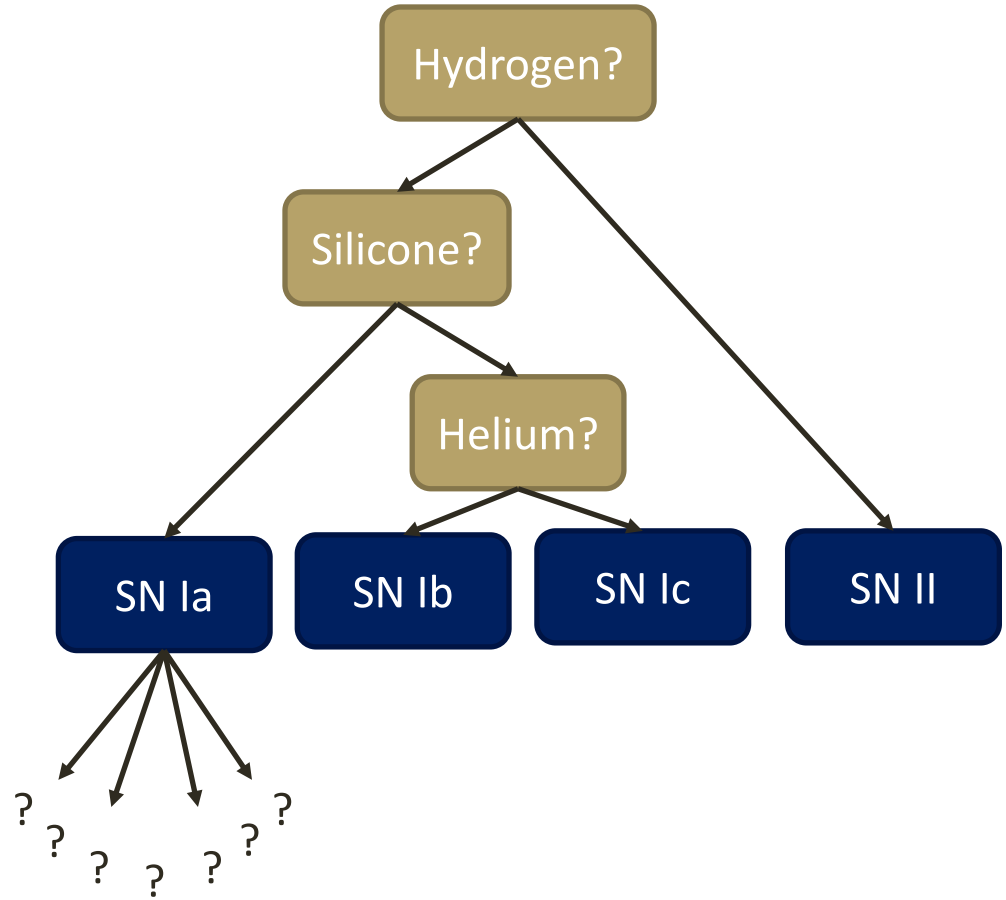
Supernova Classification:
How to Find What You’re Looking For



Daniel Perrefort
https://djperrefort.github.io

University of Pittsburgh

April 3 2021

Let’s talk about…

1. How Do You Classify SNe?
2. Classifying SNe Ia in the LSST Era
3. Properties of 91bg-like SNe in SDSS

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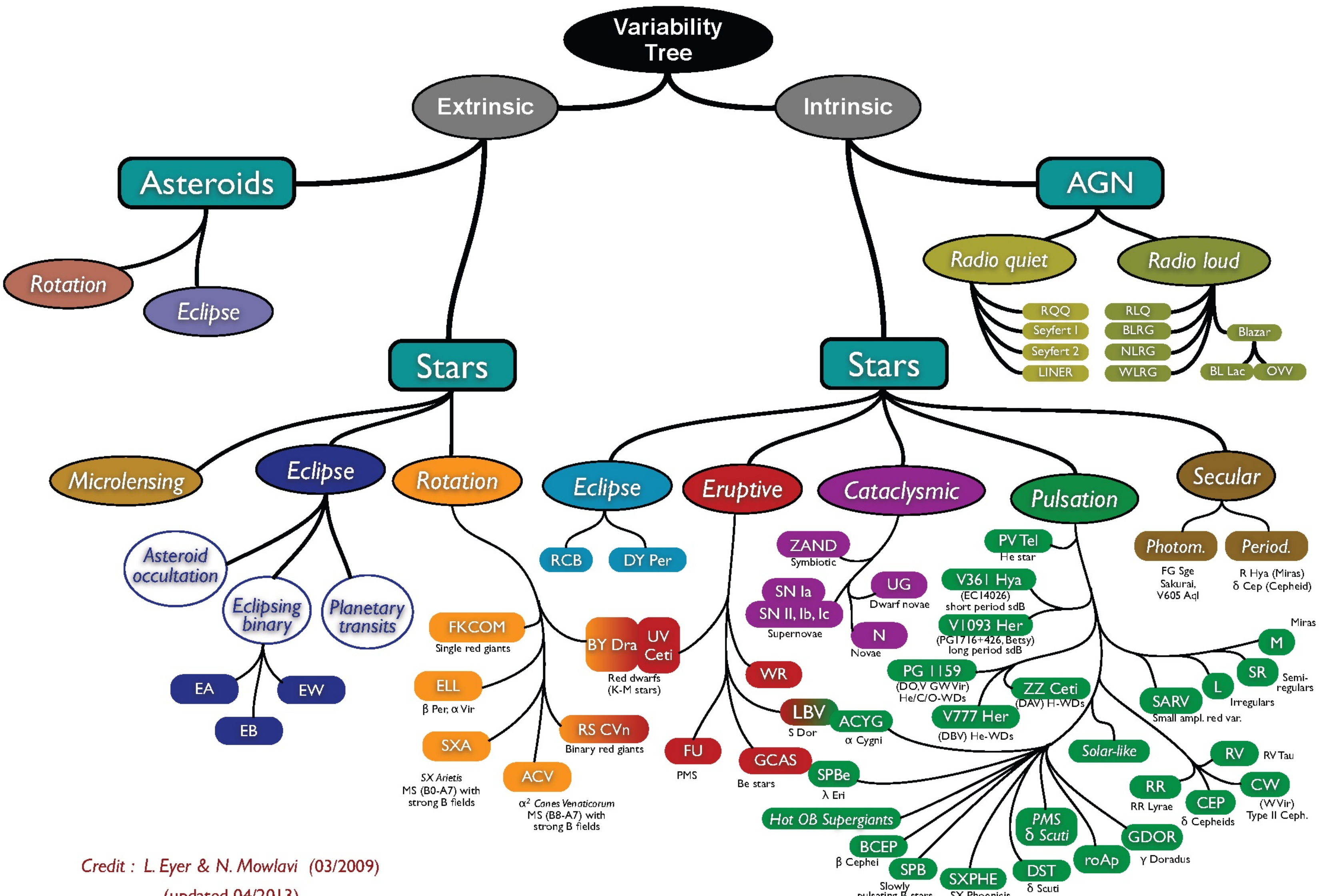
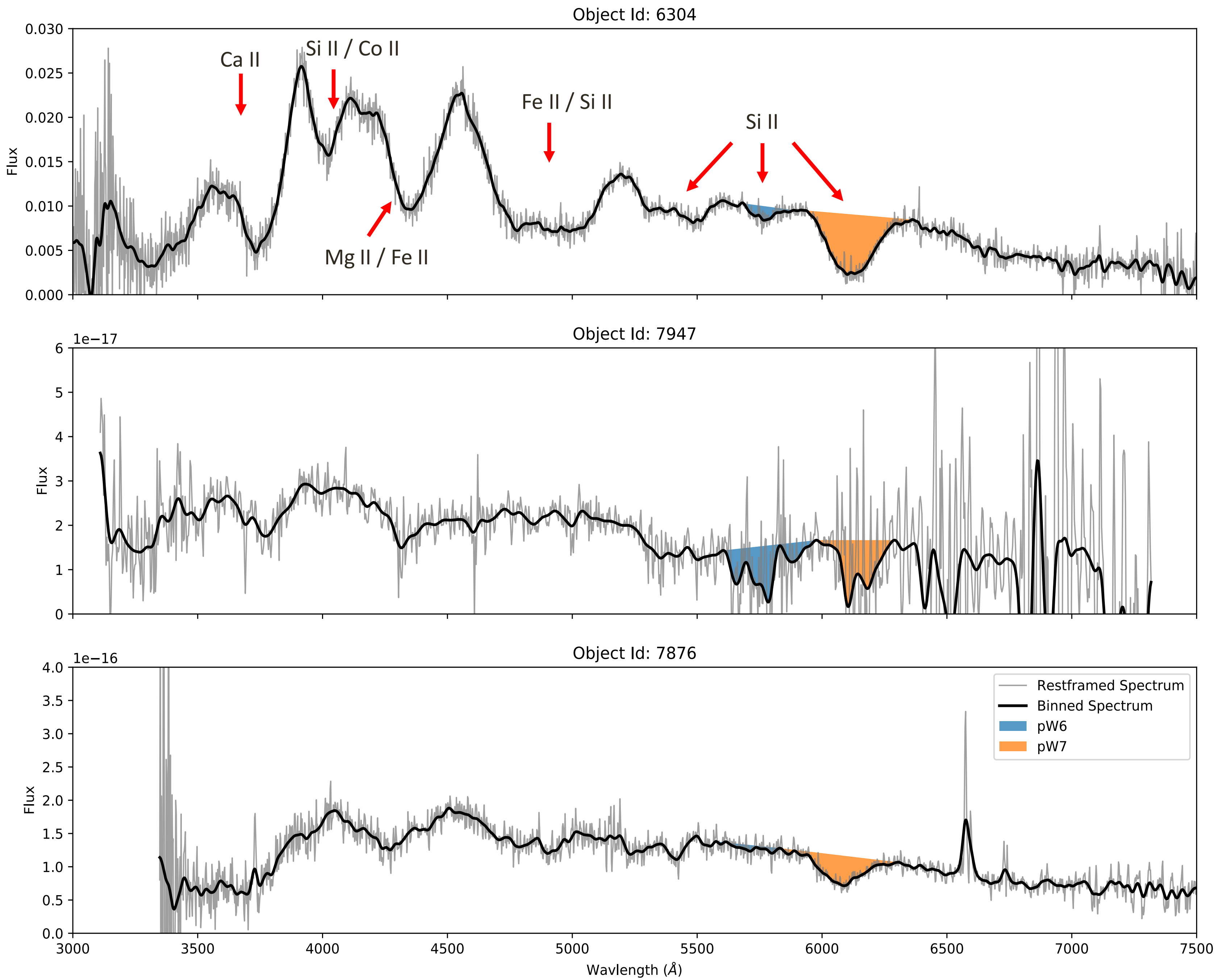
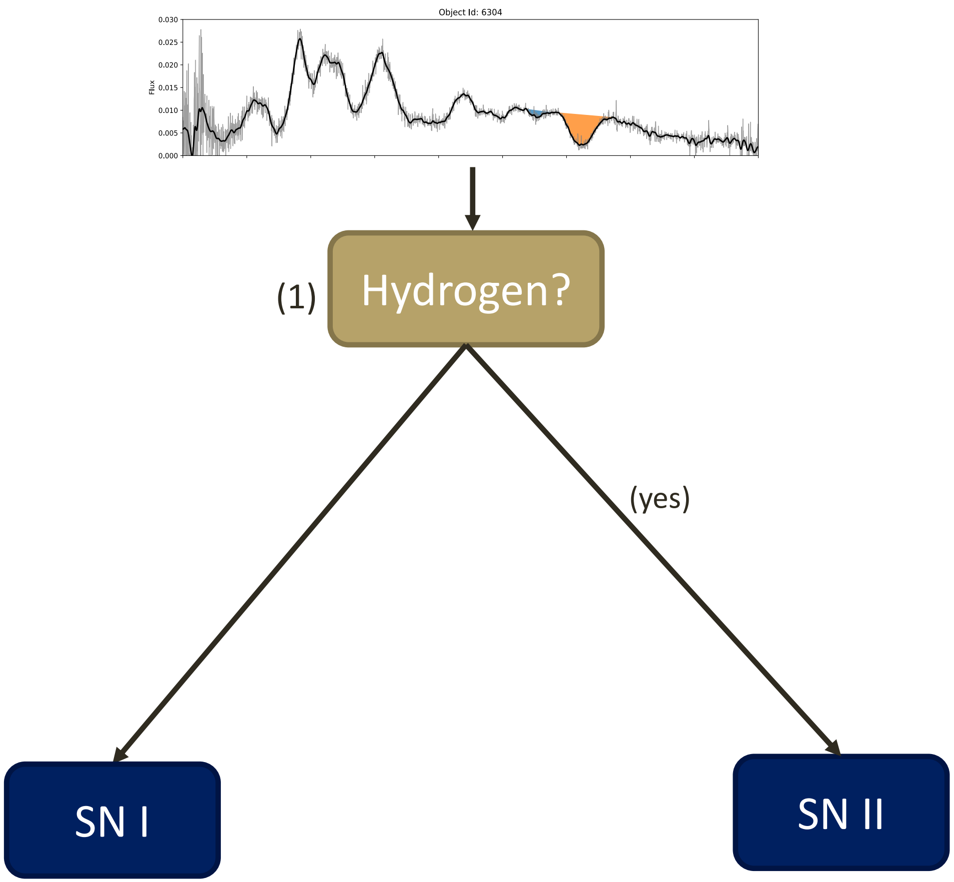
The Variability Landscape



Credit : L. Eyer & N. Mowlavi (03/2009)
(updated 04/2013)

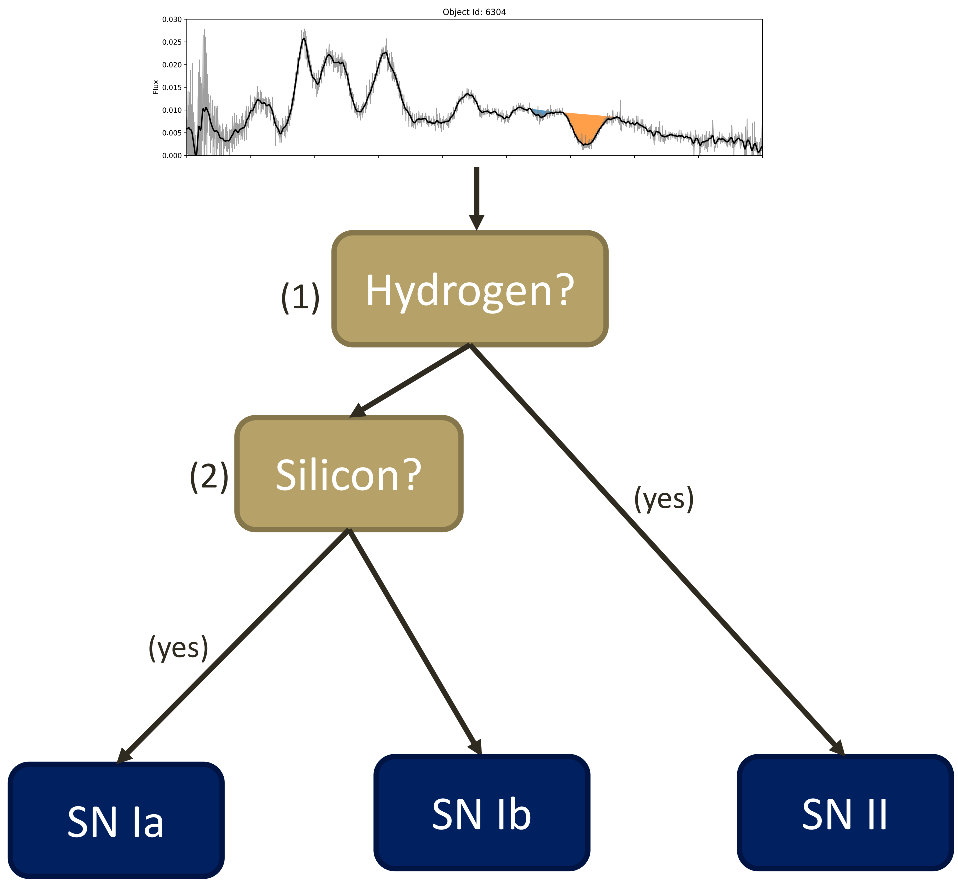

Object Id: 6304
Ca II
Si II / Co II
Fe II / Si II
Si II
Mg II / Fe II
Object Id: 7947
Object Id: 7876
Restframed Spectrum
Binned Spectrum
pW6
pW7
Flux
Wavlength (Å)

