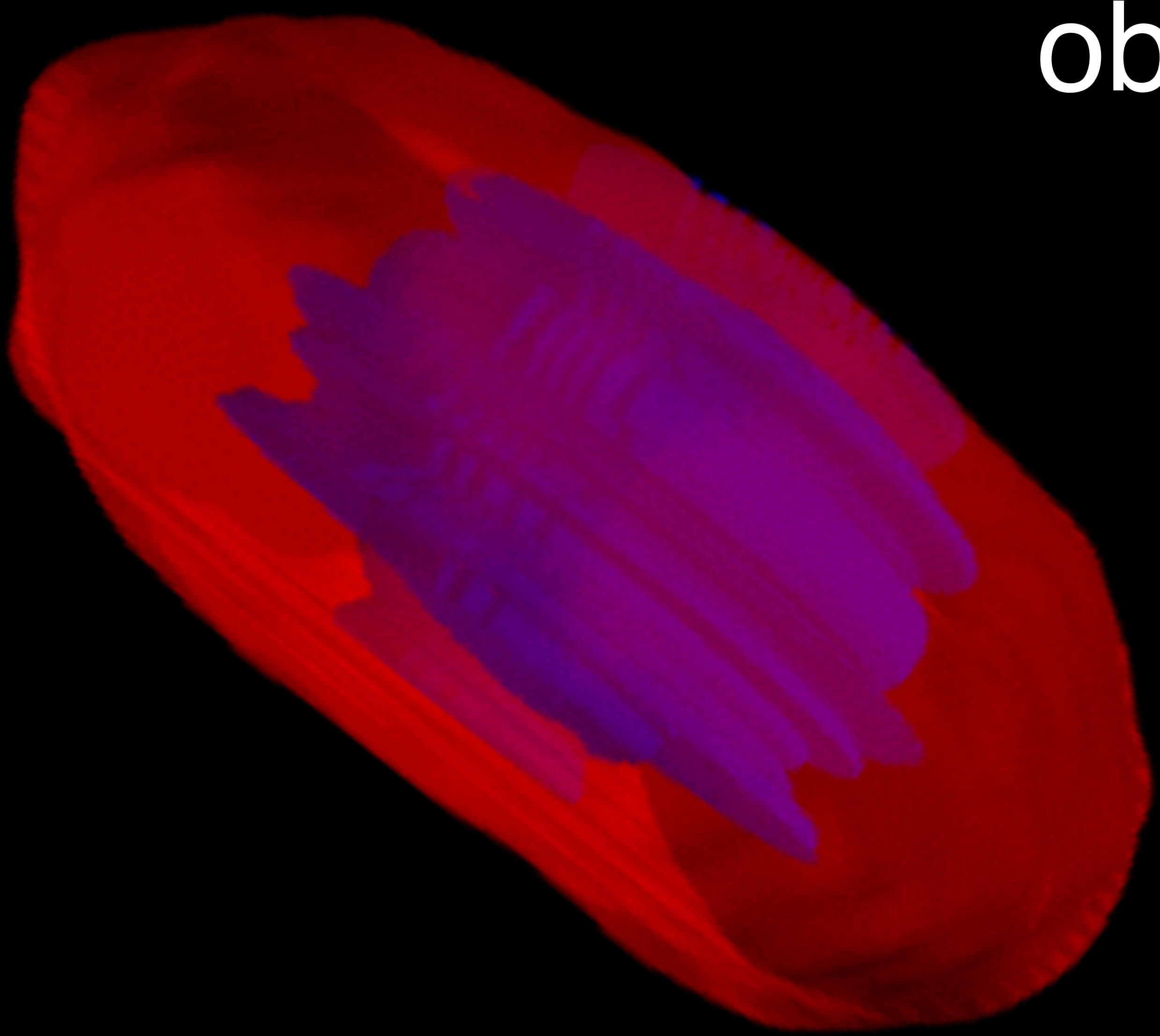


radioactive light curves from compact object mergers

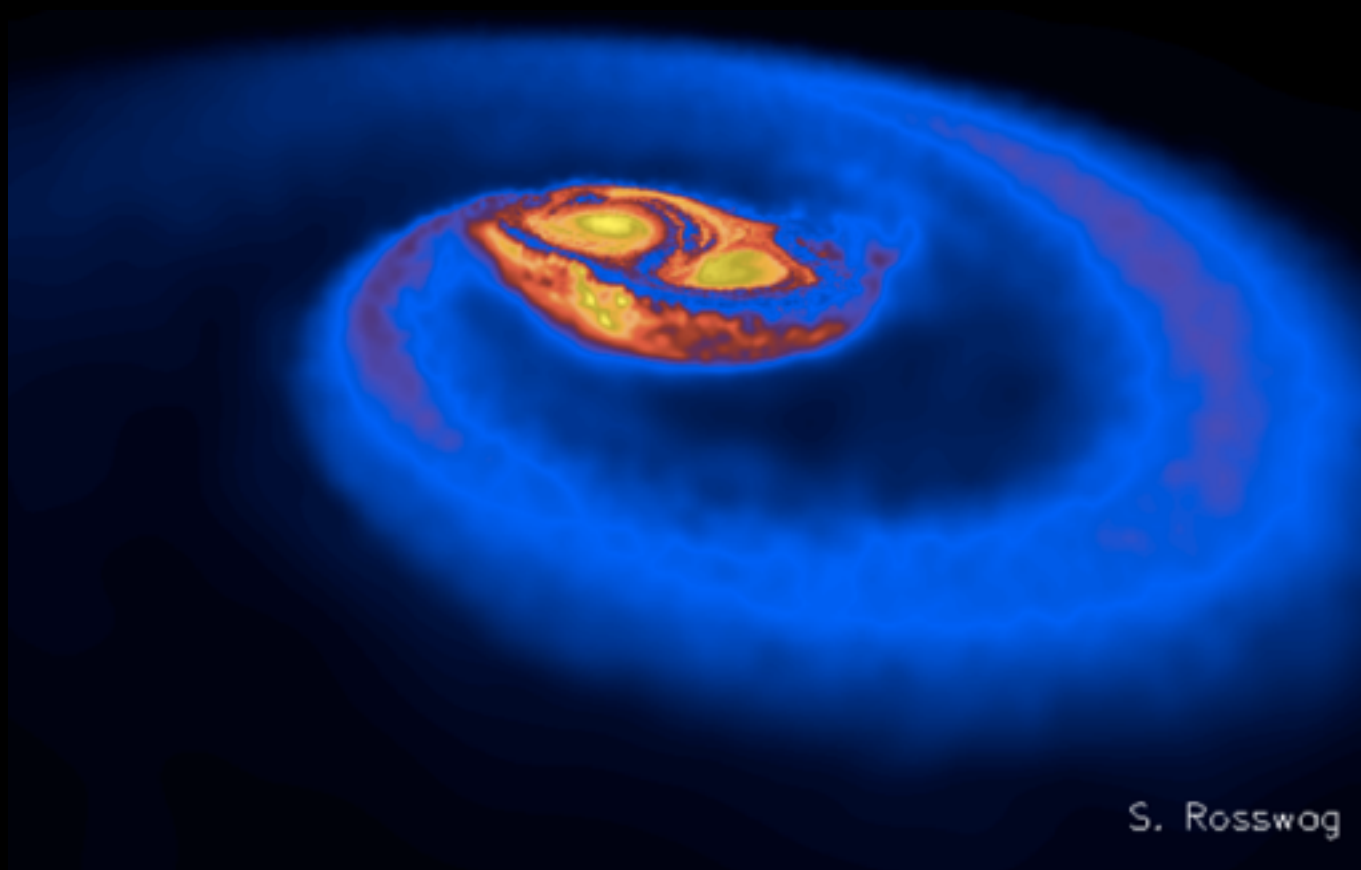
daniel kasen
UC Berkeley/LBNL

r. fernandez, b. metzger,
j. barnes, n. badnell,
s. rosswog, l. roberts,
e. ramirez-ruiz

ejecta from compact object mergers

$M_{ej} \sim 10^{-4} - 10^{-2}\ M_{sun}$

dynamical ejecta



t ~ ms

$Y_e \sim 0.05 - 0.1$

“strong” r-process

(A > 130)

disk winds

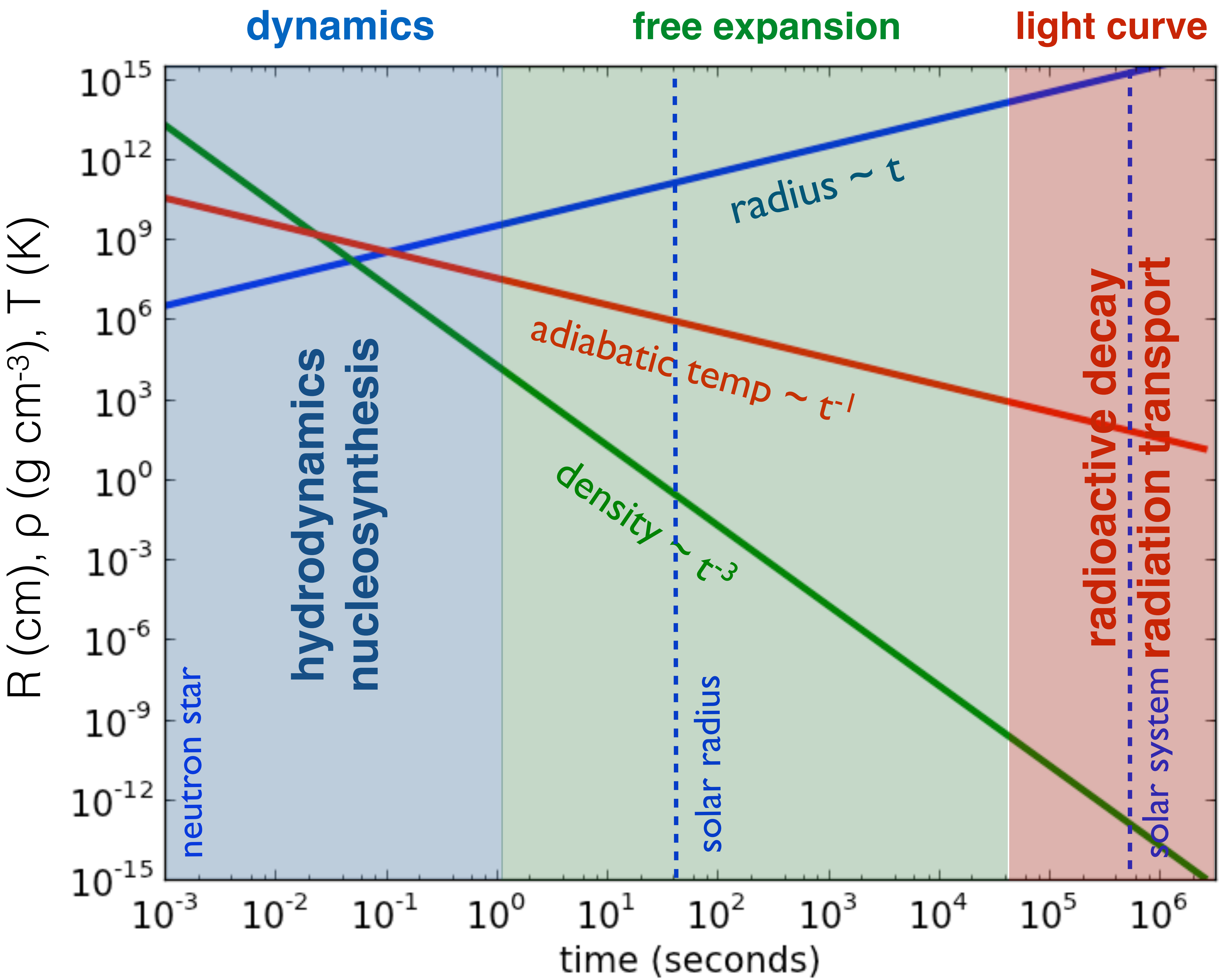
t ~ sec

$Y_e \sim 0.2 - 0.4$

“strong” and/or “weak (A < 130)

