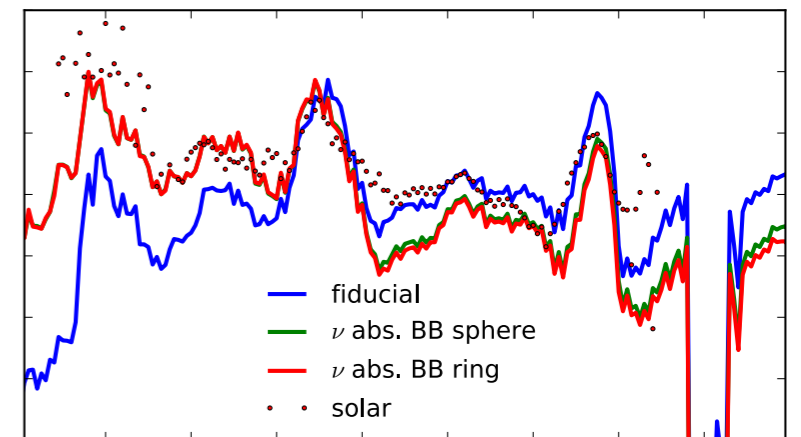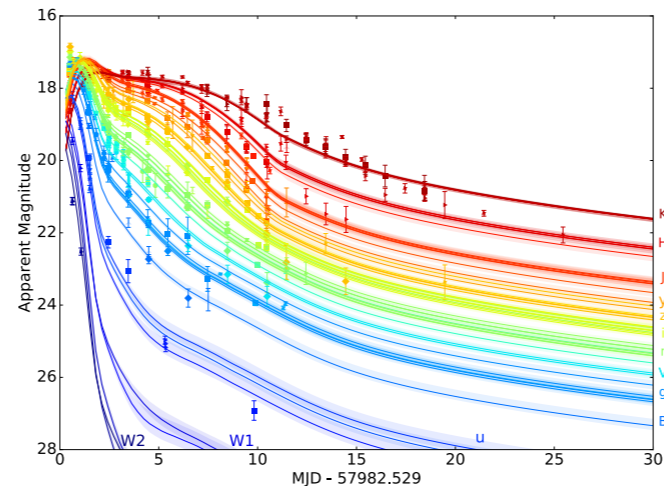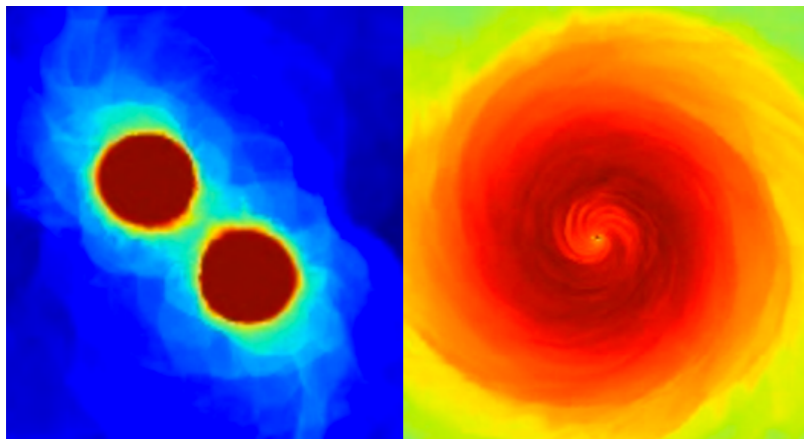# COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

GW170817: Implications for the astrophysical site of the r-process

Daniel M. Siegel

NASA Einstein Fellow

Center for Theoretical Physics & Columbia Astrophysics Laboratory, Columbia University

FRIB and the GW170817 kilonova, MSU, July 16-27, 2018

I.
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
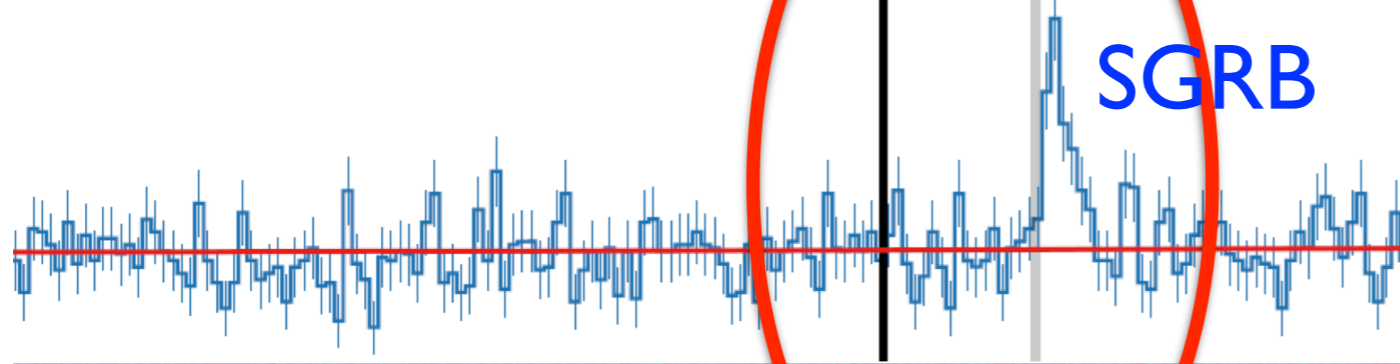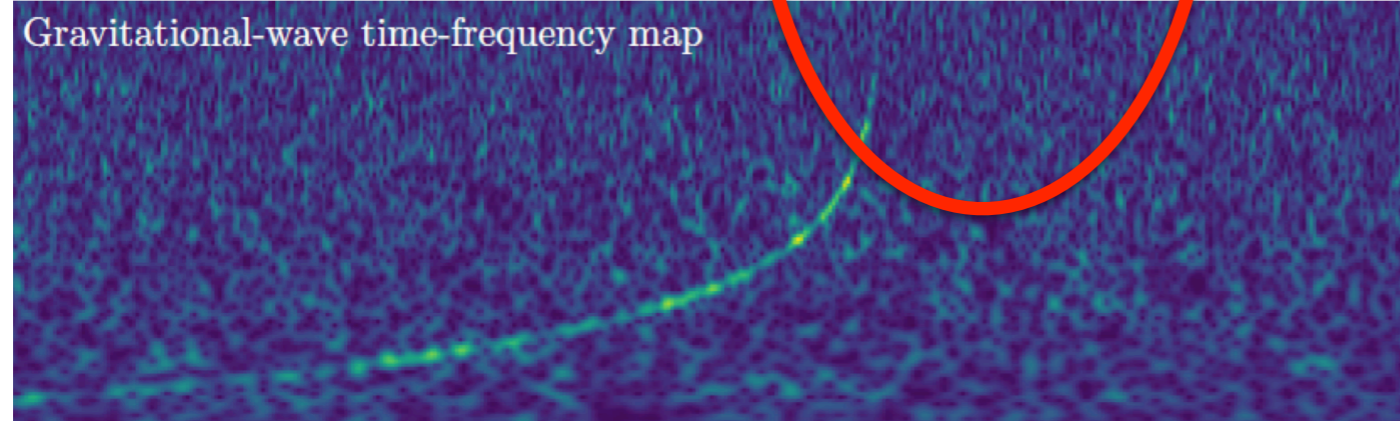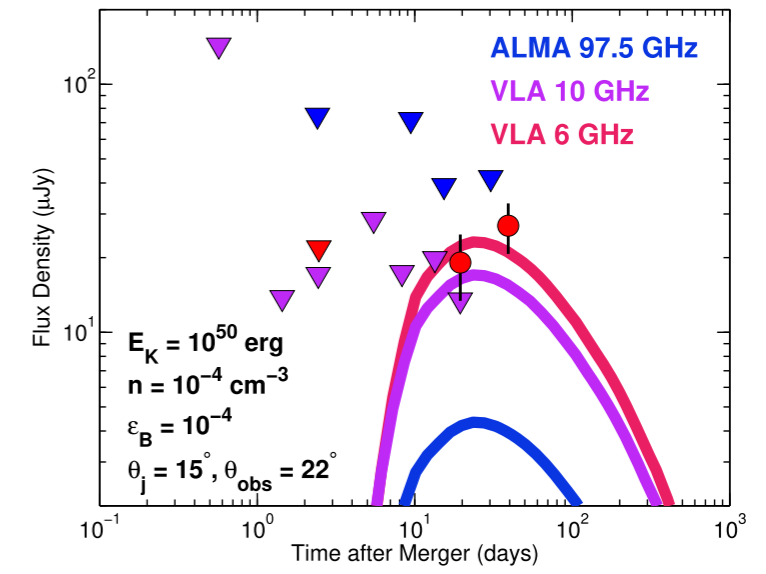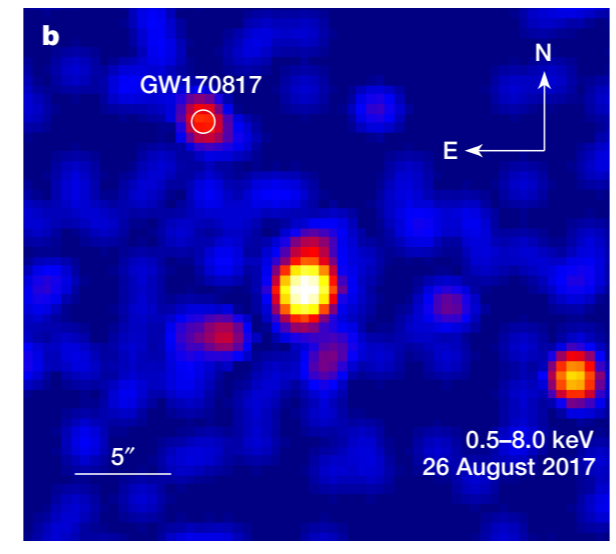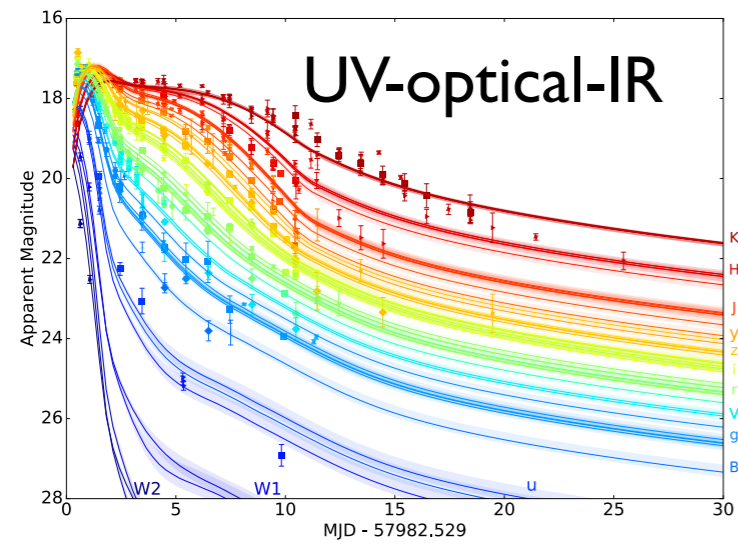
The r-process and s-process

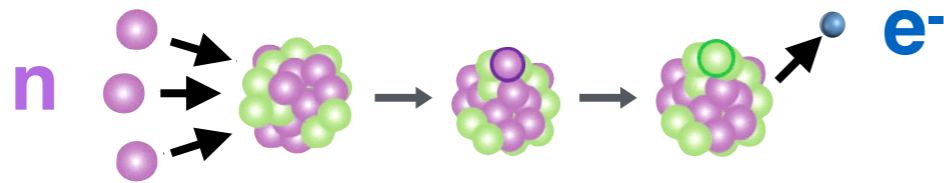Burbidge, Burbidge, Fowler, Hoyle (1957), Cameron (1957):

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

Burbidge, Burbidge, Fowler, Hoyle ("B²FH")

Cameron

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

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.

speculated that r-process requires explosive environment of supernovae

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
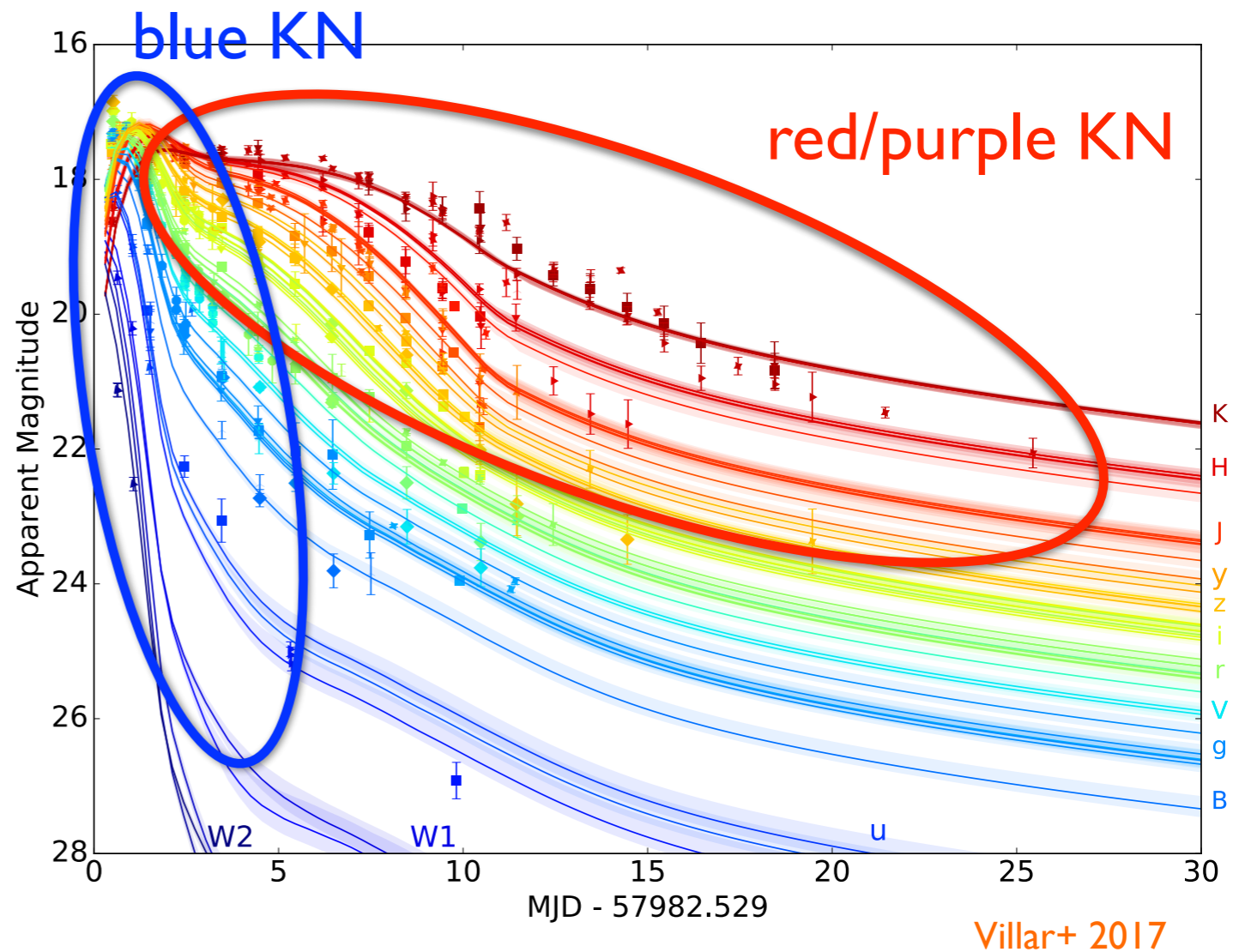
- two ("red-blue") or multiple components expected from merger simulations

