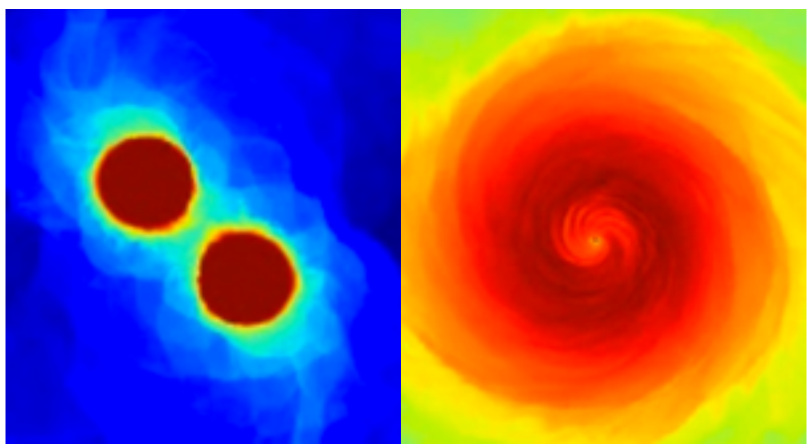
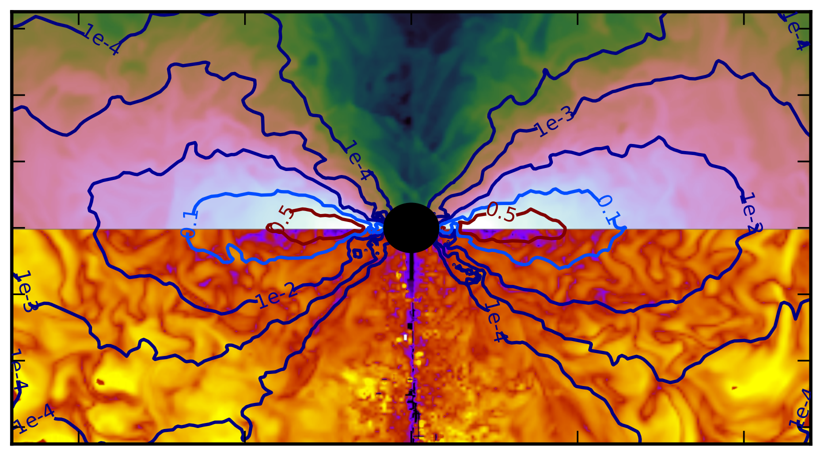
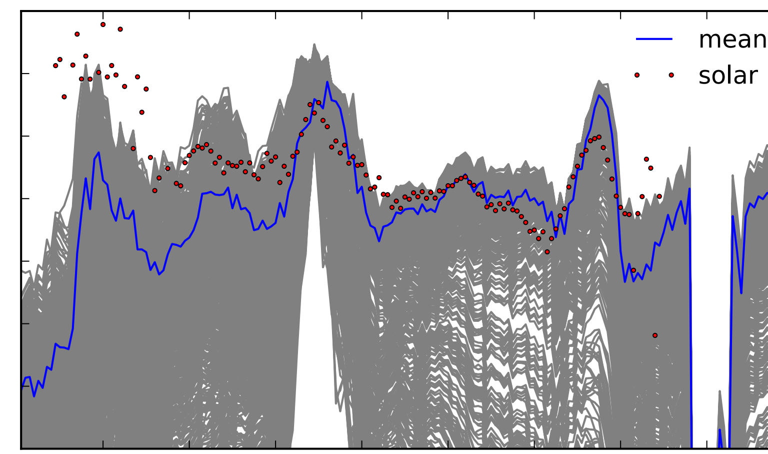
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

GRMHD simulations of remnant accretion disks from neutron star mergers







Daniel M. Siegel

NASA Einstein Fellow

Center for Theoretical Physics, Columbia Astrophysics Laboratory, Columbia University

INT workshop 2017, Univ. Washington, July 31- Aug 4, 2017

LIGO: NS mergers

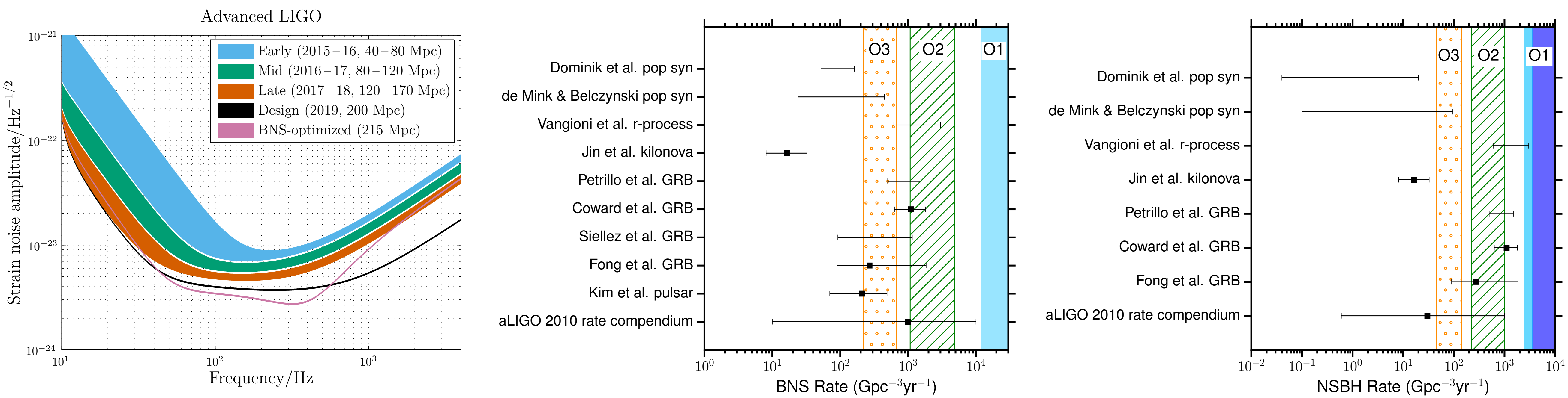
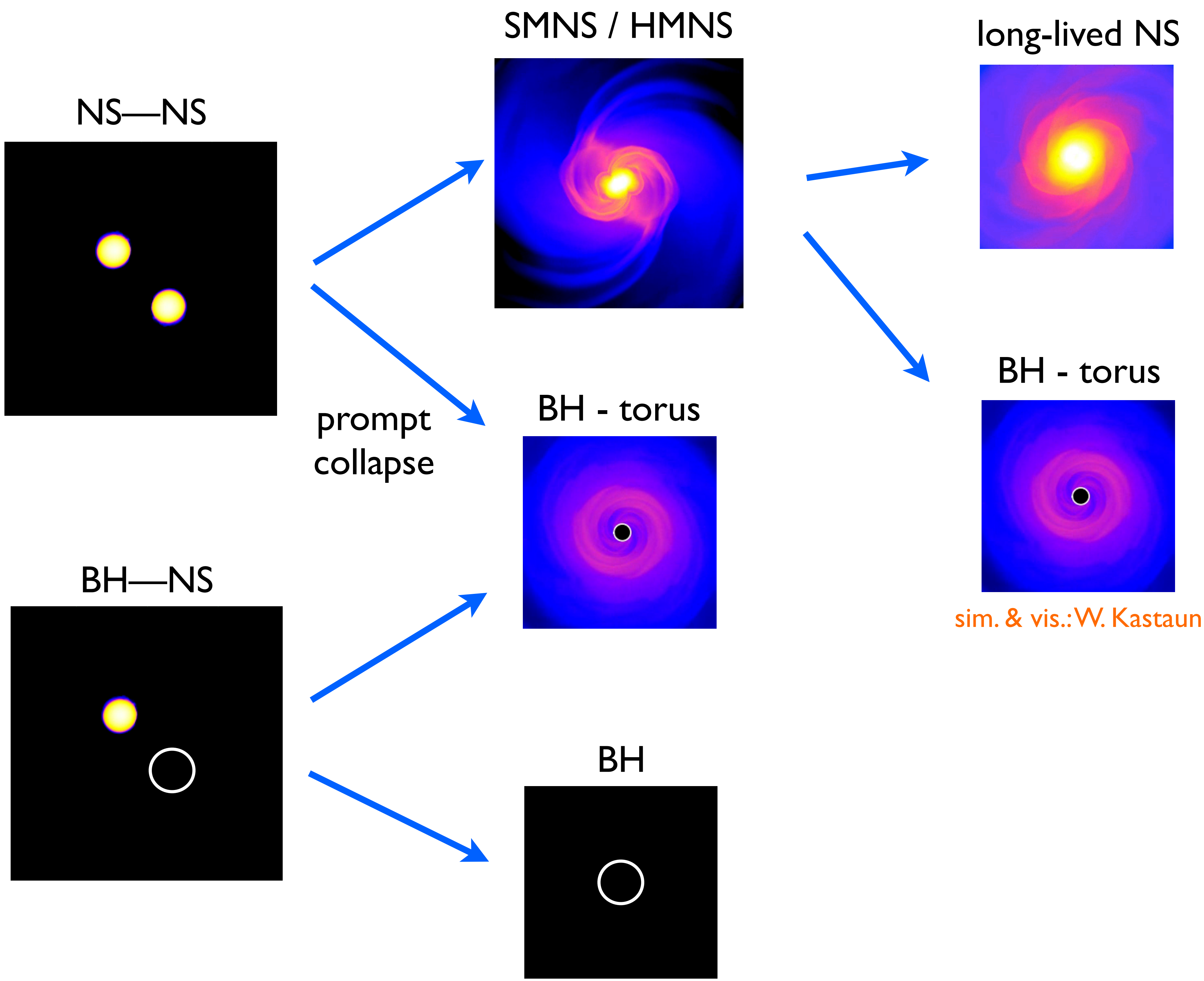


Fig.: Sensitivity of LIGO to BNS mergers (left) and sensitivity vs. predicted NS merger rates (right) Abbott+ 2016c

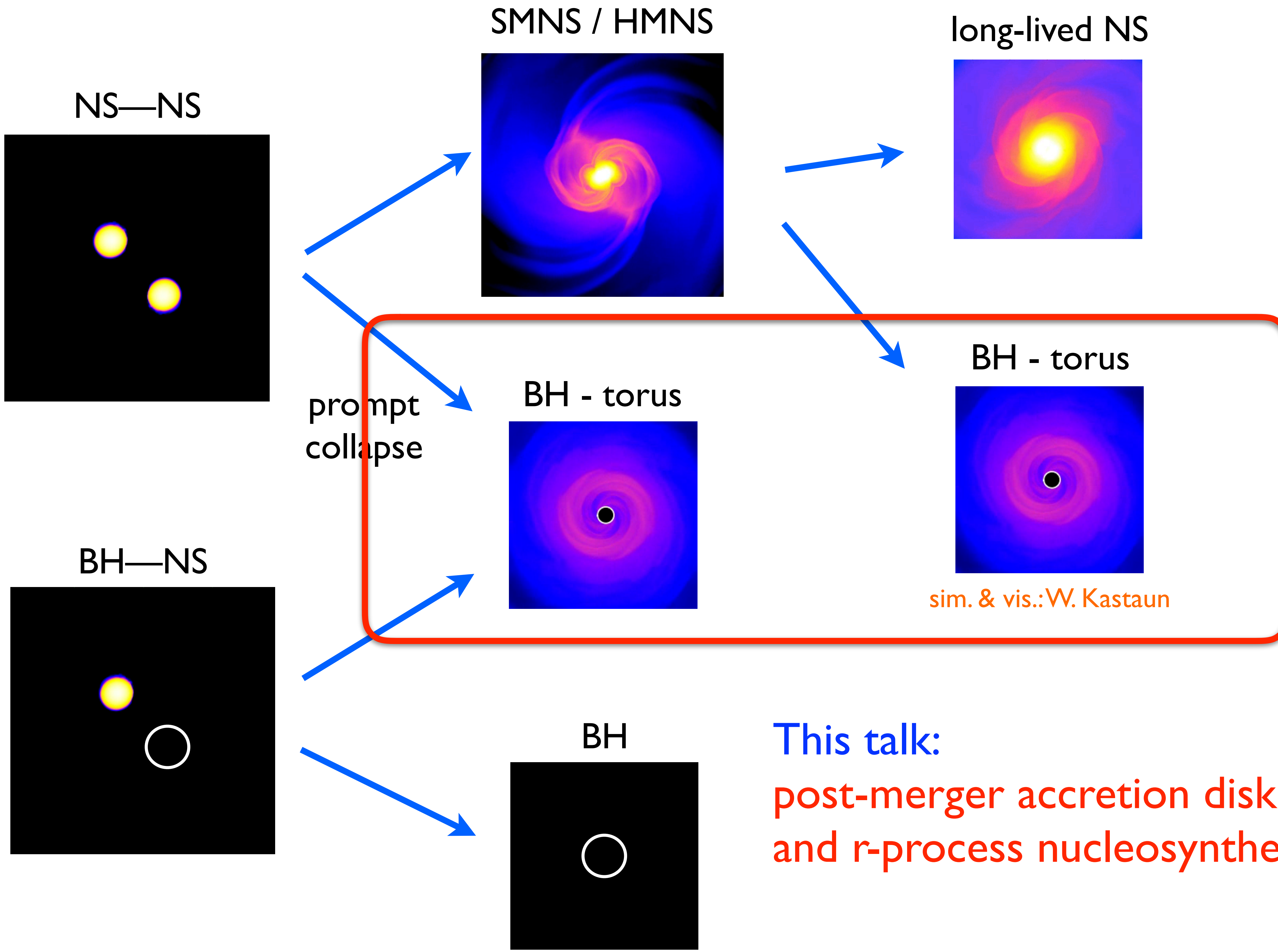
LIGO will probe deeply into the predicted NS merger rate distributions by 2018 (O3)