Evolution of SN Classification



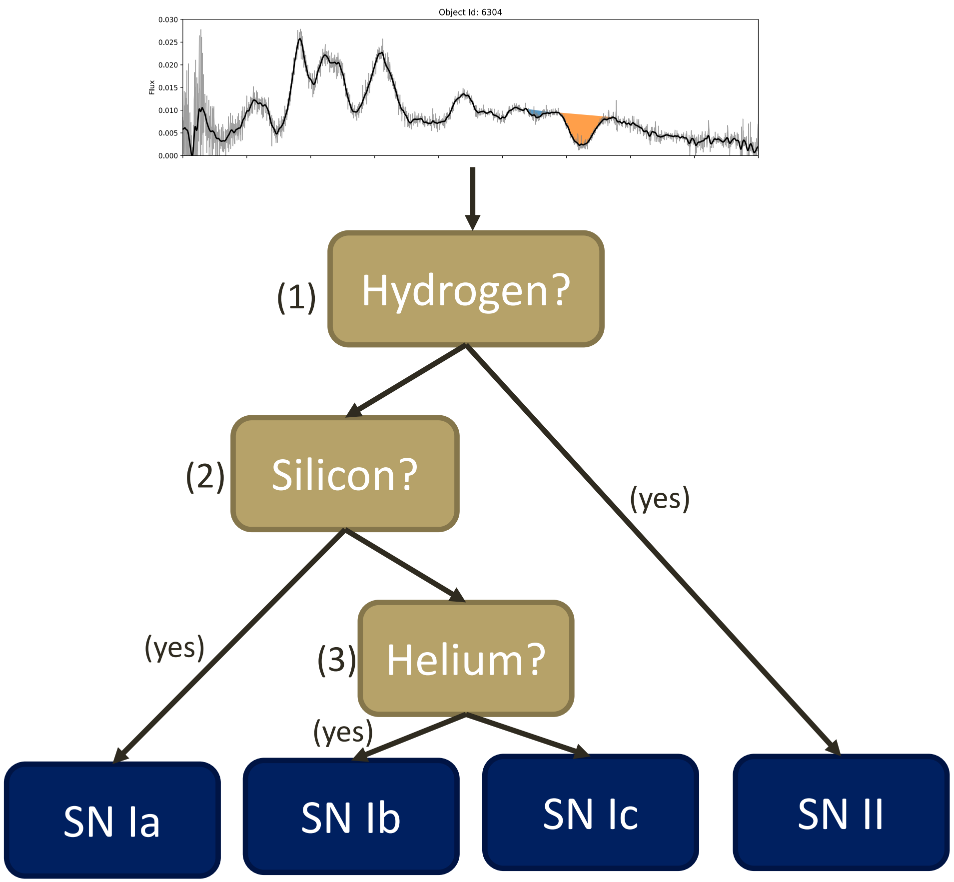
1. Minkowski (1941): Introduces type I/II

Evolution of SN Classification



1. Minkowski (1941): Introduces type I/II
2. Wheeler Levreault (1985) and Elias+ (1985): Introduces type Ib

Evolution of SN Classification



1. Minkowski (1941): Introduces type I/II
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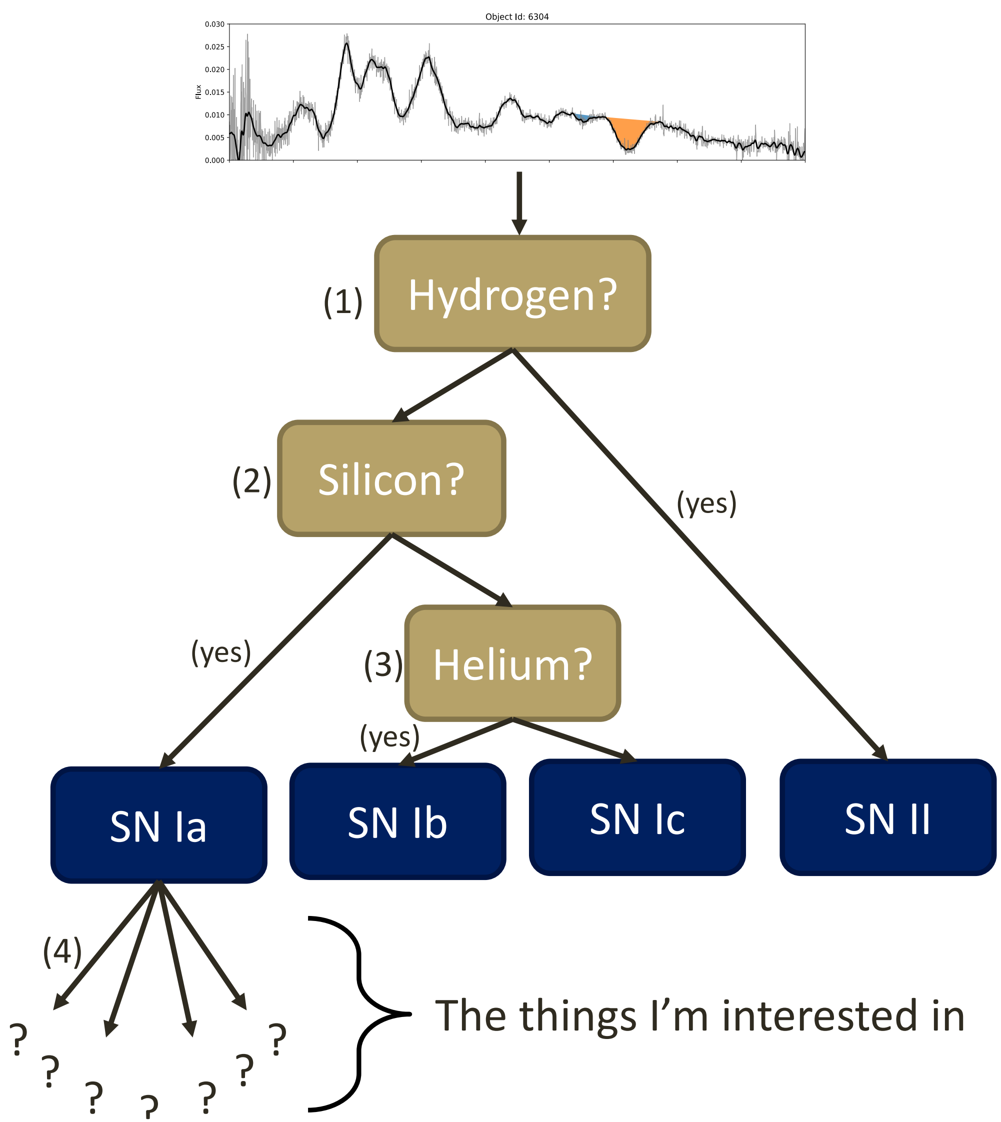

1. Minkowski (1941): Introduces type I/II
2. Wheeler Levreault (1985) and Elias+ (1985): Introduces type Ib
3. Wheeler Harkness (1990): Introduces type Ic
4. Peculiar SNe Ia:
   - SN 1991T (Filippenko 1992a)
   - SN 1991bg (Filippenko 1992b)
   - SNe Iax (Li 2003)
   - SNe Ia-CSM (Green 2008)
   - Super-mass (Howell et al. 2006)
   - SN 2002es (Ganeshalingam 2012)

Defining Peculiar SNe

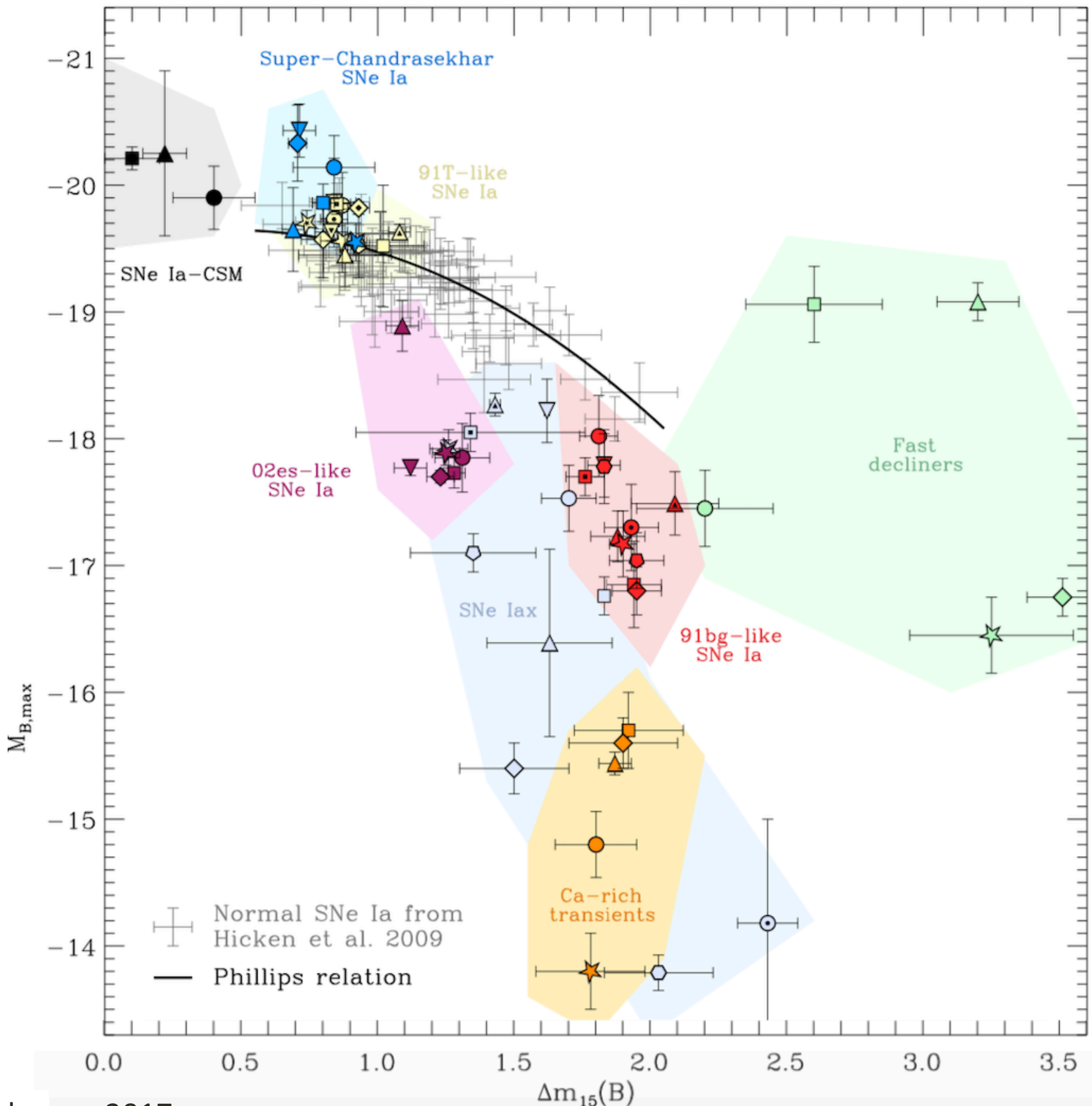

Figure: Taubenberger 2017

Defining Peculiar SNe

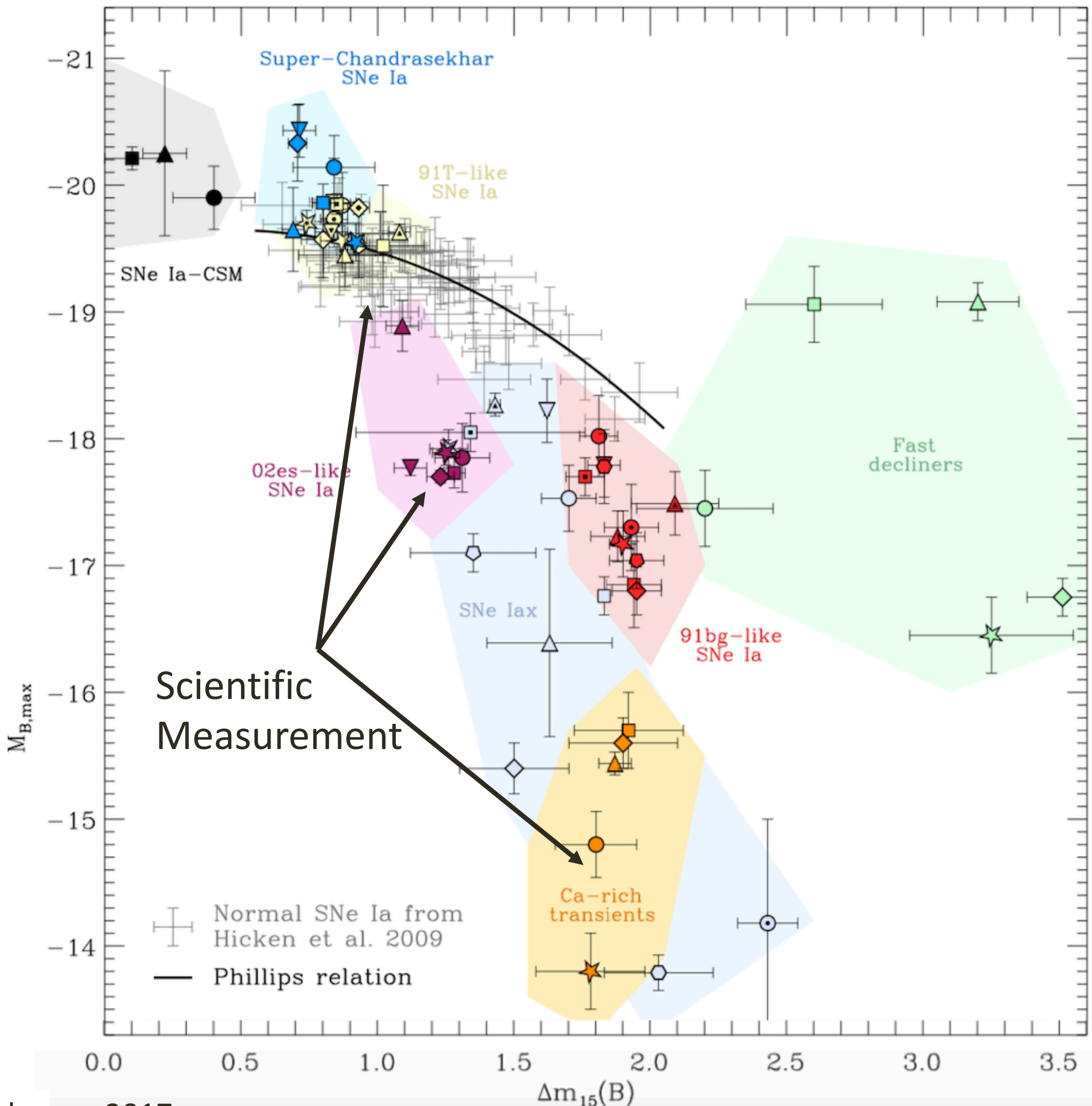

Figure: Taubenberger 2017

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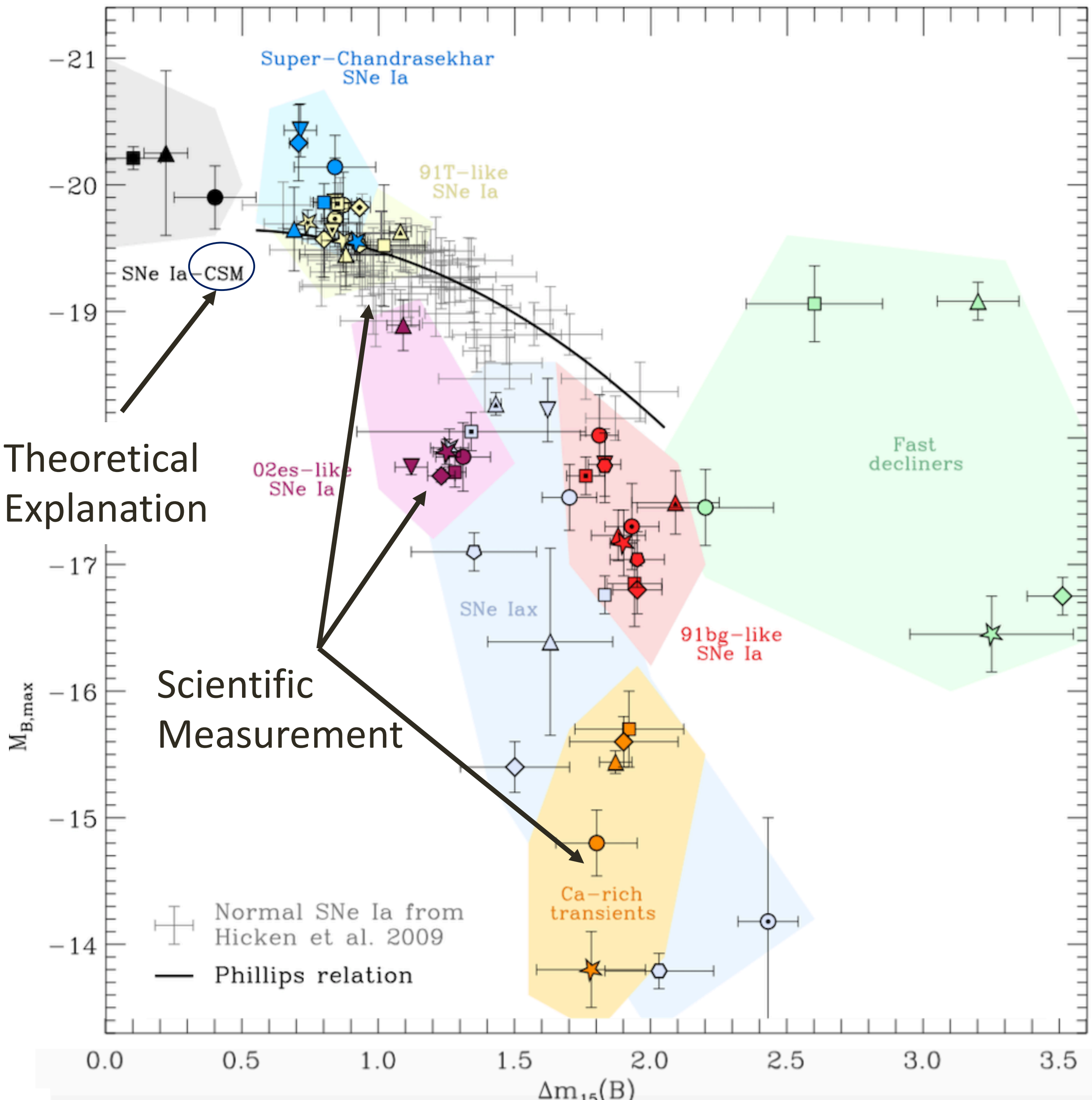