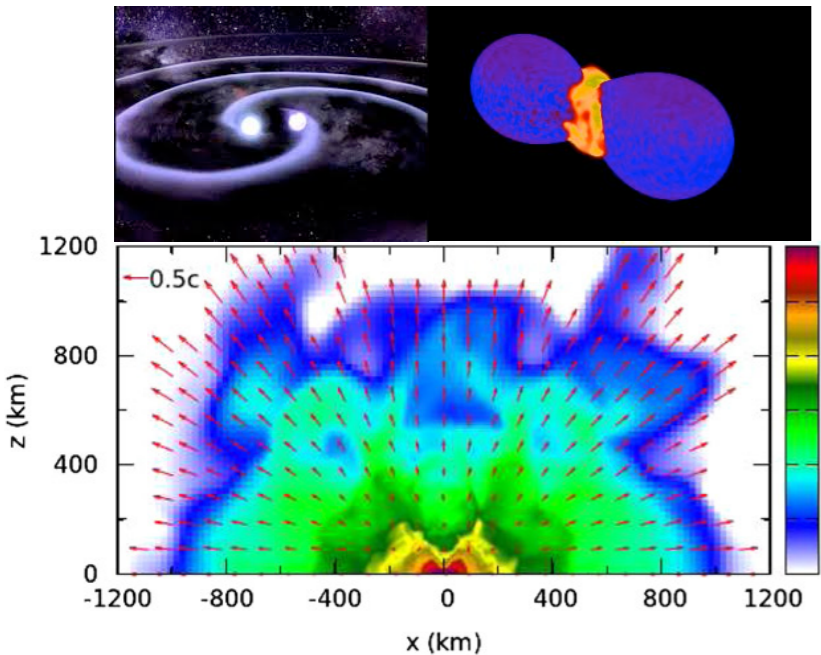- single component models might be possible, but require fine-tuning of Y_e

  Smartt+ 2017
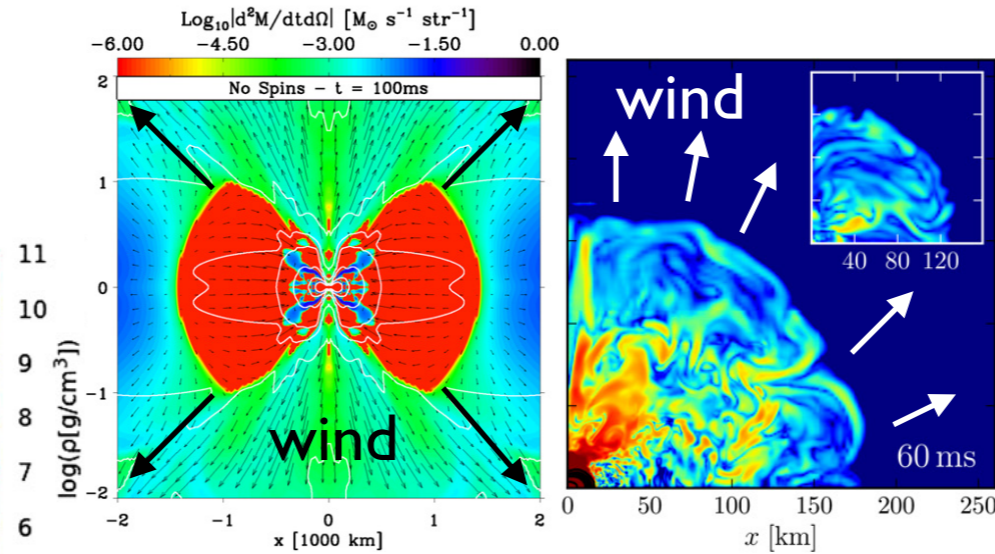 Waxman+ 2017

II.
Mass ejection
GW170817 phenomenology

dynamical ejecta (~ms)   winds from NS remnant (~10ms-1s)   accretion disk (~10ms-1s)

Hotokezaka+ 2013, Bauswein+ 2013

Dessart+ 2009

Siegel+ 2014
Ciolfi, Siegel+ 2017

Siegel & Metzger 2017, 2018a

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

combined see Metzger 2018

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

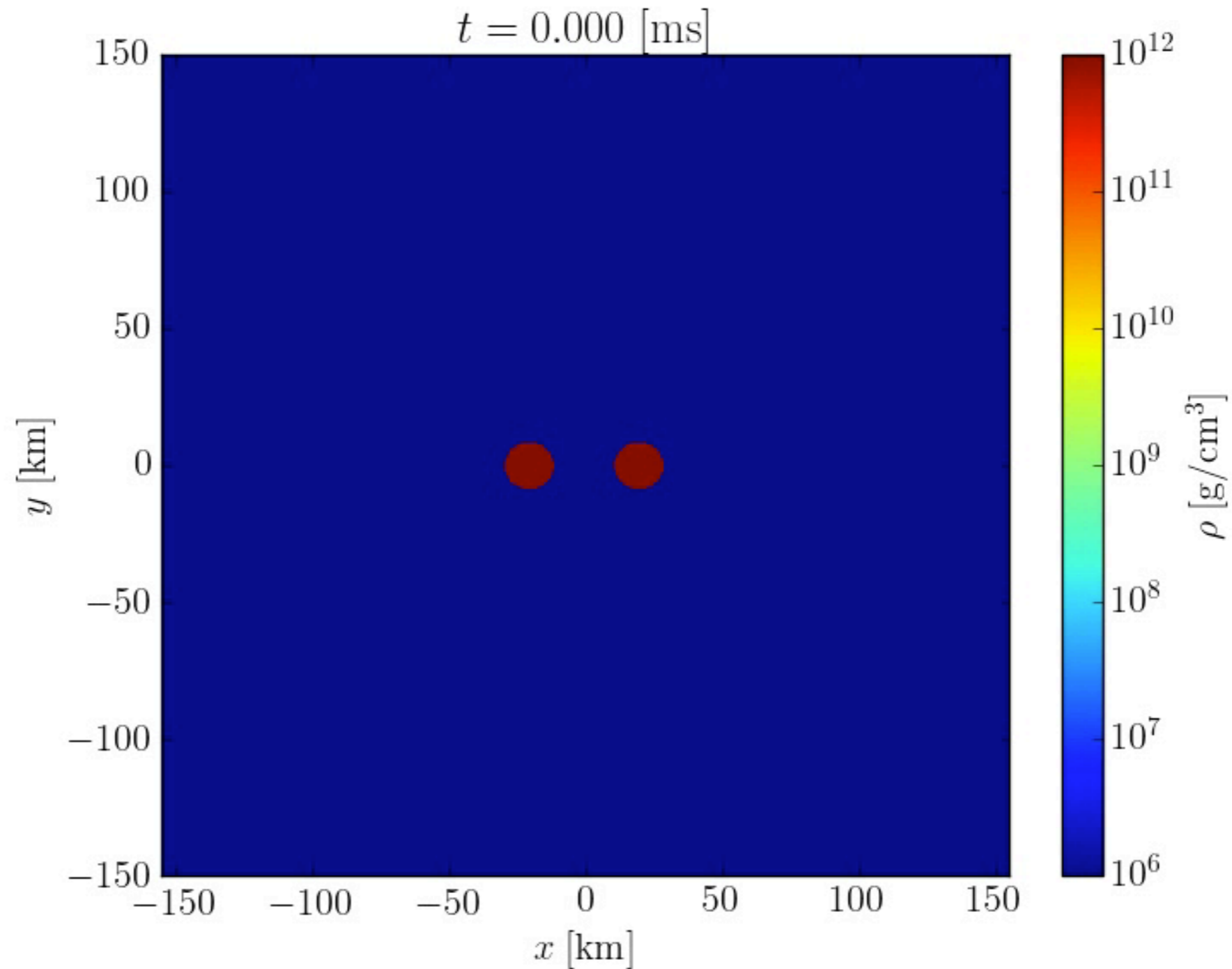Siegel & Metzger 2017, 2018

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

lower limit

Dynamical ejecta and winds

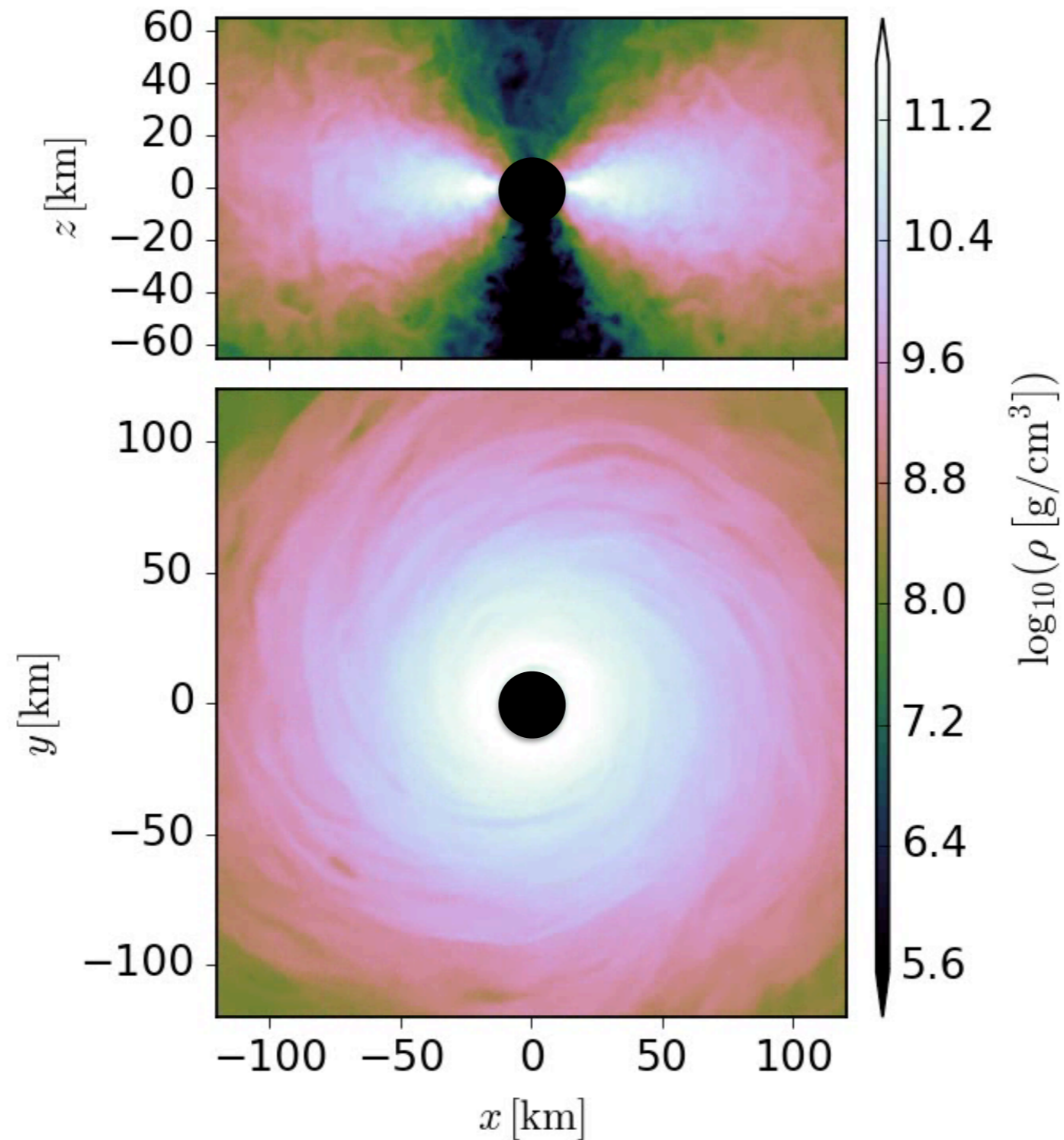Movie: BNS merger showing dynamical ejecta and winds from remnant NS   Ciolfi, Siegel+2017

Accretion disk formation

Movie: BNS merger and formation of
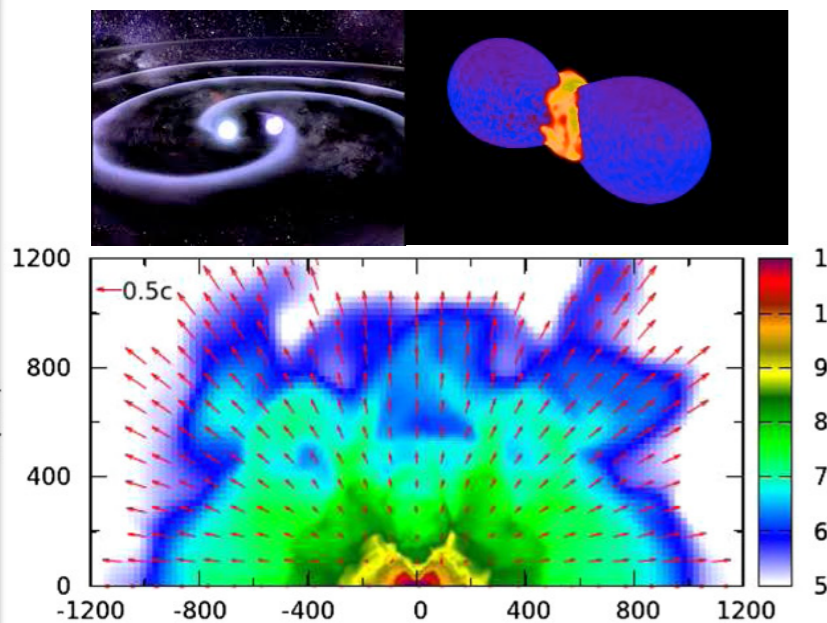post-merger accretion disk   Radice+ 2016

