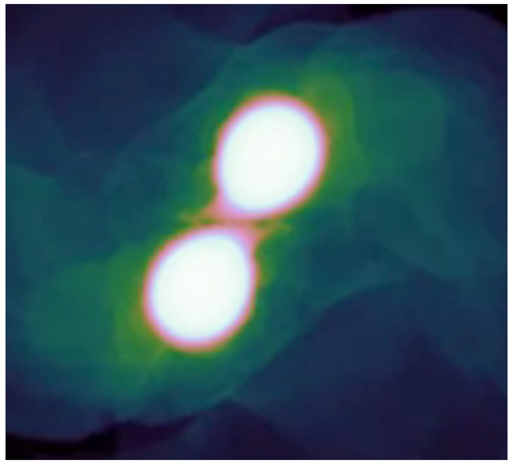
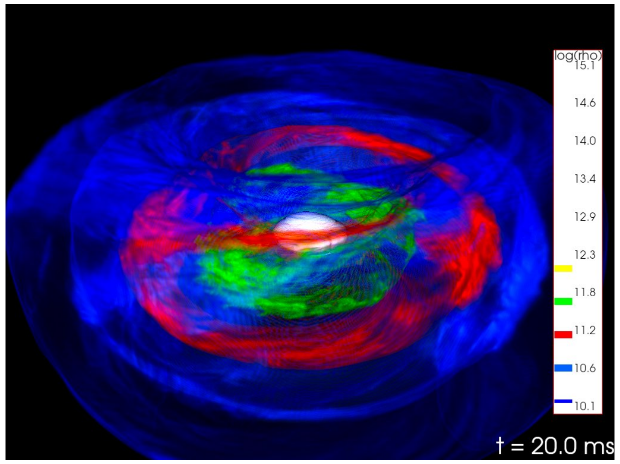
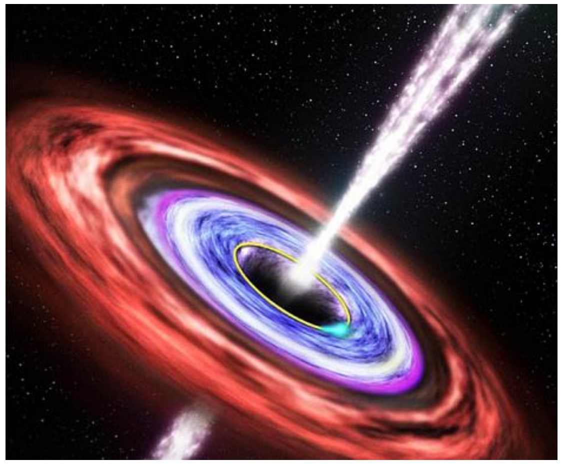
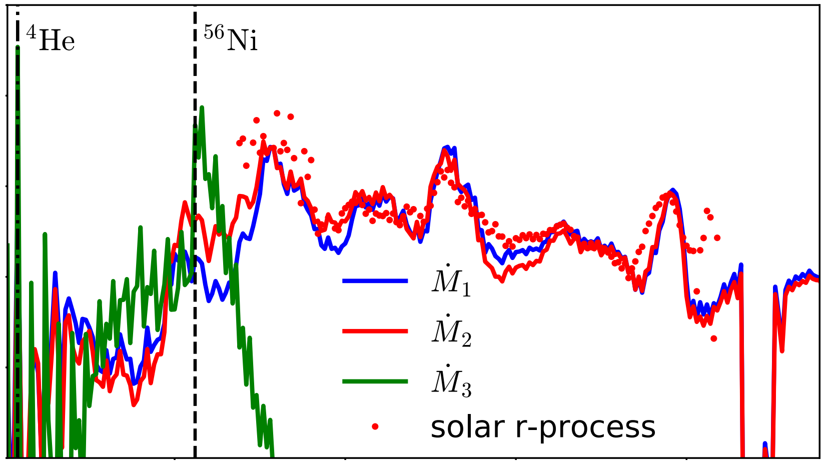
Strong Gravity and the Synthesis of Heavy Elements in the Universe









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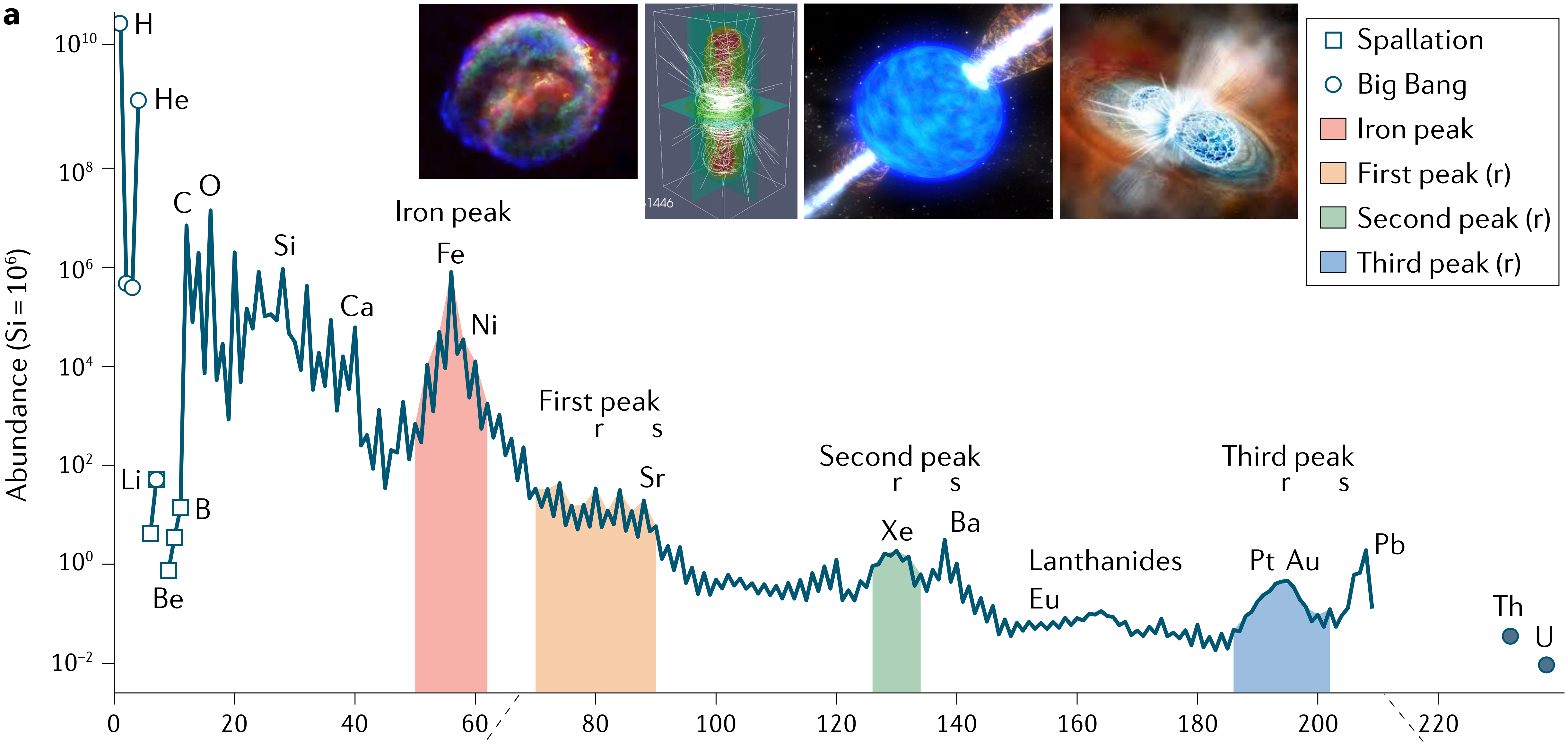
Outline

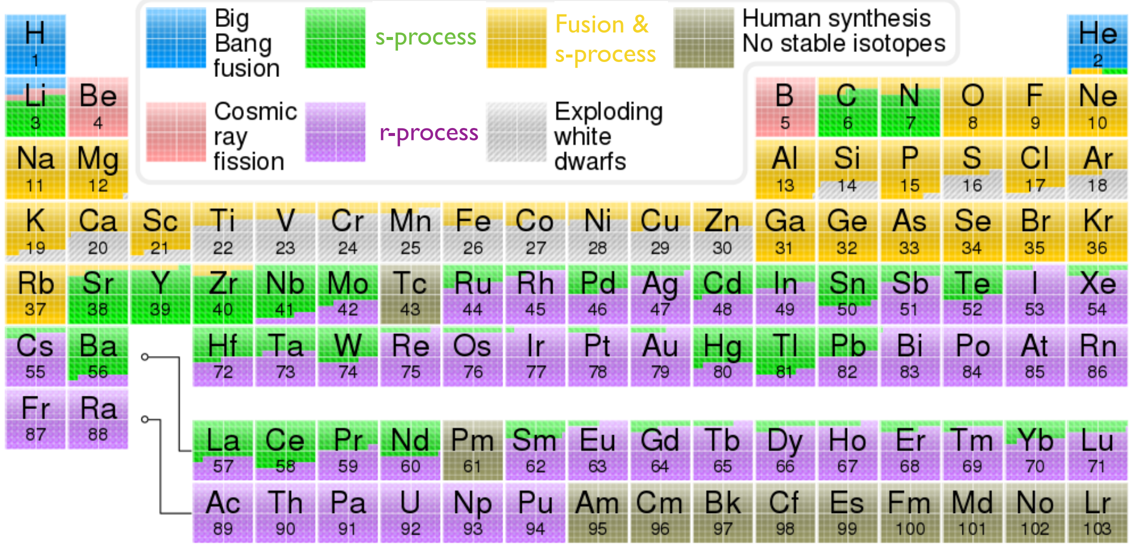
- Some constraints on r-process sites
- Neutron-star mergers
- Some conjectures
- R-process in collapsars
- Massive collapsars and ‘super-kilonovae’

I.

Some constraints on r-process sites

Inventory of the elements in the Universe

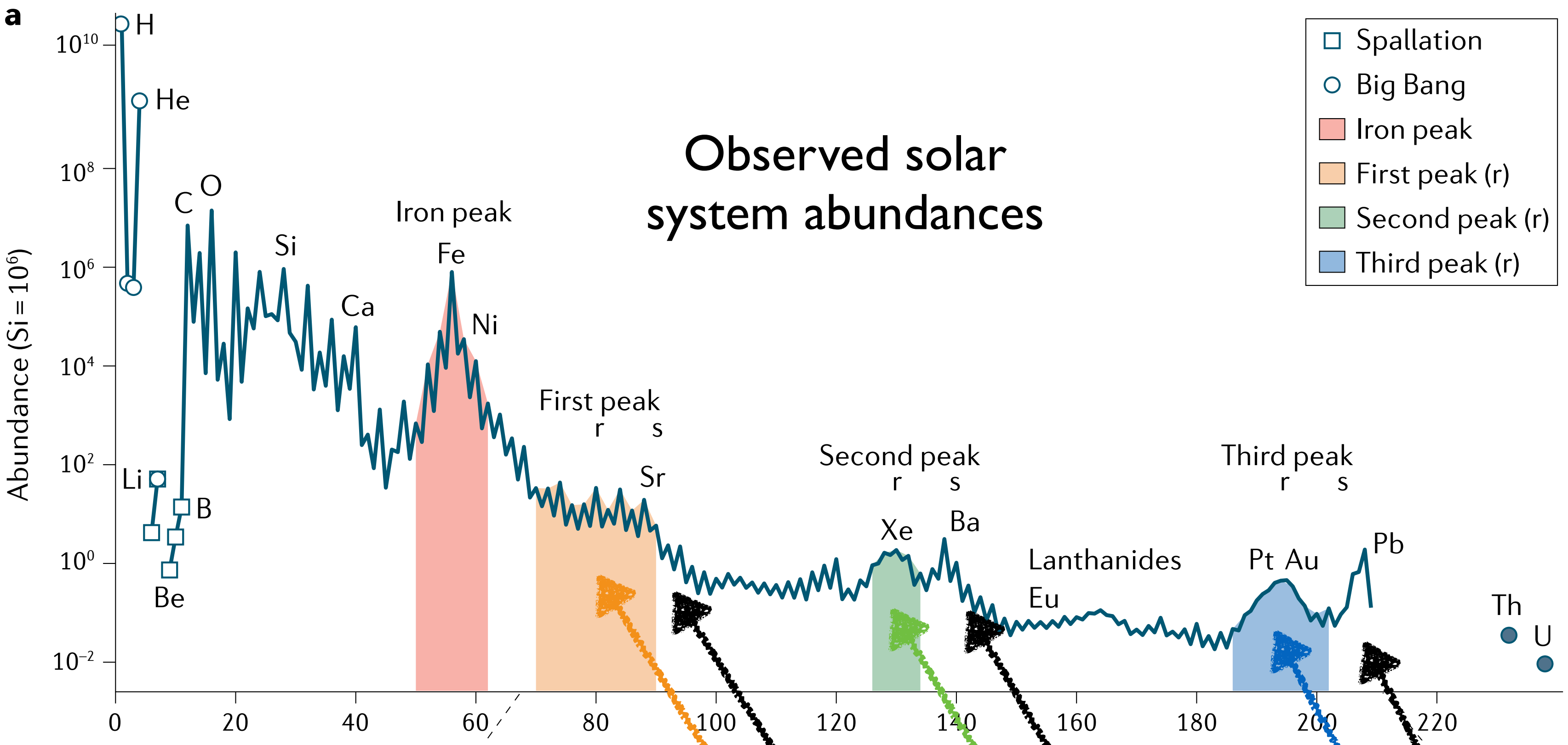




Siegel 2022, Nature Rev. Phys.

How does the universe
populate the periodic table?

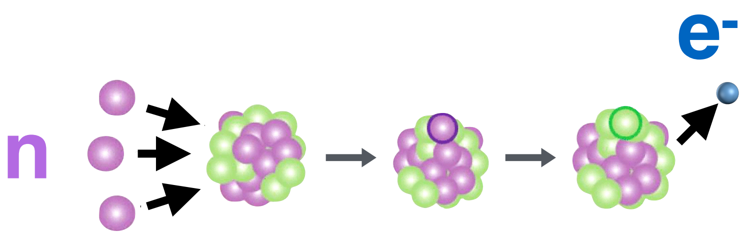
The r-process and s-process



Observed solar system abundances

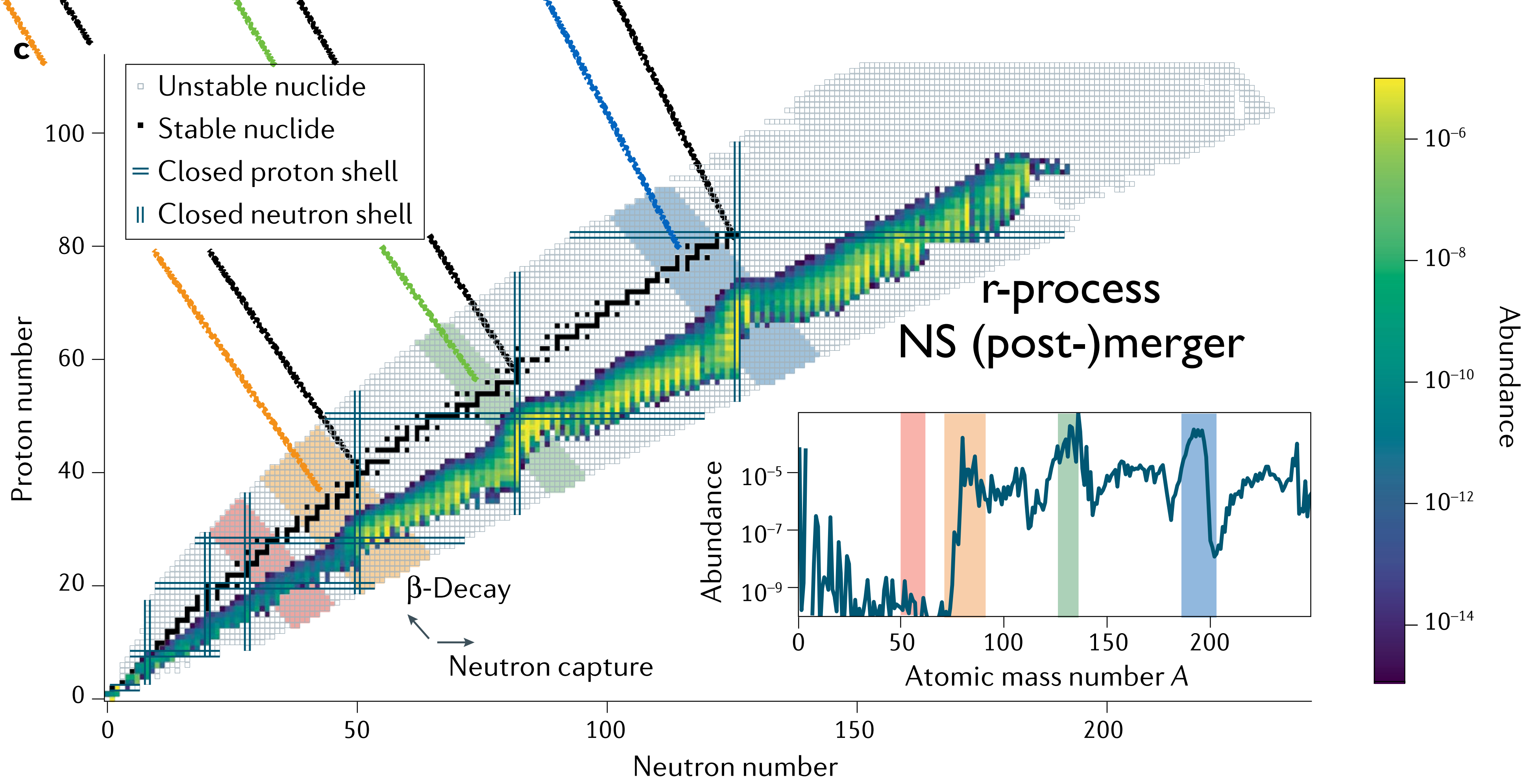
Abundance peaks reflect long β-decay timescales and increased stability of nuclei near closed neutron shells

Siegel 2022, Nature Rev. Phys.

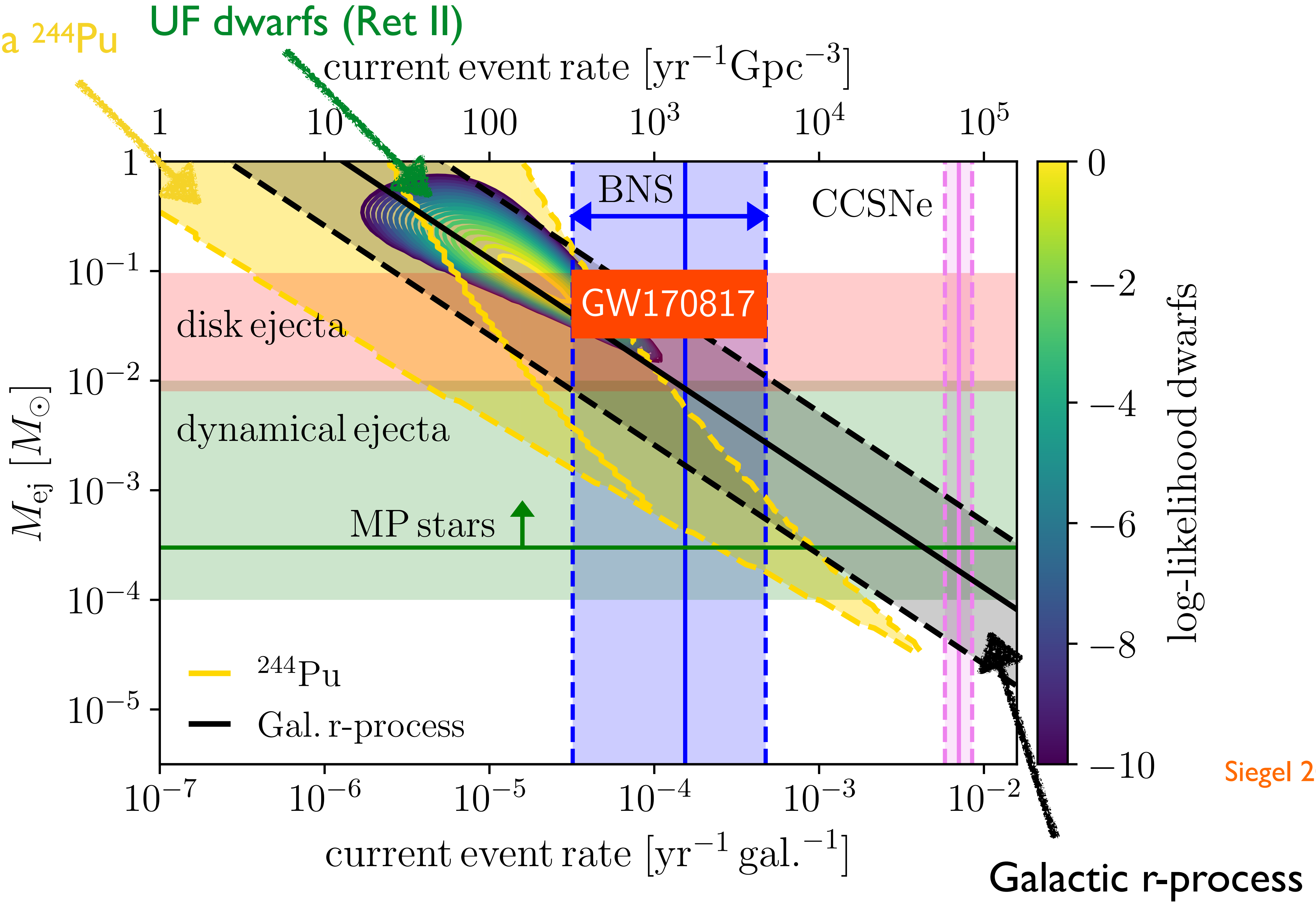


s-process: timescale for neutron capture longer than for β-decay

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



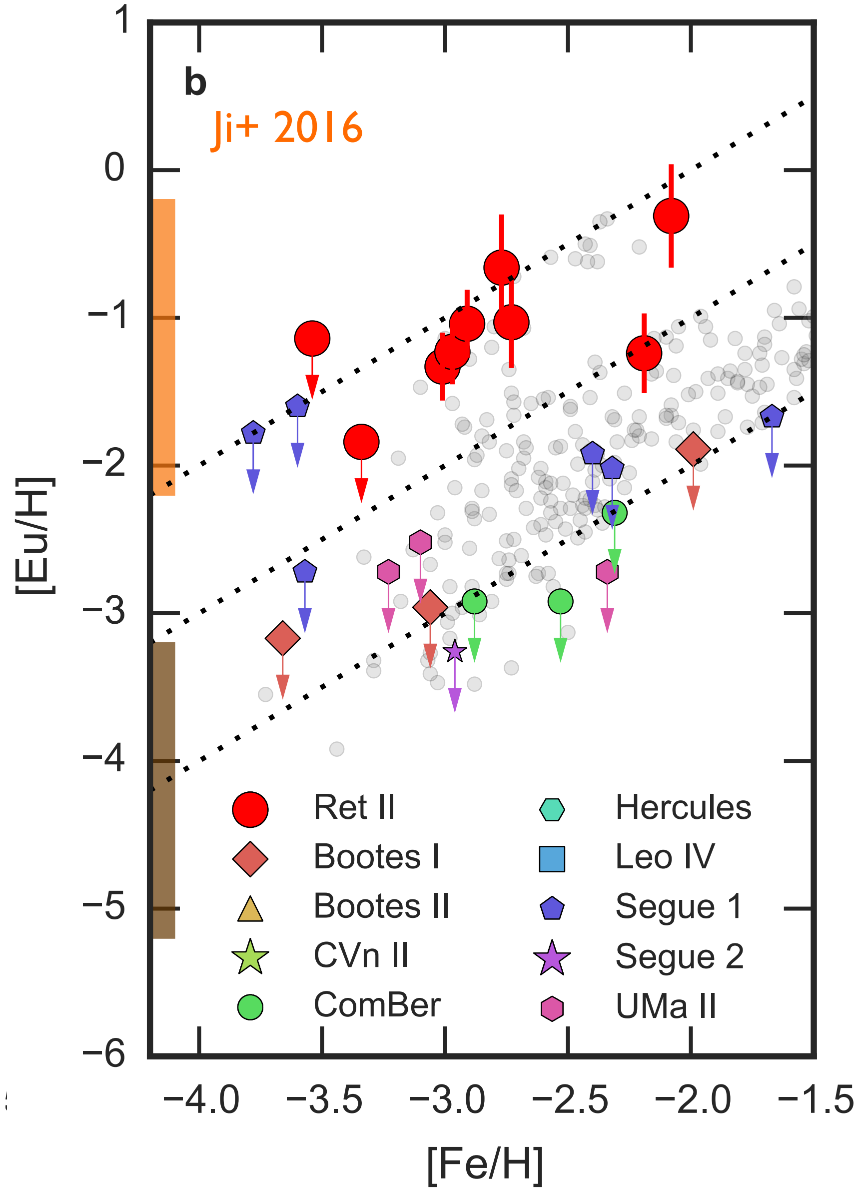
The main r-process originates in rare high-yield events



