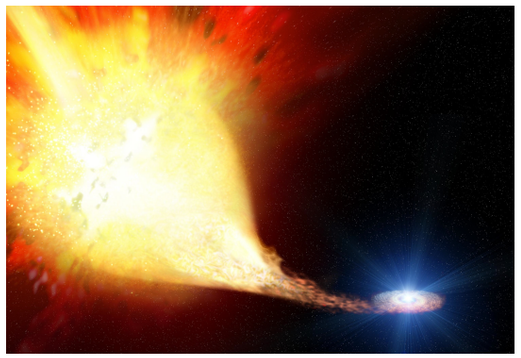
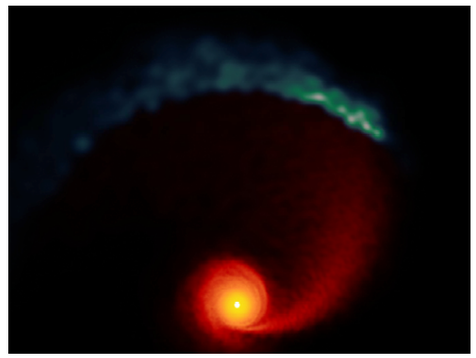



Constraining the explosions and progenitors of Type Ia supernovae

Dr. Kate Maguire

Queen's University Belfast

Science & Technology Facilities Council

European Research Council

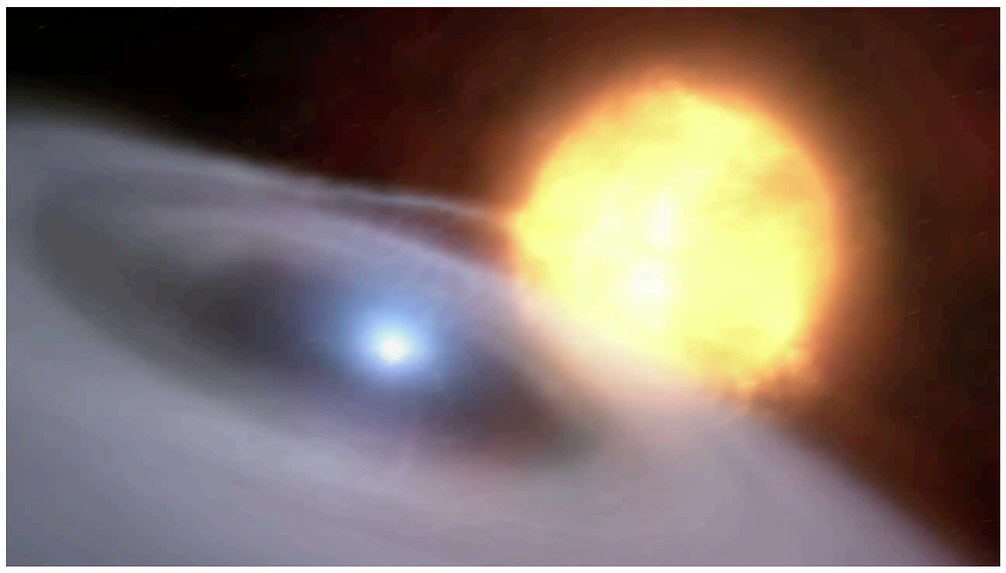
Established by the European Commission


Importance of Type Ia supernovae

- Endpoint of stellar evolution in interacting binary systems
- Vital role in chemical enrichment - main producers of iron in the Universe
- Best known as cosmological distance indicators

What systems explode as normal Type Ia supernovae?

Case 1: Single-degenerate



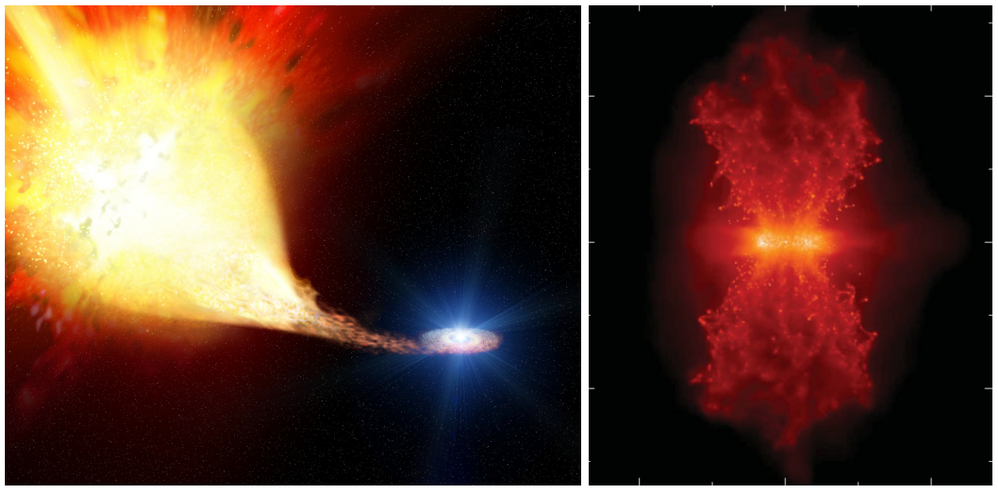
Red giant? Main-sequence star?

Case 2: Double-degenerate

Another white dwarf?

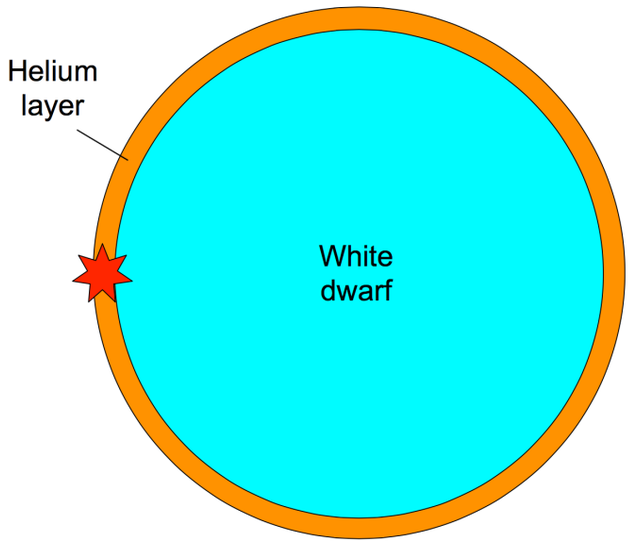
- Progenitor system has never been directly detected
- These are subtle signatures

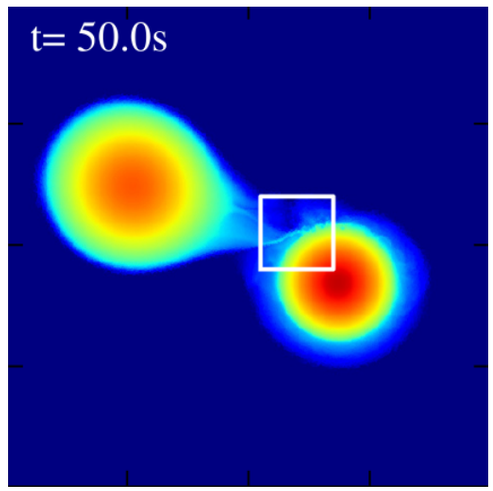
‘Popular’ progenitor models: Chandra and sub-Chandra



Delayed detonation of a **$M_{chandra}$** white dwarf? (Whelan & Iben 1973; Nomoto 1982, Blinnikov & Khokhlov 1986)

Detonation of He shell on a **sub-$M_{chandra}$** white dwarf (Shen+ 2010)





Violent merger of a **sub-$M_{chandra}$** white dwarf (Pakmor+ 2012)

What observations can distinguish between explosion scenarios?

What observations can distinguish between explosion scenarios?

Around max.

Flux

>150 days

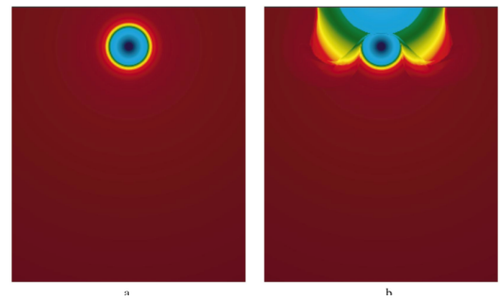
0 d
SN explosion

Timeline from explosion

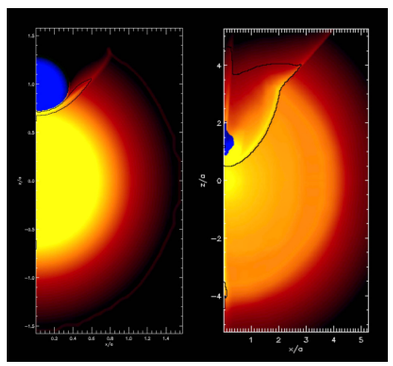
~250 d

Host galaxy studies

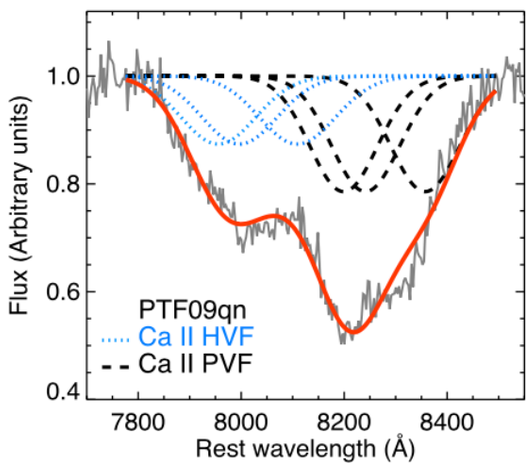
Companion star interaction



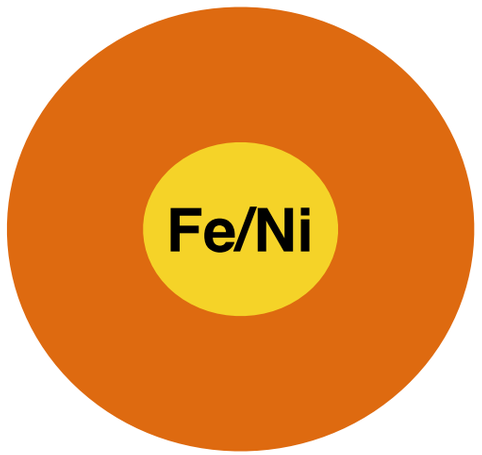
Companion star/ CSM interaction/ Nickel mixing



