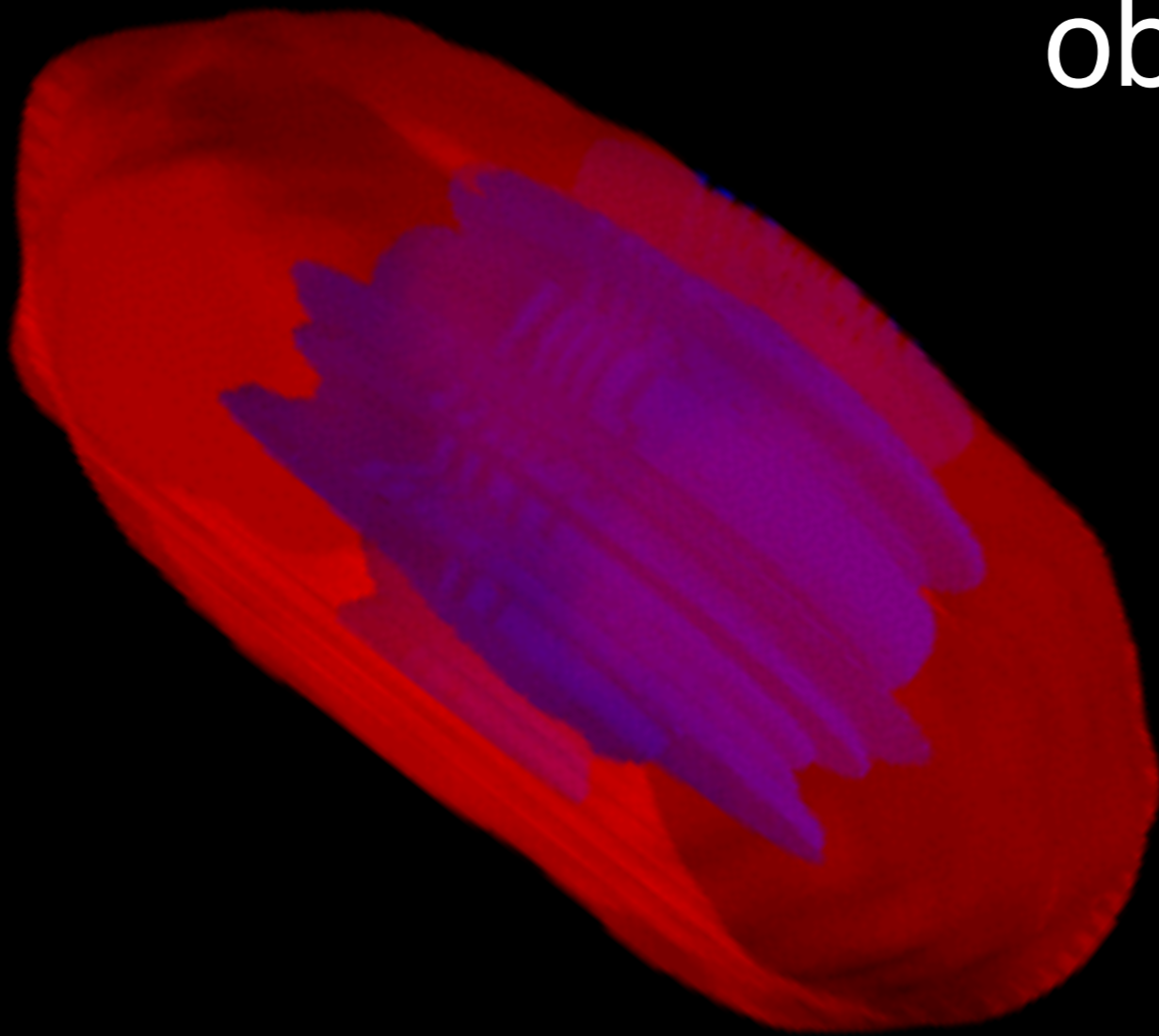


radioactive light curves from compact object mergers



daniel kasen

UC Berkeley/LBNL

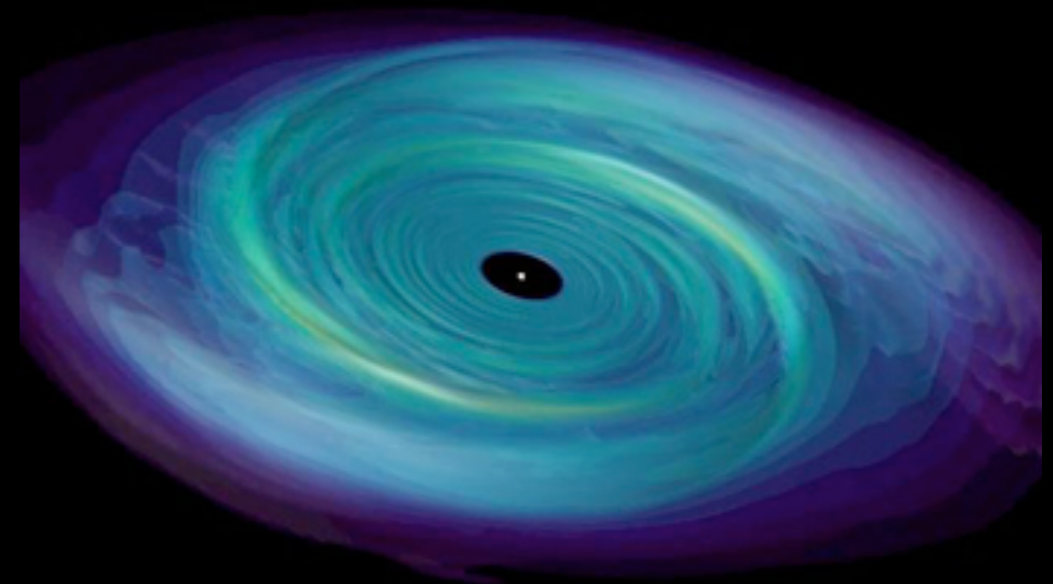
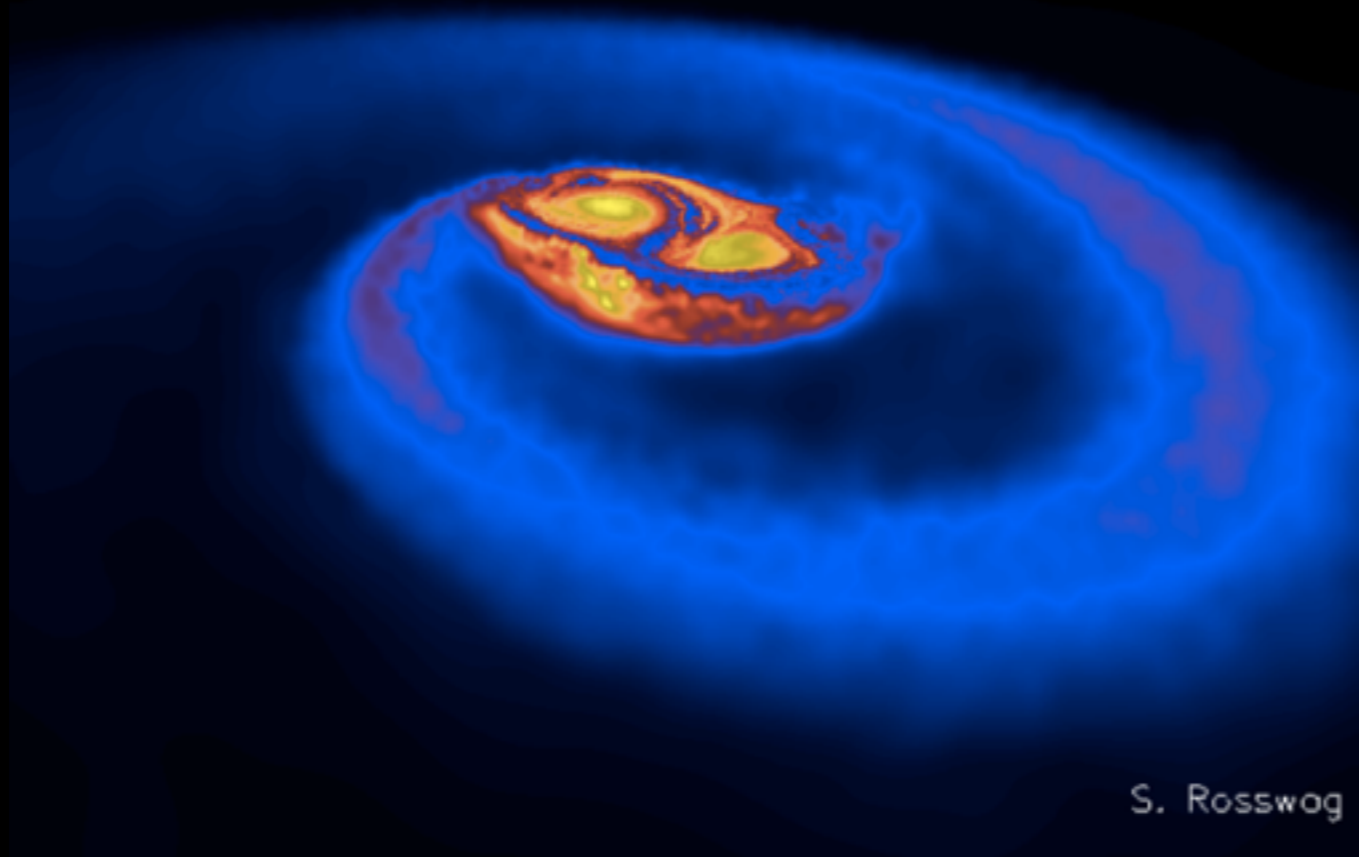
r. fernandez, b. metzger,
j. barnes, n. badnell,
s. rosswog, l. roberts,
e. ramirez-ruiz

ejecta from compact object mergers

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

dynamical ejecta

disk winds



$t \sim \text{ms}$

$Y_e \sim 0.05 - 0.1$

“strong” r-process
($A > 130$)