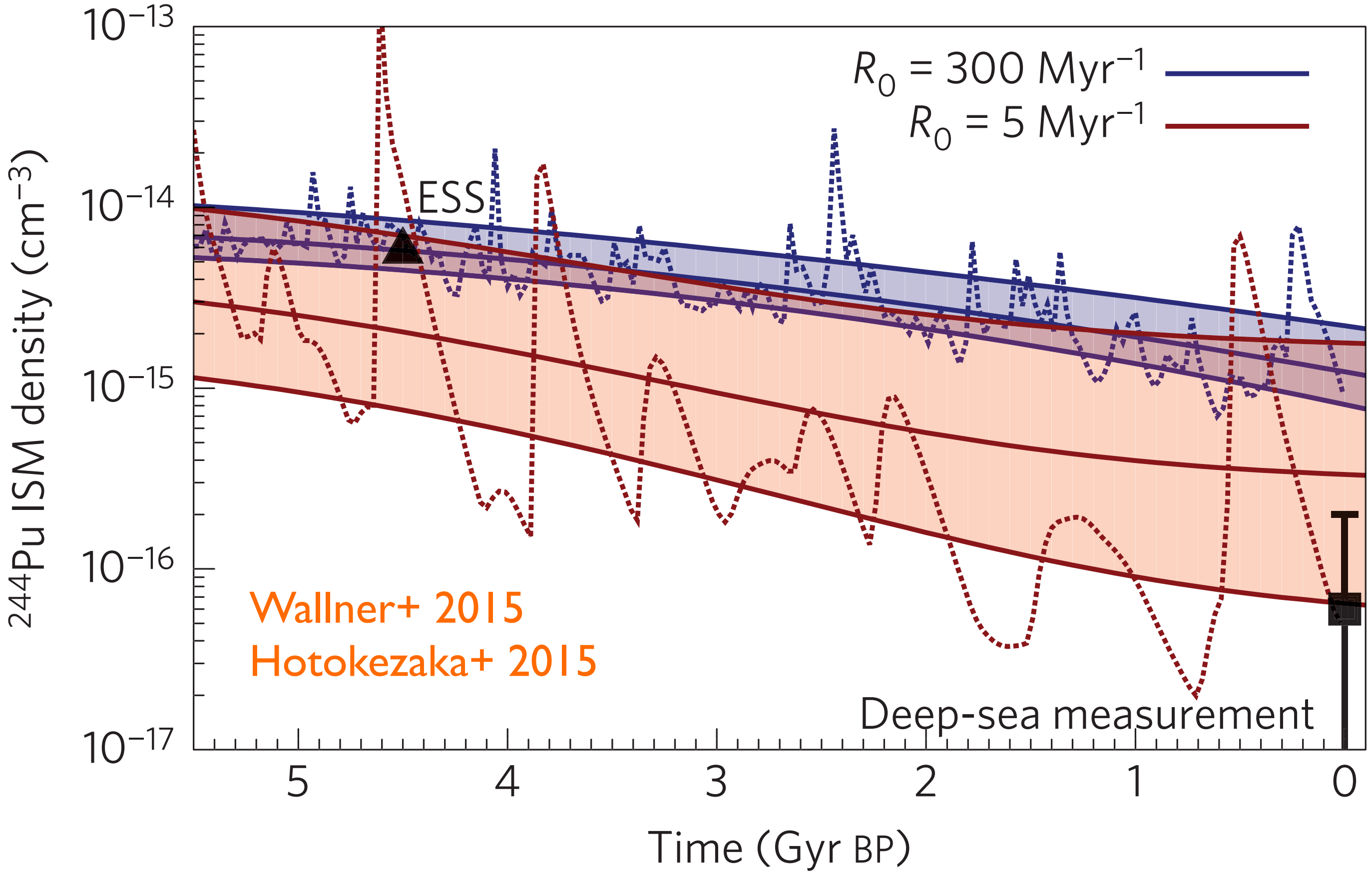
Siegel 2019

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

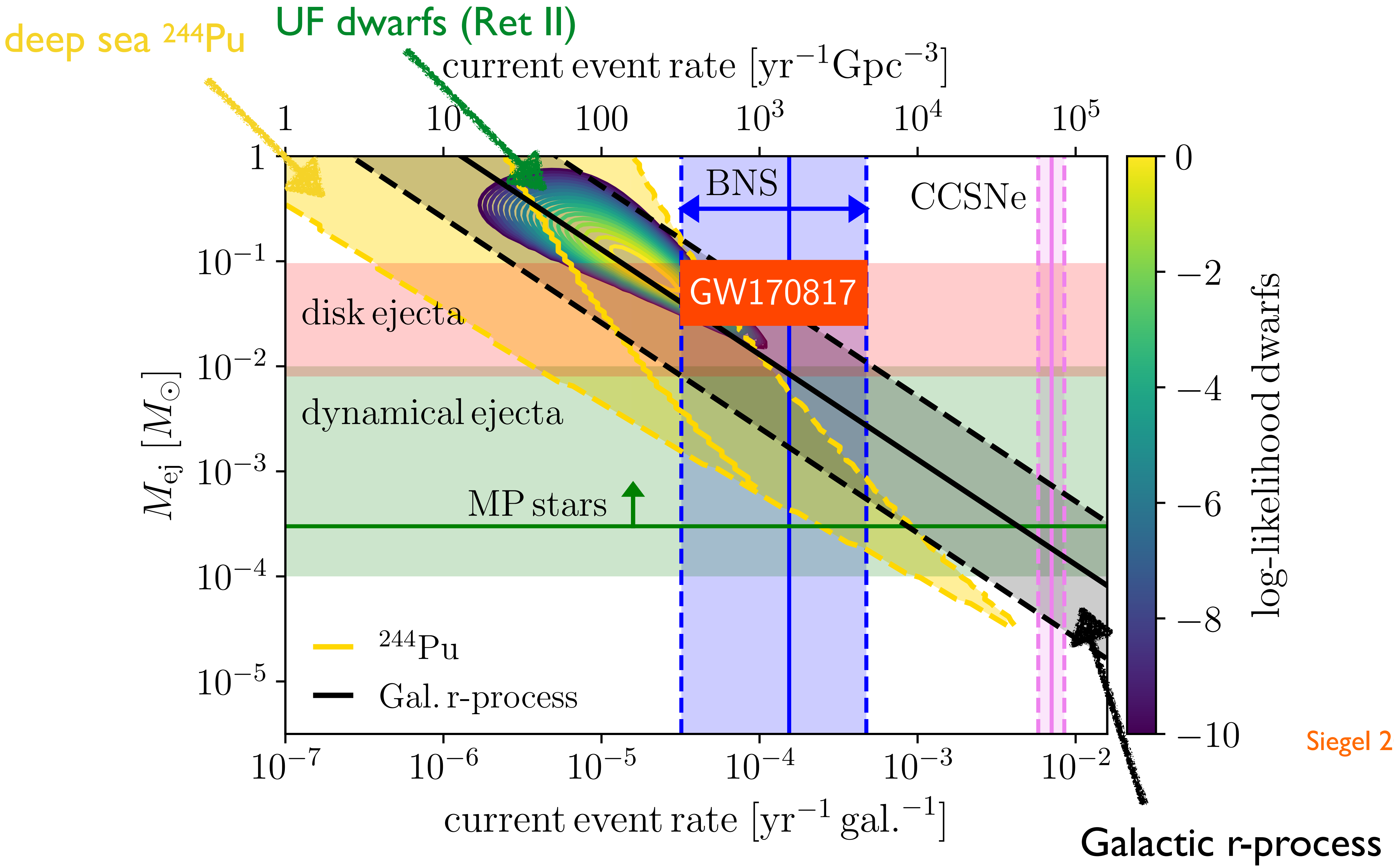
early Galactic history


Ji+ 2016

recent Galactic history


Wallner+ 2015
Hotokezaka+ 2015

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



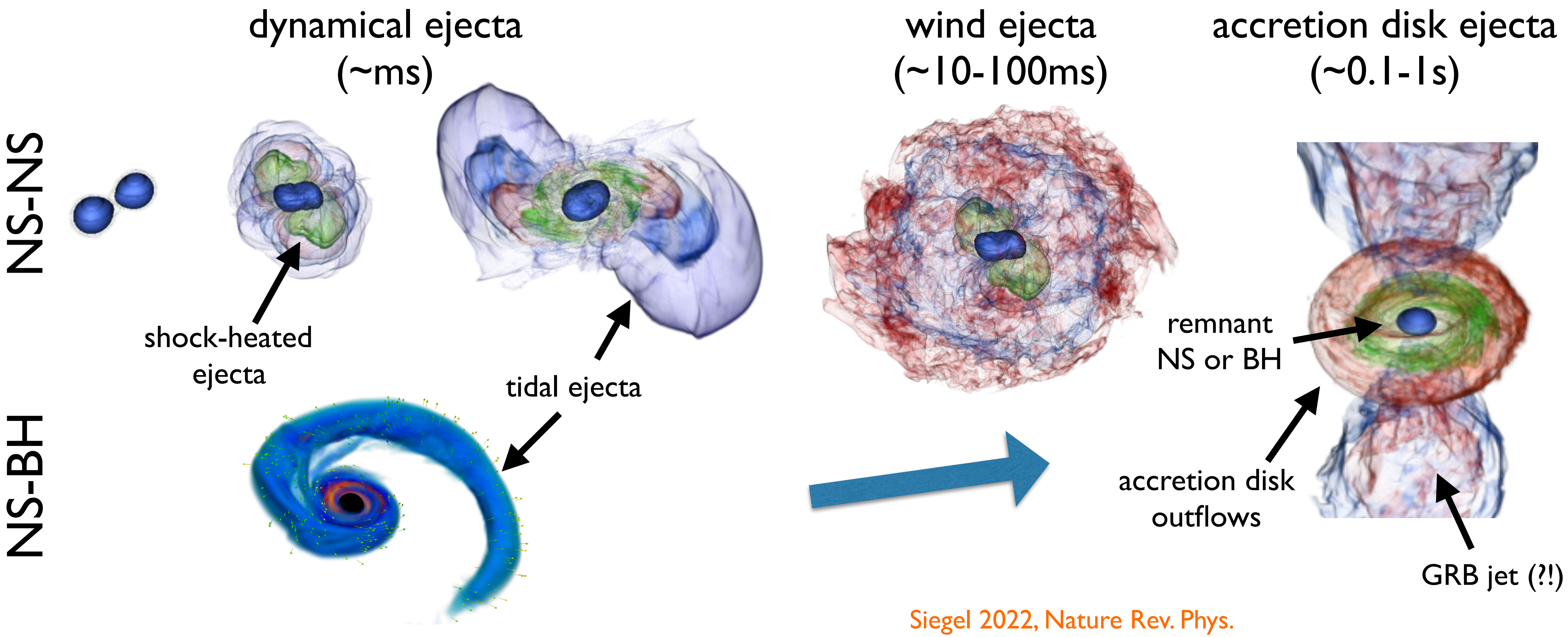
Siegel 2019

- → 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

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.

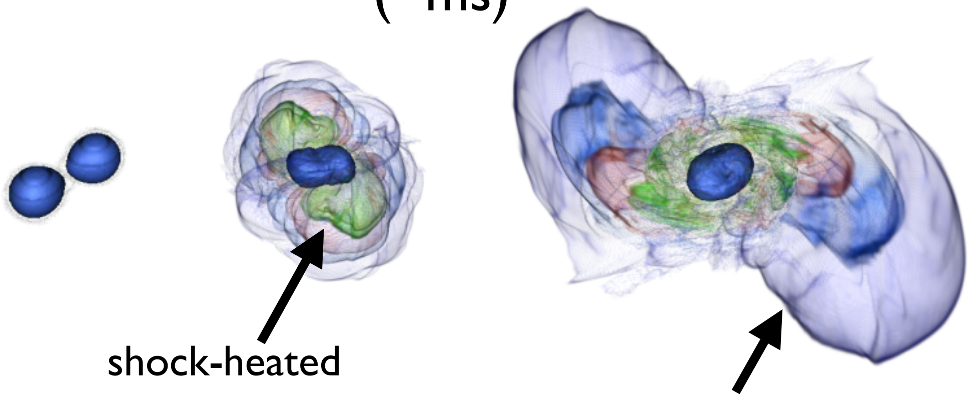
Some complications for NS-NS (complex post-merger phenomenology):

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

Focus here on NS-NS (NS-BH subdominant wrt r-process) Chen+ 2021

Fast dynamical ejecta: neutron precursor

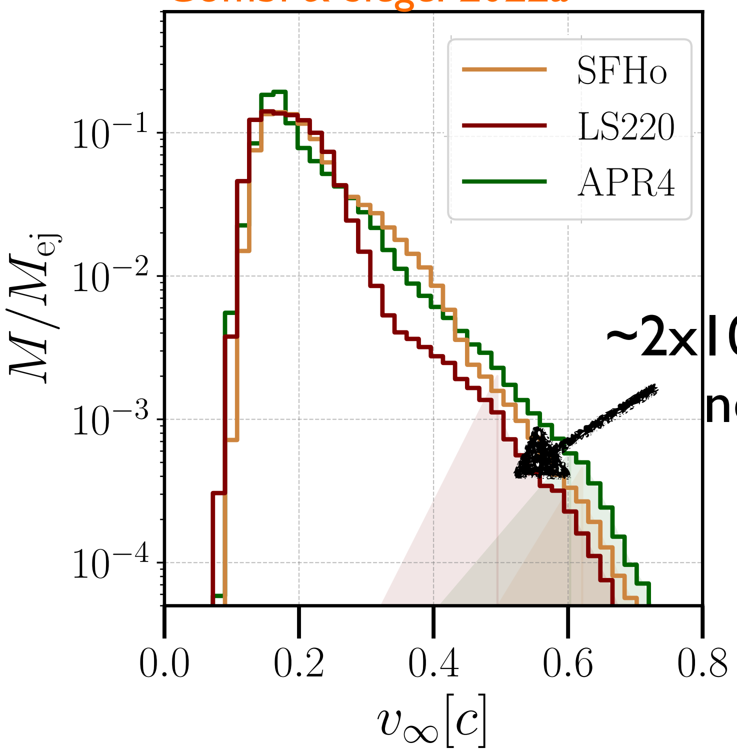
dynamical ejecta (~ms)



shock-heated ejecta

tidal ejecta

Combi & Siegel 2022a



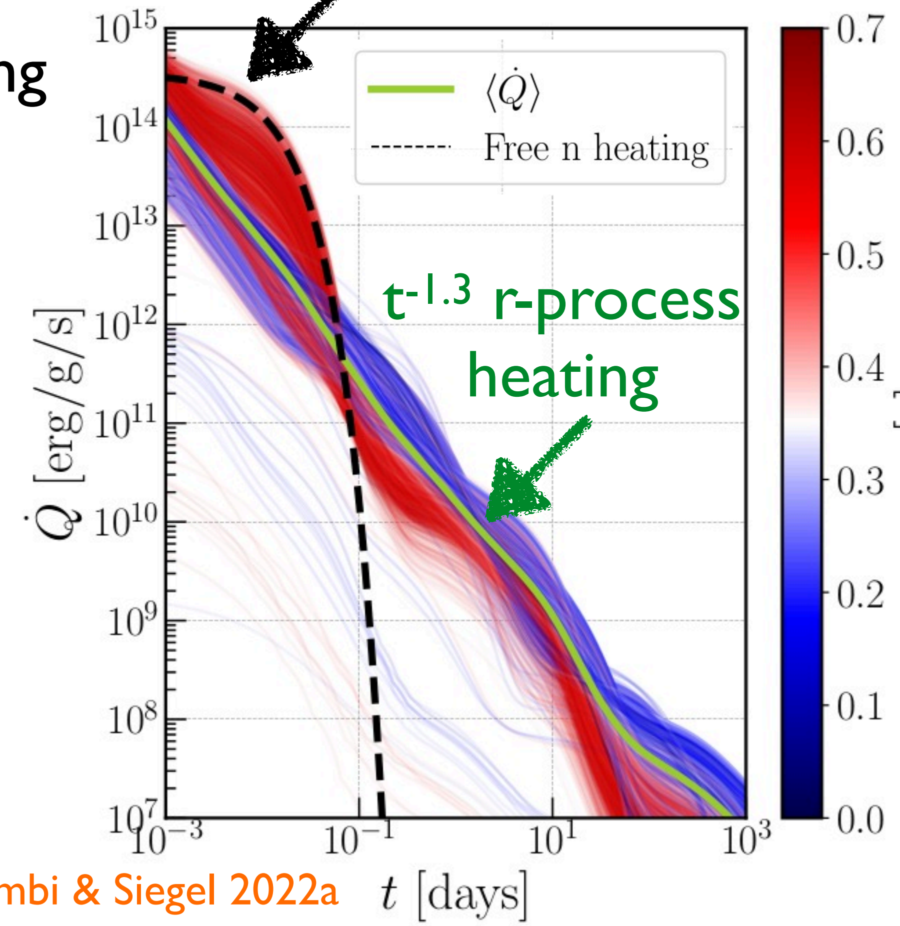
~2x10^{-5} M_{sun} free neutrons

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

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

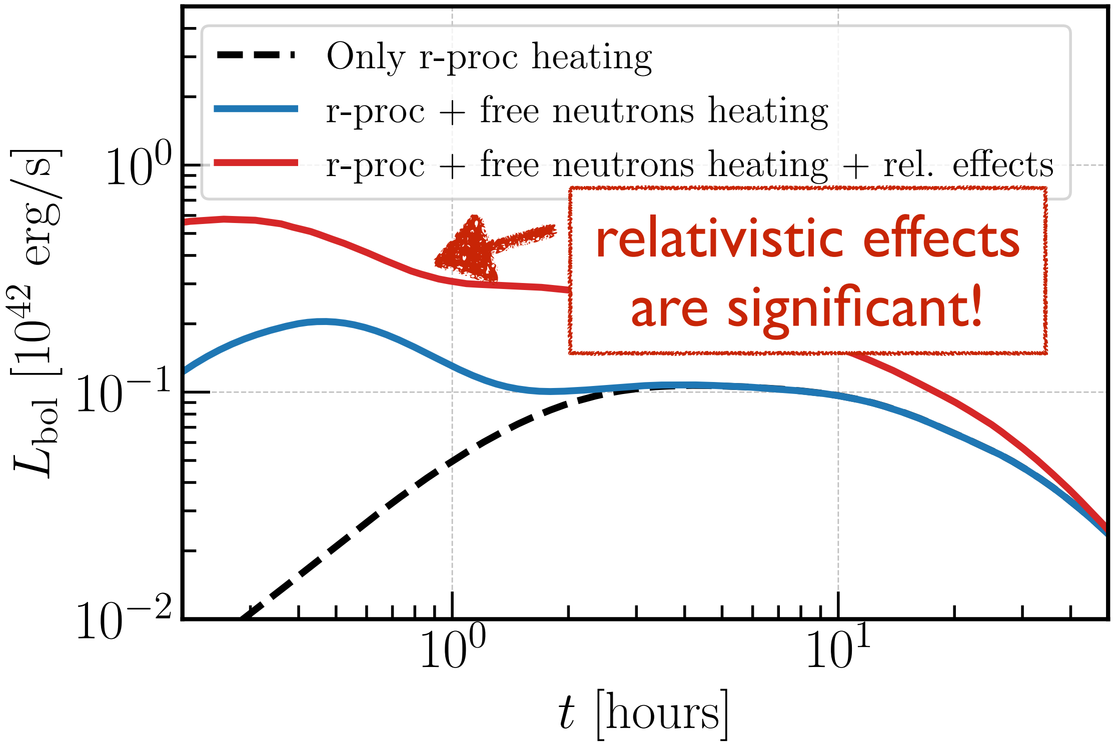
Nuclear heating in ejecta

free neutron decay



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

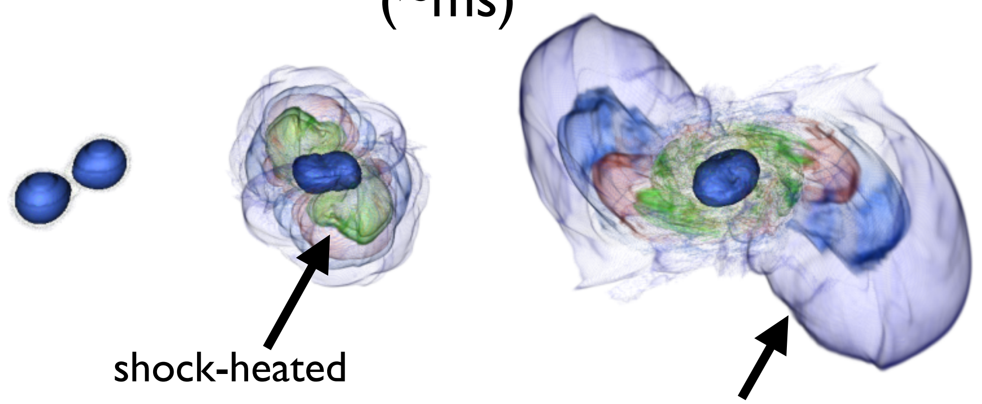
Combi & Siegel 2022a



relativistic effects are significant!