⟶ exciting discoveries expected soon

NS mergers remnants

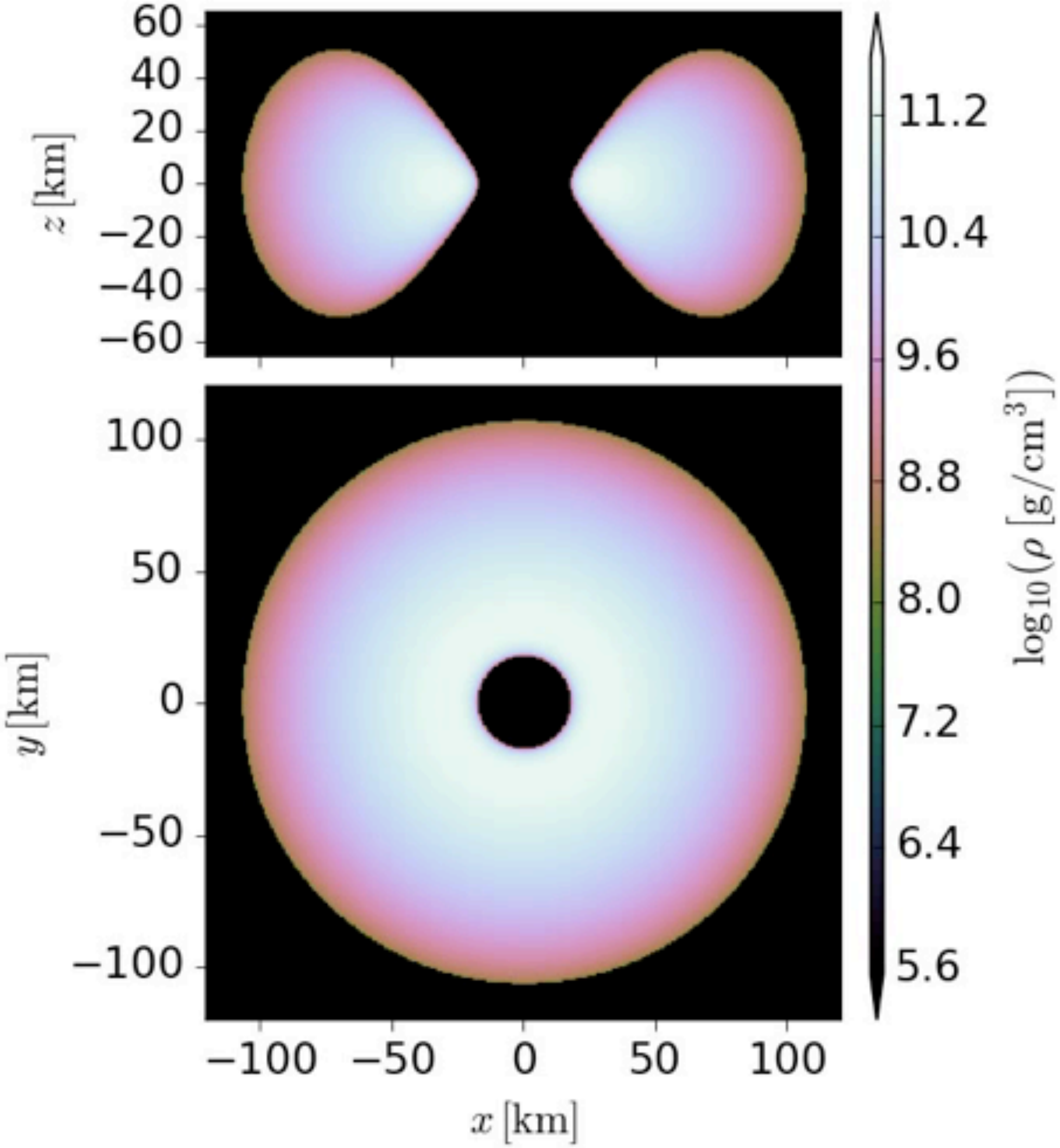


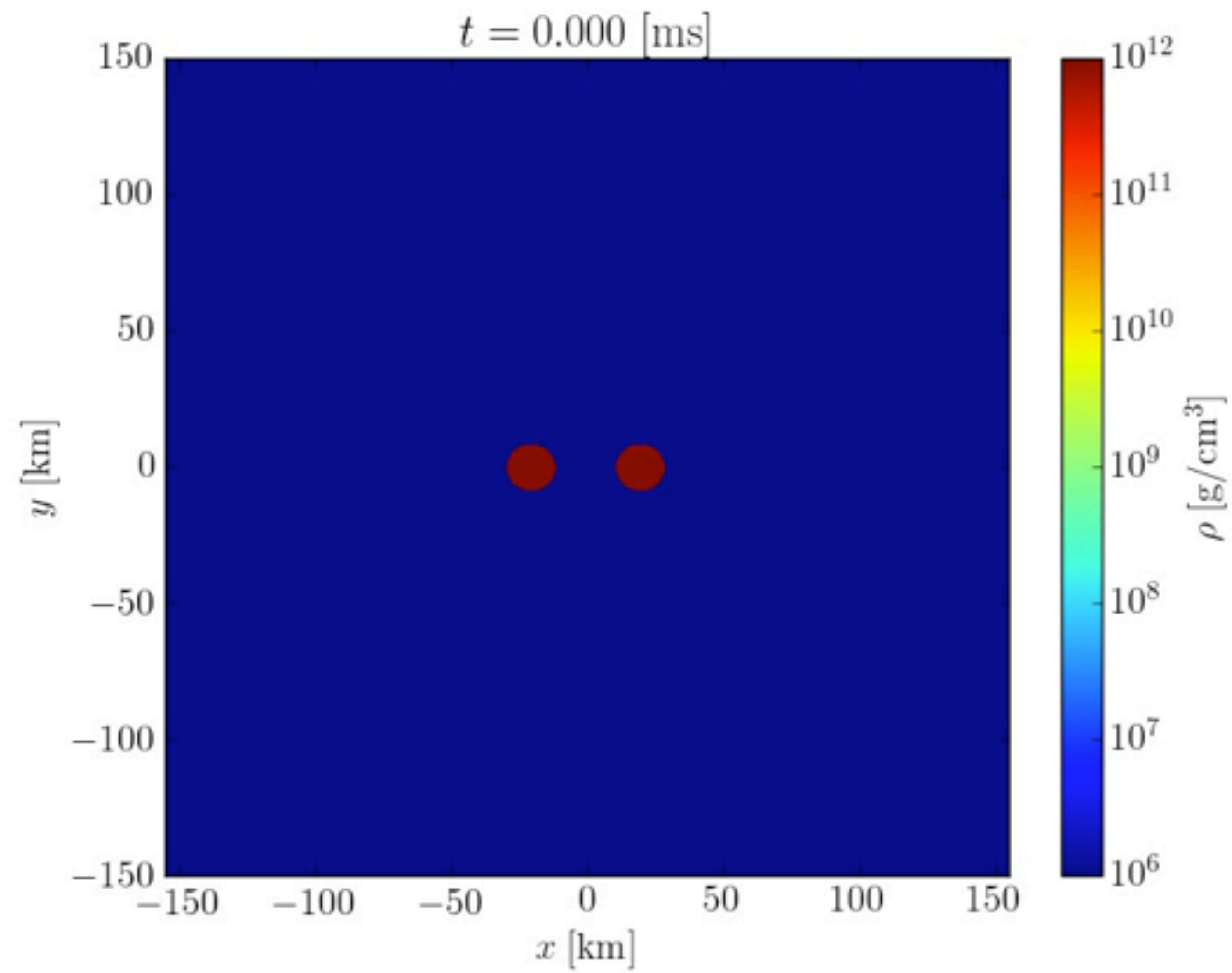
NS mergers remnants



This talk:
post-merger accretion disks and r-process nucleosynthesis

NS post-merger accretion disks: formation





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

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

courtesy D. Radice

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

Siegel & Metzger 2017a

NS post-merger accretion disks: numerical setup

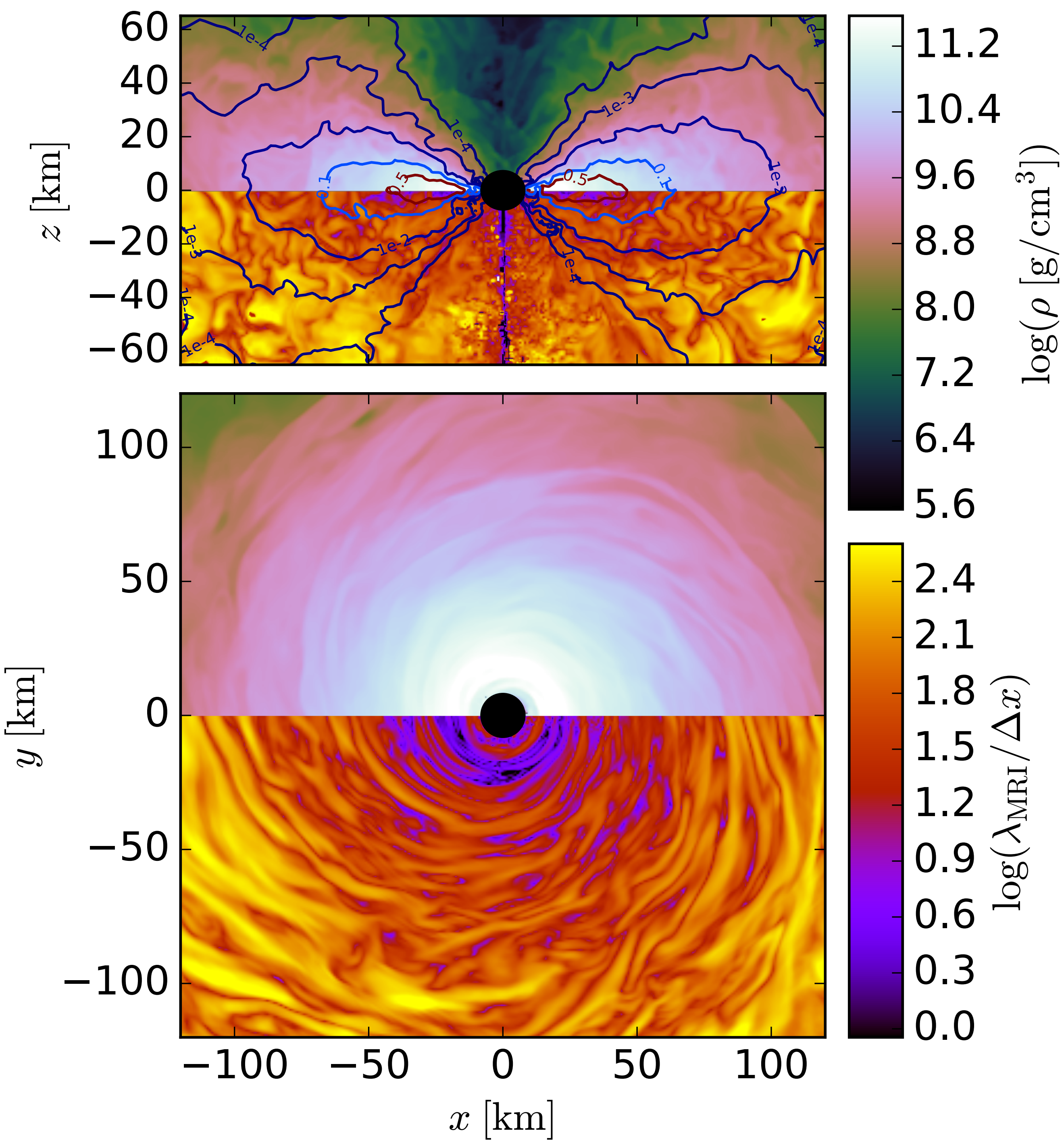


Fig.: disk properties; contours: optical depth for electron neutrinos

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

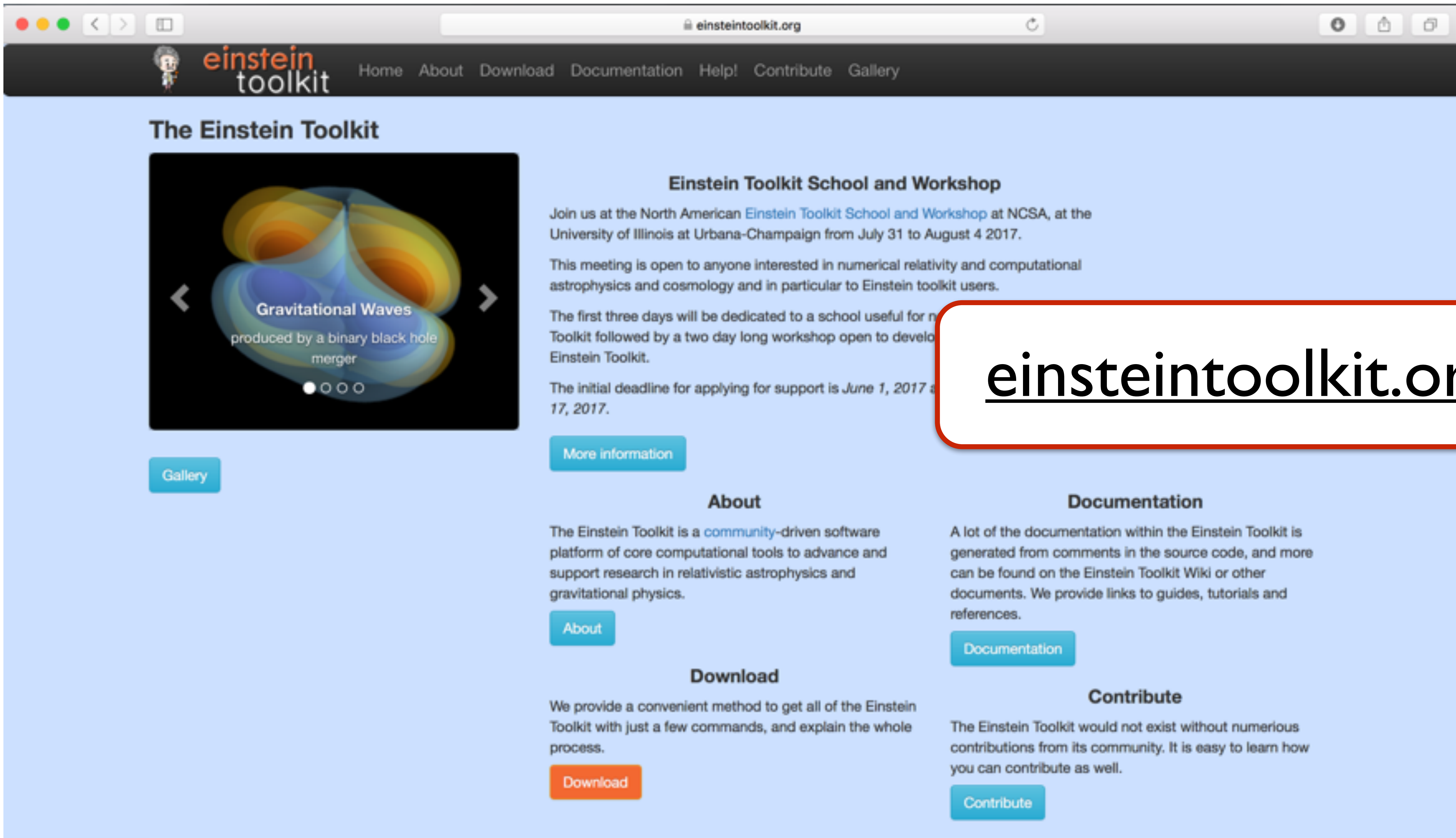
First self-consistent simulations modeling r-process nucleosynthesis from disk outflows from first principles:

- 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:

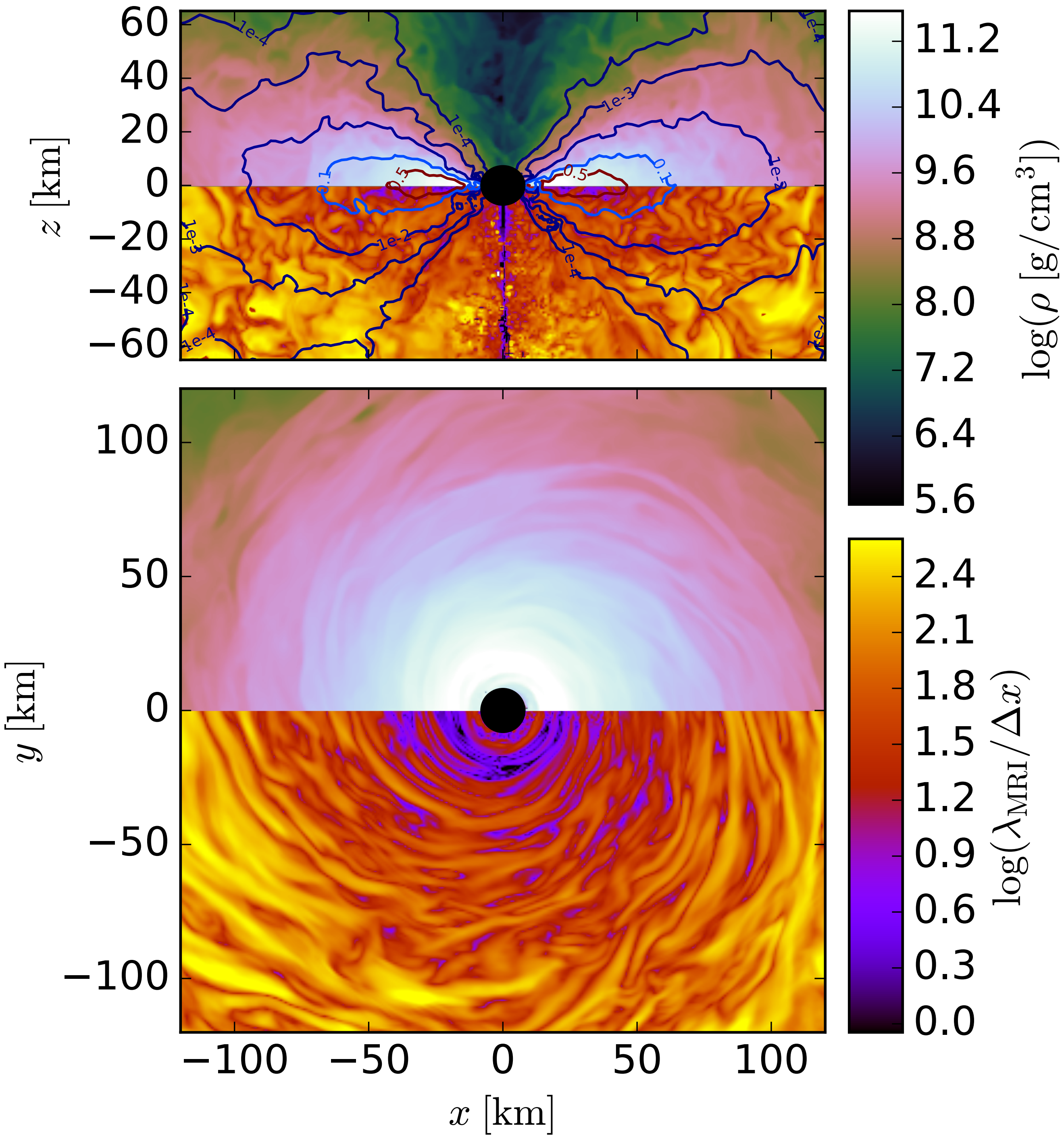
Fernandez & Metzger 2013
Metzger & Fernandez 2014
Fernandez+ 2015
Fernandez+ 2017
Just+ 2015

GRHydro: part of the Einstein Toolkit



einsteintoolkit.org

NS post-merger accretion disks: numerical setup



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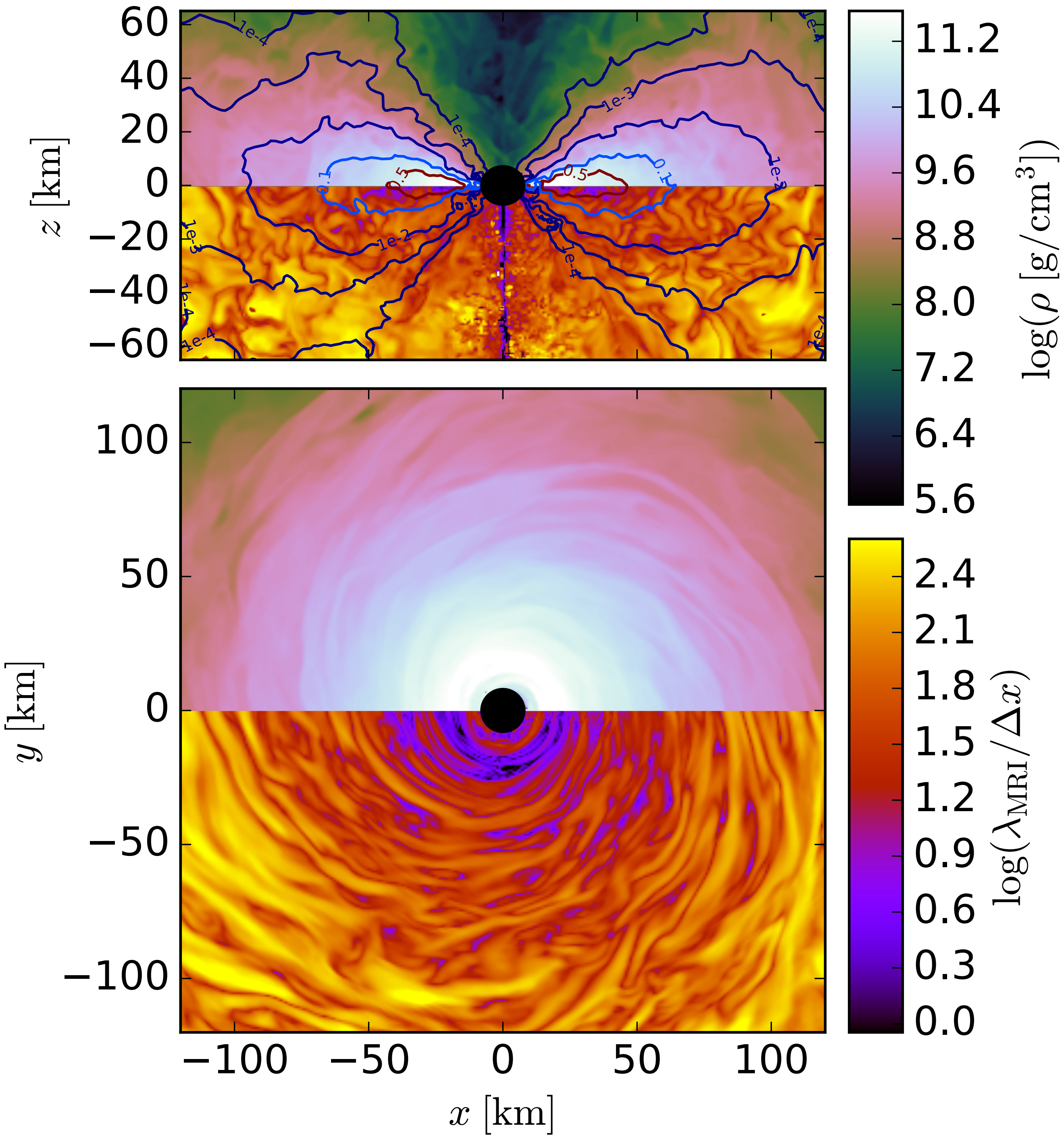
Onset of MHD turbulence



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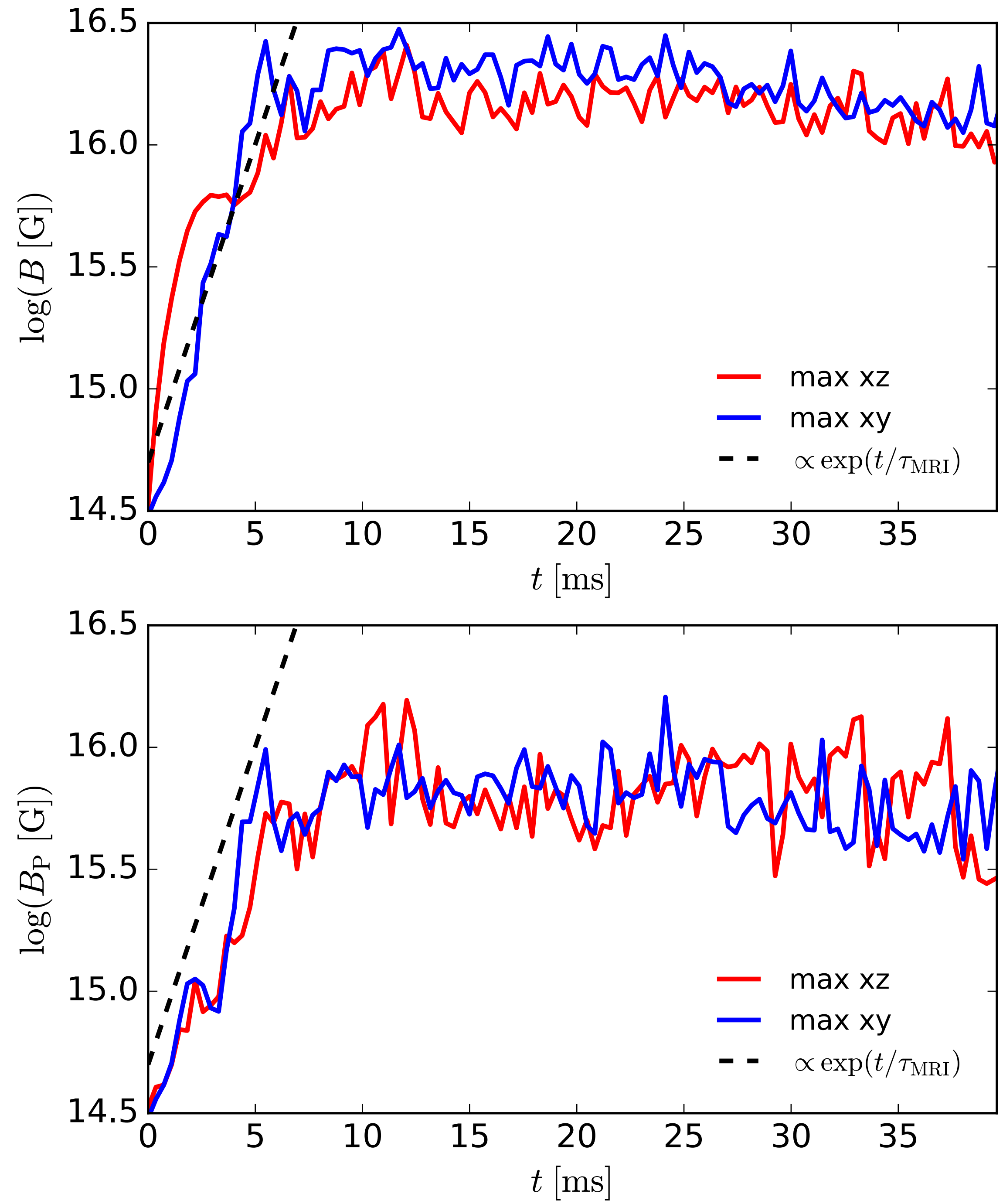
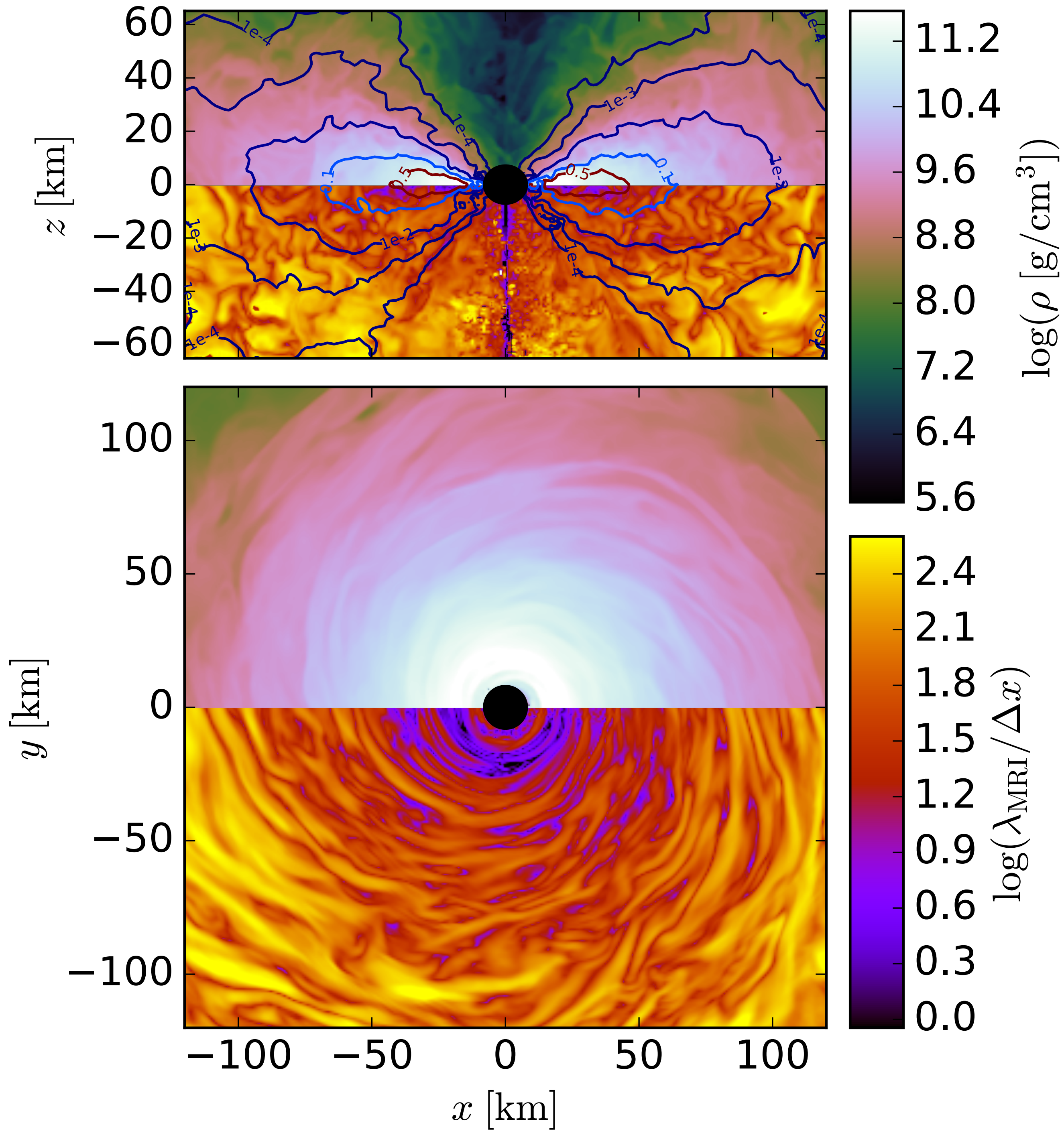