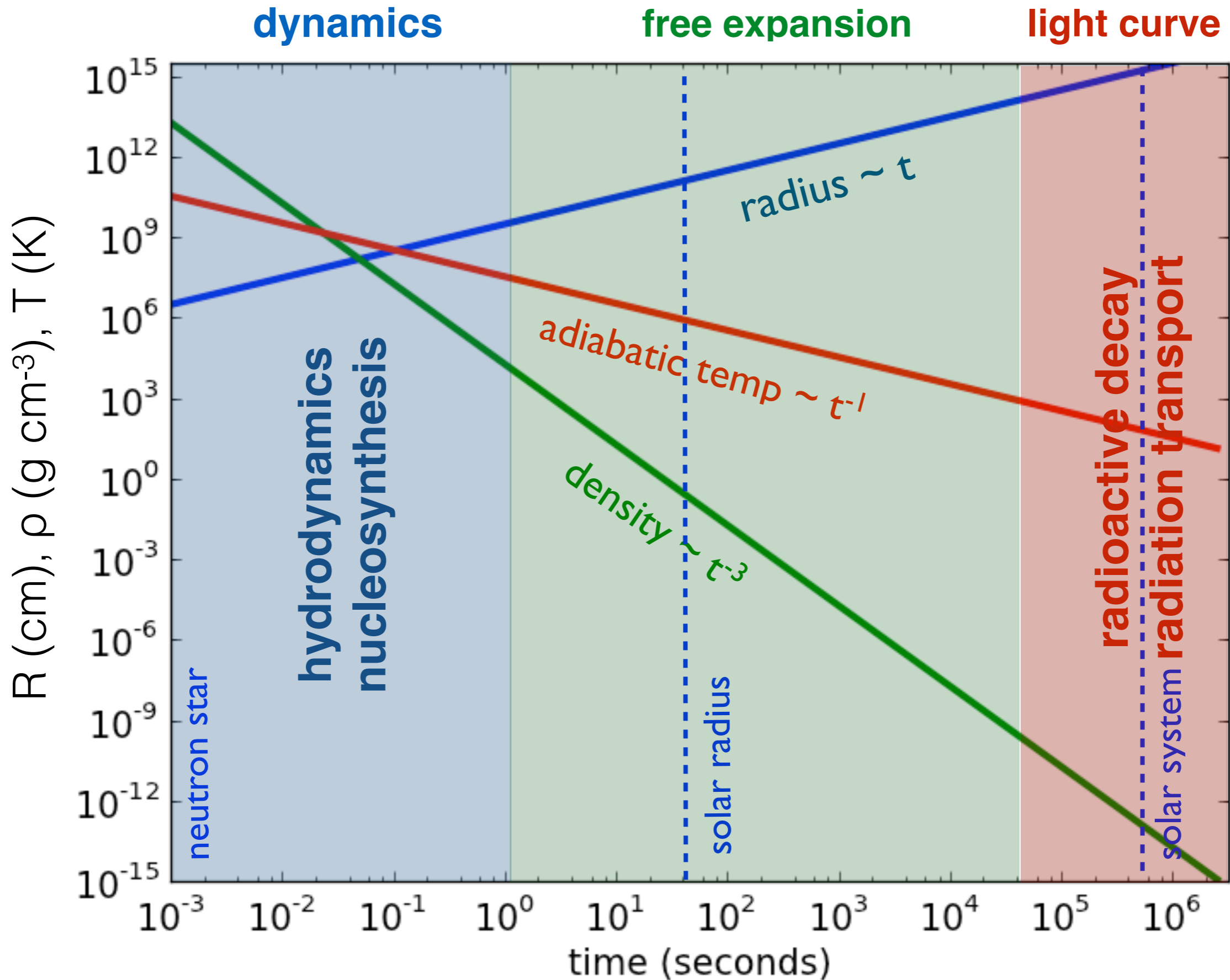
$t \sim \text{sec}$

$Y_e \sim 0.2 - 0.4$

“strong” and/or “weak ($A < 130$)”
depending on neutrino irradiation

S. Rosswog

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

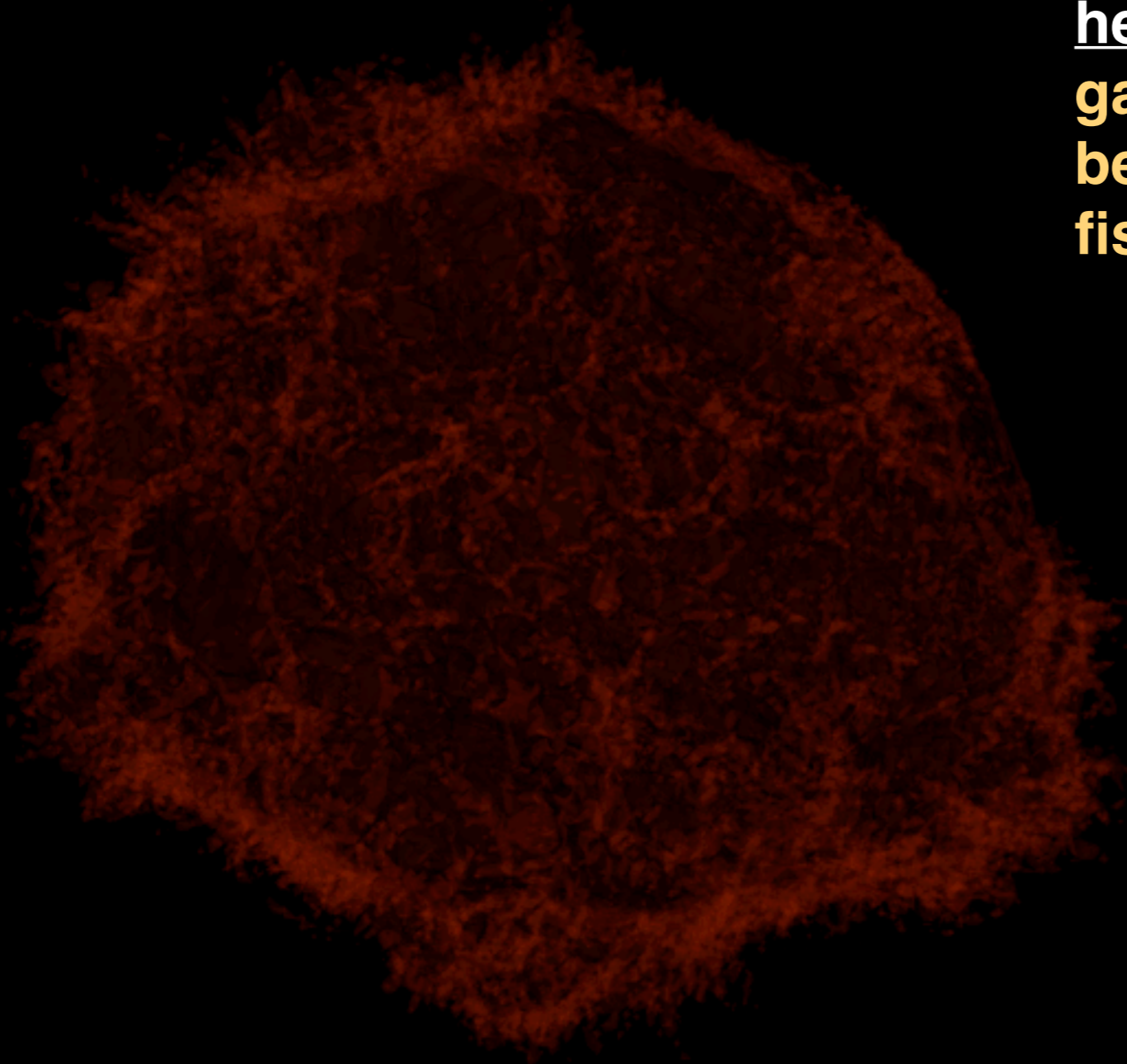
gamma-rays: compton/photoabsorption

betas: coulomb collisions, ionization

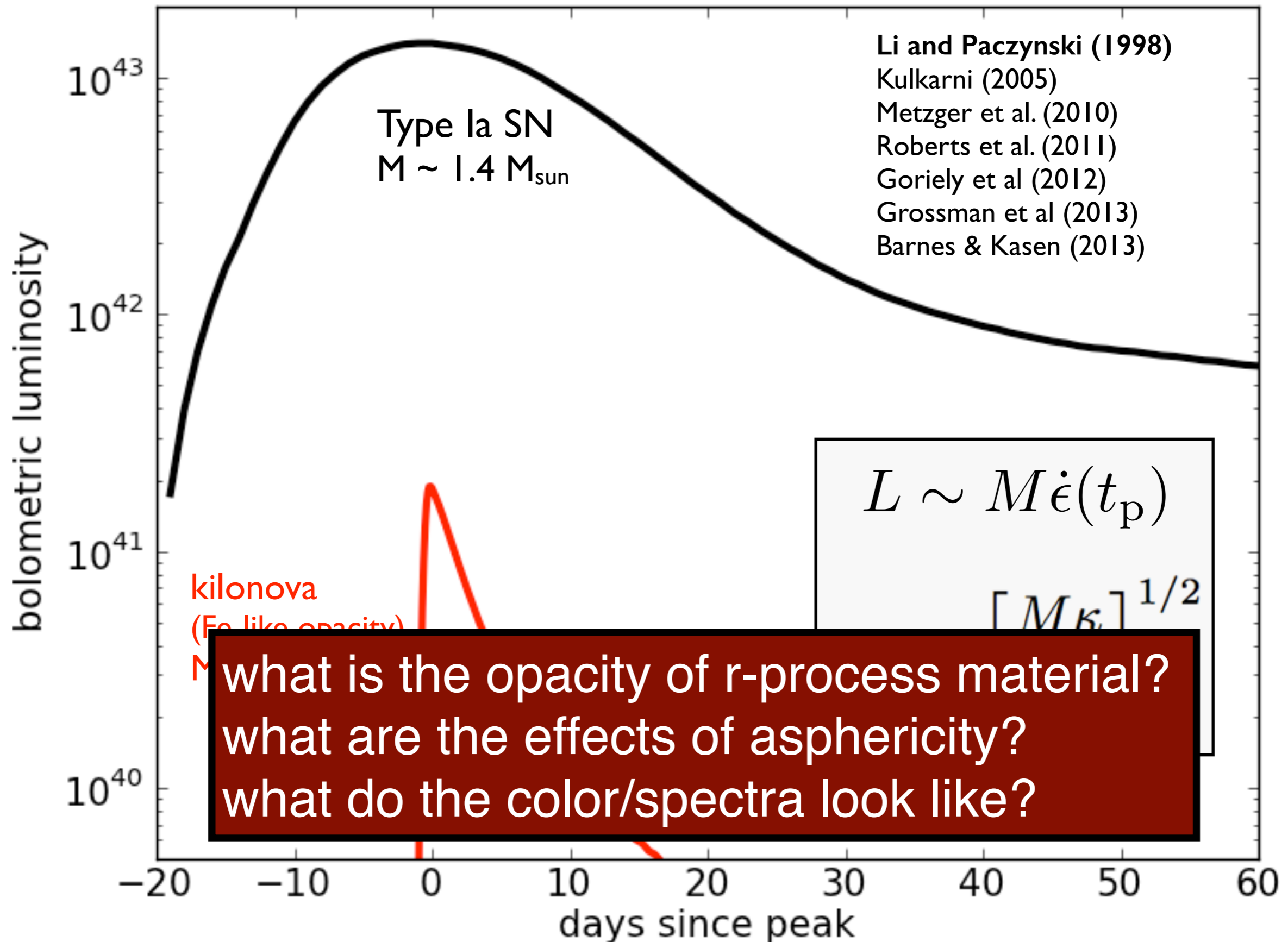
fission, alphas: coulomb collisions

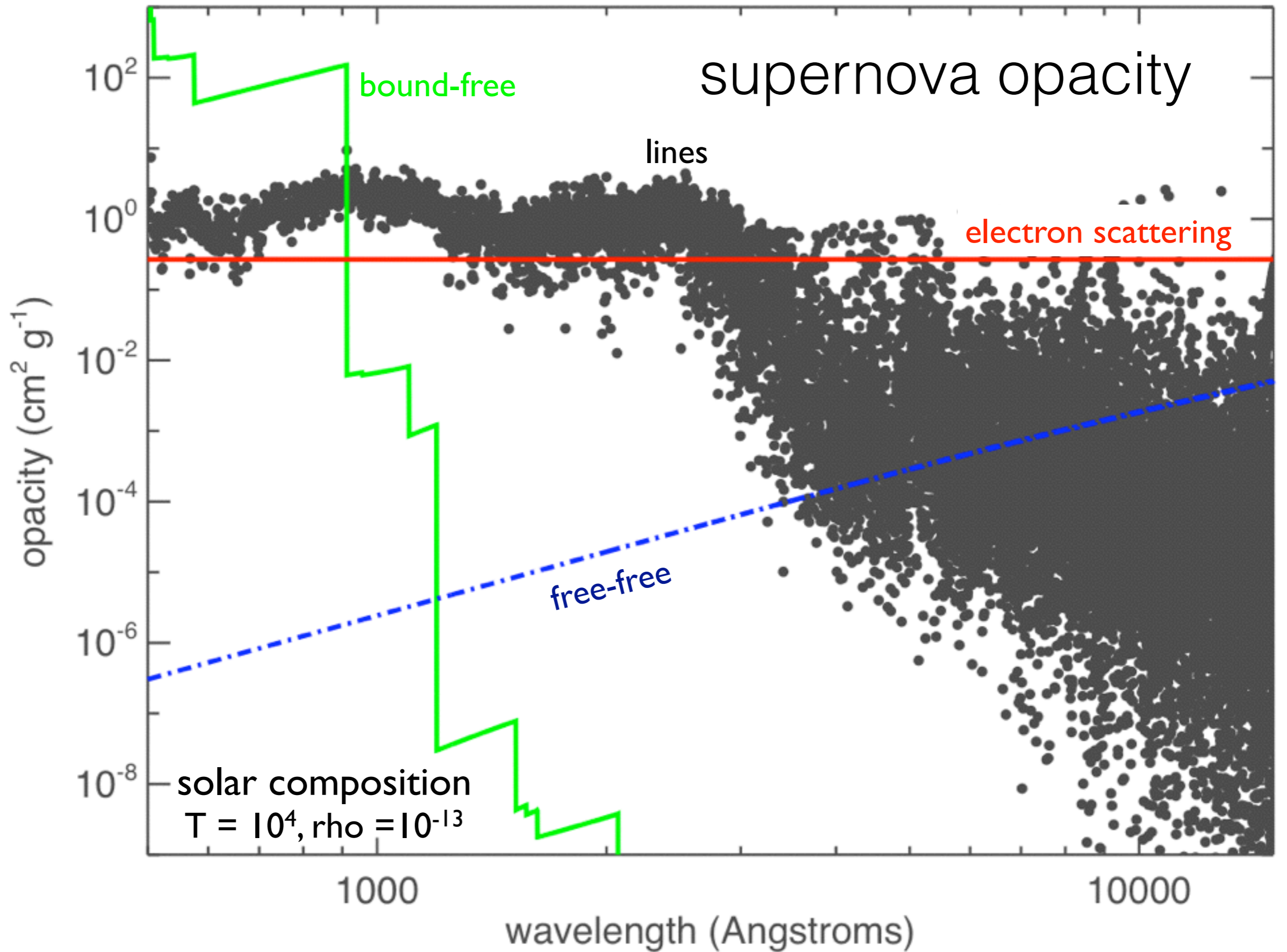
**re-emitted thermal
optical/infrared photons
gradually diffuse out**

