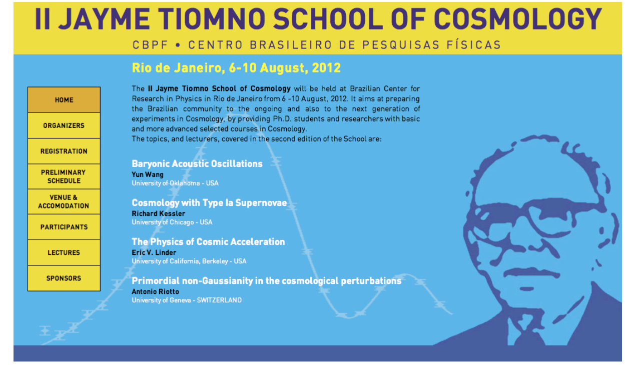

Lectures on Cosmology with Type Ia Supernovae: **Explosion Models**

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Rio de Janeiro, Brazil

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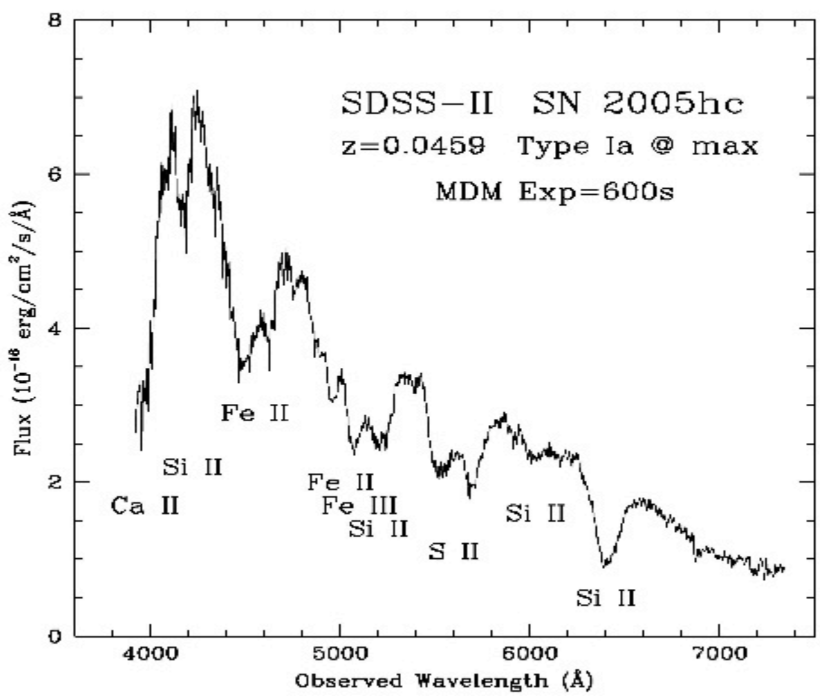
What is a Type Ia Supernova ?

- A CO white dwarf (WD) accretes matter from a large companion.
- Upon reaching Chandrasakar mass (1.4 $M_\odot$), it detonates and burns partly into iron-peak elements.
- Intermediate mass elements (IME: Ca, Si ...) leave strong spectral features.



What is a Type Ia Supernova ?

- We do NOT see a SNIa as it explodes (expected to be bright in X-rays)
- We eventually see photons from radioactive nuclei releasing γ-rays (~ 1 MeV) that down-scatter to optical. Main contributors are
  - ^{56}**Ni** ($\tau_{½}$ = 6 days)
  - ^{56}**Co** ($\tau_{½}$ = 77 days)
- Most optical photons created very early, but are absorbed by dense medium. More on this later.

Could a nearby supernova explosion have caused a mass extinction?

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ABSTRACT

We examine the possibility that a nearby supernova explosion could have caused one or more of the mass extinctions identified by palaeontologists. We discuss the likely rate of such events in the light of the recent identification of Geminga as a supernova remnant less than 100 pc away and the discovery of a millisecond pulsar about 150 pc away, and observations of SN 1987A. The fluxes of γ radiation and charged cosmic rays on the Earth are estimated, and their effects on the Earth's ozone layer discussed. A supernova explosion of the order of 10 pc away could be expected every few hundred million years, and could destroy the ozone layer for hundreds of years, letting in potentially lethal solar ultraviolet radiation. In addition to effects on land ecology, this could entail mass destruction of plankton and reef communities, with disastrous consequences for marine life as well. A supernova extinction should be distinguishable from a meteorite impact such as the one that presumably killed the dinosaurs.

What Can we Hope to Learn From SN Explosion-Model Simulations

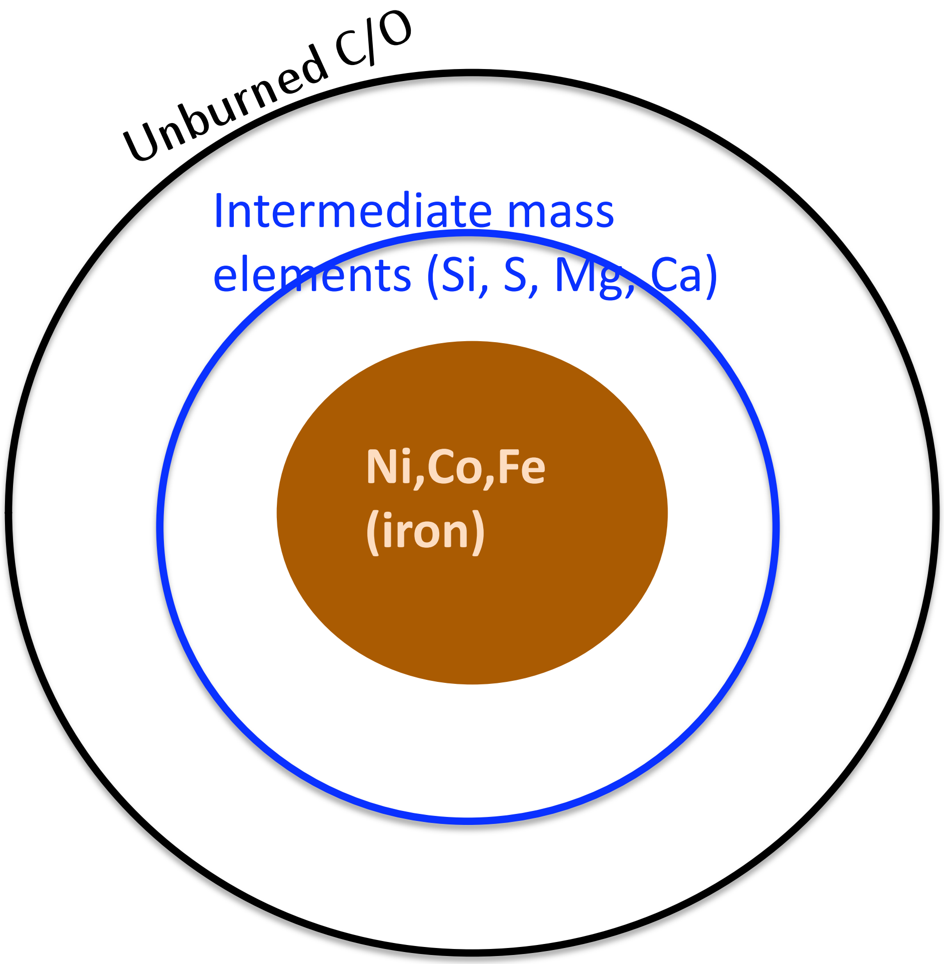
Question	Current knowledge
How do they detonate ?	Speculative
What drives the optical light curve ?	Heating ejecta by radioactive decay of ^{56}Ni and ^{56}Co
What drives the correlation between brightness and stretch/ color ?	^{56}Ni mass drives brightness. Color & stretch correlations not understood.
Why is there 0.1 mag 'intrinsic' scatter after corrections … are there additional corrections ?	Speculative: Viewing angle ? Detonation location(s) ? Metalicity ?

Three Major Steps to Simulating SNIa

- Simulate explosion during first minute using hydro code. Output is map of velocity, density, composition.
- Simulate yield of radioactive elements that emit and absorb visible light.
- Use radiation transfer codes (Sedona, Phoenix) to simulate light curves and spectra from few days to months after explosion: MeV photons heat ejecta and radiate visible and IR light.

➔ **compare to data**

Explosion Model Overview



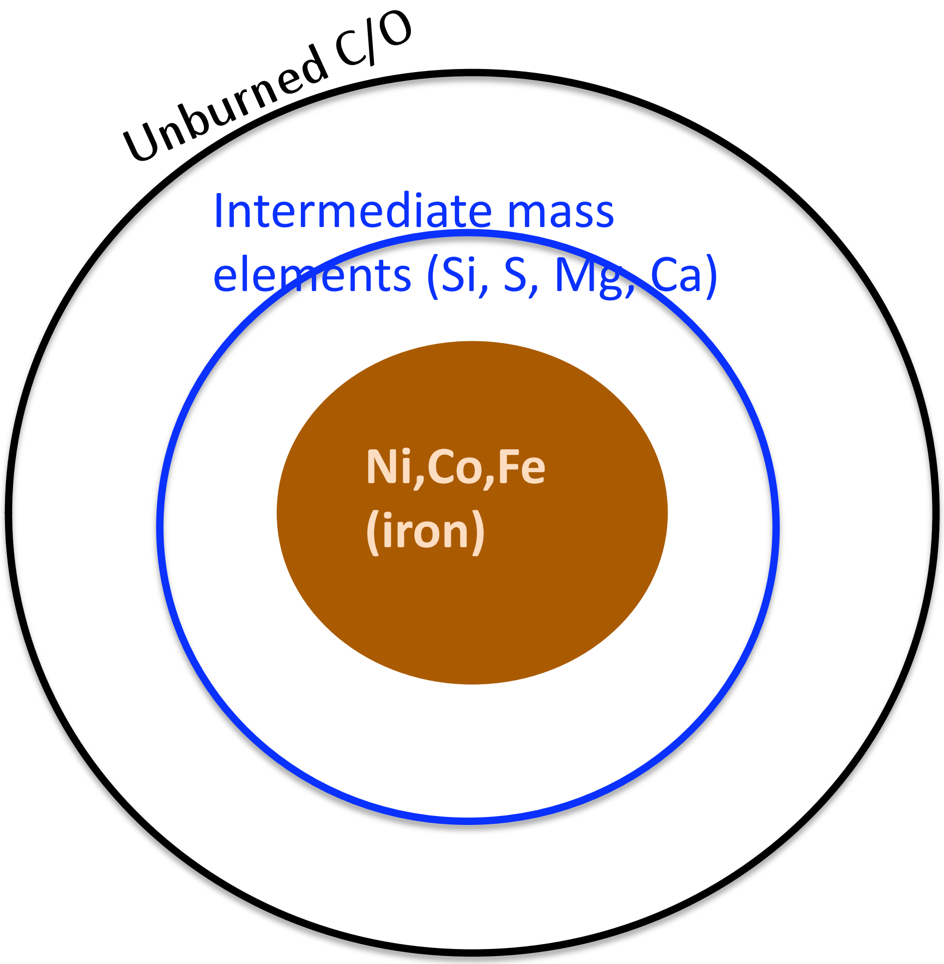
Deflagration (sub-sonic flame) burns too little iron ➔ dimmer than observed

Detonating a WD burns everything to iron ➔ ×2 brighter than observed.

