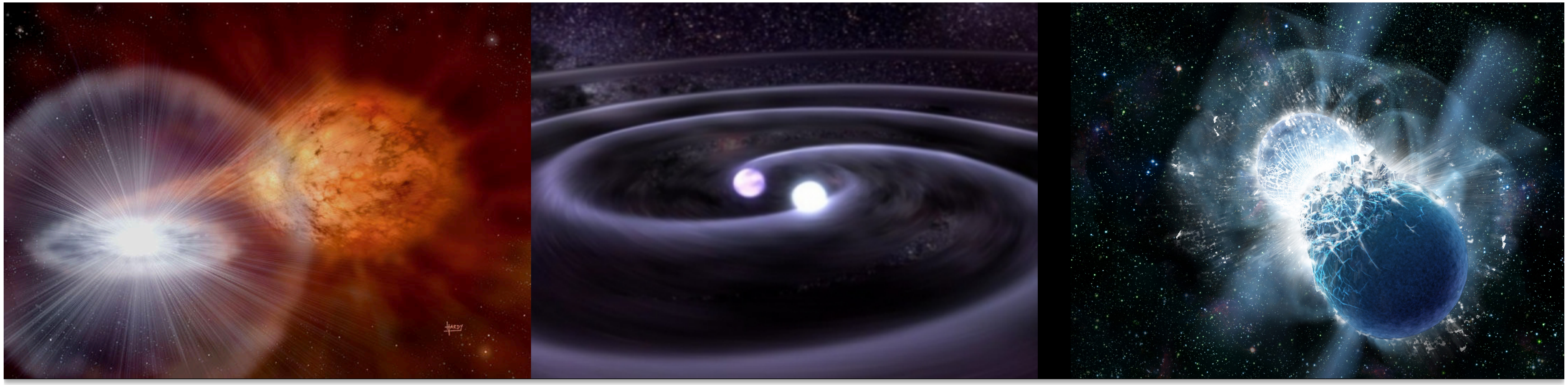

Constraints on the explosion mechanism and progenitors of Type Ia supernovae

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John Hillier
University of Pittsburgh

Alexei Khokhlov
University of Chicago

Journées de la SF2A 2015 - Atelier PNPS/PNHE "Stades Ultimes"

A one-dimensional Chandrasekhar-mass delayed-detonation model for the broad-lined Type Ia supernova 2002bo
Blondin, S., Dessart, L., Hillier, D. J. 2015. MNRAS, **448**, 2766

Critical ingredients of Type Ia supernova radiative-transfer modelling
Dessart, L., Hillier, D. J., Blondin, S., Khokhlov, A. M. 2014. MNRAS, **441**, 3249

Constraints on the explosion mechanism and progenitors of type Ia supernovae
Dessart, L., Blondin, S., Hillier, D. J., Khokhlov, A. M. 2014. MNRAS, **441**, 532

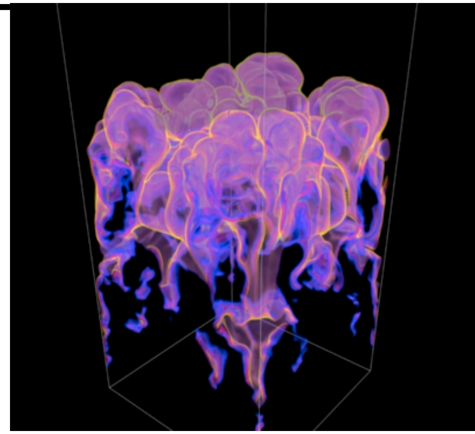
[CoIII] versus NaID in type Ia supernova spectra
Dessart, L., Hillier, D. J., Blondin, S., Khokhlov, A. M. 2014. MNRAS, **439**, 3114.

One-dimensional delayed-detonation models of Type Ia supernovae: Confrontation to observations at bolometric maximum
Blondin, S., Dessart, L., Hillier, D. J., Khokhlov, A. M. 2013. MNRAS, **429**, 2127

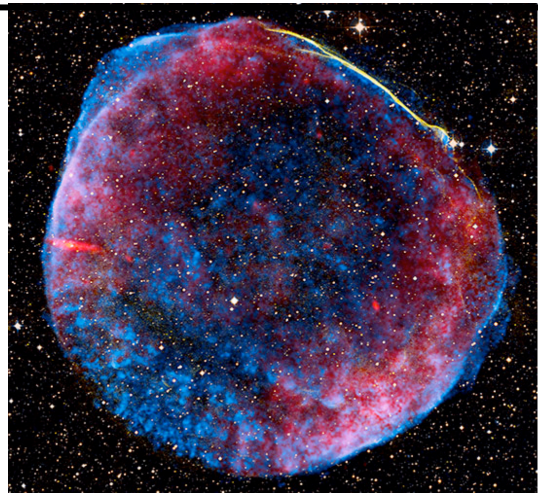
Astrophysical Relevance of Type Ia Supernovae

Chemical evolution
main producers of iron

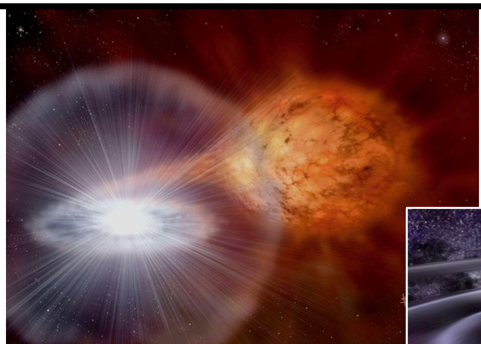
Explosive nucleosynthesis
combustion, turbulence

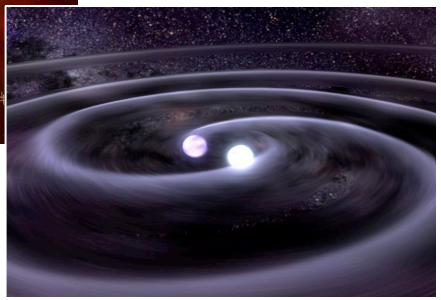


Cosmic-Ray Acceleration
supernova remnants

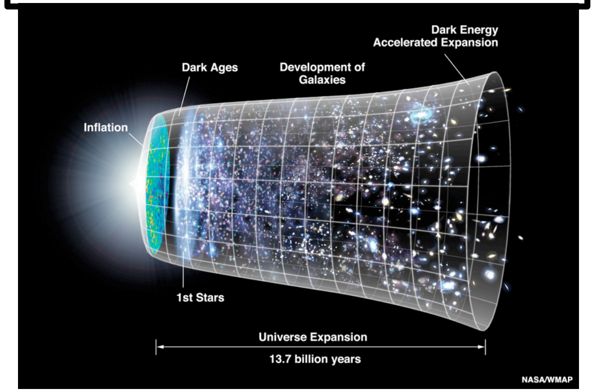


Binary stellar evolution
mass transfer, grav. waves



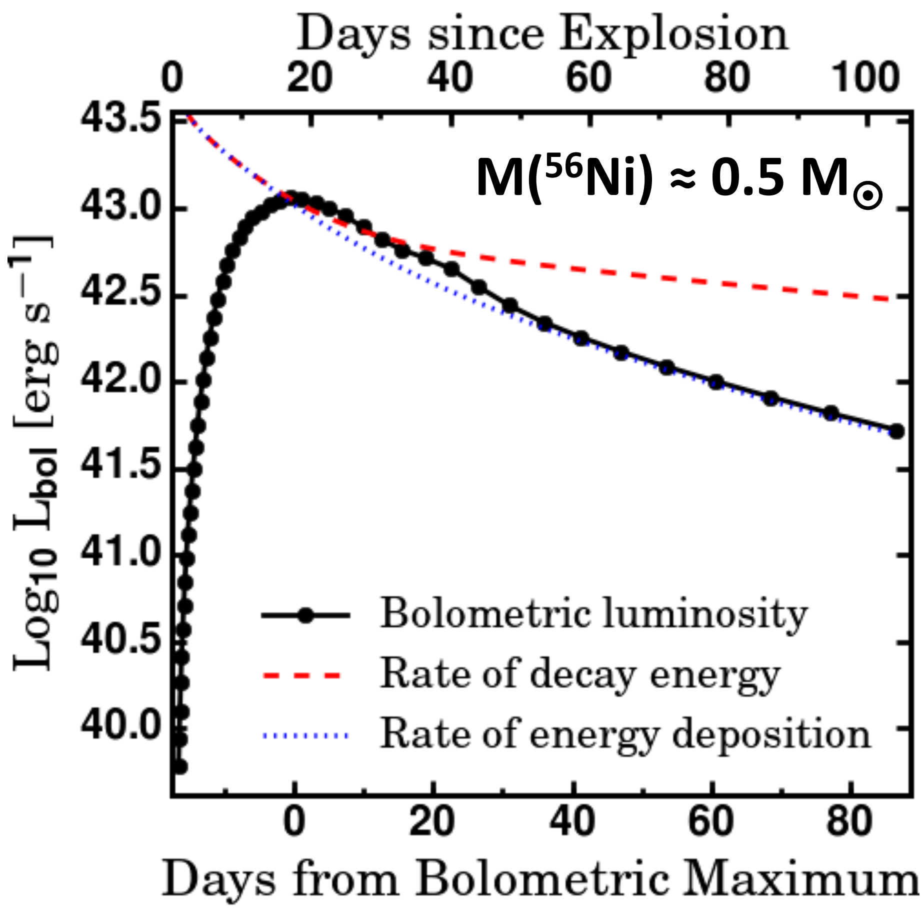


Cosmology, Dark Energy
distance measurements

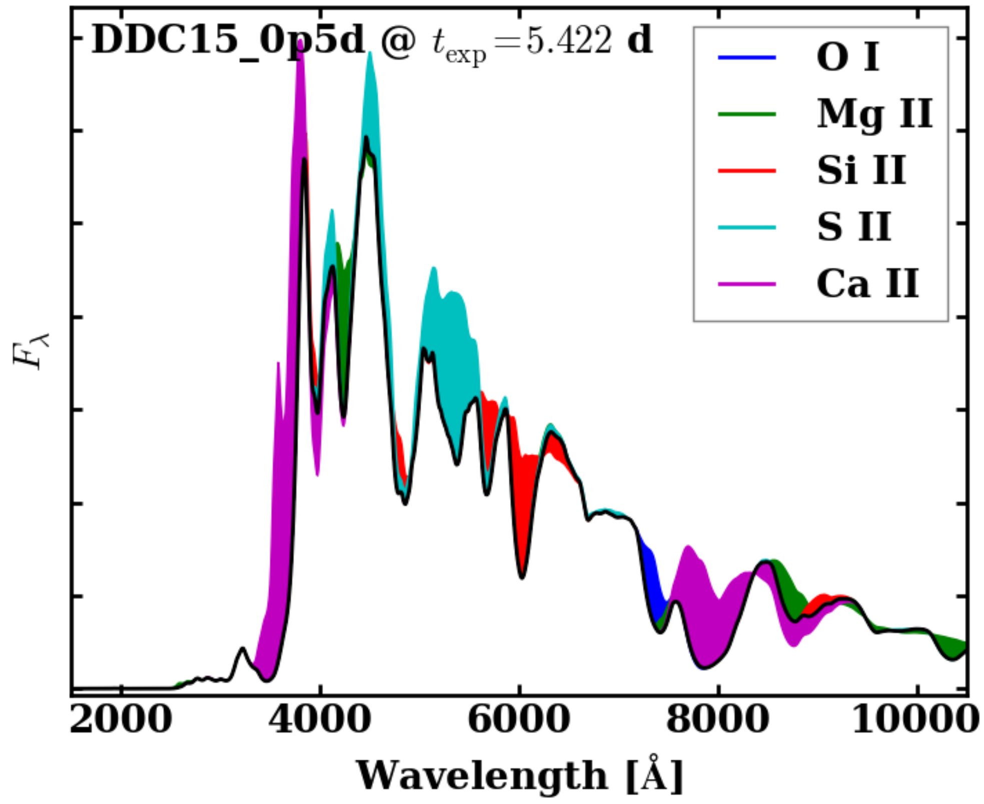


SN Ia Standard Model

*Thermonuclear disruption of a **C/O WD star** near the Chandrasekhar mass ≈ 1.4 $M_\odot$*



