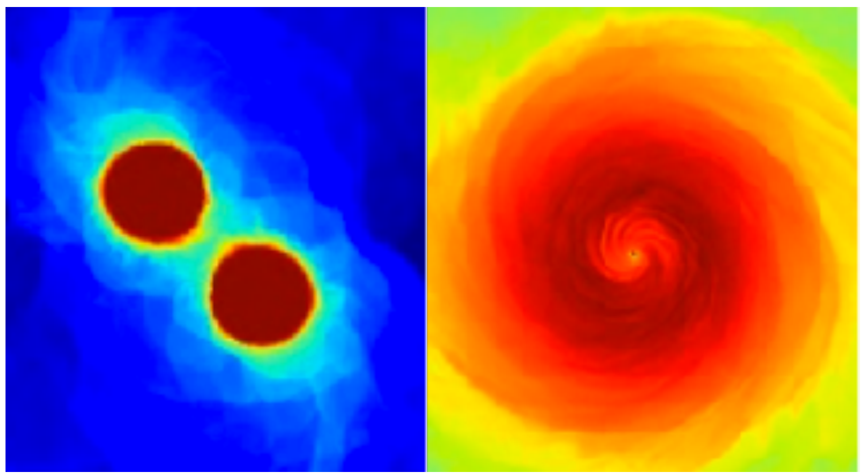
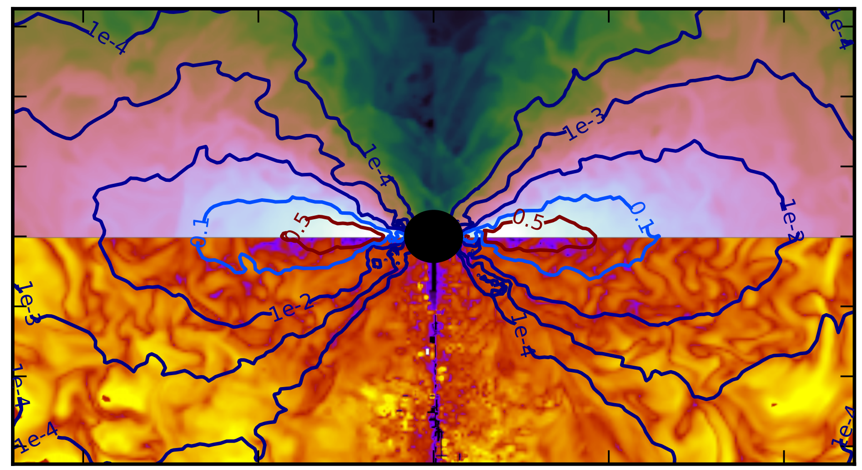
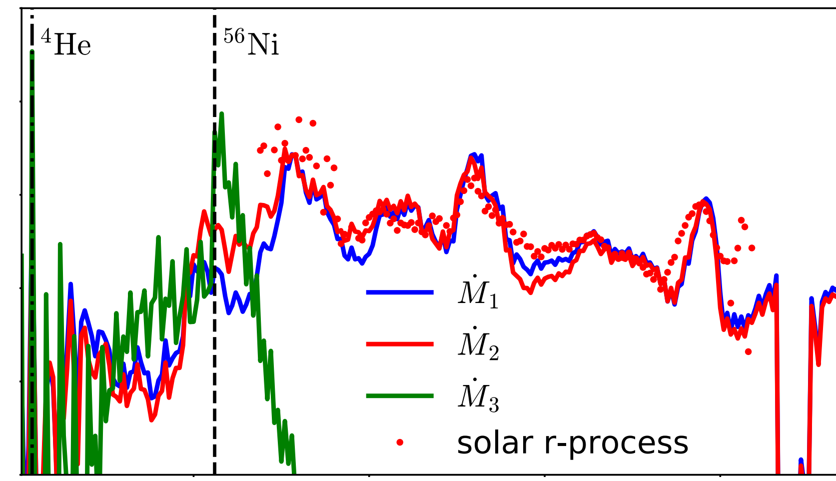
Forging the Universe's gold







Daniel M. Siegel

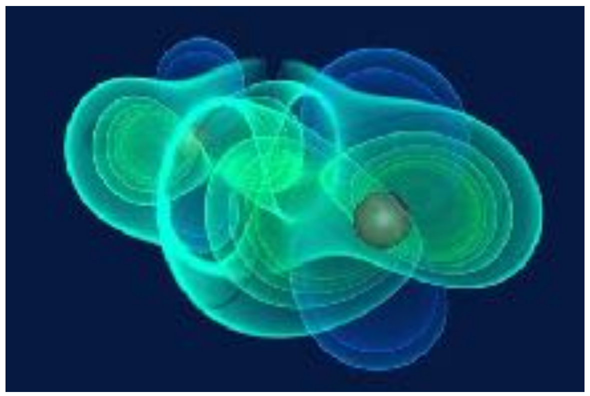
Perimeter Institute for Theoretical Physics

University of Guelph

Theory Canada 14, TRIUMF & UBC, Vancouver, May 31, 2019

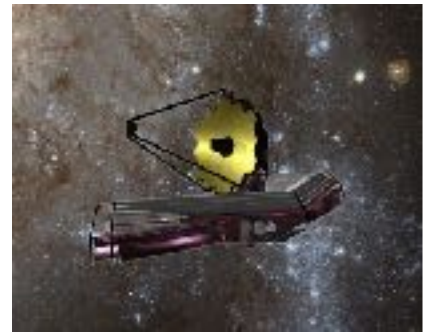
Exciting times for physics

Strong gravity



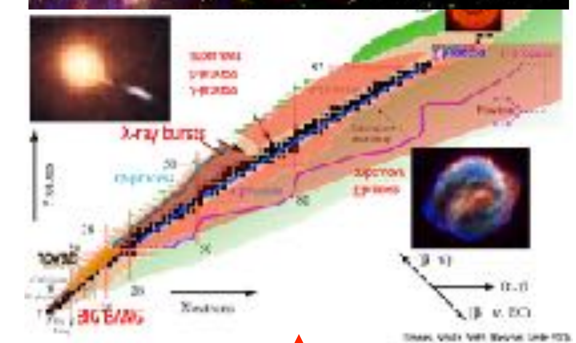
Gravitational waves

Transient astronomy



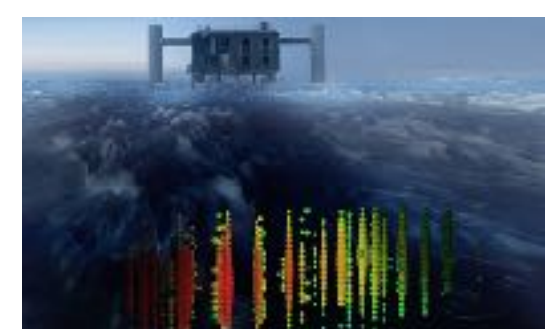
Electromagnetic counterparts

Nuclear astrophysics



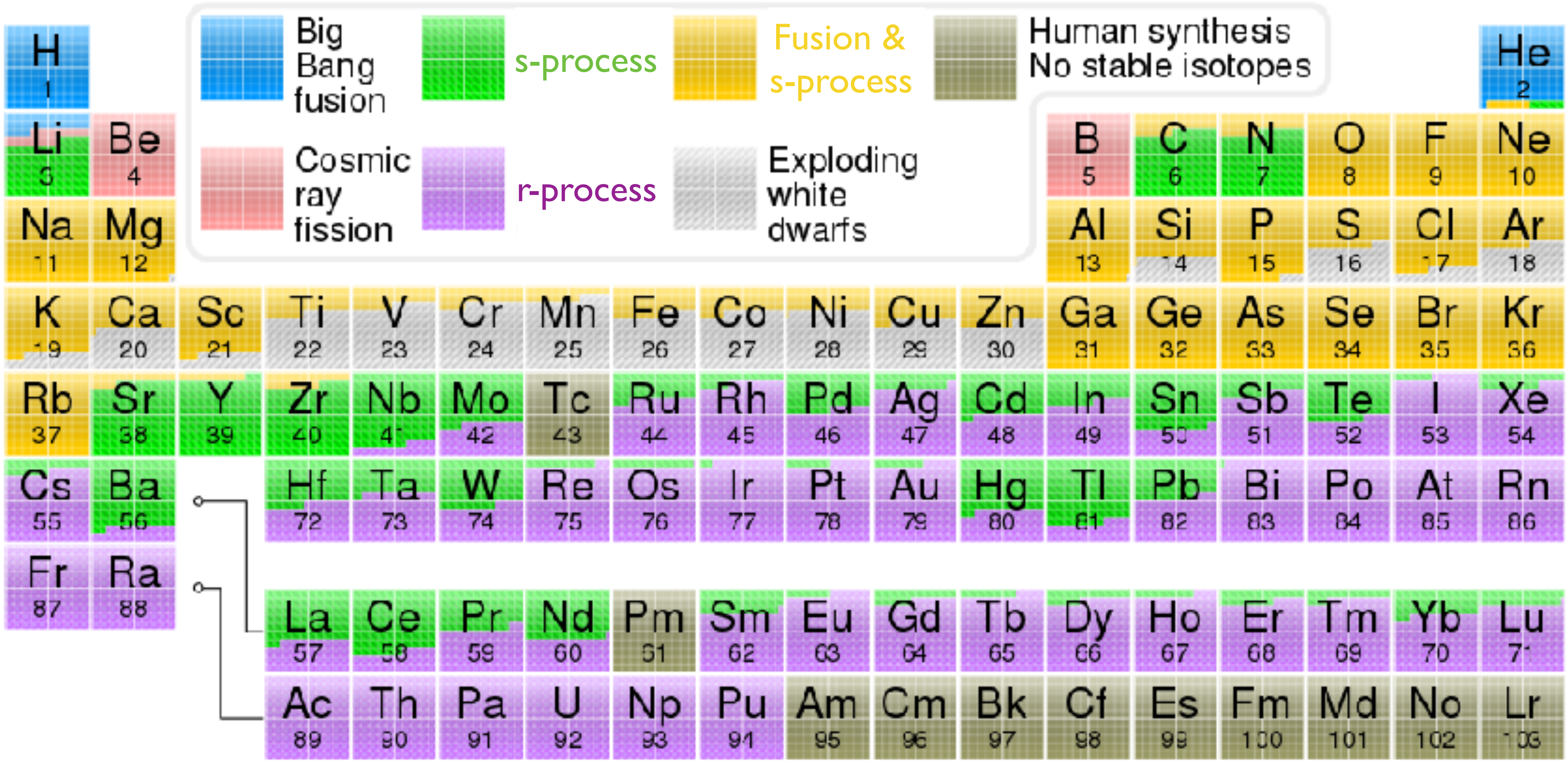
Nuclear theory & experiments

LIGO/Virgo gravitational wave detectors (just started O3!)



Astroparticle physics

The origin of the elements

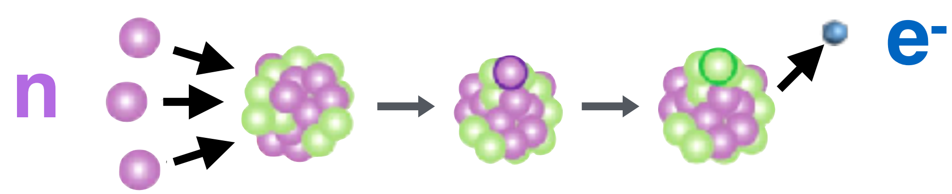


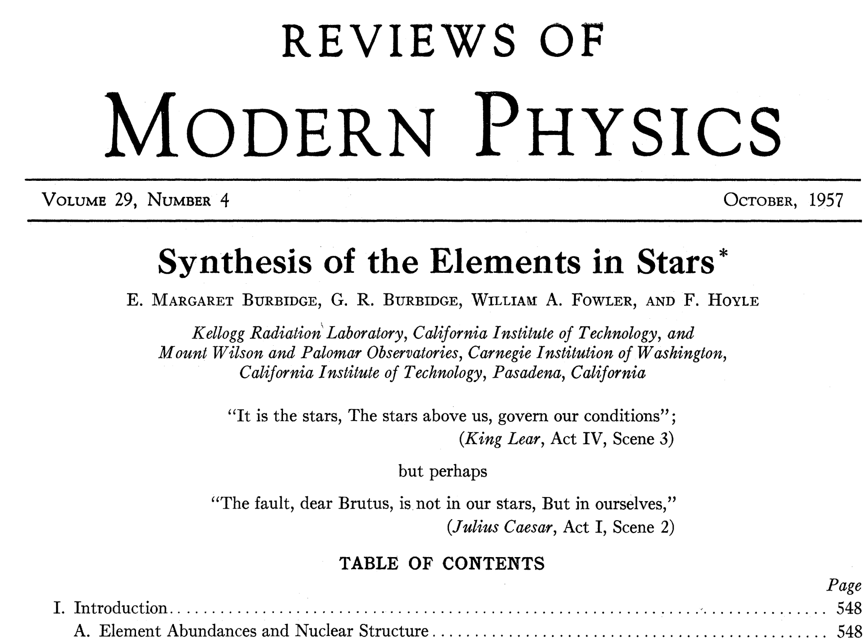
How are the *heavy* (r-process) elements formed?

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

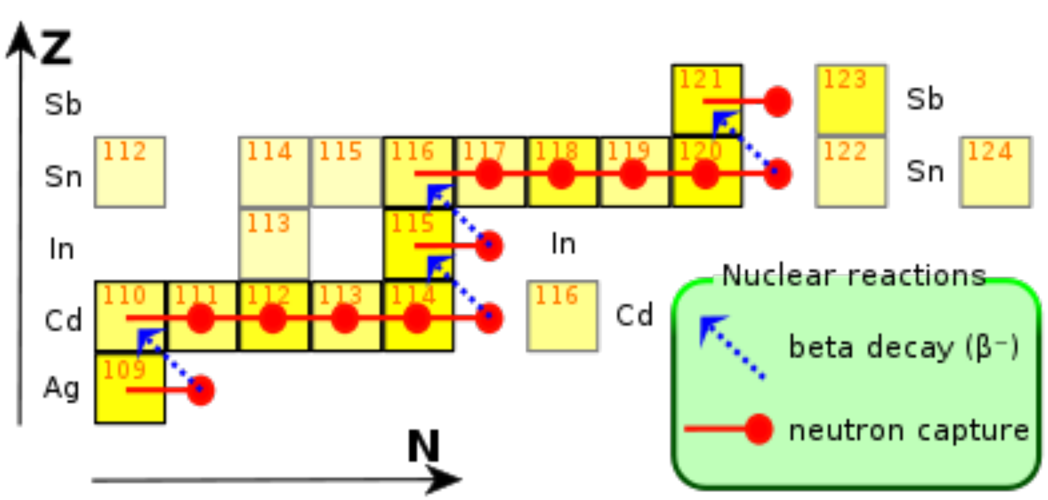
slow neutron capture (s-process):

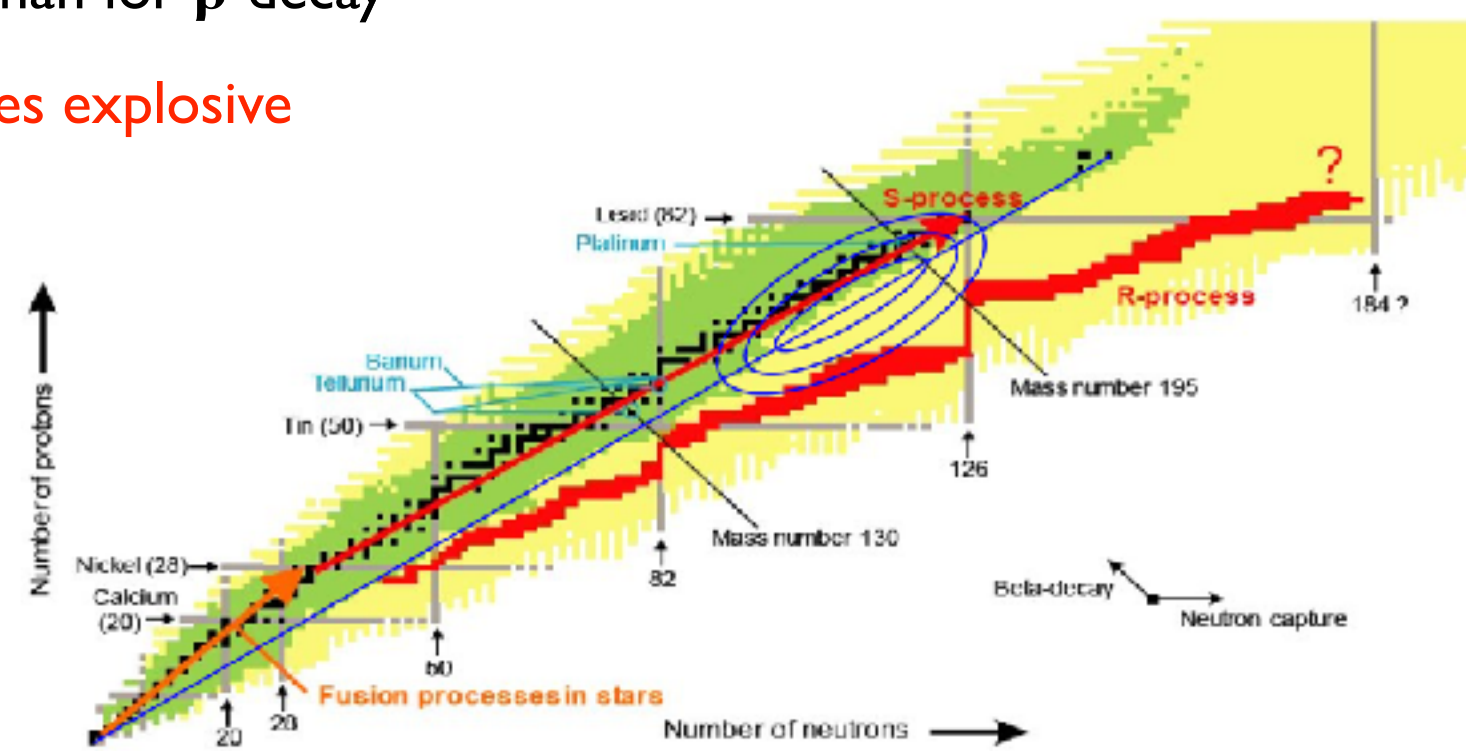
timescale for neutron capture longer than for β-decay

rapid neutron capture (r-process):

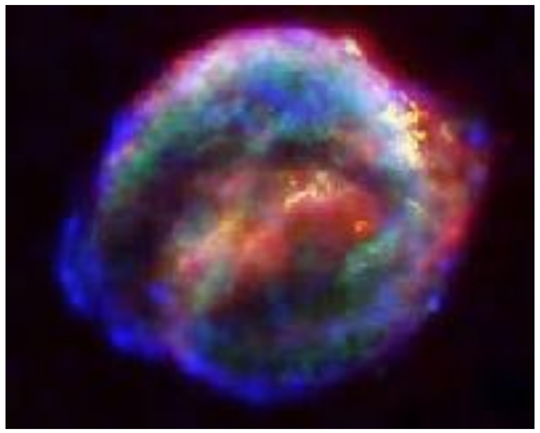
timescale for neutron capture shorter than for β-decay

→ speculated that r-process requires explosive environment of supernovae





r-process contenders

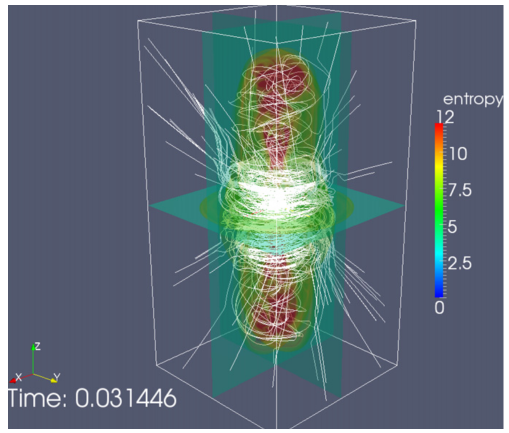


regular core-collapse supernovae

Qian & Woosley 1996
Hüdepohl+ 2010
Roberts+ 2012
Martinez-Pinedo+ 2012
Janka 2016
Fischer+ 2018

disfavored by observations & theory

Wallner+ 2015
Hotokezaka+ 2015



MHD supernovae

Winteler+ 2012
Nishimura+ 2017
Moesta+ 2014
Moesta+ 2018

likely light r-process only

Moesta+ 2018
Siegel+ 2019

Collapsars

MacFadyen & Woosley 1999
Siegel+ 2019

heavy & light r-process

Siegel+ 2019

Neutron star mergers

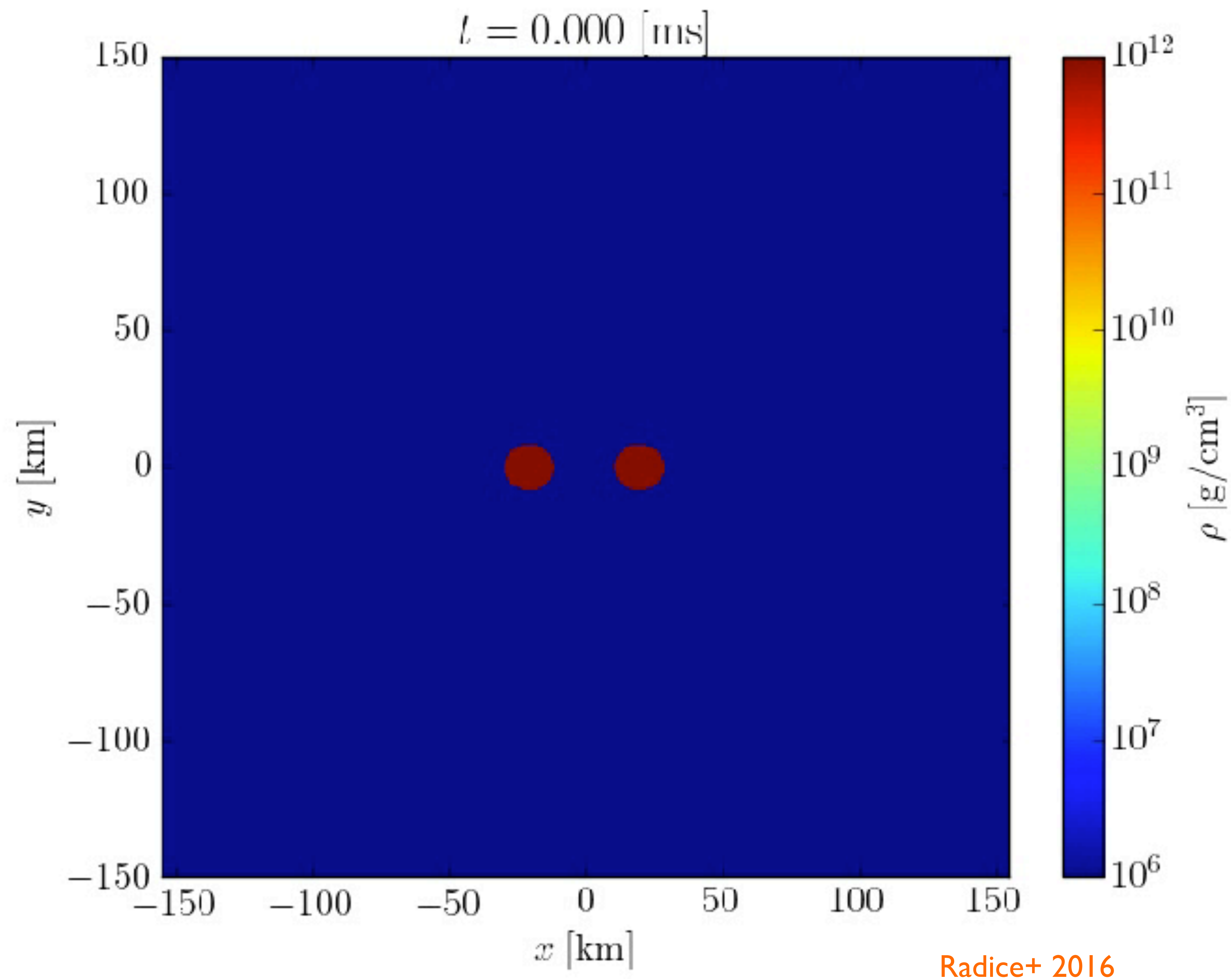
Lattimer & Schramm 1974
Symbalisty & Schramm 1982
Eichler+ 1989
Meyer 1989
Davis+ 1994
Ruffert+ 1996

heavy & light r-process

Siegel & Metzger 2017
Radice+ 2018

I.
r-process in neutron star mergers

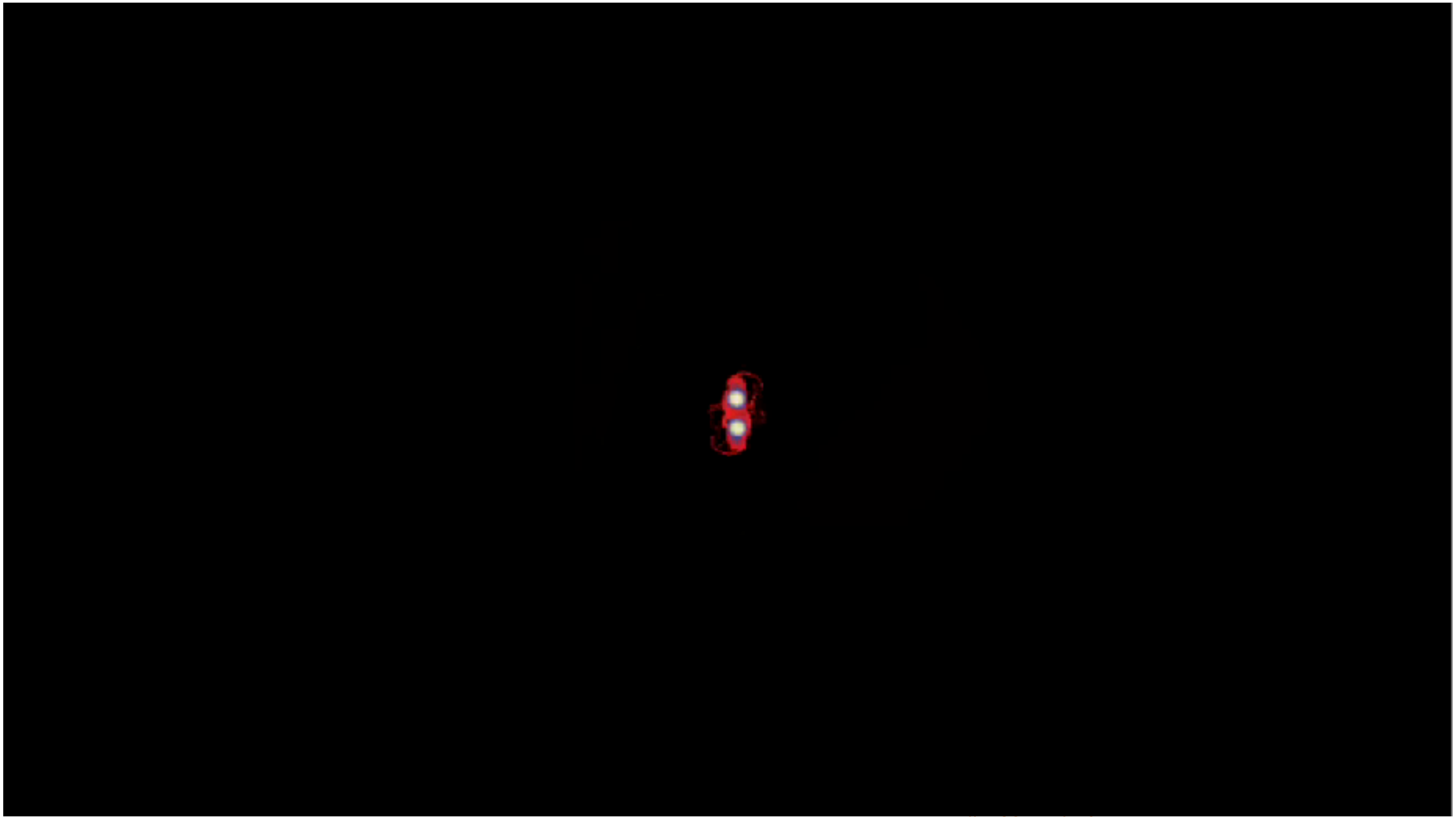
NS-NS merger → black hole



Radice+ 2016

Movie: BNS merger with prompt black-hole formation, showing dynamical ejecta and disk formation

