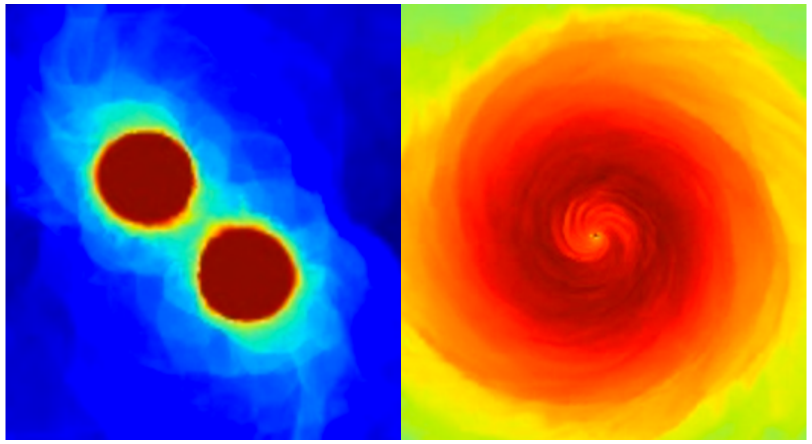
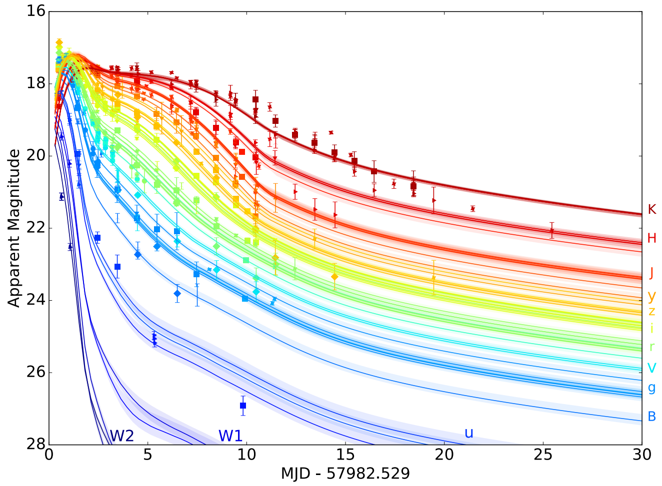
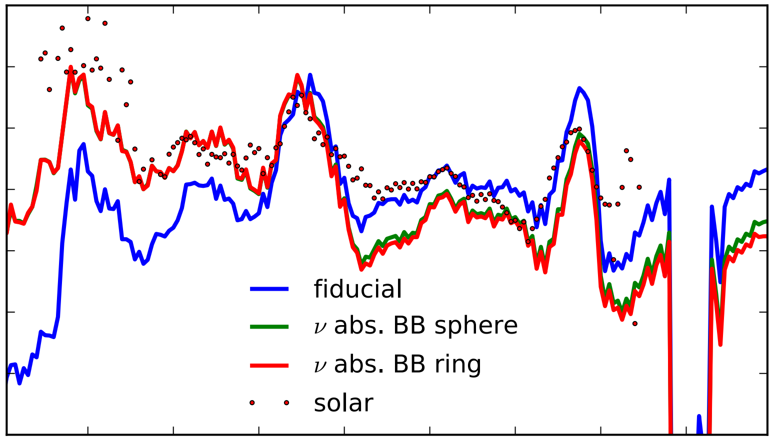
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Neutron star mergers, kilonovae, and the origin of the heavy elements







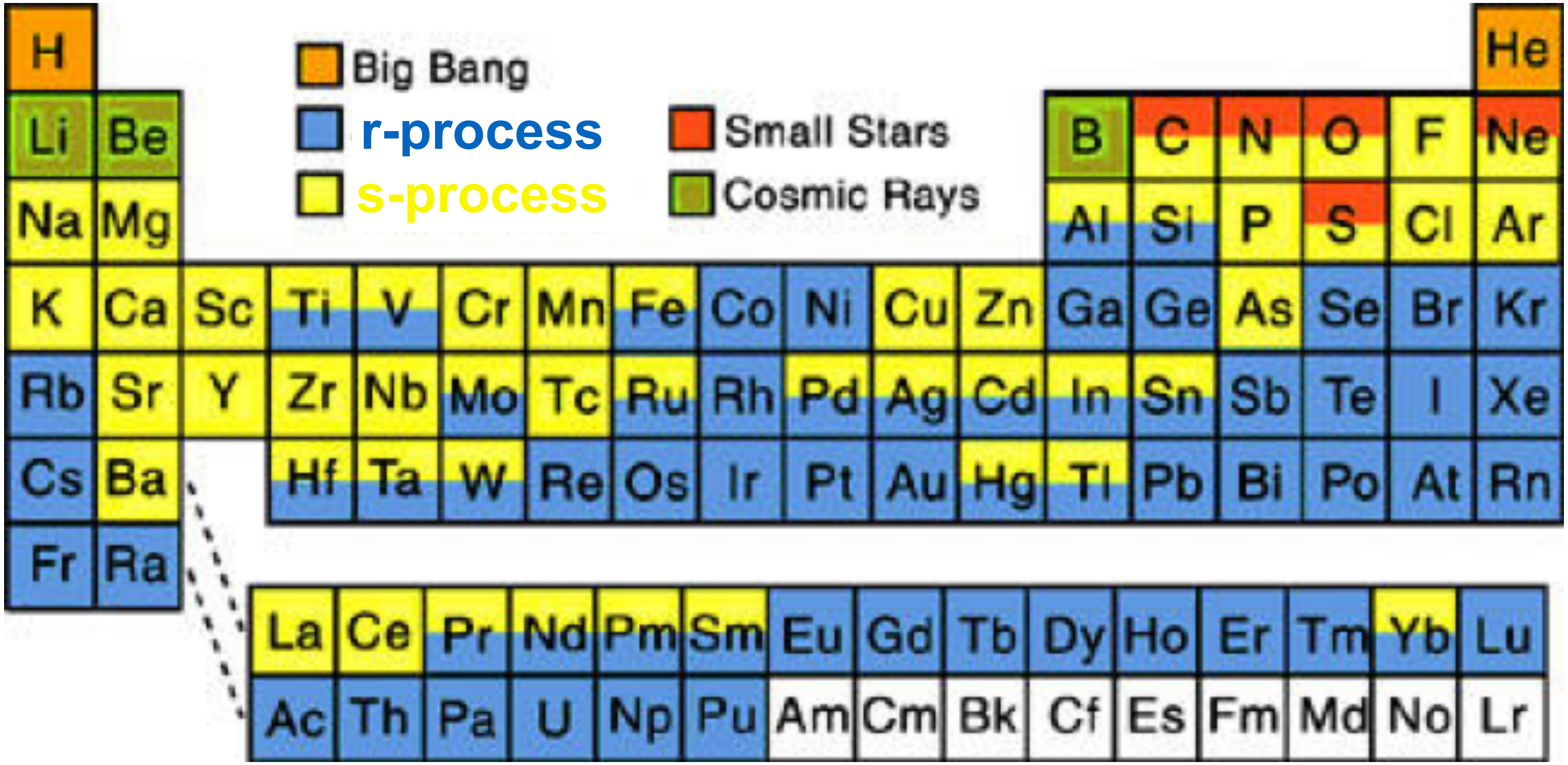
Daniel M. Siegel

NASA Einstein Fellow

Center for Theoretical Physics & Columbia Astrophysics Laboratory, Columbia University

14th Rencontres du Vietnam (VHEPU 2018), Quy Nhon, August 13-17, 2018

The origin of the elements

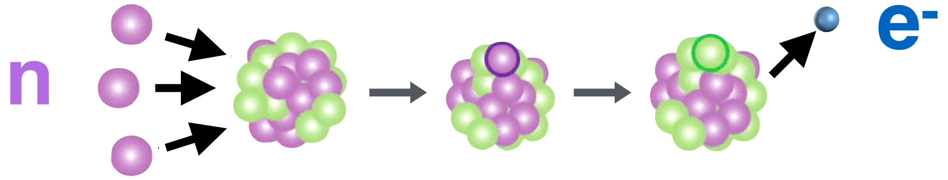


How are the heavy elements formed?

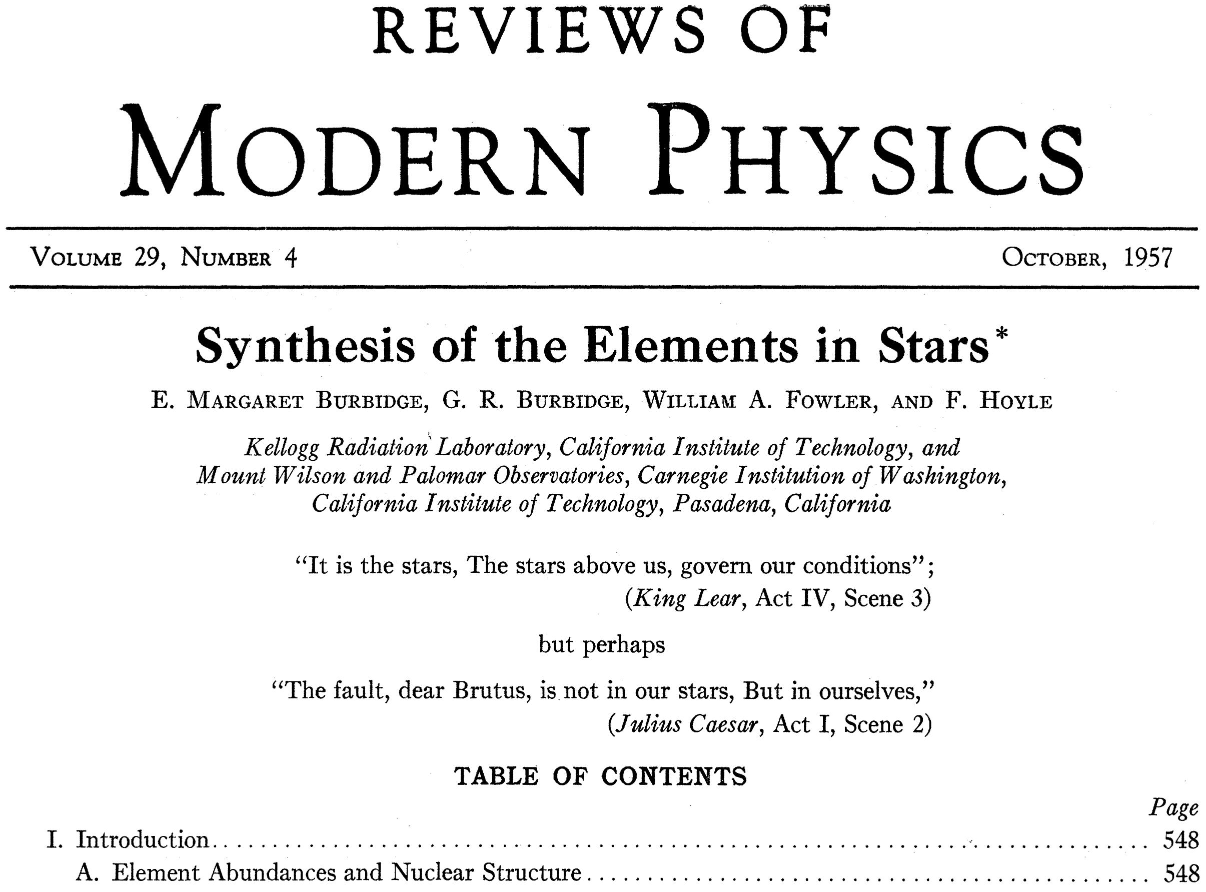
The r-process and s-process

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

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



Burbidge, Burbidge, Fowler, Hoyle (“B^2FH”)



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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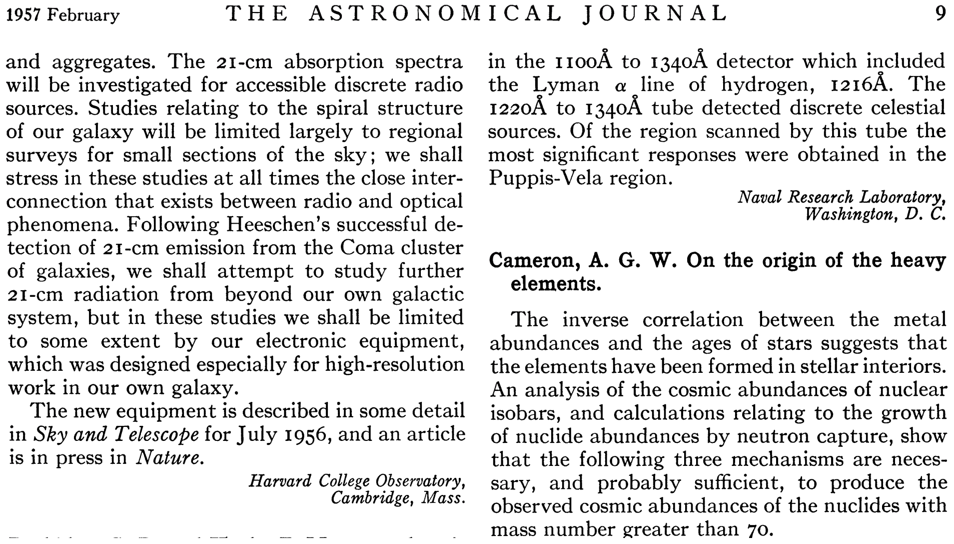


1957 February THE ASTRONOMICAL JOURNAL 9

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.

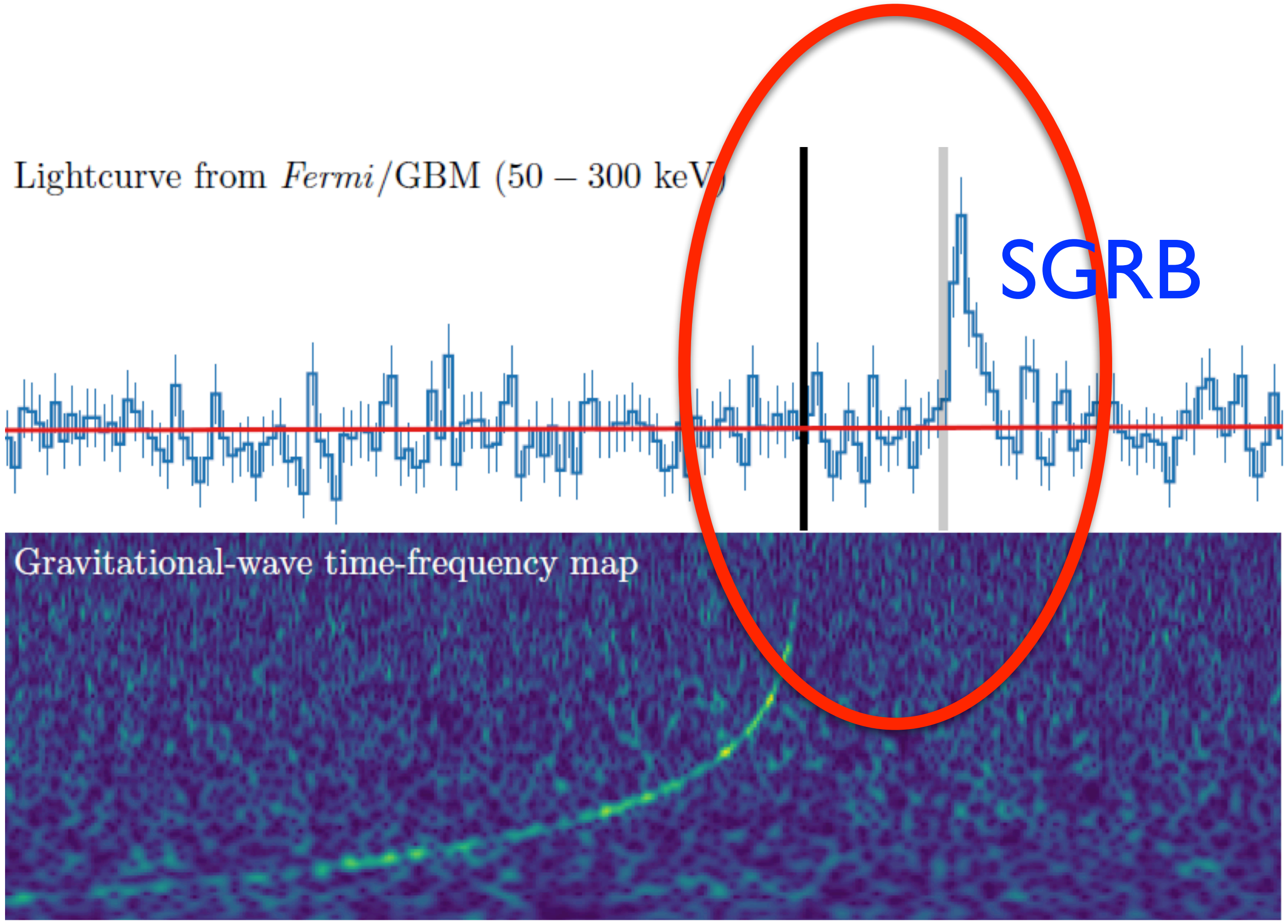
Cameron

speculated that r-process requires explosive environment of supernovae

1.

