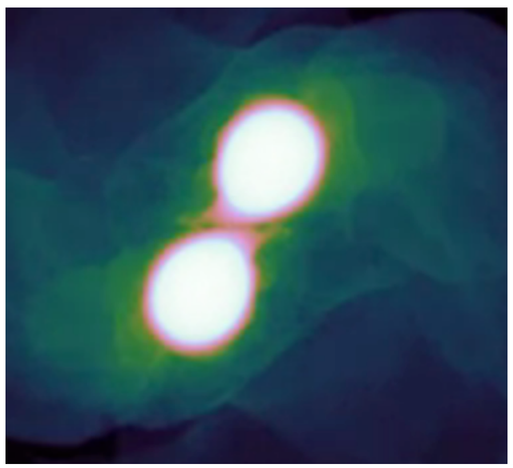
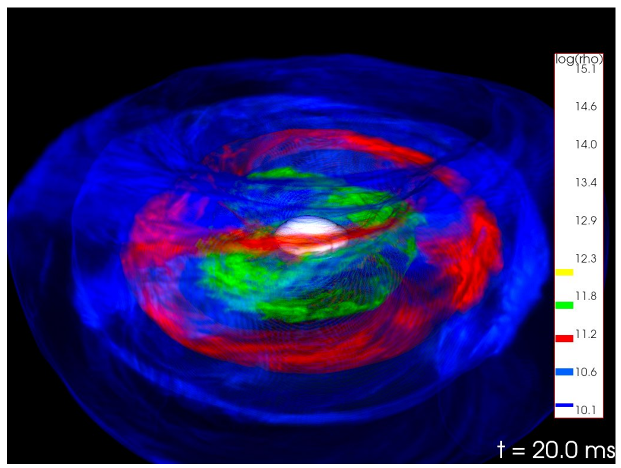
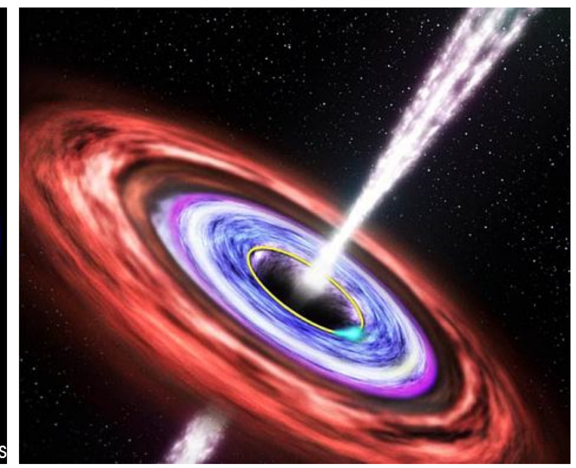
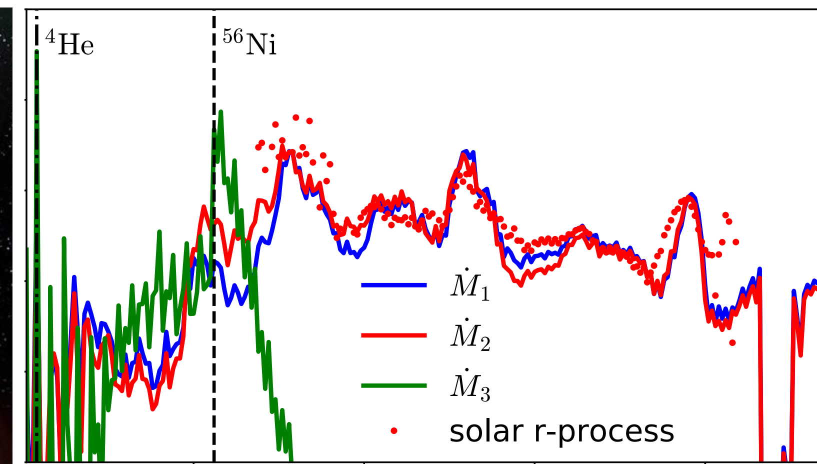
EM signatures from NS mergers









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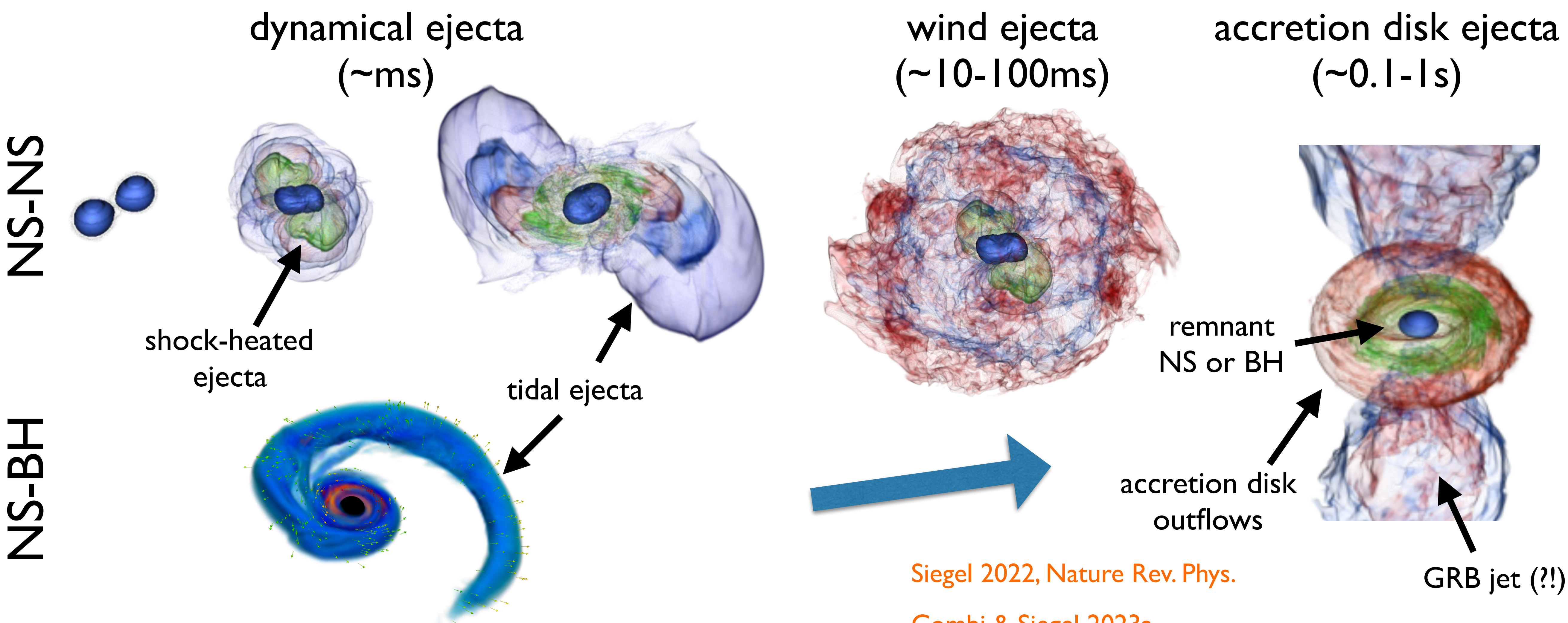
University of Guelph, Canada

PERIMETER INSTITUTE

UNIVERSITY of GUELPH

MICRA 2023, ECT* Trento, 11-15 Sep 2023

Outflows power EM transients



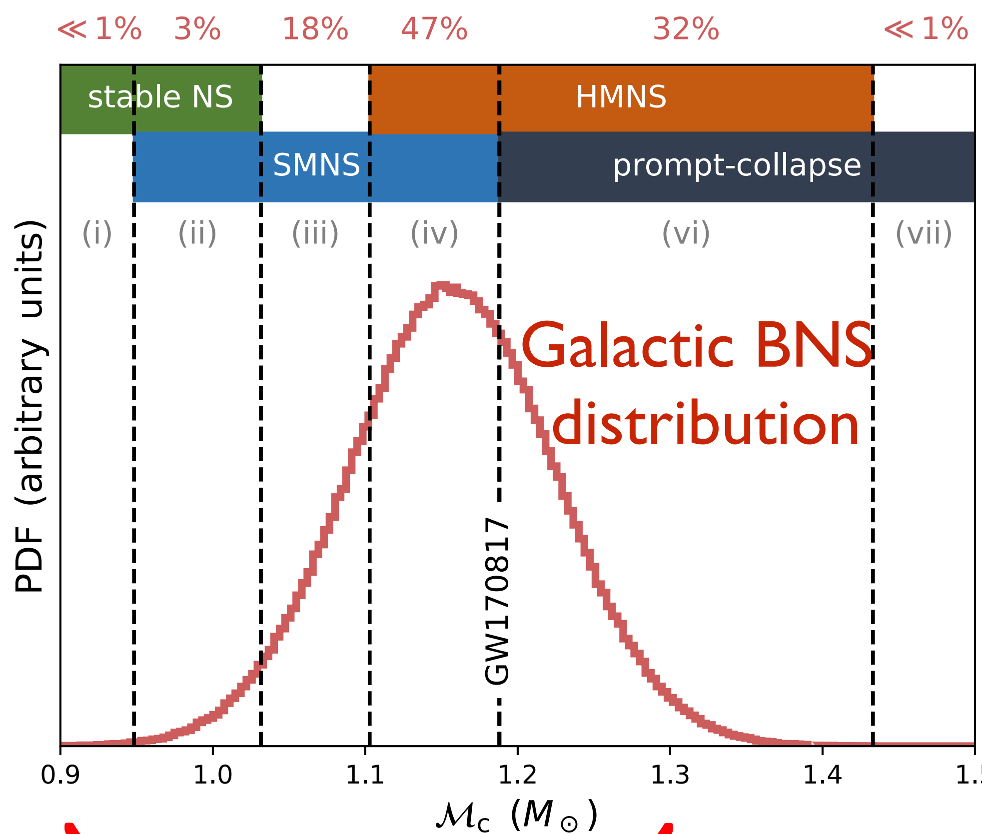
Siegel 2022, Nature Rev. Phys.

Combi & Siegel 2023a

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

- plasma instabilities
  (Kelvin-Helmholtz, Rayleigh-Taylor, Magnetorotational Instability)
- weak interactions, MHD effects, magnetically & neutrino-driven stellar and disk winds
- dynamical spacetime, gravitational waves, non-linear (magneto-)hydrodynamics

Remnant diversity & distribution



Margalit & Metzger 2019

massive disks

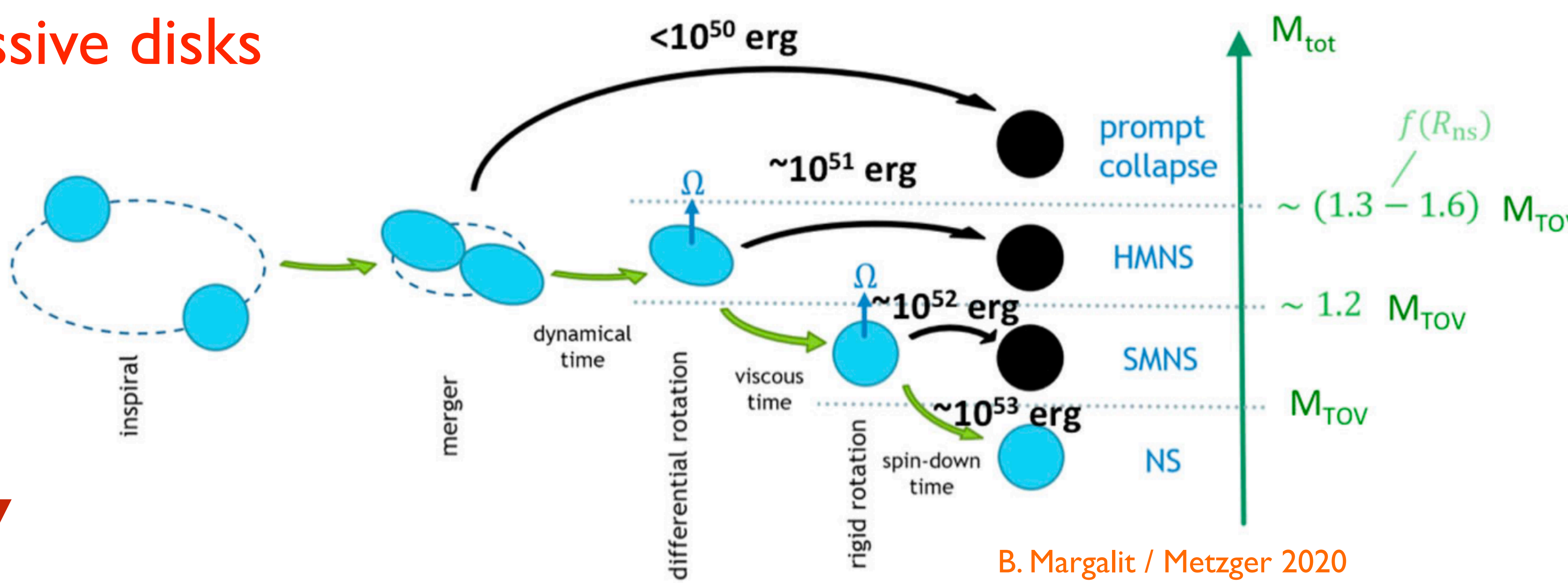
Delayed BH formation produces massive accretion disks:

~70-9x % of BNS mergers (?)

→ Expect r-process in BNS mergers dominated by accretion disk

E_{rot}

EM emission

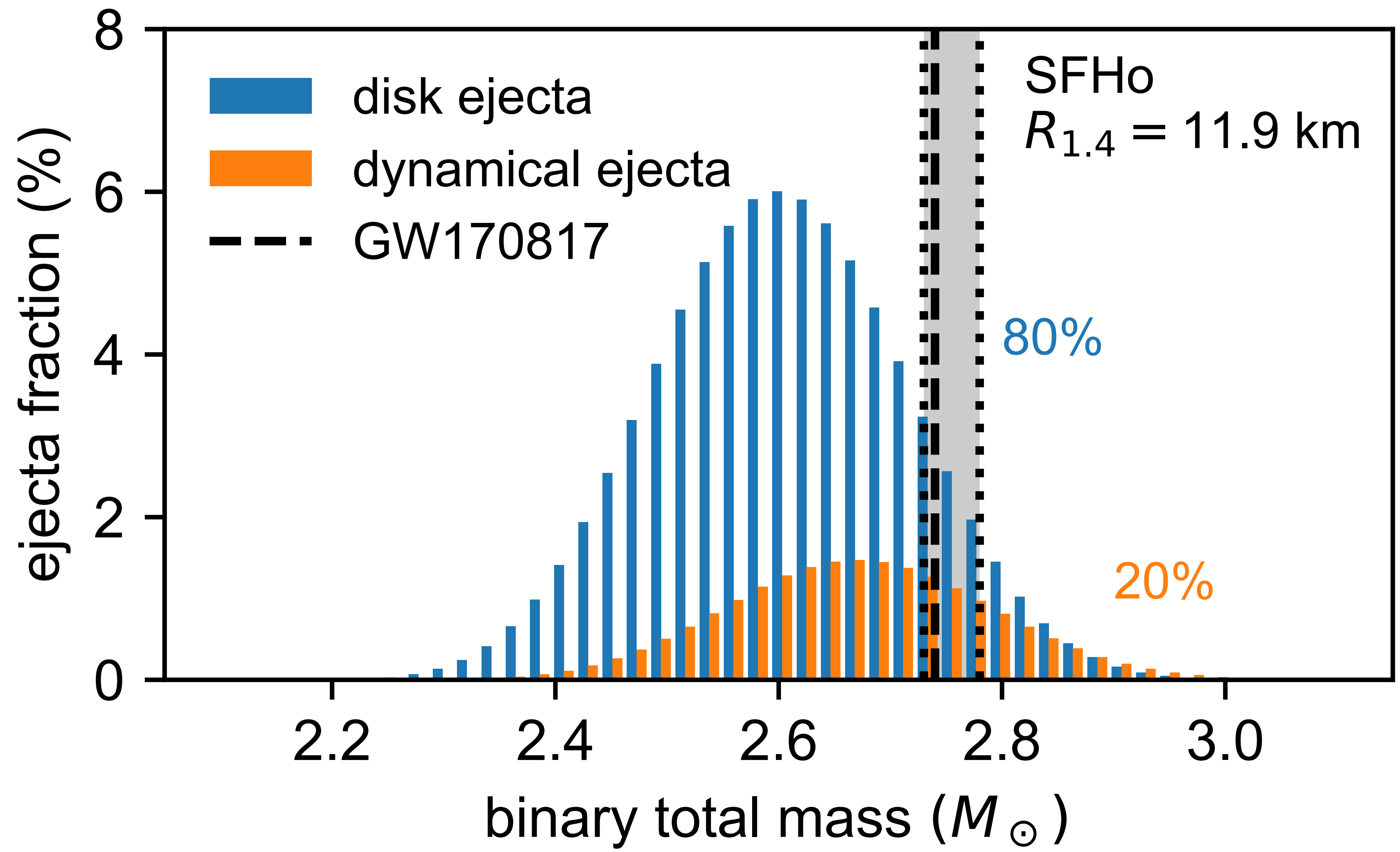


B. Margalit / Metzger 2020

massive disks

Future GW events: exploring BNS parameter space

Siegel 2022, Nature Rev. Phys.



Expected ejecta distribution for galactic BNS distribution

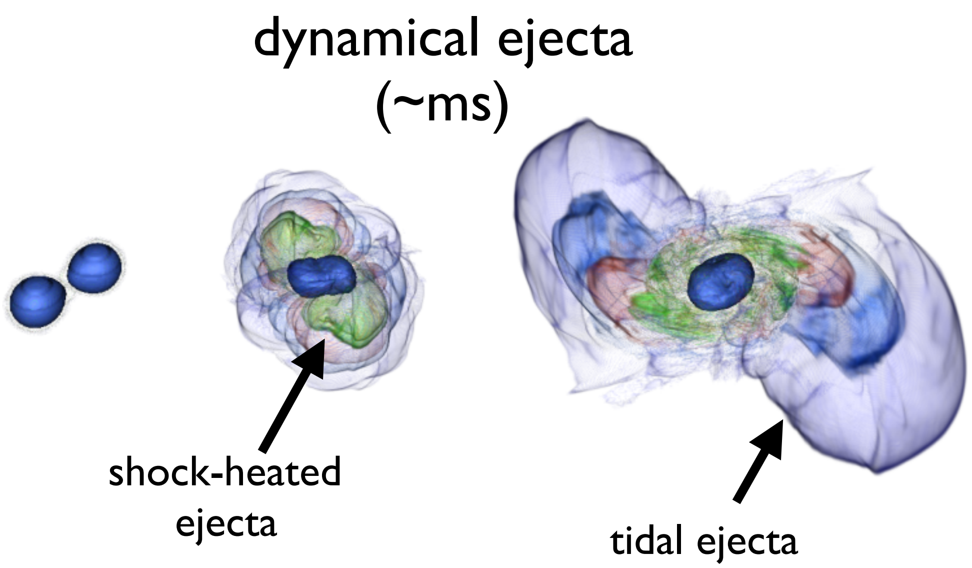
(based on ejecta fitting formulae by Krüger & Foucart 2020)

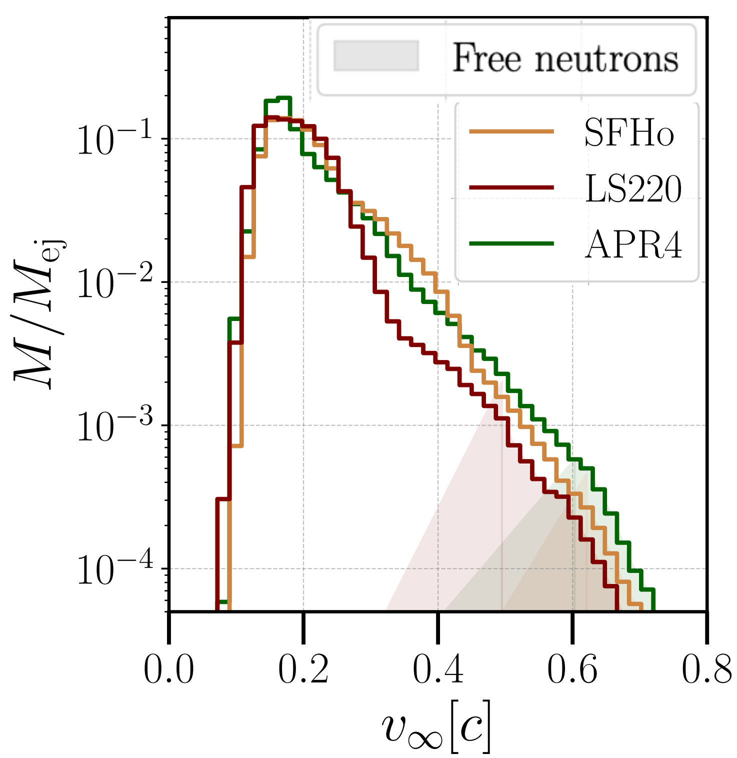
Conjecture: *Outflows from compact (neutrino-cooled) accretion disks synthesize most of the heavy r-process elements in the Universe.*

- Focus here on BNS (NS-BH subdominant wrt r-process) Chen+ 2021
- Support from early blue post-merger ejecta Combi & Siegel 2023b
- Further support from collapsar accretion disks Siegel+ 2019

I.
Dynamical Ejecta & EM transients

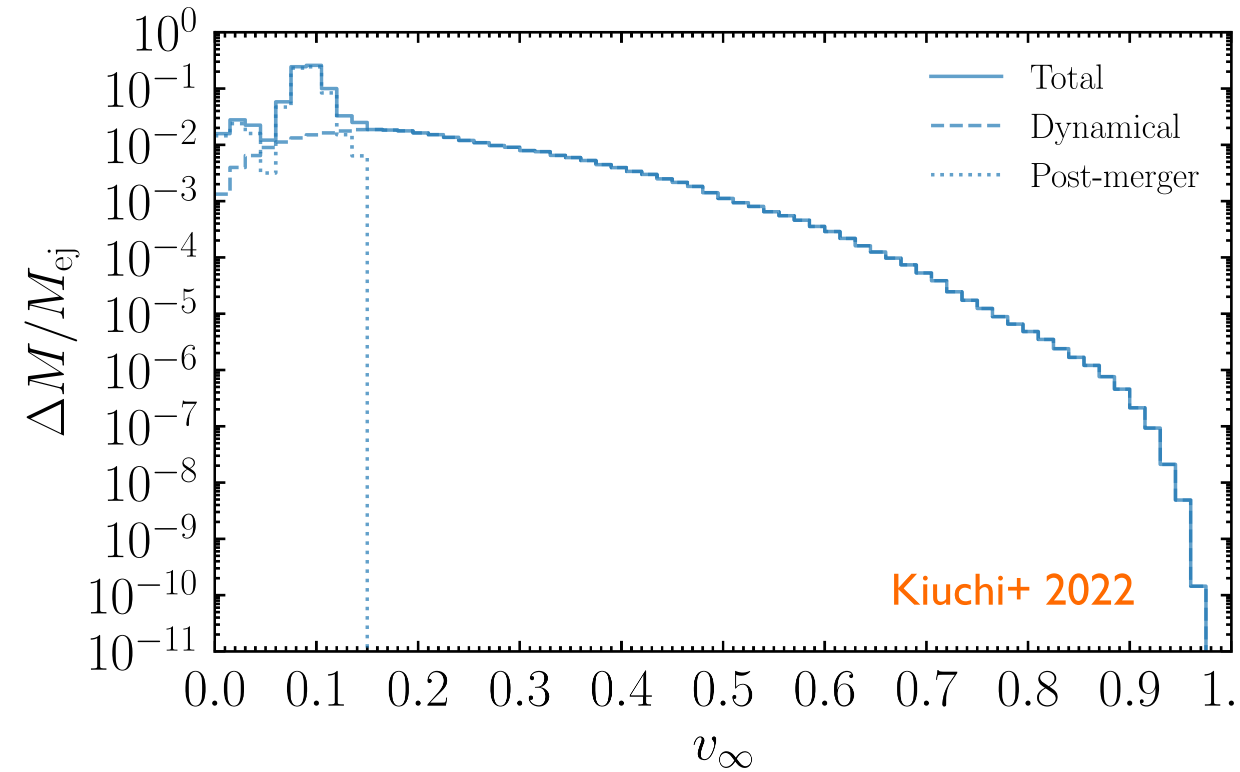
Fast dynamical ejecta

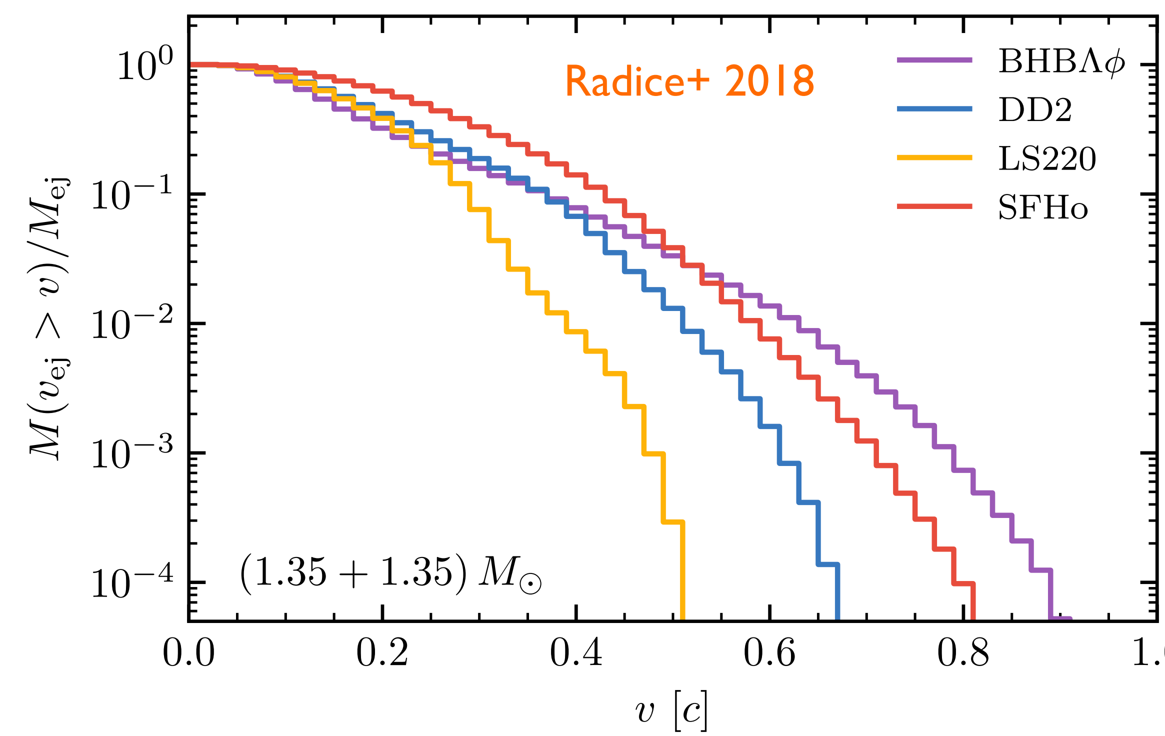




Combi & Siegel 2023a

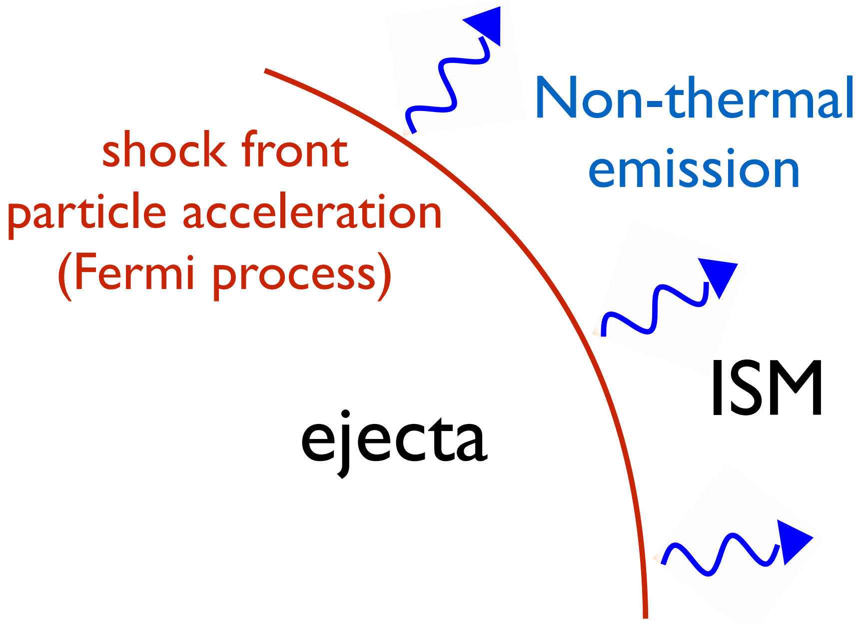
fast, high-Y_e (>0.25), shock-heated ejecta drives shock wave into the ISM





