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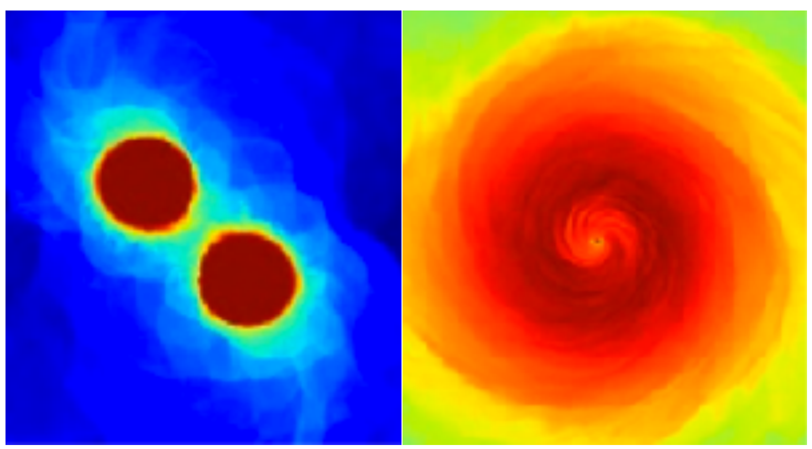
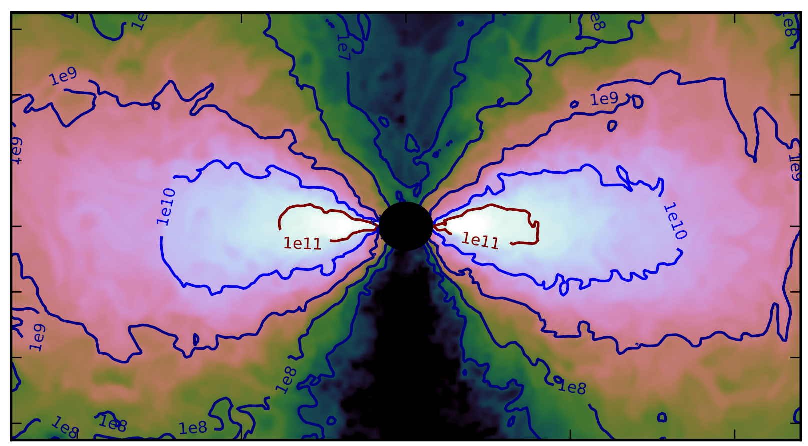
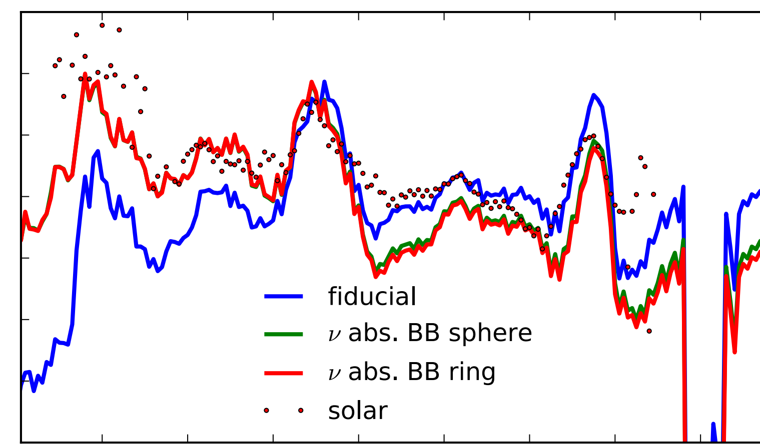
The Cosmic Origin of the Heavy Elements: Implications from the Neutron Star Merger GW170817







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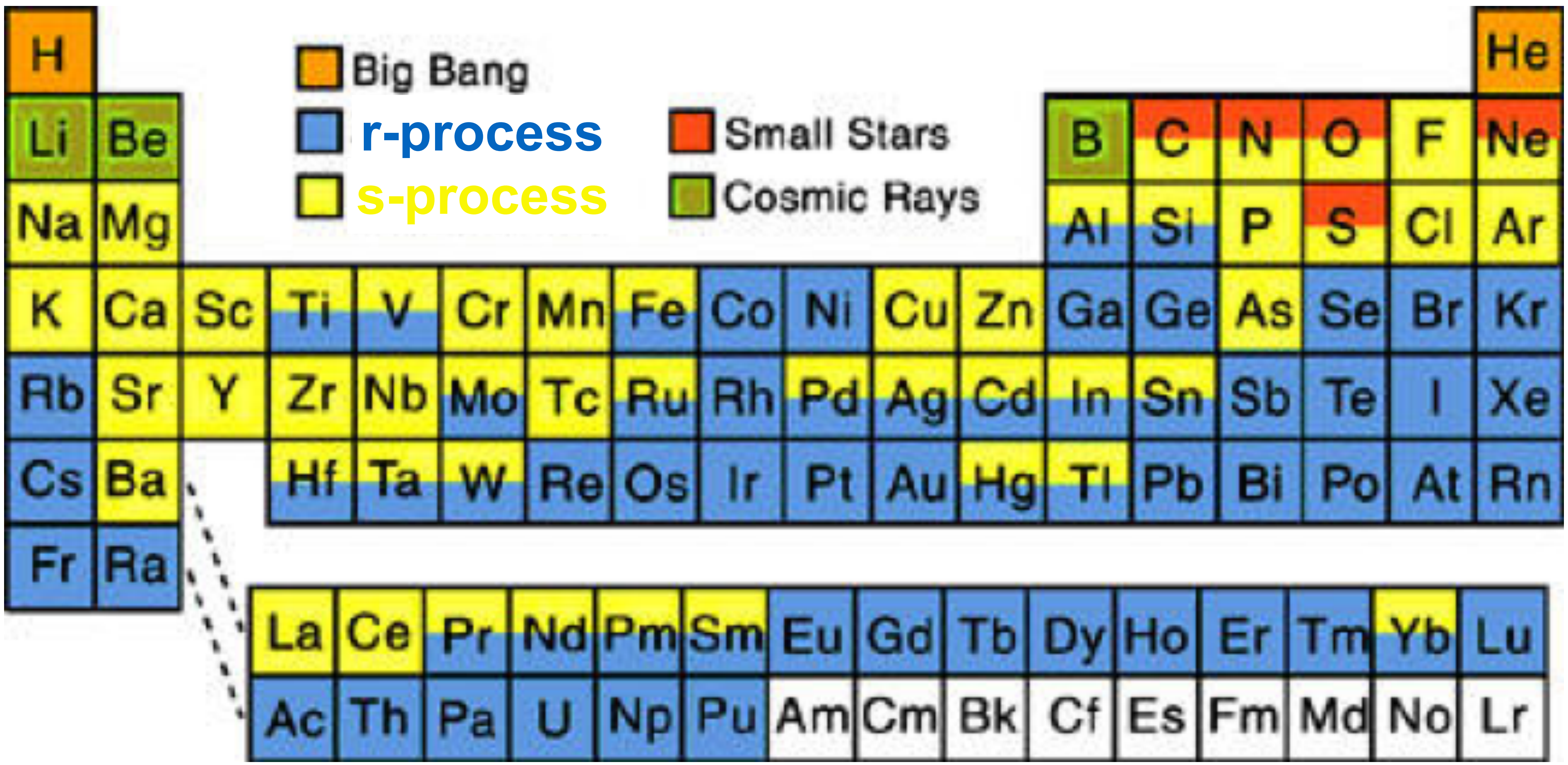
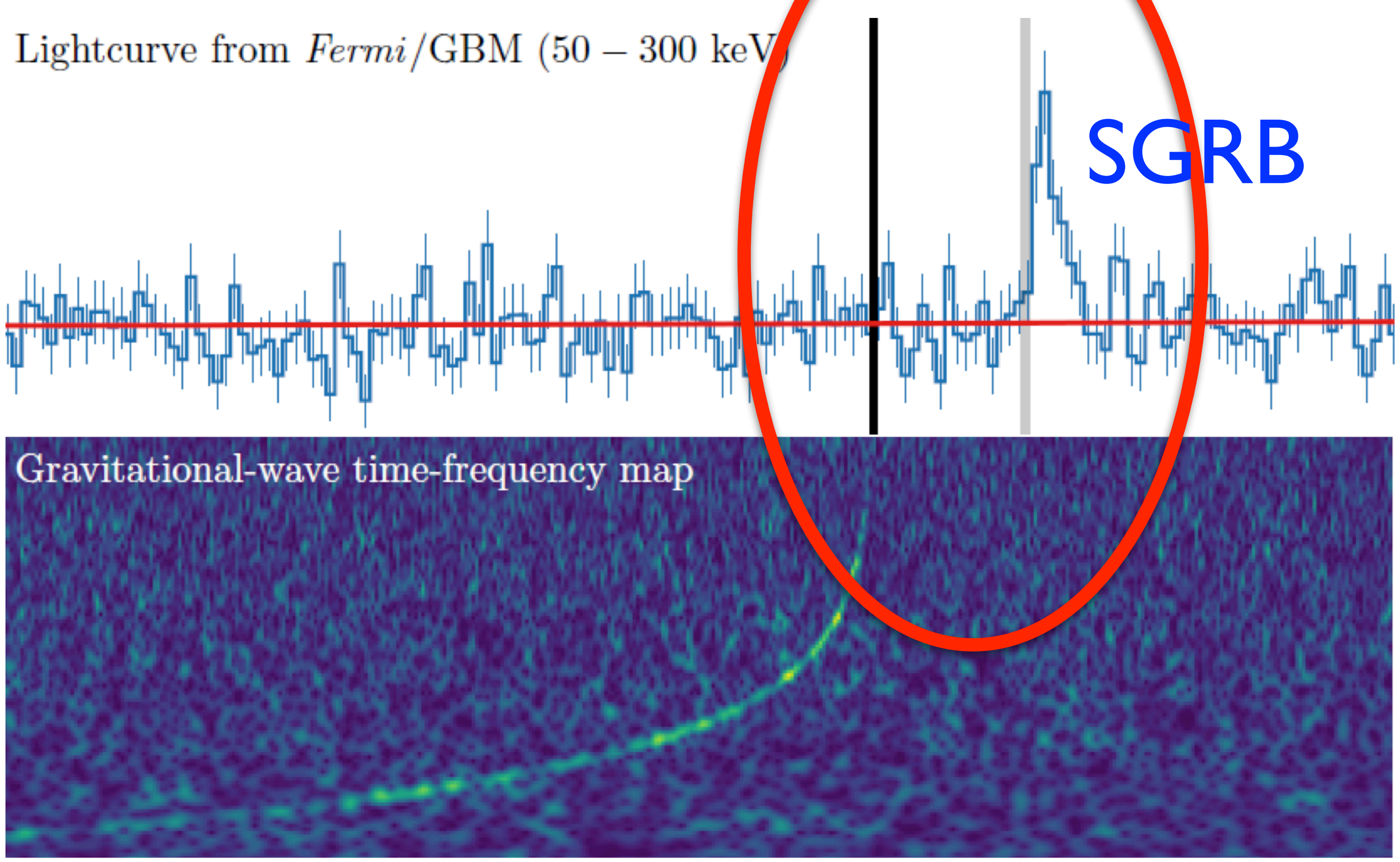
CIPANP, Palm Springs, May 30, 2018

