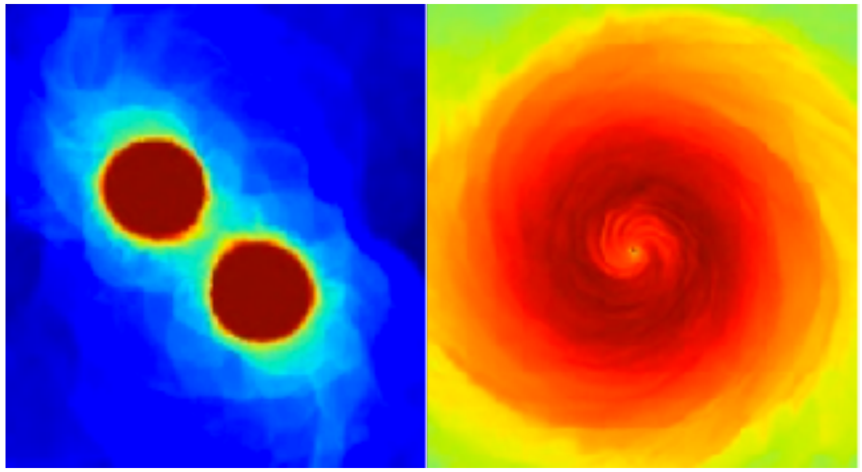
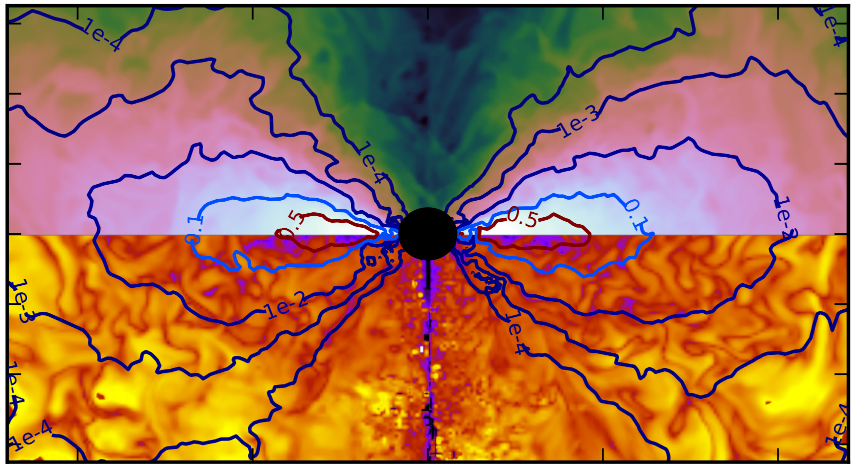
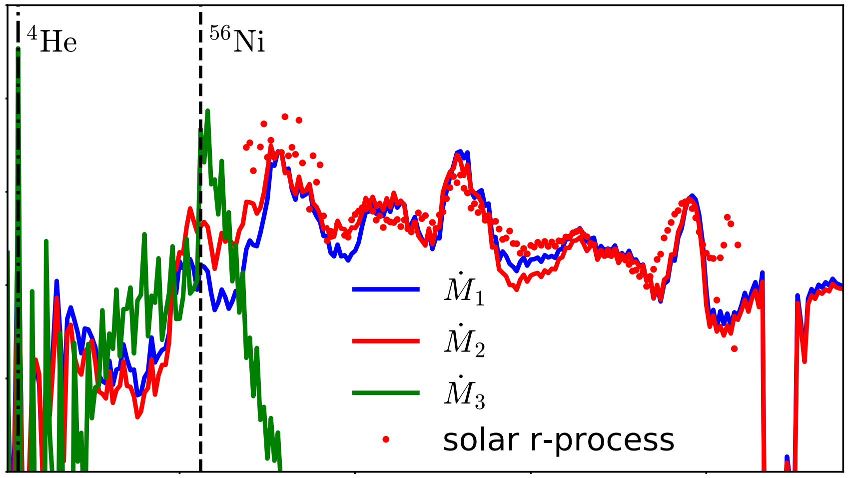
R-processes in Merging Neutron Stars (& beyond)







Daniel M. Siegel

Perimeter Institute for Theoretical Physics

University of Guelph

KITP conference *Merging Visions*, UC Santa Barbara, June 23-27, 2019

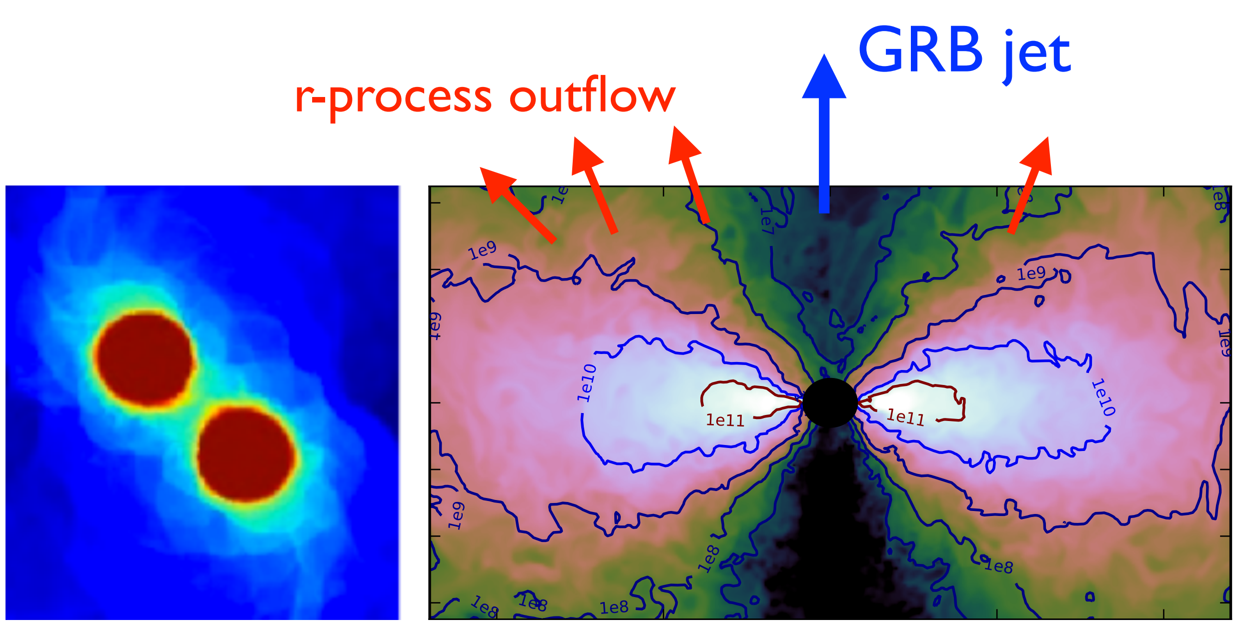
Conjecture:

Outflows from compact accretion disks synthesize most of the Galactic heavy r-process elements

NS mergers

short GRBs

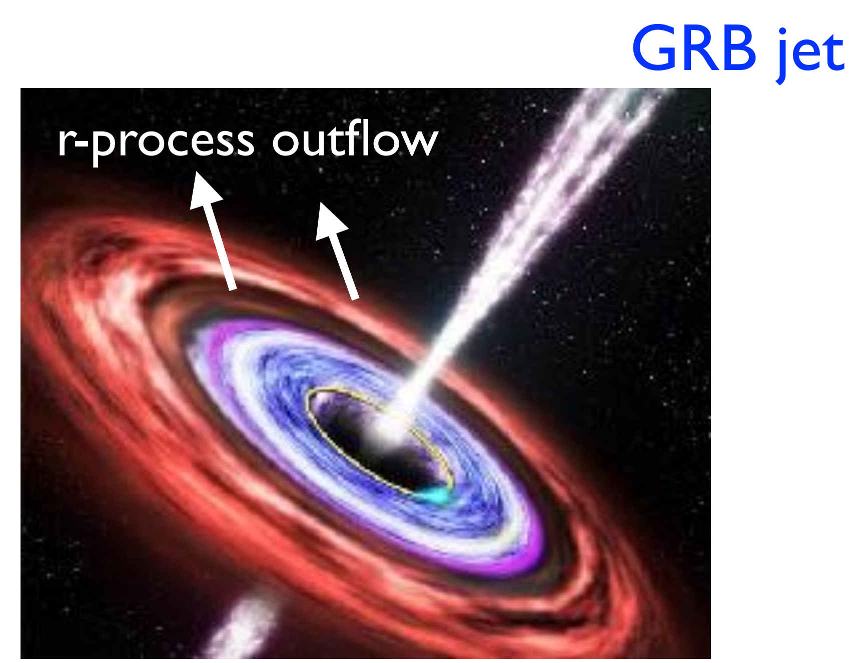
Siegel & Metzger 2017, PRL



Collapsars

long GRBs, GRB supernovae (SNe Type Ic-BL)

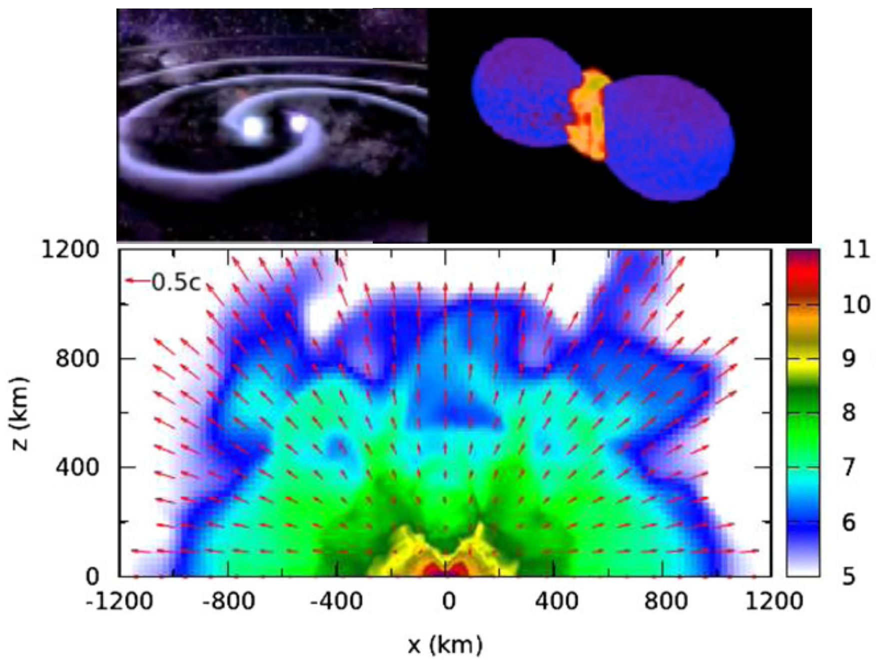
Siegel, Barnes, Metzger 2019, Nature



I.
r-process in neutron star mergers

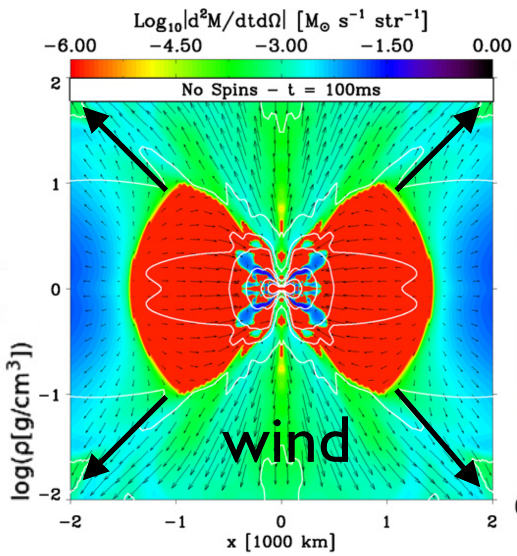
Sources of r-process ejecta in NS mergers

dynamical ejecta (~ms)

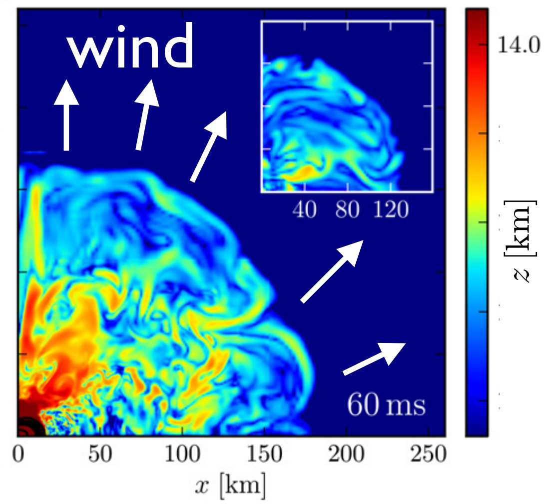


Hotokezaka+ 2013, Bauswein+ 2013

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

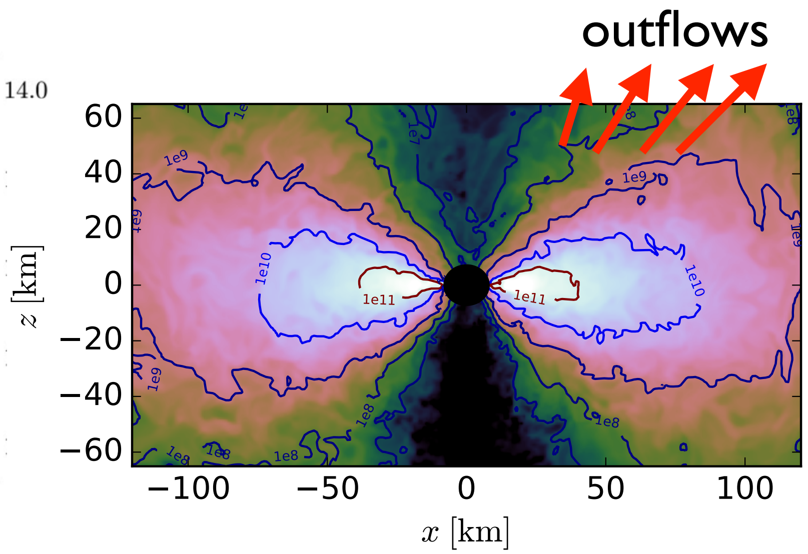


Dessart+ 2009



Siegel+ 2014
Ciolfi, Siegel+ 2017

accretion disk (~10ms-1s)



Fernandez & Metzger 2013
Just+ 2015
Siegel & Metzger 2017 PRL

tidal ejecta
shock-heated ejecta

(see Andreas' talk)

