Modeling SN Light Curves and Spectra: Clues to the Progenitor

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- What we can do or not do with analytics
- Difficulties in modeling
  - Initial Conditions
  - Transport issues: Transport, opacities, coupling
  - Radiation hydrodynamics
- Experiments

Analytic Estimates

- First Pass, an expanding sphere:

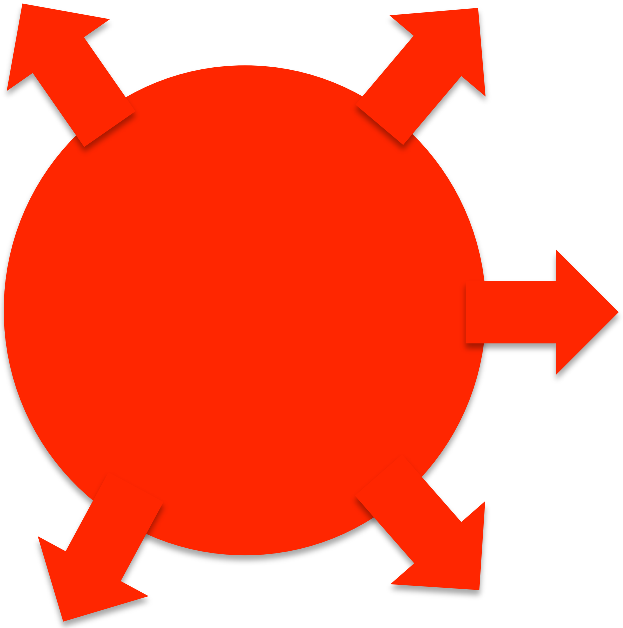
$$L = 4\pi r^2 \sigma T^4$$

- If we assume adiabatic expansion:

$$S \propto aT^3/\rho \rightarrow T \propto S^{1/3} M^{1/3} r^{-1}$$

$$\rightarrow L \propto r^{-2} M^{4/3} S^{1/3}$$

- What is missing?
  - ➢ Entropy at photosphere is not constant: Transport, ^{56}Ni decay, shock heating.
  - ➢ Photosphere doesn't expand with ejecta. Is a photosphere even well-defined?



Deviations from adiabatic assumption (Energy not dominated by thermal energy):

- Energy sources: ^{56}Ni decay, Shock Heating
- Cooling (diffusion timescale important)
- Arnett et al. (1980,1982) produced semi-analytic solutions incorporating 56Ni decay and cooling.
- For a simple sphere, shock heating can be estimated by:

$$aT^4 Vol. = K.E. \rightarrow T = (3E_{explosion}/(4\pi r^3 a))^{1/4}$$

Including these effects already pushes toward semi-analytic solutions and most still make simplifying assumptions on the opacities. In the 80s, we started using simulations to estimate light curves.

Applying Early Light-Curve Models

Litvinova and Nadezhin (1985) derived relations for ejecta mass (m), radius (r) and explosion energy (E) as a function of V magnitude, time since explosion (t) and photospheric velocity (v) based on their simulations:

- lg(E(foe)) = 0.135 V + 2.34lg(t) +3.13lg(v) -4.205
- lg(M(solar)) = 0.234 V + 2.91lg(t) + 1.96lg(v) -1.829
- Lg(R(solar)) = -0.572V – 1.07lg(t)-2.74lg(v) -3.350