The origin of the elements



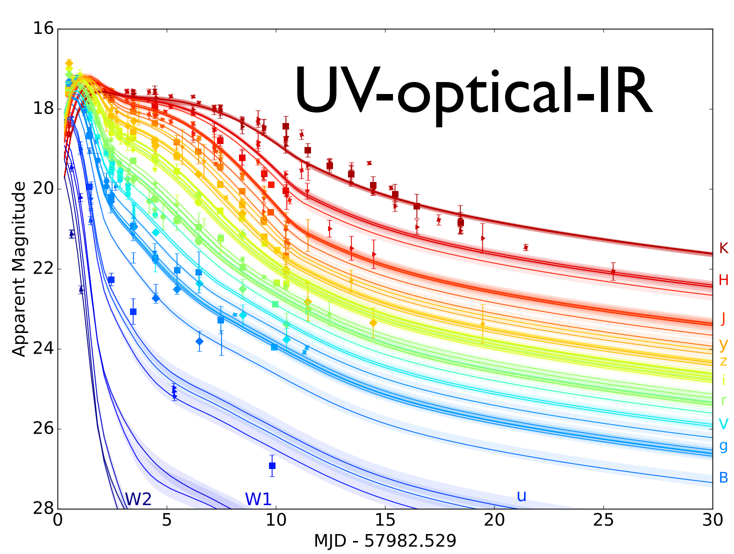
How are the heavy elements formed?

GW170817 and the firework of EM counterparts

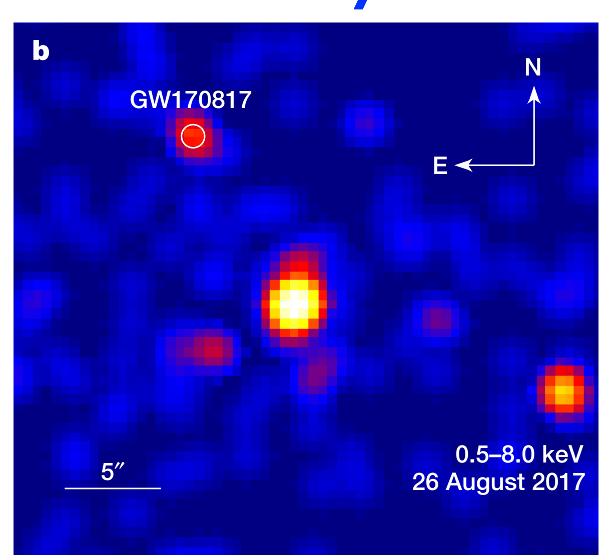


- unique event in astronomy, maybe most important observation since SN 1987A
- unprecedented level of multi-messenger observations
- confirms association of BNS to SGRBs
- kilonova provides strong evidence for synthesis of r-process material

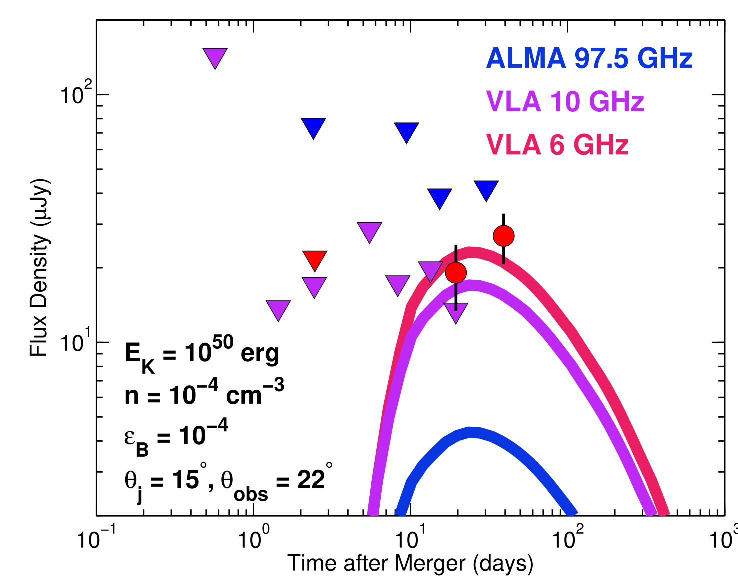
kilonova



X-rays



radio



The kilonova of GW170817

- blue kilonova properties:

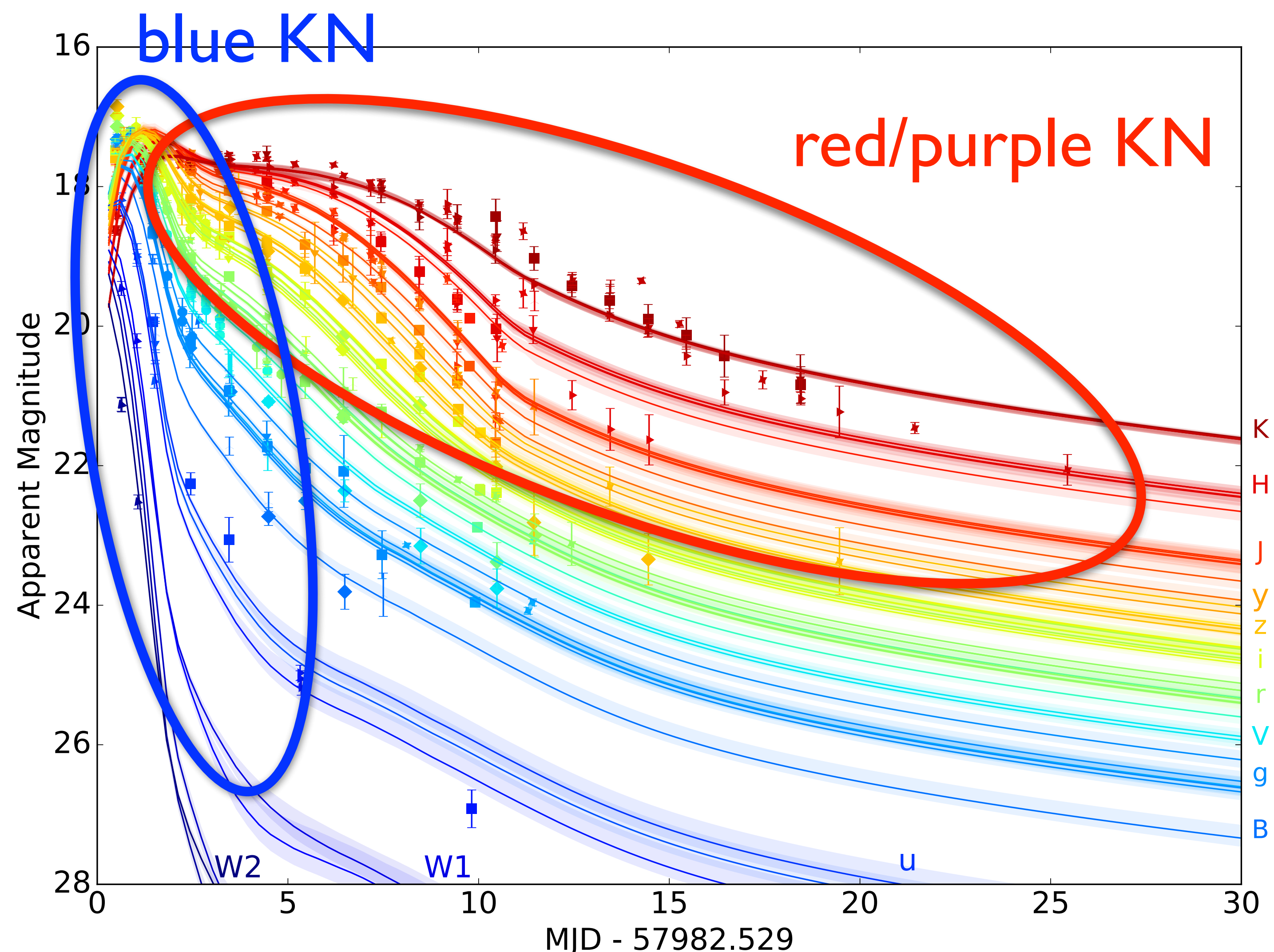
$M_{ej} \sim 10^{-2} M_{sun}$
$v_{ej} \sim 0.2\text{-}0.3c$
$Y_e > 0.25$
$X_{La} < 10^{-4}$

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

- two ("red-blue") or multiple components expected from merger simulations
- single component models might be possible, but require fine-tuning of Y_e

Smartt+ 2017
Waxman+ 2017

Mass ejection generates kilonovae

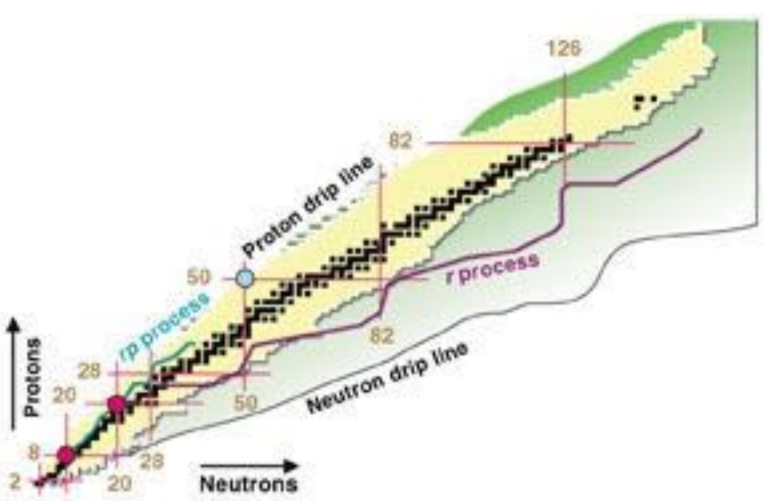
neutron rich ejecta from
NS-NS or NS-BH mergers
(Y_e~0.1-0.4)

