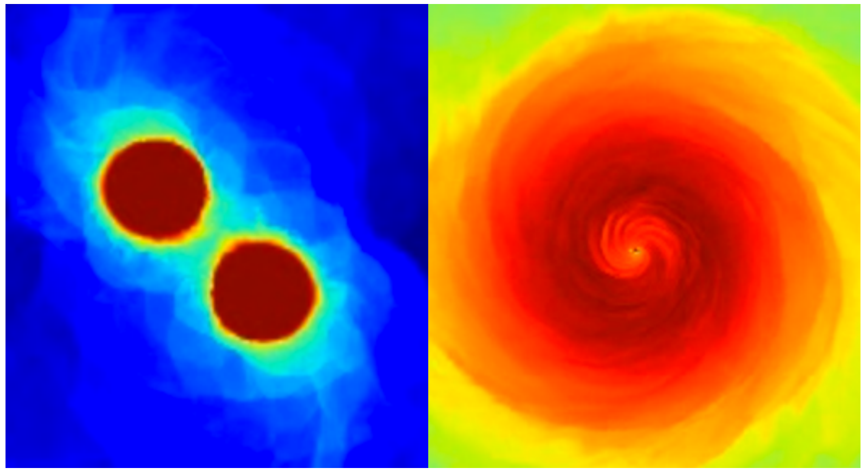
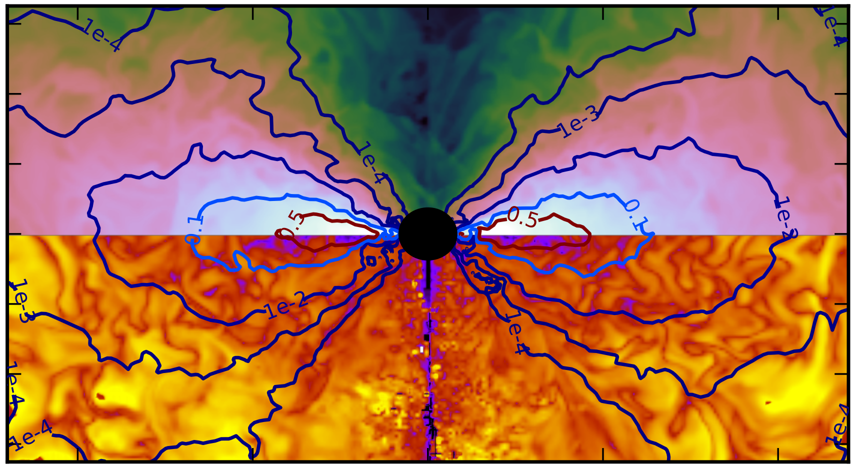
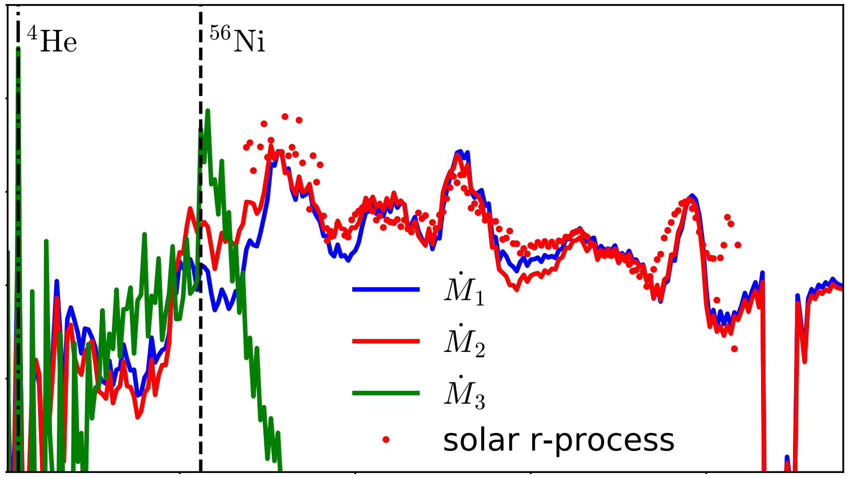
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

The cosmic origin of the heavy elements



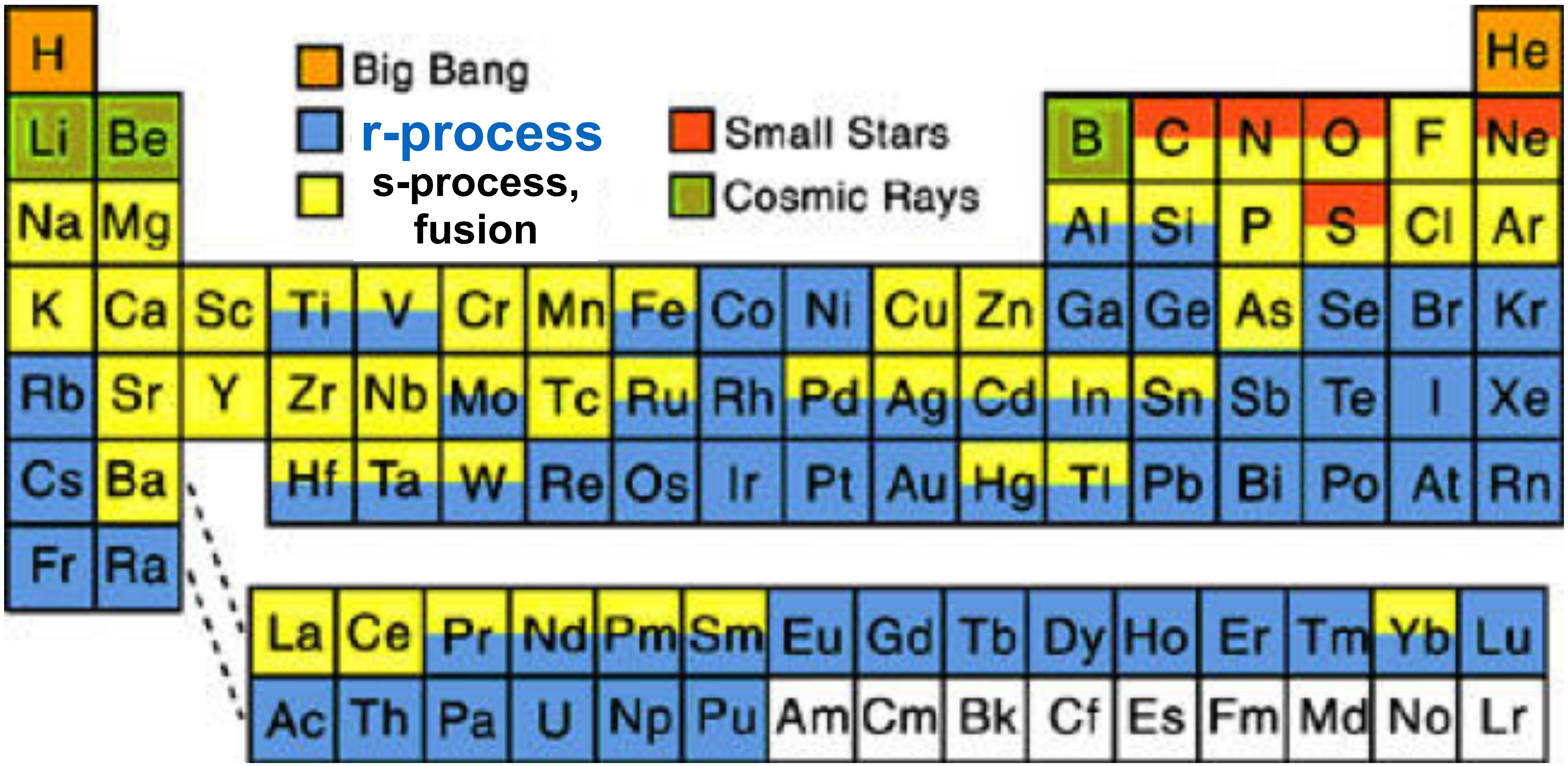




Daniel M. Siegel
Center for Theoretical Physics & Columbia Astrophysics Laboratory
Columbia University

Einstein Fellows Symposium, Harvard-Smithsonian Center for Astrophysics, Oct 2-3, 2018

The origin of the elements

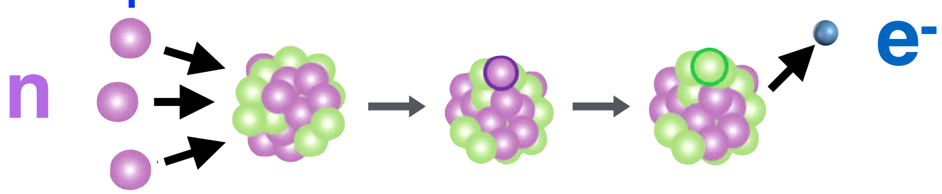


How are the *heavy elements* formed?