Figure: Taubenberger 2017

Defining Peculiar SNe

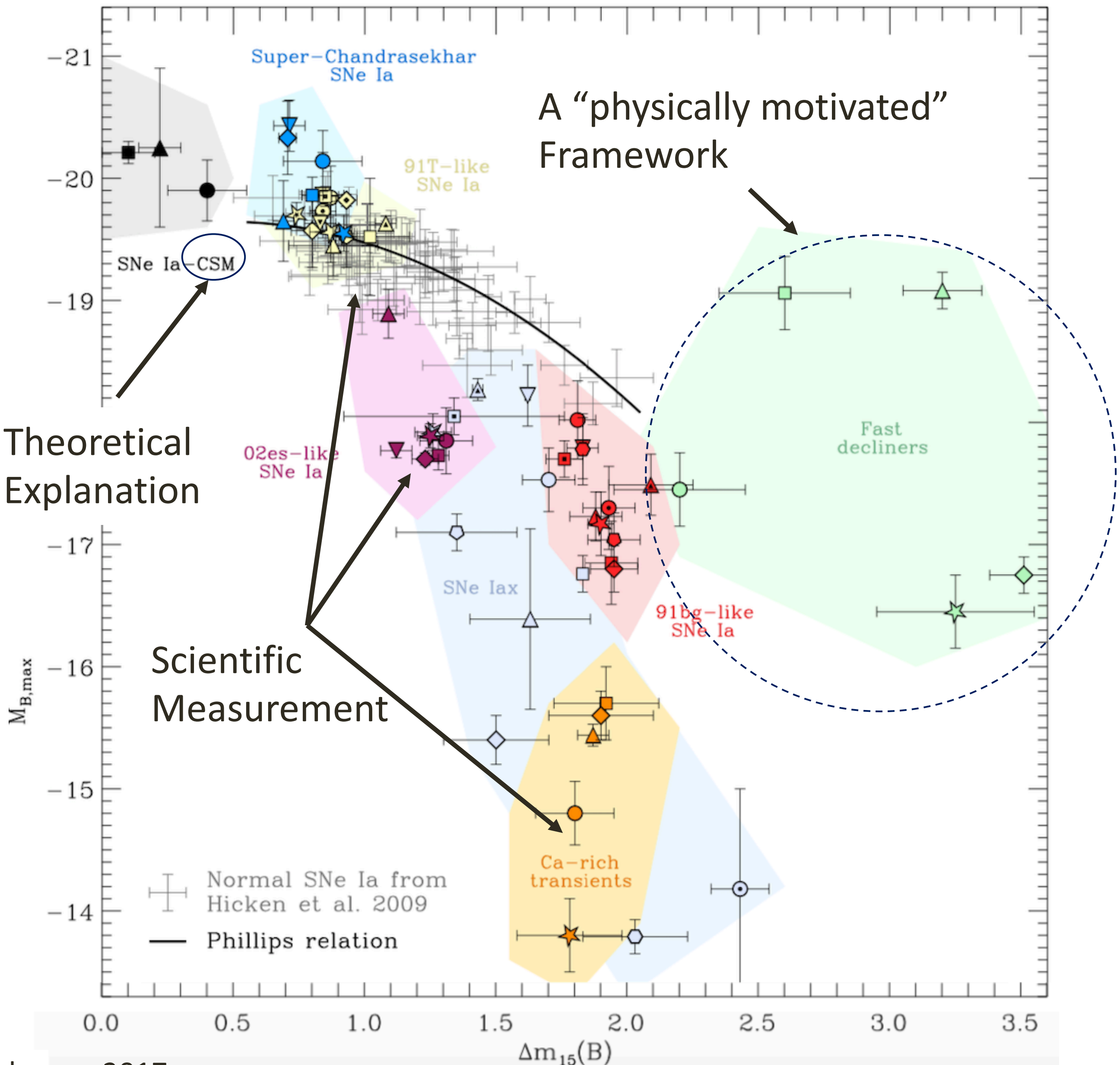
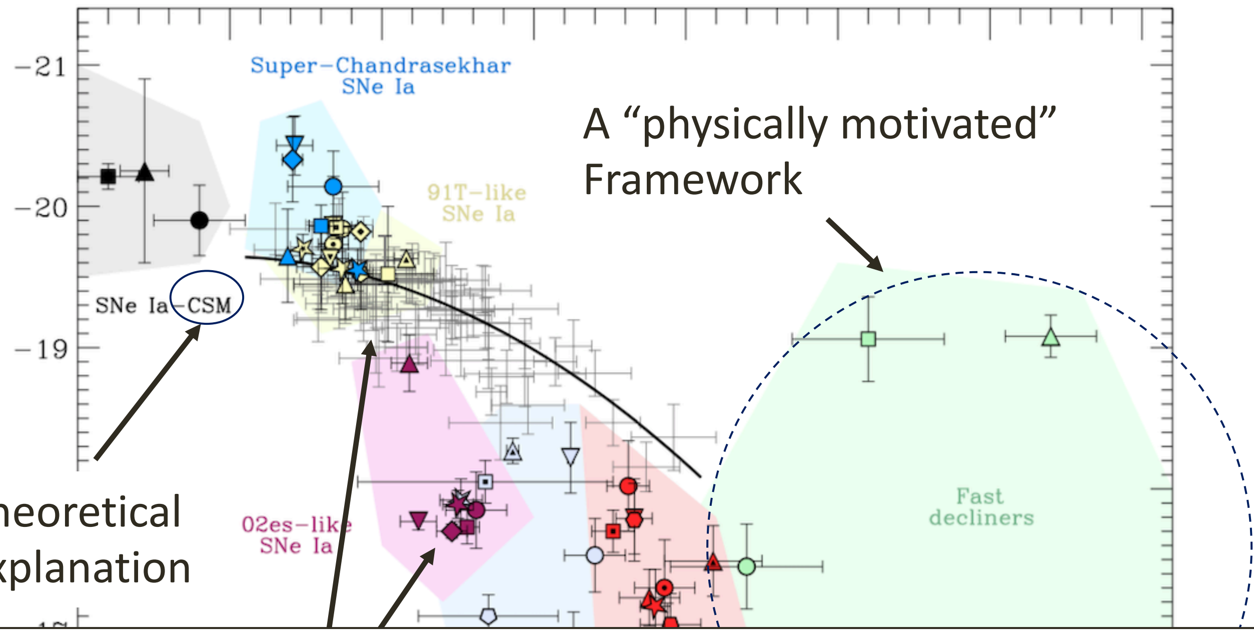


Figure: Taubenberger 2017

Defining Peculiar SNe



A "physically motivated" Framework

Theoretical Explanation

Problem 1

"... [supernova] class names are not systematically defined according to a set of underlying principles, some of the class names are quite opaque to non-experts and form a barrier for general astrophysicists in following the SN literature, and some class names mix observational properties with physical interpretation that may be debated..." - Gal-Yam (*2016*)

Figure: Taubenberger 2017

SN Ia Sub-types Vary in their:

- Rates
- Chemical yields
- Ejecta velocities / energy yield
- Host galaxy biases
  - Mass
  - Star formation
  - Distances

Key Questions:

- What causes this variety?
- Are there multiple physical mechanisms?
- Are there continuous or discrete subtypes?

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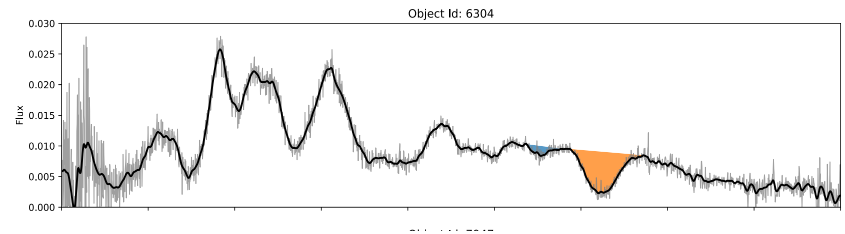
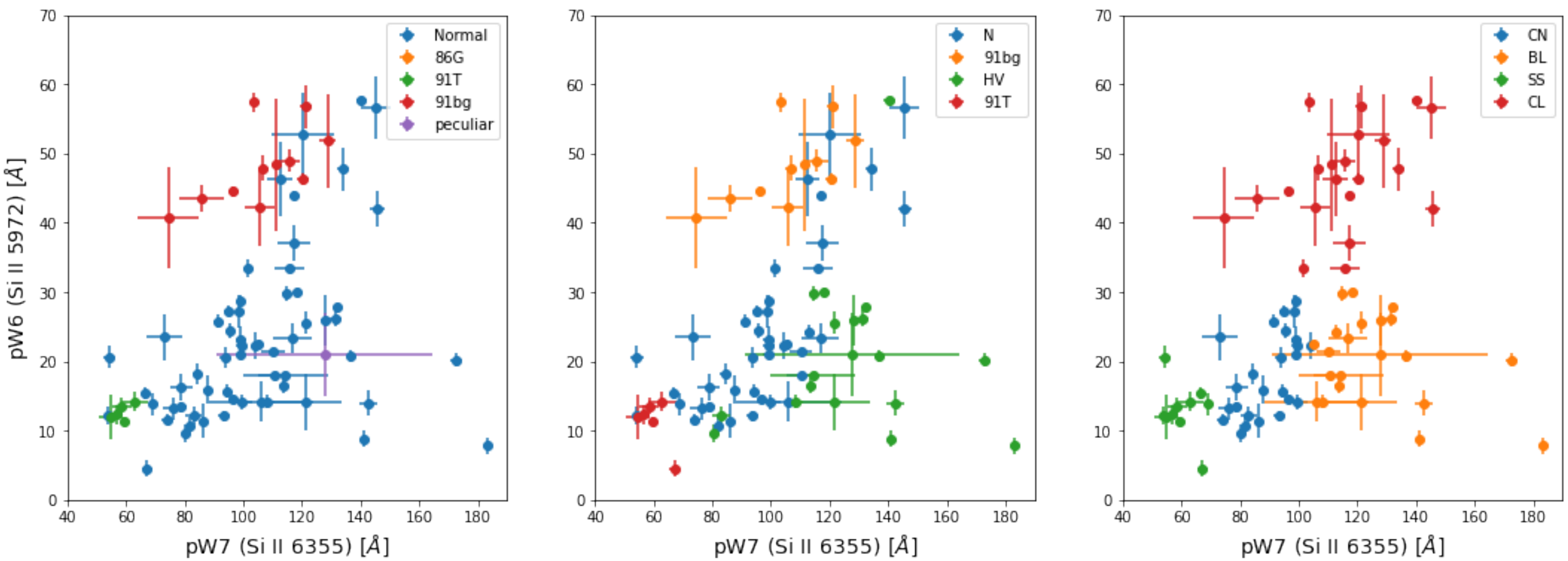


Discrete groups?



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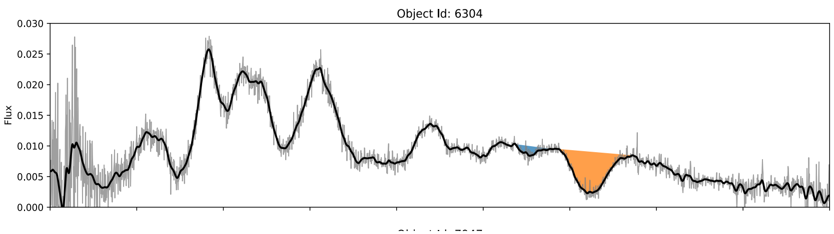
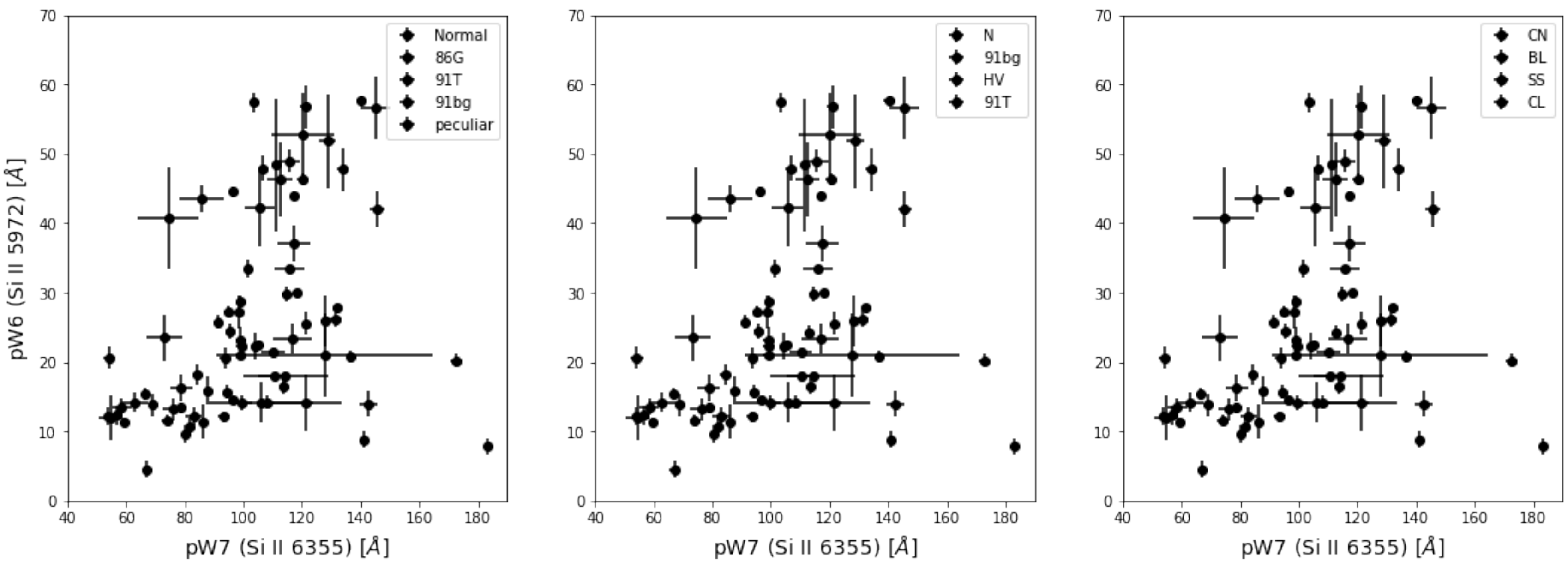
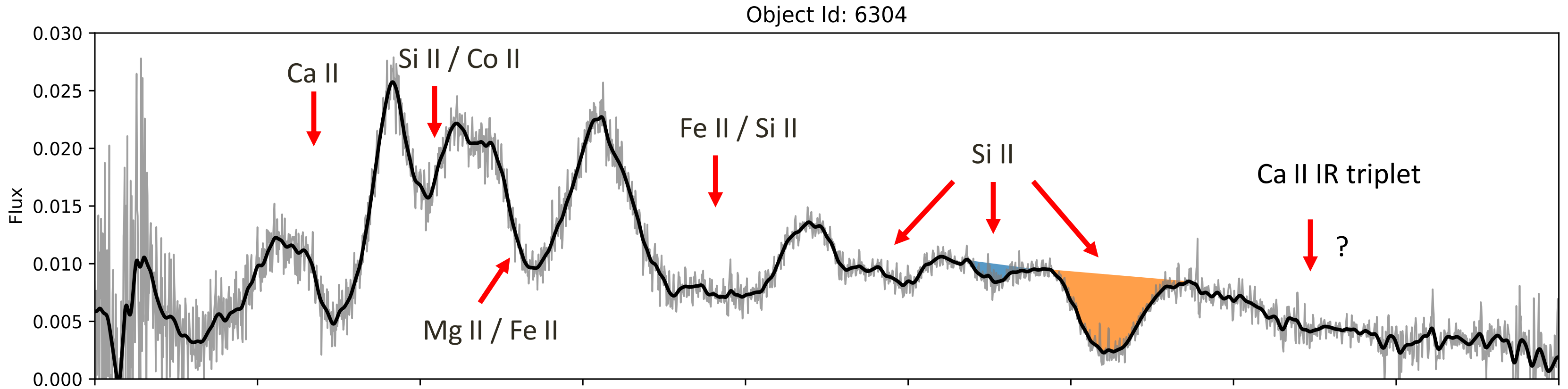


