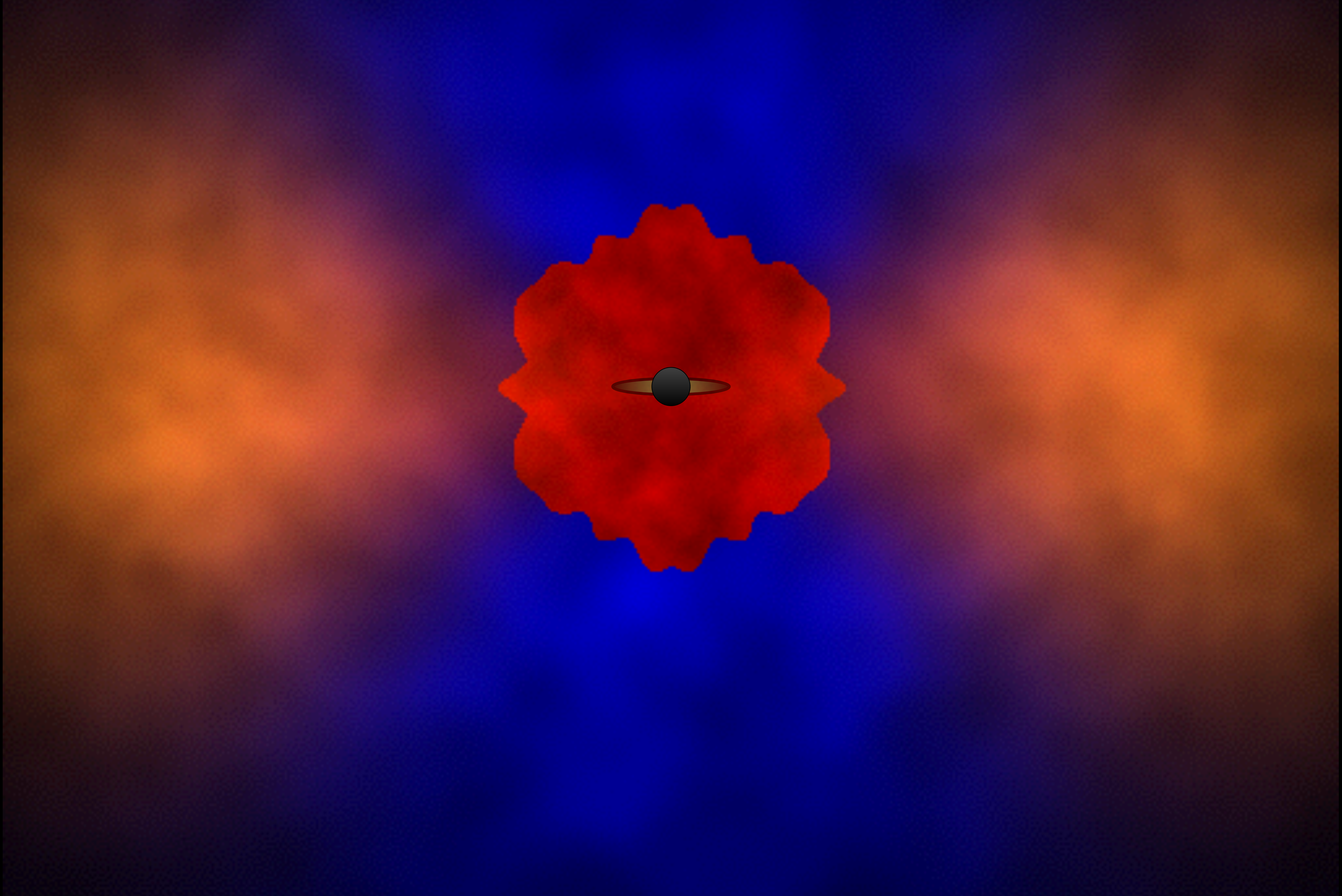
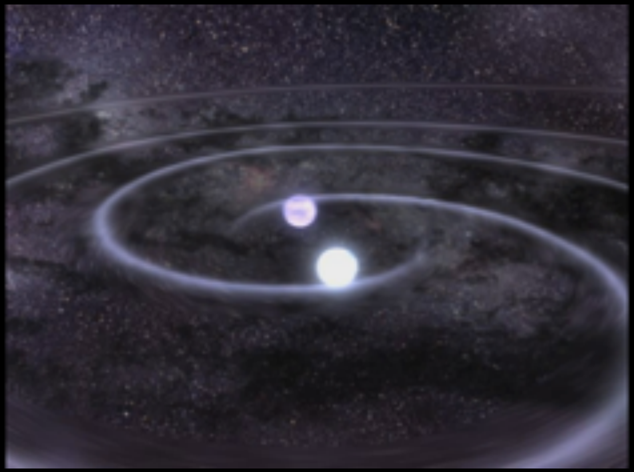
Gravitational Waves and Electromagnetic Signals from a Neutron Star Merger

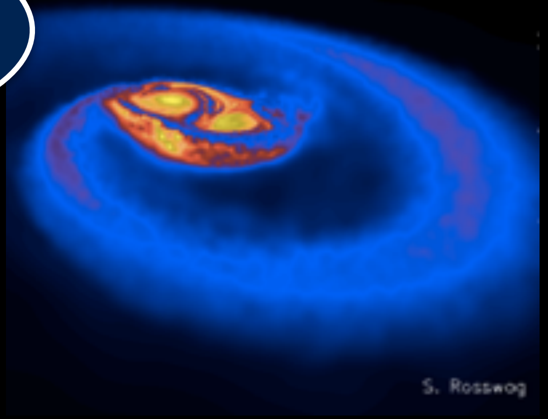


end-to-end physics of NS mergers



binary
evolut
(10^6-10^9 years)
Final inspiral
(minutes)

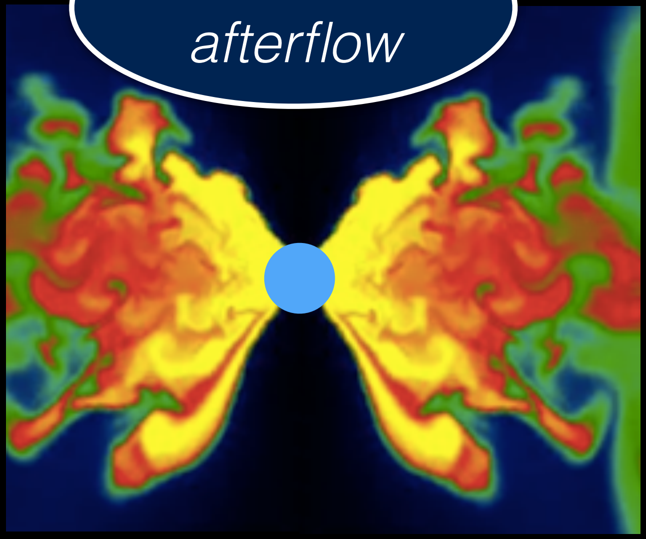
gravitational waves



merger dynamics
(miliseconds)

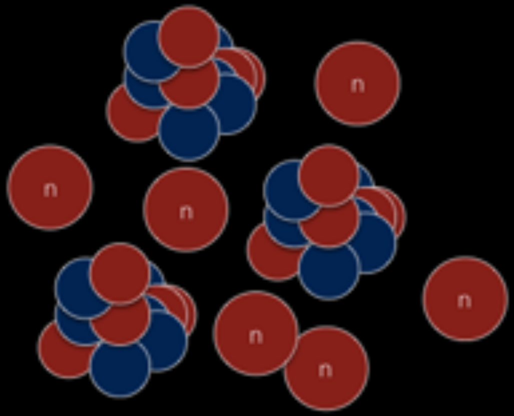
hydrodynamics, general relativity, nuclear equation of state, neutrino physics,

GRB + afterflow



post-merger accretion (seconds)

hydrodynamics, gravity, neutrino physics,nuclear reactions, magnetic fields



nucleosynthesis
(seconds)

r-process reaction networks, nuclear data inputs

radioactivity
(days-weeks)

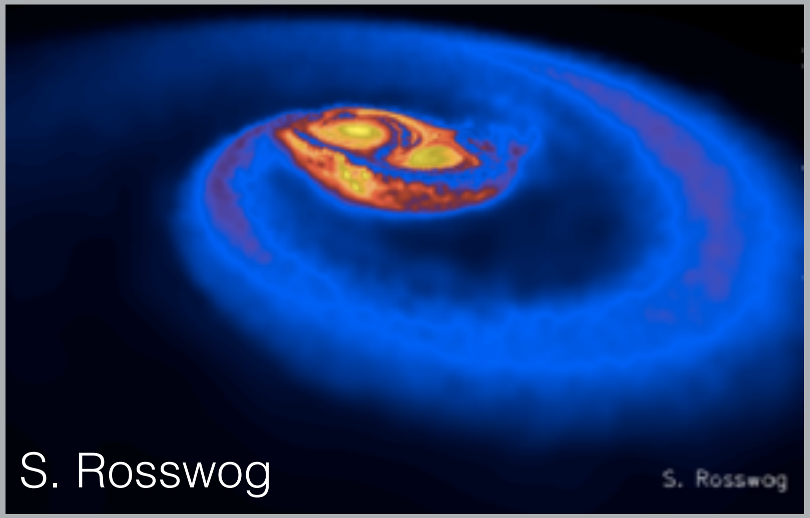
nuclear decay chains
(alpha, beta, gamma, fission)
thermalization

optical/IR "kilonova"

radiation transport
(days weeks)
Time-dependent spectral Boltzmann transport
Atomic microphysics

