Type Ia Supernova: A Standardizable Candle
CosmoVerseSchool @ Sofia May 25-29

Y. S. Murakami | Johns Hopkins University

Type Ia Supernova:

1. **SNe Ia as a Standardizable Candle: *Classical Picture***
2. **SNe Ia in Distance Ladder: *Coding Demo***
3. **Assessing Sysetematics & New Surveys: *Modern Picture***

- What is a Type Ia supernova?
- How does it help cosmology?
- Where does the data come from?
- How can I use data for my own analysis?
- Outlook – a new generation of supernova cosmology

Type Ia Supernova: A Standardizable Candle

Part I: Observational Facts
Part II: SNe Ia data: from telescope to "m_B"
Part III: Major SNe Ia surveys/dataset

→ Measure expansion history of the universe

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- Known, Fixed Luminosity
- Available at a wide range of redshifts
- Variation can be corrected from additional observables

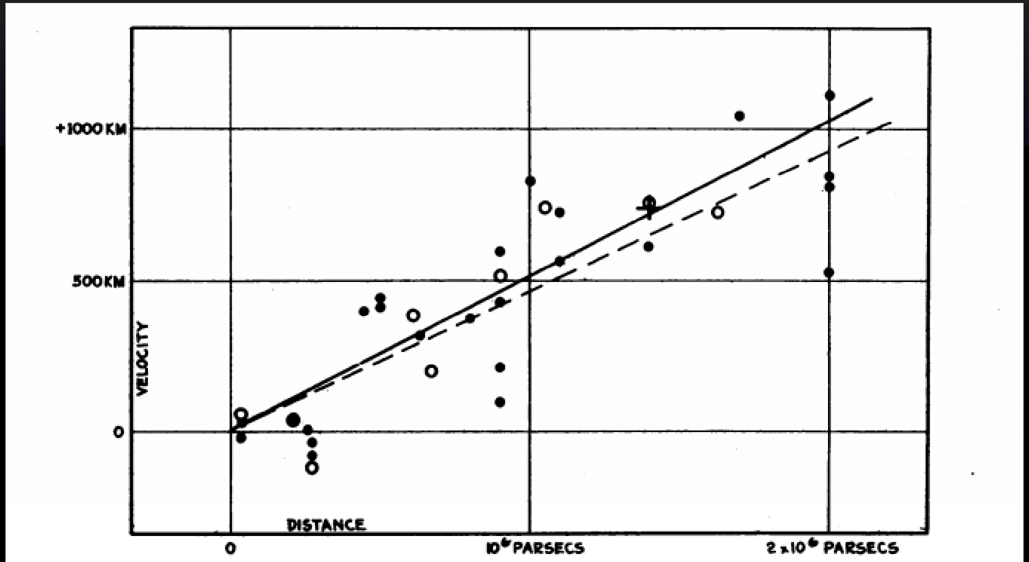

FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

→ Measure expansion history of the universe with Standard / *Standardizable* candles

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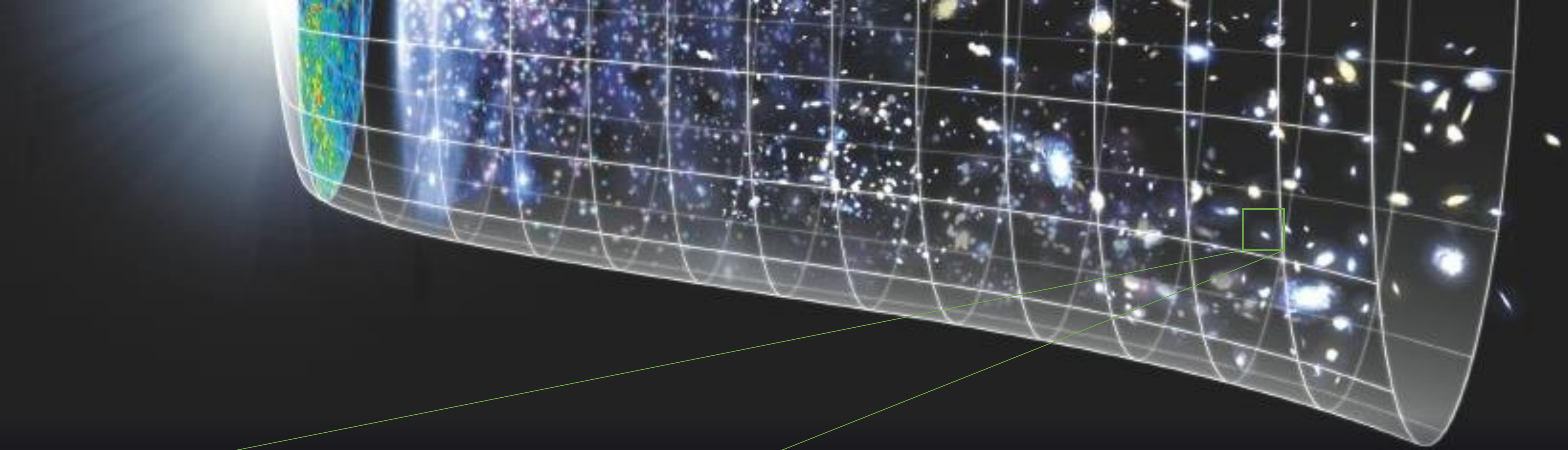
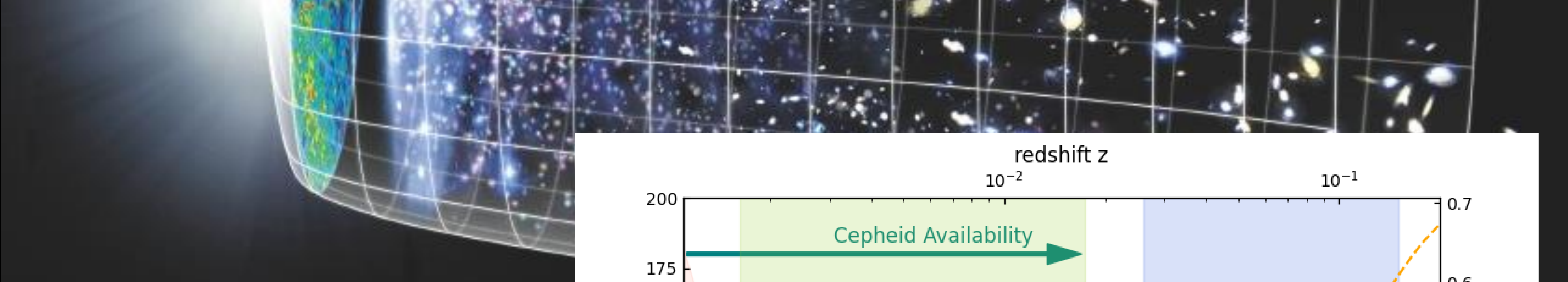


Type Ia supernova ($SN\ Ia$):

extremely bright standardizable candle

- Known, Fixed Luminosity
- Available at a wide range of redshifts
- Variation can be corrected from additional observables

→ One of the most successful standardizable candles



Q: Why do we need SNe Ia?

Designing the experiment:

- Peculiar velocity
- Cepheids availability
  (Per-host noise vs. Statistics)
- SNe Ia availability
  (Per-SN noise vs. Statistics)
- Model-dependent systematics

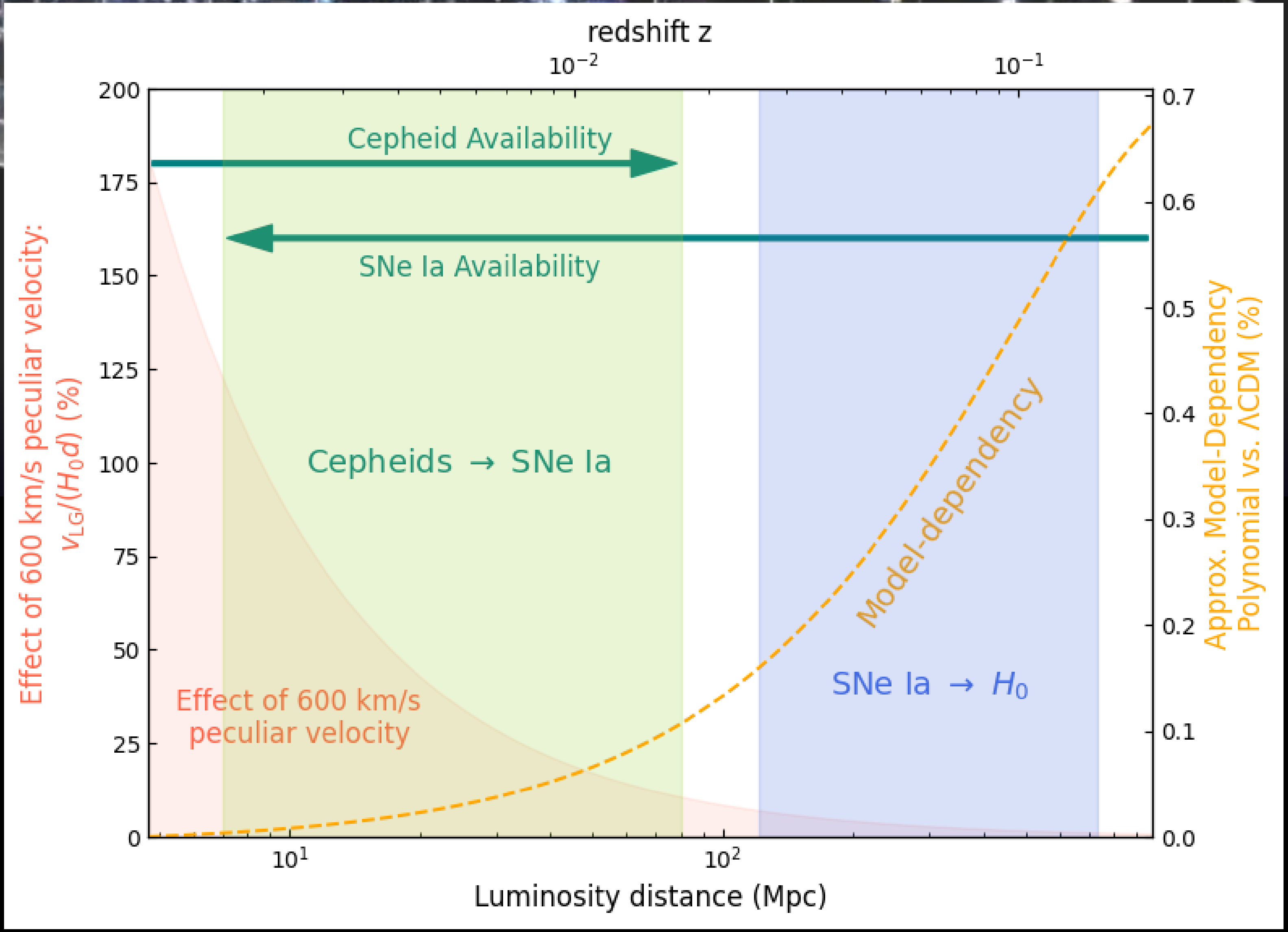
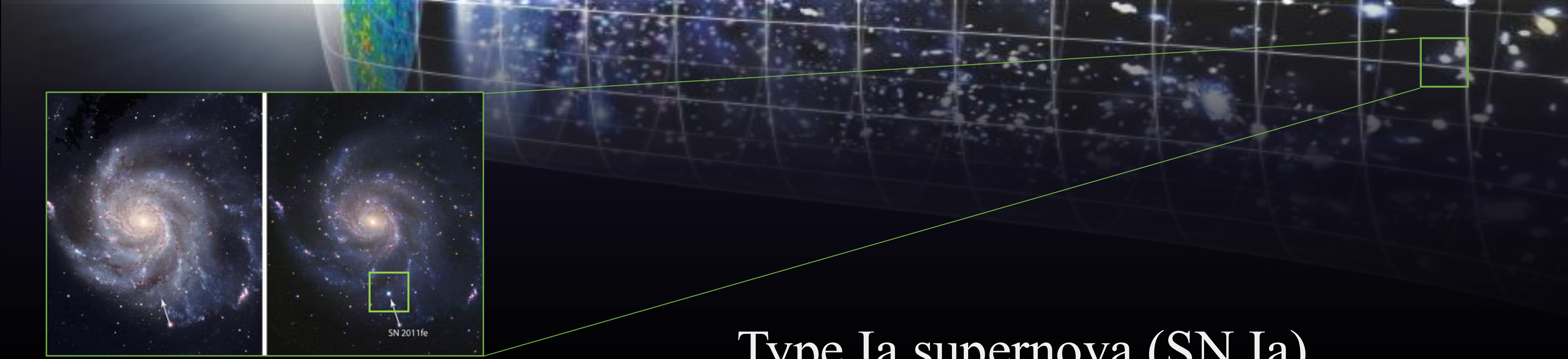


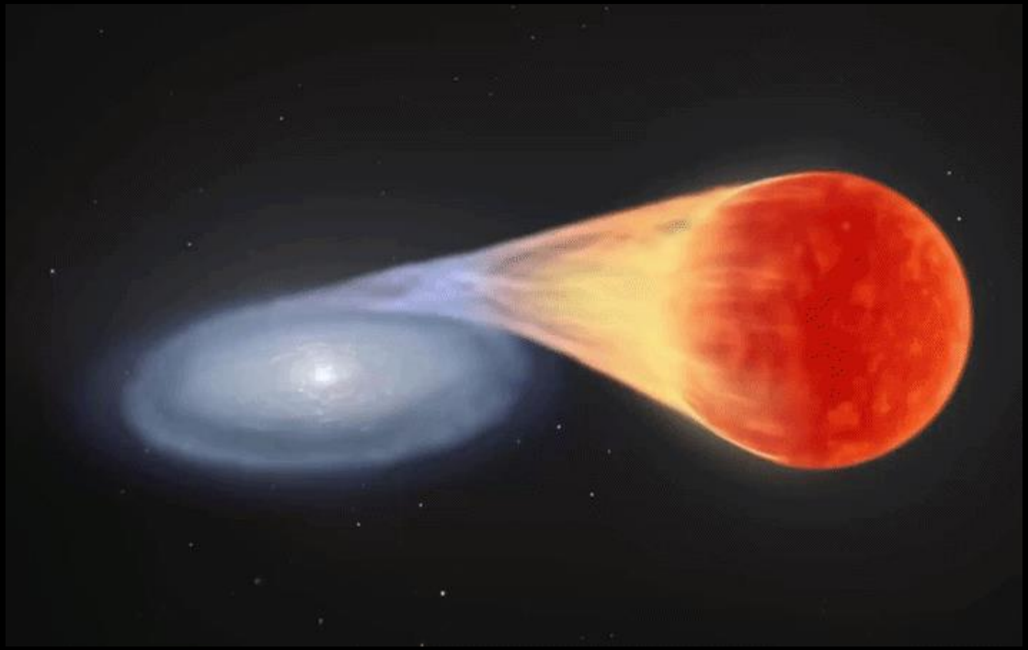
Image: YM



Type Ia supernova (SN Ia)

Extra-bright New Star

Fig. 1: Nova the cat



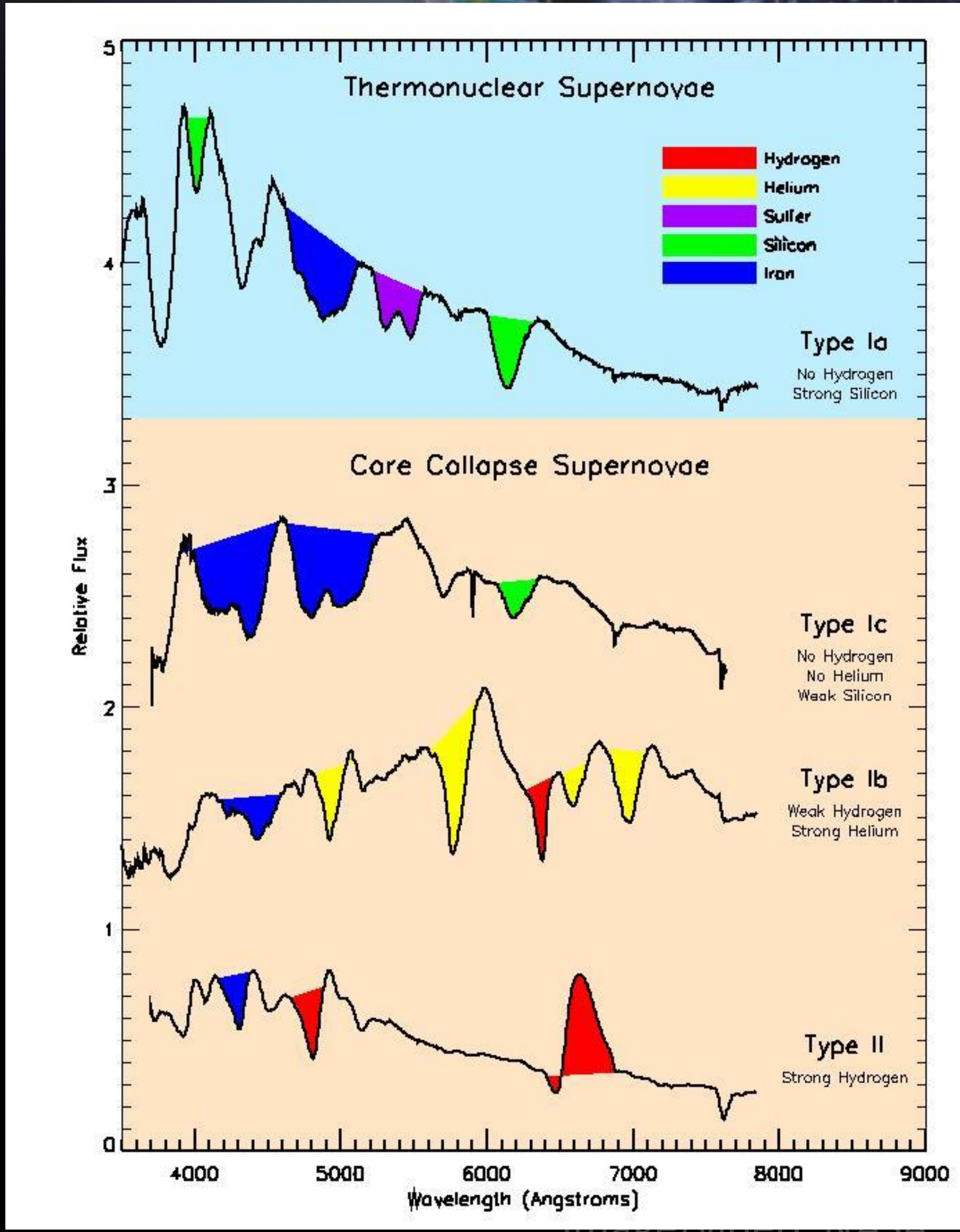
Image/video: NASA

Observation:

- A sudden (~two weeks) appearance of a new star
- As bright as the entire galaxy
- No progenitor has been observed

Theory says:

- A thermonuclear explosion of White Dwarf
- Mass transfer from binary companion (MS, WD, etc.) or merger causes explosion



Image/video: NASA

Credit: Dan Kasen

Type Ia supernova (SN Ia)

No Hydrogen, Strong Silicon + Sulfur

Fig. 1: Nova the cat

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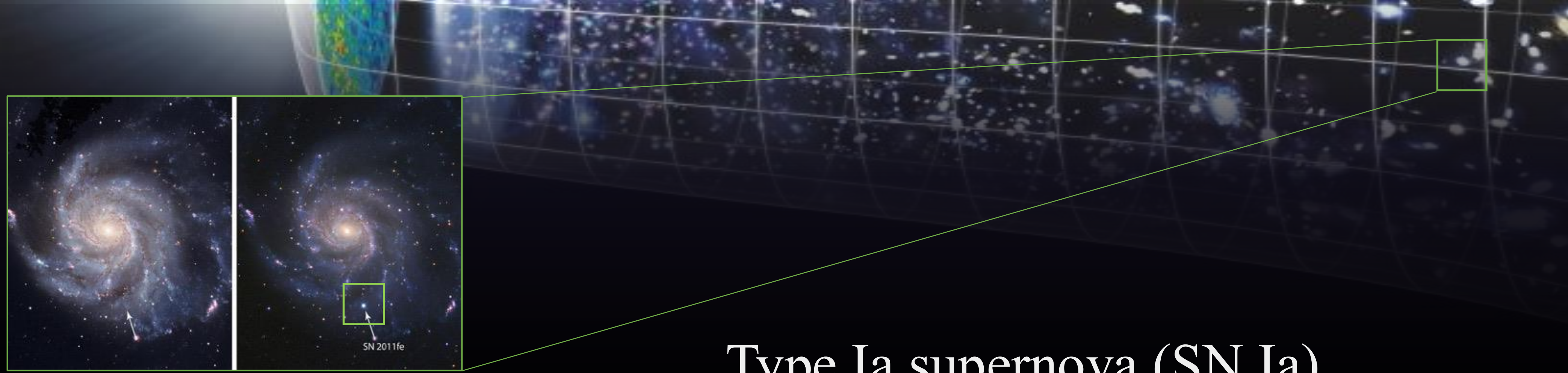