Blondin et al. (2015)

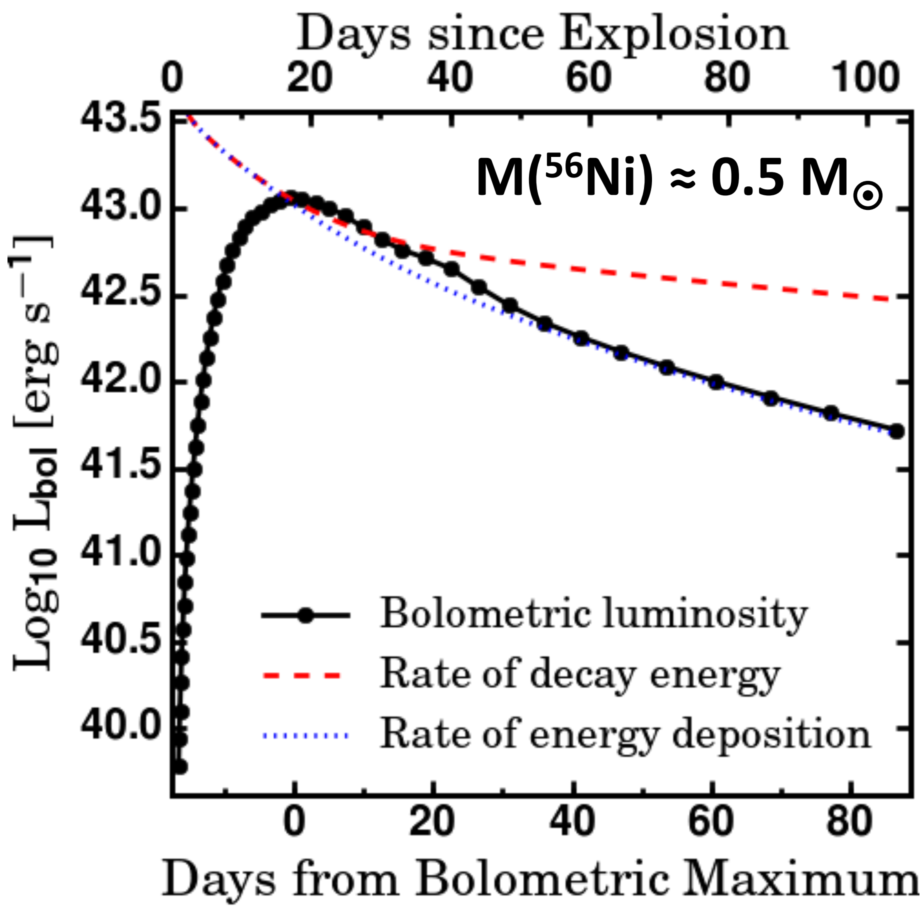


Light-curve powered by **^{56}Ni decay**

Spectra indicate **chemical stratification**

SN Ia Standard Model

*Thermonuclear disruption of a **C/O WD star** near the Chandrasekhar mass ≈ 1.4 $M_\odot$*



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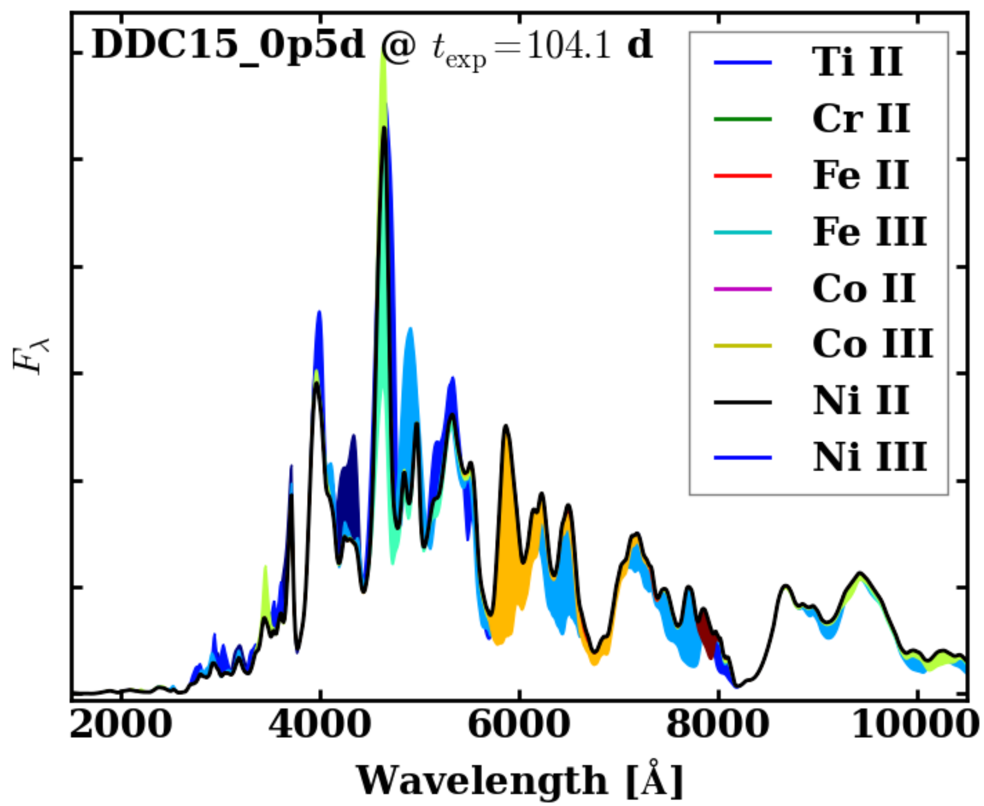
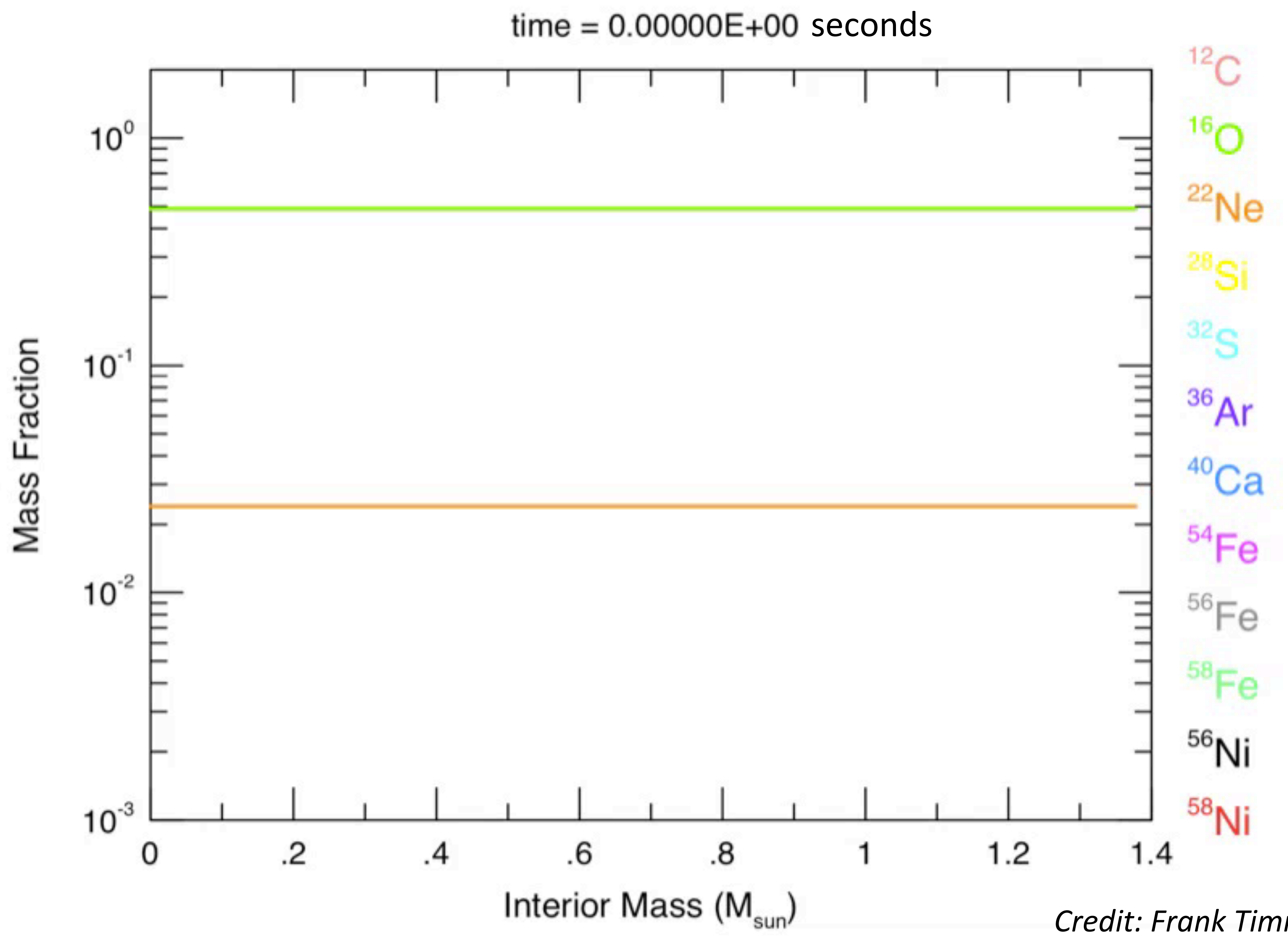