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



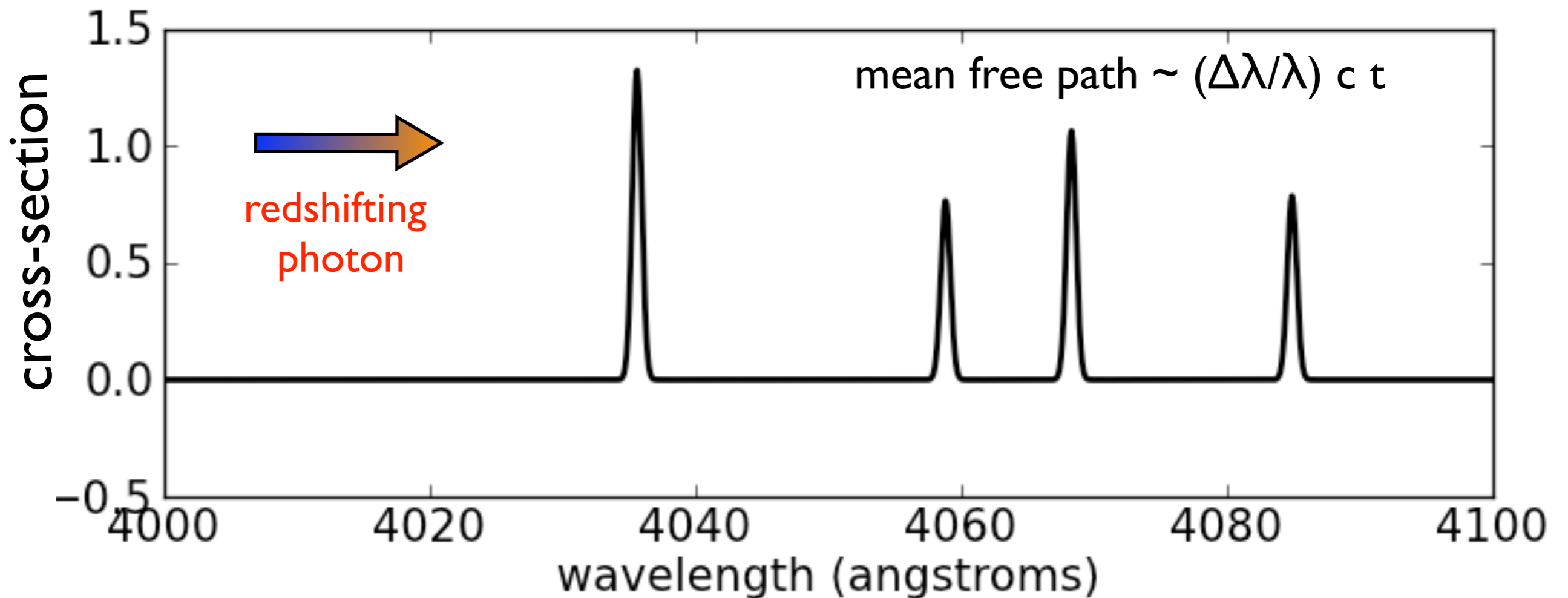
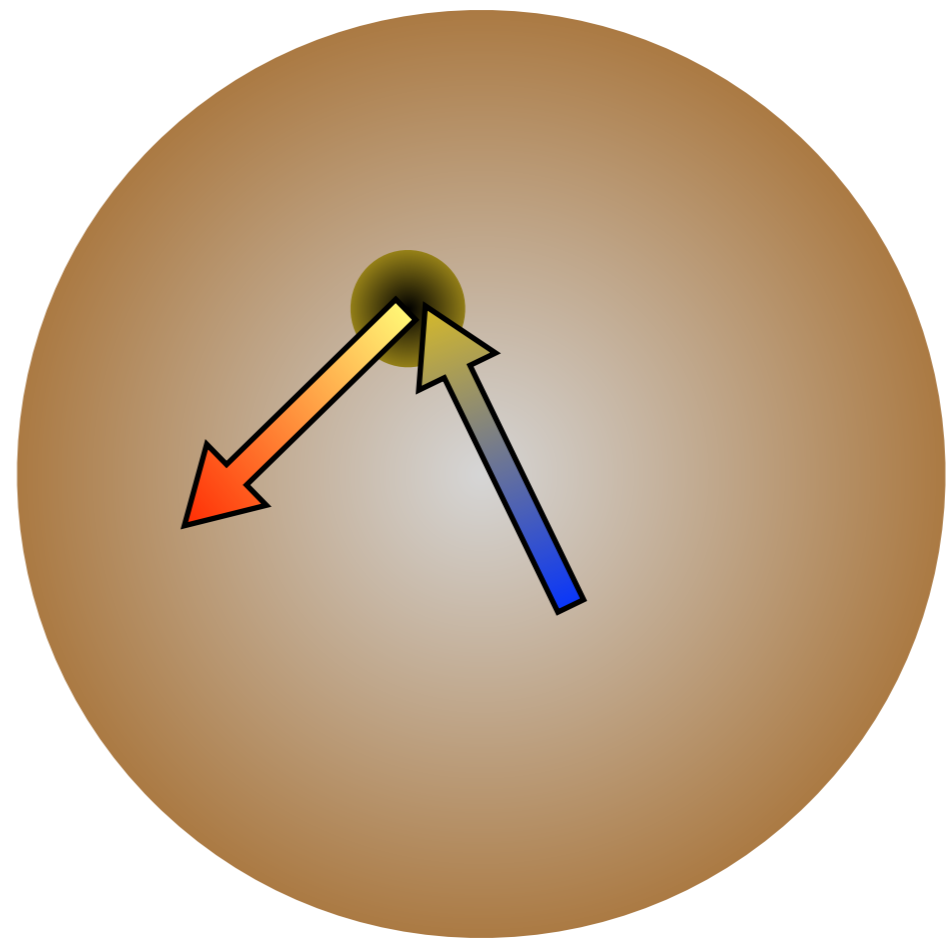
radioactively powered transients (kilonovae)





line interactions in an expanding (hubble-like) flow

mean free path set by
density of lines



opacity and atomic complexity

s-shell (g=2)

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

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

p-shell (g=6)

d-shell (g=10)

hydrogen 1 H 1.0079															helium 2 He 4.0026			
lithium 3 Li 6.941	beryllium 4 Be 9.0122																	
sodium 11 Na 22.990	magnesium 12 Mg 24.305																	
potassium 19 K 39.098	calcium 20 Ca 40.078																	
rubidium 37 Rb 85.468	strontium 38 Sr 87.62																	
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
francium 87 Fr [223]	radium 88 Ra [226]	89-102 **	yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	aluminum 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
			lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
			lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnium 110 Uun [271]	ununium 111 Uuu [272]	ununbium 112 Uub [277]	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
													thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
													ununquadium 114 Uuq [289]					

* Lanthanide series

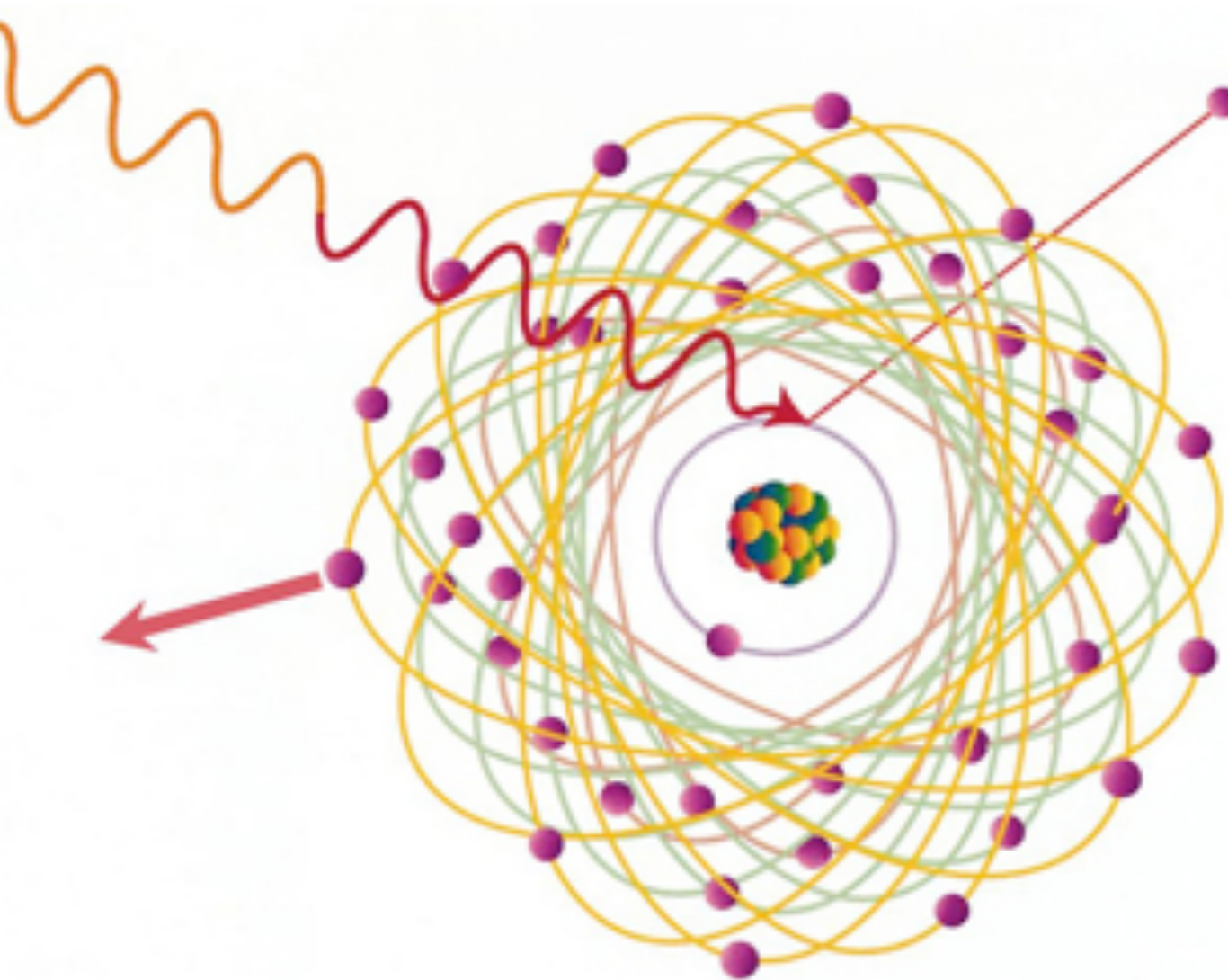
** Actinide series

lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

f-shell
(g=14)

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 $\lambda > 1 \mu\text{m}$

Autostructure calculations

kasen, badnell, and barnes (2013)

(~40,000,000 lines)

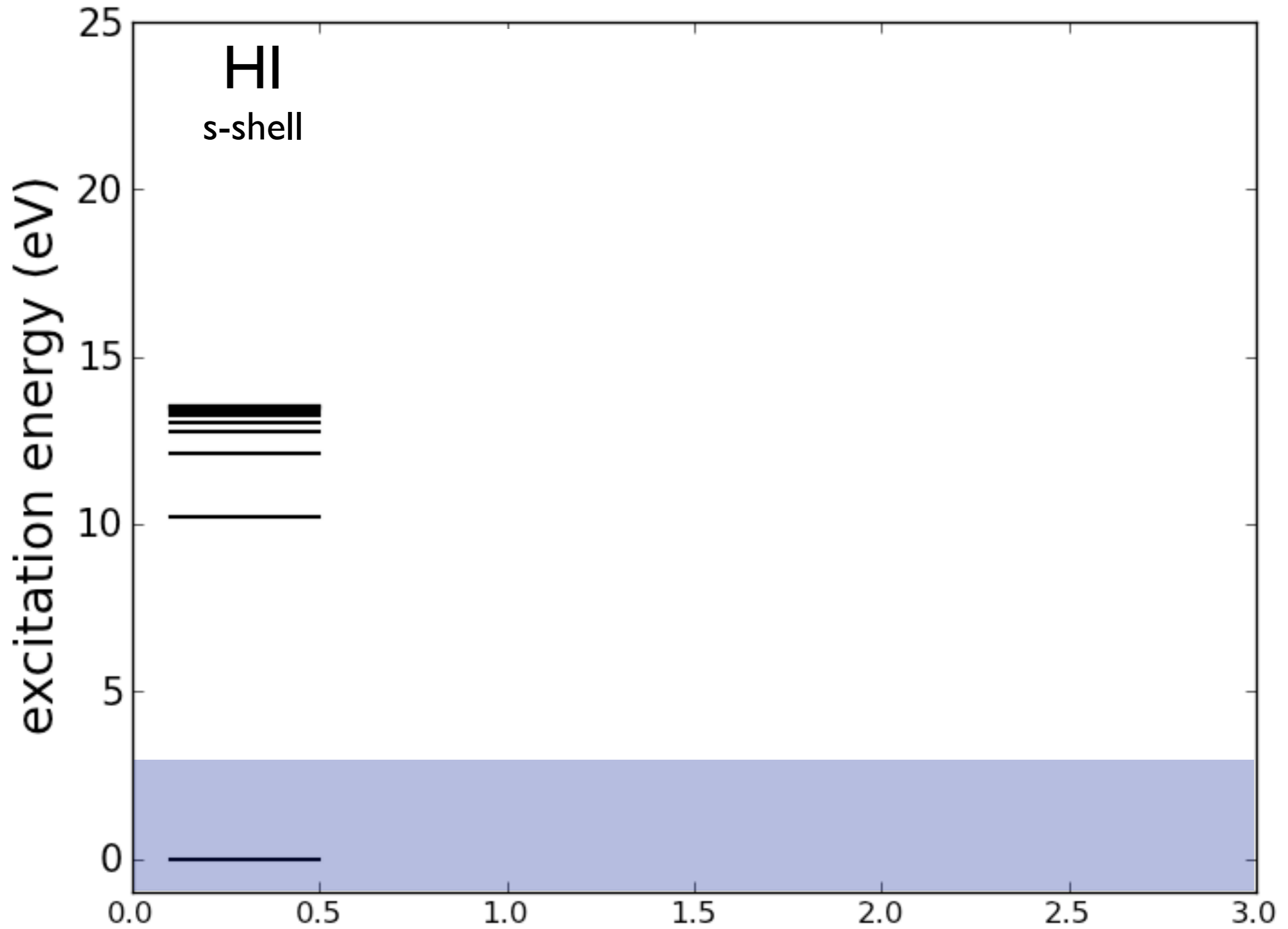
ab-initio calculations for Nd, Cd, Os,...

extrapolated to other species

more work underway....