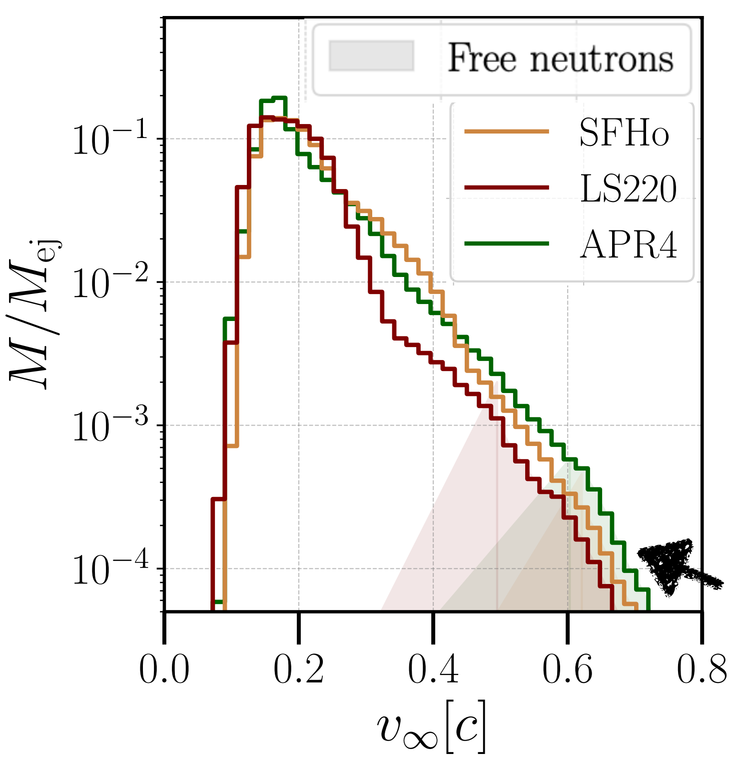
See also: Hotokezaka+ 2018, Dean+ 2021, Bauswein+ 2013, Rosswog+ 2023

Fast dynamical ejecta: X-ray to radio afterglow

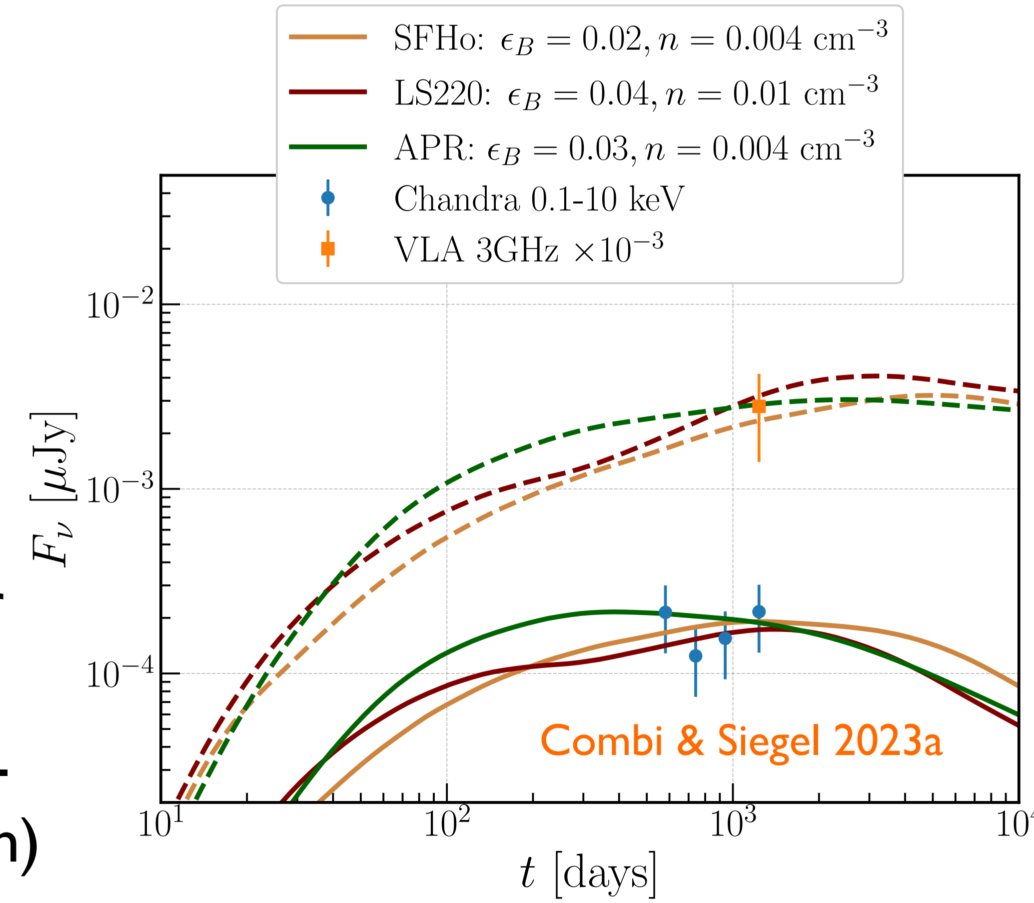


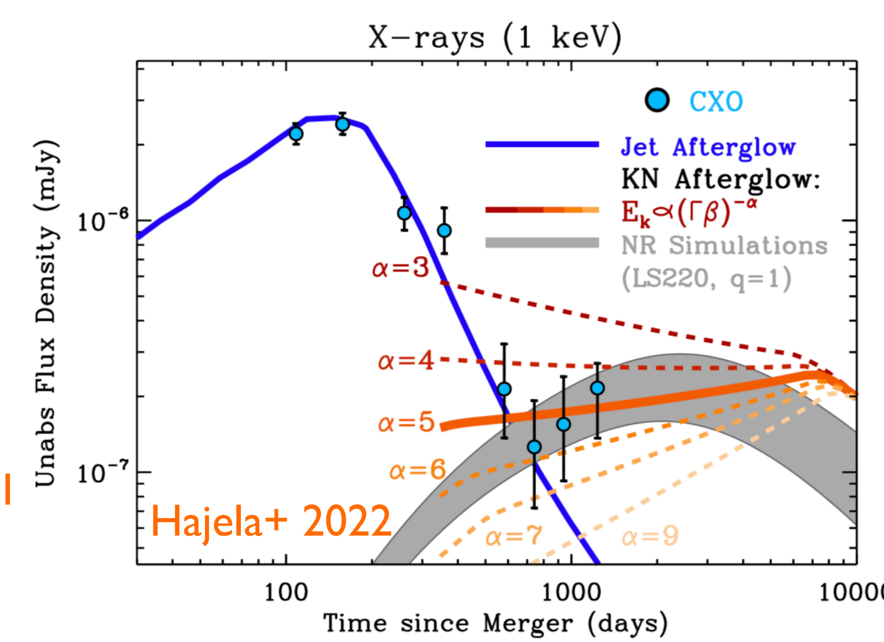
Combi & Siegel 2023a

- full numerical solution of Fokker-Planck equation (Syn+IC cooling, Syn self-Compton, self-absorption)
- angle-dependent scheme
- all relativistic effects



~5×10^{-6} M_{sun}
>0.6c ejecta





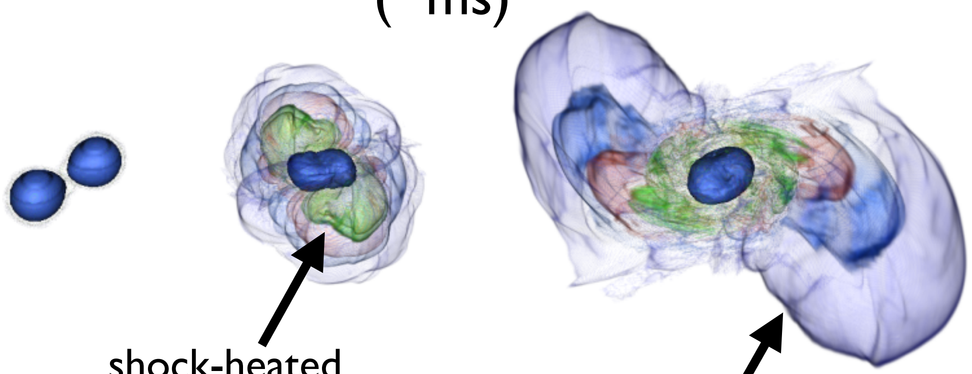
- fast, high-Y_e (>0.25), shock-heated ejecta
- GW170817: source of X-ray-radio afterglow, timescale of years

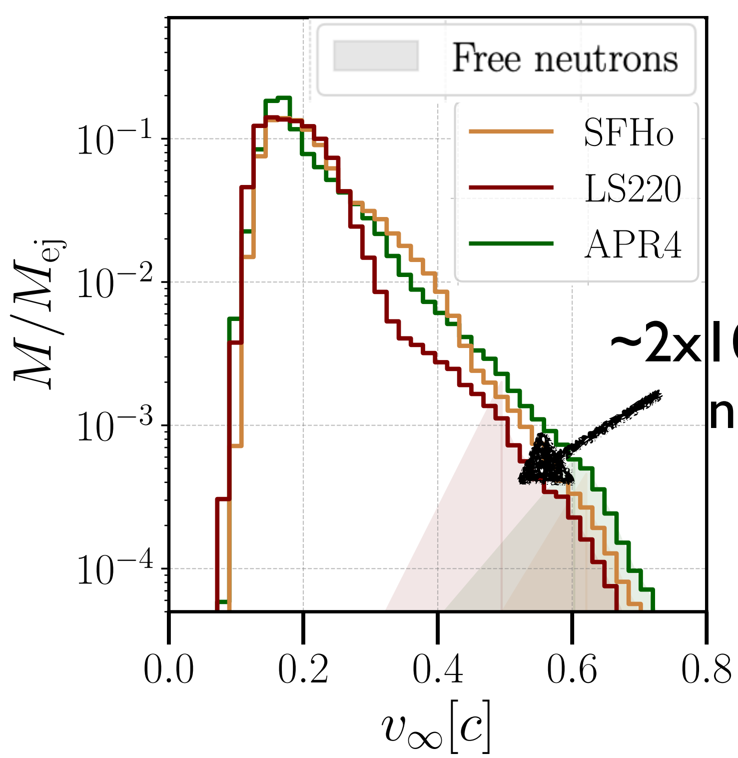
Hajela+ 2022
Troja+ 2022
Balasubramanian+ 2021
Nedora+ 2021
Hotokezaka+ 2018

→ Helps distinguish BNS vs. NS-BH

Fast dynamical ejecta: neutron precursor

dynamical ejecta
(~ms)

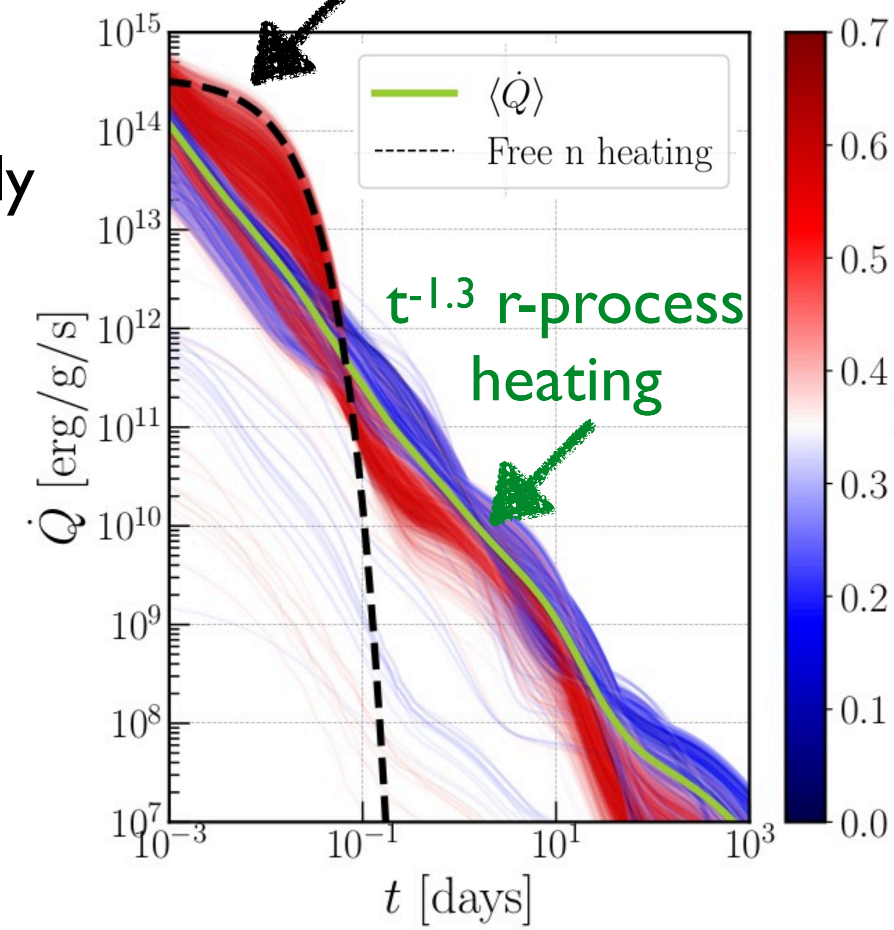


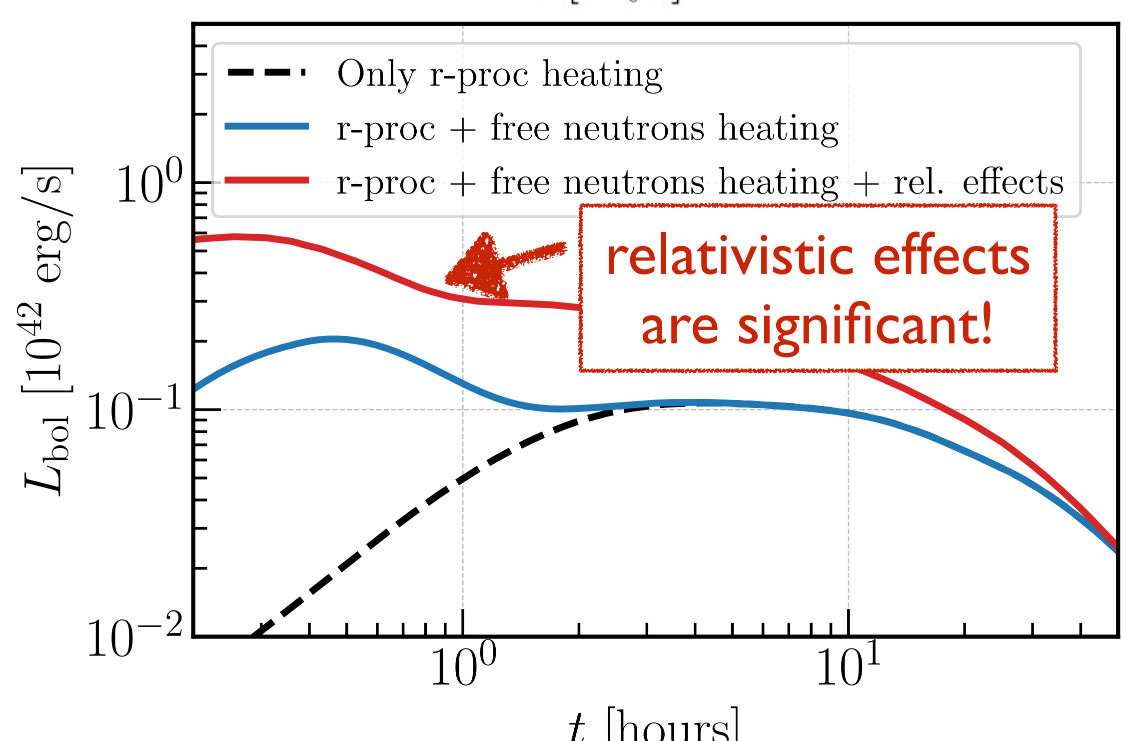


~2x10^{-5} M_{sun} free neutrons

Combi & Siegel 2023a

Nuclear heating, directly from tracers



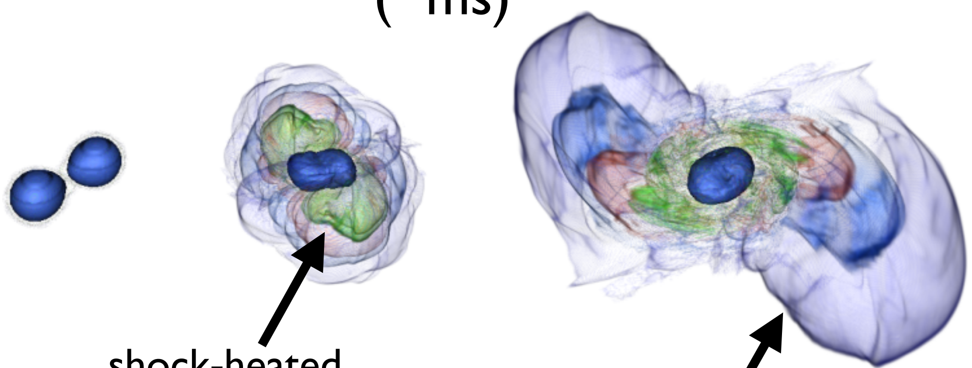


fast, high-Y_e (>0.25), shock-heated ejecta leads to free neutrons

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

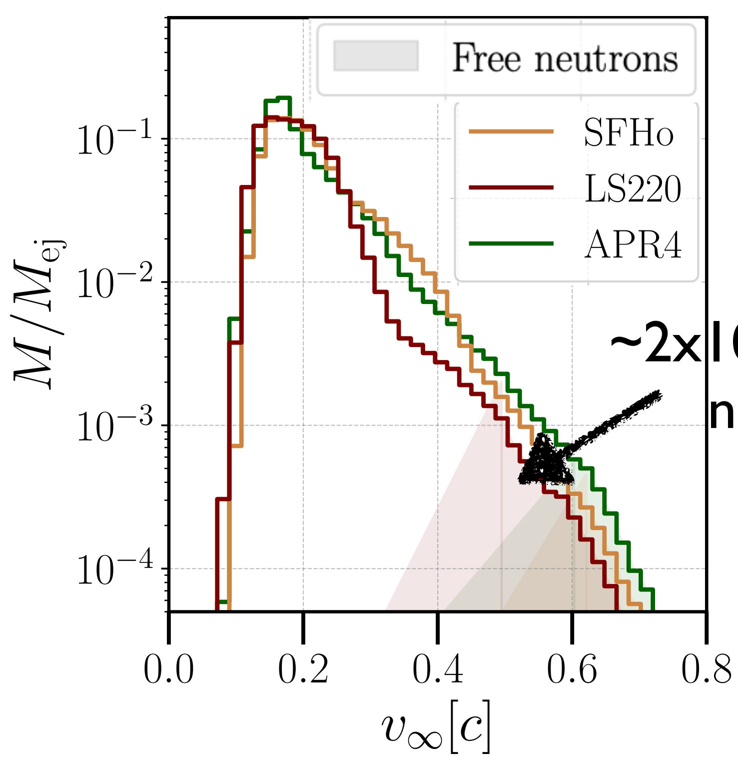
Fast dynamical ejecta: neutron precursor

dynamical ejecta
(~ms)



shock-heated ejecta

tidal ejecta



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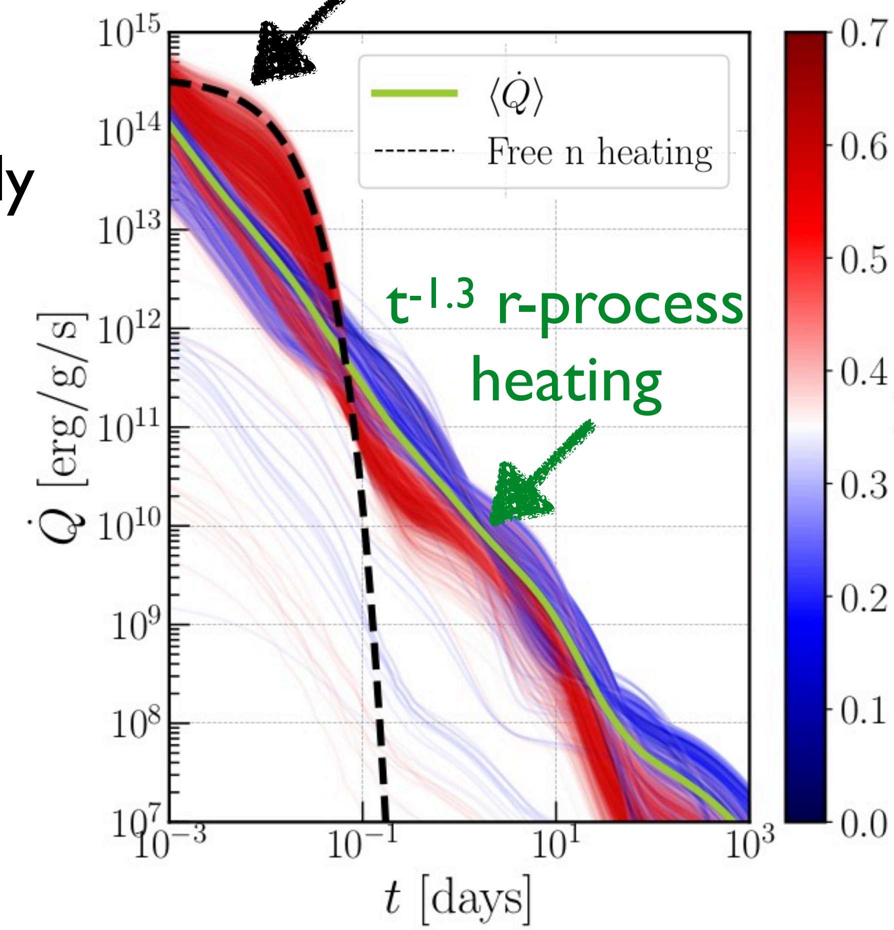
Combi & Siegel 2023a

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

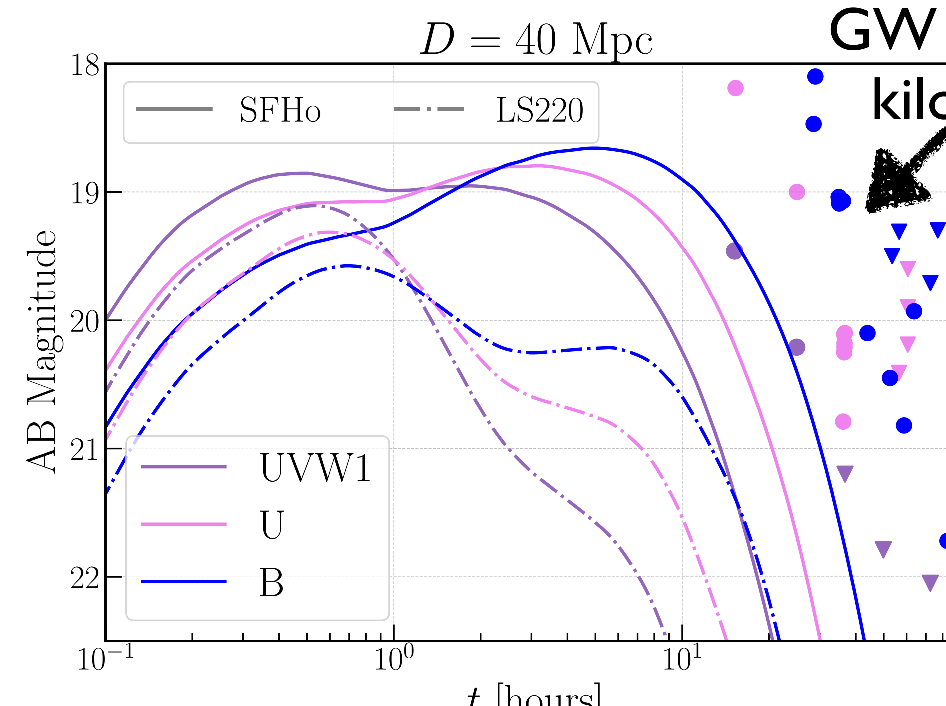
→ distinguish BNS vs. NS-BH

Nuclear heating, directly from tracers

free neutron decay

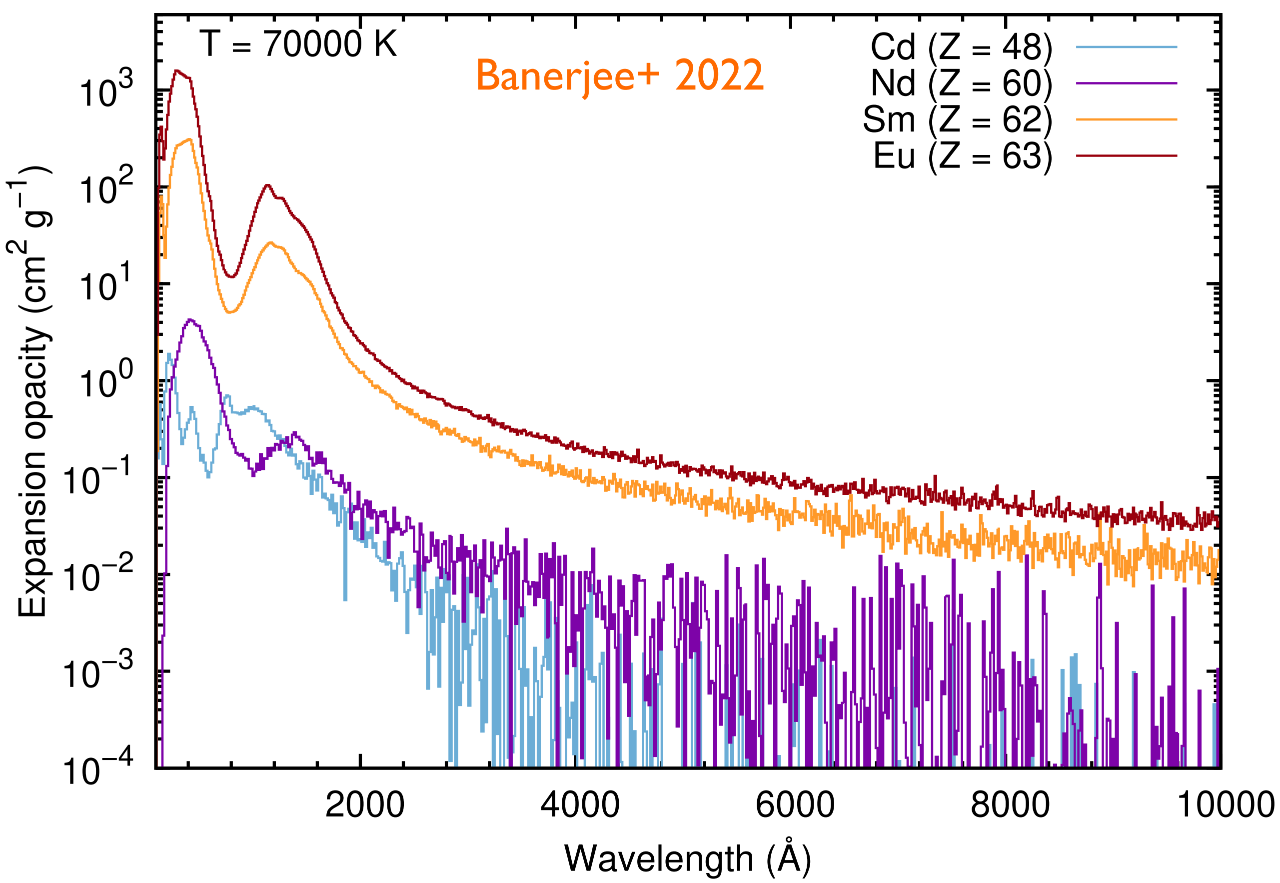


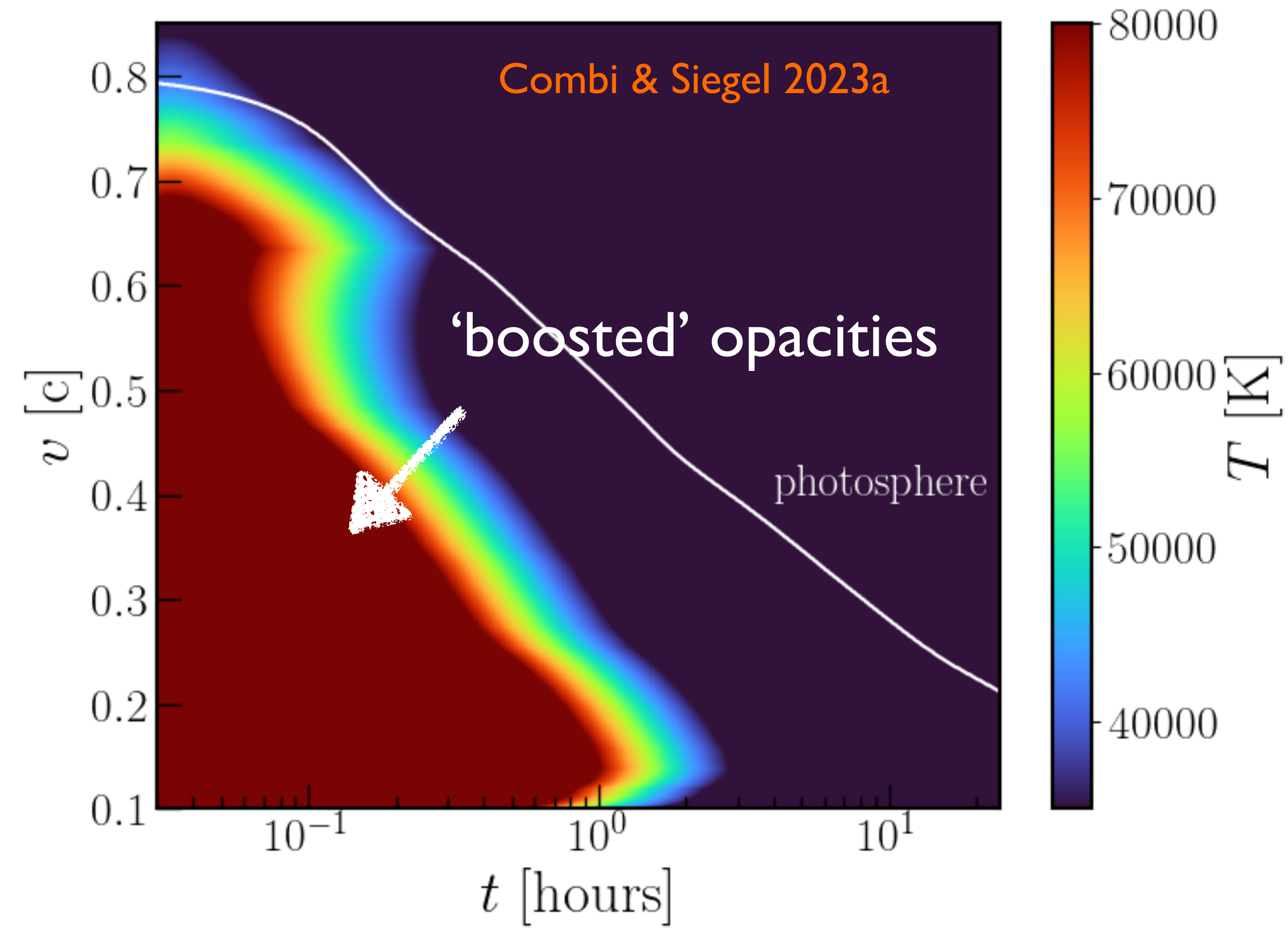
$t^{-1.3}$ r-process heating



GW170817 kilonova

Early UV/optical emission:
Threatened by highly ionized La at high temperatures?



