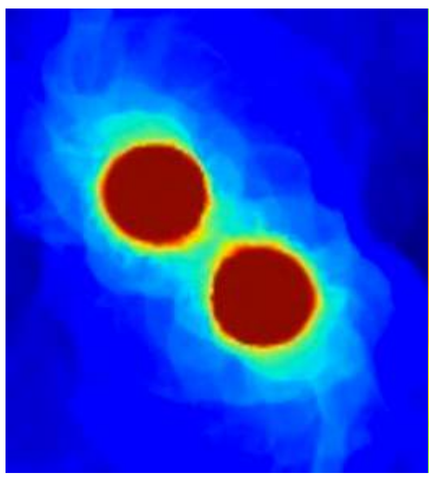
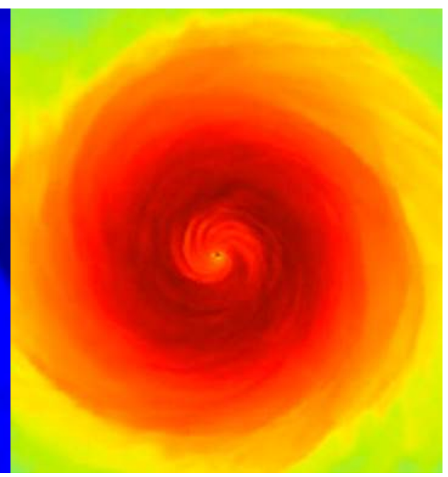
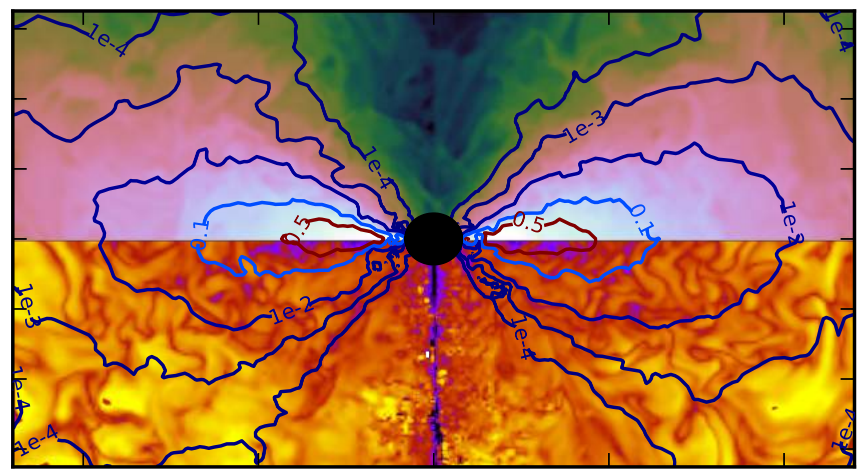
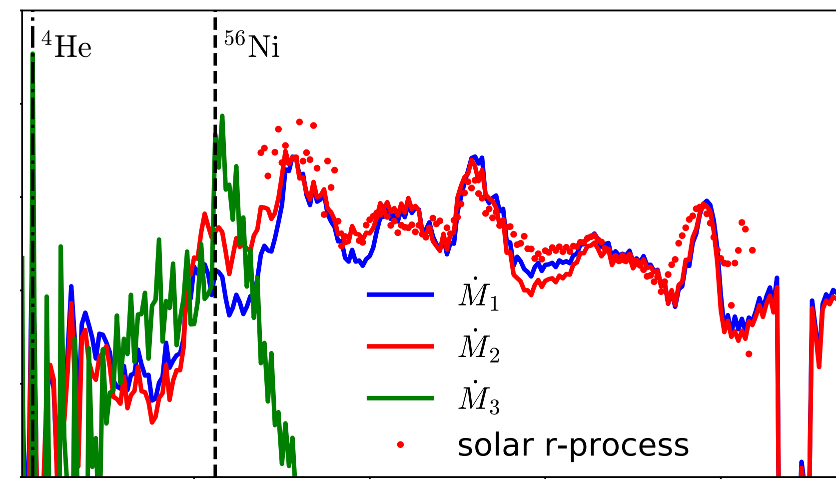
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

ICTP school: kilonovae slides









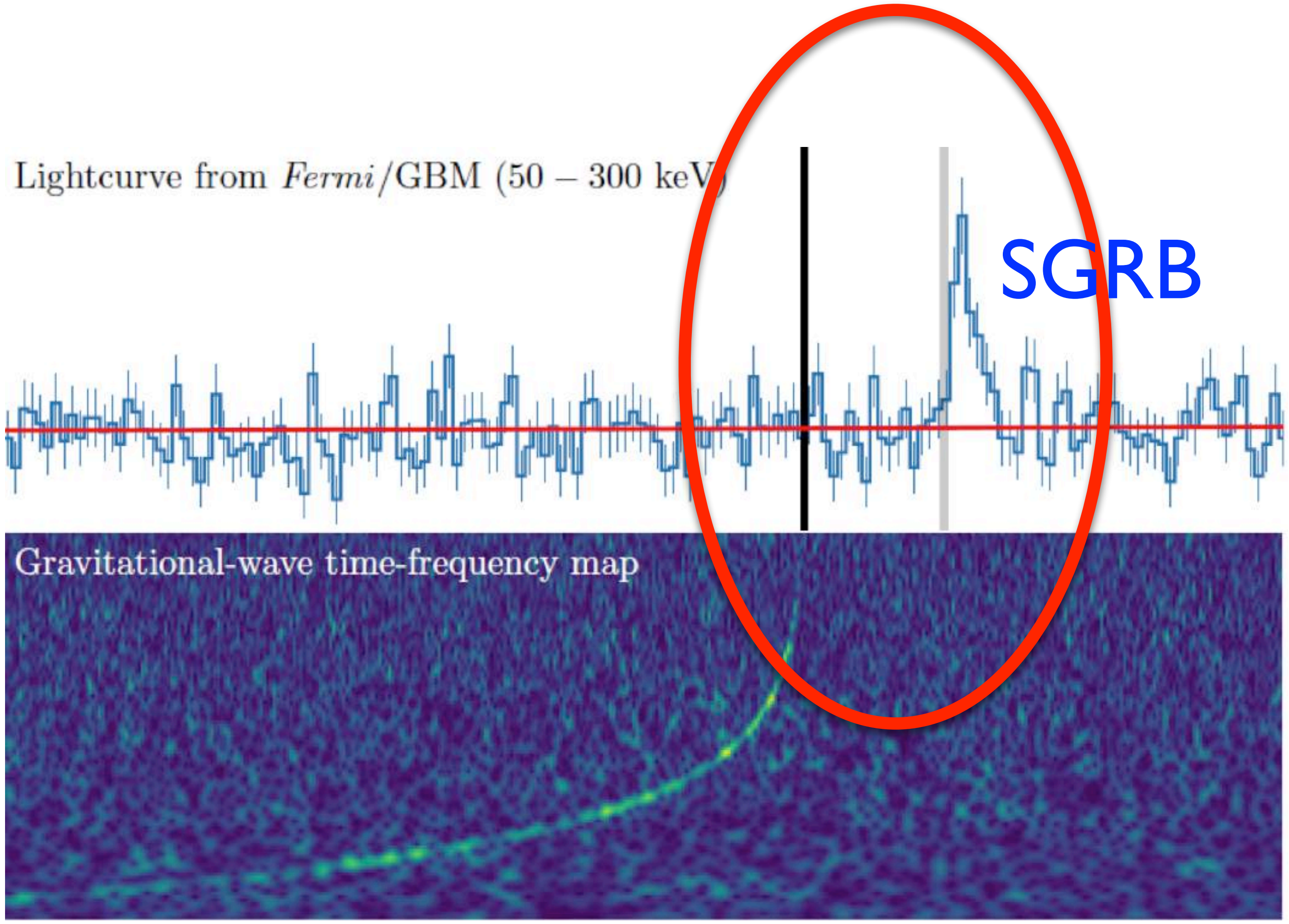
Daniel M. Siegel

Center for Theoretical Physics & Columbia Astrophysics Laboratory

Columbia University

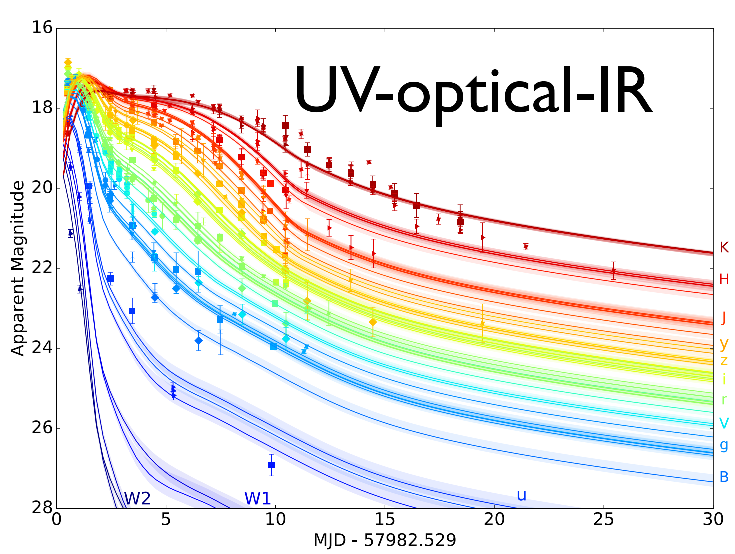
ICTP school *The Sound of Space-time: The Dawn of Gravitational Wave Science*,
Sao Paulo, Dec 10-14, 2018

GW170817 and the firework of EM counterparts

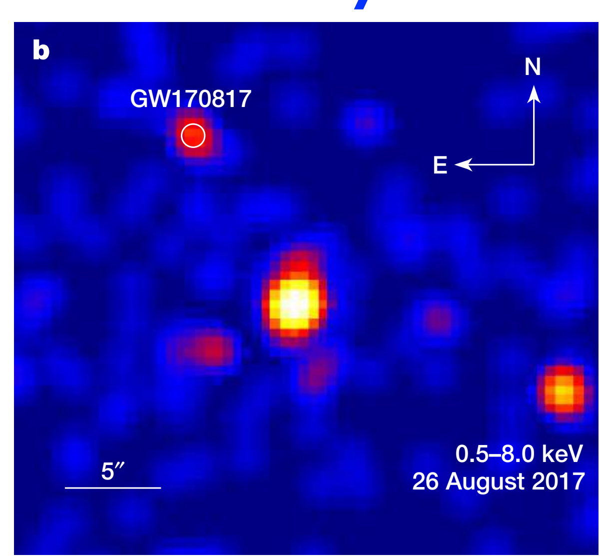


- unique event in astronomy, maybe most important observation since SN 1987A
- unprecedented level of multi-messenger observations
- confirms association of BNS to SGRBs
- kilonova provides strong evidence for synthesis of r-process material

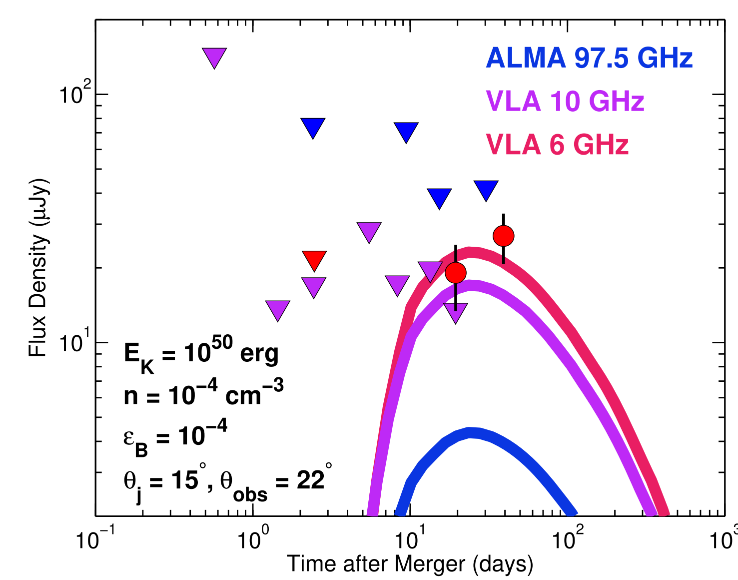
kilonova



X-rays



radio



The kilonova of GW170817

- blue kilonova properties:

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

'lanthanide-free'