Fig.: Onset of the magnetorotational instability (MRI), showing exponential growth of the magnetic field

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

Onset of MHD turbulence



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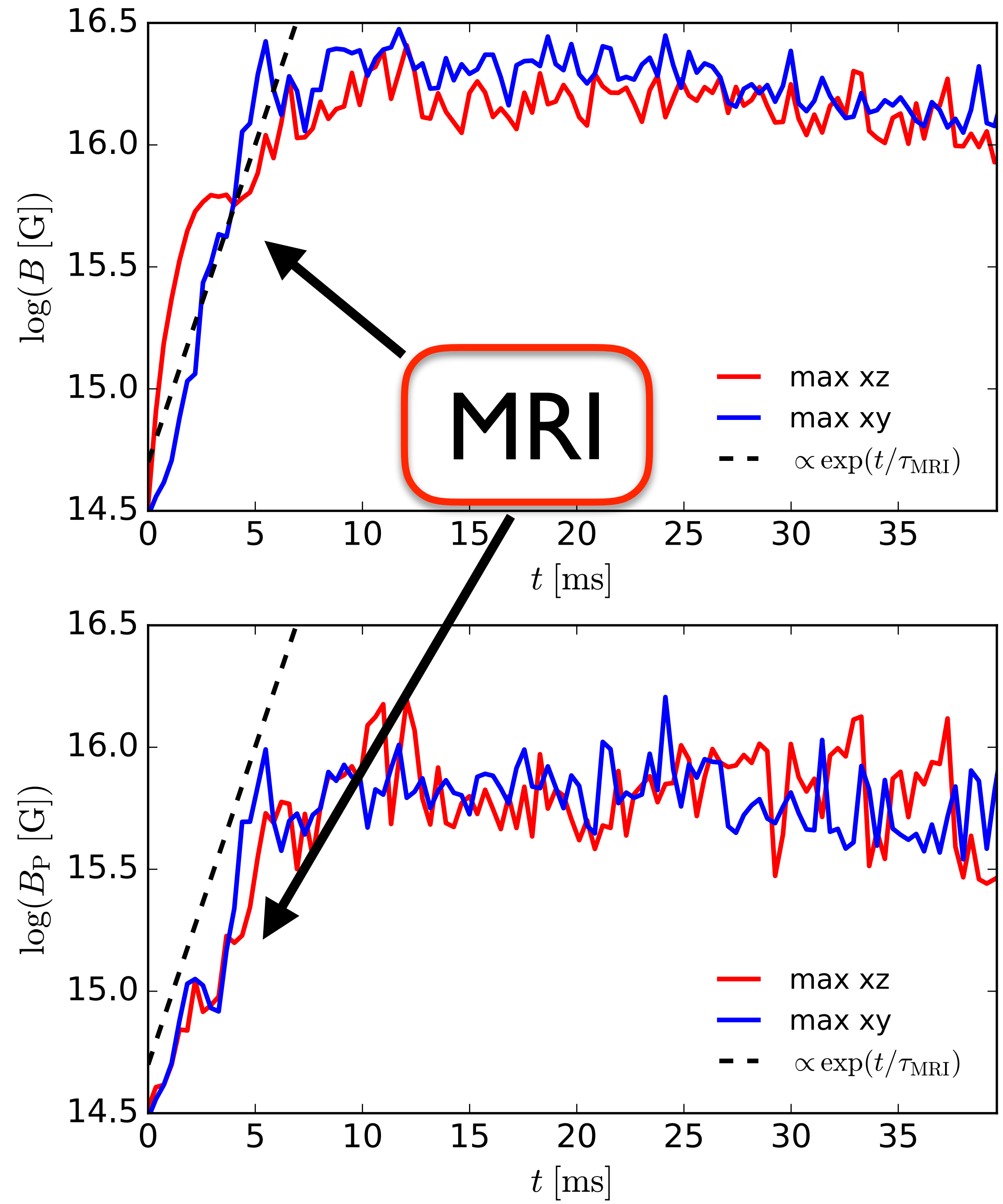

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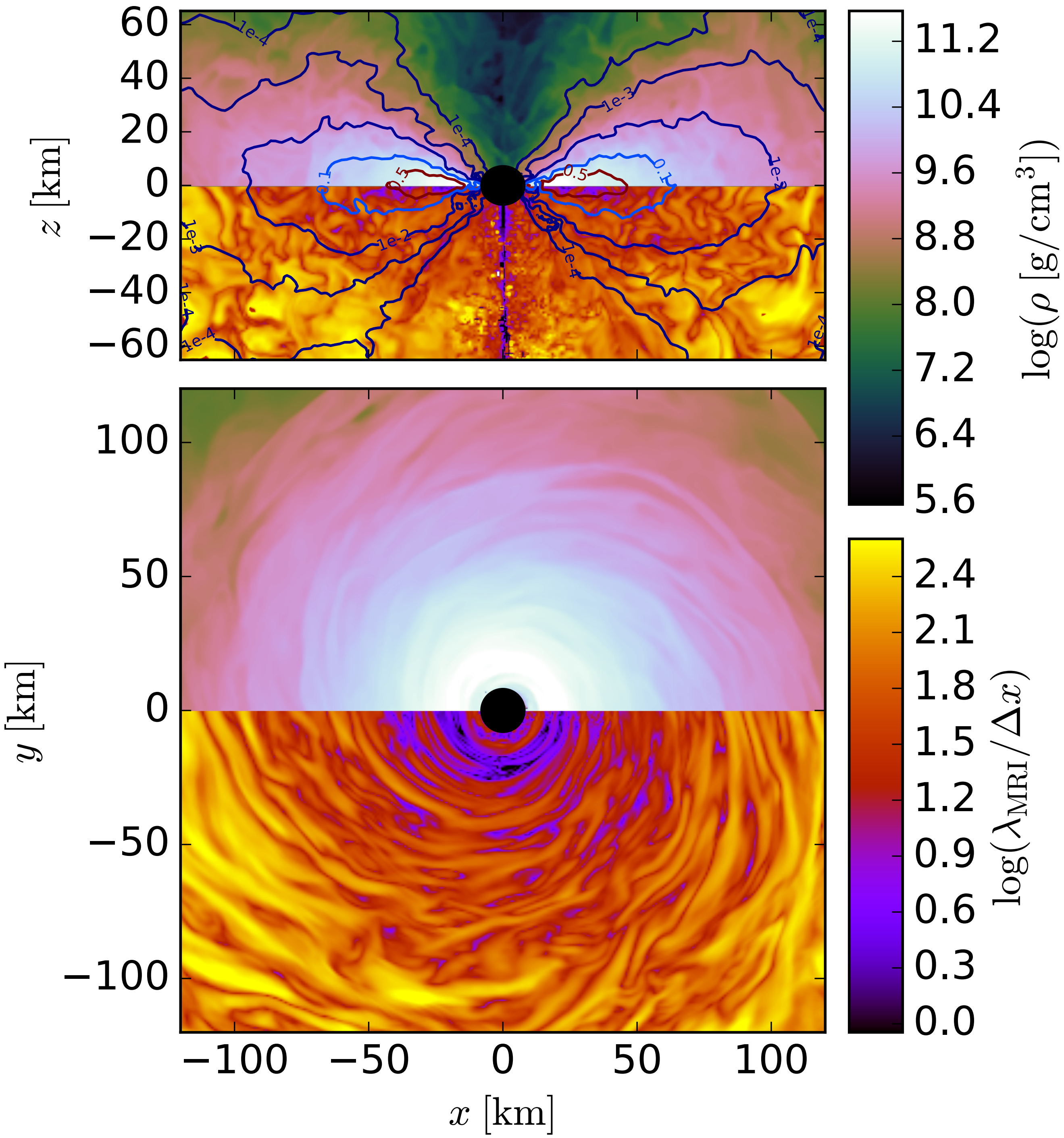

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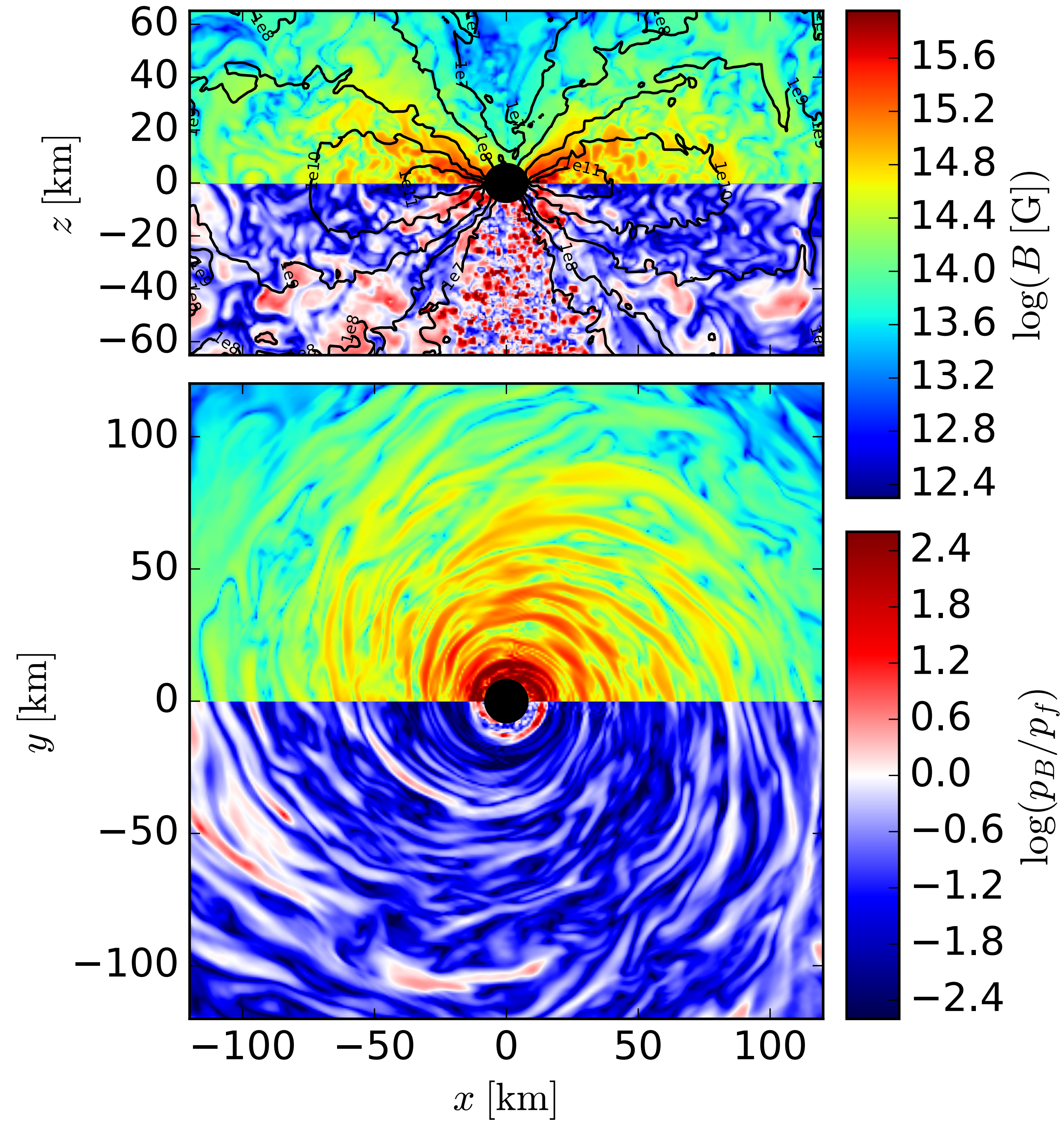