~1s ↓ decompression
rapid neutron capture (r-process)

heavy radioactive elements

~ days ↓ alpha, beta decay
nuclear fission
further expansion

thermal emission (kilonova)
(quasi isotropic, long lasting: ~days)



Most simple kilonova model:

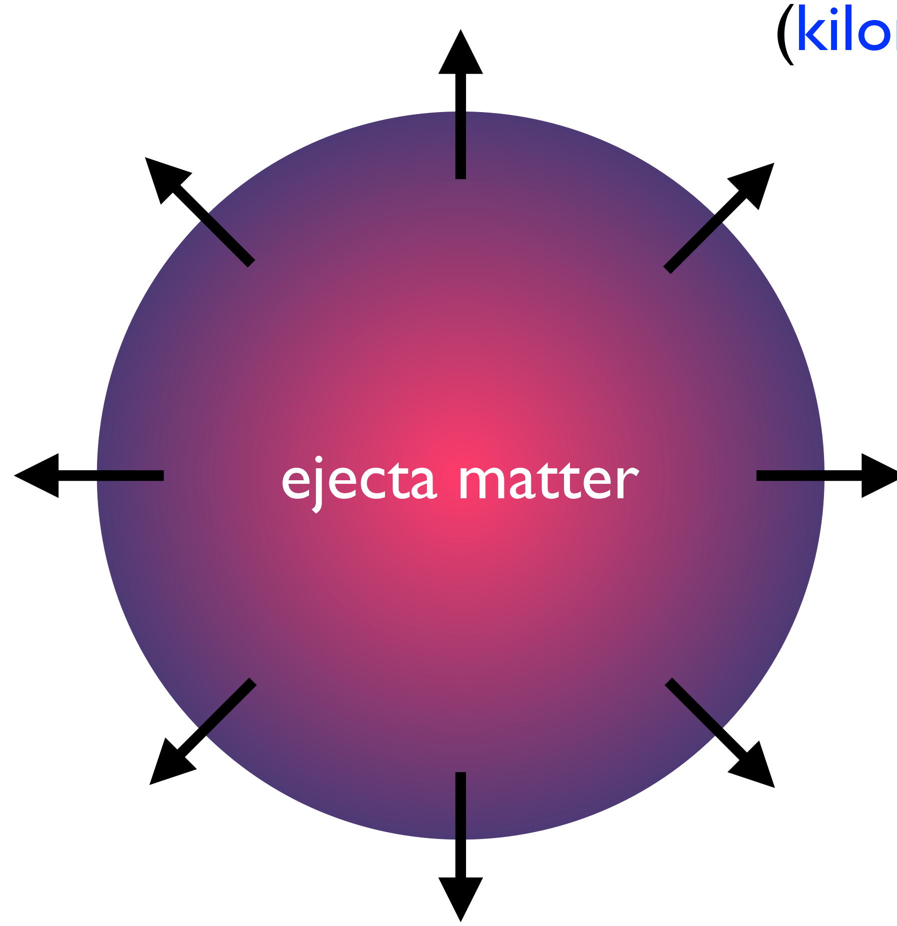
Piran+ 2013, Metzger+ 2017

$$\frac{dE_v}{dt} = -\frac{E_v}{t} - \frac{E_v}{t_{\rm diff}} + \dot{Q}_v$$

adiabatic losses

radiative luminosity (kilonova)

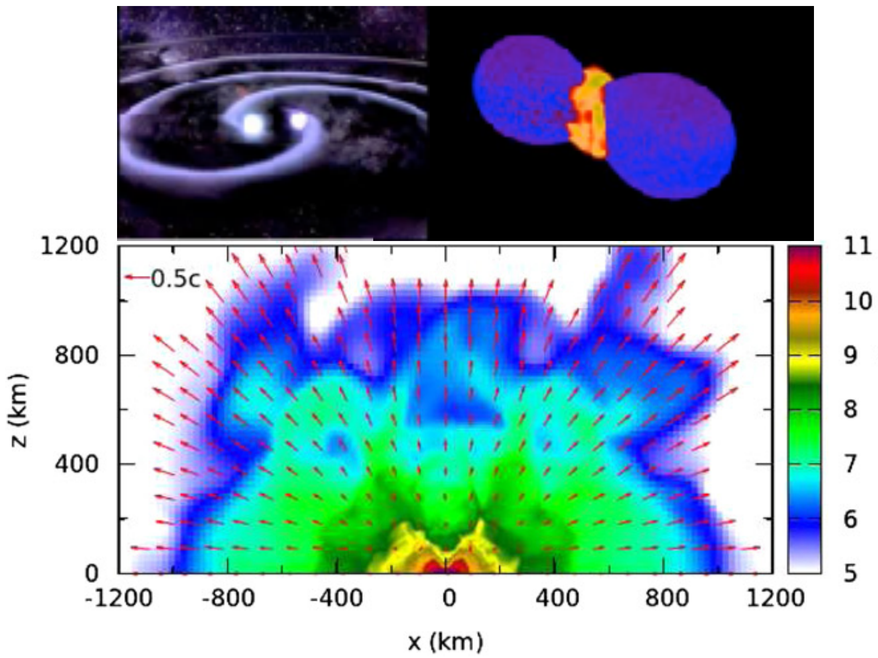
radioactive heating (r-process)



homologous expansion

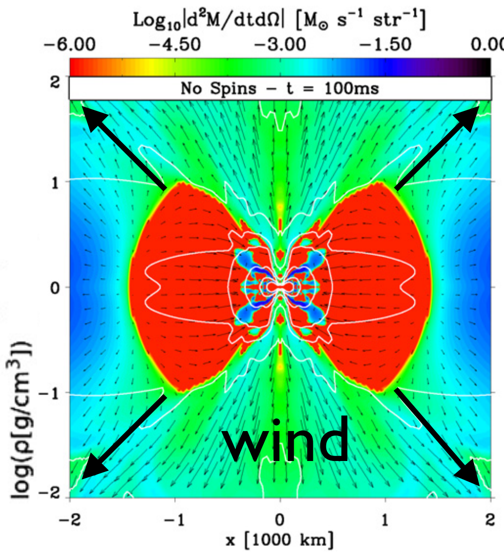
Sources of ejecta in NS mergers

dynamical ejecta (~ms)

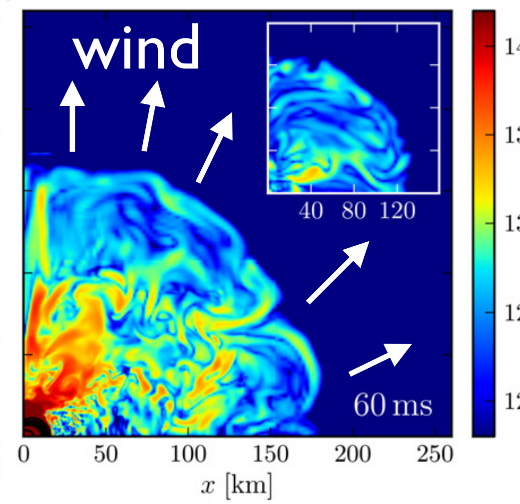


Hotokezaka+ 2013, Bauswein+ 2013

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

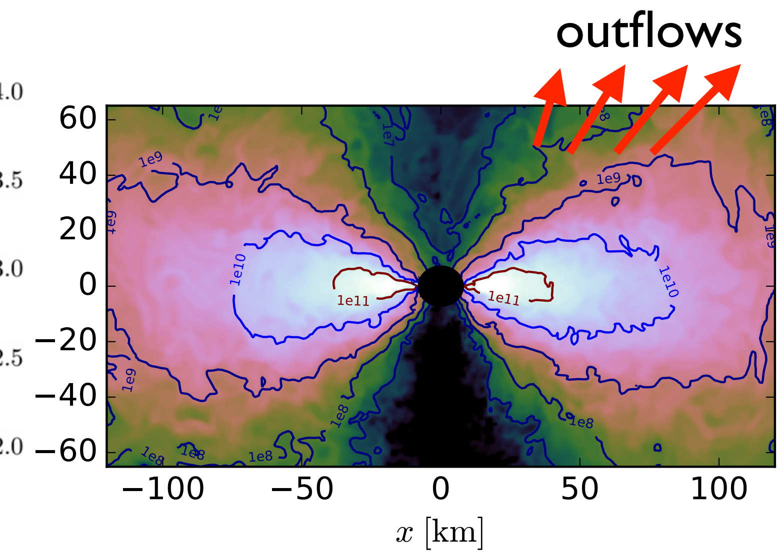


Dessart+ 2009



Siegel+ 2014
Ciolfi, Siegel+ 2017

accretion disk (~10ms-1s)