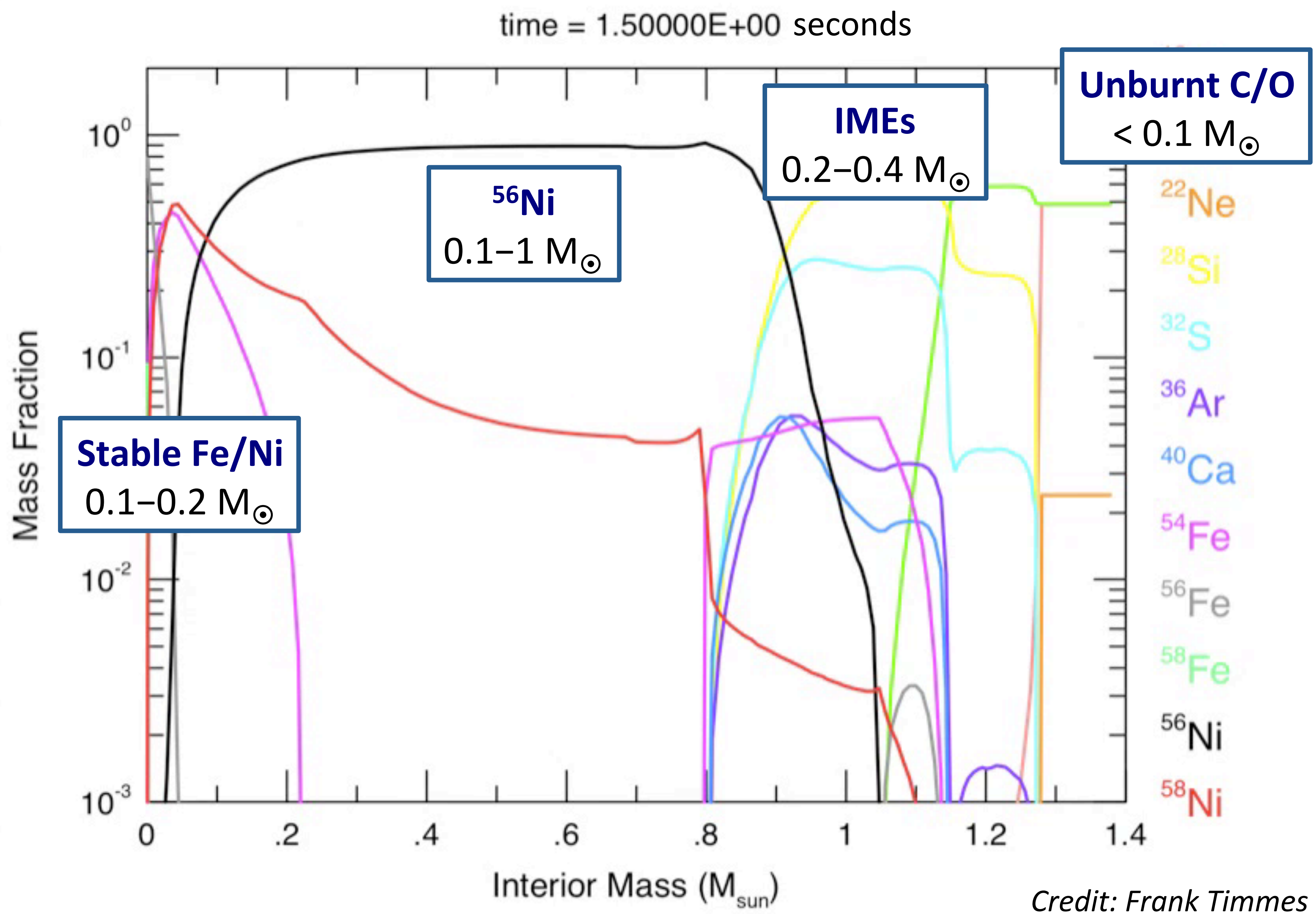
Spectra indicate **chemical stratification**

Explosive Interlude…



Credit: Frank Timmes

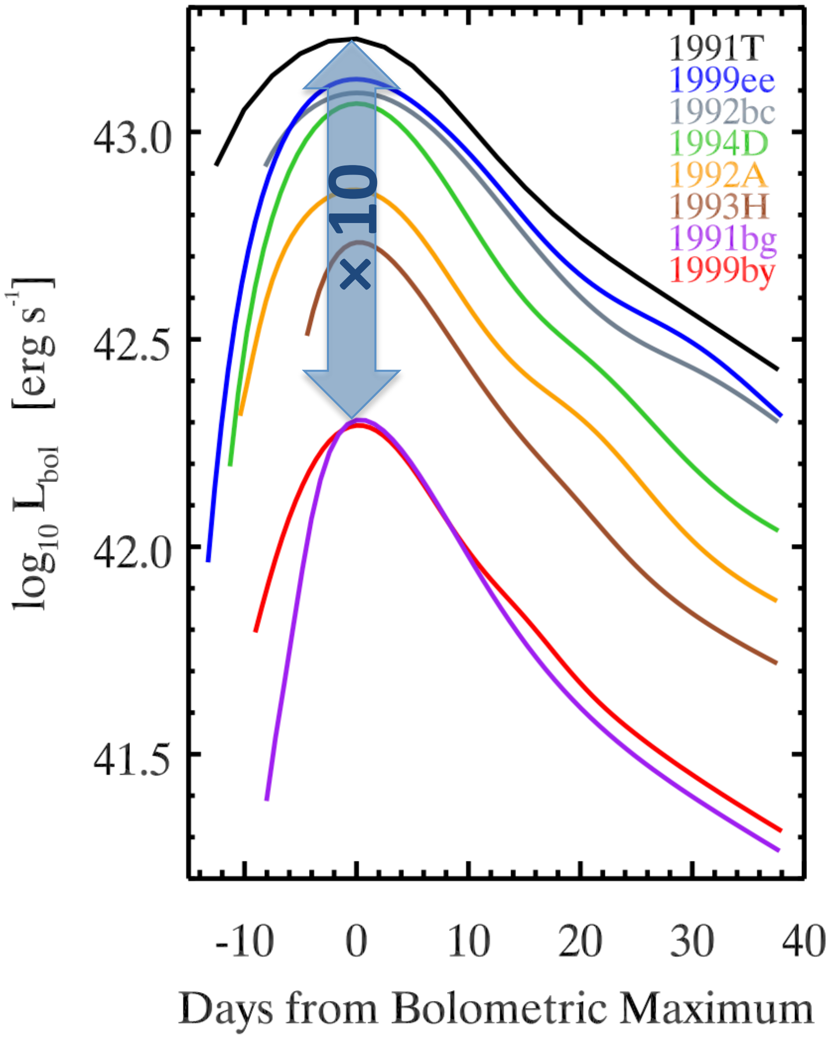
Explosive Interlude…



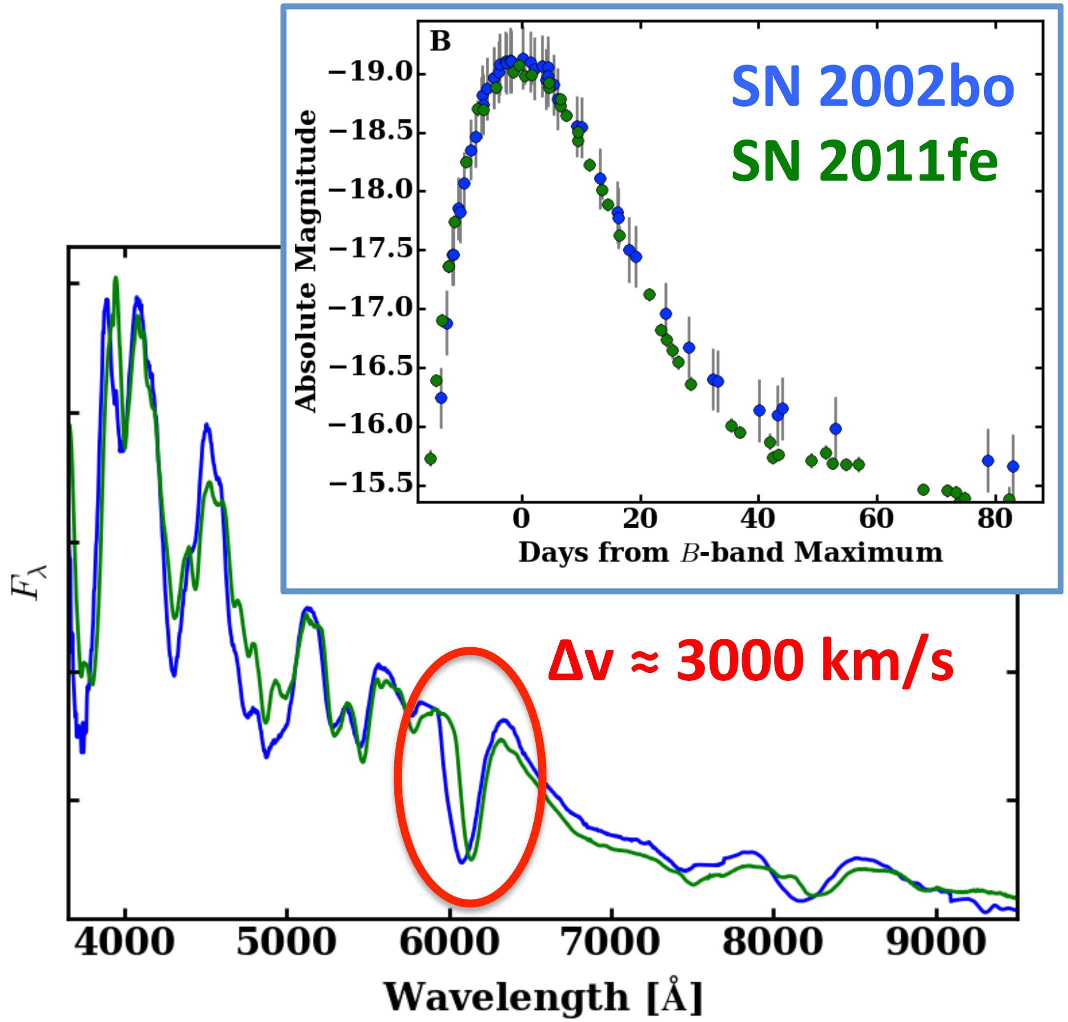
Credit: Frank Timmes

Observed Diversity of SN Ia Population

Variation in **peak luminosity**



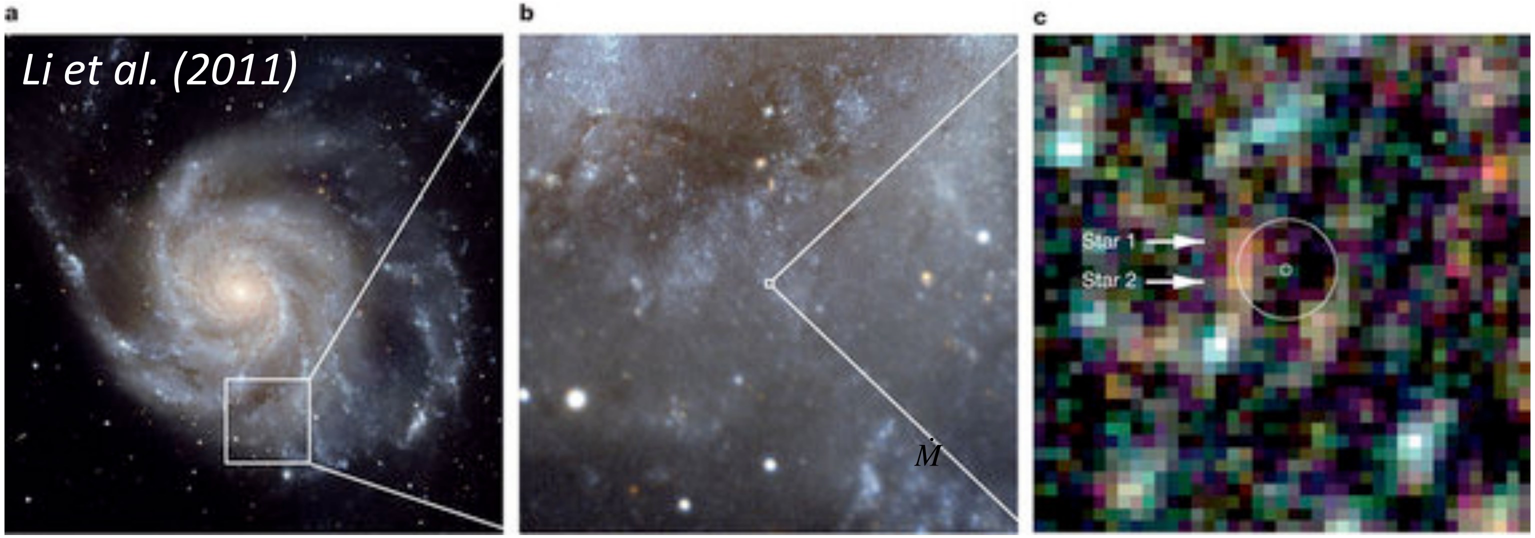
Diversity **at a given luminosity**



*Evidence for **multiple progenitor channels** and **explosion mechanisms**?*

Difficulties in Constraining SN Ia Progenitors

No direct detection of SN Ia progenitors (e.g., SN 2011fe in M101, D=6.4 Mpc)



