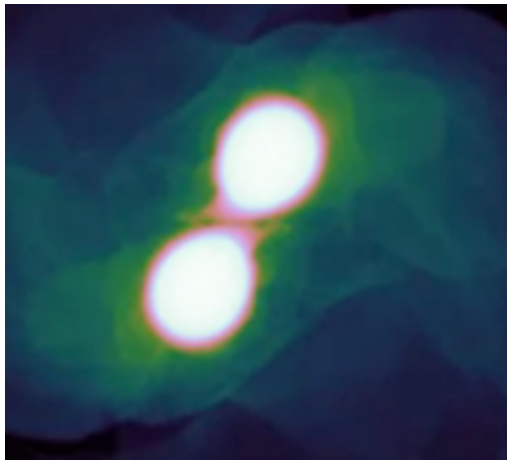
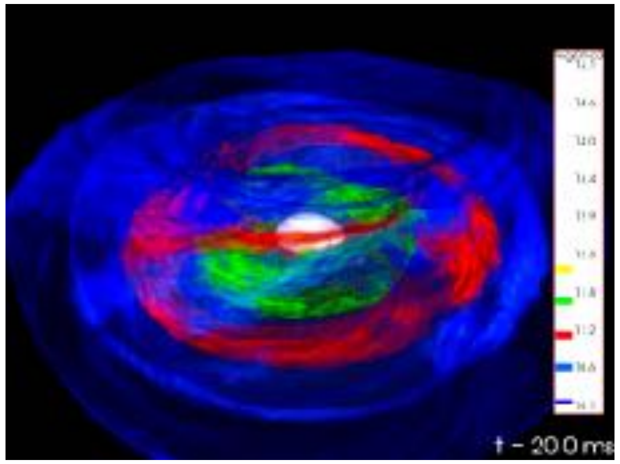
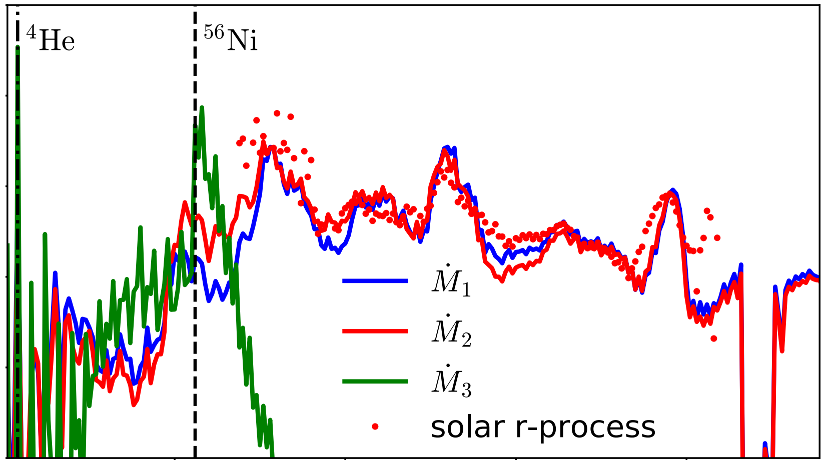
R-process nucleosynthesis in neutron-star mergers and other explosive events







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PERIMETER INSTITUTE

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INT workshop, May 23-27, 2022

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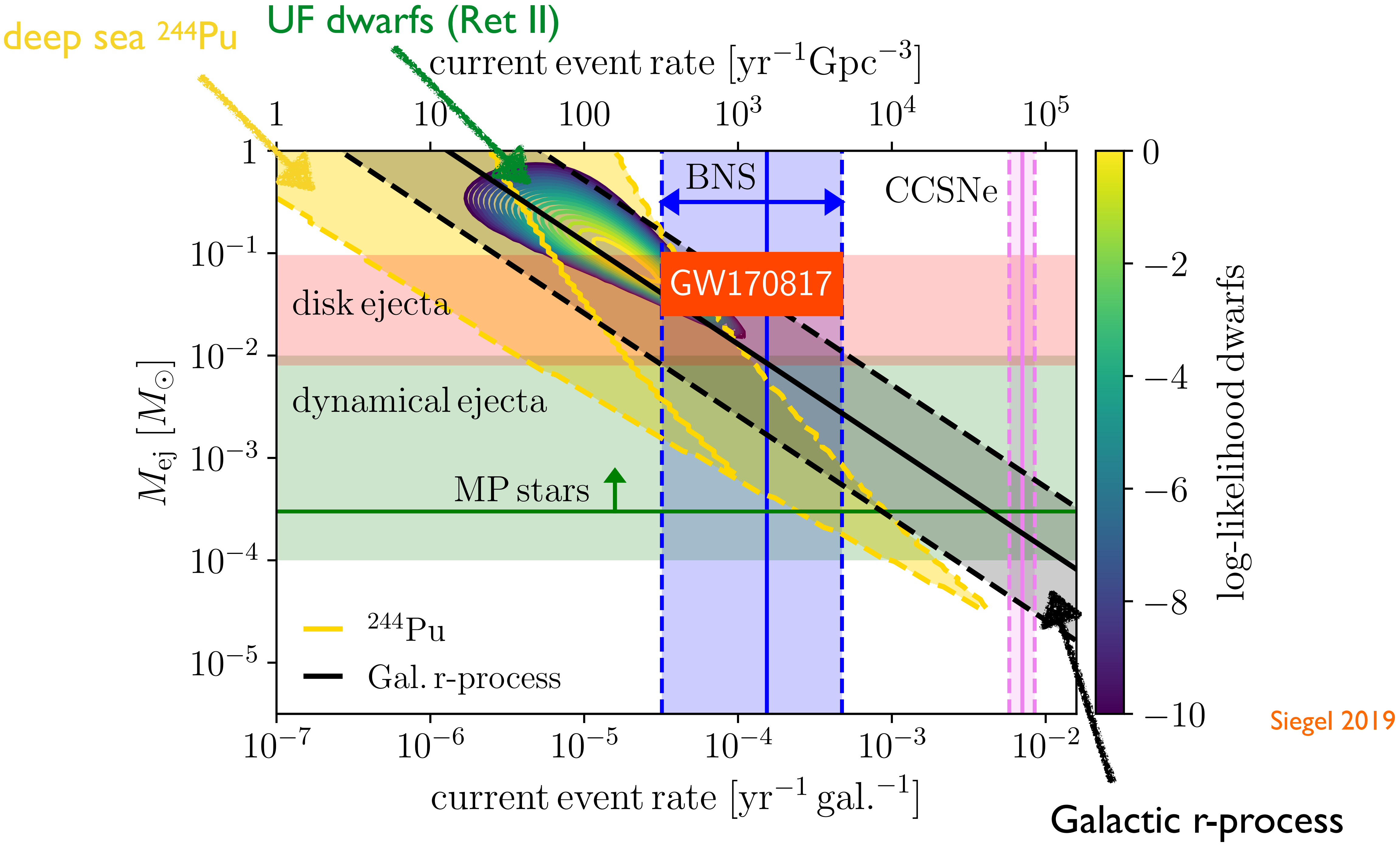
Outline

- Some constraints on r-process sites
- Neutron-star mergers
- Some conjectures
- R-process in collapsars
- Massive collapsars and ‘super-kilonovae’

I.

Some constraints on r-process sites

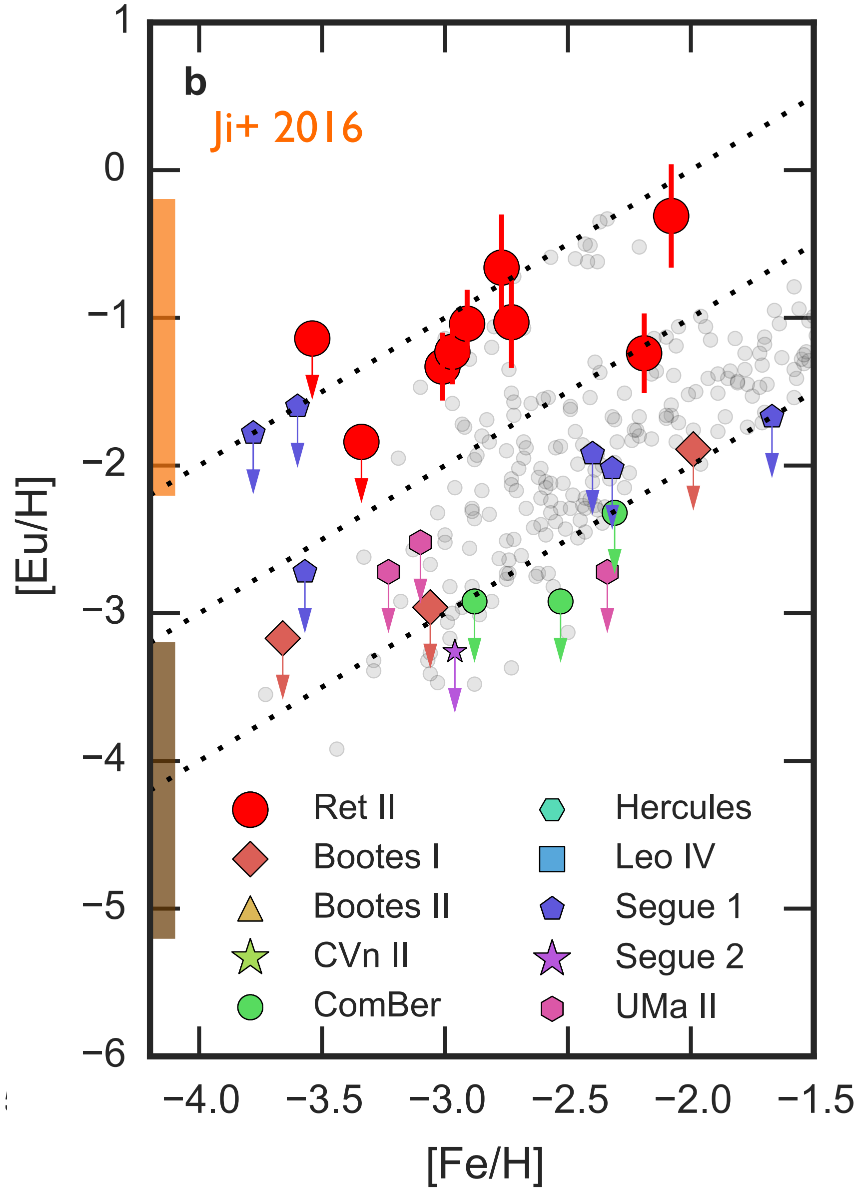
The main r-process originates in rare high-yield events



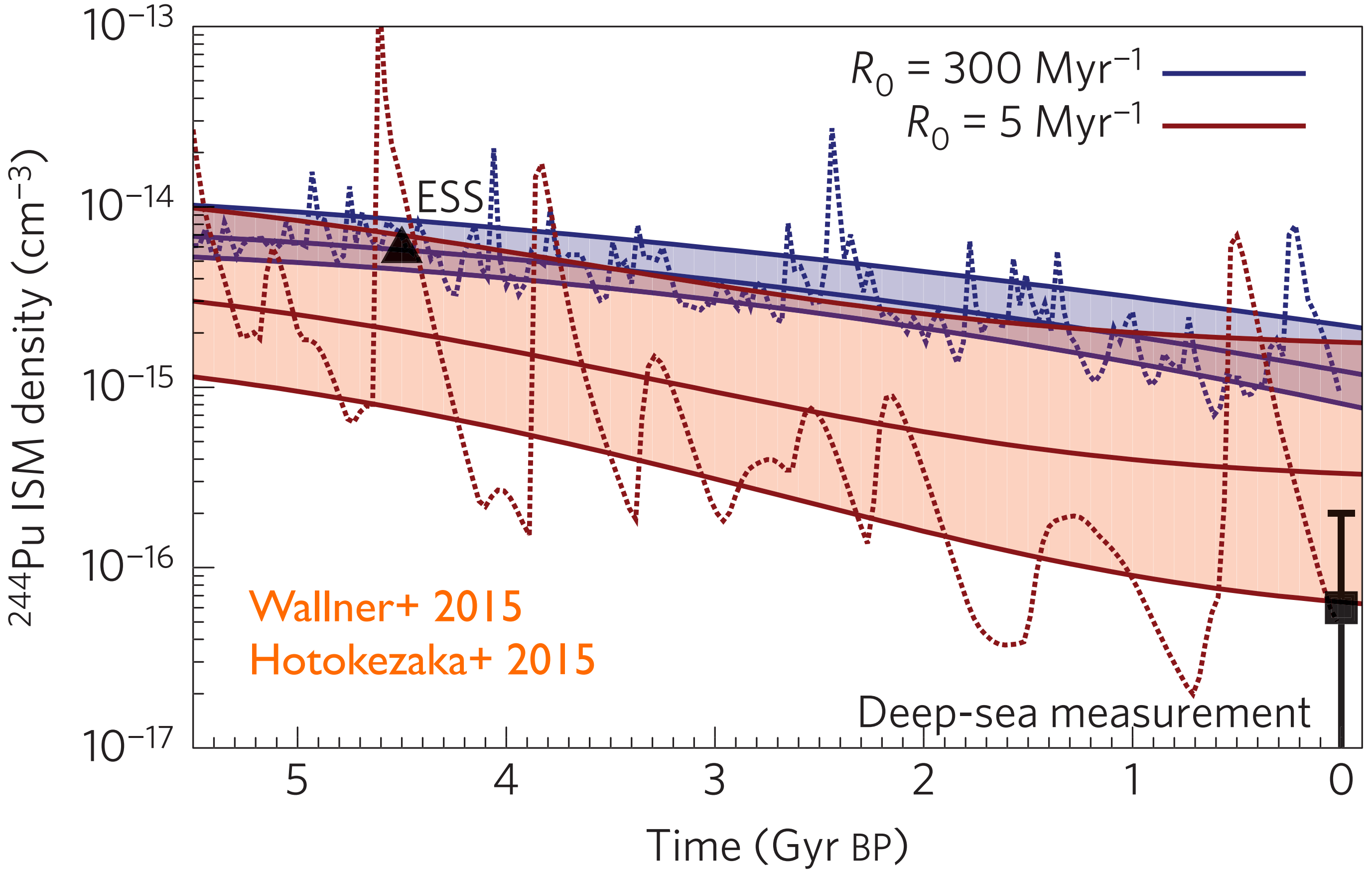
Siegel 2019

The main r-process originates in rare high-yield events

early Galactic history



recent Galactic history



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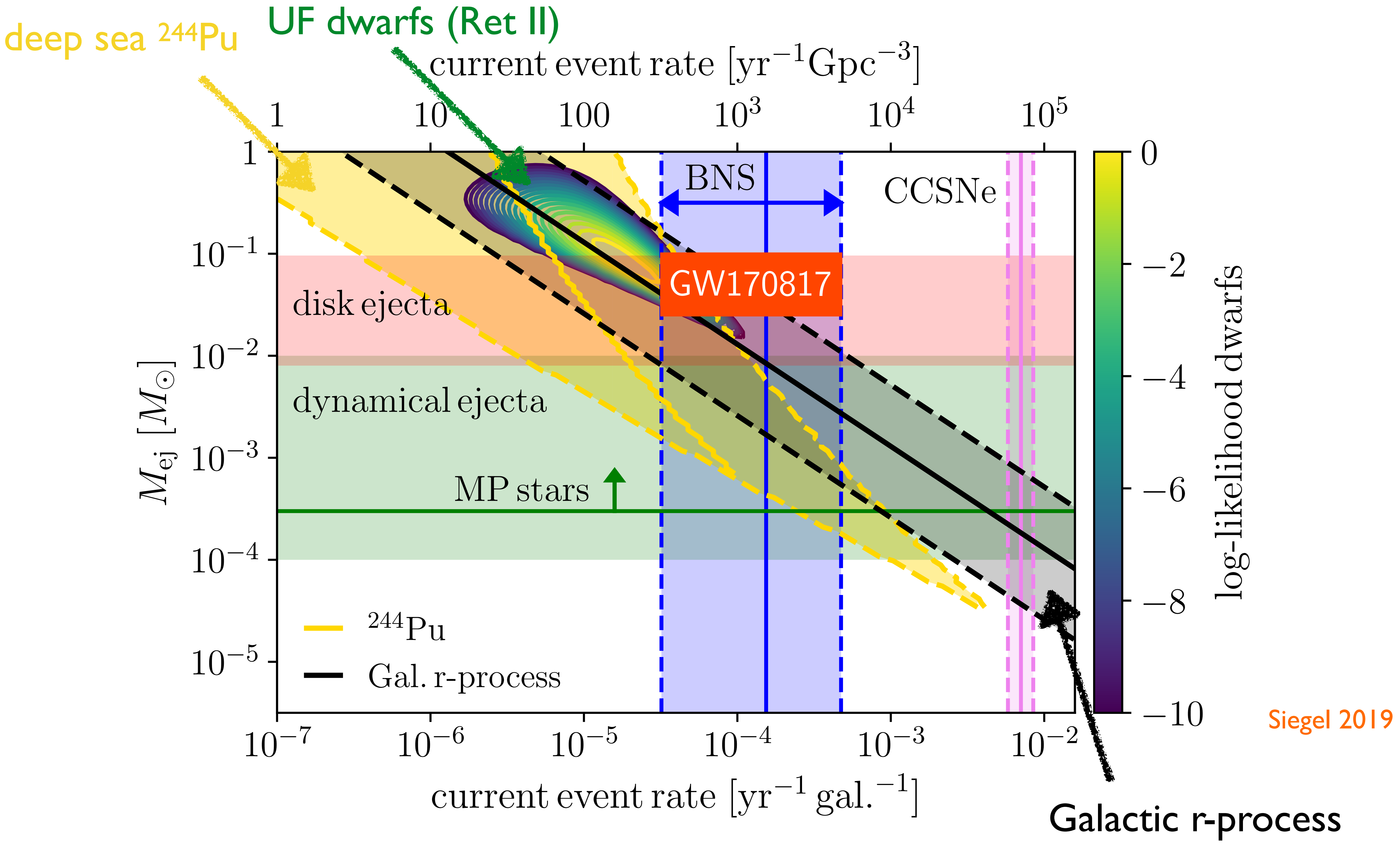


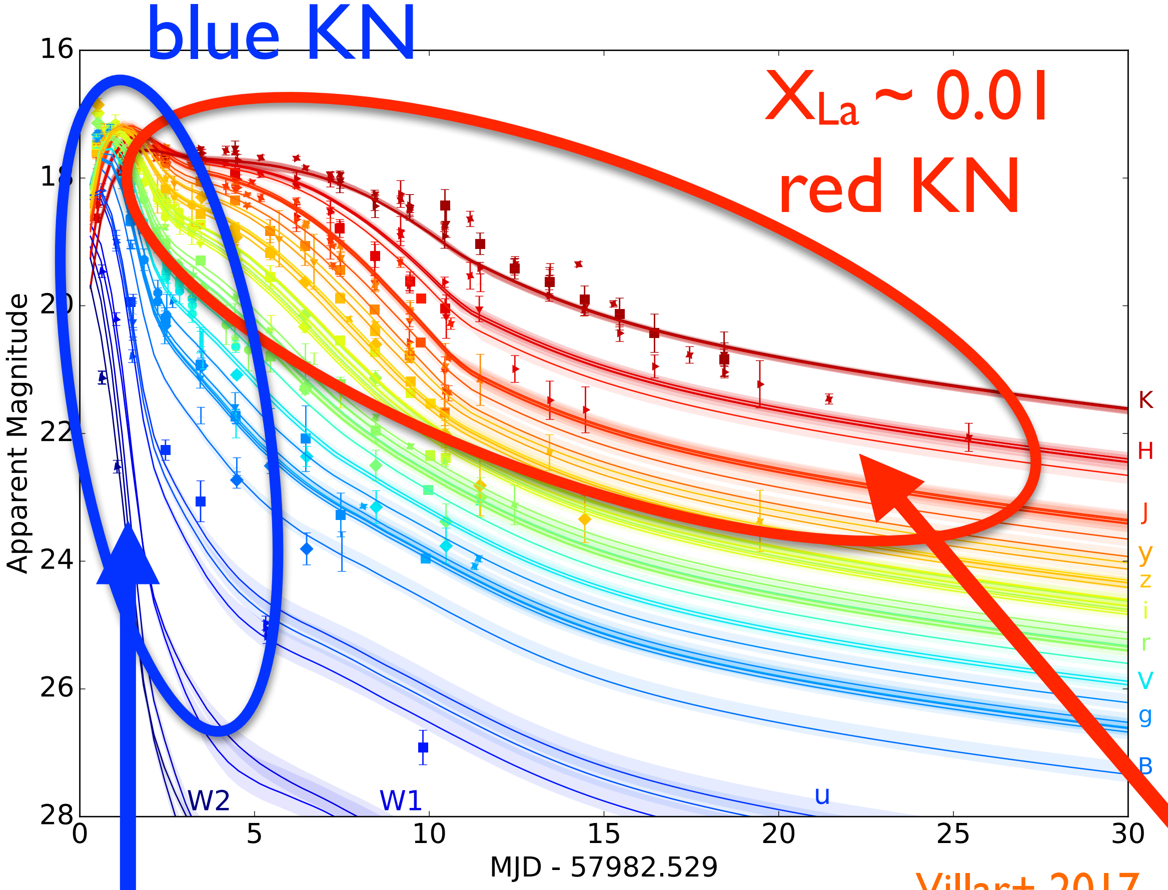
Siegel 2019

- → Main r-process is *high-yield low-rate* both in *recent and early* Galactic history
- → Dynamical ejecta in BNS mergers unlikely main r-process site

