Optical properties of superluminous supernovae (Type I)

Matt Nicholl

With QUB / Oxford, PESSTO, E. Berger, P. Blanchard, T.-W. Chen, S. Gomez…

QUEEN'S UNIVERSITY BELFAST

European Research Council
Established by the European Commission

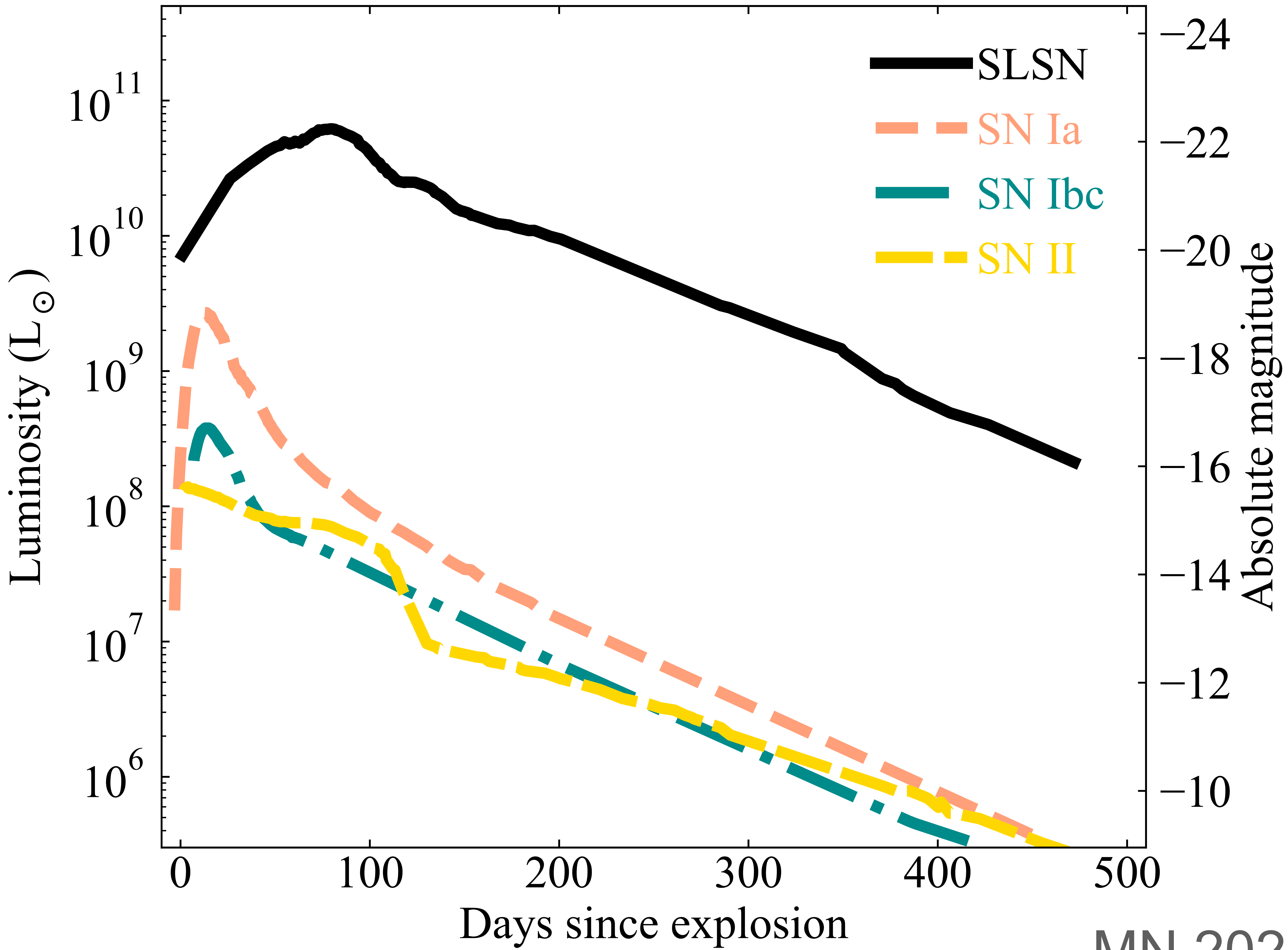
How luminous?

Originally: M_{opt} < −21 mag

- $L_{opt} \gtrsim$ few × 10^{43} erg/s
- 10 - 100 × typical SN

Long duration:

- $\int L_{opt}\, dt \sim 10^{51}$ erg
- 100 - 1000 × typical SN
- Comparable to kinetic energy



MN 2021

Surprisingly elusive

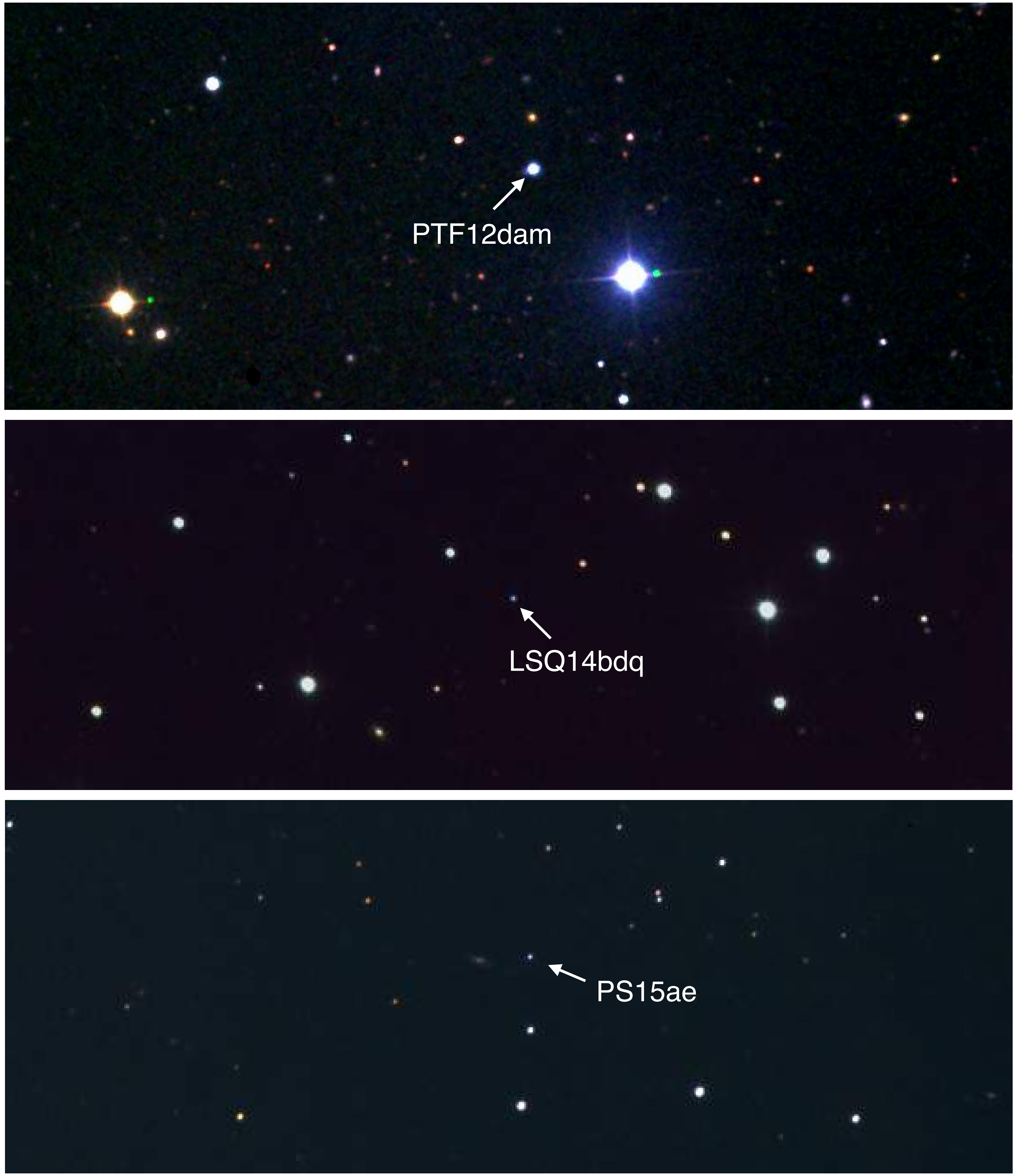
Visible to z ~ 0.5 with 1m survey telescope

But only discovered in ~2010

Reason 1: low rate

1 per 10^3-10^4 SNe by volume

(<1 per 100 SNe detected)

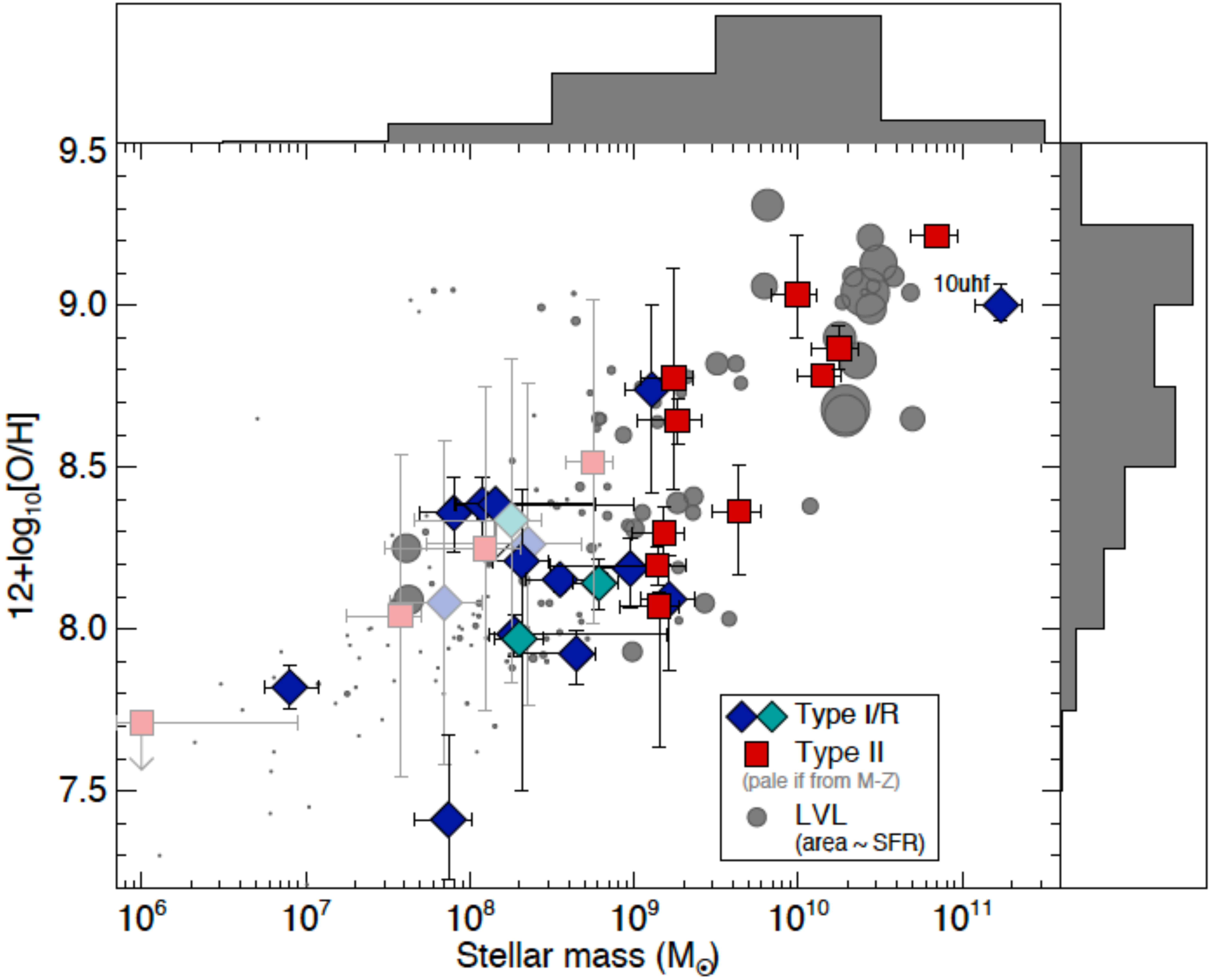


Host galaxies

Reason 2:

Faint galaxies ignored by older surveys

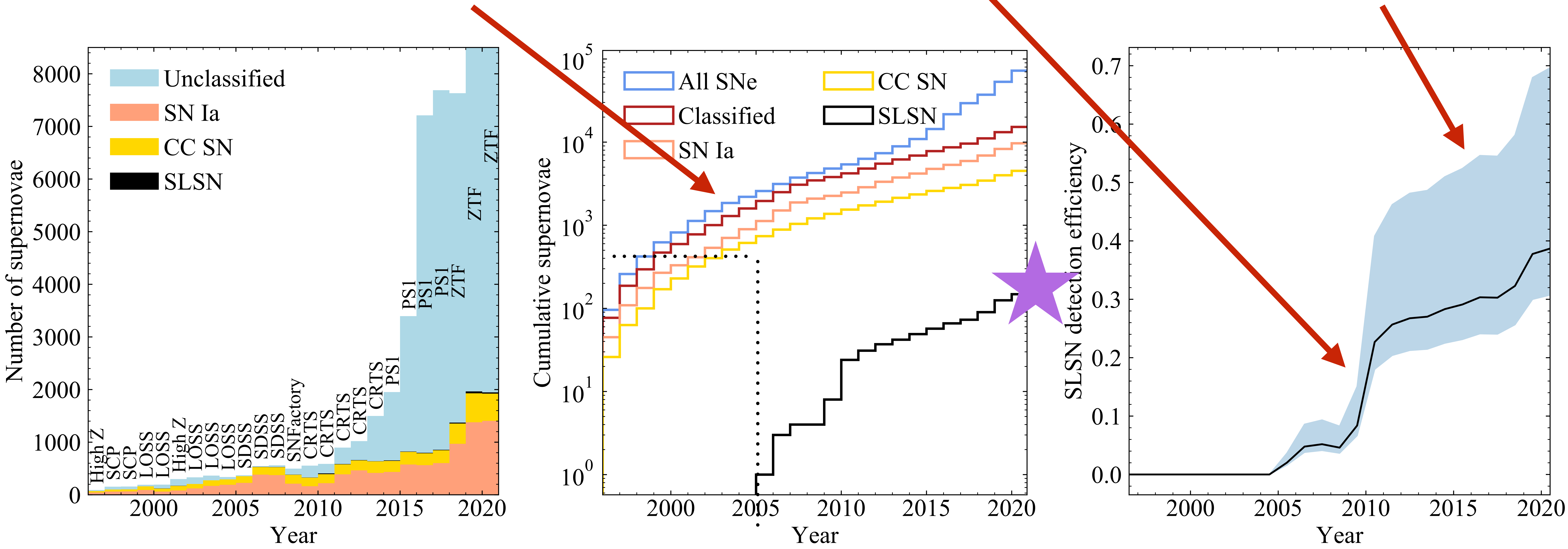
SLSNe occur in low-Z dwarf galaxies



Perley+ 2016

Today: SLSNe from wide-field surveys

Reach raw numbers… …Remove galaxy bias… …Know what to look for!



Now few hundred known SLSNe: Gomez+2024, Aamer+2025

MN 2021, using Bright Supernova page, OSC and TNS

Big questions

Short-term:

- What is the power source?
- What are the progenitors?
    - Why (almost) all at low metallicity?

Long-term:

- What does this tell us about stellar evolution?
- May be more common at high-z: early stars and galaxy evolution

Possible power sources

Large nickel mass?

- Require up to ~10 $M_\odot$ of ^{56}Ni
- Needs a very massive progenitor (PISN?)

Internally heated

Externally heated

Circumstellar interaction?

- Kinetic energy converted to thermal energy in CSM shock
- Need CSM mass comparable to ejecta mass

Central engine?

- Rapidly rotating neutron star or BH
- Similar to gamma-ray burst engine but lasting days, not seconds

(Something else???)

Superluminous supernovae *Type I*

Now defined spectroscopically

Very blue spectra, low-EW optical lines

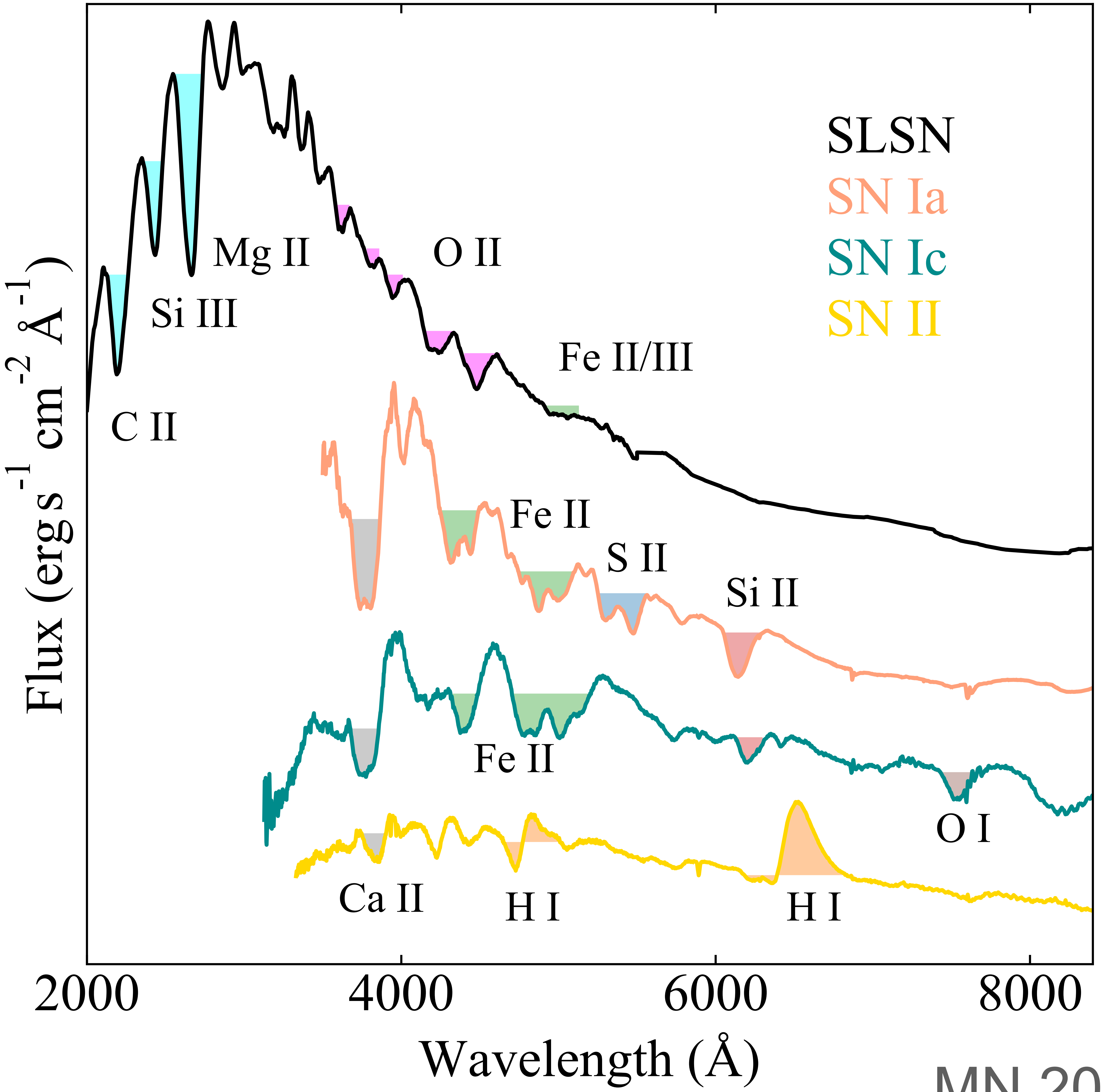
O II lines close to maximum light

- Blue + O II => hot ejecta

Some Fe III, later Fe II

Much stronger lines in NUV: IMEs such as Mg, Si, C

Note: H-rich population also exists — seem to CSM-powered (cf SNe IIn)

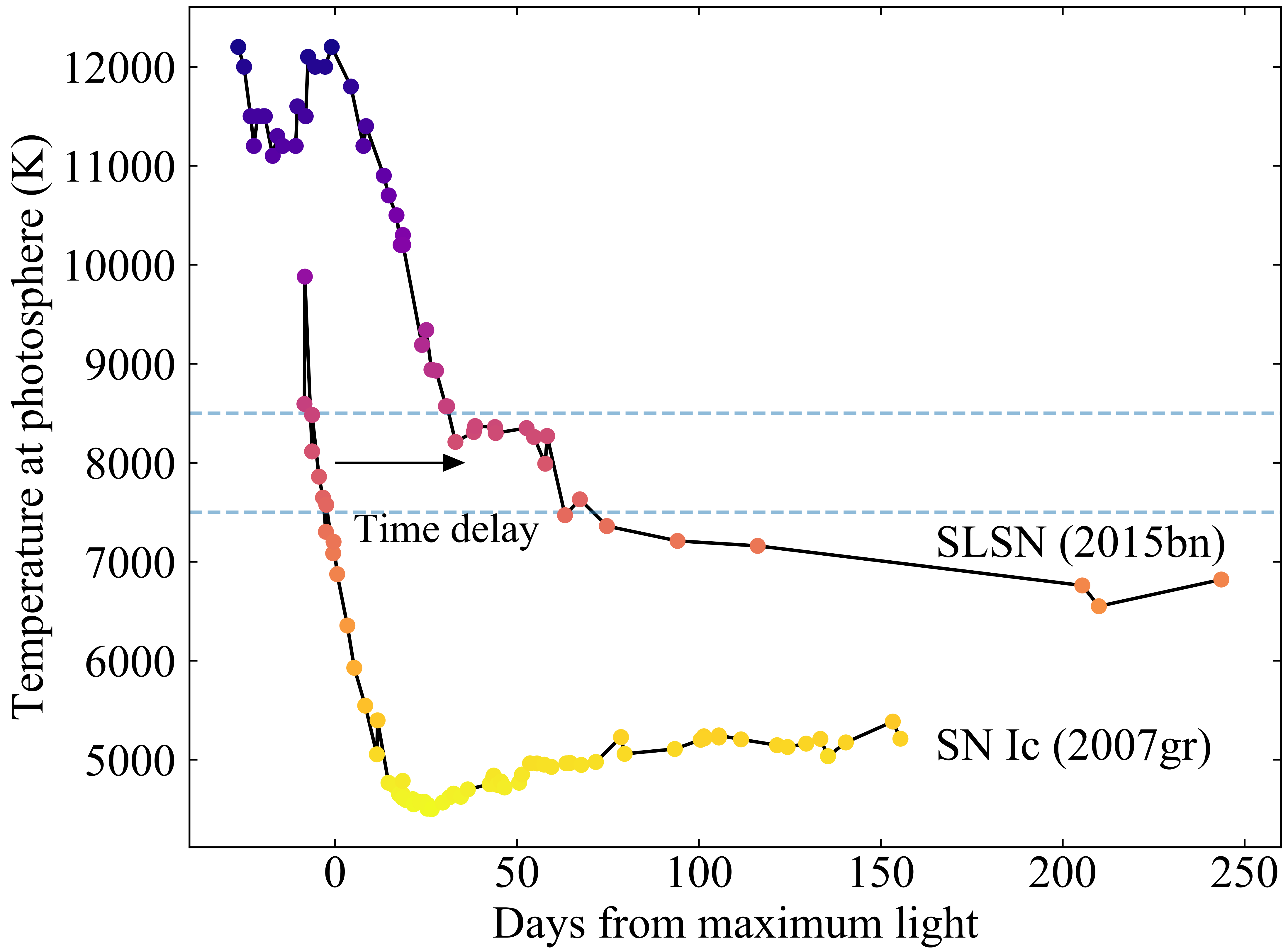


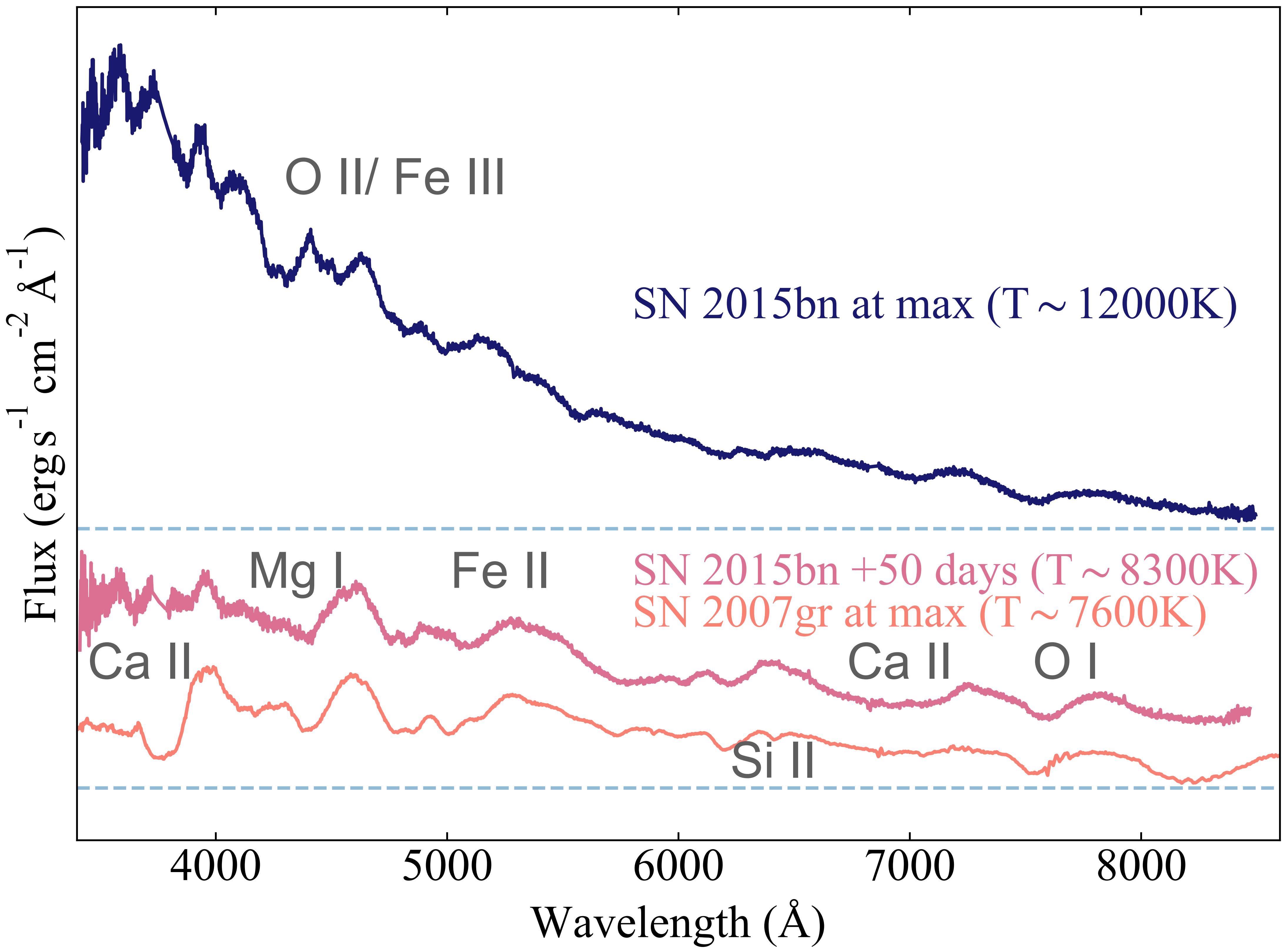
MN 2021

Superluminous, or super-hot?

By ~ few weeks after peak, temperature is same as SN Ic at peak

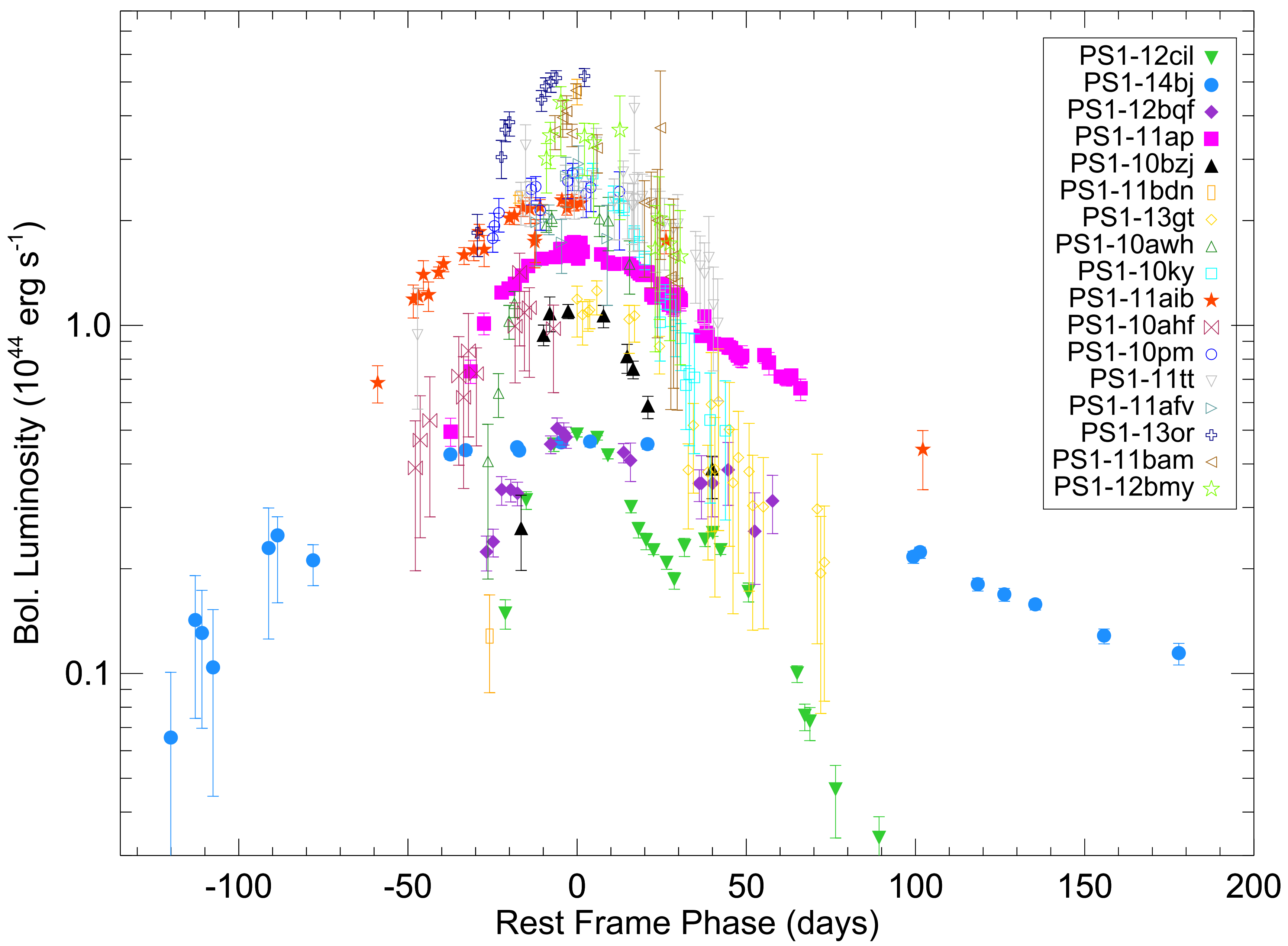
When temperature is the same, spectra are very similar!