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

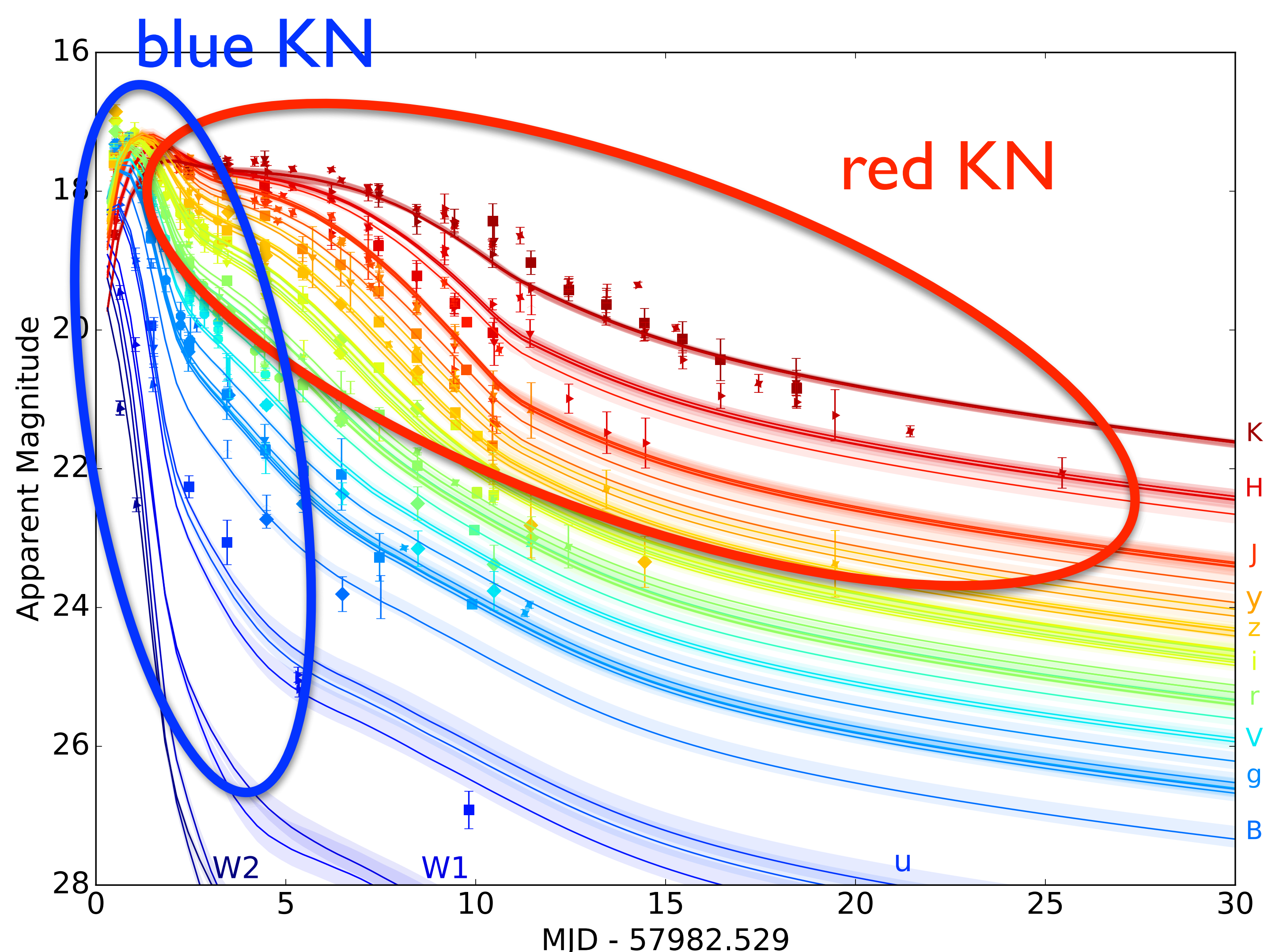
- red kilonova properties:

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

heavy r-process elements!

'lanthanide-rich'

Kilpatrick+ 2017
Kasen+ 2017
Kasliwal+ 2017
Drout+ 2017
Cowperthwaite+ 2017
Chornock+ 2017
Villar+ 2017
Coughlin+ 2018



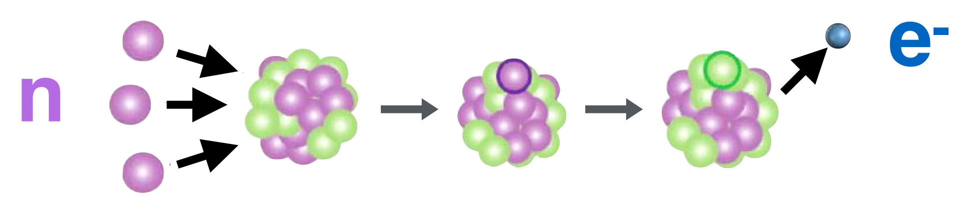
Villar+ 2017

two ("red-blue") or multiple components expected from merger simulations
(we shall see later)

The r-process in a nutshell

The r-process and s-process

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

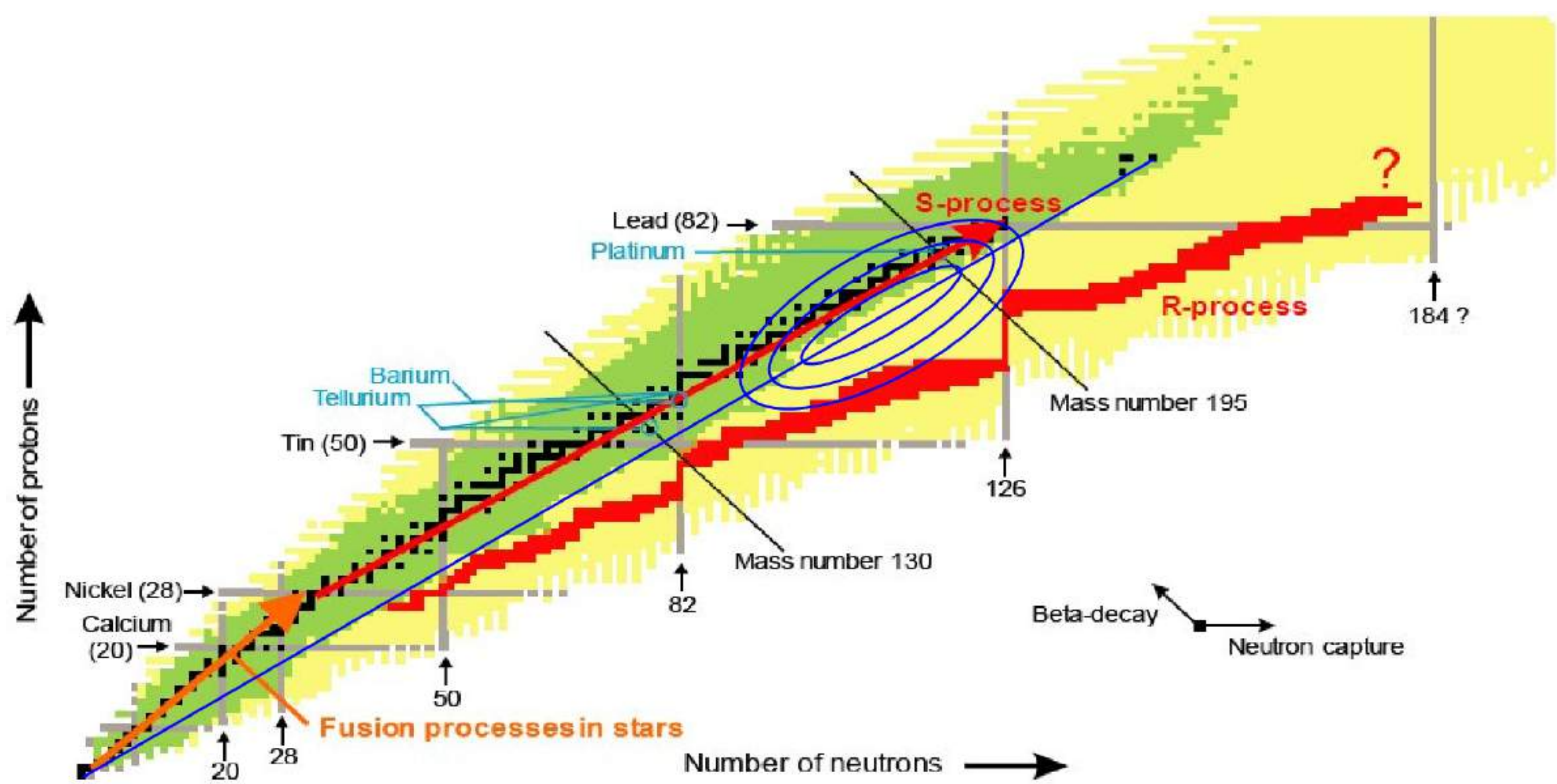


slow neutron capture (s-process):

timescale for neutron capture longer than for β-decay

rapid neutron capture (r-process):

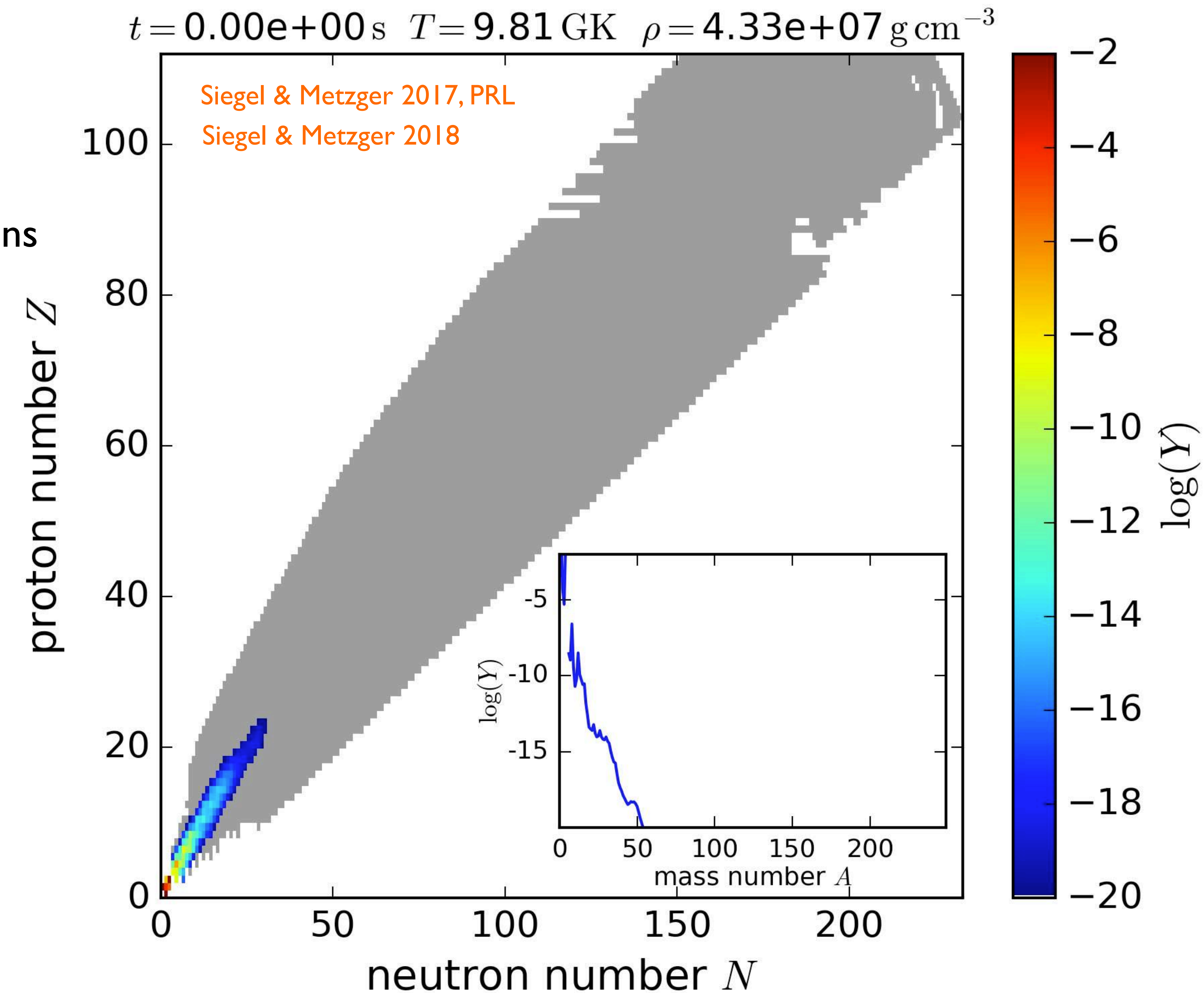
timescale for neutron capture shorter than for β-decay