Challenge for explosion model:

- produce ~ 0.7 $M_\odot$ of ^{56}Ni
- produce IMEs at appropriate velocity to match spectra.
- stretch & color correlations with brightness.

Explosion Model Overview

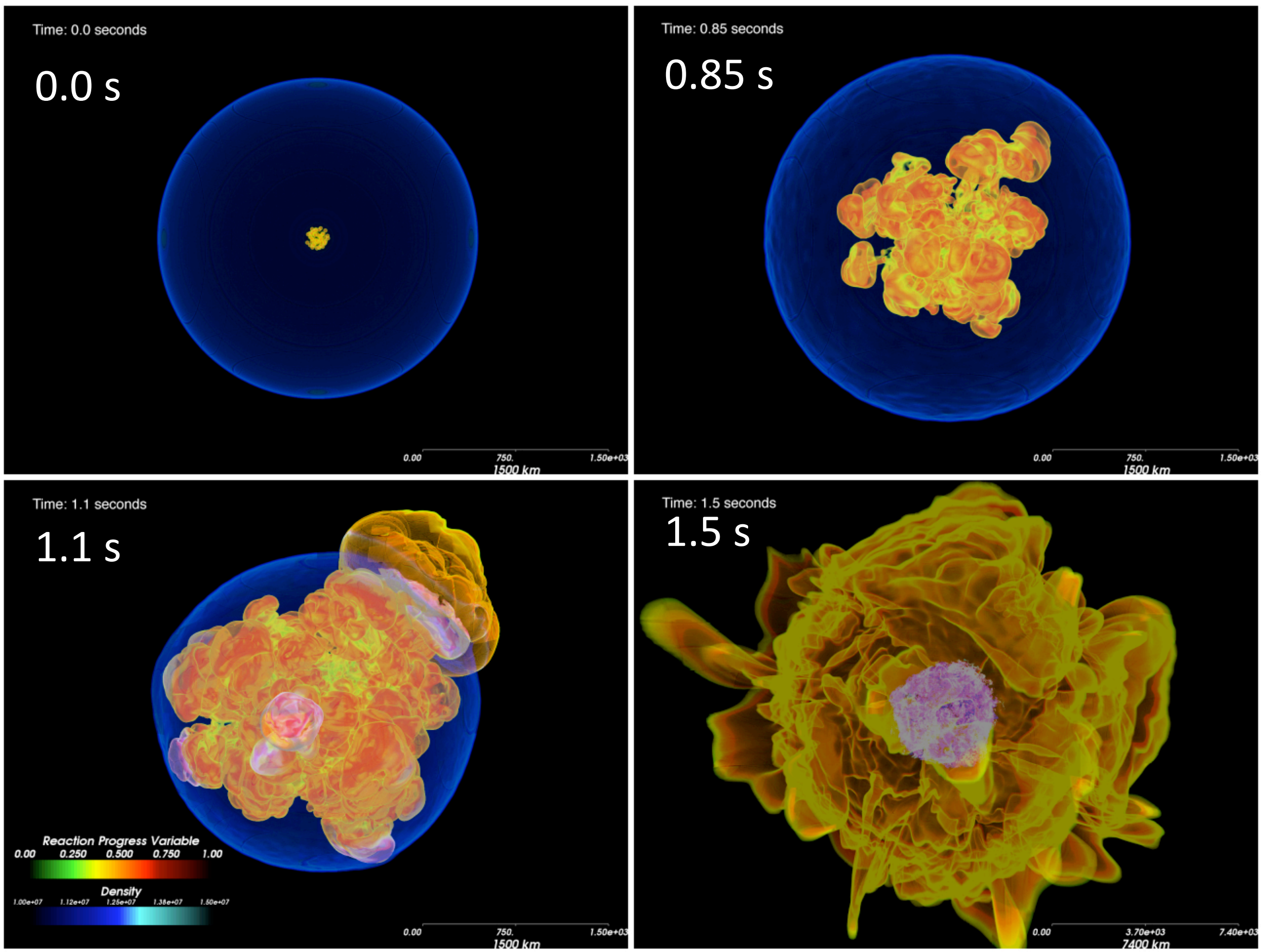


Two viable models:

DDT: Deflagration to Detonation Transition

GCD: Gravitationally Confined Detonation

Deflagration to Detonation Transition Model (DDT)



Flame bubbles rise to surface via buoyancy.

Ad-hoc detonations added where the flame(s) exit the WD.

Gravitationally Confined Detonation Model (GCD)

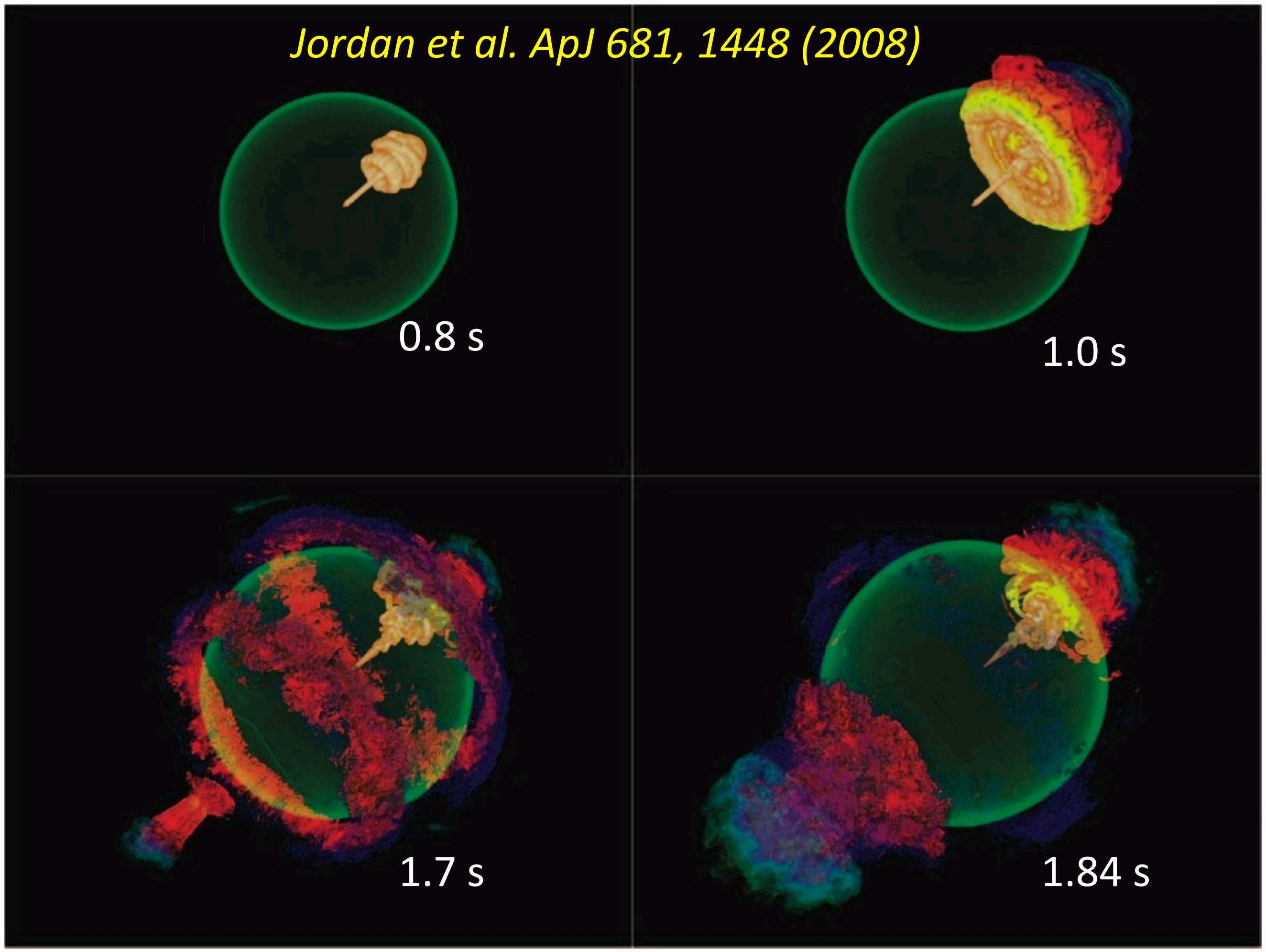


FIG. 2.—Images showing very hot matter and the star at different times for the same simulation as in Fig. 1. The images are volume renderings of the surface of the star [defined as the region in which $\rho = (1.5-2.0) \times 10^7$ g cm^{-3}] and the regions where the temperature is very high [i.e., where $T = (1.5-4.0) \times 10^9$ K, and blue is the coolest and orange-white is the hottest temperature] at: 0.8 s, when the bubble has become R-T unstable and developed into a mushroom shape (*top left*); 1.0 s, as the bubble breaks through the surface of the star (*top right*); 1.7 s, shortly before the hot ash from the bubble collides at the opposite point on the surface of the star (*bottom left*); and 1.84 s, the moment when the inward jet has compressed and heated stellar material ahead of it to detonation conditions (*bottom right*).

Flame bubble exits WD surface.

