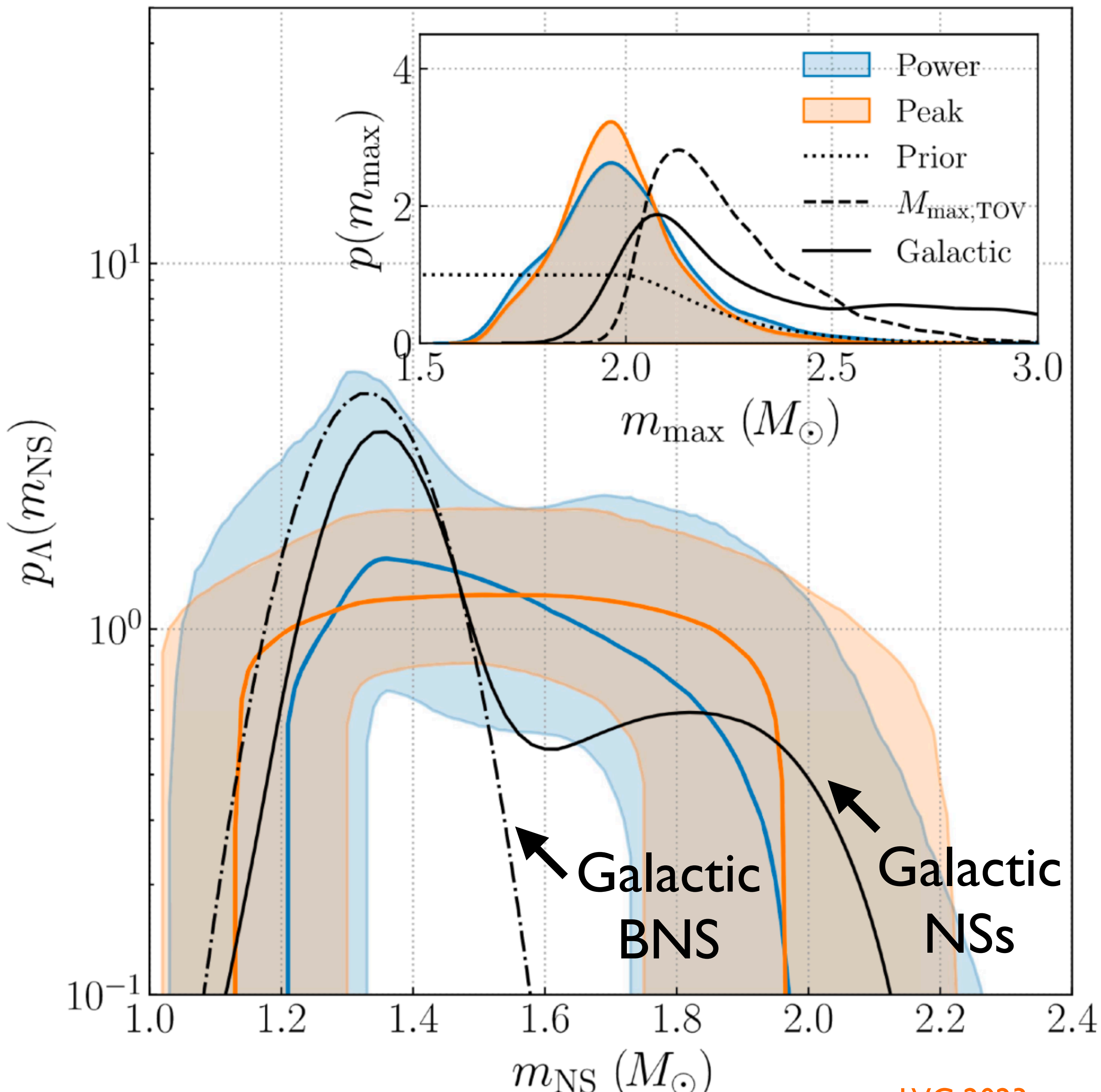
- NS mergers give rise to various ejecta components with a broad range of properties
- First self-consistent ab initio modelling of multiple EM counterparts from NR simulations with relativistic effects underway, key to interpret future observations
- Non-thermal + magnetar enhanced kilonovae from mergers 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 ?!