The GW170817 kilonova

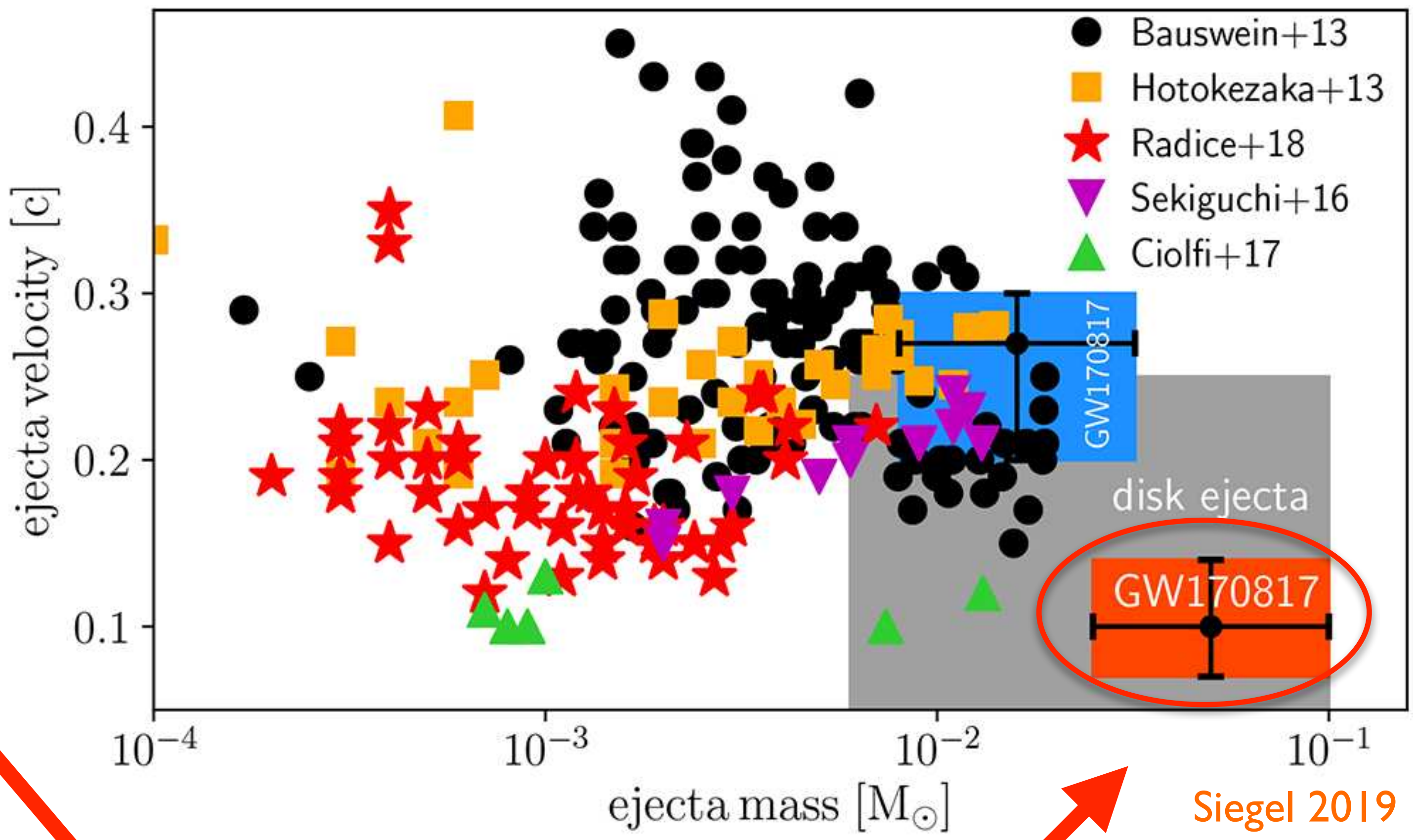
$X_{La} < 10^{-4}$
blue KN

$X_{La} \sim 0.01$
red KN



Villar+ 2017

BNS merger simulations: dynamical ejecta



Siegel 2019

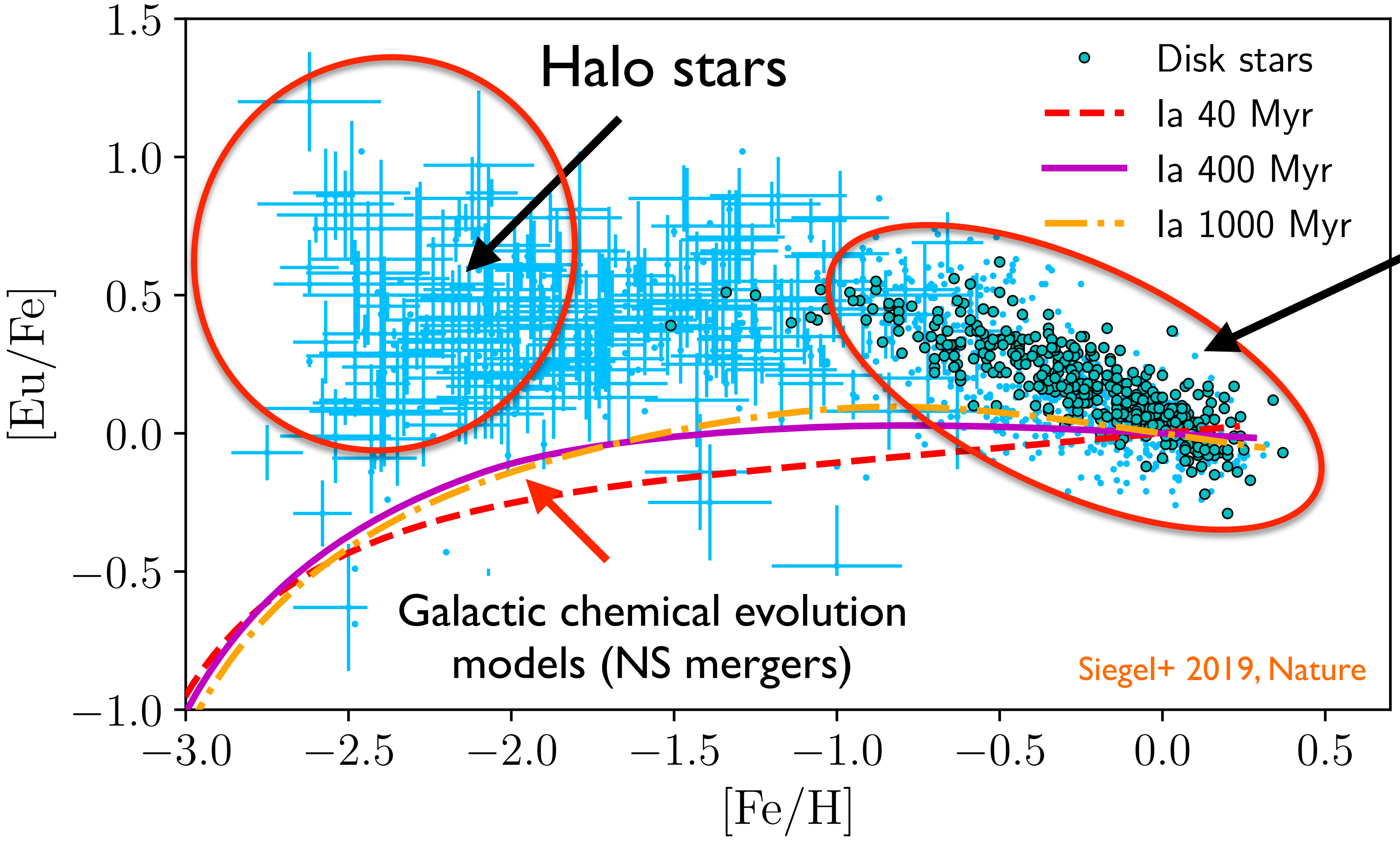
post-merger winds?
neutron precursor at
early times?

likely disk ejecta

Kasen+ 2017

Siegel & Metzger, PRL 2017

Are NS mergers alone? Hints from chemical evolution…



Halo stars

Galactic disk stars

Galactic chemical evolution models (NS mergers)

Siegel+ 2019, Nature

Van de Voort+ 2015, 2019
Shen+ 2015
Wehmeyer+ 2015
Safarzadeh+ 2019
Bekki & Tsujimoto 2017
Zevin, Kremer, Siegel+ 2019
Kirby+ 2020

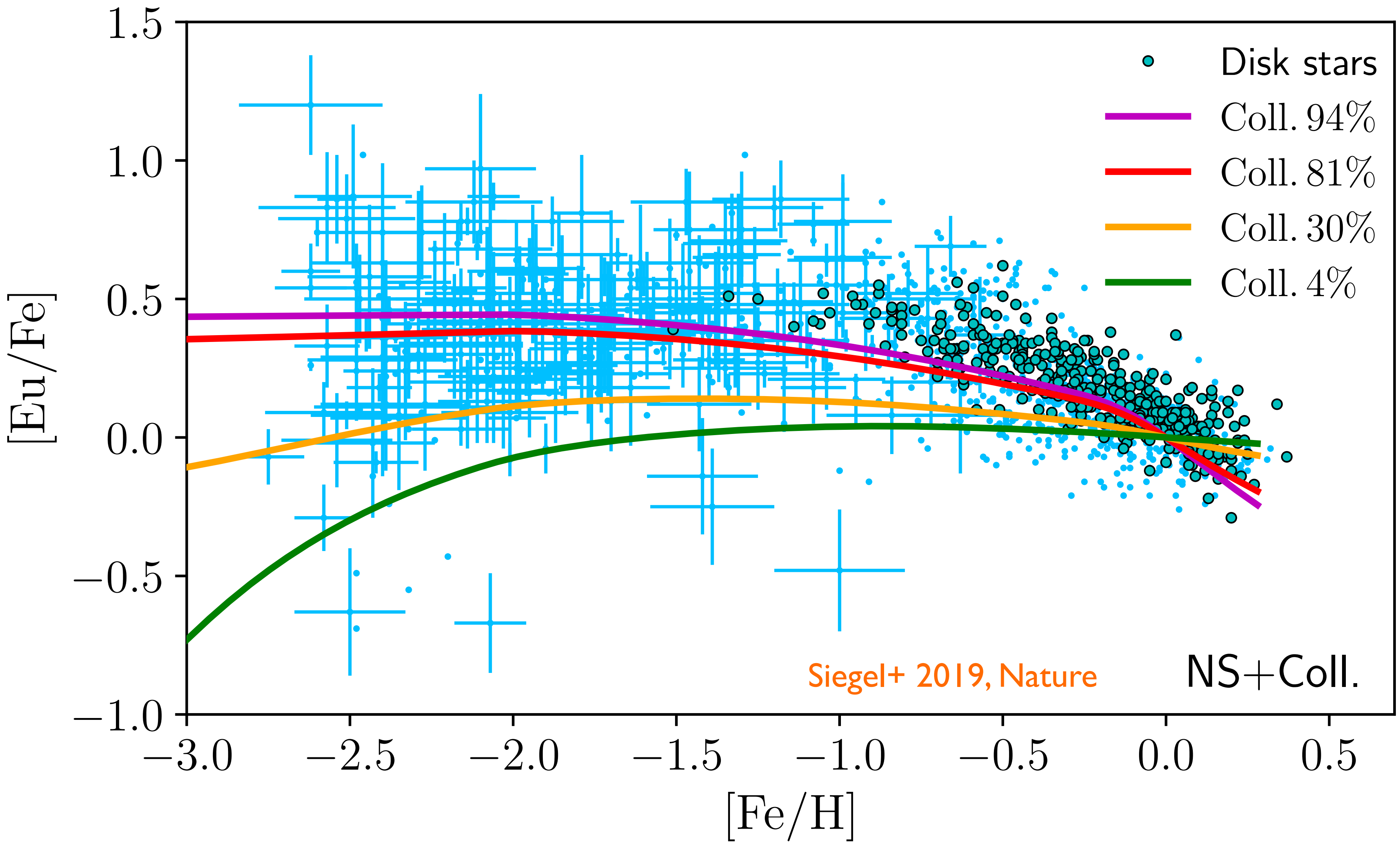
NS mergers follow star formation with a delay time distribution $\sim t^{-1}$

⟶ challenge for *early* Eu enrichment in the halo, dwarf galaxies, globular clusters

⟶ challenge for *late* Eu enrichment of Galactic disk stars

Côté+ 2017, 2018
Hotokezaka+ 2018a
Siegel+ 2019

Are NS mergers alone? Hints from chemical evolution…



Contribution of collapsars

(or MHD supernovae if similar properties)

Rare CCSNe (collapsars, MHD supernovae) enrich ISM promptly without delay

⟶ naturally provide behaviour for both *early and late* Eu enrichment in the Galaxy

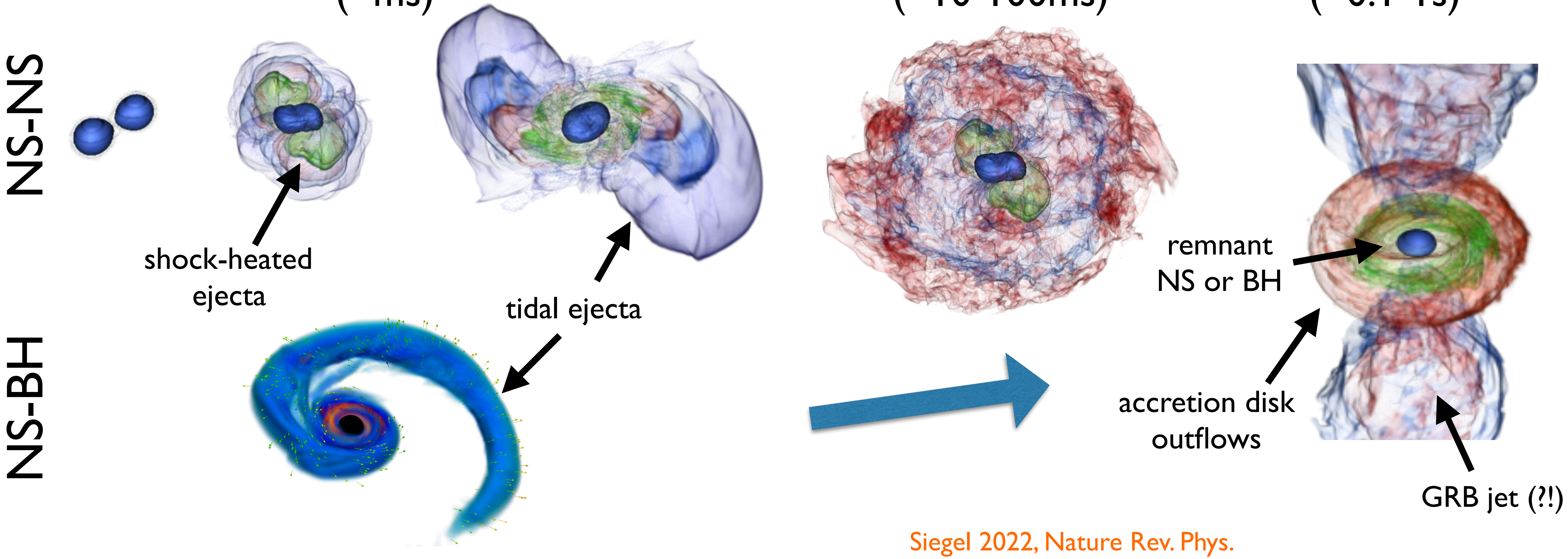
Côté+ 2017, 2018
Hotokezaka+ 2018a
Siegel+ 2019

more on chemical evolution: see *Kevin Schlaufman's talk*

II.

Neutron-star mergers

Neutron-star mergers



dynamical ejecta
(~ms)

wind ejecta
(~10-100ms)

accretion disk ejecta
(~0.1-1s)

NS-NS

NS-BH

shock-heated
ejecta

tidal ejecta

remnant
NS or BH

accretion disk
outflows

GRB jet (?!)

Siegel 2022, Nature Rev. Phys.

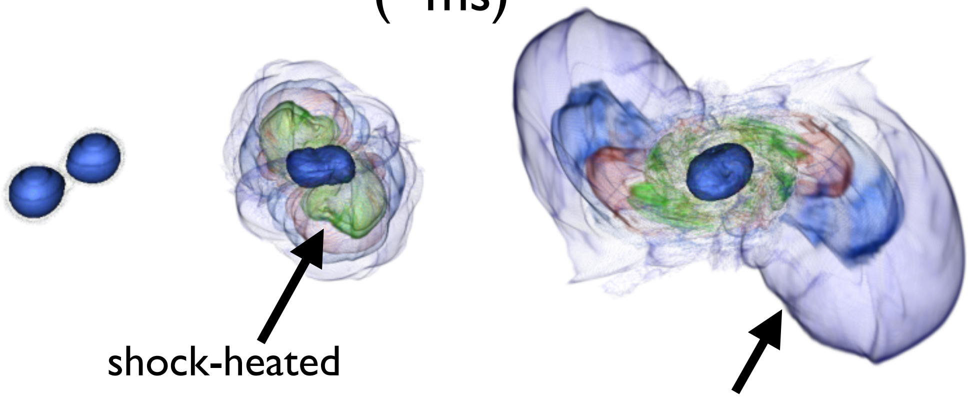
Some complications for NS-NS (complex post-merger phenomenology):

- magnetically driven winds
- neutrino-driven winds
- GWs, non-linear (magneto-)hydrodynamics

Focus here on BNS (NS-BH subdominant wrt r-process): see *Hsin-Yu Chen's talk*

Fast dynamical ejecta: neutron precursor

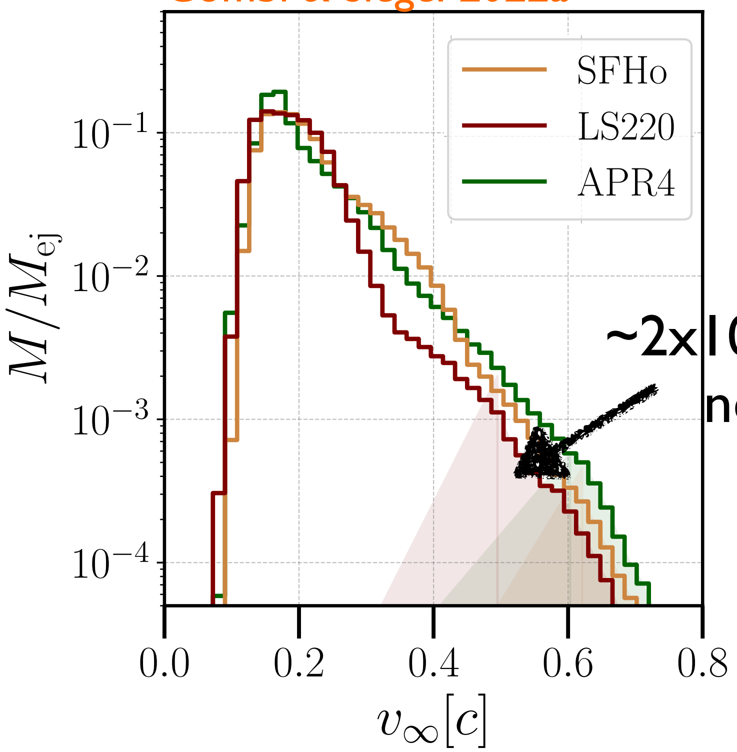
dynamical ejecta
(~ms)



shock-heated
ejecta

tidal ejecta

Combi & Siegel 2022a



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

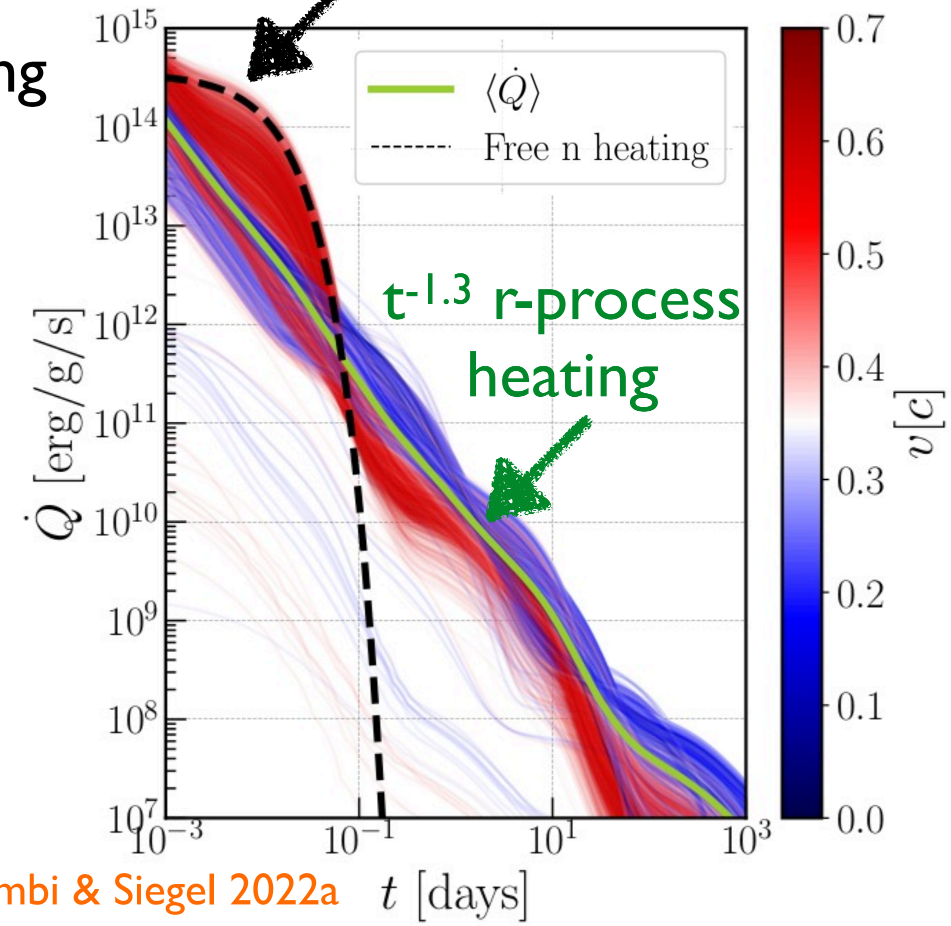
see *Oliver Just's talk*

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

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

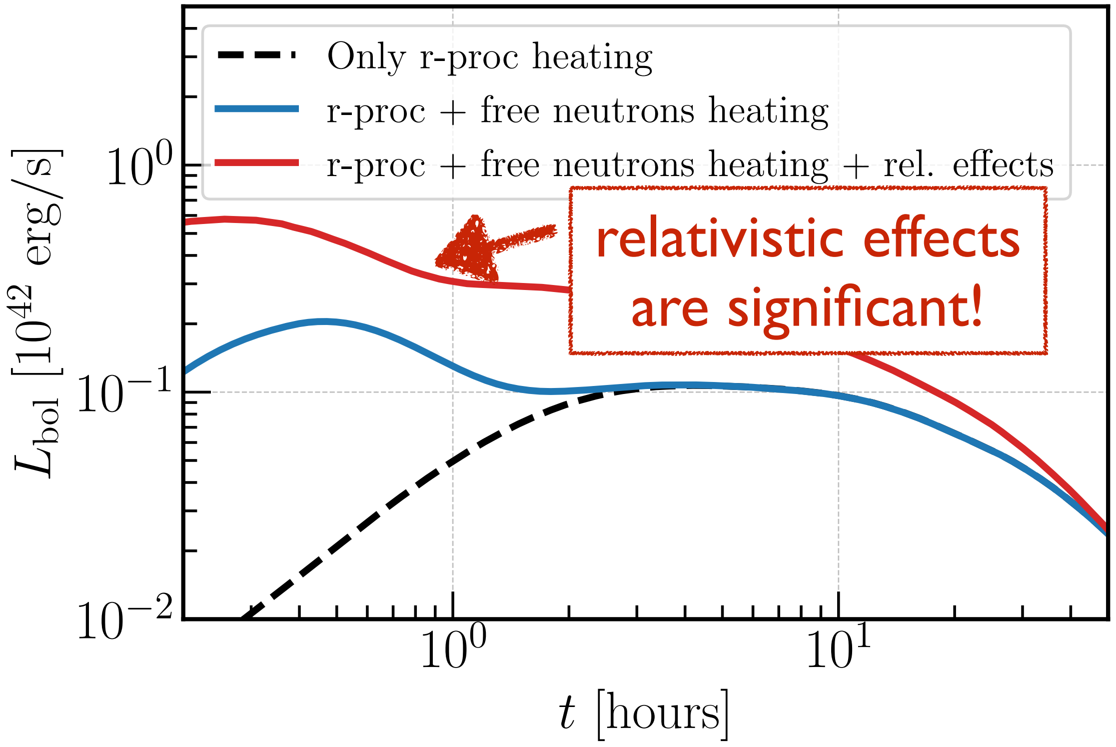
Nuclear heating in ejecta

free neutron decay



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

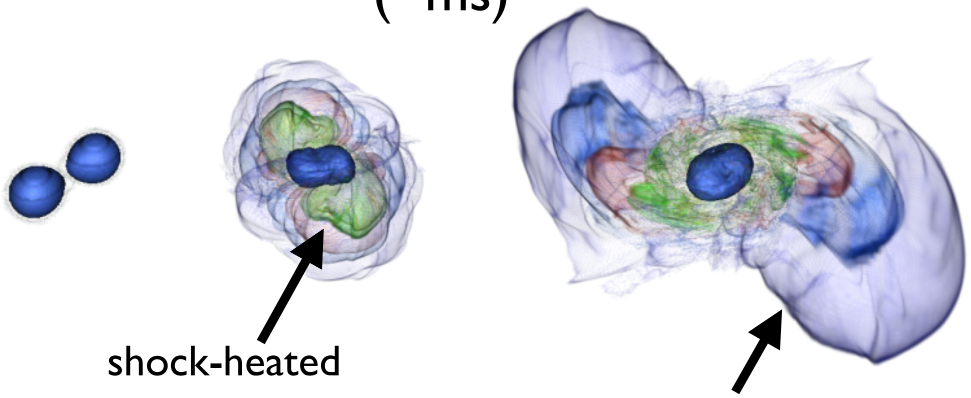
Combi & Siegel 2022a



relativistic effects are significant!