Siegel & Metzger 2017, 2018

tidal ejecta
shock-heated ejecta

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

$v \gtrsim 0.2c$

neutrino-driven wind

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

magnetically driven wind

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

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

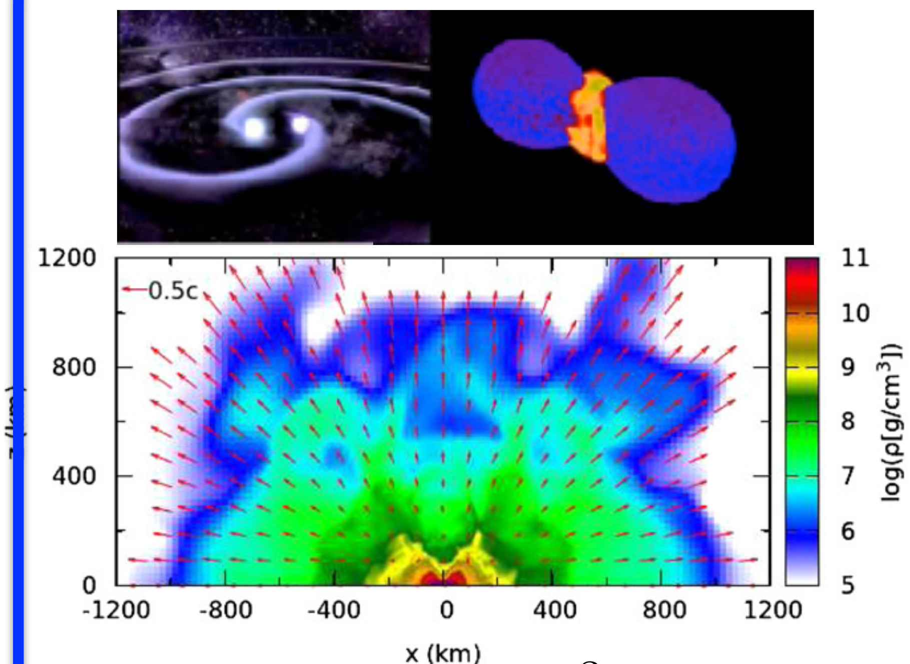
Siegel & Metzger 2017, 2018

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

lower limit

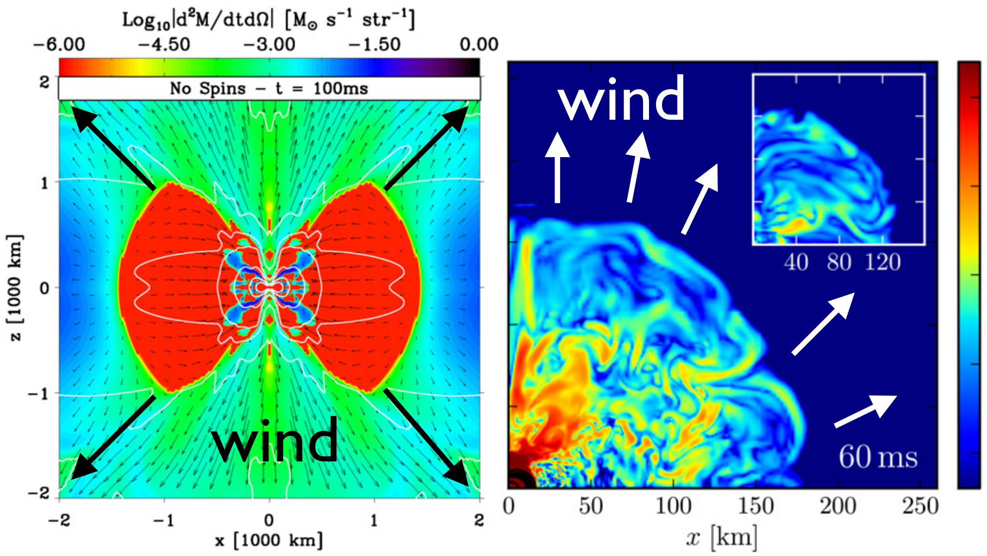
Sources of ejecta for kilonova in GW170817

dynamical ejecta (~ms)



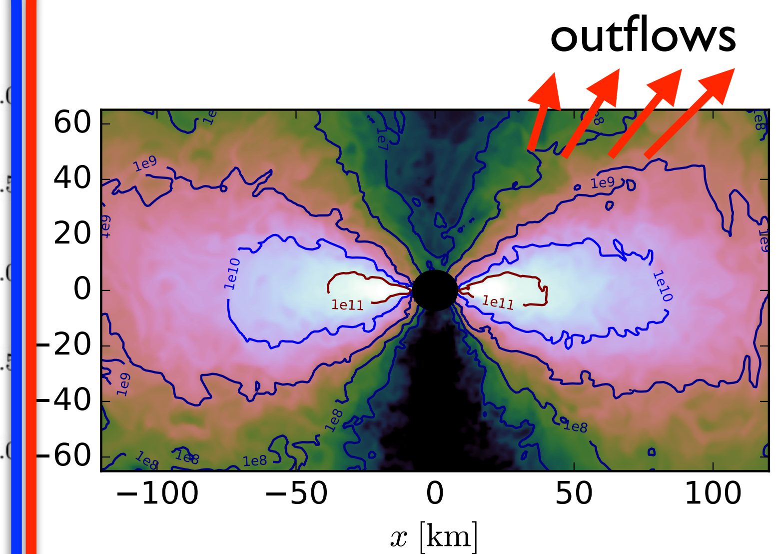
$$M_{\rm tot} \lesssim 10^{-3} {\rm M}_\odot$$
$$v \gtrsim 0.2c$$

winds from NS remnant (~ms-1s)



$$\dot{M}_{\rm in} \sim (10^{-3} - 10^{-2}) {\rm M}_\odot {\rm s}^{-1}$$
$$v \lesssim 0.1c$$

accretion disk (~10ms-1s)



$$M_{\rm tot} \gtrsim 10^{-2} M_\odot$$
$$v \sim 0.1c$$

blue KN in GW170817

⟶ requires large amount of shock heated ejecta to obtain high $Y_e > 0.25$

⟶ requires metastable NS phase

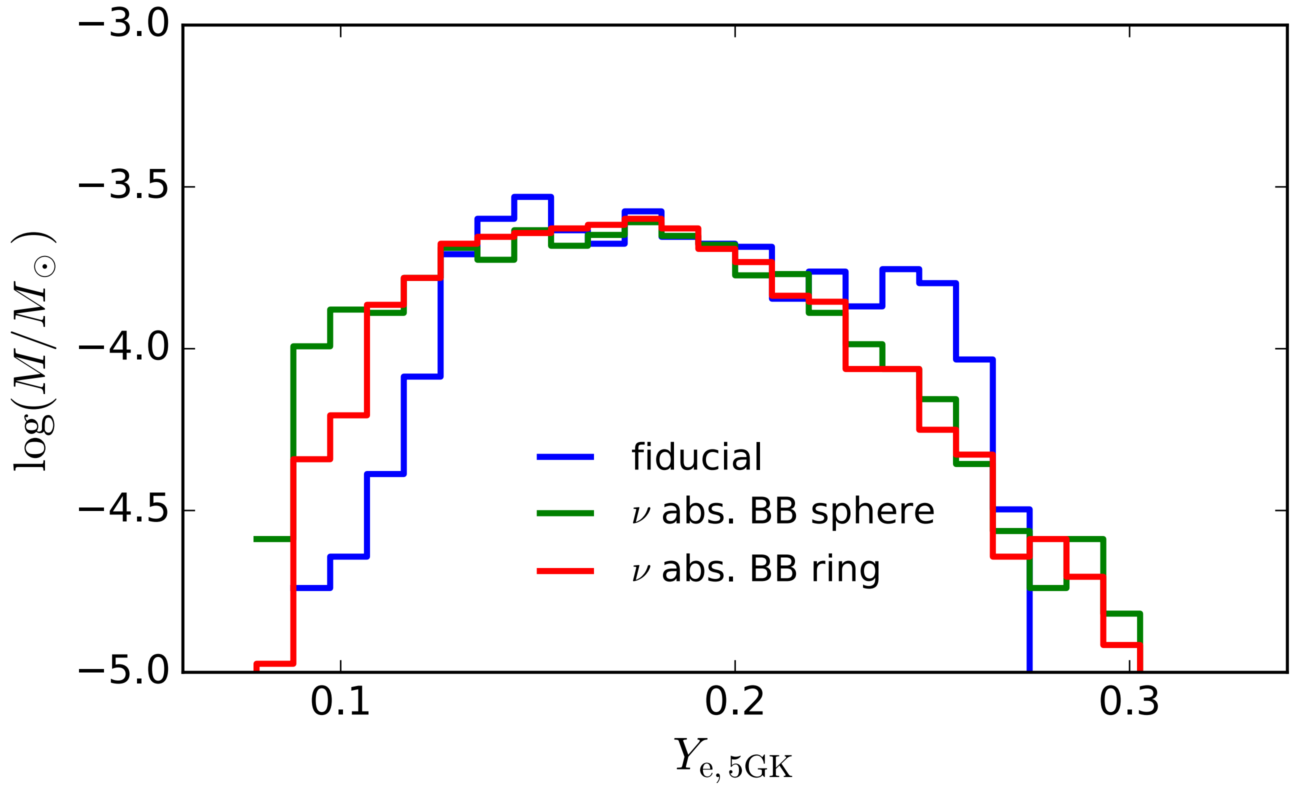
⟶ requires EOS with small NS radius (~12 km)

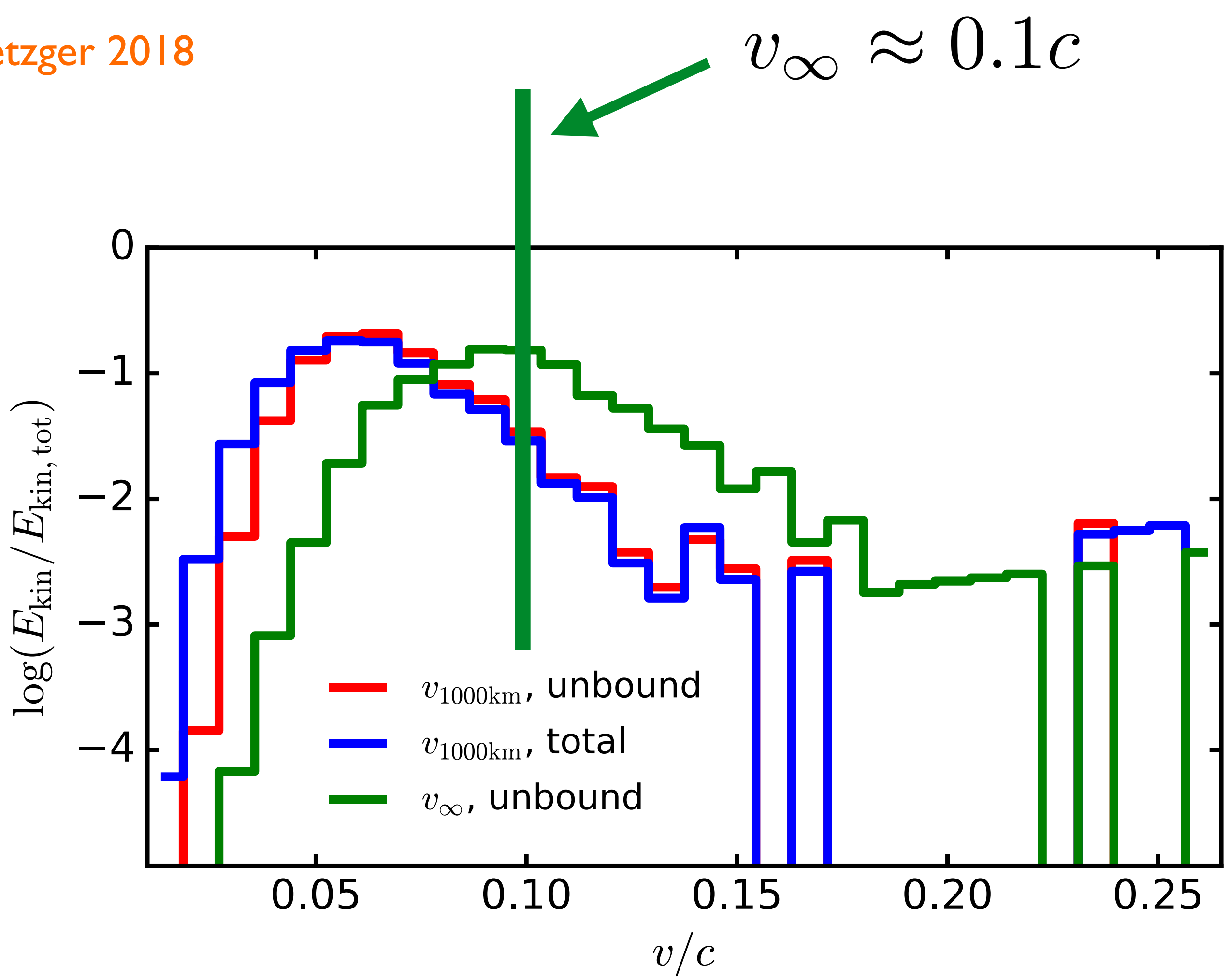
red KN in GW170817

⟶ produces the heavy r-process elements in GW170817 ($Y_e < 0.25$)