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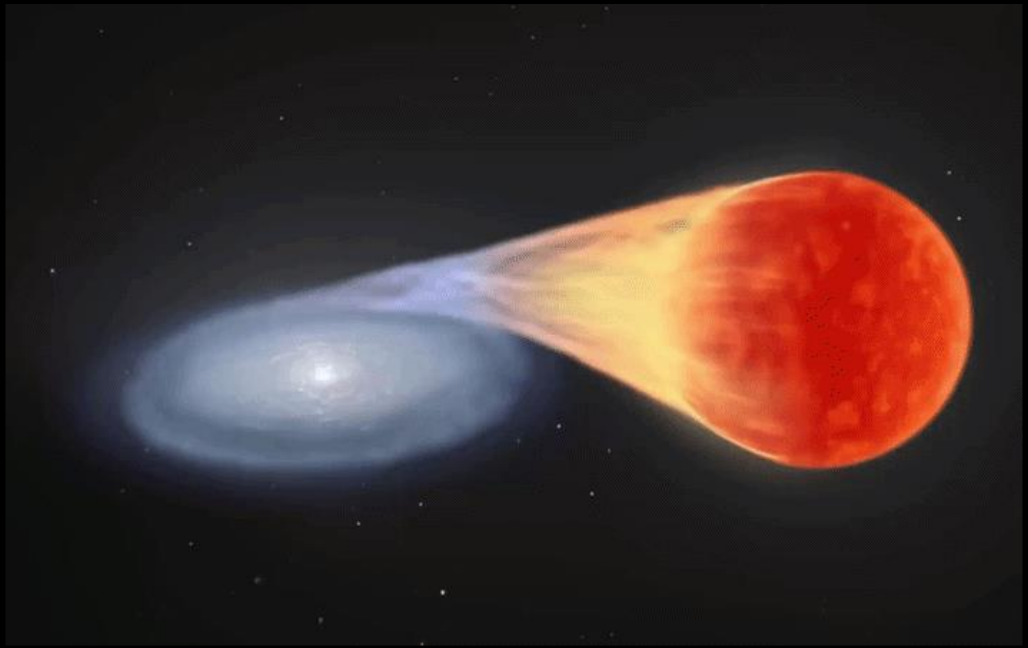

Image/video: NASA

Brightness is relatively tight (~0.4 mag)
Textbook explanation:

- White Dwarf (degenerate electrons) supported by Femi pressure loses to self gravity at Chandrasekhar mass (Mch) near 1.4Msun, ignites carbon
- Slowly approaches Mch by accreting mass from binary companion

More accurate explanation (example):

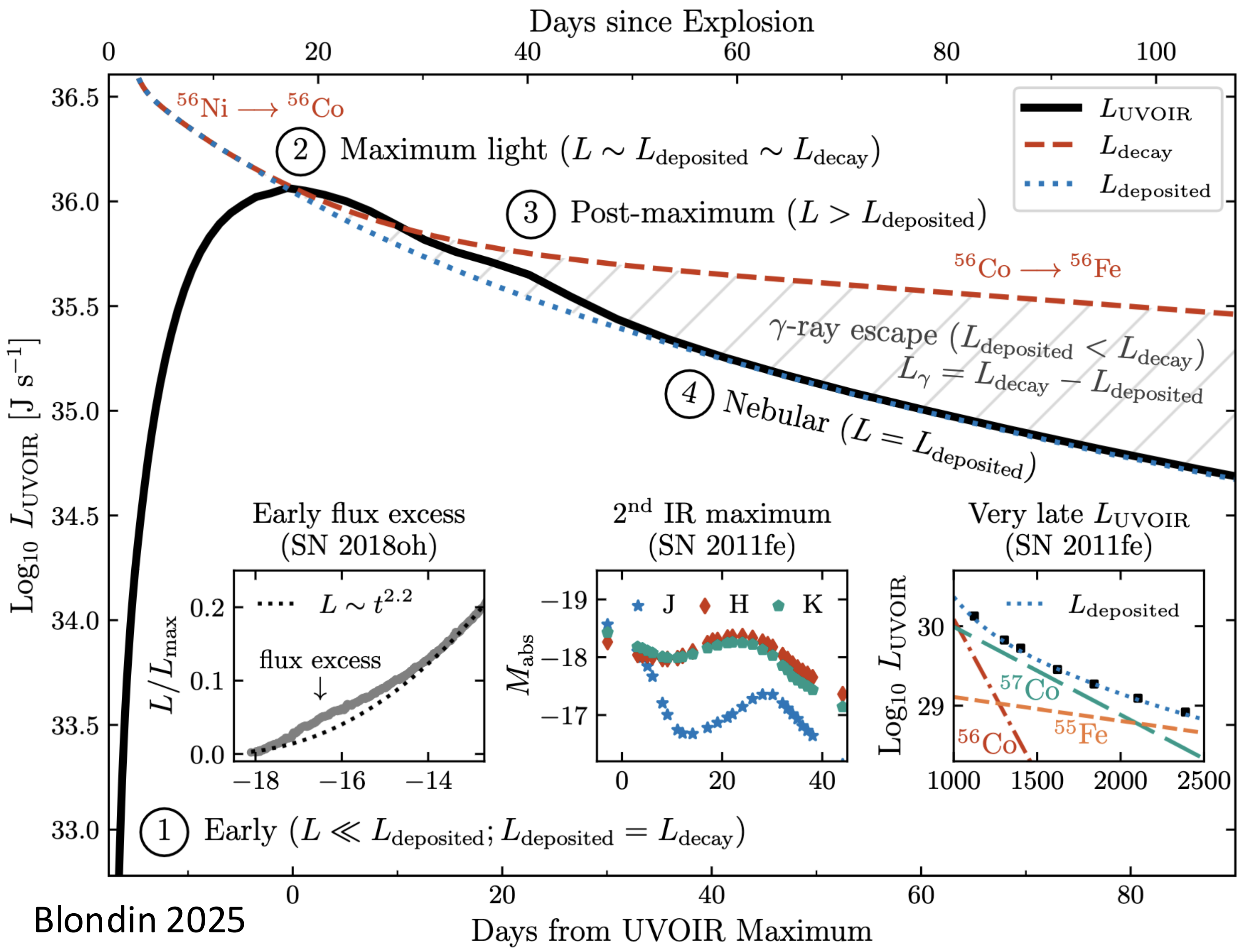
- Carbon ignites at the temperature near Mch
- Outer He shell flash + shock wave starts carbon burn

Type Ia supernova (SN Ia): Fueled by ^{56}Ni-^{56}Co decay

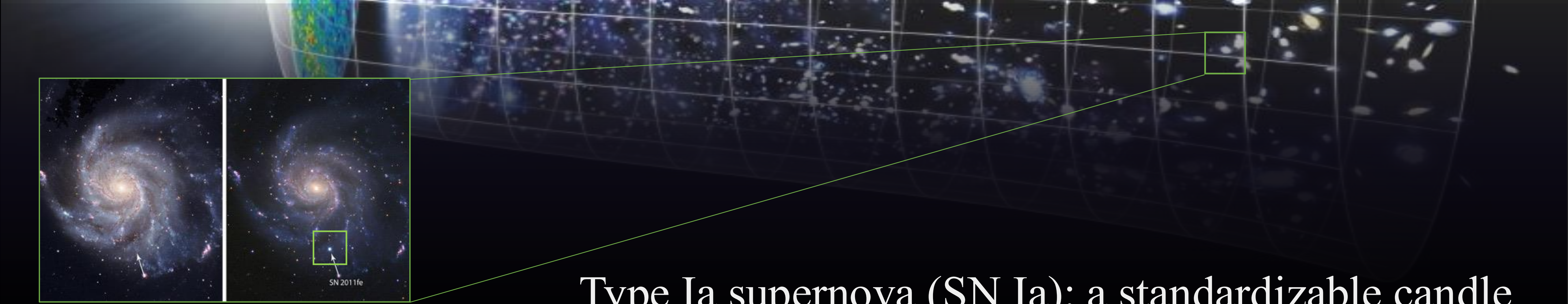
Ejecta captures energy from gamma-ray
→ Compton scattering
→ Thermal radiation + line-transitions

$$^{56}\mathrm{Ni} \xrightarrow[t_{1/2}=6.1\,\mathrm{days}]{Q_\gamma=1.7\,\mathrm{MeV}} {}^{56}\mathrm{Co} + \gamma + \nu_e\ (\mathrm{EC})$$

$$\xrightarrow[t_{1/2}=77.2\,\mathrm{days}]{Q_\gamma=3.6\,\mathrm{MeV};\,Q_{e^+}=0.1\,\mathrm{MeV}} {}^{56}\mathrm{Fe} + \gamma + \nu_e\ (\mathrm{EC})$$

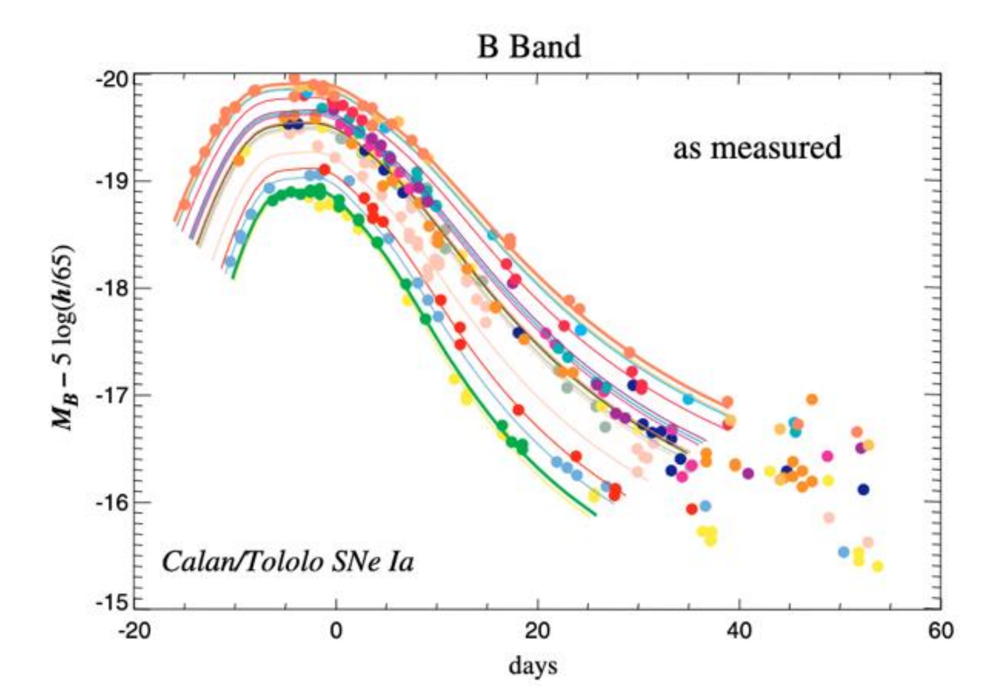


Blondin 2025



Type Ia supernova (SN Ia): a standardizable candle

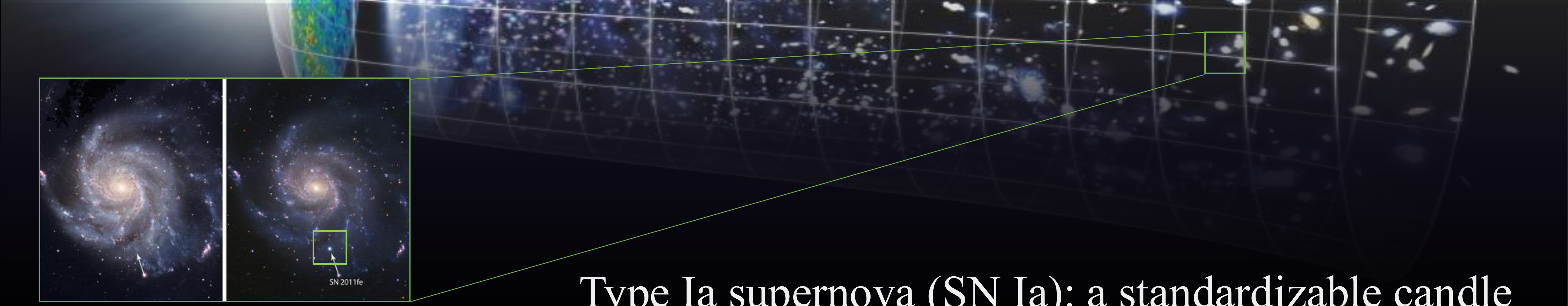
Brightness



Time

Light Curve provides:

- Overall brightness
- Decline rate
- Color



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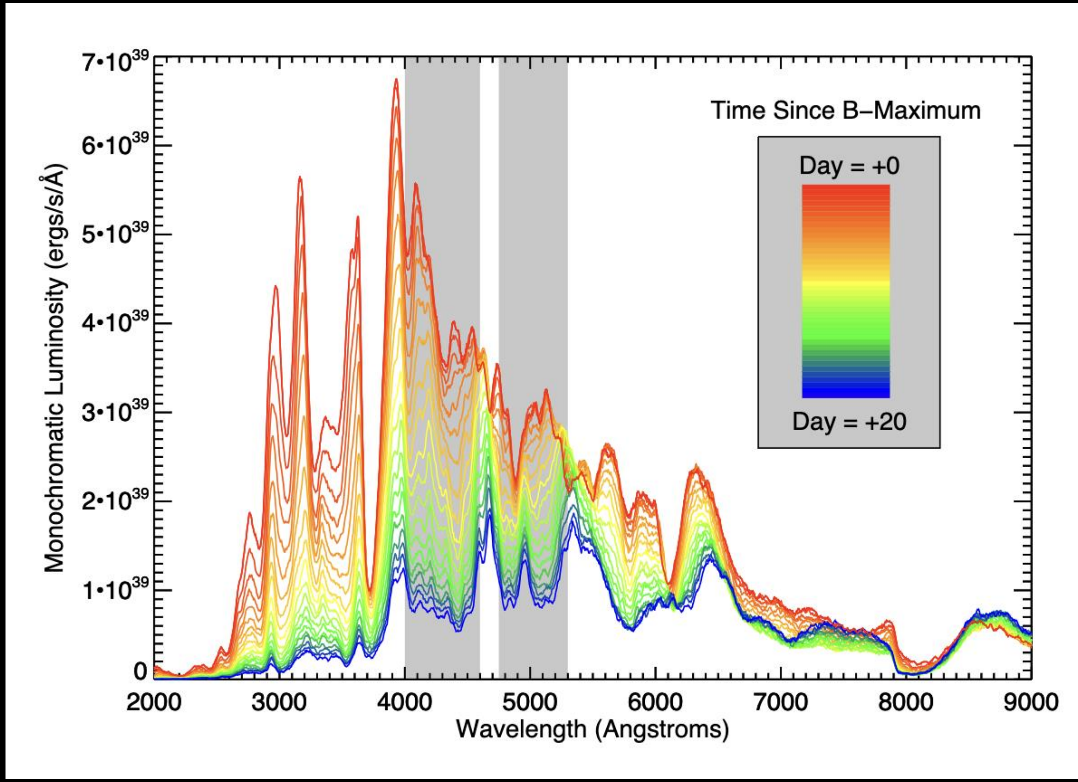


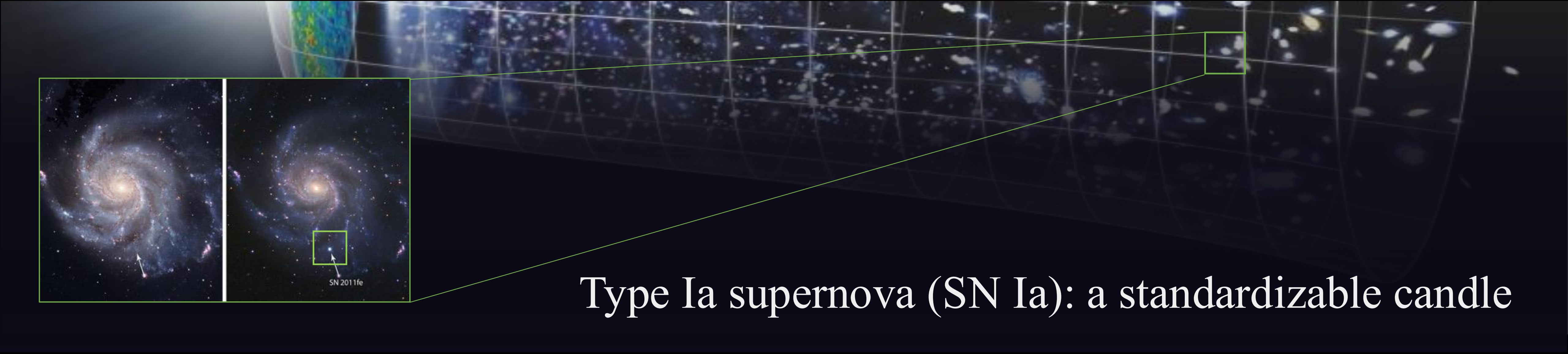
Brightness is relatively tight (~0.4 mag):

Mostly determined by:

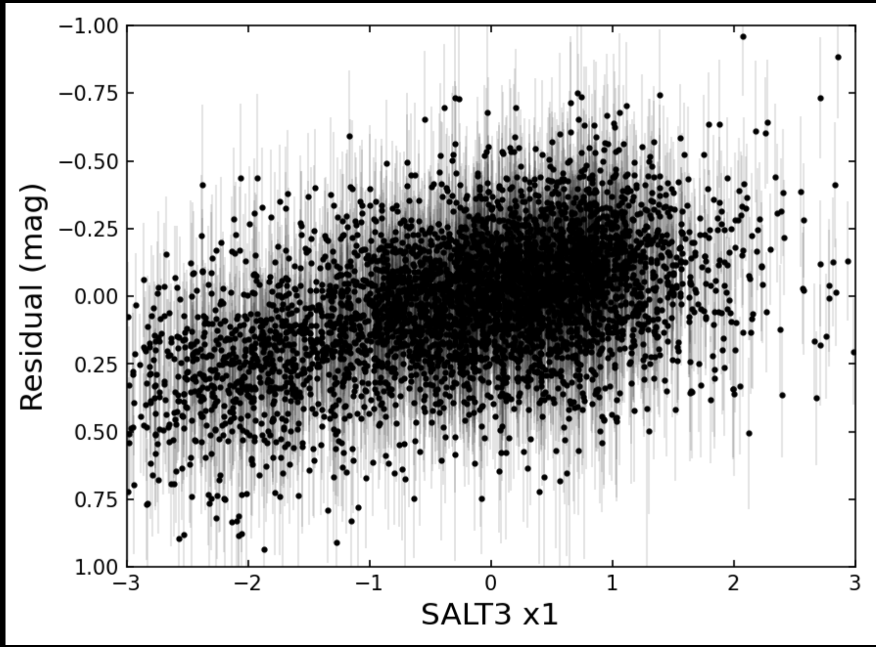
+ Stretch-Luminosity relation (Ni mass)
+ Color-Luminosity relation (intrinsic + dust)

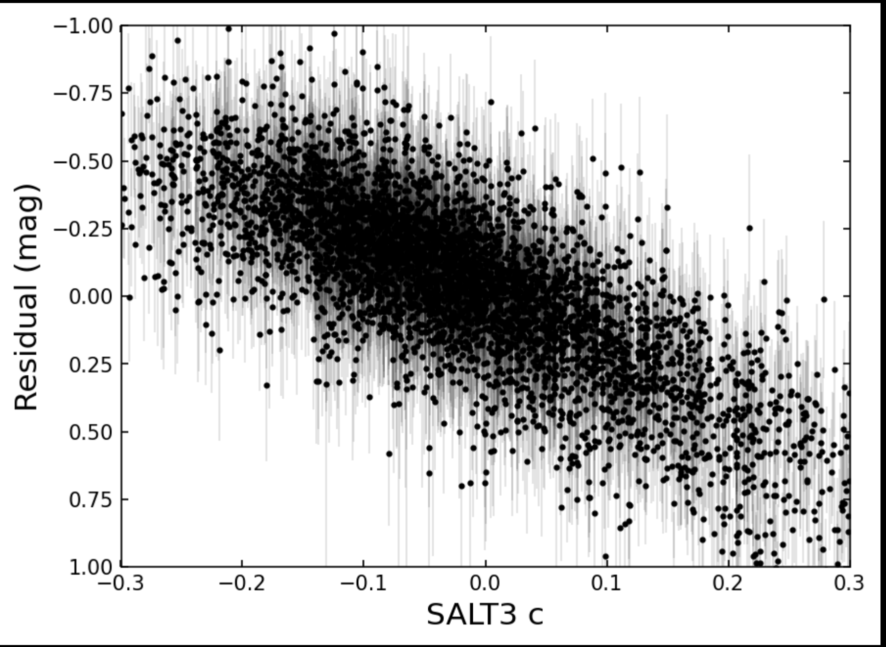
Kasen&Woosley 2006

Type Ia supernova (SN Ia): a standardizable candle



Brightness





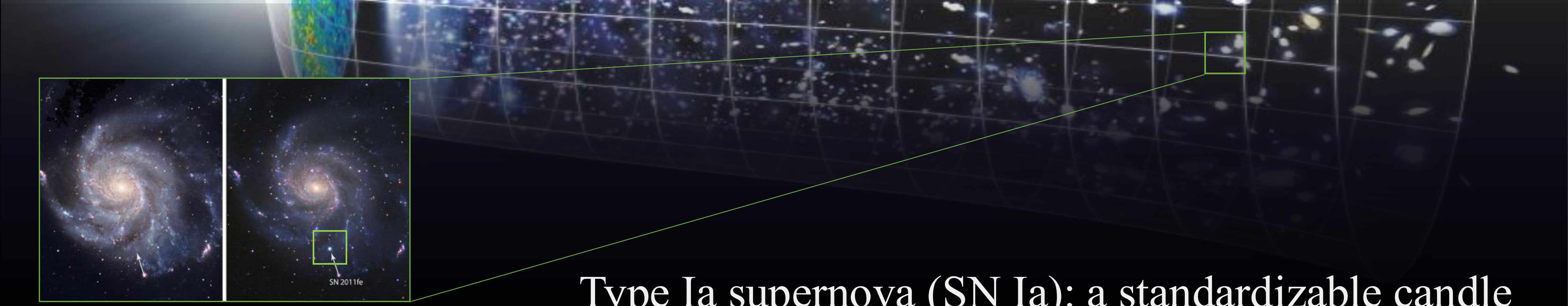
Fast ← decline → slow

Blue ← color → Red

Light Curve provides:

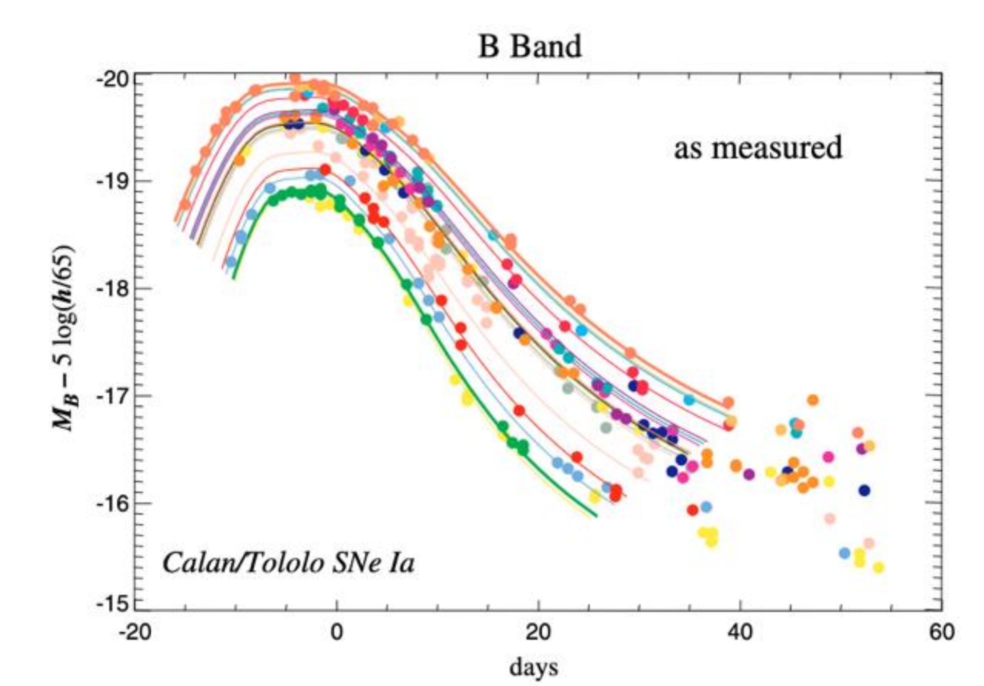
- Overall brightness
- Decline rate
- Color

figures: YM

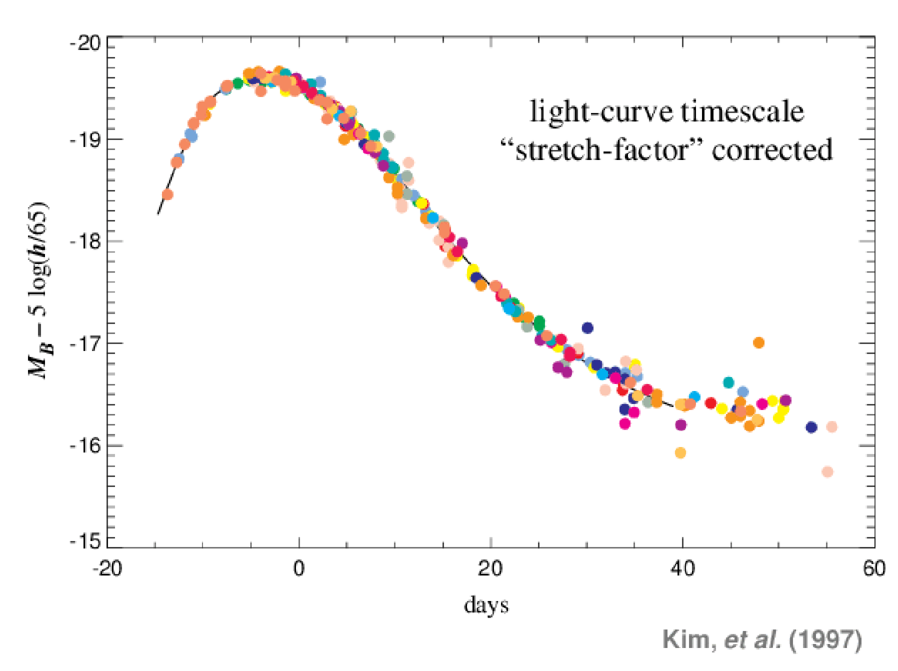


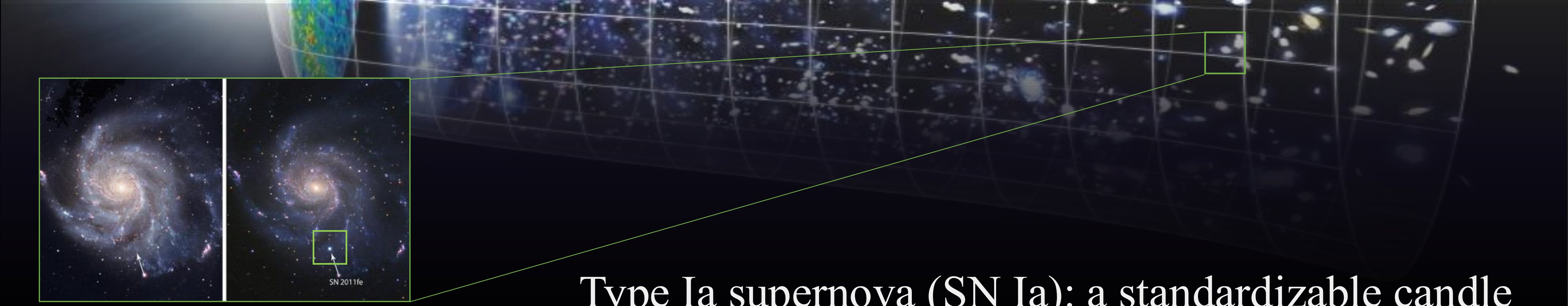
Type Ia supernova (SN Ia): a standardizable candle

~0.4 mag error per SN



~0.10 - 0.15 mag error per SN





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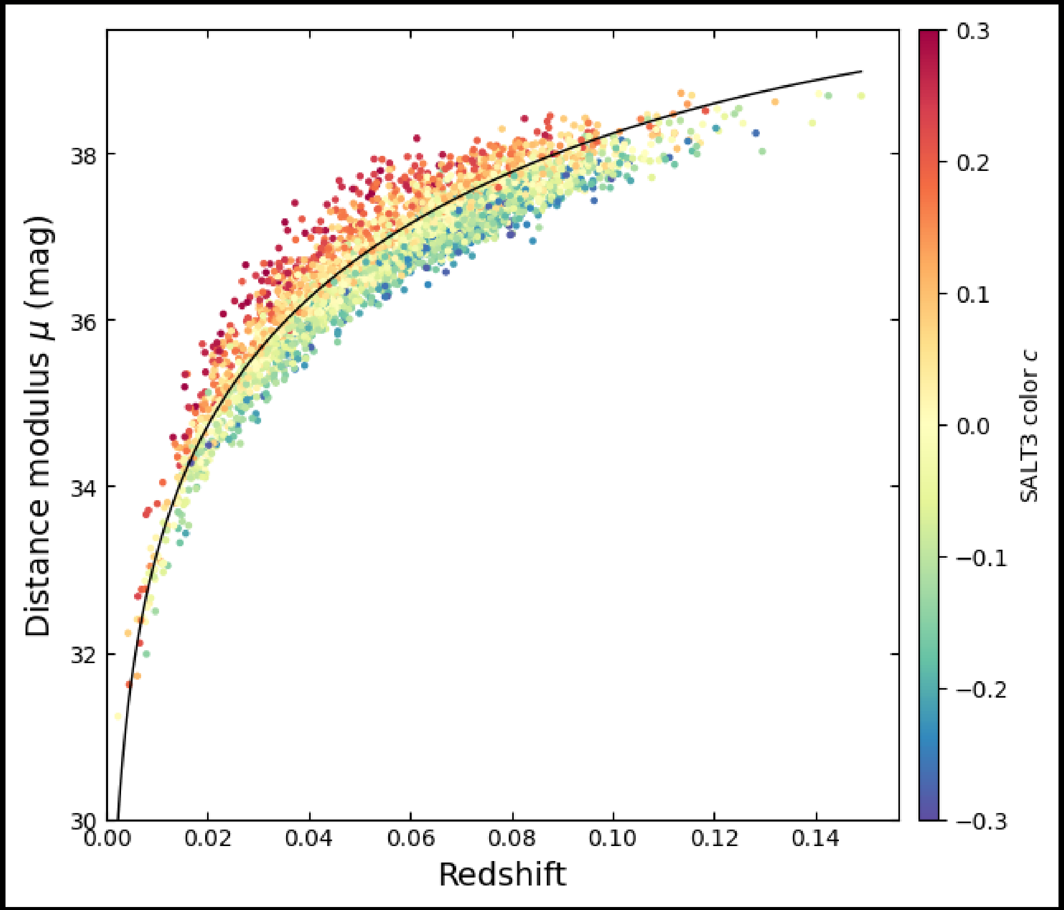

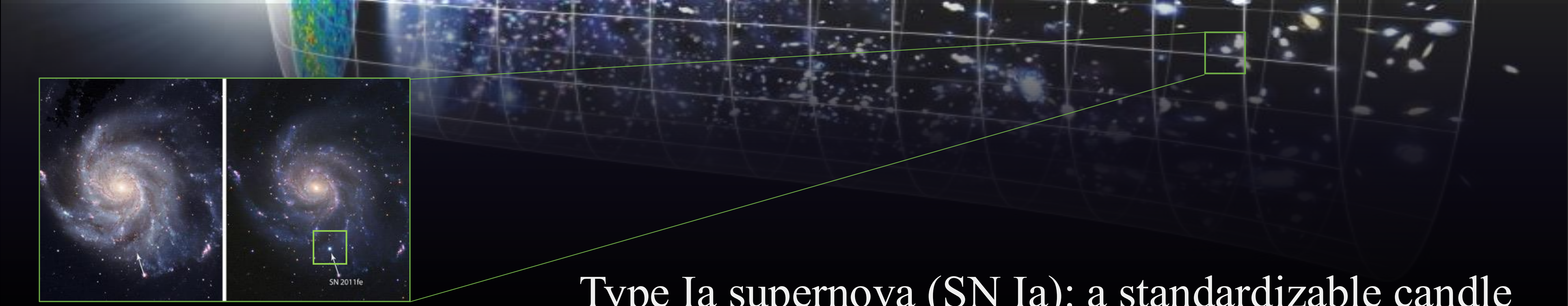

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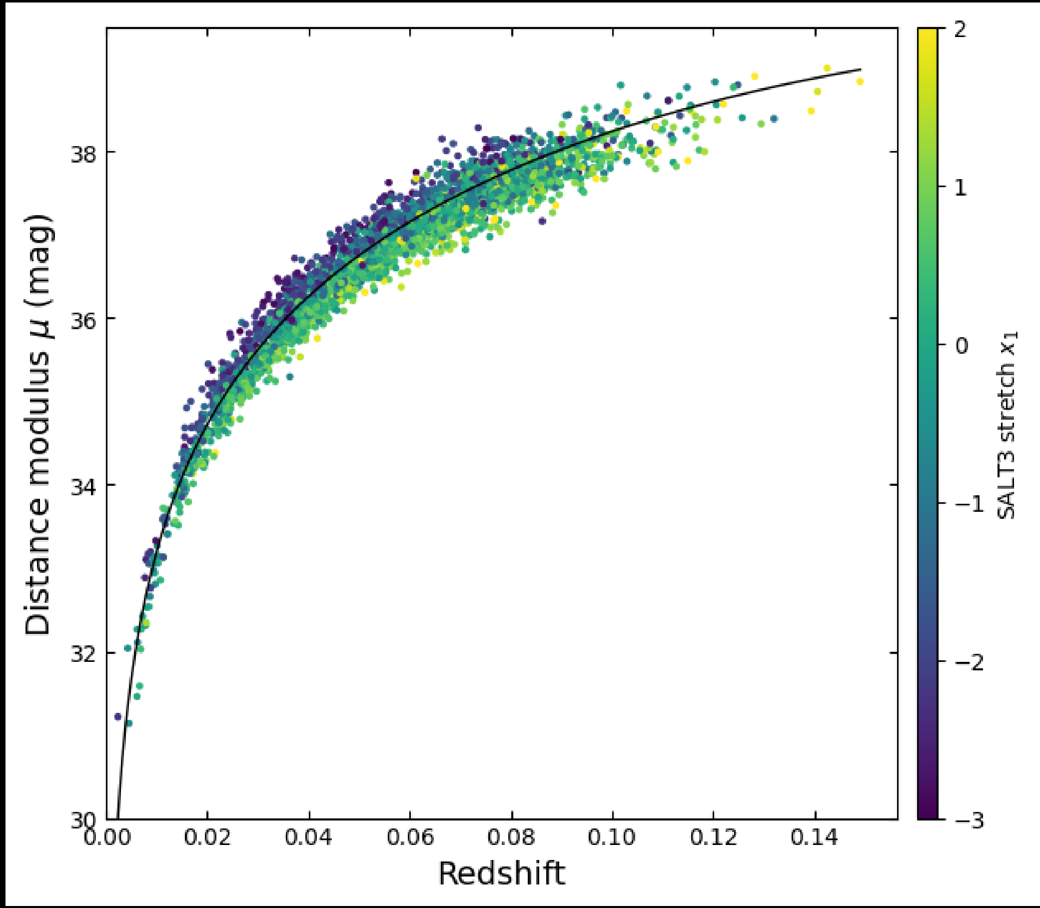

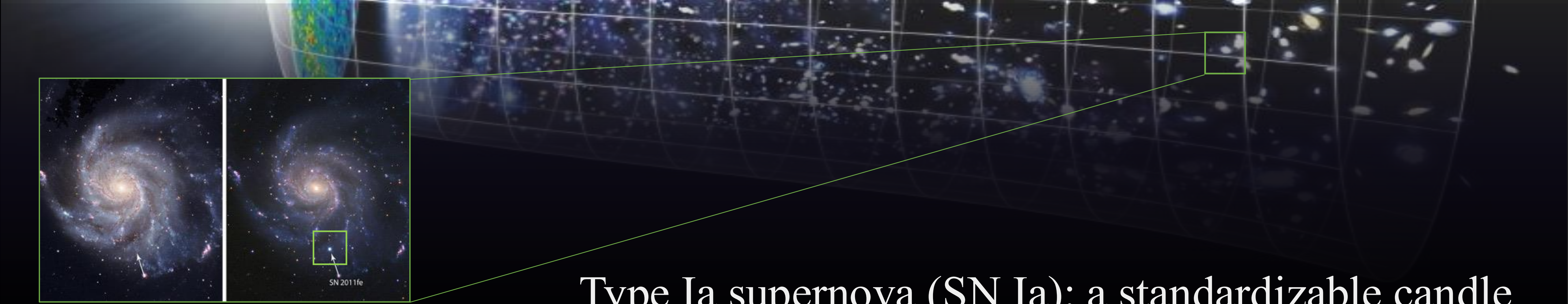

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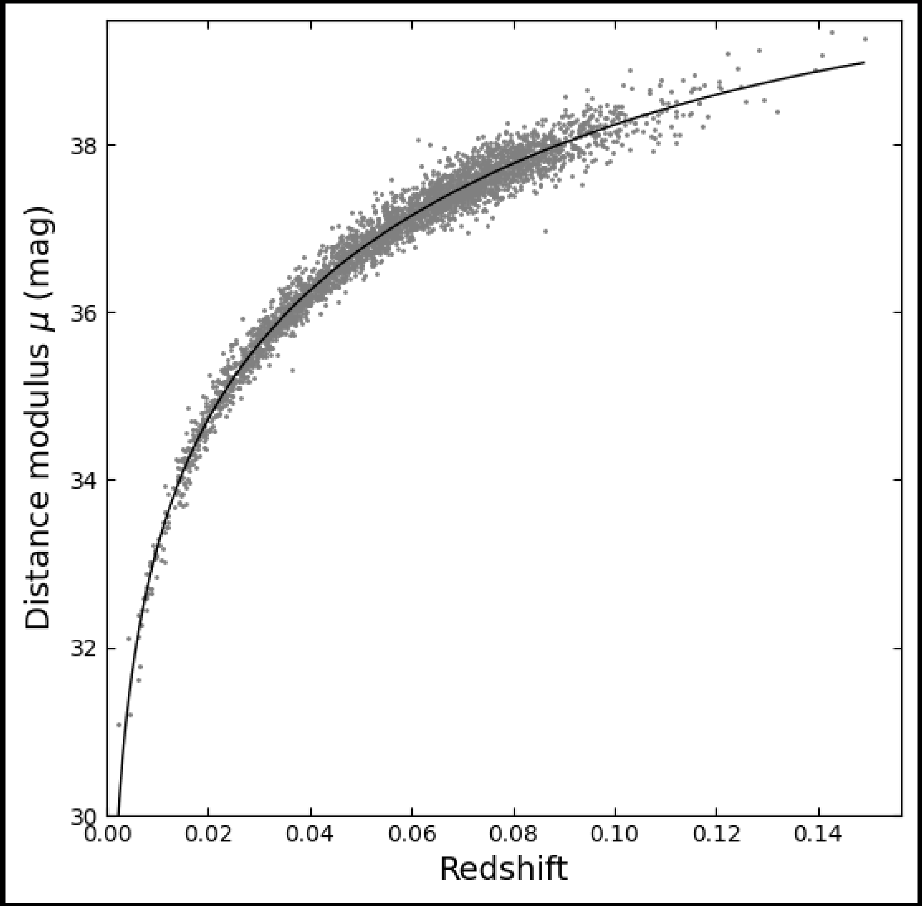