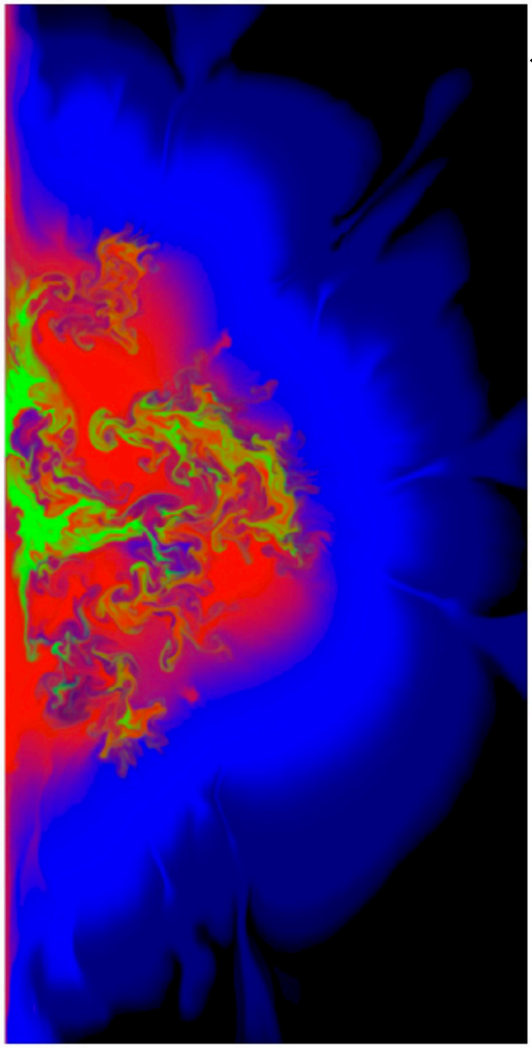
Ash flows around to opposite pole.

Detonation occurs naturally without ad-hoc parameters.

Caveat: initial state is assumed.

Comparison of DDT and GCD

DDT



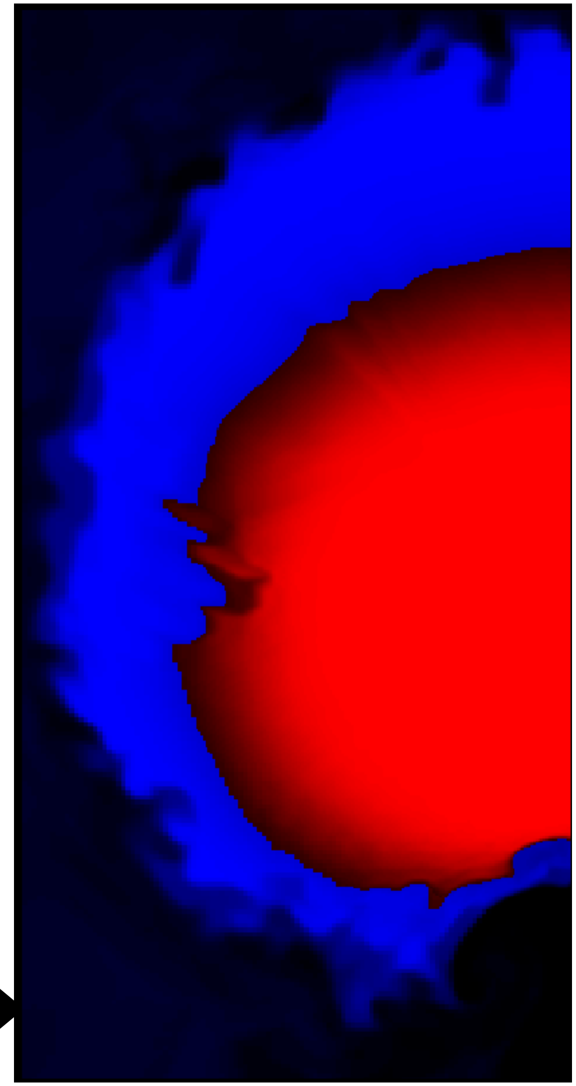
Kasen et al, 2009

- Turbulently mixed inner layers (Ni)
- Smooth outer layers (IME's)

■ Si, Mg
■ Stable Fe, Ni
■ Radioactive ^{56}Ni

- Smooth inner layers (Ni)
- Turbulently mixed outer layers (IME's)

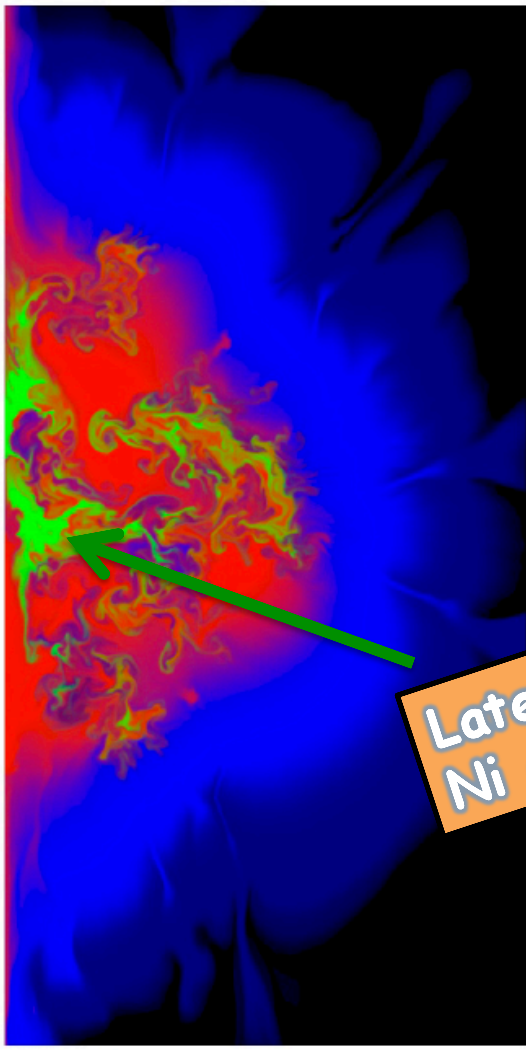
GCD



Jordan et al., in prep

Experimental Signatures

DDT



Kasen et al, 2009

- Turbulently mixed inner layers (Ni)
- Smooth outer layers (IME's)

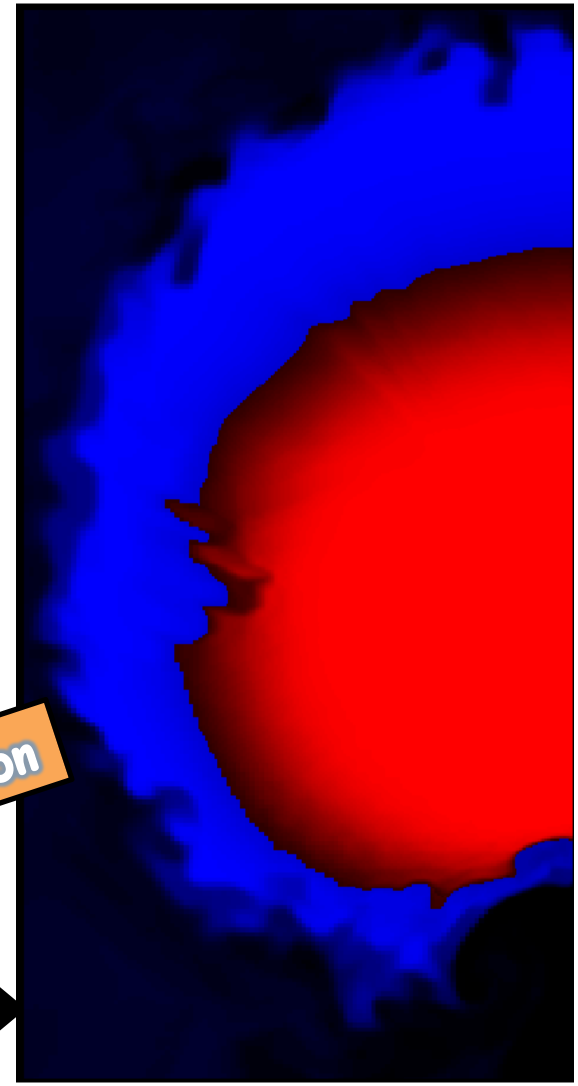
■	Si, Mg
■	Stable Fe, Ni
■	Radioactive ^{56}Ni

Late-time Ni absorption

polarization

- Smooth inner layers (Ni)
- Turbulently mixed outer layers (IME's)

GCD

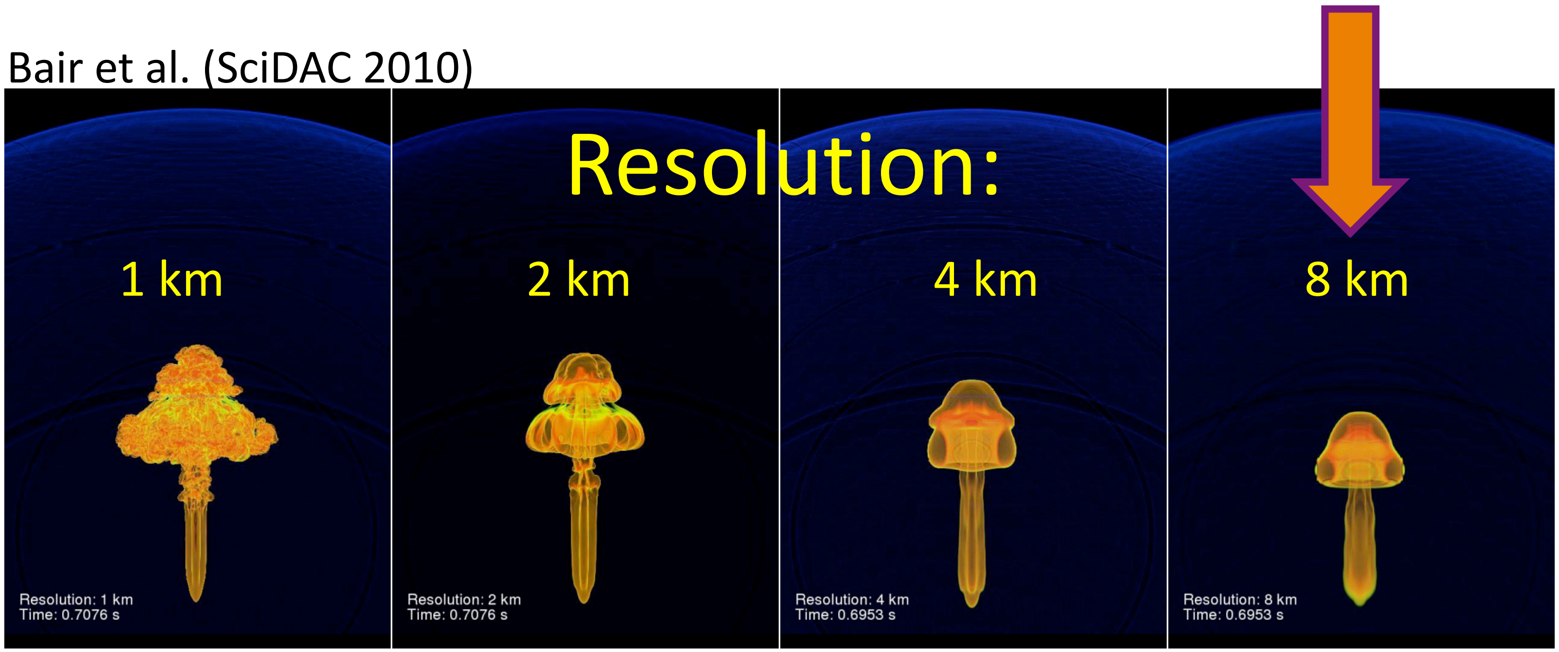


Jordan et al., in prep

Grid Size

Current/typical GRID size is 8 km for explosion model.
Corrections applied based on high-resolution sims of single flame.
Each ×2 reduction in (3D) grid size ➔ 2^4 = ×16 more computing.