  ⟶ *Novel BH-disk GRB jet formation mechanism*
- jet/polar outflows create ~hr kilonova precursor
- 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

Appendix

Remnant diversity & distribution



LVC 2023

O3 NS masses

- High-M wing largely determined by outlier and NSBH events
- BNS mass distribution may be genuinely different from NSBH (binary stellar evolution)

Super-Kilonovae detection prospects

- Targeted follow-up of very bright long GRBs in the IR with Roman, JWST
- Blind searches with *Optical/IR surveys* (Rubin/Roman)

SuperKN Light Curve Models and Survey Detection Rates

Model	$M_{\rm ej}$ ($M_\odot$)	$v_{\rm ej}$ (c)	$M_{\rm Ni}$ ($M_\odot$)	$M_{\rm lrp}$ ($M_\odot$)	$X_{\rm La}$ (10^{-3})	$R^{(a)}_{\rm Rubin}$ (yr^{-1})	$R^{(b)}_{\rm Roman}$ (yr^{-1})
a	8.6	0.1	0.019	0.83	1.4	0.01	0.02
b	31.0	0.1	0.012	8.28	17.0	0.03	0.4
c	35.6	0.1	0.087	23.2	4.0	0.1	2
d	50.0	0.1	0.53	9.59	0.53	0.1	4
e	60.0	0.1	0.0	5.6	0.17	0.2	0.01

Rubin: sensitive to ^{56}Ni-rich, light r-process models

Roman: sensitive to lanthanide-rich models

- scaled-up, beaming corrected GRB rate using Salpeter IMF, out to z = 0.1
- 10 deg^2 Roman WFI survey with filters F062, F158 and F184 to ~27th mag
- detection = at least 3 SNR>3 points

Uncertainties: intrinsic event rates, stellar structure, accretion dynamics & wind composition/mixing, …

Novel post-merger physics: Neutrino oscillations

Li & Siegel 2021, PRL

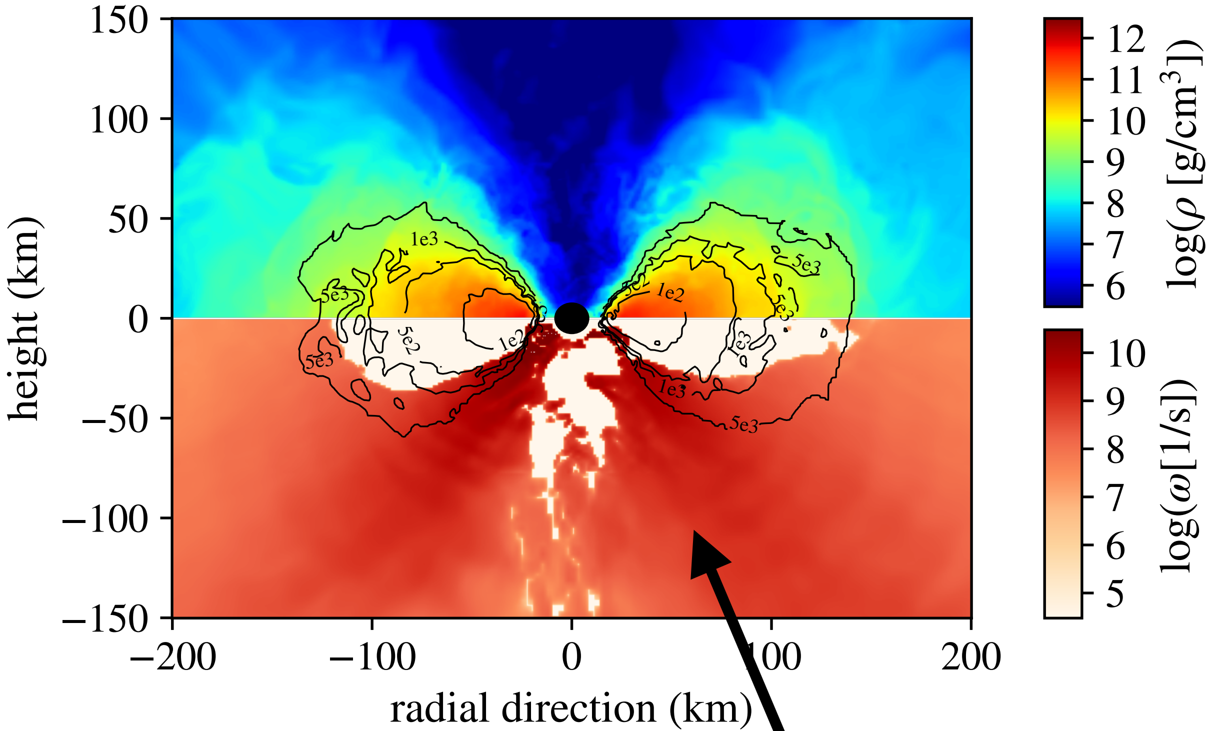
Free-streaming neutrinos:

$$i v^\mu \partial_\mu \rho_\nu = [H, \rho_\nu] \qquad H = H_V + H_M + H_\nu$$

vacuum oscillations

self-interaction

matter interaction
(MSW effect)



instability region: ubiquitous flavor conversions
~ns timescales

Conditions for fast conversions:

$$\Phi_0 = \sqrt{2} G_F \hbar^{-1} n_\nu = 1.92 \times 10^9 \mathrm{s}^{-1} \left(\frac{n_\nu}{10^{31} \mathrm{cm}^{-3}} \right)$$

- GRMHD + M1 neutrino transport
- dispersion relation approach, approximate equipartition

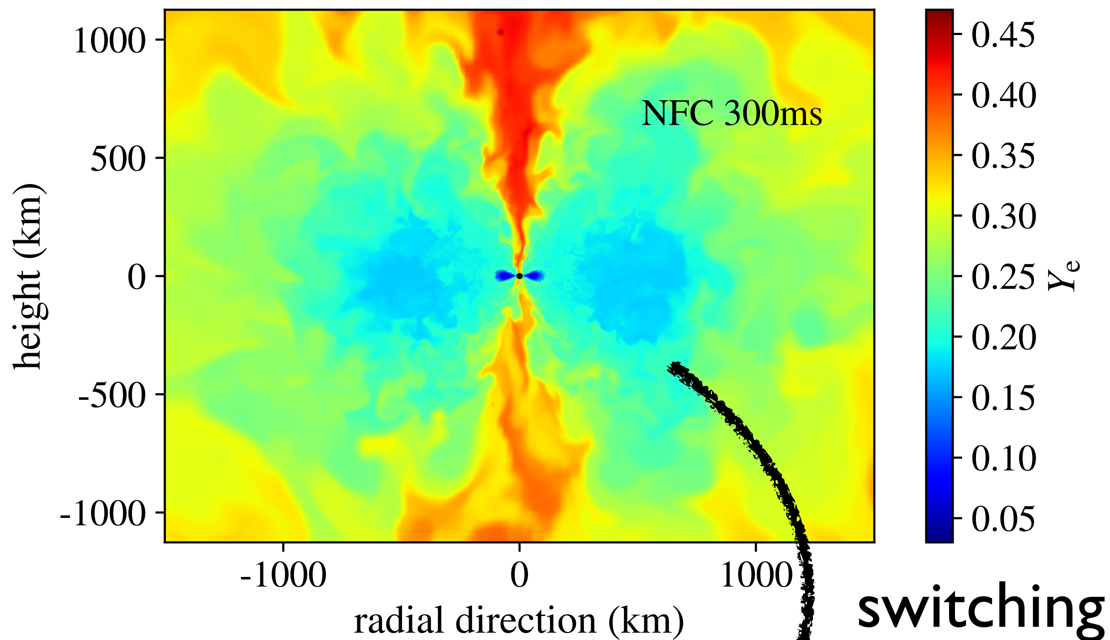
First astrophysical simulation with *fast conversions included dynamically*, also relevant to core-collapse supernovae