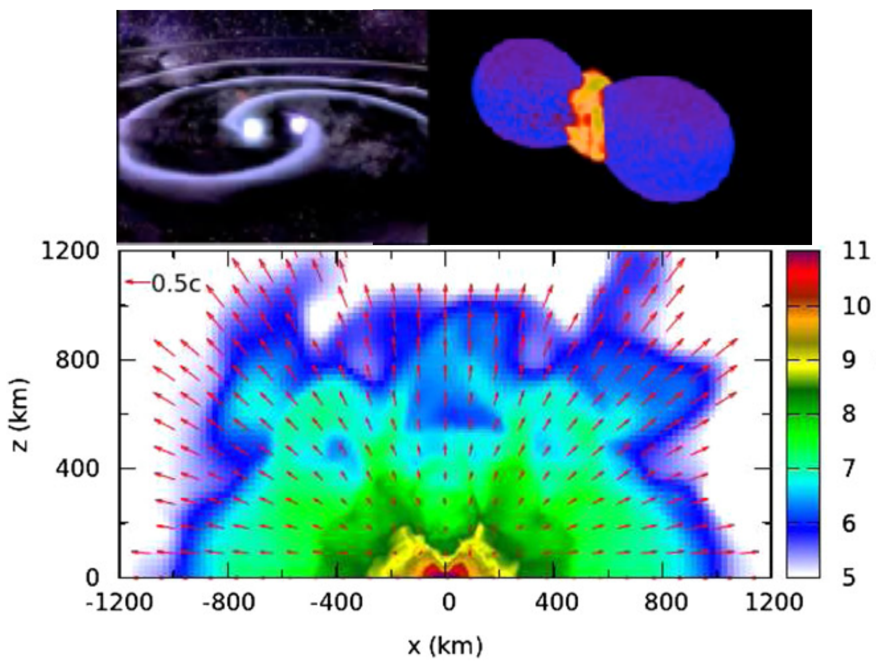
neutrino- and magnetically driven wind

(NS-NS mergers only!)

disk outflows

Sources of r-process ejecta in NS mergers

dynamical ejecta (~ms)



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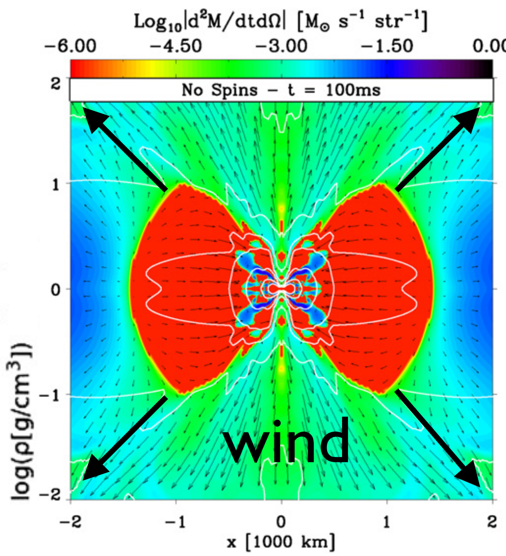

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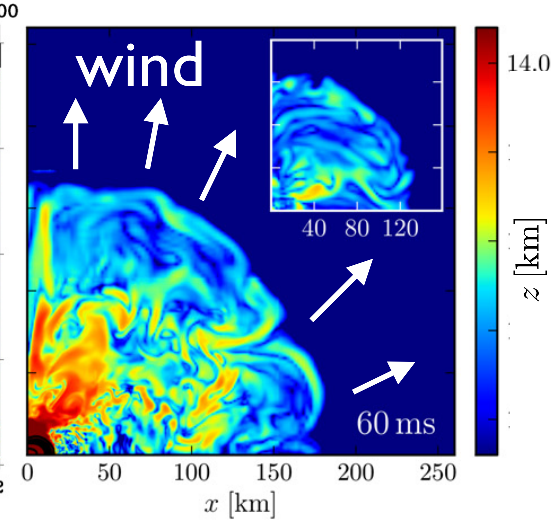

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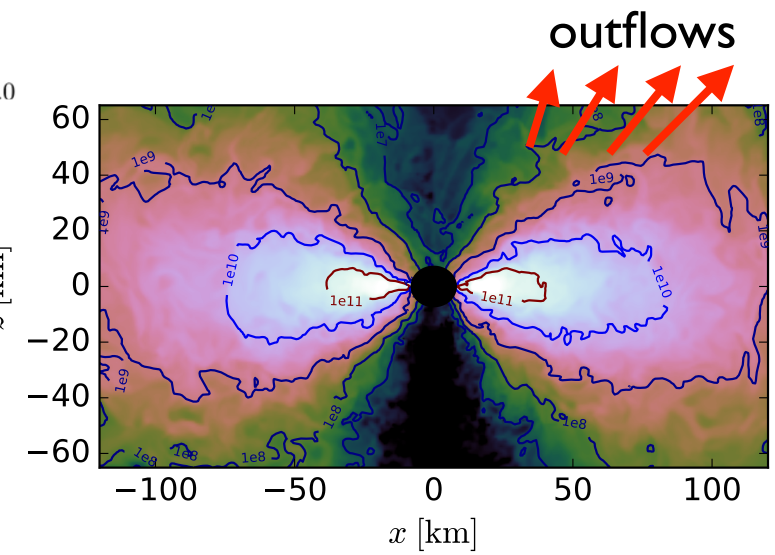

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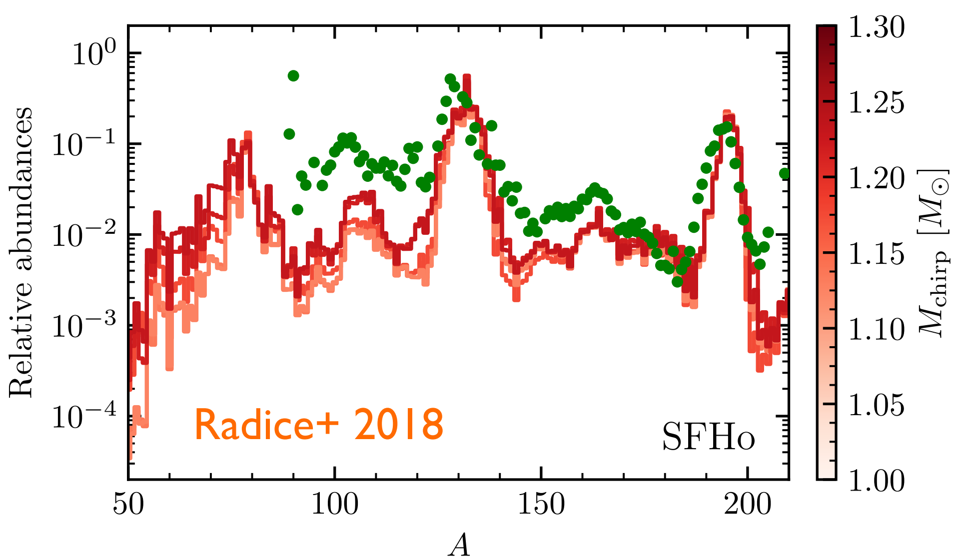
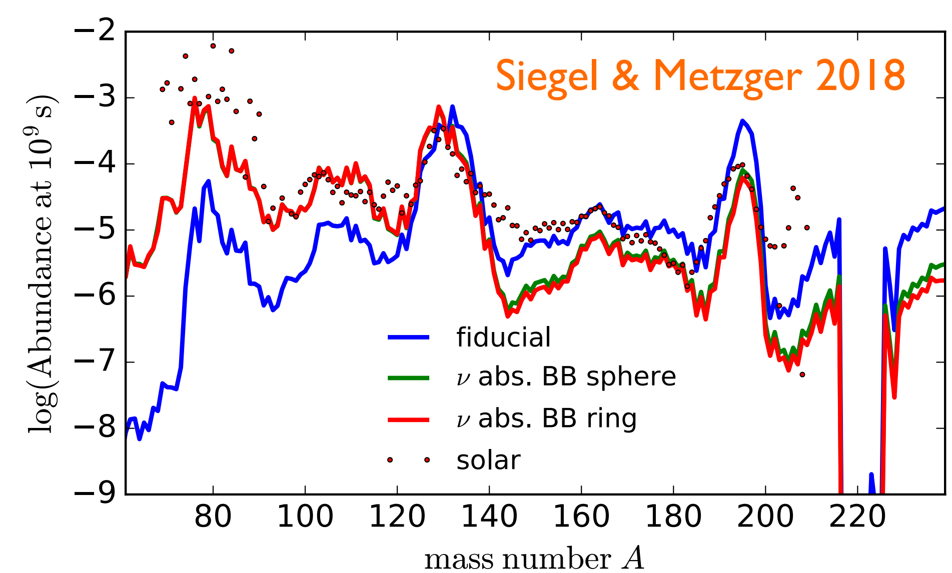


neutrino- and magnetically driven wind

(NS-NS mergers only!)

disk outflows



The GW170817 kilonova: direct r-process signature

- blue kilonova properties:

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

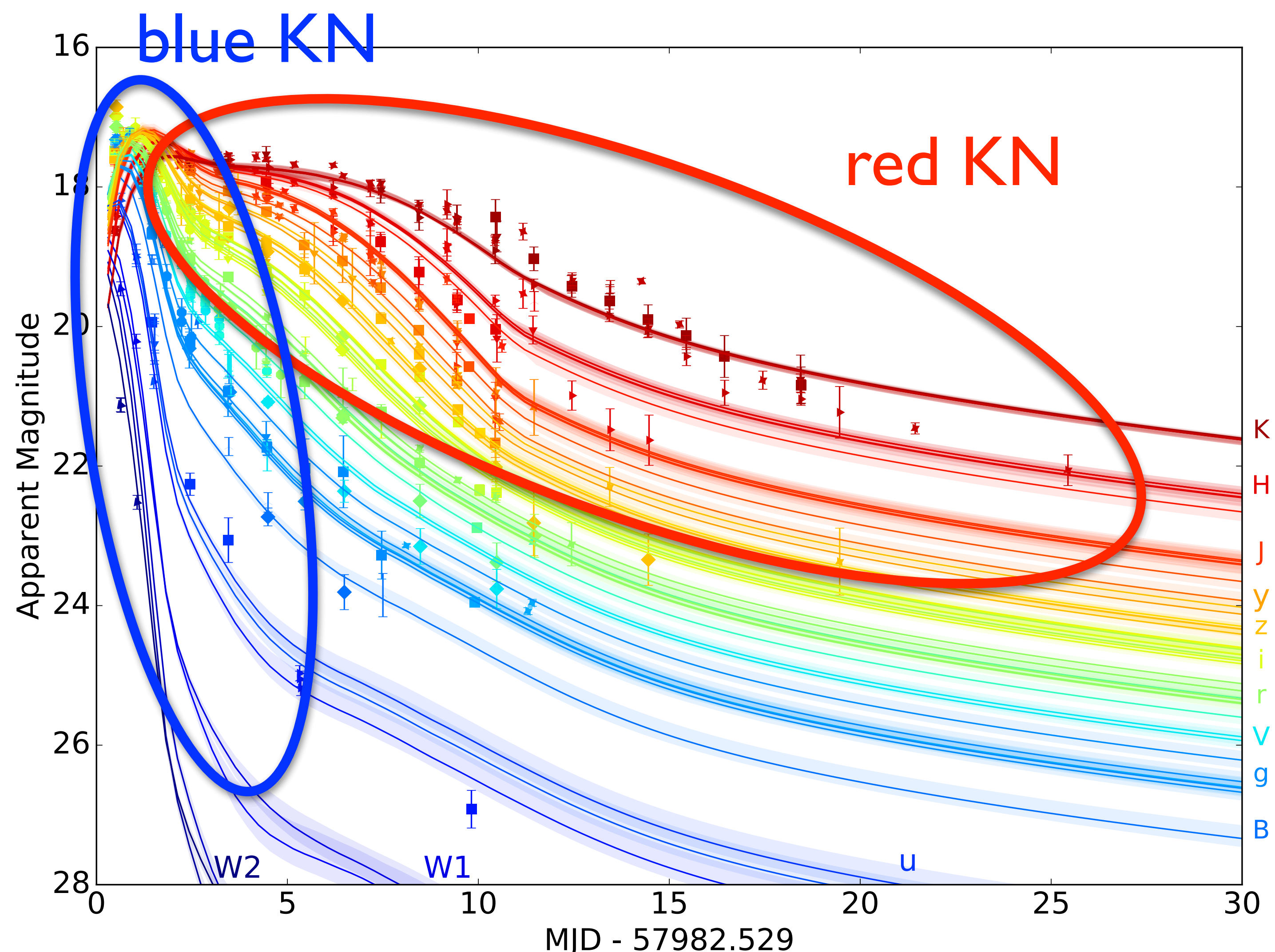
  Kilpatrick+ 2017
  Kasen+ 2017
  Nicholl+ 2017
  Villar+ 2017
  Coughlin+ 2018

- 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

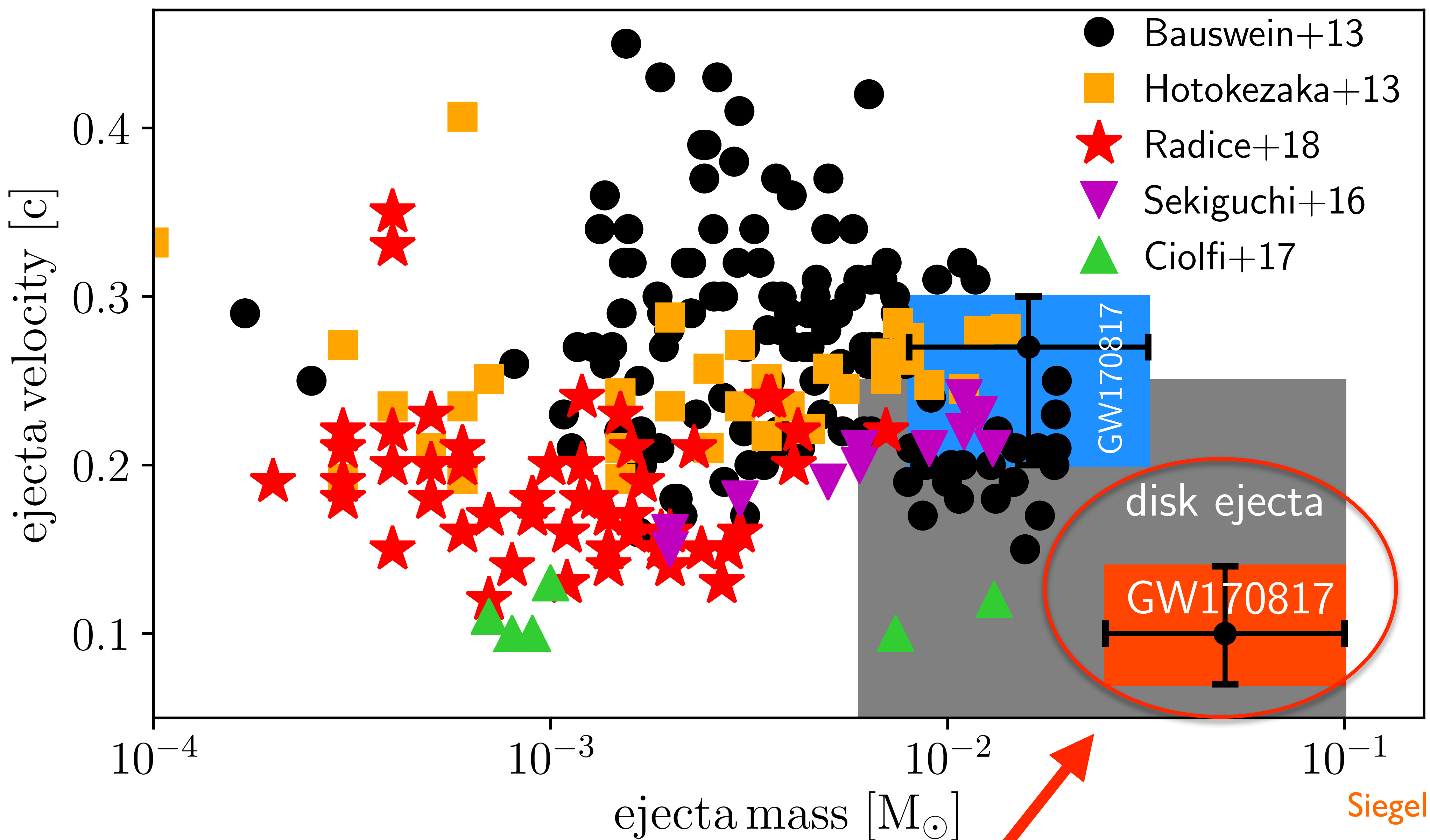
see also:
Wu+ 2019
Villar+ 2018
Kasliwal+ 2019