Excluded:
- ✗ Red Giants
- ✗ $M > 3.5\ M_\odot$
- ✗ He star
- ✗ RNe $M_V \gtrsim 0$

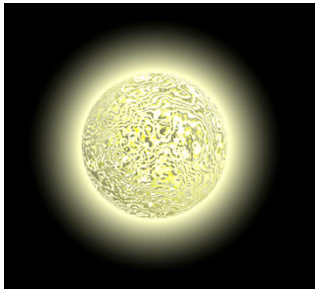
Indirect constraints from:

- ✧ potential progenitor populations (recurrent Novae, binary WDs, …)
- ✧ early post shock-breakout luminosity ($R_{prog} < 0.1\ R_\odot$ for SN 2011fe)
- ✧ interaction with binary companion + CSM ($\dot{M} \lesssim 10^{-9}\ M_\odot\ yr^{-1}$ from radio/X-ray limits)
- ✧ surviving companion star in SN remnants
- ✧ SN rates *vs.* host stellar population

*Need constraints from **numerical simulations**!*

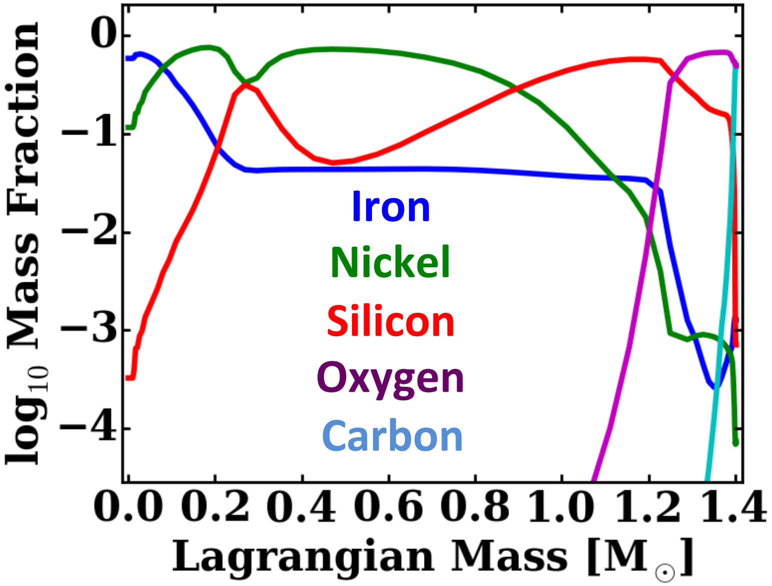
Numerical Setup for SN Ia Modelling

1. C/O WD
Hydrostatic
$X_C \approx X_O \approx 0.5$



Magic

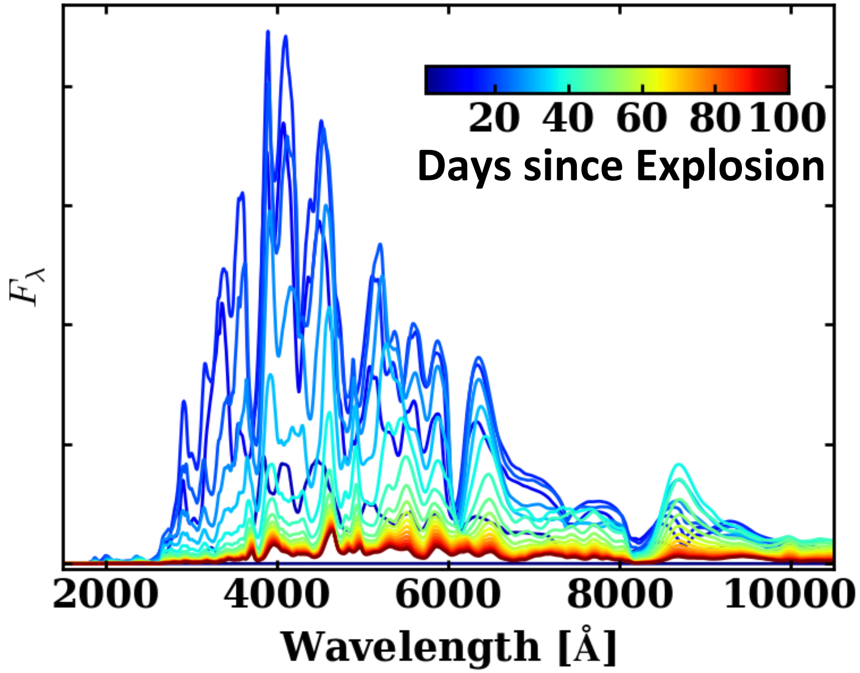
2. Explosion
1D hydro + burning
Homologous expansion
v(r) ∝ r @ t_{exp} < 1 min



1st Law

3. Radiative Transfer
1D non-LTE (CMFGEN)
Time-dependent *D/Dt*
Non-local energy deposition
Non-thermal effects

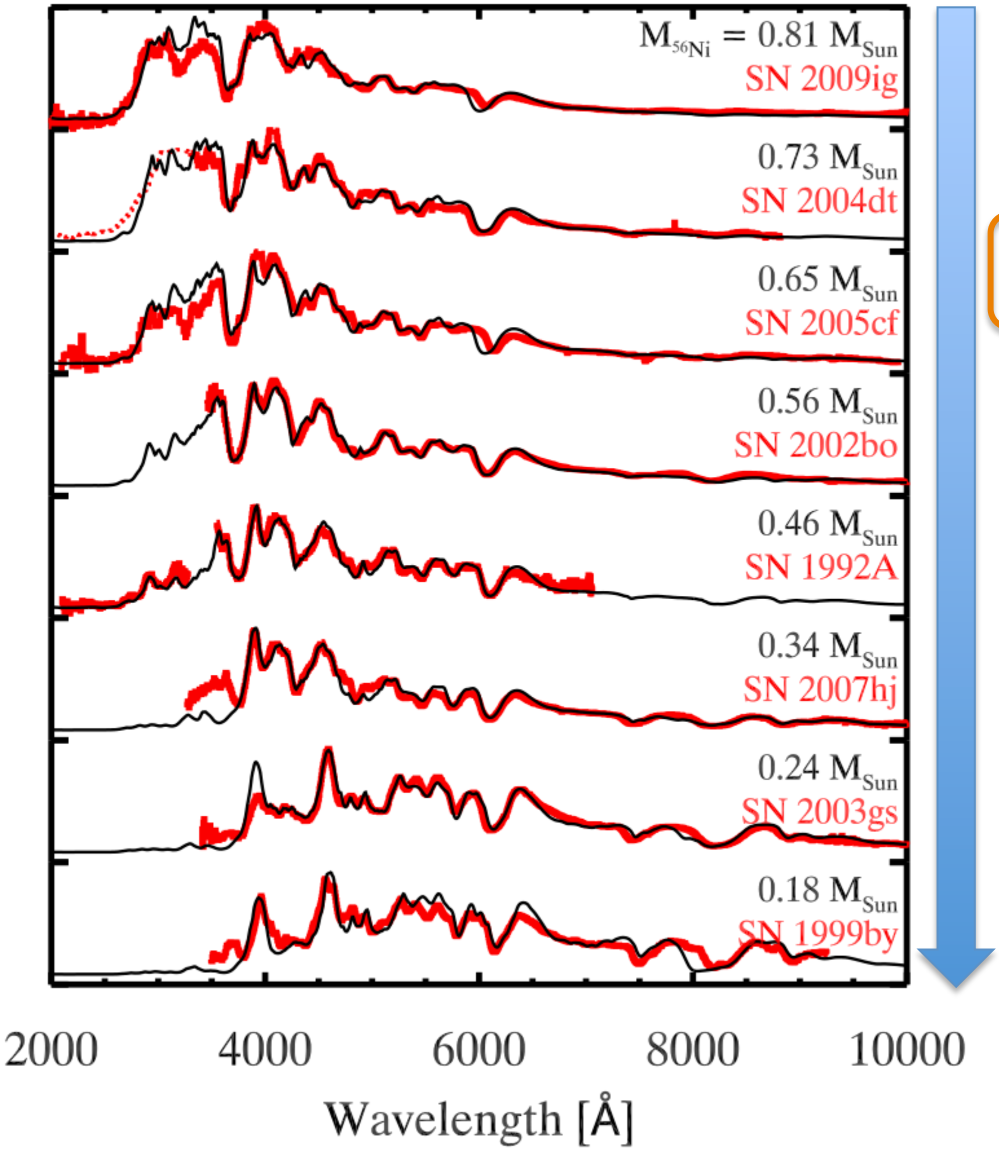
Hillier & Dessart (2012)



4. Comparison to Observations

Chandrasekhar-mass Delayed-Detonation Models

Maximum-light spectra *(Blondin et al. 2013)*



Initial **deflagration** transitions to a **detonation** at a fixed density, ρ_{tr}

Lower ρ_{tr} ⇒ *Less* ^{56}*Ni* ⇒ *Lower* L_{peak}

… but *same* kinetic energy !