NS-NS merger ➡ neutron star

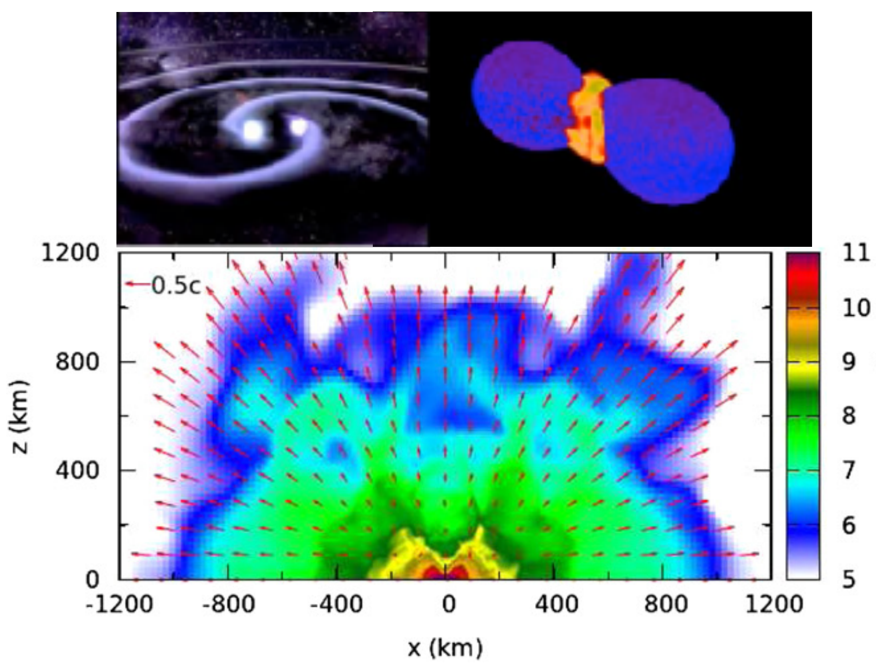


Movie: BNS merger showing dynamical ejecta and winds from remnant neutron star

Ciolfi, Siegel+2017

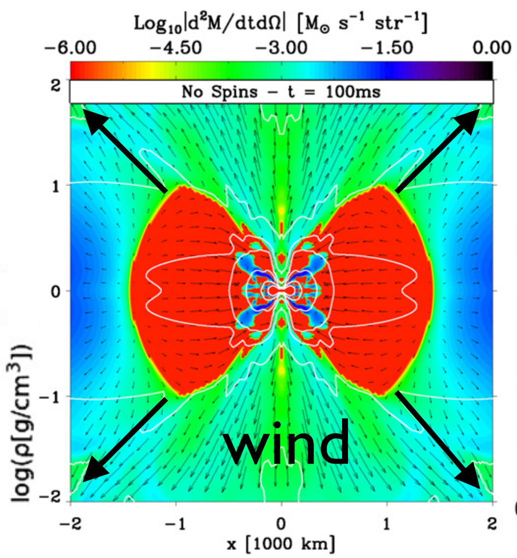
Sources of ejecta in NS mergers

dynamical ejecta (~ms)

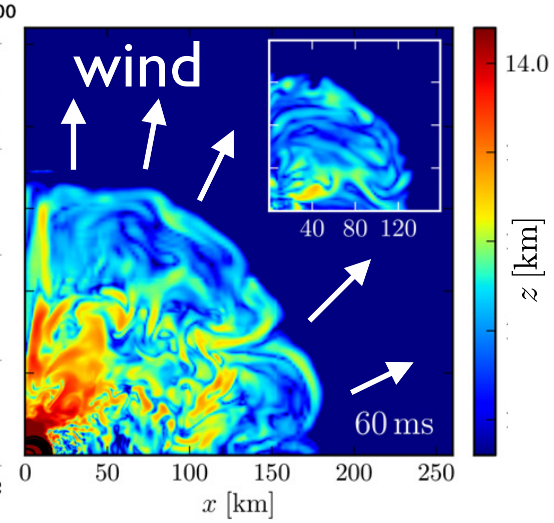


Hotokezaka+ 2013, Bauswein+ 2013

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

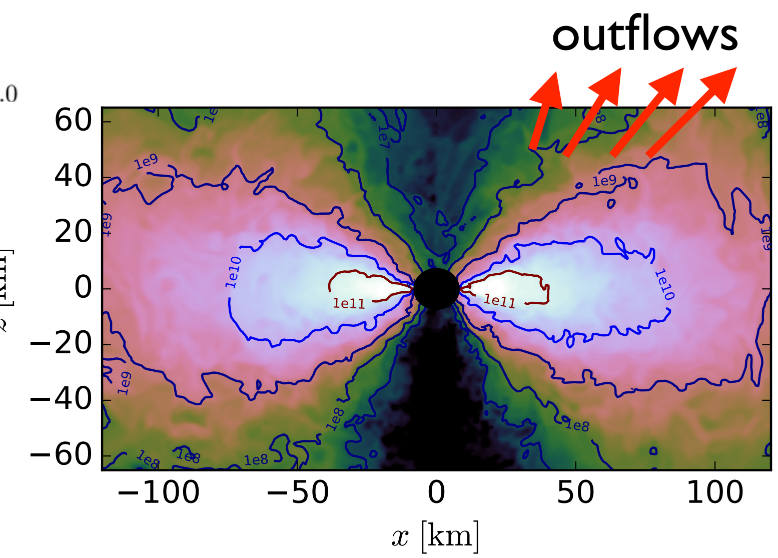


Dessart+ 2009



Siegel+ 2014
Ciolfi, Siegel+ 2017

accretion disk (~10ms-1s)



Siegel & Metzger 2017 PRL

tidal ejecta
shock-heated ejecta

neutrino- and magnetically
driven wind

(NS-NS mergers only!)

disk outflows

The GW170817 kilonova: direct r-process signature

- blue kilonova properties:

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

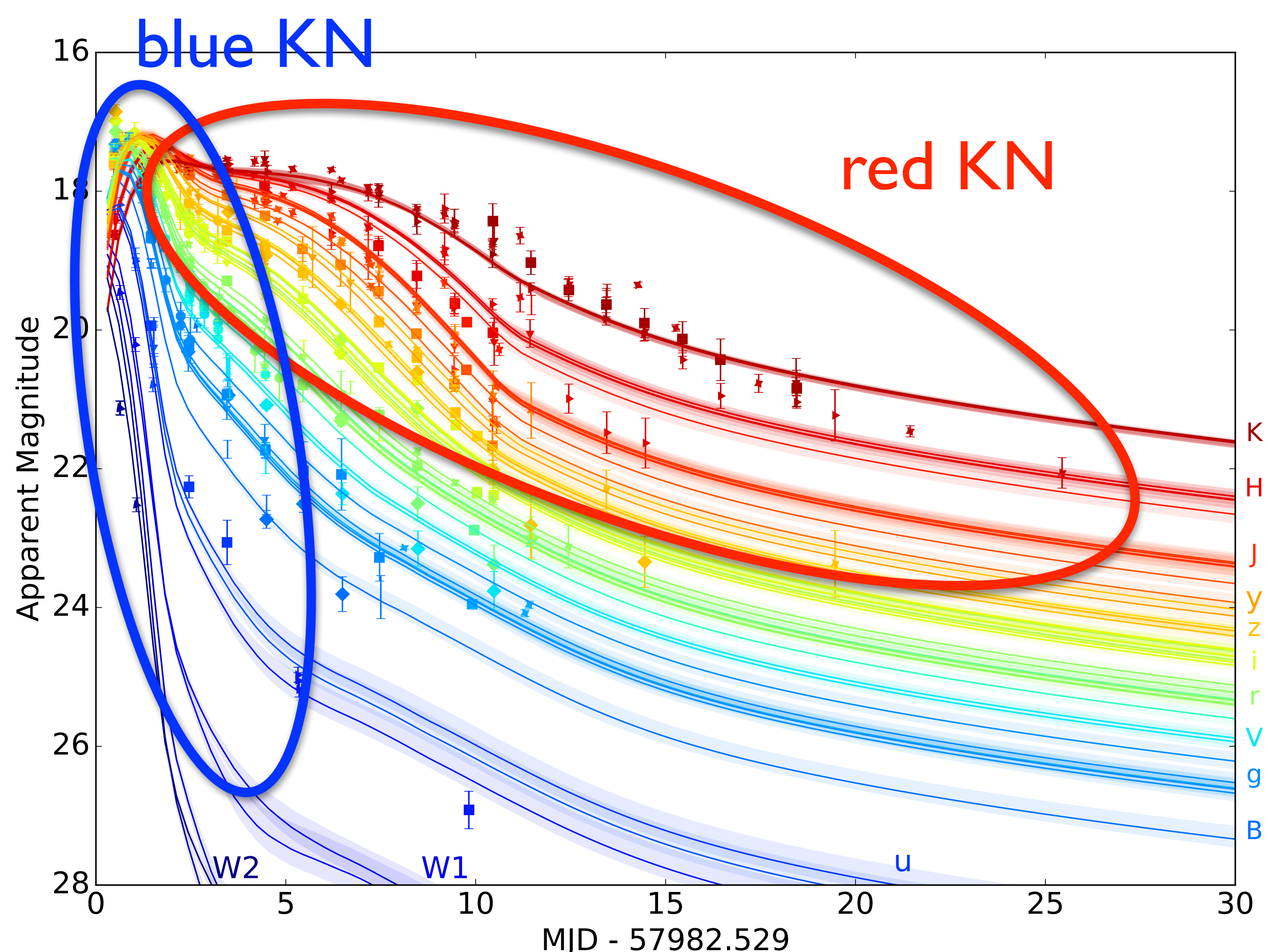
Kilpatrick+ 2017
Kasen+ 2017
Nicholl+ 2017
Villar+ 2017
Coughlin+ 2018

- 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

High opacities of the Lanthanides

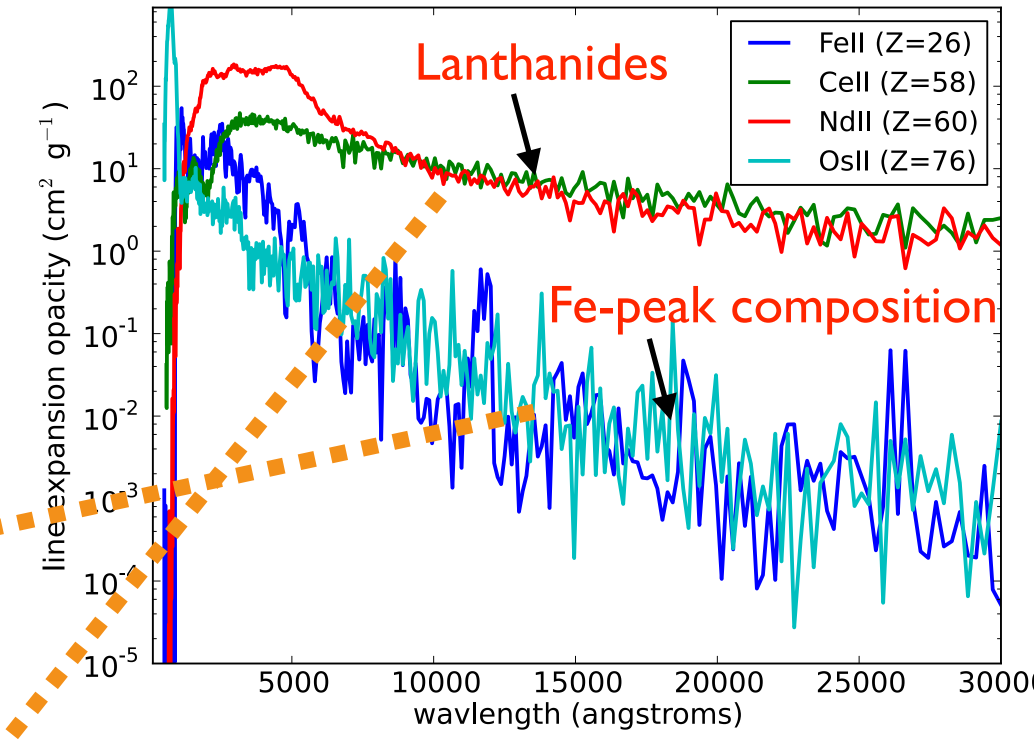
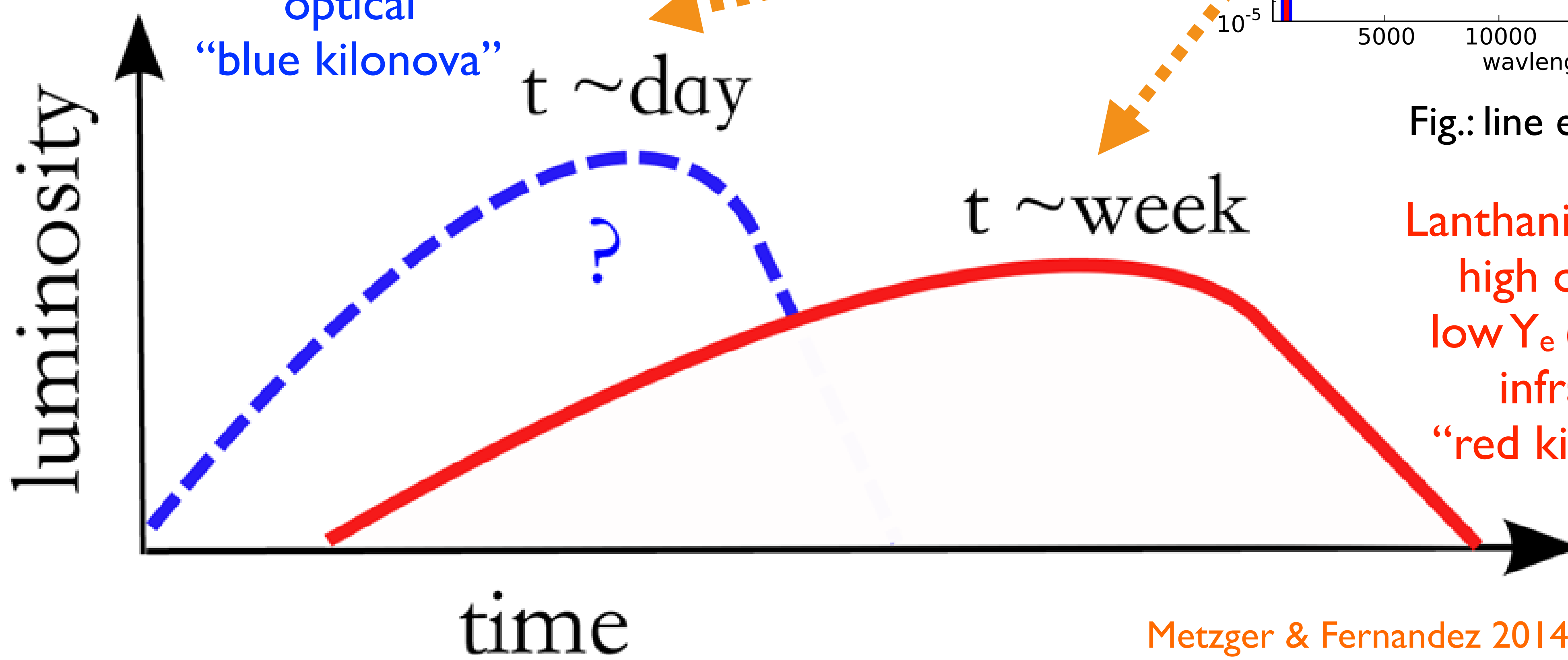


Fig.: line expansion opacities

Kasen+ 2013

Lanthanide "free"
low opacity
high Y_e (> 0.25)
optical
"blue kilonova"



Lanthanide "rich"
high opacity
low Y_e (< 0.25)
infrared
"red kilonova"

Metzger & Fernandez 2014

Fig.: kilonova lightcurves probe composition (Lanthanide mass fraction).

The GW170817 kilonova: direct r-process signature

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Nicholl+ 2017
Villar+ 2017
Coughlin+ 2018

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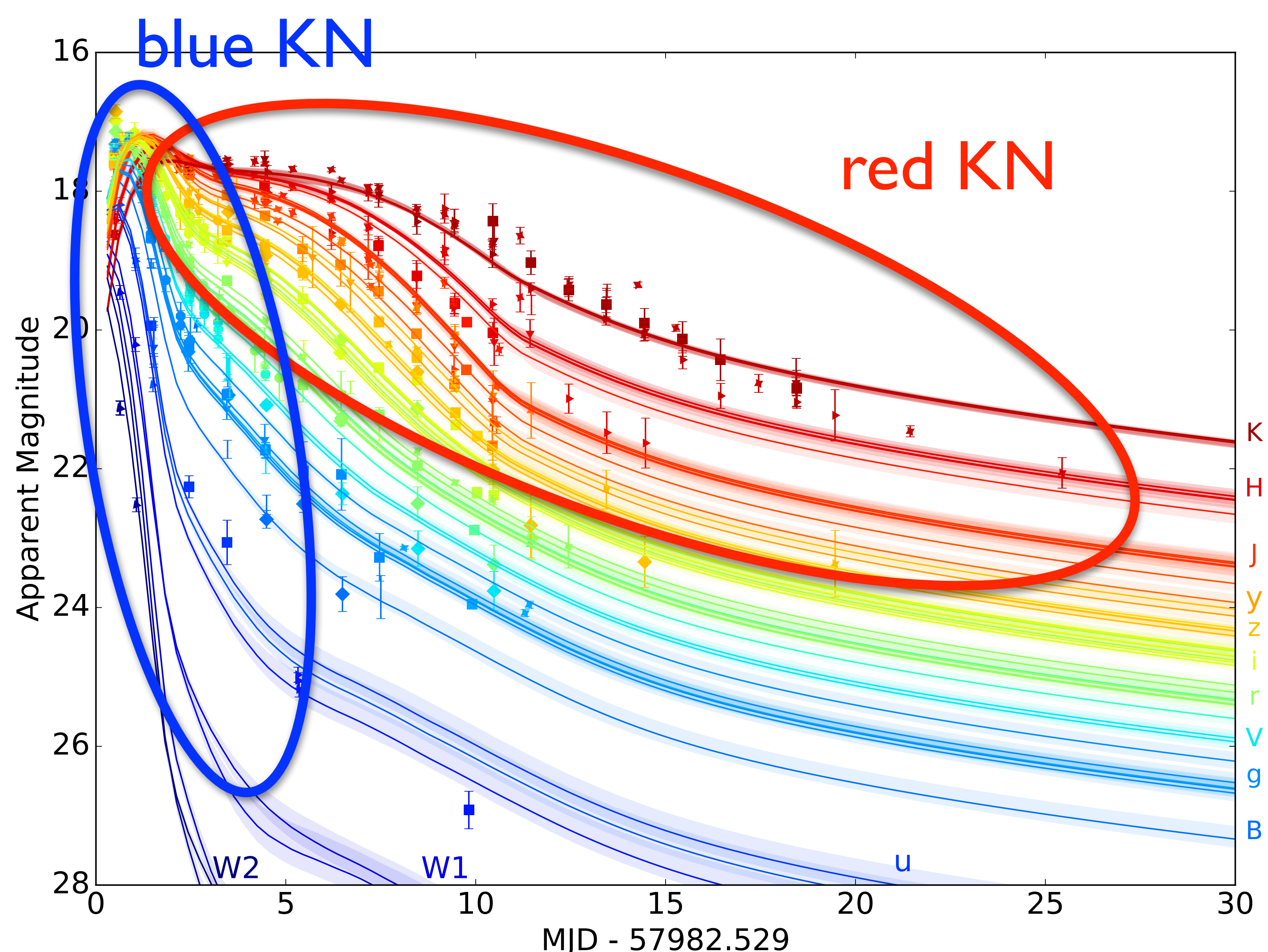
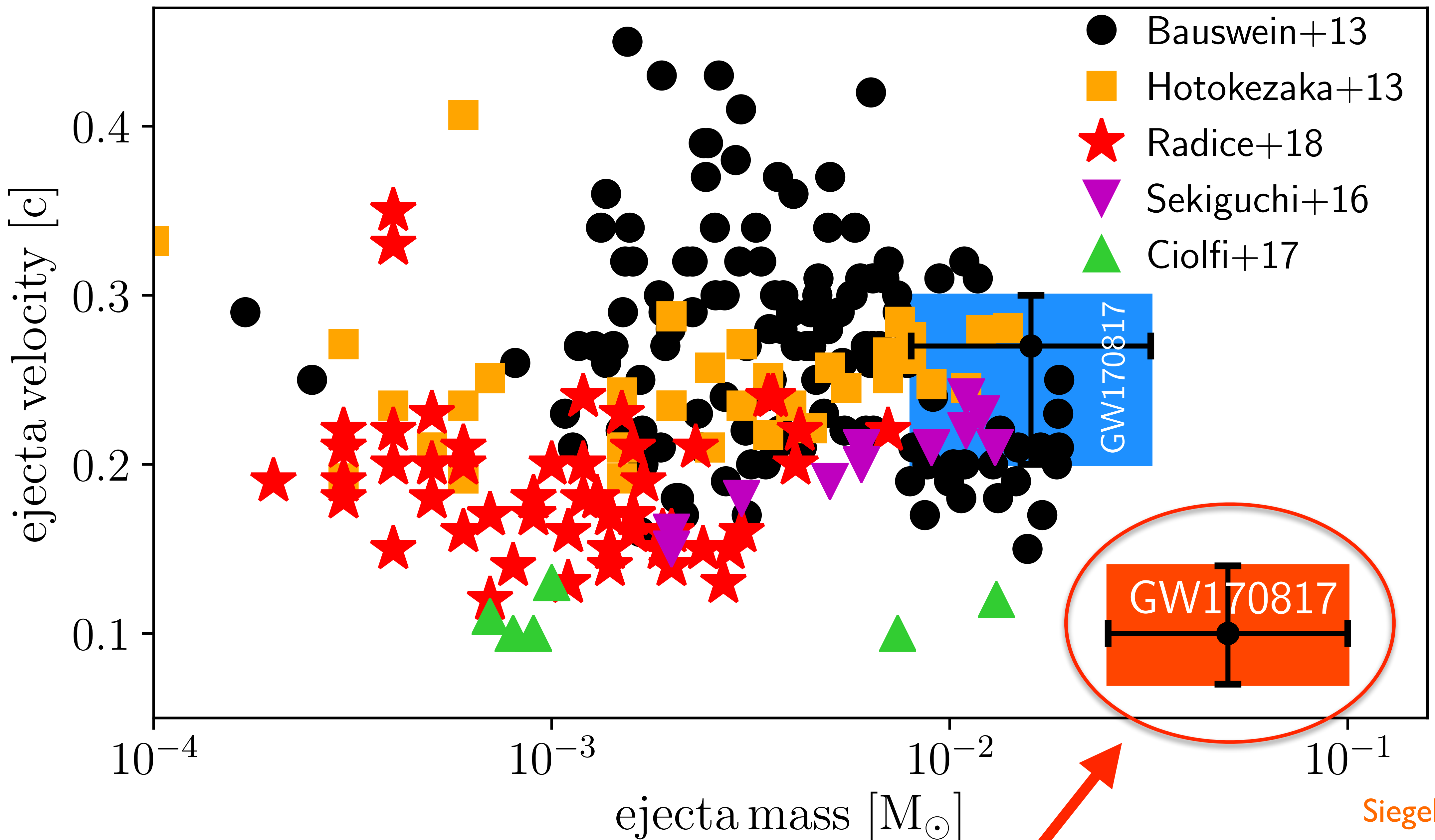
Coughlin+ 2018