MERGER MASS EJECTION

dynamical
t ~ milliseconds

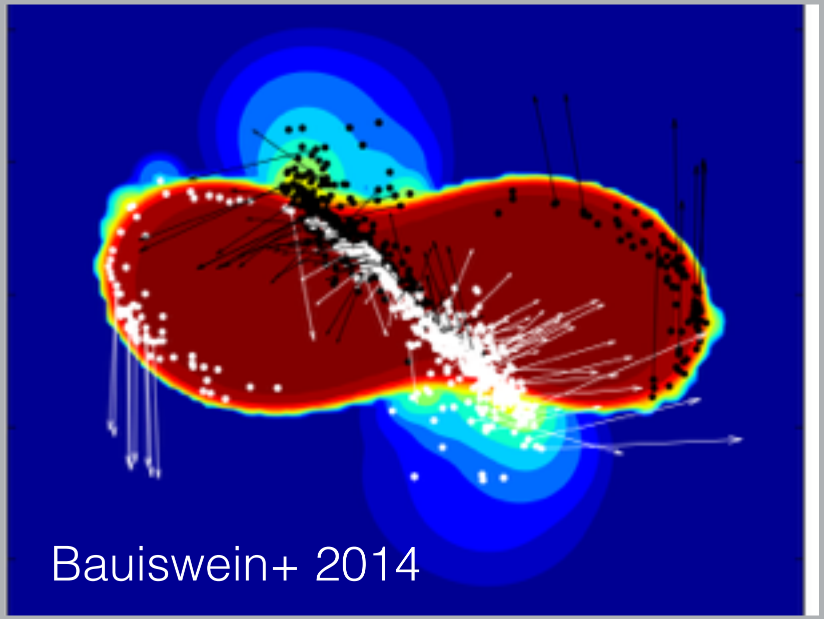

S. Rosswog

tidal tail ejecta

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

$v \sim 0.2c - 0.3c$

very neutron rich, $Y_e \lesssim 0.1$


Bauiswein+ 2014

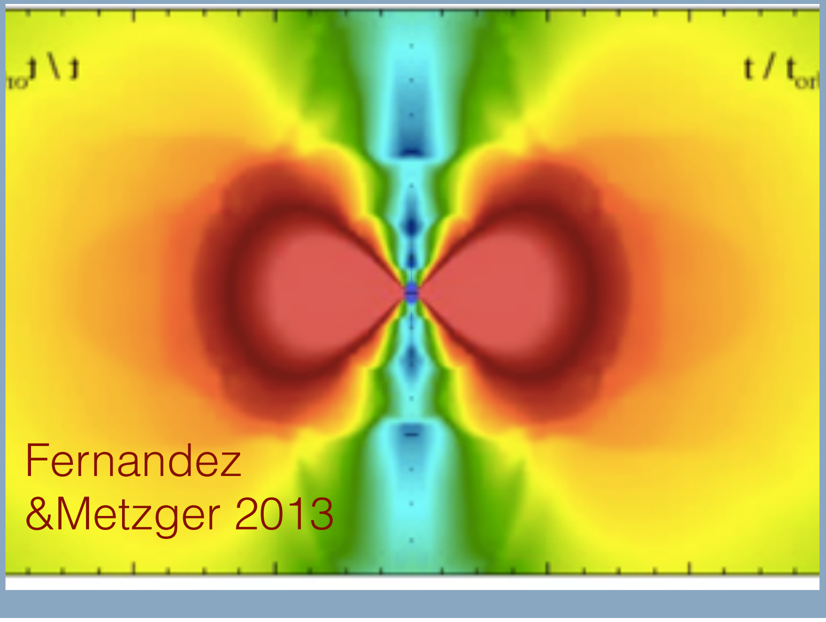
“squeezed” polar ejecta

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

$v \sim 0.2c - 0.3c$

less neutron rich $Y_e \gtrsim 0.25$

post-merger
t ~ seconds


Fernandez
&Metzger 2013

disk wind ejecta

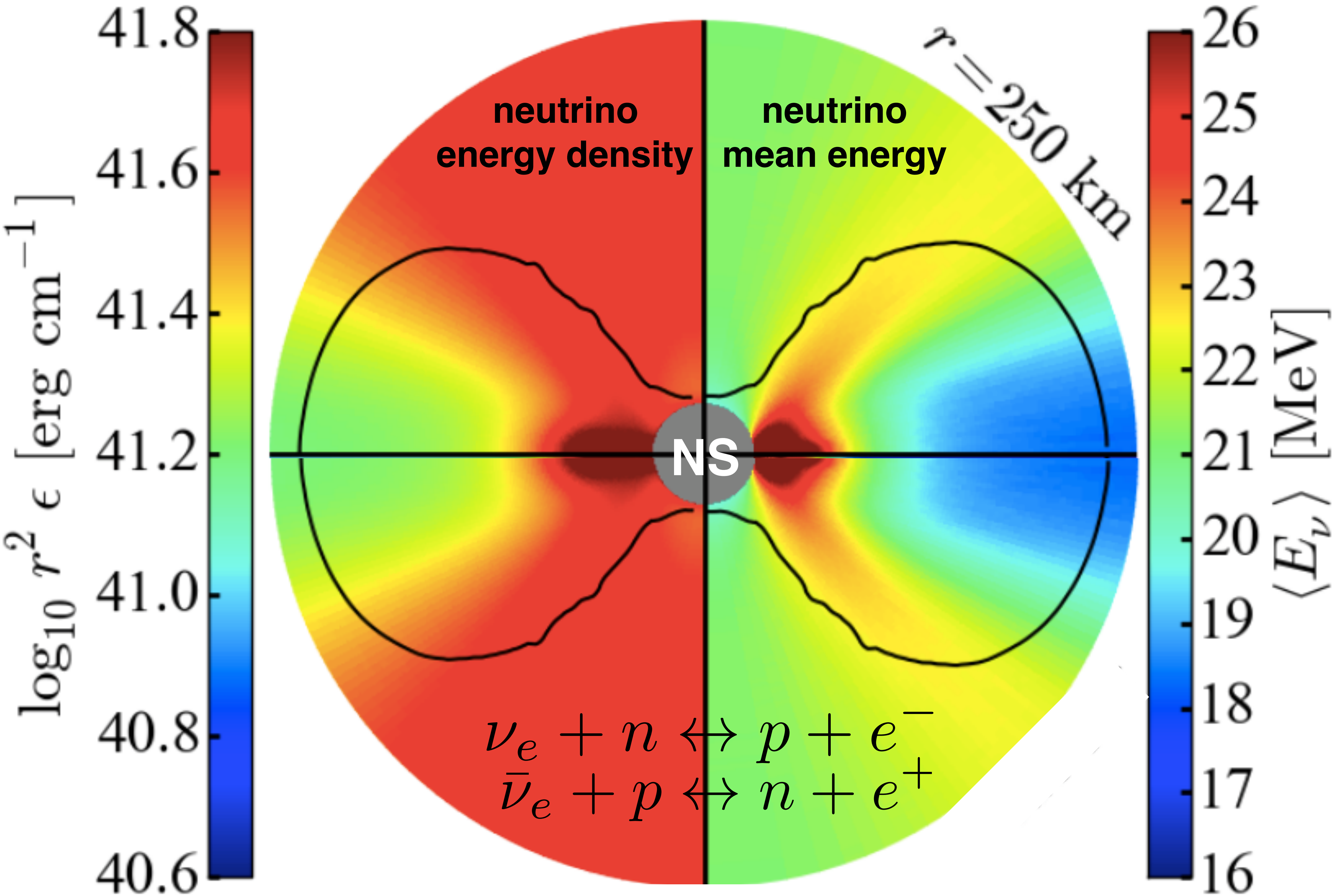
$M \sim 10^{-2} - 10^{-1}\ M_{sun}$

$v \sim 0.05c - 0.1c$

range of $Y_e = 0.1 - 0.4$

neutrino irradiation of NS merger ejecta

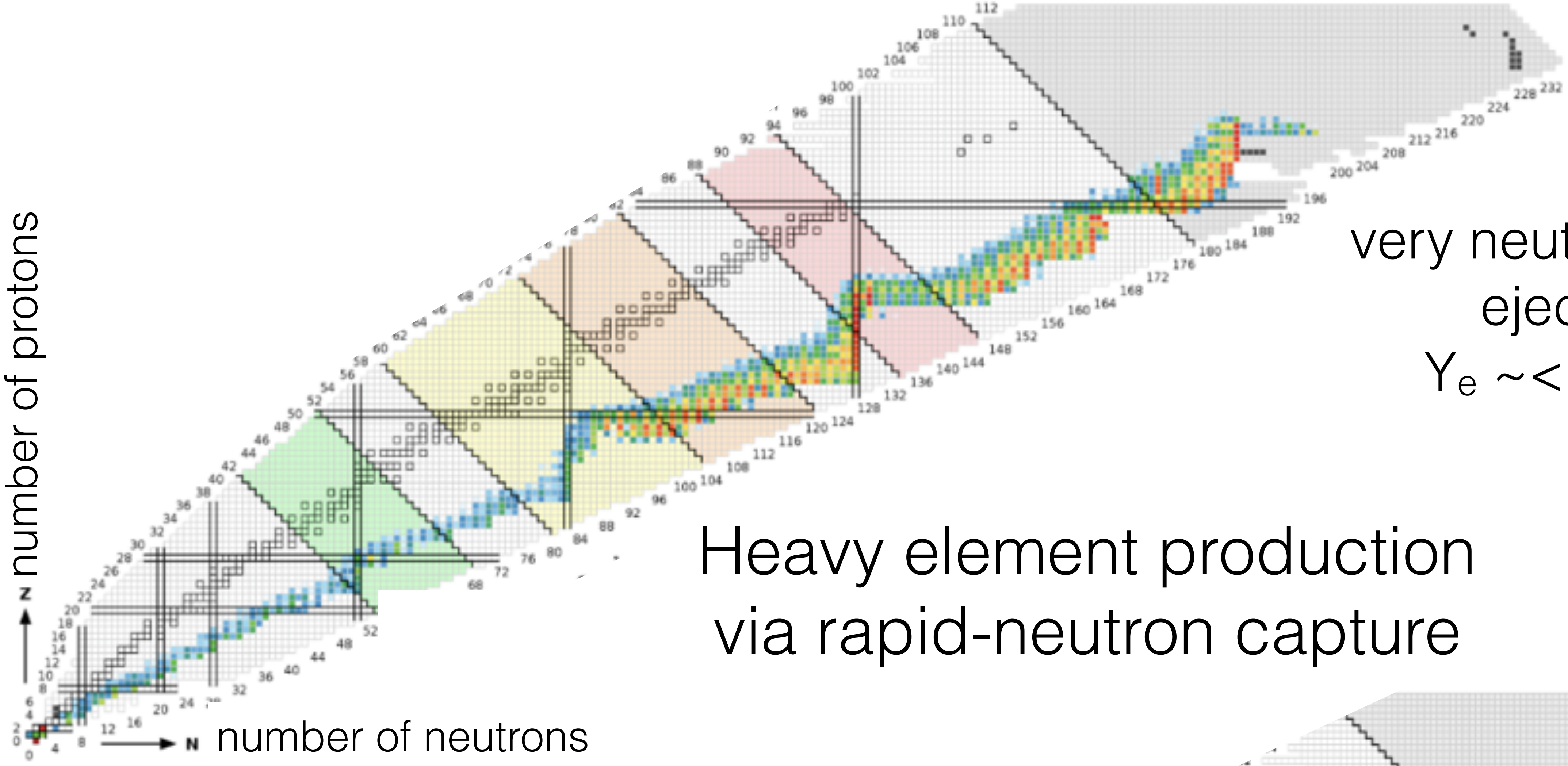
weak interactions drive Y_e closer to 0.5 (e.g., Metzger & Fernandez 2013)



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

richers, kasen, et al 2015

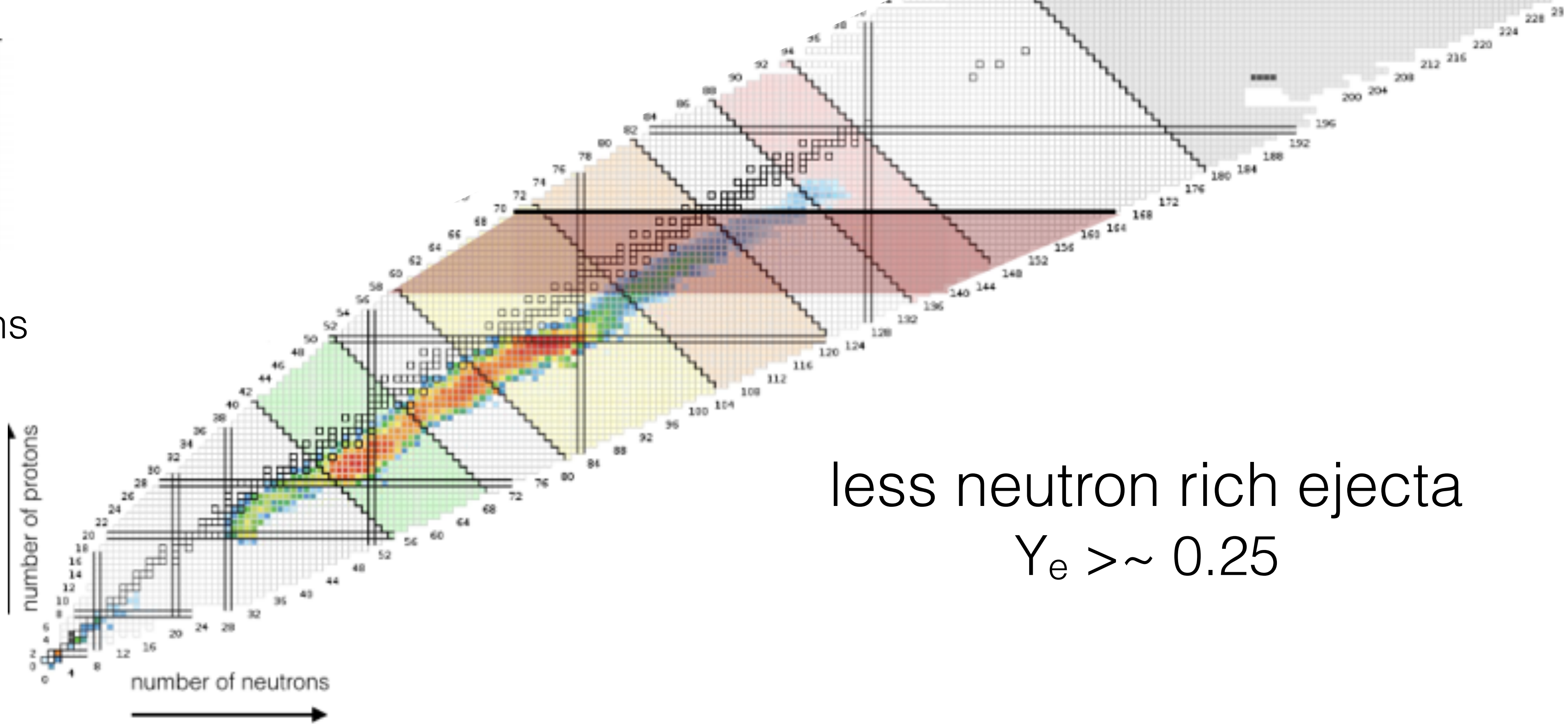
Heavy element production via rapid-neutron capture



very neutron rich ejecta
Y_e ~< 0.25

Sky Net
github.com/jlippuner/SkyNet

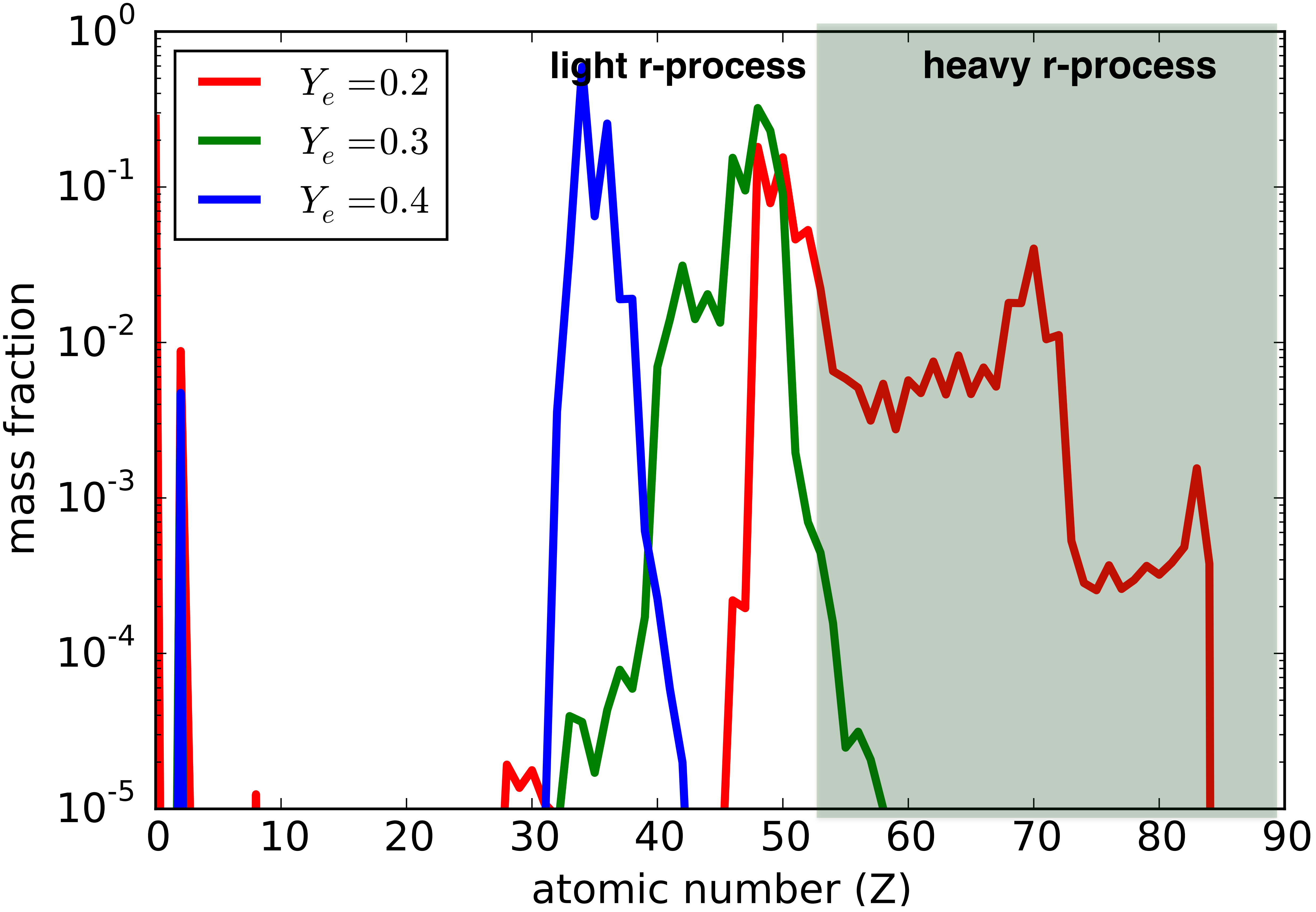
Nuclear reaction network calculations
Jonas Lippuner



