COLUMBIA UNIVERSITY
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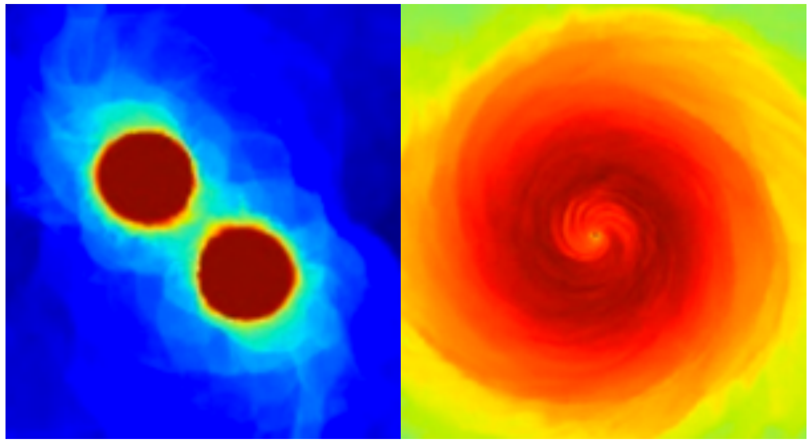
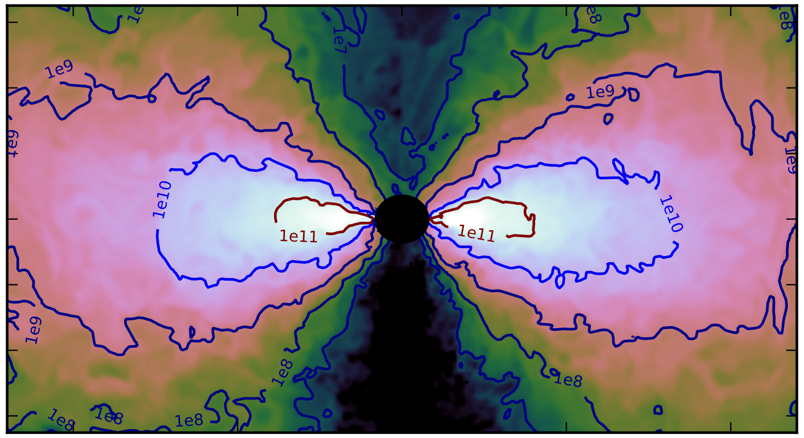
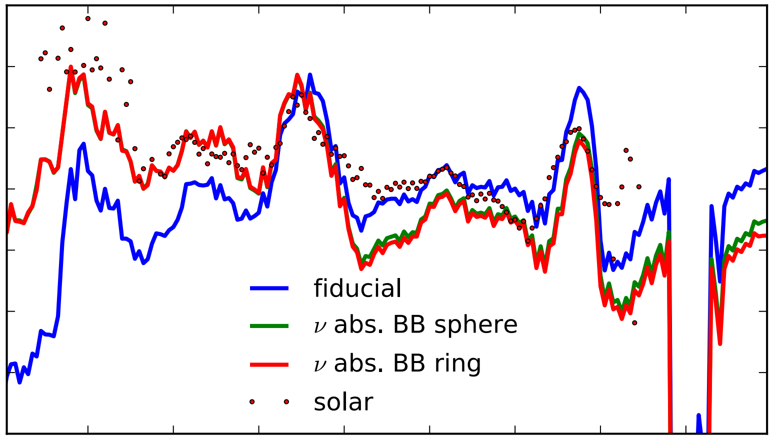
NS post-merger simulations: disk winds and the red kilonova from GW170817







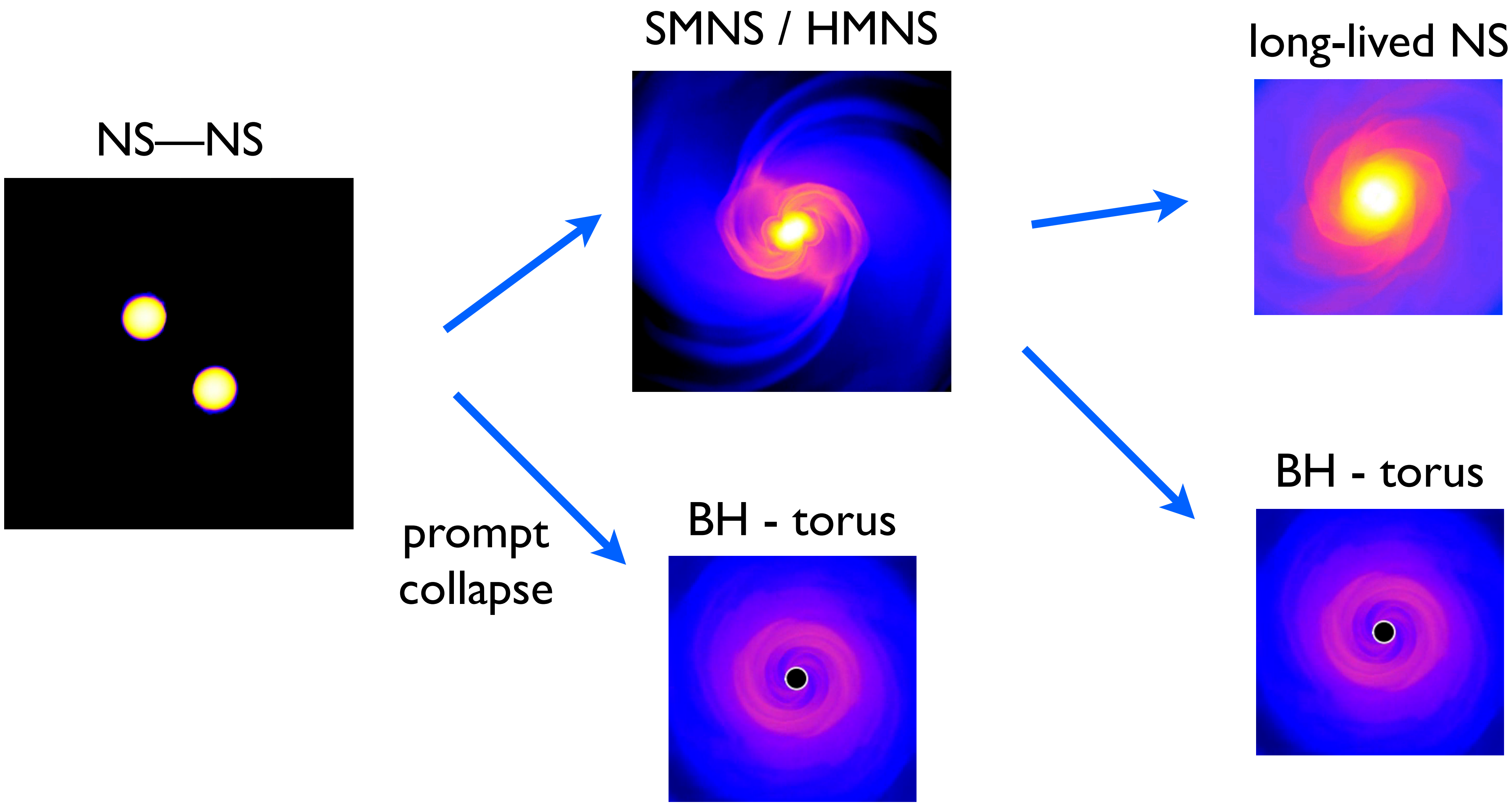
Daniel M. Siegel

NASA Einstein Fellow

Center for Theoretical Physics, Columbia Astrophysics Laboratory, Columbia University

GW170817: The First Double NS merger, KITP Santa Barbara, Dec 5-8, 2017

BNS merger phenomenology


NS—NS

SMNS / HMNS

long-lived NS

prompt collapse

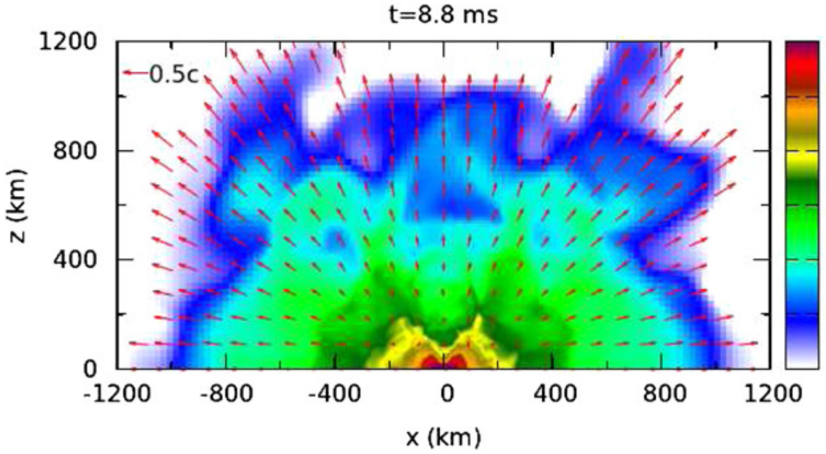
BH - torus

BH - torus

Outcome depends on EOS and binary parameters
(masses, mass ratio, spin, …)

Sources of ejecta in BNS mergers

dynamical ejecta (~ms)



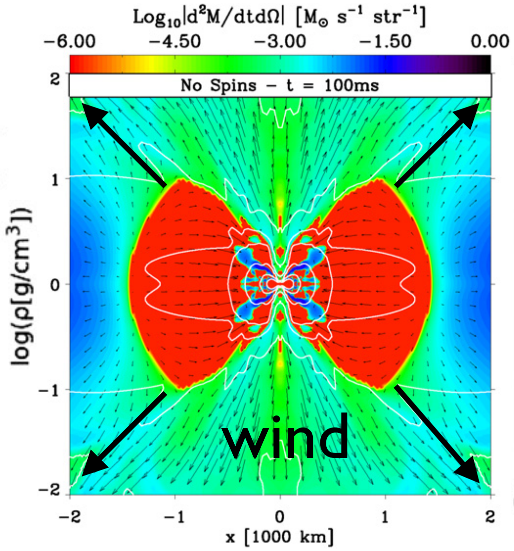
Hotokezaka+ 2013
Bauswein+ 2013

tidal ejecta
shock-heated ejecta

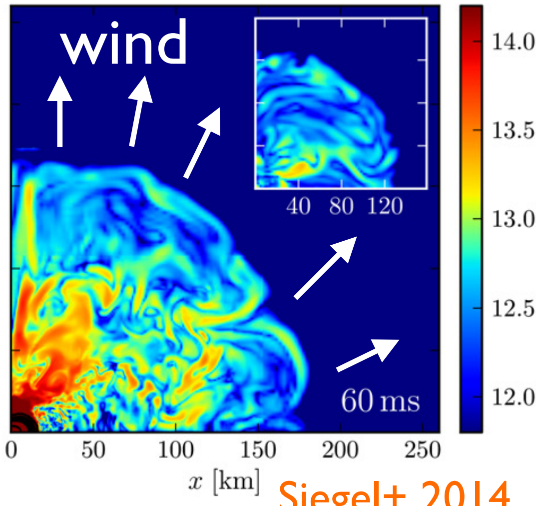
$M_{\rm tot} \lesssim 10^{-3} {\rm M}_\odot$

$v \gtrsim 0.2c$

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



Dessart+ 2009



Siegel+ 2014
Ciolfi, Siegel+ 2017

neutrino-driven wind

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

magnetically driven wind

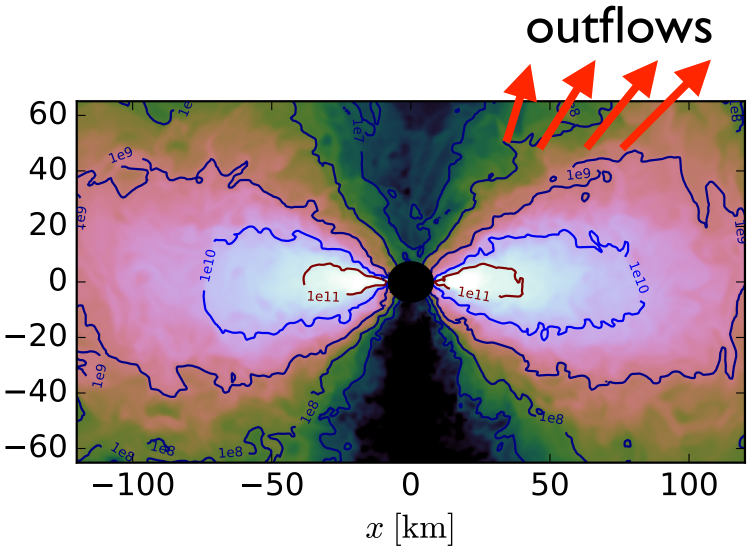
$\dot{M}_{\rm in} \sim (10^{-3} - 10^{-2}) {\rm M}_\odot {\rm s}^{-1}$

viscous ejecta

Shibata+ 2017
Radice 2017

$v \lesssim 0.1c$

accretion disk (~10ms-1s)



Siegel & Metzger 2017 a,b

thermal outflows
from accretion disk

$M_{\rm tot} \gtrsim 0.3 - 0.4 M_{\rm disk}$

$v \sim 0.1c$

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 a,b

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

lower limit

The kilonova of GW170817

- blue kilonova properties:

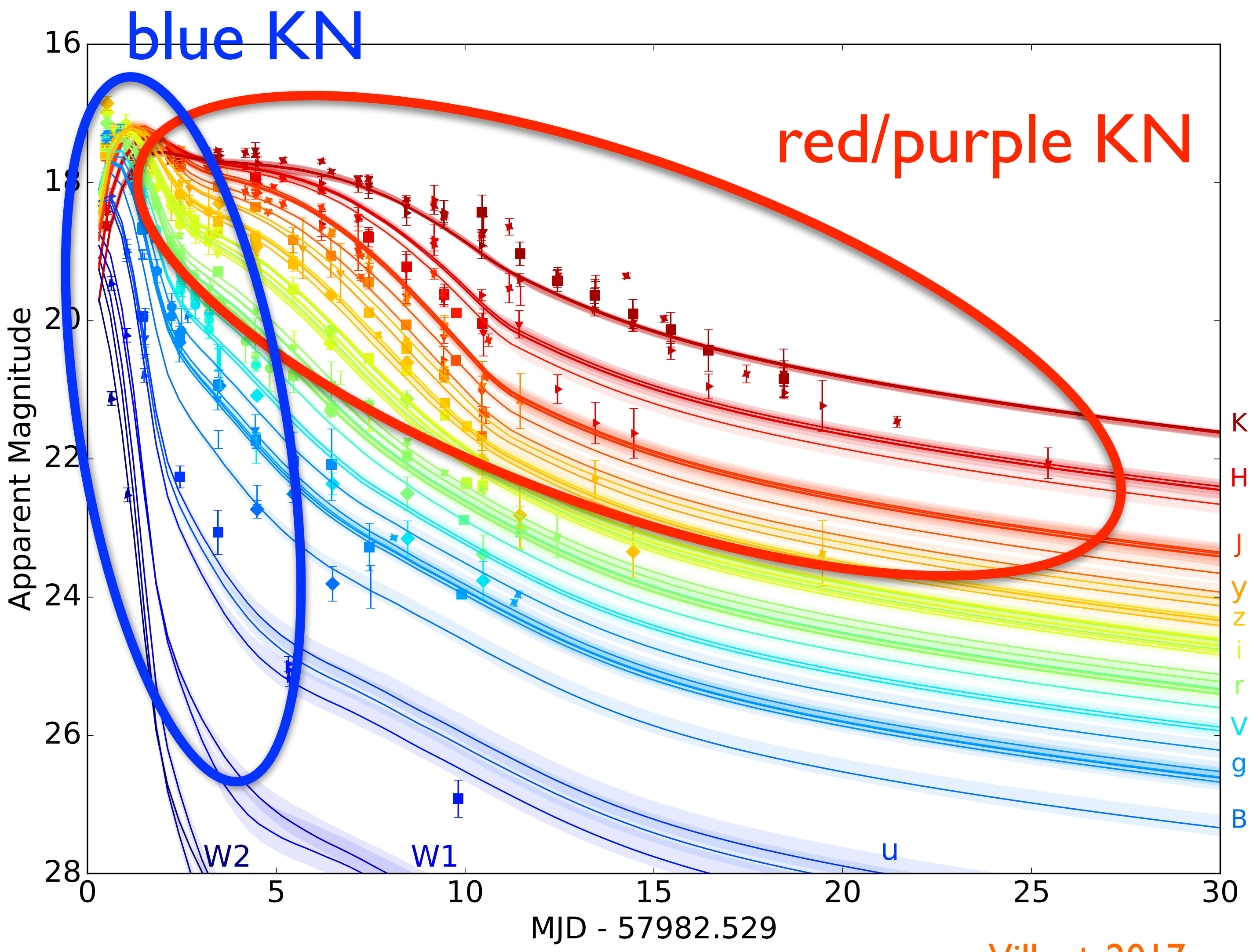
$M_{ej} \sim 10^{-2} M_{sun}$
$v_{ej} \sim 0.2\text{-}0.3c$
$Y_e > 0.25$
$X_{La} < 10^{-4}$

Kilpatrick+ 2017
Kasen+ 2017
Nicholl+ 2017
Villar+ 2017

- red/purple kilonova properties:

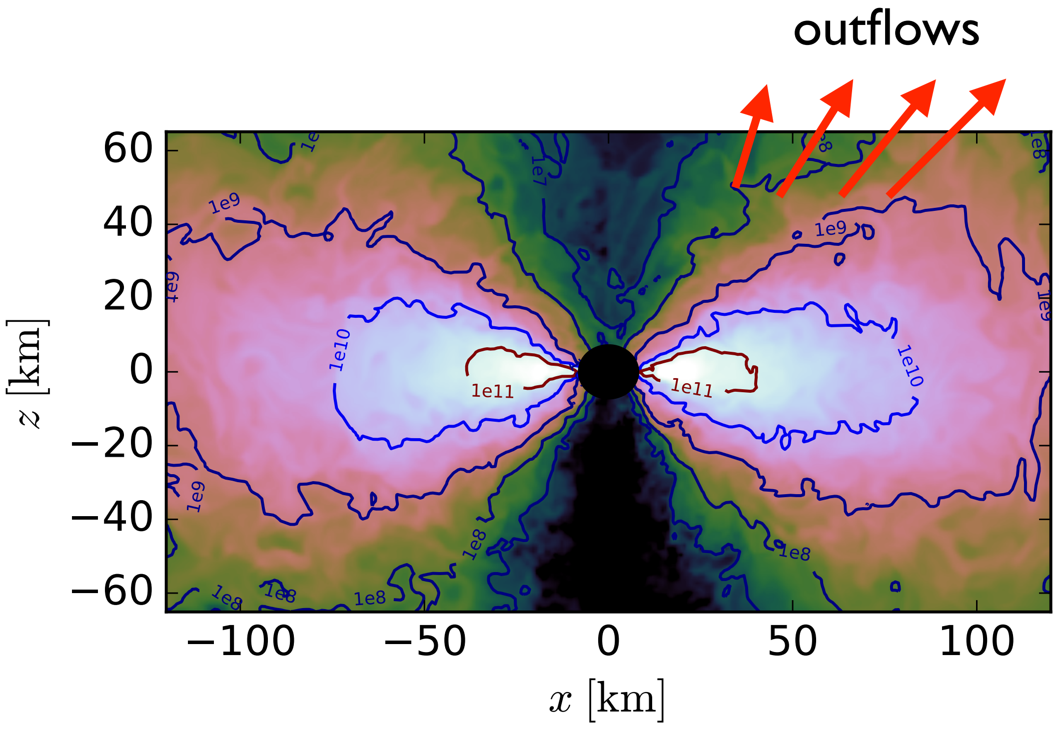
$M_{ej} \sim 4\text{-}5 \times 10^{-2} M_{sun}$
$v_{ej} \sim 0.08\text{-}0.14c$
$Y_e < 0.25$
$X_{La} \sim 0.01$

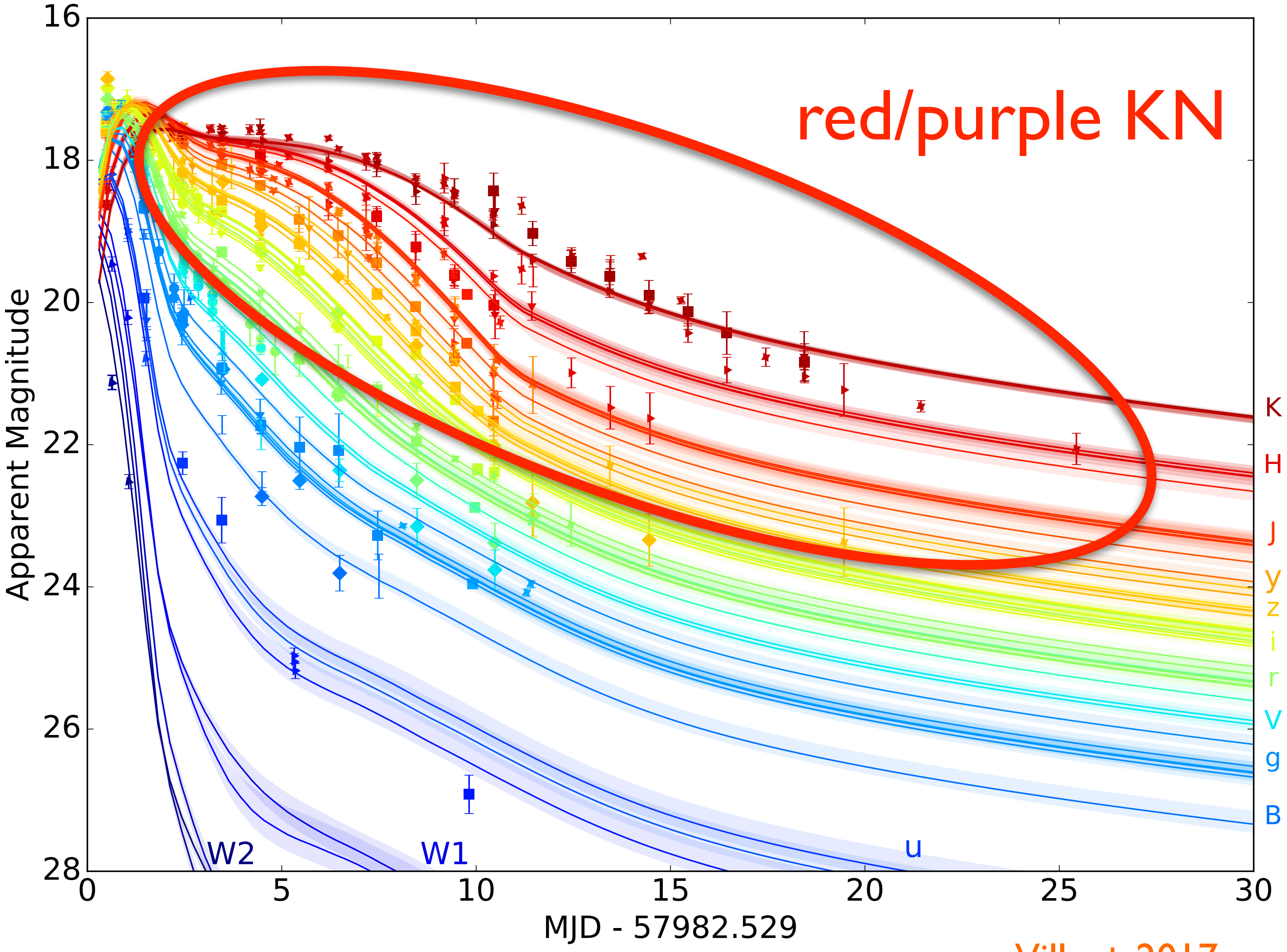
Kilpatrick+ 2017
Kasen+ 2017
Kasliwal+ 2017
Drout+ 2017
Cowperthwaite+ 2017
Chornock+ 2017
Villar+ 2017



Villar+ 2017

The kilonova of GW170817





Villar+ 2017

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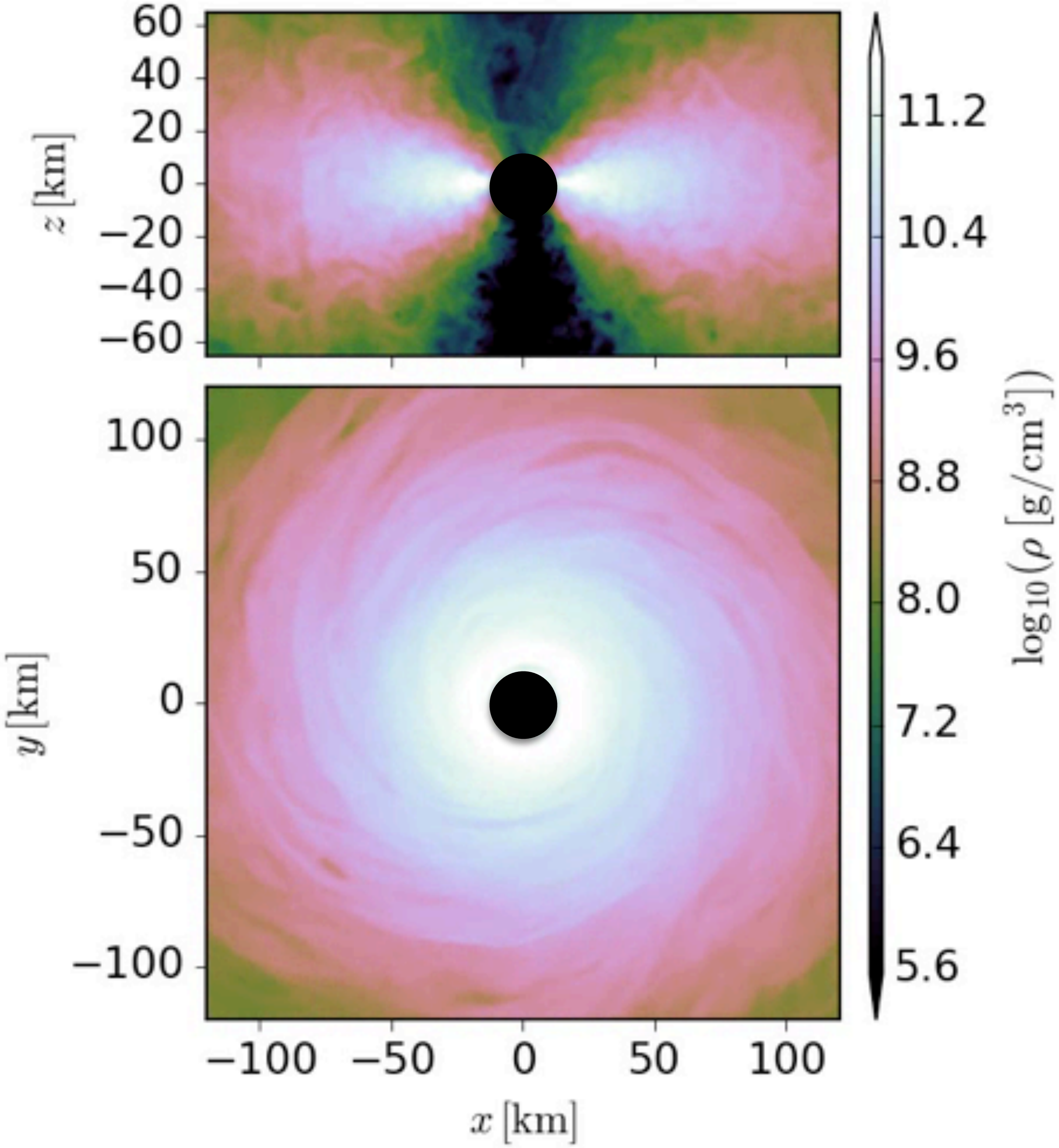
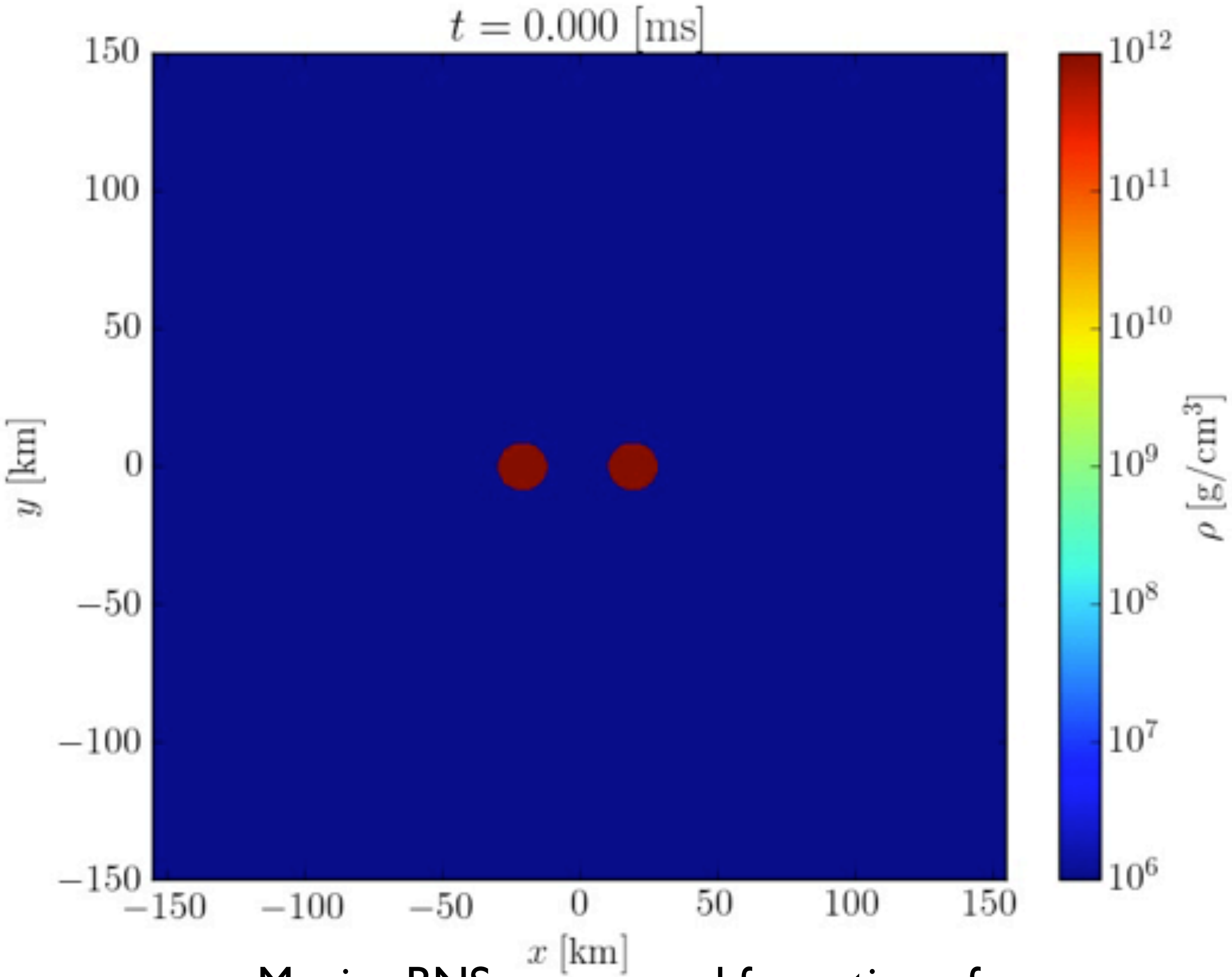
BNS post-merger accretion disks





