Simulating stellar explosions:

supernovae and neutron star mergers

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Luke Shingles, Christine Collins
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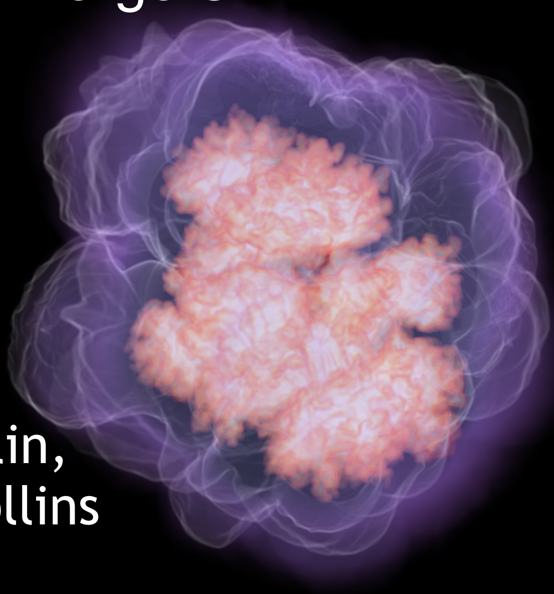
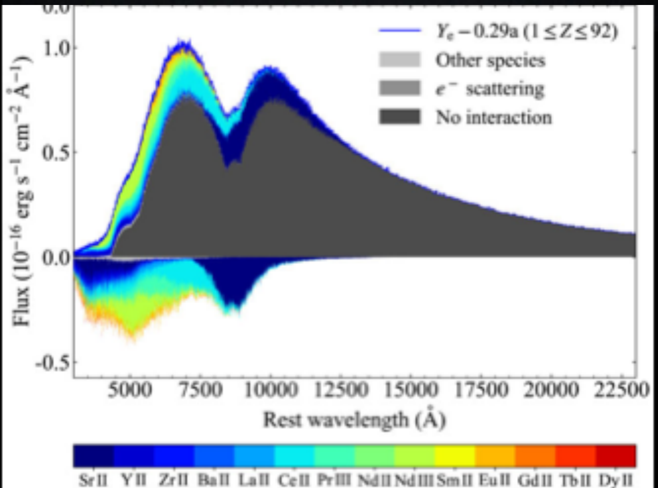
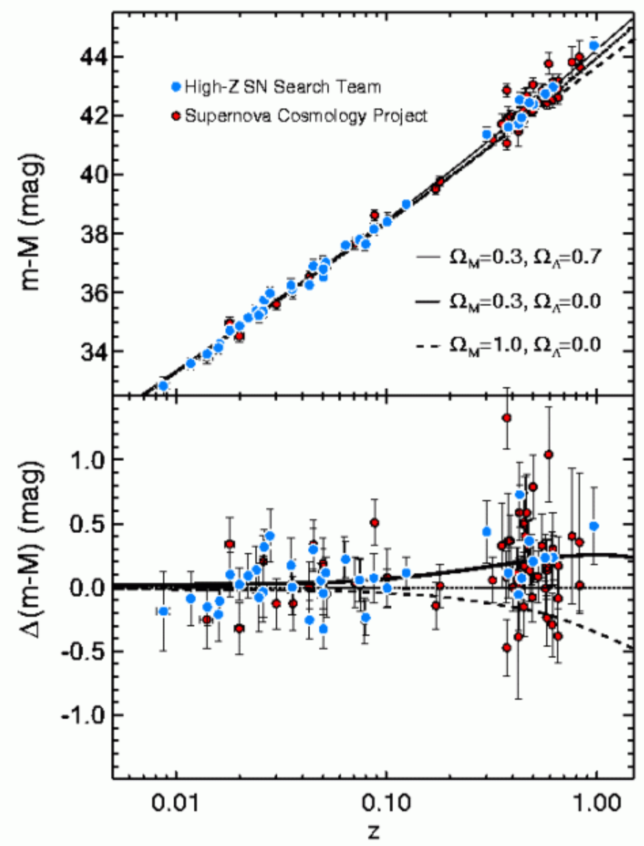
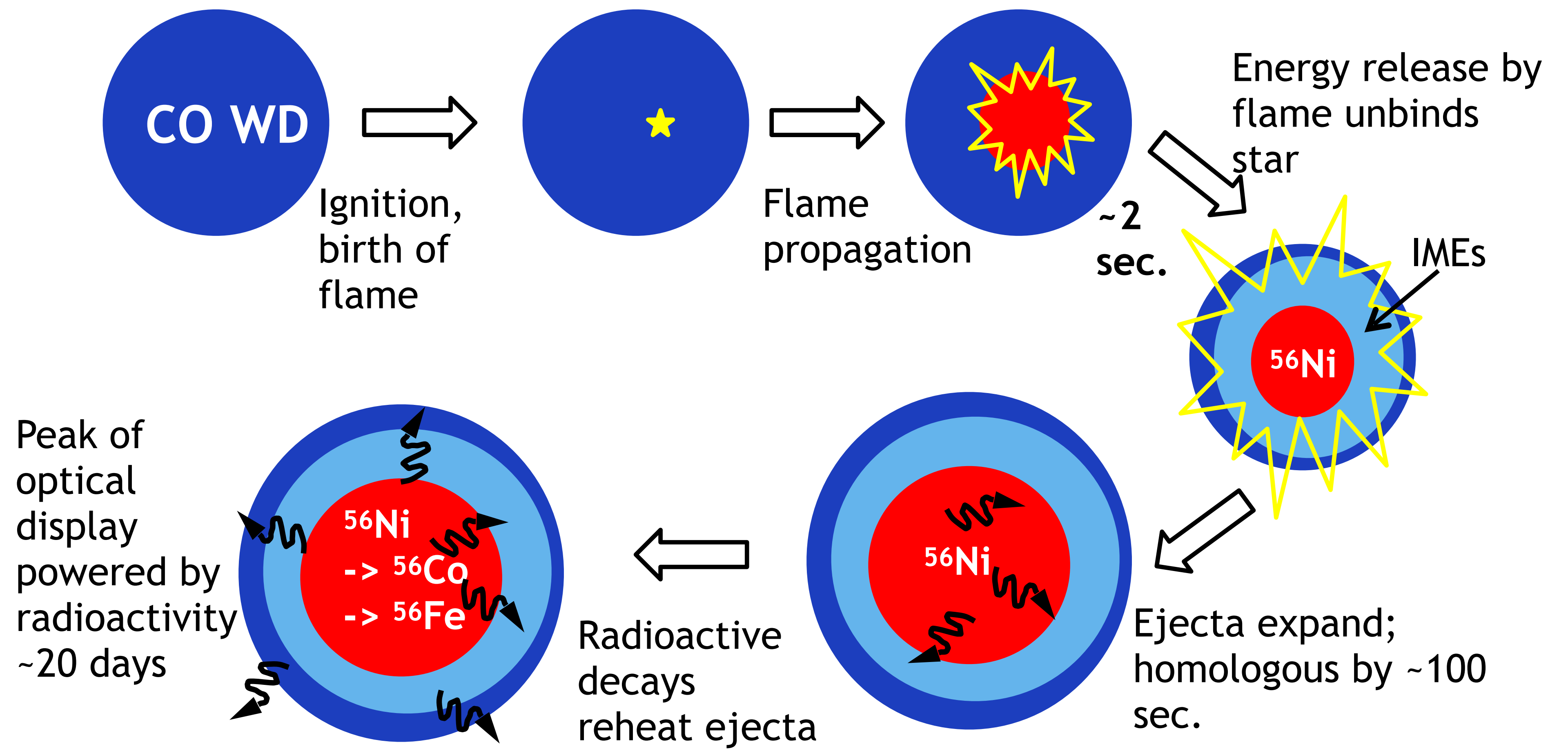




Type Ia supernovae

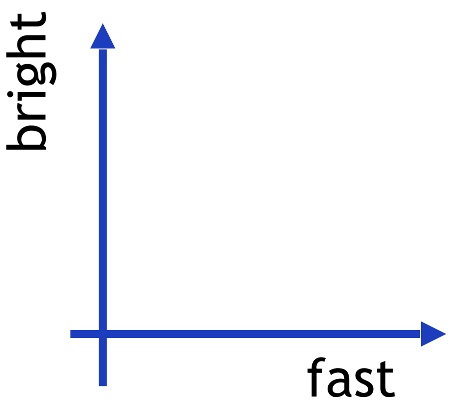


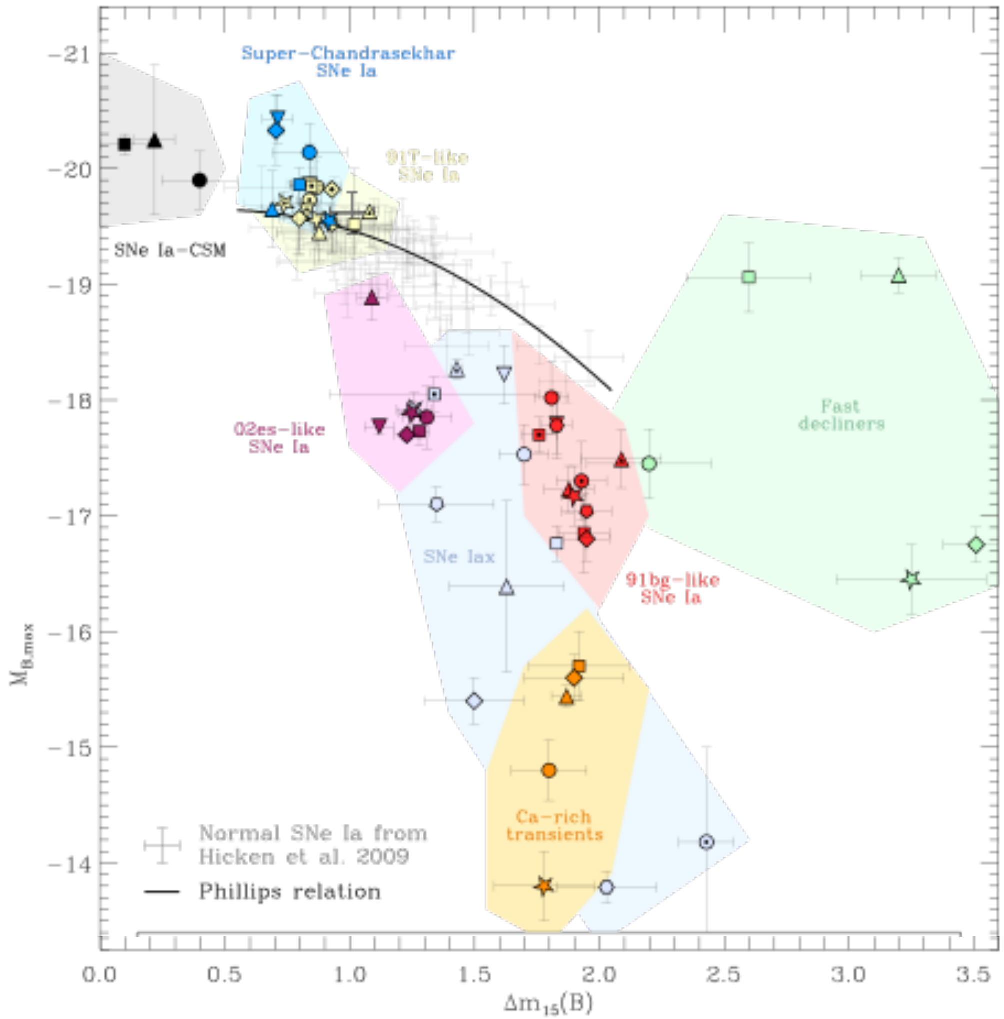
Established picture for SN Ia explosion



Supernovae Ia: diverse and complex

Taubenberger 17





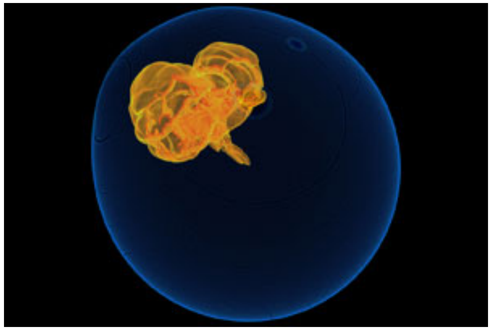
What is the physics at work?