Disk outflows

Siegel & Metzger 2018





composition

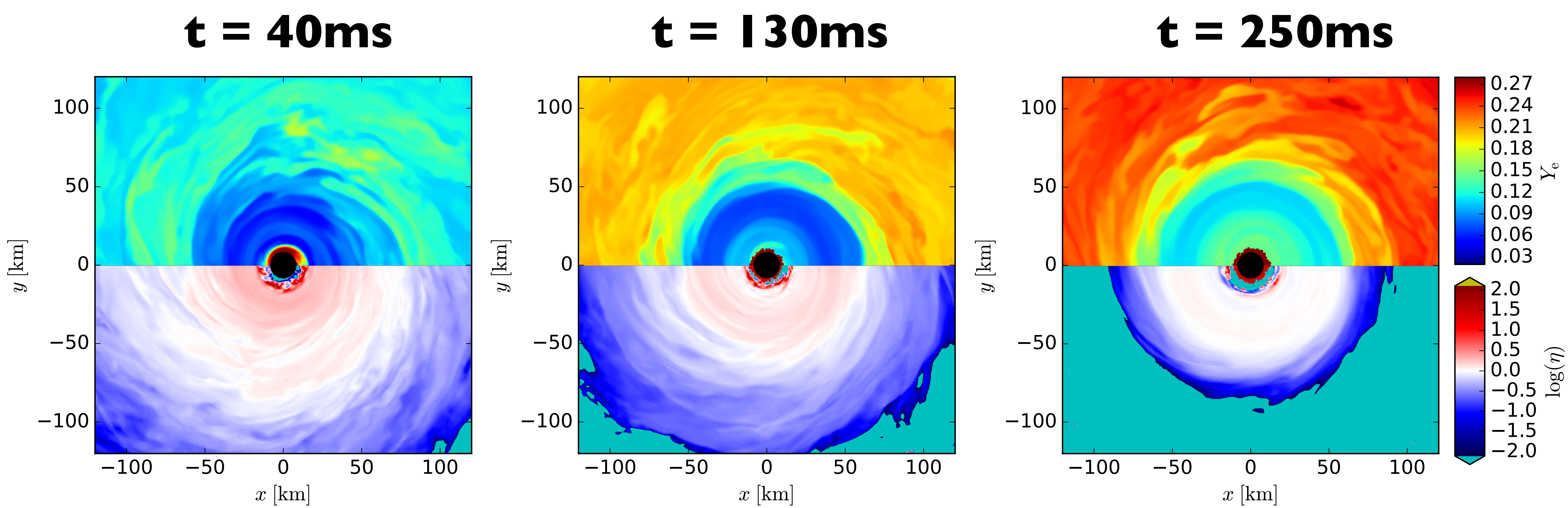
$$Y_{\rm e} \approx 0.1 - 0.3$$

ejecta velocities

$$v_\infty \approx 0.1c$$

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

Why are the disk outflows neutron-rich?



Siegel & Metzger 2018

Neutron-rich conditions favor:

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

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

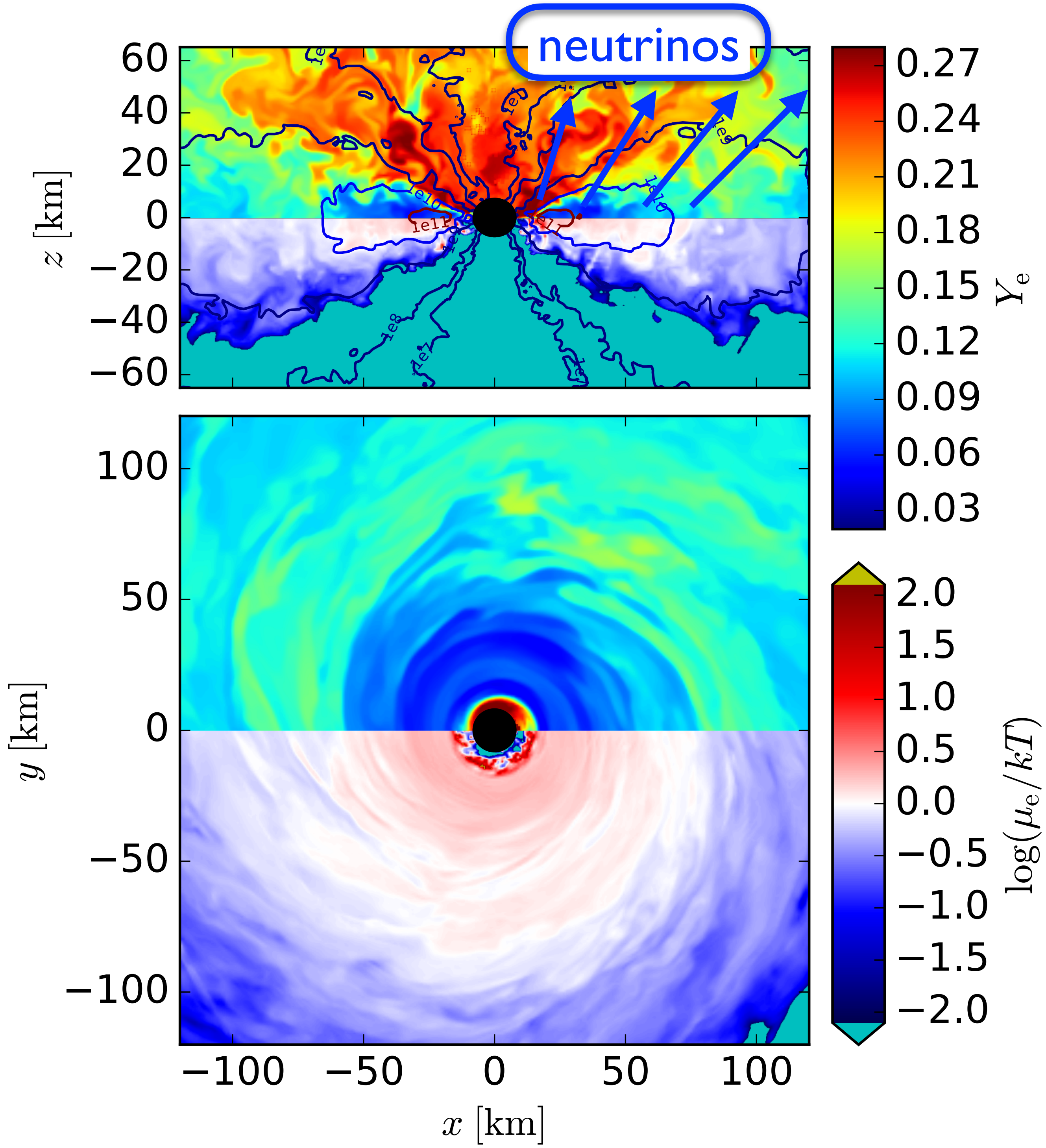


Fig.: disk properties; contours: rest-mass density

Siegel & Metzger 2017, PRL   Siegel & Metzger 2018

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:

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

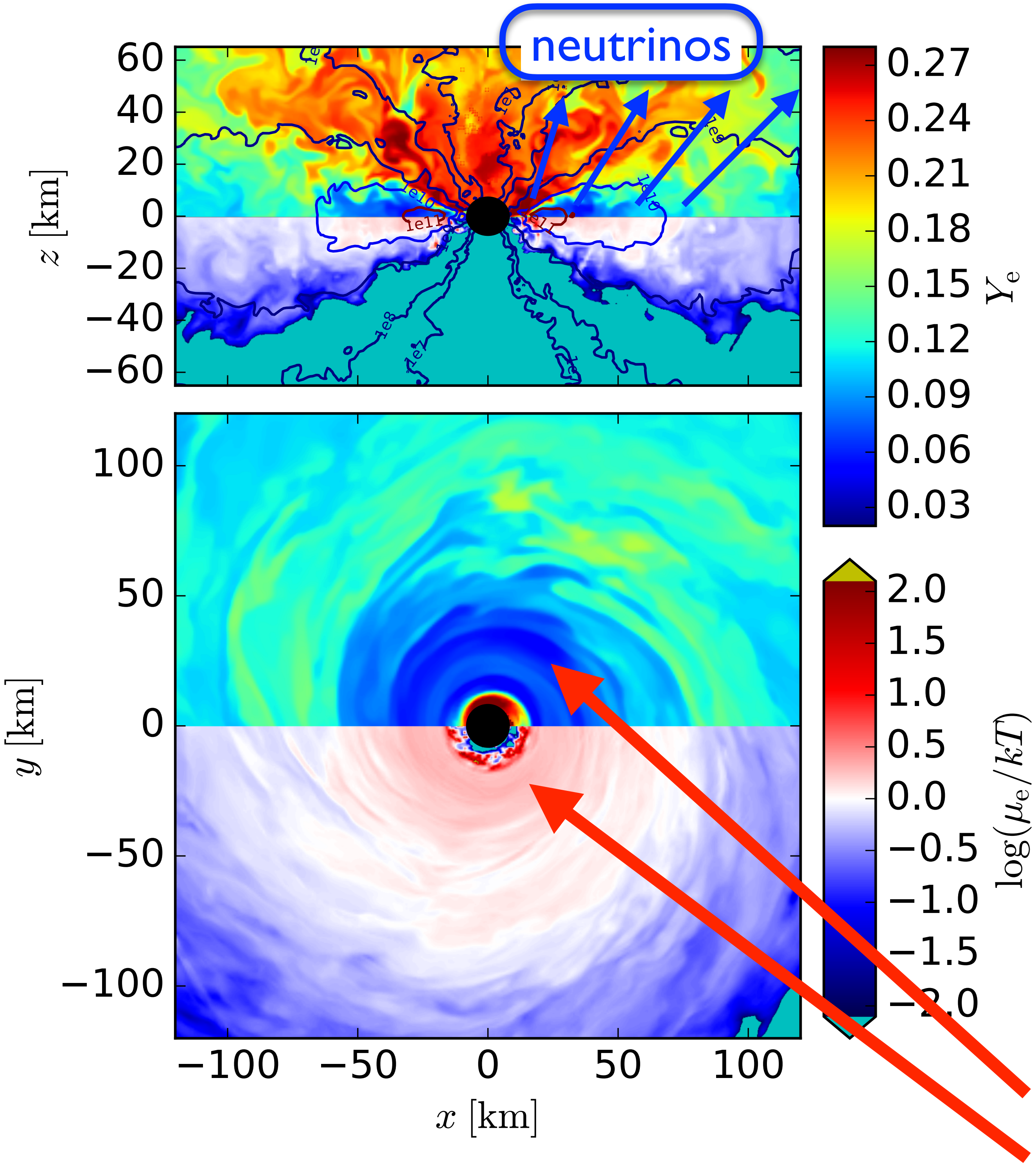
$$e^- + e^+ \to \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$$