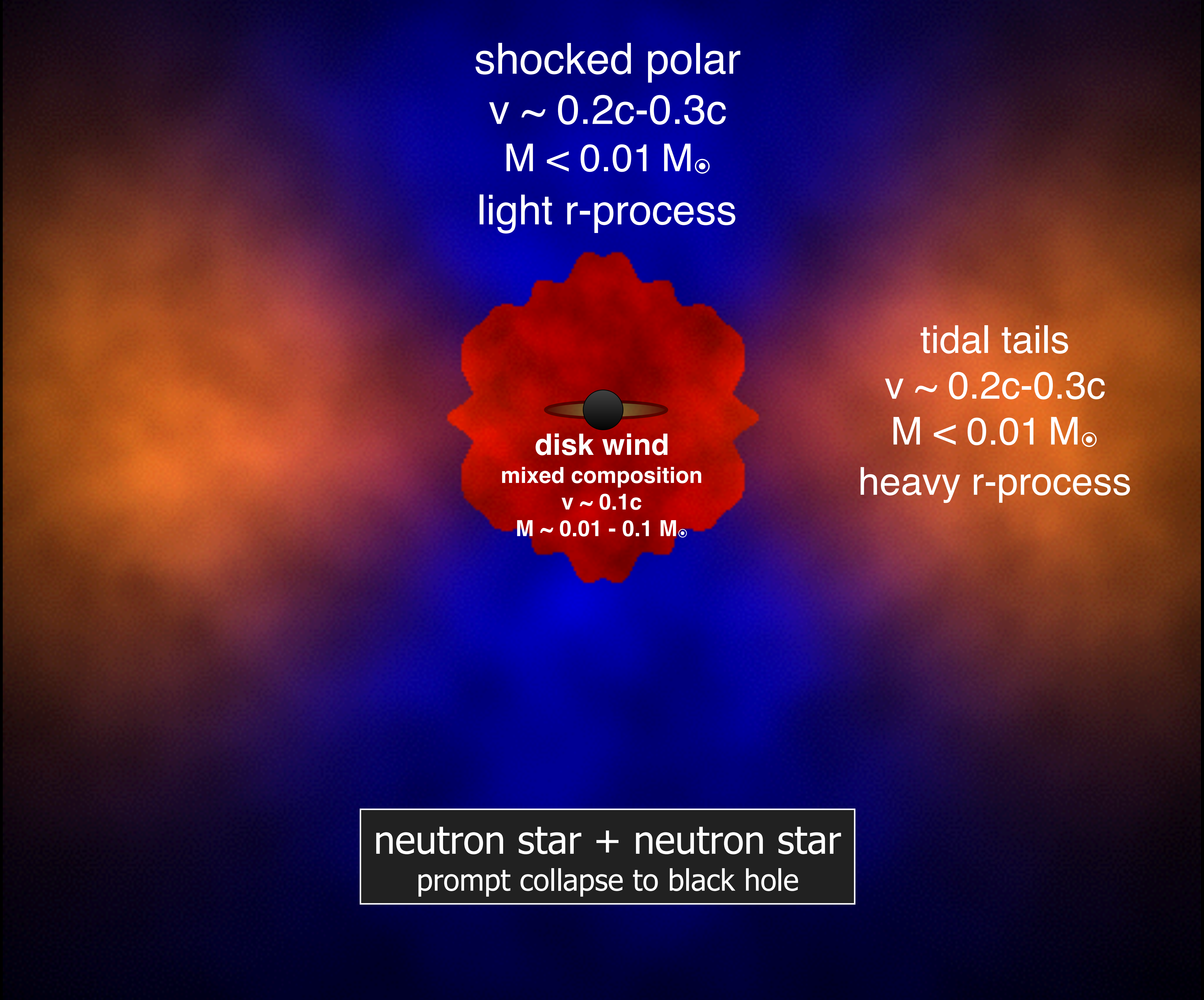
less neutron rich ejecta
Y_e >~ 0.25

Abundances from r-process nucleosynthesis

reaction networks calculations for fixed entropy & expansion time



Schematic view of NS merger ejecta



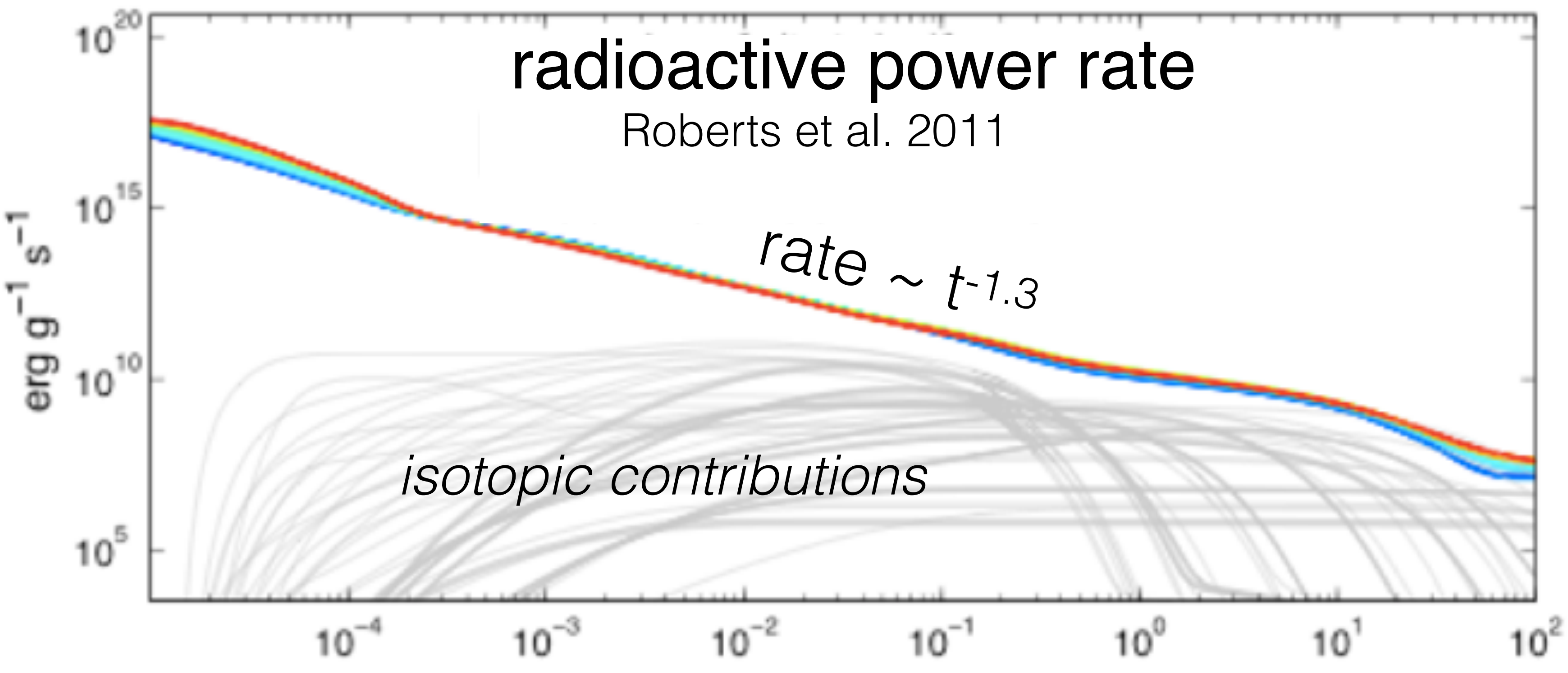
shocked polar
$v \sim 0.2c\text{-}0.3c$
$M < 0.01\ M_\odot$
light r-process

disk wind
mixed composition
$v \sim 0.1c$
$M \sim 0.01 - 0.1\ M_\odot$

tidal tails
$v \sim 0.2c\text{-}0.3c$
$M < 0.01\ M_\odot$
heavy r-process

neutron star + neutron star
prompt collapse to black hole

Radioactive decay and thermalization



radioactive power rate

Roberts et al. 2011

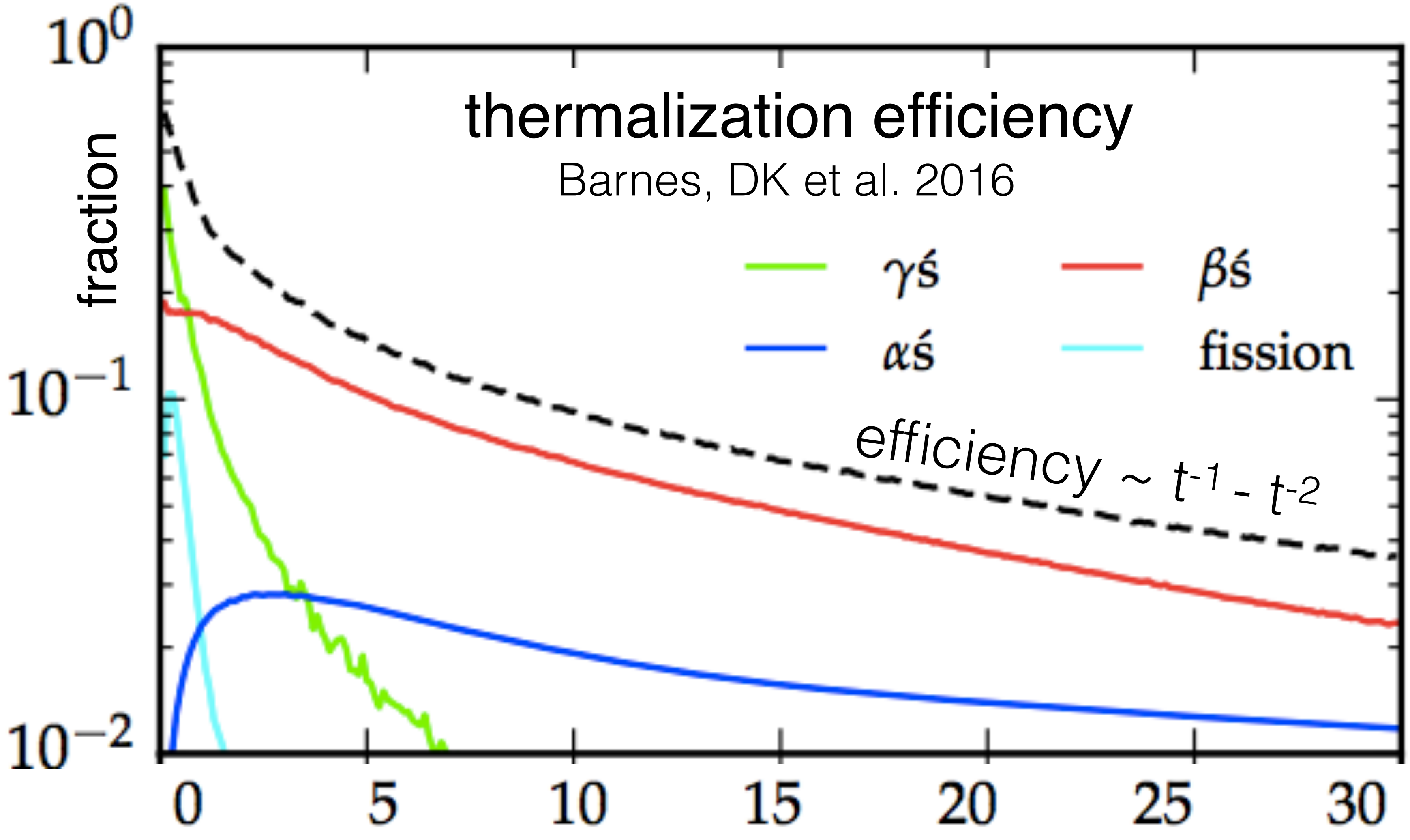
rate ~ $t^{-1.3}$

isotopic contributions

time in days

Radioactive power

Metzger+2010
Roberts+2011



thermalization efficiency

Barnes, DK et al. 2016

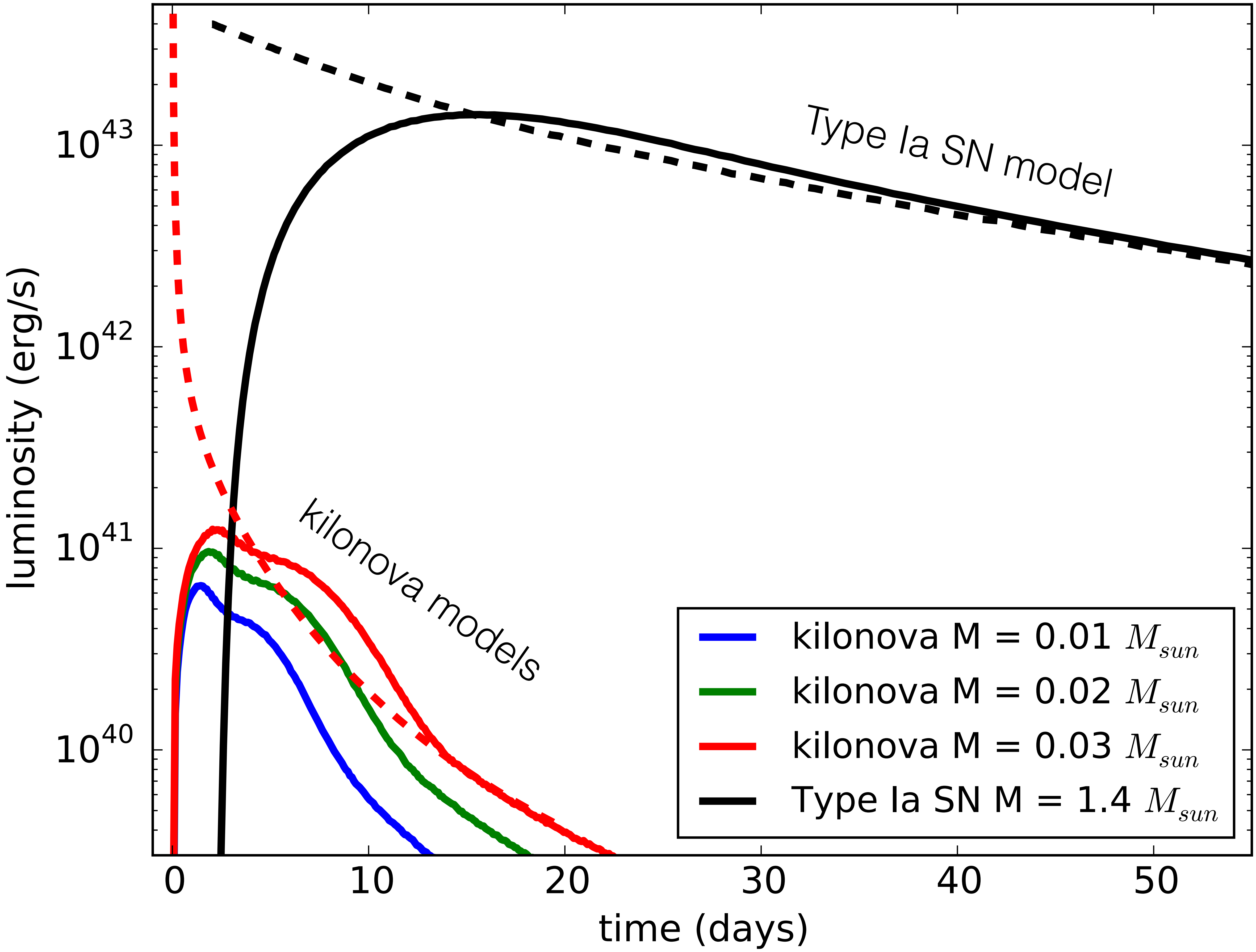
efficiency ~ t^{-1} - t^{-2}

time in days

Thermalization efficiency

Barnes, Kasen, Wu,
Martinez-Pineda 2016

Radioactive kilonova light curve models



modeling kilonova light curves and spectra

solution to the radiation transport (Boltzmann) equation

$$\boxed{\frac{1}{c}\frac{dI_\nu}{dt} + \frac{dI_\nu}{ds} = \underset{\substack{\uparrow \\ \text{absorption}}}{-\chi_{\rm abs} I_\nu} + \underset{\substack{\uparrow \\ \text{emission}}}{\eta} + \frac{\chi_{\rm sc}}{4\pi} \underset{\substack{\uparrow \\ \text{scattering}}}{\oint I_\nu d\Omega'}}$$