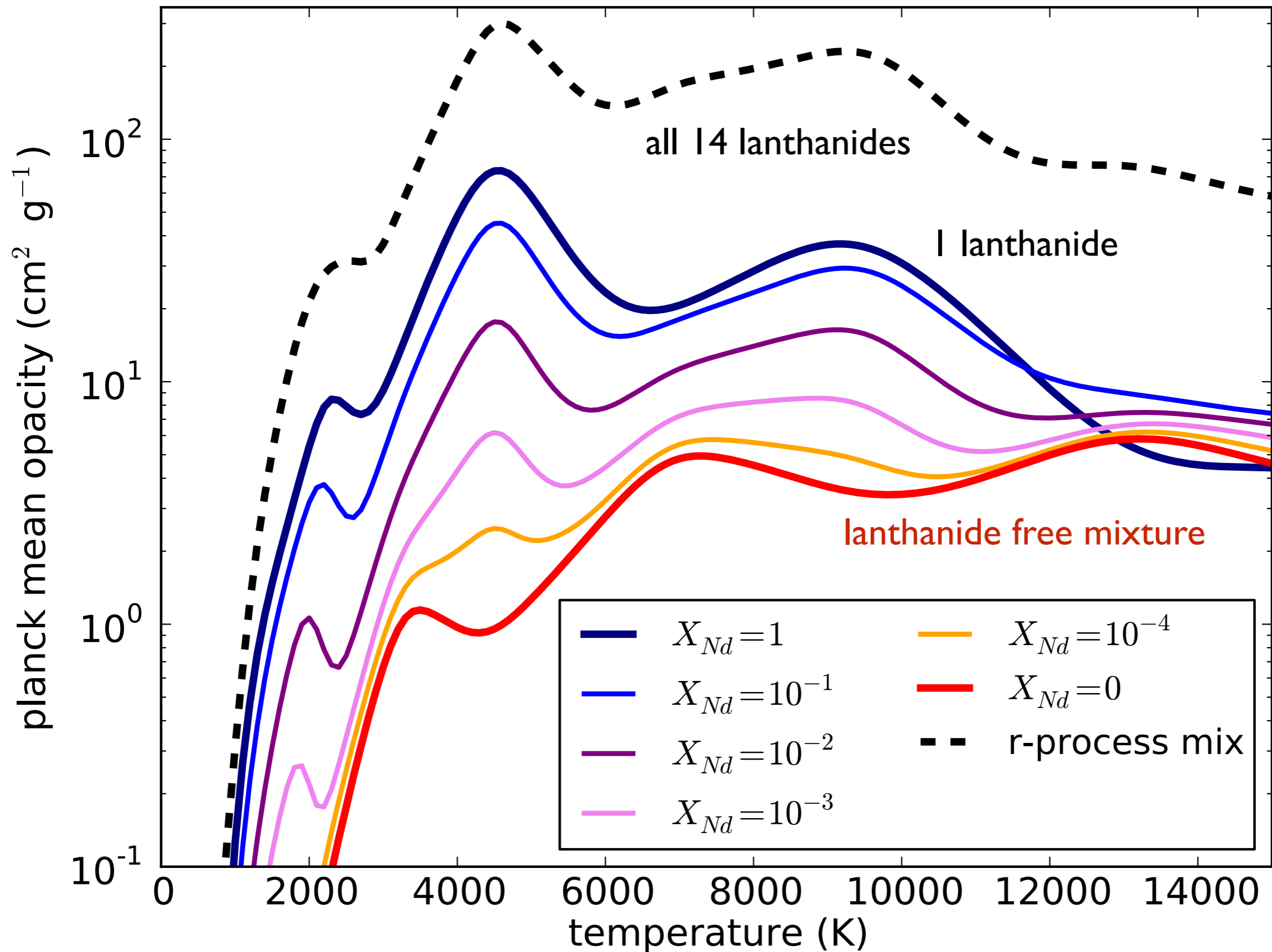
atomic level energy structure

kasen+ 2013



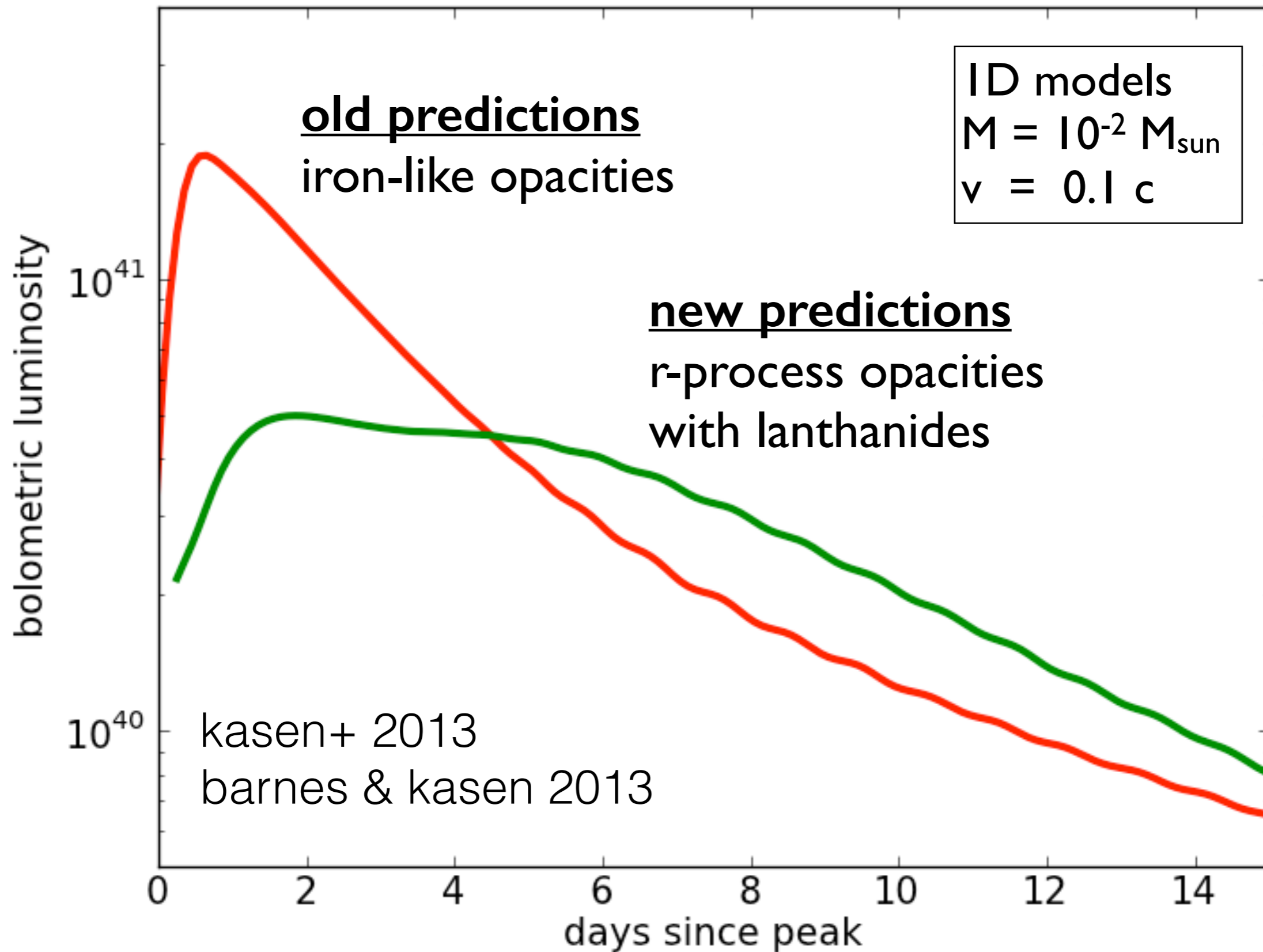
mean opacities different composition

kasen, badnell, barnes 2013

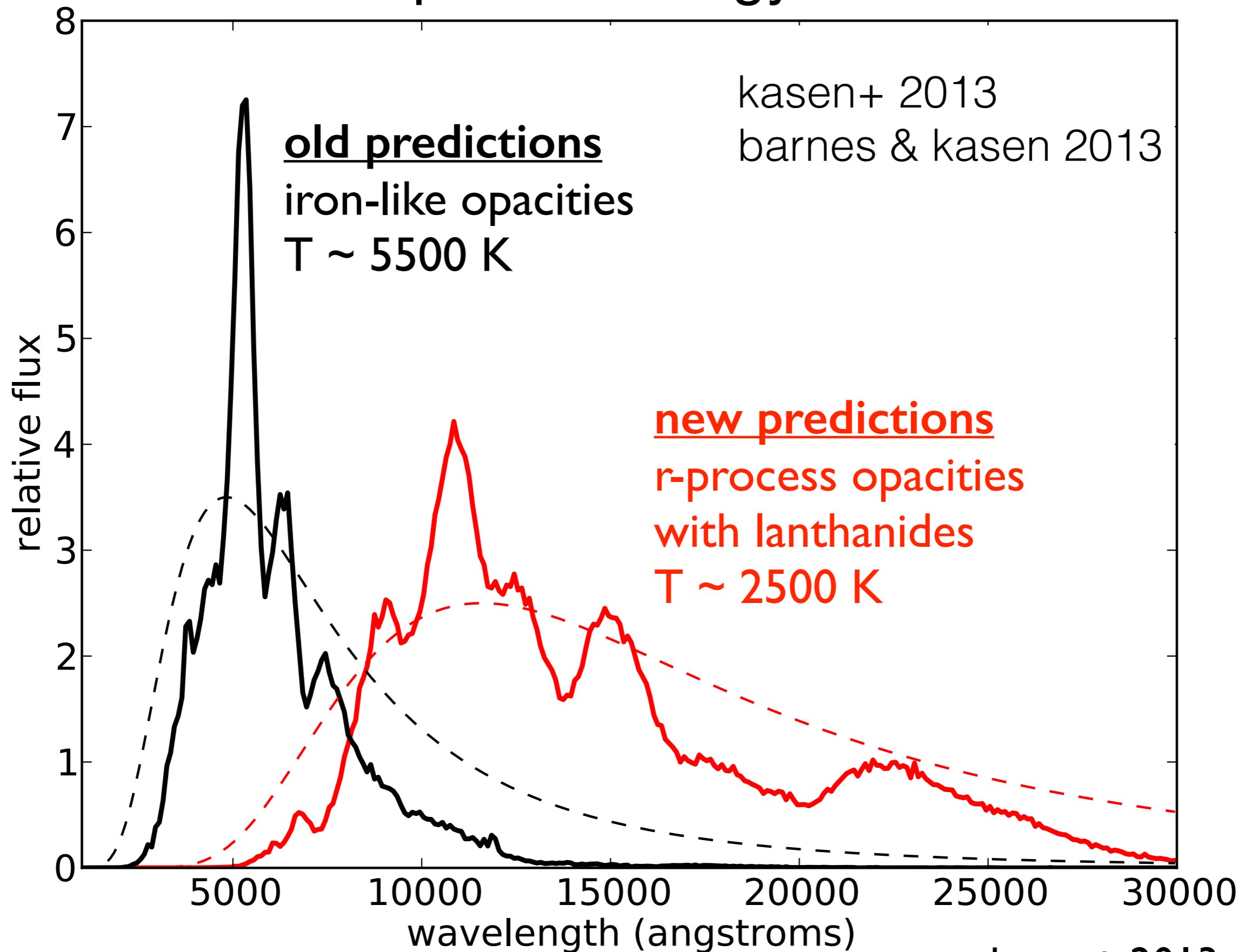


light curves of radioactive transients

effect of high lanthanide opacity



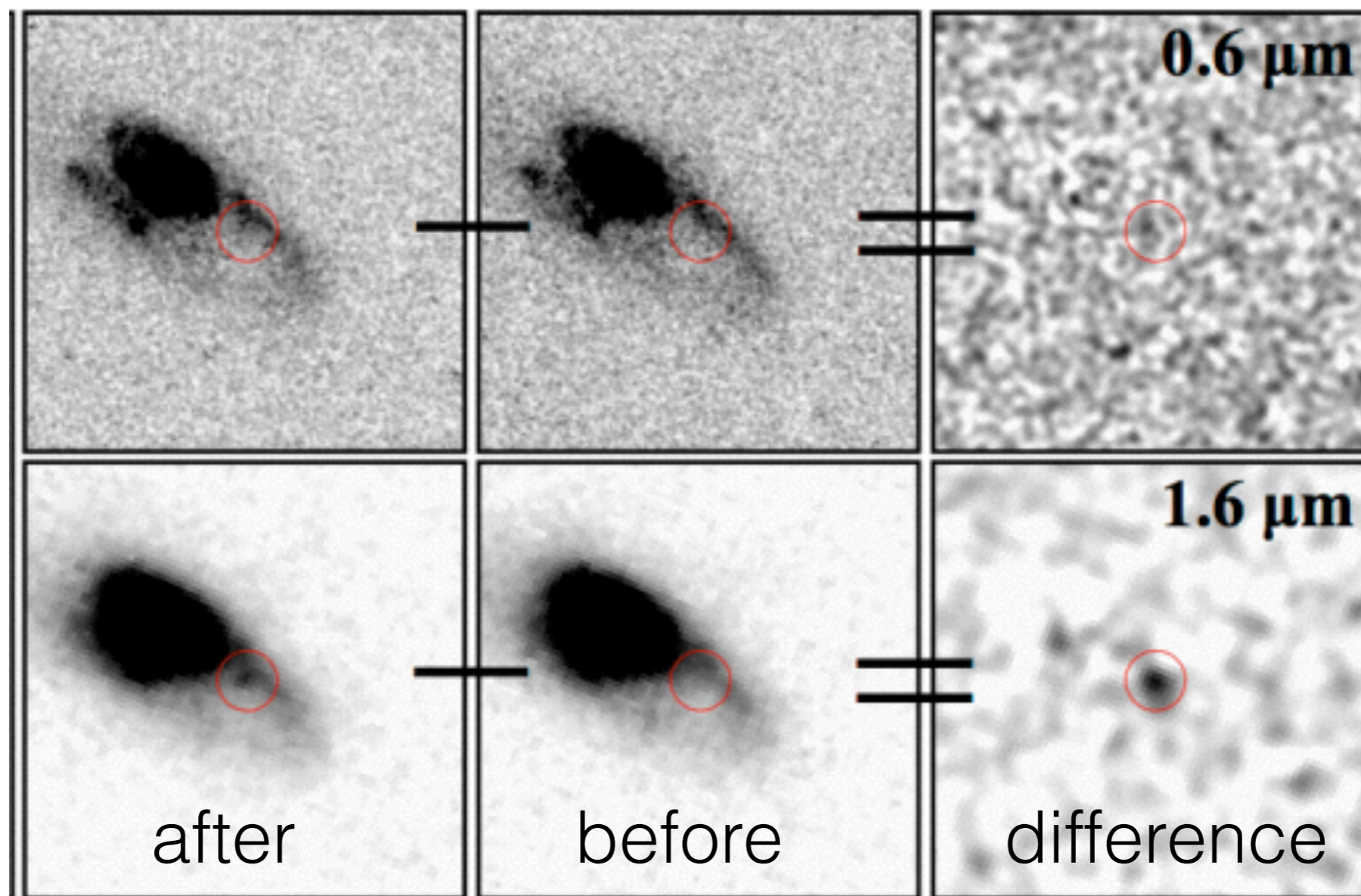
model spectral energy distribution