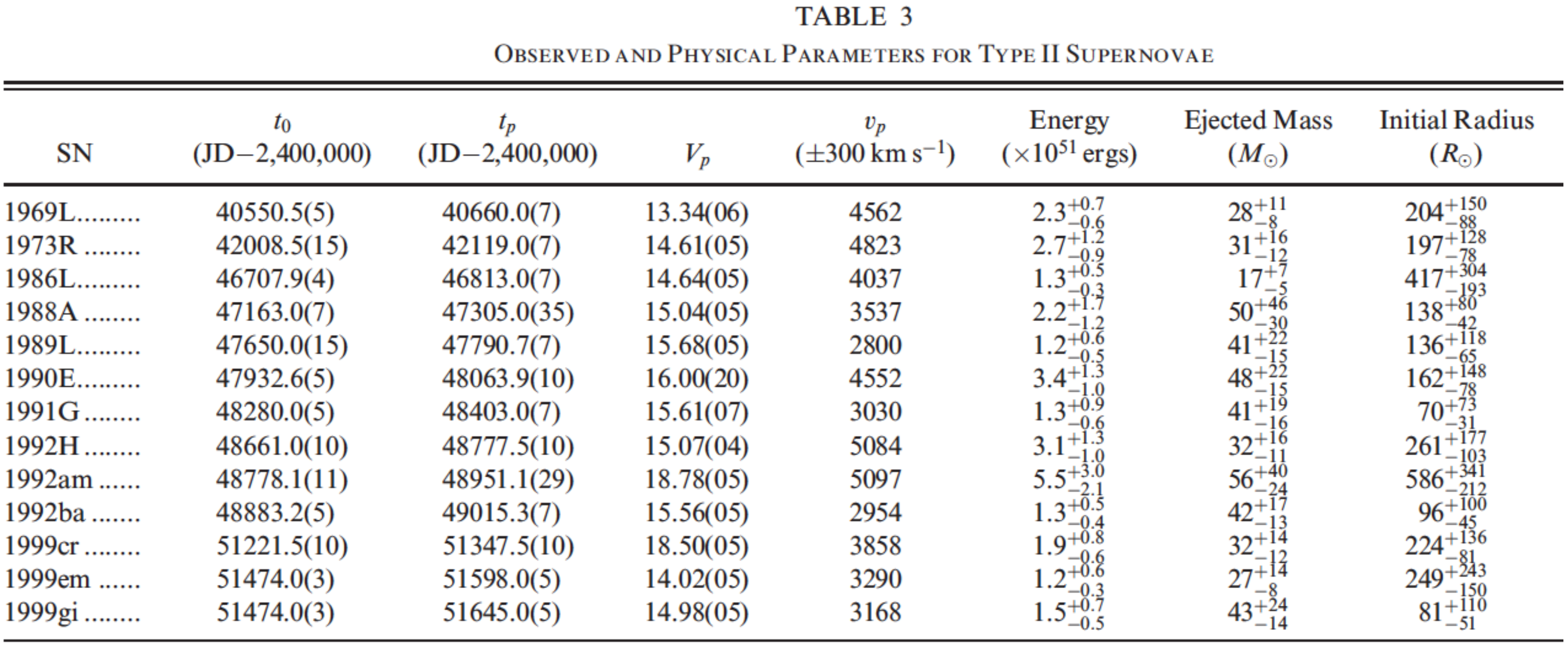


TABLE 3

OBSERVED AND PHYSICAL PARAMETERS FOR TYPE II SUPERNOVAE

SN	t_0 (JD−2,400,000)	t_p (JD−2,400,000)	V_p	v_p (±300 km s^{-1})	Energy (×10^{51} ergs)	Ejected Mass ($M_\odot$)	Initial Radius ($R_\odot$)
1969L.........	40550.5(5)	40660.0(7)	13.34(06)	4562	$2.3^{+0.7}_{-0.6}$	28^{+11}_{-8}	204^{+150}_{-88}
1973R	42008.5(15)	42119.0(7)	14.61(05)	4823	$2.7^{+1.2}_{-0.9}$	31^{+16}_{-12}	197^{+128}_{-78}
1986L.........	46707.9(4)	46813.0(7)	14.64(05)	4037	$1.3^{+0.5}_{-0.3}$	17^{+7}_{-5}	417^{+304}_{-193}
1988A	47163.0(7)	47305.0(35)	15.04(05)	3537	$2.2^{+1.7}_{-1.2}$	50^{+46}_{-30}	138^{+80}_{-42}
1989L.........	47650.0(15)	47790.7(7)	15.68(05)	2800	$1.2^{+0.6}_{-0.5}$	41^{+22}_{-15}	136^{+118}_{-65}
1990E.........	47932.6(5)	48063.9(10)	16.00(20)	4552	$3.4^{+1.3}_{-1.0}$	48^{+22}_{-15}	162^{+148}_{-78}
1991G	48280.0(5)	48403.0(7)	15.61(07)	3030	$1.3^{+0.9}_{-0.6}$	41^{+19}_{-16}	70^{+73}_{-31}
1992H	48661.0(10)	48777.5(10)	15.07(04)	5084	$3.1^{+1.3}_{-1.0}$	32^{+16}_{-11}	261^{+177}_{-103}
1992am	48778.1(11)	48951.1(29)	18.78(05)	5097	$5.5^{+3.0}_{-2.1}$	56^{+40}_{-24}	586^{+341}_{-212}
1992ba	48883.2(5)	49015.3(7)	15.56(05)	2954	$1.3^{+0.5}_{-0.4}$	42^{+17}_{-13}	96^{+100}_{-45}
1999cr	51221.5(10)	51347.5(10)	18.50(05)	3858	$1.9^{+0.8}_{-0.6}$	32^{+14}_{-12}	224^{+136}_{-81}
1999em	51474.0(3)	51598.0(5)	14.02(05)	3290	$1.2^{+0.6}_{-0.3}$	27^{+14}_{-8}	249^{+243}_{-150}
1999gi	51474.0(3)	51645.0(5)	14.98(05)	3168	$1.5^{+0.7}_{-0.5}$	43^{+24}_{-14}	81^{+110}_{-51}

Hamuy (2003) fits with this formulae predict extremely high masses (too high to be believed).

Breakout Analytics

- Shock Breakout also has the potential to probe the star:

$$t_{diff} = (\delta r/\lambda)^2 \lambda/c \quad \text{where } \lambda = (\kappa\rho)^{-1}$$

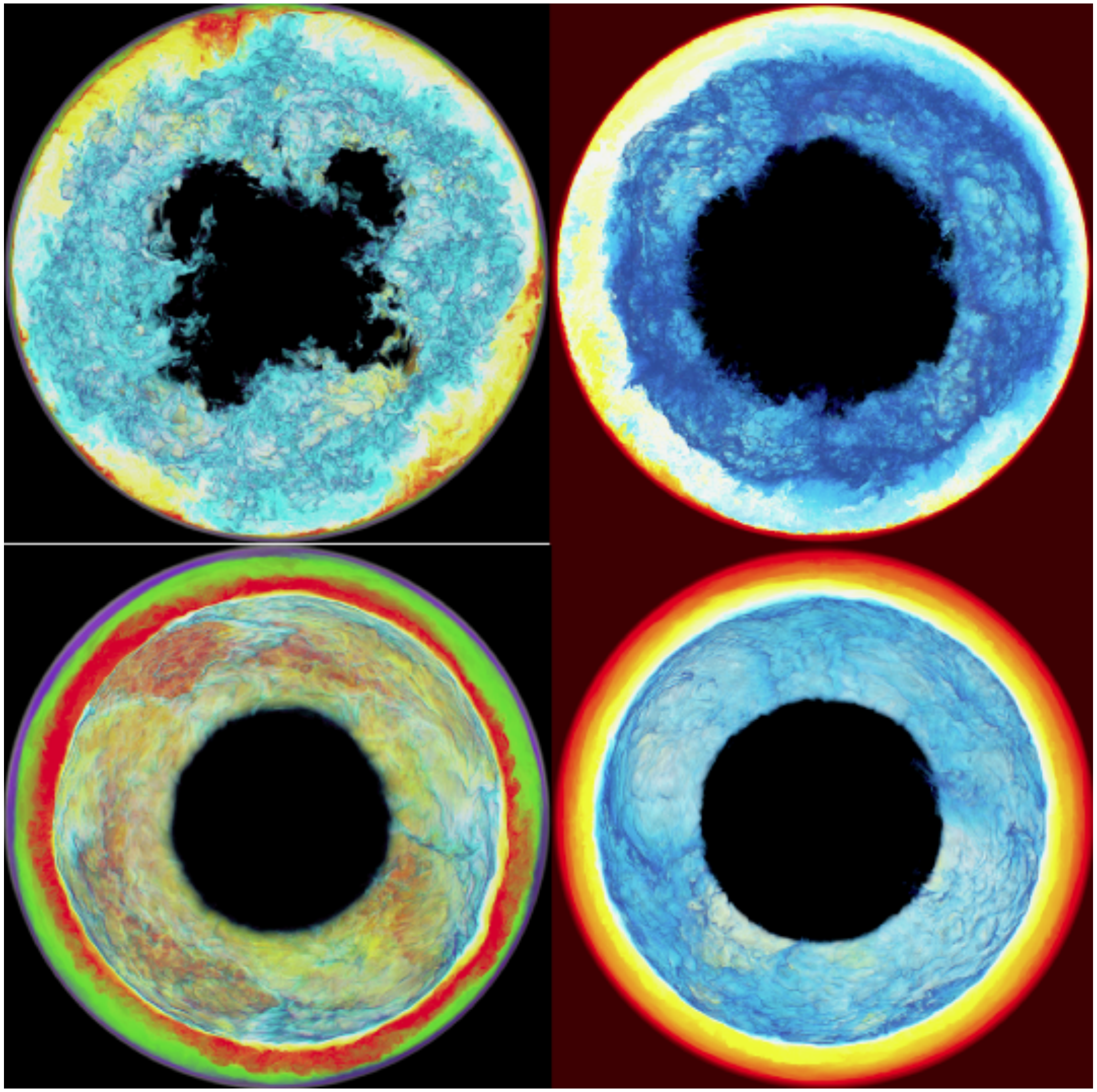
$$v_{diff} = \delta r/t_{diff} = c/(\delta r \kappa \rho)$$

- When $v_{shock} < v_{diff}$, shock breakout occurs. With the shock velocity and time of shock breakout, we can measure the stellar radius and density.
- This is an order of magnitude estimate. Worse yet, there is not a single photosphere for all wavelengths.