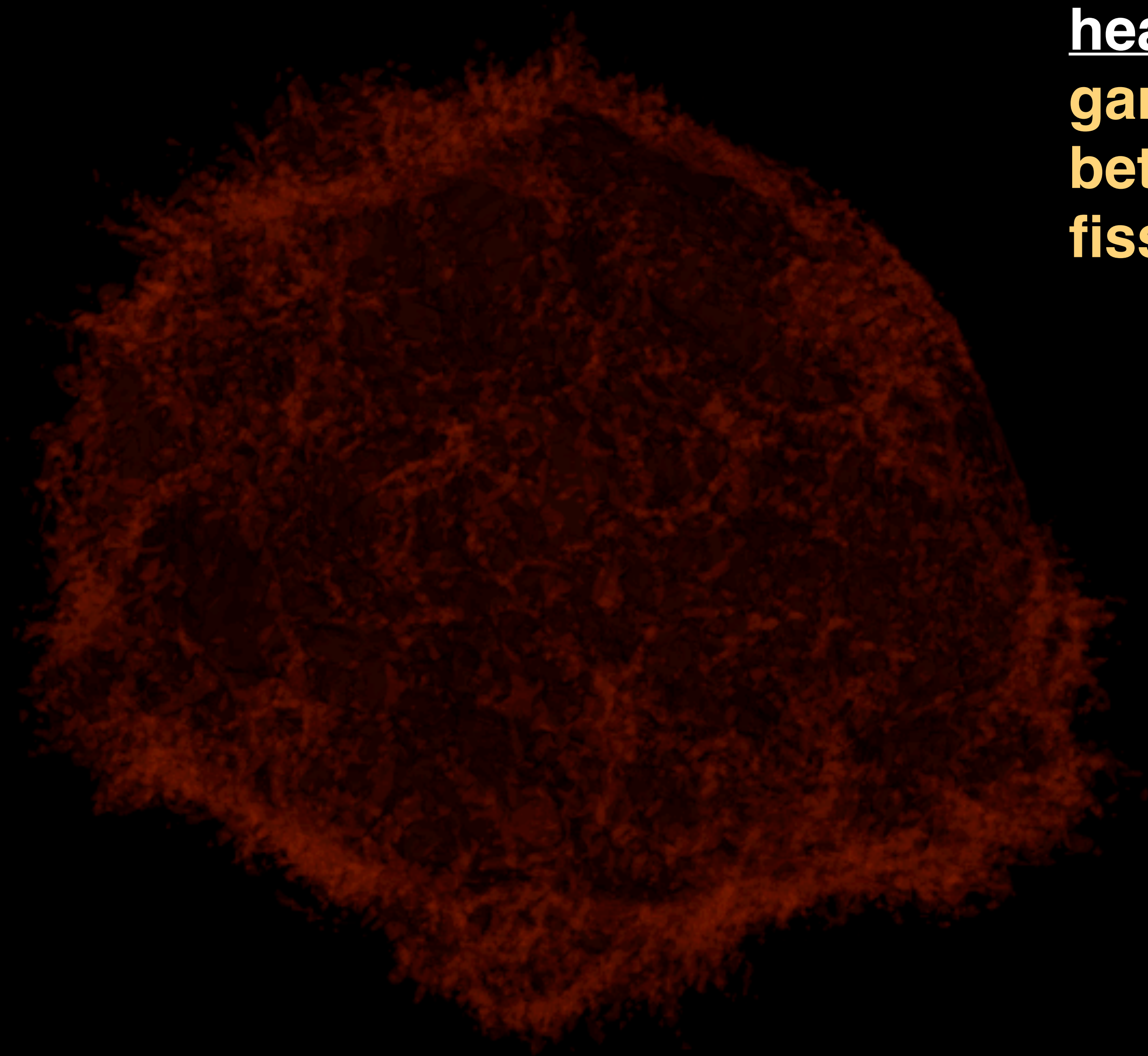
depending on neutrino irradiation

expansion of merger ejecta



multi-D time dependent radiative transfer

SEDONA code - Kasen et al. *ApJ* (2006), Kasen (2008), Roth & Kasen (2014)



freely expanding cloud

heated by radioactivity

gamma-rays: compton/photoabsorption

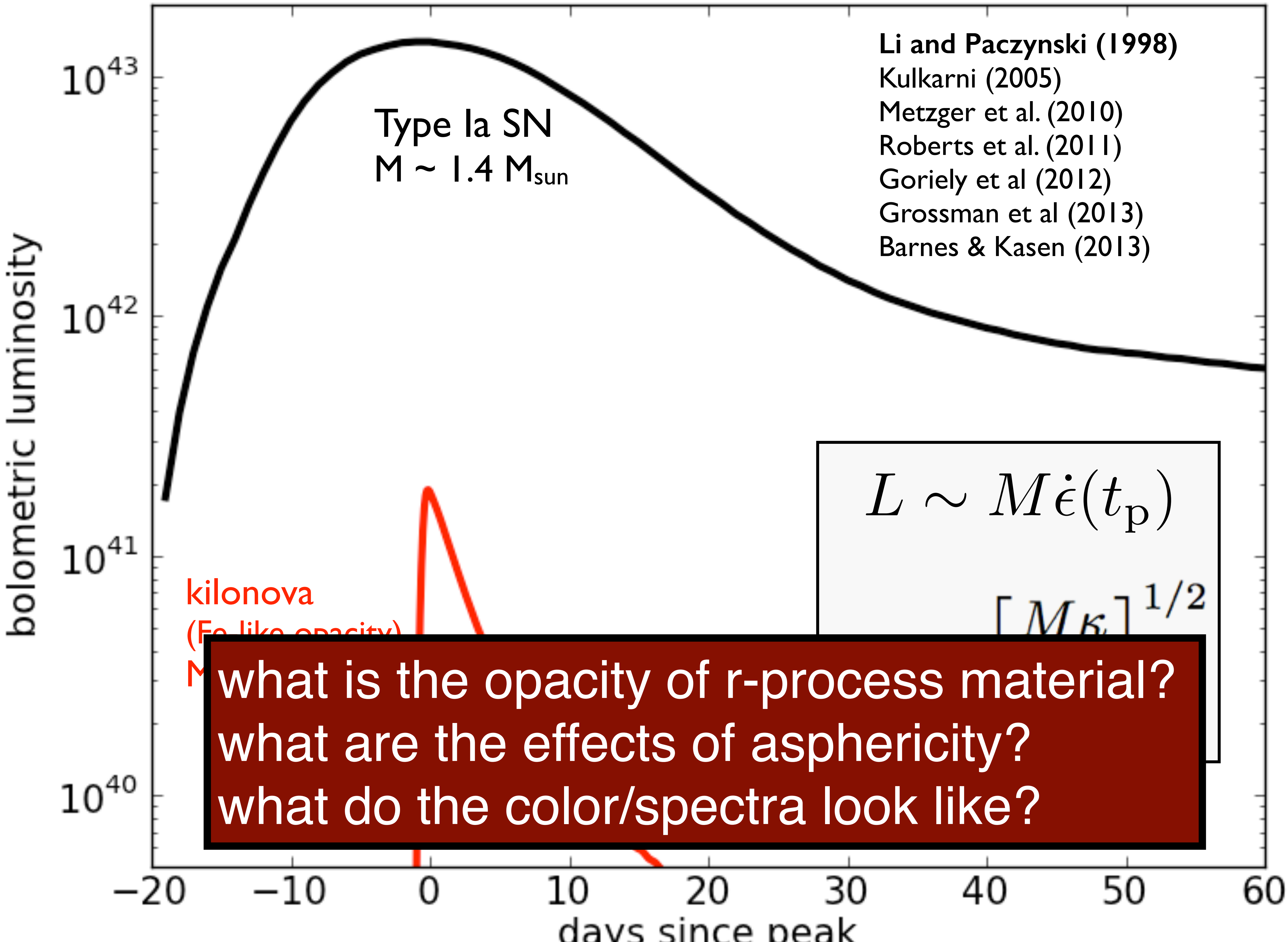
betas: coulomb collisions, ionization

fission, alphas: coulomb collisions

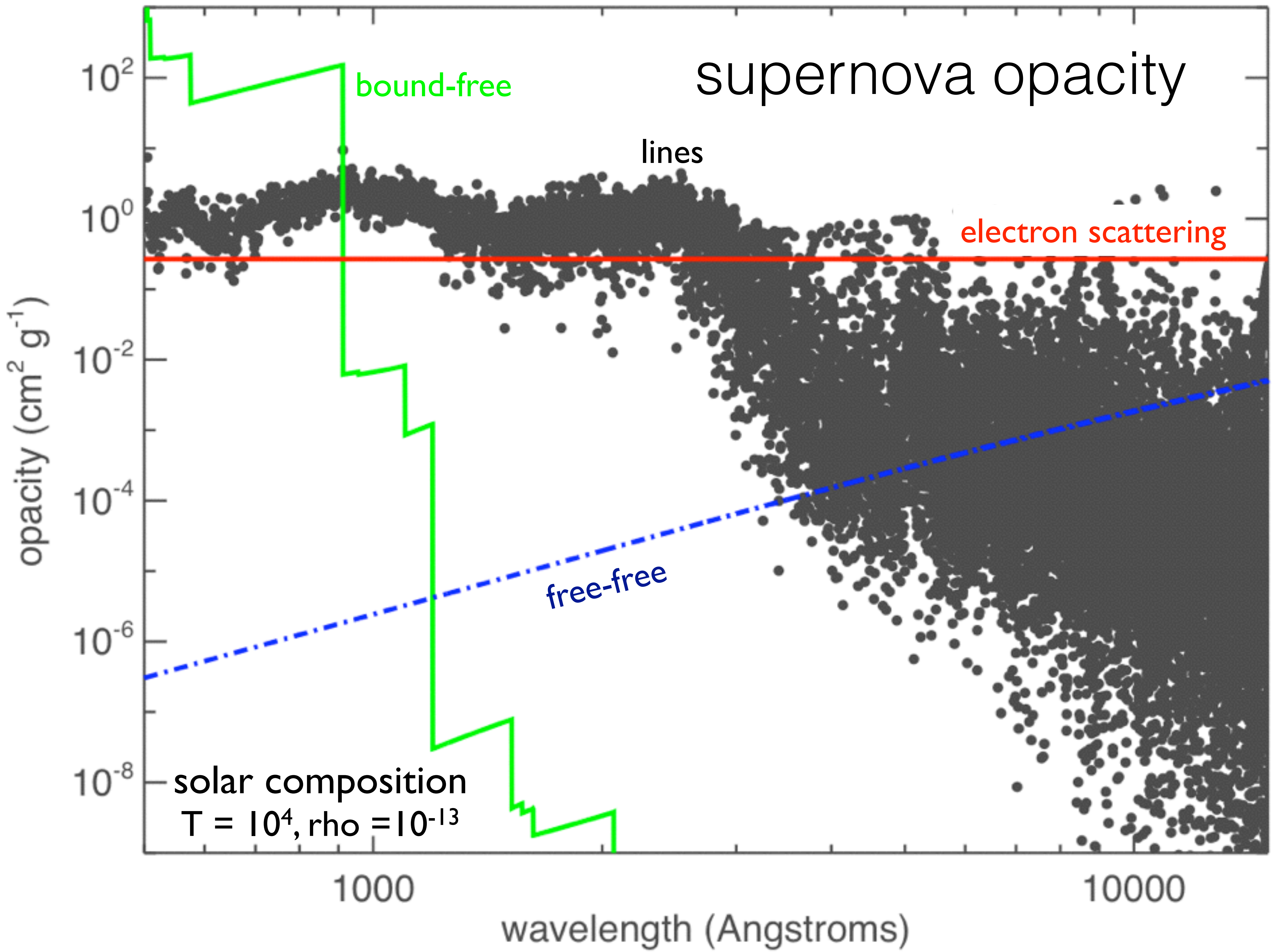
re-emitted thermal optical/infrared photons gradually diffuse out

main opacity: lines
must calculate thermodynamic evolution, ionization/exctiation state with detailed atomic data

radioactively powered transients (kilonovae)



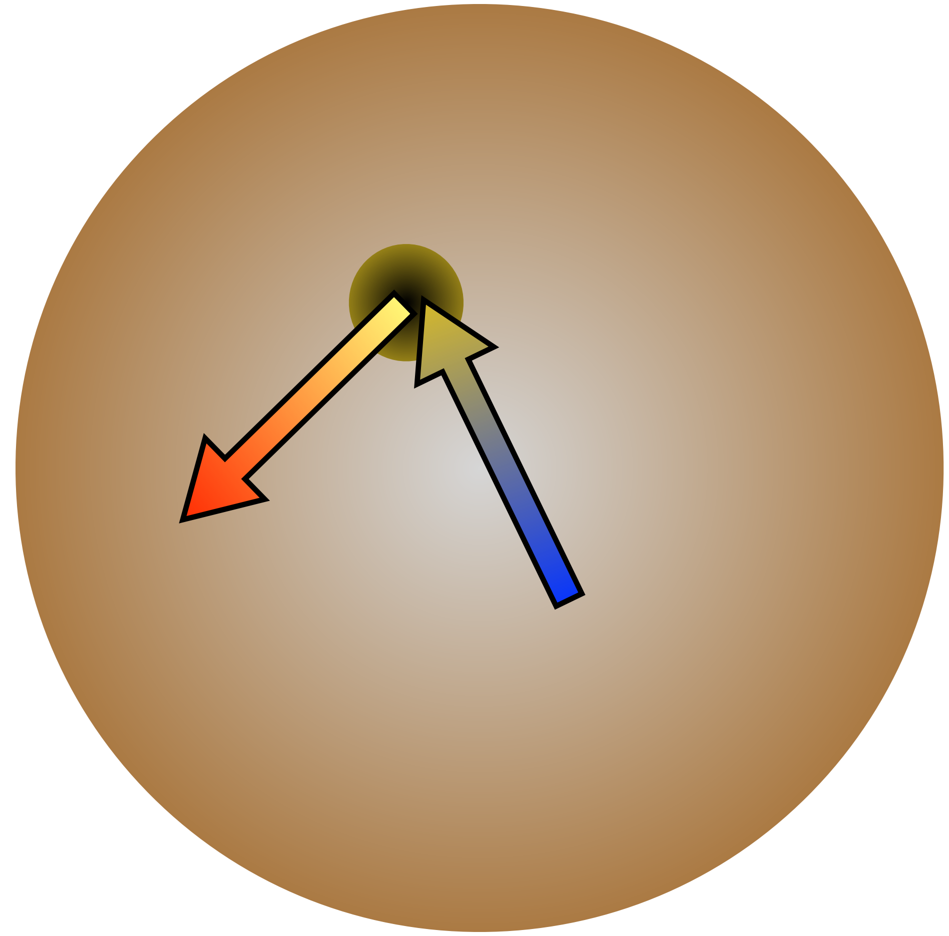
what is the opacity of r-process material?
what are the effects of asphericity?
what do the color/spectra look like?

