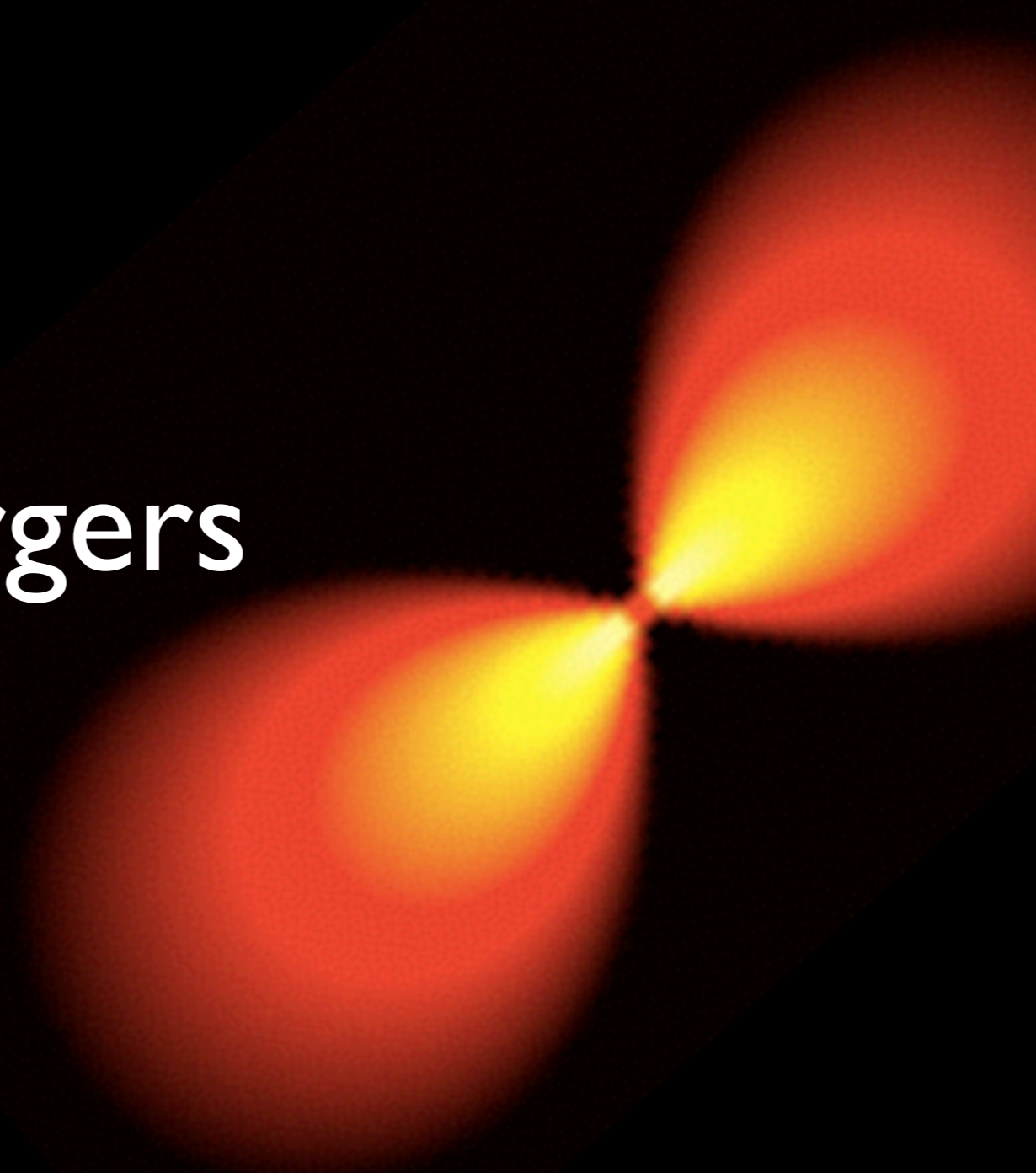


nucleosynthesis and light curves of compact object mergers

daniel kasen (UCB/LBNL)

w/ J. Barnes, N. Badnell, R. Fernandez,
L. Roberts, B. Metzger, E. Ramirez-Ruiz,
W. Lee, E. Quataert, S. Rosswog

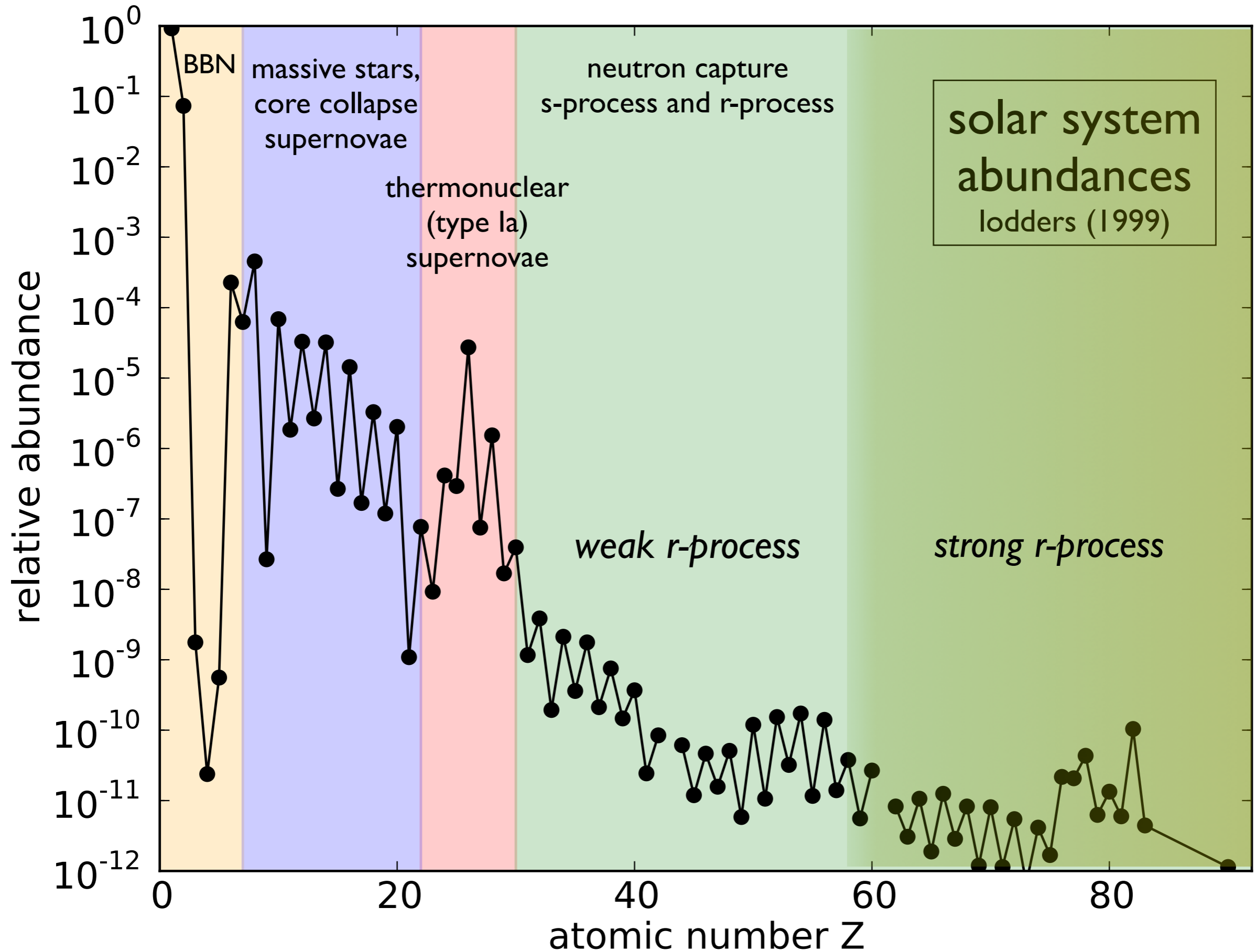




compact object mergers
two big questions

1. nature of gravitational wave sources
2. origin of the heavy elements (r-process nucleosynthesis)

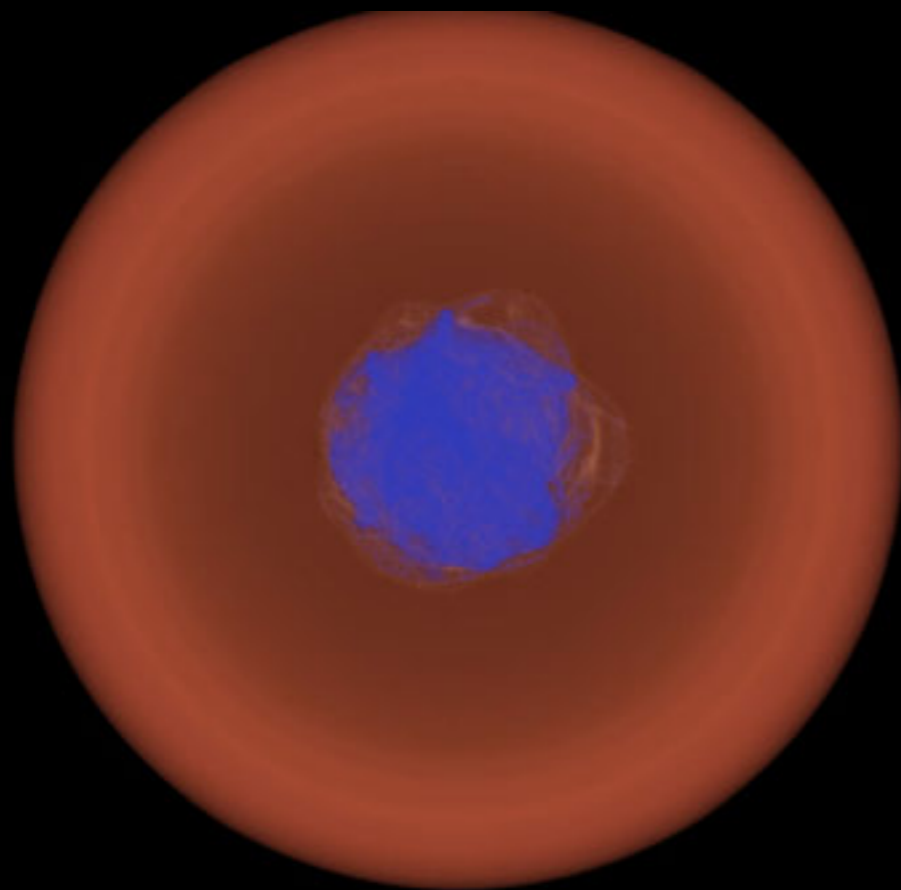
nucleosynthesis of the heavy elements



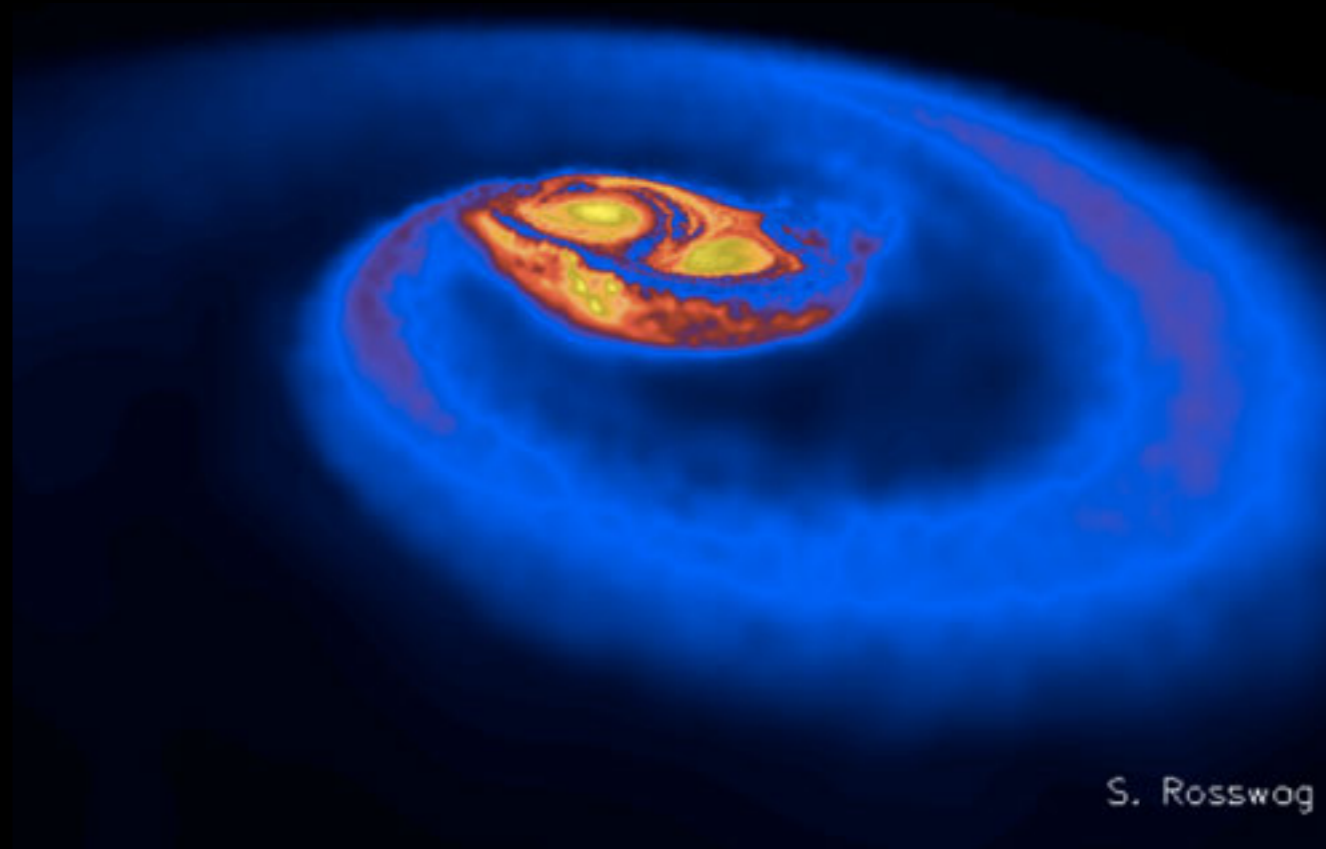
possible r-process sites

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

core-collapse supernovae



neutron star merger



S. Rosswog

neutrino driven wind from
a proto-neutron star

small r-process mass ($\sim 10^{-6} - 10^{-5} M_{\text{sun}}$?)

common and optically bright

low r-process purity

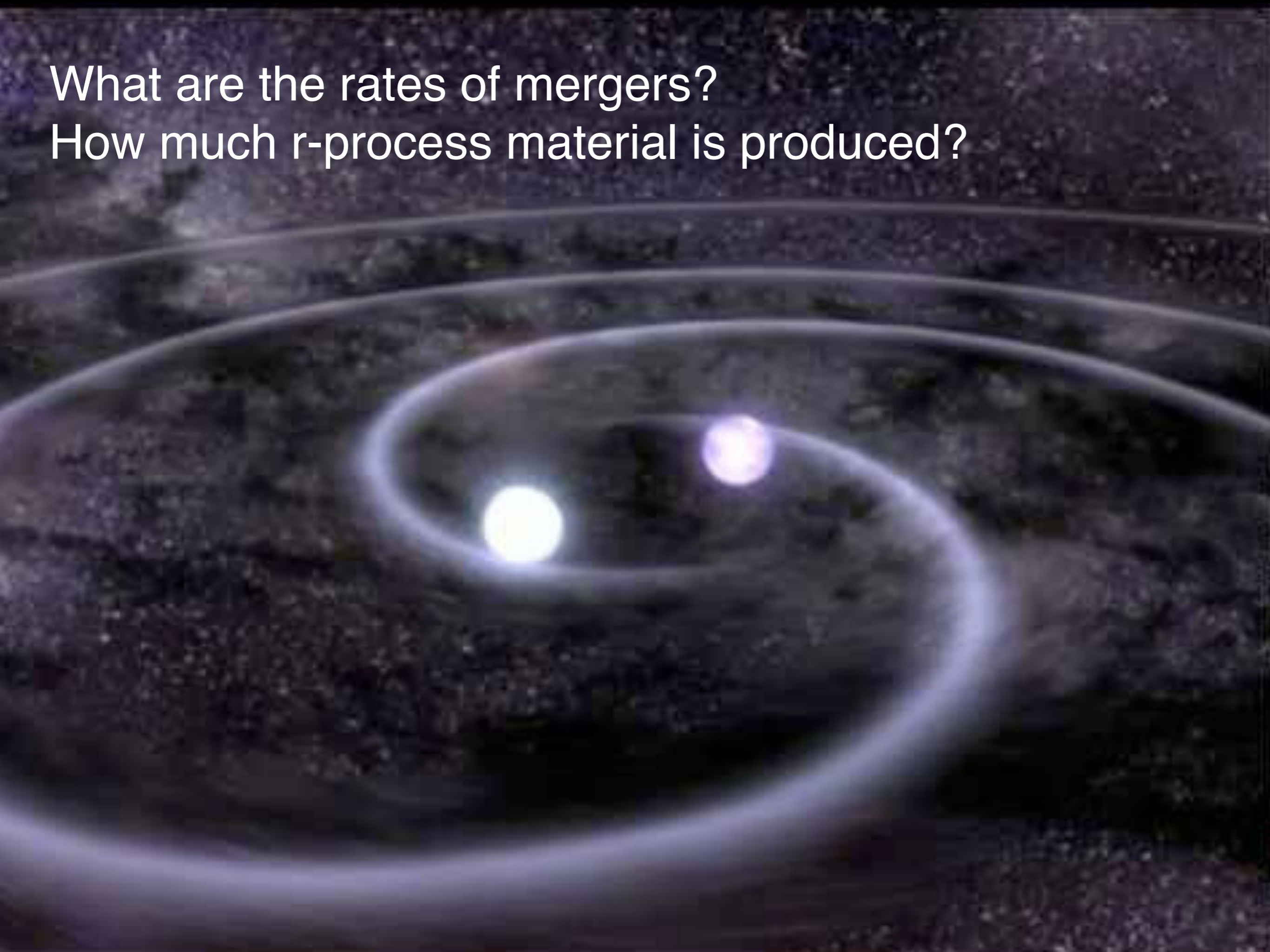
dynamical ejecta
or disk winds

larger r-process mass ($\sim 10^{-4} - 10^{-2} M_{\text{sun}}$?)