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 and kilonova in GW170817

dynamical ejecta (~ms)

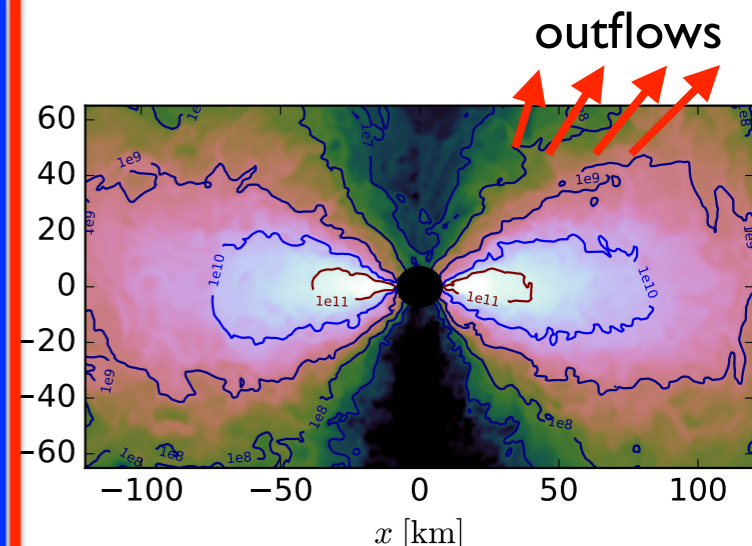$$M_{\rm tot} \lesssim 10^{-3} {\rm M}_\odot$$
$$v \gtrsim 0.2c$$

winds from NS remnant (~ms-1s)
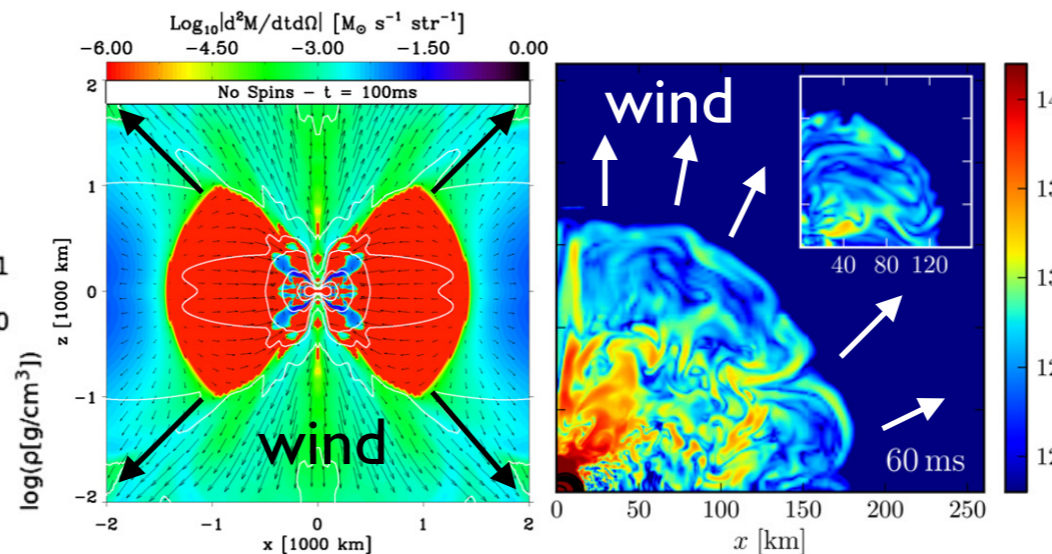
$$\dot{M}_{\rm in} \sim (10^{-3} - 10^{-2}) {\rm M}_\odot {\rm s}^{-1}$$
$$v \lesssim 0.1c$$

accretion disk (~10ms-1s)

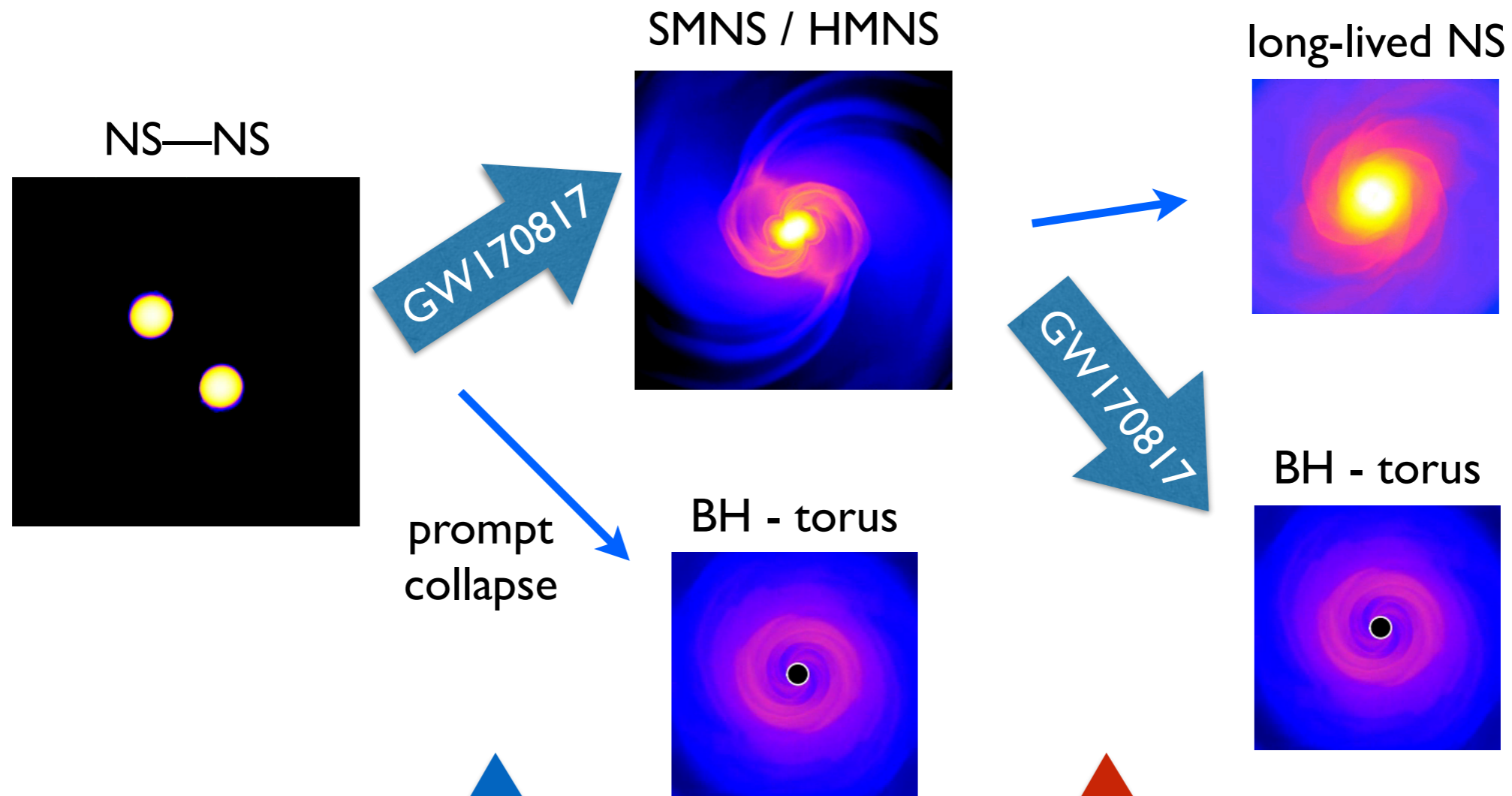$$M_{\rm tot} \gtrsim 10^{-2} M_\odot$$
$$v \sim 0.1c$$

blue KN in GW170817

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

$\longrightarrow$ requires metastable NS phase

$\longrightarrow$ requires EOS with small NS radius (~12 km)

red KN in GW170817

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

Scenario for GW170817

NS—NS

SMNS / HMNS

long-lived 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

III.
How are the heavy elements produced?
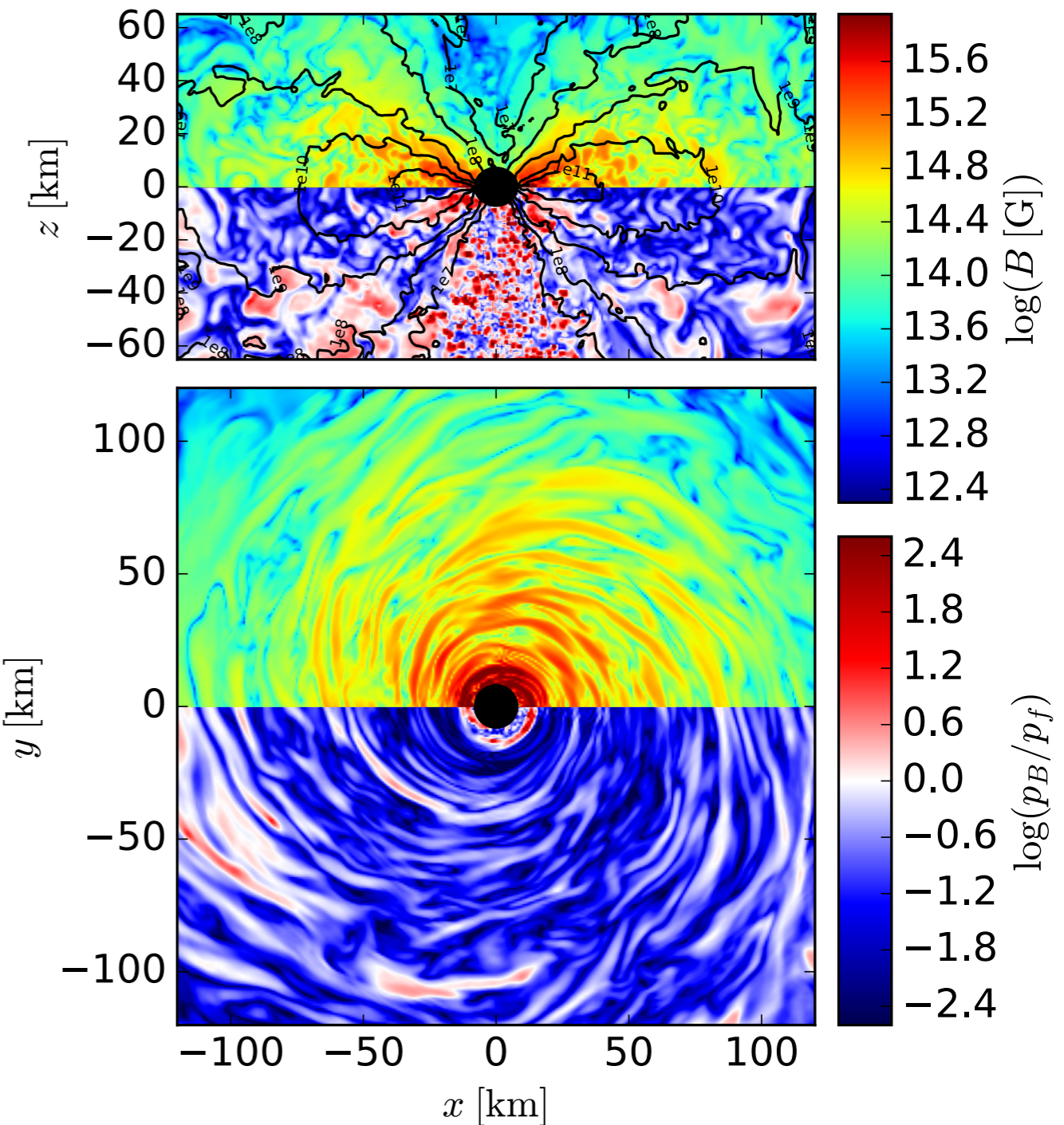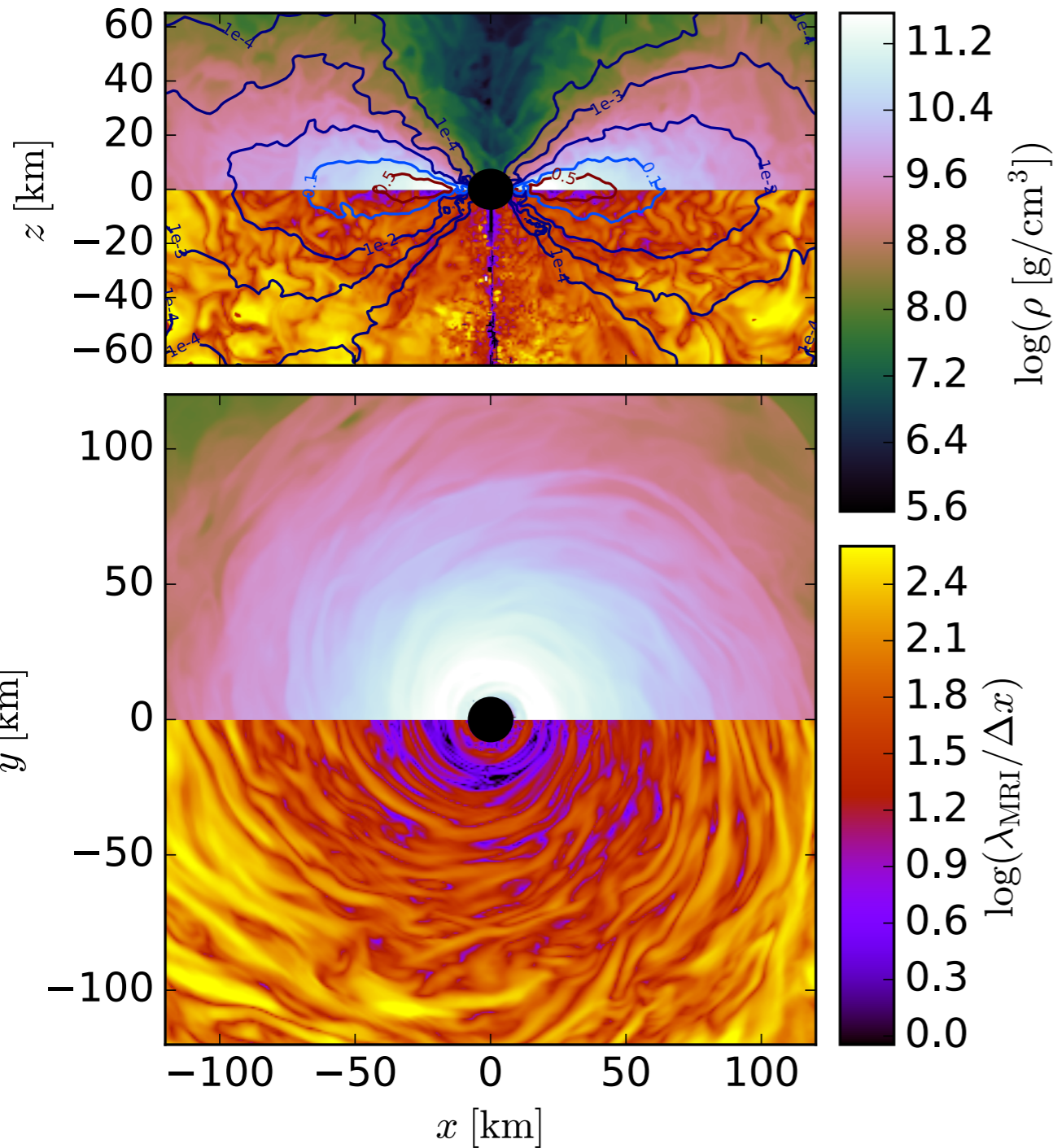
Post-merger accretion disks: MHD turbulence