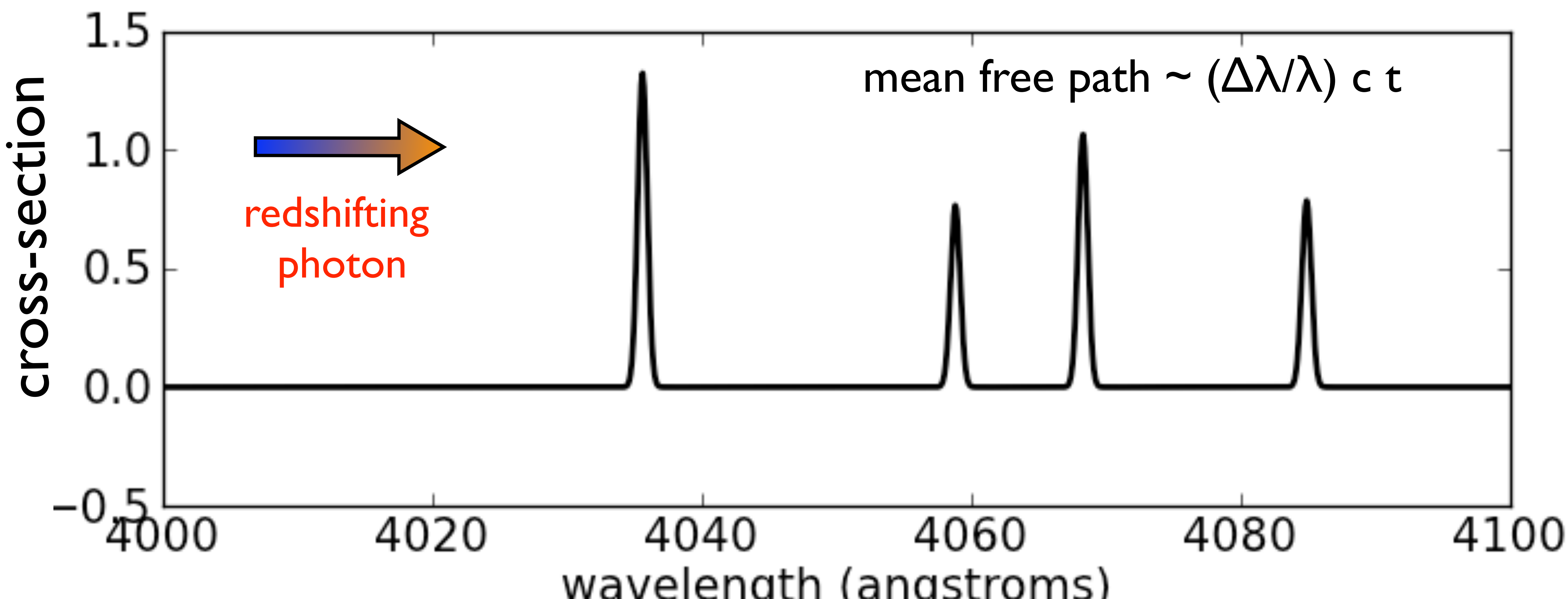


supernova opacity
bound-free
lines
electron scattering
free-free
solar composition
T = 10^4, rho =10^-13
opacity (cm^2 g^-1)
wavelength (Angstroms)
10^2
10^0
10^-2
10^-4
10^-6
10^-8
1000
10000

line interactions in an expanding (hubble-like) flow

mean free path set by density of lines



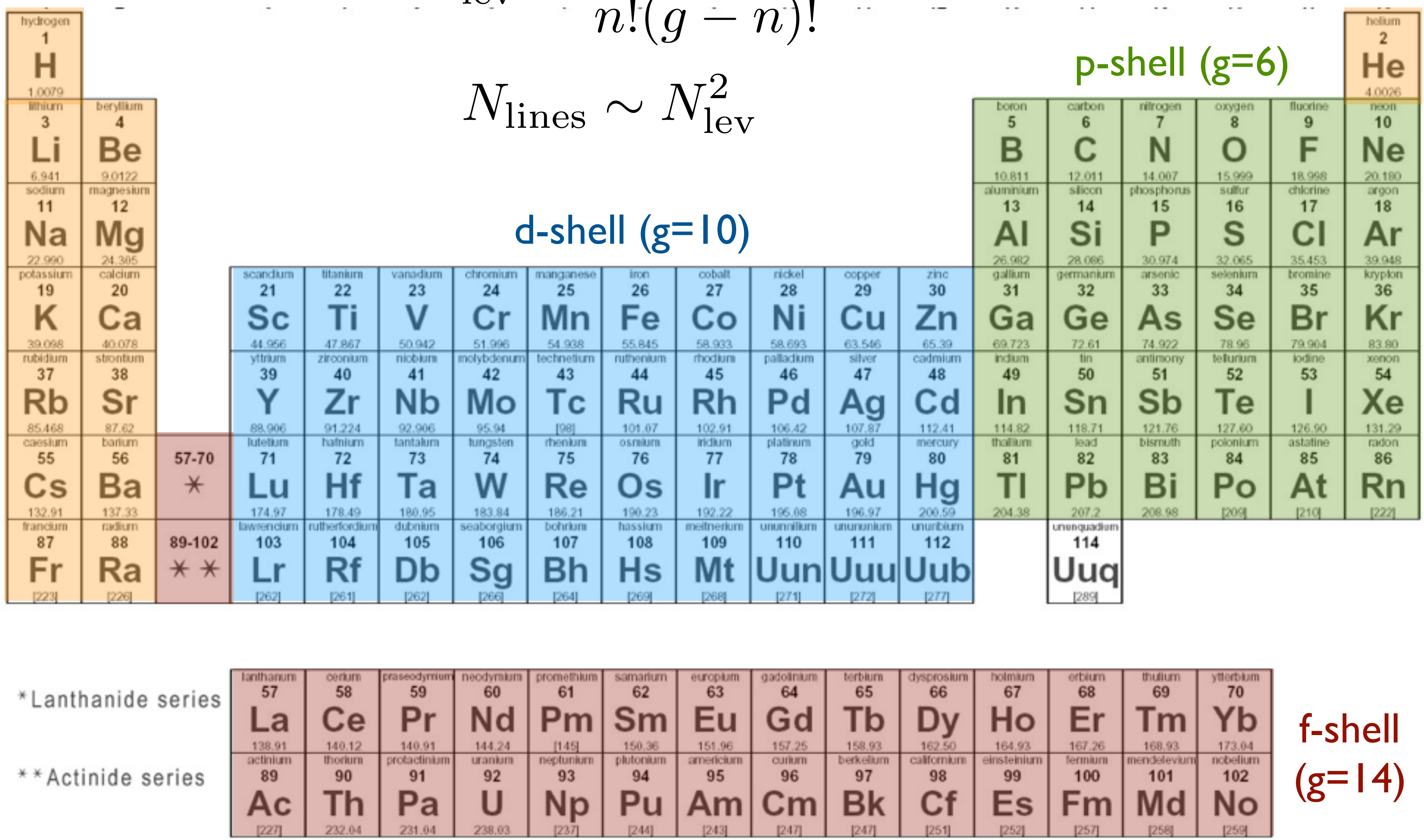


opacity and atomic complexity

s-shell (g=2)

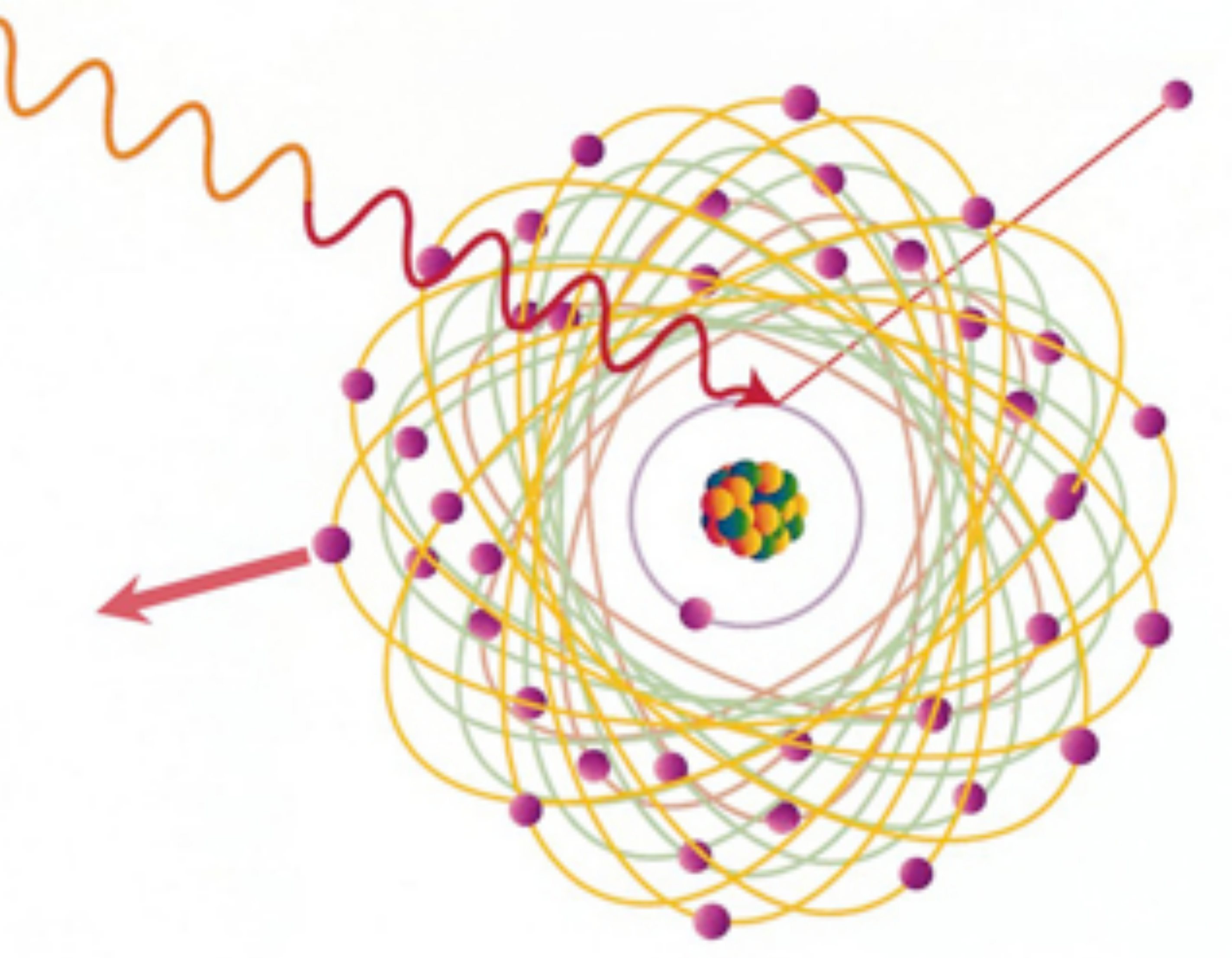
$$N_{\rm lev} \sim \frac{g!}{n!(g-n)!}$$

$$N_{\rm lines} \sim N_{\rm lev}^2$$



atomic structure and radiative data

limited data available for high Z species



atomic structure modeling
needed for level/line data

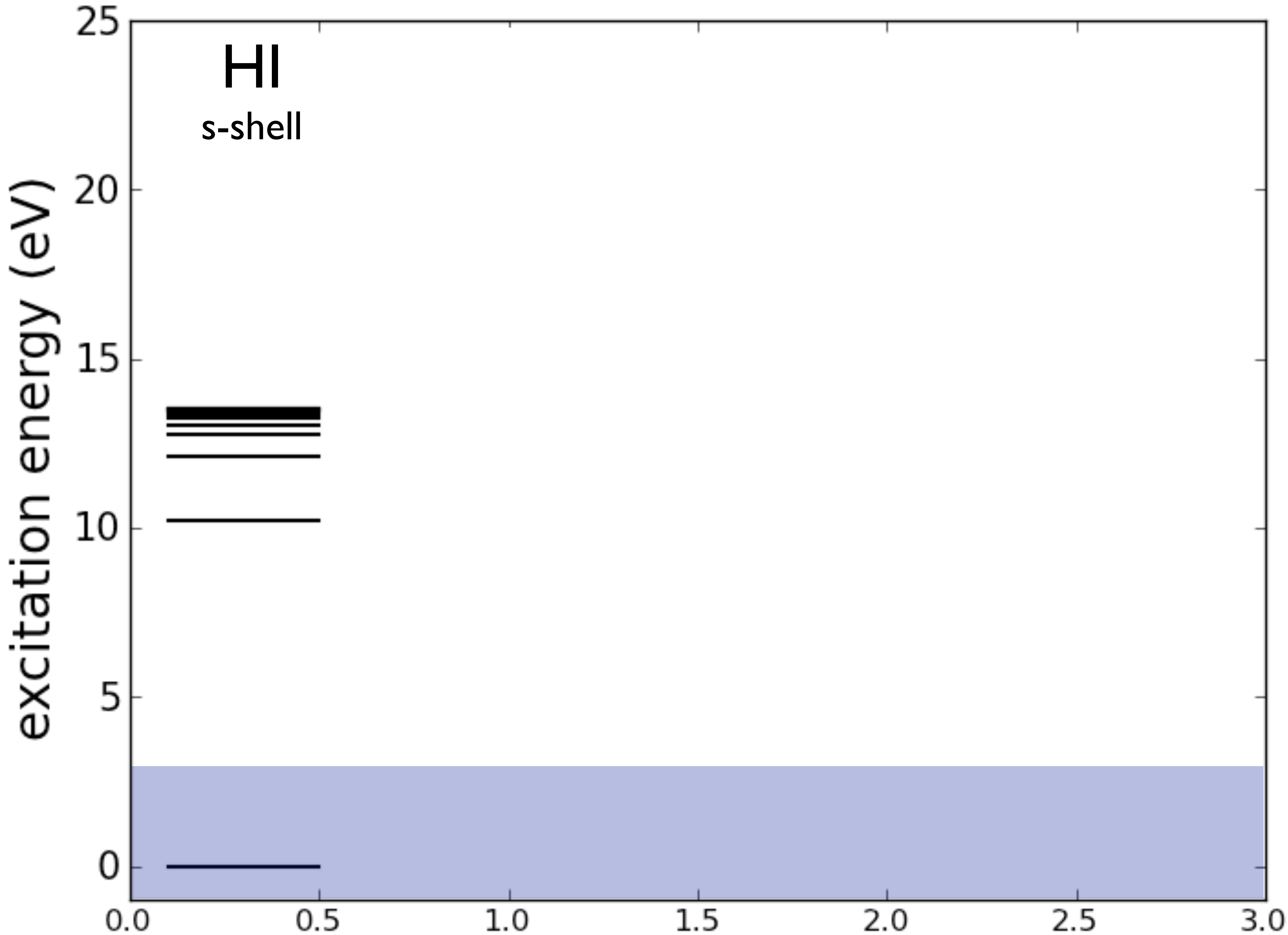
VALD database (Kurucz, MONS)
(~500,000 lines)
very incomplete for most ions Z > 28
no line data for higher ionization states
almost no data for λ > 1 μm

Autostructure cacluations
kasen, badnell, and barnes (2013)
(~40,000,000 lines)
ab-initio calculations for Nd, Cd, Os,…
extrapolated to other species

more work underway….