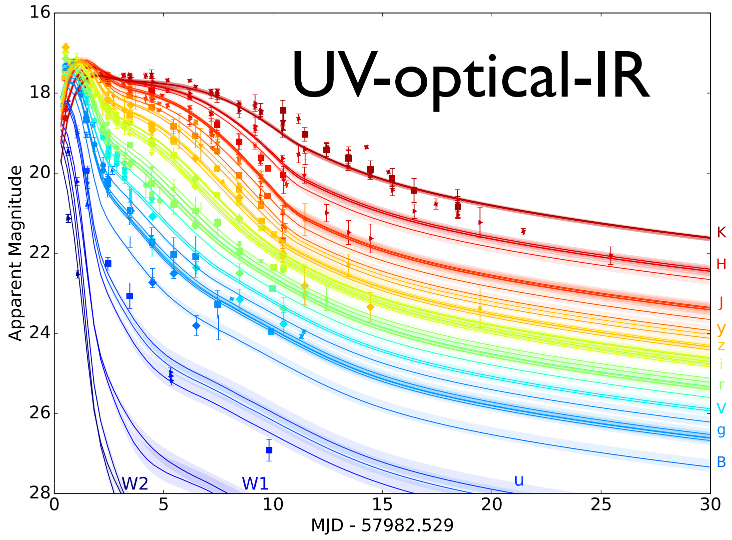
Observations

GW170817 and the firework of EM counterparts

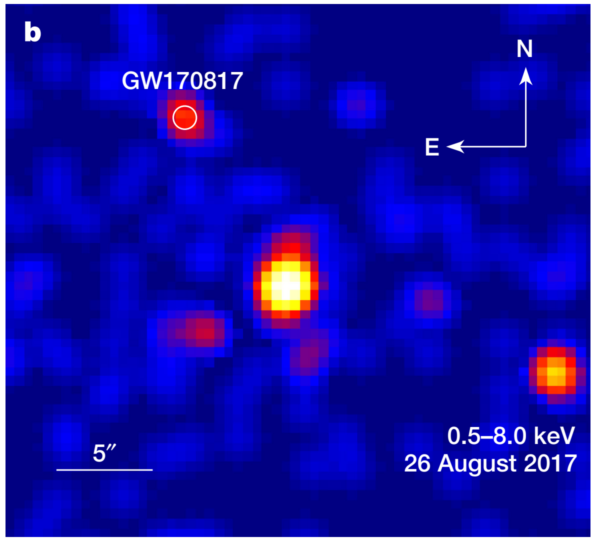


- unique event in astronomy, unprecedented level of multi-messenger observations
- confirms association of BNS to SGRBs
  - ⟶ Archival data: SGRB spectral properties may not be unusual Burns+ 2018
  - ⟶ VLBI obs.: SGRB morphology may not be unusual Mooley+ 2018b
- kilonova provides strong evidence for synthesis of r-process material

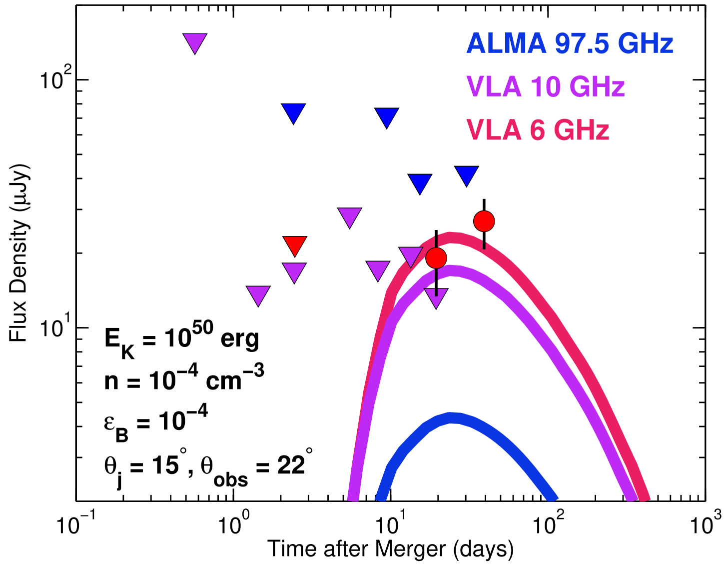
kilonova



X-rays



radio



The kilonova of GW170817

- blue kilonova properties:

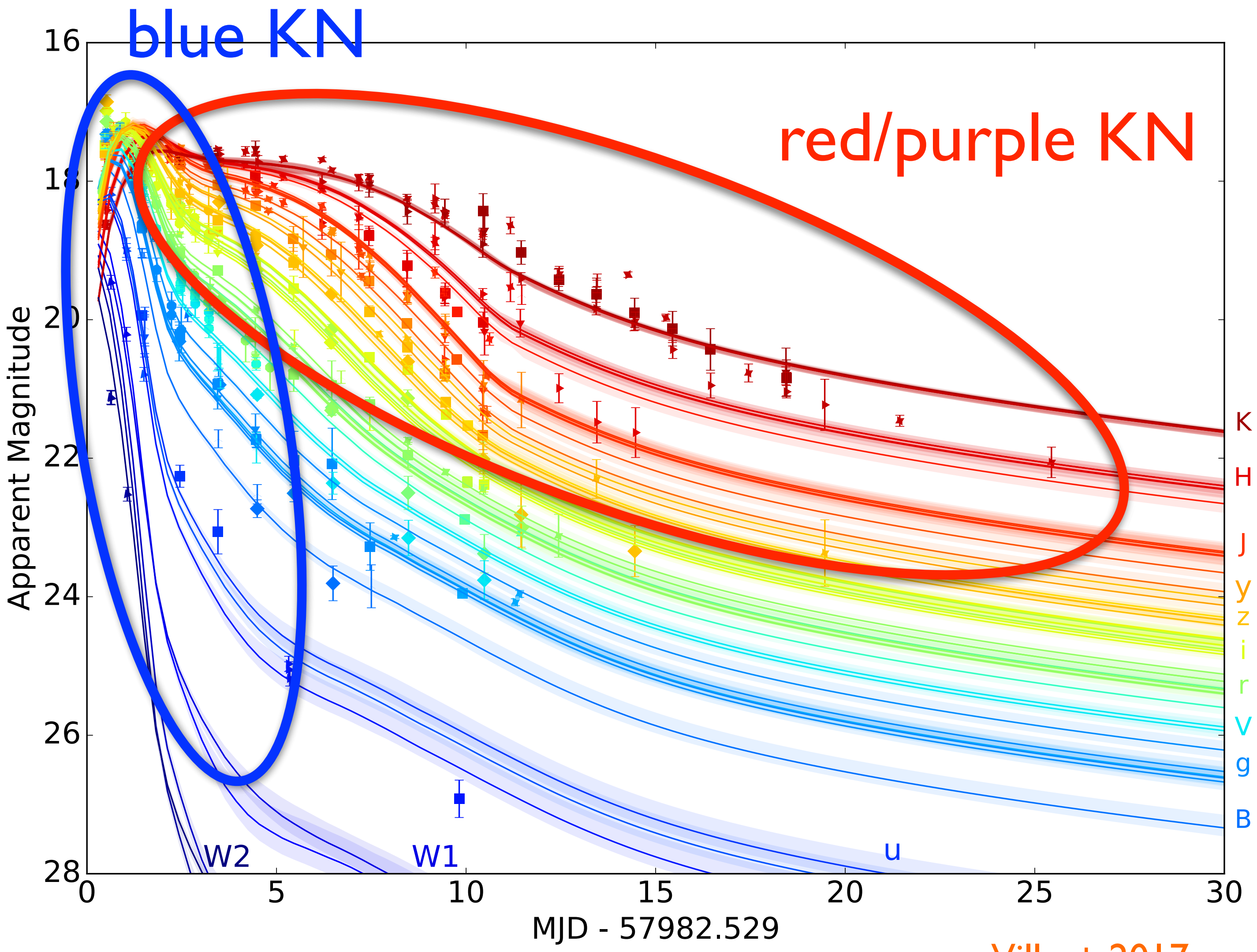
$M_{ej} \sim 10^{-2} M_{sun}$
$v_{ej} \sim 0.2\text{-}0.3c$
$Y_e > 0.25$
$X_{La} < 10^{-4}$

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

- red/purple 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



Villar+ 2017

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

Smartt+ 2017
Waxman+ 2017

II.
Kilonovae

Mass ejection generates kilonovae

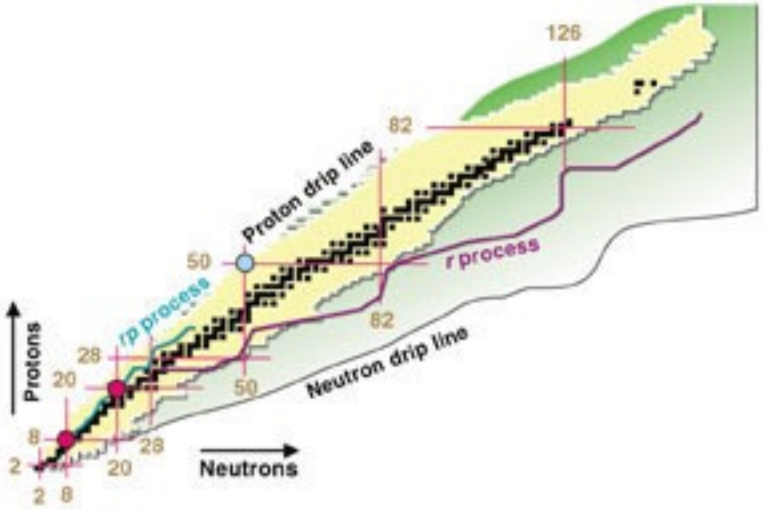
neutron rich ejecta from
NS-NS or NS-BH mergers
(Y_e~0.1-0.4)

~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:

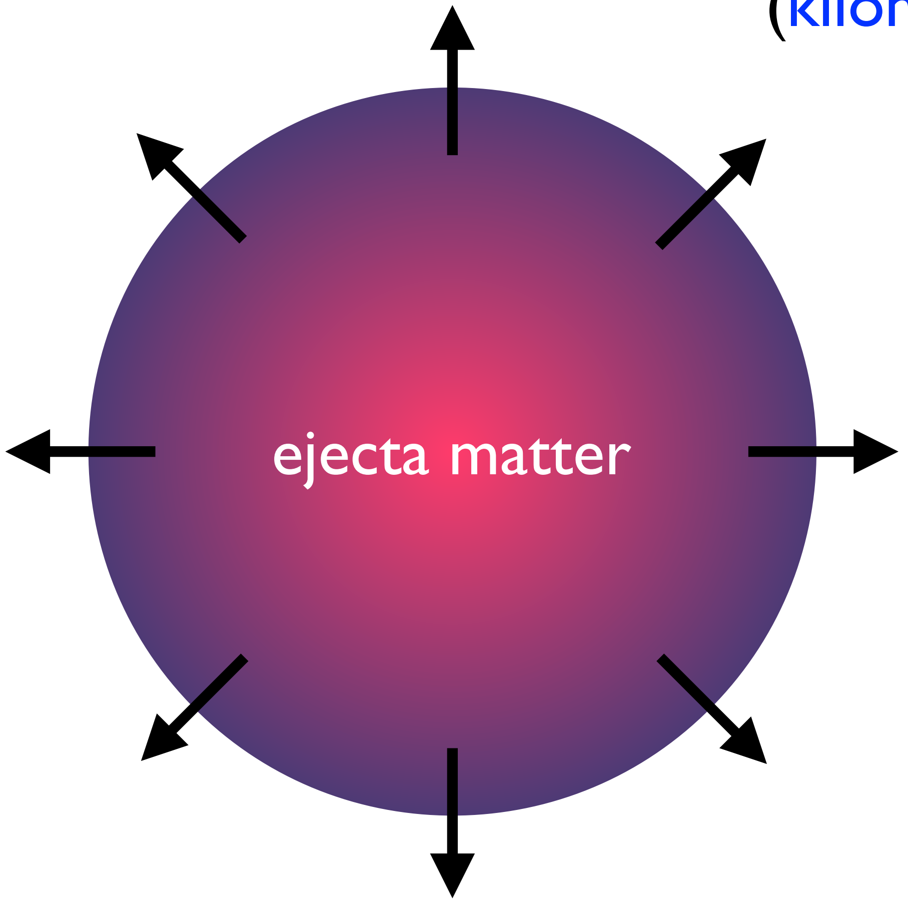
Piran+ 2013, Metzger+ 2017

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

adiabatic losses

radiative luminosity
(kilonova)

radioactive
heating
(r-process)

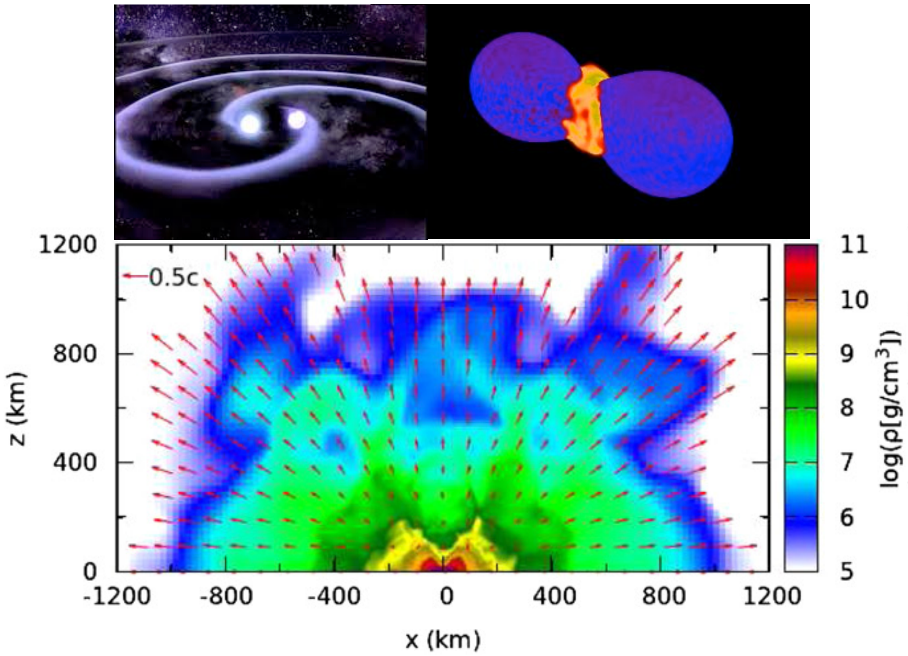


homologous
expansion

III.
Mass ejection
GW170817 phenomenology

Sources of ejecta in NS mergers

dynamical ejecta (~ms)



