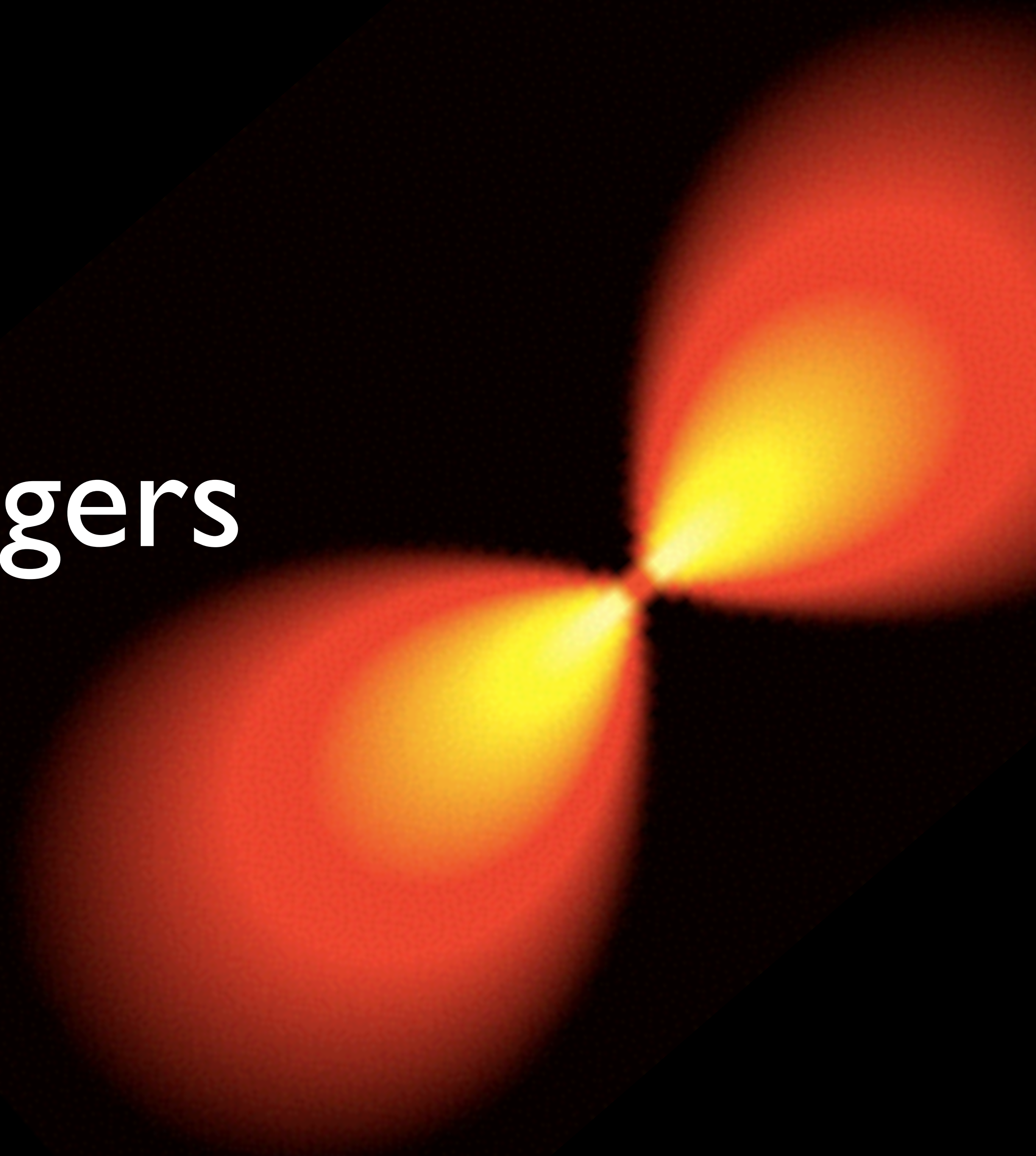
nucleosynthesis and light curves of compact object mergers



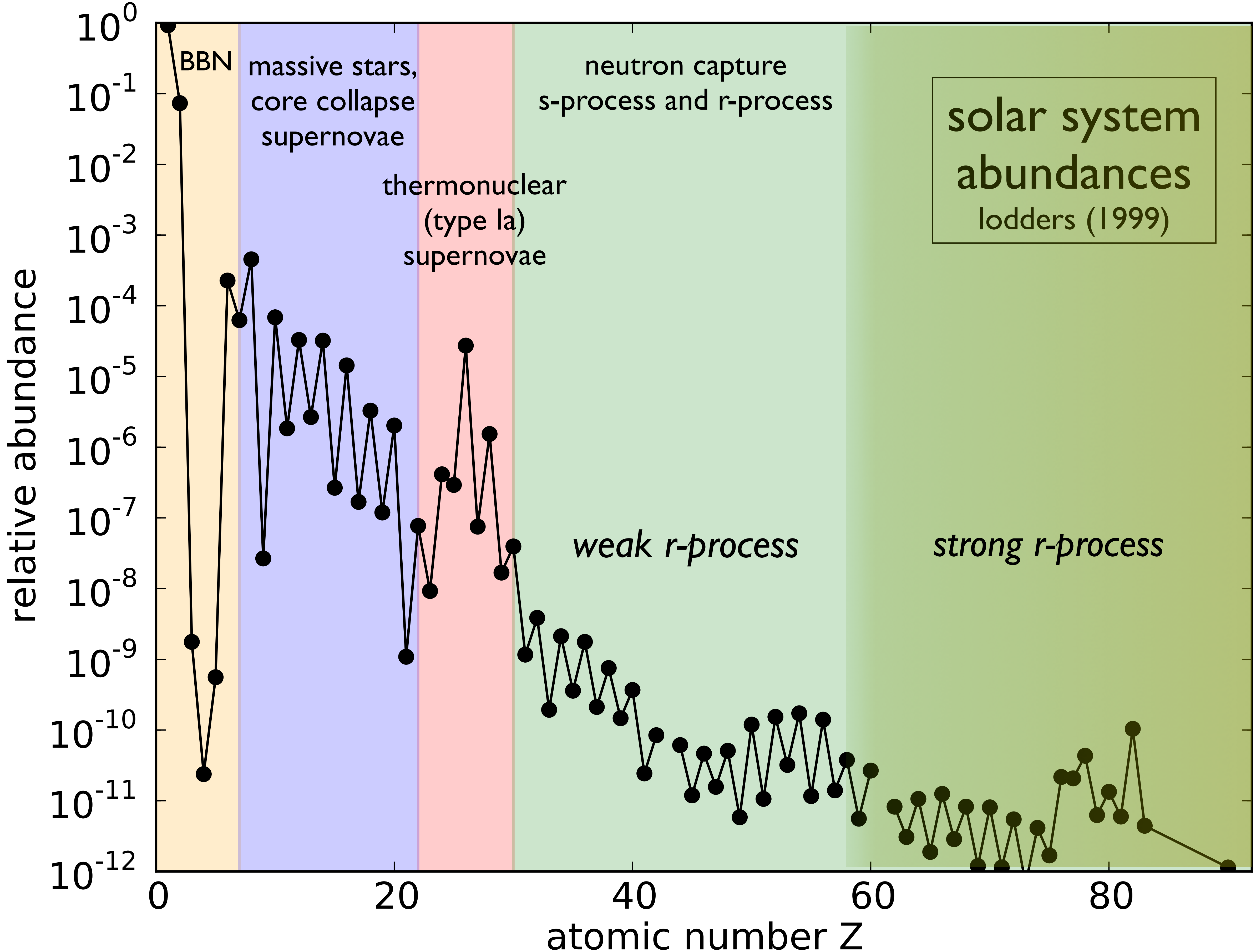
daniel kasen (UCB/LBNL)
w/ J. barnes, N. badnell, R. Fernandez, L. Roberts, B. Metzger, E. Ramirez-Ruiz, W. Lee, E. Quataert, S. Rosswog

compact object mergers
two big questions

1. nature of gravitational wave sources

2. origin of the heavy elements (r-process nucleosynthesis)

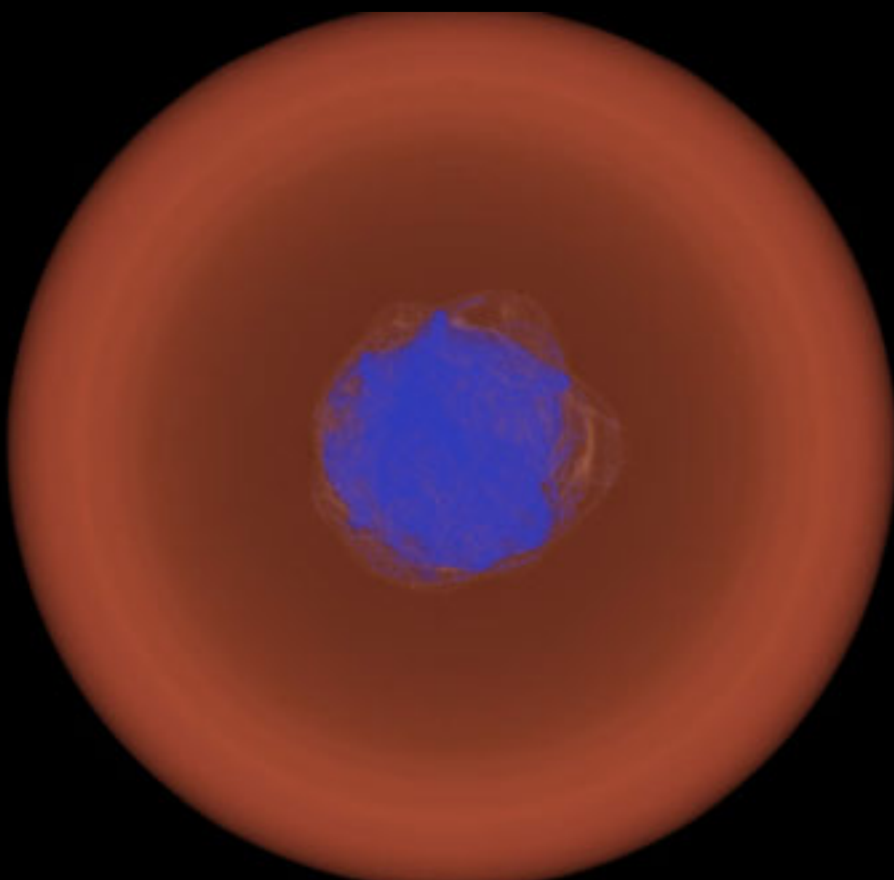
nucleosynthesis of the heavy elements



possible r-process sites

need neutron rich ejecta: $Y_e = n_p/(n_n + n_p) < 0.5$

core-collapse supernovae



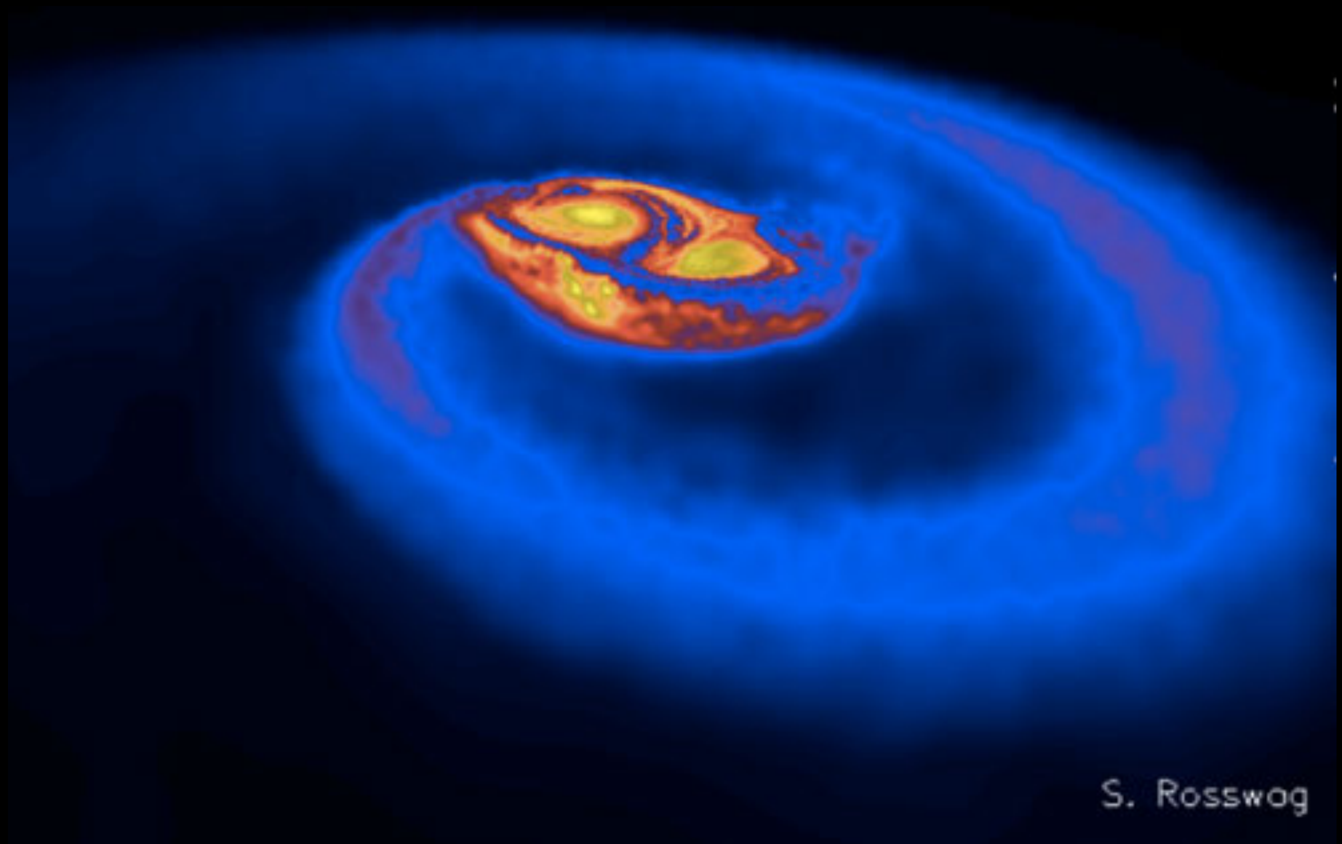
neutrino driven wind from a proto-neutron star

small r-process mass (~10^{-6} - 10^{-5} M_{sun}?)

common and optically bright

low r-process purity

neutron star merger



dynamical ejecta or disk winds

larger r-process mass (~10^{-4} - 10^{-2} M_{sun}?)

rare and optically dim

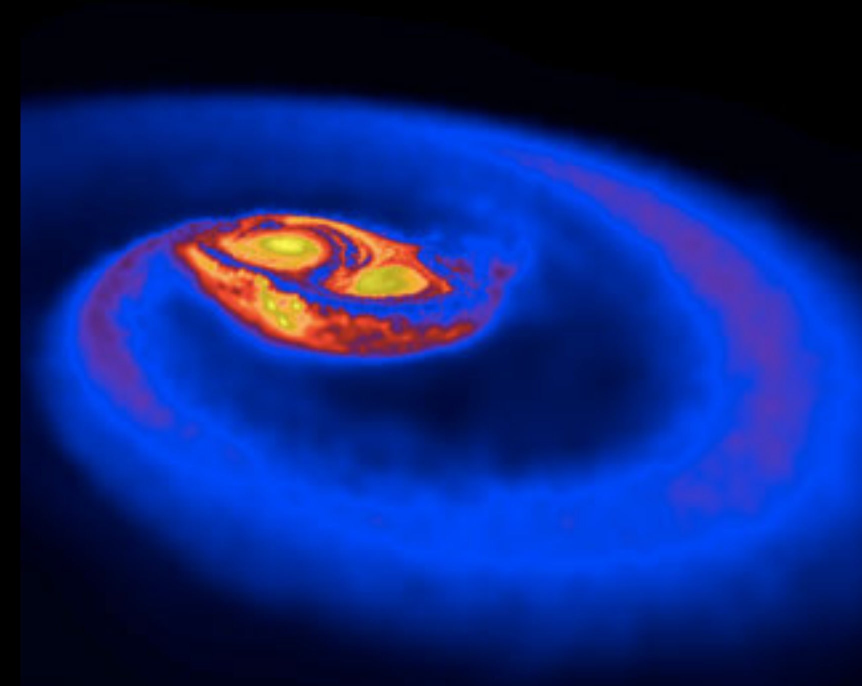
high r-process purity

What are the rates of mergers?
How much r-process material is produced?