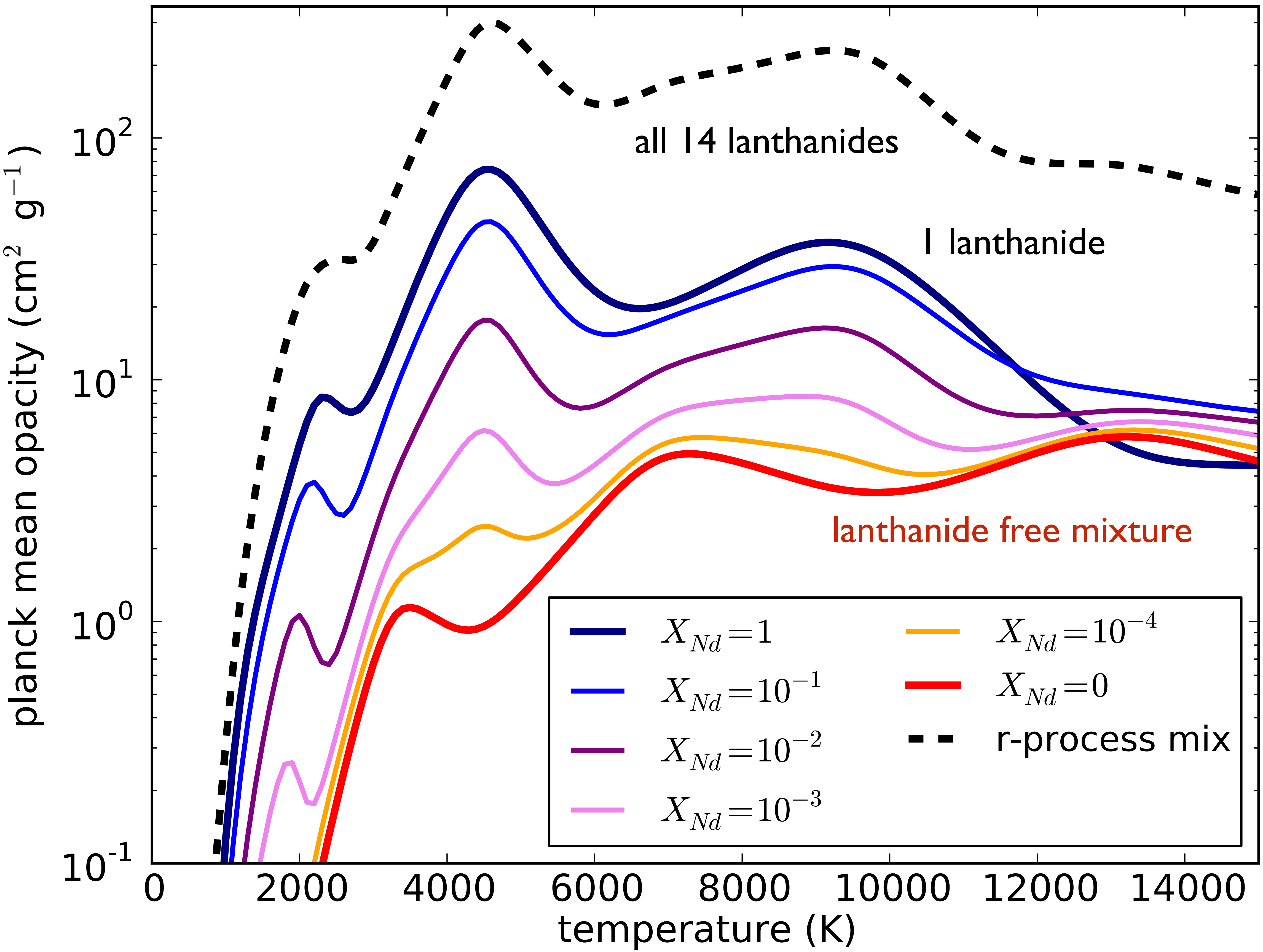
atomic level energy structure

kasen+ 2013



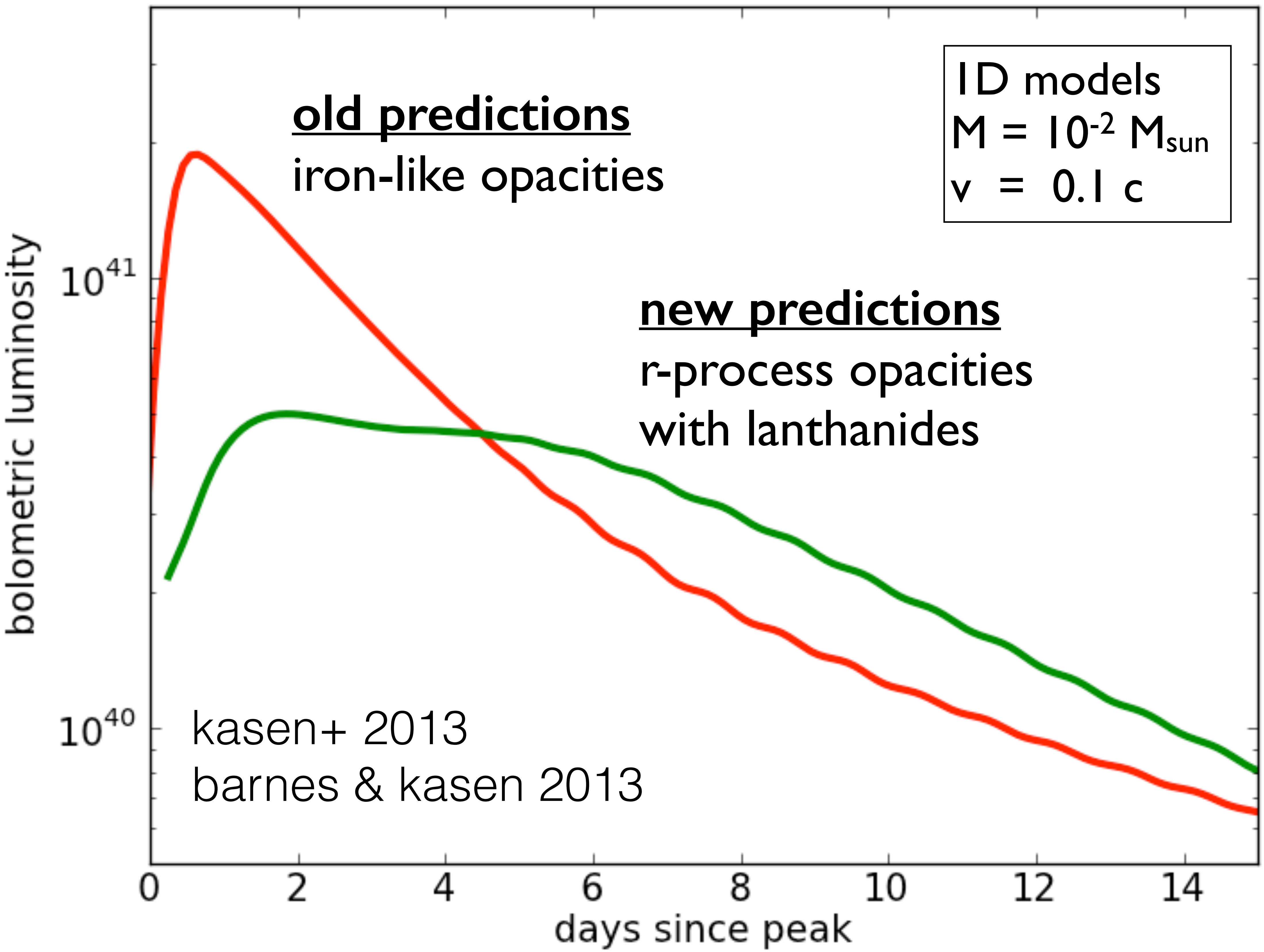
mean opacities different composition

kasen, badnell, barnes 2013

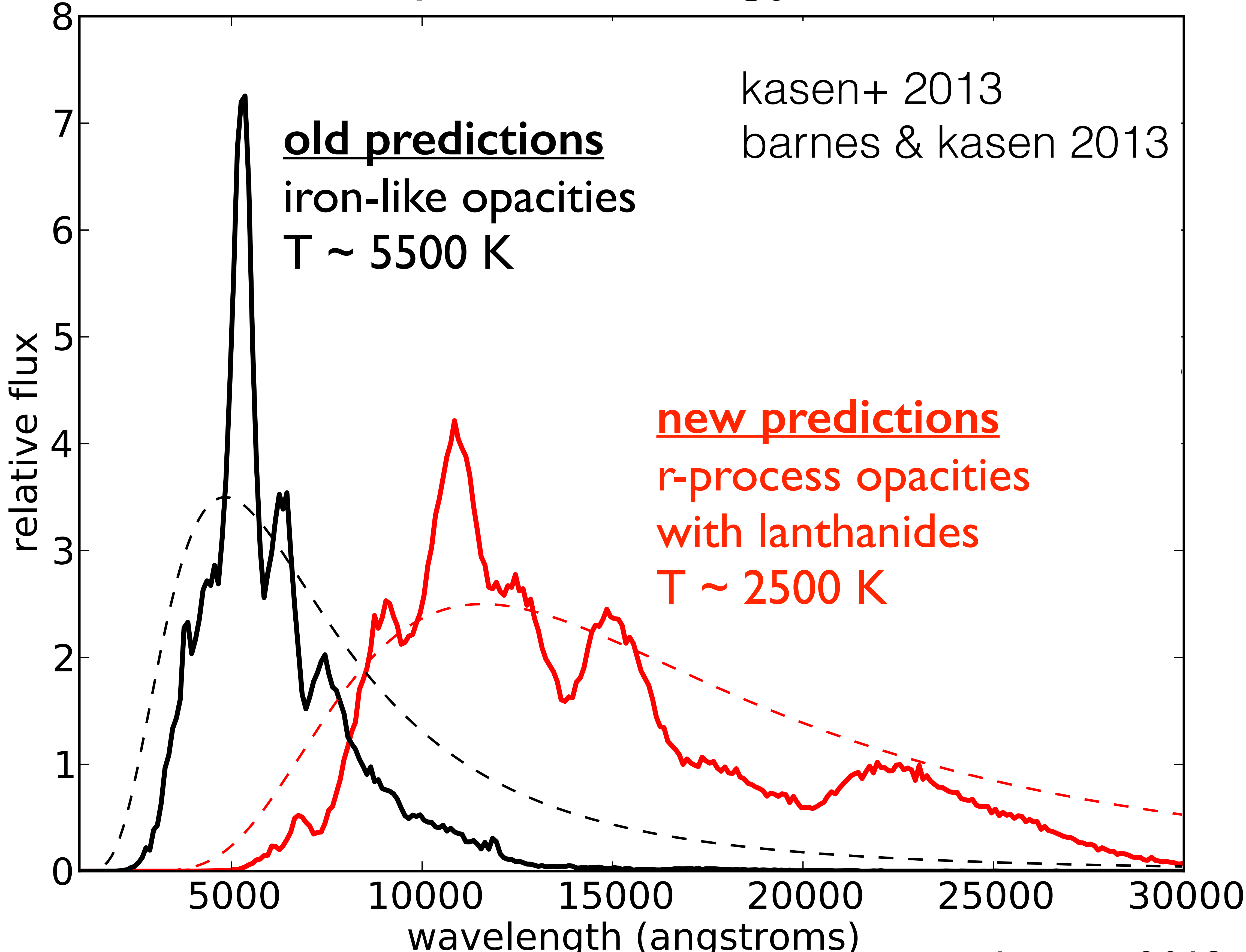


light curves of radioactive transients

effect of high lanthanide opacity



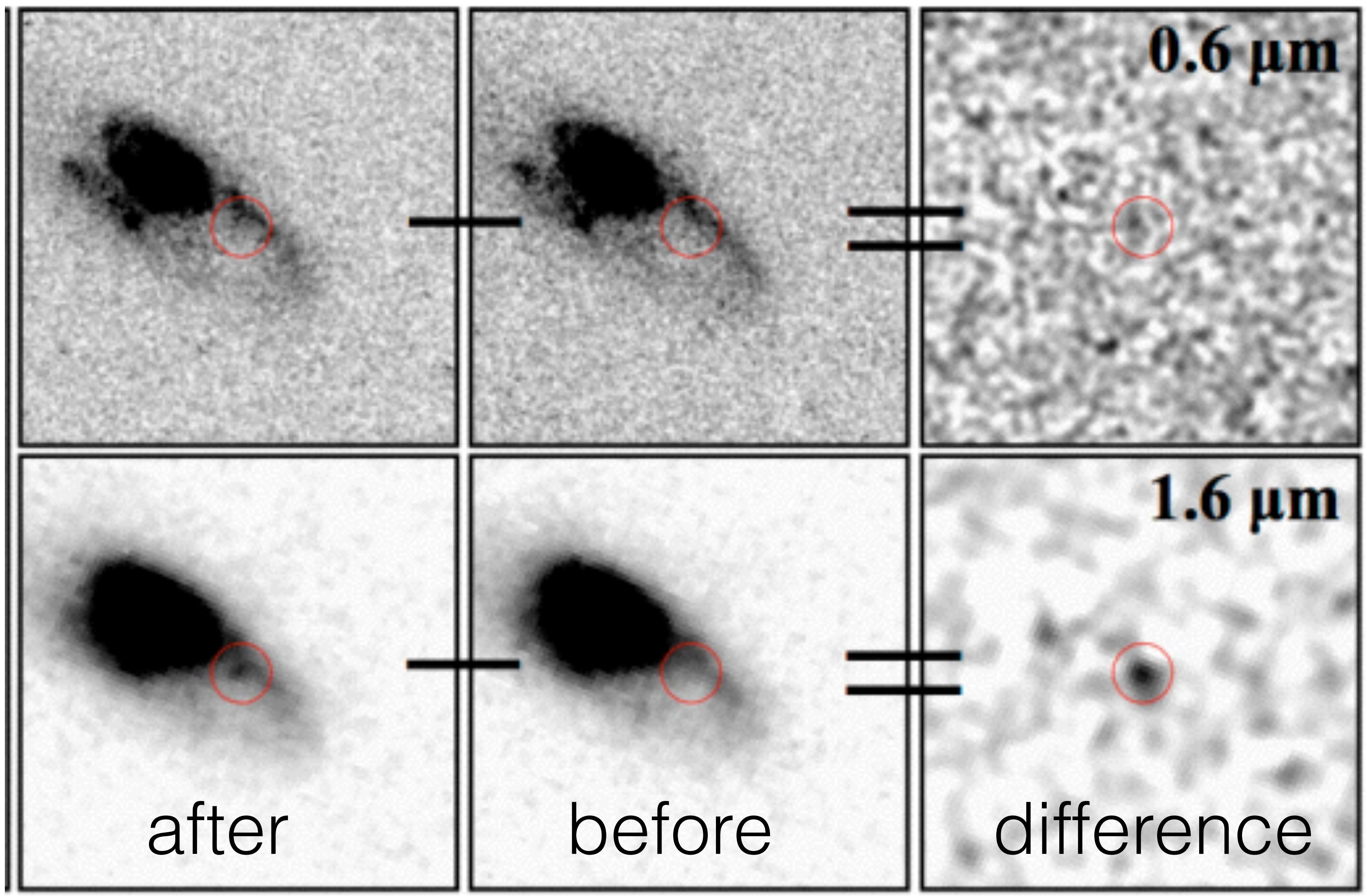