Hotokezaka+ 2013, Bauswein+ 2013

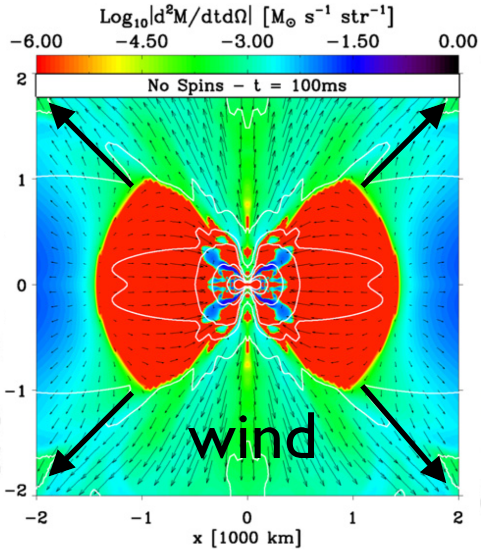
tidal ejecta

shock-heated ejecta

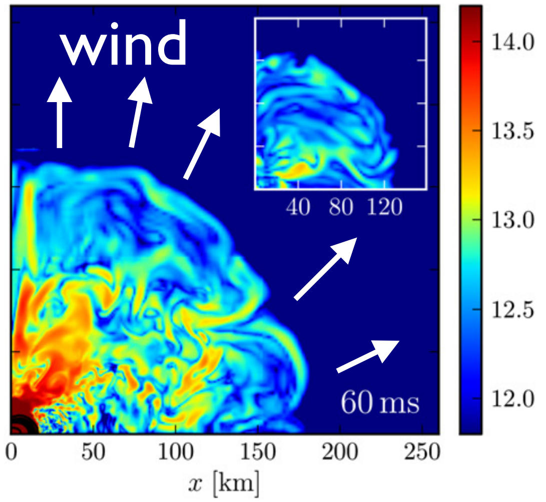
$$M_{\rm tot} \lesssim 10^{-3} \rm M_\odot$$

$$v \gtrsim 0.2c$$

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



Dessart+ 2009



Siegel+ 2014

Ciolfi, Siegel+ 2017

neutrino-driven wind

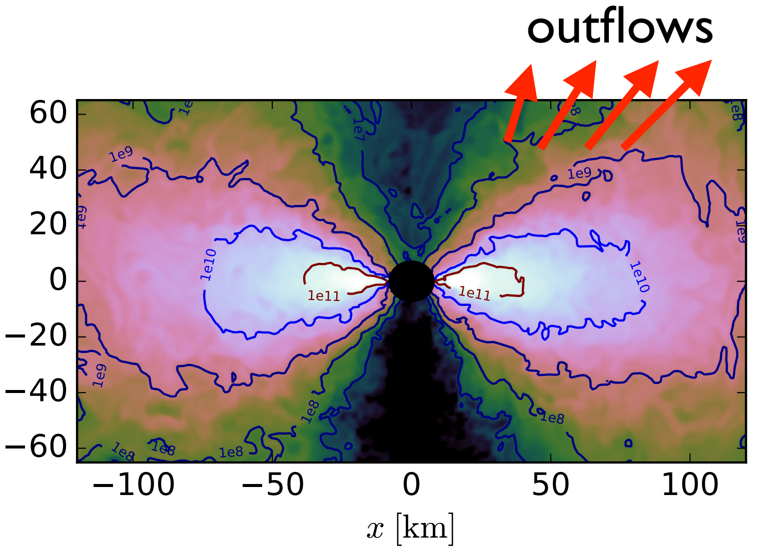
$$\dot{M}_{\rm in} \sim (10^{-4} - 10^{-3}) \rm M_\odot s^{-1}$$

magnetically driven wind

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

combined see Metzger 2018

accretion disk (~10ms-1s)



Siegel & Metzger 2017, 2018a

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

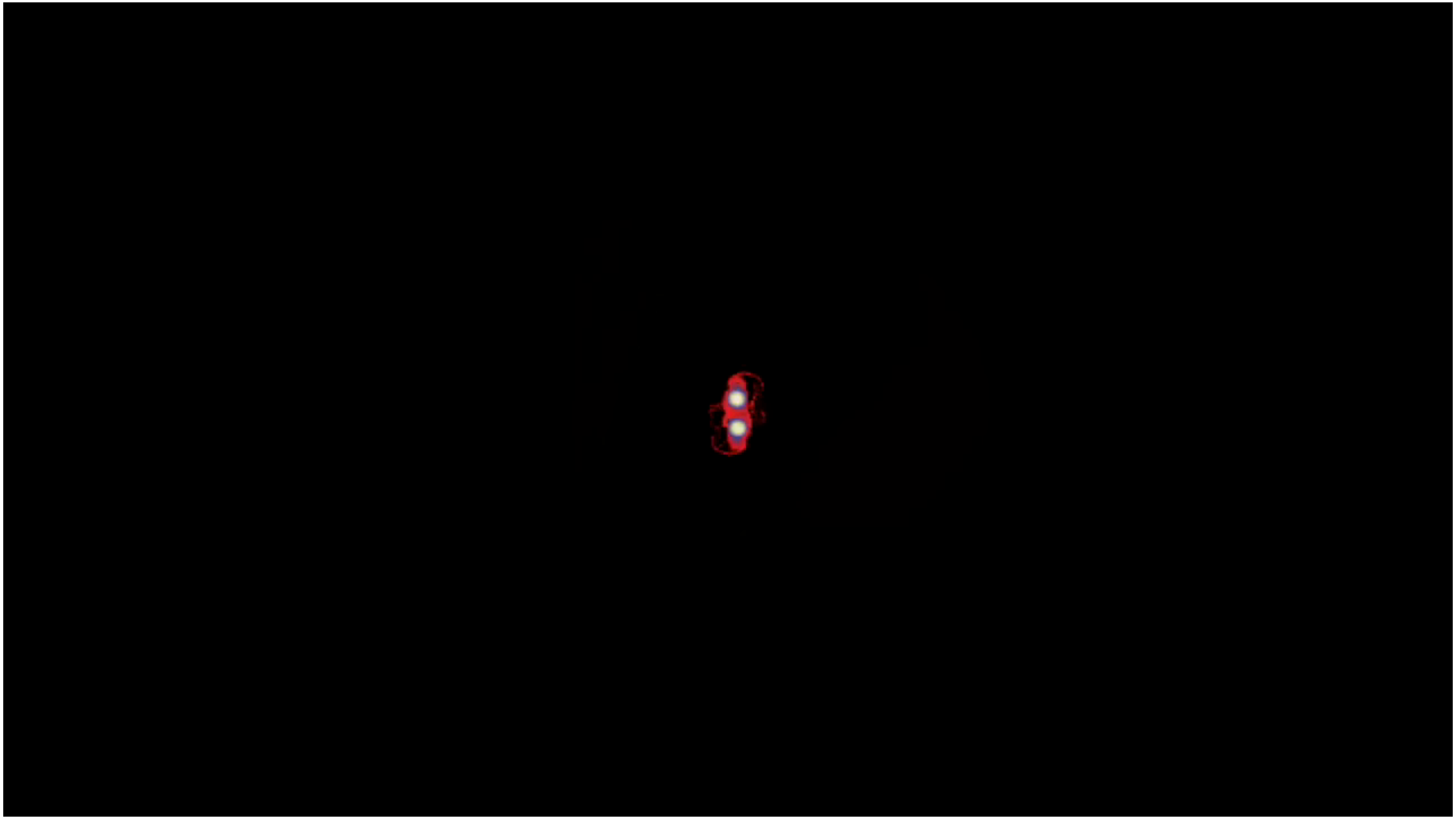
Bauswein+ 2013
Radice+ 2016, 2017
Sekiguchi+ 2016
Palenzuela+2015
Lehner+2016
Ciolfi, Siegel+2017

Siegel & Metzger 2017, 2018

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

lower limit

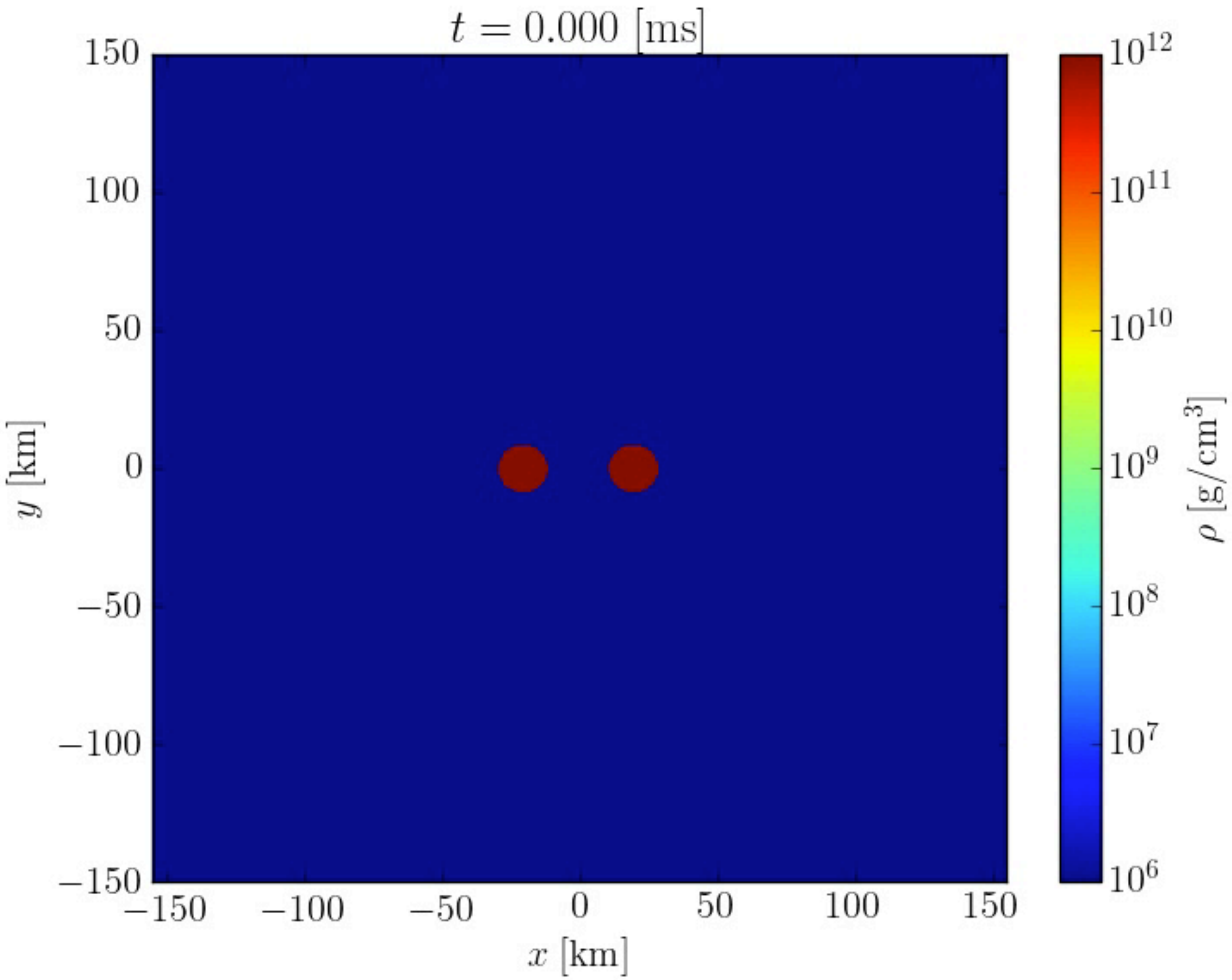
Dynamical ejecta and winds



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

Ciolfi, Siegel+2017

Accretion disk formation



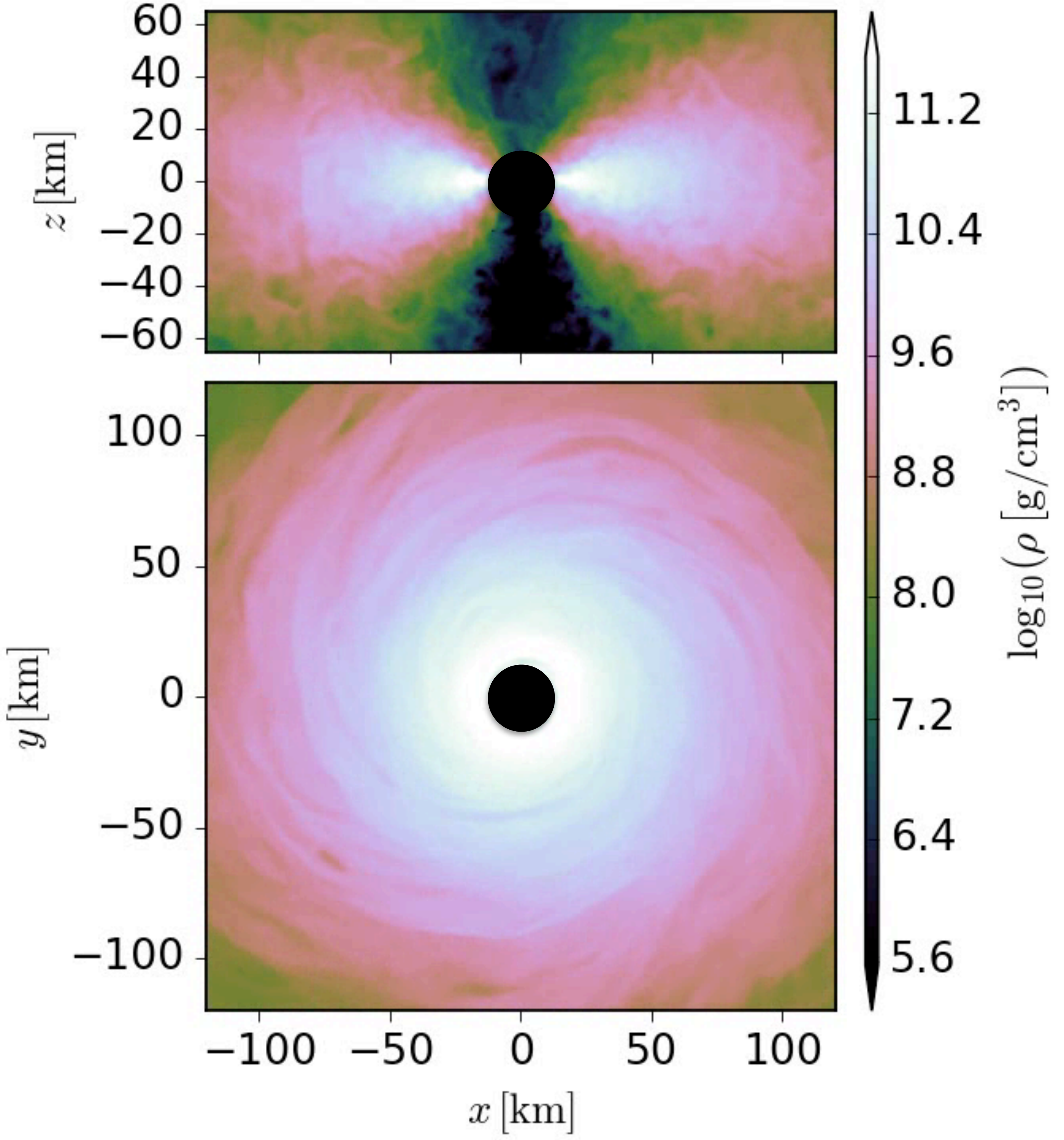
Movie: BNS merger and formation of post-merger accretion disk