life-cycle of compact object mergers

binary stellar evolution
t ~ 10^6 - 10^9 years; r ~ 1 AU

inspiral →

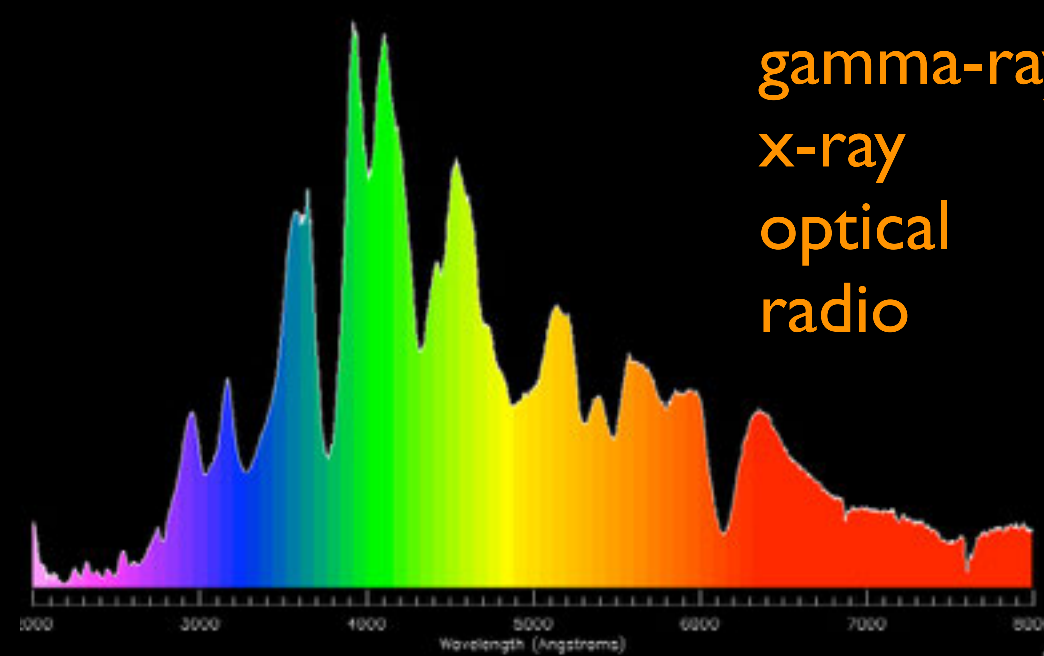


merger dynamics
t ~ ms - sec; r ~ 50 km

outflows →

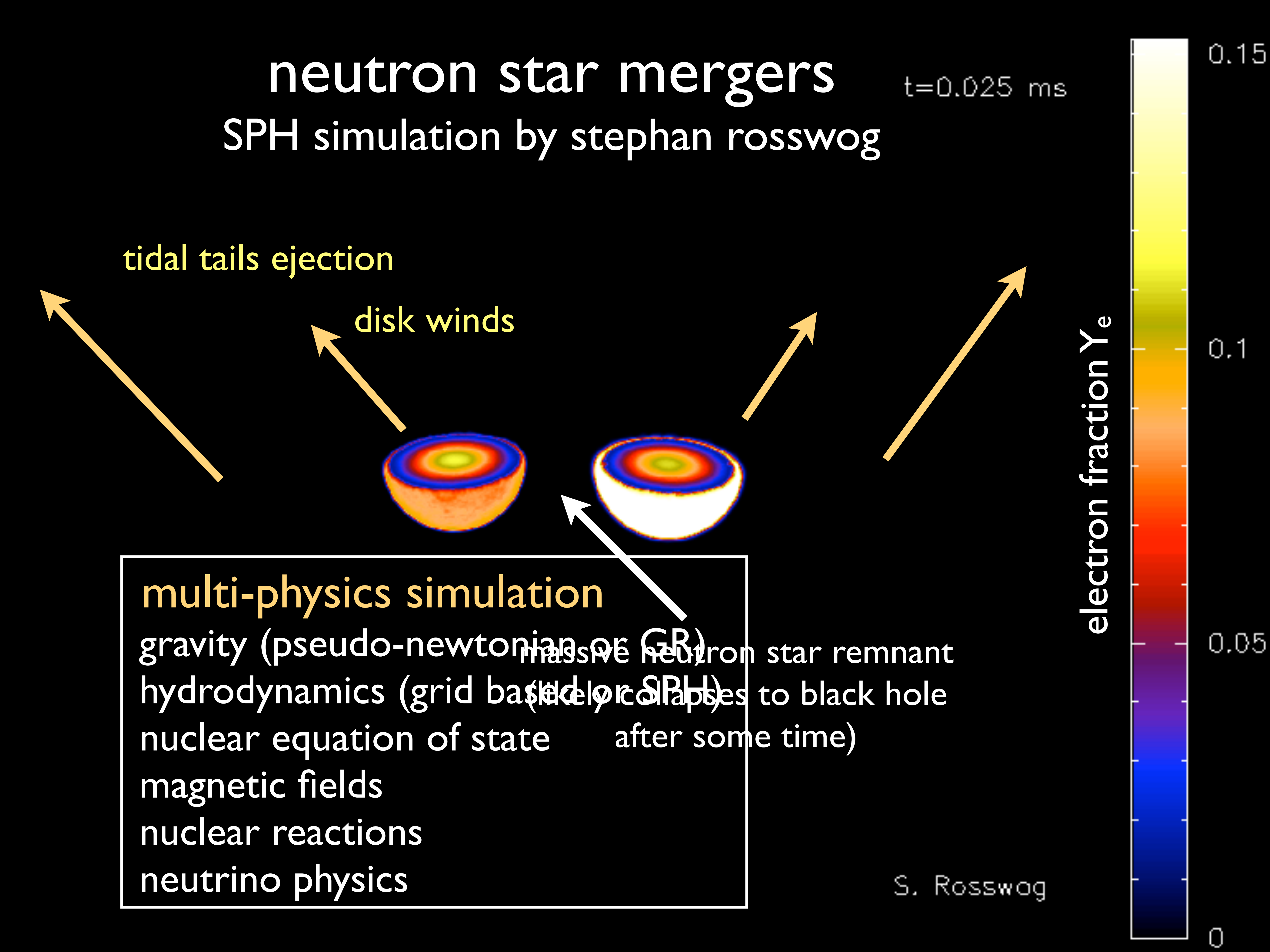
radiation transport
t ~ days, r ~ 100 AU

emission →

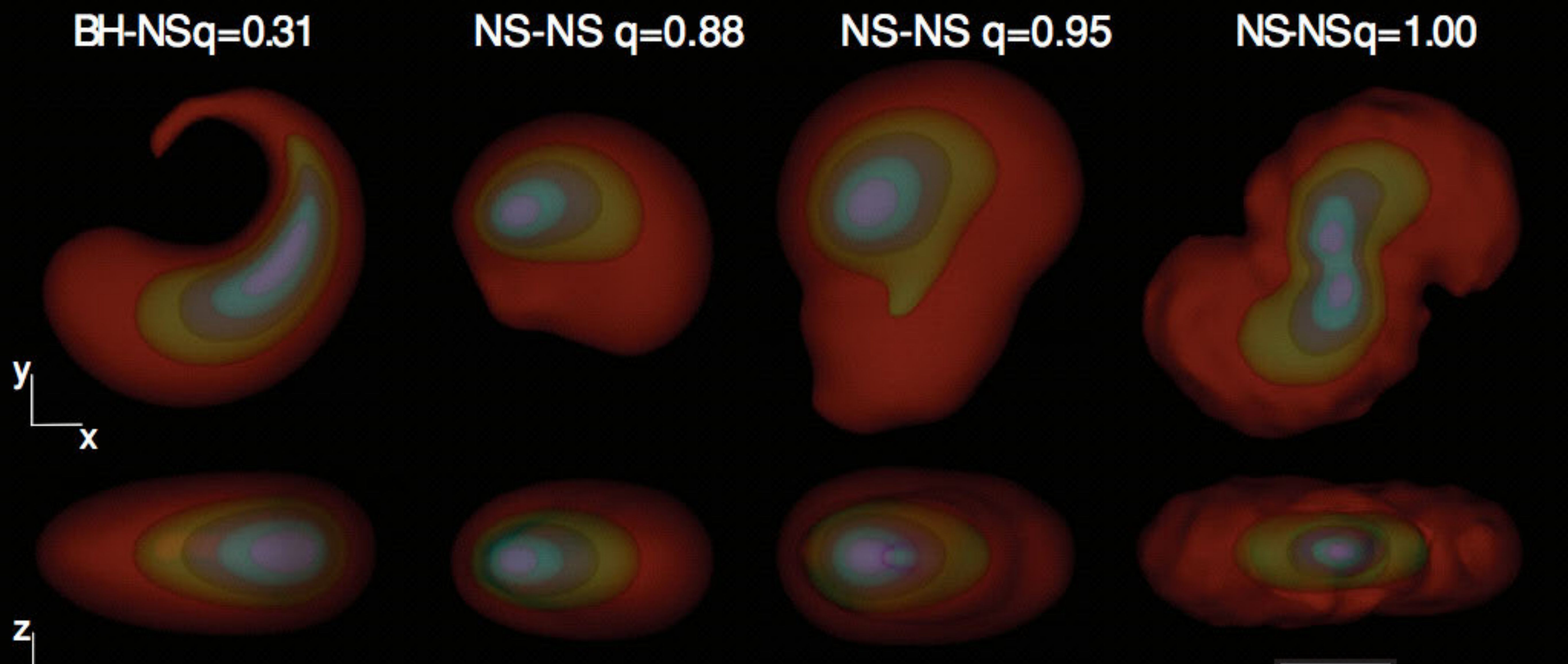


gamma-ray
x-ray
optical
radio

observations

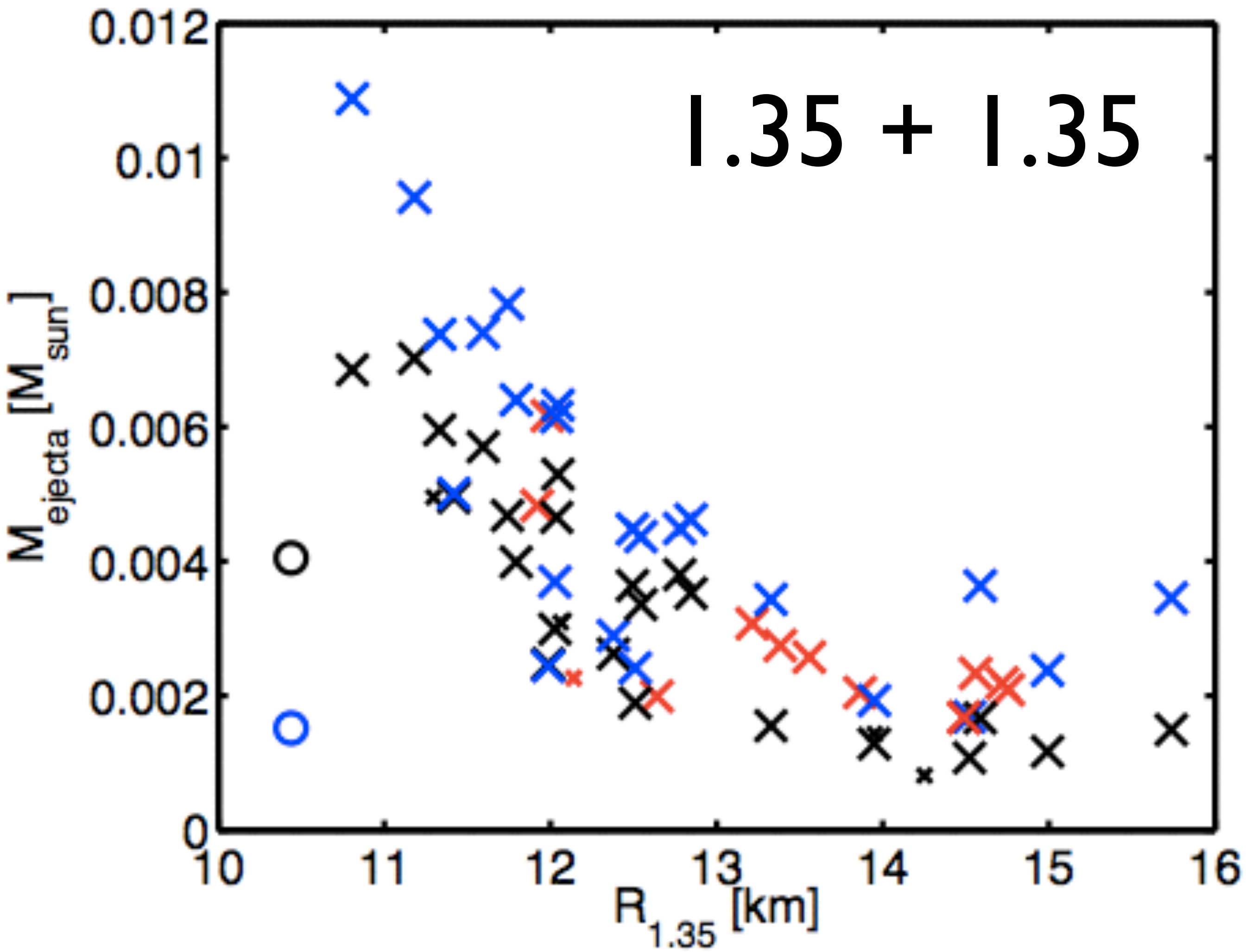

neutron star mergers
SPH simulation by stephan rosswog
t=0.025 ms
tidal tails ejection
disk winds
multi-physics simulation
gravity (pseudo-newtonian or GR)
hydrodynamics (grid based or SPH)
nuclear equation of state
magnetic fields
nuclear reactions
neutrino physics
massive neutron star remnant
(likely collapses to black hole
after some time)
S. Rosswog
electron fraction Y_e
0.15
0.1
0.05
0

3D dynamical ejecta models



0.060 M_{sun} 0.057 M_{sun} 0.047 M_{sun} 0.057 M_{sun}

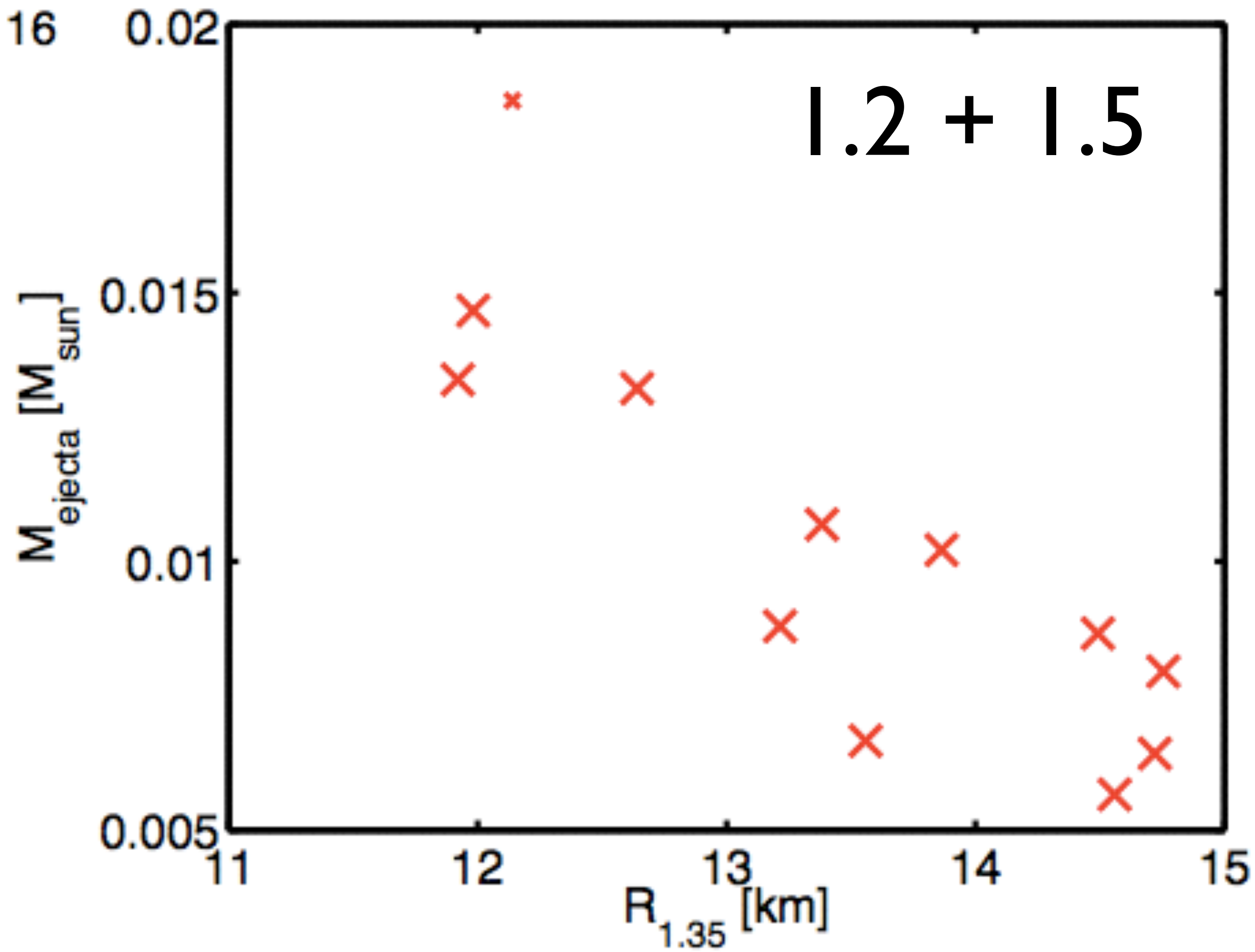
roberts, kasen, lee, & ramirez-ruiz (2011)



dynamical ejecta

ejected mass depends on

- nuclear equation of state
- mass ratio
- NS + NS or NS + BH
- treatment of gravity
- numerics?



GR (conformally flat)
SPH merger simulations

bauswein, goriely, and janka (2014)