model spectral energy distribution



kasen+ 2013

GRB130603B

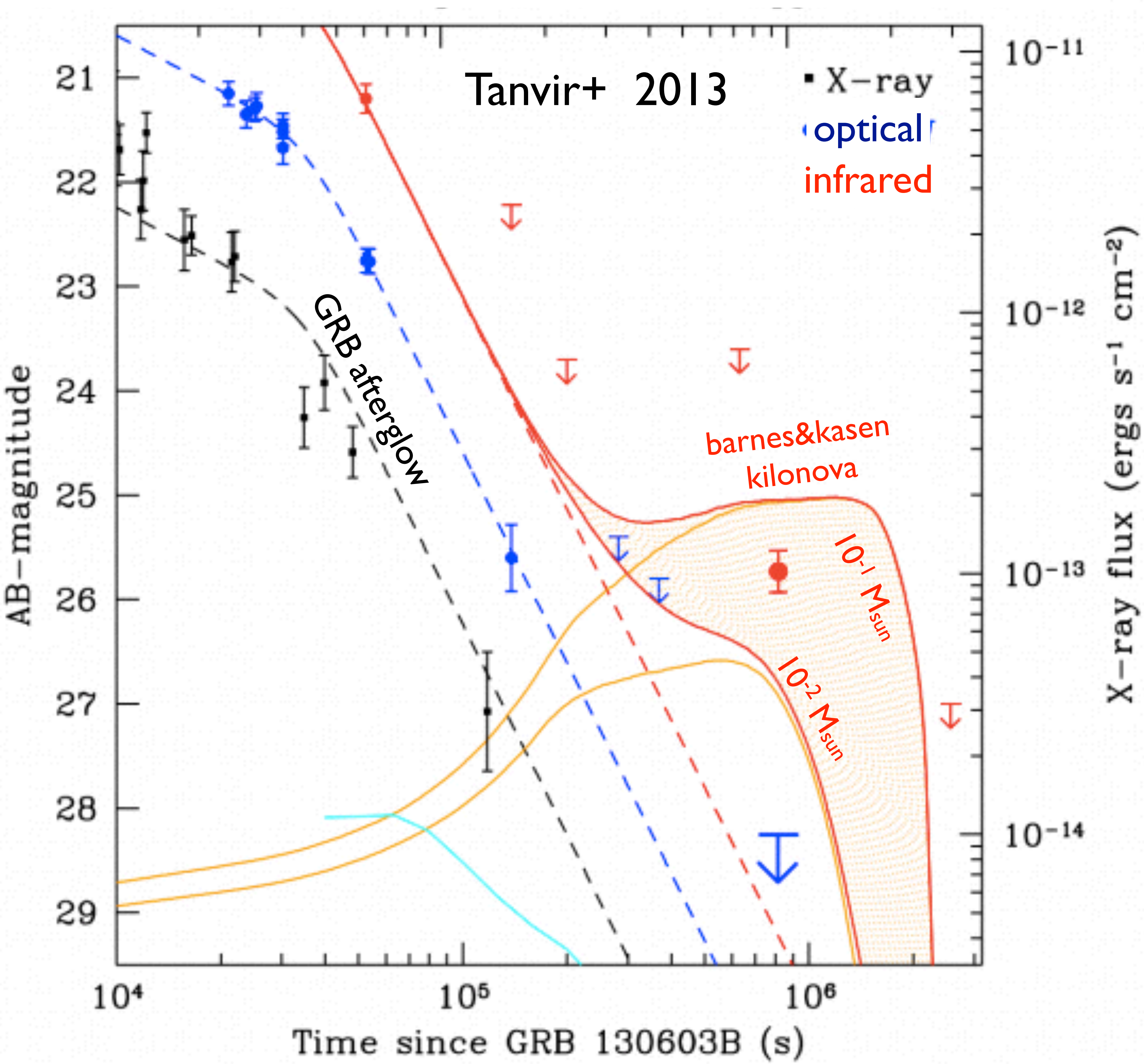
relatively nearby short GRB (z = 0.356)



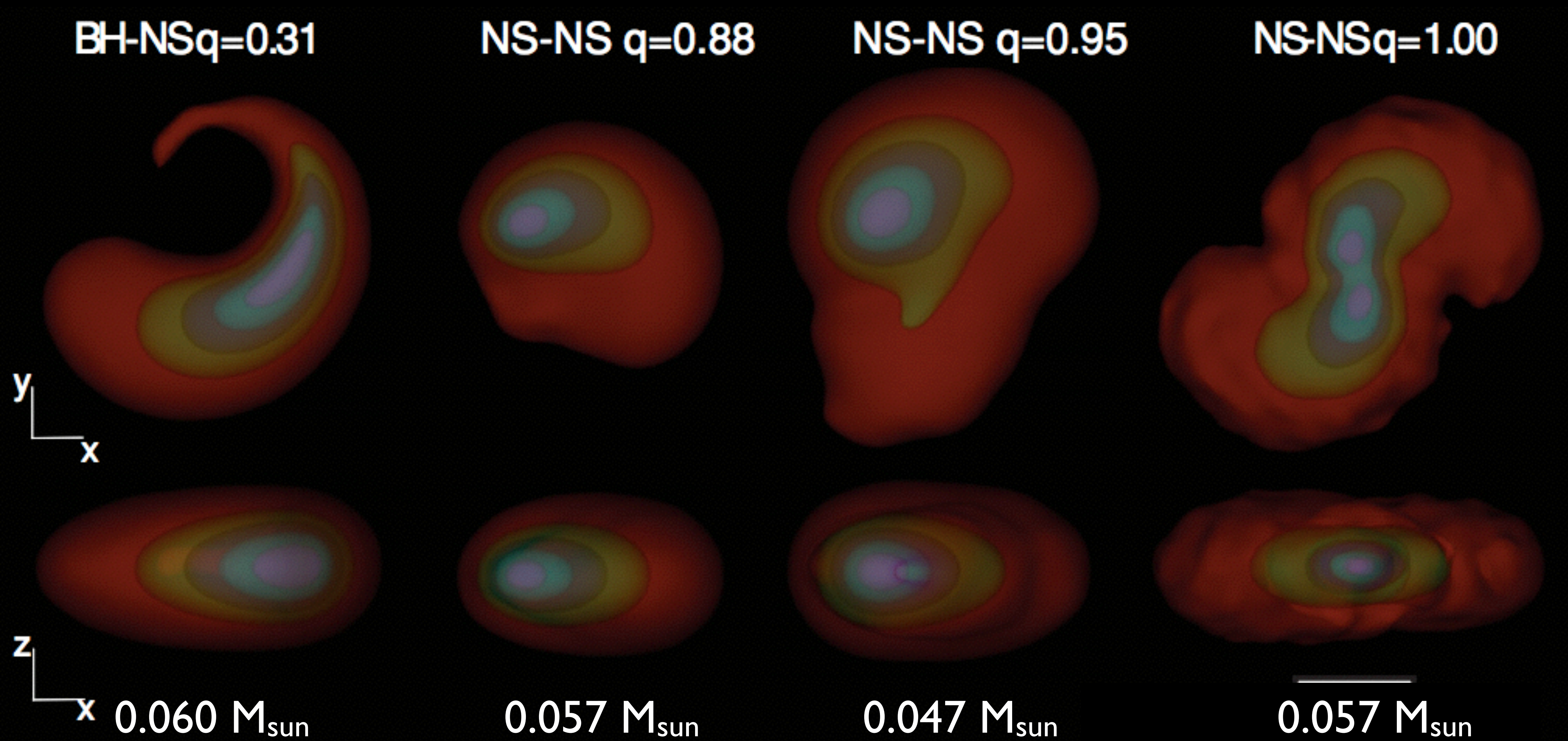
deep infrared imaging with HST
triggered ~1 week after burst

Tanvir+ 2013
c.f. Berger 2013

discovery of an r-process kilonova?