Fast dynamical ejecta: neutron precursor

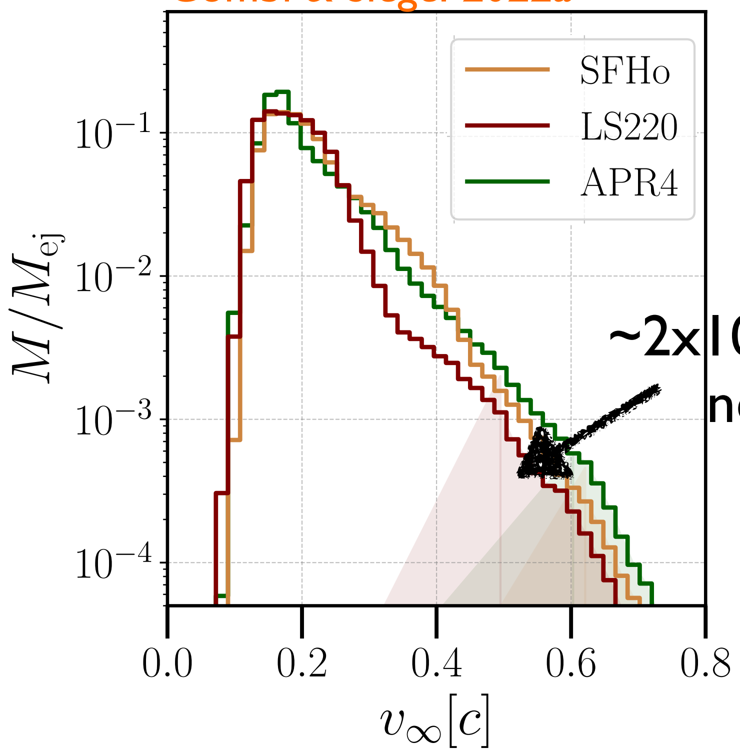
dynamical ejecta
(~ms)



shock-heated
ejecta

tidal ejecta

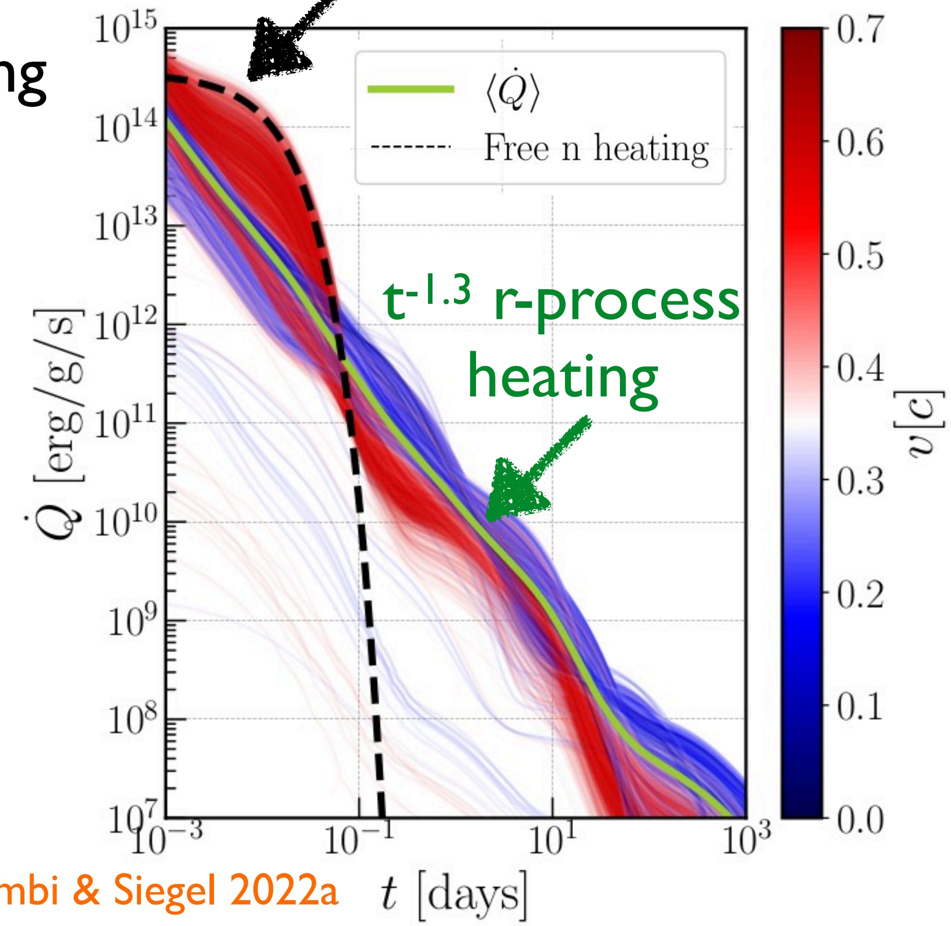
Combi & Siegel 2022a



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

Nuclear heating in ejecta

free neutron decay



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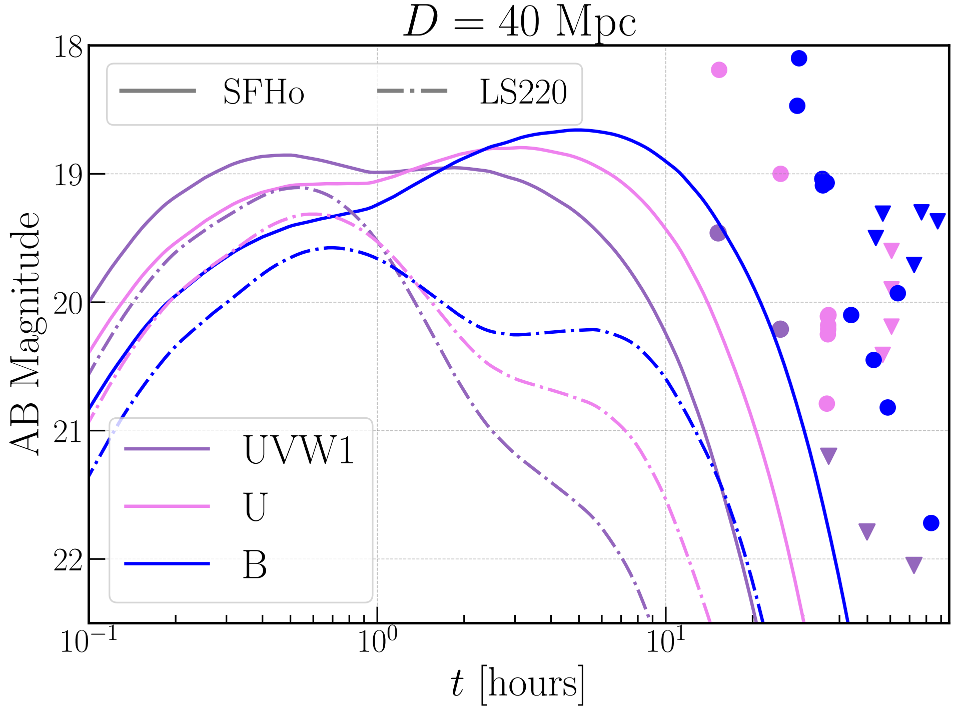
Combi & Siegel 2022a



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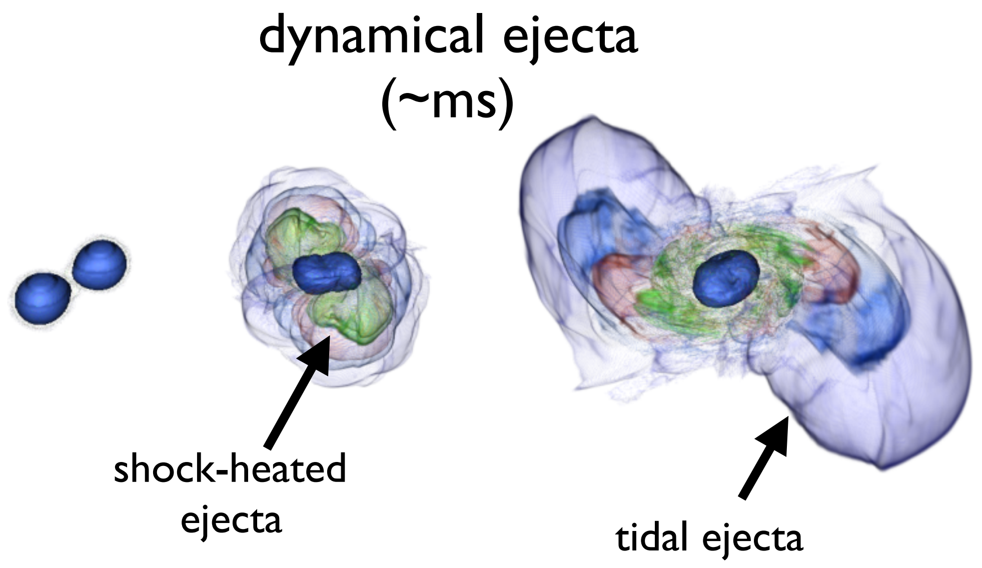
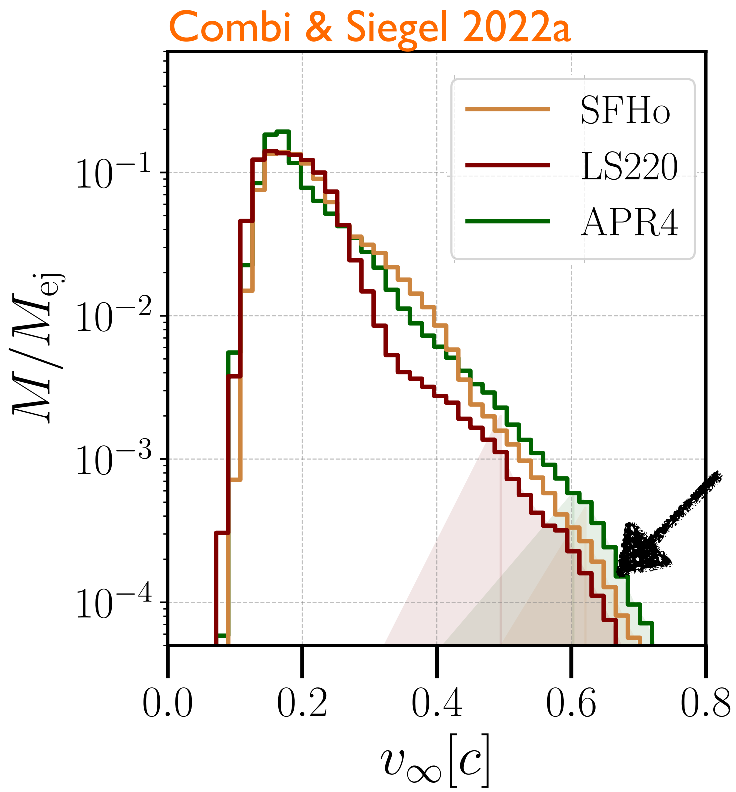
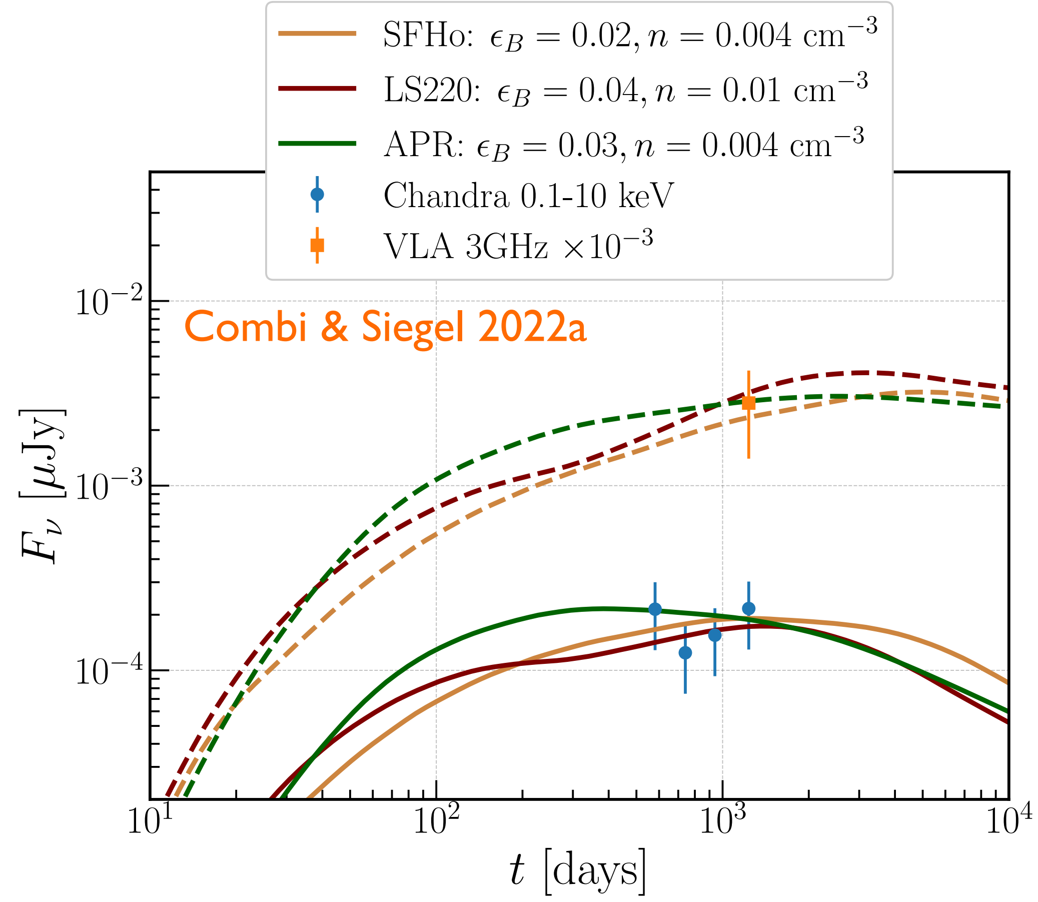
Fast dynamical ejecta: X-ray to radio afterglow

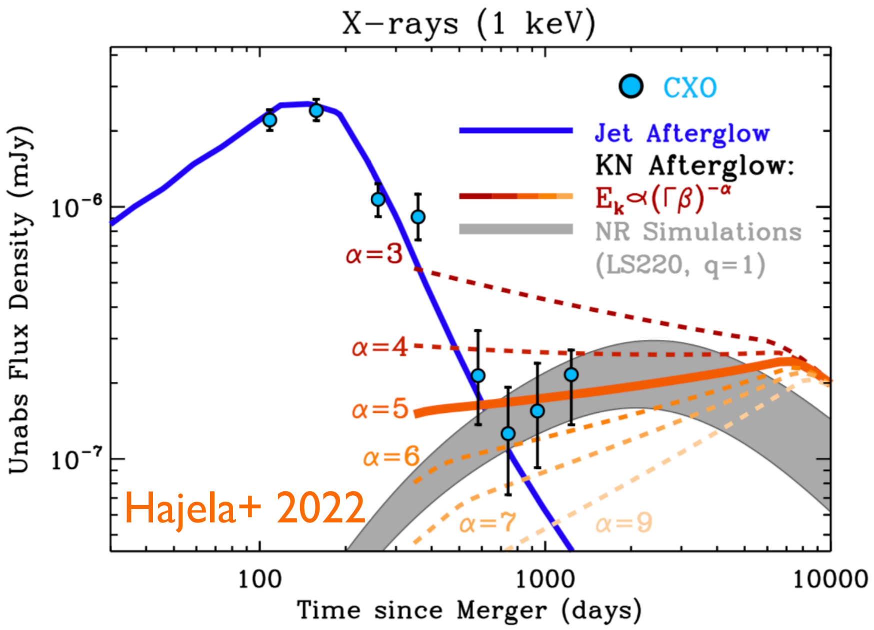




~5x10^{-6} M$_{\rm sun}$
>0.6c ejecta

- fast, high-Y$_{\rm e}$ (>0.25), shock-heated ejecta
- GW170817: source of X-ray-radio afterglow, timescale of years

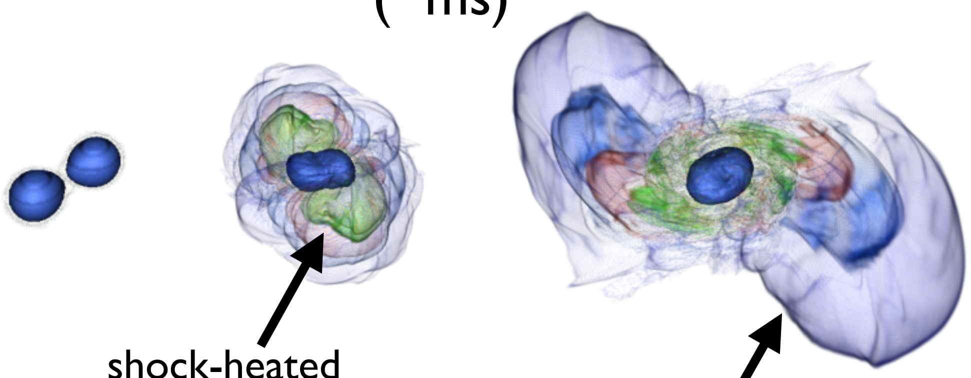




Hajela+ 2022
Troja+ 2022
Balasubramanian+ 2021
Nedora+ 2021
Hotokezaka+ 2018

Nucleosynthesis: dynamical ejecta

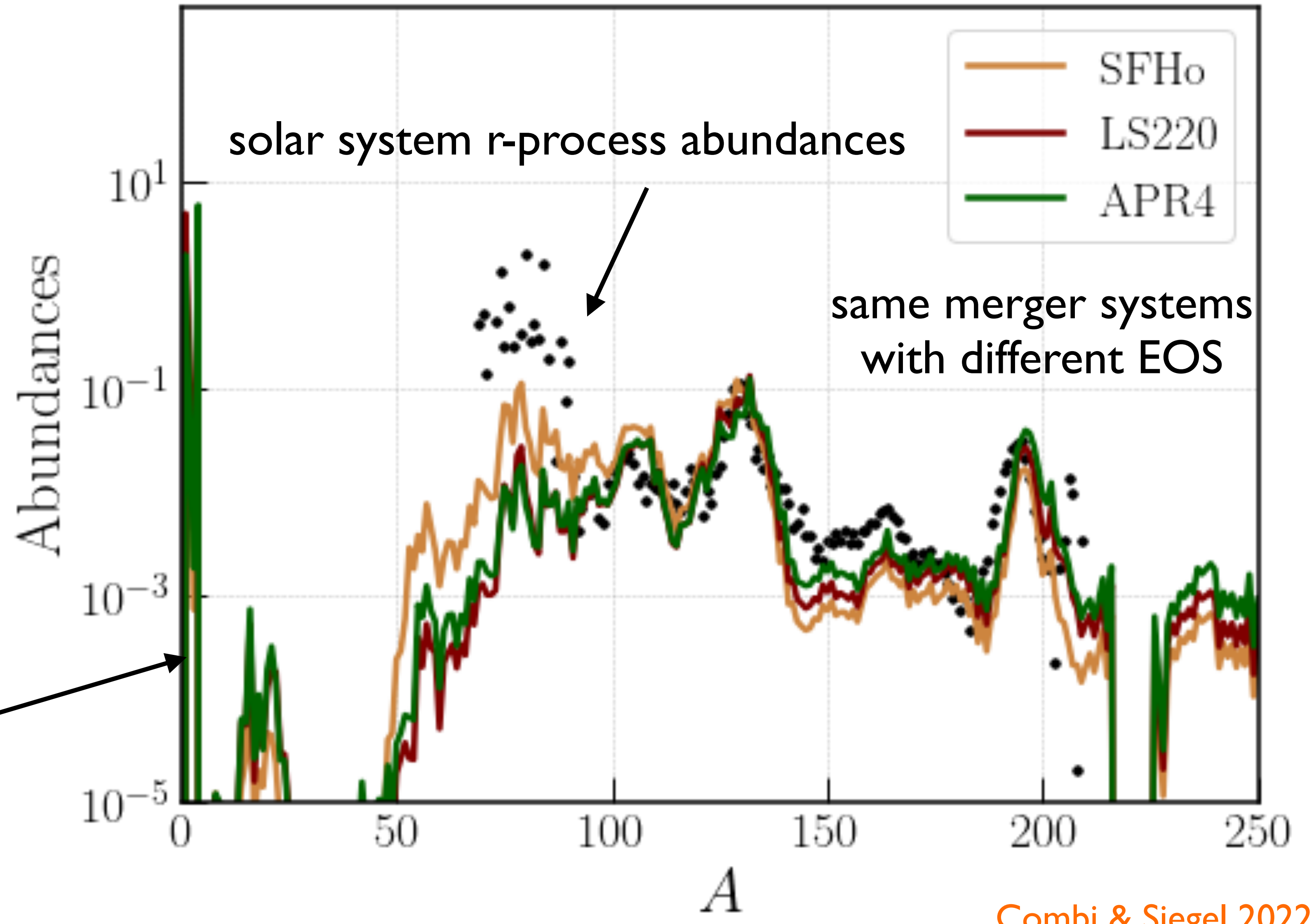
dynamical ejecta
(~ms)



shock-heated
ejecta

tidal ejecta

free neutrons



solar system r-process abundances

same merger systems
with different EOS

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
- typically ~10^{-3} M_{sun} per event, likely subdominant wrt post-merger ejecta