r-process nucleosynthesis in expanding outflows

higher Z isotopes

↑ beta decay

seeds, ^{4}He, n → (neutron captures) → heavier neutron-rich isotopes

↑ alpha chain

^{12}C, ^{4}He, n

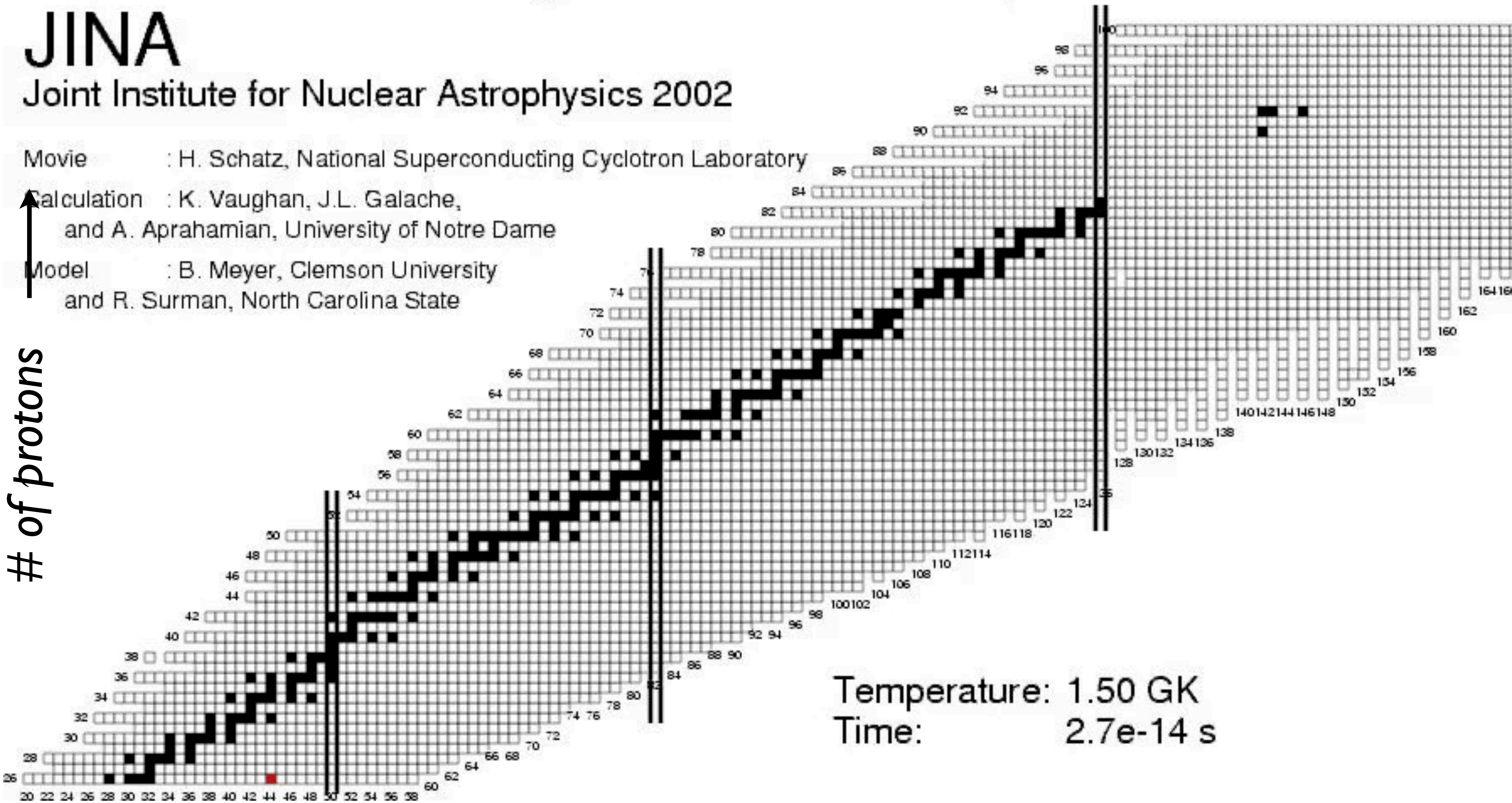
↑ triple alpha

^{4}He, n

↑ recombination to alpha particles

n, p

Nucleosynthesis in the r-process

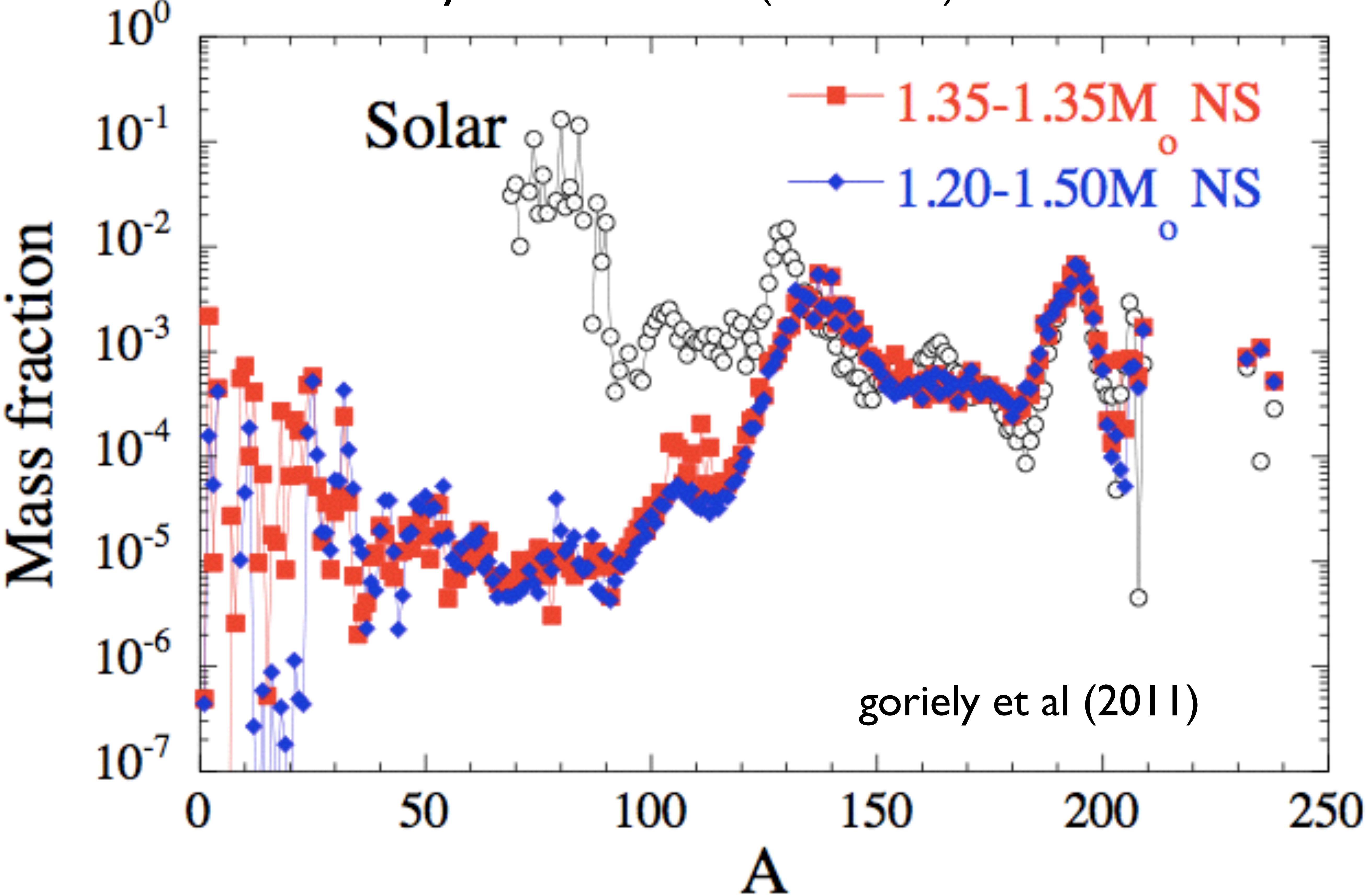


# of protons

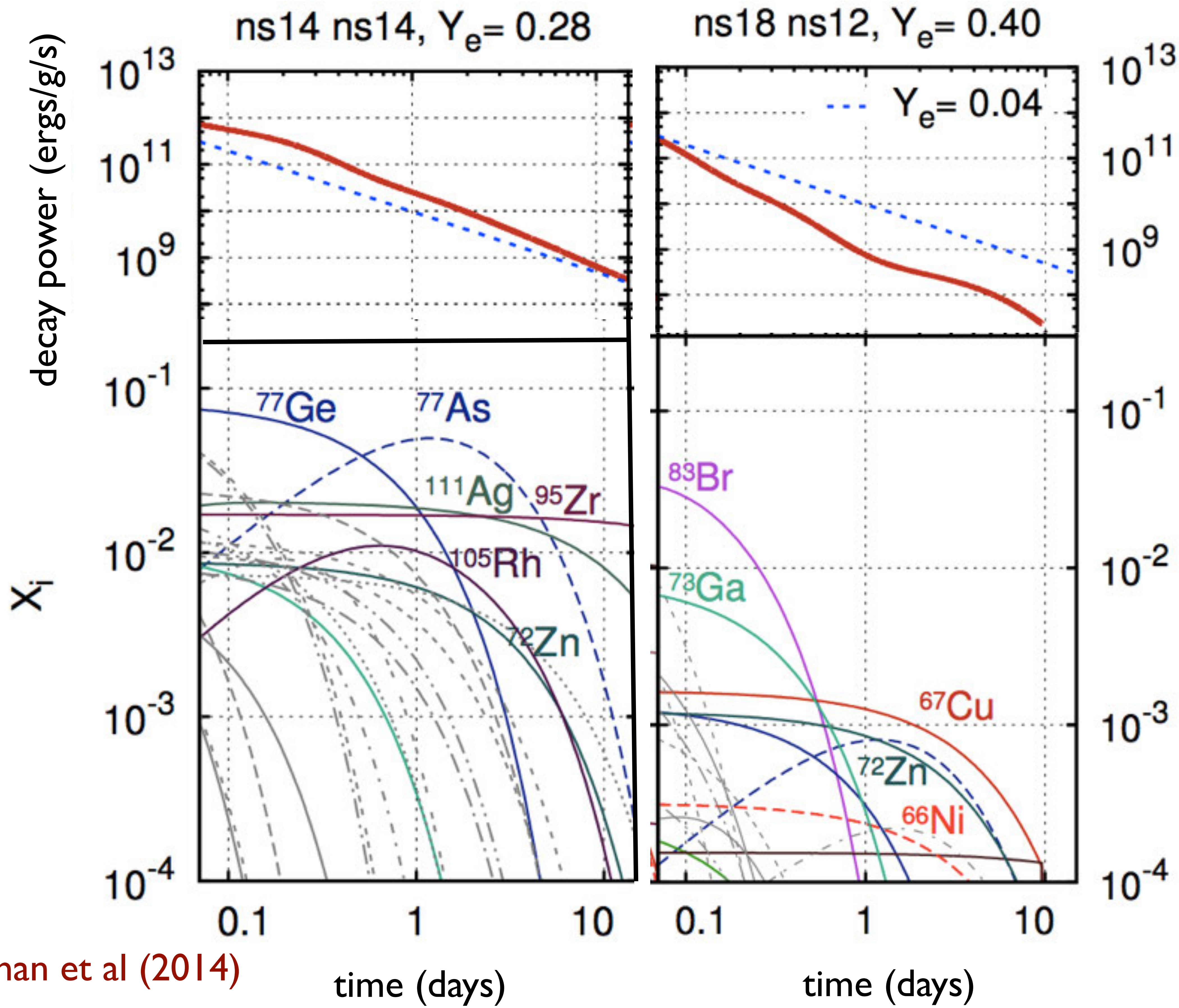
# of neutrons

r process nucleosynthesis in dynamics ejecta

very neutron rich (Ye ~ 0.1) material

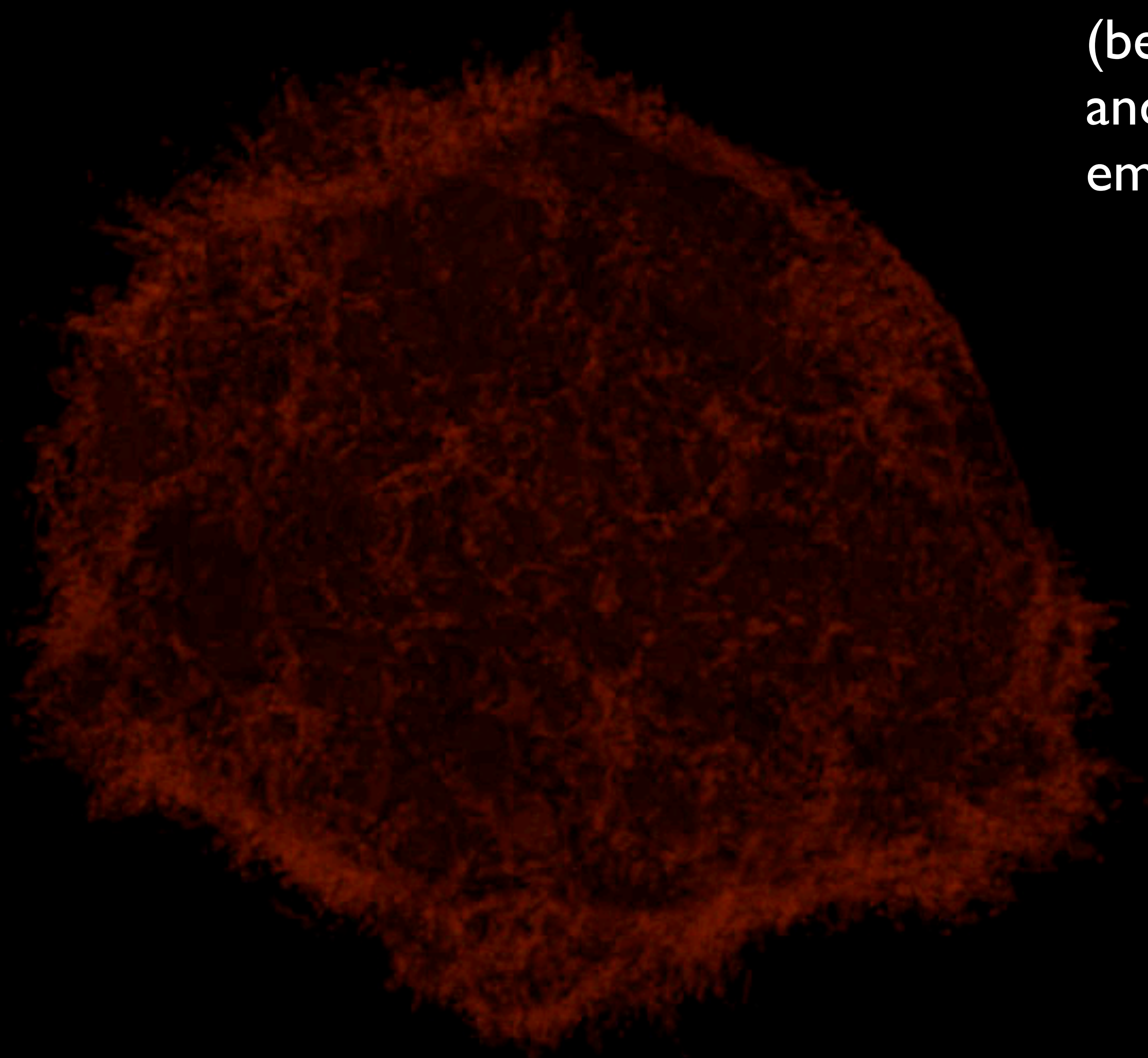


radioactive heating (beta decays)



grossman et al (2014)

radioactively powered transients
a kilonova

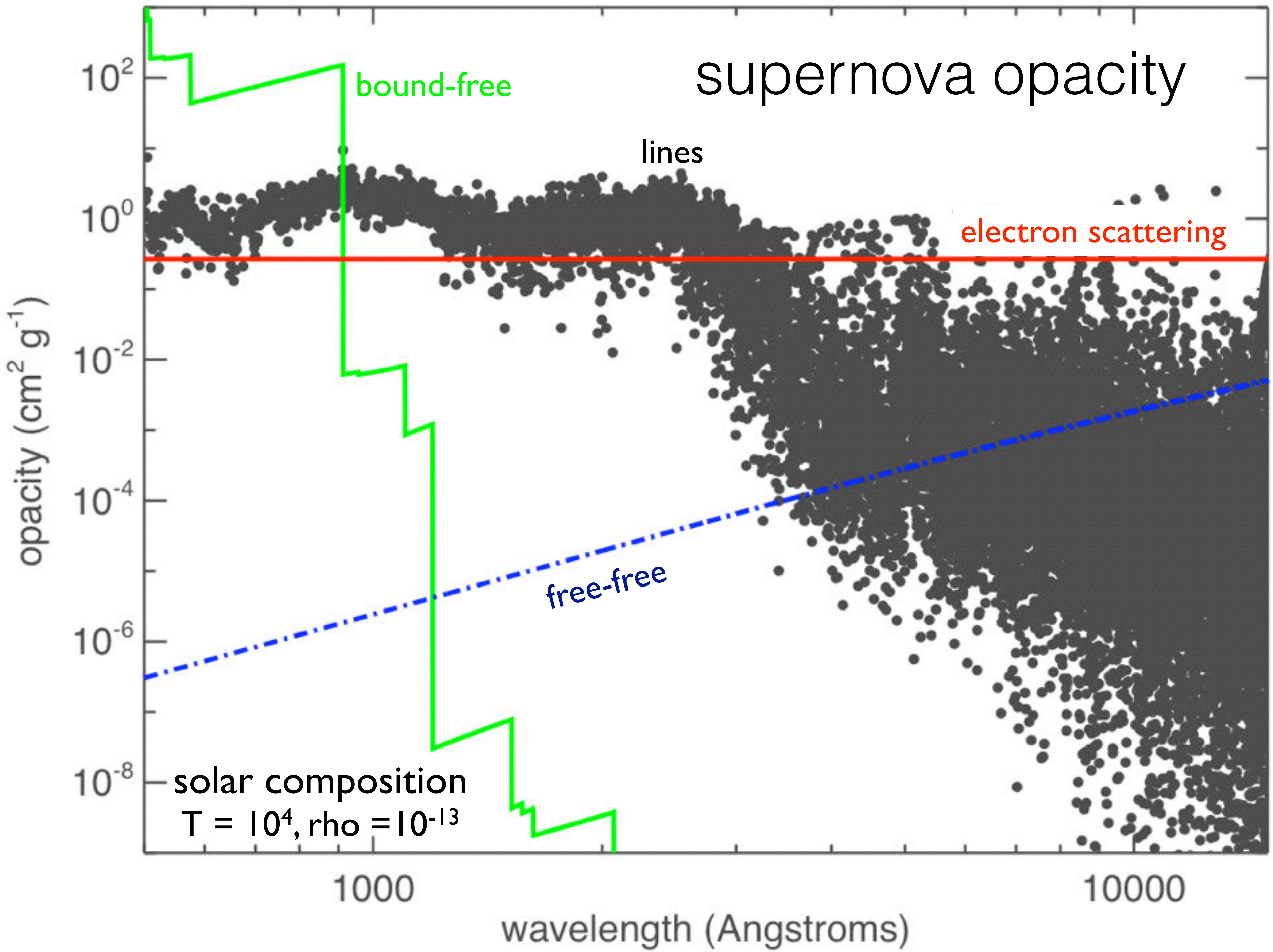


Radioactive decay deposits energy (betas, gamma-rays, fission fragments) and heats the expanding debris, which emits thermally.

$$L \sim M \dot{\epsilon}(t_{\rm p})$$

$$t_{\rm d} \sim \left[\frac{M \kappa}{v c}\right]^{1/2}$$

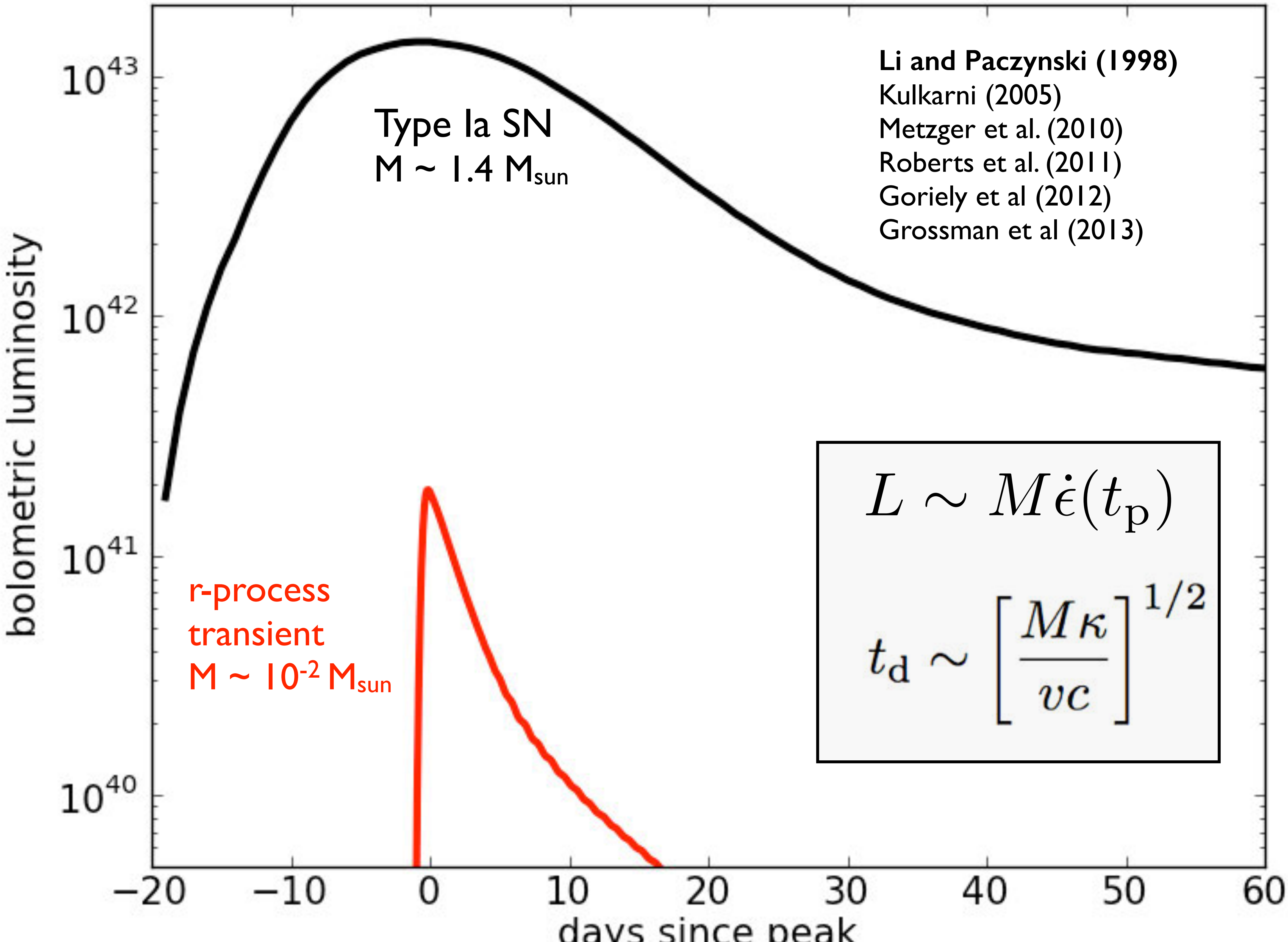
what is the opacity of a heavy metal cloud? (lines dominate)