Novel post-merger physics: Neutrino oscillations

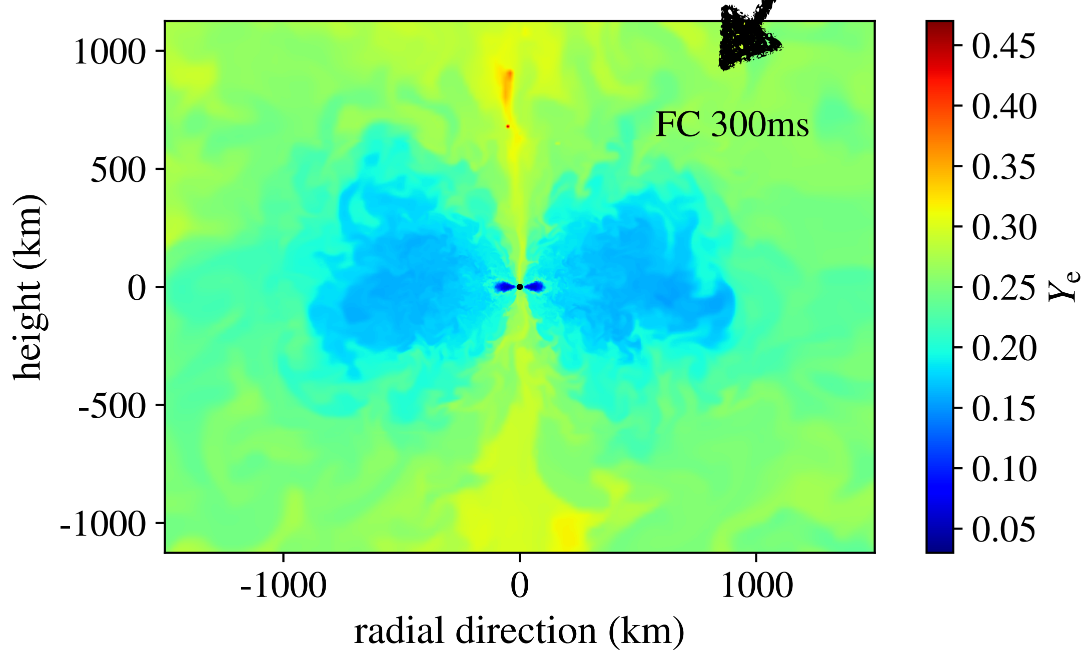
Li & Siegel 2021, PRL

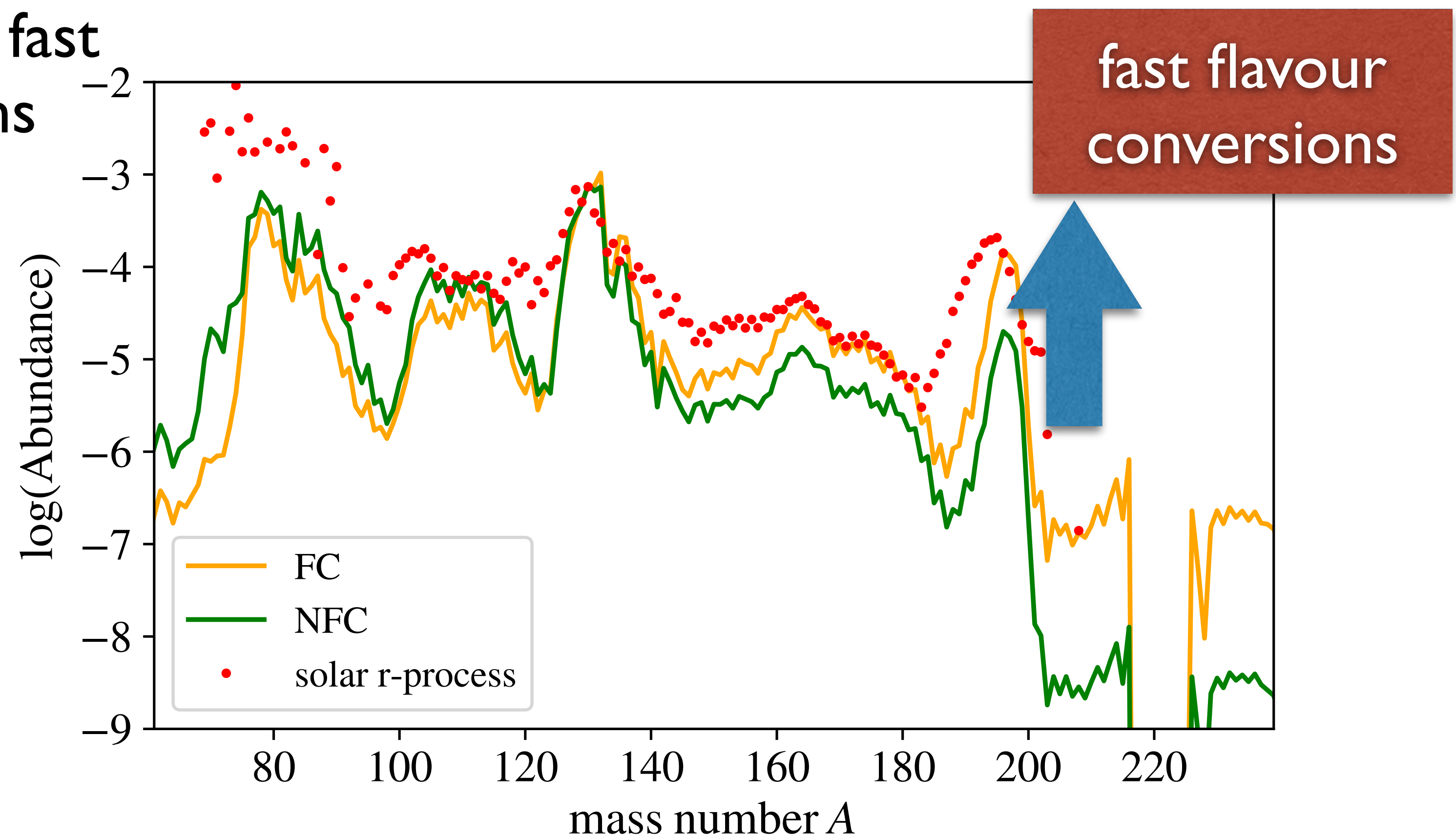
ejecta composition changes significantly (more neutron-rich)