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

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

Radice+ 2016

Siegel & Metzger 2017a, PRL Siegel & Metzger 2017b

Disk simulations: numerical setup

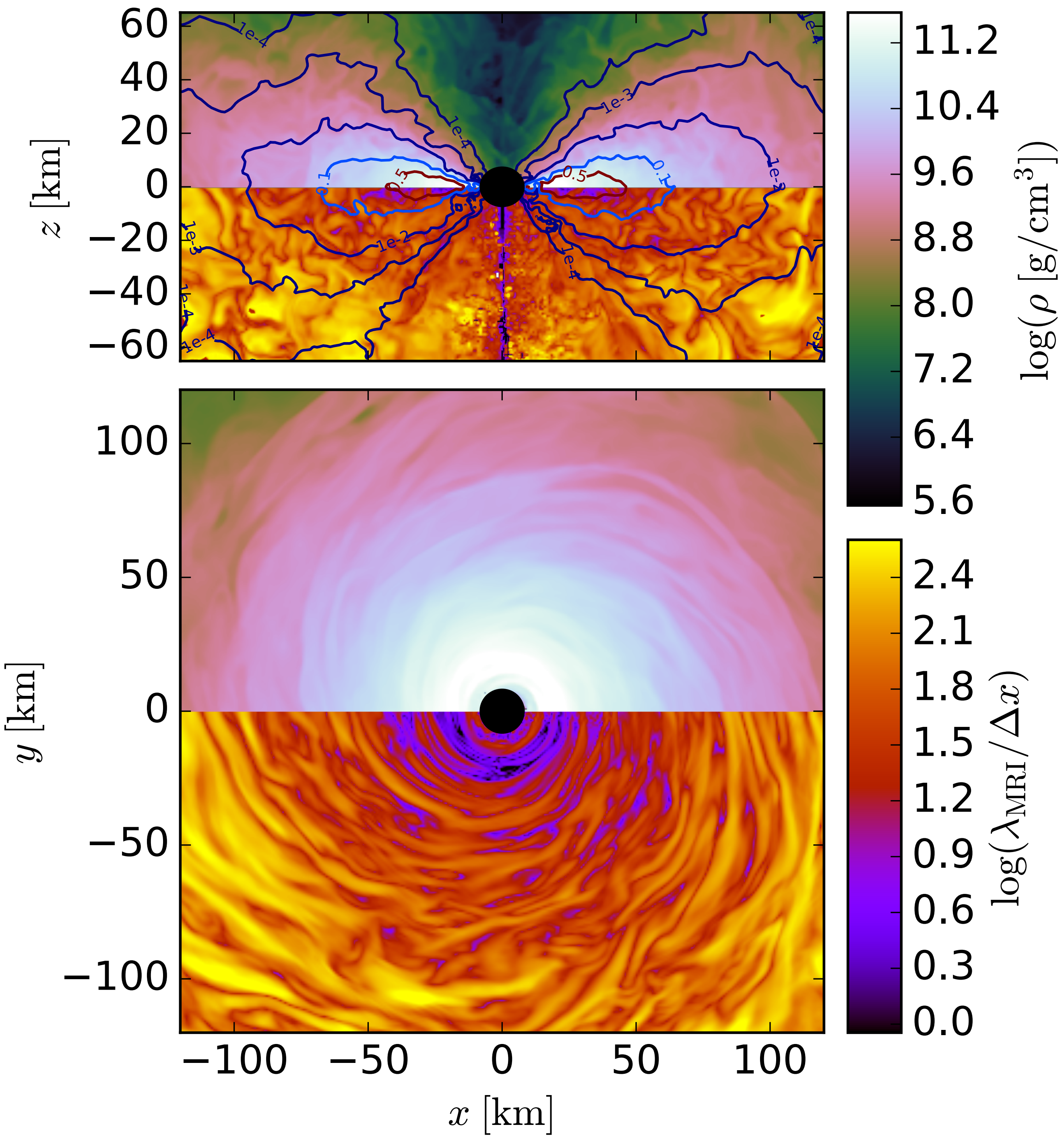


Fig.: disk properties; contours: optical depth for electron neutrinos

Siegel & Metzger 2017a, PRL Siegel & Metzger 2017b

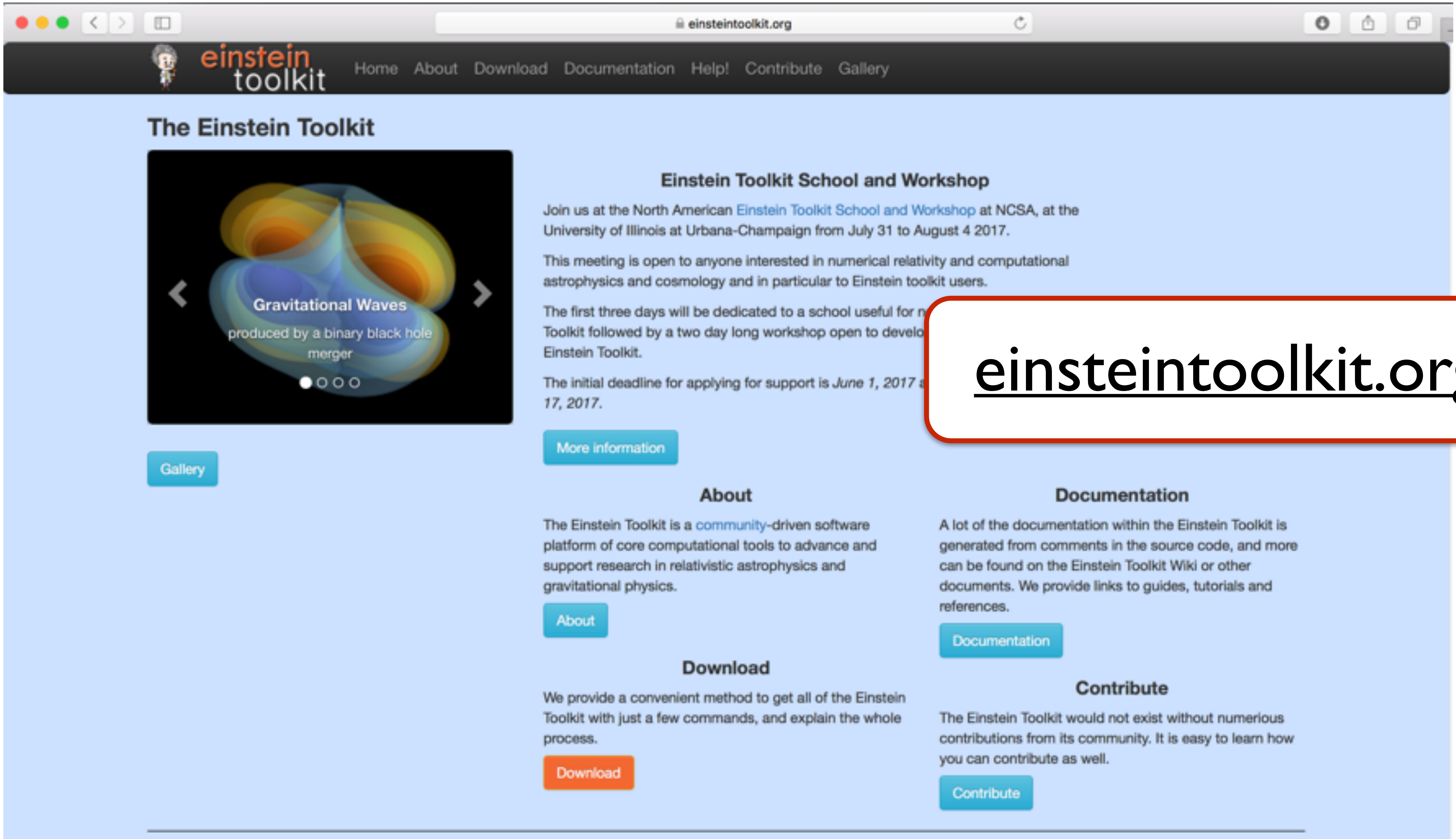
First self-consistent simulations modeling r-process nucleosynthesis from disk outflows from first principles:

- GRMHD: magnetic instabilities (MRI) mediating turbulence (transport of angular momentum) in the disk (*Einstein Toolkit, GRHydro*; Loeffler+ 2012, Moesta+ 2014)
- weak interactions in GRMHD
- 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
Fernandez+ 2015
Fernandez+ 2017
Just+ 2015

GRHydro: part of the Einstein Toolkit



The Einstein Toolkit

Einstein Toolkit School and Workshop

Join us at the North American Einstein Toolkit School and Workshop at NCSA, at the University of Illinois at Urbana-Champaign from July 31 to August 4 2017.

This meeting is open to anyone interested in numerical relativity and computational astrophysics and cosmology and in particular to Einstein toolkit users.

The first three days will be dedicated to a school useful for n Toolkit followed by a two day long workshop open to develo Einstein Toolkit.

The initial deadline for applying for support is *June 1, 2017 a 17, 2017.*

About

The Einstein Toolkit is a community-driven software platform of core computational tools to advance and support research in relativistic astrophysics and gravitational physics.

Documentation

A lot of the documentation within the Einstein Toolkit is generated from comments in the source code, and more can be found on the Einstein Toolkit Wiki or other documents. We provide links to guides, tutorials and references.

Download

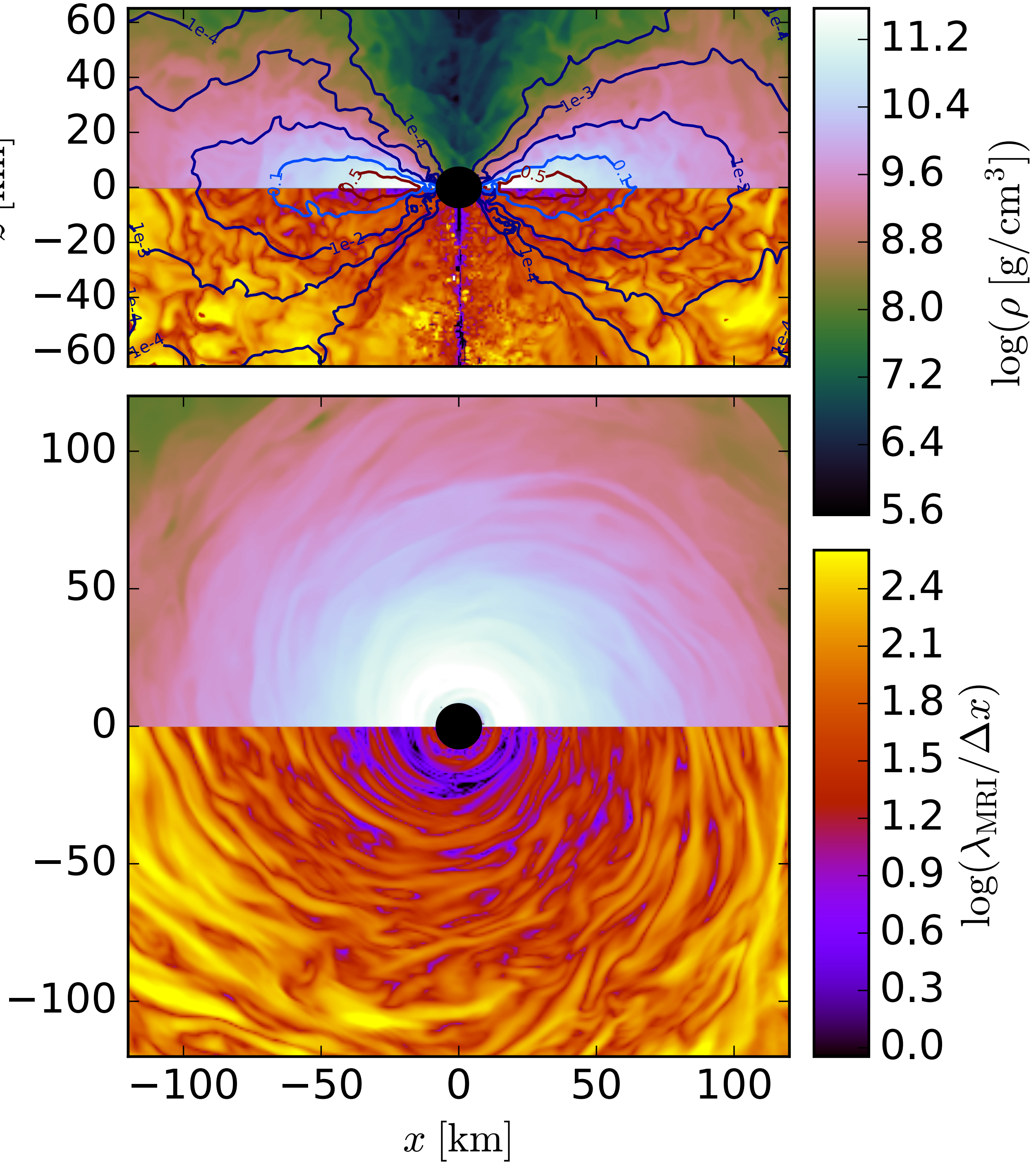
We provide a convenient method to get all of the Einstein Toolkit with just a few commands, and explain the whole process.