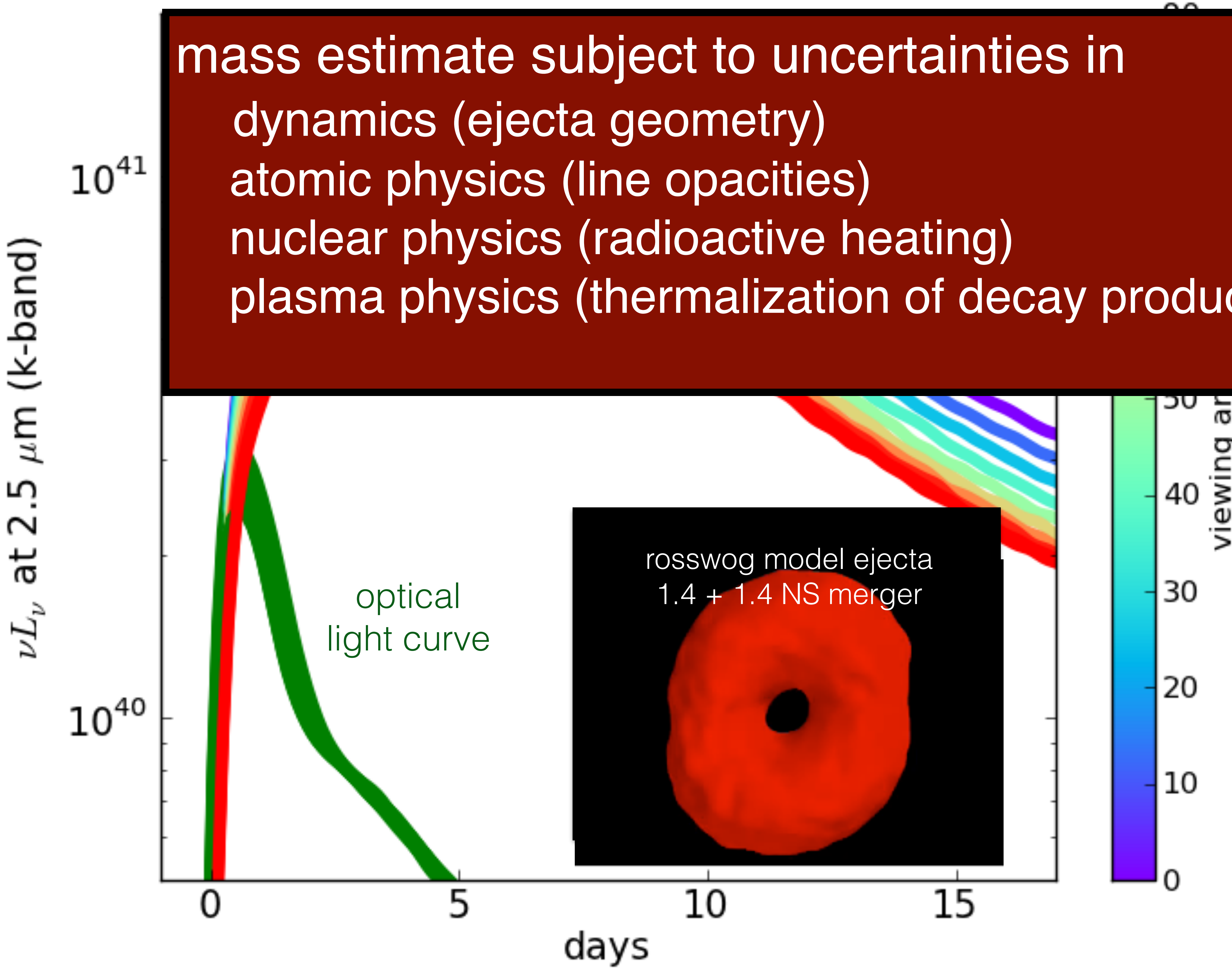
3D dynamical ejecta models



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

model kilonova light curve

0.025 M_{sun} of dynamical ejecta

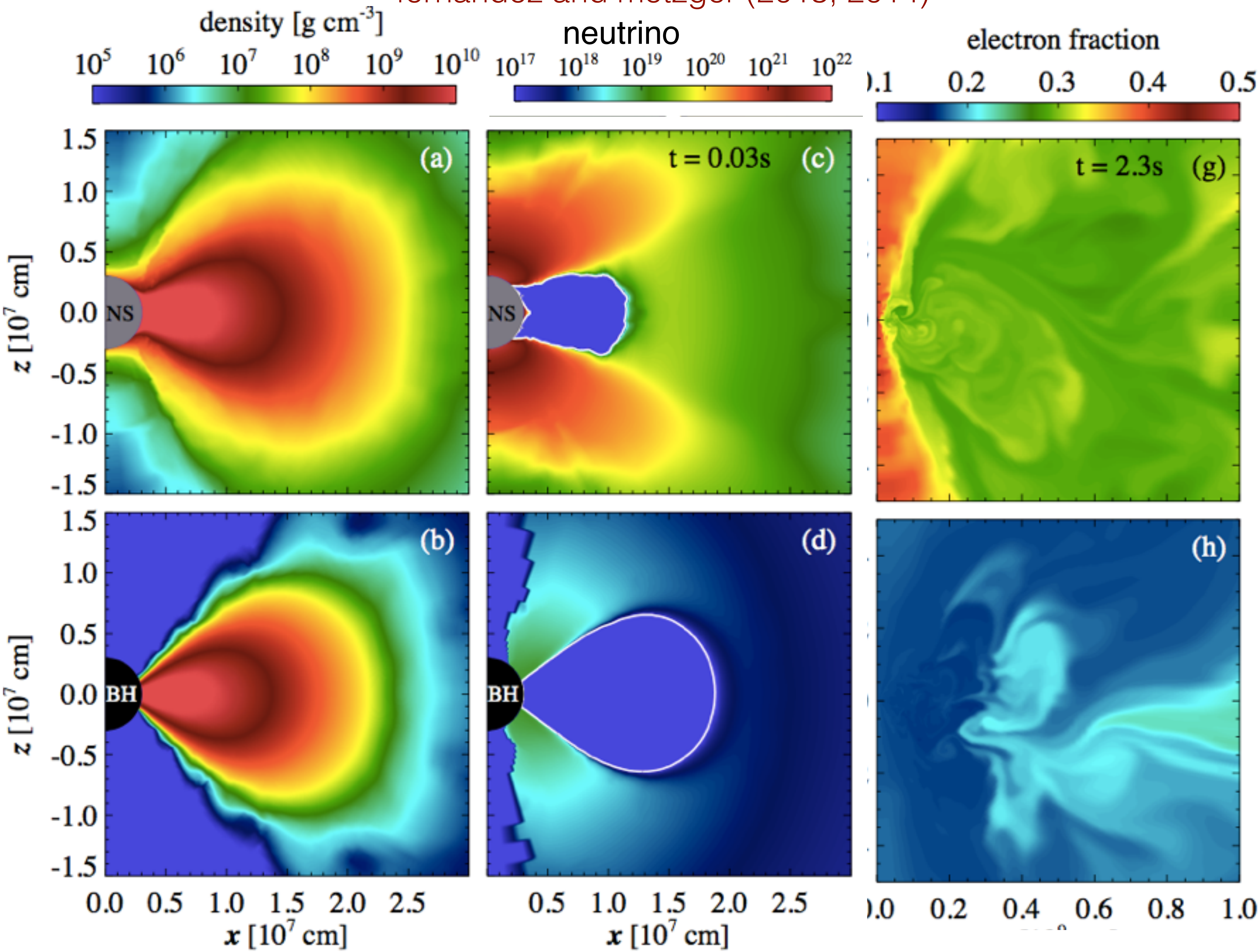


mass estimate subject to uncertainties in

- dynamics (ejecta geometry)
- atomic physics (line opacities)
- nuclear physics (radioactive heating)
- plasma physics (thermalization of decay products)

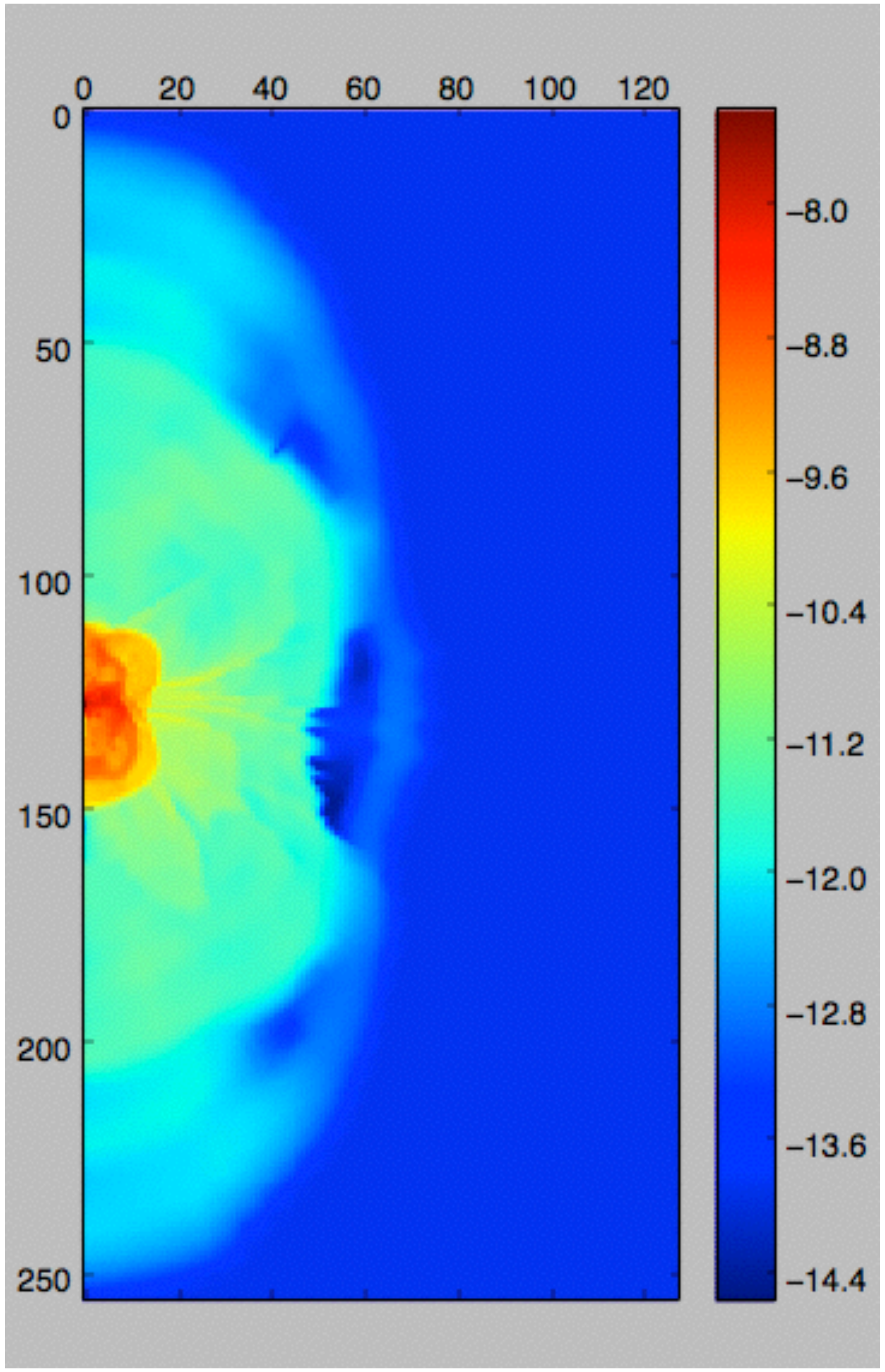
post-merger ejection in disk winds

fernandez and metzger (2013, 2014)

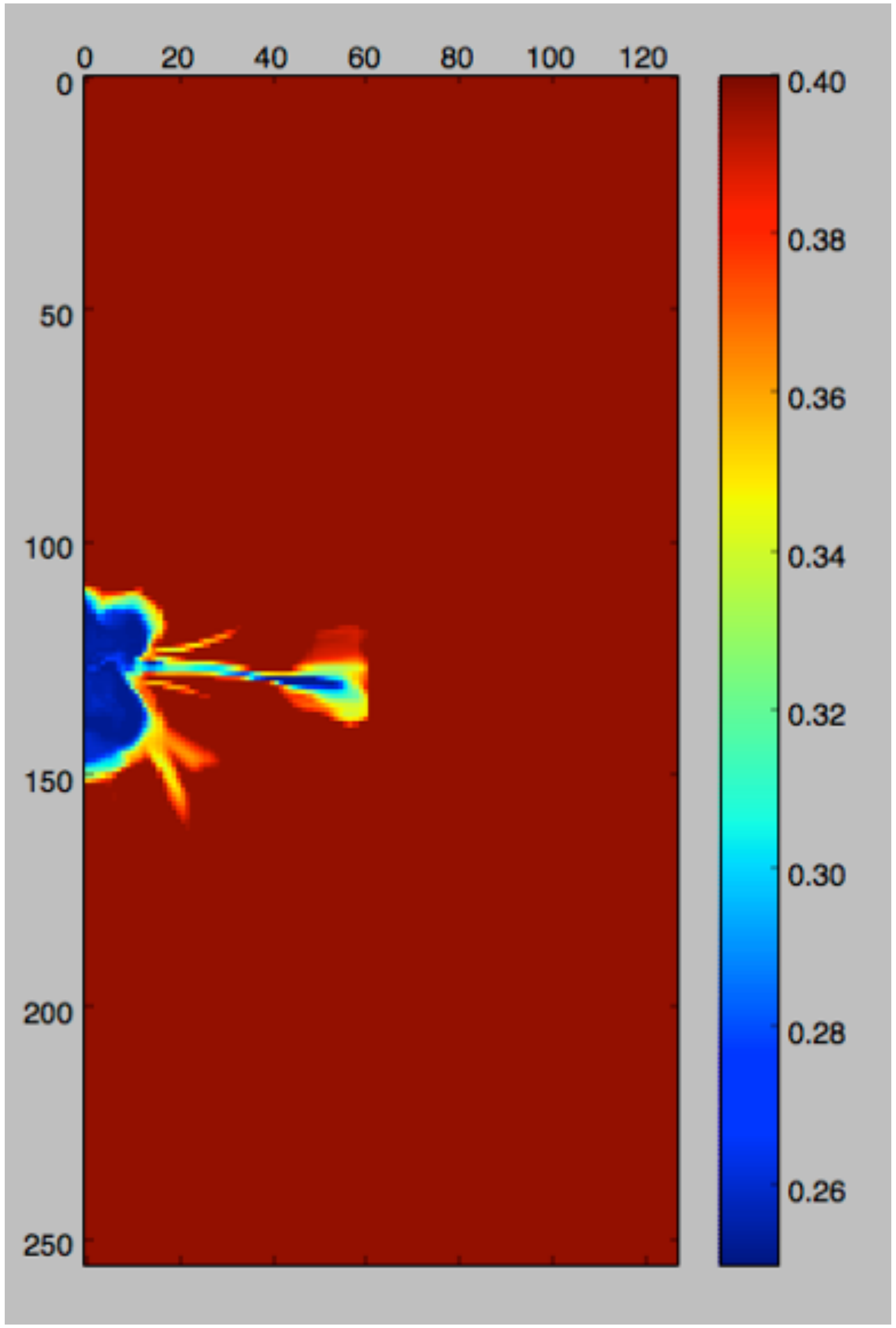


ejected disk wind (NS lives 30 ms)