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

Post-merger accretion disks: MHD turbulence
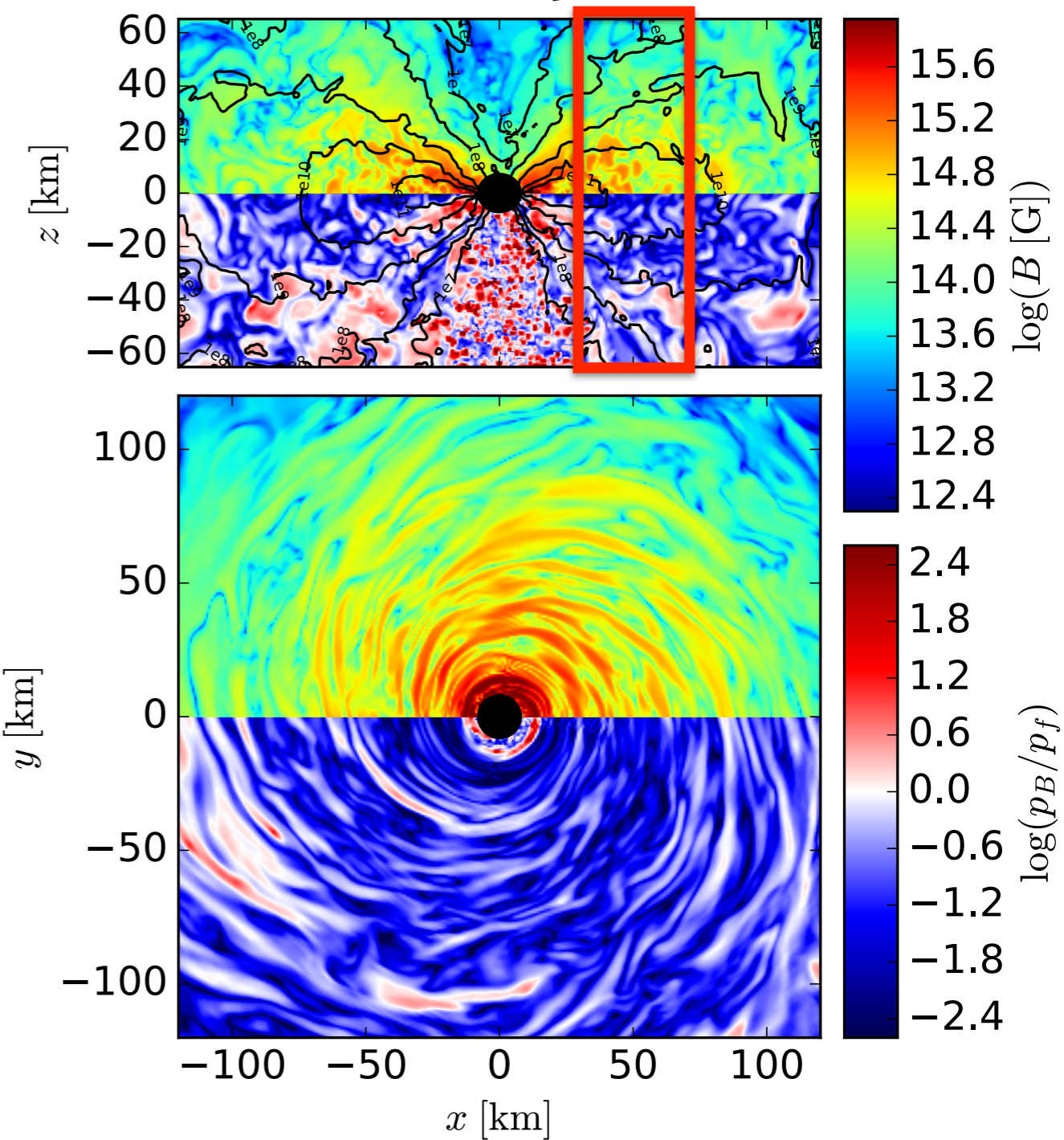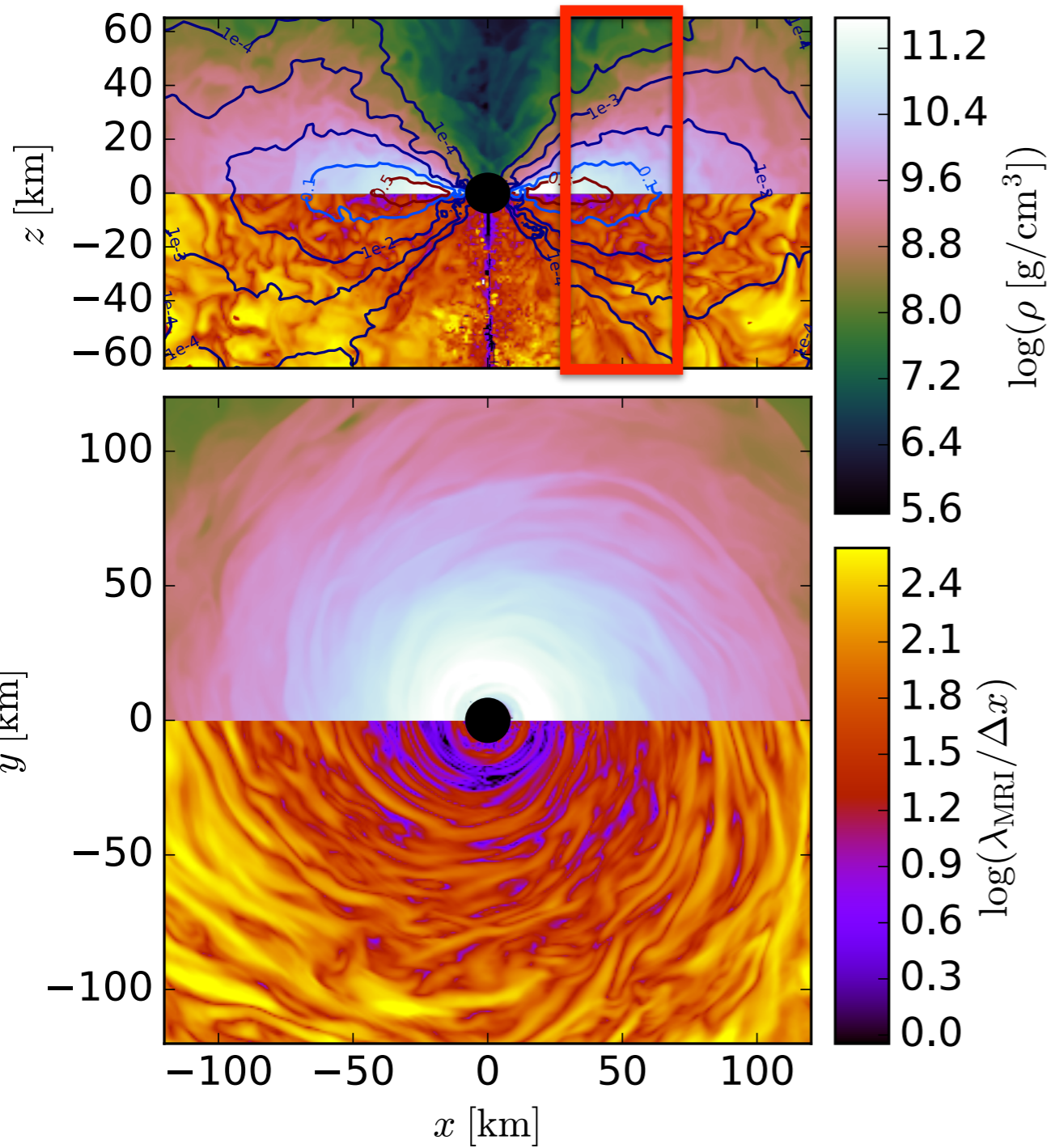
average radially for space-time diagram

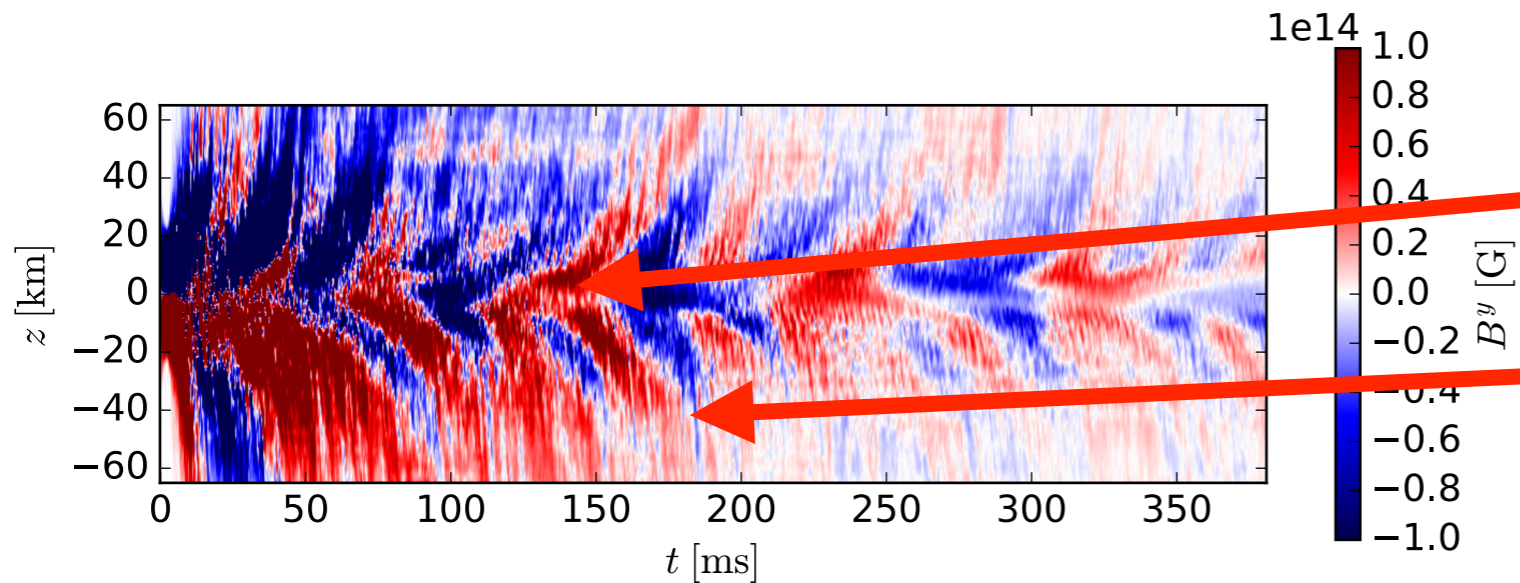Fig.: disk properties; contours: optical depth for electron neutrinos

Siegel & Metzger 2017, PRL   Siegel & Metzger 2018a

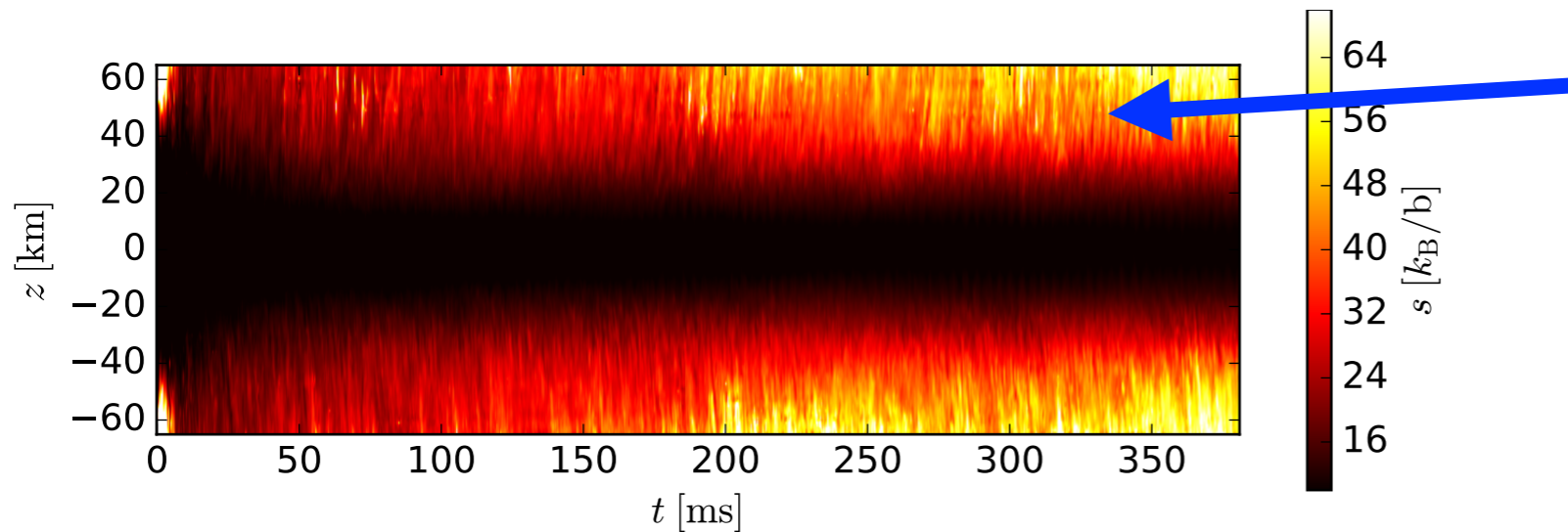Fig.: magnetic fields in the disk; contours: rest-mass density