Fast dynamical ejecta: neutron precursor

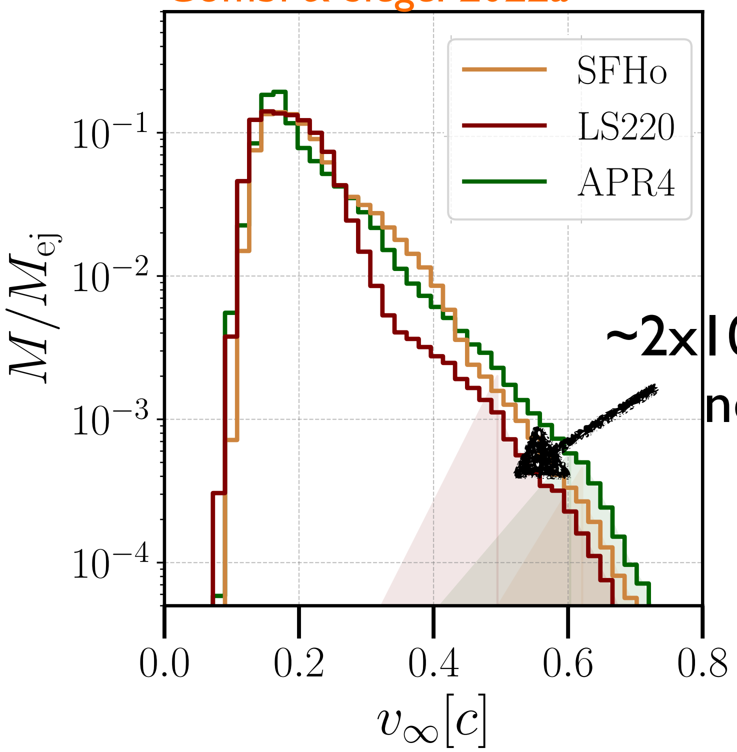
dynamical ejecta
(~ms)



shock-heated
ejecta

tidal ejecta

Combi & Siegel 2022a

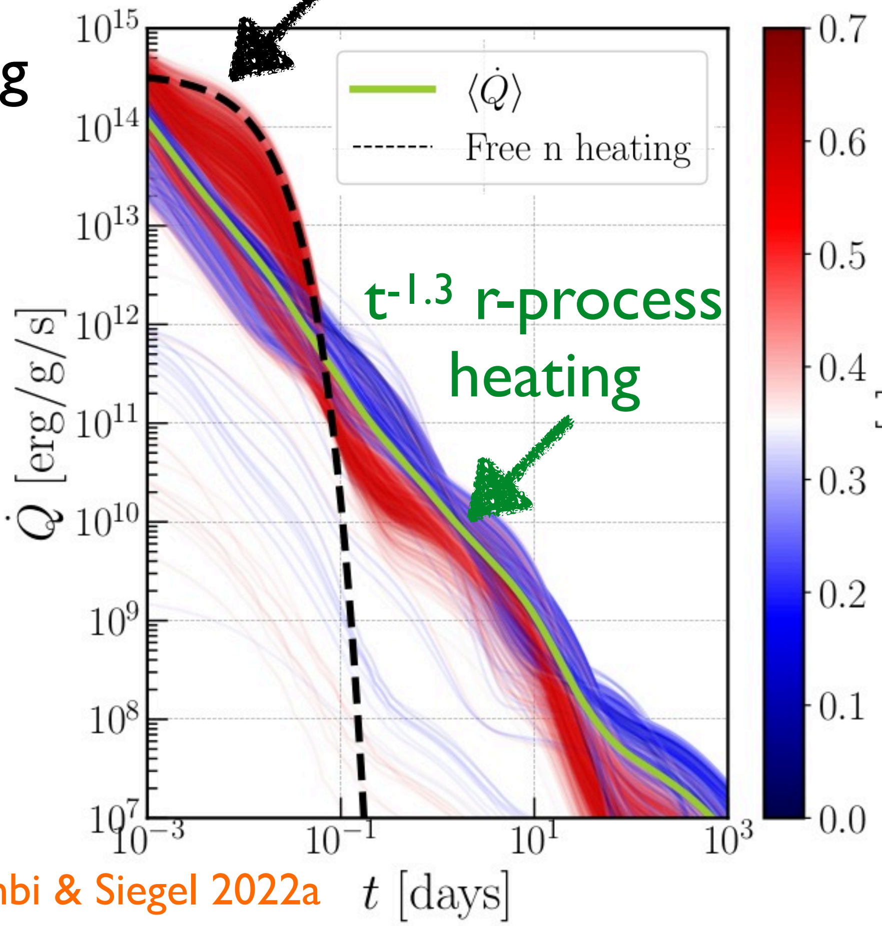


$\sim 2\text{x}10^{-5}\ M_{\rm sun}$ free neutrons

see *Oliver Just's talk*

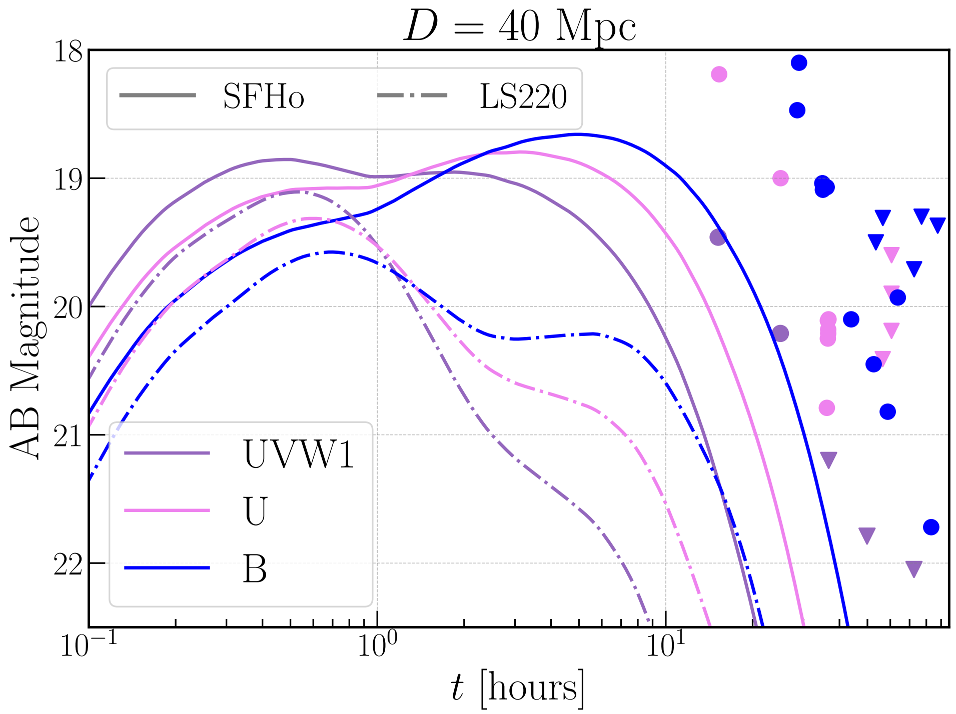
Nuclear heating
in ejecta

free neutron decay



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

Combi & Siegel 2022a

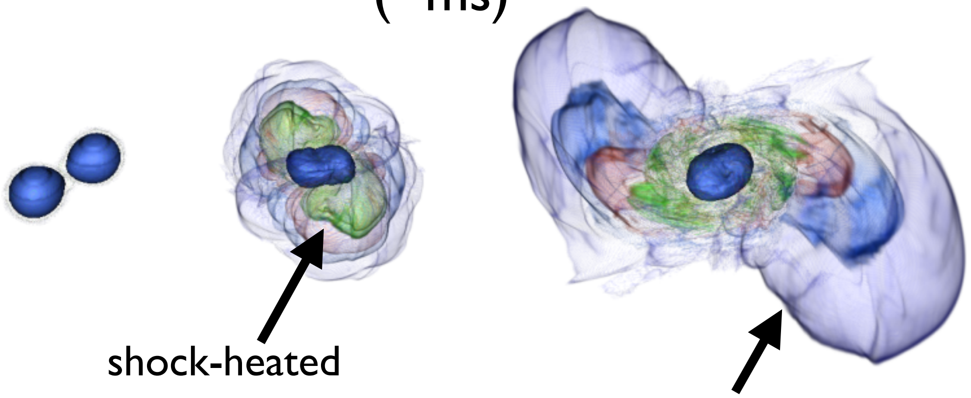


fast, high-Y_e (>0.25), shock-heated ejecta leads to free neutrons

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

Fast dynamical ejecta: X-ray to radio afterglow

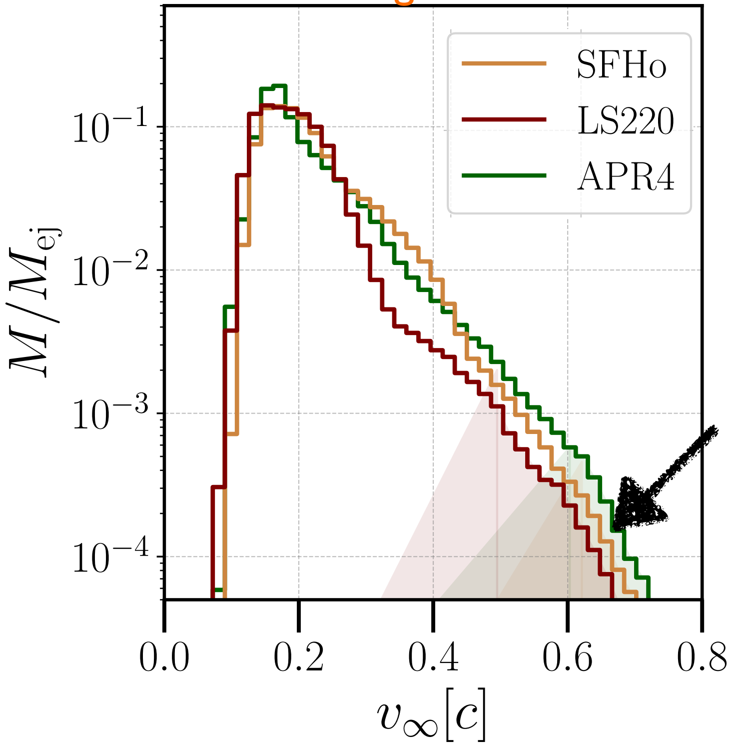
dynamical ejecta
(~ms)



shock-heated
ejecta

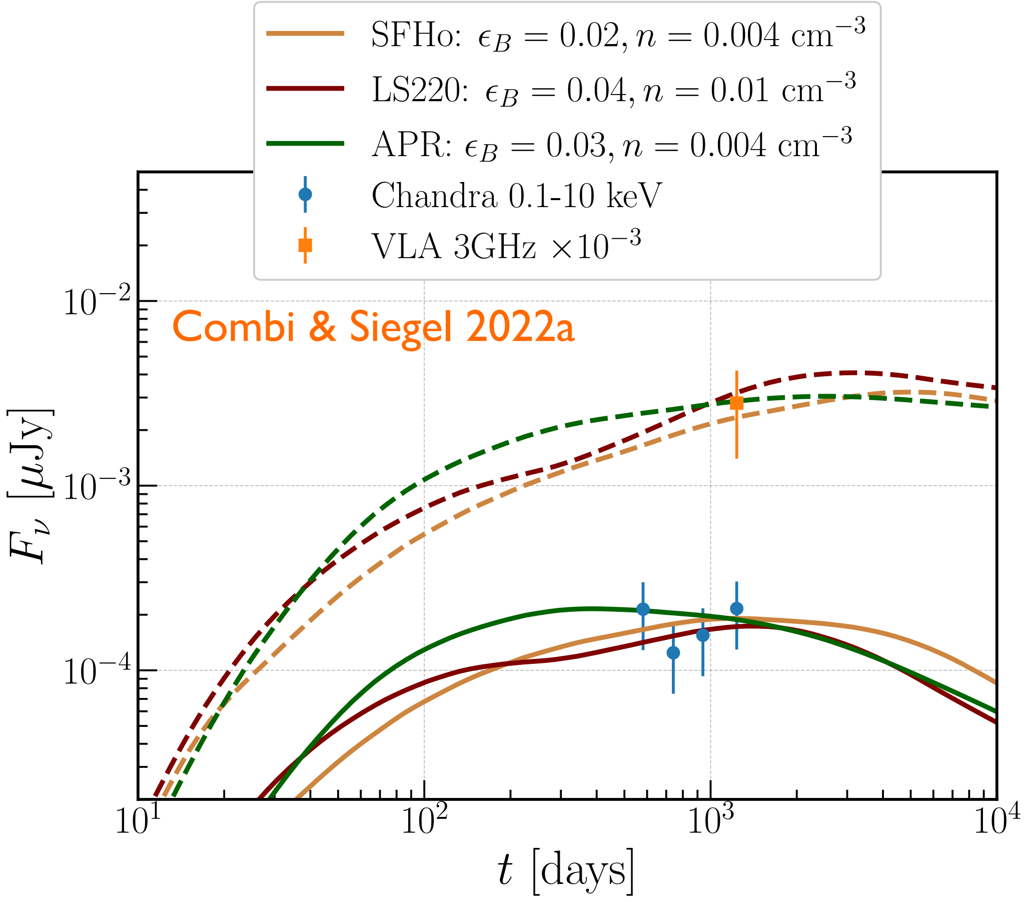
tidal ejecta

Combi & Siegel 2022a

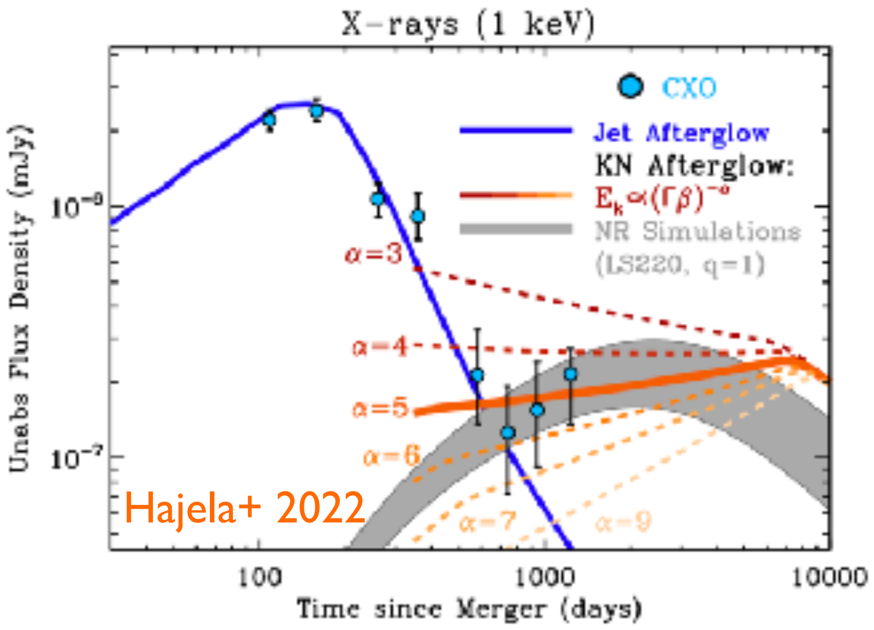


~5x10^{-6} M$_{\mathrm{sun}}$
>0.6c ejecta

see *Coleman Dean's talk*



Combi & Siegel 2022a



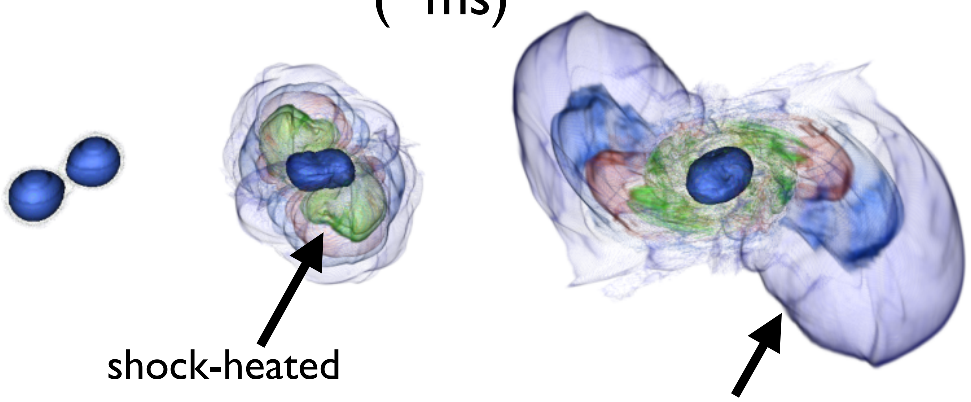
Hajela+ 2022

- fast, high-Y$_{\mathrm{e}}$ (>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

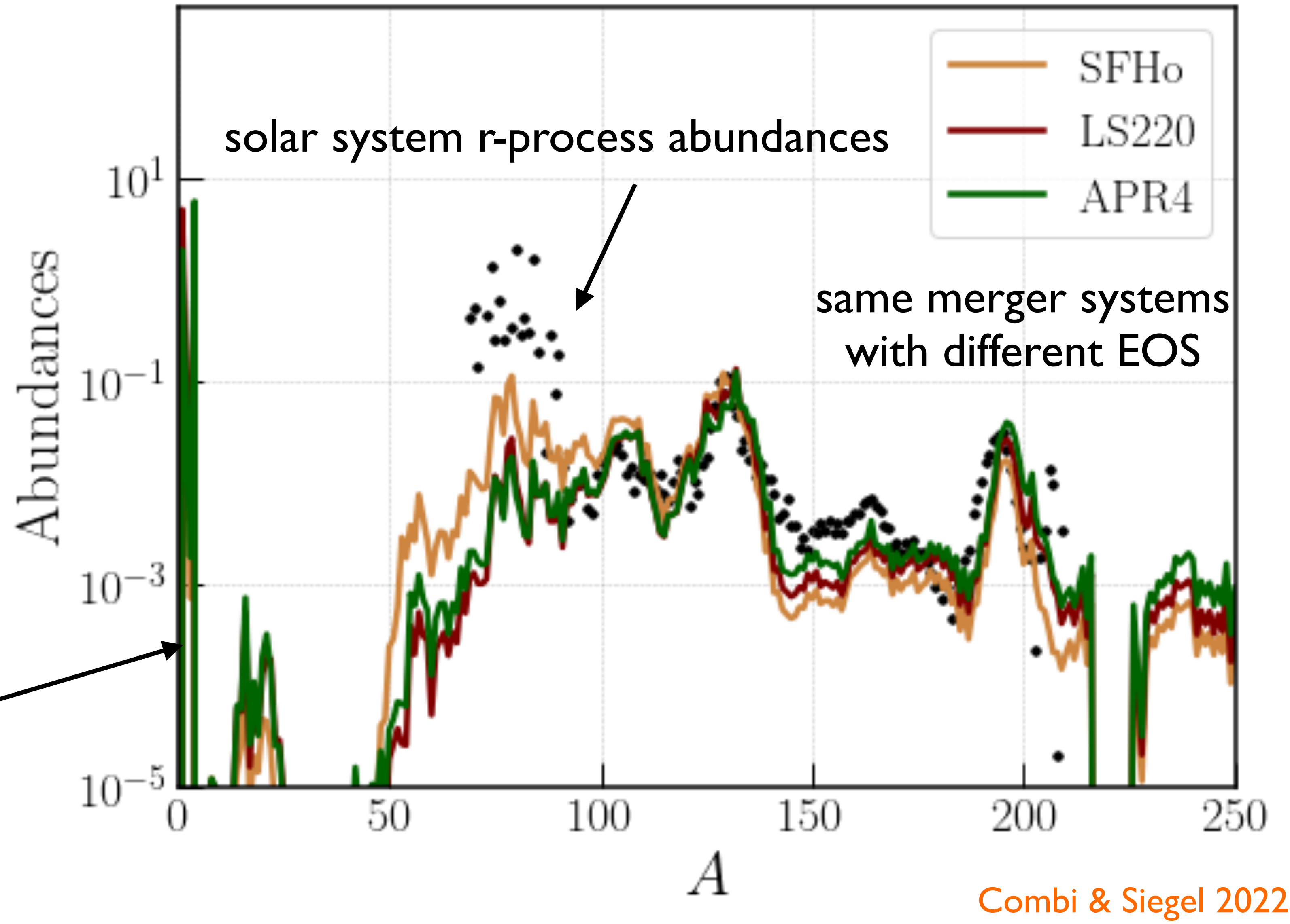
Nucleosynthesis: dynamical ejecta

dynamical ejecta (~ms)



shock-heated ejecta

tidal ejecta



free neutrons

Combi & Siegel 2022a

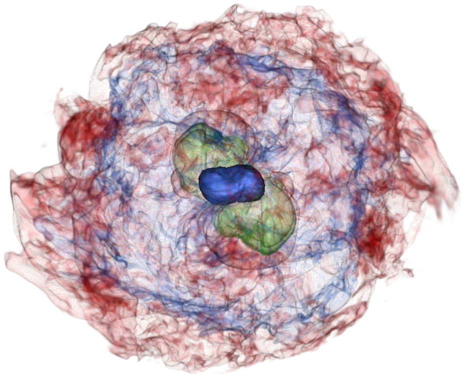
- robust 2nd - 3rd peak r-process
- original mechanism for producing heavy elements in mergers Rosswog+ 1999
- moderate variations among light r-process elements depending on EOS, mass ratio, neutrino transport
- “neutron precursor” of kilonovae (free neutron-decay powering UV transient)

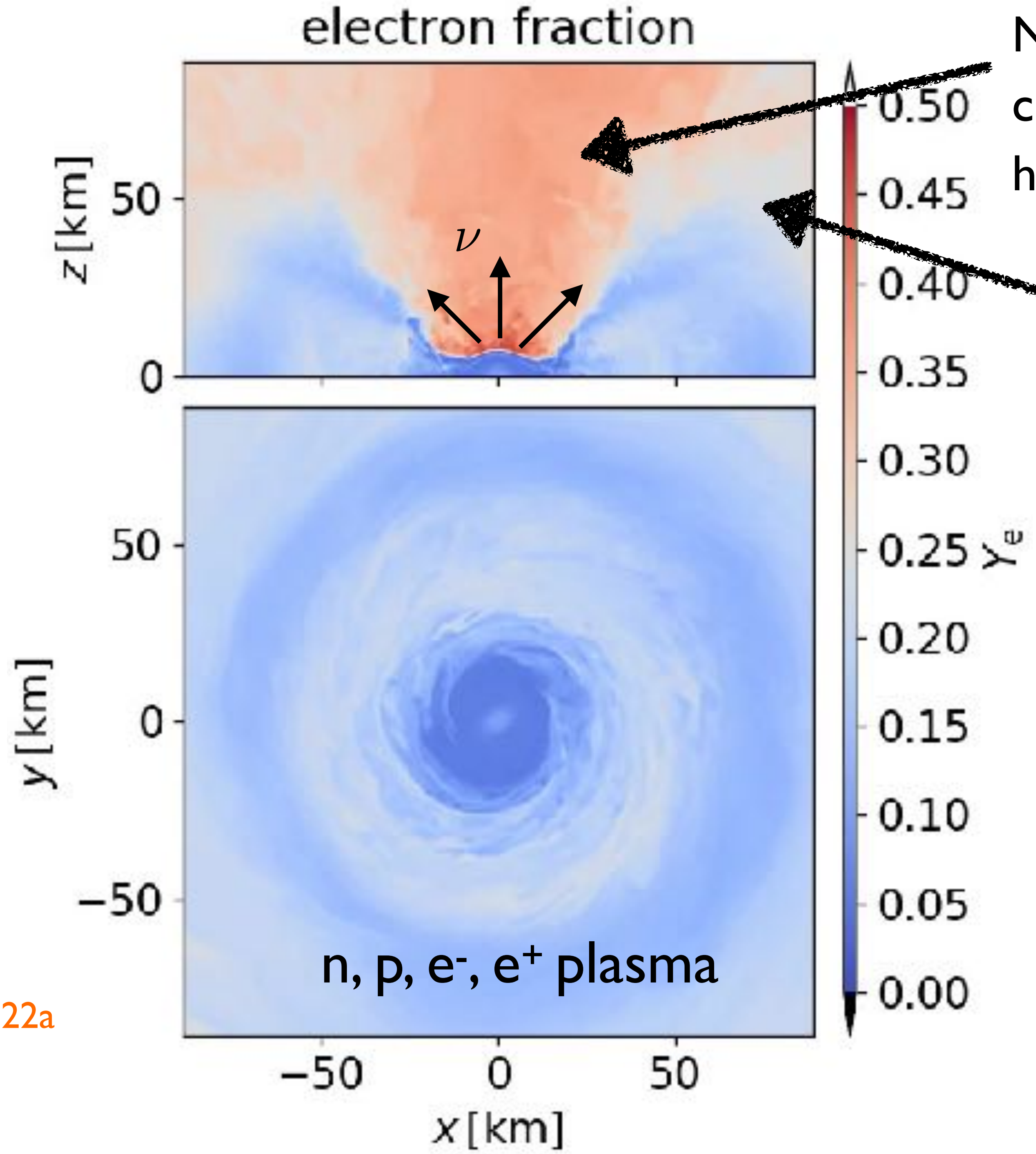
Radice+ 2018
Kullmann+ 2021
Fujibayashi+ 2022

Metzger+ 2015
Kullmann+ 2021

Post-merger winds

wind ejecta
(~10-100ms)





Neutrino irradiation changes the composition of the ejecta: high-Y_e (>0.25), hot ejecta

medium-Y_e, hot disk wind ejecta

Composition (Y_e) determined by:
(radiation transport!)