Radice+ 2016

Accretion disk outflows

Siegel & Metzger 2017, PRL

Siegel & Metzger 2018a

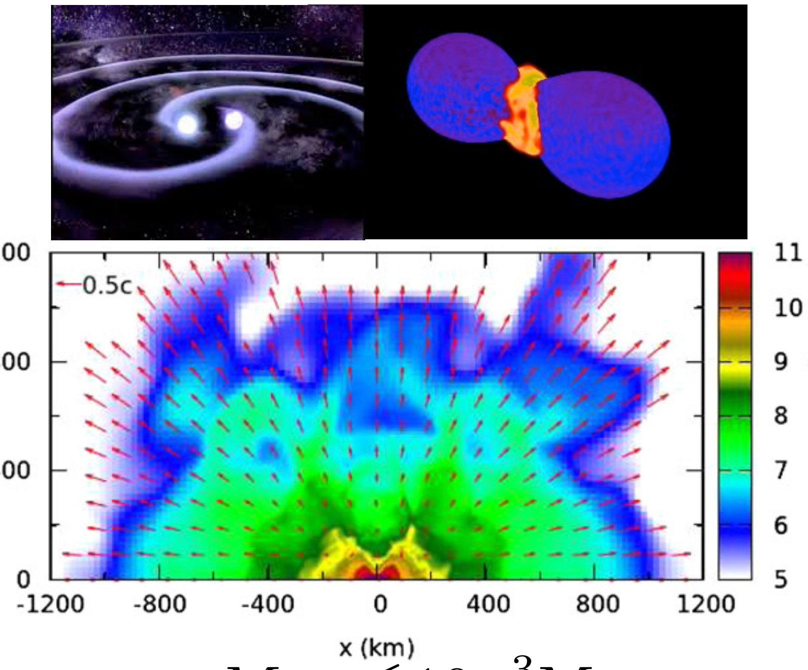


$t = 20.113\,\mathrm{ms}$

Movie: long-term evolution of post-merger accretion disk, M_{BH}=3Msun (spin: 0.8), M_{disk}=0.02Msun

Sources of ejecta for kilonova in GW170817

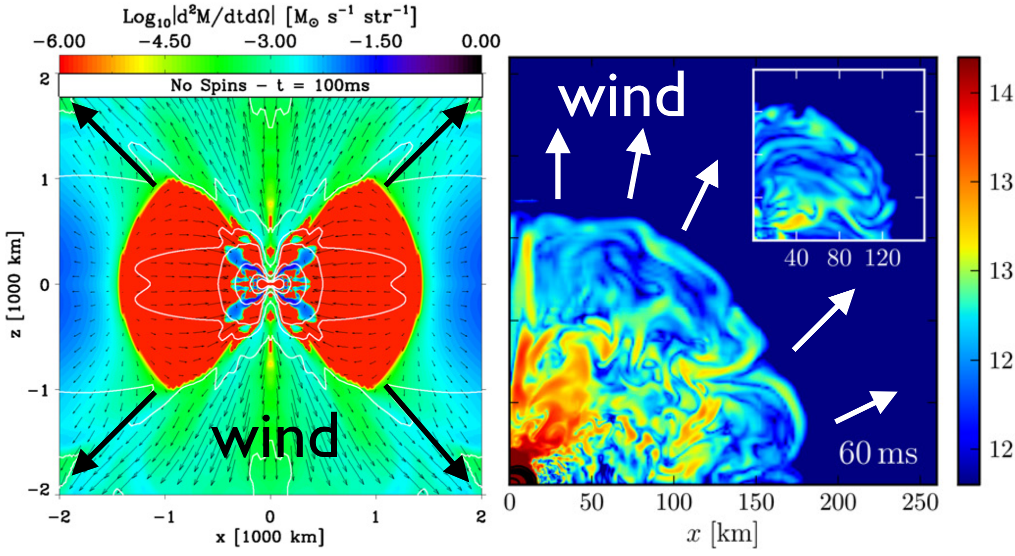
dynamical ejecta (~ms)



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

$$v \gtrsim 0.2c$$

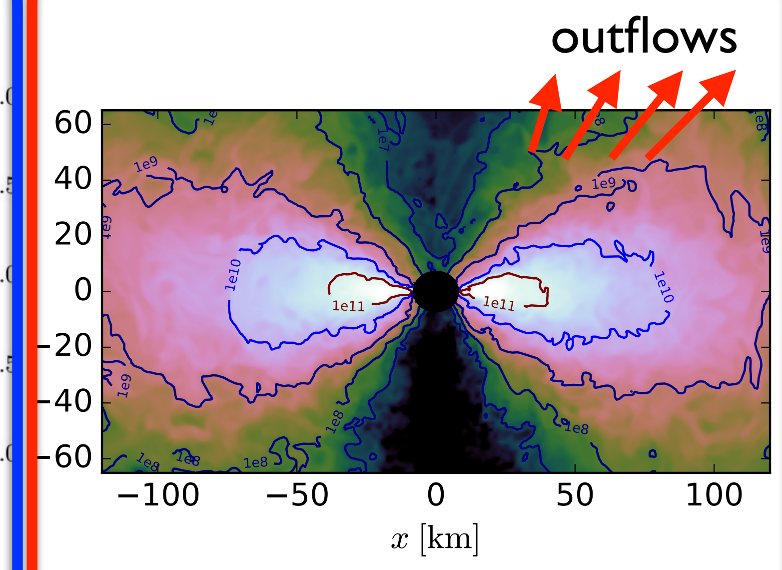
winds from NS remnant (~ms-1s)



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

$$v \lesssim 0.1c$$

accretion disk (~10ms-1s)



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

$$v \sim 0.1c$$

blue KN in GW170817

→ requires large amount of shock heated ejecta to obtain high $Y_e > 0.25$

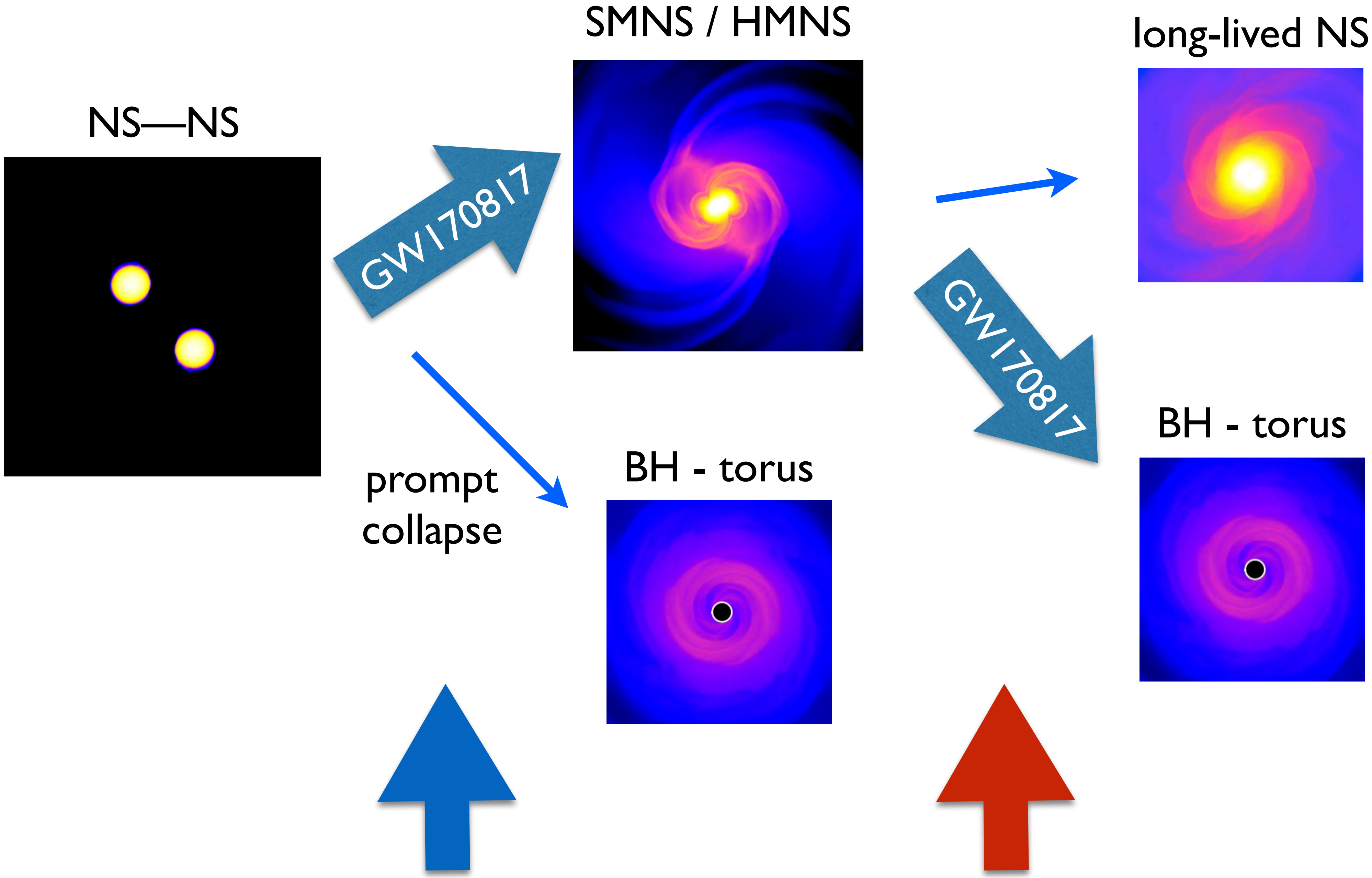
→ requires metastable NS phase

→ requires EOS with small NS radius (~12 km)

red KN in GW170817

→ produces the heavy r-process elements in GW170817 ($Y_e<0.25$)

Scenario for GW170817



SMNS / HMNS

long-lived NS

NS—NS

GW170817

GW170817

prompt collapse

BH - torus

BH - torus

blue kilonova
with $10^{-2} M_{sun}$

presence of red/purple kilonova
absence of energy injection by NS

Margalit & Metzger 2017

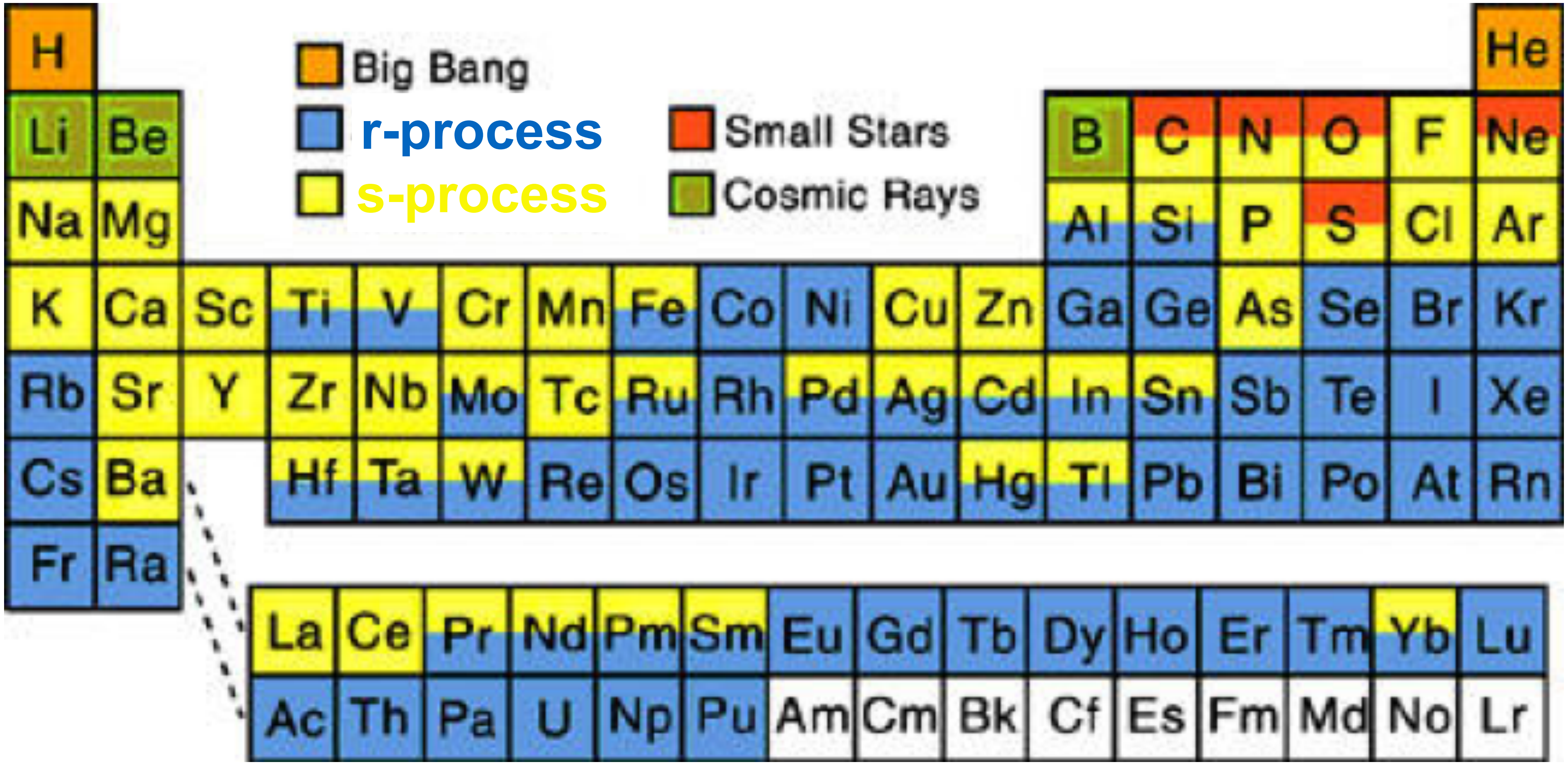
IV.

How are the heavy elements produced?

-

post-merger accretion disks

The origin of the elements



How are the heavy elements formed?