kasen+ 2013

GRB130603B

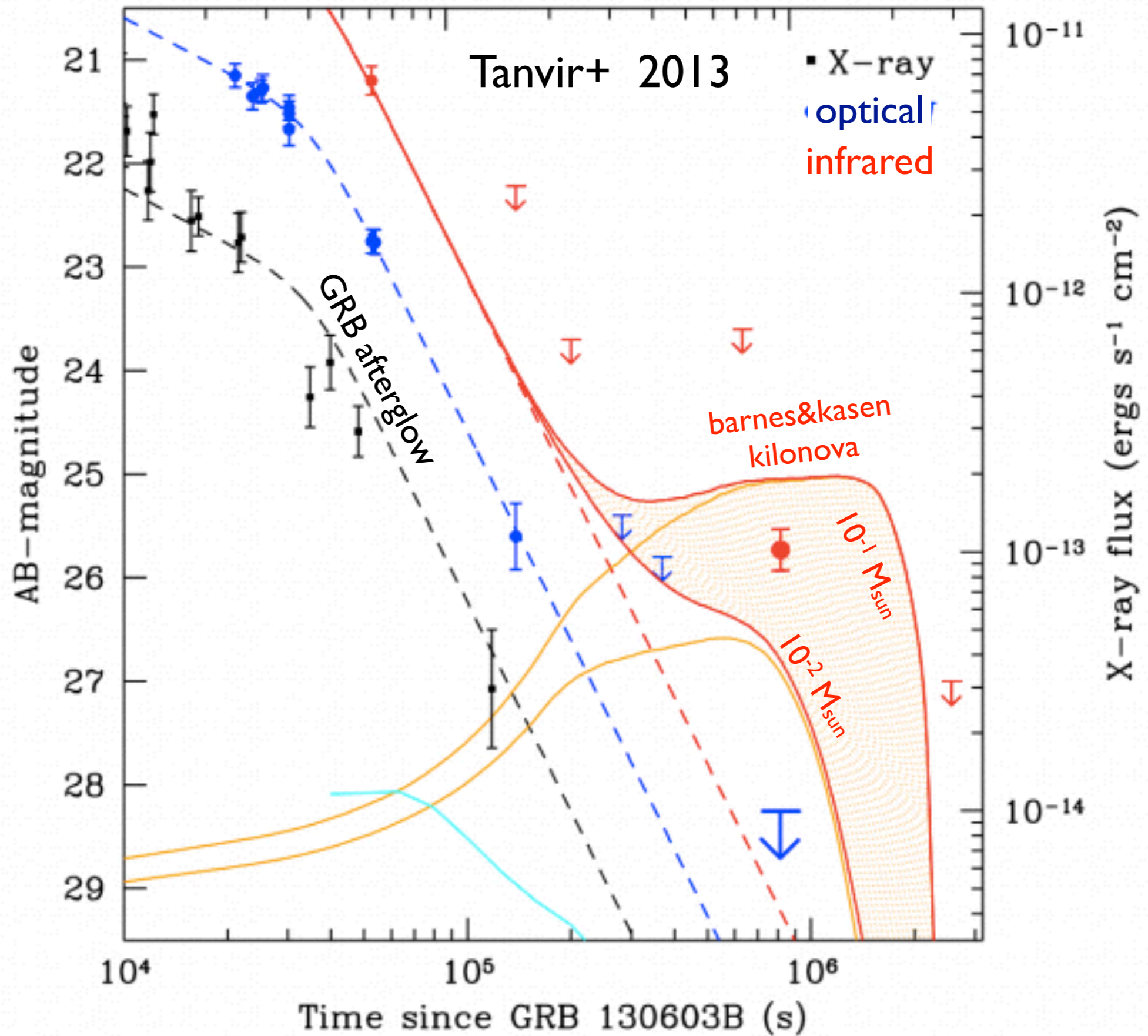
relatively nearby short GRB ($z = 0.356$)



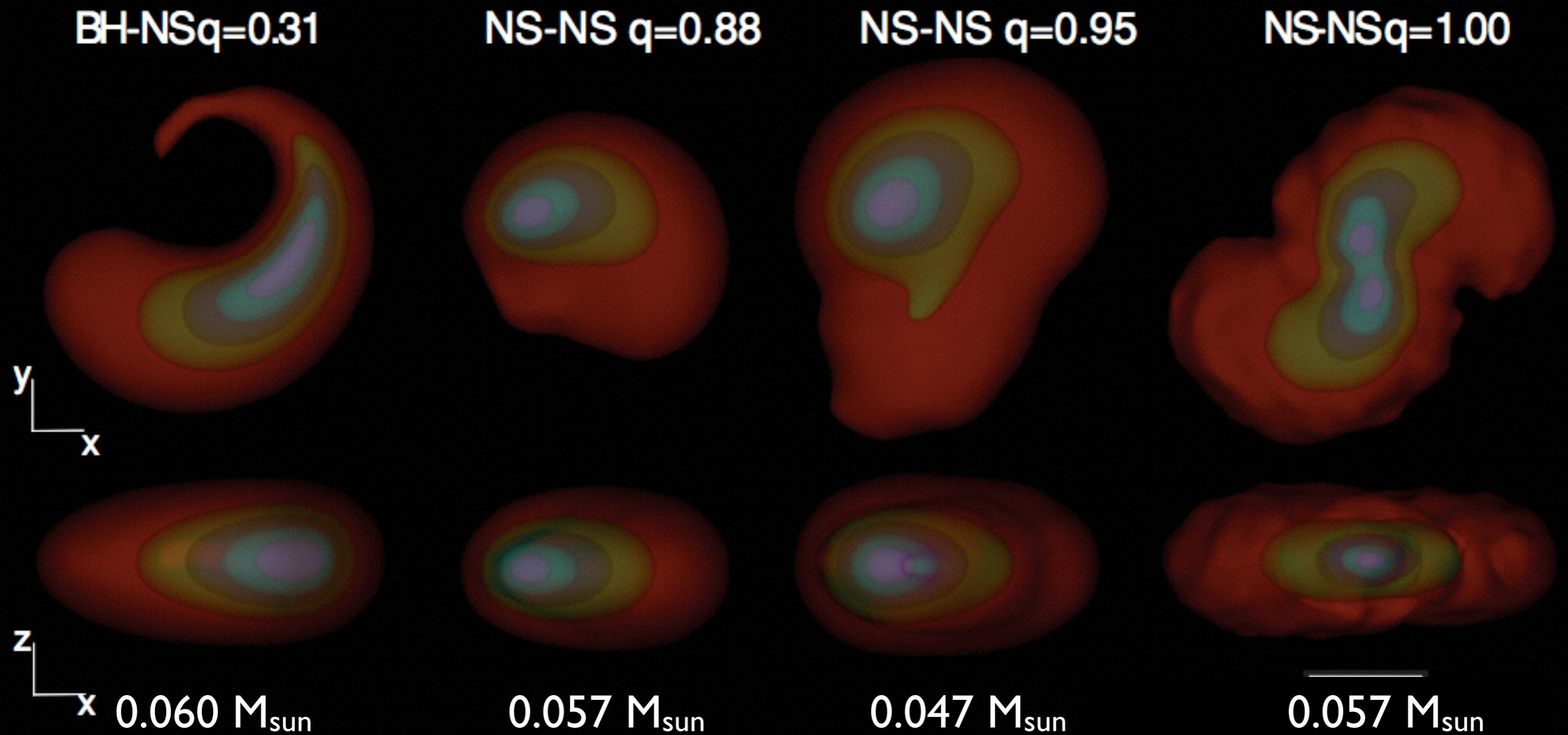
deep infrared imaging with HST
triggered ~ 1 week after burst

Tanvir+ 2013
c.f. Berger 2013

discovery of an r-process kilonova?



3D dynamical ejecta models

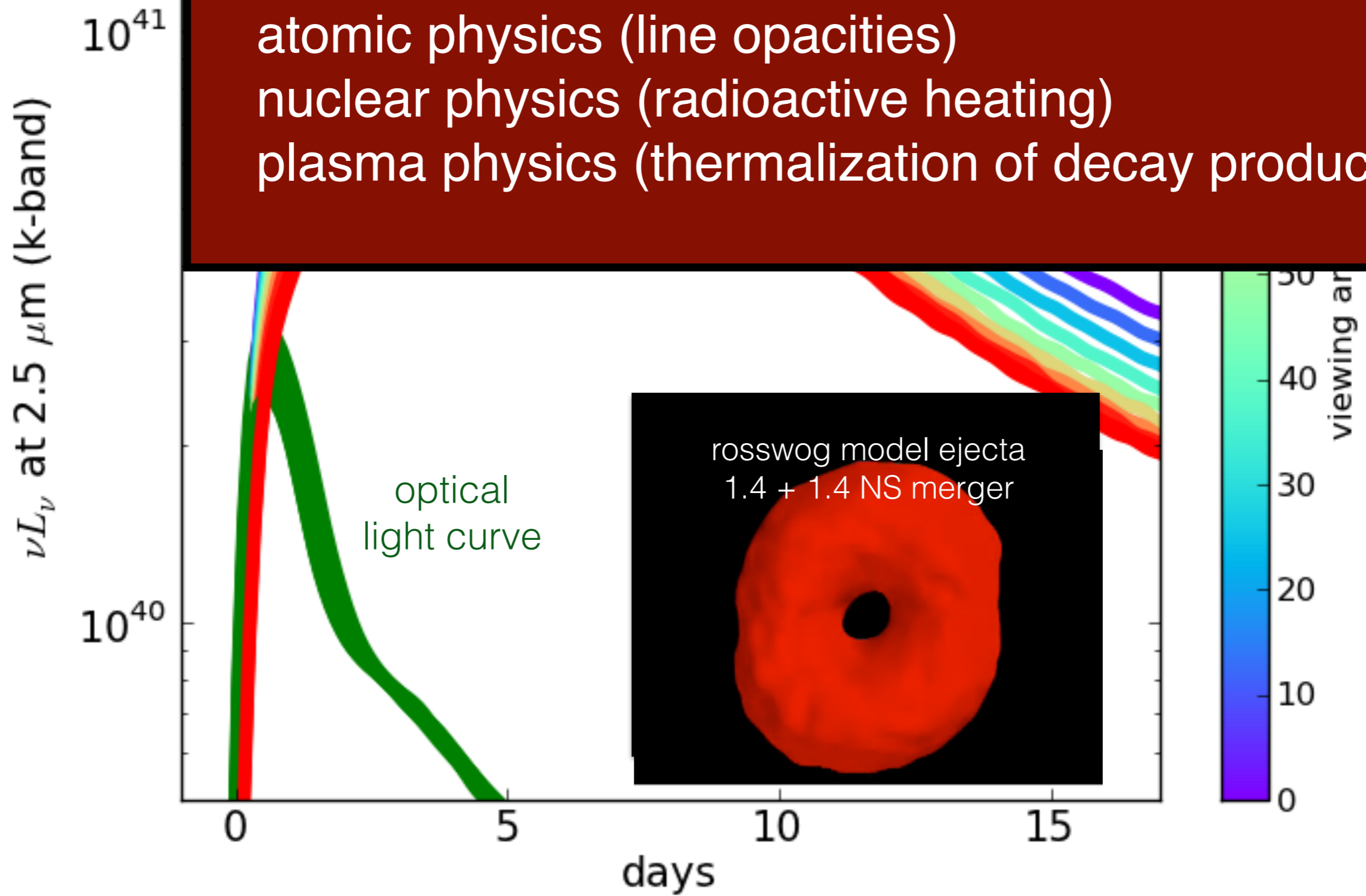


roberts, kasen, lee, & ramirez-ruiz (2011)