High-velocity features/polarisation

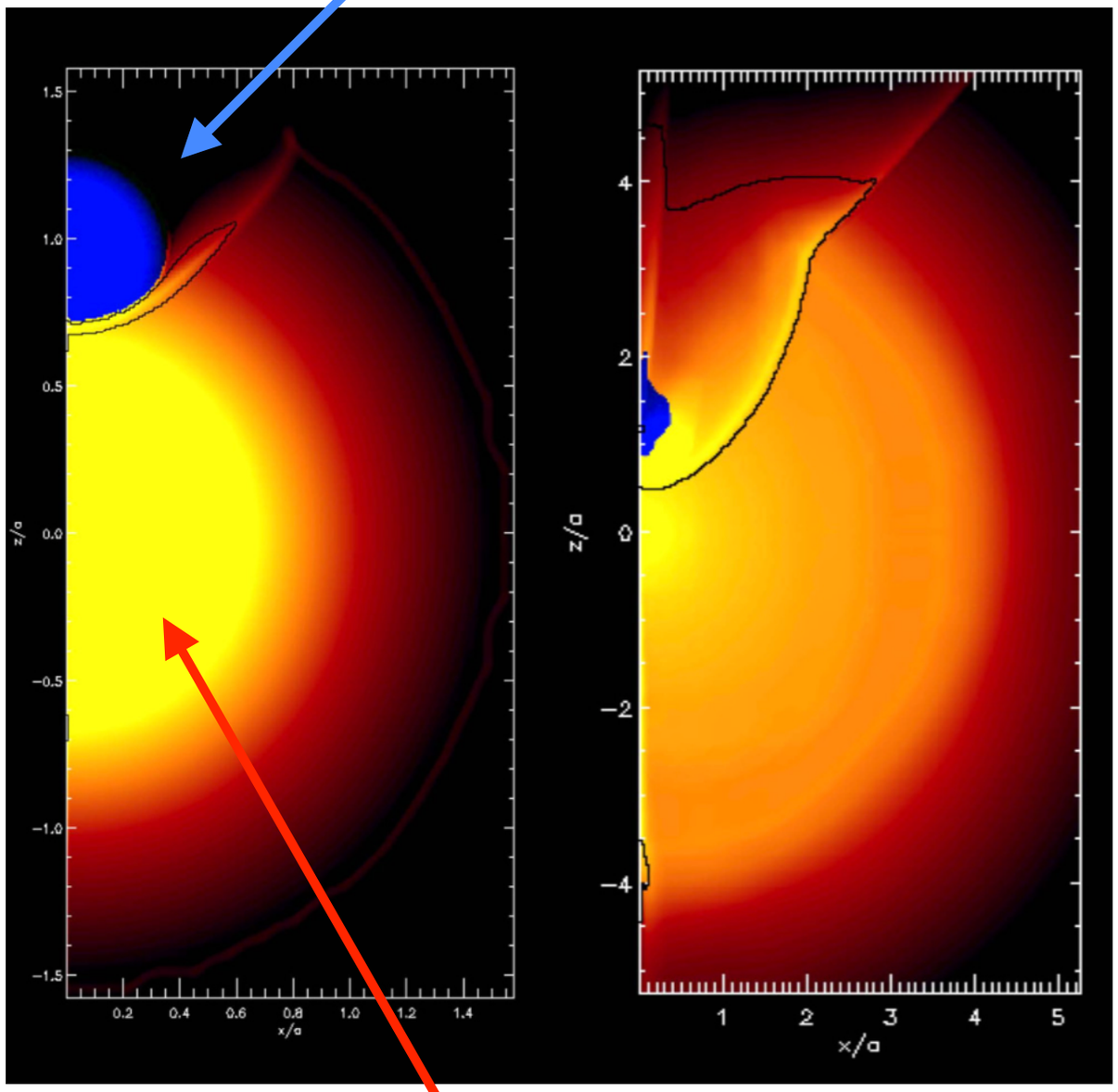


Core nucleosynthesis & asymmetries



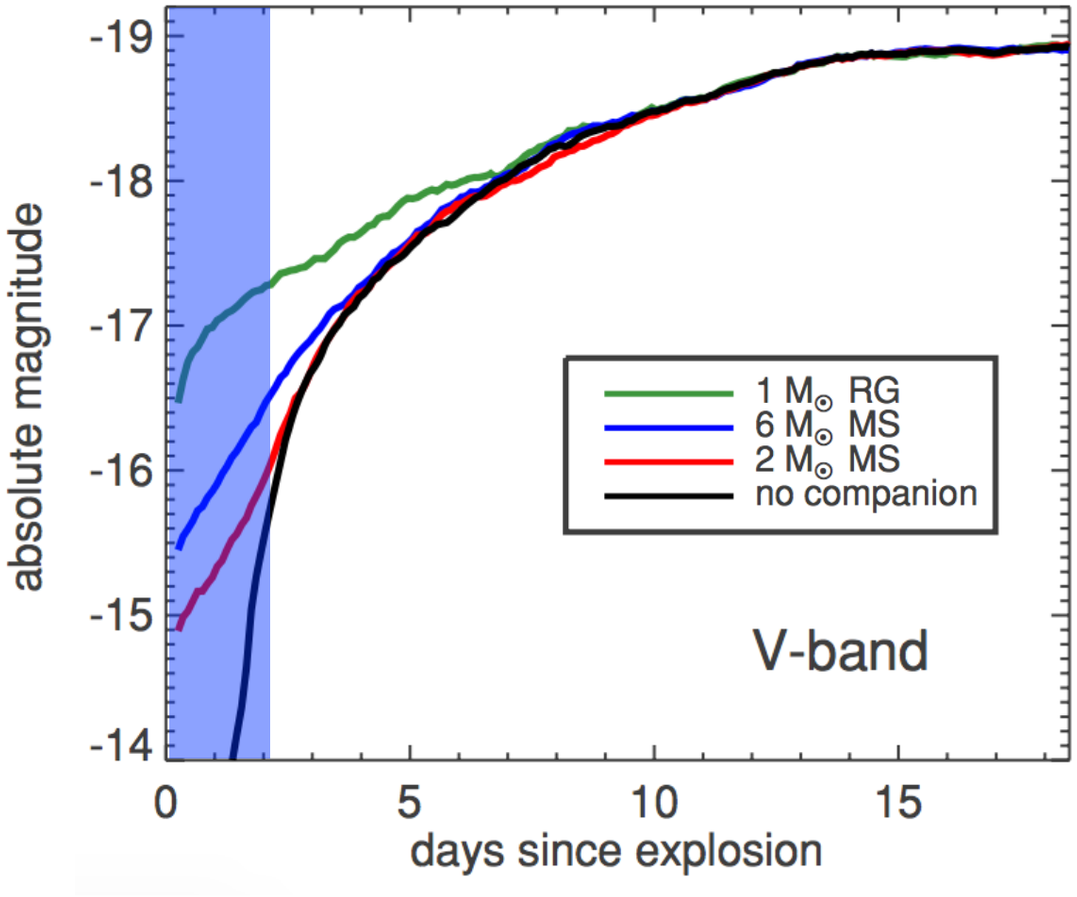
Interaction with a companion star

Companion star



SN Ia ejecta

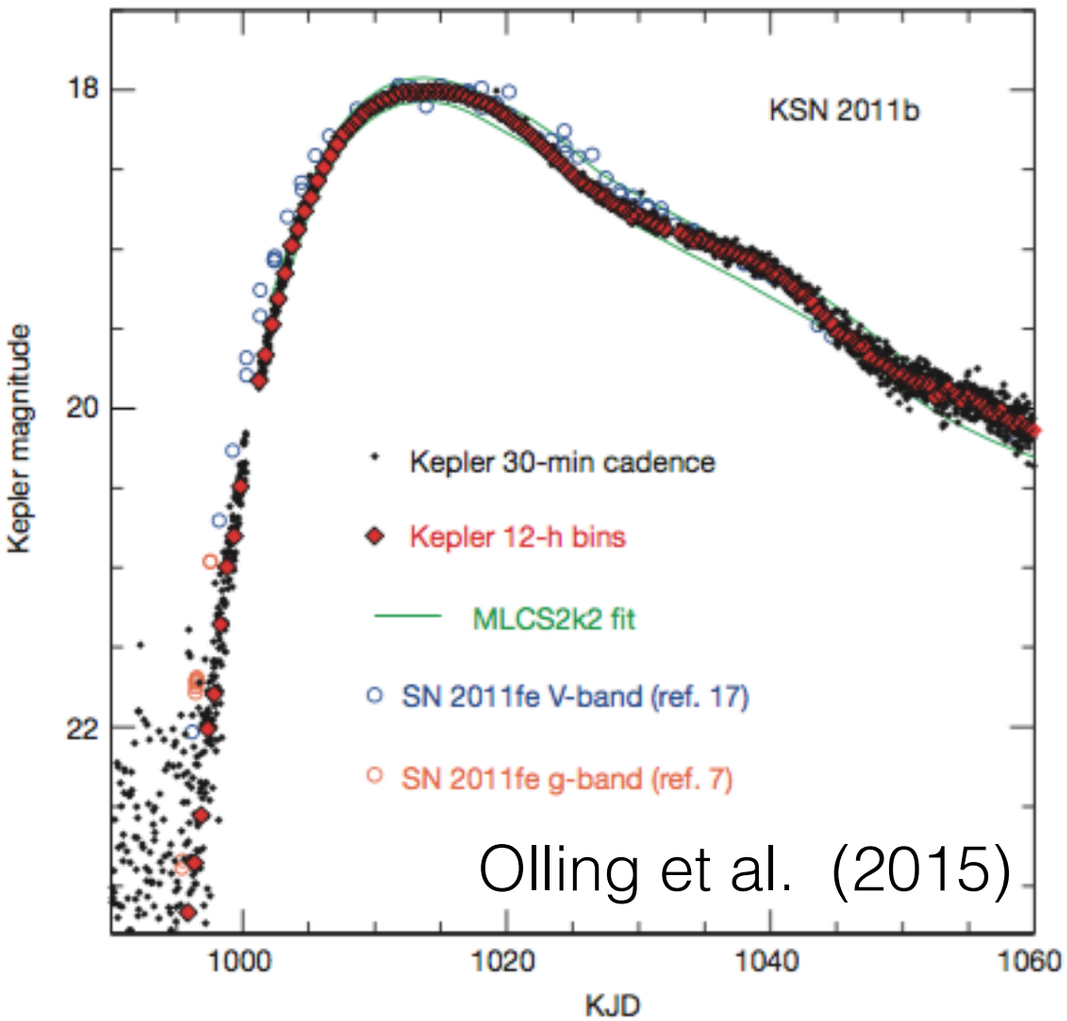
Model predictions
of Kasen (2010)



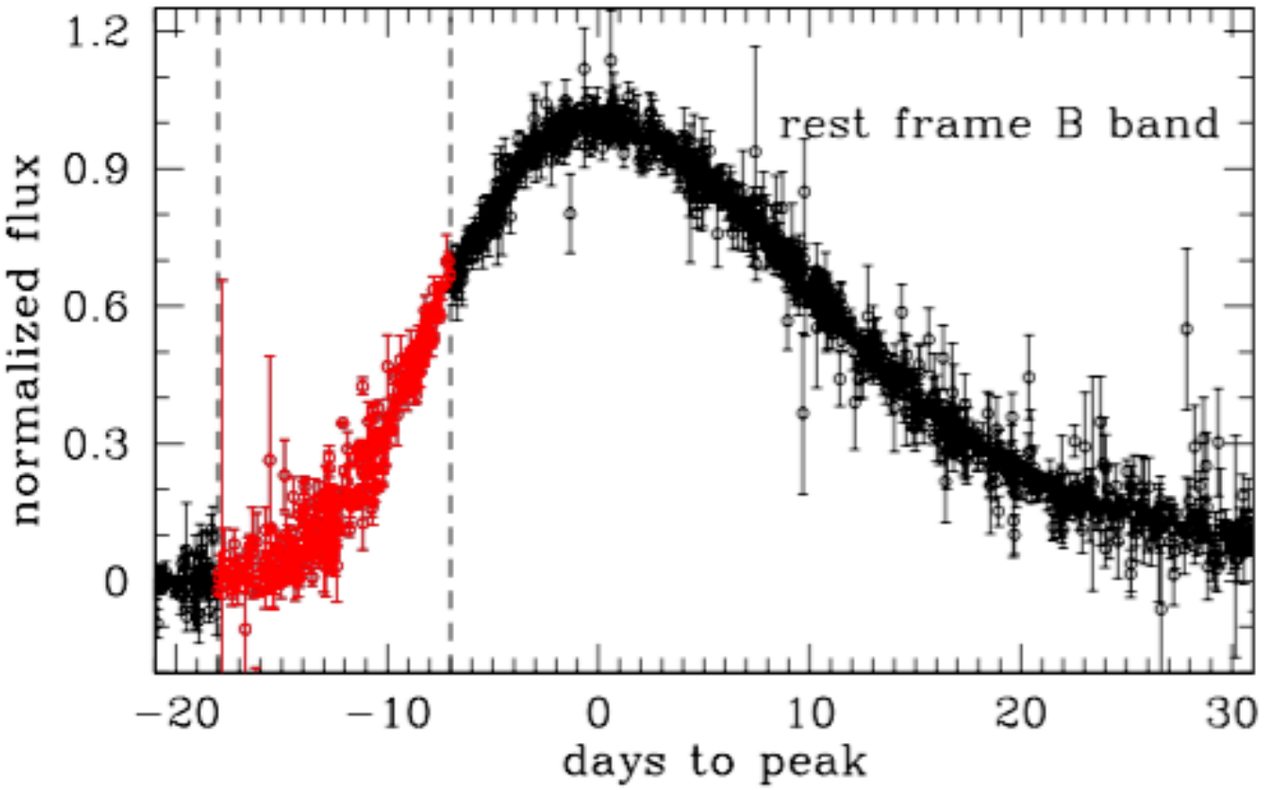
- Bump in the early-time light curves

Searches for companion star interaction

- **Stacked light curves** from Supernova Legacy Survey
- ~90 SNe Ia at z<0.7
- <20% with red giant companions



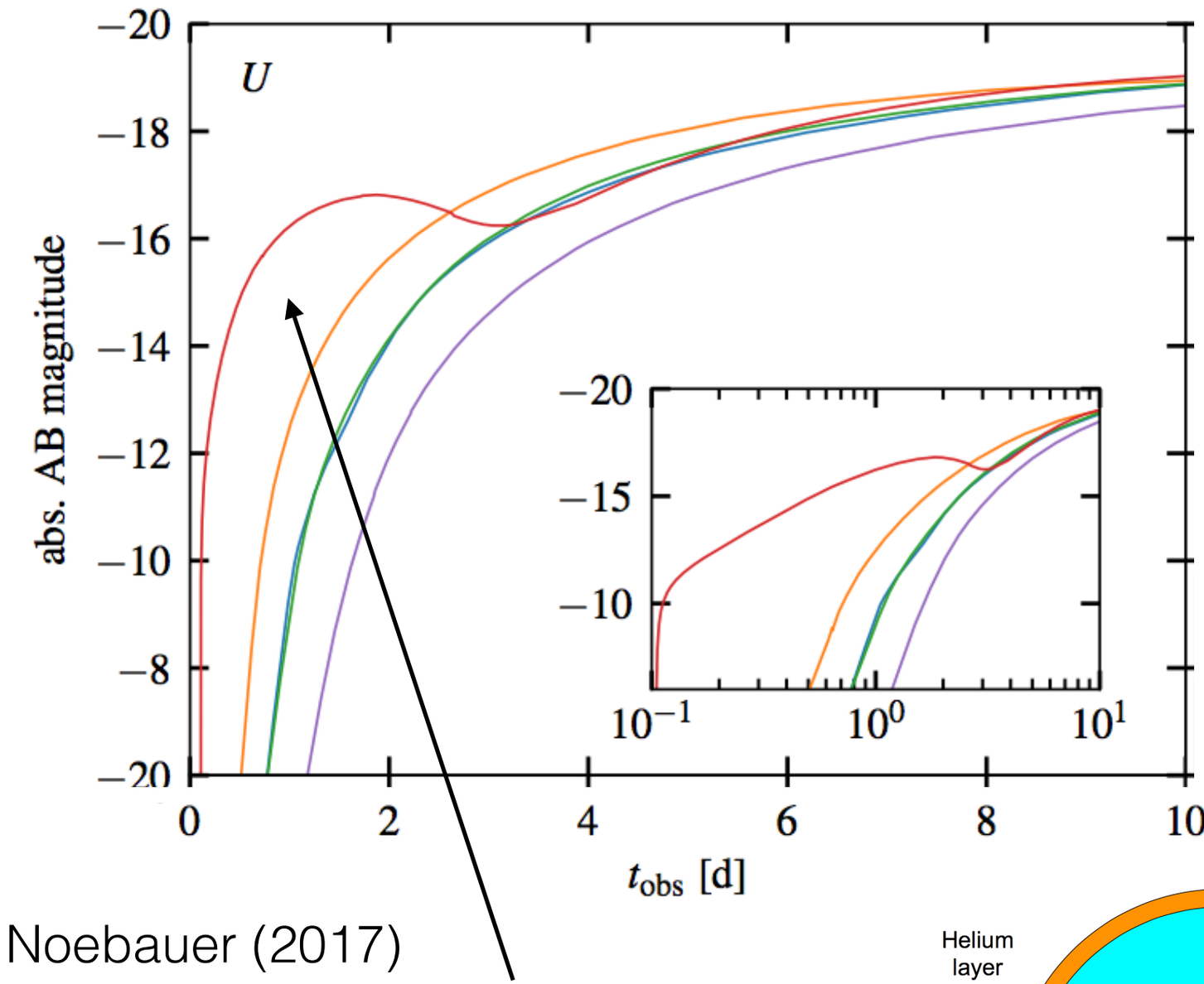
Olling et al. (2015)



Bianco et al. (2011)

- Three Kepler light curves - 30 min cadence
- Rule out red giant (and some main sequence) companions for two objects

Different explosion mechanisms also produce variations



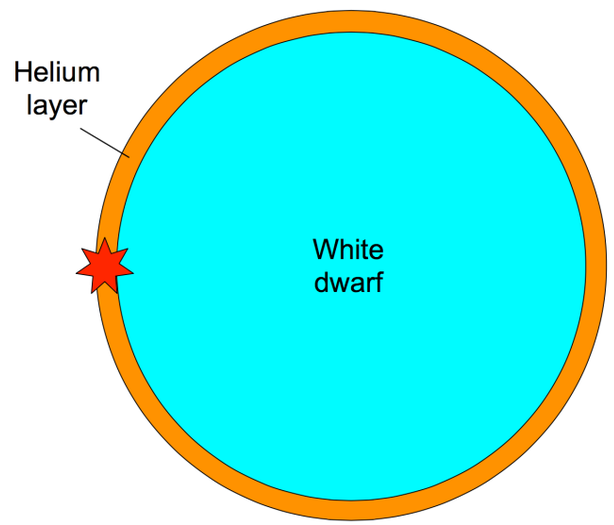
Noebauer (2017)

Mchandra DDT

Double detonation

Merger

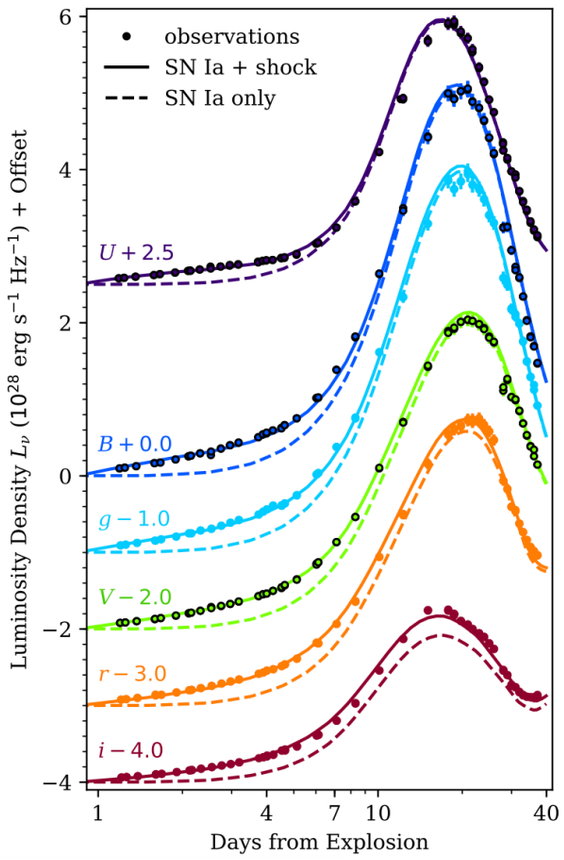
Decay of
^{48}Cr and ^{52}Fe



0.06 $M_\odot$ of He

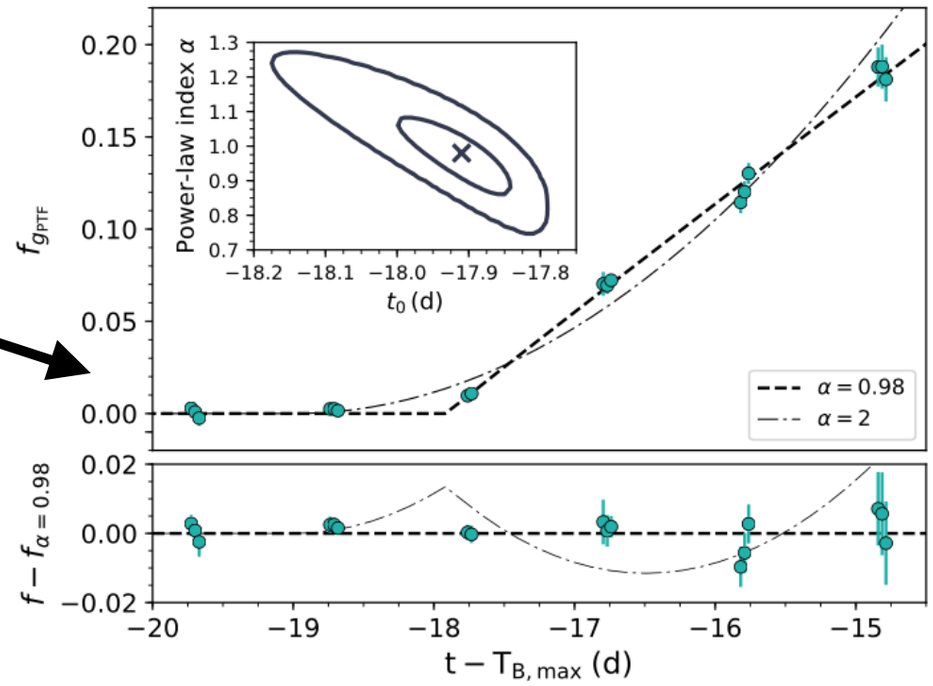
Handful of well-studied objects

SN 2017cbv - **companion interaction** or **CSM interaction** or **nickel mixing**?

