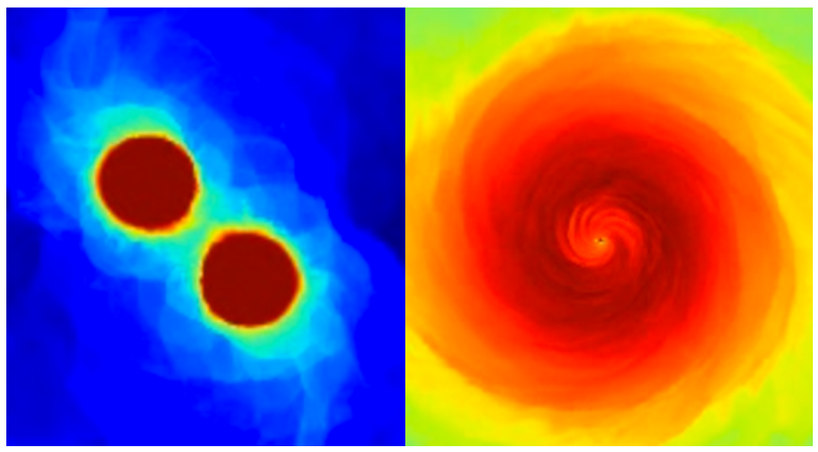
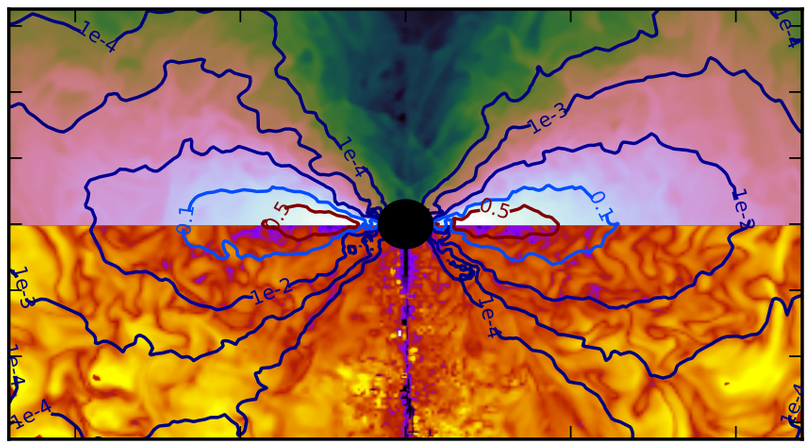
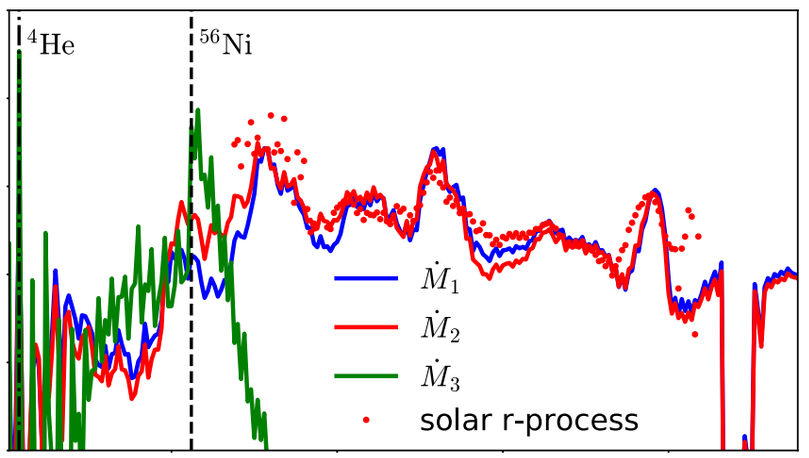
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

ICTP school: kilonovae slides







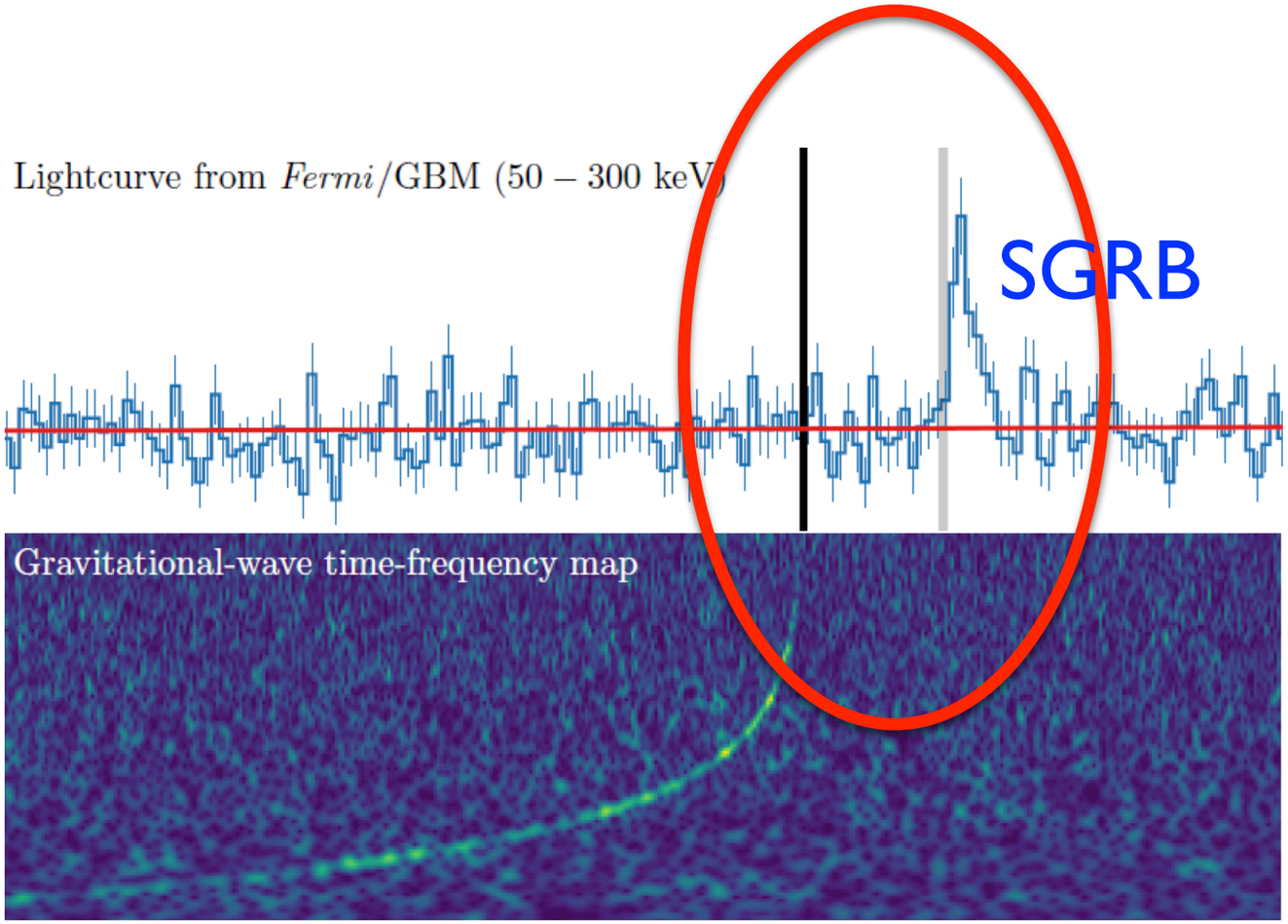
Daniel M. Siegel

Center for Theoretical Physics & Columbia Astrophysics Laboratory

Columbia University

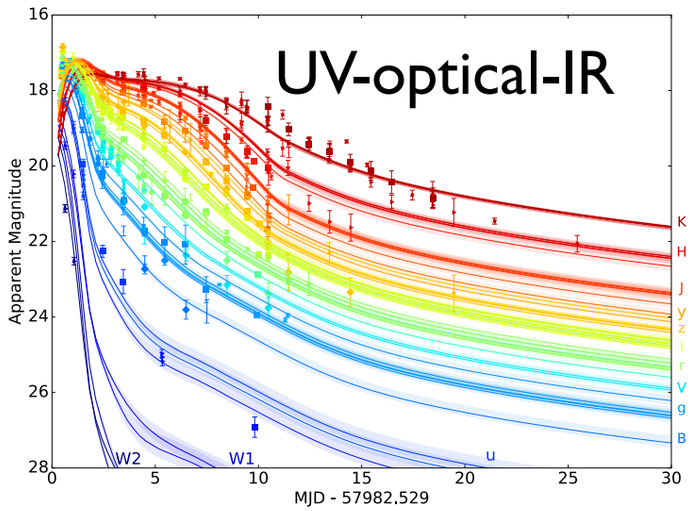
ICTP school *The Sound of Space-time: The Dawn of Gravitational Wave Science*,
Sao Paulo, Dec 10-14, 2018

GW170817 and the firework of EM counterparts

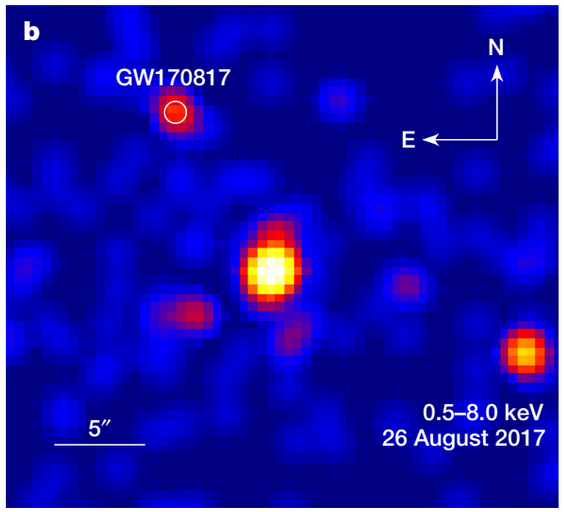


- unique event in astronomy, maybe most important observation since SN 1987A
- unprecedented level of multi-messenger observations
- confirms association of BNS to SGRBs
- kilonova provides strong evidence for synthesis of r-process material

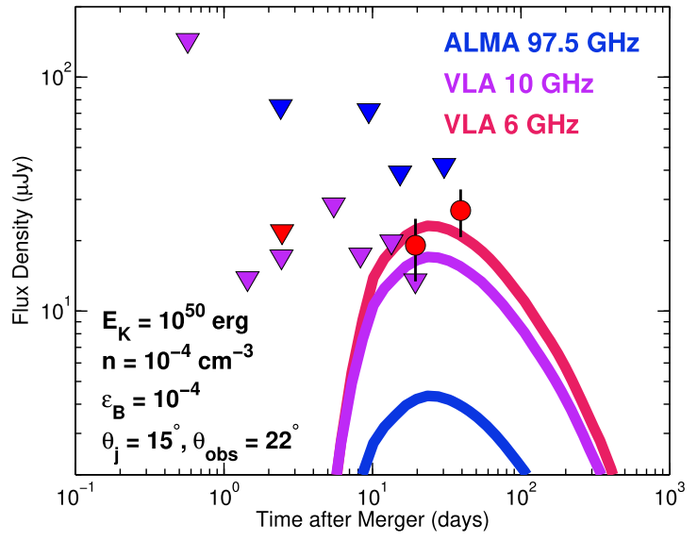
kilonova



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:

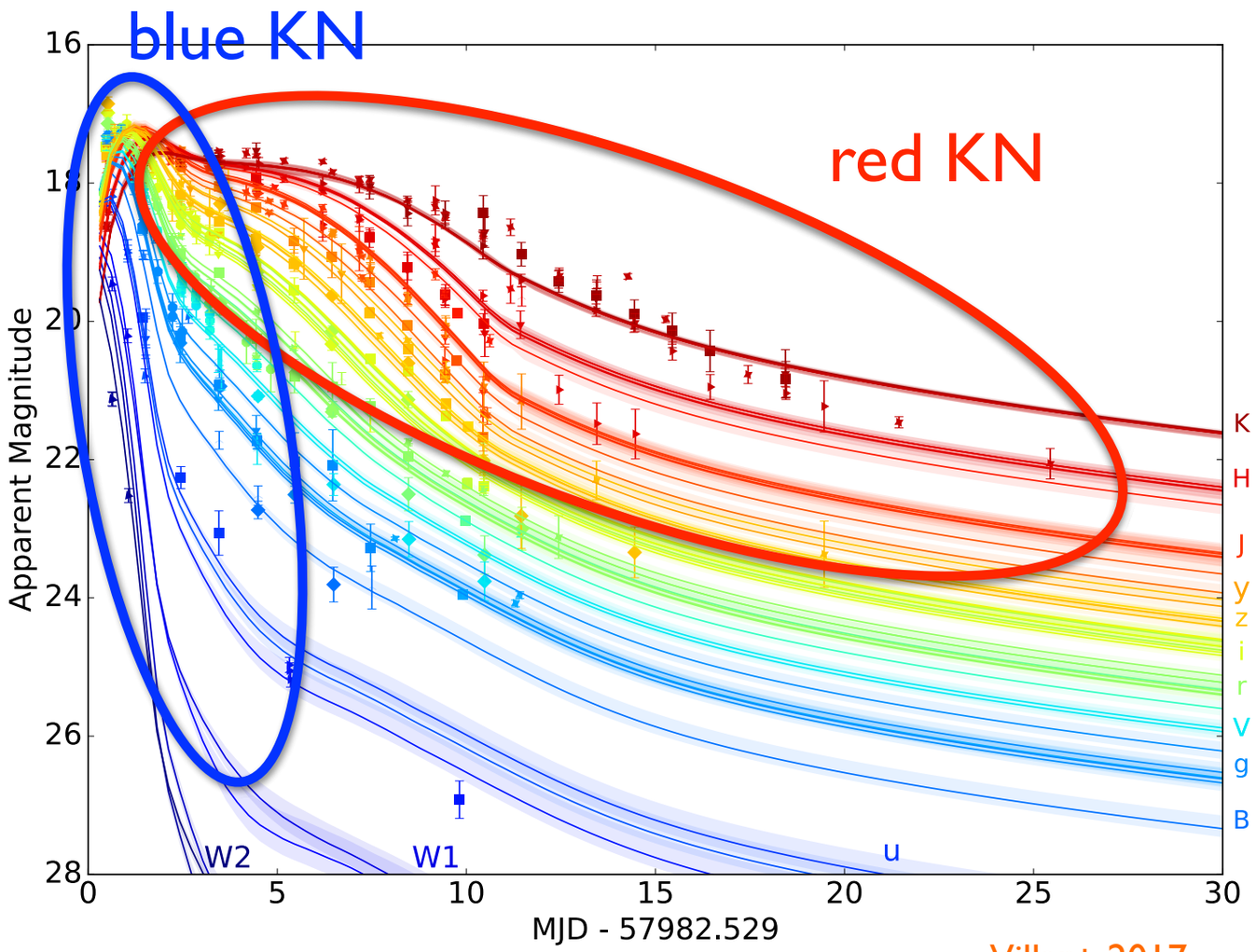
  $M_{ej} \sim 4\text{-}5 \times 10^{-2} M_{sun}$
  $v_{ej} \sim 0.08\text{-}0.14c$
  $Y_e < 0.25$
  $X_{La} \sim 0.01$

  ↓

  heavy r-process elements!

  'lanthanide-rich'

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



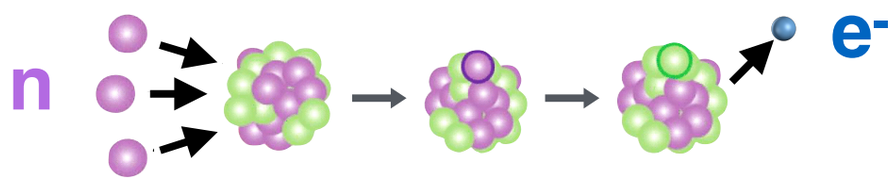
Villar+ 2017

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

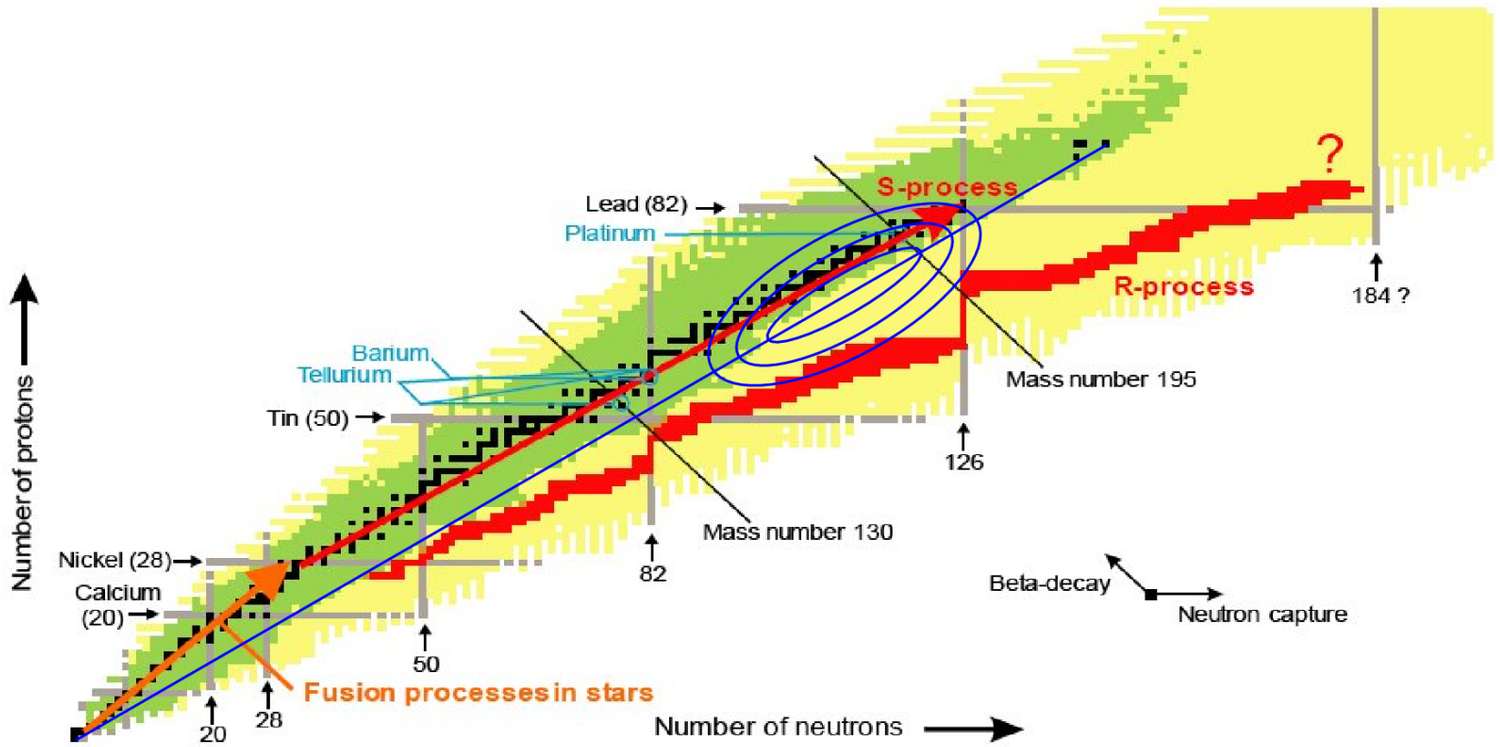


slow neutron capture (s-process):

timescale for neutron capture longer than for β-decay

rapid neutron capture (r-process):

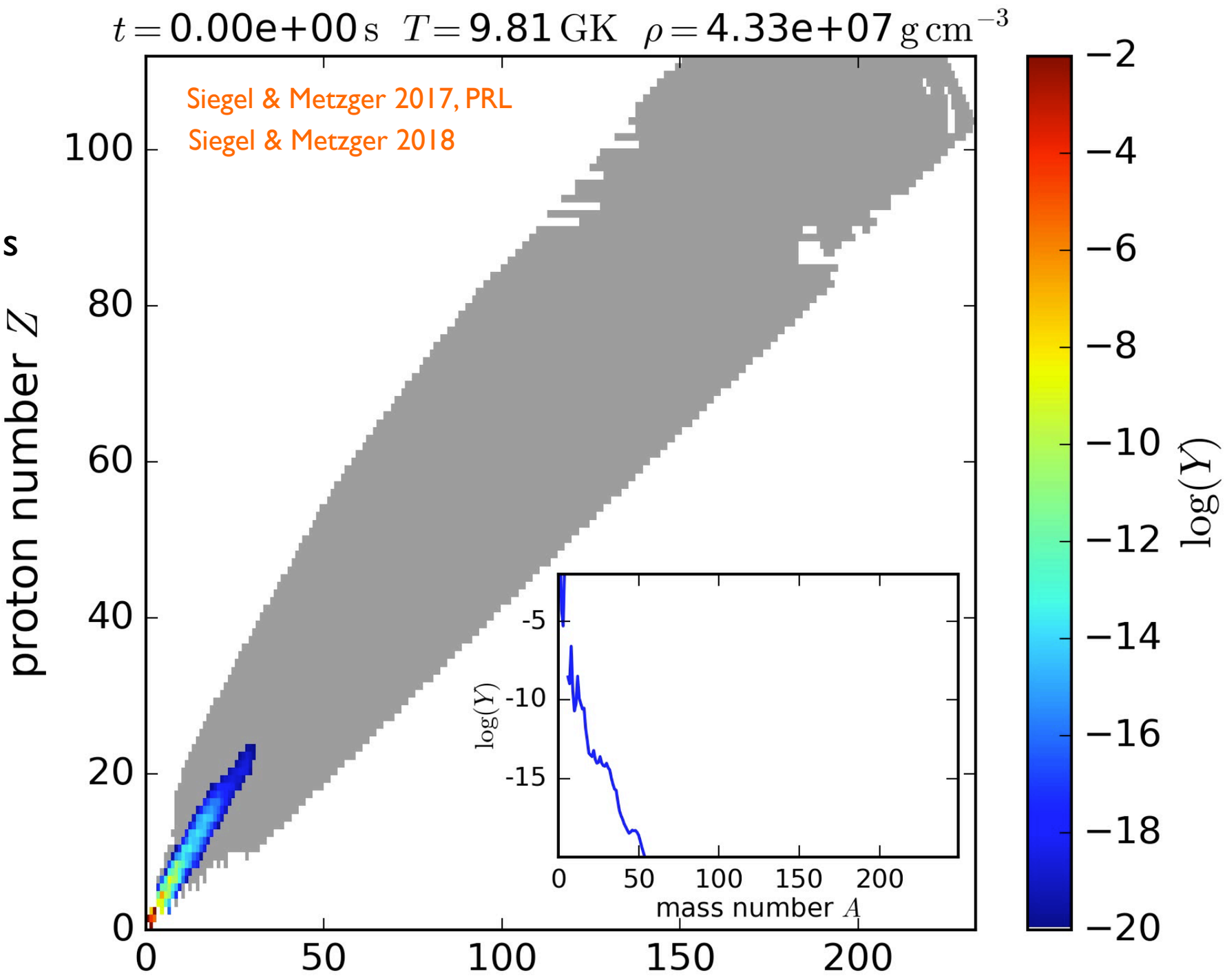
timescale for neutron capture shorter than for β-decay