Decreasing

^{56}Ni mass

Temperature

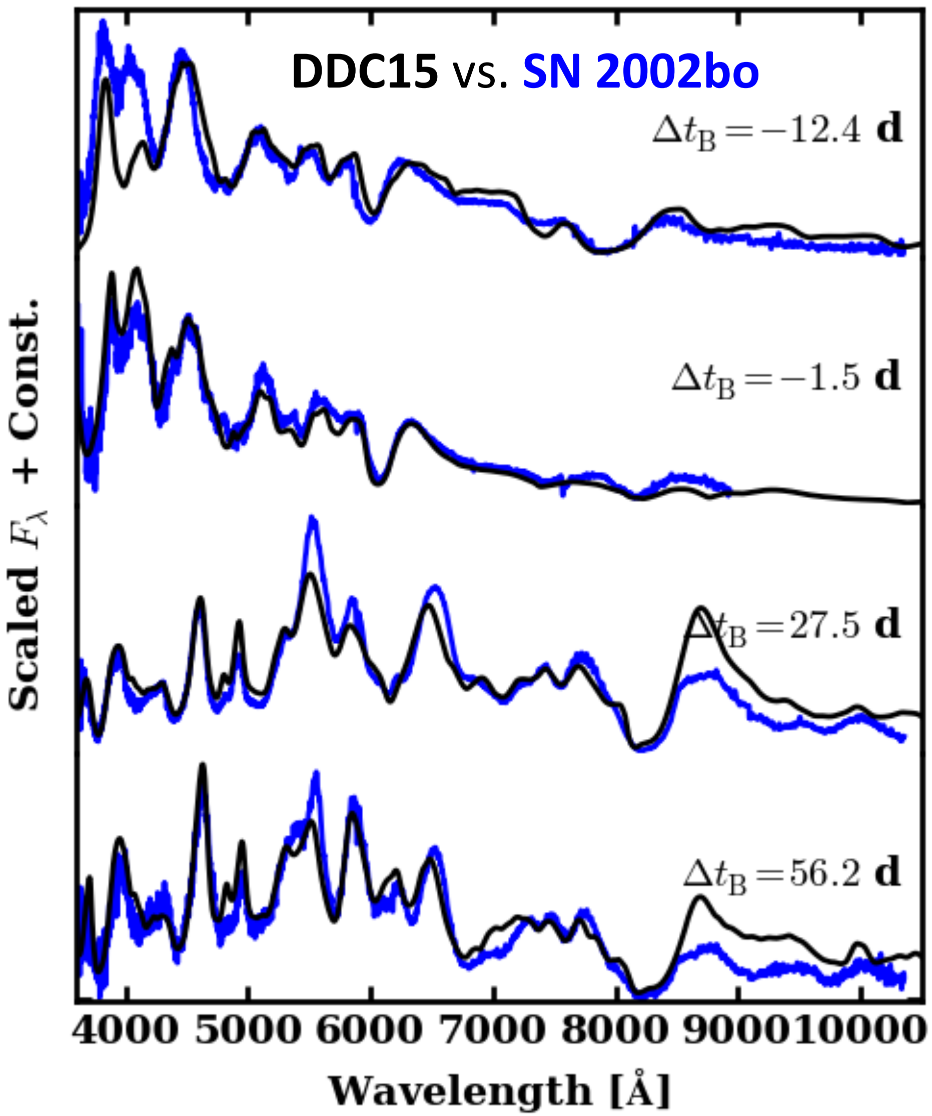
Ionization

Chandrasekhar-mass Delayed-Detonation Models

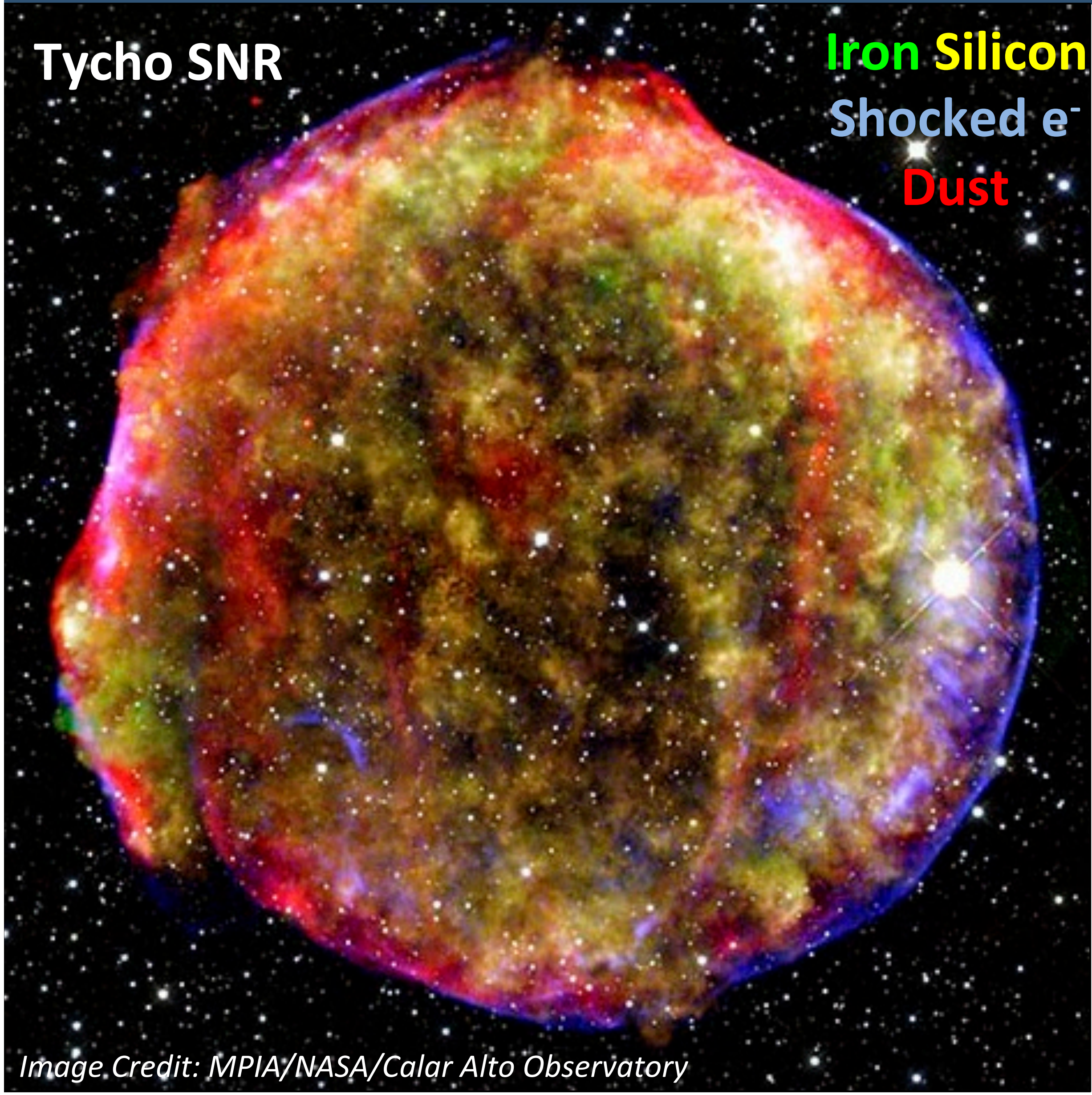
Blondin et al. (2015)

Good match to **spectral evolution** between 1−100 d past explosion

✔ chemical stratification
✔ spherical symmetry
✔ no fine-tuning!



Link to SN Ia Remnants



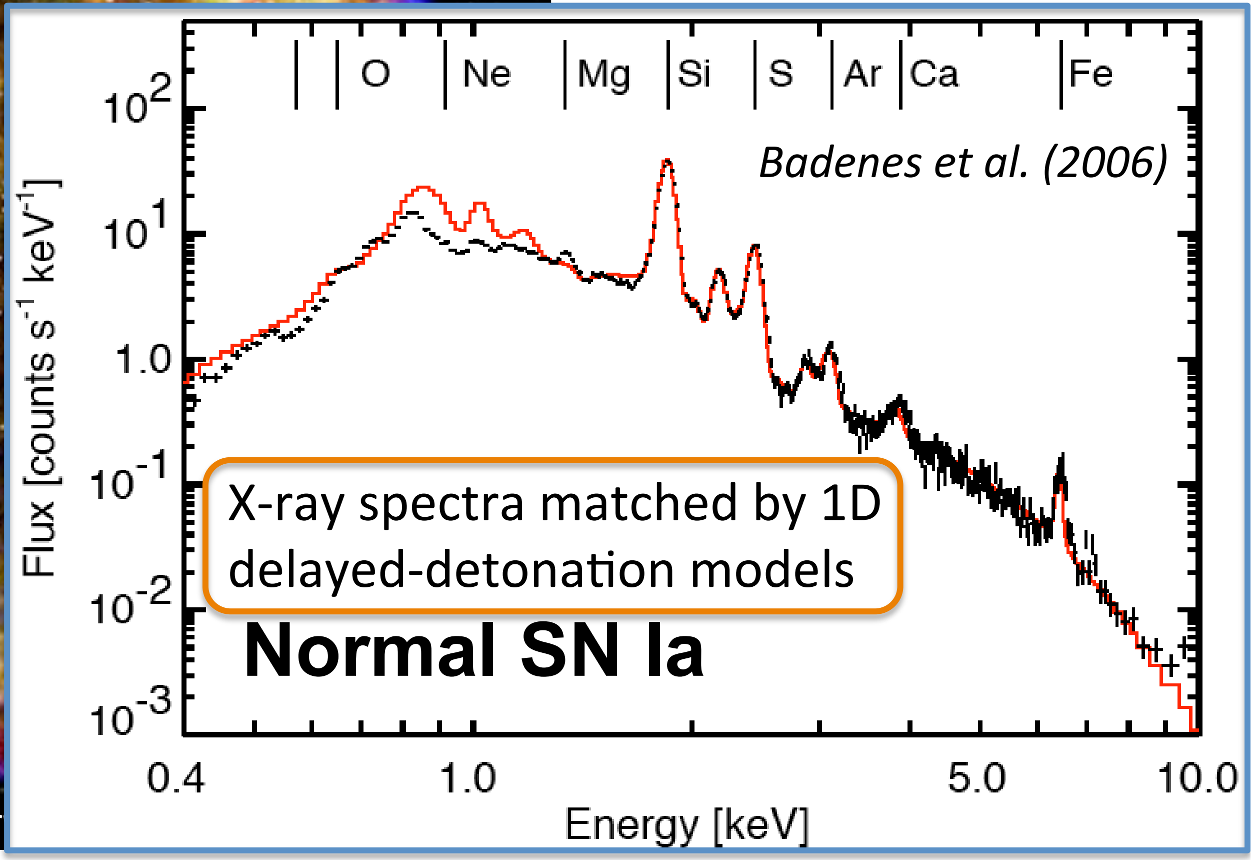
✔ spherically symmetric

✔ stratified ejecta

Link to SN Ia Remnants

✔ spherically symmetric

✔ stratified ejecta



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Blondin et al. (2015)