- 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 GW170817 kilonova: theory faces observations

BNS merger simulations: dynamical ejecta

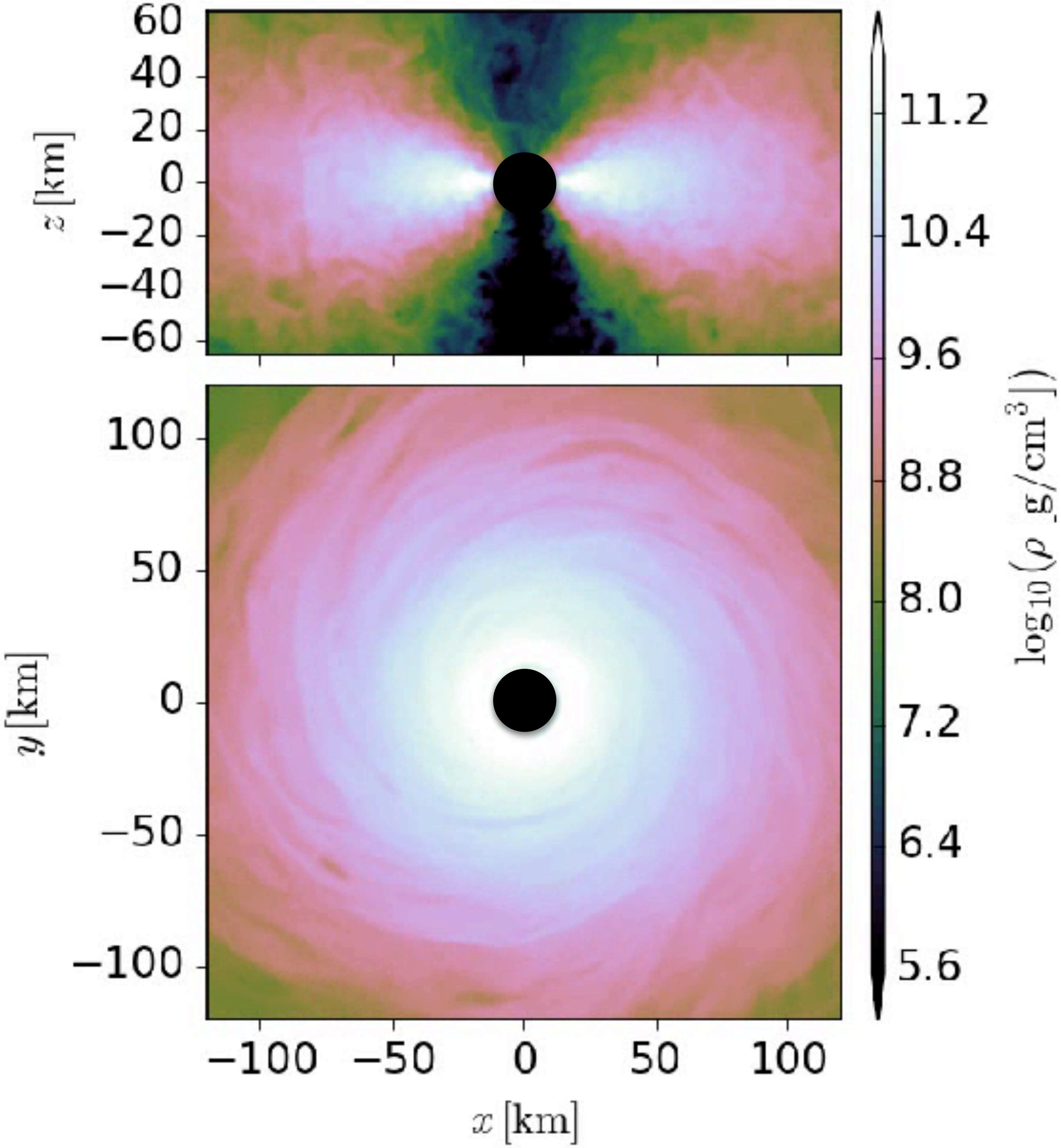


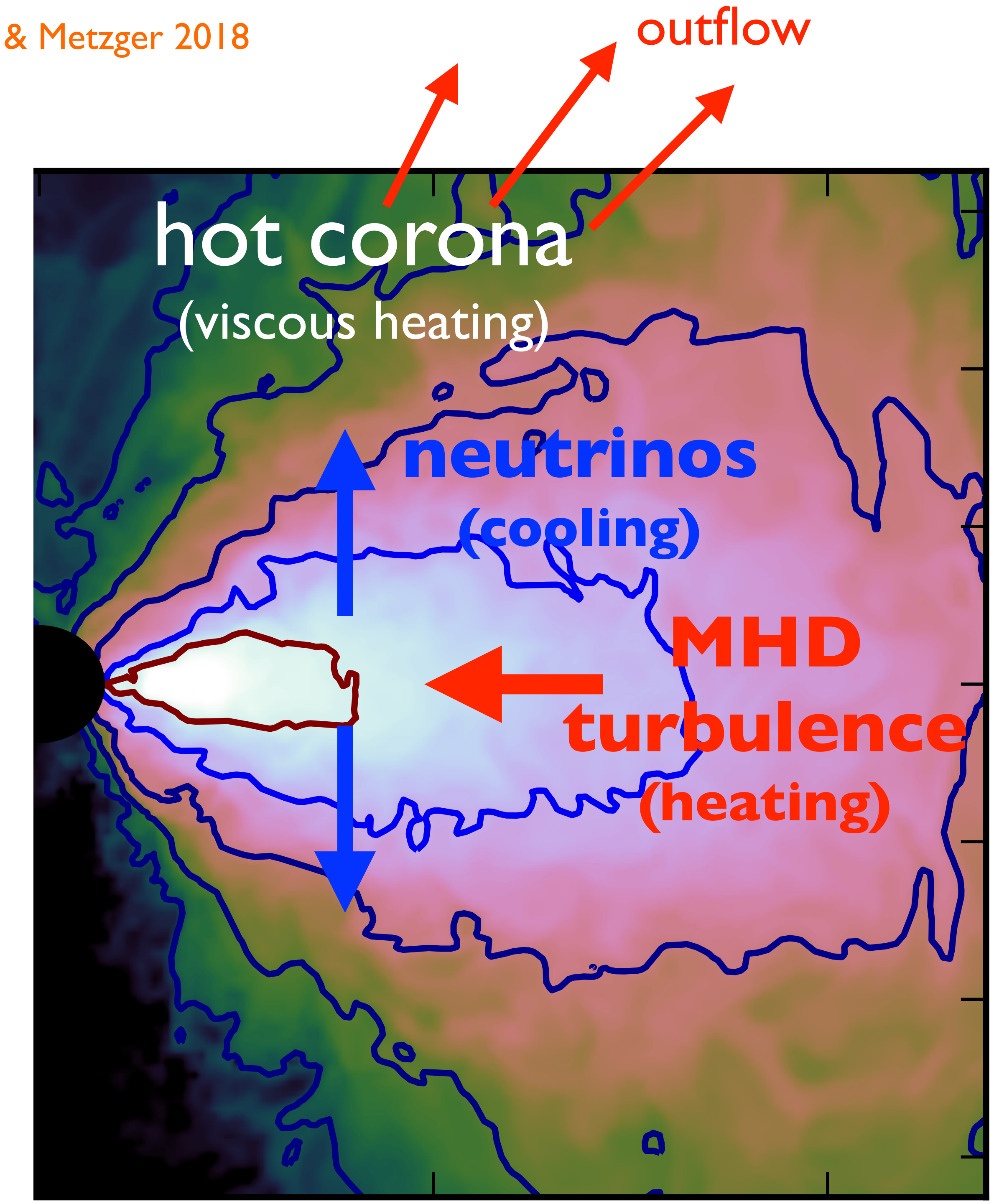
Siegel 2019

inconsistent with dynamical ejection
consistent with post-merger accretion disk

Post-merger accretion disk outflows

Siegel & Metzger 2017, PRL   Siegel & Metzger 2018



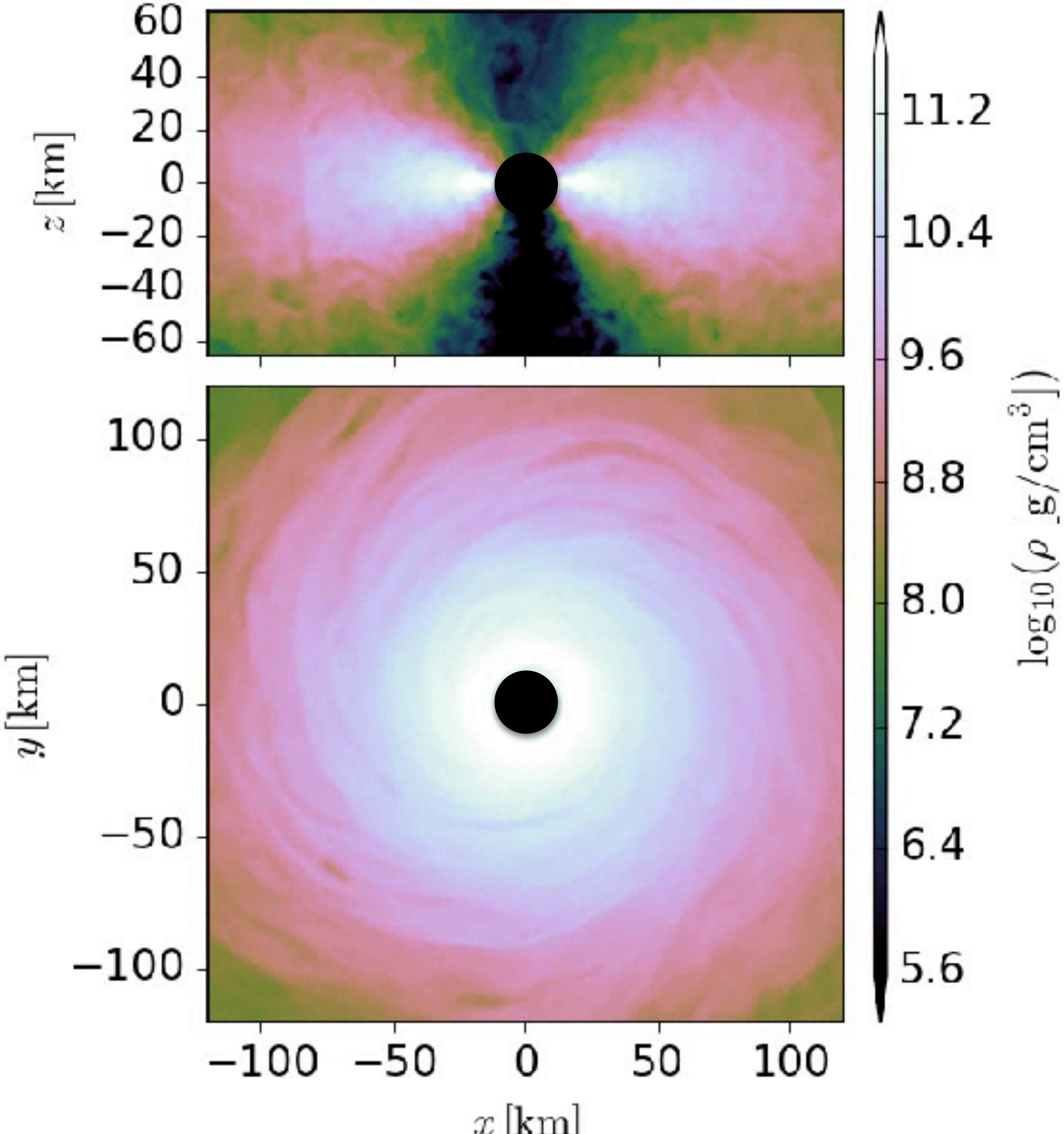


heating-cooling imbalance in corona
launches thermal wind

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

Post-merger accretion disk outflows

Siegel & Metzger 2017, PRL   Siegel & Metzger 2018



Similar wind properties:

Fernandez+ 2019
Miller+ 2019

Some variations in the (subdominant) blue component

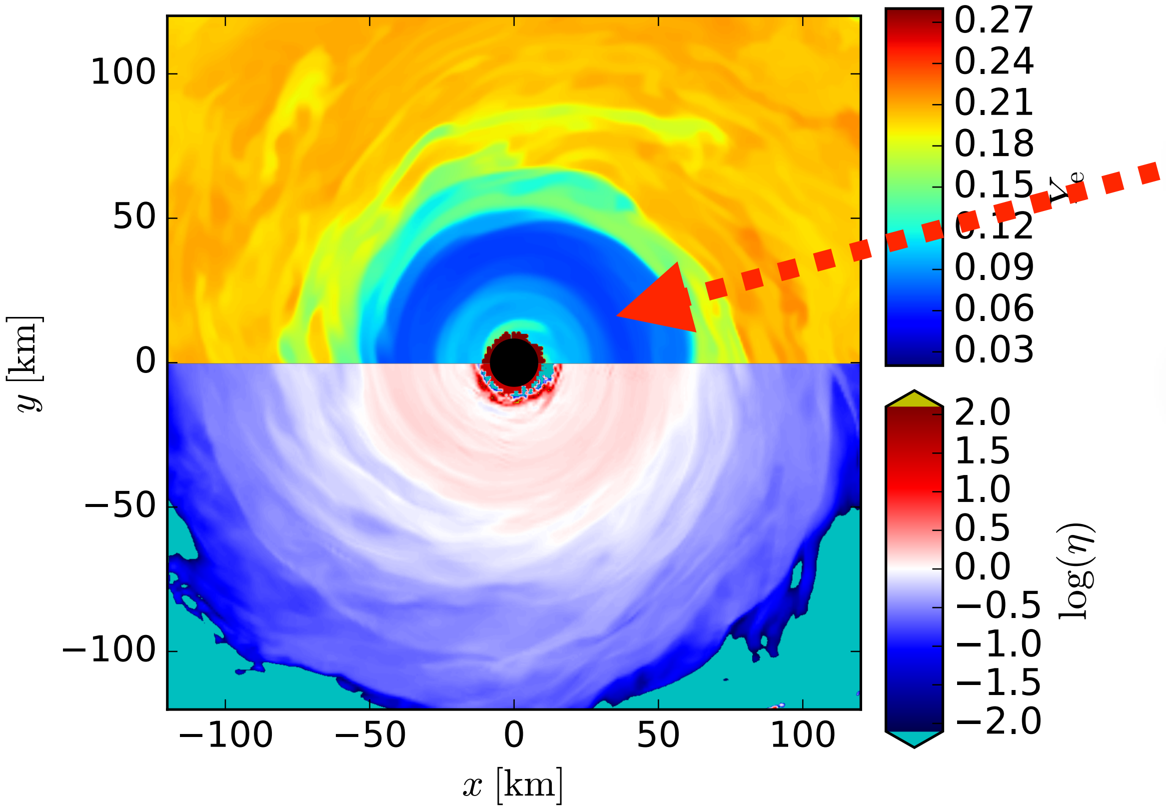
Previous 2D Newtonian alpha-disk simulations:

Fernandez & Metzger 2013
Just+ 2015

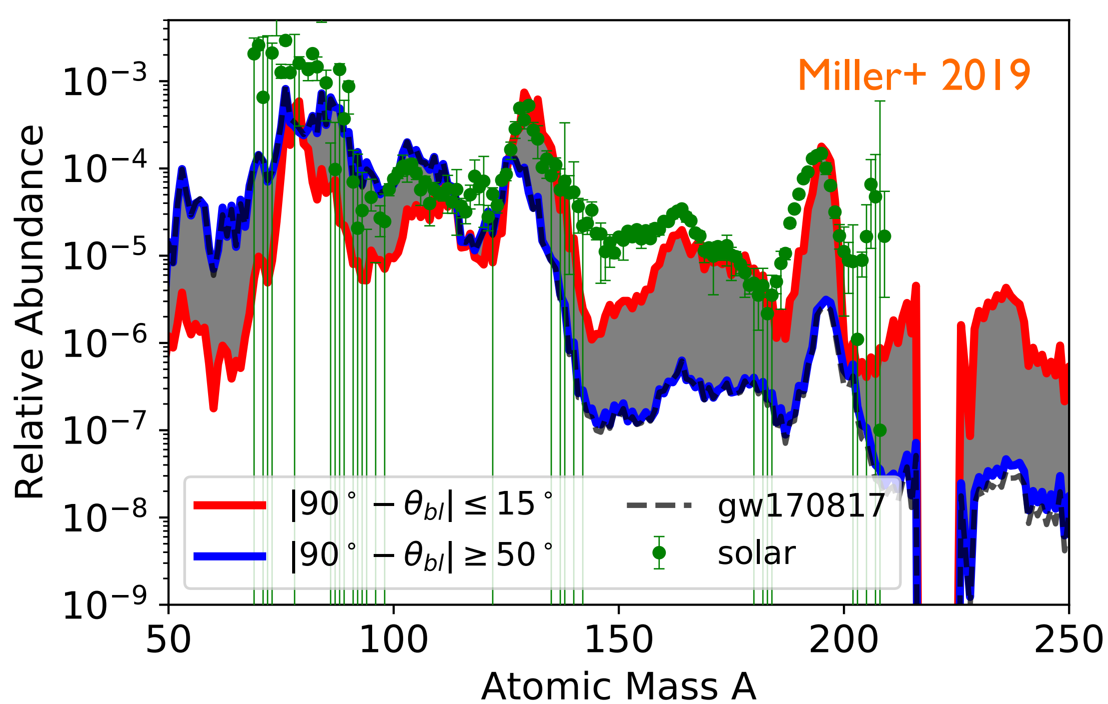
$t = 20.113\,\mathrm{ms}$

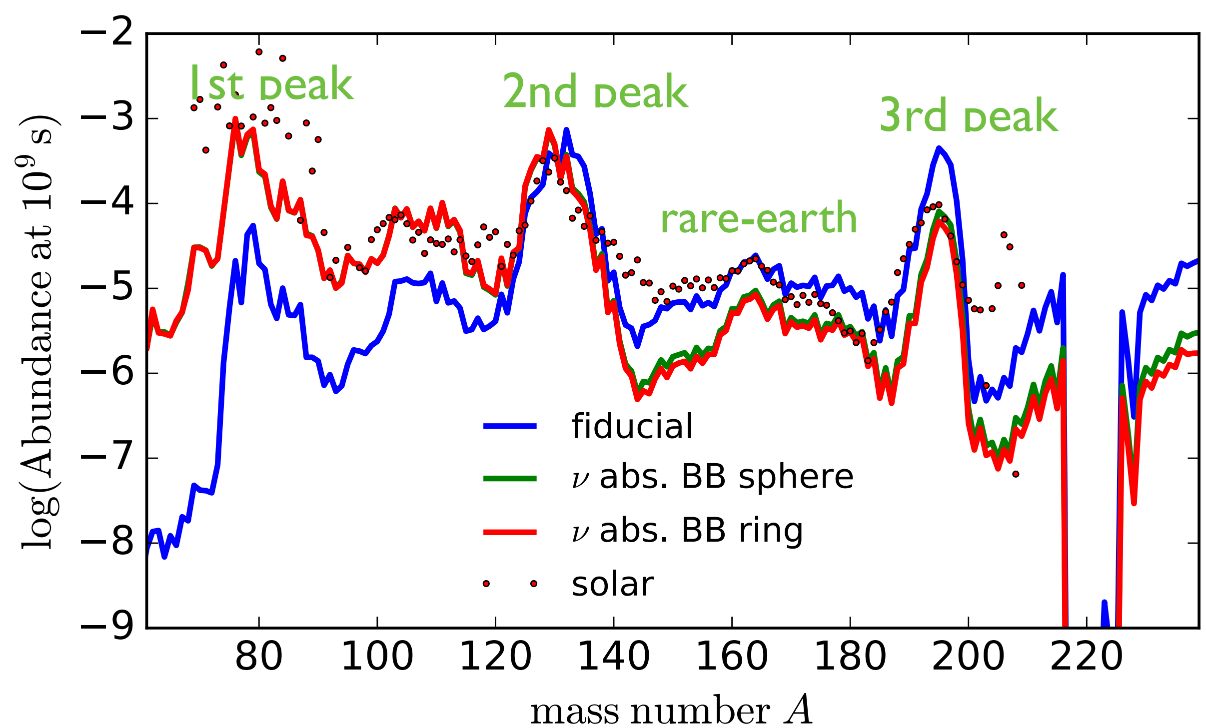
Disk outflows and the red kilonova

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

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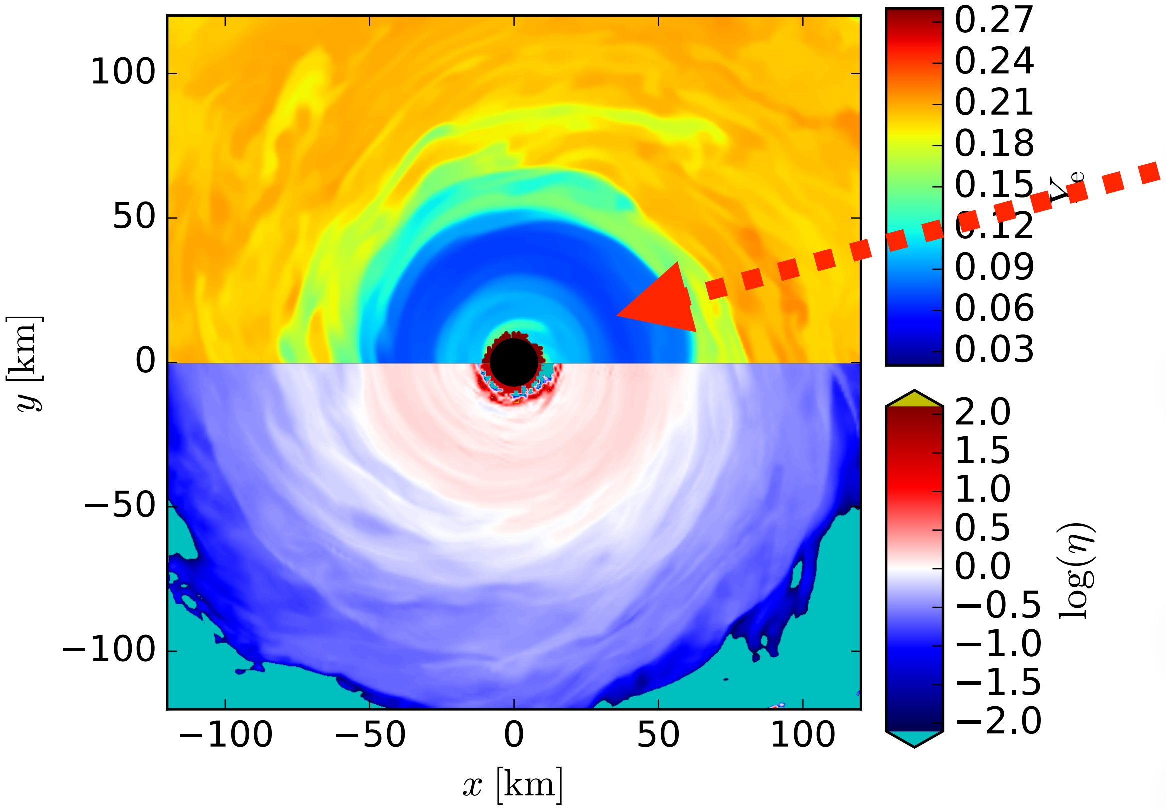

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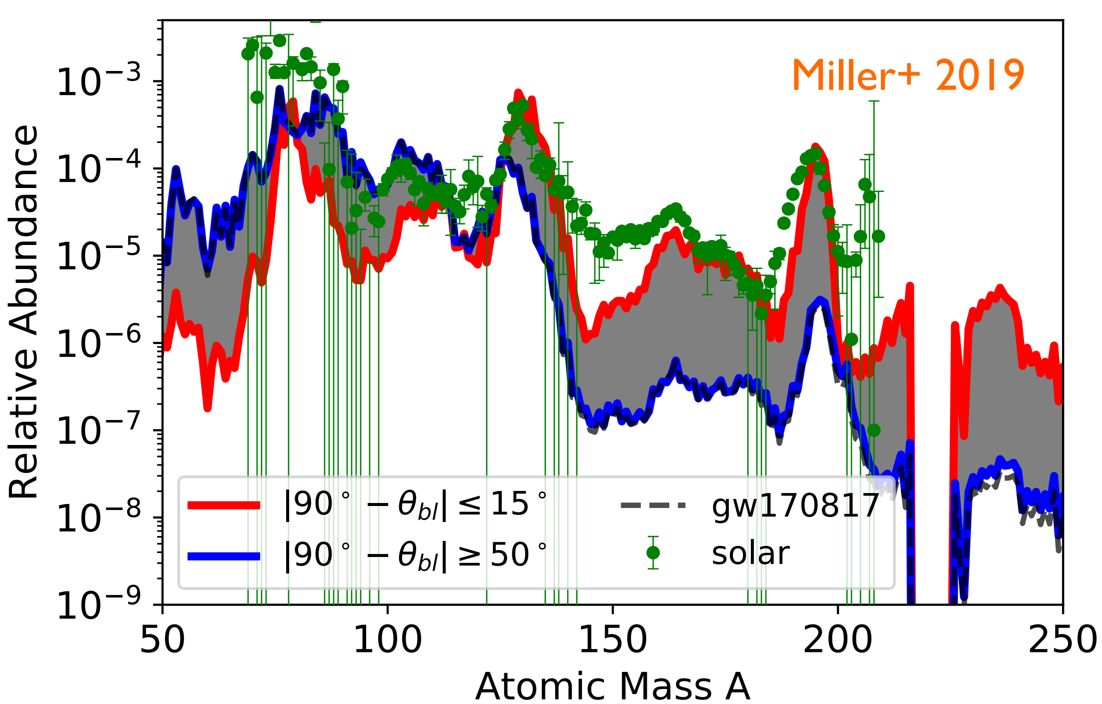
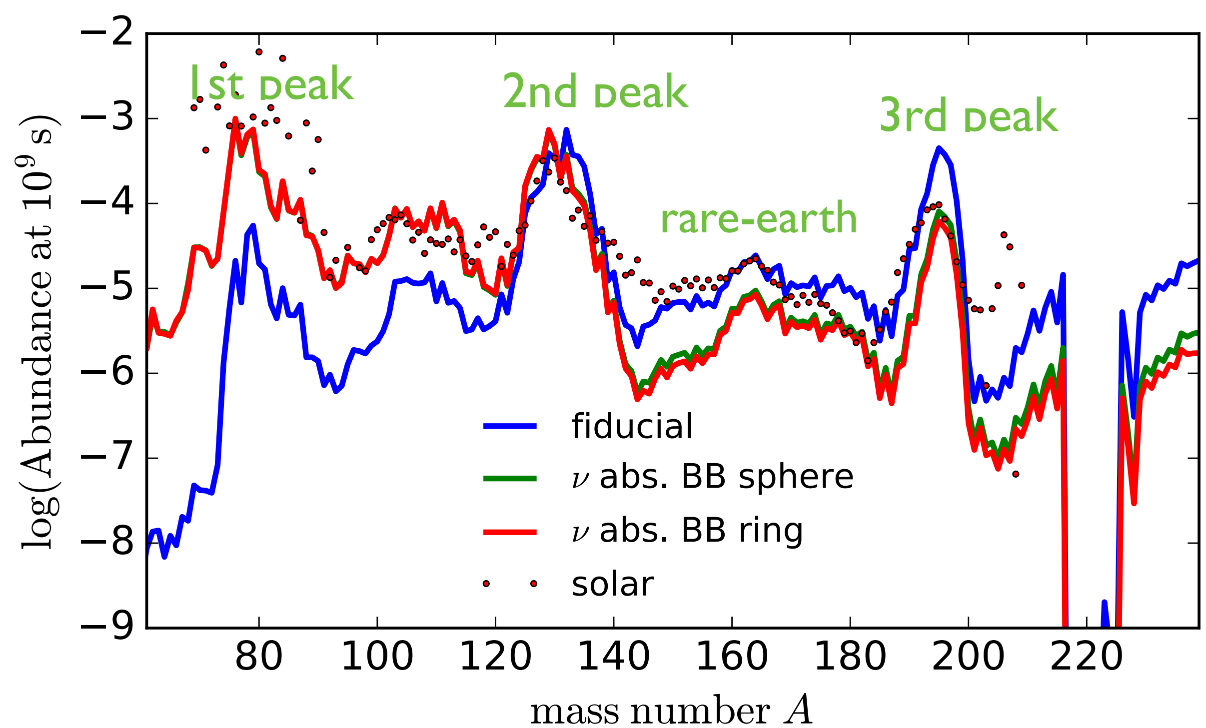
- Slow outflow velocities (~0.1c)
- Large amount of ejecta ($\gtrsim 10^{-2} M_\odot$) (30-40% of disk mass)