$I_\nu(x, y, z, \nu, \theta, \phi, t)$ = photon field specific intensity

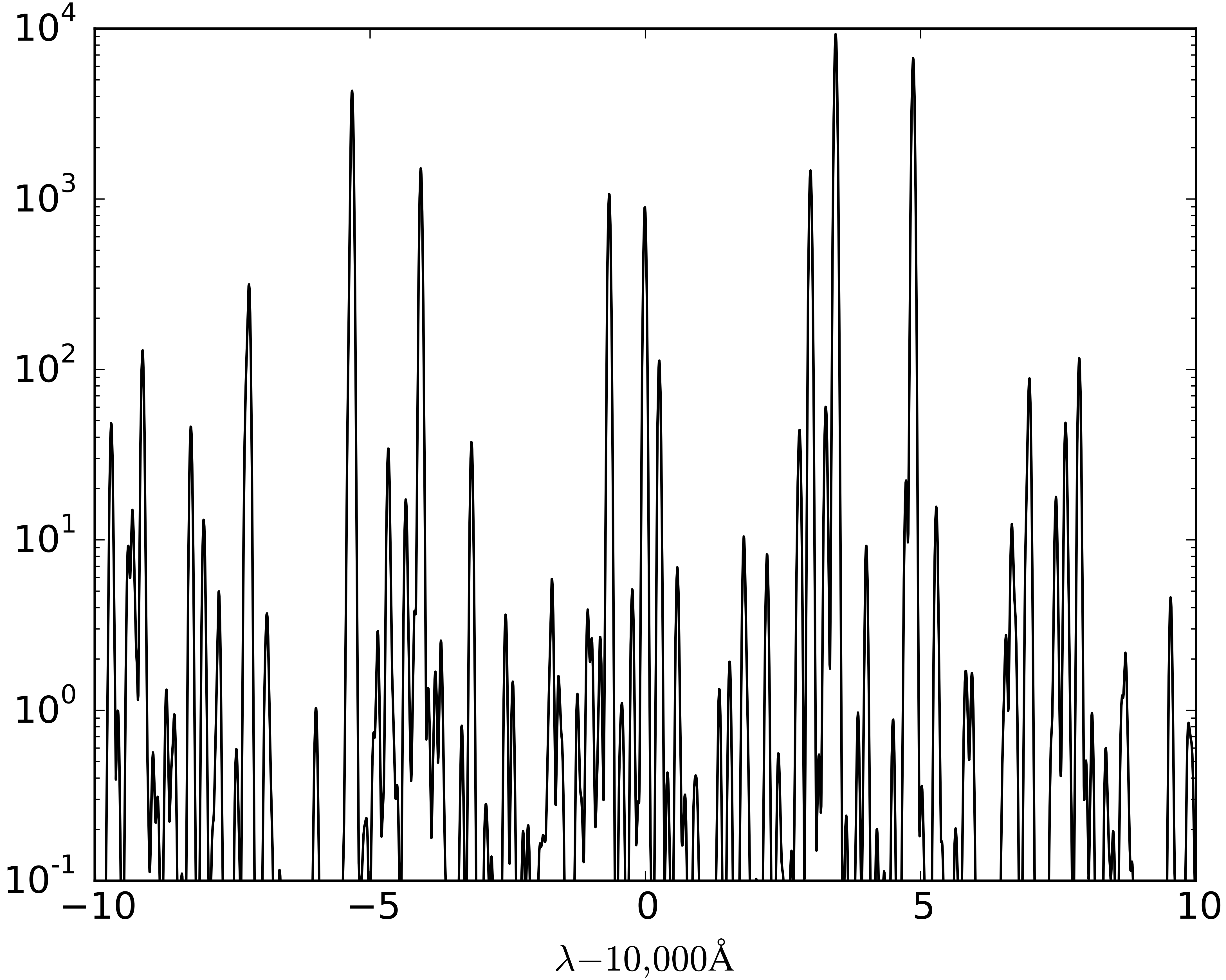
$\chi(x, y, z, \nu, t)$ = opacity coefficient

$\eta(x, y, z, \nu, t)$ = emissivity

χ and η set primarily by numerous blended atomic line transitions
depends on ionization/excitation state of gas
(level populations assumed to be local thermodynamic equilibrium)

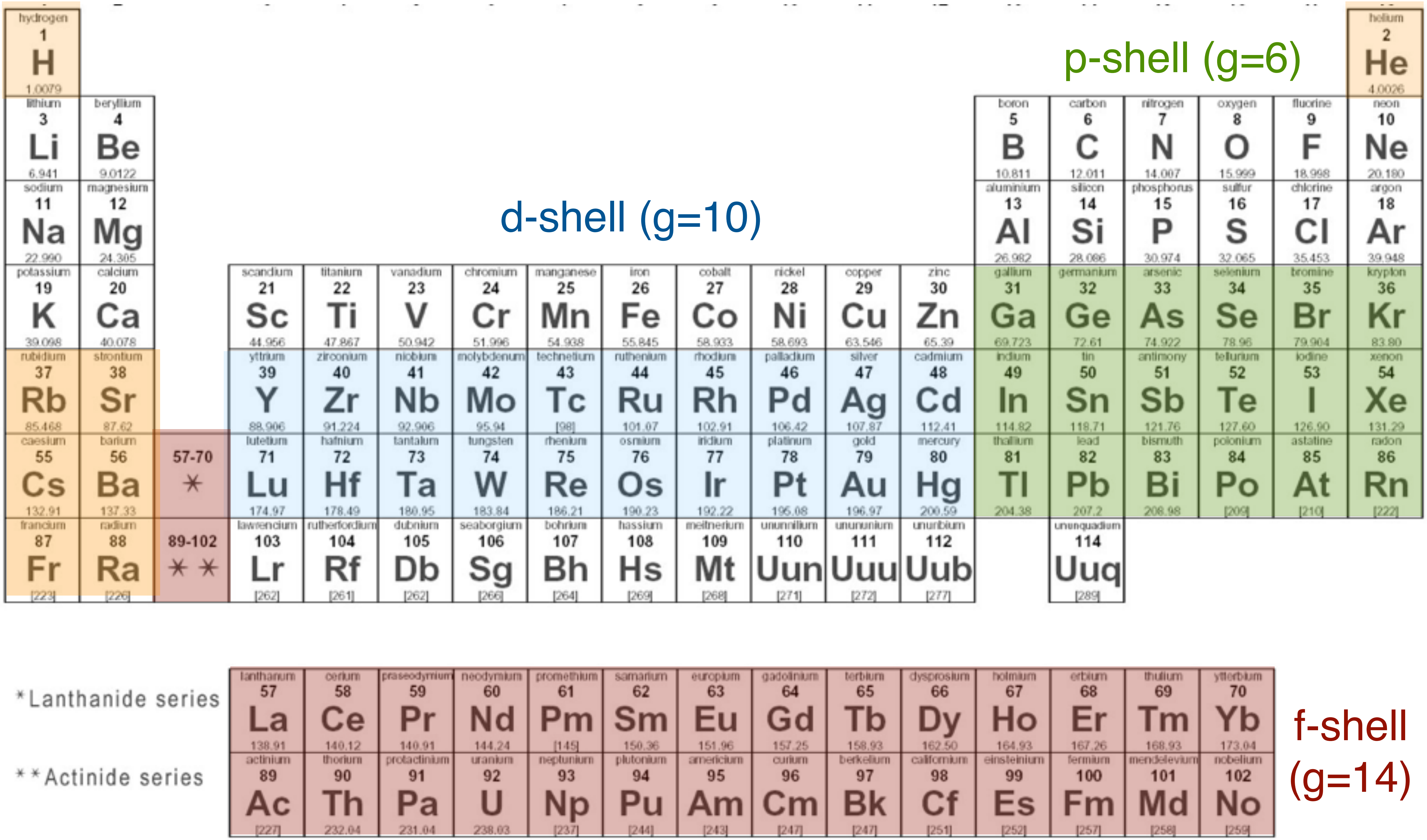
Transport solved by Monte Carlo methods (Sedona code)
e.g,. Kasen+2006, Roth and Kasen (2015)

opacity of r-process kilonova ejecta



r-process opacity and atomic complexity

limited experimental line data
requires atomic structure modeling



s-shell (g=2)

p-shell (g=6)

d-shell (g=10)

f-shell (g=14)

hydrogen 1 H 1.0079																		helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122												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
sodium 11 Na 22.990	magnesium 12 Mg 24.305												aluminium 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
potassium 19 K 39.098	calcium 20 Ca 40.078		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	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
rubidium 37 Rb 85.468	strontium 38 Sr 87.62		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	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
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	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	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]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 * *	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]	ununnilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]				

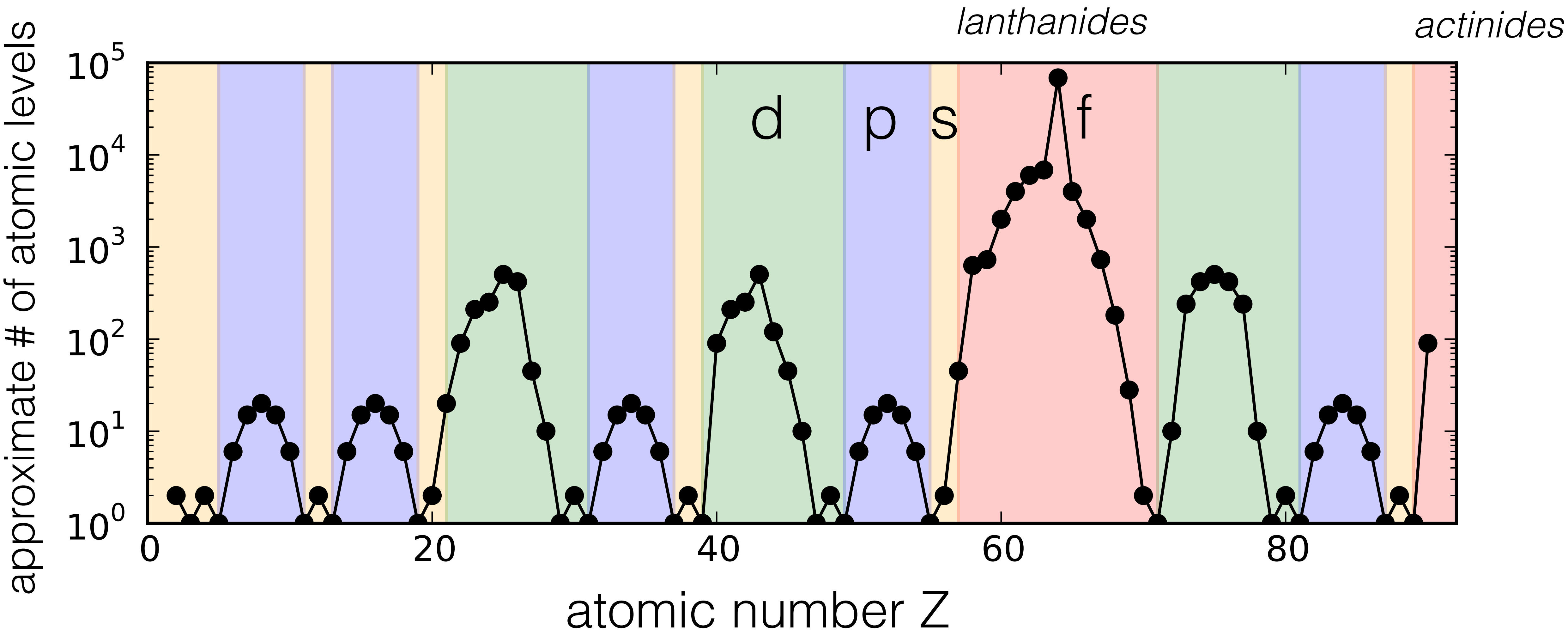
*Lanthanide series	lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
* *Actinide series	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]

r-process opacity and atomic complexity

Half-filled shells have more complex configurations

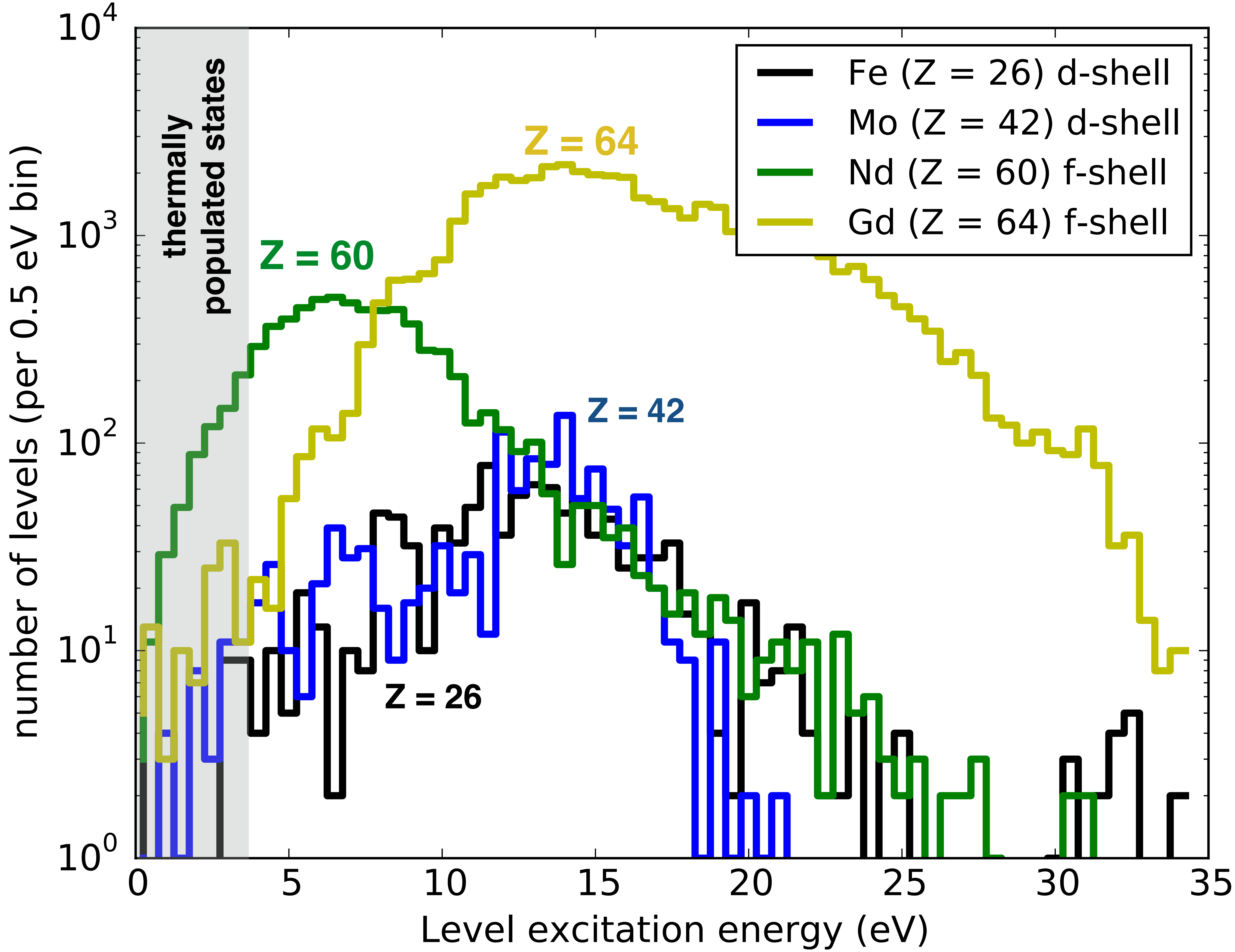
Atomic line/level data is still sparse (especially in infrared)