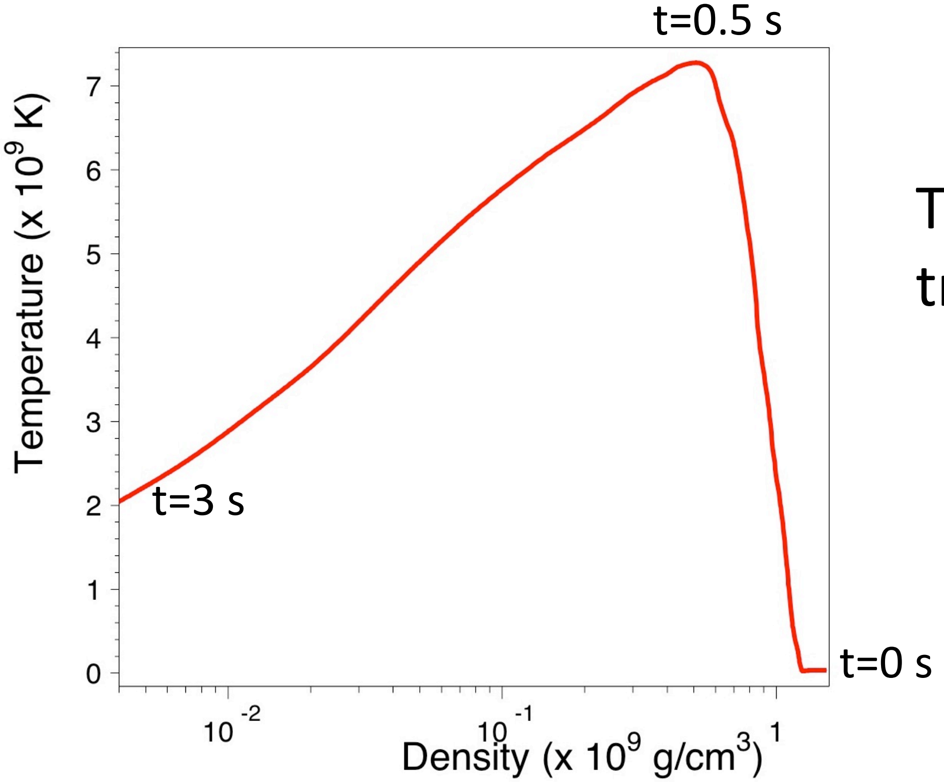
Bair et al. (SciDAC 2010)



Note: actual flame thickness is < 1 cm !!!

Nucleosynthetic Yield

- After explosion, go back and get thermal history from (100s-1000s) of random tracer particles. Use network equations to solve for yields.

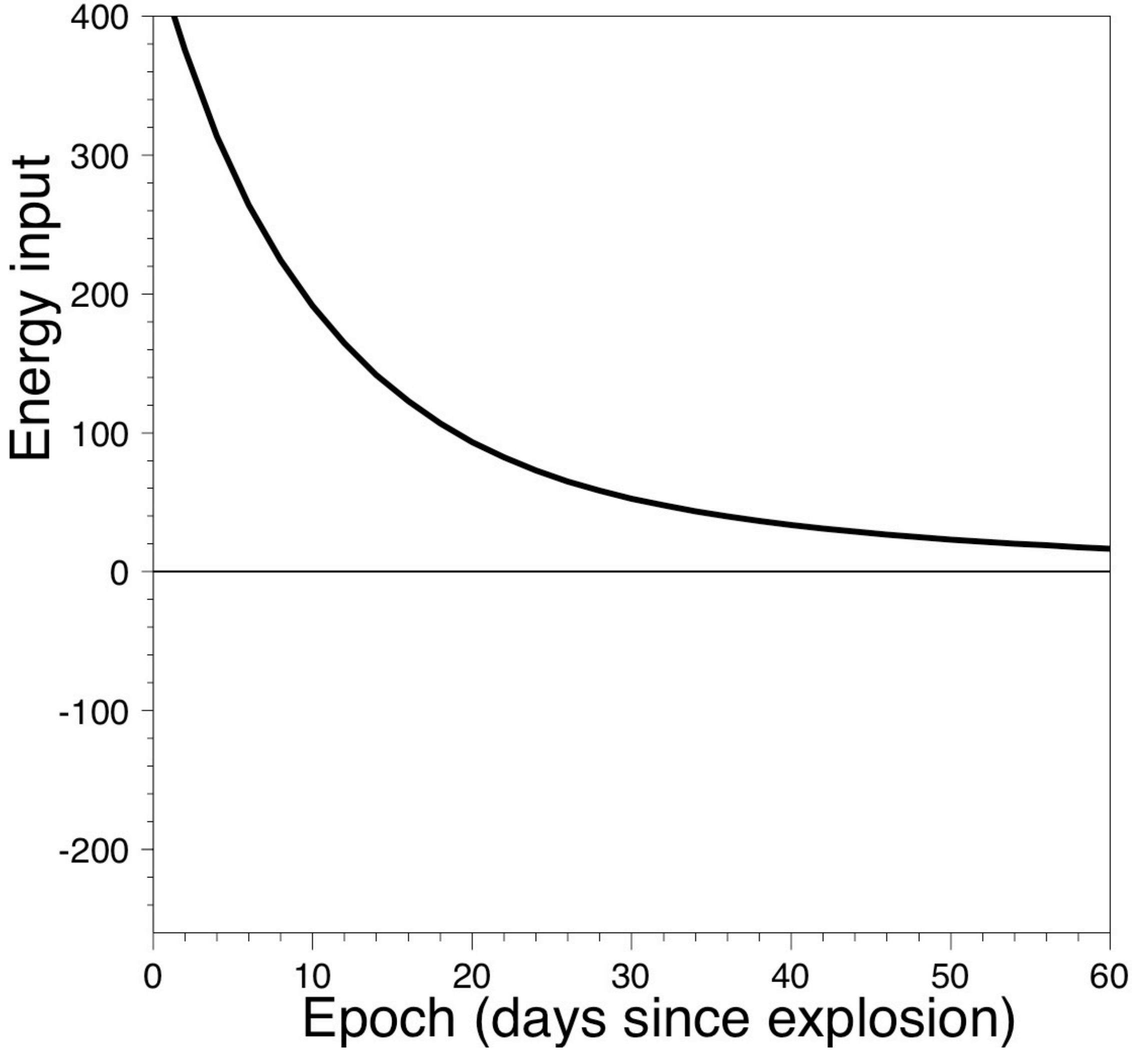


Trajectory of one tracer particle.

Radiation Transfer

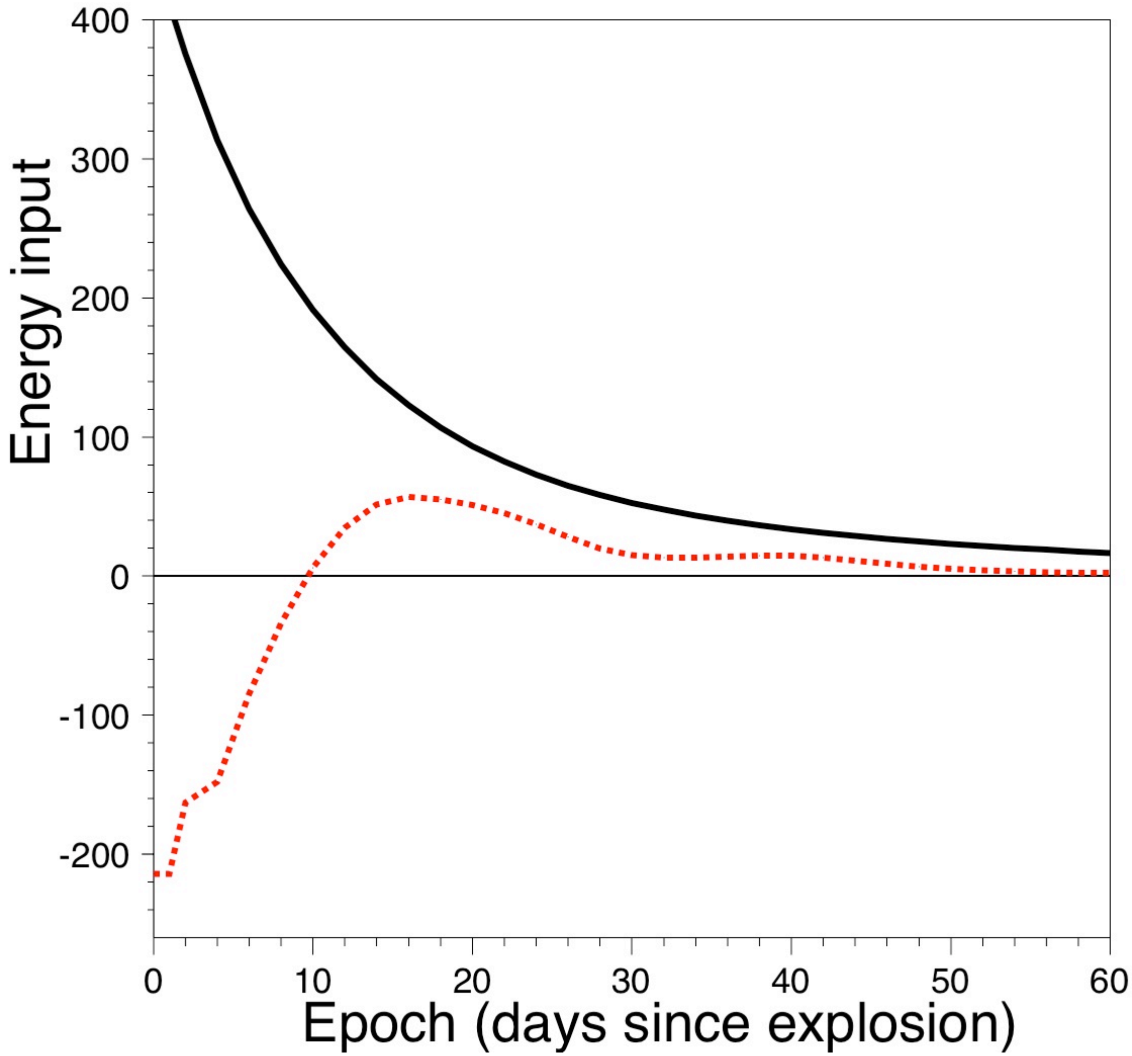
- Radioactive ^{56}Ni and ^{56}Co ($\tau_{½}$ = 6 and 77 days) heat the expanding envelope and radiate visible and IR photons.
- At early times the visible photons are trapped by the opaque envelope; later the expanding envelope becomes more transparent to the reservoir of visible photons.
- Spectrum is affected by millions of atomic absorption and emissions lines.
- Max ‘visible’ brightness occurs almost 3 weeks after explosion.