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

Heating rates

Heating rates

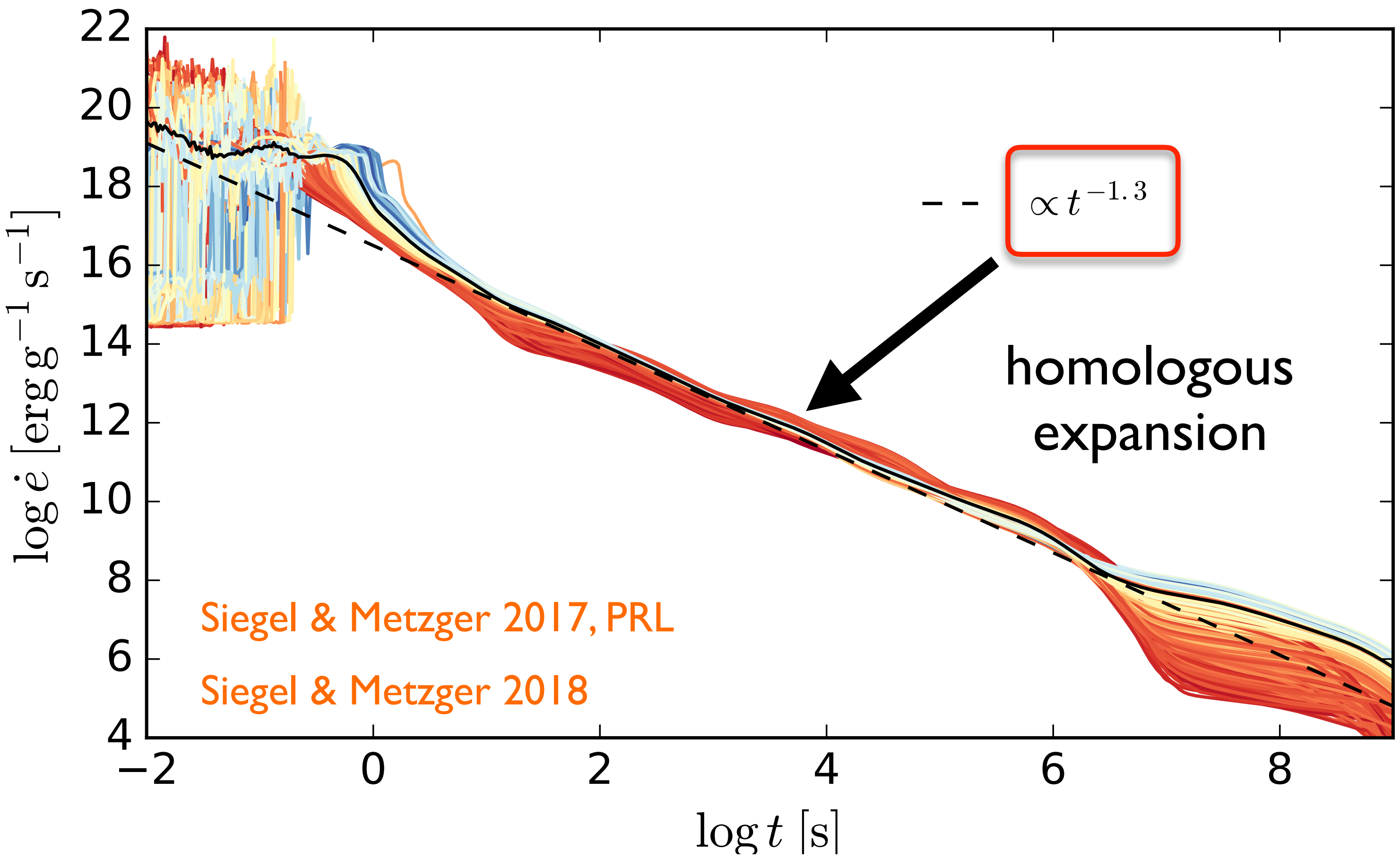
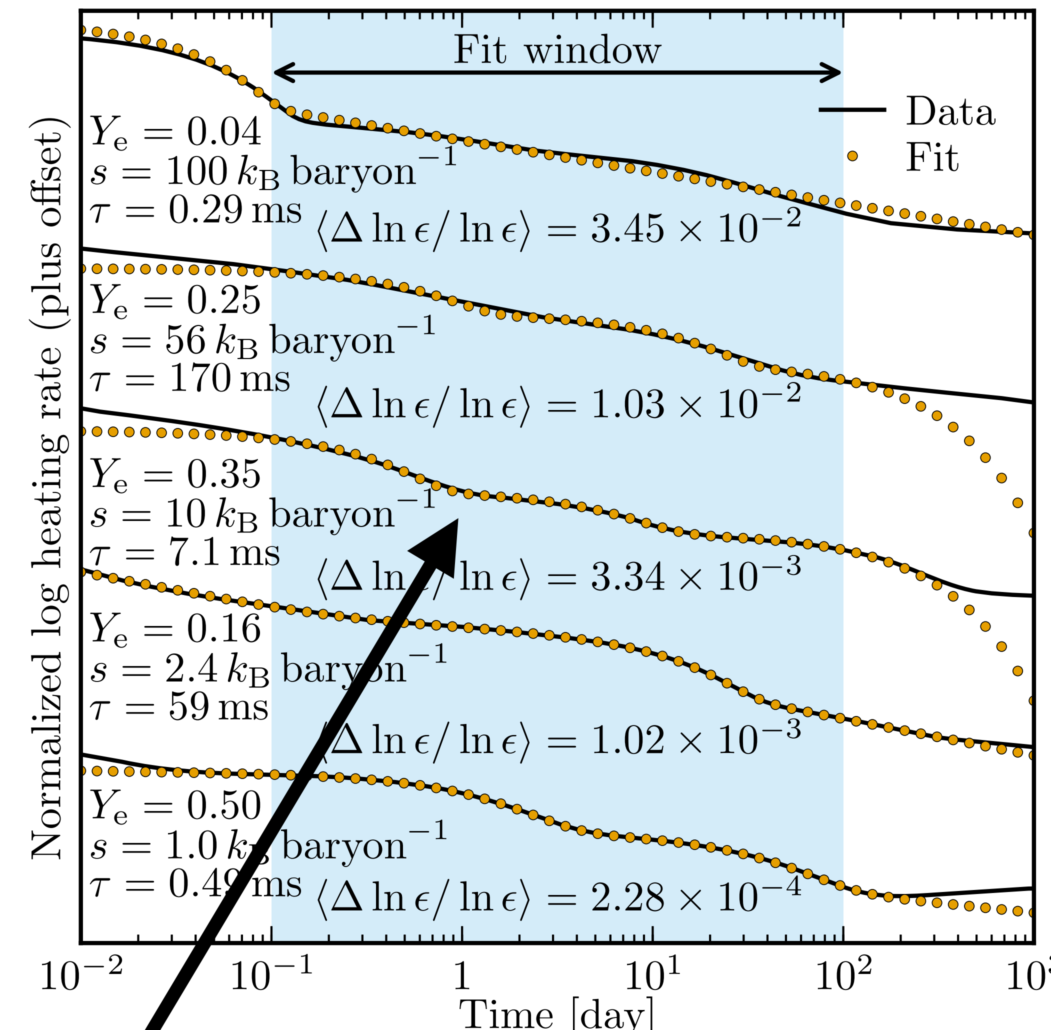


Fig: heating rates from r-process nucleosynthesis in simulations of post-merger disk outflows (lanthanide rich).



Lippuner & Roberts 2015

bumps and wiggles appear for lanthanide-poor conditions due to dominance of individual isotopes

Fig: heating rates from r-process nucleosynthesis for individual trajectories, varying electron fraction, specific entropy and the expansion timescale.

Bumps due to single isotopes expected even in lanthanide-rich scenario on timescales ~months

$\longrightarrow$ may lead to observational identification of specific isotopes Wu+ 2018

Thermalization efficiency

Barnes+ 2016

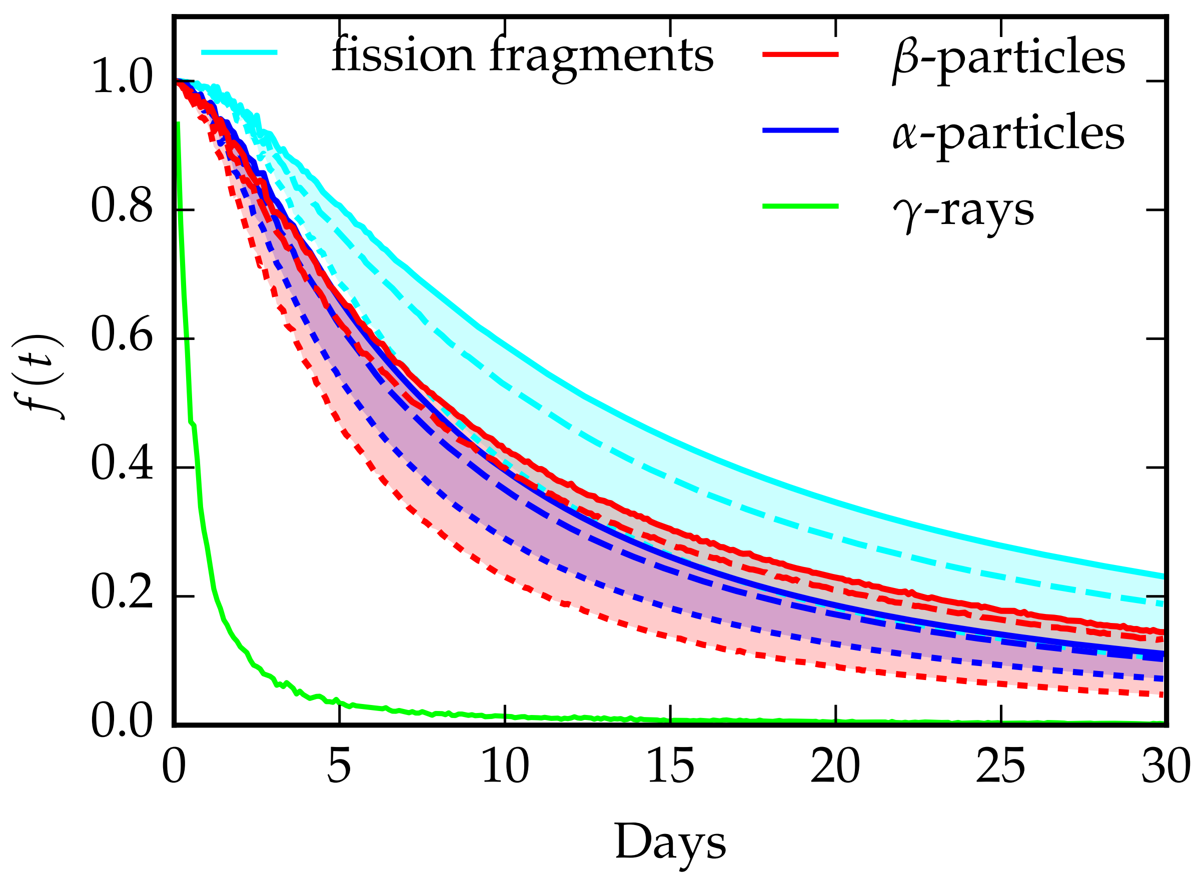


Fig: Example of thermalization efficiencies for all particles, assuming ejecta with M_{ej} = 5e-3 Msun, v_0 = 0.2c.

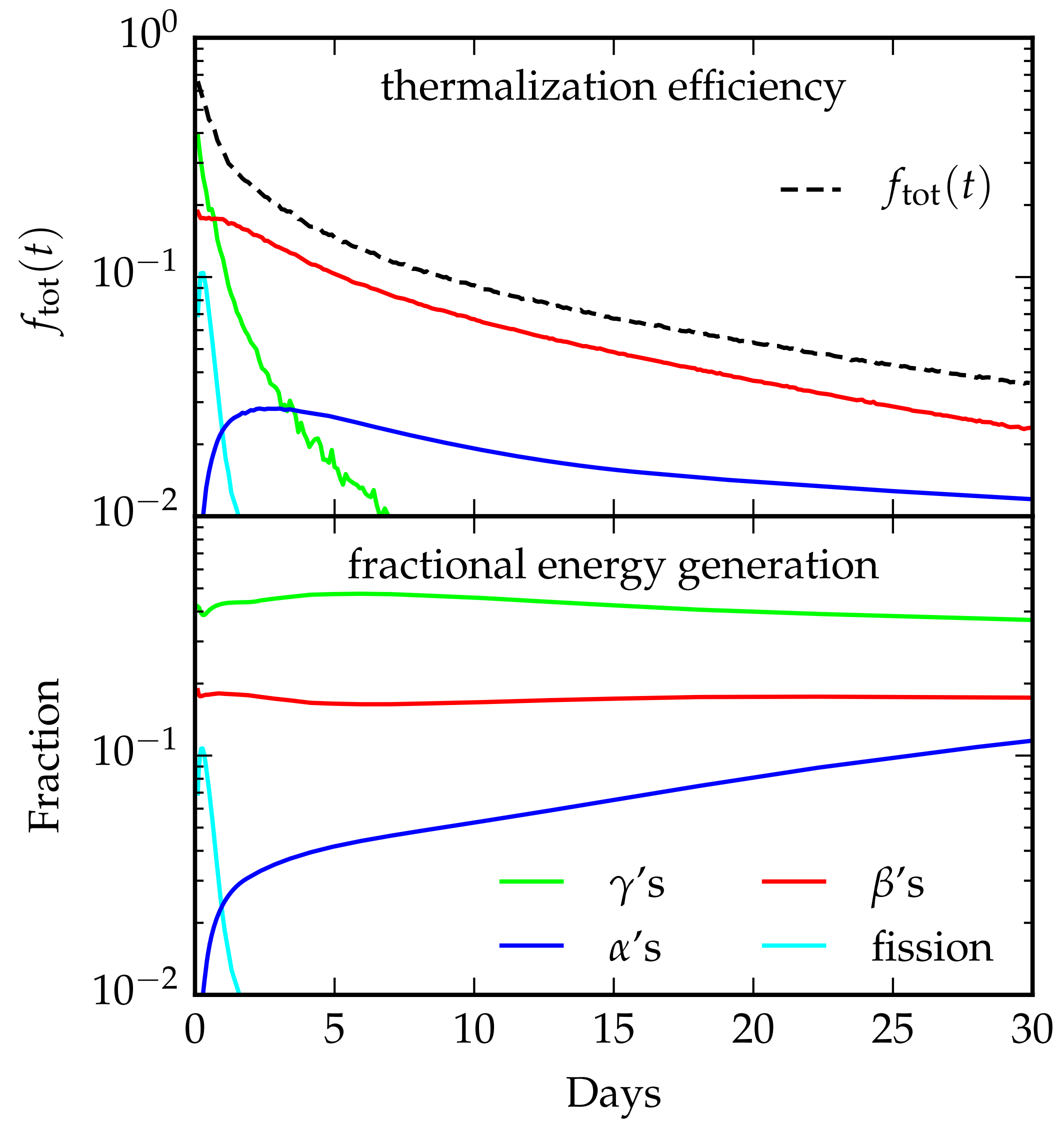


Fig: Thermalization efficiency of all particles convolved with their fractional energy generation.