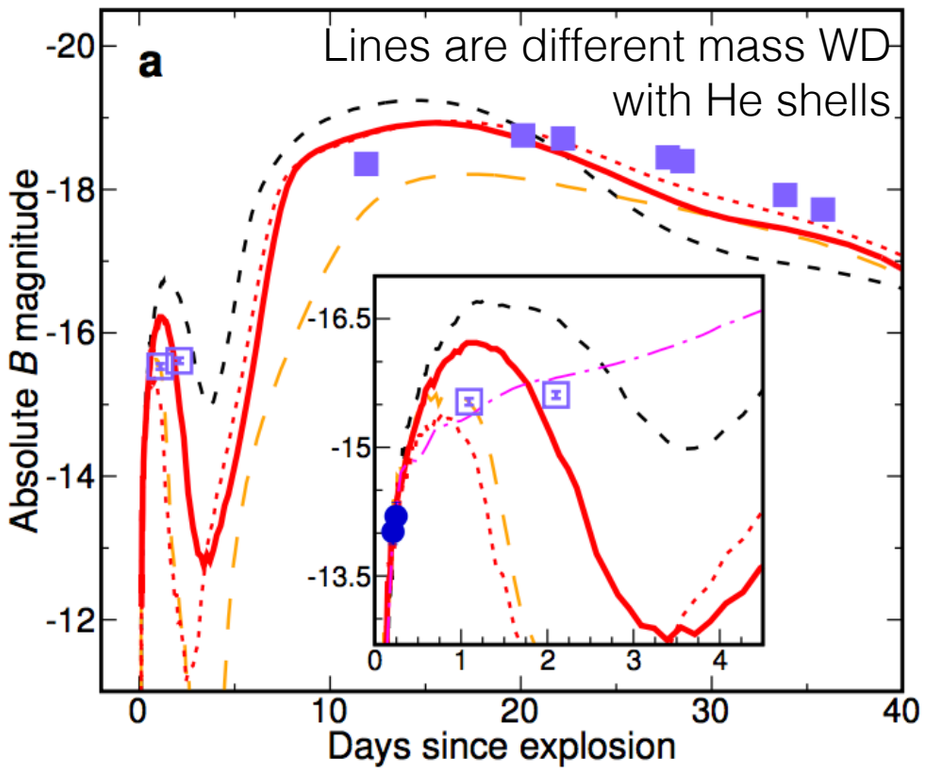


Hosseinzadeh et al. (2017)

iPTF16abc - rigorous **mixing** or **interaction with diffuse material?**



Miller et al. (2017)

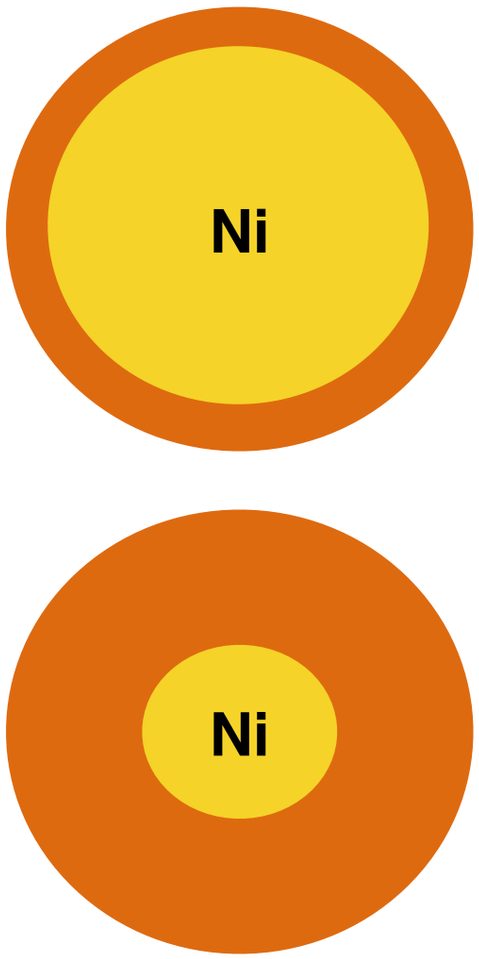


Jiang et al. (2017)

MUSSES1604D - **He-shell detonation (see talk by Ji-an Jiang)**

Parameter study of early light curve models, TURTLS

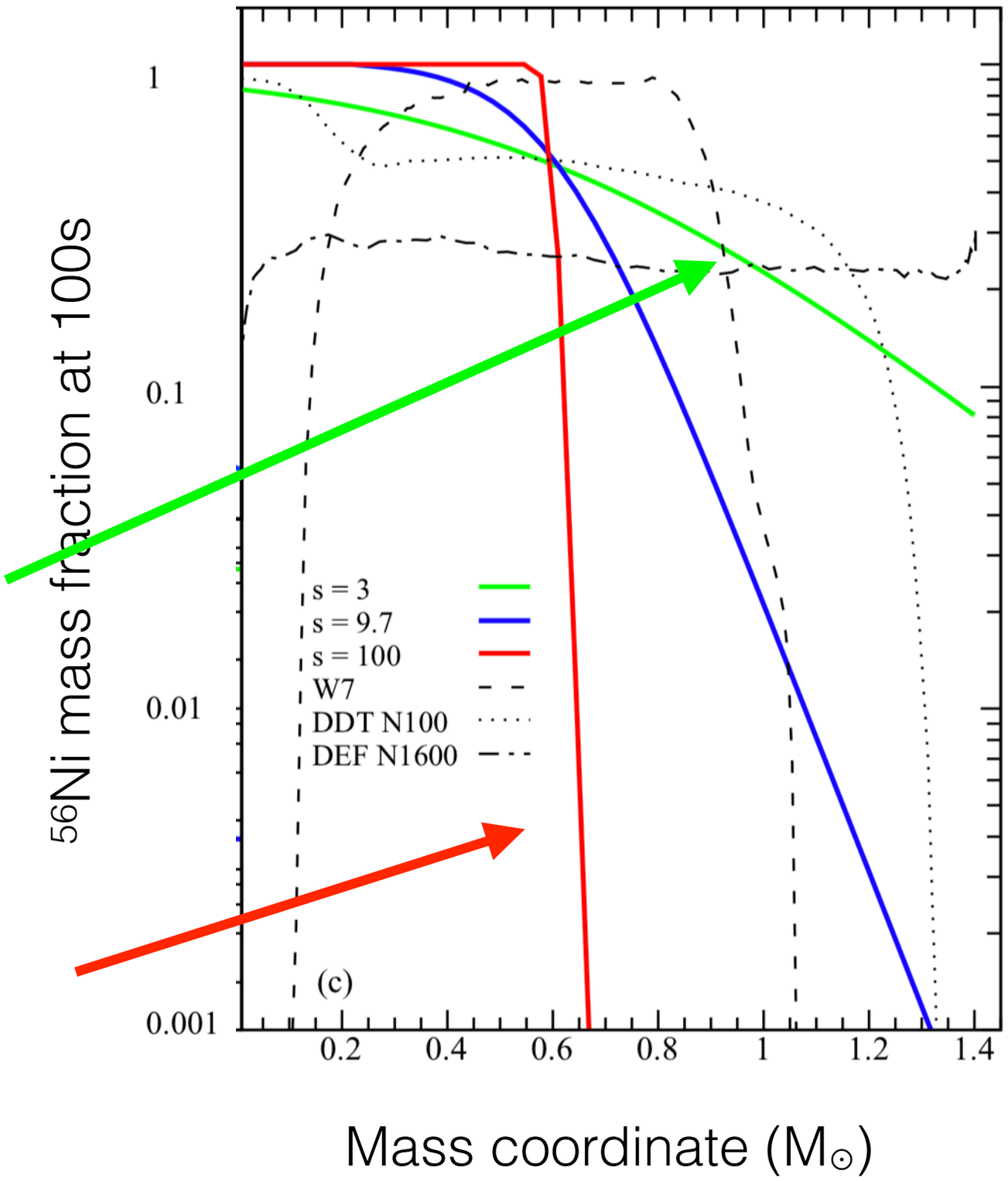
- Monte Carlo LTE radiative transfer code, **TURTLS** (Magee+ 2018)
- Different progenitor models have different Ni distributions + effects of asymmetry



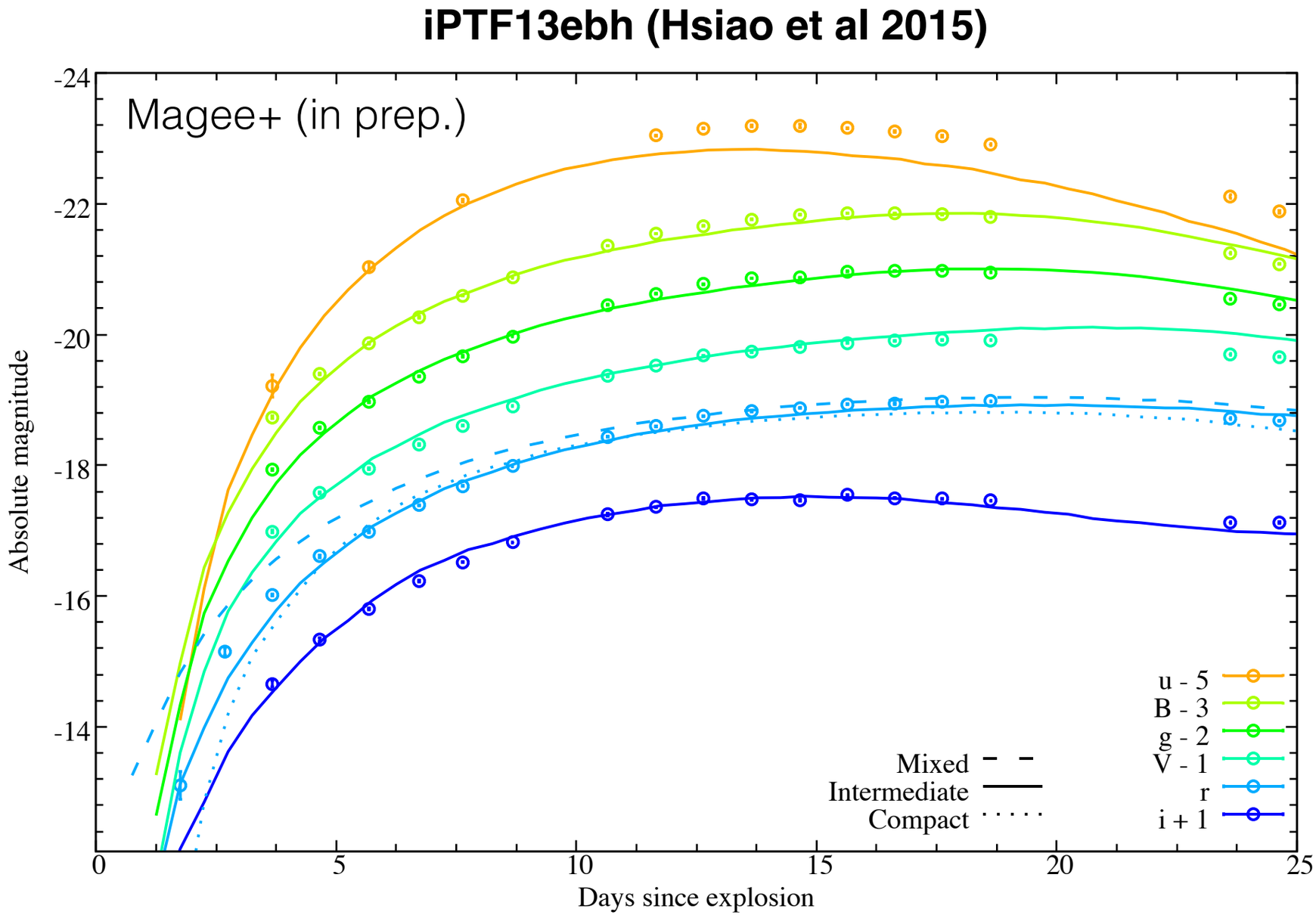
Most mixed

Least mixed

Magee+ (2018)

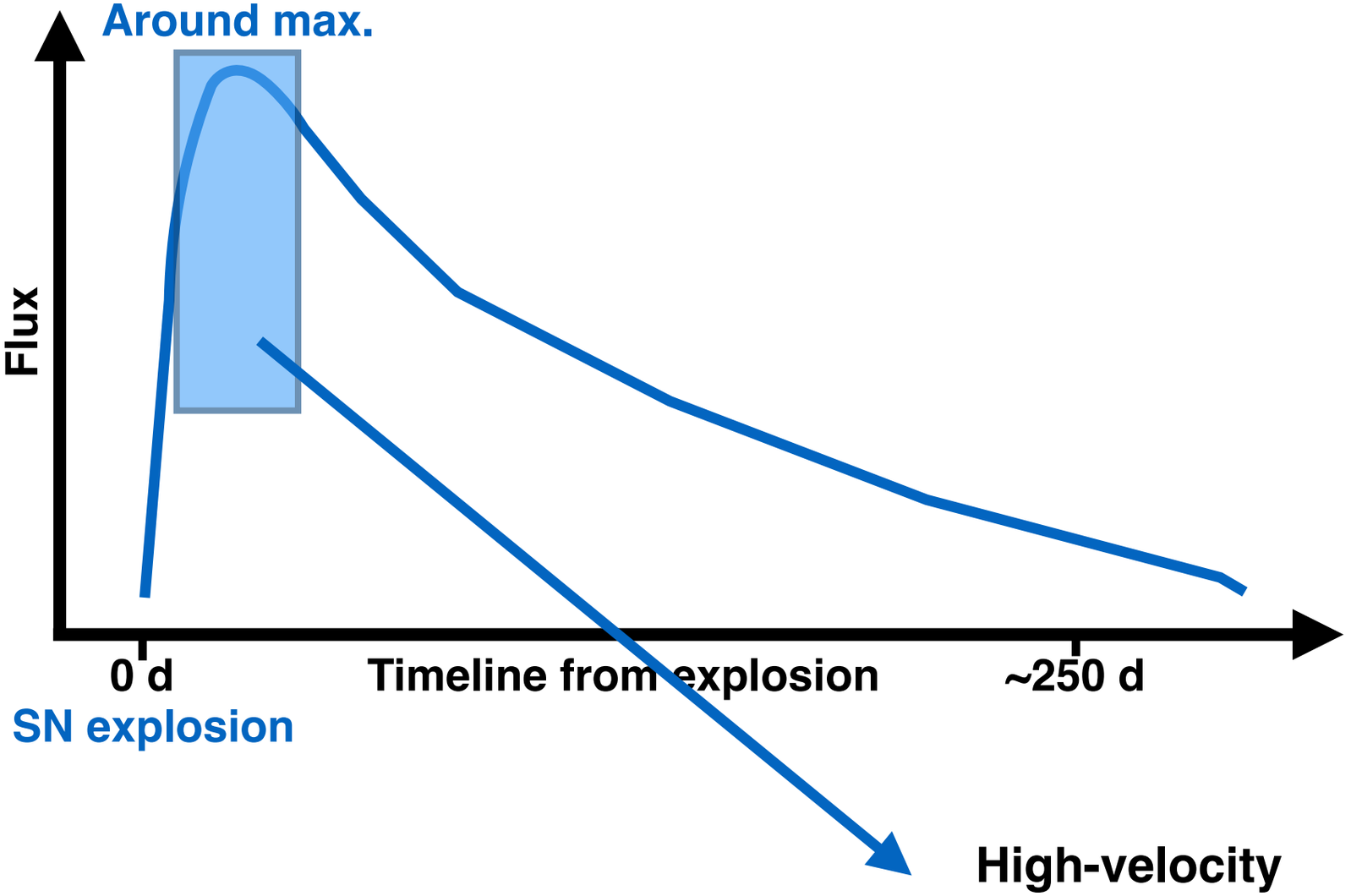


Parameter study of early light curve models, TURTLS

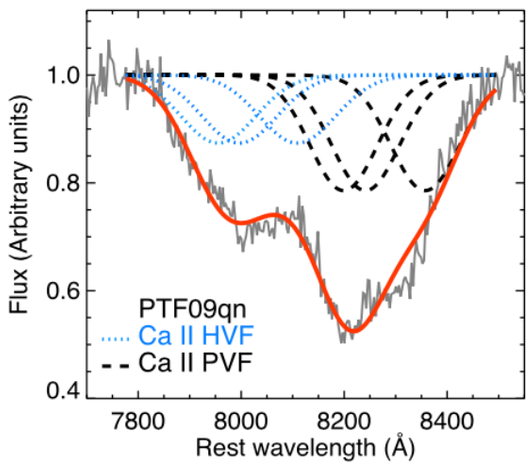


- Varying density profiles, transition velocities, Ni and ejecta masses
- Extending to include He shell detonations & CSM (Magee, KM+ in prep)
- Compare to early light curves (literature and new samples e.g. ATLAS)

What observations can distinguish between explosion scenarios?