The r-process and s-process

Burbidge, Burbidge, Fowler, Hoyle (1957), Cameron (1957):

The heavy elements (A > 62) are formed by neutron capture onto seed nuclei



slow neutron capture (s-process):

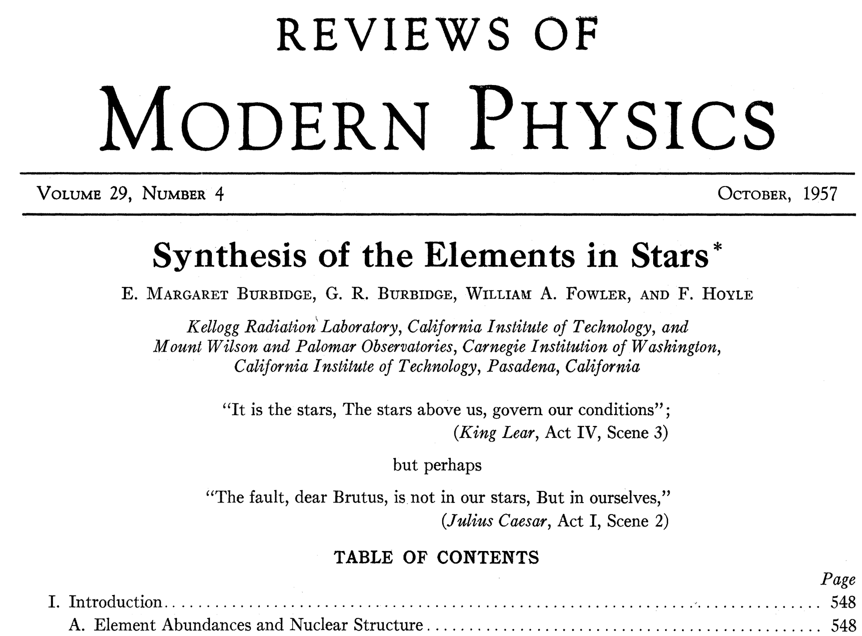
timescale for neutron capture longer than for β-decay

rapid neutron capture (r-process):

timescale for neutron capture shorter than for β-decay

⟶ speculated that r-process requires explosive environment of supernovae

⟶ NS mergers proposed by Lattimer & Schramm (1974) but not favored until recently



REVIEWS OF
MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

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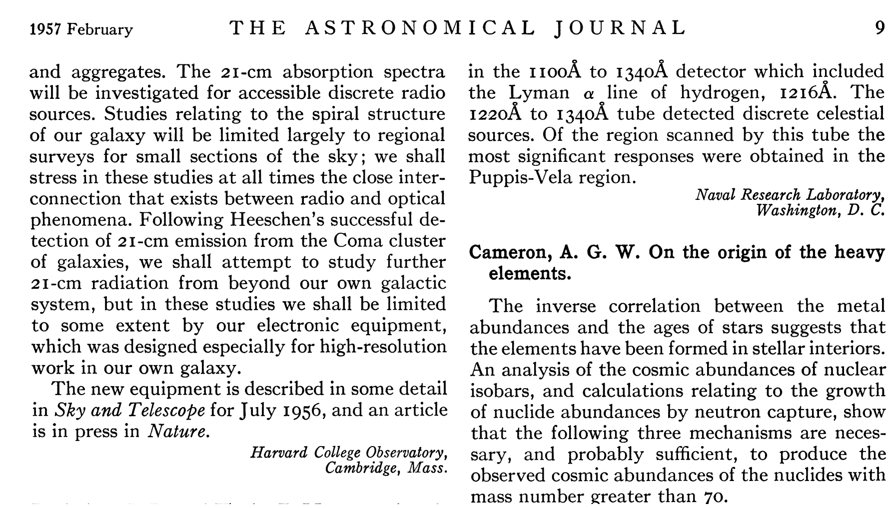


1957 February THE ASTRONOMICAL JOURNAL 9

and aggregates. The 21-cm absorption spectra will be investigated for accessible discrete radio sources. Studies relating to the spiral structure of our galaxy will be limited largely to regional surveys for small sections of the sky; we shall stress in these studies at all times the close interconnection that exists between radio and optical phenomena. Following Heeschen's successful detection of 21-cm emission from the Coma cluster of galaxies, we shall attempt to study further 21-cm radiation from beyond our own galactic system, but in these studies we shall be limited to some extent by our electronic equipment, which was designed especially for high-resolution work in our own galaxy.

The new equipment is described in some detail in *Sky and Telescope* for July 1956, and an article is in press in *Nature*.

Harvard College Observatory, Cambridge, Mass.

in the 1100Å to 1340Å detector which included the Lyman α line of hydrogen, 1216Å. The 1220Å to 1340Å tube detected discrete celestial sources. Of the region scanned by this tube the most significant responses were obtained in the Puppis-Vela region.

Naval Research Laboratory, Washington, D. C.

Cameron, A. G. W. On the origin of the heavy elements.

The inverse correlation between the metal abundances and the ages of stars suggests that the elements have been formed in stellar interiors. An analysis of the cosmic abundances of nuclear isobars, and calculations relating to the growth of nuclide abundances by neutron capture, show that the following three mechanisms are necessary, and probably sufficient, to produce the observed cosmic abundances of the nuclides with mass number greater than 70.

The kilonova of GW170817

- blue kilonova properties:

  $M_{ej} \sim 10^{-2} M_{sun}$
  $v_{ej} \sim 0.2\text{-}0.3c$
  $Y_e > 0.25$
  $X_{La} < 10^{-4}$

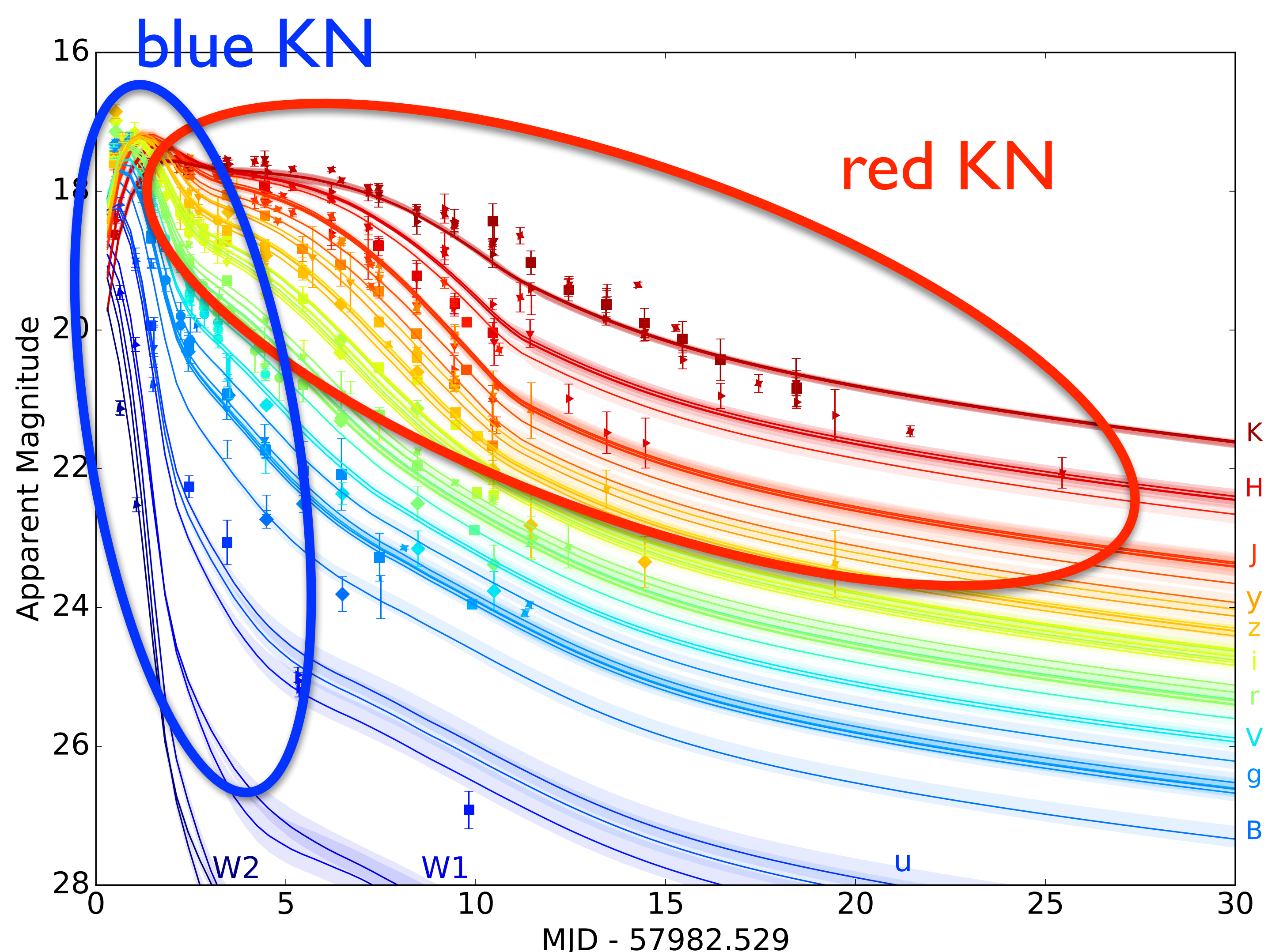
  Kilpatrick+ 2017
  Kasen+ 2017
  Nicholl+ 2017
  Villar+ 2017
  Coughlin+ 2018