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

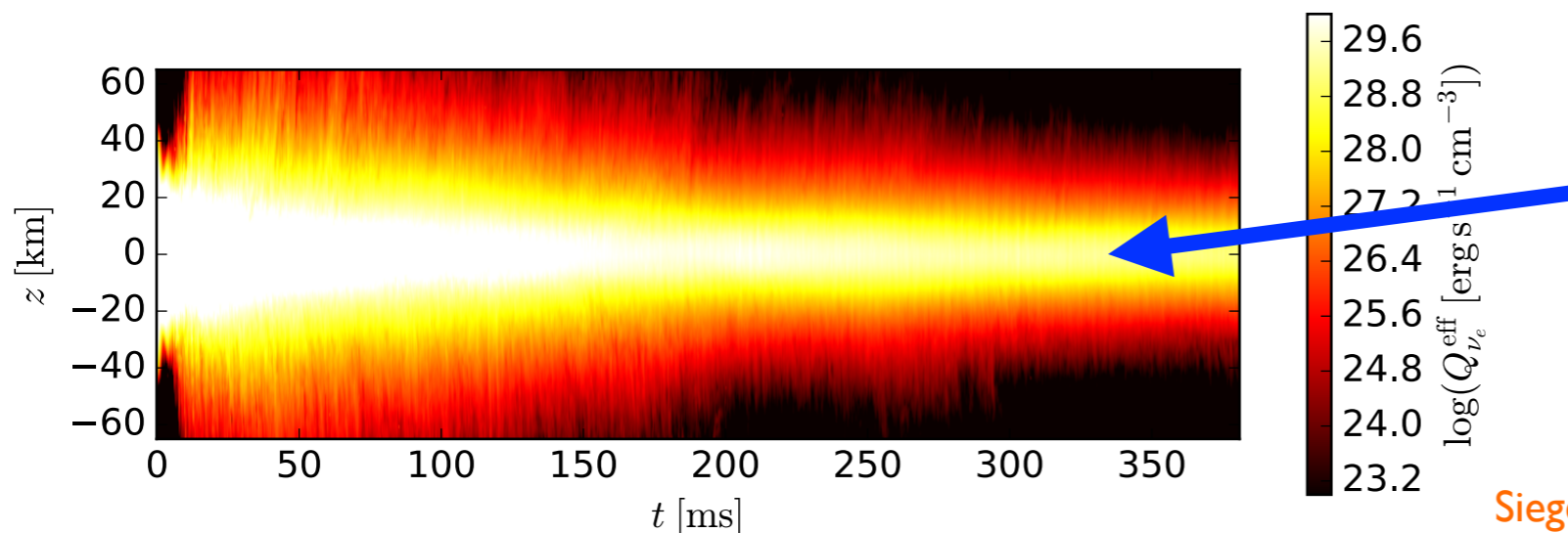# Accretion disk dynamo: butterfly diagram

magnetic energy is generated in the mid-plane

- migrates to higher latitudes

- dissipates into heat off the mid-plane

→ "hot corona"

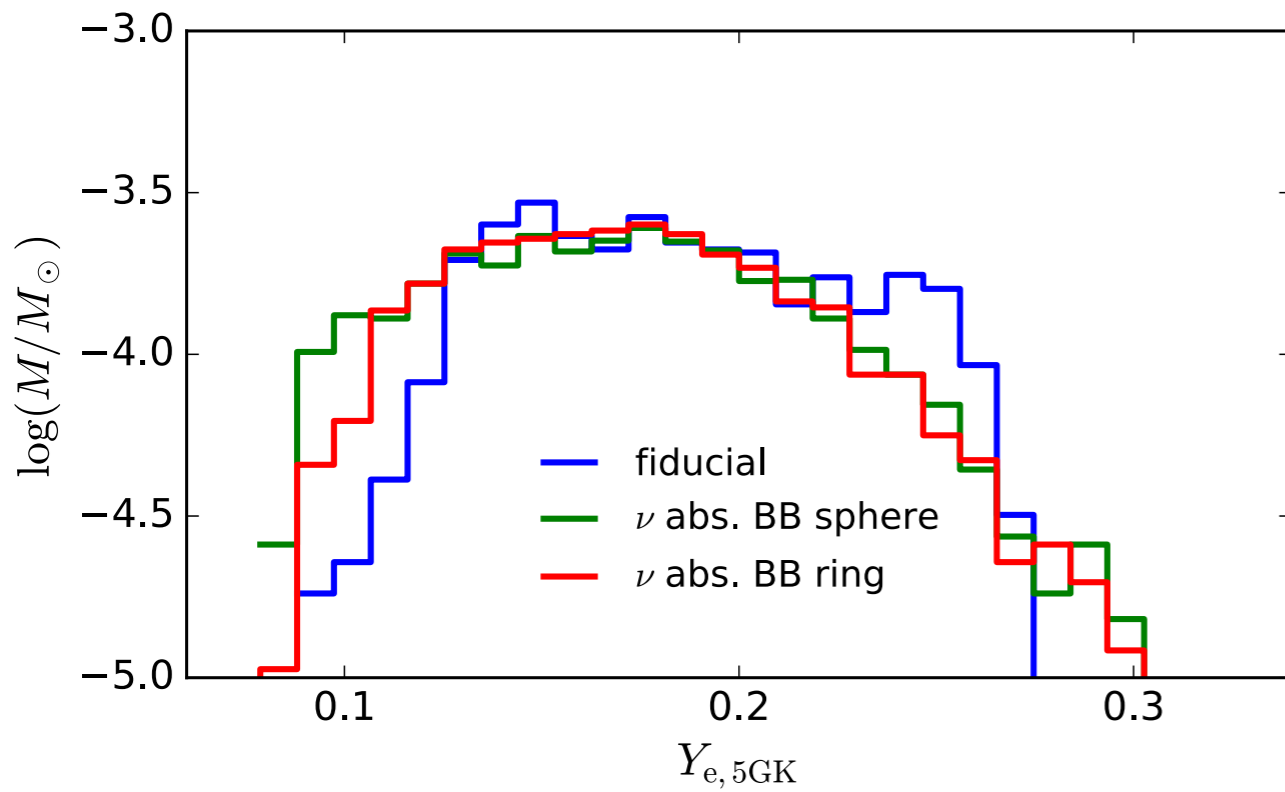hot corona launches thermal outflows (neutron-rich wind)

NS post-merger accretion disk are cooled from the mid-plane by neutrinos (rather than from the EM photosphere)!
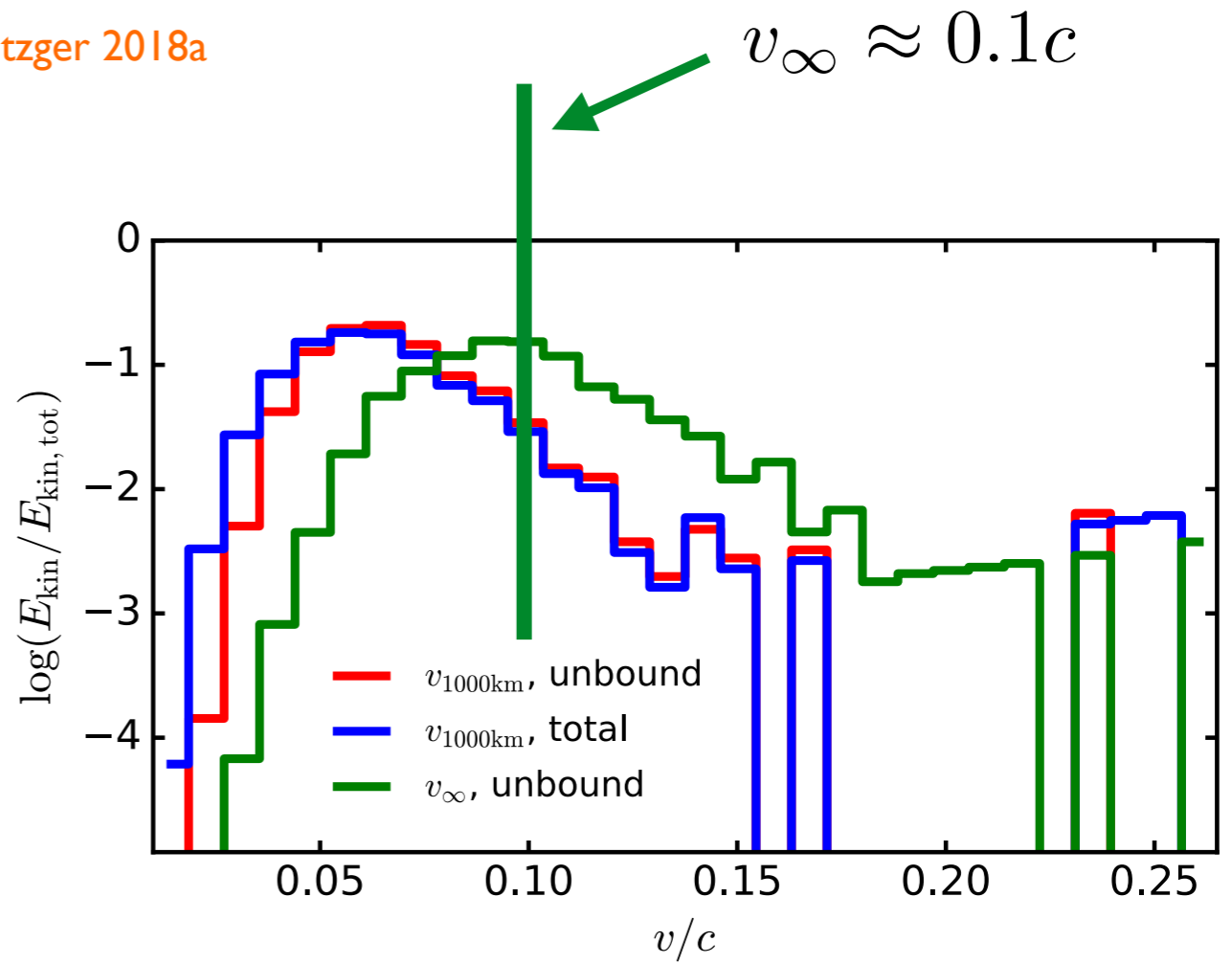
Siegel & Metzger 2018a

Disk outflow properties

Siegel & Metzger 2018a

$v_\infty \approx 0.1c$
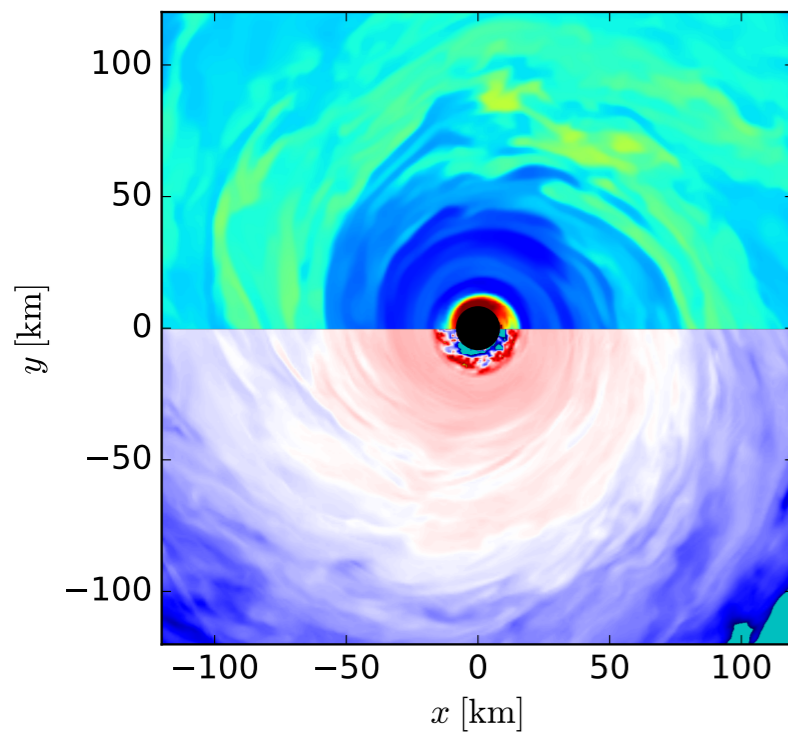

ejecta composition

$$Y_e \approx 0.1 - 0.3$$

ejecta velocities

$$v_\infty \approx 0.1c$$

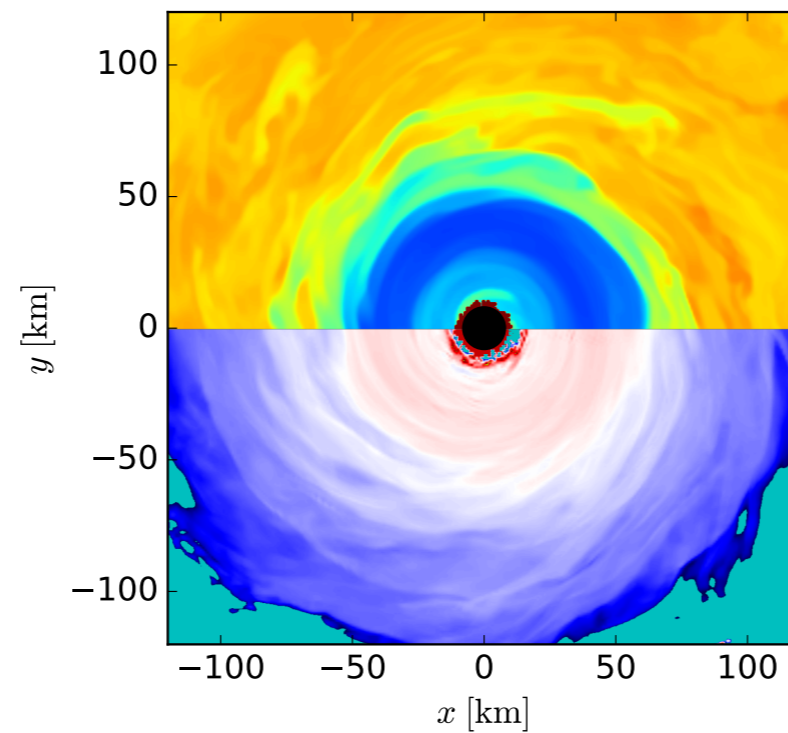corresponds to ~8MeV per baryon in nuclear binding energy release

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

Why are the disk outflows neutron-rich?