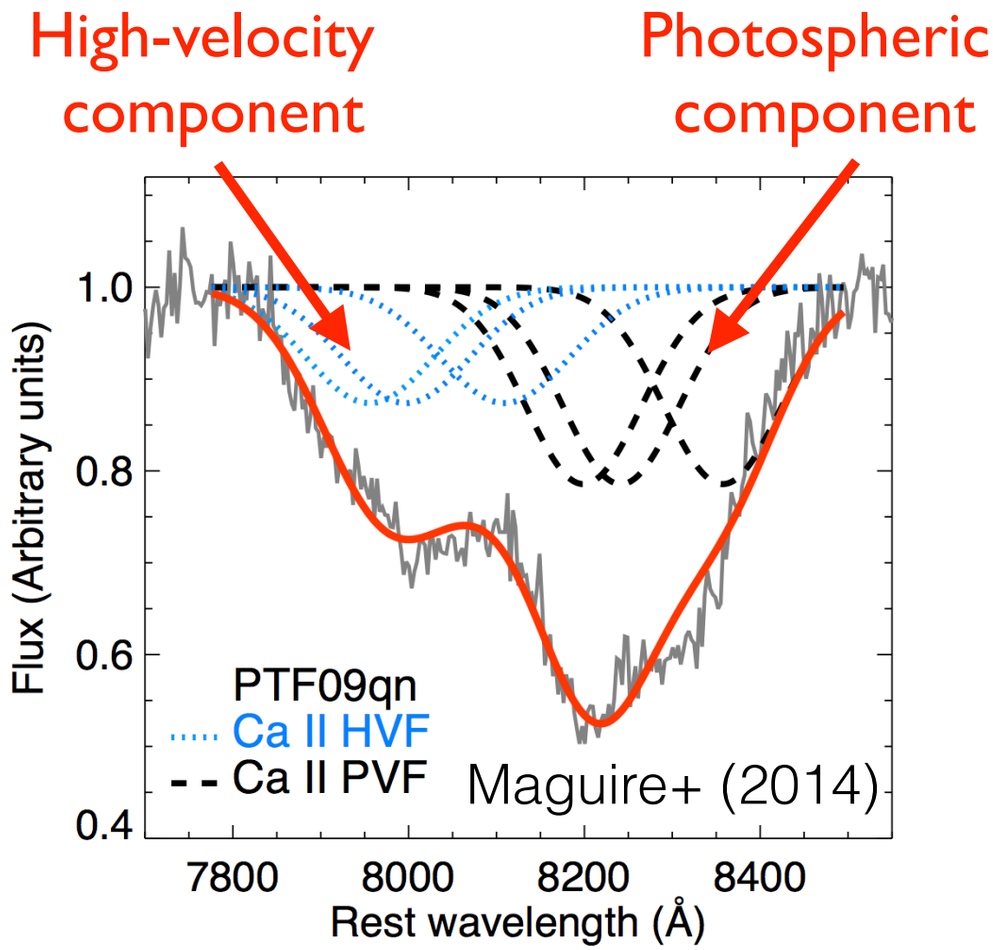


High-velocity features/polarisation

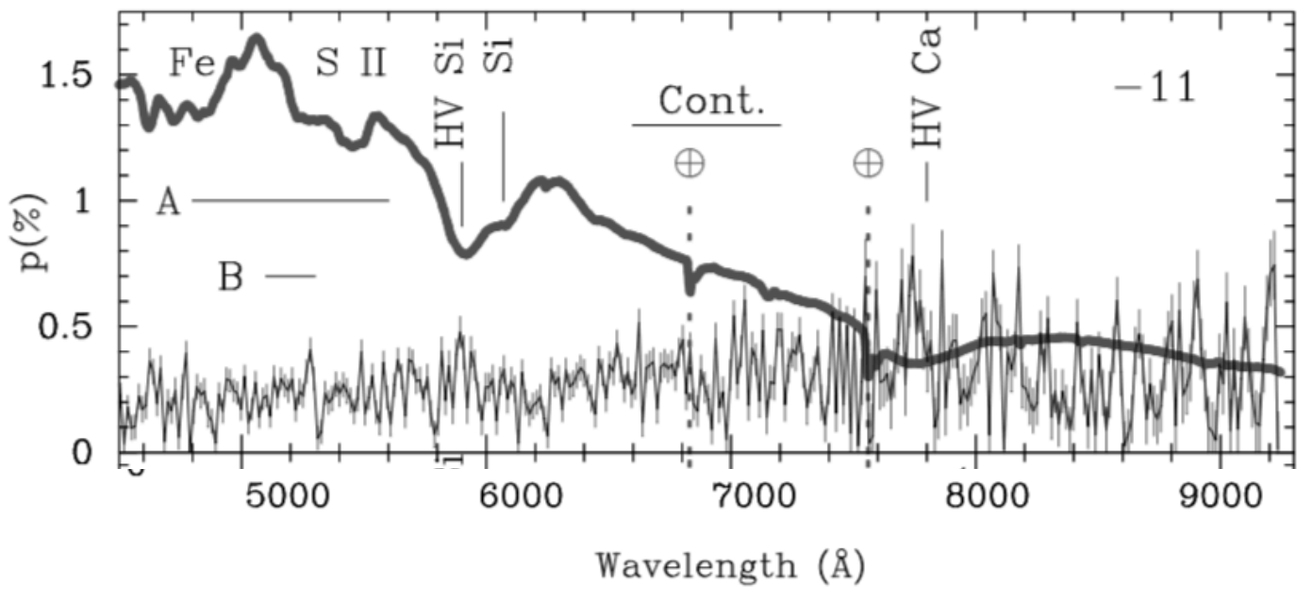


High-velocity Ca II features

- Seen in many SNe Ia (Childress+ 2014,Silverman+ 2015) — >80-90% of pre-max SN Ia spectra in PTF sample (Maguire+ 2014)
- Strength of HV component is stronger in broader SNe Ia that occur in higher sSFR rates hosts (Maguire+ 2014, Pan+ 2014)

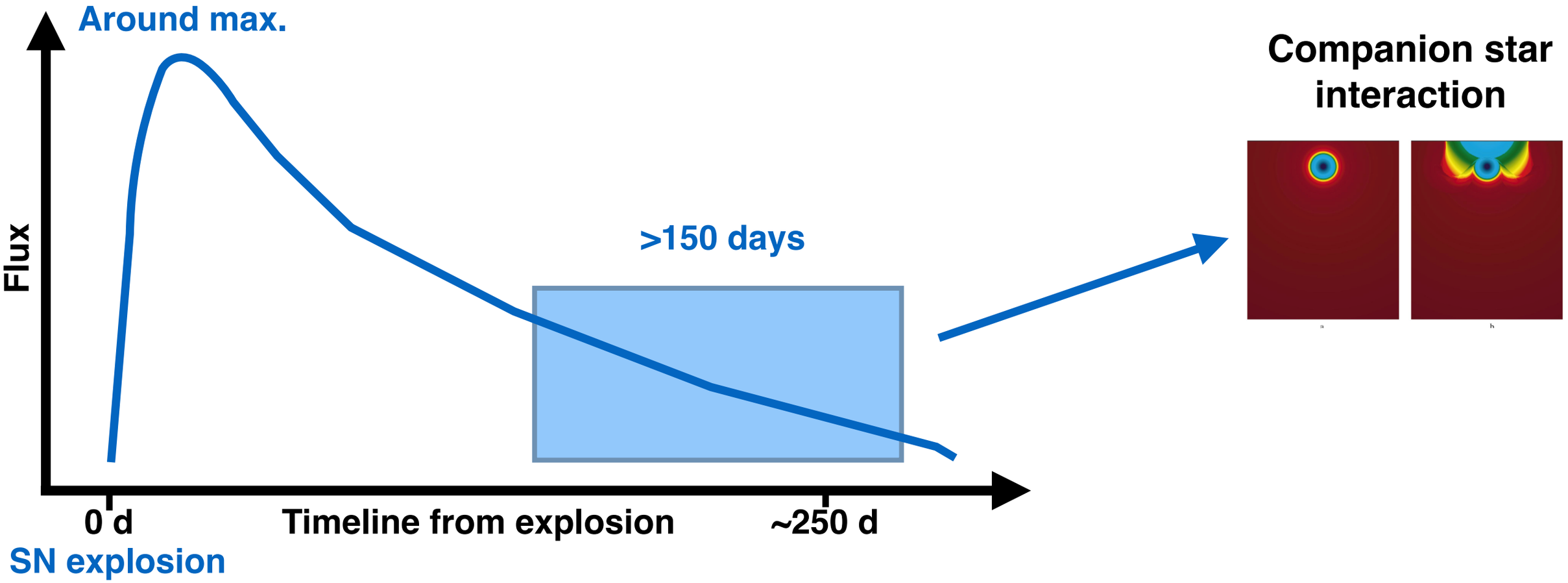


SN 2012fr (Maund+ 2013)

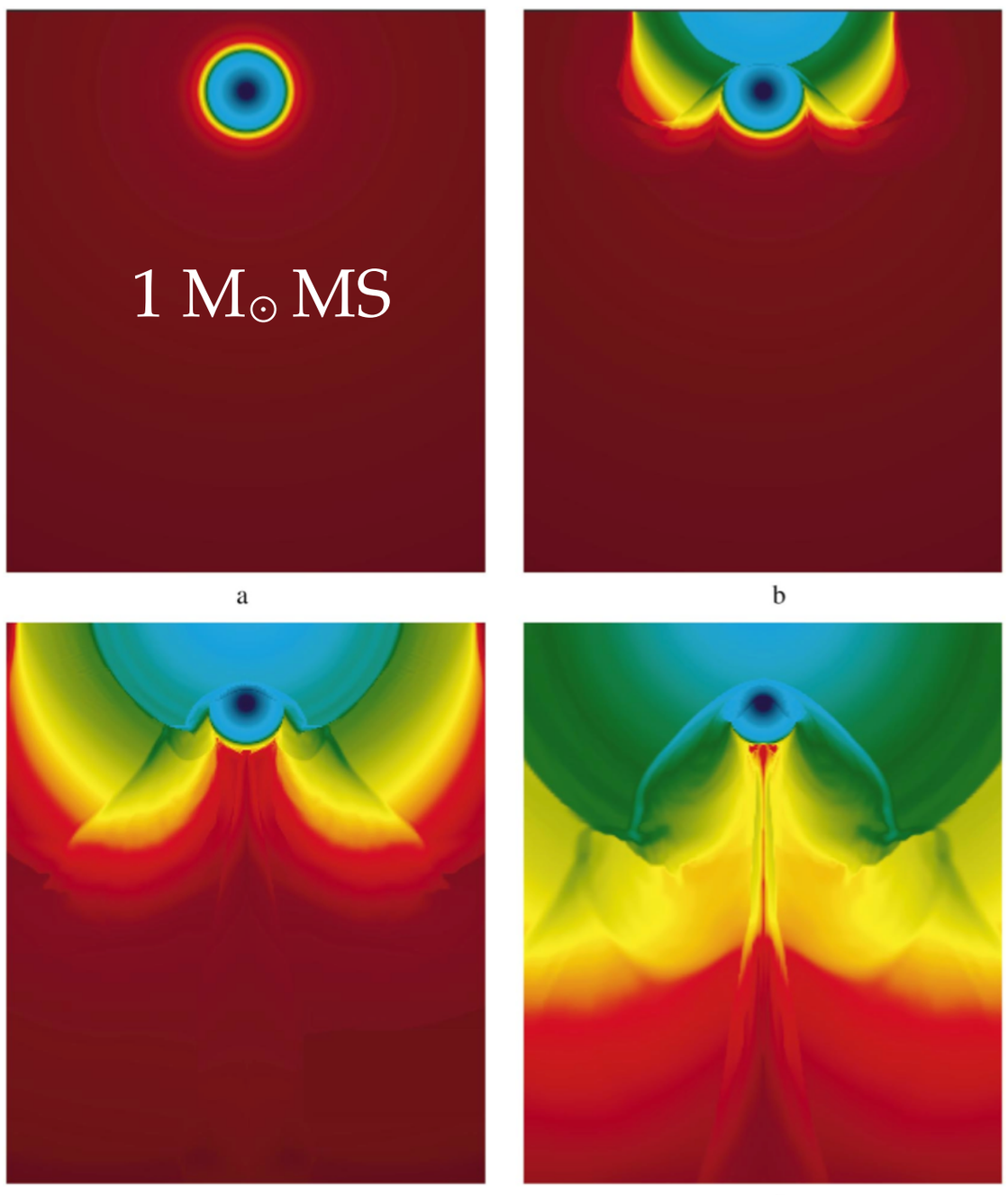


- Low continuum polarisation
- **But** strong polarisation across Si II HV and Ca II HV (p=0.85%) features
- Due to CSM or intrinsic to the SN?

What observations can distinguish between explosion scenarios?



Hydrogen/Helium-rich companion material



Marietta et al. (2000)

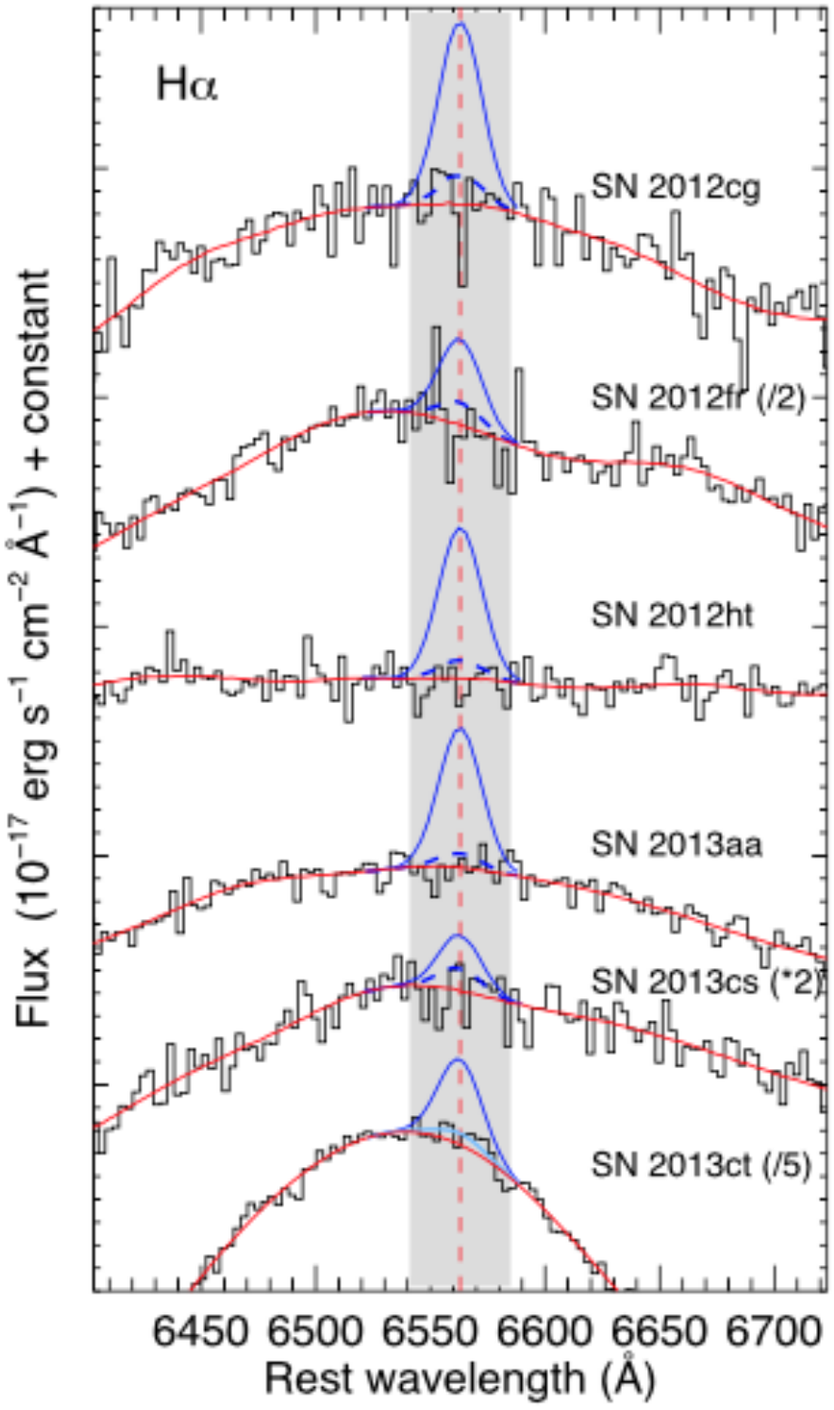
- Originally predicted in Wheeler+ (1975) & new modelling (Marietta+ 2000, Pan+ 2010, 2012, Liu+ 2013)
- Predicted to be present at low velocities (~500-1000 km/s)
- WD+He < WD+MS < WD+RG

Little mass lost (~0.05 $M_\odot$)

Nearly whole envelope mass lost (~0.3 $M_\odot$)