- red kilonova properties:

  $M_{ej} \sim 4\text{-}5 \times 10^{-2} M_{sun}$
  $v_{ej} \sim 0.08\text{-}0.14c$
  $Y_e < 0.25$
  $X_{La} \sim 0.01$

  Kilpatrick+ 2017
  Kasen+ 2017
  Kasliwal+ 2017
  Drout+ 2017
  Cowperthwaite+ 2017
  Chornock+ 2017
  Villar+ 2017
  Coughlin+ 2018

heavy r-process elements!



Villar+ 2017

- two ("red-blue") or multiple components expected from merger simulations
- single component models might be possible, but require fine-tuning

Smartt+ 2017
Waxman+ 2017

The kilonova of GW170817

- blue kilonova properties:

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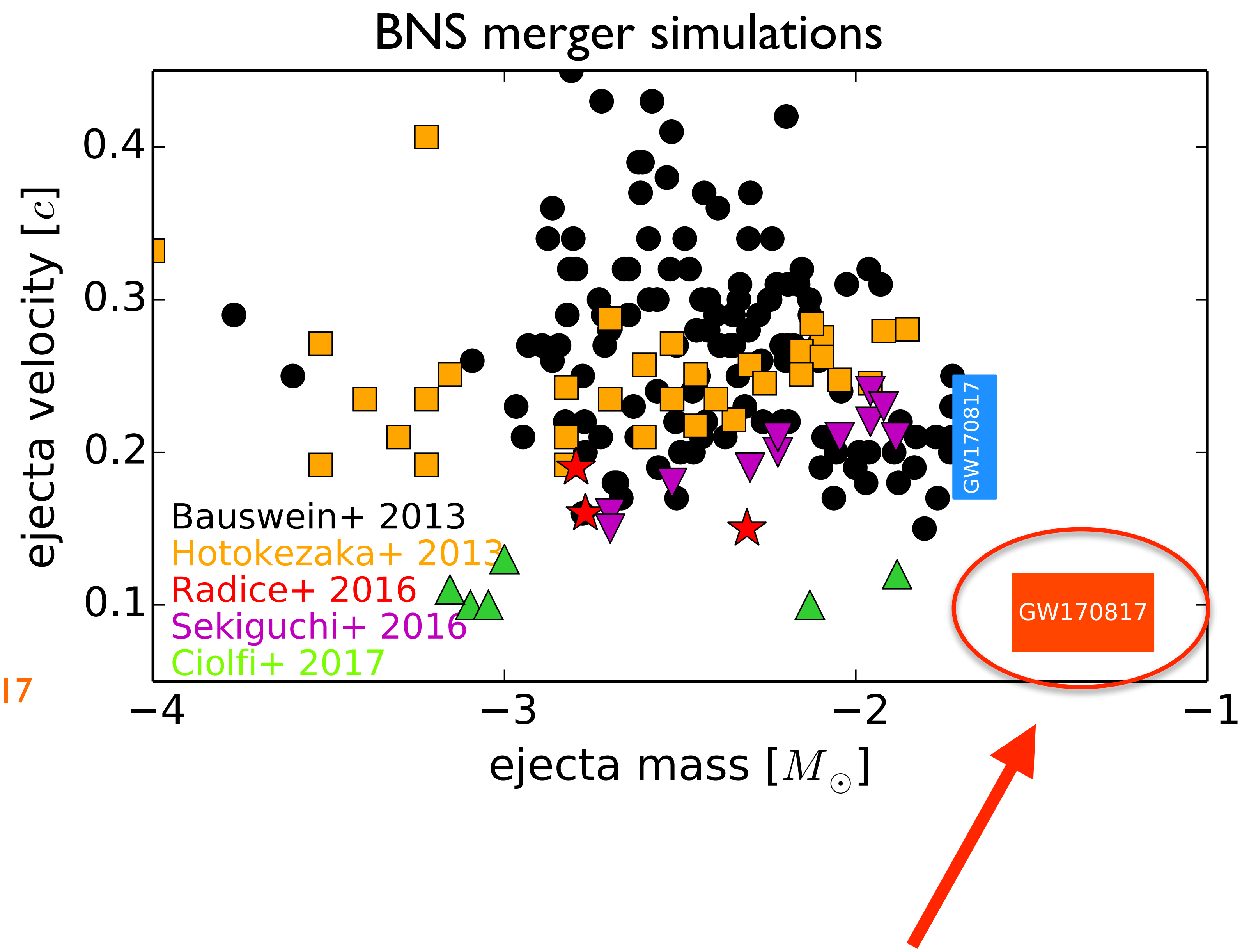
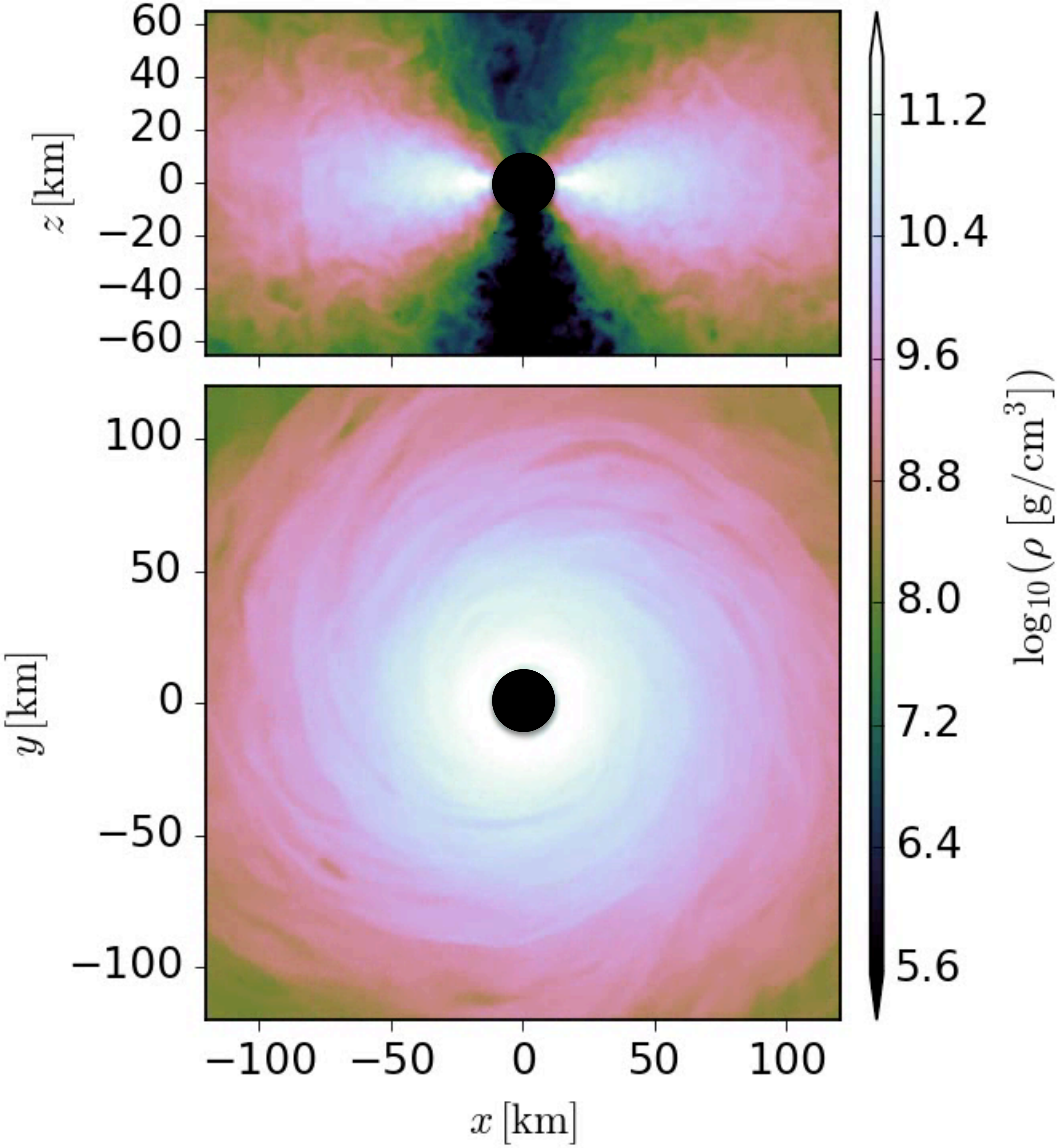