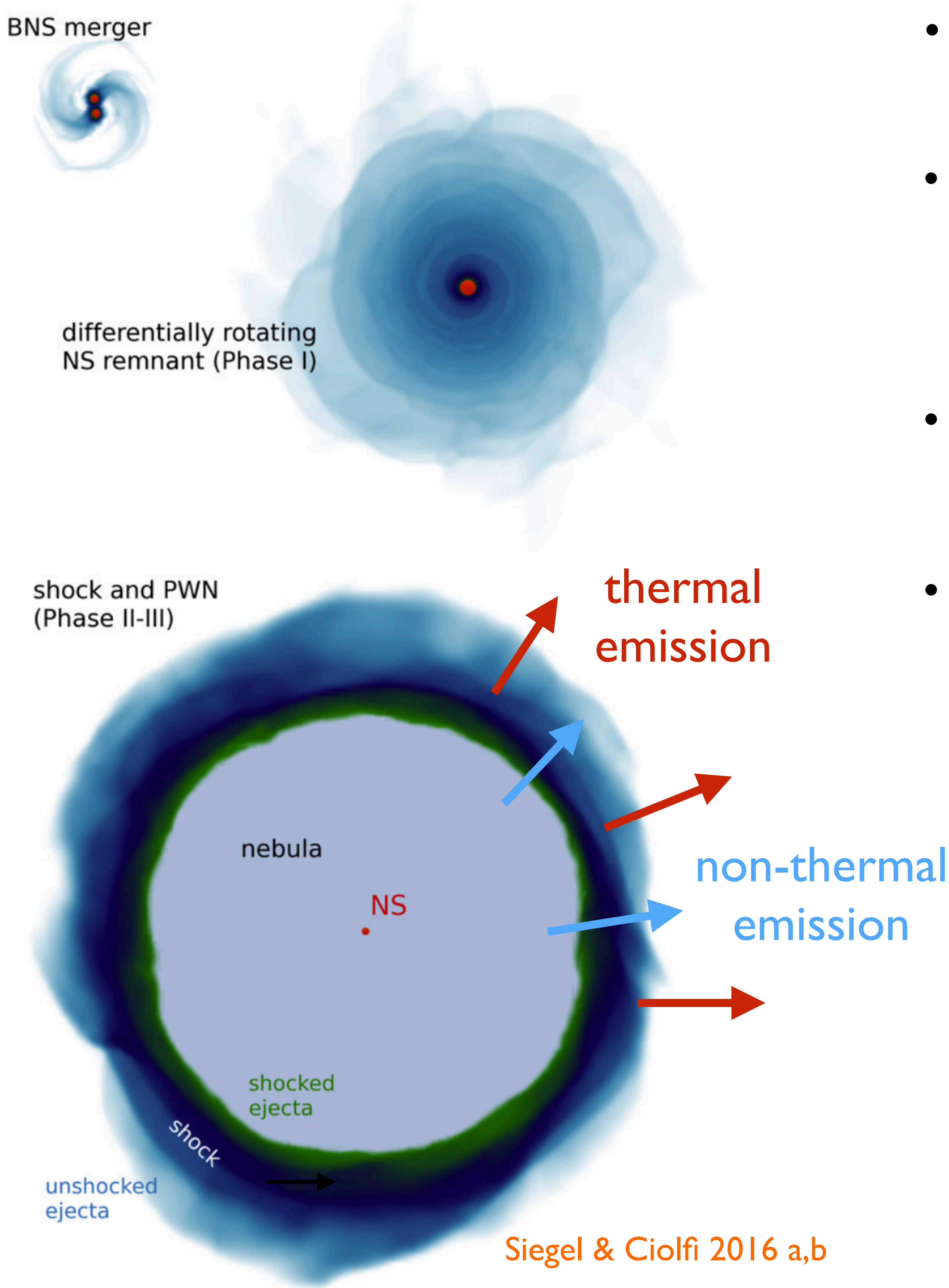


- highly ionized lanthanides at T ~ 7000 K boost opacities by orders of magnitude
- early kilonova photosphere, however, resides at high velocity (low-T) coordinates

⟶ Likely not a big concern for early UV/optical emission

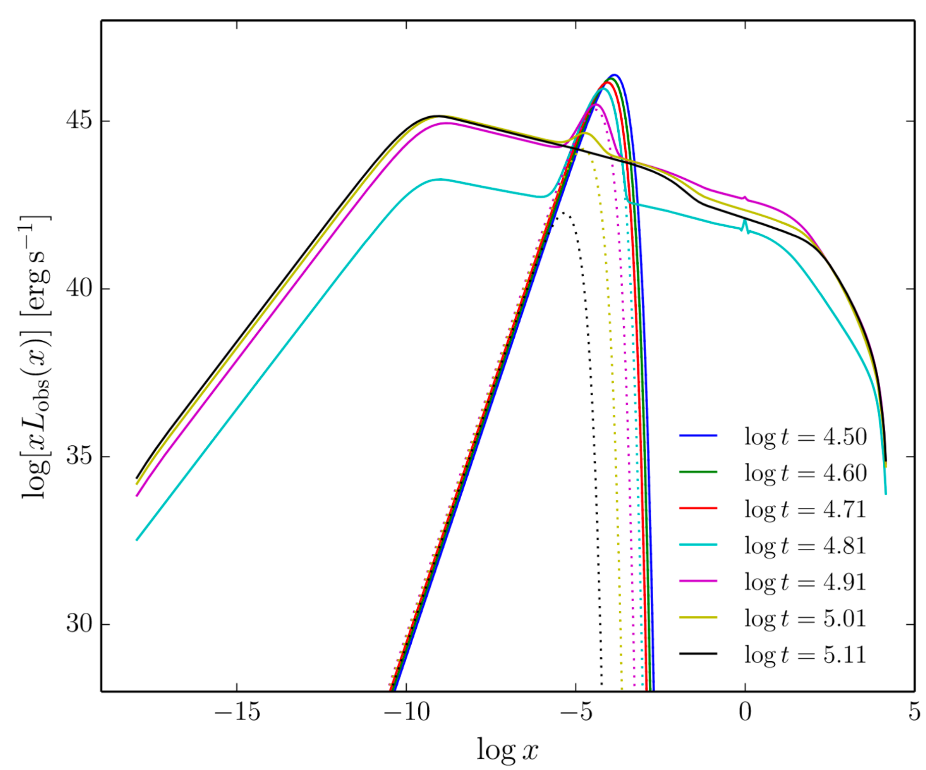
II.
Non-thermal EM from long-lived remnant NSs

EM emission from systems with long-lived NSs



Siegel & Ciolfi 2016 a,b

- E_{rot} ~ 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

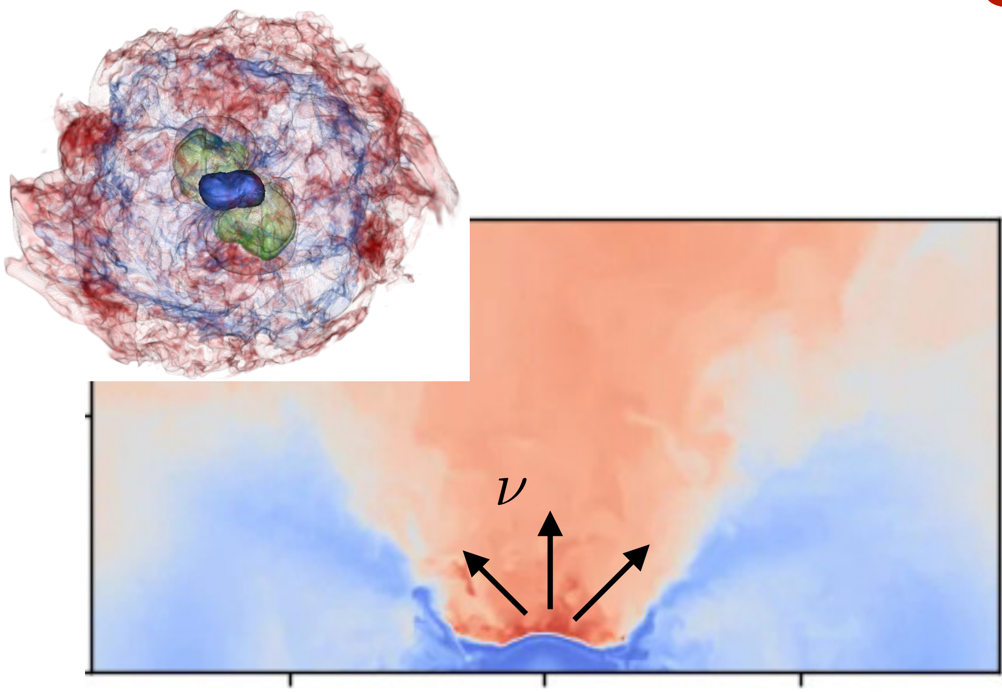


III.
Post-merger EM phenomena: Jets & kilonovae

Largely based on: Combi & Siegel 2023b

Post-merger: B-field amplification

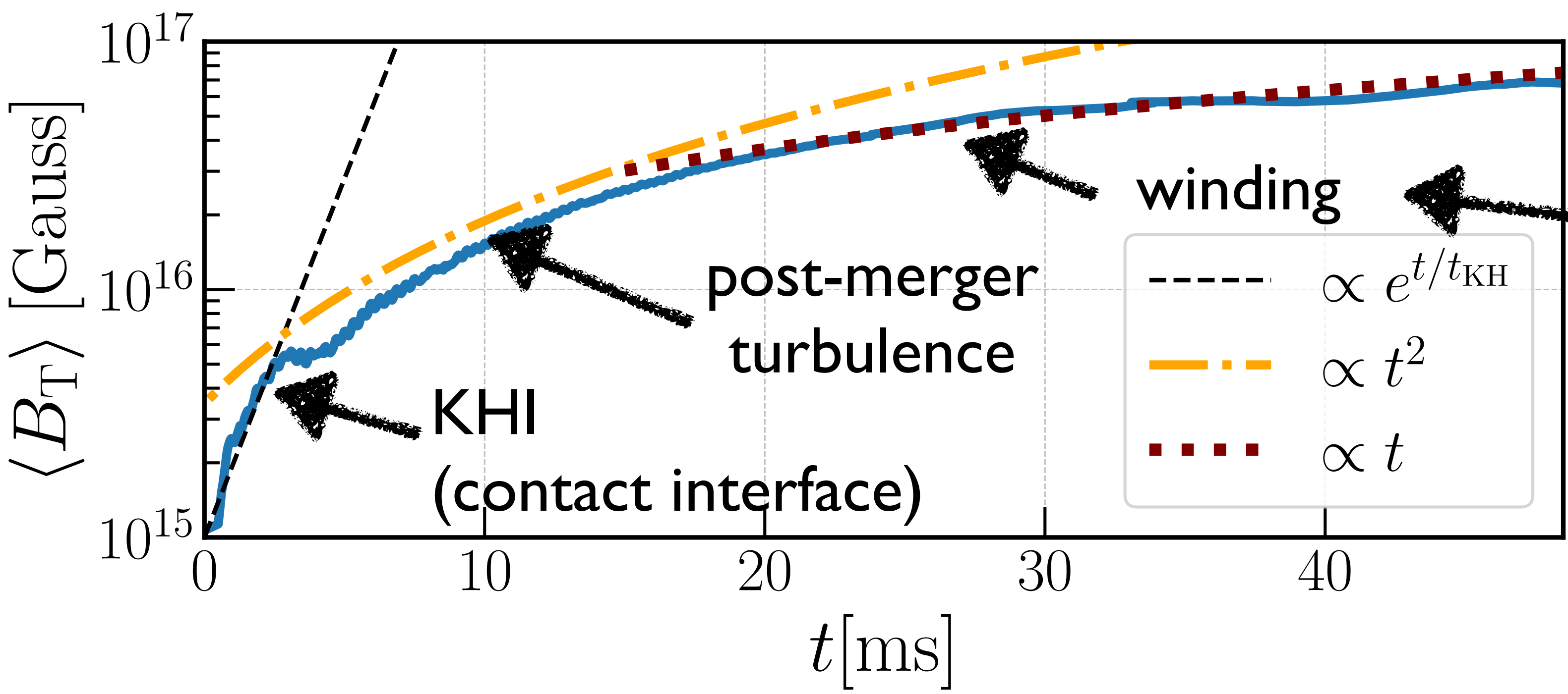
wind ejecta
(~10-100ms)



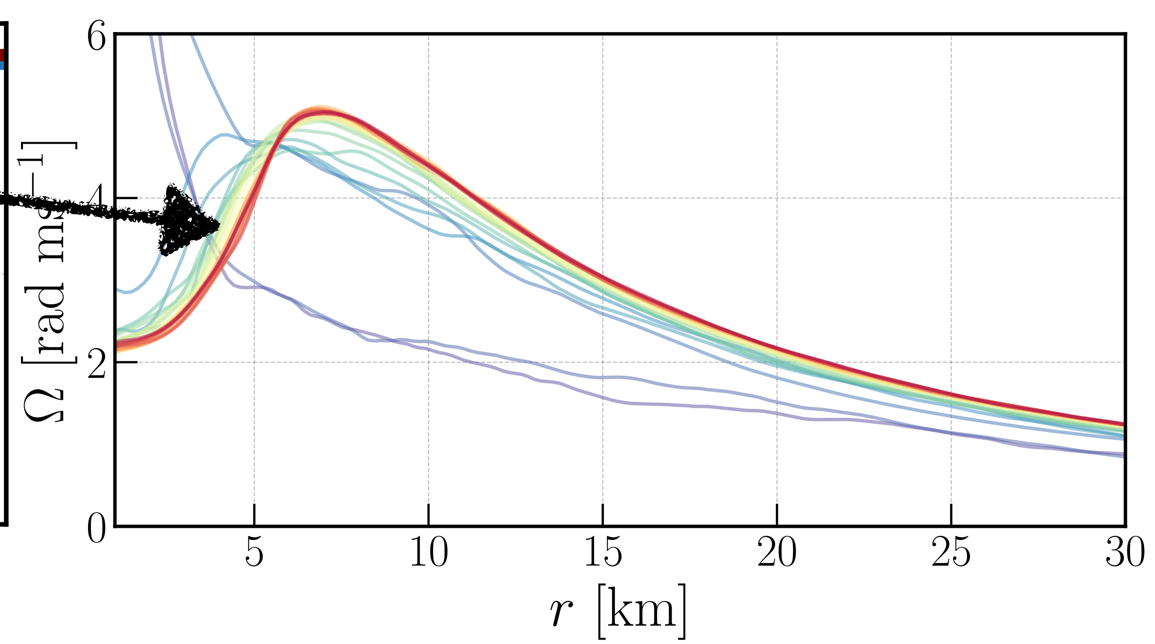
Magnetic field amplification during merger & within remnant:

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

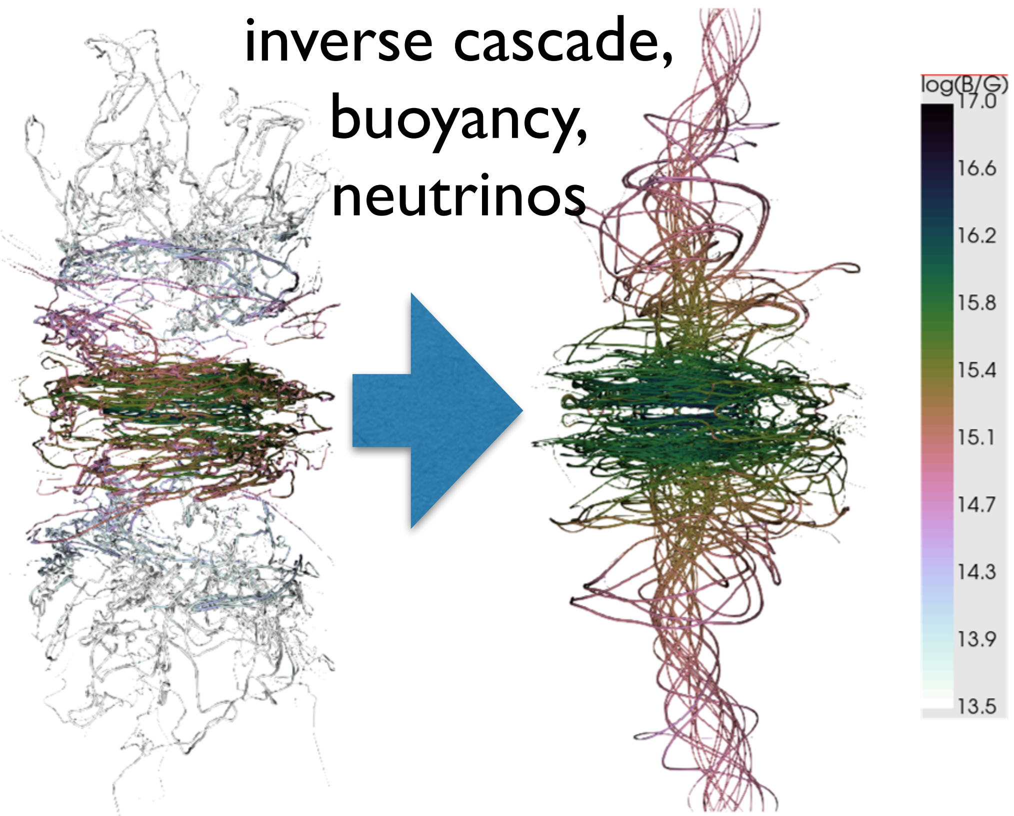
toroidal magnetic field amplification



angular rotation profile



Post-merger: B-field amplification



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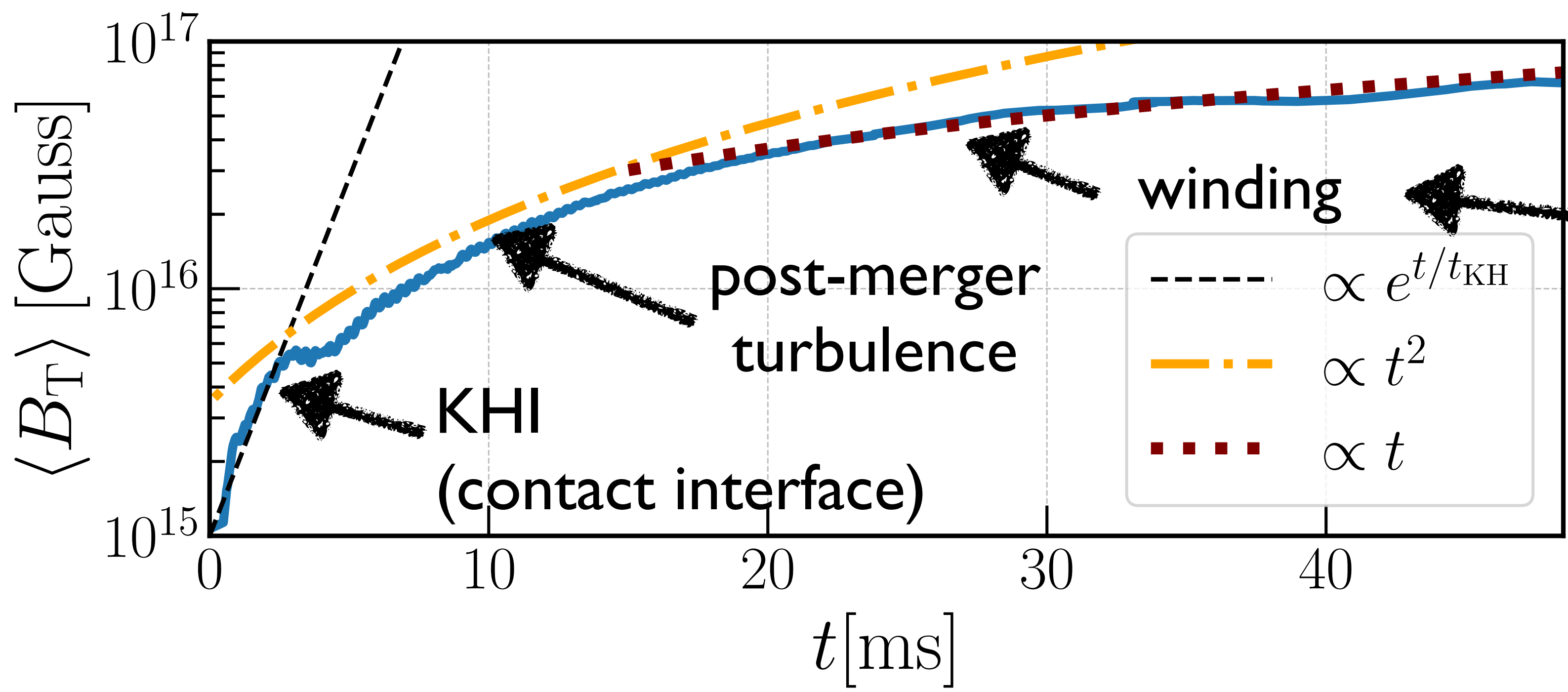
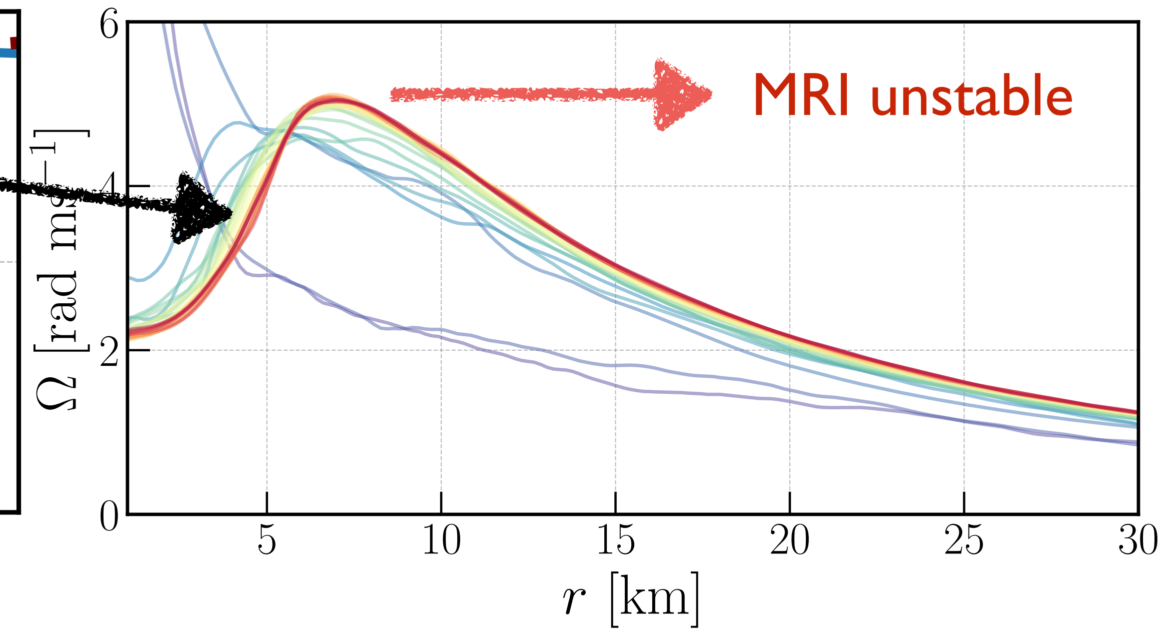
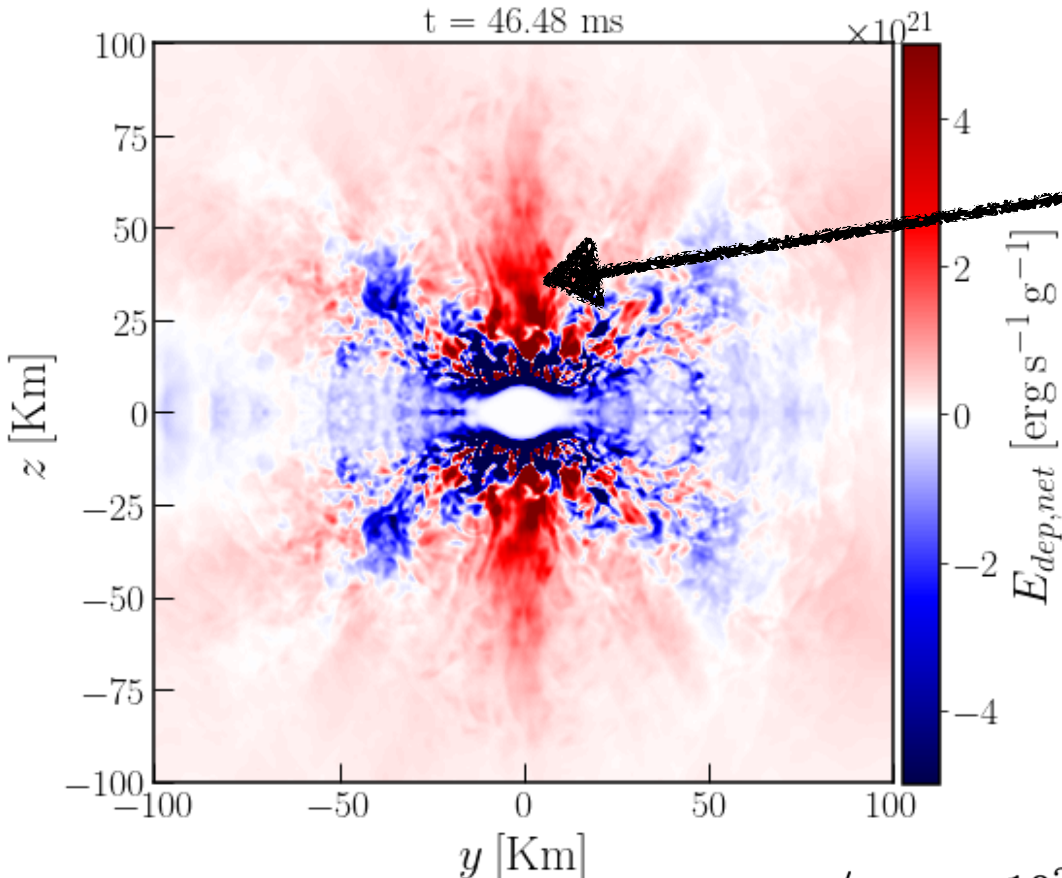


angular rotation profile

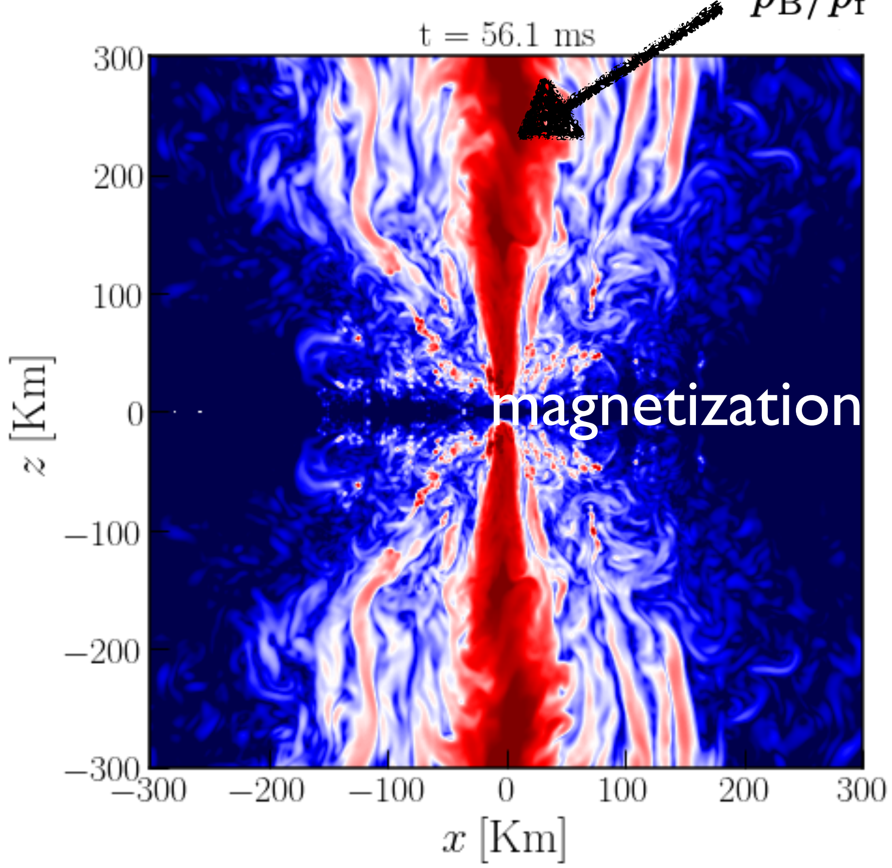


Magnetic tower with neutrinos—a 'jet' emerges



- Neutrino absorption in polar regions helps generating magnetic tower and 'stabilizing' jet structure
- Self-consistent formation of a 'jet' from a remnant NS

$p_B/p_f \approx 10^2$



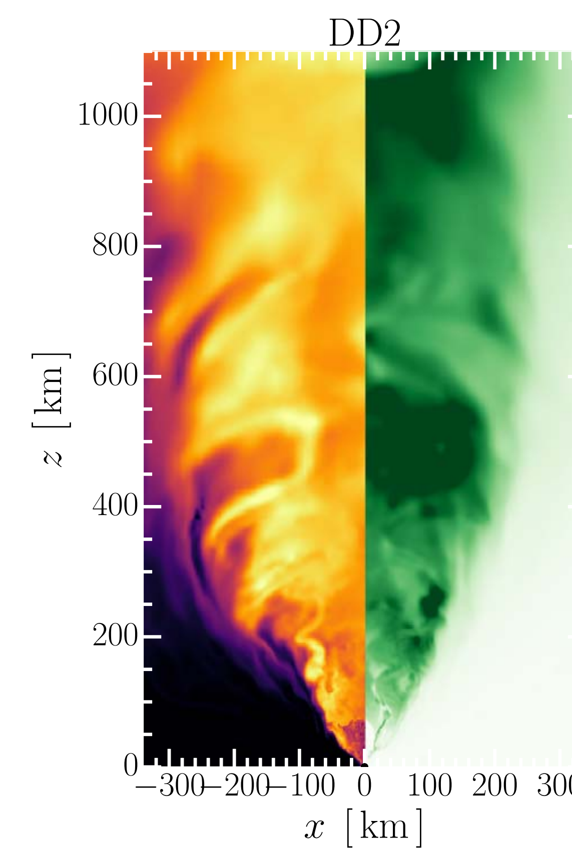
Mösta+ 2020, Curtis+ 2023

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

See Pablo Bosch's talk!