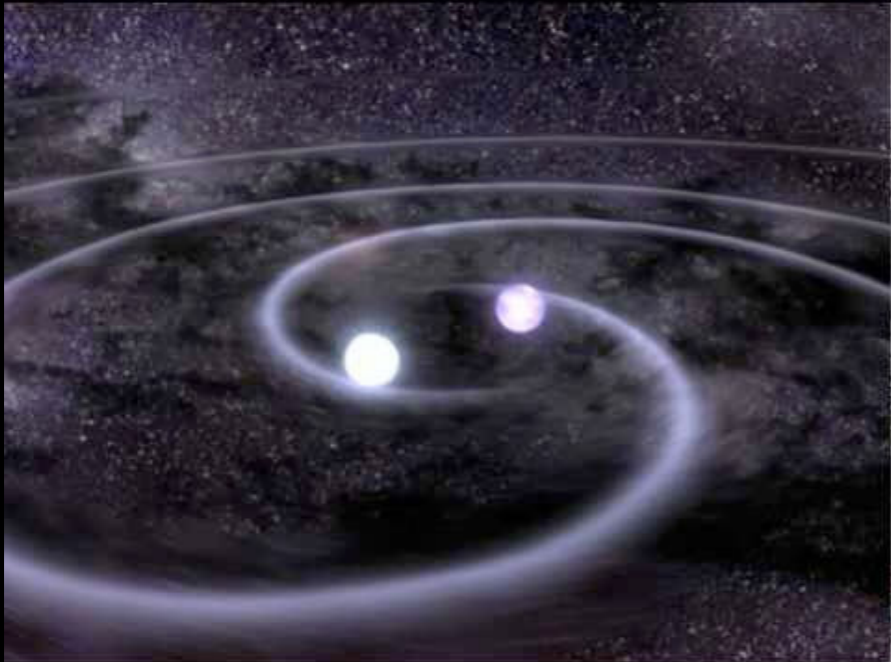
rare and optically dim

high r-process purity

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

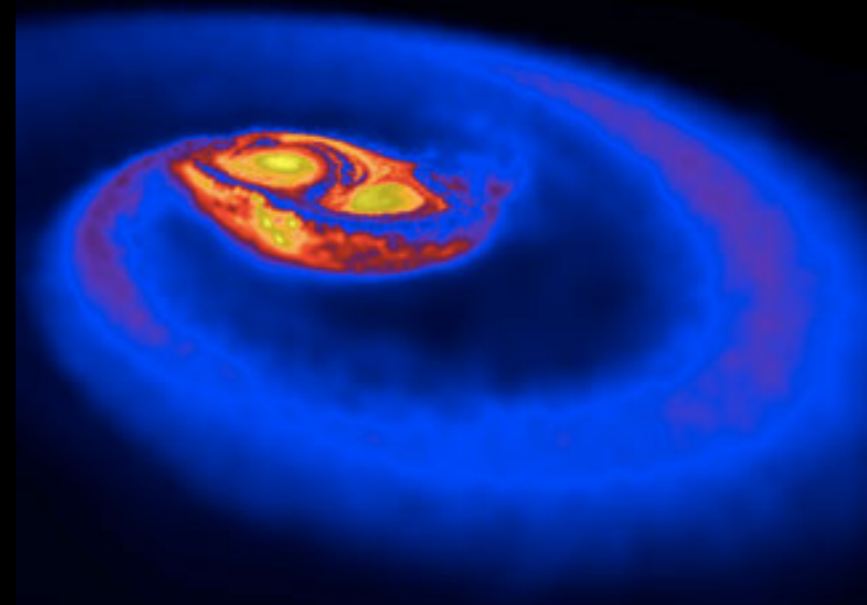


life-cycle of compact object mergers



binary stellar evolution
 $t \sim 10^6 - 10^9$ years; $r \sim 1$ AU

inspiral



outflows

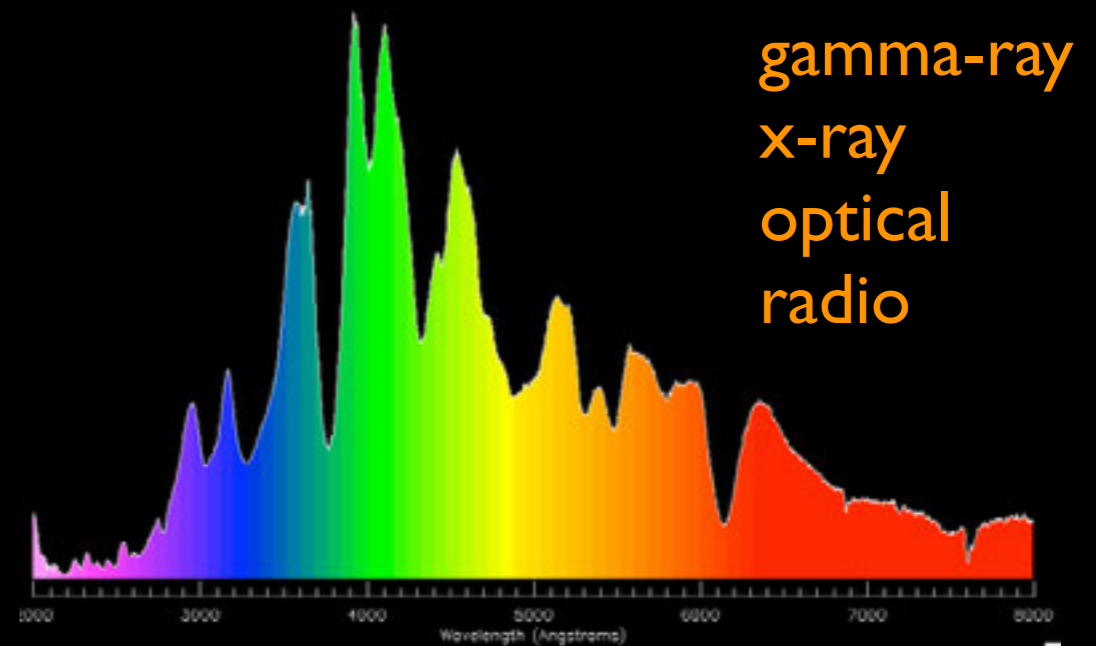


merger dynamics
 $t \sim$ ms - sec; $r \sim 50$ km



radiation transport
 $t \sim$ days, $r \sim 100$ AU

emission



observations

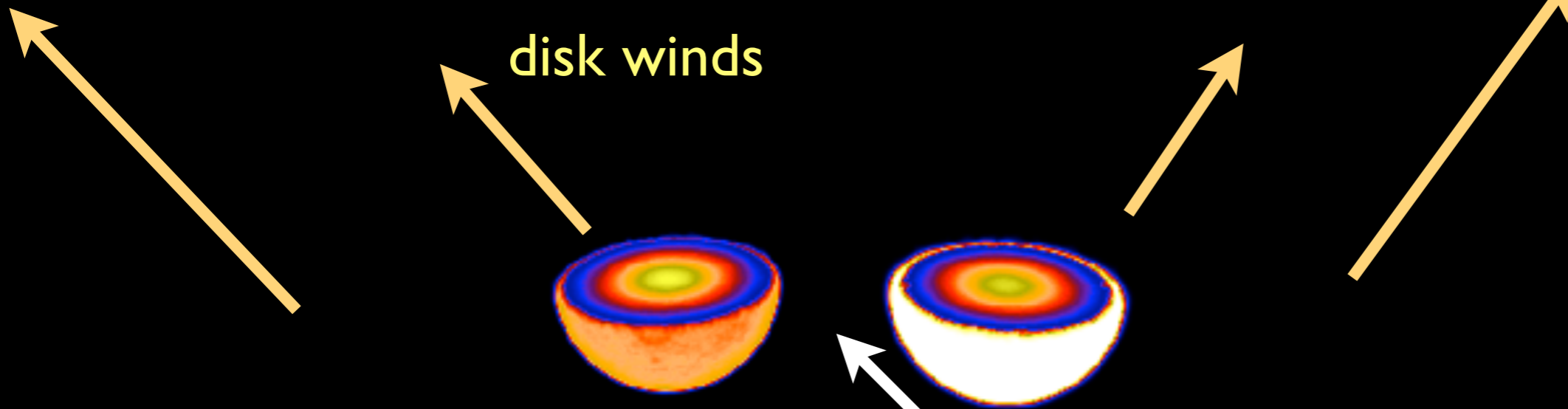
neutron star mergers

SPH simulation by stephan roswog

$t=0.025$ ms

tidal tails ejection

disk winds



electron fraction Y_e

0.15

0.1

0.05

0

multi-physics simulation

gravity (pseudo-newtonian or GR) massive neutron star remnant

hydrodynamics (grid based or SPH) (tidal tails) collapses to black hole

nuclear equation of state (after some time)

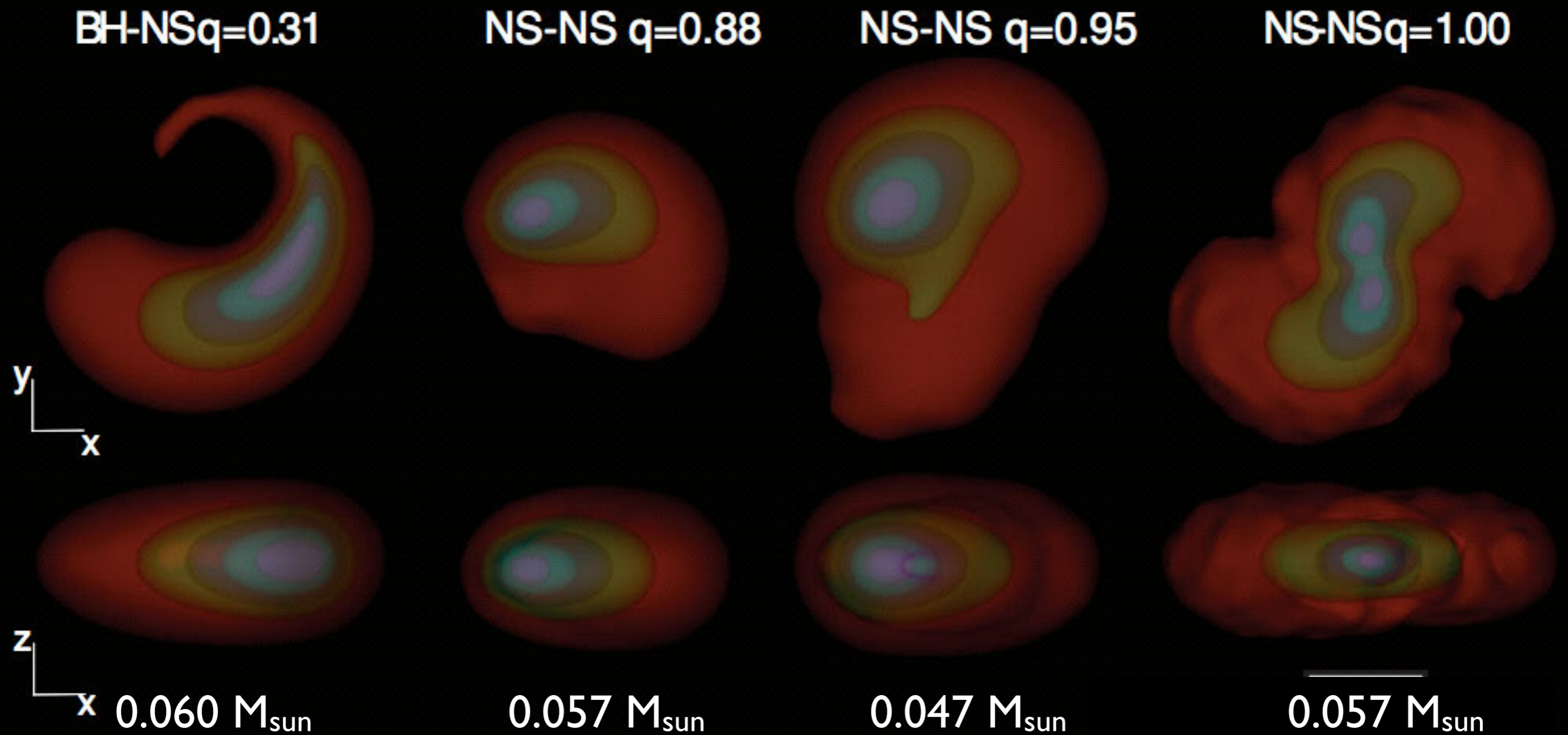
magnetic fields

nuclear reactions

neutrino physics

S. Rosswog

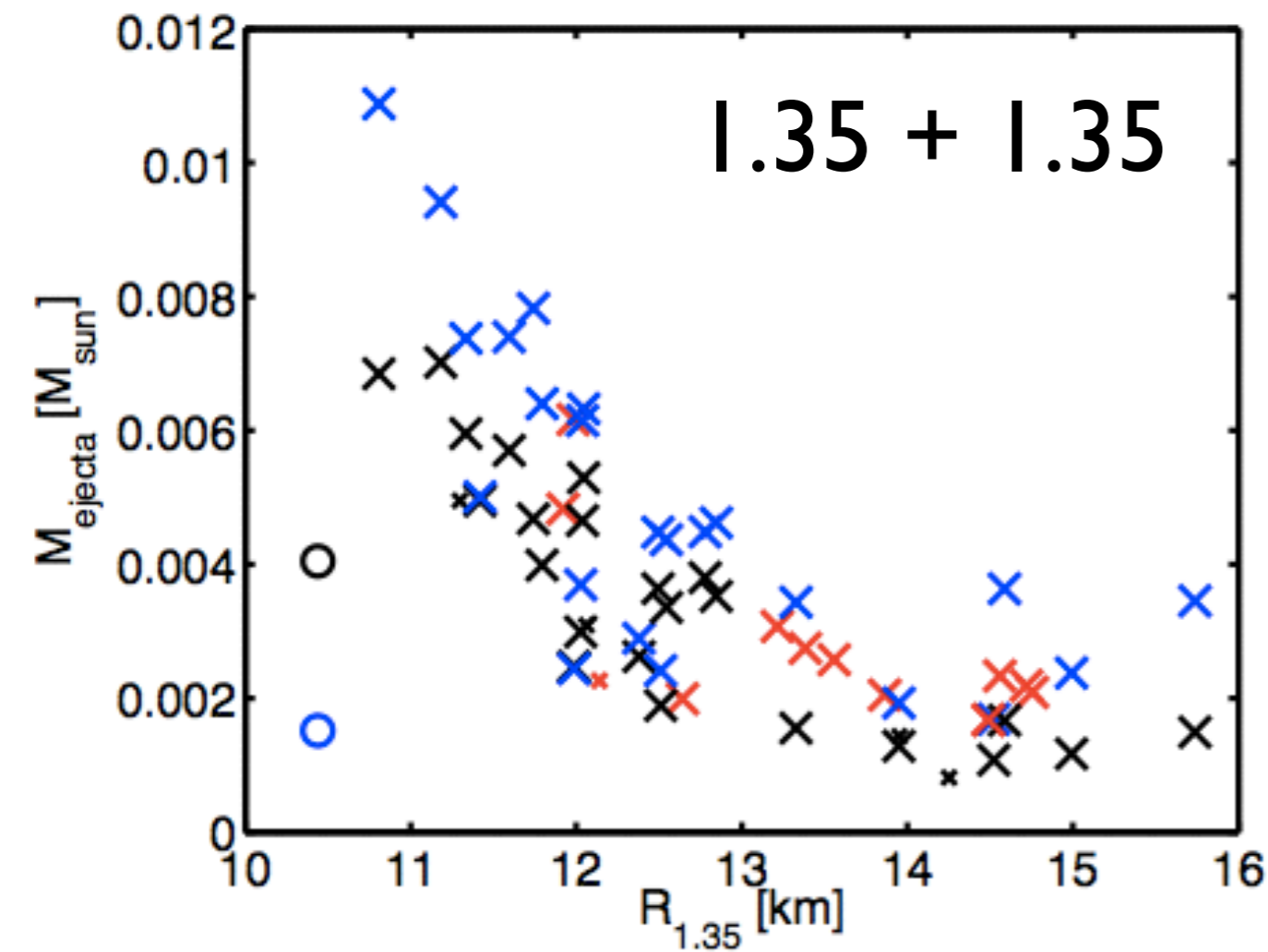
3D dynamical ejecta models



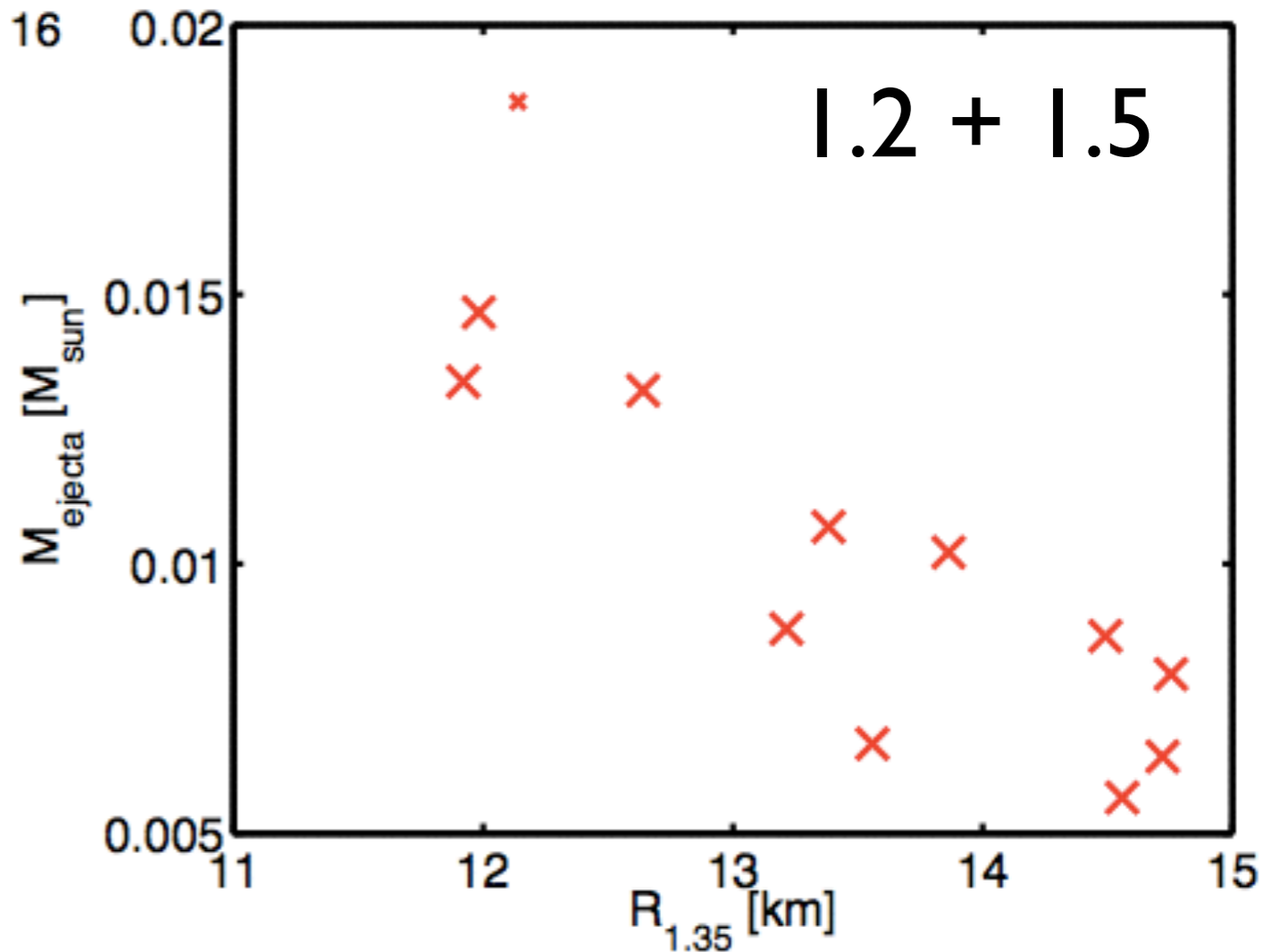
roberts, kasen, lee, & ramirez-ruiz (2011)