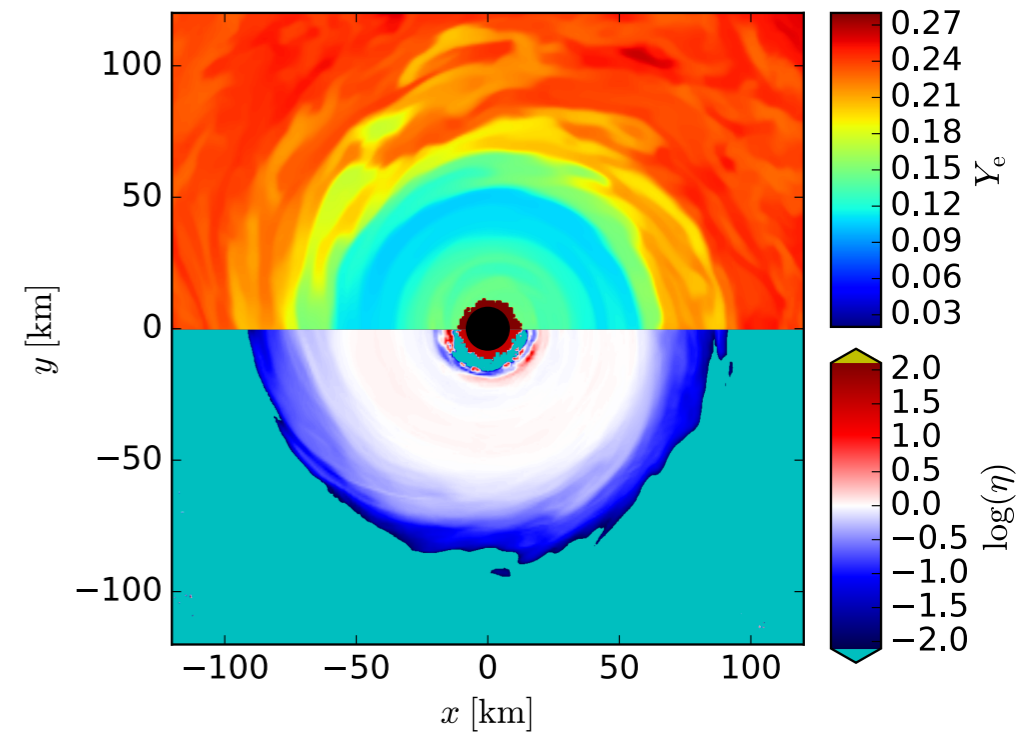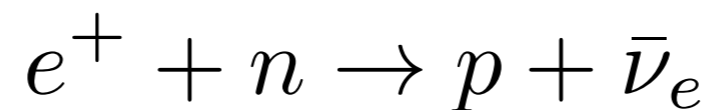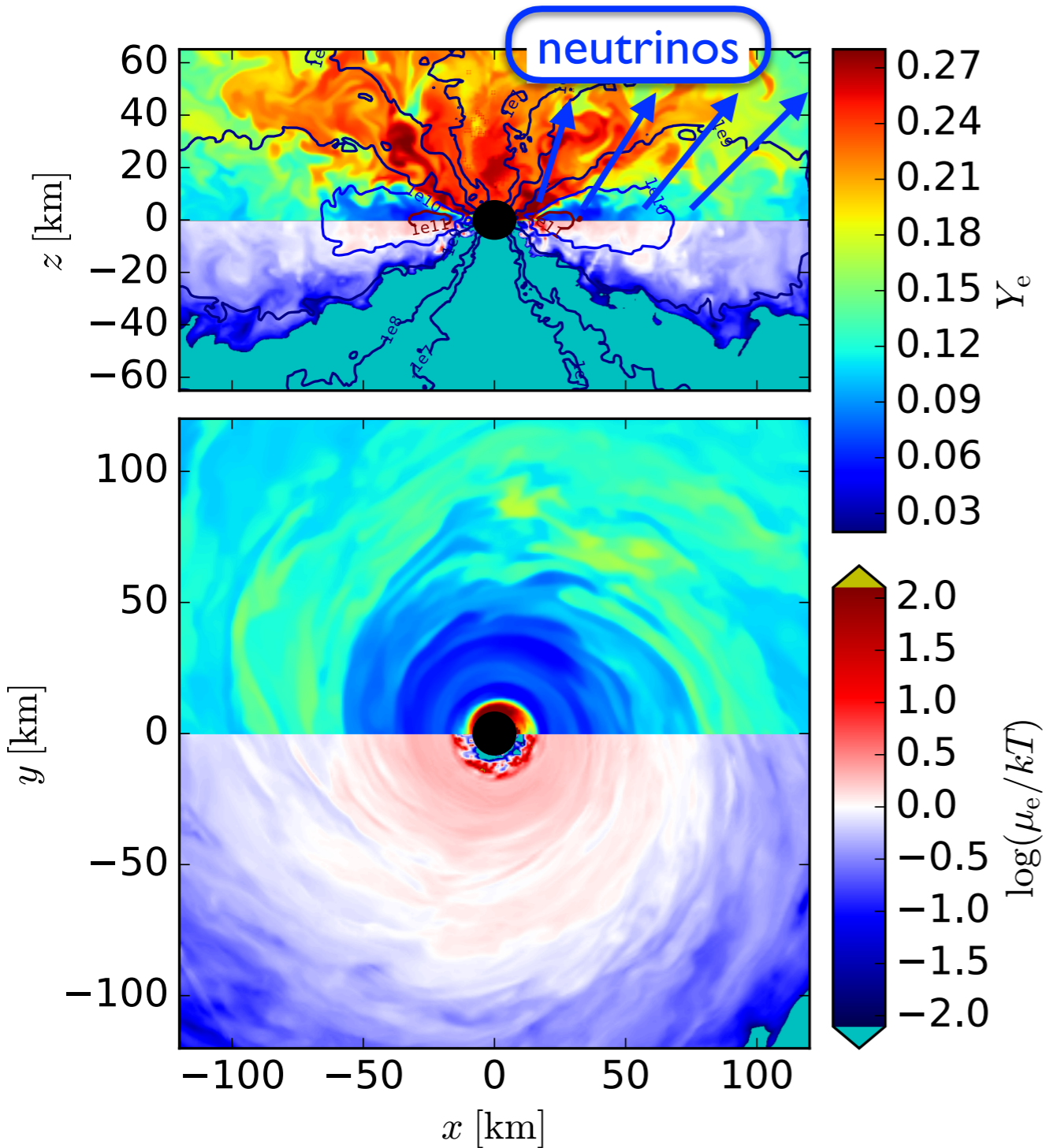**t = 40ms**　　**t = 130ms**　　**t = 250ms**

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
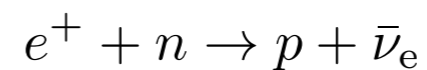

Fig.: disk properties; contours: rest-mass density

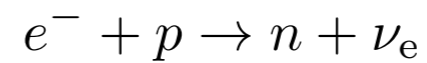Siegel & Metzger 2017, PRL   Siegel & Metzger 2018a

Neutrino-cooled accretion disks self-regulate themselves to mild degeneracy (low Y_e matter):
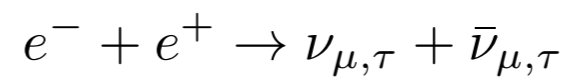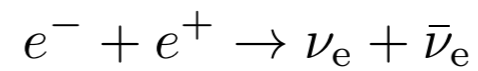
Beloborodov 2003, Chen & Beloborodov 2007, Metzger+ 2009

- **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:
  $$e^- + e^+ \rightarrow \nu_e + \bar{\nu}_e$$
  $$e^- + e^+ \rightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$$
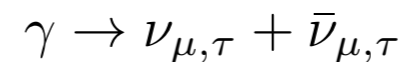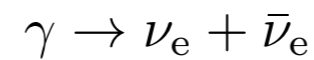
  plasmon decay:
  $$\gamma \rightarrow \nu_e + \bar{\nu}_e$$
  $$\gamma \rightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$$

Self-regulation: keeping a neutron-rich reservoir

Fig.: disk properties; contours: rest-mass density
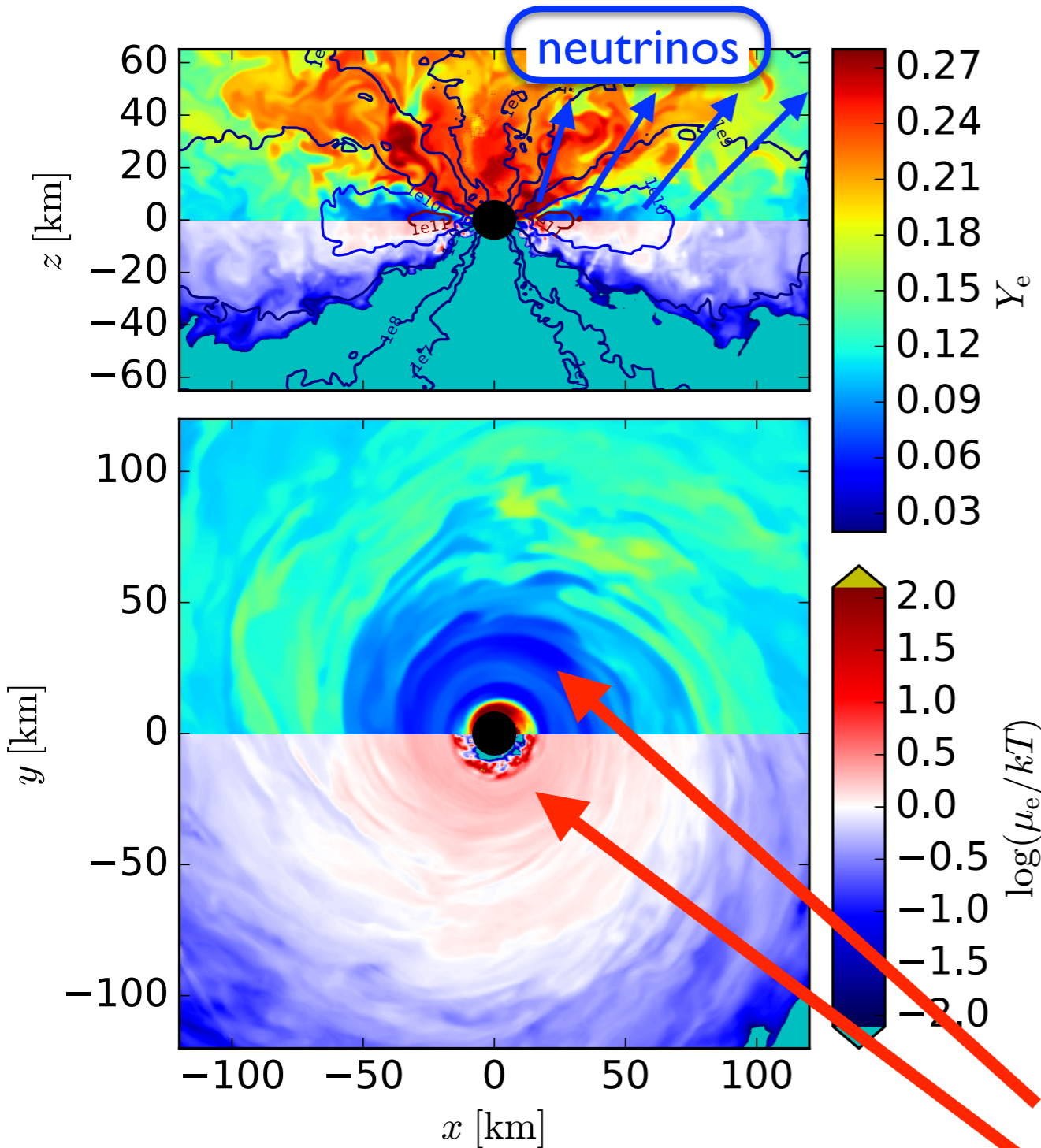
Neutrino-cooled accretion disks self-regulate themselves to mild degeneracy (low Y_e matter):

