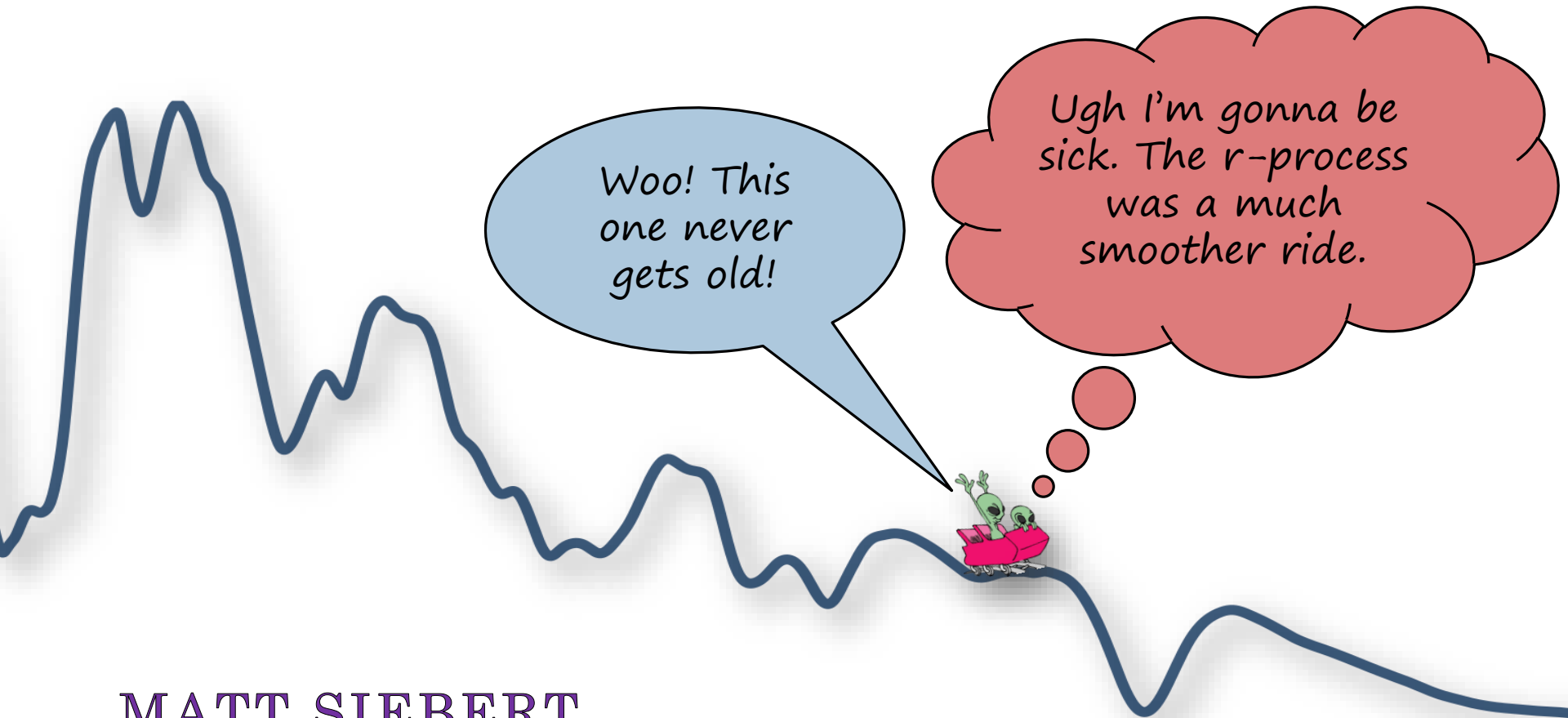
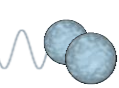


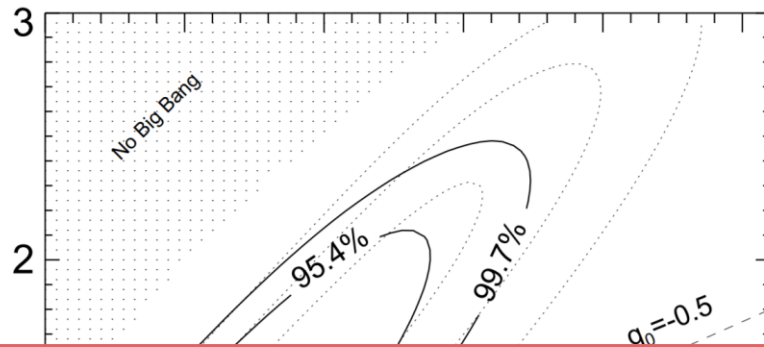
Familiar and **Exotic** Events in the Current Transient Landscape