Difficulties in Modeling Supernovae

- Initial Conditions
- ➢ Progenitor structure, circumstellar medium (progenitor mass ejections), explosion energy, explosion asymmetry
- Radiation Transport
- ➢ Simplifications in solving the Boltzmann Equation
- ➢ Opacities: number of levels, LTE vs. NLTE, steady state approximations
- ➢ Ion/electron coupling
- Radiation Hydrodynamics
- ➢ 1T, 2T, 3T (radiation/matter decupling)
- ➢ Hydrodynamic shocks and radiation
- ➢ Radiation effects on hydrodynamics

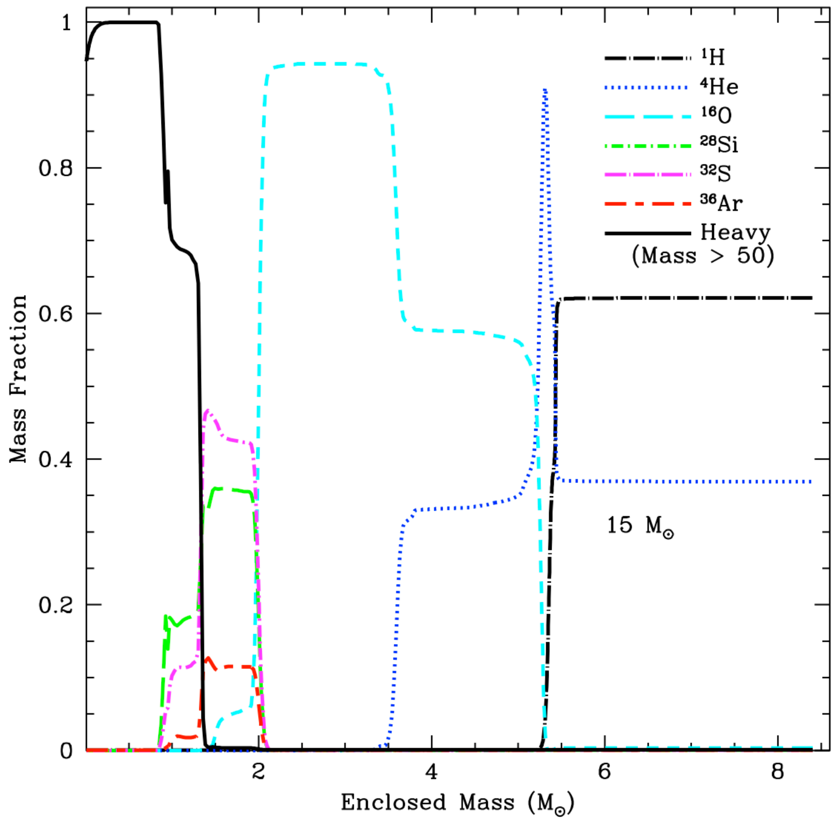
Shell Burning

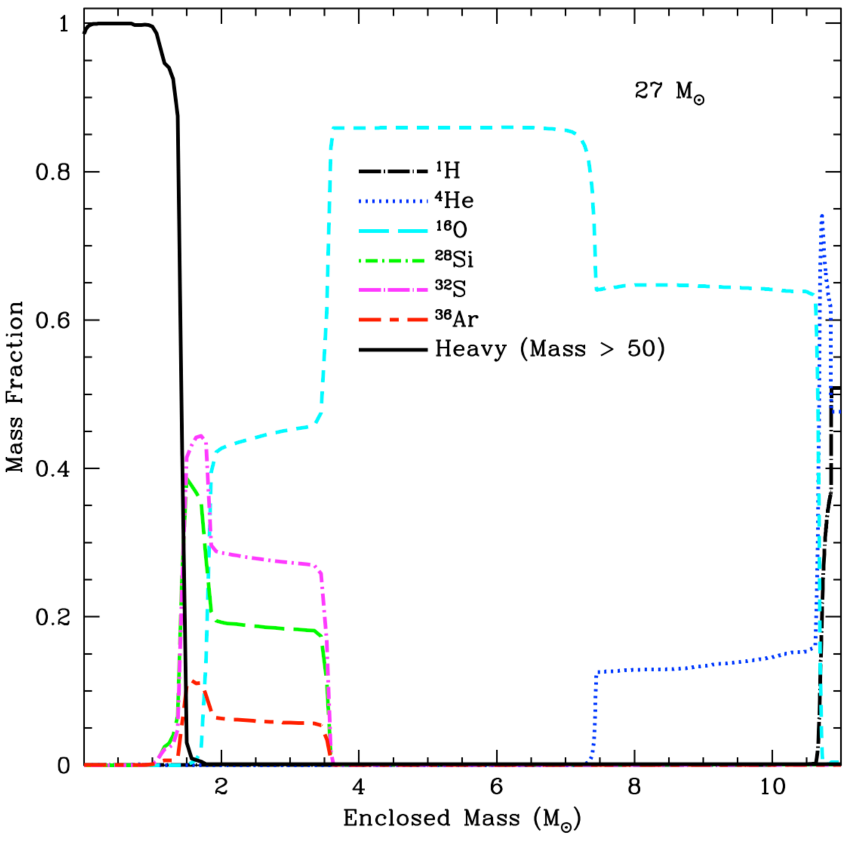


- Shell burning can be explosive (Smith & Arnett 2013, Arnett et al. 2014, Herwig et al. 2014). This will alter the core masses as well as the circumstellar medium.

Stellar Models Key

- New mixing algorithms may burn helium (through more dynamic shell burning), increasing the Ic/Ib ratio (Frey et al. 2013)





Binaries and mass loss

- Binary searches in clusters suggest that >50% of massive stars are in close binaries (Kobulnicky et al. 2012, Sana et al. 2012).
- Mass transfer, Common envelope will affect circumstellar media and, in some cases, stellar structure.
- The strength and asymmetries in wind mass loss has also changed over the last decade.
- All these, mixing, winds, binary effects, can dramatically alter the light curves and we have a lot of work to understand these effects.