plasmon decay:

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

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

Self-regulation: 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

↓

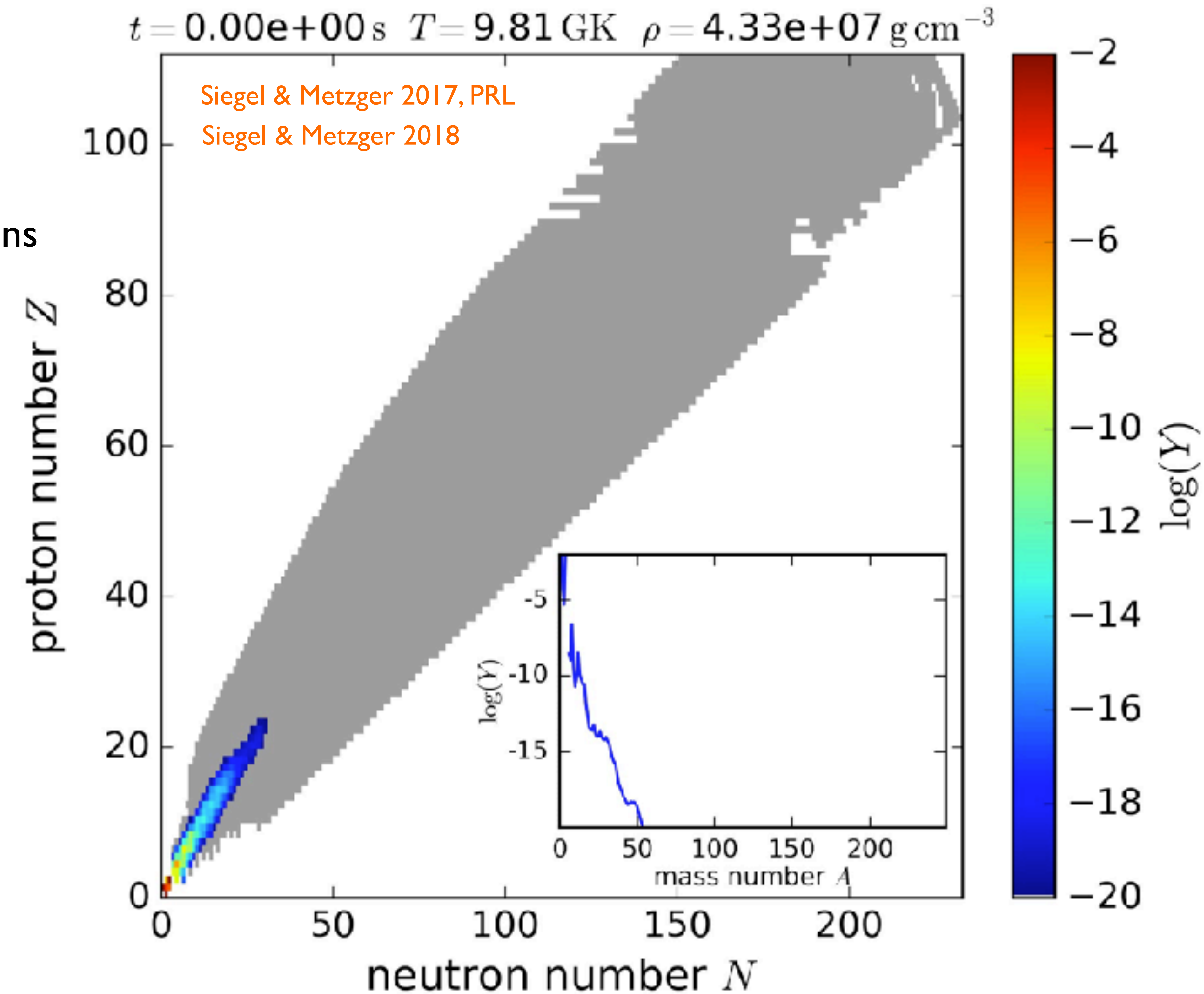
lower degeneracy μ_e/kT

direct evidence of self-regulation

r-process nucleosynthesis in disk outflows

nuclear reaction network (*SkyNet*)