MATT SIEBERT



Accelerating Universe



$$\frac{\ddot{a}}{a} = - \frac{4\pi G}{3} (\rho + 3p) + \frac{\Lambda}{3}$$

acceleration

gravity

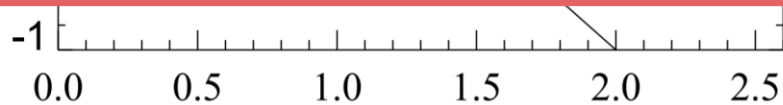
cosmological constant

slows down expansion

speeds up expansion

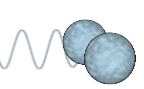
Λ

$$w = \frac{p}{\rho c^2} = -1$$



Ω_M Riess et al. 1998

Perlmutter et al. 1999



What is Dark Energy?

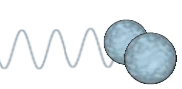
The Cosmological
Constant Problem

$$\rho_{vac}^{(theory)} \sim 10^{120} \rho_{vac}^{(obs)}$$

The Coincidence
Problem

$$\Omega_m \sim \Omega_\Lambda$$

Why now?



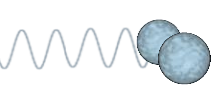
SNe Ia are ~~NOT~~ Standard Candles



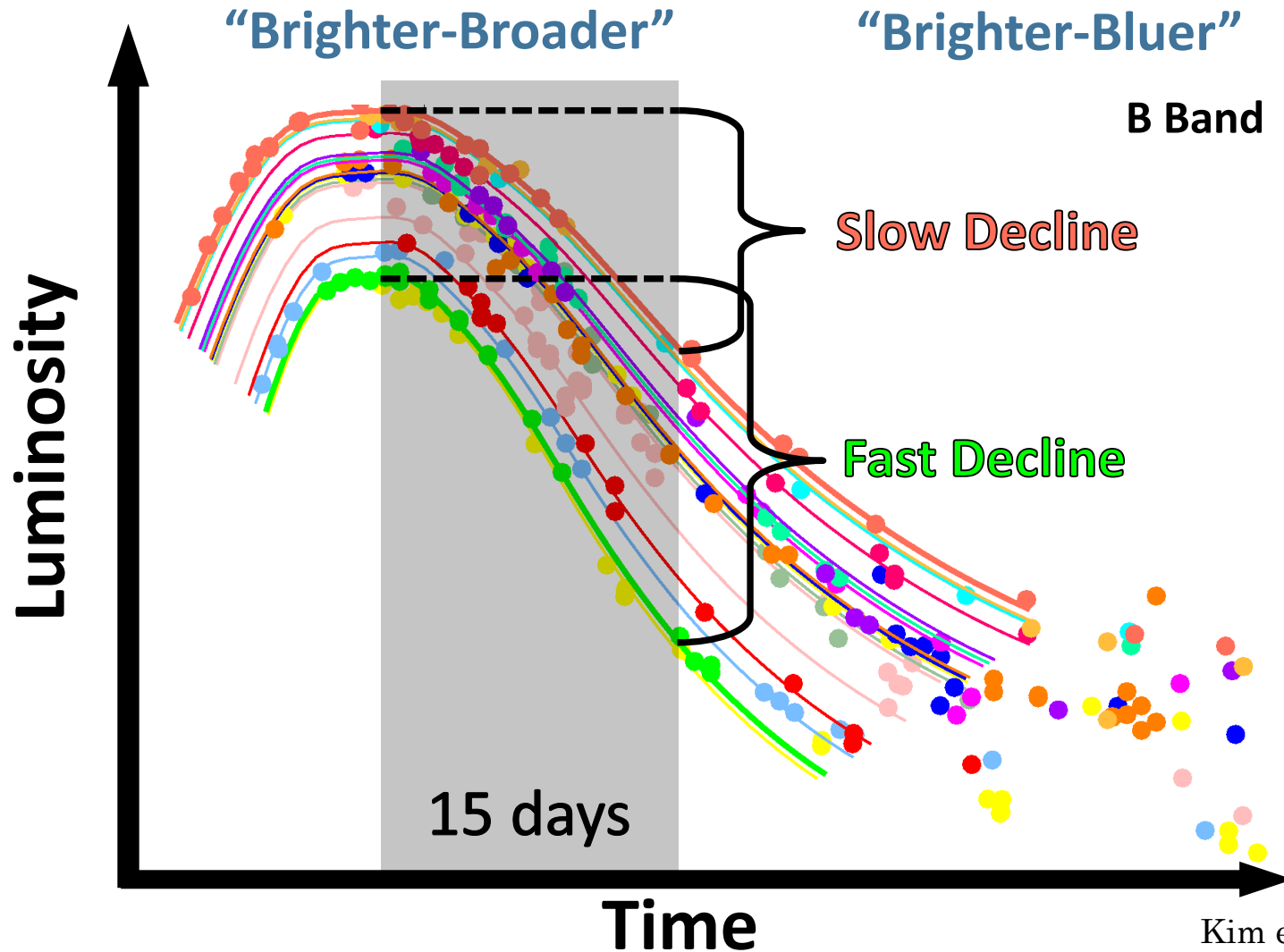
$$D = \left(\frac{L}{4\pi F} \right)^{1/2}$$