Observed ejecta properties of red kilonova inconsistent with known classical ejection mechanisms in NS mergers

Post-merger accretion disk outflows

Siegel & Metzger 2017, PRL

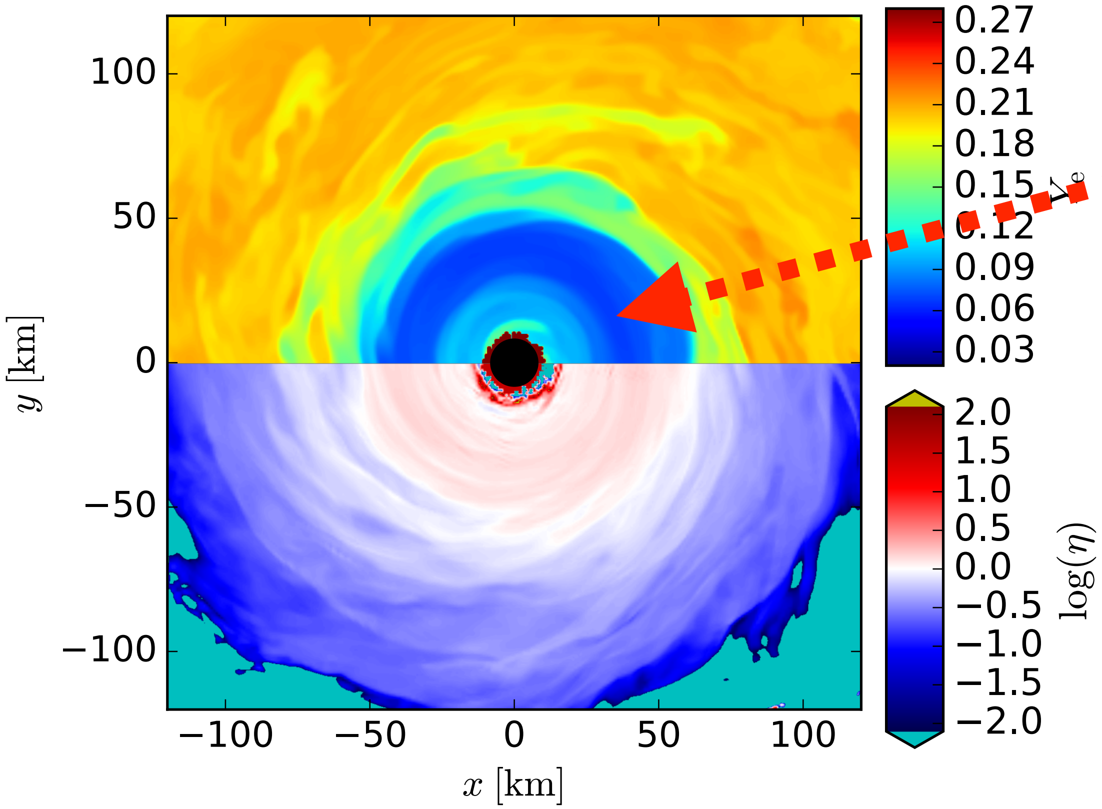
Siegel & Metzger 2018a



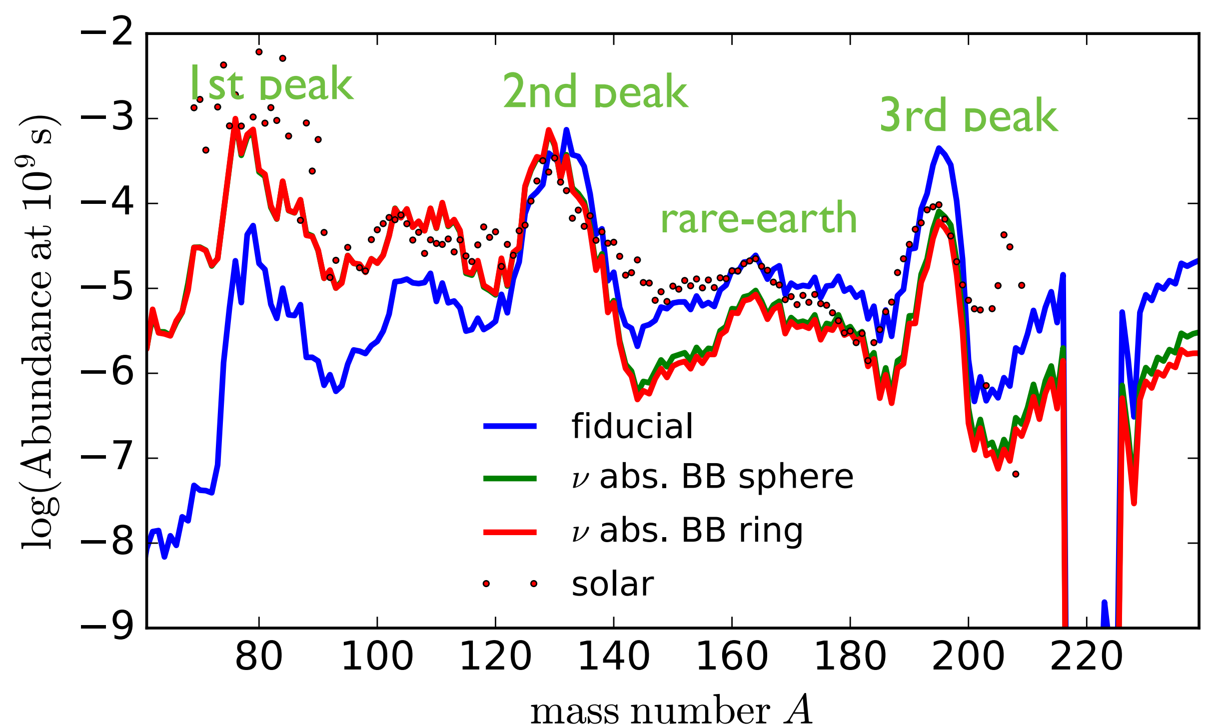
$t = 20.113\,\mathrm{ms}$

Disk outflows and the red kilonova

Siegel & Metzger 2017, PRL
Siegel & Metzger 2018

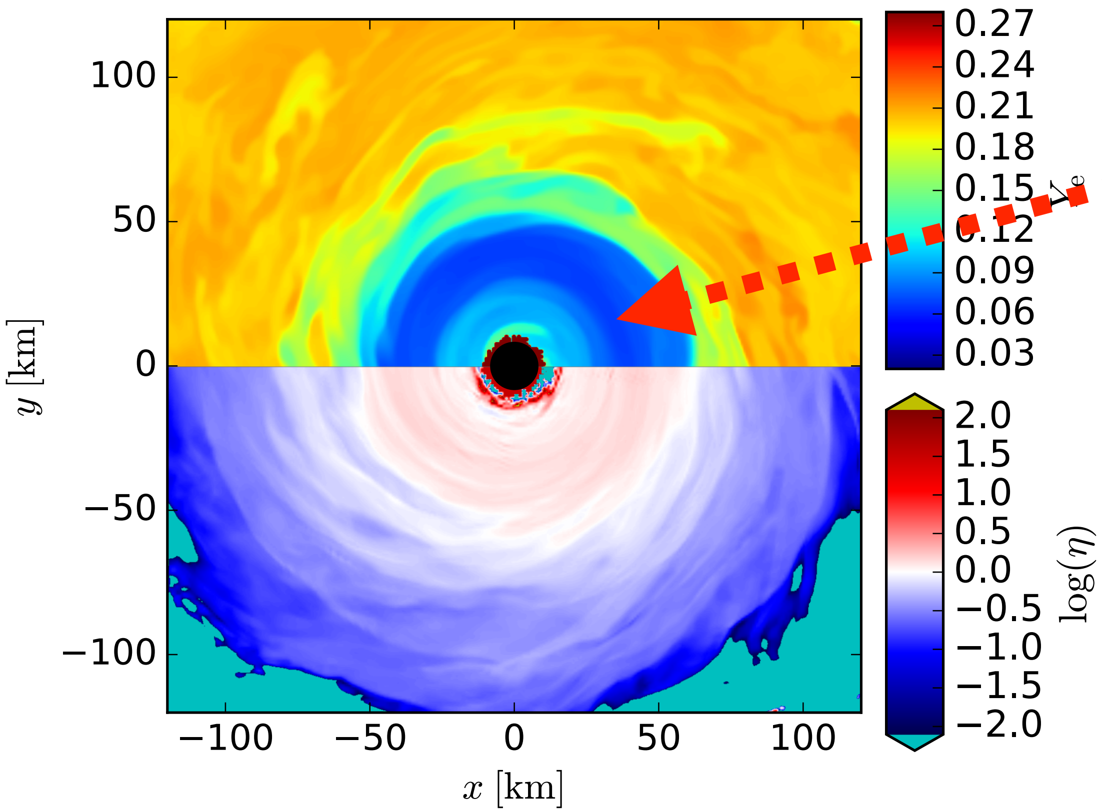


- Neutron-richness: self-regulation mechanism in degenerate inner disk provides neutron rich outflows (Y_e<0.25)
- Production of full range of r-process nuclei, excellent agreement with observed r-process abundances (solar, halo stars)