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

seeds, ${}^4\text{He}$, n



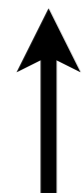
alpha chain

${}^{12}\text{C}$, ${}^4\text{He}$, n



triple alpha

${}^4\text{He}$, n



recombination to alpha particles

n, p



neutron
captures

heavier neutron-rich
isotopes



beta decay

higher Z
isotopes

Nucleosynthesis in the r-process

JINA

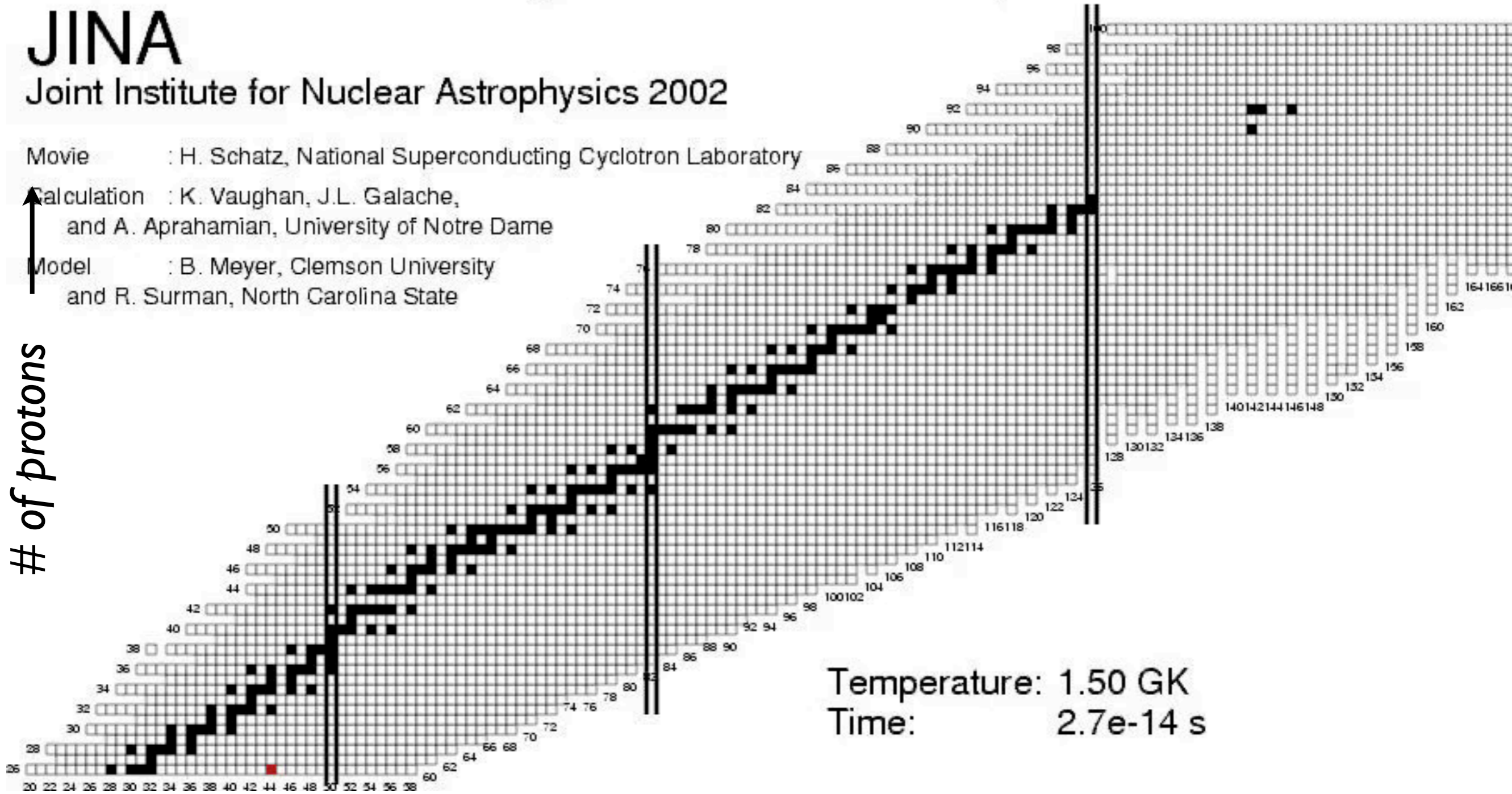
Joint Institute for Nuclear Astrophysics 2002

Movie : H. Schatz, National Superconducting Cyclotron Laboratory

Calculation : K. Vaughan, J.L. Galache,
and A. Aprahamian, University of Notre Dame

Model : B. Meyer, Clemson University
and R. Surman, North Carolina State

of protons

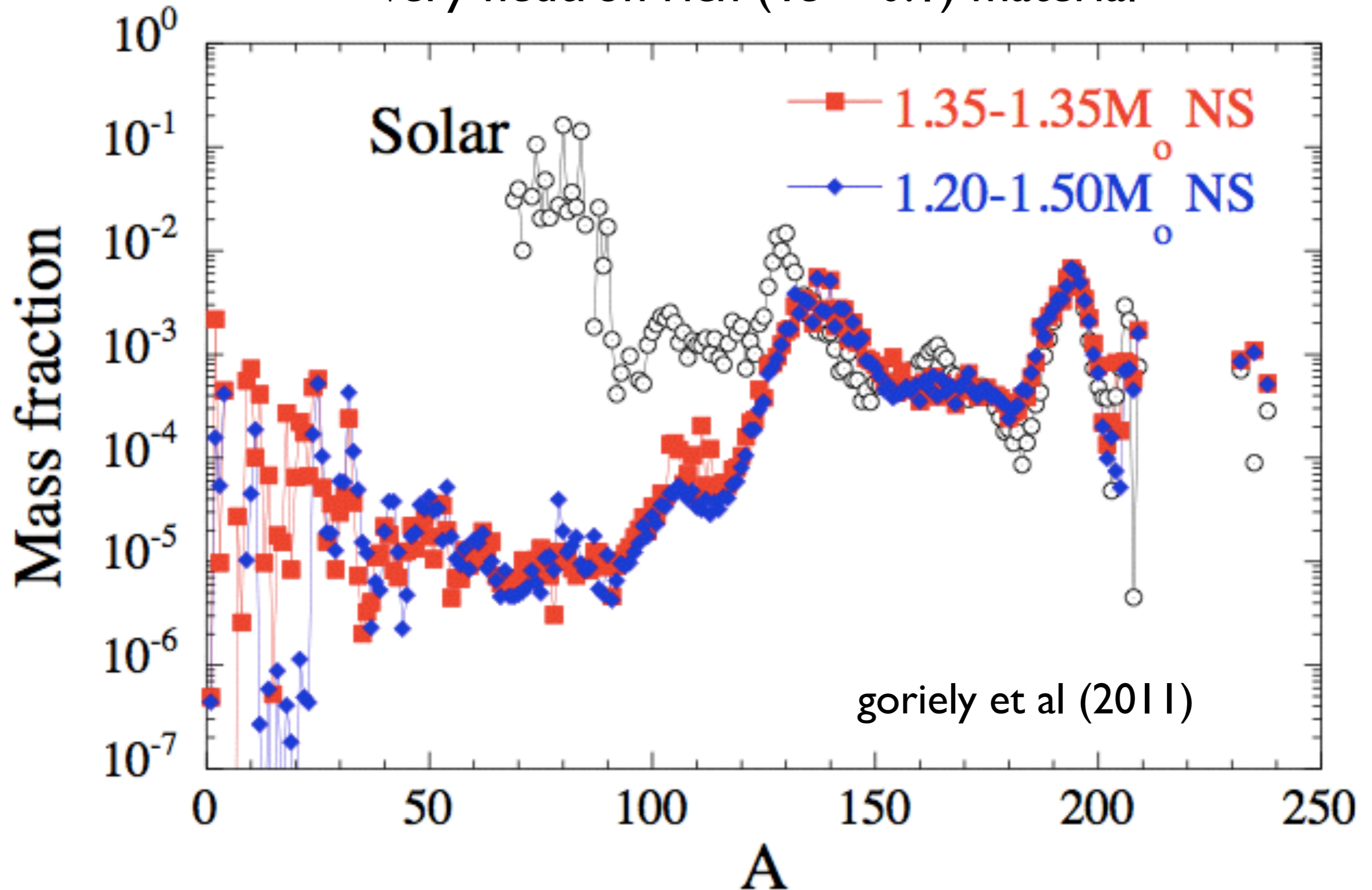


Temperature: 1.50 GK
Time: $2.7e-14$ s

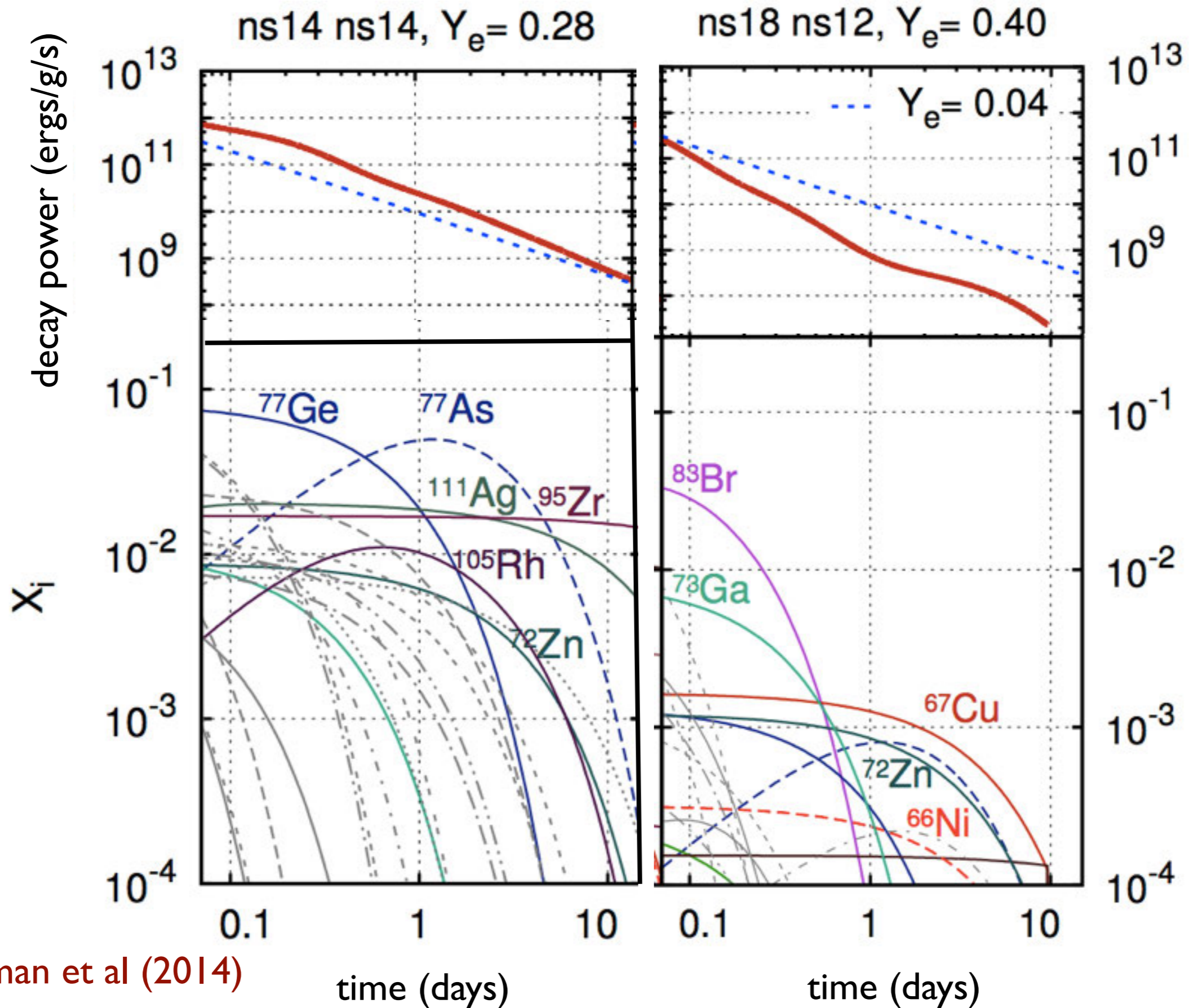
of neutrons →

r process nucleosynthesis in dynamics ejecta

very neutron rich ($Y_e \sim 0.1$) material



radioactive heating (beta decays)



radioactively powered transients

a kilonova

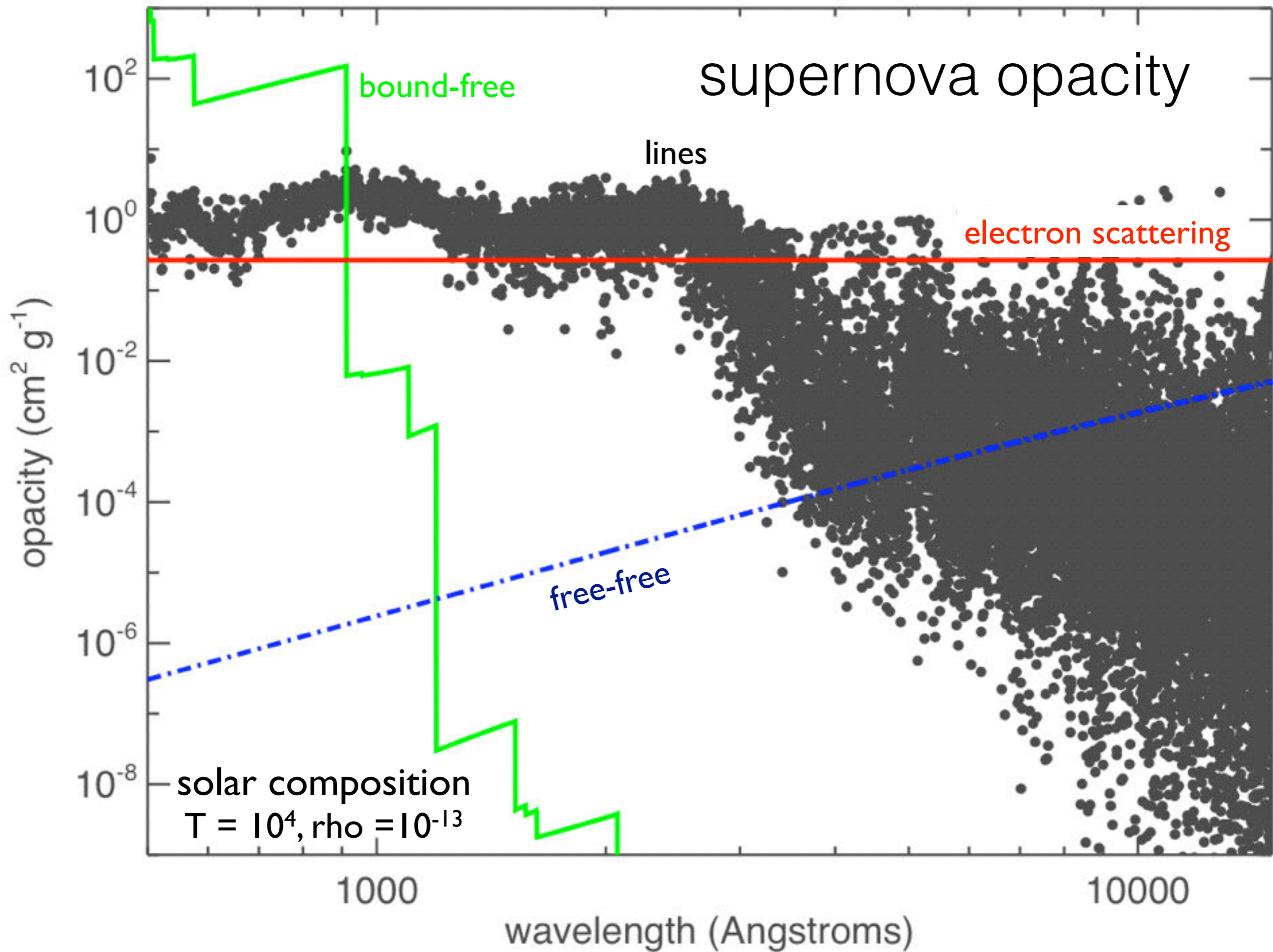
Radioactive decay deposits energy (betas, gamma-rays, fission fragments) and heats the expanding debris, which emits thermally.


