COLUMBIA UNIVERSITY
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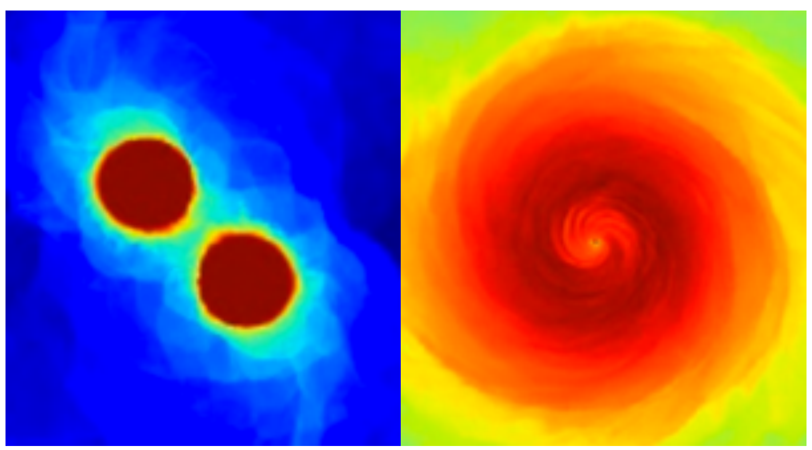
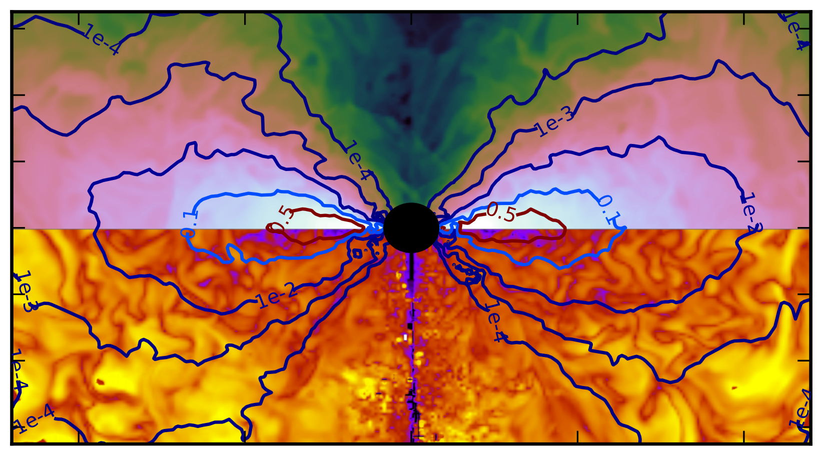
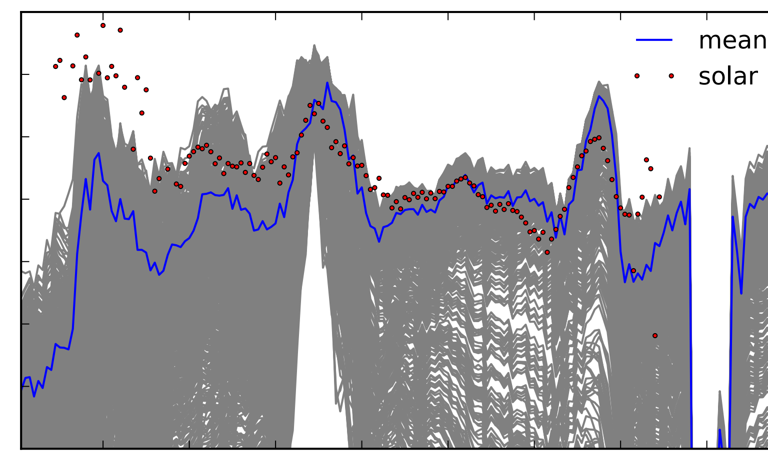
Neutron star post-merger simulations: origin of kilonovae and the heavy elements