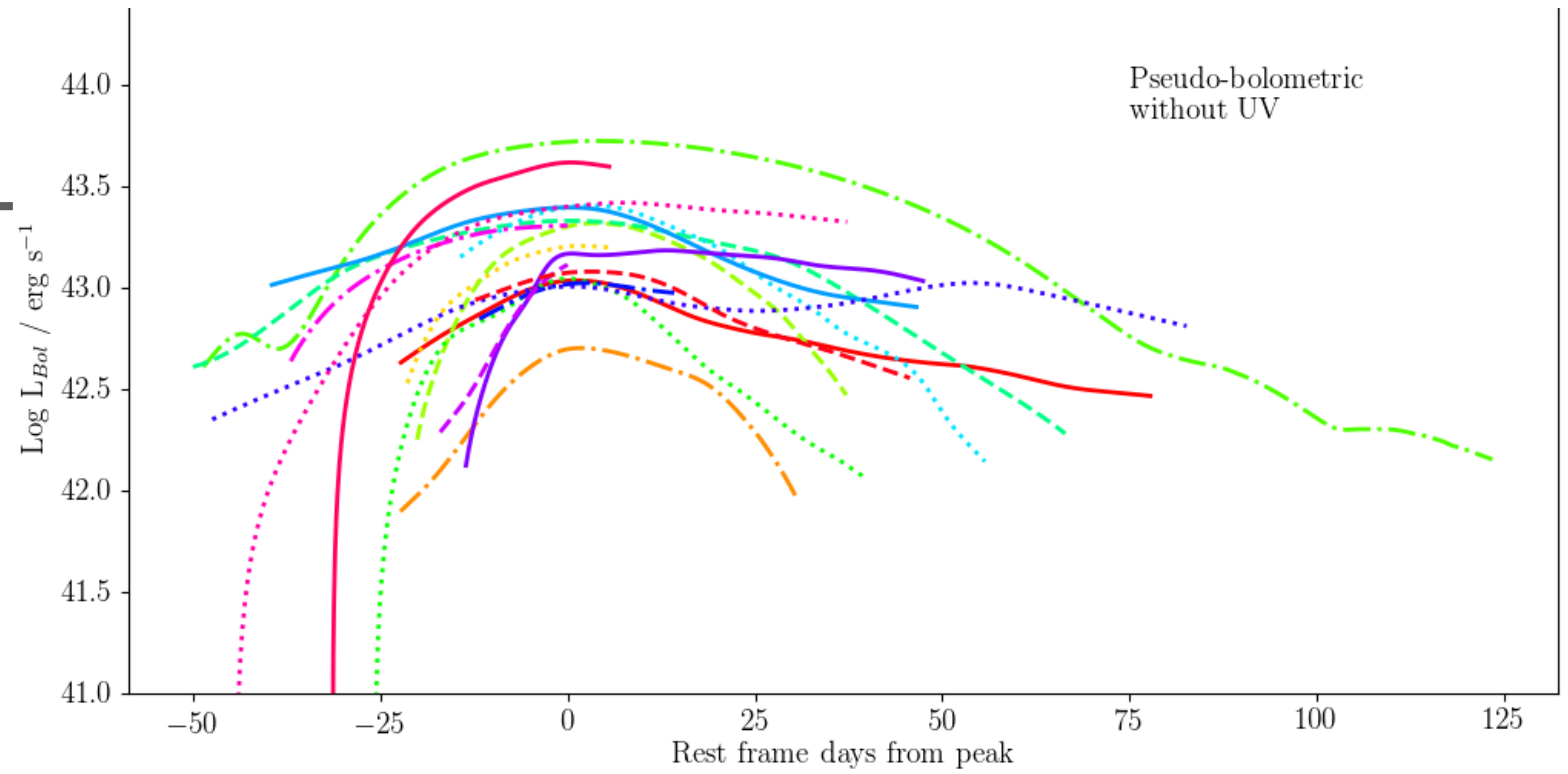
MN 2021

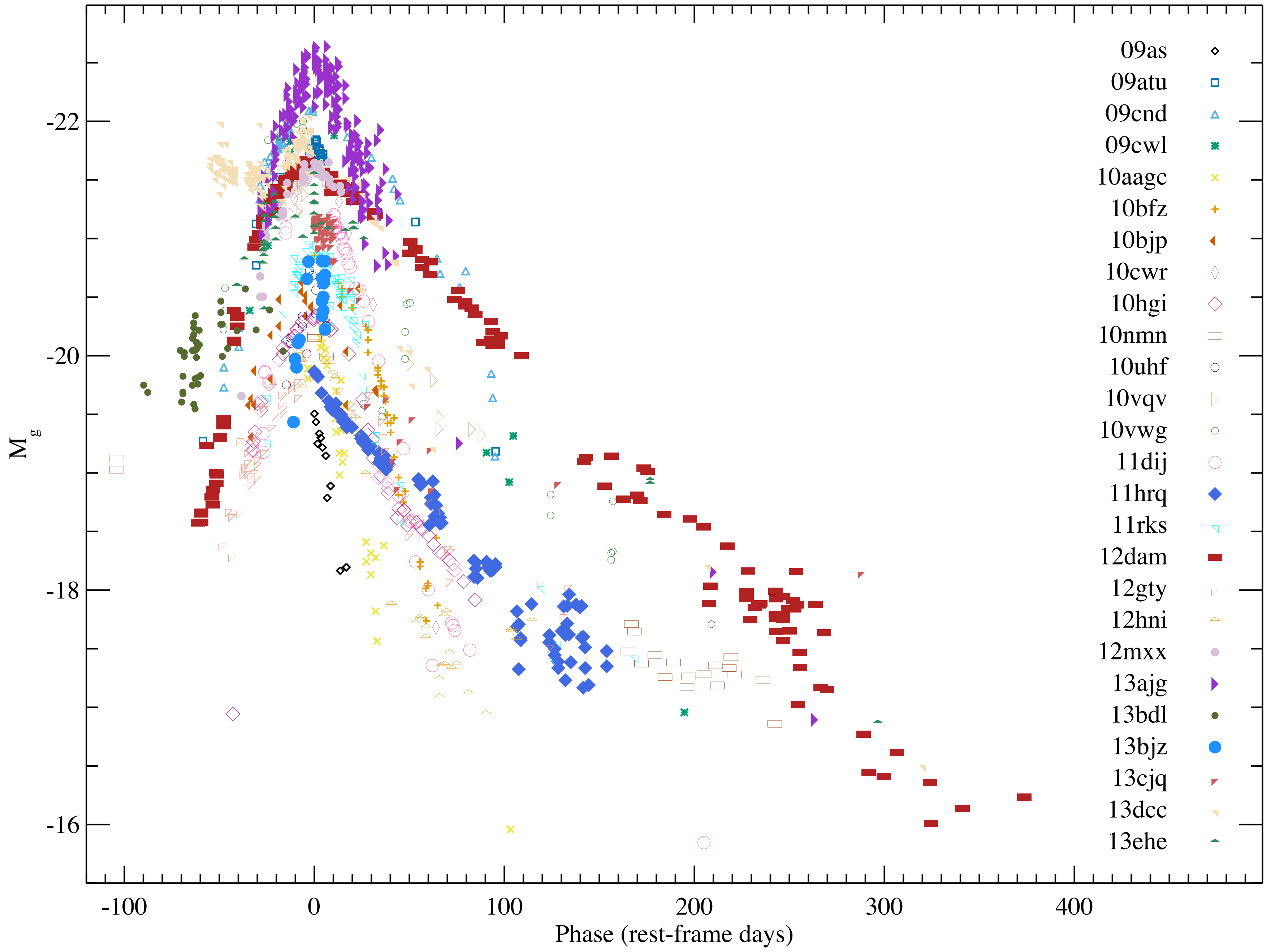
Optical light curves of SLSNe I: very diverse



PanSTARRS: Lunnan+ 2018

DES: Angus+ 2020





PTF: De Cia+ 2018

No *obvious* width-luminosity relation
(but see Inserra+ 2021)

Luminosity function: gap or continuum?

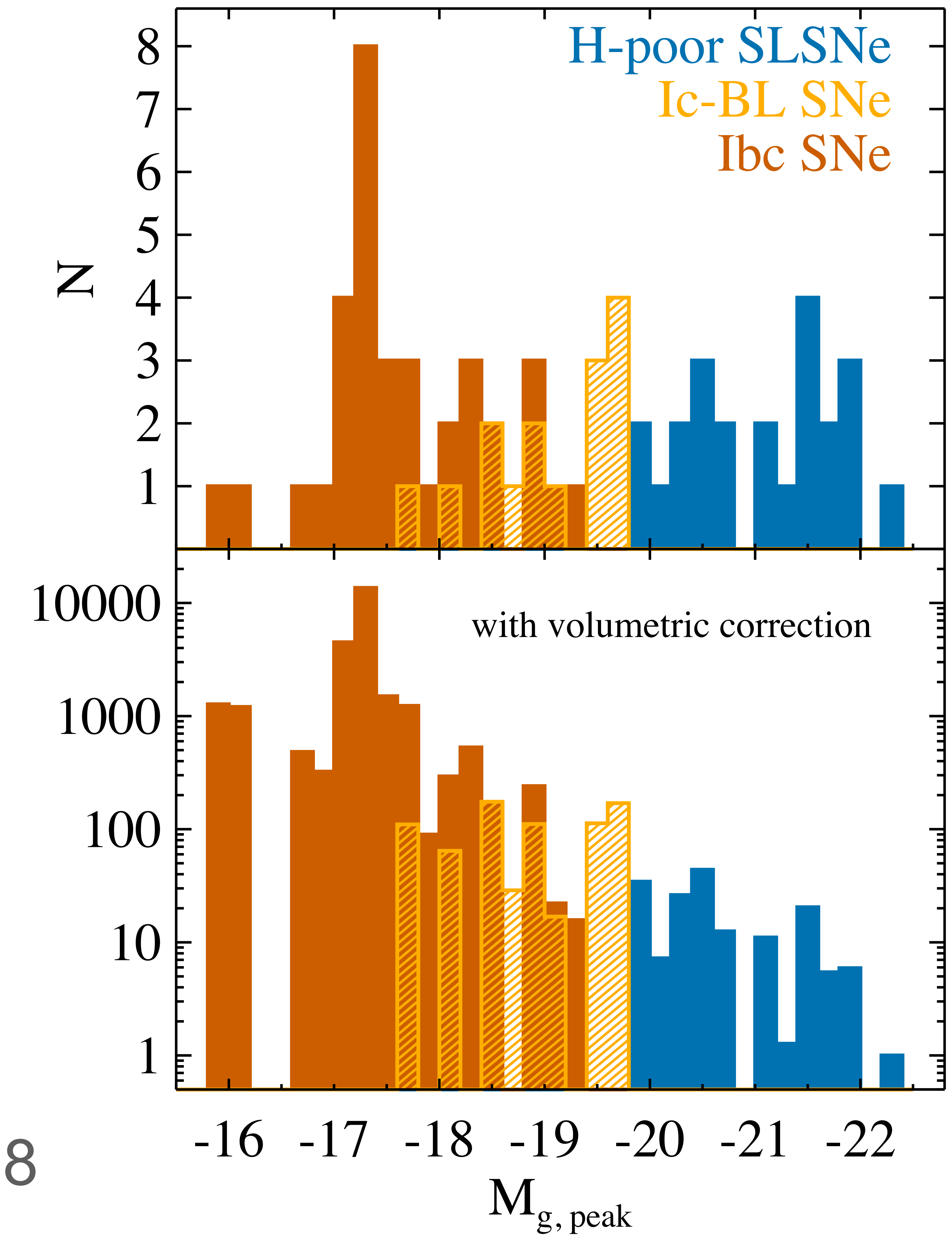
Objects with SLSN-like spectrum now seen fainter than −21 mag

If SLSNe are SNe Ic with extra heating, expect no gap between brightest SNe Ic and faintest SLSNe

- Seems to be the case in large samples

Brightest SLSNe have optical peak M ≈ −22.5 mag

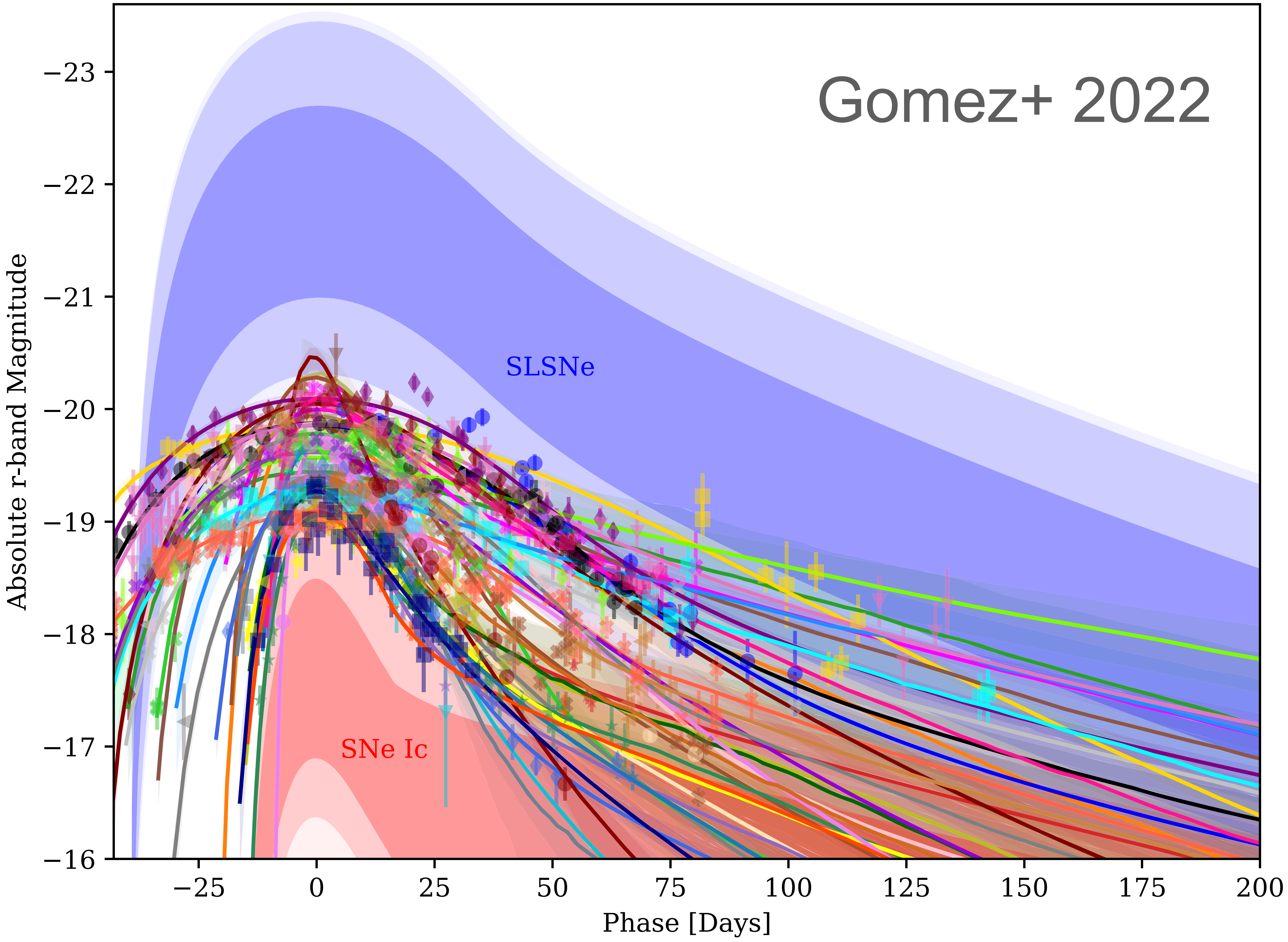
- Physical upper limit?



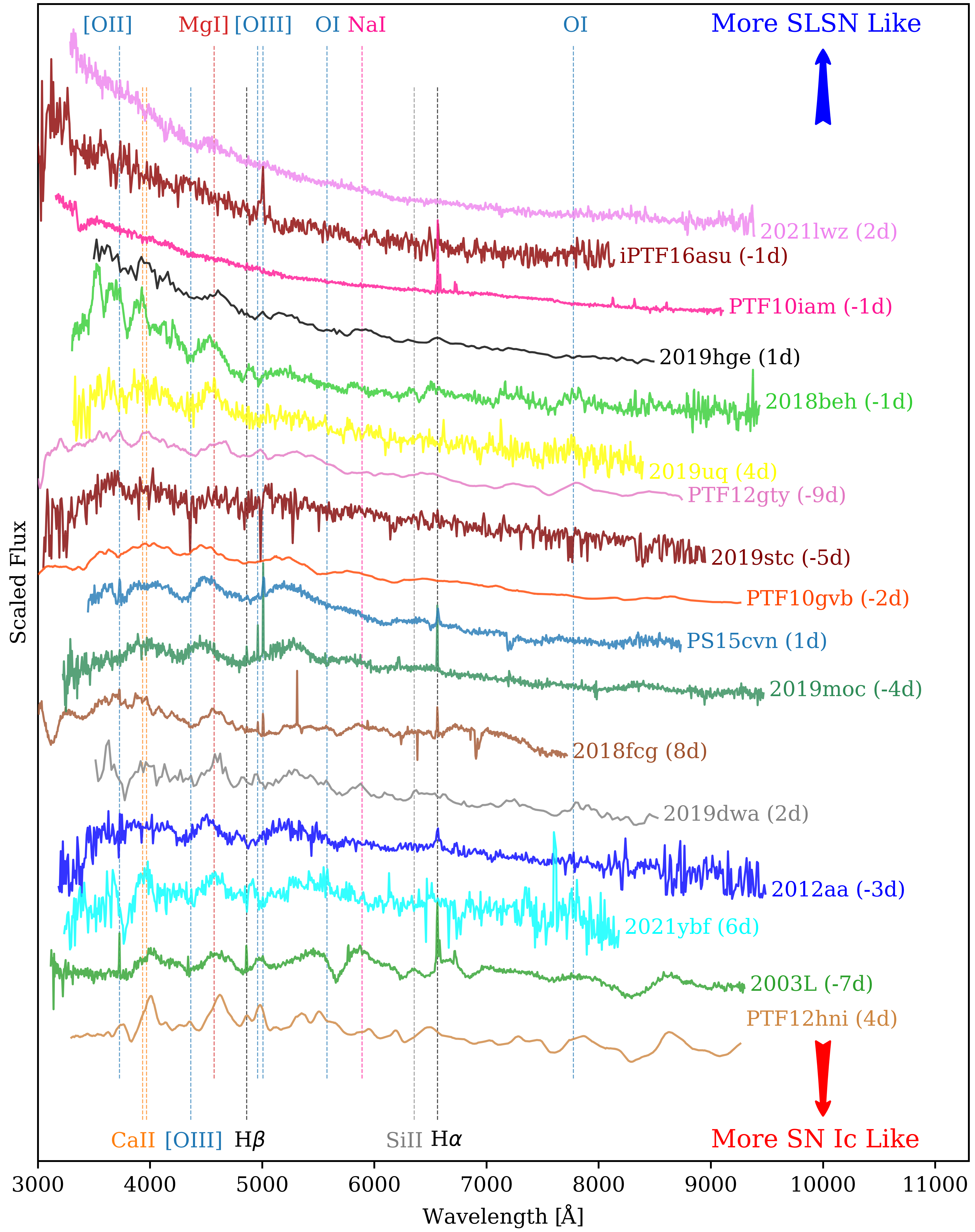
De Cia+ 2018

“Luminous” supernovae

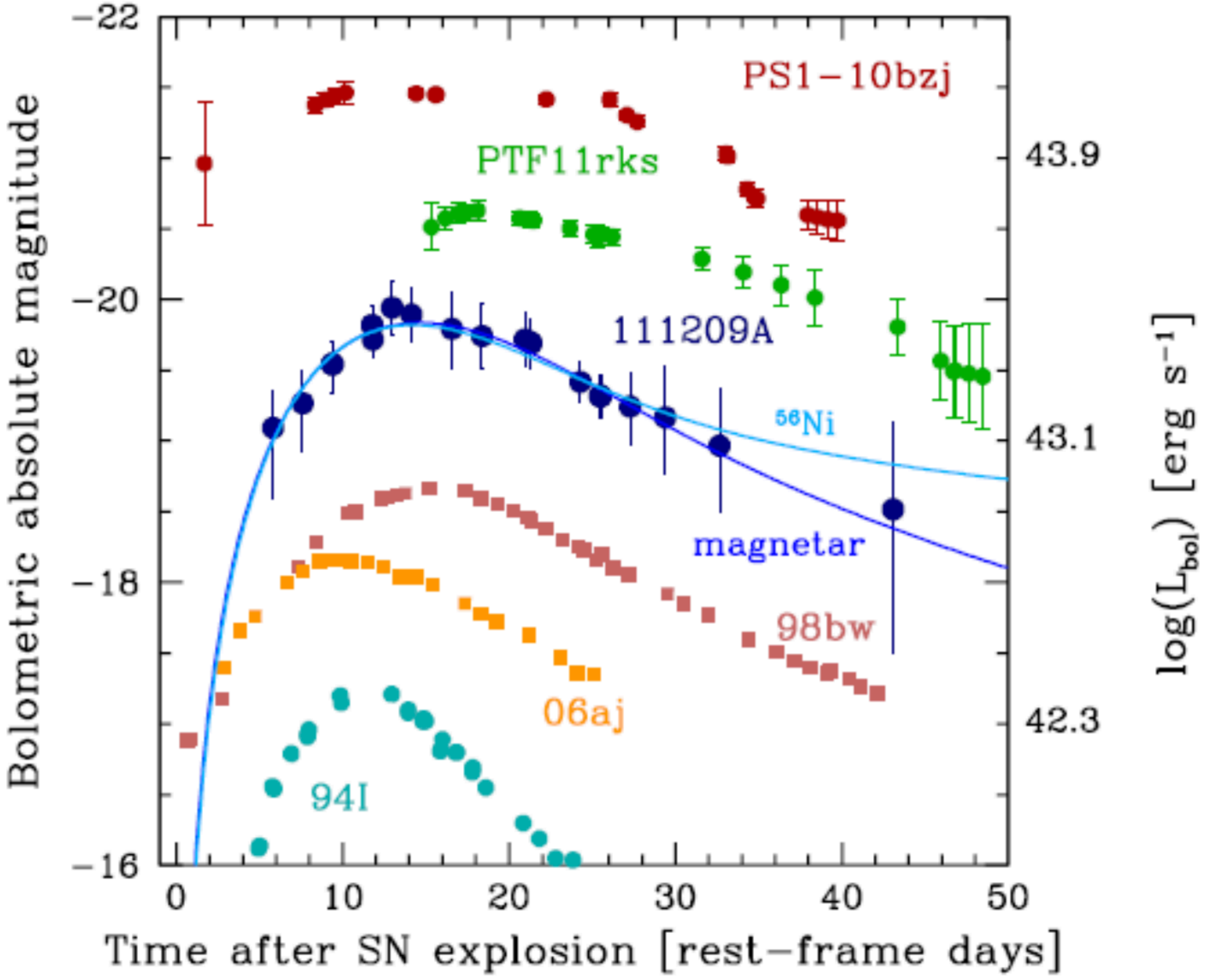
Like SLSNe, events in the ‘gap’ have wide range of timescales

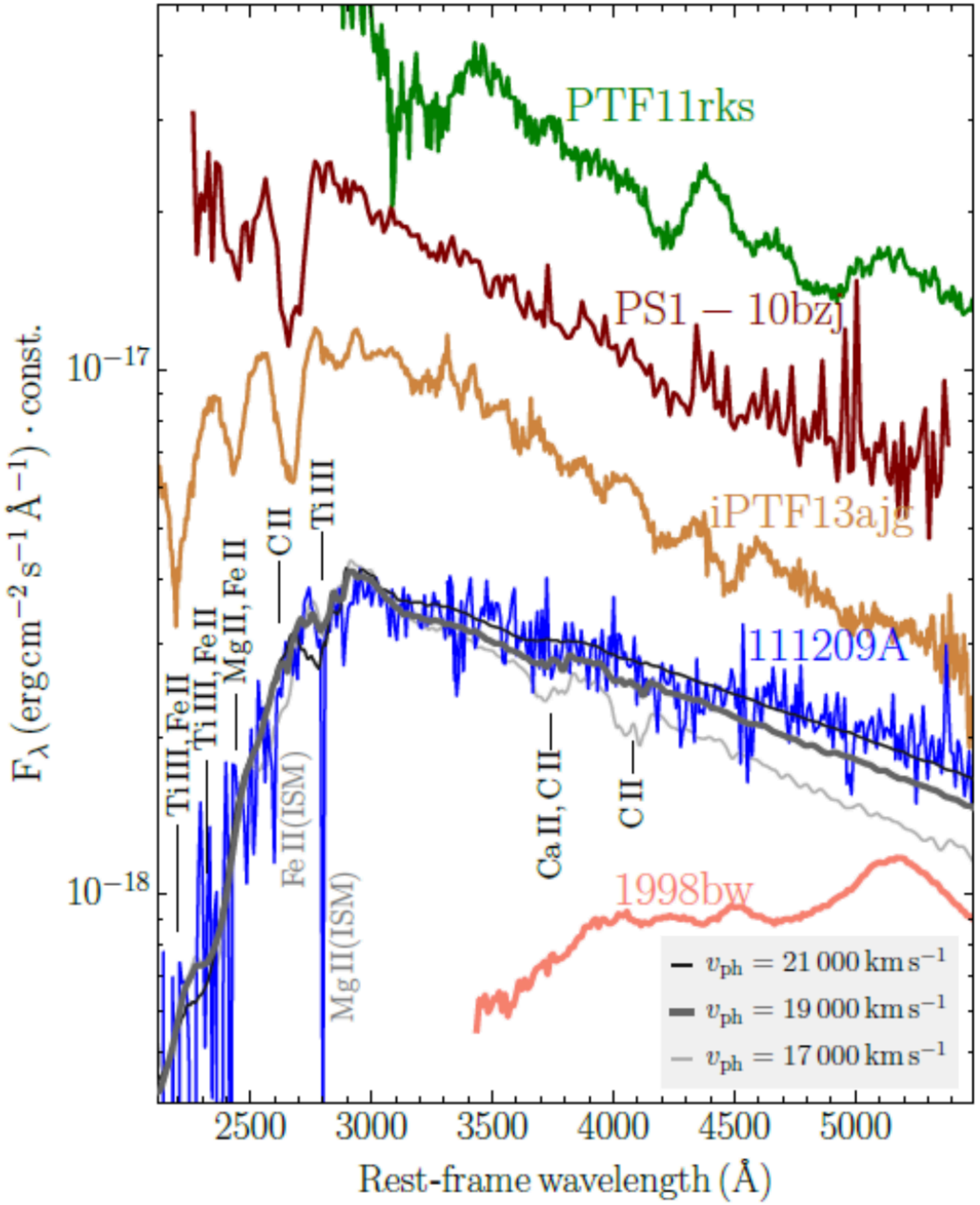


Brighter => bluer spectra



LSN 2011kl: coincident with hours-long GRB





Greiner+ 2015

“Bumps” and “wiggles”

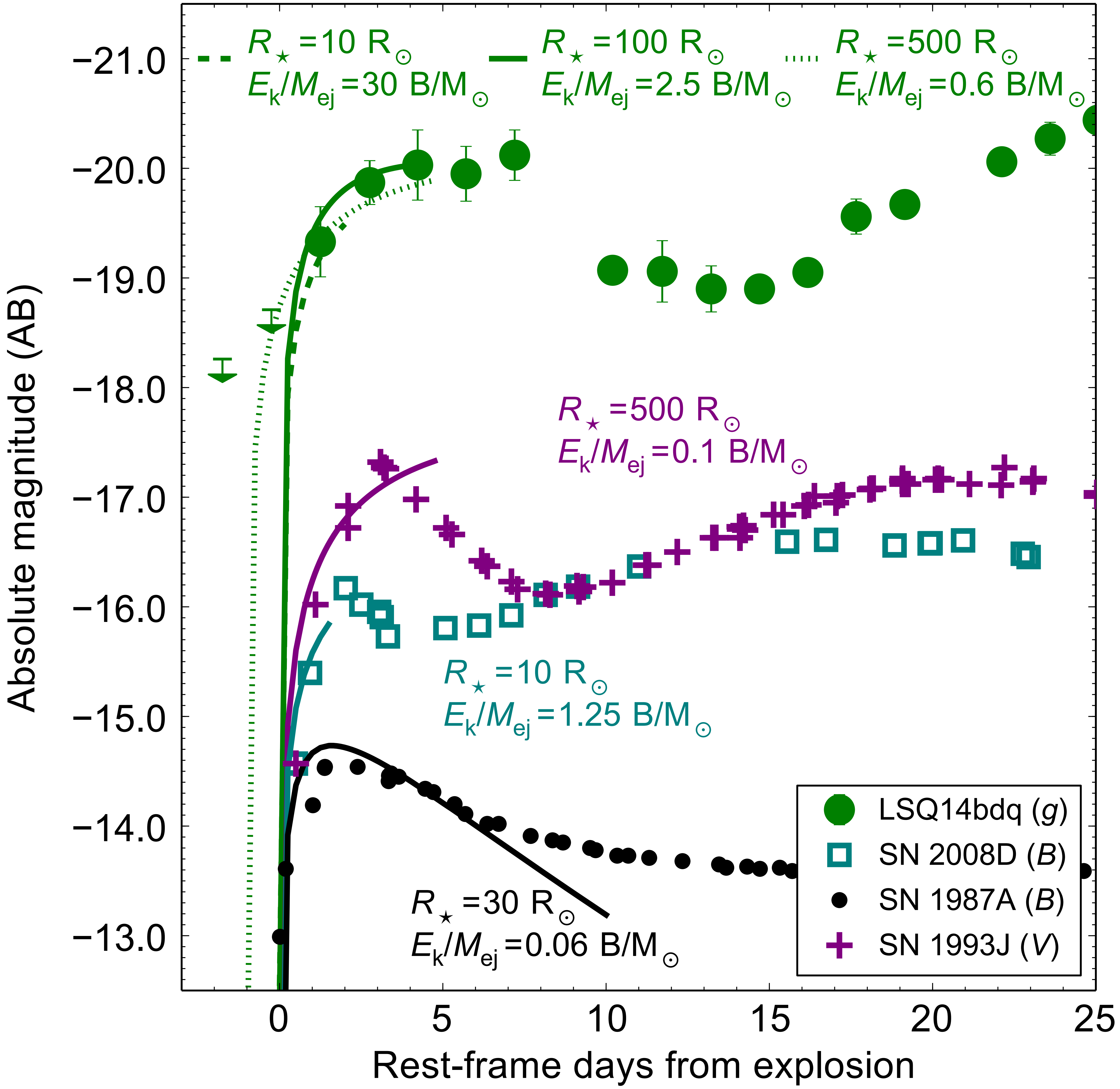
~20% (Angus+ 2020) of SLSNe have double-peaked light curves

Initial peak or ‘bump’ resembles shock cooling in e.g. SNe IIb

But very luminous!

Requires either very extended material or very high energy input per solar mass

Probes immediate environment?



MN+ 2015

“Bumps” and “wiggles”

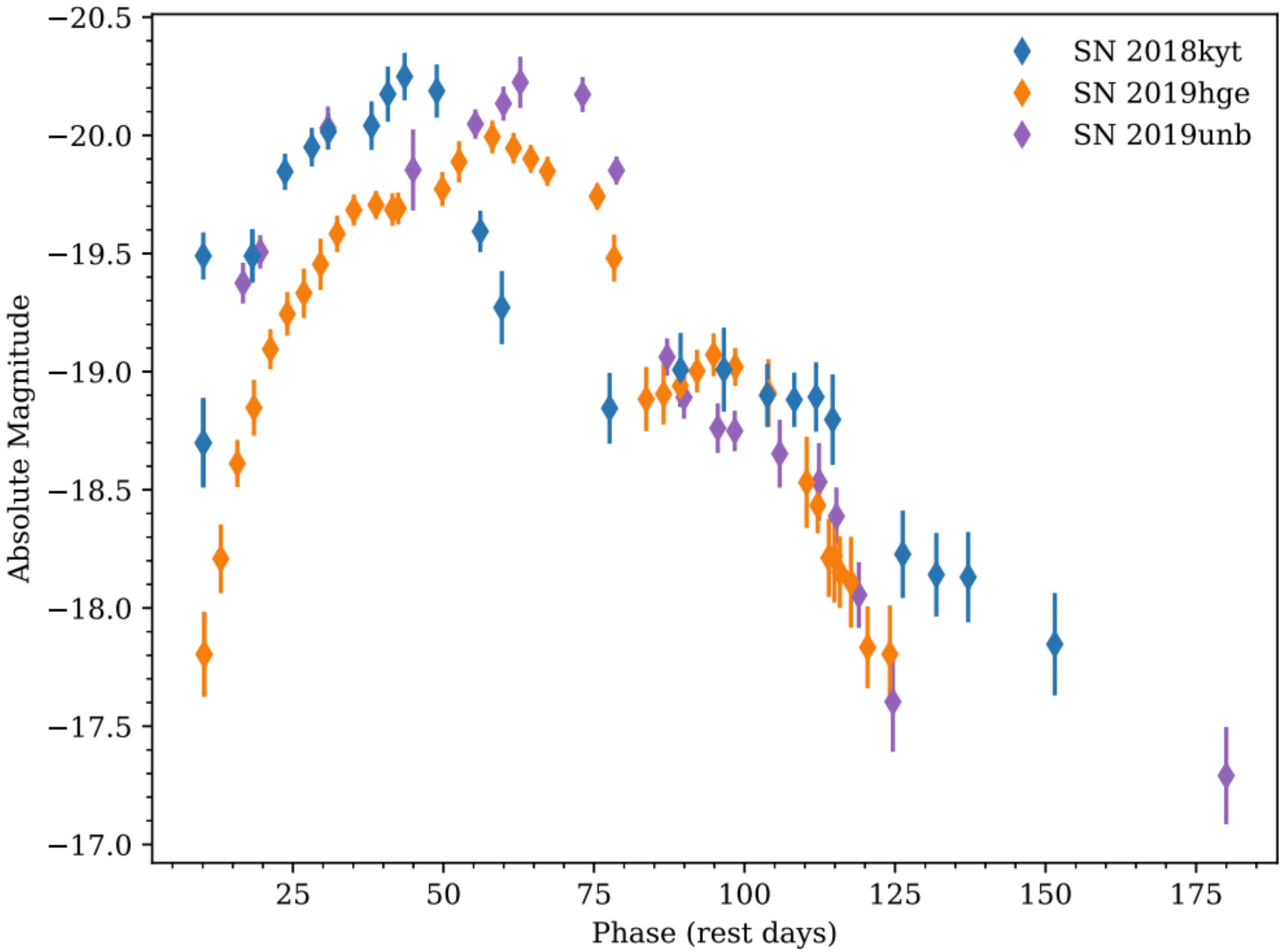
~40% show post-peak wiggles

Typically appear around ~few × t_{rise}

Changes in internal heating rate?

Ionisation breakout?

Interaction with low-mass CSM shells?