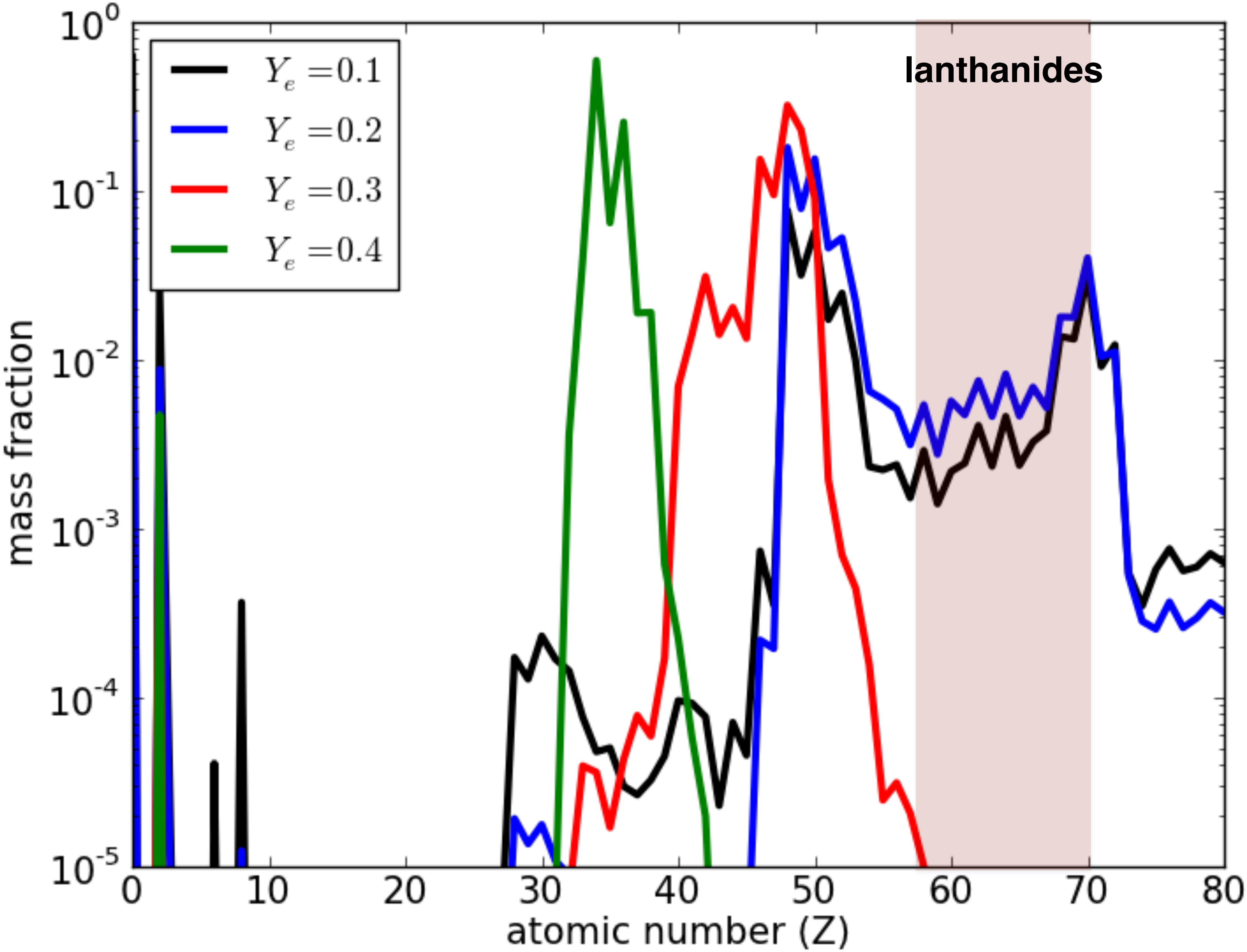
log$_{10}$ density



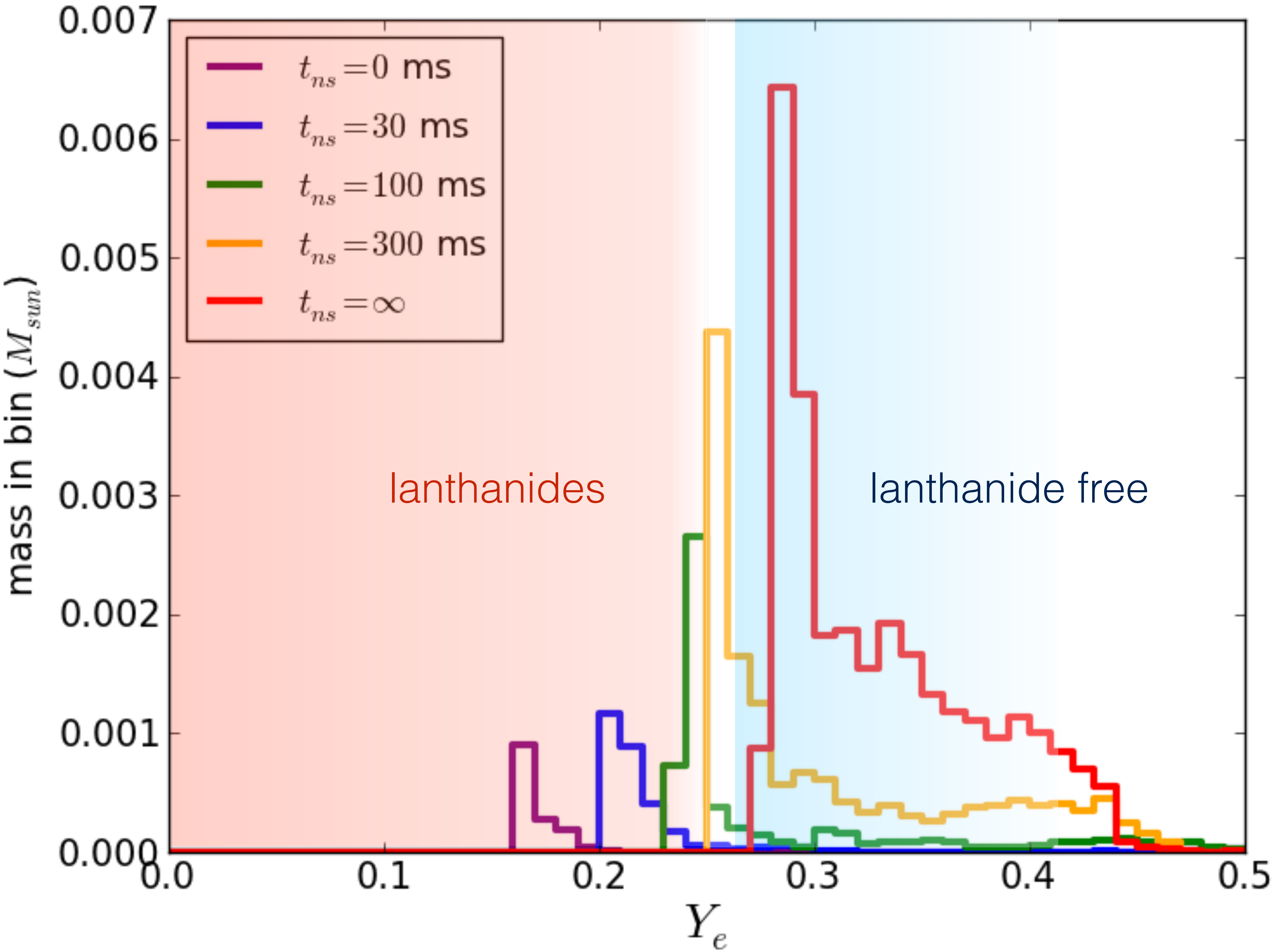
Y_e



estimated final abundances
(parameterized wind nucleosynthesis calculations)

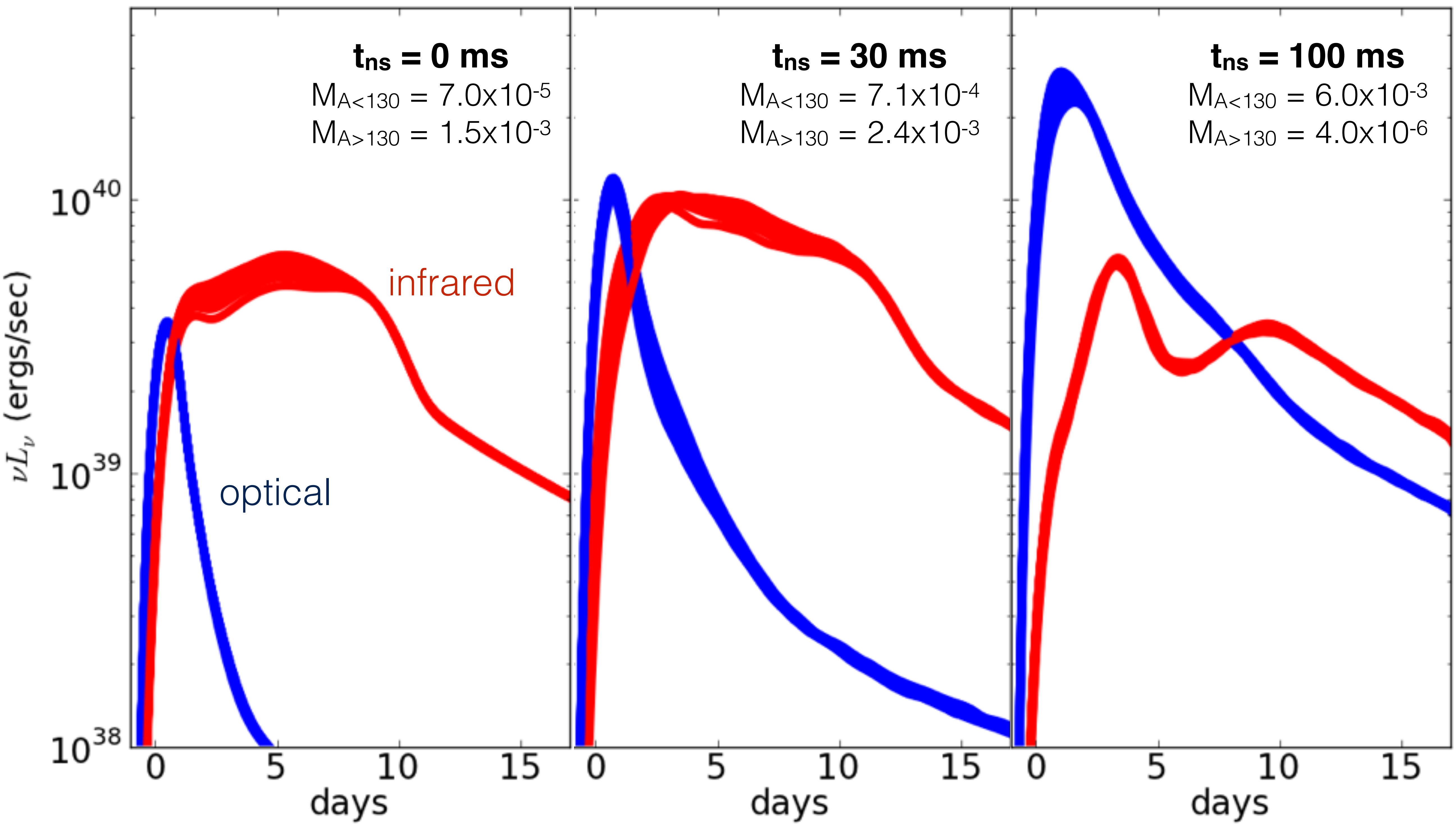


Y_e distribution of wind ejecta



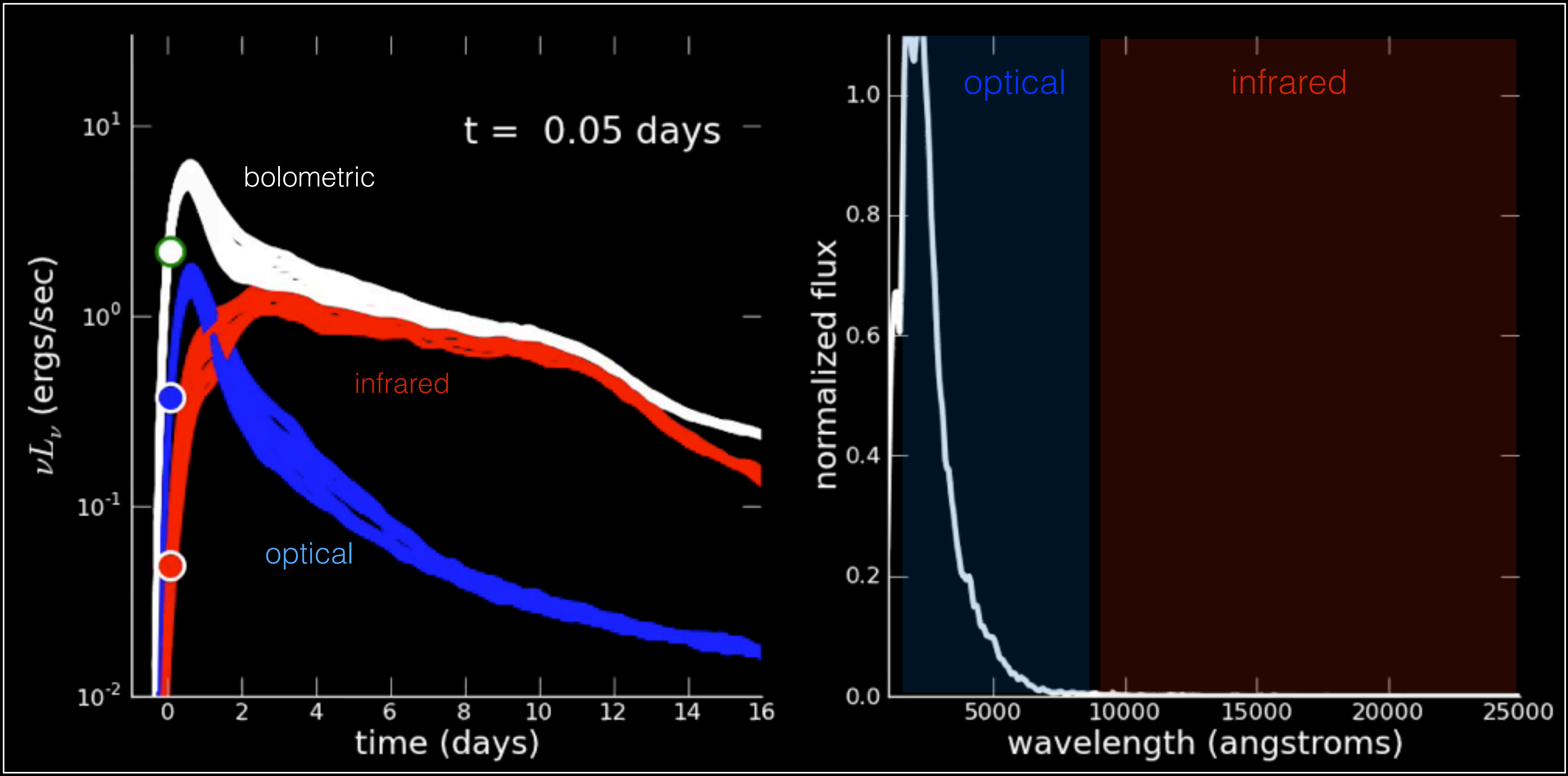
optical and infrared light curves of winds