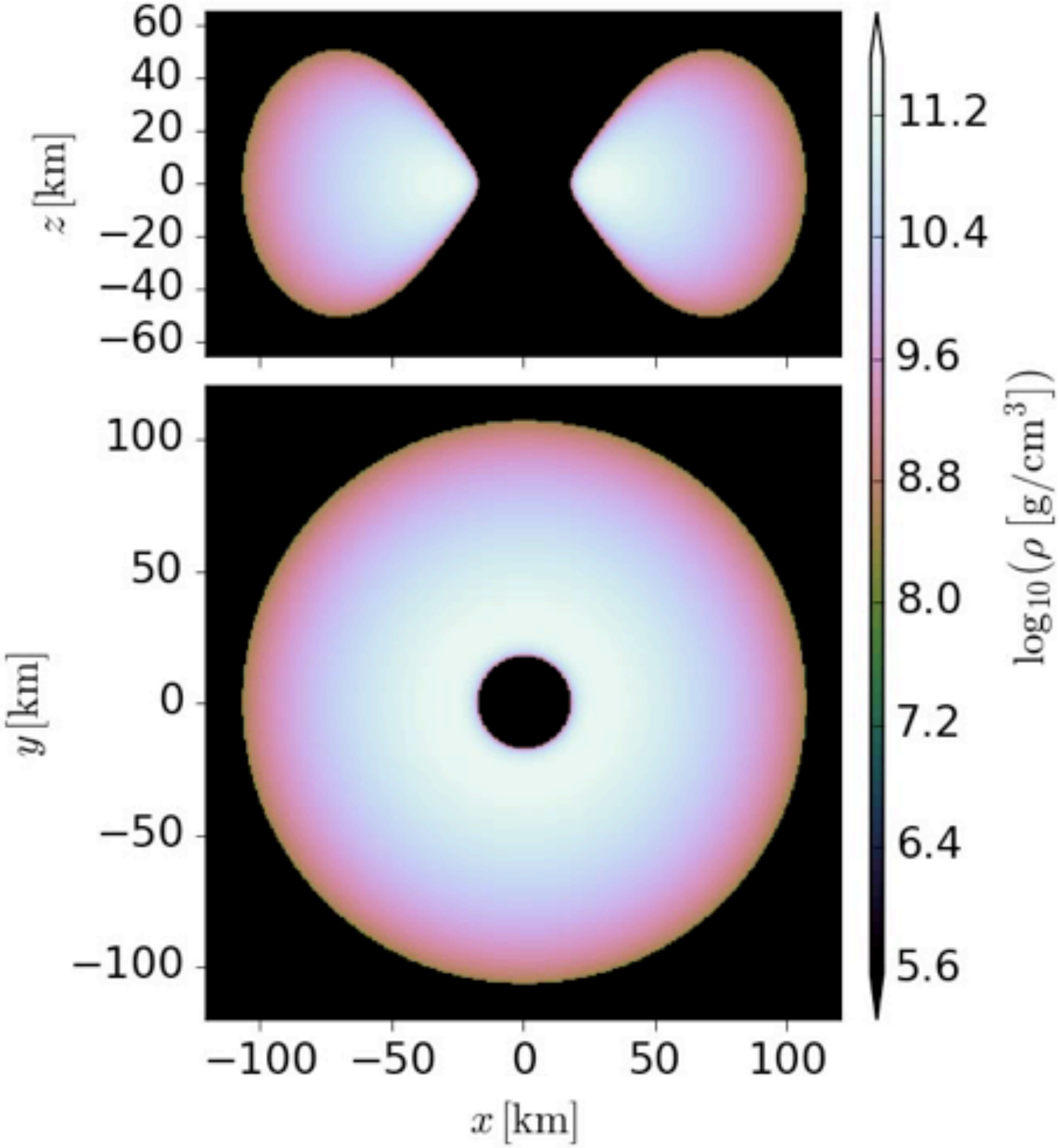
Daniel M. Siegel

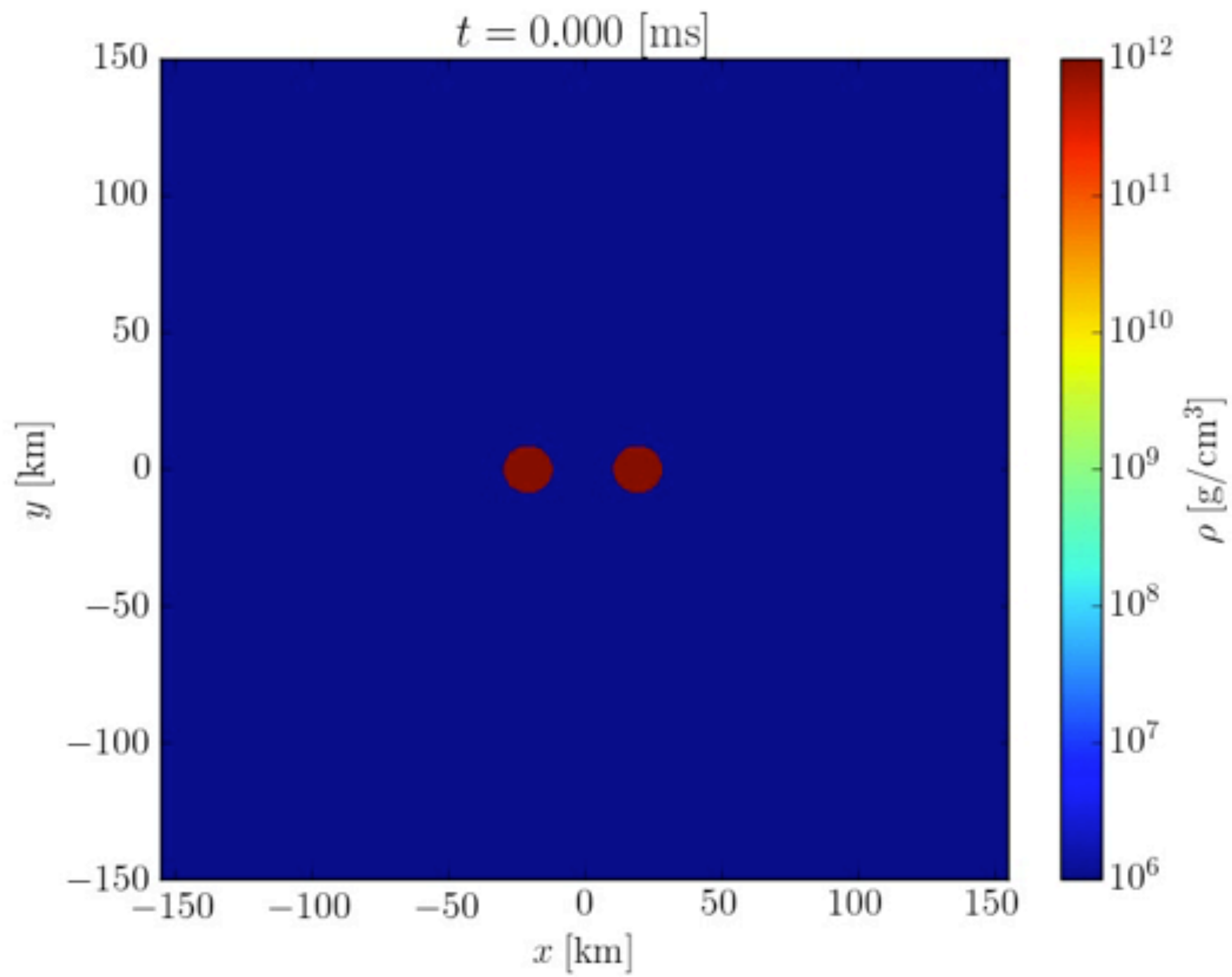
Center for Theoretical Physics & Columbia Astrophysics Laboratory

Columbia University

Einstein Fellows Symposium, Harvard-Smithsonian Center for Astrophysics, Oct 12-13, 2017

NS post-merger accretion disks: formation





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

$t = 0.000\,\mathrm{ms}$

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

Radice+ 2016

Siegel & Metzger 2017a

NS post-merger accretion disks: numerical setup

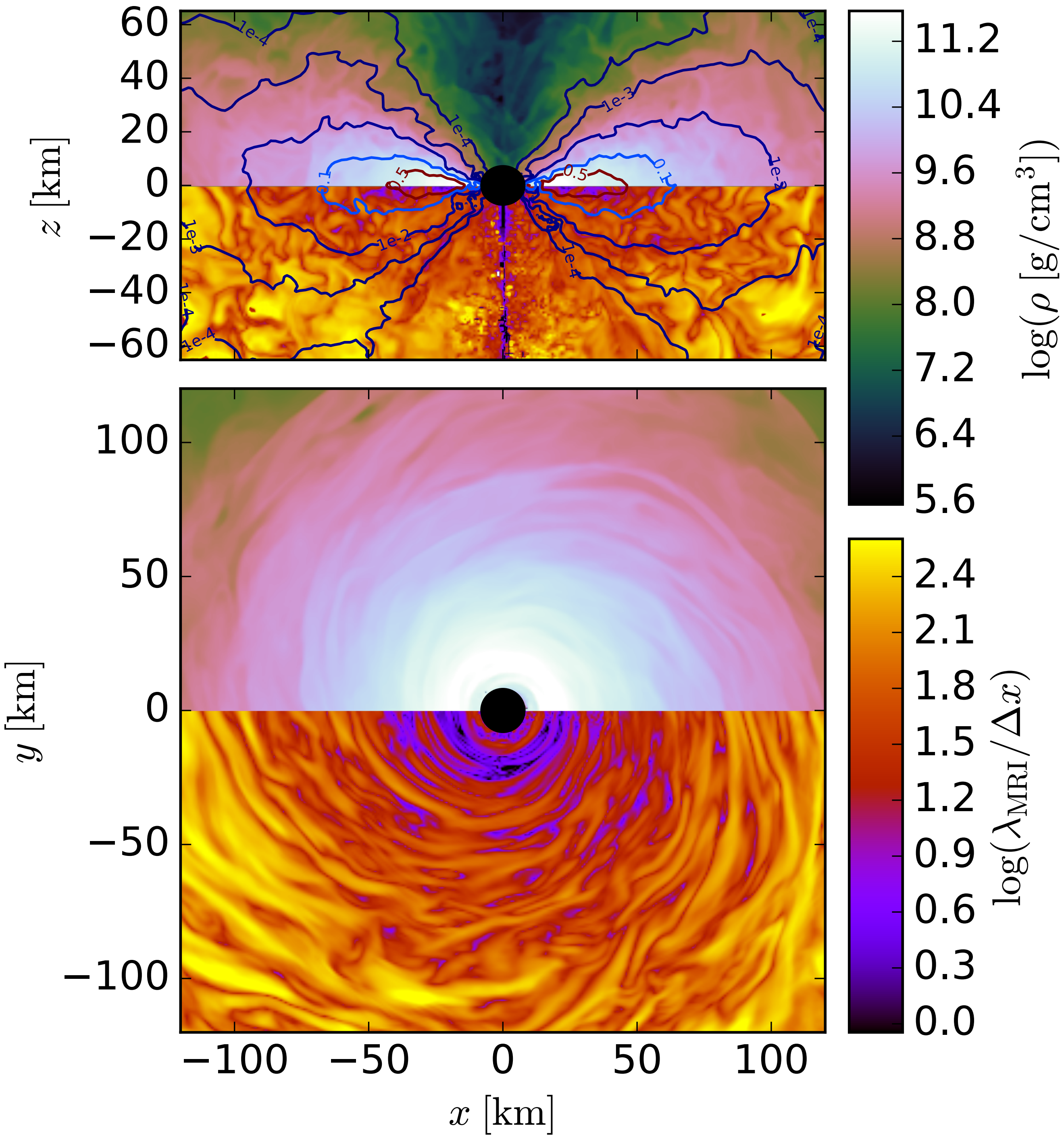


Fig.: disk properties; contours: optical depth for electron neutrinos

Siegel & Metzger 2017a Siegel & Metzger 2017b, in prep.