Radiation Transport

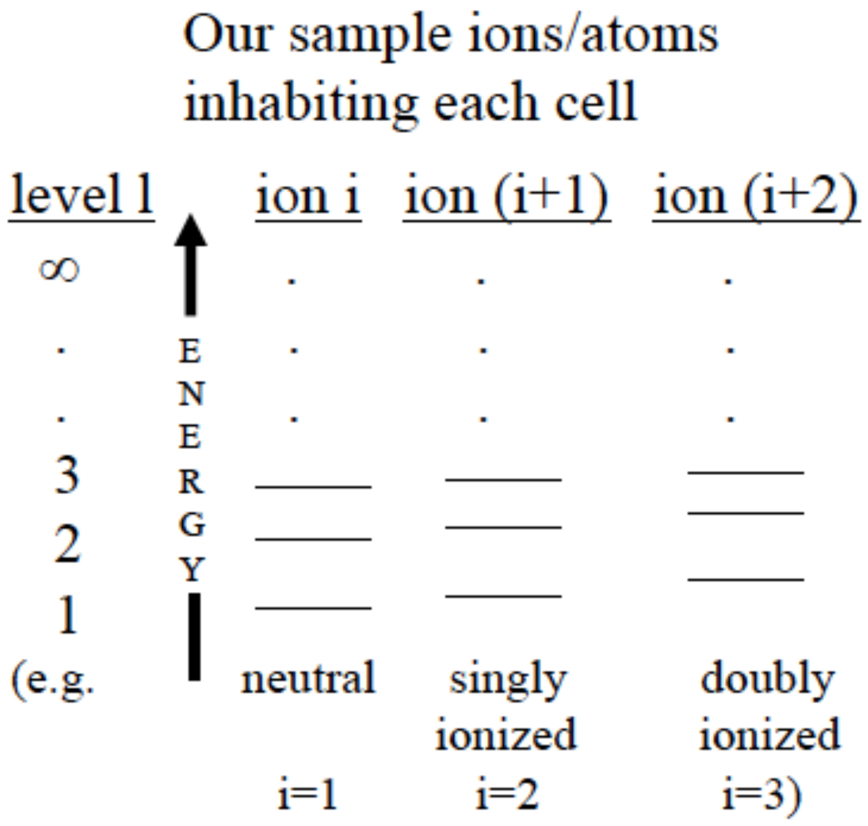
$$\frac{1}{c}\frac{\partial I}{\partial t}+\overbrace{\Omega\bullet\nabla I+(\sigma_a+\sigma_s)I}^{\text{Streaming and Removal Term}}=$$

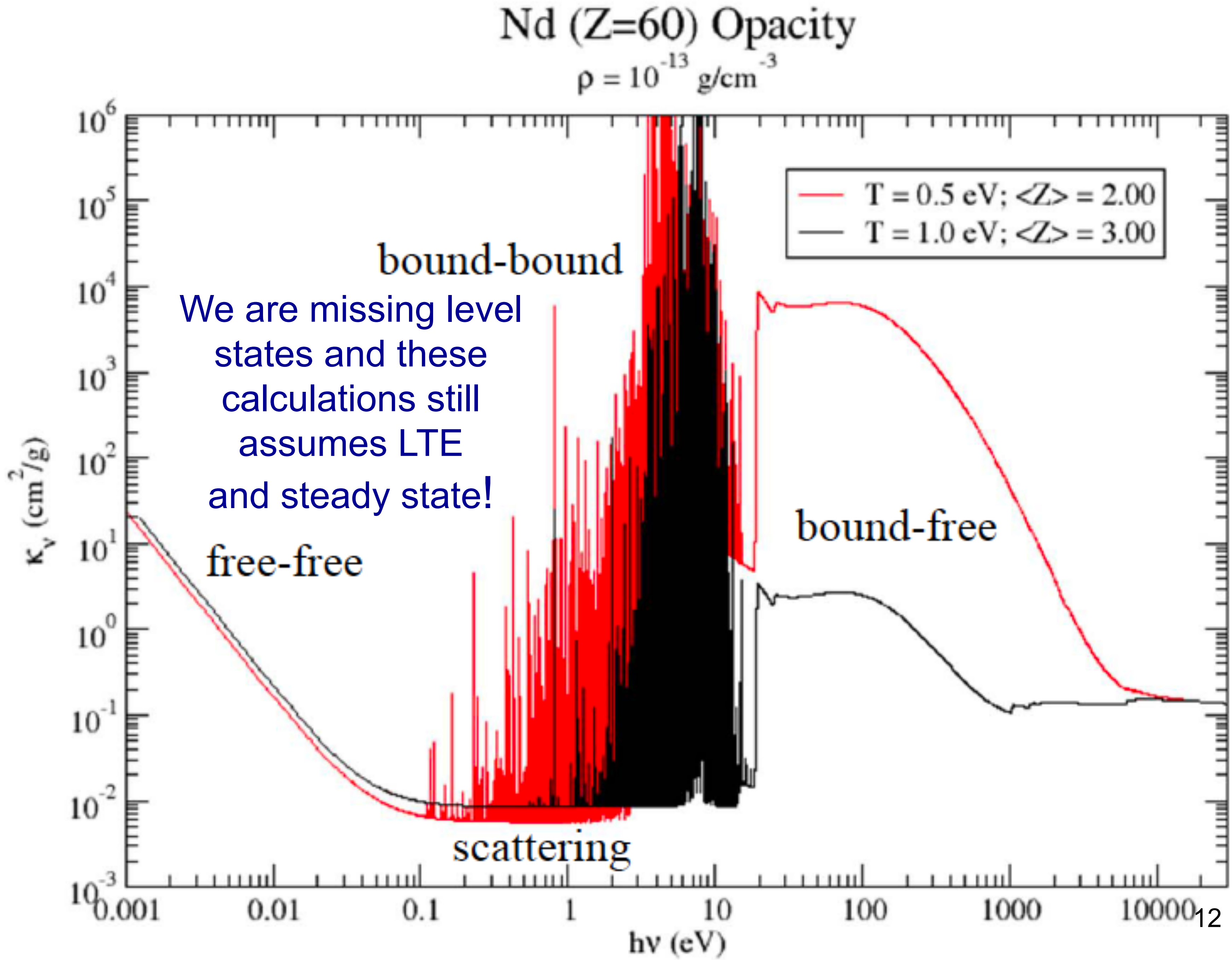
$$\int\int \overbrace{I(r,t,\Omega',E')\sigma(E'\rightarrow E,\Omega'\rightarrow\Omega)}^{\text{Scattering Term}}d\Omega'\,dE'+\overbrace{S(r,t,\Omega,E)}^{\text{Source Term}}$$

- Average over angle:
  - First moment: diffusion
  - Second moment: Variable Eddington Factor
- Average over Energy Group: Gray (Rosseland, Planck)
- Remove time dependent term
- Ignore Spatial Terms

Accurate Opacities critical: the kilanova example

- The presence of heavy elements at such cold temperatures requires the calculation of near-neutral ions with many (> 50) bound electrons.
- Furthermore, the presence of the $4f^4$ subshell (lanthanides) requires the seniority quantum number to properly account for the angular momentum coupling when calculating the fine-structure levels (extra code development was required to obtain atomic structure)
- Just 25 configurations leads to 27,000 levels and 300,000,000 lines.