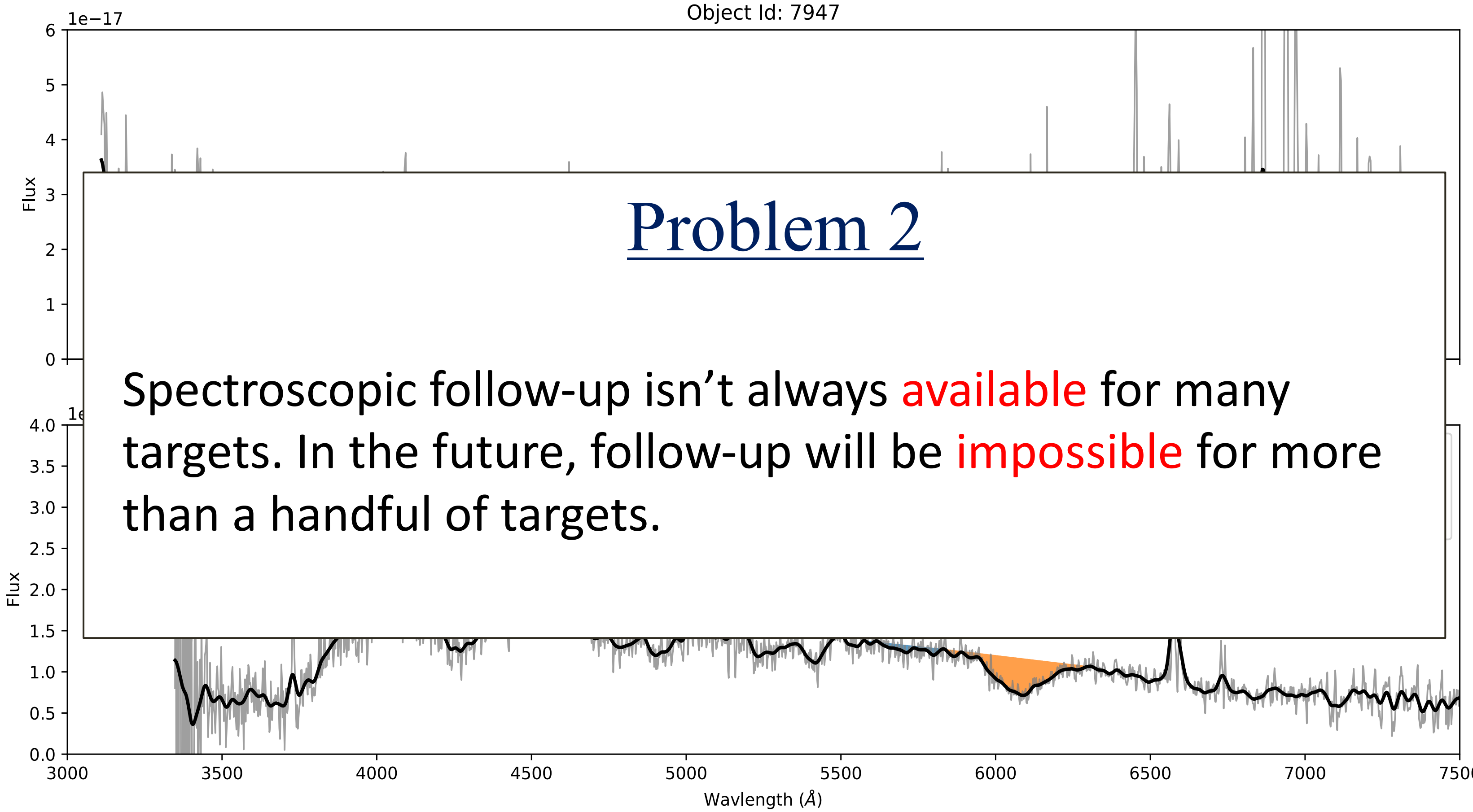
Discrete groups? Or continuous Distribution?

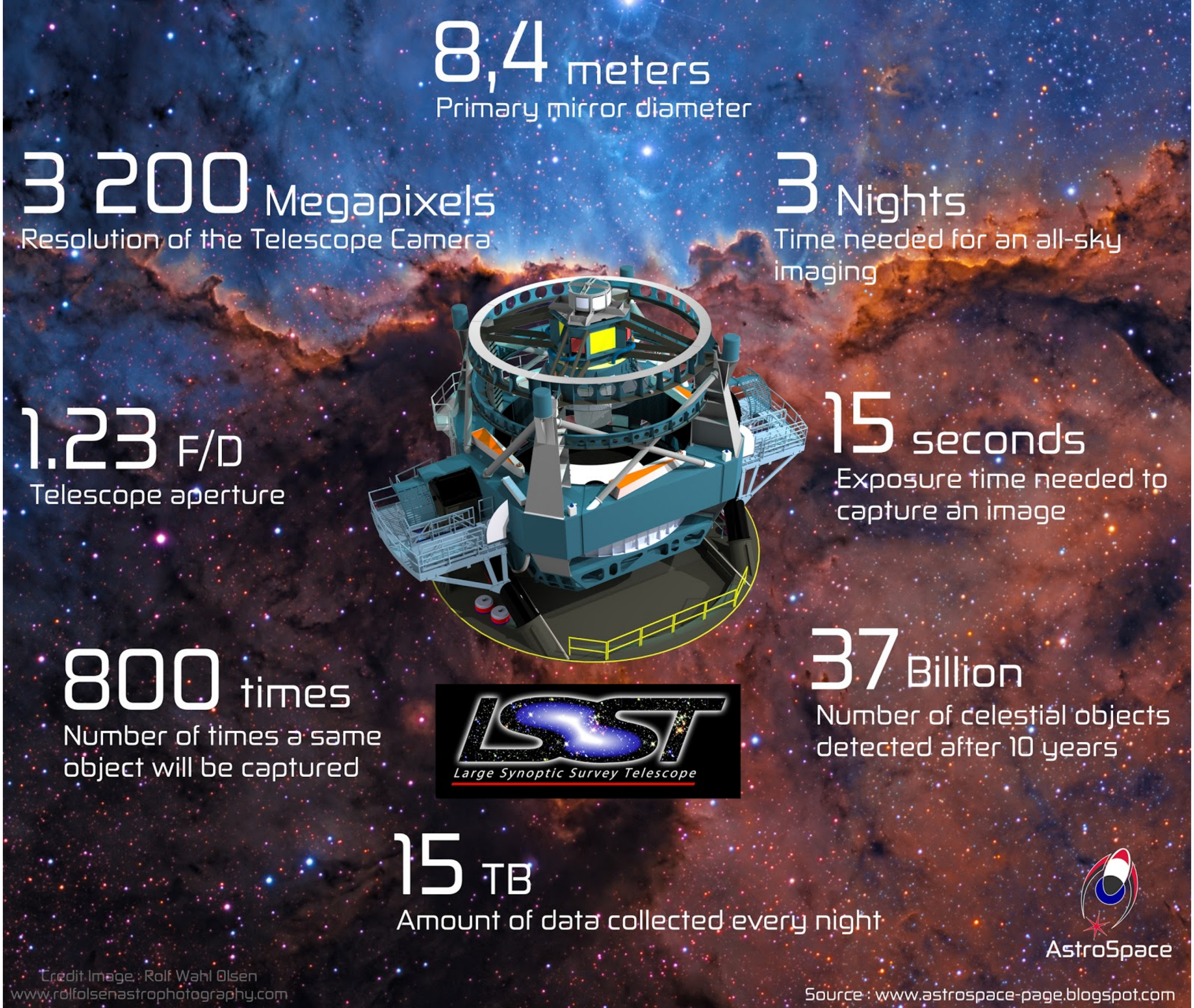




Problem 2

Spectroscopic follow-up isn't always available for many targets. In the future, follow-up will be impossible for more than a handful of targets.




8,4 meters
Primary mirror diameter
3 200 Megapixels
Resolution of the Telescope Camera
3 Nights
Time needed for an all-sky imaging
1.23 F/D
Telescope aperture
15 seconds
Exposure time needed to capture an image
800 times
Number of times a same object will be captured
LSST
Large Synoptic Survey Telescope
37 Billion
Number of celestial objects detected after 10 years
15 TB
Amount of data collected every night
AstroSpace
Credit Image : Rolf Wahl Olsen
www.rolfolsenastrophotography.com
Source : www.astrospace-page.blogspot.com

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GROVE
SIMAQ
M10 008

Approaches to Phot. Classification

Classify Everything

- Lends well to ML (Scalable)
- Useful for data filtering and performance metrics
- Tackles multiple science cases

(Dai et al. 2018; Muthukrishna et al. 2019; Pasquet, Johanna et al. 2019)

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Identify a Single Class

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- Interpret in terms of physical parameters
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Cons:

- Targeted at specific science cases
- Very model dependent

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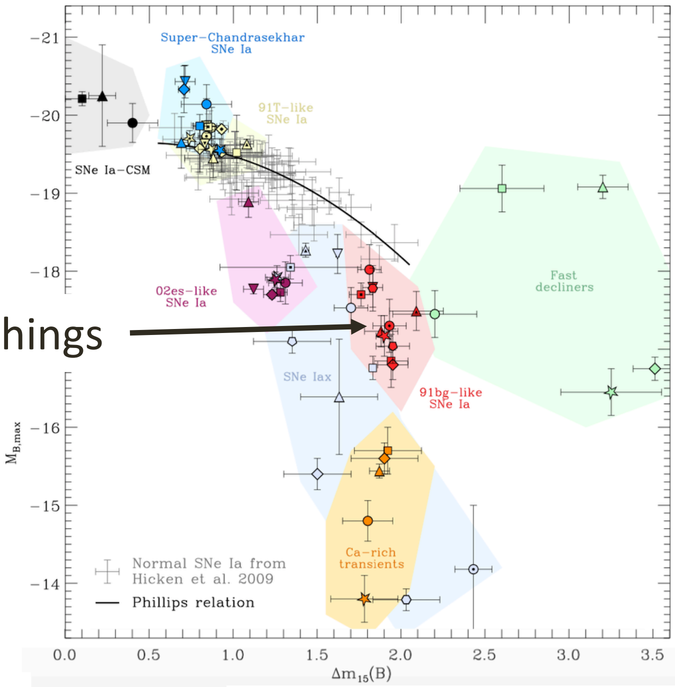
(González-Gaitán 2014; Blondin 2007 Perrefort 2020 - submitted)

Characterizing a 91bg



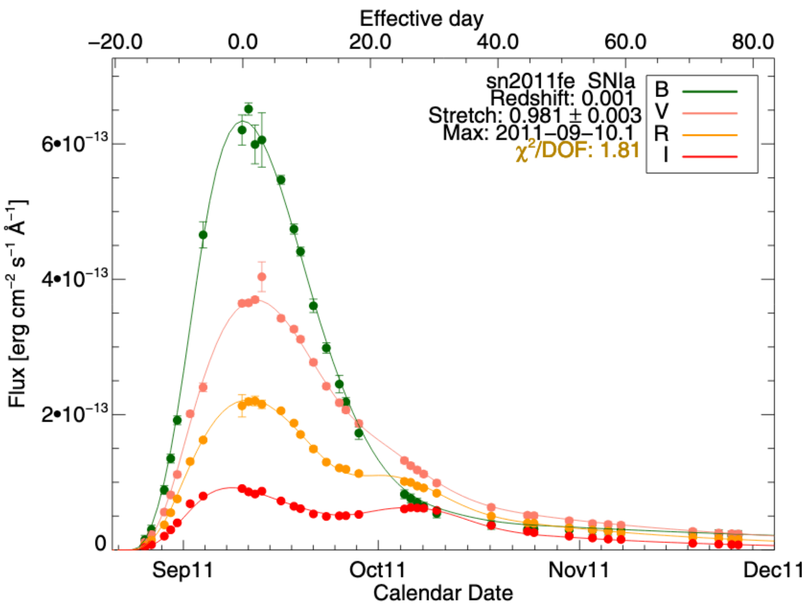
These things

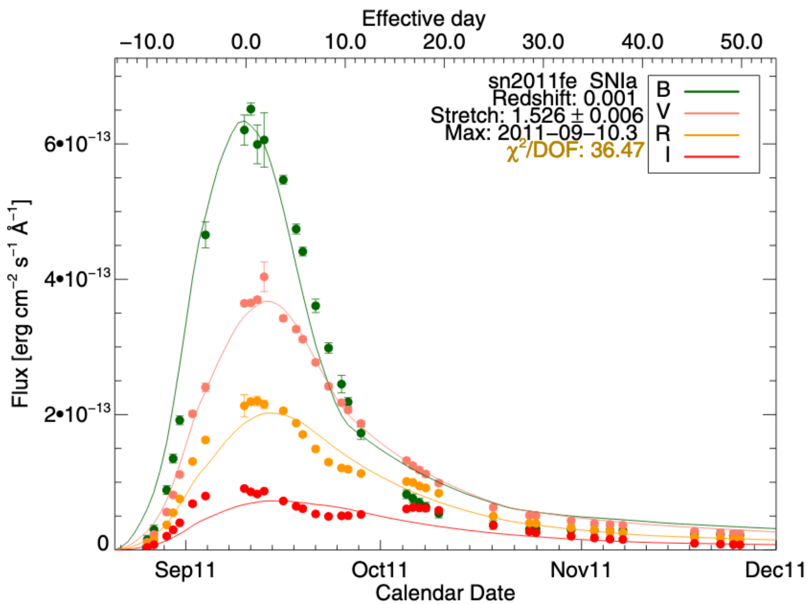
Figure: Taubenberger 2017

- Cooler due to stronger Ti lines
- Sub-luminous (~1.1 mag)
- Redder / faster declining light curves
- No secondary maximum in redder bands
- Reach reddest point faster (+15d) than normal (+30 d)
- Older, more massive host environments
- Normal Ejecta velocities

(Note that many of these distinctions can be observed photometrically)

Normal SN


Effective day
−20.0
0.0
20.0
40.0
60.0
80.0
sn2011fe SNIa
Redshift: 0.001
Stretch: 0.981 ± 0.003
Max: 2011−09−10.1
χ²/DOF: 1.81
B
V
R
I
6•10⁻¹³
4•10⁻¹³
2•10⁻¹³
0
Flux [erg cm⁻² s⁻¹ Å⁻¹]
Sep11
Oct11
Nov11
Dec11
Calendar Date


Effective day
−10.0
0.0
10.0
20.0
30.0
40.0
50.0
sn2011fe SNIa
Redshift: 0.001
Stretch: 1.526 ± 0.006
Max: 2011−09−10.3
χ²/DOF: 36.47
B
V
R
I
6•10⁻¹³
4•10⁻¹³
2•10⁻¹³
0
Flux [erg cm⁻² s⁻¹ Å⁻¹]
Sep11
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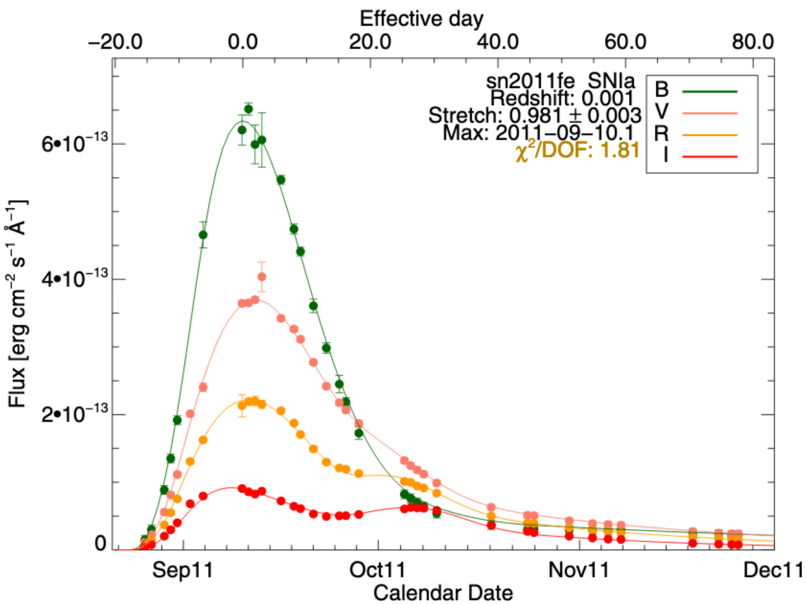
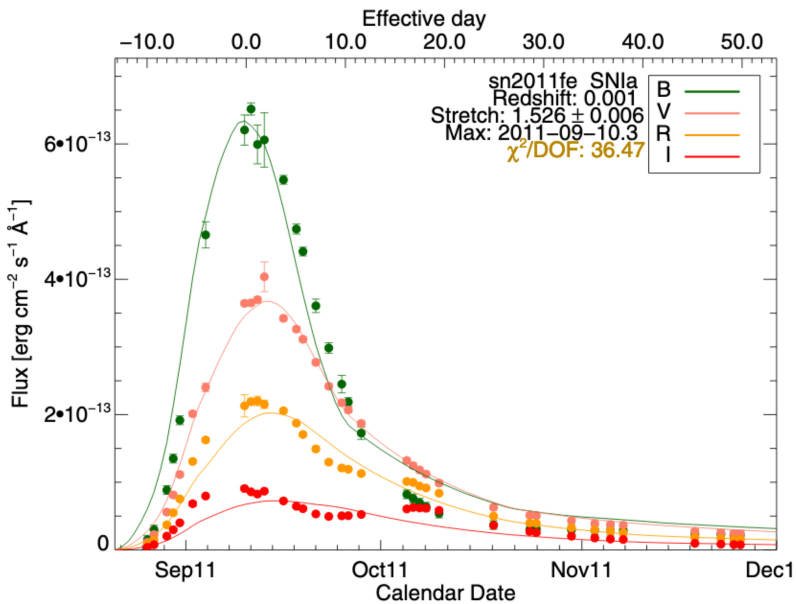
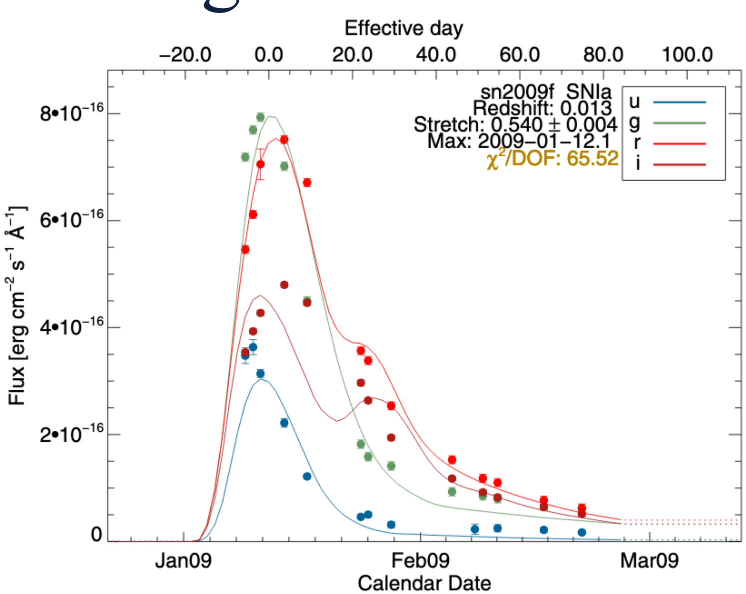
Calendar Date