Effect of thermalization efficiency on lightcurves

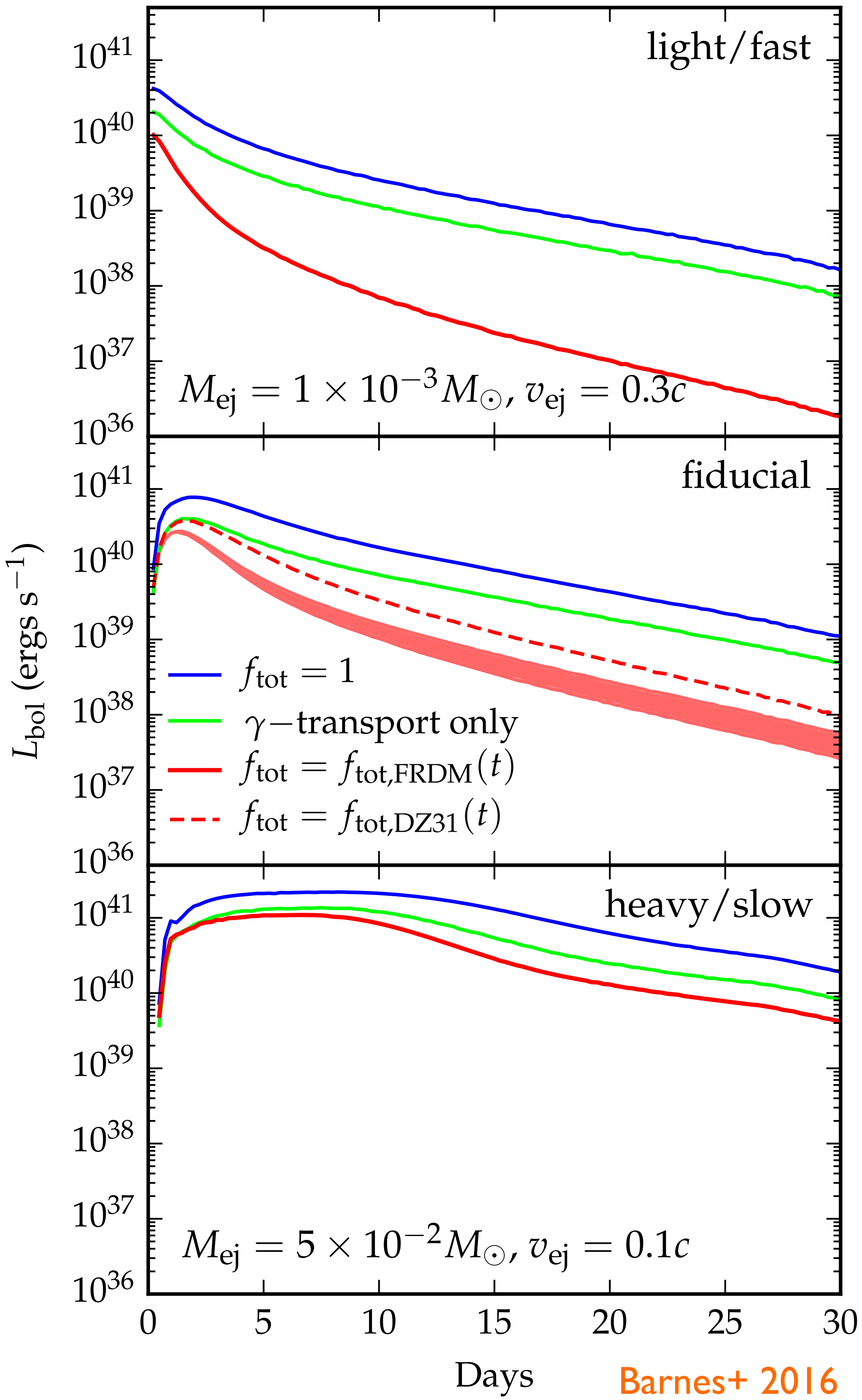
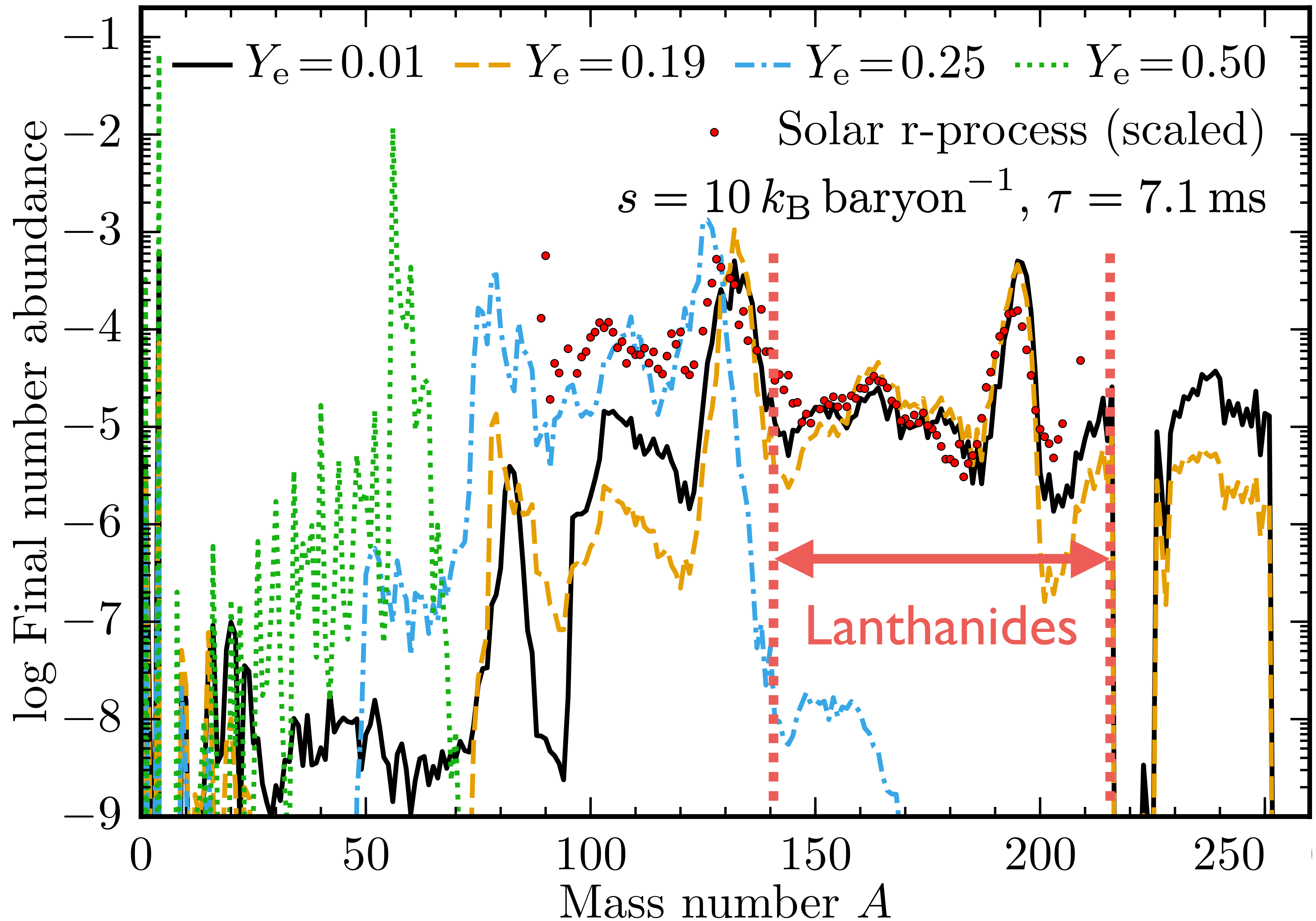


Fig: Impact of thermalization efficiency on kilonova lightcurves (bolometric luminosity). The fiducial model has parameters M_{ej} = 5e-3 Msun, v_0 = 0.2c.

Opacities

Outcome of the r-process

fewer free n per seed nucleus ⟷ more free n per seed nucleus



Lippuner & Roberts 2015

Final abundance pattern depends strongly on initial composition (Y_e)!

High opacities of the Lanthanides

Kasen+ 2013, Barnes & Kasen 2013

Number of electron configurations for a shell with *g levels* and *n electrons*:

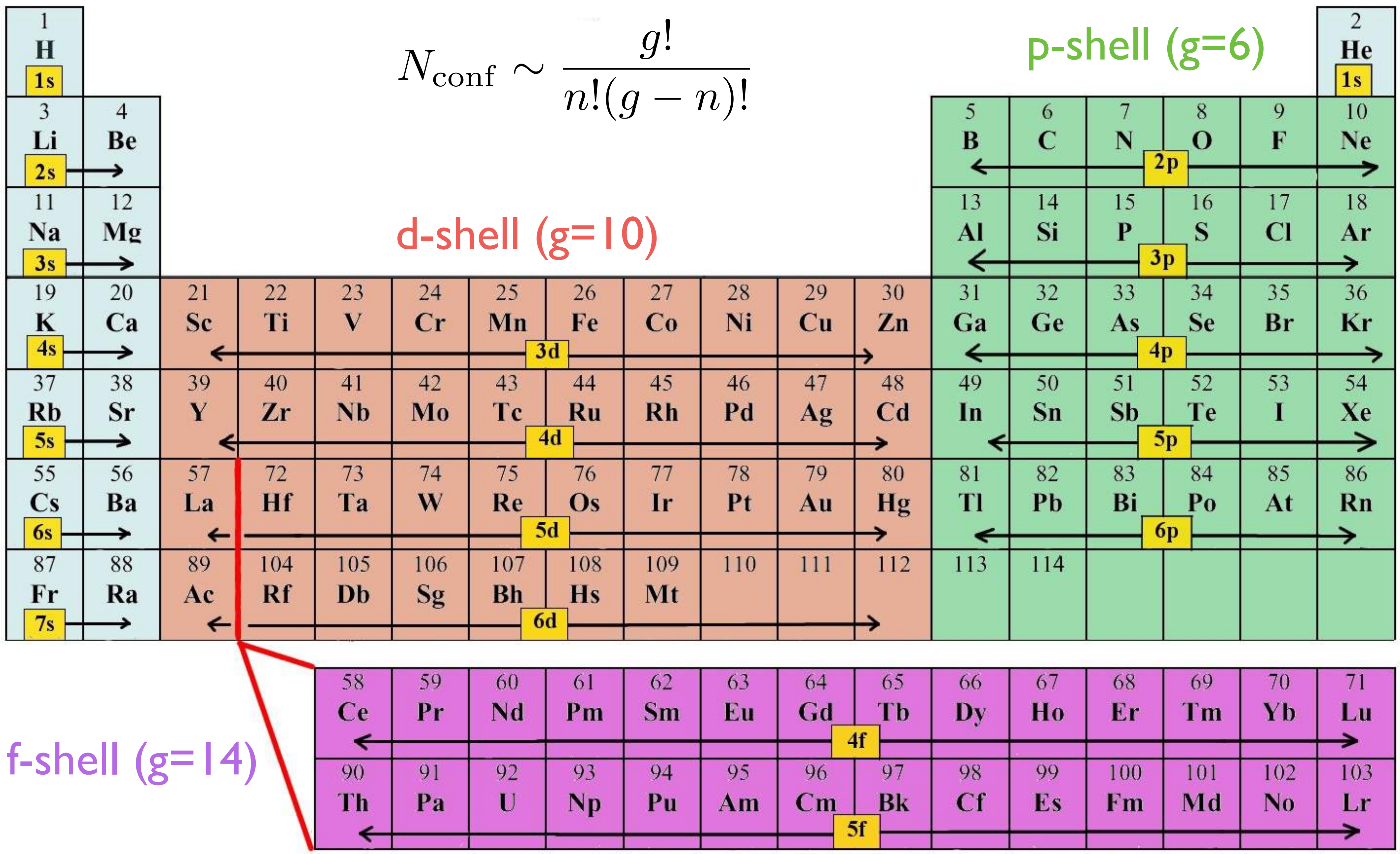
$$N_{\rm conf} \sim \frac{g!}{n!(g-n)!}$$

s-shell (g=2)

p-shell (g=6)

d-shell (g=10)

f-shell (g=14)