Villar+ 2017

The GW170817 kilonova: theory faces observations

BNS merger simulations: dynamical ejecta

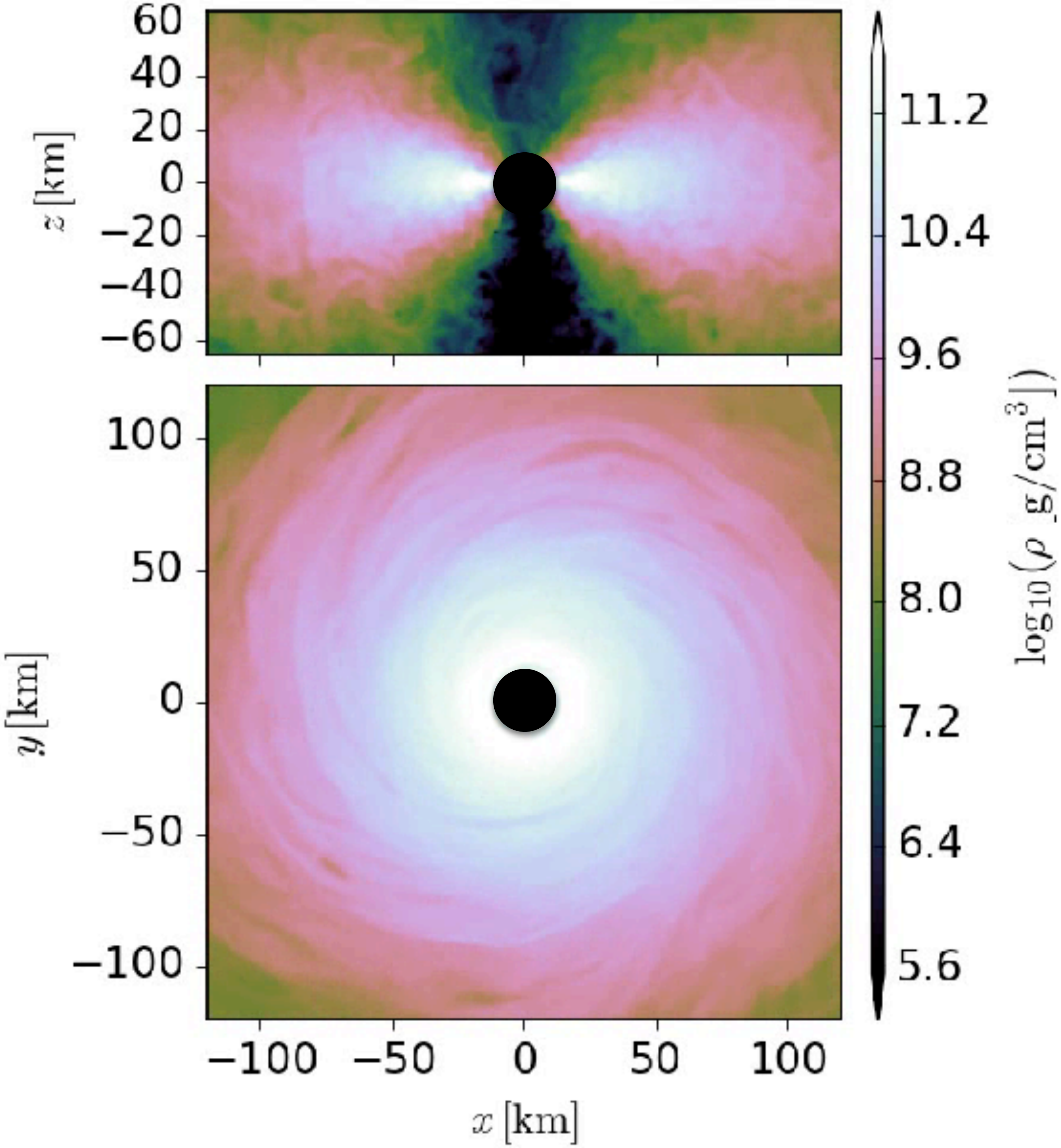


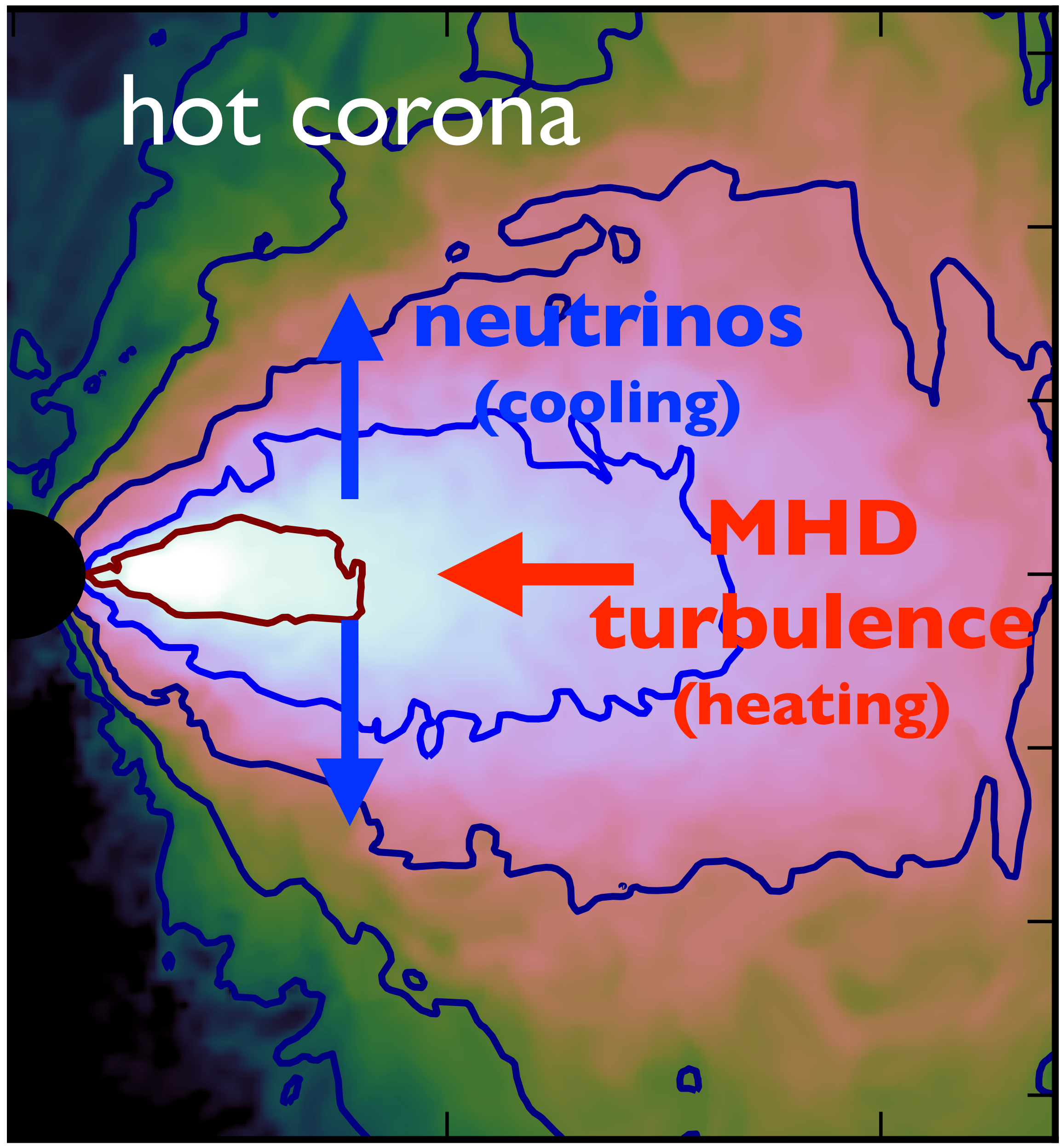
Siegel 2019

inconsistent with dynamical ejection
consistent with post-merger accretion disk

Post-merger accretion disk outflows

Siegel & Metzger 2017, PRL Siegel & Metzger 2018



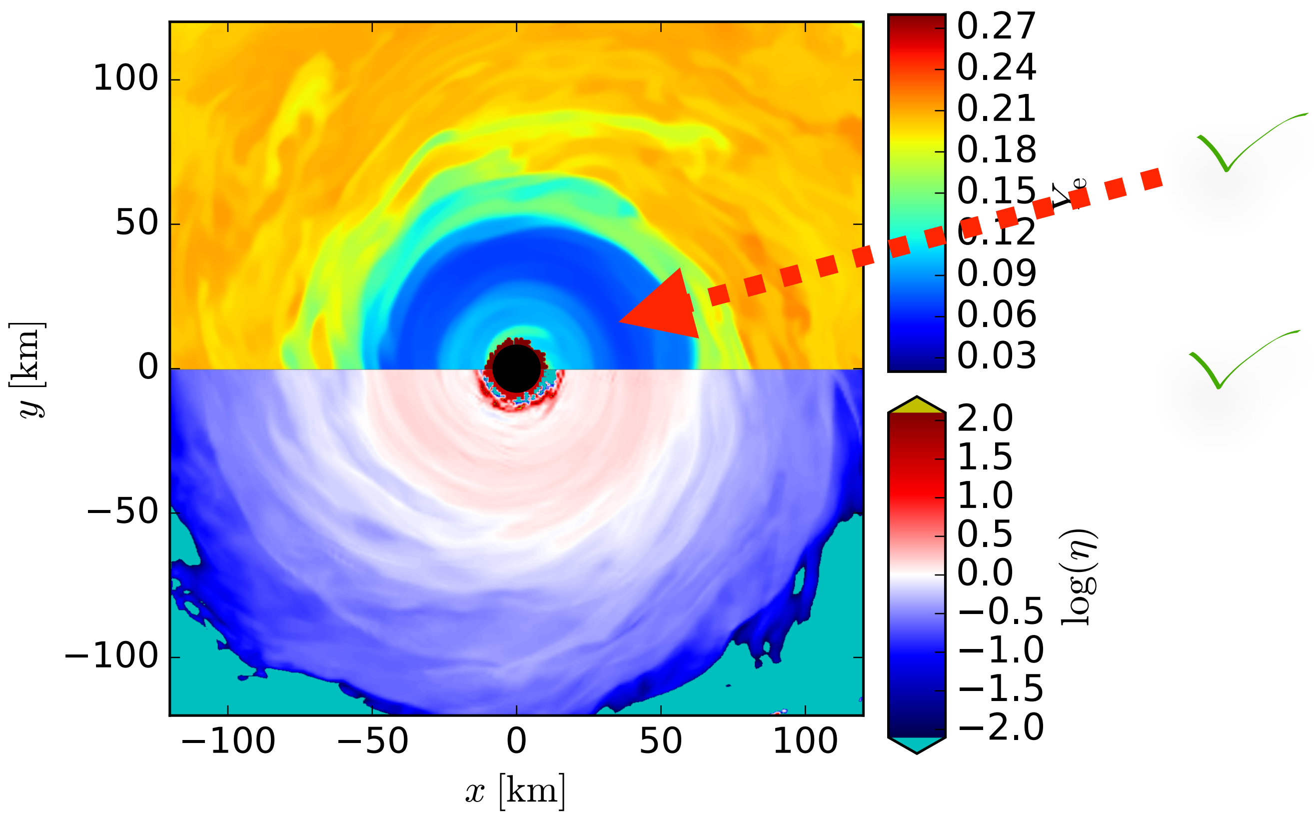


heating-cooling imbalance in corona launches thermal wind

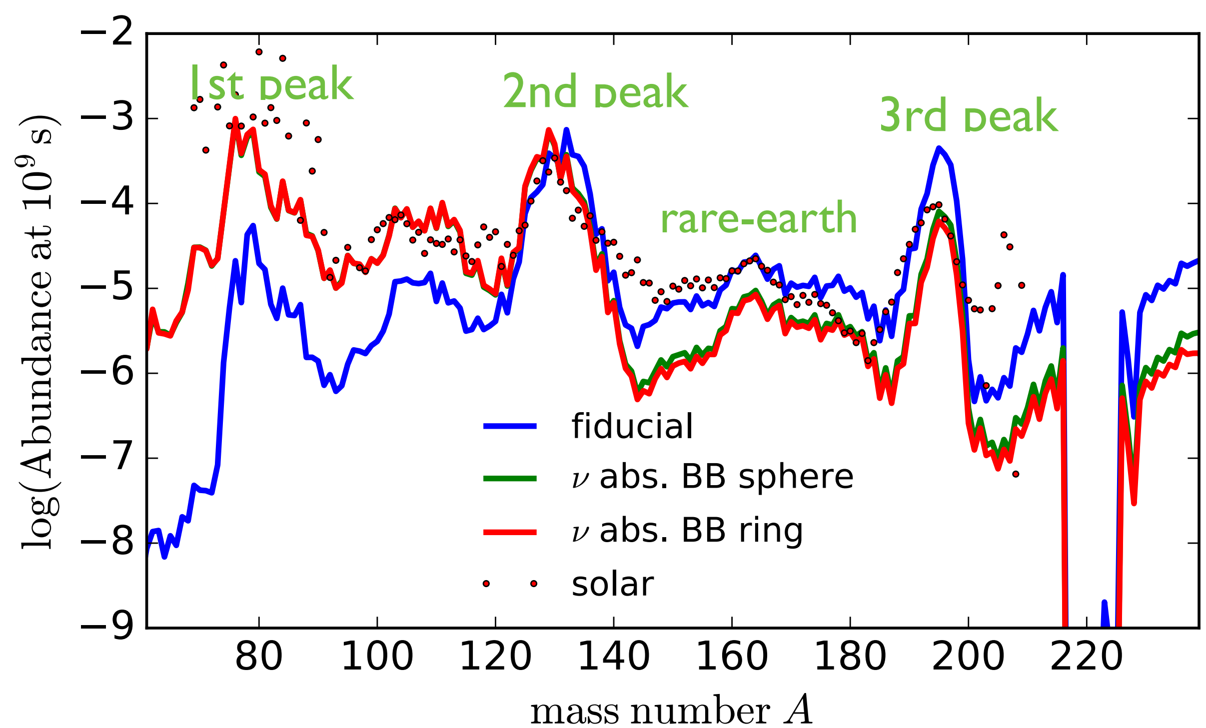
$t = 20.113\,\mathrm{ms}$

Disk outflows and the red kilonova

Siegel & Metzger 2017, PRL
Siegel & Metzger 2018



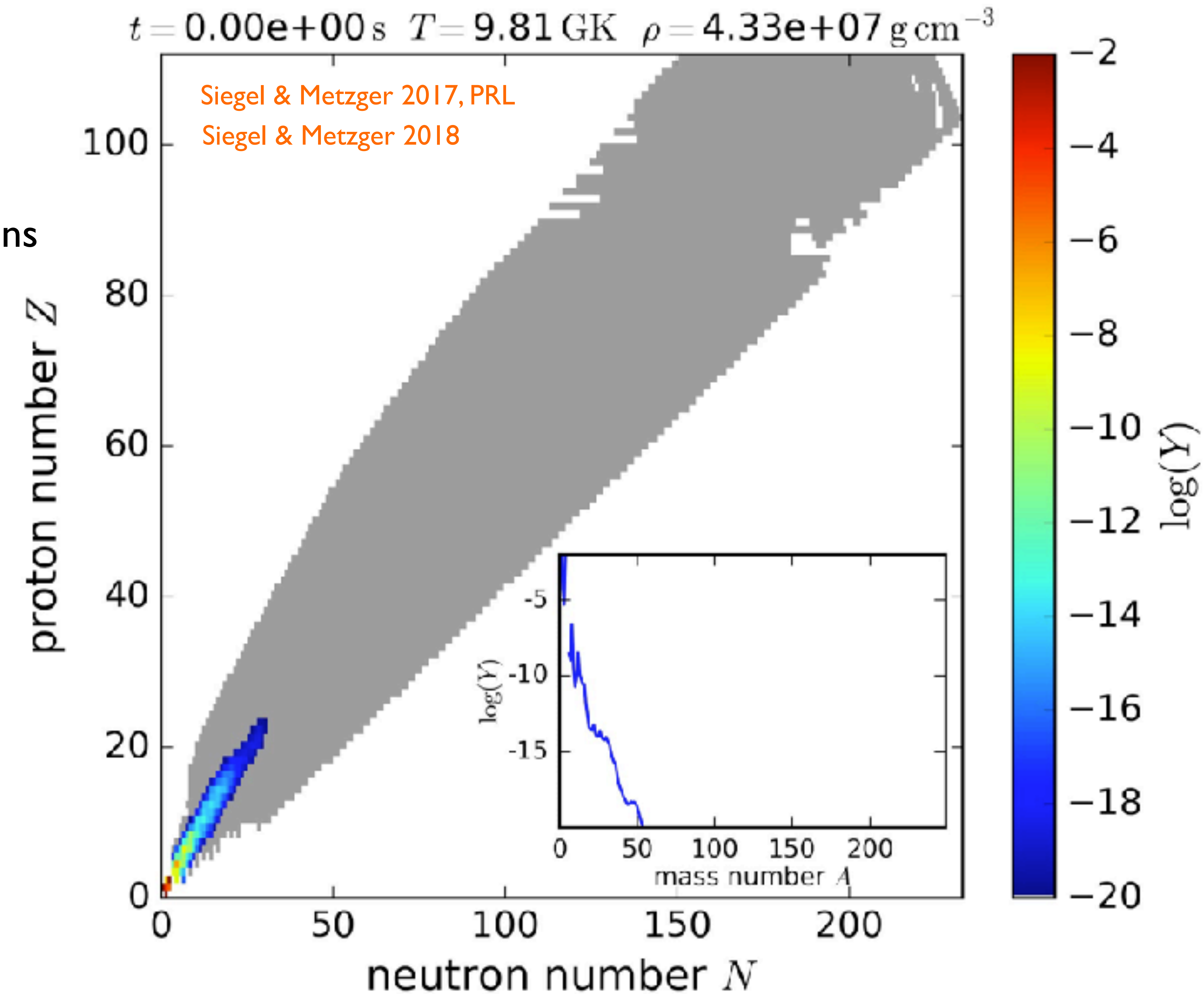
- Neutron-richness: self-regulation mechanism in degenerate inner disk provides neutron rich outflows (Y_e<0.25)
- Production of full range of r-process nuclei, excellent agreement with observed r-process abundances (solar, halo stars)



r-process nucleosynthesis in disk outflows

nuclear reaction network (*SkyNet*)

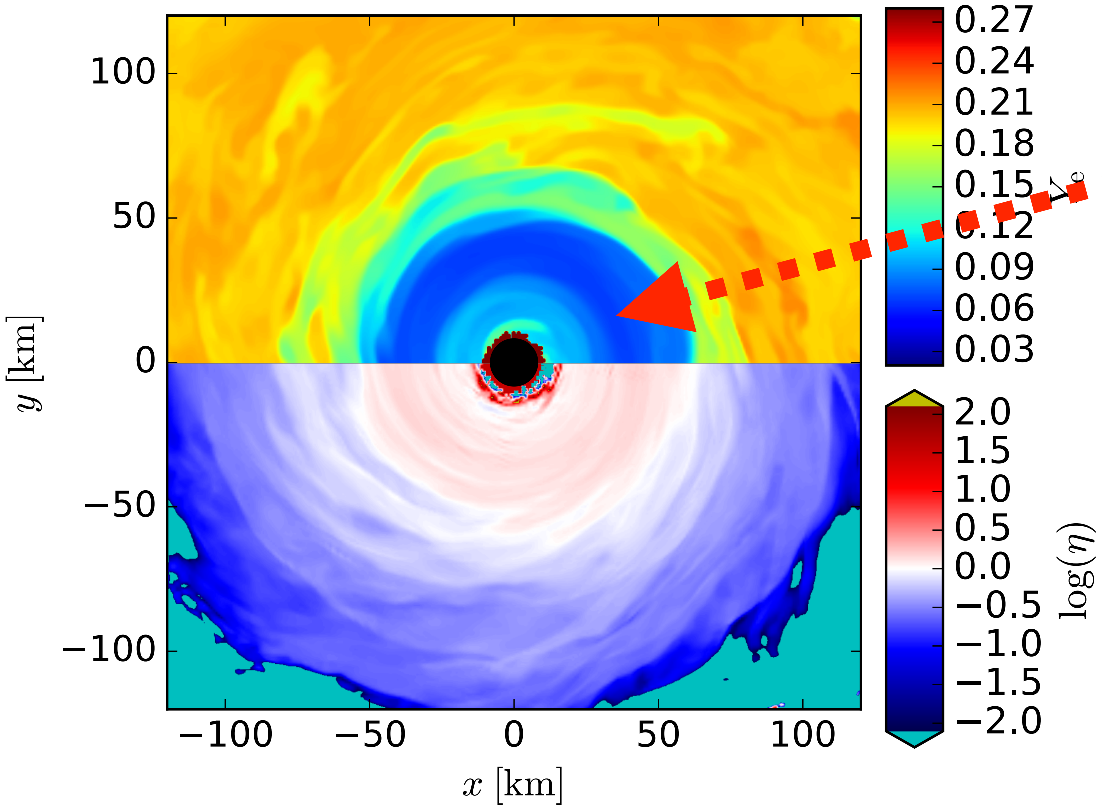
- neutron captures
- photo-dissociations
- α-, β-decays
- fission



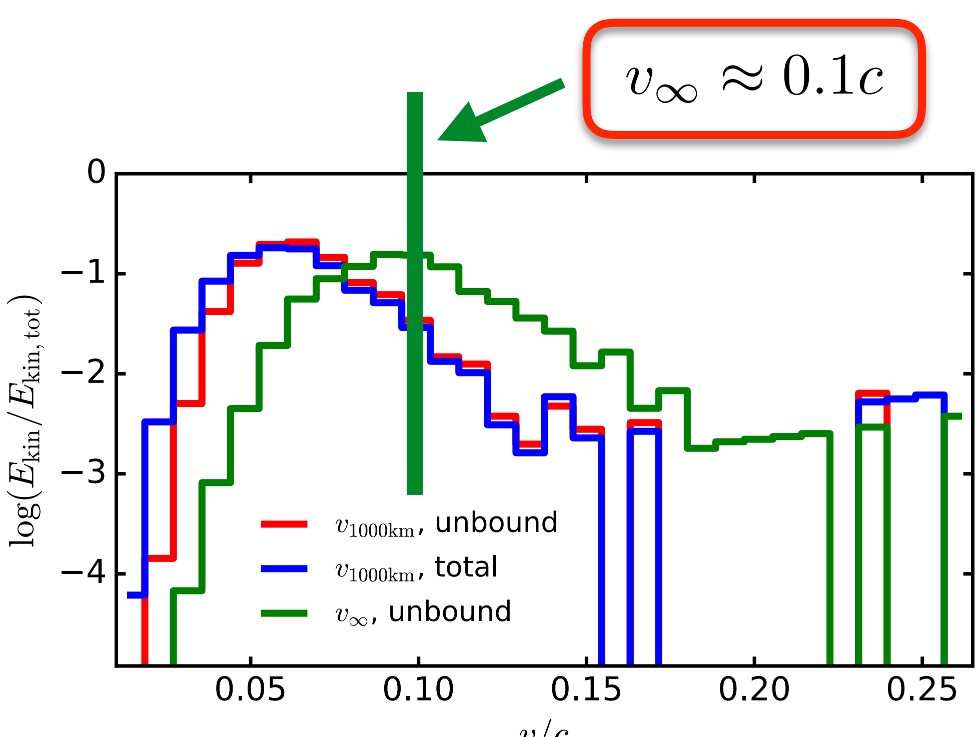
Movie: r-process nucleosynthesis from NS merger remnant disks