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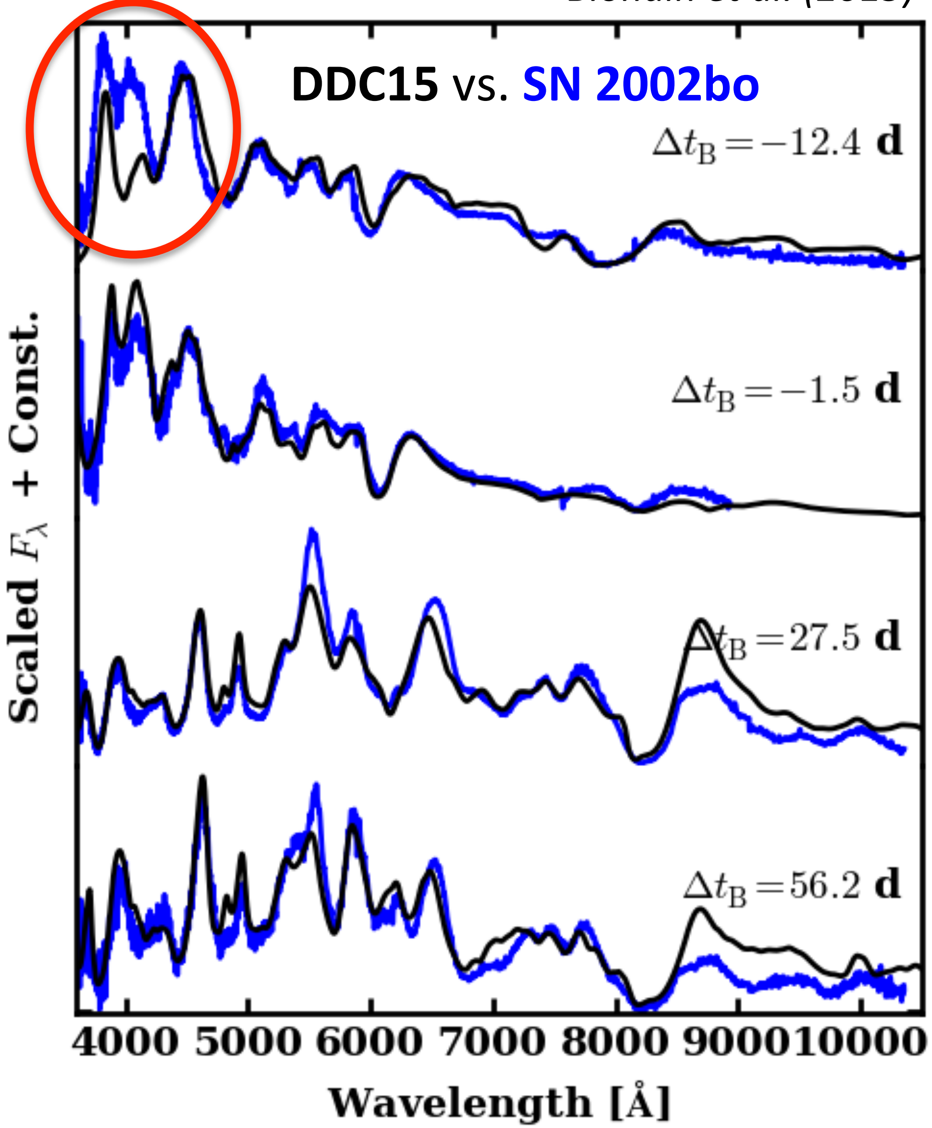
✗ too faint/cool at earliest times



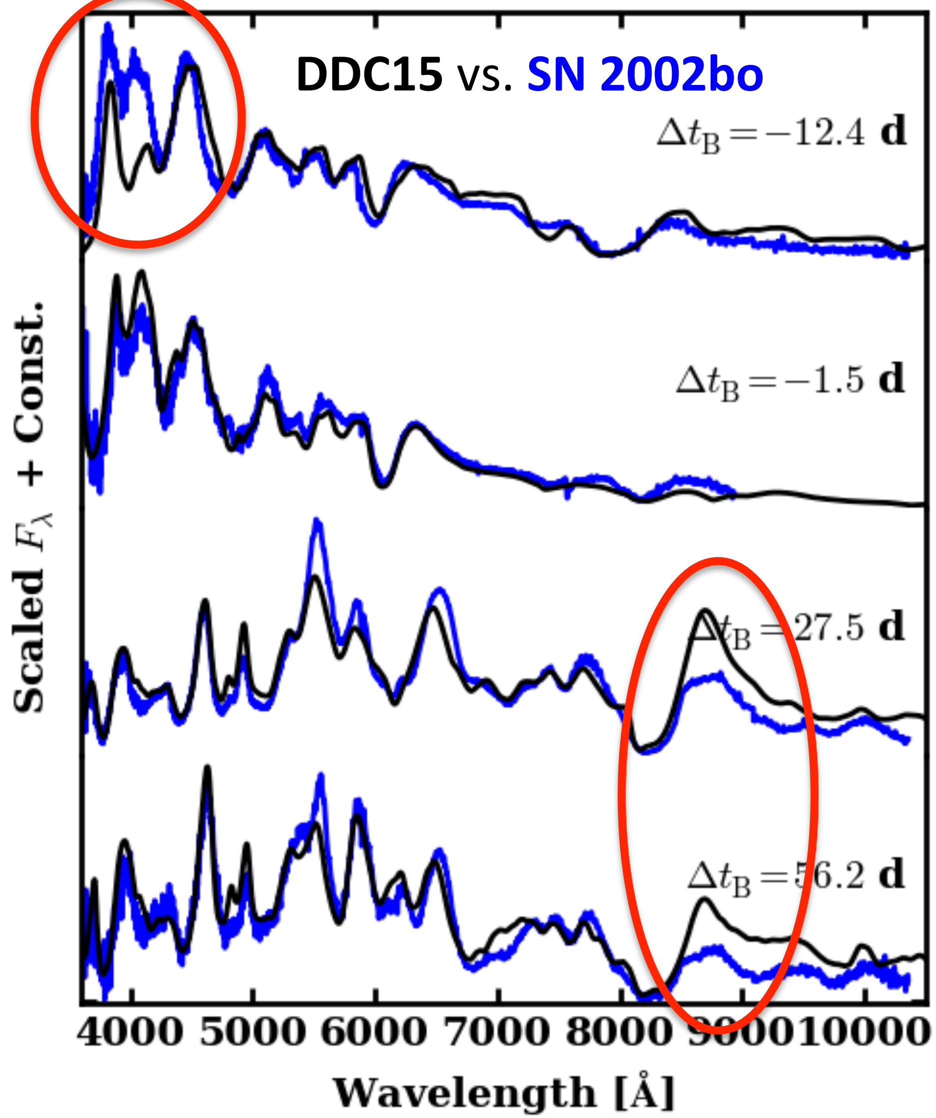
Chandrasekhar-mass Delayed-Detonation Models

Good match to **spectral evolution** between 1–100 d past explosion

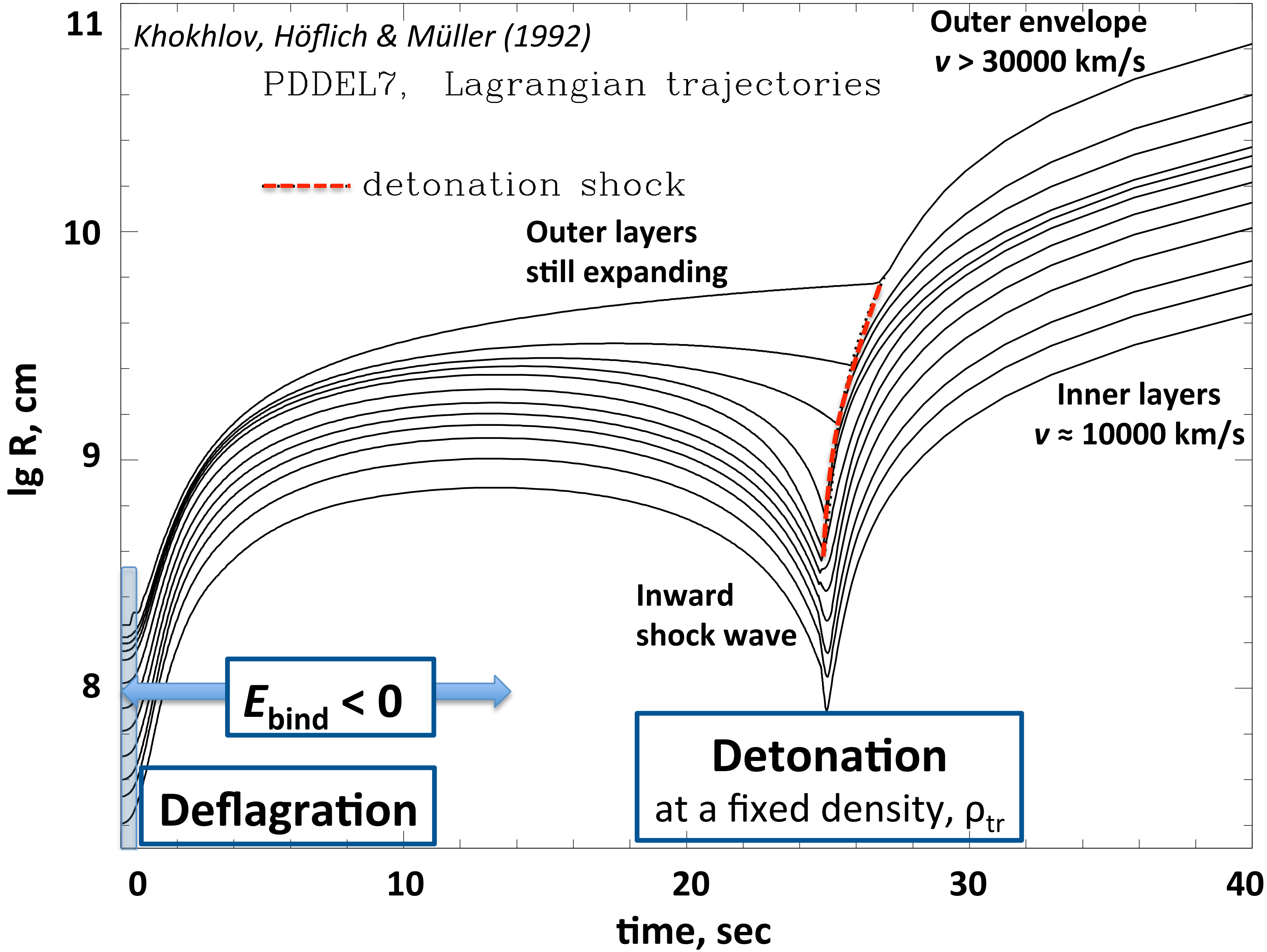
✔ chemical stratification
✔ spherical symmetry
✔ no fine-tuning!

✗ too faint/cool at earliest times
✗ Ca II 8500 Å emission (Co II ?)