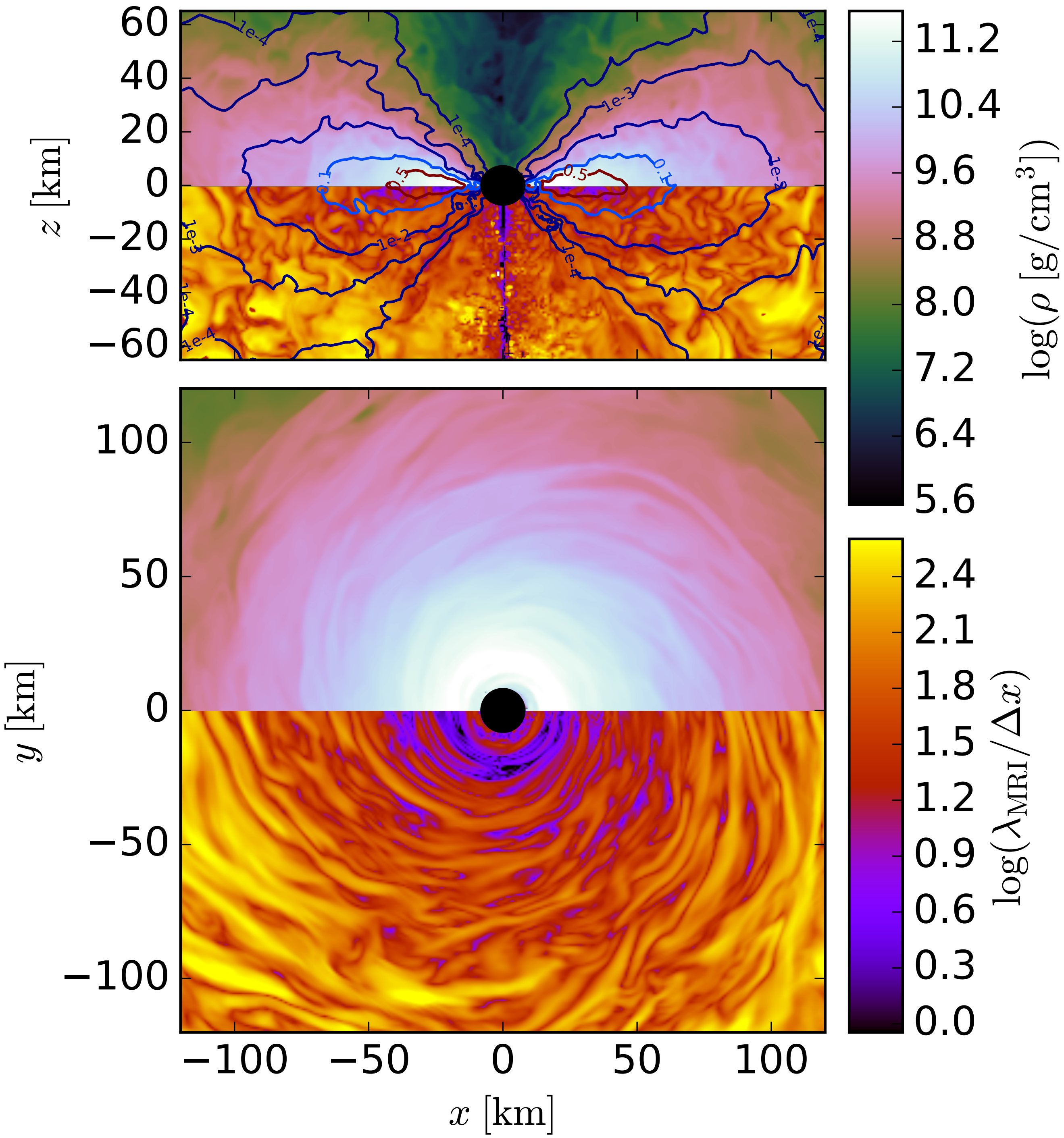
First self-consistent simulations modeling r-process nucleosynthesis from disk outflows from first principles:

- GRMHD: magnetic instabilities (MRI) mediating turbulence (transport of angular momentum) in the disk
- weak interactions in GRMHD
- 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 2015)

Previous Newtonian alpha-disk simulations:

Fernandez & Metzger 2013
Metzger & Fernandez 2014
Fernandez+ 2015
Fernandez+ 2017
Just+ 2015

MHD turbulence



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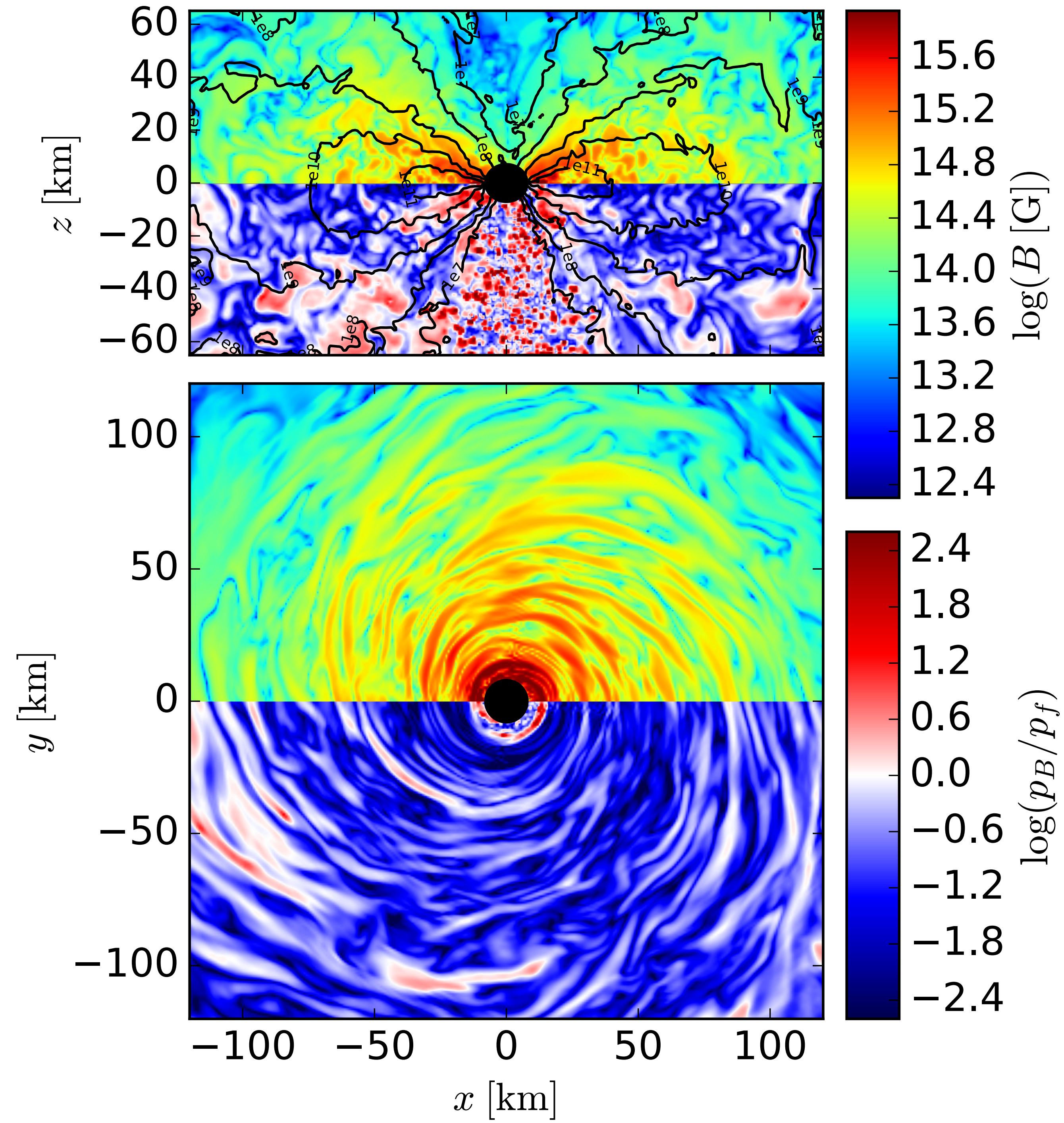