model kilonova light curve

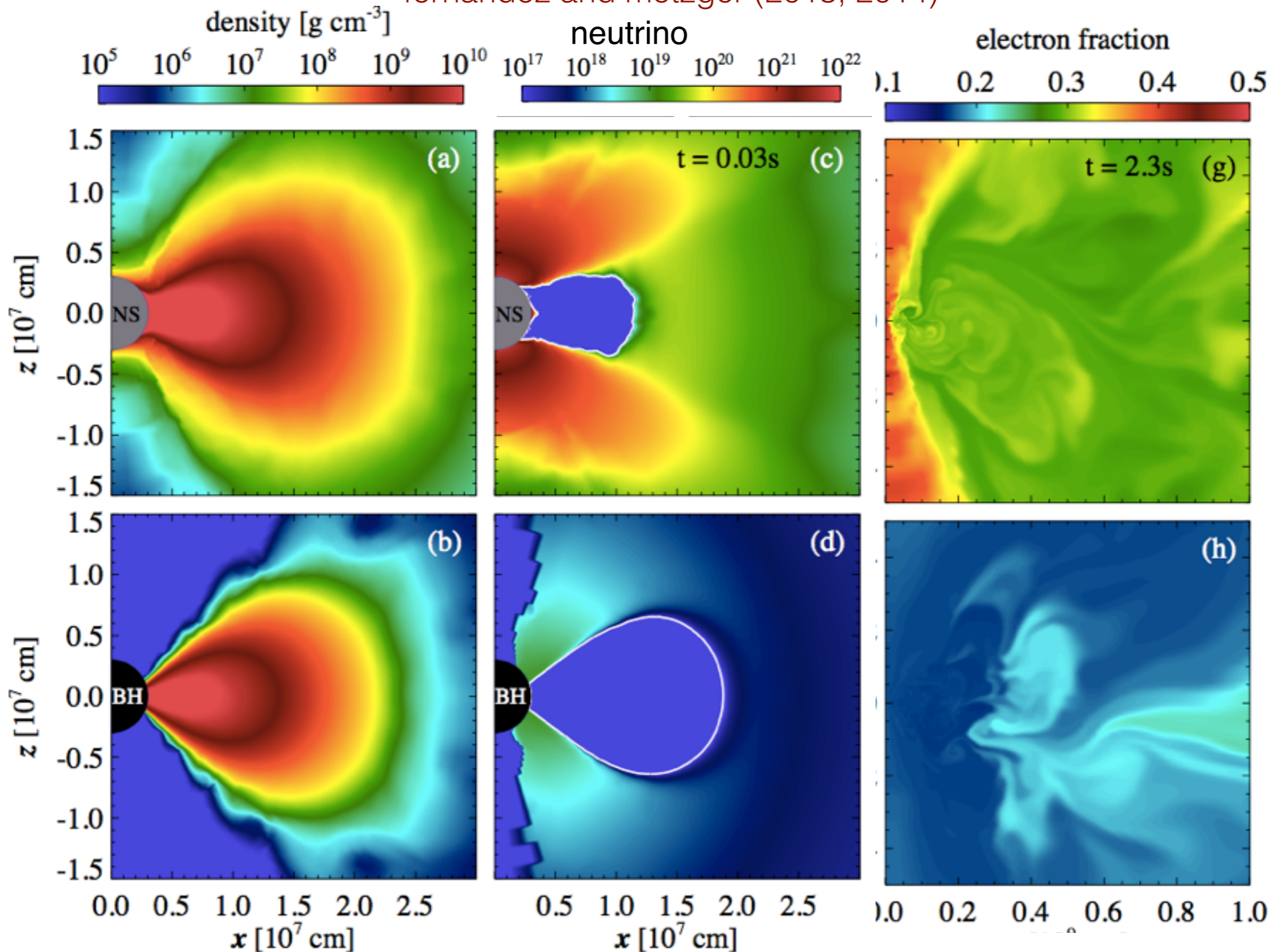
0.025 M_{sun} of dynamical ejecta

mass estimate subject to uncertainties in
dynamics (ejecta geometry)
atomic physics (line opacities)
nuclear physics (radioactive heating)
plasma physics (thermalization of decay products)



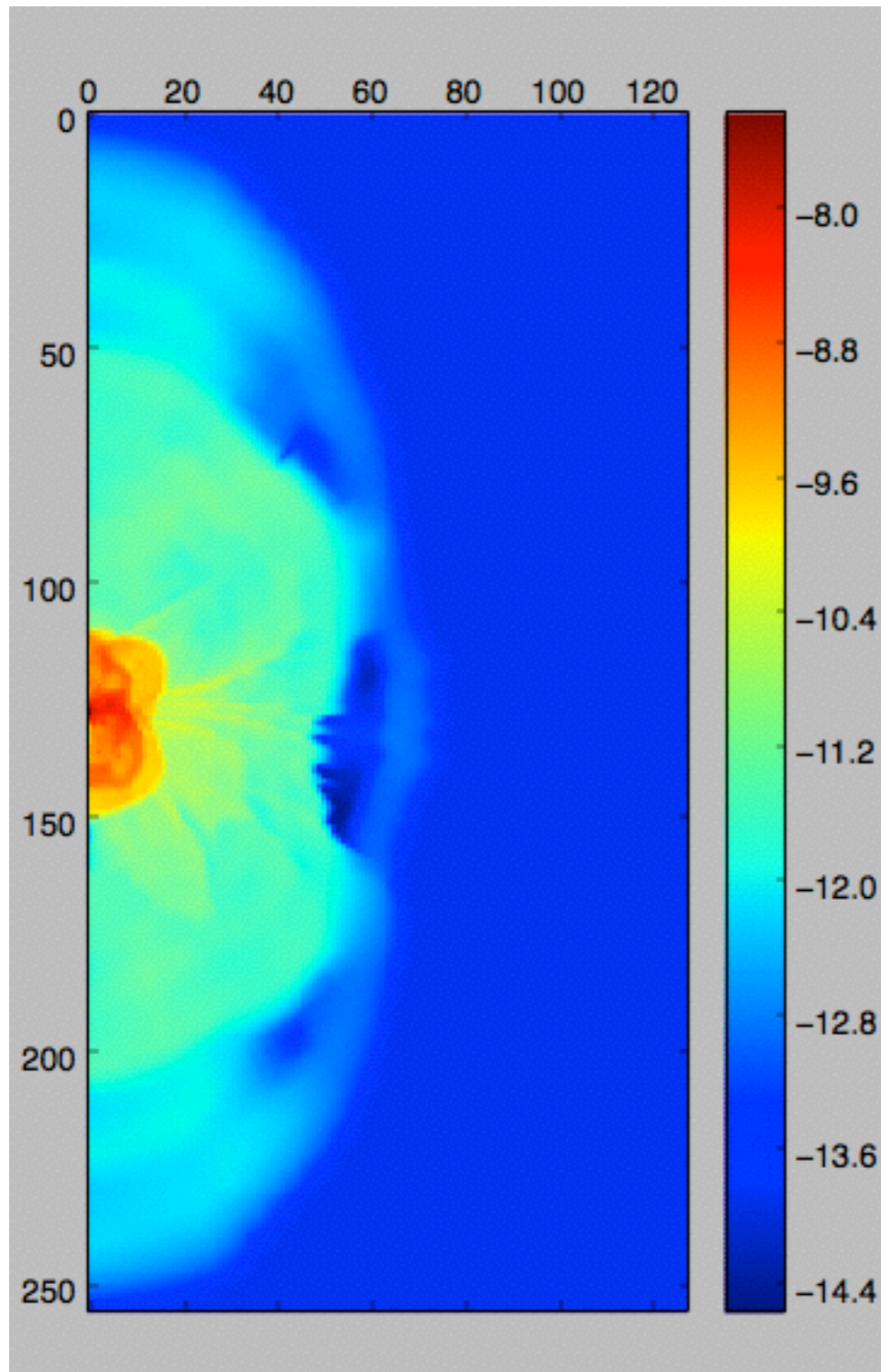
post-merger ejection in disk winds

fernandez and metzger (2013, 2014)

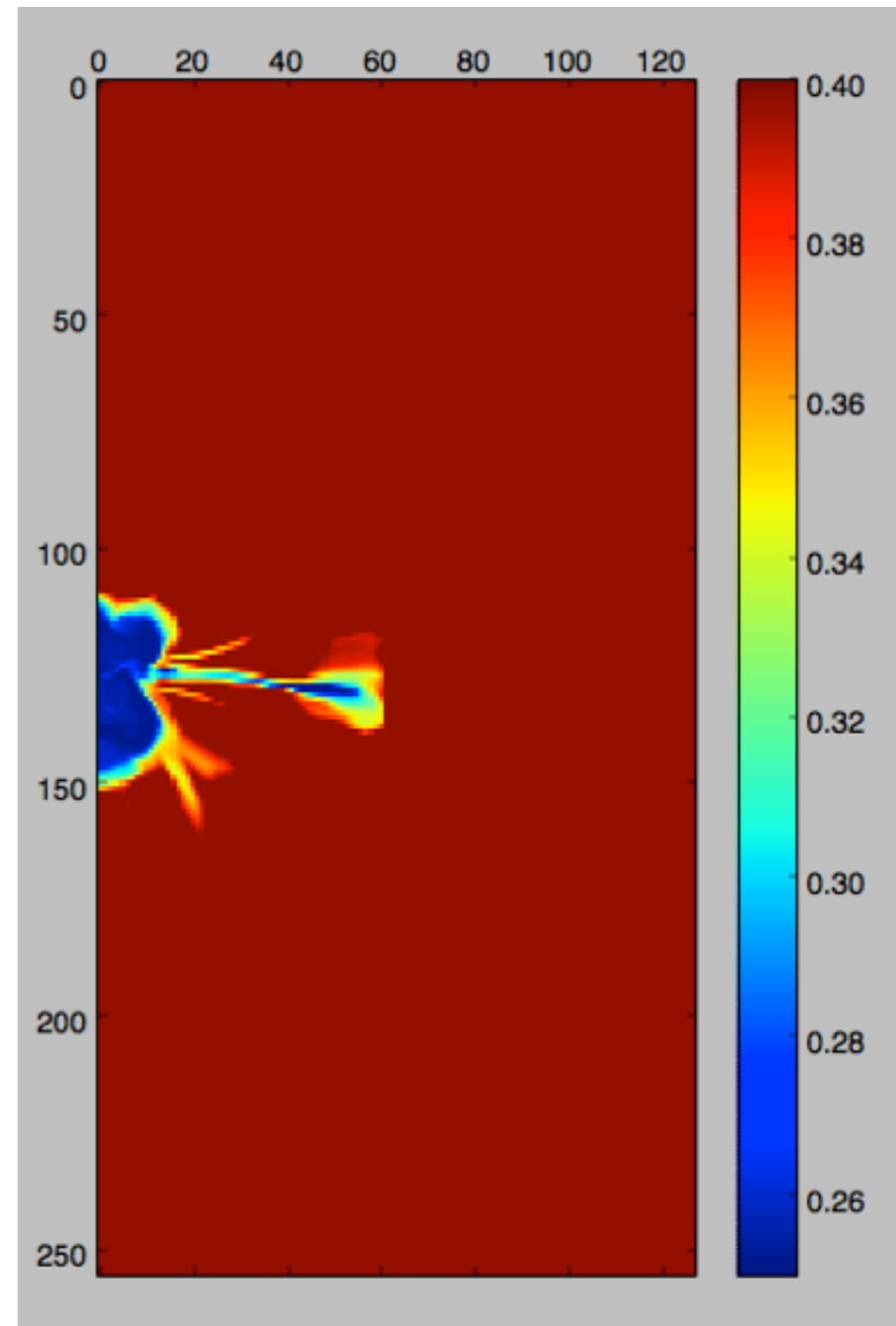


ejected disk wind (NS lives 30 ms)