Hosseinzadeh+ 2022

The Big Data era and the SLSN Catalog

Public catalog of all known SLSNe up to 31 Dec 2022

Classifications manually verified

262 events

- 30,000 light curve points
- 974 spectra
- Consistently derived parameters (observational and physical)
- Handy functions for manipulating data

Data available at:
github.com/gmzsebastian/SLSNe

Get catalog and associated code:
`pip install slsne`

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **535**, 471–515 (2024) https://doi.org/10.1093/mnras/stae2270
Advance Access publication 2024 October 3

The Type I superluminous supernova catalogue I: light-curve properties, models, and catalogue description

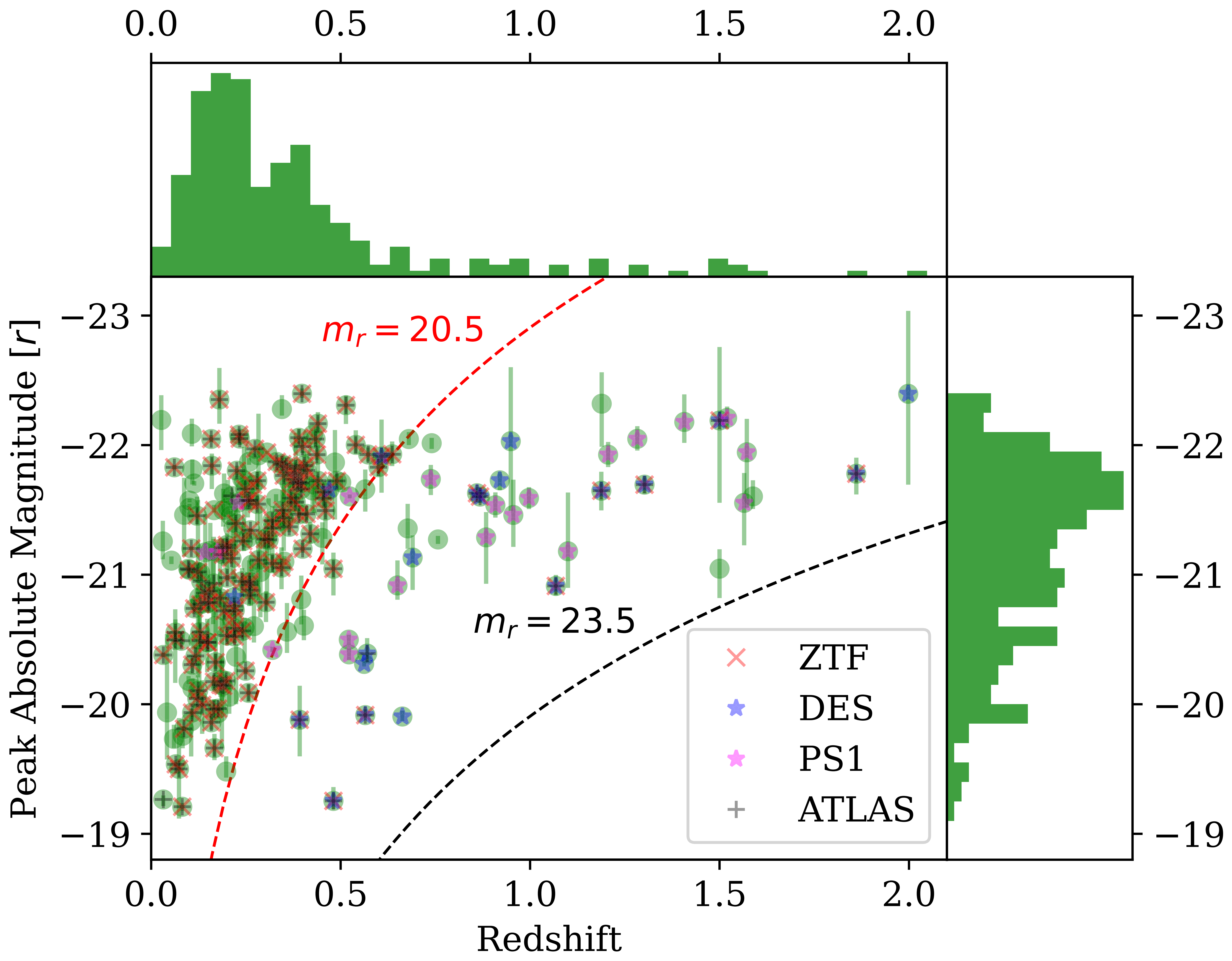
Sebastian Gomez ,[1★] Matt Nicholl ,[2★] Edo Berger ,[3,4] Peter K. Blanchard ,[3,5] V. Ashley Villar ,[3,4] Sofia Rest ,[6] Griffin Hosseinzadeh ,[7] Aysha Aamer ,[2] Yukta Ajay ,[6] Wasundara Athukoralalage ,[3] David C. Coulter ,[1] Tarraneh Eftekhari ,[5†] Achille Fiore ,[8,9] Noah Franz ,[7] Ori Fox ,[1] Alexander Gagliano ,[3,4] Daichi Hiramatsu ,[3,4] D. Andrew Howell ,[10,11] Brian Hsu ,[7] Mitchell Karmen ,[6] Matthew R. Siebert ,[1] Réka Könyves-Tóth ,[12,13,14,15] Harsh Kumar ,[3,4] Curtis McCully ,[10] Craig Pellegrino ,[16] Justin Pierel ,[1‡] Armin Rest [6,1] and Qinan Wang [6]

ROYAL ASTRONOMICAL SOCIETY
MNRAS **541**, 2674–2706 (2025) https://doi.org/10.1093/mnras/staf1113
Advance Access publication 2025 July 10

The Type I superluminous supernova catalogue – II. Spectroscopic evolution in the photospheric phase, velocity measurements, and constraints on diversity

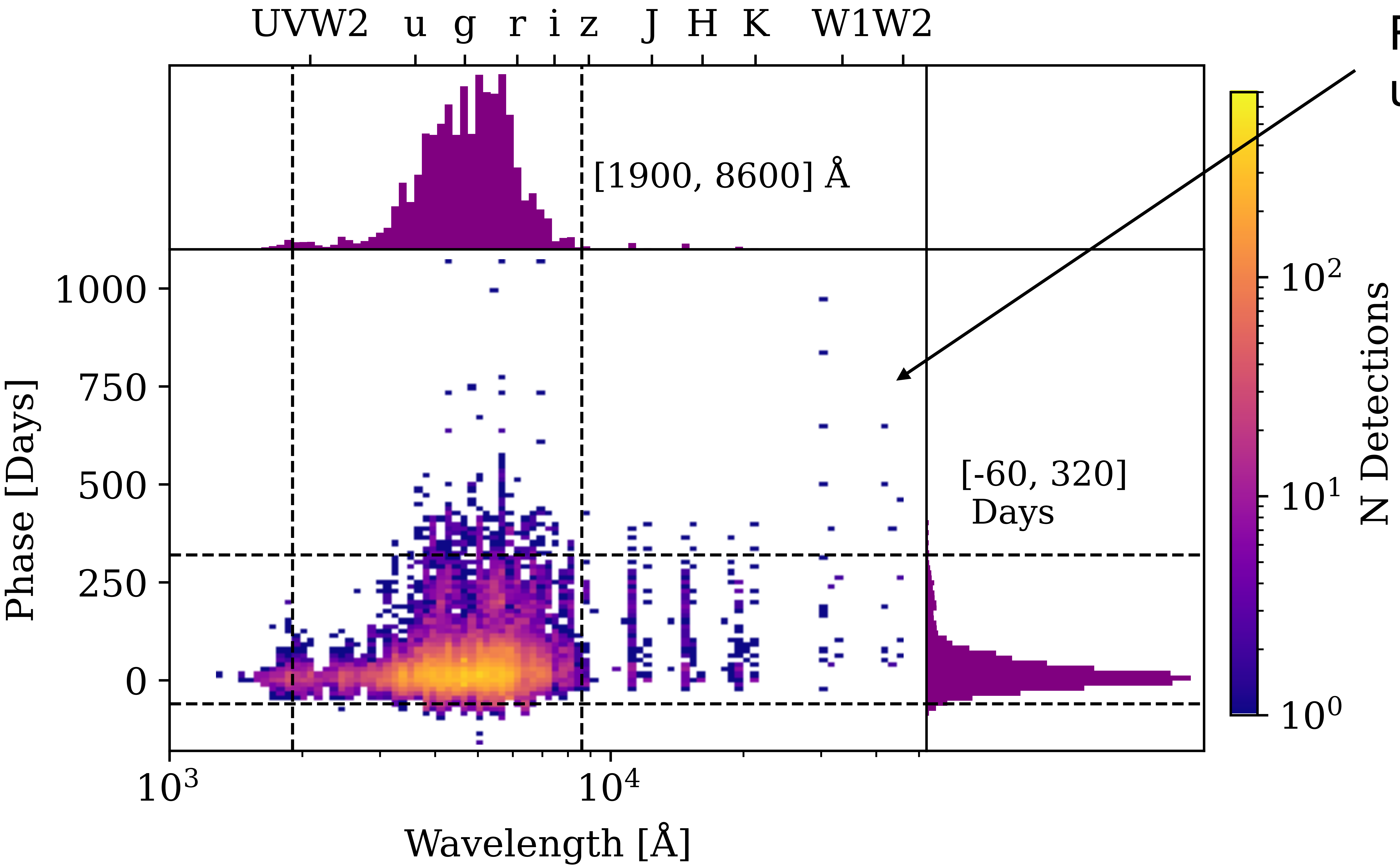
Aysha Aamer ,[1★] Matt Nicholl ,[1] Sebastian Gomez ,[2] Edo Berger ,[2,3] Peter Blanchard ,[2] Joseph P. Anderson ,[4,5] Charlotte Angus ,[1] Amar Aryan ,[6] Chris Ashall ,[7] Ting-Wan Chen ,[6] Georgios Dimitriadis ,[8] Lluís Galbany ,[9,10] Anamaria Gkini ,[11] Mariusz Gromadzki ,[12] Claudia P. Gutiérrez ,[10,9] Daichi Hiramatsu ,[2,3] Griffin Hosseinzadeh ,[13] Cosimo Inserra ,[14] Amit Kumar ,[15,16] Harsh Kumar ,[2] Hanindyo Kuncarayakti ,[17,18] Giorgos Leloudas ,[19] Paolo Mazzali,[20,21] Kyle Medler ,[7] Tomás E. Müller-Bravo ,[22,23] Mauricio Ramirez,[24,5] Aiswarya Sankar.K ,[6] Steve Schulze ,[25] Avinash Singh ,[11] Jesper Sollerman ,[11] Shubham Srivastav ,[26] Jacco H. Terwel [22] and David R. Young [1]

Redshift and magnitude distributions



Gomez+ 2024

SLSN Catalog: photometry

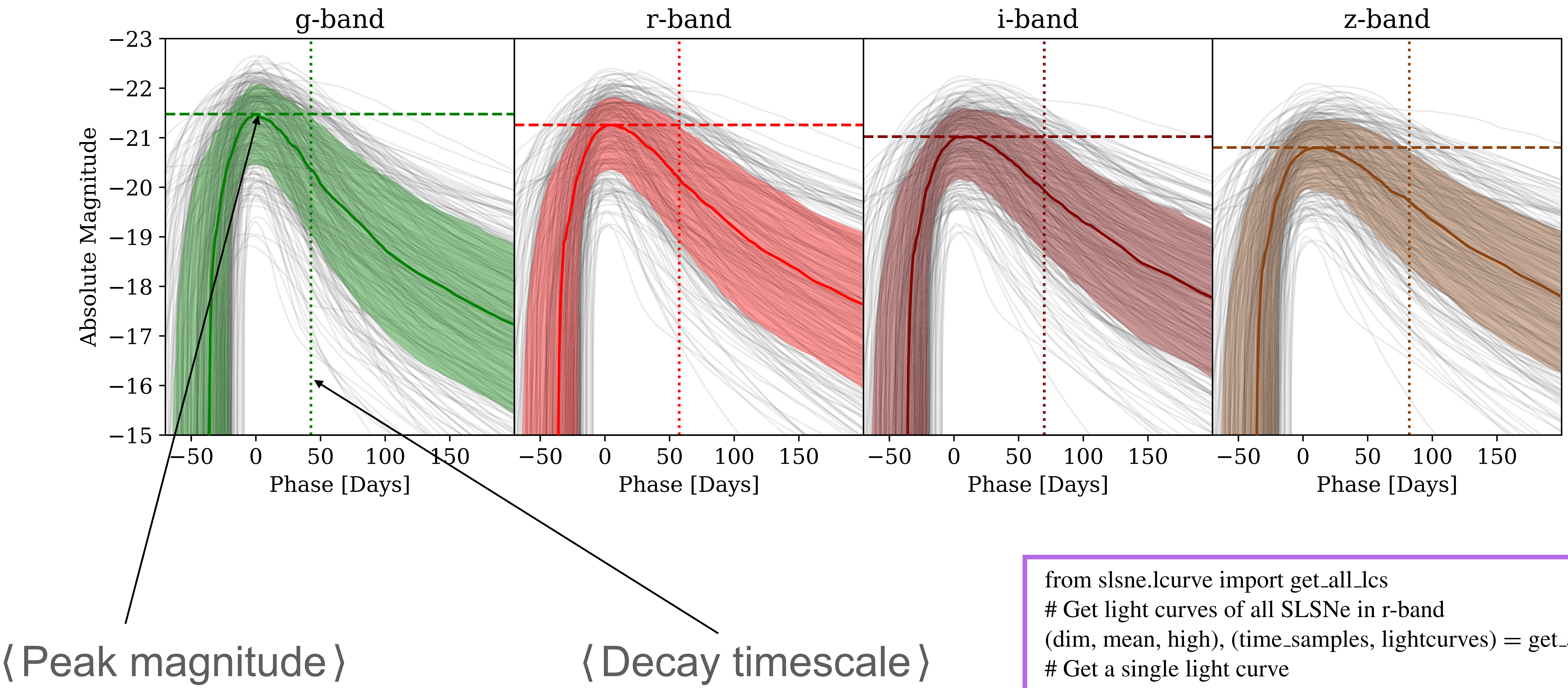


Relatively unexplored in IR

Gomez+ 2024

Light curve distributions

Gomez+ 2024




```
from slsne.lcurve import get_all_lcs
# Get light curves of all SLSNe in r-band
(dim, mean, high), (time_samples, lightcurves) = get_all_lcs('r')
# Get a single light curve
time_samples, r_2018lfe = get_all_lcs('r', names = '2018lfe')
```

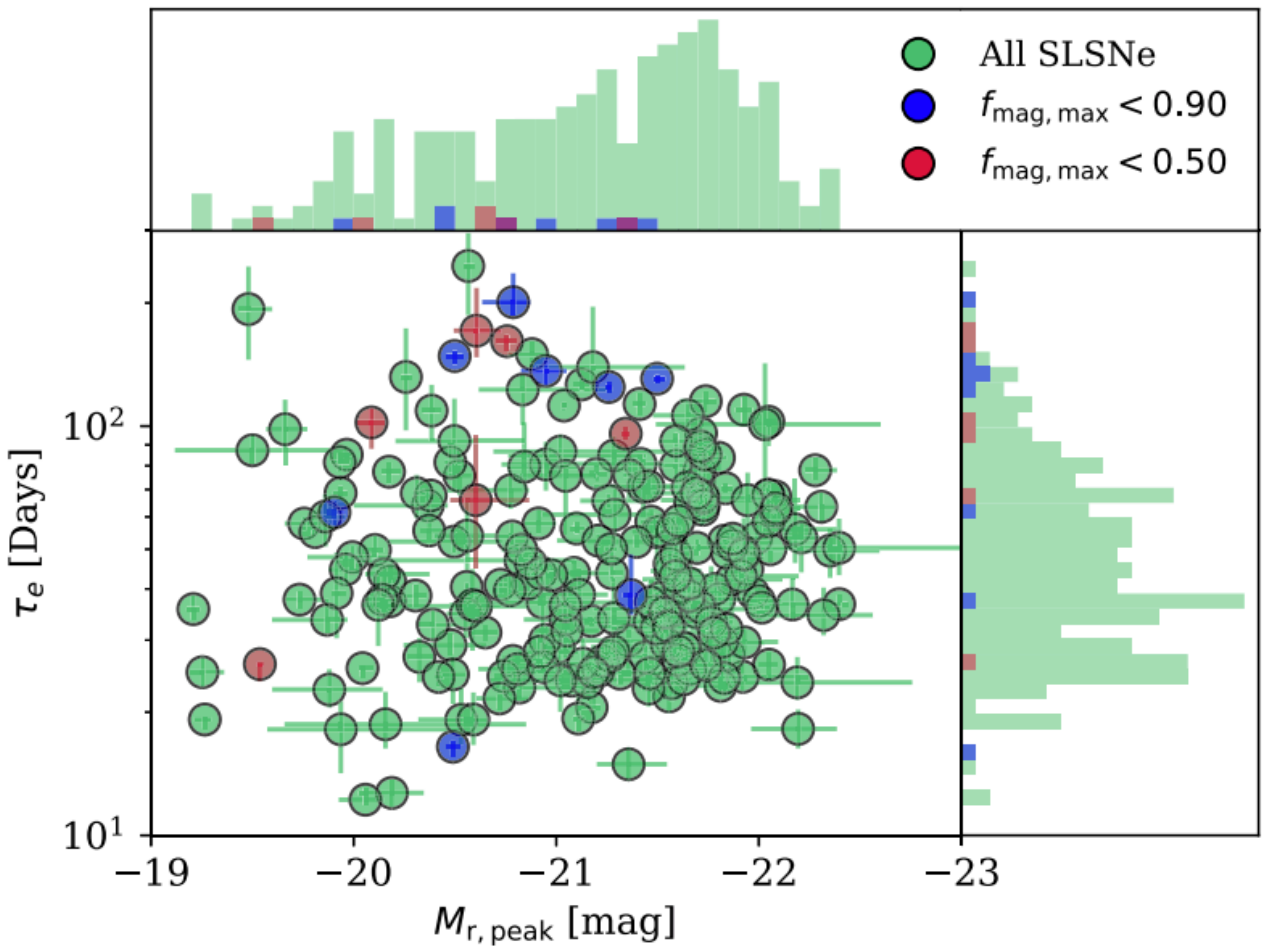
A simple but important observation

Normal SNe are heated by ^{56}Ni decay, timescale and energy per unit mass fixed

For more luminosity, need more mass

SLSNe show a *wide*, *uncorrelated* range of decline rates and luminosities

- Not all SLSNe can be powered by Ni
- It is *required observationally* that the true power source has at least one more degree of freedom than Ni: separate normalisation and duration



Gomez+ 2024

But not too much freedom!

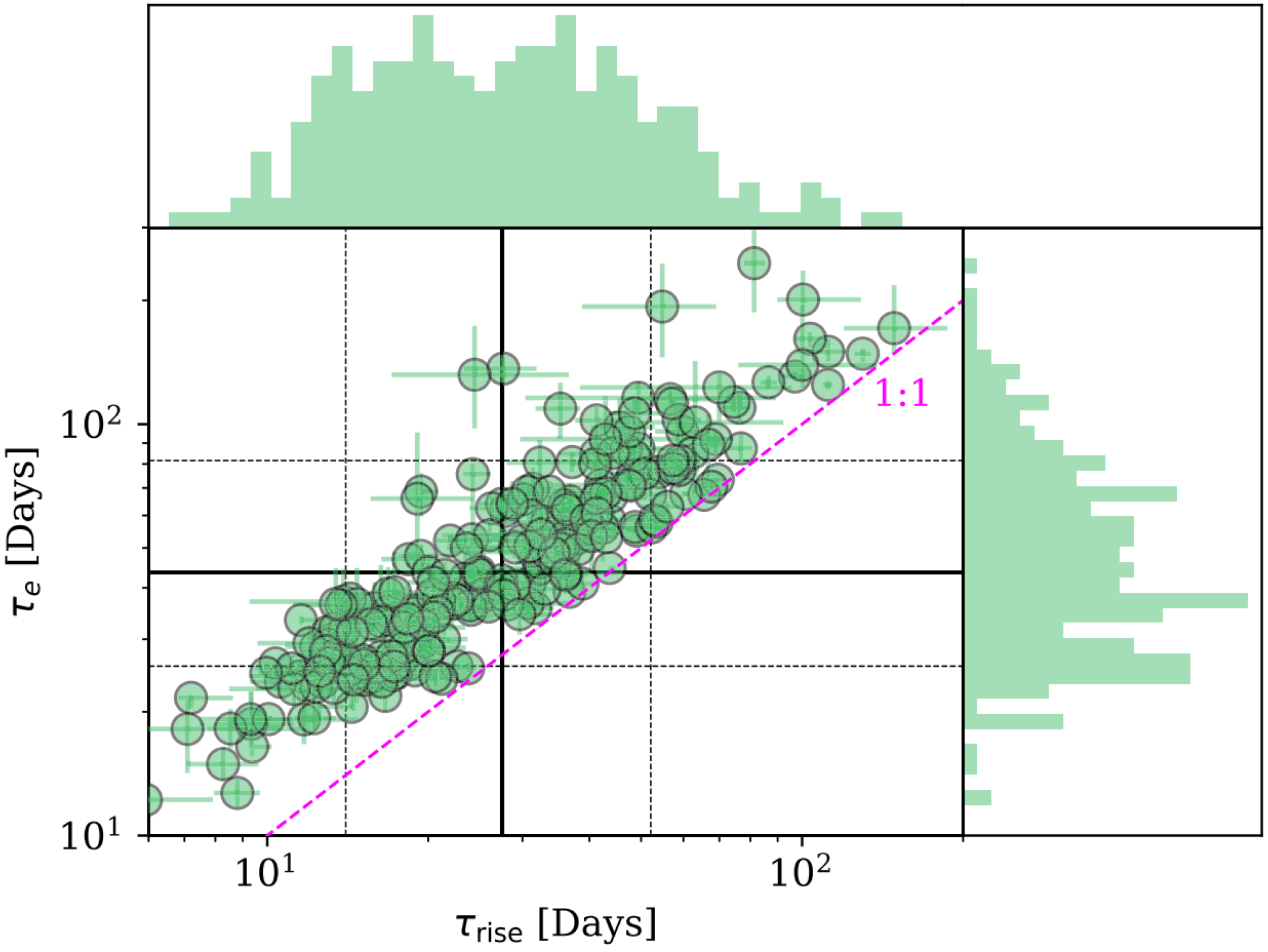
Light curves have similar intrinsic shape

Fade time ~1.5–2 × rise time

Natural in centrally-powered models

CSM models are more flexible

Gomez+ 2024



Light curve fits: magnetar + nickel (MOSFiT)

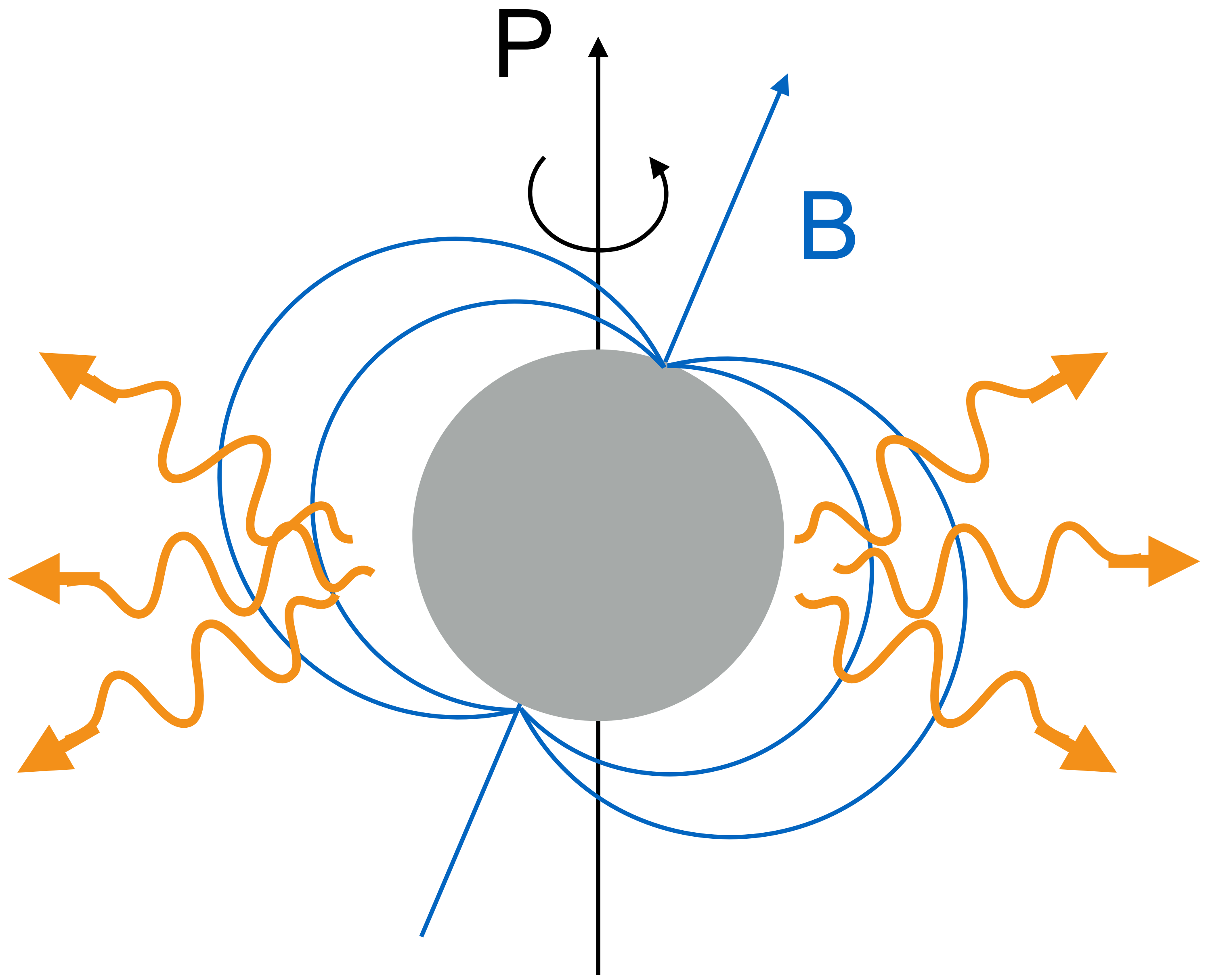
Rotational energy of millisecond magnetar
~ 10^{52} erg/s

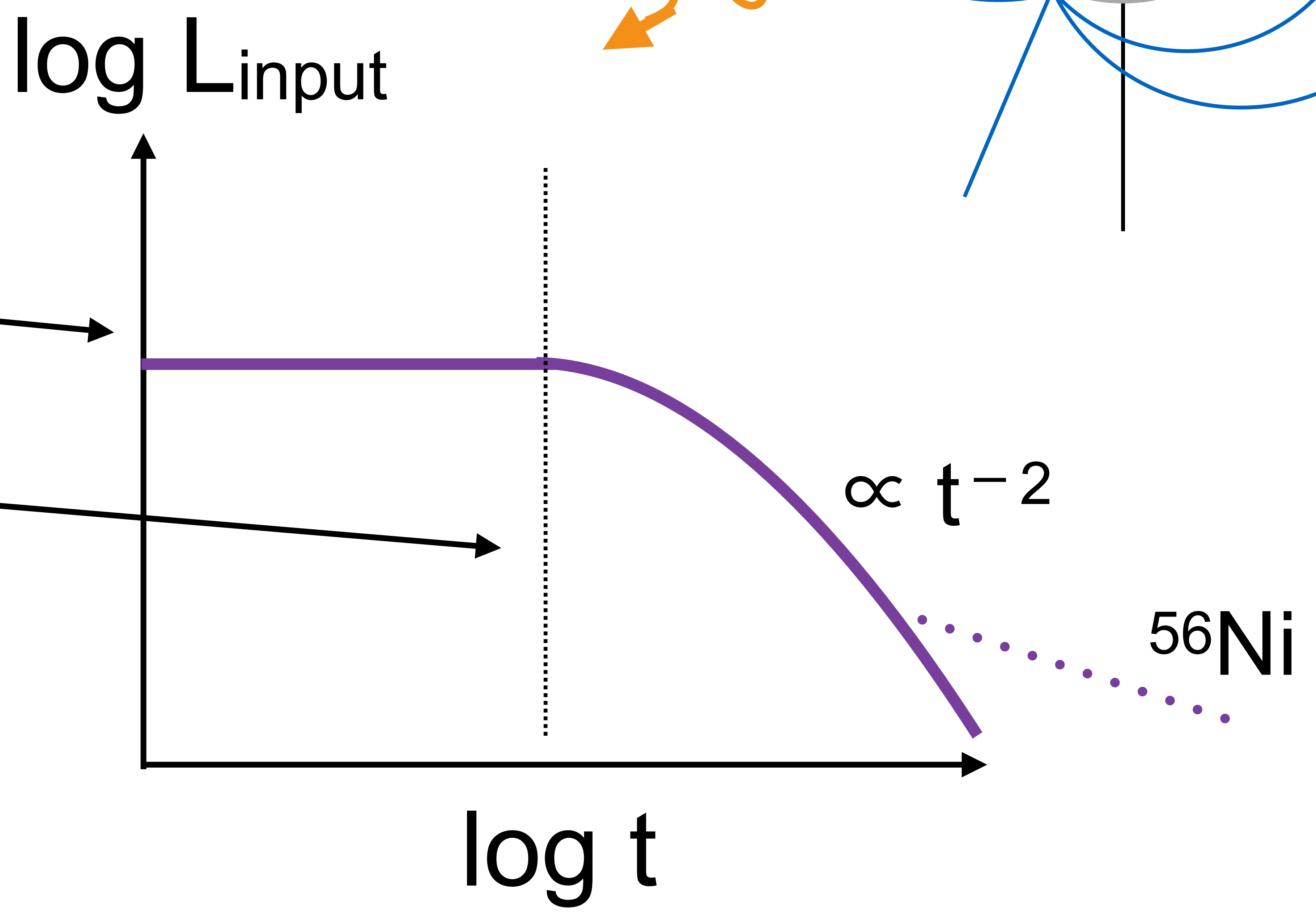
Energy extracted* via dipole spin-down
(Ostriker & Gunn 1971, Thompson+ 2004,
Kasen & Bildsten 2010, Woosley 2010…)

Power ~ B^2/P^4

Timescale ~ P^2/B^2

Arnett diffusion formalism to get mass, velocity



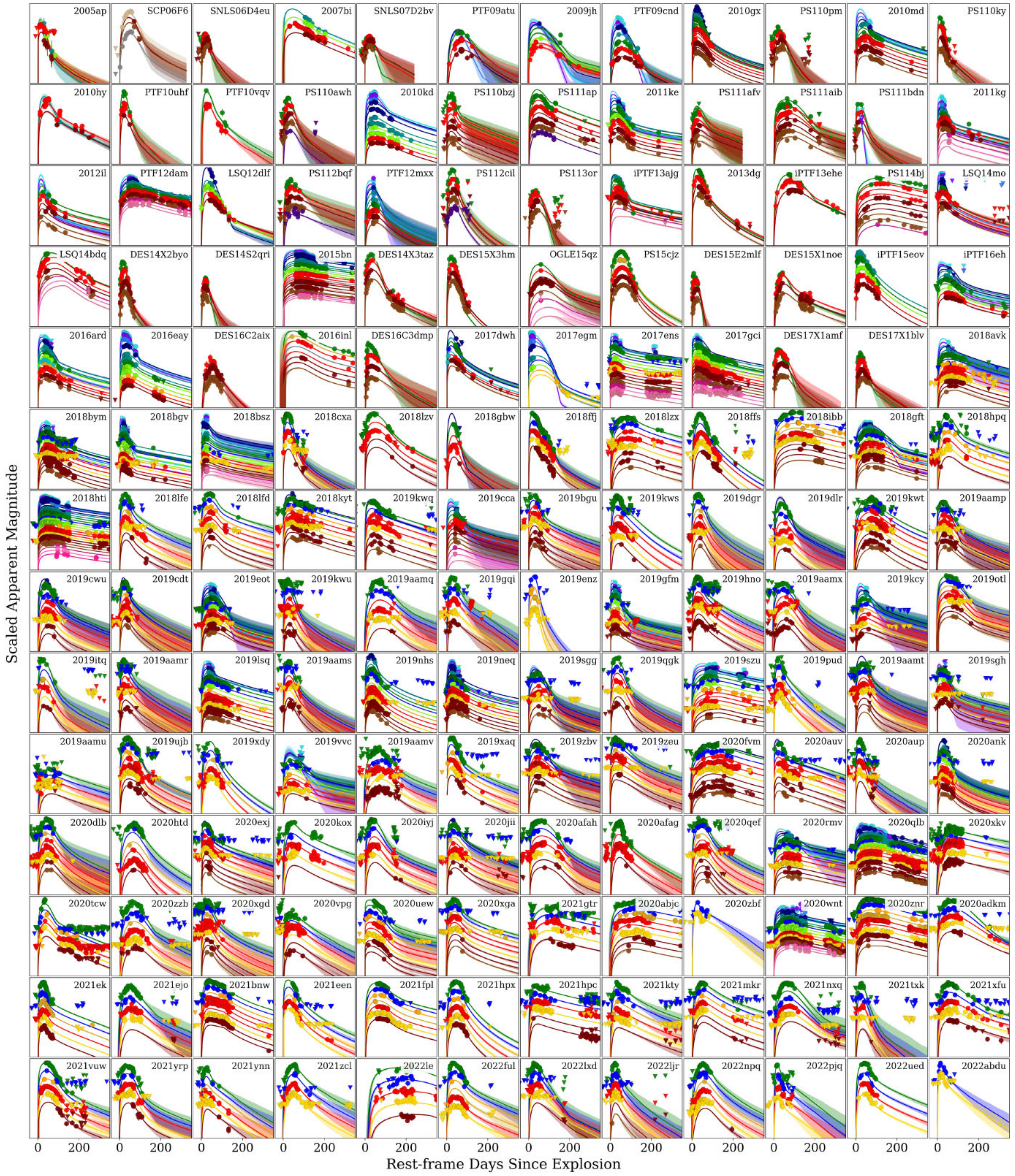


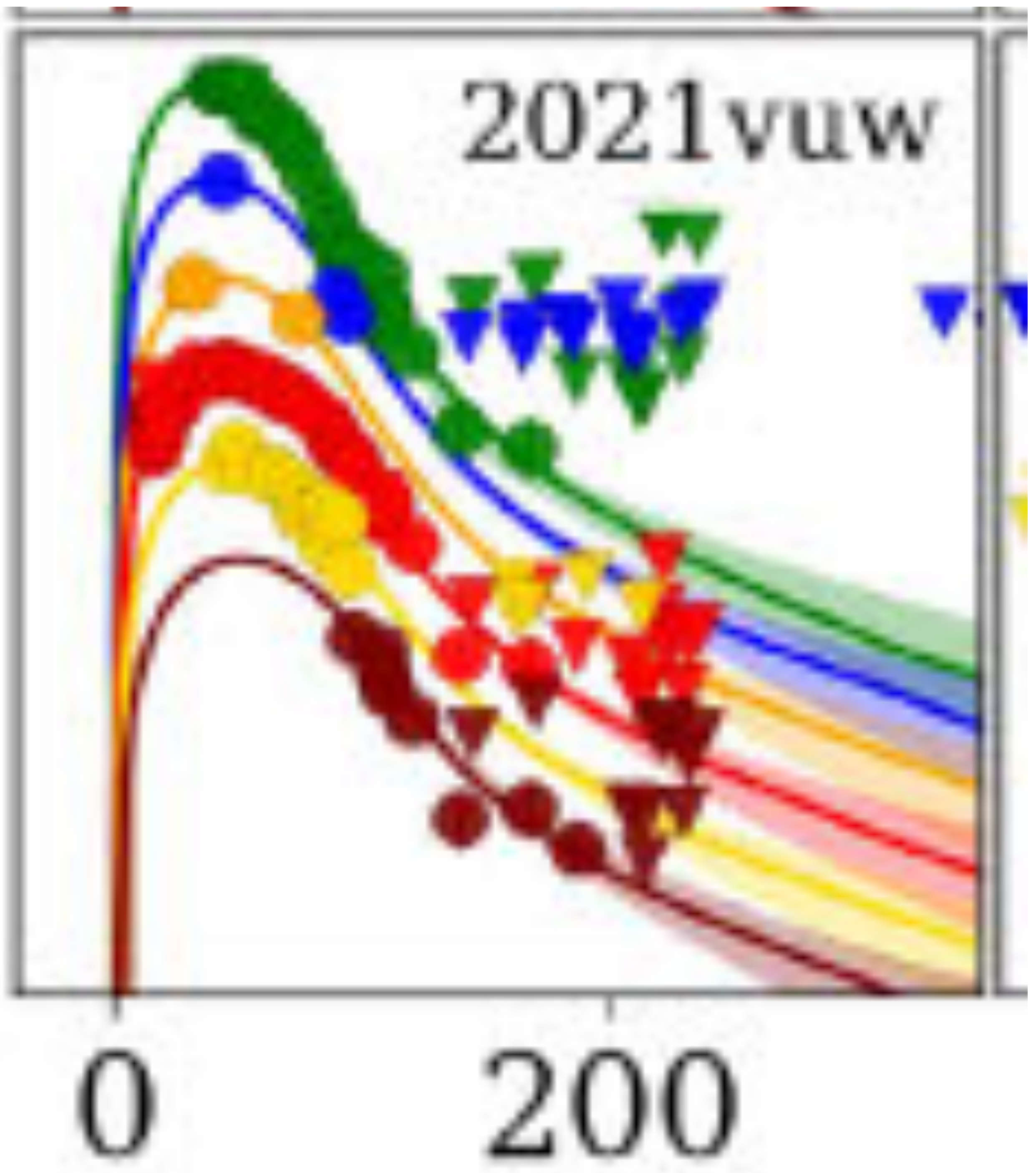
** How does it couple to ejecta? Unclear*