Most & Quataert 2023

(using α-dynamo)



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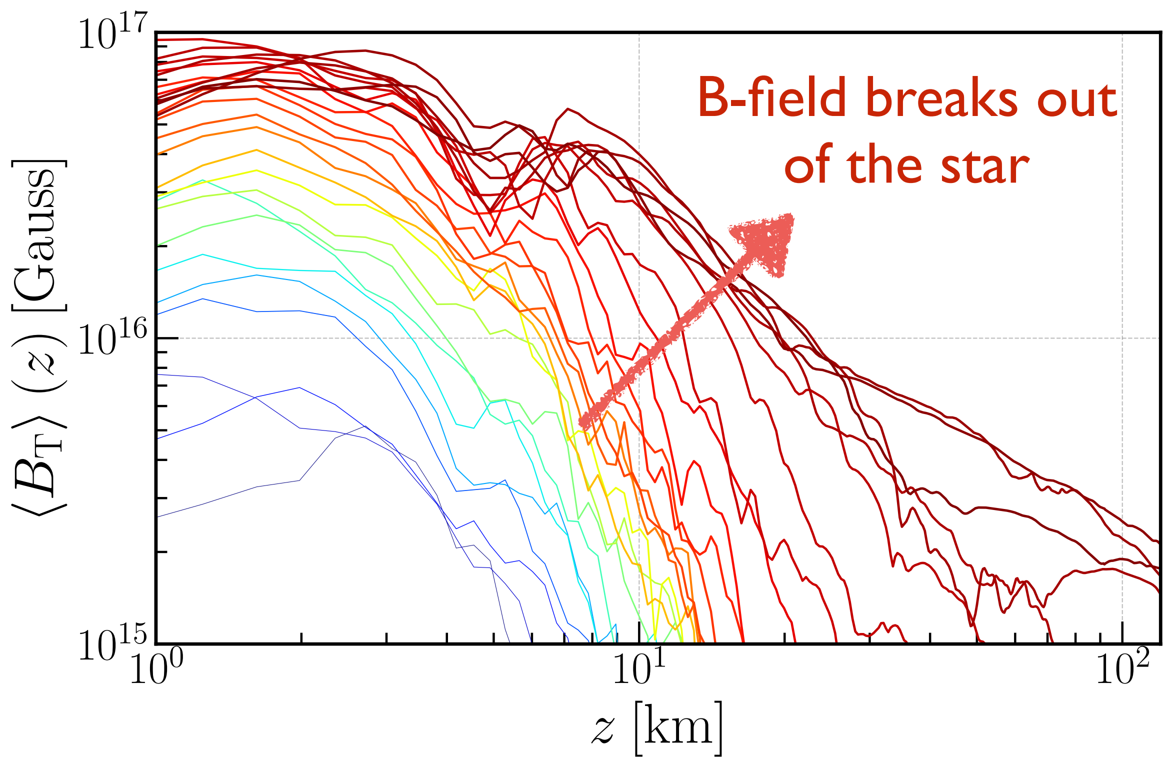

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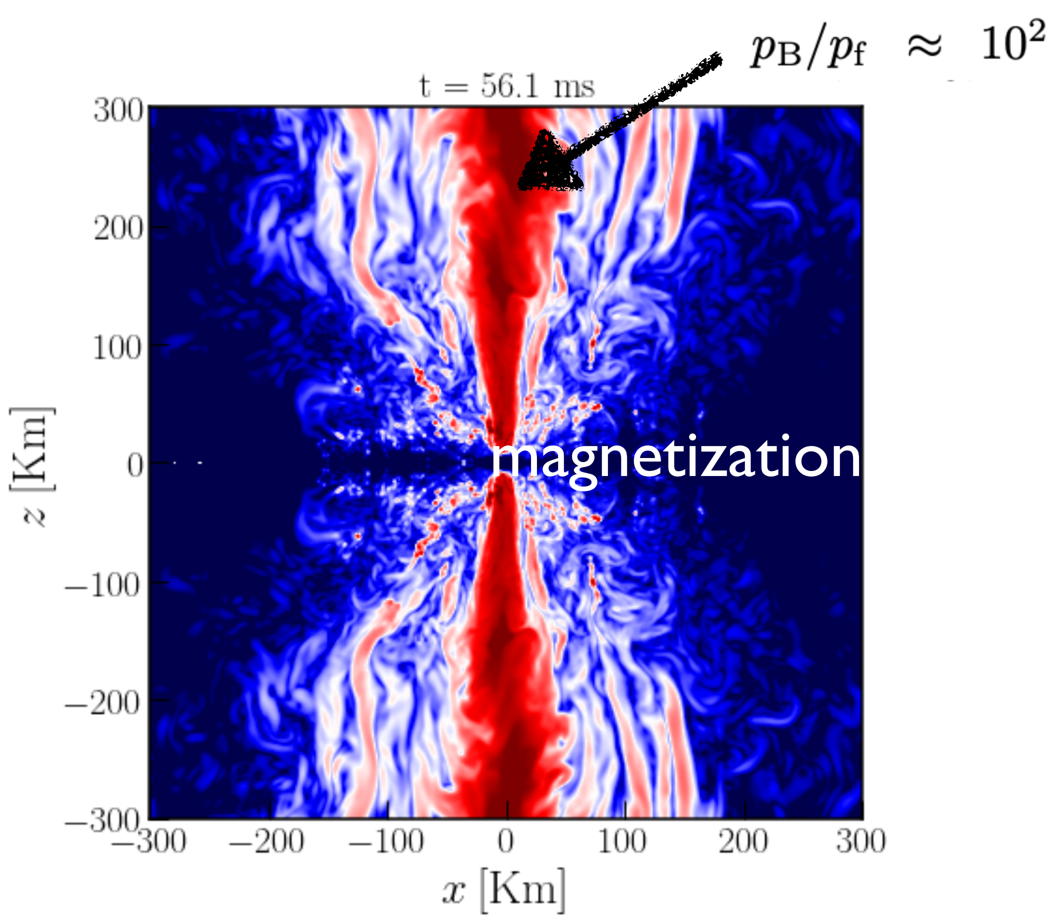

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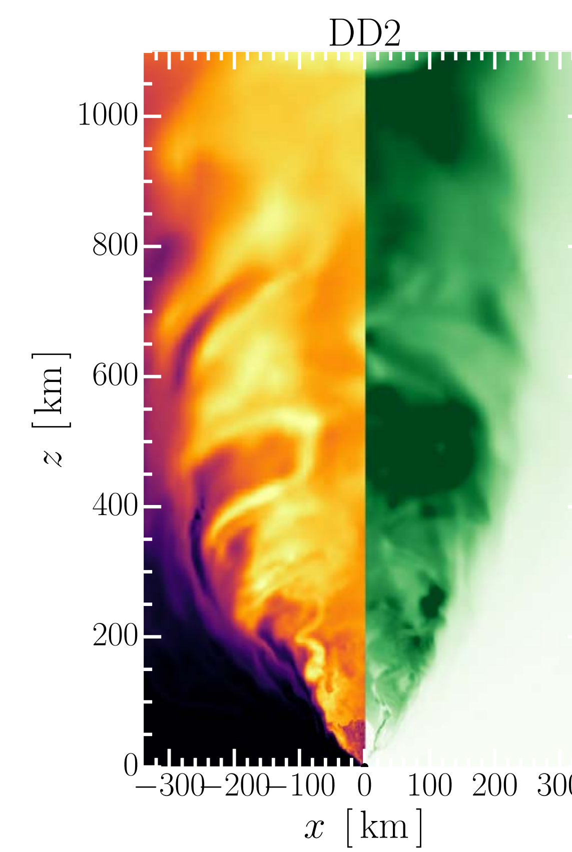

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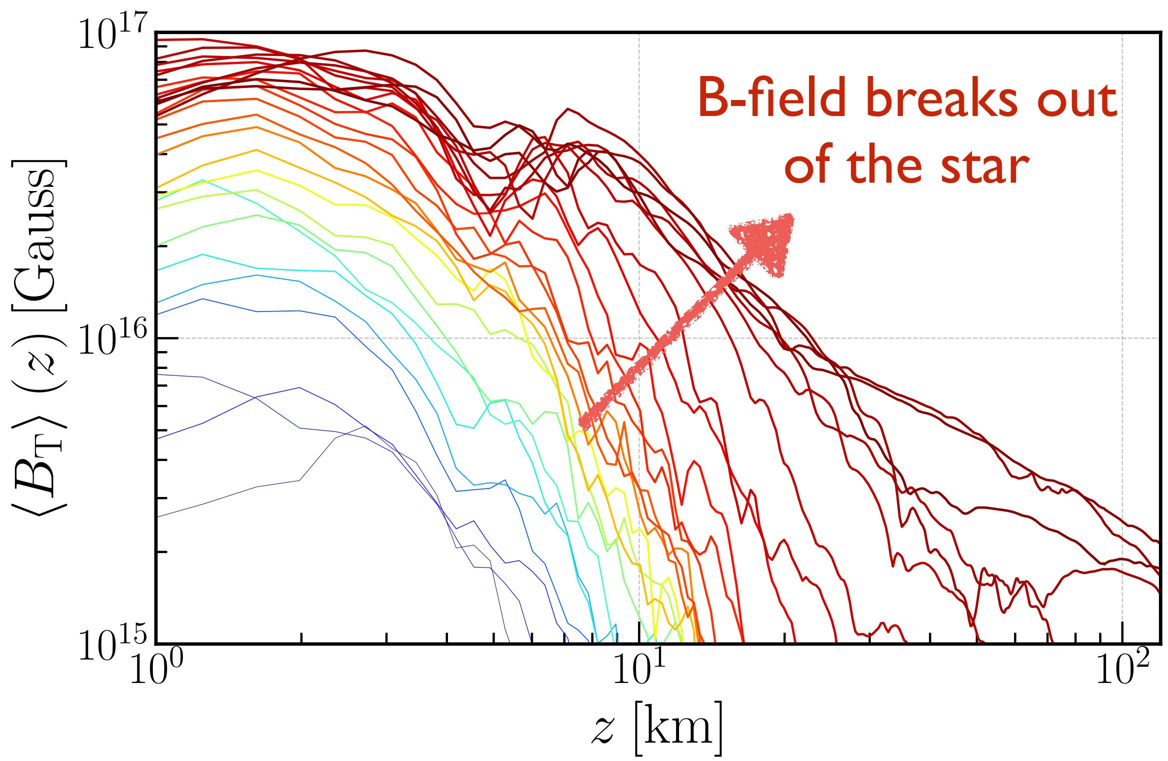

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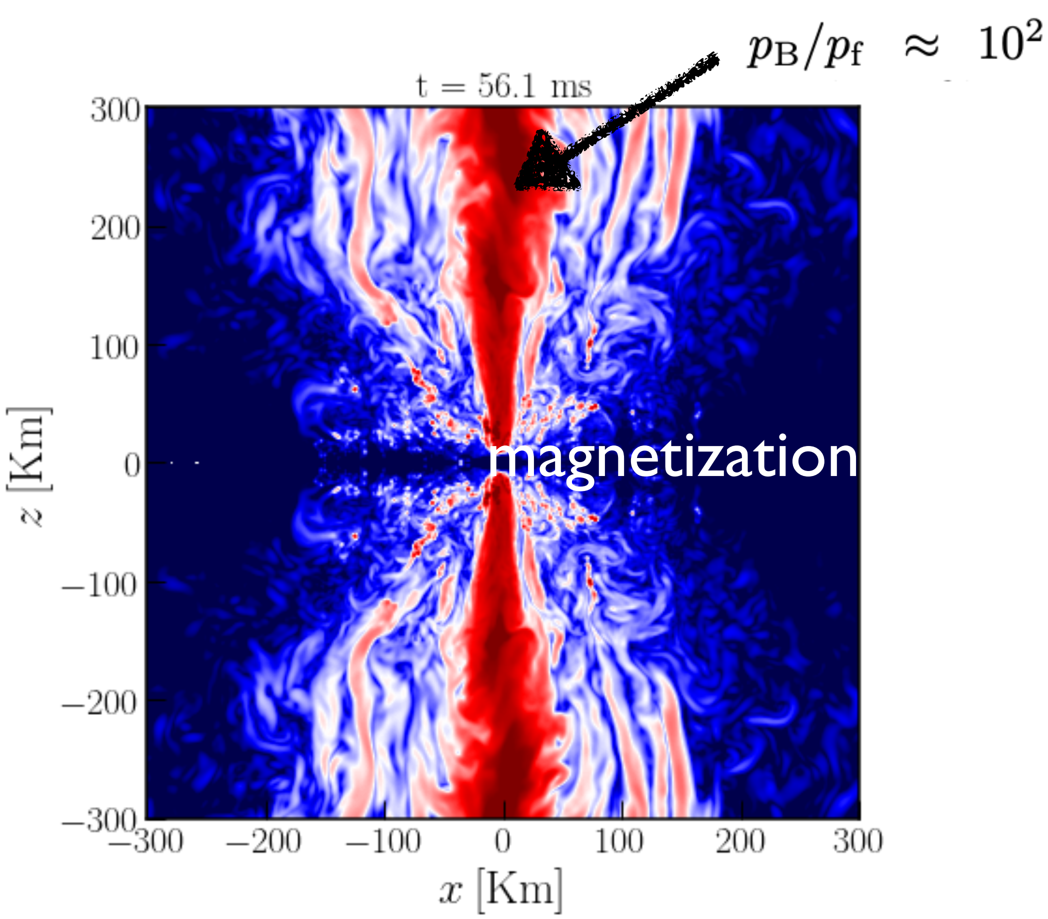

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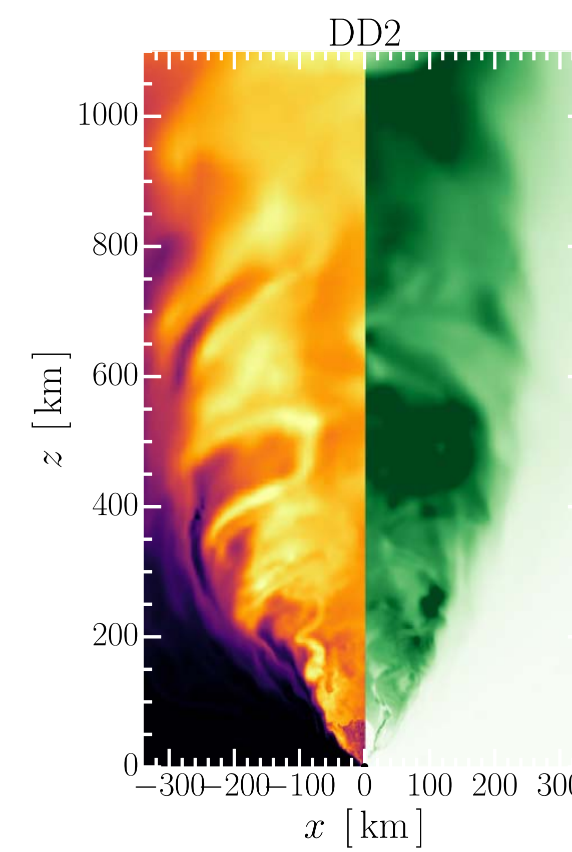

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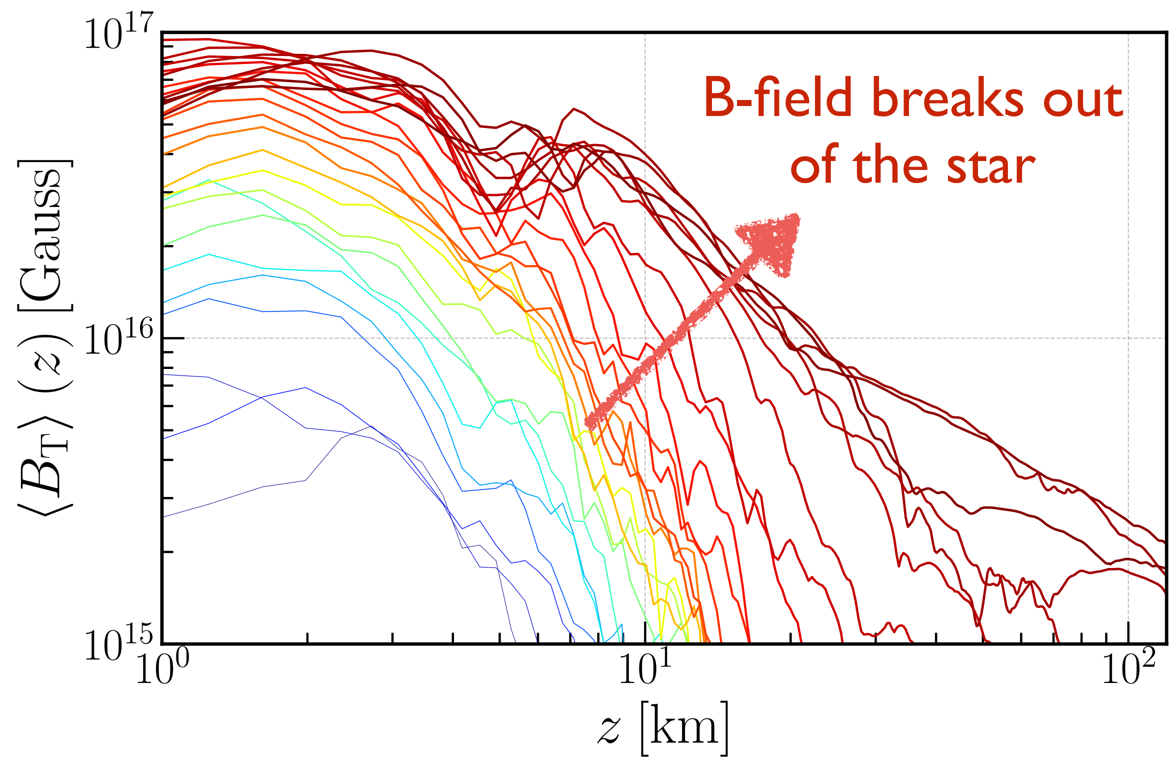

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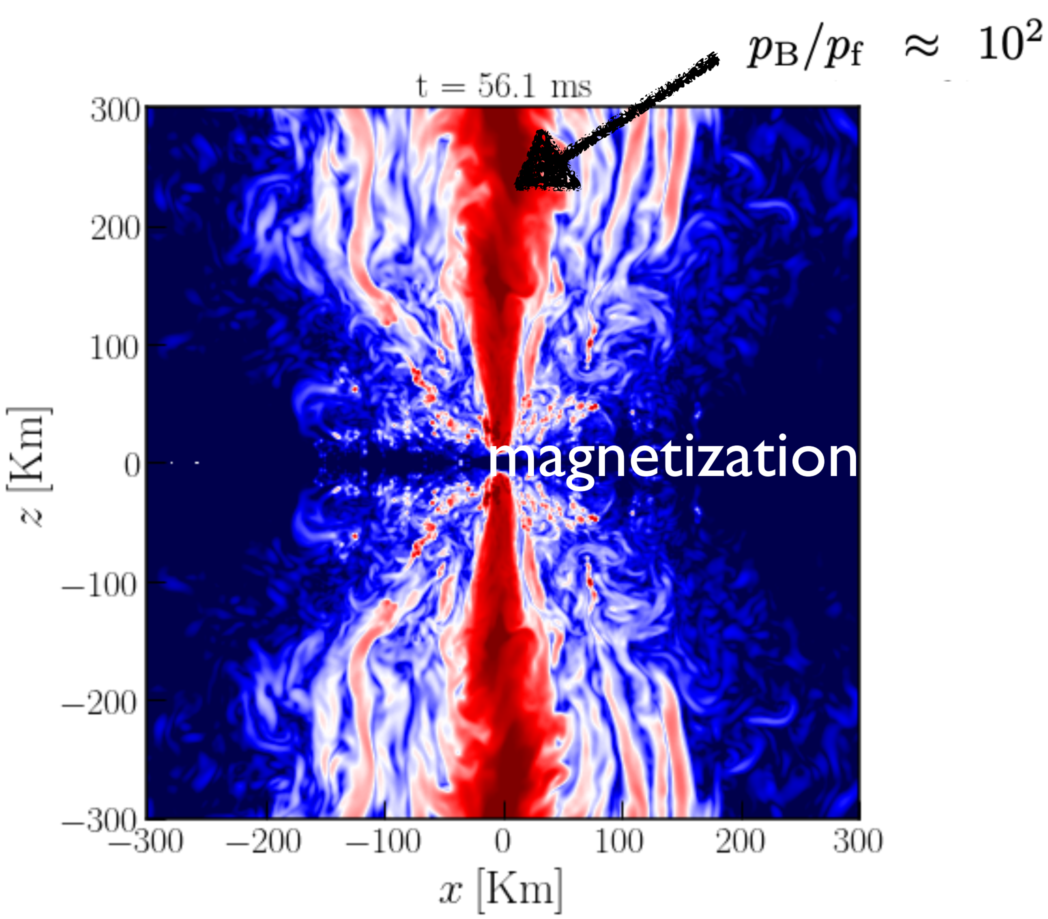
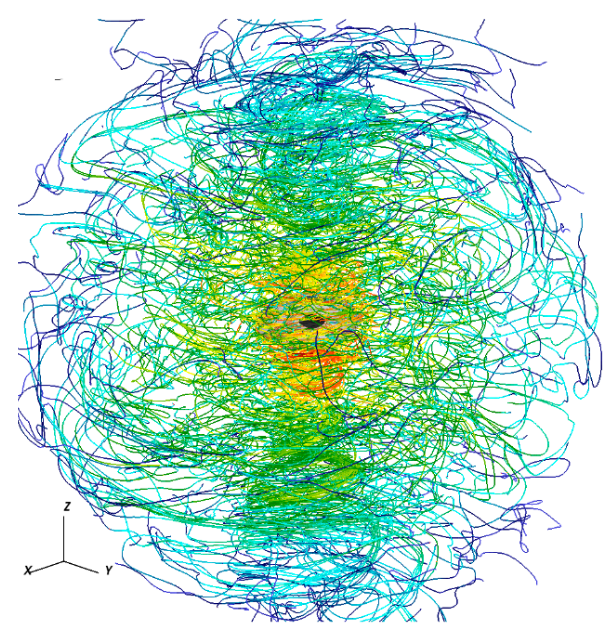


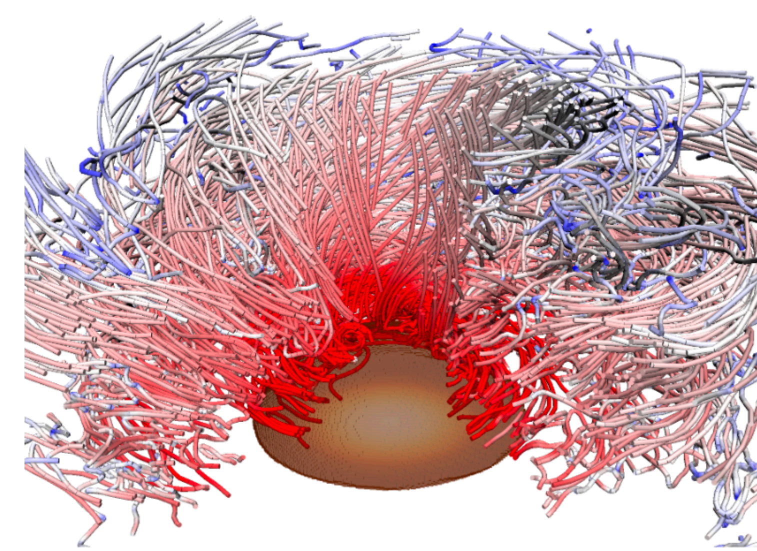
Aguilera-Miret+ 2023

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



Kiuchi+ 2023

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



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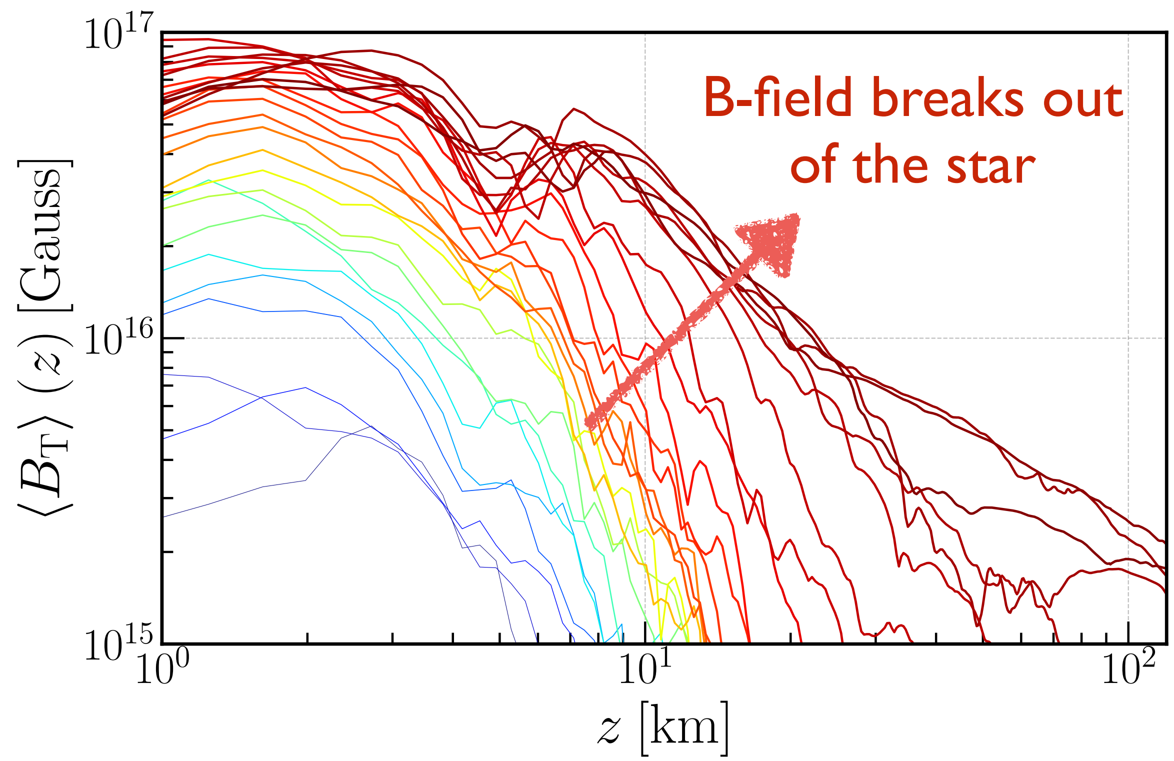

