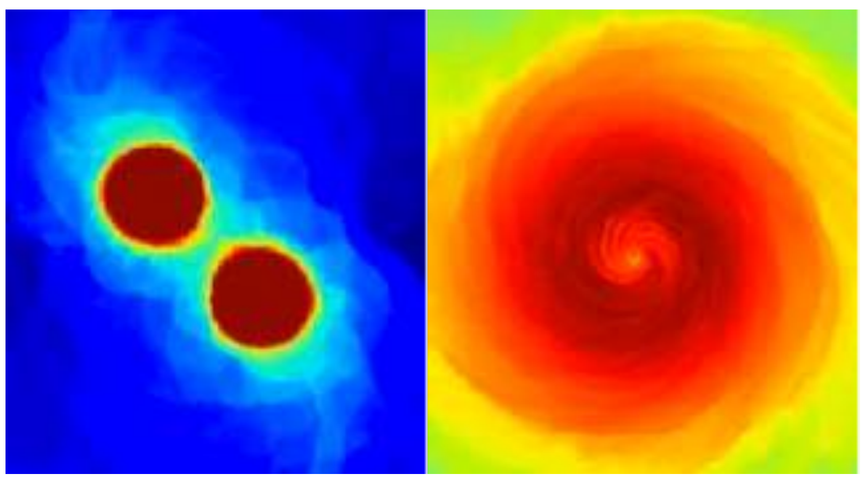
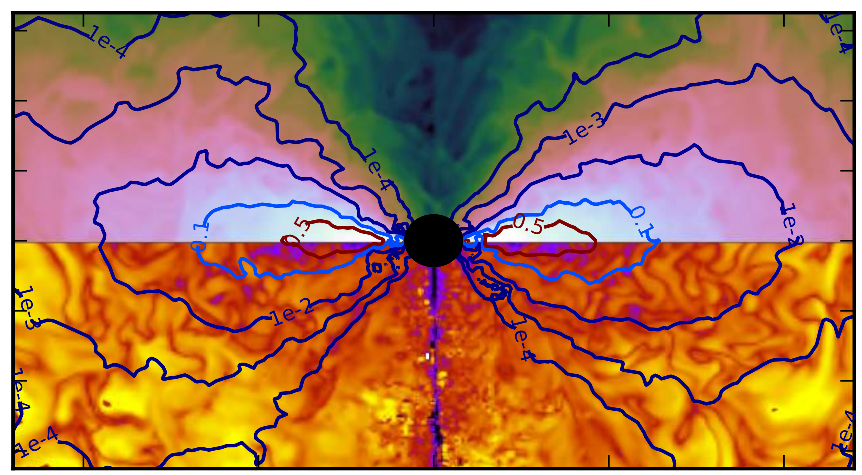
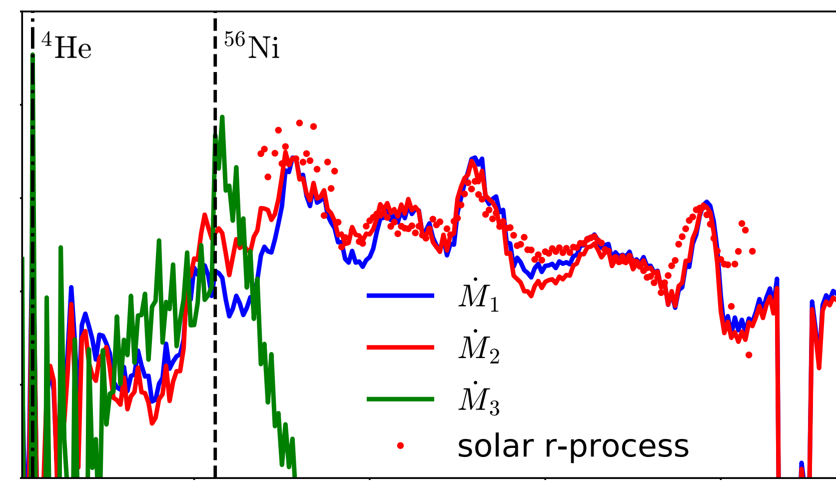
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Multimessenger astrophysics and the cosmic origin of the heavy elements







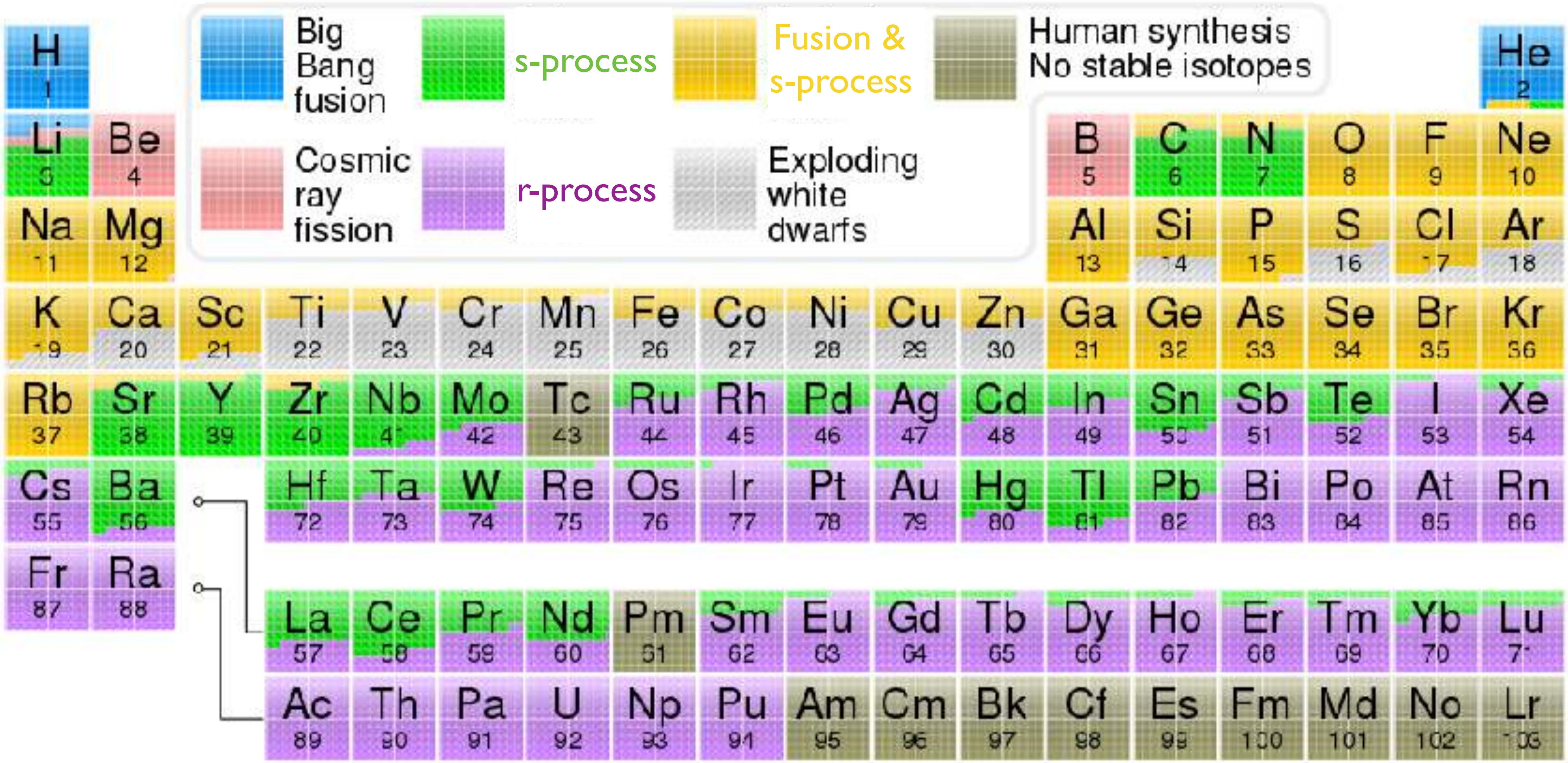
Daniel M. Siegel

Center for Theoretical Physics & Columbia Astrophysics Laboratory

Columbia University

IFT colloquium, Sao Paulo, Dec 12, 2018

The origin of the elements

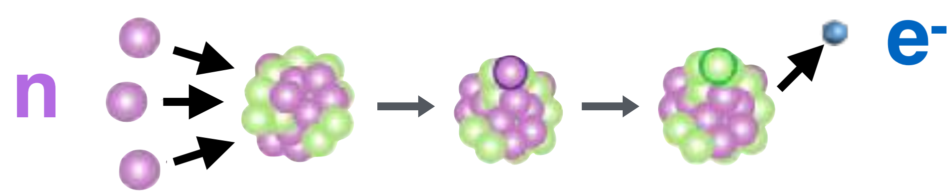


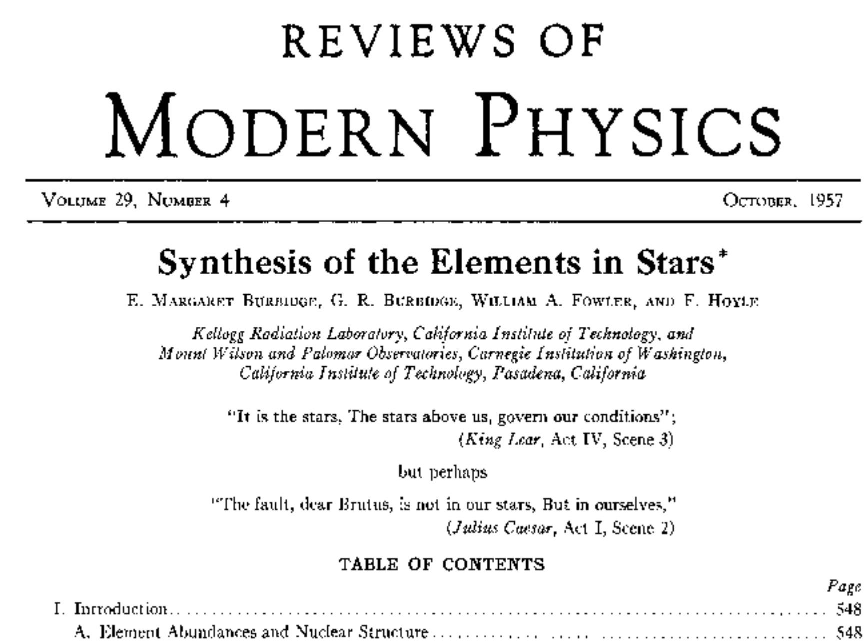
How are the *heavy* elements formed?

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





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)

TABLE OF CONTENTS

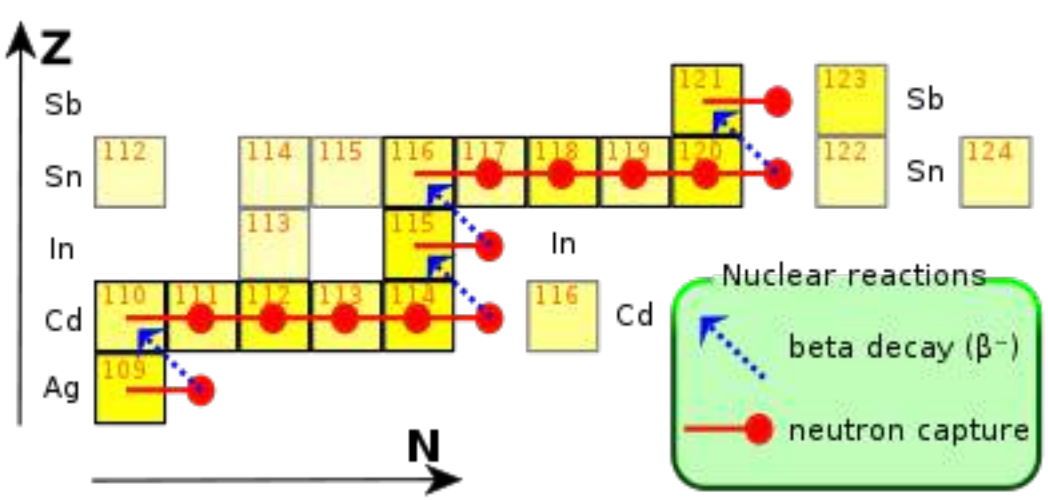
slow neutron capture (s-process):

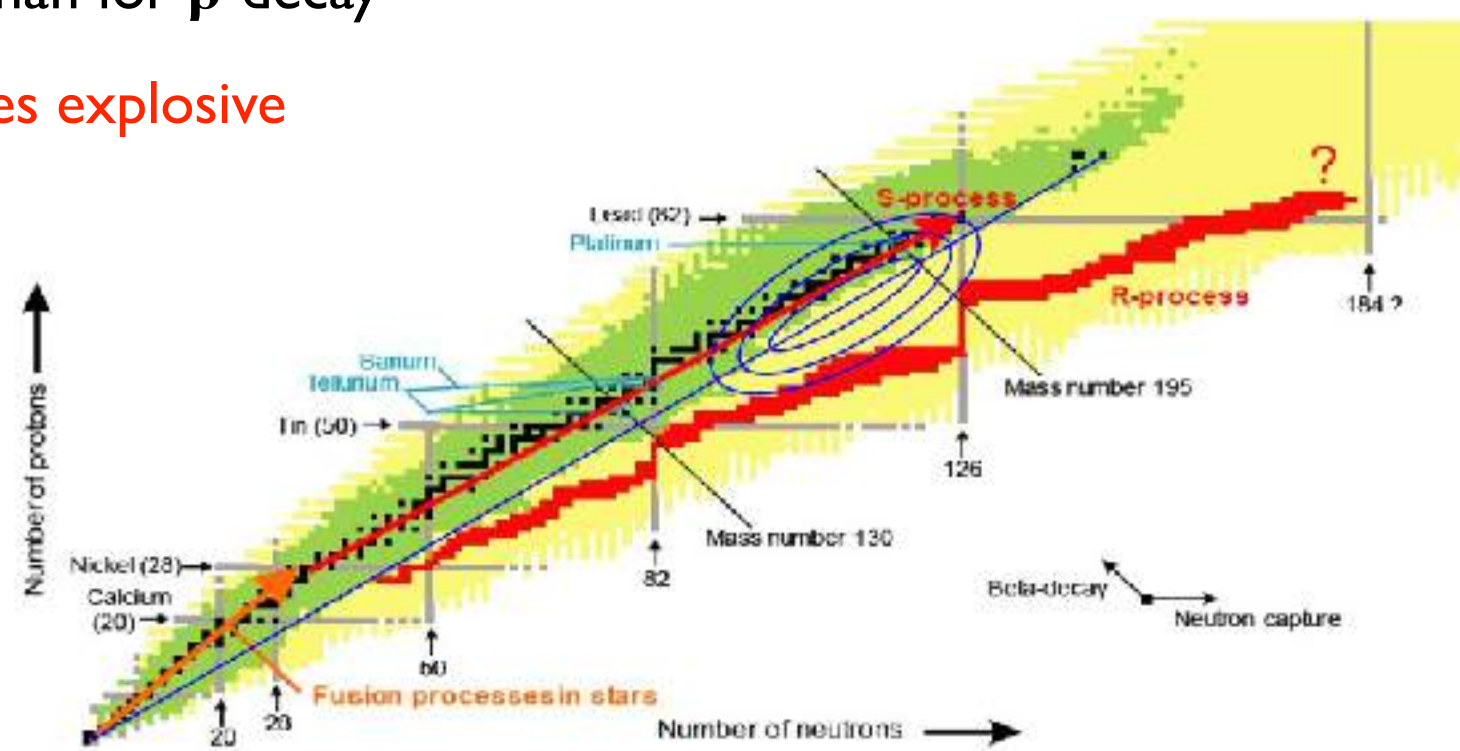
timescale for neutron capture longer than for β-decay

rapid neutron capture (r-process):

timescale for neutron capture shorter than for β-decay

→ speculated that r-process requires explosive environment of supernovae





Neutron star mergers and r-process

Lattimer & Schramm (1974):

BLACK-HOLE–NEUTRON-STAR COLLISIONS

JAMES M. LATTIMER AND DAVID N. SCHRAMM
Departments of Astronomy and Physics, The University of Texas at Austin
Received 1974 March 13; revised 1974 July 12

ABSTRACT

The tidal breakup of a neutron star near a black hole is examined. A simple model for the interaction is calculated, and the results show that the amount of neutron-star material ejected into the interstellar medium may be significant. Using reasonable stellar statistics, the estimated quantity of ejected material is found to be roughly comparable to the abundance of *r*-process material.