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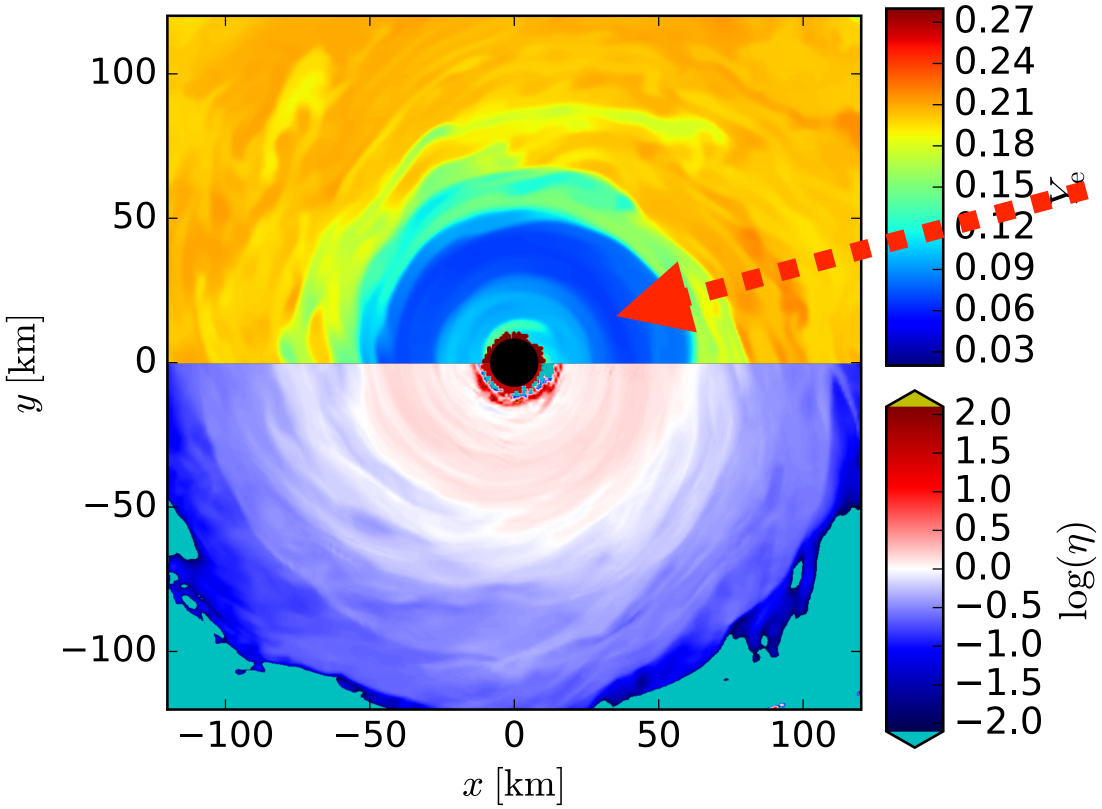

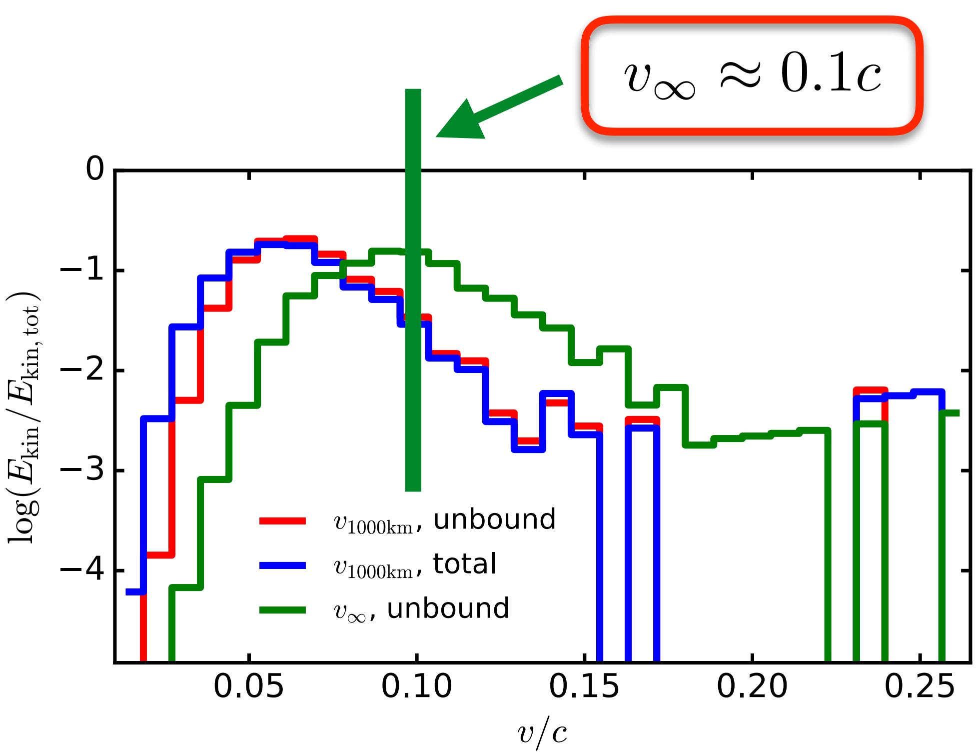

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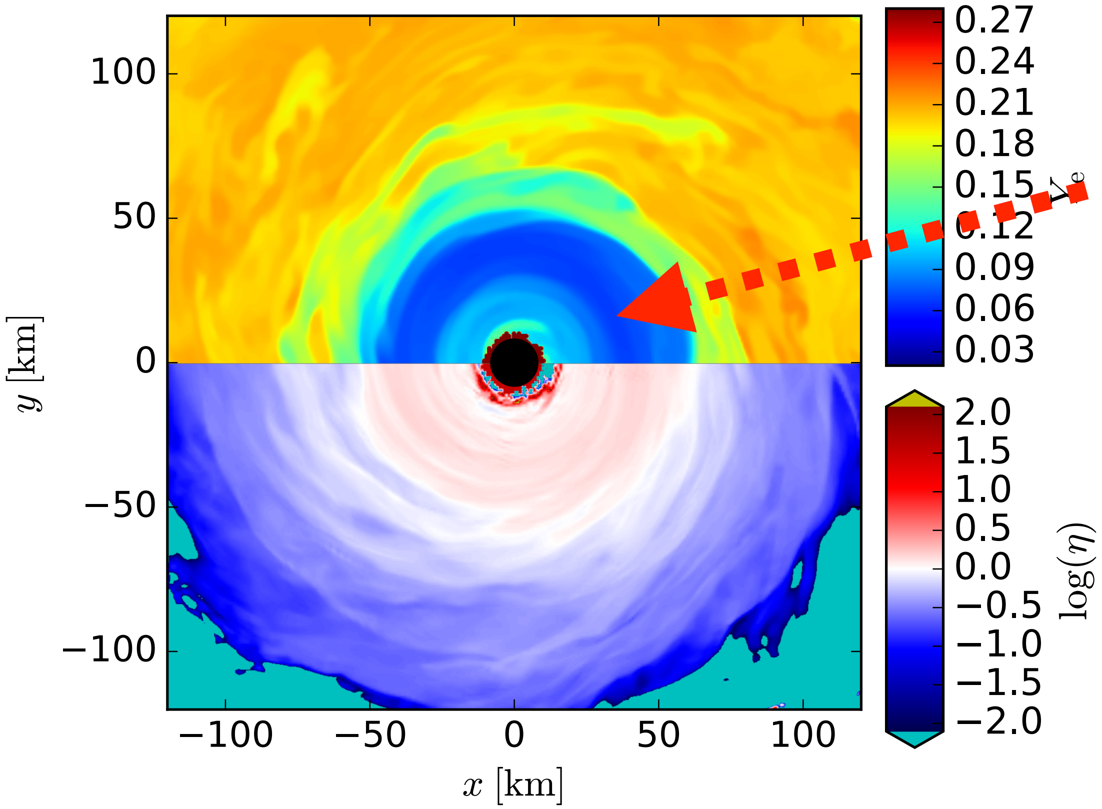

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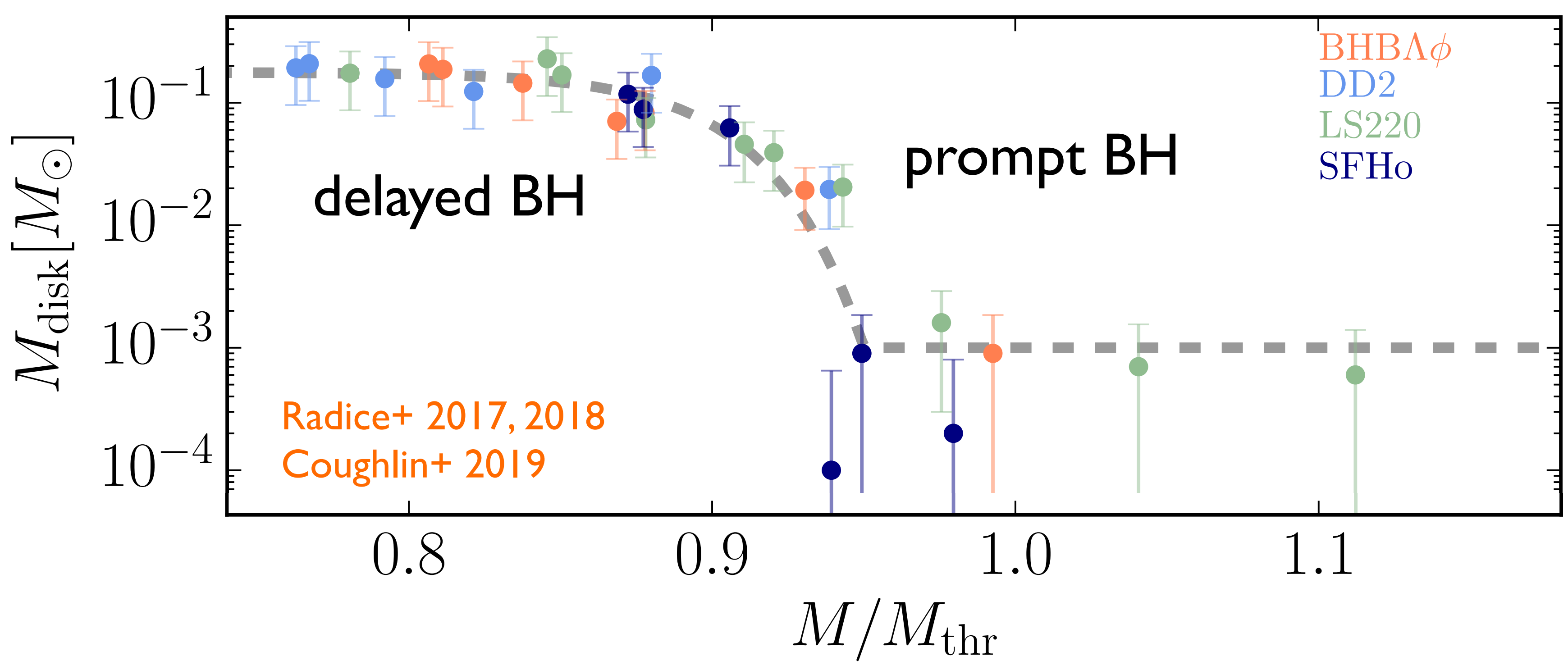
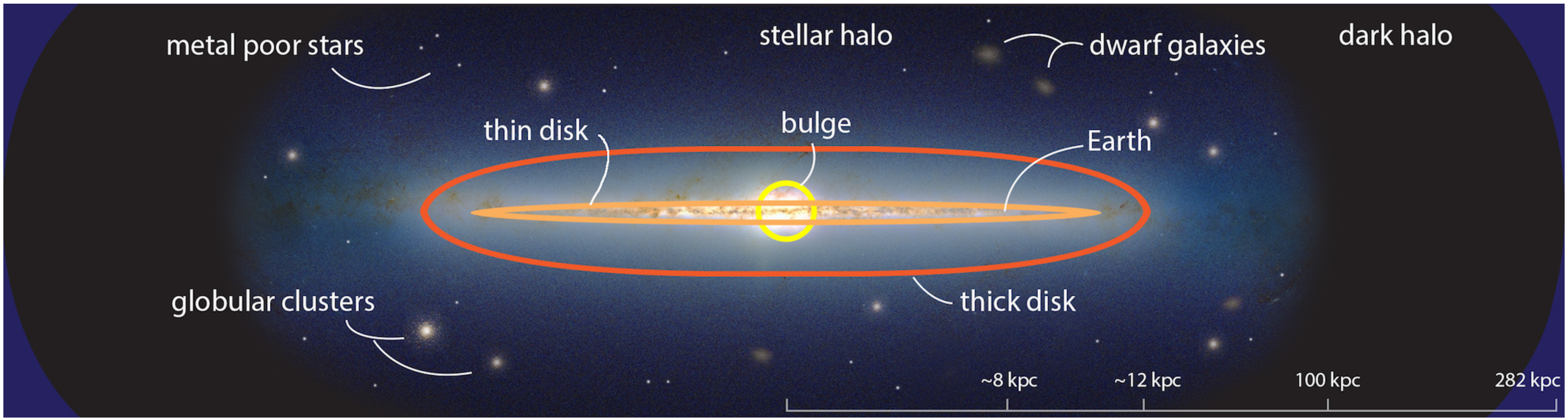
Delayed BH formation produces massive accretion disks



II.
Chemical evolution

Basic anatomy of the Milky Way



Frebel 2018

Challenges for r-process from NS mergers

- halo stars at very low metallicity
  - maybe need hierarchical assembly of halo from sub-halos
  - maybe need cross-pollution of sub-halos

Van de Voort+ 2015
Shen+ 2015
Wehmeyer+ 2015
Ishimaru+ 2015
Hirai+ 2015
Komiya+ 2016

- (UF) dwarf galaxies Ji+ 2016 Hansen+ 2017
  - need extremely low kick velocities <10 km/s, short merger times < 1Gyr
    Beniamini+ 2016 (but very sensitive on initial separation < Rsun)
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- globular clusters
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  - or need 2nd epoch of star formation from AGB winds, short merger times <100 Myr
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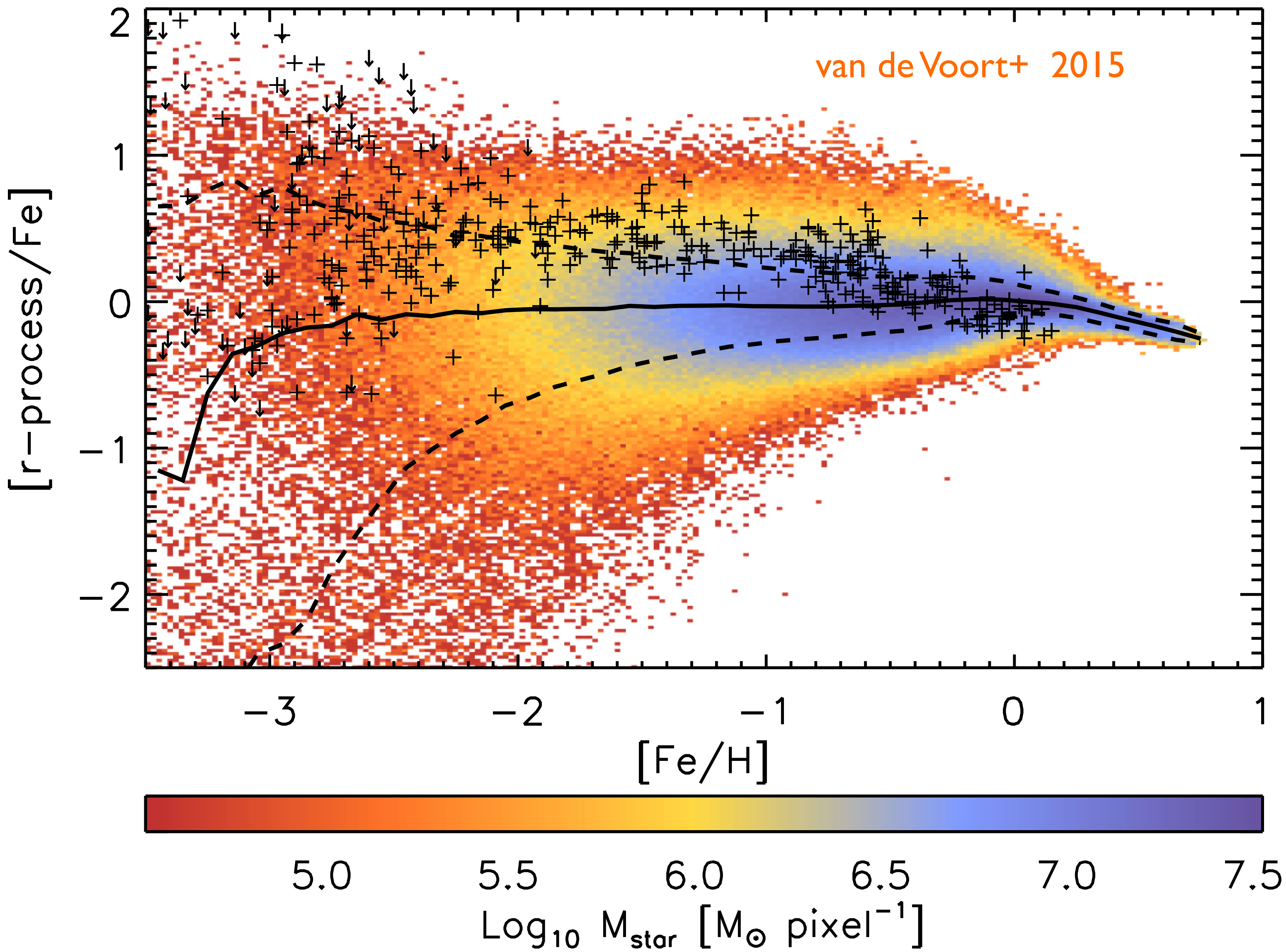