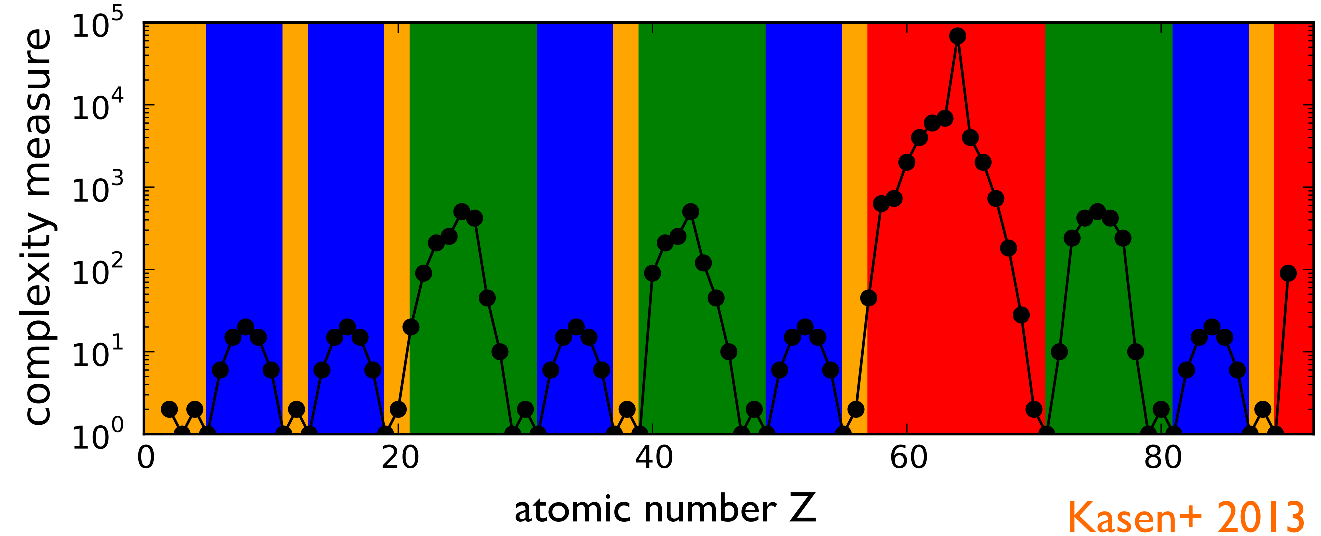
High opacities of the Lanthanides

Kasen+ 2013, Barnes & Kasen 2013

open shells

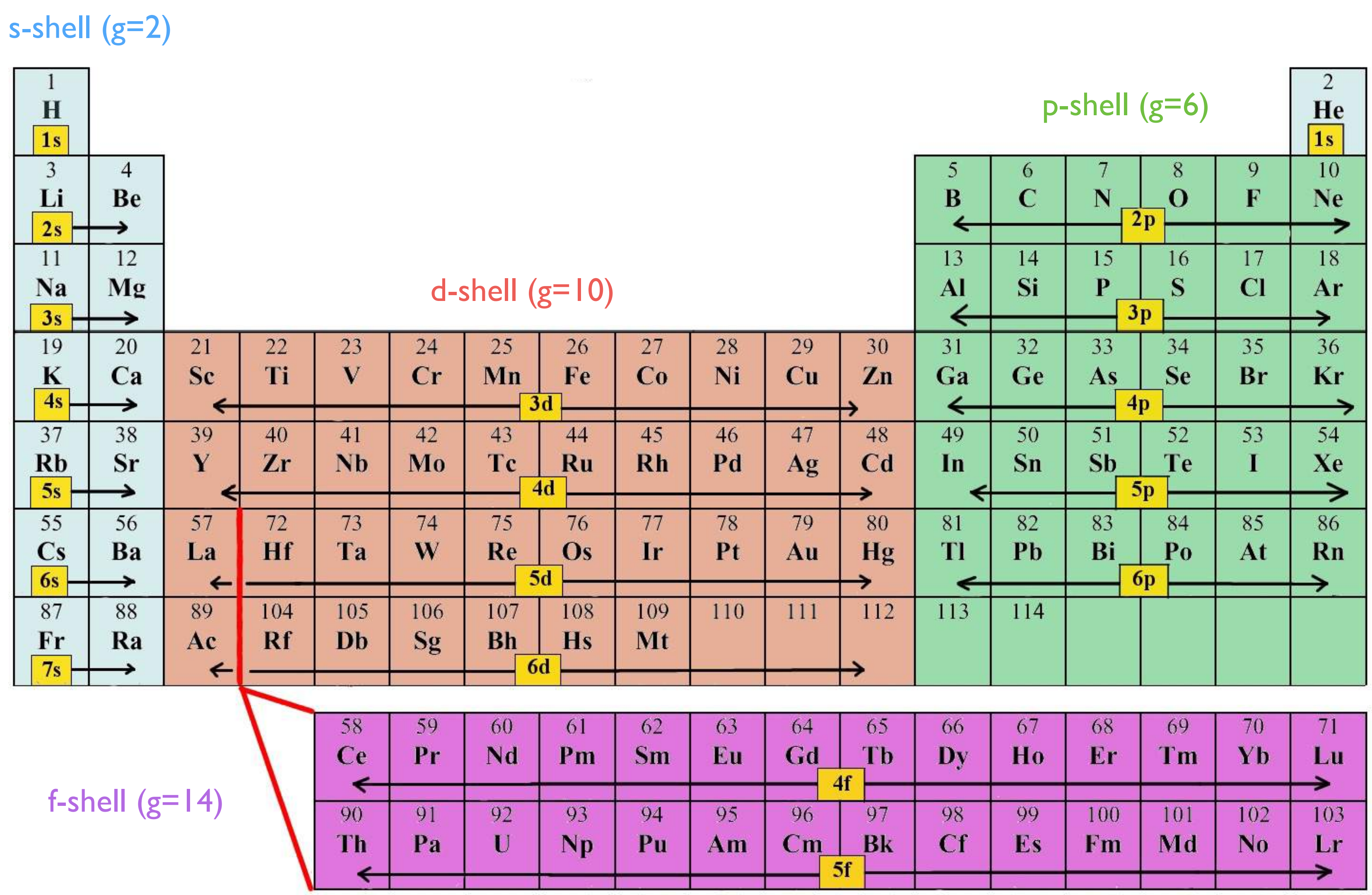
configurations: $N_{\rm conf} = \Pi_i \dfrac{g_i!}{n_i!(g_i - n_i)!}$

opacity: $\kappa \sim N_{\rm lines} \sim N_{\rm conf}^2$



Kasen+ 2013

shells: s p d f



High opacities of the Lanthanides

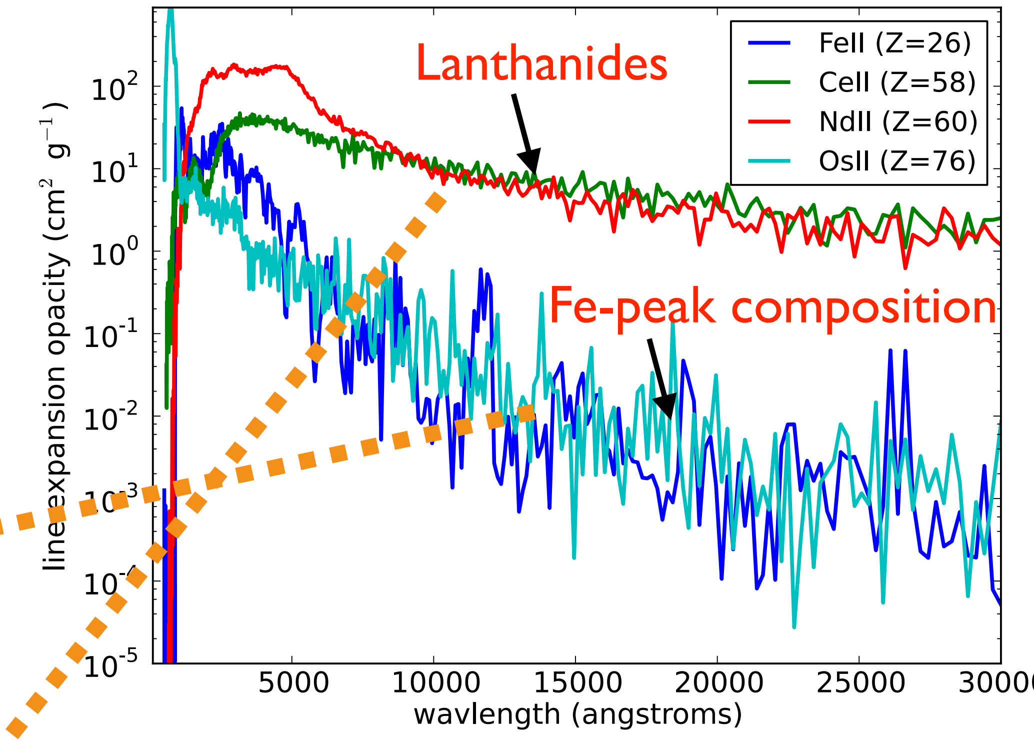
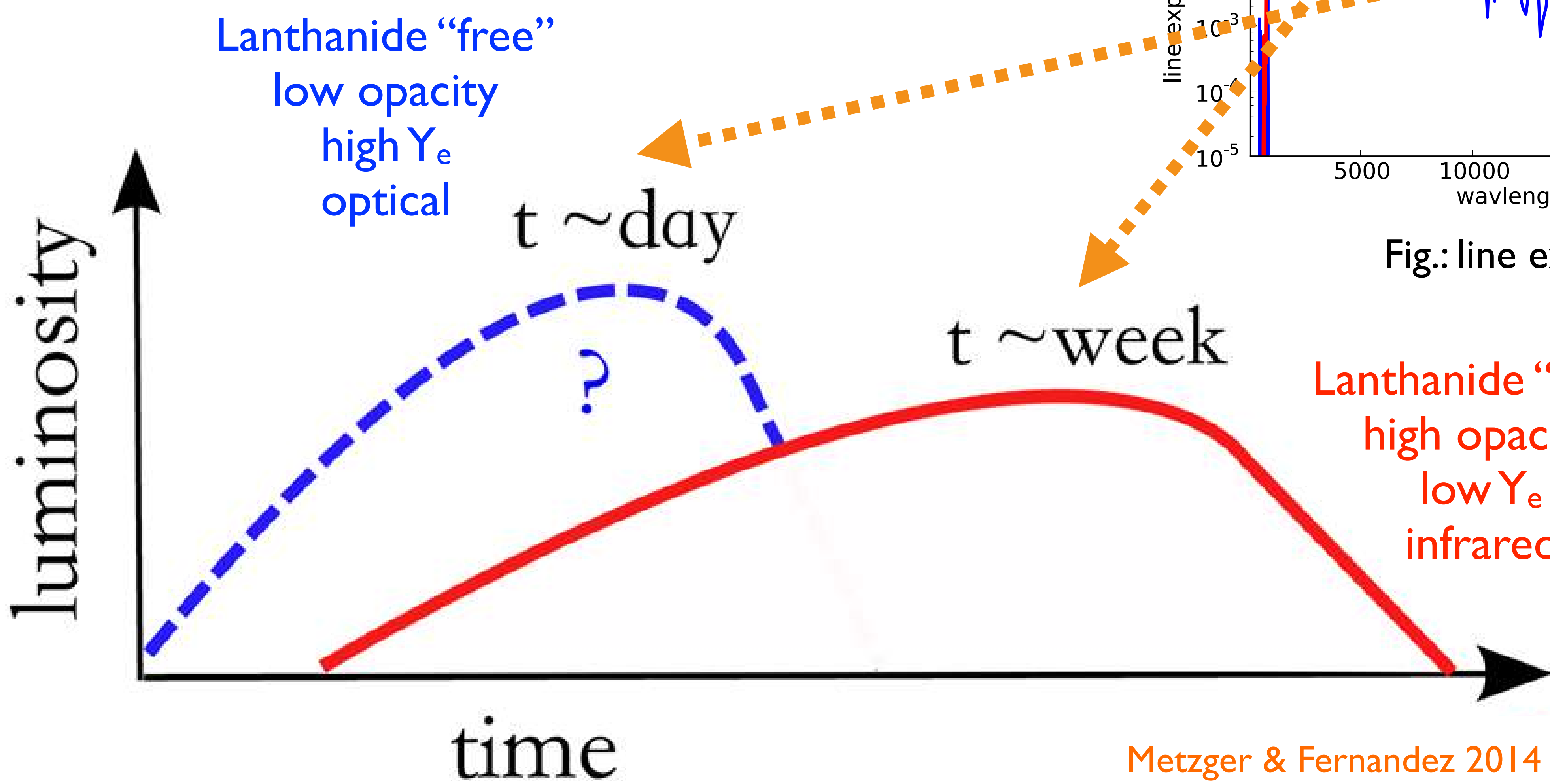