Fig.: magnetic fields in the disk; contours: rest-mass density

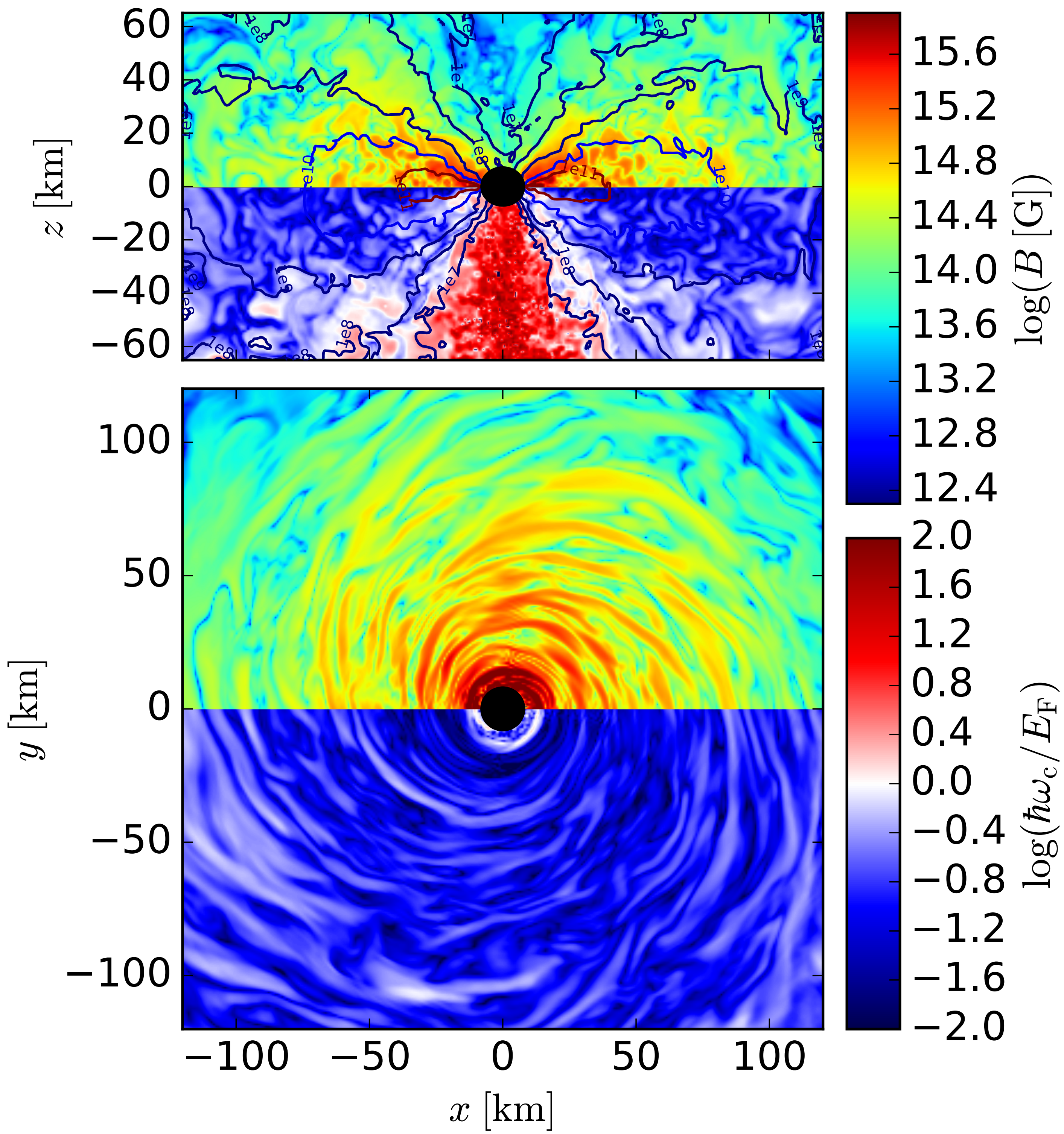
Siegel & Metzger 2017a Siegel & Metzger 2017b, in prep.

magnetic properties very similar to Ciolfi+ 2017

B-field effect on EOS and neutrino emission rates

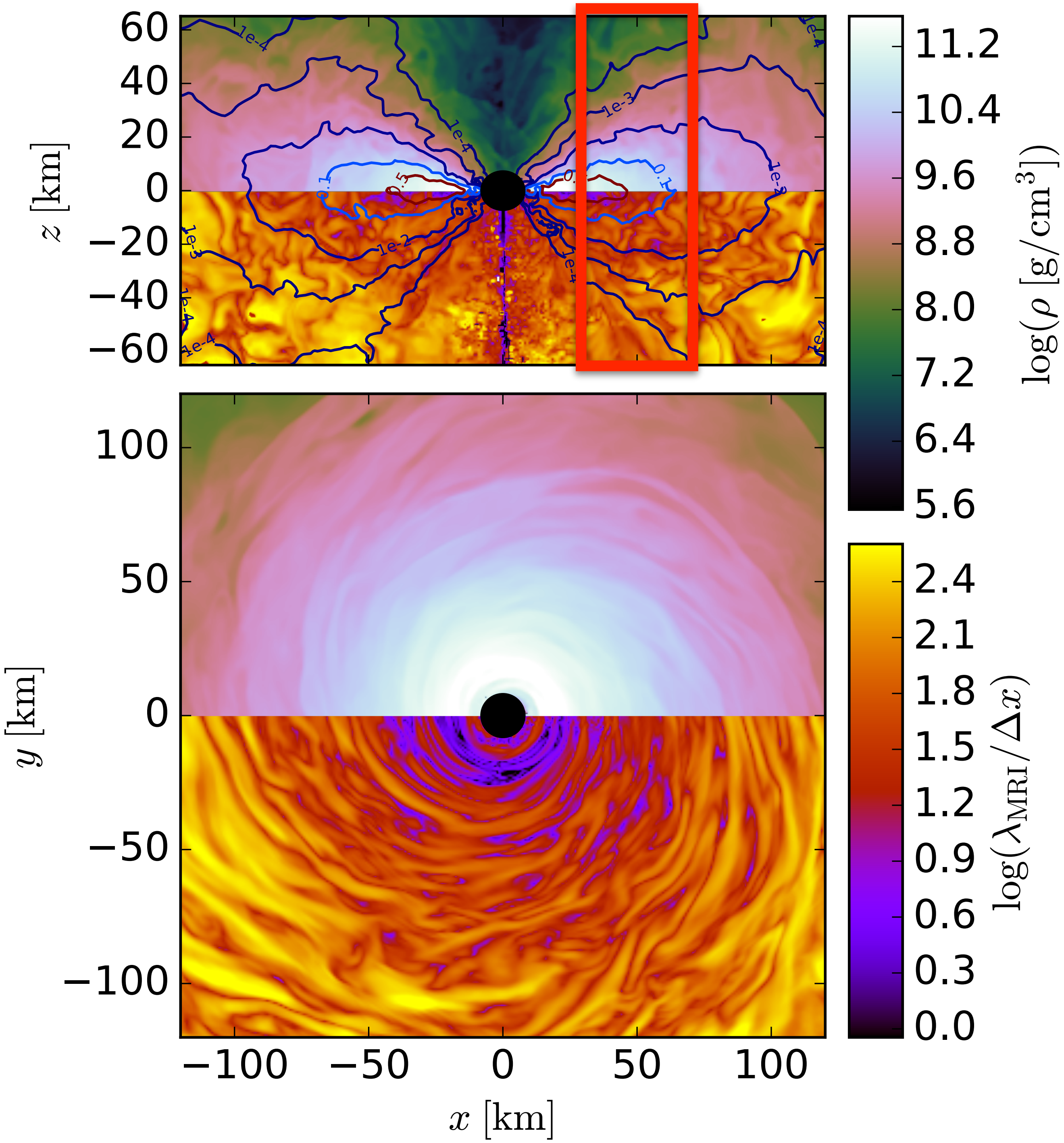
assume magnetic field effects become important when cyclotron frequency of electrons and Fermi energy become comparable:

$$\frac{\hbar\omega_c}{E_F} \gtrsim 1$$



Onset of MHD turbulence

average radially for space-time diagram



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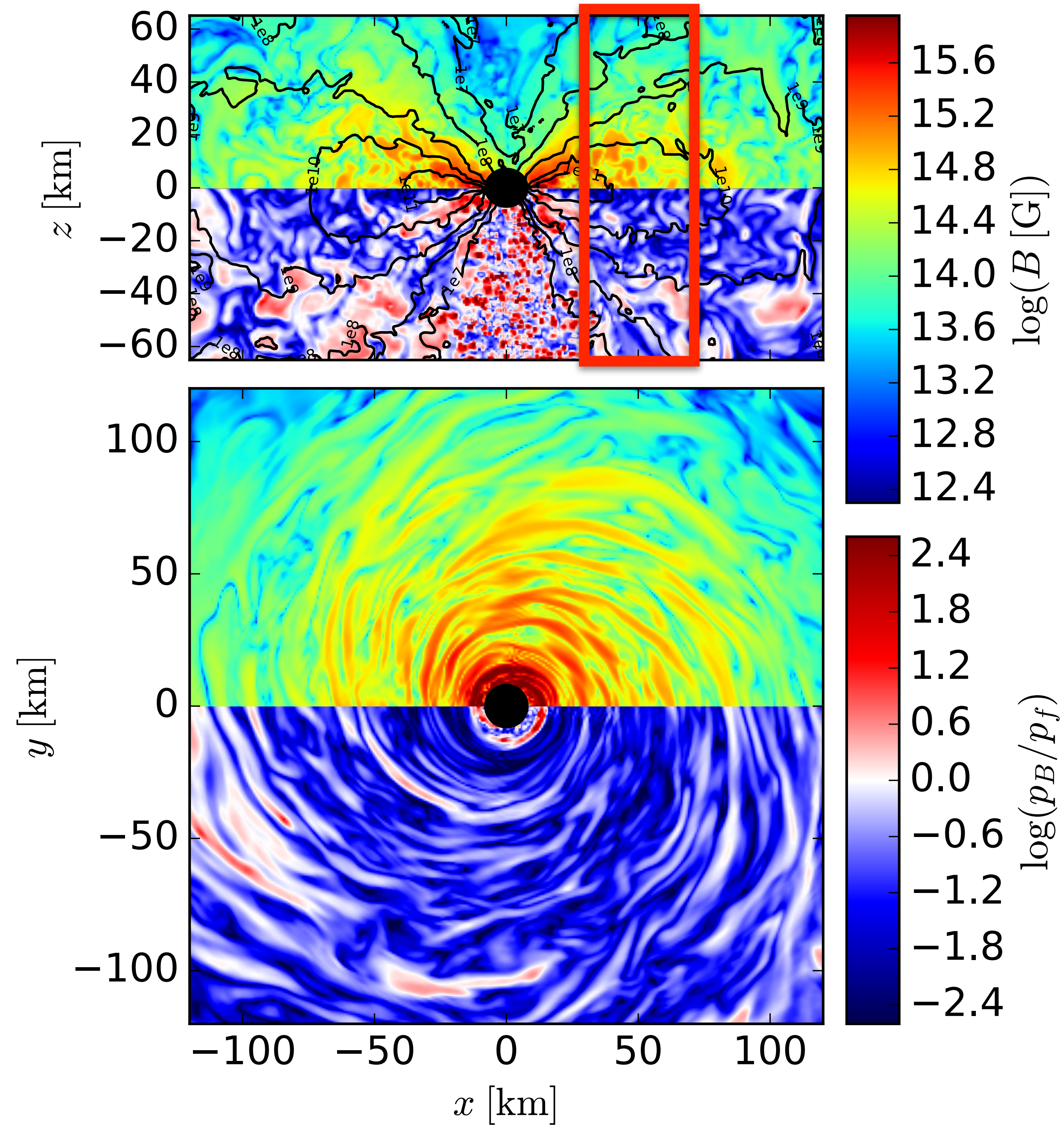

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Siegel & Metzger 2017a   Siegel & Metzger 2017b, in prep.