Radiation Energy Balance



Total dE/dt from radioactive ^{56}Ni and ^{56}Co

Radiation Energy Balance

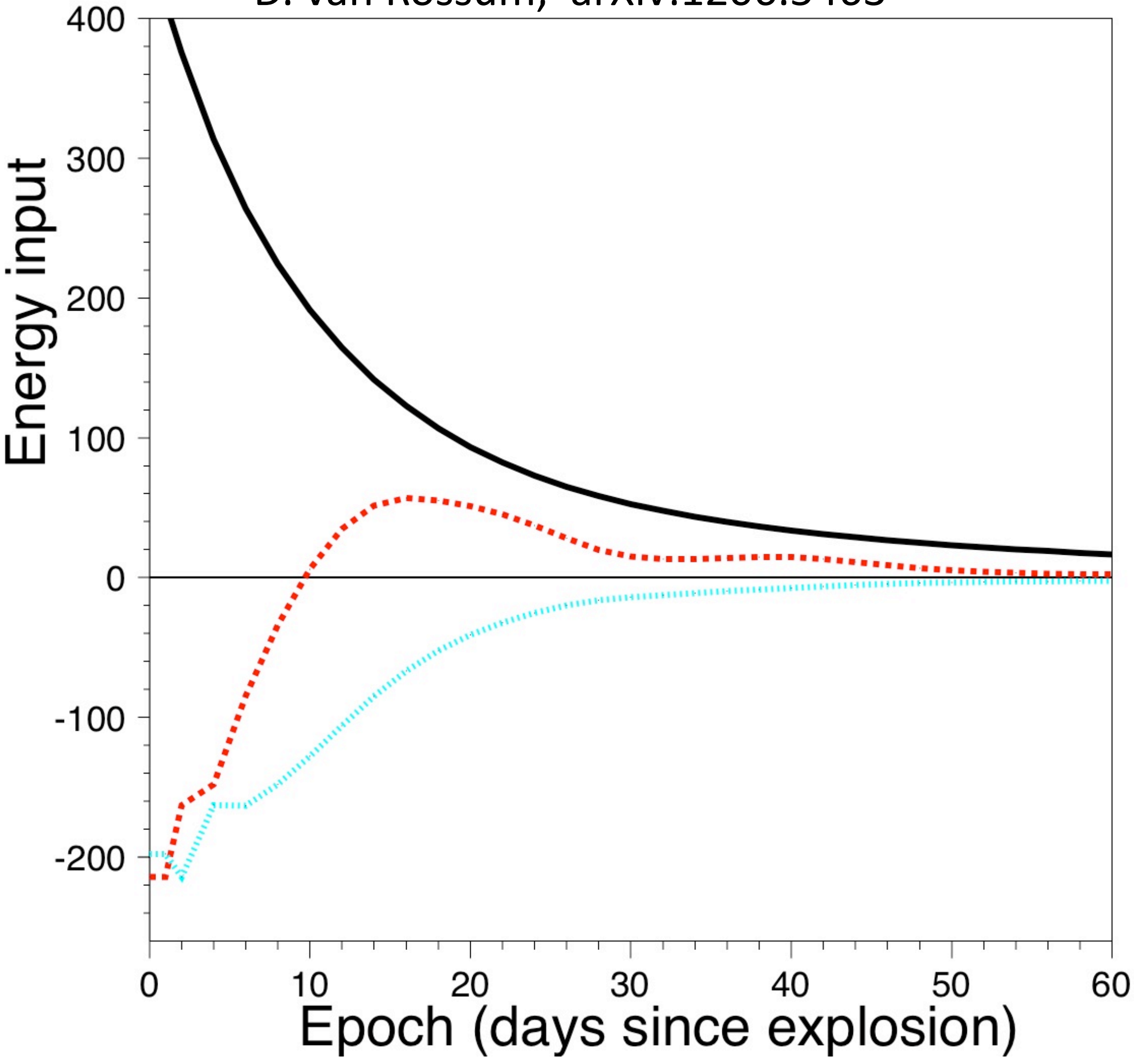


Total dE/dt from radioactive ^{56}Ni and ^{56}Co

stored energy

Radiation Energy Balance

D. van Rossum, arXiv:1206.5463



Total dE/dt from radioactive ^{56}Ni and ^{56}Co

stored energy

work done by radiation pressure

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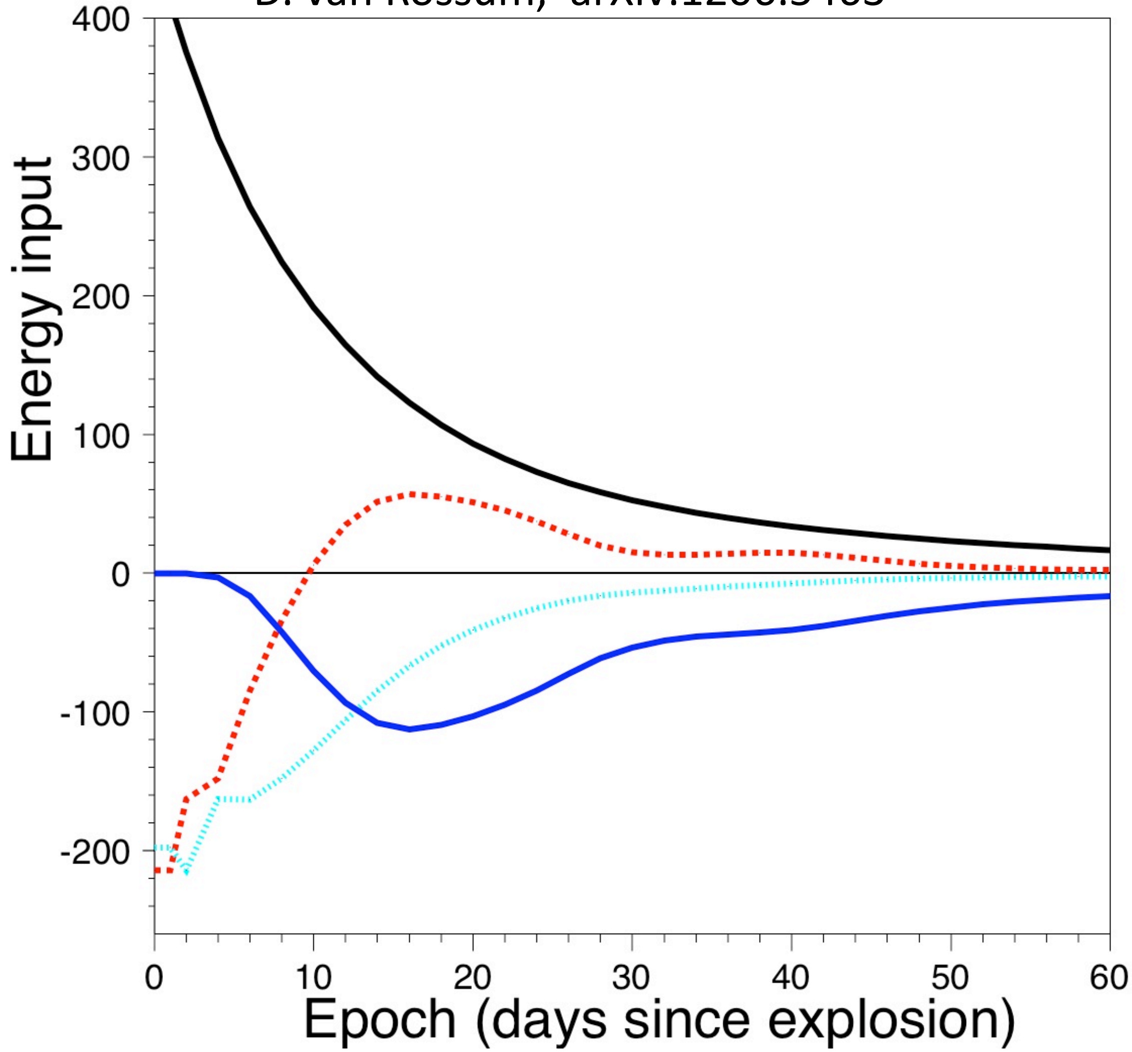
D. van Rossum, arXiv:1206.5463



Total dE/dt from radioactive ^{56}Ni and ^{56}Co

stored energy

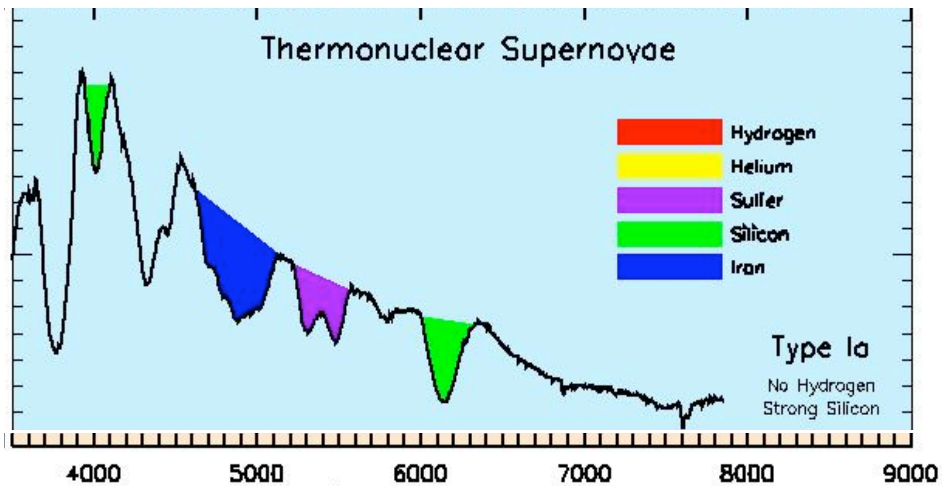
work done by radiation pressure

bolometric light curve

(Sum of curves = 0)