Light curve fits: magnetar + nickel (MOSFiT)

Good fits to bulk properties

Caveat: doesn't do bumps





Gomez+ 2024

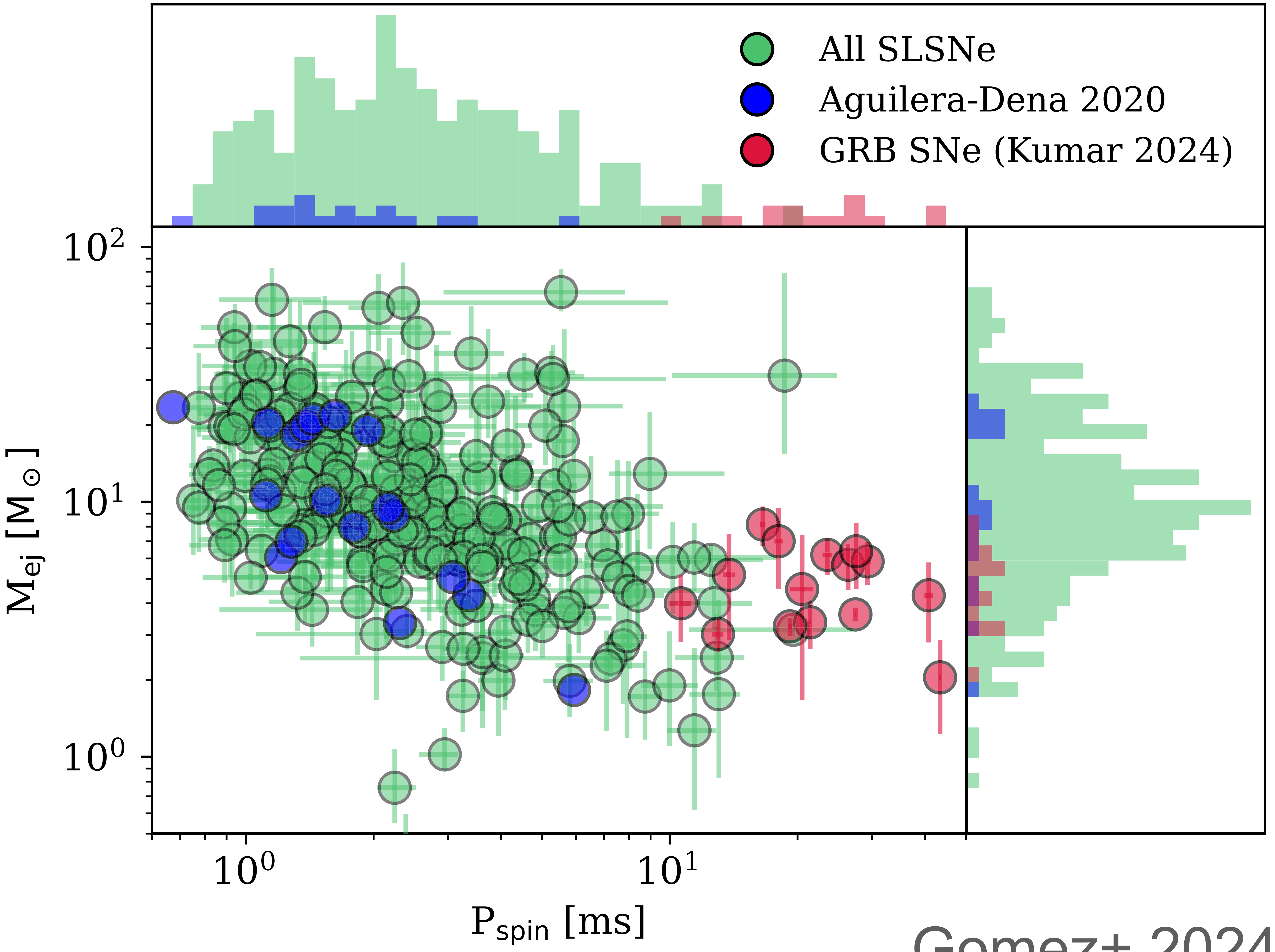
Parameters

Nickel contribution <10%

Possible mass-spin correlation

- Predicted by stellar models (Aguilera-Dena+ 2020)
- Evidence for chemically homogeneous evolution?

Faster spins than GRB magnetar fits (Kumar 2024)



Gomez+ 2024

Could a subset be Ni-powered?

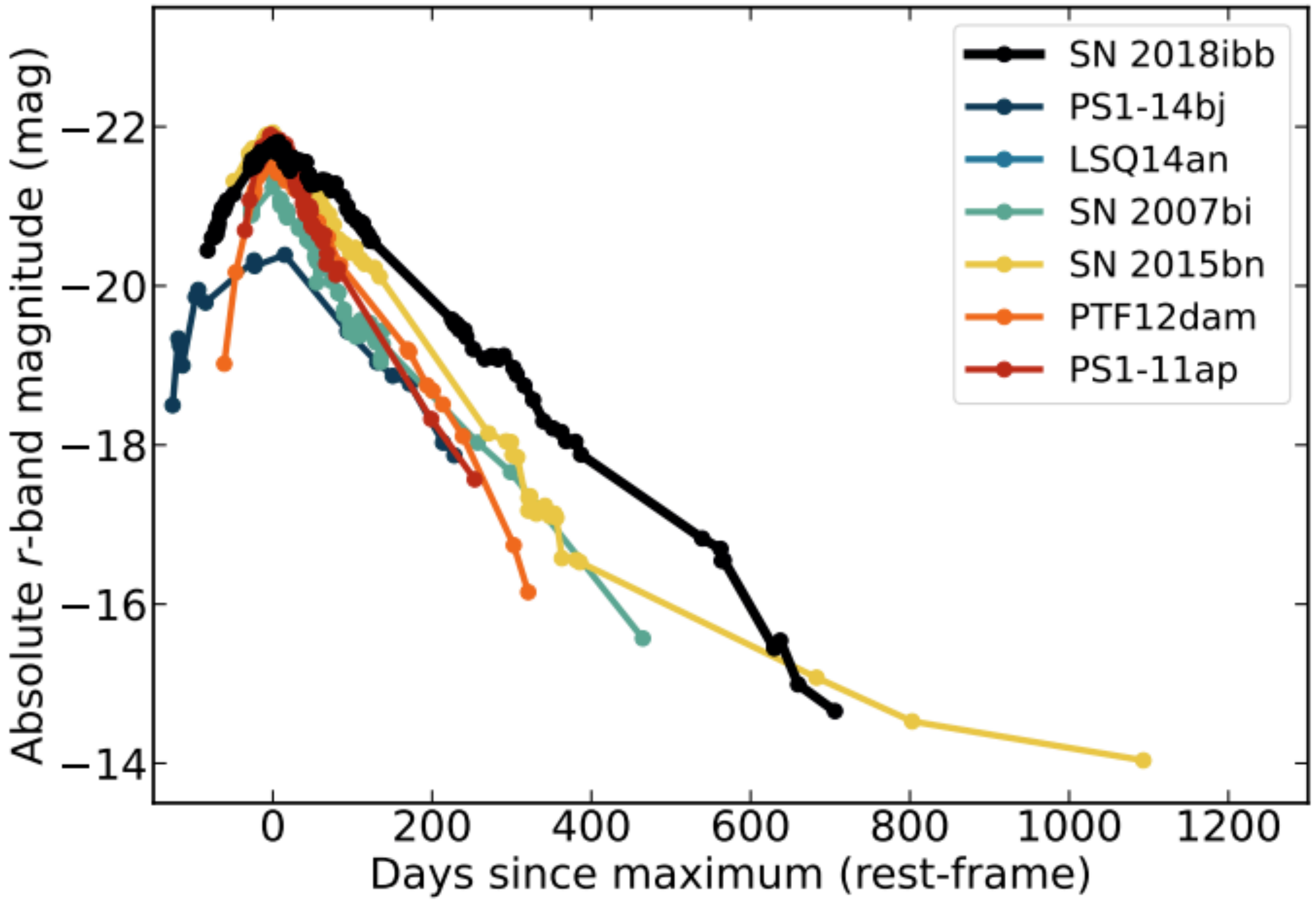
Some of the broadest light curves can be fit with ^{56}Ni

Resemble models of PISNe:

100 $M_\odot$ ejecta, 20 $M_\odot$ ^{56}Ni

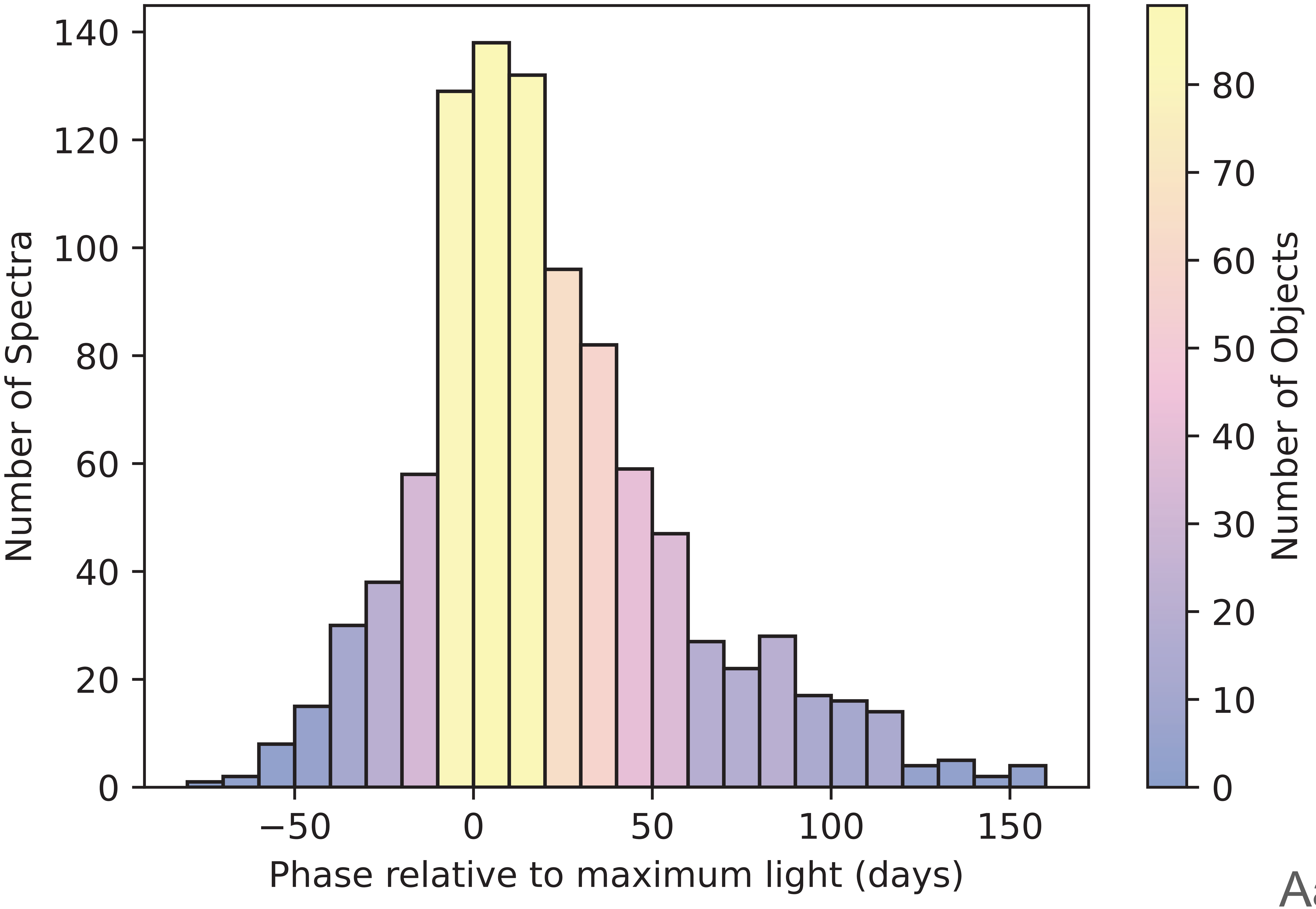
SN 2018ibb longest-lived so far

- Steve's talk!



Schulze+ 2024

SLSN Catalog: spectroscopy



Aamer+ 2025

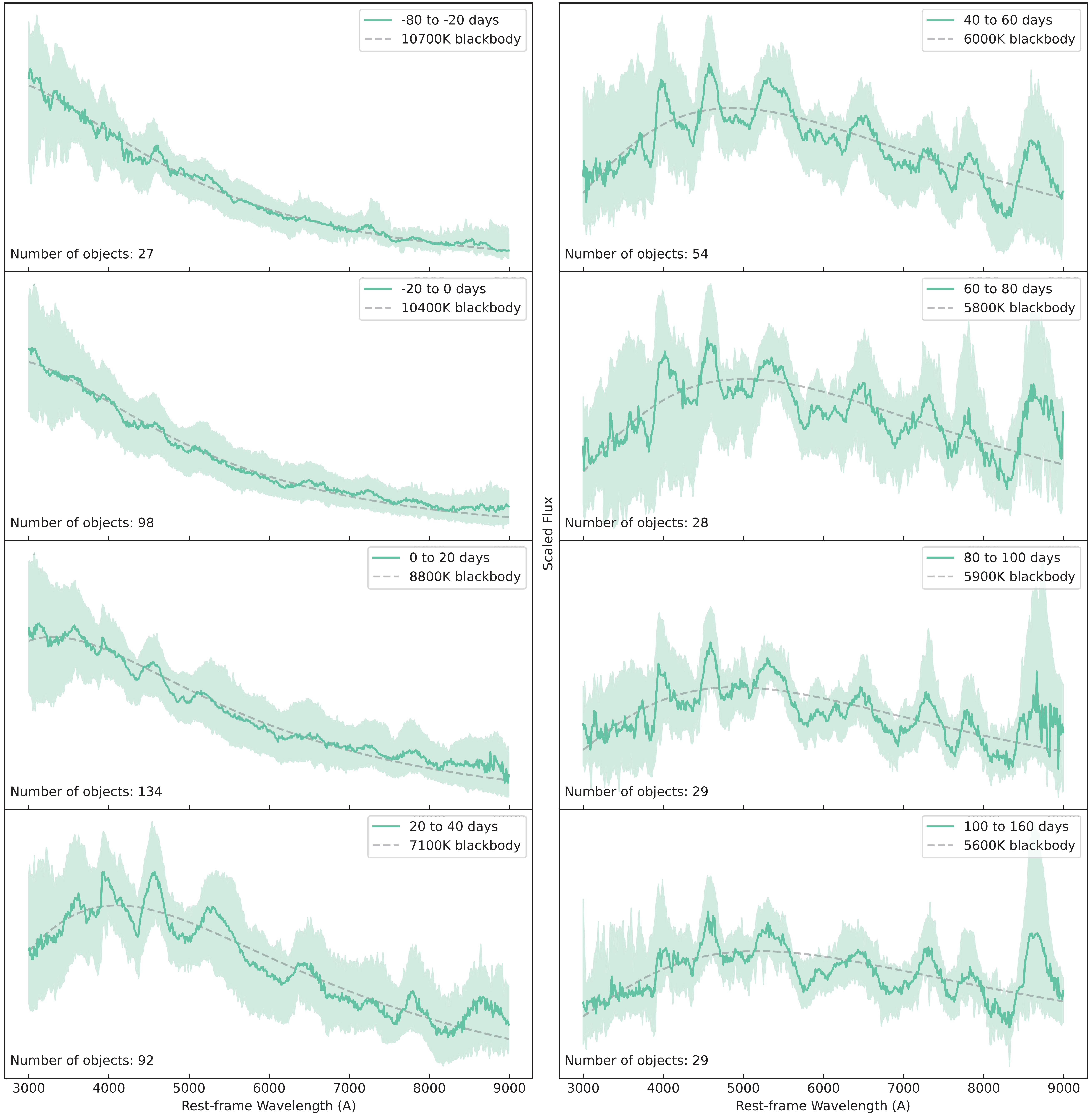
Spectroscopic properties

Aamer+ 2025

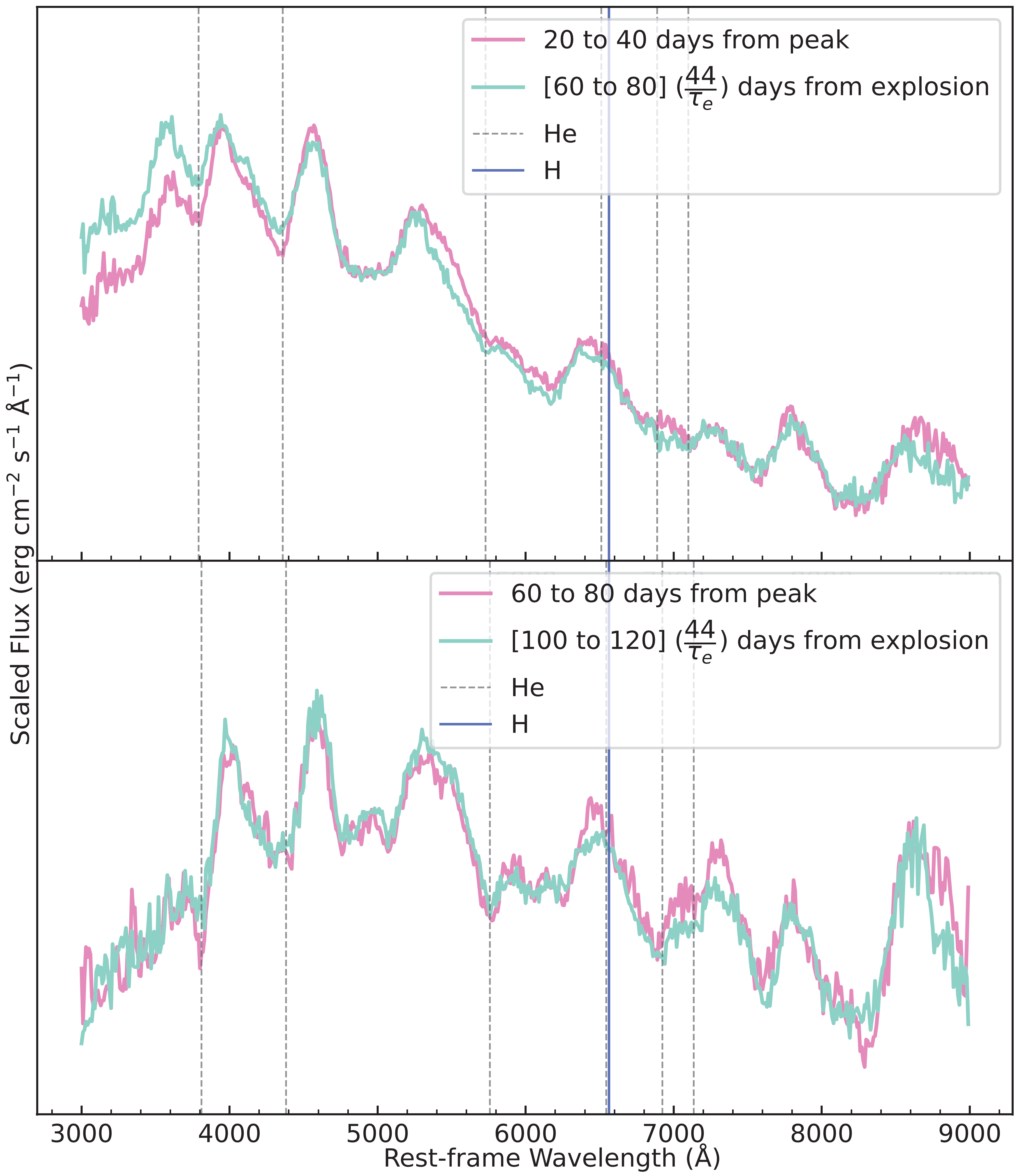
~1000 spectra:

- Telluric corrected
- Extinction and redshift corrected
- Scaled to match photometry
- Mapped to common wavelength grid

Compute average spectrum vs time

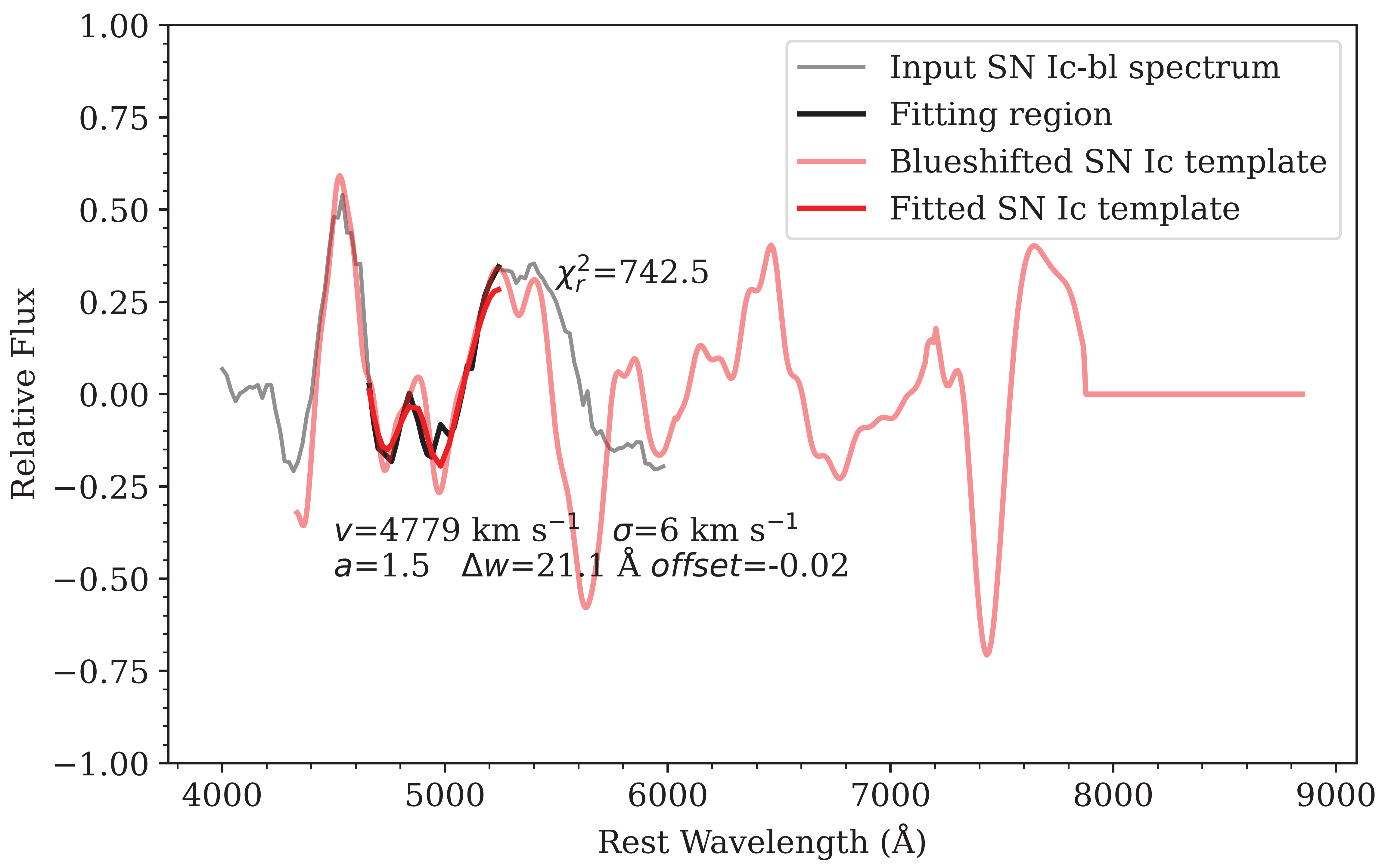


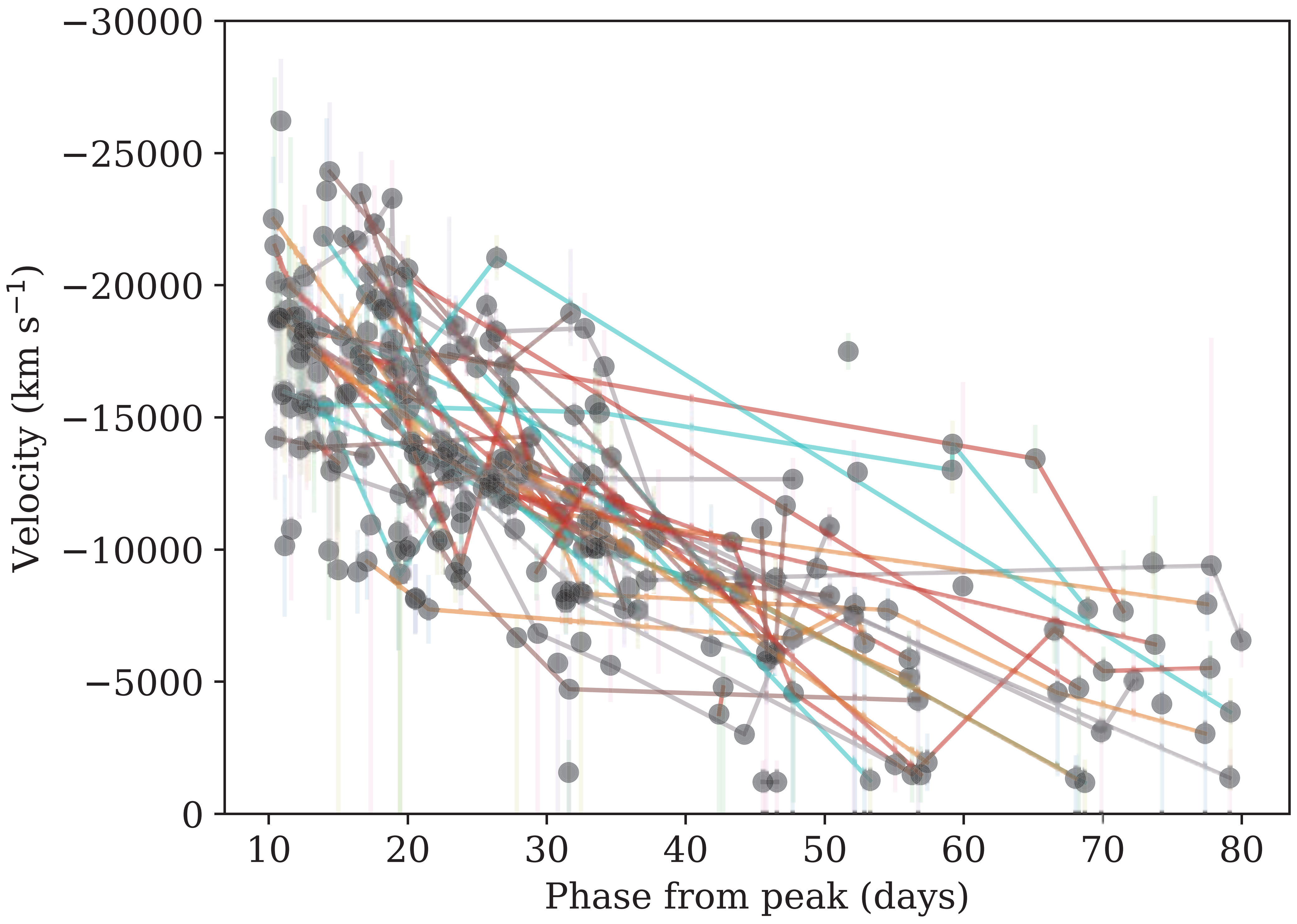
Identify weak features: Helium?



Aamer+ 2025

Fe II velocity measurements





Using code from Modjaz+ 2016, Liu+ 2017

Aamer+ 2025

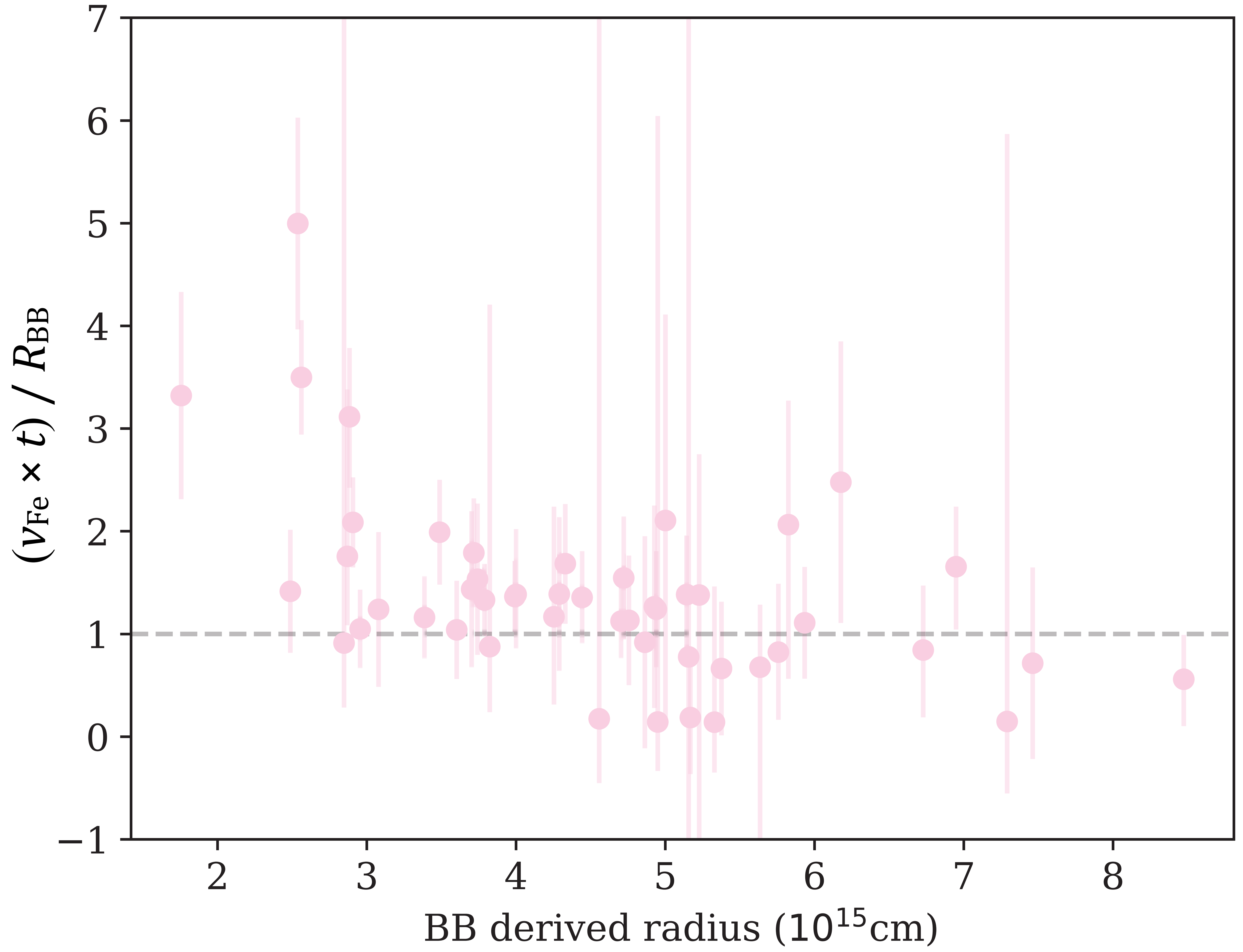
Constraints on ejecta structure

Compare radius where iron lines form (v×t) to radius from blackbody fits (Gomez+24)

Lines form at or above blackbody photosphere

Natural for homologous ejecta

Difficult to reproduce if photosphere in CSM?