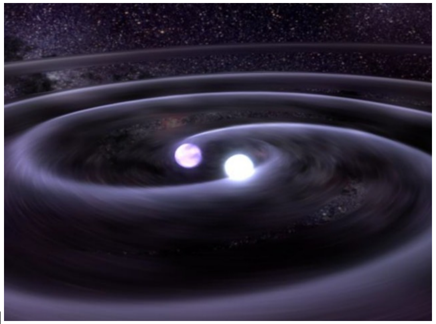
Type Ia supernova questions:

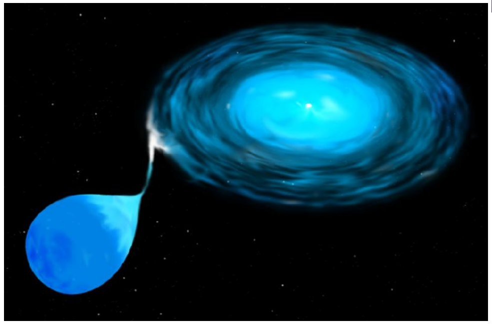
- How explosions are ignited
- Deflagration or detonation
- Chandrasekhar or sub-Chandrasekhar mass
- Progenitors and evolutionary channels

Modelling aims to understand:

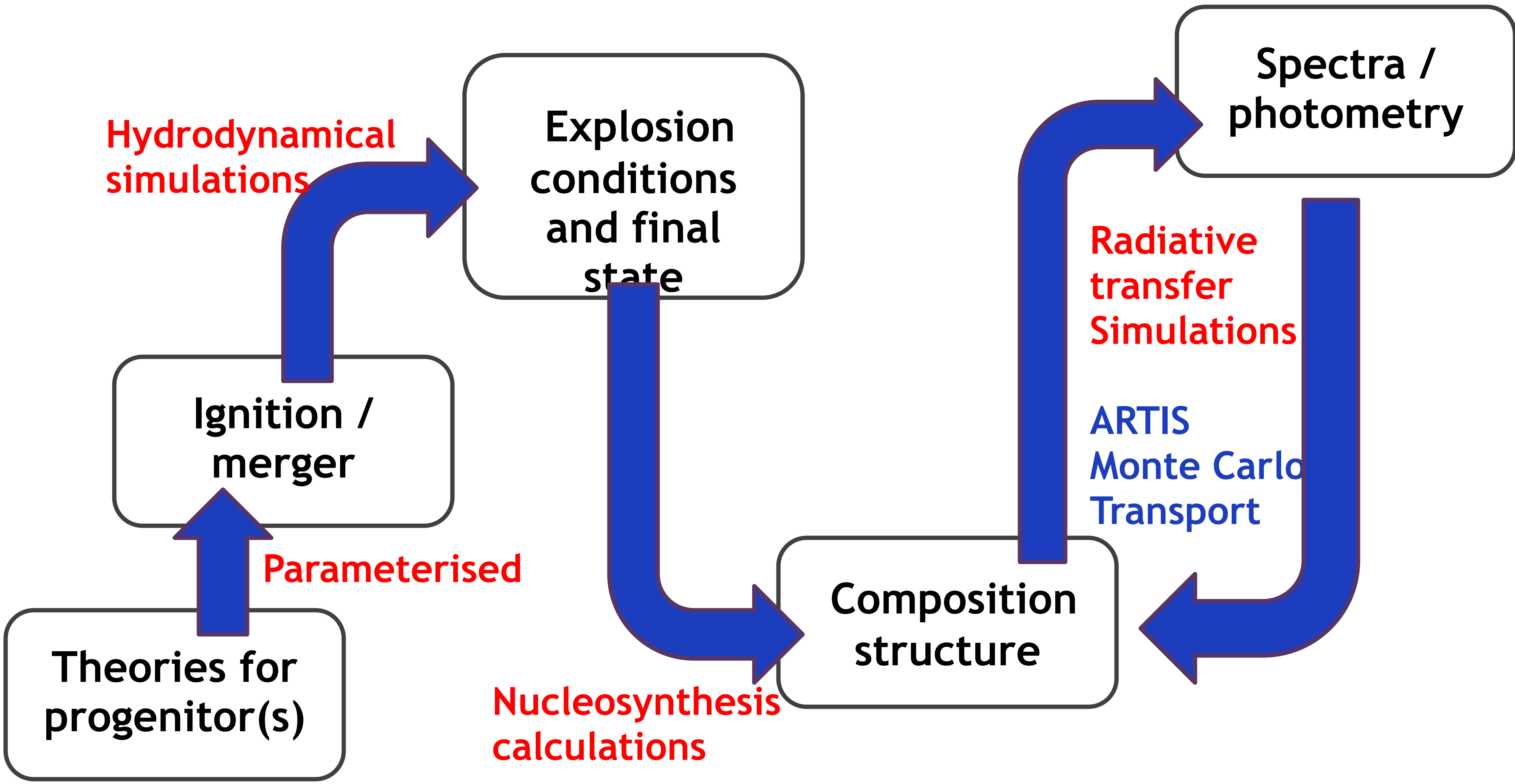
- Explosion physics and nucleosynthesis
- Origin of diversity
- Implications for cosmology samples







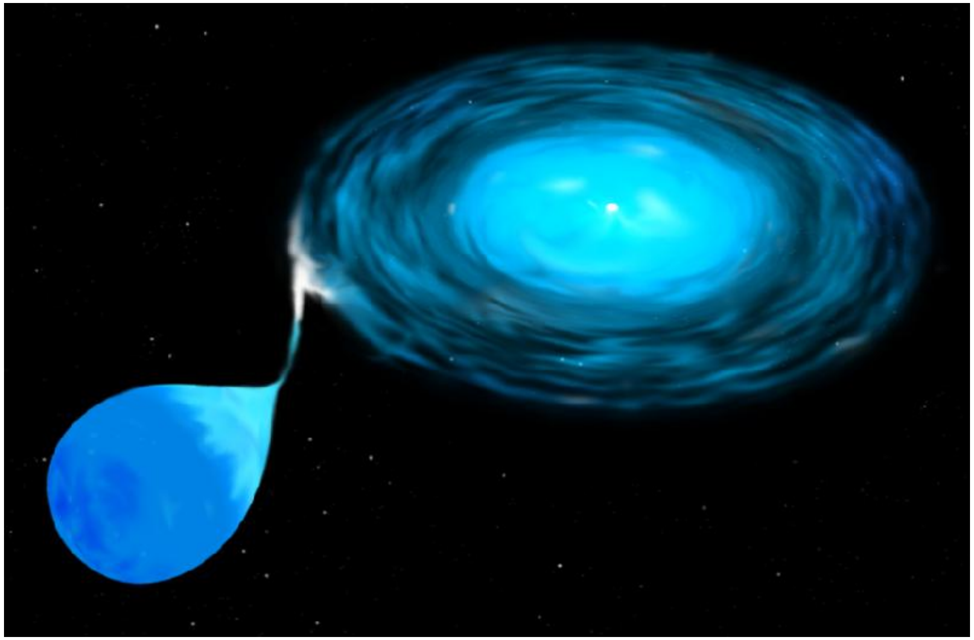
Simulating supernovae



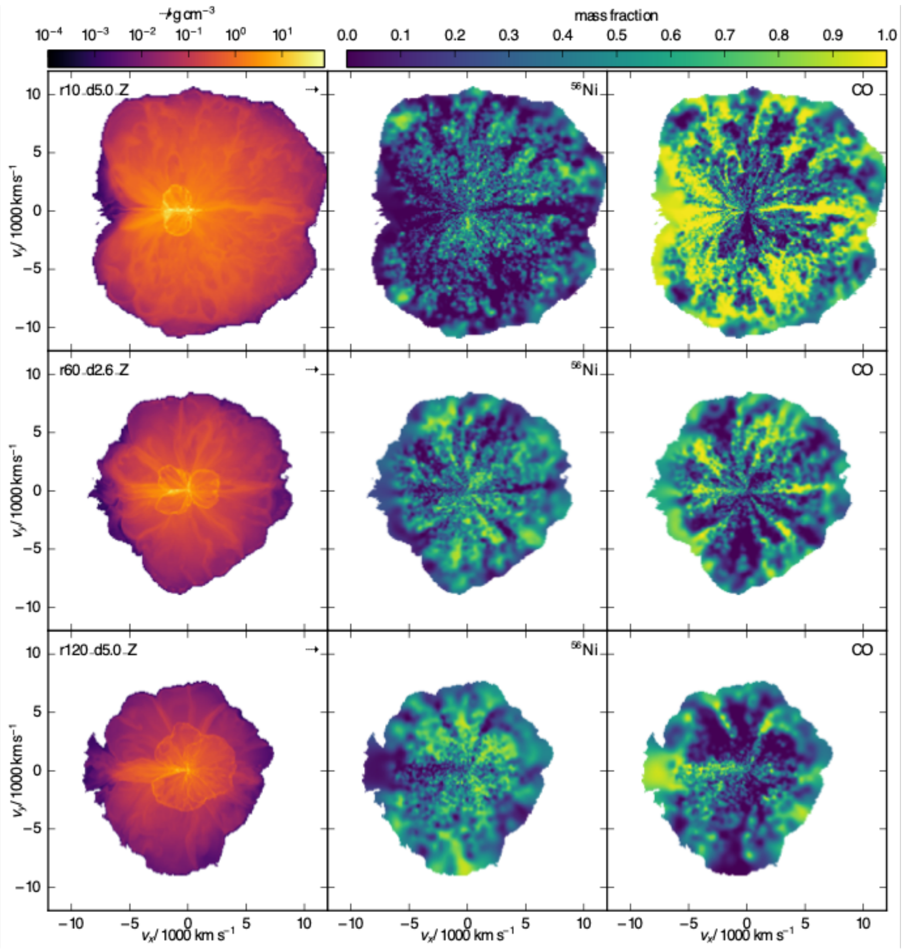
Explosion scenarios

(Near-)Chandrasekhar-mass single-degenerate scenario

- White Dwarf in binary system
- Mass-transfer grows WD mass
- Density and temperature rise
- Thermonuclear runaway ignites a deflagration