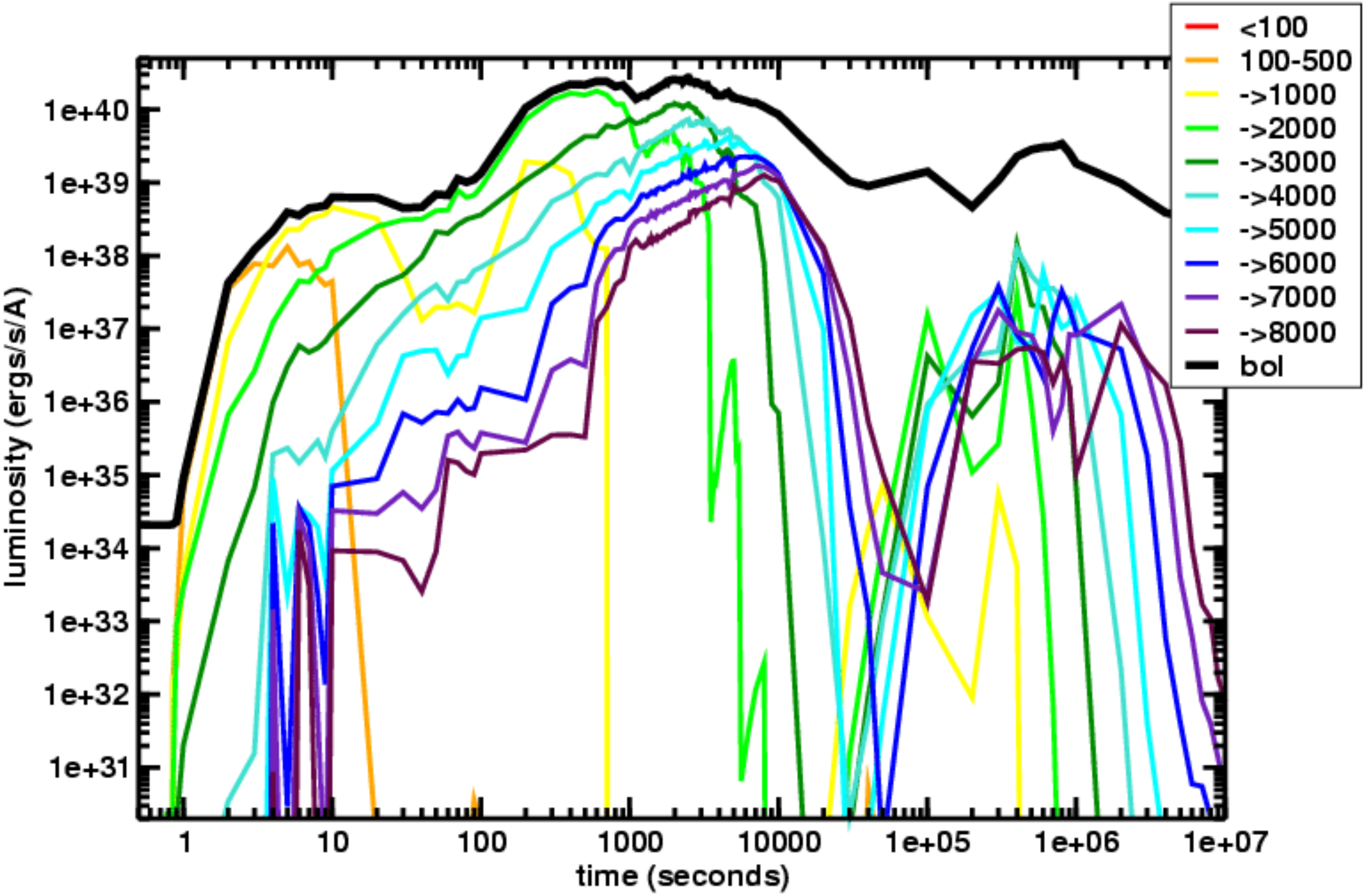


We are missing level states and these calculations still assumes LTE and steady state!

Physics of Shock Breakout: Understanding the Photosphere

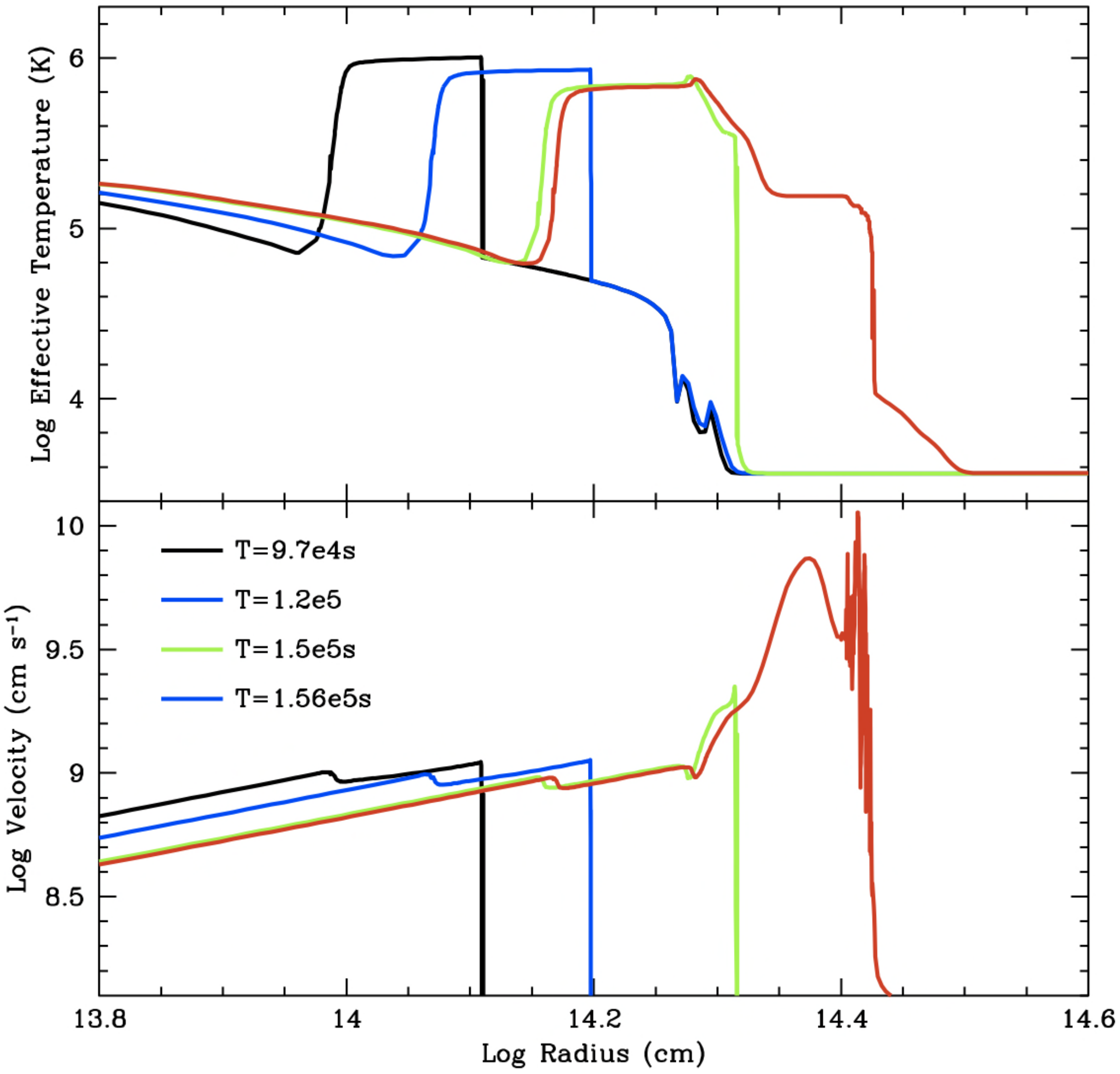
Breakout timing is wavelength dependent, averaging over angle will cause errors.