New atomic-structure calculations cover the statistical properties of all r-process species but uncertainties remain in details (kasen+ in prep)

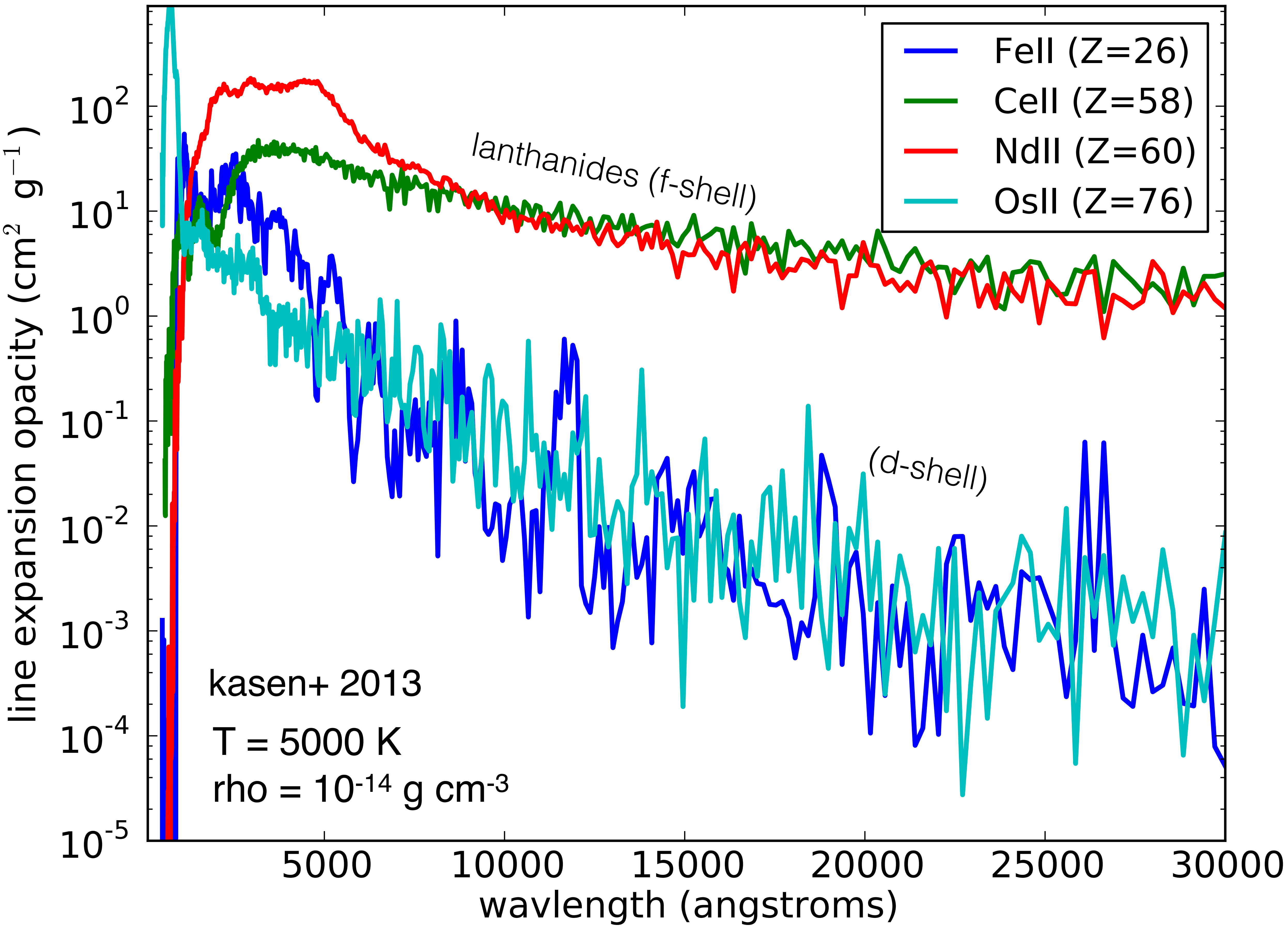


Level energy distributions - singly ionized species

atomic structure calculations of all r-process species w/ autostructure code

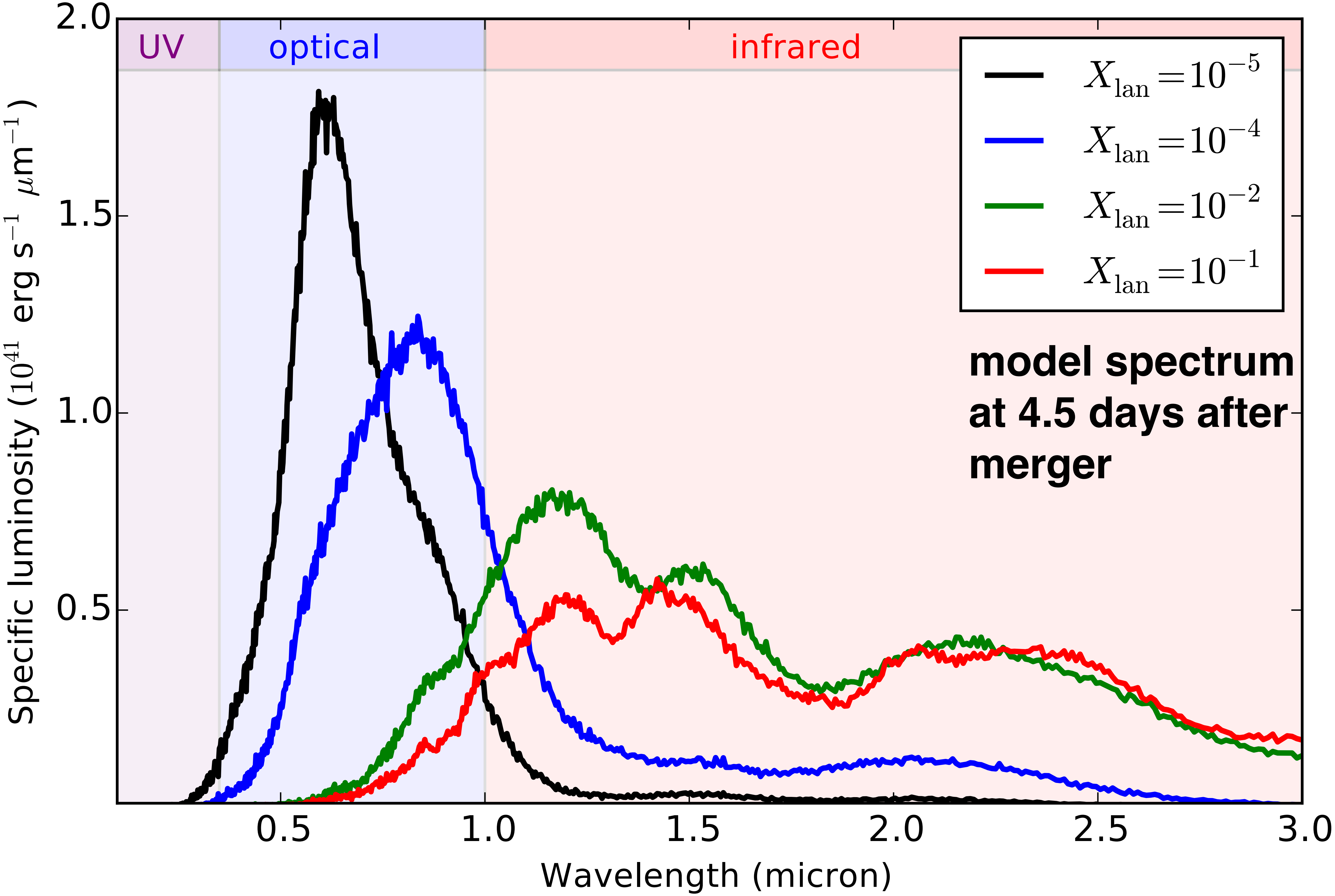


kilonova opacity from atomic structure modeling



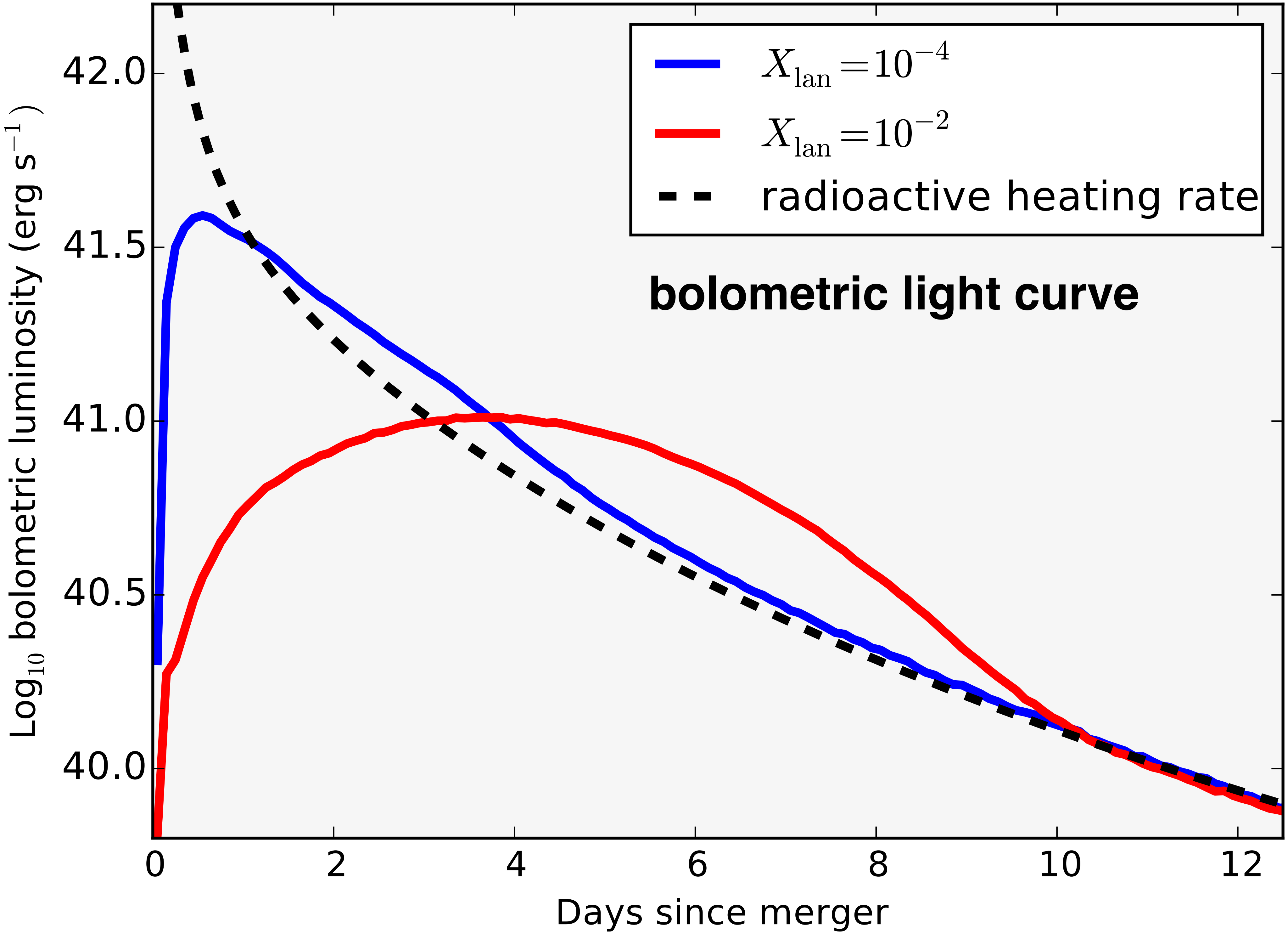
Model kilonova spectra
dependence on lanthanide fraction

kasen, badnell and barnes 2013, barnes & kasen 2013, kasen+2017



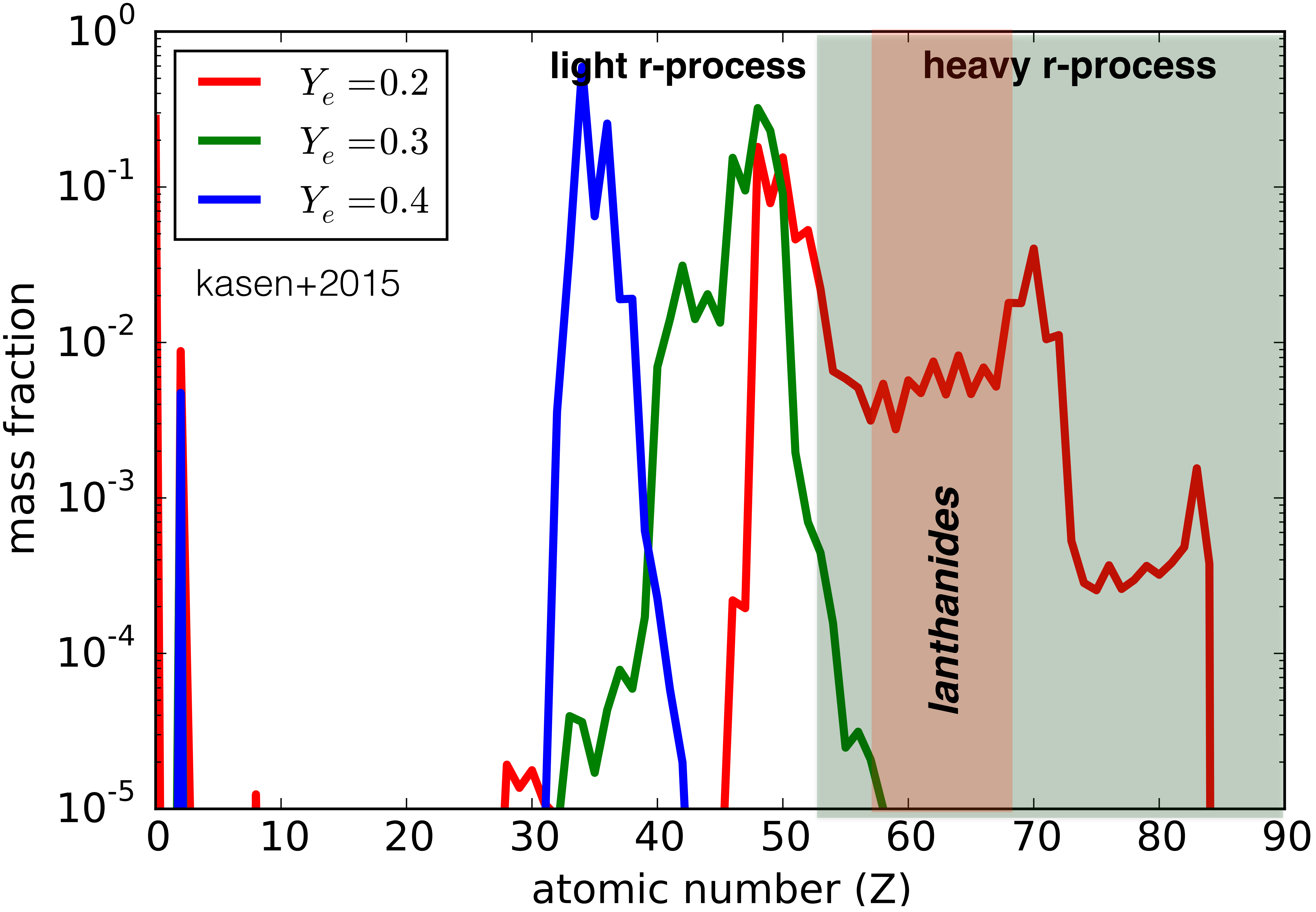
Model kilonova light curves: dependence on lanthanide fraction