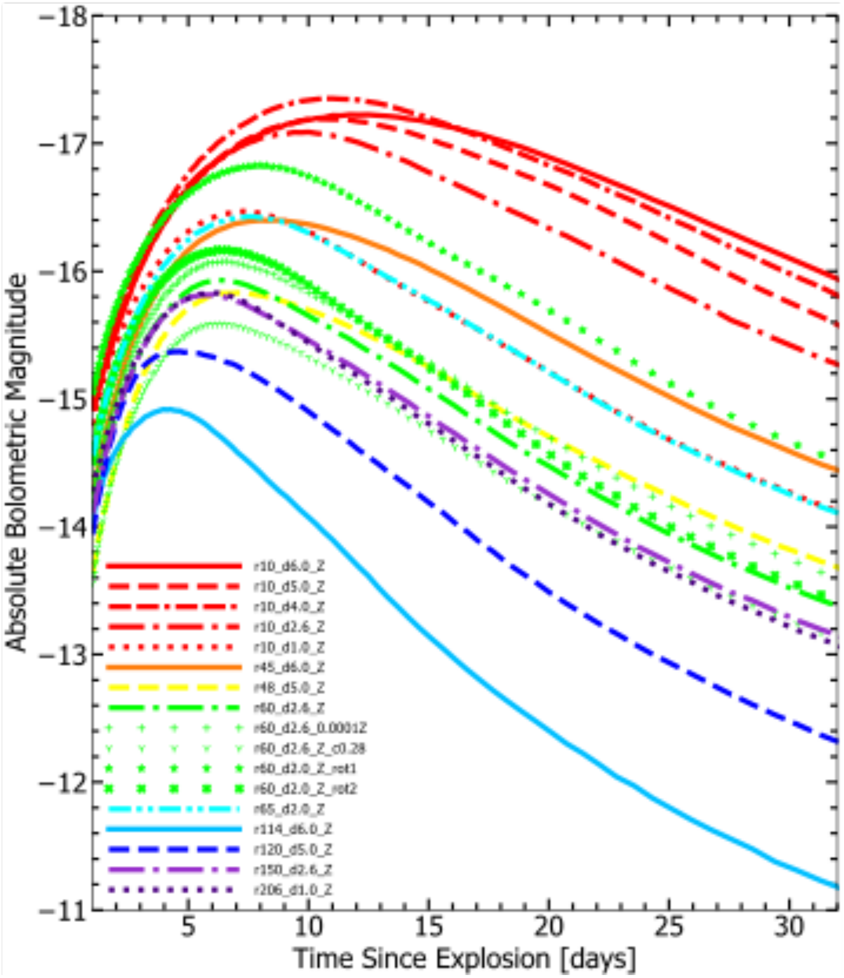
Lach et al. deflagration models



Simulations by Fink+10, Lach+21

- Low-luminosity explosions
- Partial disruption only ("zombie star" remnant)

Lach et al. deflagration models



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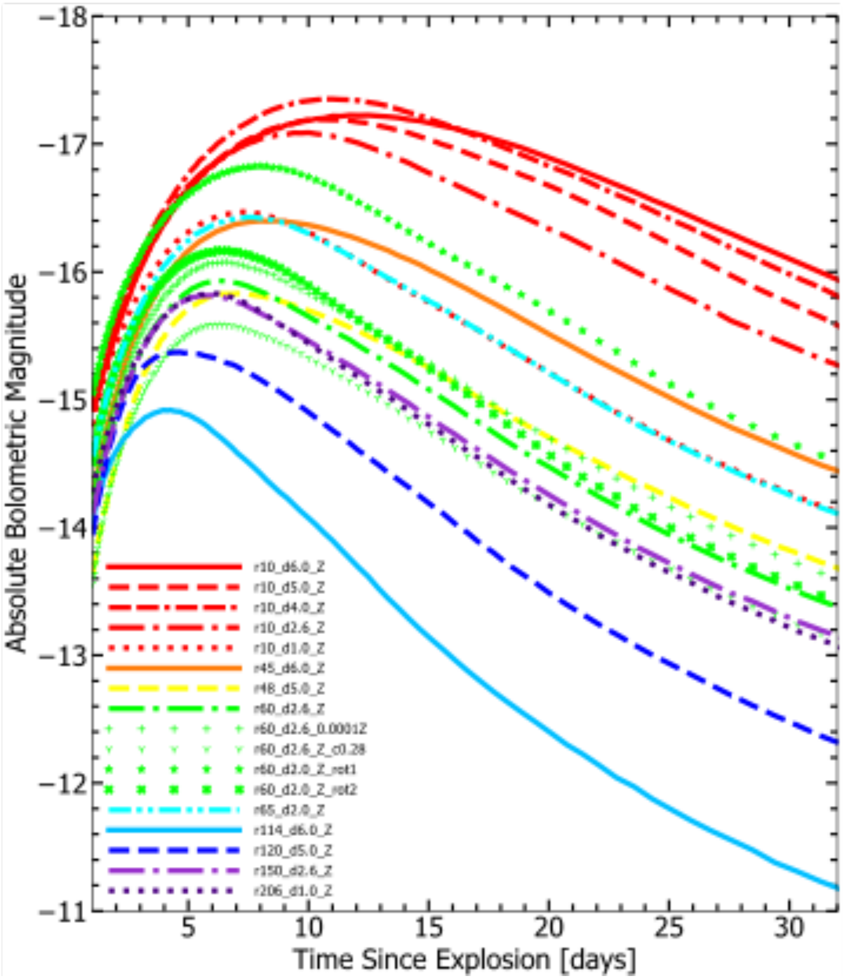

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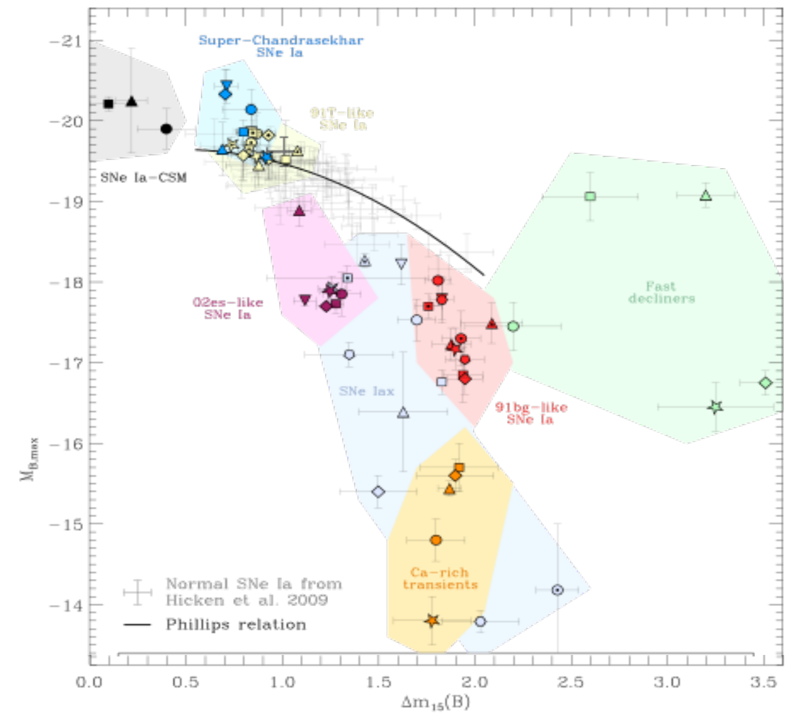