- boost in heavy r-process by factor few-10 (lanthanides, actinides)
- imprint in kilonova (becomes more 'red')
- imprint in *actinide-boost stars*? Faroqui+ 2021



switching on fast conversions





Caveat: non-linear regime of fast flavour conversions still somewhat uncertain Richers+ 2021

Other recent work: George+ 2020, Fernandez+ 2022, Just+ 2022

BH-disk nucleosynthesis regimes

ejecta Y_e absorption dominated

Miller+ 2019
Li & Siegel, PRL 2021

$$\dot{M} = \begin{cases} > \dot{M}_\nu & \text{lanthanide suppression} \\ \in [\dot{M}_{\rm ign}, \dot{M}_\nu] & \text{'full' r-process} \\ < \dot{M}_{\rm ign} & Y_e \text{ frozen} \end{cases}$$

ejecta Y_e emission dominated

$$\dot{M}_\nu \simeq 0.1 M_\odot \mathrm{s}^{-1} \left(\frac{M_{\rm BH}}{3M_\odot}\right)^{\frac{4}{3}} \left(\frac{\alpha_{\rm eff}}{0.02}\right)$$

$$\dot{M}_{\rm ign} \simeq 2\times 10^{-3} M_\odot \mathrm{s}^{-1} \left(\frac{M_{\rm BH}}{3M_\odot}\right)^{\frac{4}{3}} \left(\frac{\alpha_{\rm eff}}{0.02}\right)^{\frac{5}{3}}$$

Chen & Beloborodov 2007
Siegel+ 2019
Siegel+ 2022

Post-merger accretion disk can 'sweep through' one or more regimes while viscously spreading