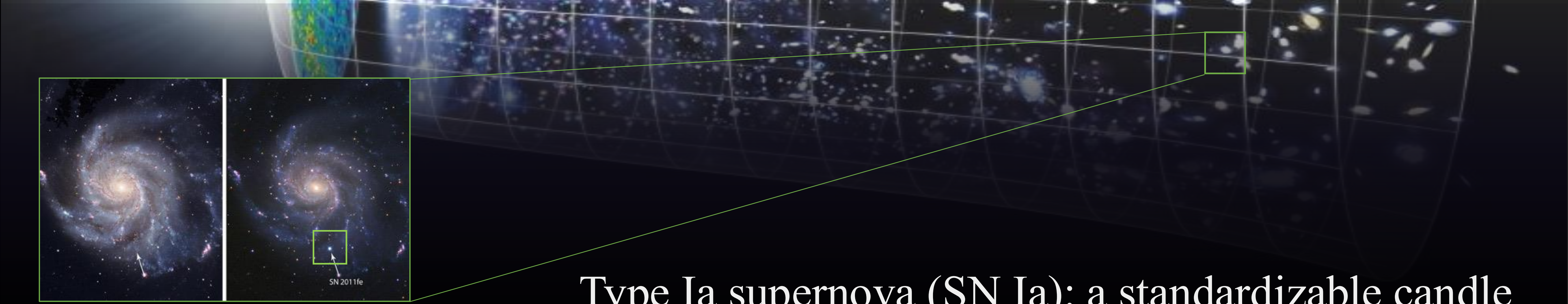

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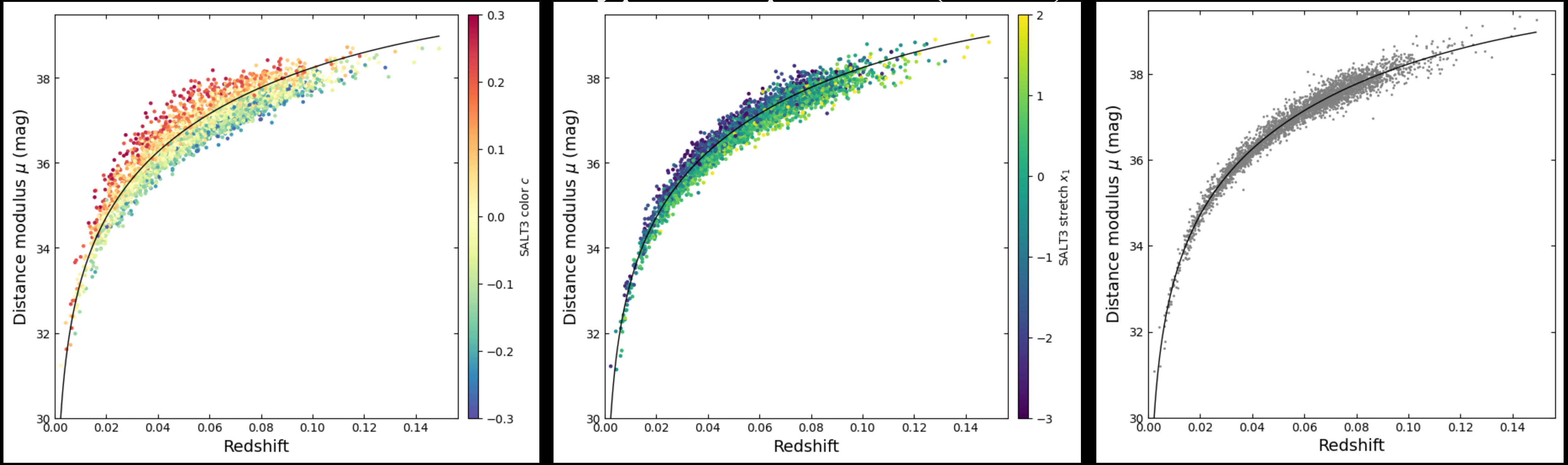
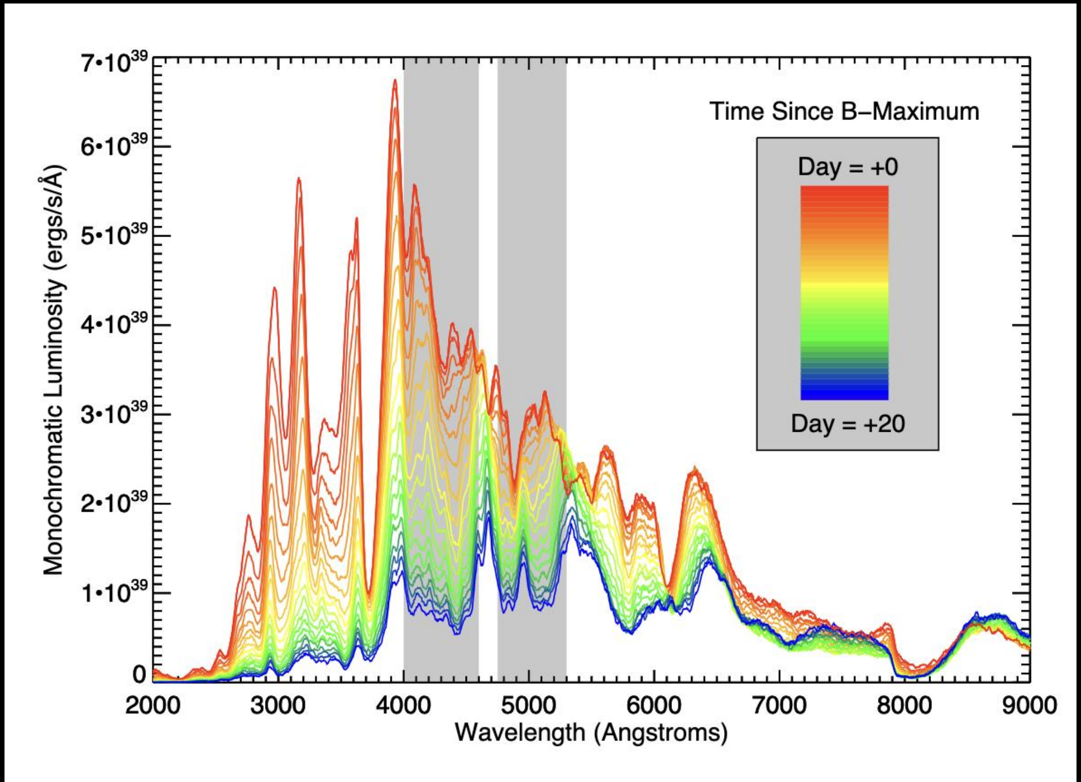
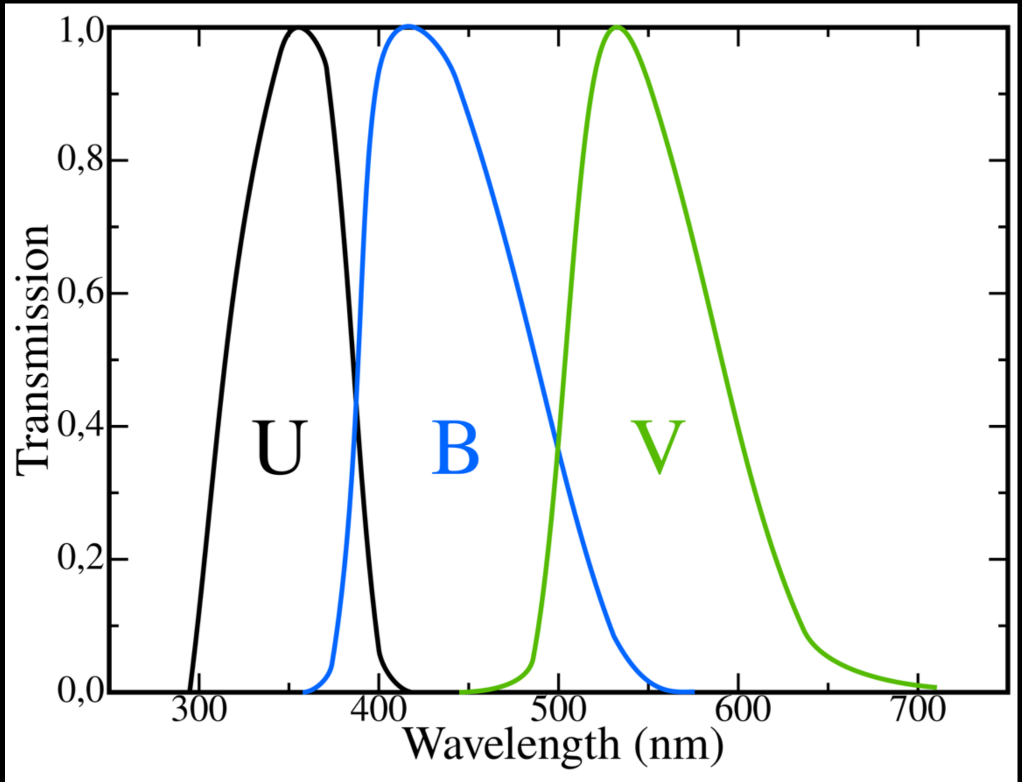


Tripp Standardization: $\mu = m_B + \alpha x_1 - \beta c - M_B$

Characterizing the light curve: B-band magnitude m_B, Stretch $\Delta m_{15}/x_1$, Color c

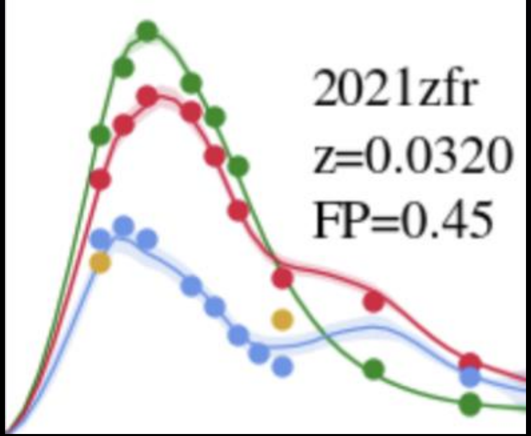
How can we capture SED evolution through broadband photometry?

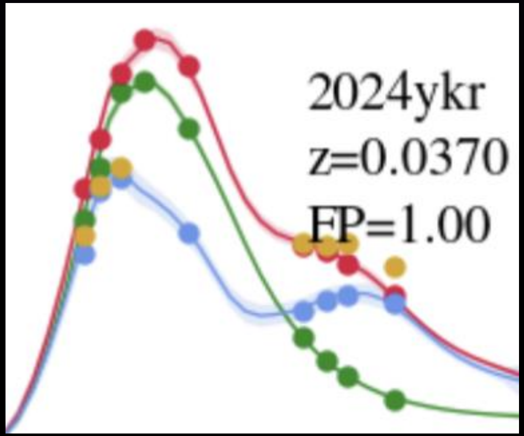




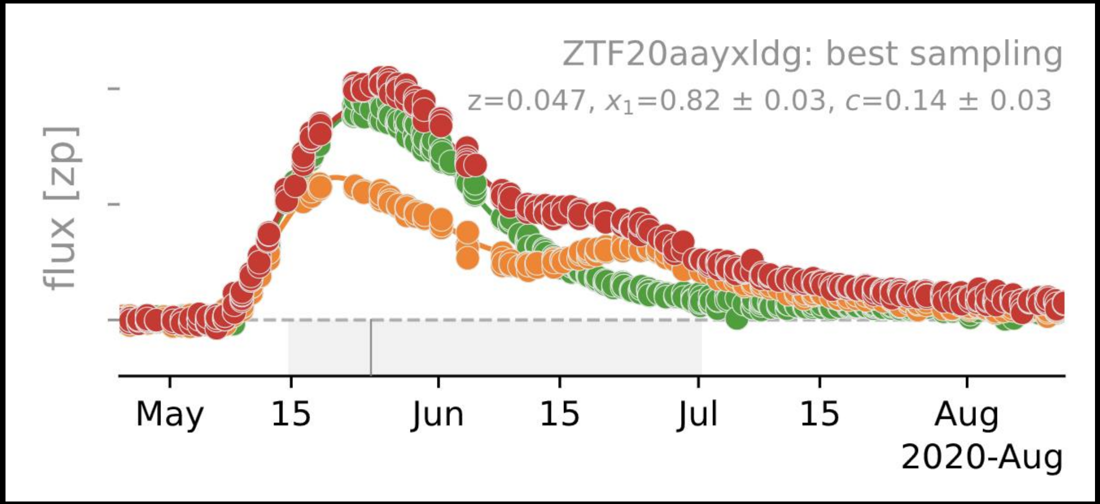
Characterizing the light curve: B-band magnitude m_B, Stretch $\Delta m_{15}/x_1$, Color c

More on this later!



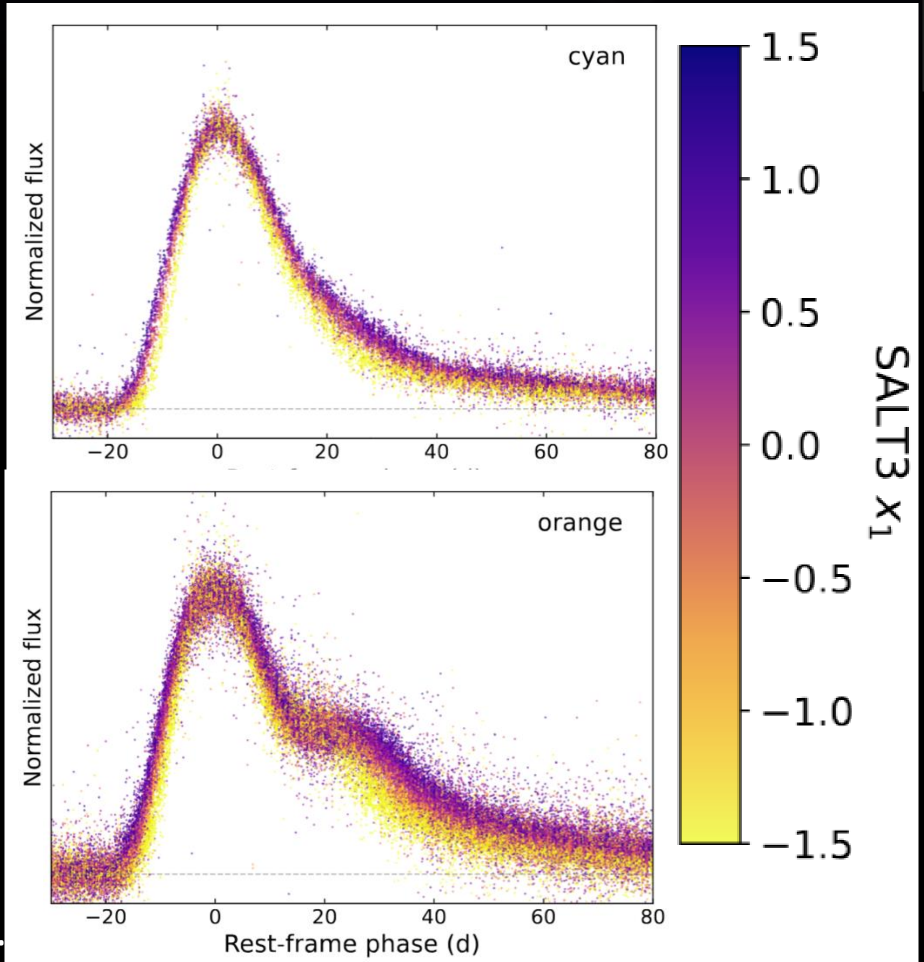


DEBASS DR0.5:
Sherman+2025



ZTF DR2:
Rigault+2025

TITAN DR2:
Murakami+ in prep.



Type Ia supernova (SN Ia): SED (Spectral Energy Distribution) Modeling

Stretch-Luminosity
- Phillips 1993
- SCP Stretch (Perlmutter+1997)

Multi-color template
- MLCS (Riess+1996)
- MLCSk2 (Jha+2007)
- SNooPy (Burns+2011)

Trained SED Model
- SALT2 (Guy+2007)
- SALT3 (Kenworthy+2021)

Hierarchical Bayesian
- BayeSN (Mandel+2022)

Spectroscopic
- SUGAR (Léget+2020)

Nearly all of them quantify:

B-band magnitude: m_B
Stretch: x_1, ΔM_{15}, s
Color: c, E(B-V)

(with some exceptions)

*You may have heard of UNITY or BBC: they are more related to cosmological analysis than light curve fitting

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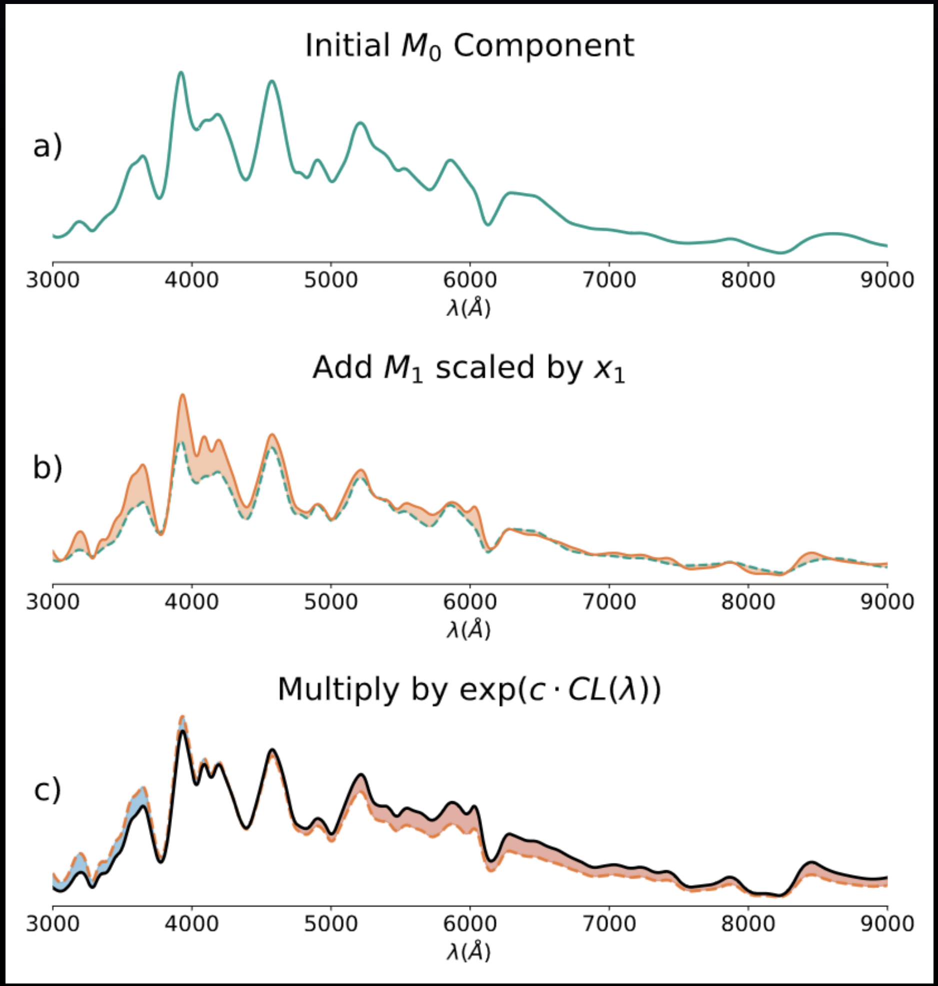

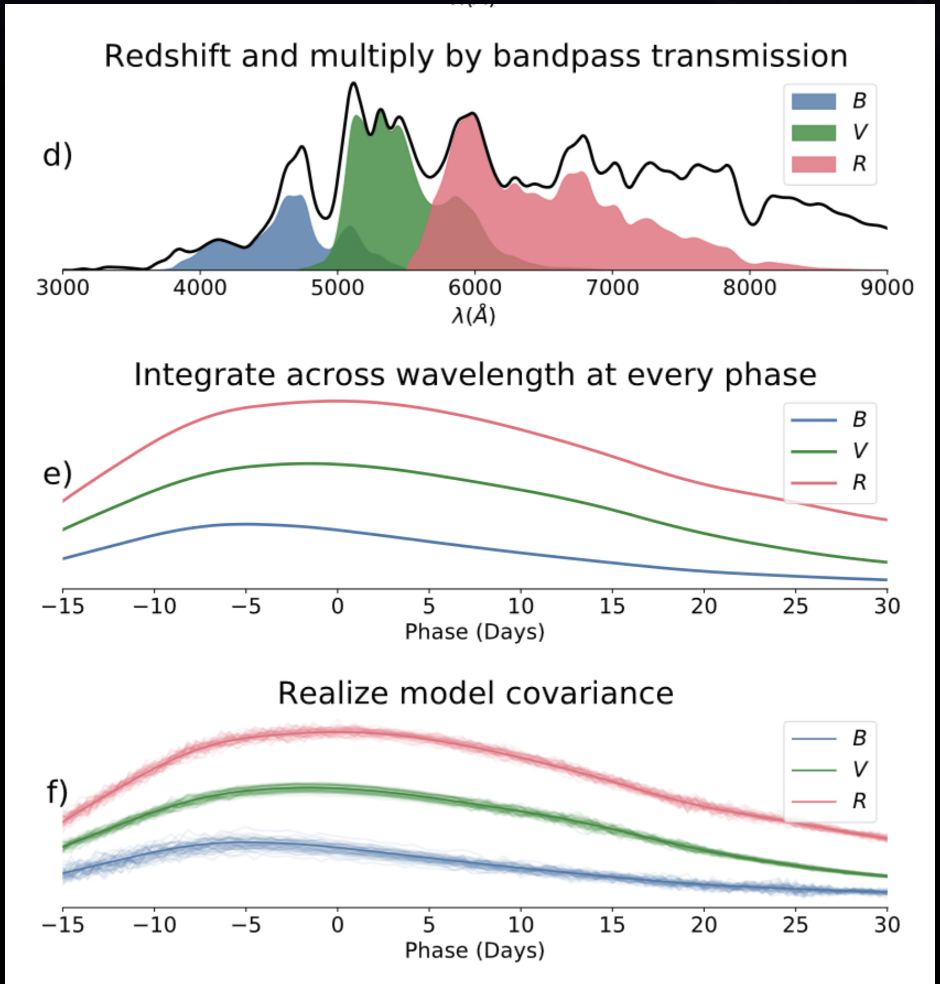

SALT3
Kenworthy+21

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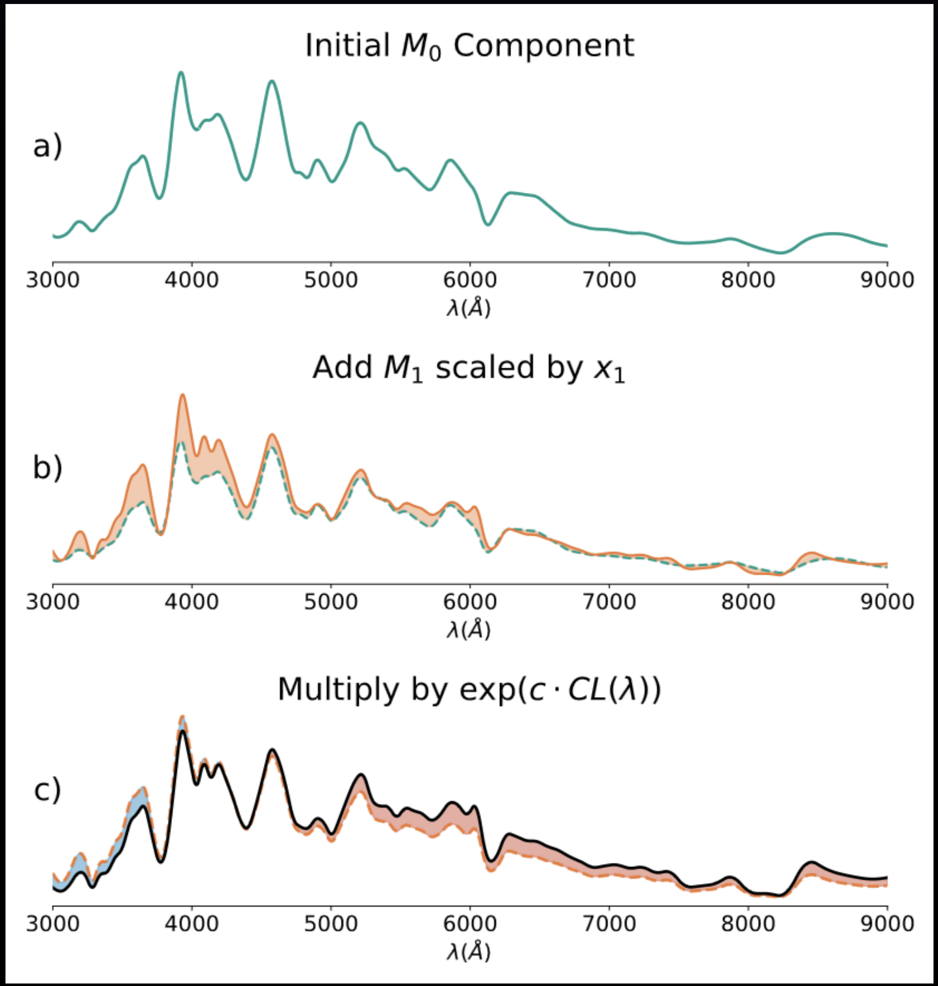