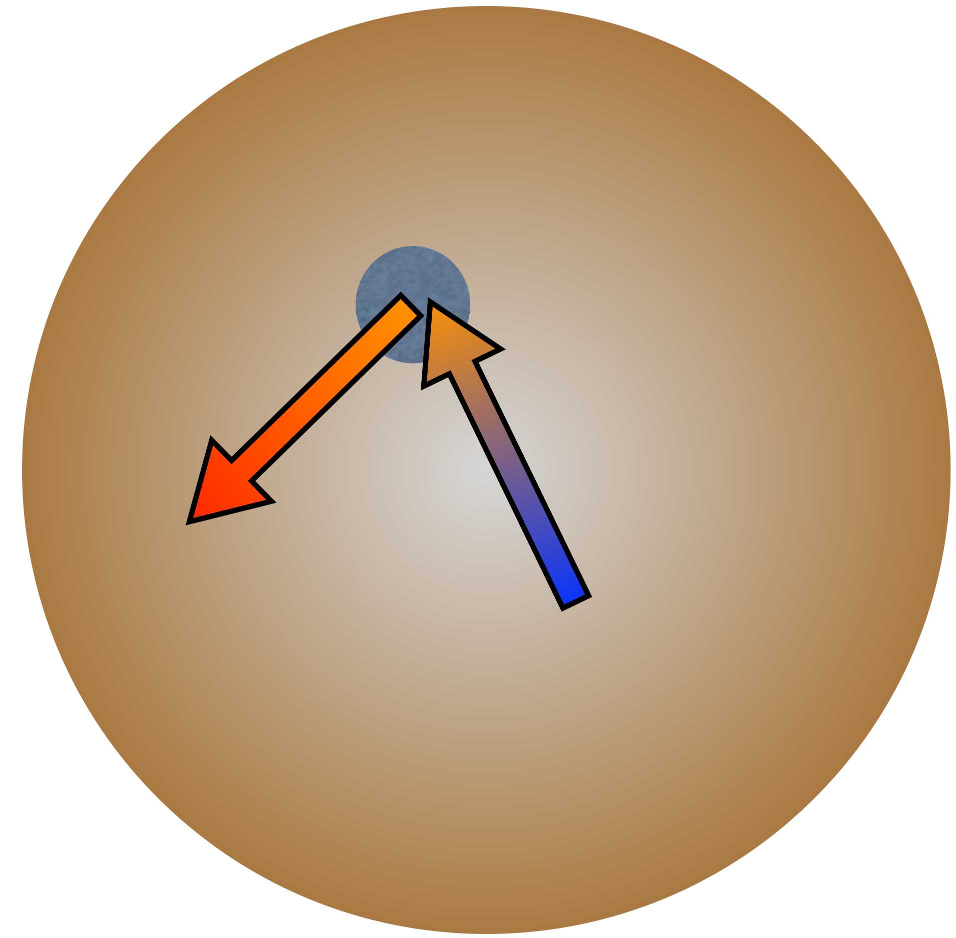
supernova opacity
bound-free
lines
electron scattering
free-free
solar composition
T = 10^4, rho =10^-13
opacity (cm^2 g^-1)
wavelength (Angstroms)
10^2
10^0
10^-2
10^-4
10^-6
10^-8
1000
10000

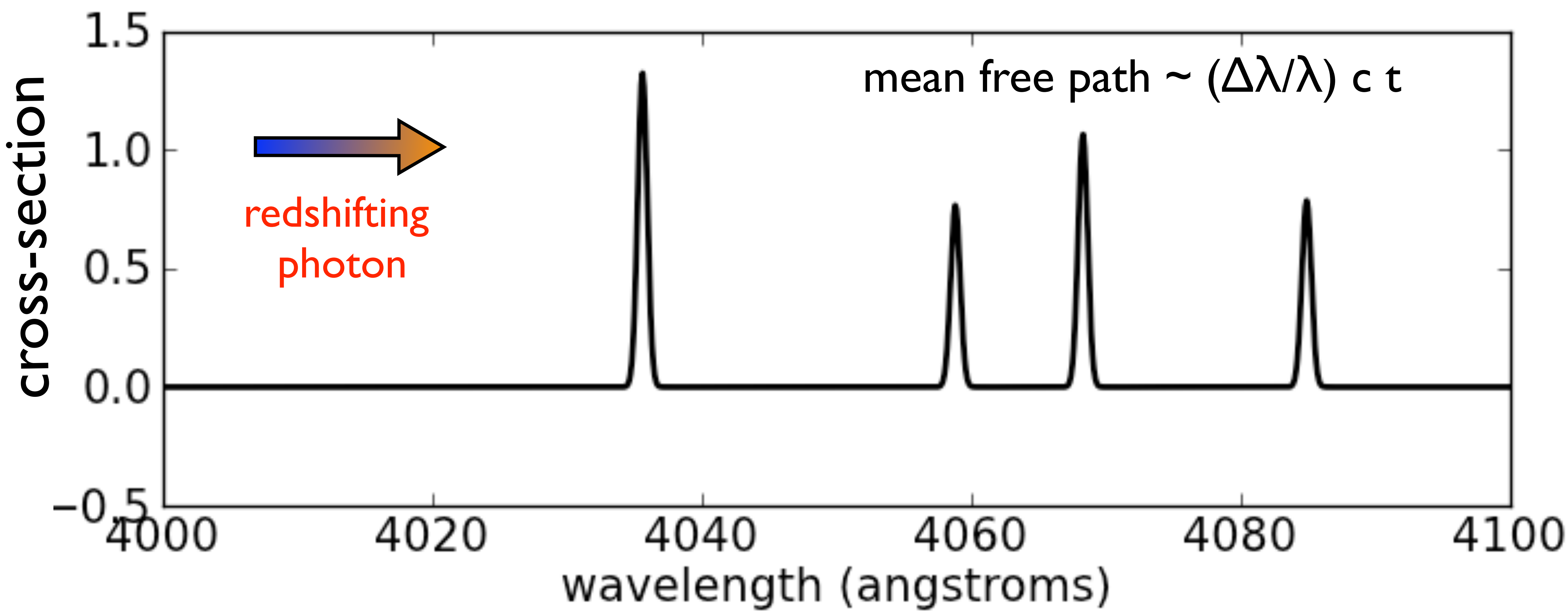
r-process supernova model light curve

iron-like opacity

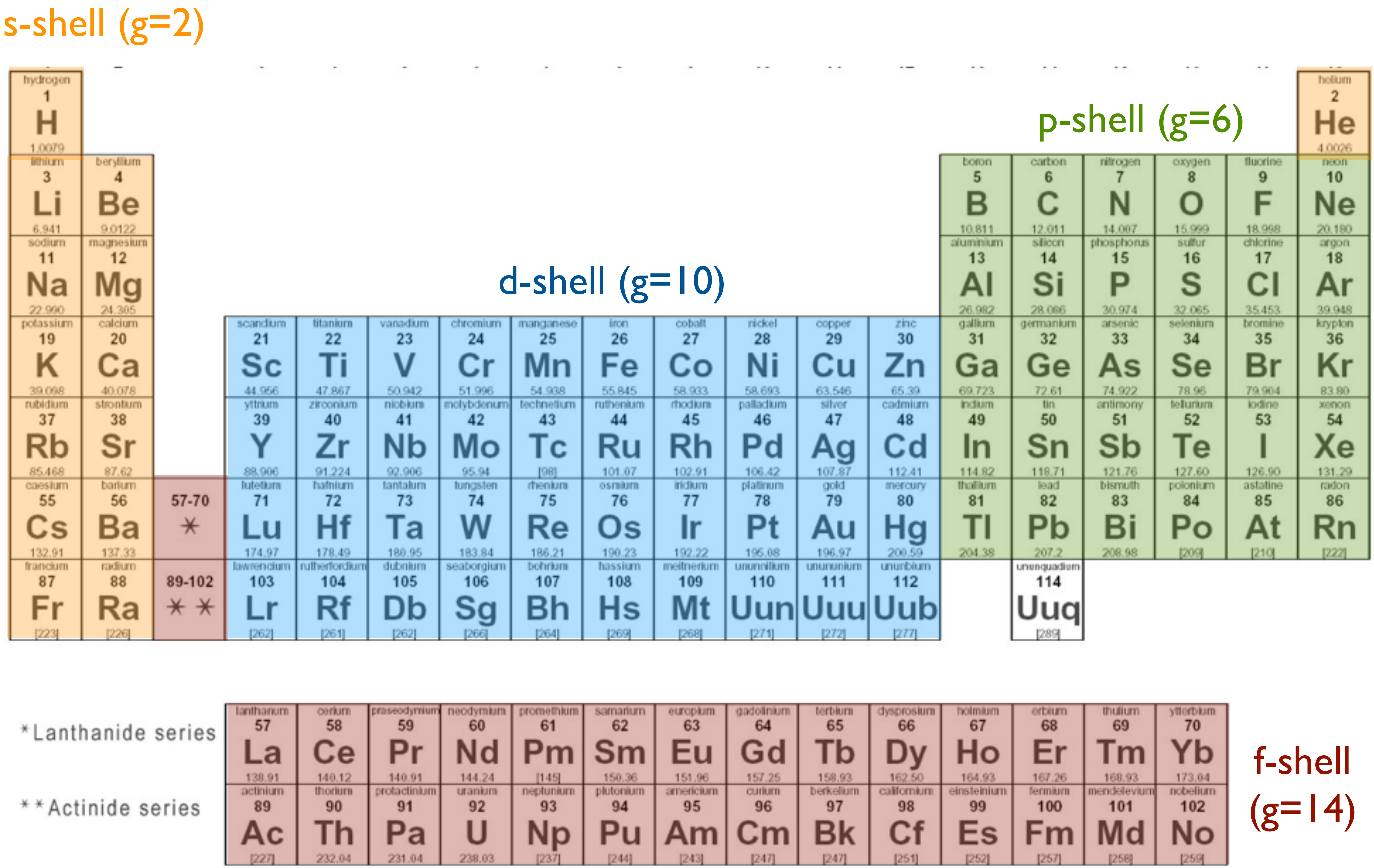


line interactions in an expanding (hubble-like) flow





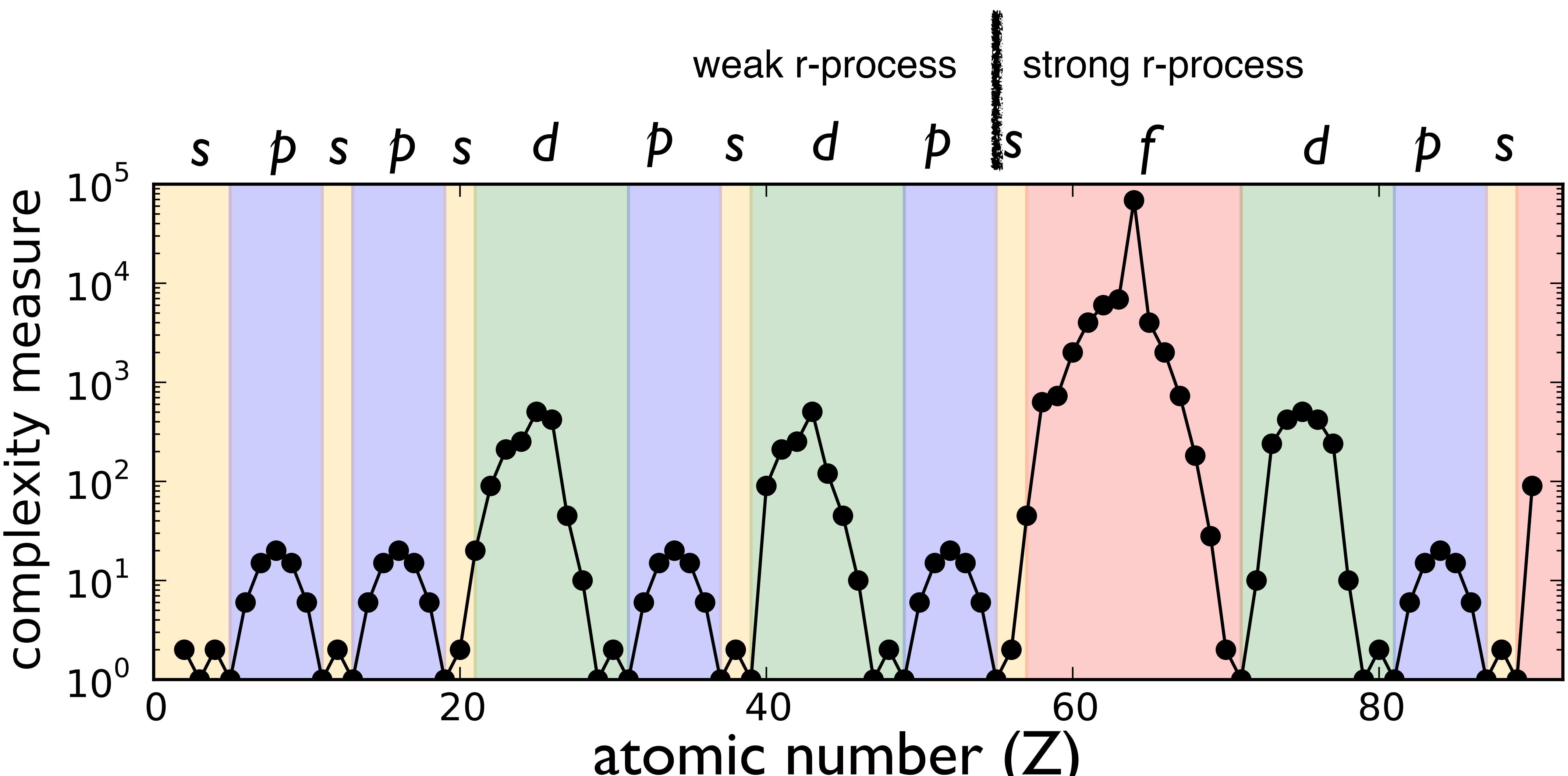
opacity and atomic complexity



atomic complexity

$$N \approx \frac{g!}{n!(g-n)!}$$

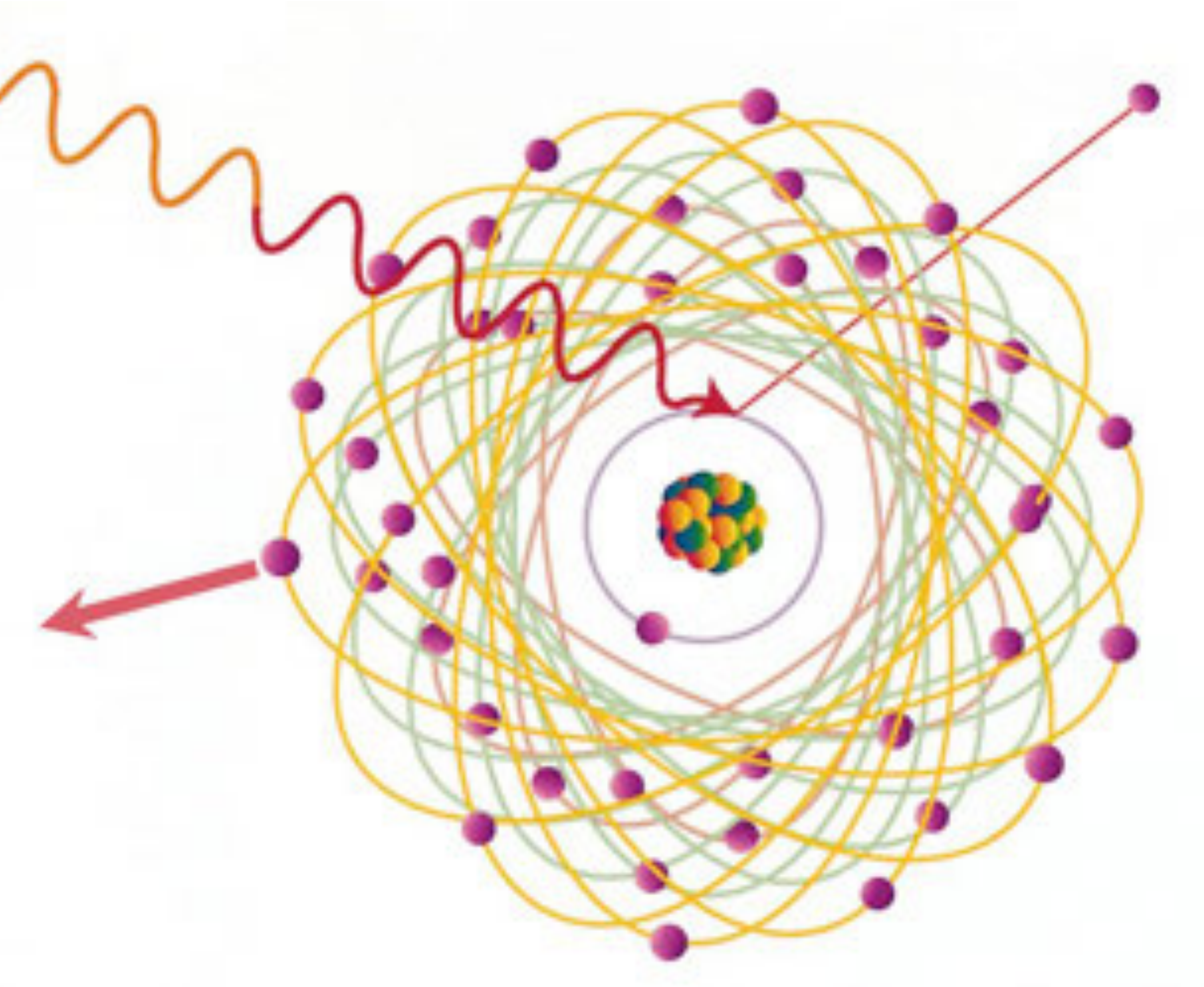
number of atomic levels N is roughly given by putting *n* indistinguishable valence electrons in *g* spots



kasen+ 2013

atomic structure and radiative data

very little data available for high Z



<u>existing data</u>

VALD database

Kurucz database

DREAM database

(MONS group)