Contribute

The Einstein Toolkit would not exist without numerious contributions from its community. It is easy to learn how you can contribute as well.

einsteintoolkit.org

Disk simulations: numerical setup



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MHD turbulence

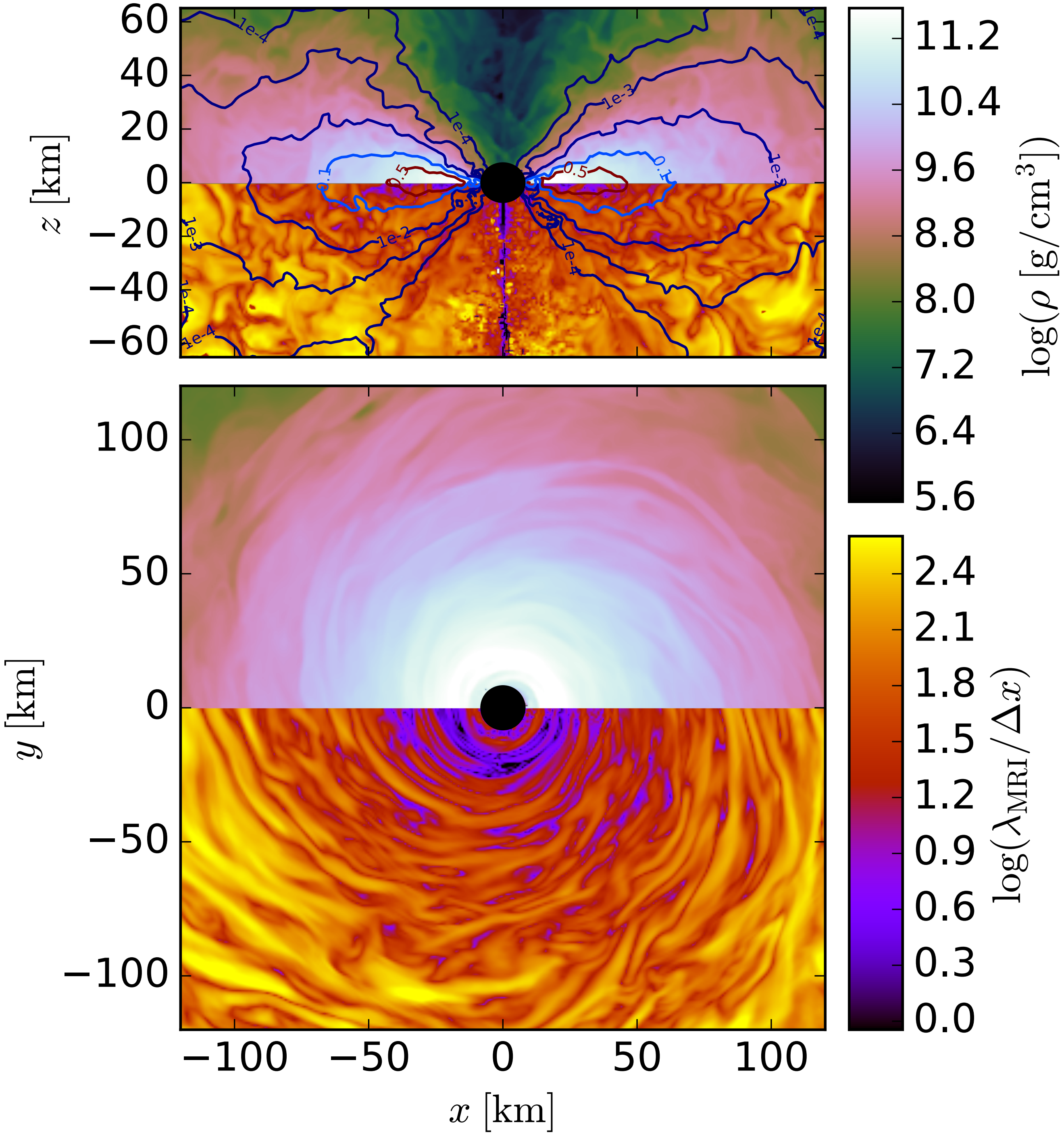


Fig.: disk properties; contours: optical depth for electron neutrinos

Siegel & Metzger 2017a, PRL Siegel & Metzger 2017b

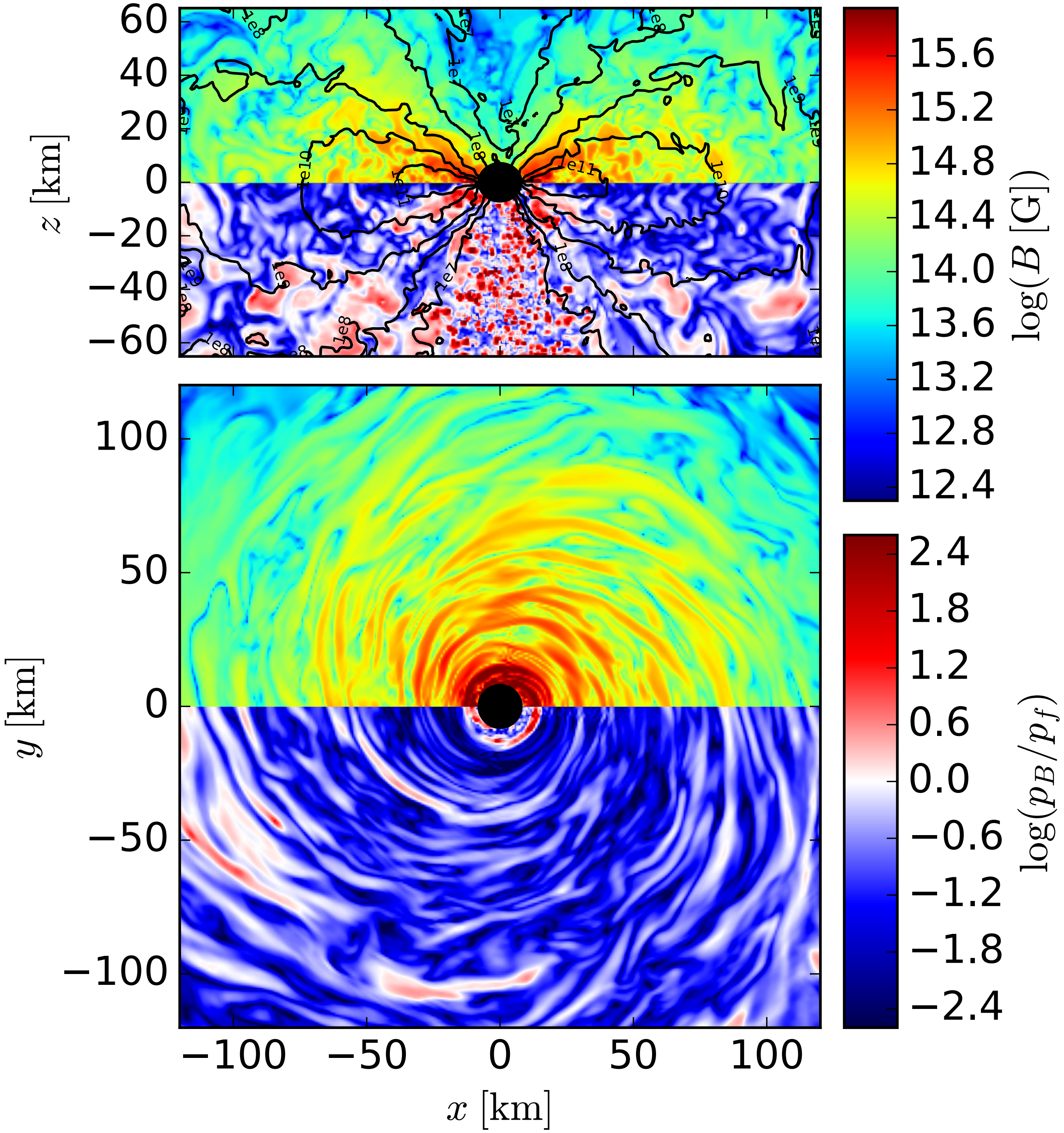
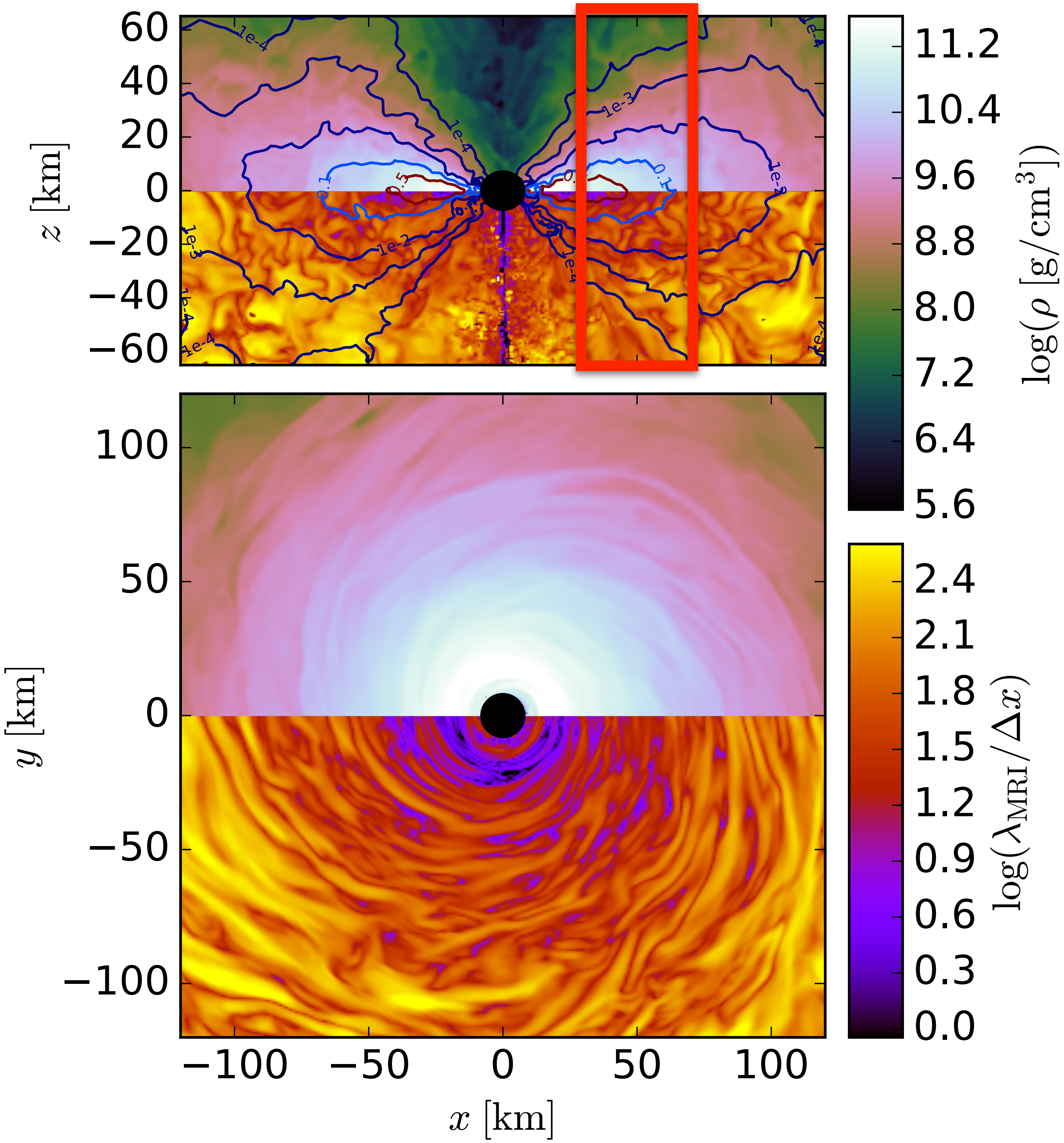


Fig.: magnetic fields in the disk; contours: rest-mass density

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

MHD turbulence

average radially for space-time diagram



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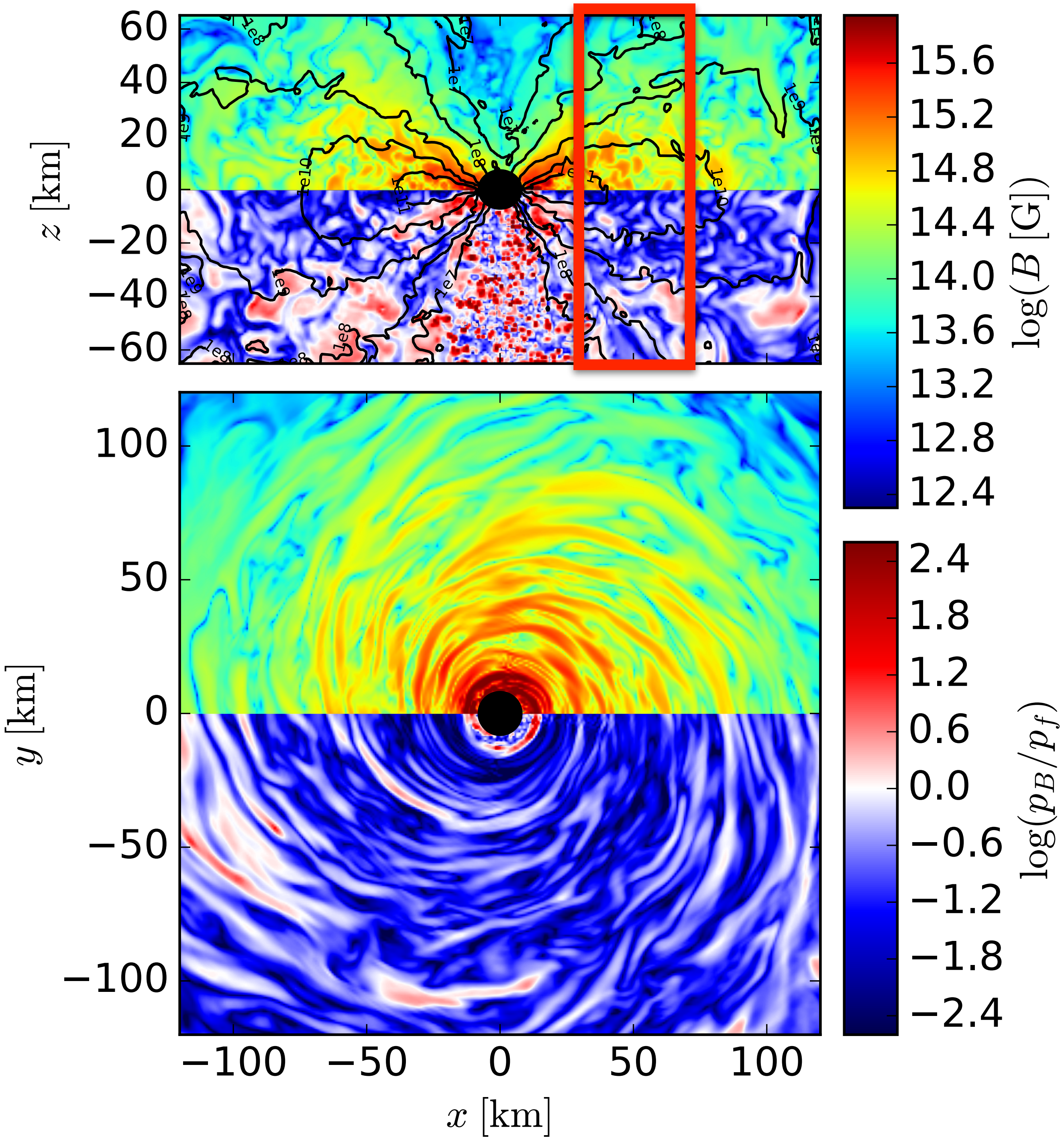
Siegel & Metzger 2017a, PRL