Type Iax versus pure deflagrations

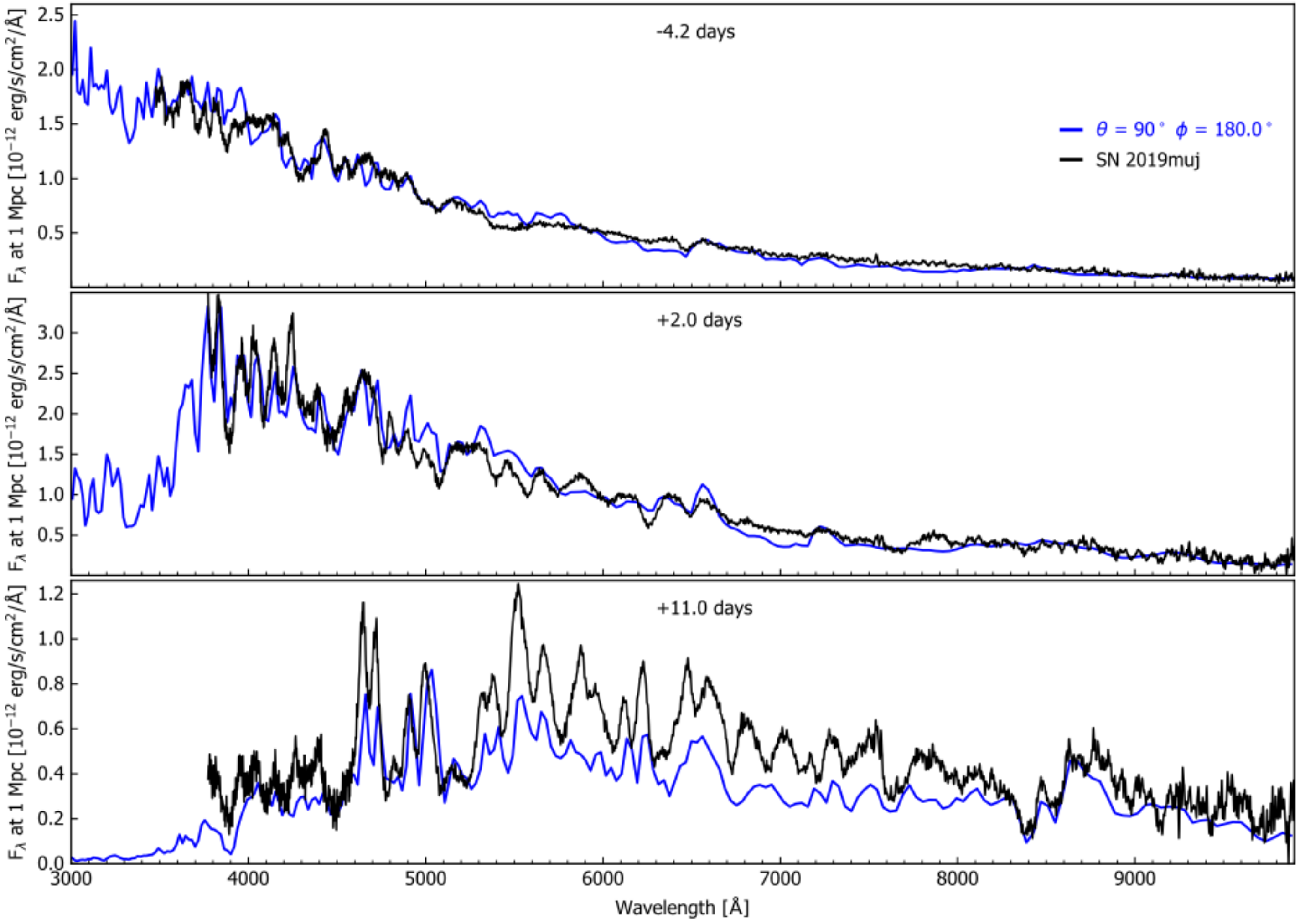


Figure from Lach, Callan +21

Type Iax versus pure deflagrations

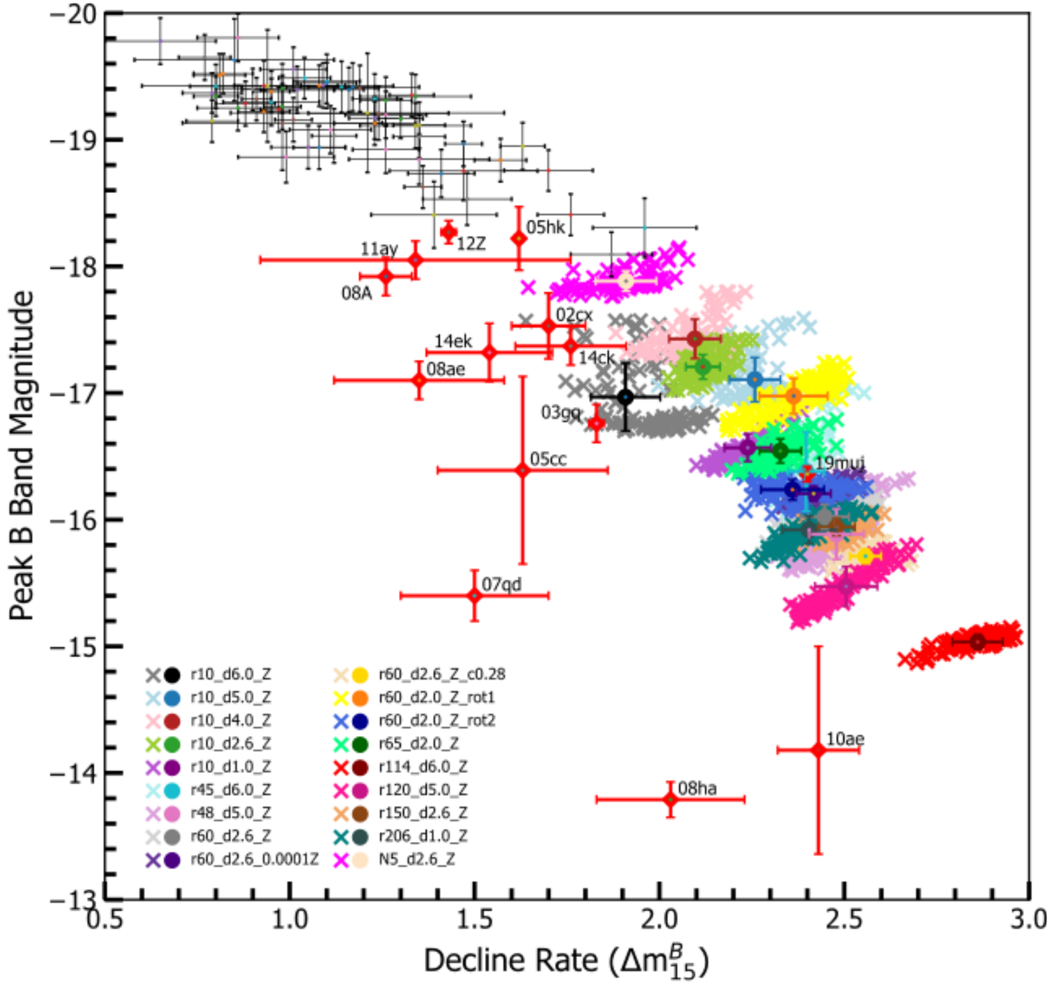


Figure from Lach+21

- Models match brightness and peak spectra well
- Decline generally too fast
- Potential role of energy from remnant (Callan PhD)

Incorporating the “zombie” star

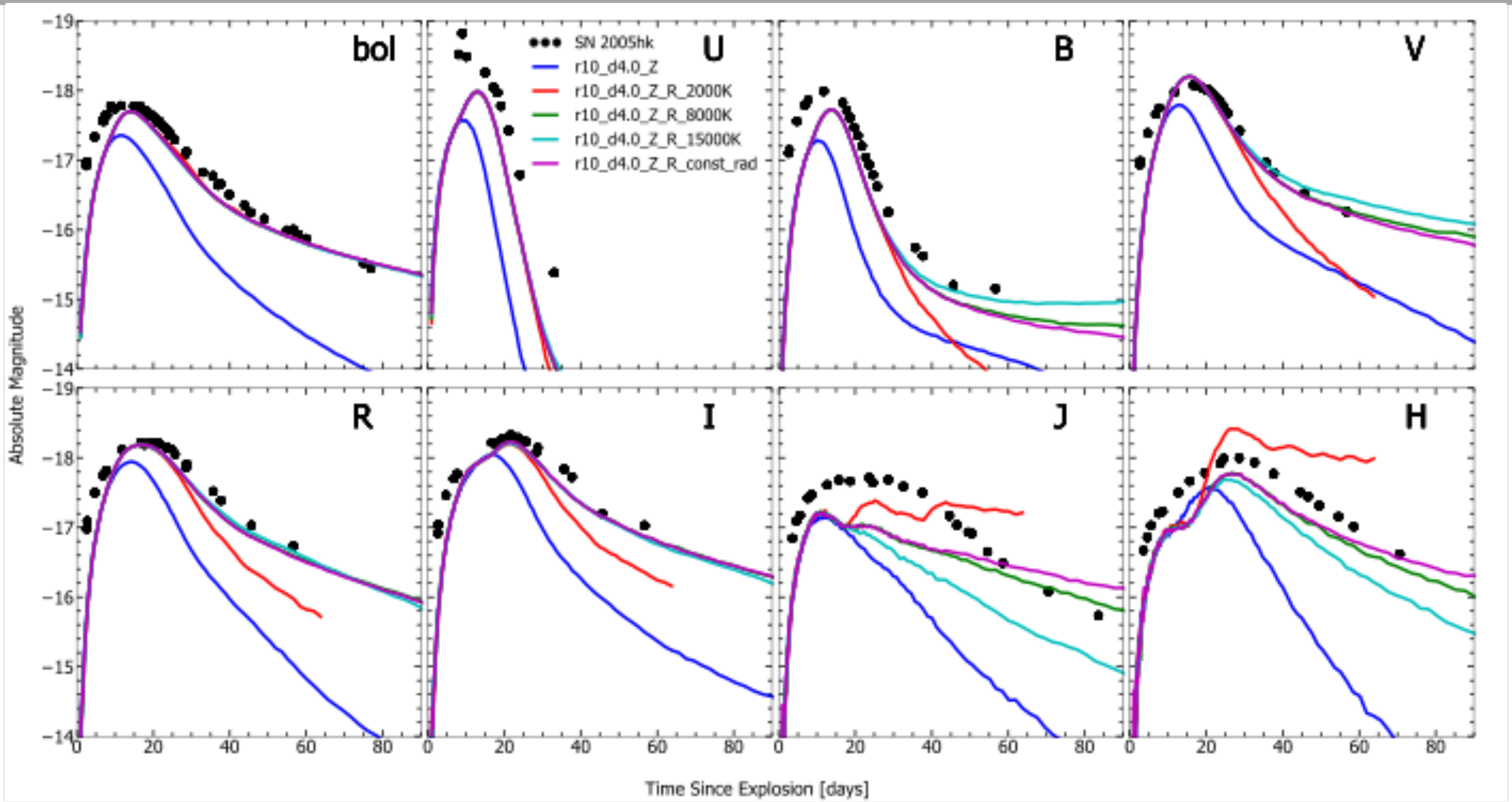


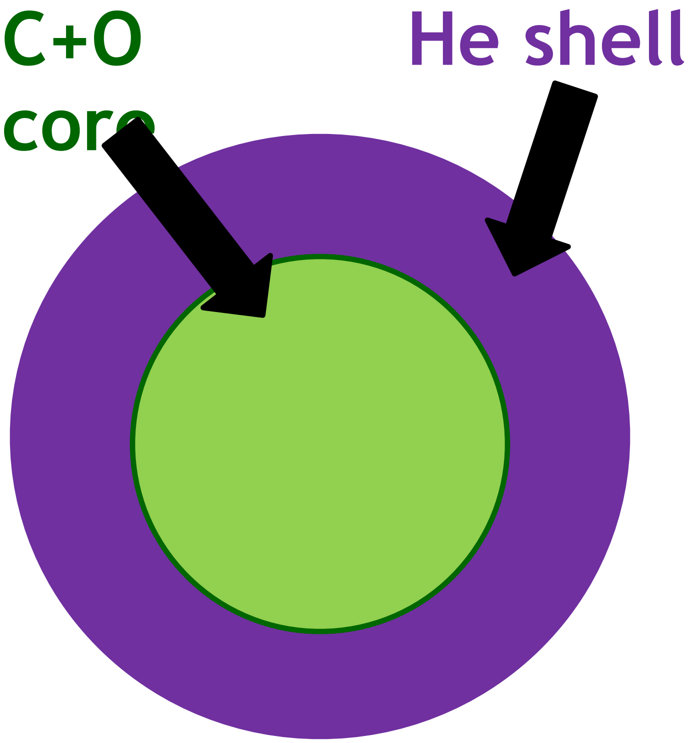
Figure from Callan+, in prep.

- Contribution from remnant slows decline

Double detonation scenario

Sub-Chandrasekhar-mass double-detonation

- WD accretes from He-rich companion
- Detonation of the He shell triggers a detonation of the C+O core



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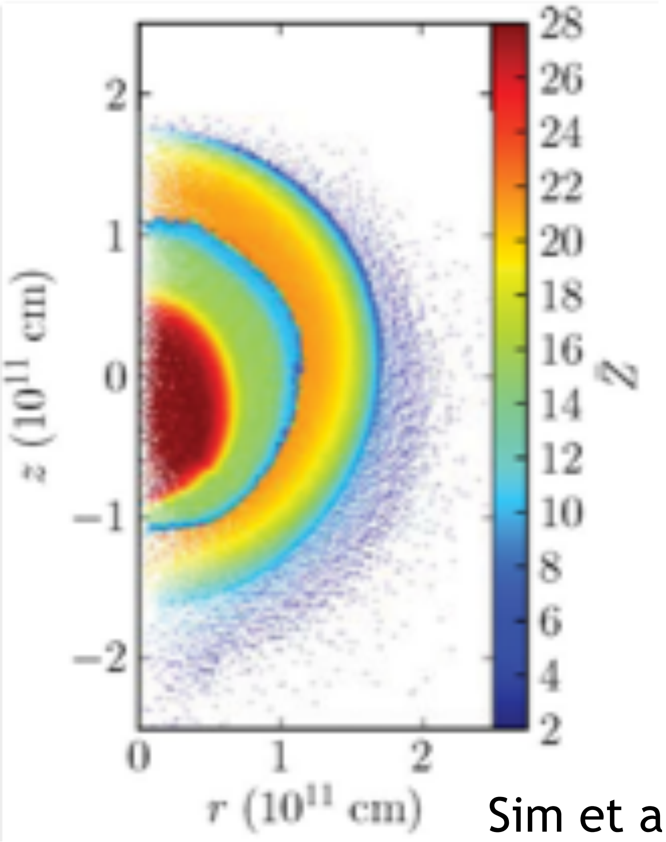
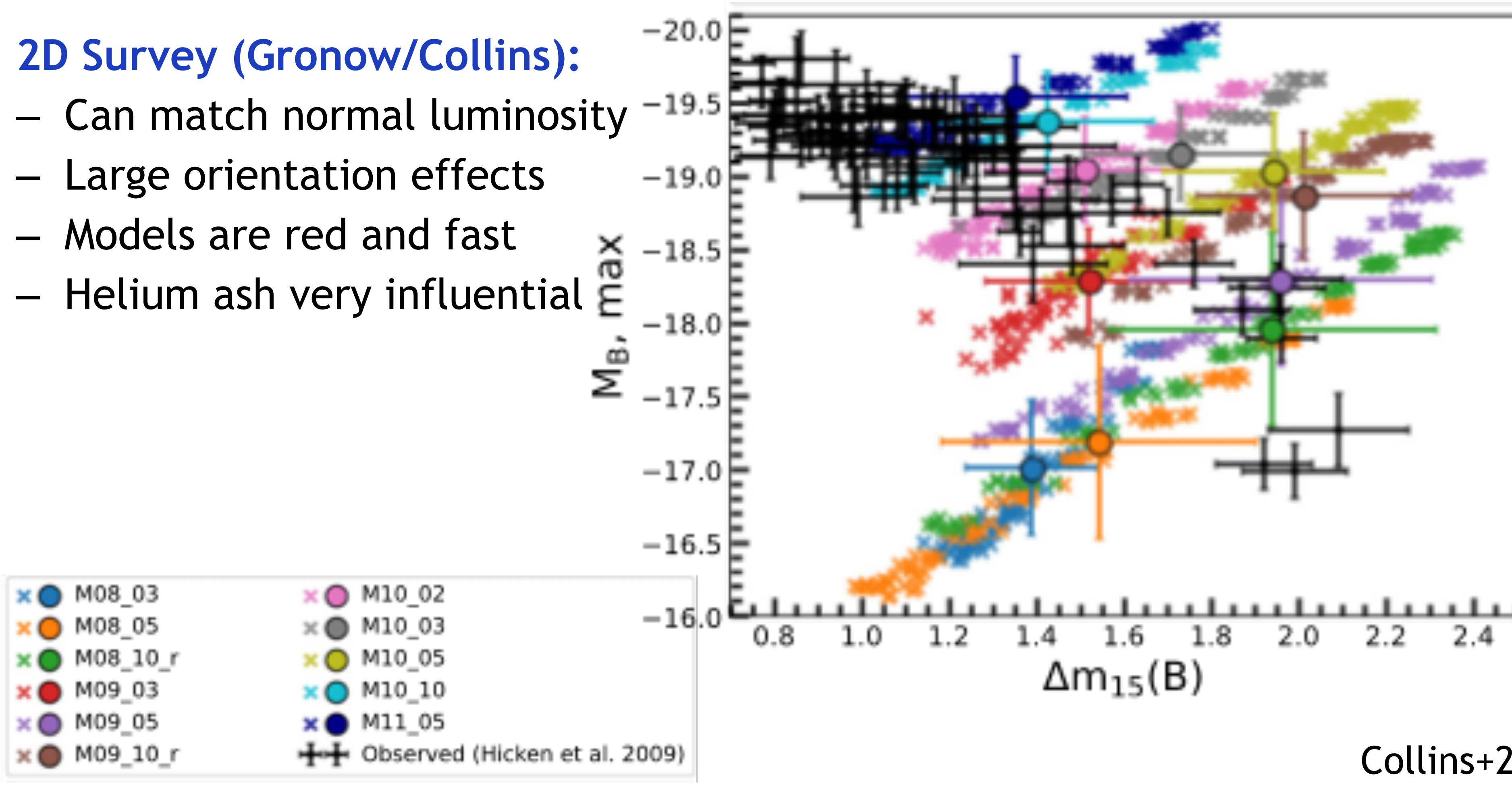