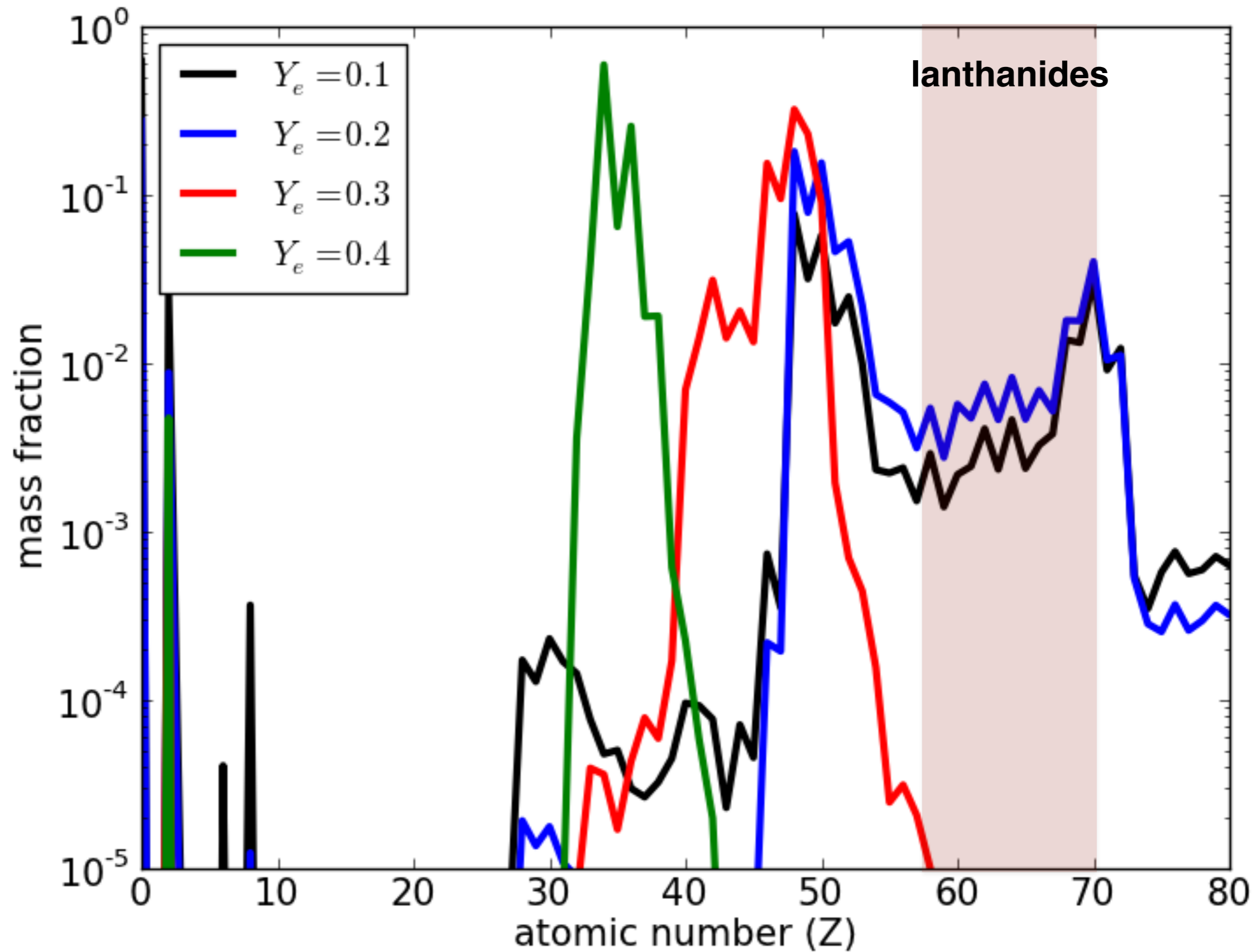
\log_{10} density



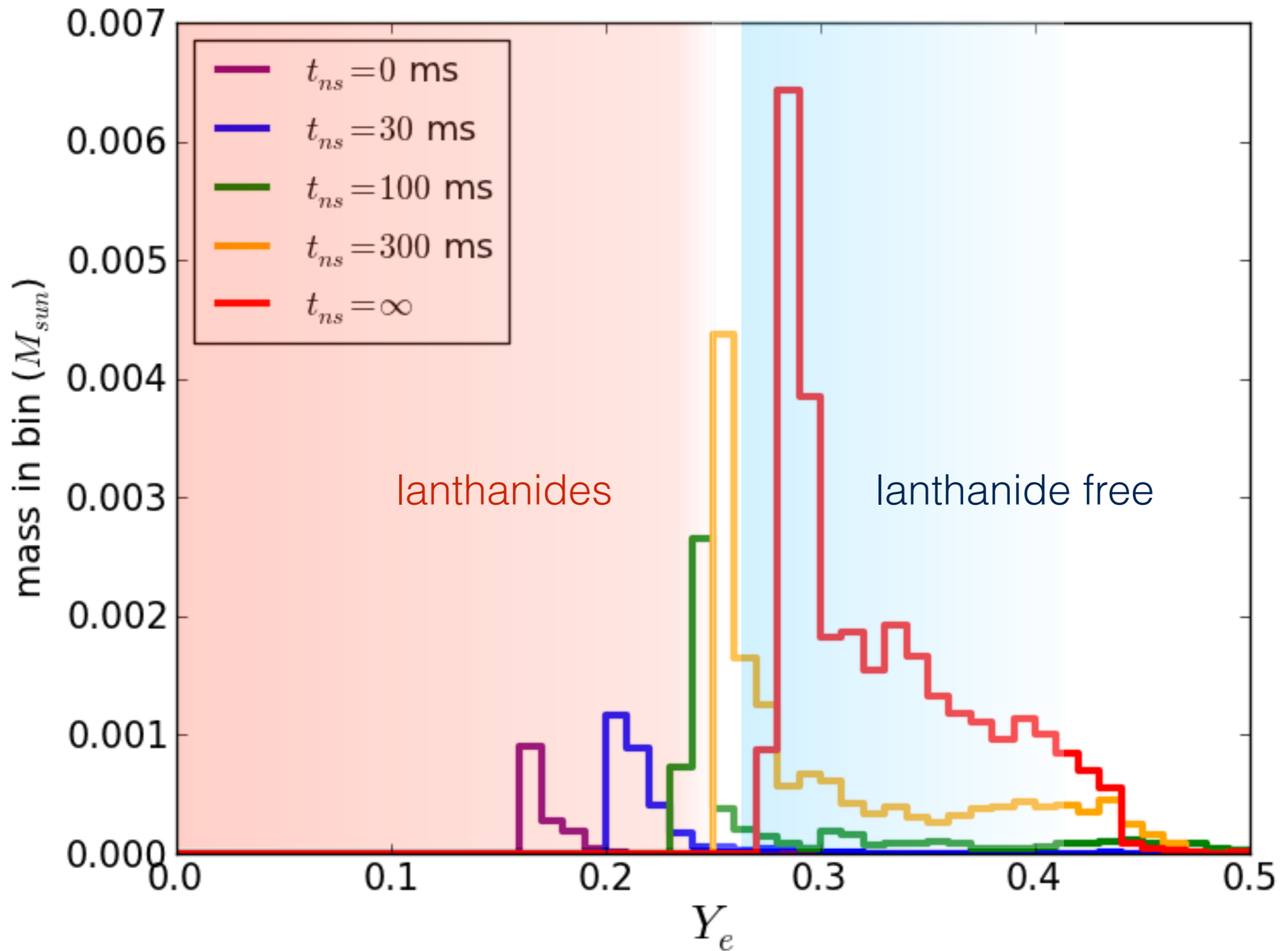
Y_e



estimated final abundances
(parameterized wind nucleosynthesis calculations)

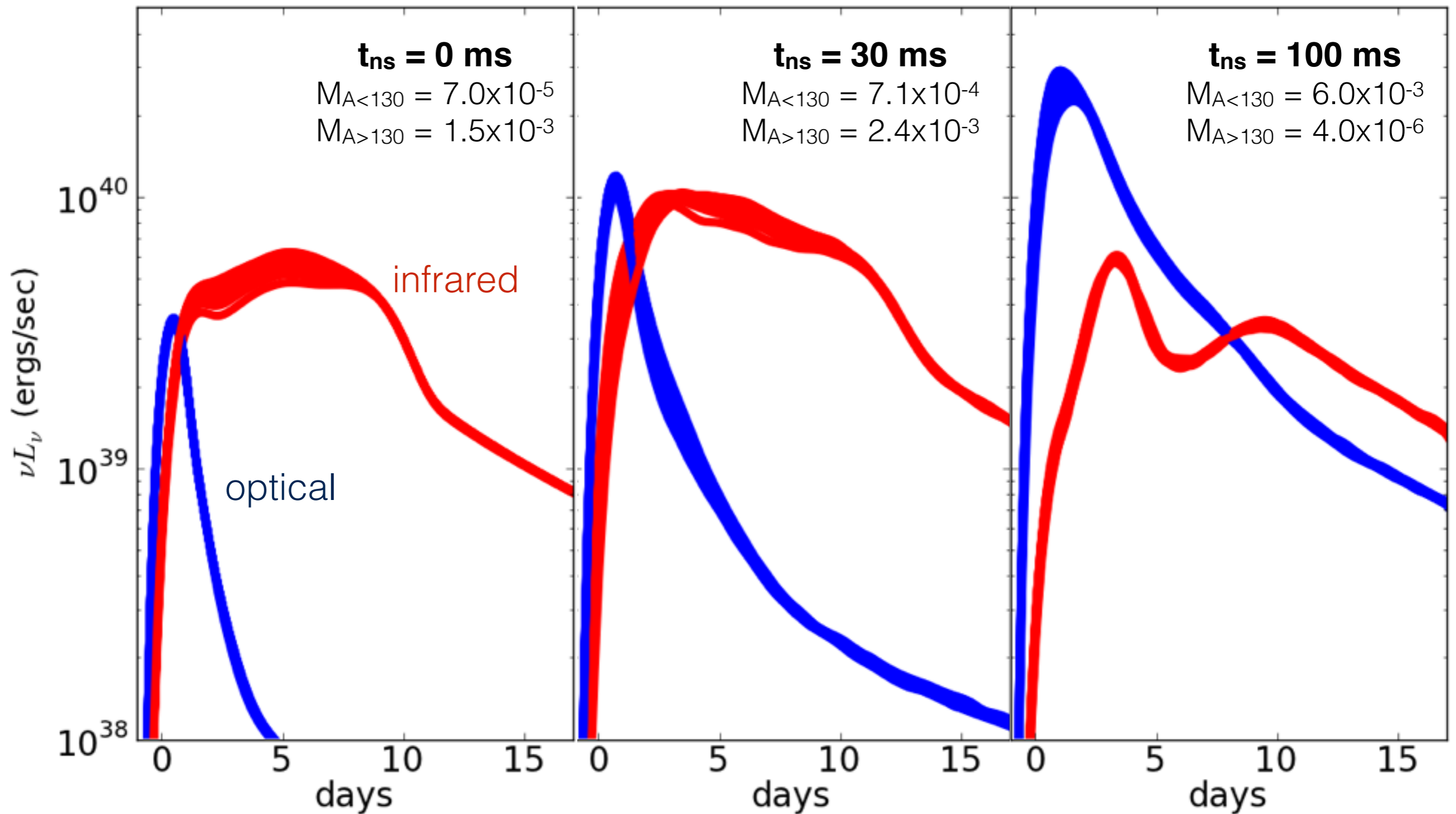


Y_e distribution of wind ejecta



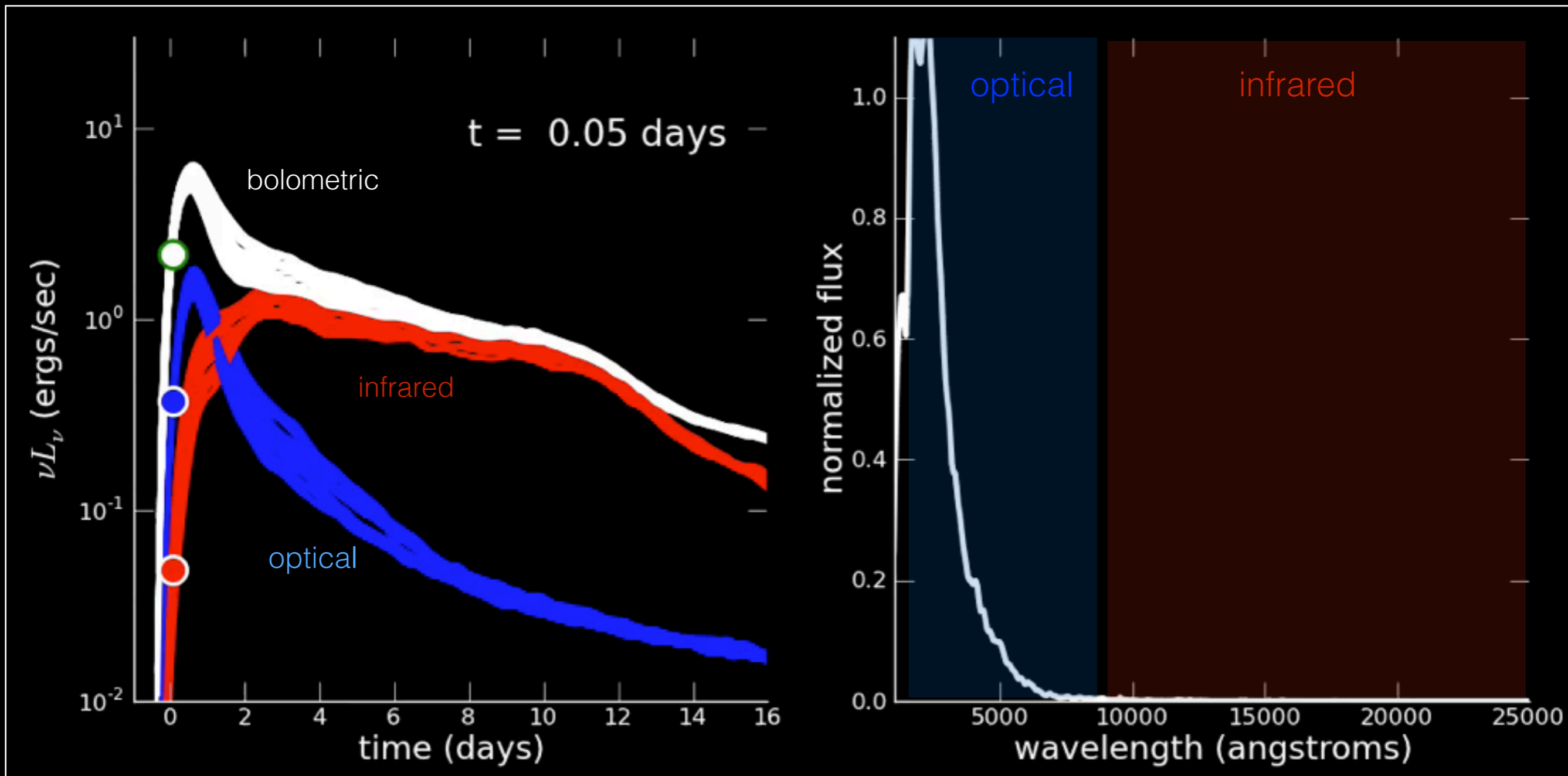
optical and infrared light curves of winds