But see also:

Shen+ 2015

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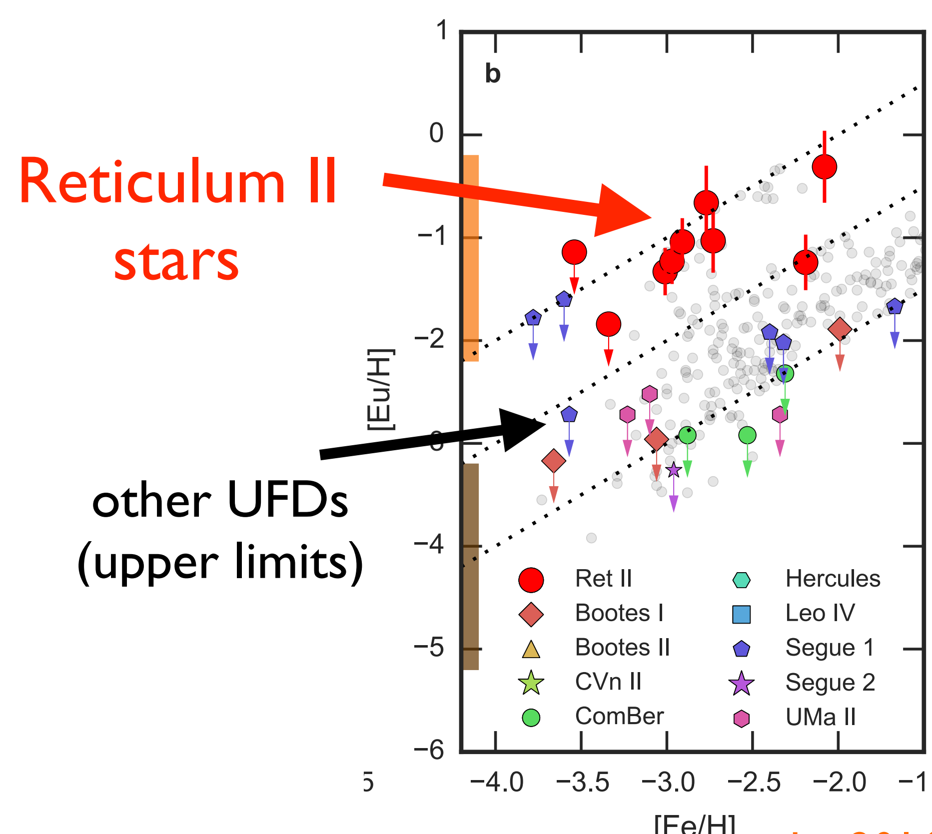

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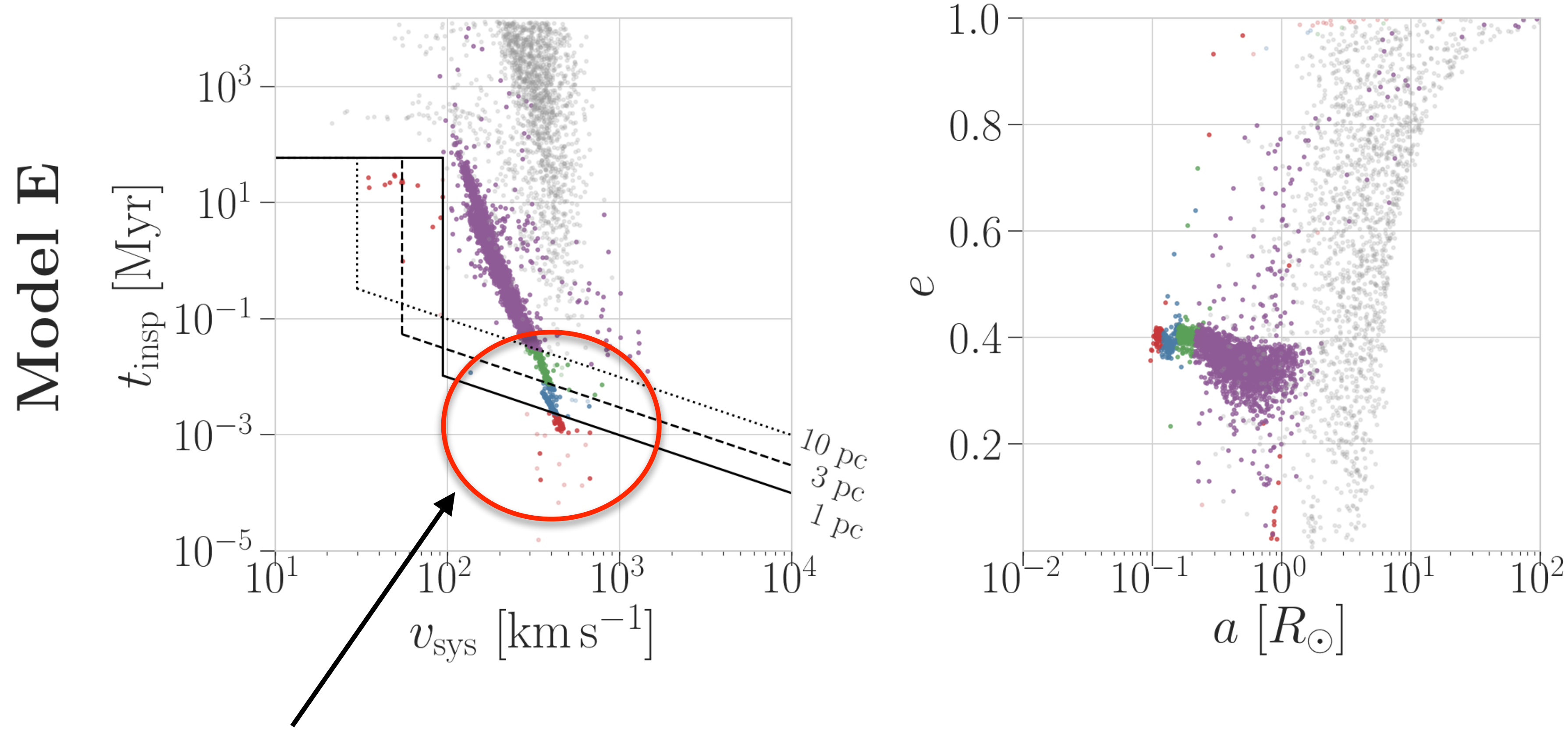
Bekki & Tsujimoto 2017
Zevin+ 2019

r-process from NS mergers in globular clusters

Zevin, Kremer, Siegel+ 2019



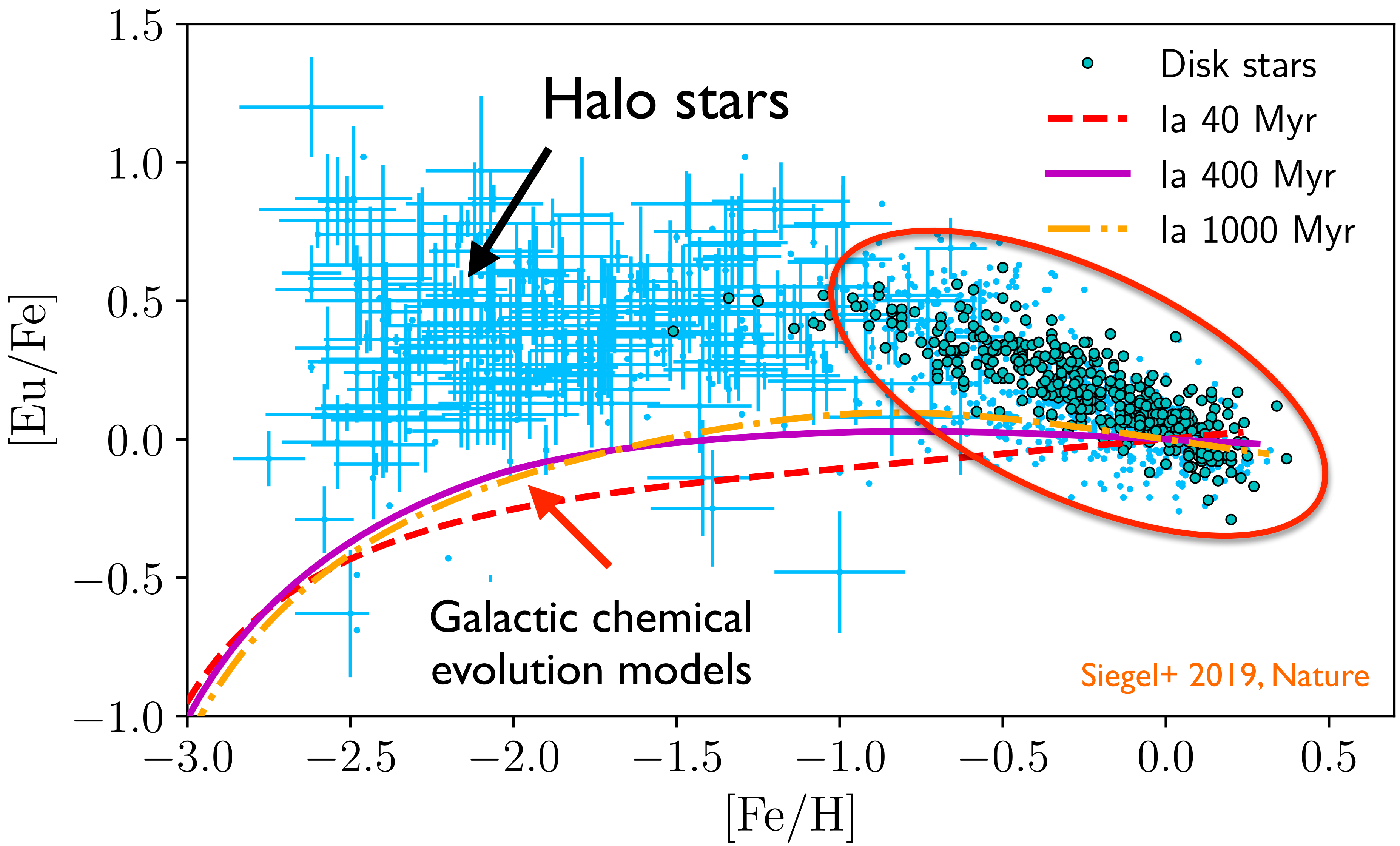
enrichment BNS candidates

find ~1 enrichment candidates ('prompt' NS mergers within viral radius) in ~2-25% of GCs, potentially consistent with observations of internal r-process spread in GCs (Roederer 2011)

BUT: need star forming gas at ~40-50 Myr after initial burst of star formation. Where should it come from?!

Challenges for r-process from NS mergers

- halo stars at
  - need hierarc
  - need cross-|
- (UF) dwarf g
  - need extren
    Beniamini+ 201
  - need surviva
- globular clus
  - need extren
  - or need 2nd



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

Challenges for r-process from NS mergers

• halo
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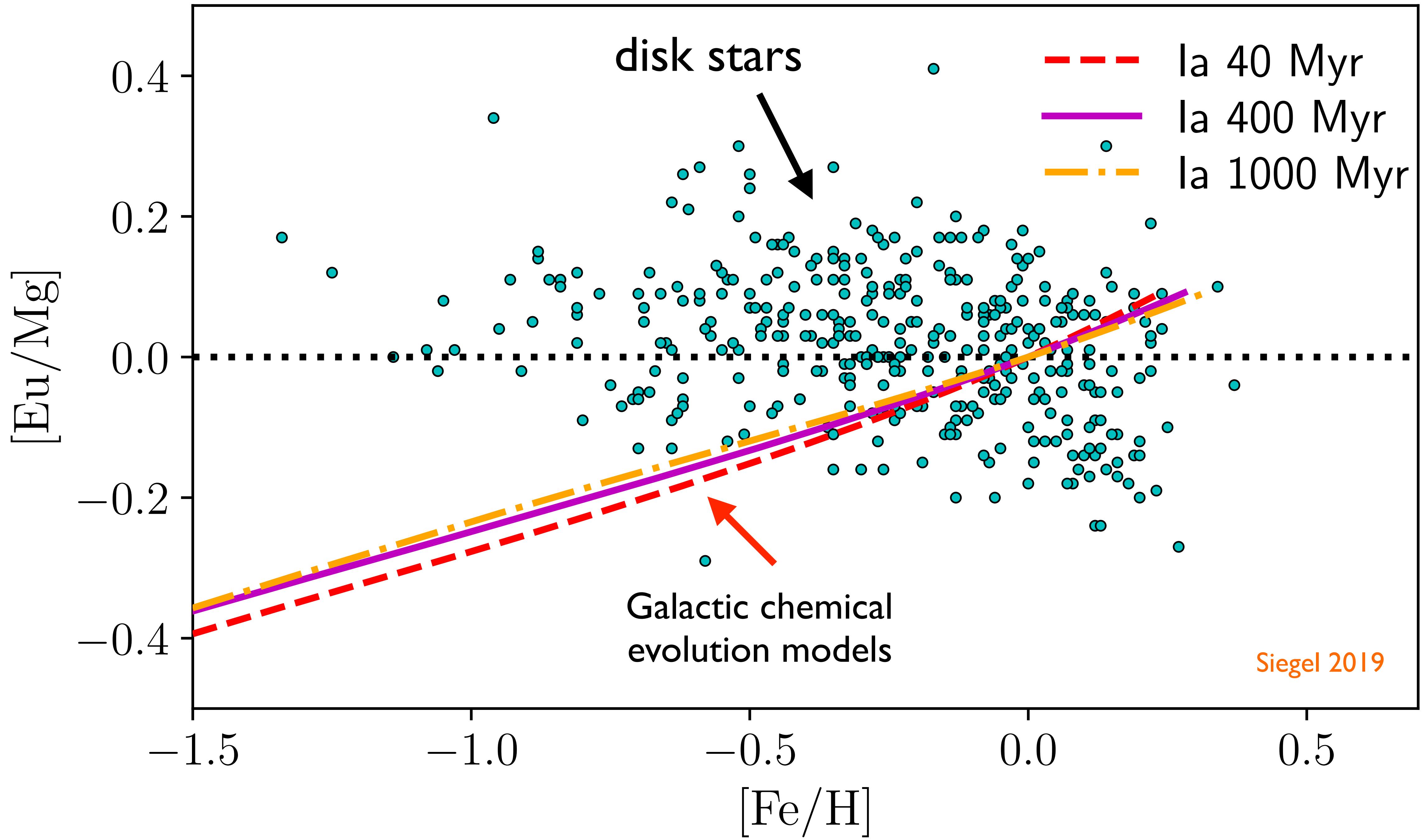