Fig.: line expansion opacities

Kasen+ 2013

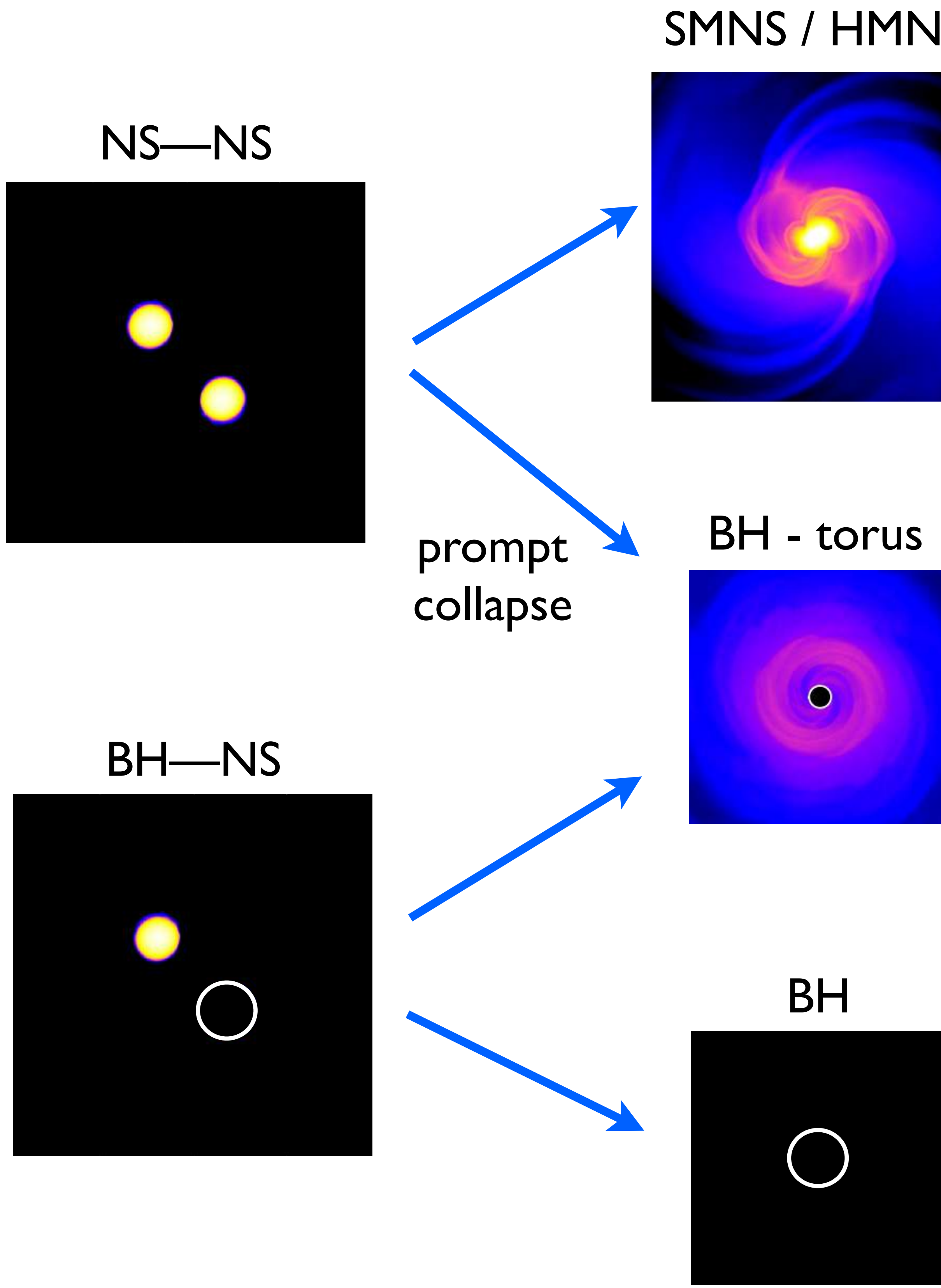


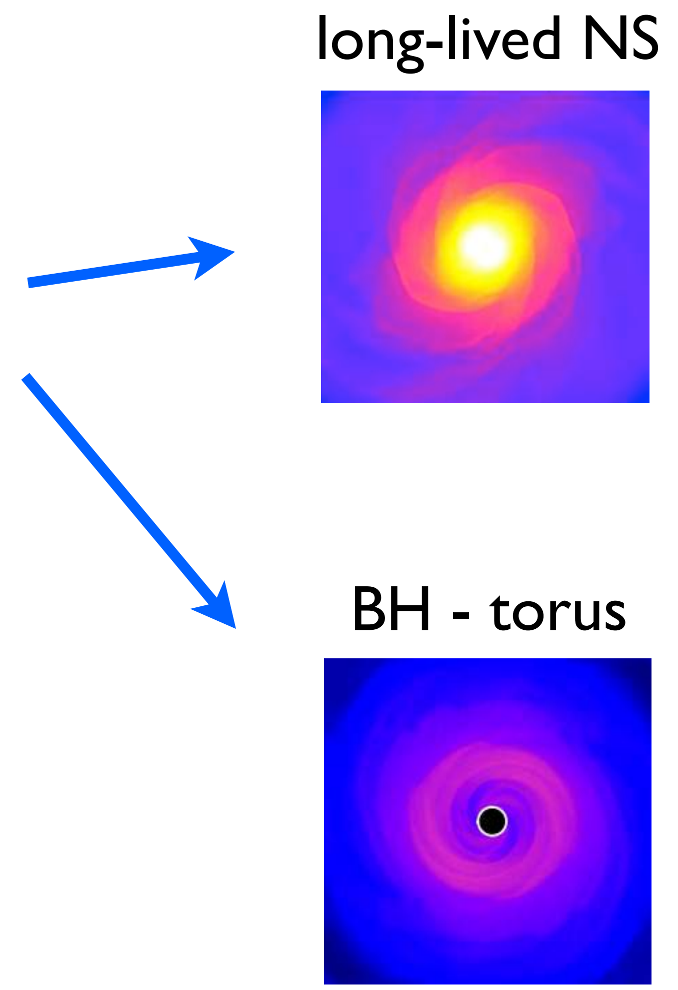
Metzger & Fernandez 2014

Fig.: kilonova lightcurves probe composition (Lanthanide mass fraction).

Origin of neutron-rich ejecta

NS merger phenomenology



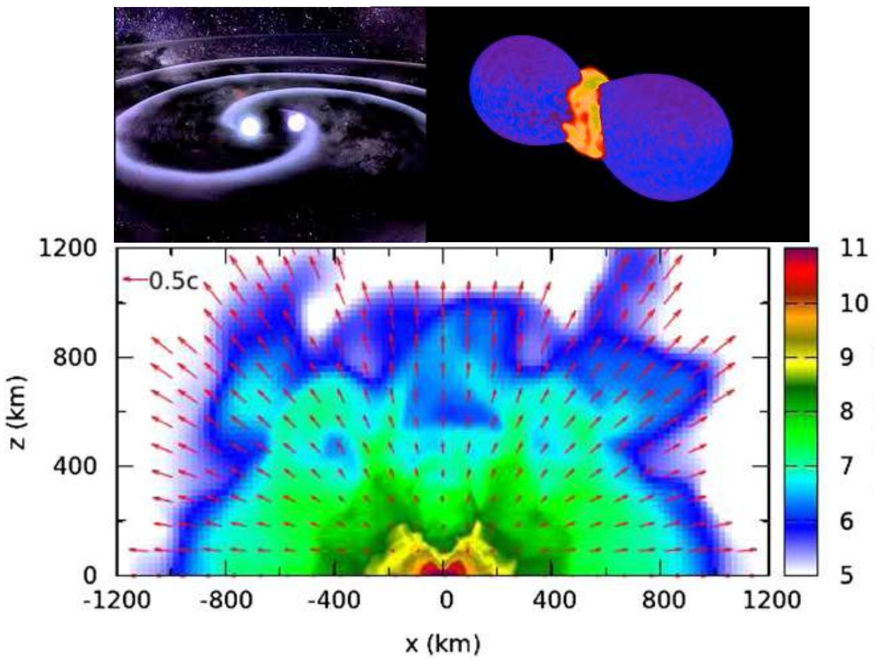


sim. & vis.: W. Kastaun

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

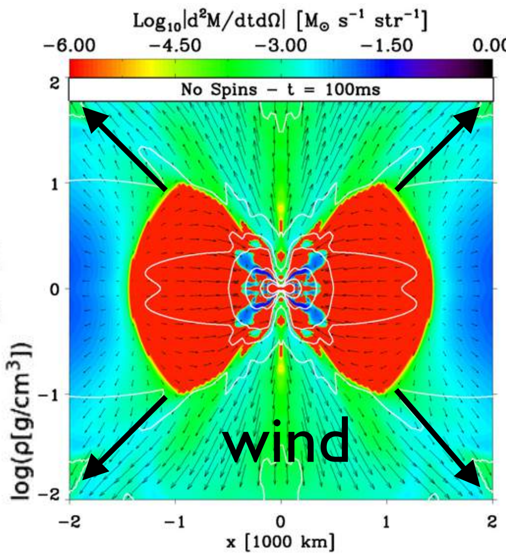
Sources of ejecta in NS mergers

dynamical ejecta (~ms)

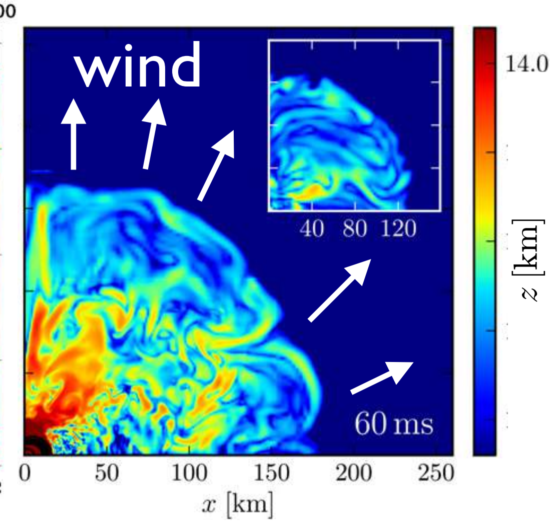


Hotokezaka+ 2013, Bauswein+ 2013

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

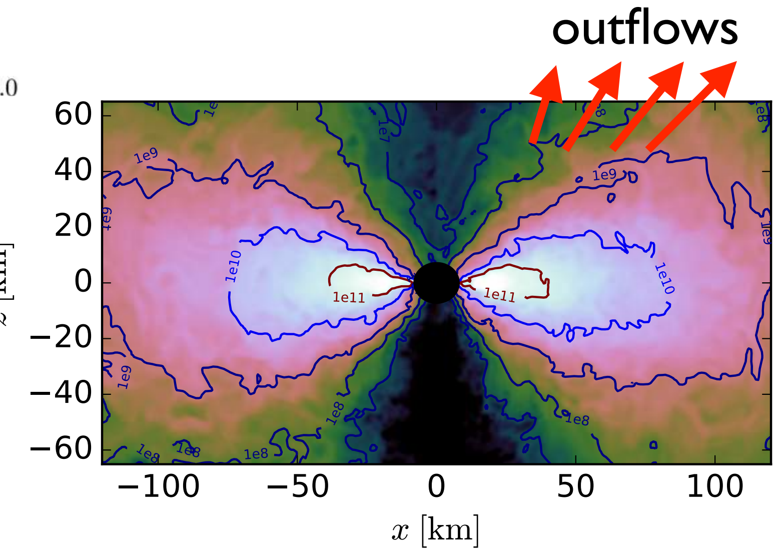


Dessart+ 2009



Siegel+ 2014
Ciolfi, Siegel+ 2017

accretion disk (~10ms-1s)



Siegel & Metzger 2017 PRL

tidal ejecta
shock-heated ejecta

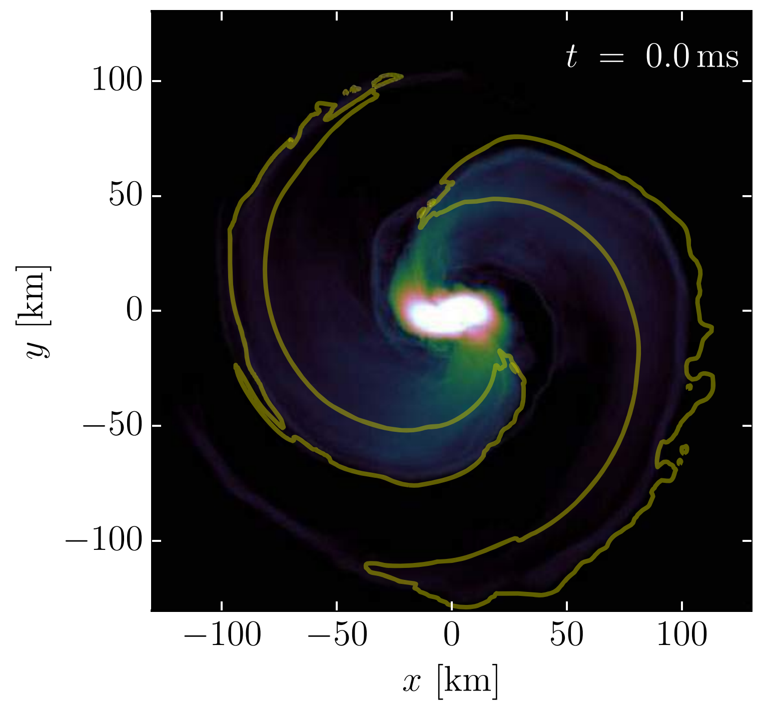
neutrino- and magnetically
driven wind

(binary NS mergers only!)

disk outflows

Dynamical ejecta (~ms)

tidal ejecta

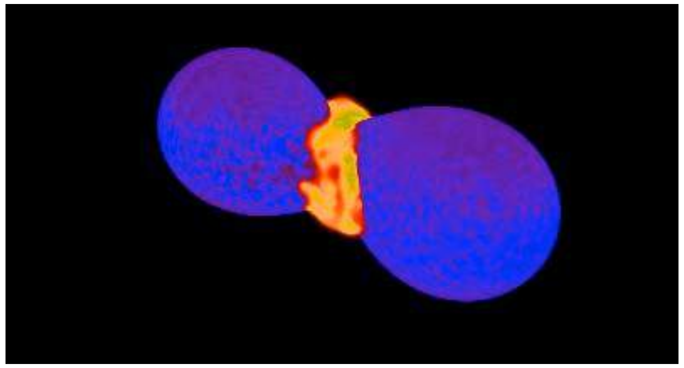


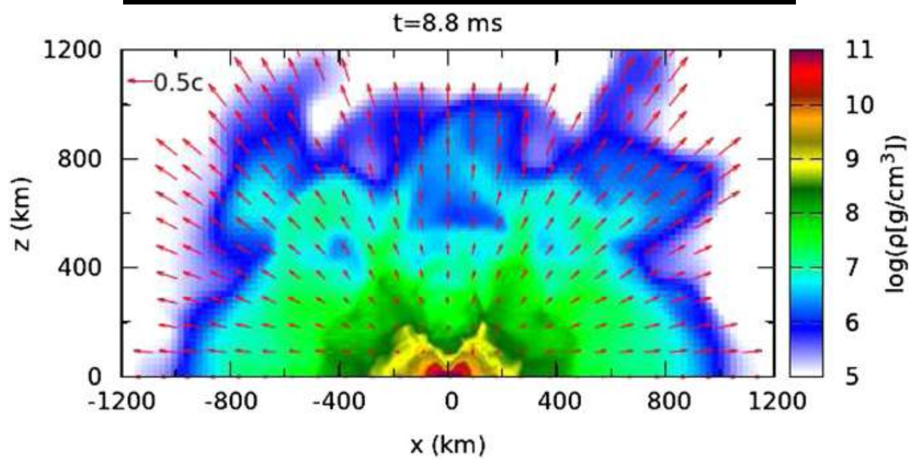
Ciolfi, Siegel+ 2017

- tidally ejected prior/at merger (leaking out of Lagrange points)
- fast: v ~ 0.2c
- cold, neutron-rich material from ('T ~ 0 K', s < 10 k_B, $Y_e < 0.1$)