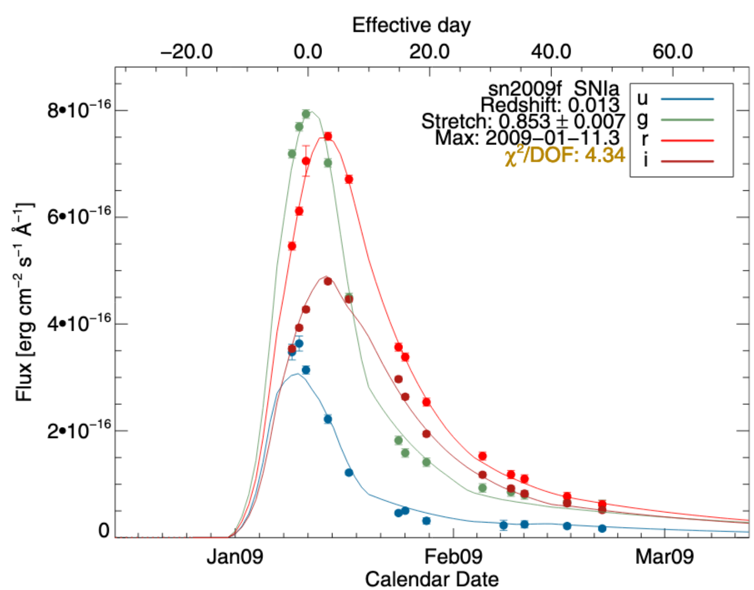
Normal SN



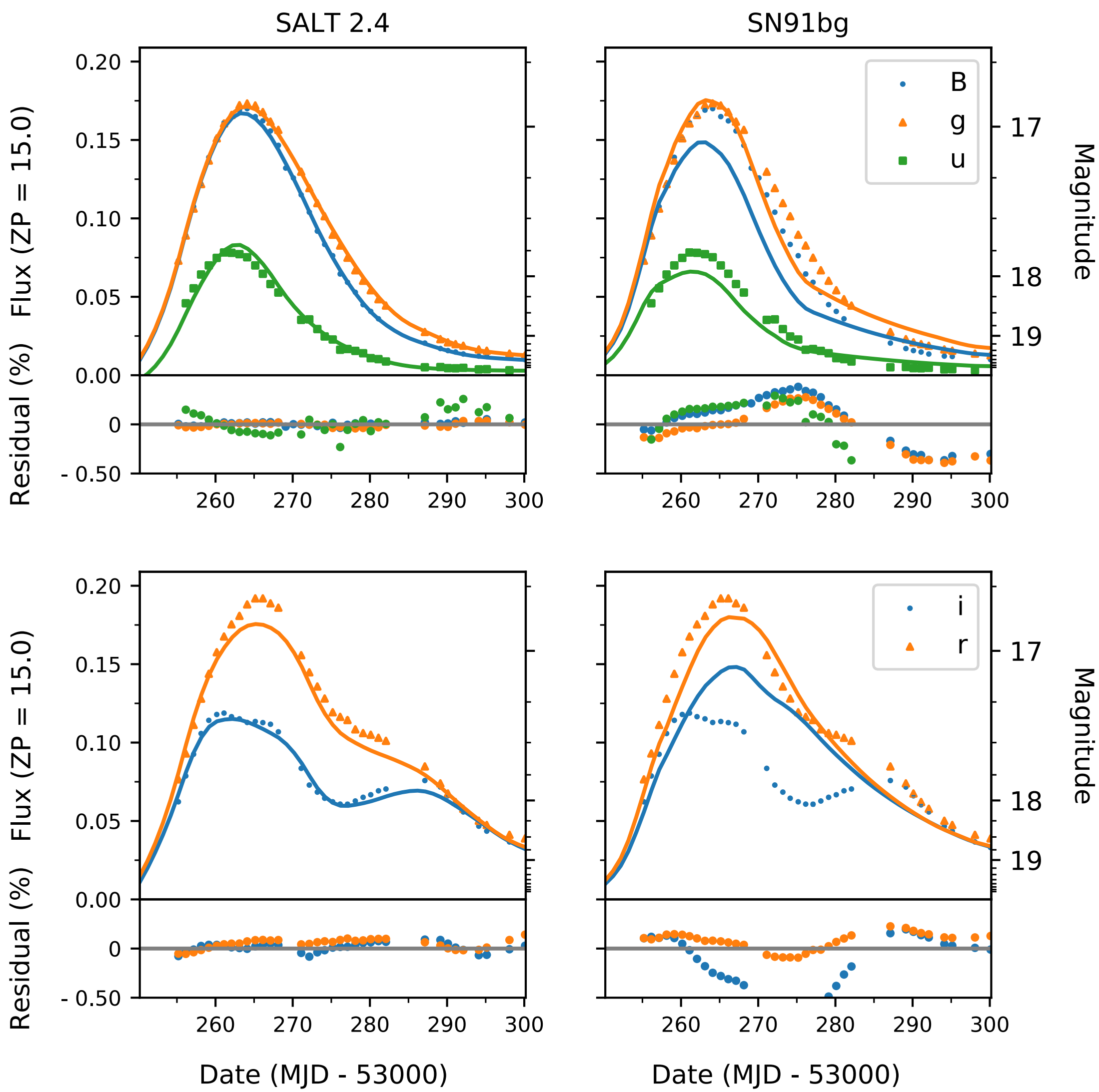


SN 1991bg-like SN





Running Multiple Fits



Empirical Classification

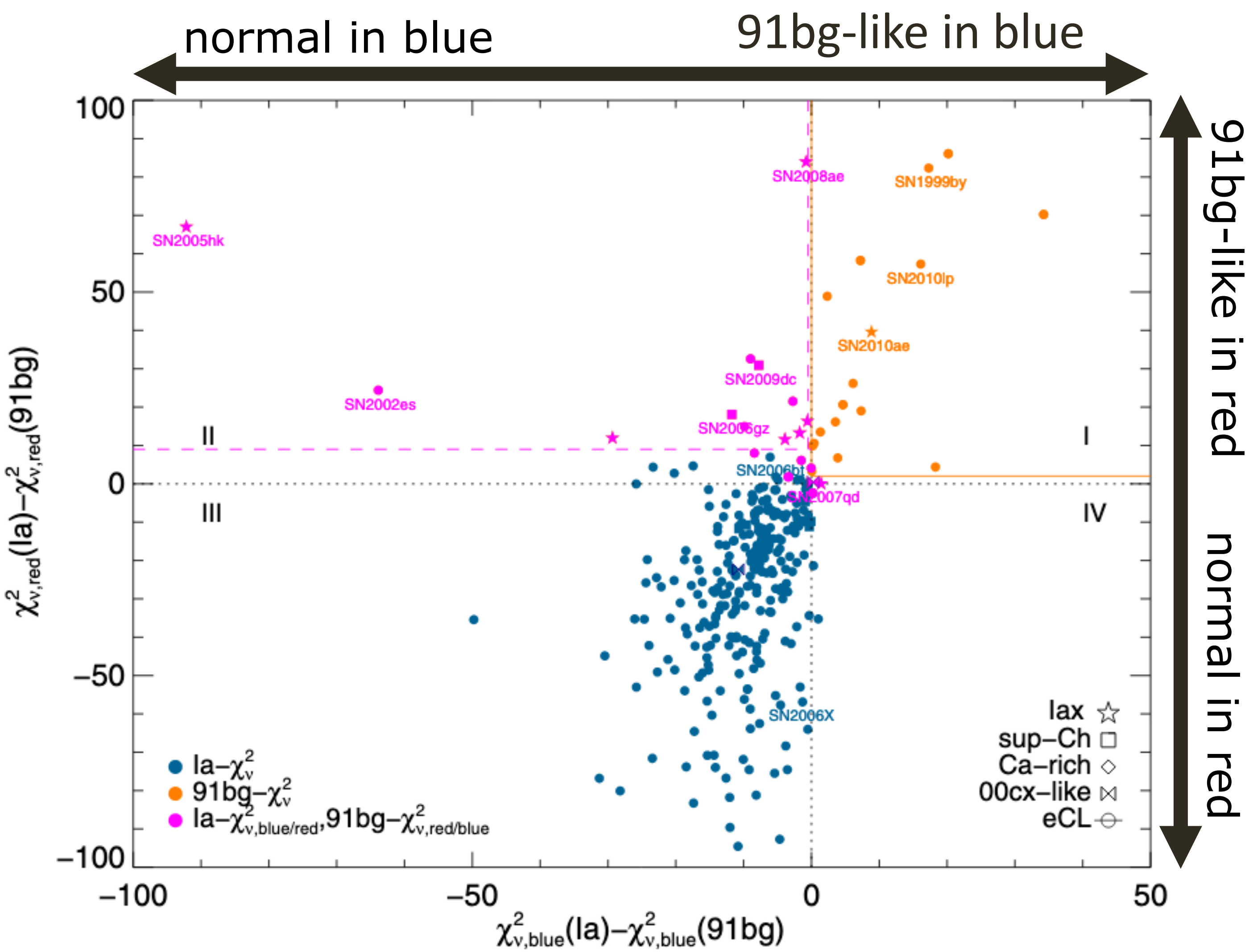
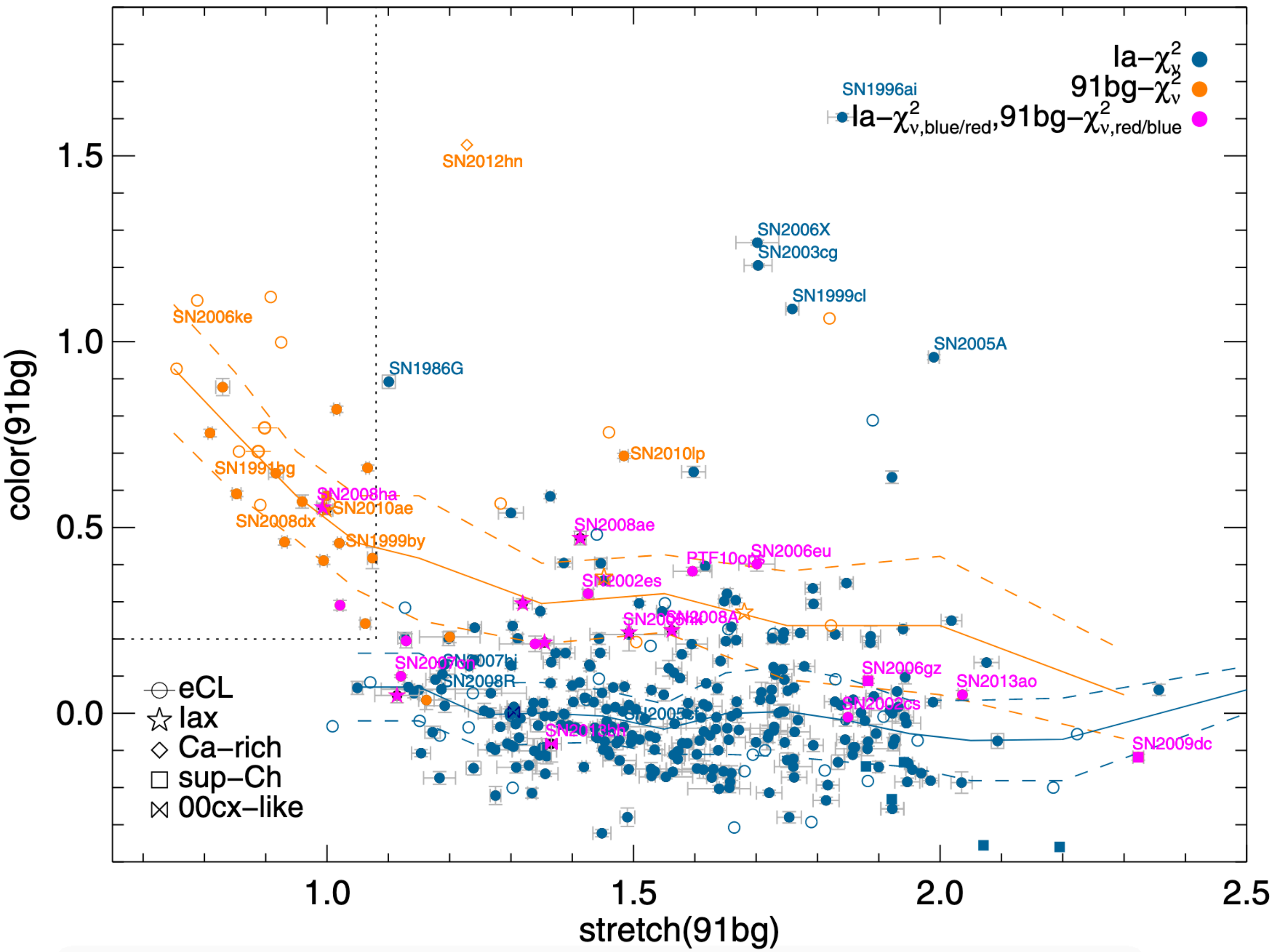


Figure: (González-Gaitán 2014)