$$L \sim M \dot{\epsilon}(t_p)$$

□

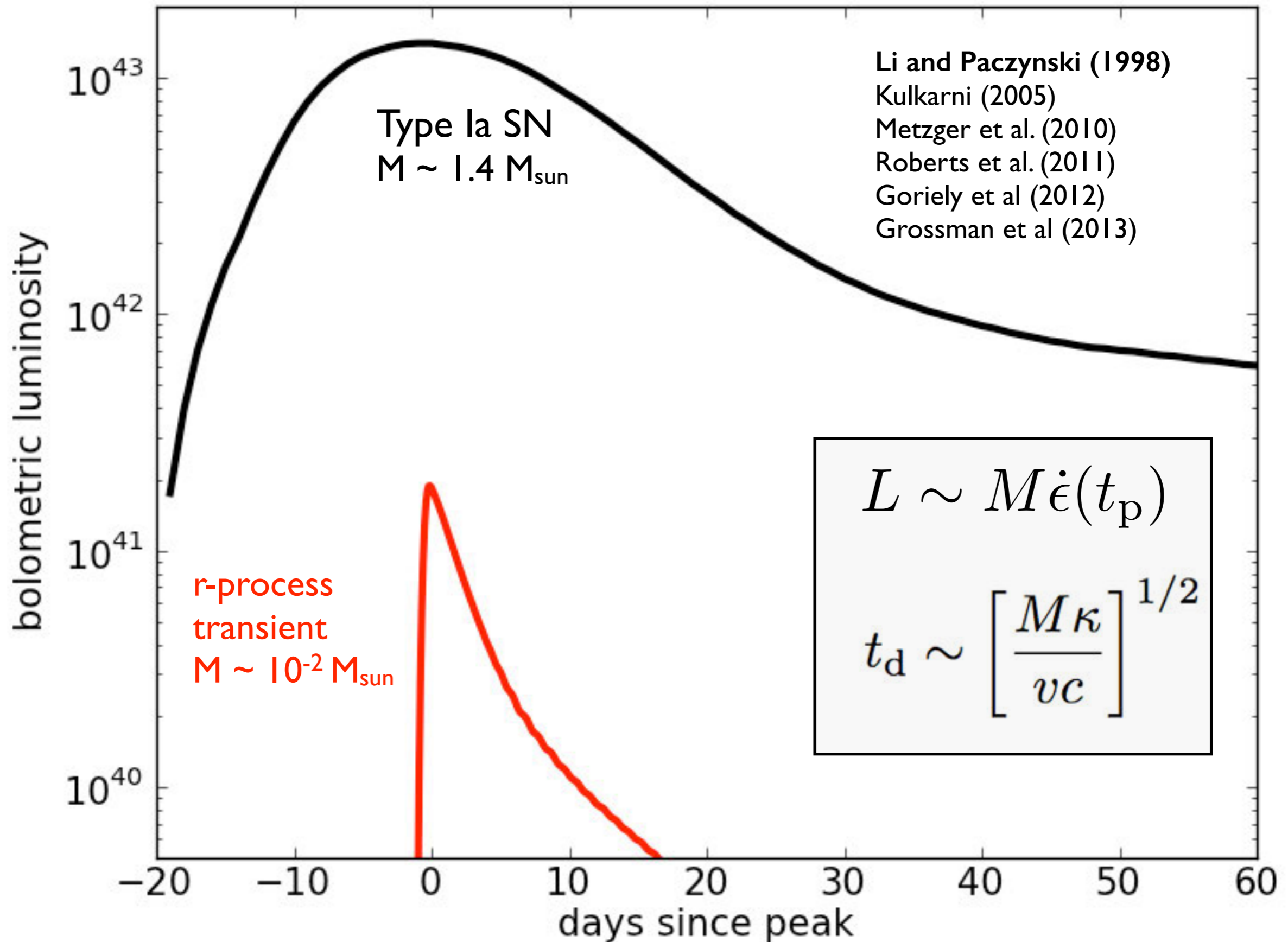
$$t_d \sim \left[\frac{M \kappa}{v c} \right]^{1/2}$$

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

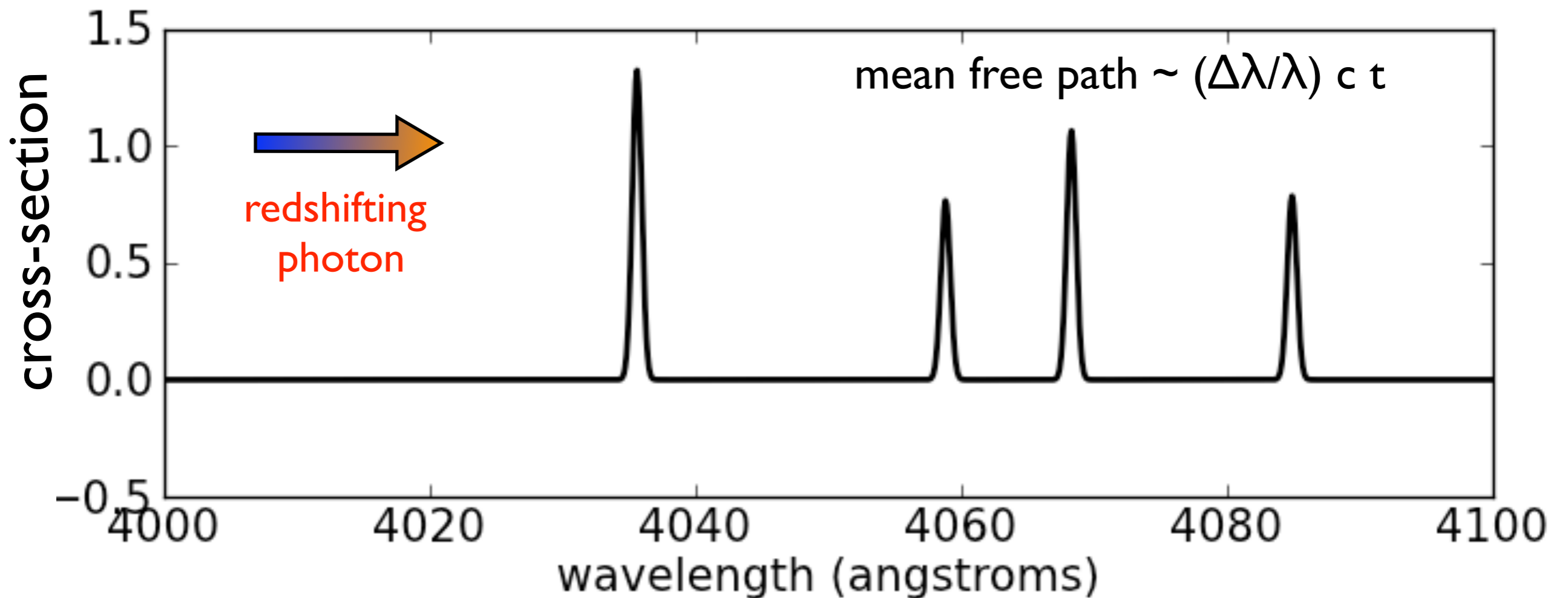
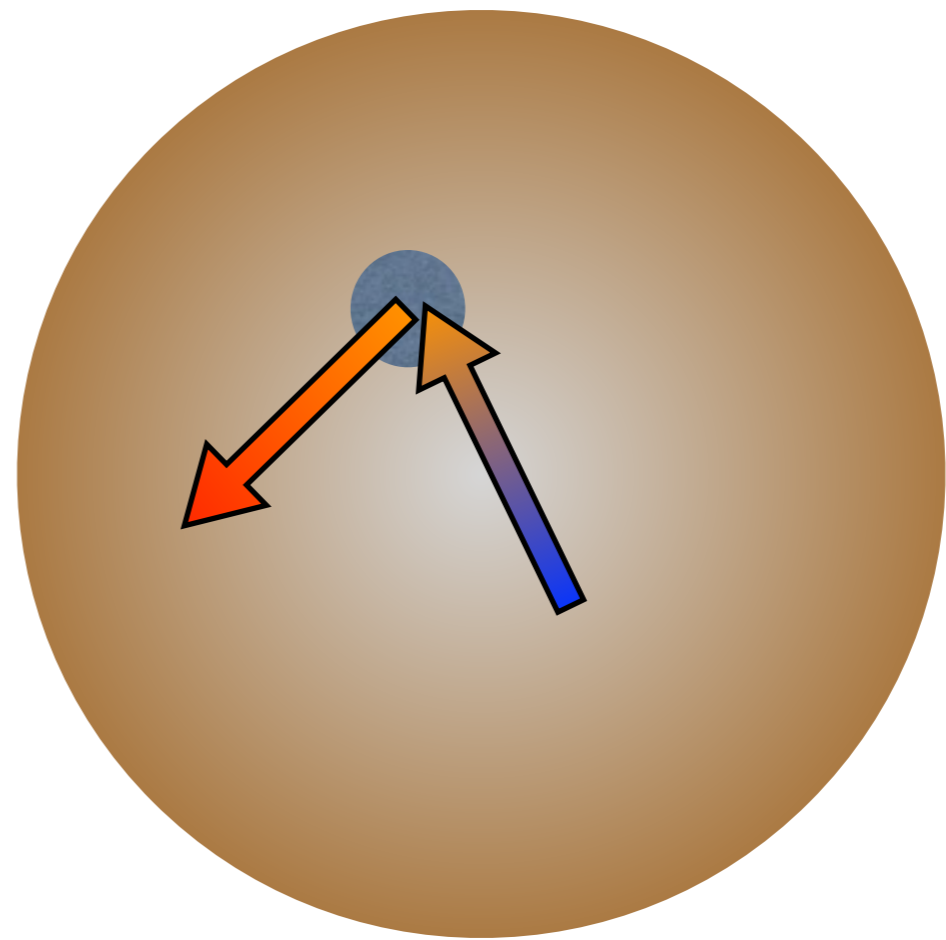


r-process supernova model light curve

iron-like opacity



line interactions
in an expanding
(hubble-like) flow



opacity and atomic complexity

s-shell ($g=2$)

hydrogen 1 H 1.0079	
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
francium 87 Fr [223]	radium 88 Ra [226]

p-shell ($g=6$)

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
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
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
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]				

d-shell ($g=10$)

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
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
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
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]	ununilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]

* 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
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]

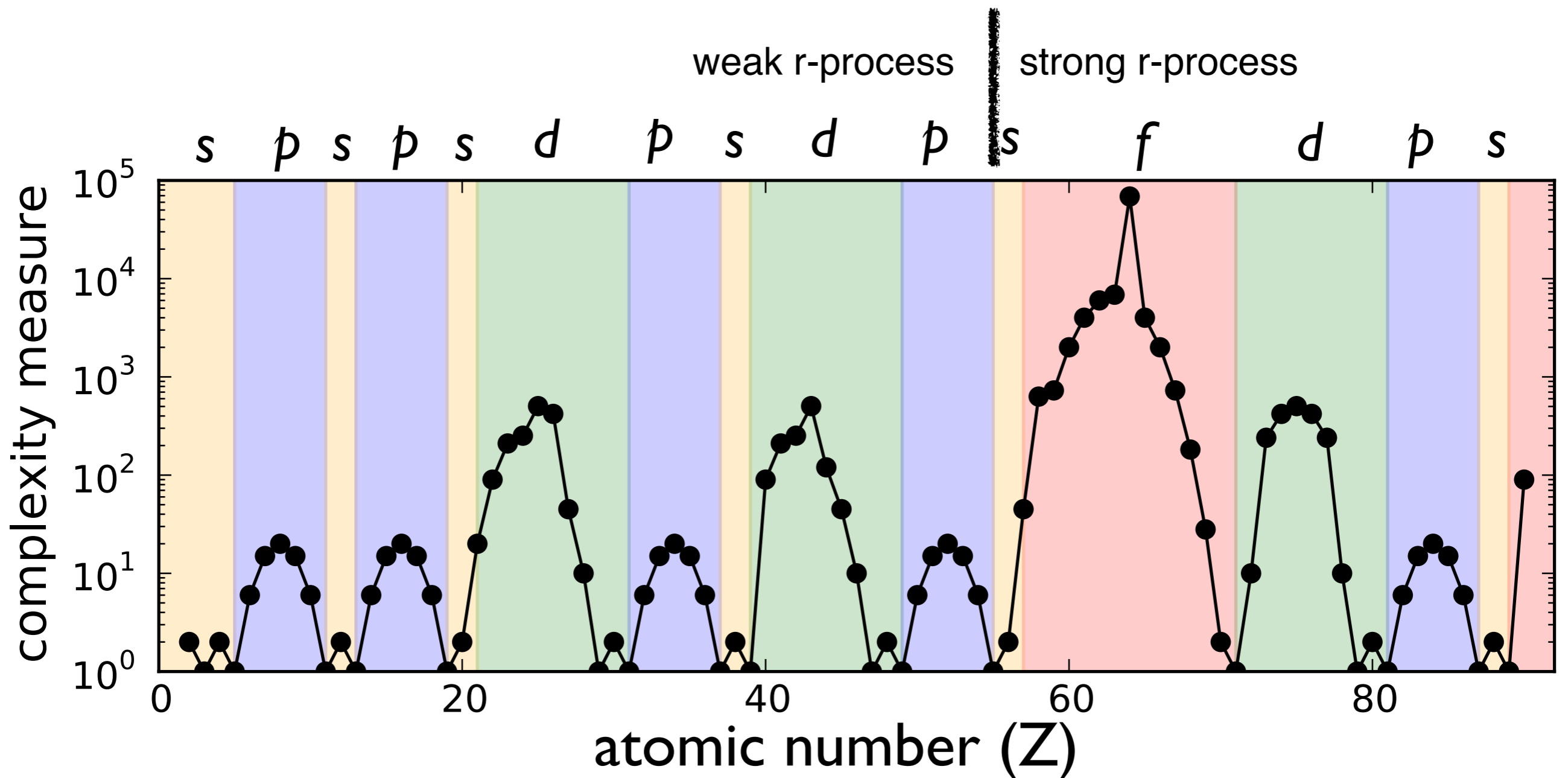
** Actinide series

f-shell
($g=14$)

atomic complexity

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

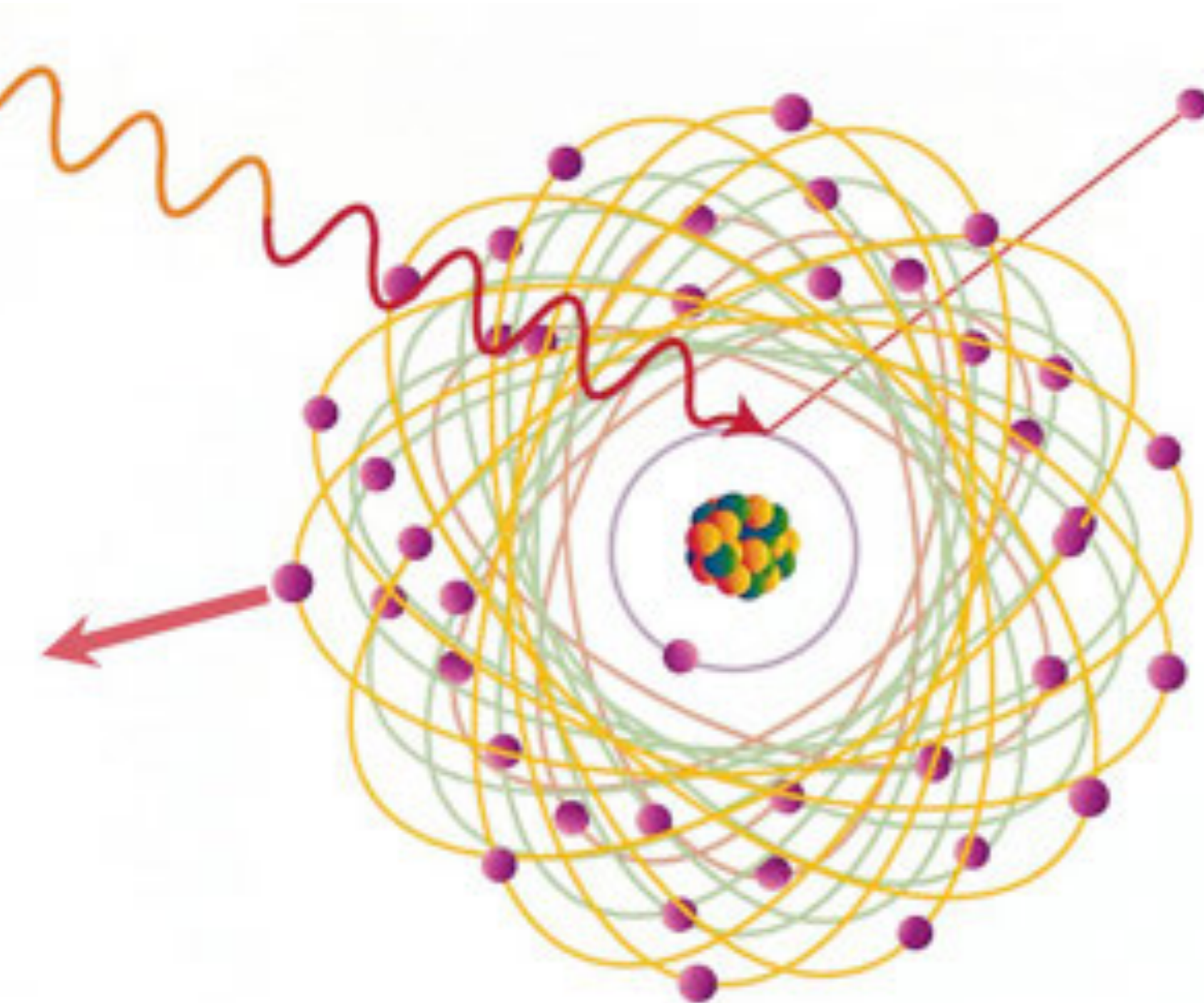
number of atomic levels N is roughly given by putting n indistinguishable valence electrons in g spots



kasen+ 2013

atomic structure and radiative data

very little data available for high Z



existing data

VALD database

Kurucz database

DREAM database

(MONS group)