fast red kilonova transient

shock-heated ejecta





Hotokezaka+ 2013, Bauswein+ 2013

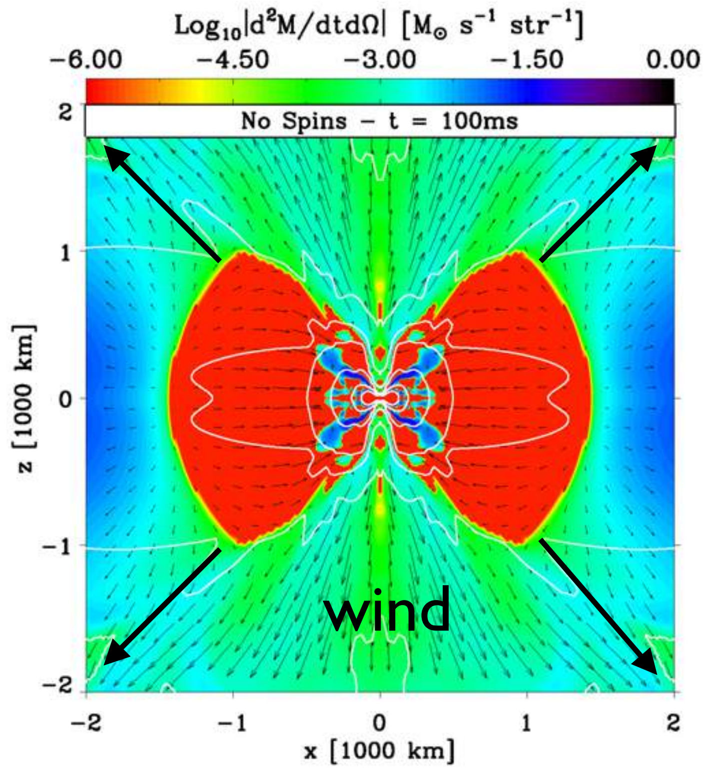
- squeezed out from the shock interface at merger
- fast: v > 0.2c
- shock-heated → hot: T ~ 10 MeV
- strong neutrino emission raises Y_e ($Y_e > 0.25$)

fast blue kilonova transient

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

Winds from remnant (metastable) NS

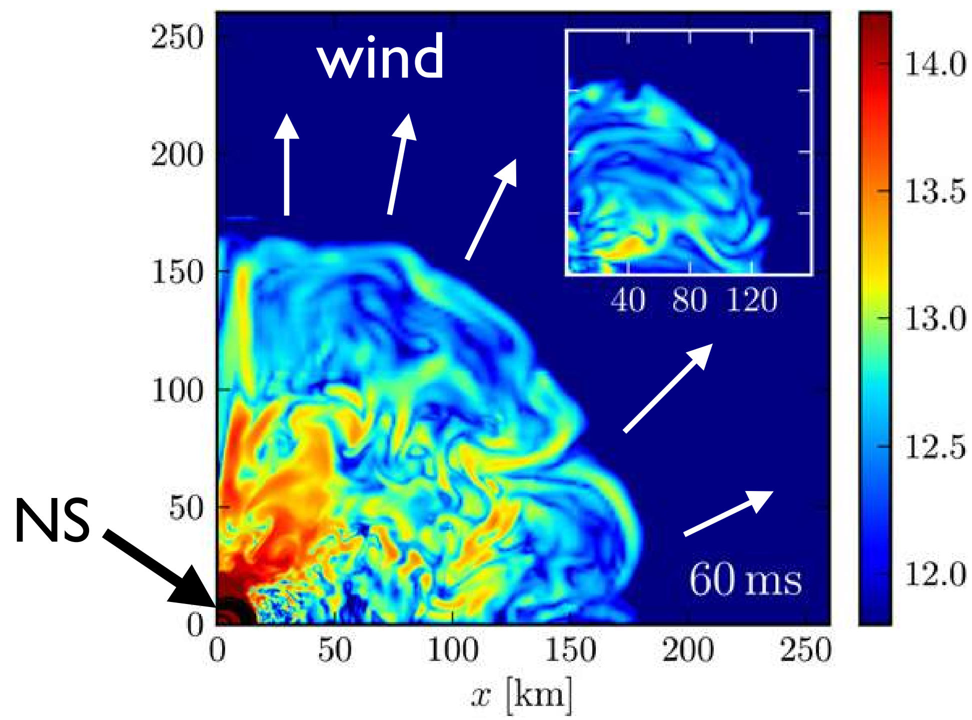
neutrino-driven winds



Dessart+ 2009

- reabsorption of neutrinos drives wind off the surface (similar to "gain layer" in core-collapse SNe)
- slow: v <~ 0.1c
- hot: T ~ 10 MeV
- $Y_e > 0.25$ (due to reabsorption of neutrinos)
- $\dot{M}_{\rm in} \sim (10^{-4} - 10^{-3}) M_\odot s^{-1}$

magnetically driven winds



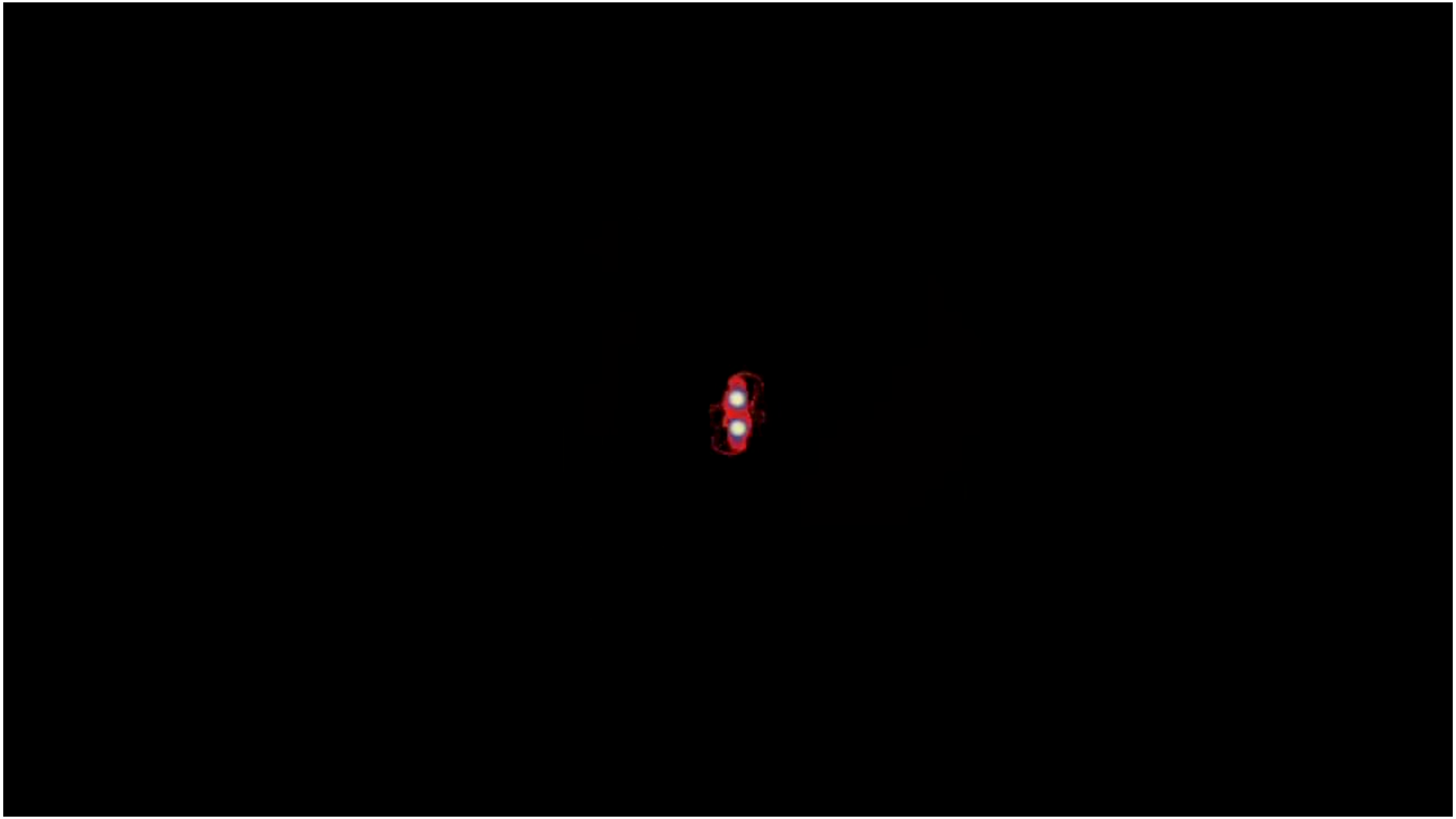
Siegel+ 2014 Ciolfi, Siegel+ 2017

- magnetic field amplification in stellar interior generates enhanced magnetic pressure that drives a wind from the surface layers (toroidal field gradients)
- slow: v <~ 0.1c
- hot: T ~ 10 MeV
- $Y_e > 0.25$ (due to neutrinos irradiation)
- $\dot{M}_{\rm in} \sim (10^{-3} - 10^{-2}) M_\odot s^{-1}$

slow blue kilonova transient

(in certain regime both mechanisms can act together and generate massive fast ejecta) Metzger+ 2018