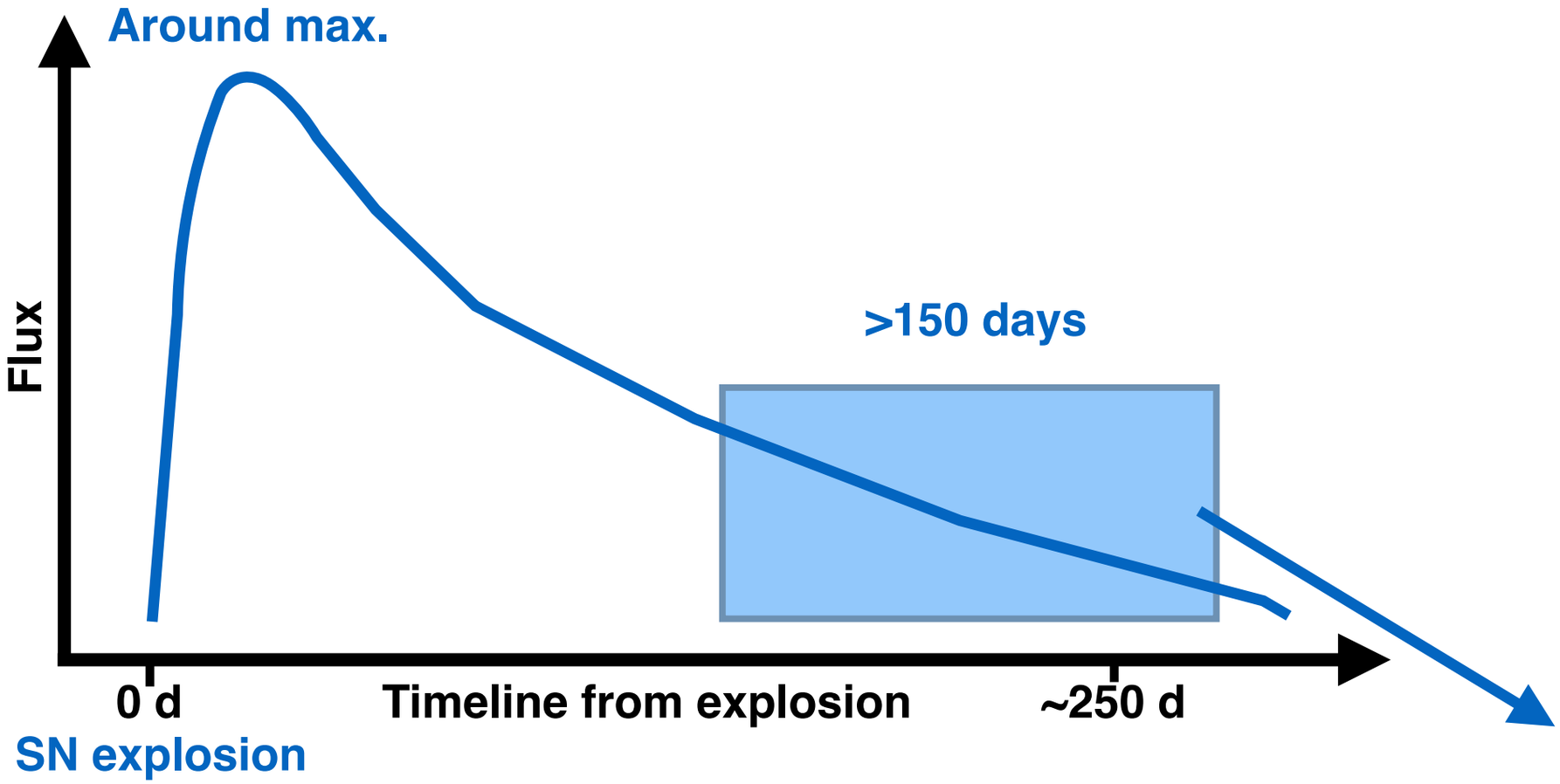
Hydrogen/Helium-rich companion material

- Now combined sample 17 SNe Ia (stripped H mass < 0.001–0.06 $M_\odot$)
- Rule out all main-sequence and red-giant companions
- **Simplest scenario: Don't have a non-WD companion accreting from a H-rich companion**
- **Ways out:**
  - Spin-up/spin-down scenario? (Justham+ 2011)
  - The H material be present but not visible

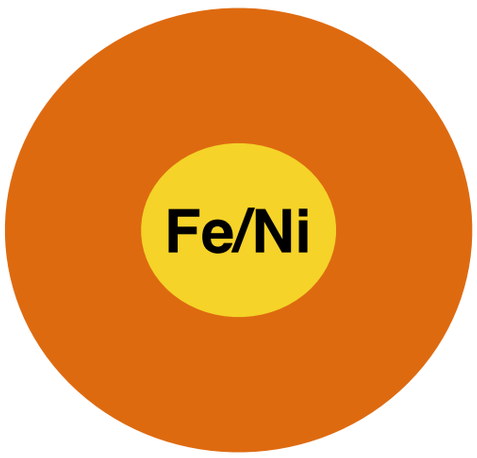


Maguire et al. (2016)

What observations can distinguish between explosion scenarios?



Nucleosynthesis & asymmetries



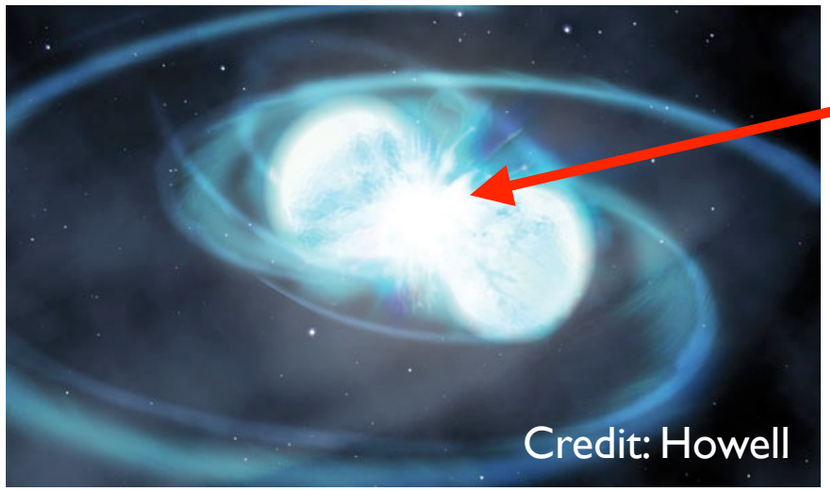
Difference in central densities

$M_{chandra}$

Higher central density

- More electron capture -> neutron-rich material
- More **stable ^{58}Ni and ^{54}Fe**

sub-$M_{chandra}$



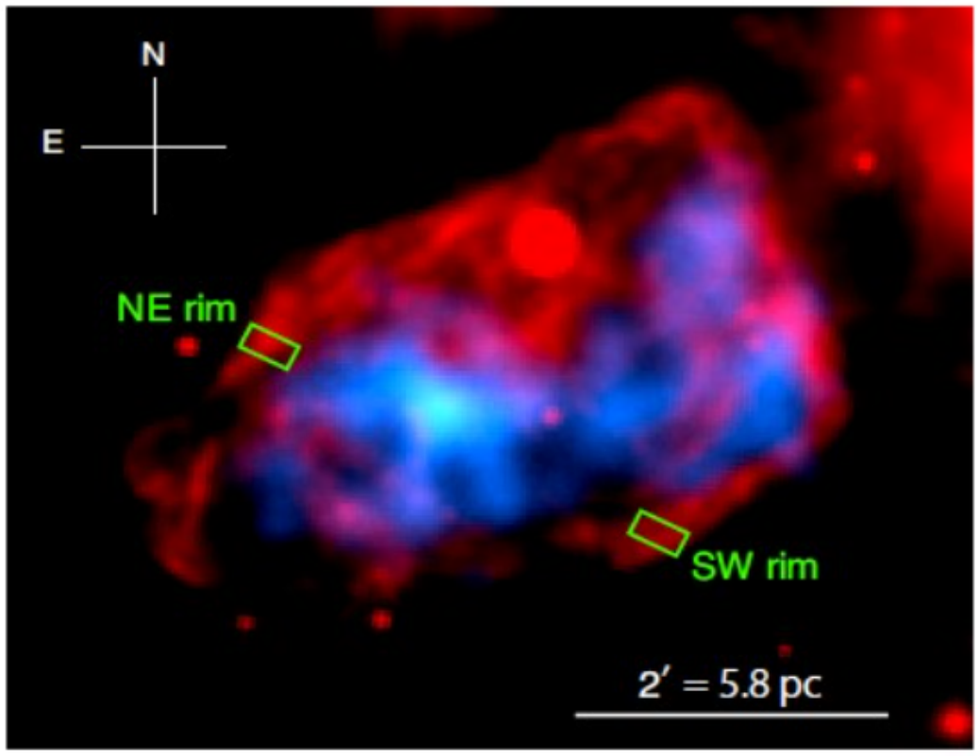
Lower central density

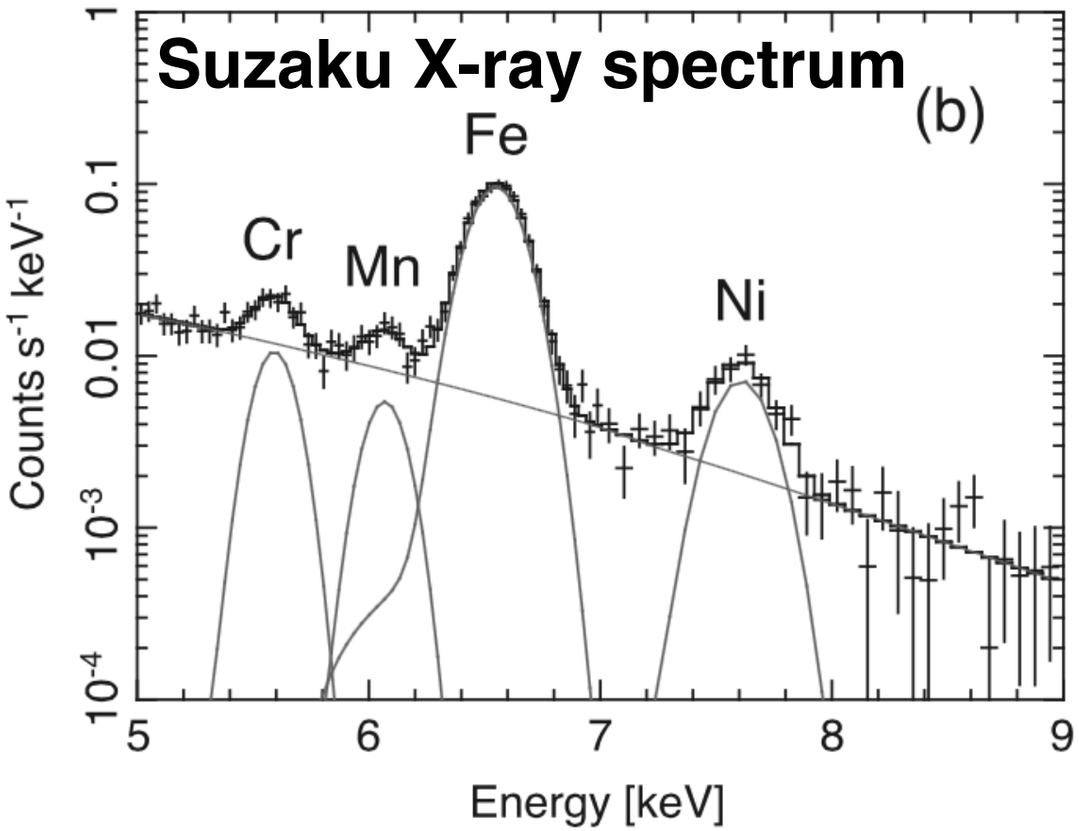
- Less electron capture
- More radioactive ^{56}Ni

Presence of significant stable material is key probe of explosion mechanism

Evidence for significant stable Ni in a SN Ia remnant

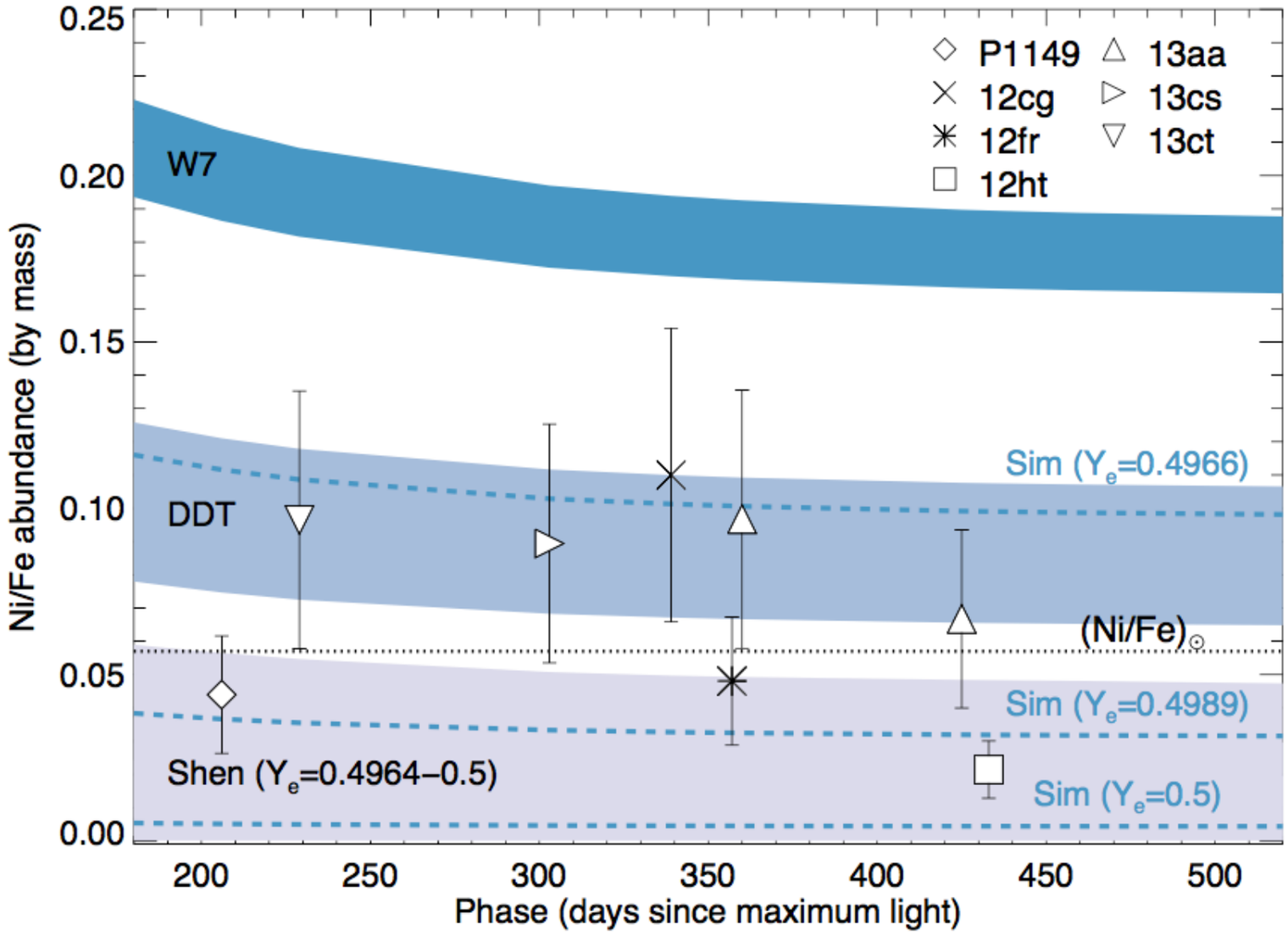
- Measure Ni/Fe abundance from X-ray spectra in SN remnants
- High Ni/Fe ratio observed for 3C 397
- Suggests high-mass white dwarf





Yamaguchi+ (2015)