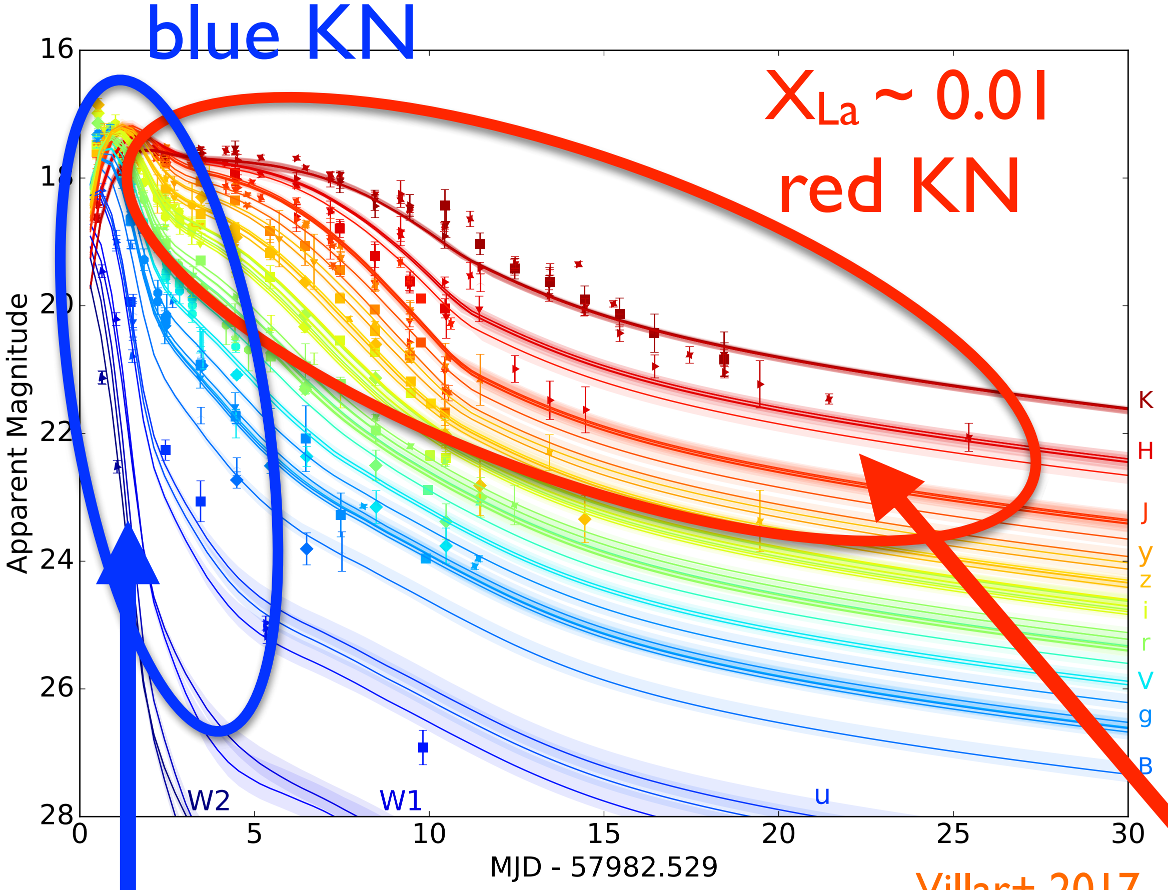
Radice+ 2018
Kullmann+ 2021
Fujibayashi+ 2022

Siegel 2019, 2022

The GW170817 kilonova

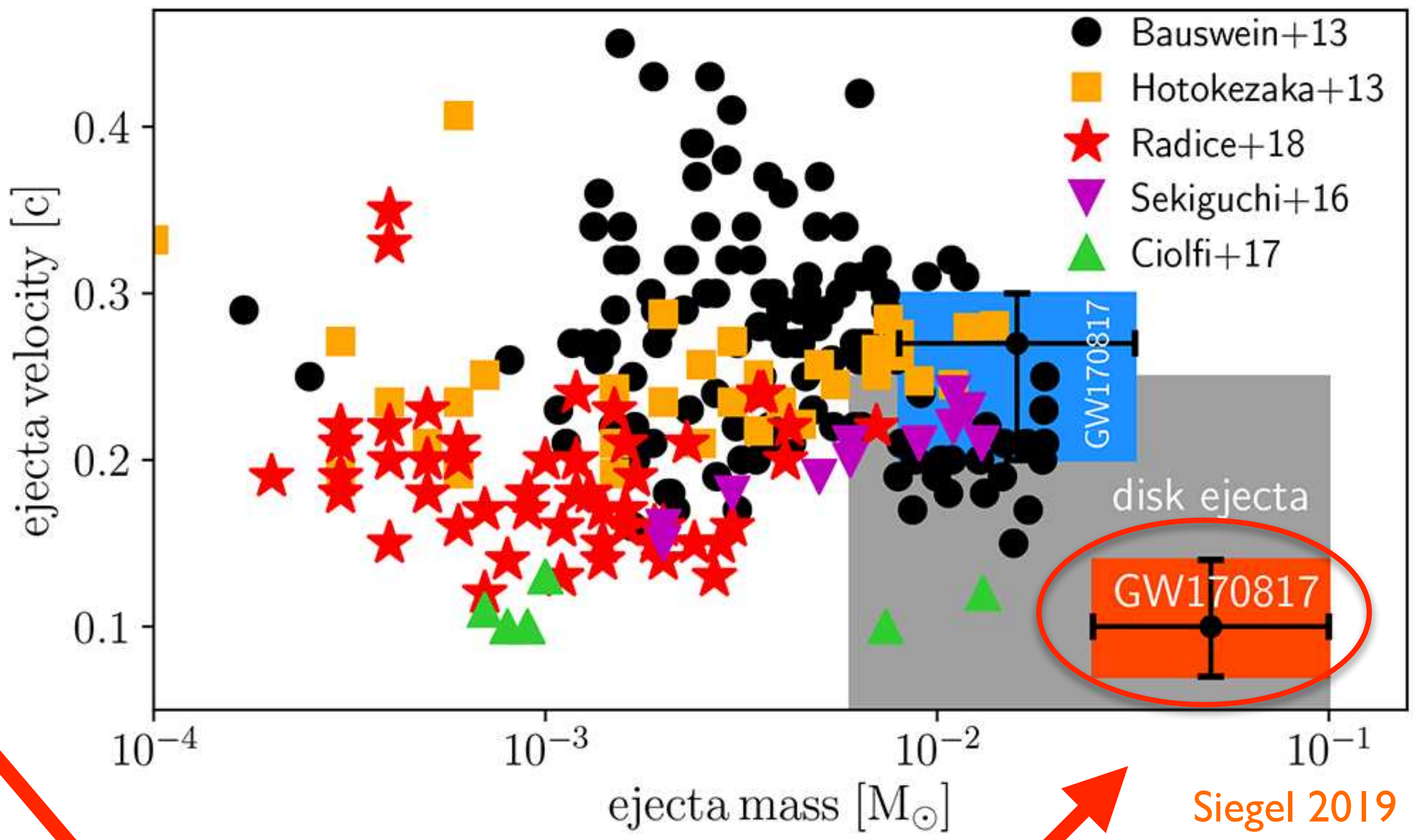
$X_{La} < 10^{-4}$
blue KN

$X_{La} \sim 0.01$
red KN



Villar+ 2017

BNS merger simulations: dynamical ejecta



Siegel 2019

post-merger winds?
neutron precursor at
early times?

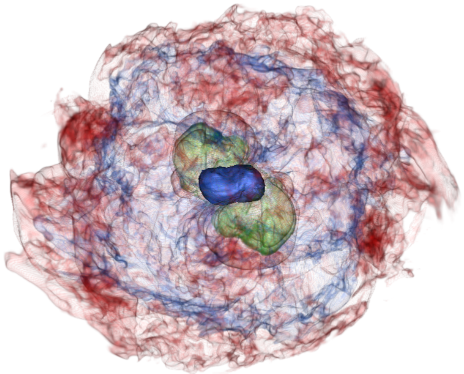
likely disk ejecta

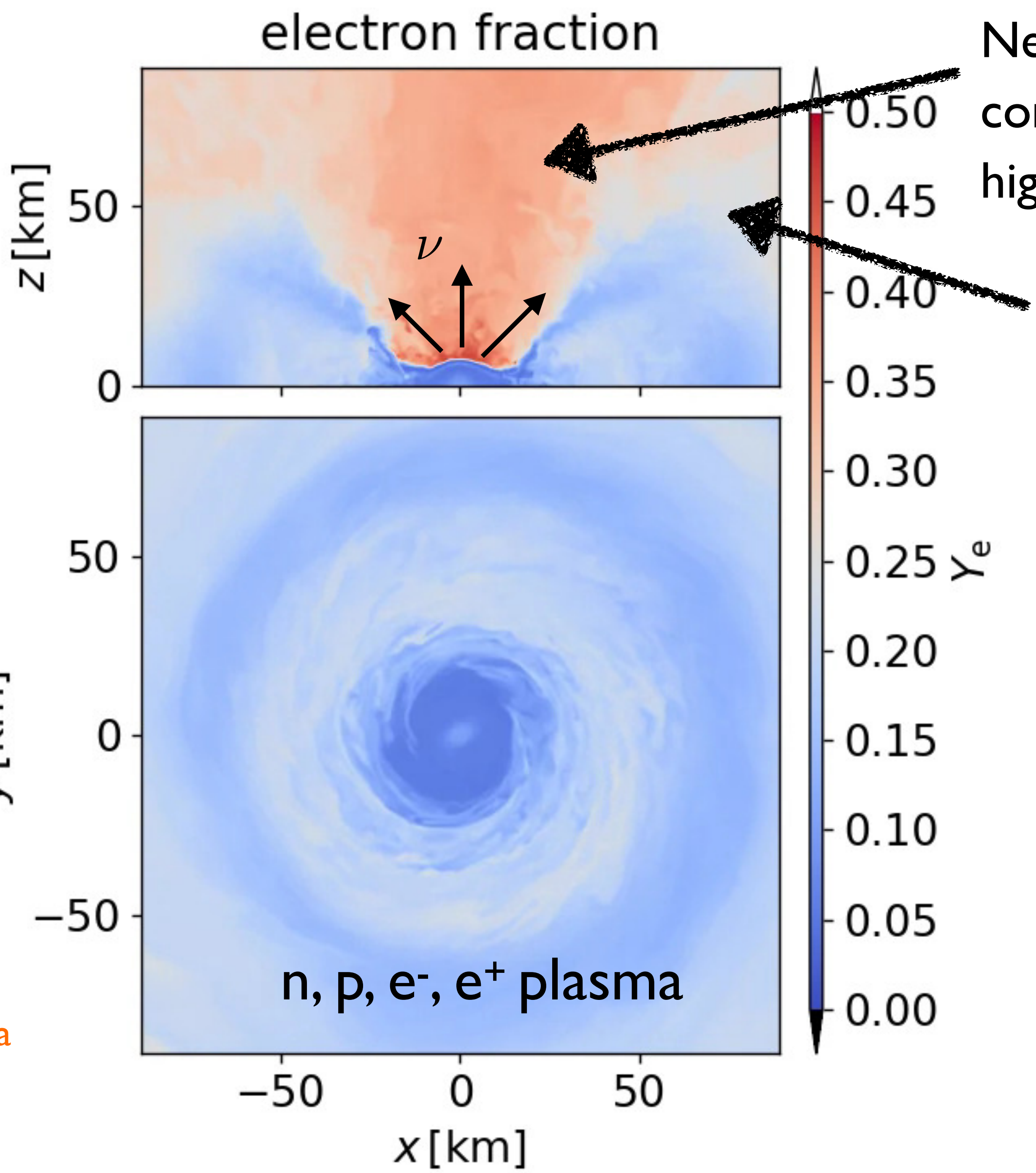
Kasen+ 2017

Siegel & Metzger, PRL 2017

Post-merger winds

wind ejecta
(~10-100ms)




electron fraction

Combi & Siegel 2022a

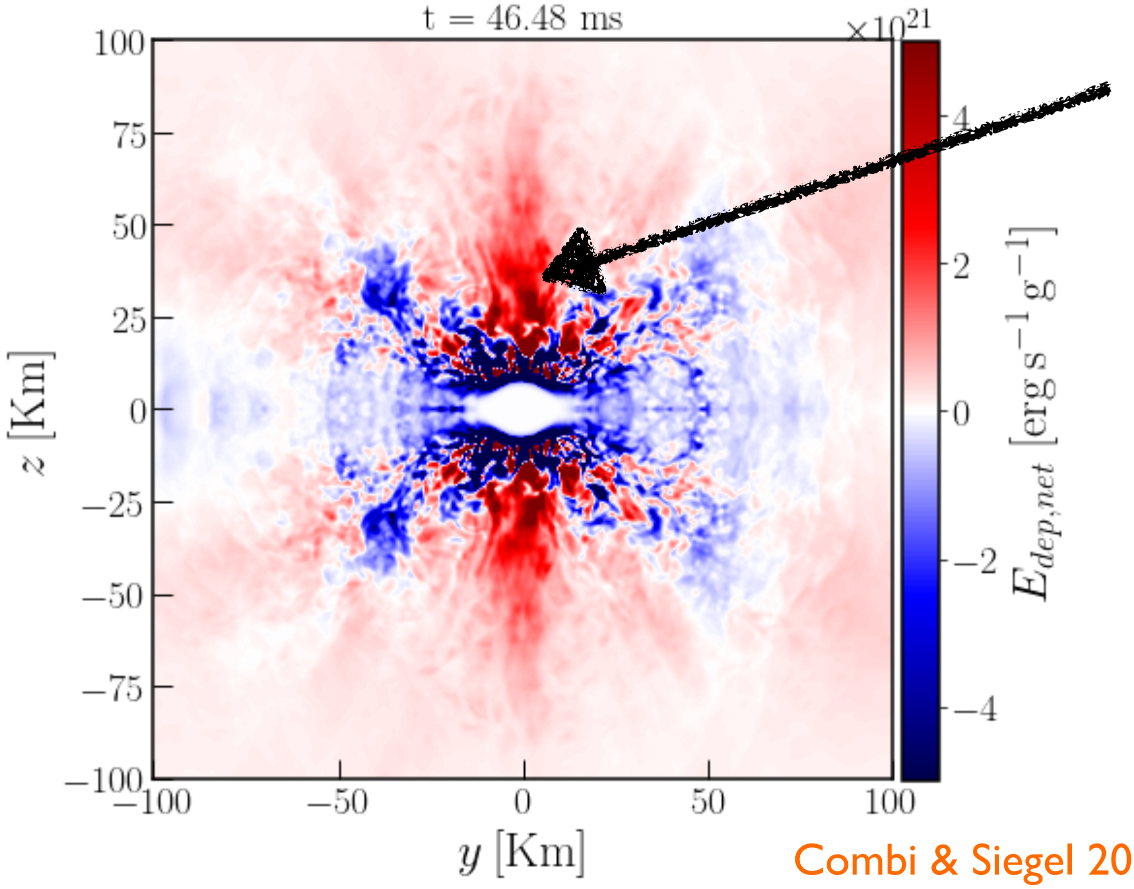
Neutrino irradiation changes the composition of the ejecta: high-Y_e (>0.25), hot ejecta

medium-Y_e, hot disk wind ejecta

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

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

Magnetic tower with neutrinos—a 'jet' emerges



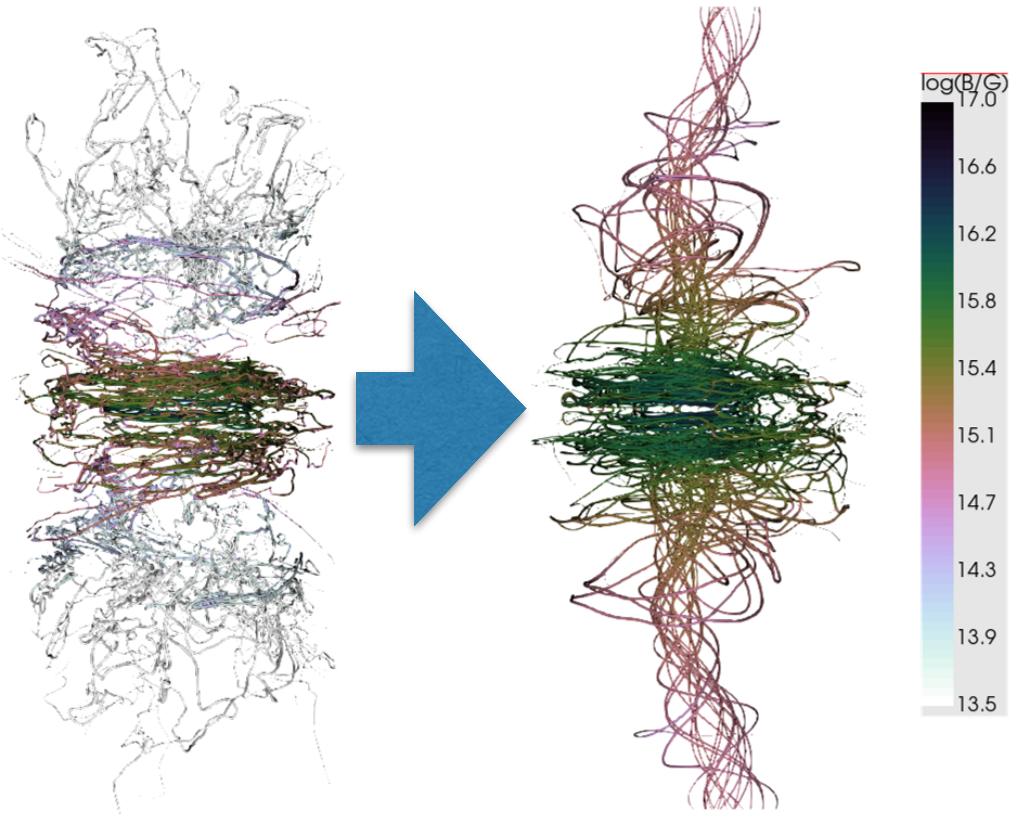
Combi & Siegel 2022b

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

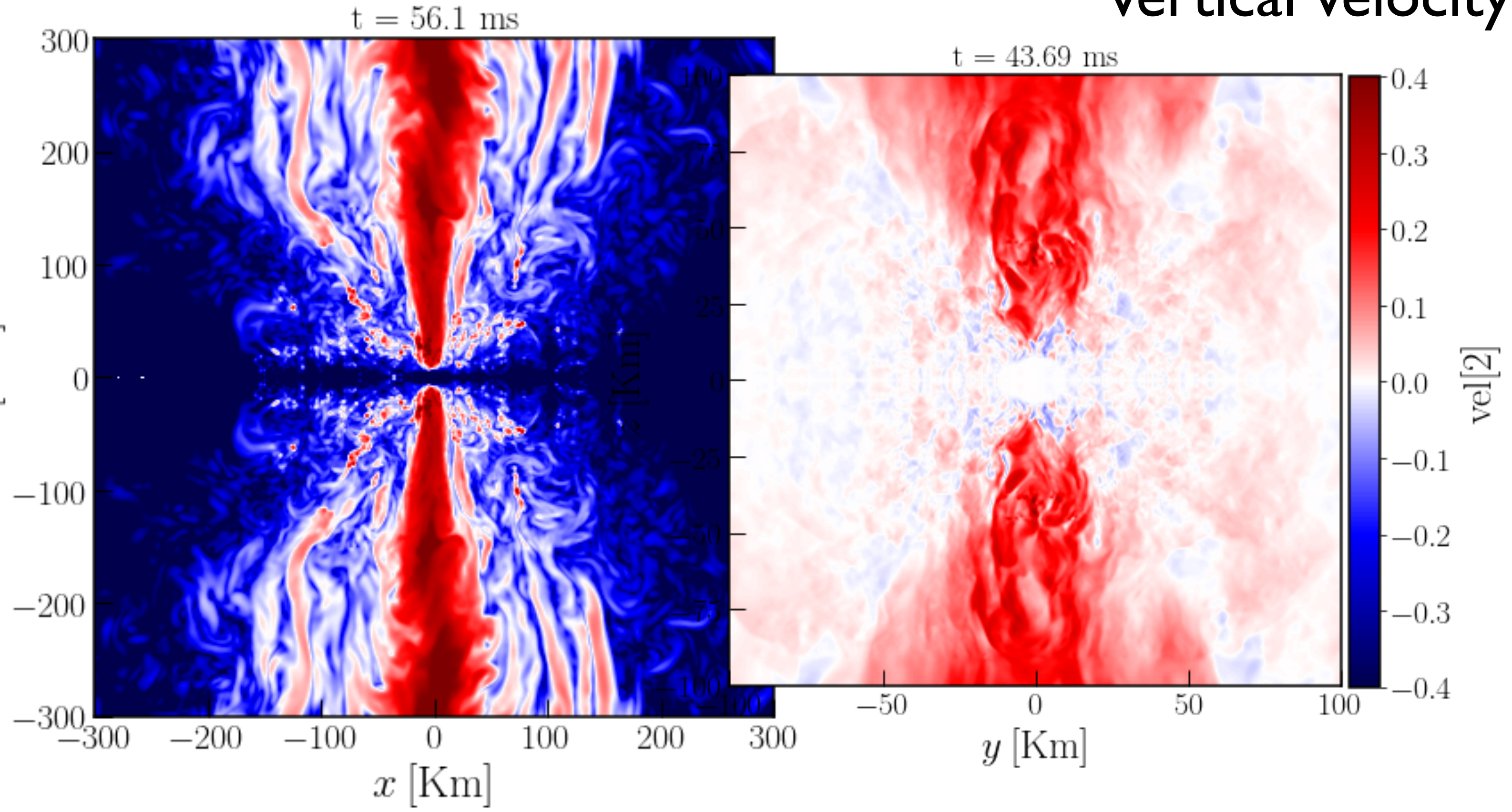
Mösta+2020
Curtis+ 2021
Combi & Siegel 2022b

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



magnetization

vertical velocity



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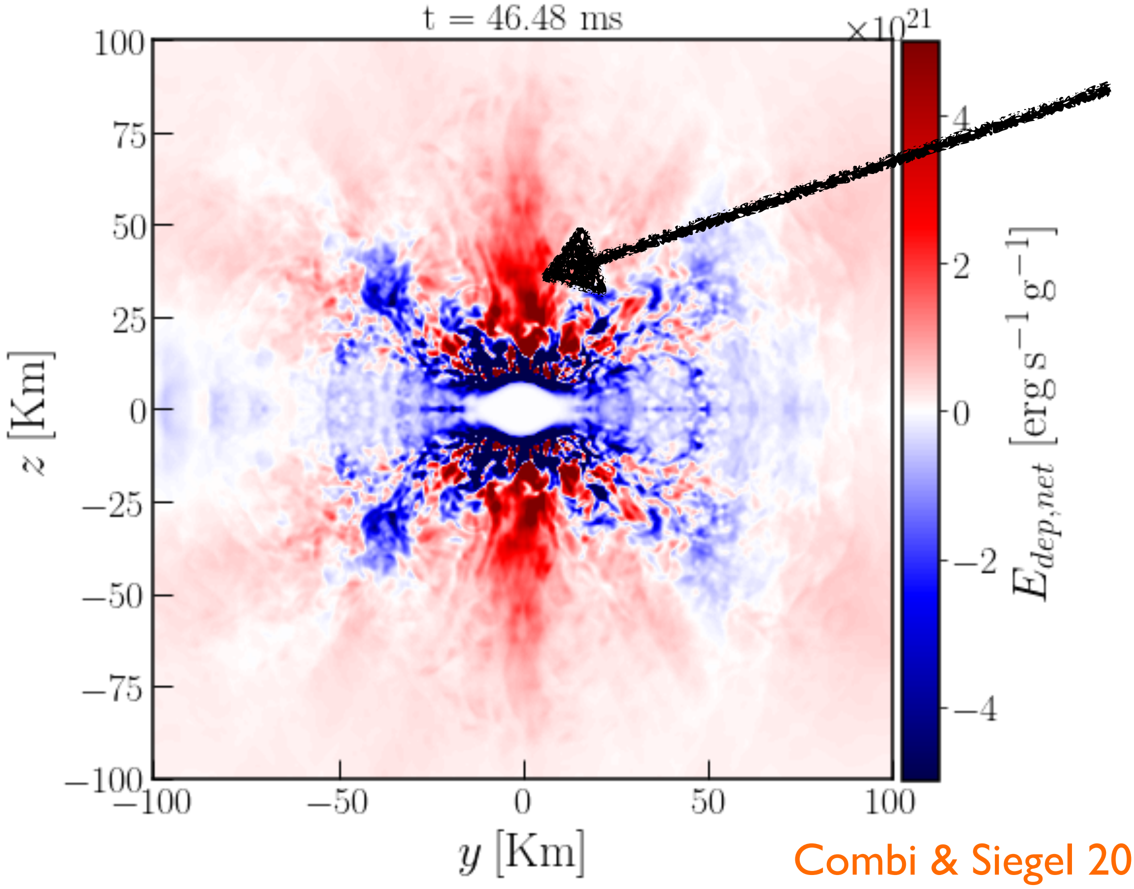