~~Constant~~
Measure

$$D = f(z, \Omega, w(z), \dots)$$

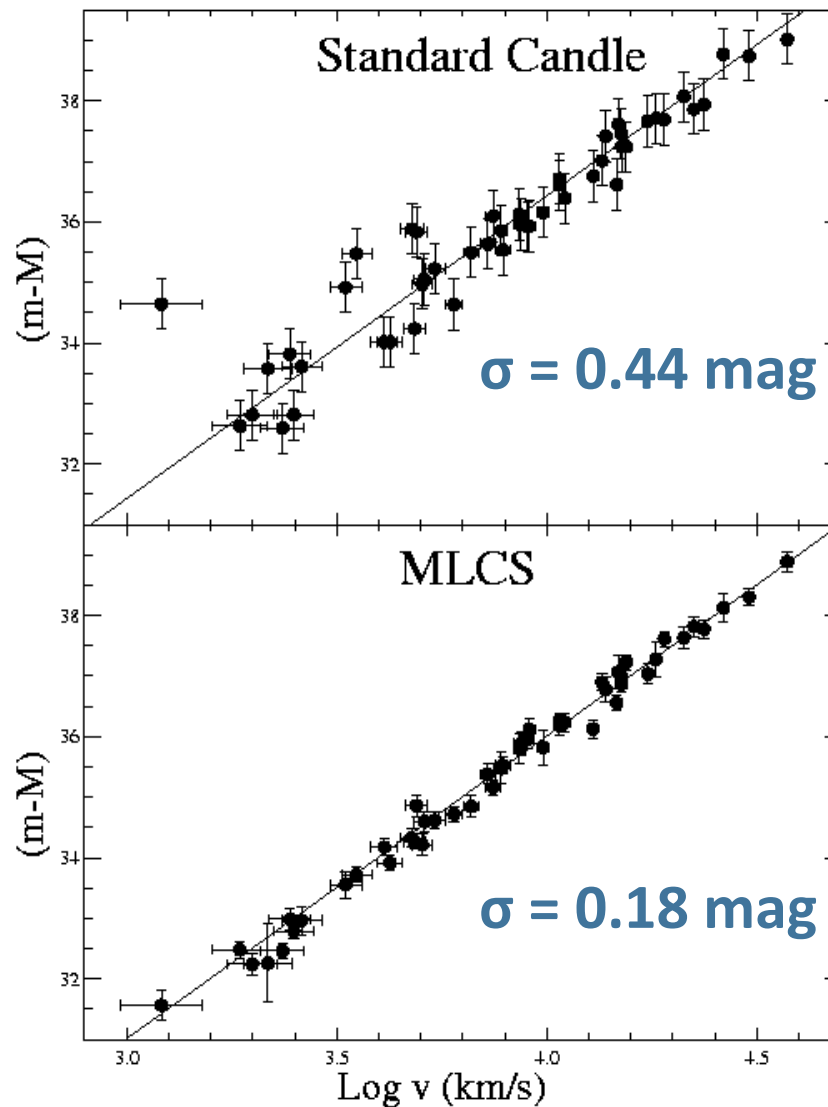


SNe Ia are Standardizable Candles