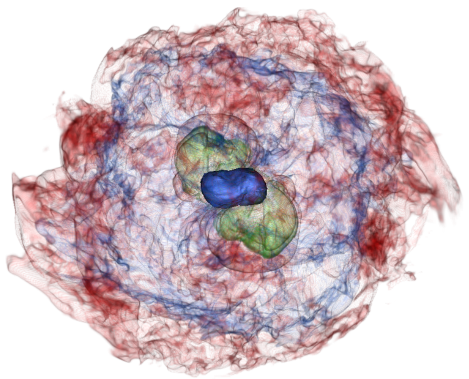
$$e^- + p \leftrightarrow n + \nu_e$$
$$e^+ + n \leftrightarrow p + \bar{\nu}_e$$

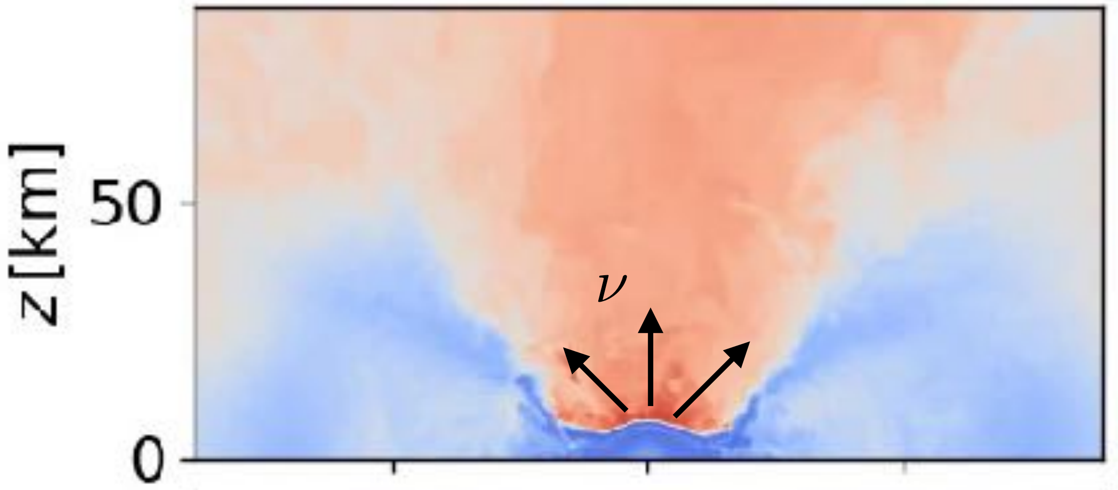
Combi & Siegel 2022a

Post-merger winds

see *Dhruv Desai's talk*

wind ejecta
(~10-100ms)

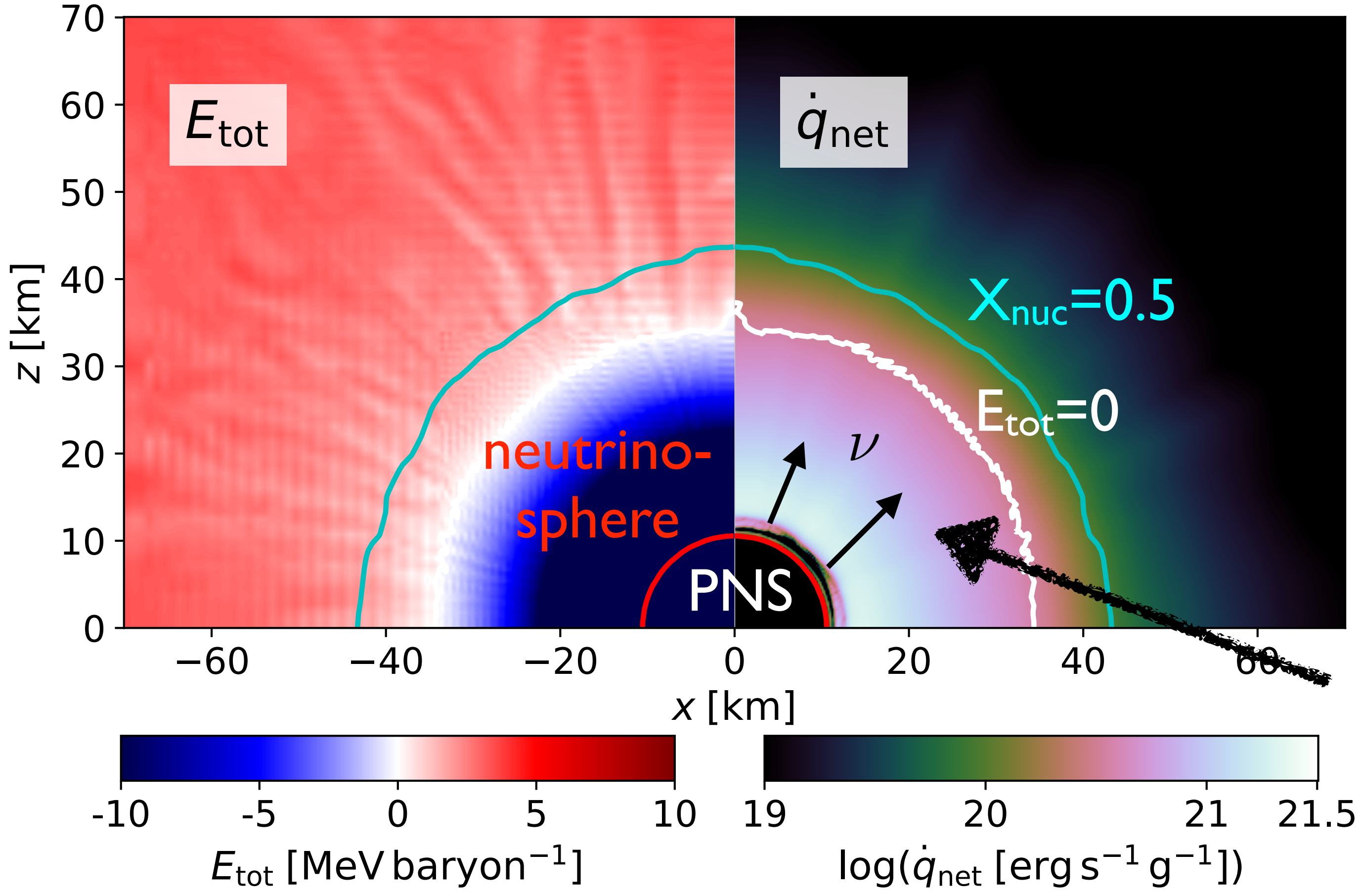




Combi & Siegel 2022a

Neutrino-driven winds similar to proto-neutron stars (PNS) in core-collapse supernovae

Perego+ 2014

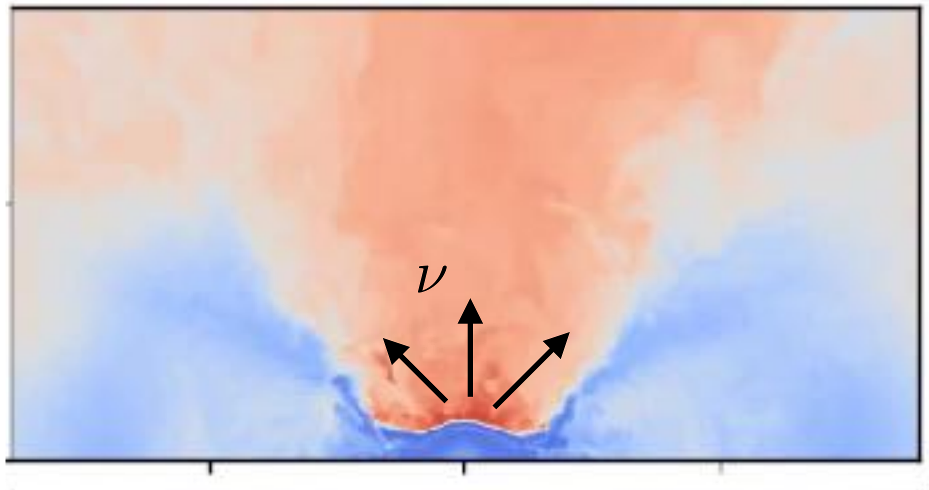


Desai, Siegel, Metzger 2022

"Gain layer"
(neutrino absorption dominates emission)

- Composition (Y_e) of wind determined by absorption
- In PNS: each nucleon absorbs ~10 neutrinos to become unbound ⟶ $Y_e \simeq 0.45$–0.55

Complication: magnetic fields



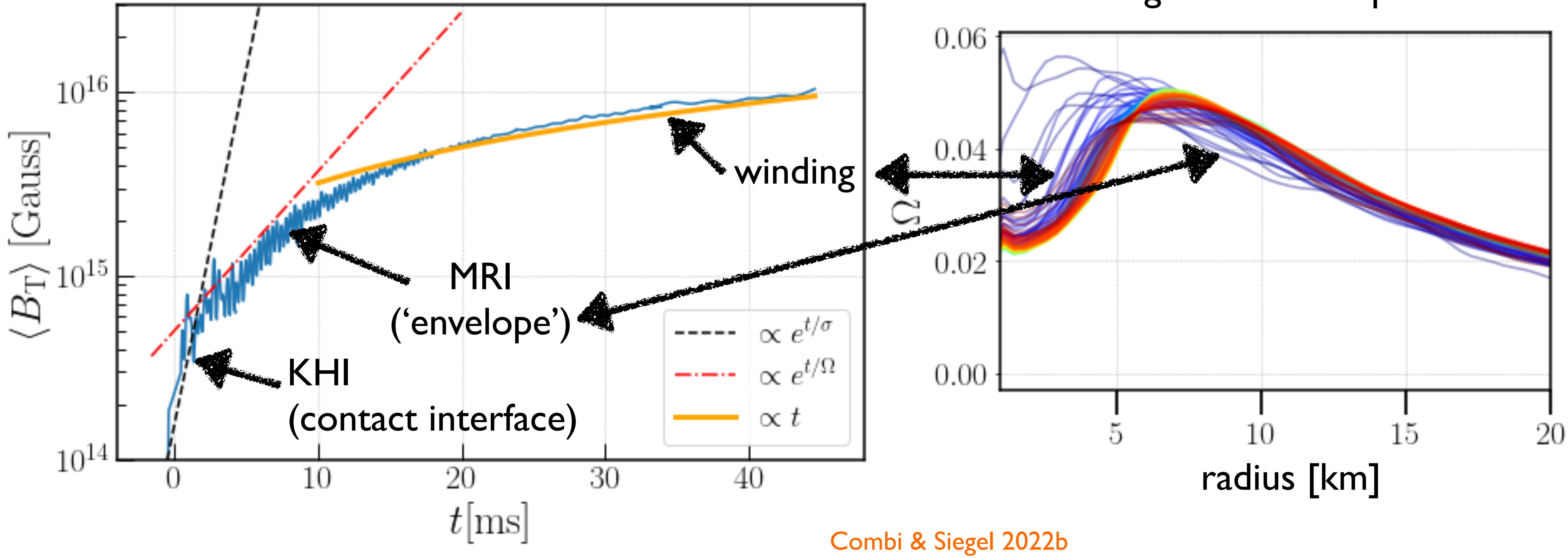
Magnetic field amplification in the remnant:

- Kelvin-Helmholtz instability (KHI)
- magneto-rotational instability (MRI)
- magnetic winding

see also
Pedro
Espino's talk

toroidal magnetic field amplification

angular rotation profile



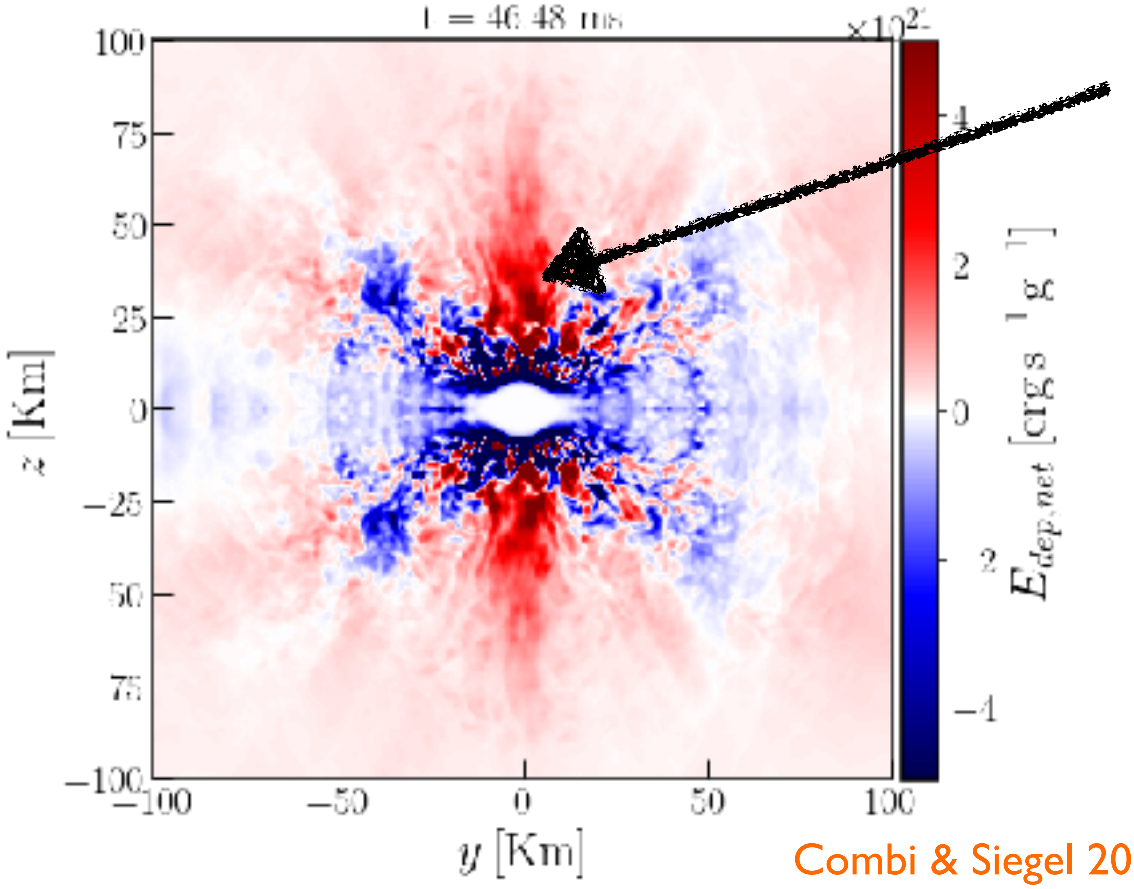
winding

MRI
('envelope')

KHI
(contact interface)

Combi & Siegel 2022b

Magnetic tower with neutrinos—a ‘jet’ emerges



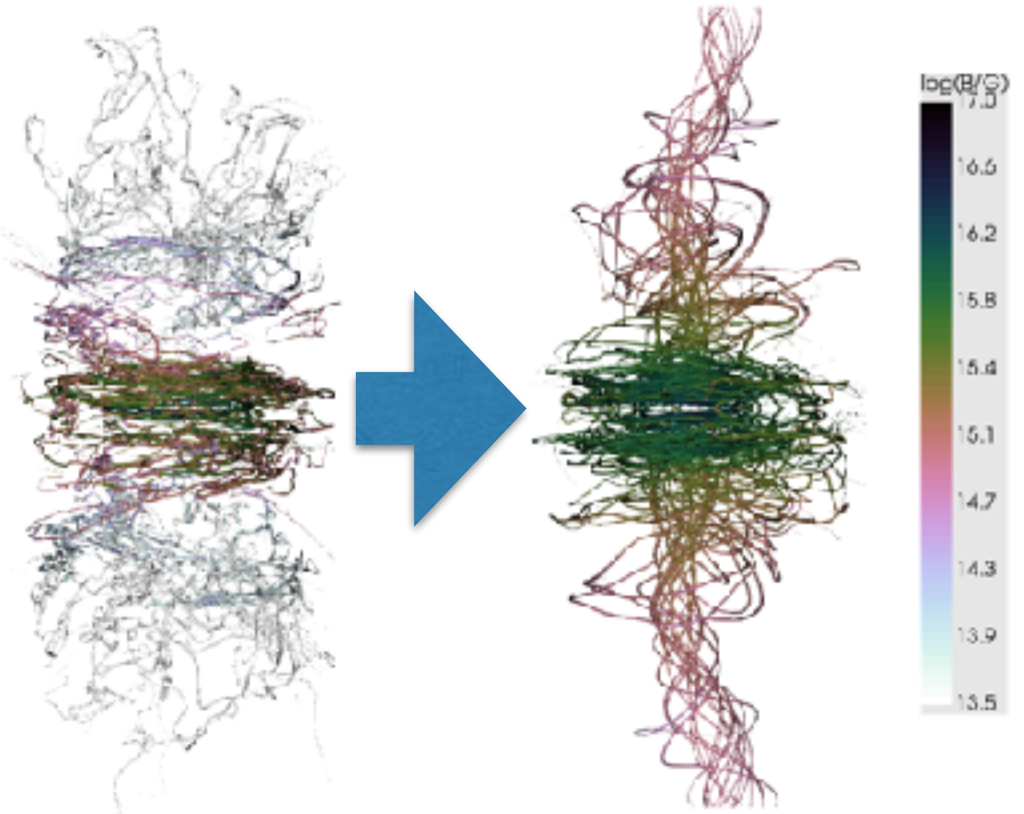
Neutrino absorption in polar regions instrumental in generating magnetic tower and ‘stabilizing’ jet structure

Fast outflow ~0.4 c with sufficiently low Y_e for 1st—2nd peak r-process

Mösta+2020
Curtis+ 2021
Combi & Siegel 2022b

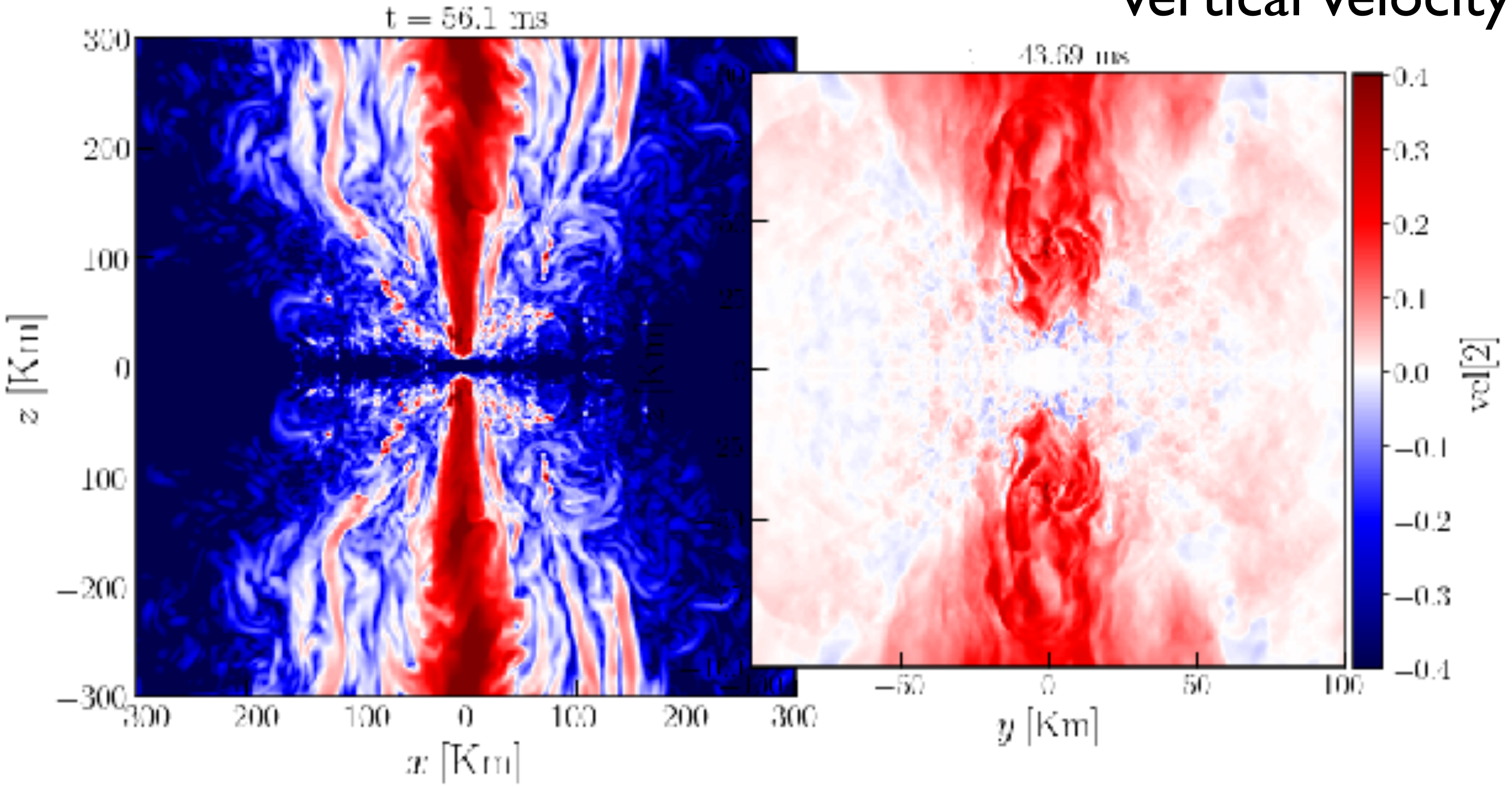
$$M_{\rm ej} \sim (10^{-3} - 10^{-2}) M_\odot \left(\frac{t_{\rm NS}}{0.1\,{\rm s}} \right)$$