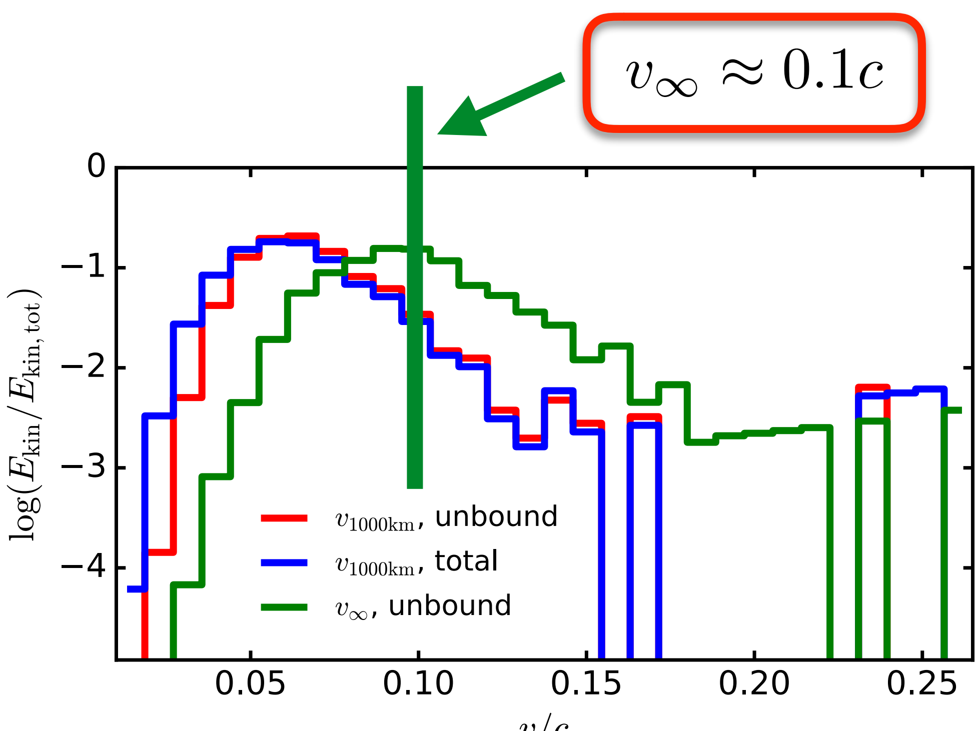


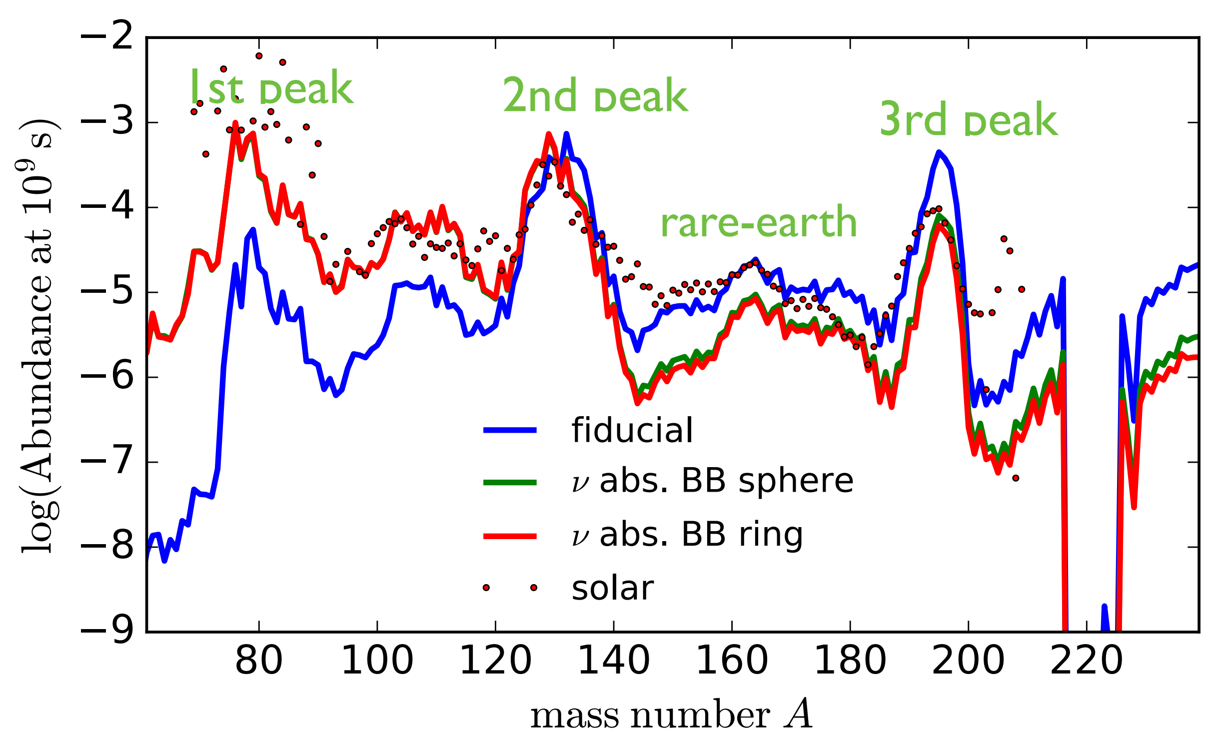
Disk outflows and the red kilonova

Siegel & Metzger 2017, PRL
Siegel & Metzger 2018

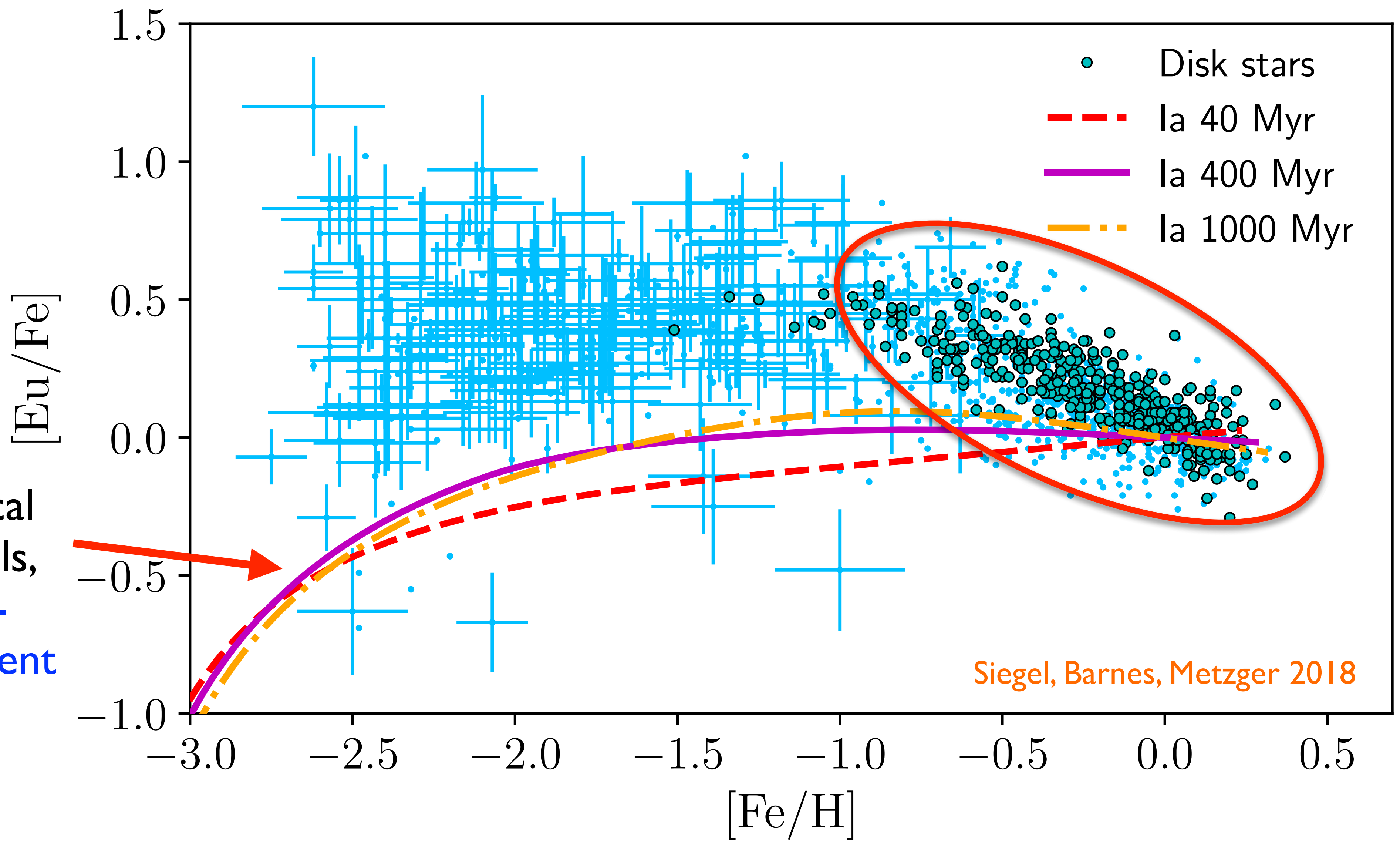


- Neutron-richness: self-regulation mechanism in degenerate inner disk provides neutron rich outflows (Y_e<0.25)
- Production of full range of r-process nuclei, excellent agreement with observed r-process abundances (solar, halo stars)
- Slow outflow velocities (~0.1c)
- Large amount of ejecta ($\gtrsim 10^{-2} M_\odot$)