Sim et al.

Double detonation scenario

2D Survey (Gronow/Collins):

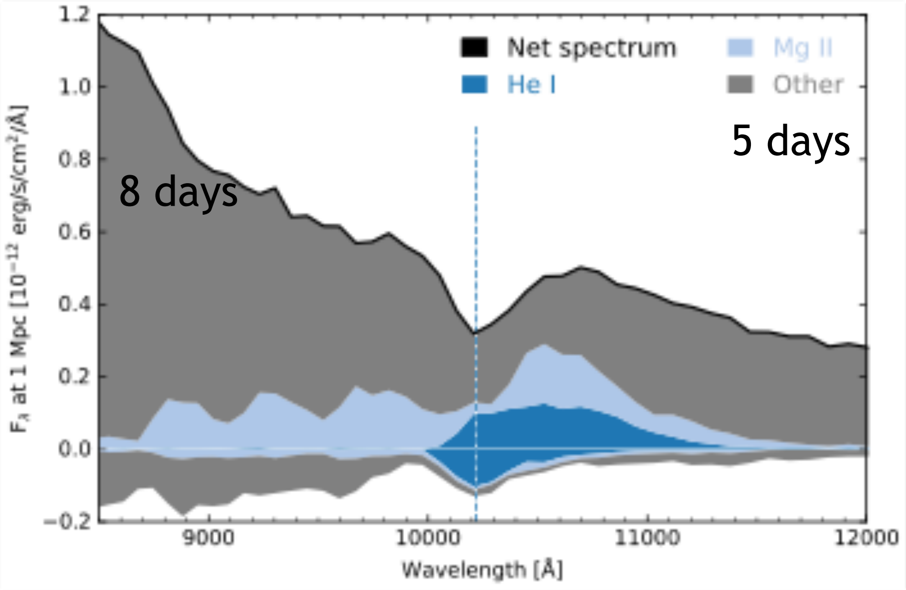
- Can match normal luminosity
- Large orientation effects
- Models are red and fast
- Helium ash very influential

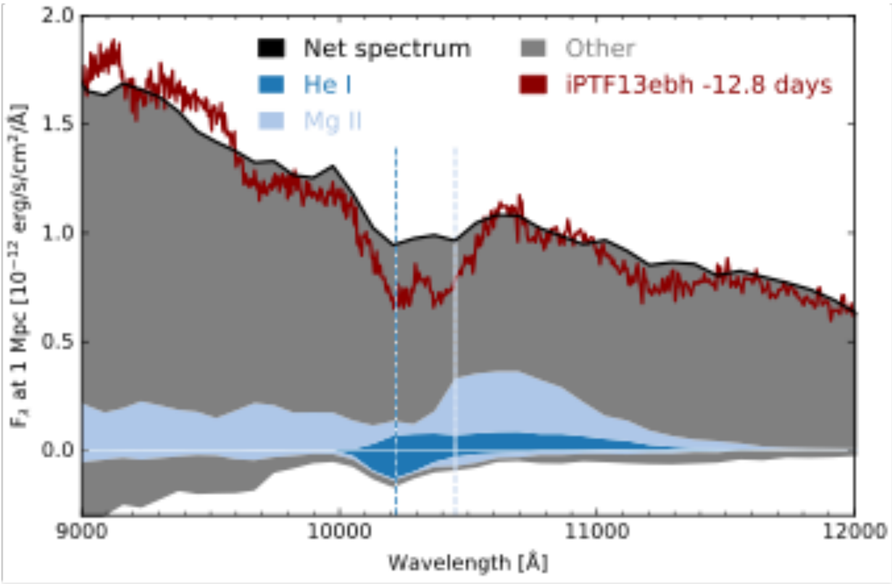


Collins+22

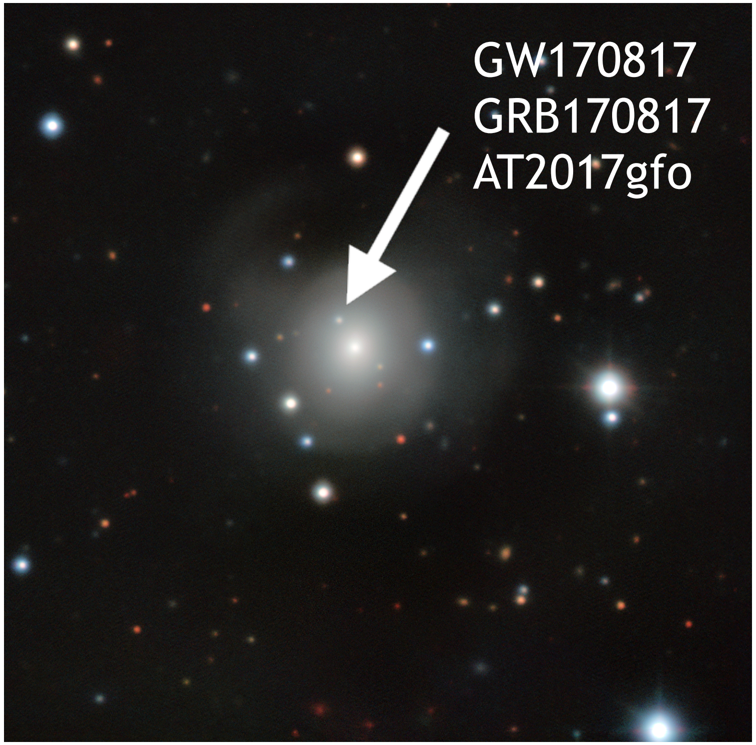
Double detonation scenario

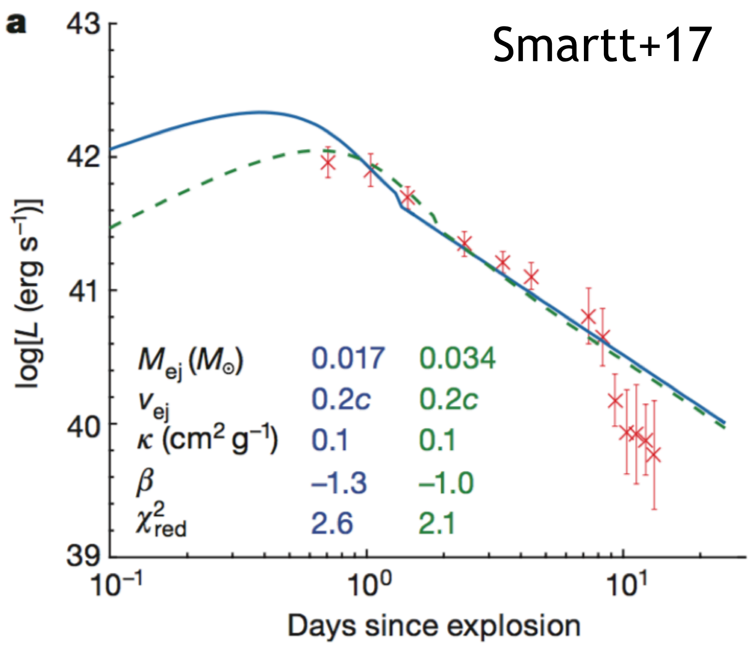
– Signatures of Helium (full NLTE simulations; Collins+ 2023)





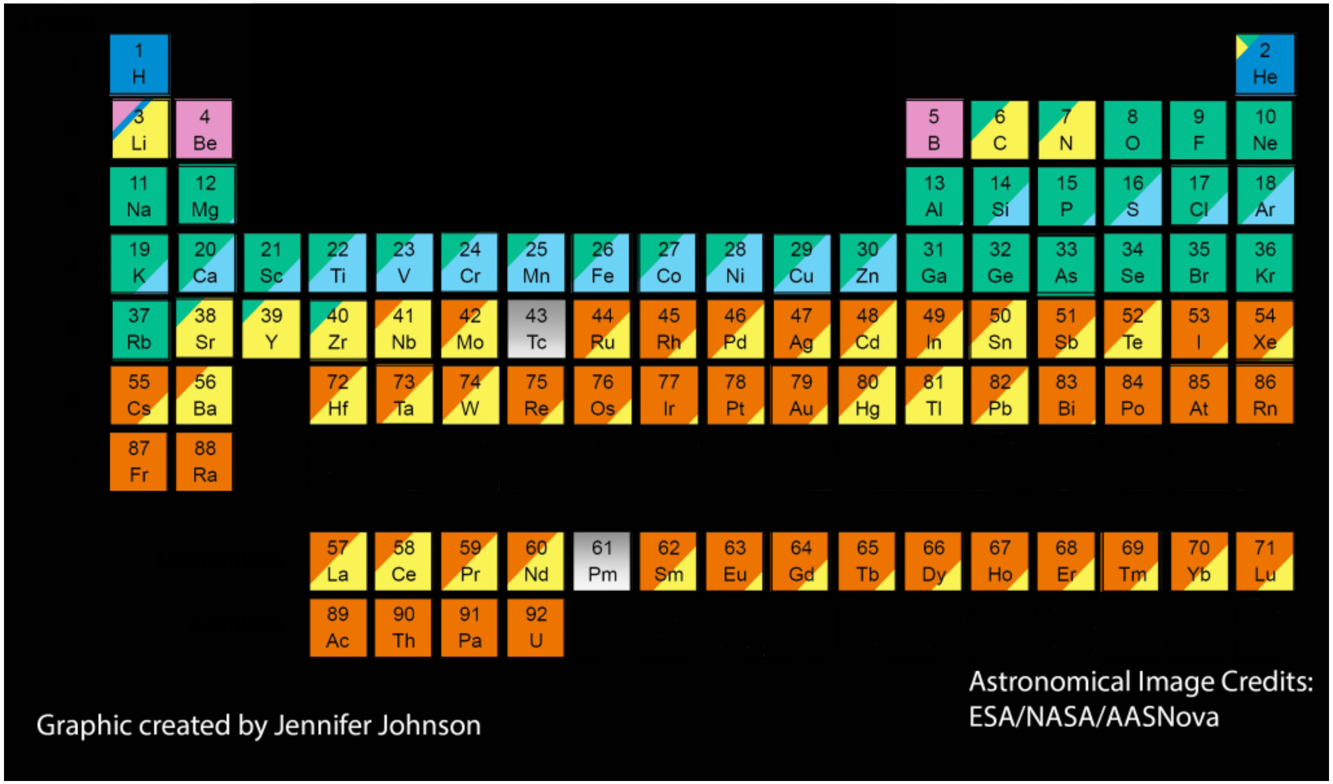
Kilonovae: neutron star mergers and the r-process