Combi & Siegel 2022b



magnetization

vertical velocity



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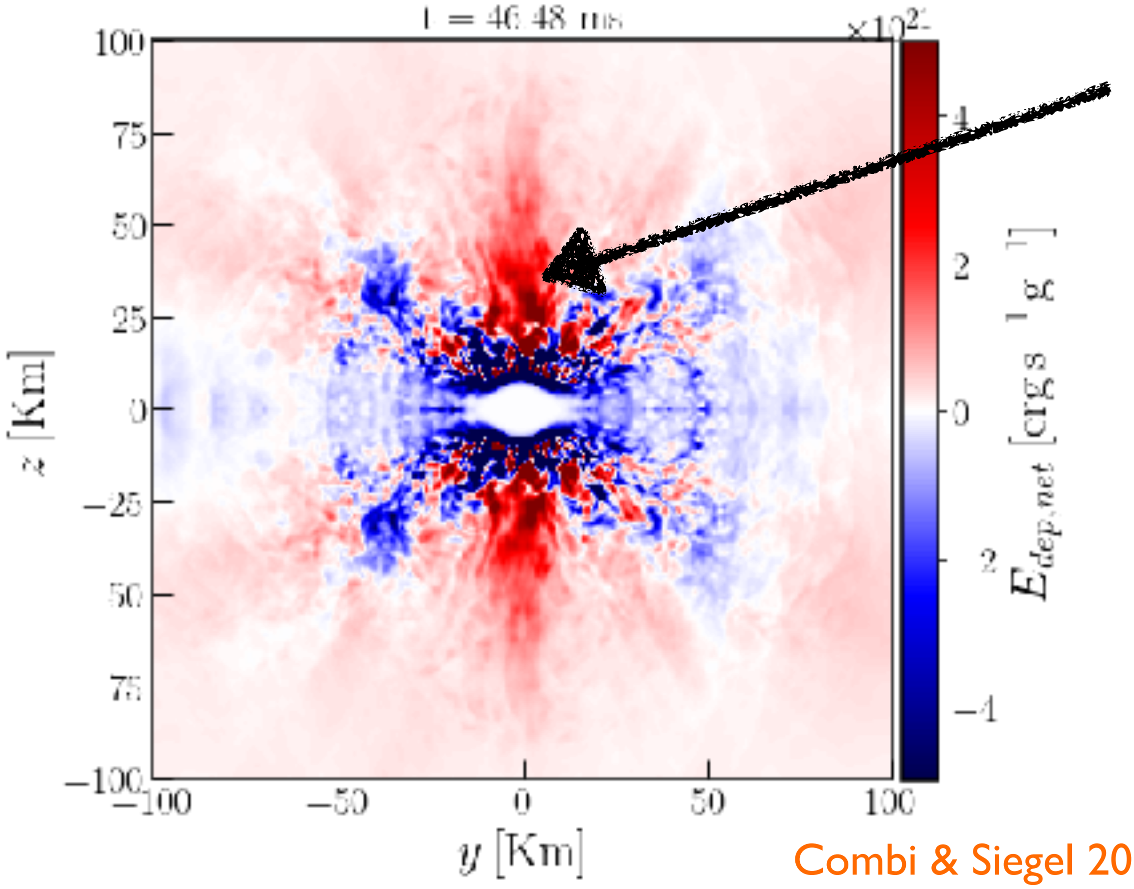

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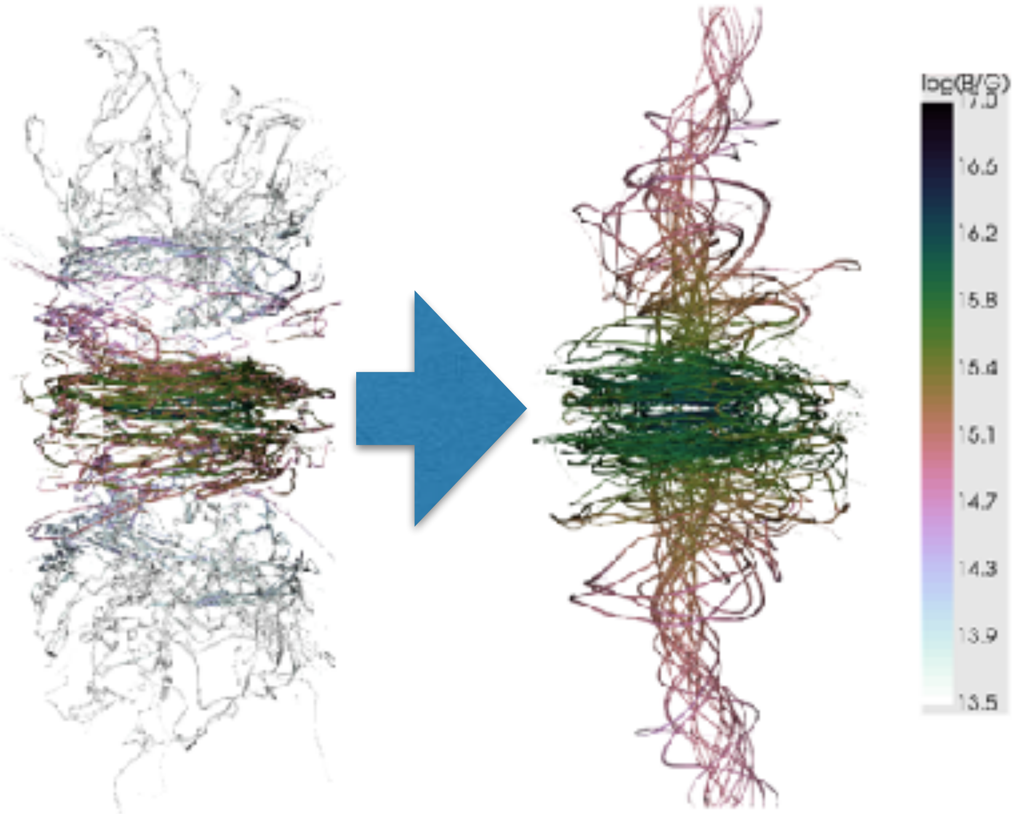
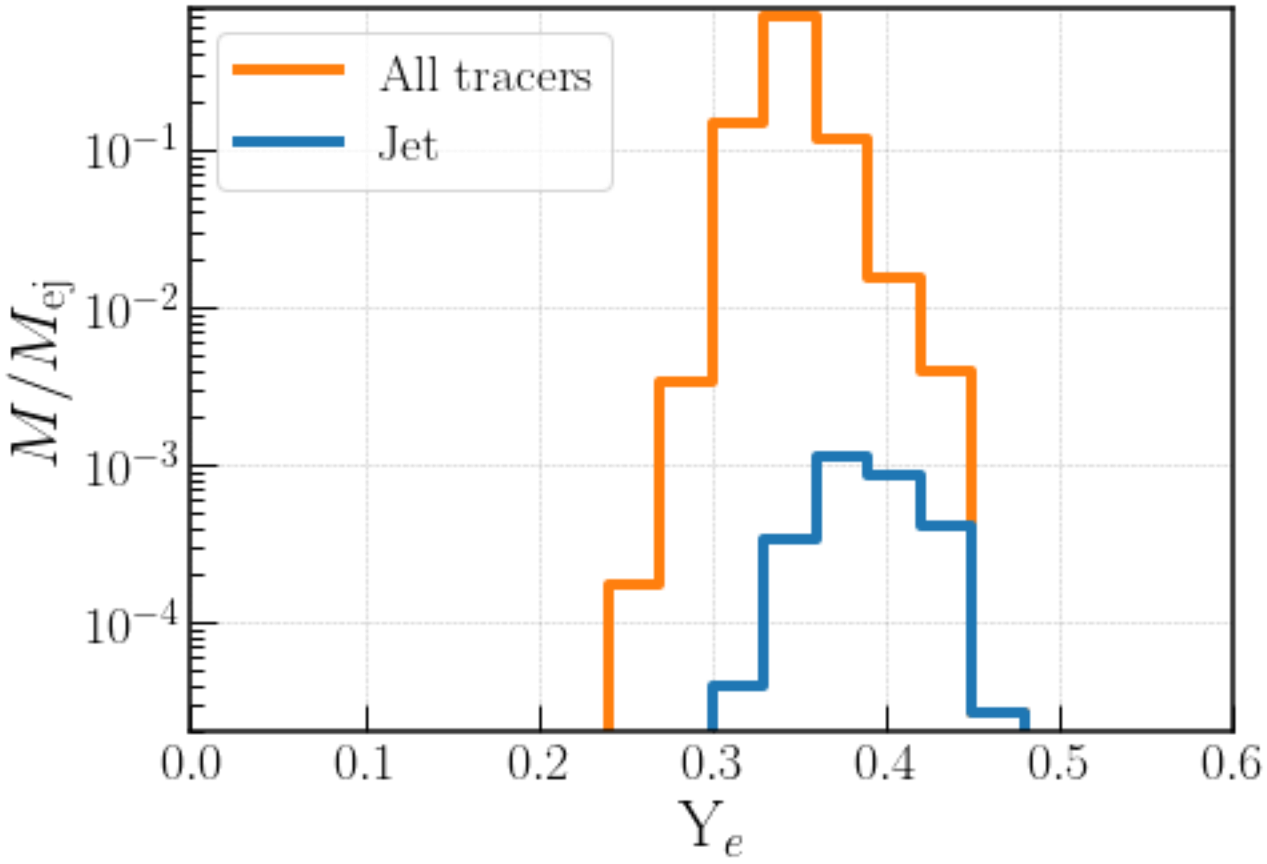
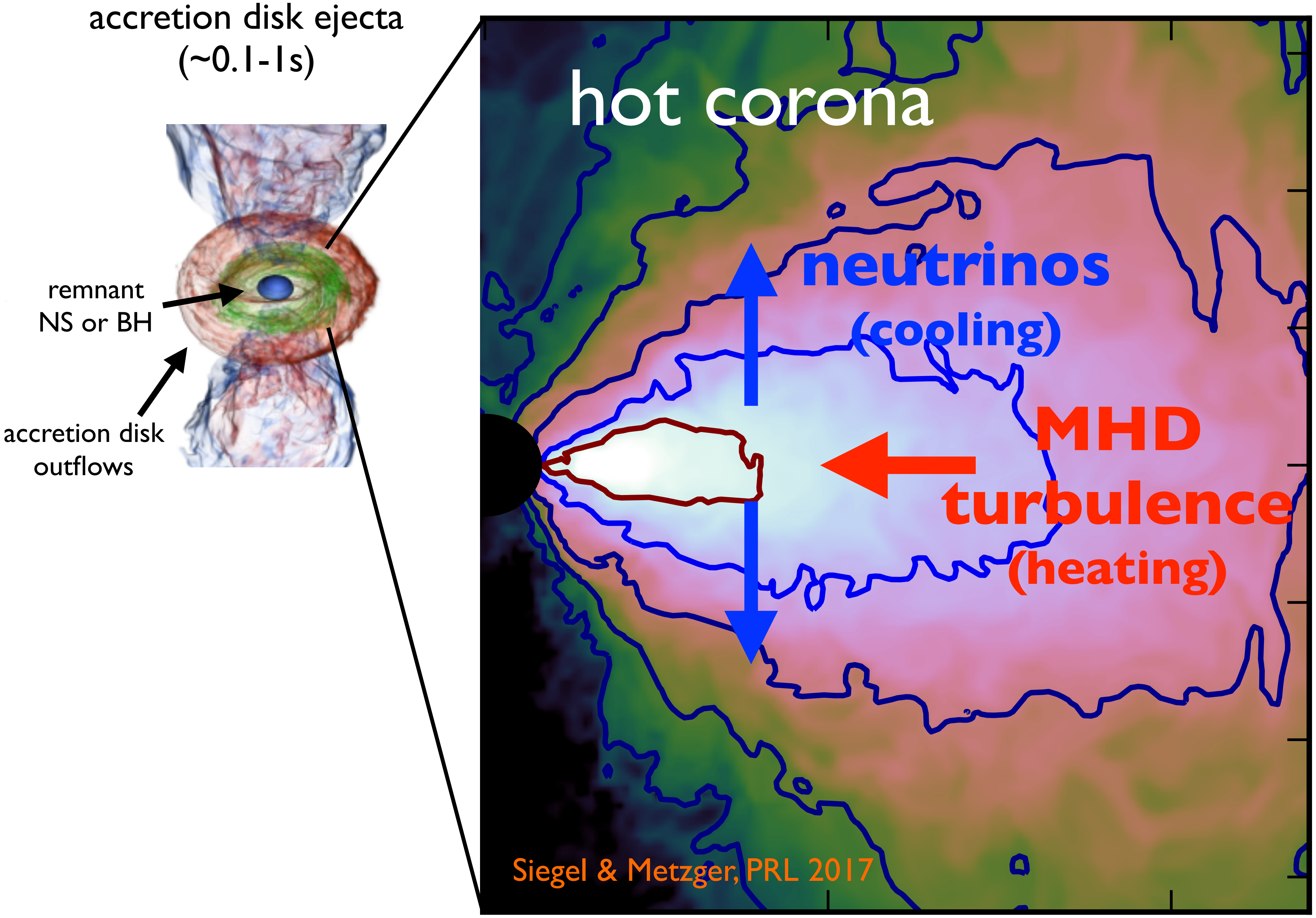




Post-merger disk ejecta



Siegel & Metzger, PRL 2017

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

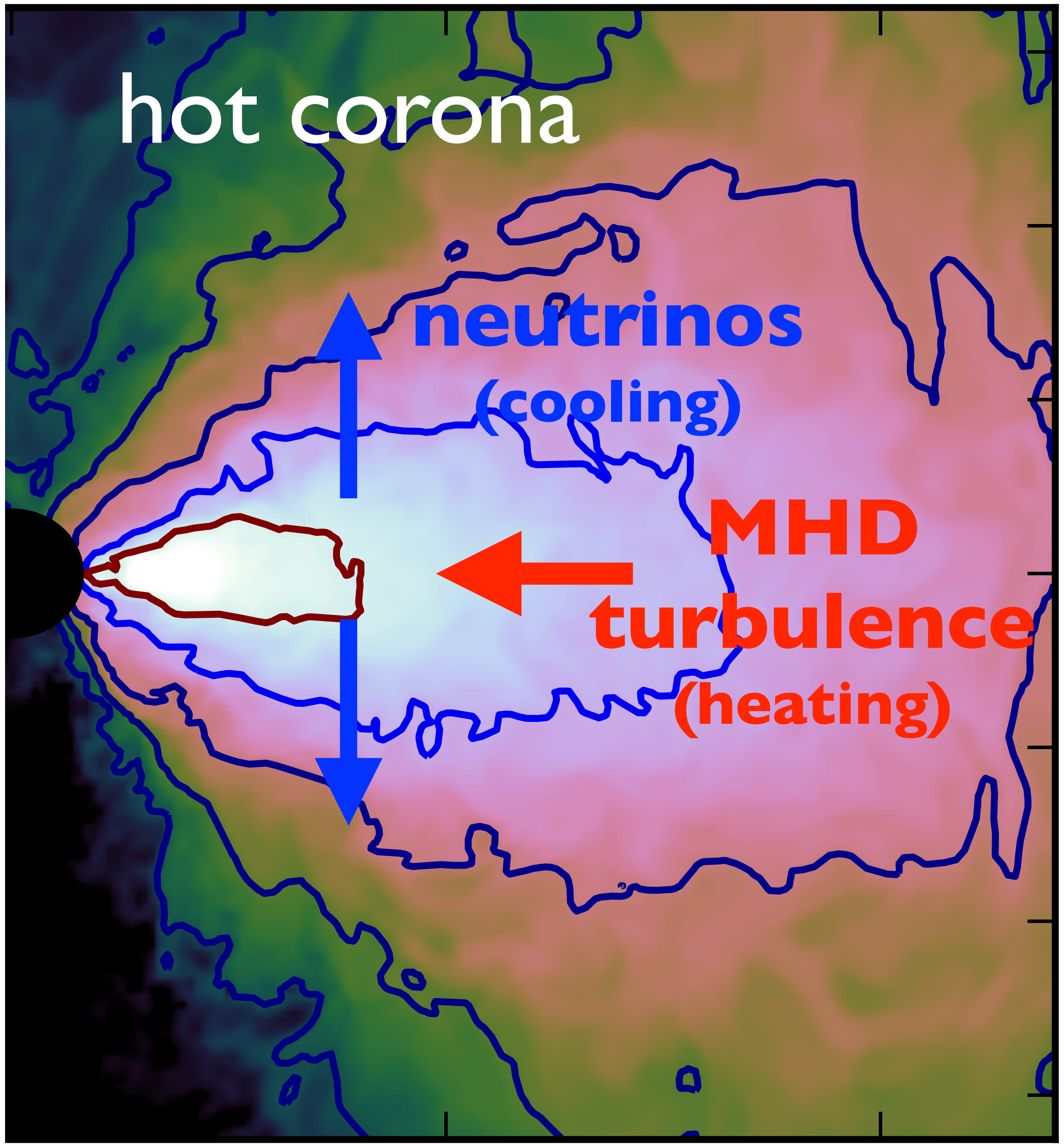
  Siegel & Metzger, PRL 2017
  Chen & Beloborodov 2007
- Total ejecta can dominate all other channels

  Siegel & Metzger 2018
  Fernandez+ 2019
- Detailed nucleosynthesis varies across parameter space

  De & Siegel 2021
  Fernandez+ 2020
  Just+ 2021

heating-cooling imbalance in corona & nuclear recombination launches wind

Post-merger disk ejecta



Siegel & Metzger, PRL 2017

heating-cooling imbalance in corona &
nuclear recombination launches wind

Weak interactions are key for composition, nucleosynthesis, kilonova

Importance of weak interactions:

neutrino emission

$$\mathcal{R} = \frac{Q_\nu^-}{Q^+} \sim \frac{1}{2}$$

viscous heating (MRI)

1D alpha-disk model

Ignition threshold: De & Siegel 2021

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

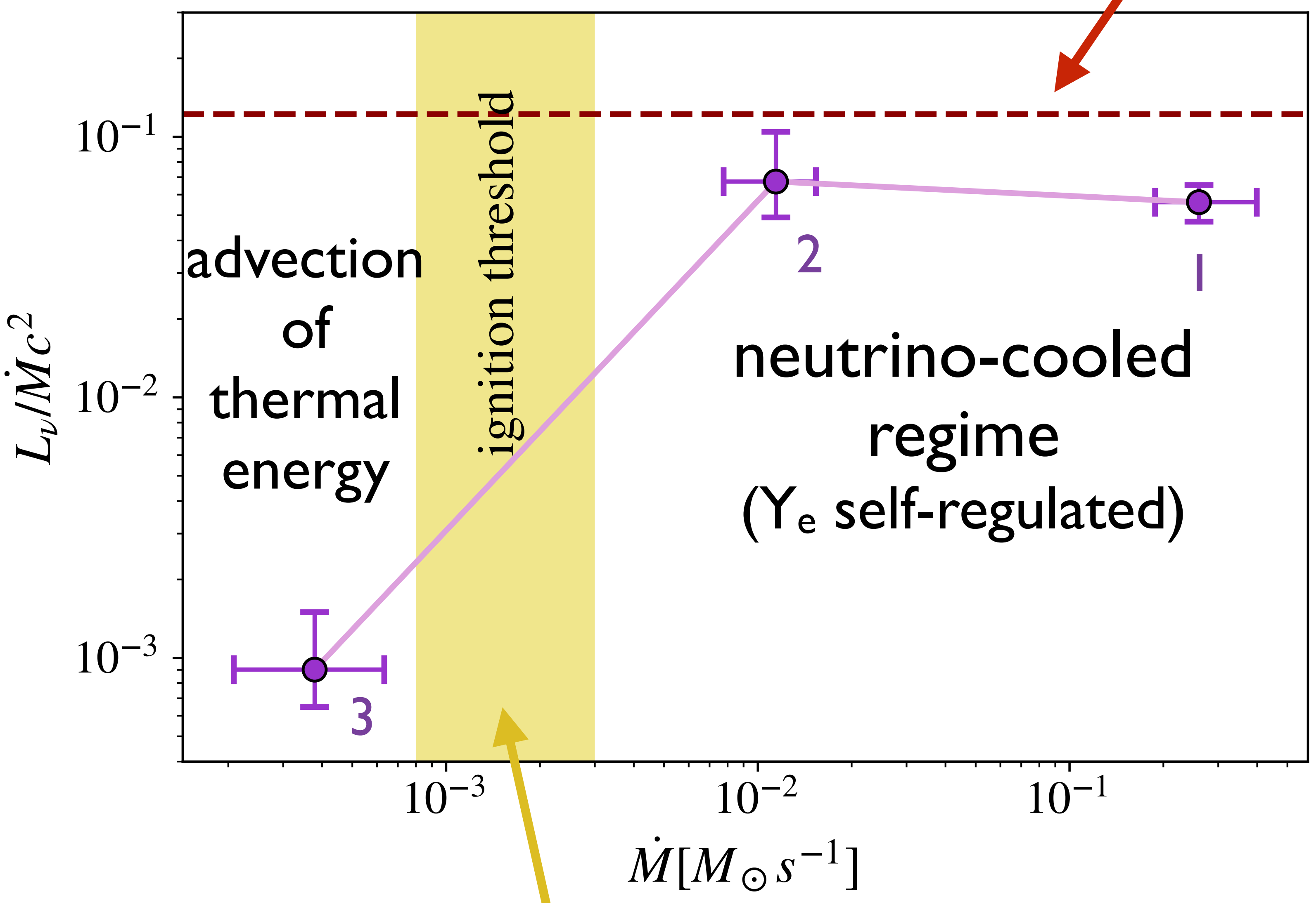
Accretion rate controls nucleosynthesis!