new calculations

autostructure code

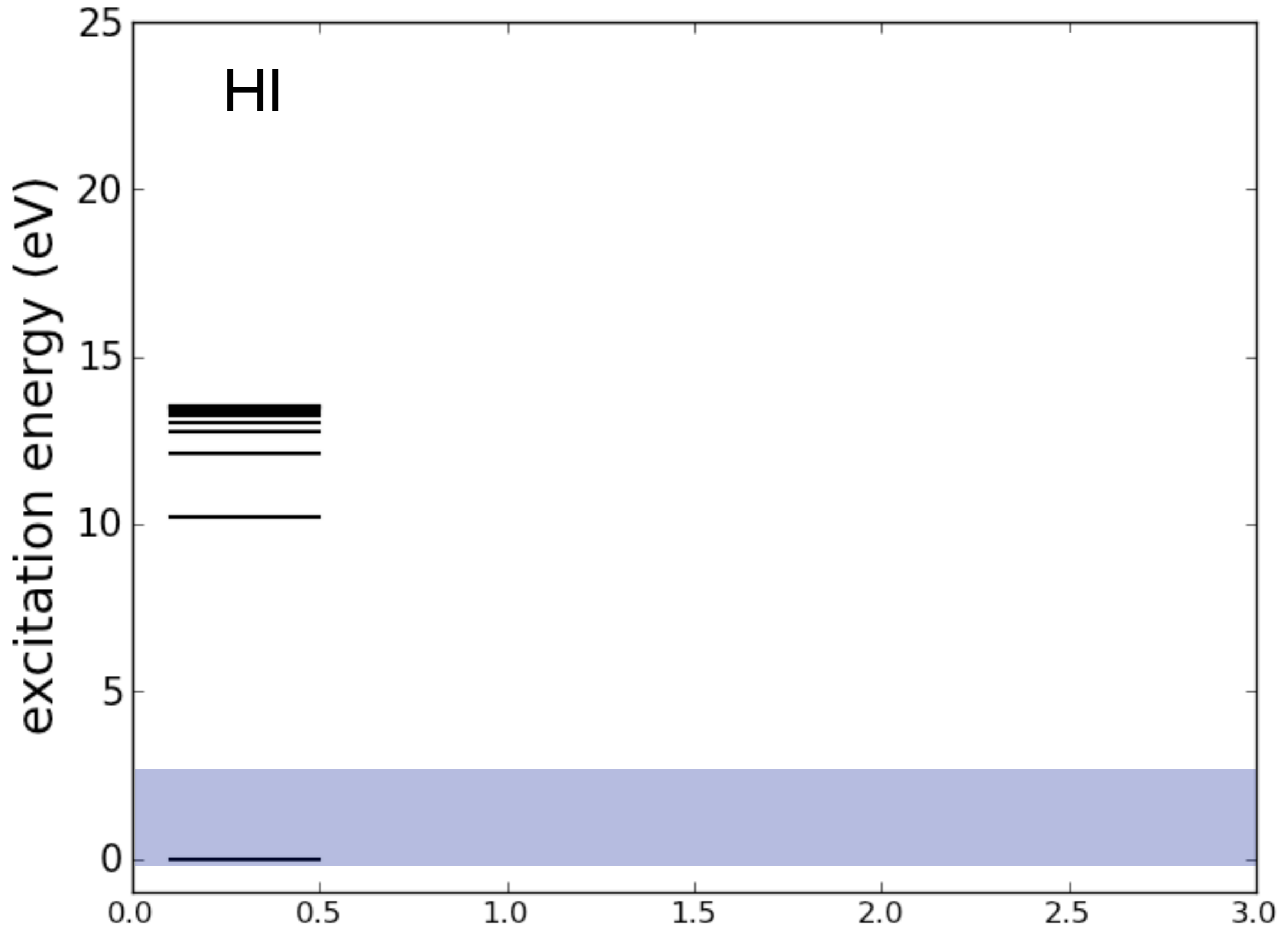
Badnell et al

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

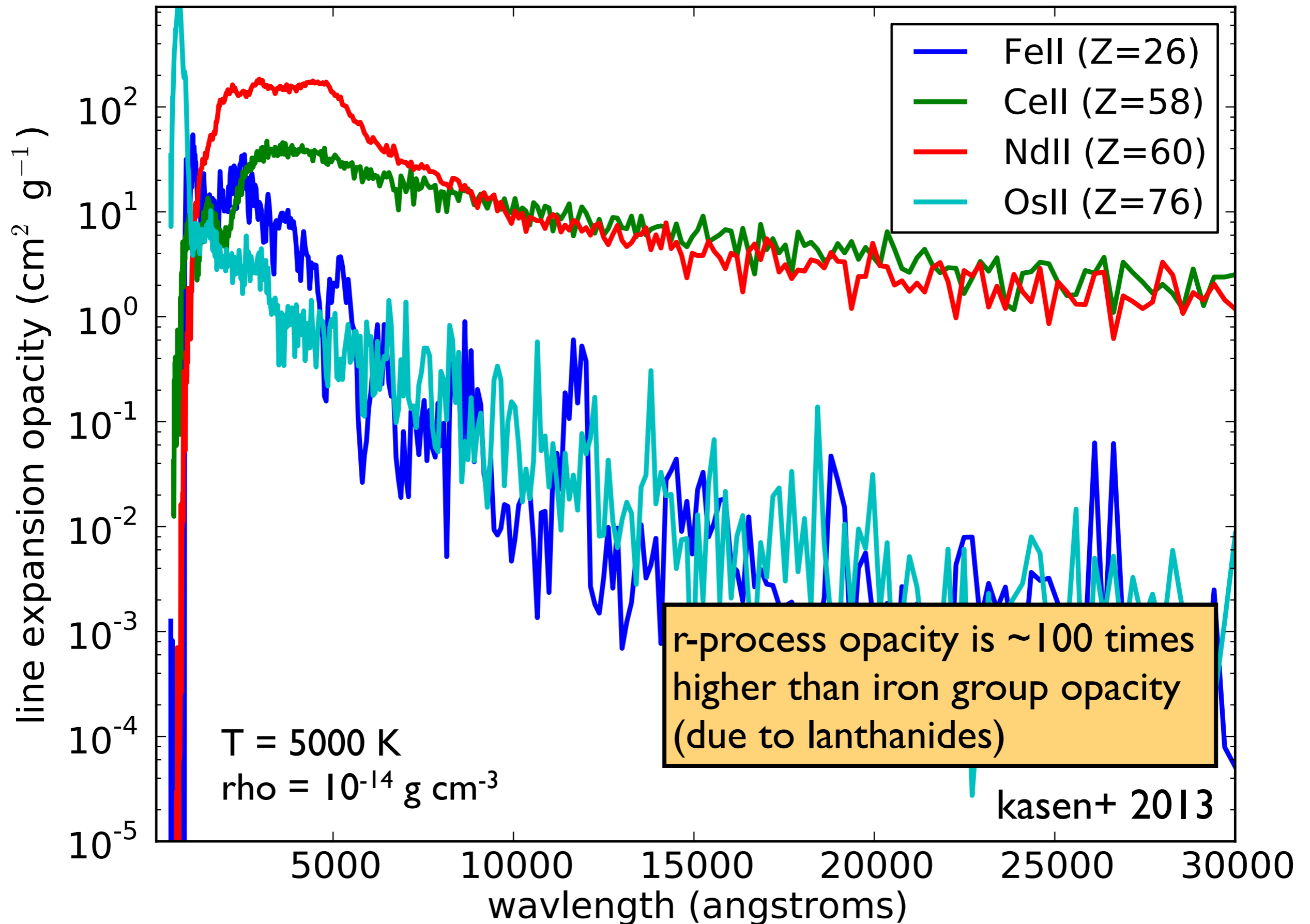
Intermediate coupling

level energy structure

kasen+ 2013

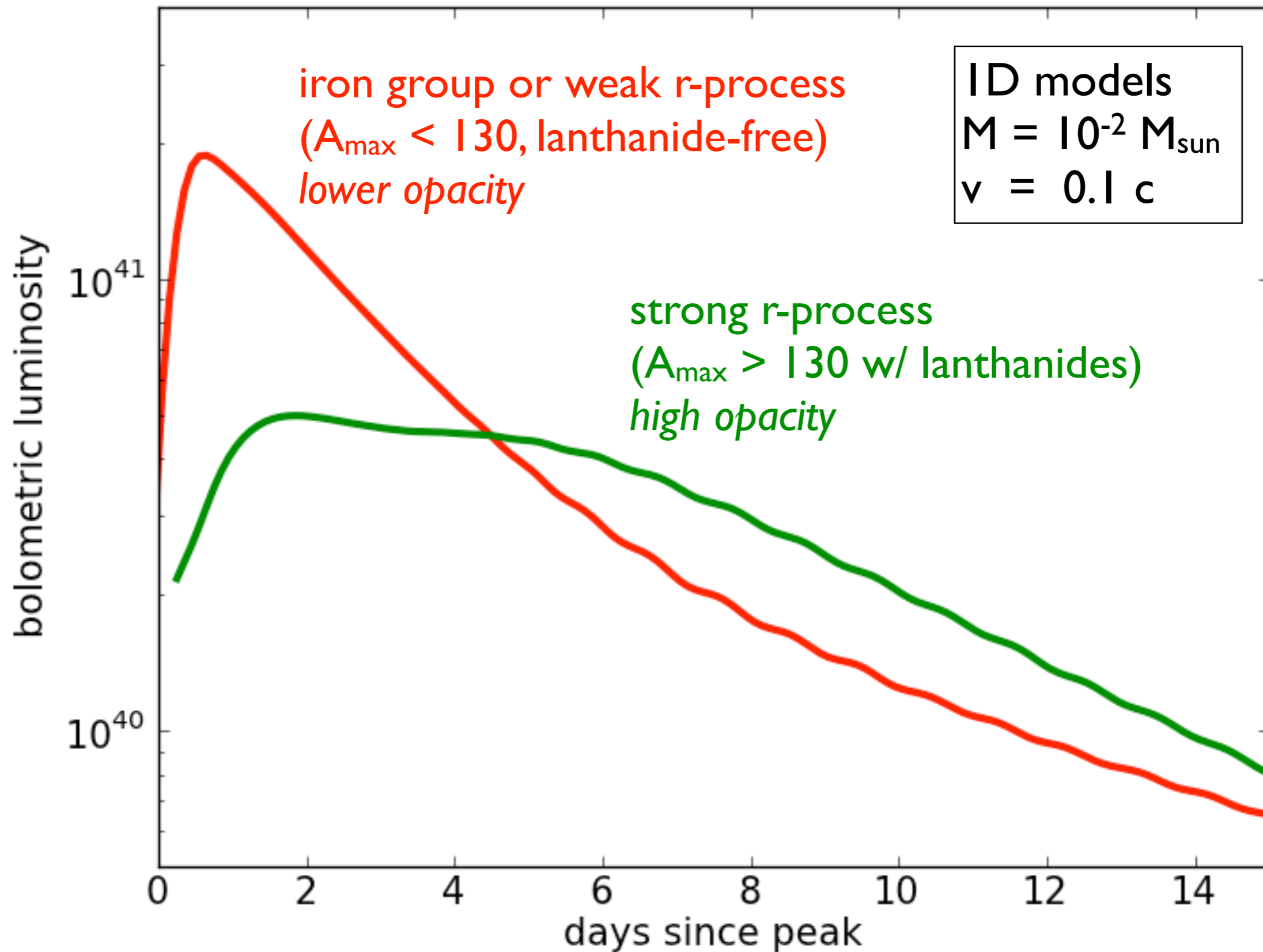


r-process opacity from lines

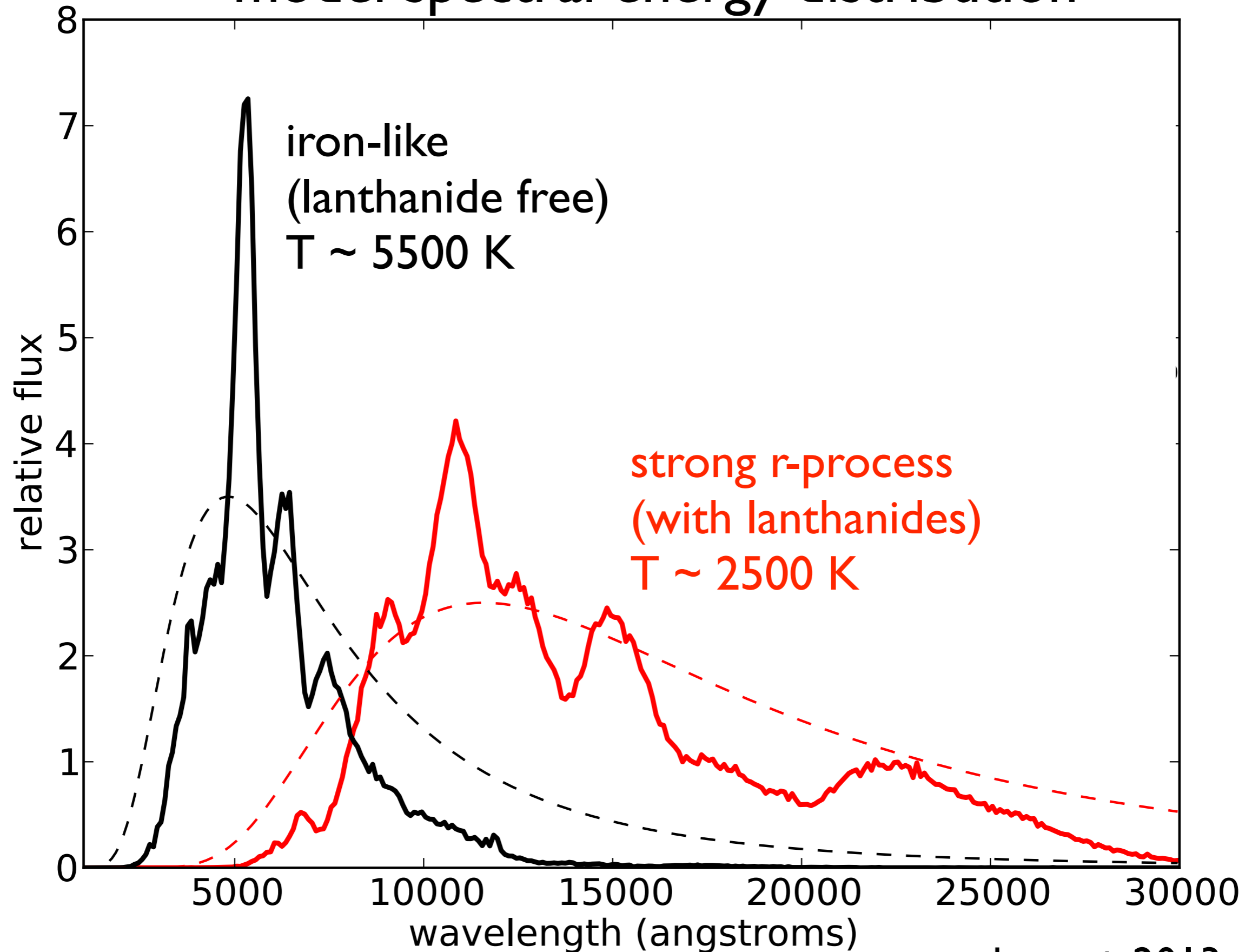


light curves of radioactive transients

multi-wavelength time-dependent transport

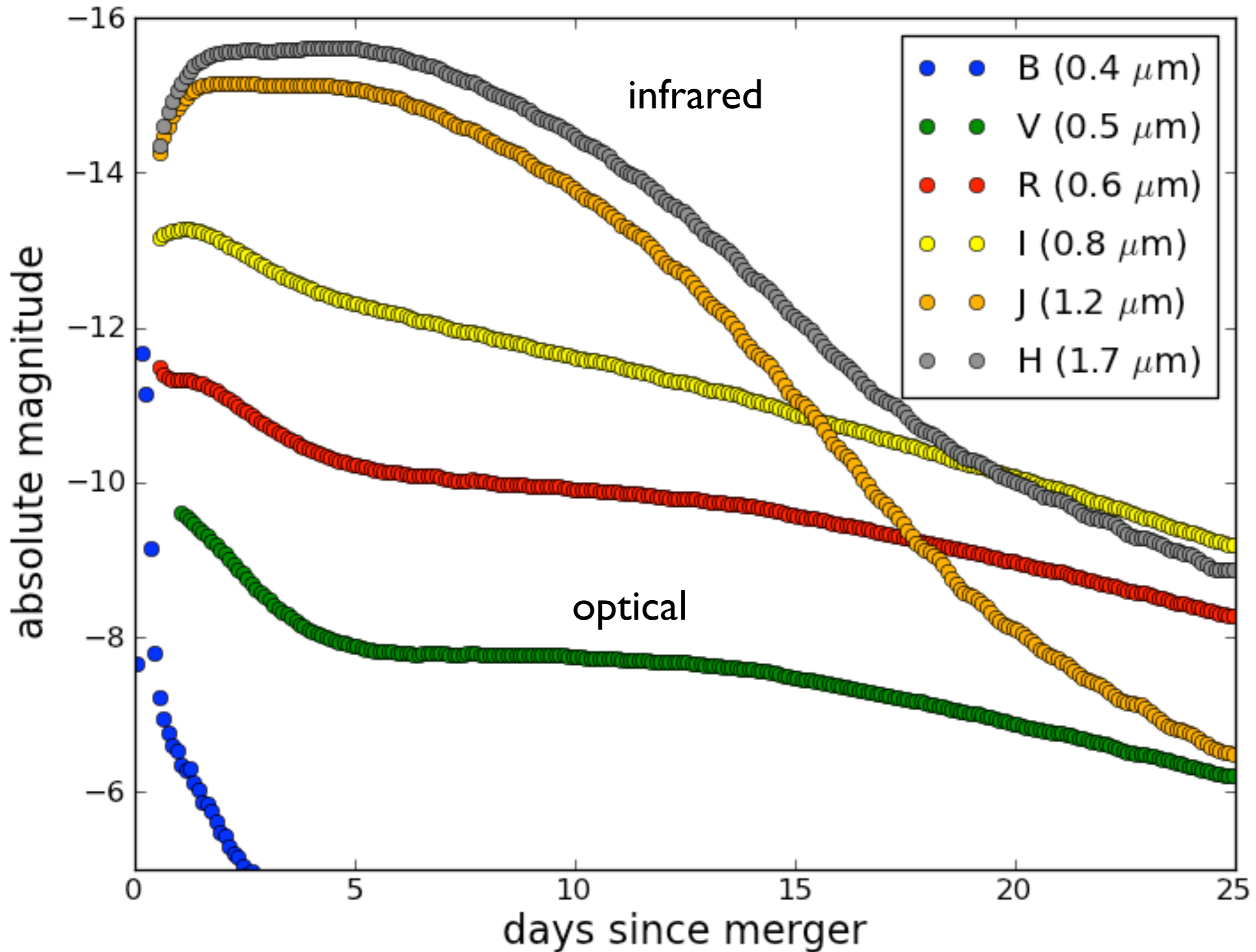


model spectral energy distribution



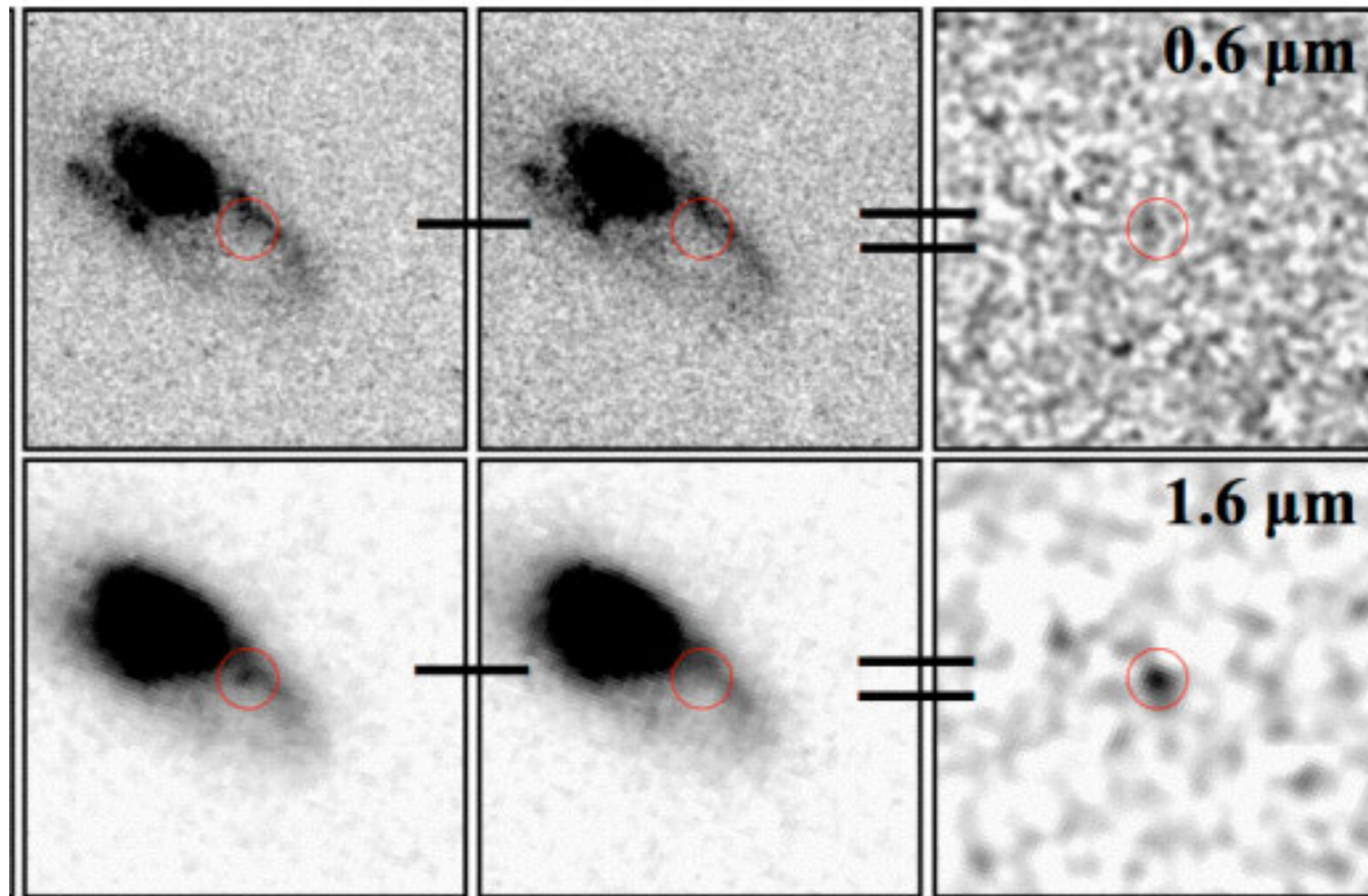
kasen+ 2013

broadband light curves - infrared!