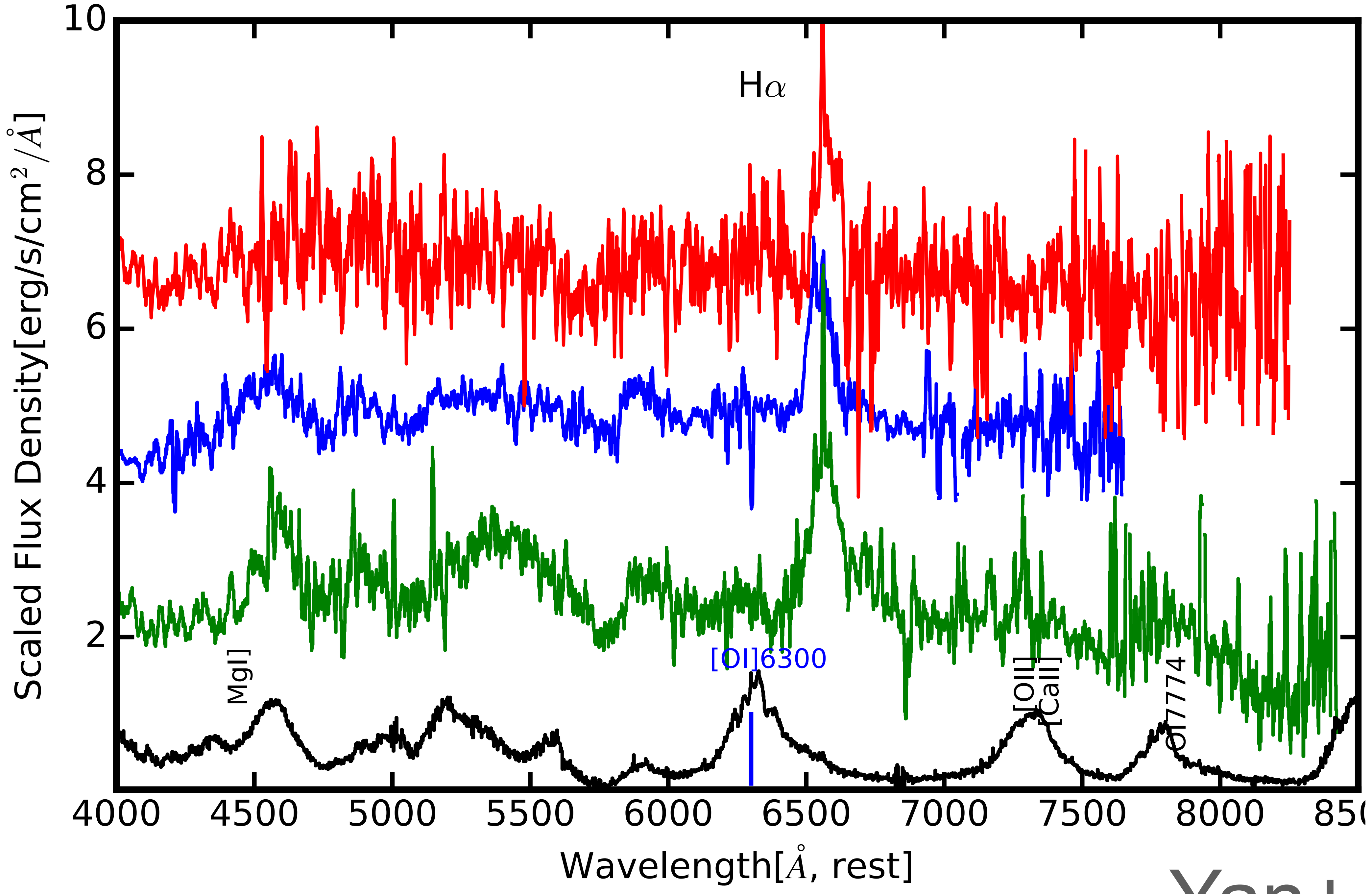


Aamer+ 2025

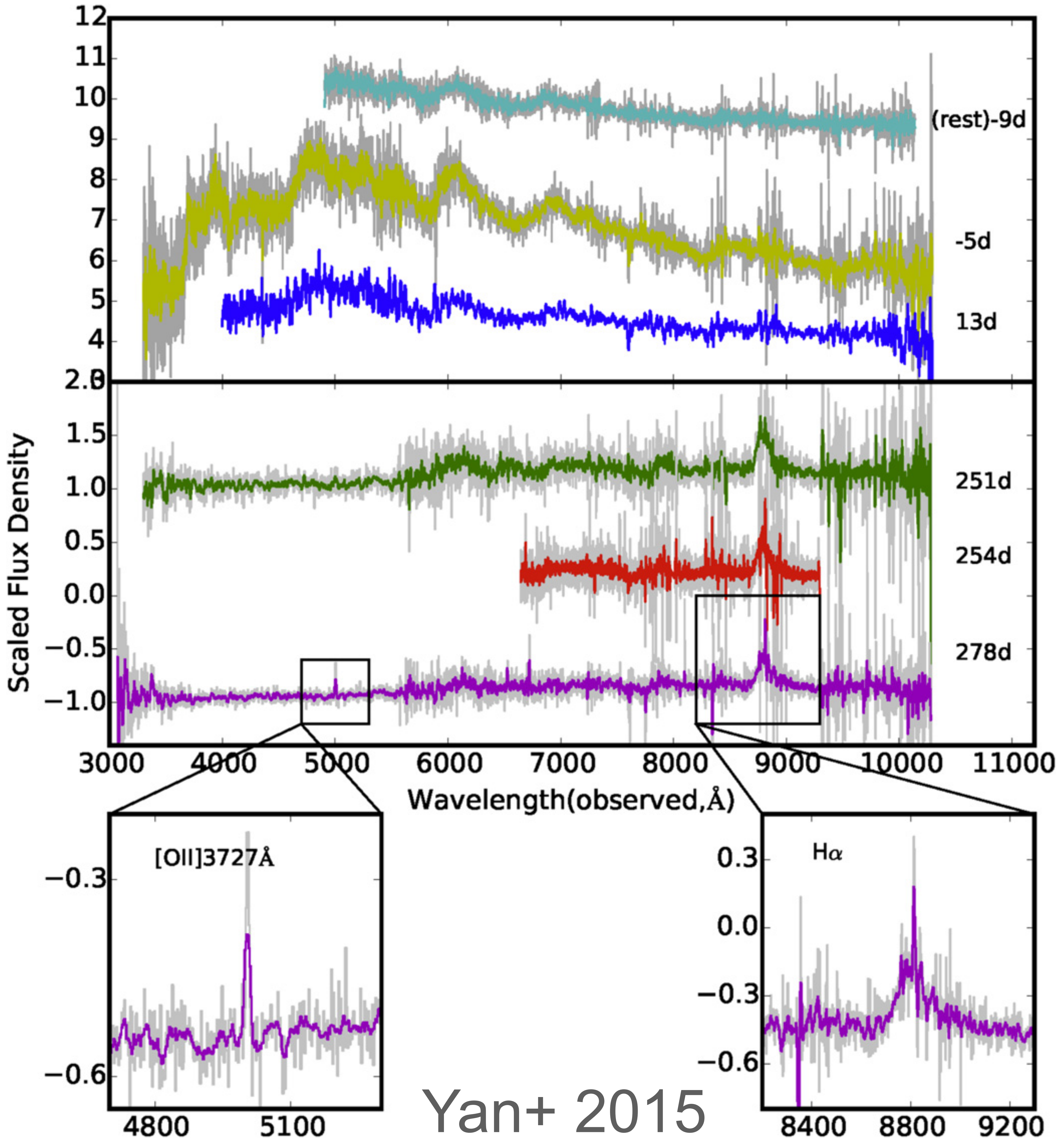
But: evidence for circumstellar material I

A few (≲10%) SLSNe show Hα emission at late times

Appears suddenly: detached shell?



Yan+ 2017



Yan+ 2015

Evidence for circumstellar material II

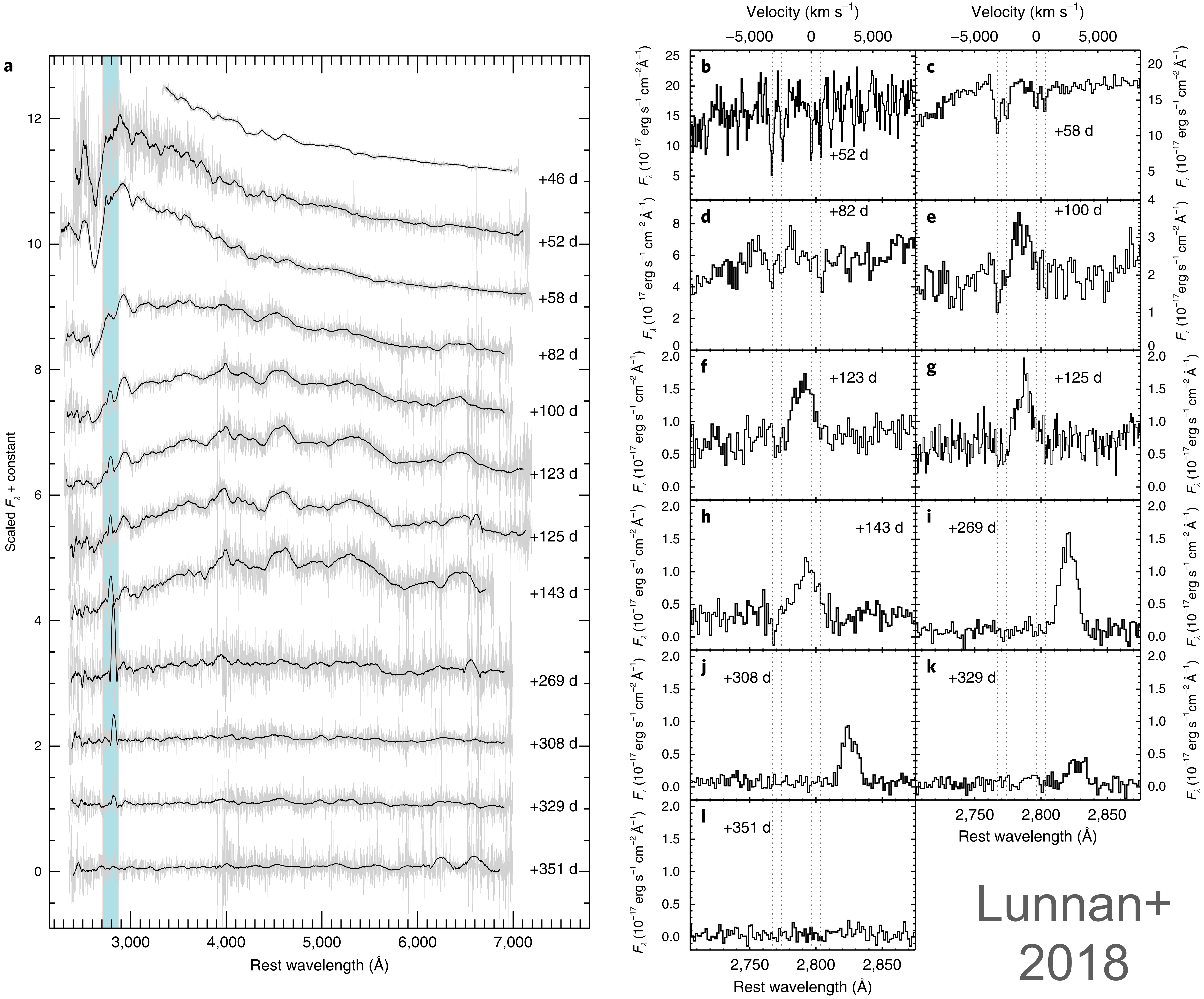
Detached shells at larger radii detected via light echoes

Mg II changes from blue-shifted absorption to redshifted reflection

Implied CSM shell at ~0.1 pc

Ejected ~decades before explosion

Complex mass-loss histories!



Lunnan+ 2018

O II lines in detail

Gal-Yam 2019

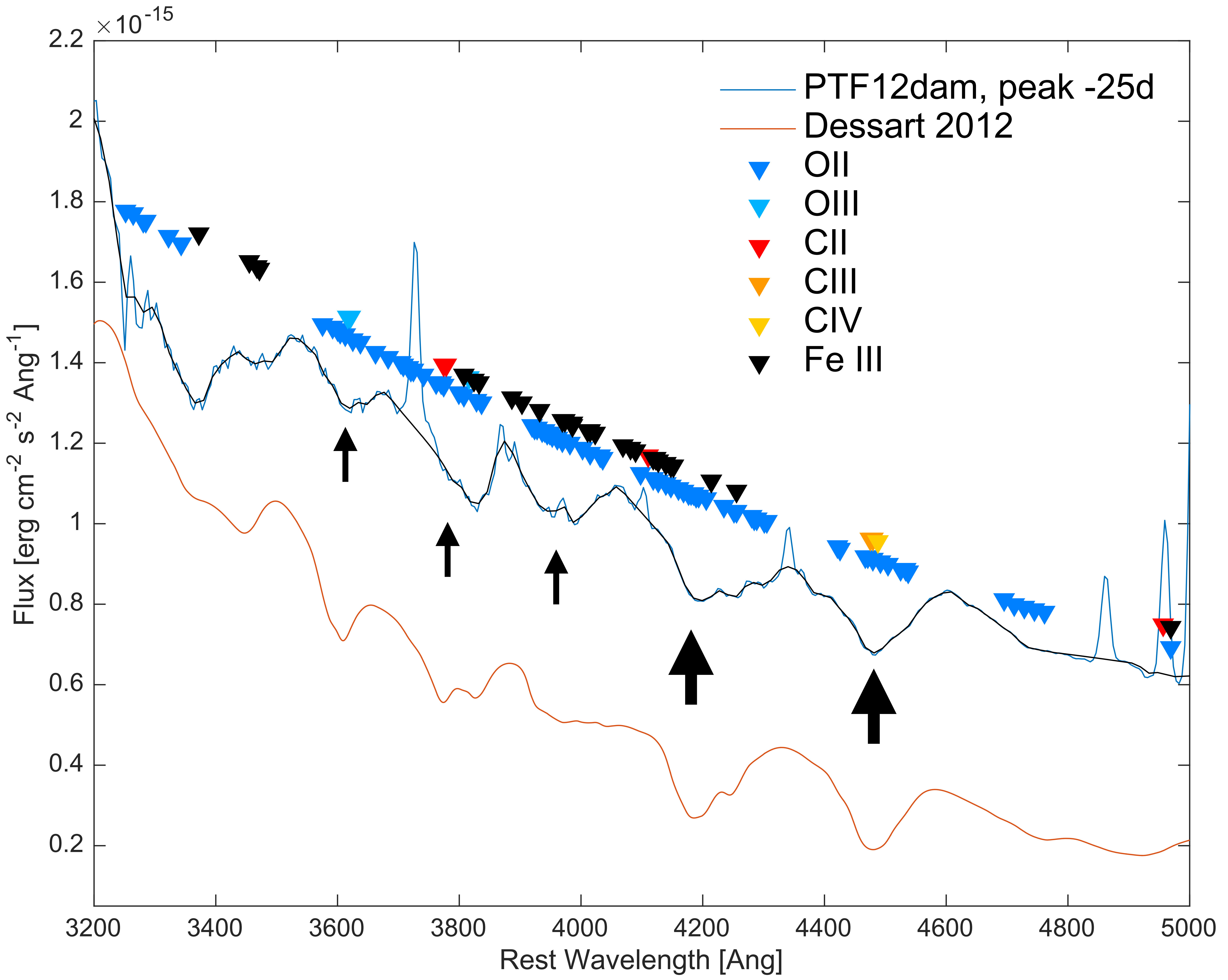
Five O II absorption lines, strongest at ~4200 and ~4450 Å

Blueshift ~ 10,000-15,000 km/s

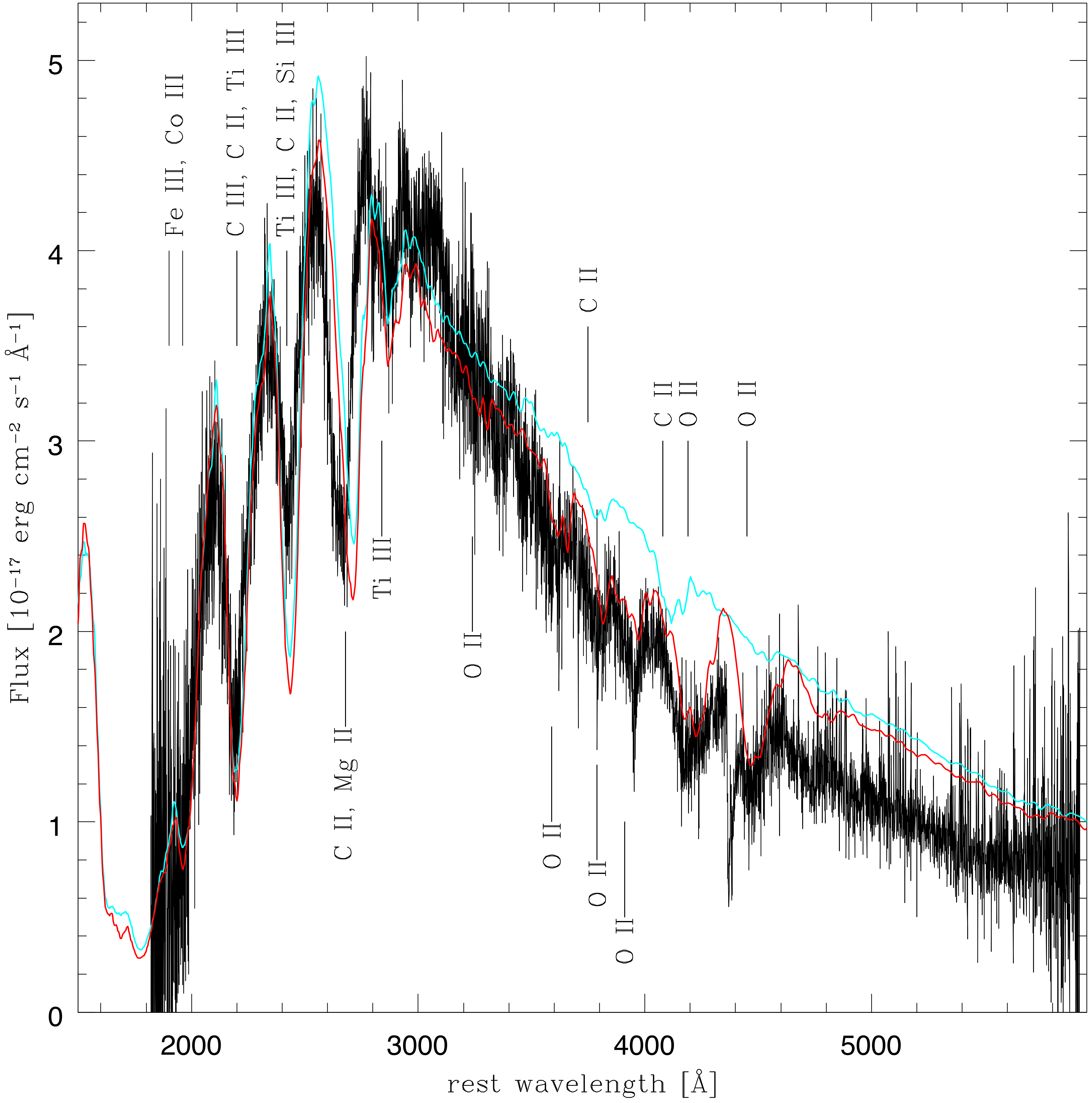
Gal-Yam 2019: width due to multiplets, not Doppler broadening

Dessart 2012: 7 M☉ ejecta, 1.5×10^{51} erg, centrally heated

- Great match
- Remarkably prescient choice of parameter values



Non-thermal excitation?



Mazzali+ 2016

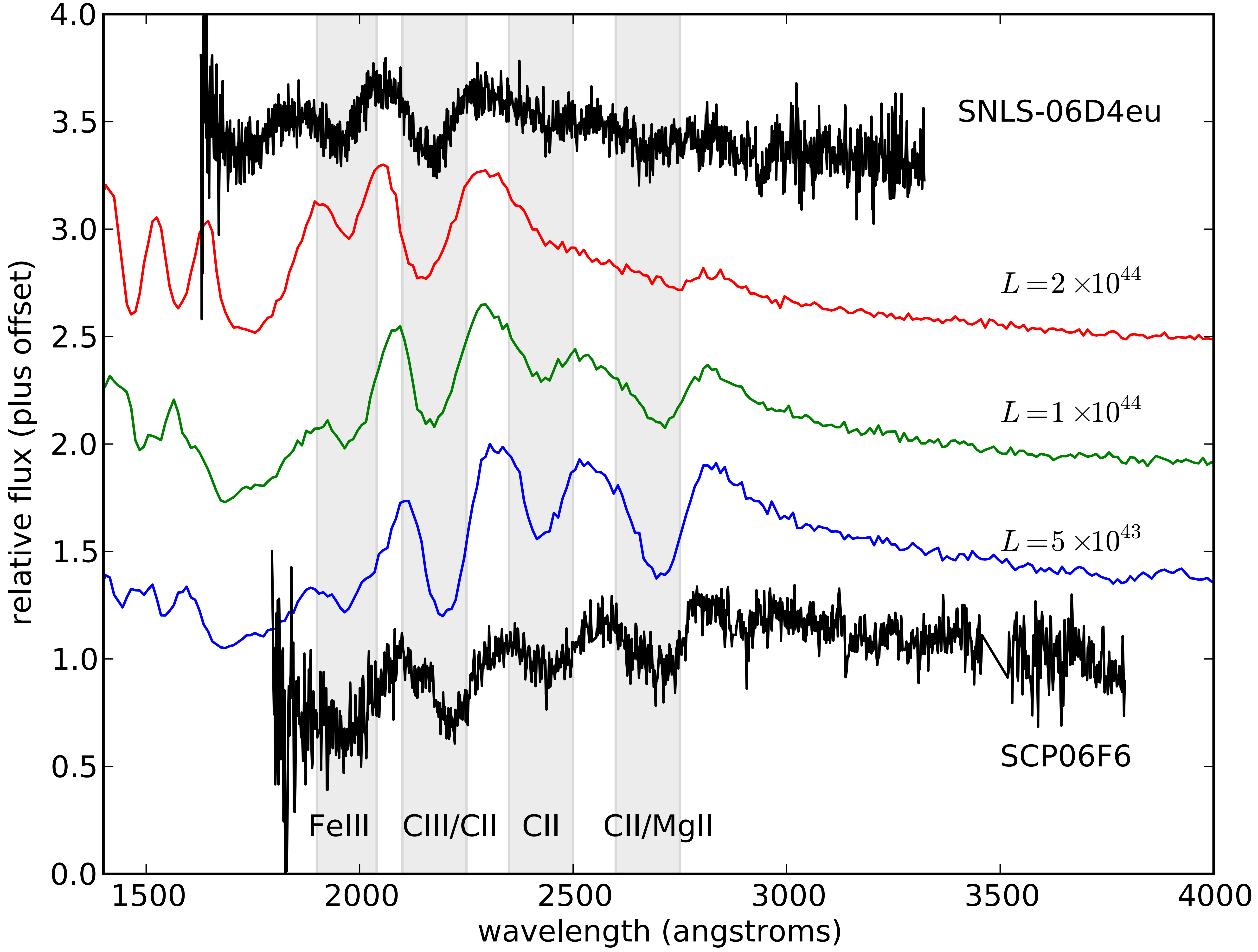
Thermal excitation only

Increase O II level occupation above thermal expectations

But debated!

Saito+ 2024: can form thermally for T ≳ 12,000 K

UV lines also reproduced by strong interior heating source



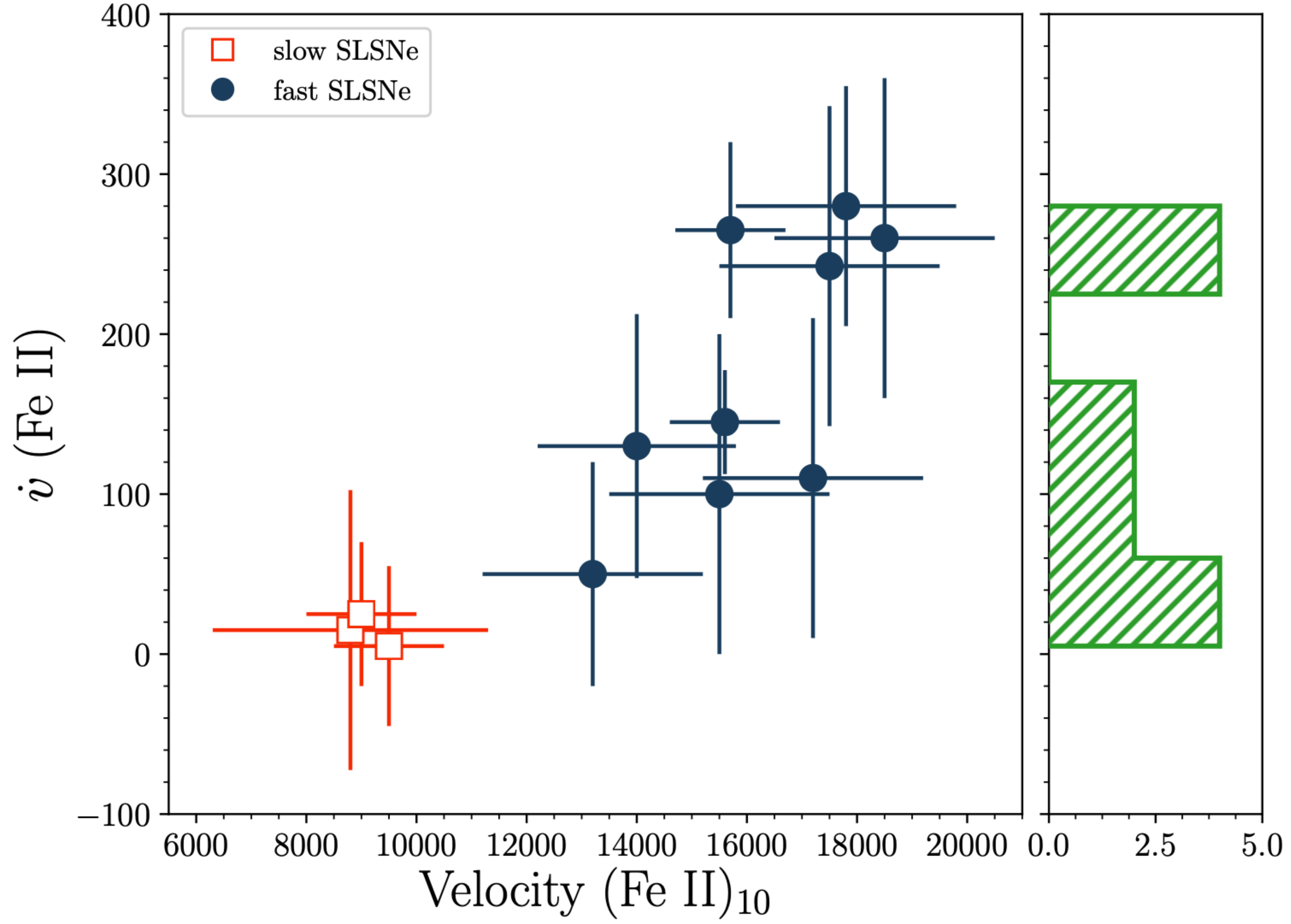
Howell+ 2013

Diversity and sub-classes

Several suggestions to group SLSN light curves into "fast" ($t_{rise} \lesssim 50$ d) and "slow" ($t_{rise} \gtrsim 50$ d)

SLSNe with slow light curves also have slow velocities

And velocity correlated with dv/dt



Inserra+ 2018

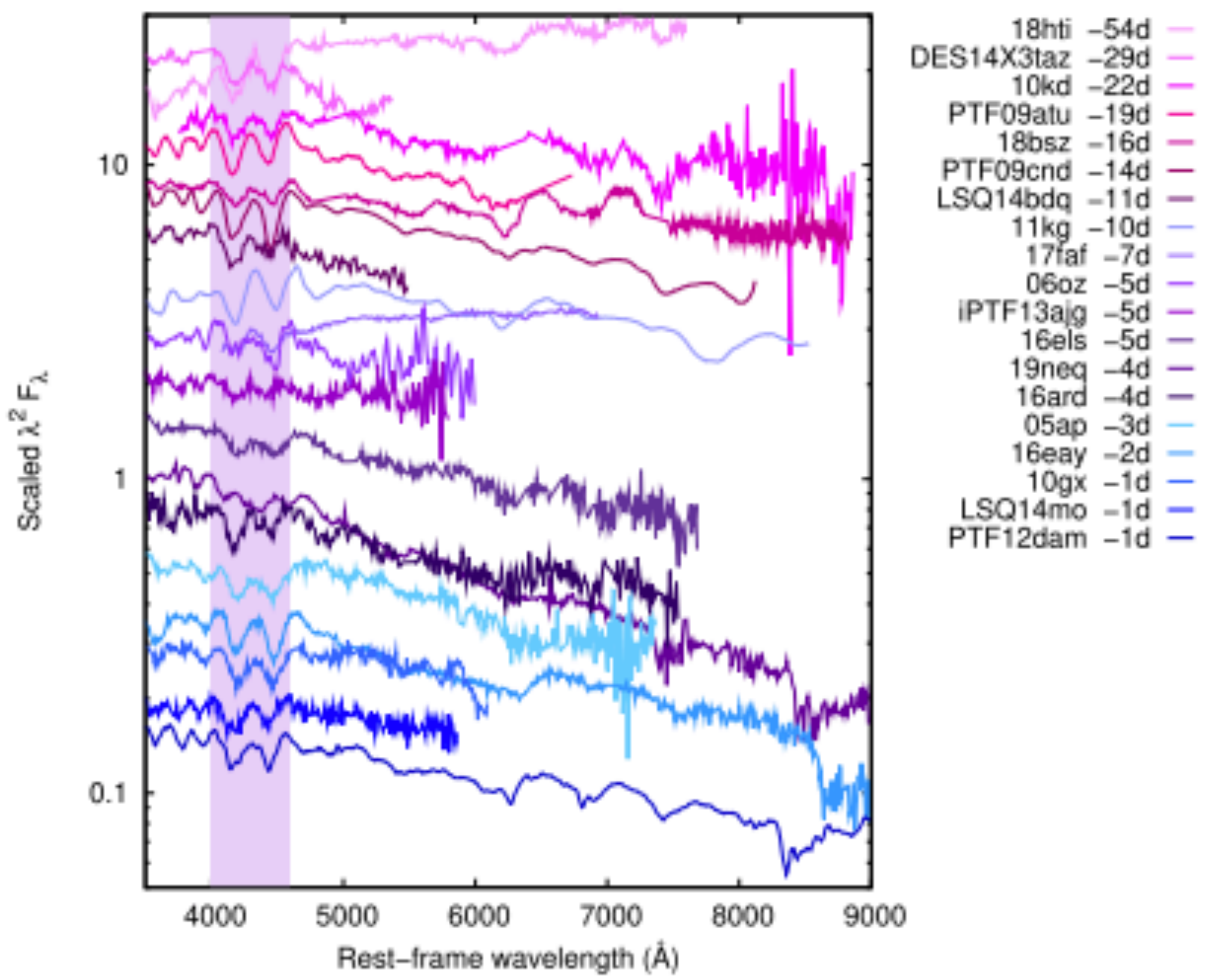
Diversity and sub-classes

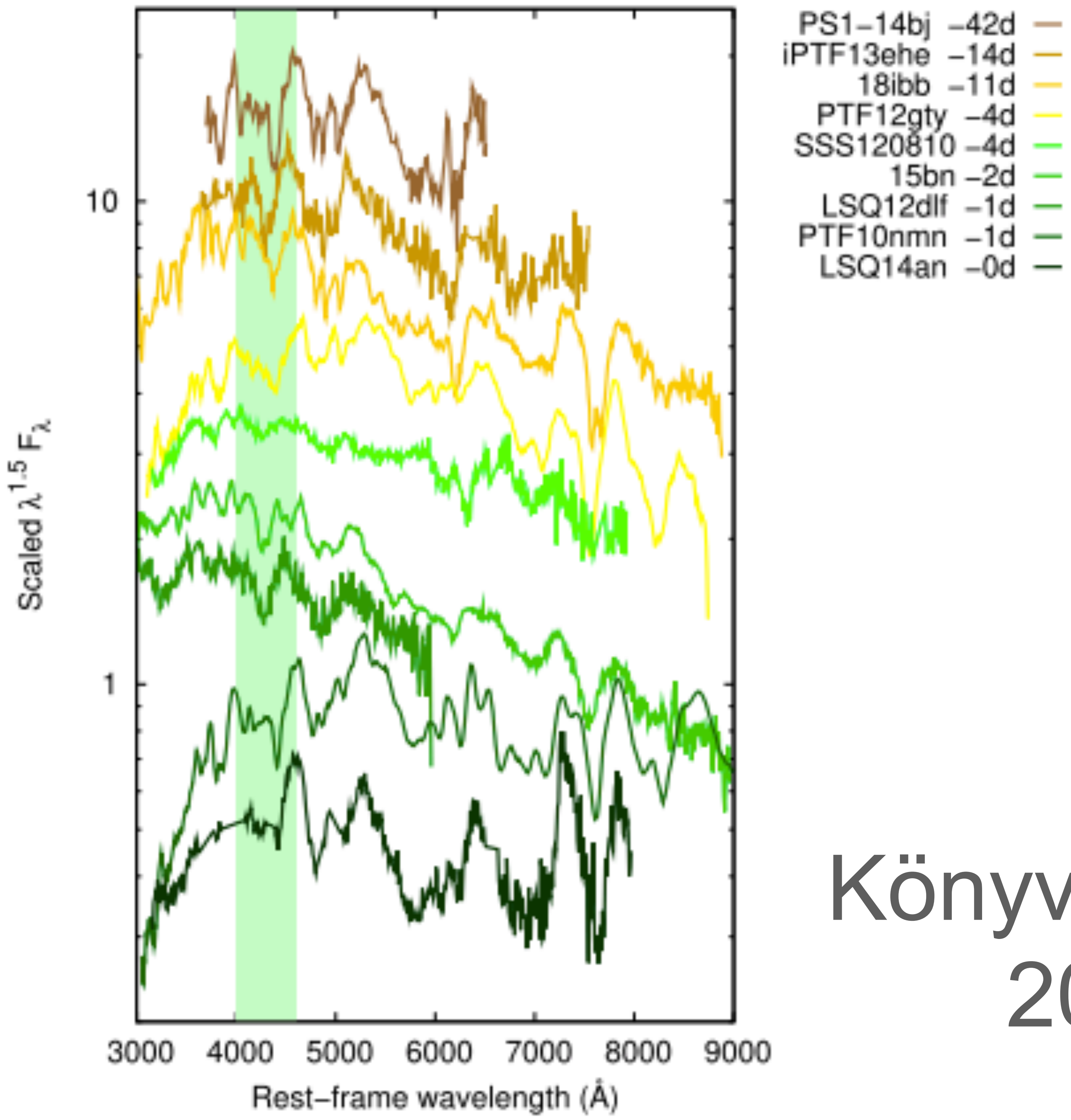
O II line profiles at peak are also diverse

- Classic 'W' shape vs '15bn-like'
- Due to temperature dependence of lines?