Post-merger accretion disks: MHD turbulence

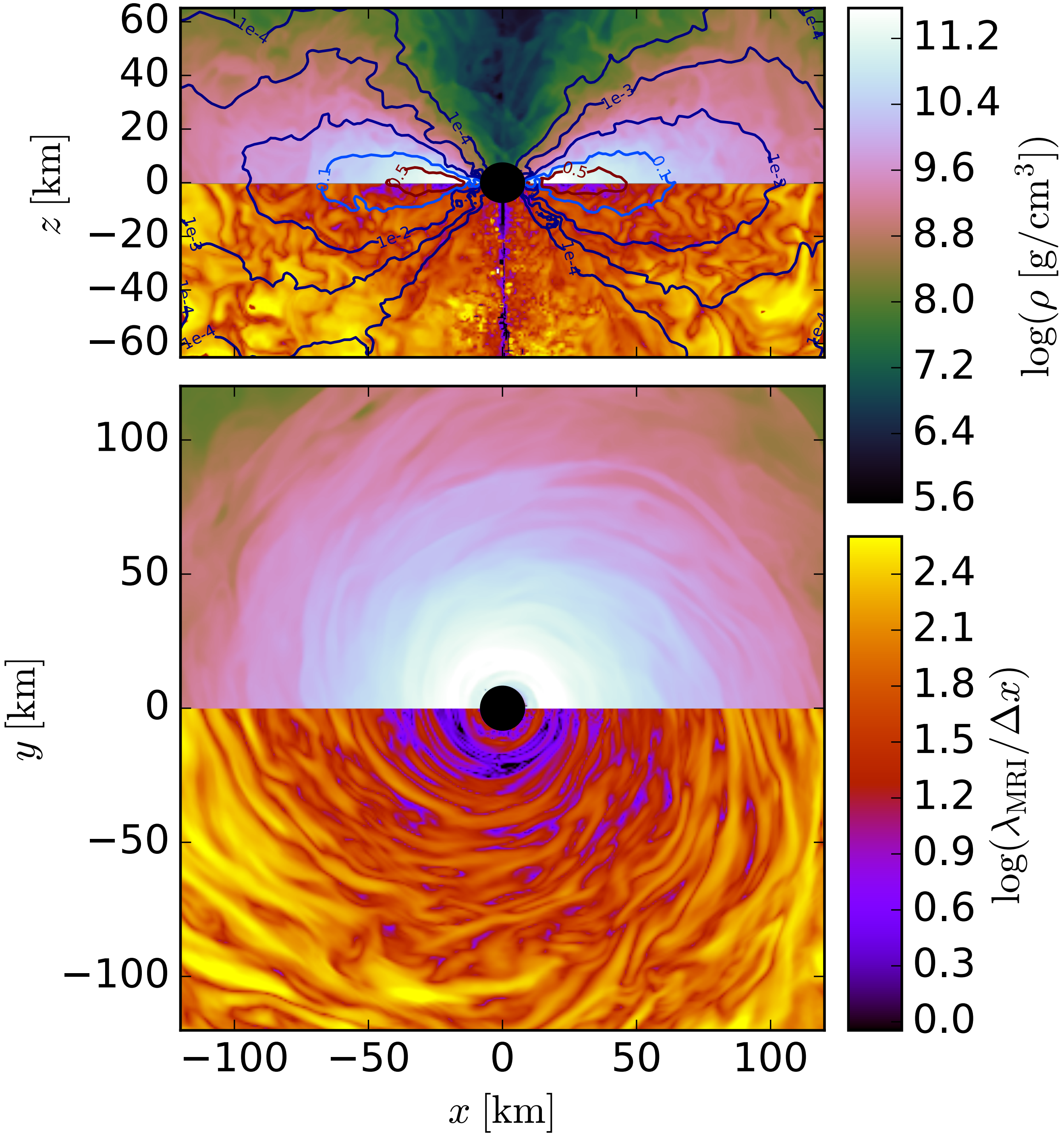


Fig.: disk properties; contours: optical depth for electron neutrinos

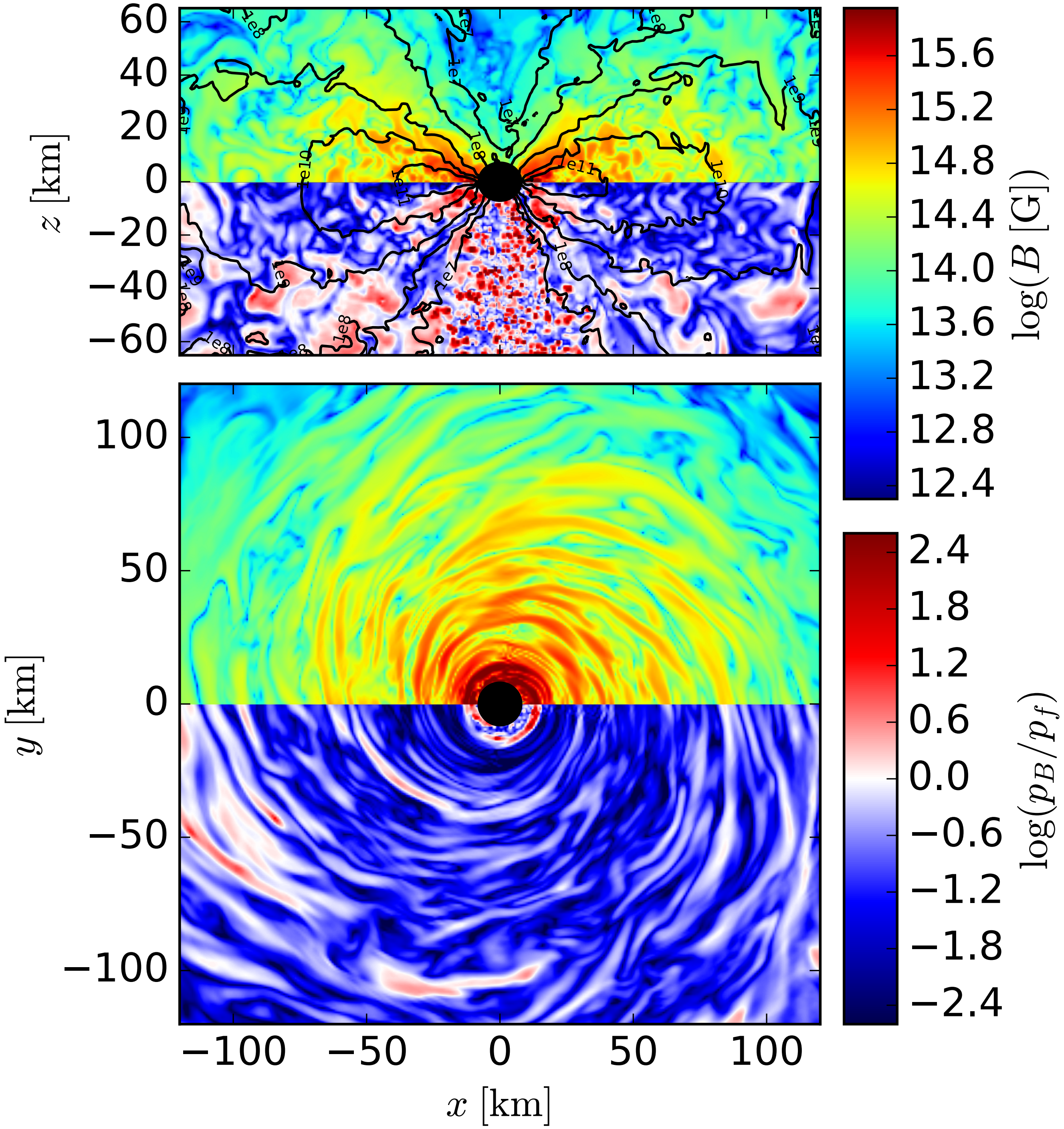


Fig.: magnetic fields in the disk; contours: rest-mass density

Siegel & Metzger 2017, PRL Siegel & Metzger 2018a

properties very similar to
Ciolfi, Siegel+ 2017, Kiuchi+ 2015

Post-merger accretion disks: MHD turbulence

average radially for space-time diagram

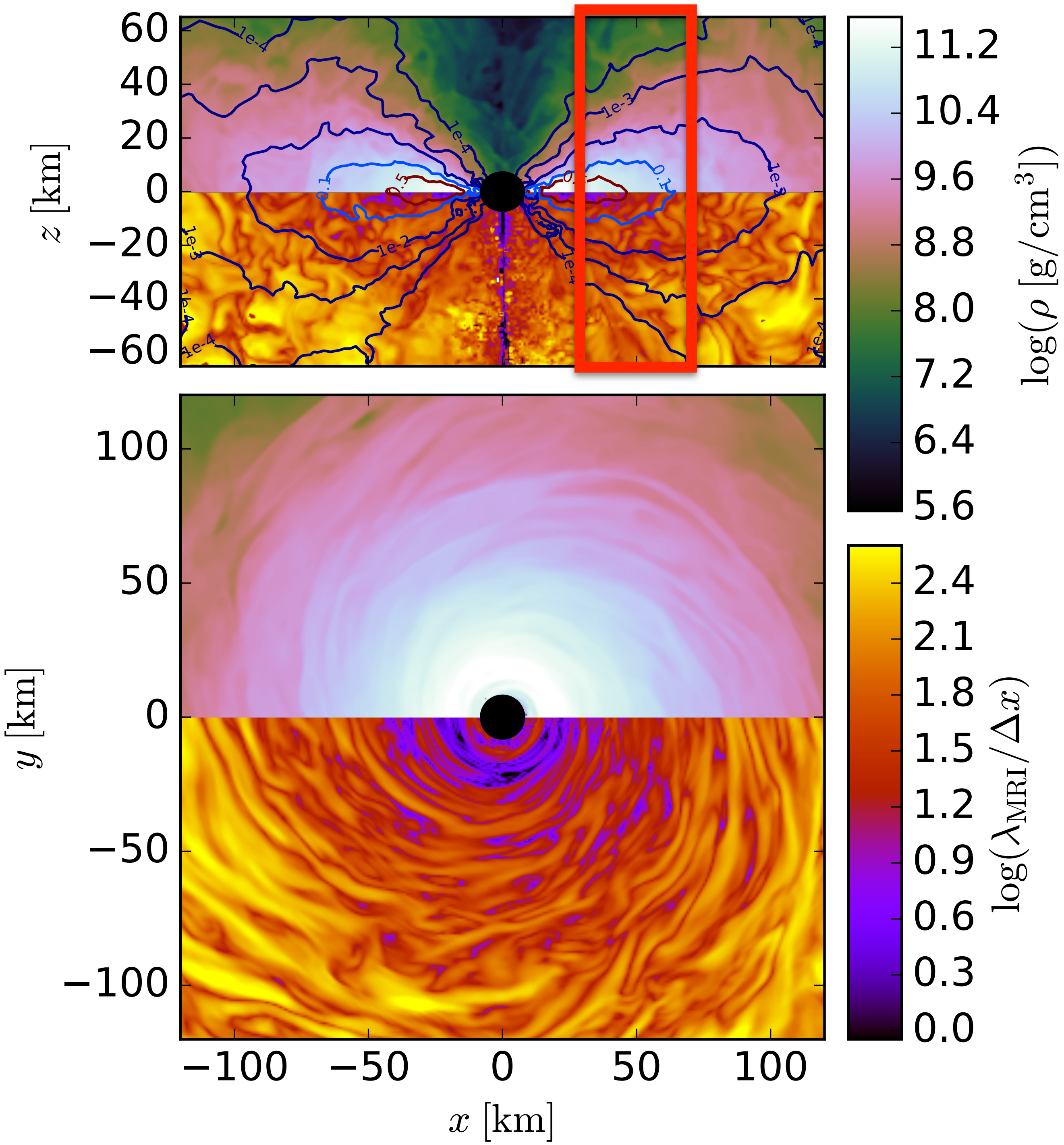


Fig.: disk properties; contours: optical depth for electron neutrinos

Siegel & Metzger 2017, PRL Siegel & Metzger 2018a

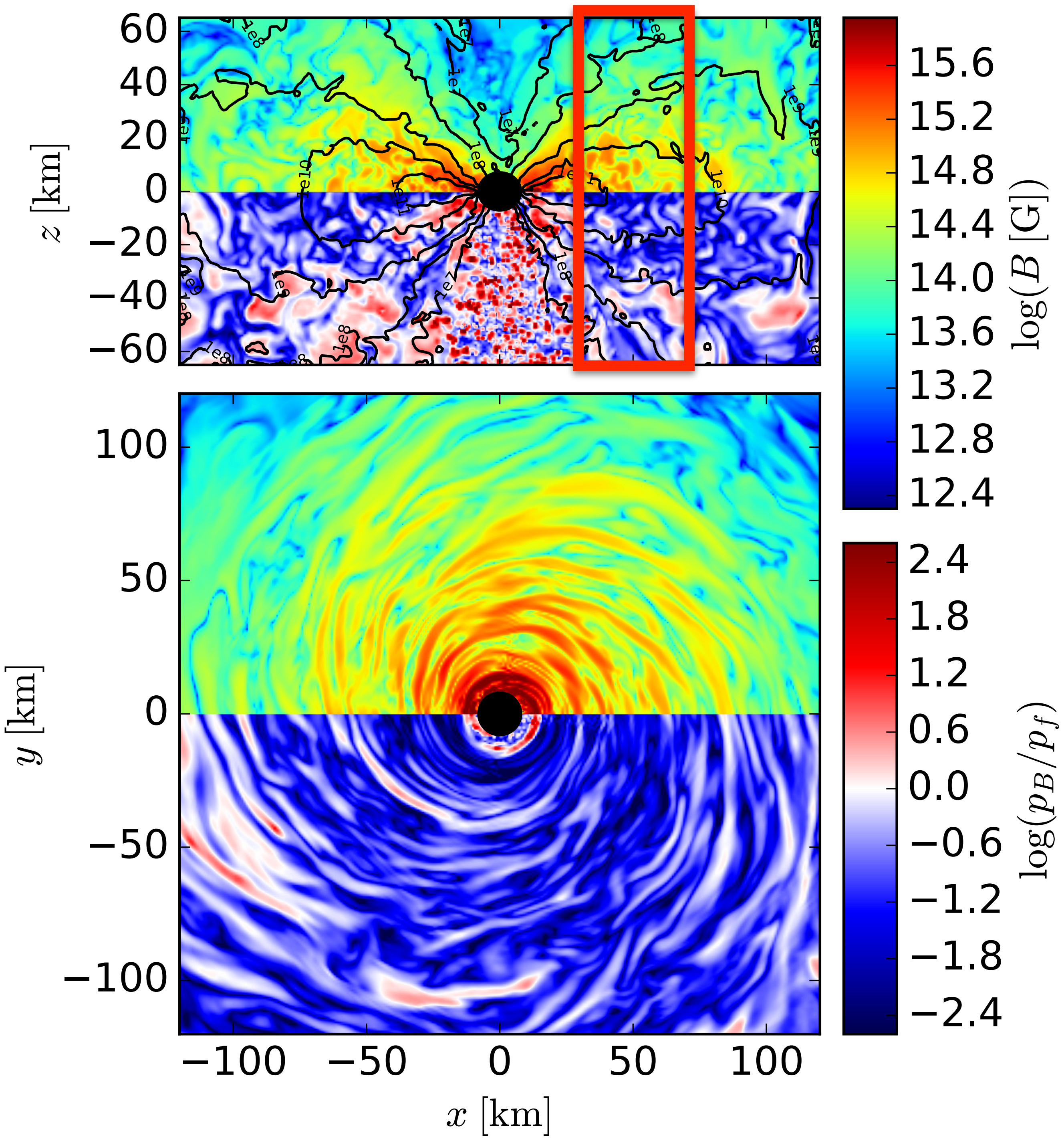
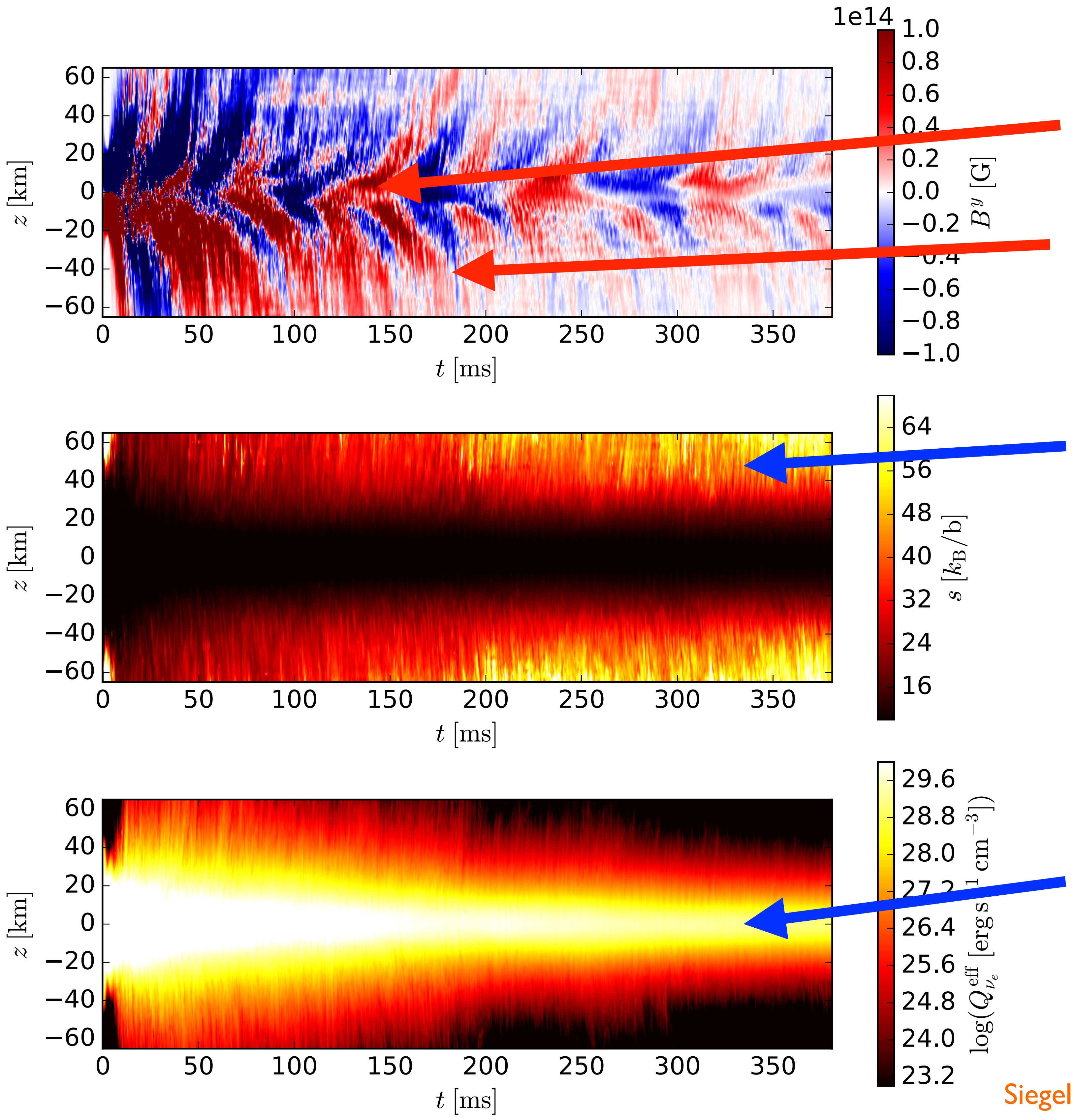