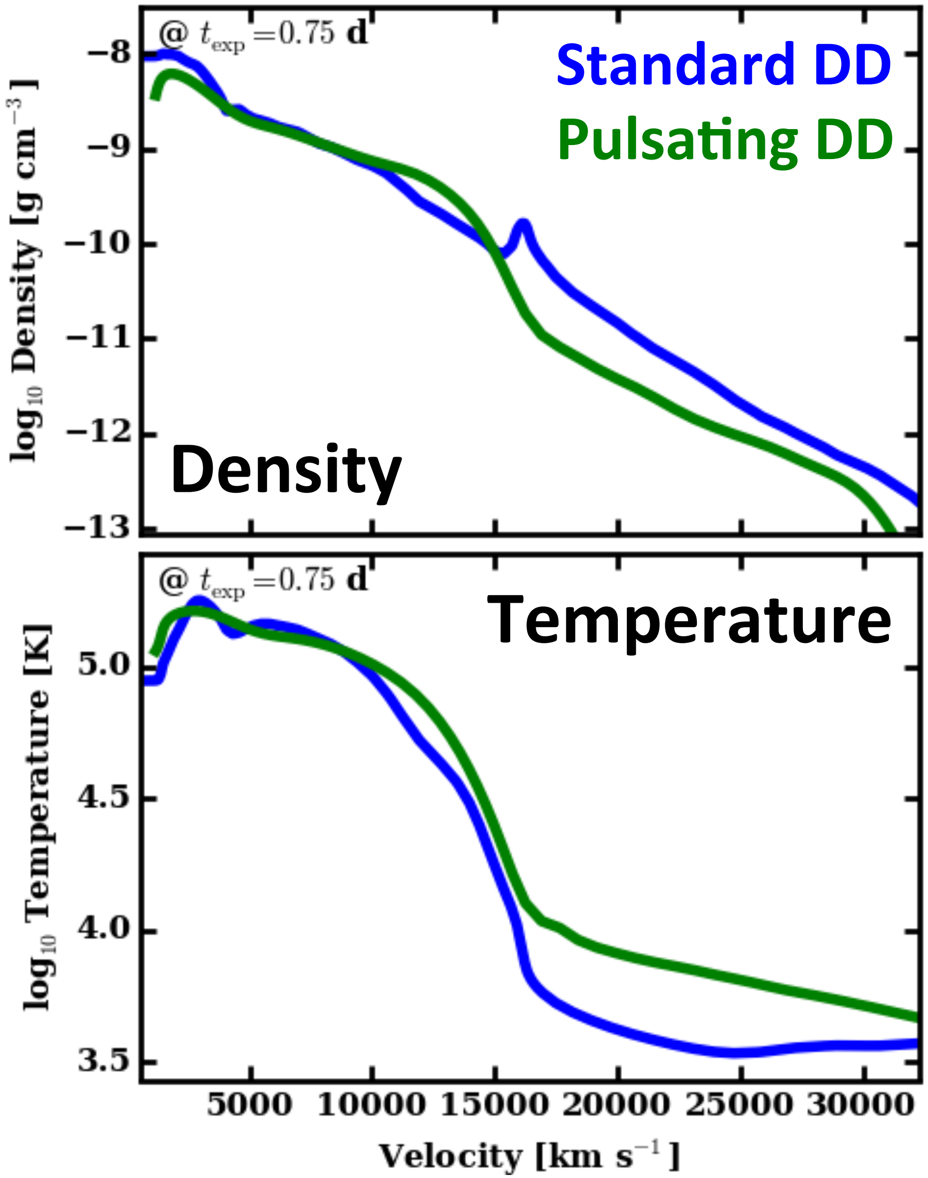
Blondin et al. (2015)



Pulsating Delayed-Detonation Models



Pulsating Delayed-Detonation Models



Pulsation leads to a **density cliff** and a **hotter outer ejecta**

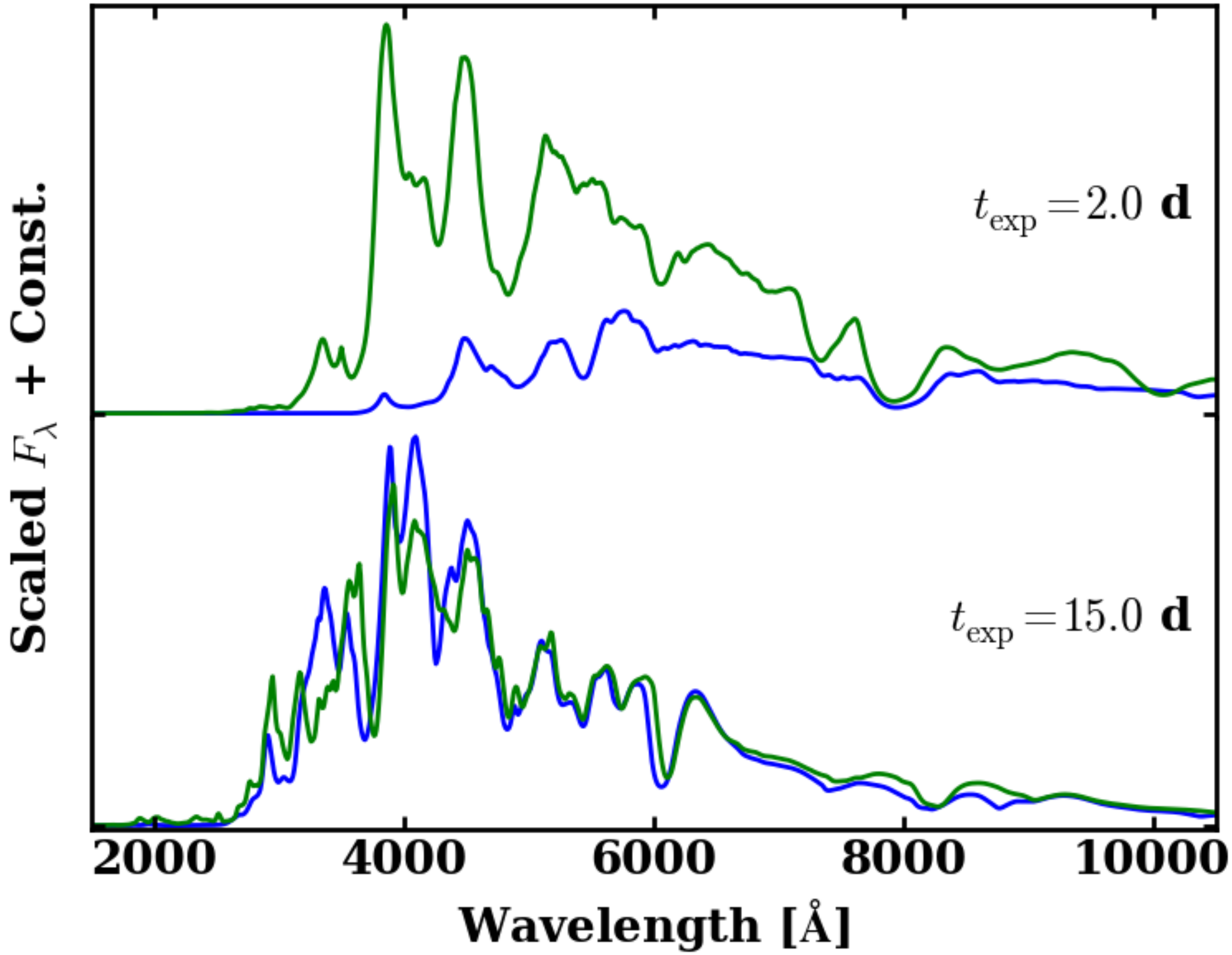
Impacts **early-time spectra**:

- ✧ unburnt C/O at large velocity
- ✧ narrower lines
- ✧ bluer optical colors

… independent of ^{56}Ni mass!

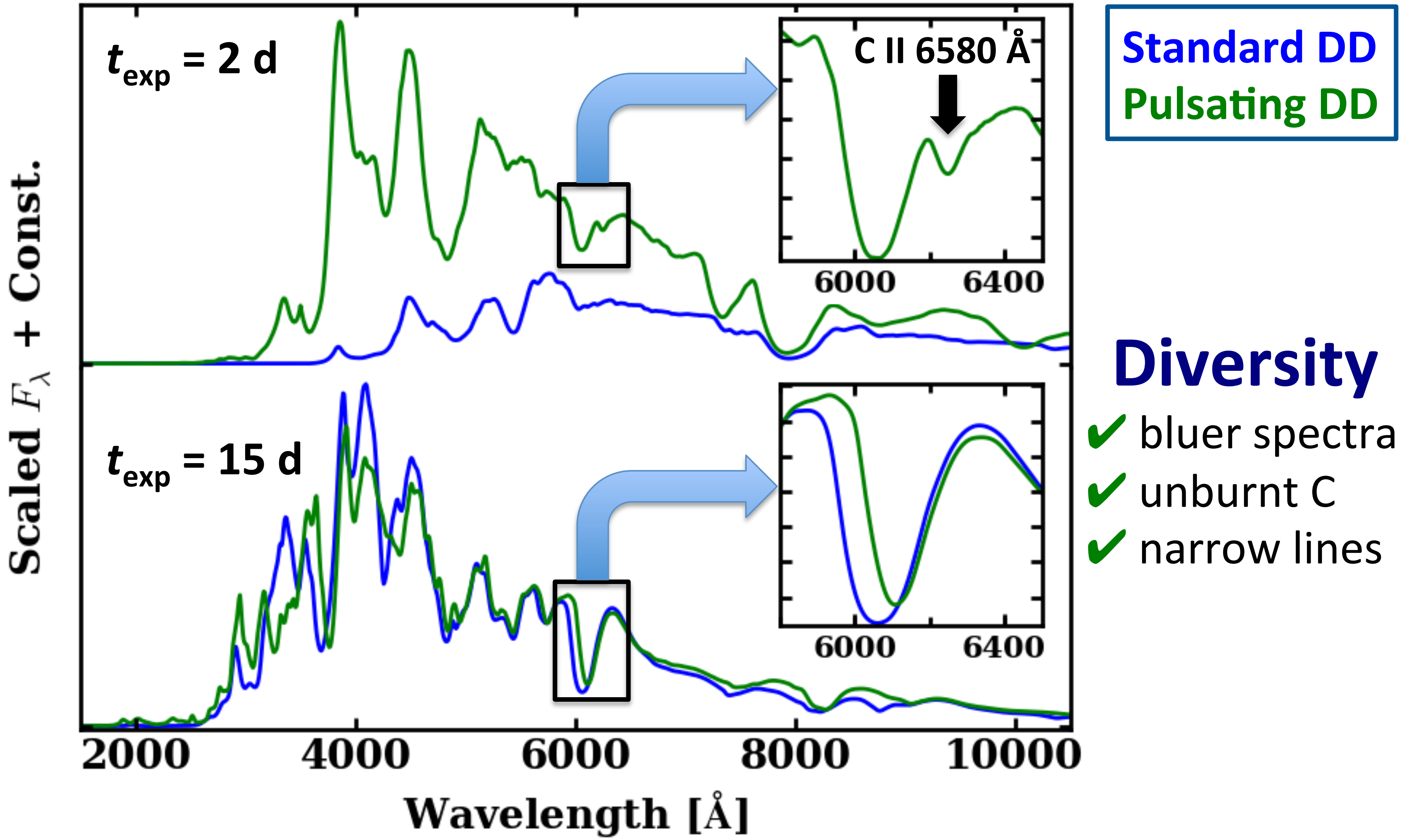
Expect similar interaction in ***double WD mergers***