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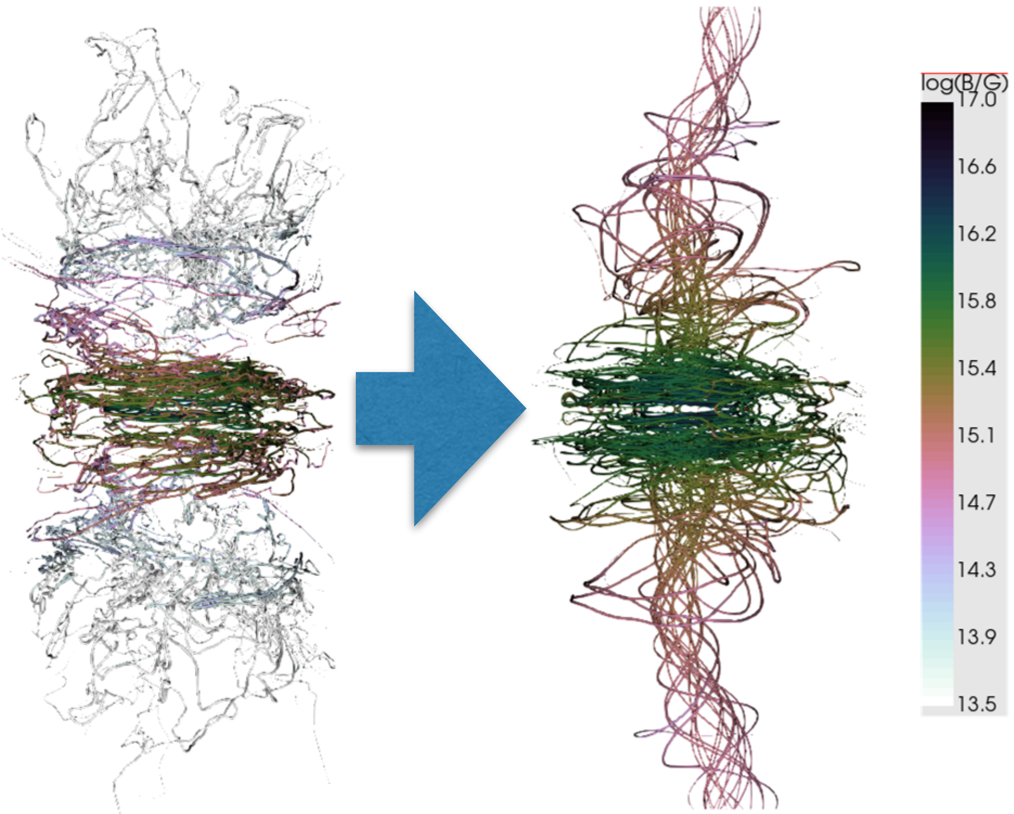
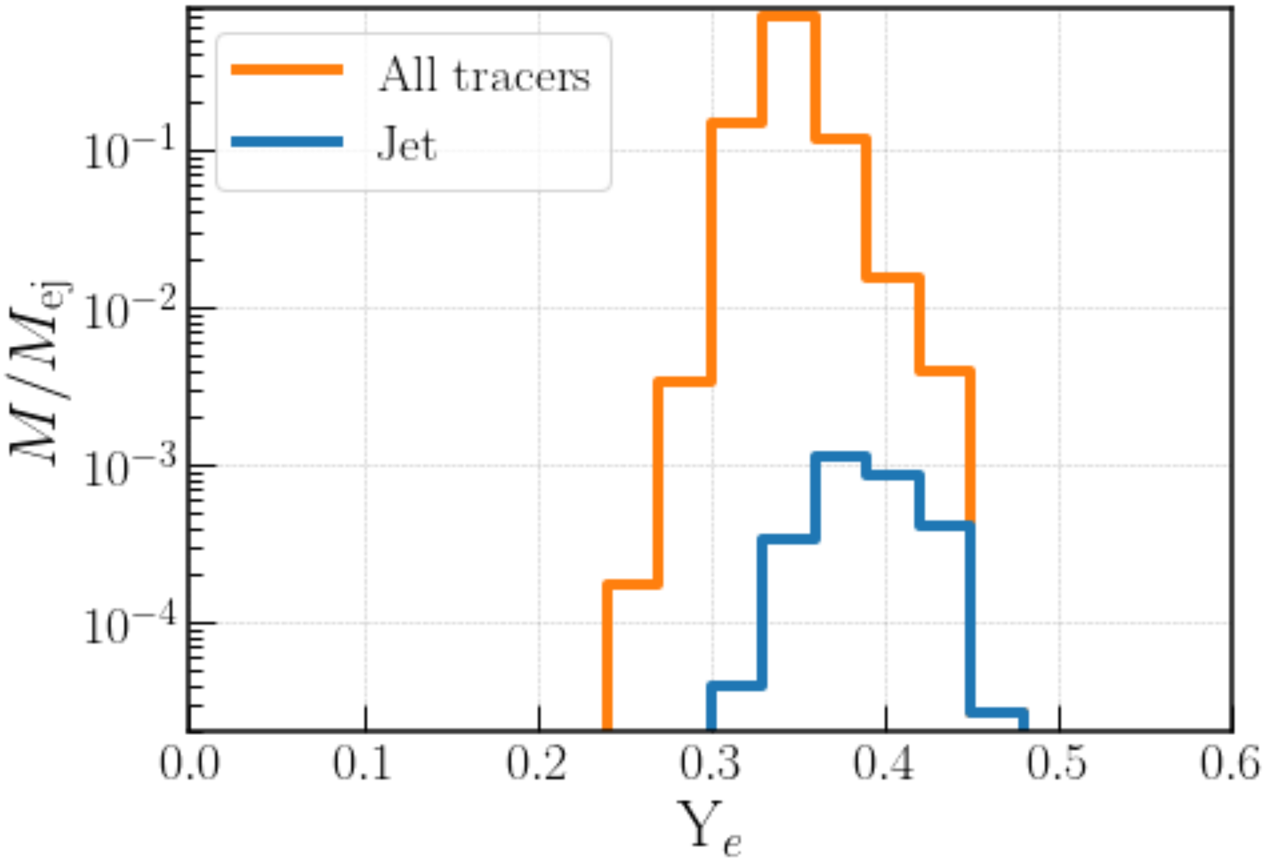
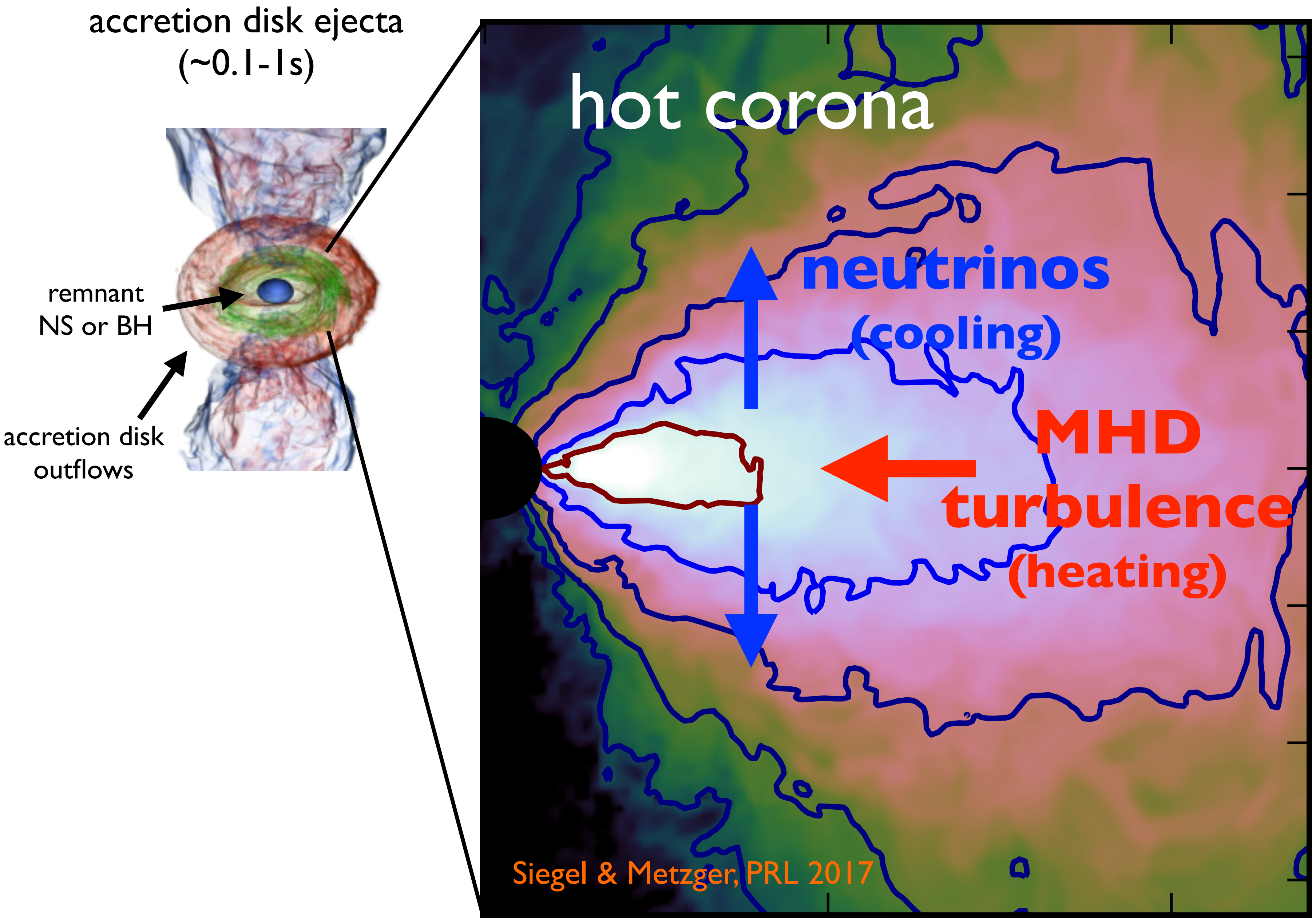




Post-merger disk ejecta



Siegel & Metzger, PRL 2017

heating-cooling imbalance in corona &
nuclear recombination launches wind

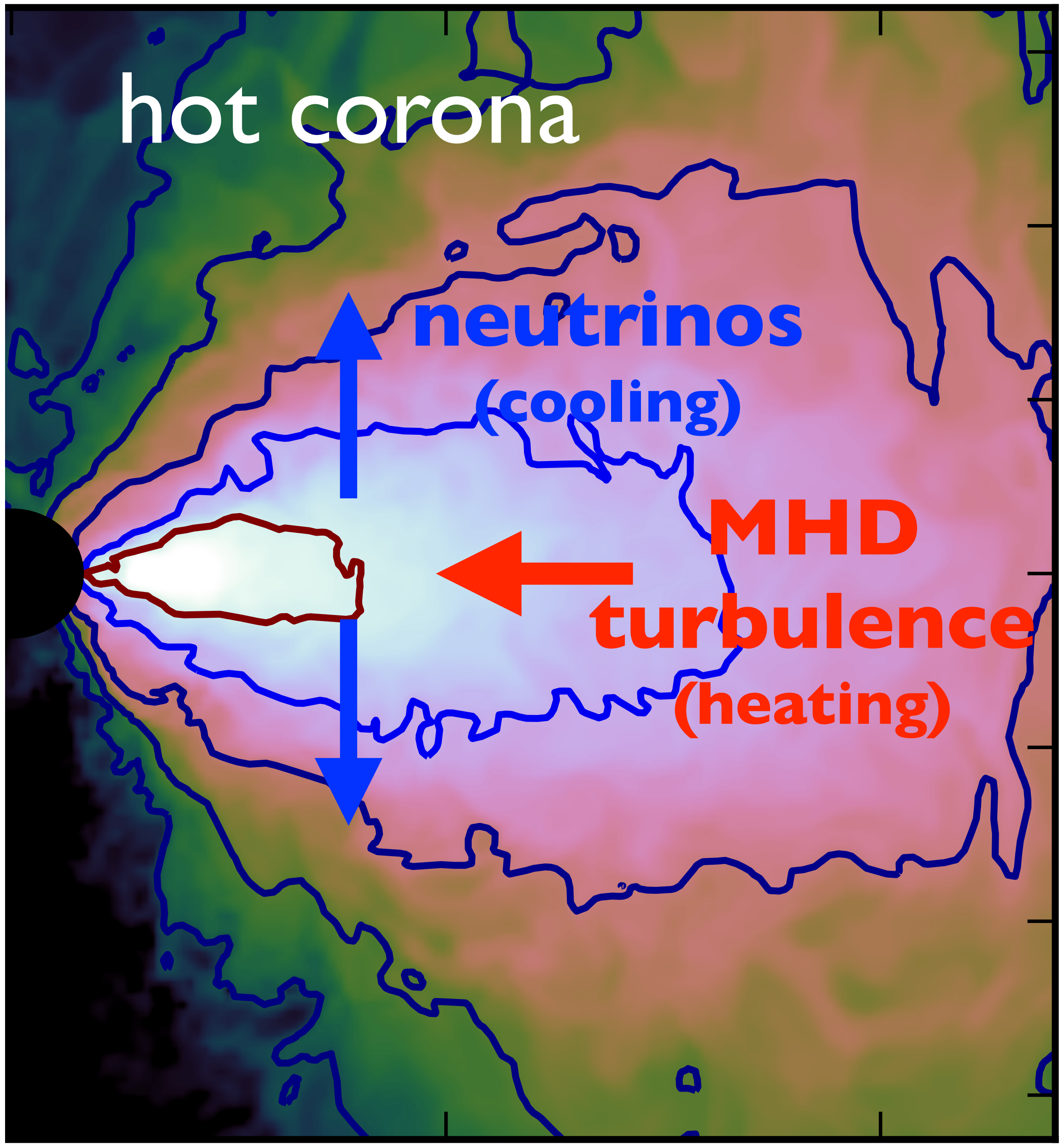
- Weak interactions are key for composition, nucleosynthesis, kilonova
- Self-regulation keeps disk neutron-rich:
  light & *heavy* r-process

  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

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

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

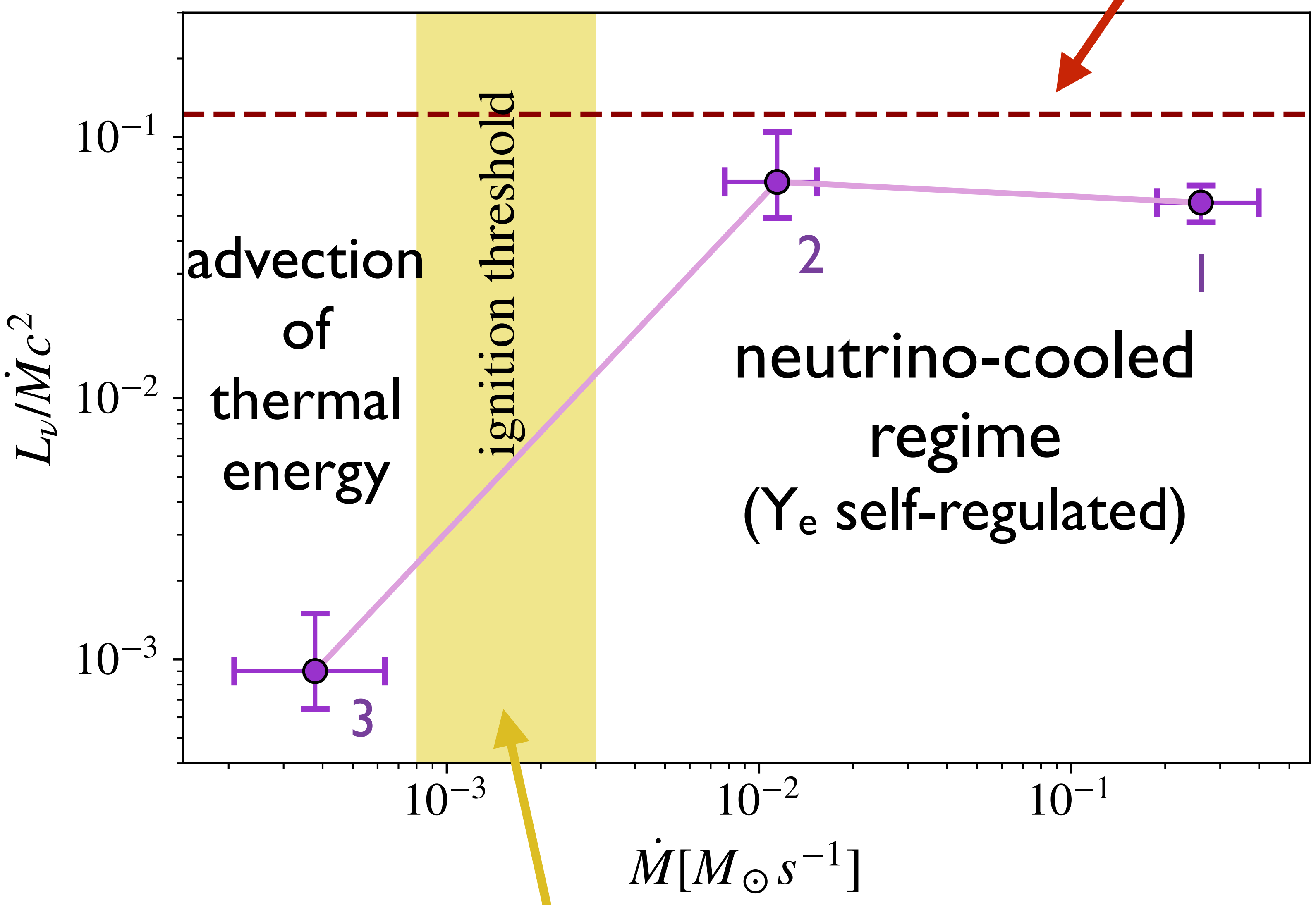
Accretion rate controls nucleosynthesis!

⟶ different ‘nucleosynthesis bands’

Ignition of weak interactions

De & Siegel 2021

maximal radiative efficiency



advection of thermal energy

neutrino-cooled regime (Y$_e$ self-regulated)

analytic estimate from 1D alpha-disk model

simulated GRMHD disks

Ejected disk mass:

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

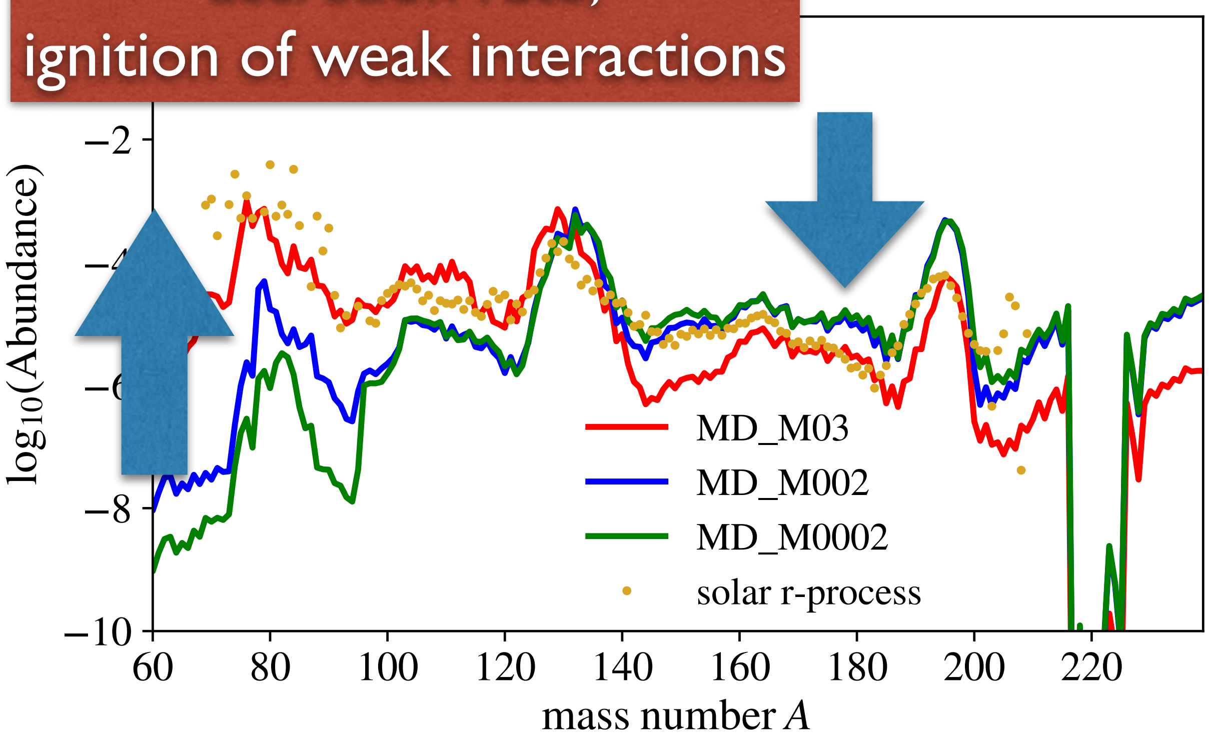
see also:
Siegel & Metzger 2018
Fernandez+ 2019, 2020
Christie+ 2019

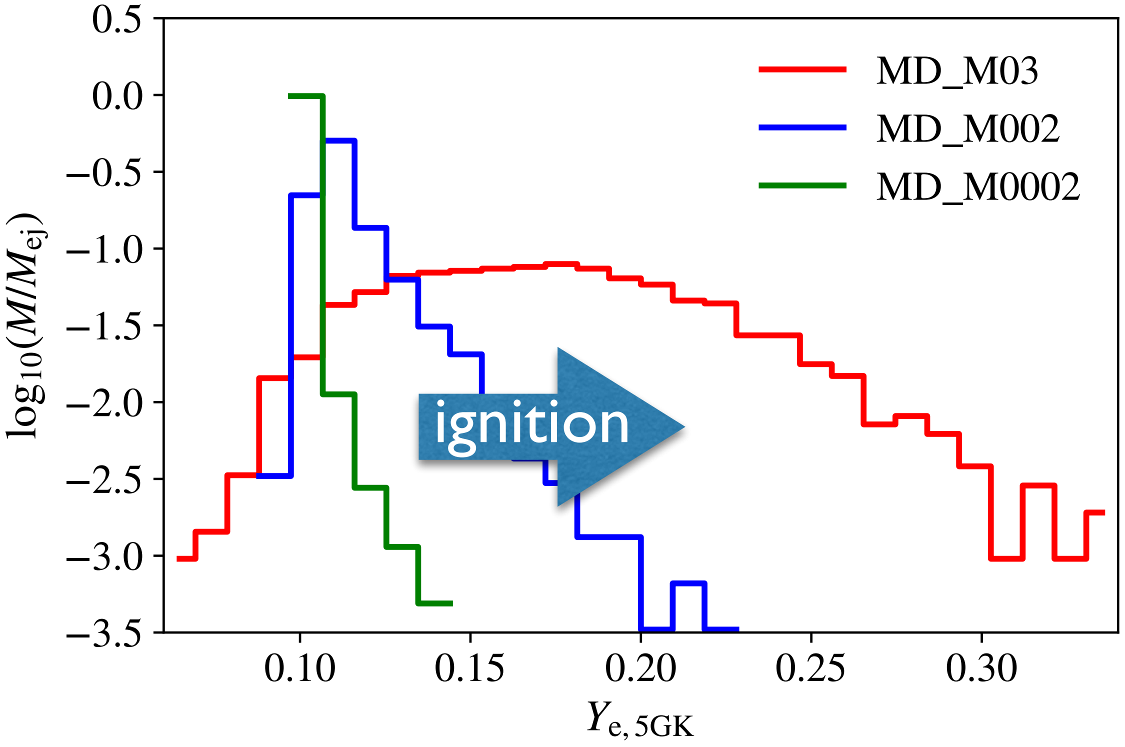
more effective evaporation in the absence of cooling!