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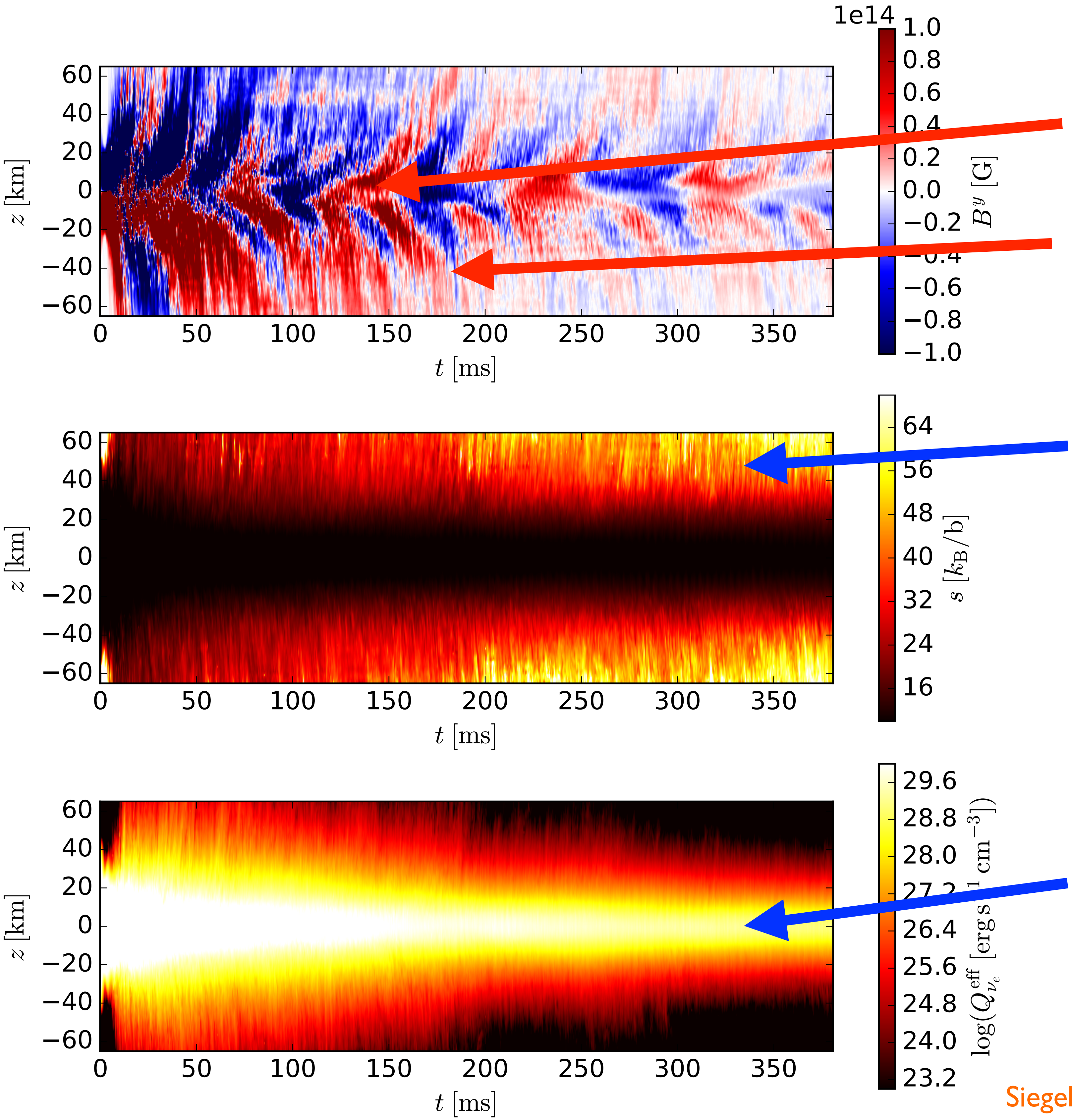
Accretion disk dynamo: butterfly diagram



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.

NS post-merger accretion disks: self-regulation

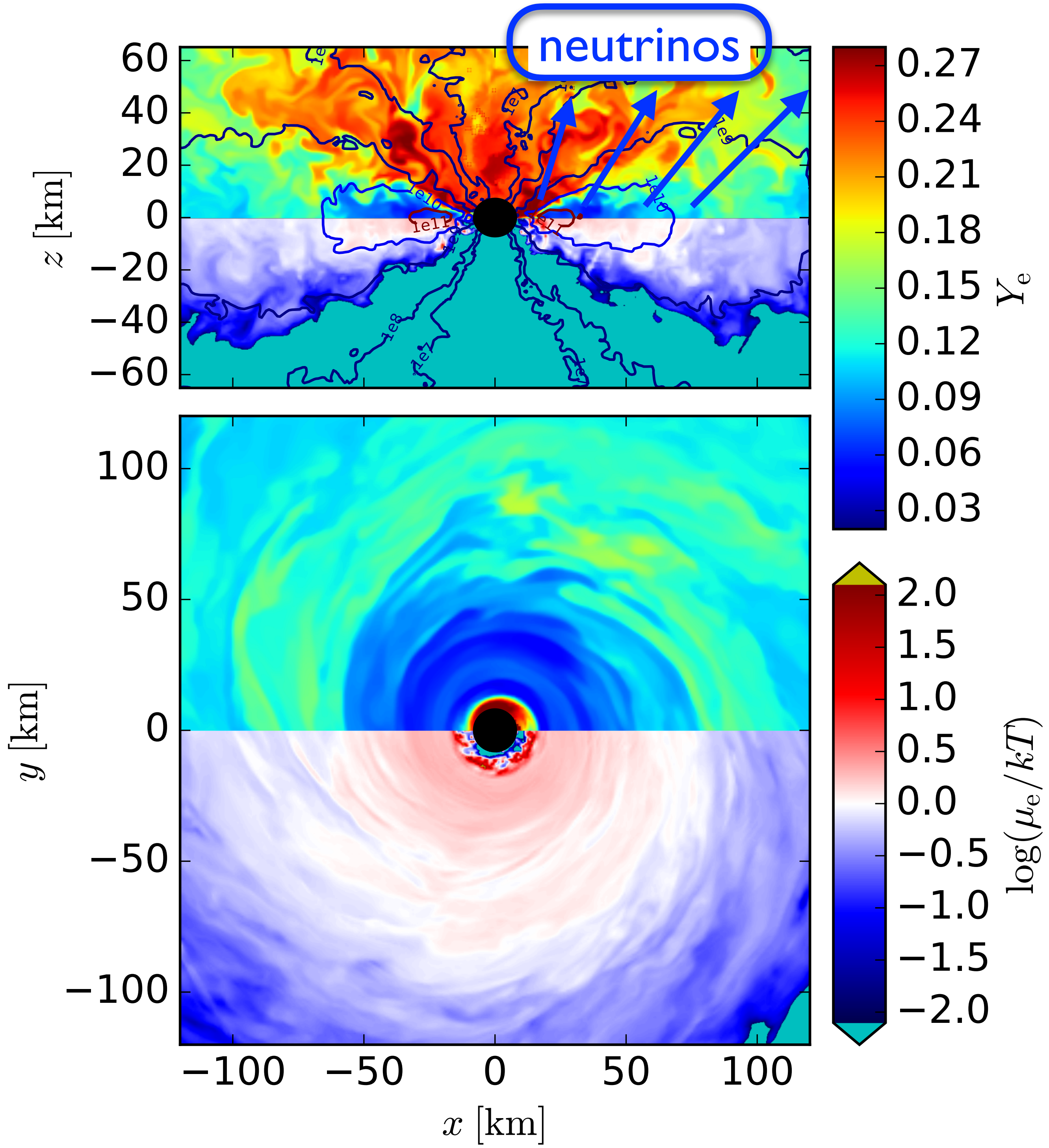


Fig.: disk properties; contours: rest-mass density

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:

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

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

pair annihilation:

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

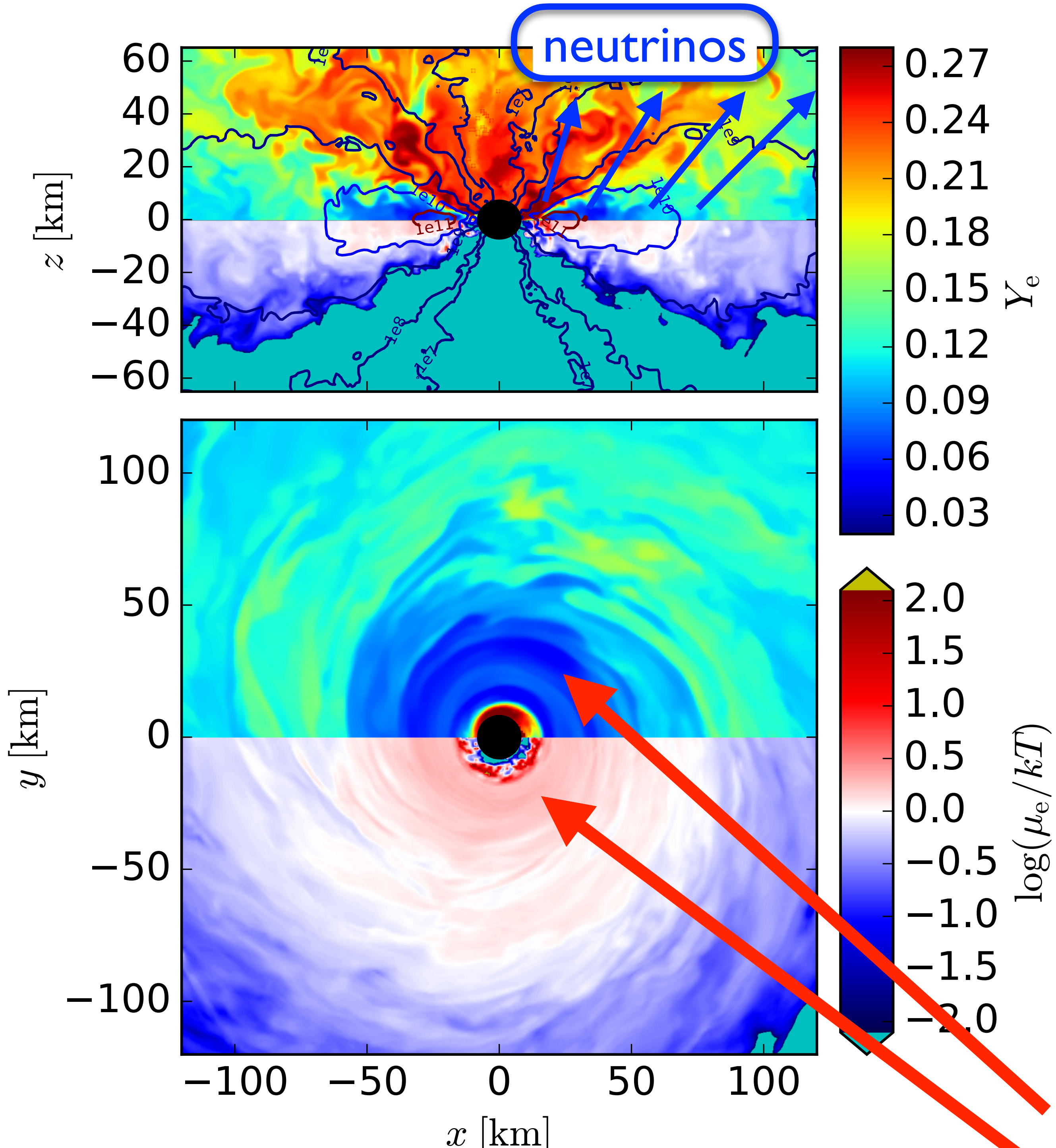
$$e^- + e^+ \rightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$$

plasmon decay:

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

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

NS post-merger accretion disks: self-regulation



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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