<u>new calculations</u>

autostructure code

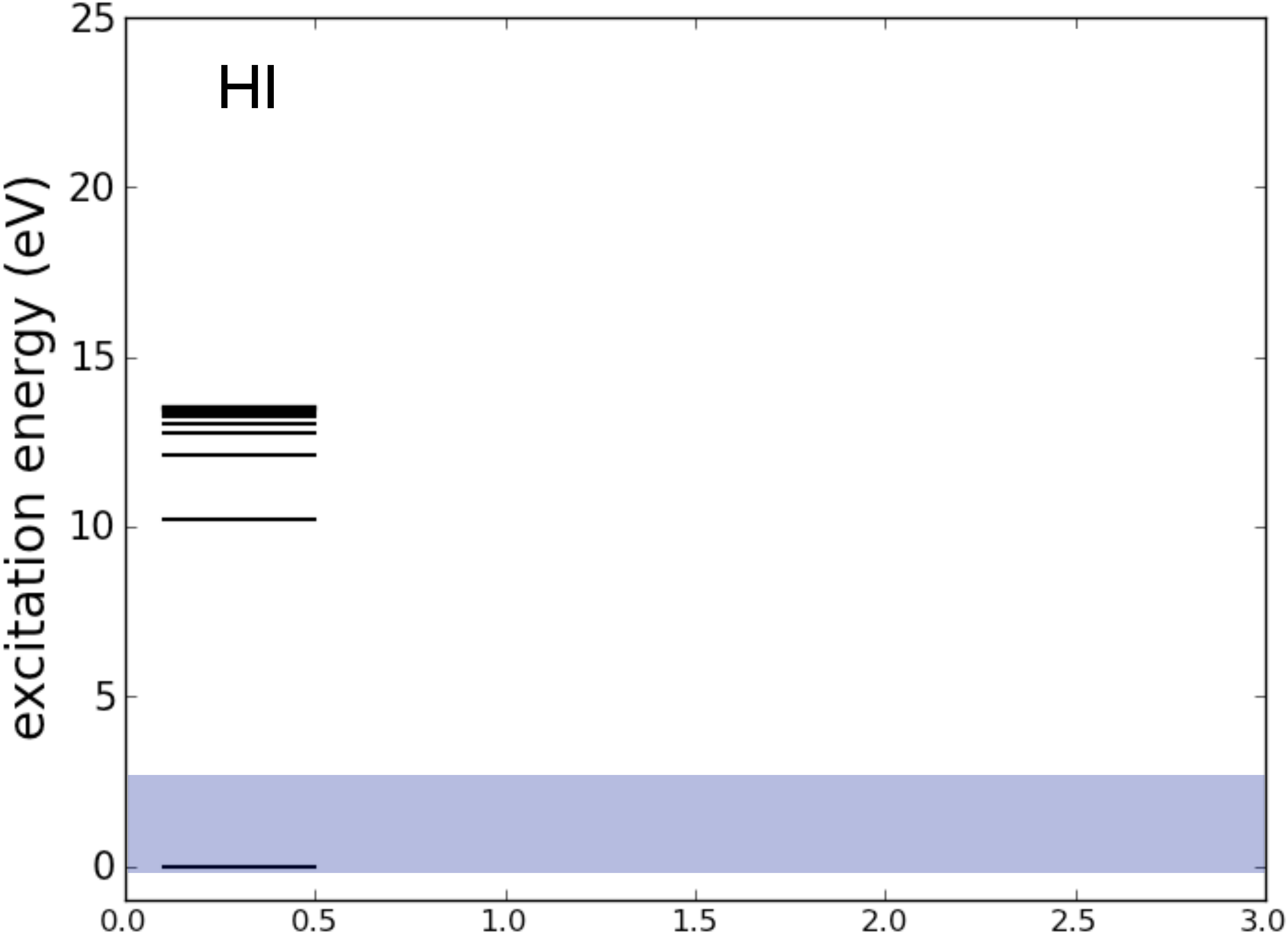
Badnell et al

Slater state expansion technique and relativistic corrections in the Breit-Pauli approximation.