Nucleosynthesis

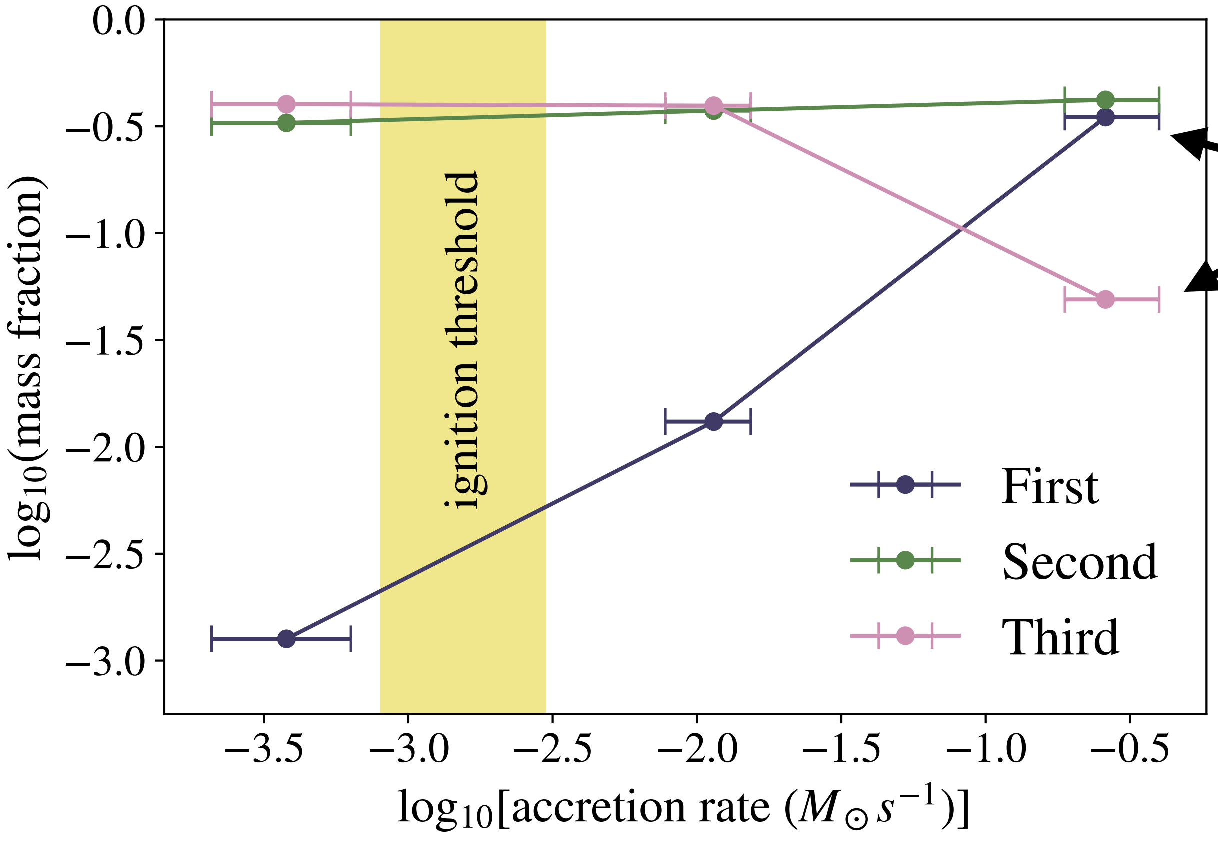
De & Siegel 2021

accretion rate,
ignition of weak interactions





R-process peaks



trends to continue as neutrino absorption becomes important

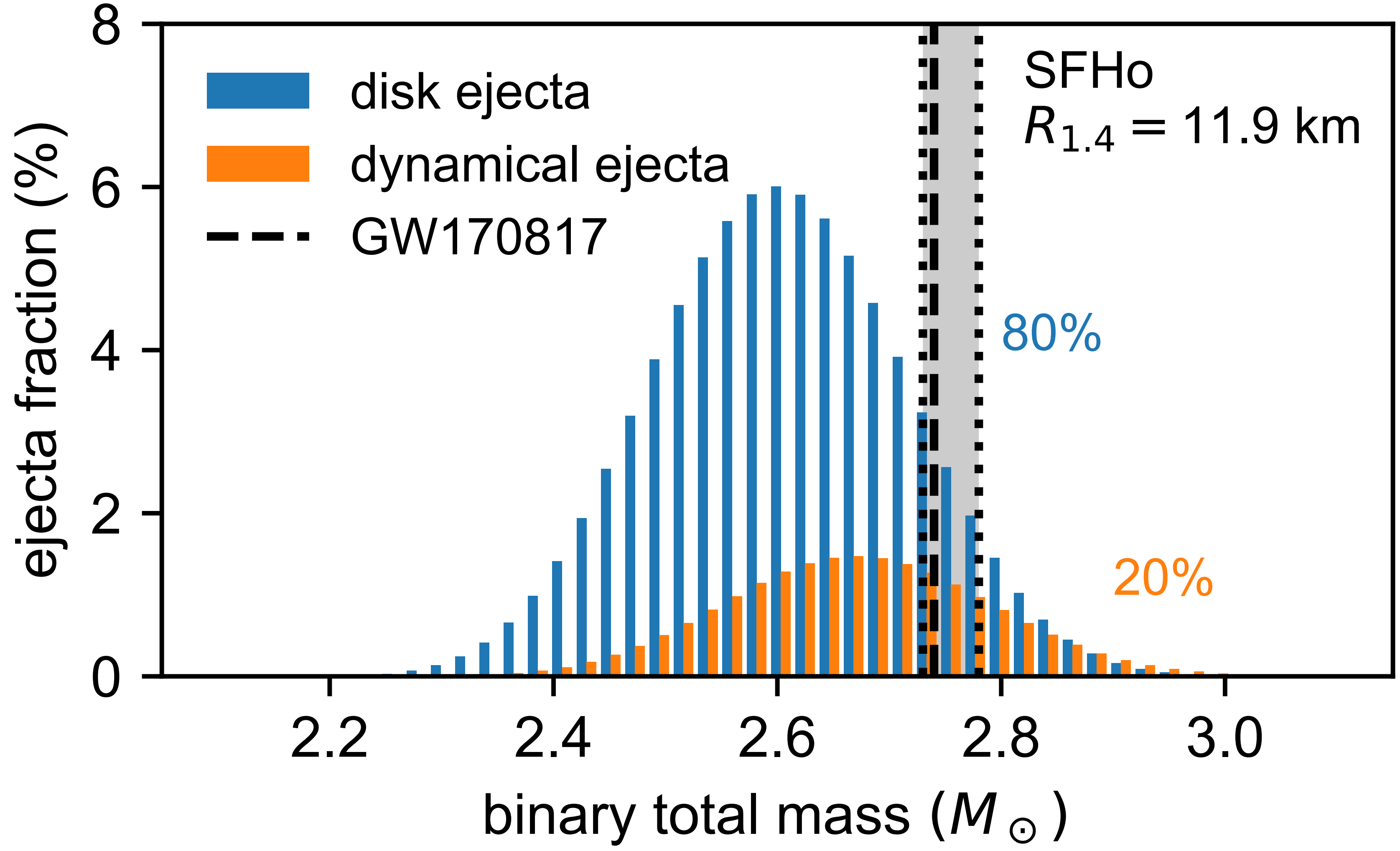
(see Miller+ 2019, Li & Siegel 2021)

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

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.*

Post-merger physics: Neutrino oscillations

Li & Siegel 2021, PRL

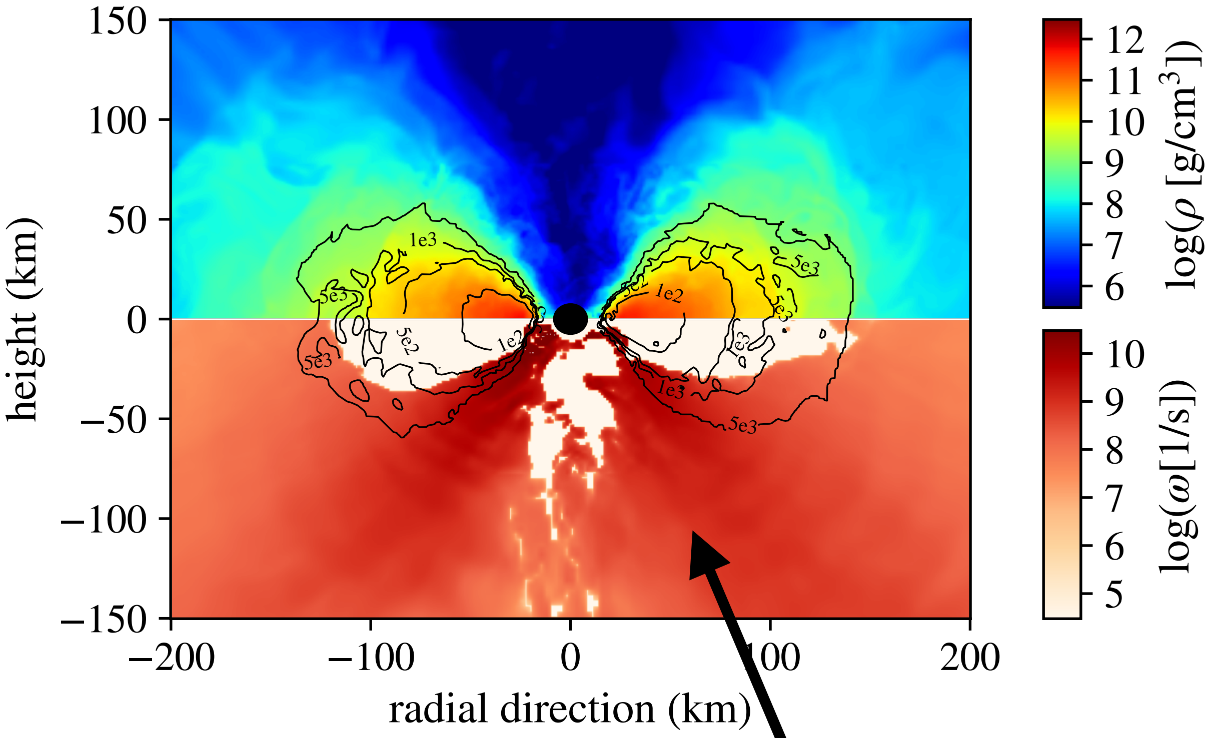
Free-streaming neutrinos:

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

vacuum oscillations

self-interaction

matter interaction
(MSW effect)



instability region: ubiquitous flavor conversions
~ns timescales

Conditions for fast conversions:

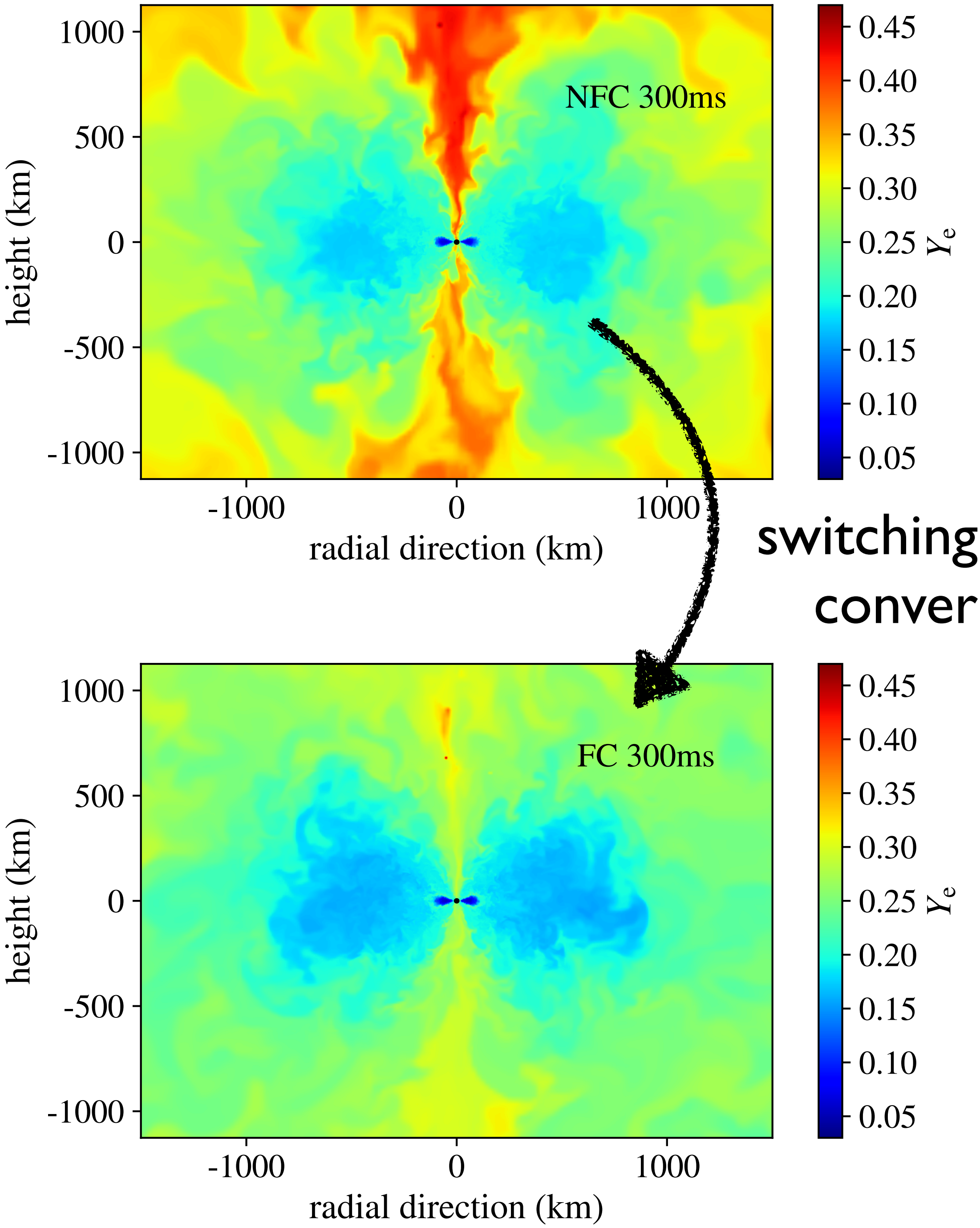
$$\Phi_0 = \sqrt{2} G_F \hbar^{-1} n_{\nu} = 1.92 \times 10^9 \mathrm{s}^{-1} \left(\frac{n_{\nu}}{10^{31} \mathrm{cm}^{-3}} \right)$$

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

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

Post-merger physics: Neutrino oscillations

Li & Siegel 2021, PRL

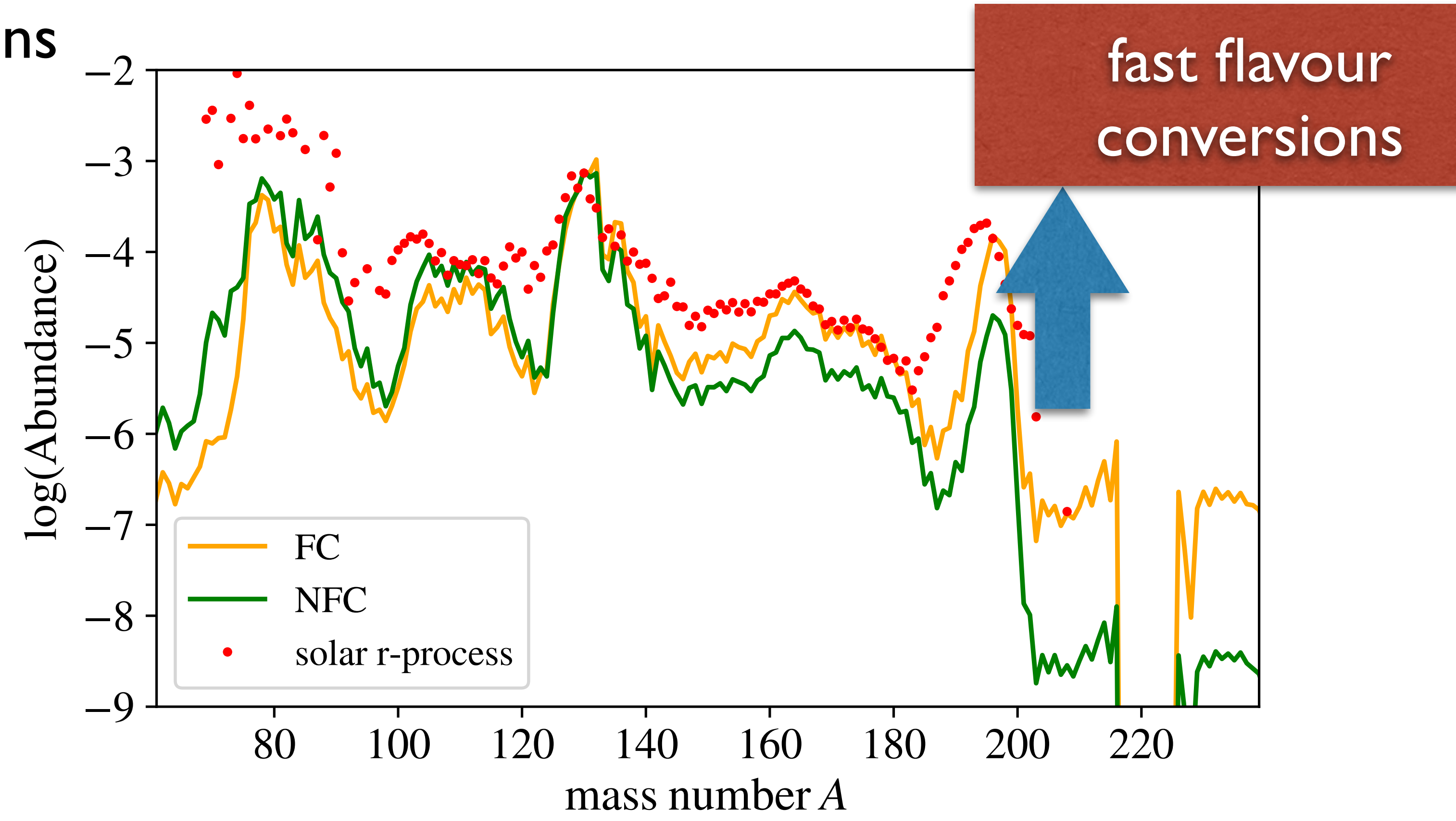


switching on fast conversions

ejecta composition changes dramatically (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

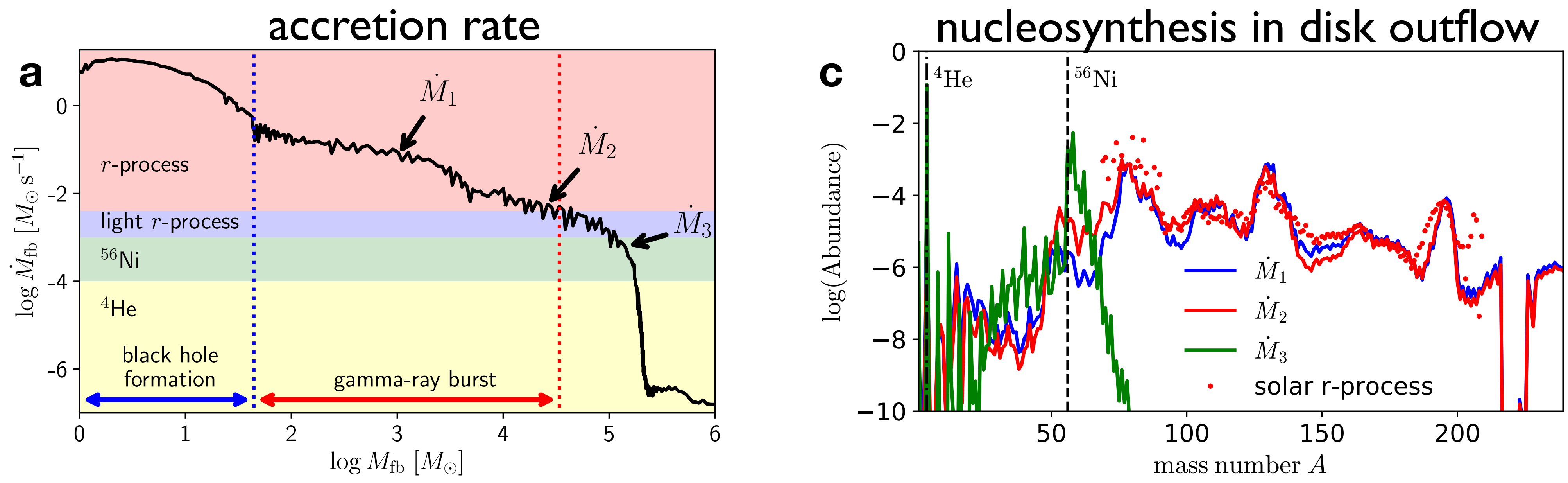


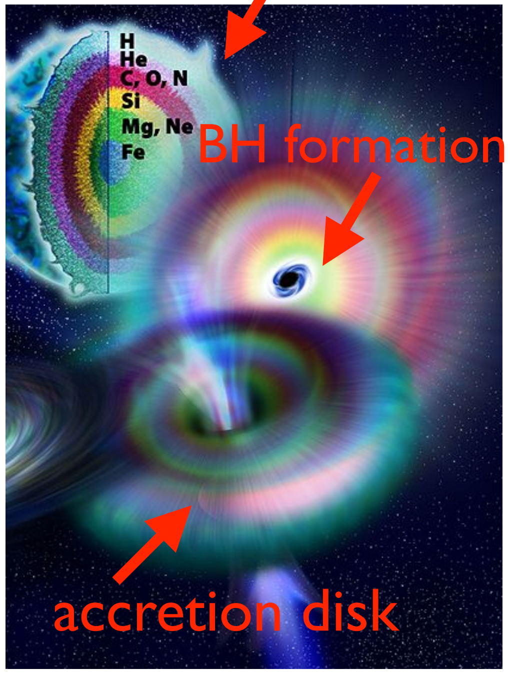
But: non-linear regime of fast flavour conversions still somewhat uncertain Richers+ 2021