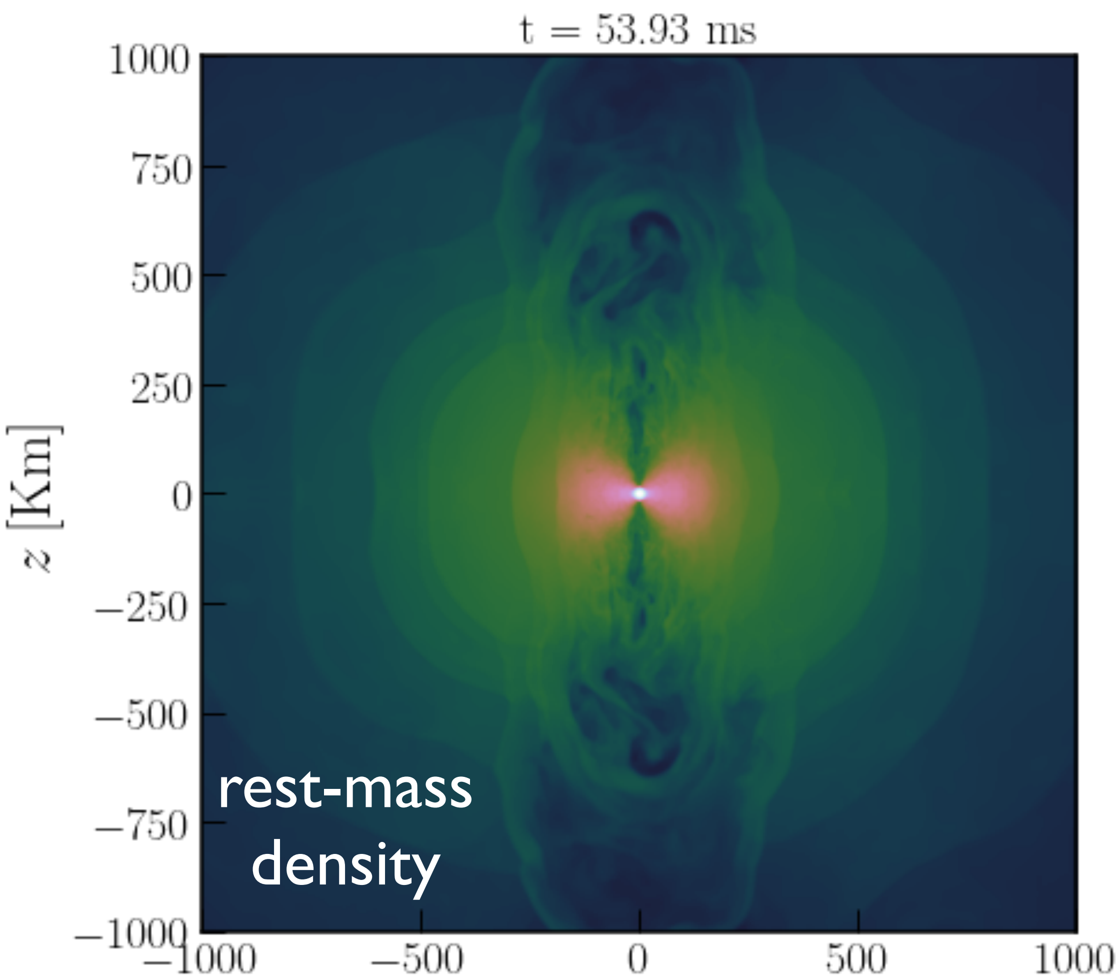

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- Self-consistent formation of a 'jet' from a remnant NS

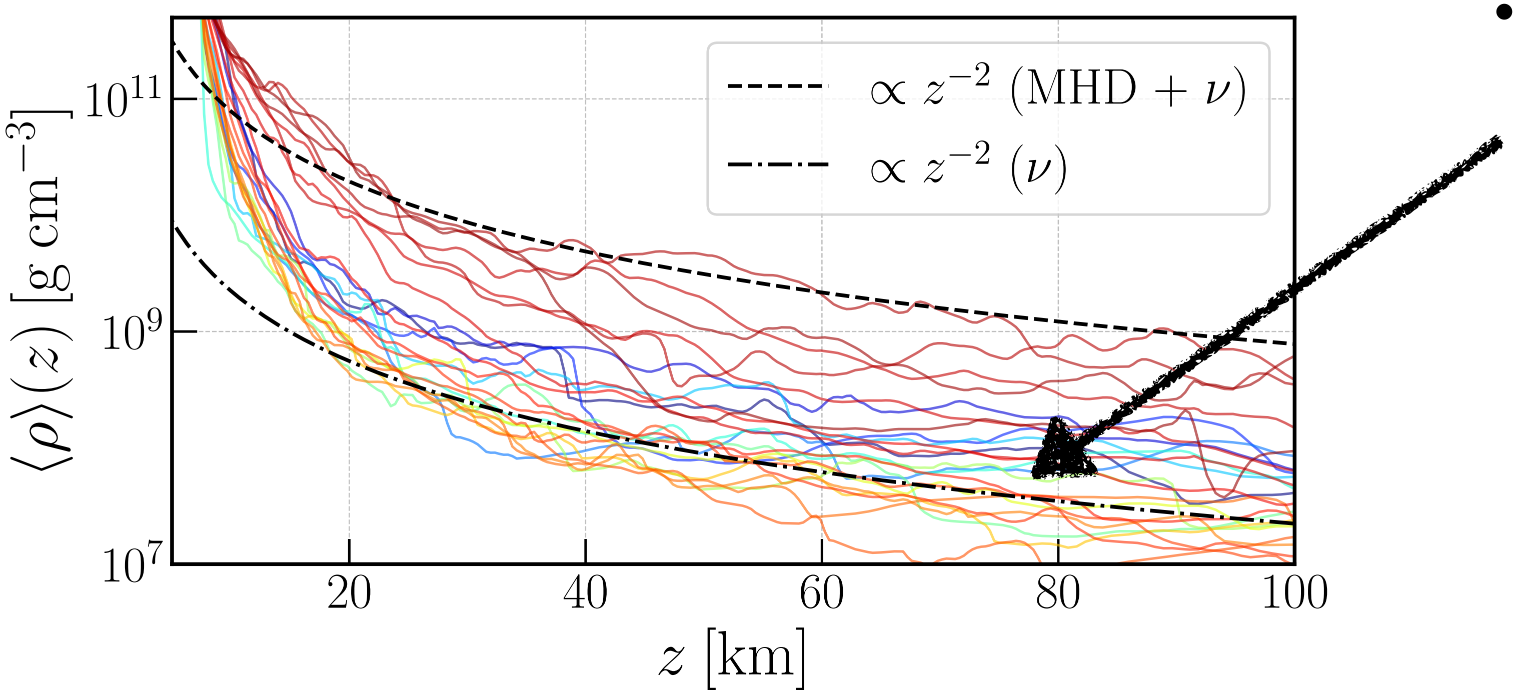
$$\sigma = L_{\rm EM}/\dot{M} \sim 5-10$$

- Maximum terminal Lorentz factor

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

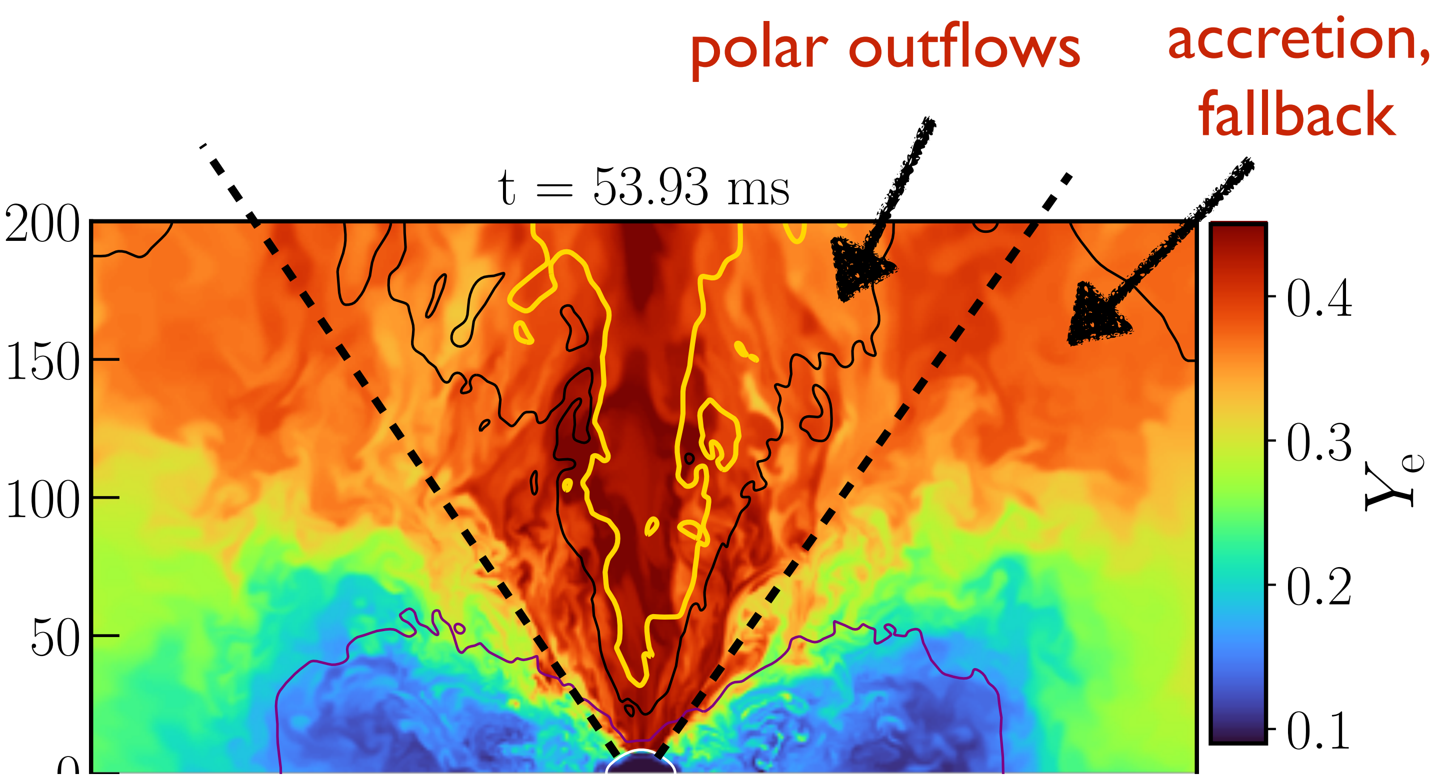
- Jet head propagates with v ~ 0.6c through dynamical ejecta and breaks out by ~50ms

Polar outflows

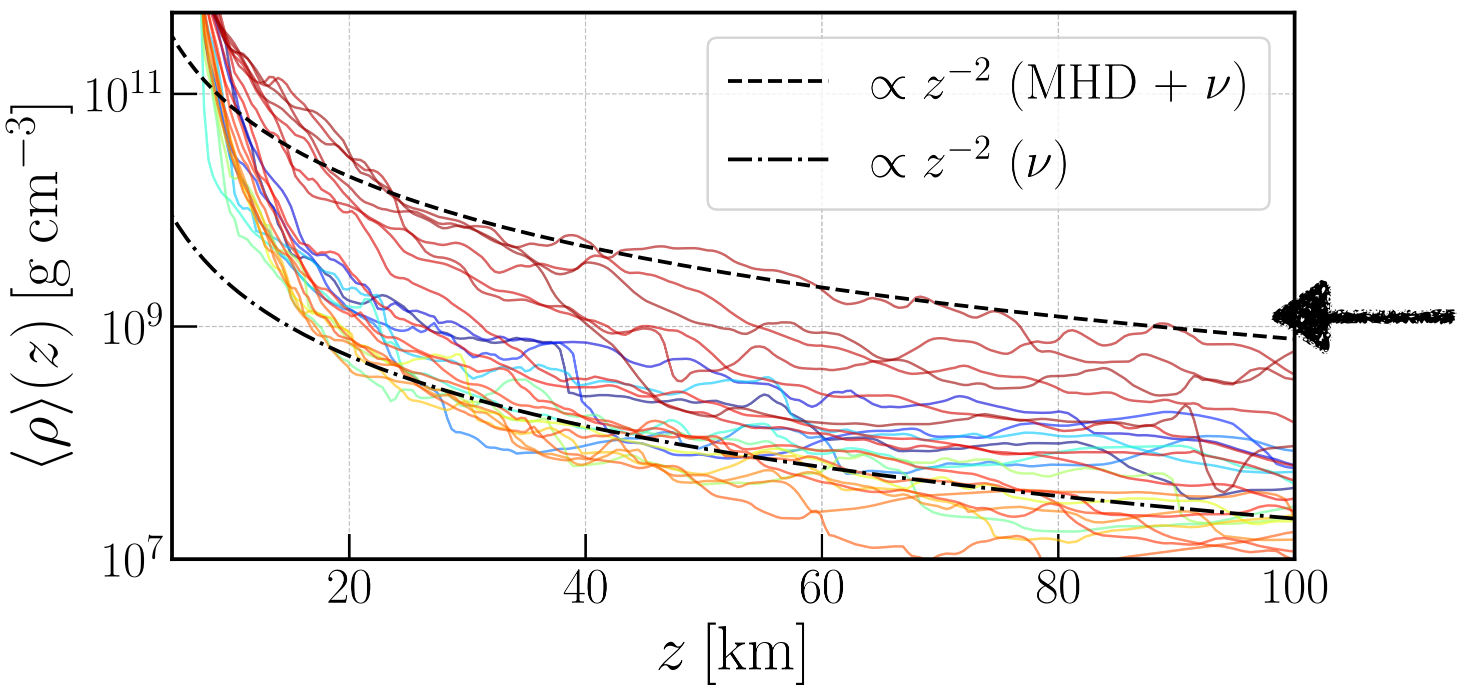


- Quasi-steady neutrino-driven wind (pre-breakout, t < 25-30 ms)

$\dot{M} \sim 10^{-3} M_{\odot}/\mathrm{s}, \quad L_{\nu} \sim \text{few} \times 10^{52} \mathrm{erg/s}$



Polar outflows



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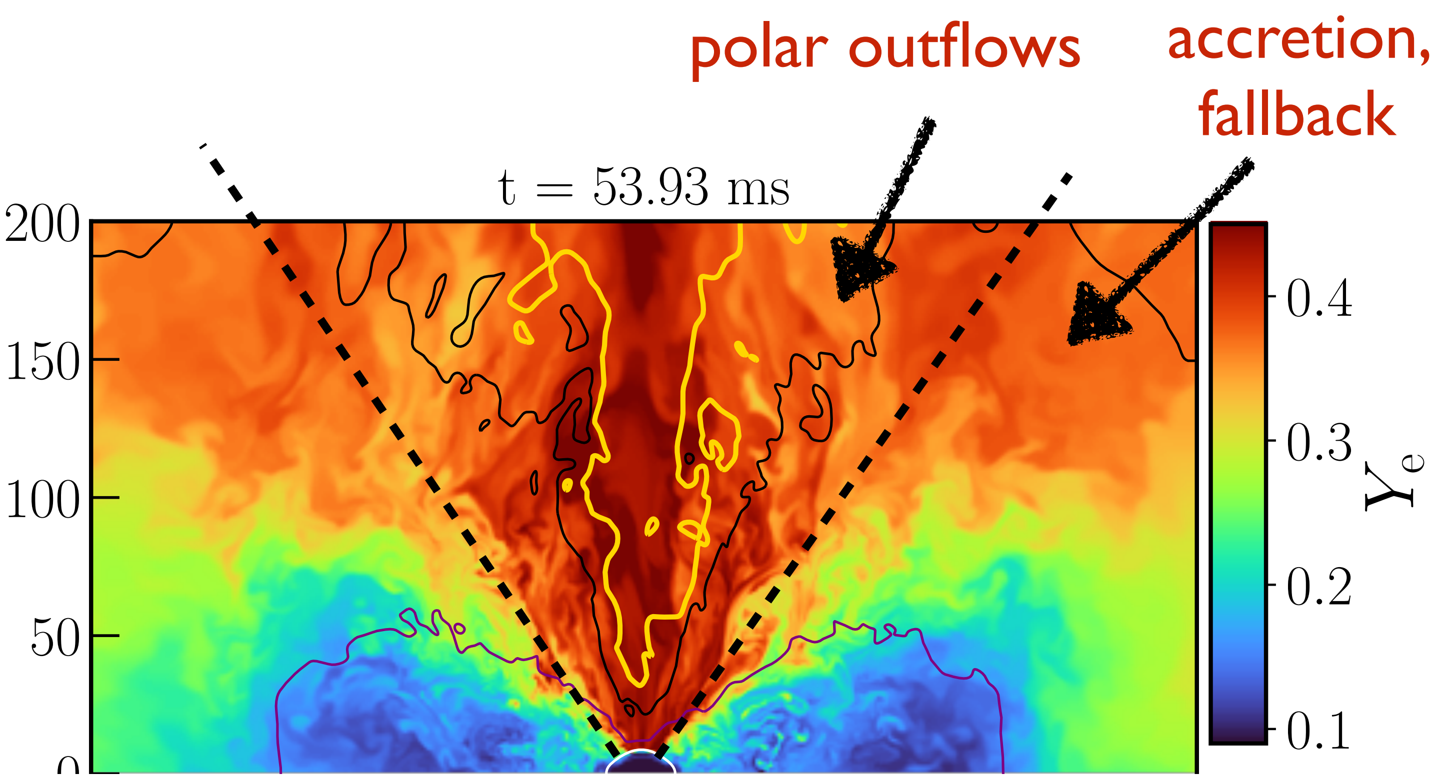
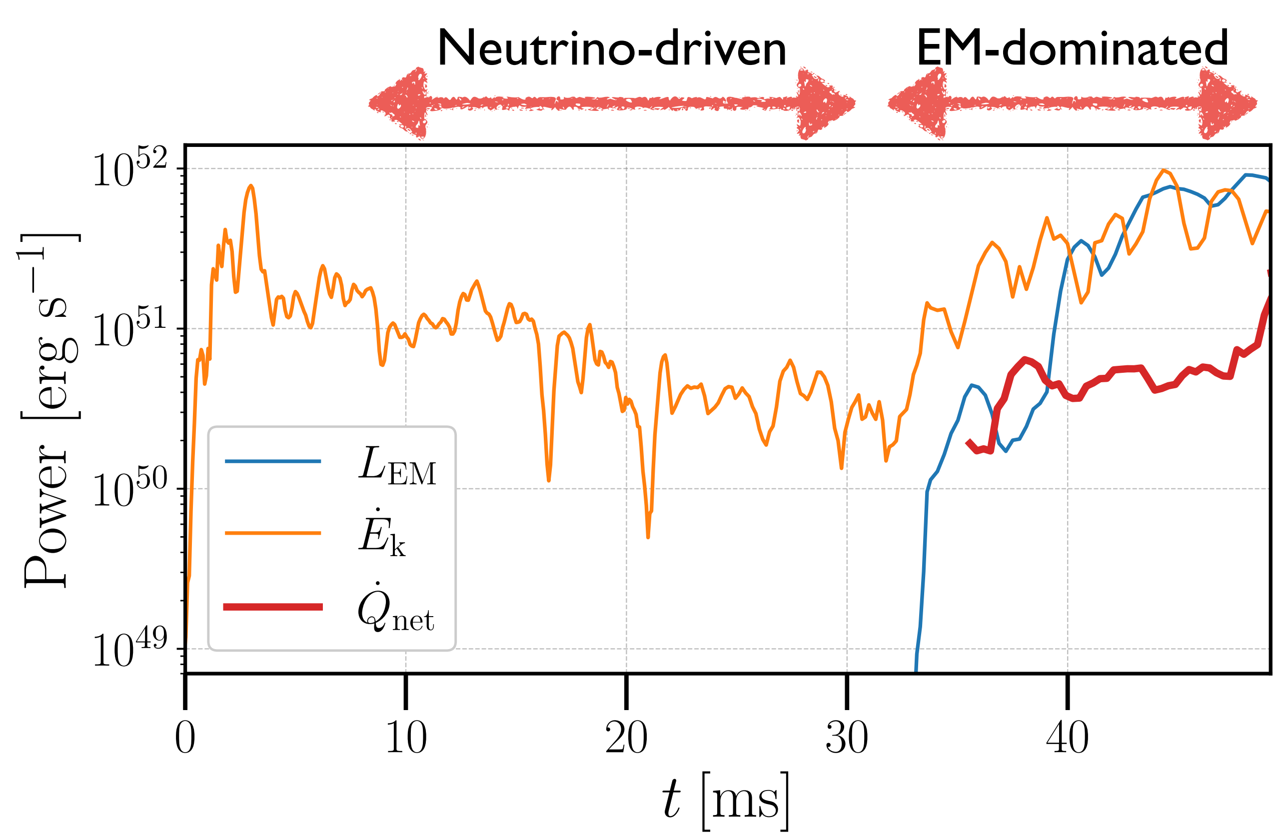
- Quasi-steady MHD + neutrino driven wind (post-breakout, t > 35 ms)

  $\dot{M} \sim 10^{-2} M_\odot/\mathrm{s}, \quad \sigma = L_{\rm EM}/\dot{M} \sim 0.1$

  flow reaches expected velocity $\langle u \rangle \approx c\sigma^{1/3}$

Properties broadly in agreement with 1D wind solutions of Metzger+ 2018





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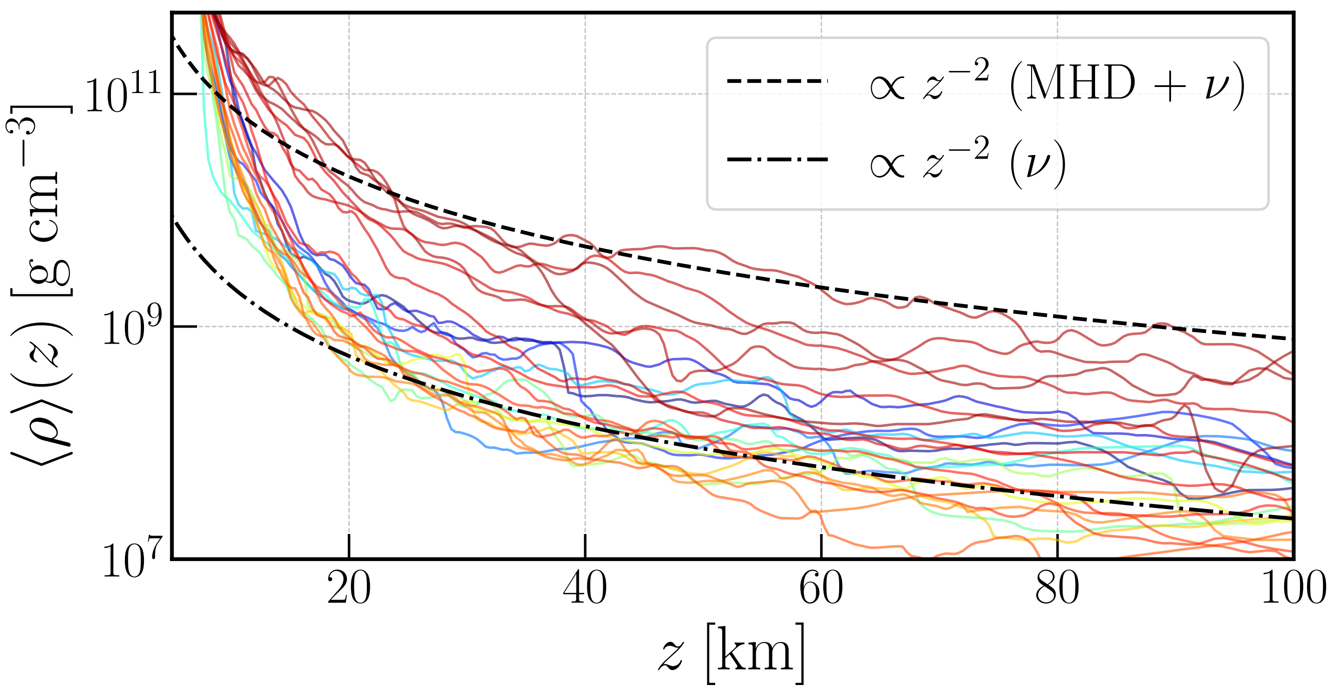