kasen, badnell and barnes 2013, barnes & kasen 2013, kasen+2017

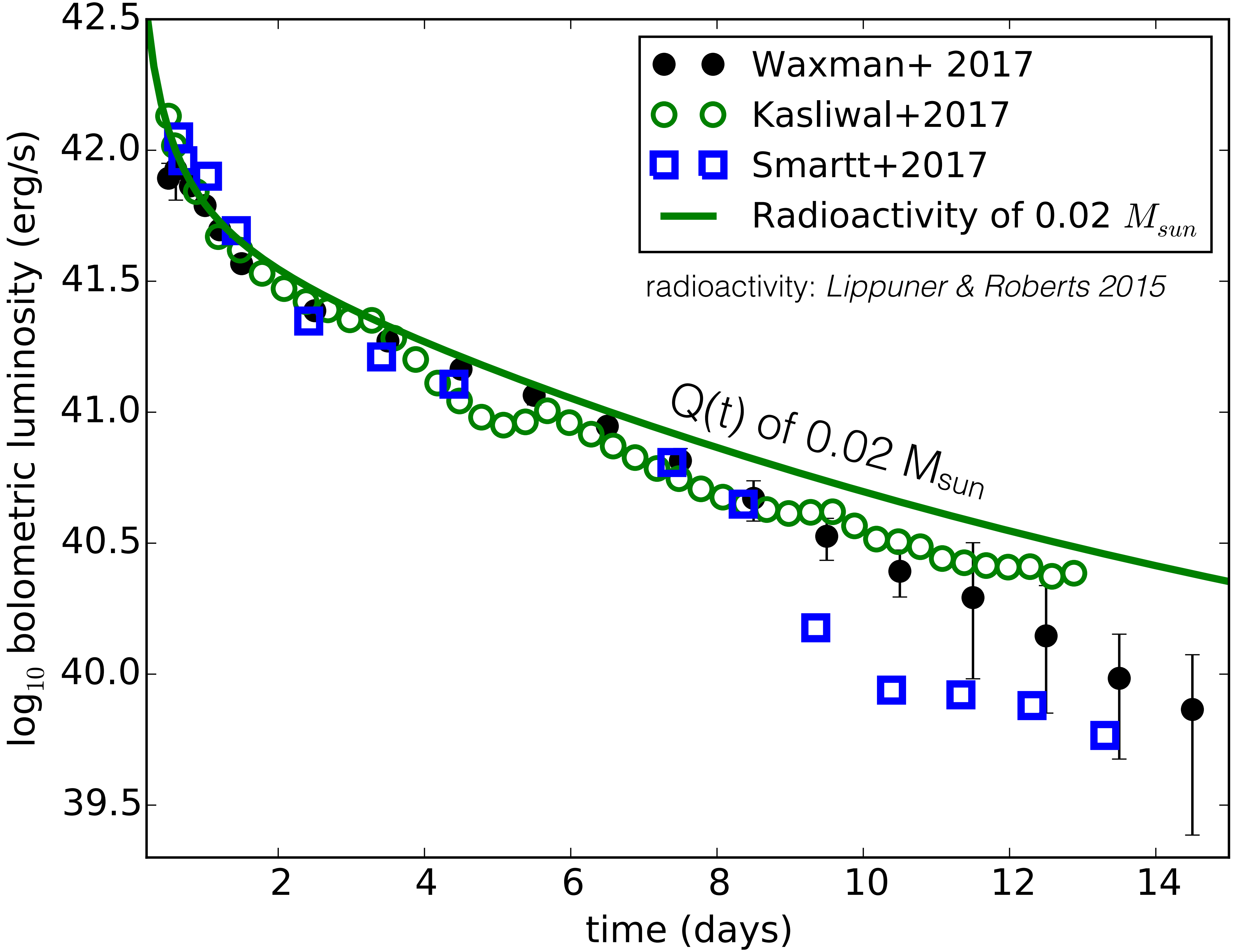


Abundances from r-process nucleosynthesis

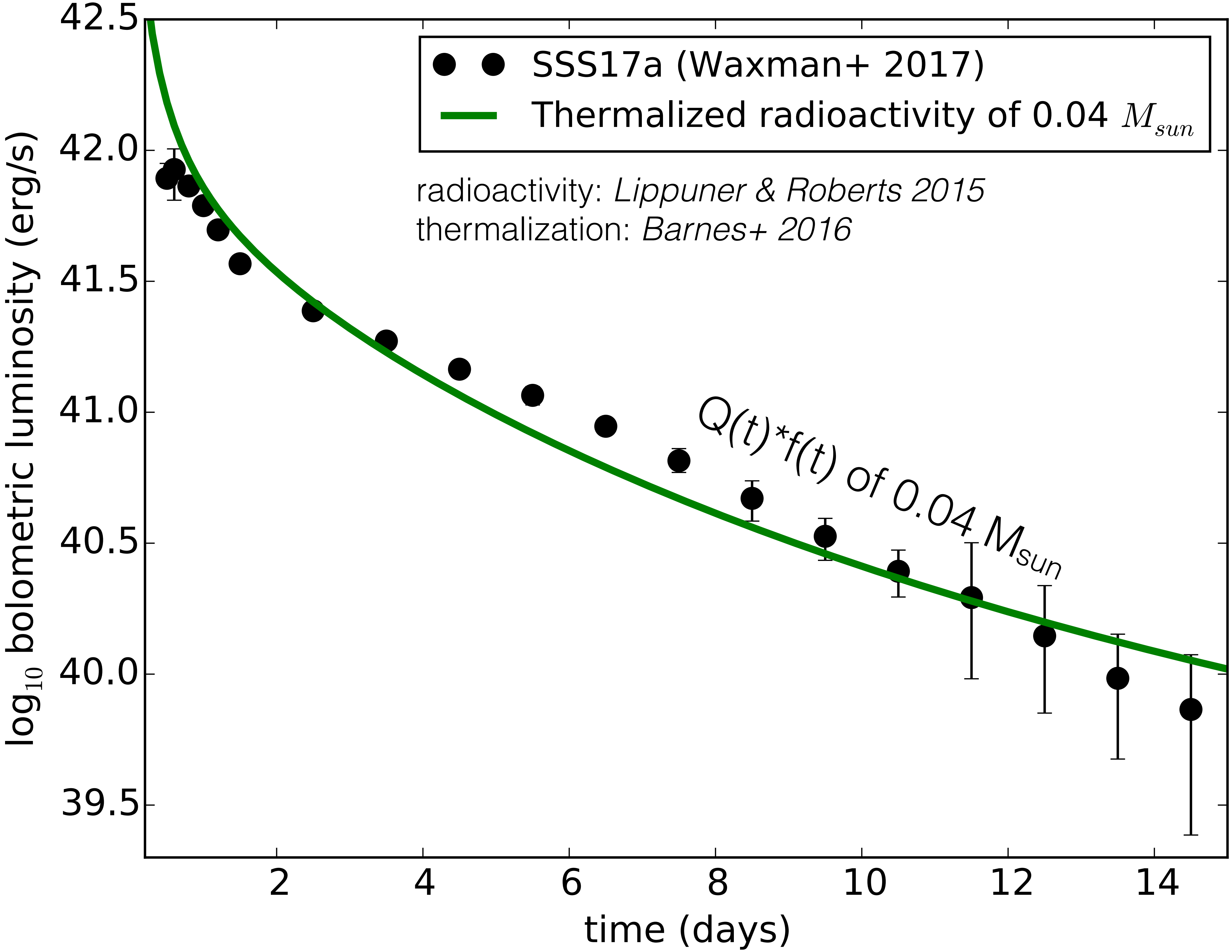
reaction networks calculations for fixed entropy & expansion time



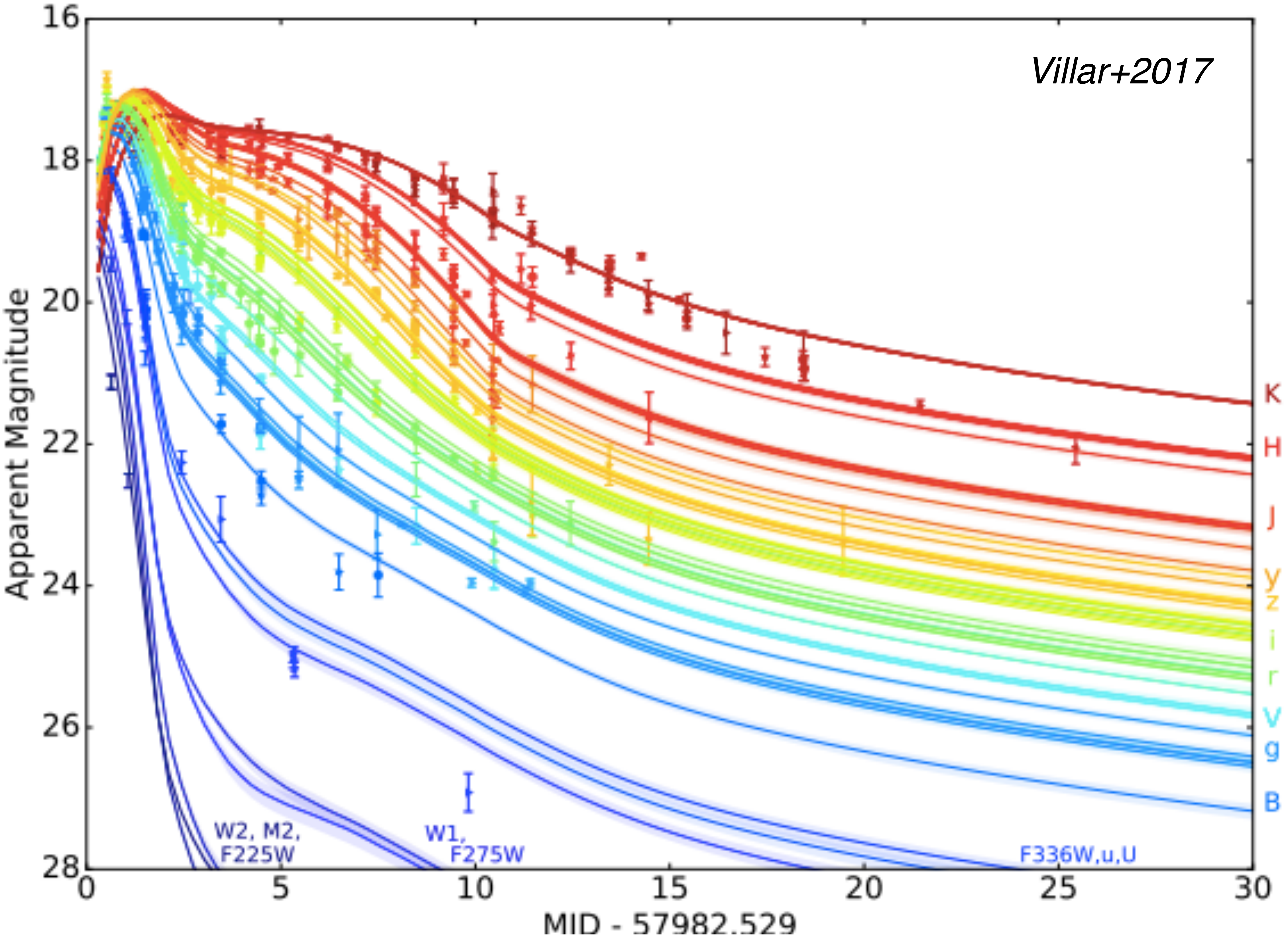
kilonova SSS17a bolometric light curve



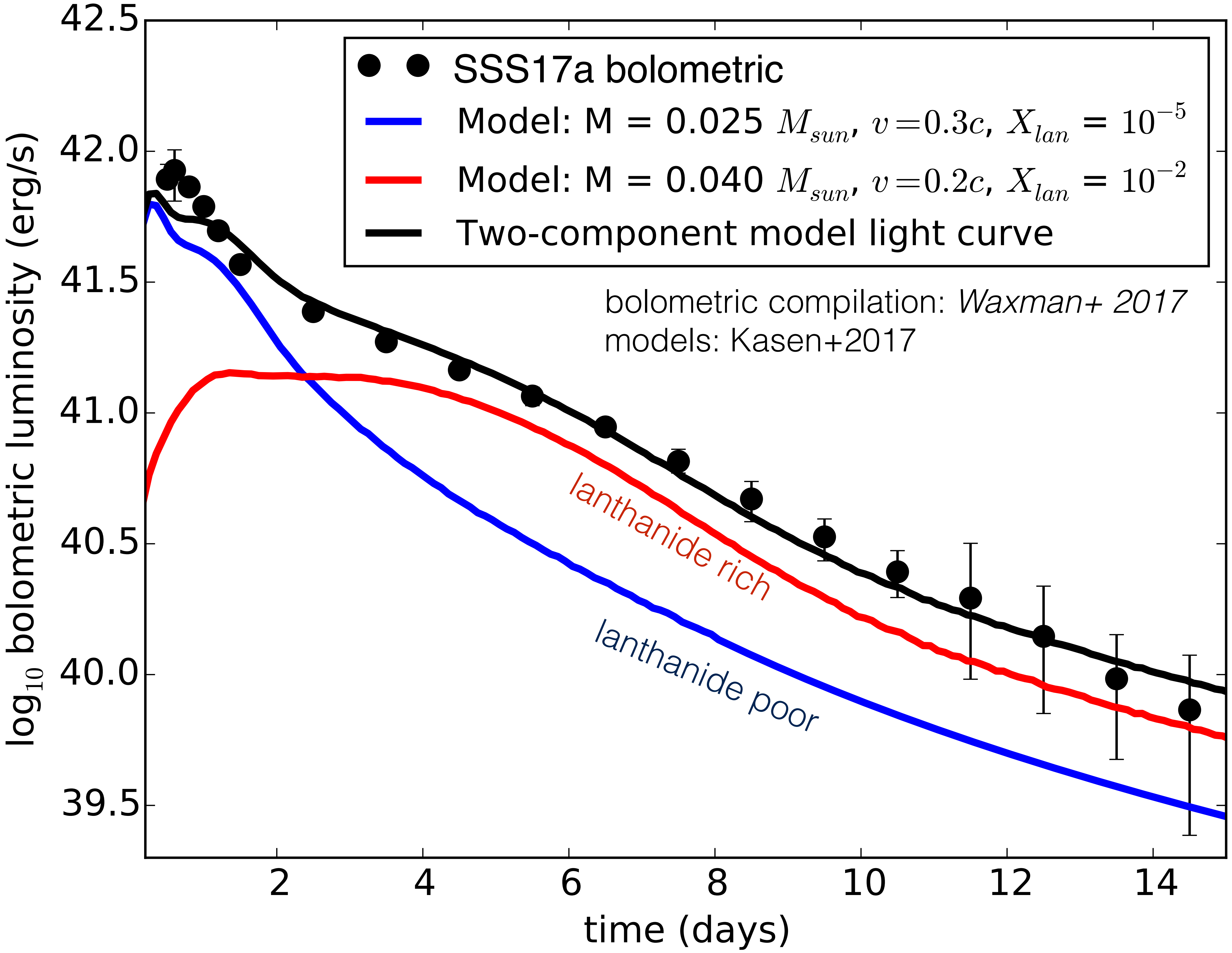
kilonova AT2017gfo bolometric light curve