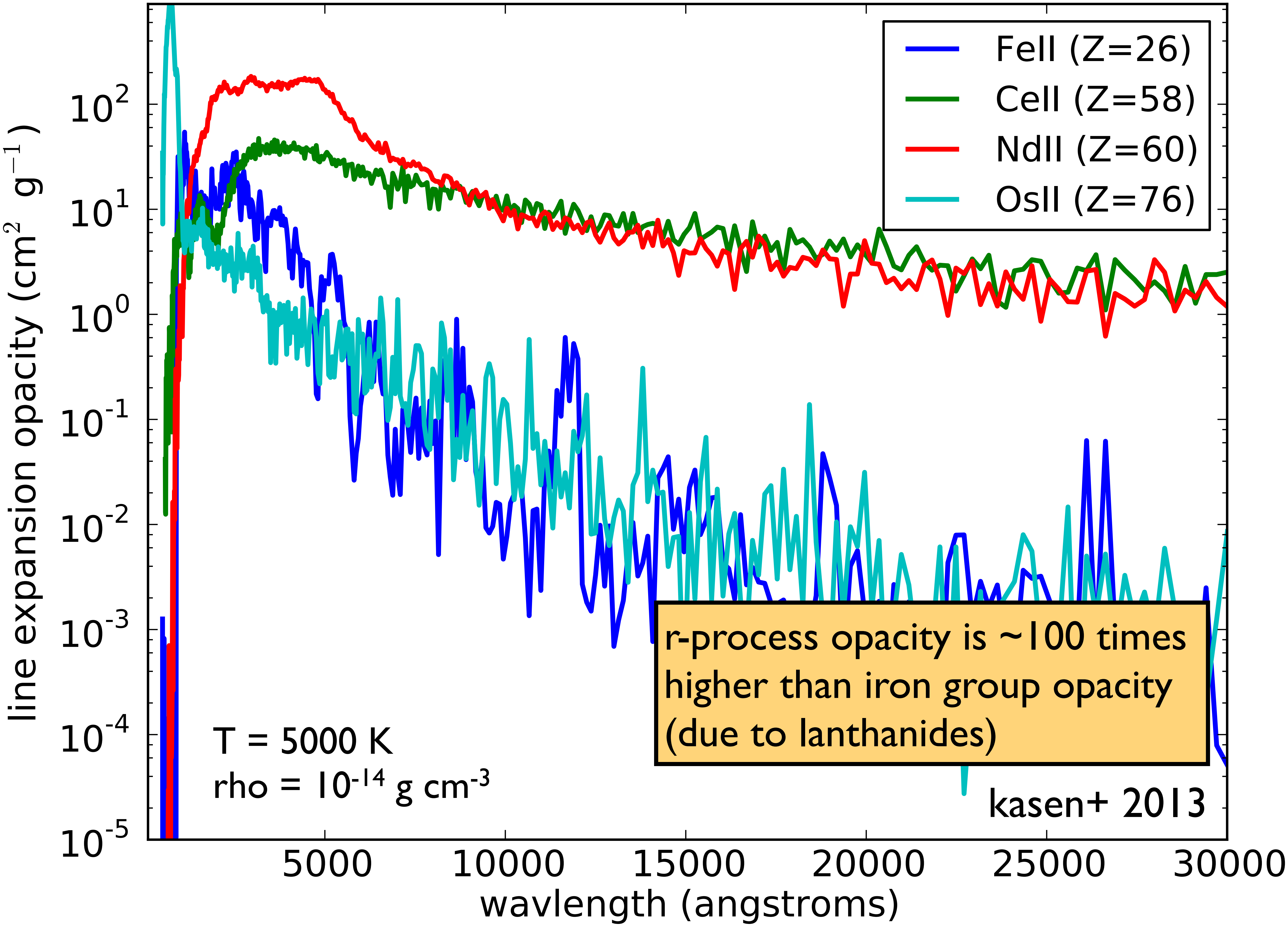
Intermediate coupling

level energy structure

kasen+ 2013

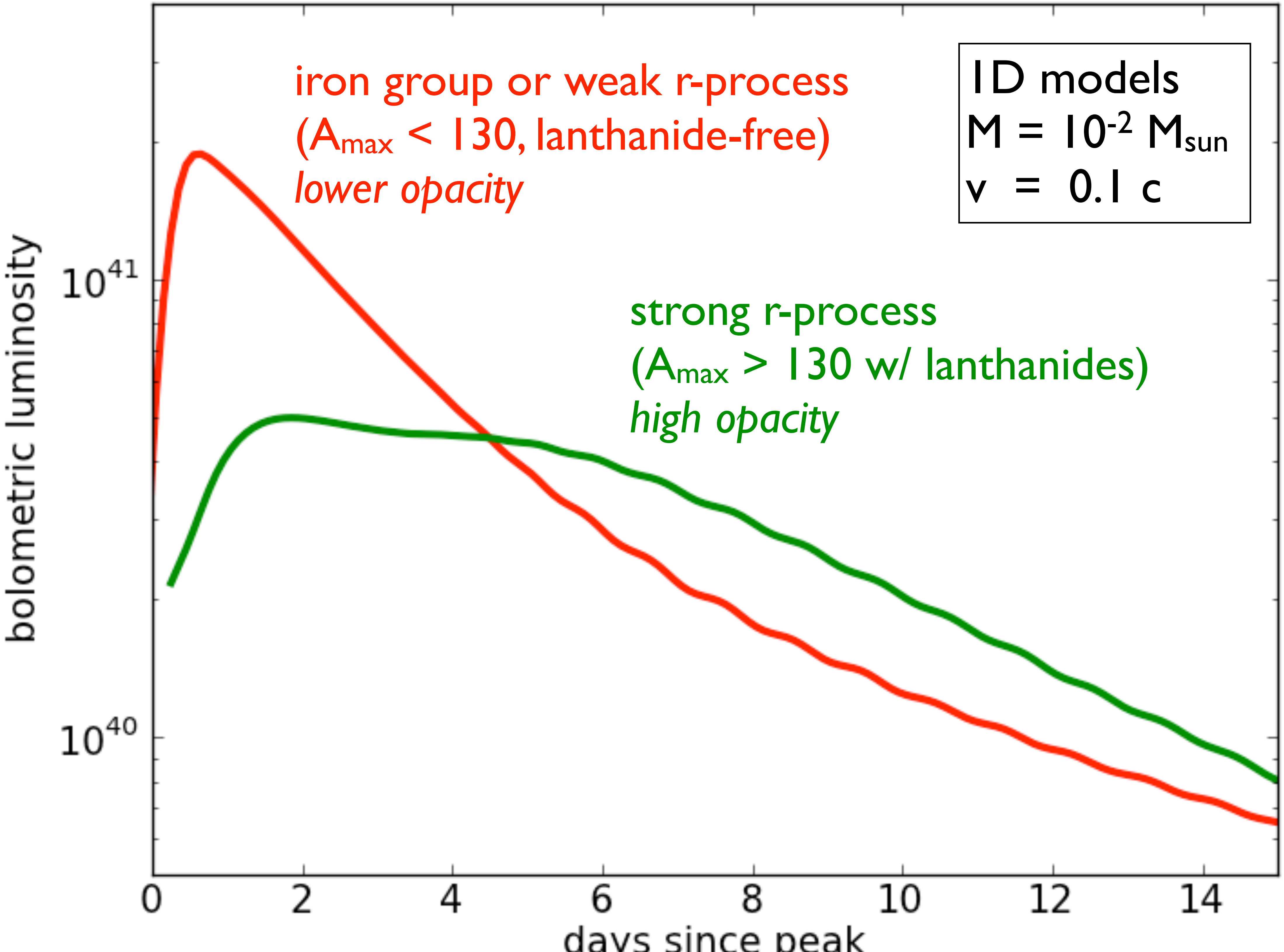


r-process opacity from lines

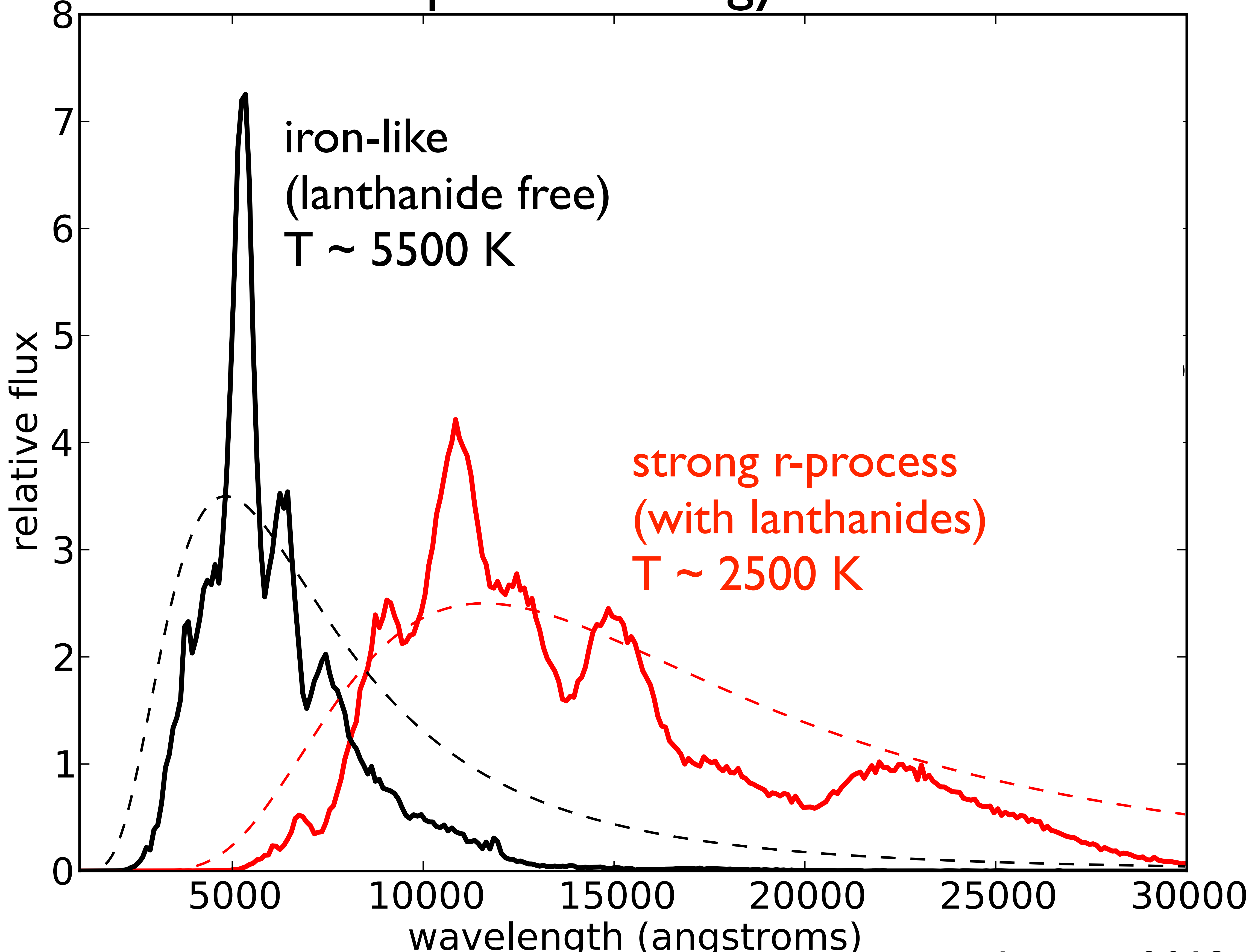


light curves of radioactive transients

multi-wavelength time-dependent transport

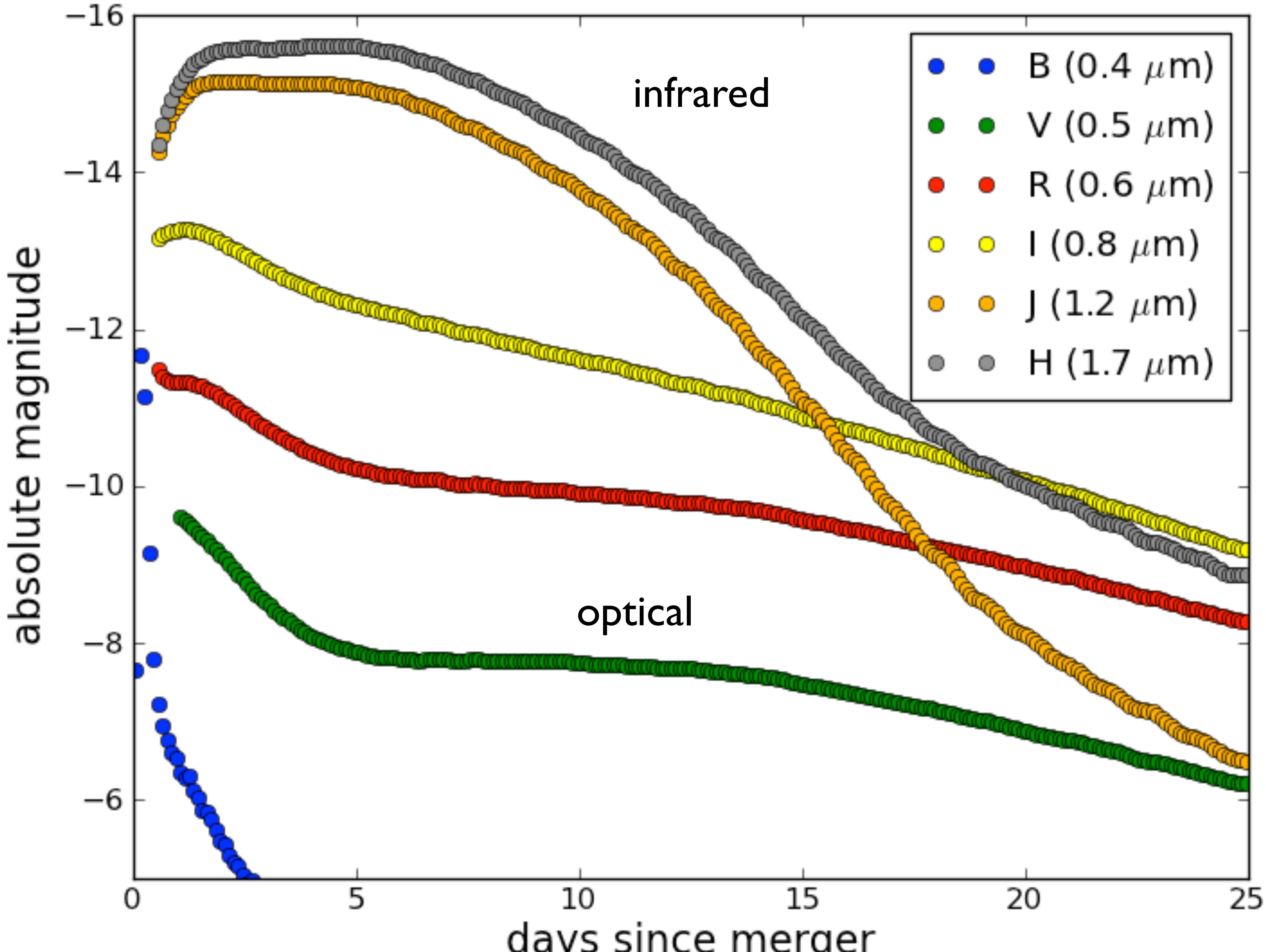


model spectral energy distribution



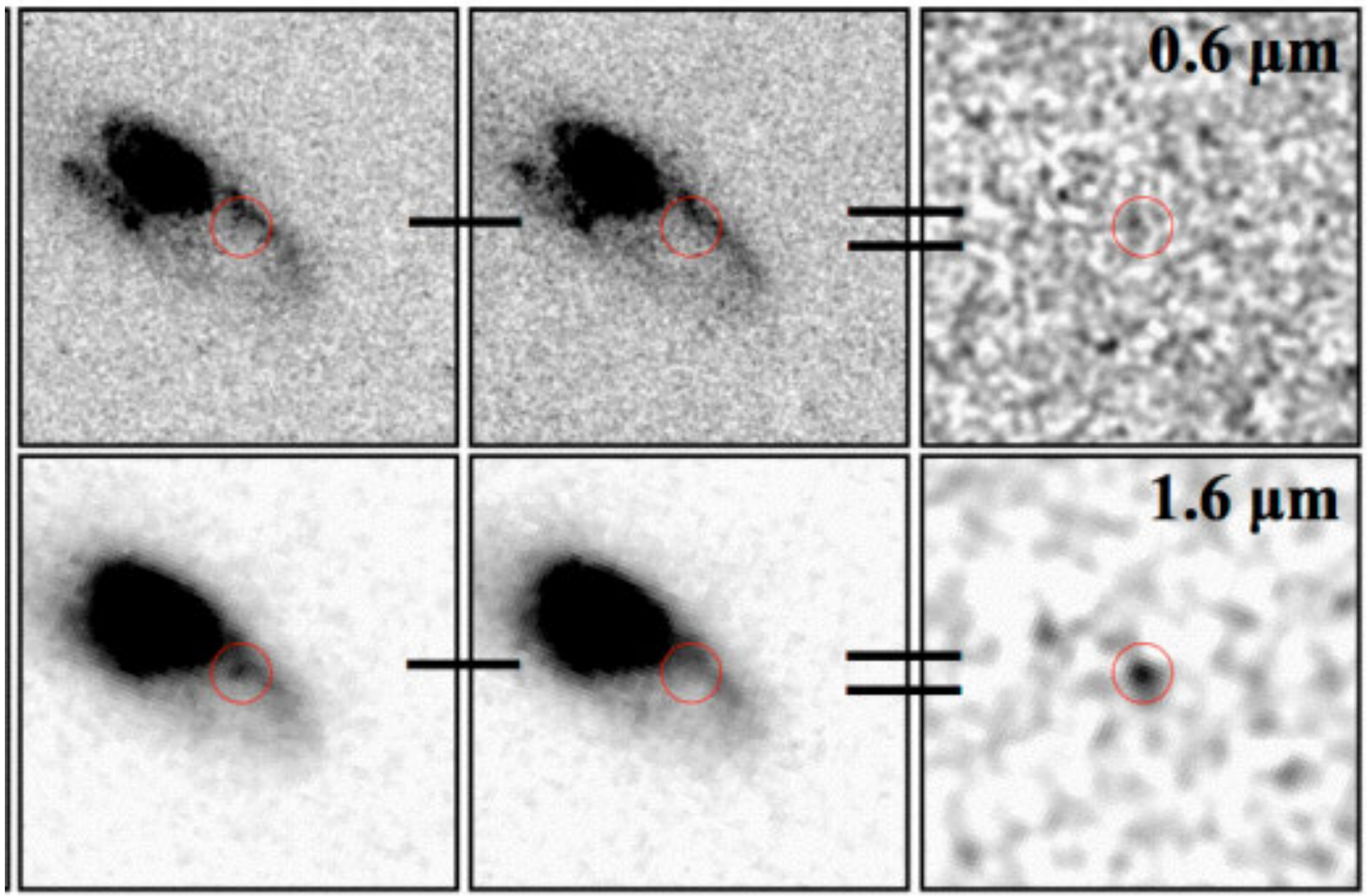
kasen+ 2013

broadband light curves - infrared!



GRB130603B

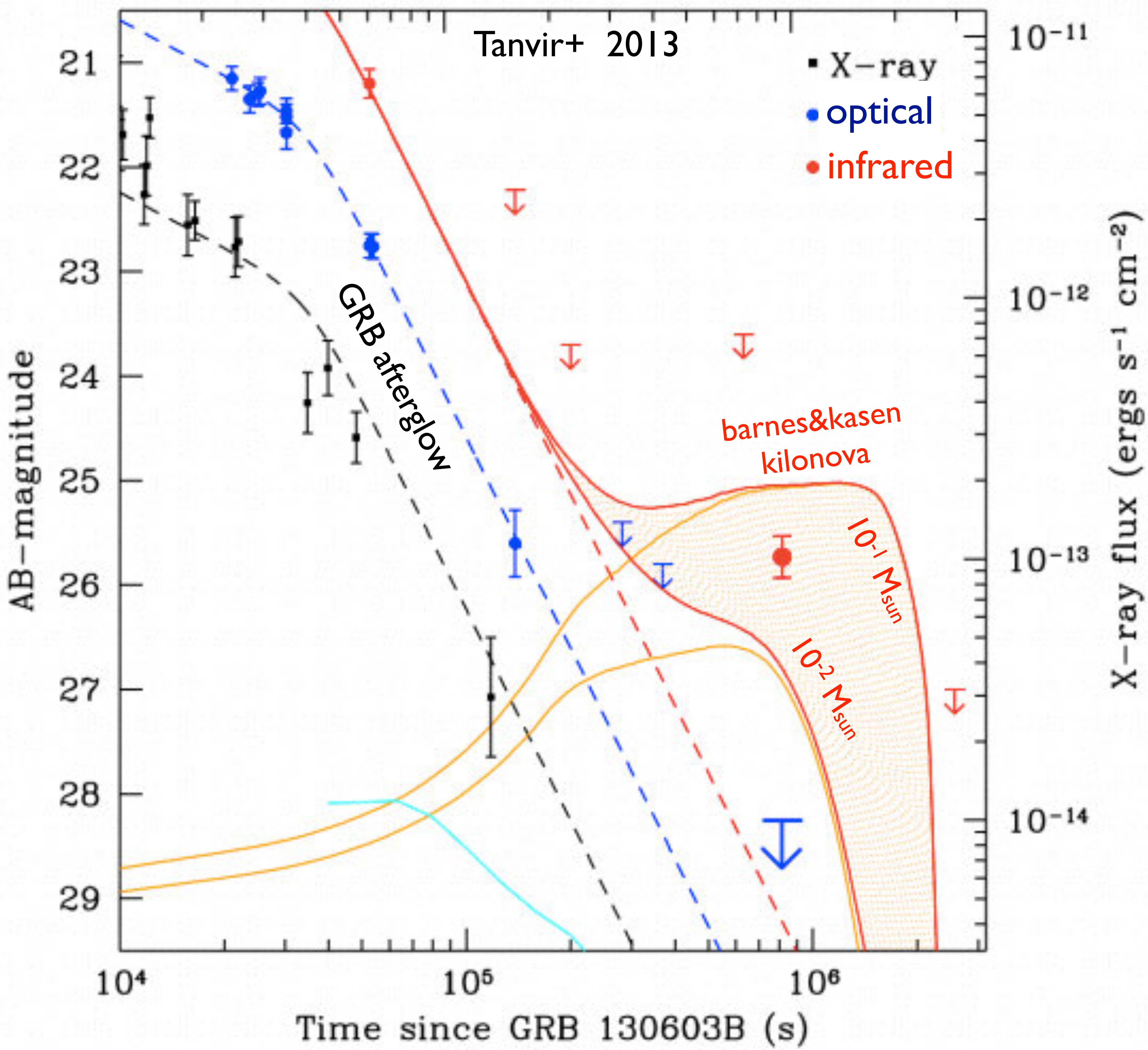
relatively nearby short GRB (z = 0.356)



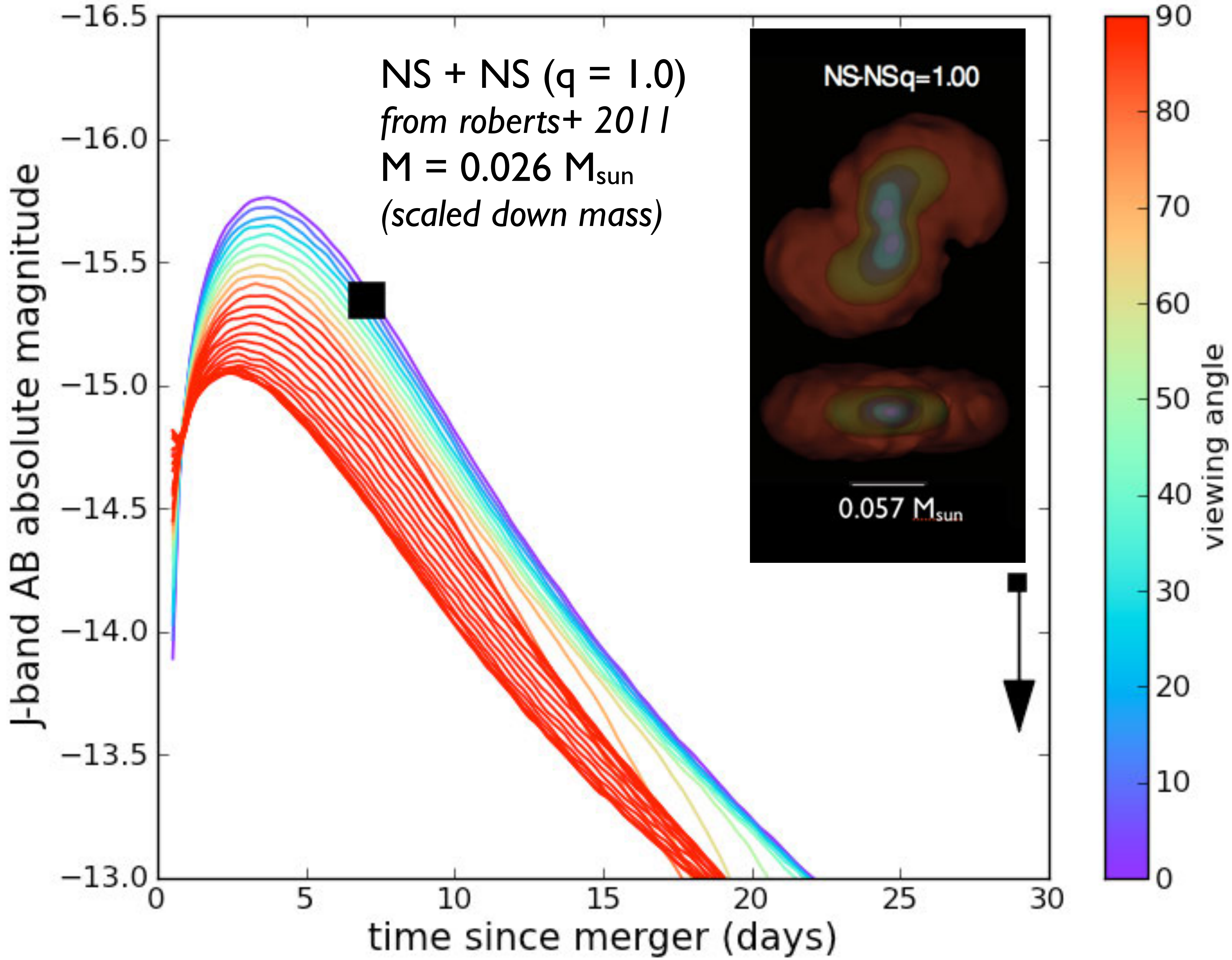
deep infrared imaging with HST
triggered ~1 week after burst

Tanvir+ 2013
c.f. Berger 2013

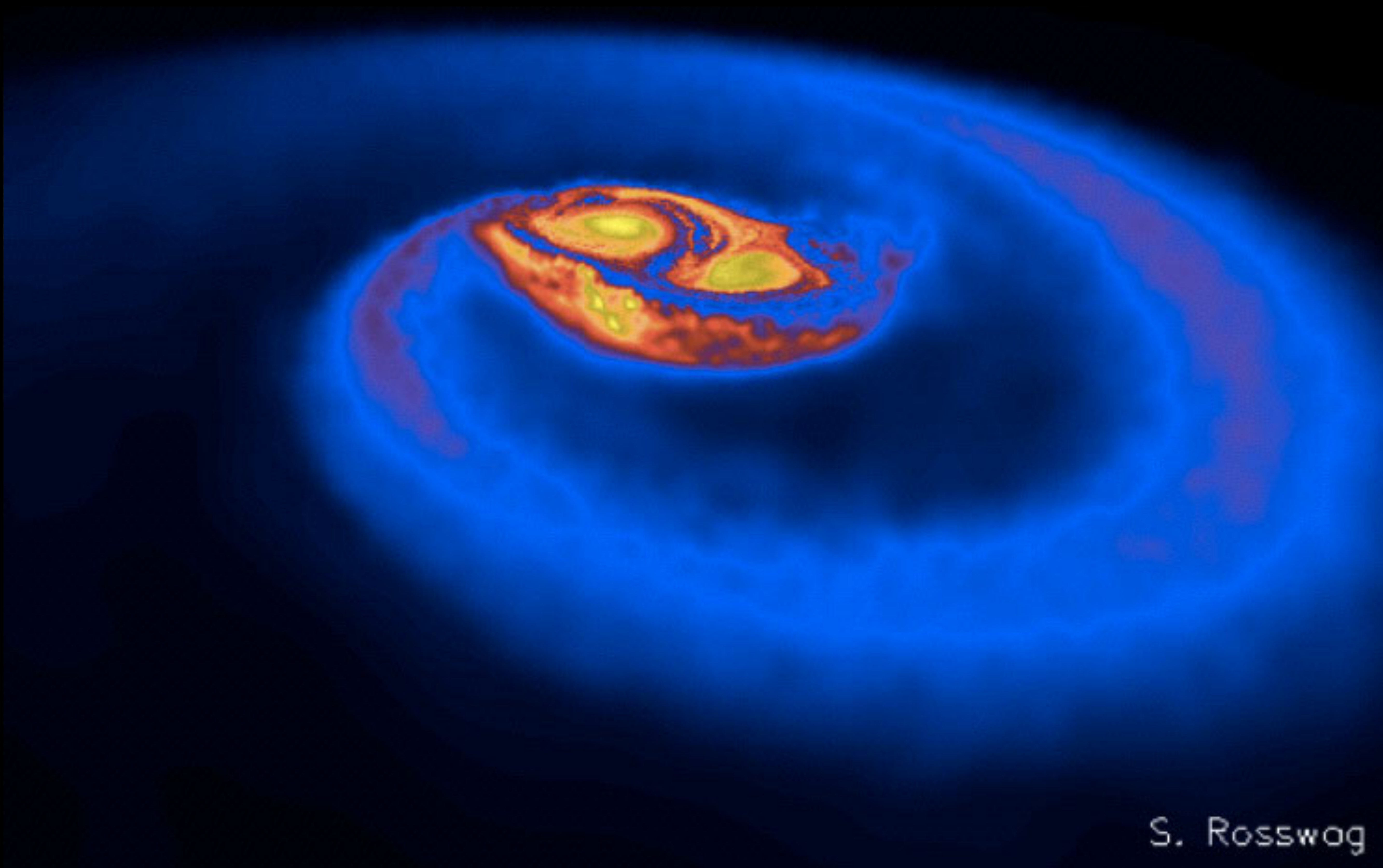
discovery of an r-process kilonova?