Frey et al. (2013)

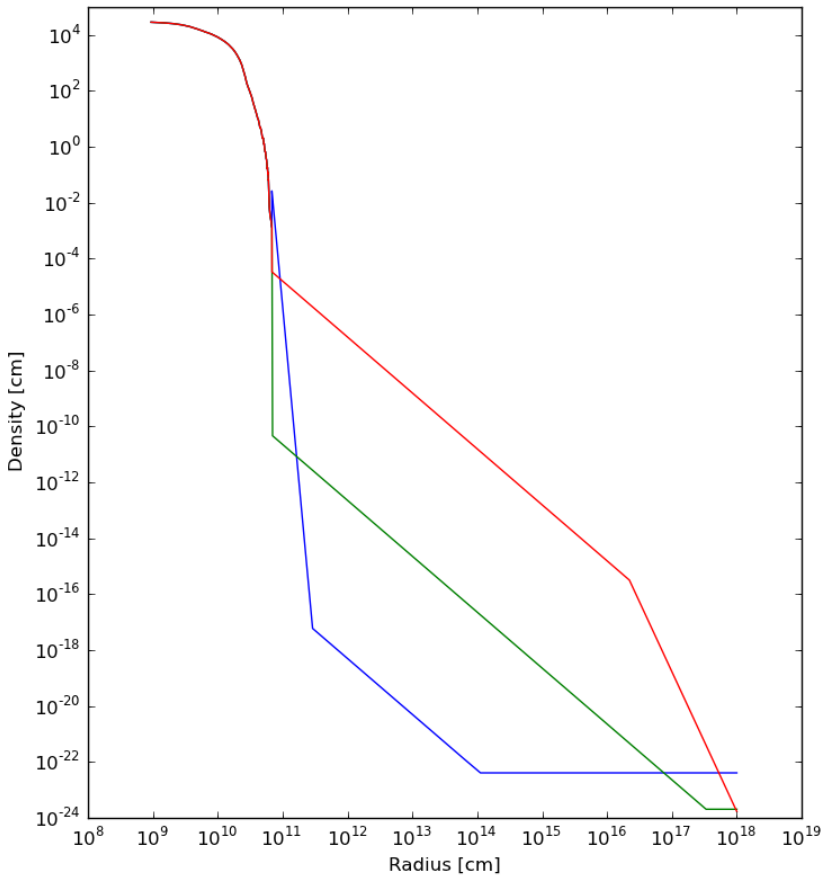


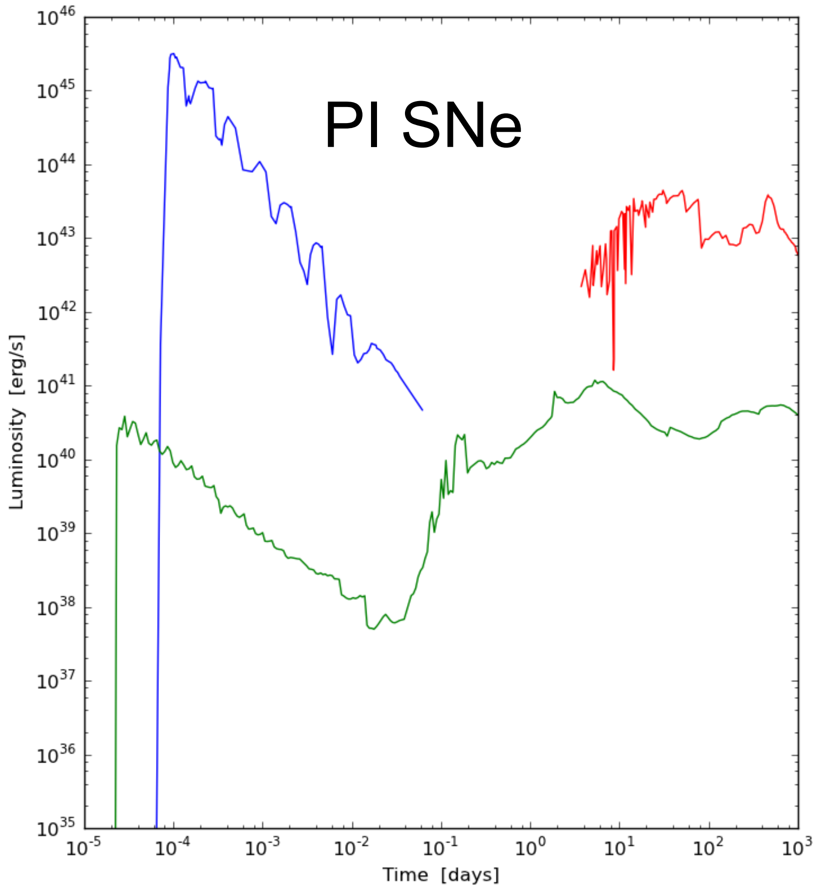
Radiation Hydrodynamics in Shock Breakout

- Even when the radiation is trapped, it can lead the shock – the shock position moves faster than Sedov solution would predict.
- After breakout, the radiation begins to decouple from the material.