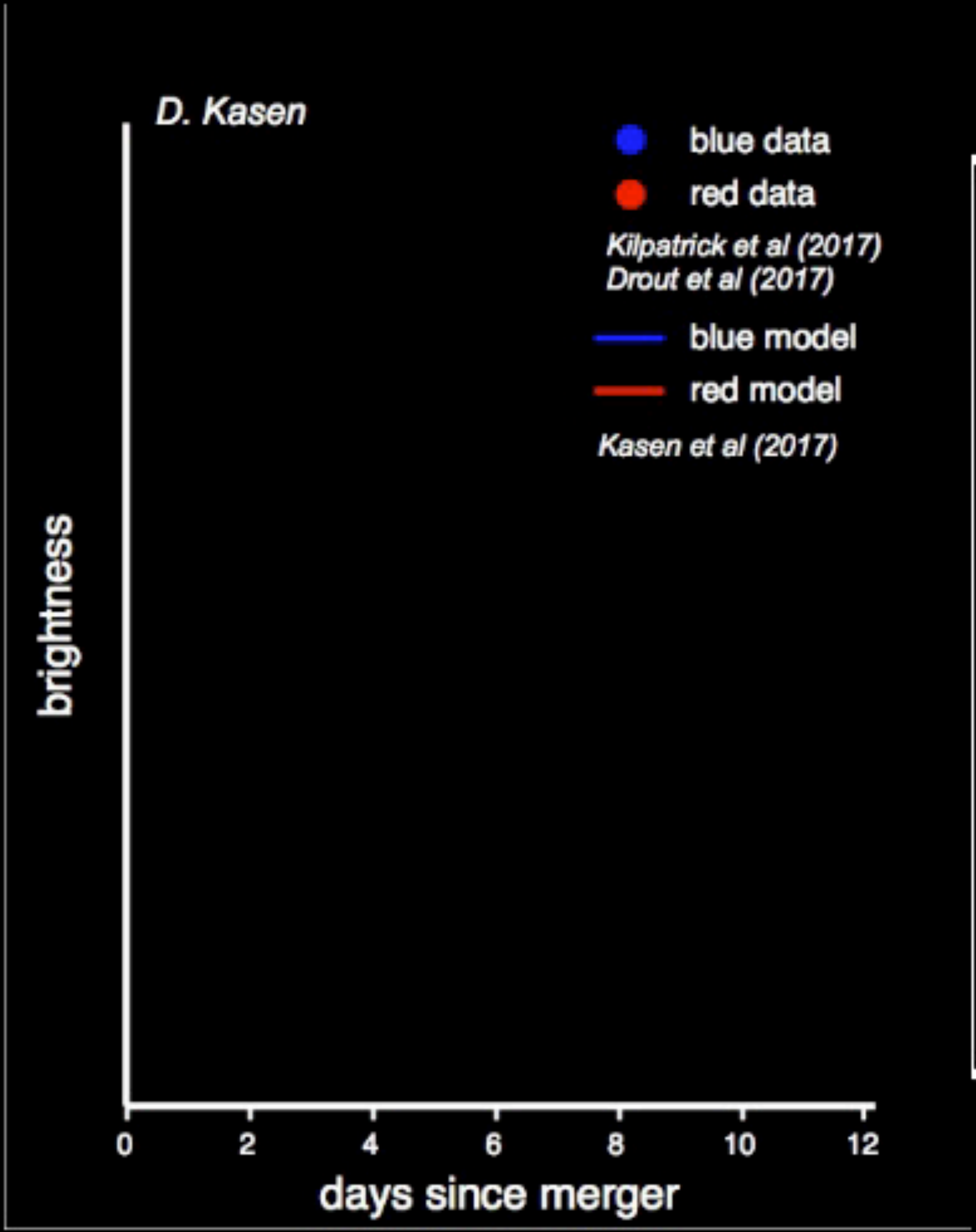
Multi-wavelength photometry of SSS17a

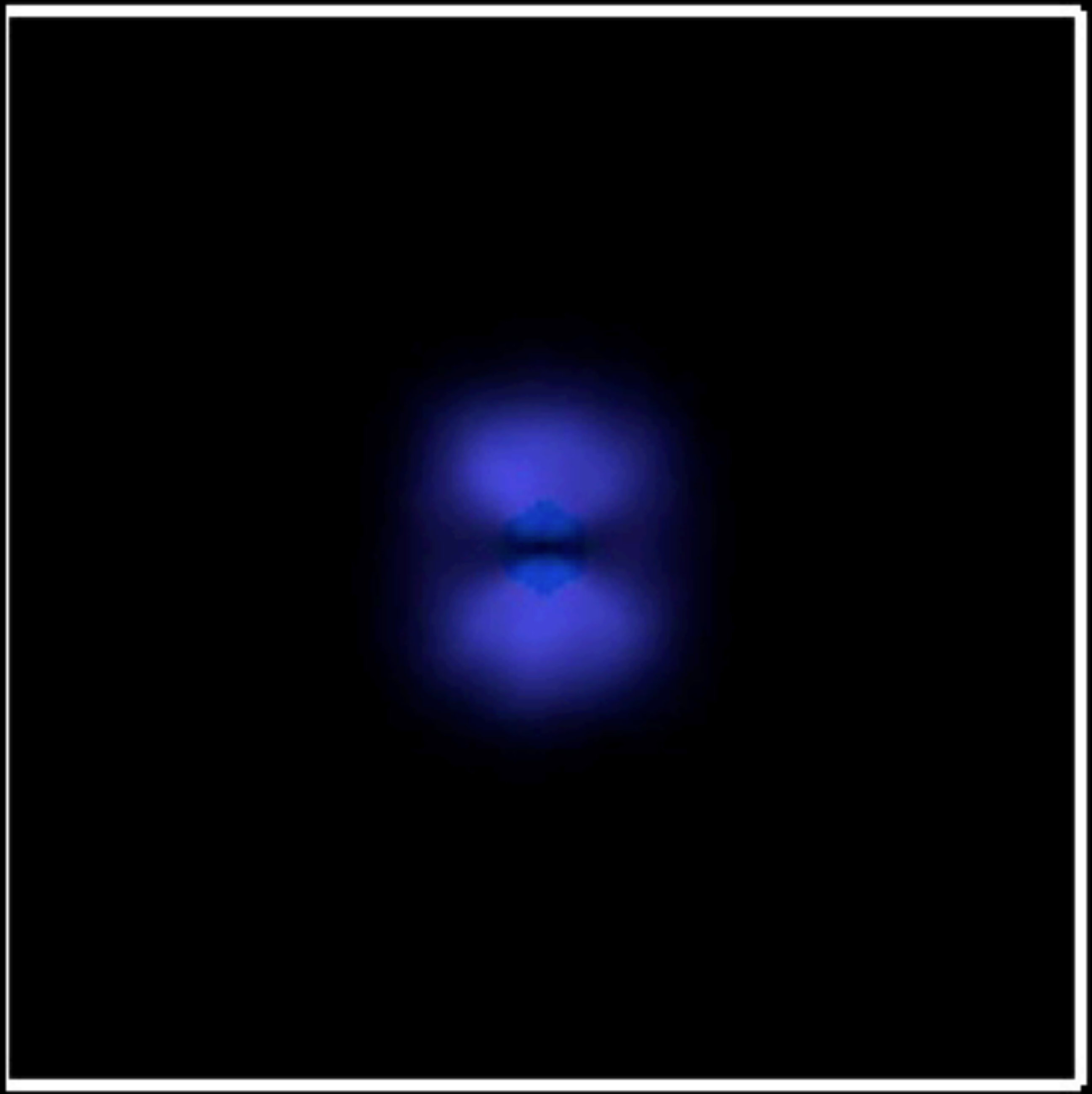


kilonova SSS17a bolometric light curve



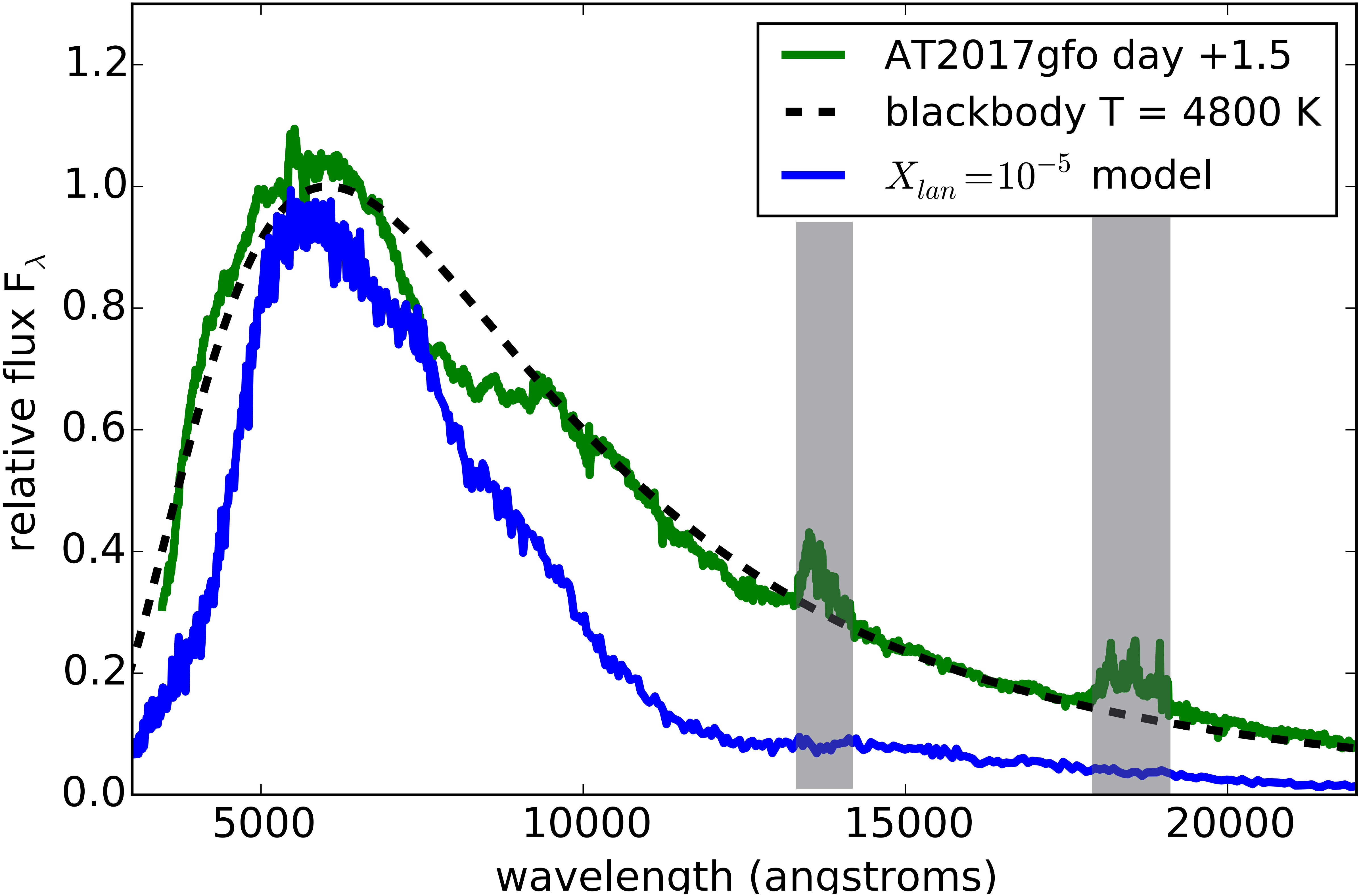
bolometric compilation: *Waxman+ 2017*
models: Kasen+2017