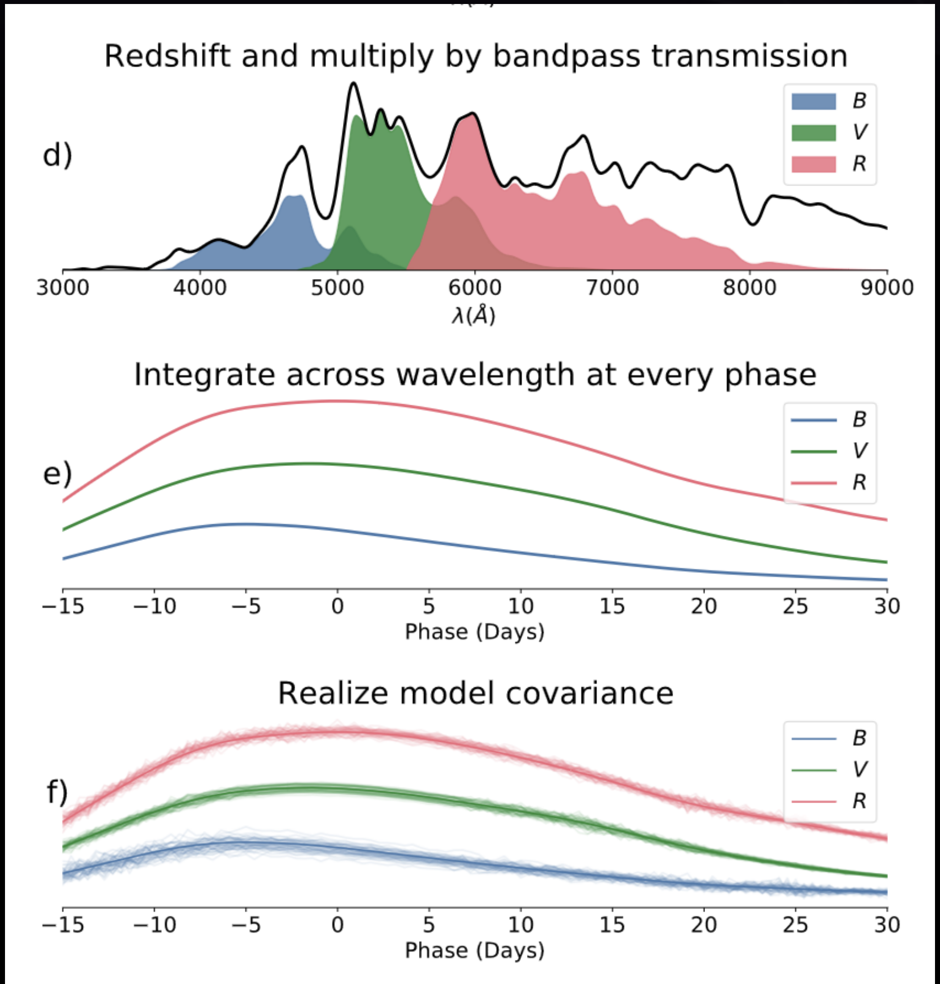

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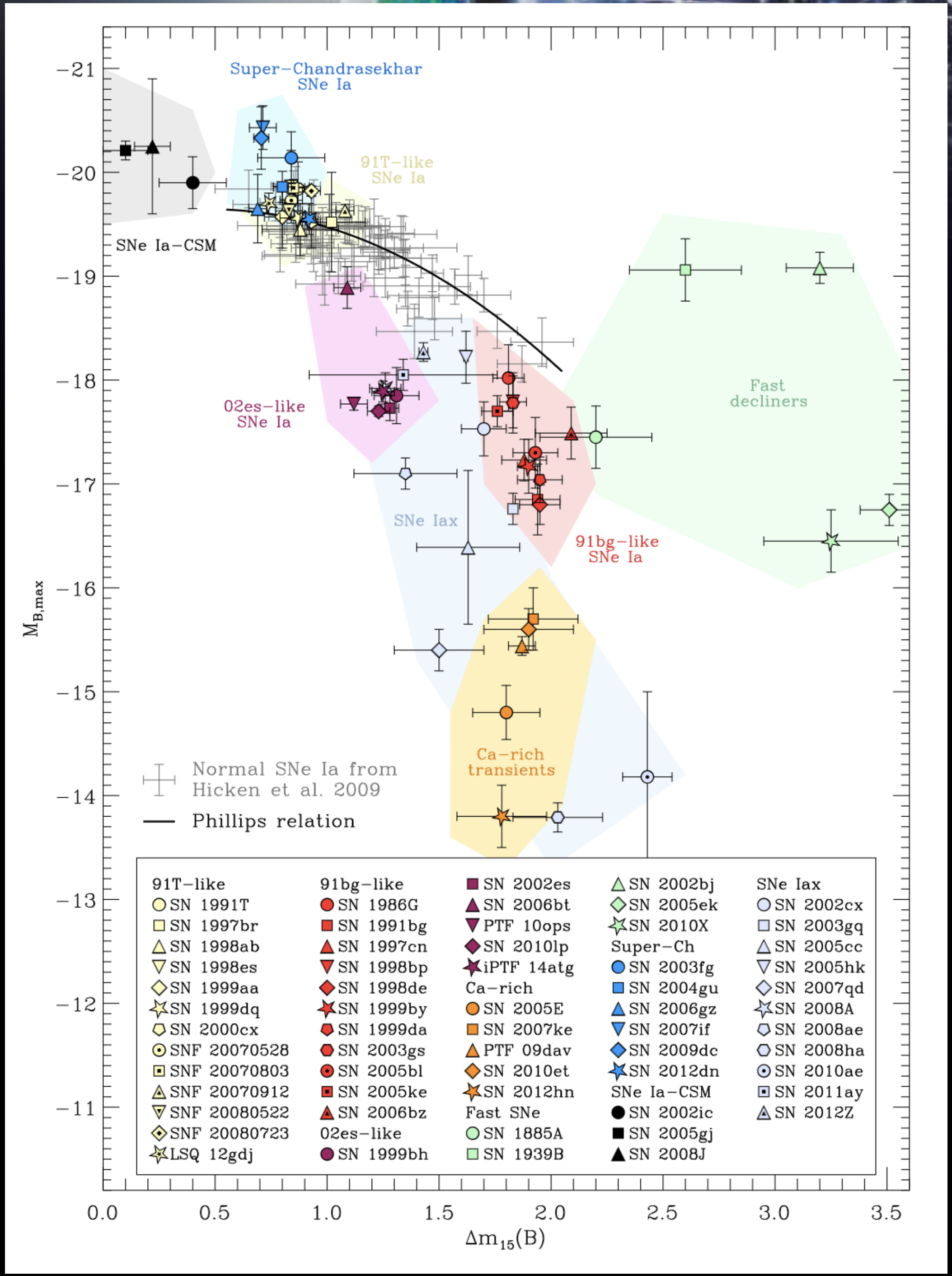


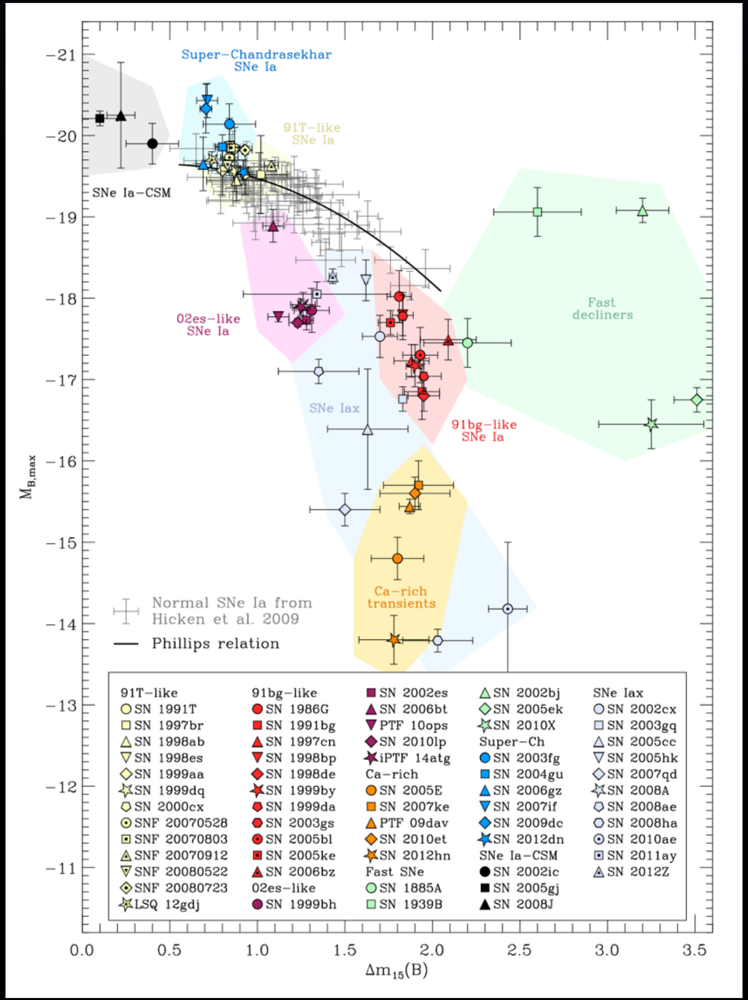
Type Ia supernova (SN Ia): not everything is suited for cosmology

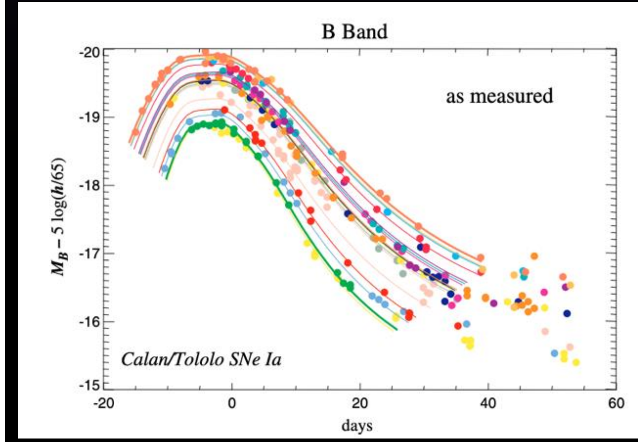
Names relevant for cosmology:

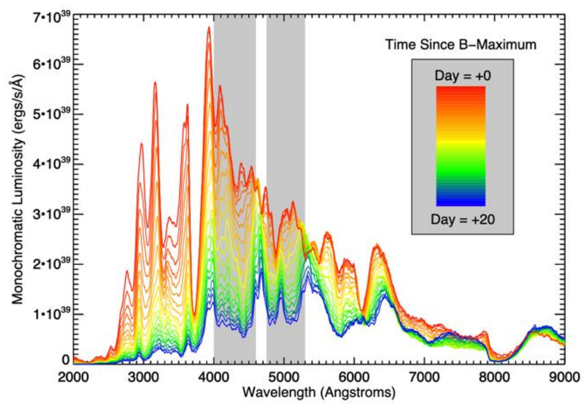
- ”normal” SNe Ia:
  - perfect for cosmology
  - follows tight stretch-luminosity relation
- ”91T-like” SNe Ia:
  - Hotter, more Ni mass
  - OK for cosmology, still on stretch-luminosity relation
- “91bg-like” SNe Ia:
  - Cooler, less Ni mass
  - Generally excluded from cosmology

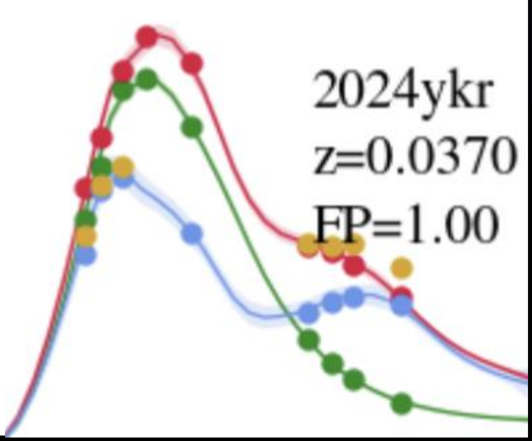
Taubenberger 2017

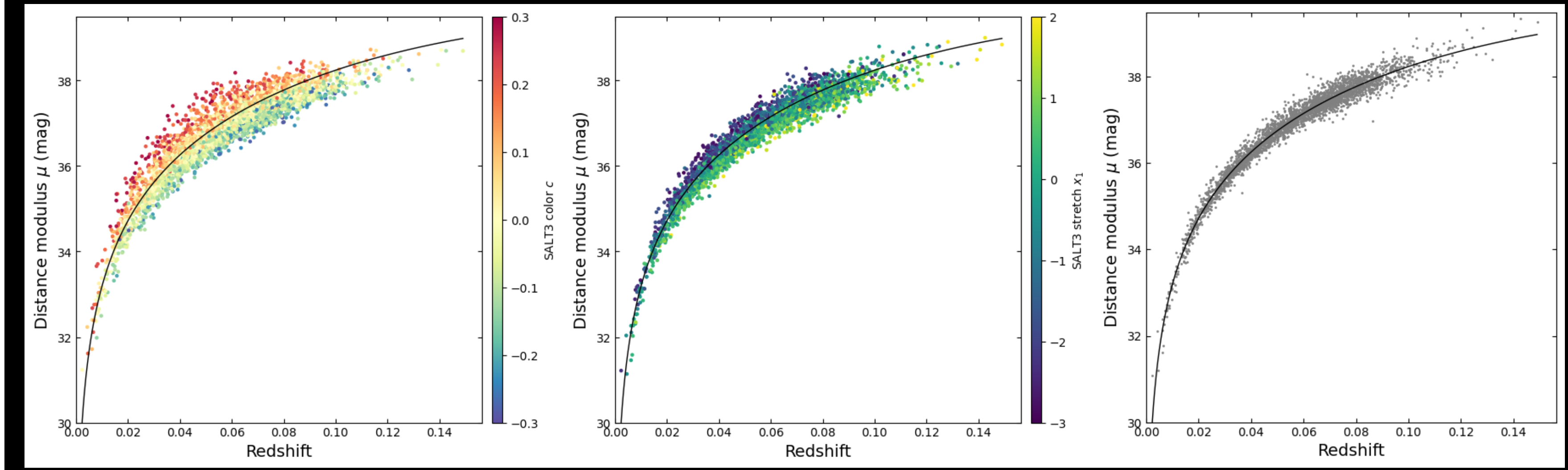
Recap: Type Ia supernova (SN Ia): A Standardizable Candle











Type Ia Supernova: A Standardizable Candle

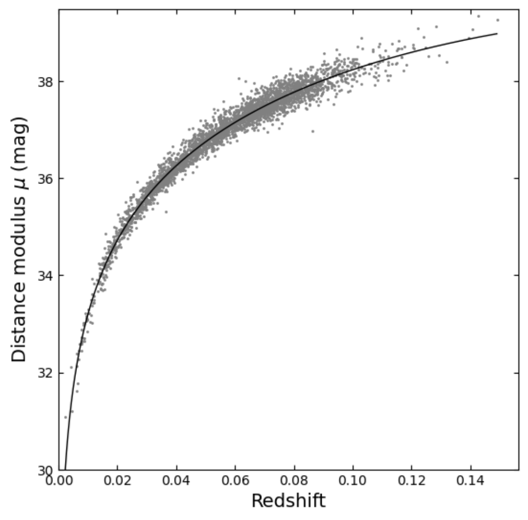
Part I: Observational Facts

Part II: SNe Ia data: from telescope to "m_B"

Part III: Major SNe Ia surveys/dataset

Type Ia supernova (SN Ia): from Observation to mB

- Detection
- Follow-up observations
- Photometry
- Photometric Calibration
- Spectroscopic classification
- Host galaxy association
- Host galaxy spectroscopy



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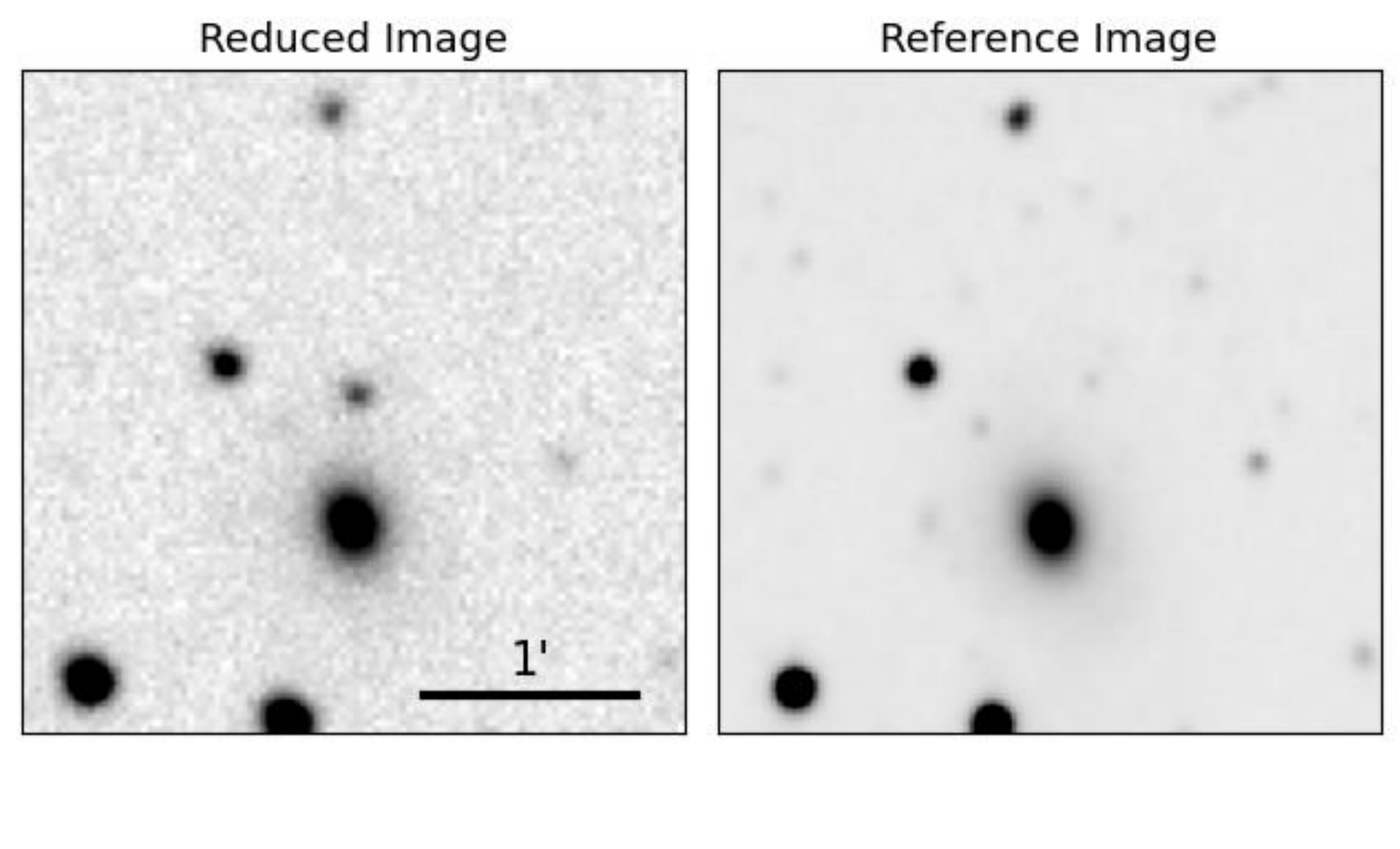