IV.
r-process in collapsars

Post-merger physics in other systems: *collapsars*

Siegel, Barnes, Metzger 2019, Nature

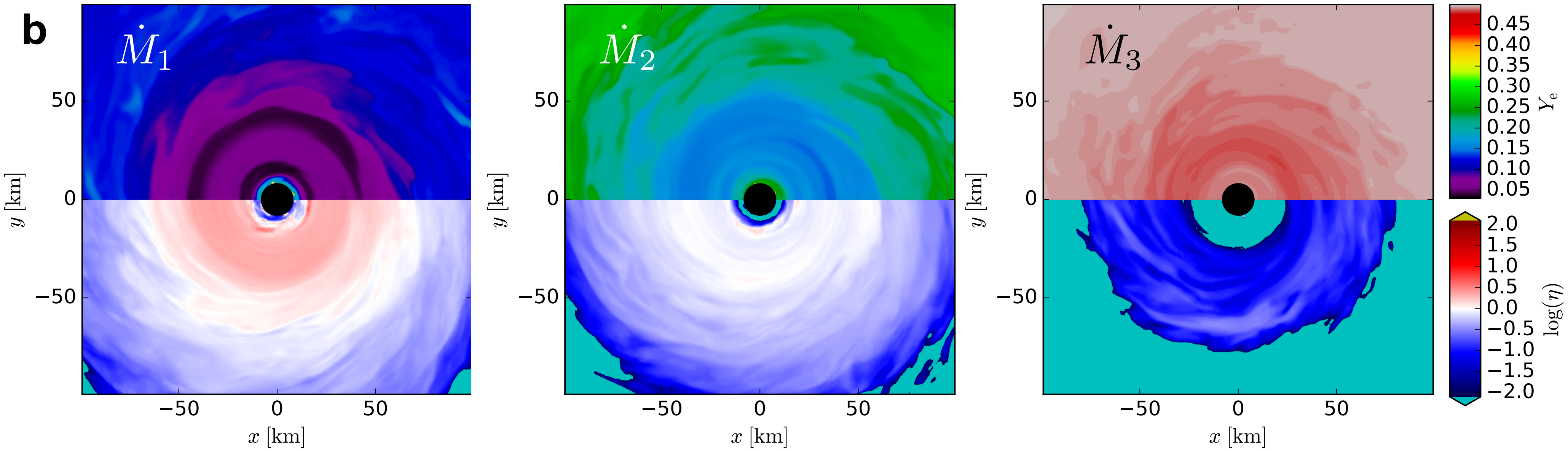




core collapse

BH formation

accretion disk



Y_e

degeneracy

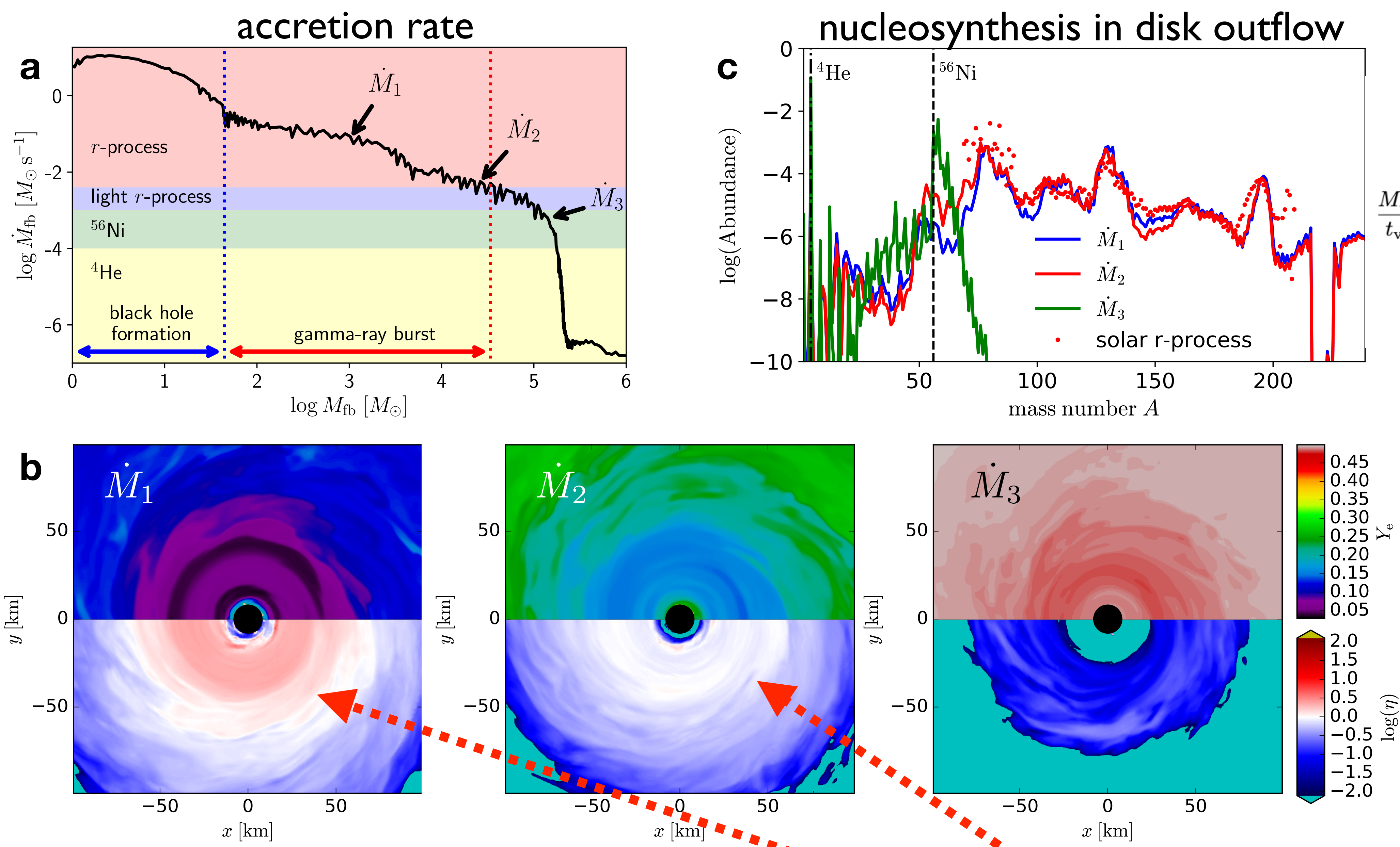
$$e^- + p \rightarrow n + \nu_e$$

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

Post-merger physics in other systems: *collapsars*

Siegel, Barnes, Metzger 2019, Nature

Siegel+ 2022



Y_e

degeneracy

nucleosynthesis bands:

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

Neutron-richness:

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

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

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

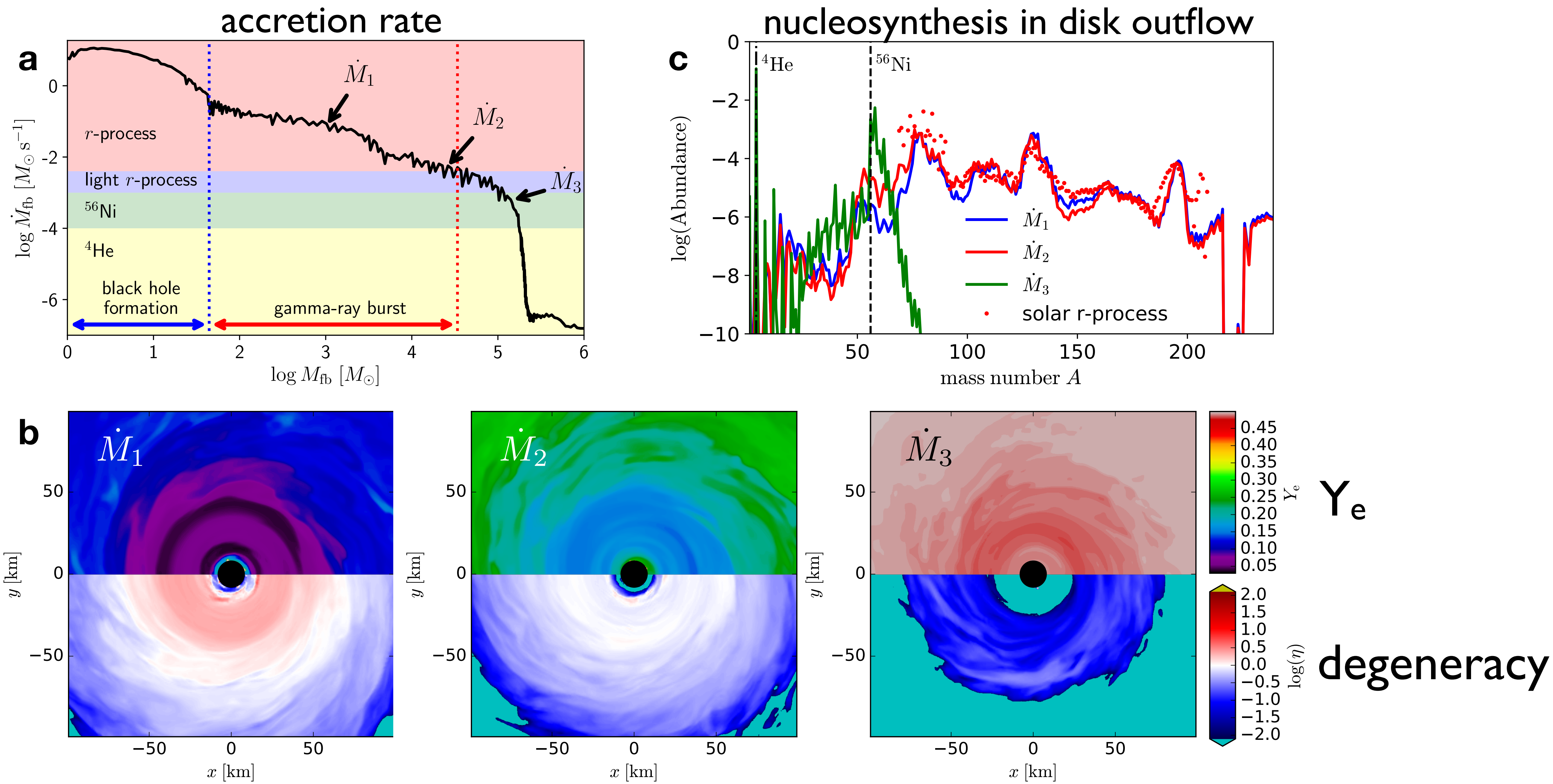
→ degenerate electrons

Y_e ~ 0.1

outflows produce r-process nuclei

Post-merger physics in other systems: *collapsars*

Siegel, Barnes, Metzger 2019, Nature

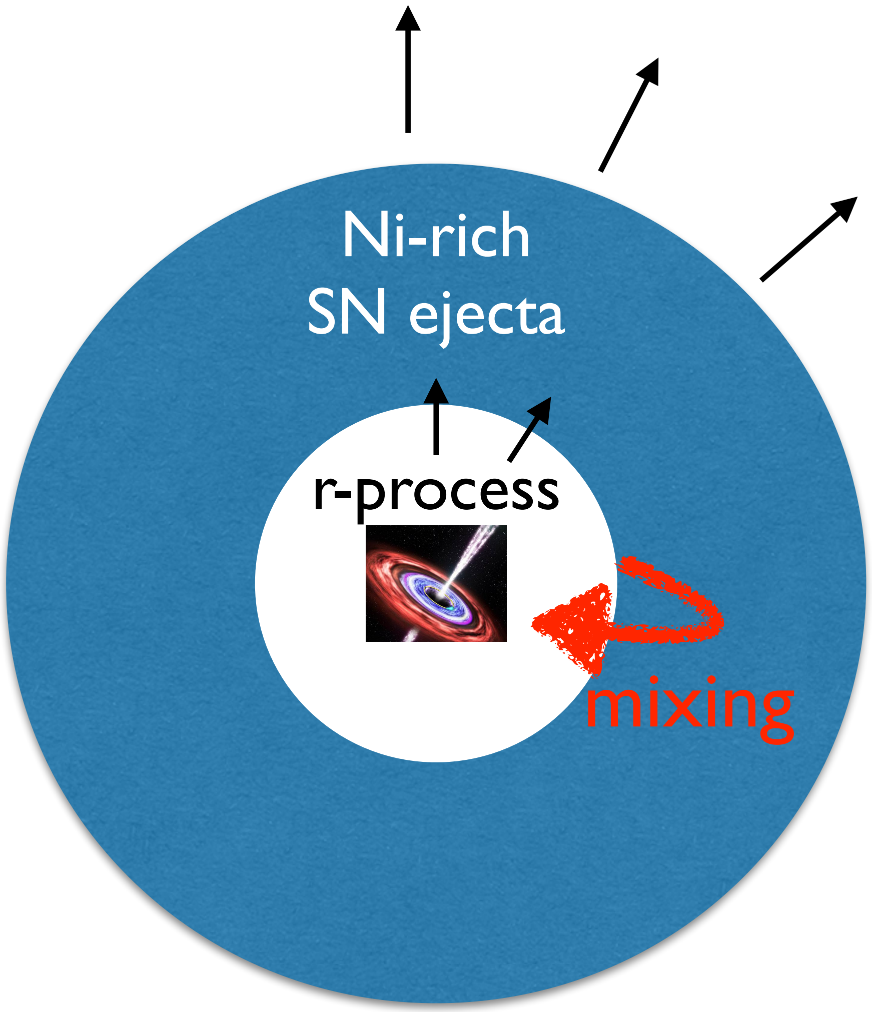


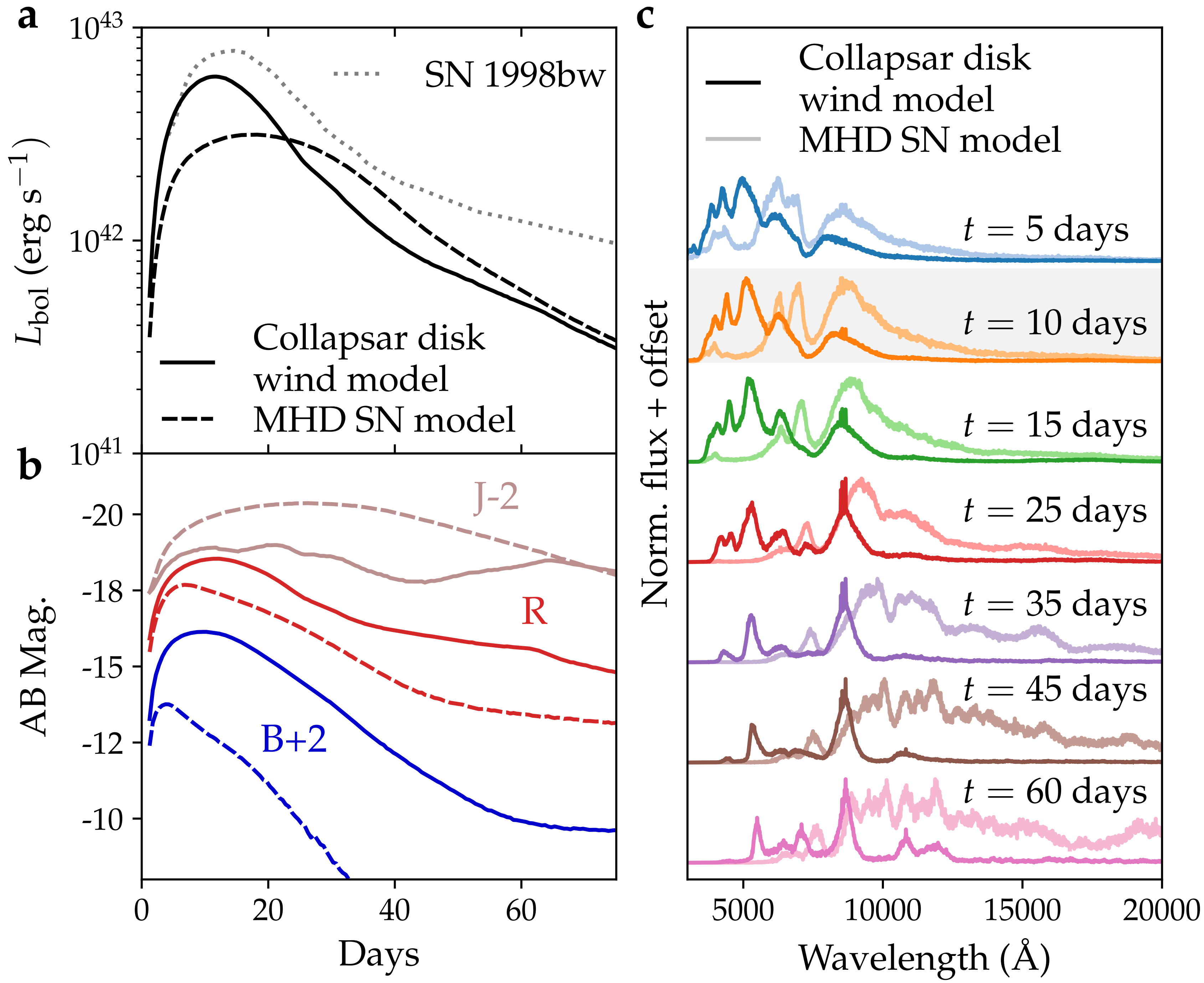
- 0.05–1 $M_{\rm sun}$ of r-process material per event over-compensates lower rates relative to mergers
- self-regulation over wide range of accretion rates produced well-defined nucleosynthesis pattern similar to solar
- may dominate r-process production by mergers

See also:

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

How to observe?





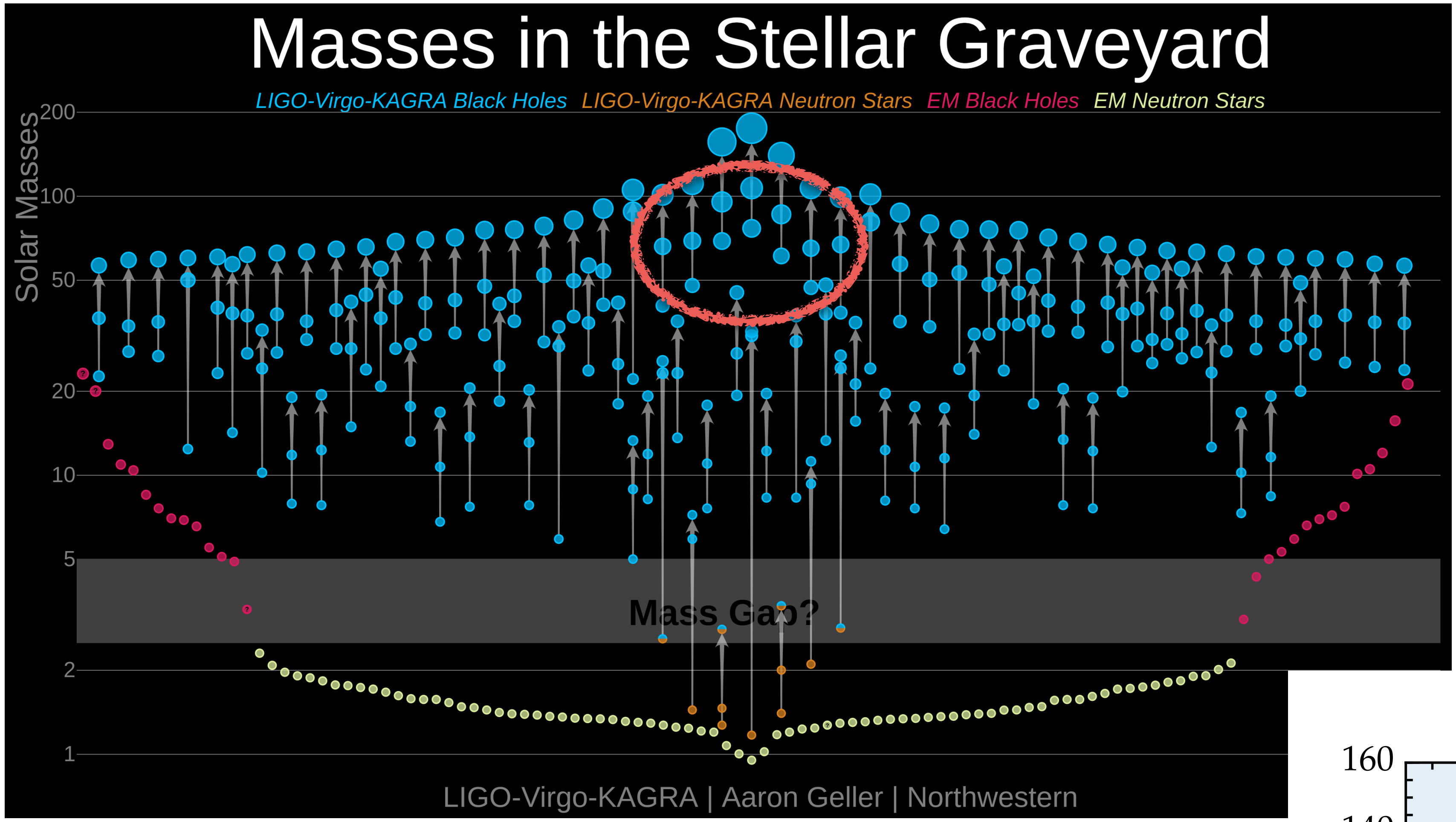
r-process elements lead to near-infrared excess at late times:
'kilonova within a supernova'

Siegel, Barnes, Metzger 2019, Nature
Barnes & Metzger 2022

V.