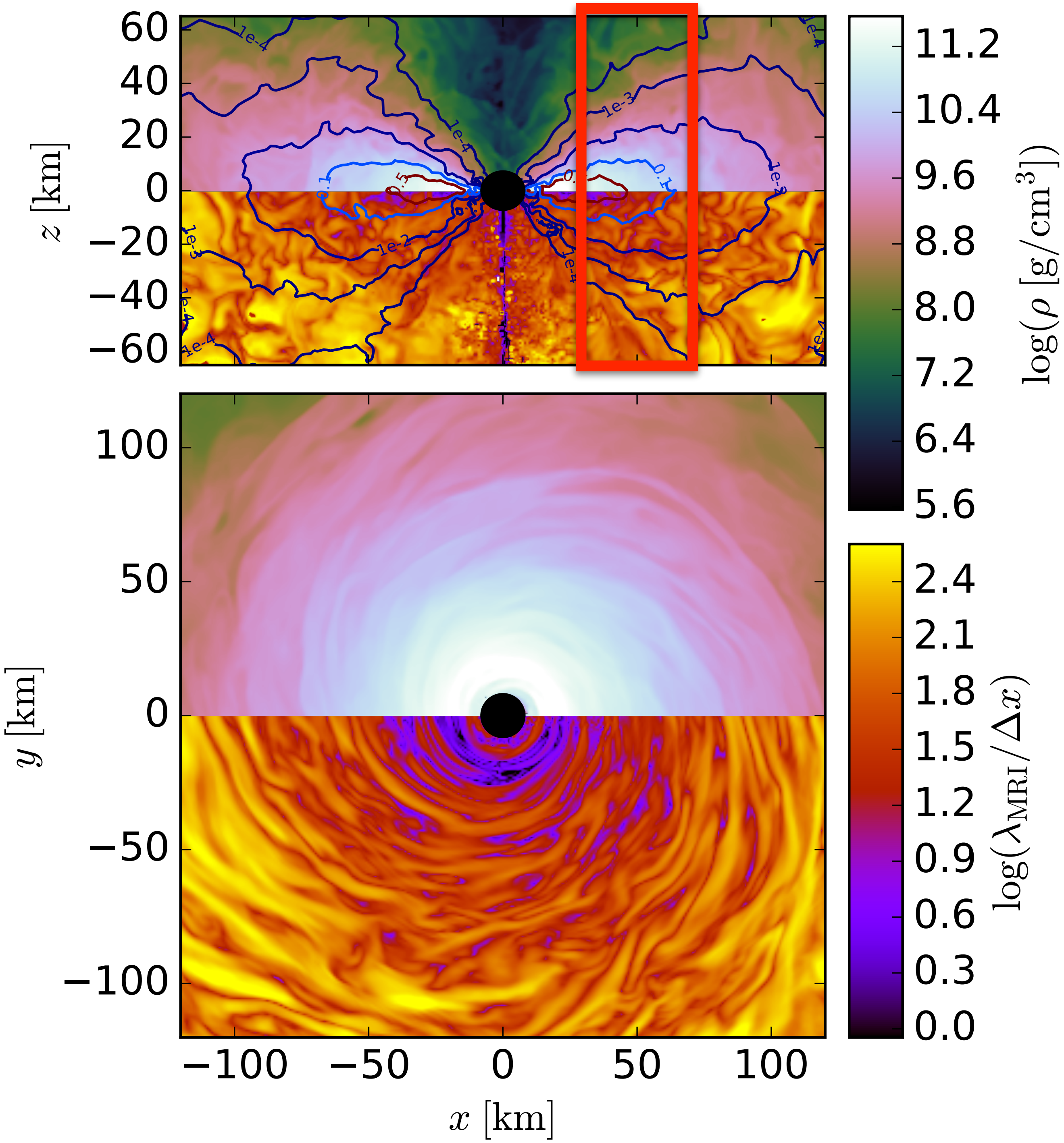
Fig.: magnetic fields in the disk; contours: rest-mass density

Siegel & Metzger 2017a Siegel & Metzger 2017b, in prep.

magnetic properties very similar to Ciolfi+ 2017

MHD turbulence

average radially for space-time diagram



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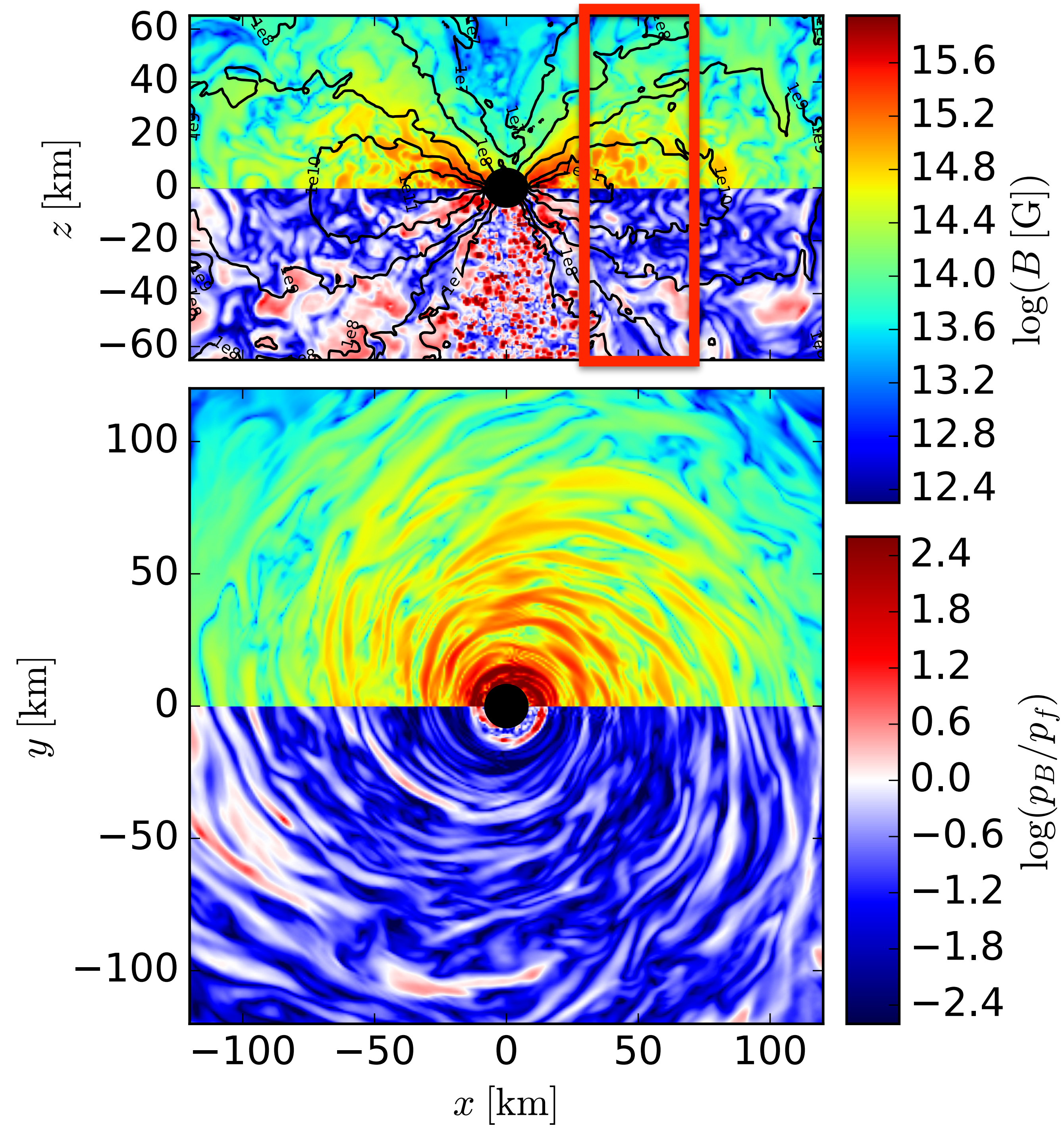
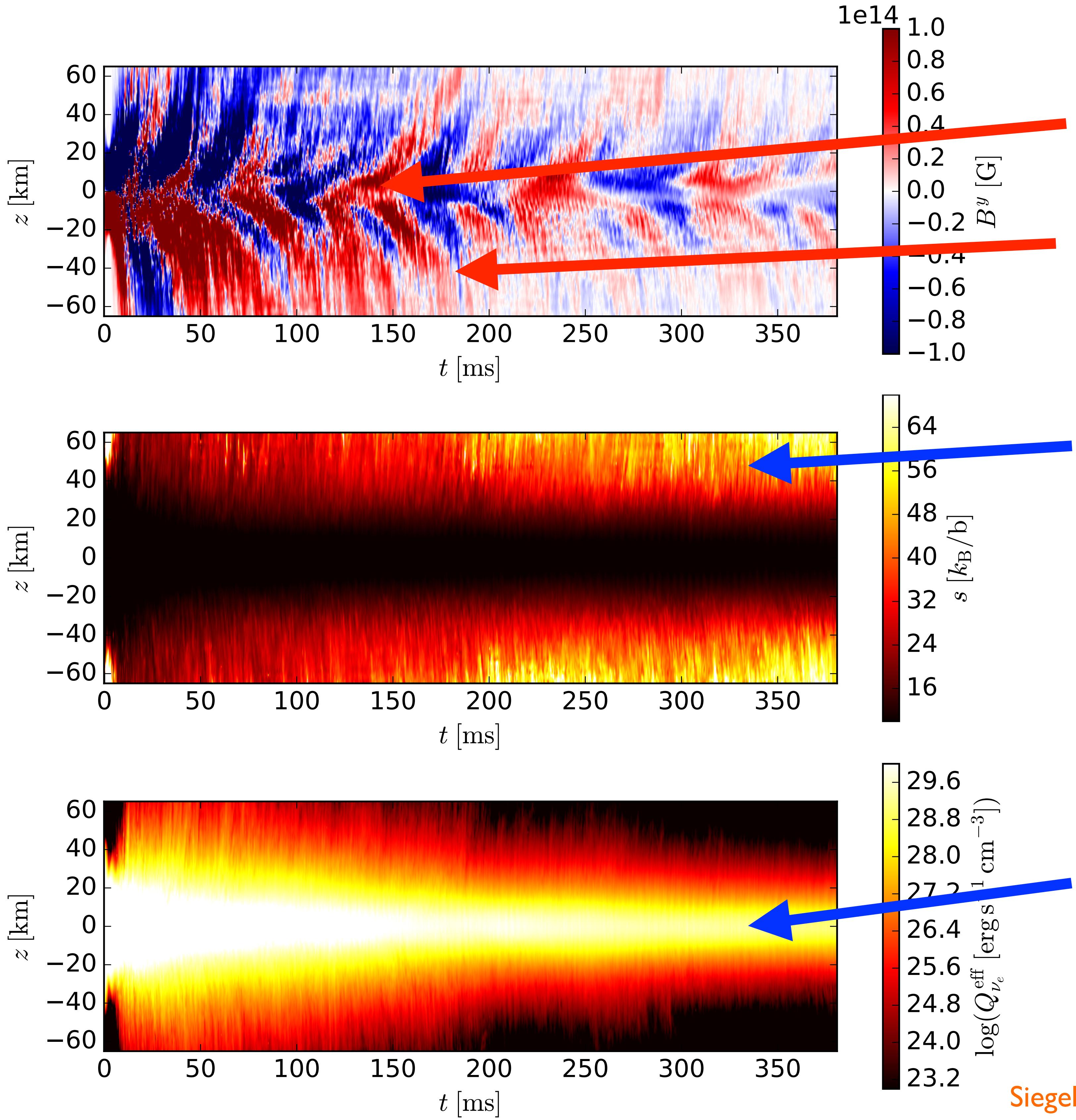