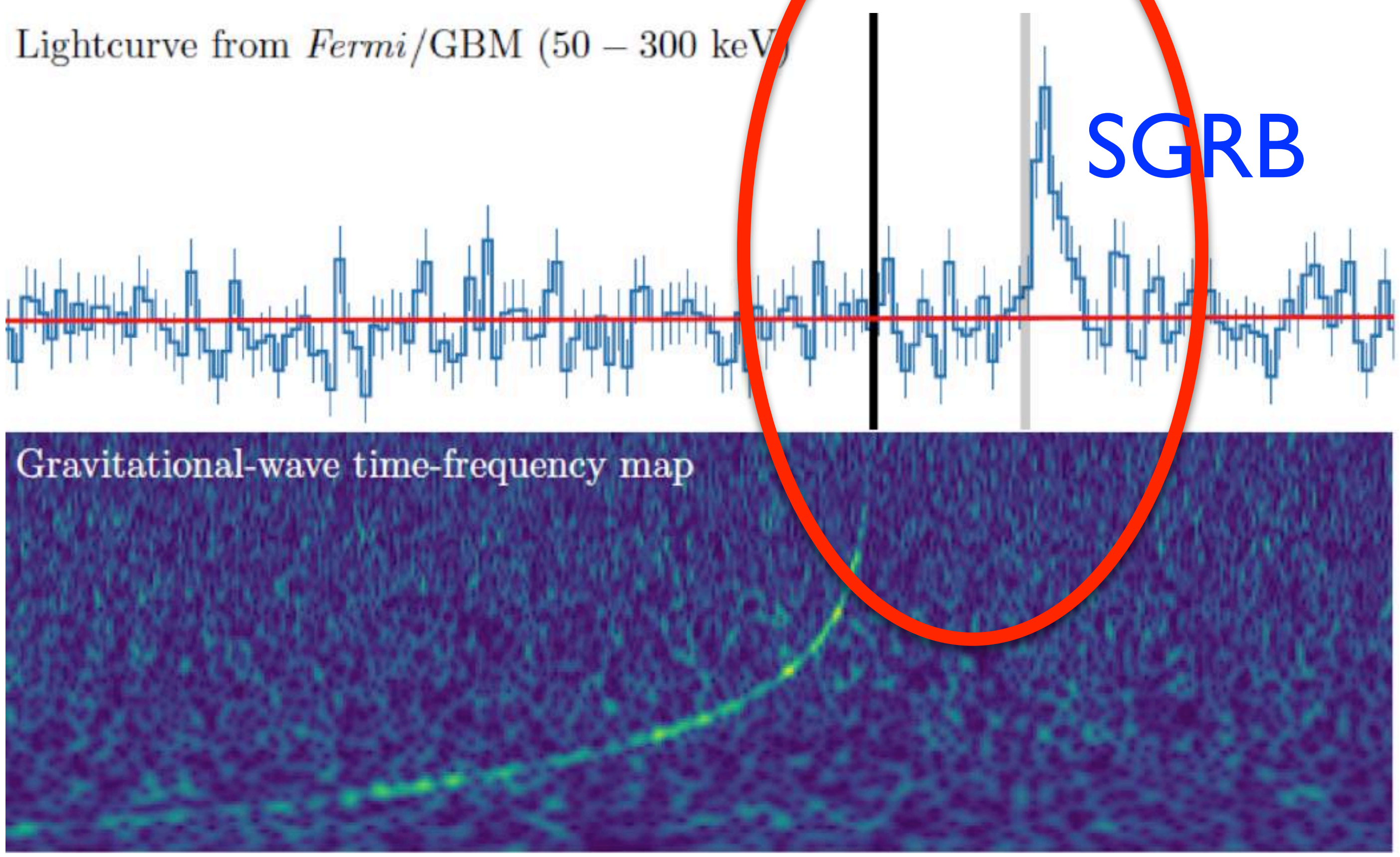
Subject headings: black holes — hydrodynamics — mass loss — neutron stars

Lattimer

Schramm

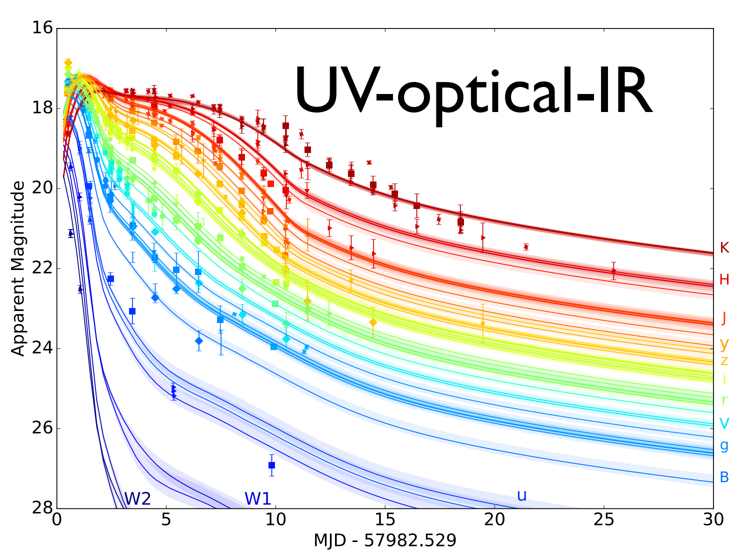
- dynamical expansion of n-rich matter provides a natural r-process site
- though predicted 40 years ago, this idea for the r-process had not been favored until very recently

GW170817 and the firework of EM counterparts

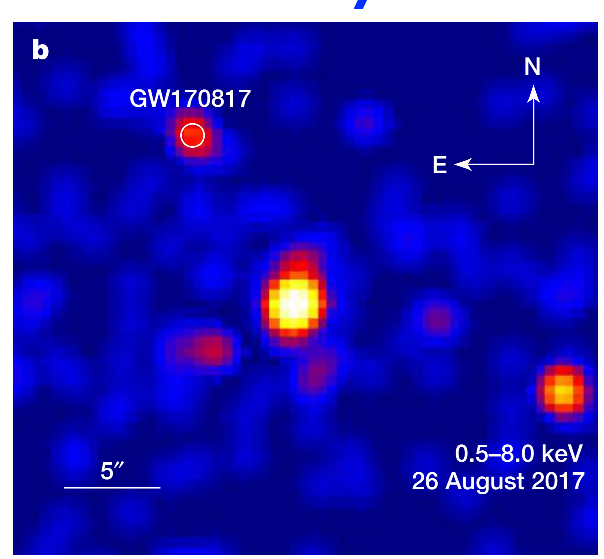


- unique event in astronomy, maybe most important observation since SN 1987A
- unprecedented level of multi-messenger observations
- confirms association of BNS to SGRBs
- kilonova provides strong evidence for synthesis of r-process material

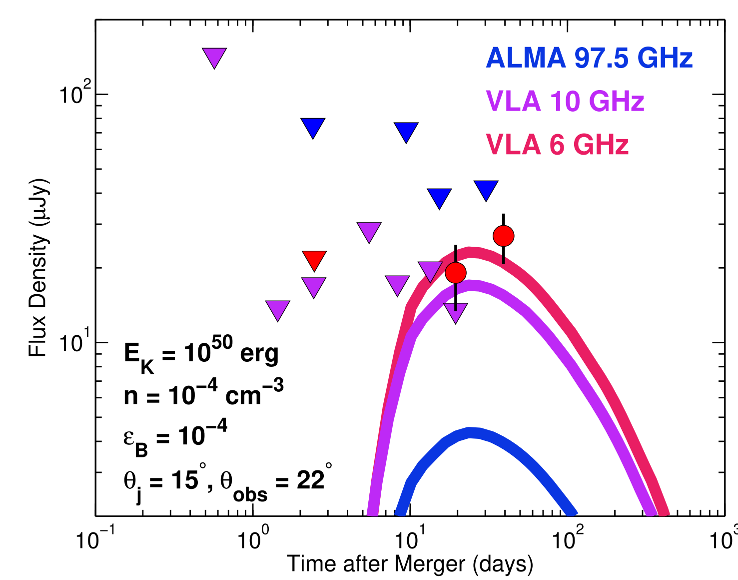
kilonova



X-rays



radio



The kilonova of GW170817

- blue kilonova properties:

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

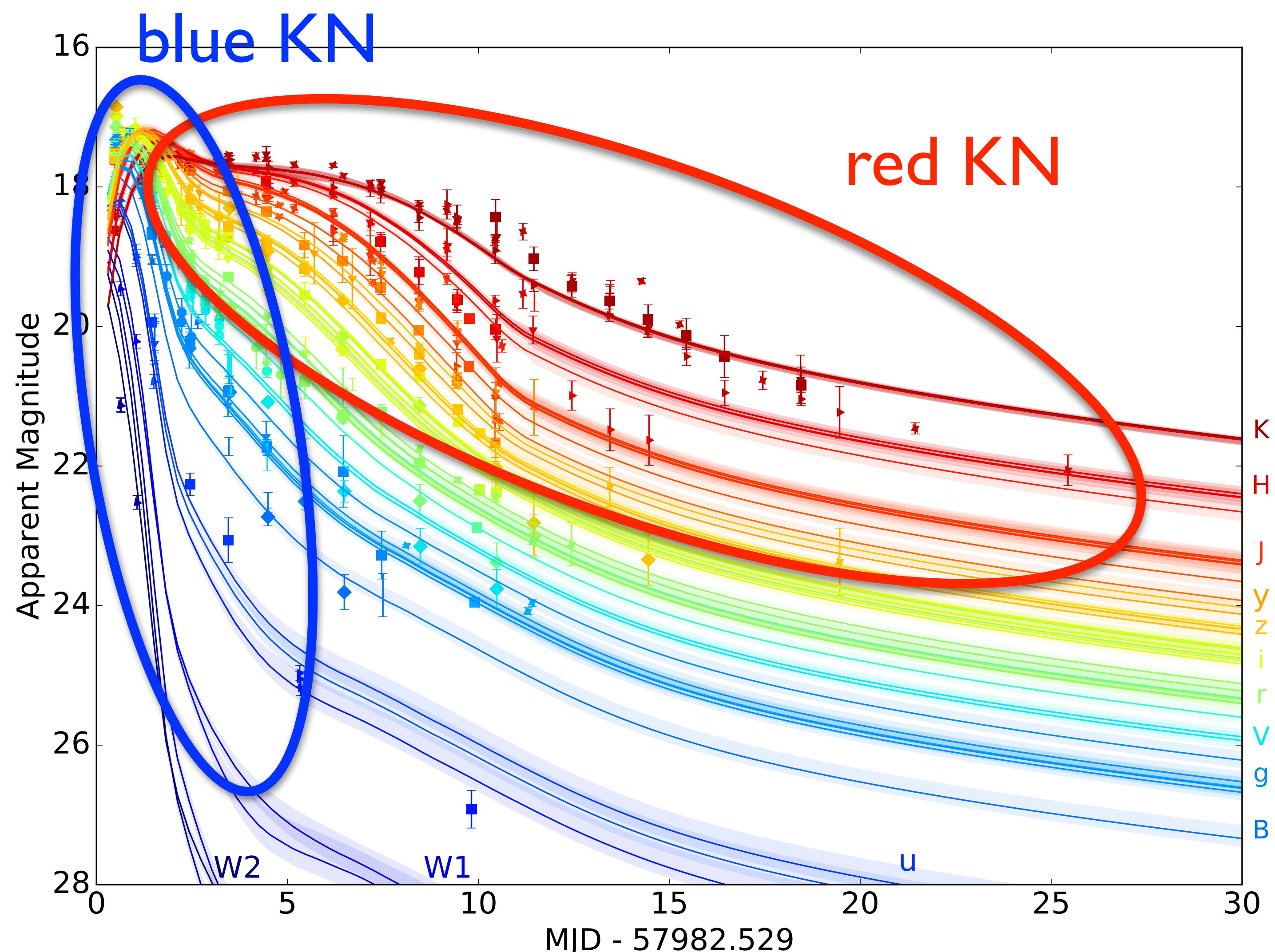
  Kilpatrick+ 2017
  Kasen+ 2017
  Nicholl+ 2017
  Villar+ 2017
  Coughlin+ 2018

- red kilonova properties:

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

  → heavy r-process elements!

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



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

Mass ejection generates kilonovae

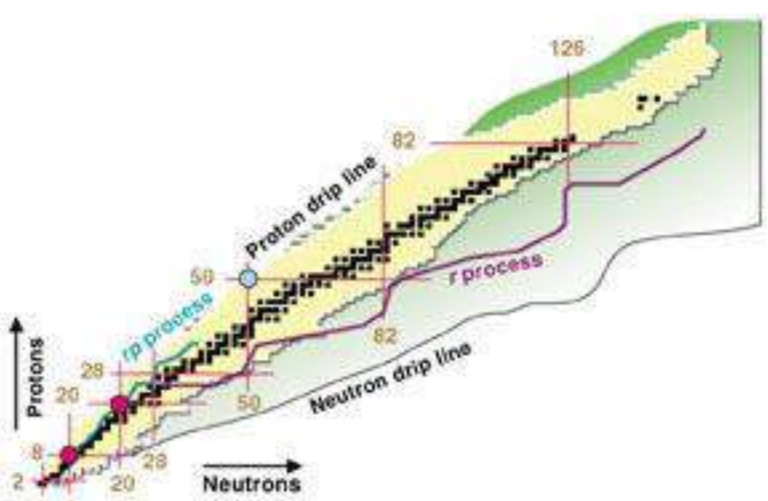
neutron rich ejecta from
NS-NS or NS-BH mergers
(Y_e~0.1-0.4)

~1s — decompression
rapid neutron capture (r-process)

heavy radioactive elements

~ days — alpha, beta decay
nuclear fission
further expansion

thermal emission (kilonova)
(quasi isotropic, long lasting: ~days)



Most simple kilonova model:

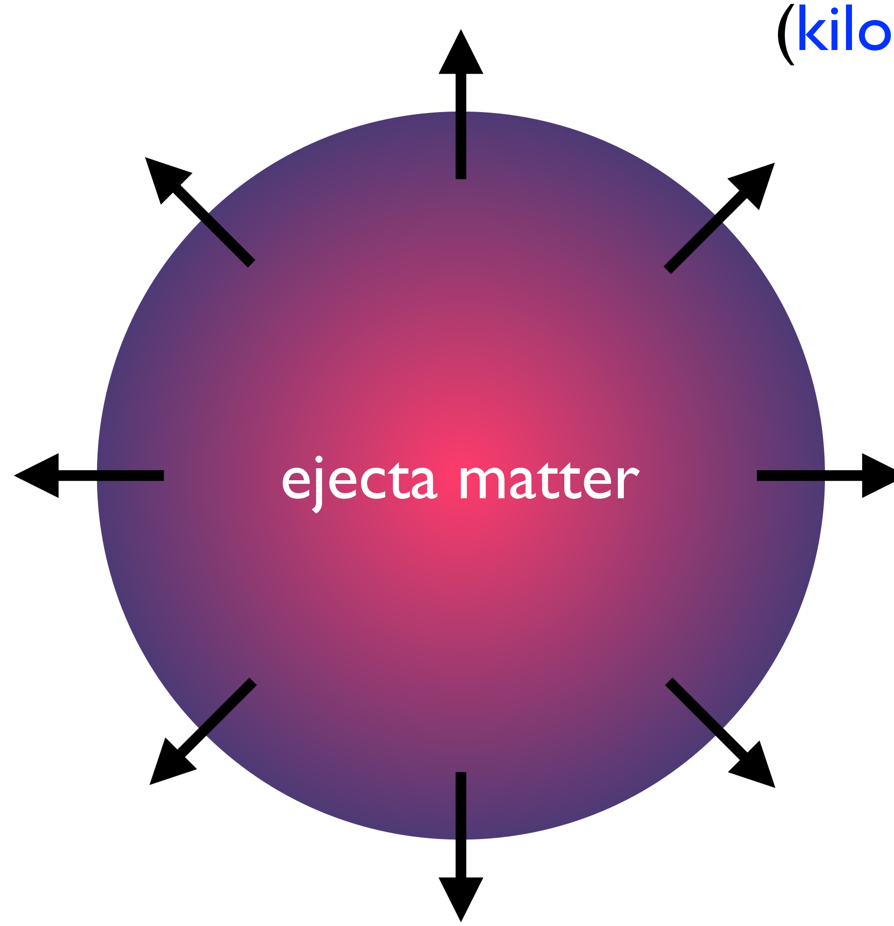
Piran+ 2013, Metzger+ 2017

$$\frac{dE_v}{dt} = -\frac{E_v}{t} - \frac{E_v}{t_{\rm diff}} + \dot{Q}_v$$

adiabatic losses

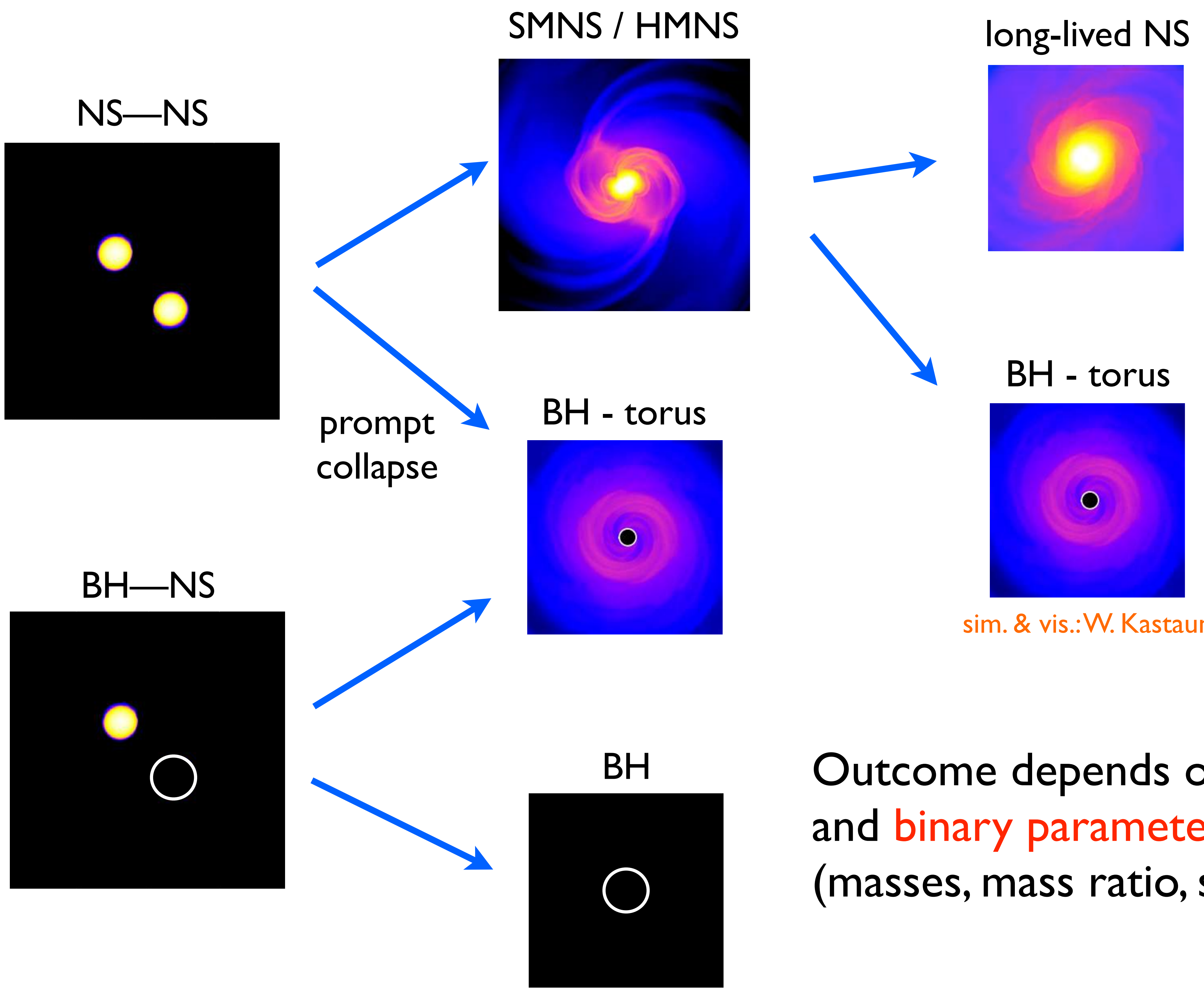
radiative luminosity (kilonova)