Siegel & Metzger 2017b



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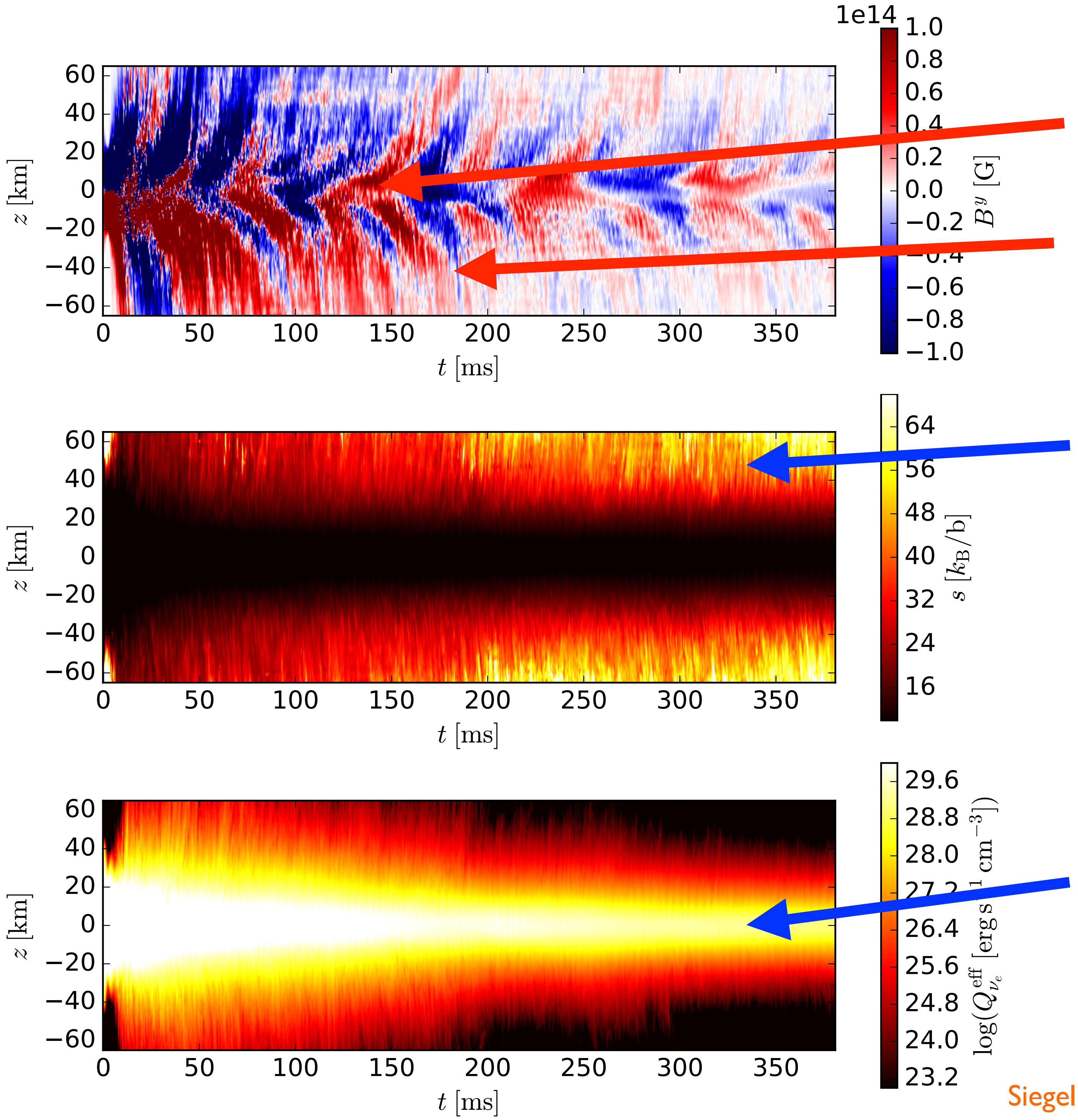
Accretion disk dynamo: butterfly diagram



magnetic energy is generated in the mid-plane

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

→“hot corona”

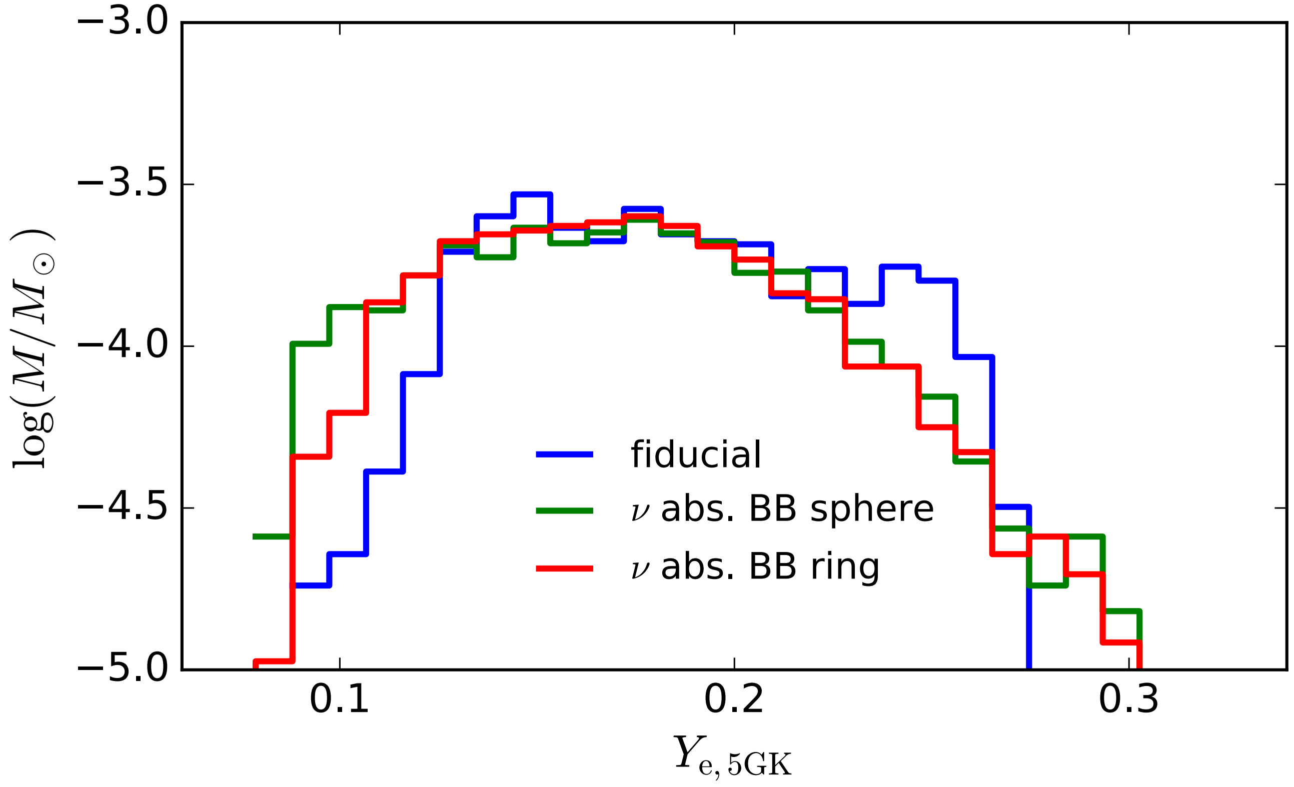
hot corona launches thermal outflows (neutron-rich wind)

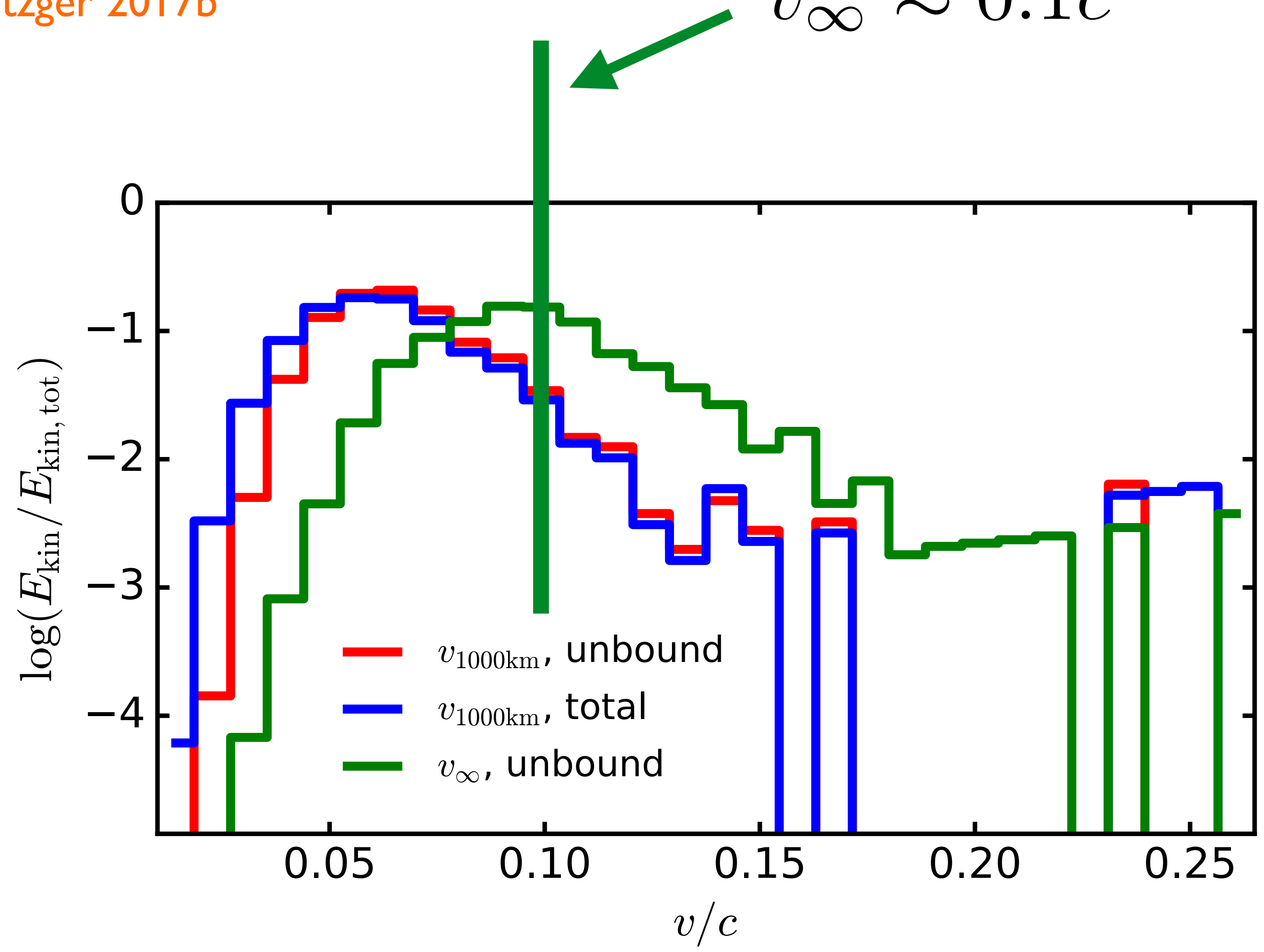
NS post-merger accretion disk are cooled from the mid-plane by neutrinos (rather than from the EM photosphere)!

Siegel & Metzger 2017b

Disk outflows

Siegel & Metzger 2017b





$v_\infty \approx 0.1c$

composition

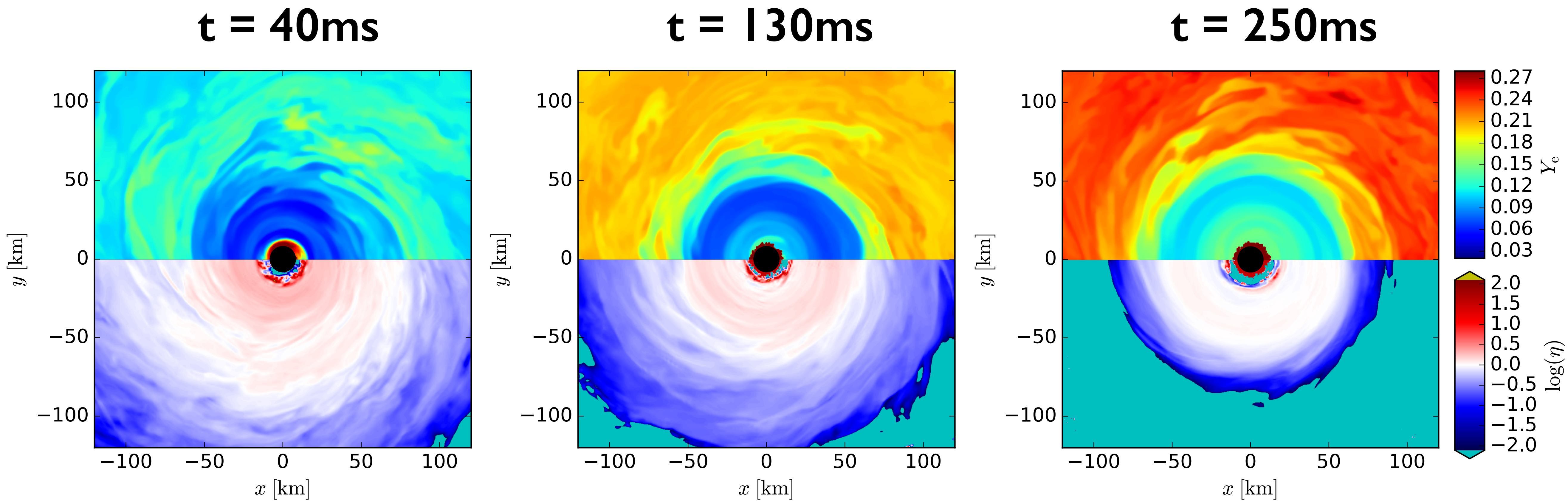
$$Y_{\rm e} \approx 0.1 - 0.3$$

ejecta velocities

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

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

Why are the disk outflows neutron-rich?