GRB 130603B

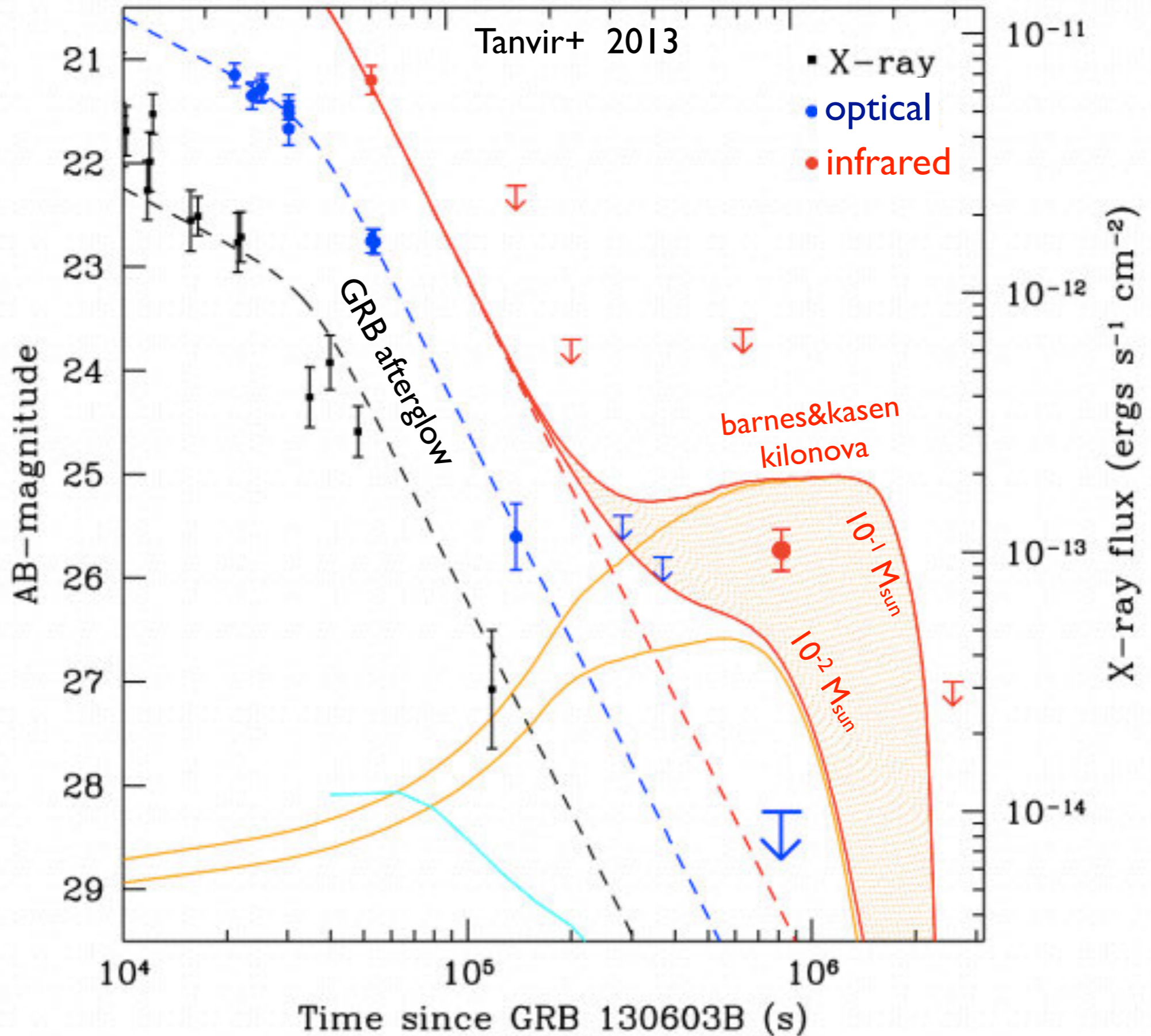
relatively nearby short GRB ($z = 0.356$)



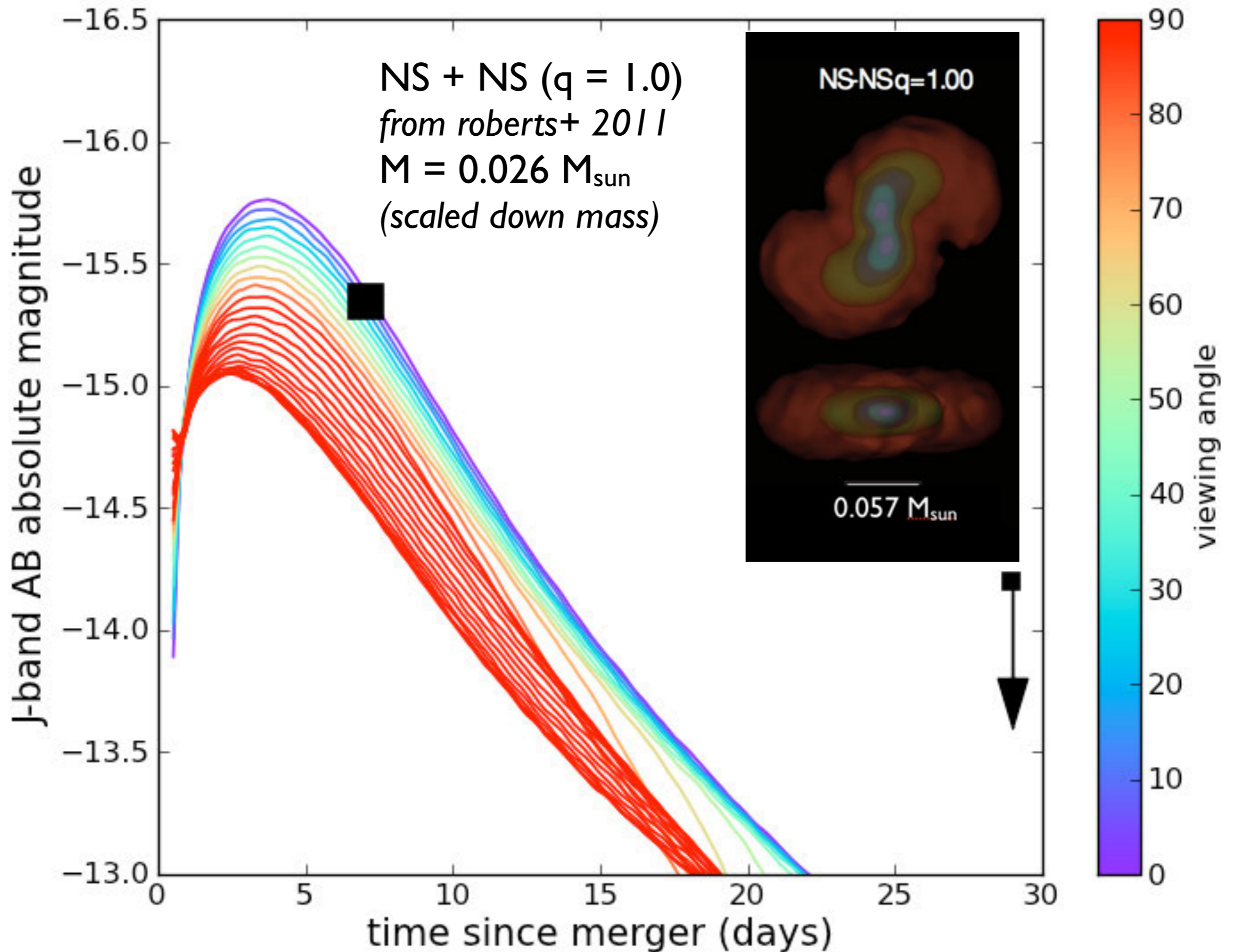
deep infrared imaging with HST
triggered ~ 1 week after burst

Tanvir+ 2013
c.f. Berger 2013

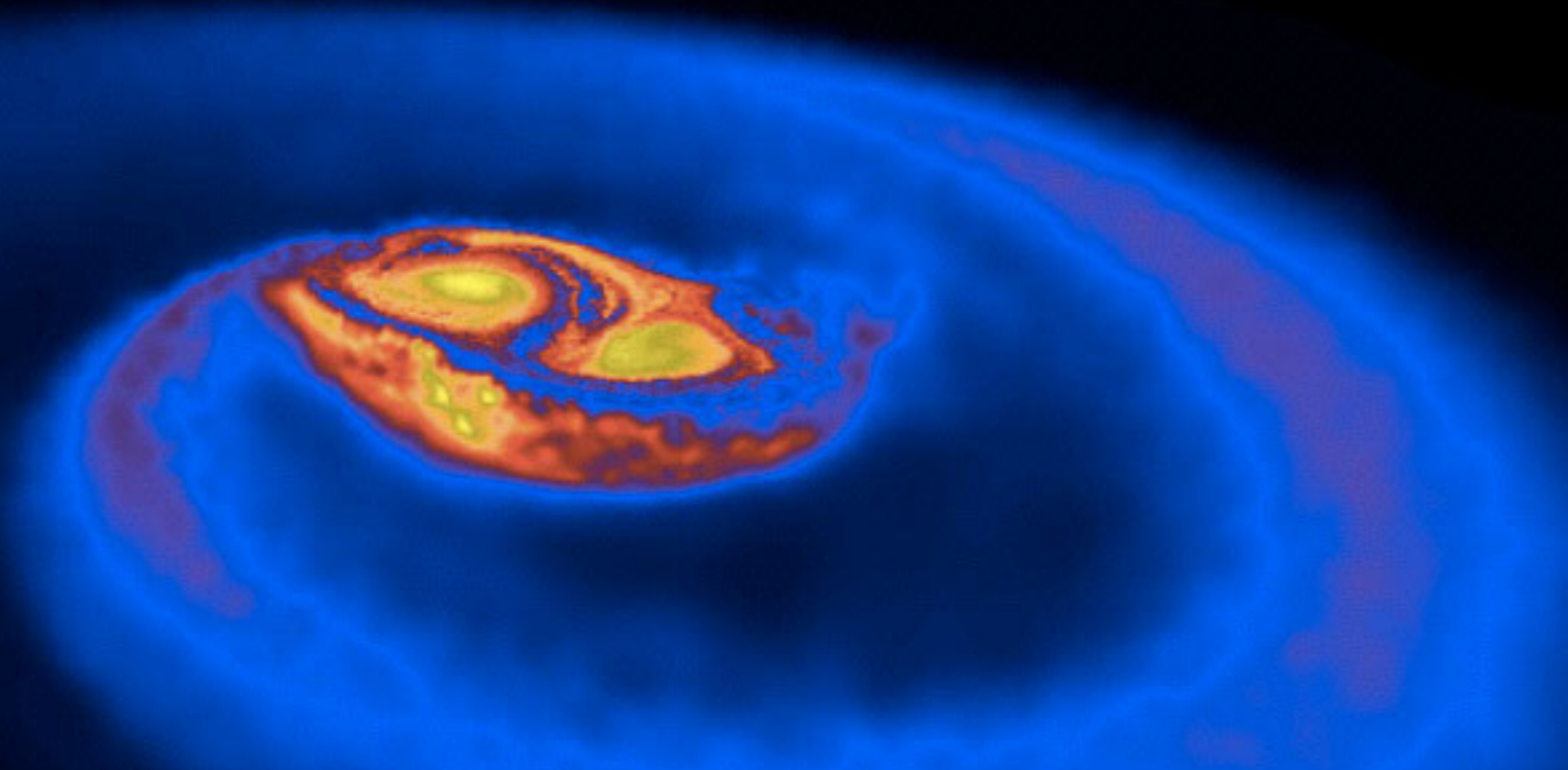
discovery of an r-process kilonova?



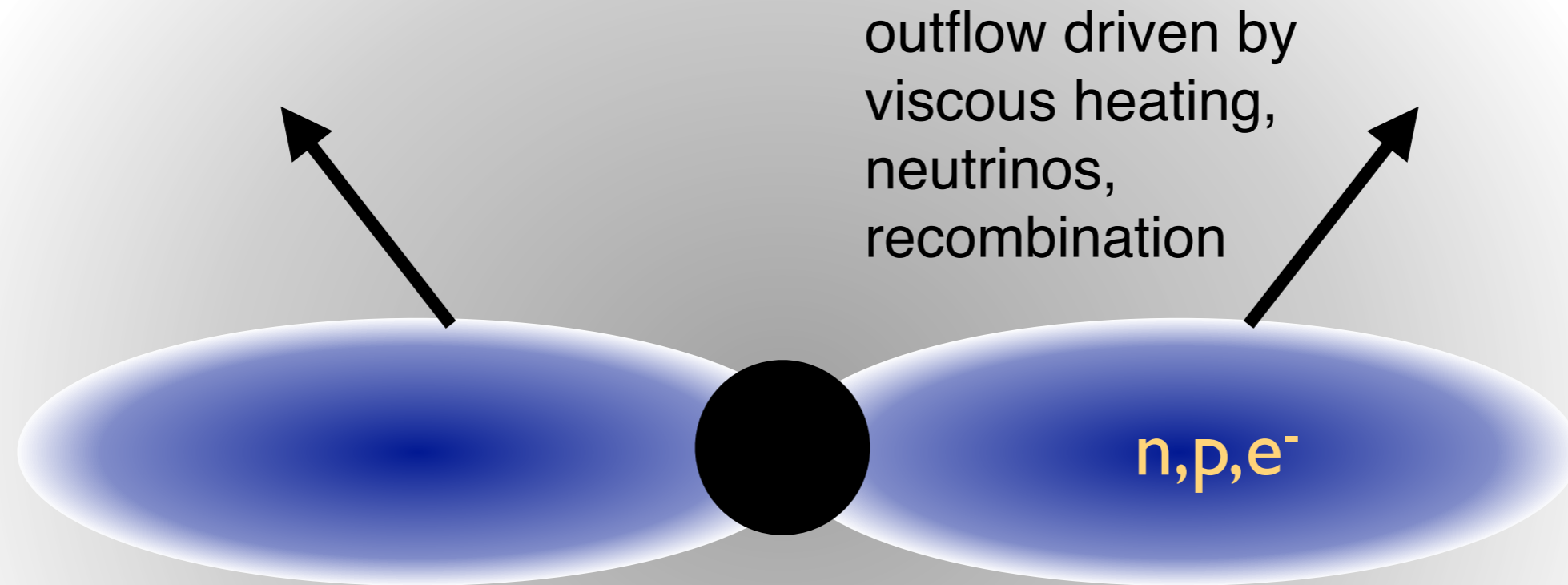
3D kilonova transport models



post-merger (longer term) mass outflows



post-merger (longer term) viscous evolution



outflow driven by
viscous heating,
neutrinos,
recombination

n,p,e⁻

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

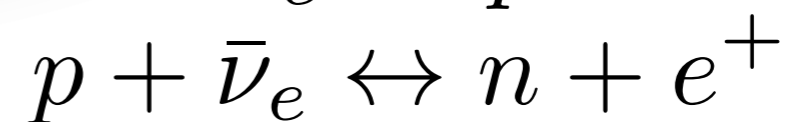
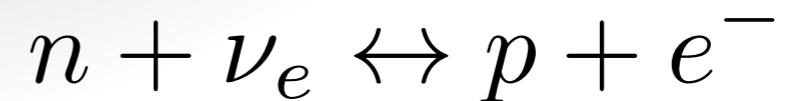
$$M_{\text{rem}} \sim 3 M_{\odot}$$