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

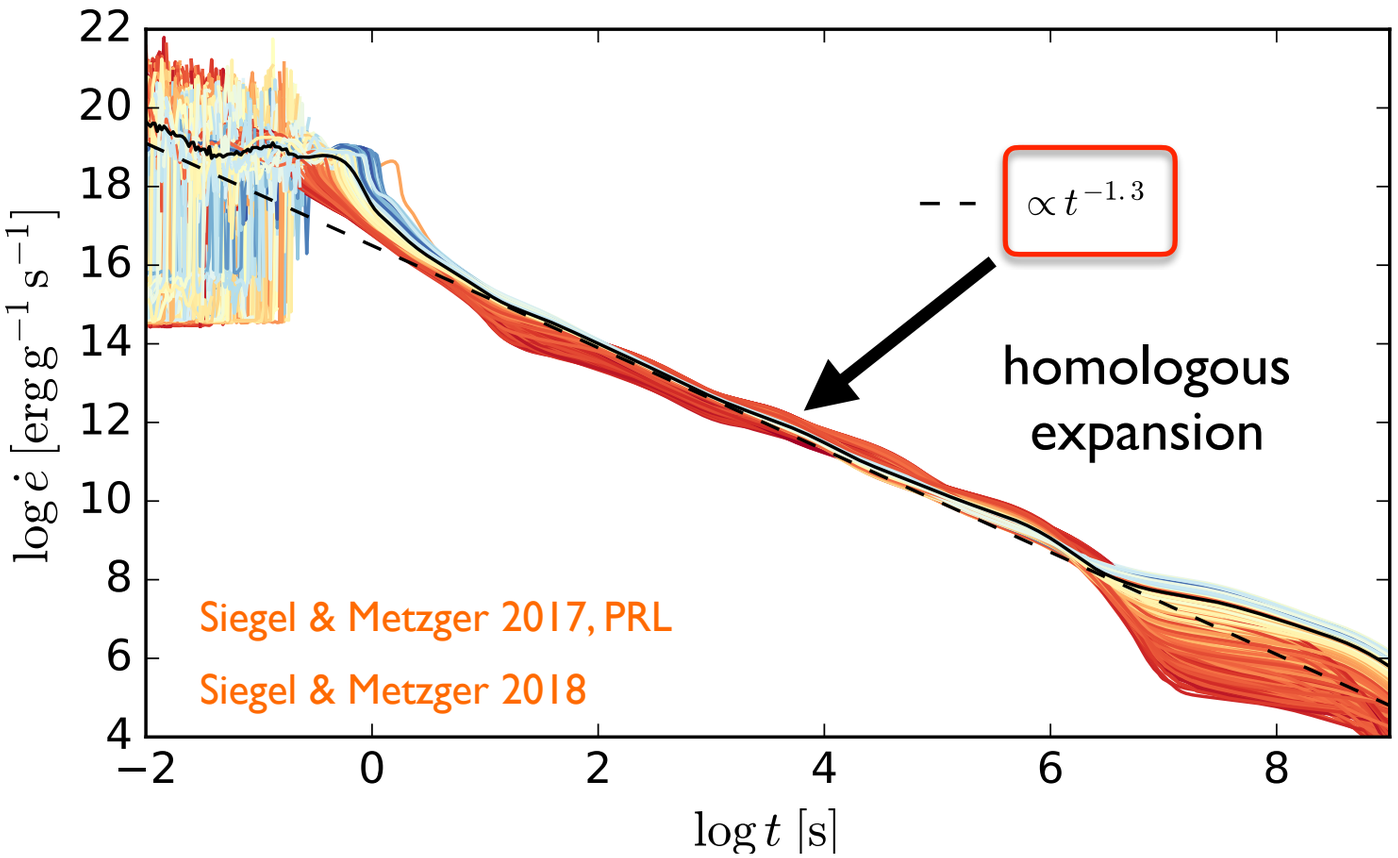
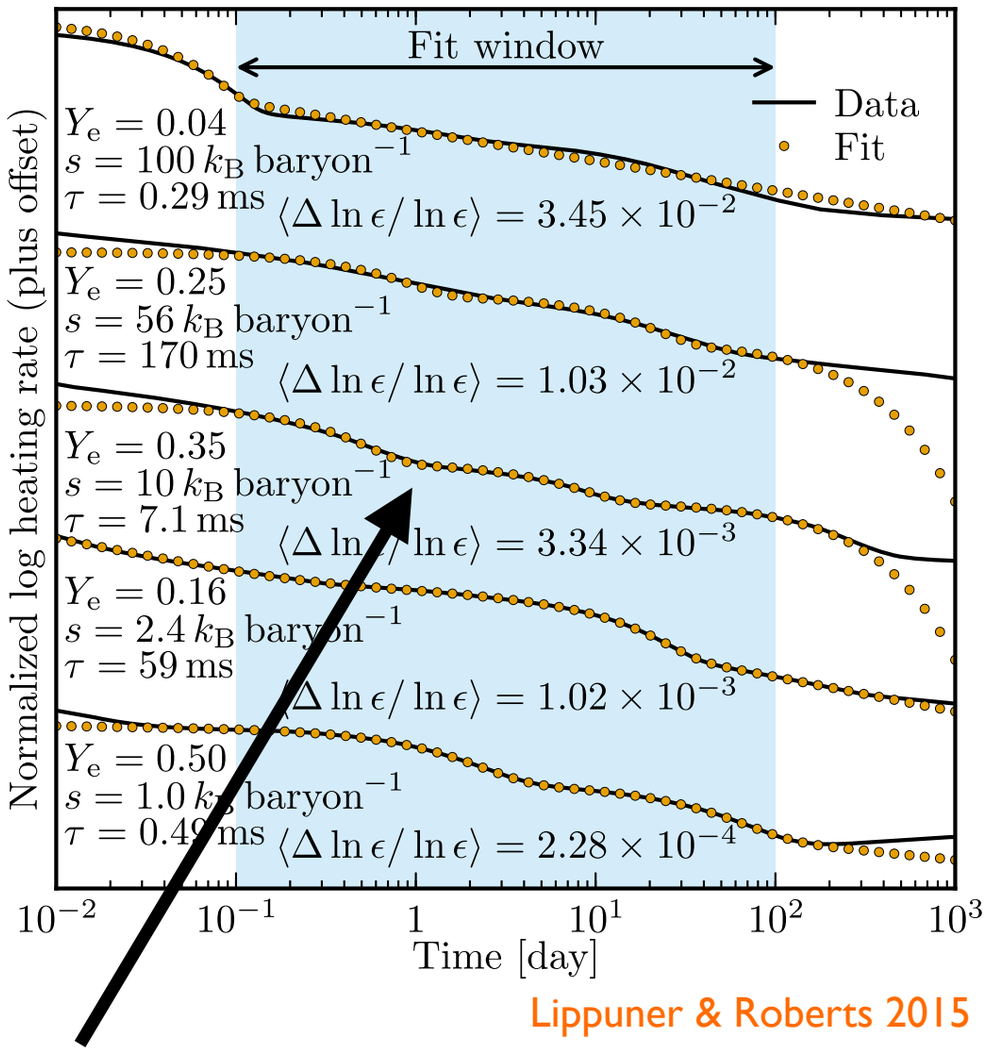


Fig: heating rates from r-process nucleosynthesis in simulations of post-merger disk outflows (lanthanide rich).



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

⟶ may lead to observational identification of specific isotopes Wu+ 2018

Thermalization efficiency

Barnes+ 2016

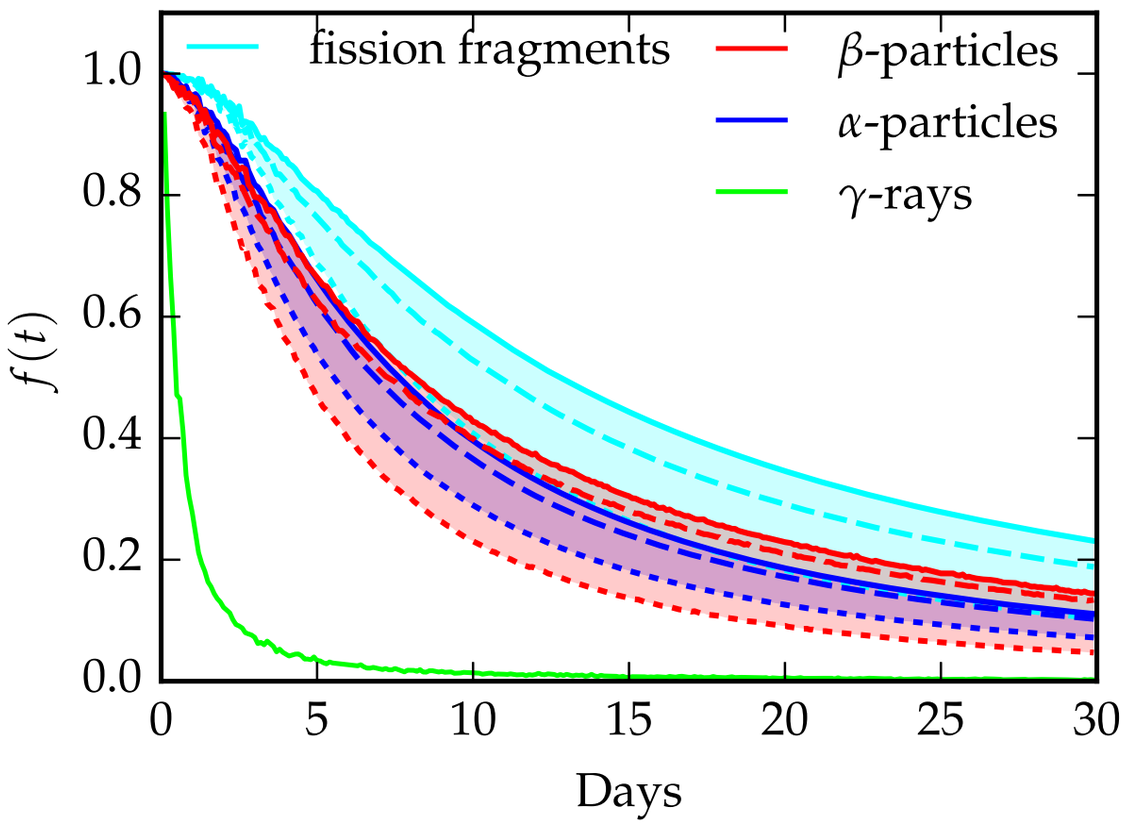


Fig: Example of thermalization efficiencies for all particles, assuming ejecta with M_{ej} = 5e-3 Msun, v_0 = 0.2c.

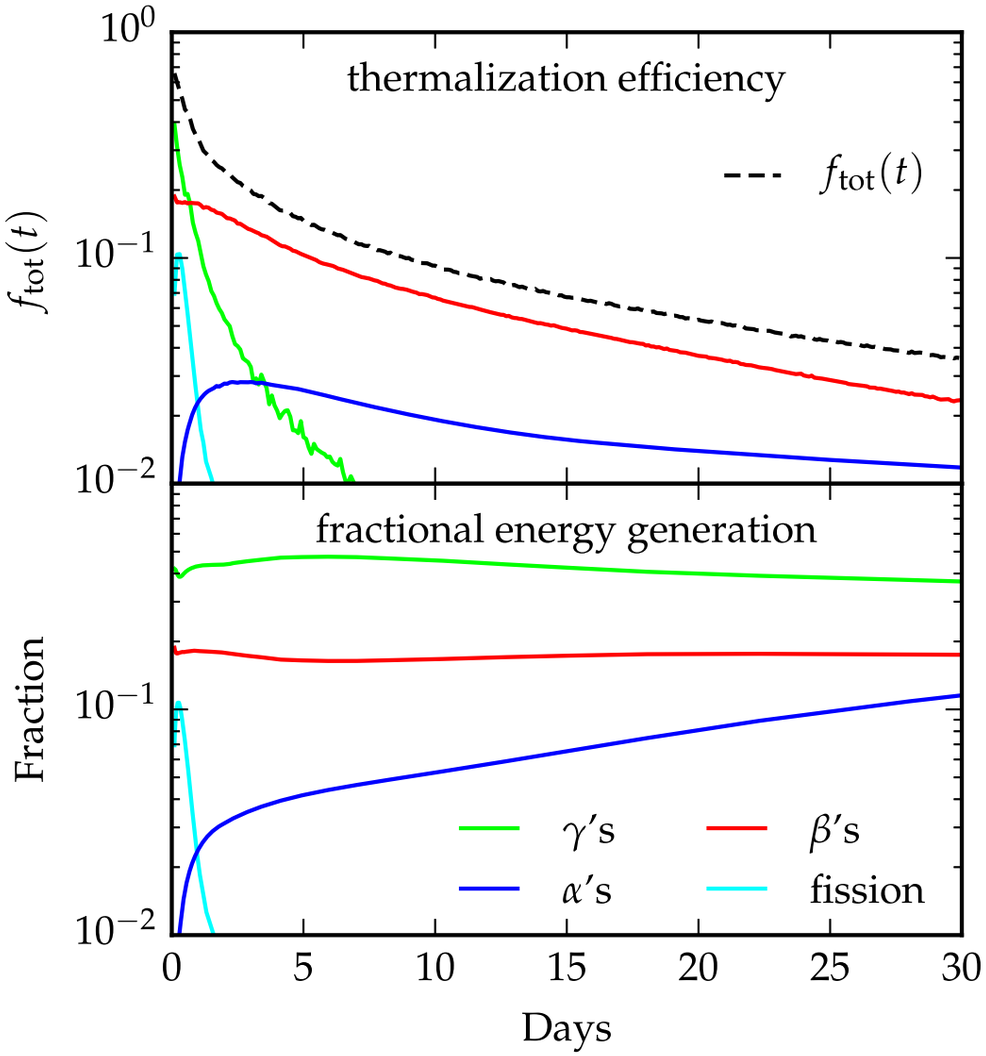


Fig: Thermalization efficiency of all particles convolved with their fractional energy generation.