3D kilonova transport models

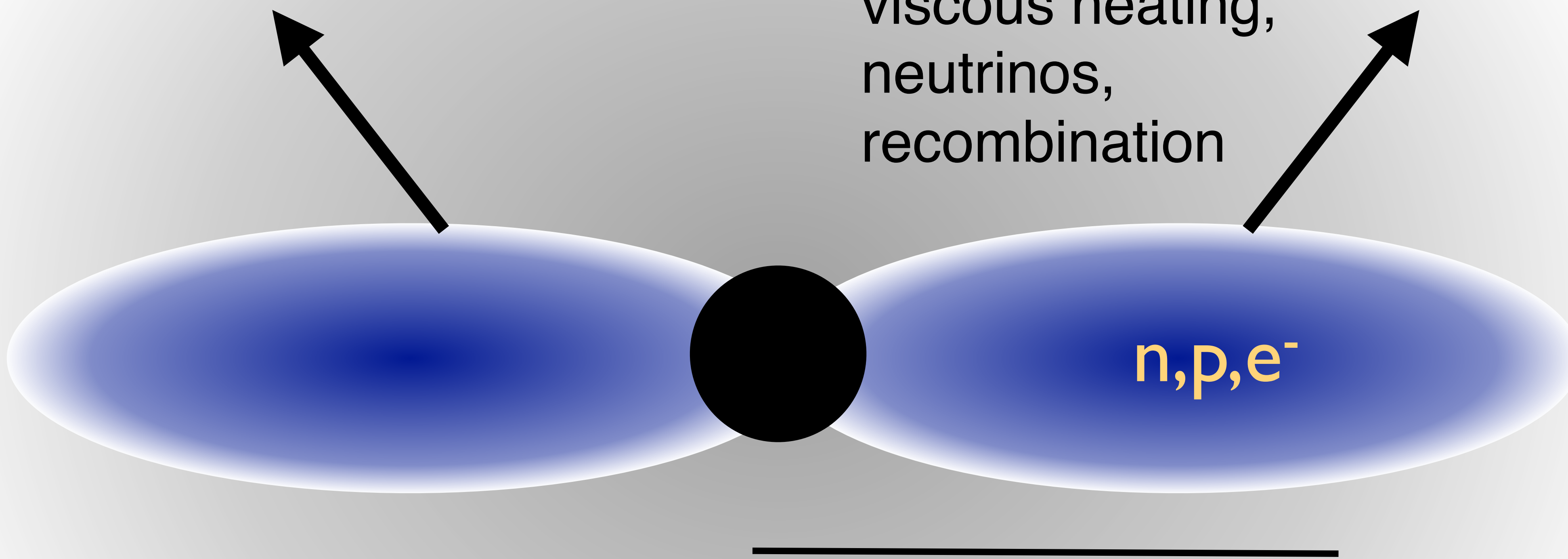


post-merger (longer term) mass outflows



post-merger (longer term) viscous evolution

outflow driven by
viscous heating,
neutrinos,
recombination



$R_d \approx \text{few } R_{\rm NS} \approx 50 \text{ km}$

$M_{\rm rem} \sim 3 \ M_\odot$

$M_{\rm disk} \sim 10^{-3} - 10^{-1} \ M_\odot$

orbital time scale ~ msec
viscous time scale ~ sec

neutrino irradiation
increases the Y_e of disk

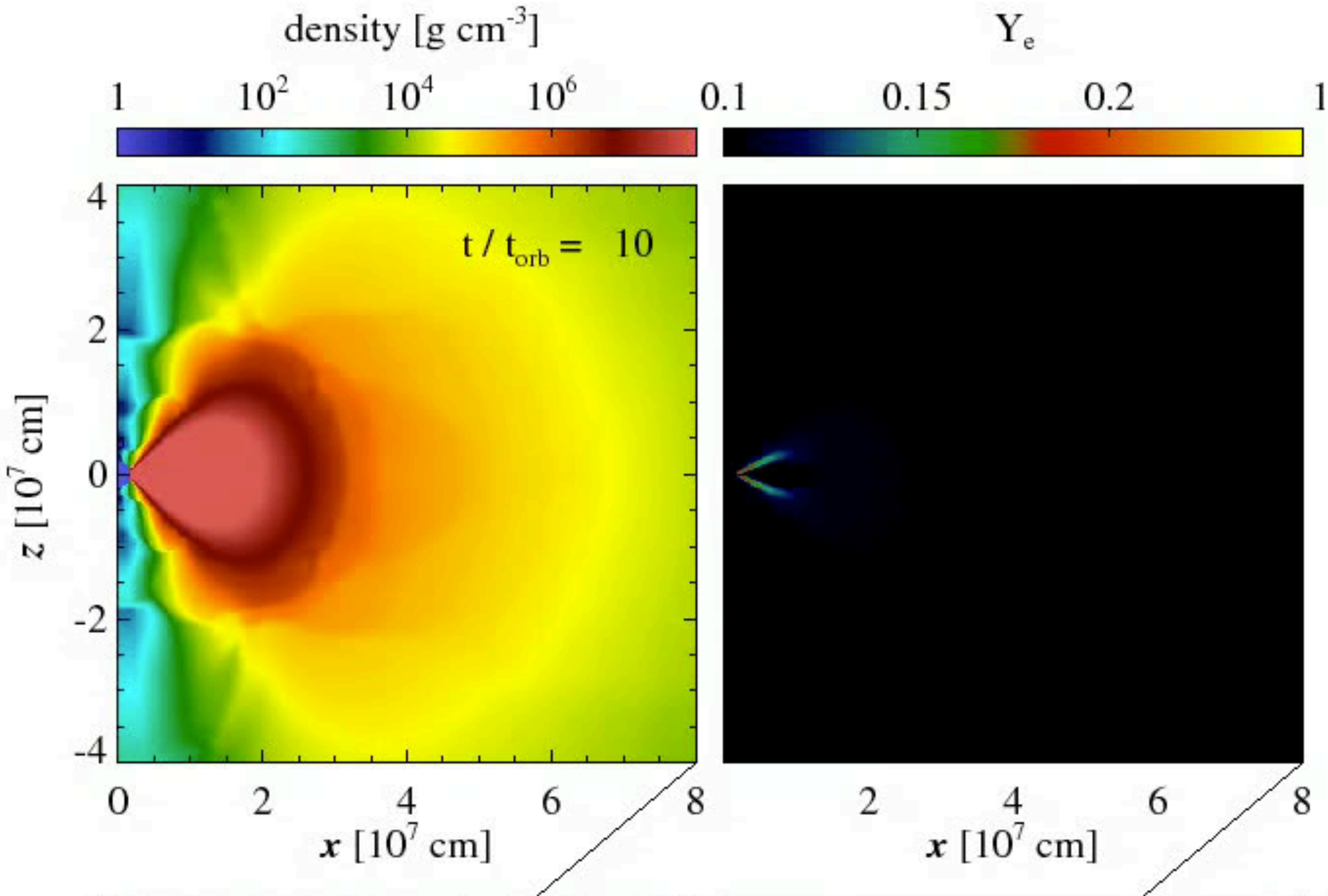
$n + \nu_e \leftrightarrow p + e^-$

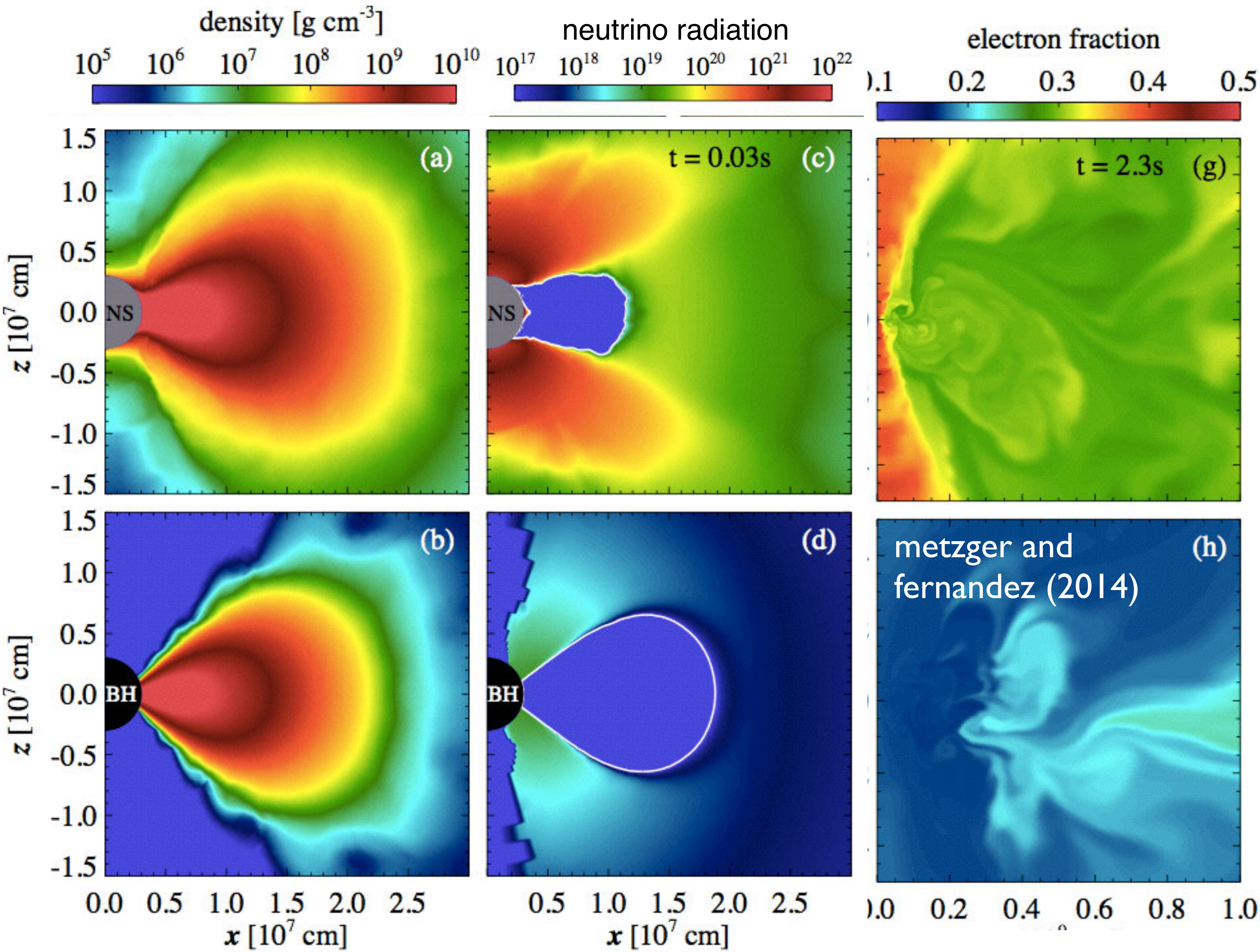
$p + \bar{\nu}_e \leftrightarrow n + e^+$

post-merger ejection in disk winds

viscous, nuclear, or neutrino driven, on longer timescales ~1s

fernandez and metzger (2013)

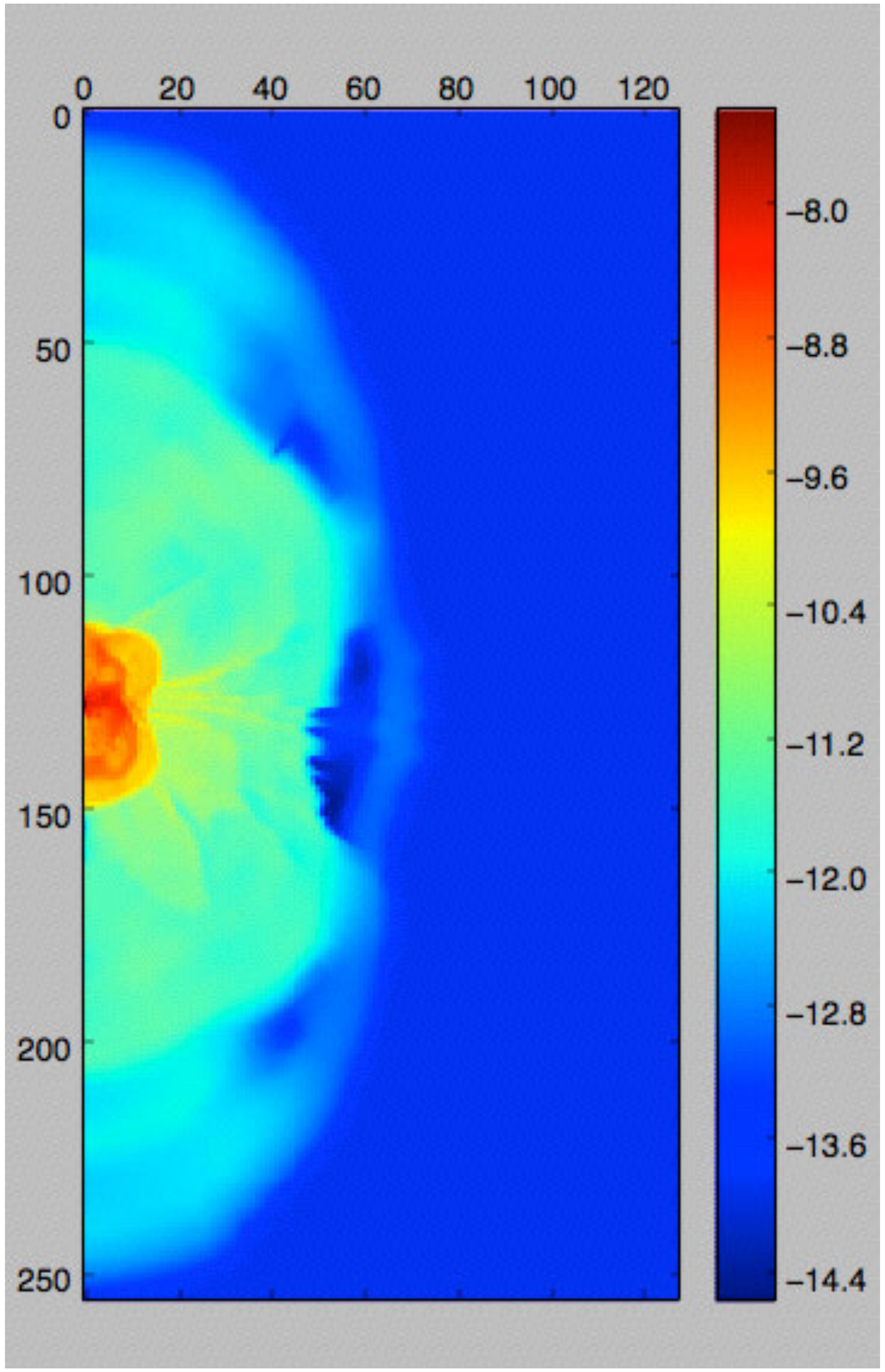




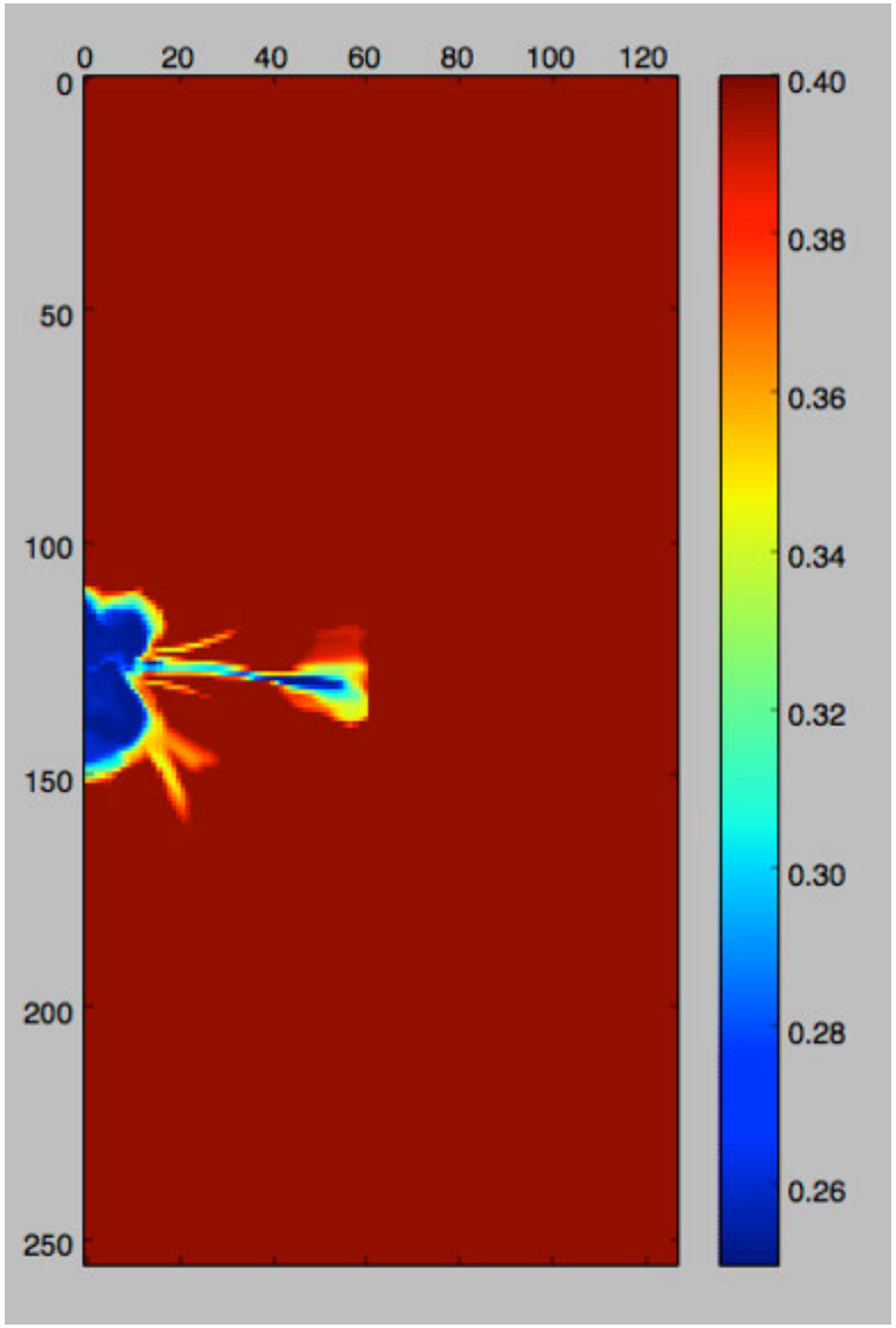
density [g cm^-3]
10^5 10^6 10^7 10^8 10^9 10^10
neutrino radiation
10^17 10^18 10^19 10^20 10^21 10^22
electron fraction
.1 0.2 0.3 0.4 0.5
(a)
t = 0.03s (c)
t = 2.3s (g)
NS
NS
(b)
(d)
BH
BH
metzger and
fernandez (2014)
(h)
z [10^7 cm]
z [10^7 cm]
1.5 1.0 0.5 0.0 -0.5 -1.0 -1.5
0.0 0.5 1.0 1.5 2.0 2.5
x [10^7 cm]
0.5 1.0 1.5 2.0 2.5
x [10^7 cm]
.0 0.2 0.4 0.6 0.8 1.0

ejected disk wind (NS lives 30 ms)