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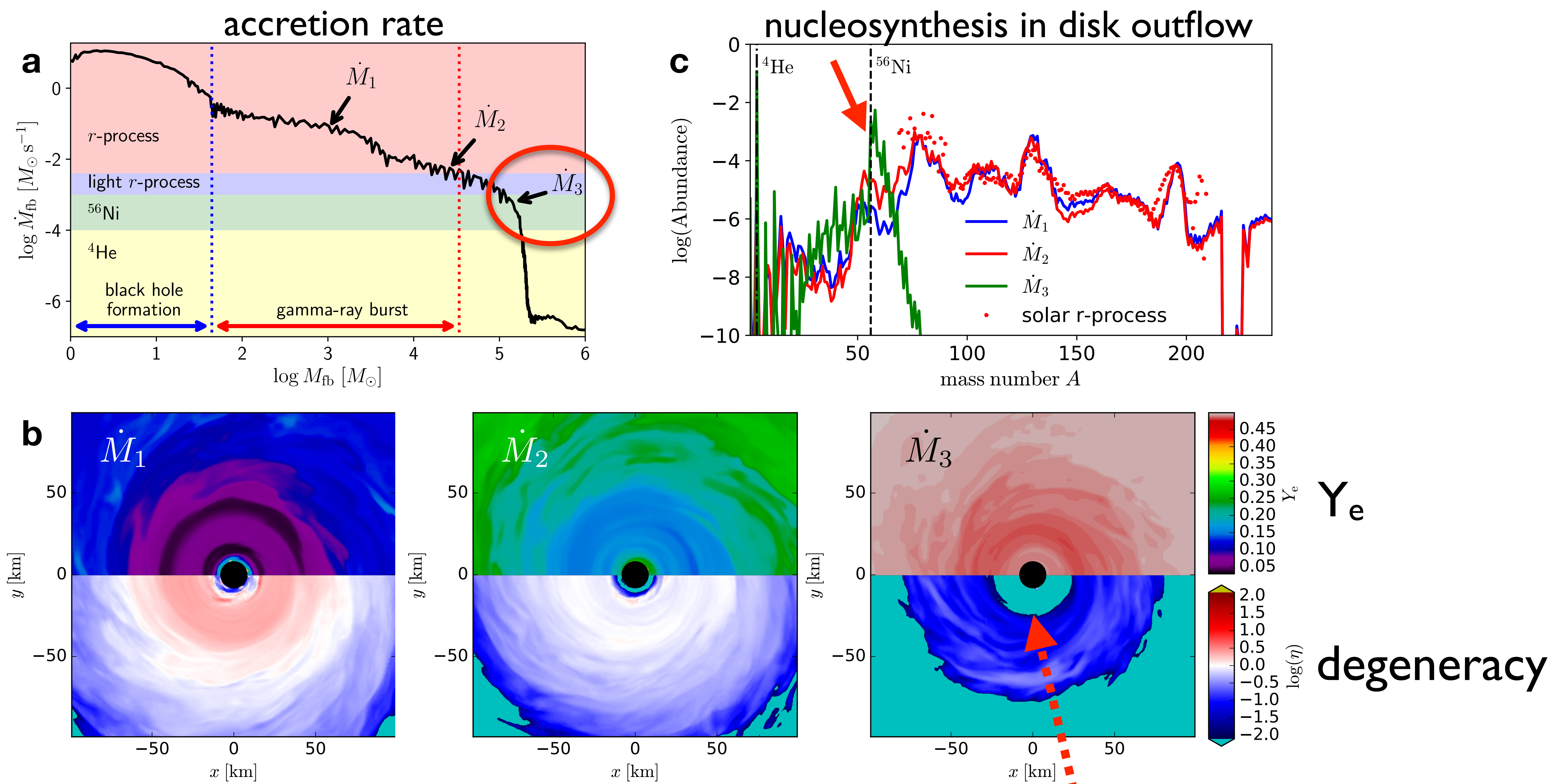
III.
Collapsars

r-process in collapsars

Siegel, Barnes, Metzger 2019, Nature



Neutron-richness:

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

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

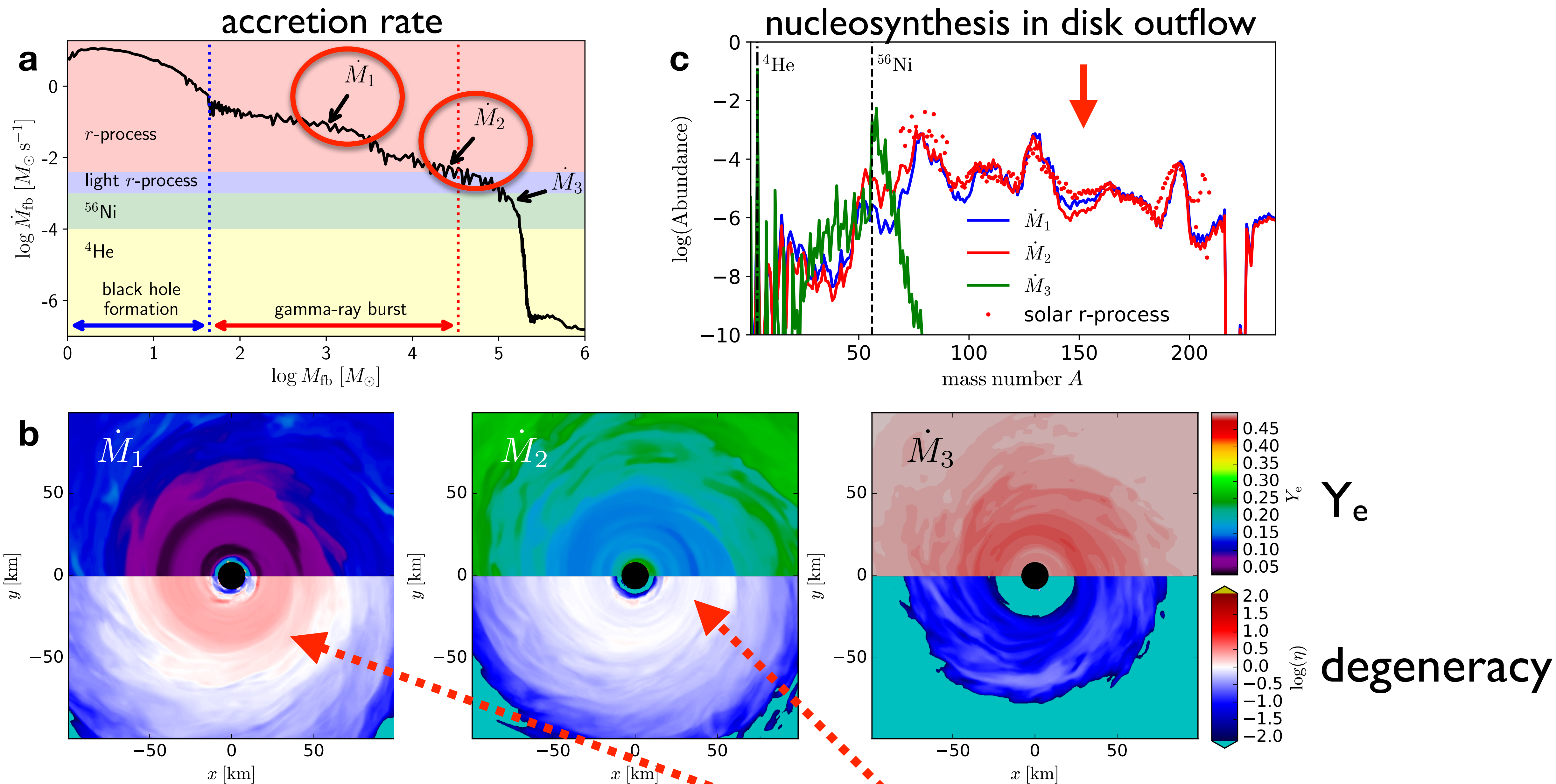
Low disk densities (low $\dot{M}$):

$Y_e \sim 0.5$

outflows produce ^{56}Ni

r-process in collapsars

Siegel, Barnes, Metzger 2019, Nature



Neutron-richness:

e^+ creation

$\gamma \to e^+ + e^-$

suppressed!

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

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

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 2019, Nature

1) Purely empirically (long vs. short GRBs):

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

2) From Galactic r-process content

assume collapsars as main contribution to Galactic r-process:

$$m_{\rm r,coll} \sim X_{\rm r} f_Z^{-1} \frac{\dot{\rho}_{\rm SF}(z=0) f_{\rm b}}{R_{\rm LGRB}(z=0)} \approx 0.08 - 0.3 M_\odot \left(\frac{f_Z}{0.25}\right)^{-1} \left(\frac{X_{\rm r}}{4\times10^{-7}}\right) \left(\frac{f_b}{5\times10^{-3}}\right)$$

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

3) Purely theoretically (simulations & pre-supernova models)

per event r-process yield as probed by simulations: $\text{few} \times 10^{-2} - 1\, M_\odot$

→ consistent with 1) and 2)

Collapsars vs. challenges for NS mergers (?)

- halo stars at very low metallicity
  - maybe need hierarchical assembly of halo from sub-halos
  - maybe need cross-pollution of sub-halos

but: potential concern if single SN, closed system
Macias & Ramirez-Ruiz 2019

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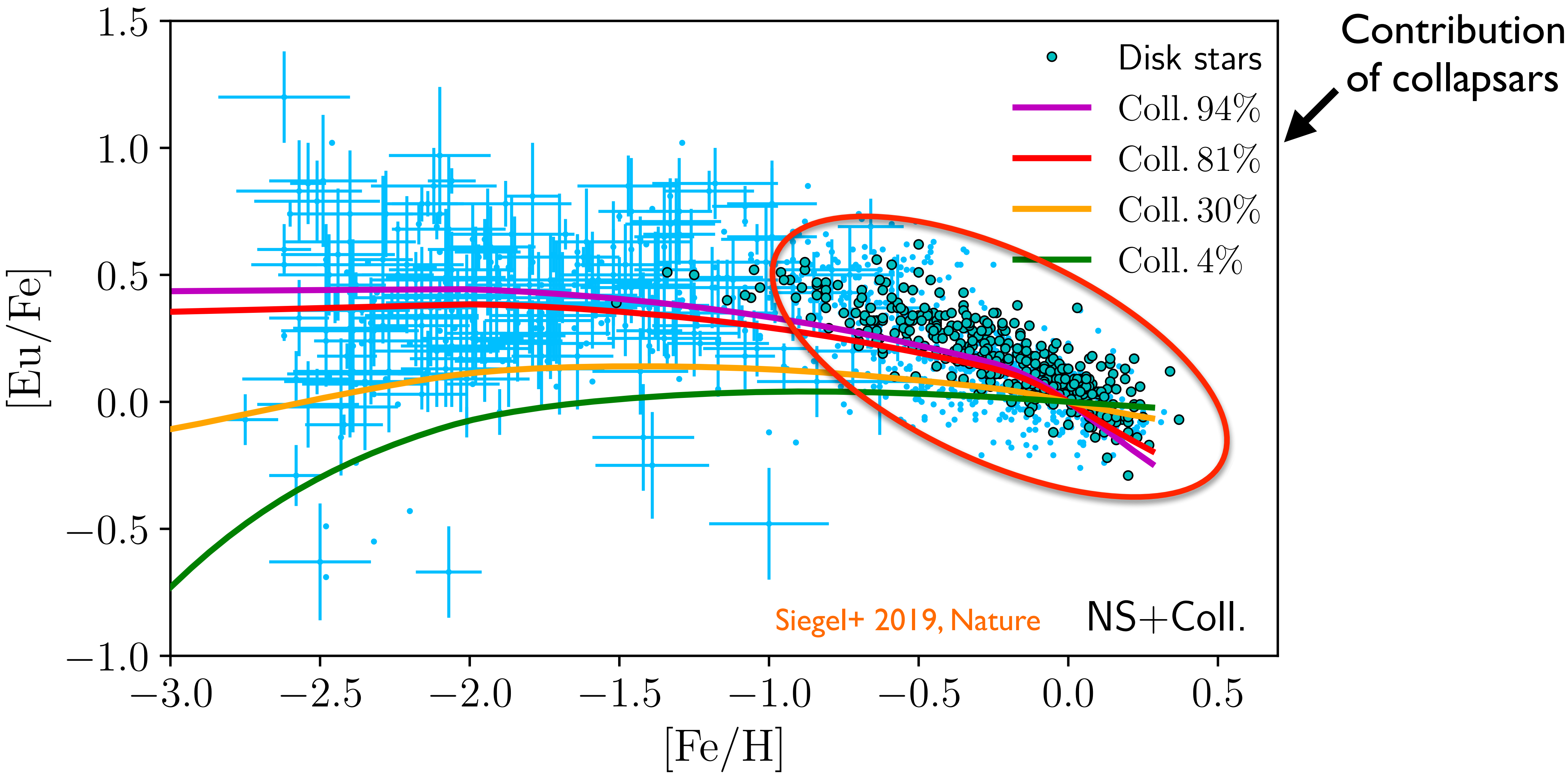
Collapsars vs. challenges for NS mergers