multi-dimensional radiative transport calculations

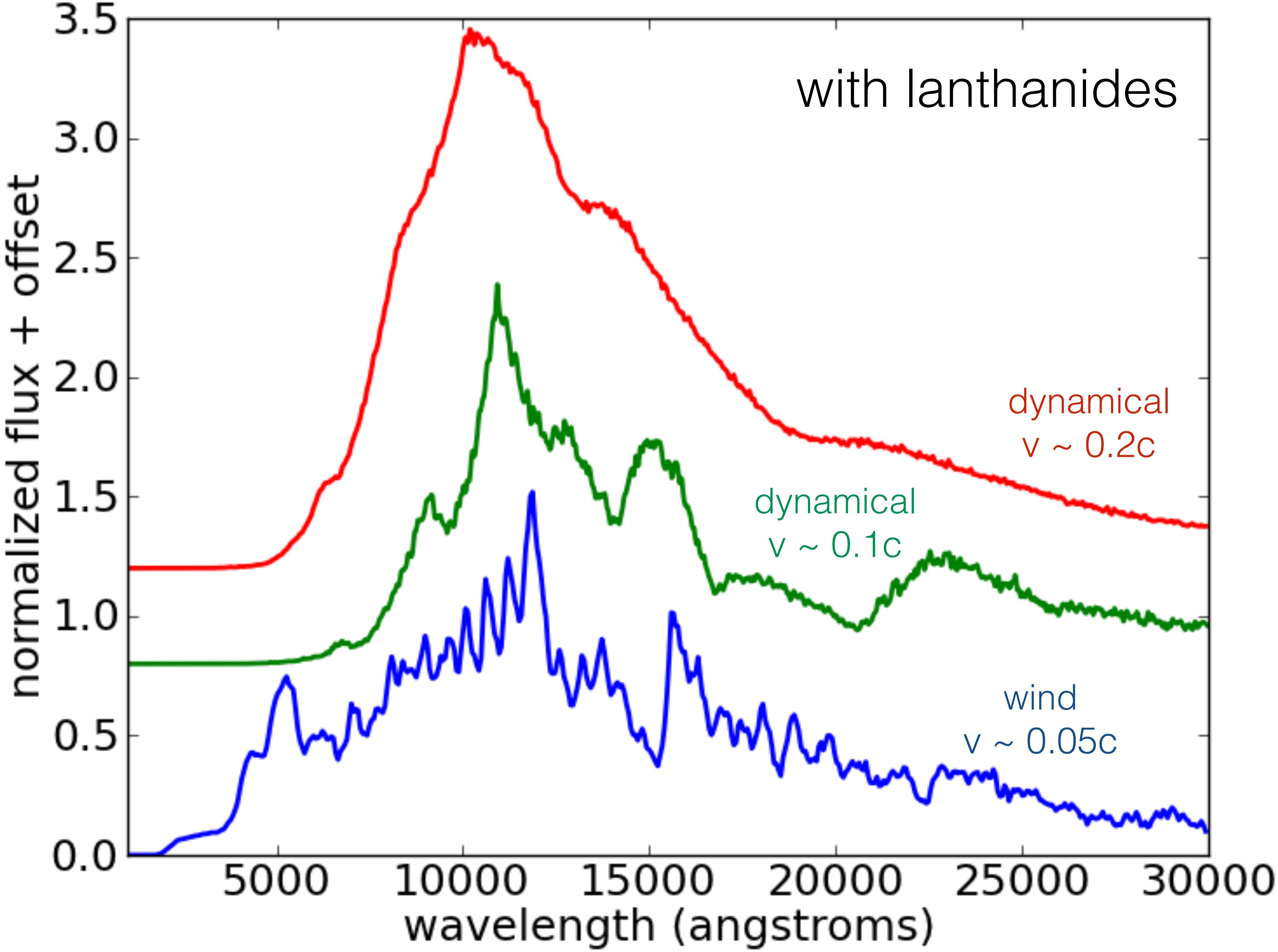


light curve and spectral evolution

t_{ns} = 30 ms

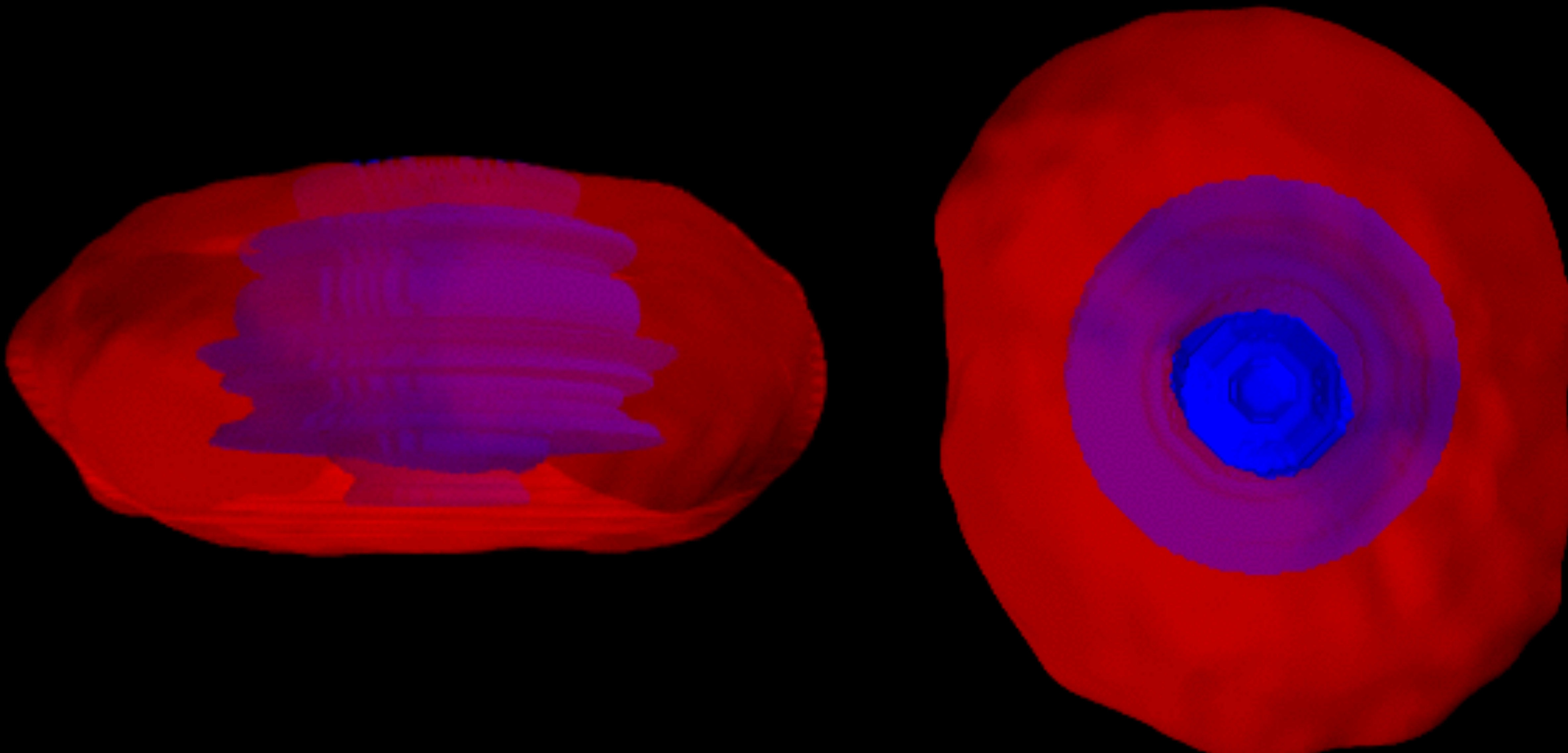


synthetic spectra of NS merger ejecta



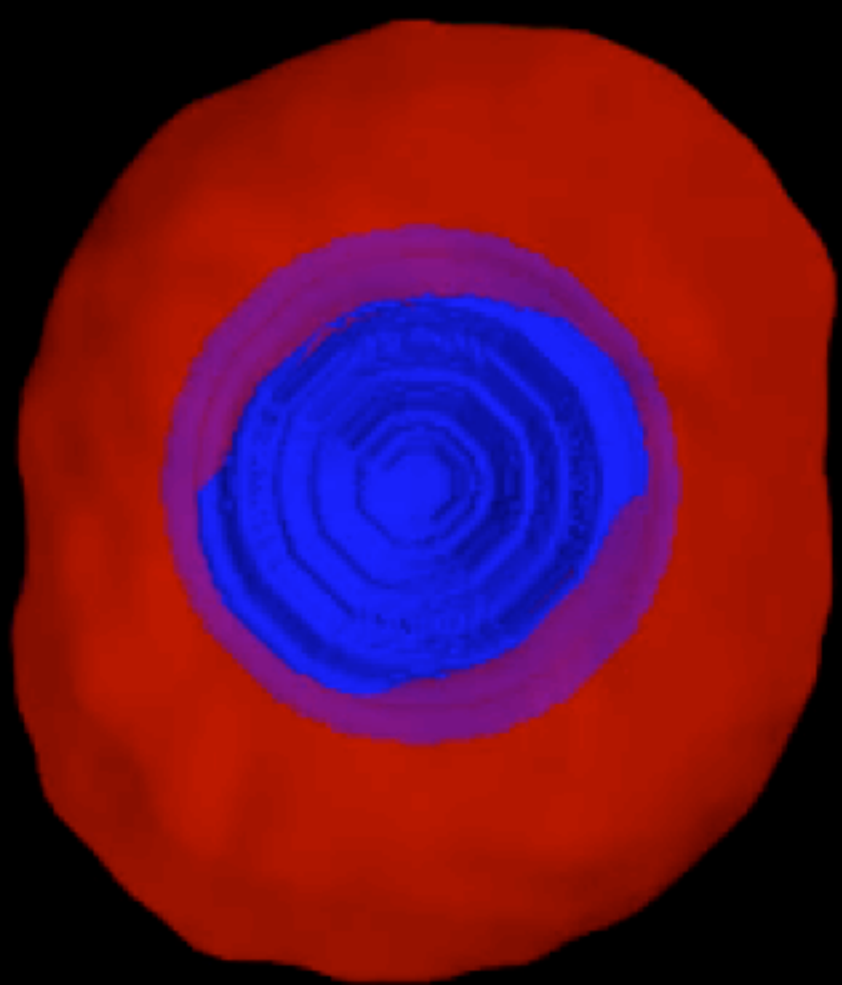
multiple ejecta components

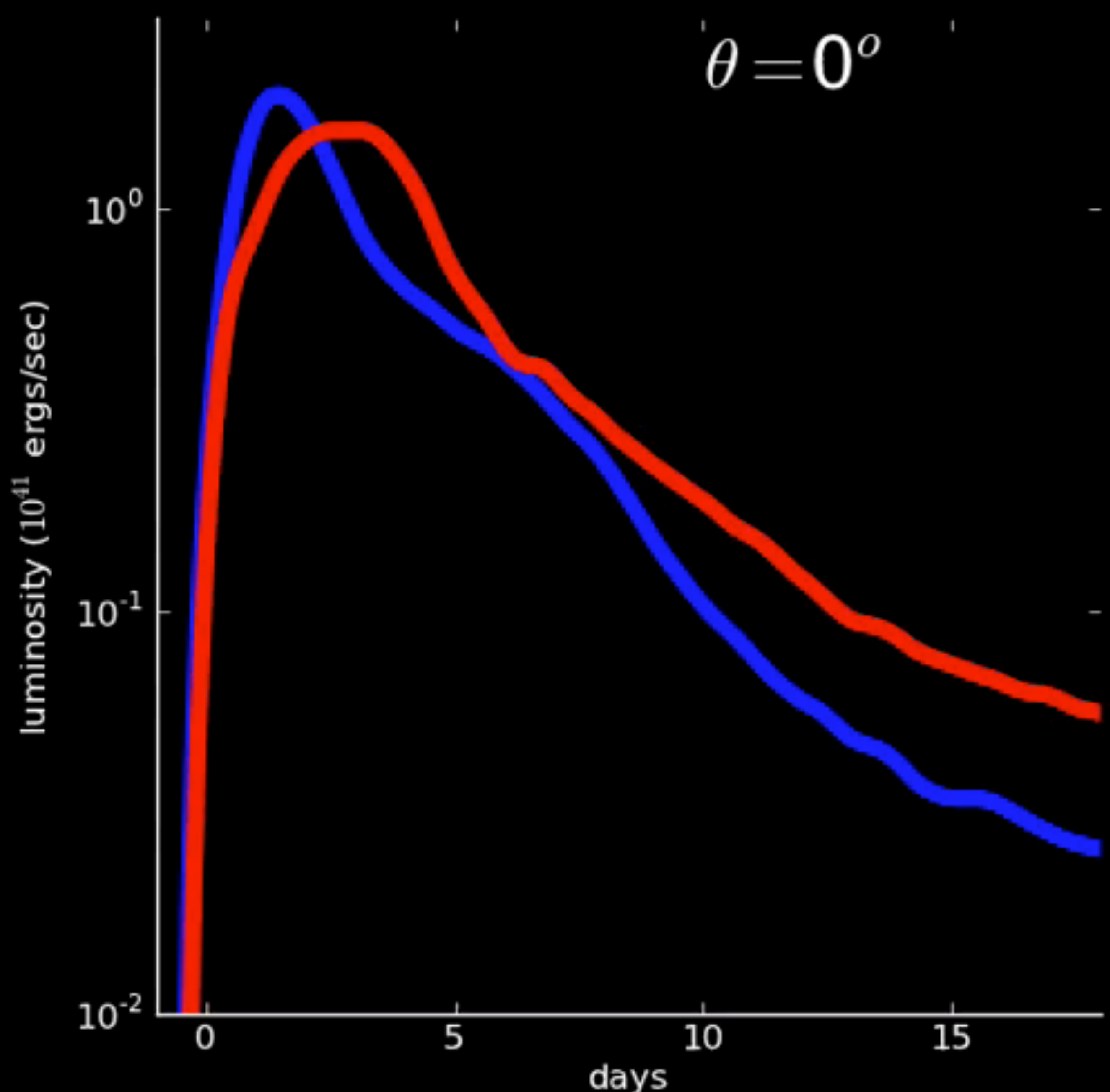
disk wind inside dynamical ejecta



multiple ejecta components

t = 100 ms disk wind inside 10^{-2} M_{sun} dynamical ejecta





takeaways

- kilonovae are a direct probe of r-process nucleosynthesis *at the production site*
- modeling kilonova light curves measures ejected mass
- kilonova color is a strong diagnostic of composition
  lanthanides (A > 130) = red
  lanthanide-free (A < 130) = blue
- kilonova spectra carry more detailed information about ejecta velocity and composition
- may be able to untangle multiple components:
  1) dynamical, 2) high Y_e wind, 3) low Y_e wind