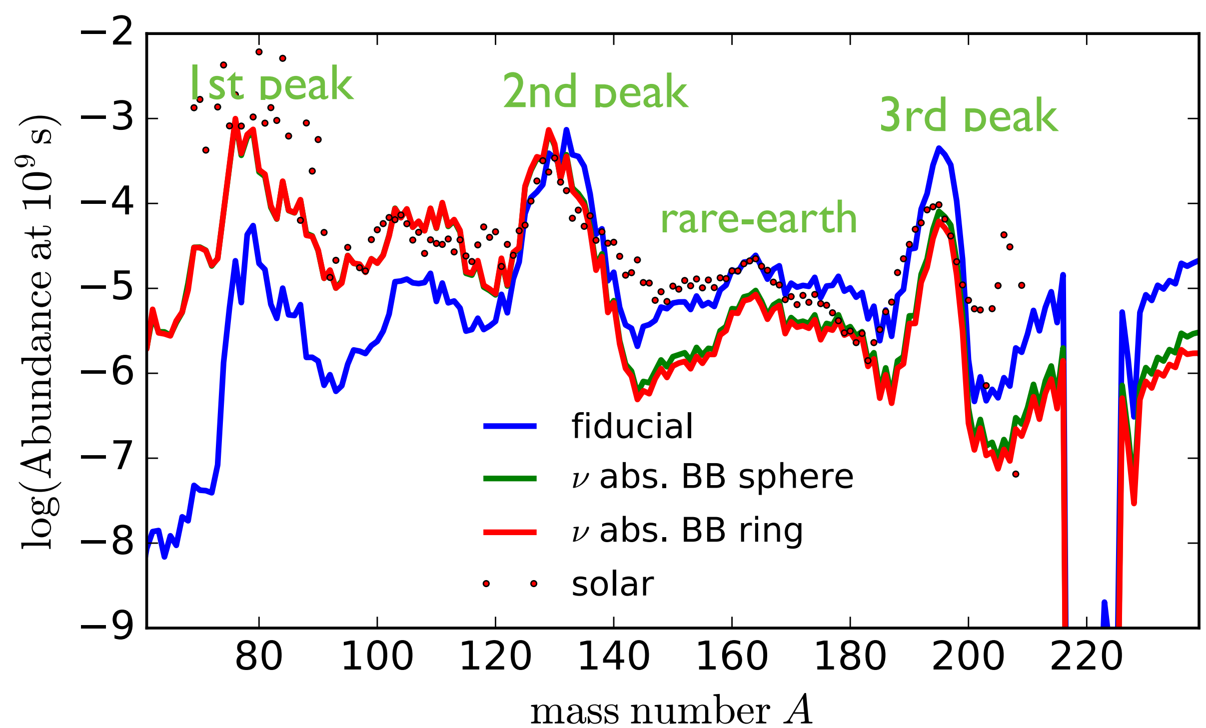
Disk outflows and the red kilonova

Siegel & Metzger 2017, PRL
Siegel & Metzger 2018



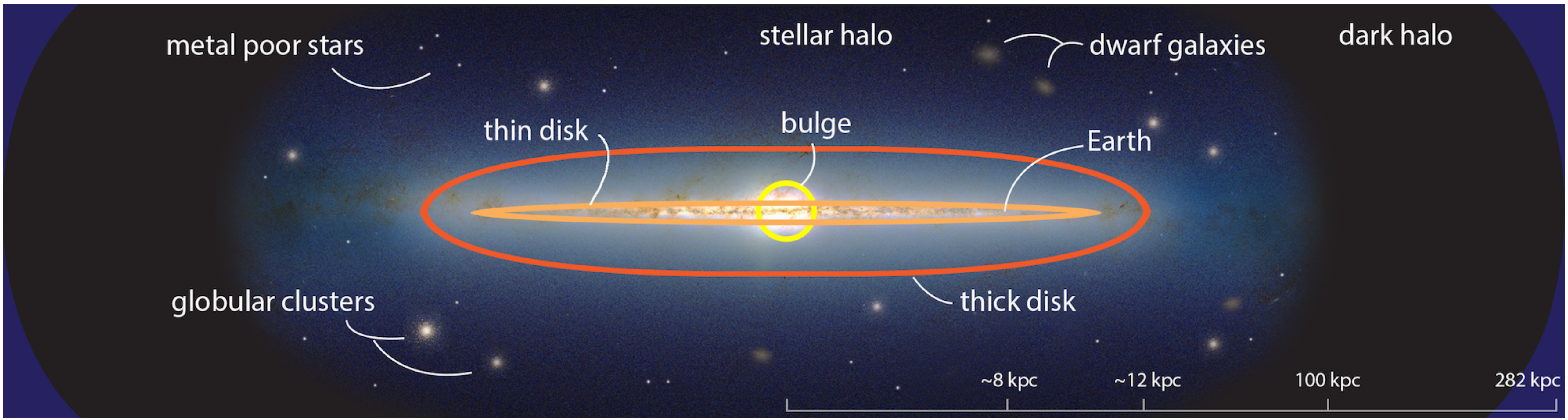
- Neutron-richness: self-regulation mechanism in degenerate inner disk provides neutron rich outflows (Y_e<0.25)
- Production of full range of r-process nuclei, excellent agreement with observed r-process abundances (solar, halo stars)
- Slow outflow velocities (~0.1c)
- Large amount of ejecta ($\gtrsim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





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

  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
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  - 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)

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

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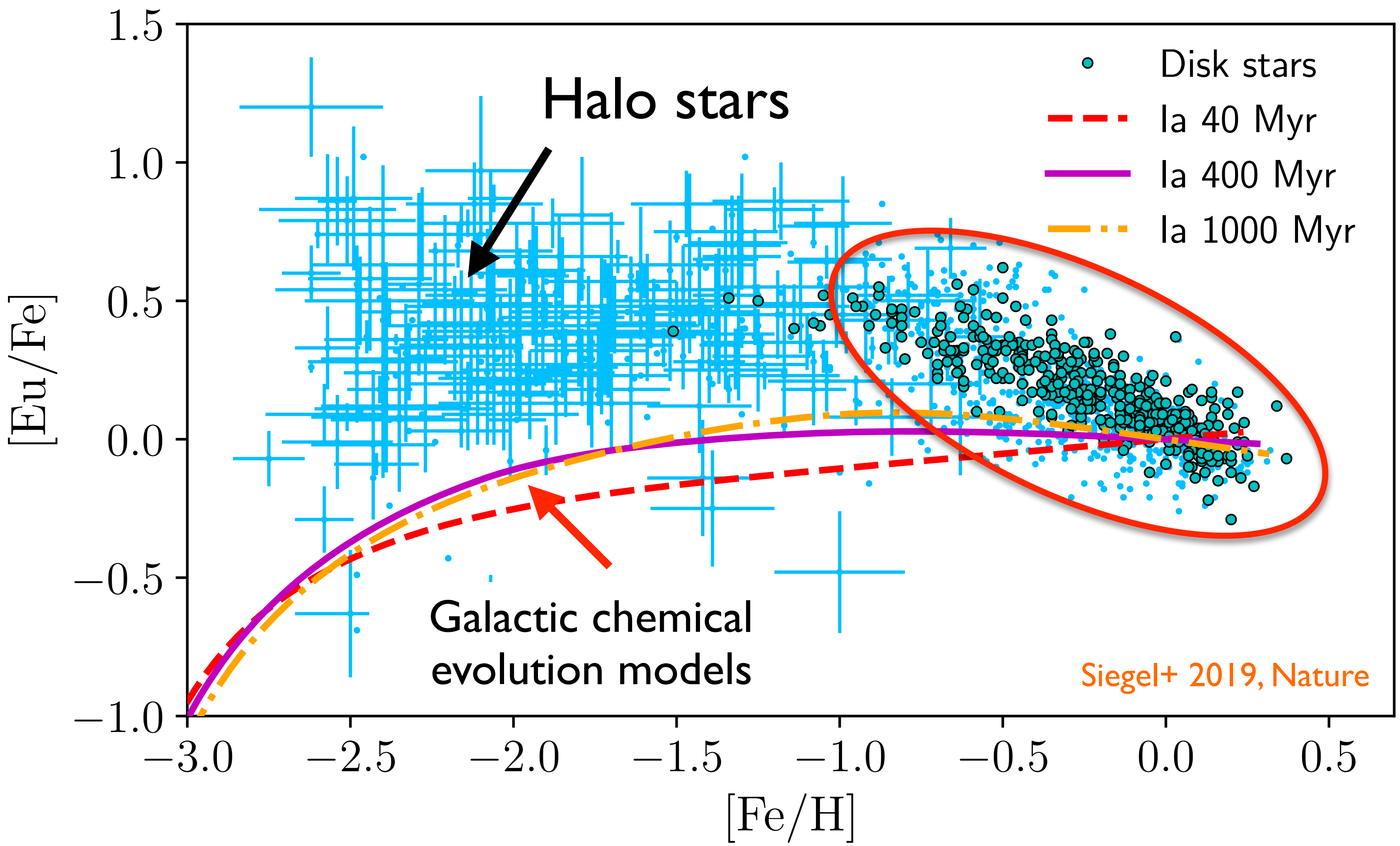
- halo stars at
  - need hierarc
  - need cross-|
- (UF) dwarf g
  - need extren
    Beniamini+ 201
  - need surviva
- globular clus
  - need extren
  - or need 2nd



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

Challenges for r-process from NS mergers

- halo
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  - or
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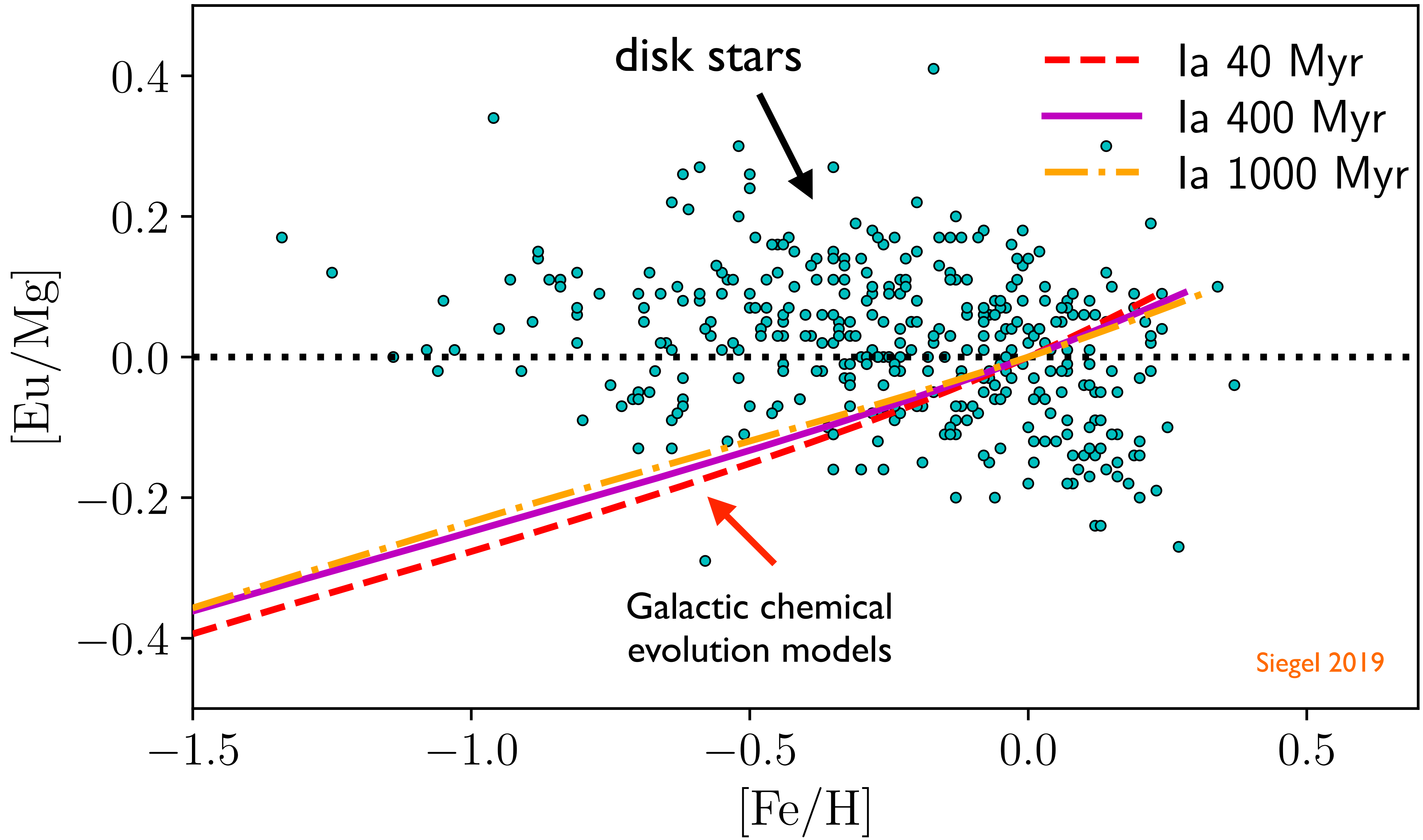

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  NS mergers inconsistent with Eu/Mg evolution of disk stars Siegel 2019

III.
Collapsars

Collapsars

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

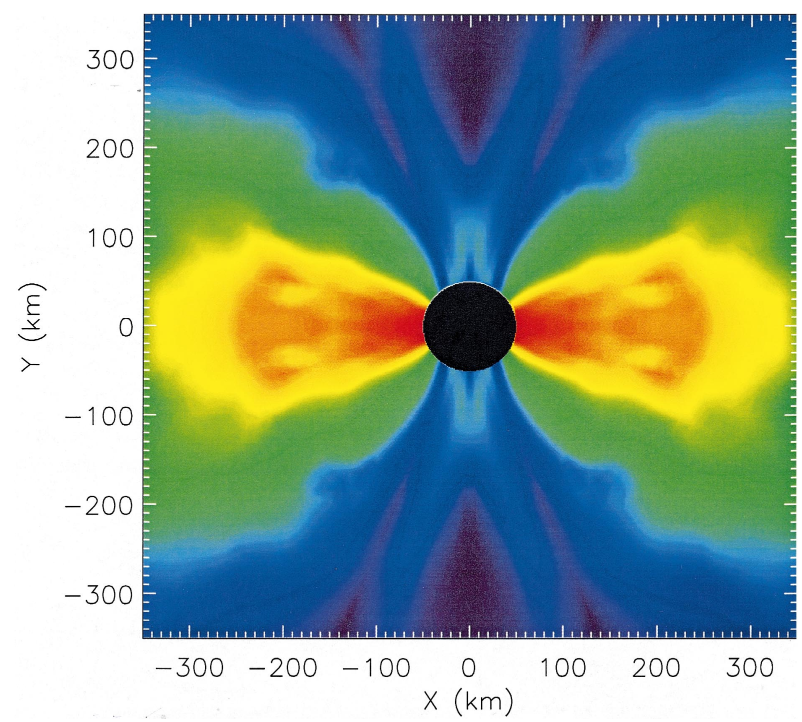
  ⟶ "failed explosion" (direct collapse to a BH)

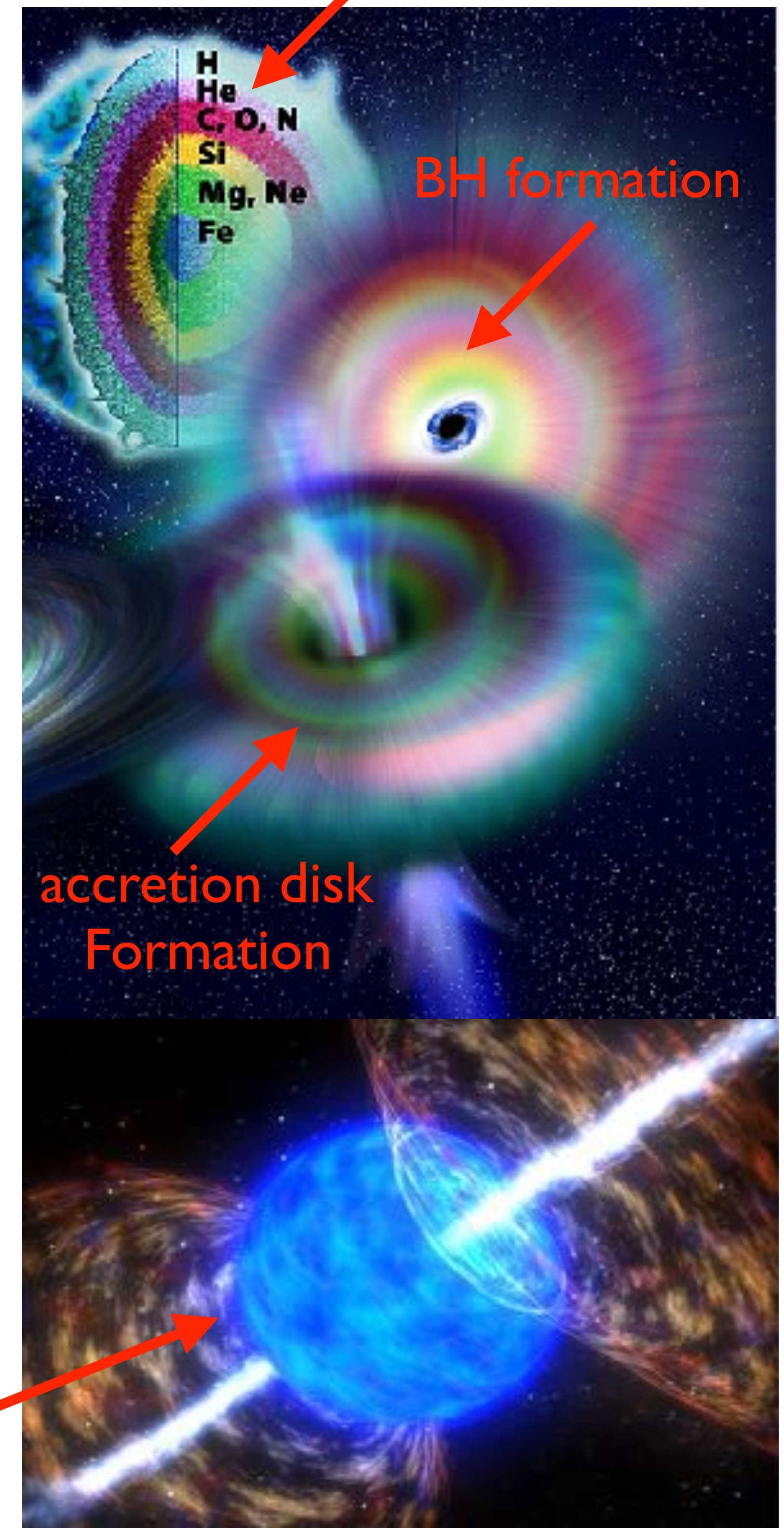
  ⟶ "weak explosion" (proto-NS collapses due to fallback material)

- 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)

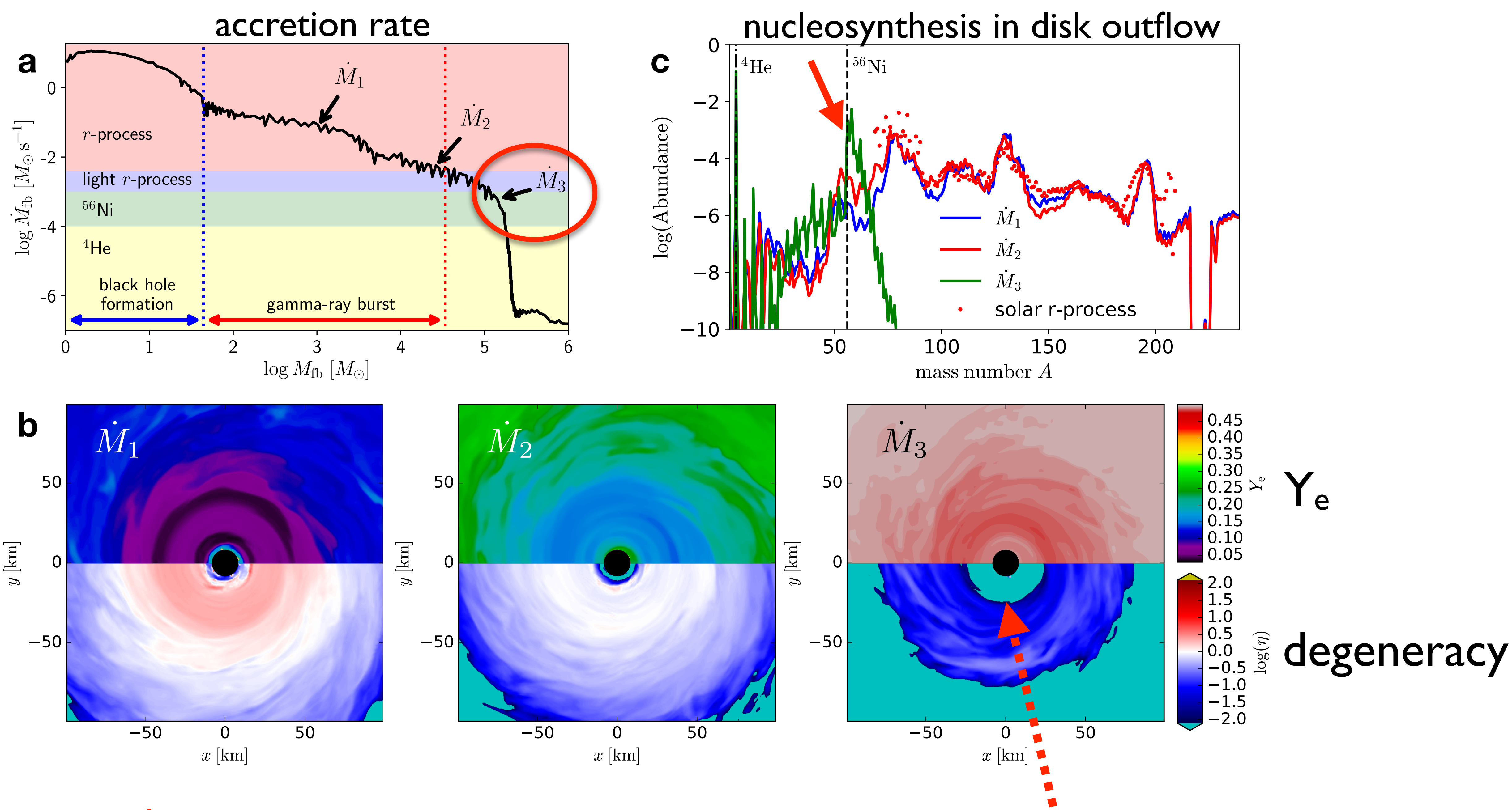
MacFadyen & Woosley 1999





r-process in collapsars

Siegel, Barnes, Metzger 2019, Nature



Neutron-richness:

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

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

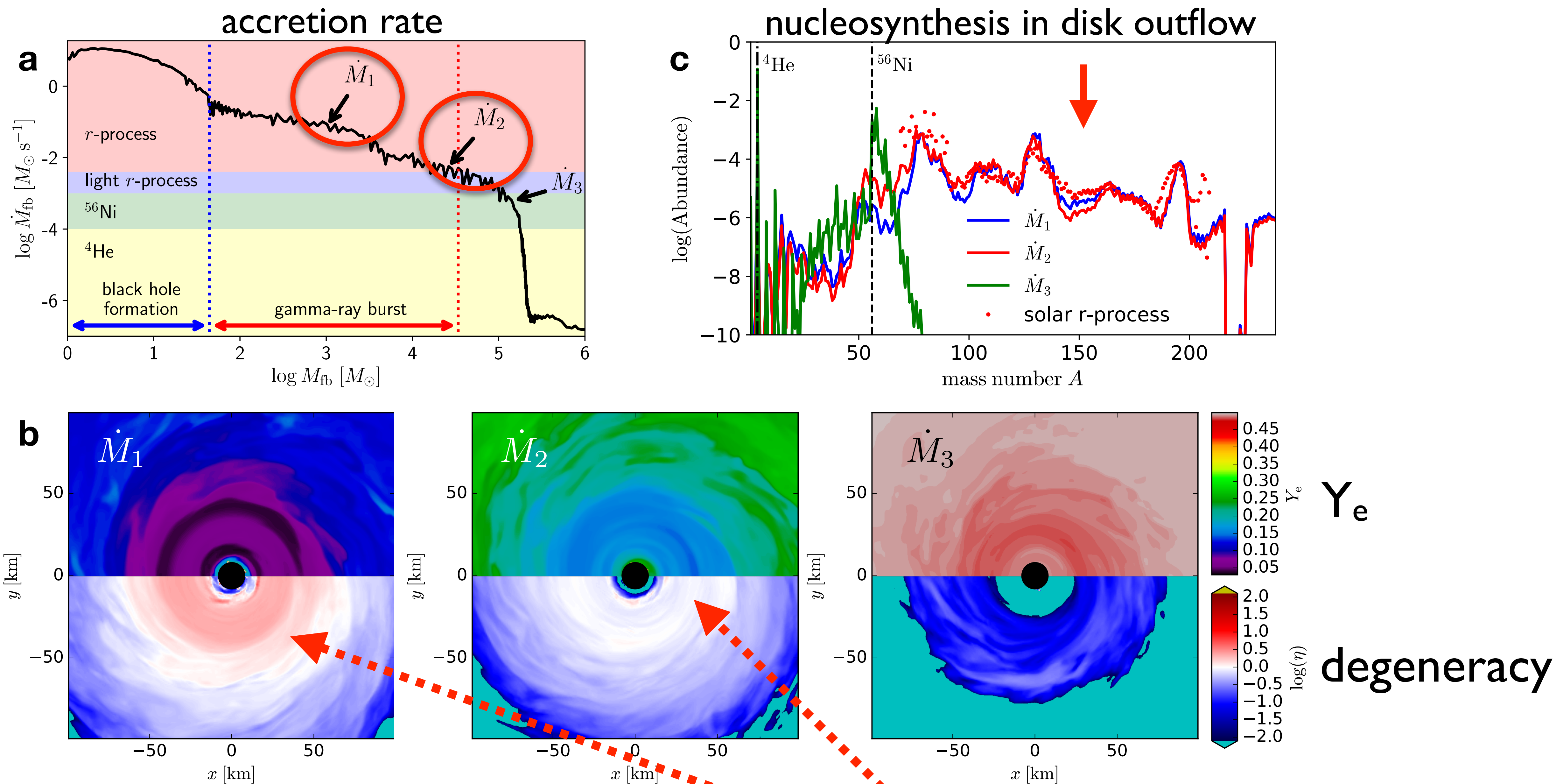
Low disk densities (low $\dot{M}$):