radioactive heating (r-process)



homologous expansion

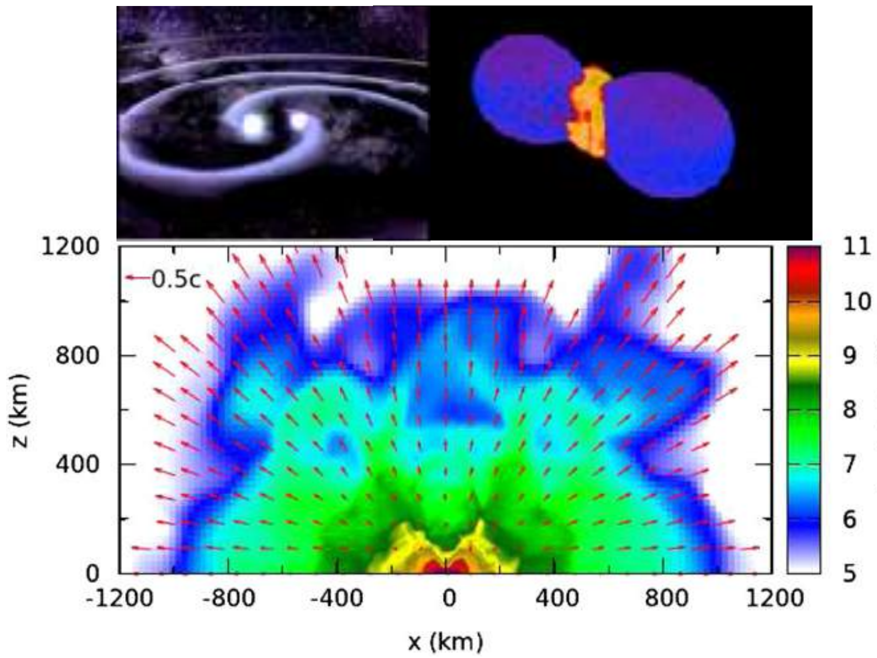
NS merger phenomenology



Outcome depends on EOS and binary parameters (masses, mass ratio, spin, ...)

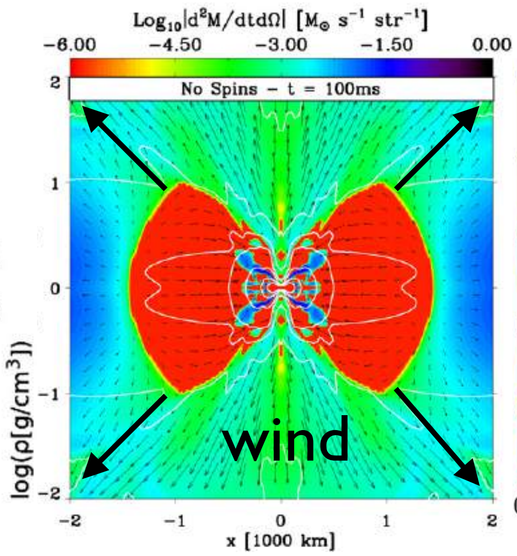
Sources of ejecta in NS mergers

dynamical ejecta (~ms)

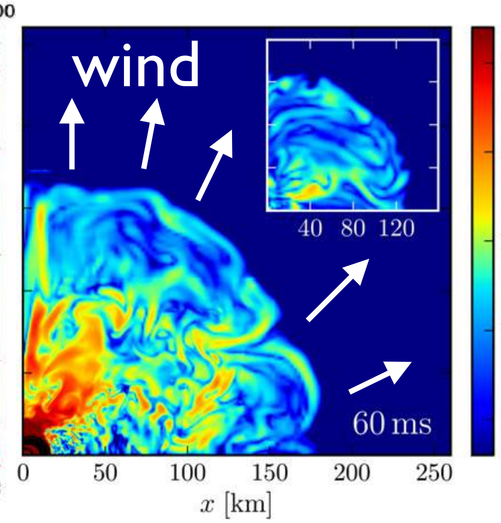


Hotokezaka+ 2013, Bauswein+ 2013

winds from NS remnant (~10ms-1s)

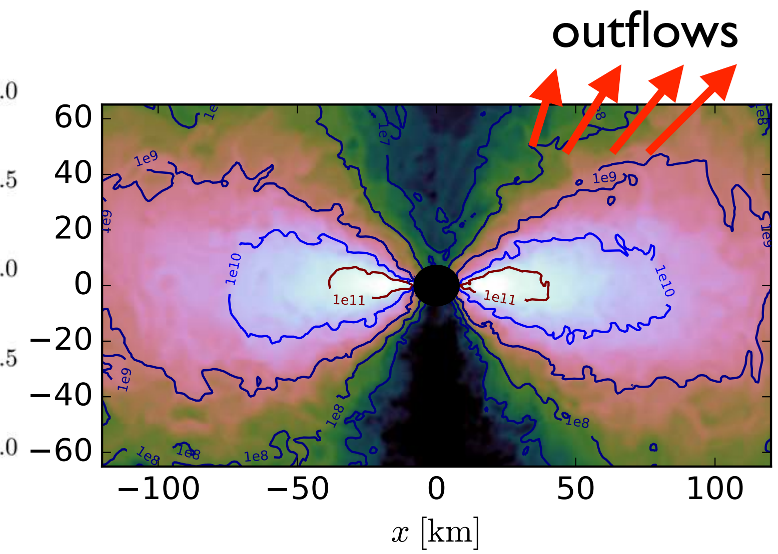


Dessart+ 2009



Siegel+ 2014
Ciolfi, Siegel+ 2017

accretion disk (~10ms-1s)



Siegel & Metzger 2017, 2018

tidal ejecta
shock-heated ejecta

$M_{\rm tot} \lesssim 10^{-3} \rm M_\odot$

$v \gtrsim 0.2c$

neutrino-driven wind

$\dot{M}_{\rm in} \sim (10^{-4} - 10^{-3}) \rm M_\odot s^{-1}$

magnetically driven wind

$\dot{M}_{\rm in} \sim (10^{-3} - 10^{-2}) \rm M_\odot s^{-1}$

thermal outflows

$M_{\rm tot} \gtrsim 0.3 - 0.4 M_{\rm disk}$

$v \sim 0.1c$

Overall ejecta mass per event:

$$\lesssim 10^{-3} - 10^{-2}\, M_\odot$$

strongly depends on EOS and mass ratio

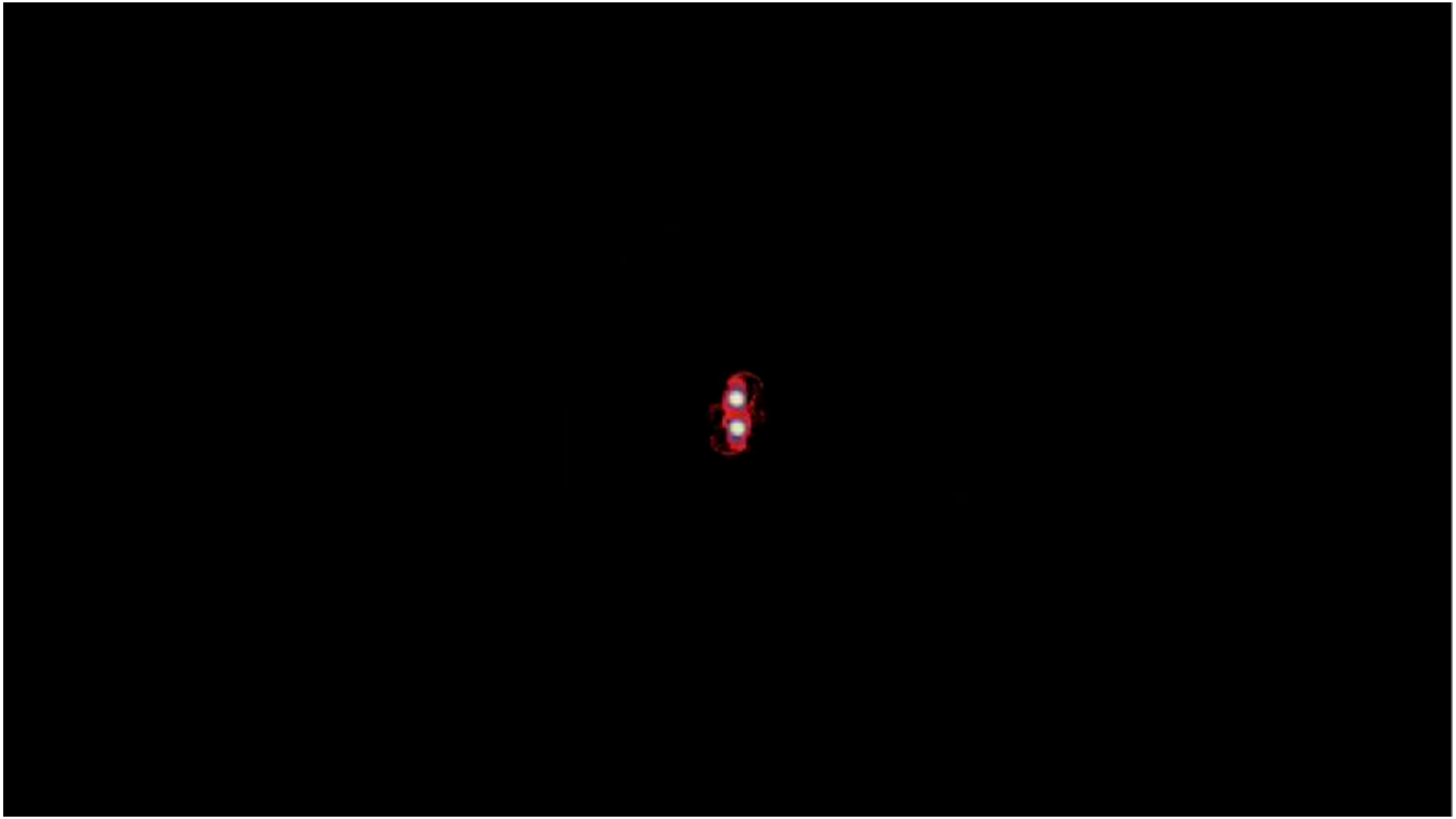
Bauswein+ 2013
Radice+ 2016, 2017
Sekiguchi+ 2016
Palenzuela+2015
Lehner+2016
Ciolfi, Siegel+2017