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

orbital time scale \sim msec

viscous time scale \sim sec

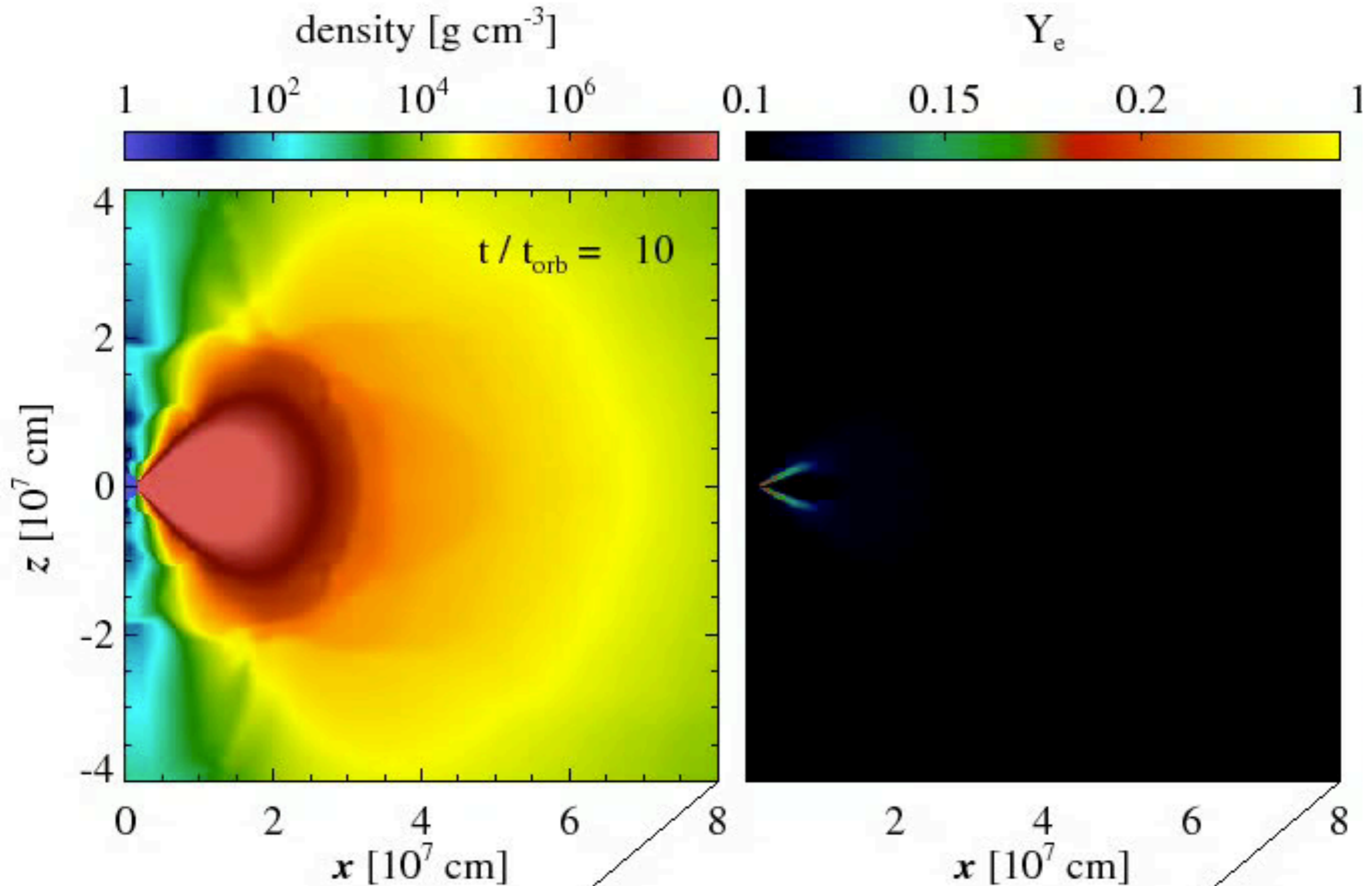
neutrino irradiation
increases the Y_e of disk

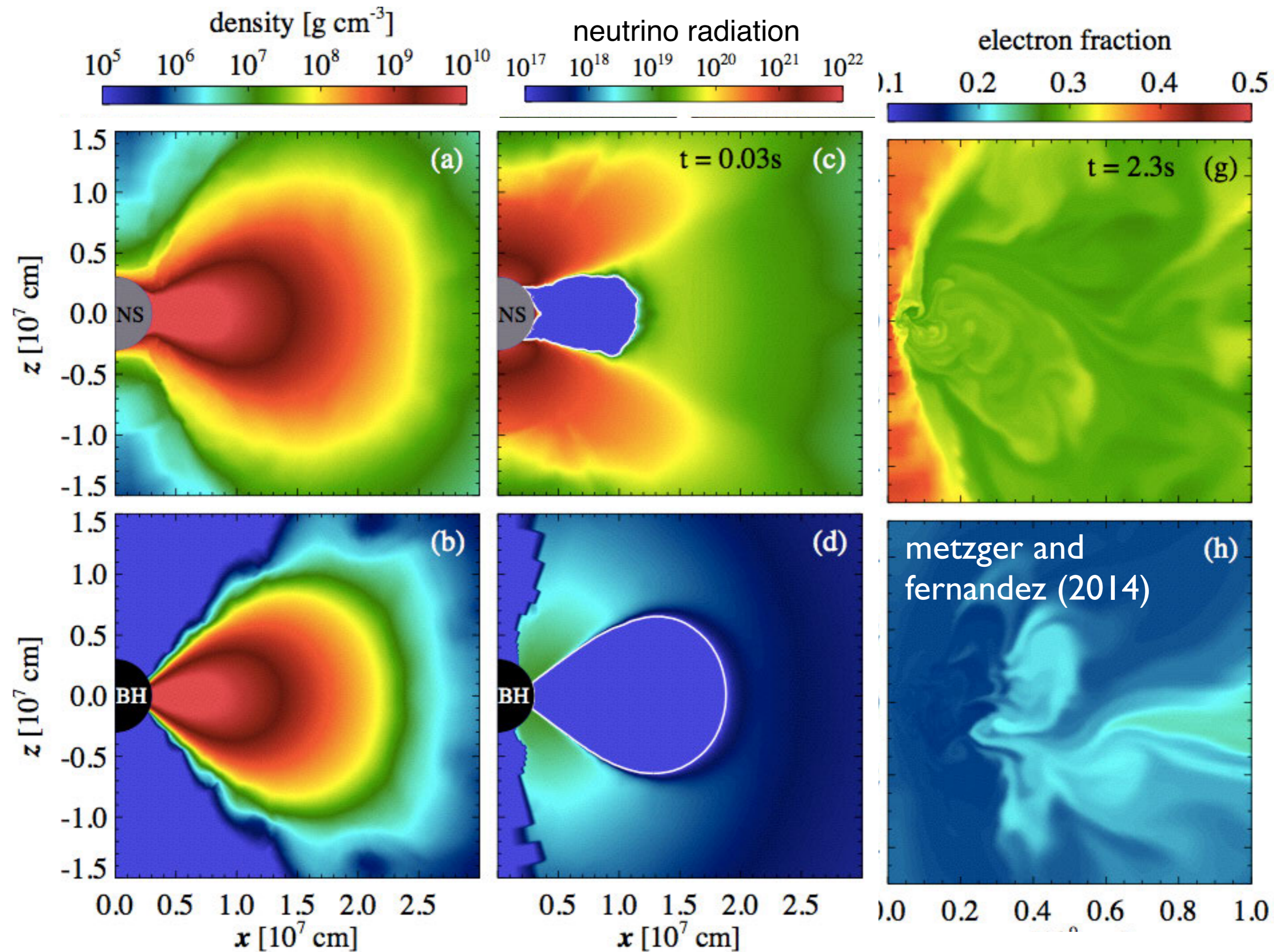


post-merger ejection in disk winds

viscous, nuclear, or neutrino driven, on longer timescales $\sim 1s$

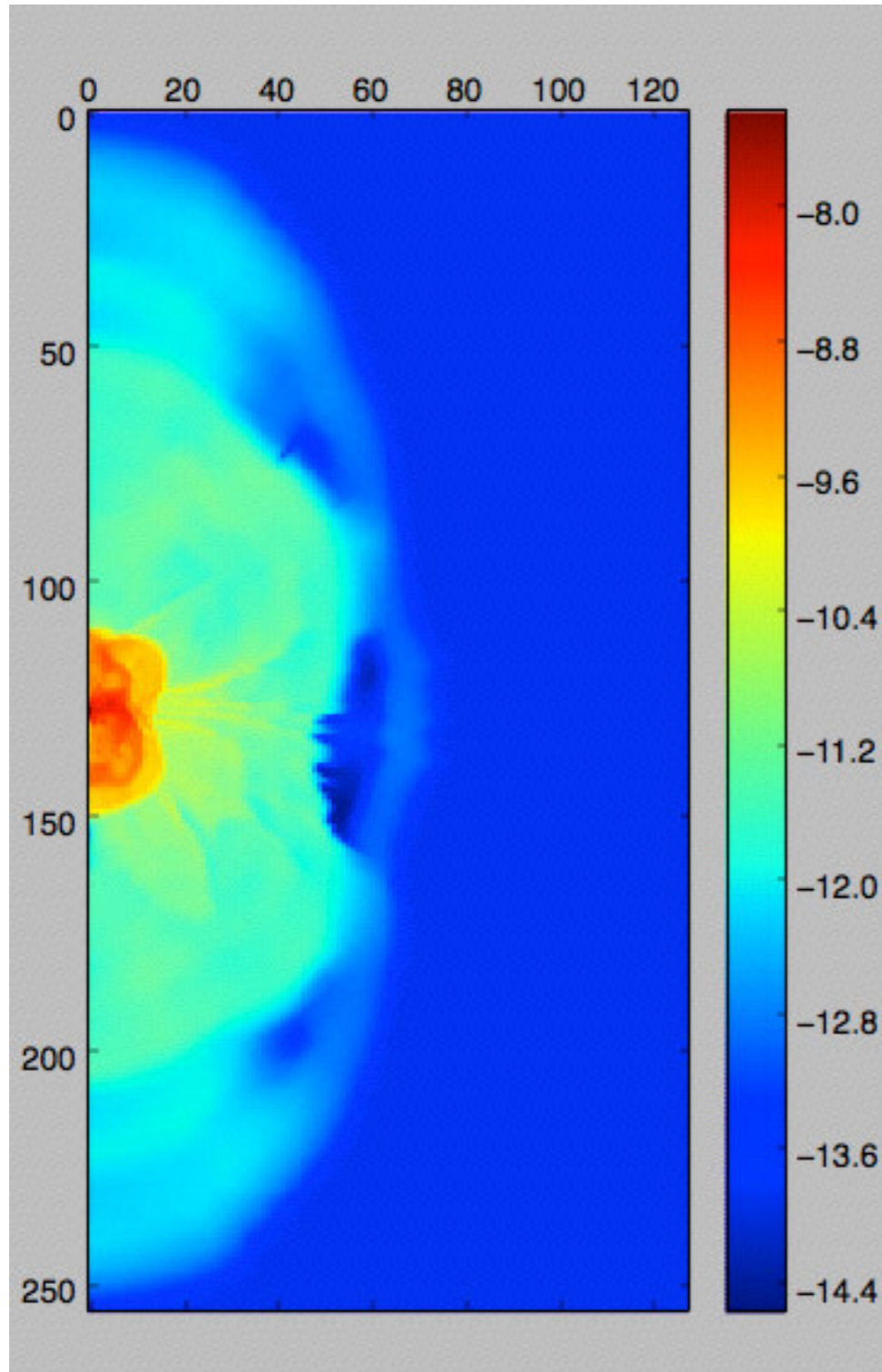
fernandez and metzger (2013)



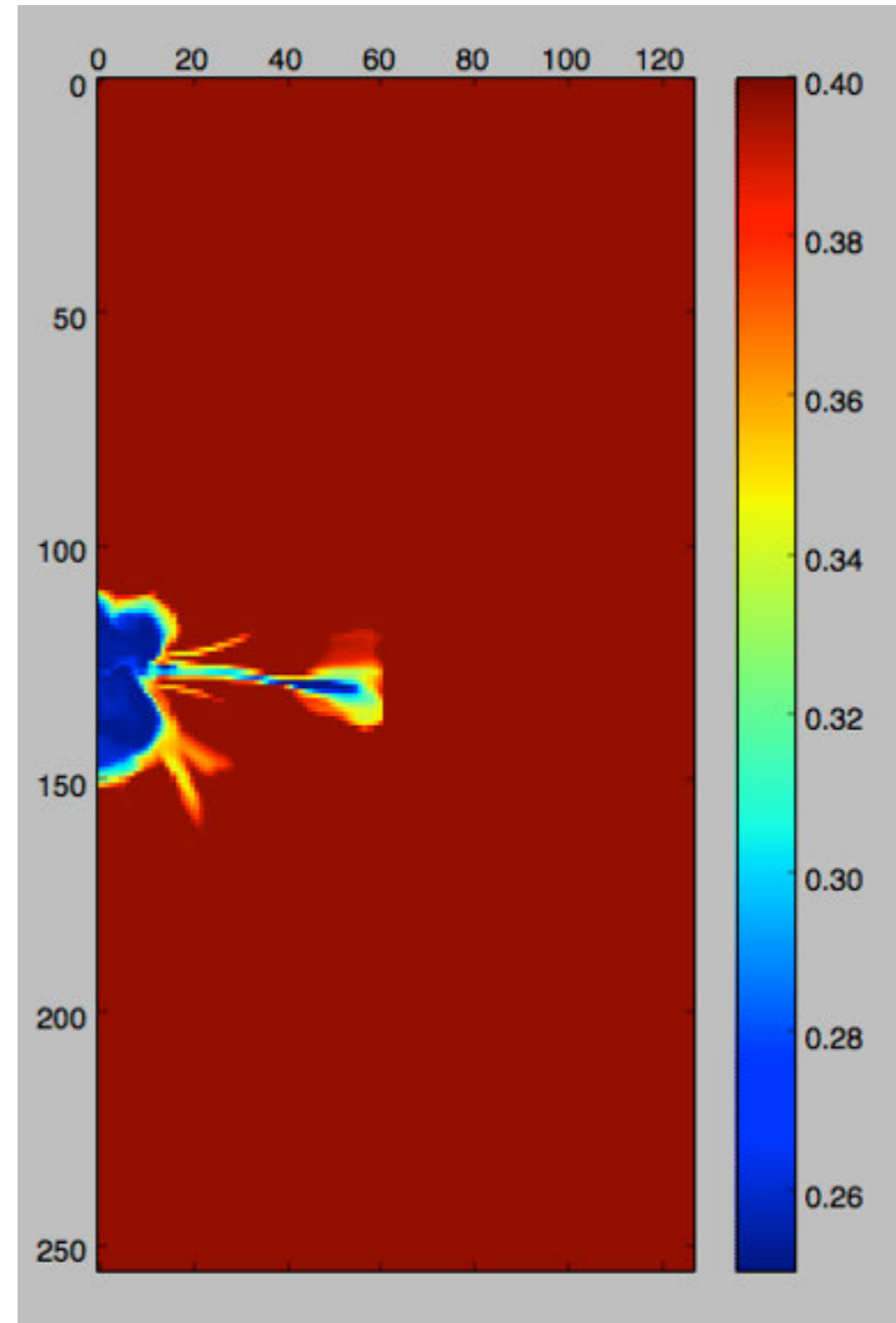


ejected disk wind (NS lives 30 ms)