'Slow' SLSNe more likely to be in 15bn group

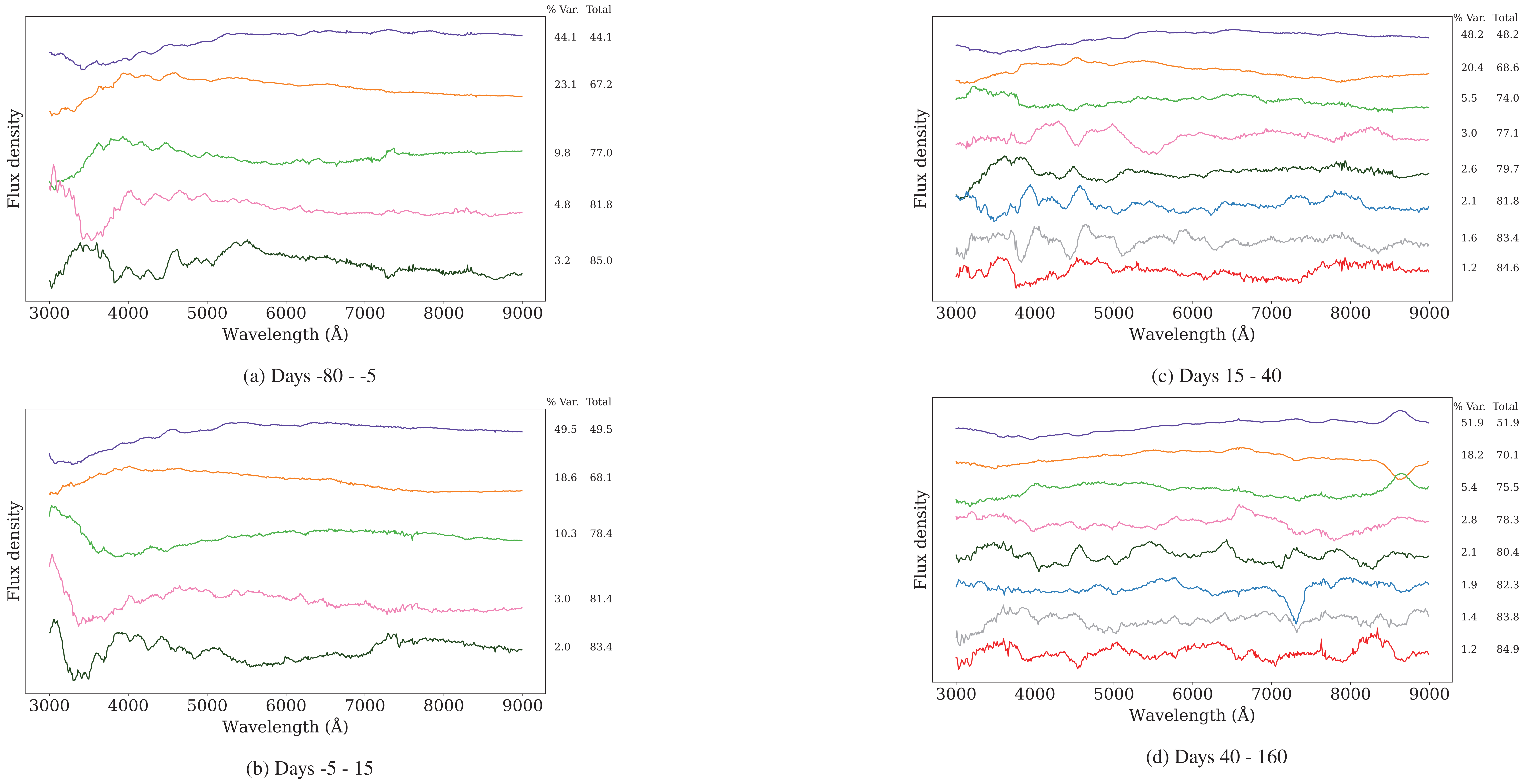
Two classes, or a continuum?





Könyves-Tóth 2022

Principal component analysis with SLSN Catalog



More diverse (more components) at later times

Aamer+ 2025

Clustering

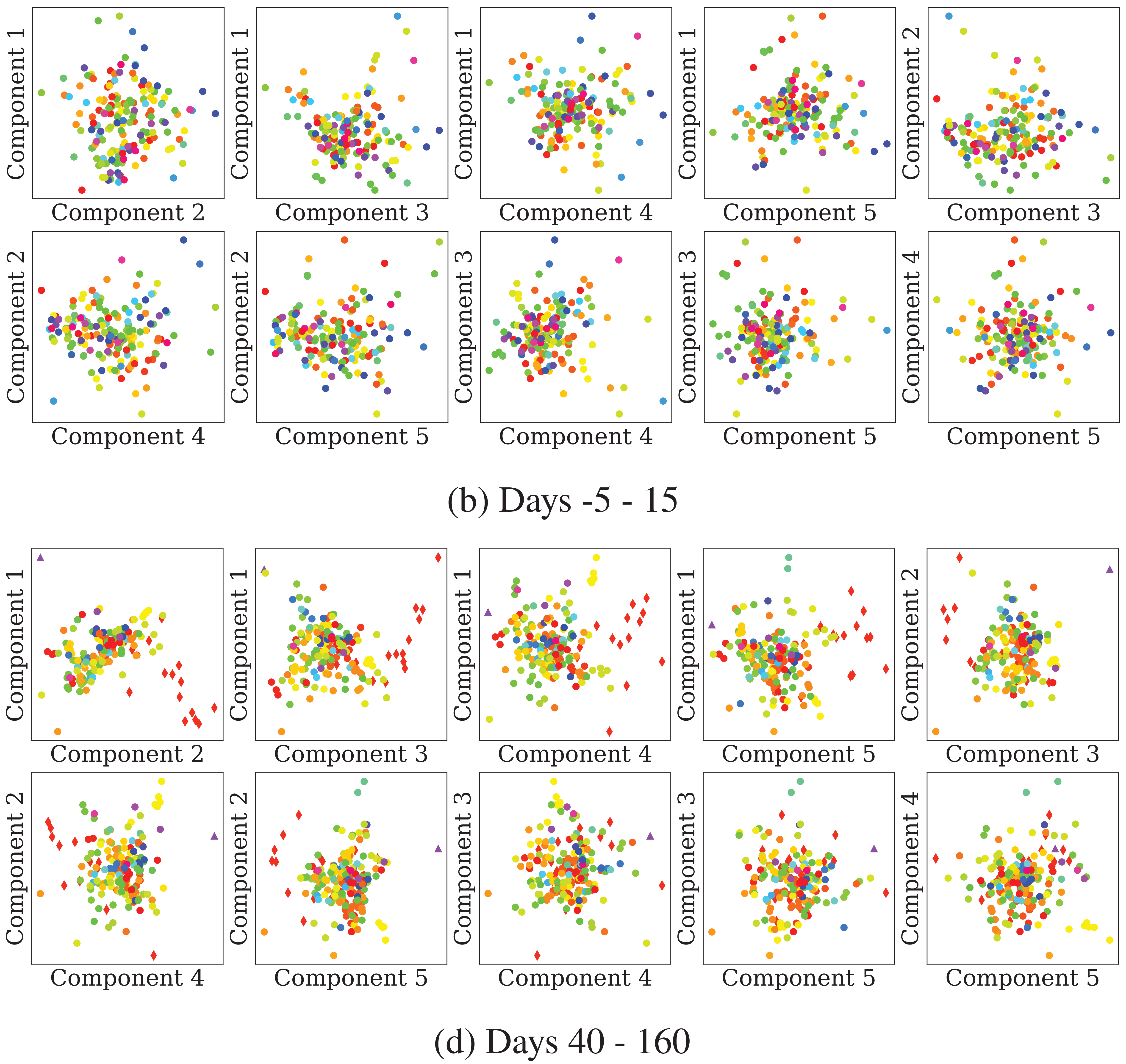
How much of each component needed to explain a given spectrum?

Early times:

- no evidence for multiple populations

Late times:

- one event a clear outlier — 2017egm
- During phase with huge light curve bumps! (Lin+23, Zhu+23)

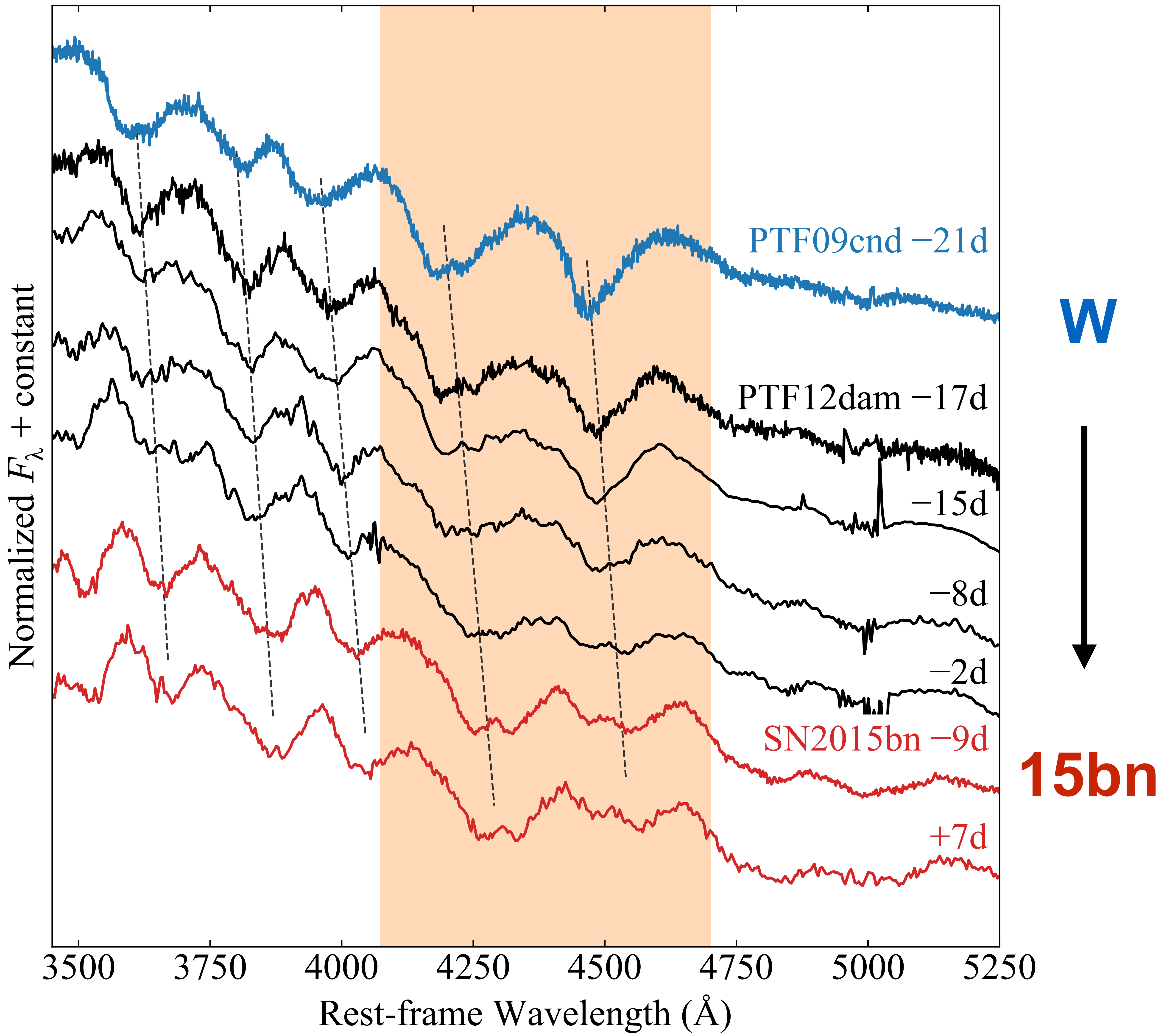


Aamer+ 2025

Line evolution up close

PTF12dam: SLSN evolves smoothly from W-like to 15bn-like as it cools

- Classes clearly related
- Range of temperatures?



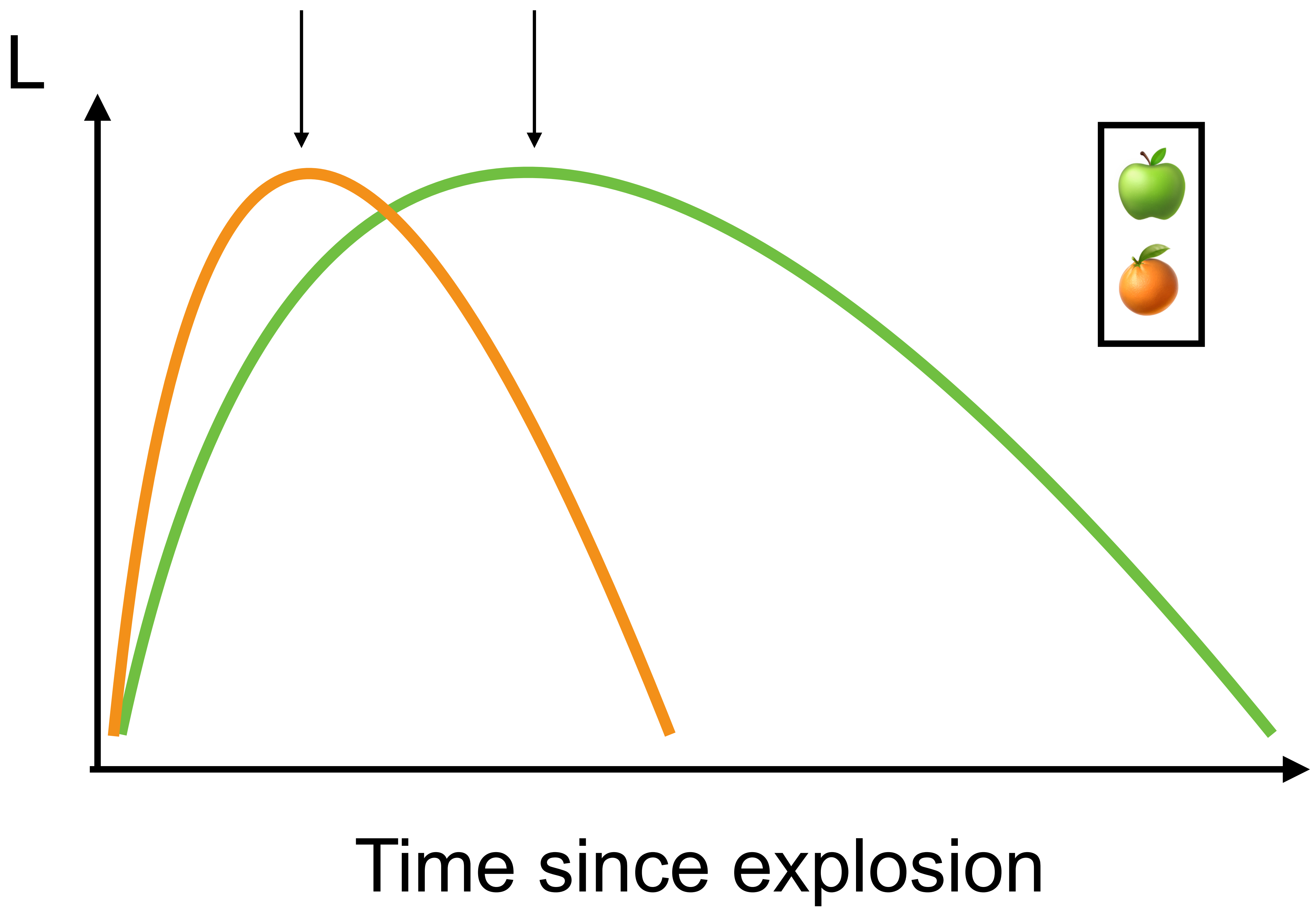
MN 2026

Line evolution up close

Line profiles, velocities, and velocity gradients are sensitive to size, location and temperature of photosphere:

- Which depend on time *since explosion*

Wide range of rise times => peak spectra obtained at very different times since explosion!



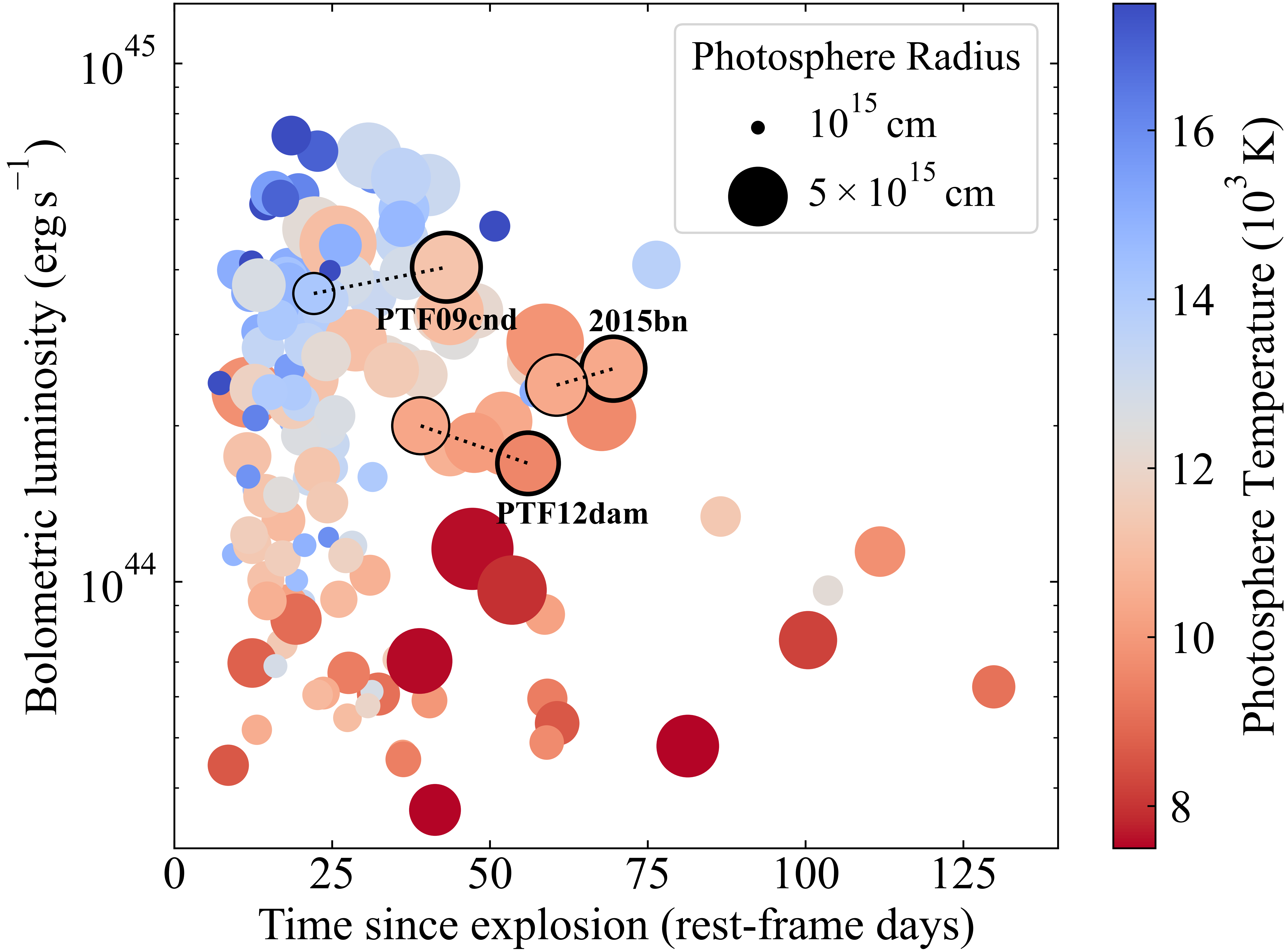
Diverse rise times lead to diverse temperatures

Brightness +
Time +
Temperature +
Radius

= BTTR way to connect light curves and spectra

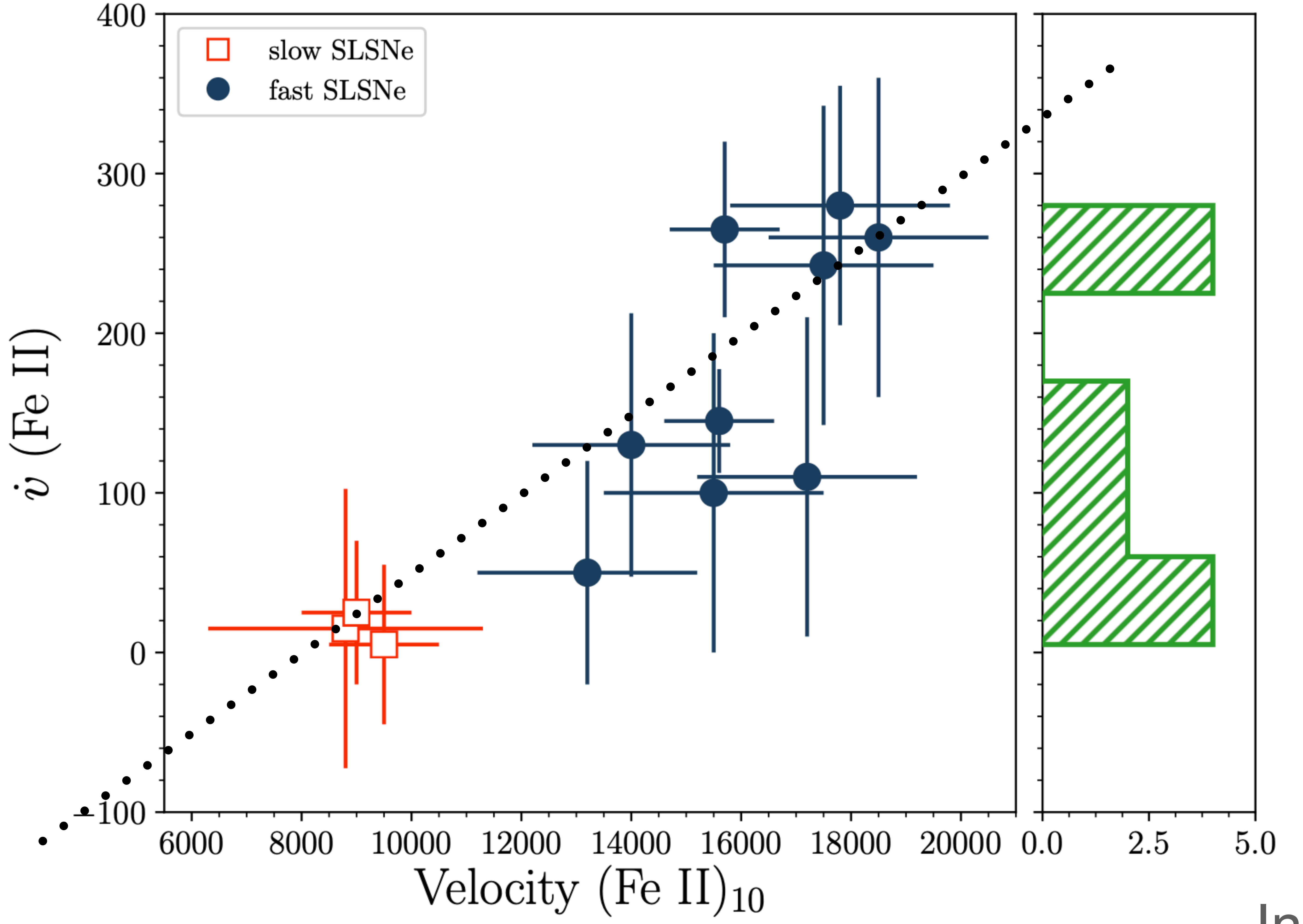
Long-rising events are more expanded and therefore redder at peak

- Less likely to show strong W-shaped O II line



MN 2026, data from Gomez+ 2024

Can rise times also explain v and dv/dt ?

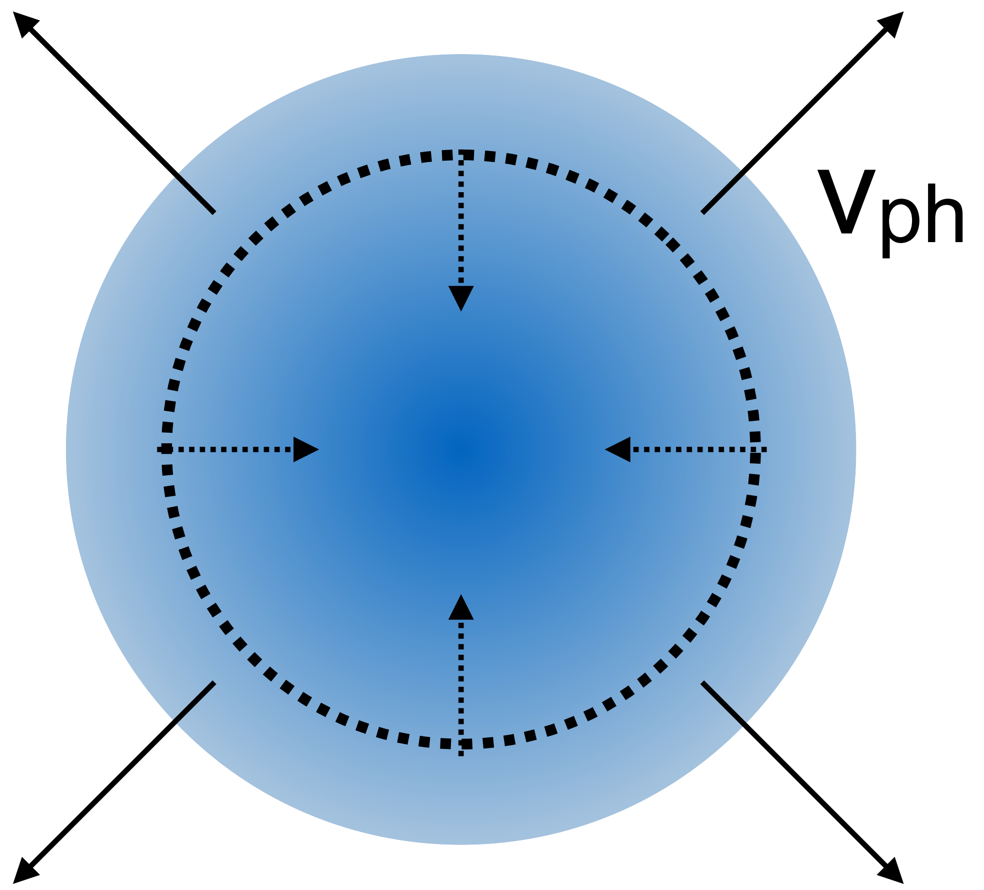


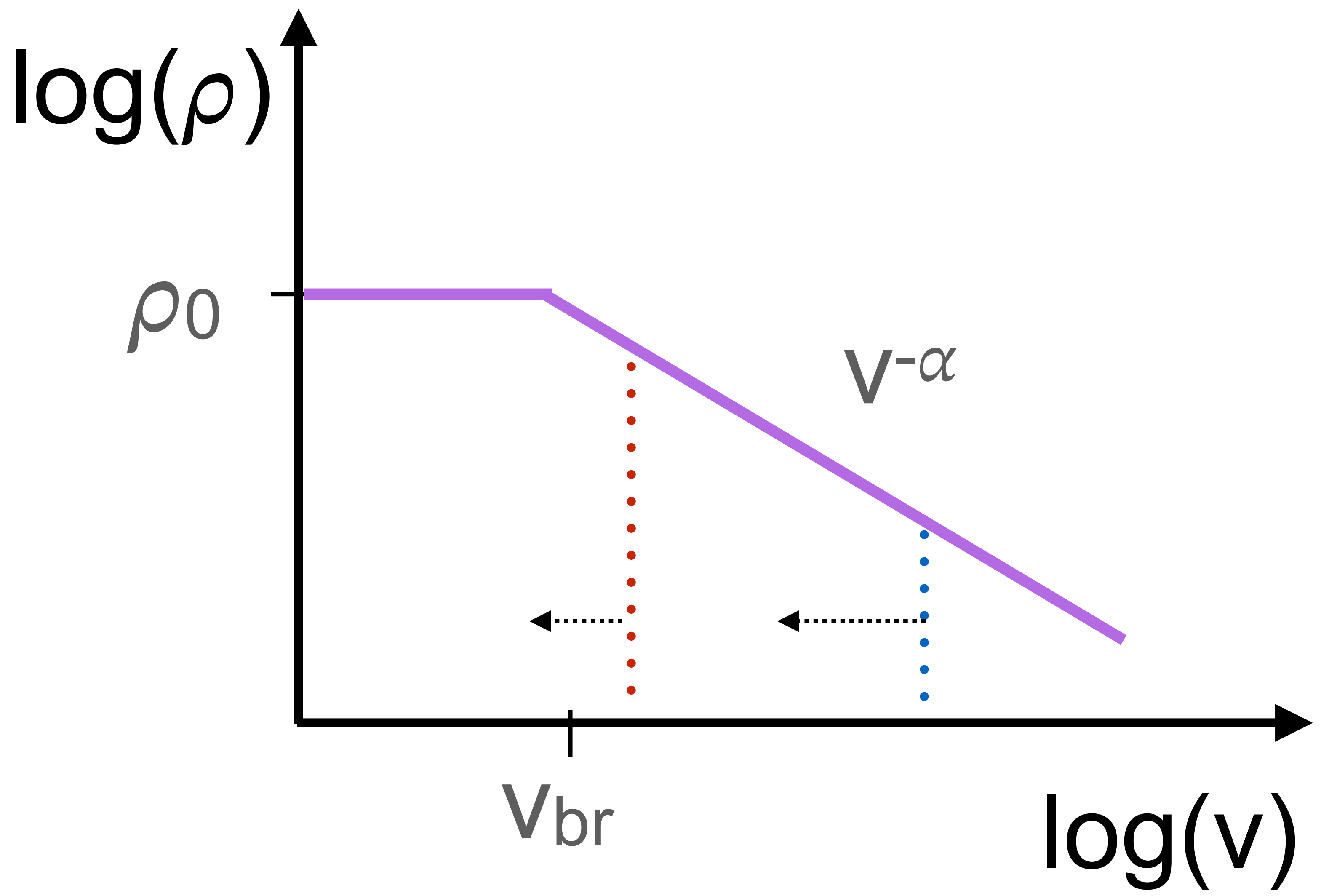
Inserra+ 2018

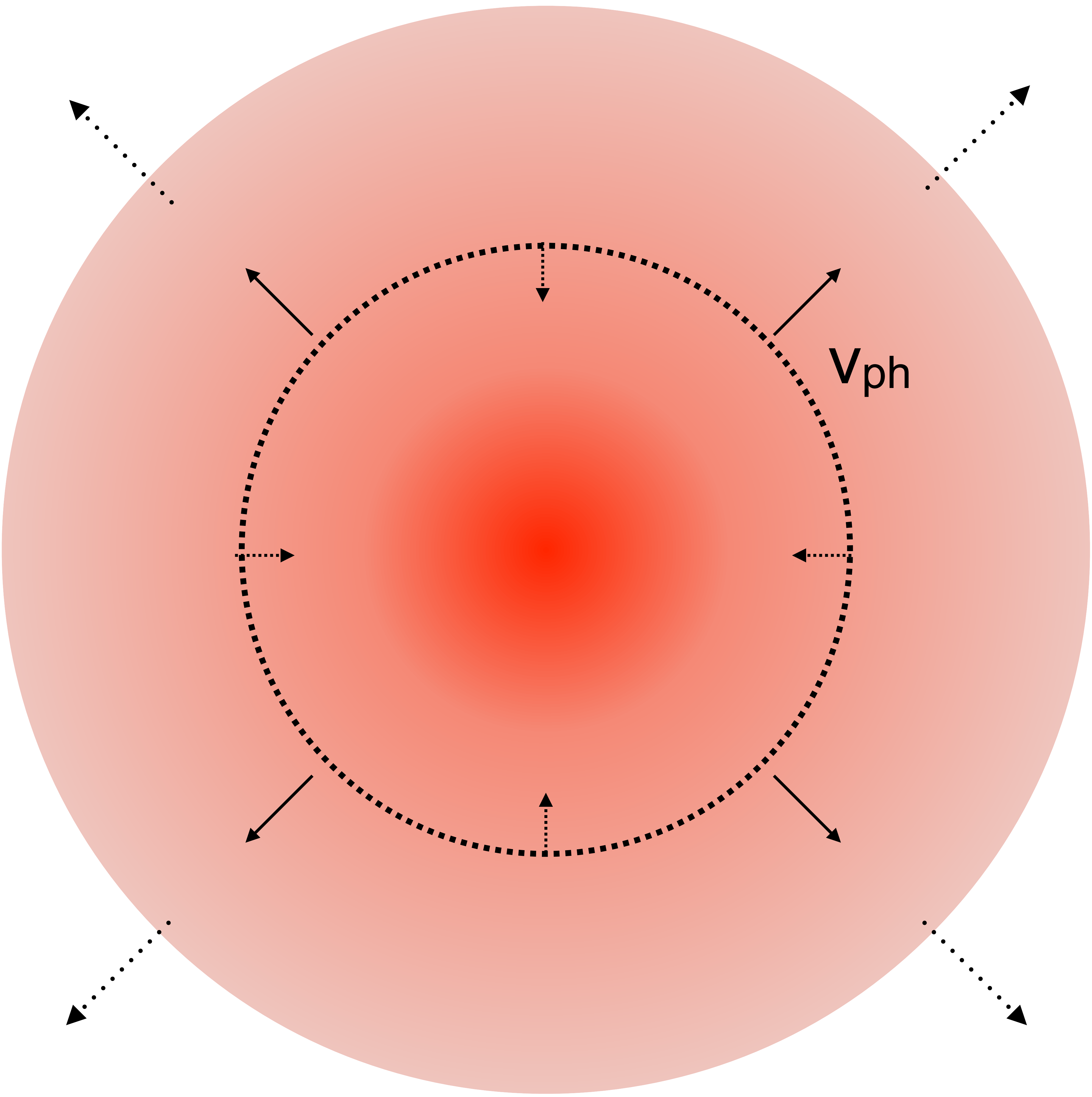
Toy model

Homologous expansion: $v \propto r$

Power-law density







<u>Fast rising event at peak:</u>
Photosphere still in outer ejecta
Observe high velocity at photosphere
Receding quickly through outer envelope