Comparing stable Ni predictions with observations



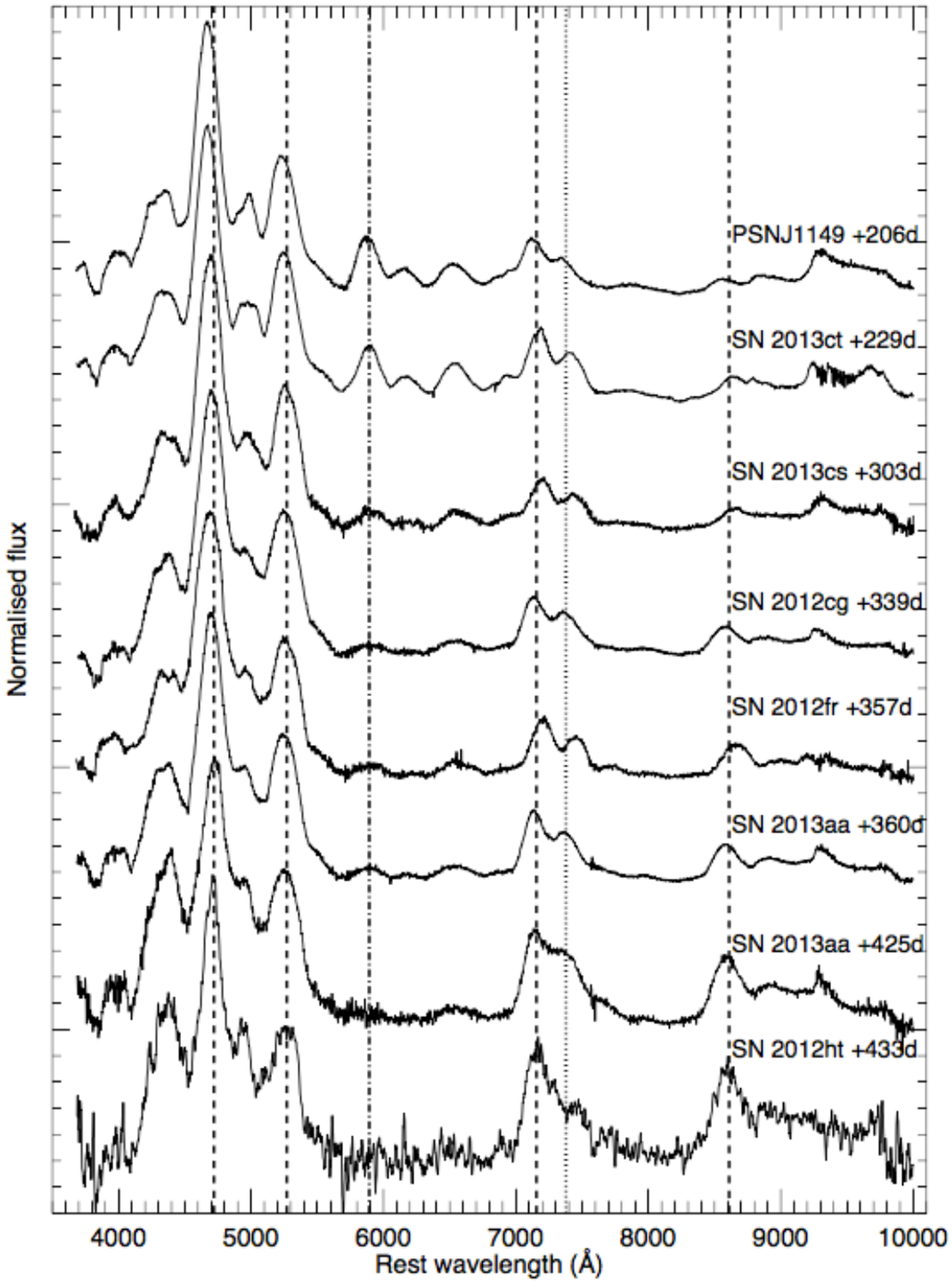
Maguire+ (2018)

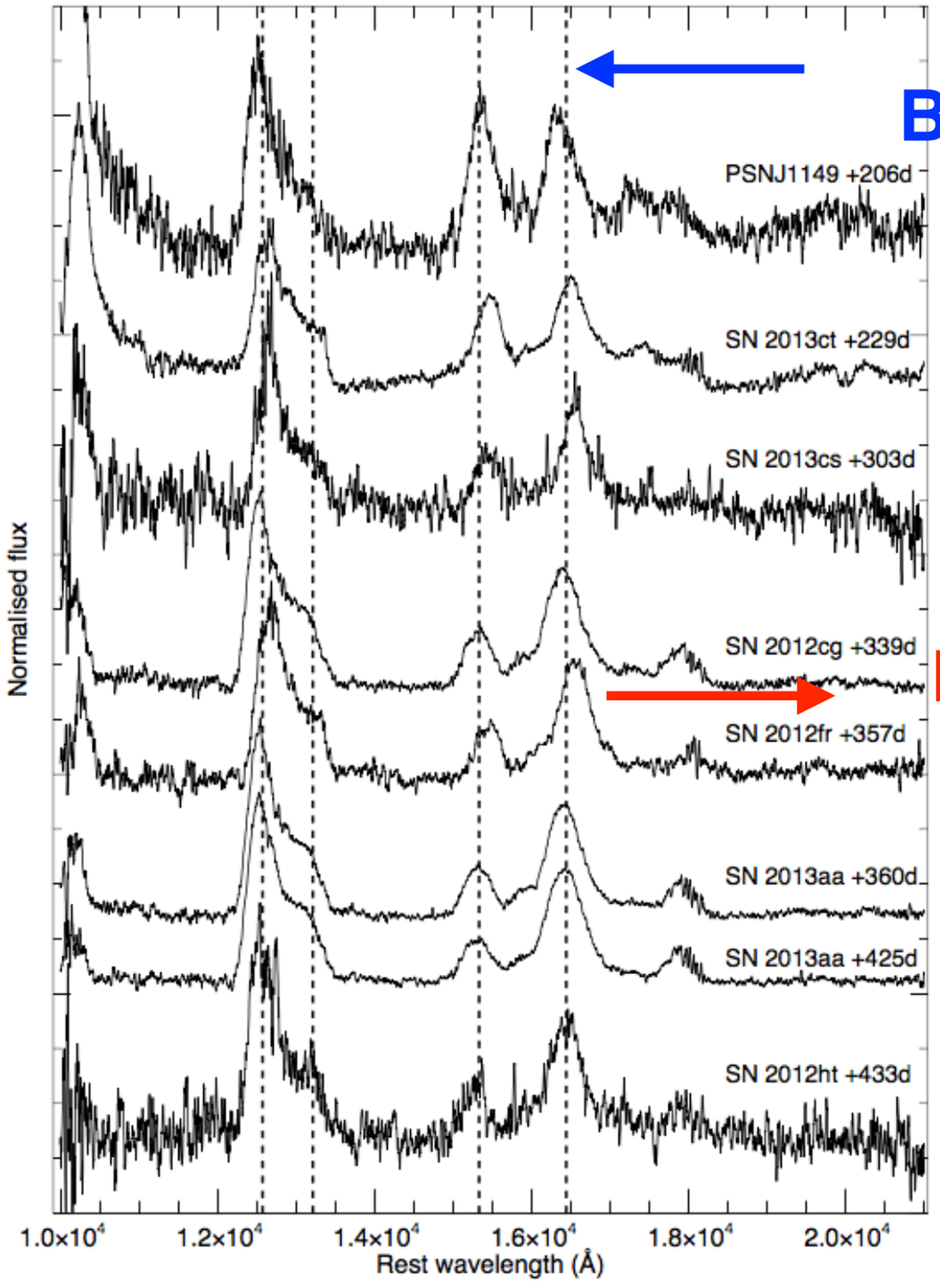
Model predictions for $M_{chandra}$ explosion channels

Model predictions for sub-$M_{chandra}$ explosion channels

- Majority are consistent with **Chandrasekhar-mass explosions**
- To explain with sub-$M_{chandra}$ explosions, need to increase white dwarf metallicity
- But absolute scale is uncertain - non-LTE radiative transfer modelling needed (Shingles+ submitted)

Line shifted from rest wavelength





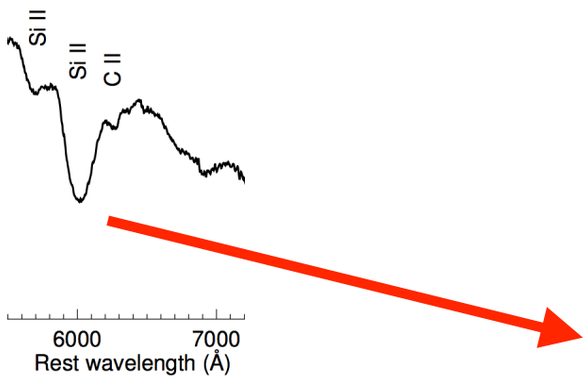
Blueshifted

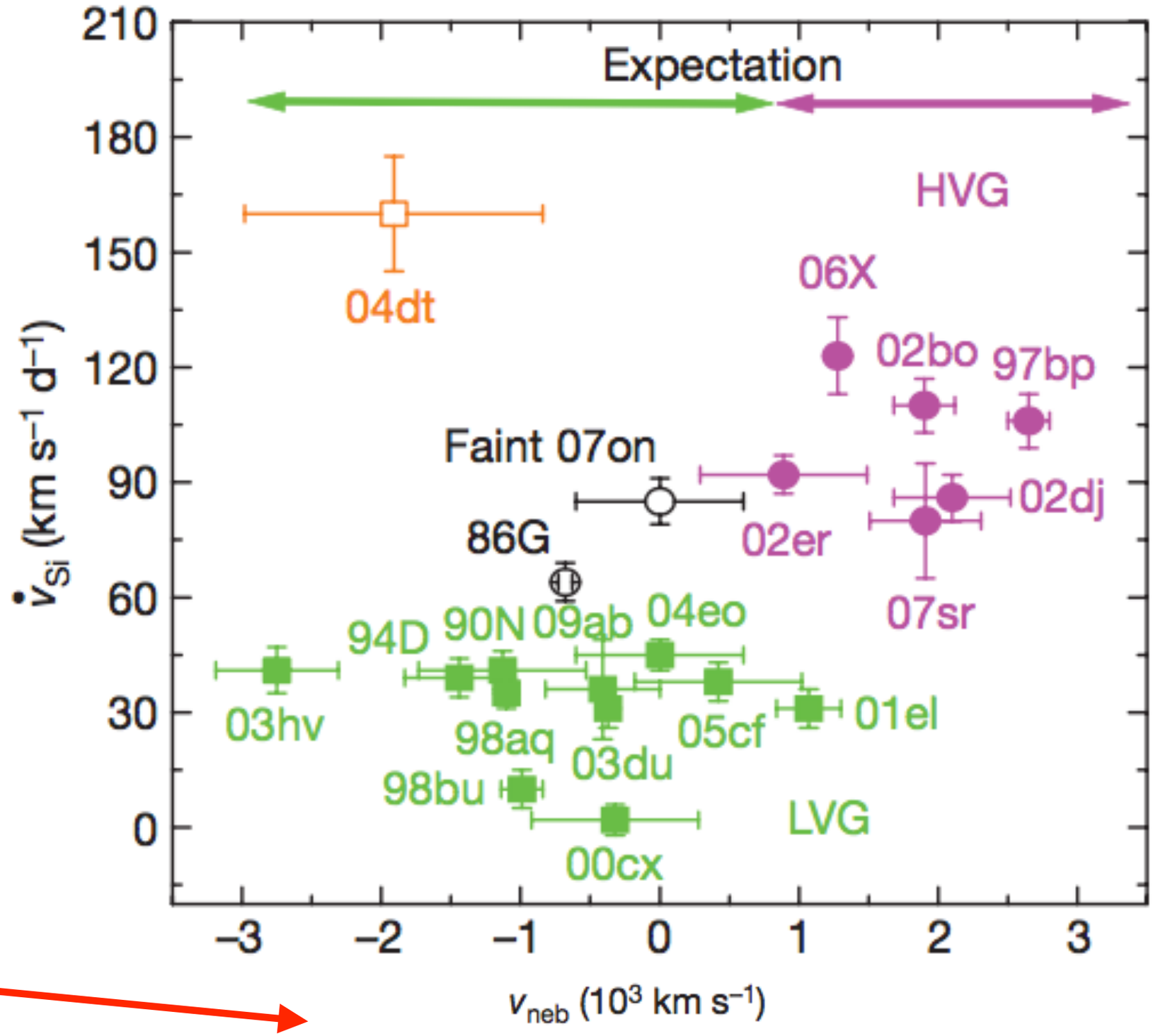
Redshifted

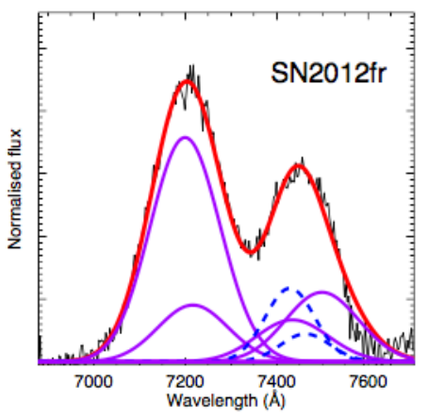
Explosion geometry

Maeda+ (2010)

From early-time spectra





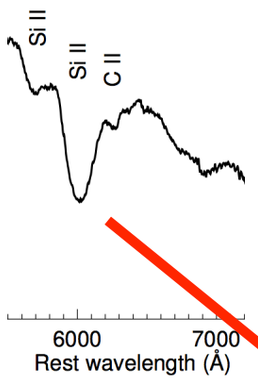


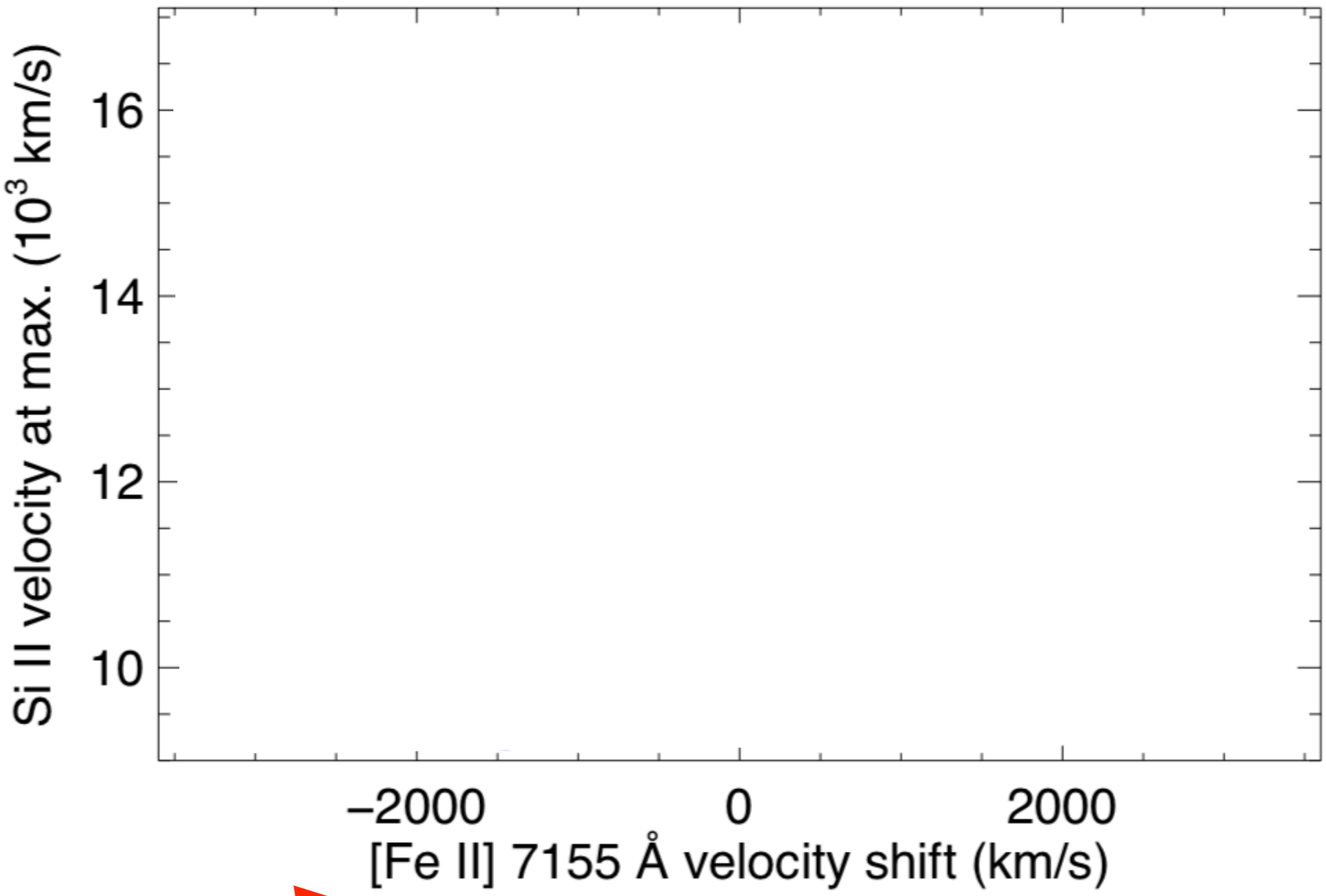
From late-time spectral shifts

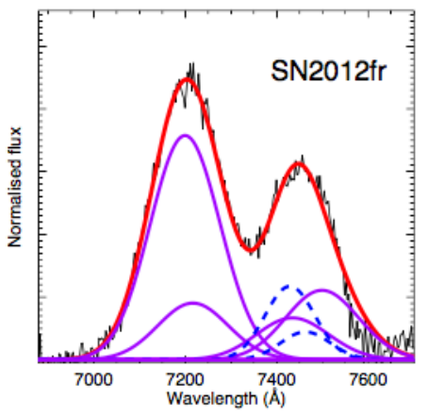
Explosion geometry - updated sample from Maeda+ (2010)

From early-time spectra

Maguire+ (2018)