⟶ different 'nucleosynthesis bands'

Ignition of weak interactions

De & Siegel 2021

maximal radiative efficiency



analytic estimate from 1D alpha-disk model

simulated GRMHD disks

Ejected disk mass:

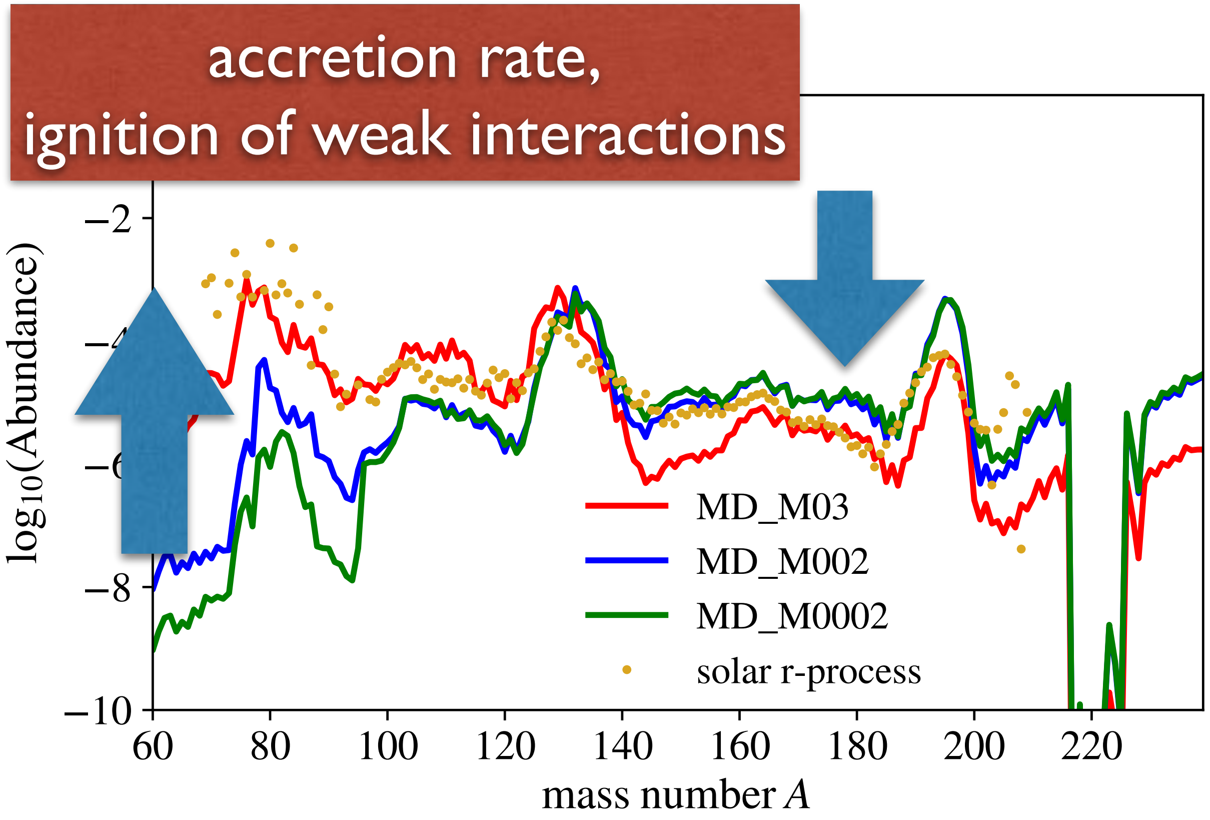
1	~ 35%
2	~ 35%
3	~ 60%

see also:
Siegel & Metzger 2018
Fernandez+ 2019, 2020
Christie+ 2019

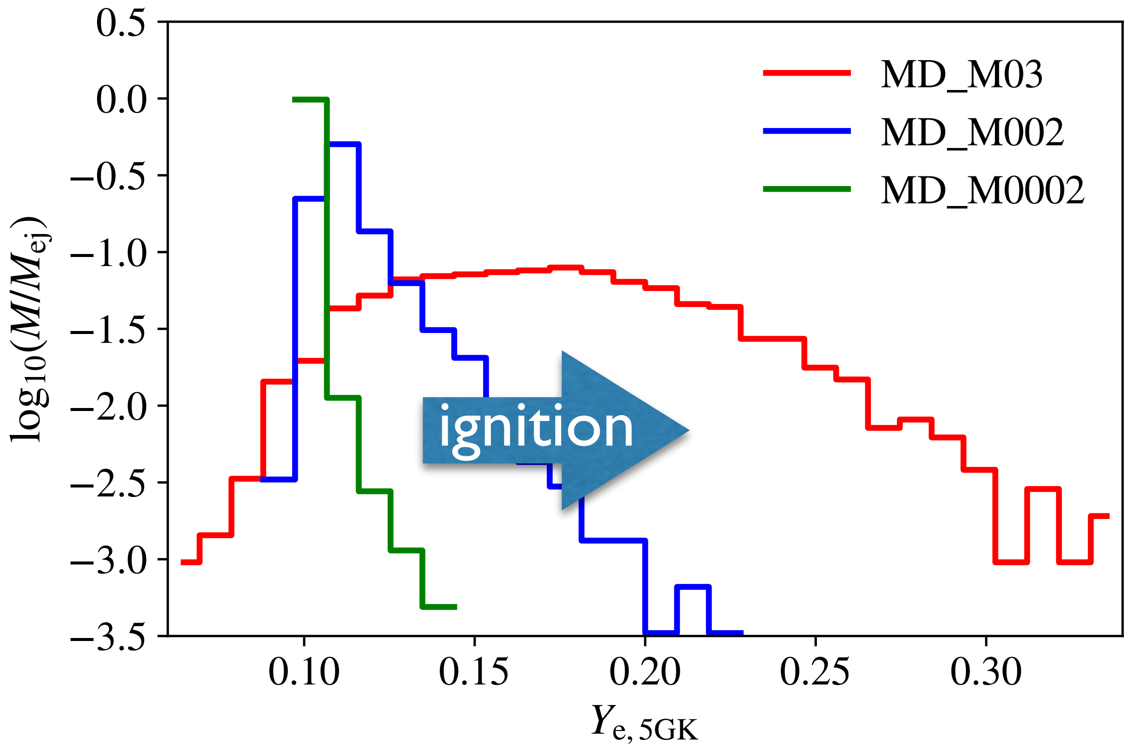
more effective evaporation in the absence of cooling!

Nucleosynthesis

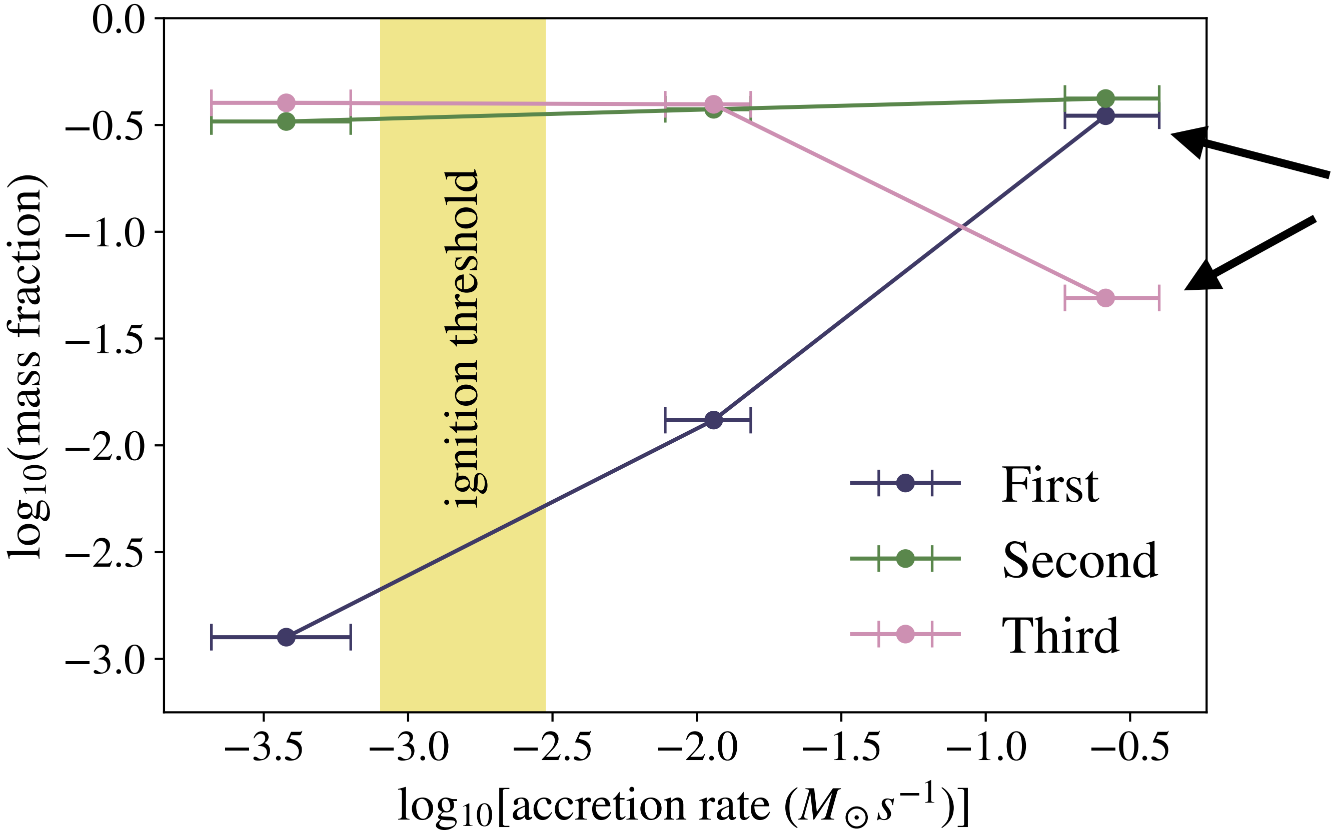
De & Siegel 2021



accretion rate, ignition of weak interactions



R-process peaks



trends to continue as neutrino absorption becomes important

(see Miller+ 2019, Li & Siegel 2021)

self-regulation above ignition leads to well-defined nucleosynthesis pattern similar to solar over wide range of accretion rates (disk masses)

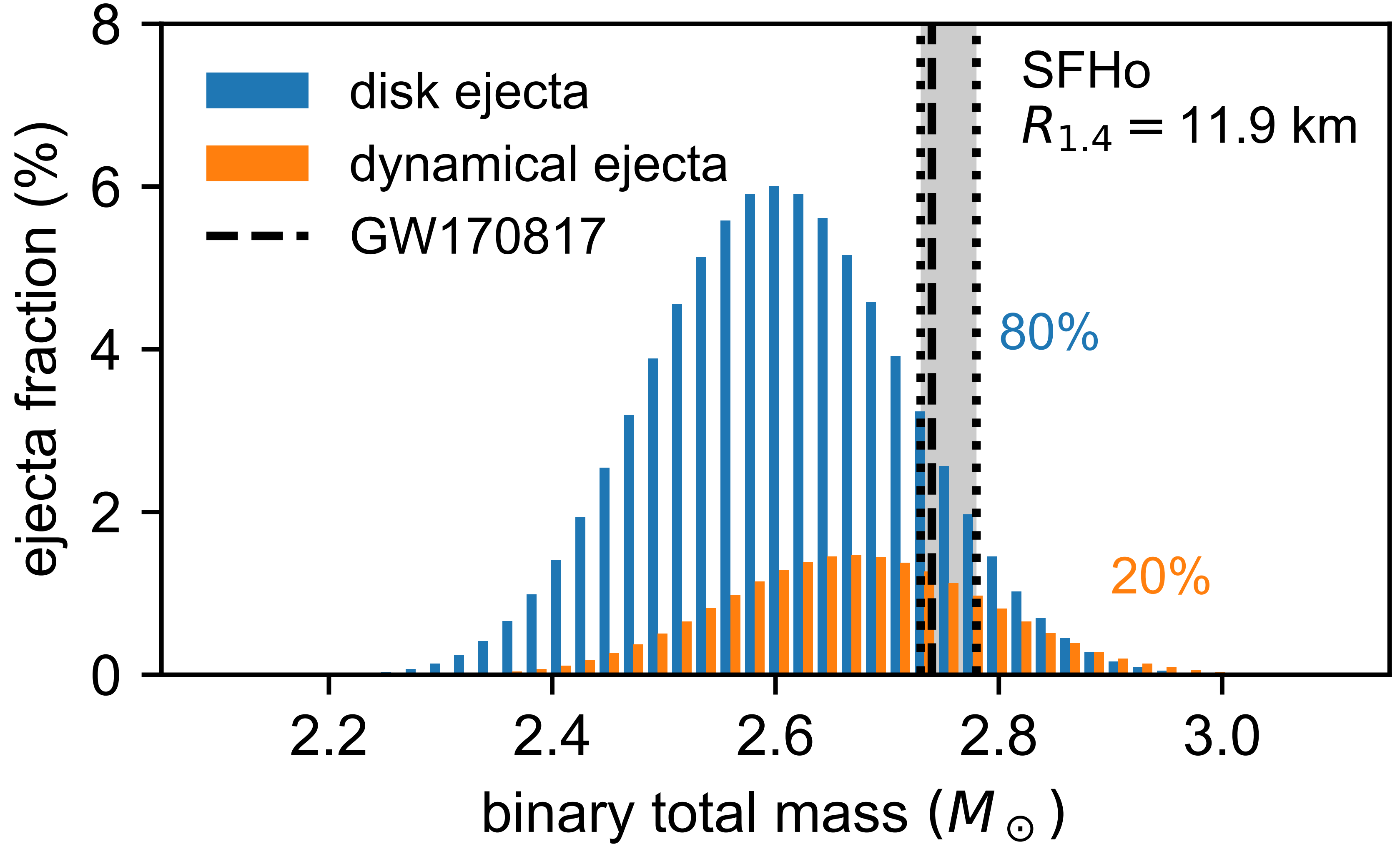
more on disks: *Steven Fahlman and Ariadna Murguia Berthier's talks*

III.

Conjectures

Future GW events: exploring BNS parameter space

Siegel 2022, Nature Rev. Phys.



Expected ejecta distribution for galactic BNS distribution

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

Conjecture: self-regulation and universality

Siegel 2019, Siegel 2022, Nat. Rev. Phys.

- Post-merger disks may dominate BNS ejecta (in a population sense)

- Typical disks (BNS similar to Galactic DNS) are born above ignition in the self-regulated regime

  Radice+ 2018, Fujibayashi 2022, Combi & Siegel 2022a

  → well defined nucleosynthesis regime, similar to solar, robust 2nd-3rd peak pattern

  → most/significant disk mass ejected during this self-regulated phase < 0.5-1s ('MHD driven outflows')

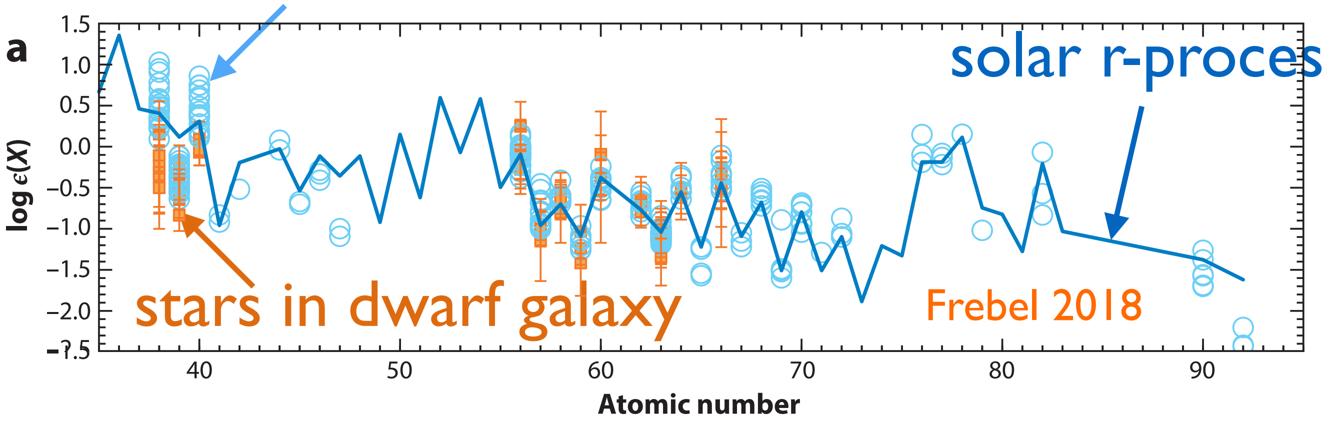
- Additional light r-process elements from

  → late-time viscous outflows

  Fernandez+ 2013
  Just+ 2015
  Fujibayashi+ 2022

  → other ejecta channels (determined by BNS distribution)

halo stars

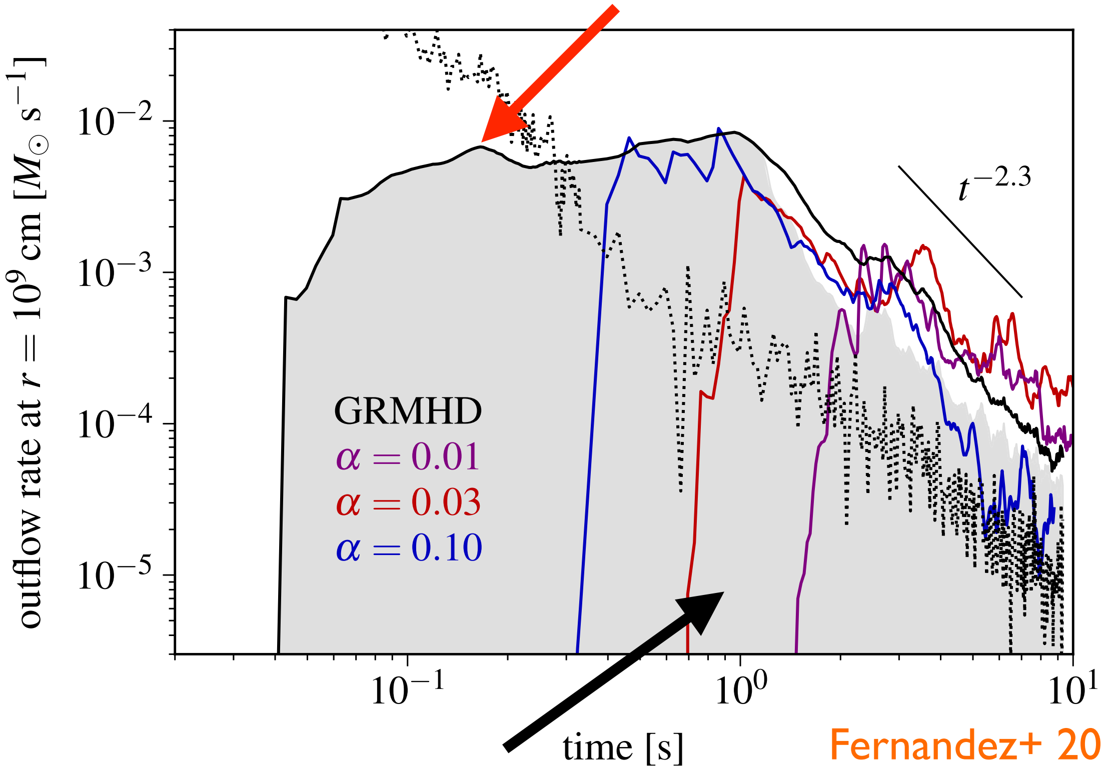


solar r-process

stars in dwarf galaxy

Frebel 2018

GRMHD outflows are early!