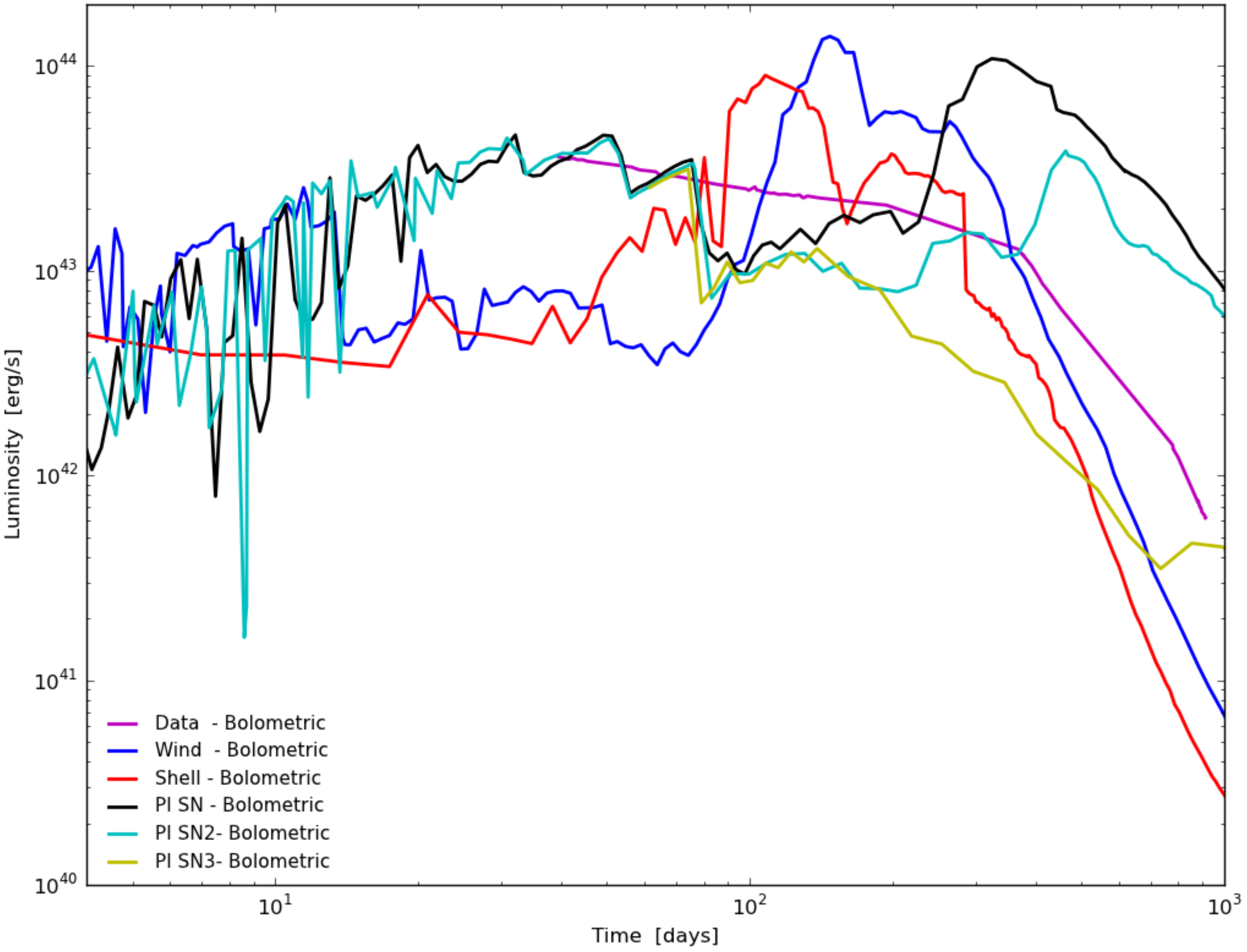


Hydrodynamic Shocks can Drive Emission: For massive star progenitors, the circumstellar medium is king!



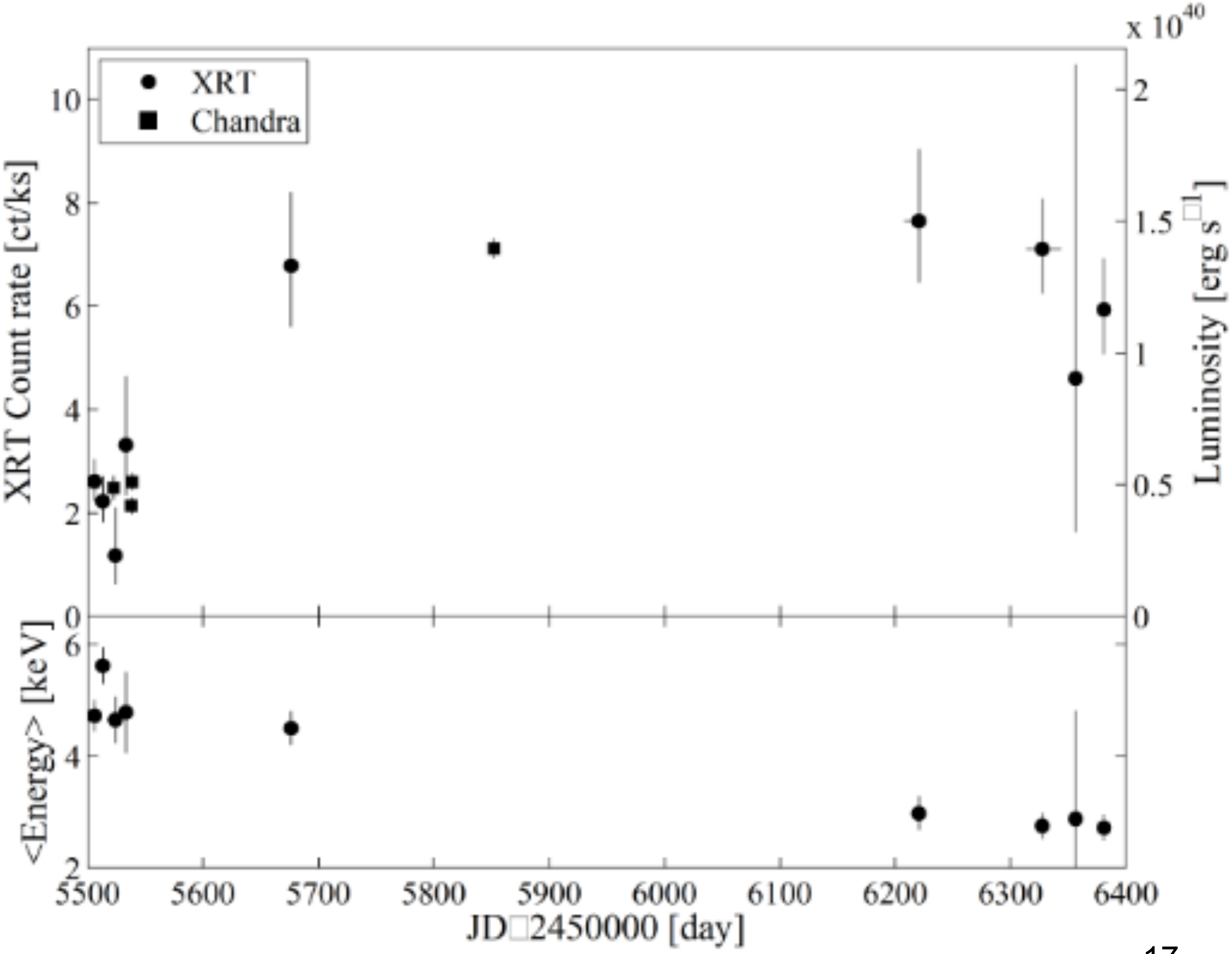


We can still infer extreme conditions, but details more difficult. For example, Ofek's basic conclusions for SN2010jl still hold: strong explosion, large circumstellar mass.