Siegel & Metzger 2017, 2018

$$\gtrsim 10^{-2} M_\odot$$

lower limit

Dynamical ejecta and winds

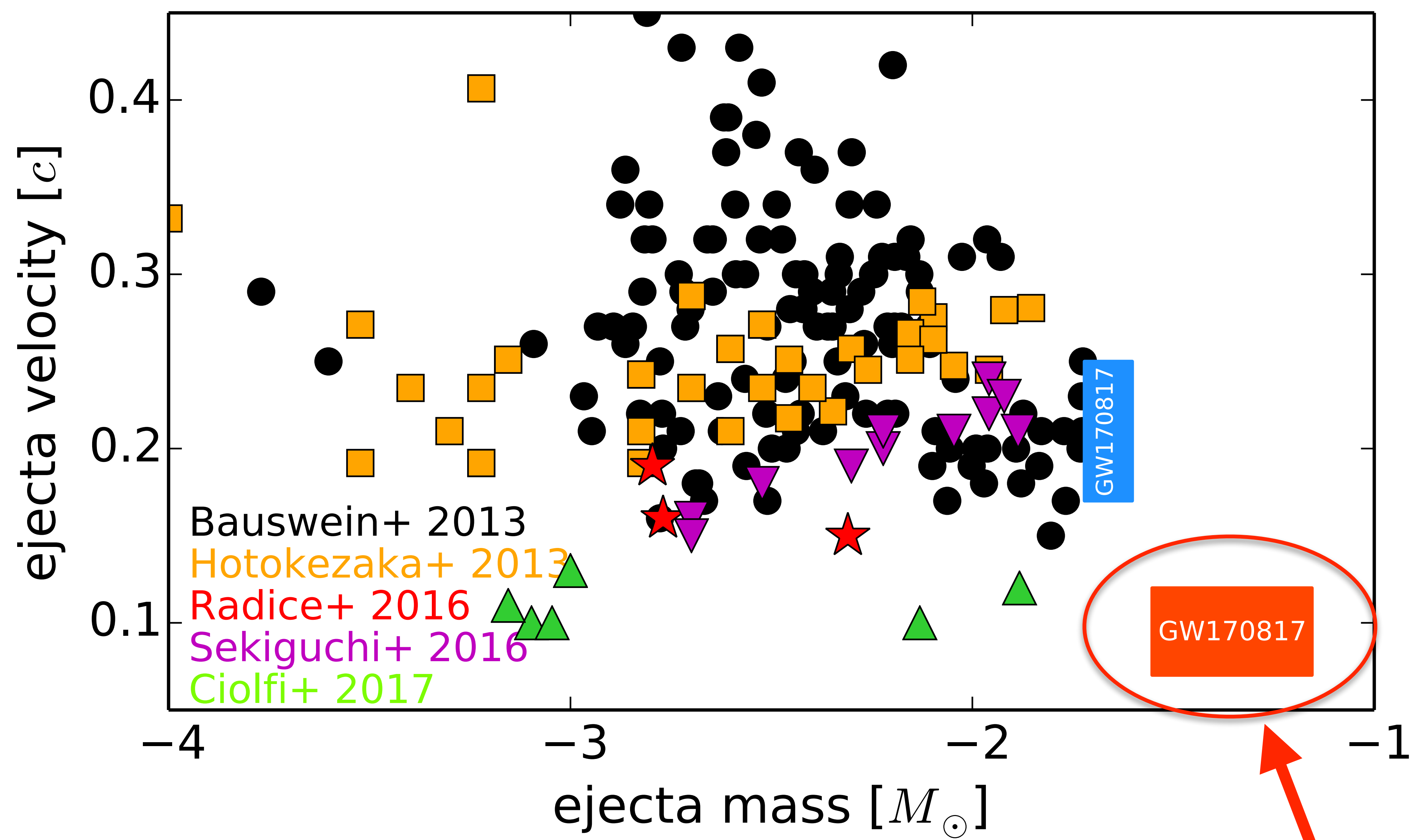


Movie: BNS merger showing dynamical ejecta and winds from remnant NS

Ciolfi, Siegel+2017

The kilonova of GW170817

BNS merger simulations: dynamical ejecta

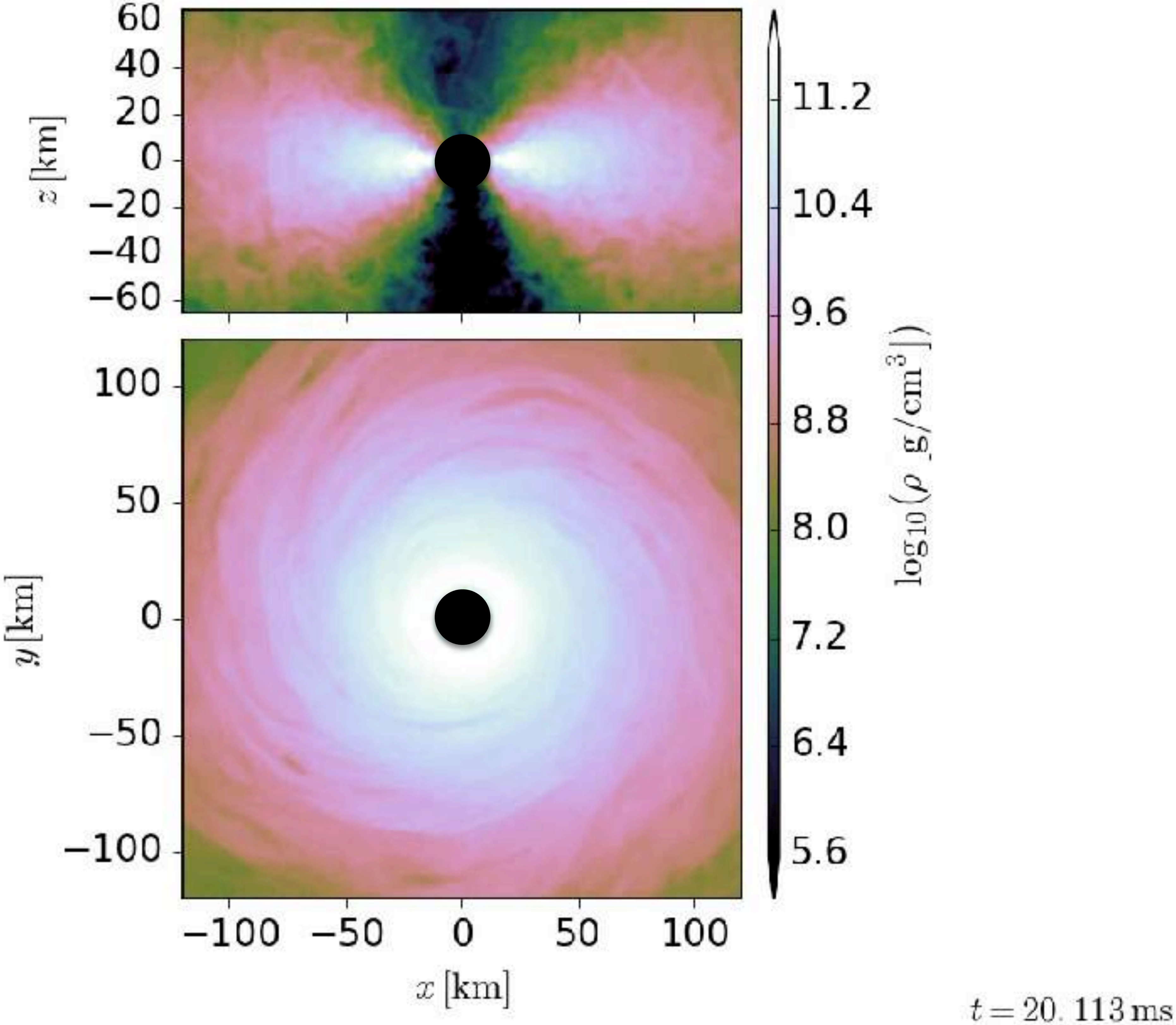


Observed ejecta properties of red kilonova inconsistent with known classical ejection mechanisms in NS mergers

Post-merger accretion disk outflows

Siegel & Metzger 2017, PRL

Siegel & Metzger 2018a



See also:

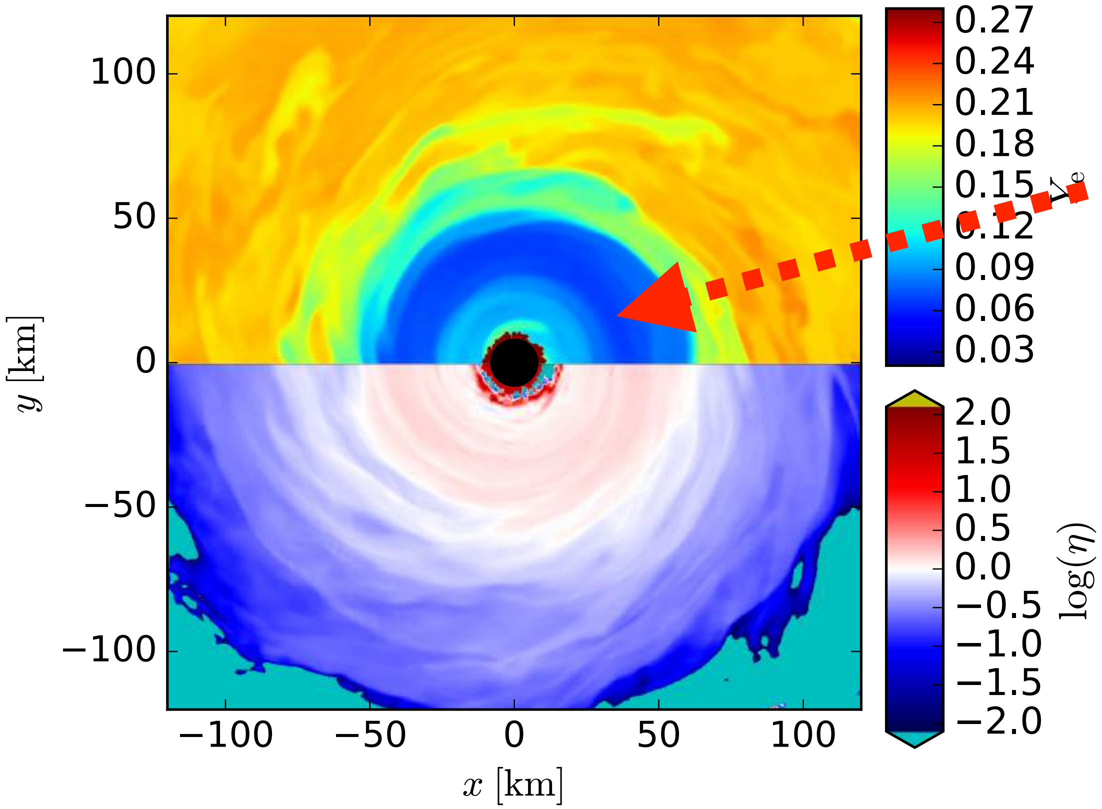
Fernandez+ 2013, 2015

Just+ 2015

Fernandez+ 2018

Disk outflows and the red kilonova

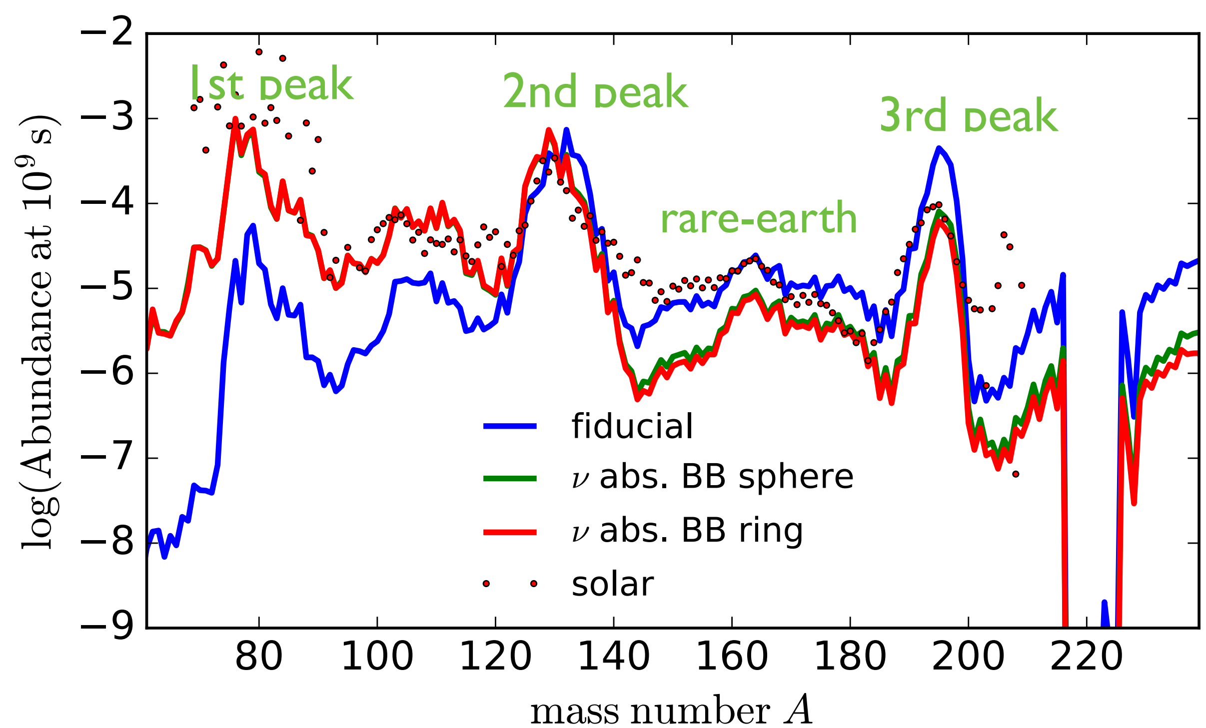
Siegel & Metzger 2017, PRL
Siegel & Metzger 2018



- Neutron-richness: self-regulation mechanism in degenerate inner disk provides neutron rich outflows (Y_e<0.25)

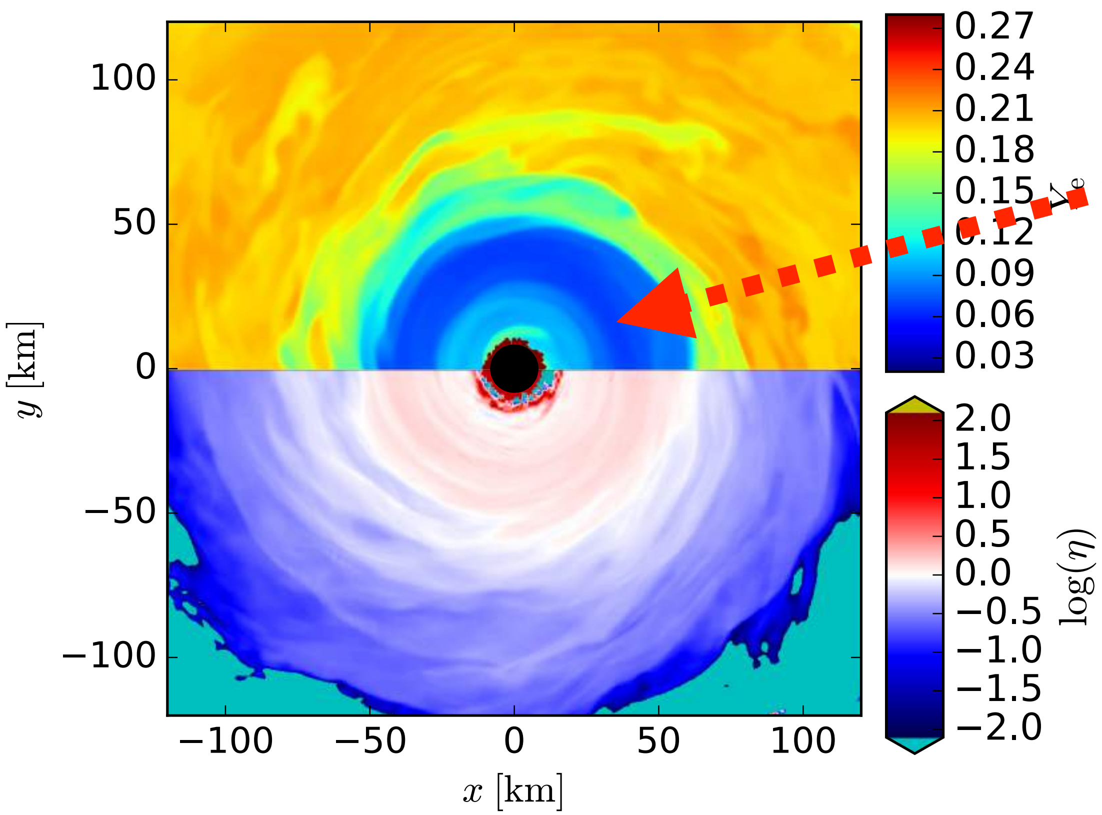
Naively, neutron-rich conditions favor:

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

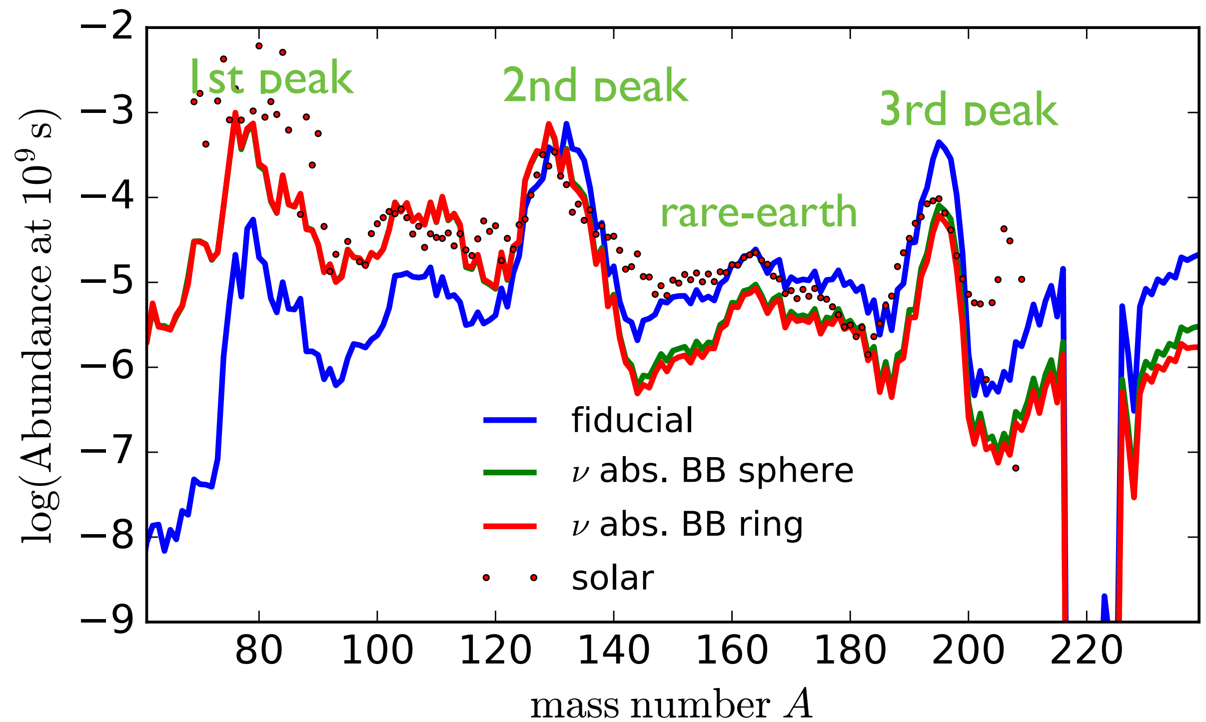


Disk outflows and the red kilonova

Siegel & Metzger 2017, PRL
Siegel & Metzger 2018



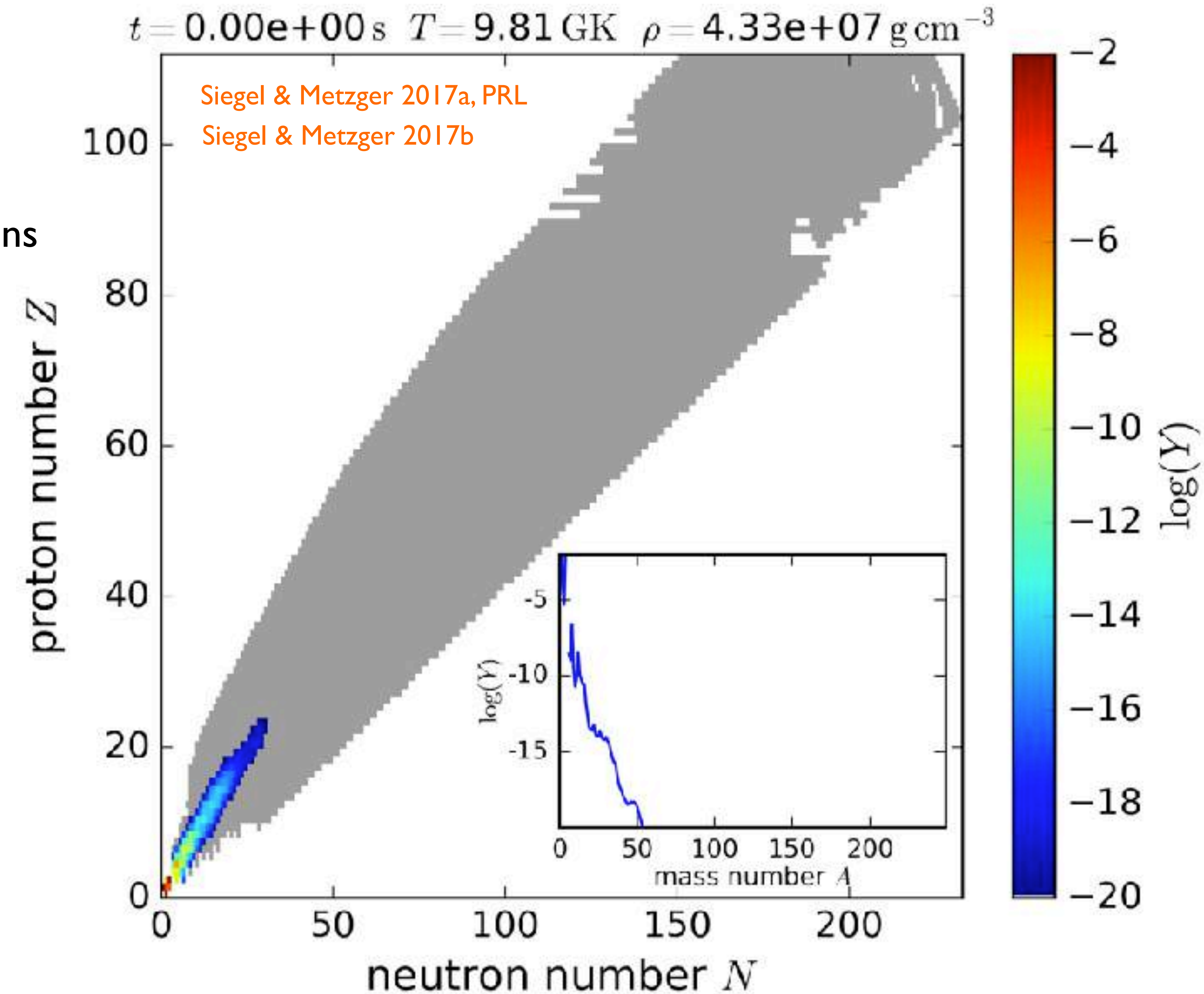
- Neutron-richness: self-regulation mechanism in degenerate inner disk provides neutron rich outflows (Y_e<0.25)
- Production of full range of r-process nuclei, excellent agreement with observed r-process abundances (solar, halo stars)



r-process nucleosynthesis in disk outflows

nuclear reaction network (*SkyNet*)