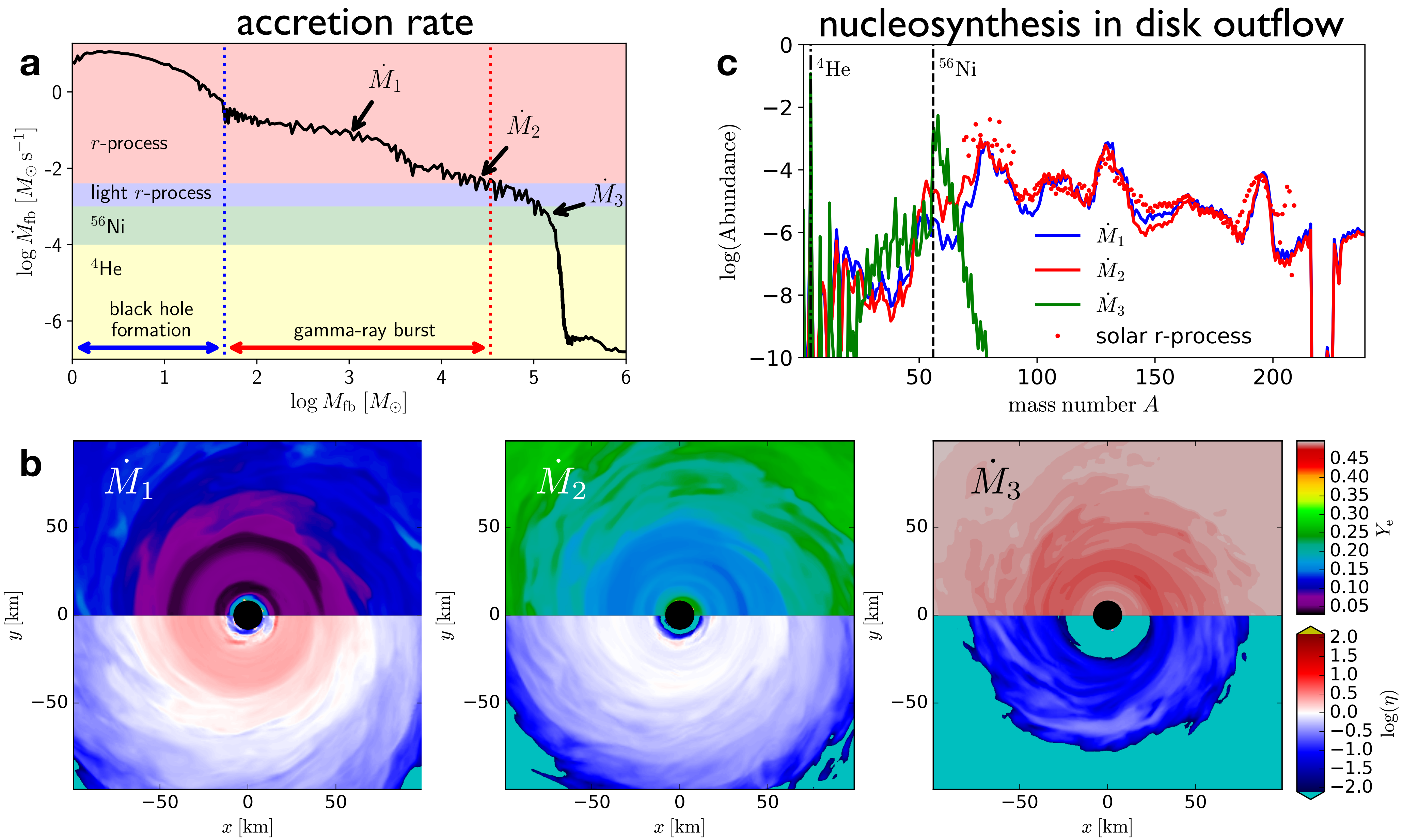
Fernandez+ 2019

viscous disk outflows starting at t_{visc}~1s

IV.
r-process in collapsars

Post-merger physics in other systems: *collapsars*

Siegel, Barnes, Metzger 2019, Nature



Y_e

degeneracy

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

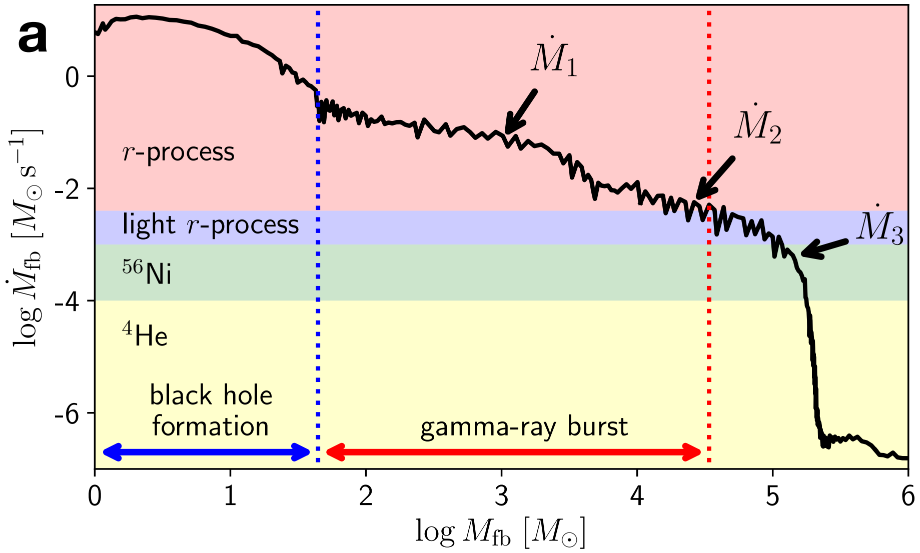
$$e^+ + n \rightarrow p + \bar{\nu}_e$$

Post-merger physics in other systems: *collapsars*

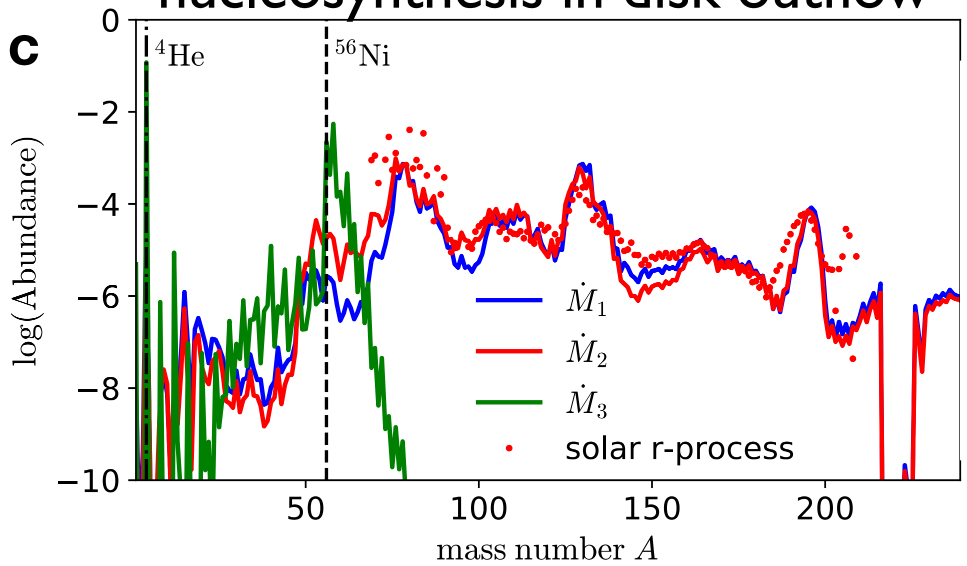
Siegel, Barnes, Metzger 2019, Nature

Siegel+ 2022

accretion rate

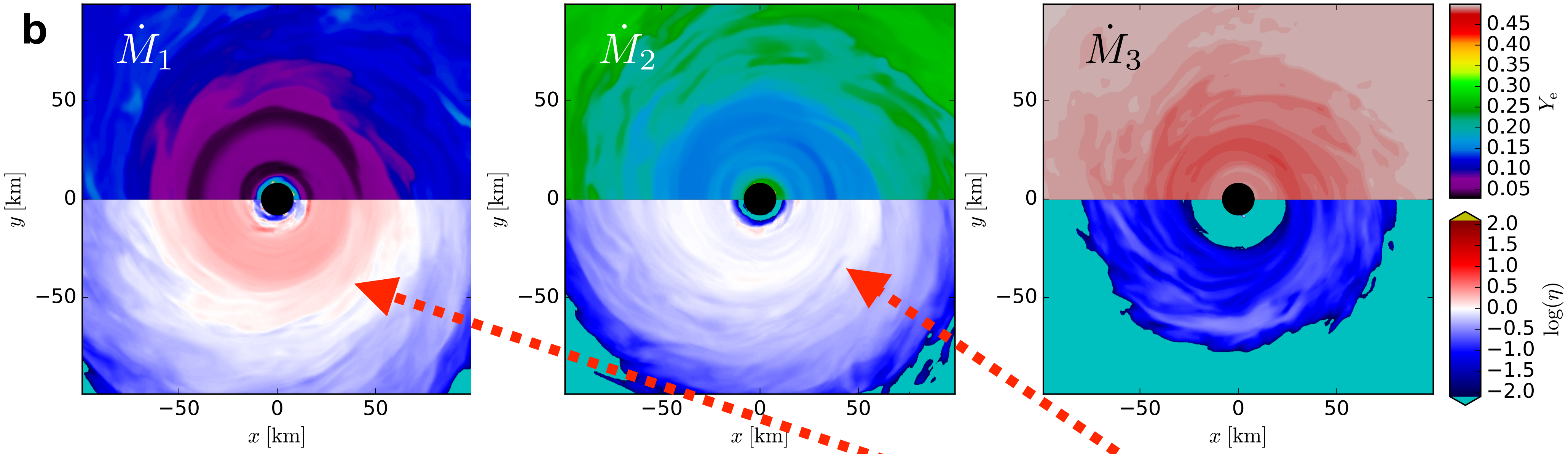


nucleosynthesis in disk outflow



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

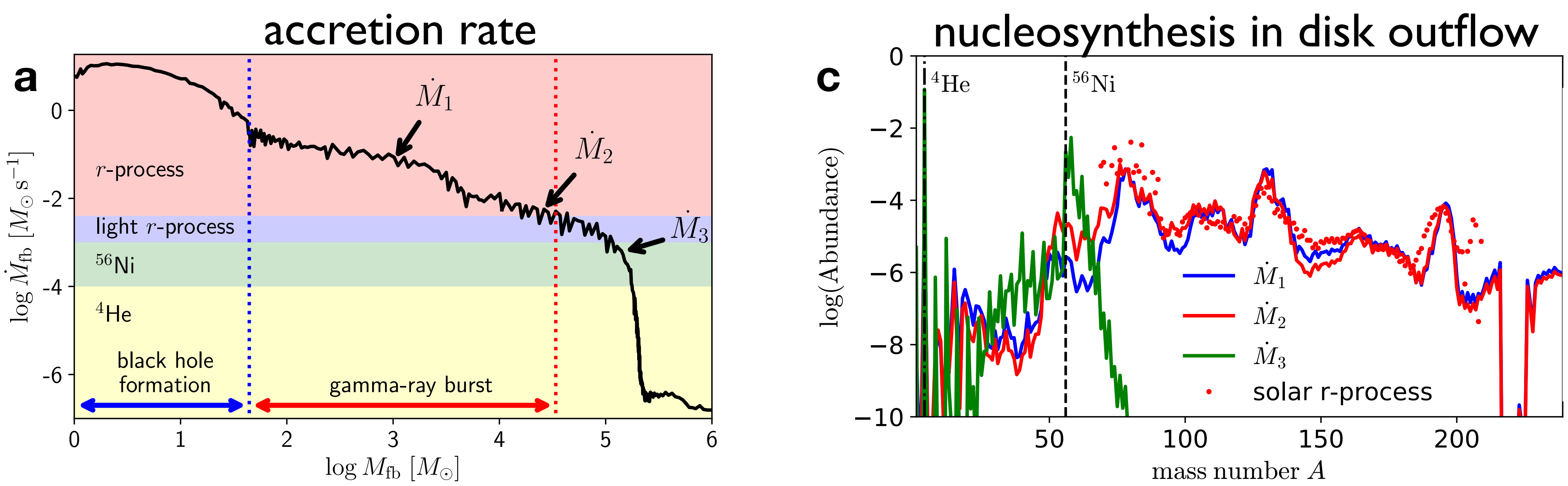
Post-merger physics in other systems: *collapsars*

Siegel, Barnes, Metzger 2019, Nature

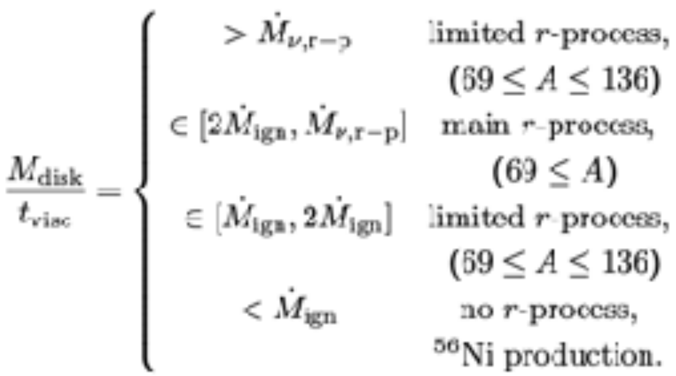
Siegel+ 2022

accretion rate

nucleosynthesis in disk outflow



nucleosynthesis bands:



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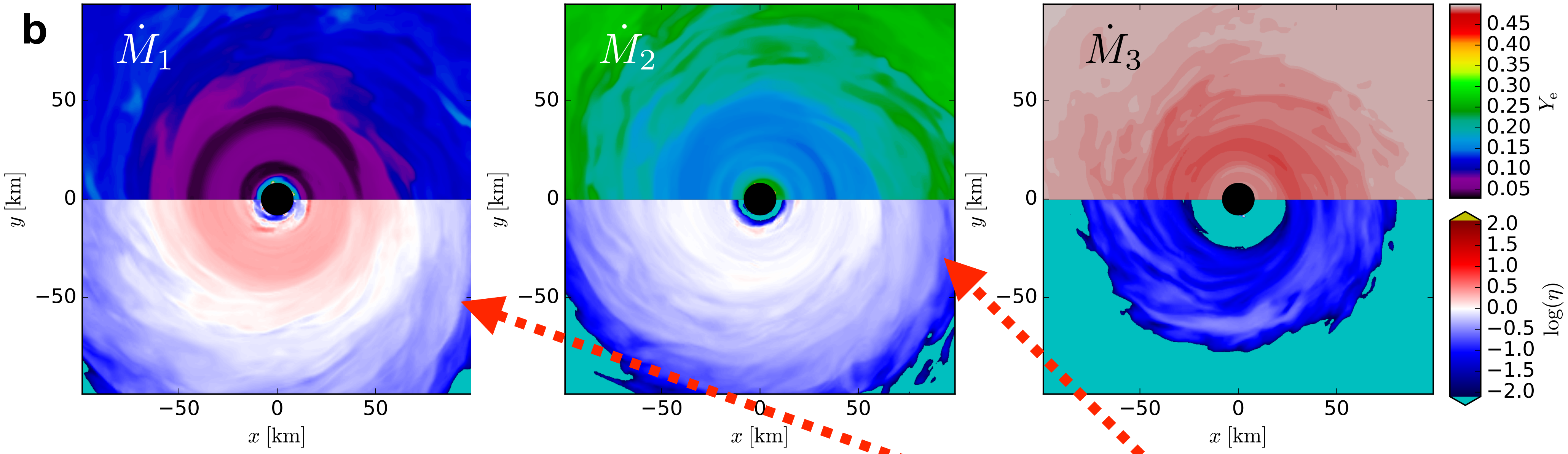

Y_e

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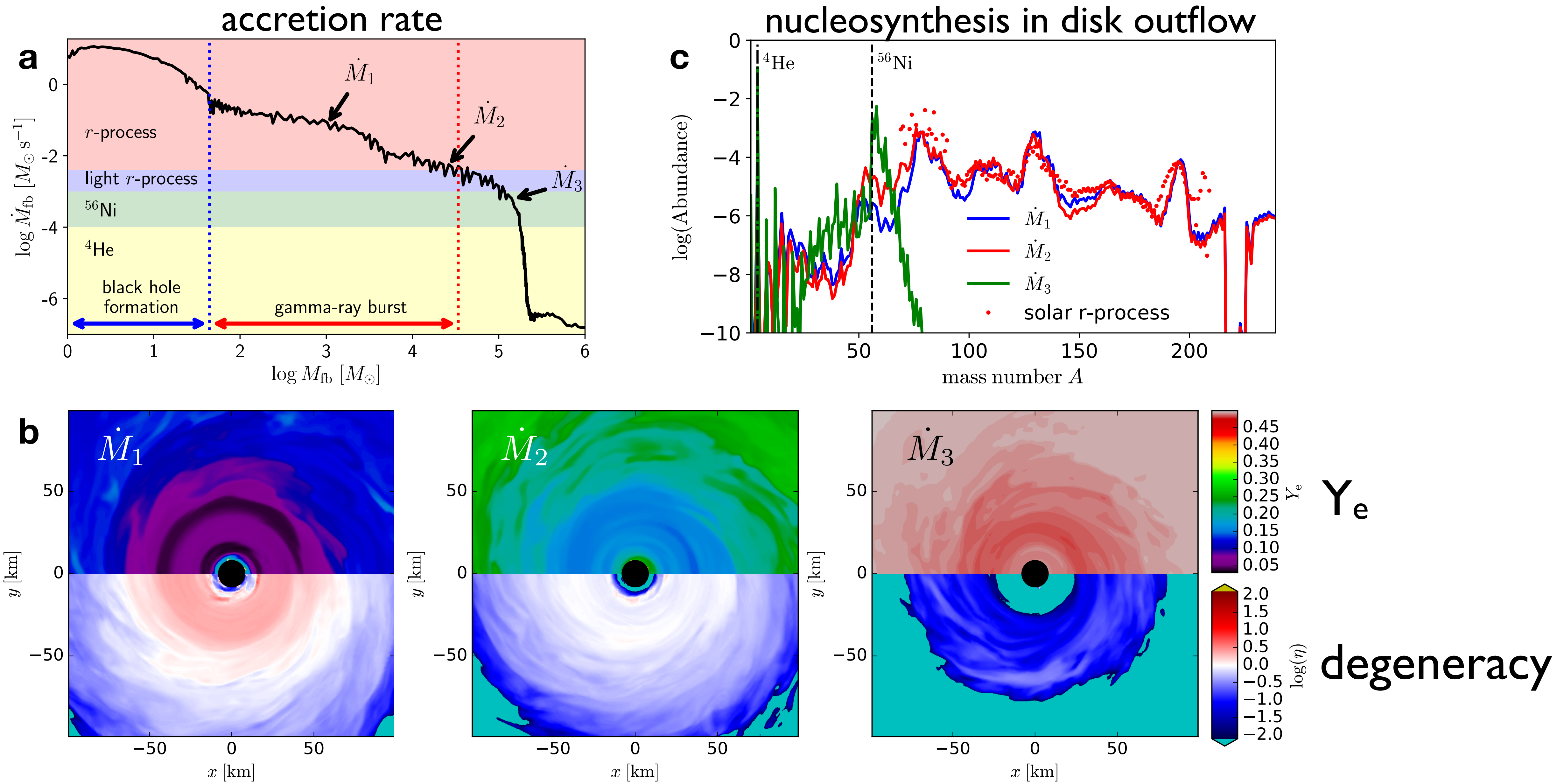
Post-merger physics in other systems: *collapsars*

Siegel, Barnes, Metzger 2019, Nature

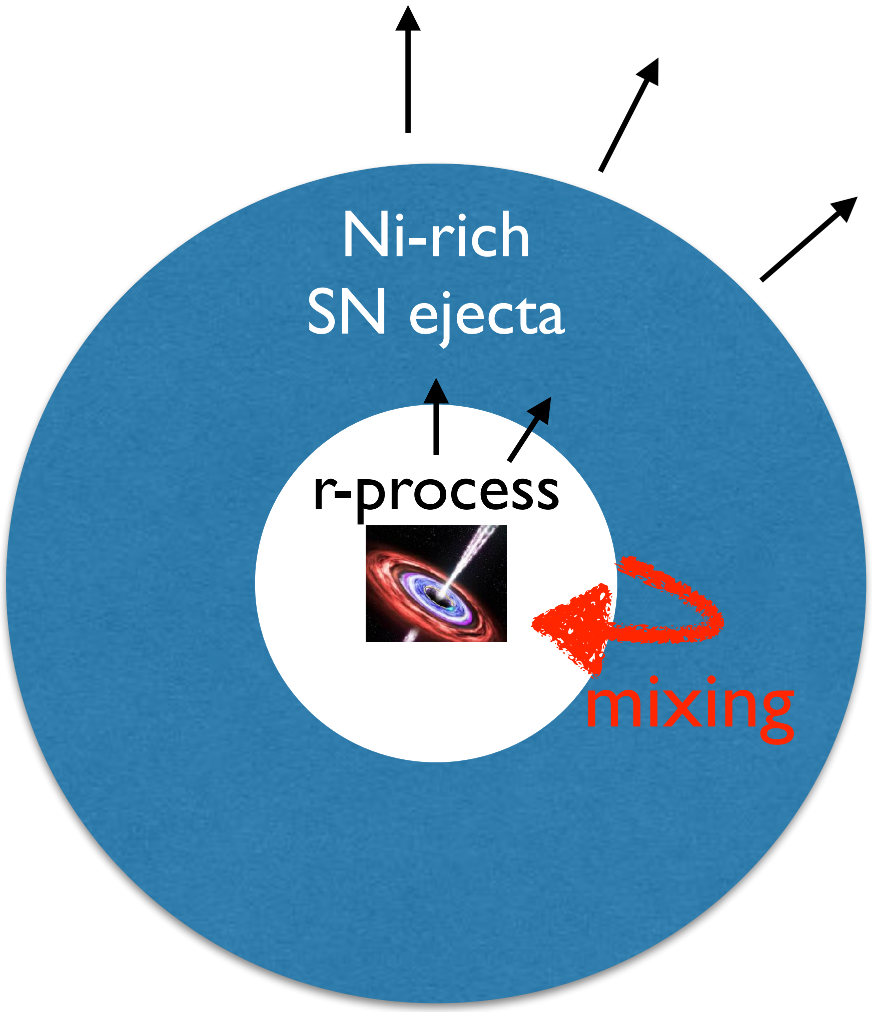


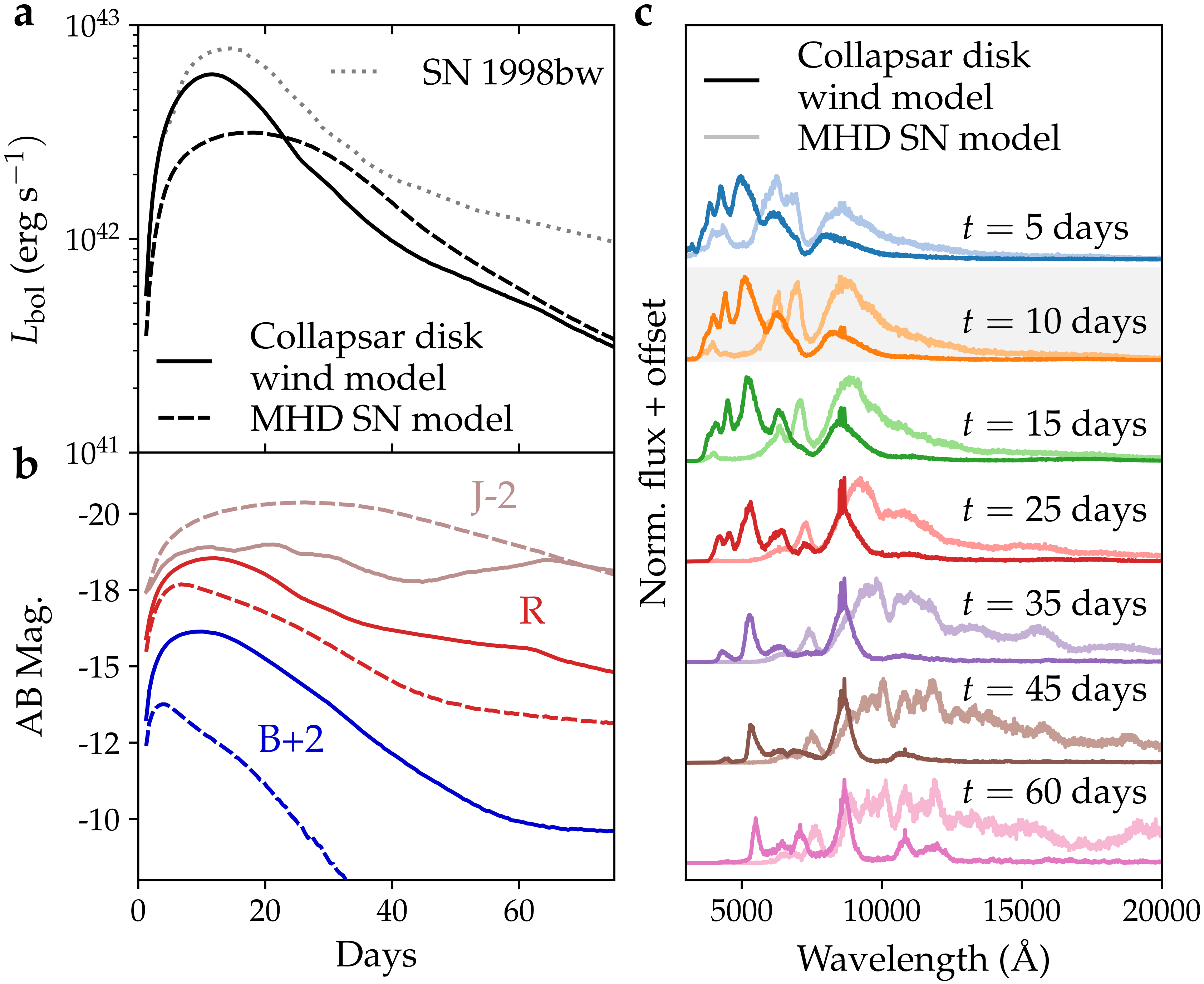
- 0.05–1 M_{sun} of r-process material per event over-compensates lower rates relative to mergers
- self-regulation over wide range of accretion rates produced well-defined nucleosynthesis pattern similar to solar
- may dominate r-process production by mergers

See also:

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

How to observe?





Siegel, Barnes, Metzger 2019, Nature

Barnes & Metzger 2022

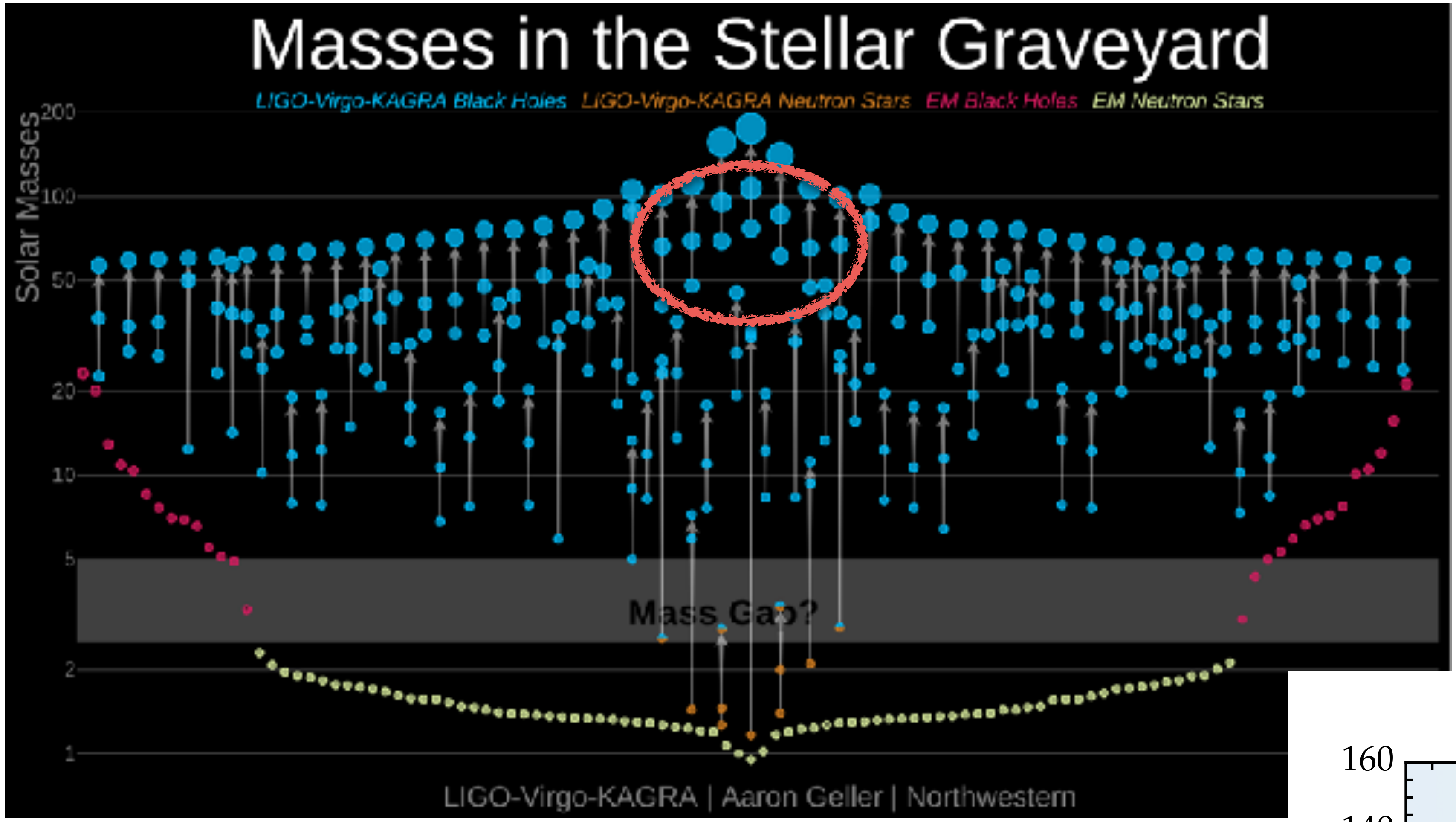
r-process elements lead to near-infrared excess at late times:
'kilonova within a supernova'

see *Shreya Anand's talk*

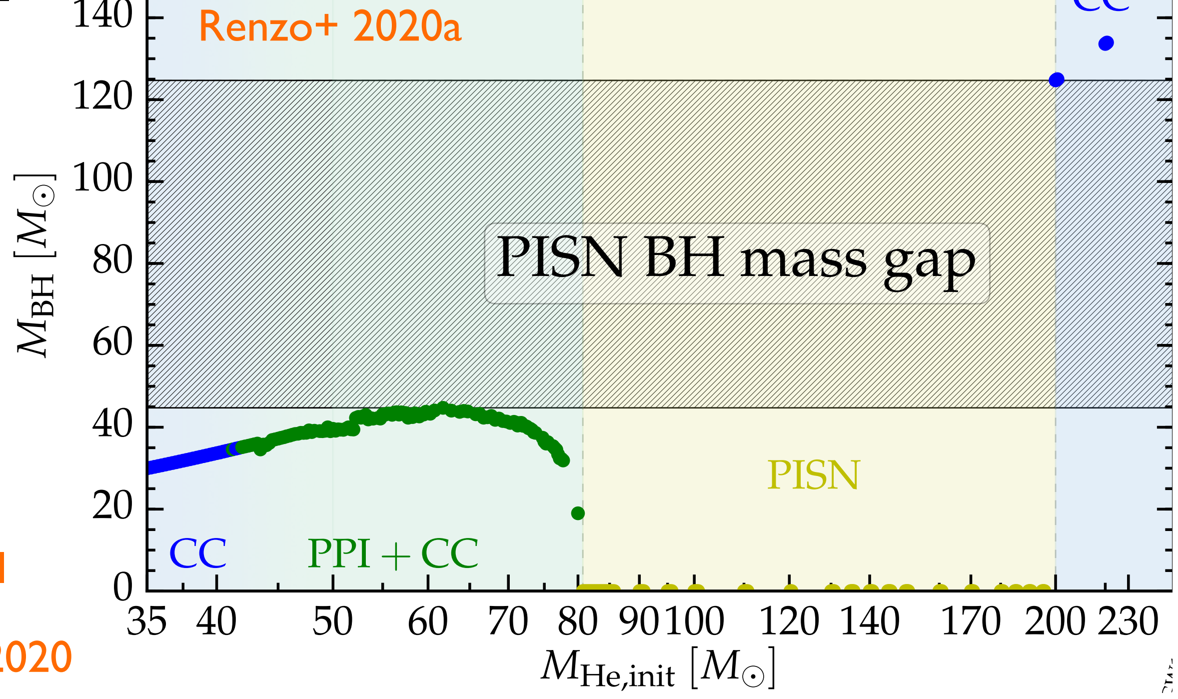
V.