$Y_e \sim 0.5$

outflows produce ^{56}Ni

r-process in collapsars

Siegel, Barnes, Metzger 2019, Nature



Neutron-richness:

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

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

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 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:

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

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

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

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  - maybe need hierarchical assembly of halo from sub-halos
  - maybe need cross-pollution of sub-halos

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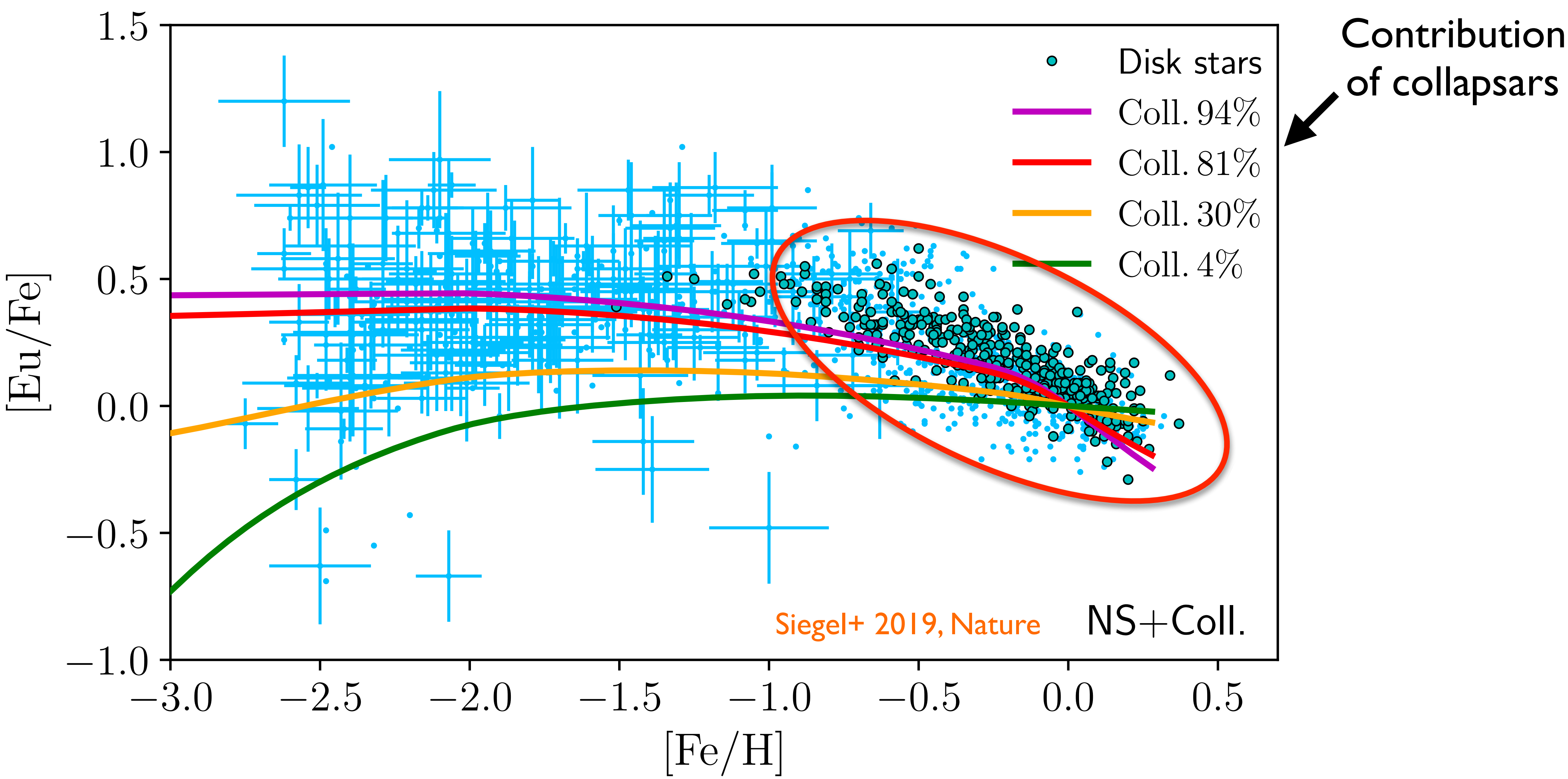
Collapsars vs. challenges for NS mergers



- r-process vs. Fe evolution (disk stars)

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

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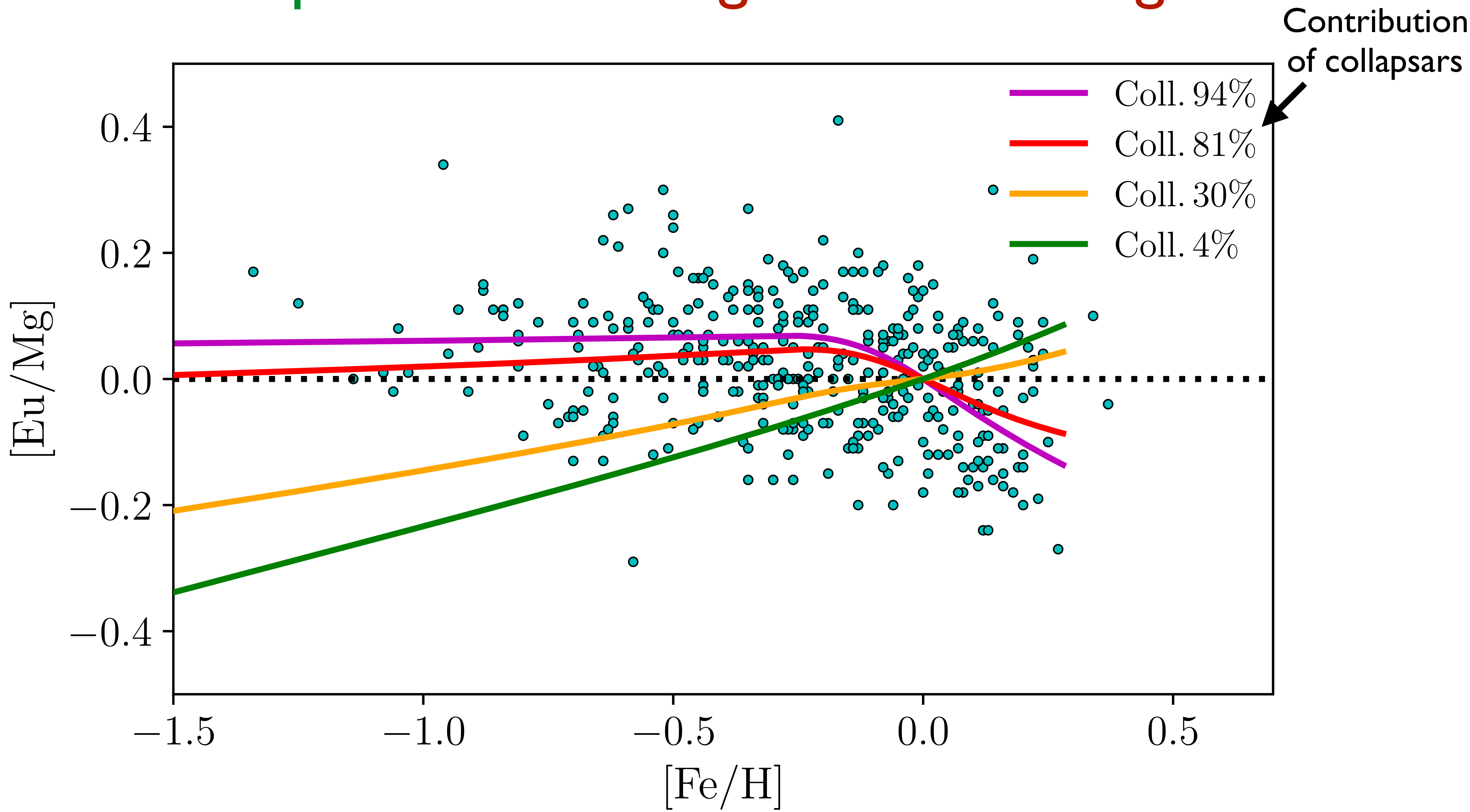

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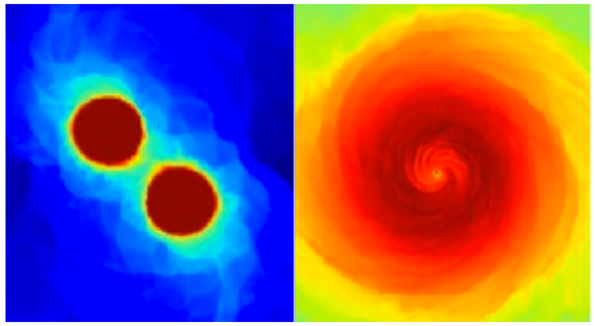
Conclusions

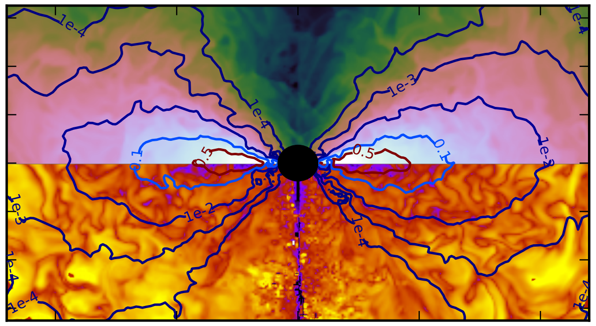
Core-collapse supernovae:

- ordinary CC-SNe unlikely to produce any r-process elements
- MHD supernovae may contribute to the light r-process



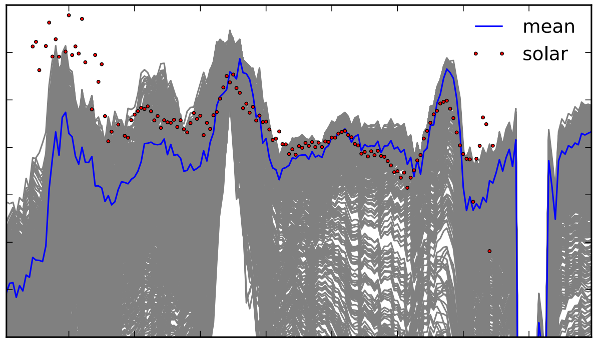
NS mergers:

- 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

Collapsars: likely dominant contribution to Galactic r-process



→ similar physics as in NS post-merger disks

→ lower event rate overcompensated by higher yield

→ overcome observational challenges of merger-only models for Galactic r-process

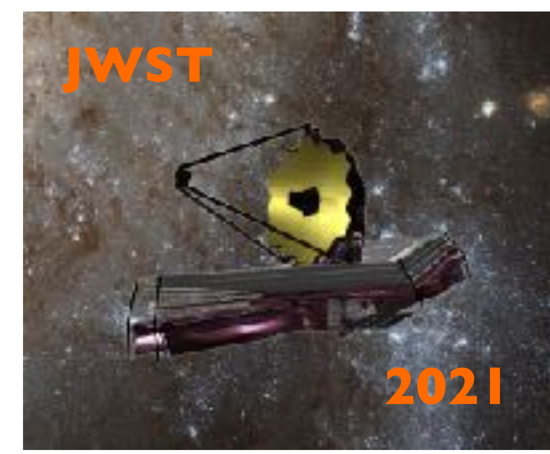
→ direct observational imprint of r-process in late-time GRB supernova lightcurves & spectra

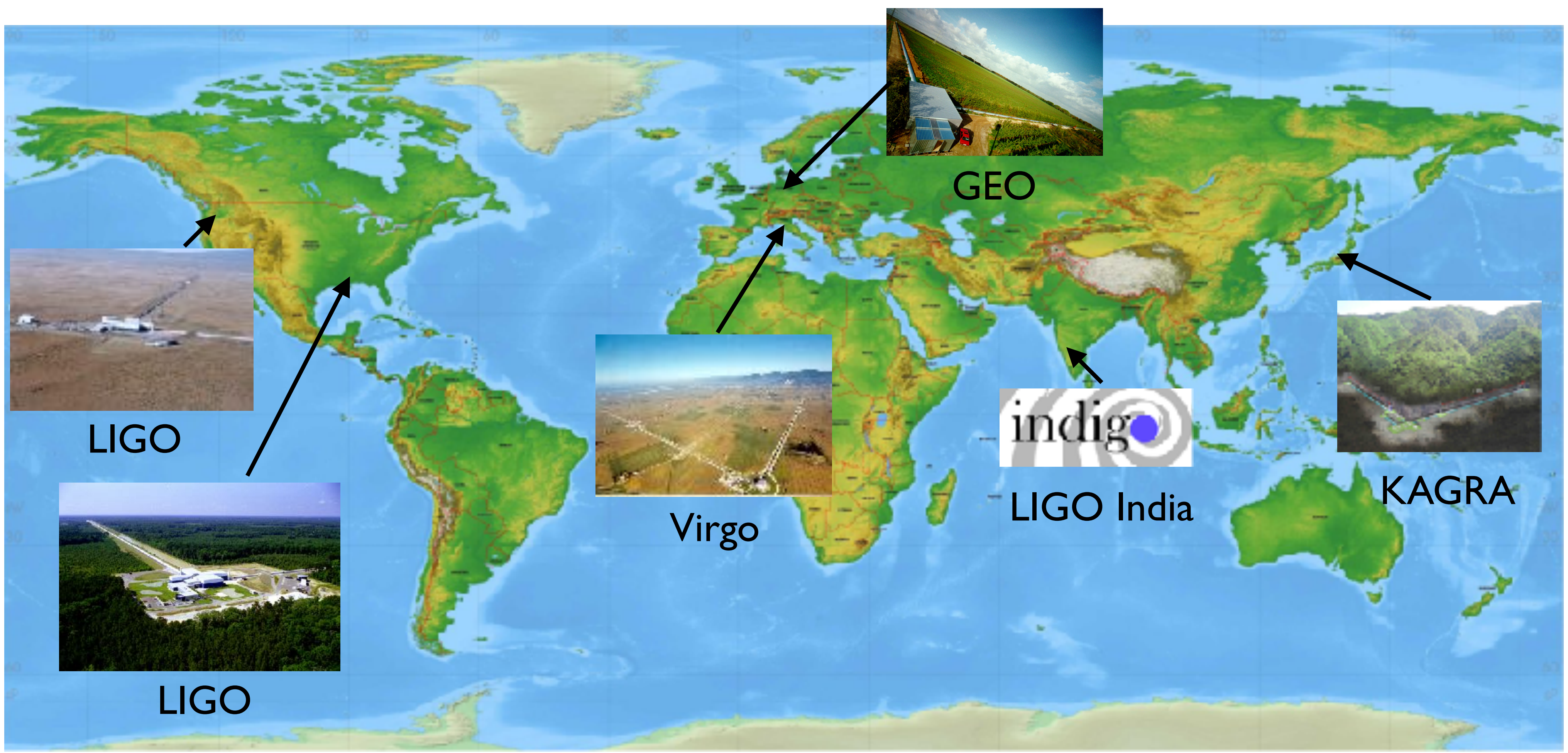
→ GRB supernova radiation transport modeling likely rules out MHD supernovae to produce lanthanides

Outlook: some thoughts on the future

Population of NS mergers & kilonovae:

- better understand post-merger evolution
  (instabilities, complex interplay between gravity, EM and thermal effects, weak interactions)
- How ubiquitous are massive disks?
  Dominate overall mass ejection?
- Merger rates, contribution of BH-NS





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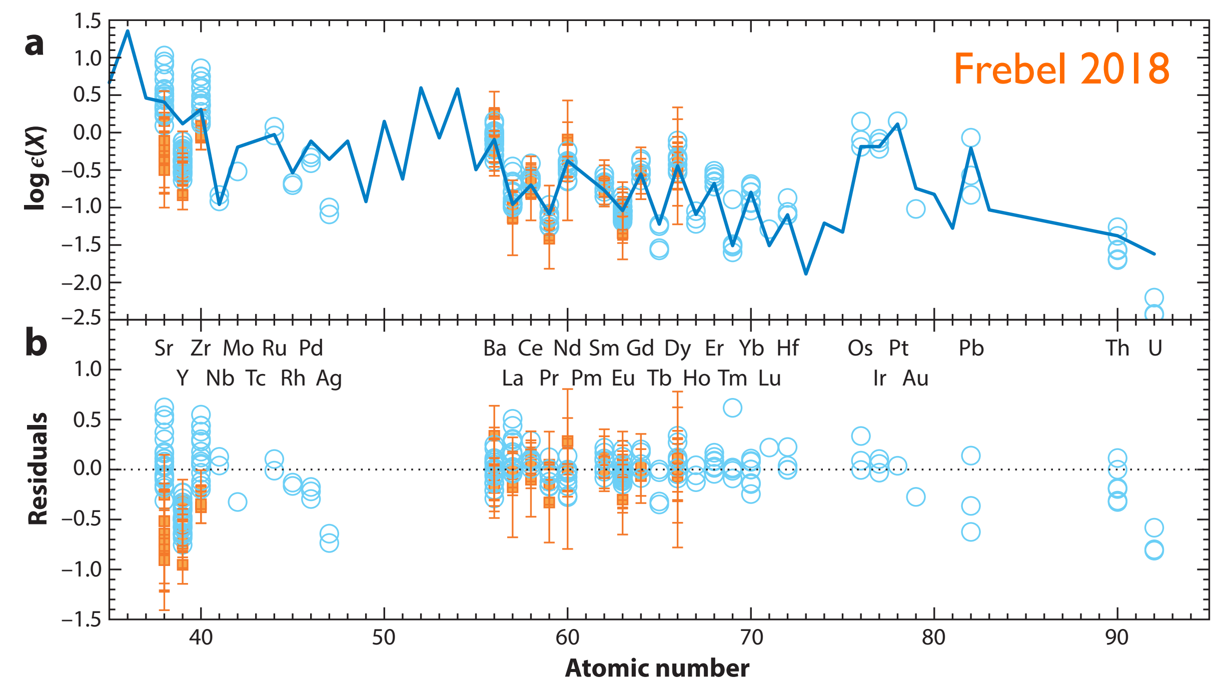
  - → contribution to r-process of other ejecta channels: dynamical ejecta, winds
  - → origin of actinide boost stars?
  - → light r-process and diversity
- neutrino oscillations?



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Long GRBs/collapsars: kilonovae in supernovae

- look for r-process features in nearby SN Ic-BL (~1-2 yr^{-1} at <100 Mpc): VLT
- more distant GRB supernovae with ELT

Other astrophysical sites?

Outlook: some thoughts on the future

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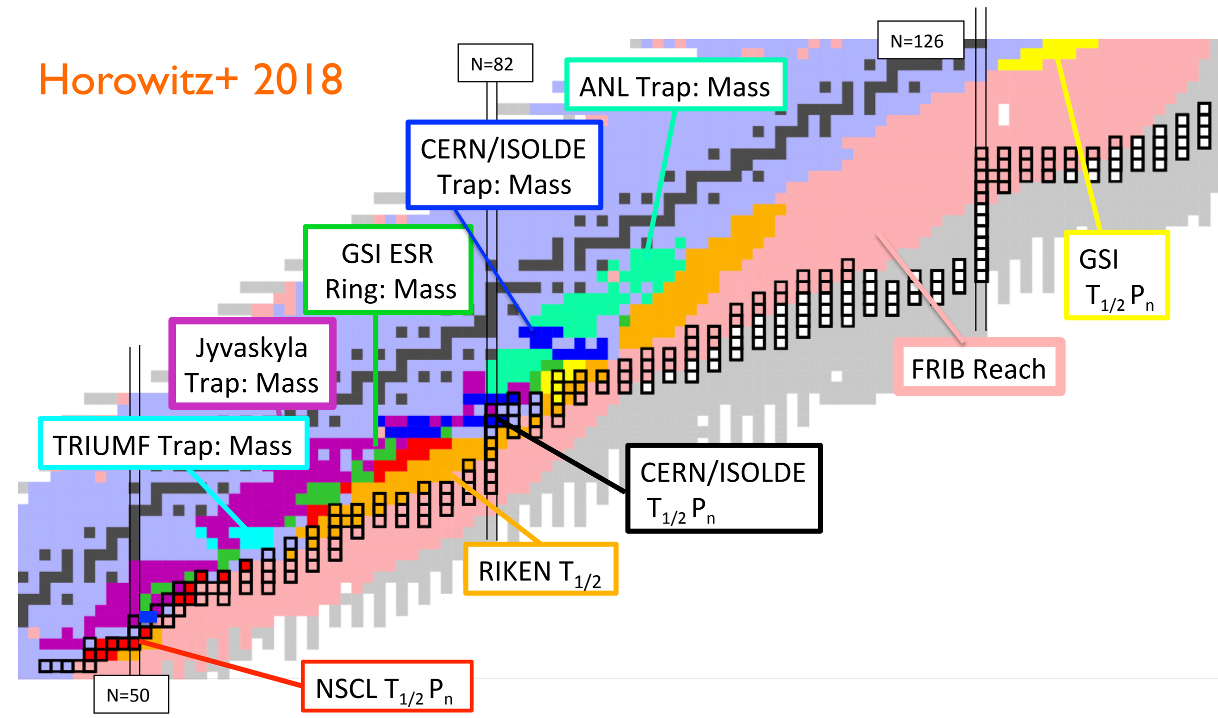

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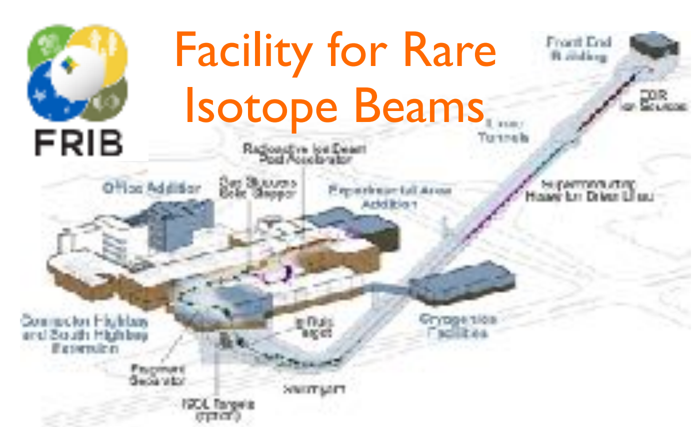


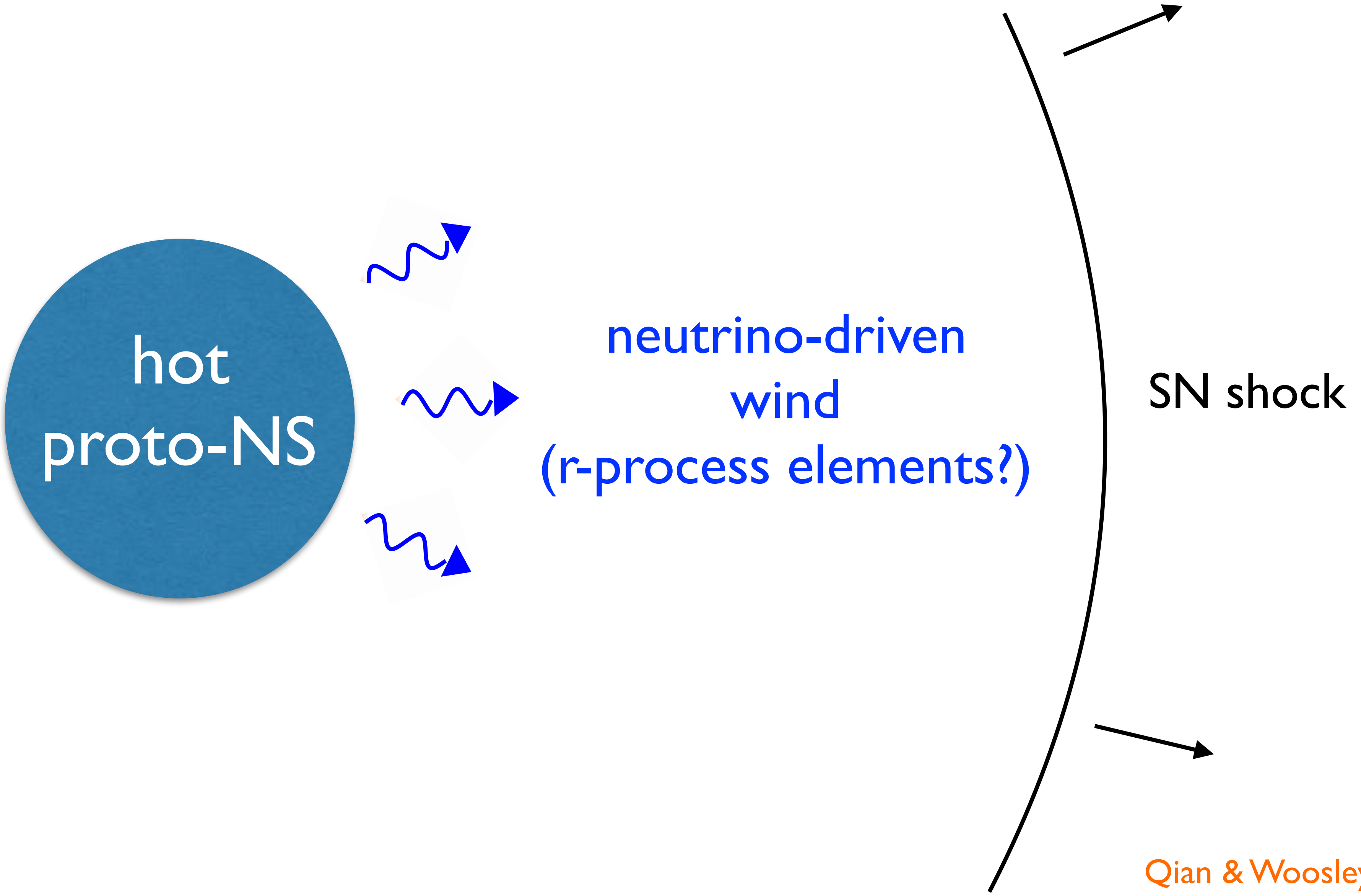
Other astrophysical sites?