Effect of thermalization efficiency on lightcurves

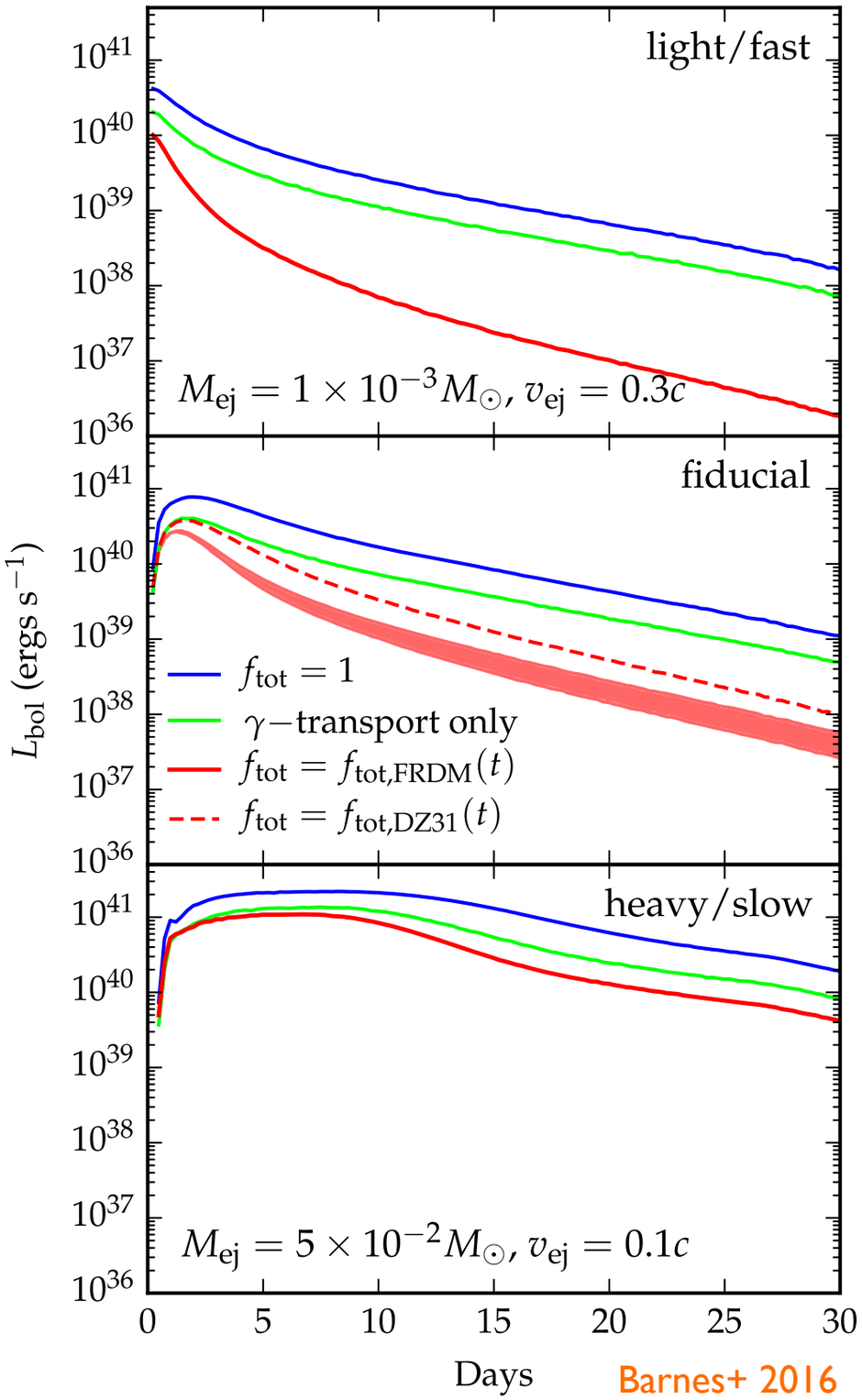
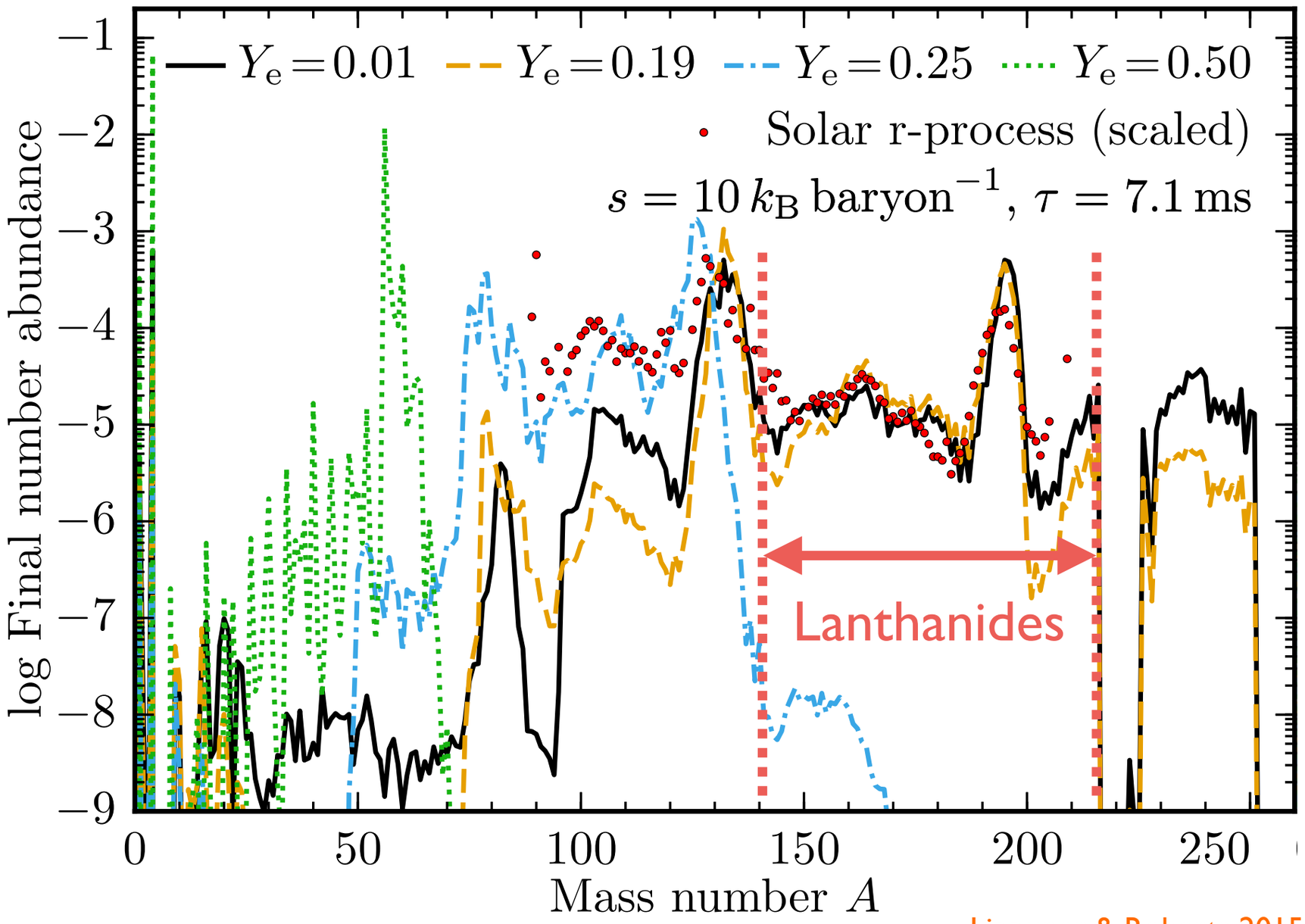


Fig: Impact of thermalization efficiency on kilonova lightcurves (bolometric luminosity). The fiducial model has parameters M_{ej} = 5e-3 Msun, v_0 = 0.2c.

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*:

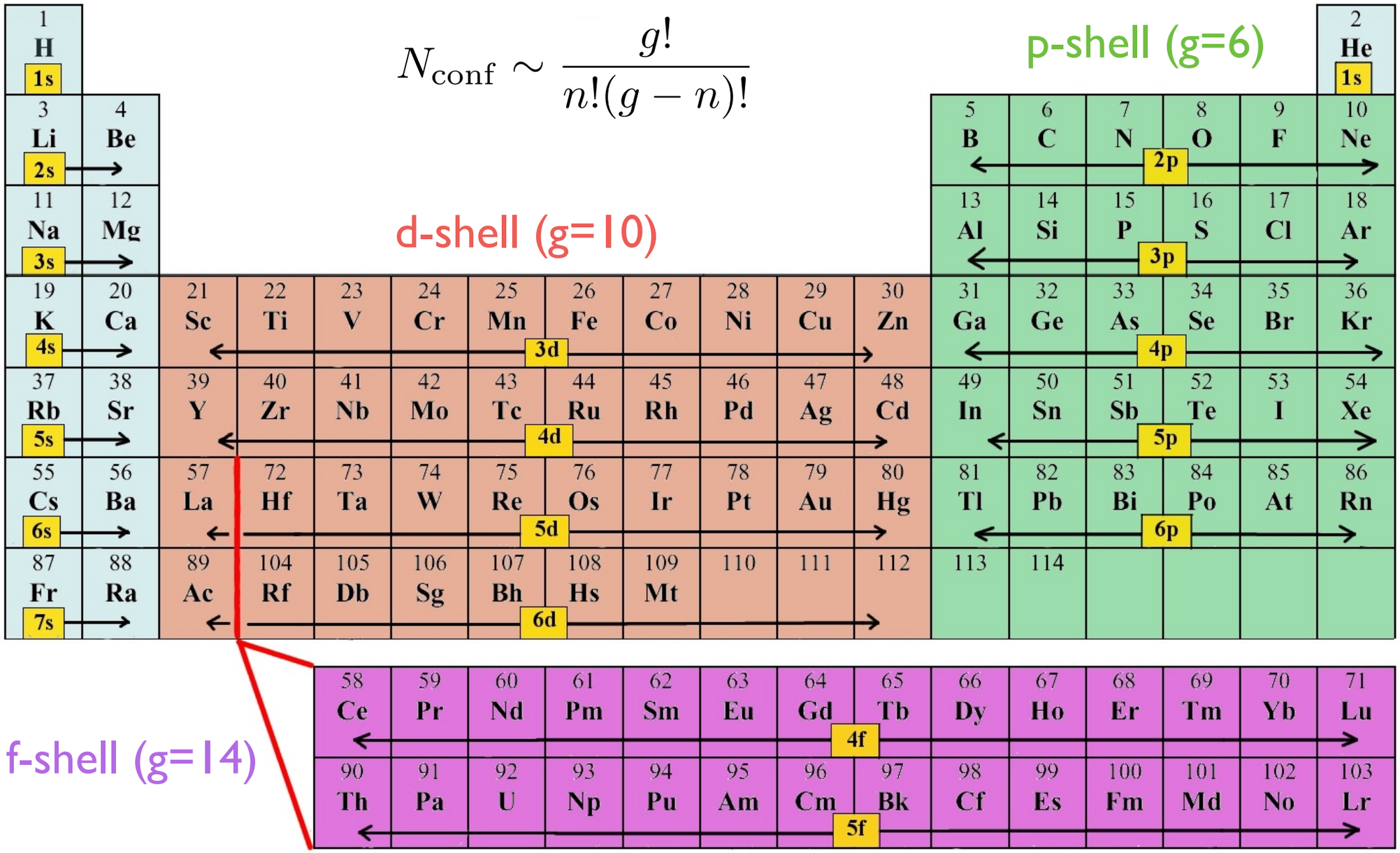
$$N_{\rm conf} \sim \frac{g!}{n!(g-n)!}$$

s-shell (g=2)

p-shell (g=6)

d-shell (g=10)

f-shell (g=14)