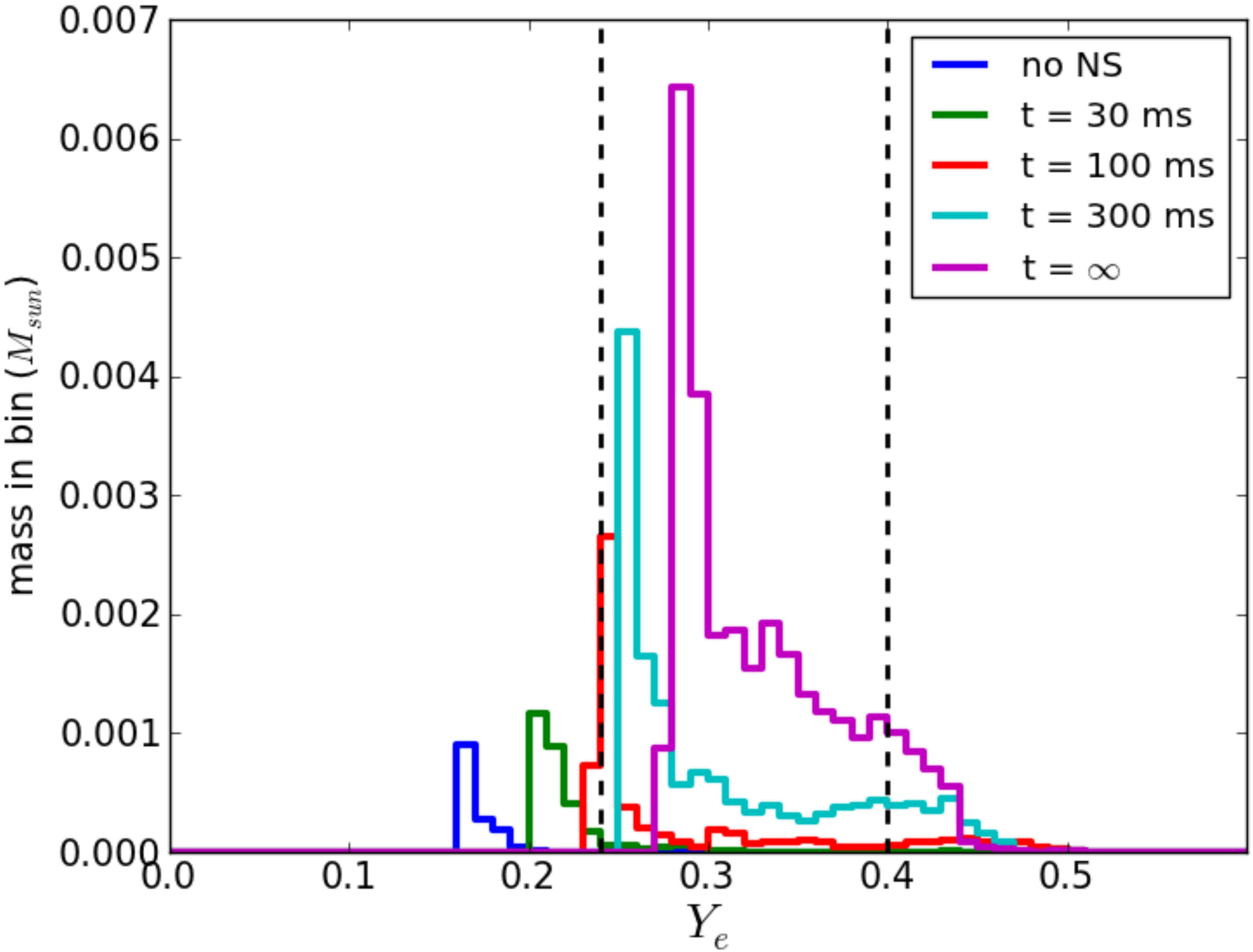
log$_{10}$ density



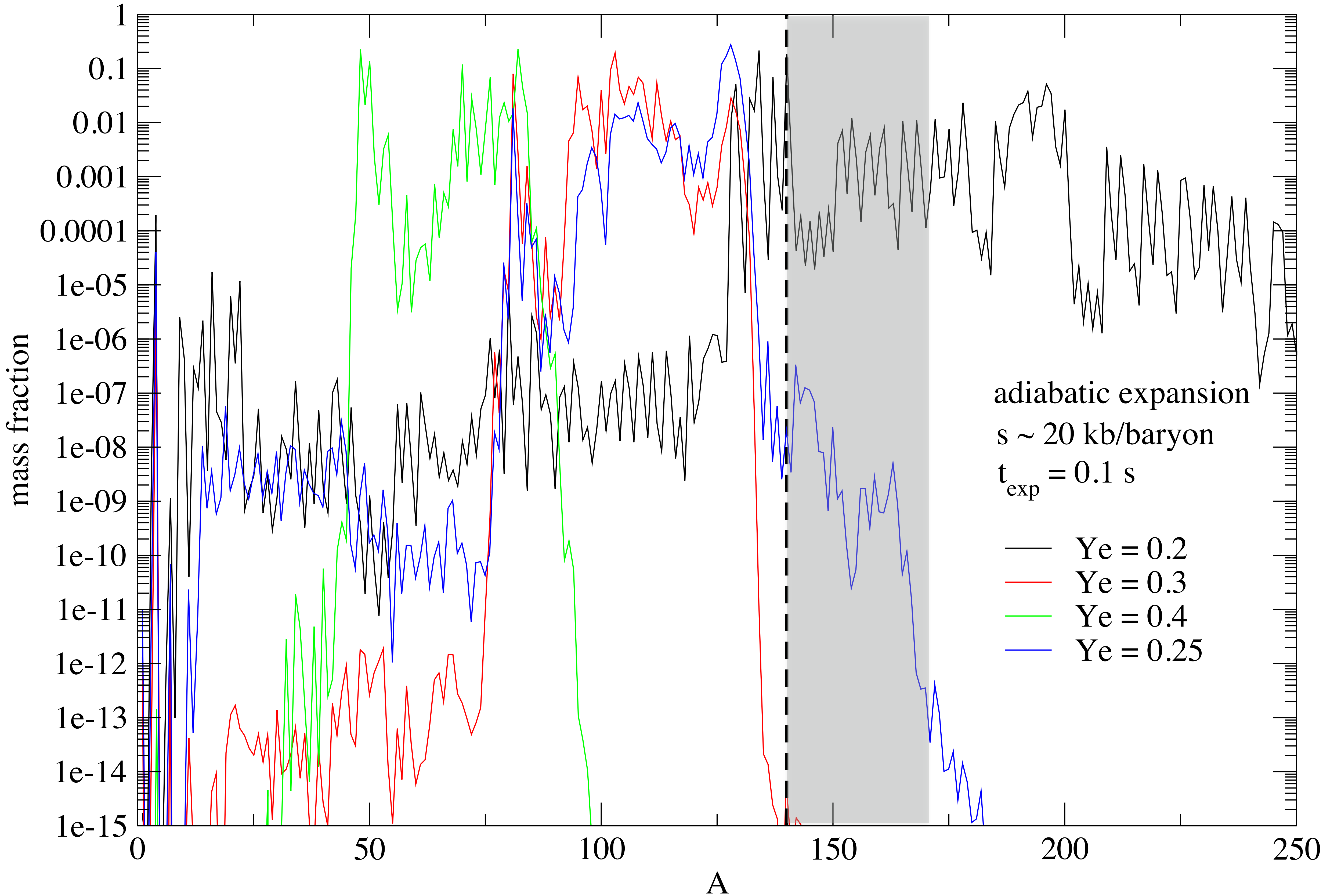
Y_e



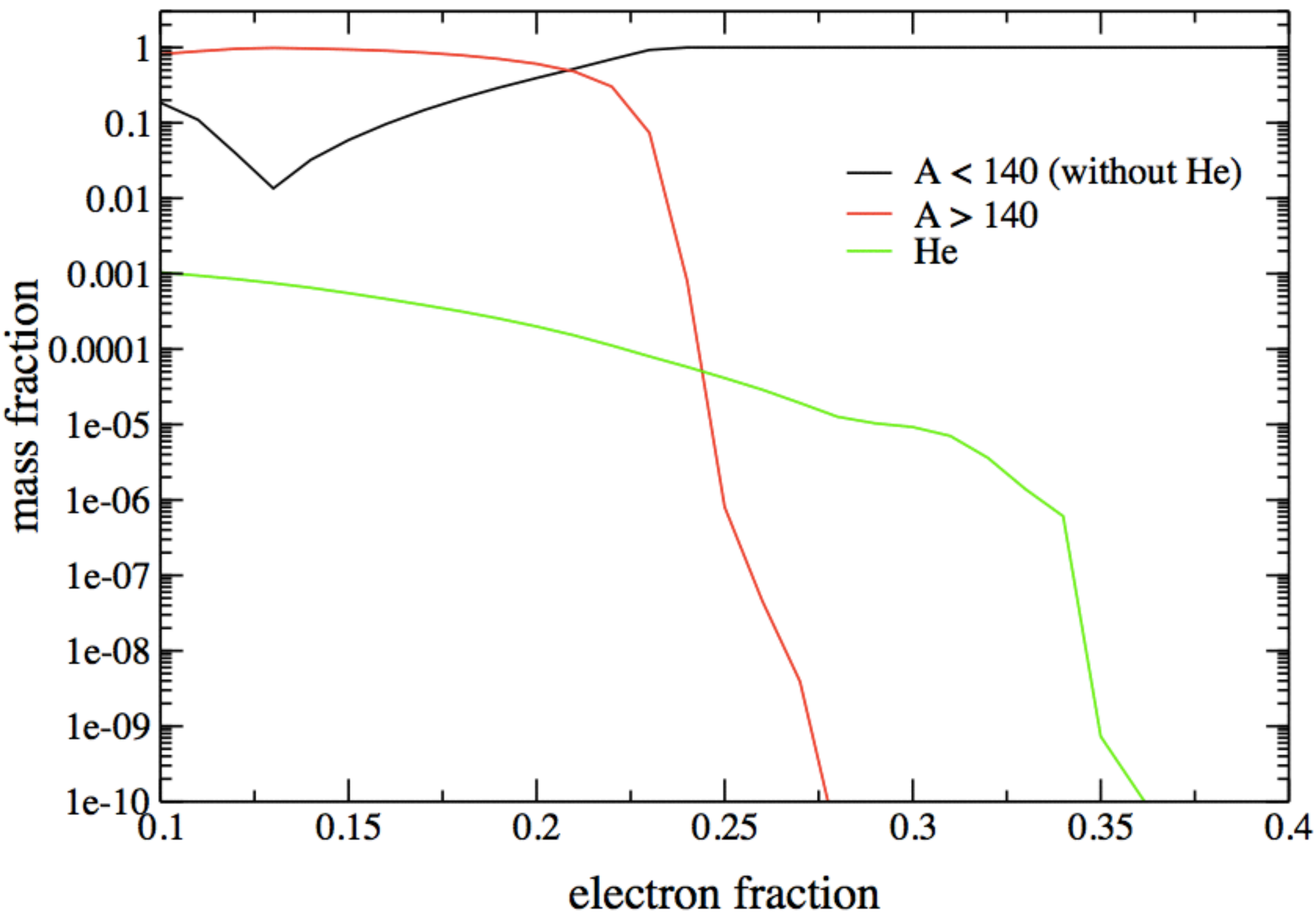
ejected mass - distribution in Y_e



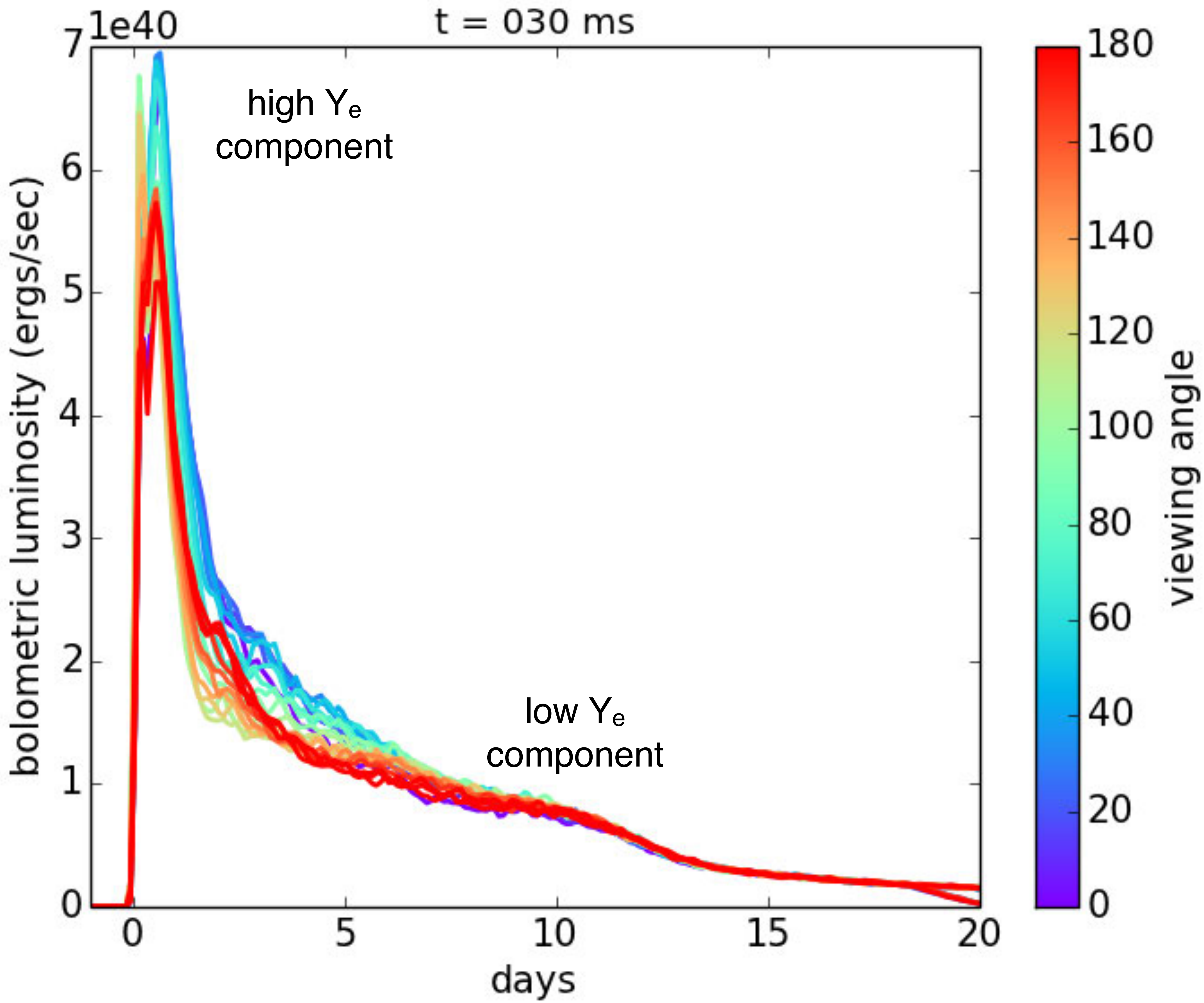
r-process nucleosynthesis (from torch)



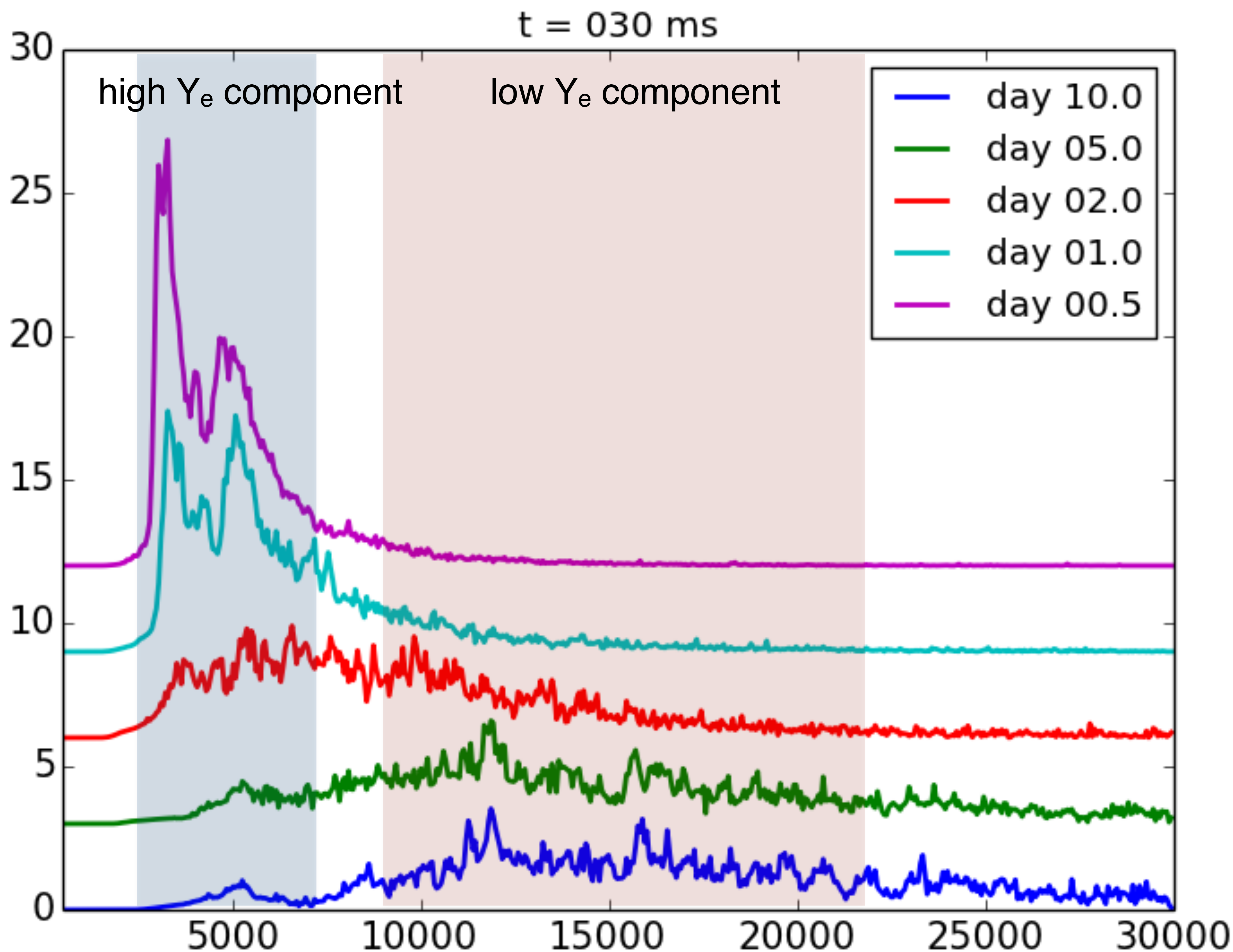
r-process nucleosynthesis (from torch)



light curve of disk wind (30 ms neutron star)

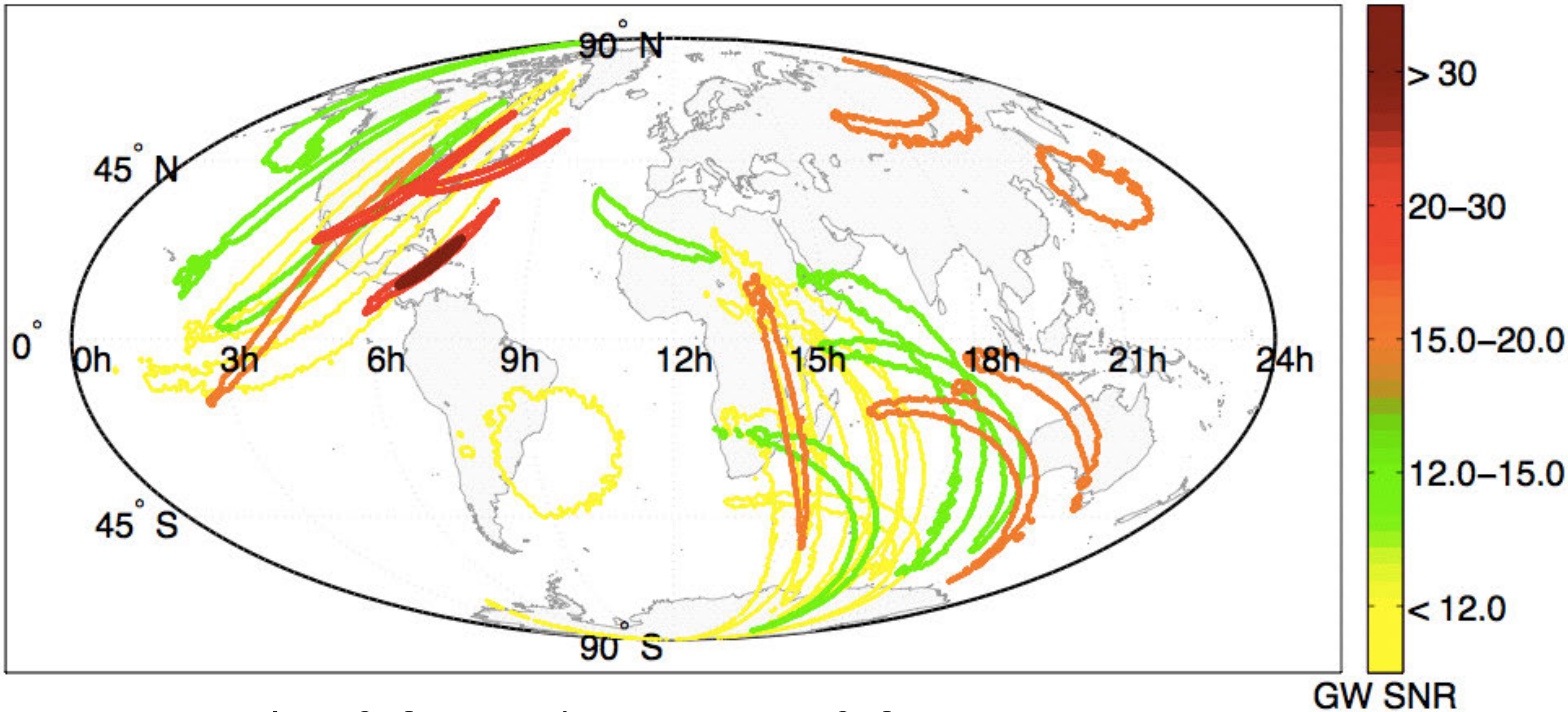


spectra of disk wind (30 ms neutron star)



follow up of LIGO sources

kasliwal & nissanke (2013)



w/ LIGO Hanford and LIGO Livingston

~100 square degree uncertainties

origin of the r-process (counting up the gold)

kilonova observations + models
average r-process mass ejected
advanced LIGO GW detections
neutron star merger rates

but need to improve simulations

dynamical calculations (GR, EOS)
neutrino transport
photon transport (opacities)