- neutron captures
- photo-dissociations
- α-, β-decays
- fission

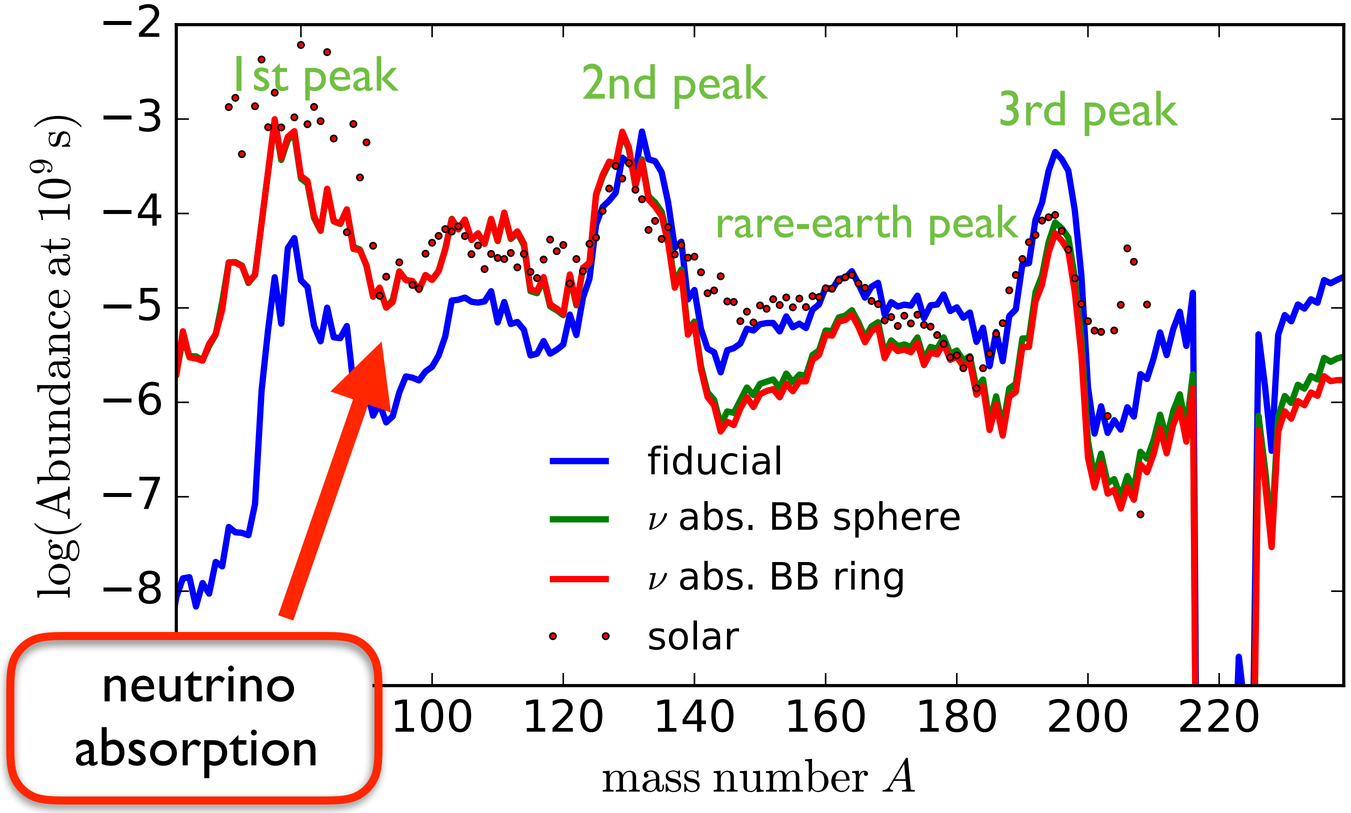


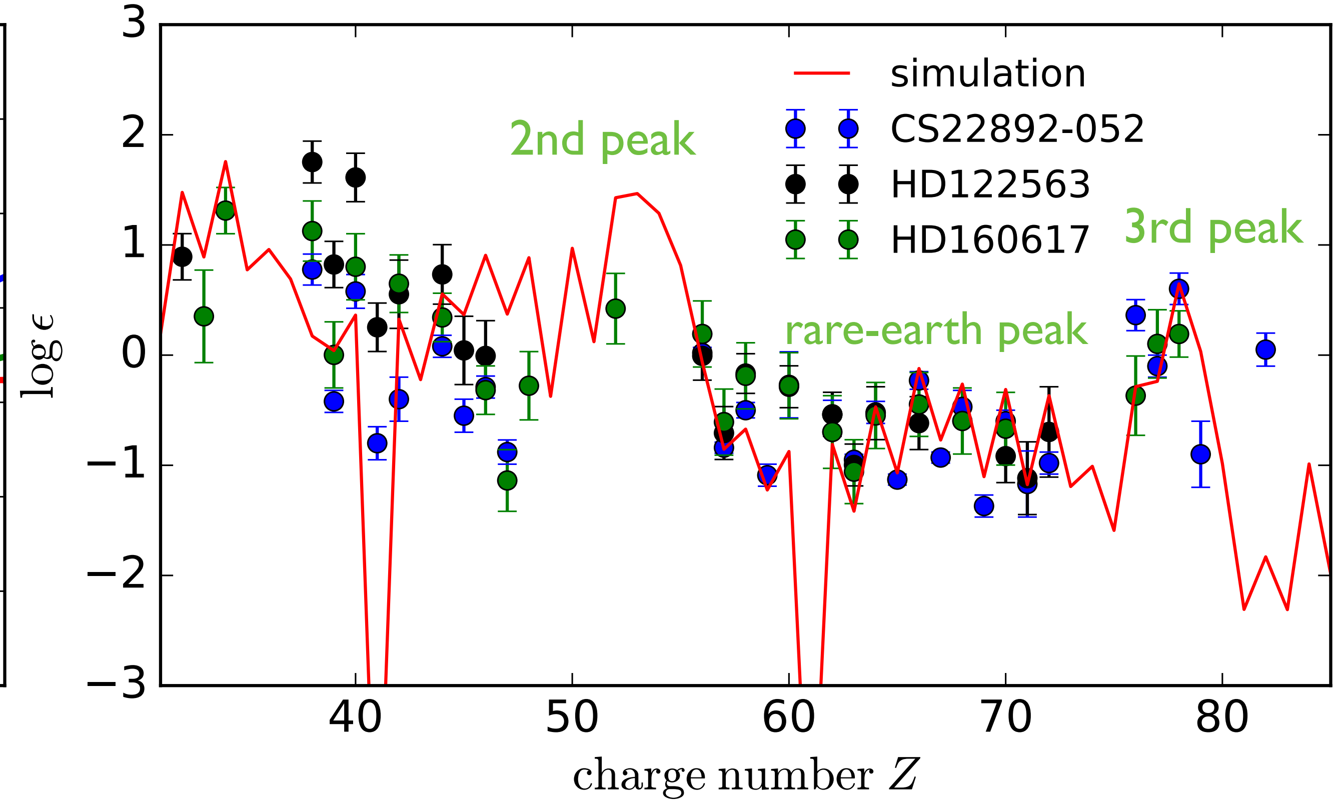
Movie: r-process nucleosynthesis from NS merger remnant disks

r-process nucleosynthesis in disk outflows

Siegel & Metzger 2017, PRL

Siegel & Metzger 2018

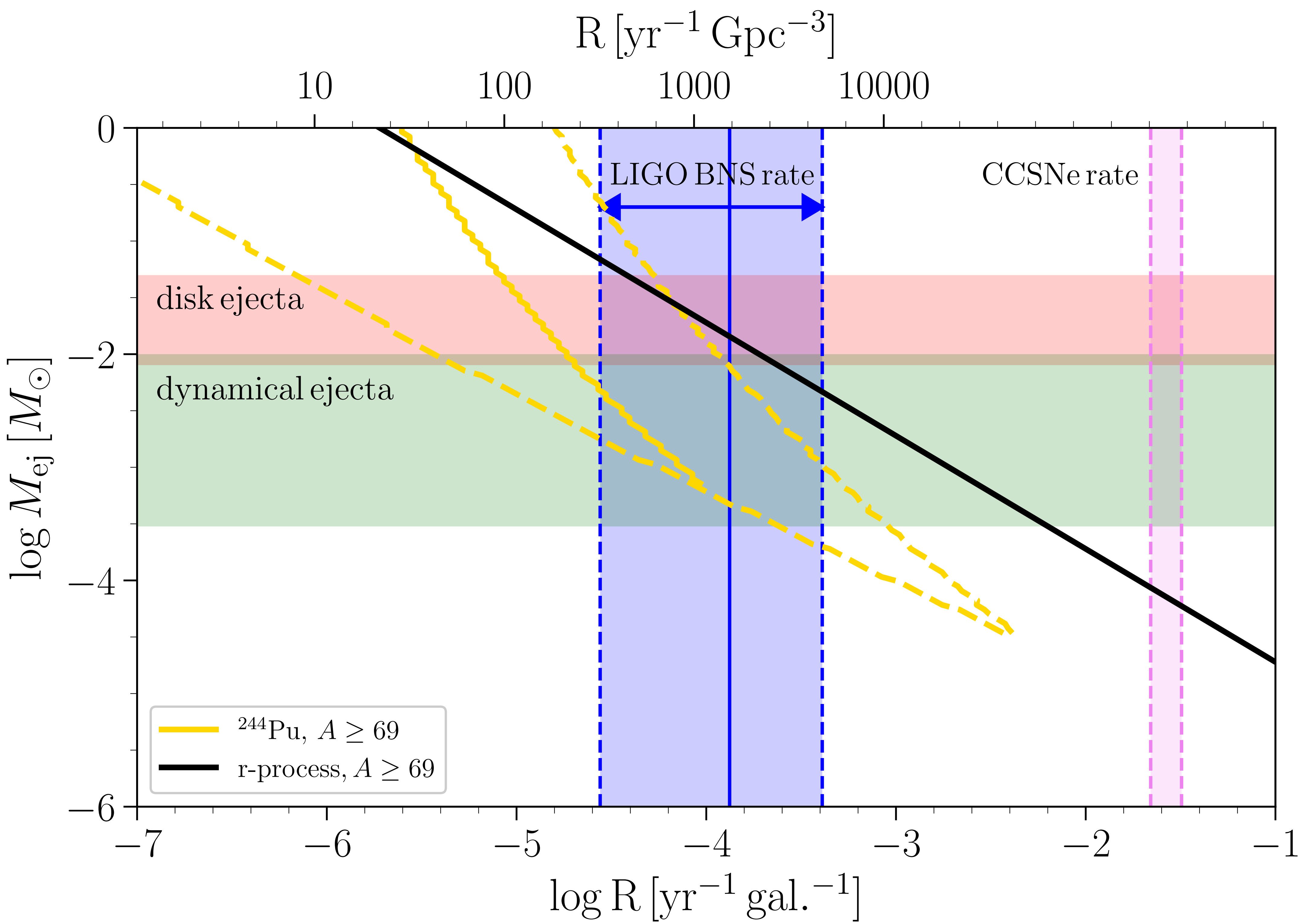




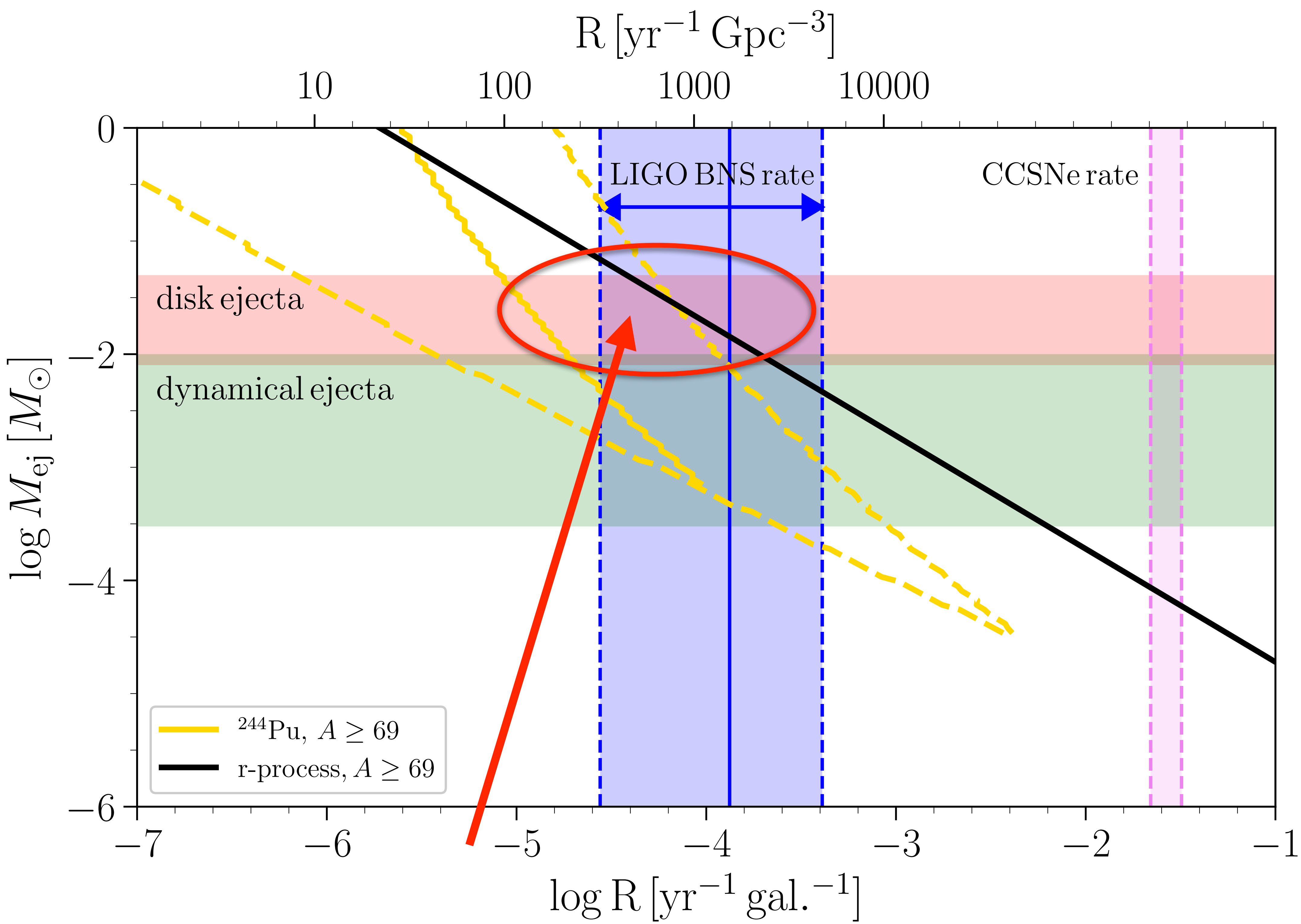
- robust 2nd and 3rd peak r-process!
- including neutrino absorption: additional good fit to 1st & 2nd peak elements

→ production of all r-process elements!