Dynamical ejecta and winds

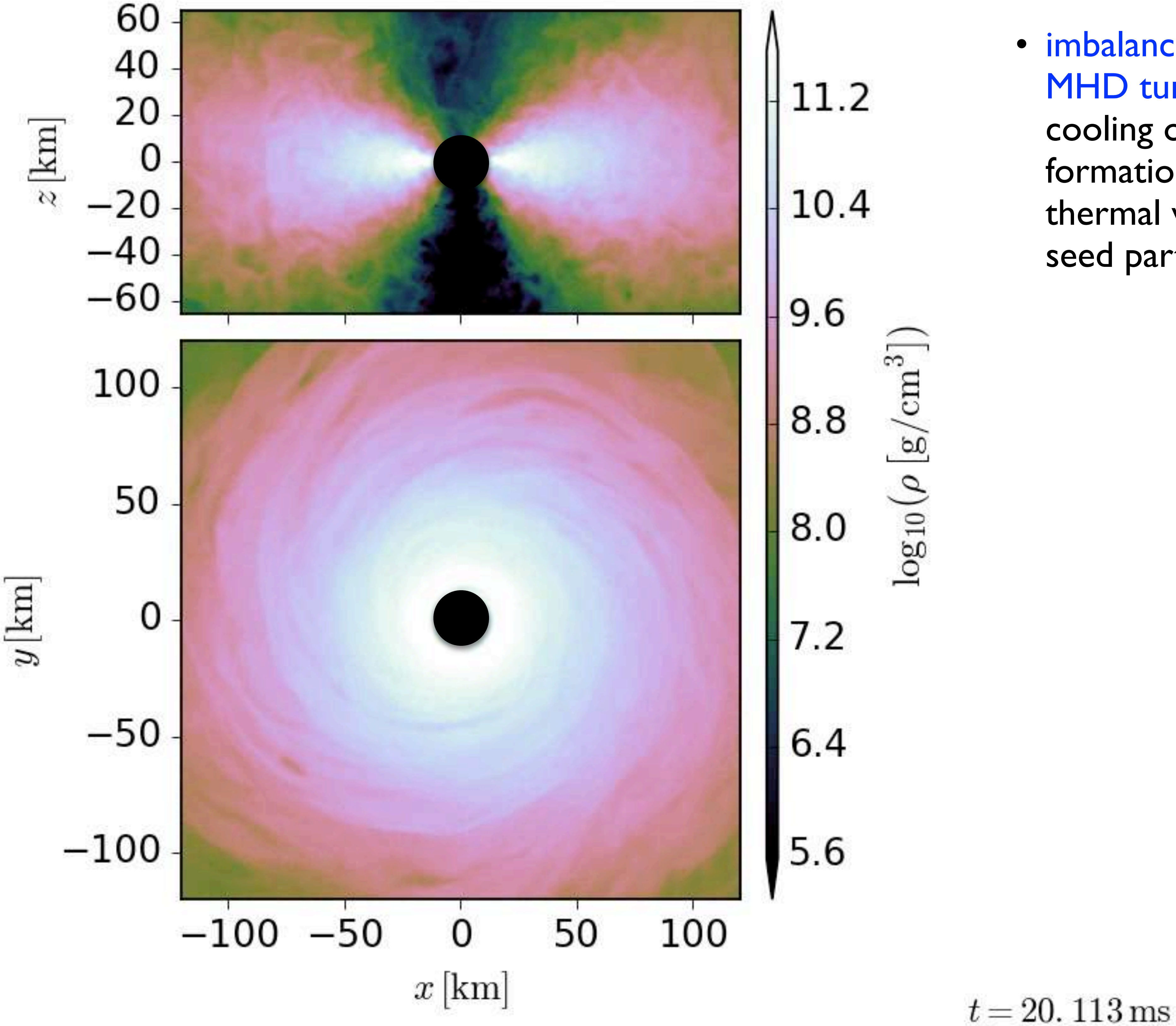


Movie: BNS merger showing dynamical ejecta and winds from remnant NS

Ciolfi, Siegel+ 2017

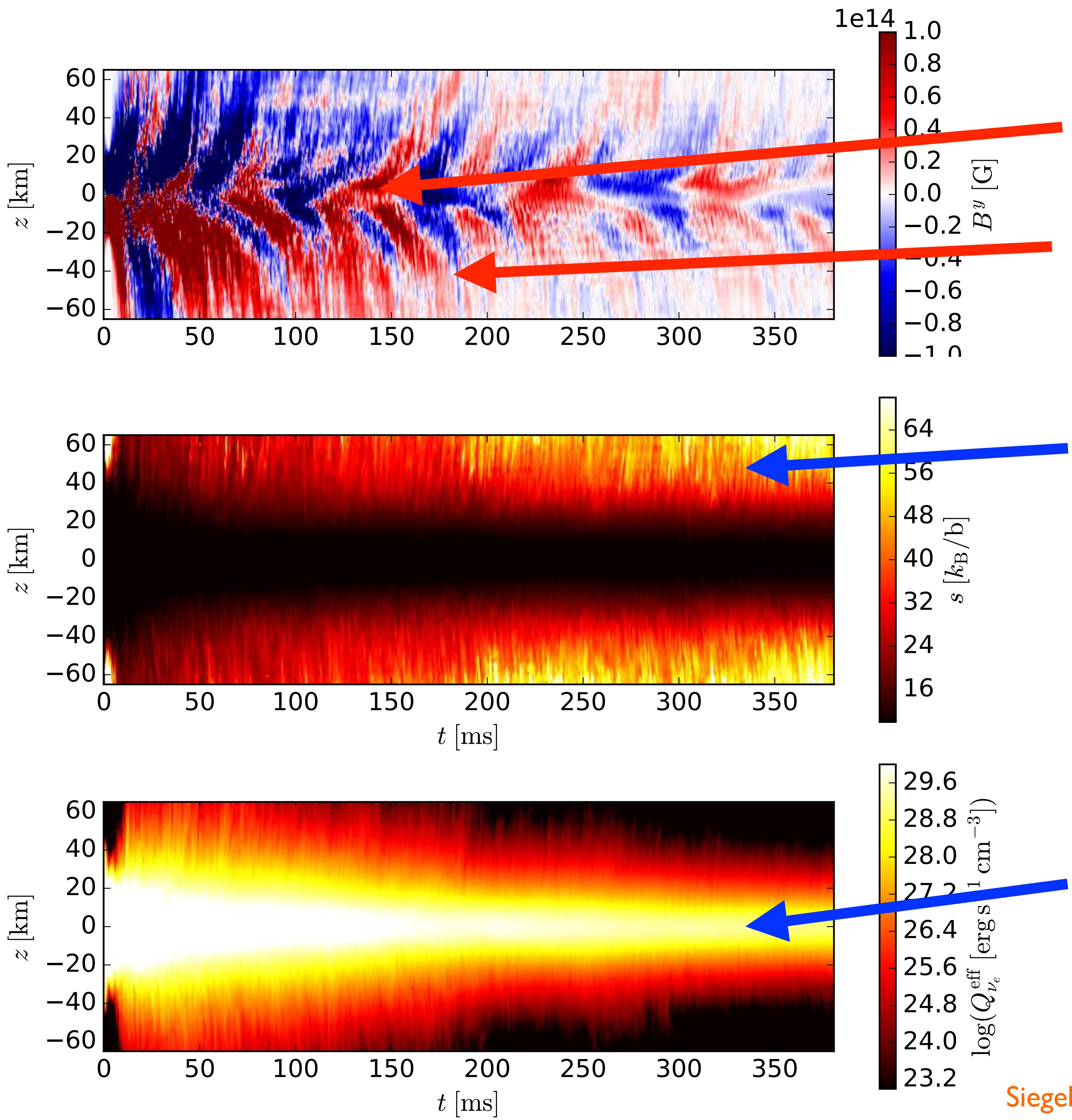
Post-merger accretion disk outflows

Siegel & Metzger 2017, PRL   Siegel & Metzger 2018a



- imbalance of viscous heating from MHD turbulence and neutrino cooling off the disk midplane leads to formation of hot corona that launches thermal winds, further acceleration by seed particle formation

Accretion disk dynamo & generation of outflows



magnetic energy is generated in the mid-plane

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

→ "hot corona"

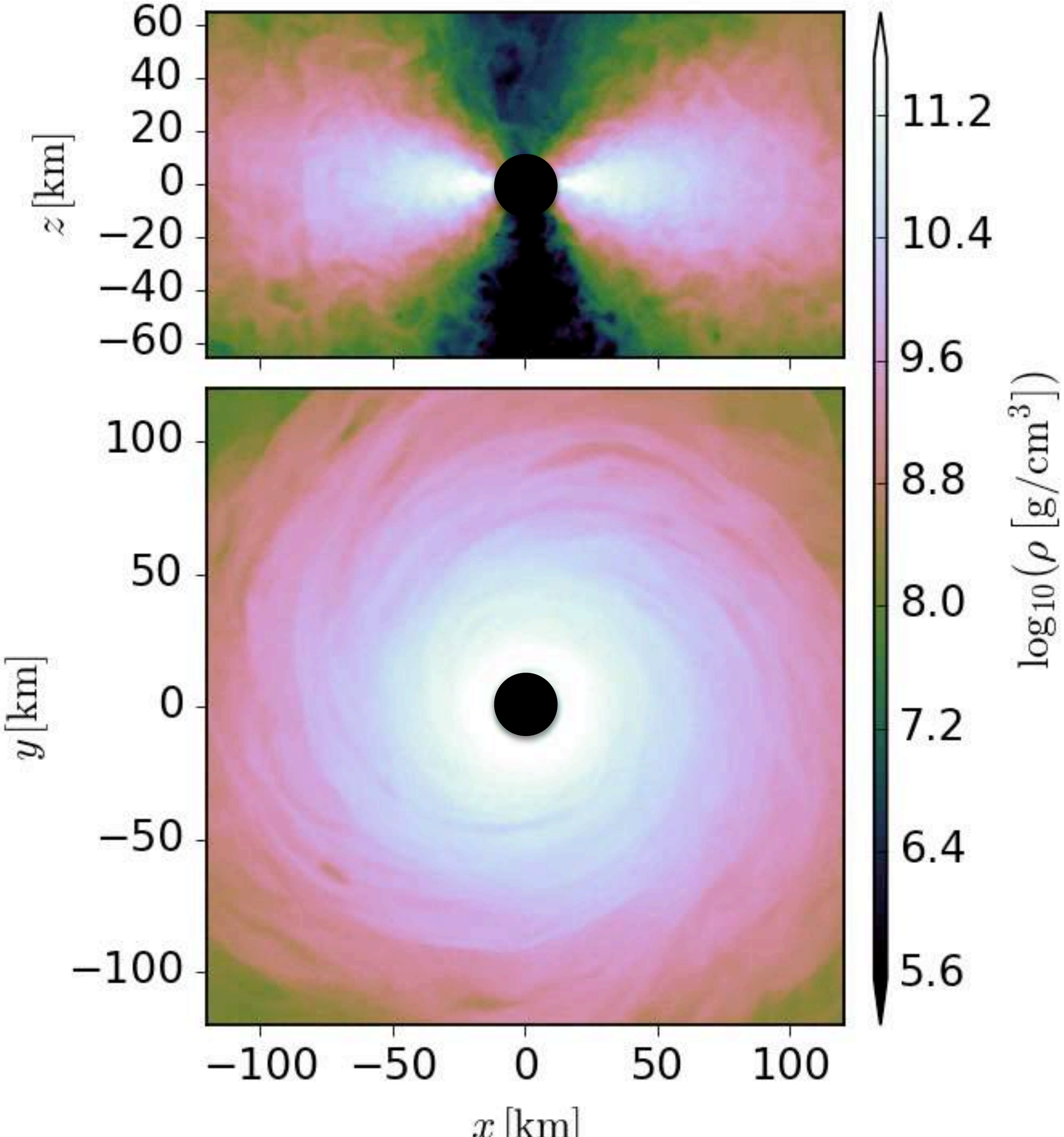
hot corona launches thermal outflows (neutron-rich wind)

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

Siegel & Metzger 2018

Post-merger accretion disk outflows

Siegel & Metzger 2017, PRL   Siegel & Metzger 2018a



- imbalance of viscous heating from MHD turbulence and neutrino cooling off the disk midplane leads to formation of hot corona that launches thermal winds, further acceleration by seed particle formation
- slow: v ~ 0.1c
- hot: T ~ 10 MeV
- $Y_e < 0.25$ if central object is a BH (due to self-regulation mechanism; details see ICTP colloquium)
- massive outflows (may dominate mass ejection in binary NS mergers):

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

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

cf. also: Fernandez+ 2018

slow red kilonova (BH)

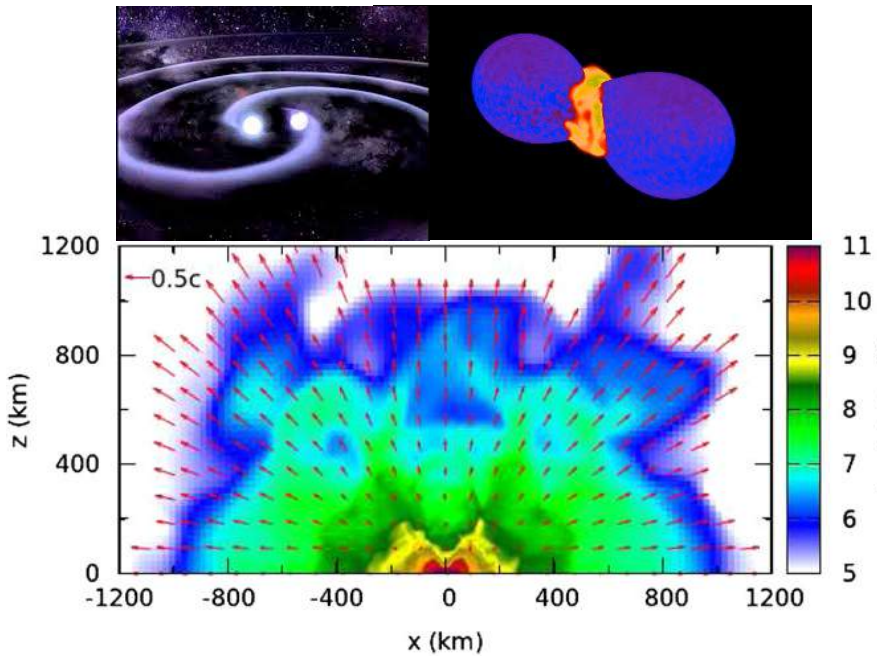
slow blue kilonova (long-lived remnant)

Lippuner+ 2017

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

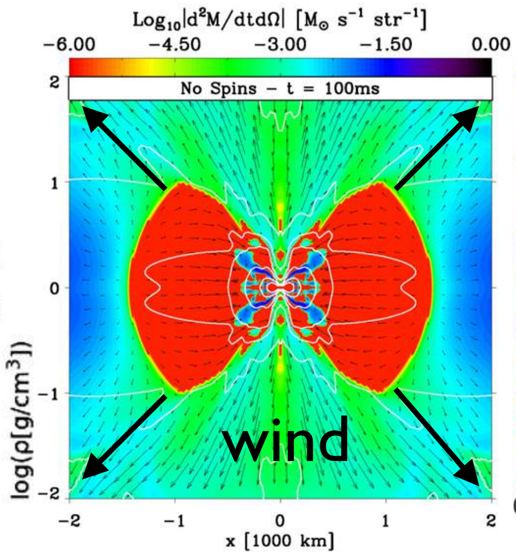
Sources of ejecta in NS mergers

dynamical ejecta (~ms)

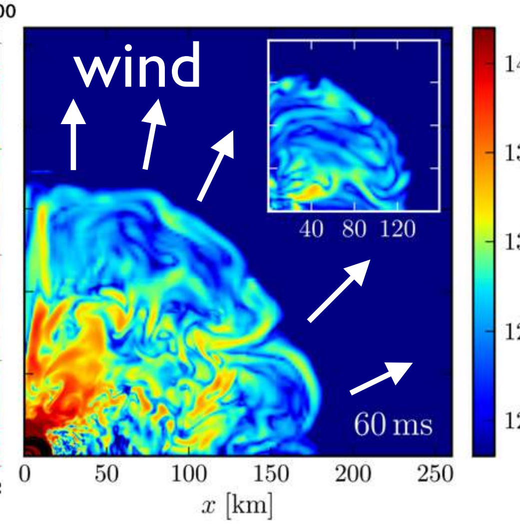


Hotokezaka+ 2013, Bauswein+ 2013

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

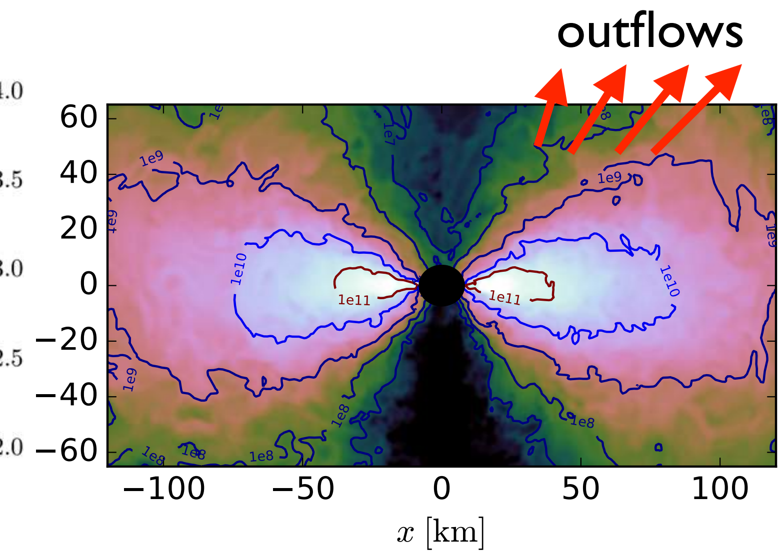


Dessart+ 2009



Siegel+ 2014
Ciolfi, Siegel+ 2017

accretion disk (~10ms-1s)



Siegel & Metzger 2017, 2018

tidal ejecta
shock-heated ejecta

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

neutrino-driven wind

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

magnetically driven wind

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

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