Empirical Classification



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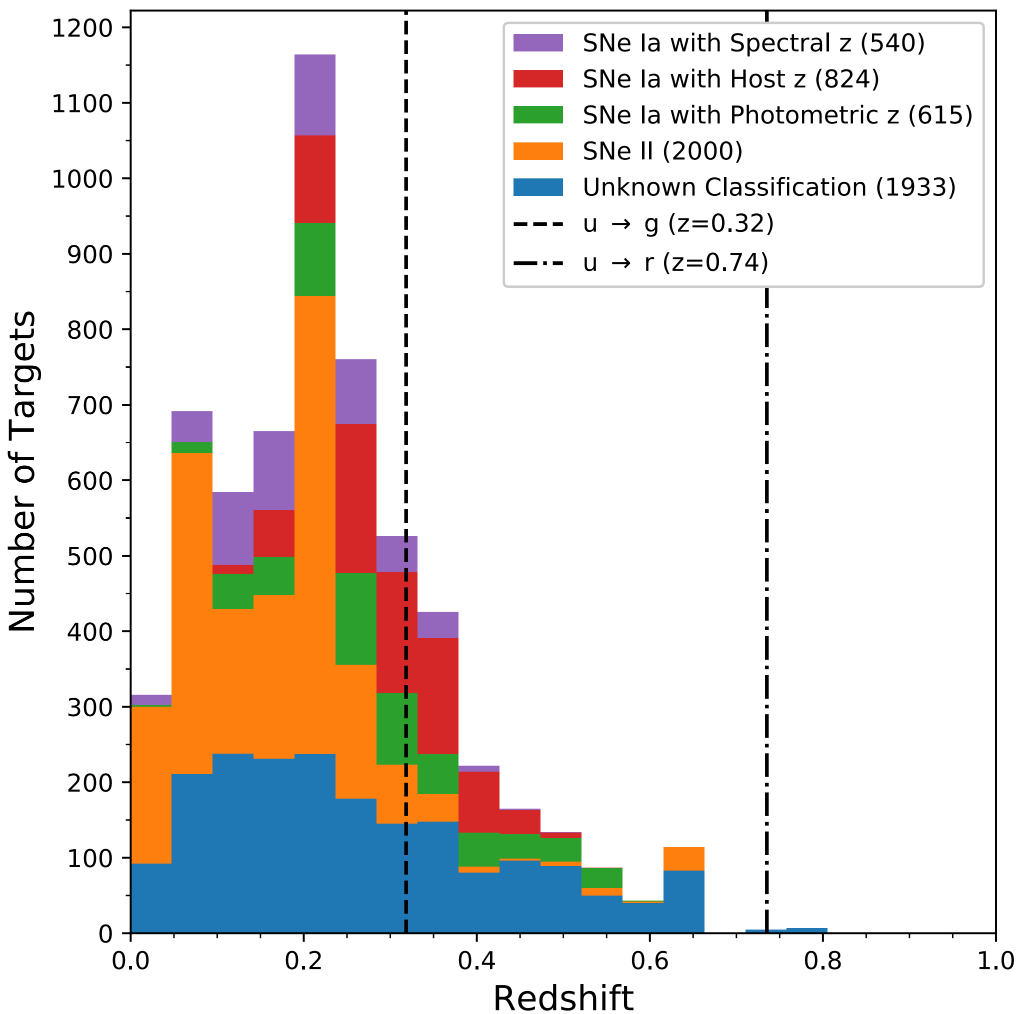
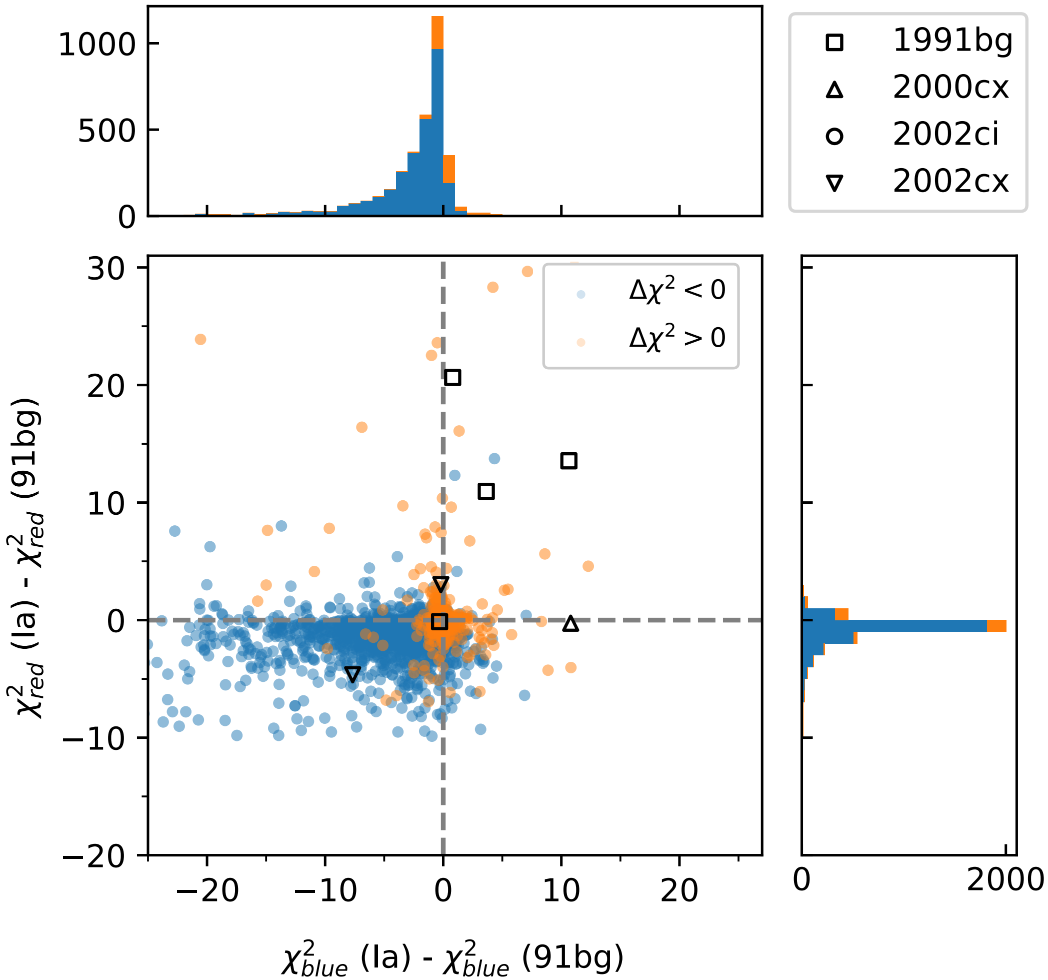
SDSS SN Sample

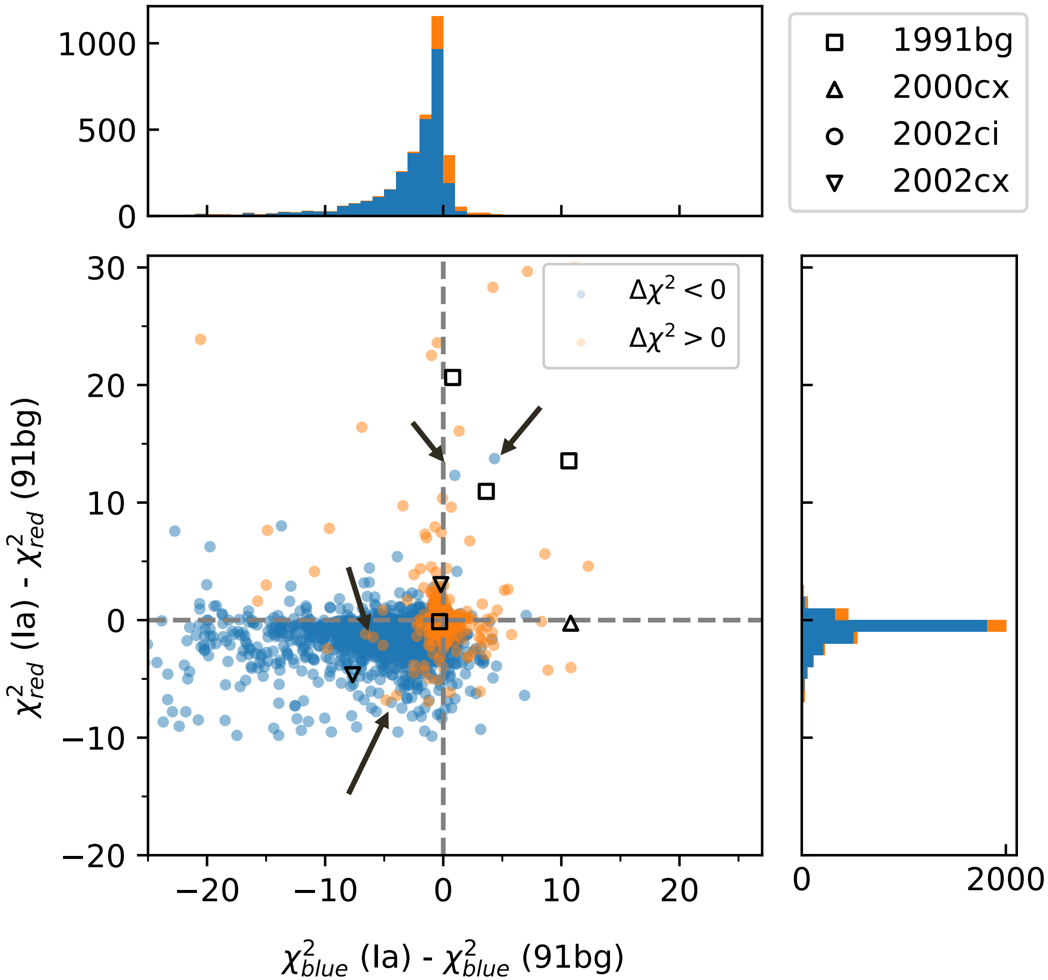


- 10,258 variable and transient sources
- Limited spectroscopic follow up (540 Sne Ia)
- Existing classifications with PSNID (Sako+ 2008)
- No Subtypes… but 4 *potential* 91bg SNe