But… what about galactic chemical *evolution*?



Galactic chemical evolution models, merger-only r-process enrichment

late-time galactic r-process enrichment (Eu/Fe decrease)
inconsistent with NS merger paradigm Côté+ 2017, 2018, Hotokezaka+ 2018a

There should be another significant source of r-process enrichment…

GW170817 points to *collapsars* as main r-process source

Siegel, Barnes, Metzger 2018

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

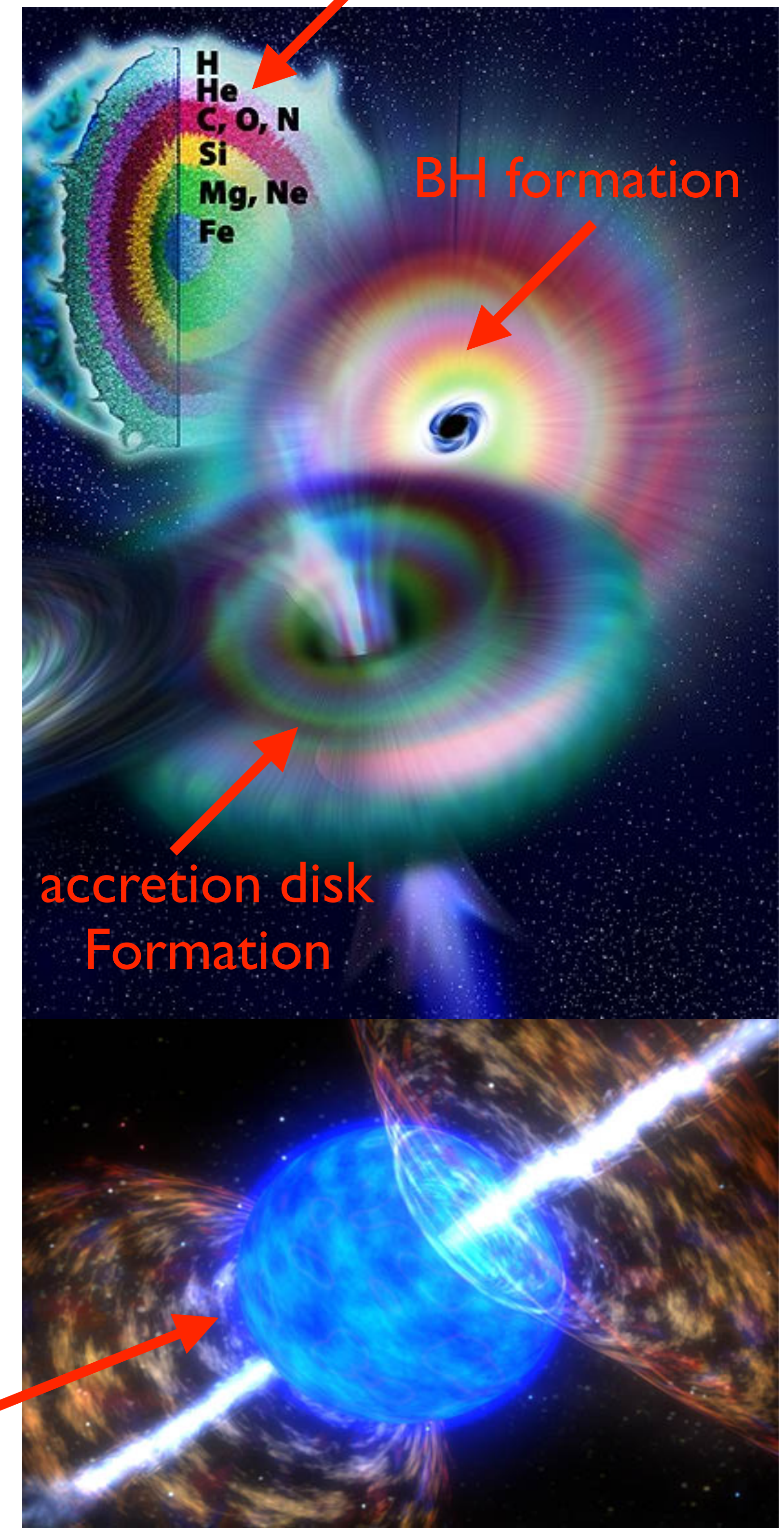
  ⟶ "failed explosion" (direct collapse to a BH)