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
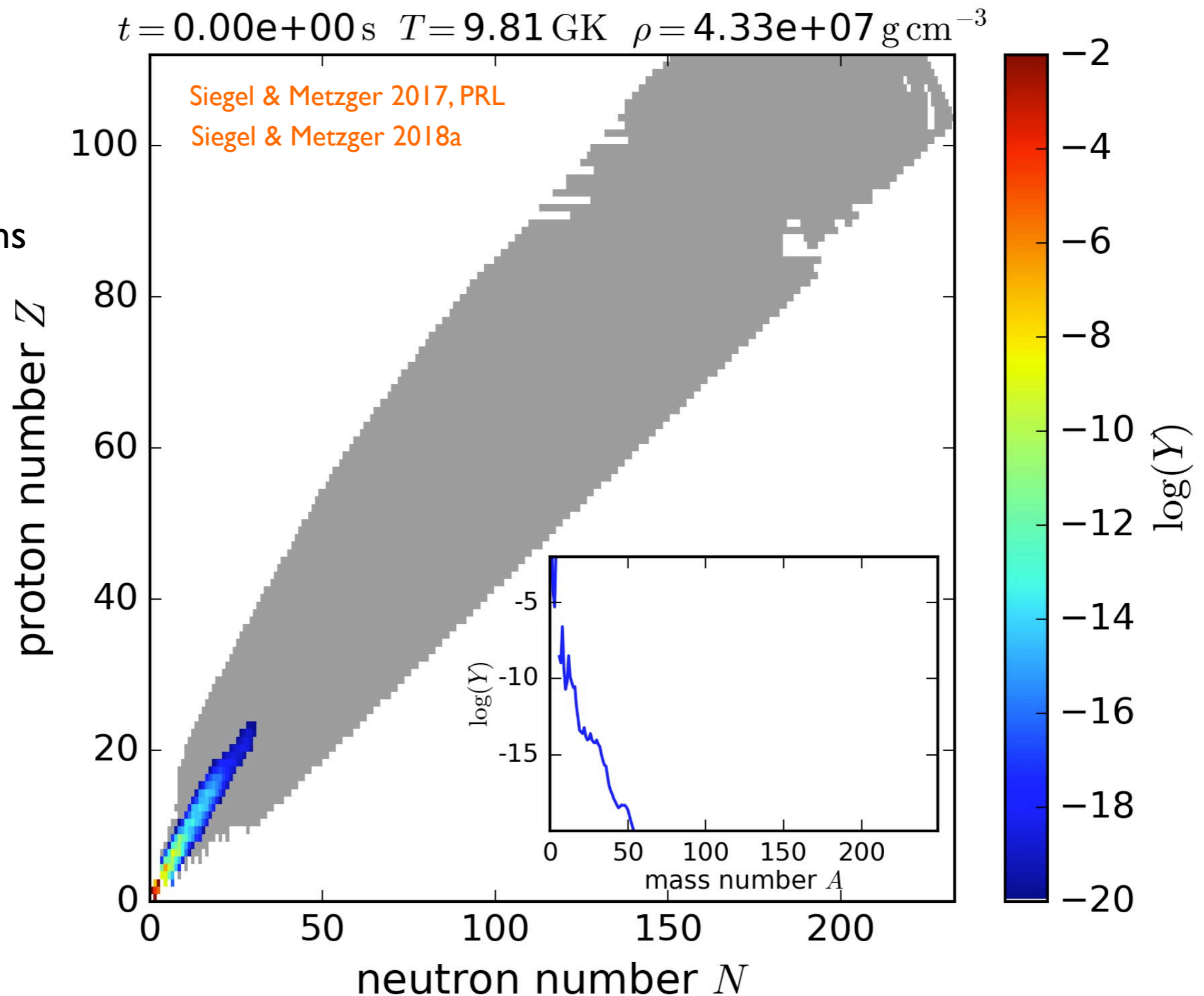
direct evidence of self-regulation

Siegel & Metzger 2017, PRL   Siegel & Metzger 2018a

r-process nucleosynthesis in disk outflows

nuclear reaction network
(SkyNet)

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

$t = 0.00e+00\,\mathrm{s}$ $T = 9.81\,\mathrm{GK}$ $\rho = 4.33e+07\,\mathrm{g\,cm^{-3}}$

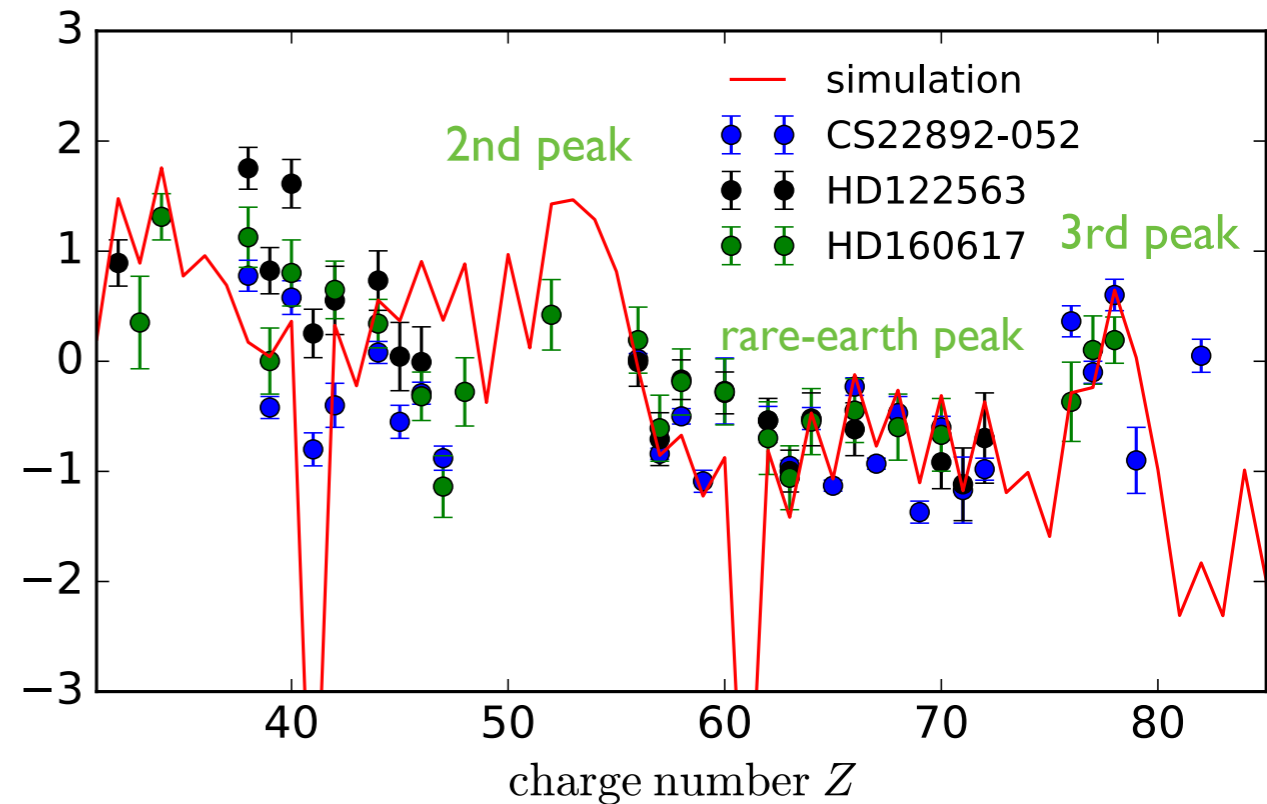Siegel & Metzger 2017, PRL
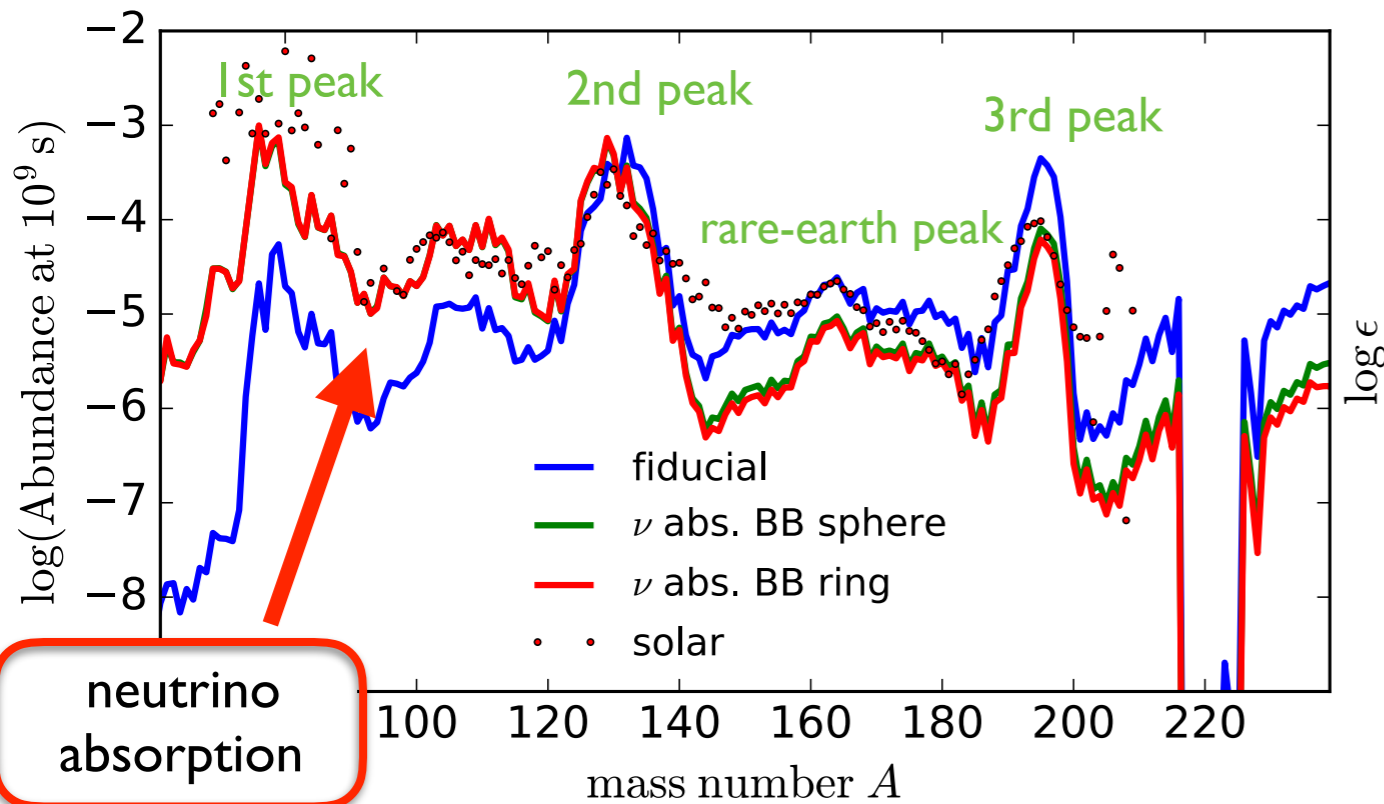Siegel & Metzger 2018a

Movie: r-process nucleosynthesis from NS merger remnant disks

r-process nucleosynthesis in disk outflows

Siegel & Metzger 2017, PRL

Siegel & Metzger 2018a

- **robust 2nd and 3rd peak** r-process!

- including **neutrino absorption**: additional good fit to **1st & 2nd peak** elements
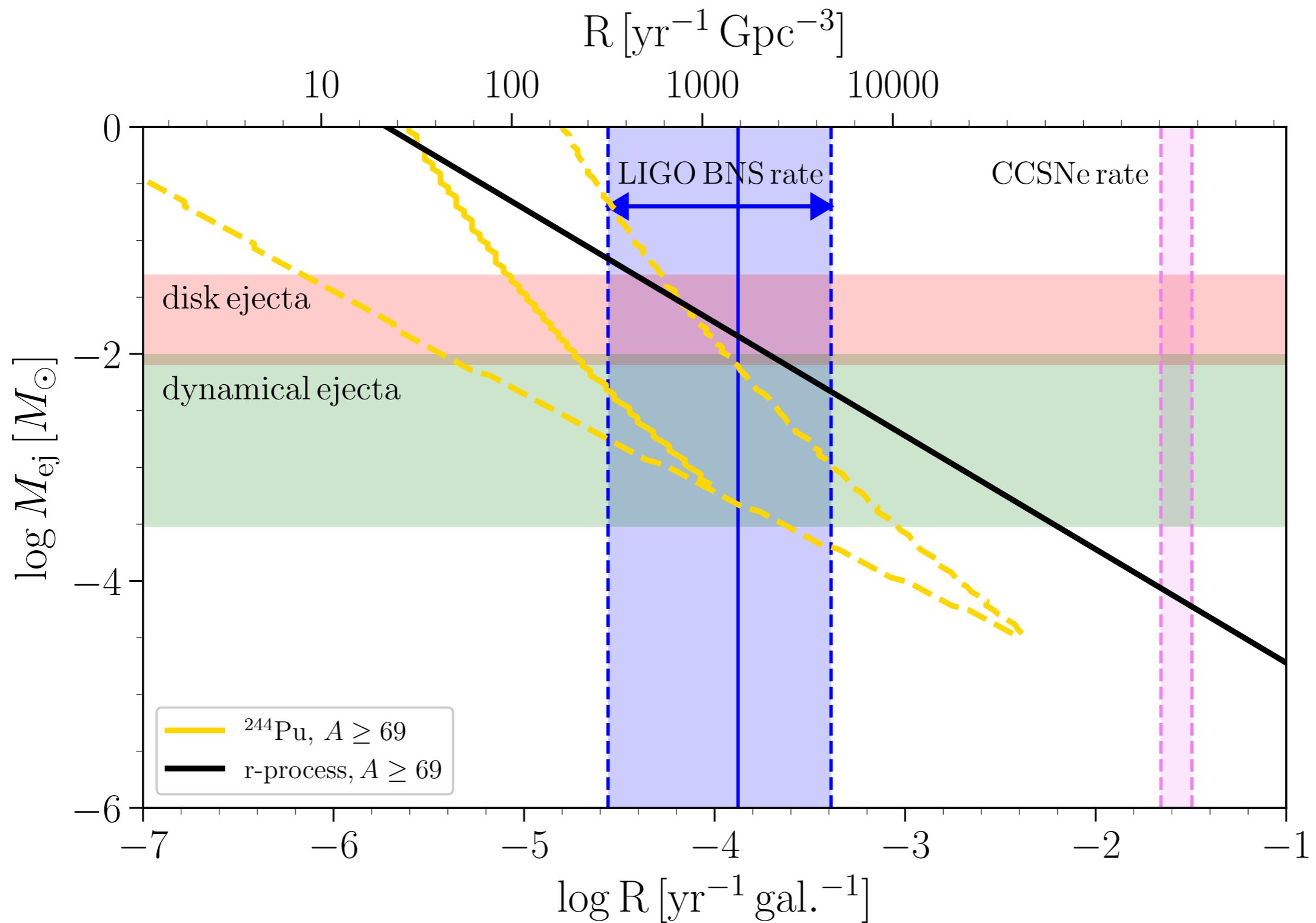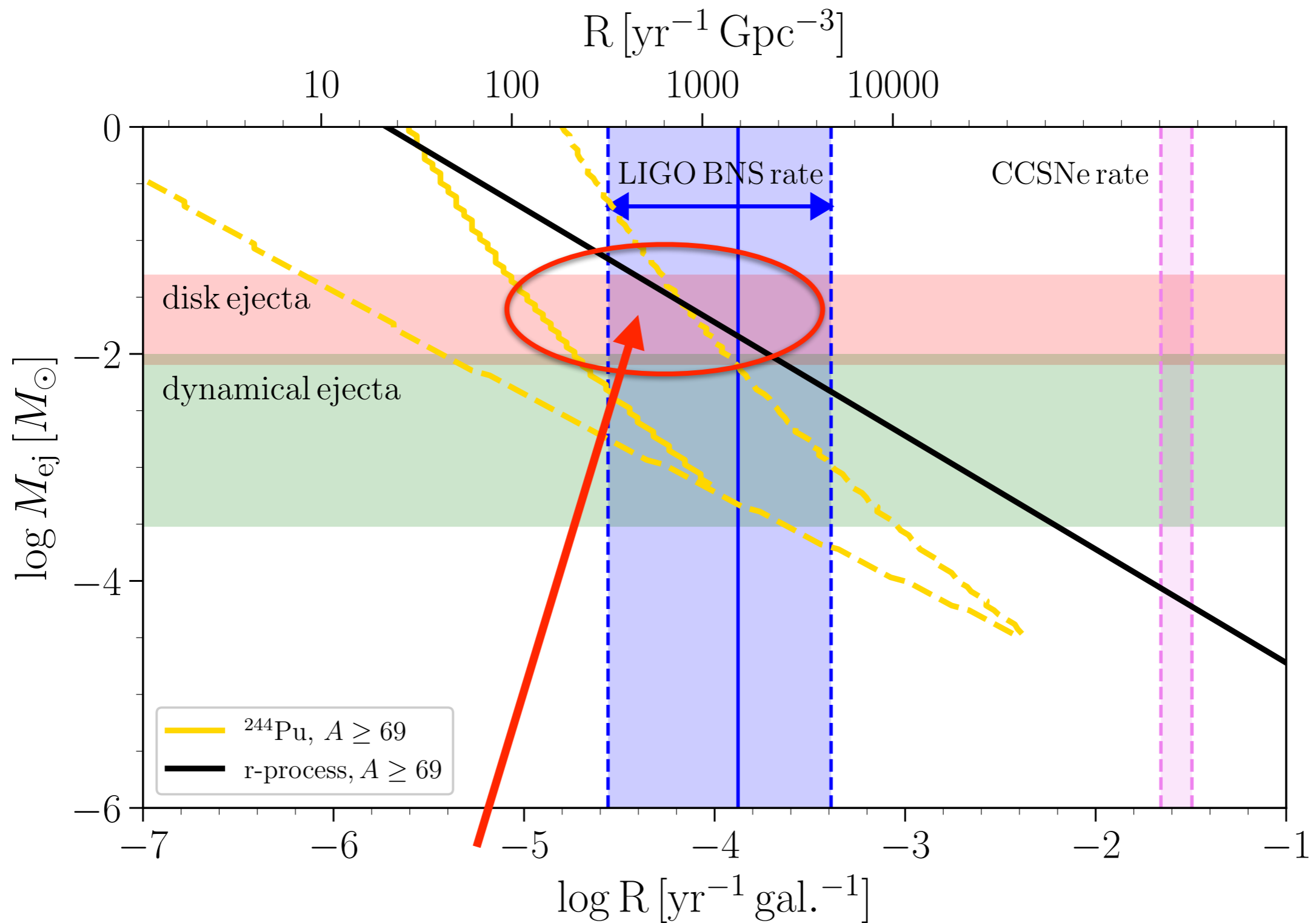
→ production of all r-process elements!