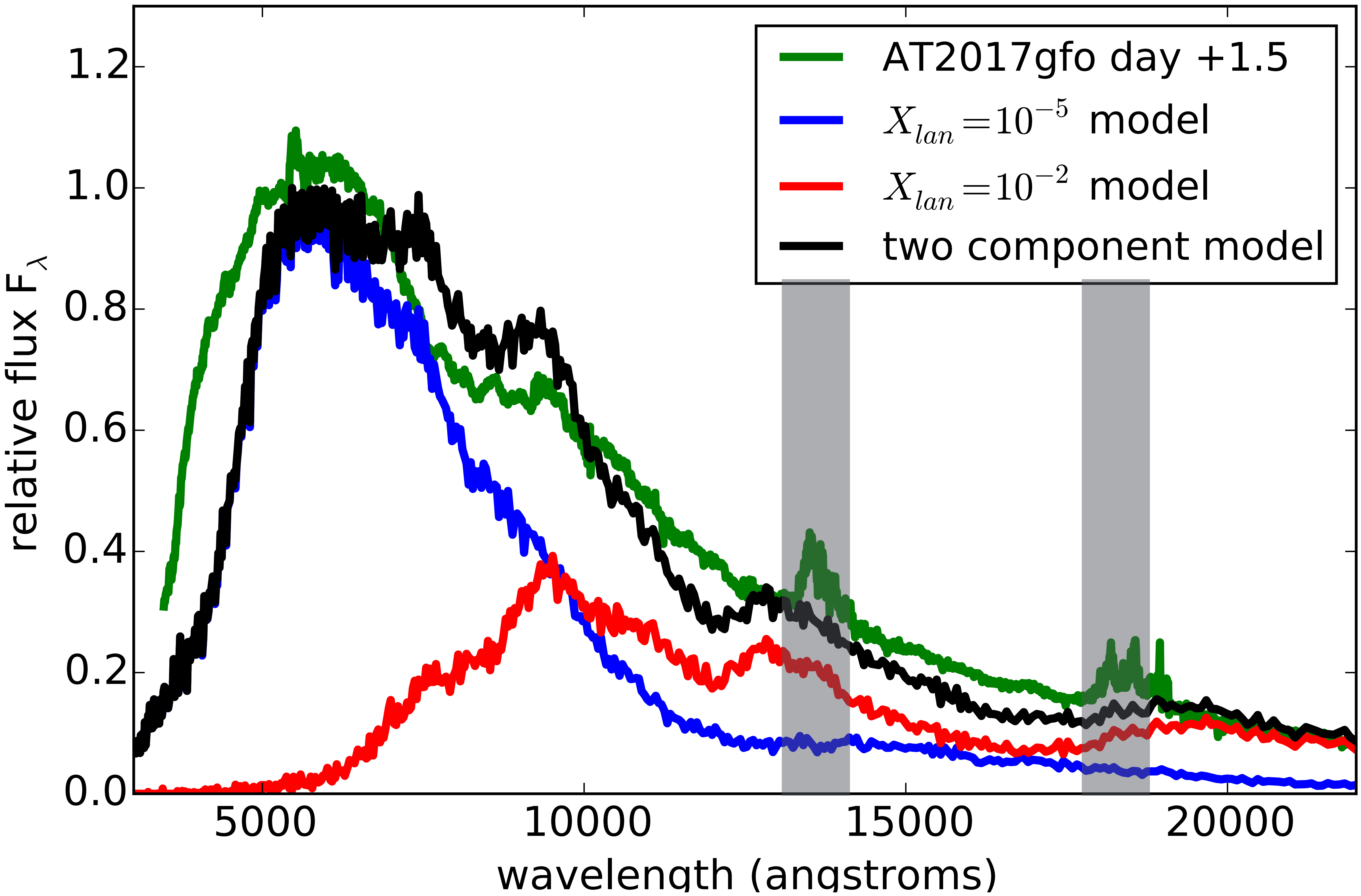


radioactive debris cloud

kilonova AT2017gfo spectrum @ day 1.5

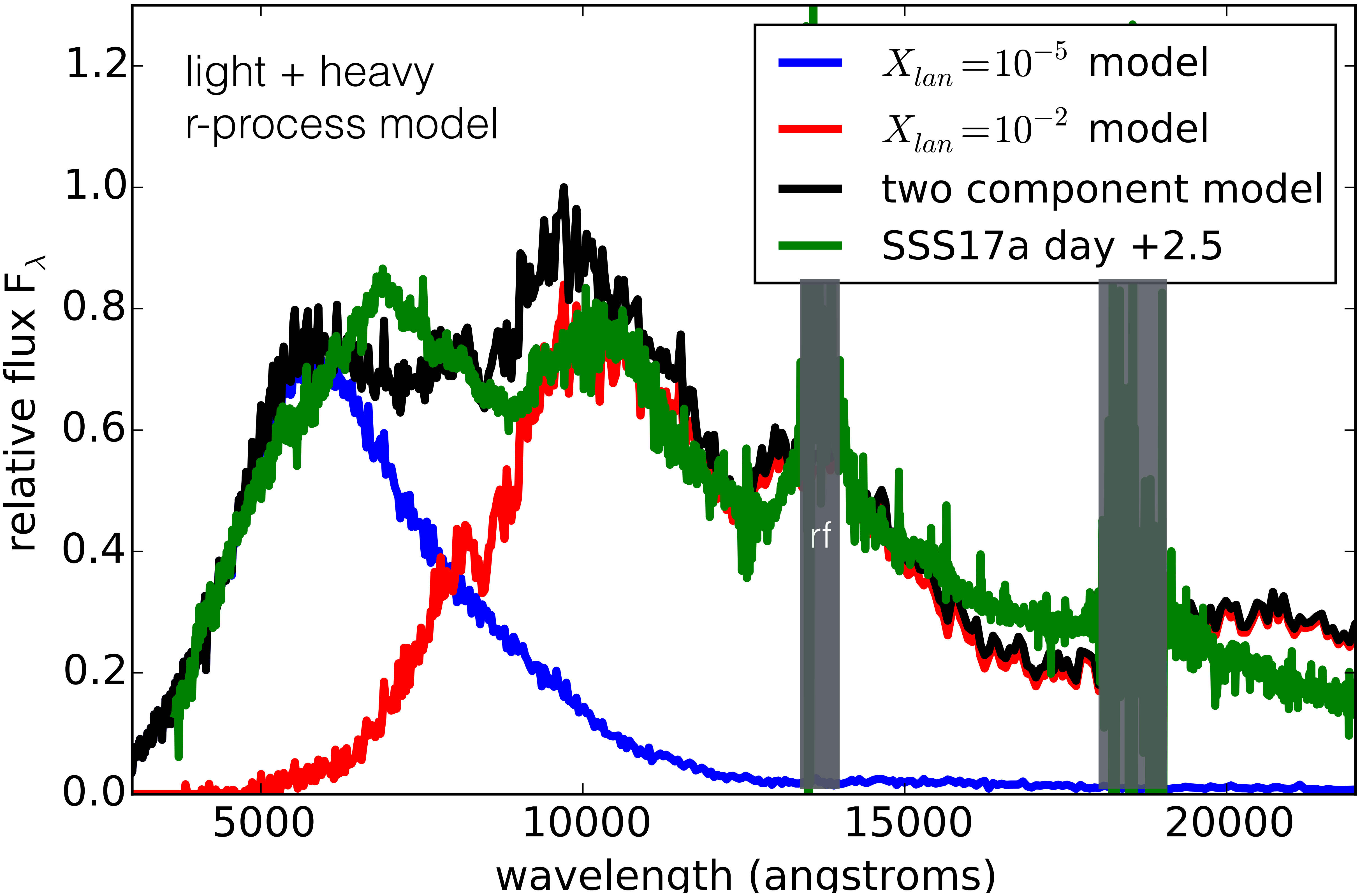


kilonova AT2017gfo spectrum @ day 1.5



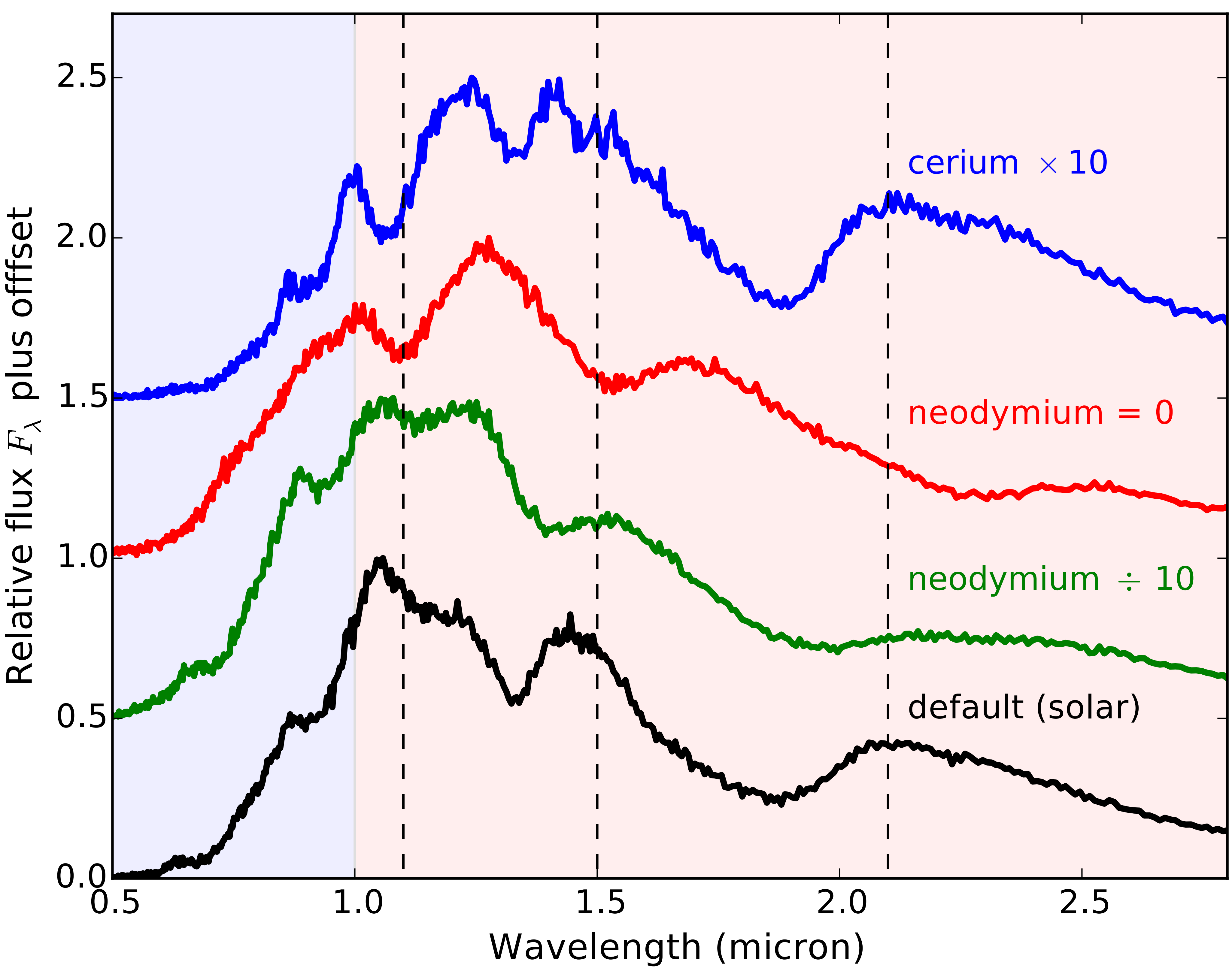
kilonova SSS17a spectrum @ day 2.5

data Pian+2017 x-shooter, models Kasen+2017



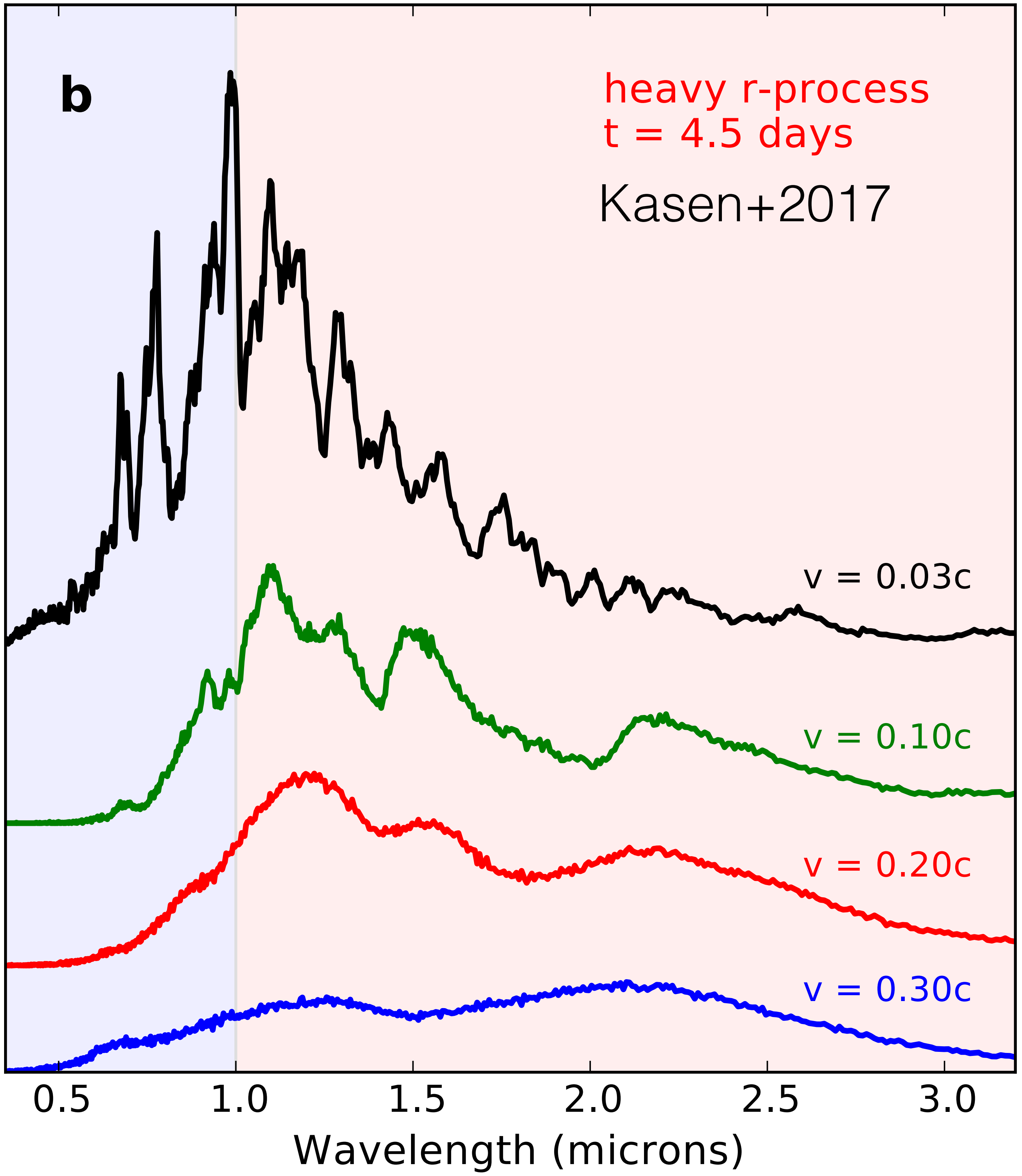
Model spectrum dependence on composition

features are Doppler-broadened blends of multiple lines



Spectral determination of ejecta velocity

(consistent with blackbody emitting radius, e.g., Drout+17, Troja+17)



GW170817: Some questions

Are neutron star mergers a site (*the* site) of the r-process?

Blue kilonova (light r-process)
$M \sim 0.025\ M_{sun}$ - $v \sim 0.3c$; $X_{lan} < 10^{-4}$

Red kilonova (heavy r-process)
$M \sim 0.04\ M_{sun}$ - $v \sim 0.1c$, $X_{lan} \sim 10^{-2}$

Merger rate (from LIGO): $R_m \sim$ 1 per 10^4 - 10^5 years per galaxy

Can potentially account for all r-process in galaxy

$$M_{galaxy} = 5 \times 10^3\ M_{sun} = f_{star} \times M_m \times R_m \times t_{gal}$$

But ejecta masses and rates are certain. Was the 1 event typical?