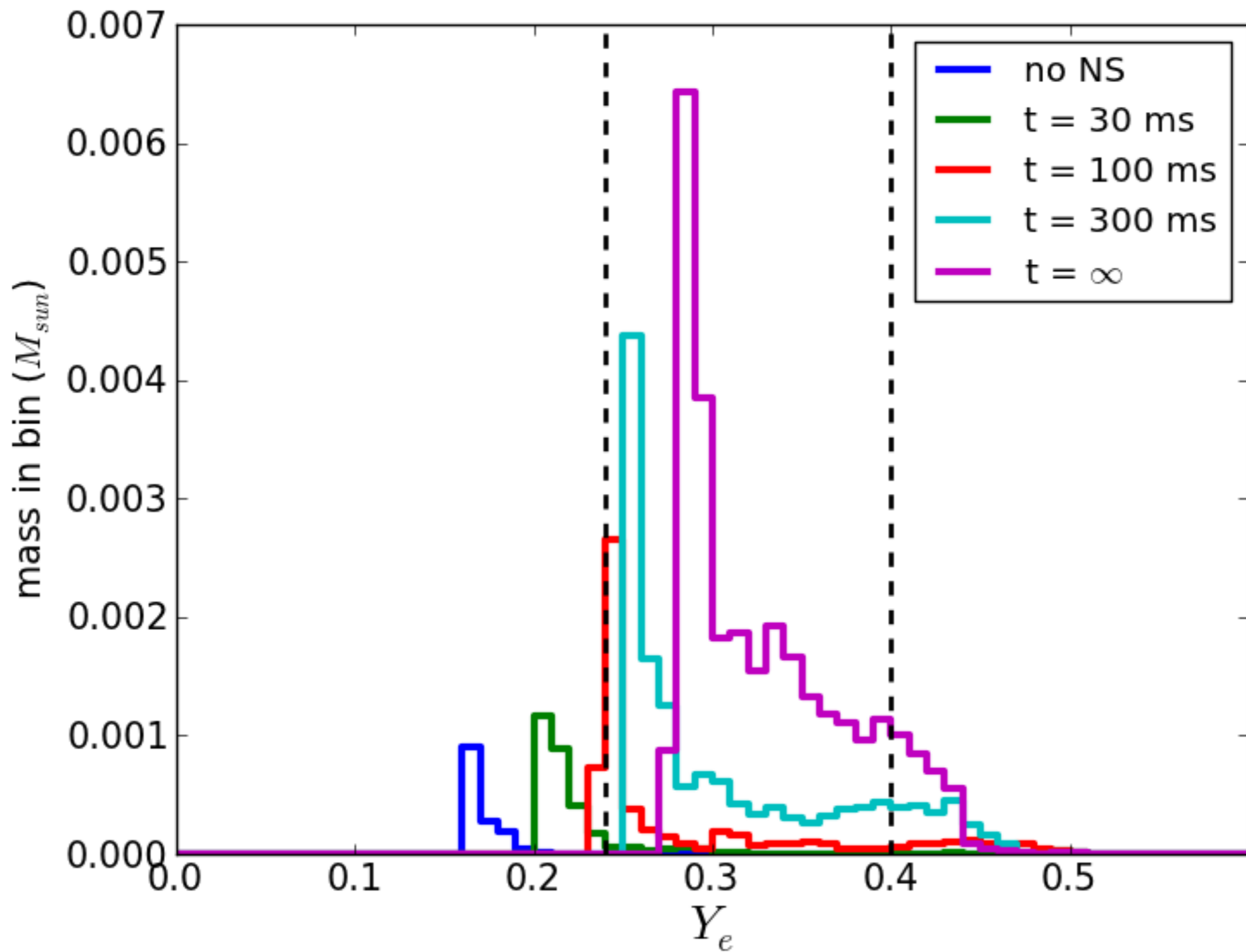
\log_{10} density



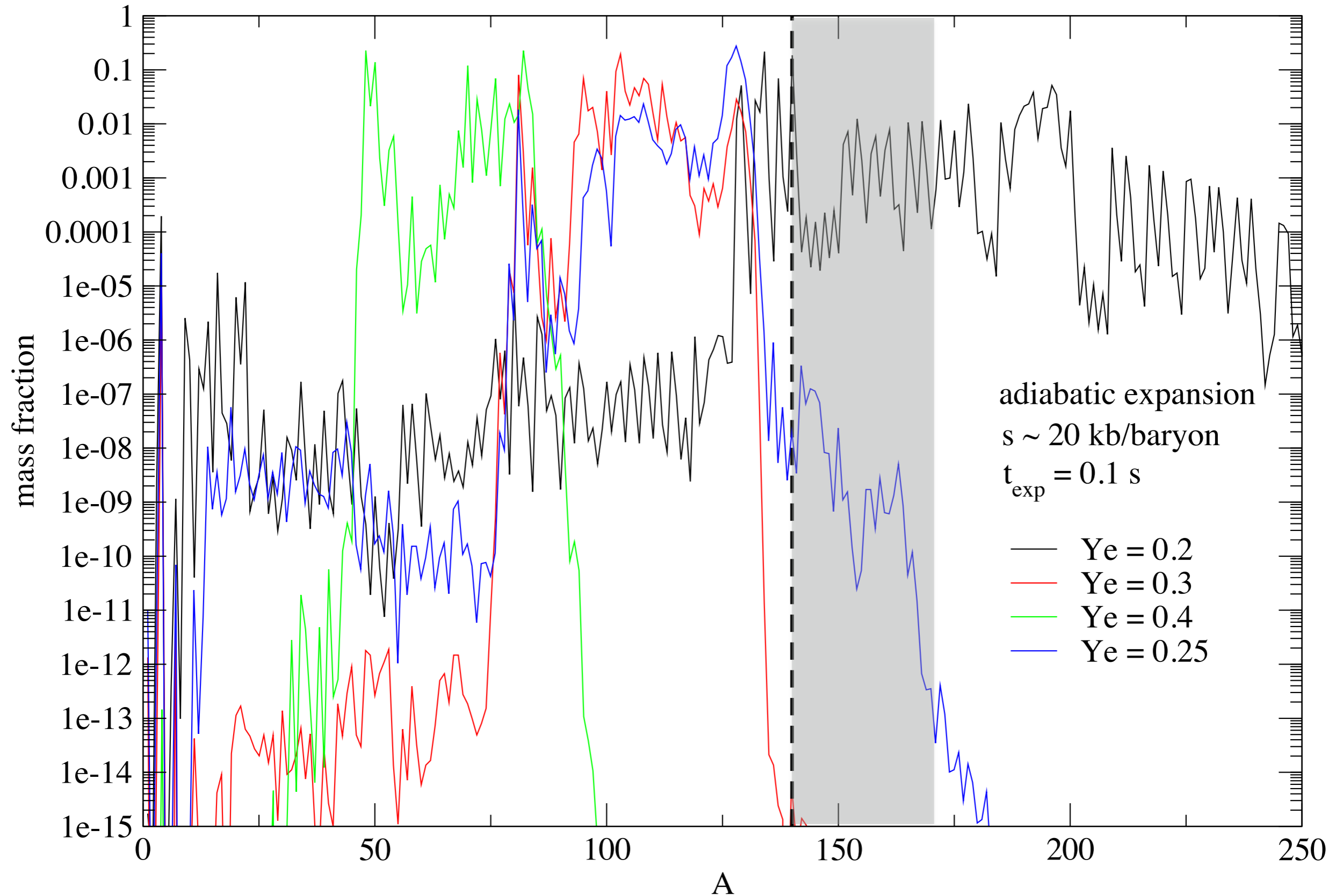
Y_e



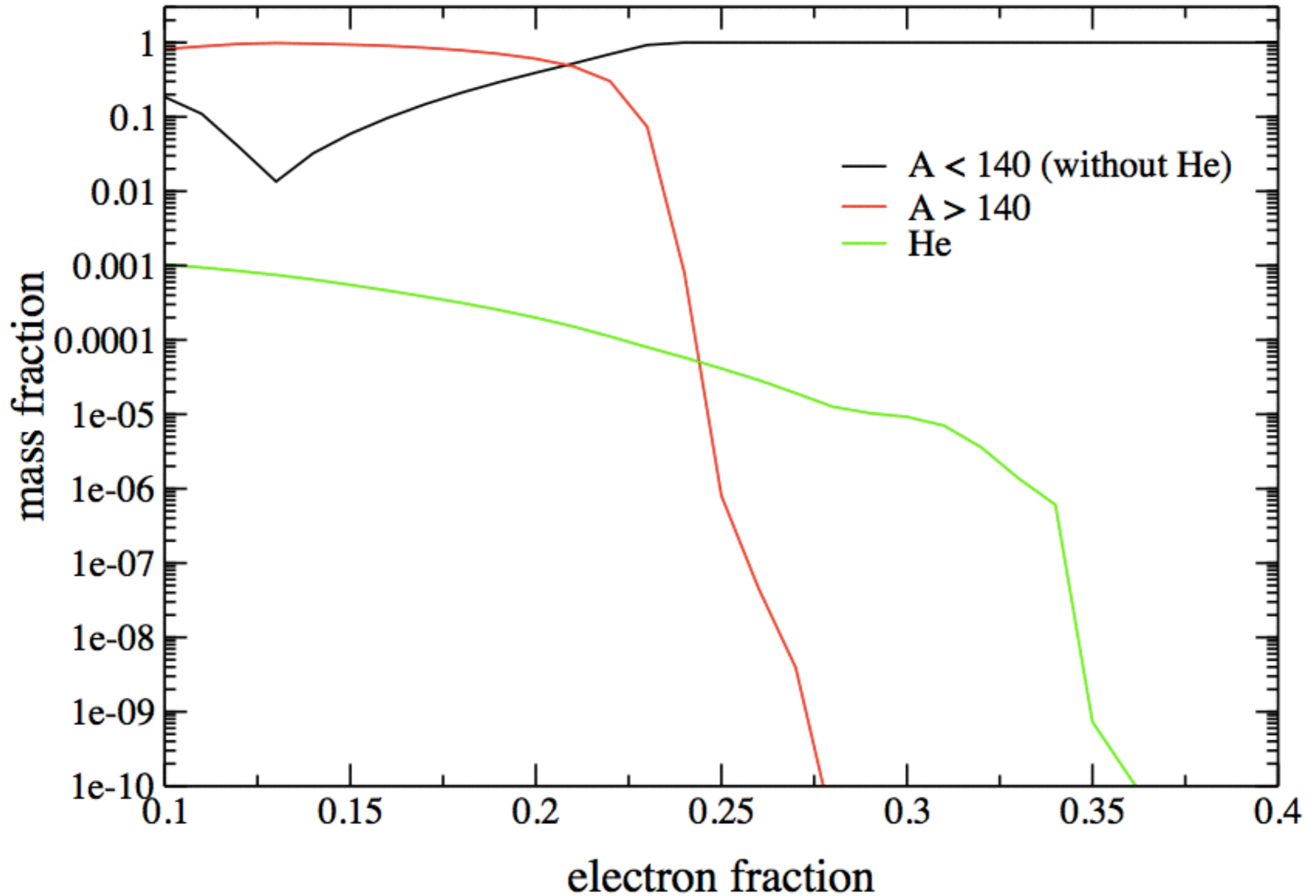
ejected mass - distribution in Y_e



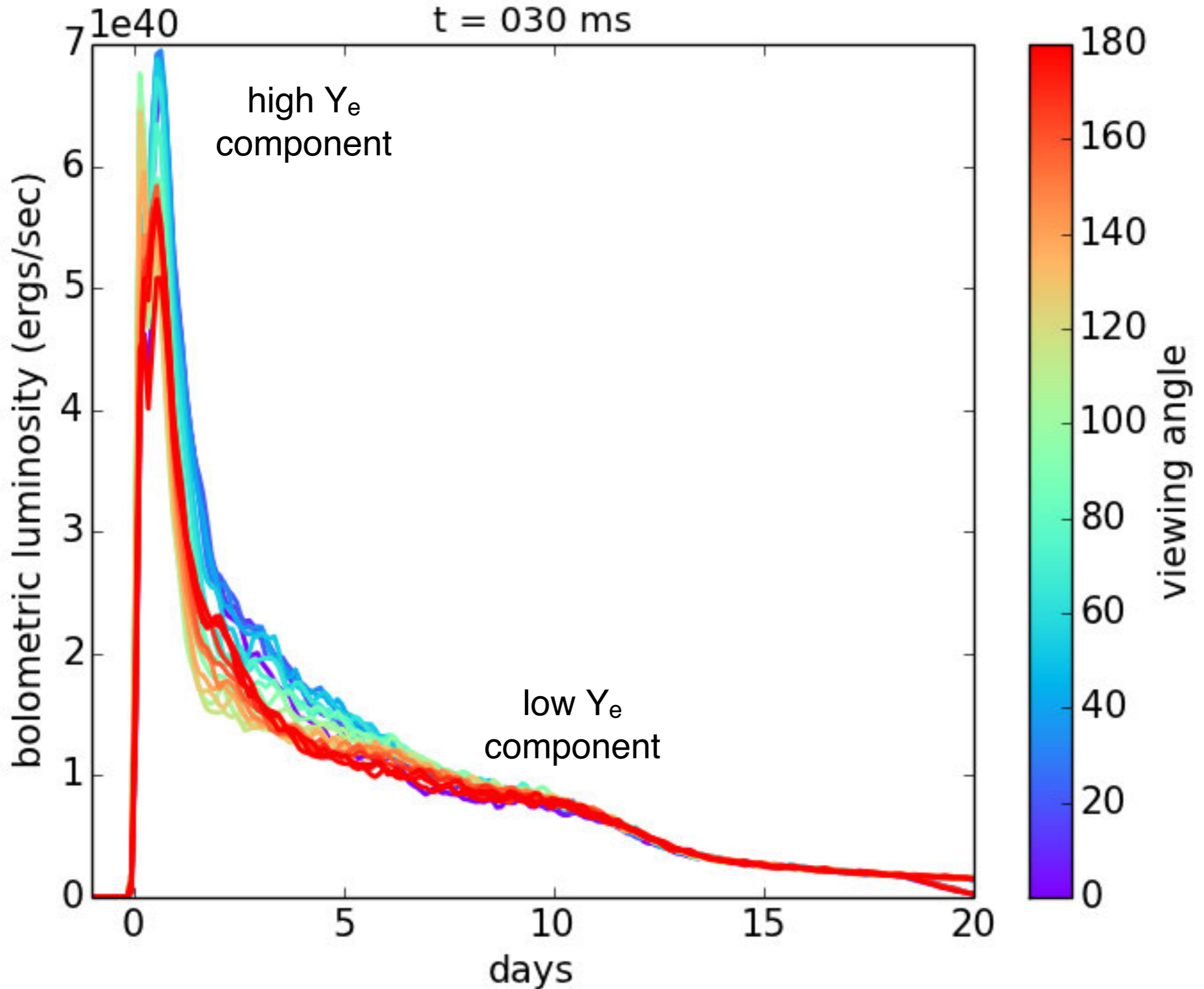
r-process nucleosynthesis (from torch)



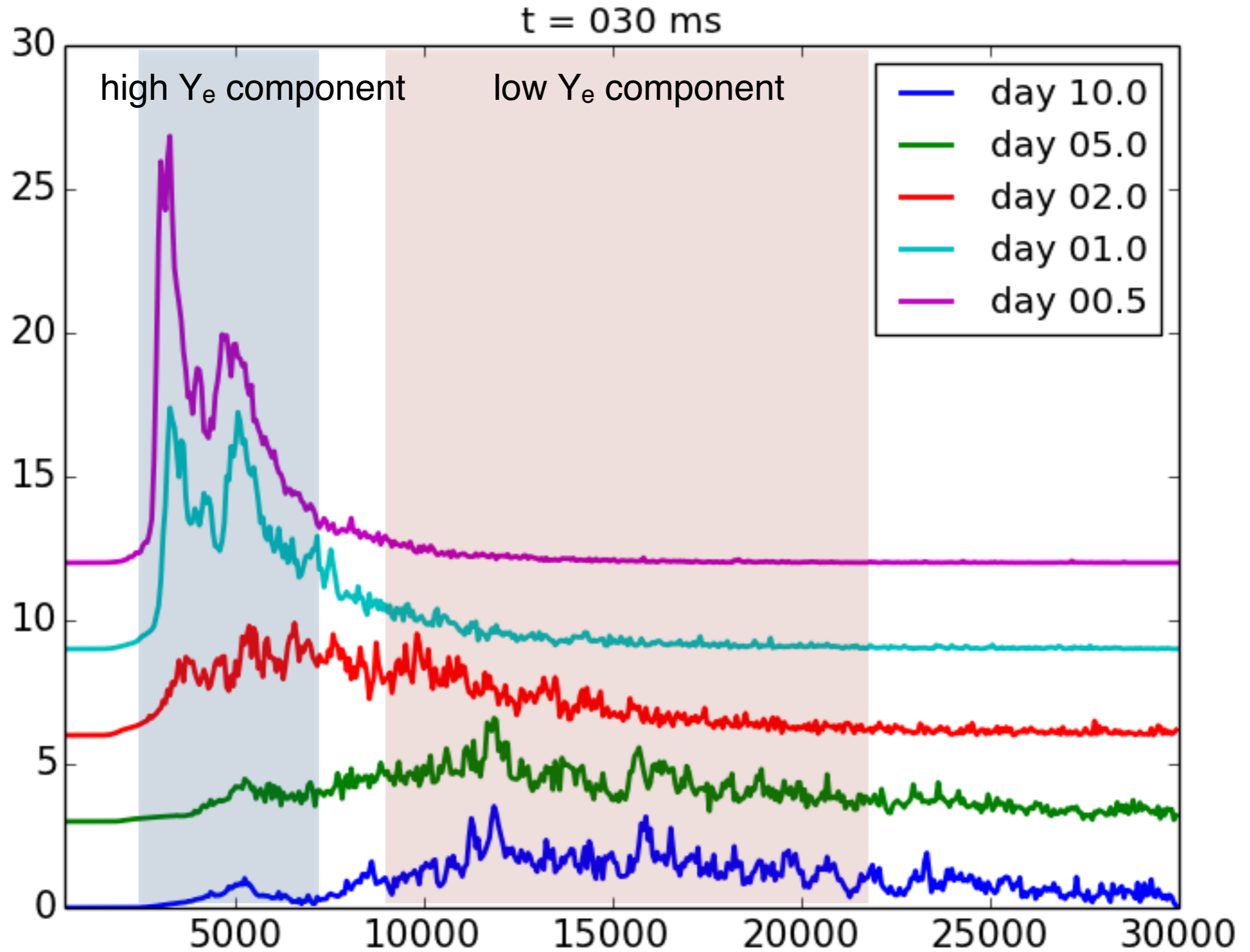
r-process nucleosynthesis (from torch)



light curve of disk wind (30 ms neutron star)

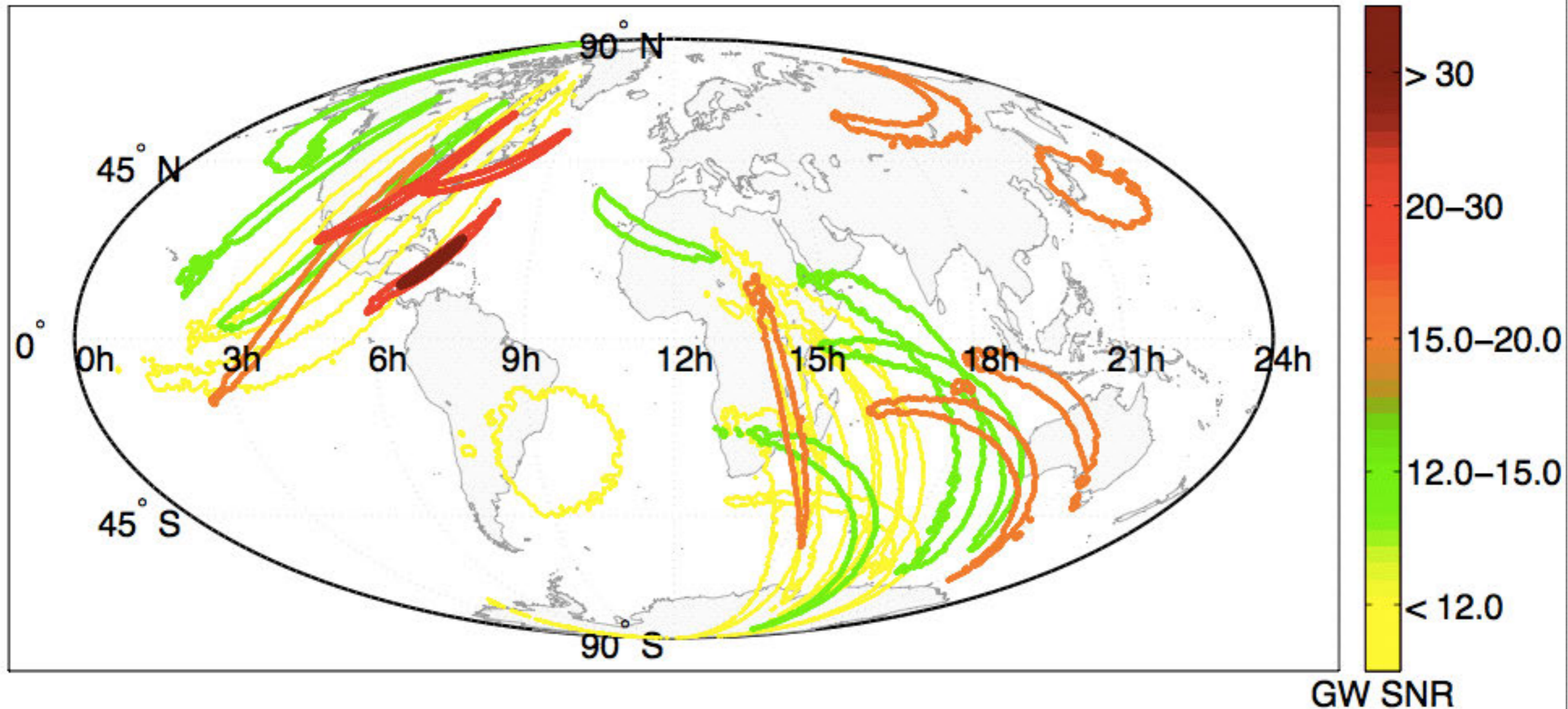


spectra of disk wind (30 ms neutron star)



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)