Nuclear physics: experimental data on r-process nuclei

Chemical evolution: chemical assembly of the Milky Way, dwarf galaxies, globular clusters

Appendix

Core-collapse supernovae

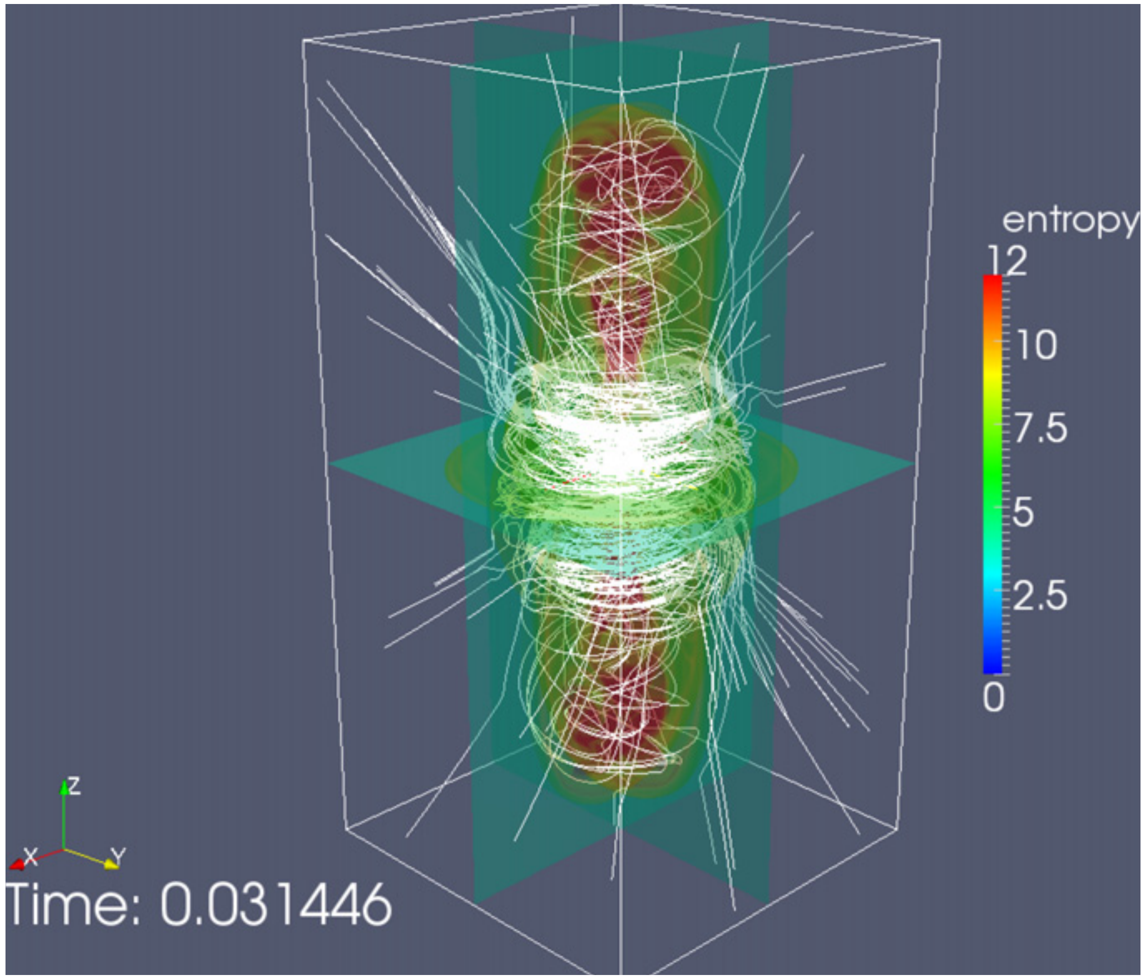


Qian & Woosley 1996
Hüdepohl+ 2010
Roberts+ 2012
Martinez-Pinedo+ 2012
Janka 2016
Fischer+ 2018

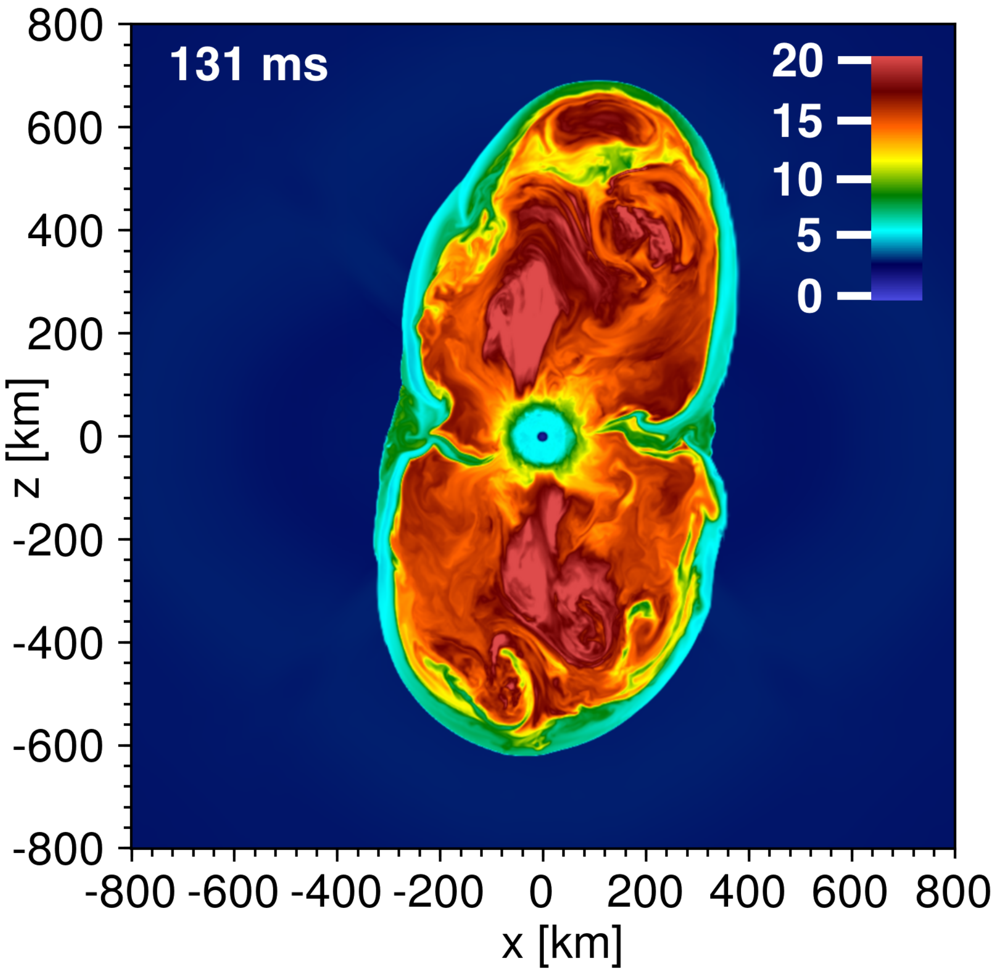
- theoretically: neutrino-driven wind mostly proton-rich
- observationally: disfavored by ^{244}Pu measurements

Wallner+ 2015
Hotokezaka+ 2015

MHD supernovae



Winteler+ 2012



Moesta+ 2018

- magnetically driven explosion (jet) could eject neutron rich material fast enough to trigger r-process Winteler+ 2012, Nishimura+ 2017

But:

- when 3D jet stability taken into account, unlikely to produce heavy r-process Mösta+ 2018 Halevi & Mösta 2018
- effect of high-opacity r-process material inconsistent with SN lightcurves & spectra Siegel+ 2019

A multi-physics challenge

Fully coupled!

General Relativity	→	Gravity
Magnetohydrodynamics	→	Gas/plasma dynamics
Nuclear Physics, weak interactions	→	Nuclear EOS, nuclear reactions, neutrino interactions
Neutrino radiation transport	→	neutrino heating & cooling

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

$$T^{\mu\nu} = T^{\mu\nu}_{\rm mat} + T^{\mu\nu}_{\rm EM} + T^{\mu\nu}_{\rm neu}$$

$$\nabla_\mu T^{\mu\nu} = \Psi^\nu$$

$$\nabla_\mu {}^\star F^{\mu\nu} = 0$$

$$\nabla_\mu (n_{\rm b} u^\mu) = 0$$

$$\nabla_\mu (n_{\rm e} u^\mu) = \mathcal{R}$$

Weak interactions (neutrinos):

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

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

$$e^+ + e^- \to \bar{\nu}_{e,\mu,\tau} + \nu_{e,\mu,\tau}$$

$$\gamma \to \bar{\nu}_{e,\mu,\tau} + \nu_{e,\mu,\tau}$$

⇒ $\Psi^\nu,\ \mathcal{R}$

State-of-the-art GRMHD

GRHydro+ Siegel & Metzger 2017 Siegel+ 2017

See also: Palenzuela+ 2015

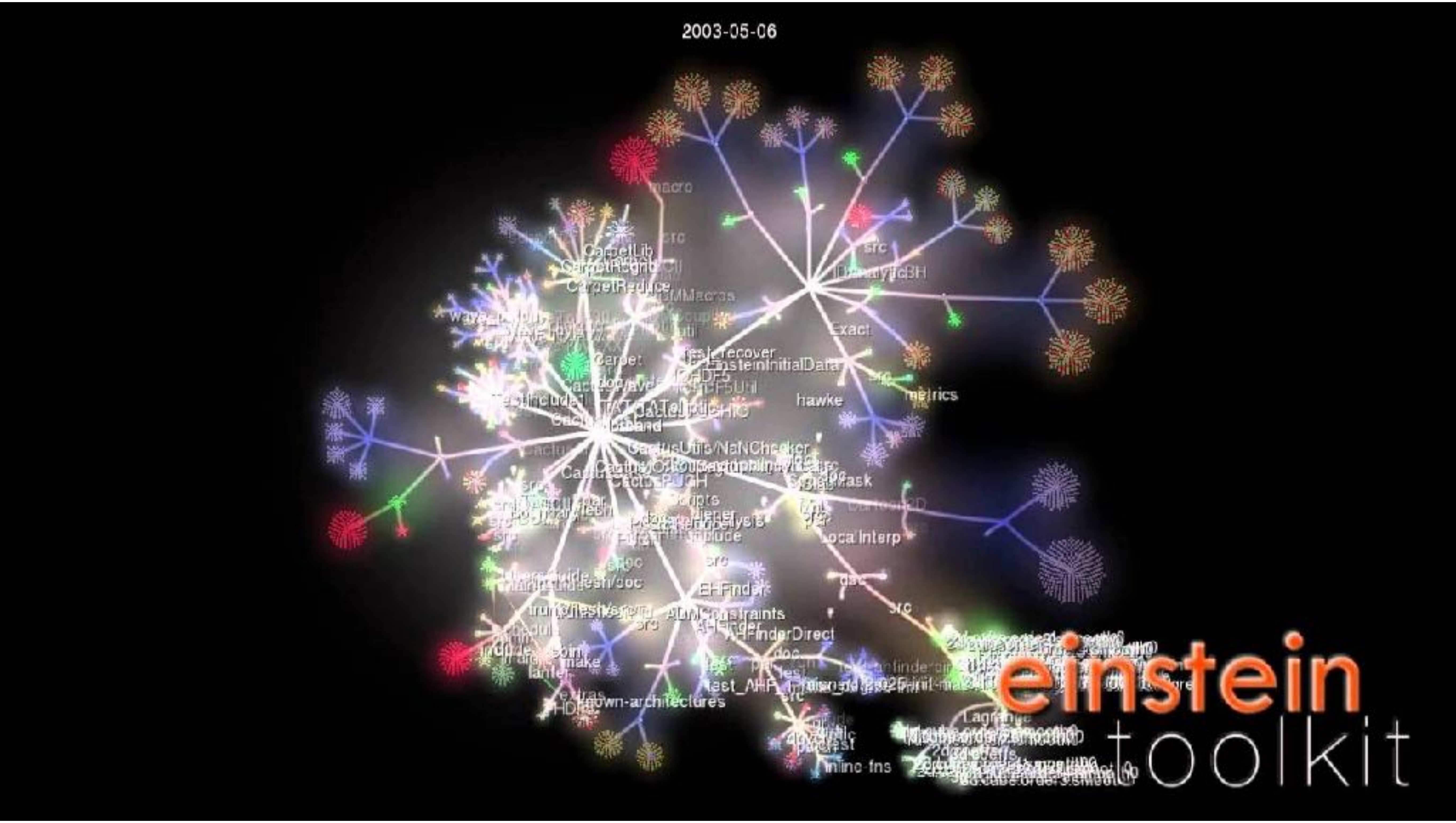
- evolved version of original GRHydro Moesta+ 2014
- ideal GRMHD
- dynamic and fixed spacetimes
- realistic (tabulated) 3-parameter nuclear EOS
- enhanced methods for primitive recovery to support evolved microphysics
- weak interactions & approximate neutrino transport
- benefits from the *Einstein Toolkit*

  ⟶ provides spacetime solver, AMR (nested, moving boxes), multi-patch spherical grids, general infrastructure for HPC

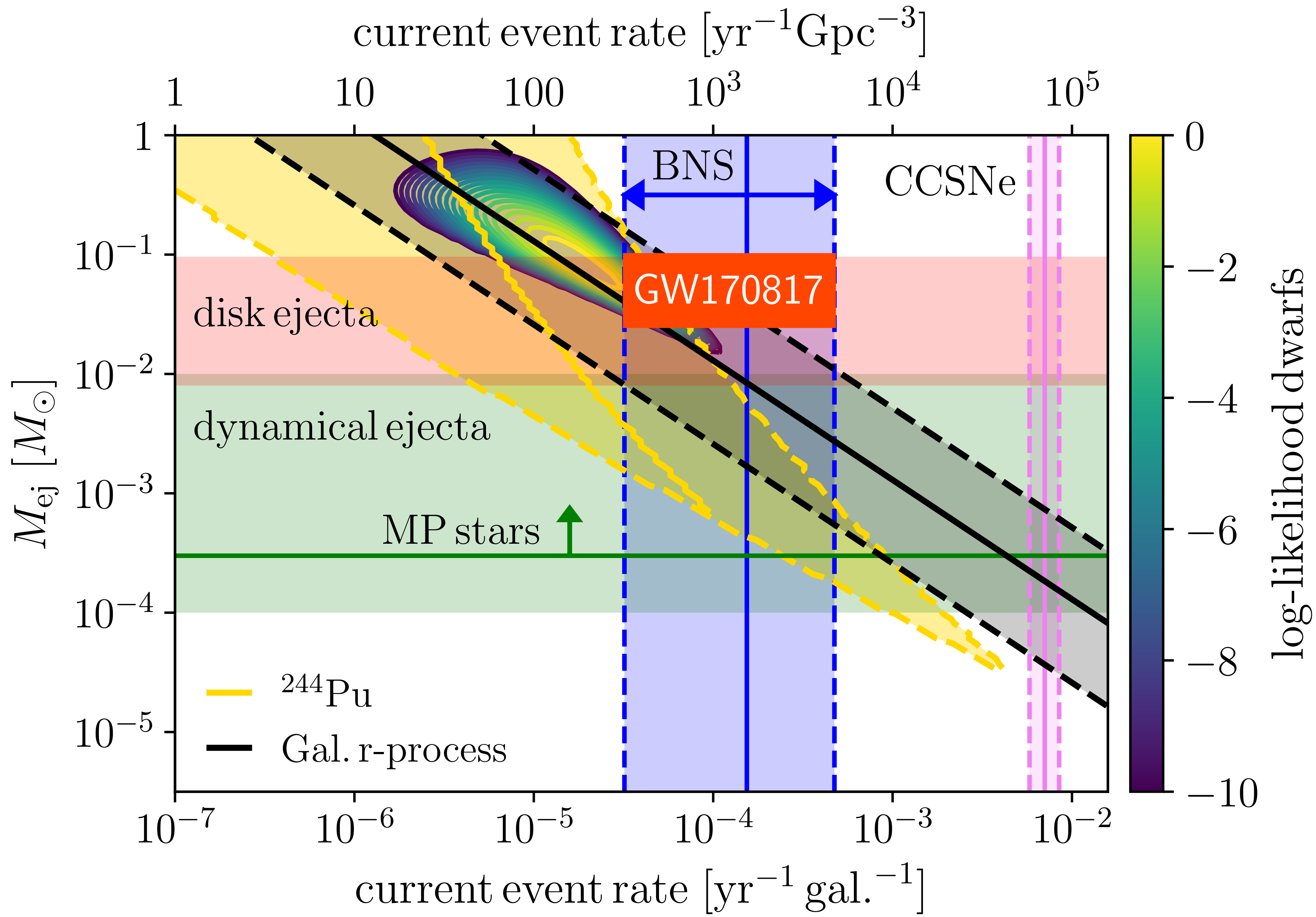
Nuclear reaction network

e.g.: *SkyNet* Lippuner & Roberts 2017

High performance computing infrastructure



Constraints on r-process nucleosynthesis

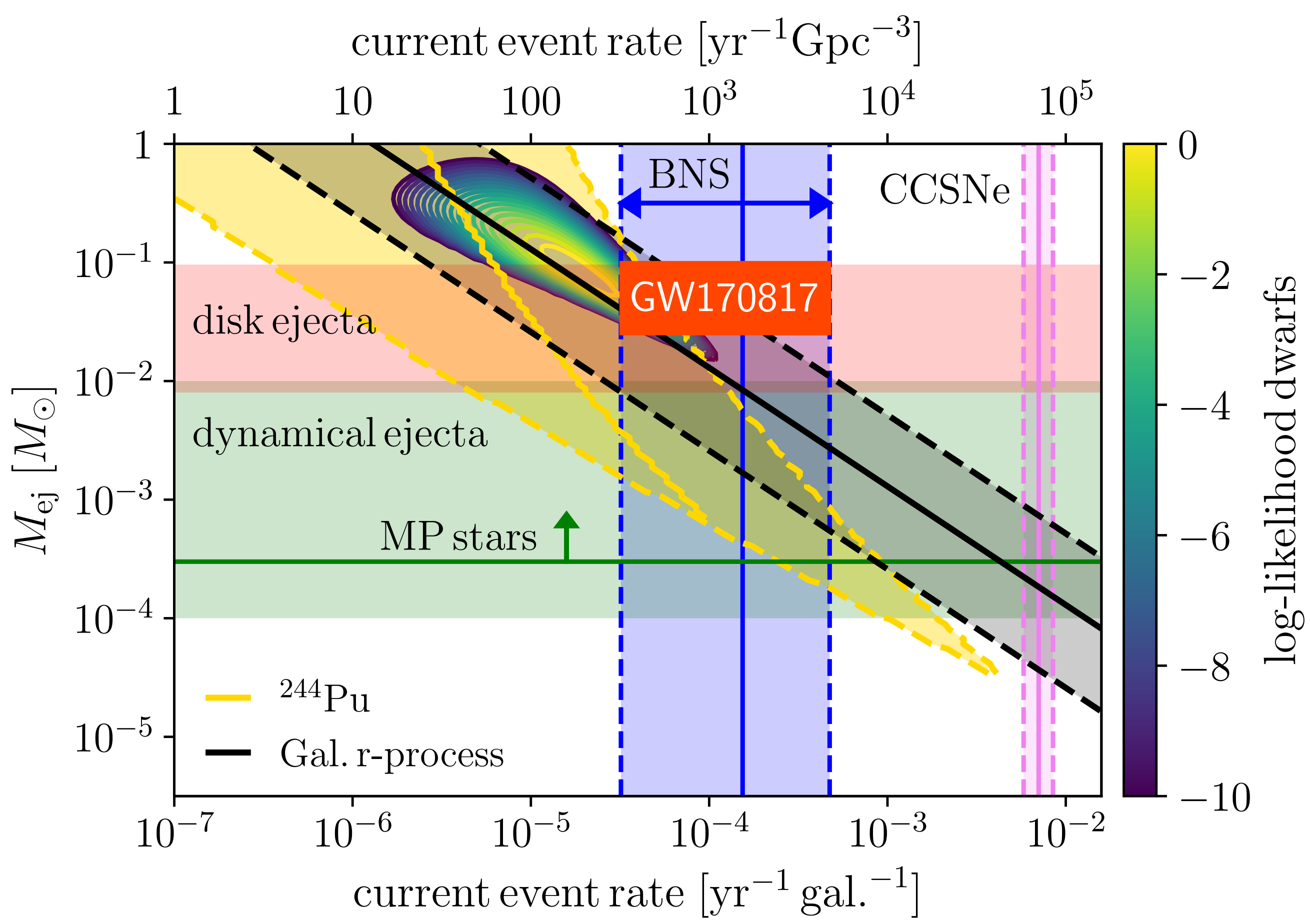


Siegel 2019

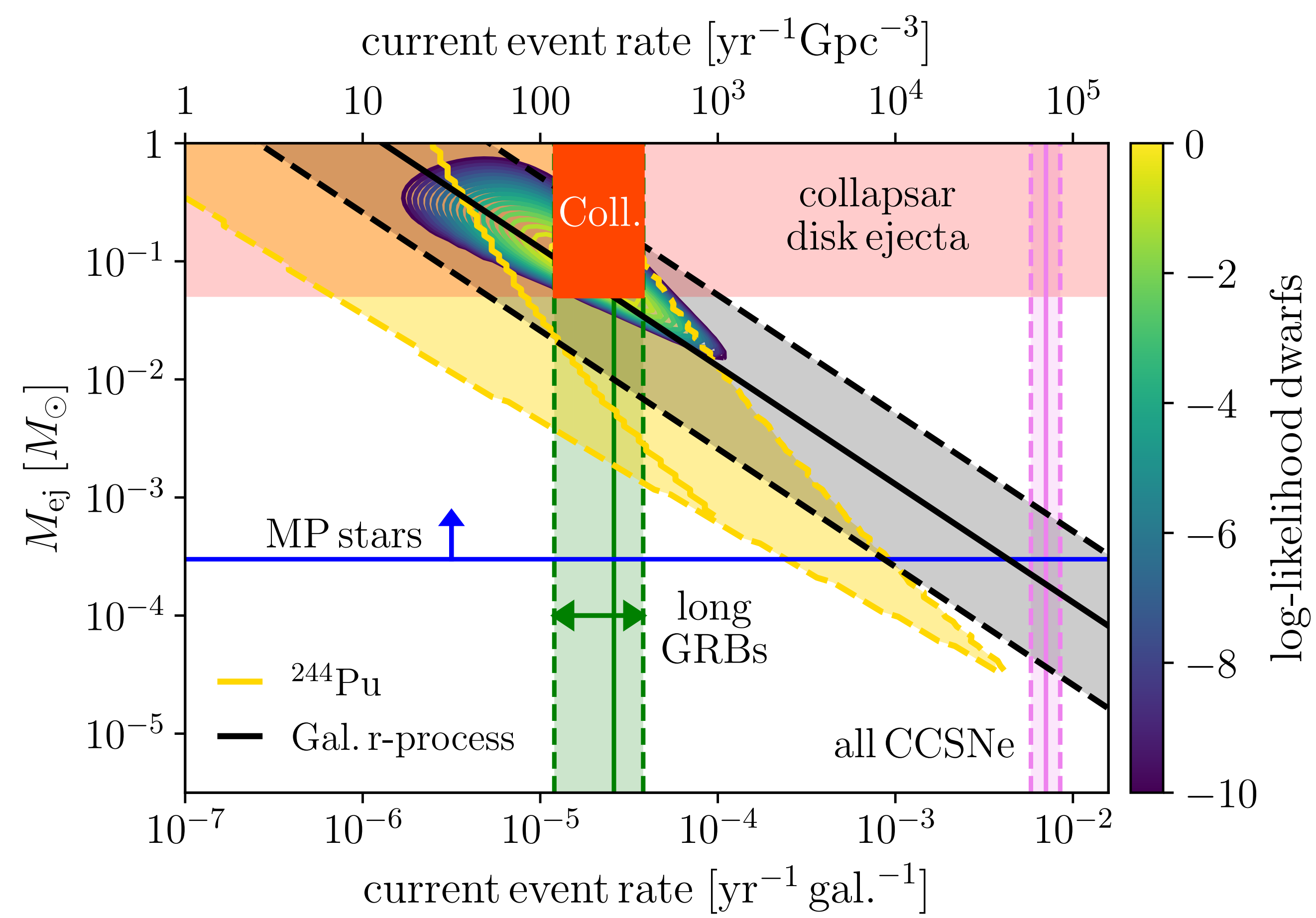
Constraints on r-process nucleosynthesis