Nucleosynthesis regimes

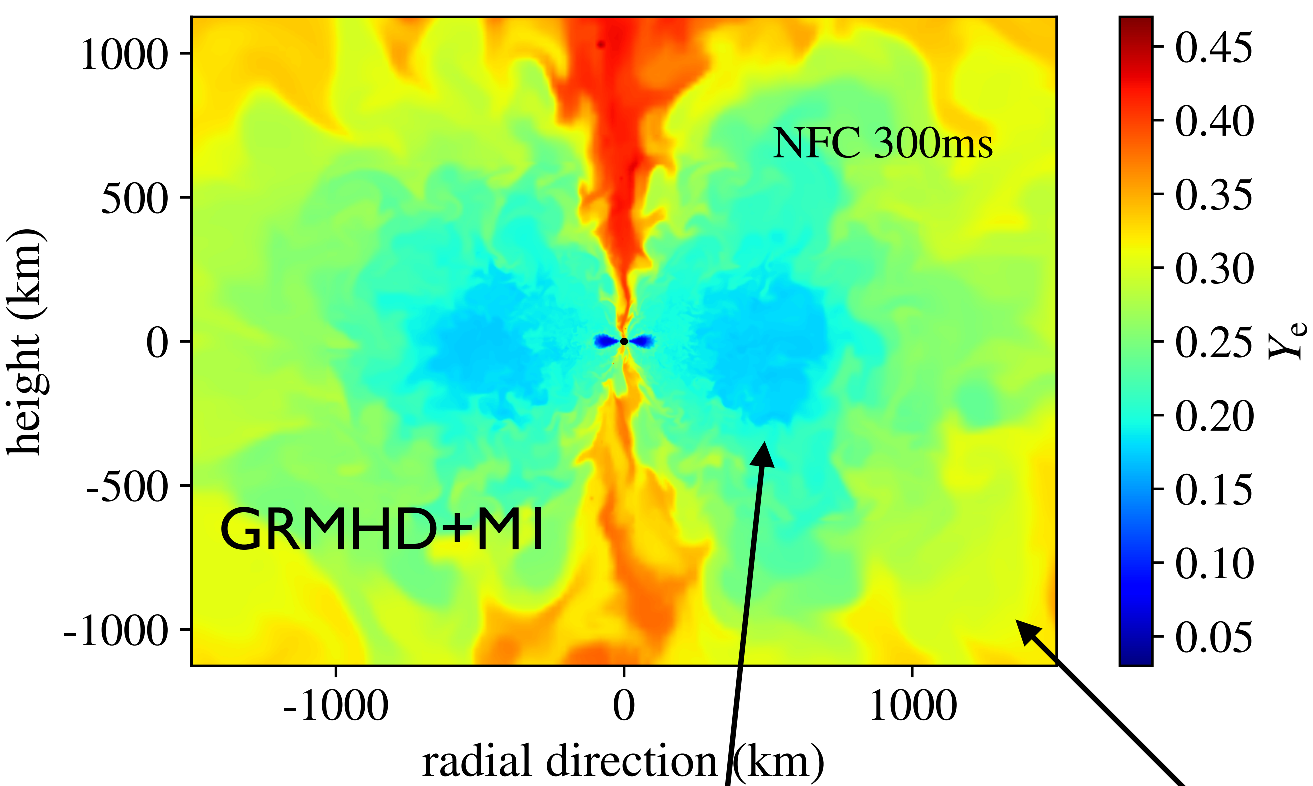
$$\dot{M} = \begin{cases} > \dot{M}_\nu & \text{lanthanide suppression} \\ \in [\dot{M}_{\rm ign}, \dot{M}_\nu] & \text{'full' r-process} \\ < \dot{M}_{\rm ign} & Y_e \text{ frozen} \end{cases}$$

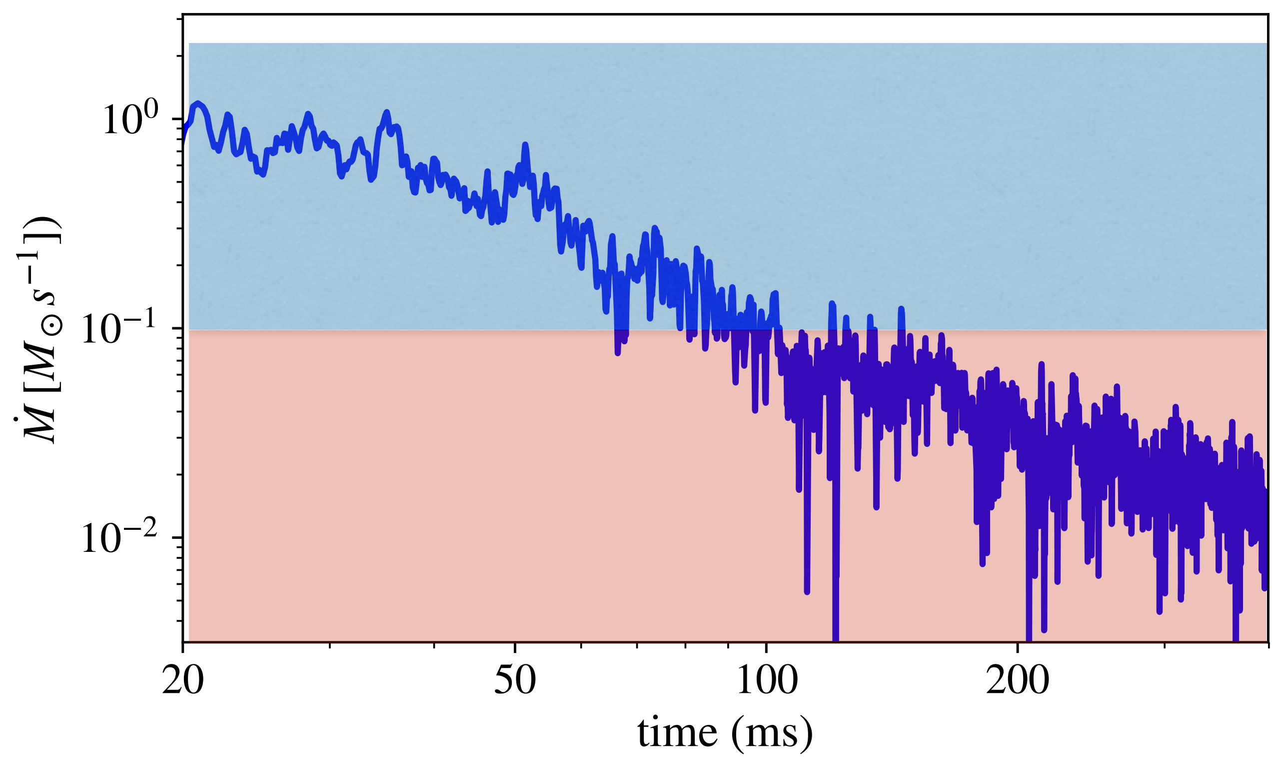
ejecta Y_e absorption dominated → lanthanide suppression