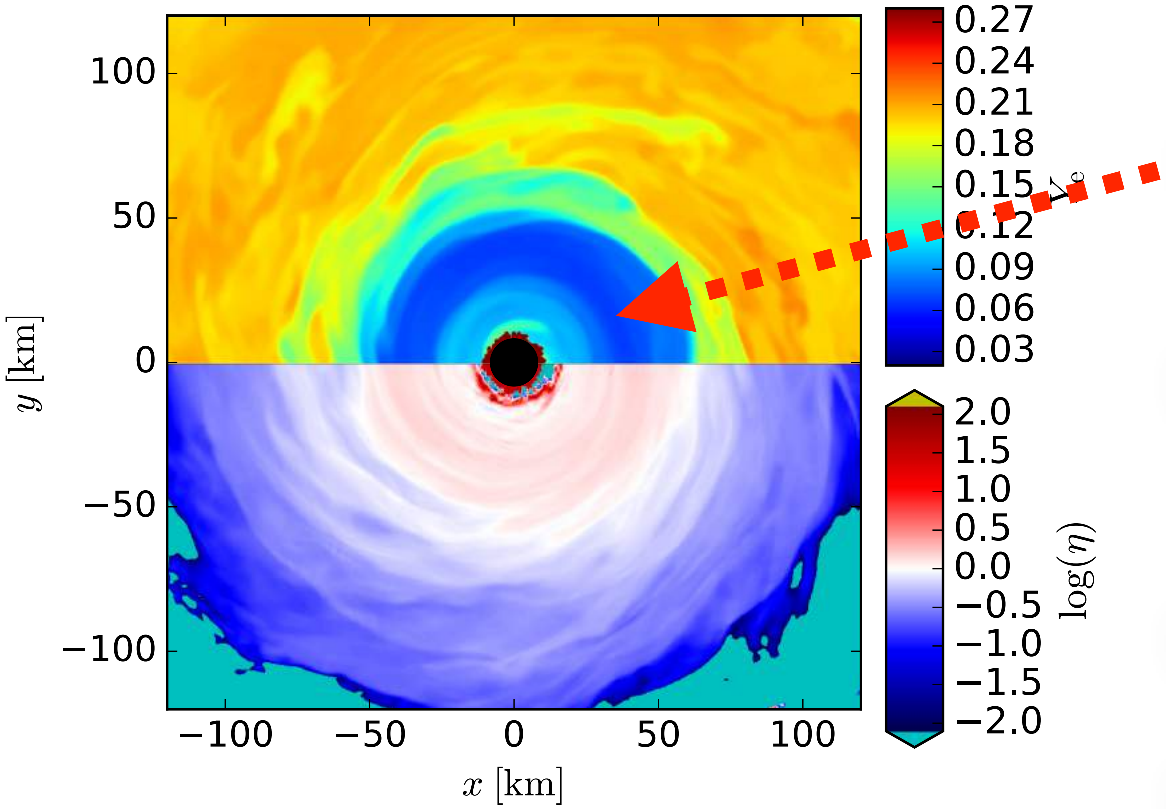
- neutron captures
- photo-dissociations
- α-, β-decays
- fission



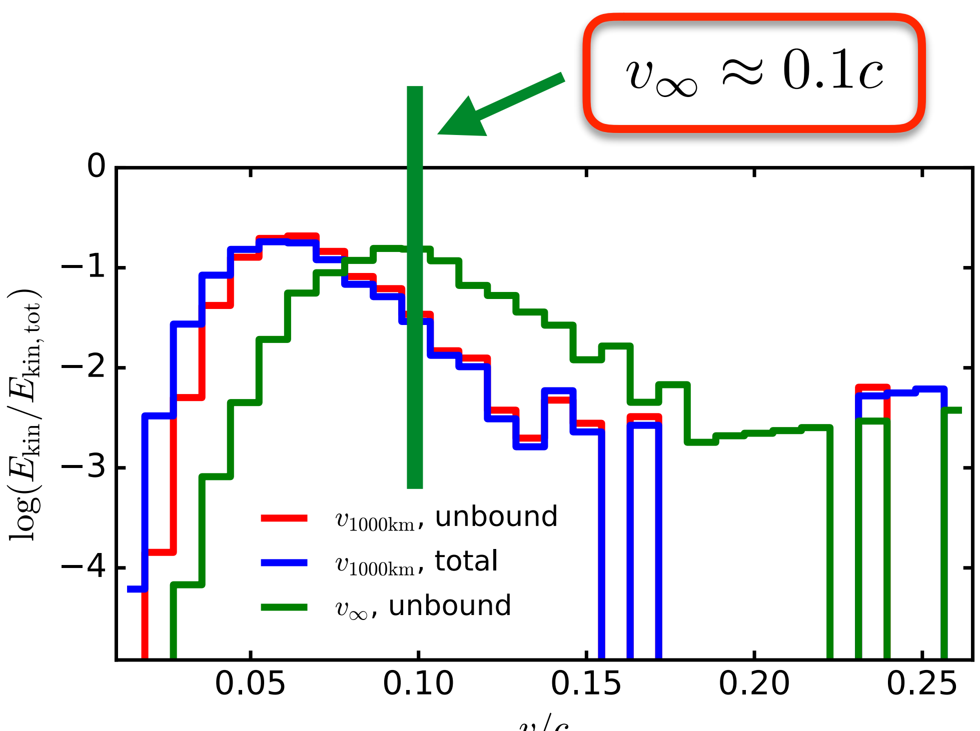
Movie: r-process nucleosynthesis from NS merger remnant disks

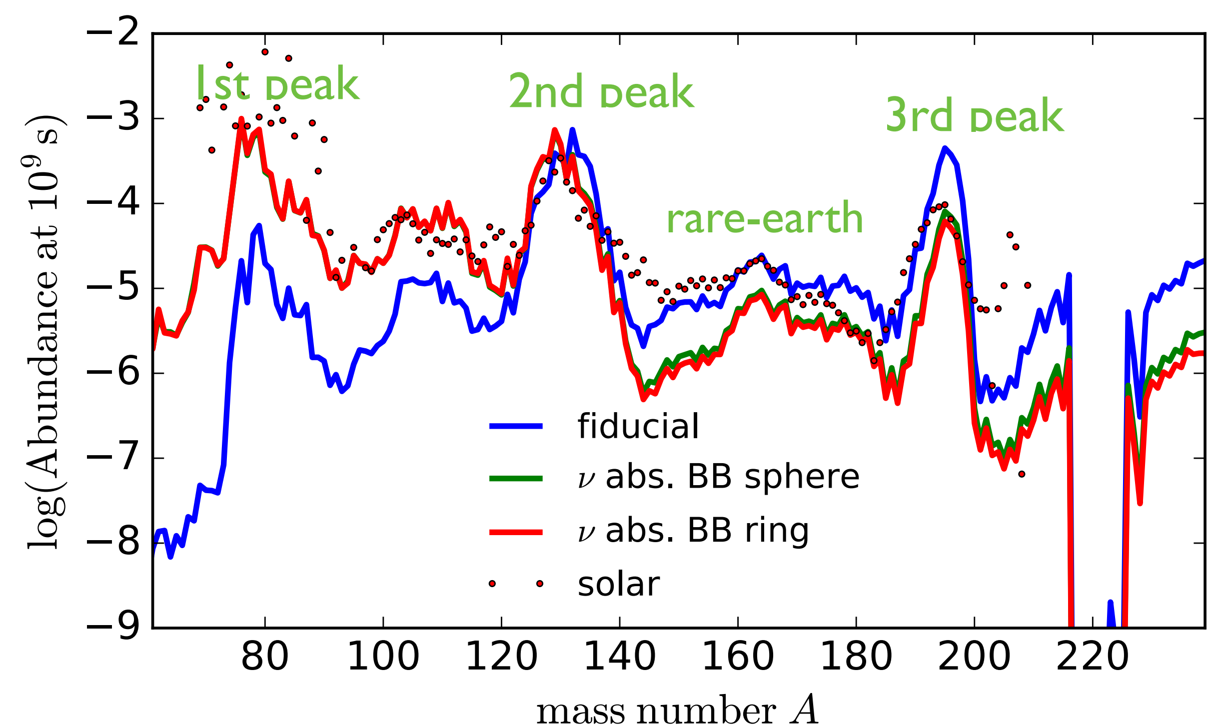
Disk outflows and the red kilonova

Siegel & Metzger 2017, PRL
Siegel & Metzger 2018

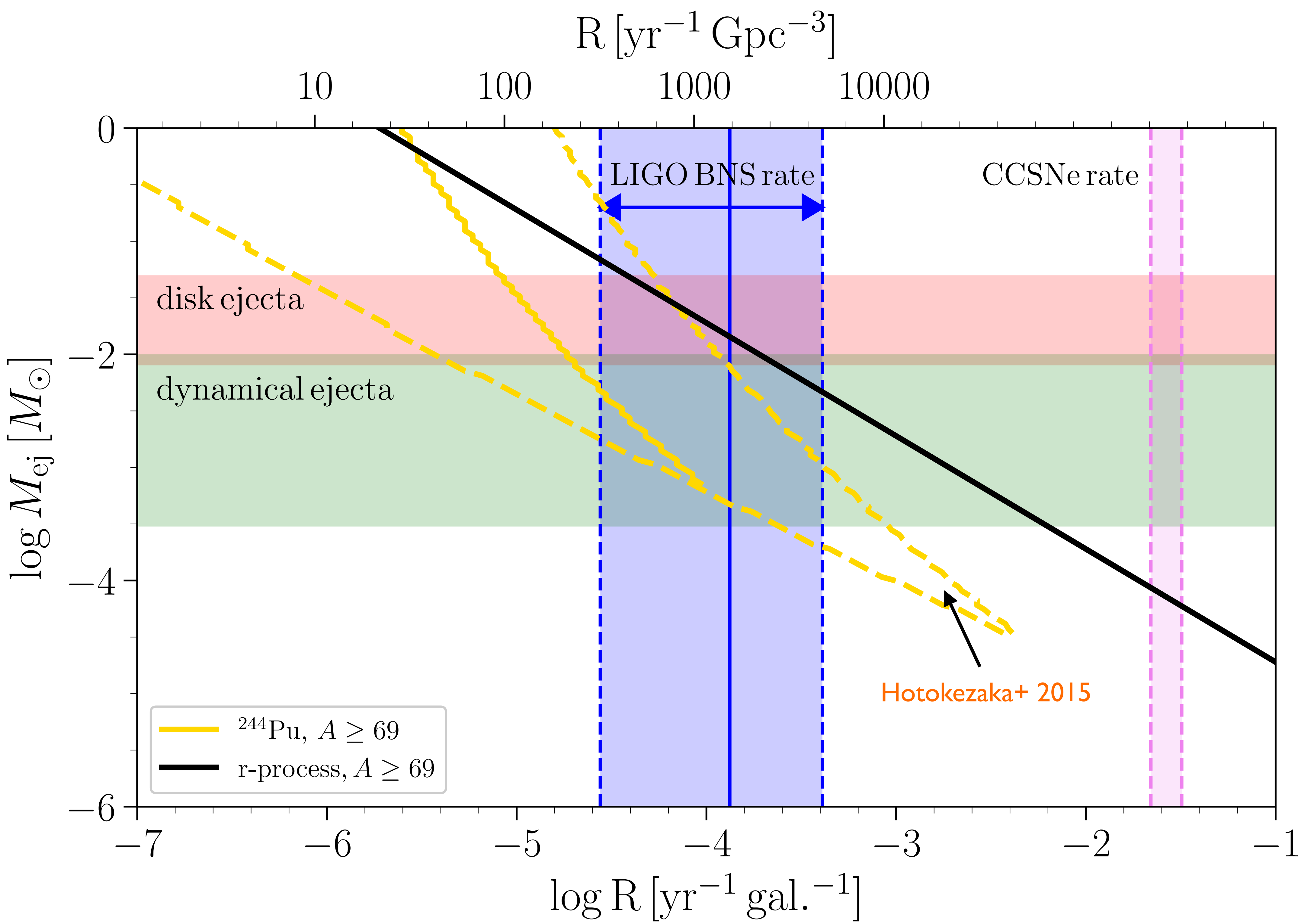


- Neutron-richness: self-regulation mechanism in degenerate inner disk provides neutron rich outflows (Y_e<0.25)
- Production of full range of r-process nuclei, excellent agreement with observed r-process abundances (solar, halo stars)
- Slow outflow velocities (~0.1c)
- Large amount of ejecta ($\gtrsim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