Siegel 2019

NS mergers



collapsars



Challenges for r-process from NS mergers

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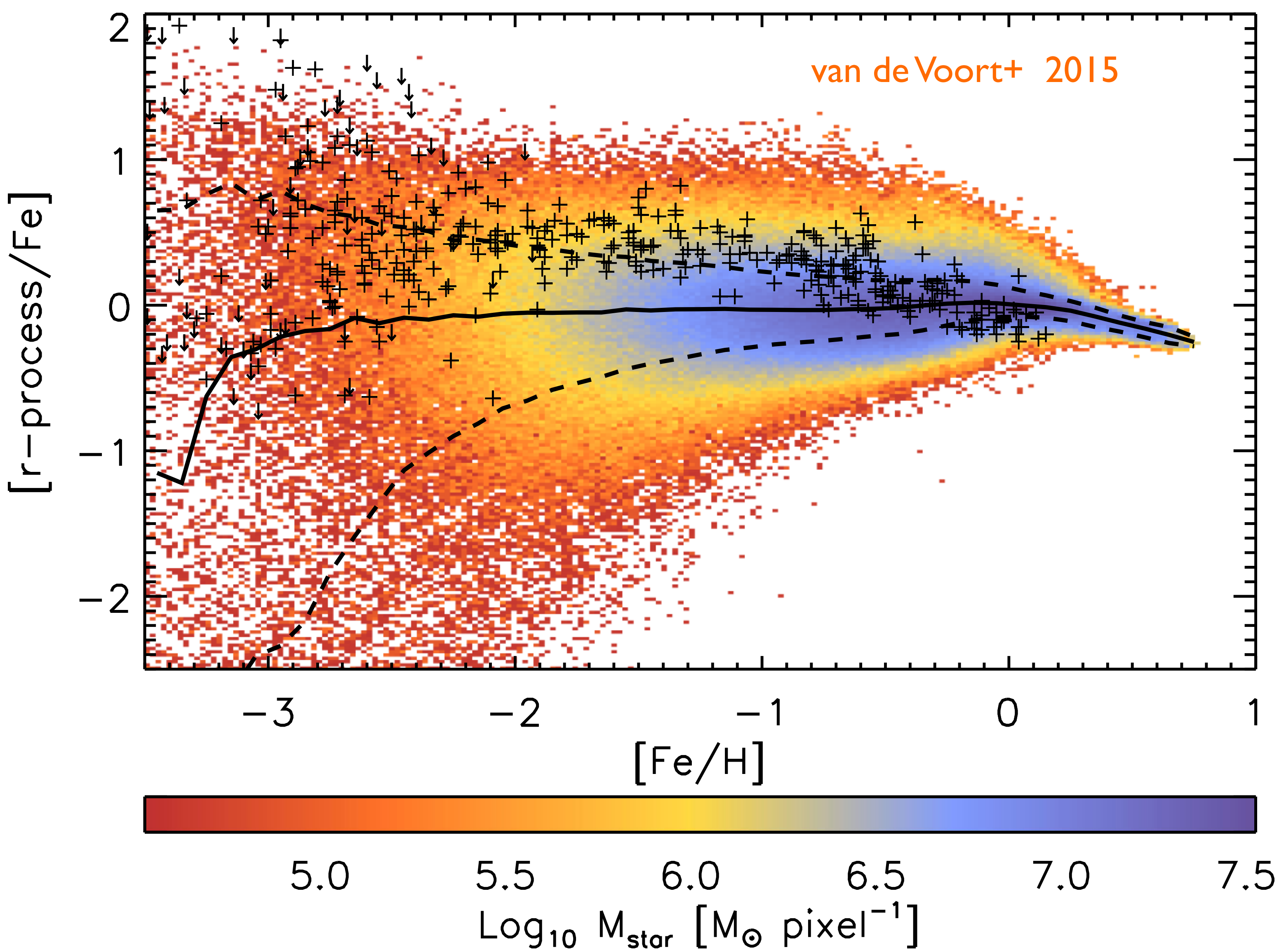
Ishimaru+ 2015
Hirai+ 2015
Komiya+ 2016



But see also:

Shen+ 2015

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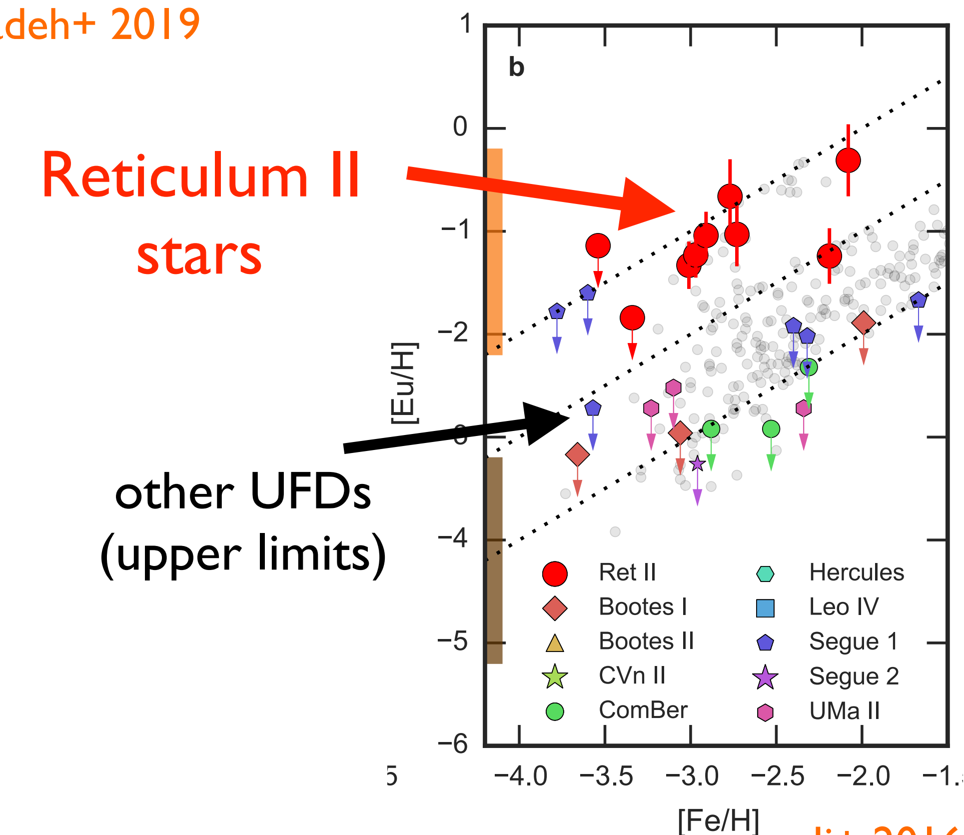

Ji+ 2016

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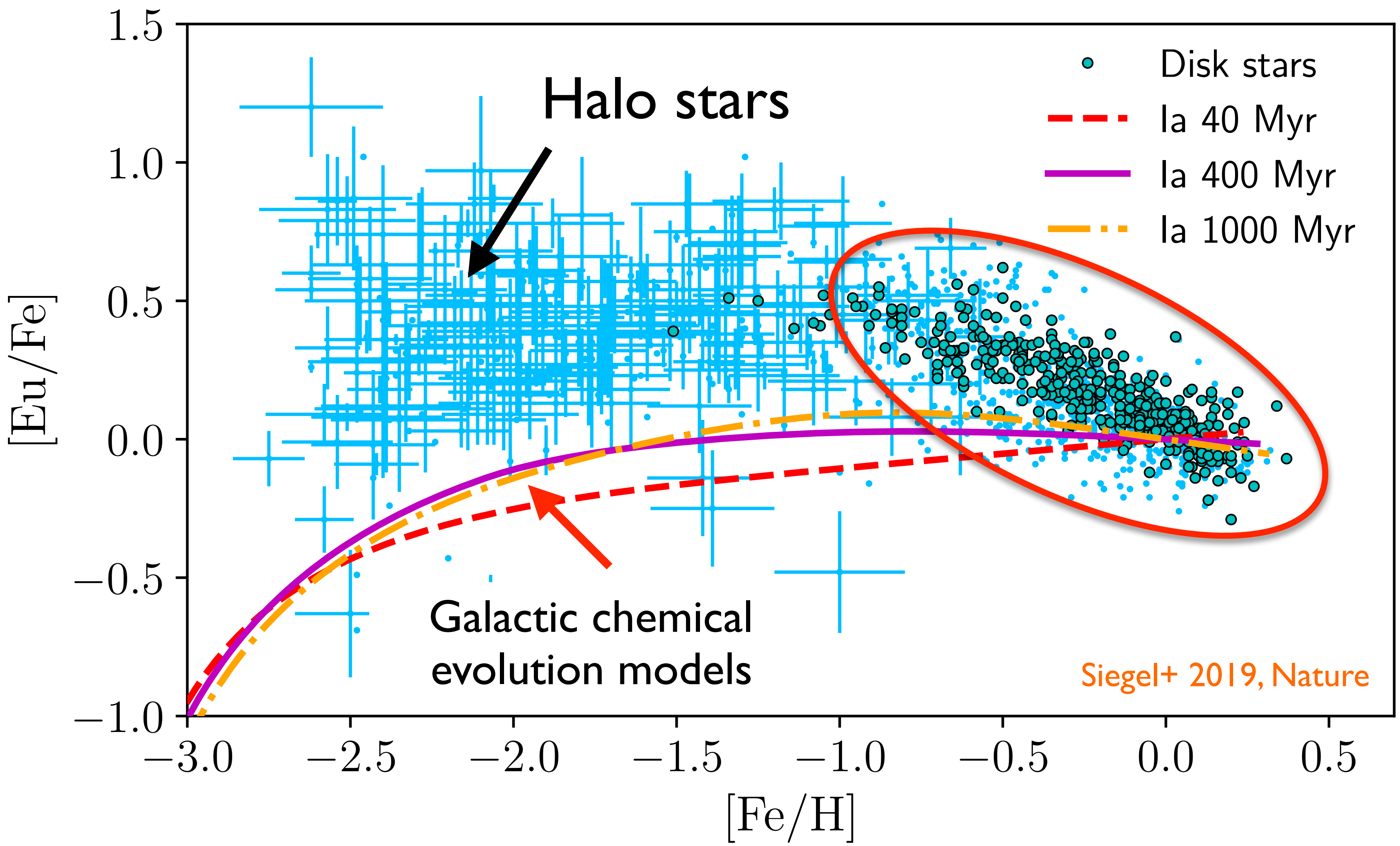

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- halo
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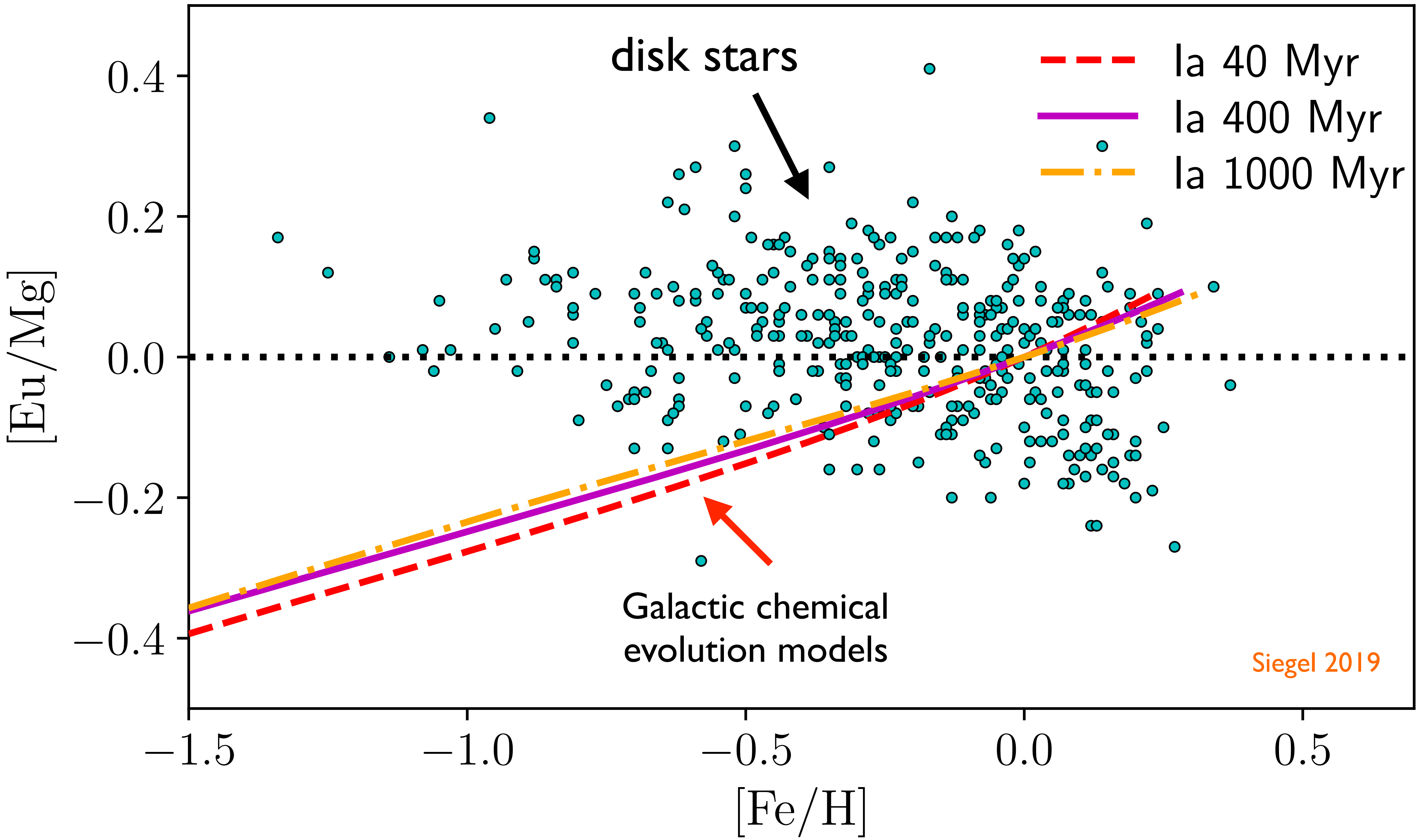

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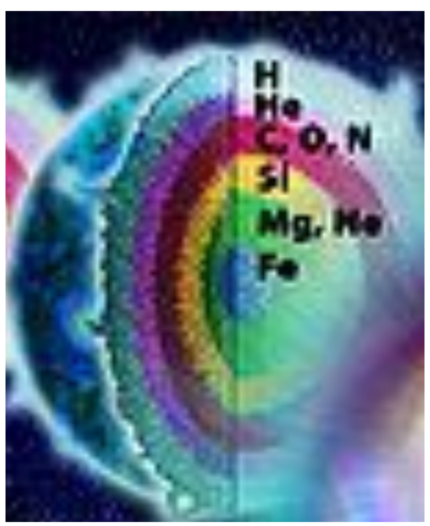
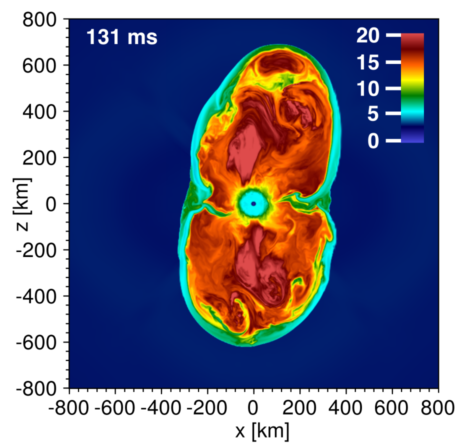
Collapsar scenario overview



core collapse



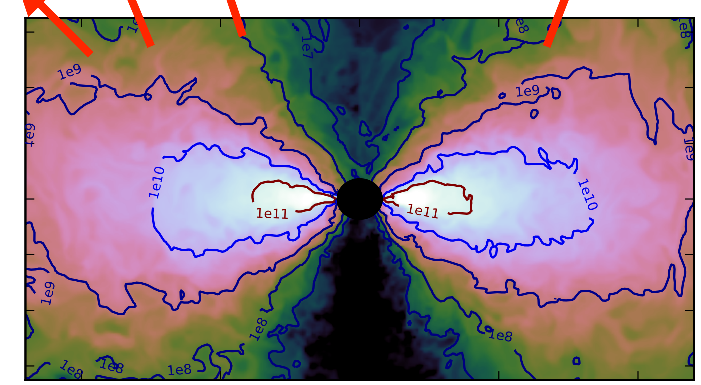
proto-magnetar
"MHD supernova"
Winteler+ 2012

contribution to (mostly) light r-process
Moesta+ 2018
Halevi & Moesta 2018

BH formation

GRB jet

r-process outflow



Collapsar accretion disk

Conjecture:

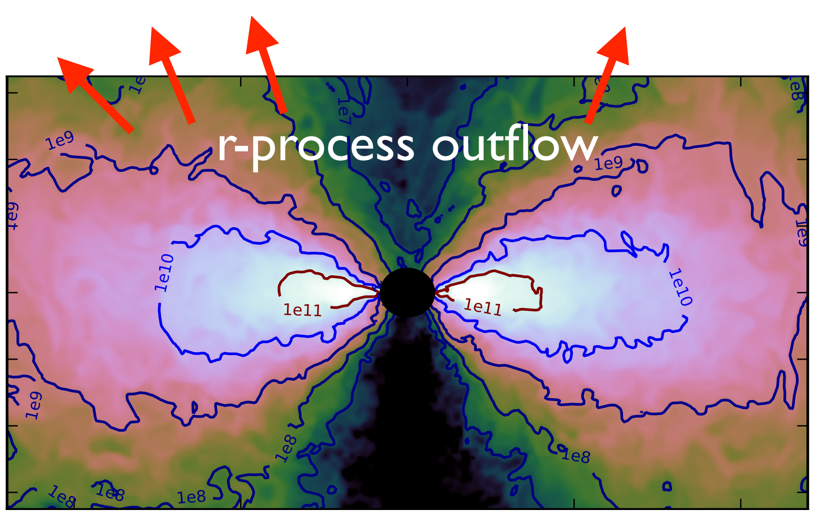
Outflows from compact accretion disks synthesize most of the Galactic heavy r-process elements

NS mergers

short GRBs

$\sim 0.03\ M_{sun}$

$\sim 1540\ \mathrm{Gpc^{-3}\ yr^{-1}}$



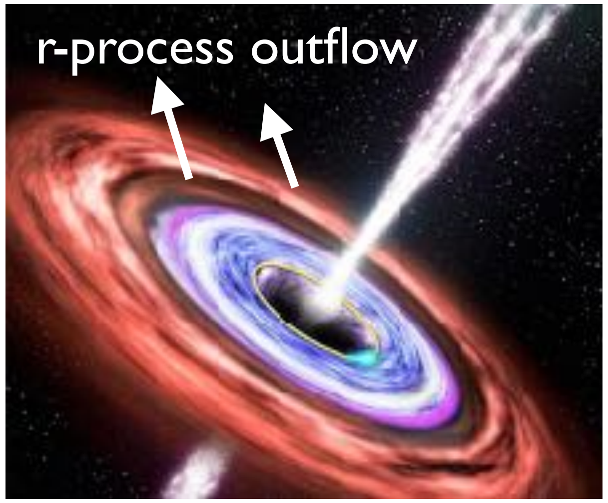
(current rates)

Collapsars

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

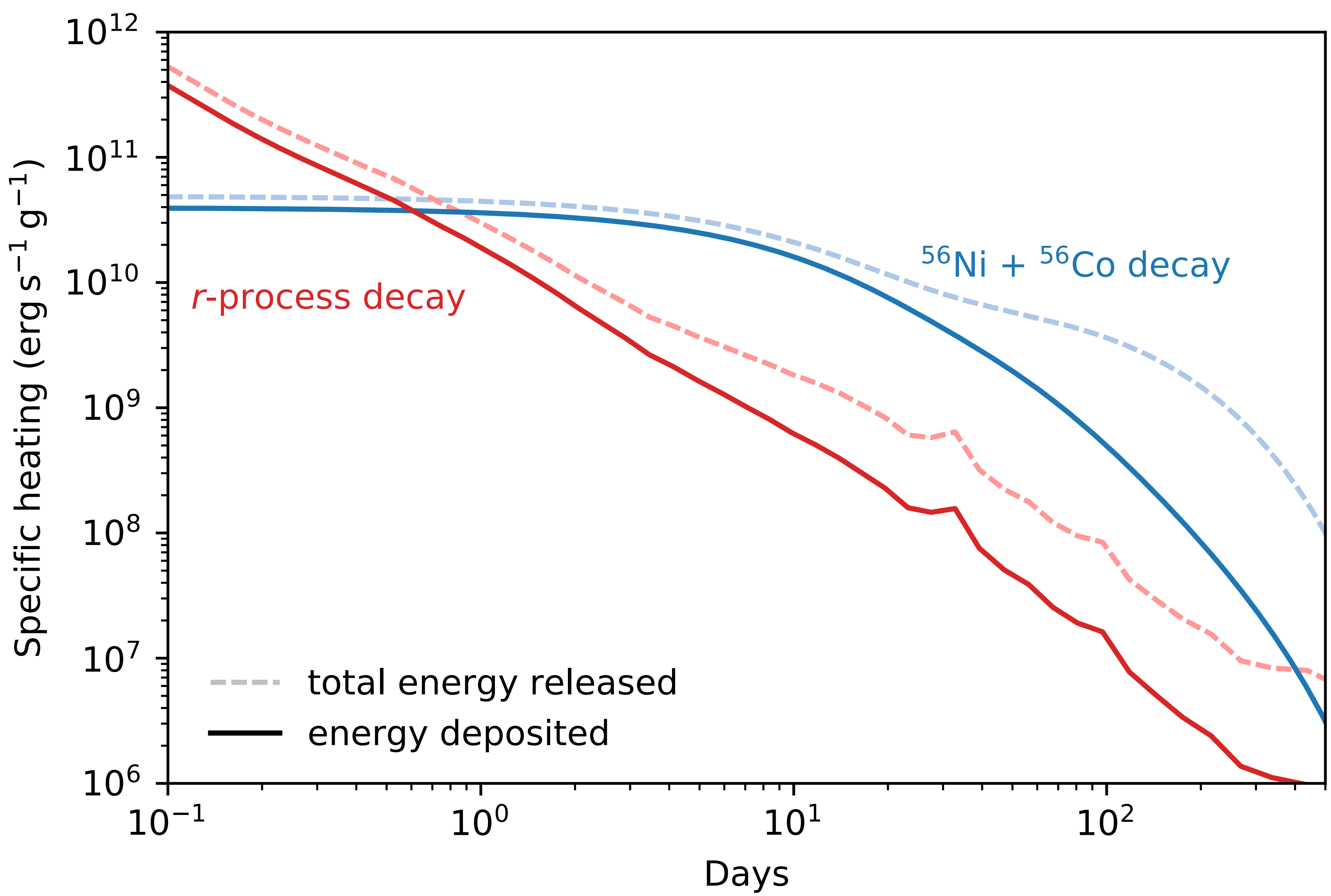
$\sim 0.08\text{-}1\ M_{sun}$

$\sim 260\ \mathrm{Gpc^{-3}\ yr^{-1}}$



How to test the collapsar scenario observationally?