Miller+ 2019
Li & Siegel, PRL 2021

ejecta Y_e emission dominated → 'full' r-process

Li & Siegel, PRL 2021





medium $\dot{M}$

high $\dot{M} \approx 1 M_\odot \mathrm{s}^{-1}$

Nucleosynthesis regimes

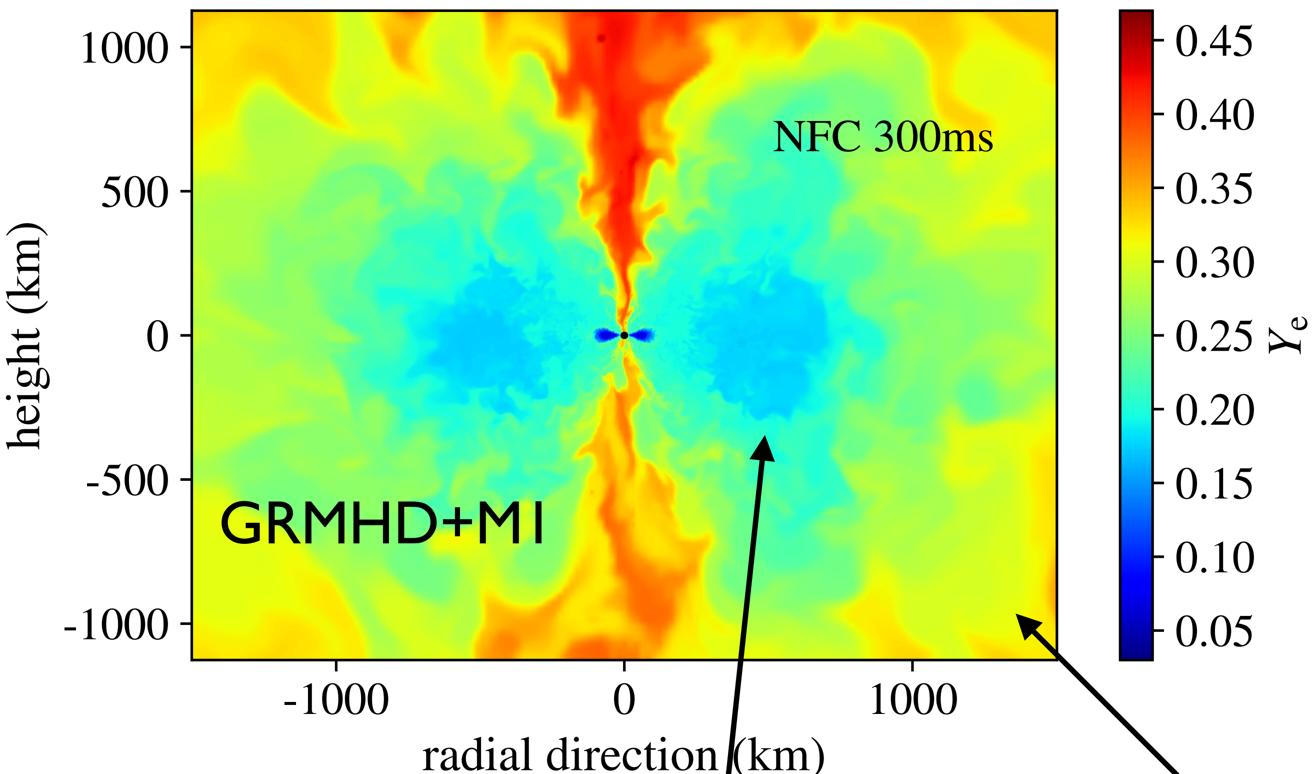
$$\dot{M} = \begin{cases} > \dot{M}_\nu & \text{lanthanide suppression} \\ \in [\dot{M}_{\rm ign}, \dot{M}_\nu] & \text{'full' r-process} \\ < \dot{M}_{\rm ign} & Y_e \text{ frozen} \end{cases}$$