Massive collapsars: ‘super-kilonovae’

Black holes in the pair-instability mass gap



PISN BH mass gap

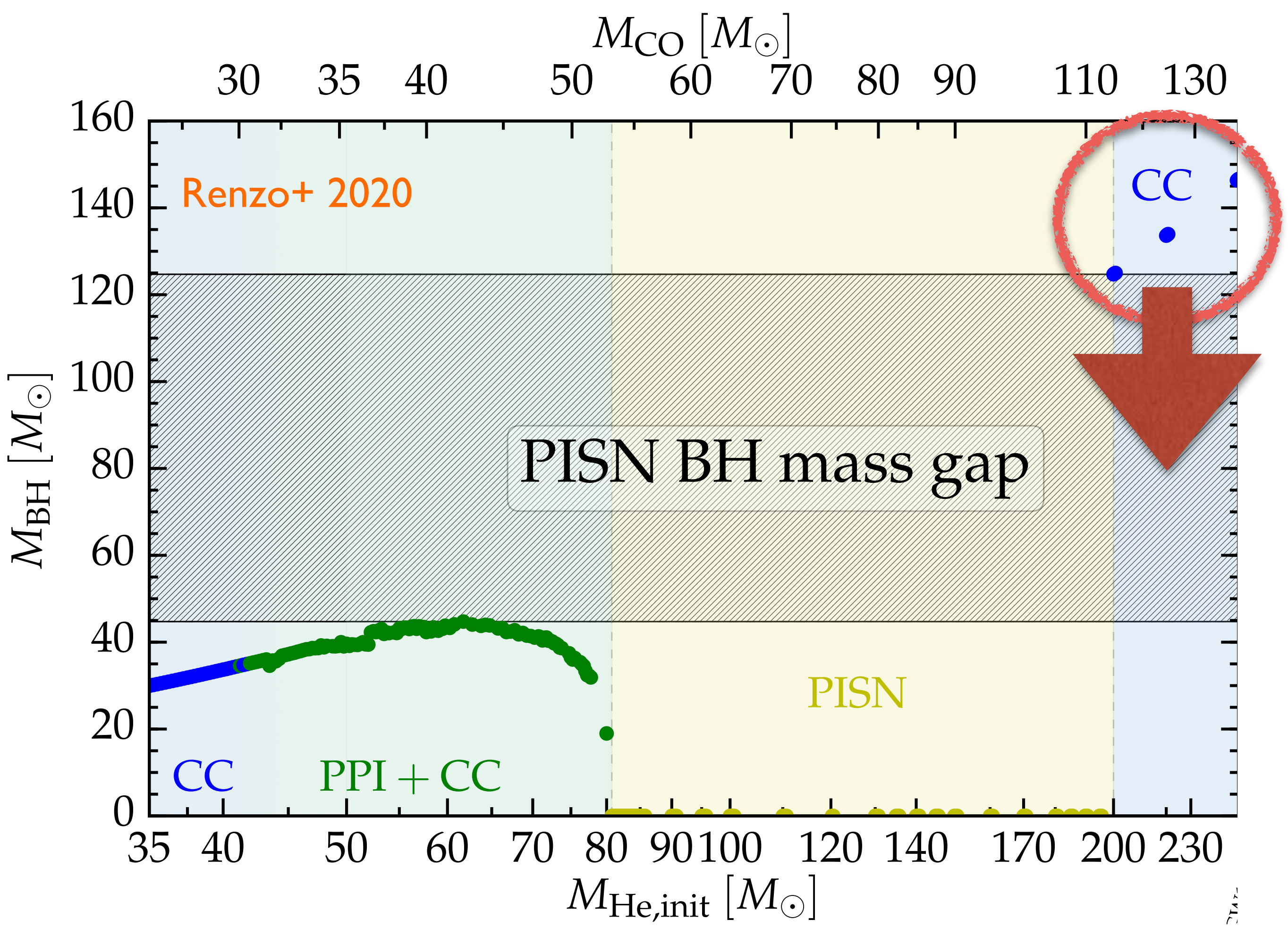


How to populate the PISN BH mass gap?

- 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 2020
- To some extent: nuclear reaction rates & rotation Woosley & Heger 2021, …

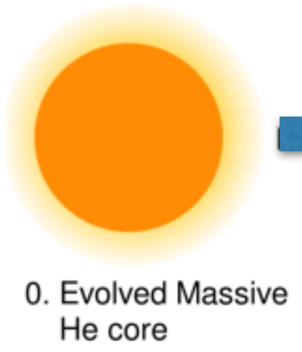
More massive examples populate the PISN mass gap

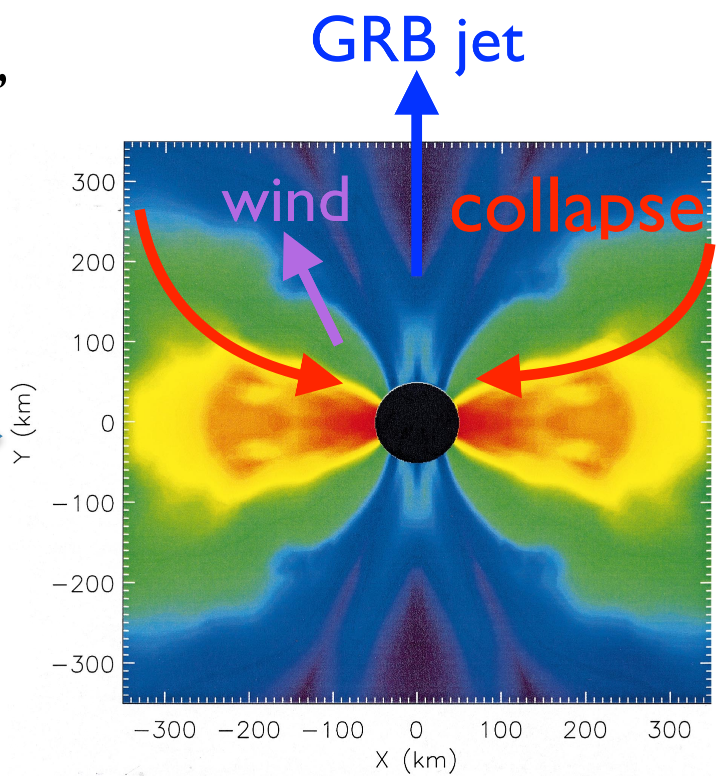
Siegel+ 2022, arXiv:2111.03094



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

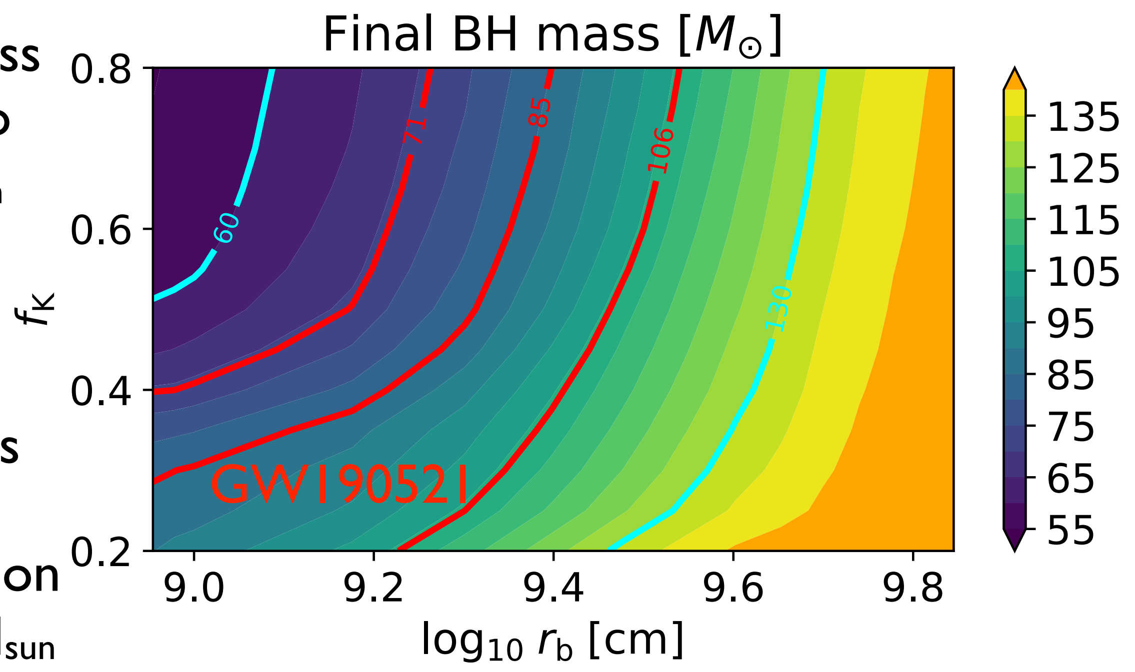
Collapse of massive, rapidly rotating progenitors > 130 $M_{\rm sun}$



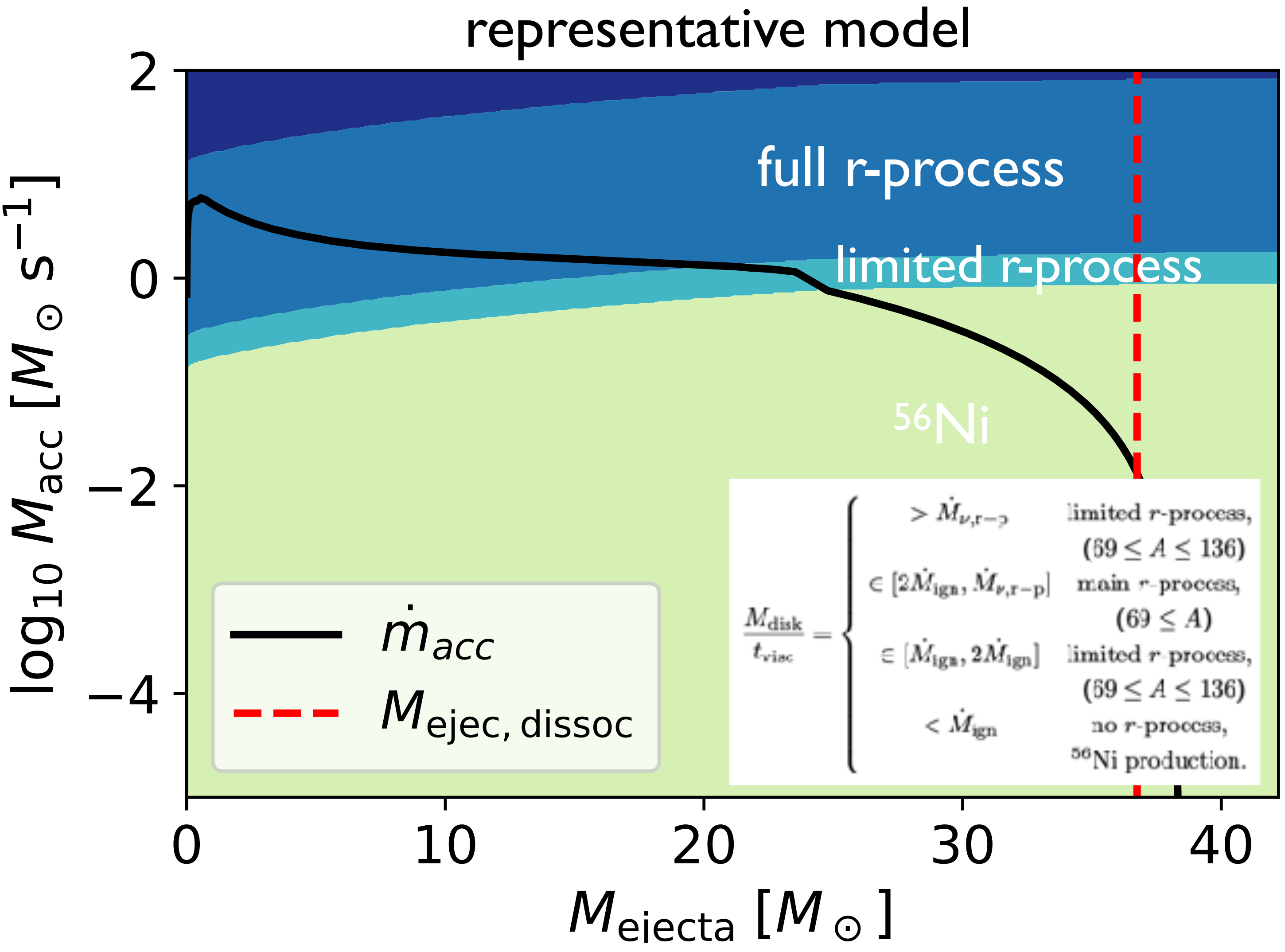


Wind mass loss up to > 50 $M_{\rm sun}$

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



Ejecta composition reflects accretion process


representative model

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

Derivation of various nucleosynthesis regimes as function of BH mass, see appendix of

Siegel+ 2022, arXiv:2111.03094

- 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, $X_{\rm La}$~ 10^{-4}–10^{-2}
- parameter space scan

$M_{\rm ej}$ ~ 10–60 $M_{\rm sun}$

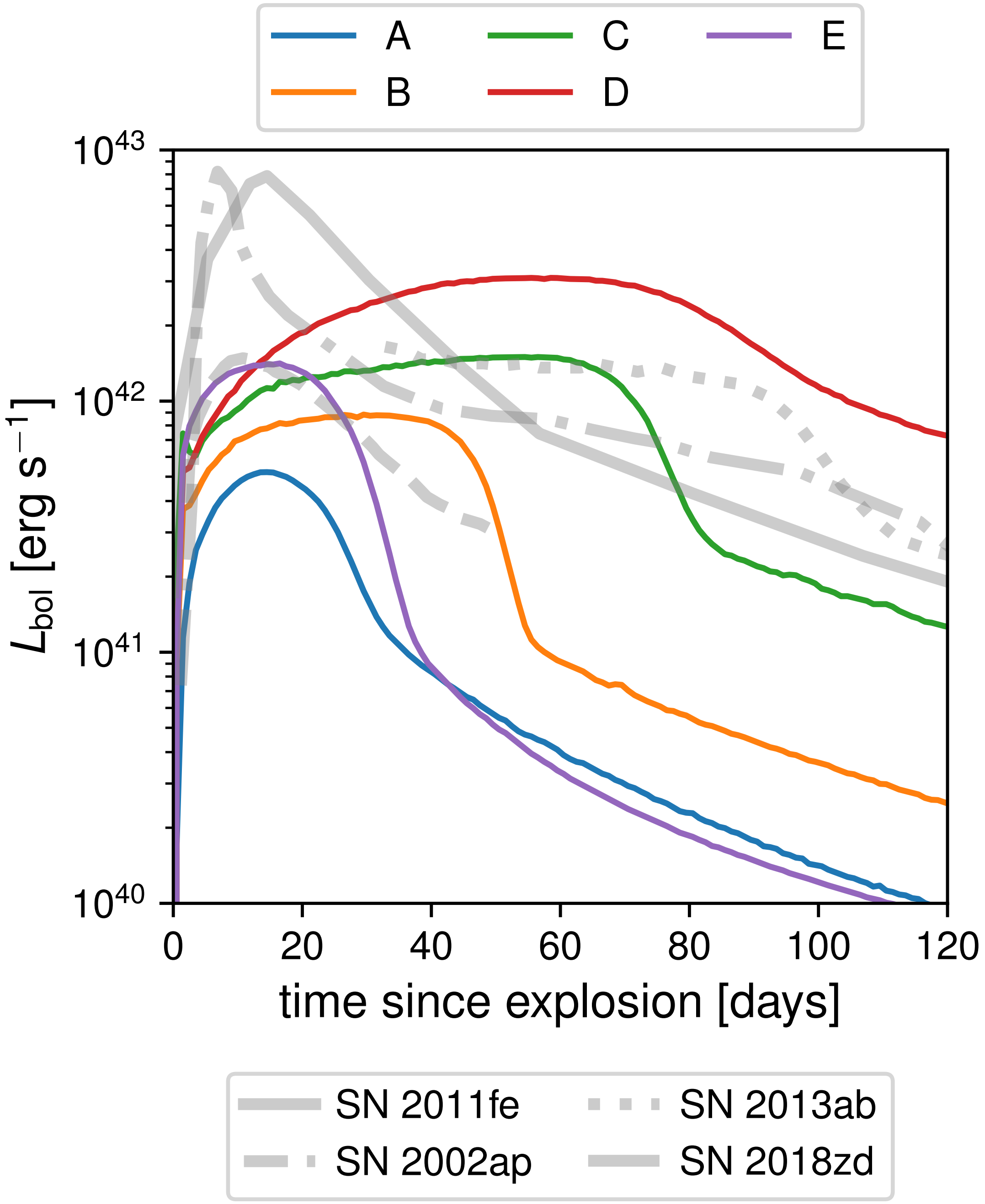
$M_{\rm ej,\, r\text{-}p}$ ~ 1–20 $M_{\rm sun}$

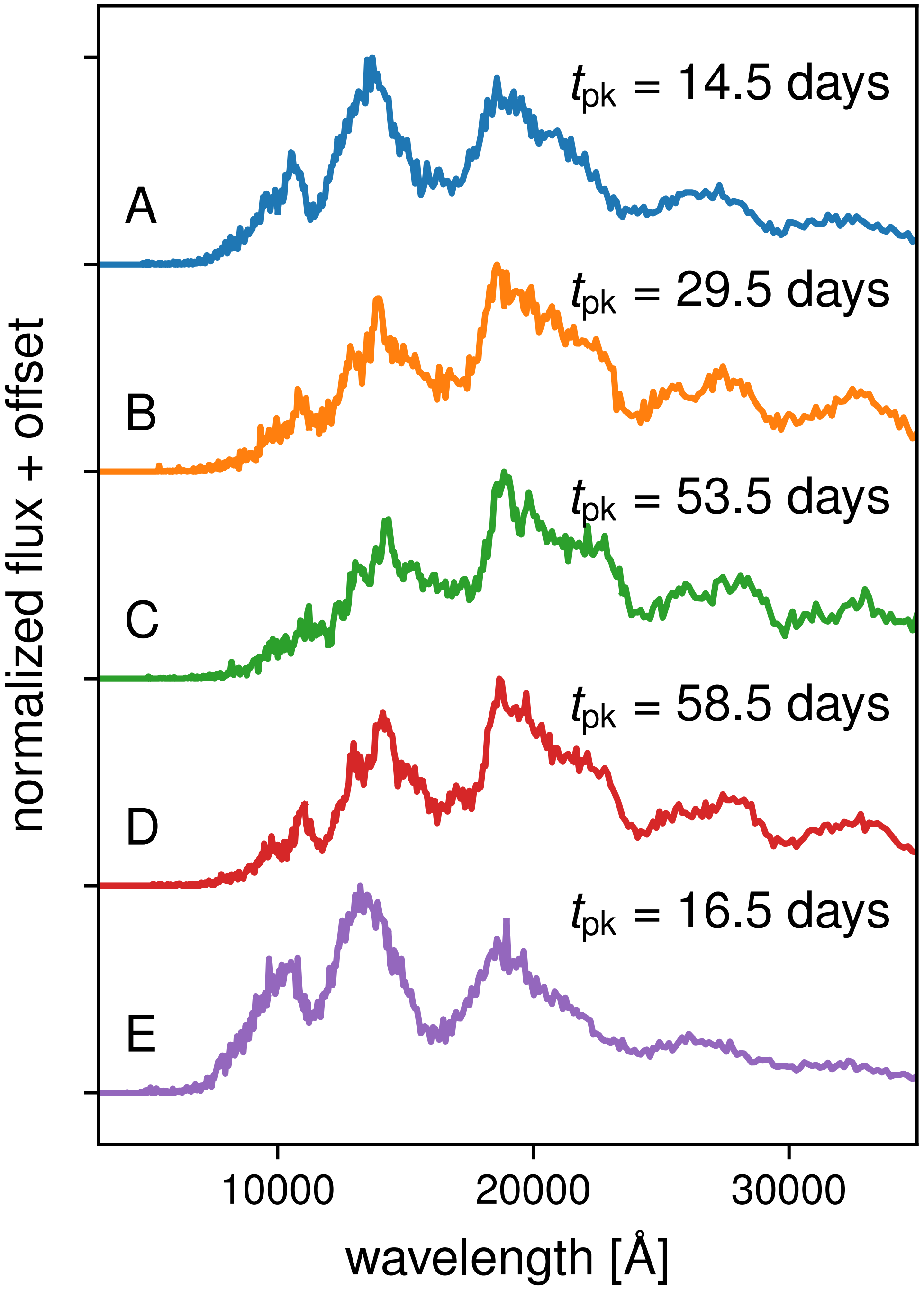
$M_{\rm ej,\, Ni56}$ ~ 0.05–1 $M_{\rm sun}$

$M_{\rm BH}$ ~ 60–130 $M_{\rm sun}$

Relatively little Fe co-production, can get to [Eu/Fe]~5 at [Fe/H] ~-5
(higher than current record holder Cain+ 2020)

EM transients: *Super-Kilonovae*





- 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 ($v \sim 0.1c$)
- up to ~few per year detectable with wide field surveys (Roman Space Telescope)

Conclusions

- The main r-process originates in high-yield, low-rate events, both in early and late Galactic history
    - dynamical ejecta in NS mergers unlikely main r-process site
- ‘Prompt’ enrichment sites (rare types of core-collapse events) have beneficial properties for chemical evolution (both early and late)
- Dynamical ejecta:
    - relativistic effects can significantly enhance neutron precursor
    - recent evidence for rebrightening of GW170817 afterglow consistent with kilonova afterglow
- Conjecture: accretion disk outflows (mergers & collapsars) may dominate Galactic r-process
- Conjecture: r-process universality (astrophysically) related to self-regulation of accretion disks above ignition threshold
- Post-merger physics in other astrophysical systems:
    - r-process in collapsars (potentially dominant wrt mergers), ‘kilonova in a supernova’
    - massive collapsars can populate the PISN mass gap and generate “super-kilonovae”