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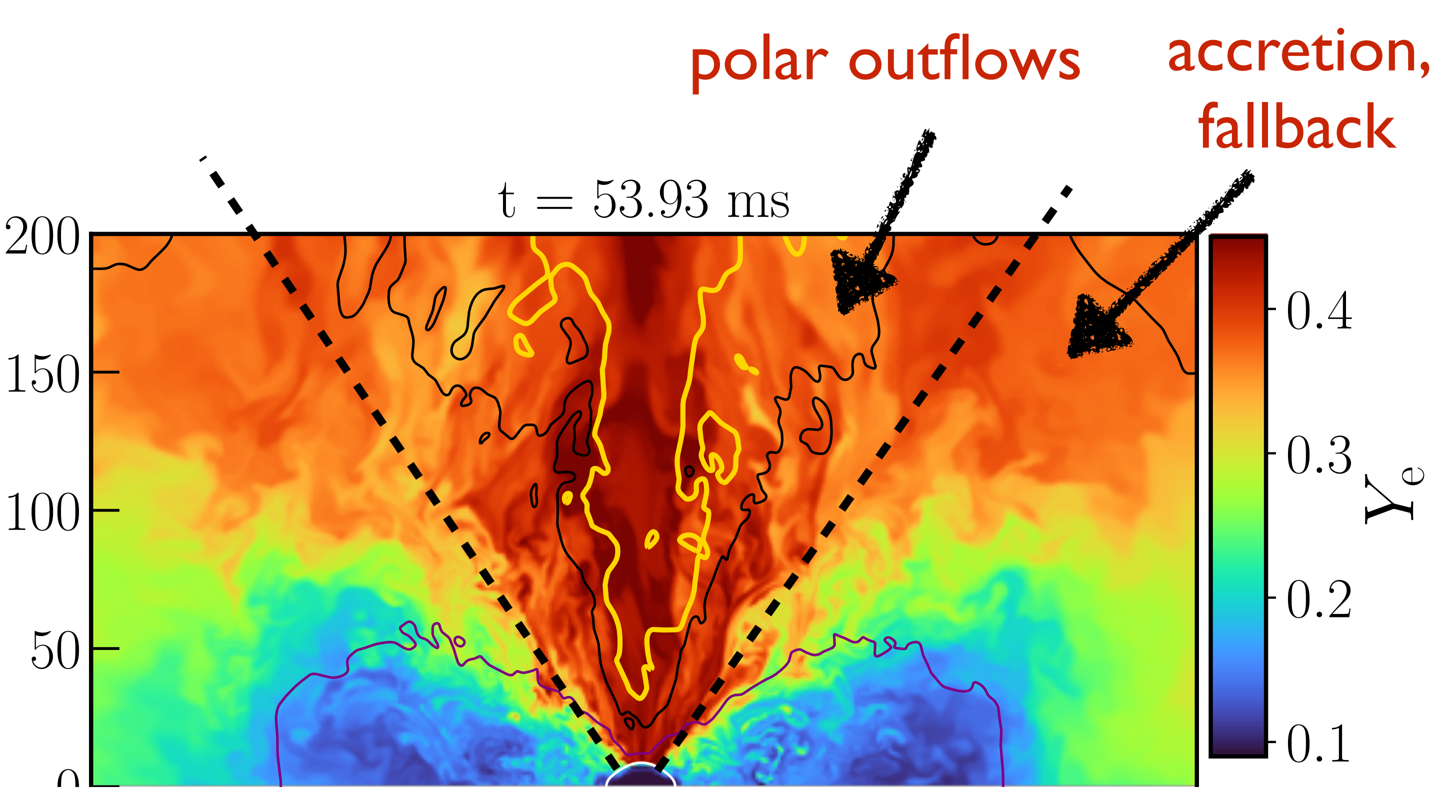
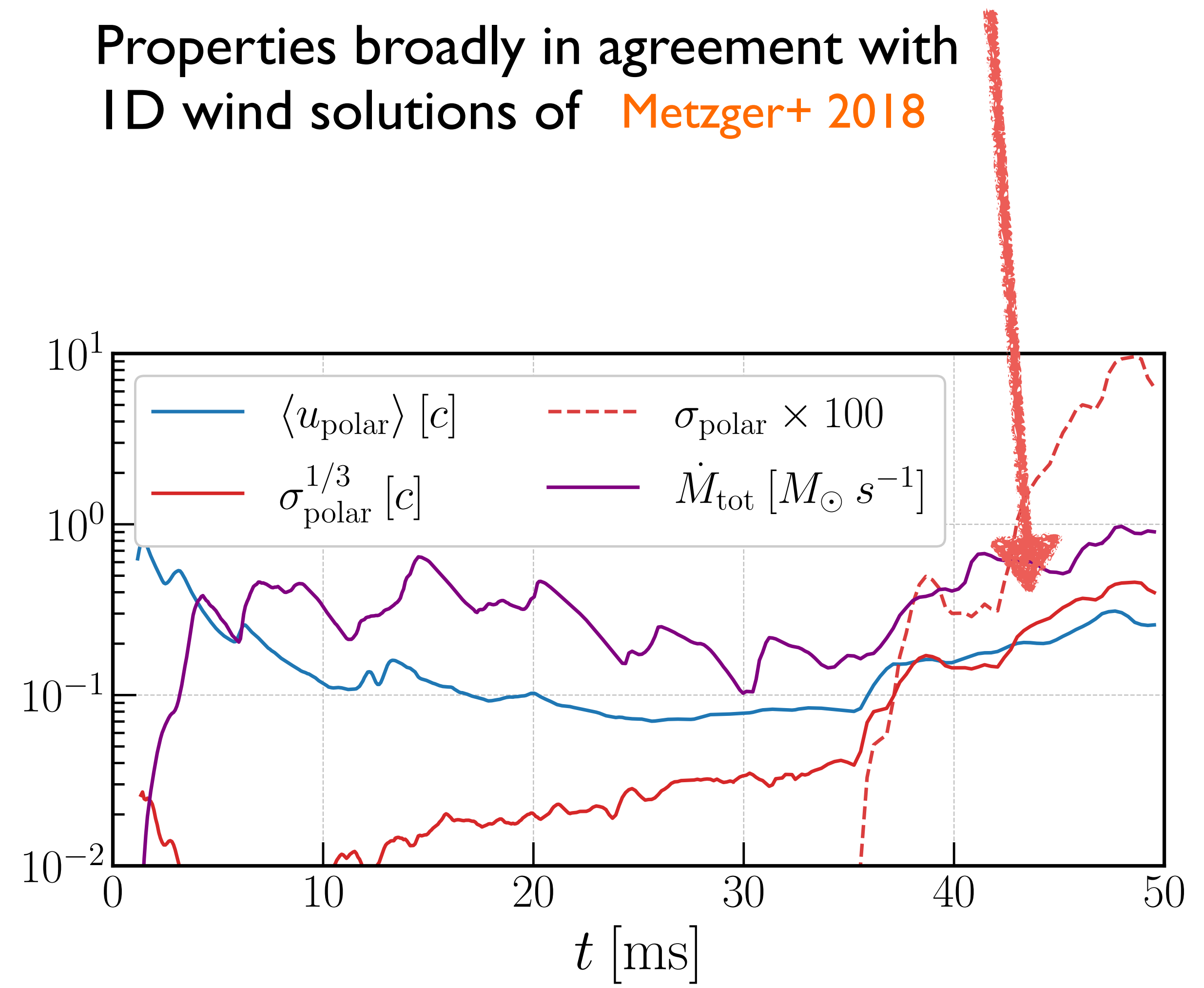
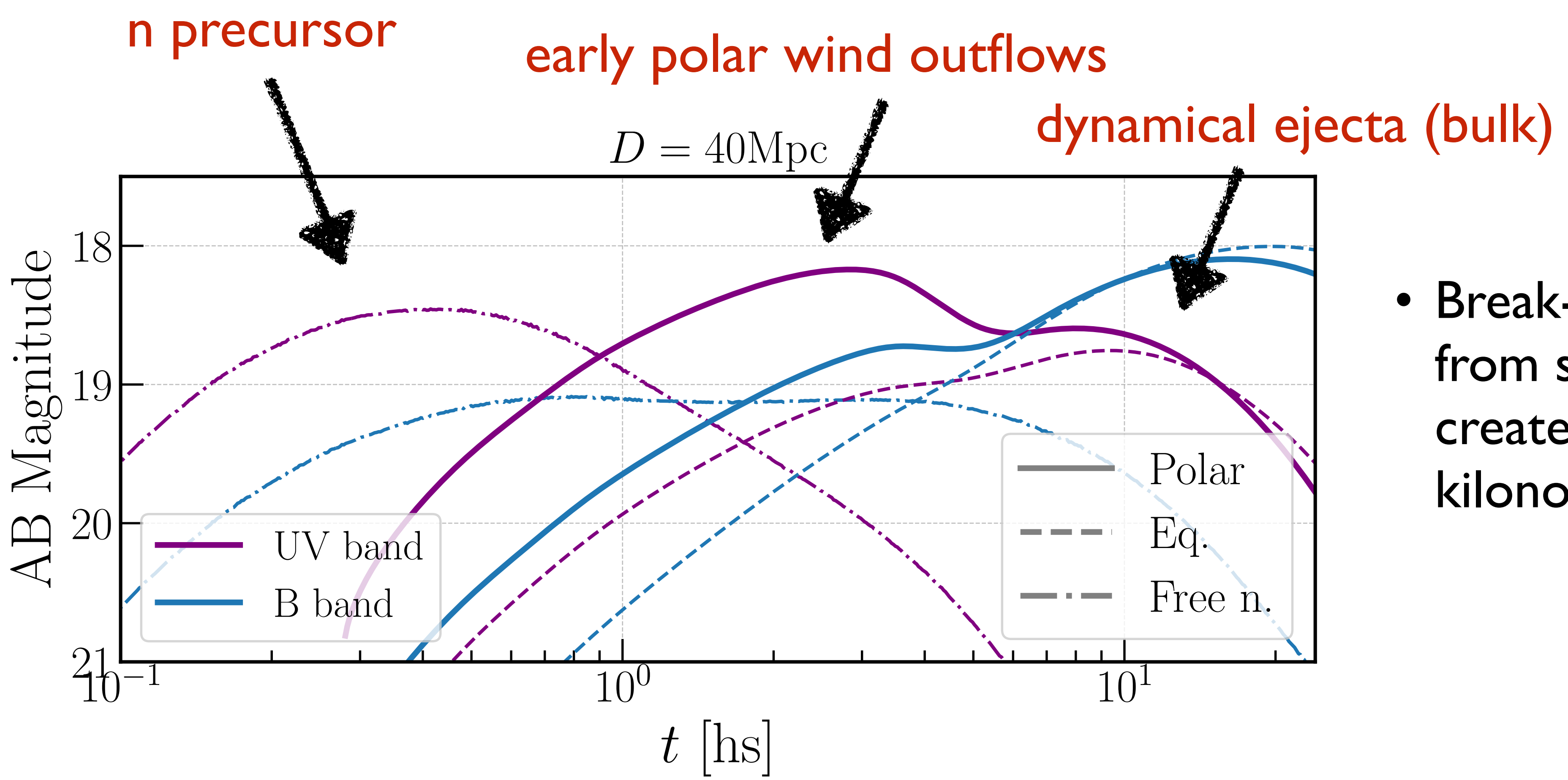
  flow reaches expected velocity $\langle u \rangle \approx c\sigma^{1/3}$

  Properties broadly in agreement with 1D wind solutions of Metzger+ 2018

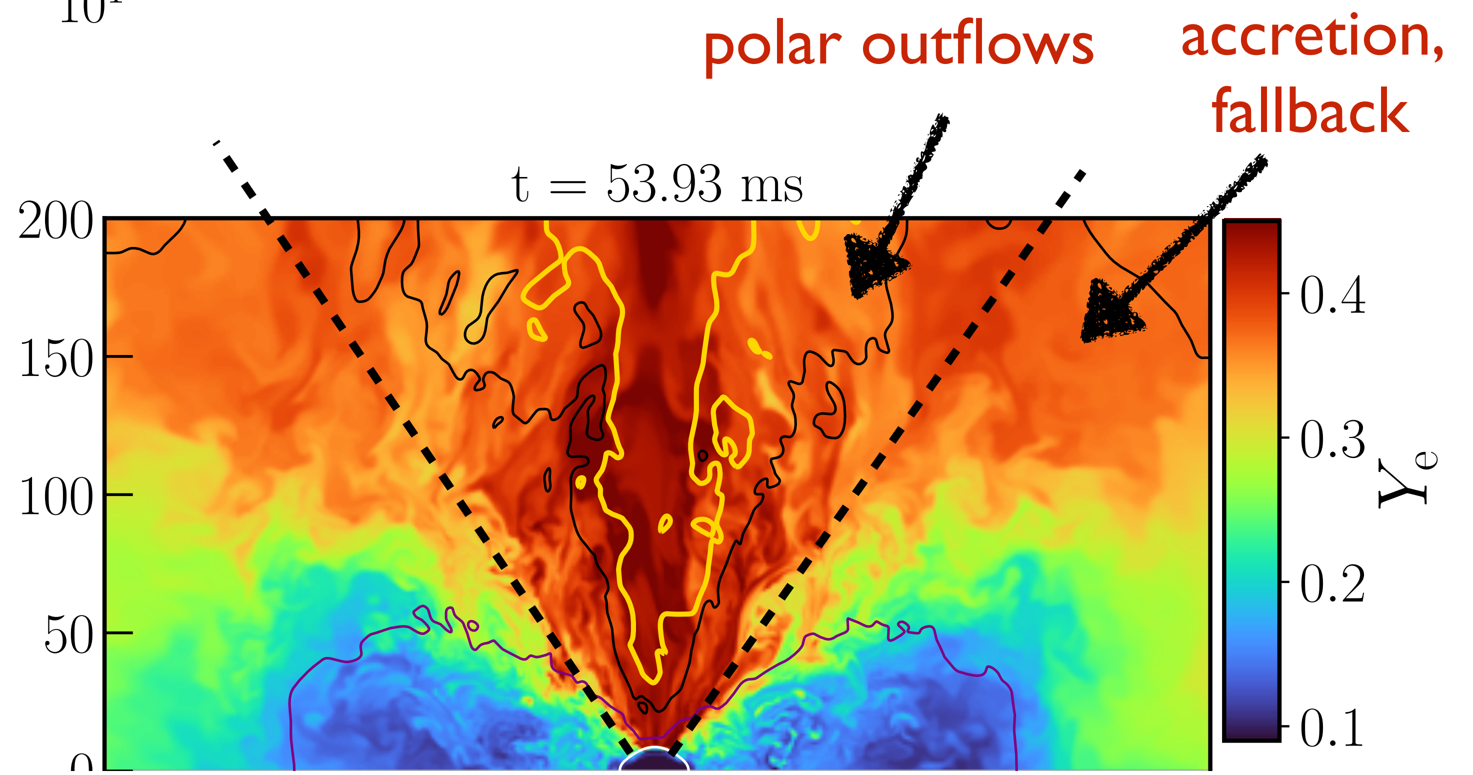




Polar MHD outflows: UV/blue precursor

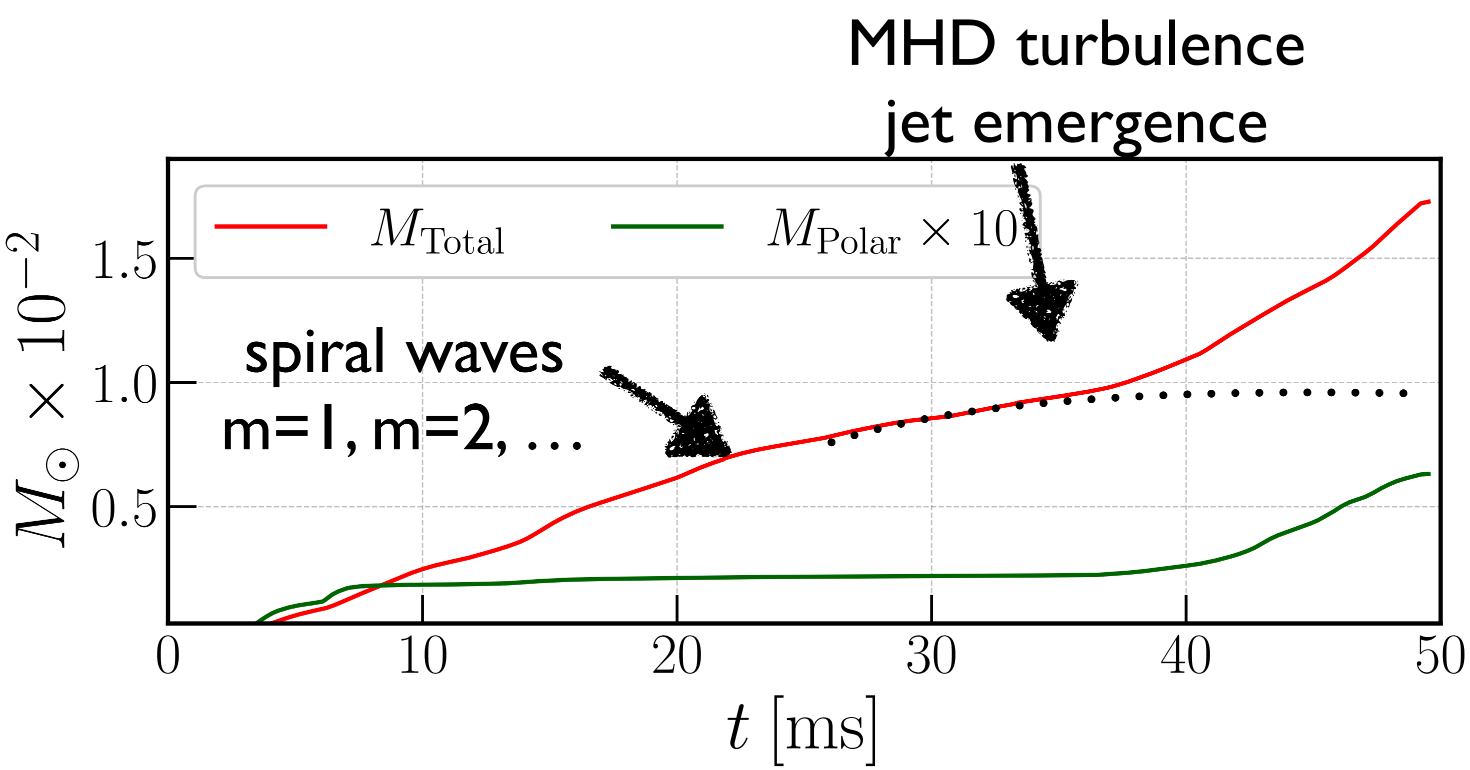


- Break-out of fast polar wind material from surrounding dynamical ejecta creates UV precursor signal to the kilonova

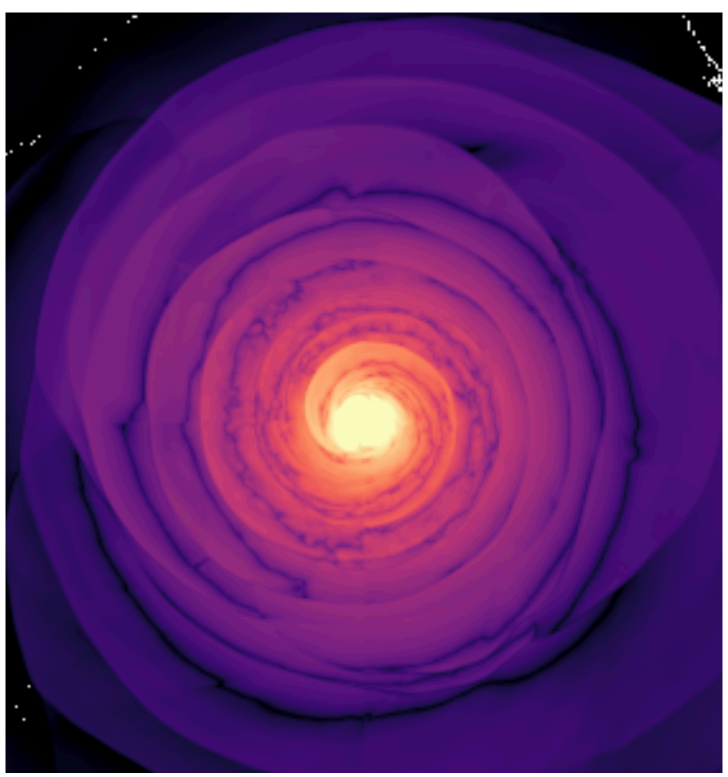


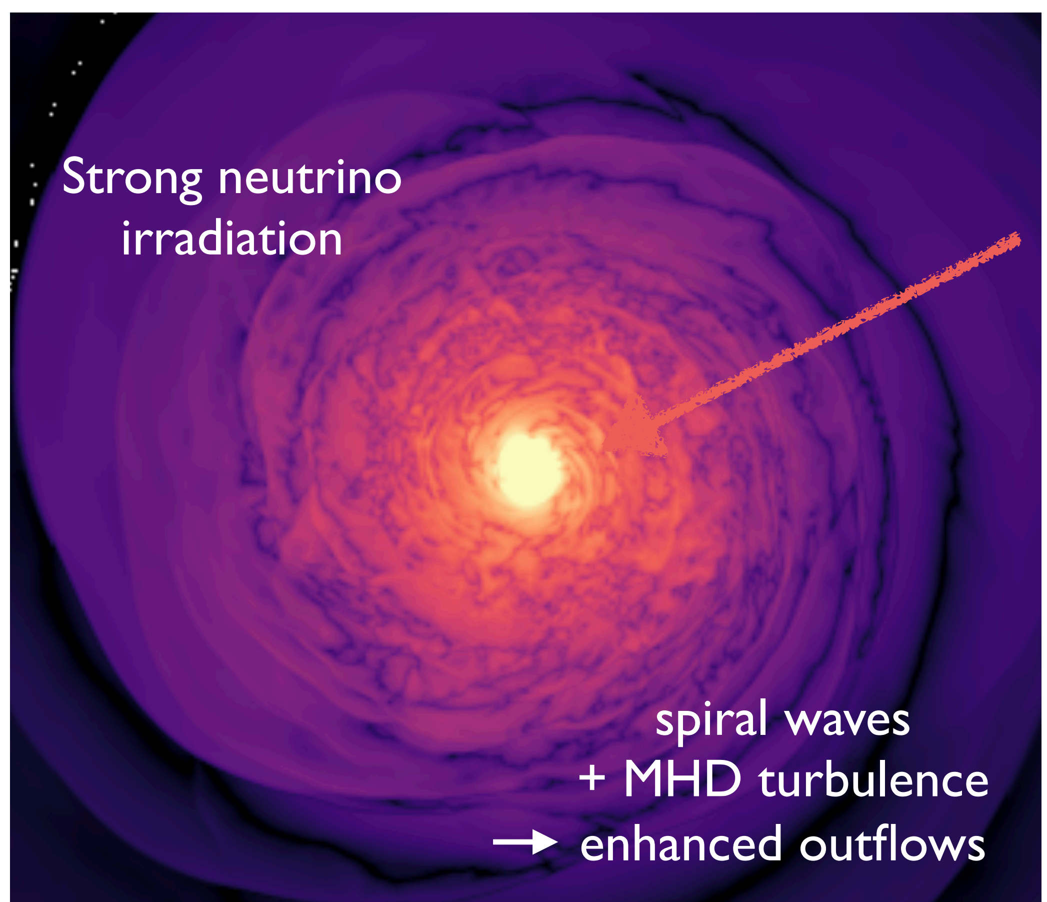
IV.
Post-merger: disk evolution & outflows

Post-merger disk evolution & outflows



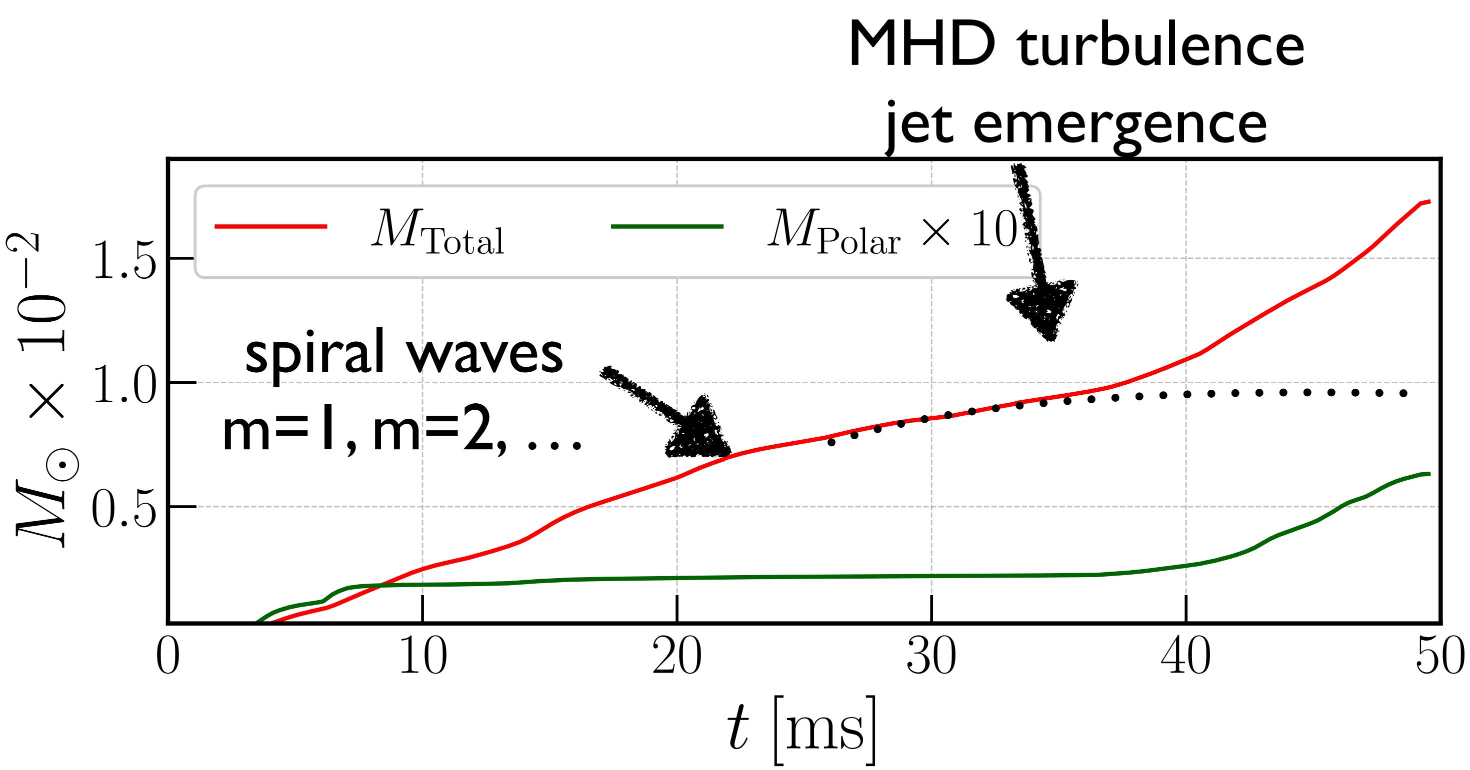
- t < 35ms mass ejection dominated by non-axisymmetric modes
  Nedora+ 2019, 2021
- Strong boost once MHD turbulence sets in (t > 40ms), reaching 2×10^{-2} M_{sun} within 50ms post-merger
- Accretion disk rapidly spreads radially due to enhanced angular momentum transport





Neutron star

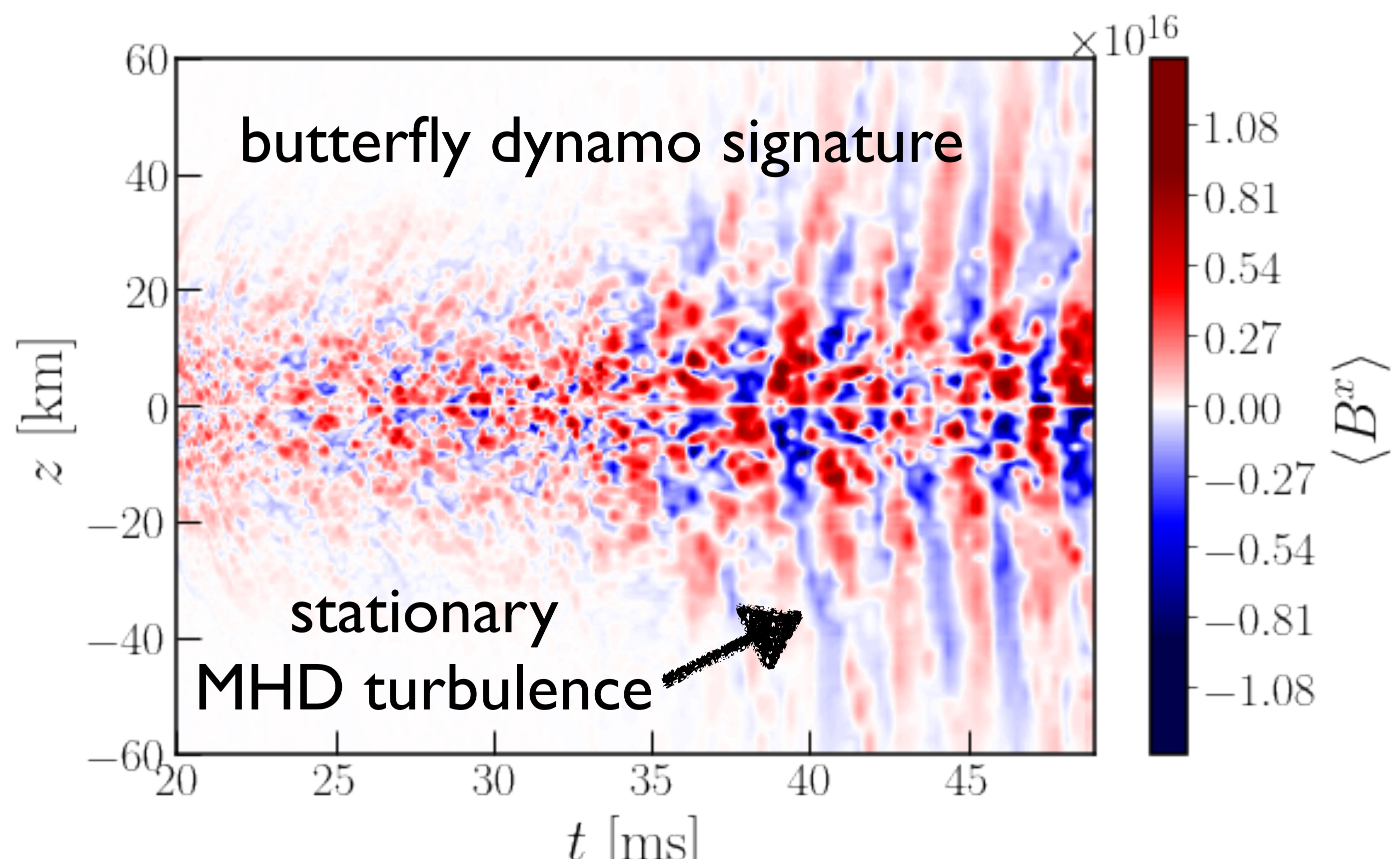
Post-merger disk evolution & outflows

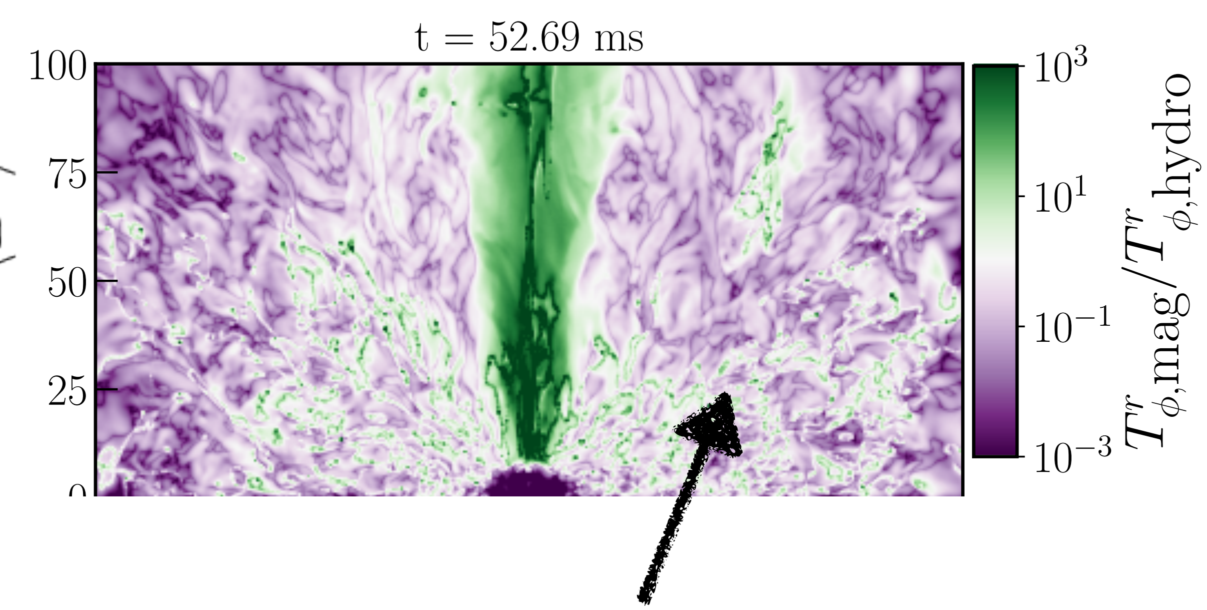


- t < 35ms mass ejection dominated by non-axisymmetric modes

Nedora+ 2019, 2021

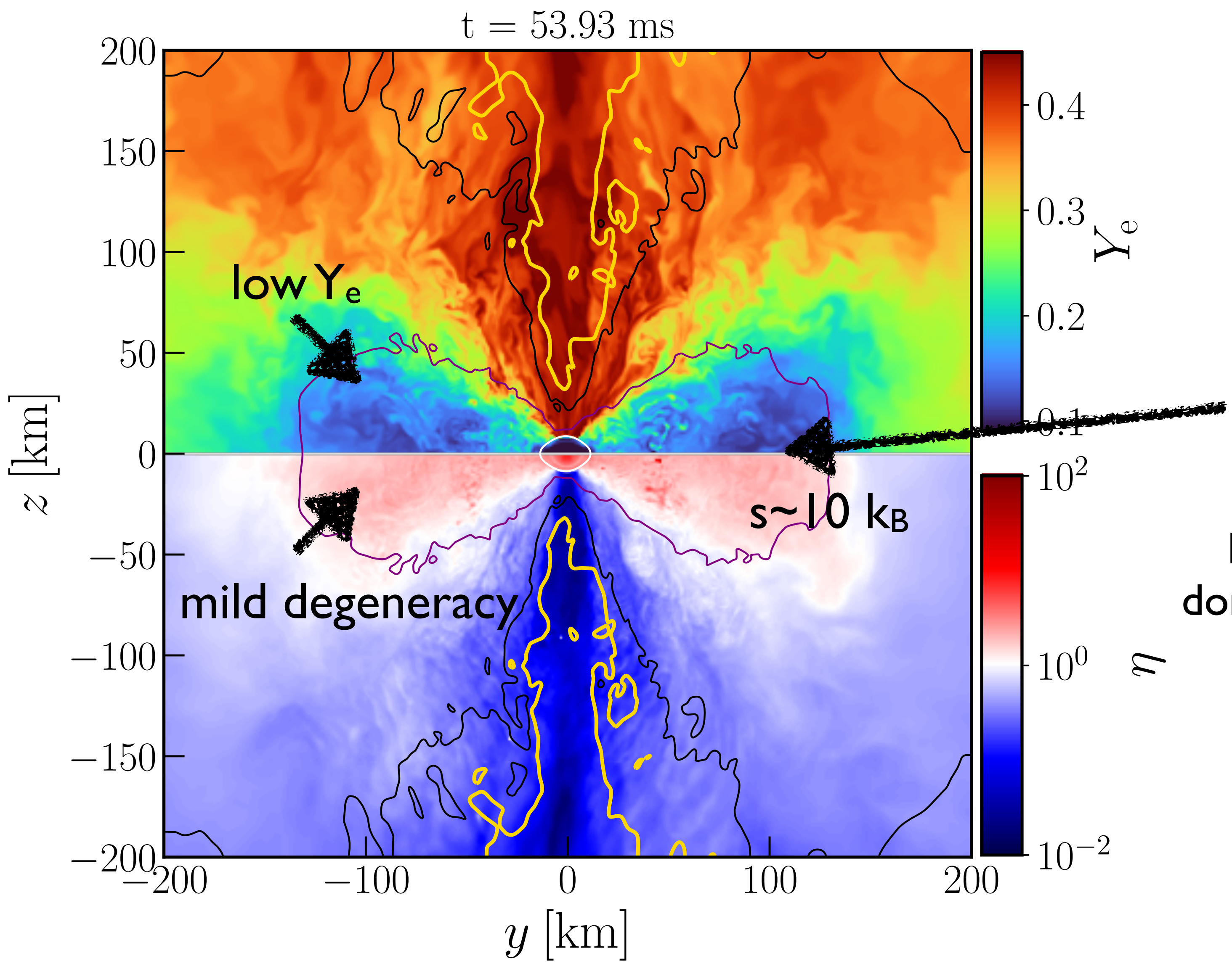
- Strong boost once MHD turbulence sets in (t > 40ms)
- Accretion disk rapidly spreads radially due to enhanced angular momentum transport
- Stresses of global magnetic field may play a role