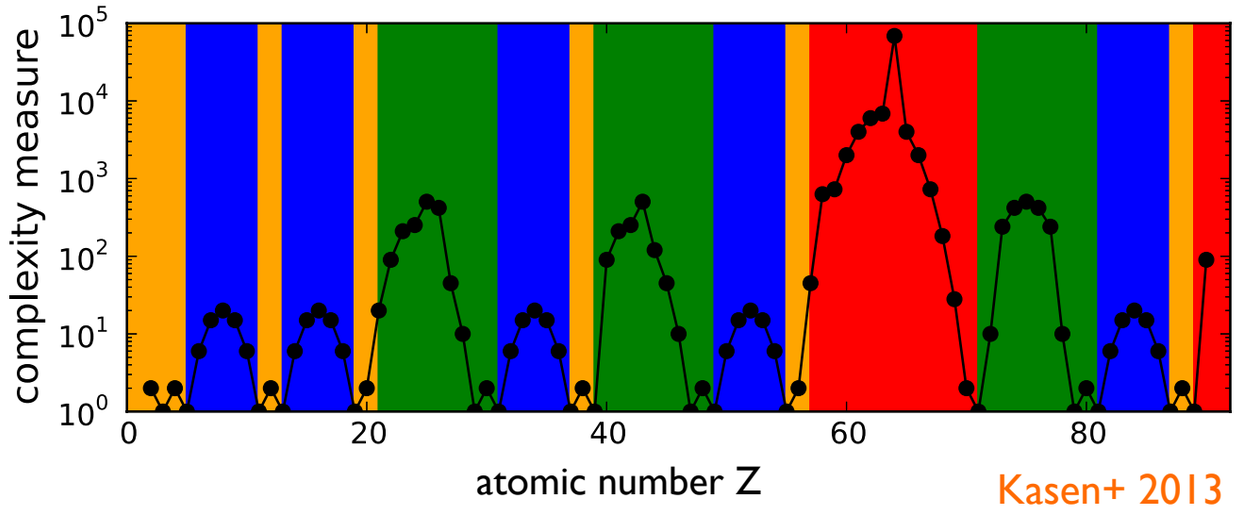
High opacities of the Lanthanides

Kasen+ 2013, Barnes & Kasen 2013

open shells

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

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



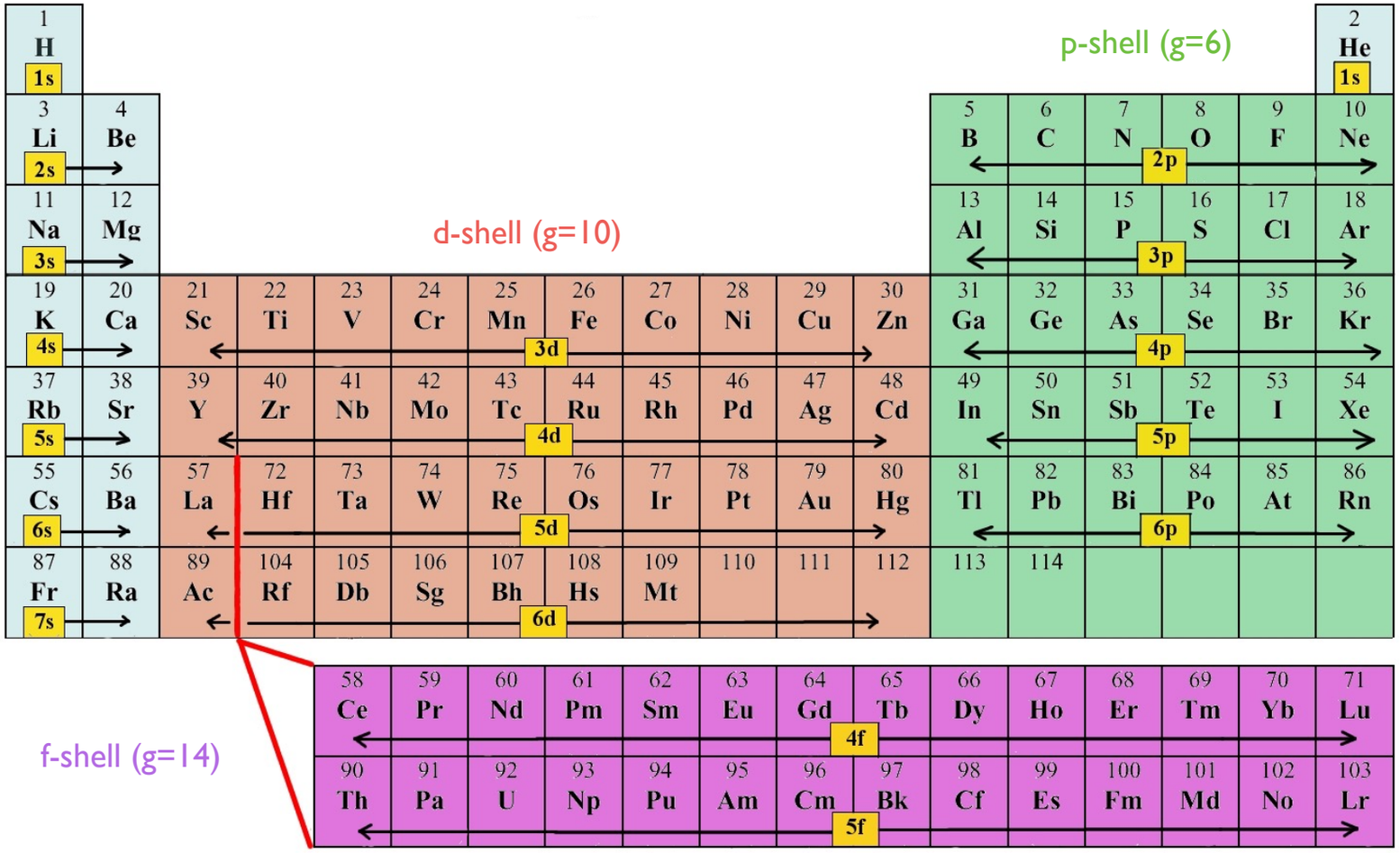
Kasen+ 2013

s-shell (g=2)

p-shell (g=6)

d-shell (g=10)

f-shell (g=14)



shells: s p d f

High opacities of the Lanthanides

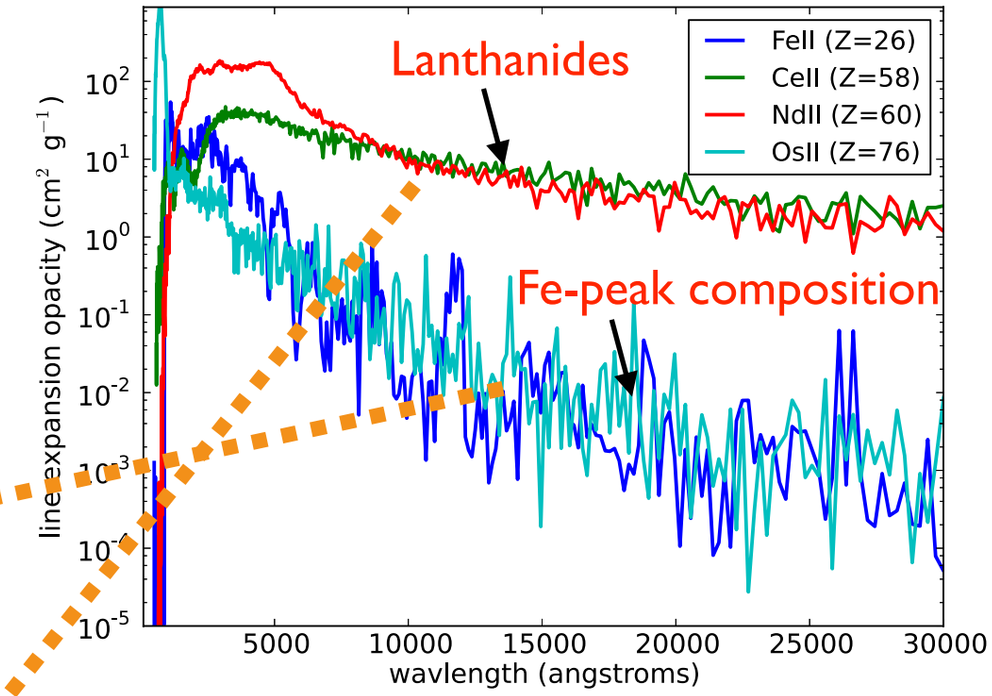
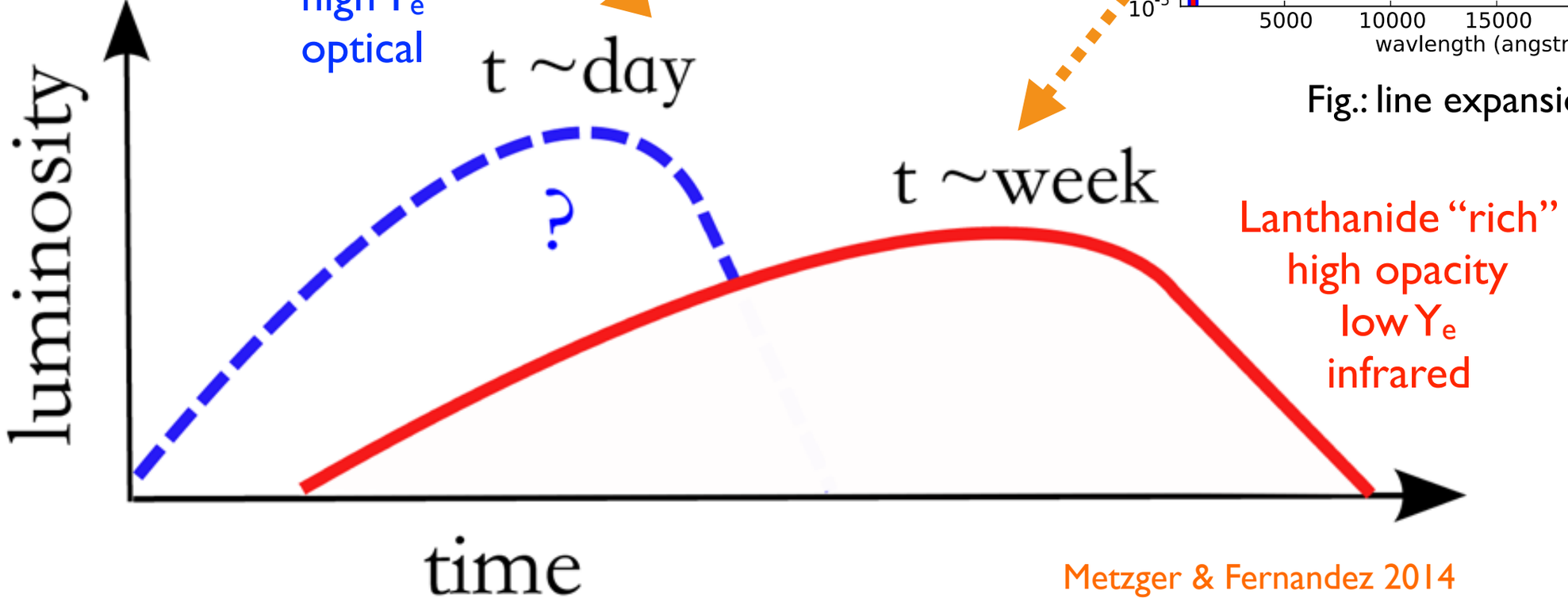