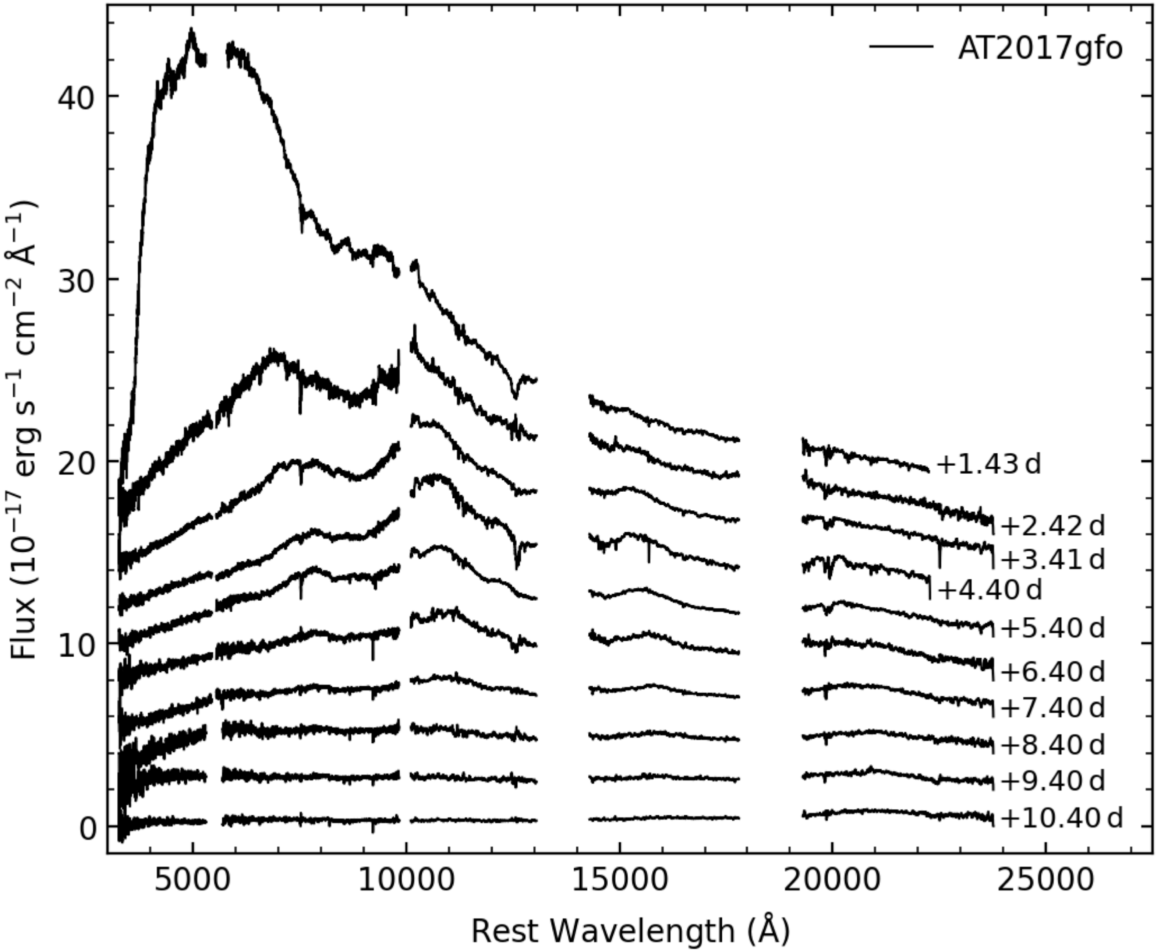
- UV, optical and NIR fading emission
- Radioactively heated, thermal emission

NS-NS mergers



- Origin of the elements (Burbidge, Burbidge, Fowler & Hoyle 1957, Cameron 1957 Lattimer & Schramm 1974, Pagel 1997)
- Neutron star physics, extreme states of matter

Spectra: feature identification



Well-calibrated spectra

Smartt et al. 2017
Pian et al. 2017

(+ HST Tanvir et al. 2017)

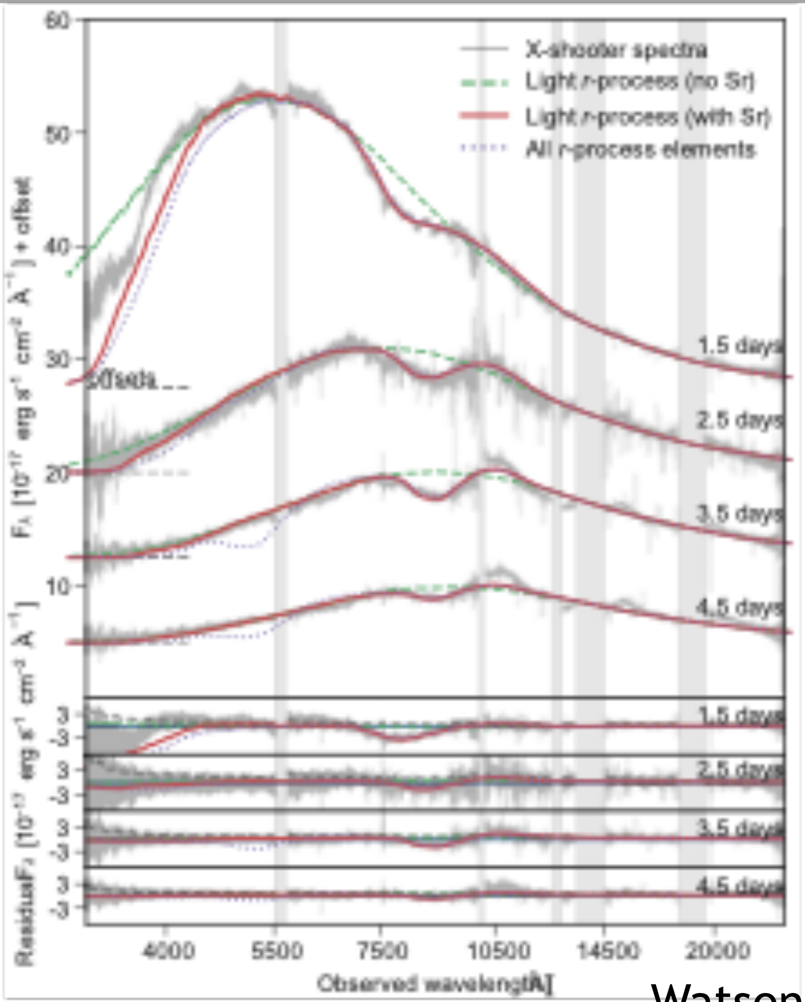
Spectra: feature identification

Empirical 1D modelling

- Smartt+ 17
- Watson+ 19
- Gillanders+ 21,22

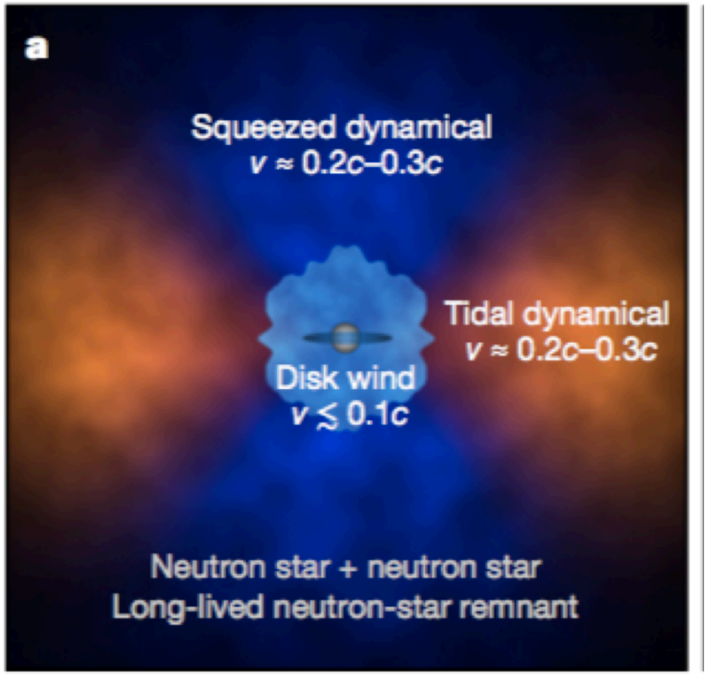
Sr identification (Watson+ 19)

- Indicative of light r-process
- Other possibilities, including He
- Recent Y identification (Sneppen+ 23)