Constraints on r-process nucleosynthesis



Constraints on r-process nucleosynthesis



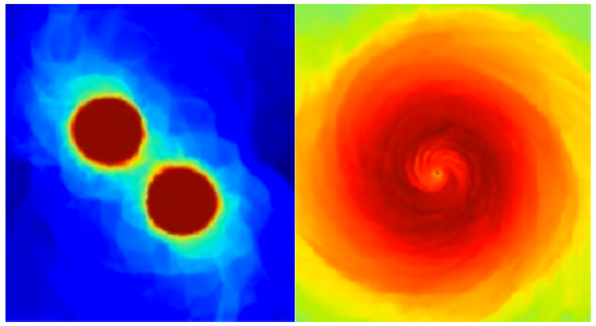
post-merger disk outflows are a promising site for the r-process!

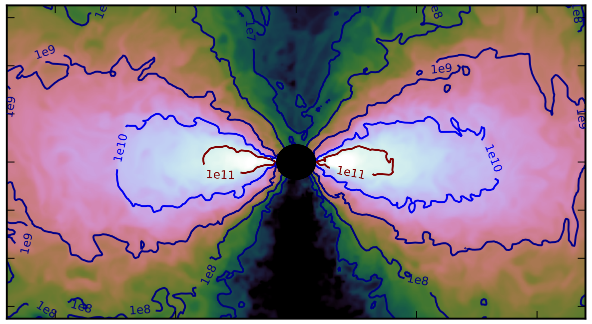
Conclusions

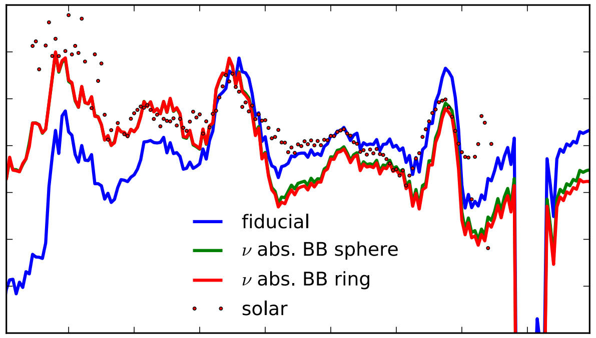
- The origin of the heavy elements has been an enduring mystery for more than 70 years
- First-principle simulations key to understand their formation (identify the site, production processes, abundance pattern etc.)
- Simulations + GW170817 + EM (kilonova) point to post-merger accretion disk winds as promising site (ubiquitous phenomenon!)

→ red KN in GW170817 consistent with winds from post-merger accretion disk

- Self-regulation provides neutron-rich outflows
- Slow outflow velocities ~0.1c
- Large amount of ejecta



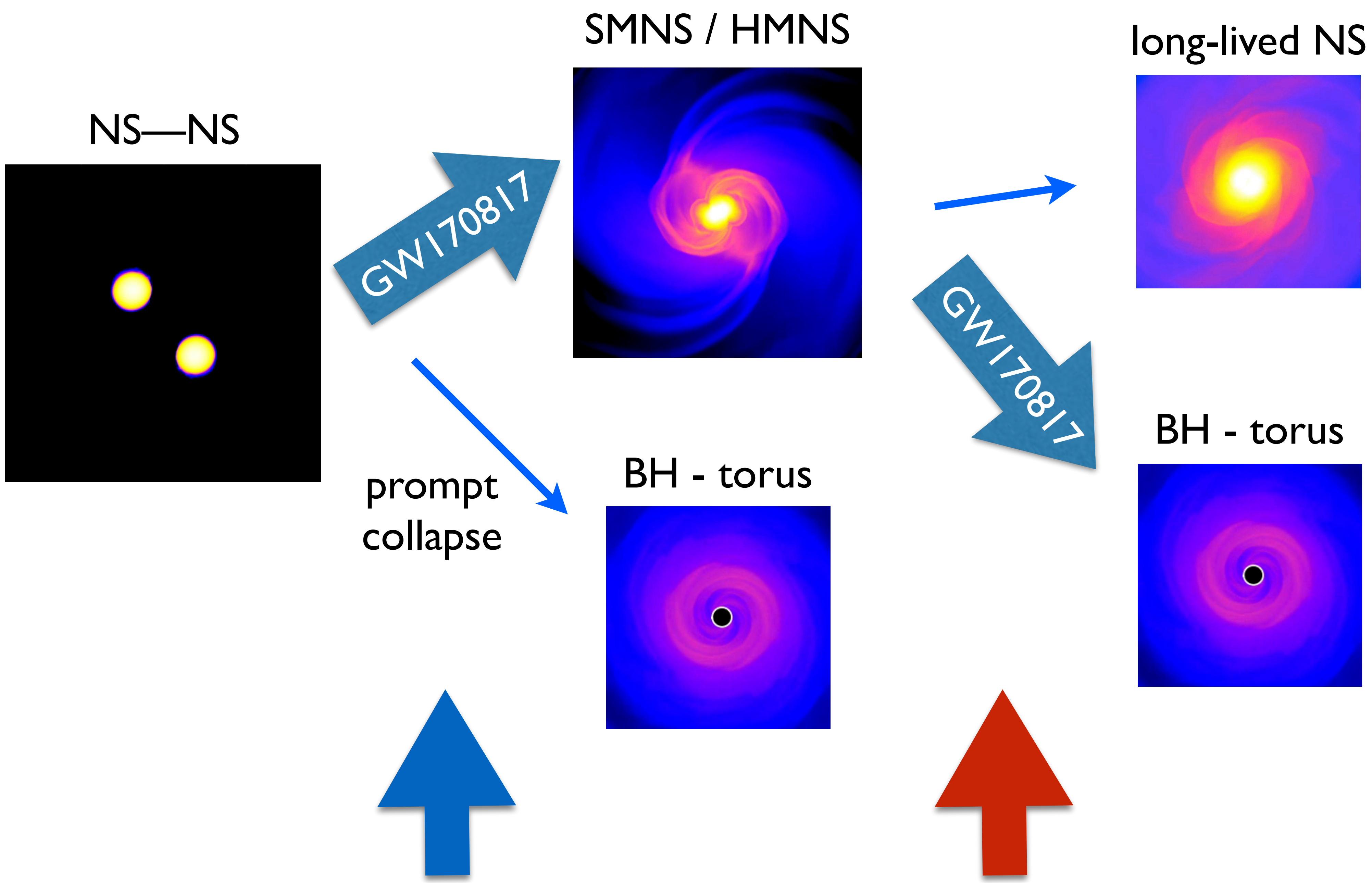




> Relative abundances, total ejecta mass, measured BNS merger rate provide
> yet strongest evidence for NS mergers being the prime production site for the r-process

Appendix

Scenario for GW170817



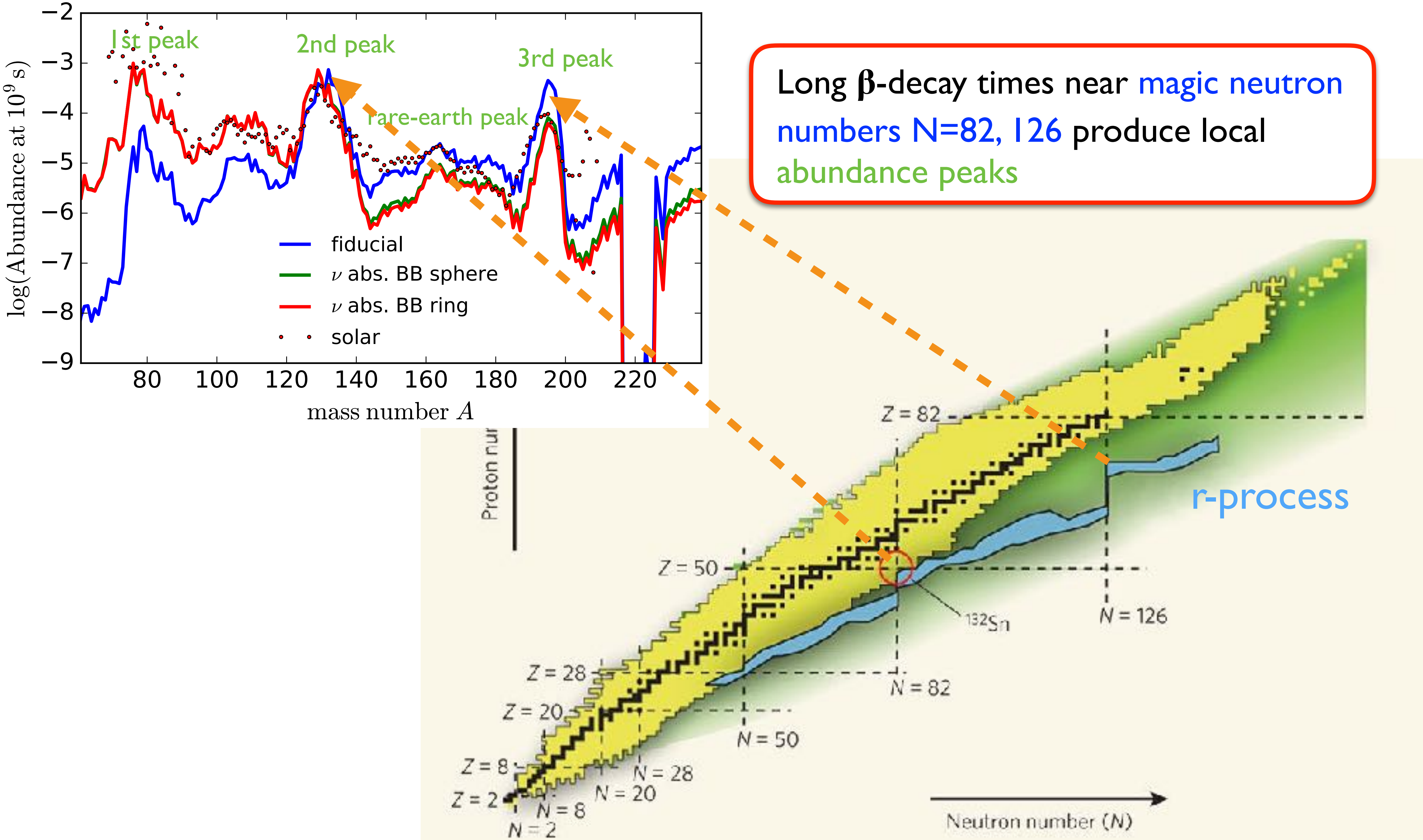
blue kilonova
with $10^{-2}M_{sun}$

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

Margalit & Metzger 2017

r-process nucleosynthesis in disk outflows

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



Long β-decay times near magic neutron numbers N=82, 126 produce local abundance peaks