Fig.: line expansion opacities

Kasen+ 2013



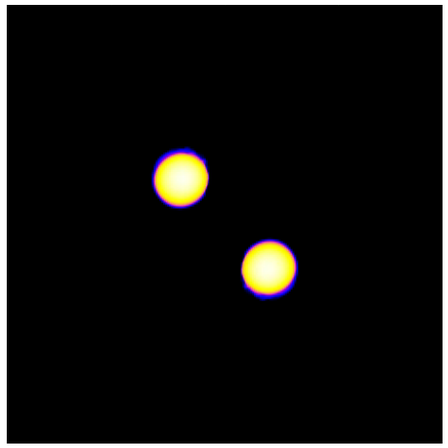
Metzger & Fernandez 2014

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

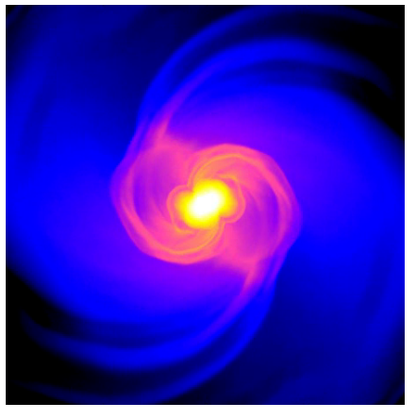
Origin of neutron-rich ejecta

NS merger phenomenology

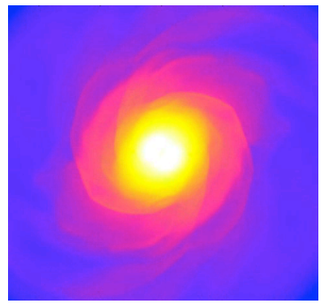
NS—NS



SMNS / HMNS

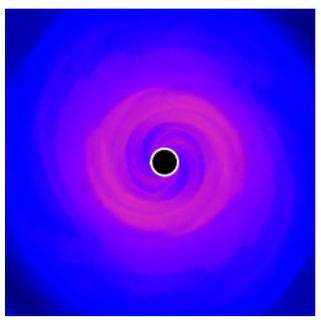


long-lived NS

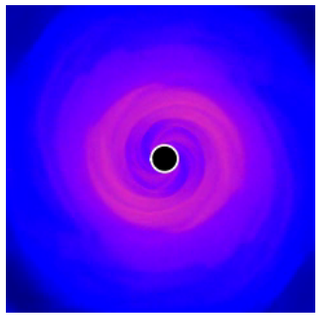


prompt collapse

BH - torus

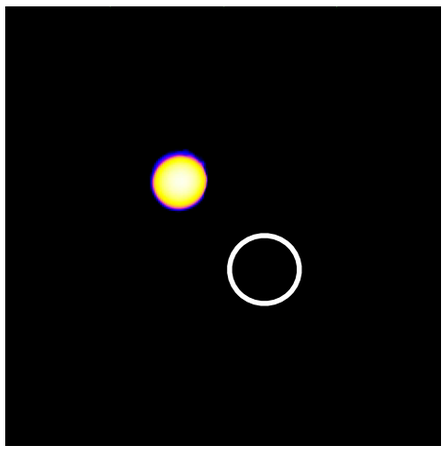


BH - torus

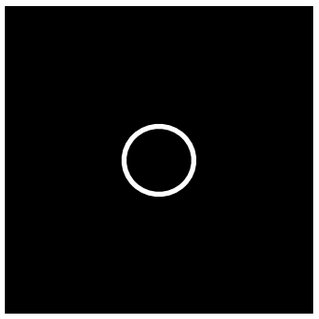


sim. & vis.: W. Kastaun

BH—NS



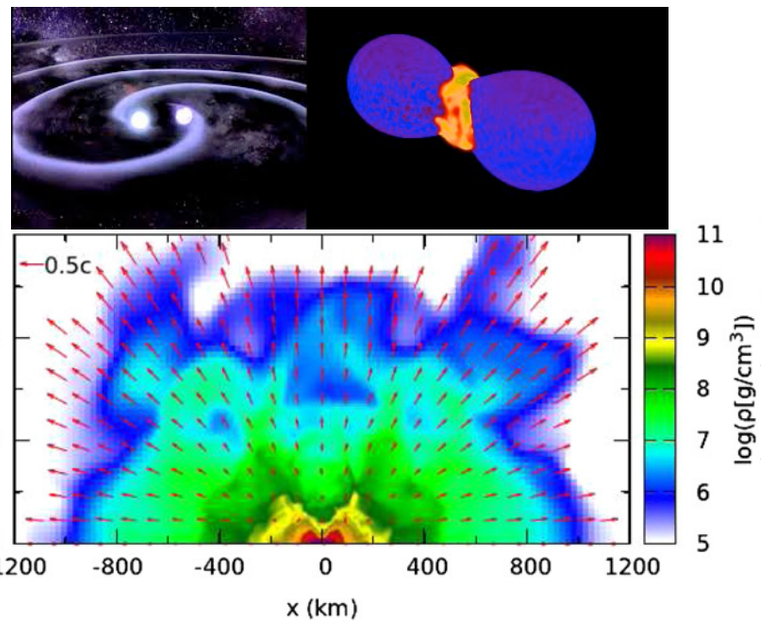
BH



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

Sources of ejecta in NS mergers

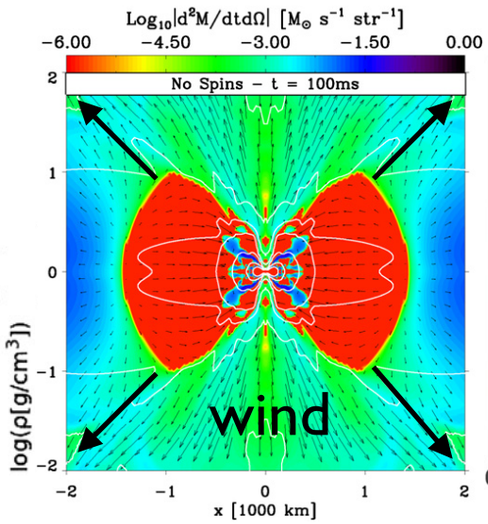
dynamical ejecta (~ms)



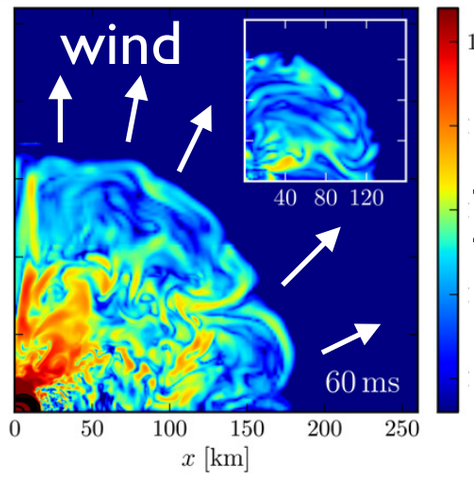
Hotokezaka+ 2013, Bauswein+ 2013

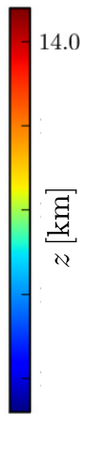
tidal ejecta
shock-heated ejecta

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



Dessart+ 2009

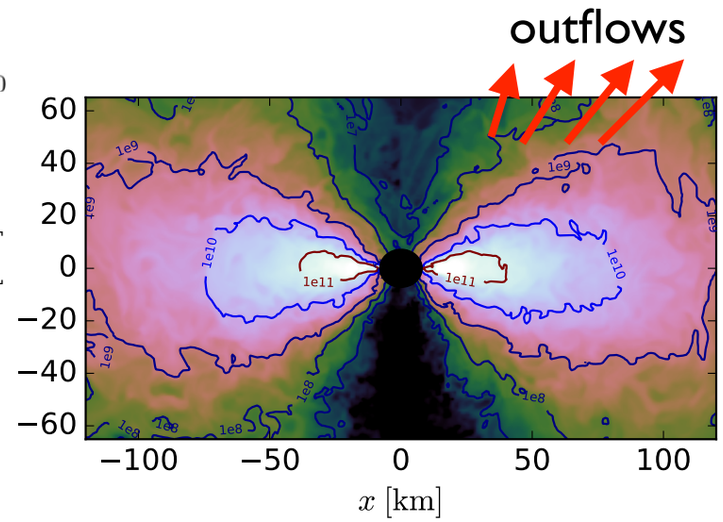




Siegel+ 2014
Ciolfi, Siegel+ 2017

(binary NS mergers only!)

accretion disk (~10ms-1s)

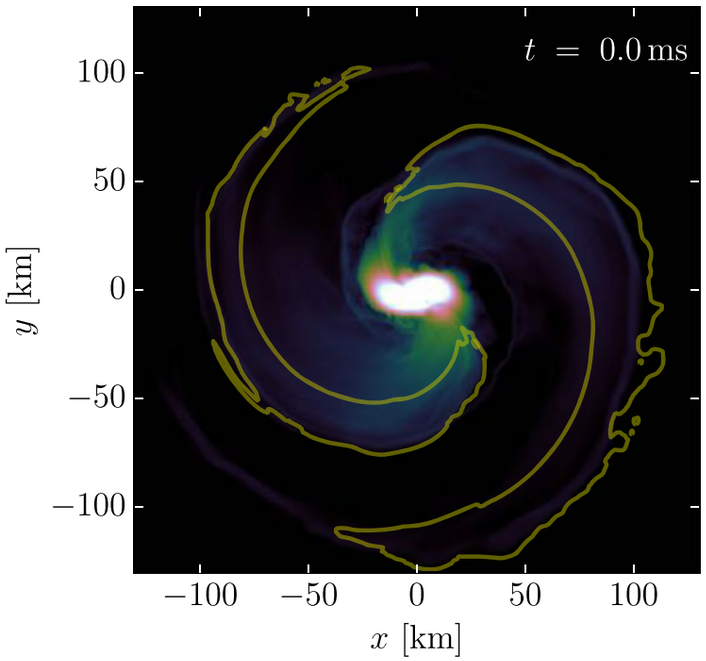


Siegel & Metzger 2017 PRL

disk outflows

Dynamical ejecta (~ms)

tidal ejecta

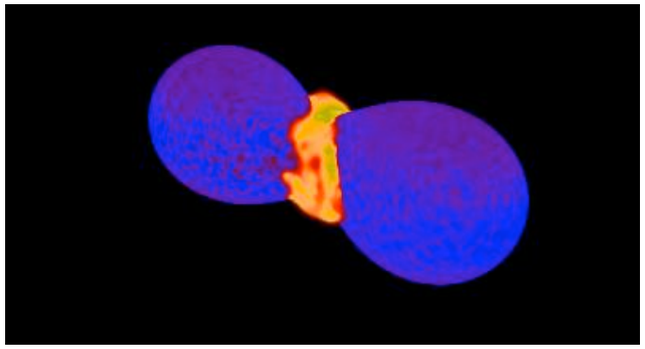


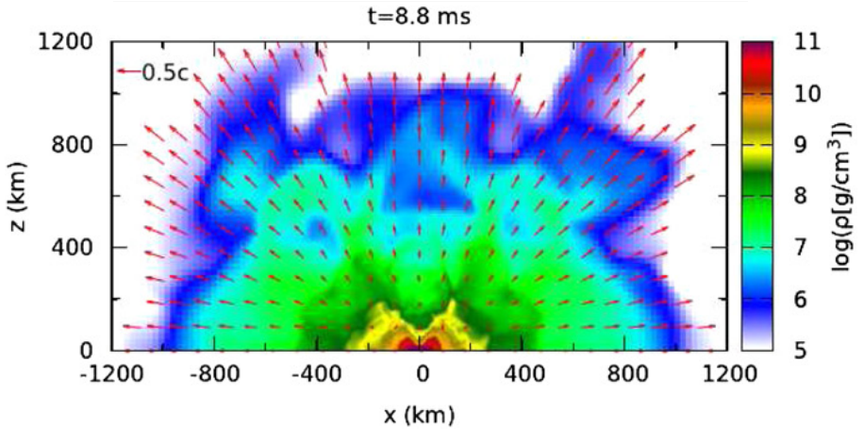
Ciolfi, Siegel+ 2017

- 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

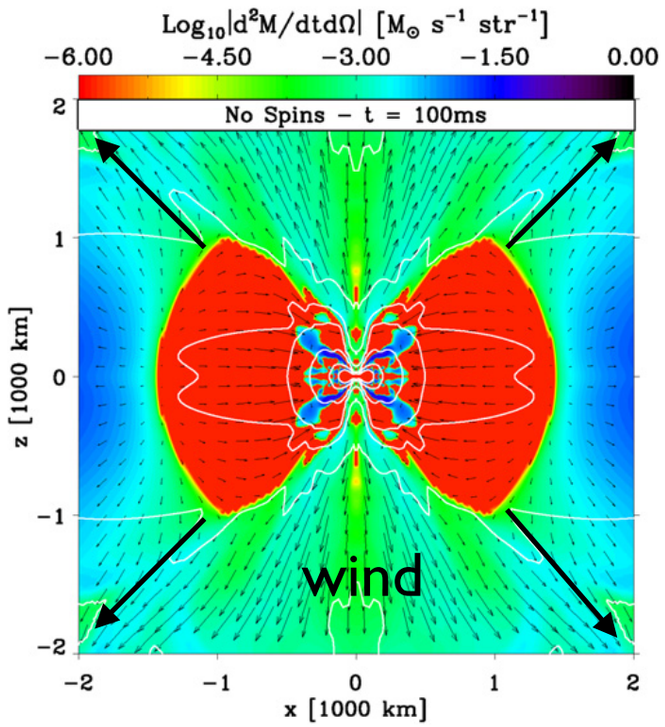
- squeezed out from the shock interface at merger
- fast: v > 0.2c
- shock-heated → hot: T ~ 10 MeV
- strong neutrino emission raises Y_e (Y_e > 0.25)