<u>Slow rising event at peak:</u>
Photosphere has reached inner ejecta
Observe lower velocity at photosphere
Receding slowly in denser ejecta

Making it quantitative

MN 2026, data from Aamer+ 2025

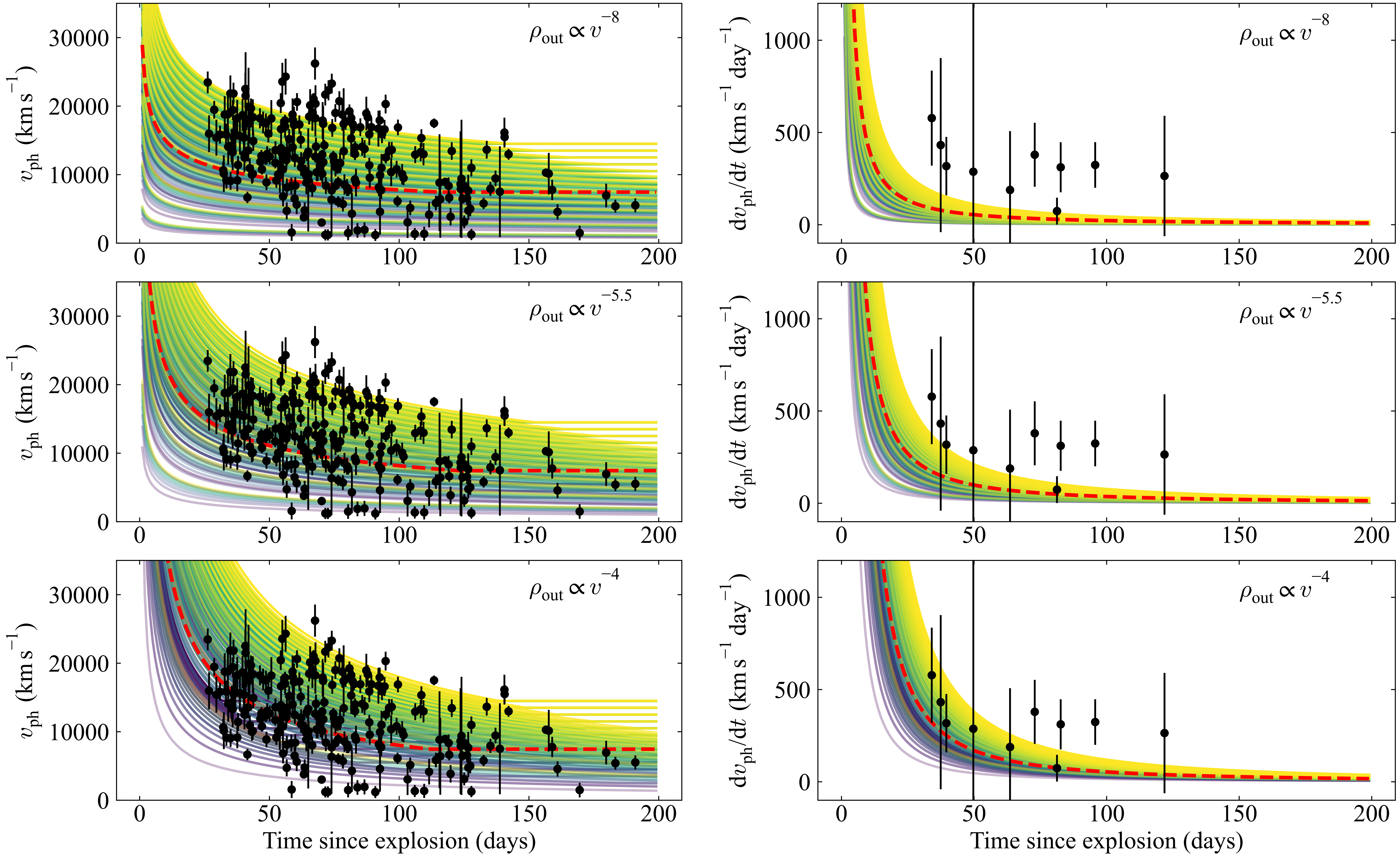
Integrate to find where $\tau(t) = 1$ to get v and dv/dt

M_{ej} ~ 2–40 $M_\odot$ (Gomez+24)

v_{br} ~ 500–15000 km/s

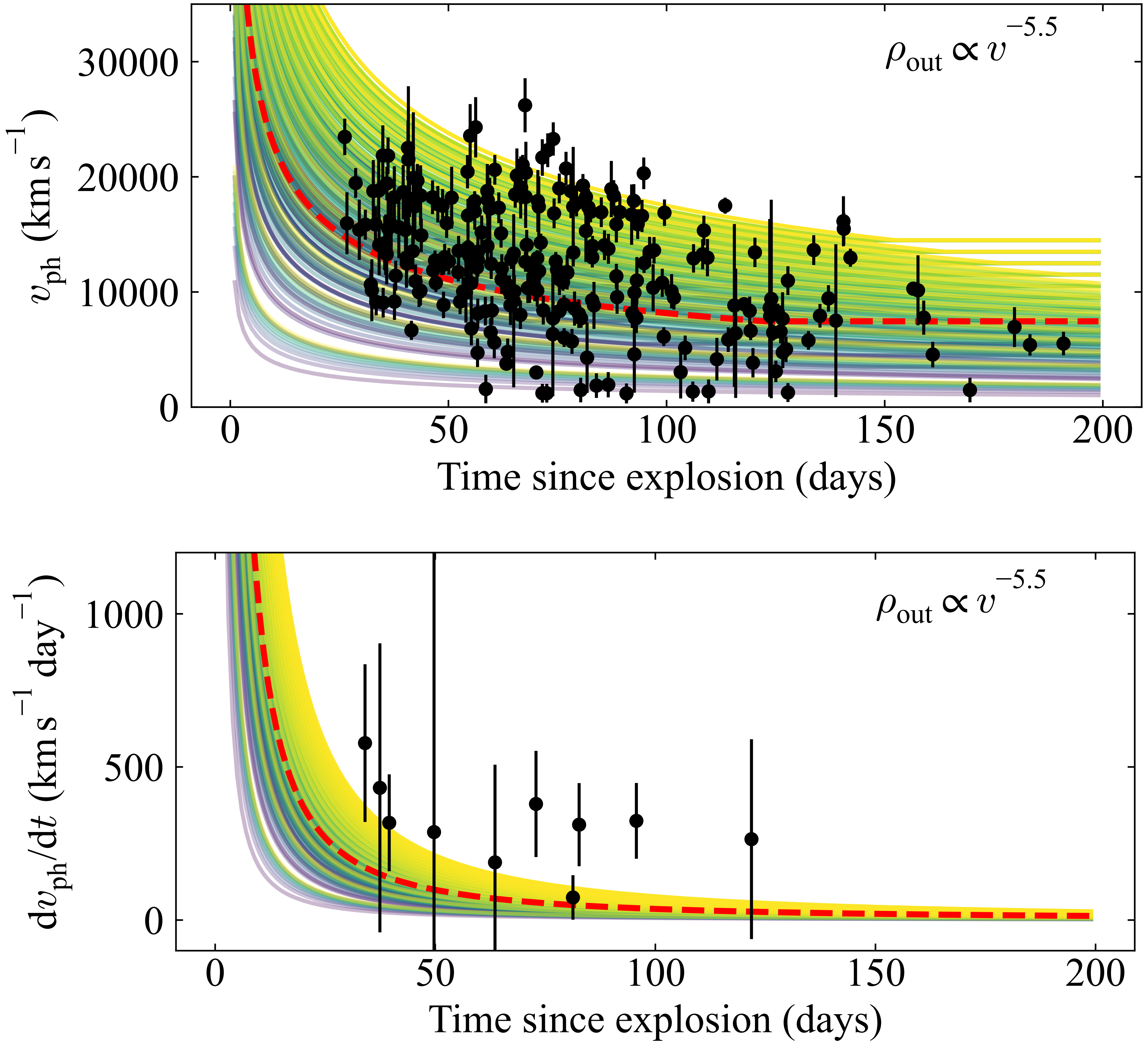
Reproduce v_{ph} from Aamer+25 only for shallow power-law!

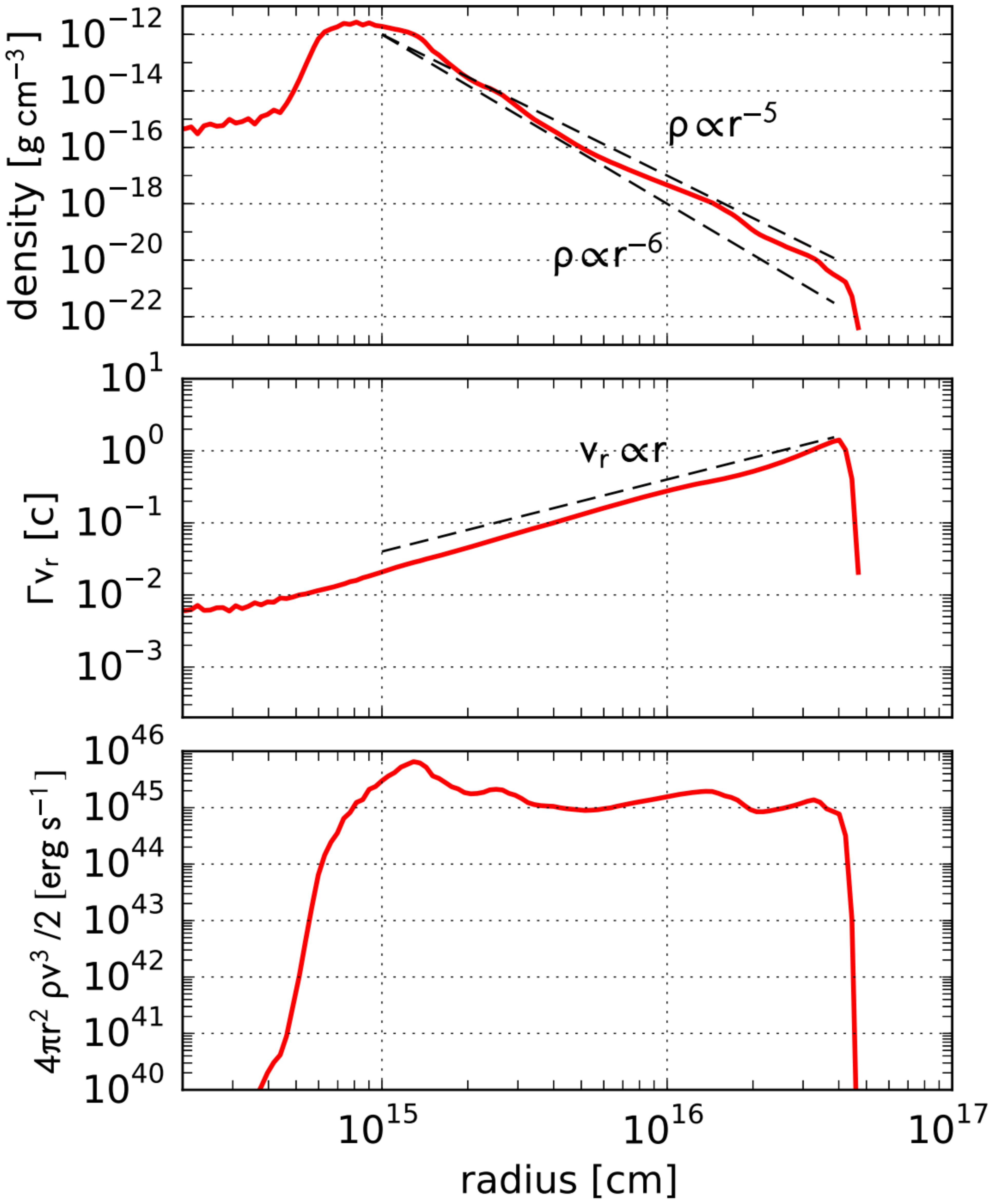
Gomez mean params ≈ Dessart 2012



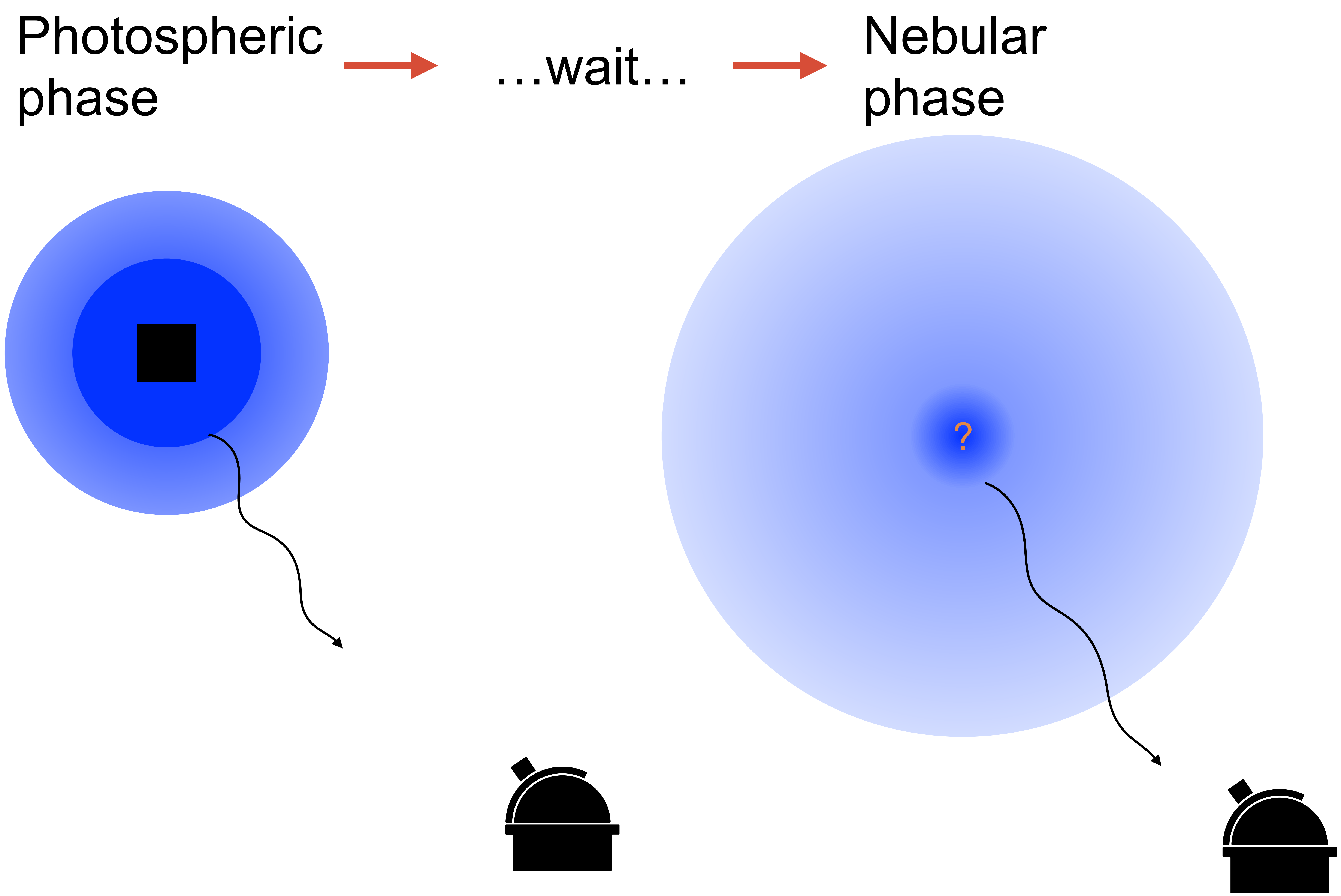
Density profile vs simulations

Suzuki & Maeda 2019





SLSNe at nebular times



Inner ejecta / engine a black box during optically thick phase

At late times, see composition and heating of interior directly

SLSNe at nebular times

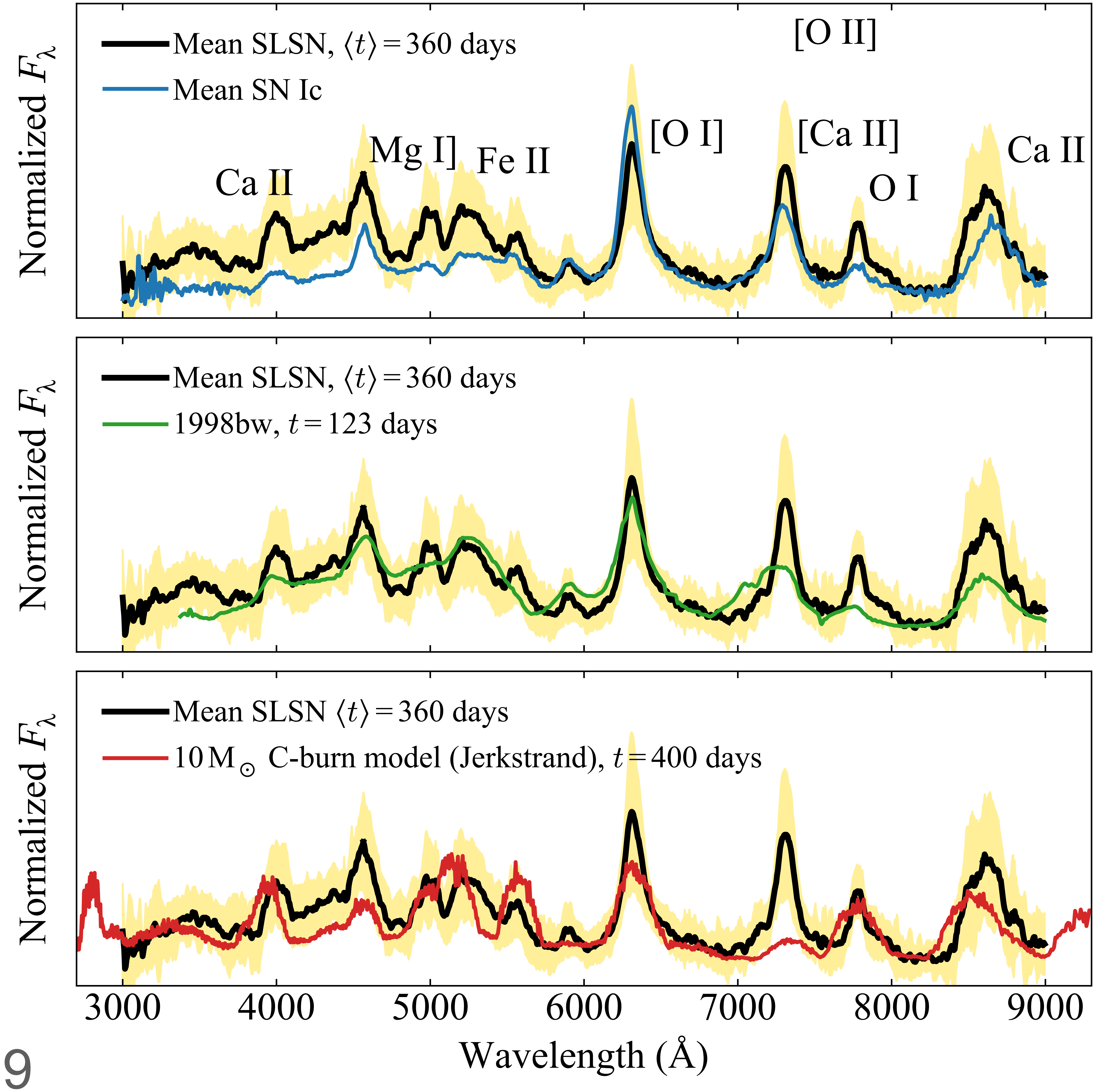
Same lines as SNe Ic, but more iron

Even better match to SNe Ic-BL / GRBs

Luminosity of [O I] 6300 line confirms ejecta mass up to few ×10 $M_\odot$

Persistent ionisation at low velocity coordinate:

- Narrow O I 7774 recombination line
- [O II] / [O III] present in many SLSNe



MN+ 2019

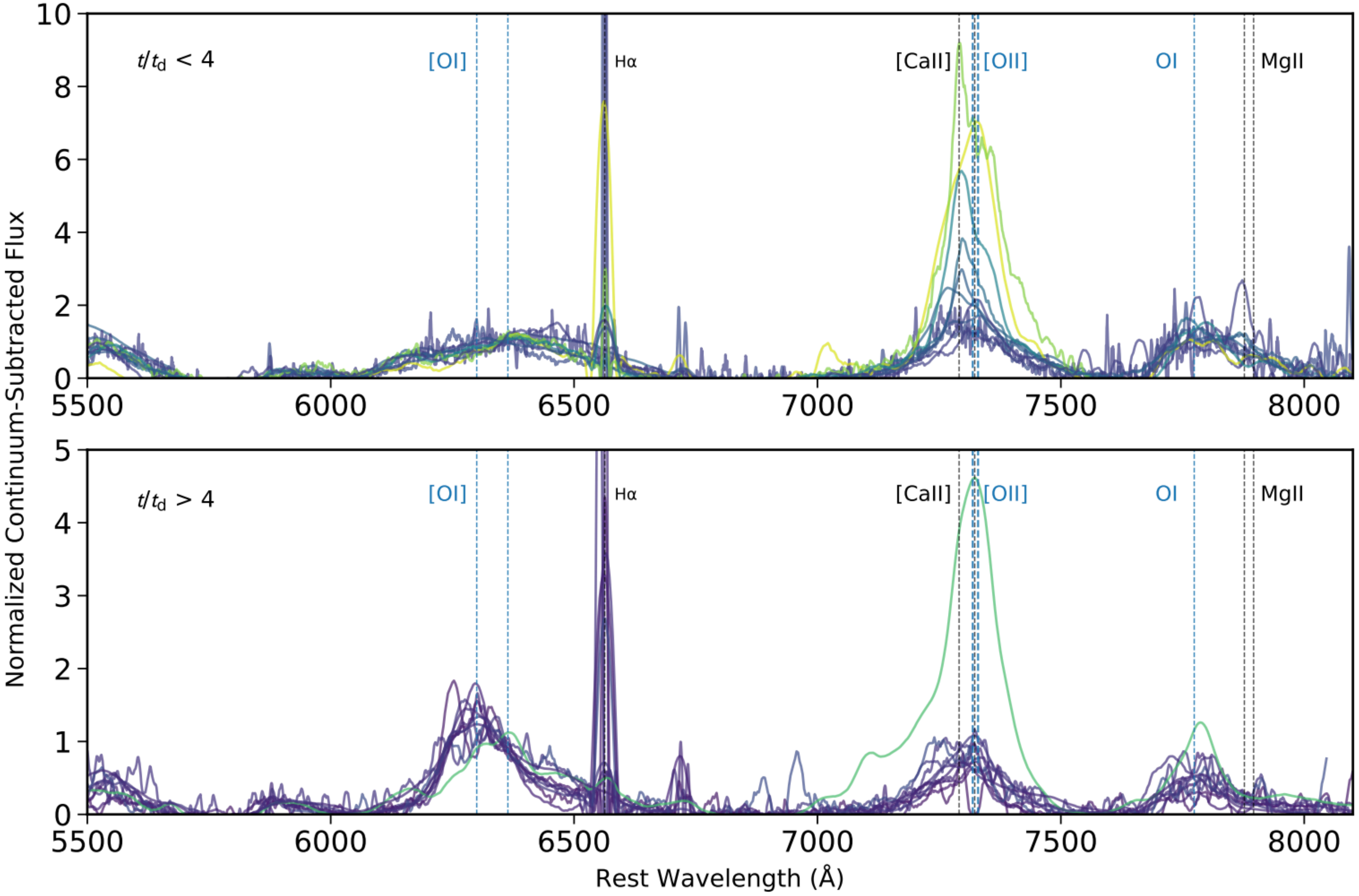
Power source from nebular spectrum

Recent result:

L_{7300} / L_{6300} probes ionisation

- ([Ca II] + [O II]) / [O I]
- More scatter at early phase

Can correlate ionisation with light curve properties…



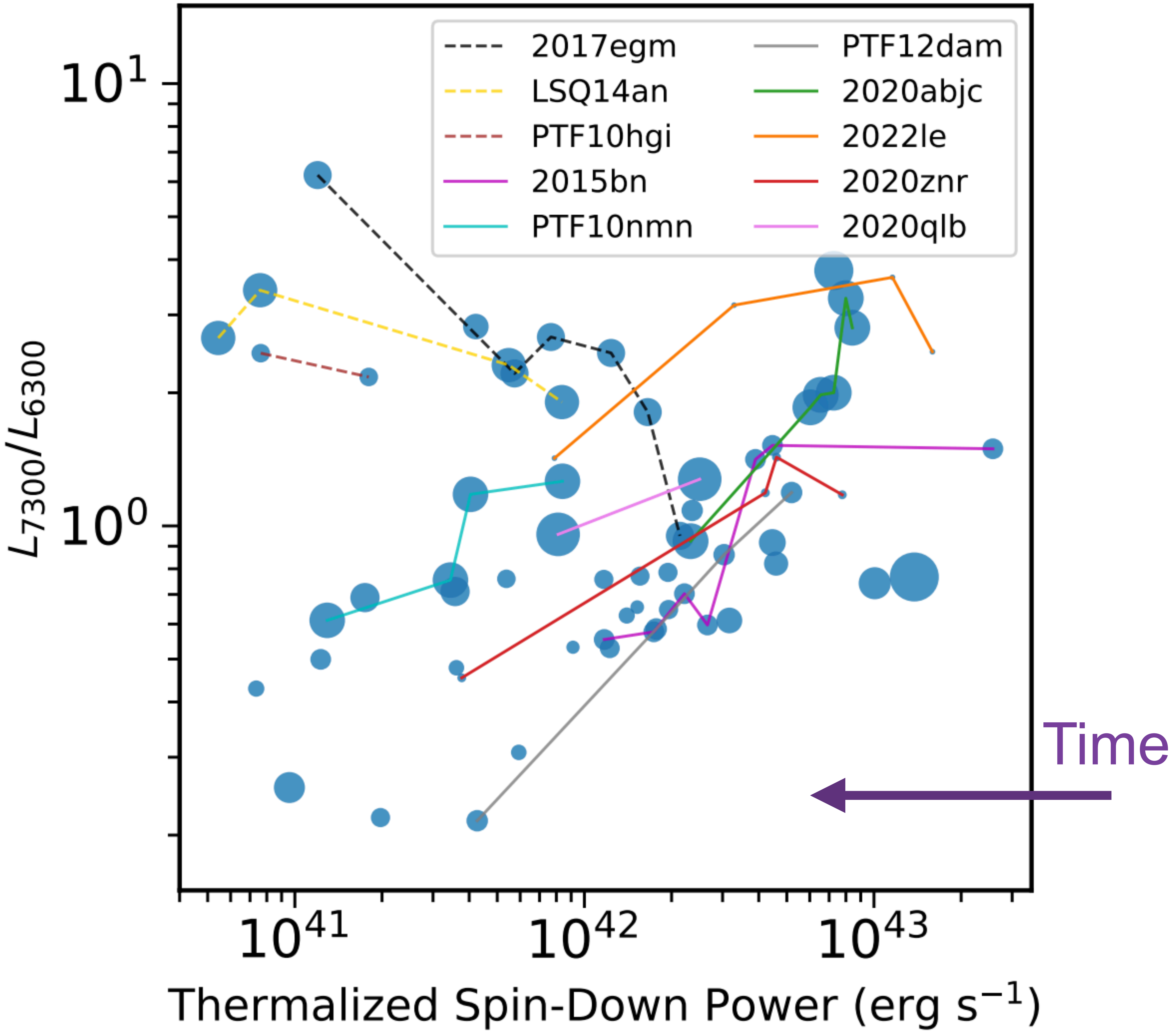
Blanchard+ 2025

Power source from nebular spectrum

For most events, ionisation is correlated with instantaneous power implied by magnetar fits

Three outliers (anti-correlated):

- 2017egm:
  known outlier (Aamer+ 2025)
- LSQ14an + PTF10hgi:
  very large L_{7300} (MN+ 2019)
  - Outliers interaction powered?

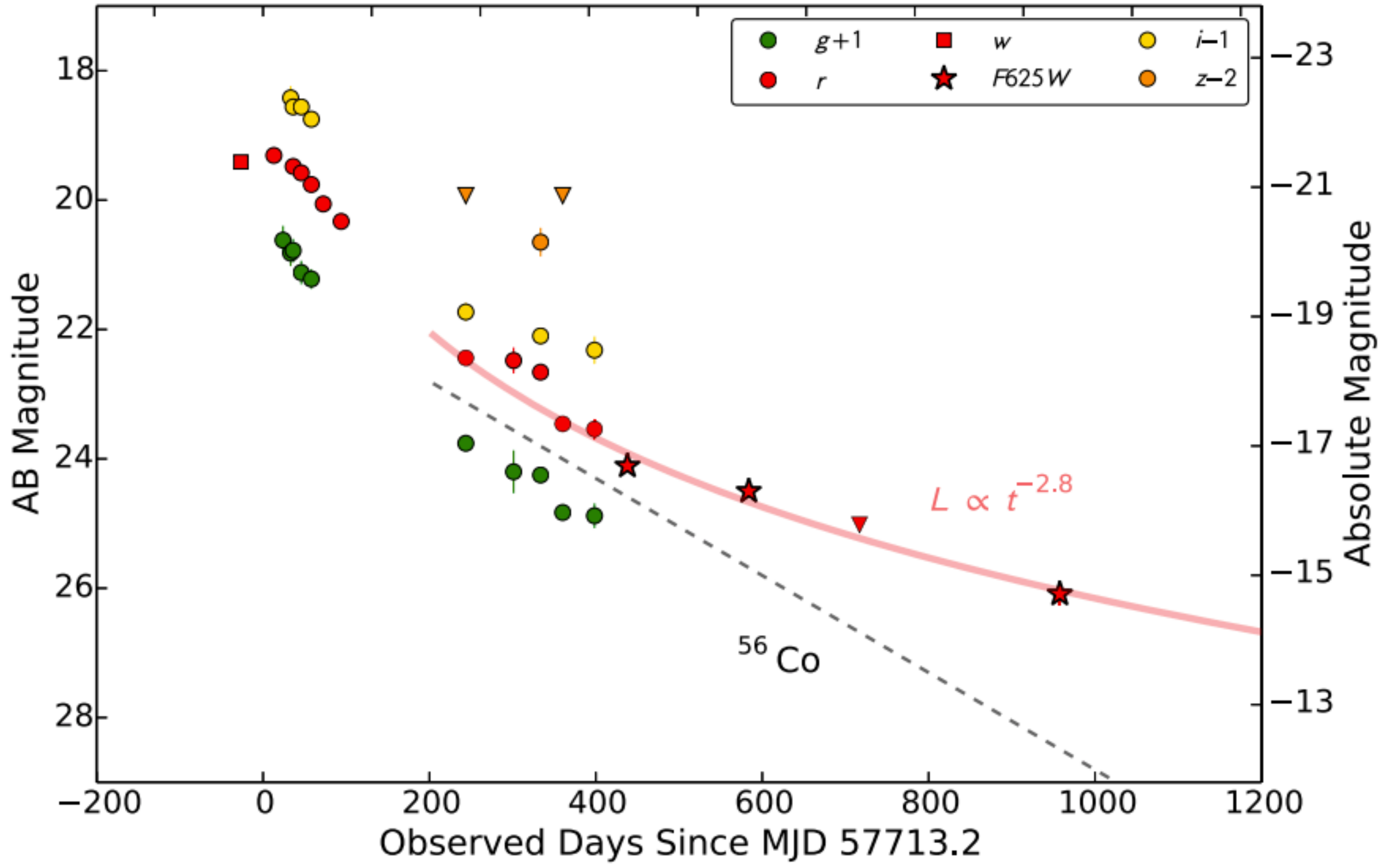


Blanchard+ 2025

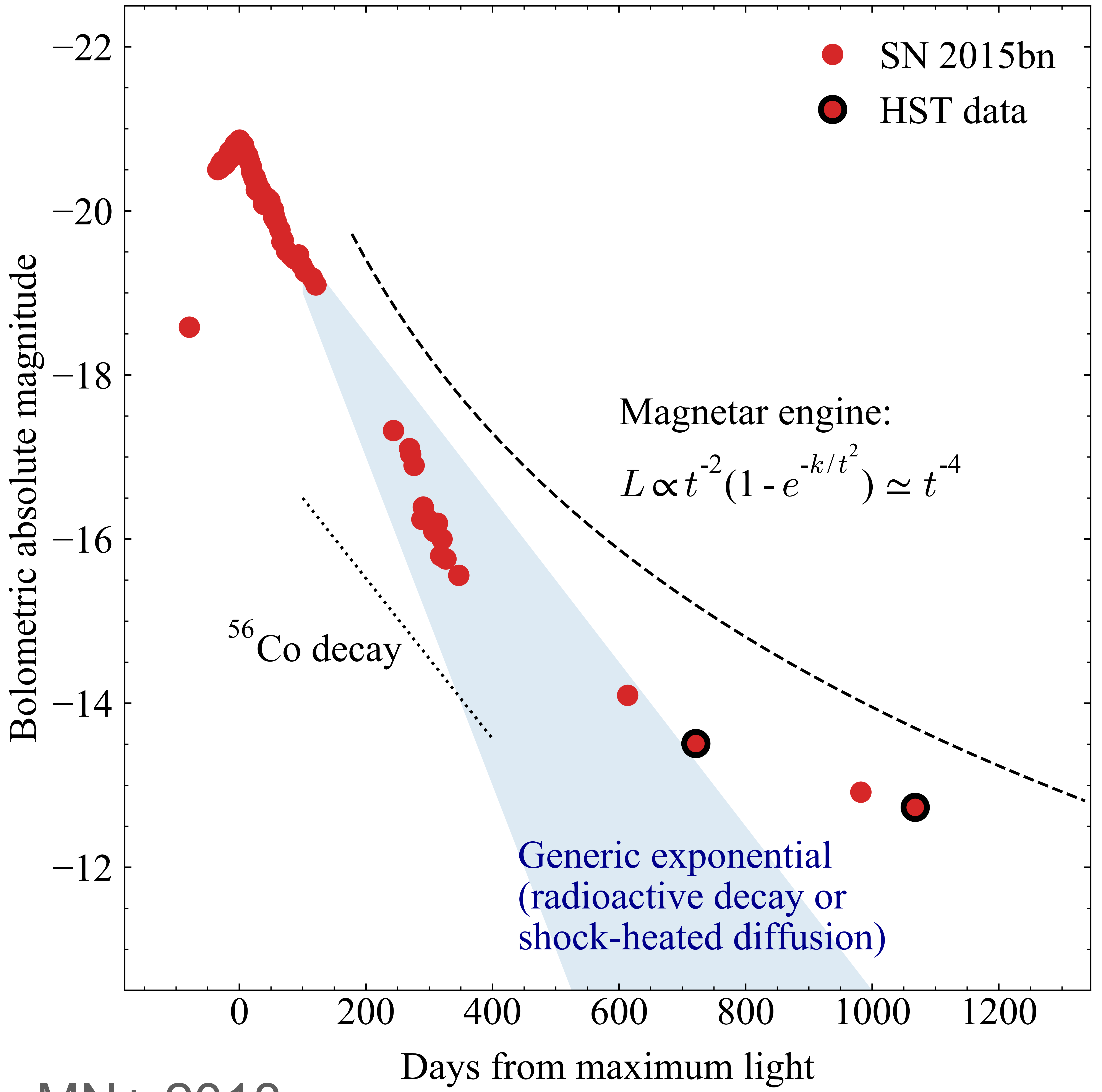
Late-time light curves

Visibly flatten and stay bright:
Can be −15 mag at ~3 years post-peak!