IV.

constraints on r-process enrichment
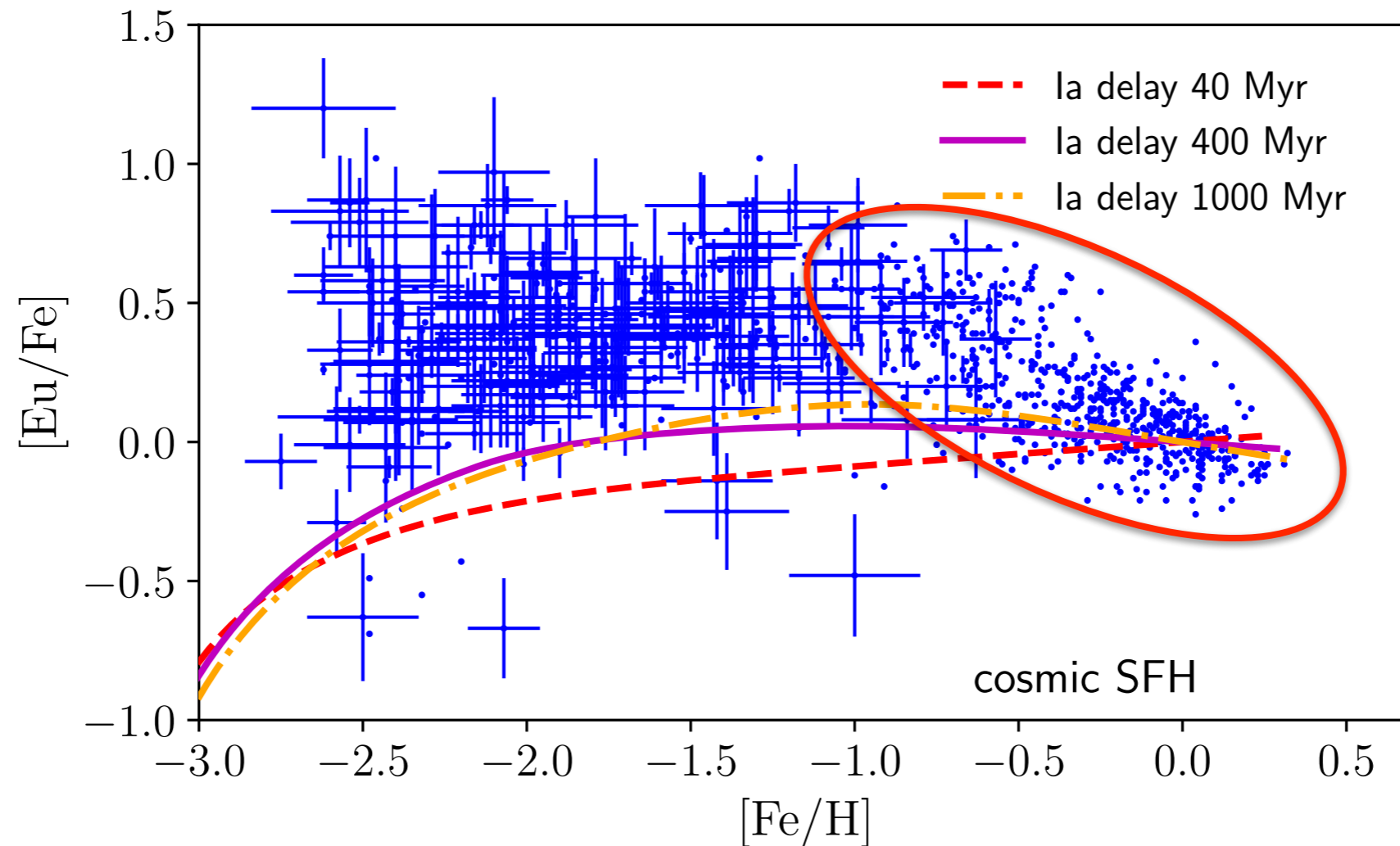
Constraints on r-process nucleosynthesis

Constraints on r-process nucleosynthesis

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

What about galactic chemical evolution?

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

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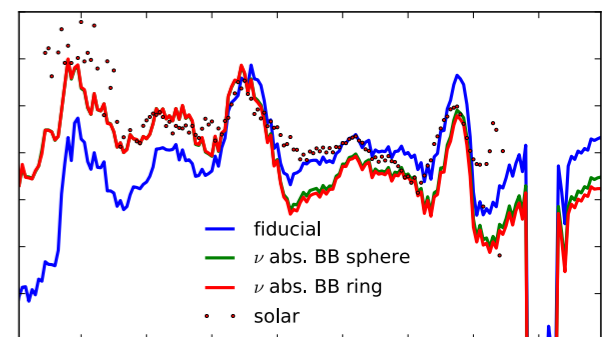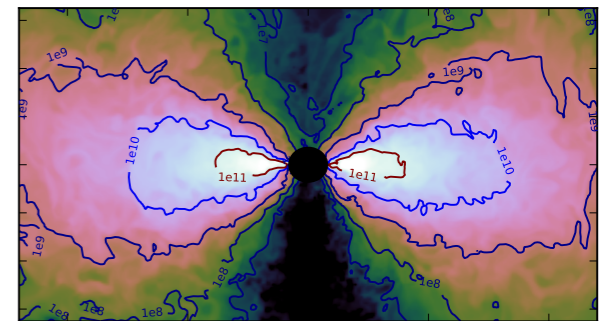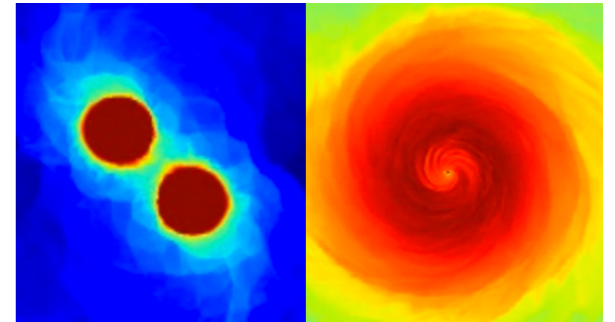
Relative abundances, total ejecta mass, measured BNS merger rate provide yet strongest evidence for NS mergers being the prime production site for the r-process
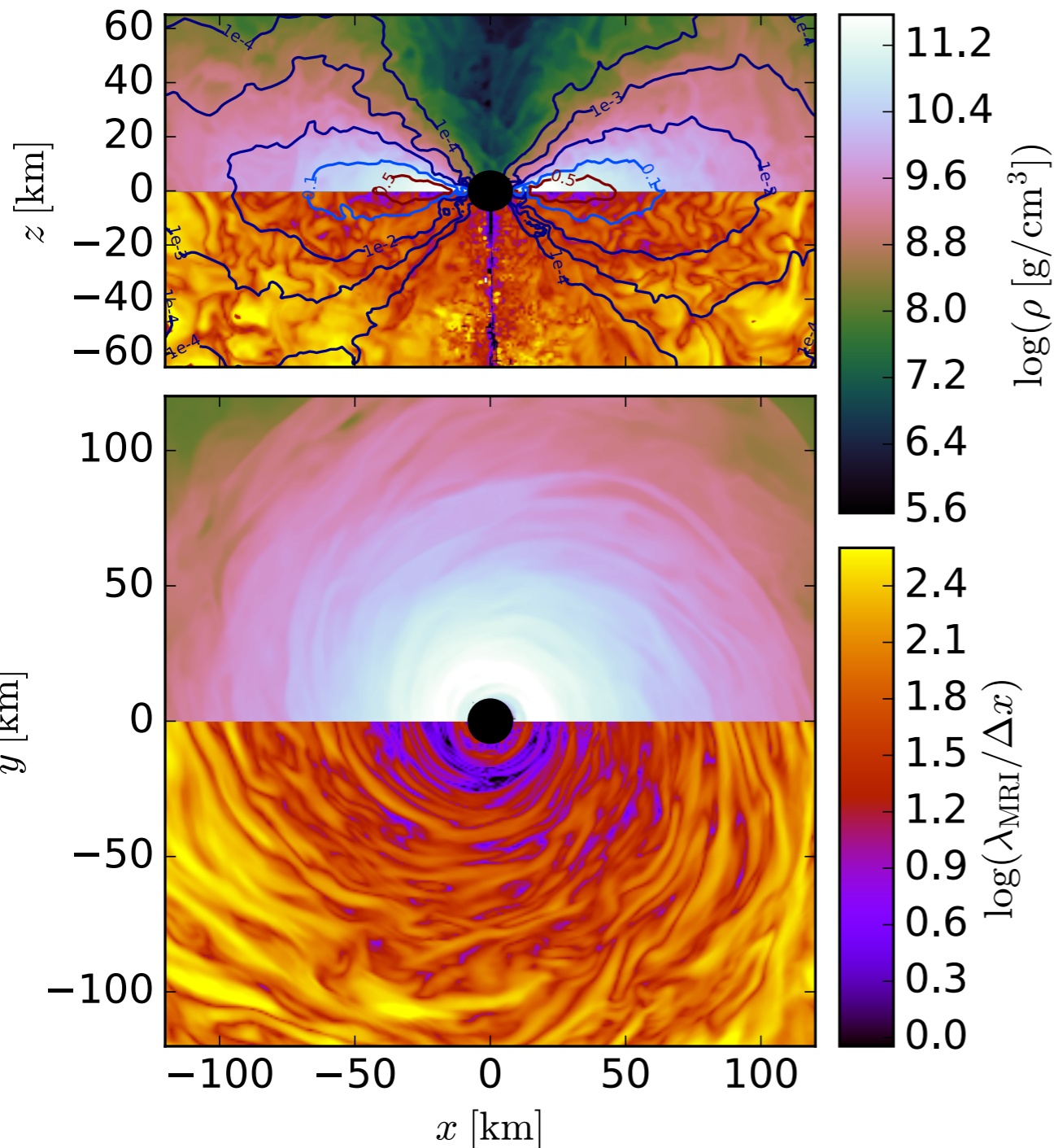
Appendix

Disk simulations: numerical setup

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

Siegel & Metzger 2017, PRL   Siegel & Metzger 2018a

First self-consistent simulations modeling r-process nucleosynthesis from disk outflows from first principles:

- GRMHD: magnetic instabilities (MRI) mediating turbulence (transport of angular momentum) in the disk (*Einstein Toolkit, GRHydro*; Loeffler+ 2012, Moesta+ 2014)

- weak interactions in GRMHD

- new enhanced methods for primitive recovery to support evolved microphysics   Siegel+ 2018
  Siegel & Moesta 2018

- approximate neutrino transport (leakage scheme)

- realistic EOS (Helmholtz EOS) valid at low temperatures and densities, capturing nuclear binding energy release from alpha-particle formation

- full r-process network calculations on disk outflows using 10^4 tracer particles (*SkyNet*; Lippuner & Roberts 2017)

Previous 2D Newtonian alpha-disk simulations:

Fernandez & Metzger 2013, 2015, 2017
Just+ 2015