fast blue kilonova transient

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

Winds from remnant (metastable) NS

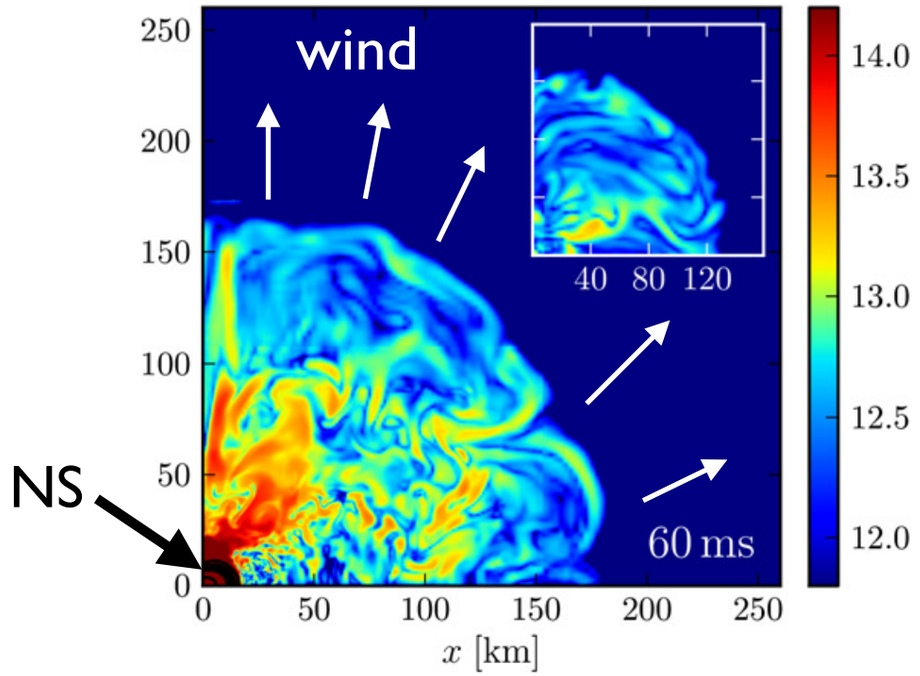
neutrino-driven winds



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

magnetically driven winds



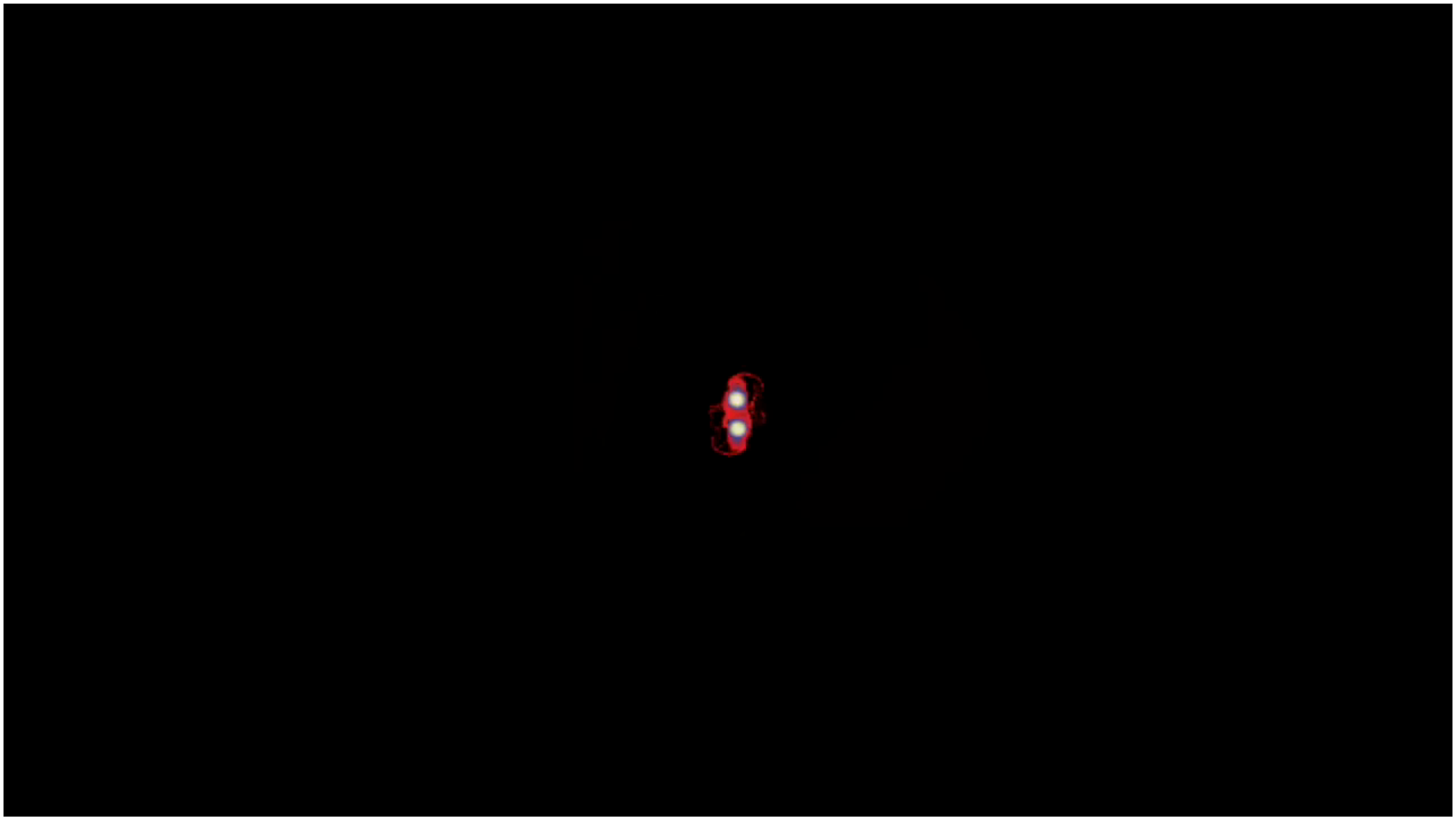
Siegel+ 2014 Ciolfi, Siegel+ 2017

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

slow blue kilonova transient

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

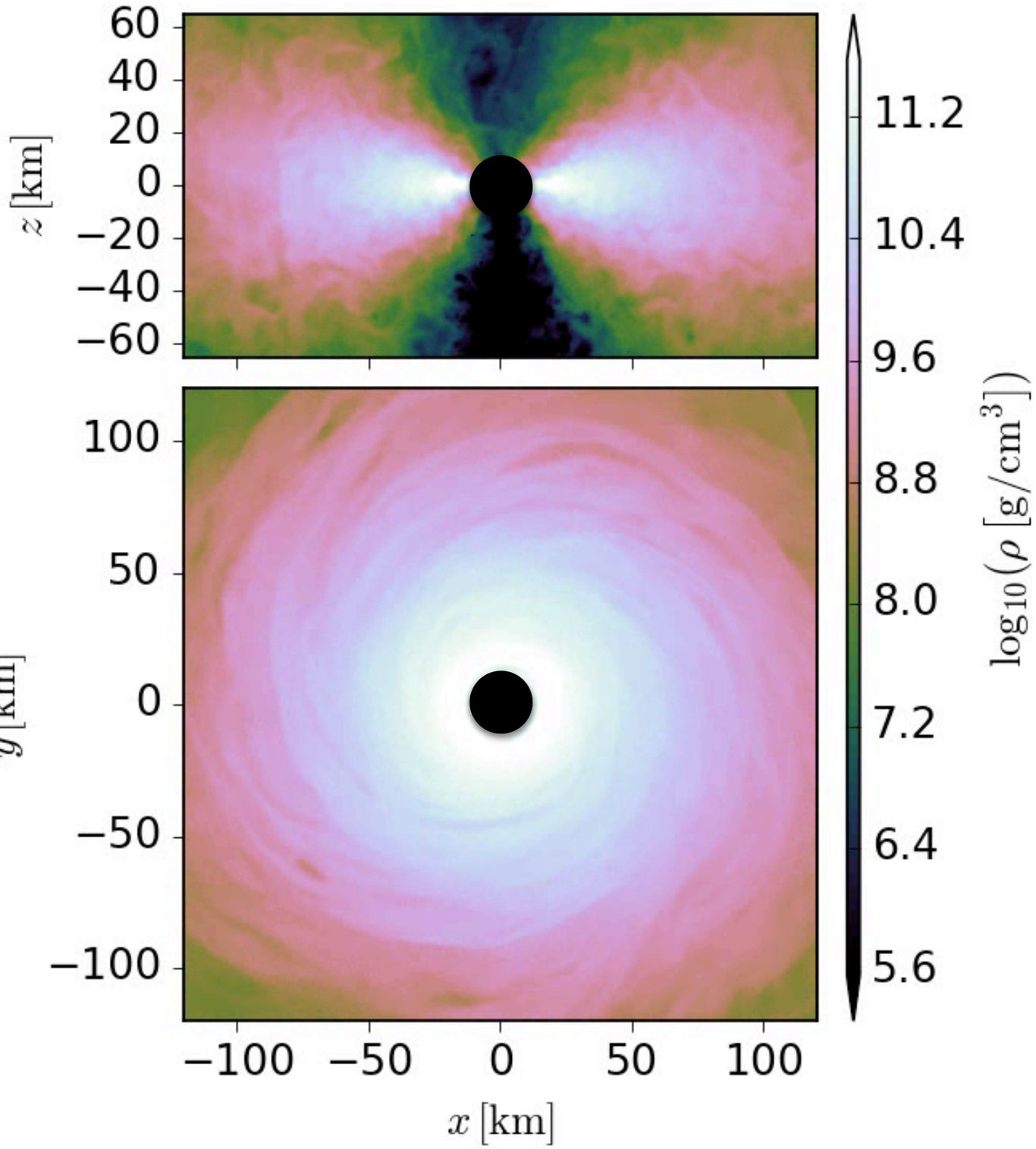
Dynamical ejecta and winds



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

Post-merger accretion disk outflows

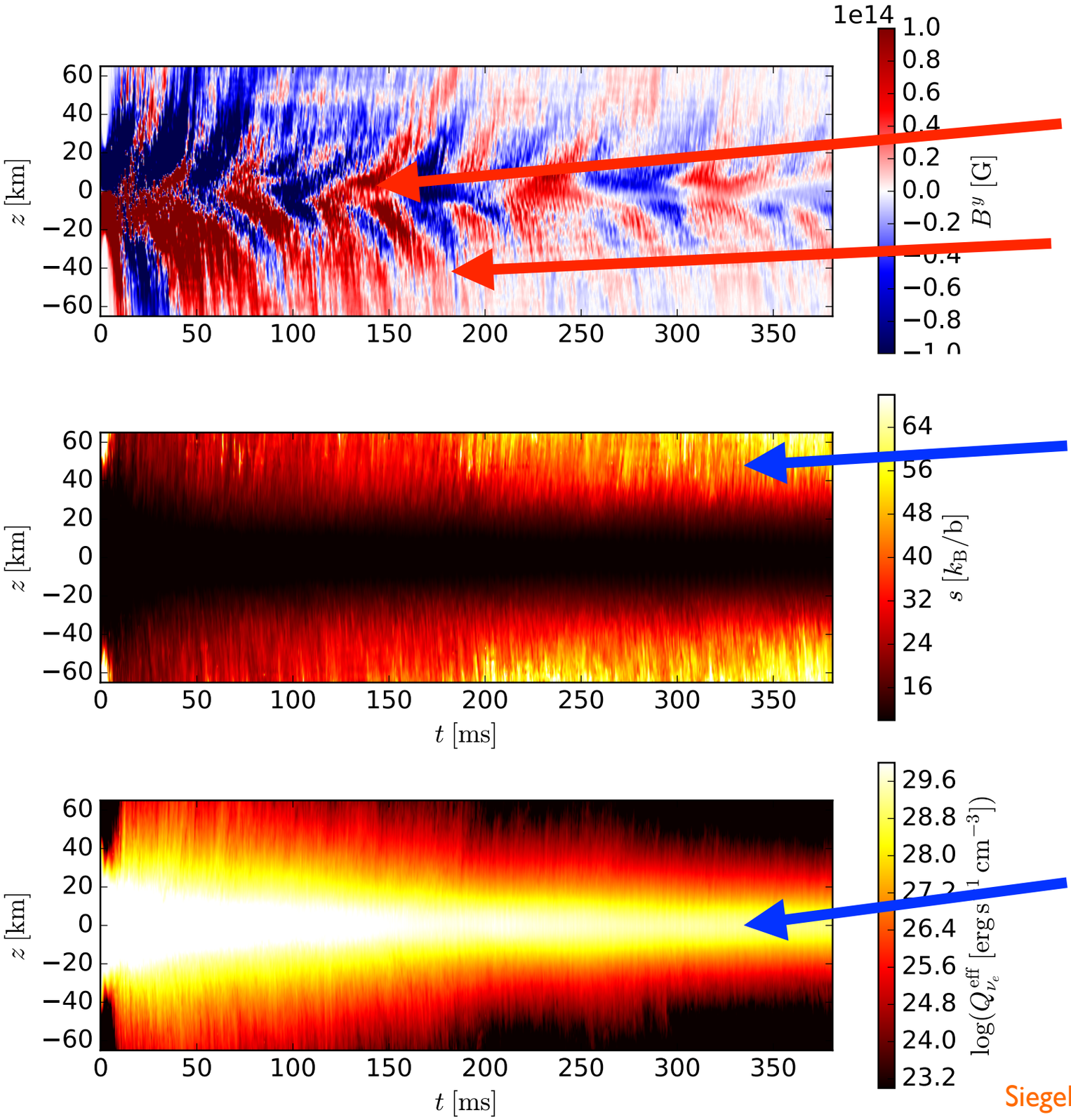
Siegel & Metzger 2017, PRL Siegel & Metzger 2018a



- 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

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

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"

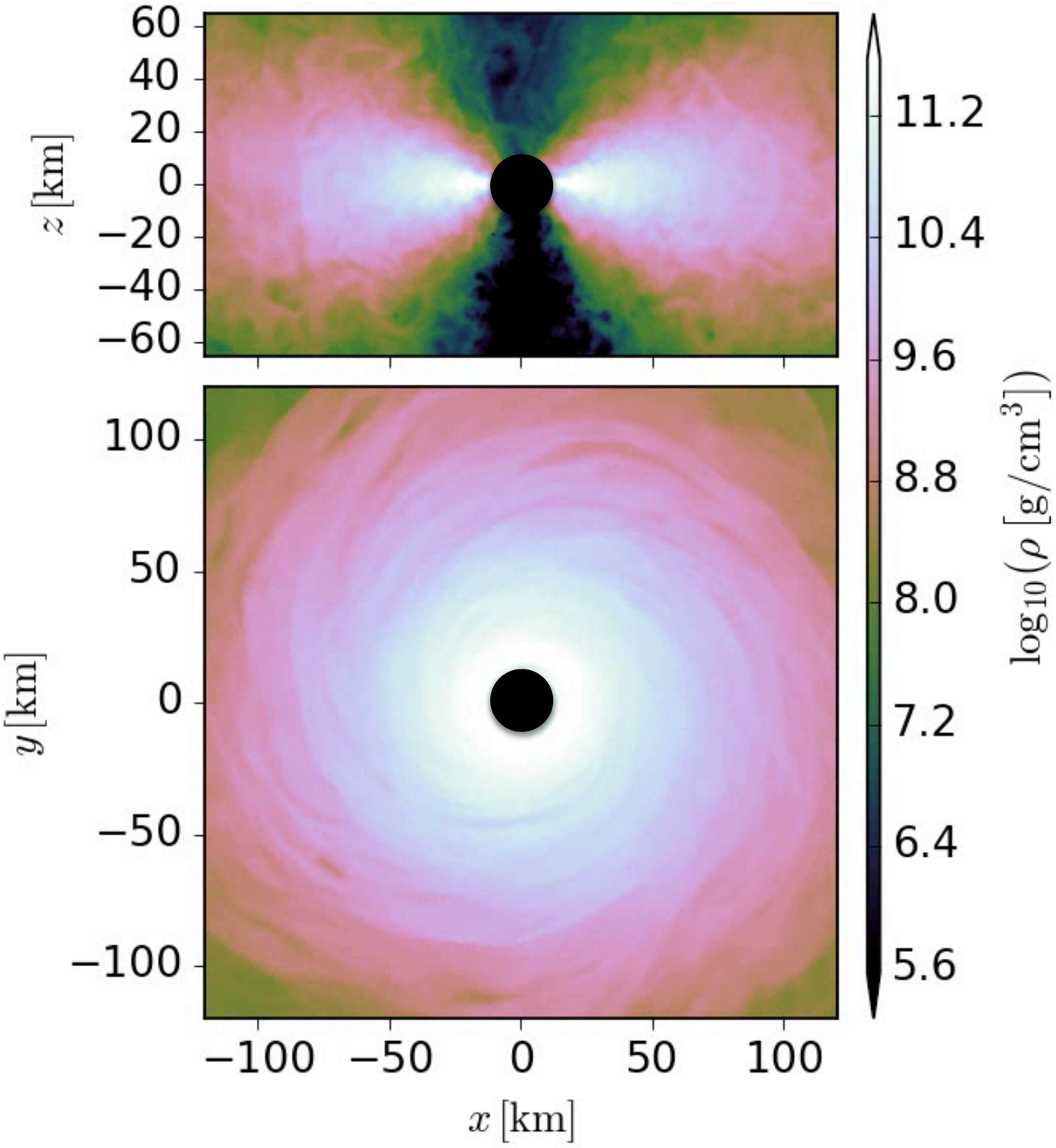
hot corona launches thermal outflows (neutron-rich wind)