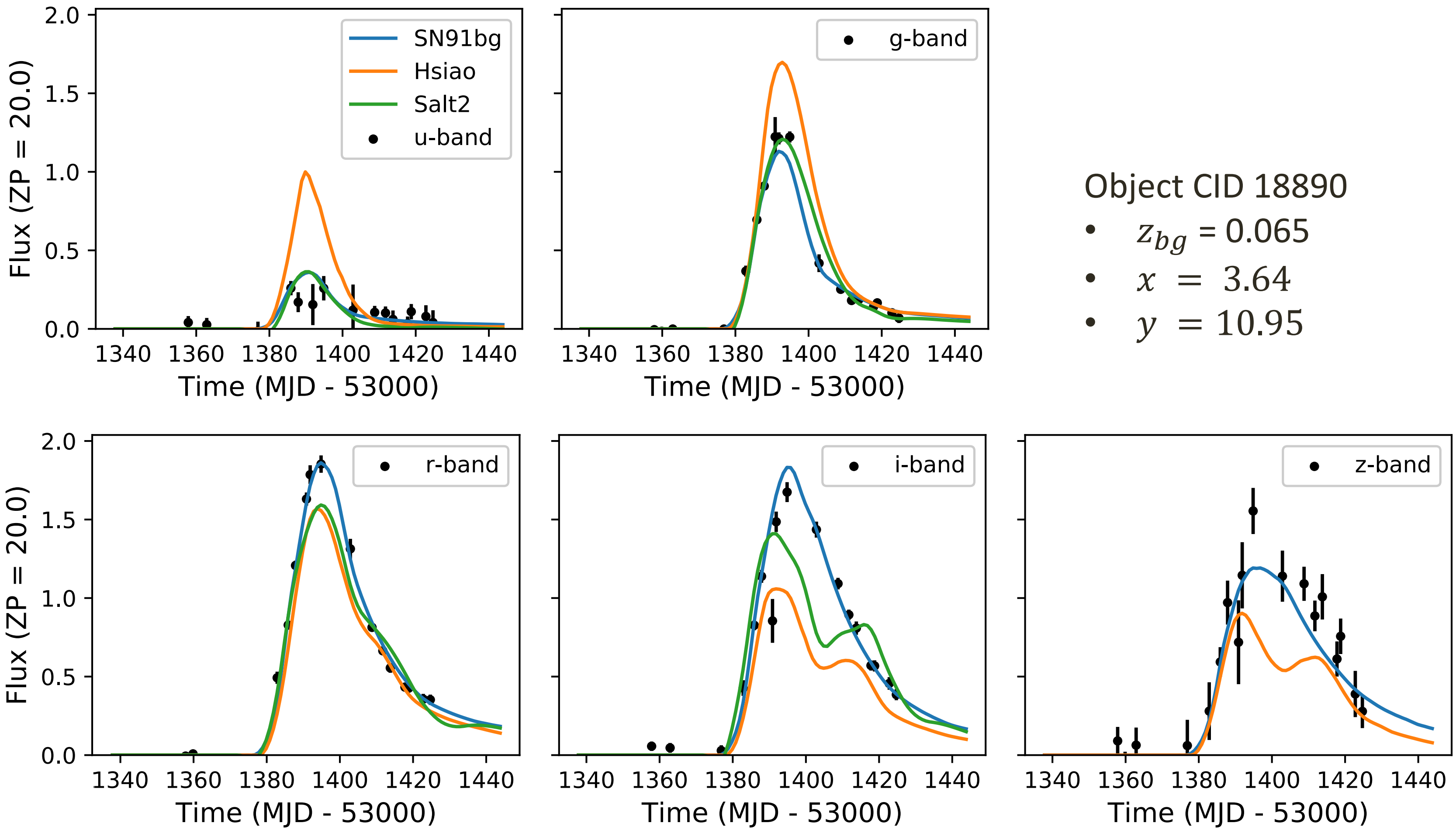
Target Classifications for SDSS



Target Classifications for SDSS



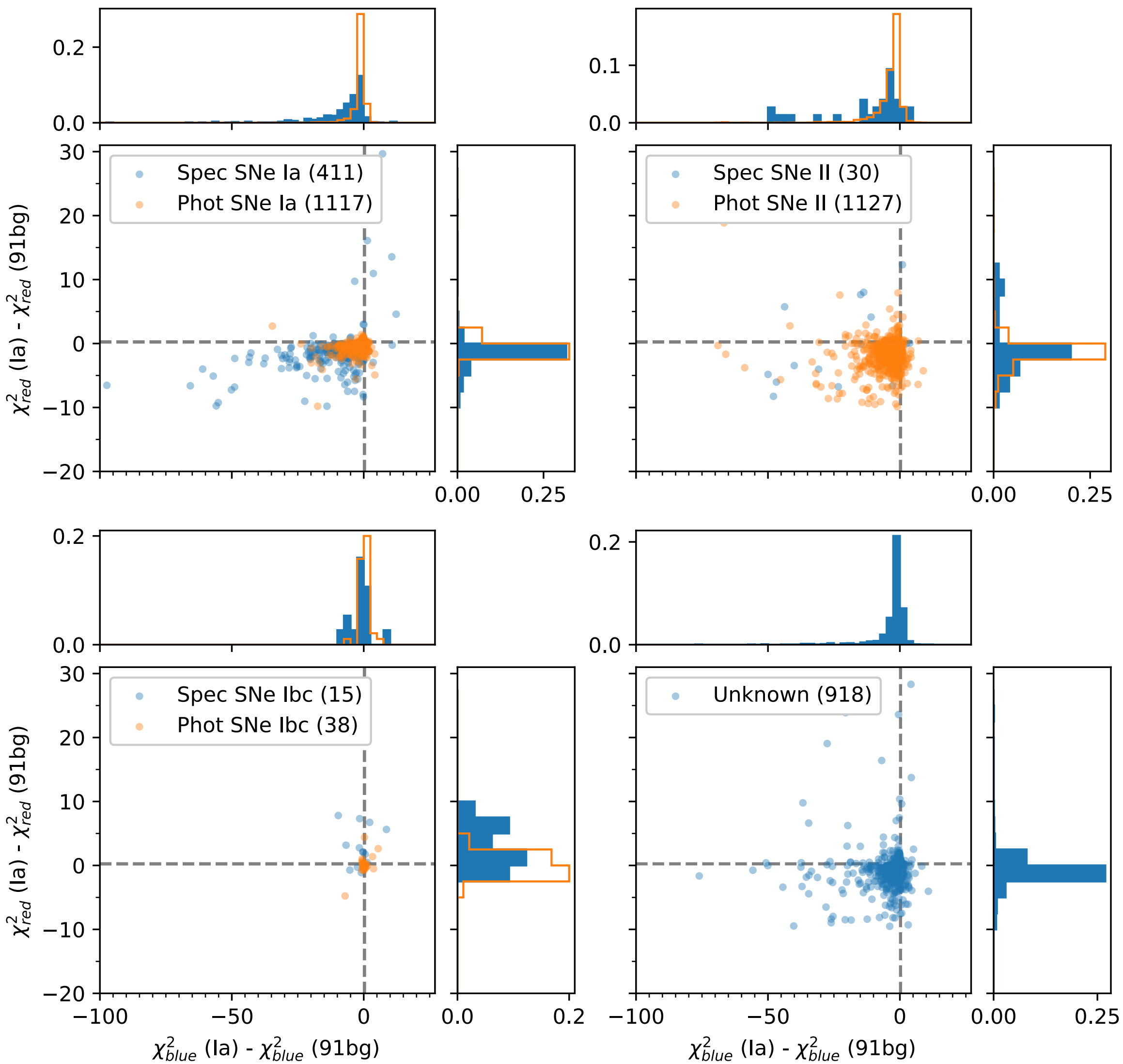
Example 91bg Object



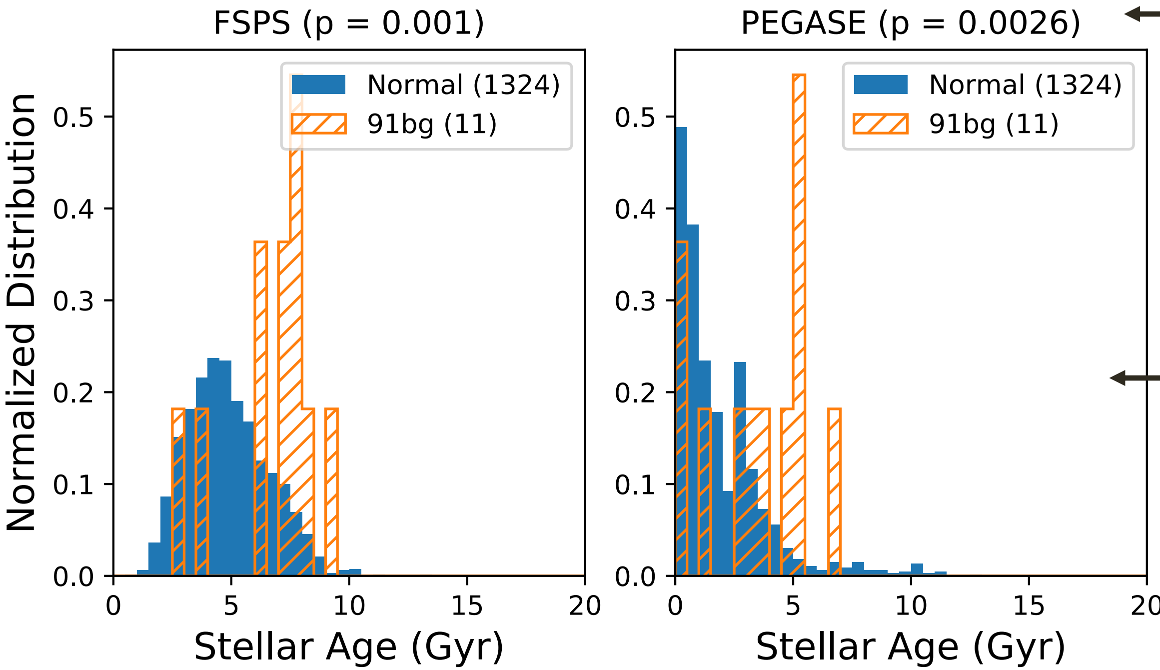
Object CID 18890

- $z_{bg} = 0.065$
- $x = 3.64$
- $y = 10.95$

Classification Comparison

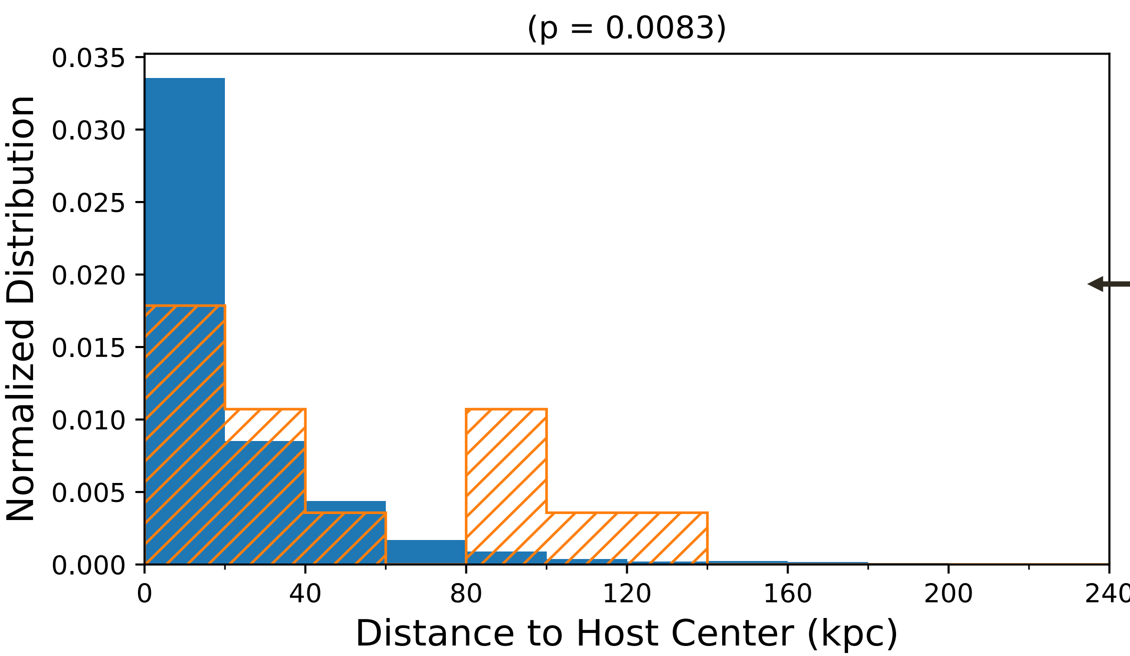


- Clustering of CC events
- No spectroscopic or photometric SNe II in 91bg quadrant
- Lack of 91bg classifications for CC SNe is surprising given redder peak colors

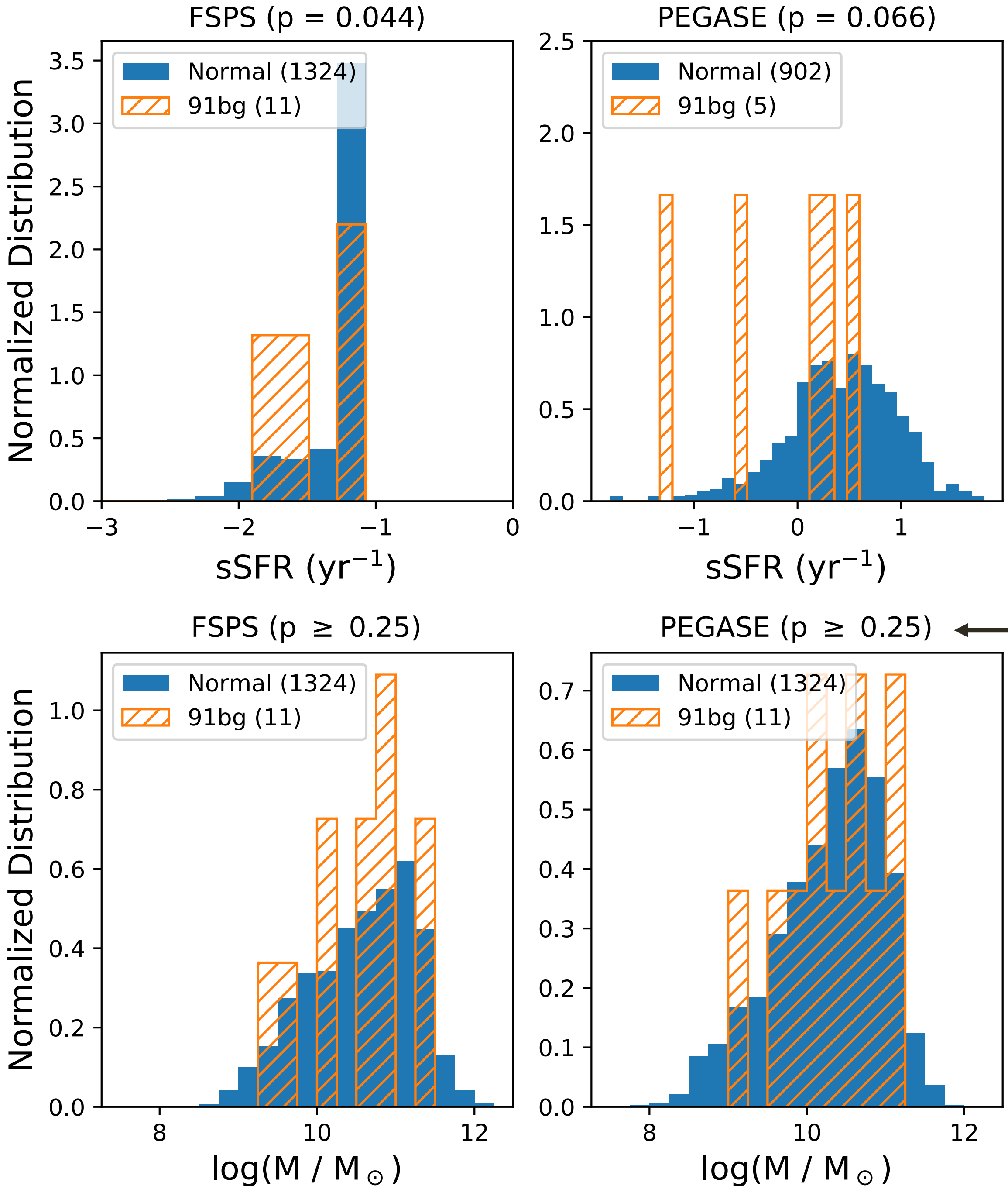


Anderson Darling test (Anderson+ 2014)