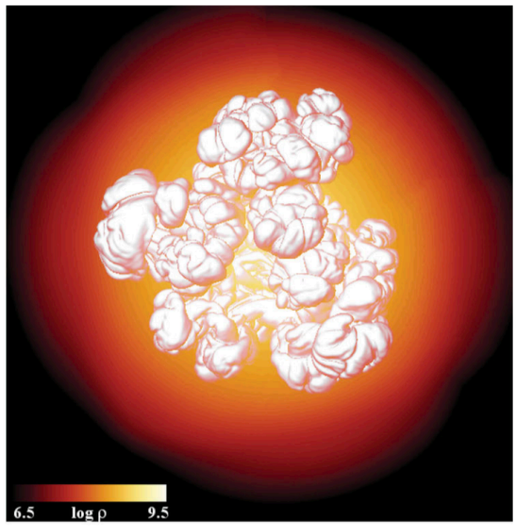


From late-time spectral shifts

Blueshifted

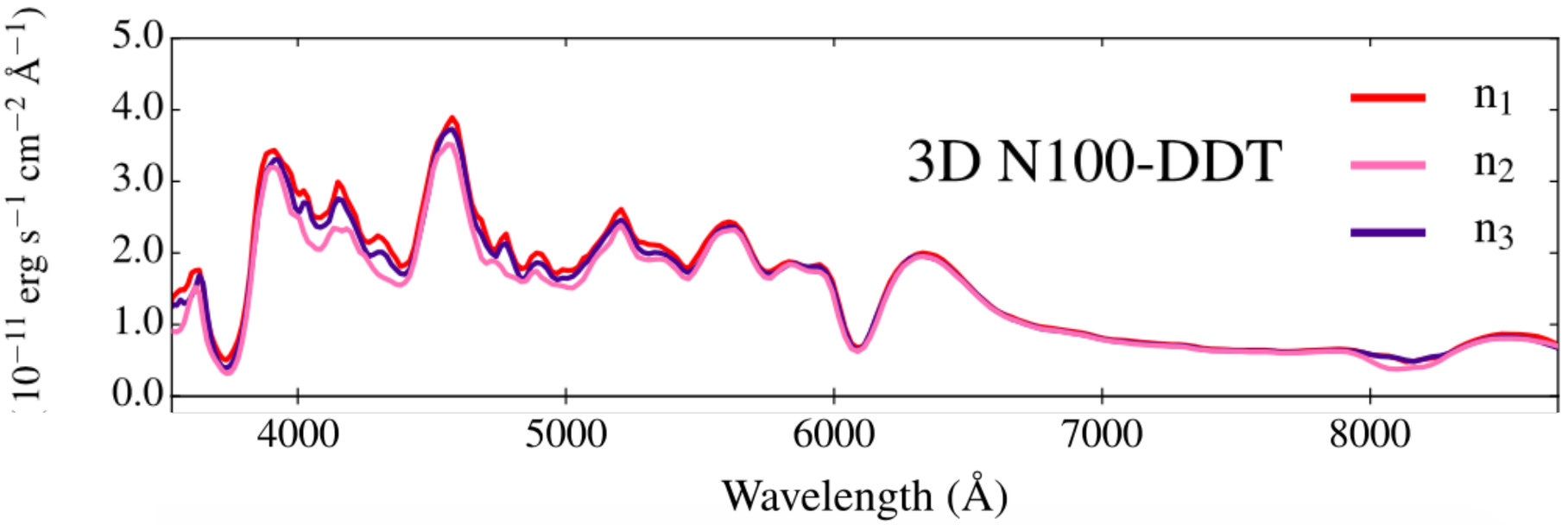
Redshifted

Delayed detonation model is too symmetric



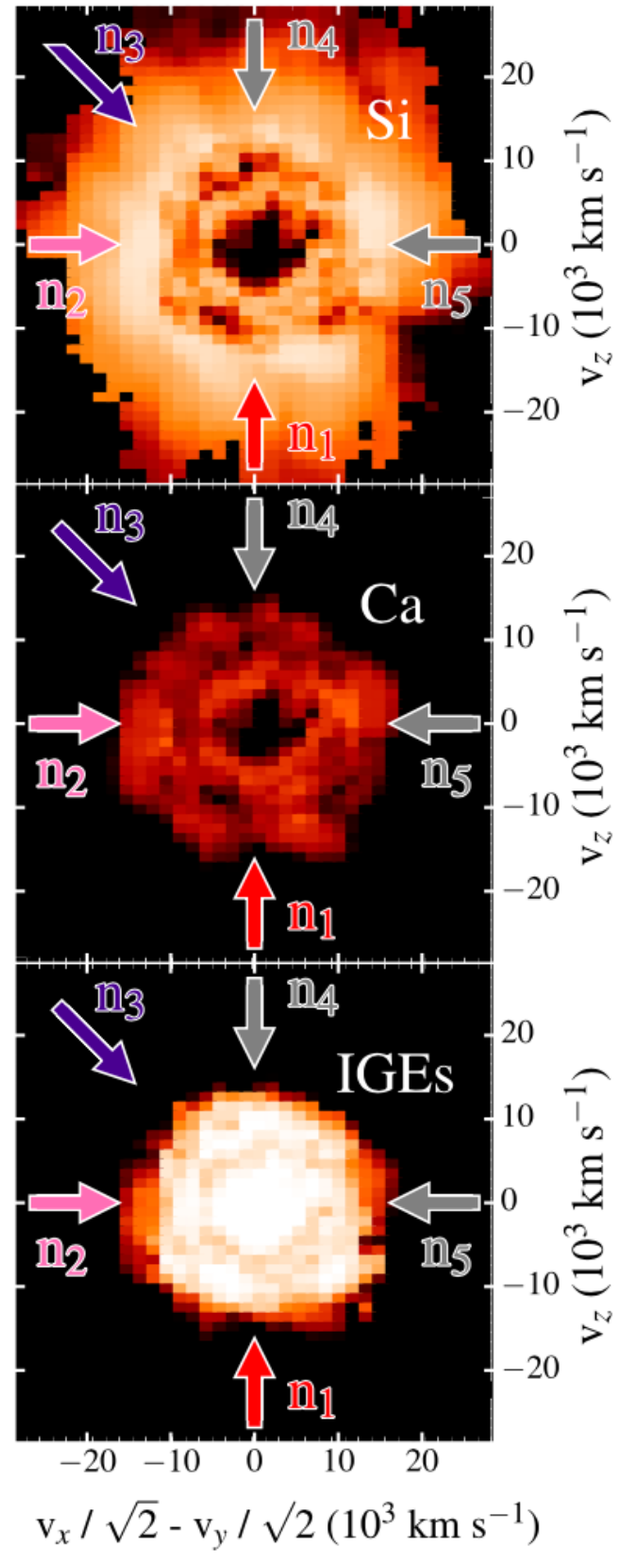
(b) N100; t = 0.70 s

- Roughly symmetric ejecta distribution
- Even for most asymmetric model of Seitenzahl+ (2013), velocity offset is only ~200 km/s

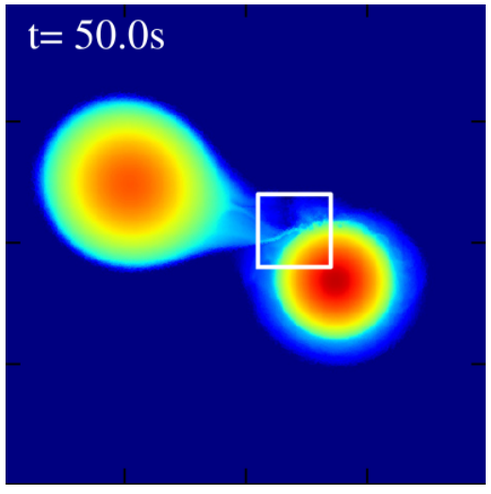


Bulla+ (2016)

Mass fractions



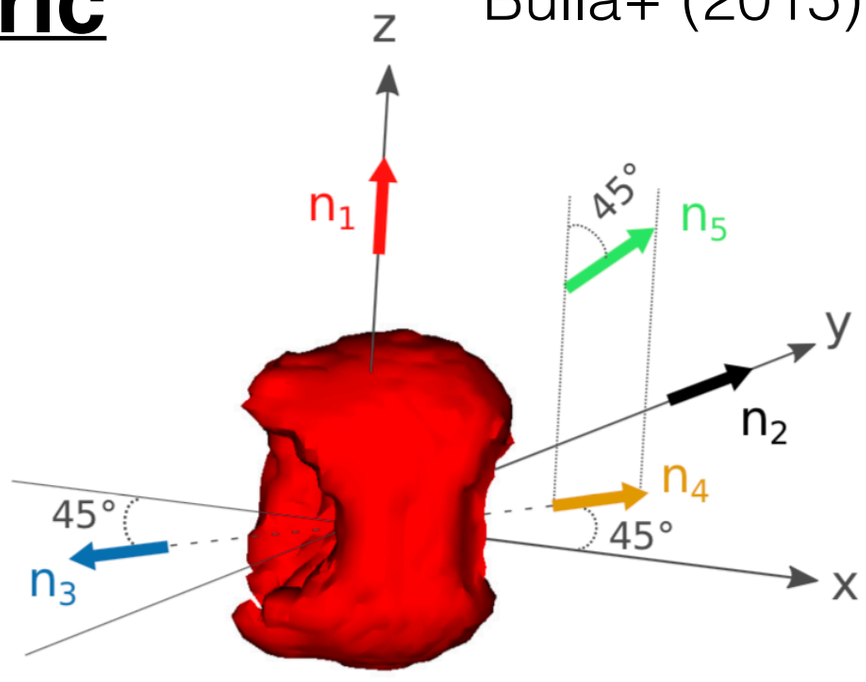
Violent merger model is too asymmetric



Pakmor+ (2015)

Nickel distribution of violent merger model (Bulla+ 2015)

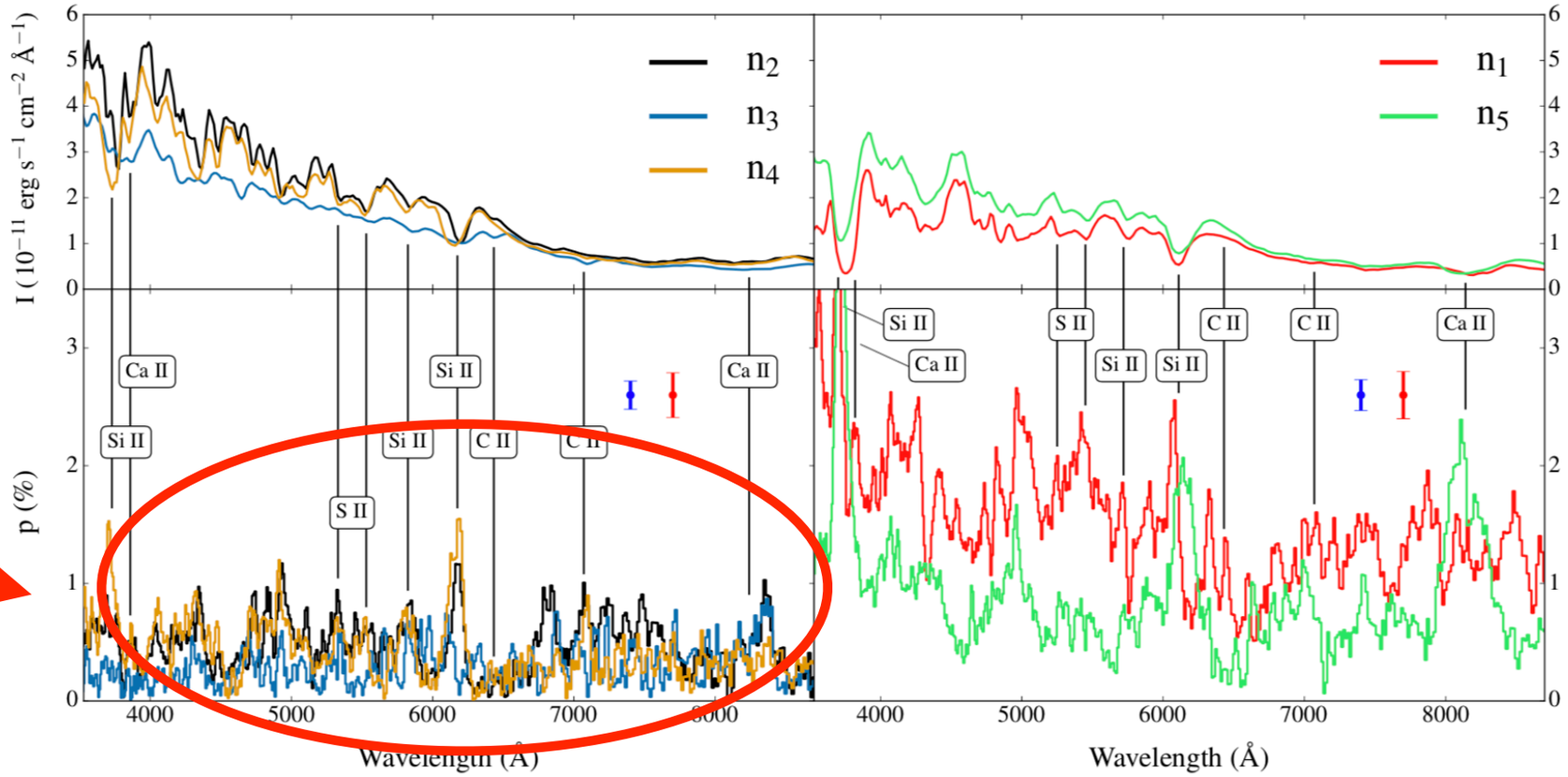
Bulla+ (2015)



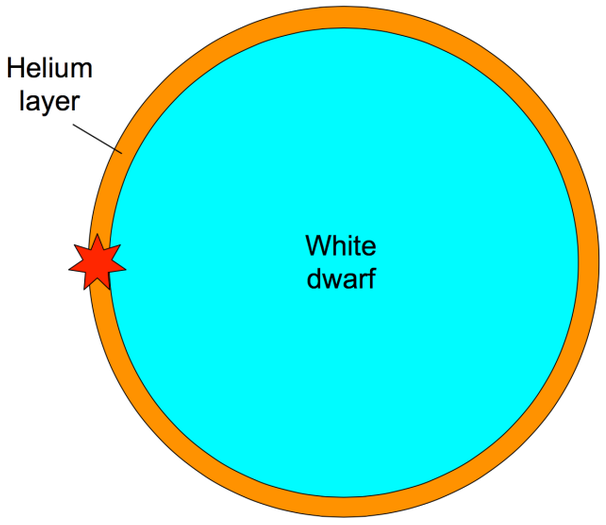
Predicts strong line polarisation not seen in SN Ia spectra