Siegel, Barnes, Metzger 2019, Nature



‘a kilonova in a supernova’

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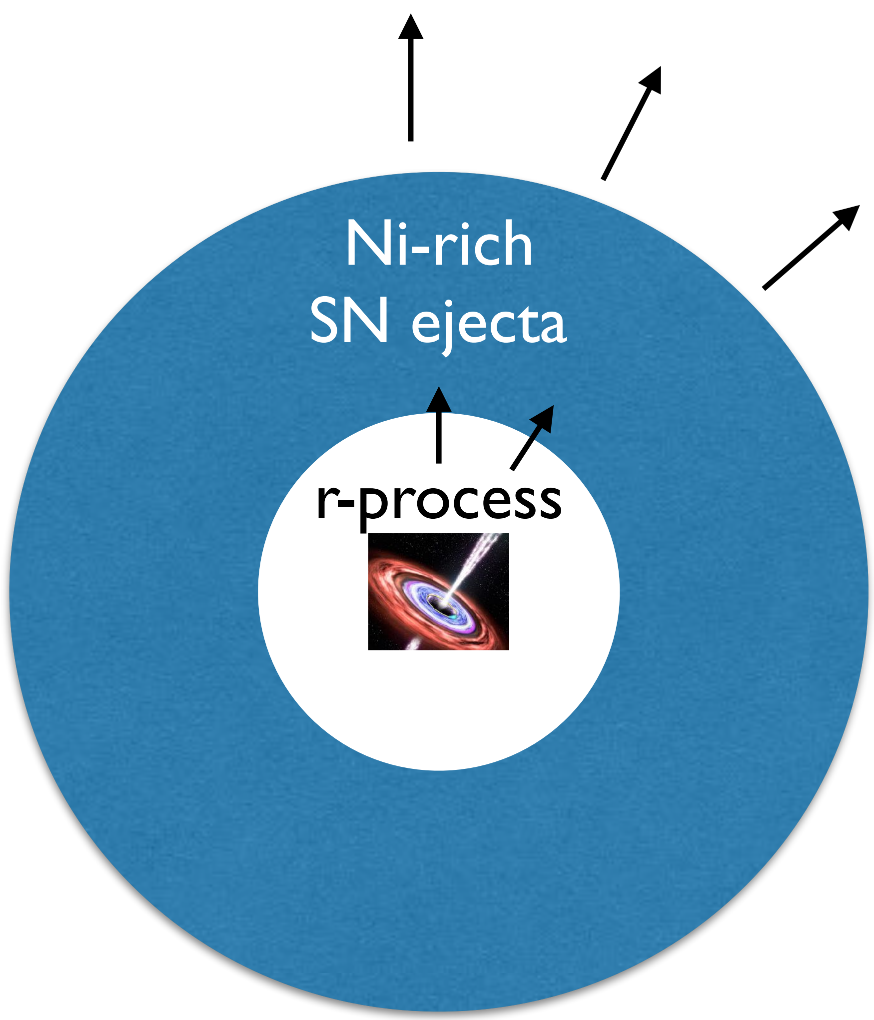
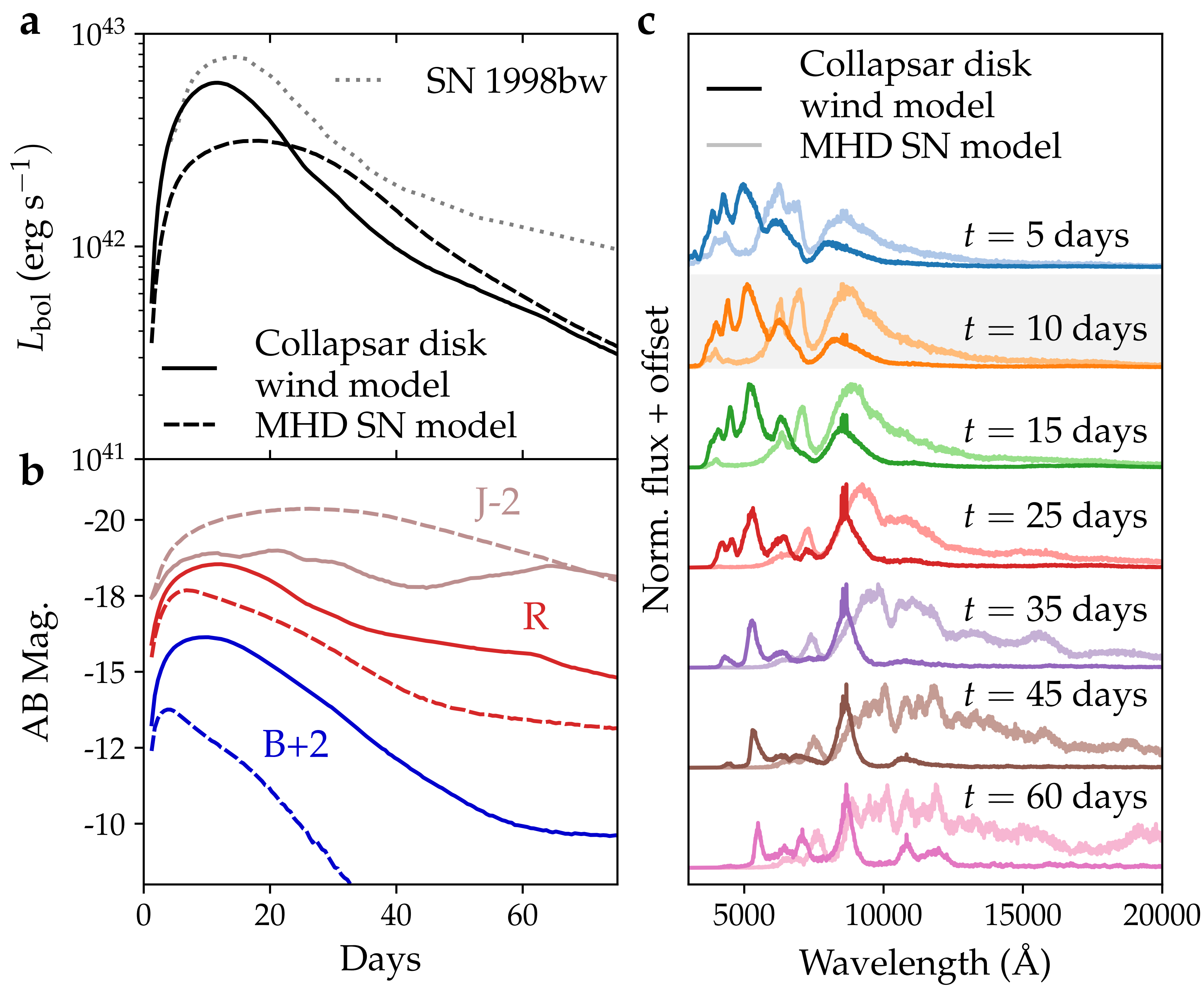
Siegel, Barnes, Metzger 2019, Nature

Collapsar scenario





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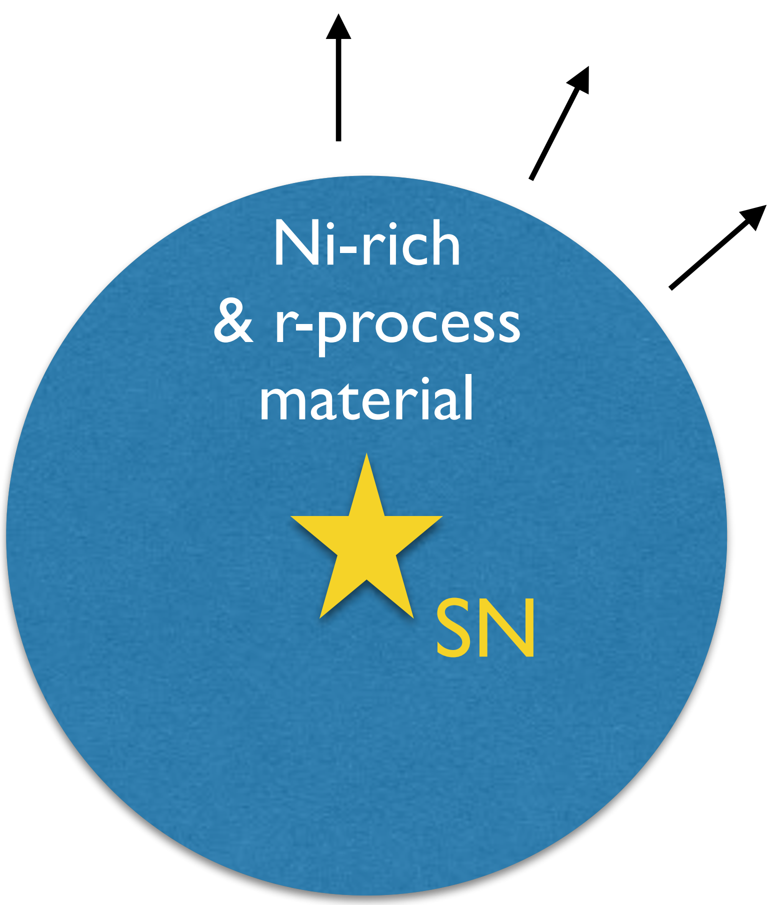
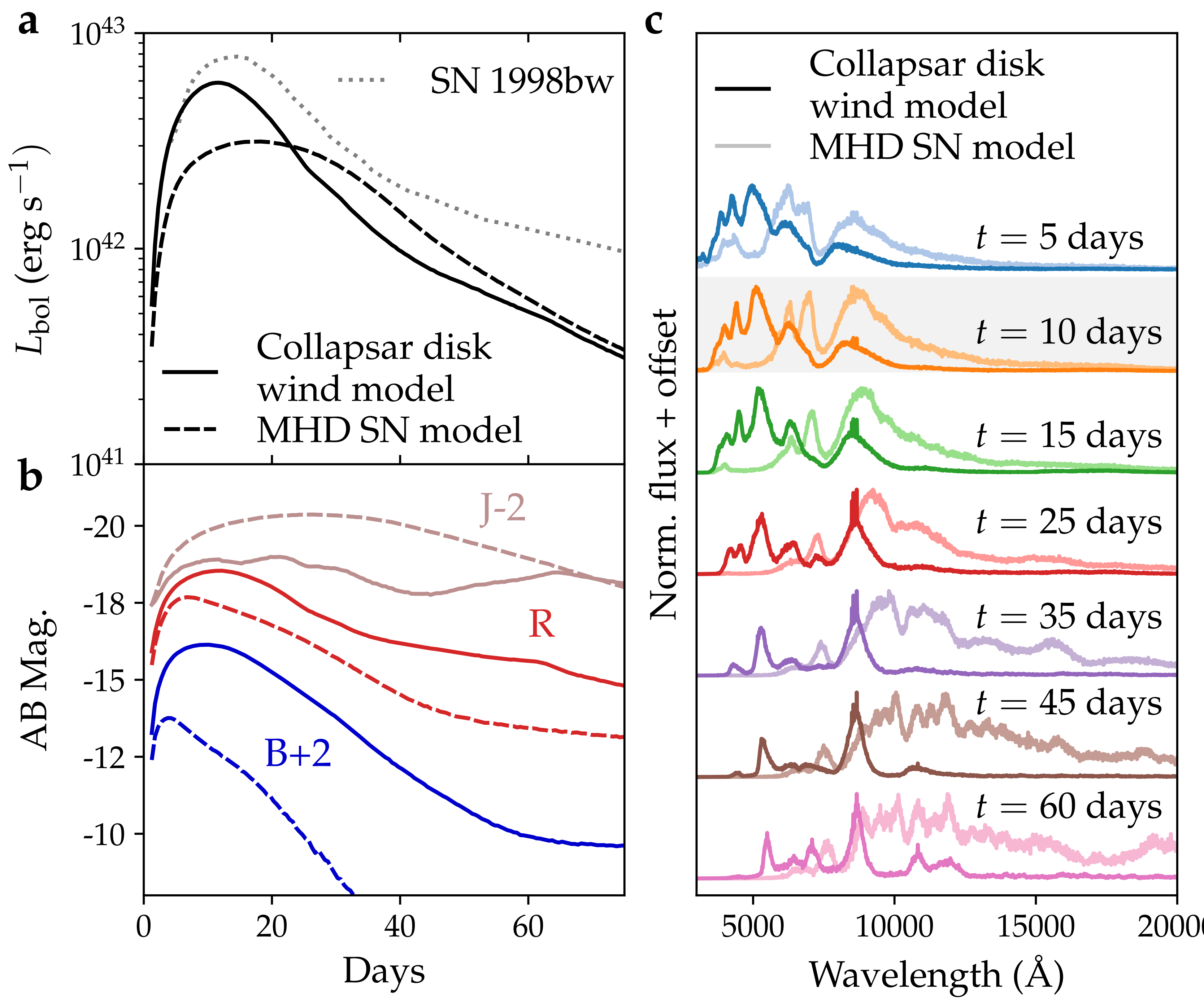
MHD SN scenario

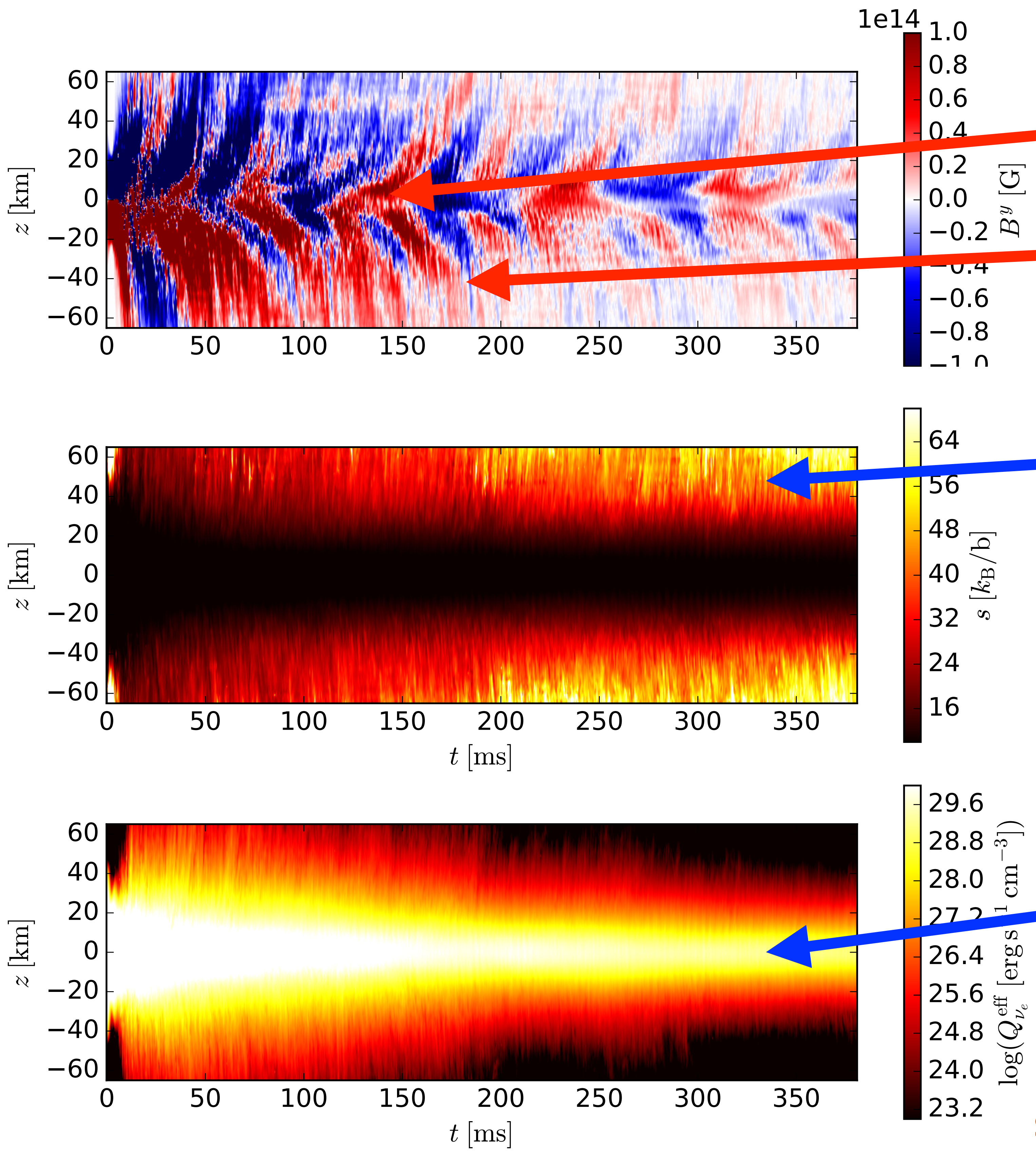


r-process material increases opacity



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

Accretion disk dynamo & generation of outflows



magnetic energy is generated in the mid-plane

- migrates to higher latitudes
- dissipates into heat off the mid-plane

→ "hot corona"

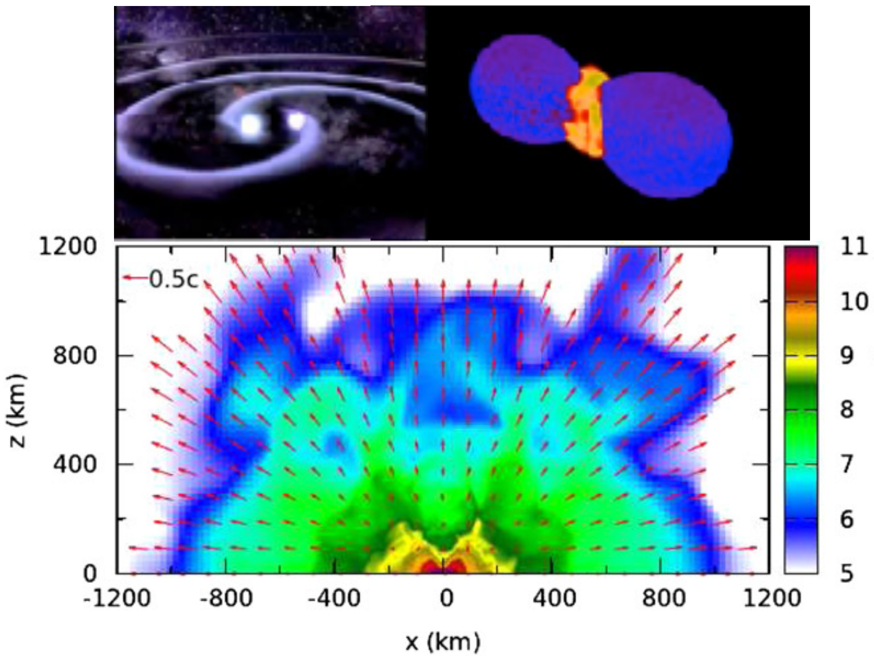
hot corona launches thermal outflows (neutron-rich wind)

NS post-merger accretion disk are cooled from the mid-plane by neutrinos (rather than from the EM photosphere)!

Siegel & Metzger 2018

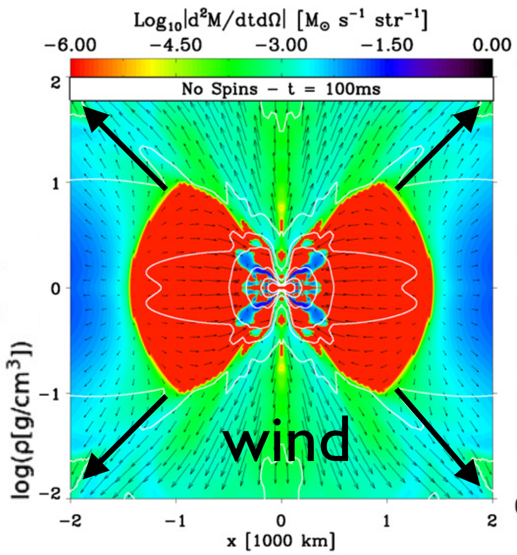
Sources of ejecta in NS mergers

dynamical ejecta (~ms)

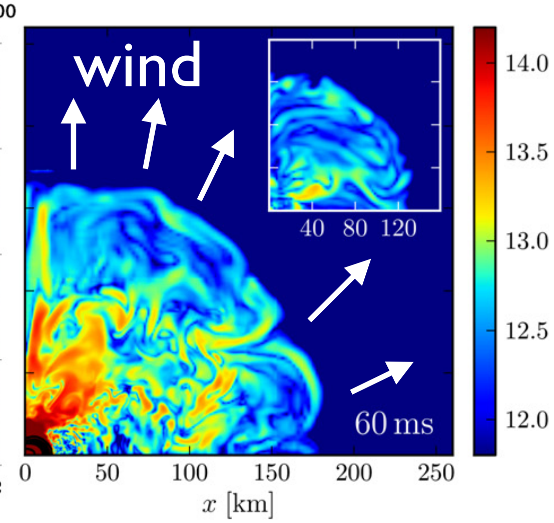


Hotokezaka+ 2013, Bauswein+ 2013

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

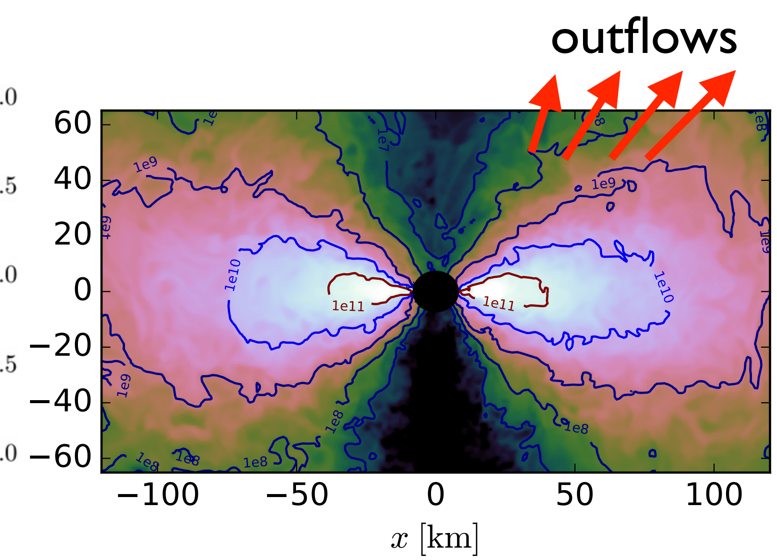


Dessart+ 2009



Siegel+ 2014
Ciolfi, Siegel+ 2017

accretion disk (~10ms-1s)



Siegel & Metzger 2017, 2018

tidal ejecta
shock-heated ejecta

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

$v \gtrsim 0.2c$

neutrino-driven wind

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

magnetically driven wind

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

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

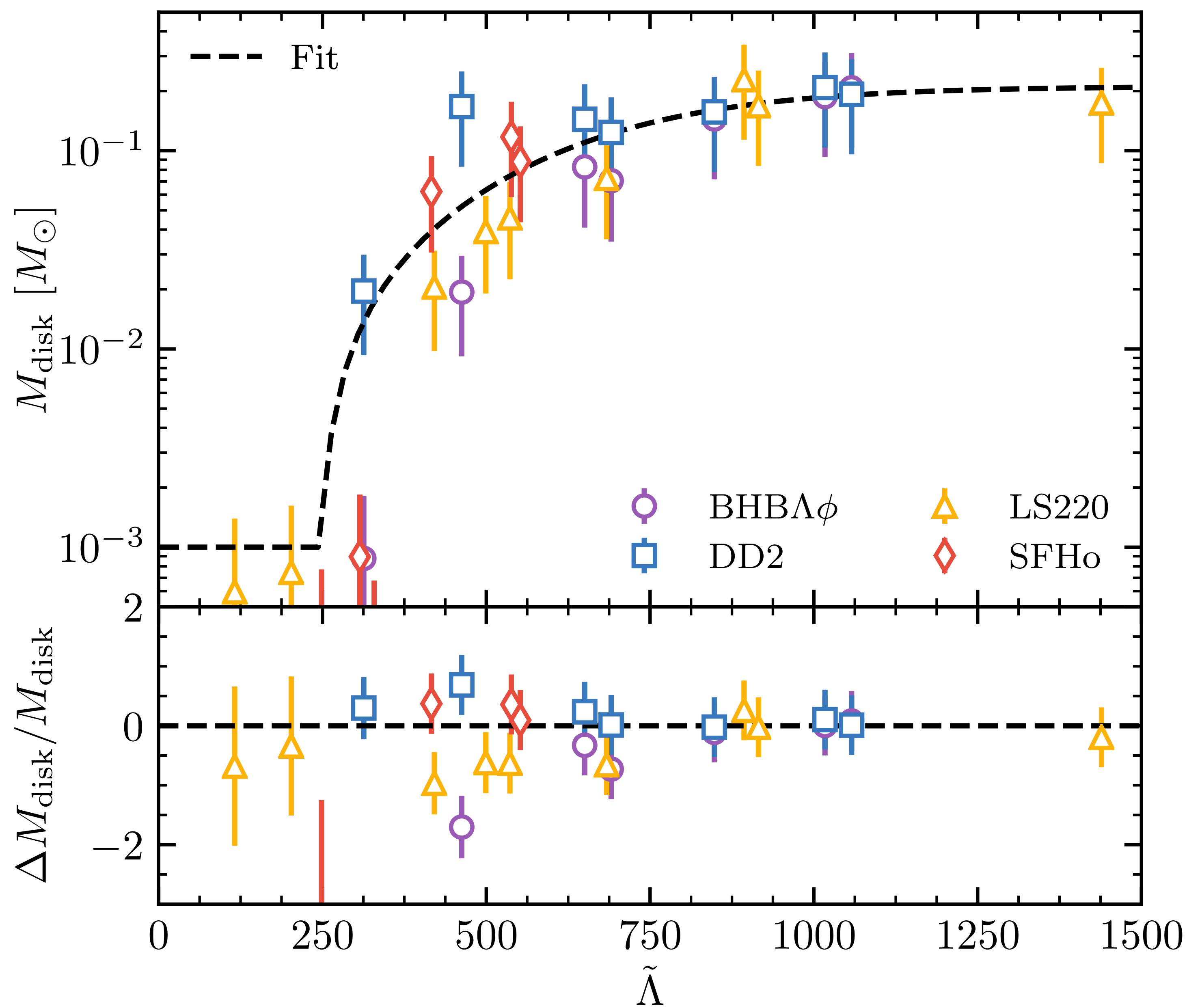
Bauswein+ 2013
Radice+ 2016, 2017
Sekiguchi+ 2016
Palenzuela+2015
Lehner+2016
Ciolfi, Siegel+2017

Siegel & Metzger 2017, 2018

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

lower limit

NS post-merger disk masses



Radice+ 2018