Siegel & Metzger 2017b

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

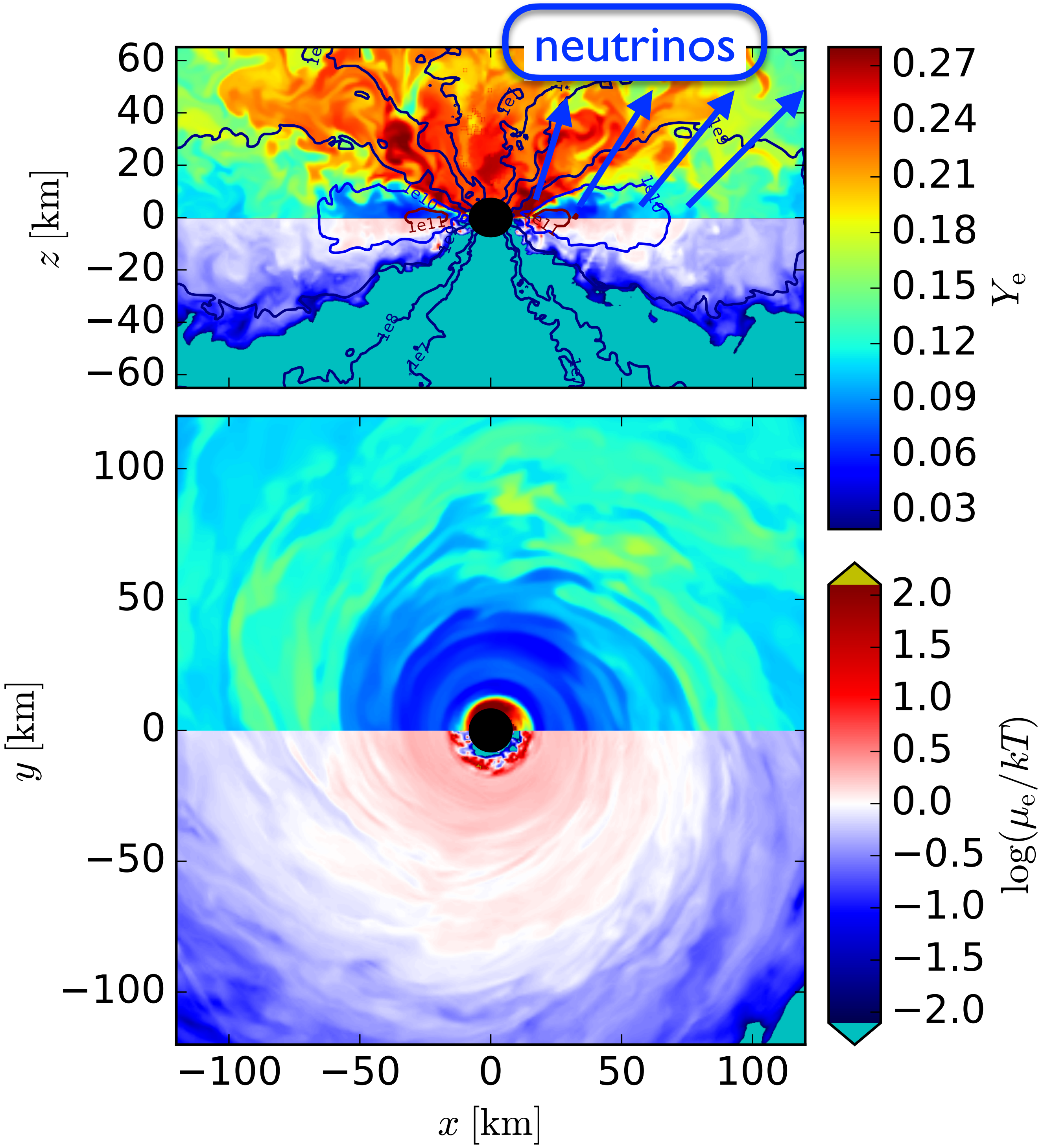


Fig.: disk properties; contours: rest-mass density

Siegel & Metzger 2017a, PRL   Siegel & Metzger 2017b

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:

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

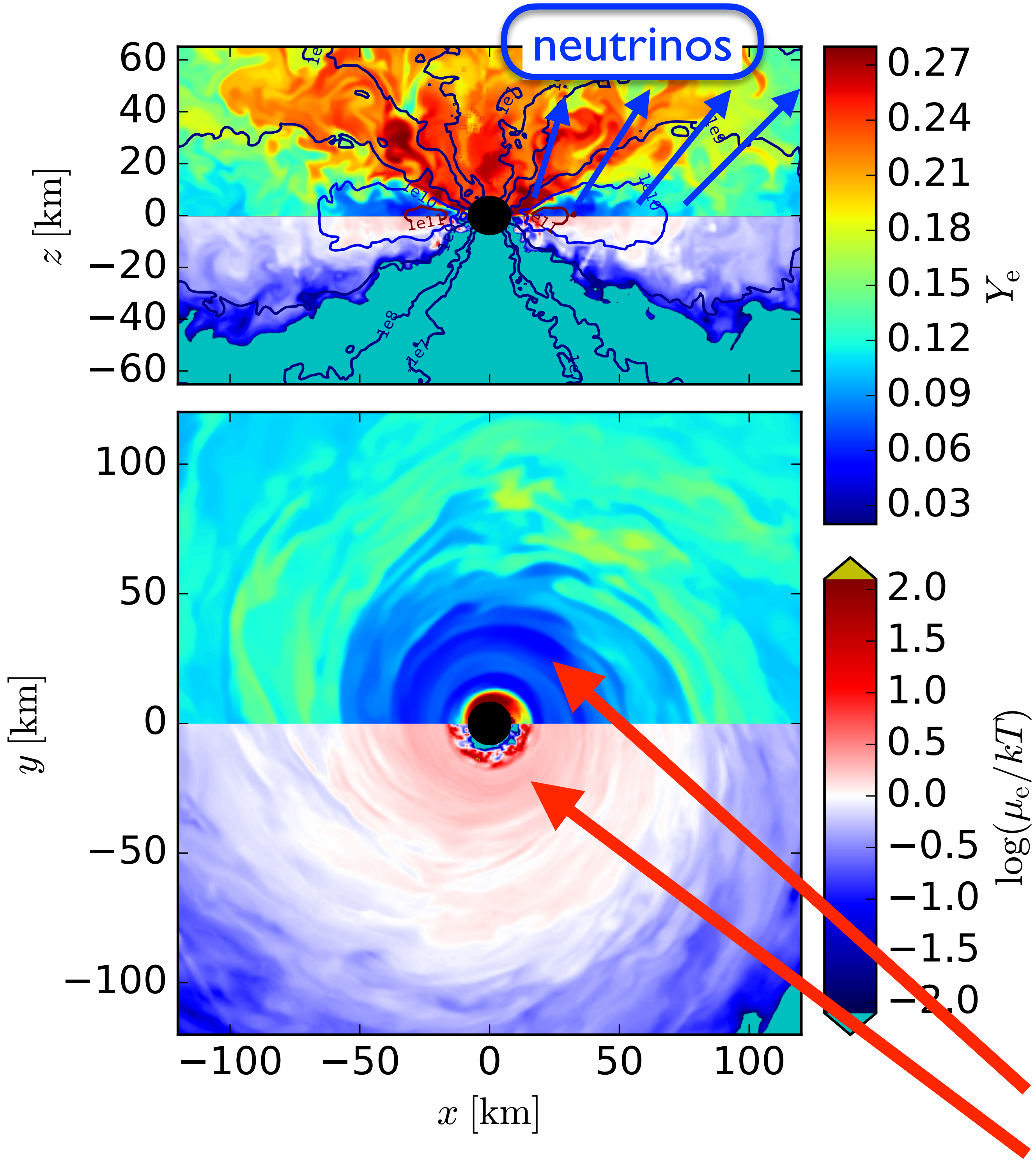
$$e^- + e^+ \rightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$$

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



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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)