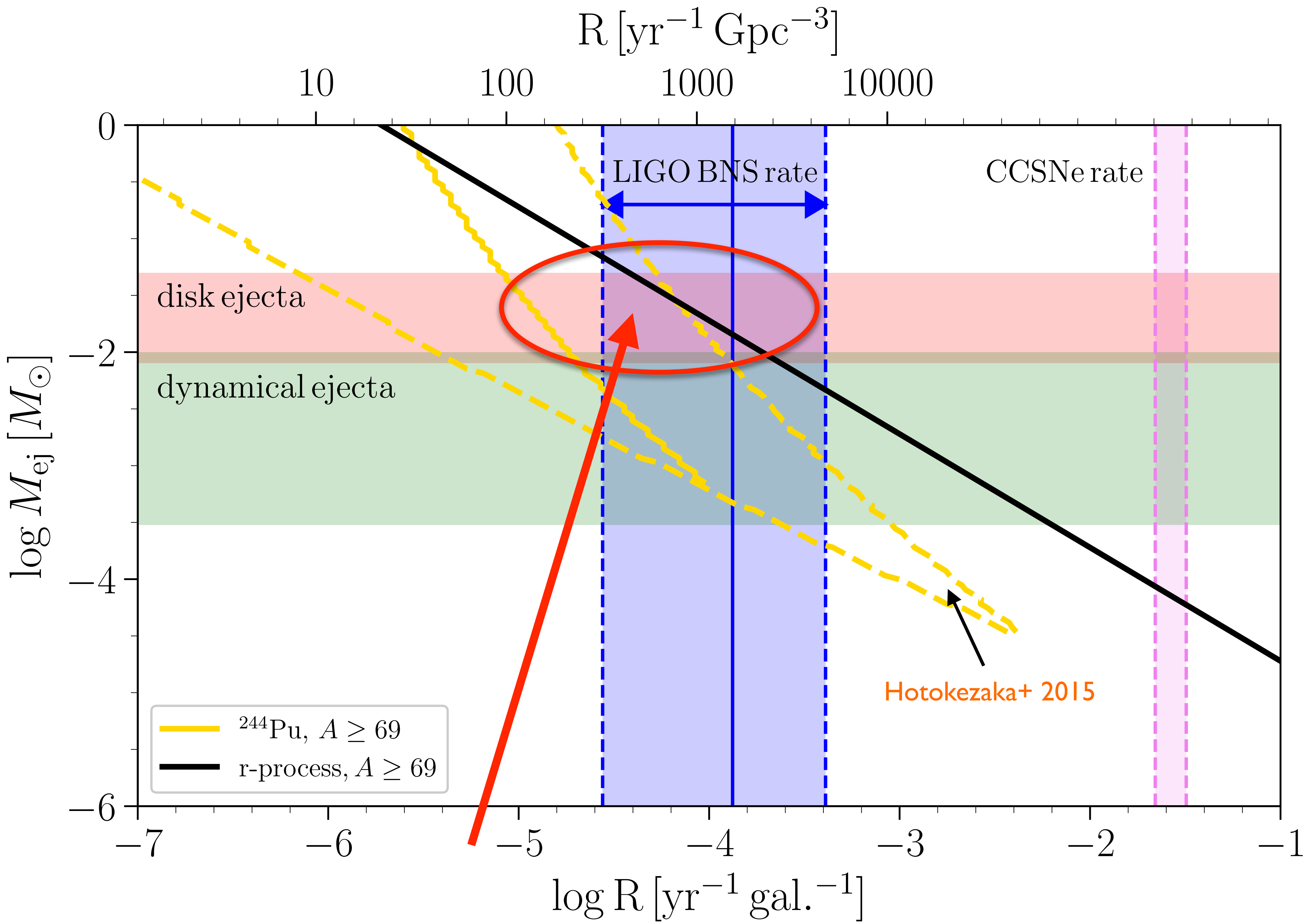




Constraints on r-process nucleosynthesis

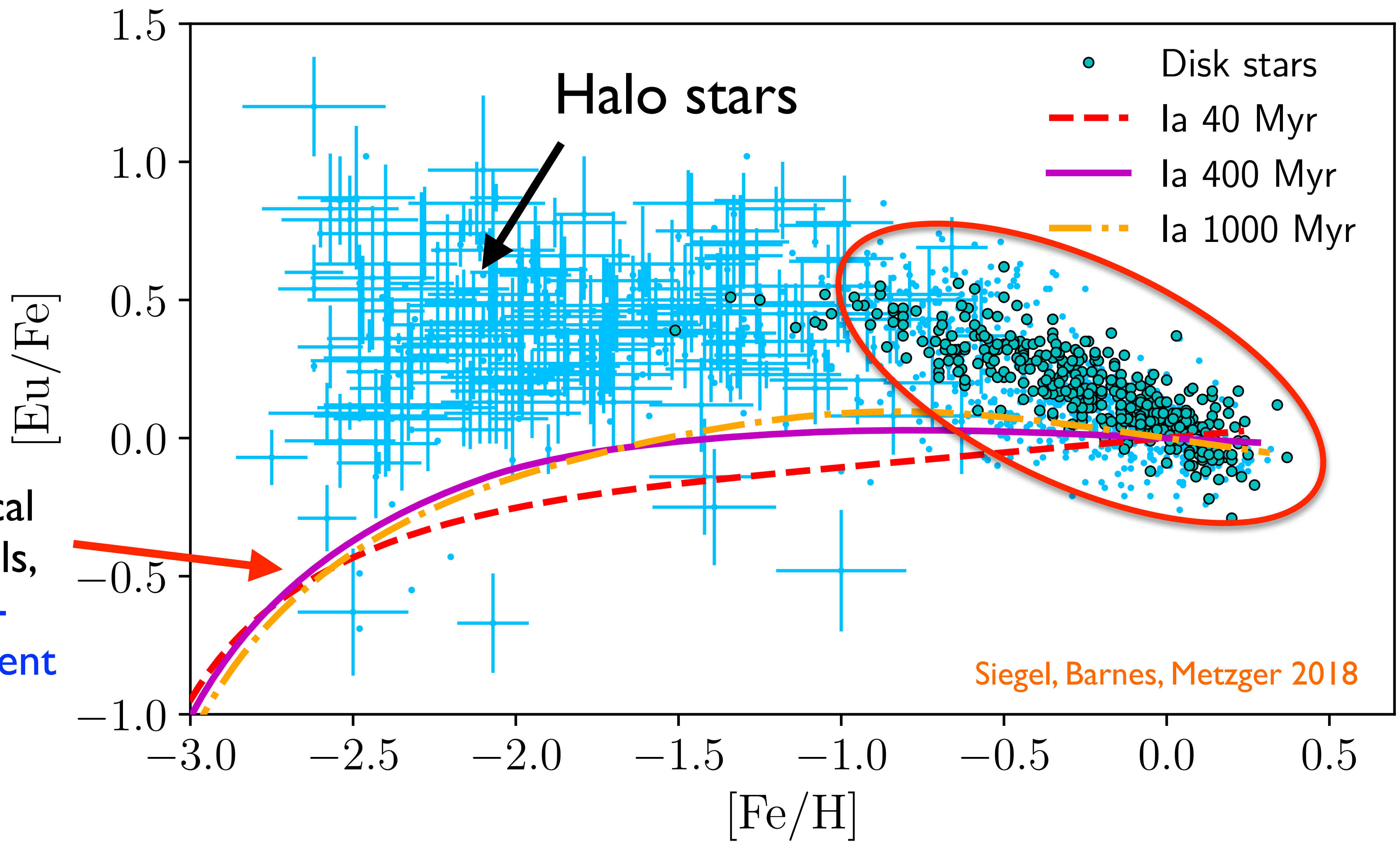


Constraints on r-process nucleosynthesis



post-merger disk outflows are a promising site for the r-process!

But… what about galactic chemical *evolution*?

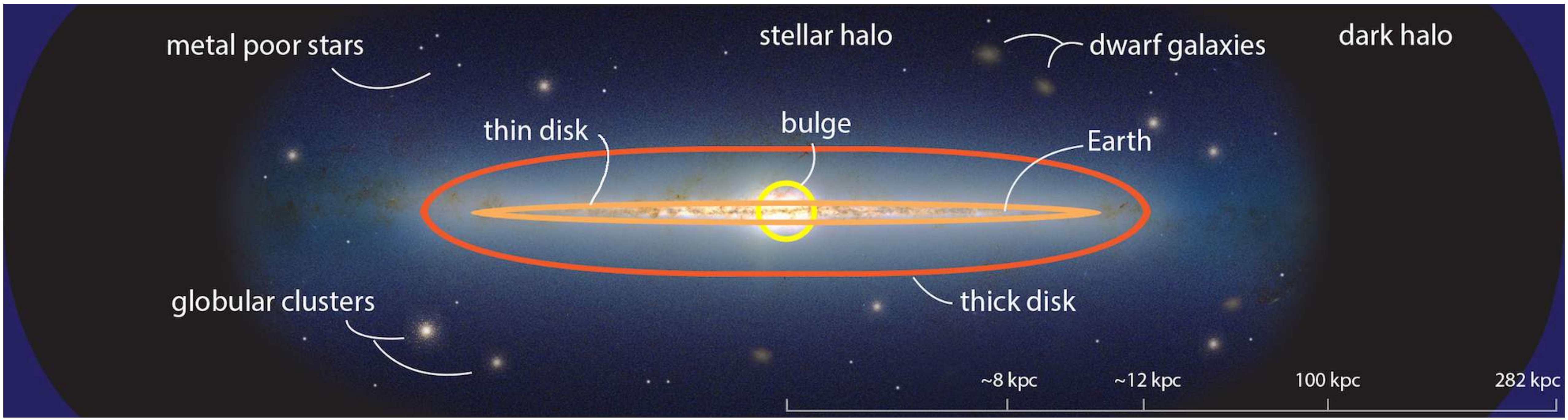


Galactic chemical evolution models, merger-only r-process enrichment

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

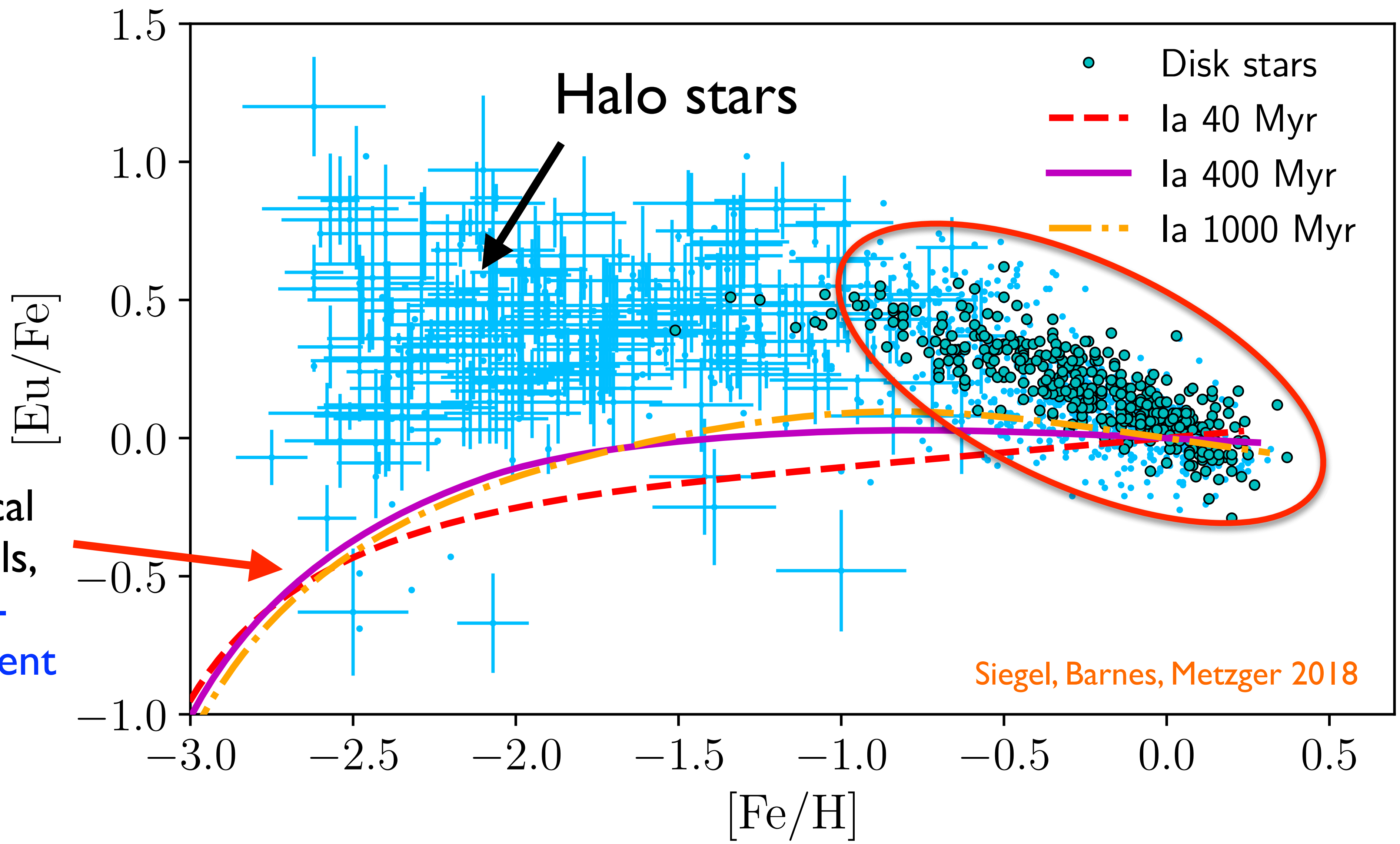
There should be another significant source of r-process enrichment…

Structure and stellar populations of the Milky Way



Frebel 2018

But… what about galactic chemical *evolution*?



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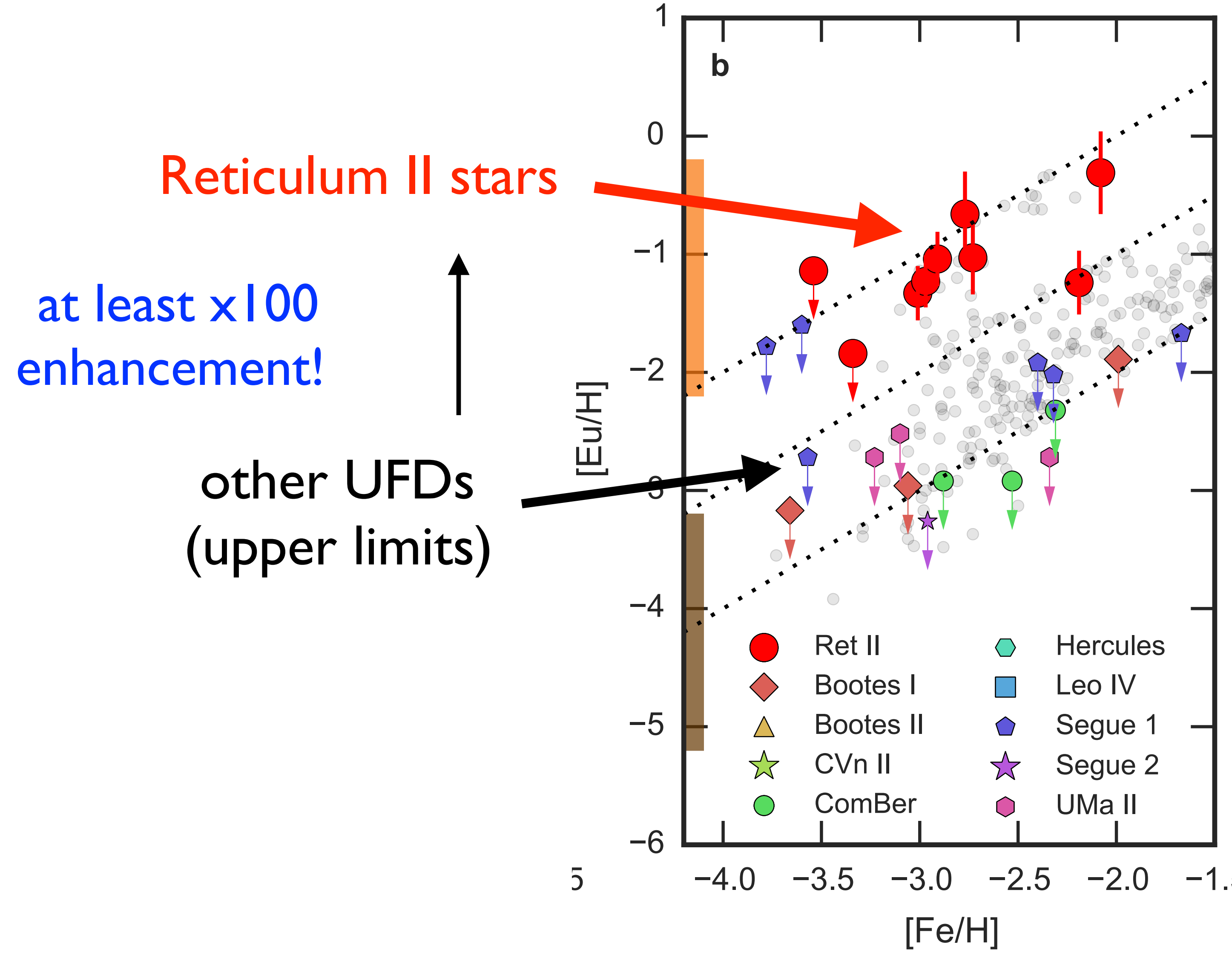
There should be another significant source of r-process enrichment…

Ultra-faint dwarfs: another challenge for mergers



Ji+ 2016, Nature

Enhancement thought to be caused by single high-yield r-process event ('clean' r-process site)

Challenges for NS mergers:

- need extremely low kick velocities <10 km/s (UFDs have low escape speeds!)
- need either very short merger timescale < 100 Myr or:
- need second epoch of star formation to feed r-process material back into stars

Not impossible: Beniamini+ 2016

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

Siegel, Barnes, Metzger 2018

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

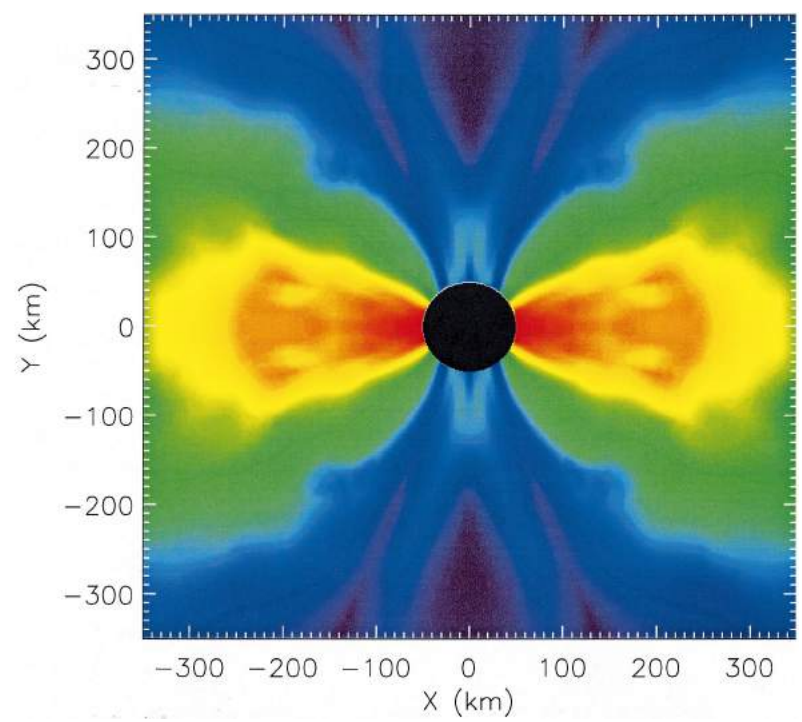
  → "failed explosion" (direct collapse to a BH)