multi-dimensional radiative transport calculations

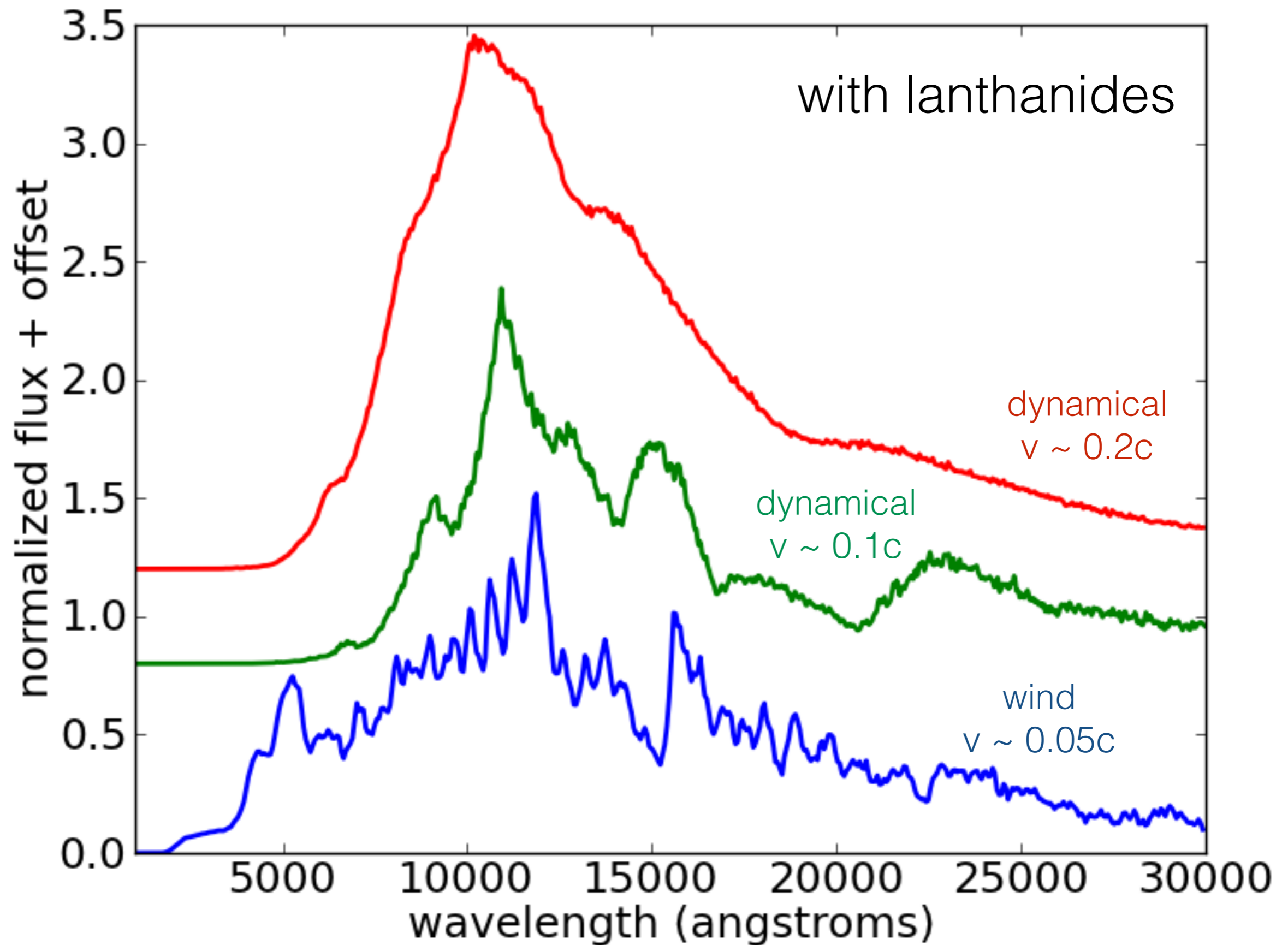


light curve and spectral evolution

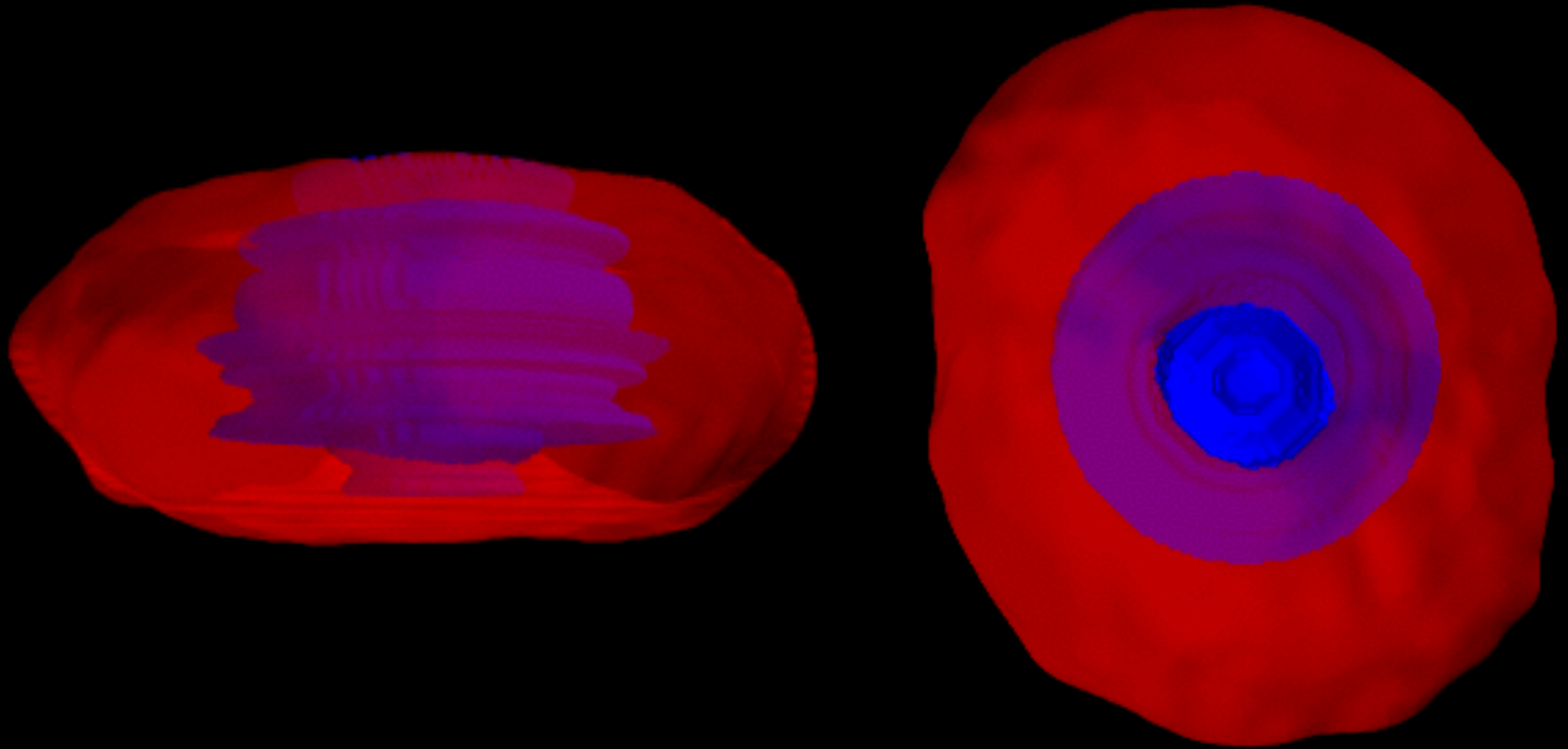
$$t_{\text{ns}} = 30 \text{ ms}$$



synthetic spectra of NS merger ejecta

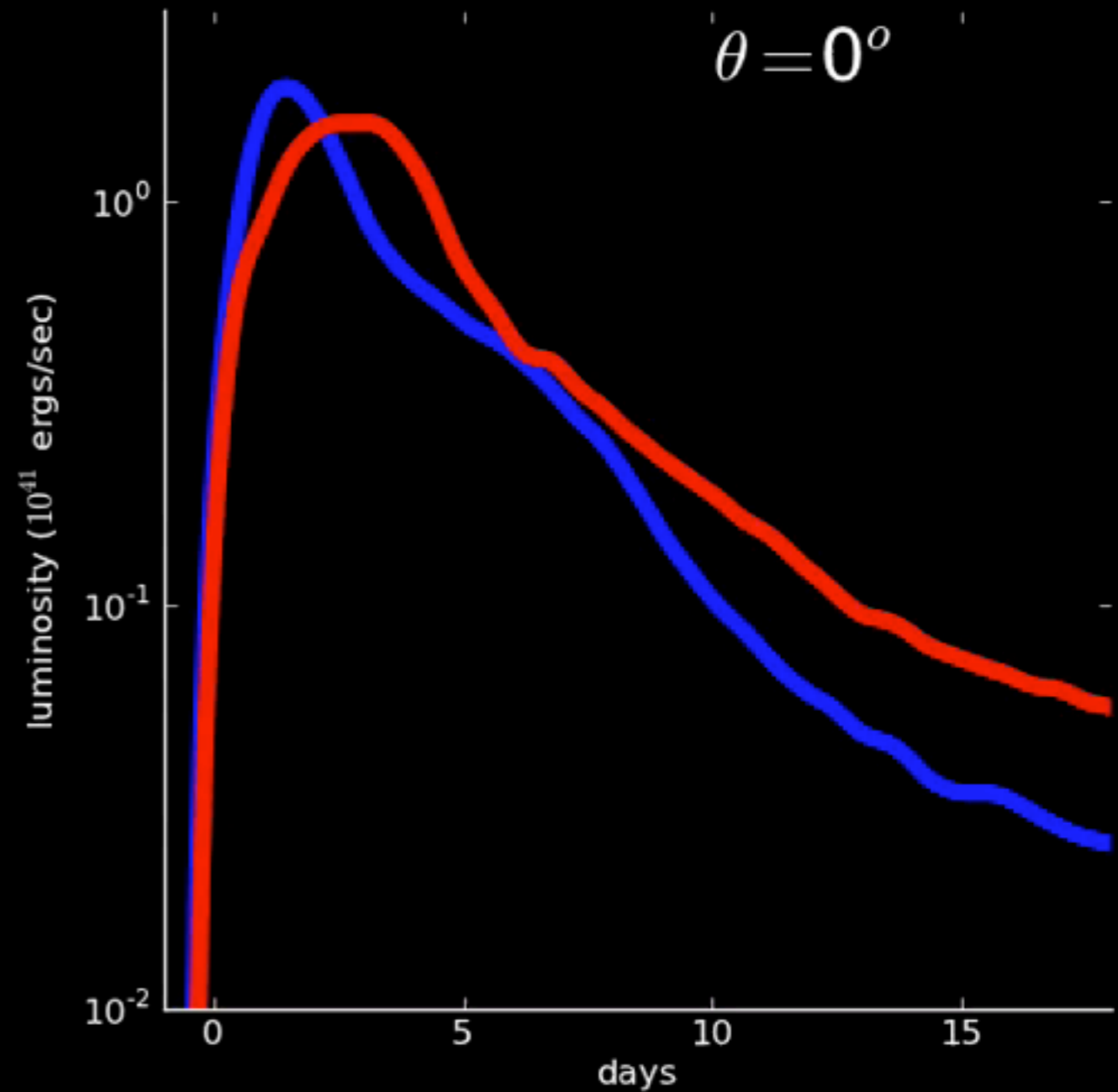
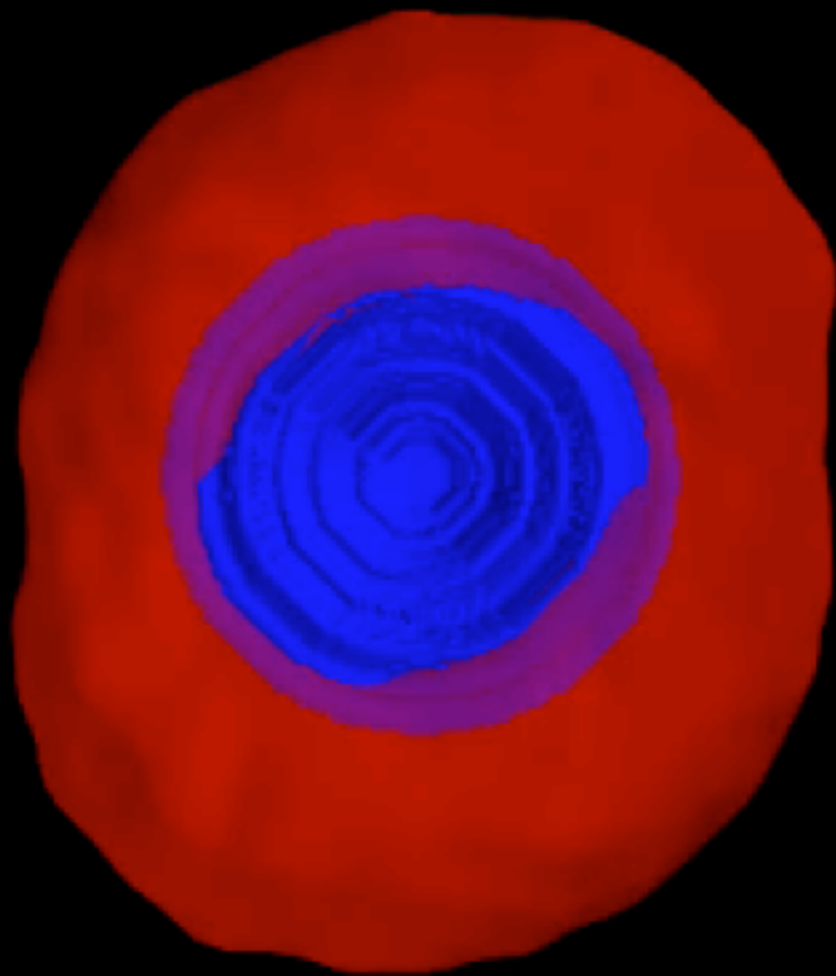


multiple ejecta components
disk wind inside dynamical ejecta



multiple ejecta components

t = 100 ms disk wind inside $10^{-2} M_{\text{sun}}$ 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