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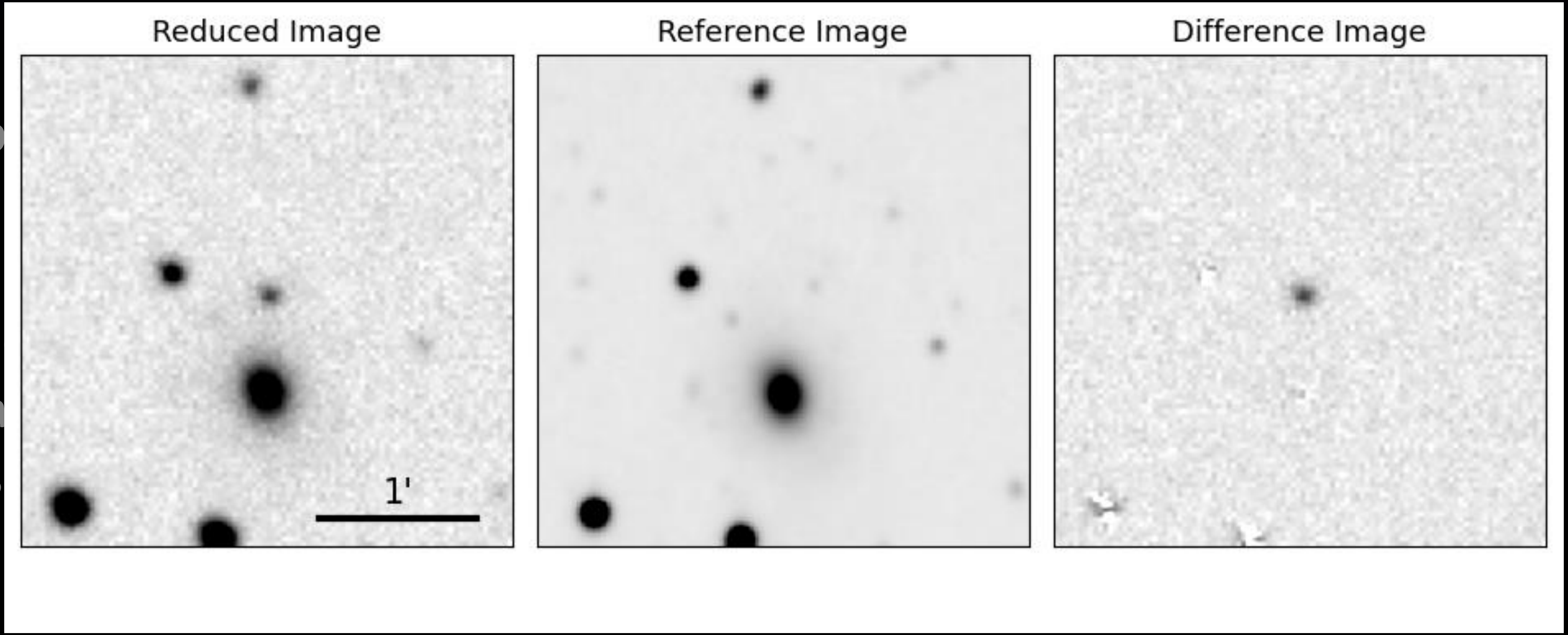

ATLAS/TITAN – Murakami et al. in prep.

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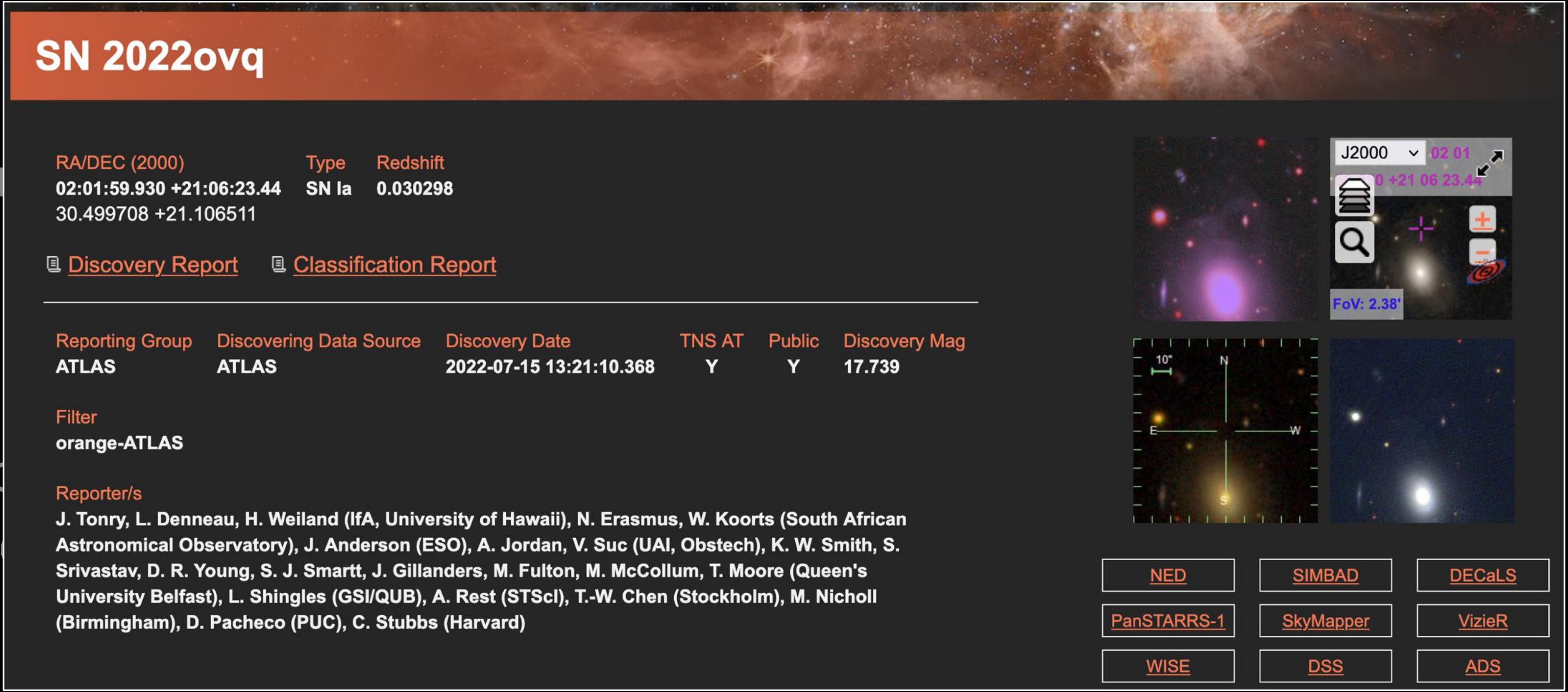

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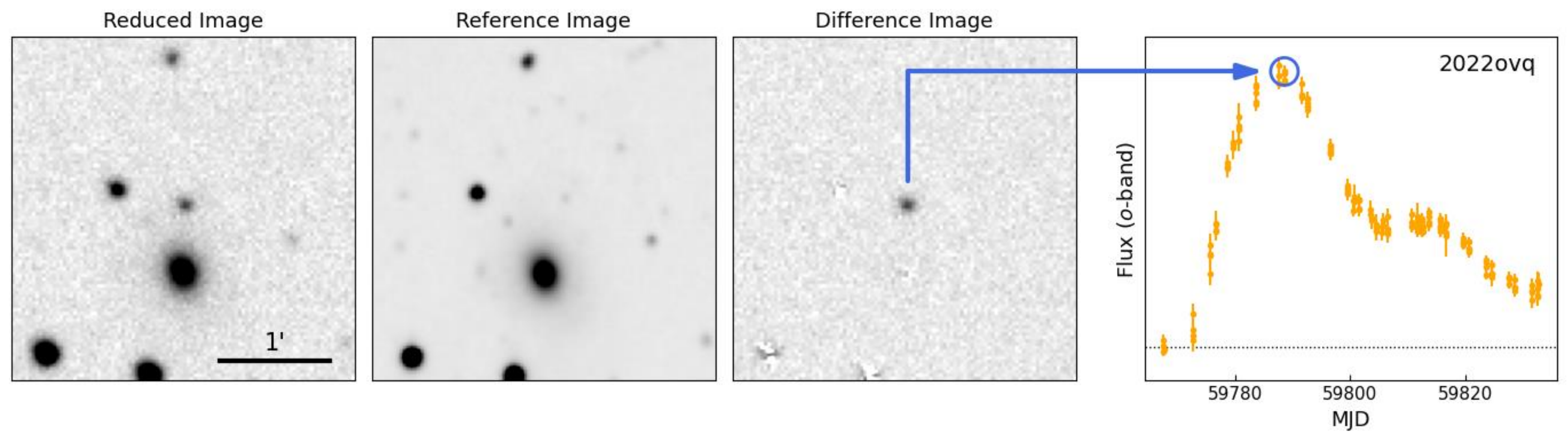

Photometry methods for SNe Ia vary

Difference Image Photometry:

- Aperture photometry (classic, no longer common)
- PSF photometry (main-stream, Pantheon+, DES, etc.)

Forward Modeling Method:

- Scene Modelling Photometry (difficult, next-gen)

Type Ia supernova (SN Ia): from Observation to mB

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Detector counts ≠ flux, but counts ∝ flux.

Two levels of calibration:

Per-night calibration (e.g., Tonry+18):

- State of atmosphere, temperature, etc. changes the proportionality constant (”zero point”; ZP)
- Determine ZP using stars with known catalog brightness

Per-detector calibration (e.g., Scolnic+15, Brou+21):

- Each telescope uses their own catalog
- Exact calibration methods may differ
- Use HST CALSPEC data to cross-calibrate ZPs across telescopes and detectors

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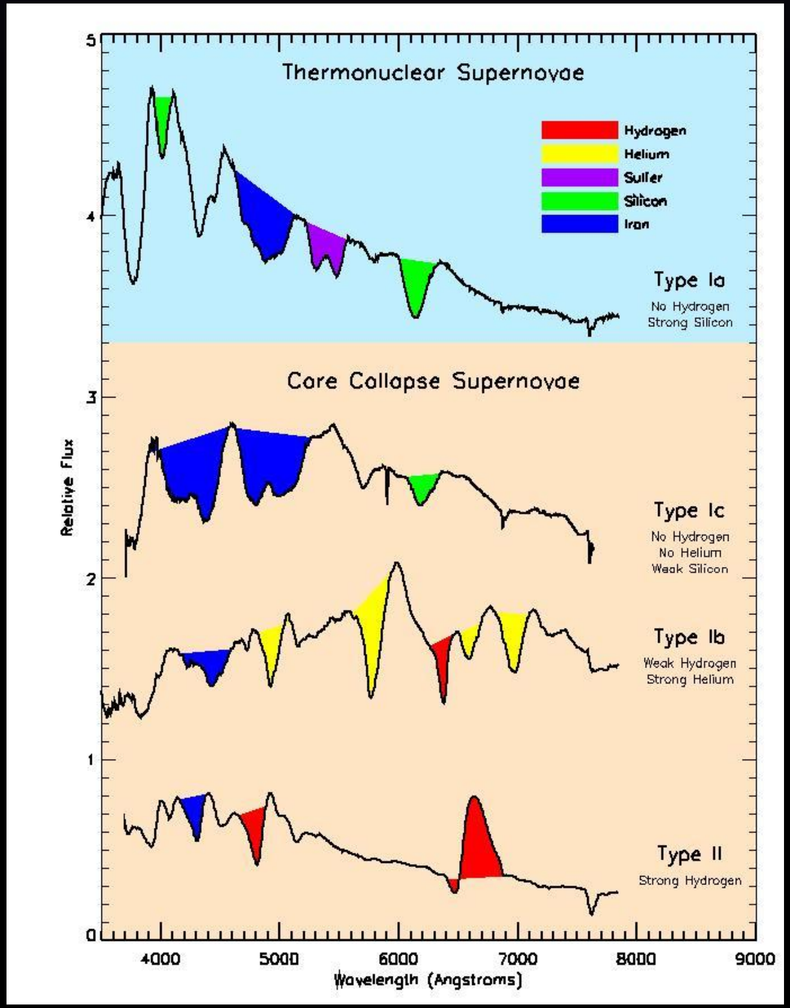

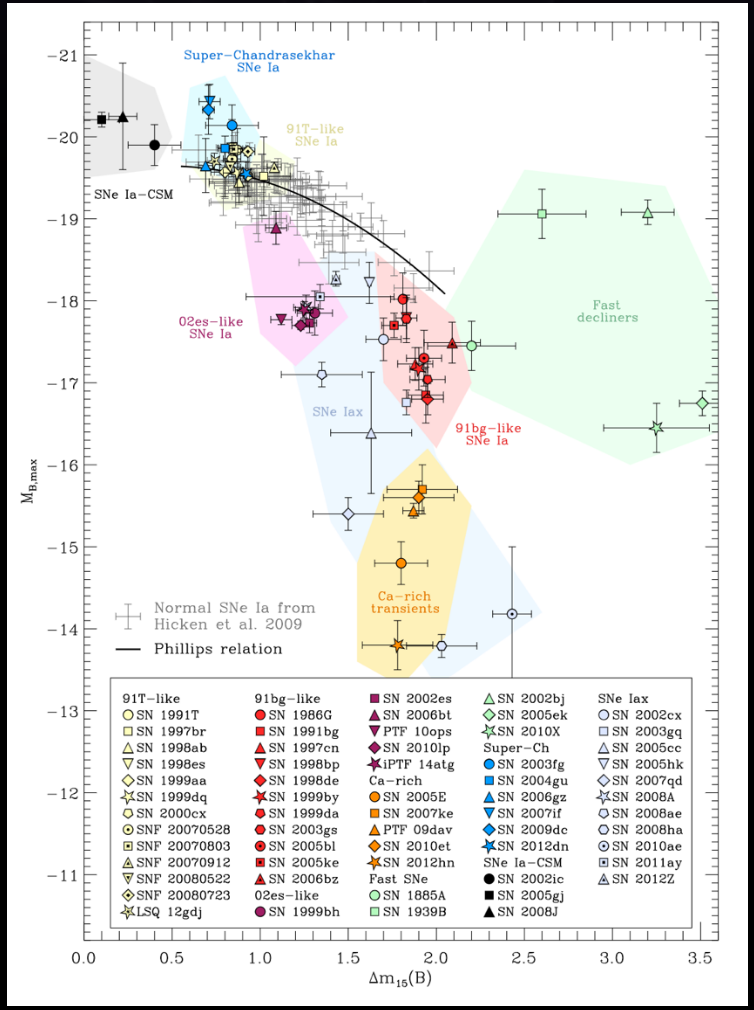

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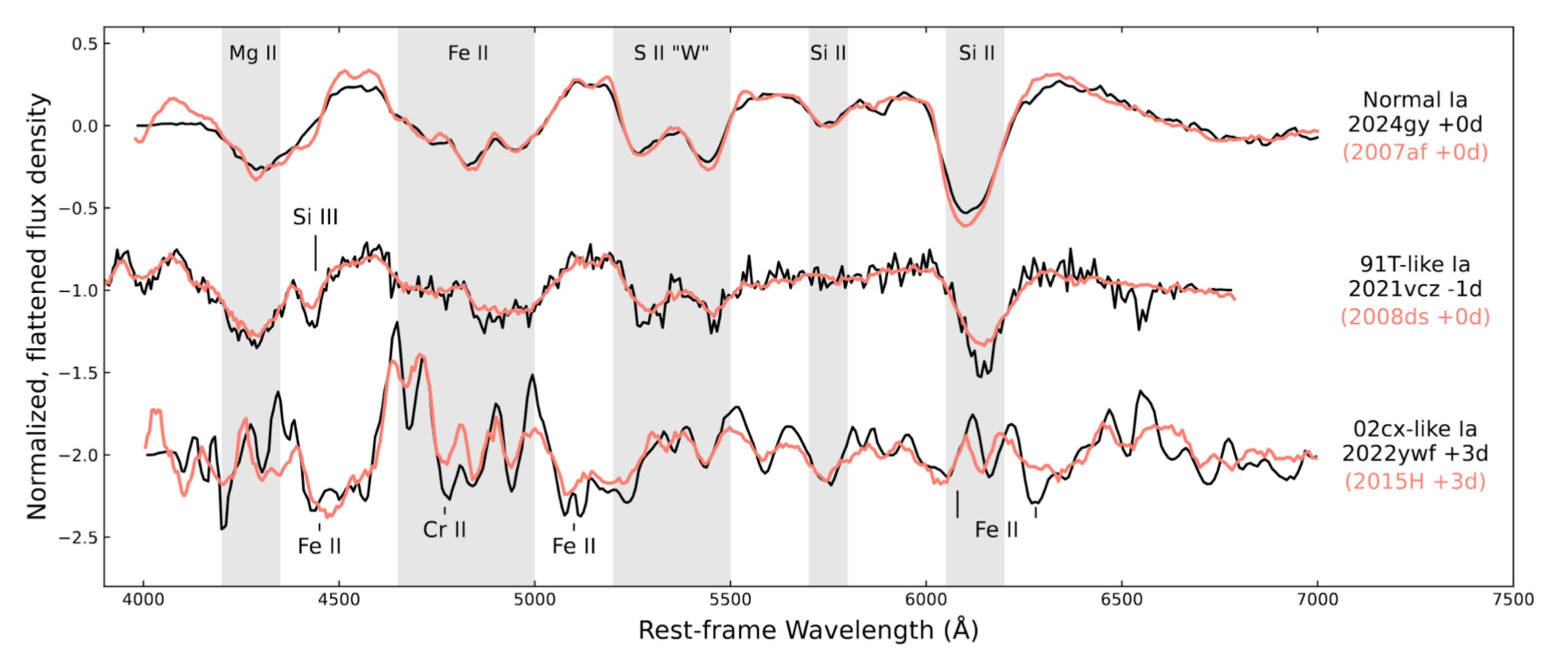
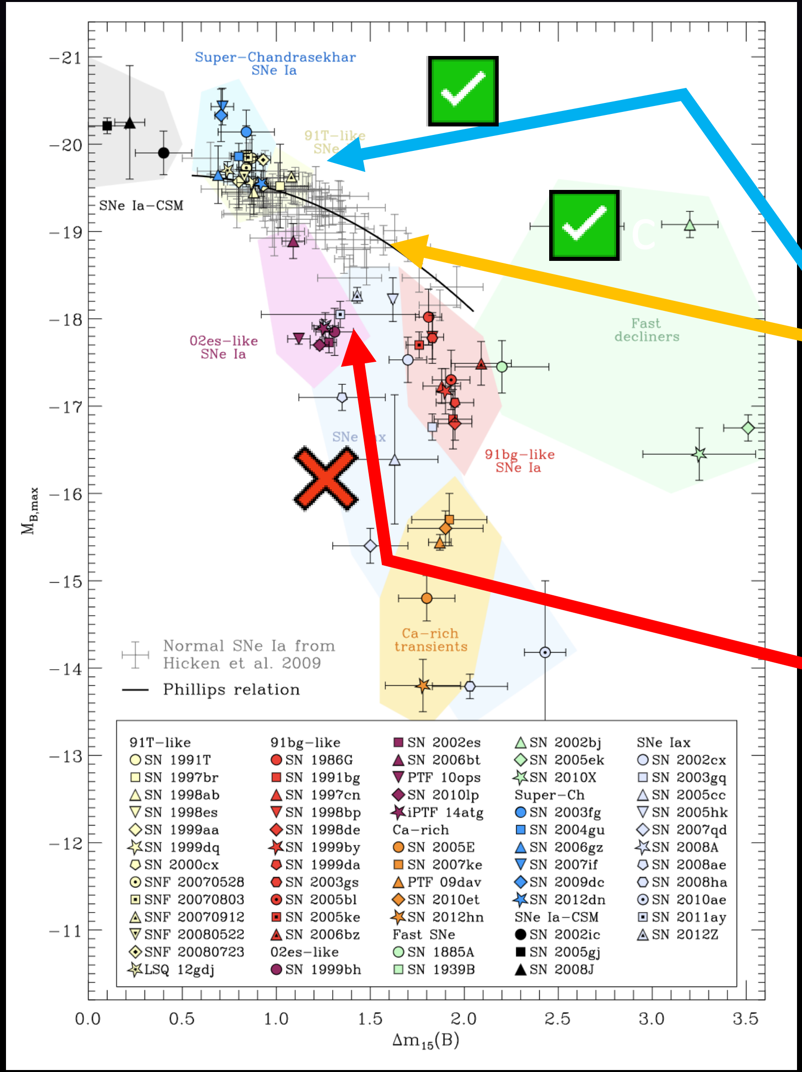
Cross-correlate spectra with known templates