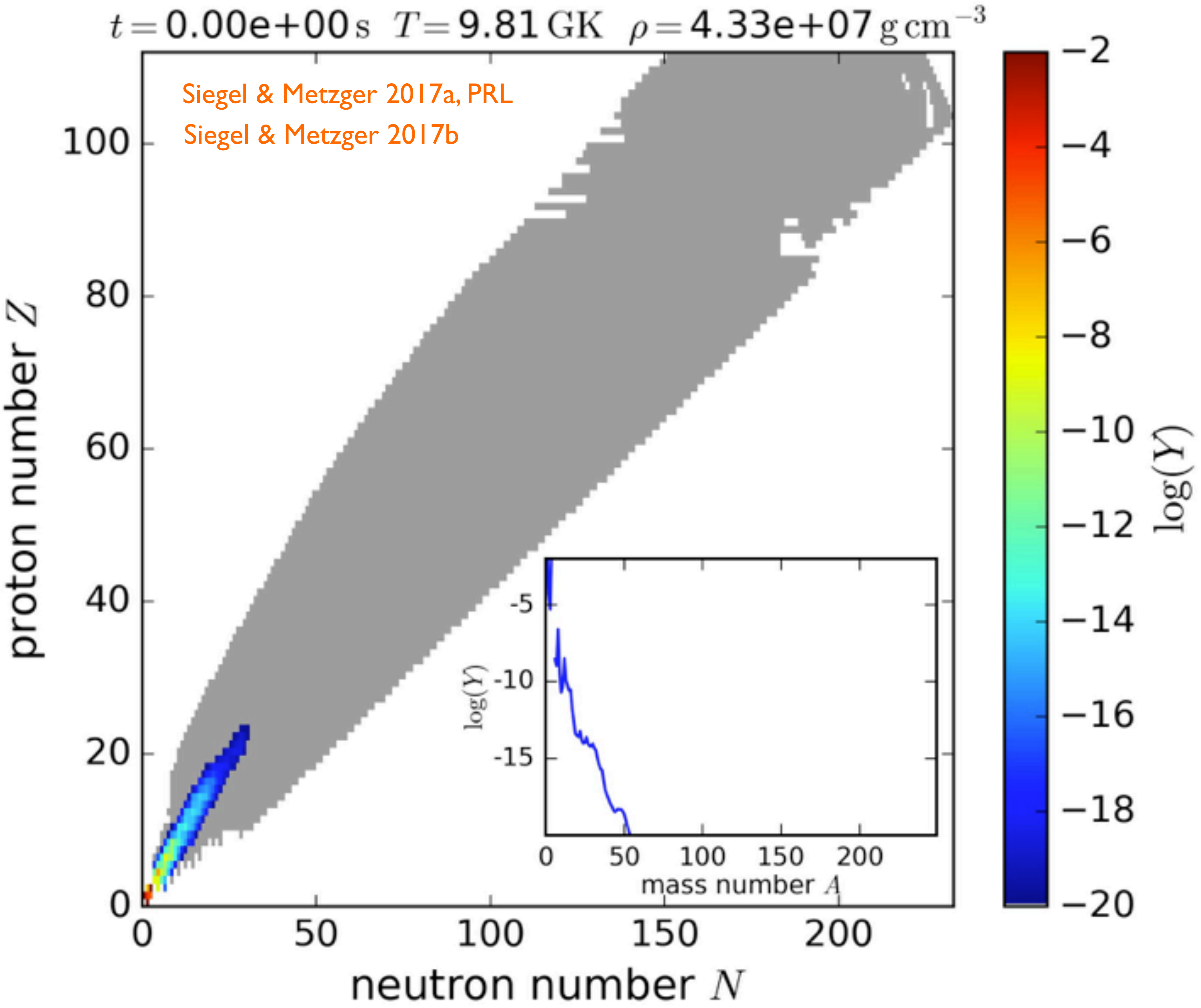
less neutrino emission, i.e., cooling

higher temperatures

lower degeneracy μ_e/kT

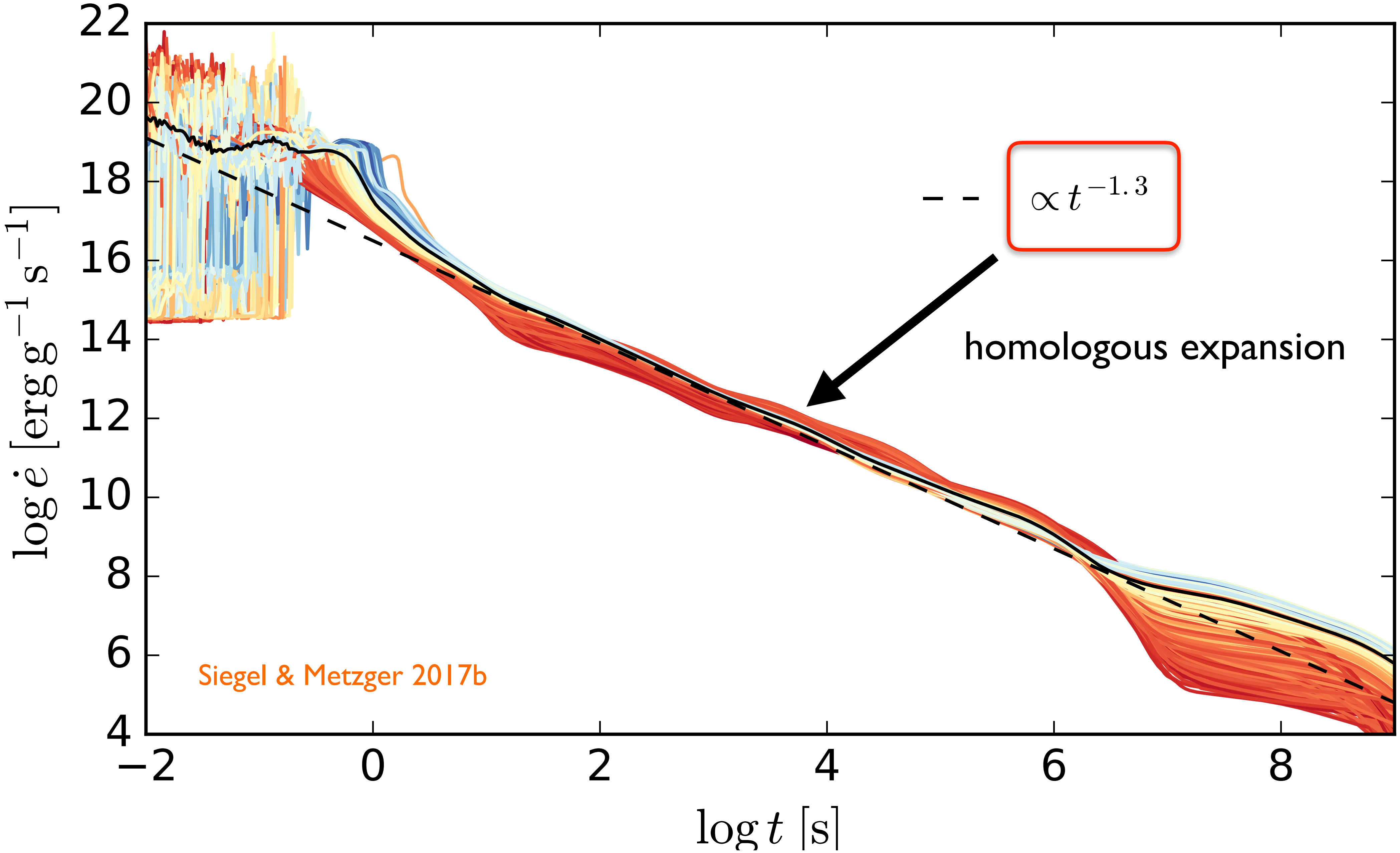
direct evidence of self-regulation

The origin of heavy nuclei: r-process nucleosynthesis



Movie: r-process nucleosynthesis from NS merger remnant disks

r-process heating rates



$\propto t^{-1.3}$

homologous expansion

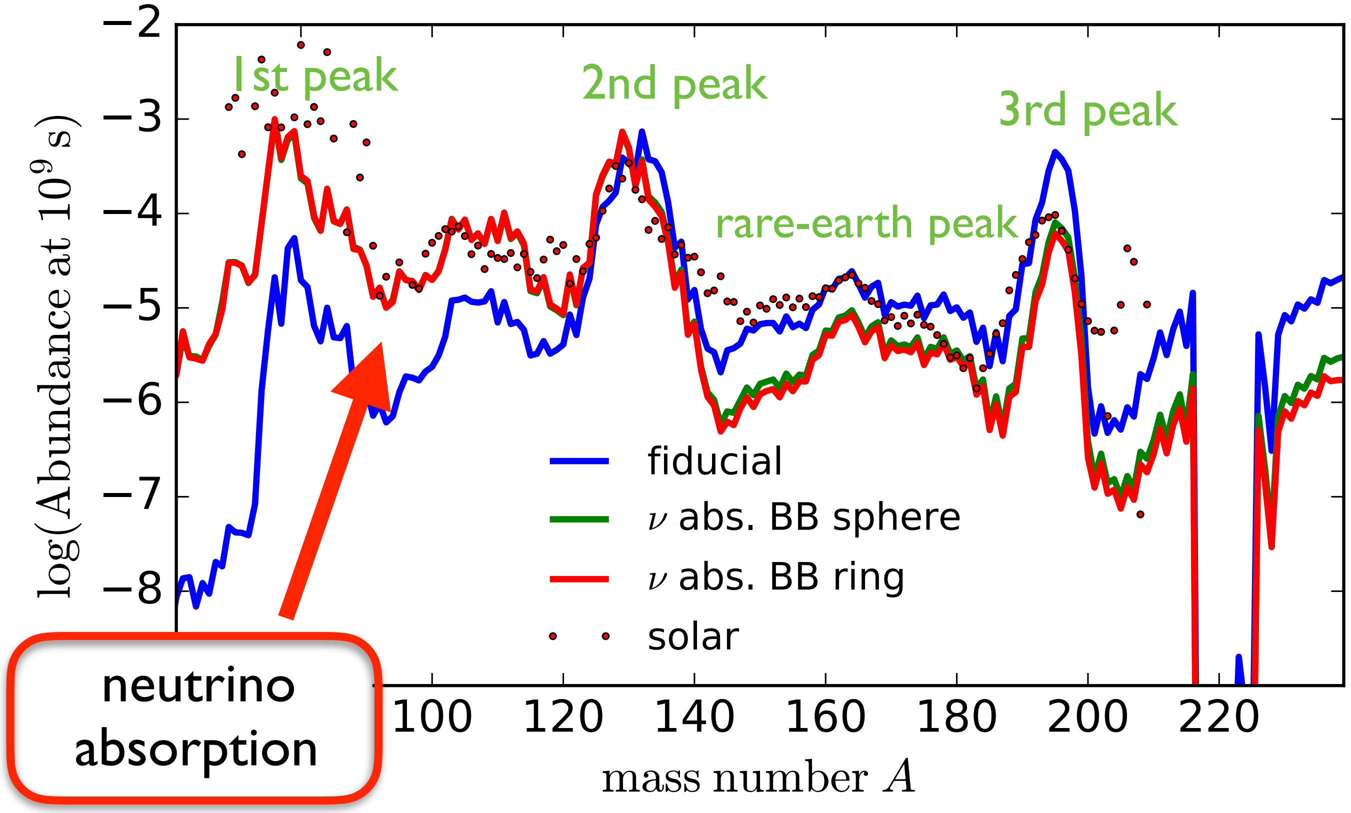
Siegel & Metzger 2017b

Fig: heating rates from r-process nucleosynthesis in disk outflows

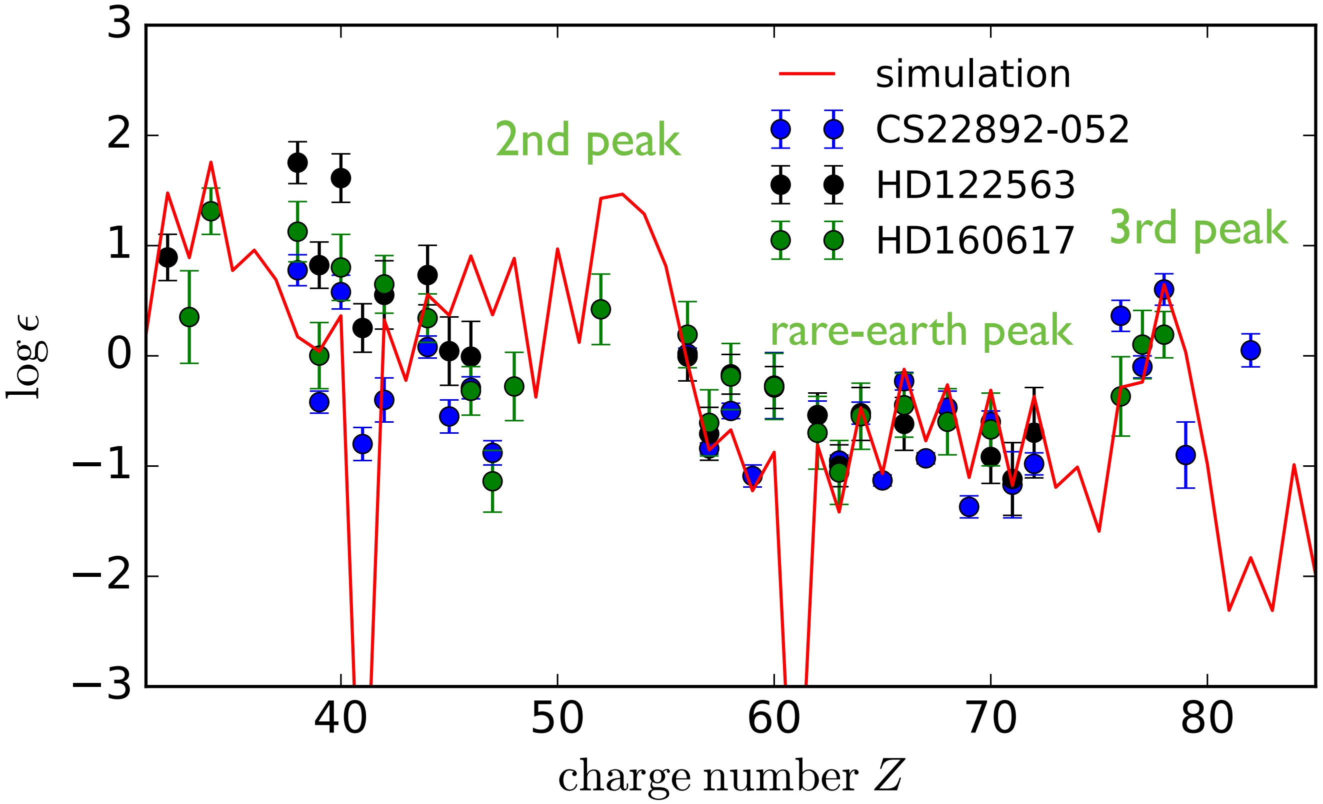
r-process nucleosynthesis

Siegel & Metzger 2017a, PRL

Siegel & Metzger 2017b



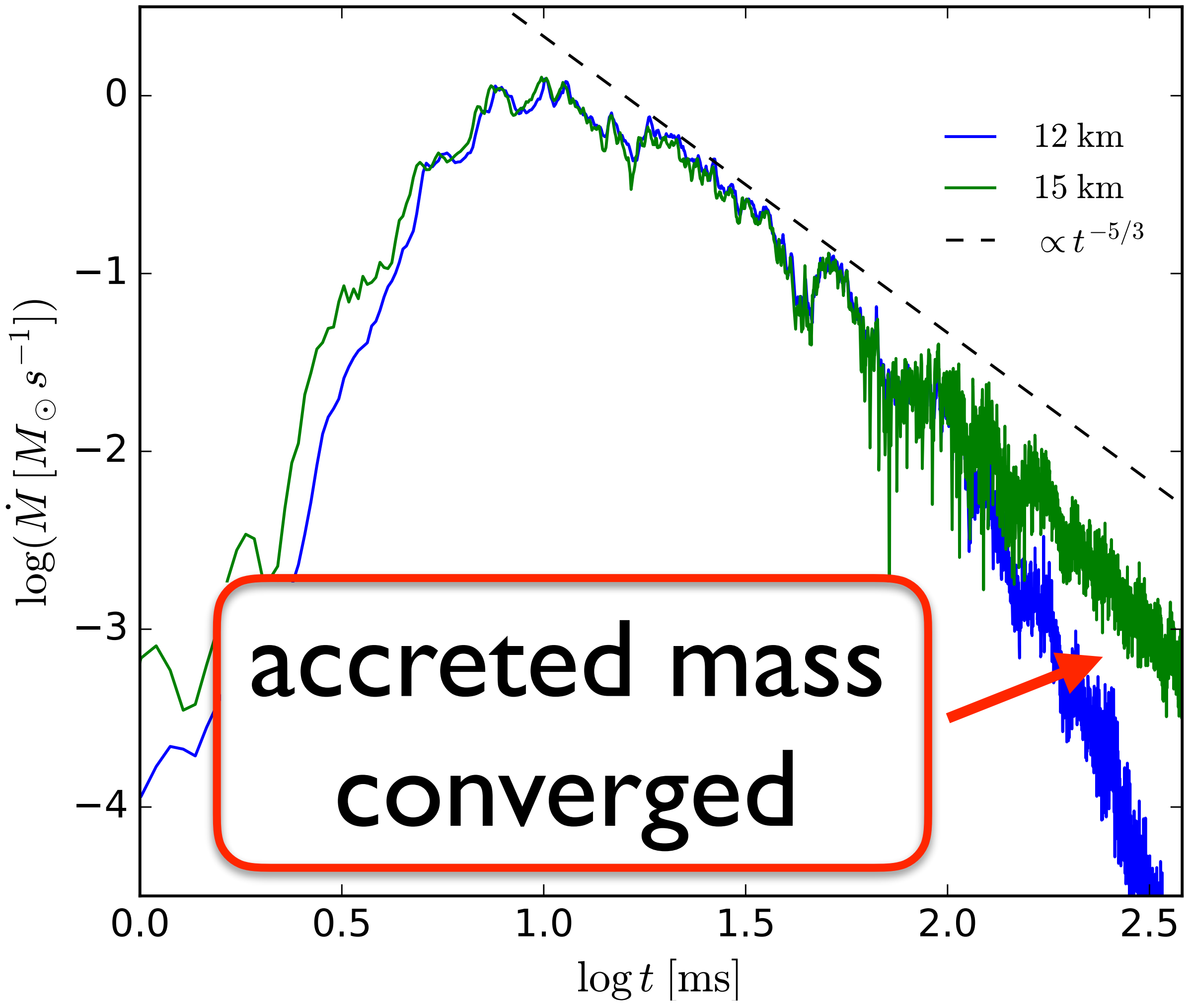
neutrino absorption



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

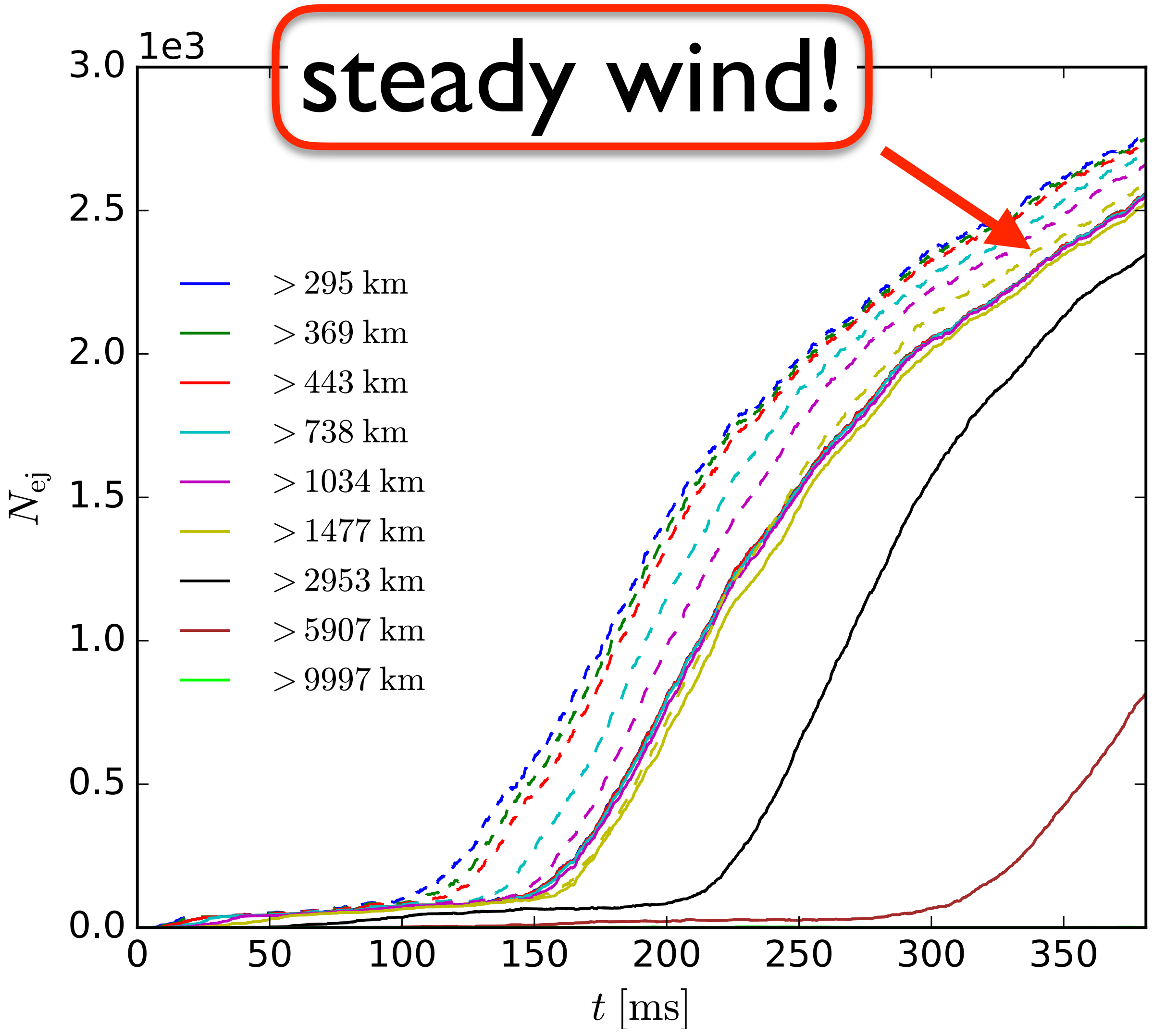
→ production of all r-process elements!

BH accretion vs. disk outflows



accreted mass converged

Fig.: accretion rate onto the BH



steady wind!