Fig.: magnetic fields in the disk; contours: rest-mass density

properties very similar to
Ciolfi, Siegel+ 2017, Kiuchi+ 2015

Accretion disk dynamo: butterfly diagram



magnetic energy is generated in the mid-plane

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

→ "hot corona"

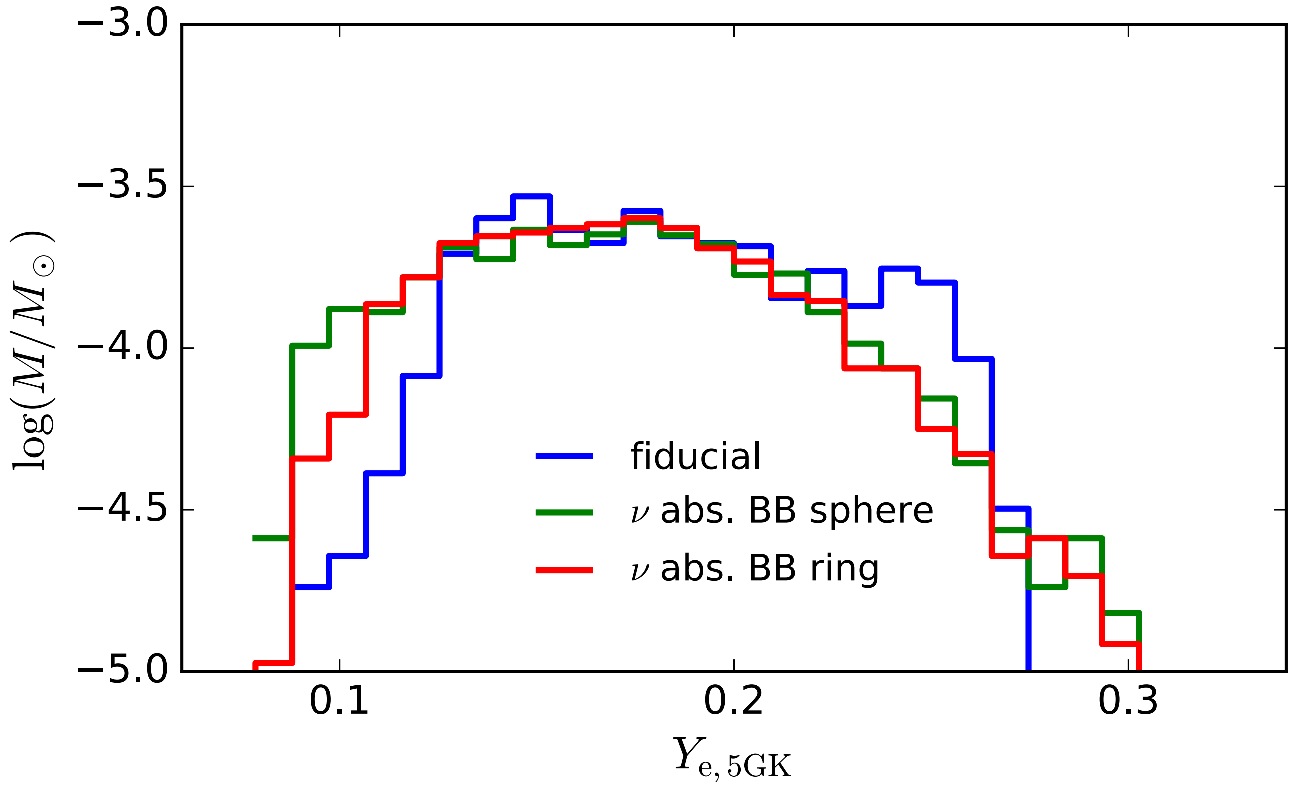
hot corona launches thermal outflows (neutron-rich wind)

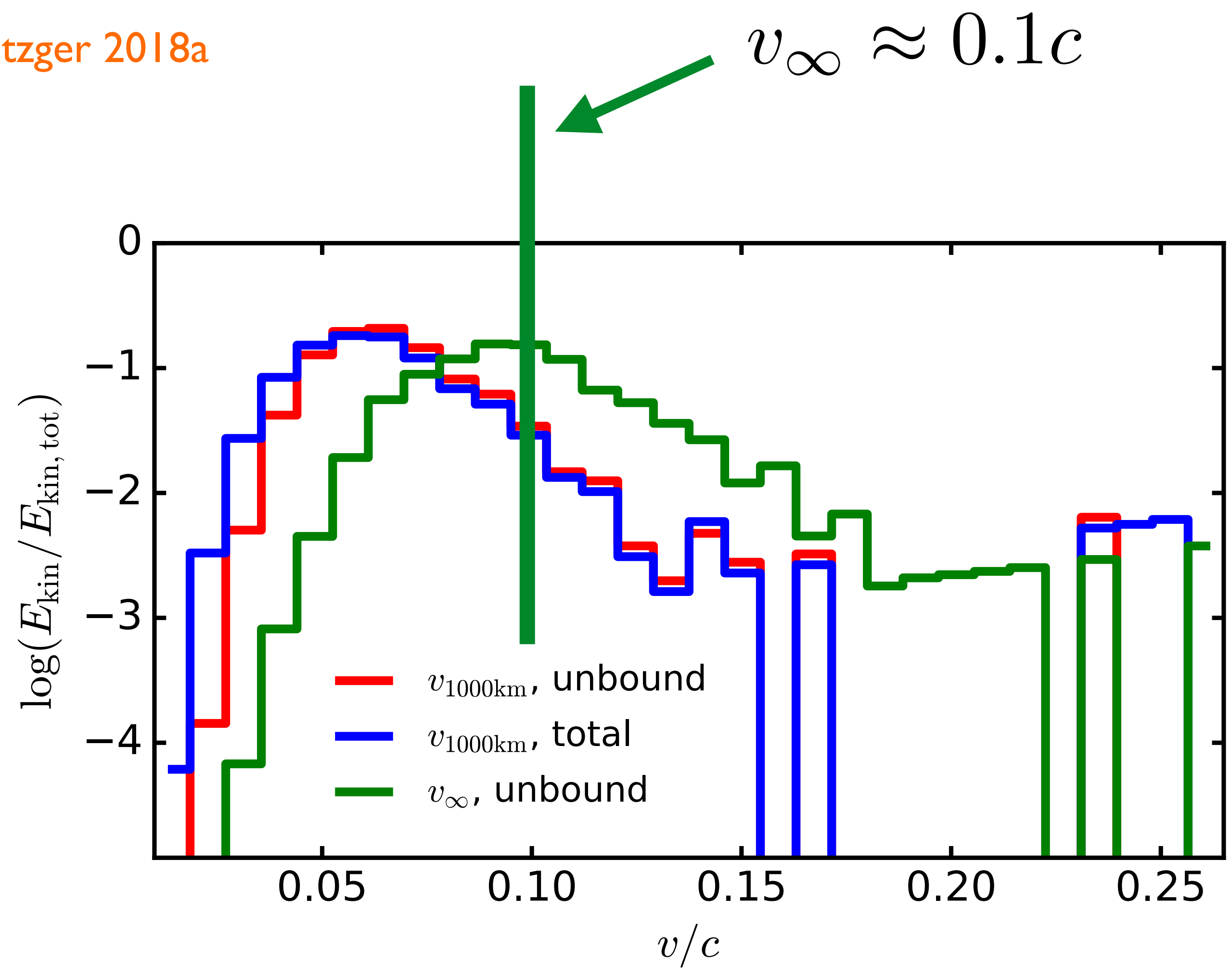
NS post-merger accretion disk are cooled from the mid-plane by neutrinos (rather than from the EM photosphere)!

Siegel & Metzger 2018a

Disk outflow properties

Siegel & Metzger 2018a





ejecta composition

$$Y_\mathrm{e} \approx 0.1 - 0.3$$

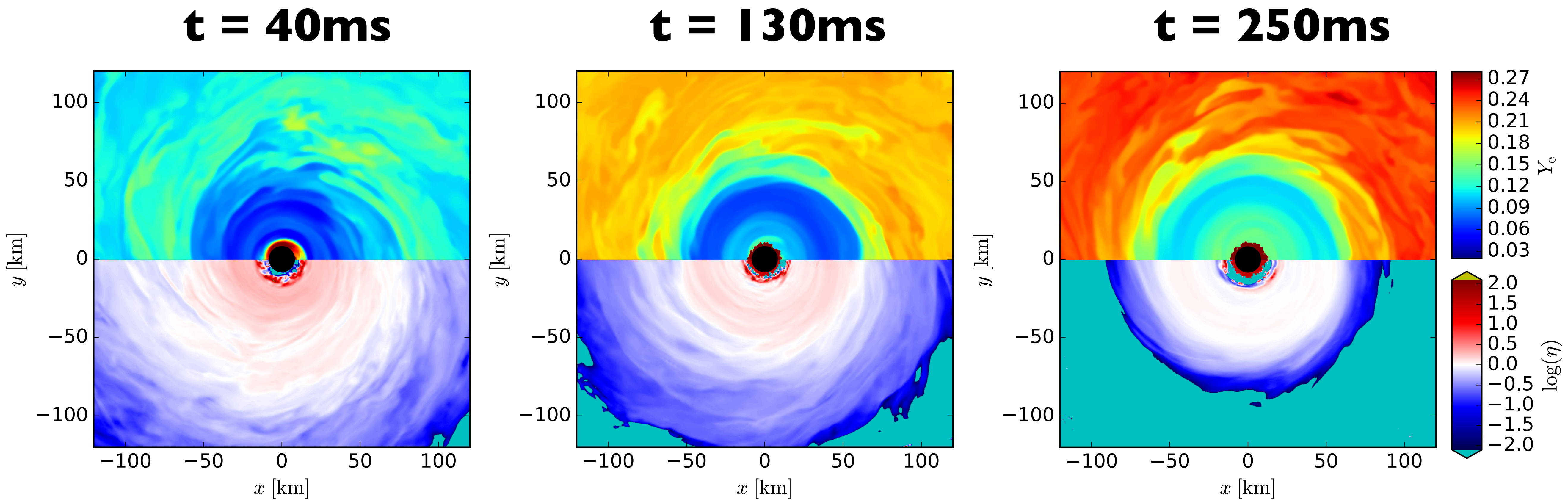
ejecta velocities

$$\boxed{v_\infty \approx 0.1c}$$

corresponds to ~8MeV per baryon in nuclear binding energy release

mass ejection due to combination of thermal winds from hot corona plus nuclear binding energy release

Why are the disk outflows neutron-rich?



Siegel & Metzger 2018a

Neutron-rich conditions favor:

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

How can the overall Y_e of the outflow stay low (~0.1-0.2)?

(and produce 3rd peak r-process elements?)

Self-regulation: keeping a neutron-rich reservoir

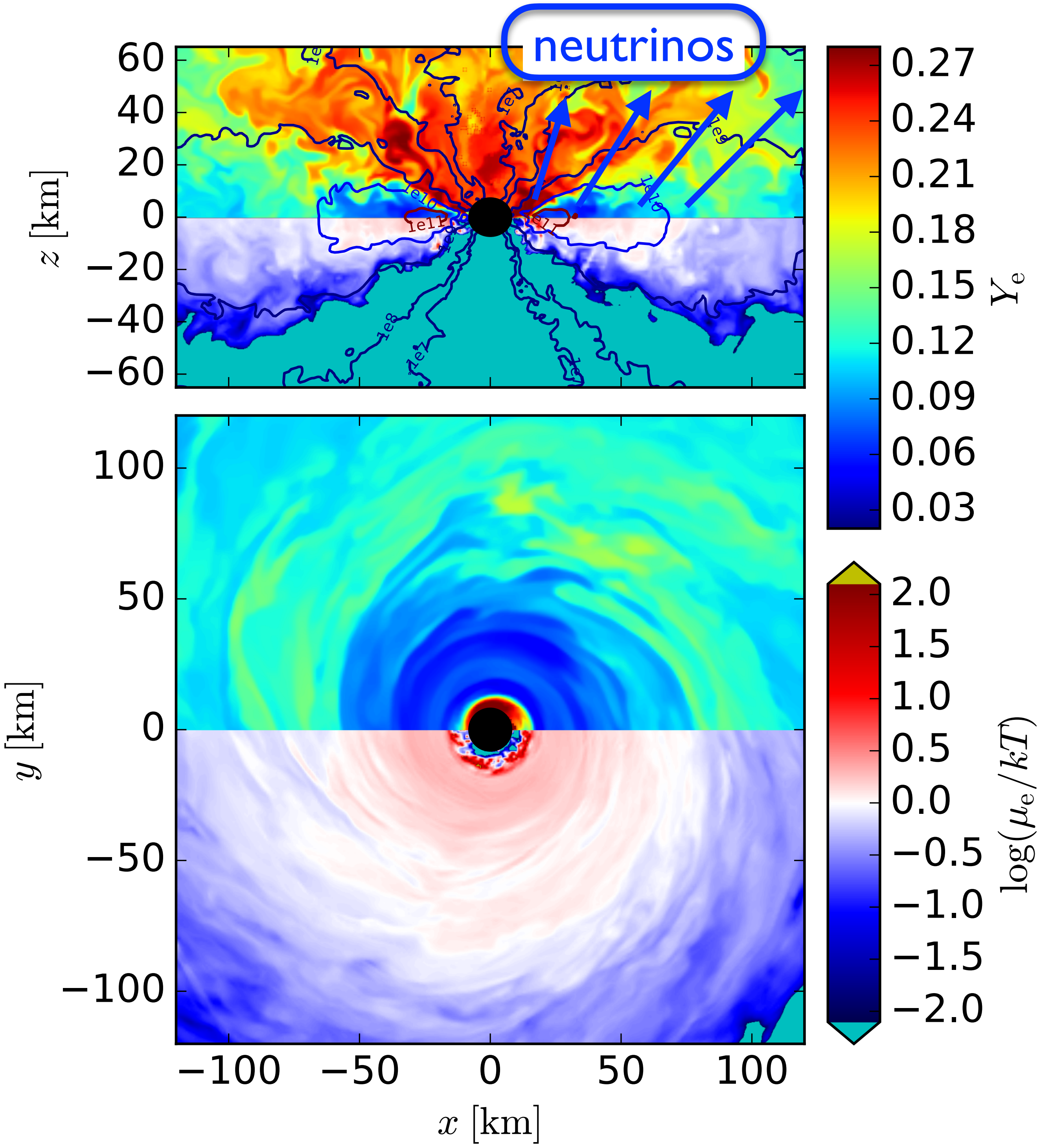


Fig.: disk properties; contours: rest-mass density

Siegel & Metzger 2017, PRL   Siegel & Metzger 2018a

Neutrino-cooled accretion disks self-regulate themselves to mild degeneracy (low Y_e matter):