Fig.: magnetic fields in the disk; contours: rest-mass density

magnetic properties very similar to Ciolfi+ 2017

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 2017b, in prep.

Self-regulation

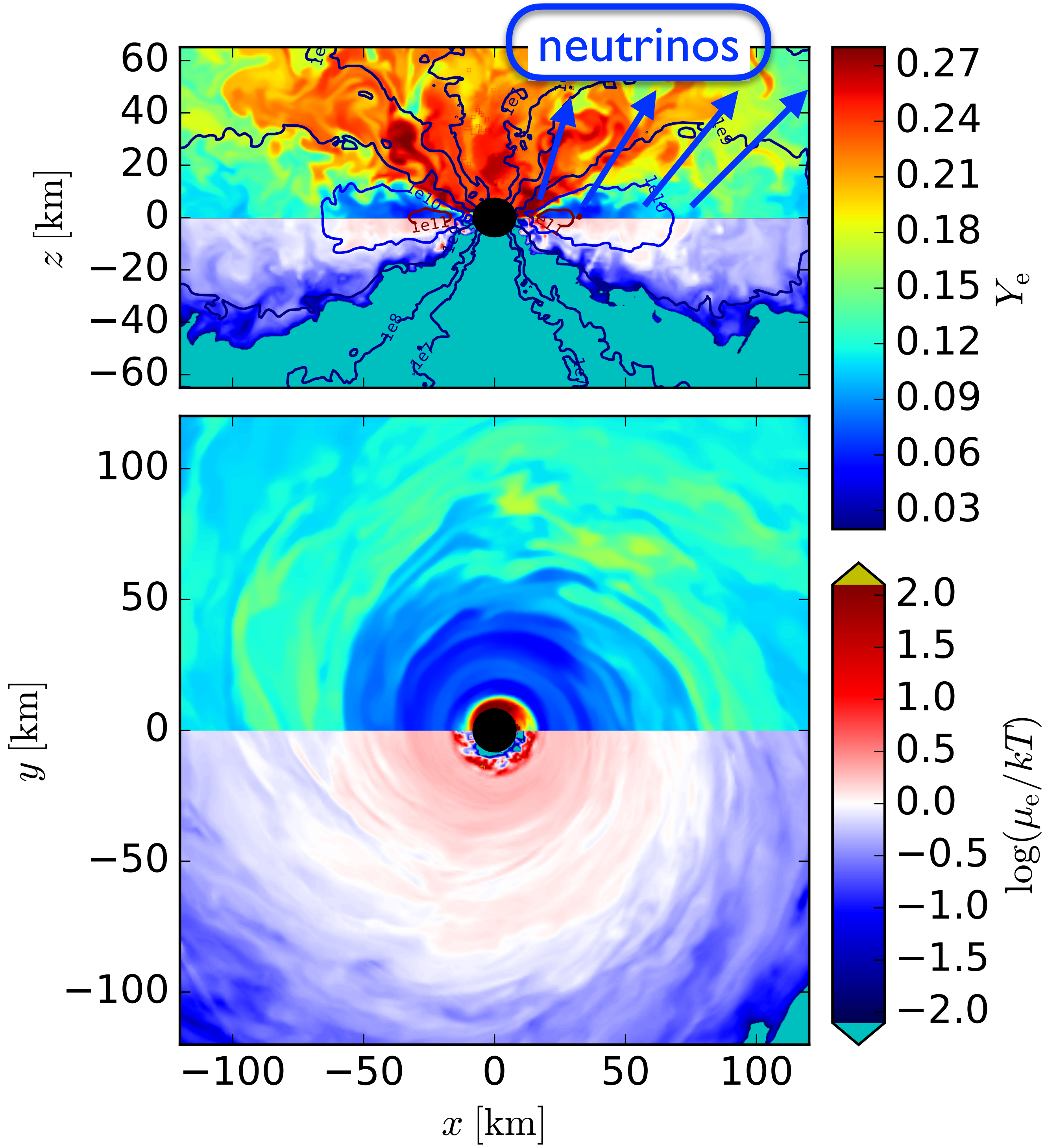


Fig.: disk properties; contours: rest-mass density

Siegel & Metzger 2017a   Siegel & Metzger 2017b, in prep.

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:

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

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

pair annihilation:

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

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

plasmon decay:

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

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

Self-regulation

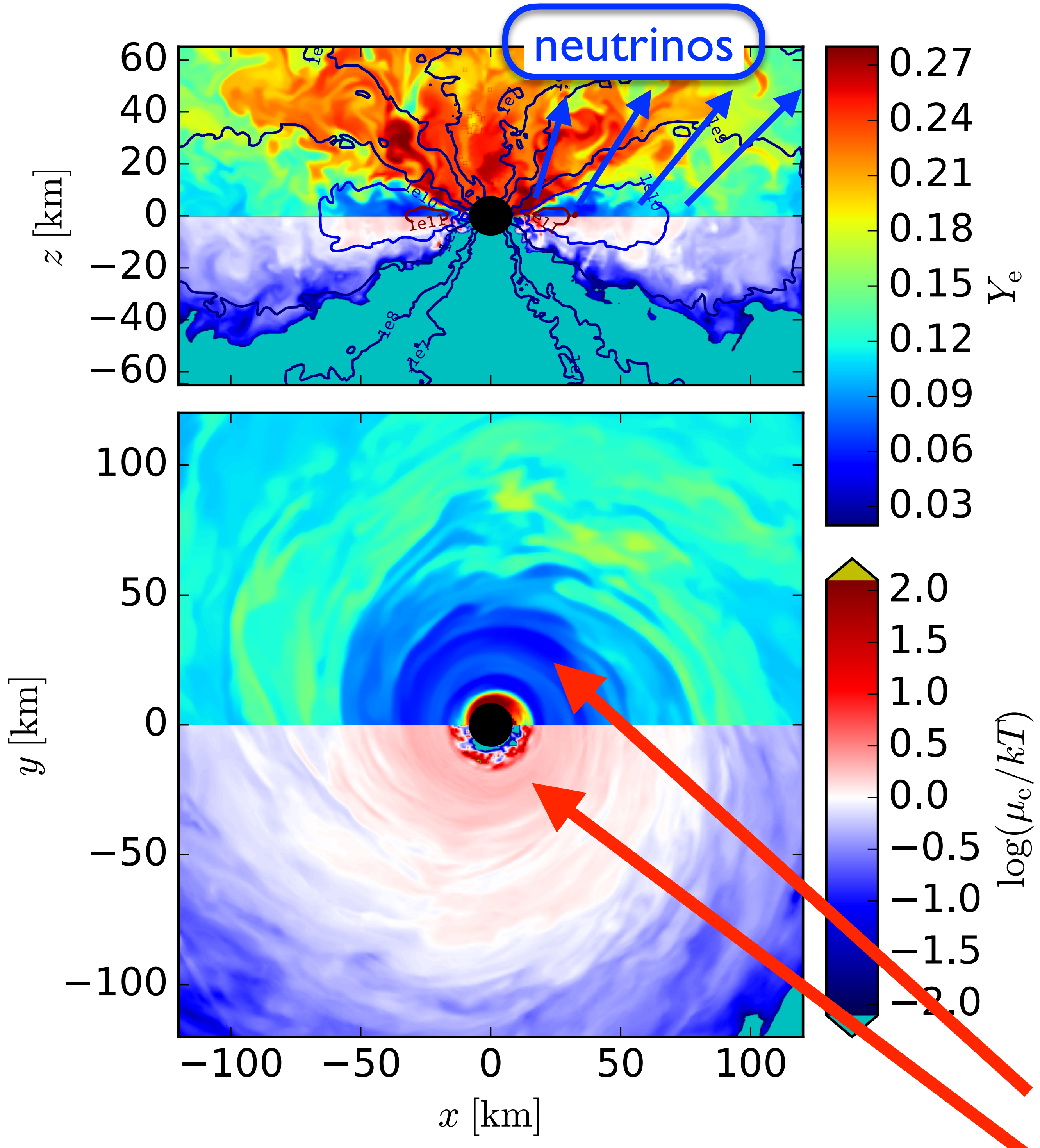


Fig.: disk properties; contours: rest-mass density

Siegel & Metzger 2017a   Siegel & Metzger 2017b, in prep.

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- 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