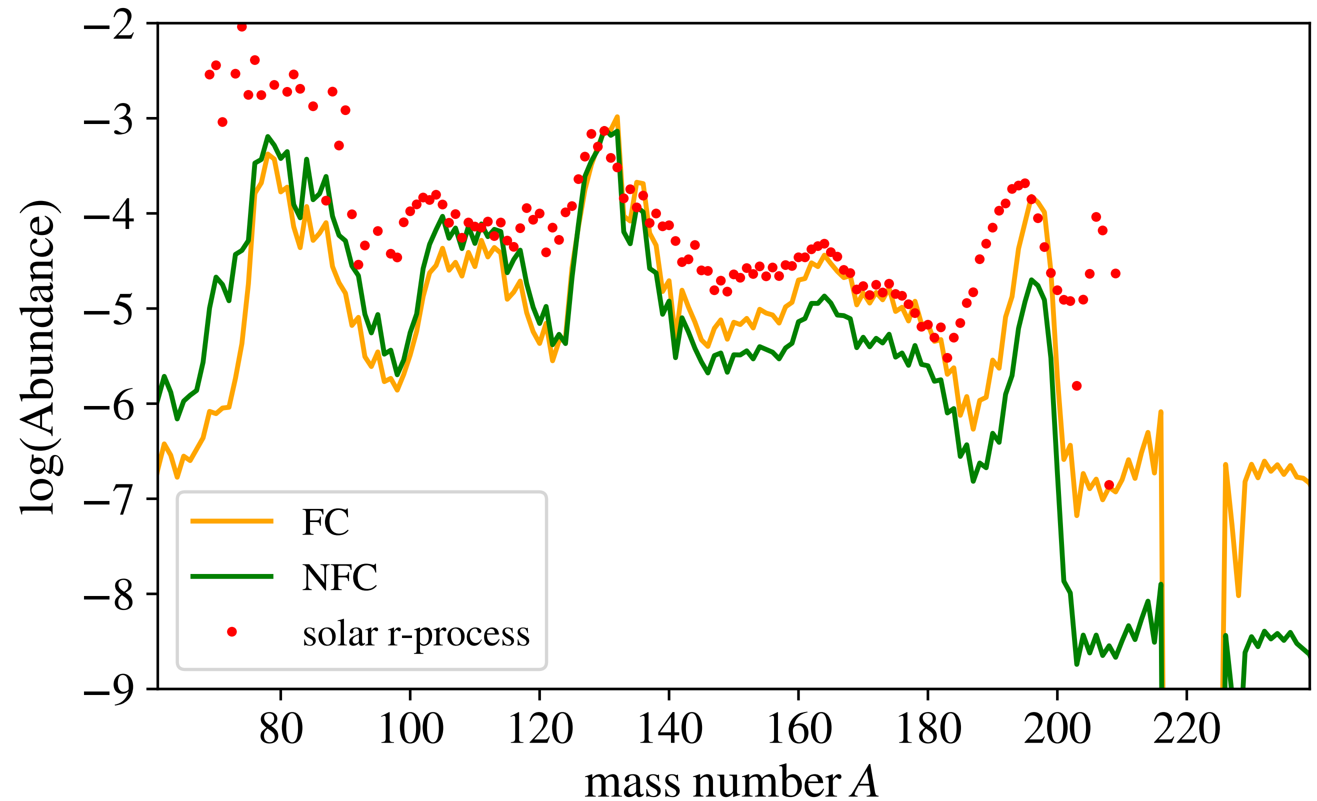
ejecta Y_e absorption dominated

Miller+ 2019
Li & Siegel, PRL 2021

ejecta Y_e emission dominated

Li & Siegel, PRL 2021





medium $\dot{M}$

high $\dot{M} \approx 1 M_\odot \mathrm{s}^{-1}$