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

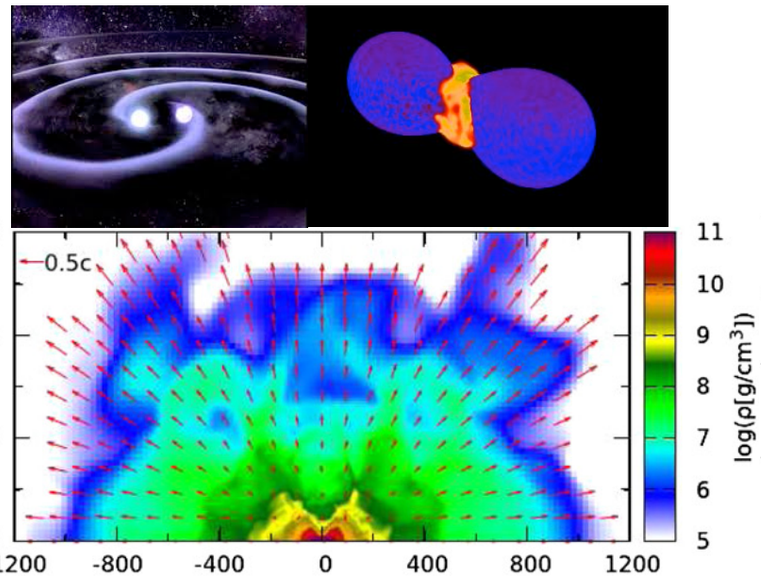
slow red kilonova (BH)

slow blue kilonova (long-lived remnant)

Lippuner+ 2017

Sources of ejecta in NS mergers

dynamical ejecta (~ms)

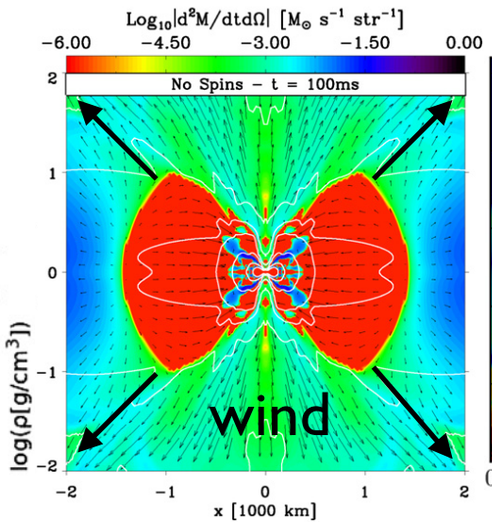


Hotokezaka+ 2013, Bauswein+ 2013

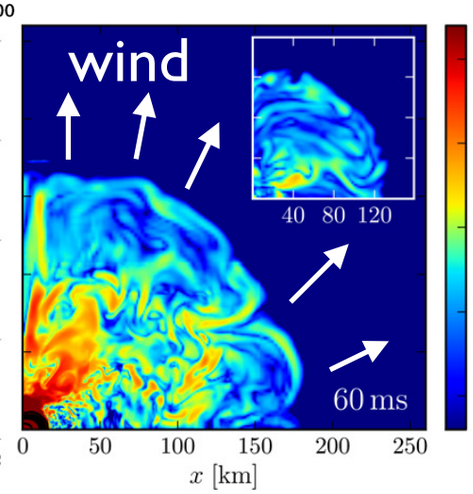
tidal ejecta
shock-heated ejecta

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

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



Dessart+ 2009



Siegel+ 2014

Ciolfi, Siegel+ 2017

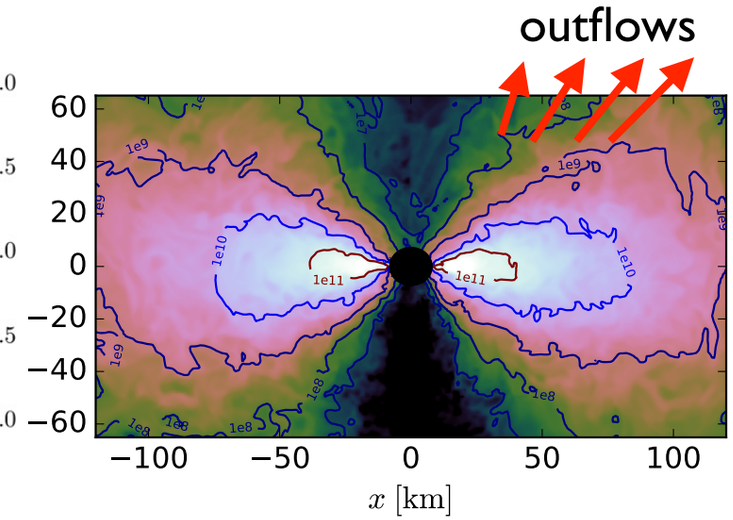
neutrino-driven wind

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

magnetically driven wind

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

accretion disk (~10ms-1s)



Siegel & Metzger 2017, 2018

thermal outflows

$$M_{\rm tot} \gtrsim 0.3 - 0.4 M_{\rm disk}$$
$$v \sim 0.1c$$

Siegel & Metzger 2017, 2018

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

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

lower limit