Interpreting Spectral Features

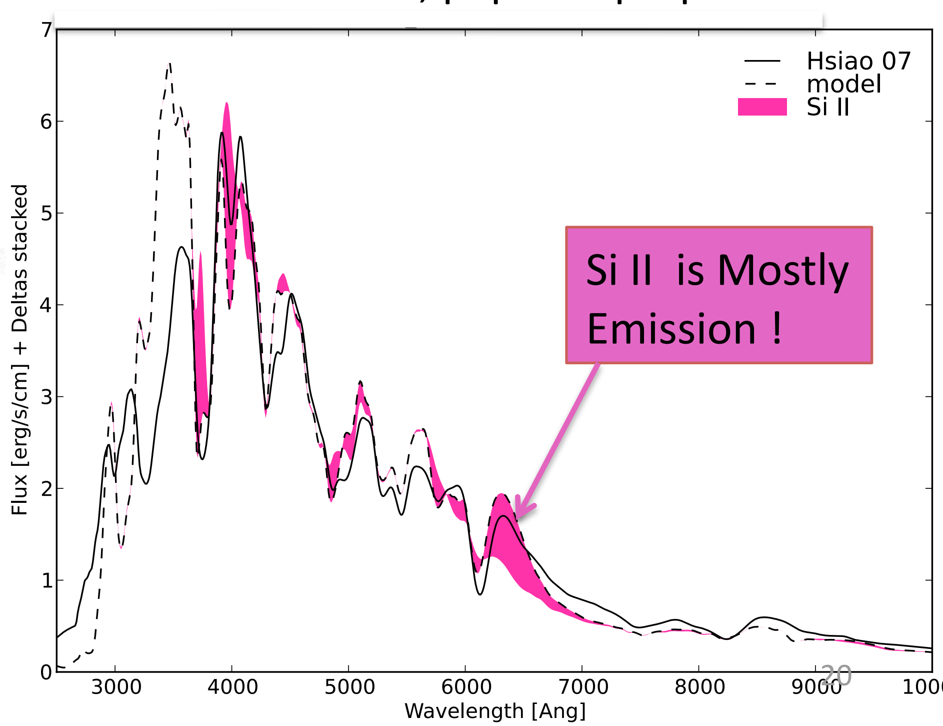
Common interpretation …



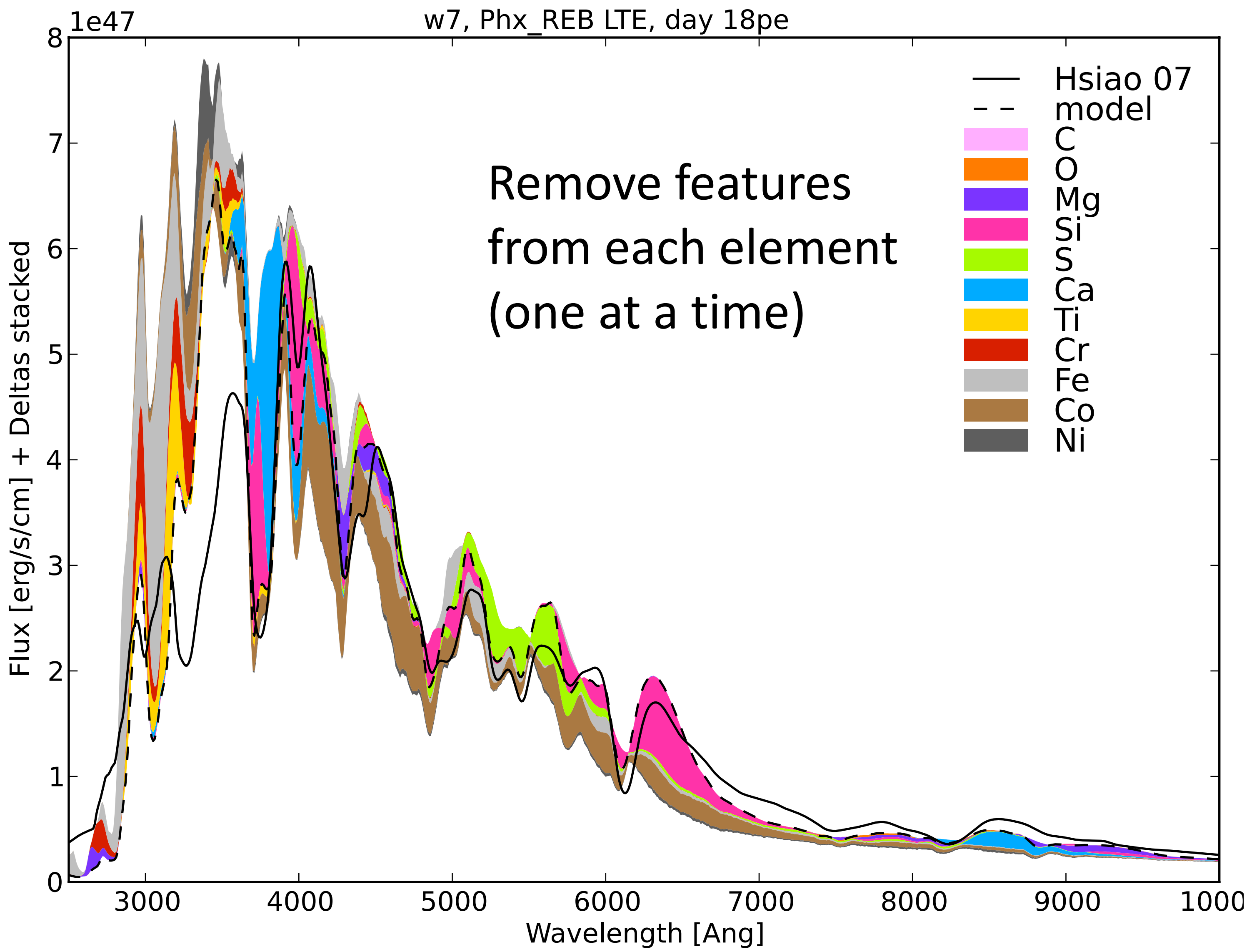
wavelength (Å)

Newer interpretation with Phoenix: remove Si II feature from simulation.