Fig.: number of tracer particles outside a given radius

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

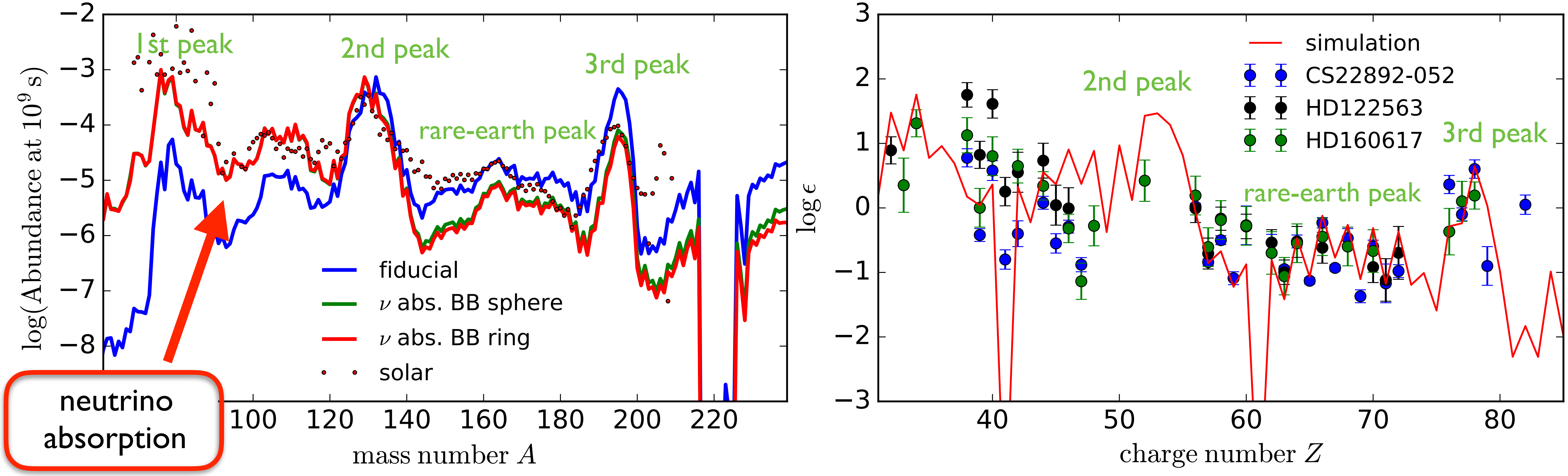
→ remaining disk mass likely unbound

→ difficult to launch jet at late times (> 200ms)

r-process nucleosynthesis

Siegel & Metzger 2017a, PRL

Siegel & Metzger 2017b



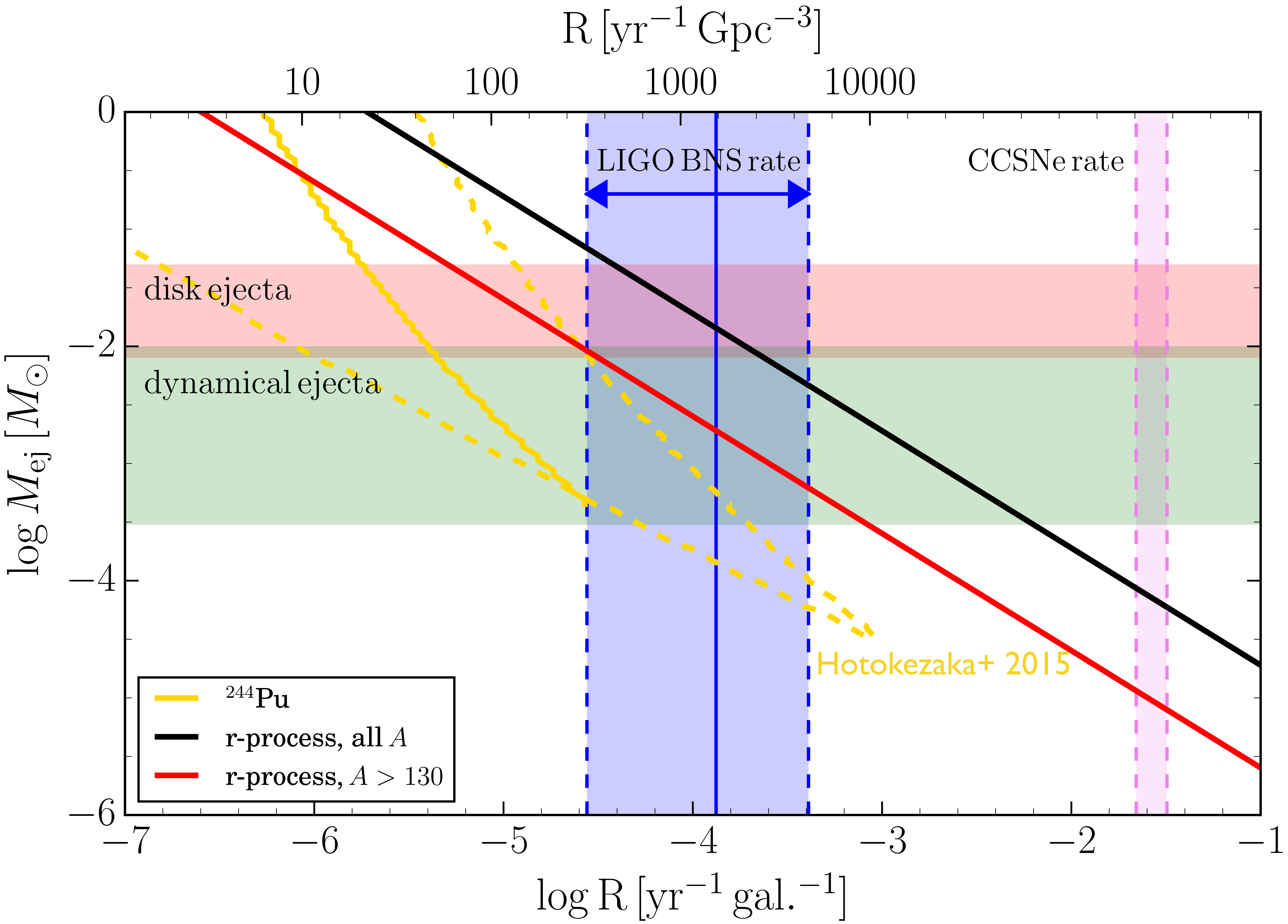
neutrino absorption

Total ejected r-process material: $\boxed{0.3 - 0.4\, M_{\rm disk}}$

$$\gtrsim 10^{-2}\left(\frac{f_{\rm ej}}{0.35}\right)\left(\frac{M_{\rm disk}}{3\times 10^{-2}M_\odot}\right)M_\odot$$

$10^{-2}\, M_\odot$ robust lower limit

Constraints on r-process nucleosynthesis



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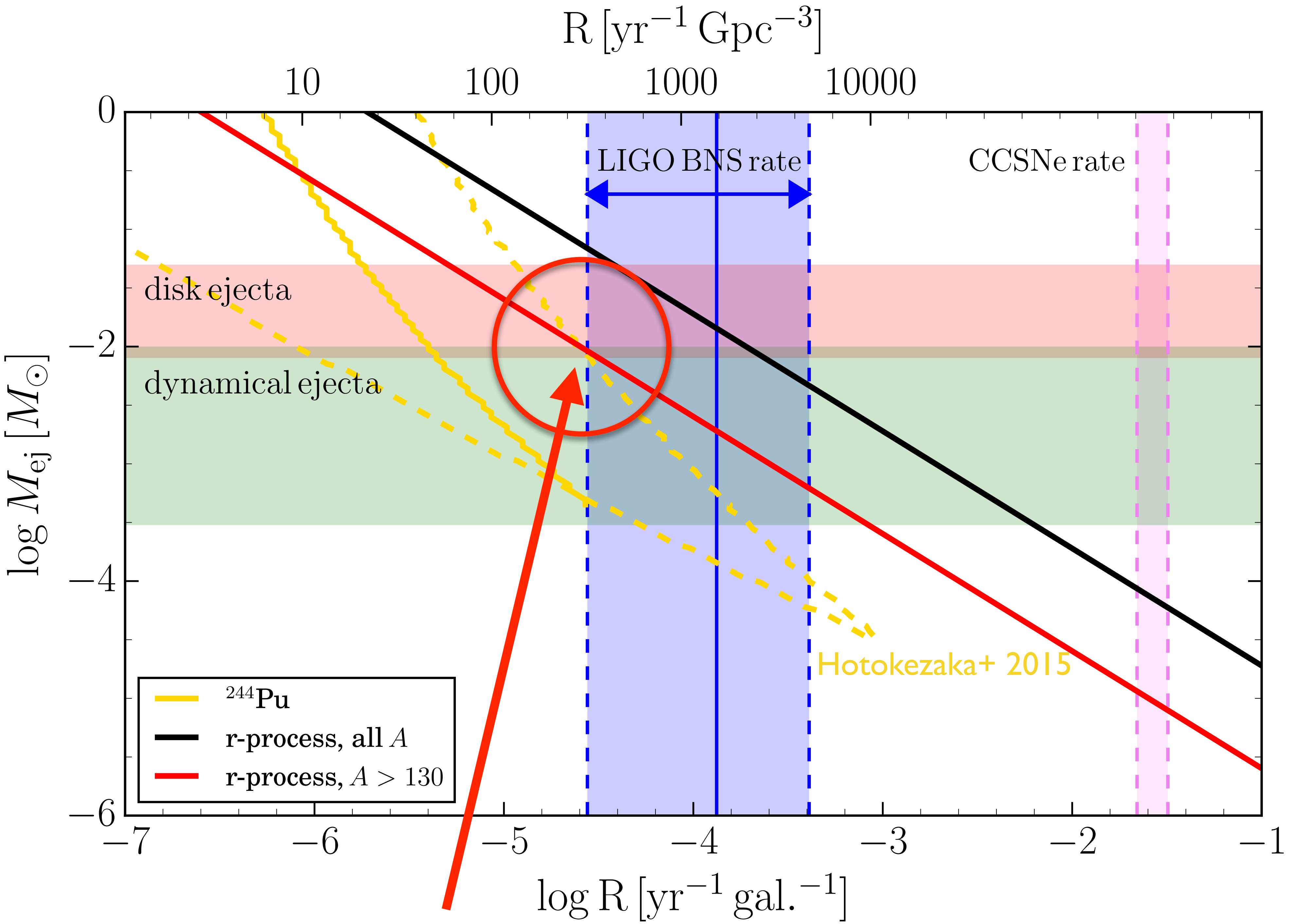
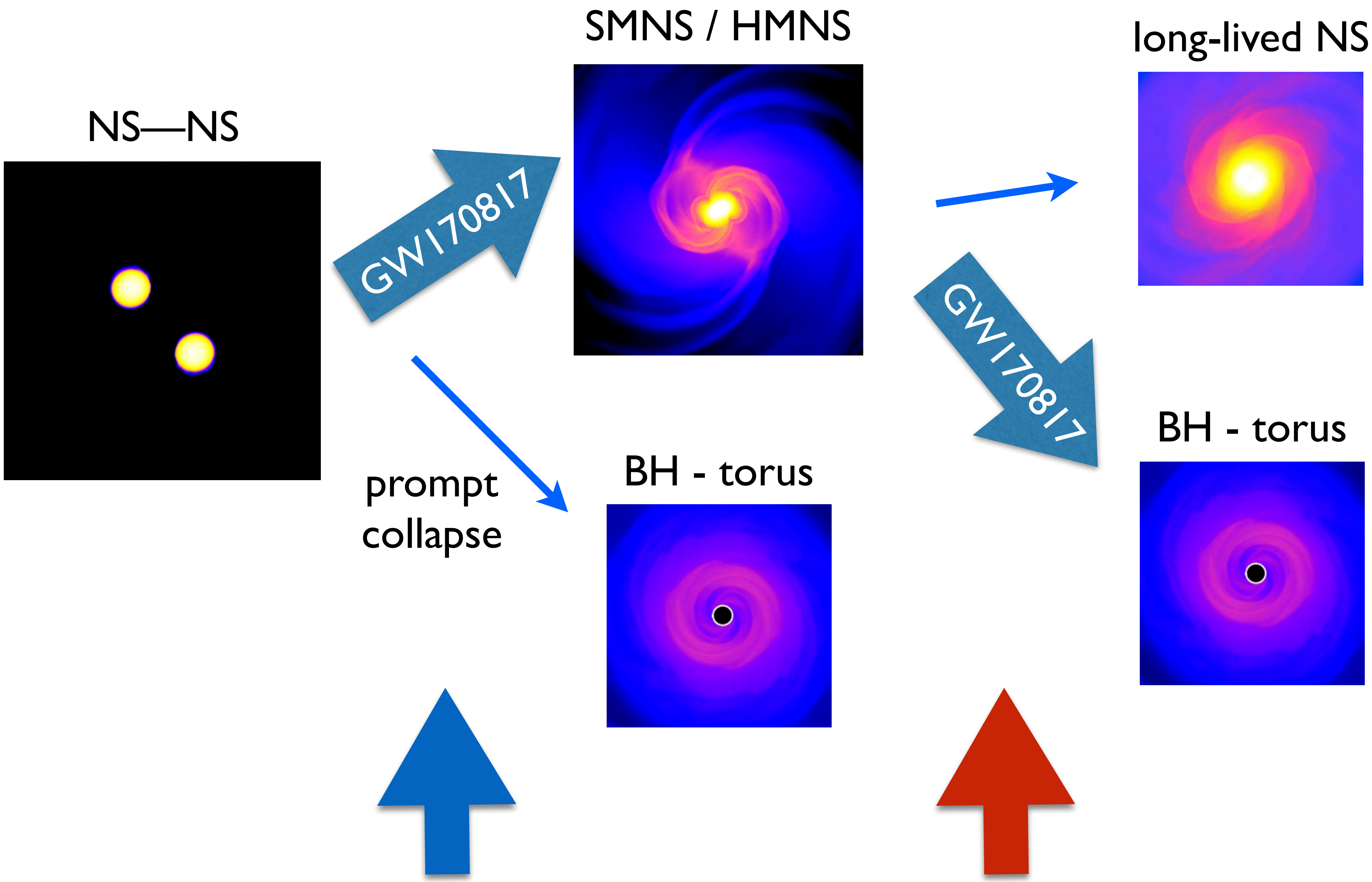


post-merger disk outflows are a promising site for the r-process

Conclusions



NS—NS

GW170817

SMNS / HMNS

long-lived NS

GW170817

prompt
collapse

BH - torus

BH - torus

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

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

Margalit &
Metzger 2017

Conclusions

Disk winds (secular, ~100ms):

- hot corona launches thermal outflows
- self-regulation keeps Ye low
- Neutrino irradiation crucial for KN and detailed abundances
- likely dominant source of ejecta in NS mergers ($\gtrsim 10^{-2}\,M_\odot$)
- slower than dynamical ejecta (~0.1c)
- may explain red KN in GW170817
- disk winds and their KN signal should be ubiquitous in NS mergers
- Relative abundances, total ejecta mass, merger rate

  → NS mergers promising prime production site for the r-process