Preference for older hosts

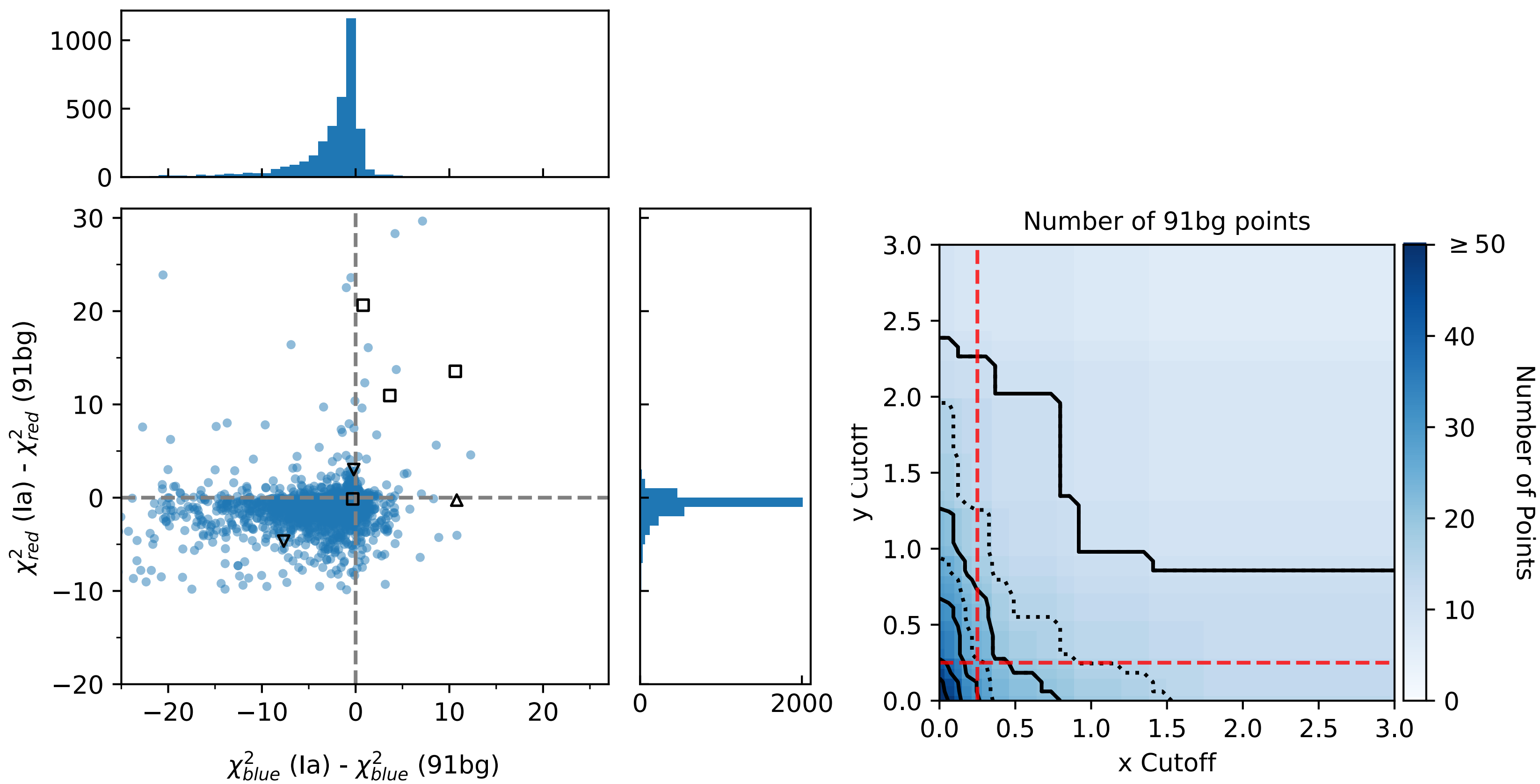


Preference for further distances

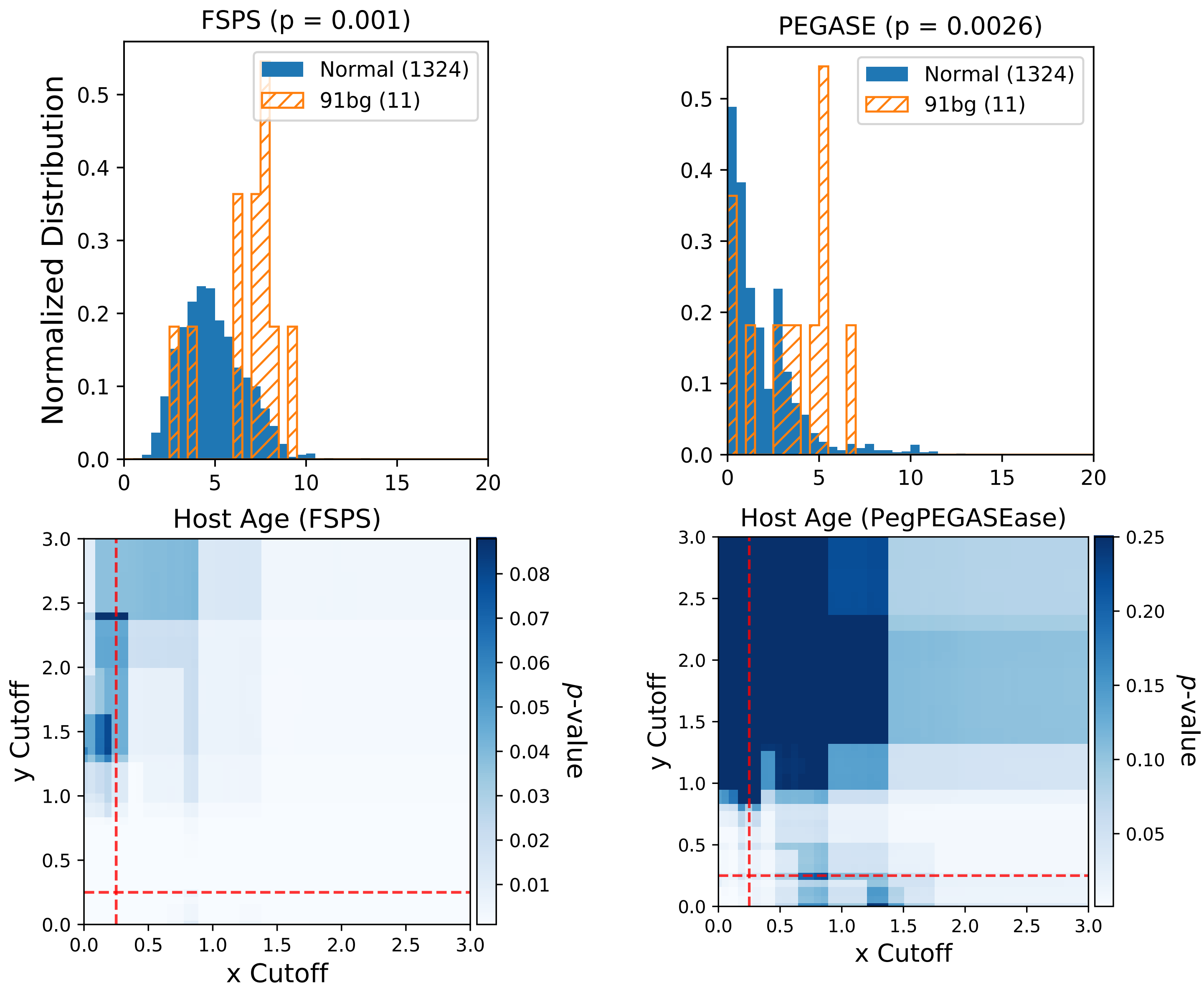


P-values depend on quadrant boundaries

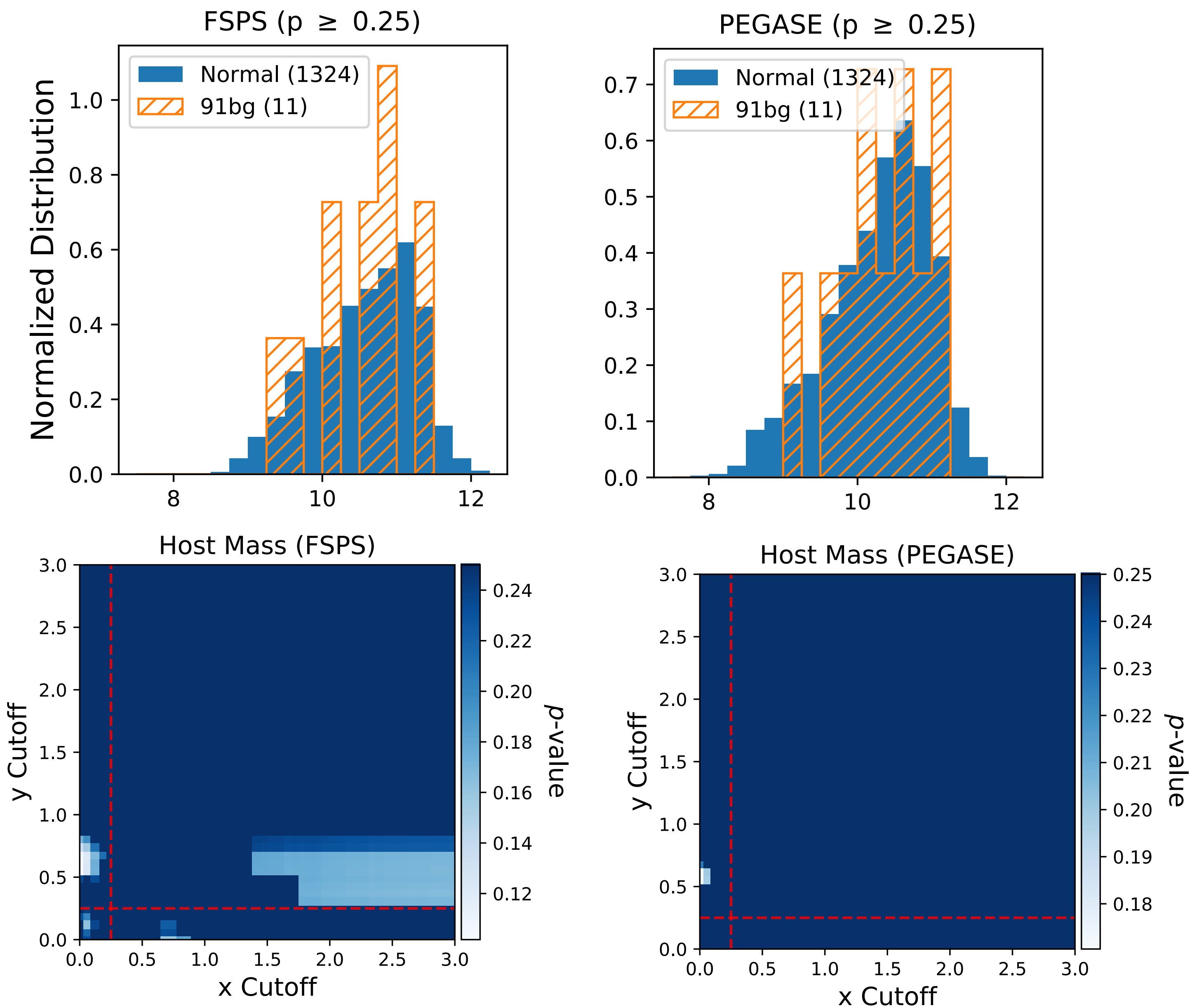
Boundary Choices



Host Stellar Age

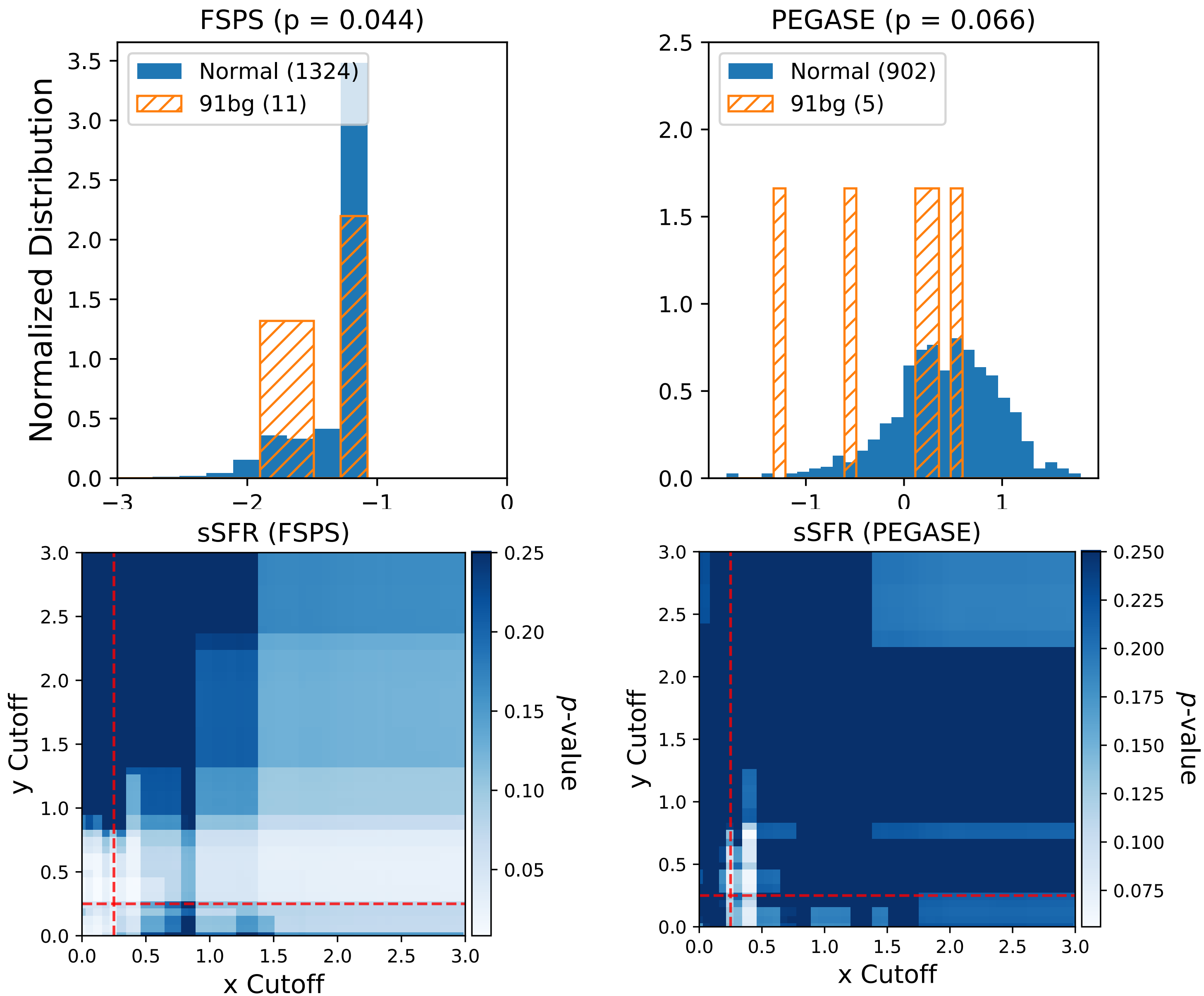


Host Mass



FSPS (p ≥ 0.25)
Normalized Distribution
Normal (1324)
91bg (11)
PEGASE (p ≥ 0.25)
Normal (1324)
91bg (11)
Host Mass (FSPS)
y Cutoff
x Cutoff
p-value
Host Mass (PEGASE)
y Cutoff
x Cutoff
p-value

Star Formation Rate



Applying Phot. Classifications

- Classifications are built to represent underlying physics
  - Photometric classifications need to recover this.
  - Thankfully light-curve morphology is driven by the underlying SED (although in a non-trivial way)
- If we estimate 10% (6% – 15%) SNe are 91bg-like, we expect on order 1000 targets with LSST
  - Improved demographic constraints
  - Targeted temporal and spectroscopic follow-up to constrain models
  - Fill in observed parameter space to determine potential for multiple physical channels
- More generally, the most diverse SNe are the rarest and are still under-represented

Conclusions

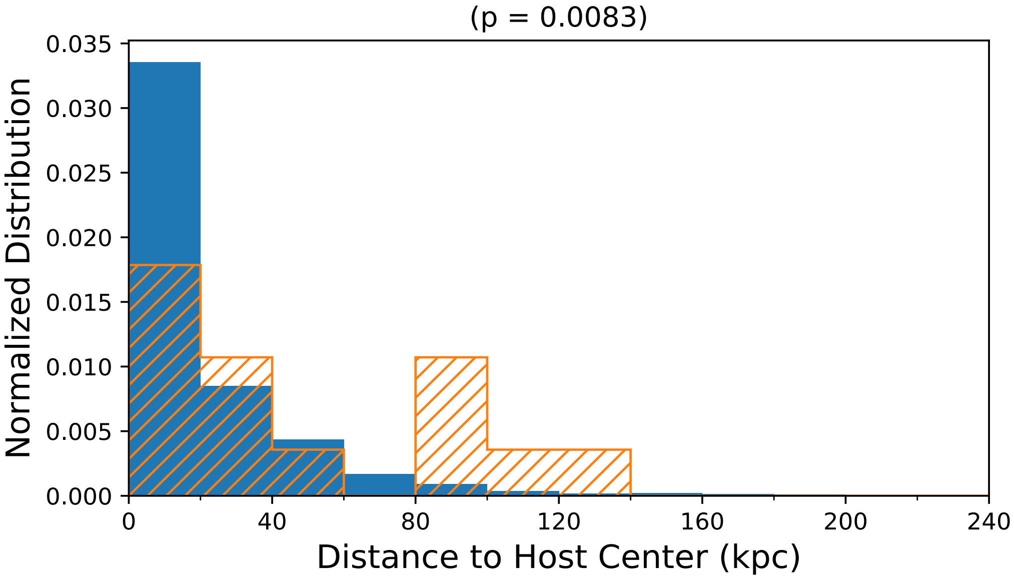
- SN (Ia) classifications are a mix of theory, observations, and physics
  - Diversity hints at physics we don't yet understand

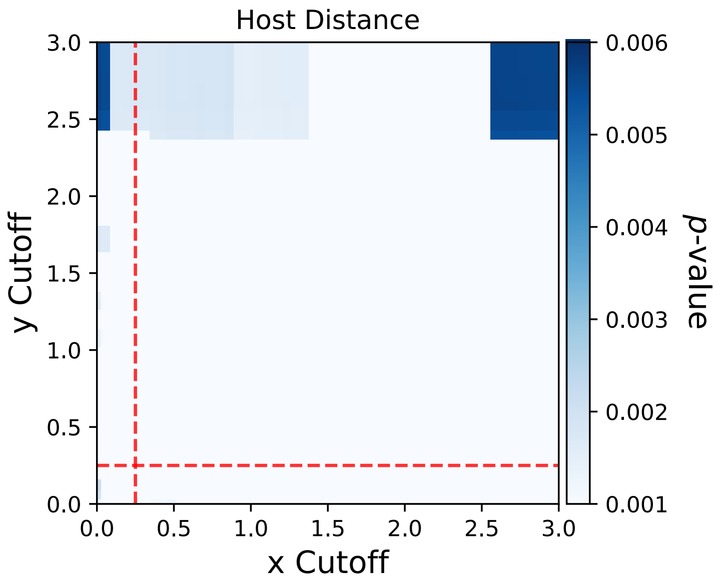
- To understand the underlying physics, we need classifications to determine how diverse the SN Ia population really is

- Once we have well sampled populations in hand (LSST!), we can understand how different (or similar) SN subtypes really are in terms of physical properties.

Questions?

Distance to Host





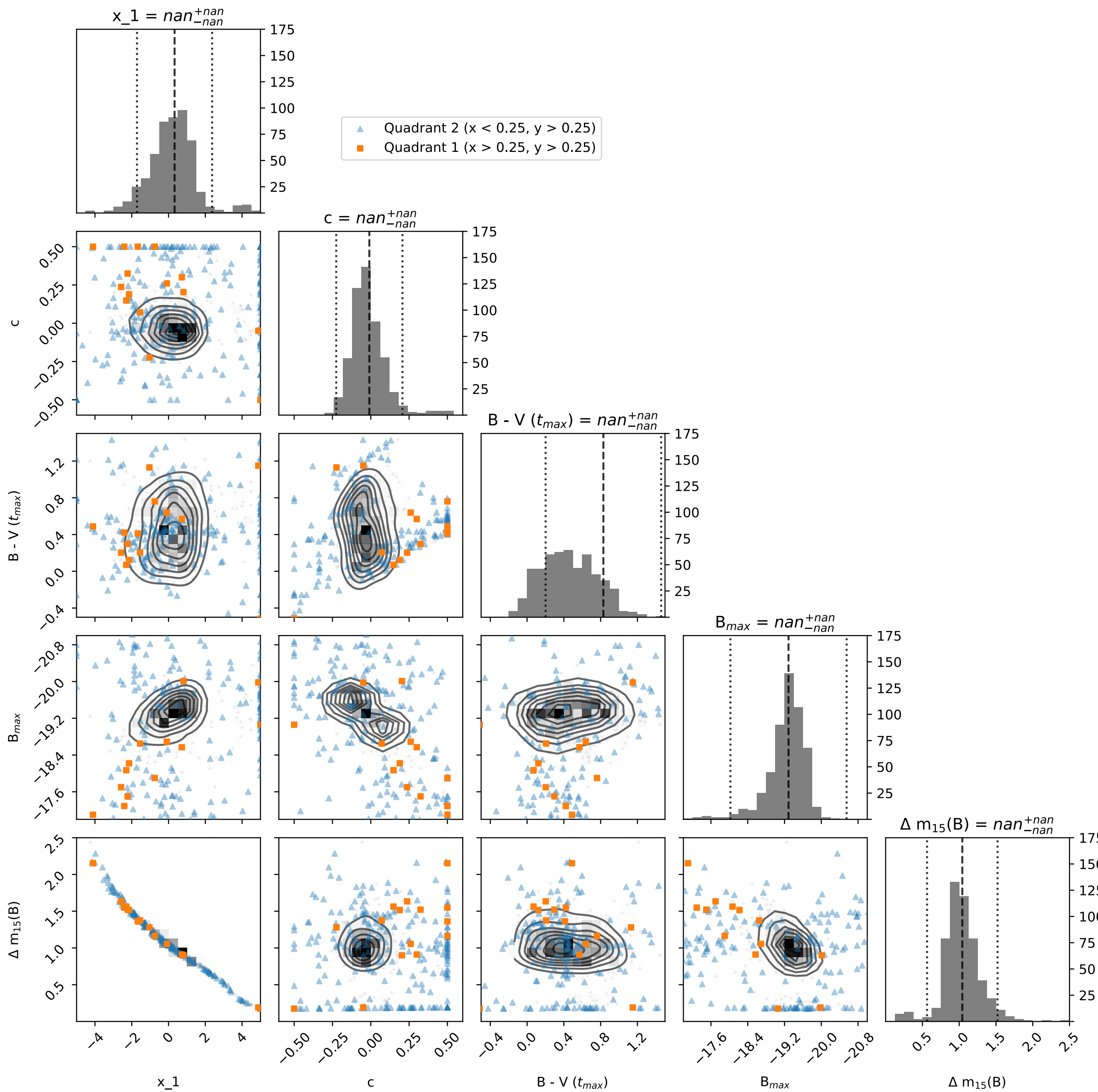


Figure: Perrefort 2020 - Submitted

Empirical Classification

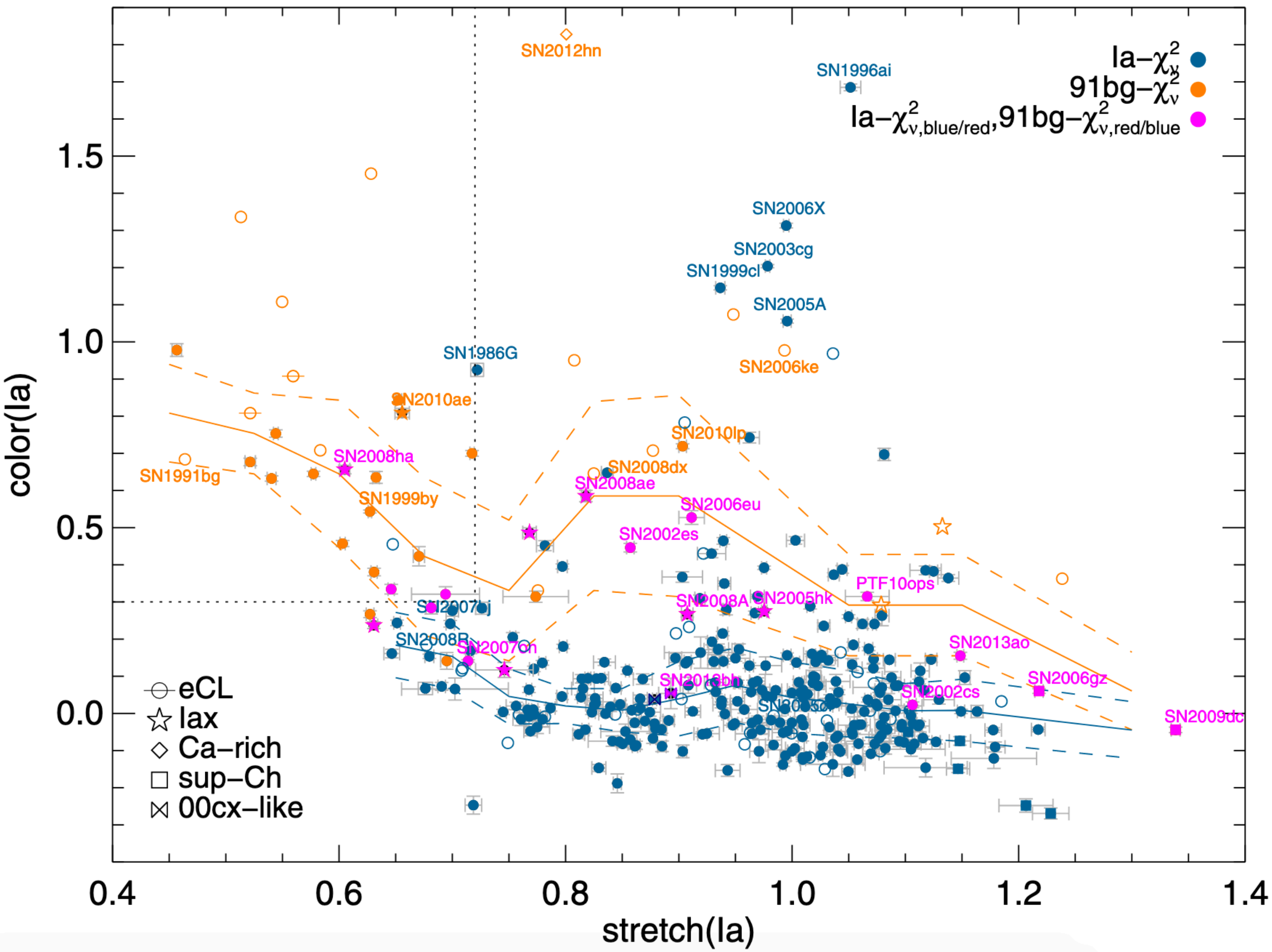


Figure: (González-Gaitán 2014)