Most direct evidence for engine to date?



Blanchard+ 2021



MN+ 2018

So are they magnetars?

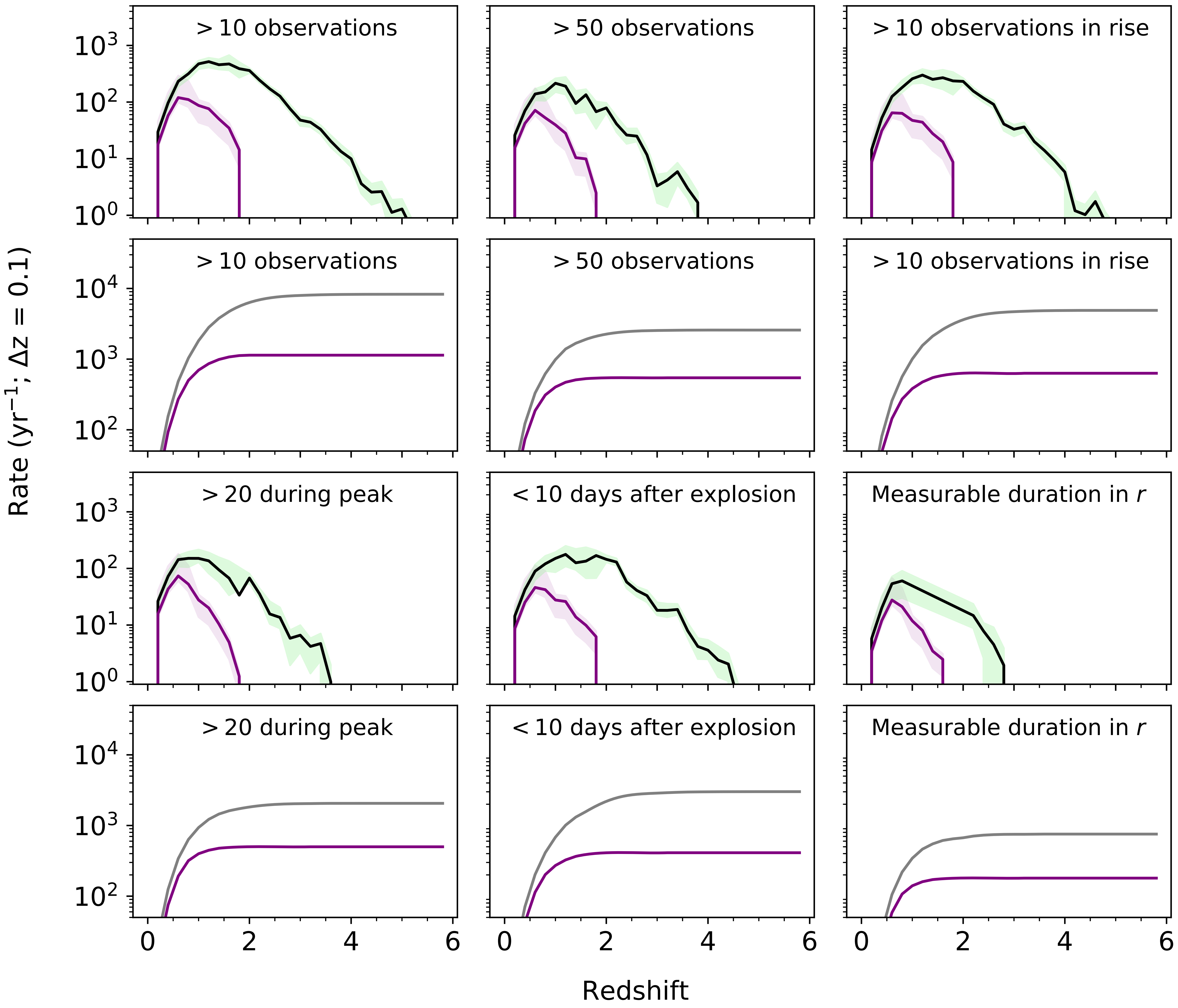
Evidence

- Photospheric properties consistent with central heating
- Shallow velocity gradients
- High ionisation at low velocity
- Late-time power-law light curves
- GRB connection (hosts and ULGRB)

Challenges

- How does the magnetar actually heat the ejecta?
- Clear evidence that some SLSNe do interact with environment
- Have no progenitor model: what stellar evolution produces millisecond magnetars?

SLSNe from Rubin + TiDES

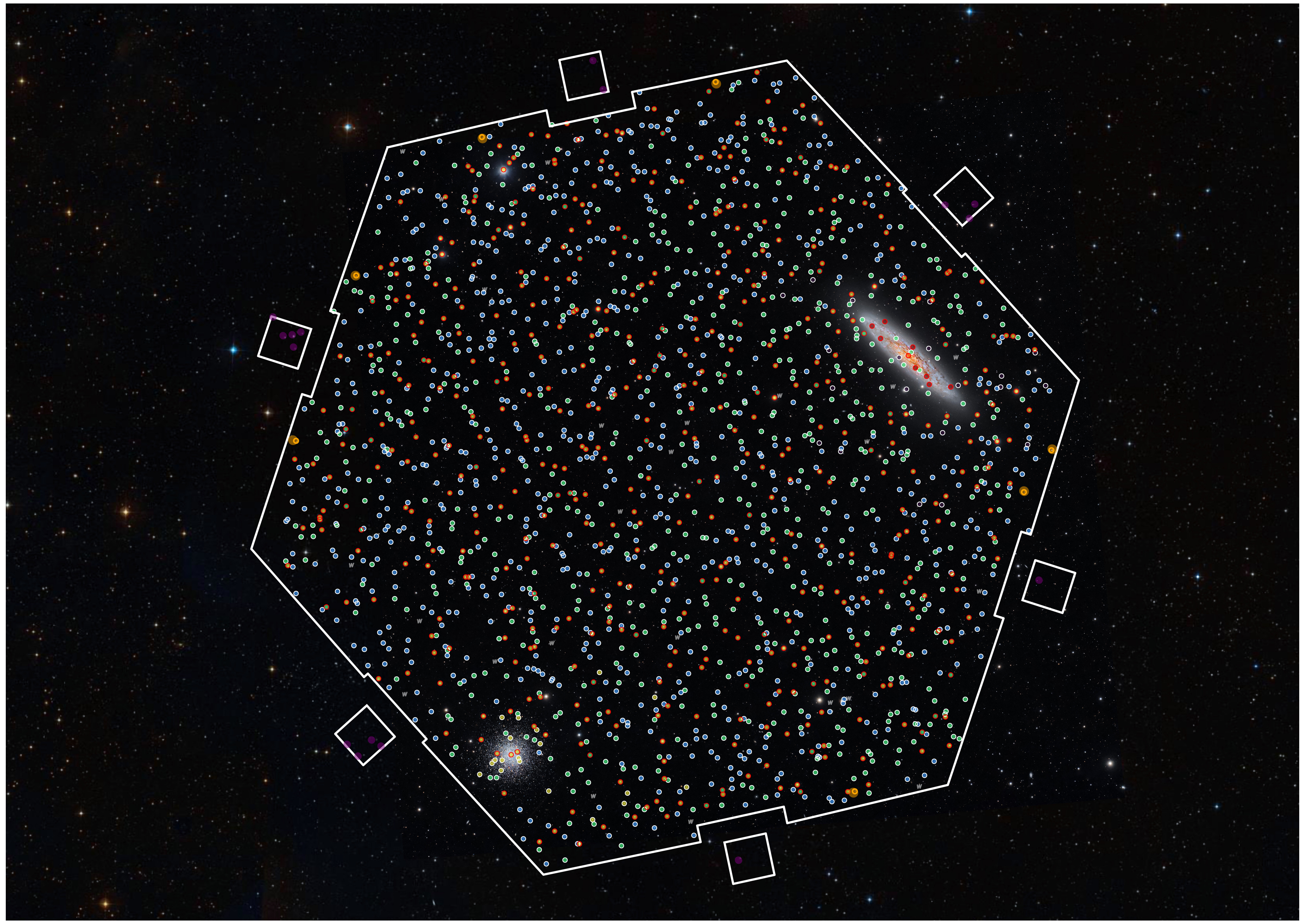


Villar+ 2018

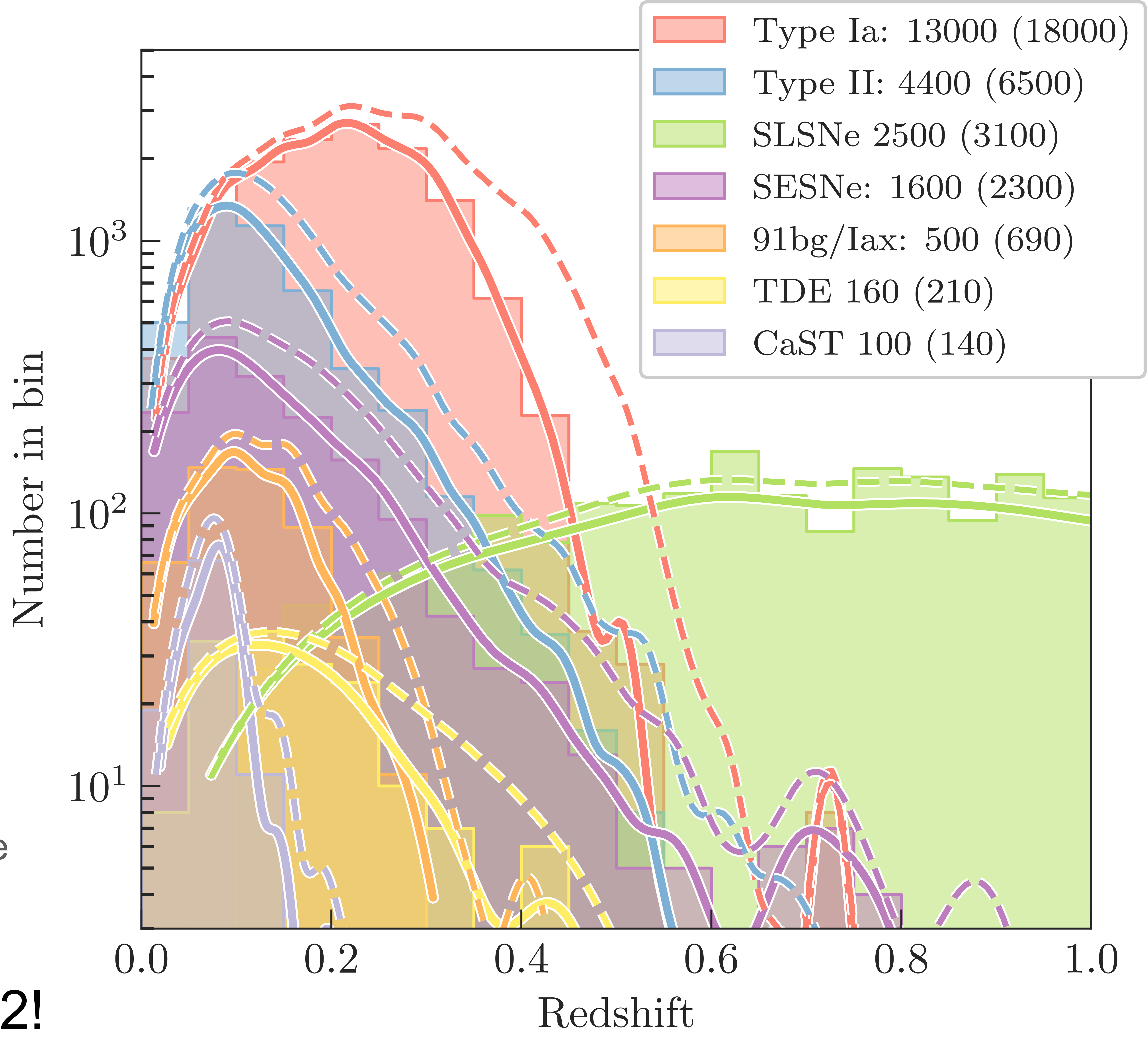
SLSNe from Rubin + TiDES

Frohmaier+ 2025

4MOST first light image



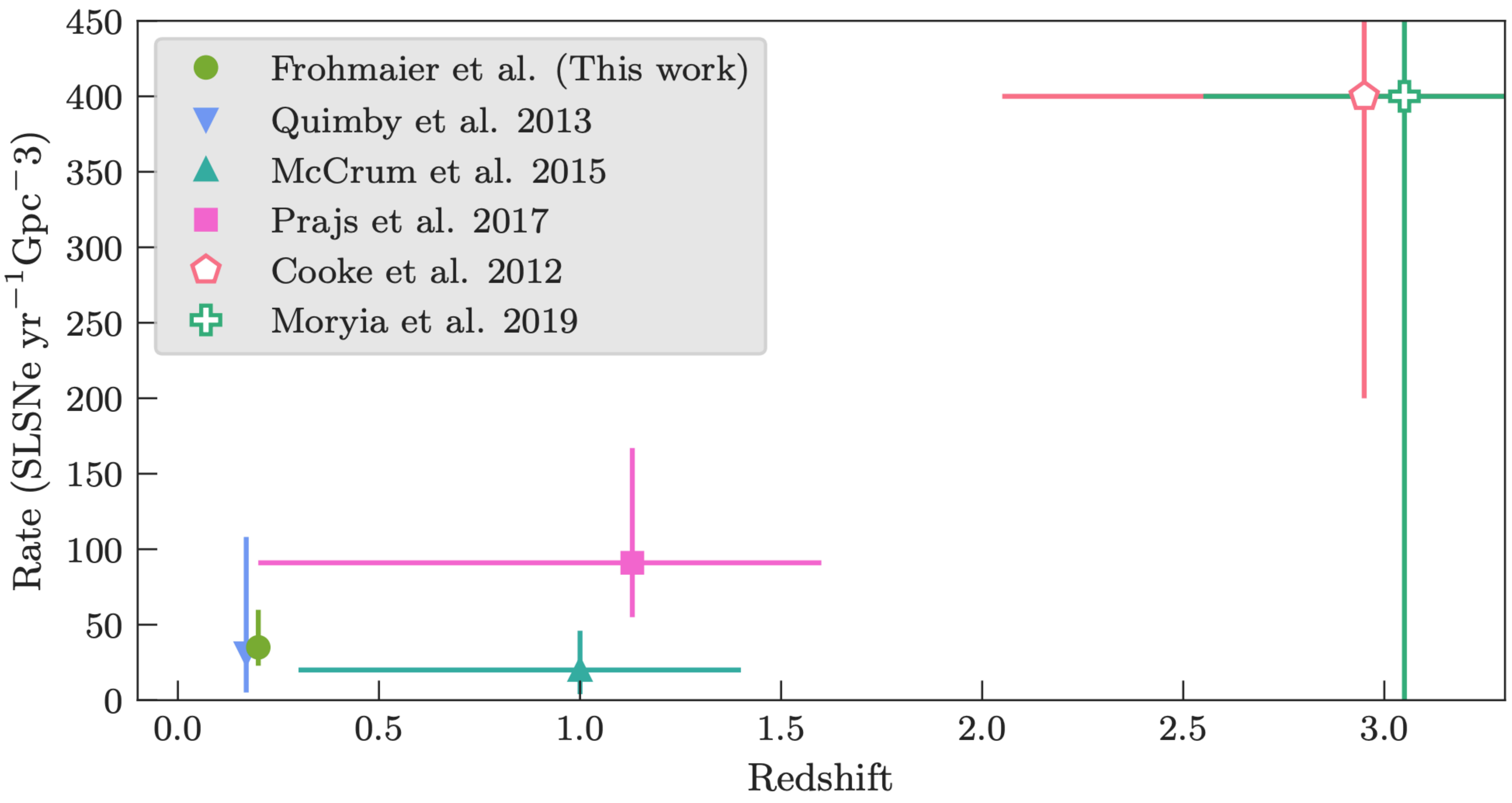
Credit: AIP/Background: Harshwardhan Pathak/Telescope Live



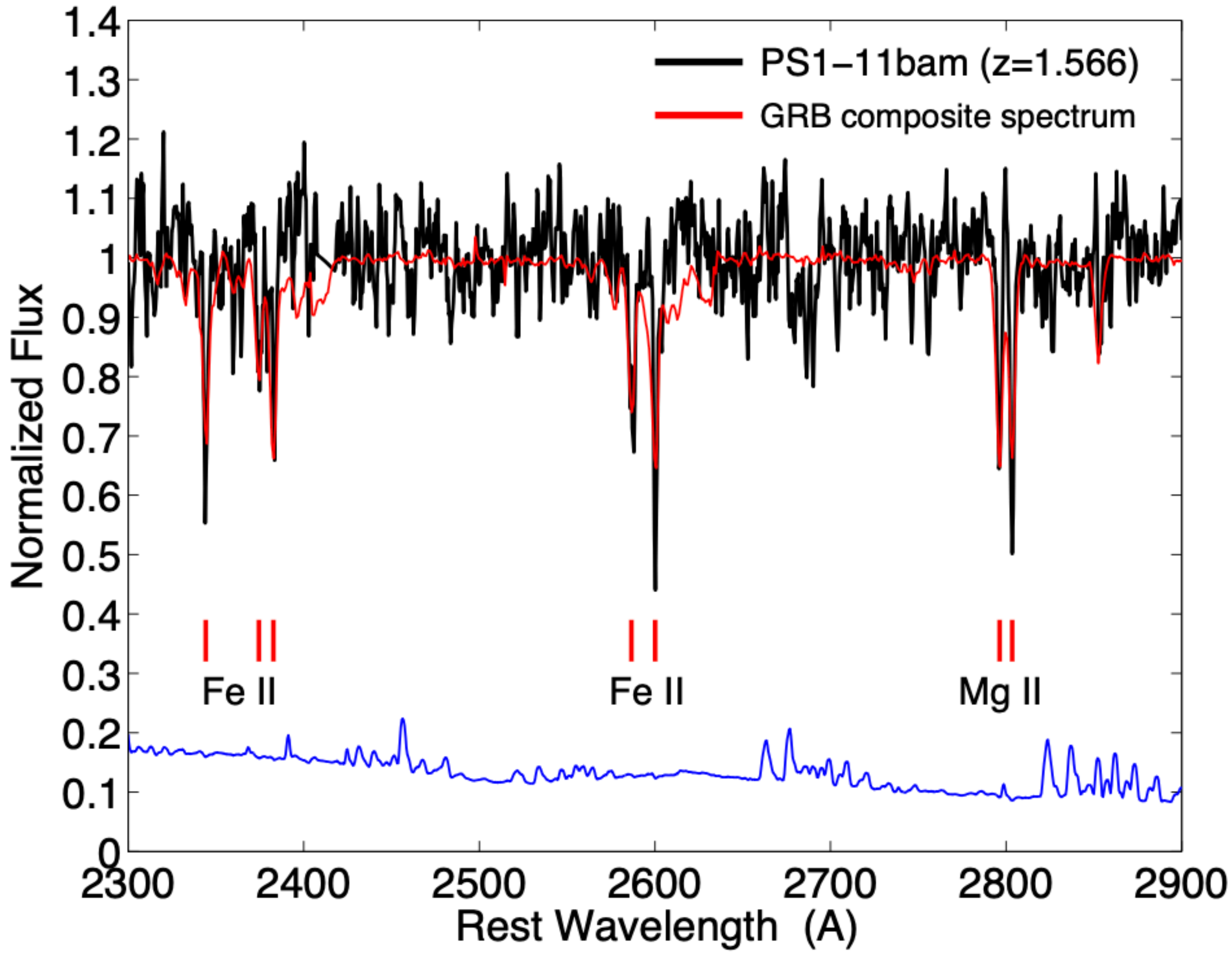
Unbiased sample of ~3000 SLSNe up to z~2!

Redshift evolution: metallicity dependence?

Need to constrain rate at z > 1

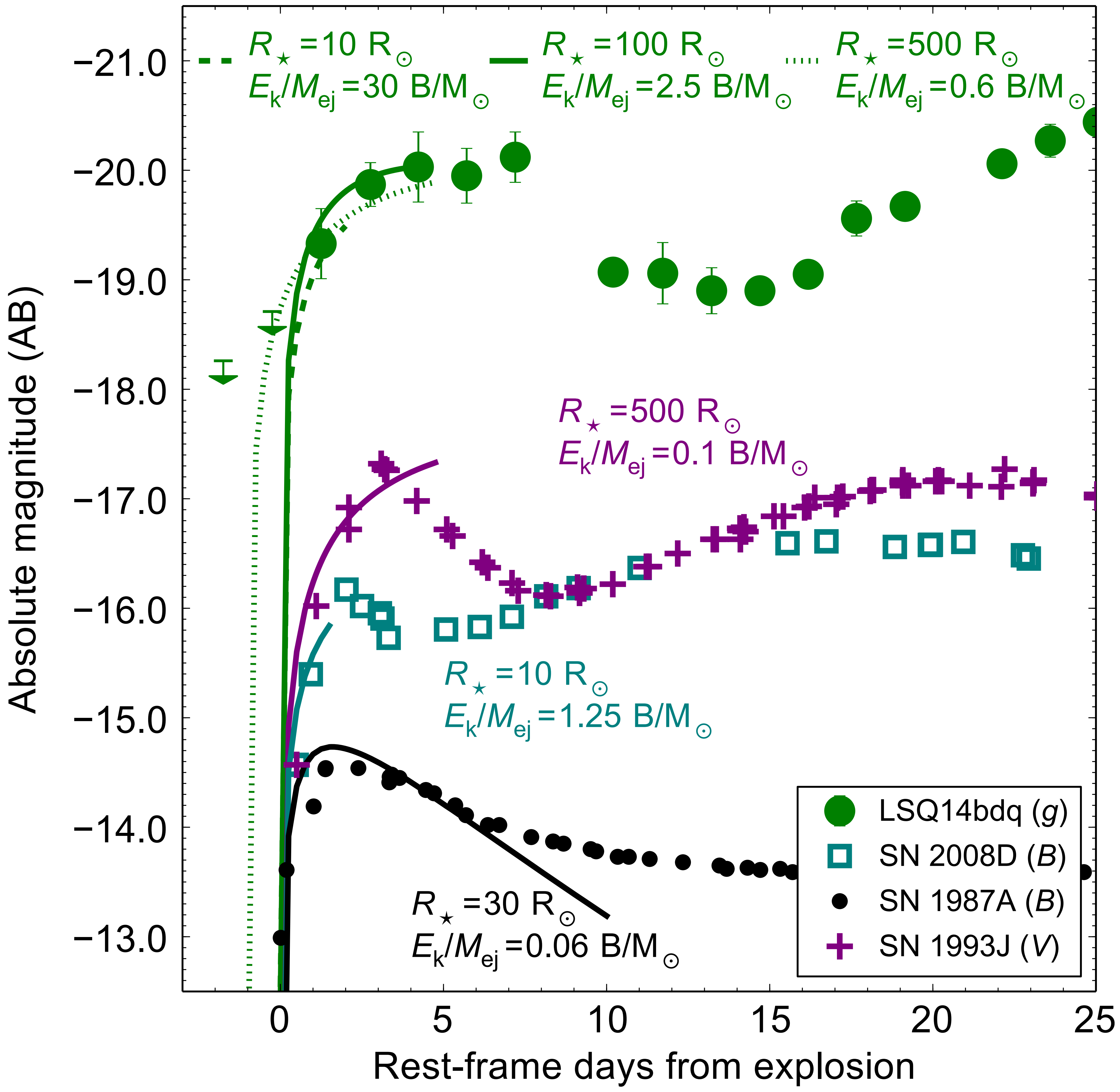


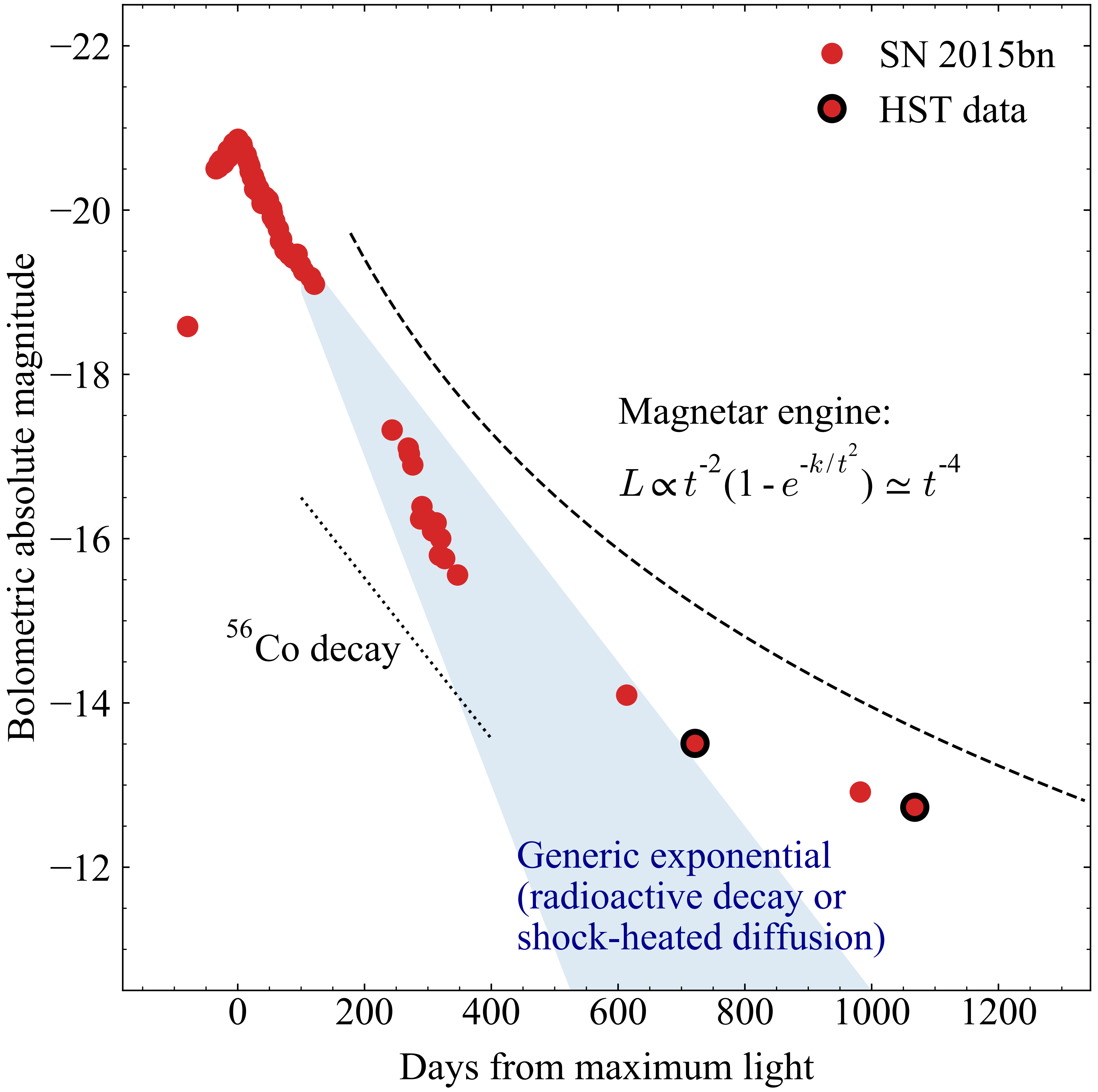
UV backlight for high-z star-formation



Berger 2012

Early spectra and late light curves (for free)



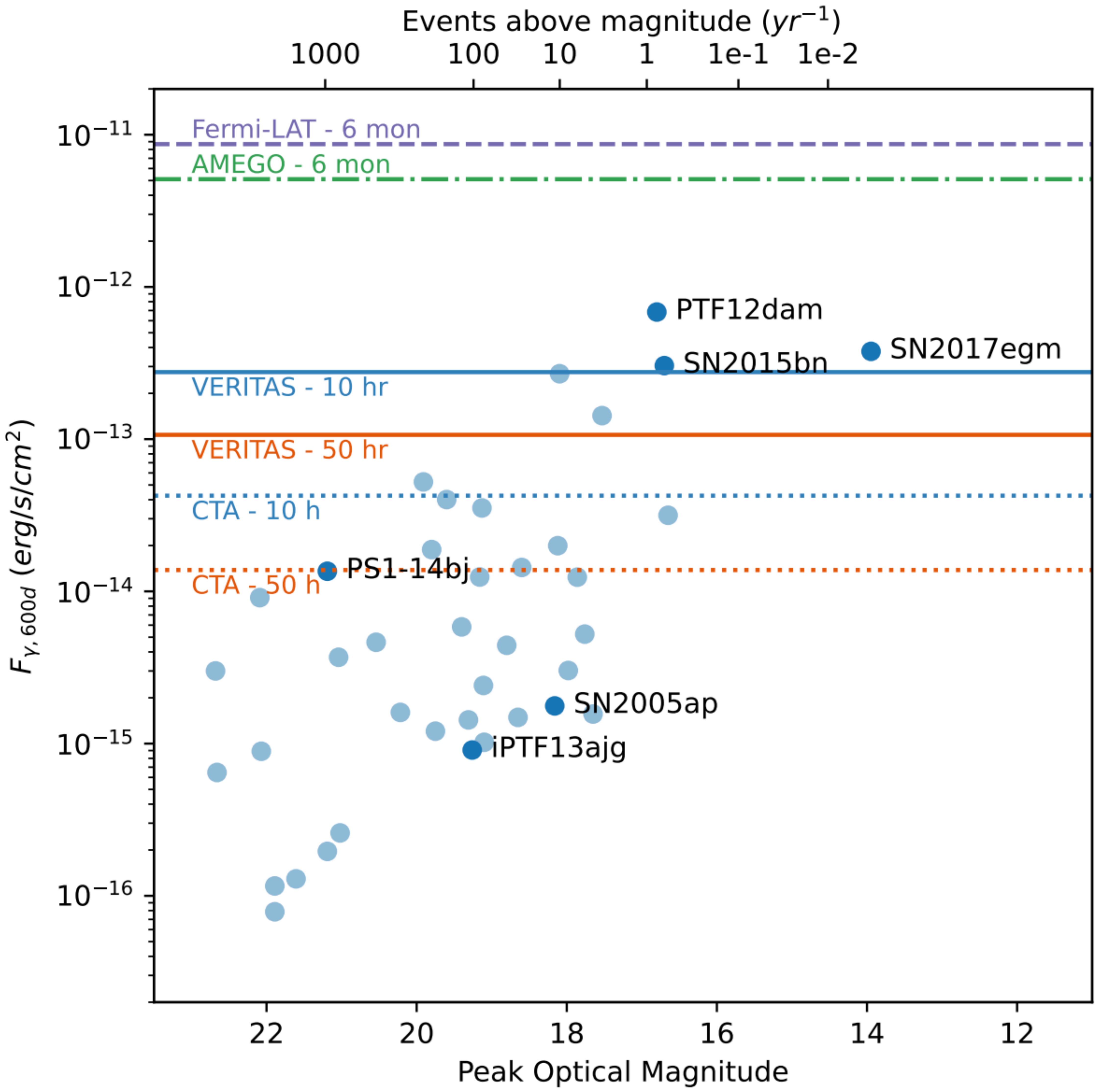


The real smoking gun?

If SLSNe are powered by magnetars, some radiation should escape and peak at GeV-TeV (Vurm & Metzger 2021)

Cherenkov Telescope Array could detect this emission for a few nearby SLSNe per year

CTA Large-Size Telescope, La Palma



Acharyya+ 2023

Conclusions

Large samples of SLSNe now becoming available

Very diverse, but properties mostly consistent with central heating source — magnetar spin-down?

But likely need CSM to describe some observables

Rubin detection rates will be a game-changer

Understand host associations, progenitors, and high-z galaxies

GeV observations could finally pin down the power source