⬇

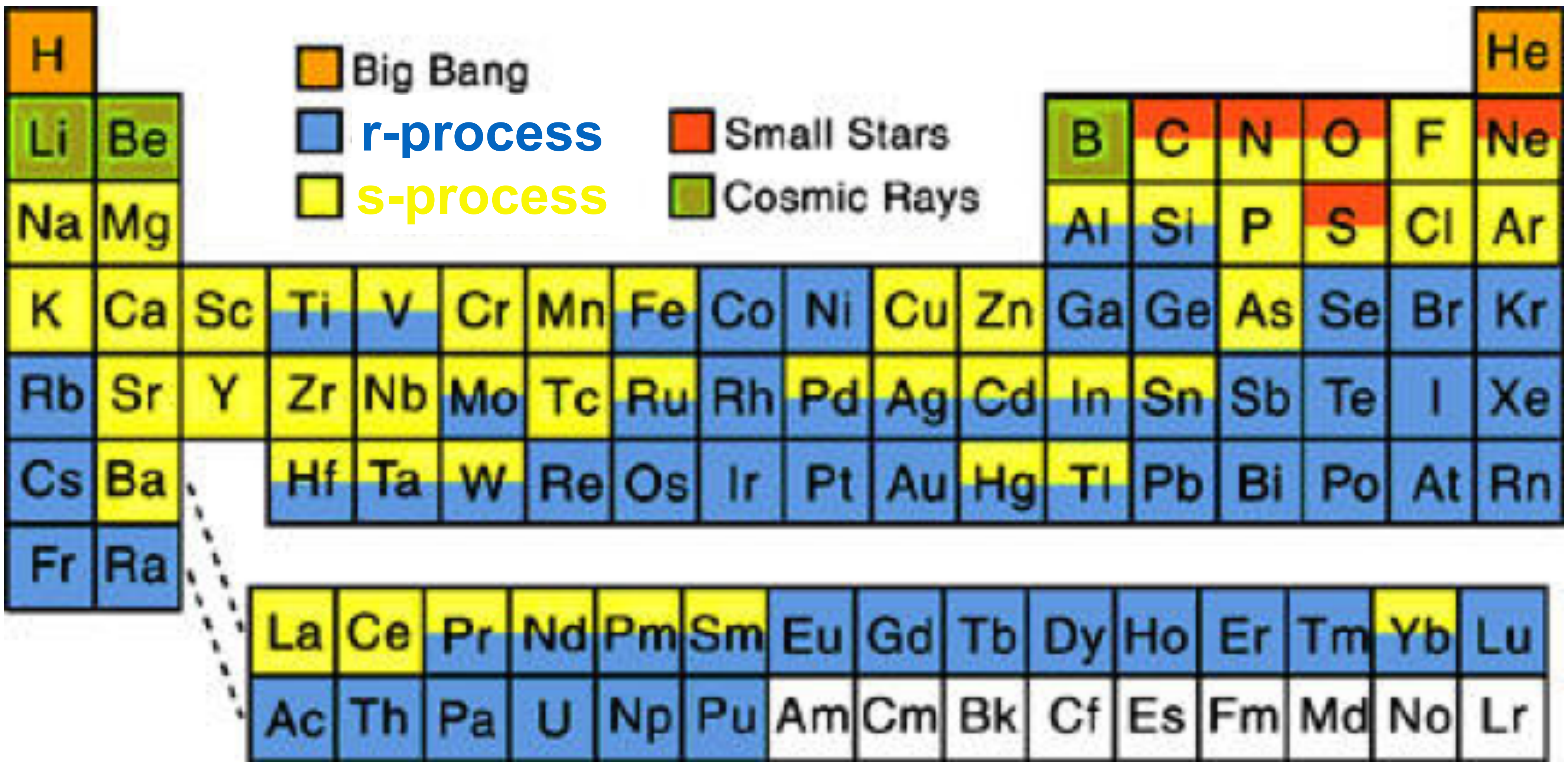
higher temperatures

⬇

lower degeneracy μ_e/kT

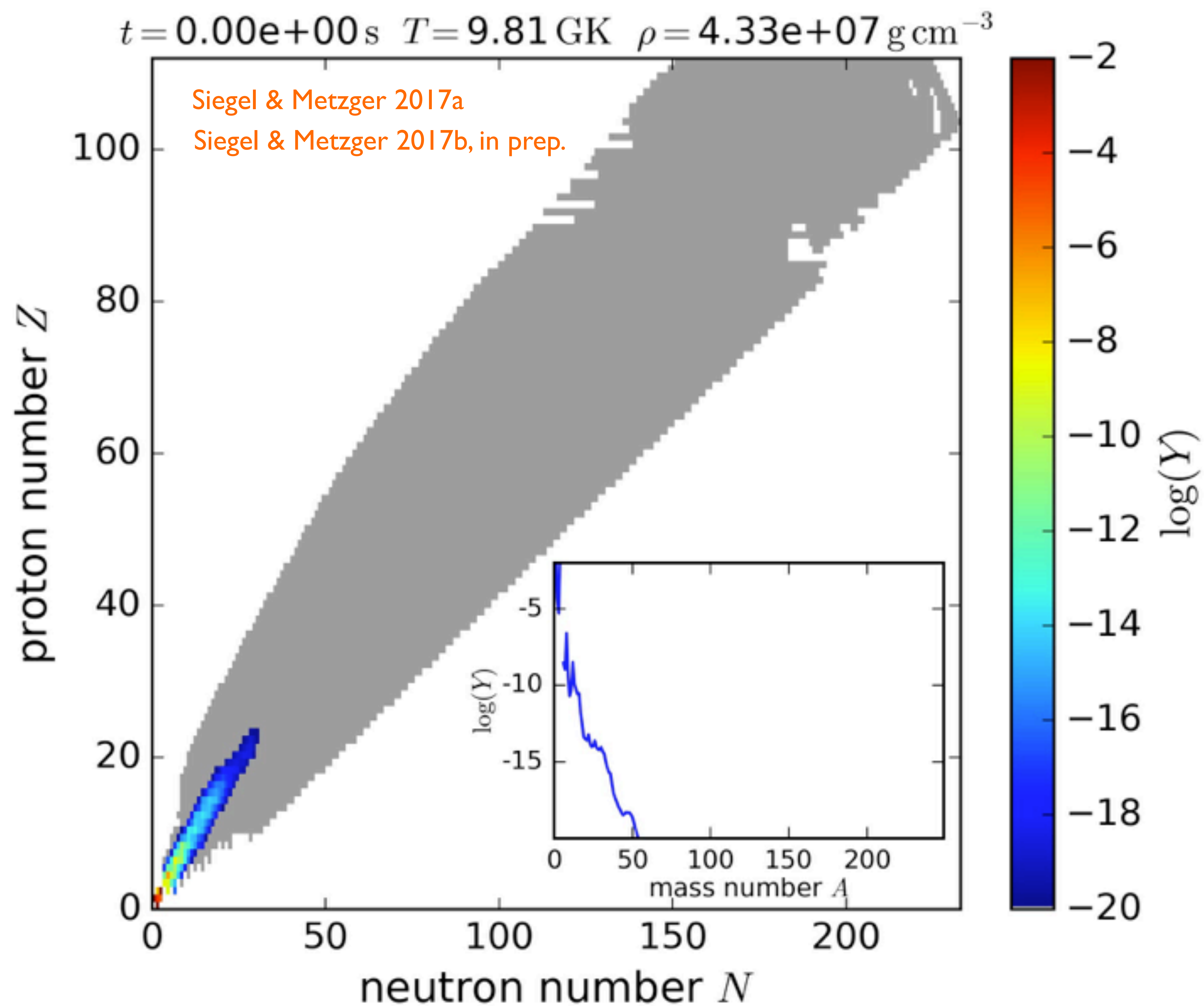
direct evidence of self-regulation

The origin of the elements



How are the heavy elements formed?

The origin of heavy nuclei: r-process nucleosynthesis

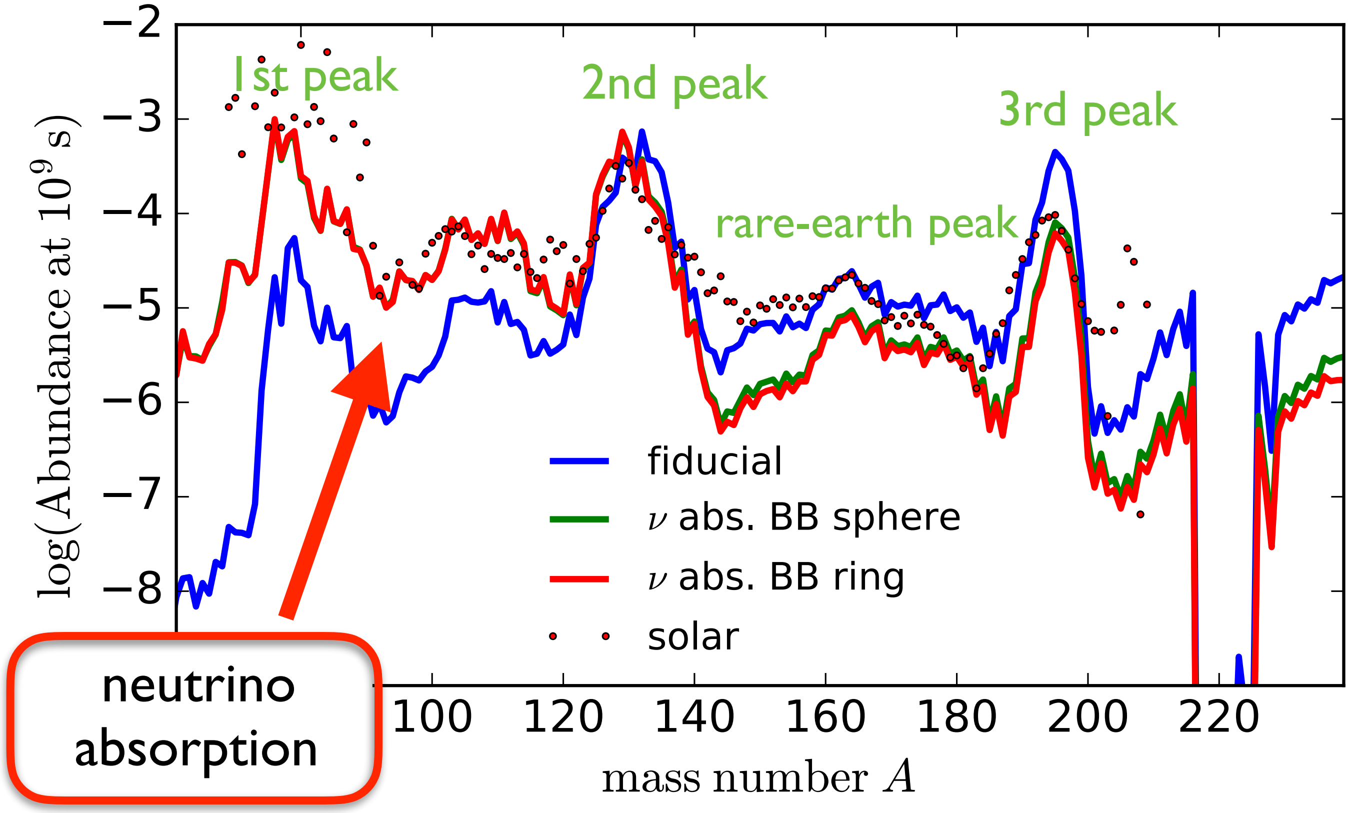


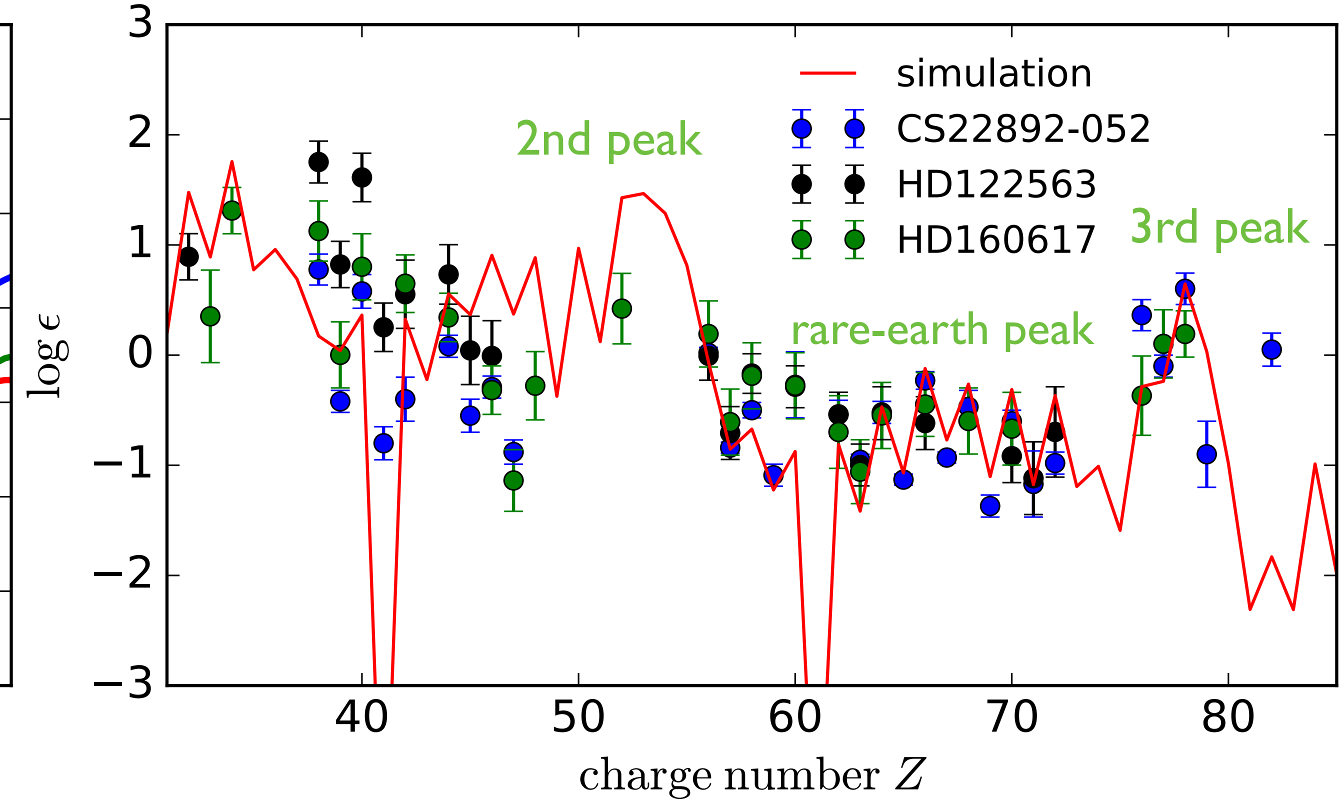
Movie: r-process nucleosynthesis from NS merger remnant disks

r-process nucleosynthesis

Siegel & Metzger 2017a

Siegel & Metzger 2017b, in prep.