↓

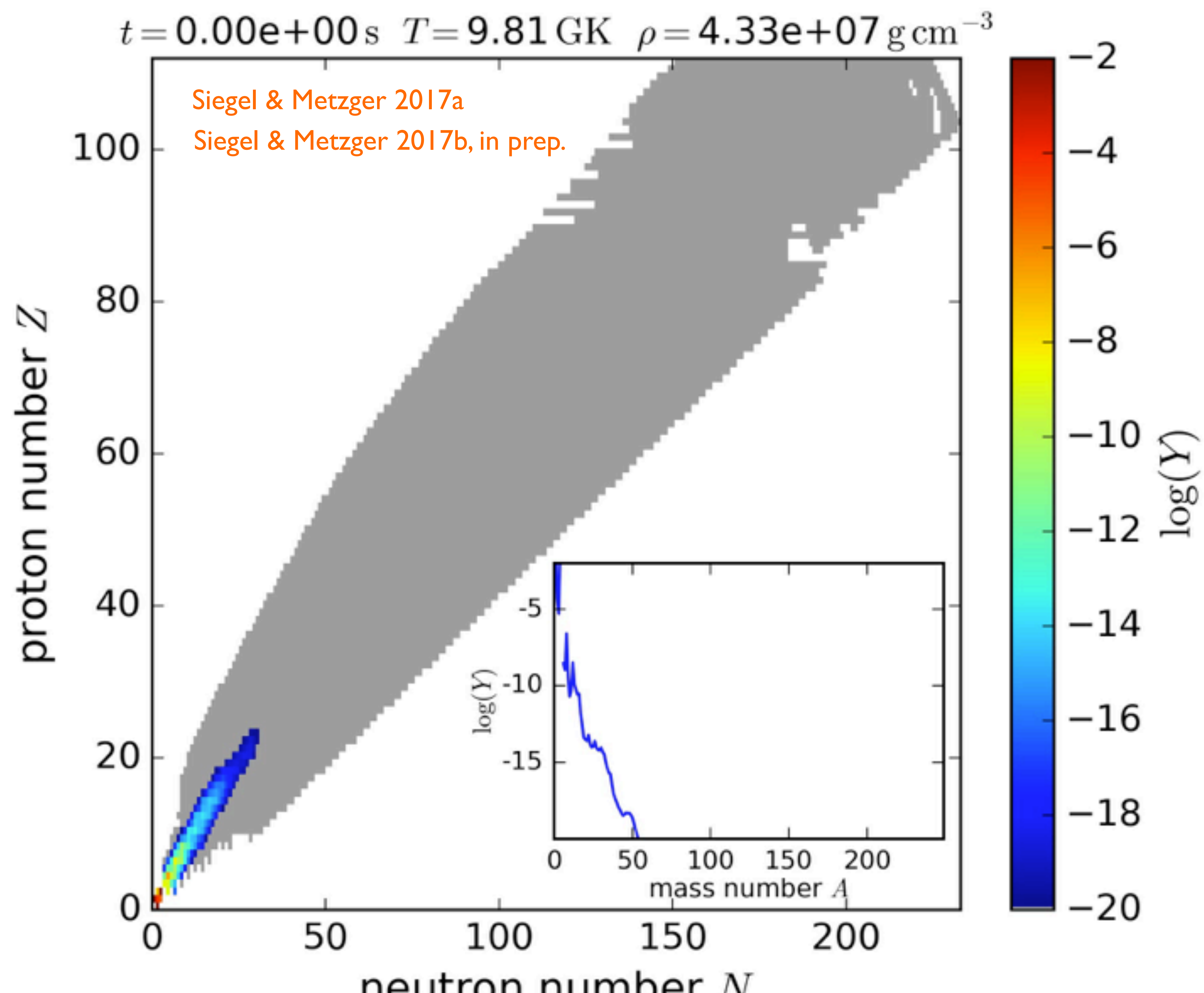
higher temperatures

↓

lower degeneracy μ_e/kT

direct evidence of self-regulation

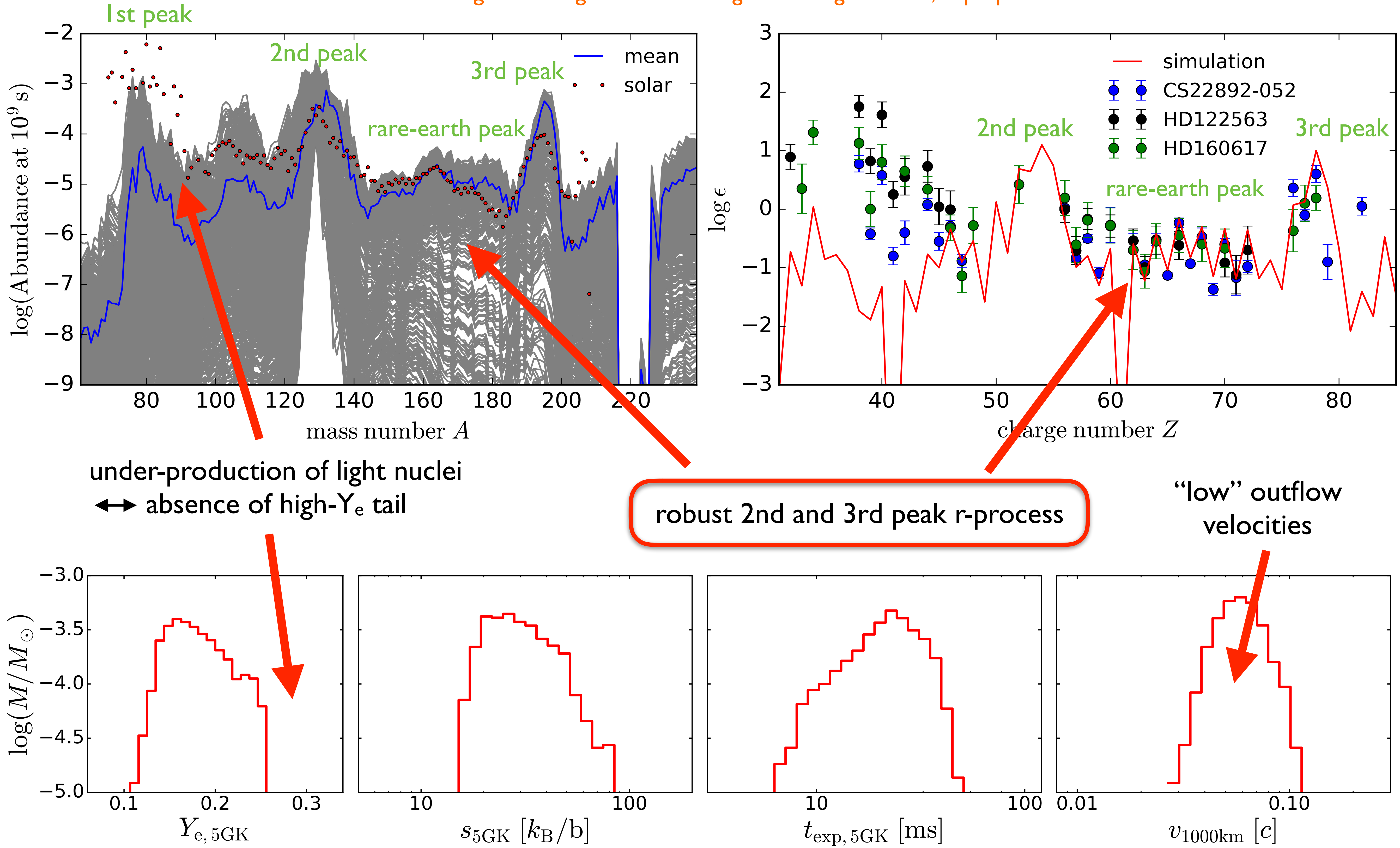
The origin of heavy nuclei: r-process nucleosynthesis



Movie: r-process nucleosynthesis from NS merger remnant disks

NS post-merger accr. disks: r-process nucleosynthesis

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



Influence of neutrino absorption

Siegel & Metzger 2017b, in prep.

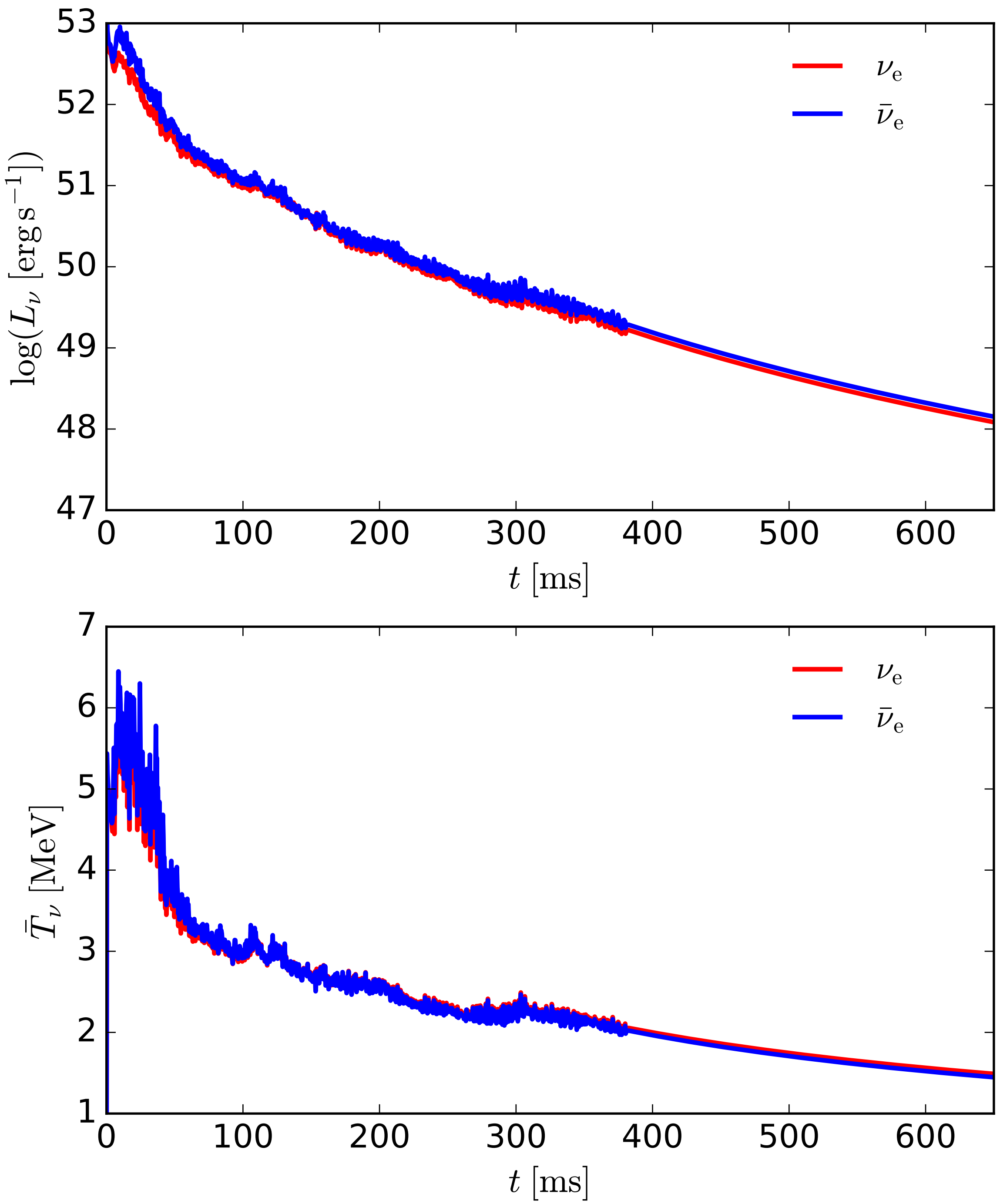
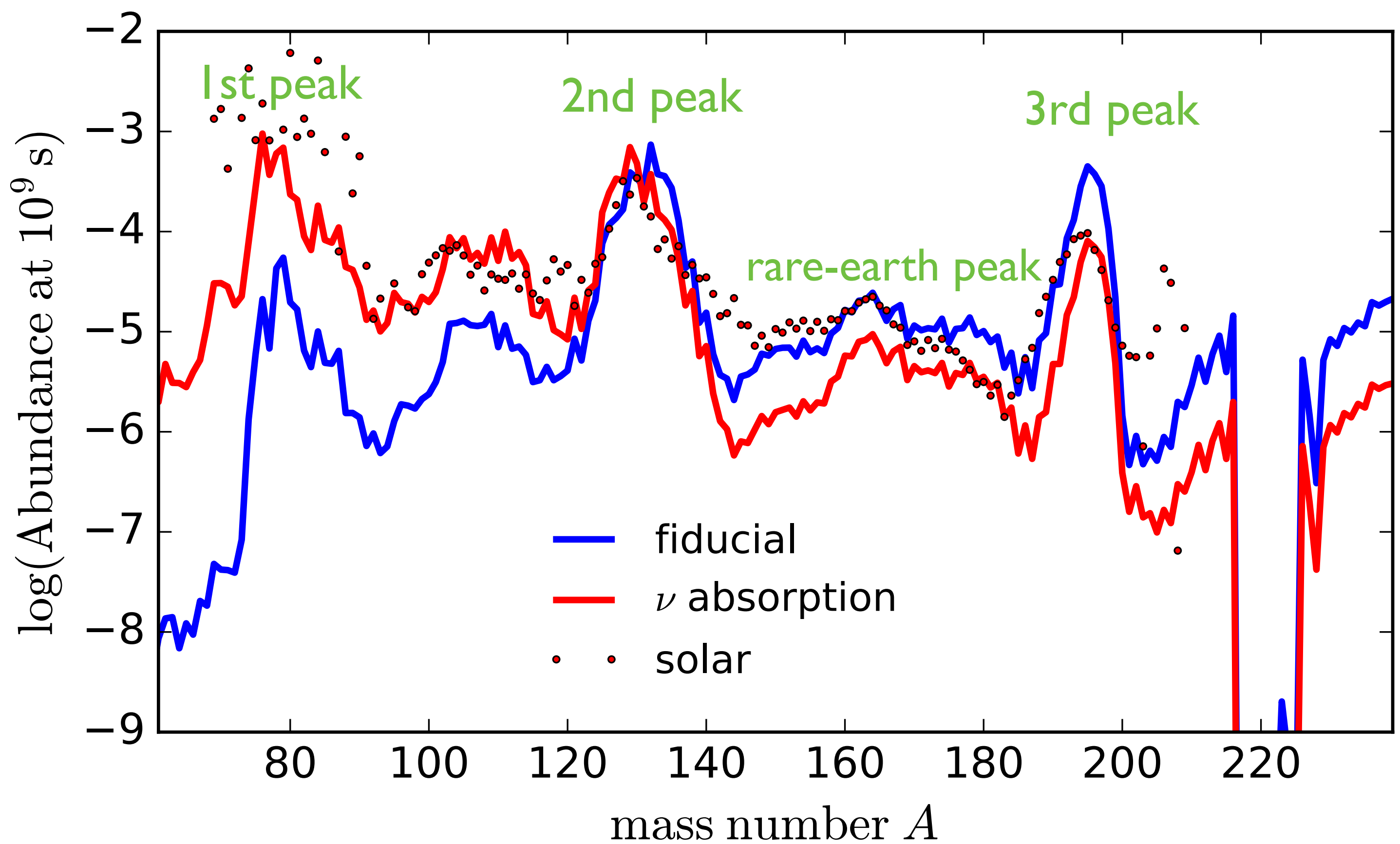


Fig.: total disk neutrino luminosity (top) and neutrino emissivity averaged neutrino temperature at emission



with neutrino absorption:

- also good fit to 1st — 2nd peak elements
- robust 2nd and 3rd peak r-process

→ production of all r-process elements

BH accretion vs. disk outflows

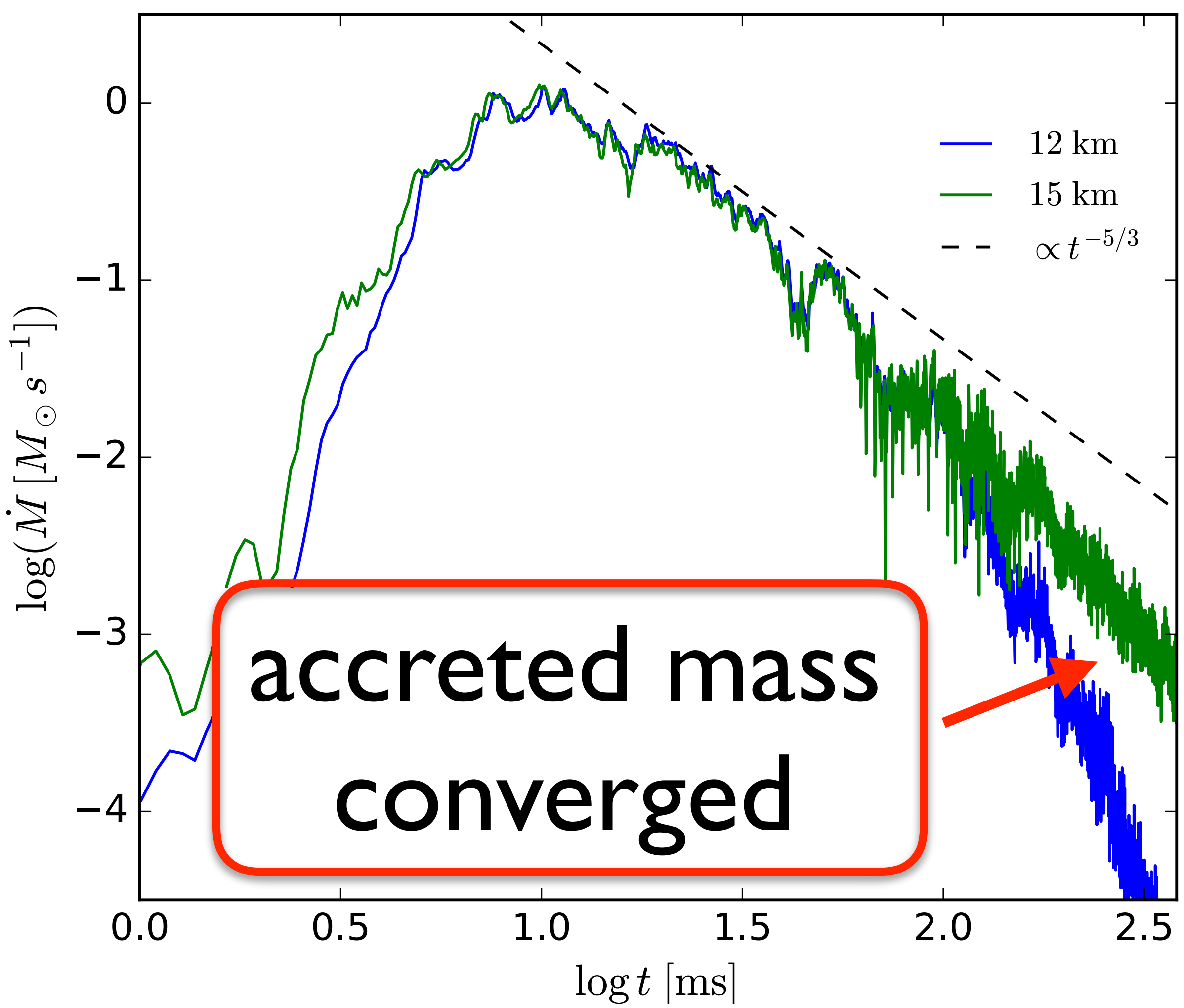


Fig.: accretion rate onto the BH

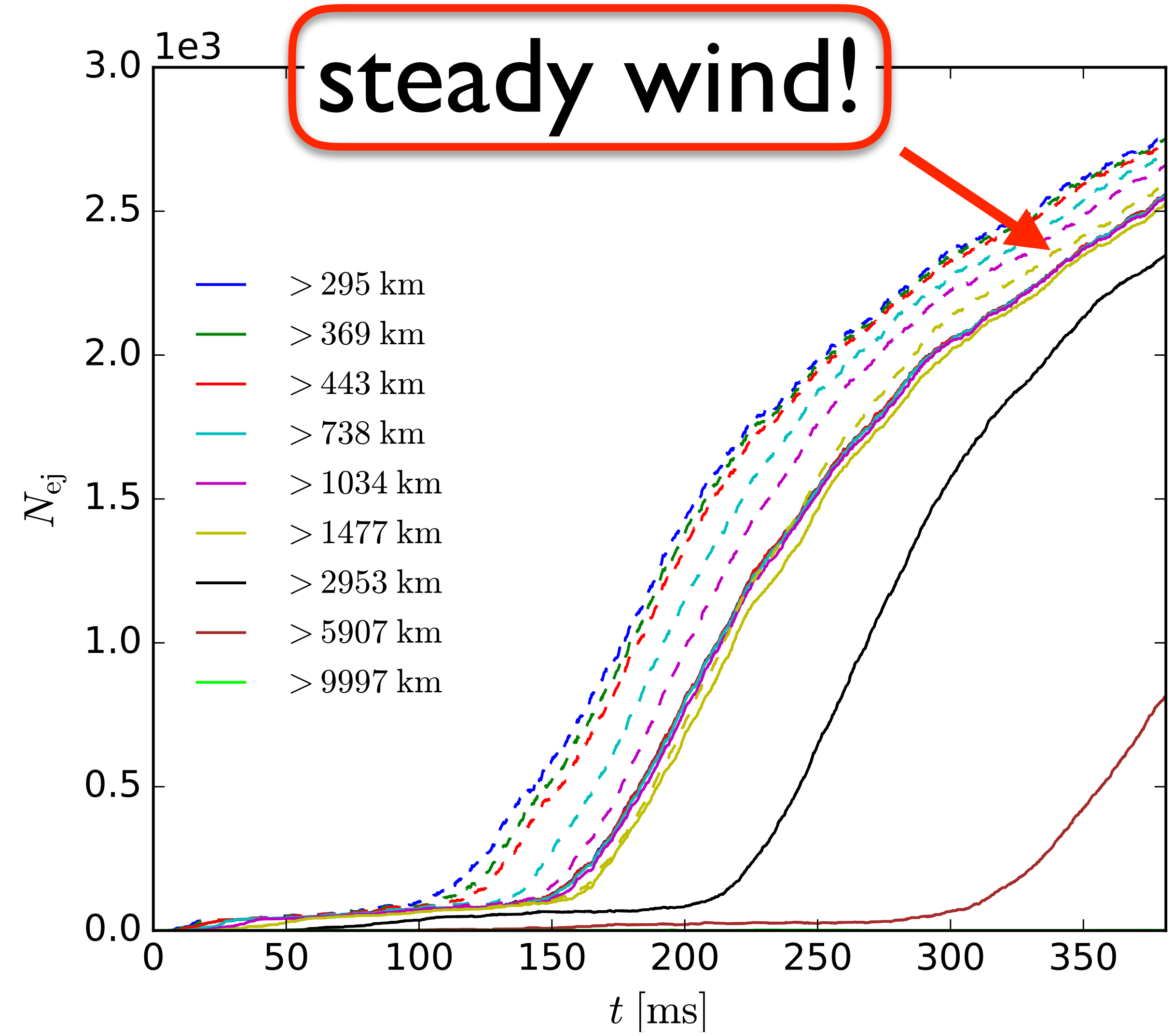


Fig.: number of tracer particles outside a given radius

By end of simulation: accreted mass converged but still steady outflows

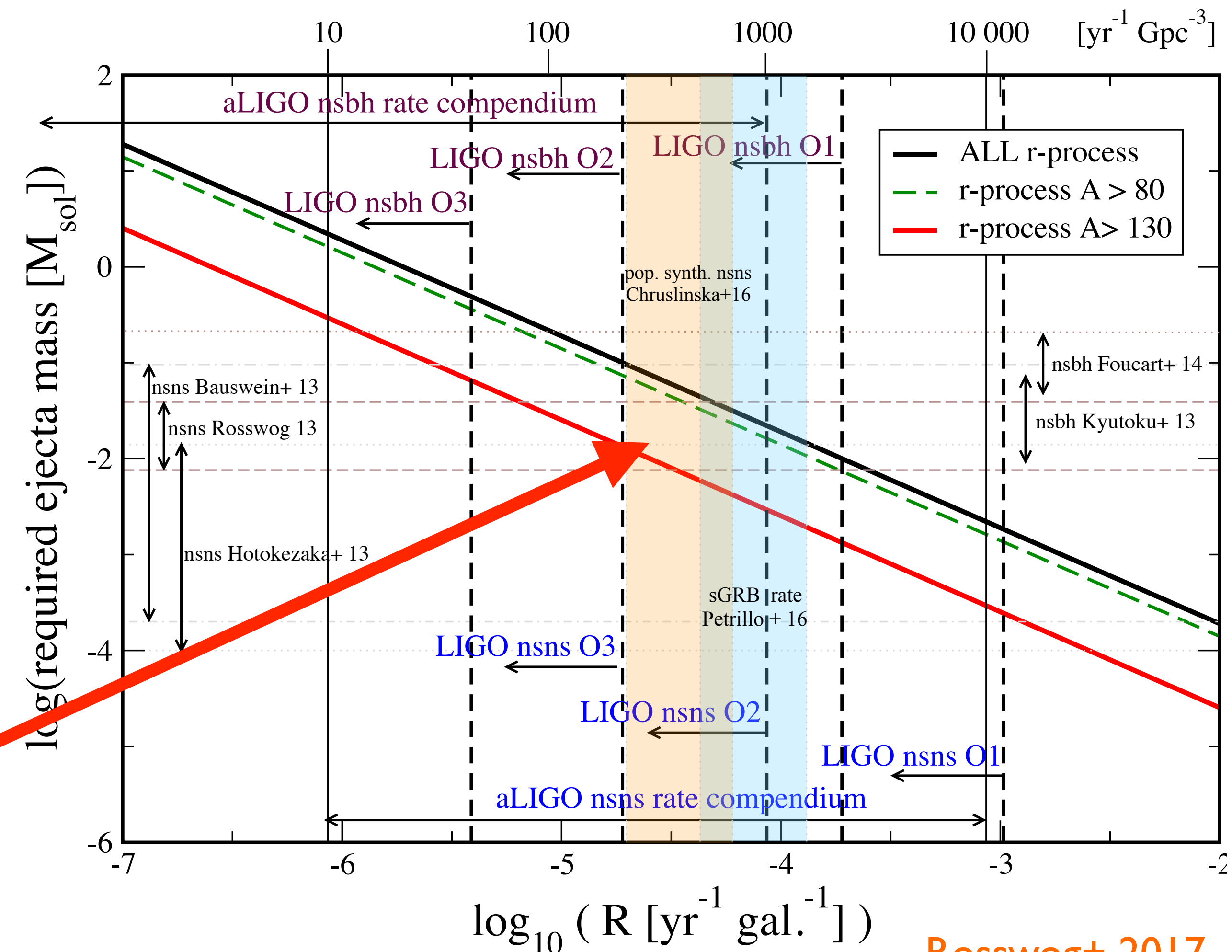
→ remaining disk mass likely unbound

NS post-merger accretion disks: r-process nucleosynthesis

GRMHD disk simulations:

Siegel & Metzger 2017a

- significantly higher ejected mass than in previous Newtonian hydro simulations
- unbound outflows >0.2 M_{disk}, likely ~0.4M_{disk}
- for disk in present simulation: > 0.005 M_{sun}, likely ~ 0.01 M_{sun}
- disk outflows alone are consistent with constraints on r-process enrichment observations



Rosswog+ 2017

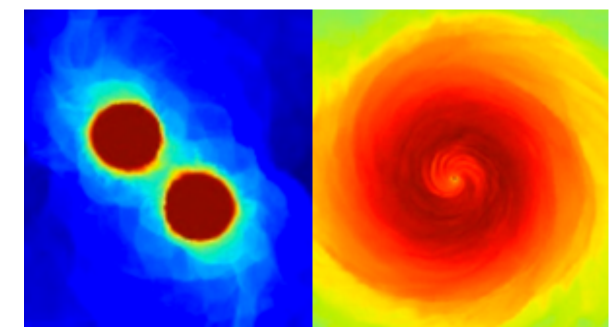
Fig.: constraints on r-process enrichment rates vs. ejected mass

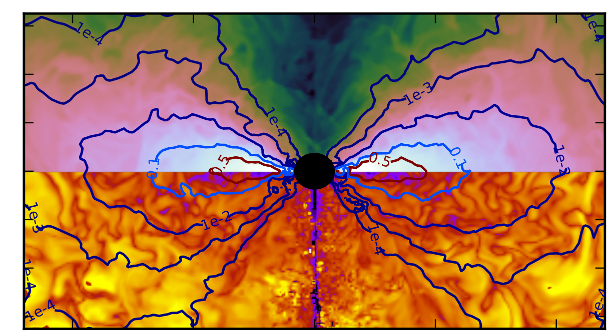
→ NS post-merger disk outflows are promising site for the r-process

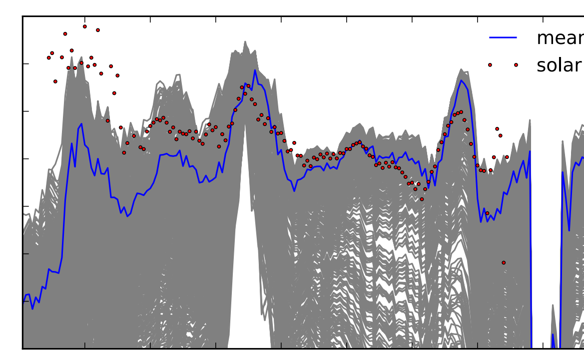
Conclusions

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
- suggest NS post-merger systems are robust site of the r-process
  - → can produce all r-process elements
  - → underproduction of light elements compensated by high-Y_e material from long-lived NS Wu+ 2016, Just+ 2015
  - → low velocity outflows enable narrow-line spectroscopy to identify composition of r-process matter
- electromagnetic signature (kilonovae) potentially most promising EM counterpart to GWs







JWST