Maxwell stresses comparable to Reynolds+advective

Post-merger disk properties

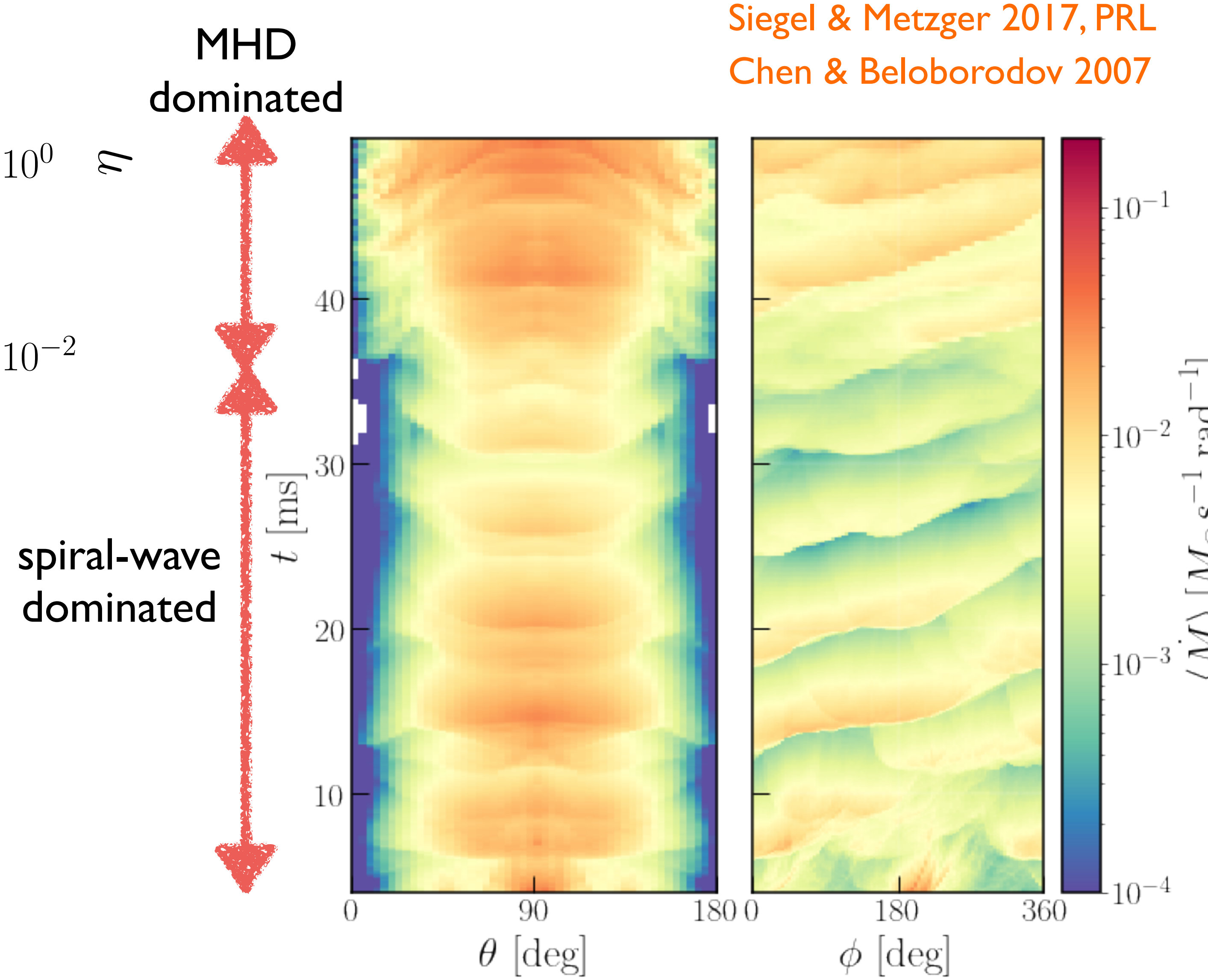


- Disk Y_e decreases from ~0.25 to ~0.15 once MHD turbulence established

- Disk enters stationary, self-regulated state based on electron degeneracy

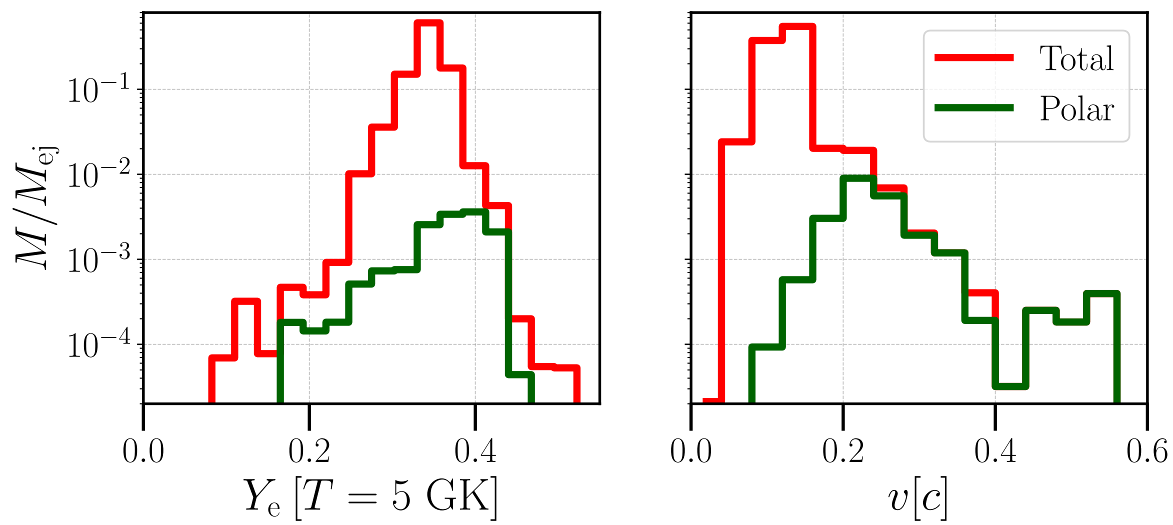
$$\dot{M} \gtrsim 1 M_\odot/\mathrm{s}, \quad M_{\rm disk} \simeq 0.19 M_\odot$$

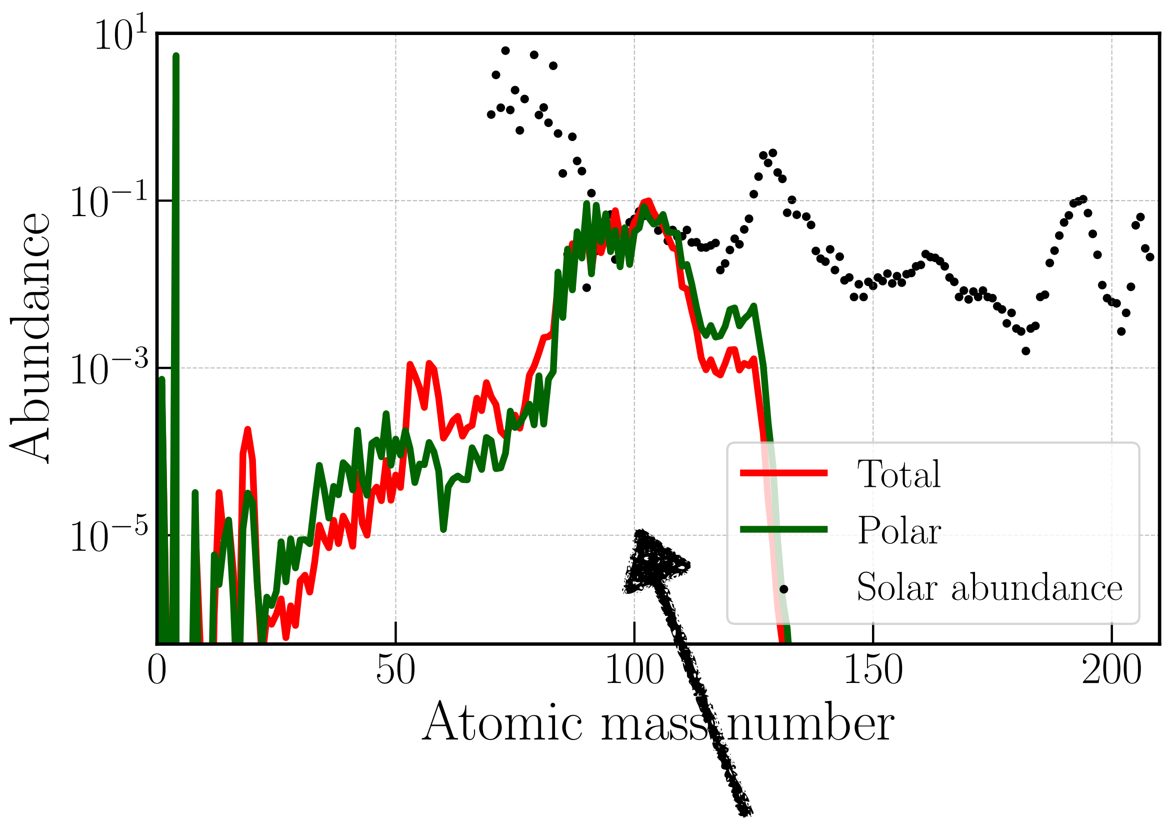
Siegel & Metzger 2017, PRL
Chen & Beloborodov 2007



- Quasi-spherical outflows quickly dominate total cumulative ejected mass

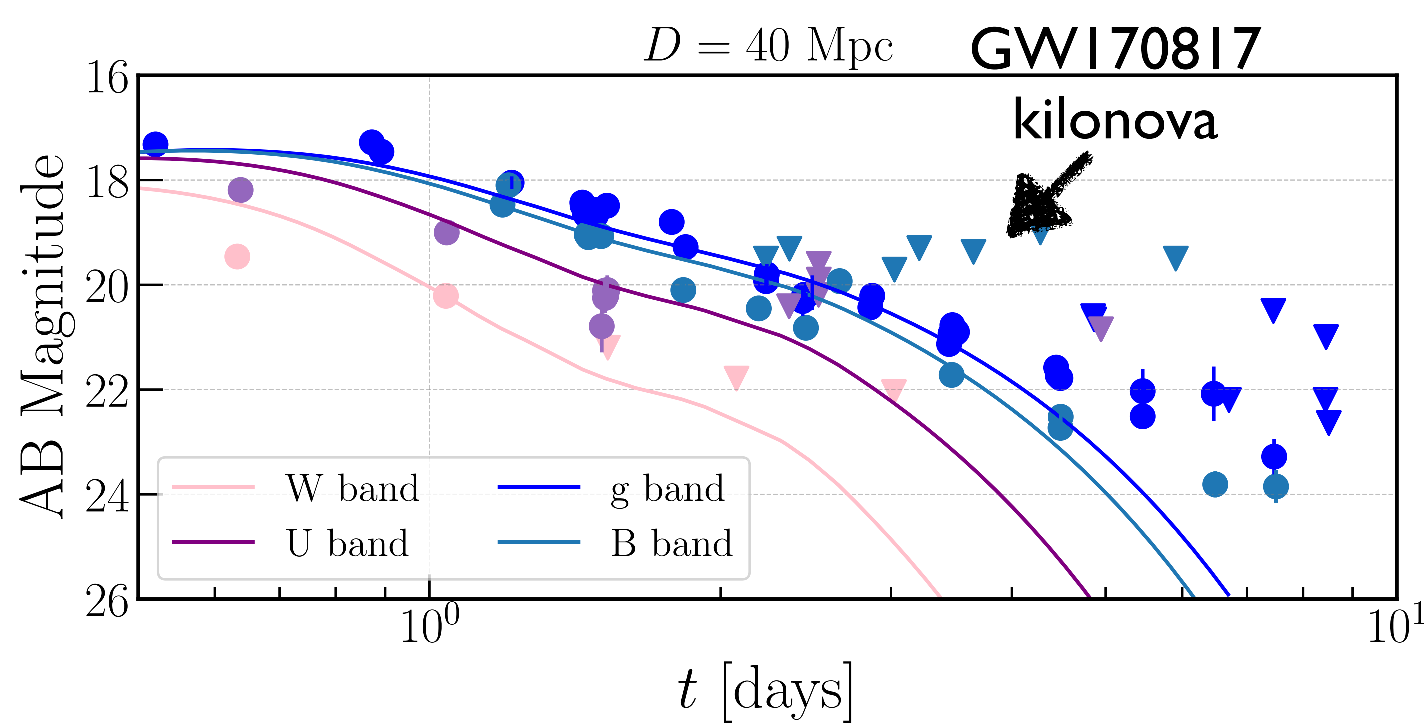
Nucleosynthesis & kilonova (from early post-merger)





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})



Conclusions

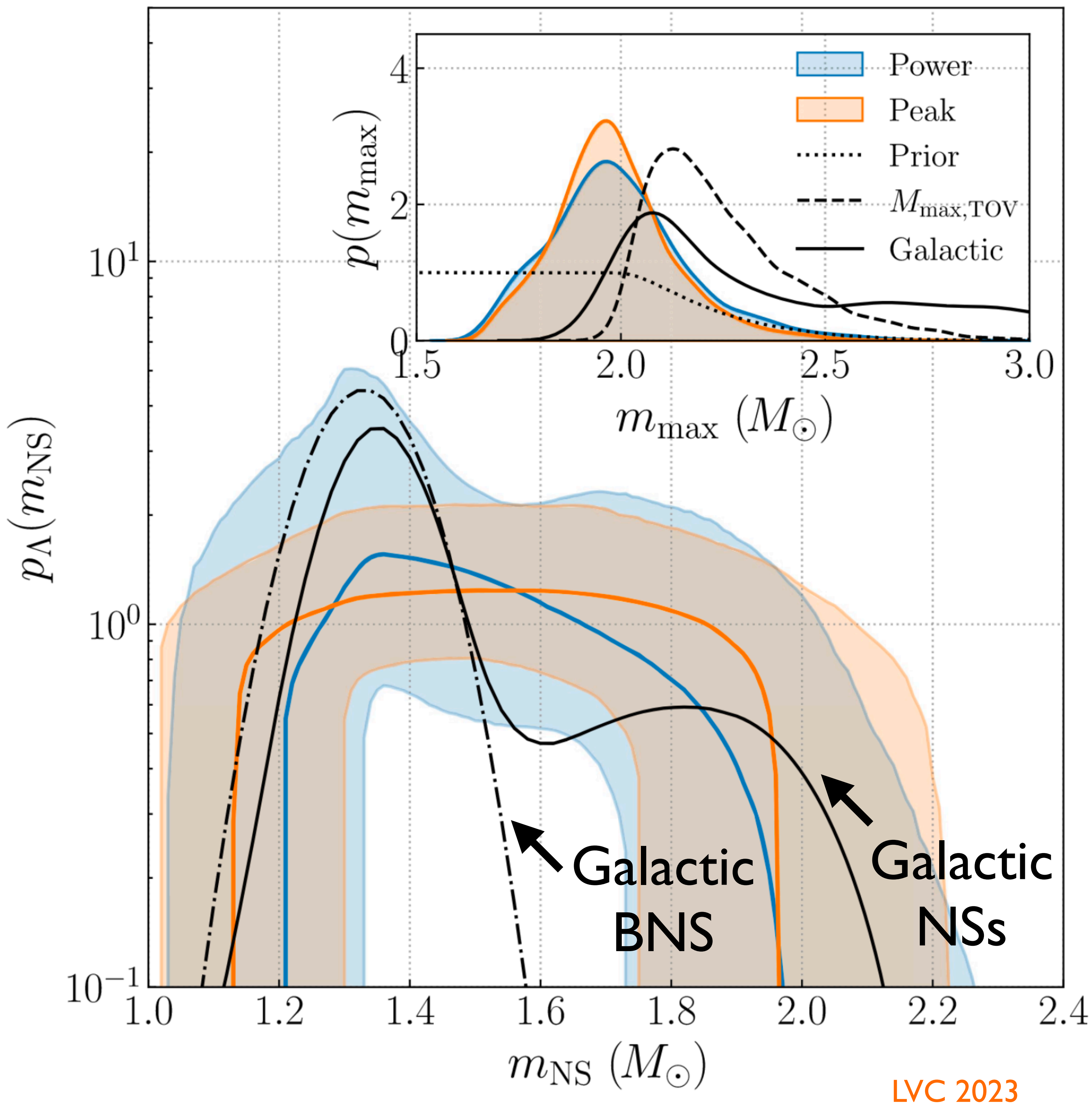
- NS mergers give rise to various r-process ejecta / kilonova components with a broad range of properties
- Post-merger ejecta likely to dominate on a population scale
- First self-consistent ab initio modelling of multiple EM counterparts from NR simulations with relativistic effects underway, exciting detection prospects
- Non-thermal + magnetar enhanced kilonovae from mergers with long-lived remnant NS, exciting detection prospects
- First self-consistent generation of a jet structure and fast winds from remnant NS
- Early winds from NS+disk consistent with blue kilonova of GW170817, jet outflows provide ~hr precursor signal

  Late winds from black hole+disk consistent with red kilonova of GW170817

- Mass ejection in a GW170817-like event: find elements of previously proposed mechanisms
  - polar MHD + ν-driven winds ⟶ subdominant here
  - Spiral waves ⟶ dominates first 30 ms
  - MHD disk turbulence ⟶ dominates > 30ms
- Only *50 ms NS lifetime* required to obtain lanthanide-free (blue) KN ejecta with ~2×10^{-2} M_{sun} with properties similar to GW170817

Appendix

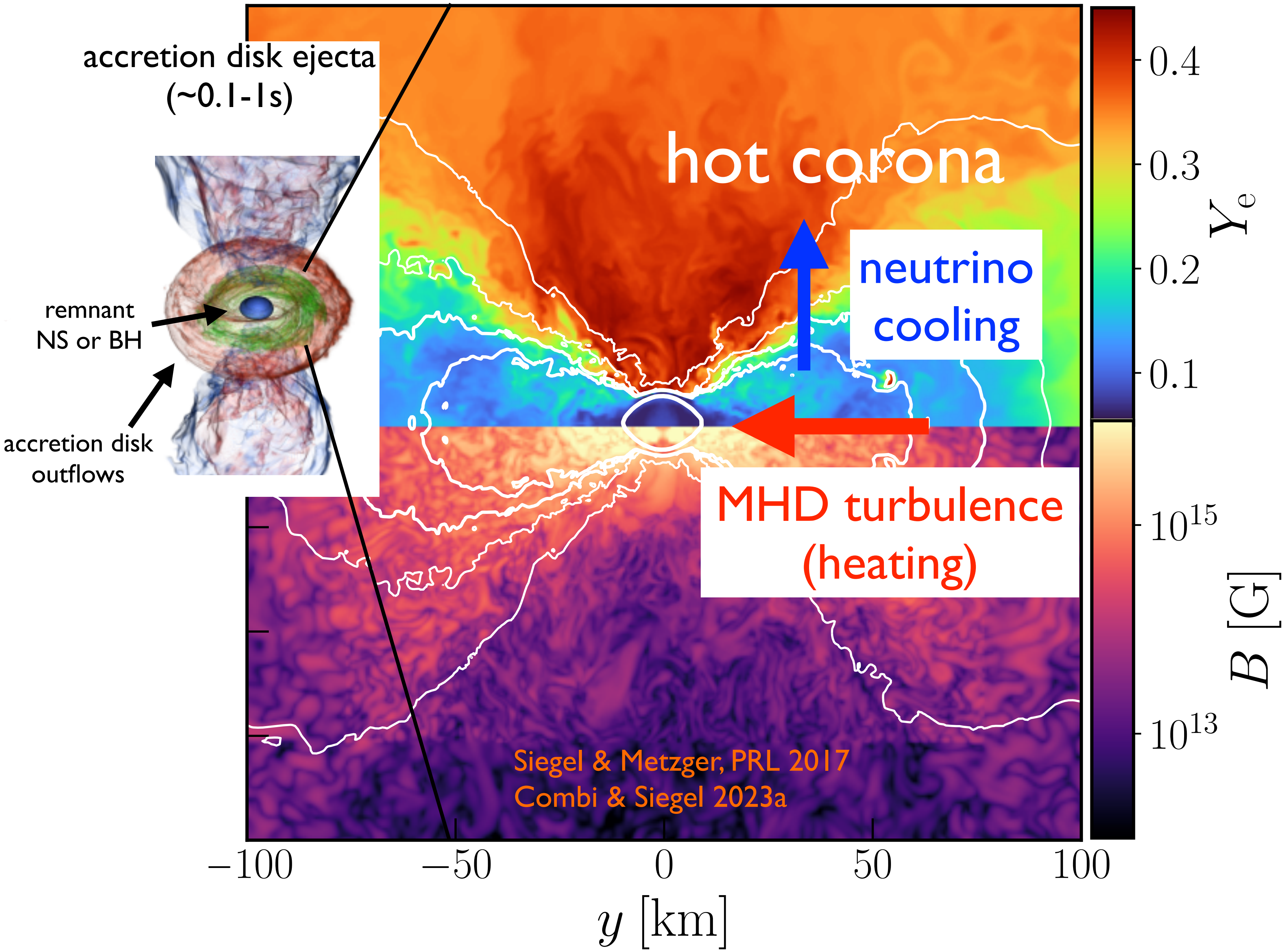
Remnant diversity & distribution



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)

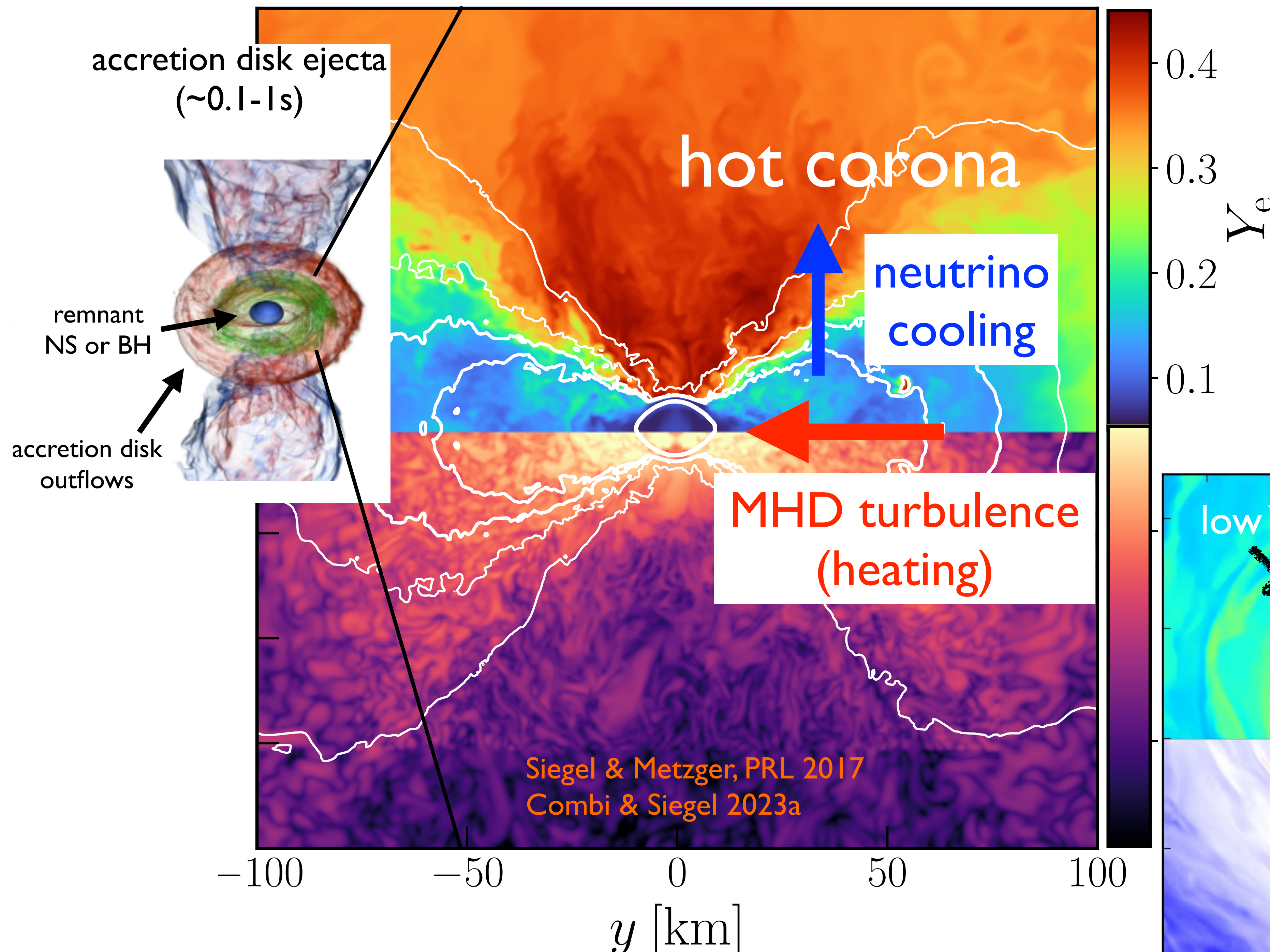
Post-merger BH-disk ejecta



- Weak interactions are key for composition, nucleosynthesis, kilonova

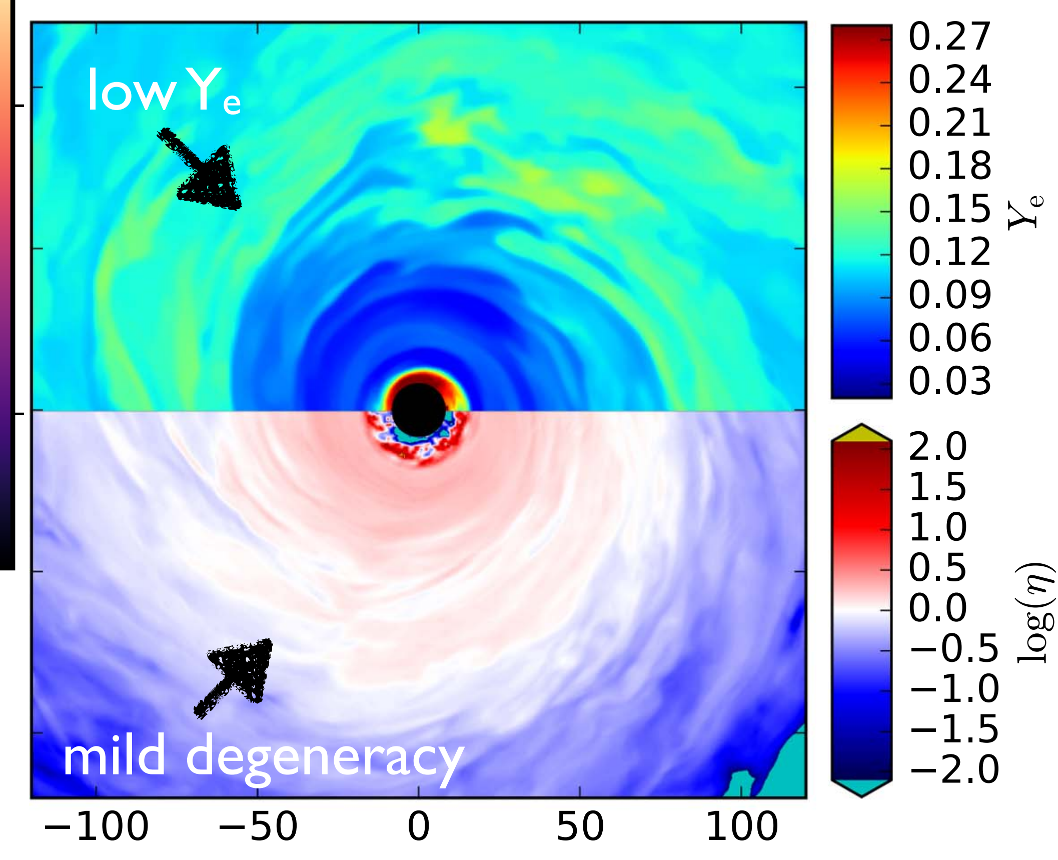
heating-cooling imbalance in corona & nuclear recombination launches disk outflow