Pulsating Delayed-Detonation Models



Standard DD
Pulsating DD

Pulsating Delayed-Detonation Models

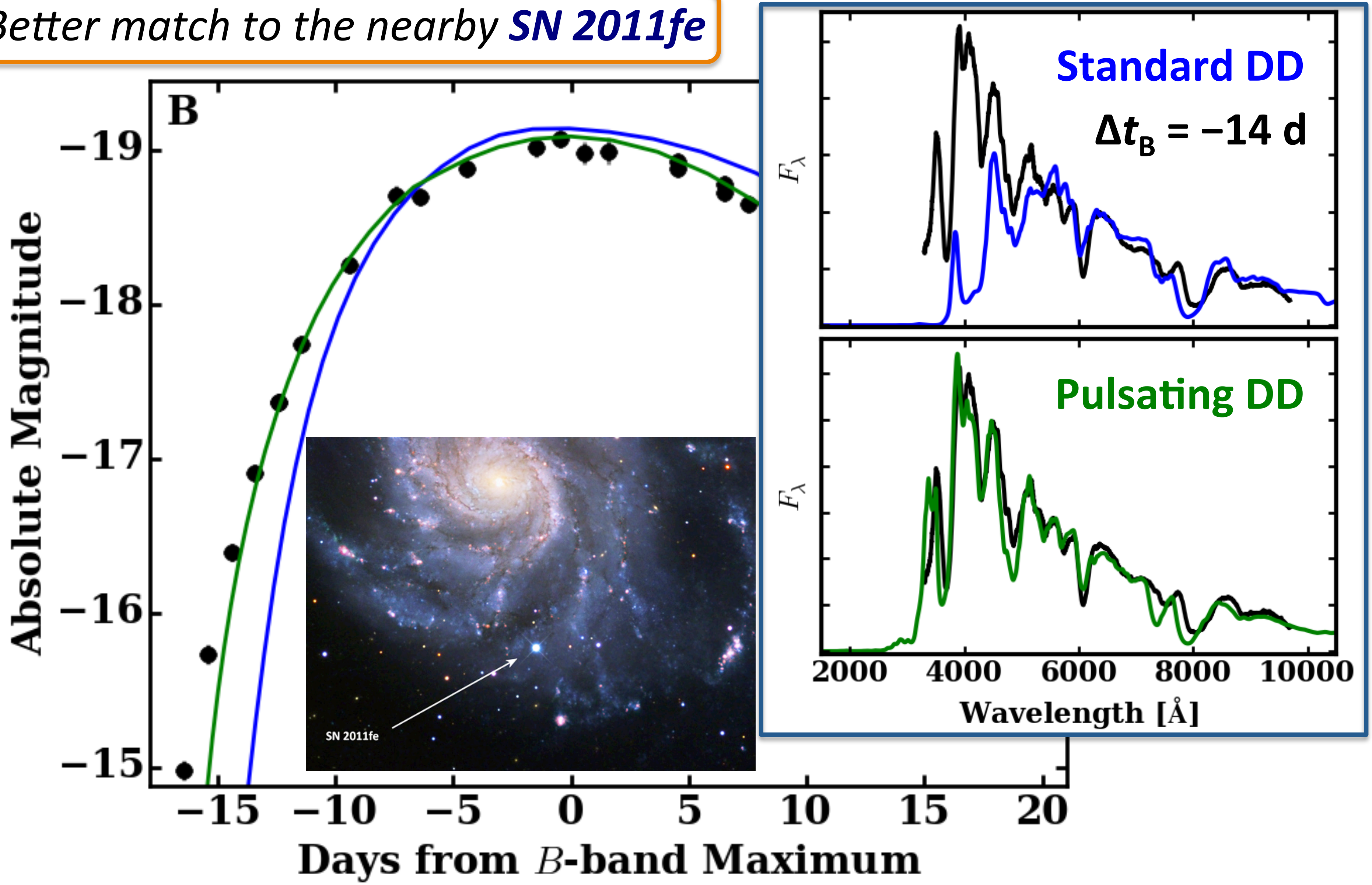


Diversity

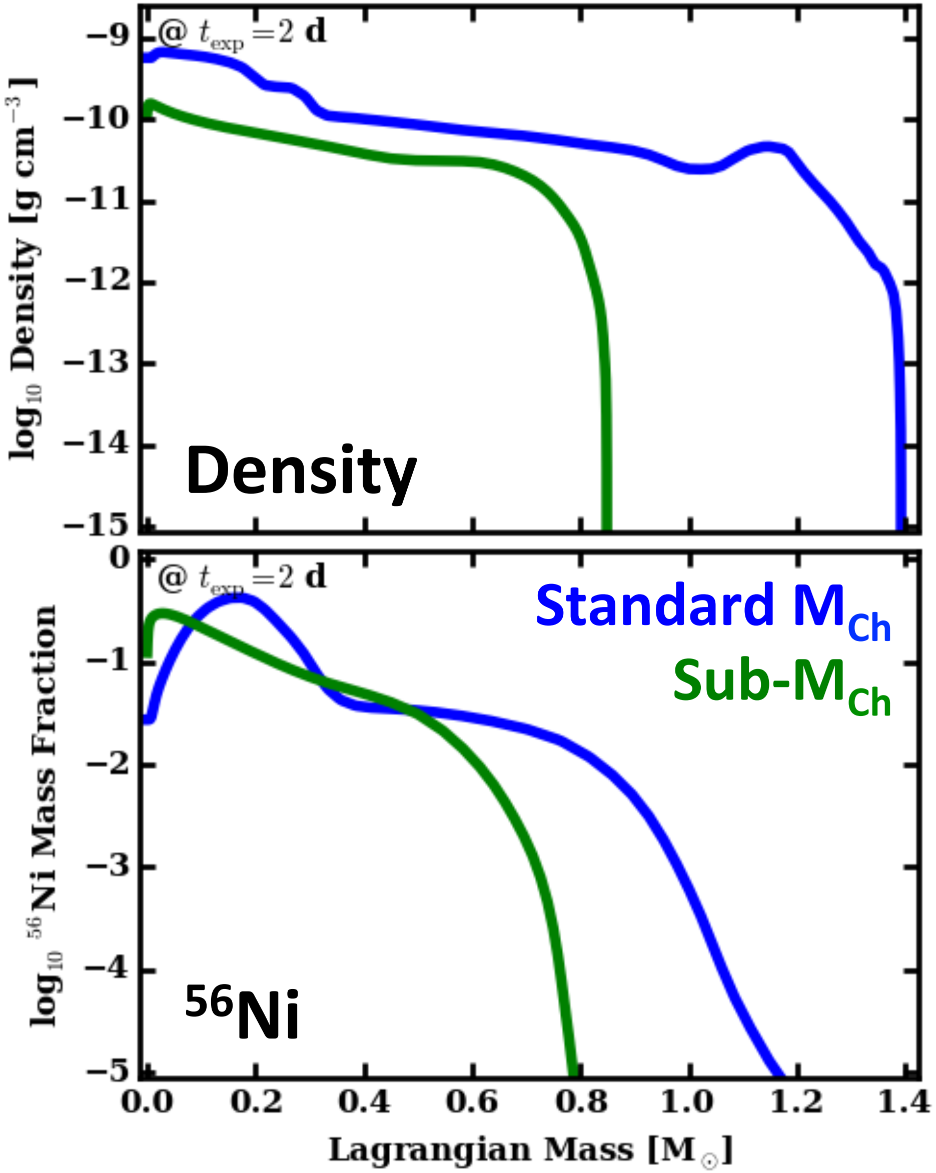
- ✔ bluer spectra
- ✔ unburnt C
- ✔ narrow lines

Pulsating Delayed-Detonation Models

Better match to the nearby ***SN 2011fe***



Sub-Chandrasekhar-Mass Models



Pure detonation of **sub-M_{Ch} WD**

Model	**M_{tot} [$M_\odot$]**	**$M(^{56}Ni)$ [$M_\odot$]**	**E_{kin} [10^{51} erg]**
DDC25	**1.41**	**0.12**	**1.19**
SCH1p5	**0.88**	**0.08**	**0.75**

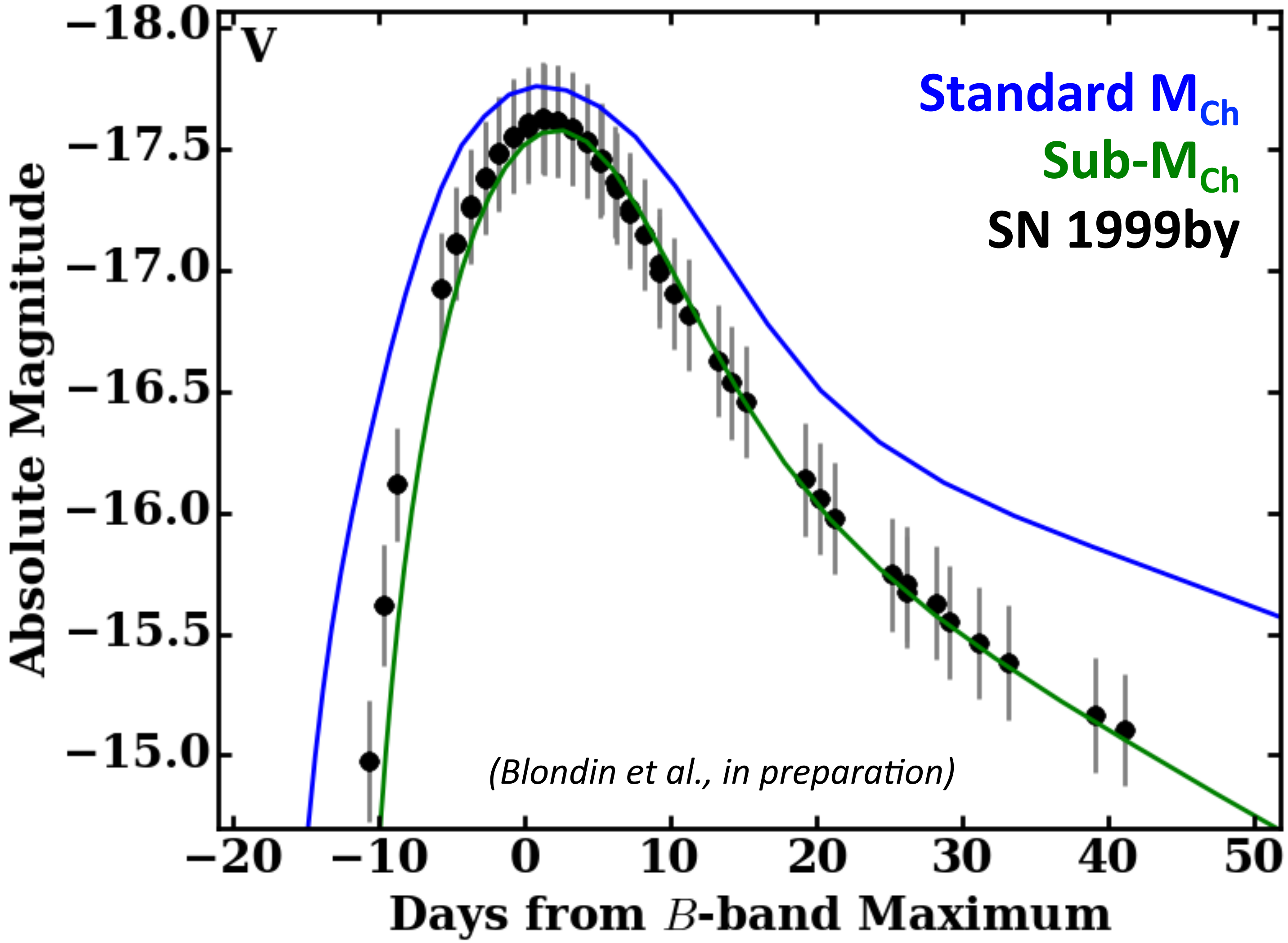
^{56}Ni extends to outermost ejecta

Impacts **light-curve evolution:**

✧ faster rise to maximum

✧ faster post-maximum decline

Sub-Chandrasekhar-Mass Models



Better match to ***subluminous events***

Conclusions & Future Work

- ✧ Standard **Chandrasekhar-mass model** matches most **normal SN Ia**
- ✧ No evidence for strong departures from **spherical symmetry**
- ✧ Pulsation/interaction produces **diversity at a given luminosity**
- ✧ Sub-luminous events appear to require **less massive progenitors**

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- ✧ Sub-luminous events appear to require **less massive progenitors**

- ✧ More realistic WD progenitors from **stellar evolution models**
- ✧ Compare 1D to **angle-averaged multi-D** explosion models

https://www-n.oca.eu/supernova/home.html