Observers in the orbital plane

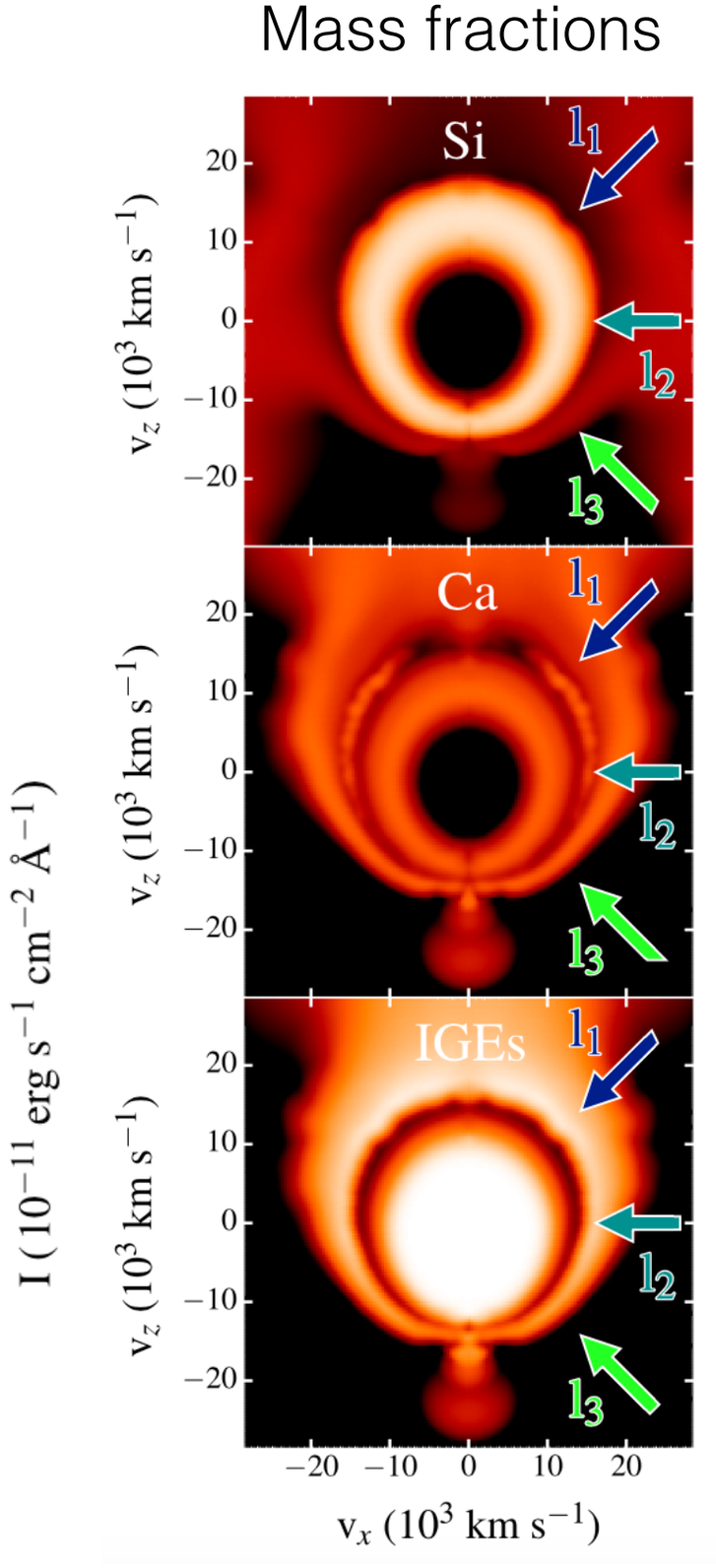
Observers out of the orbital plane



Double detonation model is just right

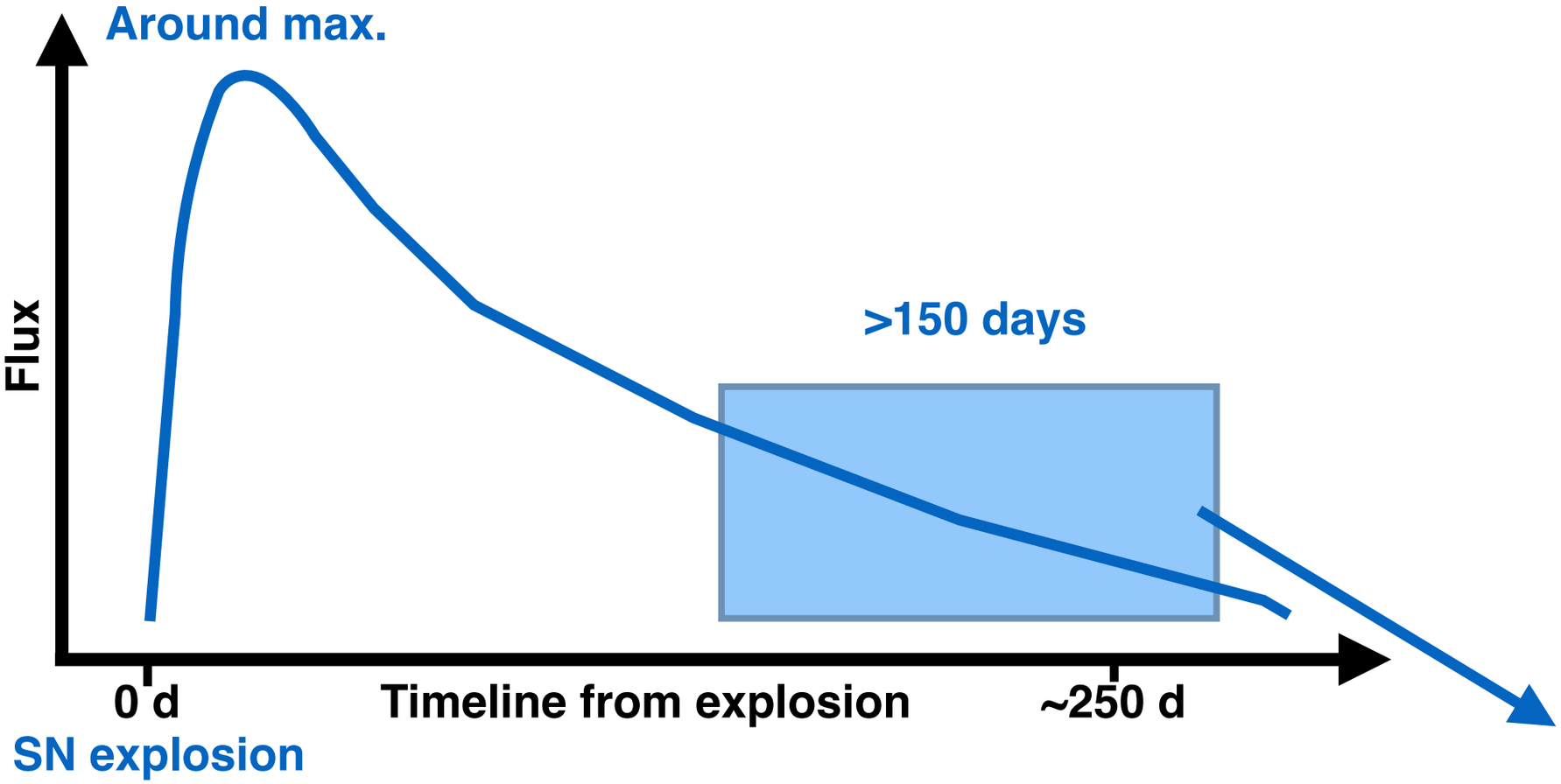


- Different viewing angles roughly predict Si II velocity vs. nebular velocity shift relationship

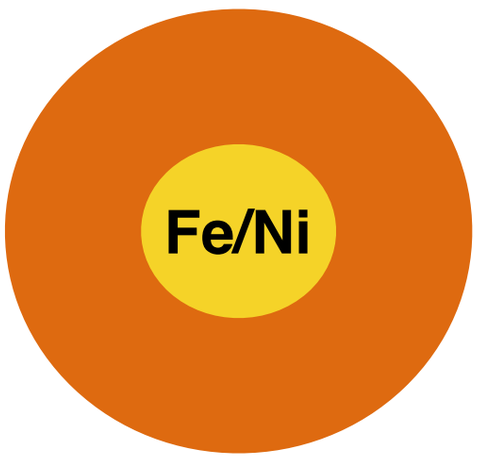


Bulla+ (2016)

What observations can distinguish between explosion scenarios?



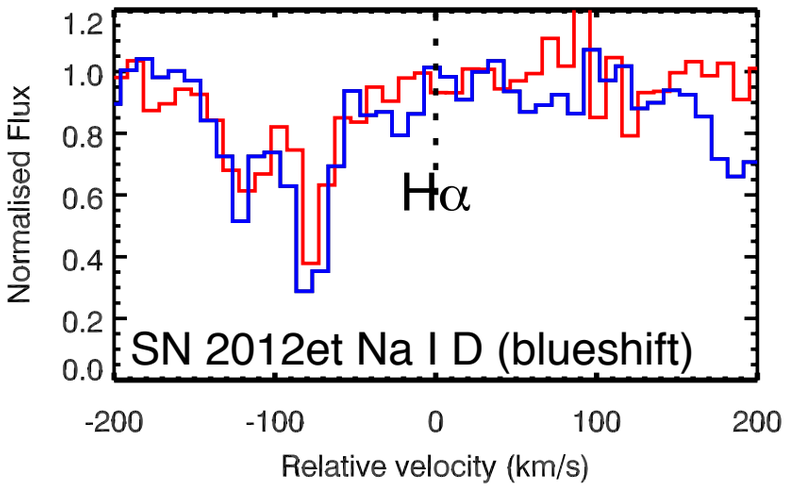
CSM interaction



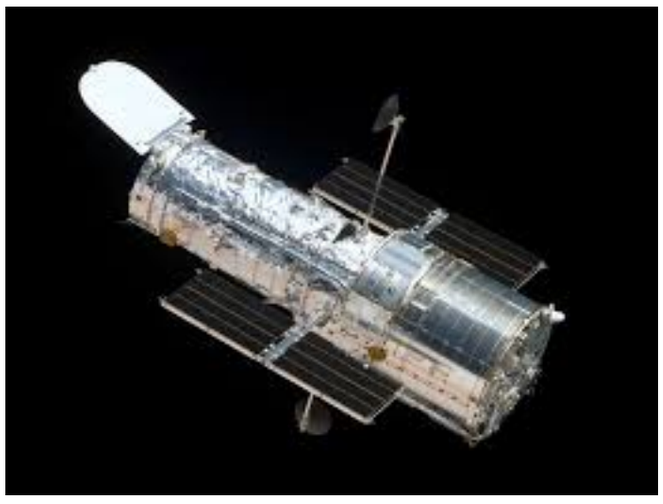
Circumstellar interaction at late times

Maguire et al. 2013

- Detection of CSM at maximum light in 20% of SNe Ia (Patat+ 2007, Sternberg+ 2011, 2014, Maguire+ 2013) located at > 10^{16} cm
- Rare Ia-CSM show strong interaction with link to 91T-like events (Leloudas et al. 2015)



Can we see the SN ejecta interacting with the CSM at late times?

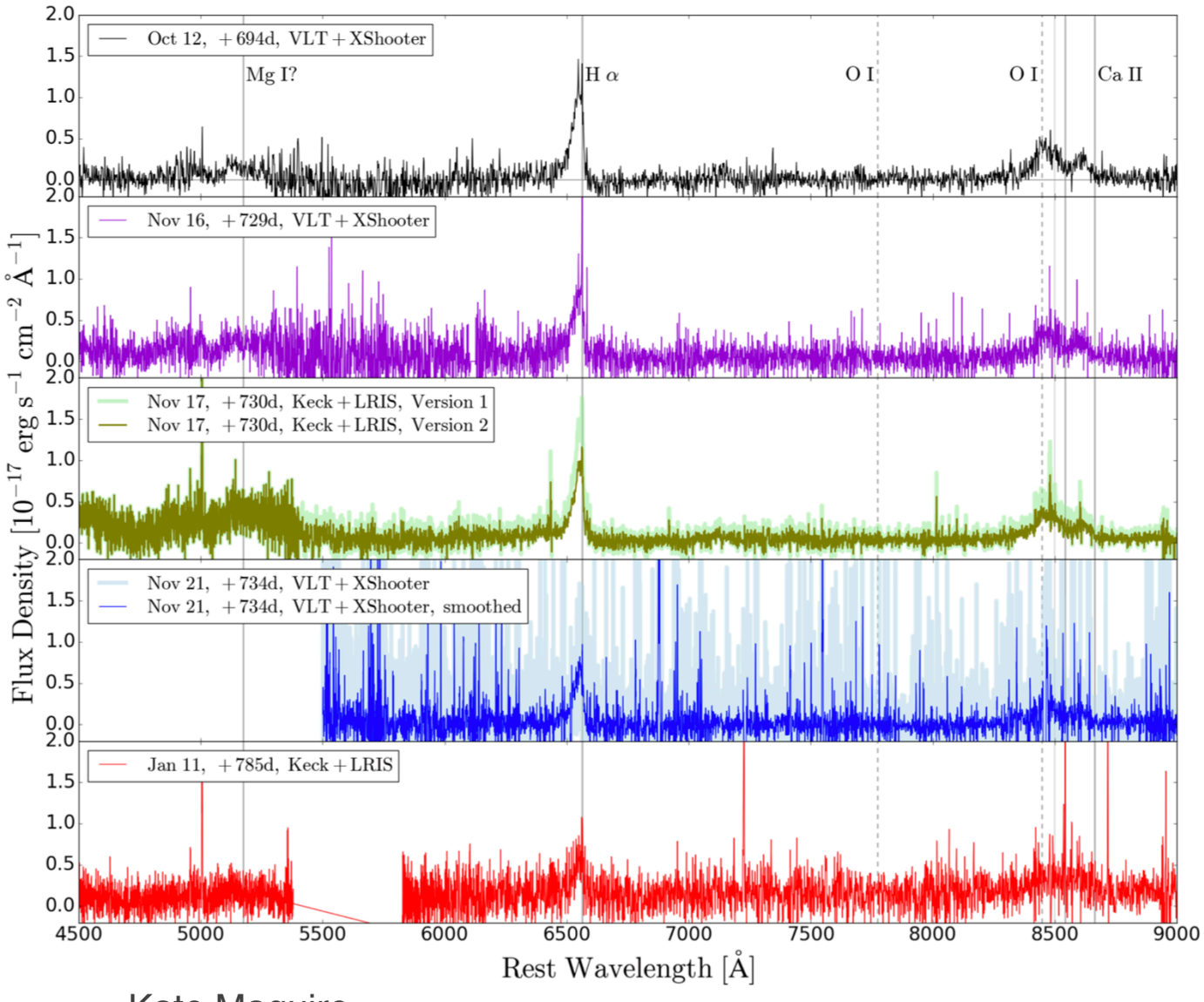


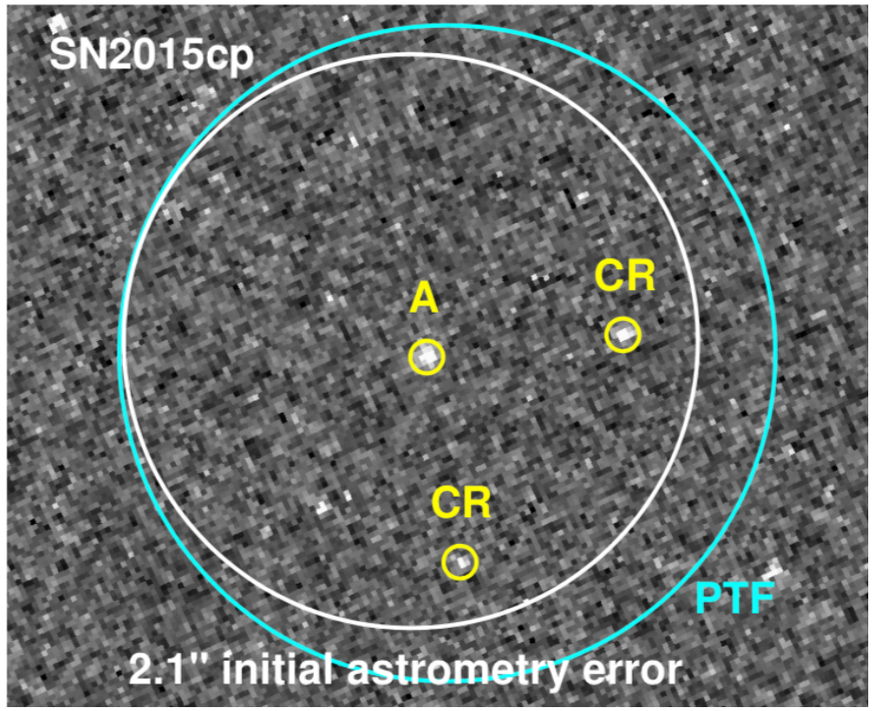
- HST NUV imaging study of 72 SNe Ia at 1-3 years after peak (P.I. Graham)
- UV contamination from hosts is low and see interaction signatures such as Mg II 2800 A

Circumstellar interaction in SN 2015cp

Graham,..KM+ 2018, submitted

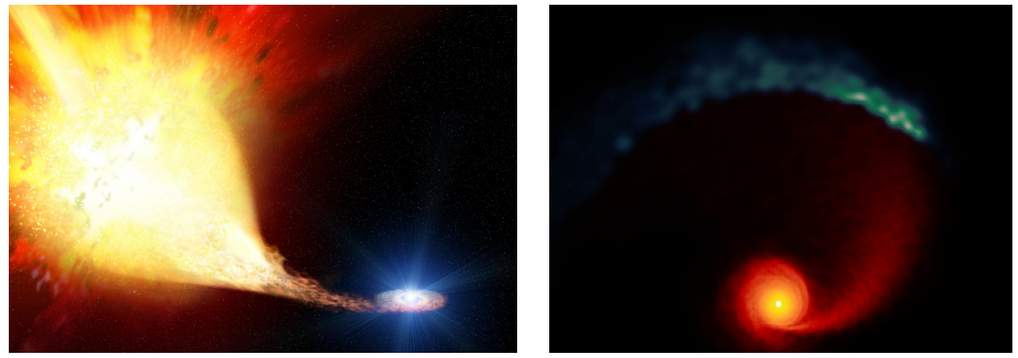
- Detection in 1 SN - SN 2015cp at 664 d
- Early spectra suggest 91T-like and 11kx event but no signs of interaction





- Follow-up observations at VLT+XSH, Keck+LRIS, STIS spectrum
- No detections with VLA, AMI, Swift
- Detection of Halpha and Ca II emission
- From timing of detection, constrain CSM mass to <0.5 Msun (Harris+ 2018 submitted)

Summary



- No companion star interaction (or stripped Hydrogen) suggest **WD binaries** but need to be careful of degeneracies
- Presence of stable material suggest **H-rich $M_{chandra}$ mass companions**
- Line shifts at late times suggest asymmetry - best agreement with **He-shell detonation of sub-Chandra WDs** (potential surviving companions observed, Shen+ 2018)
- No conclusive evidence for single channel for all objects!
- **How do we make progress?** Need low-redshift samples with very early to late-coverage spectral and light curve