Beloborodov 2003, Chen & Beloborodov 2007, Metzger+ 2009

- viscous heating via magnetic turbulence
- neutrino cooling

charged-current processes:

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

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

pair annihilation:

$$e^- + e^+ \rightarrow \nu_e + \bar{\nu}_e$$

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

plasmon decay:

$$\gamma \rightarrow \nu_e + \bar{\nu}_e$$

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

Self-regulation: keeping a neutron-rich reservoir

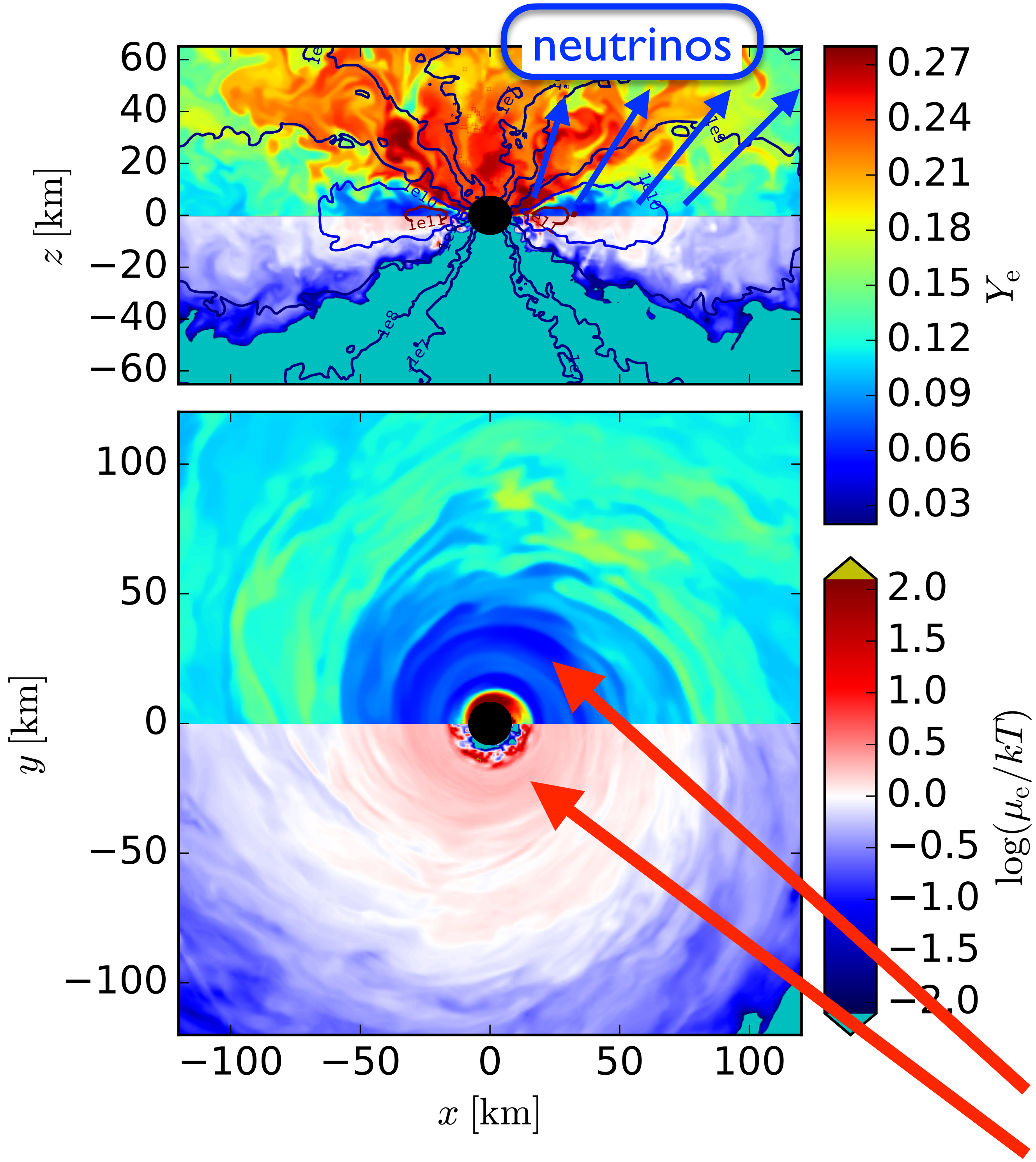


Fig.: disk properties; contours: rest-mass density

Siegel & Metzger 2017, PRL Siegel & Metzger 2018a

Neutrino-cooled accretion disks self-regulate themselves to mild degeneracy (low Y_e matter):

Beloborodov 2003, Chen & Beloborodov 2007, Metzger+ 2009

- viscous heating via magnetic turbulence
- neutrino cooling

⟶ balance with feedback mechanism:

higher degeneracy μ_e/kT

fewer e^-, e^+ (lower Y_e)

less neutrino emission, i.e., cooling

higher temperatures

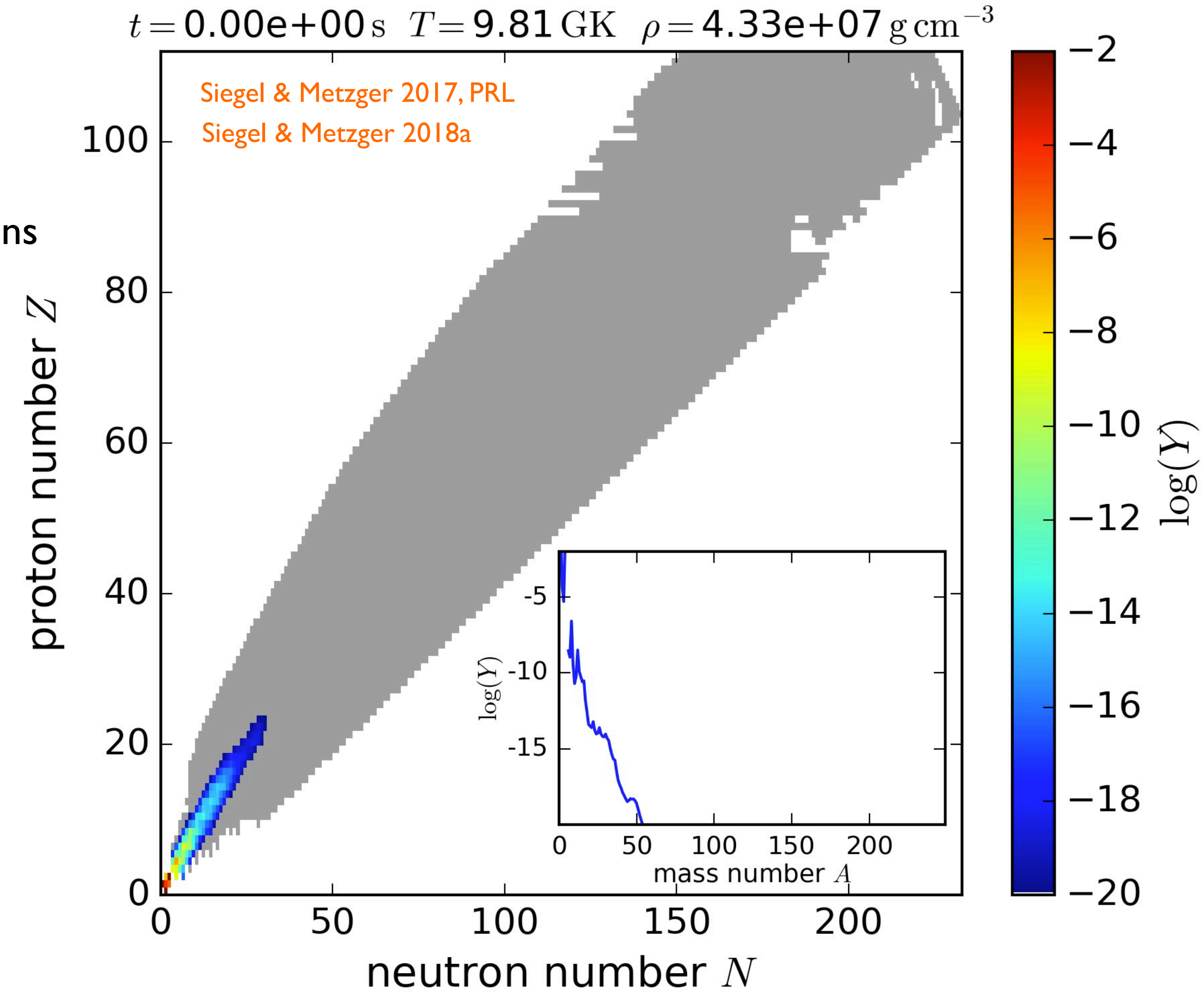
lower degeneracy μ_e/kT

direct evidence of self-regulation

r-process nucleosynthesis in disk outflows

nuclear reaction network (*SkyNet*)

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

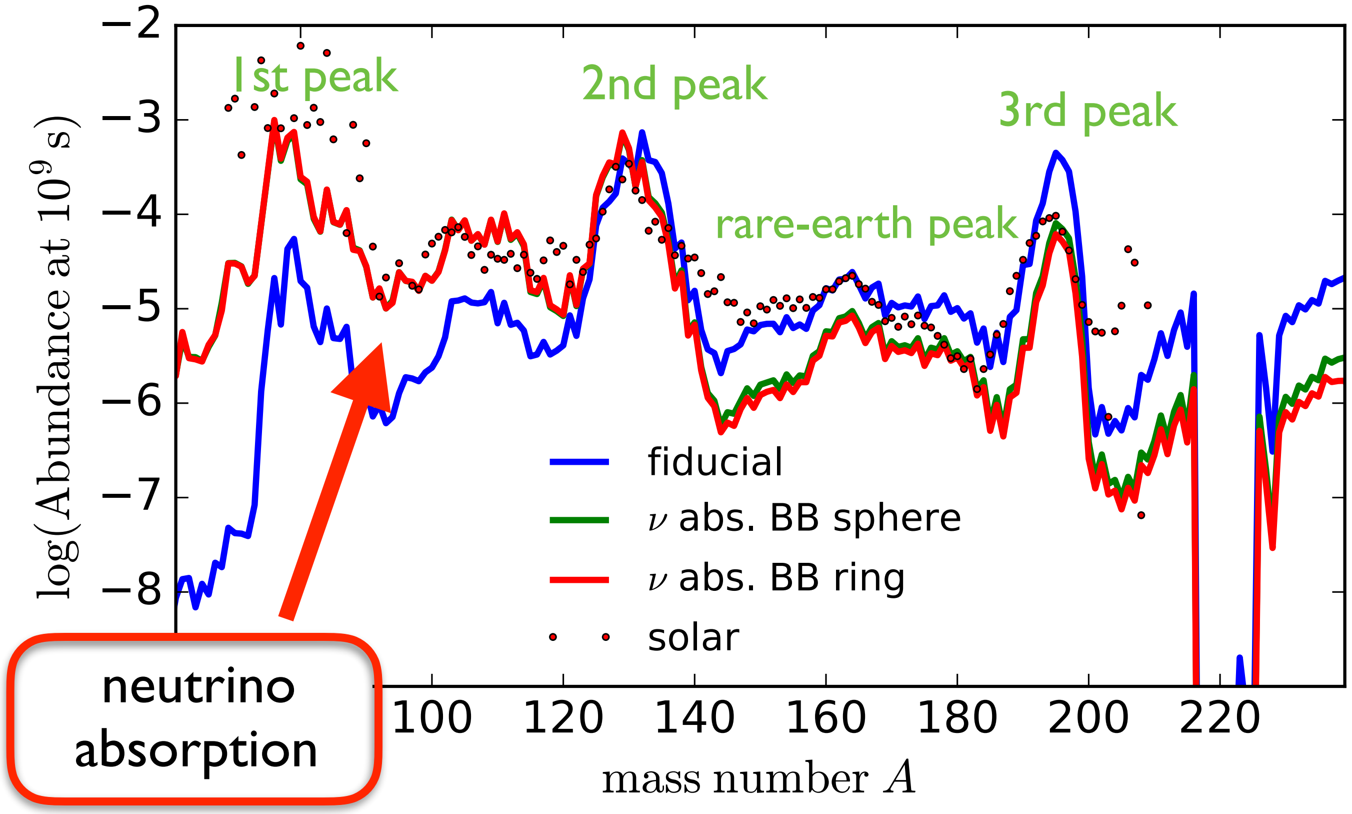


Movie: r-process nucleosynthesis from NS merger remnant disks

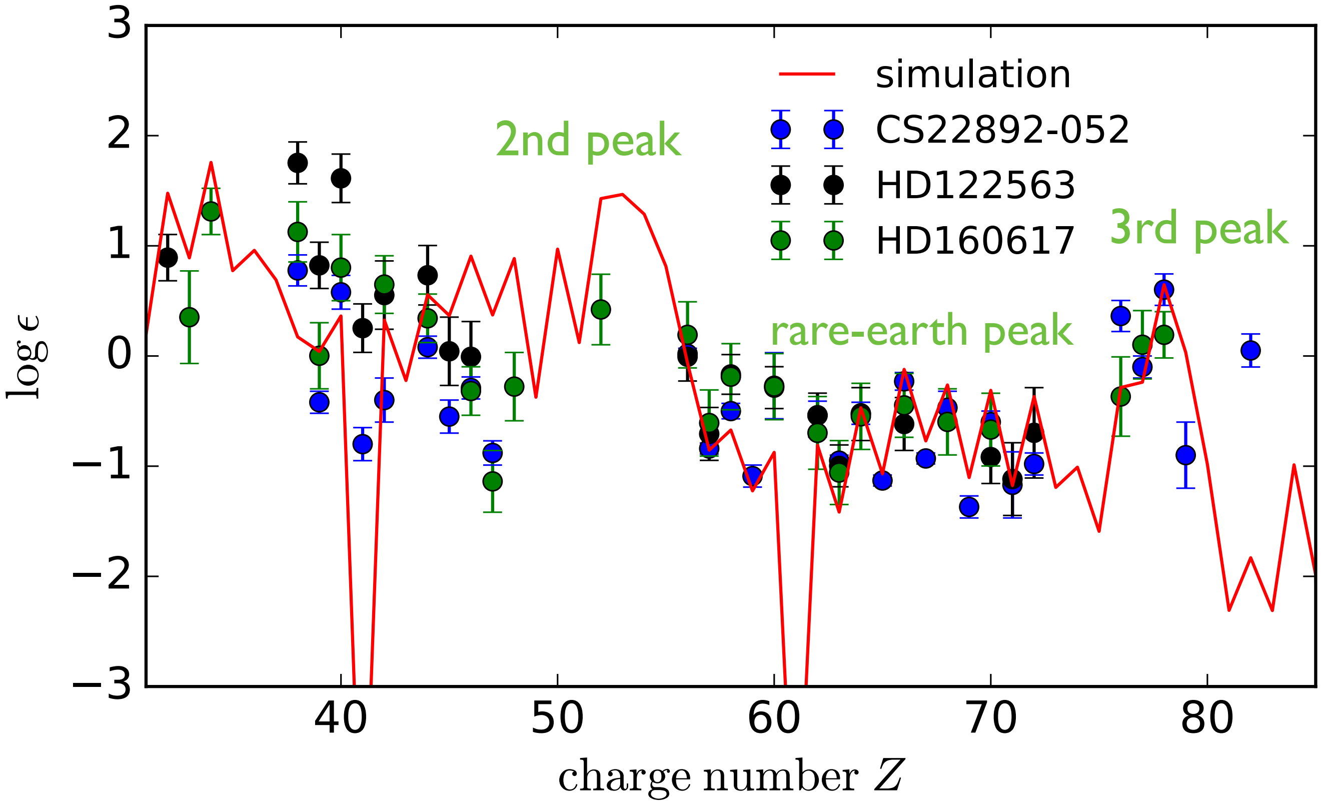
r-process nucleosynthesis in disk outflows