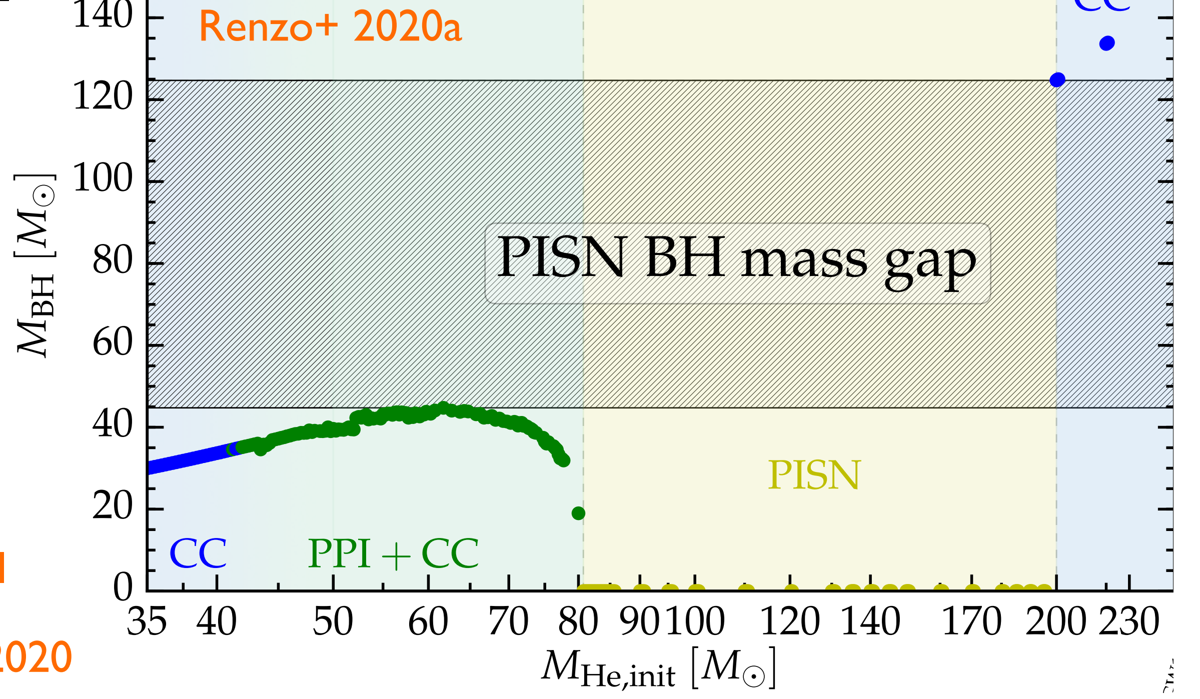
Massive collapsars: ‘super-kilonovae’

Black holes in the pair-instability mass gap



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

PISN BH mass gap

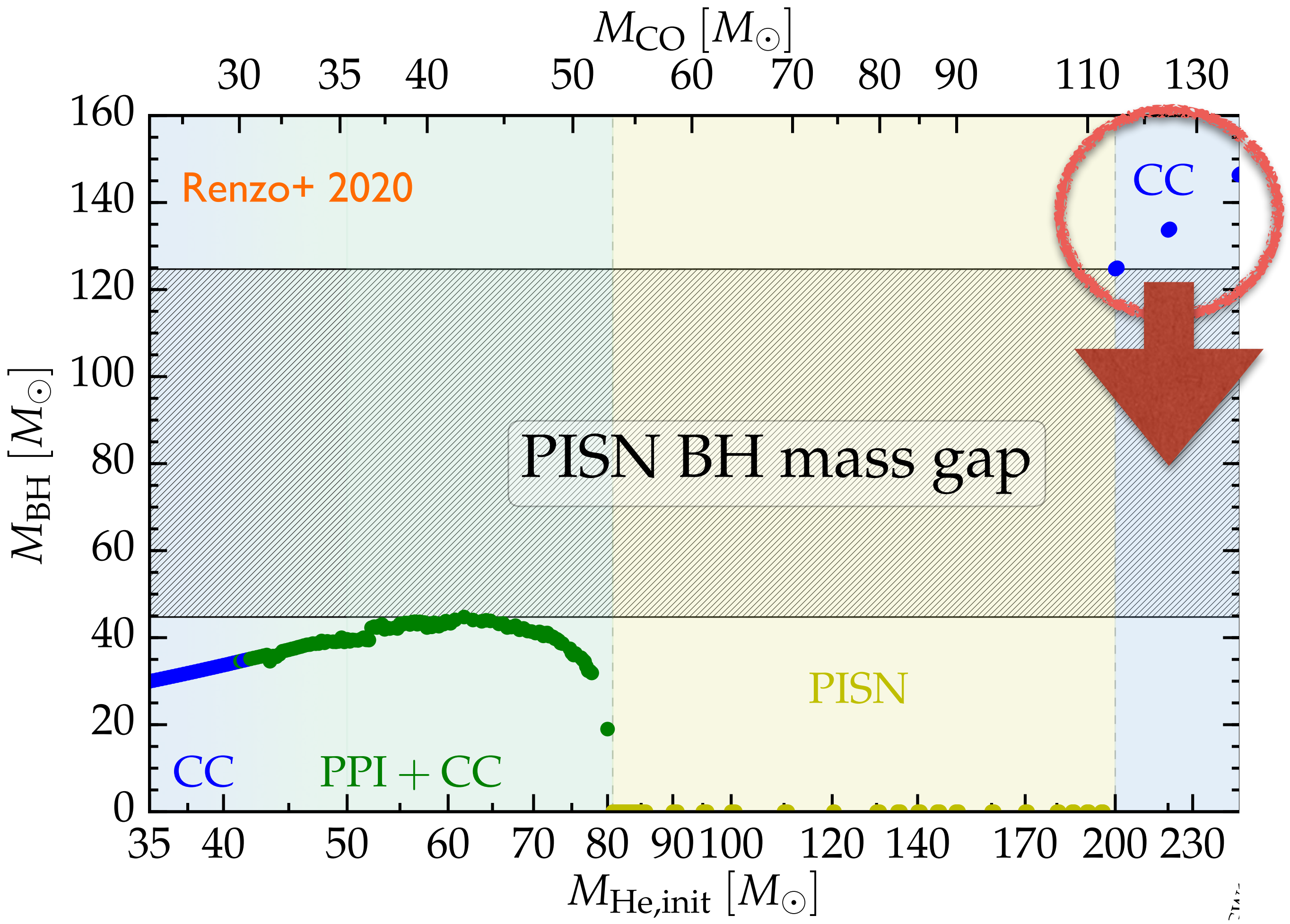


How to populate the PISN BH mass gap?

- 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, …

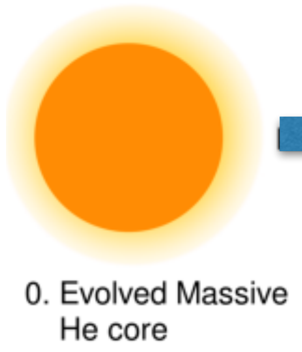
More massive examples populate the PISN mass gap

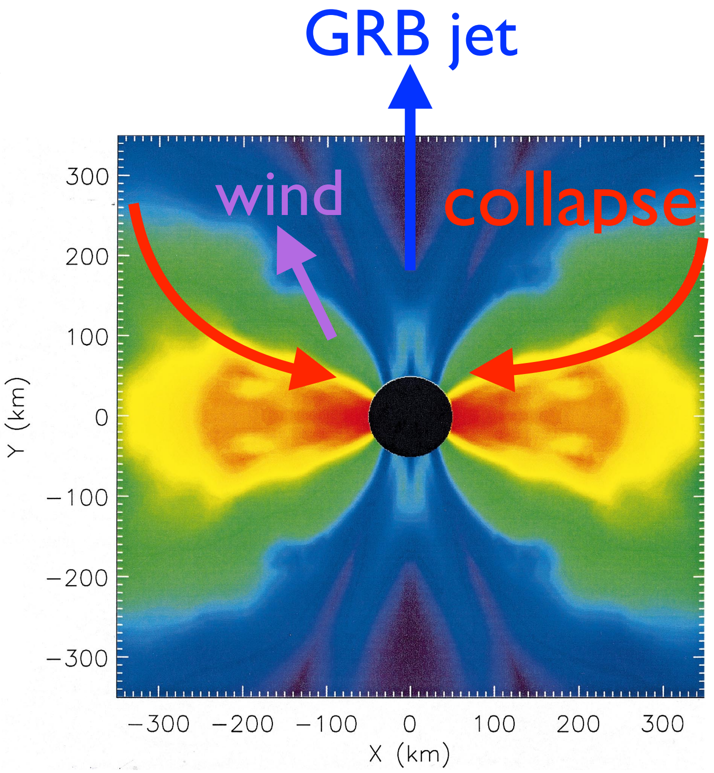
Siegel+ 2022, arXiv:2111.03094



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

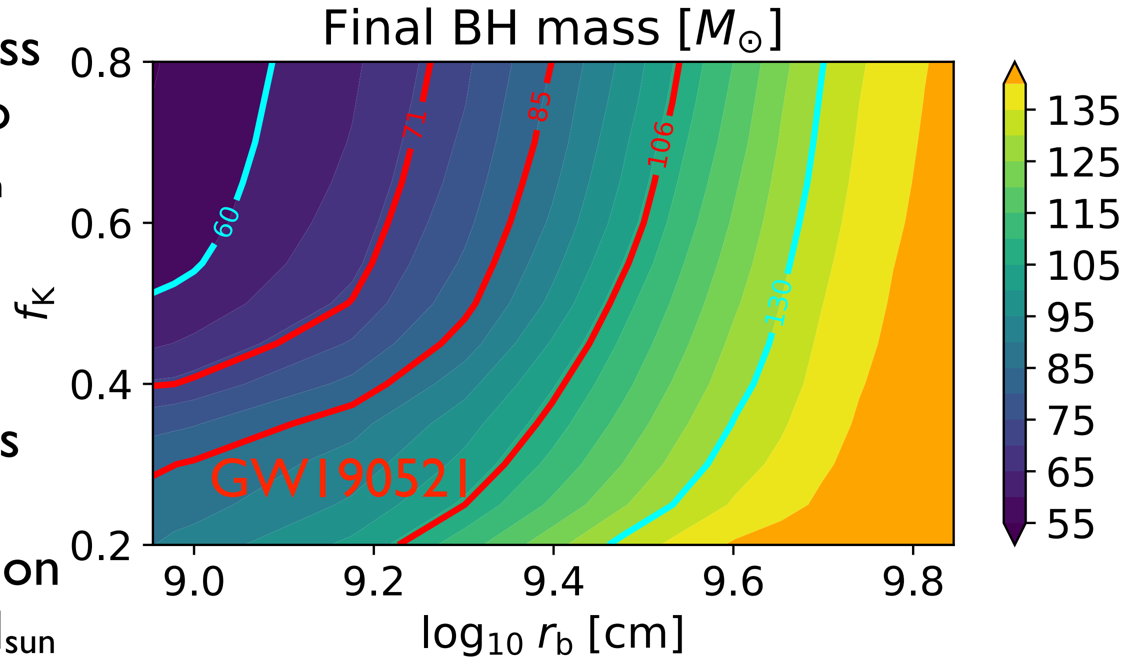
Collapse of massive, rapidly rotating progenitors > 130 $M_{\rm sun}$



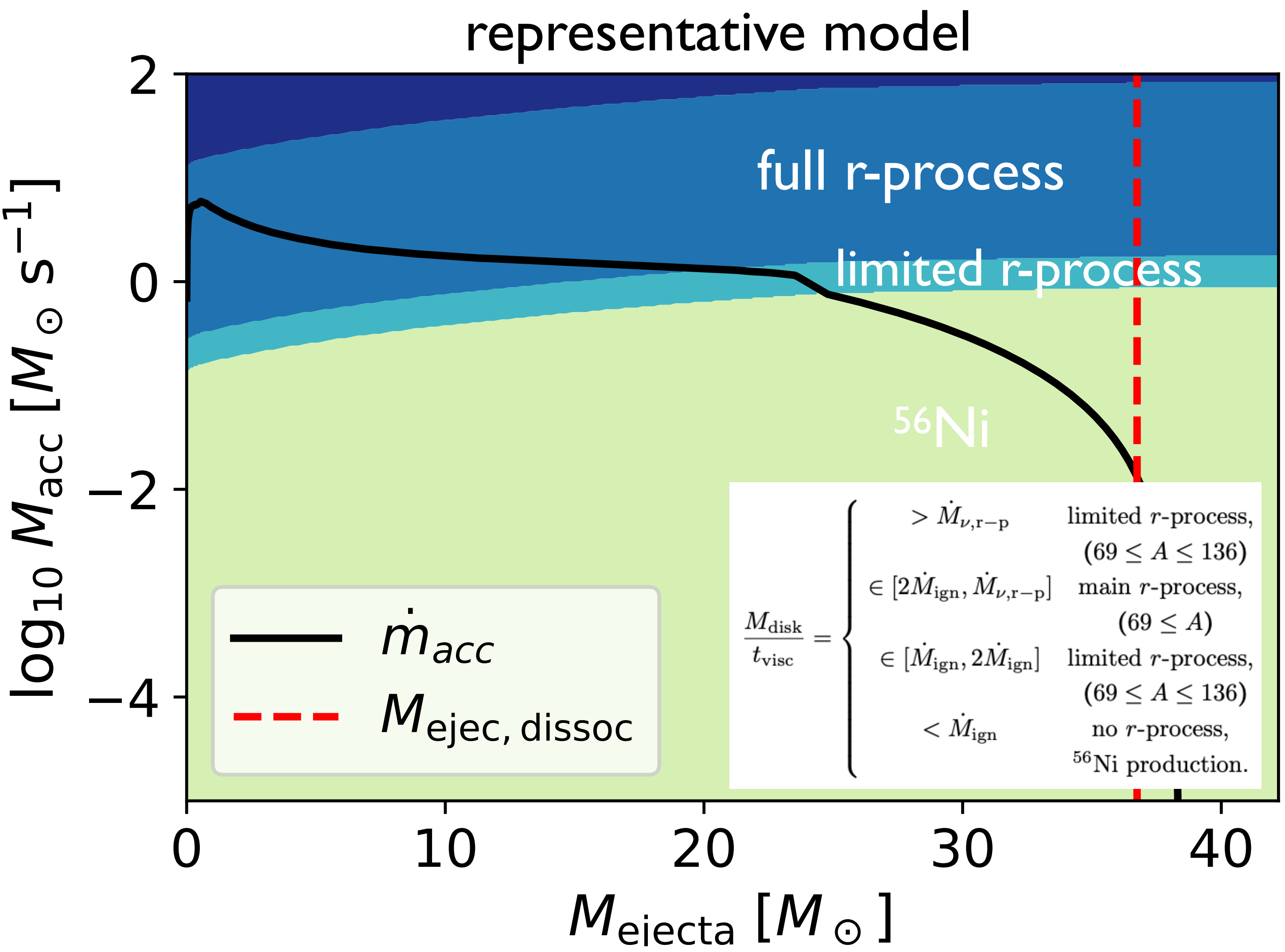


Wind mass loss up to > 50 $M_{\rm sun}$

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



Ejecta composition reflects accretion process



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

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

$M_{\mathrm{ej}} \sim 10$–$60\ M_{\mathrm{sun}}$

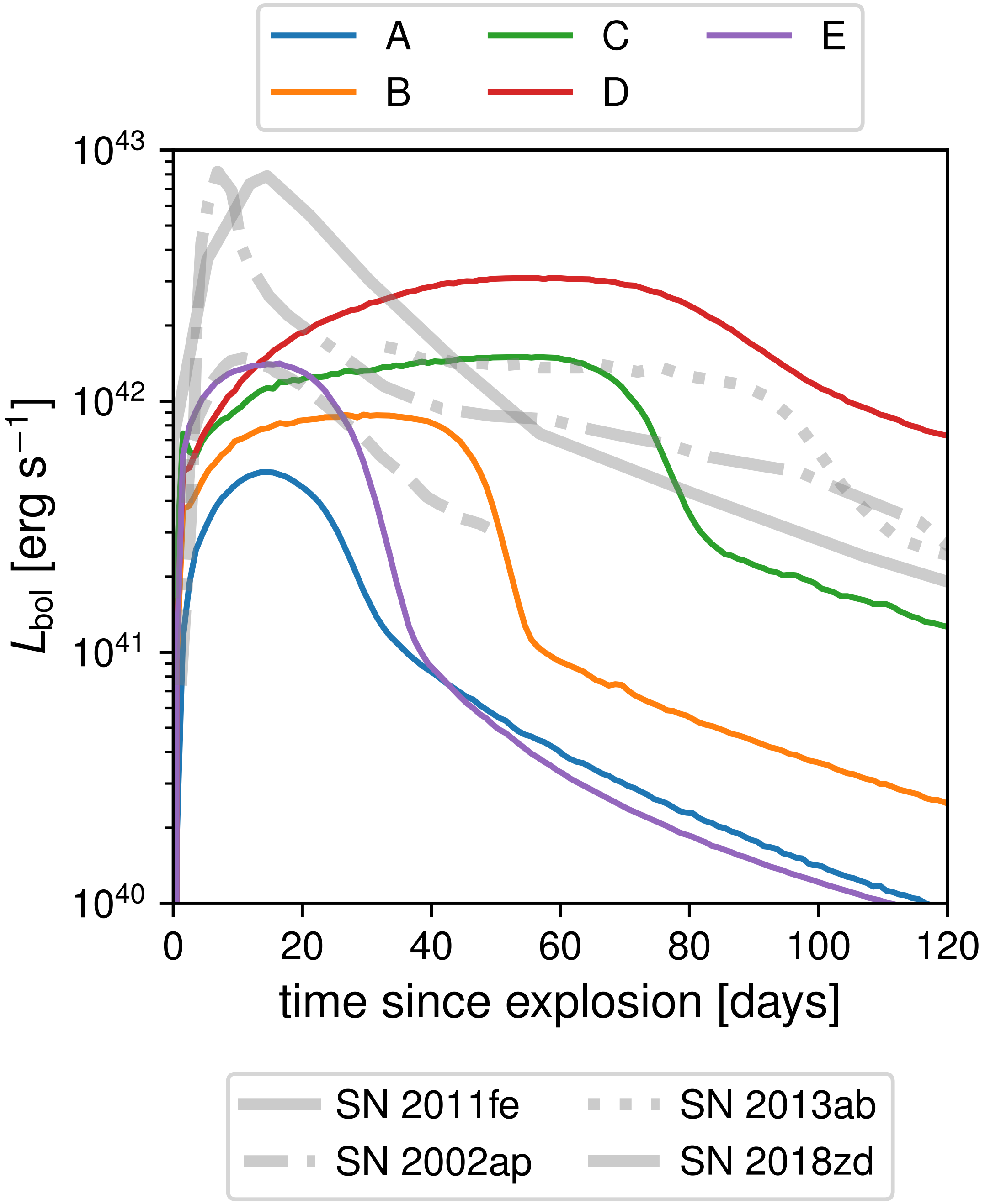
$M_{\mathrm{ej,\,r\text{-}p}} \sim 1$–$20\ M_{\mathrm{sun}}$

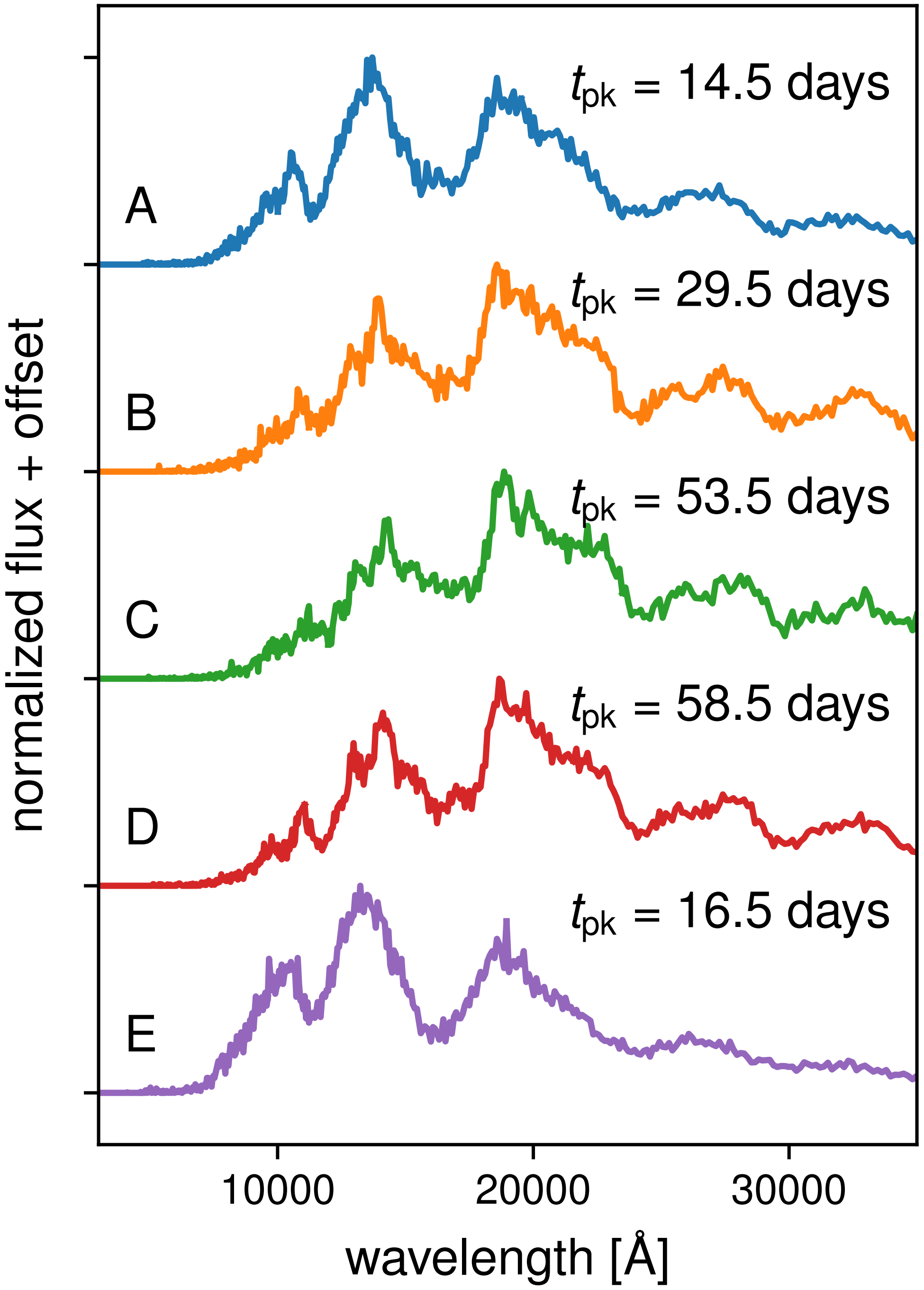
$M_{\mathrm{ej,\,Ni56}} \sim 0.05$–$1\ M_{\mathrm{sun}}$

$M_{\mathrm{BH}} \sim 60$–$130\ M_{\mathrm{sun}}$

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

- Understanding neutron-star post-merger evolution is a multi-physics, multi-scale challenge with observable imprints of fundamental physics
    - *Magnetohydrodynamics:* turbulence, angular momentum transport, jet generation
    - *Equation of state of nuclear matter, weak interactions, nucleosynthesis*
    - *neutrino radiation transport, flavour transformations*

- Conjecture: hyper-accreting black hole disk outflows (mergers & collapsars) may dominate Galactic r-process

- Post-merger physics in other strong-gravity-systems:
    - r-process in collapsars (potentially dominant wrt mergers)
    - massive collapsars can populate the PISN mass gap and generate "super-kilonovae"

- Exploring post-merger physics & the origin of heavy elements will be a central theme for multi-messenger astrophysics for many years to come