Post-merger BH-disk ejecta



- 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



Siegel & Metzger, PRL 2017

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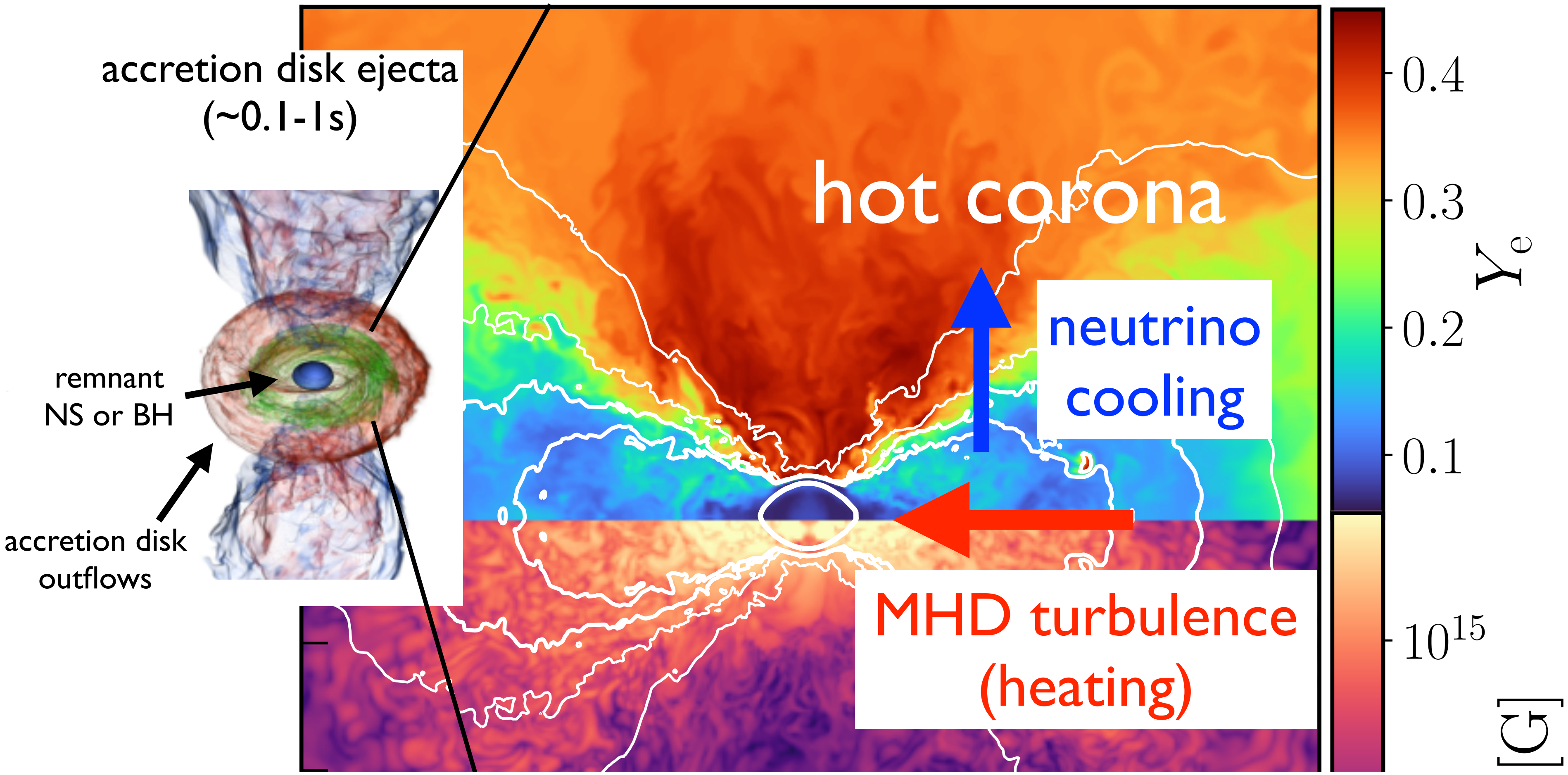

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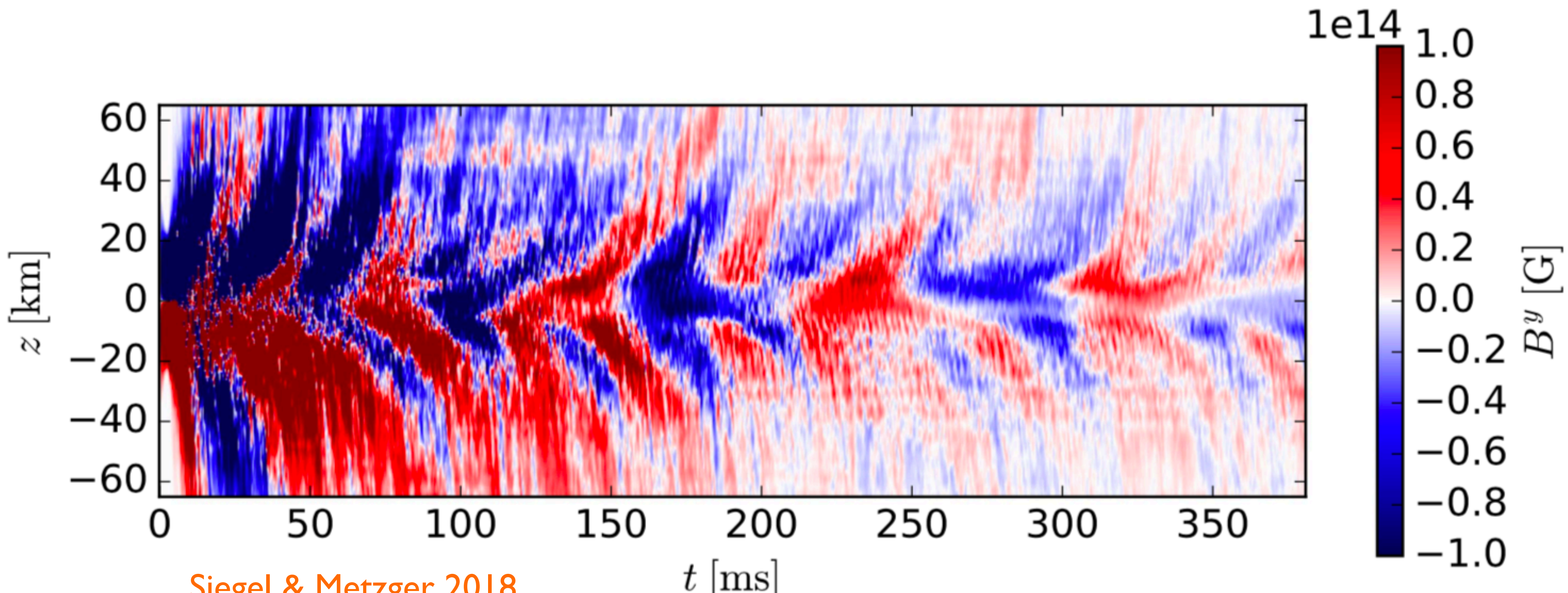
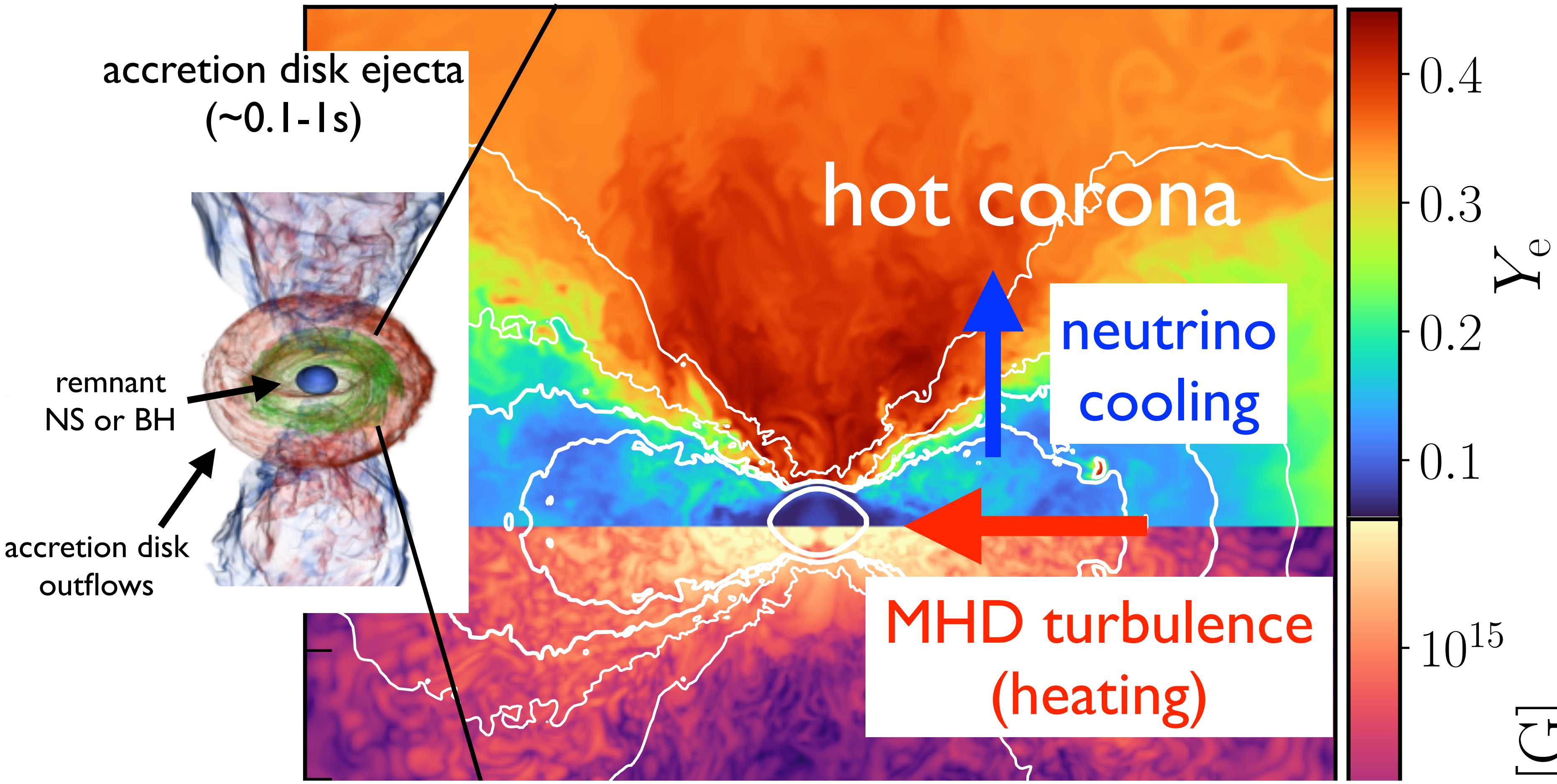
- Long-term (~s) outflows generated by self-sustained MRI dynamo

MHD dynamo signature (*'butterfly diagram'*)



Siegel & Metzger 2018

Post-merger BH-disk ejecta



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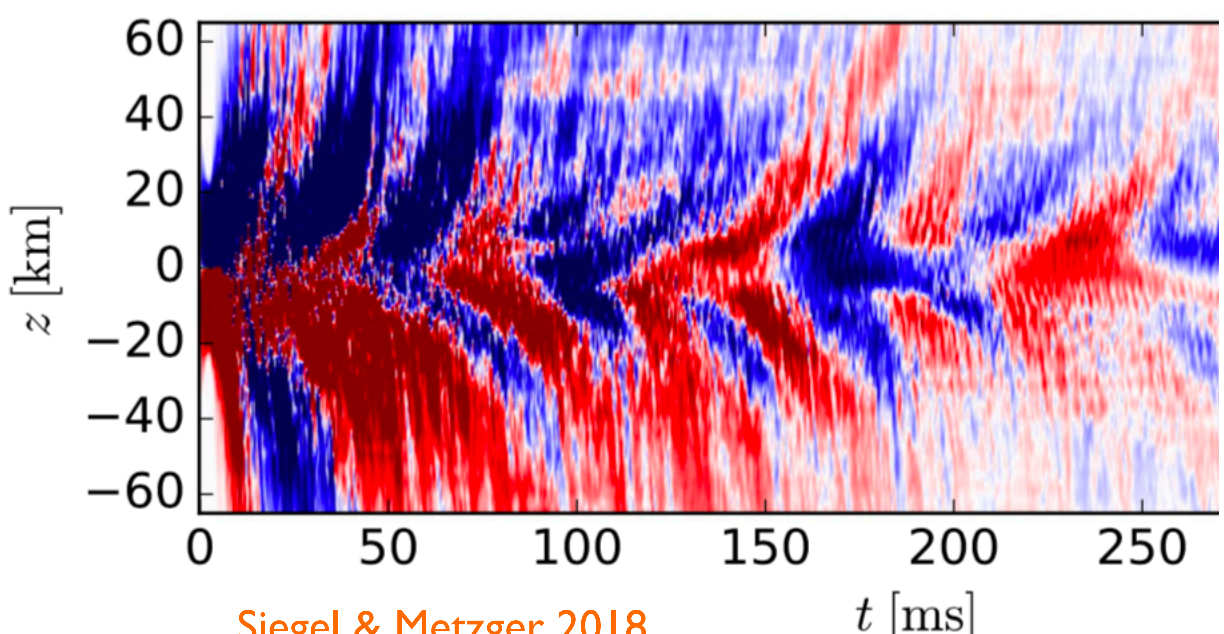
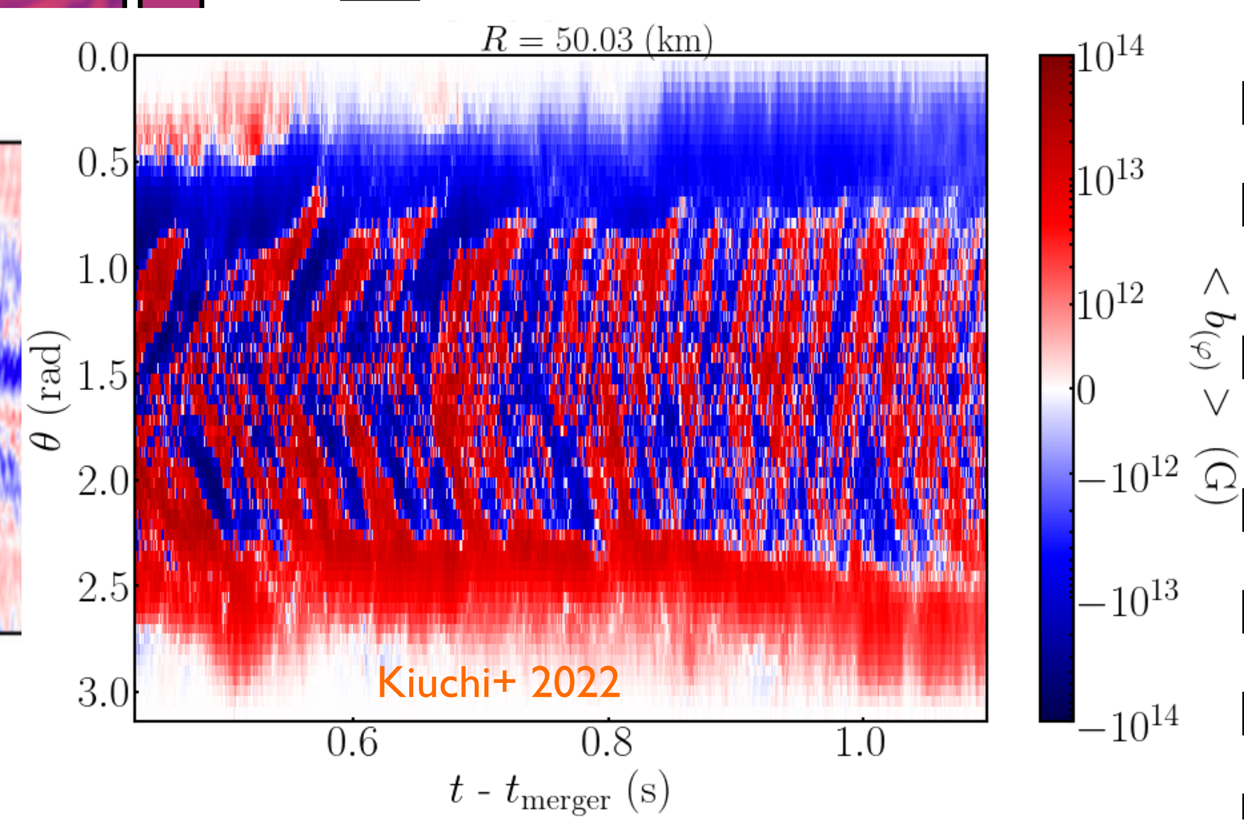
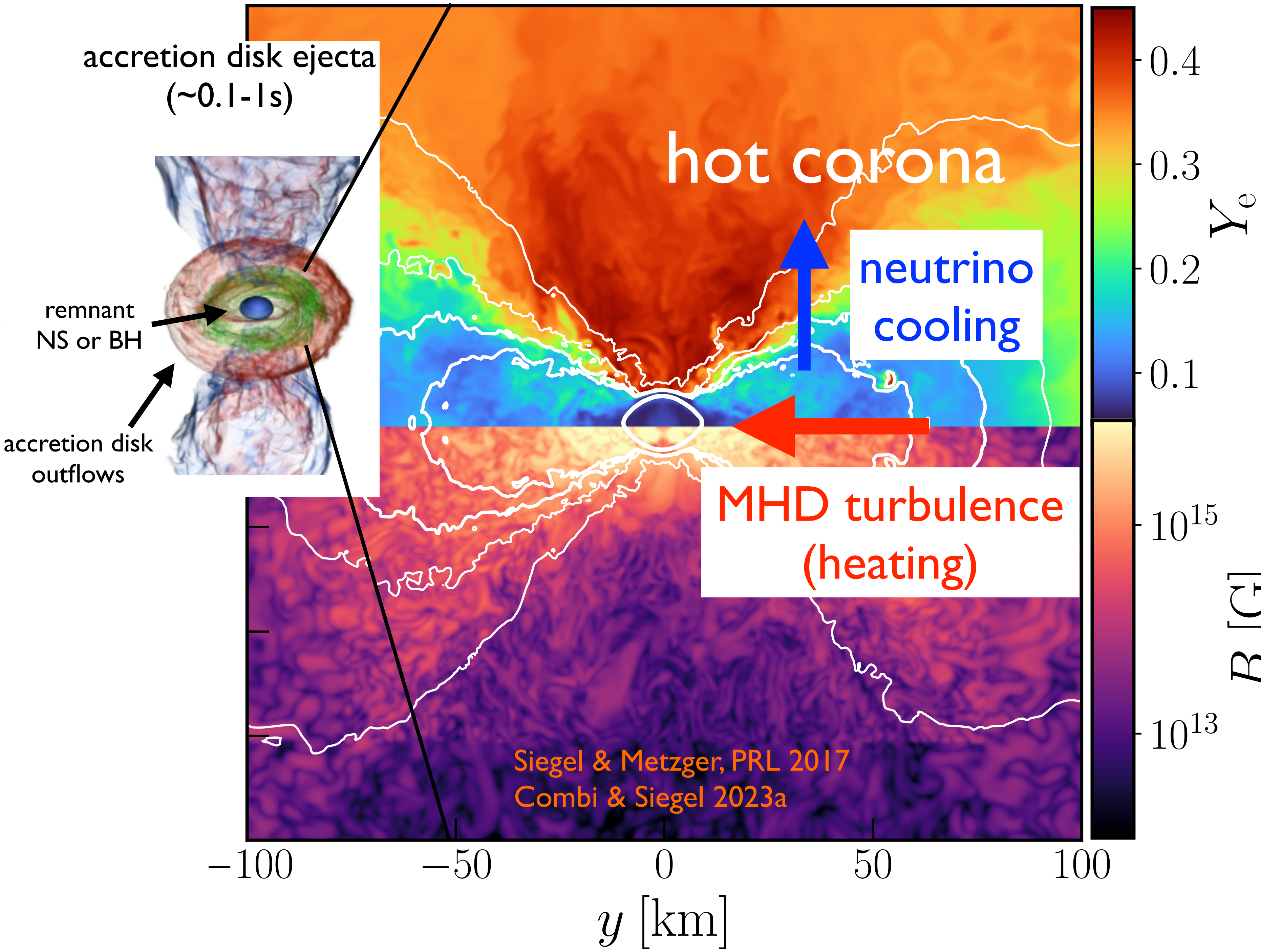


Siegel & Metzger 2018



Kiuchi+ 2022

Post-merger disk ejecta



heating-cooling imbalance in corona &
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- 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
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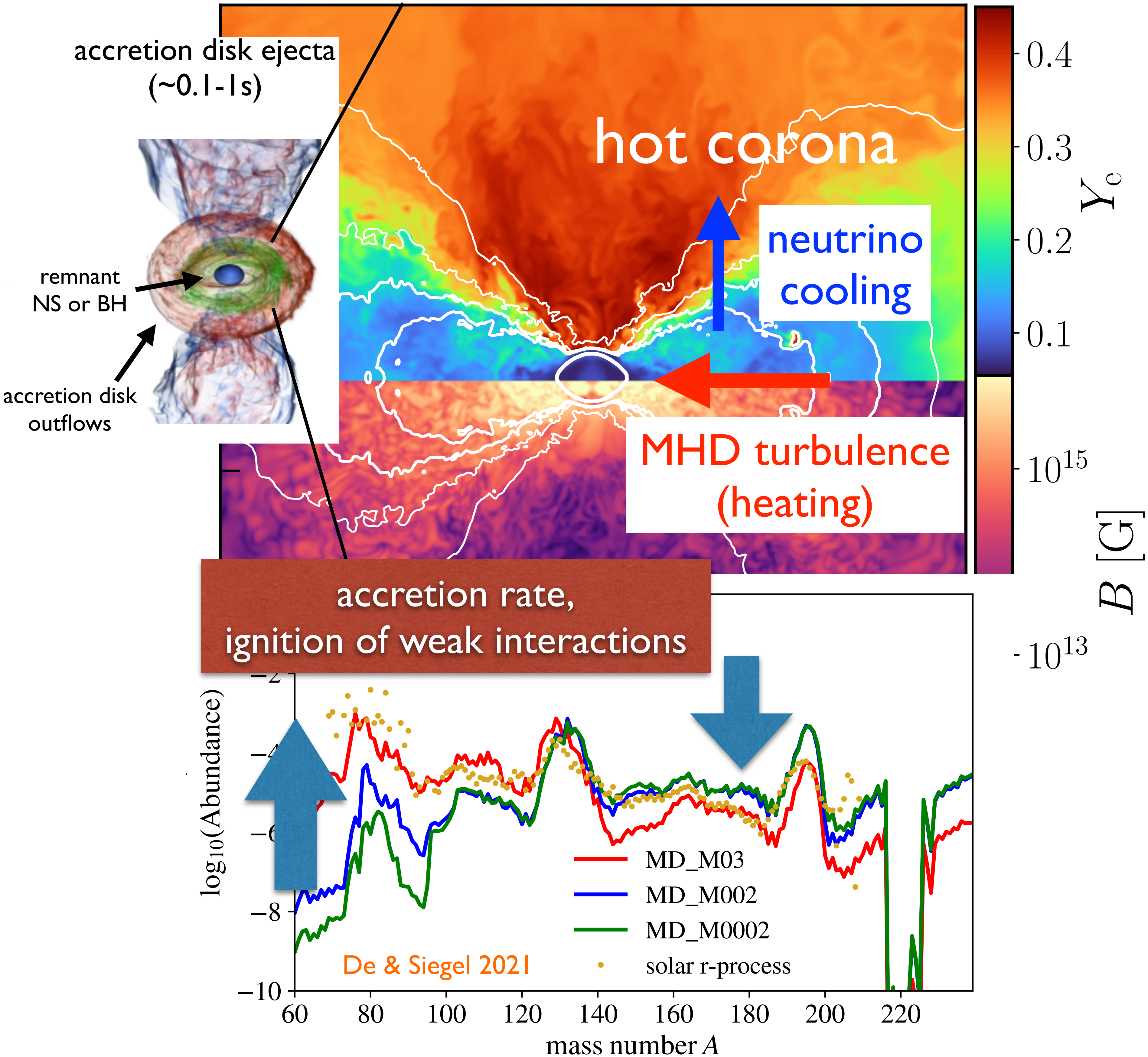
Post-merger disk ejecta



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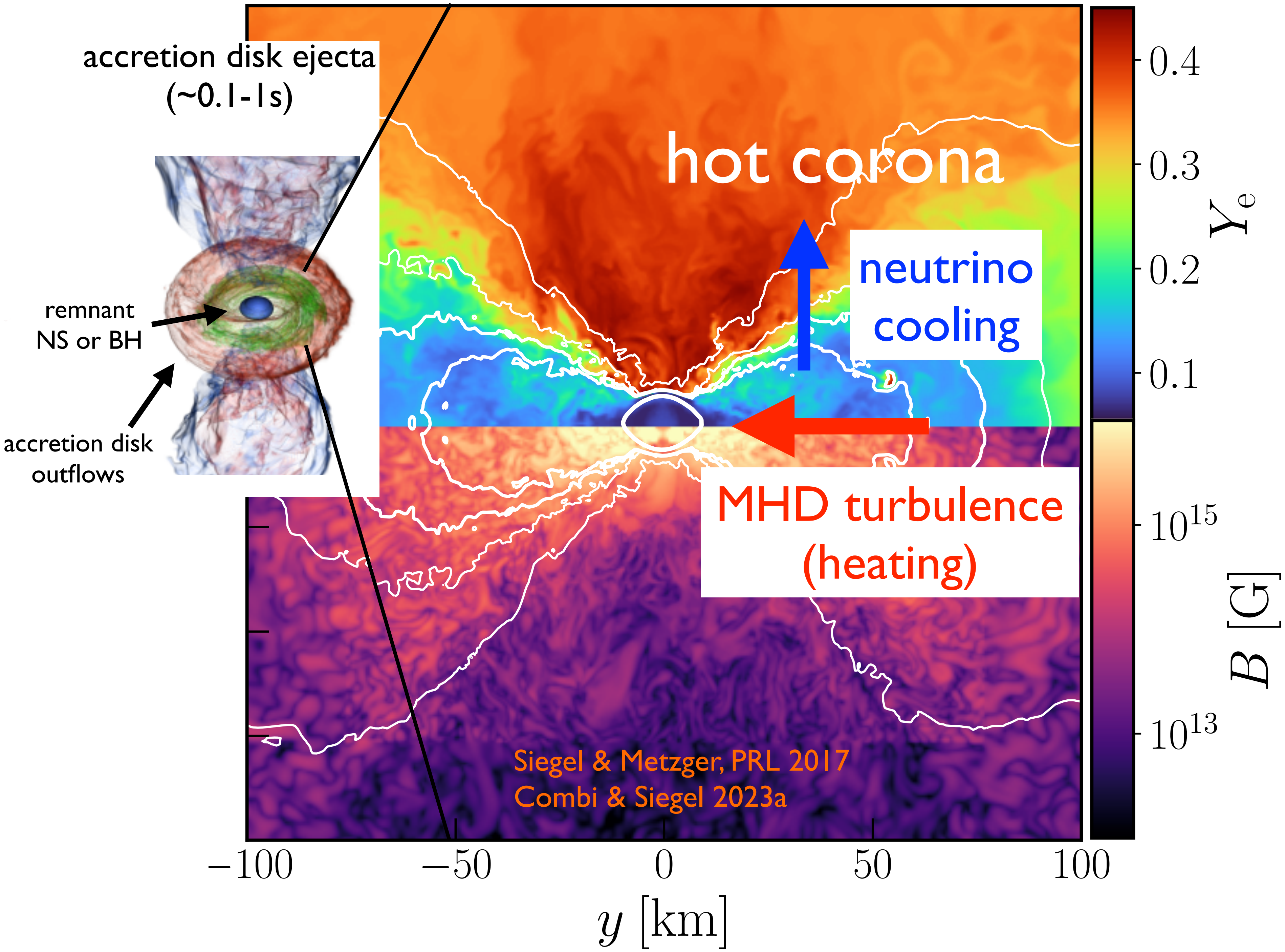

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