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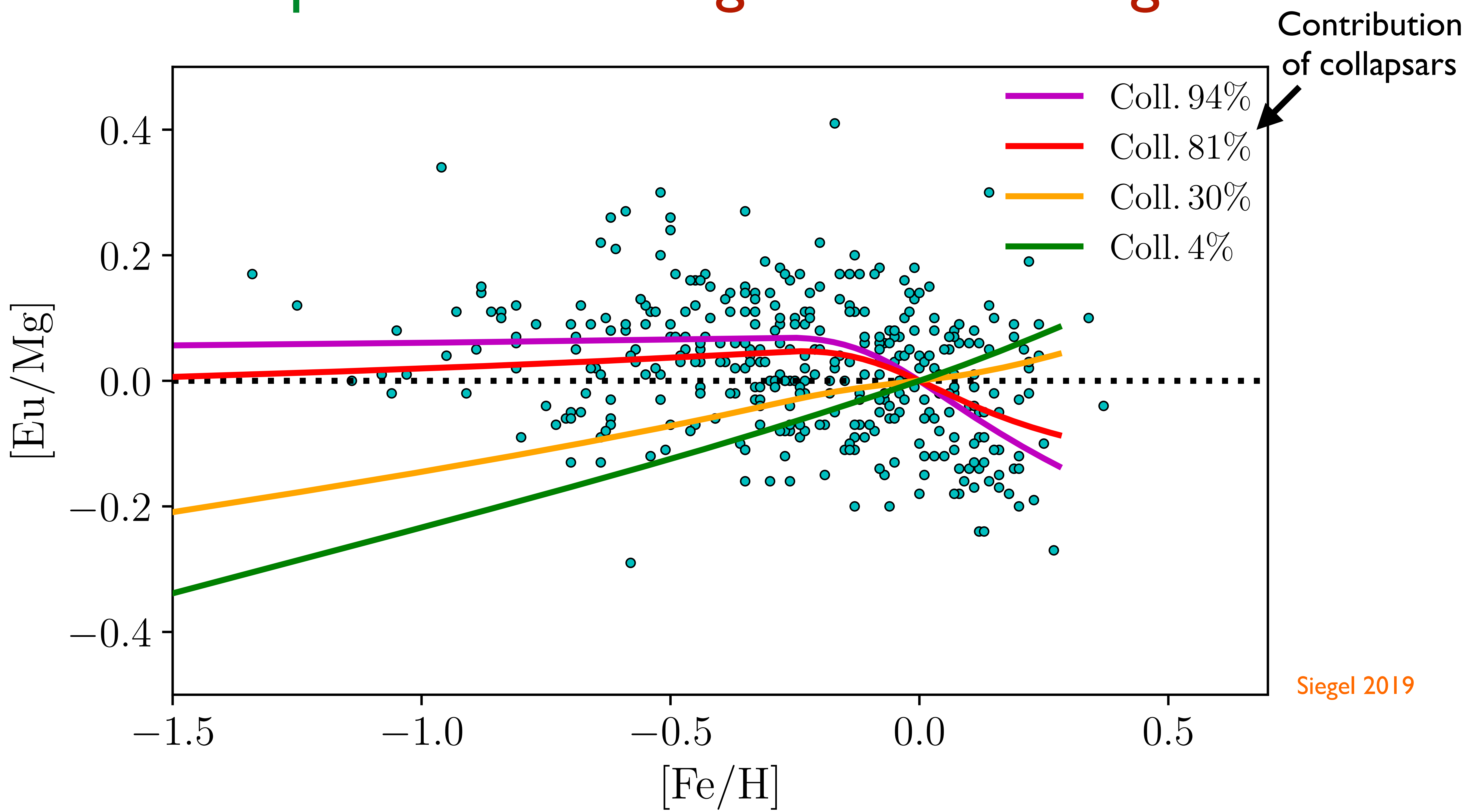
  ✓ NS mergers inconsistent with negative Eu/Fe trend (same delay-time distribution as SNe Ia)

- r-process vs. alpha-element evolution (disk stars)

  NS mergers inconsistent with Eu/Mg evolution of disk stars Siegel 2019

Collapsars vs. challenges for NS mergers



- r-process vs. alpha-element evolution (disk stars)

✓ NS mergers inconsistent with Eu/Mg evolution of disk stars

Collapsars vs. challenges for NS mergers (?)

- halo stars at very low metallicity
  - maybe need hierarchical assembly of halo from sub-halos
  - maybe need cross-pollution of sub-halos
- (UF) dwarf galaxies
  - need extremely low kick velocities <10 km/s, short merger times < 1Gyr
    Beniamini+ 2016 (but very sensitive on initial separation < Rsun)
  - need case BB mass transfer (ultra-hardened BNS), works unlikely for all UFDs
- globular clusters
  - need extremely short merger times <10 Myr
  - or need 2nd epoch of star formation from AGB winds, short merger times <100 Myr
- r-process vs. Fe evolution (disk stars)

  ✓ NS mergers inconsistent with negative Eu/Fe trend
  (same delay-time distribution as SNe Ia)
- r-process vs. alpha-element evolution (disk stars)

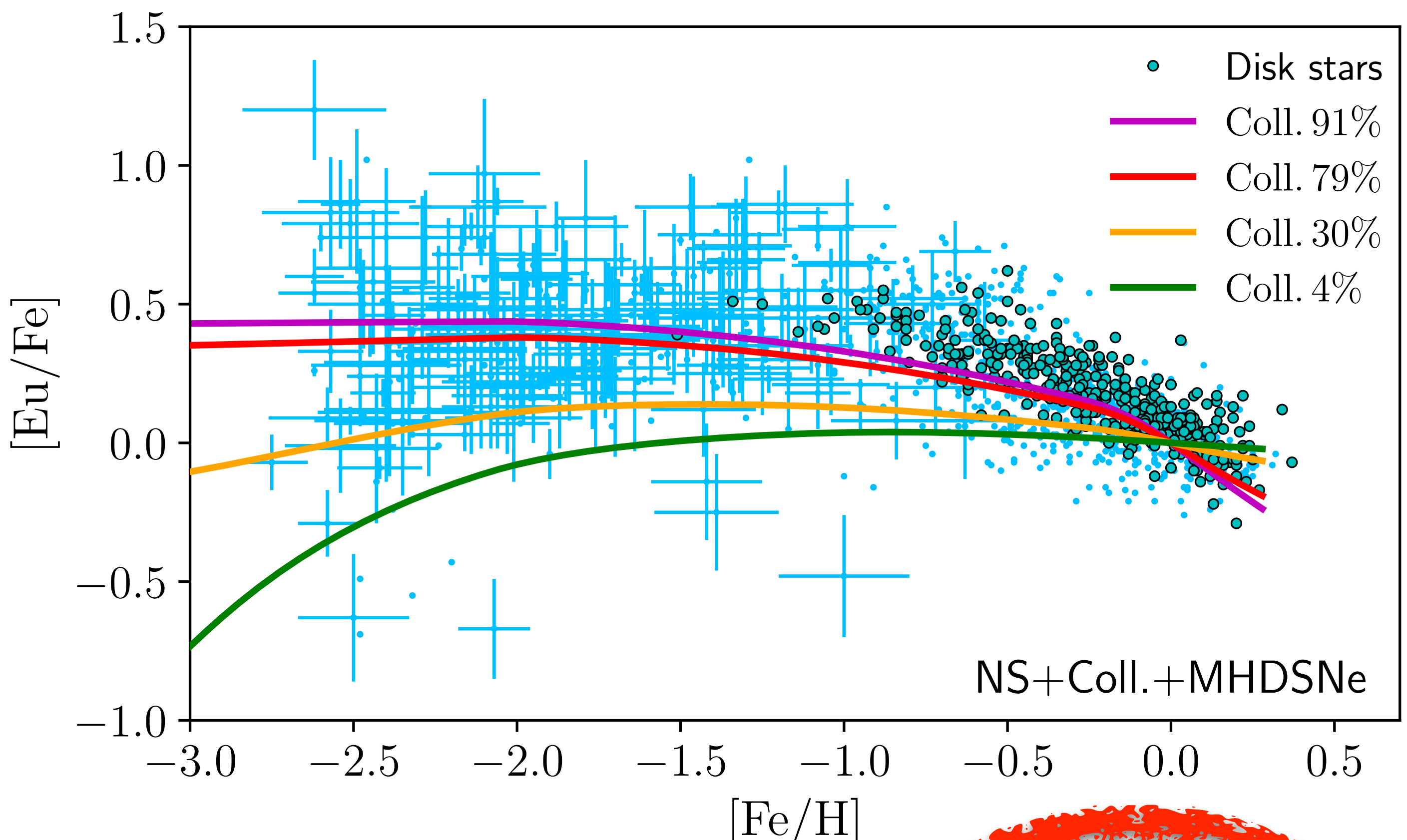
  ✓ NS mergers inconsistent with Eu/Mg evolution of disk stars

What about MHD supernovae?

- MHD SNe challenged to produce significant amounts of heavy r-process (lanthanides)

Moesta+ 2018
Halevi & Moesta 2018
Siegel, Barnes, Metzger 2019

- But: *if assumed* to produced significant lanthanides:



$f_{NS} R_{NSNS}$ $[0.5 \times 1540\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}]$	NSMs [%]	Collapsars [%]	MHD SNe [%]
0.3	6.1	91.0	2.9
1.0	18.7	78.7	2.5
10	69.4	29.6	1.0
100	95.7	4.2	0.1

Collapsars strongly dominate even in most optimistic MHD SNe case

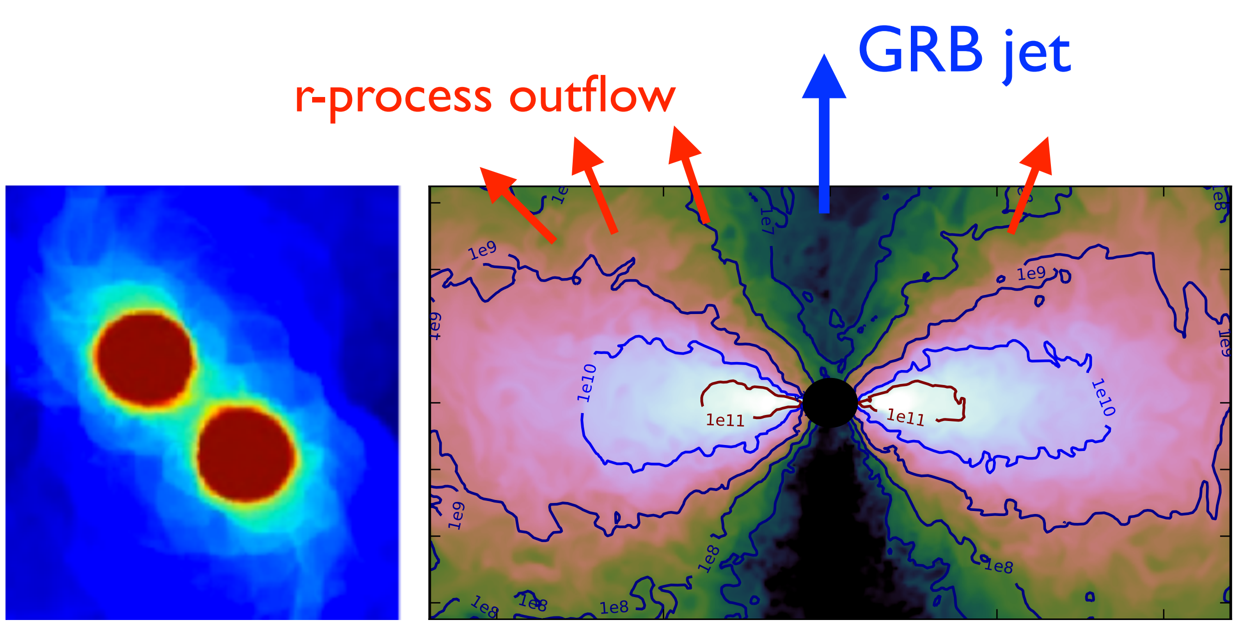
Conjecture:

Outflows from compact accretion disks synthesize most of the Galactic heavy r-process elements

NS mergers

short GRBs

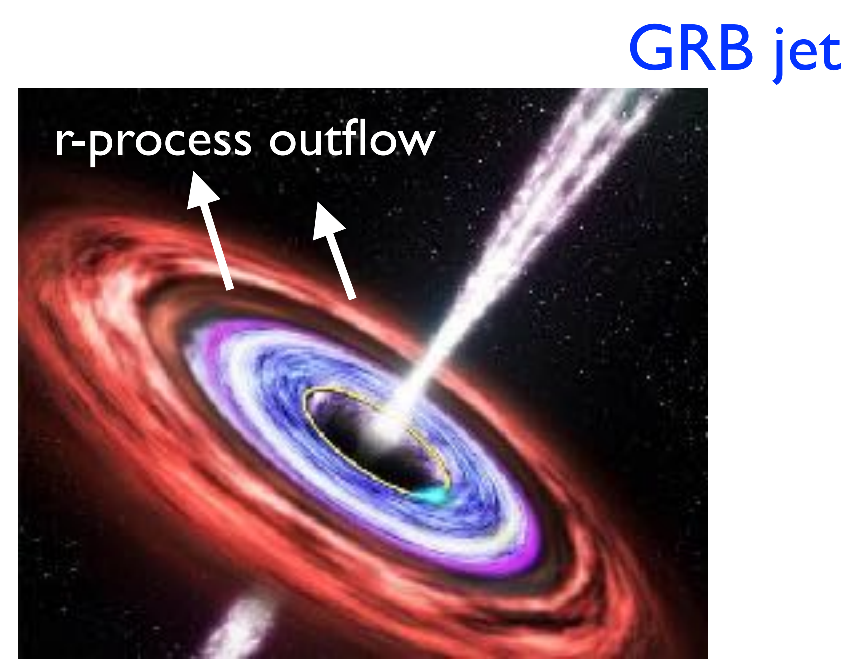
Siegel & Metzger 2017, PRL



Collapsars

long GRBs, GRB supernovae (SNe Type Ic-BL)

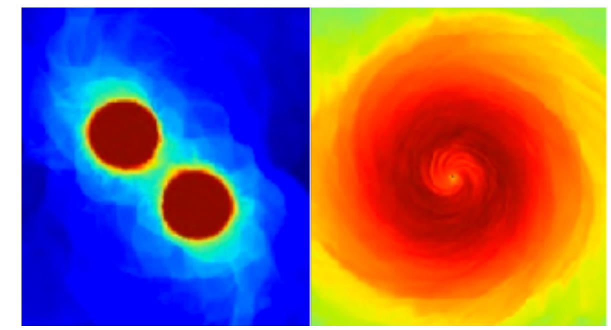
Siegel, Barnes, Metzger 2019, Nature

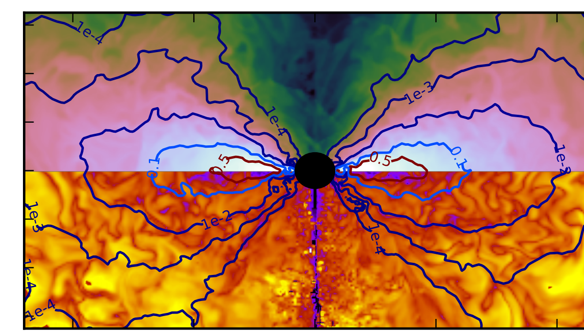


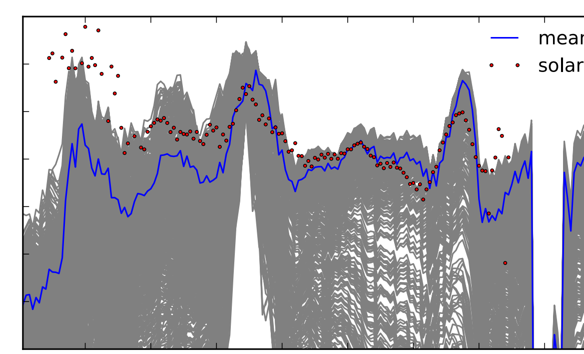
Conclusions

NS mergers:

- massive post-merger accretion disks expected to be ubiquitous, outflows can produce entire range of r-process nuclei, should dominate NS merger ejecta
- GW170817: heavy elements & red kilonova most likely originate from outflows of such disks
- contribution of BH-NS mergers?







Collapsars: likely dominant contribution to Galactic r-process

- similar physics as in NS post-merger
- lower event rate overcompensated by higher yield
- overcome observational challenges of merger-only models for Galactic r-process
- direct observational imprint of r-process in late-time GRB supernova lightcurves & spectra
- GRB supernova radiation transport modeling likely rules out MHD supernovae to produce lanthanides