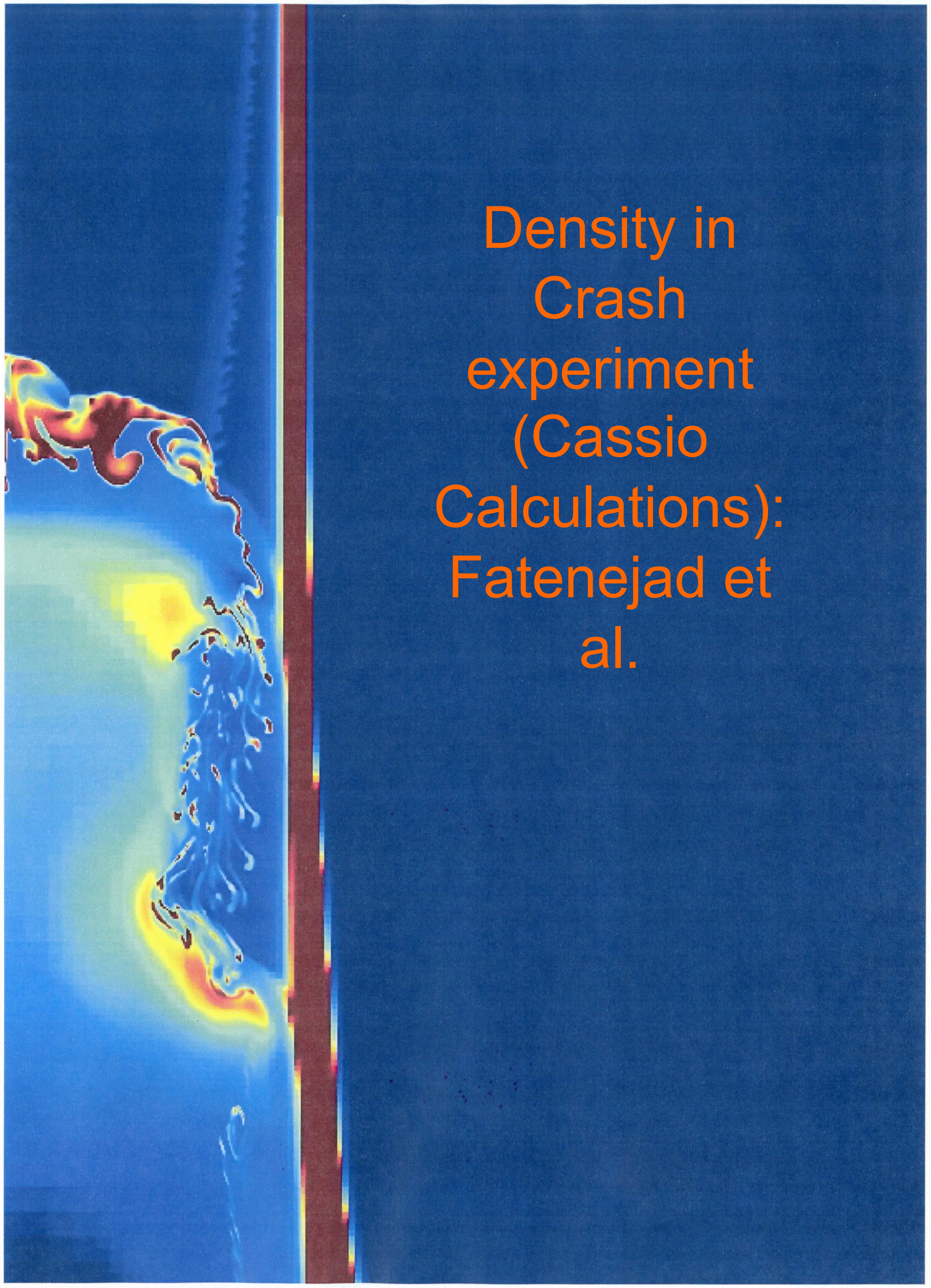
Electron/Ion Decoupling

As the density drops, the electrons are no longer coupled to the ions.
e.g. in SN 2010jl, the X-ray stayed bright for over 2 years! With the expected densities (even the large shell), the electron “temperature” will be much lower than the ion temperature.



Testing our codes: Physics experiments of Shock Breakout

- The Univ. of Michigan CRASH center developed an experiment to test shock breakout.
- This experiment demonstrated many of the difficulties with modeling shock breakout: radiation pre-heat, turbulence, ….



Density in Crash experiment (Cassio Calculations): Fatenejad et al.

Opacity Experiments

- Early results showed good agreement with iron measurements, but the most recent iron experiments do not agree with state-of-the-art atomic physics.
- Kurucz results have trouble getting agreement with the atomic physics community.

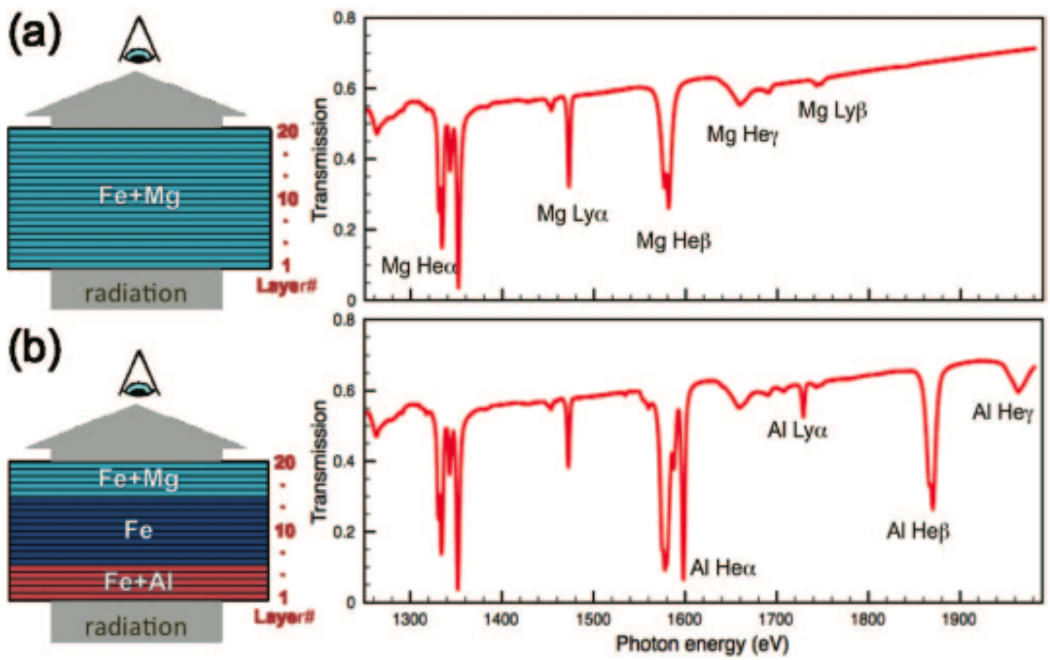


FIG. 1. The sample composition for (a) an Fe+Mg sample and (b) an Al+Fe+Mg sample and their synthetic transmission spectra under 10% gradient with the average T_e and n_e of 195 eV and 8×10^{22} cm^{-3}. Layer numbers correspond to the subscript i in Eqs. (1) and (2).

Nagayama et al. 2012

Modeling Transients

- All current efforts modeling astrophysical transients make simplifying assumptions in the progenitors, transport, hydrodynamics coupling and/or opacities.
- With these uncertainties, it is often difficult to find a unique solution (progenitor mass, explosion energy) for a given observed transient.
- We are in a unique position to tie laboratory experiments to our astrophysics studies and both fields can learn from each other.