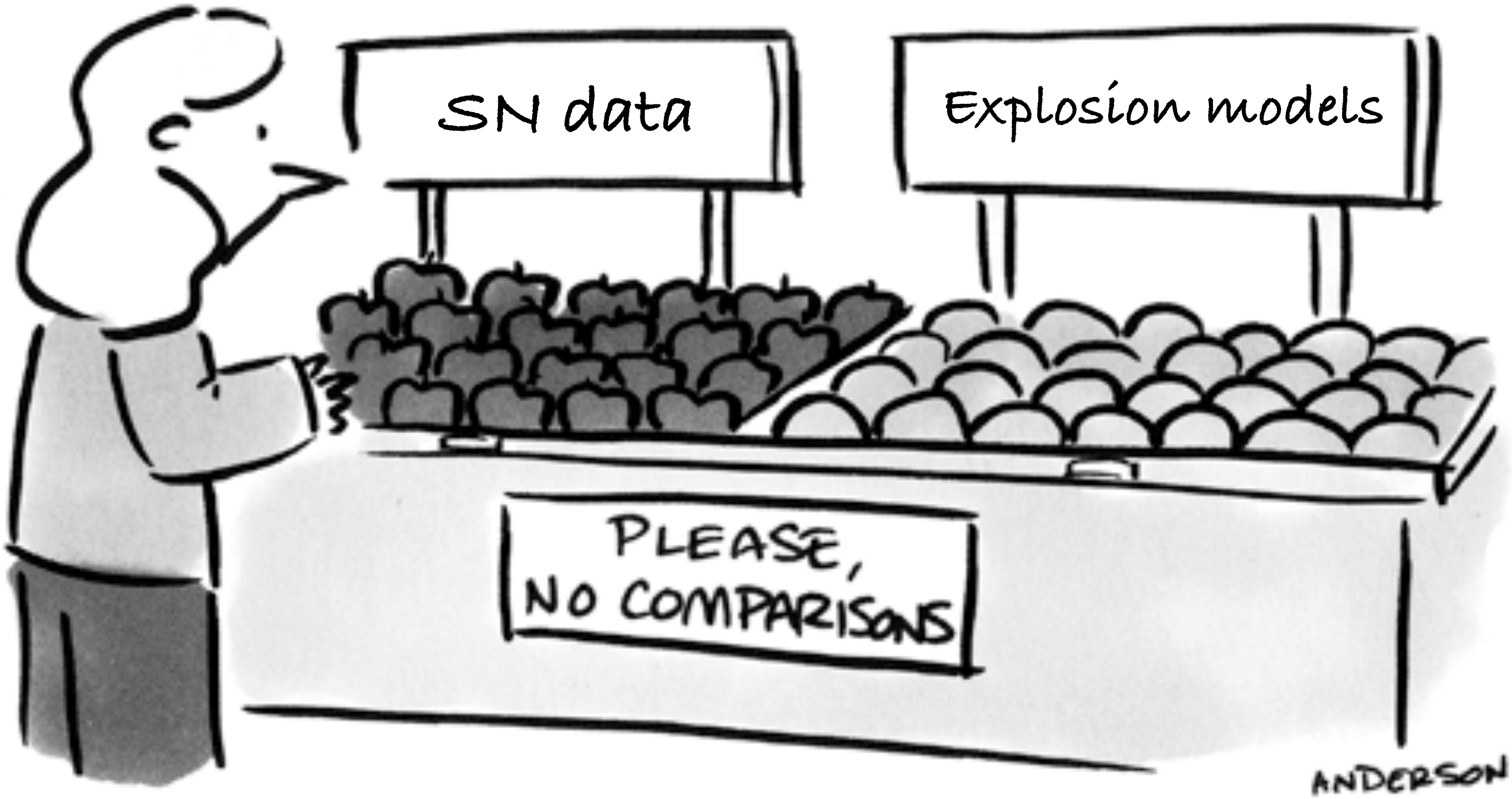
D. van Rossum, paper in prep



Interpreting Spectral Features

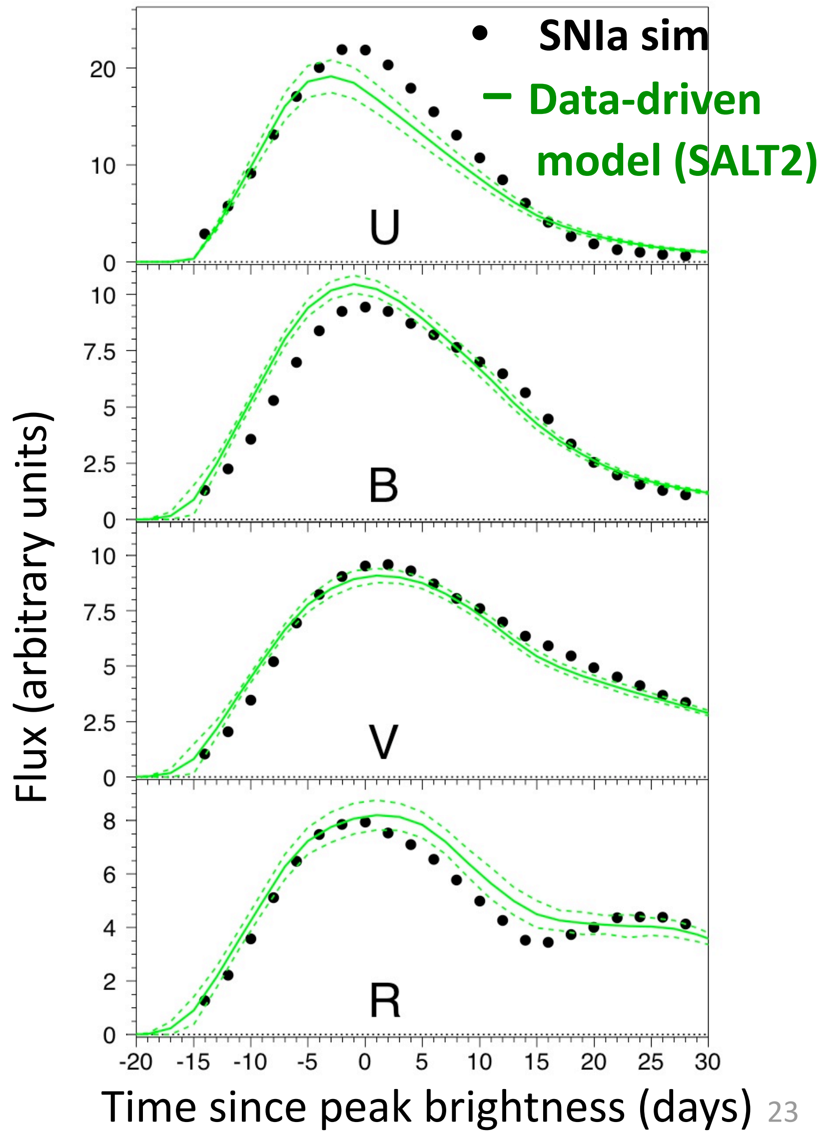


Comparisons to Data



Comparing Light Curves

- Synthesize photometric light curves from spectra generated by rad-transfer stage.
- Fit predicted light curves (from SNIa sim) exactly the same way that data are fit.



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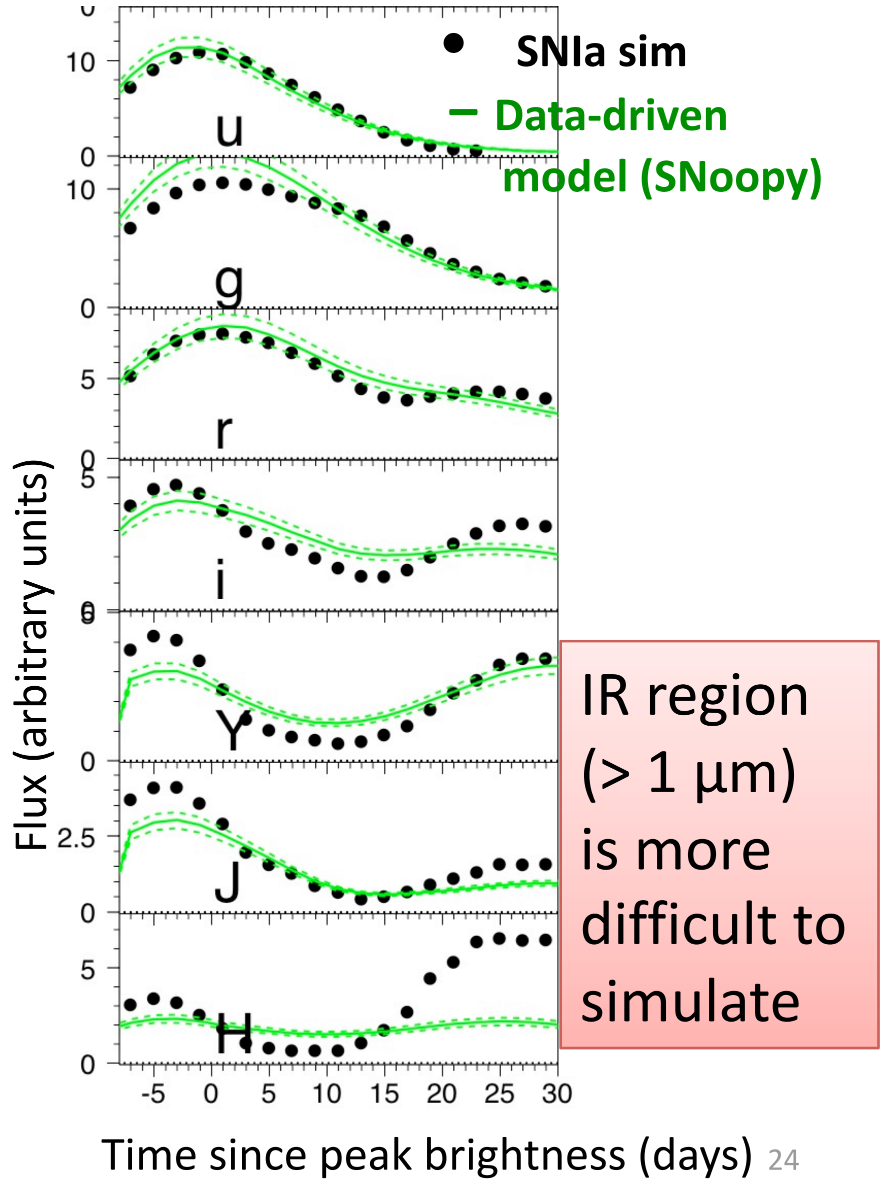
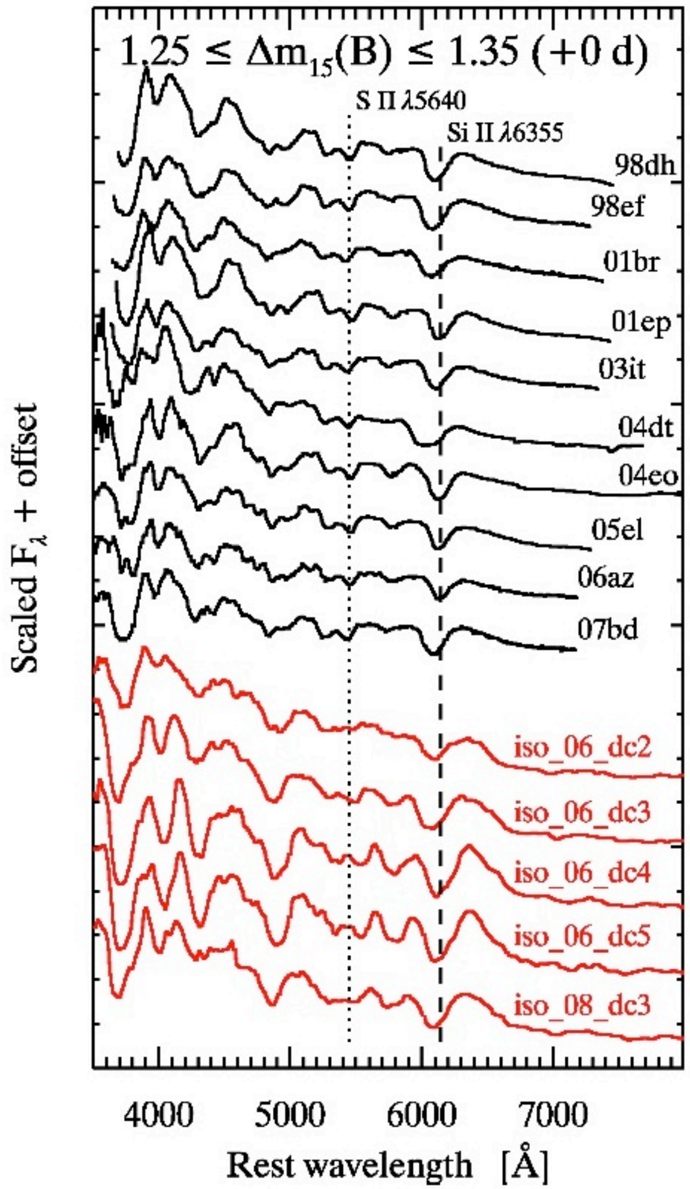


Comparing Spectra



Observed Spectra from CfA

Blondin et al., MNRAS 417, 1280 (2011)