  ⟶ "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

- Widely accepted model to generate long GRBs and their accompanying GRB SNe (hypernovae, broad-lined Type Ic)

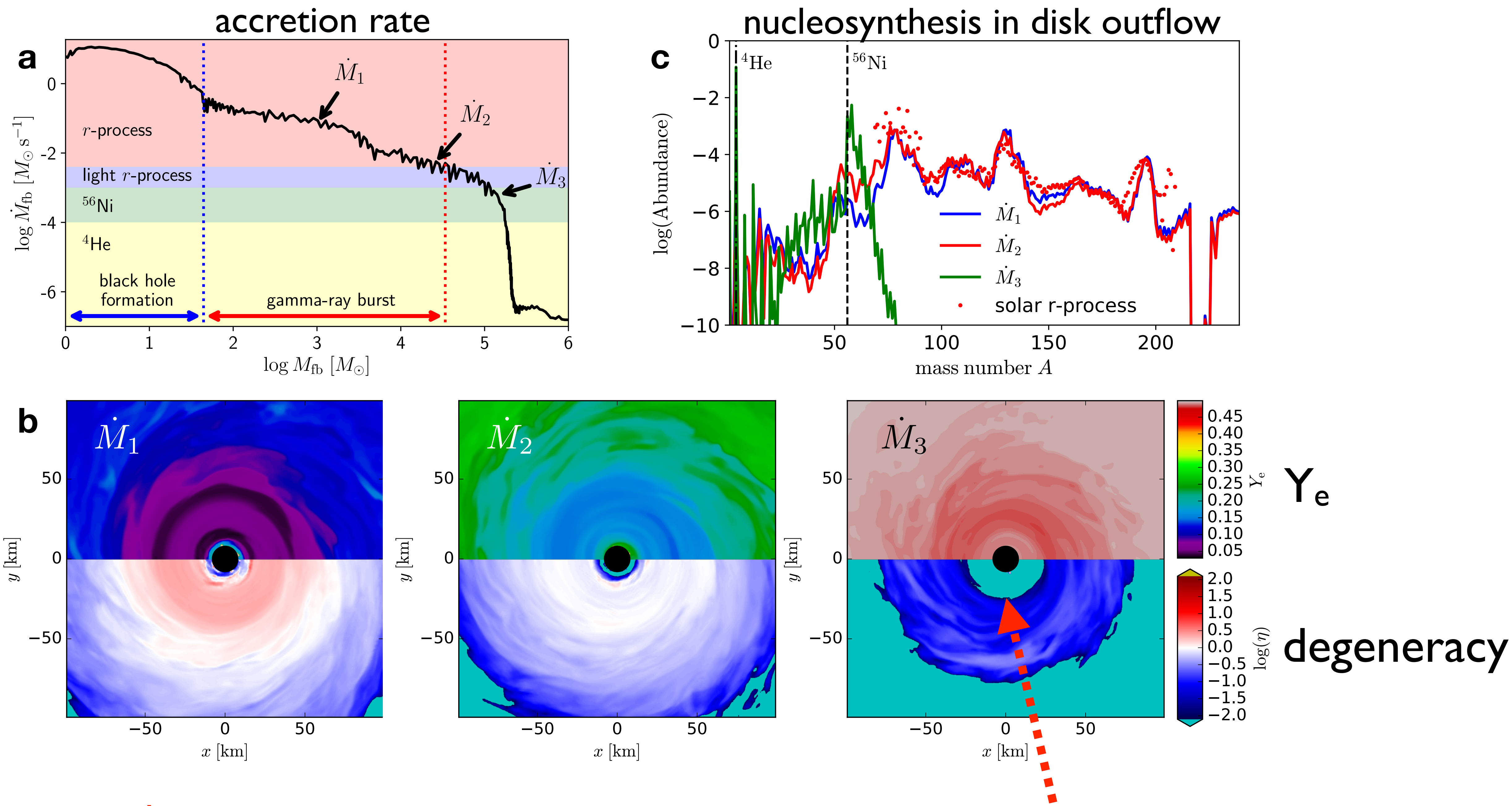
core collapse



jet punches through infalling material, generates GRB

GW170817 points to *collapsars* as main r-process source

Siegel, Barnes, Metzger 2018



Neutron-richness:

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

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

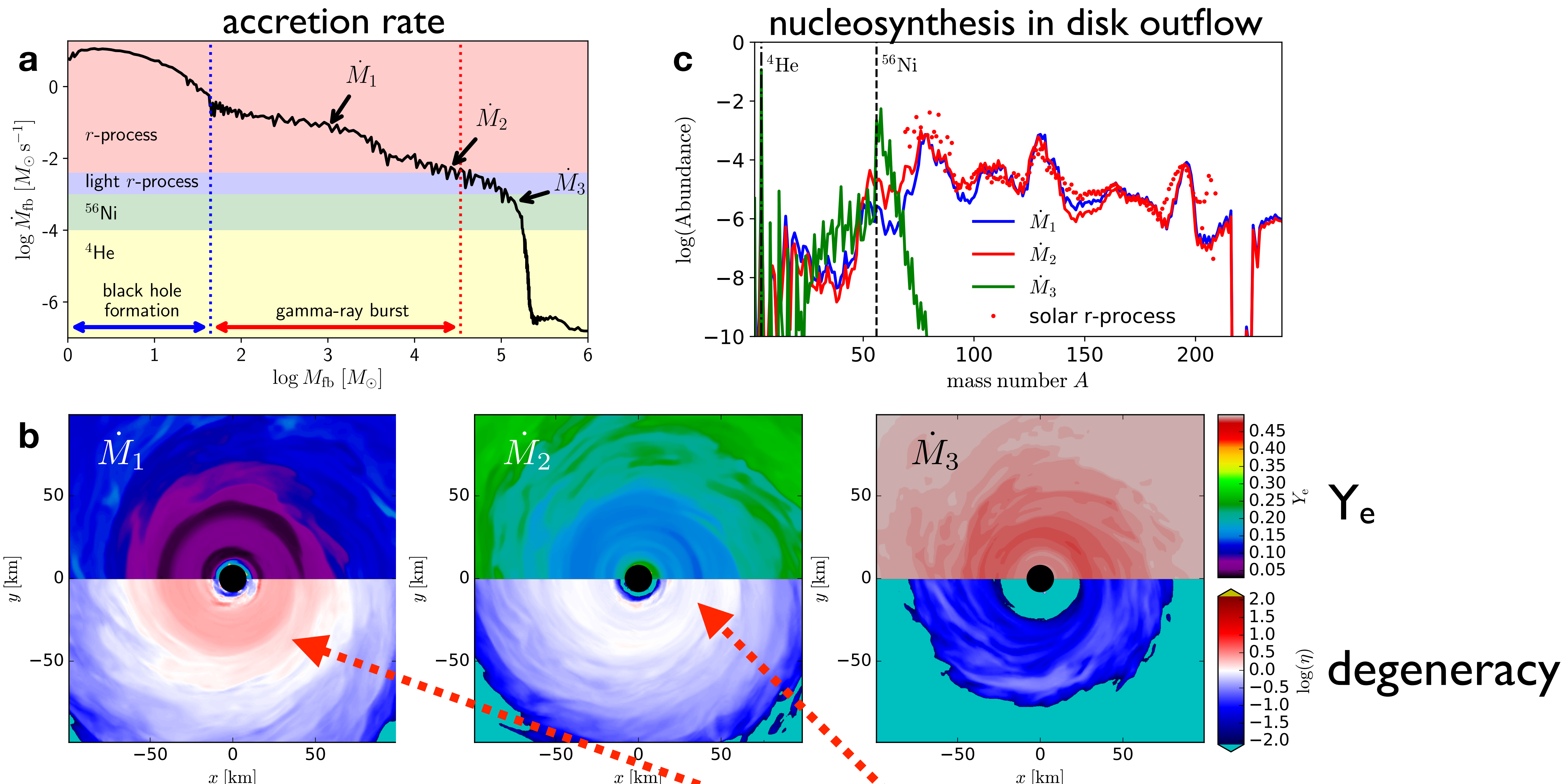
Low disk densities (low $\dot{M}$):

$Y_e \sim 0.5$

outflows produce ^{56}Ni

GW170817 points to *collapsars* as main r-process source

Siegel, Barnes, Metzger 2018



Neutron-richness:

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

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

Low disk densities (low $\dot{M}$):
→ degenerate electrons
$Y_e \sim 0.1$
outflows produce r-process nuclei

Collapsars: r-process yield

Siegel, Barnes, Metzger 2018

Relative r-process contribution:

- assume accreted mass proportional to gamma-ray energy (same physical processes in both types of bursts, similar observational properties!)

$$\frac{m_{\rm r,coll}}{m_{\rm r,merger}} \sim \frac{m_{\rm acc}^{\rm LGRB} \int R_{\rm LGRB}(z) dz}{m_{\rm acc}^{\rm SGRB} \int R_{\rm SGRB}(z) dz} > \frac{E_{\rm iso}^{\rm LGRB} R_{\rm LGRB}(z=0)}{E_{\rm iso}^{\rm SGRB} R_{\rm SGRB}(z=0)} \approx 4 - 30$$

→ dominant contribution to Galactic r-process relative to mergers

Independent absolute r-process estimate:

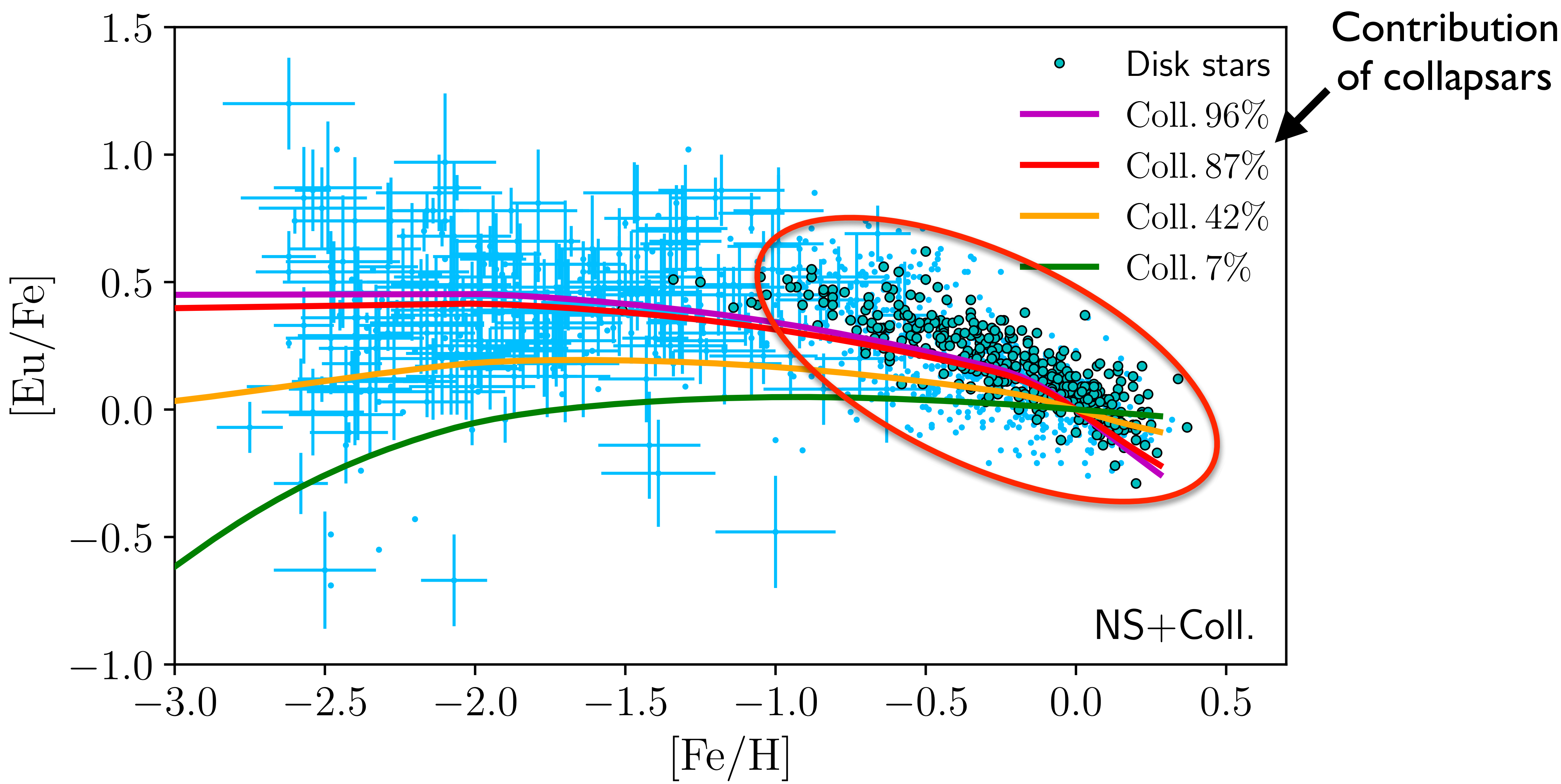
- assume collapsars as main contribution to Galactic r-process:

$$m_{\rm r,coll} \sim X_{\rm r} f_Z^{-1} \frac{\dot{\rho}_{\rm SF}(z=0) f_{\rm b}}{R_{\rm LGRB}(z=0)} \approx 0.08 - 0.3 M_\odot \left(\frac{f_Z}{0.25}\right)^{-1} \left(\frac{X_{\rm r}}{4\times 10^{-7}}\right) \left(\frac{f_b}{5\times 10^{-3}}\right)$$

→ consistent with relative estimate, using r-process yield from GW170817 (~0.05 $M_{\rm sun}$)

Collapsars: galactic chemical evolution

Siegel, Barnes, Metzger 2018



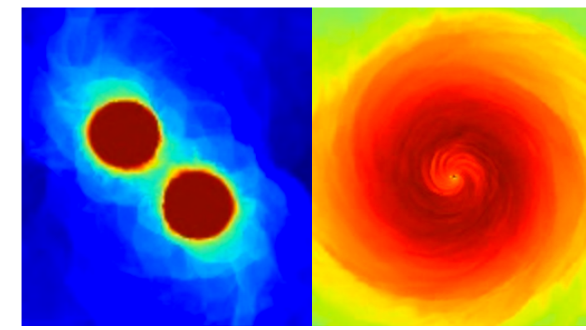
Dominant contribution to the Galactic r-process from collapsars dramatically improves evolution of r-process enrichment at high metallicity (MW disk)!

Conclusions

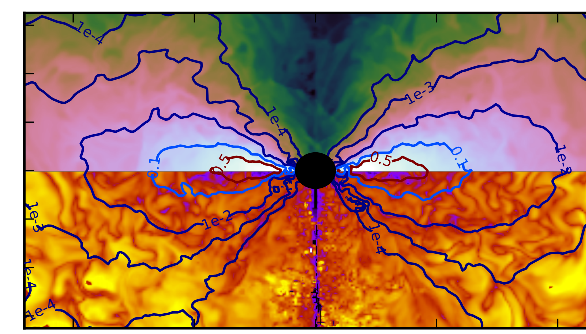
- GW170817: heavy elements & red kilonova most likely originate from outflows of post-merger accretion disk

  → can produce entire range of r-process nuclei

  → ubiquitous phenomenon



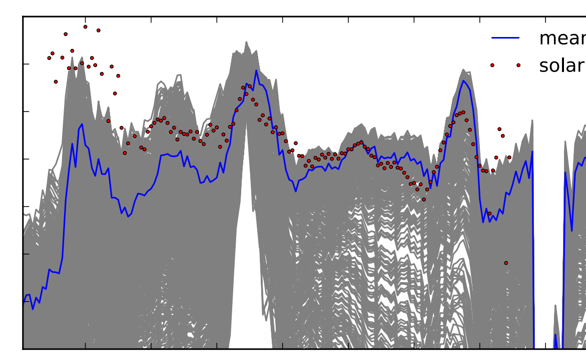
- NS mergers inconsistent with r-process enrichment of Milky Way disk



- Collapsars likely provide dominant contribution to Galactic r-process

  → similar physics as in NS post-merger disks

  → lower event rate overcompensated by higher yield (calibrated relative to GW170817)



- Collapsars help alleviate observational challenges of merger models

  → reproduce r-process enrichment at high metallicity (track star formation history)

  → don't require very short delay times and small kicks to explain enrichment in UFDs

Appendix

GW170817 points to collapsars as main r-process source

Siegel, Barnes, Metzger 2018