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

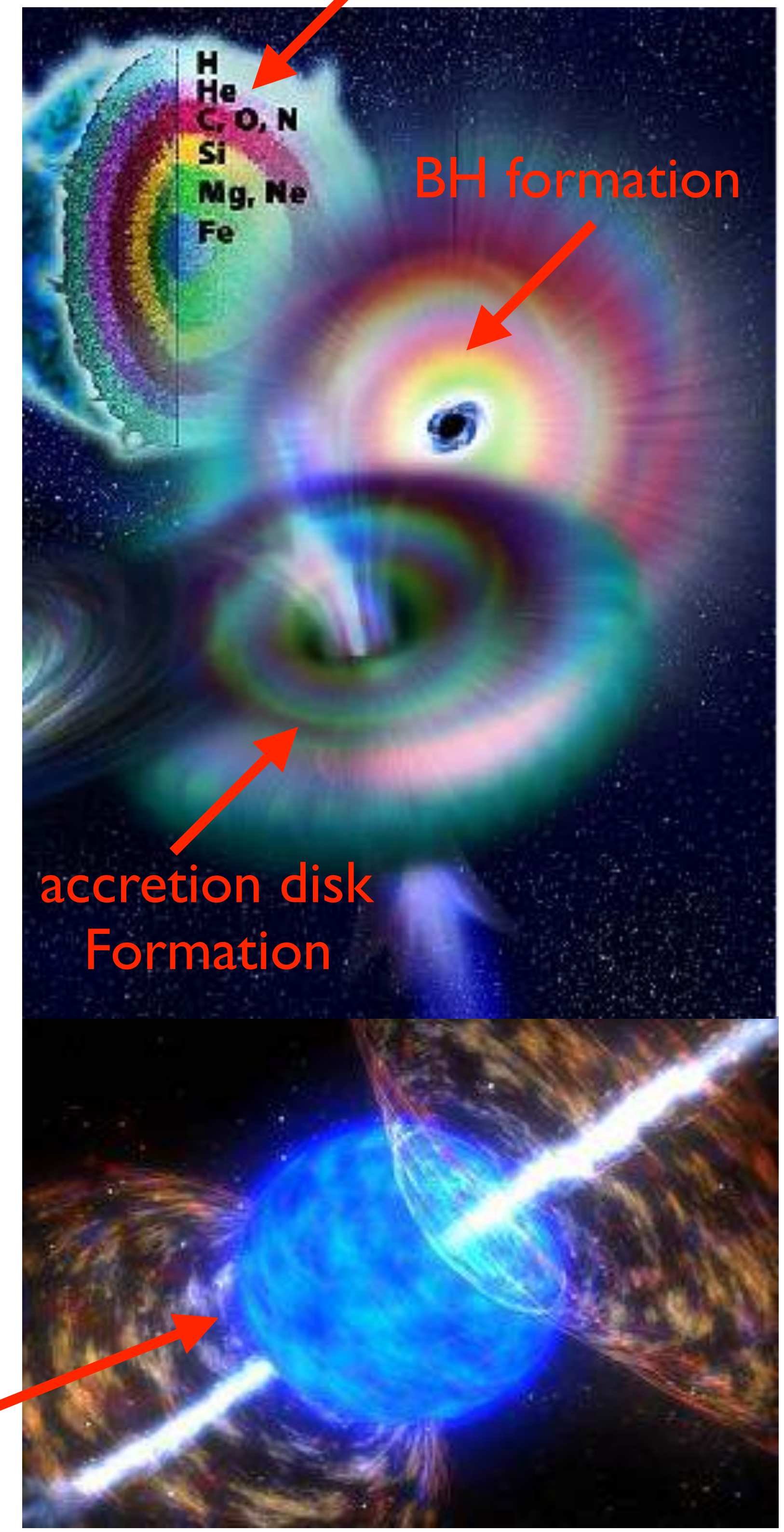
- Angular momentum of infalling stellar material leads to circularization and formation of accretion disk around the BH

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

MacFadyen & Woosley 1999

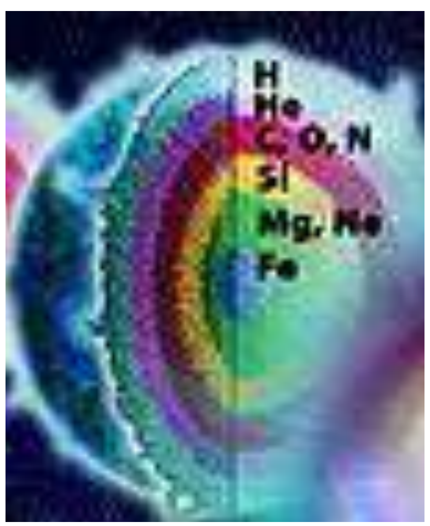


core collapse

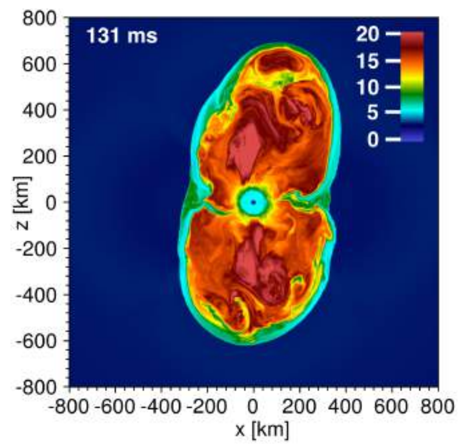


jet punches through infalling material, generates GRB

Collapsar scenario overview



core collapse



proto-magnetar
"MHD supernova"

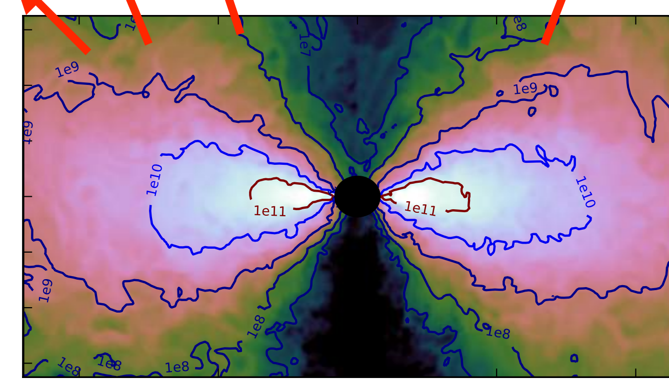
minor contribution to (mostly) light r-process

Moesta+ 2018
Halevi & Moesta 2018

BH formation

r-process outflow

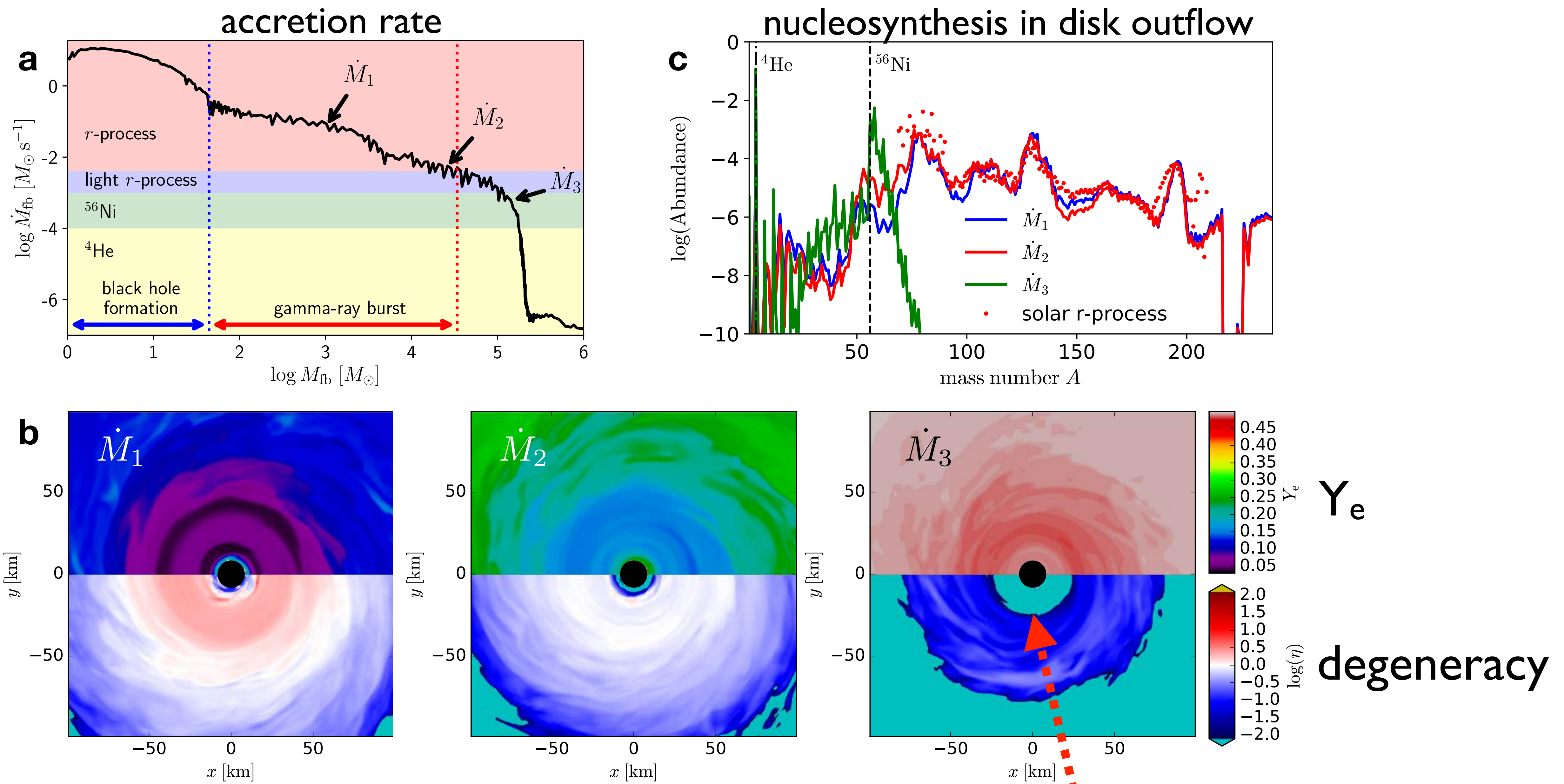
GRB jet



Collapsar accretion disk

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

Siegel, Barnes, Metzger 2018



Neutron-richness:

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

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

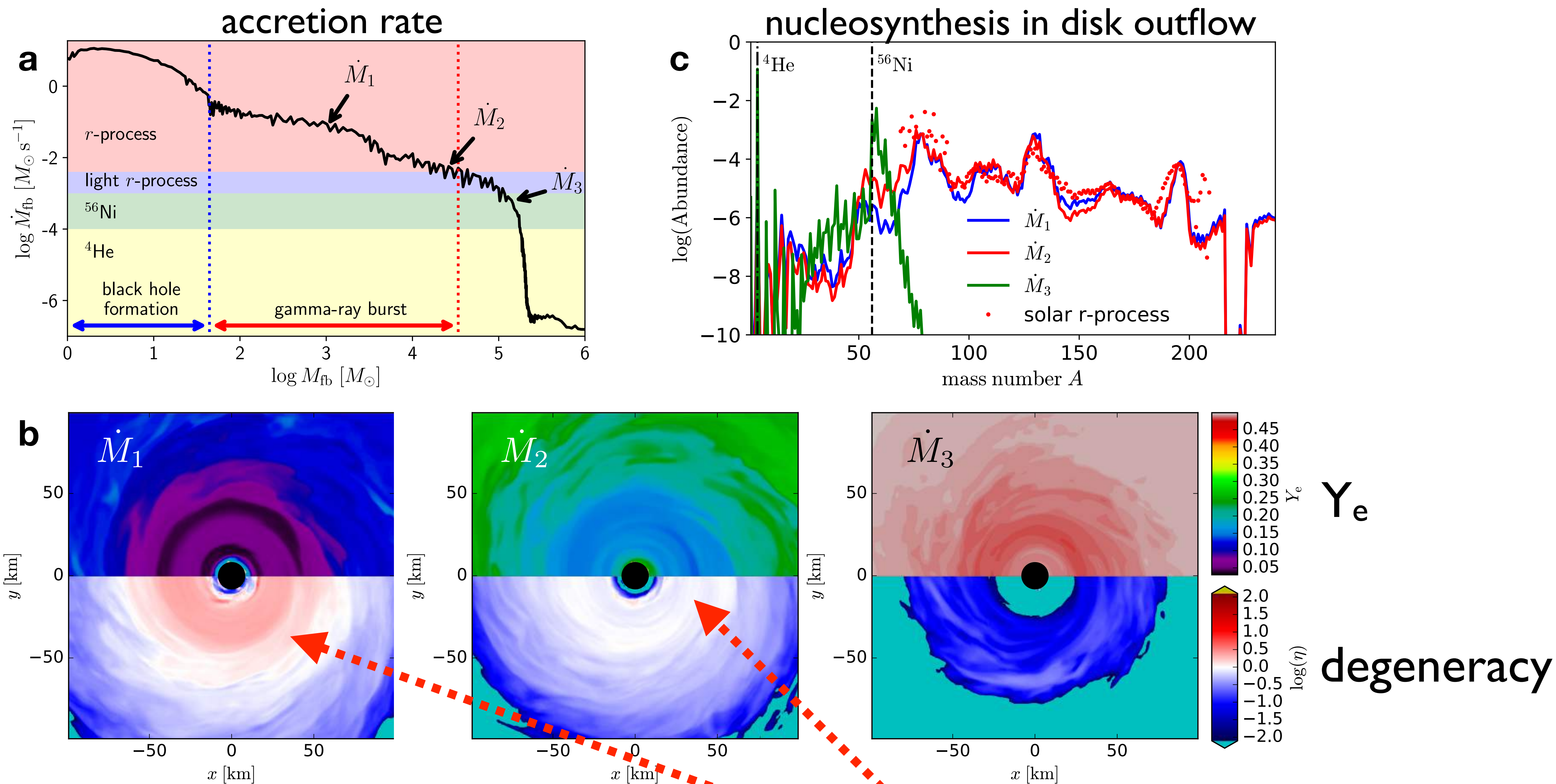
Low disk densities (low $\dot{M}$):

$Y_e \sim 0.5$

outflows produce ^{56}Ni

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

Siegel, Barnes, Metzger 2018



Neutron-richness:

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

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

High disk densities (high $\dot{M}$):
→ 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!)