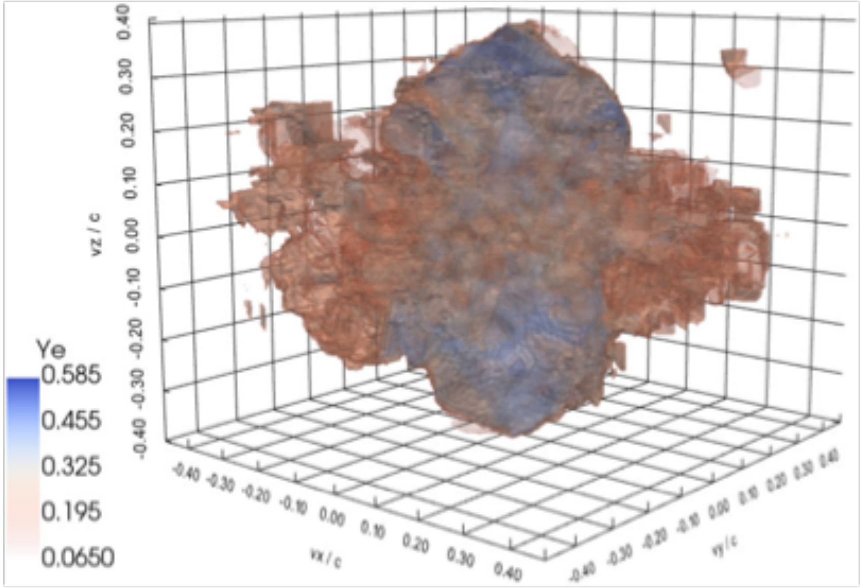


Watson+19

Complex morphology expected



Kasen+ 17, schematic

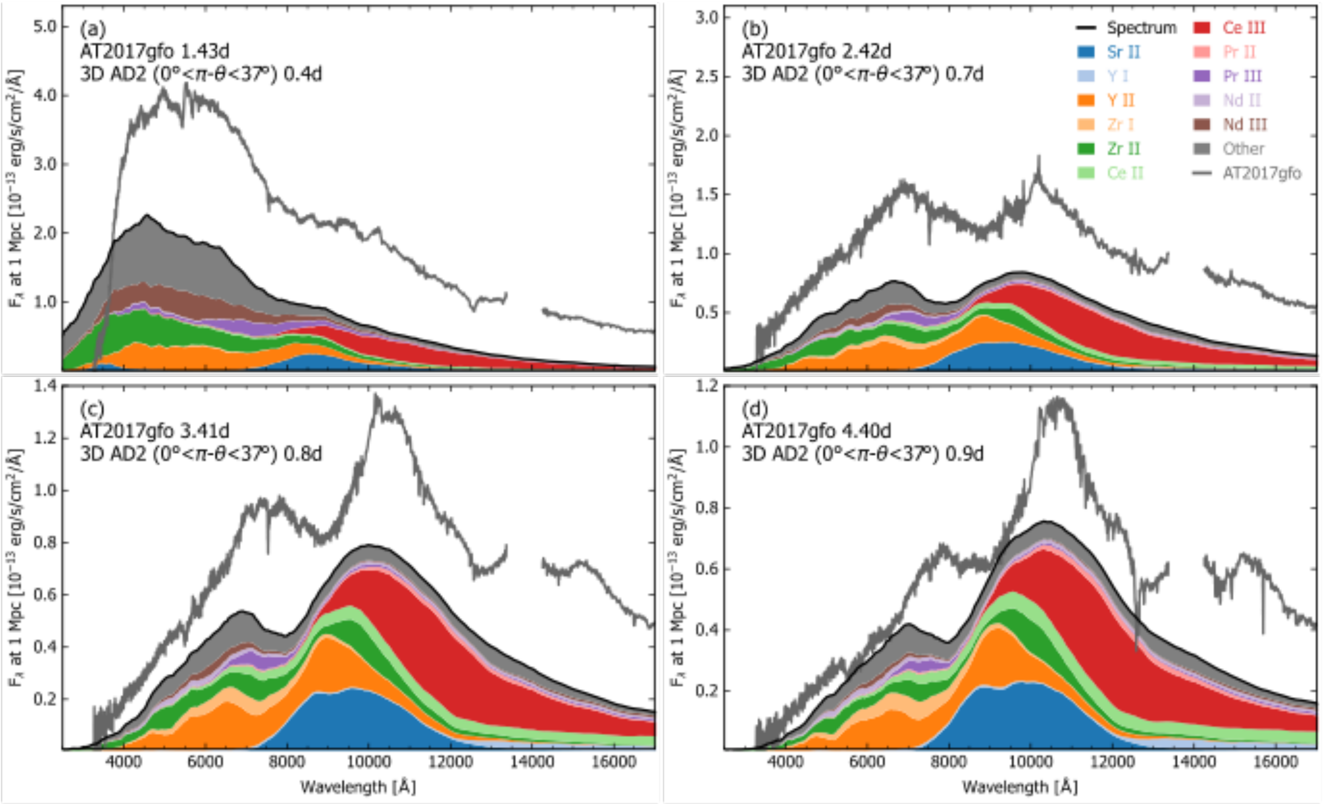


Bauswein simulation (Collins+ 23)

Multi-D transport models

First ARTIS results (Shingles et al. 2023)

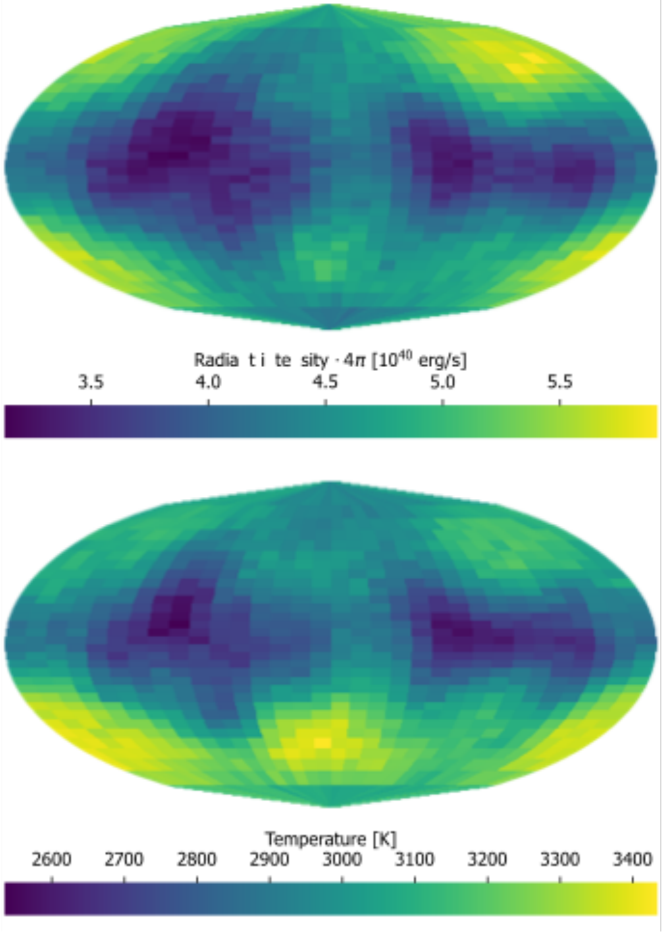
- Simulation of dynamical ejecta



Multi-D transport models

First ARTIS results (Shingles et al. 2023)

- Simulation of dynamical ejecta
- Highly aspherical



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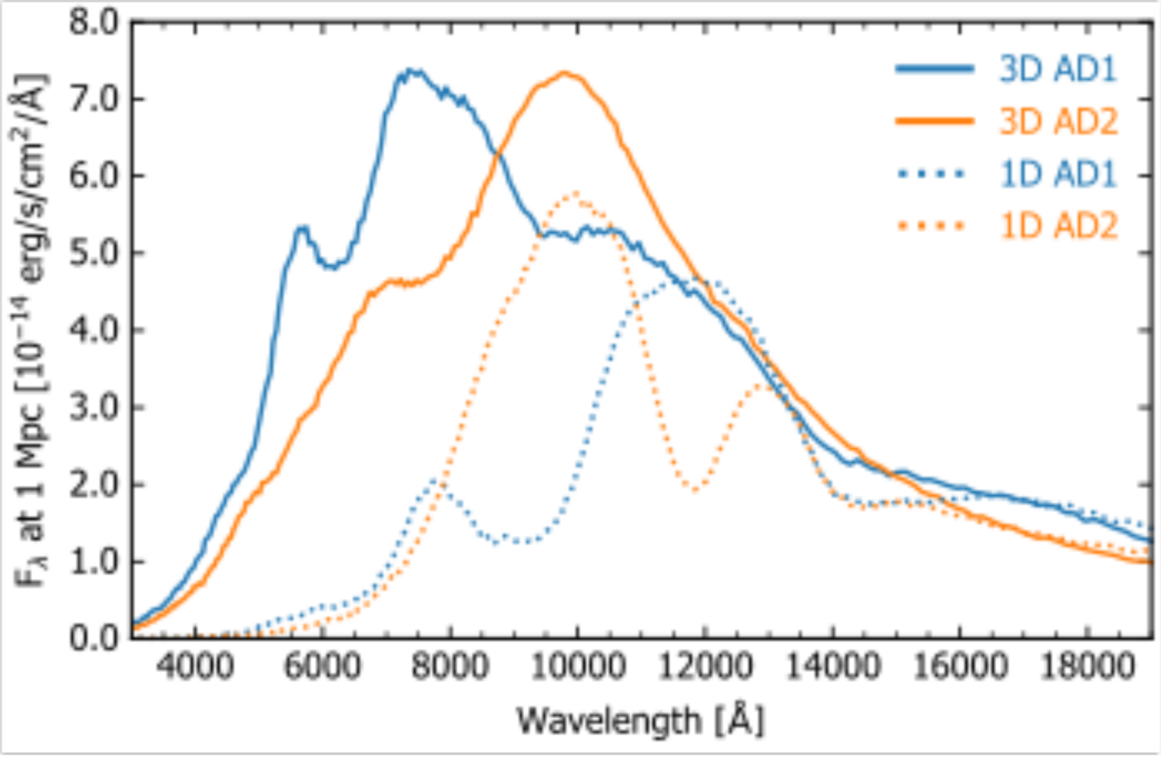
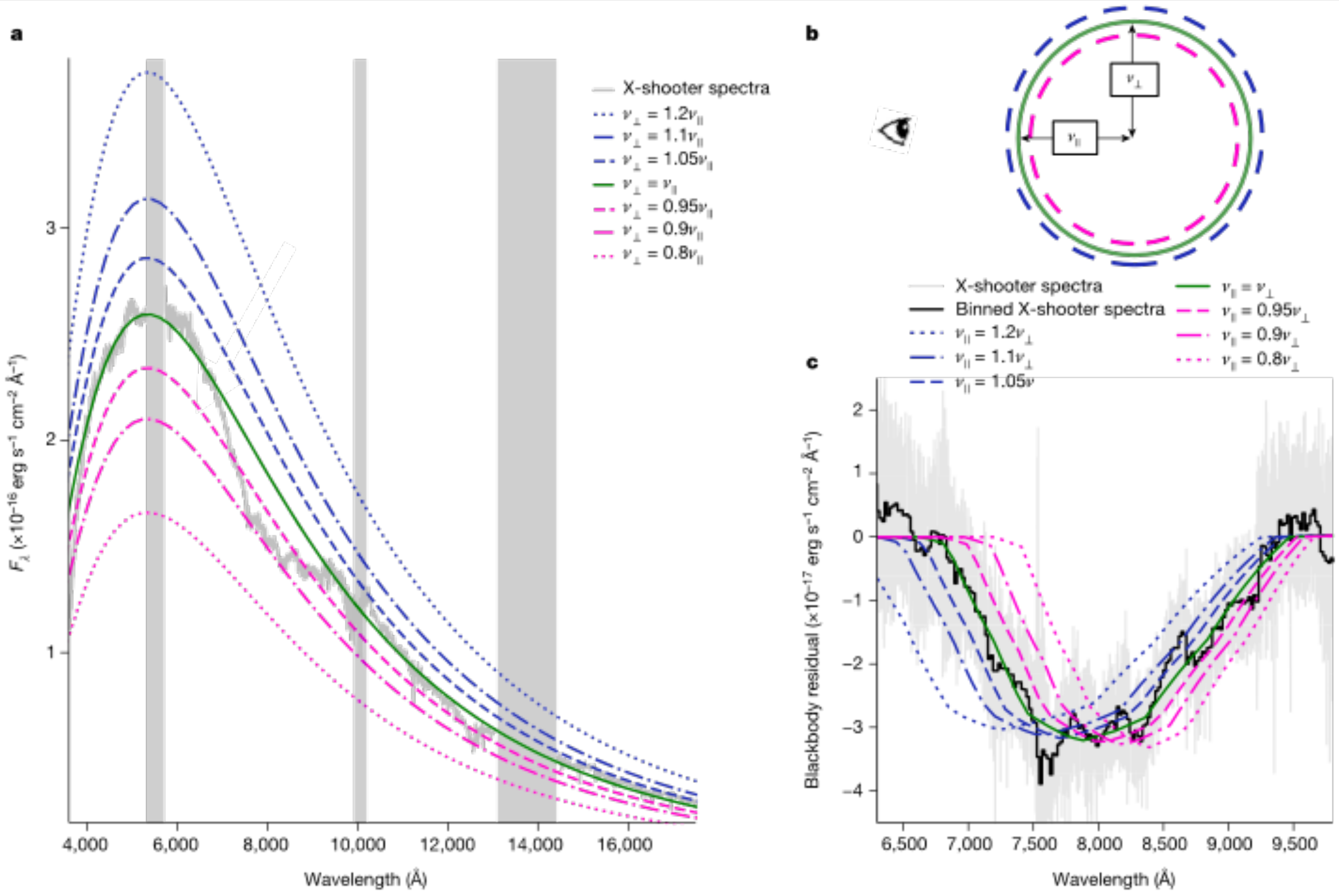


Constraining geometry



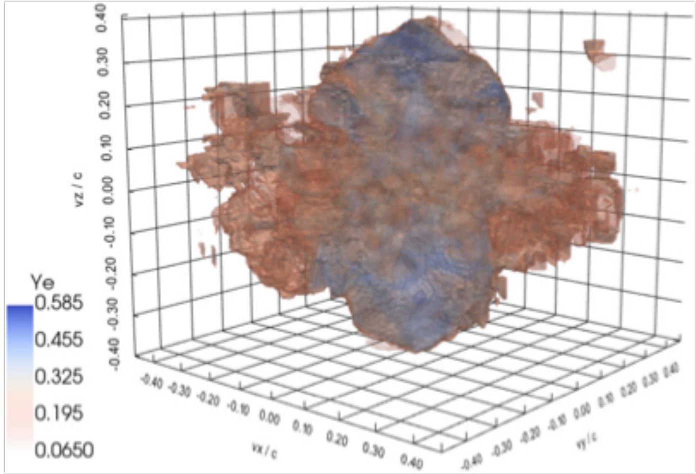
Sneppen+ 23

Does spectral analysis require / support this structure? No!