Siegel & Metzger 2017, PRL

Siegel & Metzger 2018a



neutrino absorption



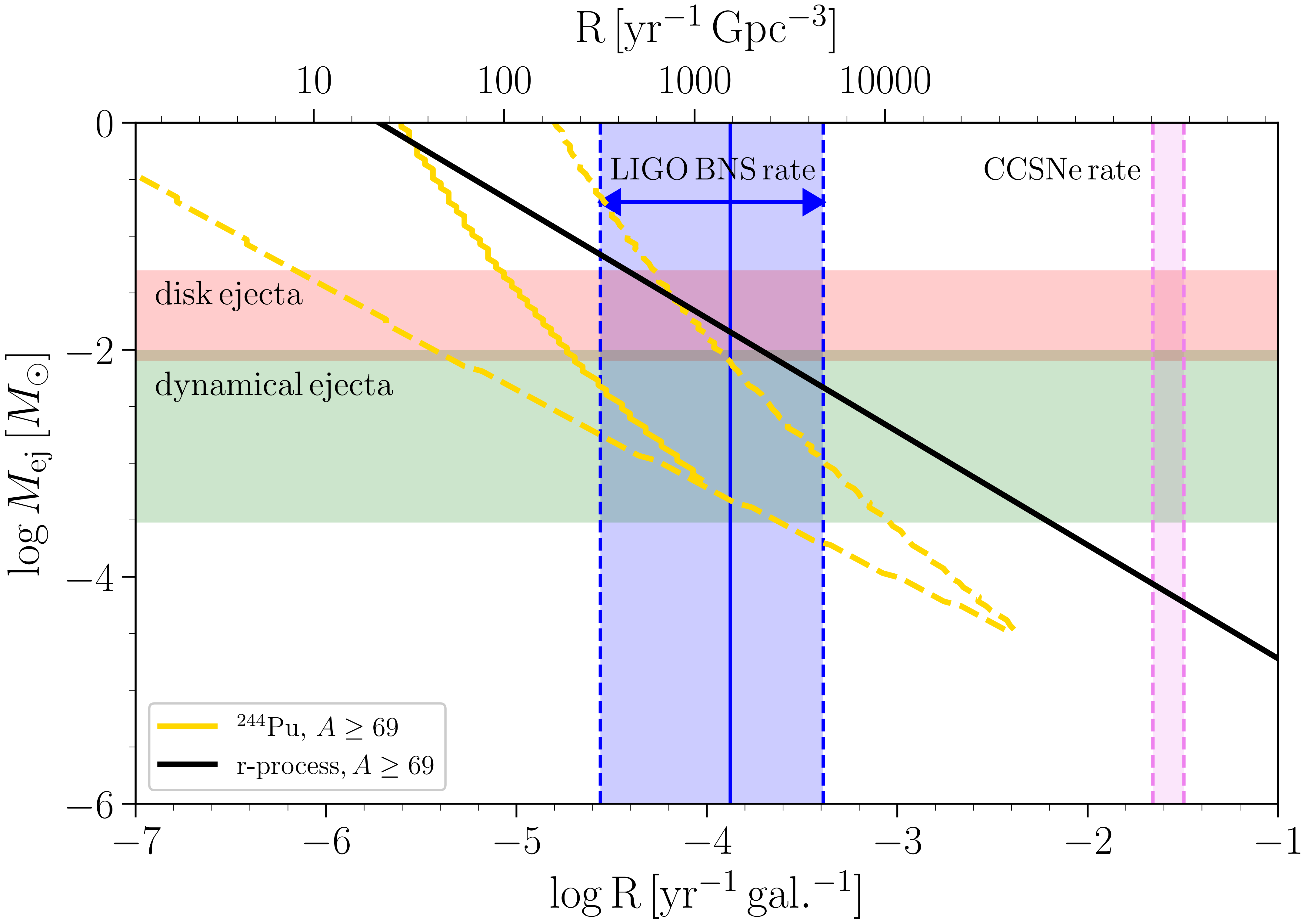
- robust 2nd and 3rd peak r-process!
- including neutrino absorption: additional good fit to 1st & 2nd peak elements

→ **production of all r-process elements!**

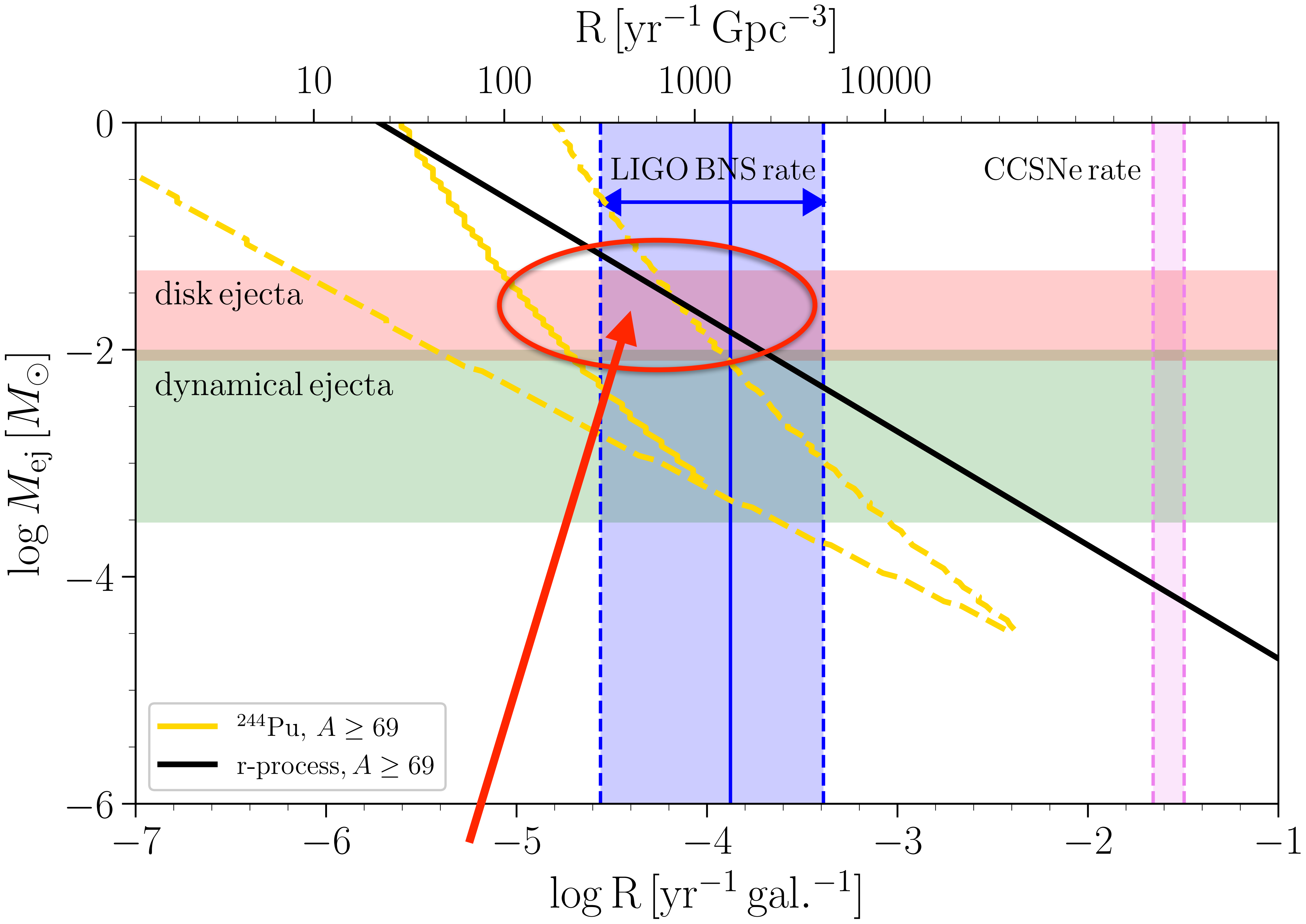
V.

Constraints on galactic r-process enrichment

Constraints on r-process nucleosynthesis

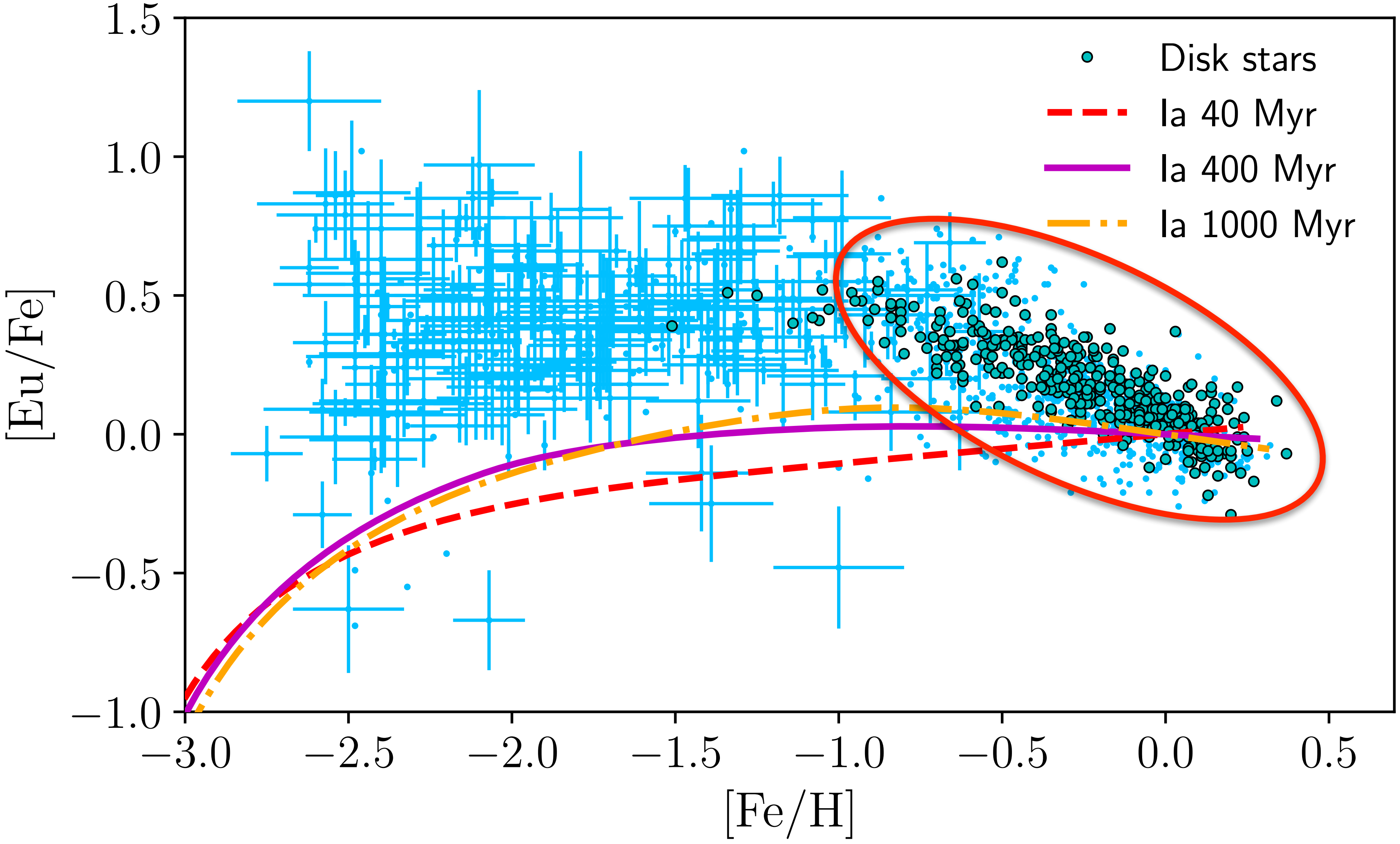


Constraints on r-process nucleosynthesis



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

But… what about galactic chemical *evolution*?

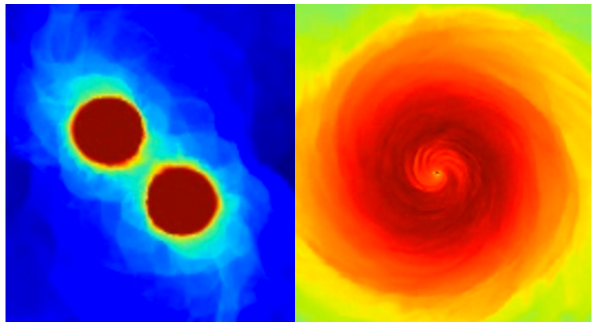


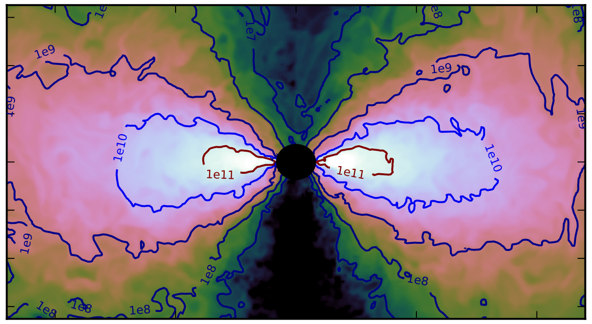
late-time Eu/Fe decrease appears to be in tension
with NS merger paradigm Côté+ 2017, 2018, Hotokezaka+ 2018a

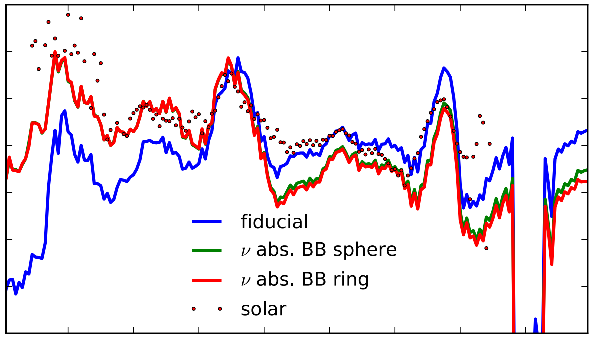
Should we be worried? Is there another significant source of r-process enrichment?

Conclusions

- Multiple kilonova components generally expected due to various ejecta mechanisms in NS mergers
- GW170817 with its exquisite kilonova data allowed us to address the origin of the heavy elements, which has been an enduring mystery for more than 70 years
- First-principle simulations key to understand kilonova properties and heavy-element formation (identify the site, production processes, abundance pattern etc.)
- Simulations + GW170817 + EM (kilonova) point to post-merger accretion disk winds as promising site (ubiquitous phenomenon!)







Relative abundances, total ejecta mass, measured BNS merger rate provide
yet strongest evidence for NS mergers being a potential prime production site for the r-process