(Blondin&Tonry 2011, Stoppa&Smartt 2026)



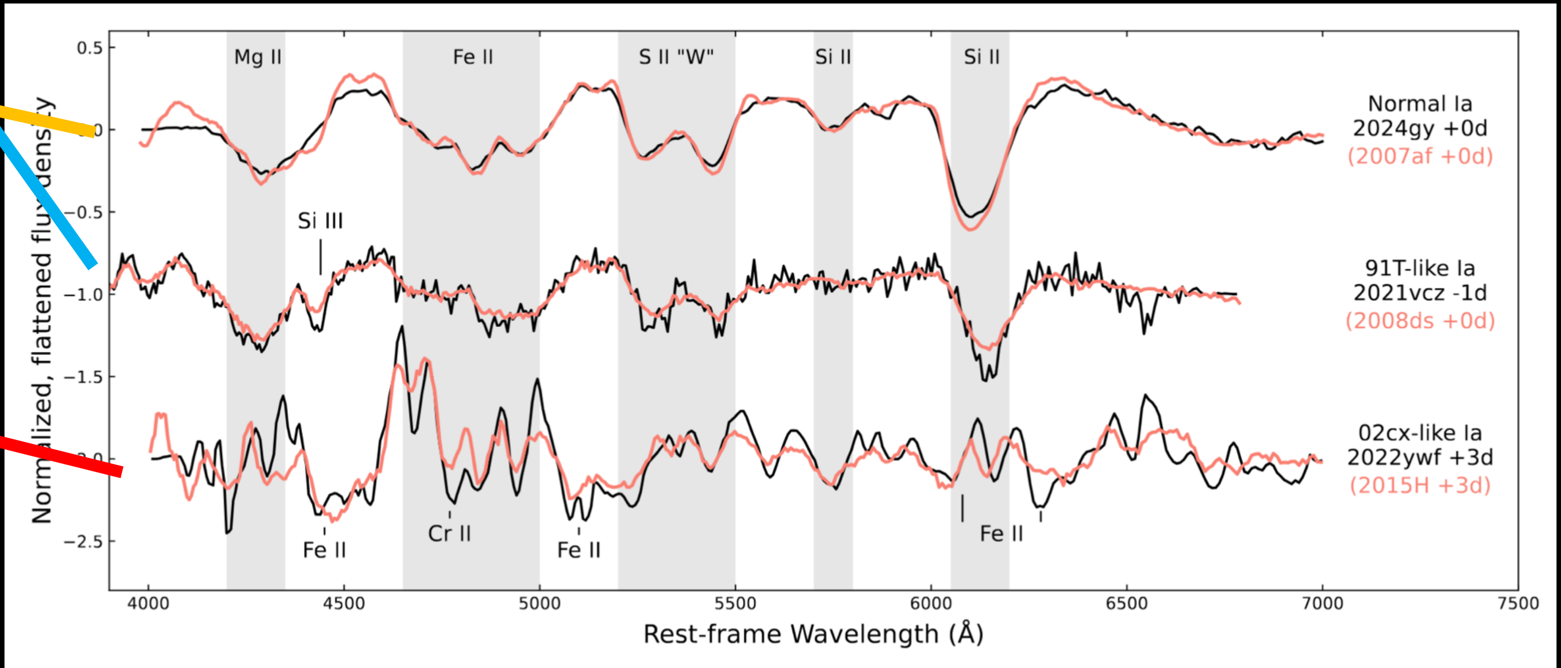
ATLAS/TITAN – Murakami+ in prep.

Type Ia supernova (SN Ia): from Observation to mB



Cross-correlate spectra with known templates

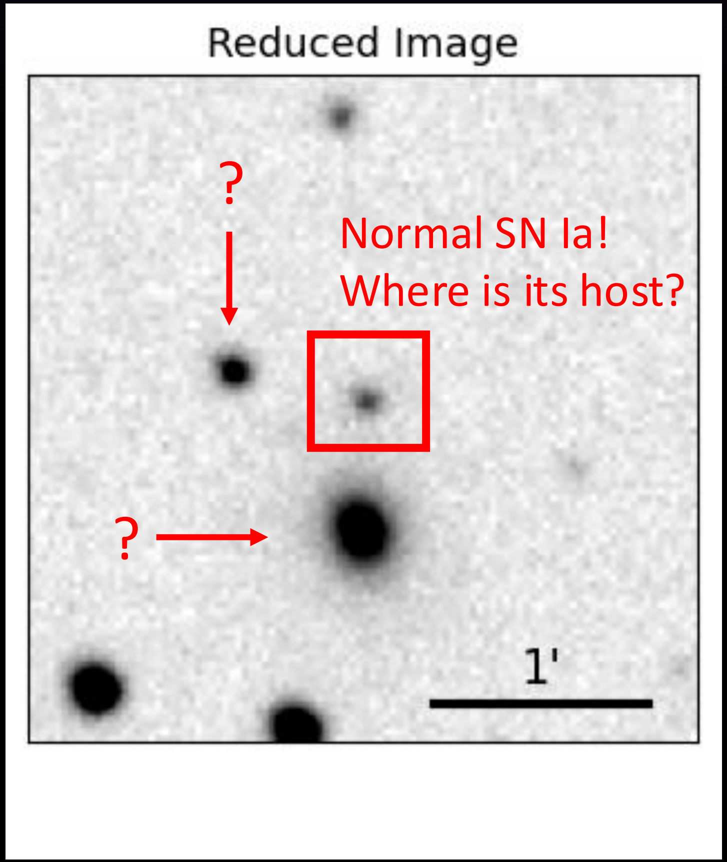
(Blondin&Tonry 2011, Stoppa&Smartt 2026)

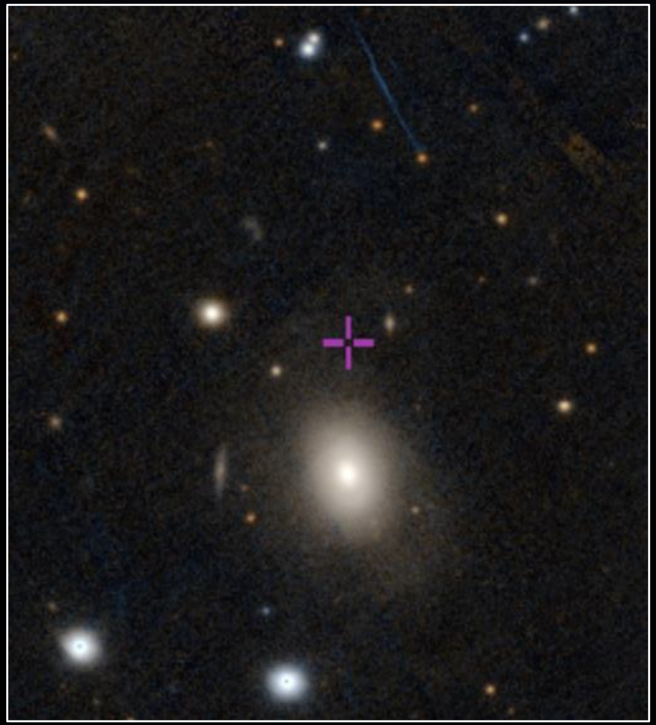


ATLAS/TITAN – Murakami+ in prep.

Type Ia supernova (SN Ia): from Observation to mB

- Detection
- Follow-up observations
- Photometry
- Photometric Calibration
- Spectroscopic classification
- Host galaxy association
- Host galaxy spectroscopy

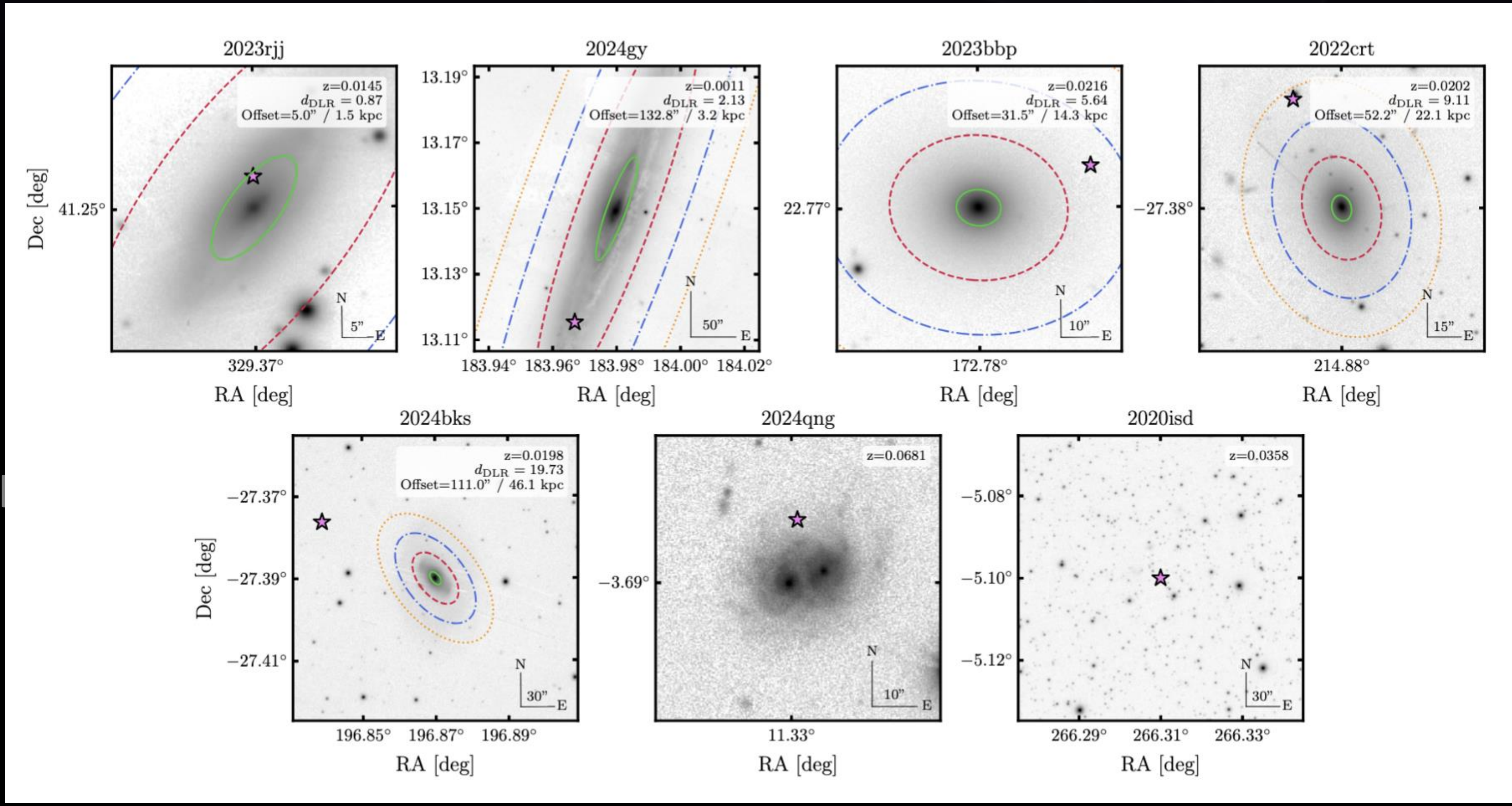




Pan-Starrs DR1 color

Type Ia supernova (SN Ia): from Observation to mB

- Detection
- Follow-up observations
- Photometry
- Photometric Calibration
- Spectroscopic classification
- **Host galaxy association**
- Host galaxy spectroscopy



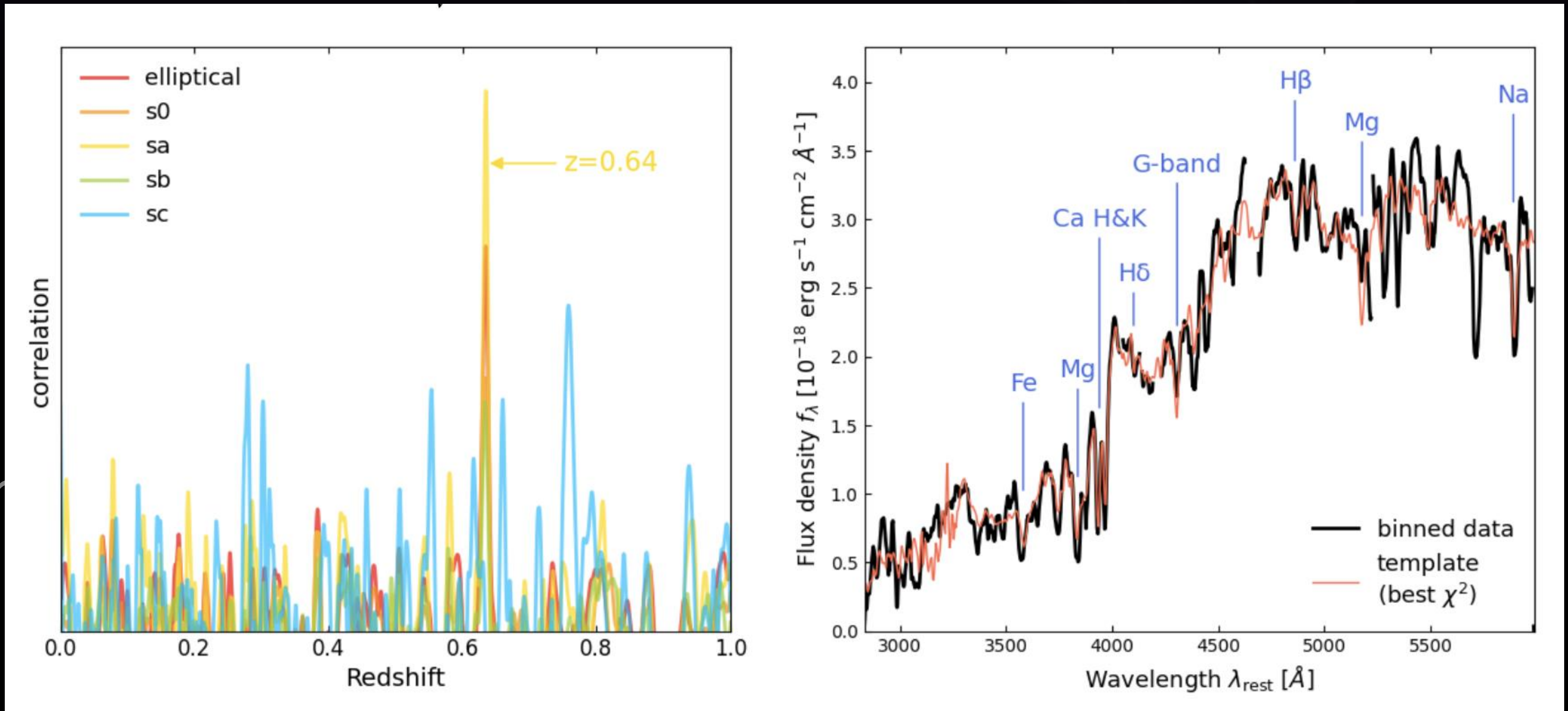
Directional Light Radius

& SN spectroscopic redshift and host redshift should roughly match

ATLAS/TITAN -- Tweddle+ in prep.

Type Ia supernova (SN Ia): from Observation to mB

- Detection
- Follow-up observations
- Photometry
- Photometric Calibration
- Spectroscopic classification
- Host galaxy association
- **Host galaxy spectroscopy**



Murakami+25

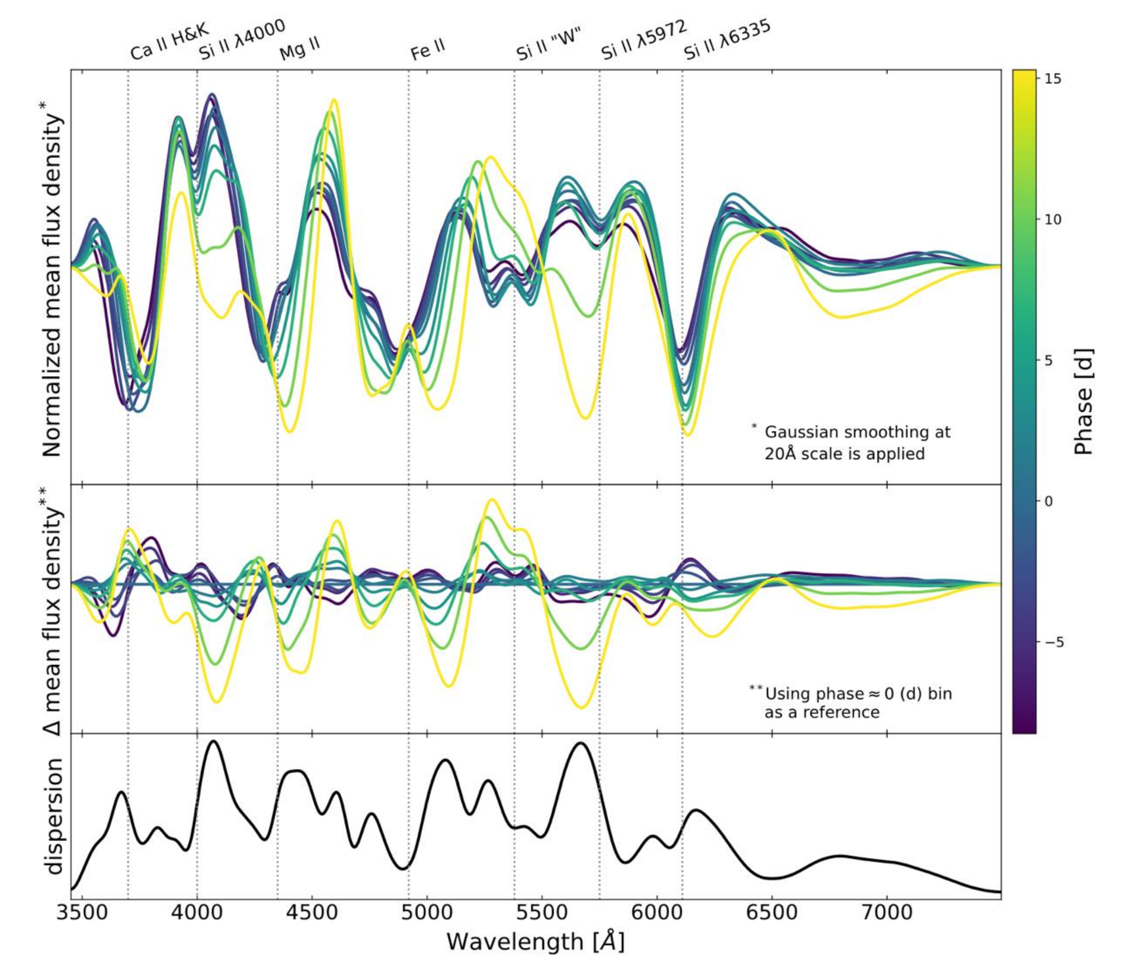
Provides spectroscopic redshift of the host galaxy (host spec-z)

Type Ia supernova (SN Ia): from Observation to mB

- Detection
- Follow-up observations
- Photometry
- Photometric Calibration
- Spectroscopic classification
- Host galaxy association
- Host galaxy spectroscopy

Q: Why not spec-z from SN spectra?