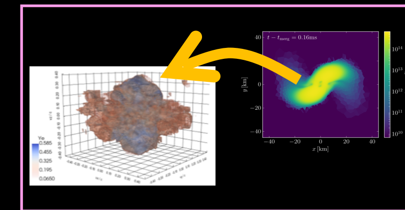
Multi-D transport models

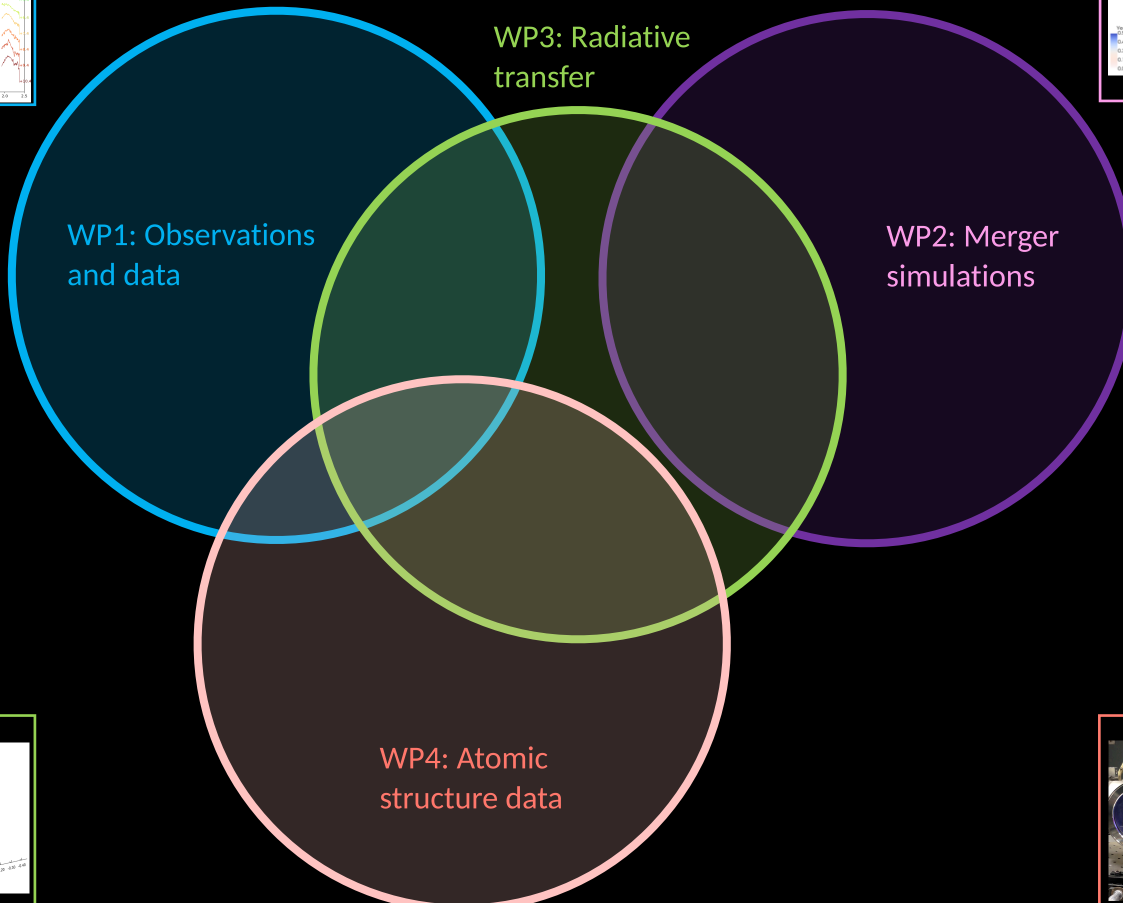
First ARTIS results (Shingles et al. 2023) - proof of concept:

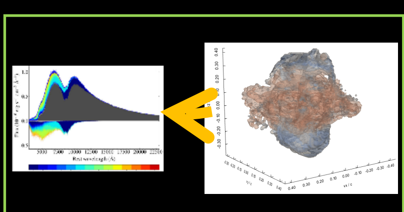
- Simulation of dynamical ejecta
- Departures from spherical symmetry are strong
- Remarkable (qualitative) agreement, but only for some orientations
- Continuing analysis to guide interpretation of observation (Collins et al. 2023, submitted)

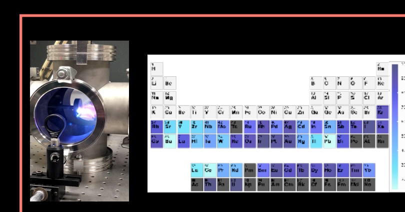


HEAVYMETAL
(ERC Synergy, from Sep 23)





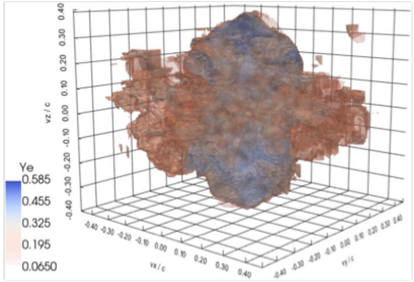




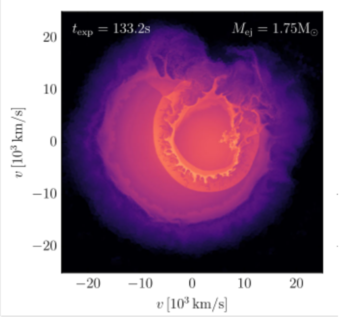
Summary

- **Radiation transport simulations are needed to test models and interpret data**

- **Multi-D and non-LTE effects matter**
  - Neglecting either leads to systematic discrepancies
  - **Just now becoming possible to address both**



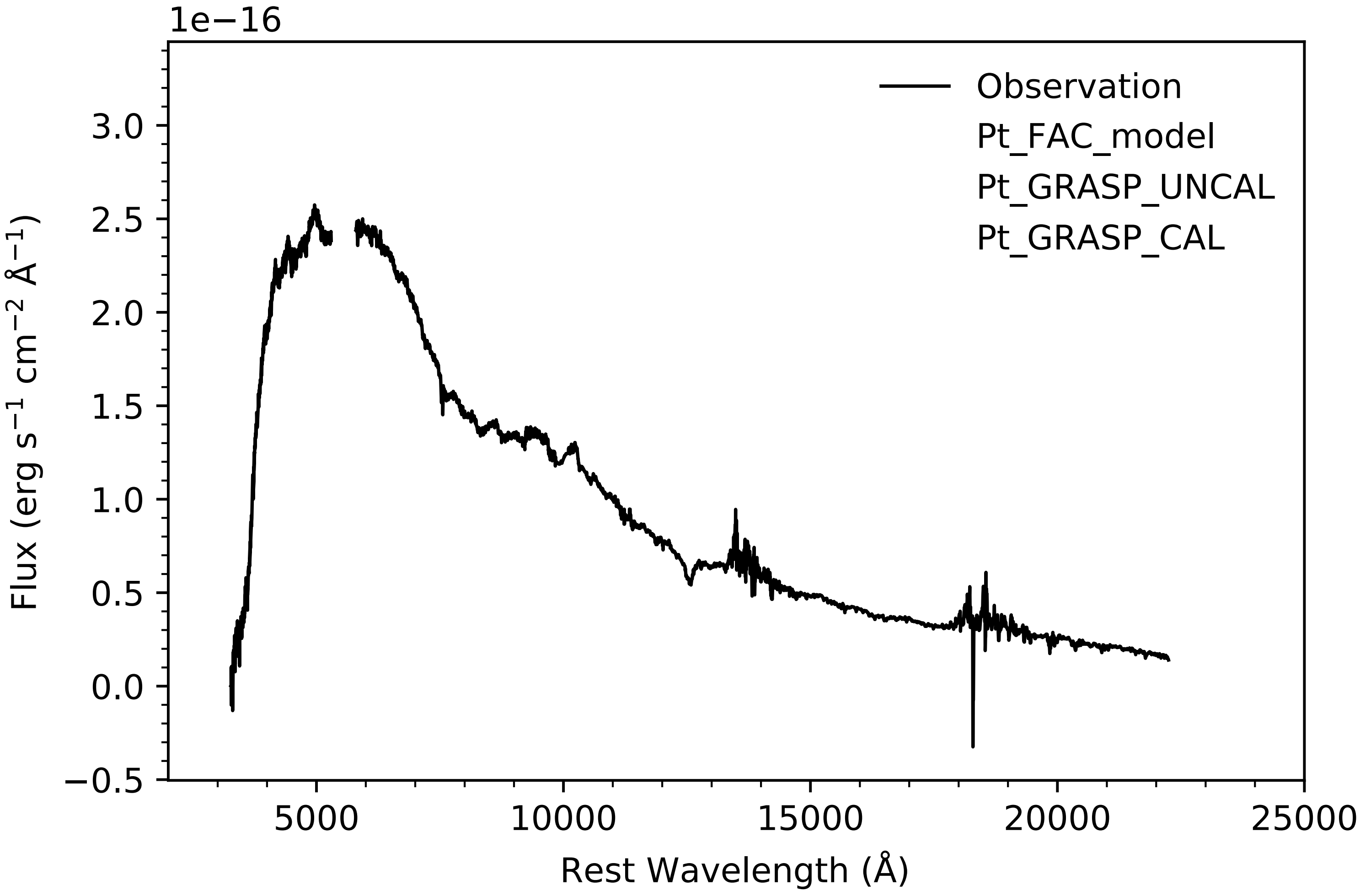
- **Type Ia supernovae**
  - Diversity motivates range of scenarios
  - Sub-Chandrasekhar detonations promising for Type Ia – **He in ignition is key**
  - Chandrasekhar mass deflagrations may account for Type Iax
  - **Promise lies in late phases to understand inner ejecta**



- **Neutron star mergers and kilonovae**
  - Demonstrated power to identify species, study stratification and geometry
  - **Realistic prospect of extracting detailed r-process information from data, but depends on combining simulation, theory, atomic physics, nuclear physics and observation**
  - Beyond lies constrains on properties of ultra-dense matter

Thank you!

Need for atomic data and calibration



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