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

→ production of all r-process elements!

r-process nucleosynthesis from NS mergers

dynamical ejecta:

Radice+ 2016

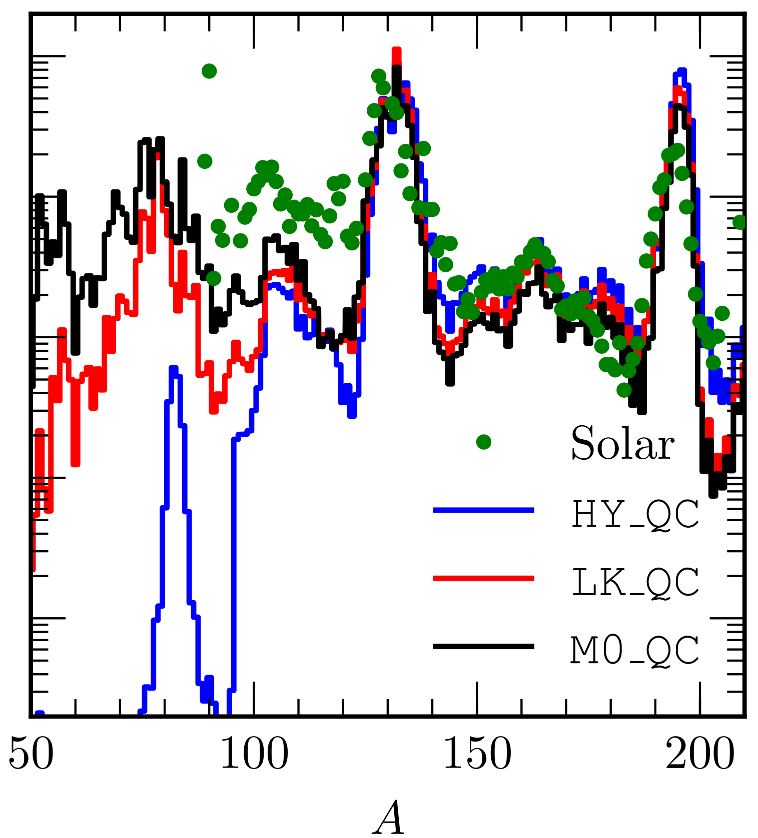


Fig.: production of r-process elements from early ejecta of a BNS merger (dynamical ejecta, neutrino-driven winds)

Post-merger accretion disk outflows:

Siegel & Metzger 2017a
Siegel & Metzger 2017b, in prep.

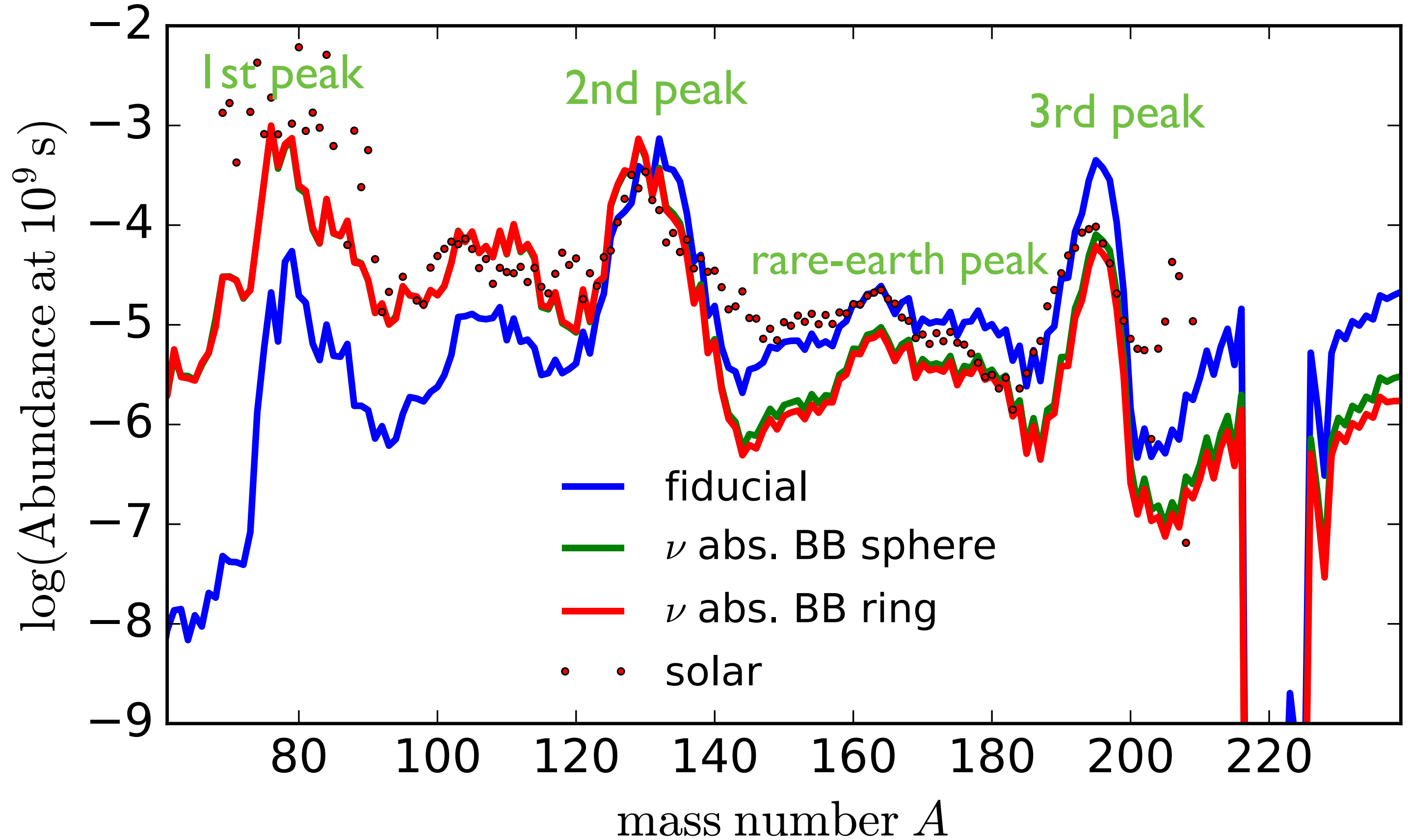


Fig.: production of all r-process elements from outflows of post-merger accretion disk

Overall ejecta mass per event:

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

strongly depends on EOS and mass ratio!

Radice+ 2016
Sekiguchi+ 2016
Palenzuela+2015
Lehner+2016
Ciolfi+2017

$$\gtrsim 0.4\, M_{\rm disk} \gtrsim 10^{-2}\, M_\odot$$

robust lower limit

Conclusions

Simulations of NS post-merger accretion disks   Siegel & Metzger 2017a   Siegel & Metzger 2017b, i. prep.

- GRMHD with weak interactions and approx. neutrino transport
- first fully self-consistent study of its kind
- evidence for hot coronae that launch thermal outflows
- first identification of self-regulation in neutrino-cooled accretion disks, implying conditions of neutron richness
- disk ejecta can be higher than dynamical ejecta from the merger
  - ⟶ main fuel to power kilonova
  - ⟶ main site of the r-process
- suggest NS post-merger systems are robust site of the r-process
  - ⟶ can produce all r-process elements