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

→ dominant contribution to Galactic r-process relative to mergers

Independent absolute r-process estimate:

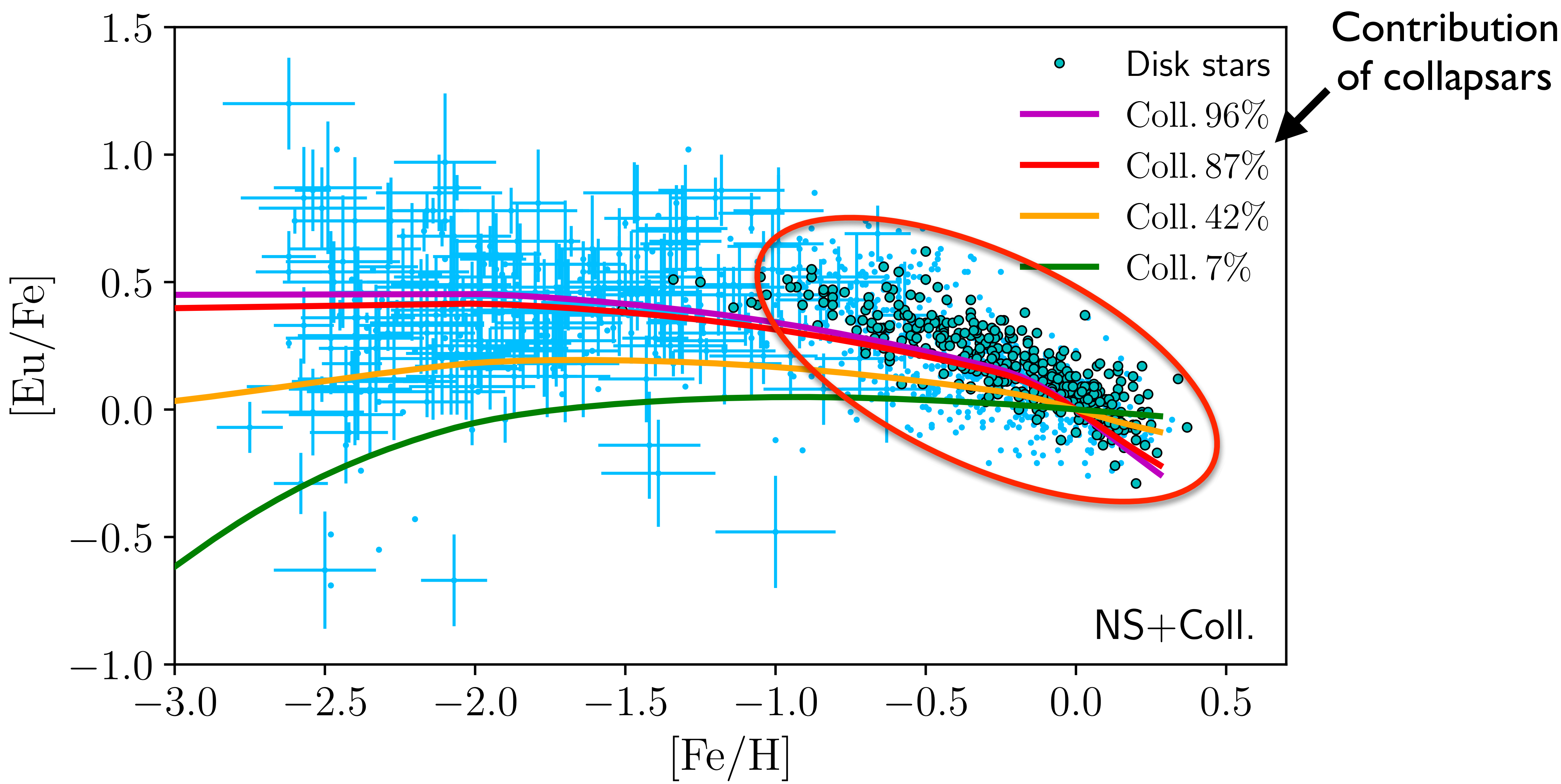
- assume collapsars as main contribution to Galactic r-process:

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

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

Collapsars: galactic chemical evolution

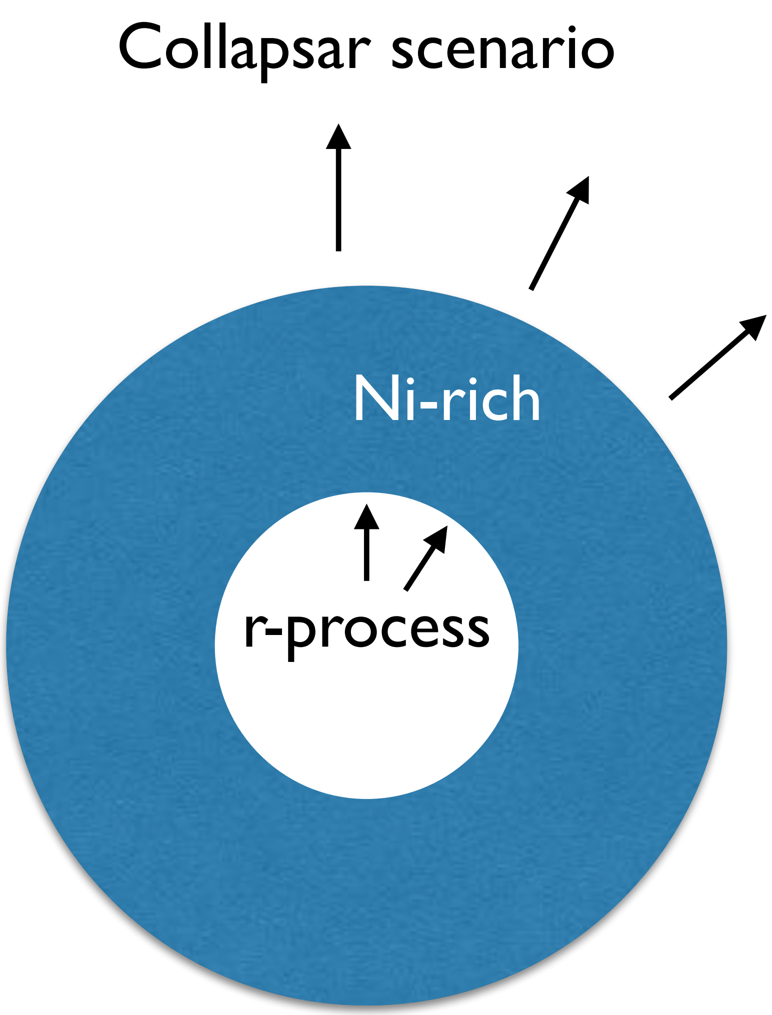
Siegel, Barnes, Metzger 2018

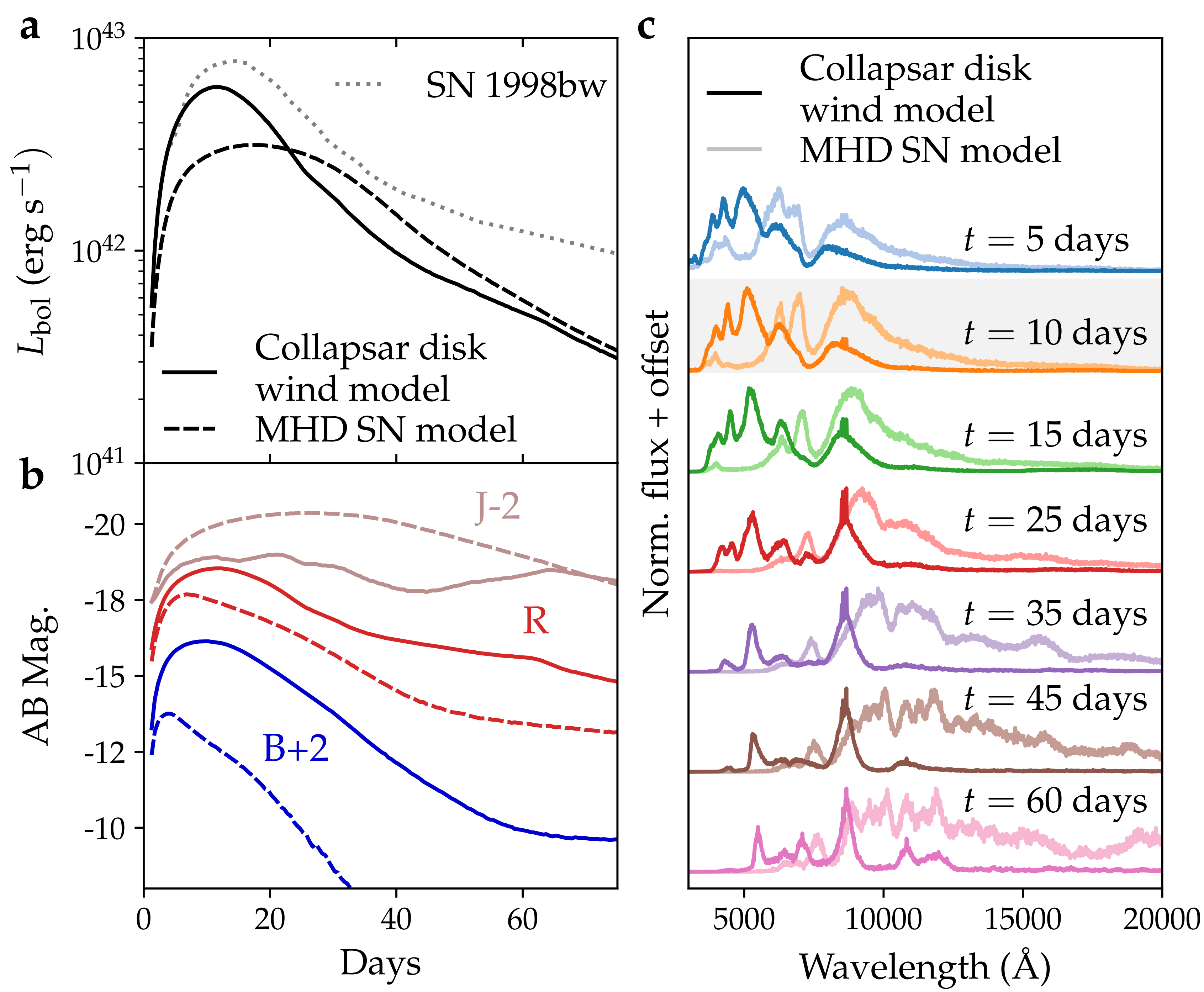


Dominant contribution to the Galactic r-process from collapsars dramatically improves evolution of r-process enrichment at high metallicity (MW disk)!

How can we test this observationally?

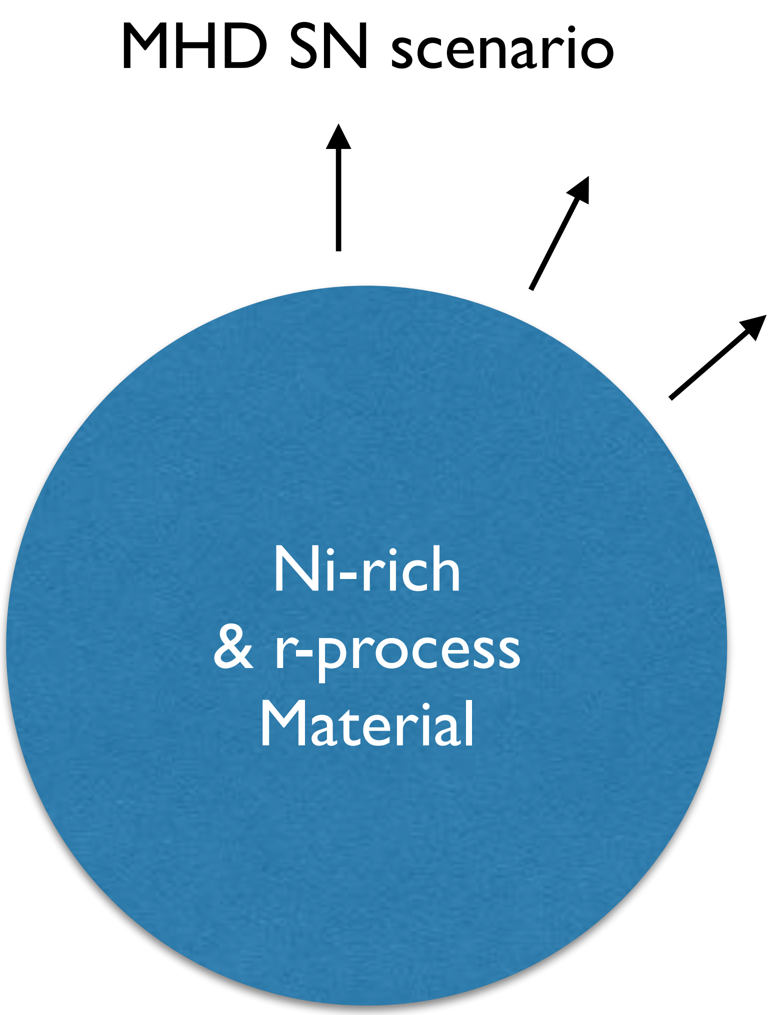
Siegel, Barnes, Metzger 2018



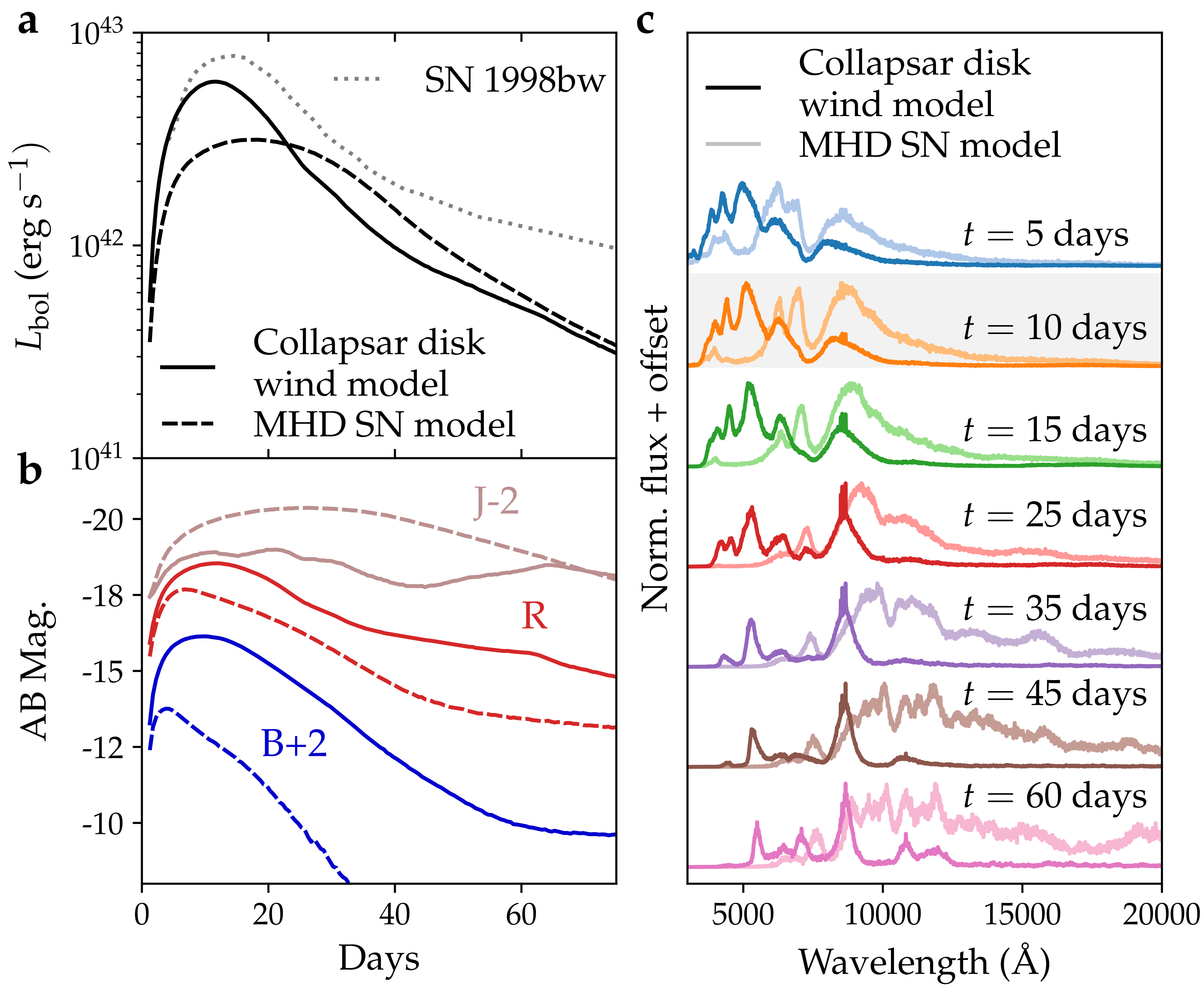


How can we test this observationally?

Siegel, Barnes, Metzger 2018



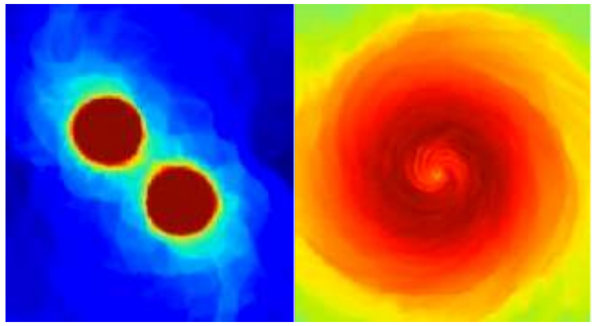
r-process material
increases opacity



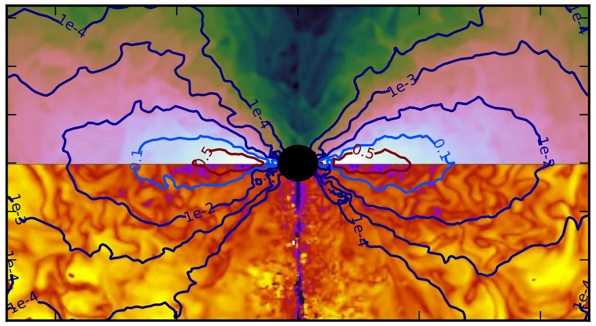
→ MHD supernovae likely rued out as significant heavy r-process source (consistent with recent 3D simulations Moesta+ 2018)

Conclusions

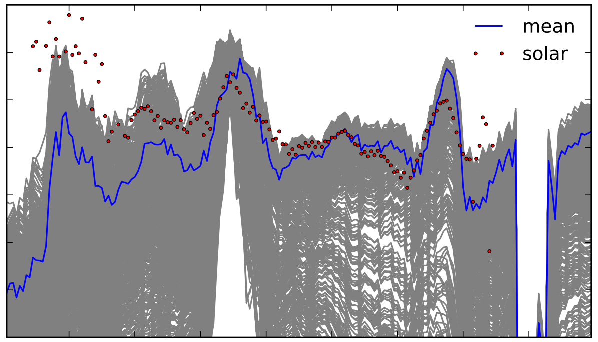
- GW170817: heavy elements & red kilonova most likely originate from outflows of post-merger accretion disk
  - → can produce entire range of r-process nuclei
  - → ubiquitous phenomenon



- NS mergers inconsistent with r-process enrichment of Milky Way disk (and challenged by UFDs)



- 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)
  - → naturally produce high levels of r-process enrichment at low metallicity
  - → don't require very short delay times and small kicks to explain enrichment in UFDs

Appendix