Explosion-model spectra

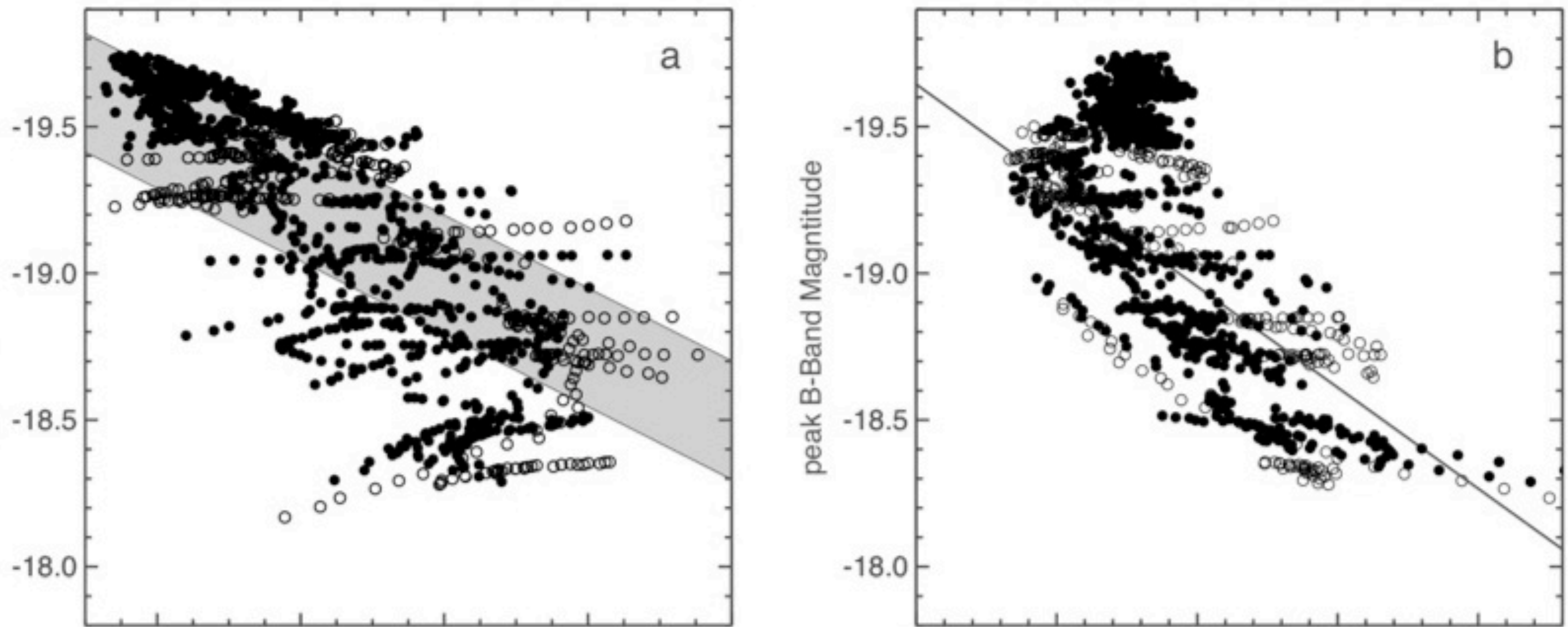
Kasen et al., Nature 460, 869, (2009)

Comparing Parameter Population

DDT in 2 dimensions: Kasen et al., Nature 460, 869 (2009)

Random ignition points -> viewing angle dependence

m_B at peak brightness

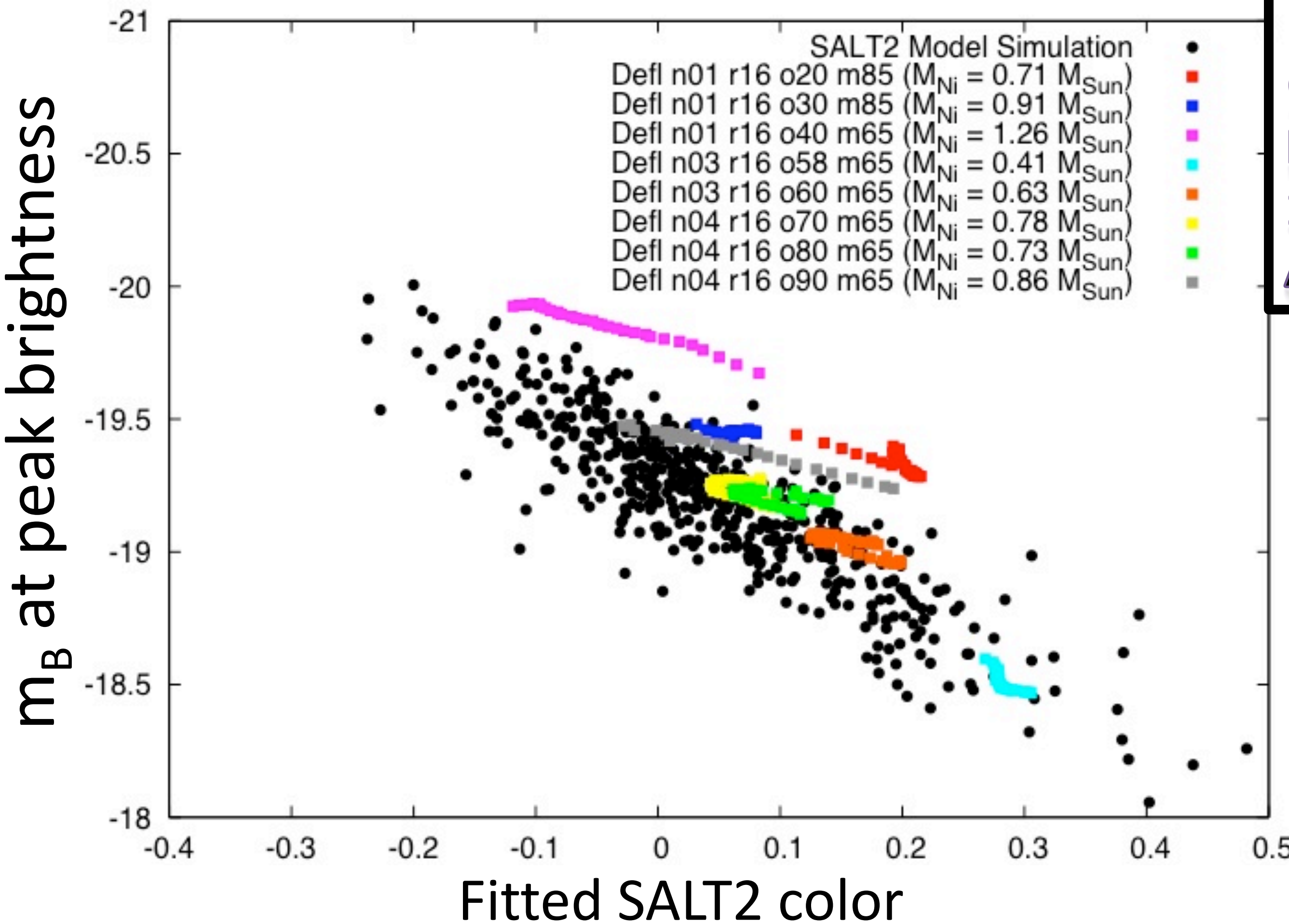


B band decline rate, Δm_{15}

B-V color at peak brightness

Comparing Parameter Population

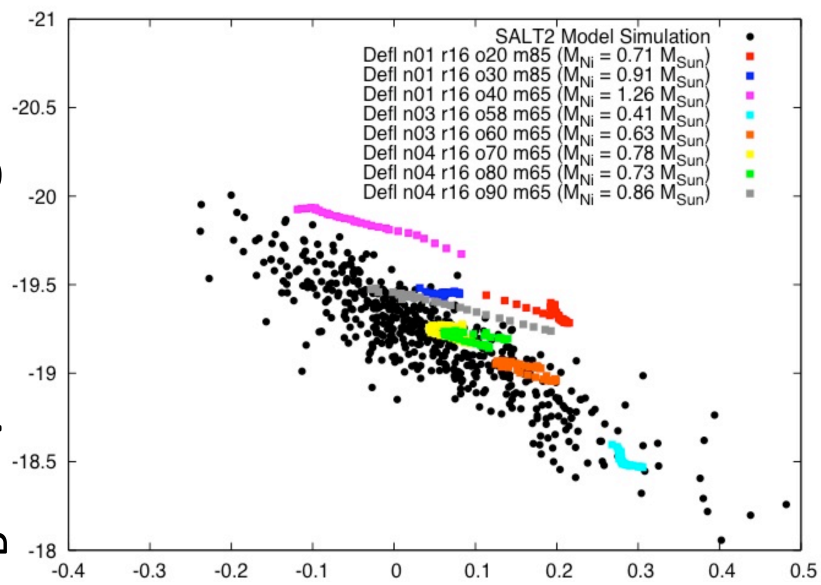
GCD in 2 dimensions: paper in prep (B. Diemer, FLASH)



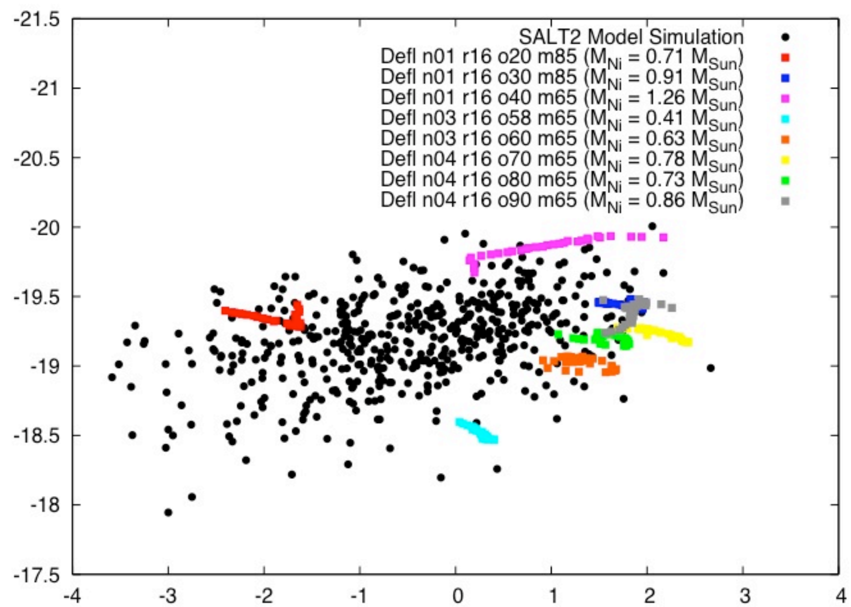
- **BEST ESTIMATE OF 'REALITY' FROM IDEAL SURVEY WITH 100% EFFICIENCY AND VERY HIGH S/N.**

Comparing Parameter Population

m_B at peak brightness



Fitted SALT2 color



Fitted SALT2 stretch (x_1)

Status

- 1D and 2D simulations capture basic properties of SNIa light curve: approximate energy released and light curve shape
- However, lower-dimensional (1D,2D) constraints incorrectly treat important effects such as turbulence.
- No consensus (yet) on initial state or on the explosion mechanism.
- Moving to 3D simulations !! (millions of CPU hours)