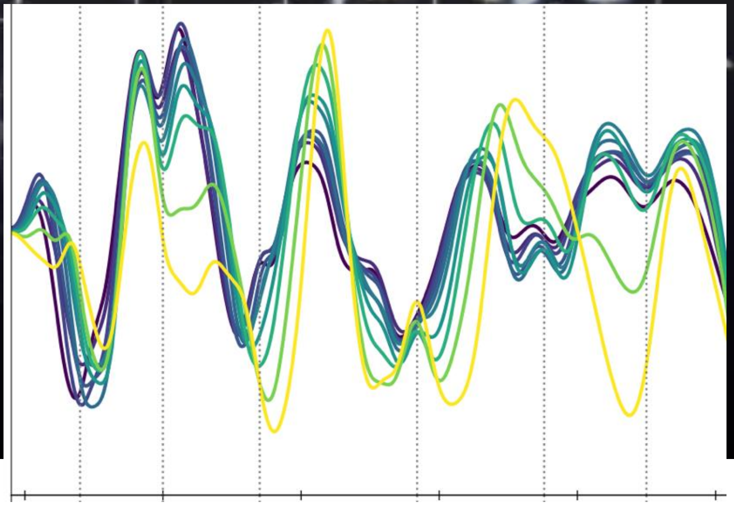
Murakami+23

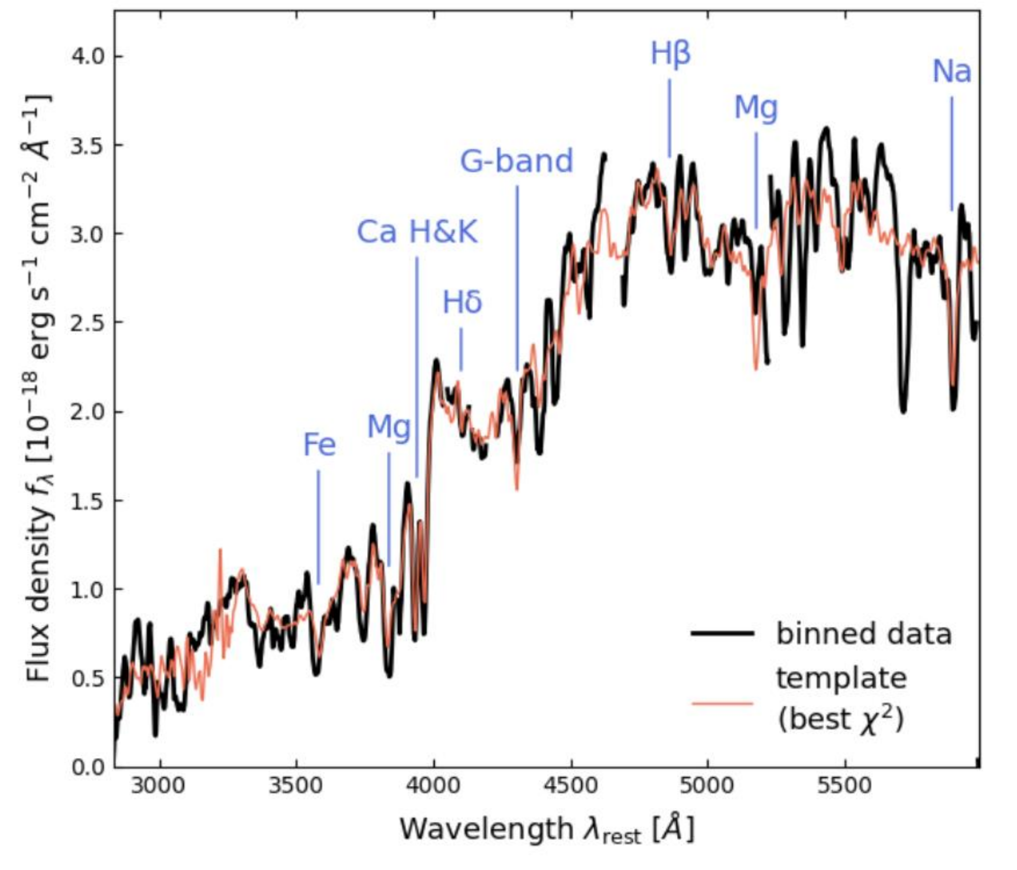


Type Ia supernova (SN Ia): from Observation to mB

Q: Why not spec-z from SN spectra?

A: You can roughly estimate,
but the uncertainty is large
(SN spec-z)



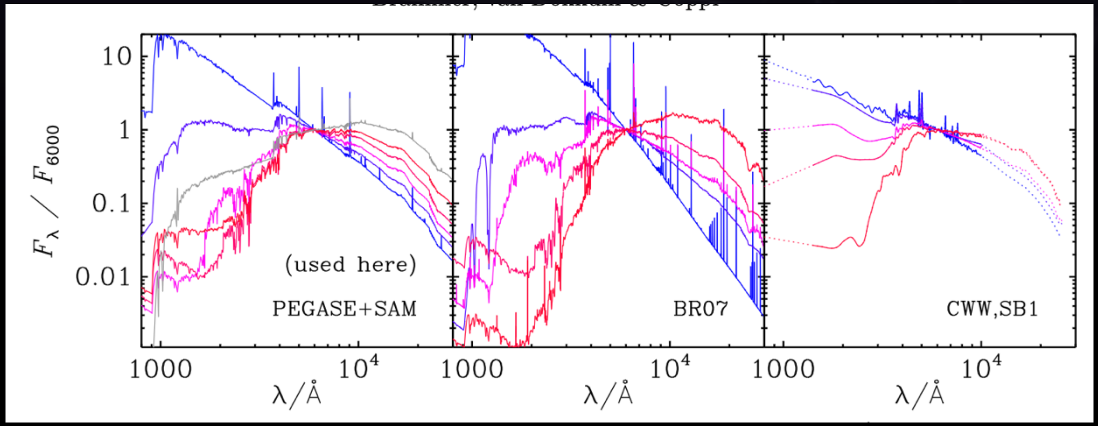


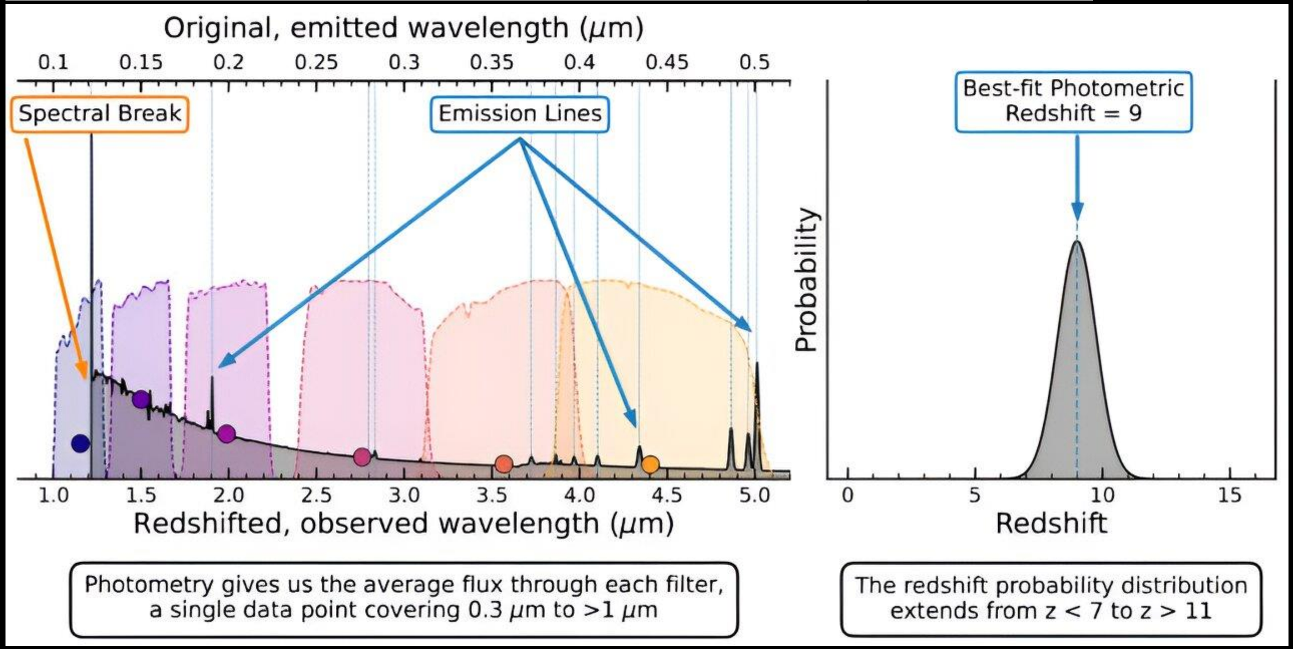
Type Ia supernova (SN Ia): from Observation to mB

Q: Why not spec-z from SN spectra?

A: You can roughly estimate,
but the uncertainty is large

Last resort:
Photometric estimation of redshift (photo-z)

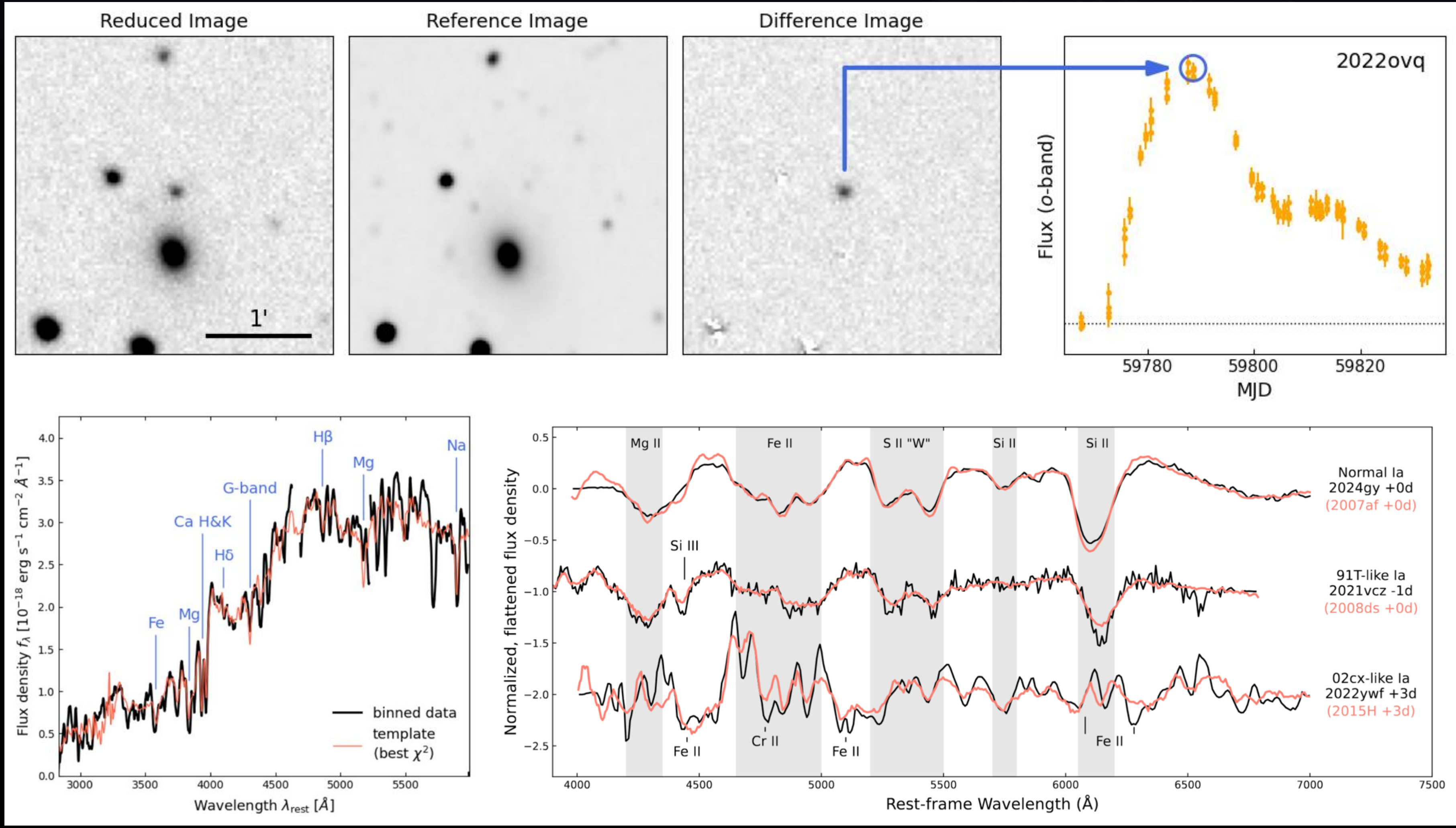




Top: Brammer+08
Bottom: Micaela Bagley

Recap: Type Ia supernova (SN Ia): from Observation to mB

- Detection
- Follow-up observations
- Photometry
- Photometric Calibration
- Spectroscopic classification
- Host galaxy association
- Host galaxy spectroscopy



Type Ia Supernova: A Standardizable Candle

Part I: Observational Facts

Part II: SNe Ia data: from telescope to "m_B"

Part III: Major SNe Ia surveys/dataset

Surveys:

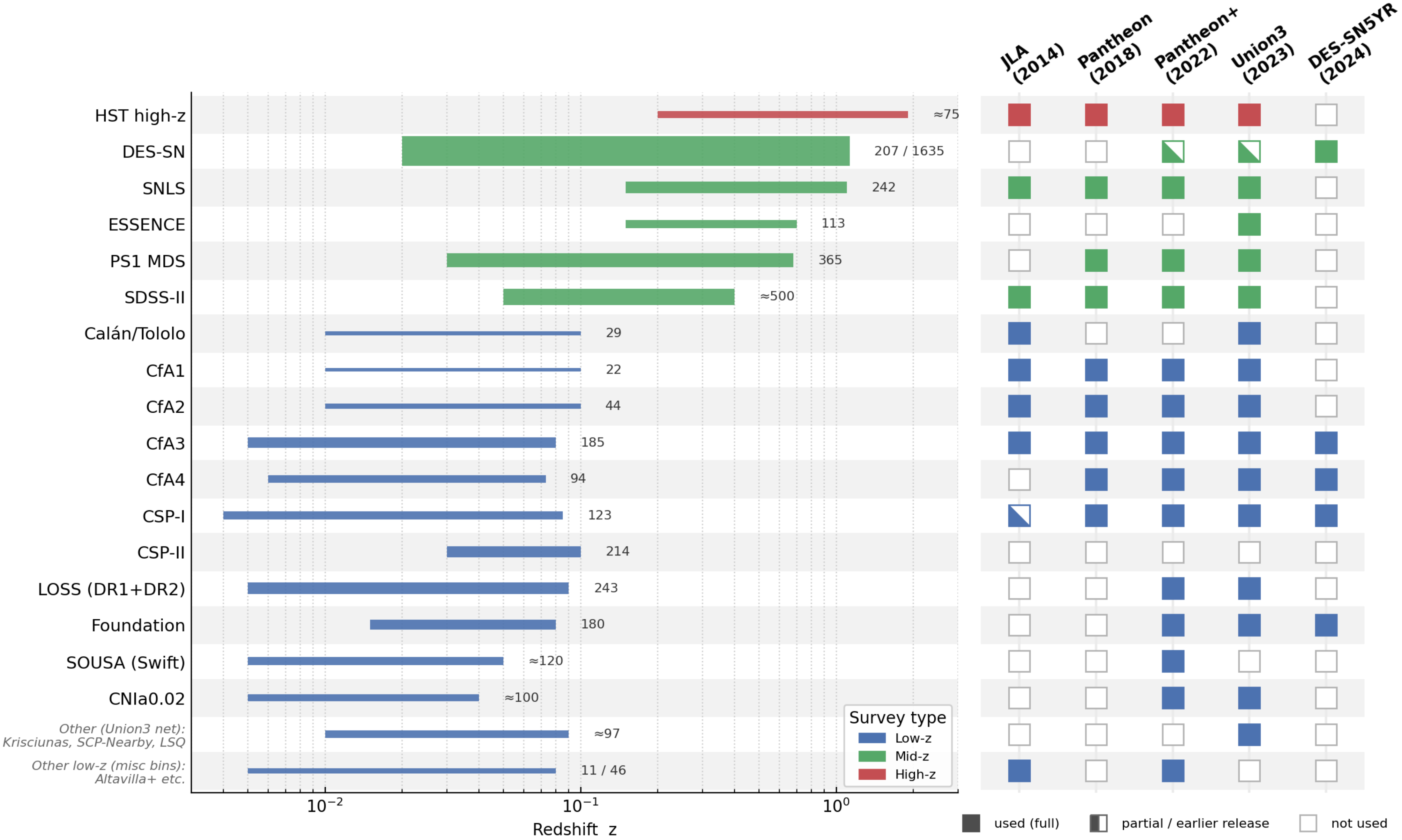
- A dedicated science program, one or a few telescopes only
- Specific redshift range *Q: why?*

Compilations:

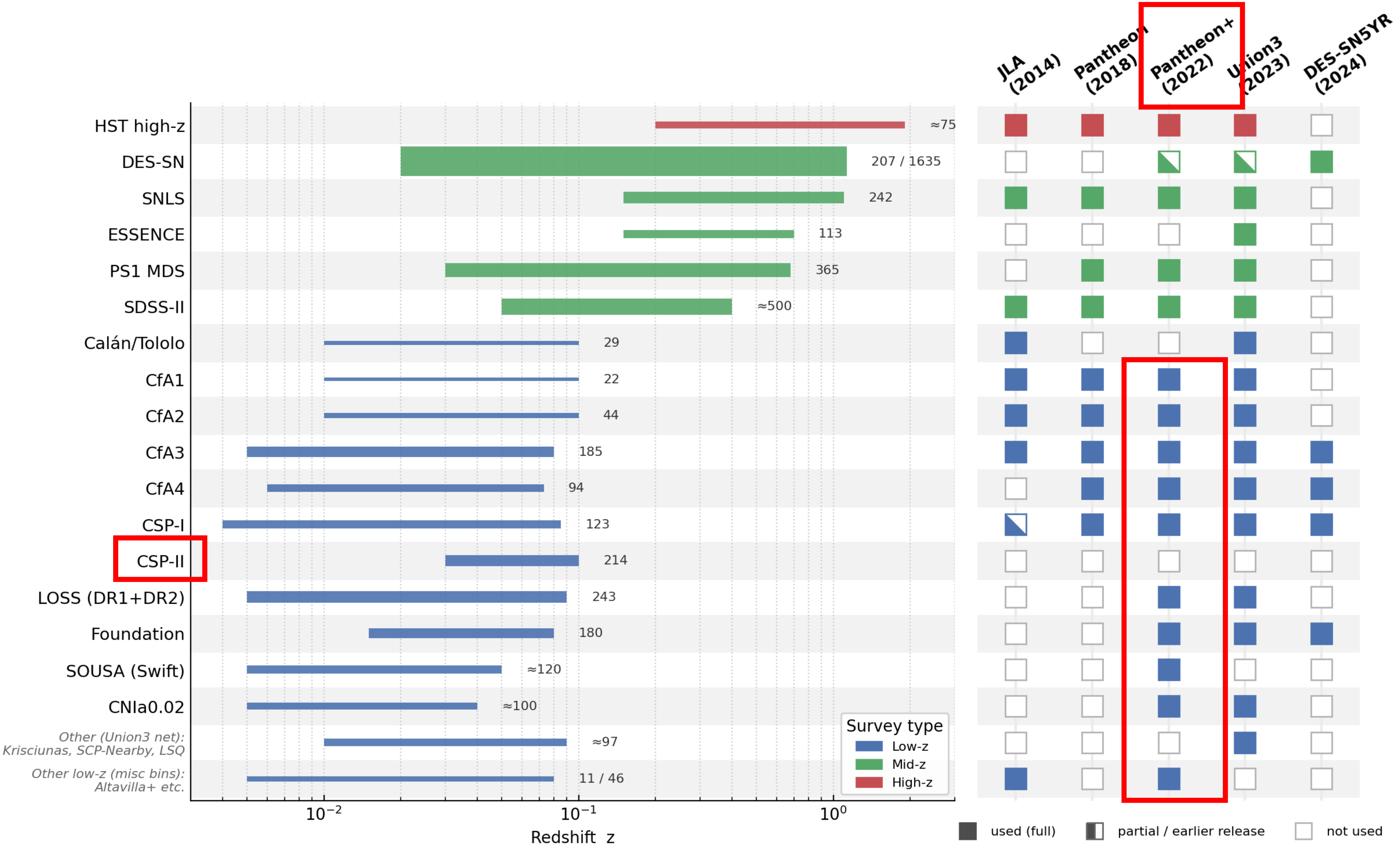
- Combine different surveys to achieve cosmological analysis
- This is what you hear more often
- Most of the work goes into cross-calibration & systematics

Unique choices for each dataset: *← This is what matters!*

- Targeted? Untargeted?
- Small-field? Wide-field?
- Spec-confirmed SNe Ia?
- Host spec-z? SN-z? or host photo-z?



Bar thickness ∝ √N (number of SNe). Half-filled cell = an earlier/partial data release of that survey (DES 3-yr in Pantheon+/Union3 vs full 5-yr in DES-SN5YR; CSP DR1 in JLA vs DR3 later).
DES-SN N: 207 (3-yr, spec) / 1635 (5-yr, phot). CSP-II is used in CSP-team H0 analyses (Uddin+24) but its photometry is unreleased and it is in none of these 5 compilations. 'Other' rows are catch-all bins. Counts and z-ranges approximate.



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