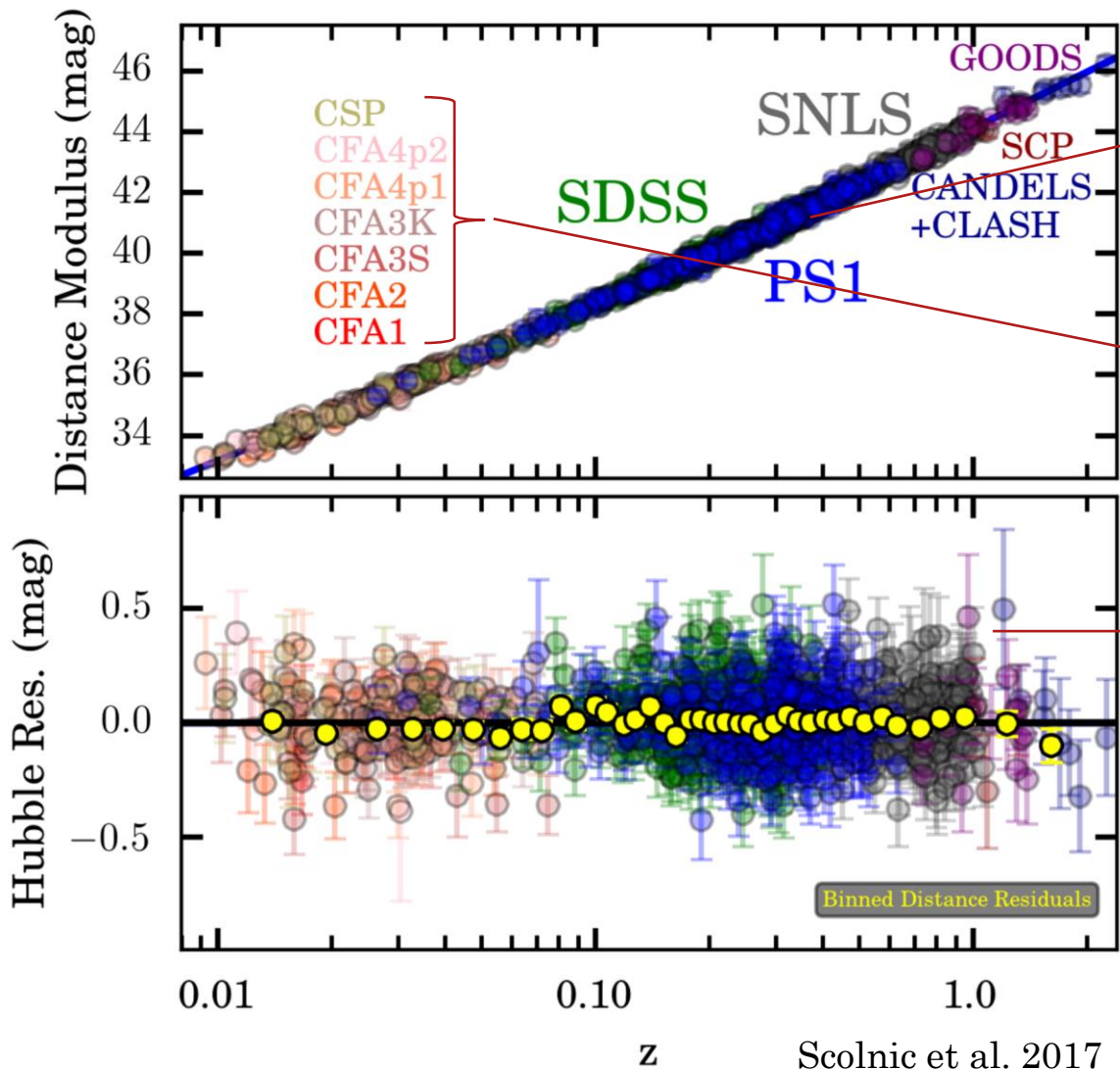




SNe Ia are Standardizable Candles



Recent Hubble Diagram



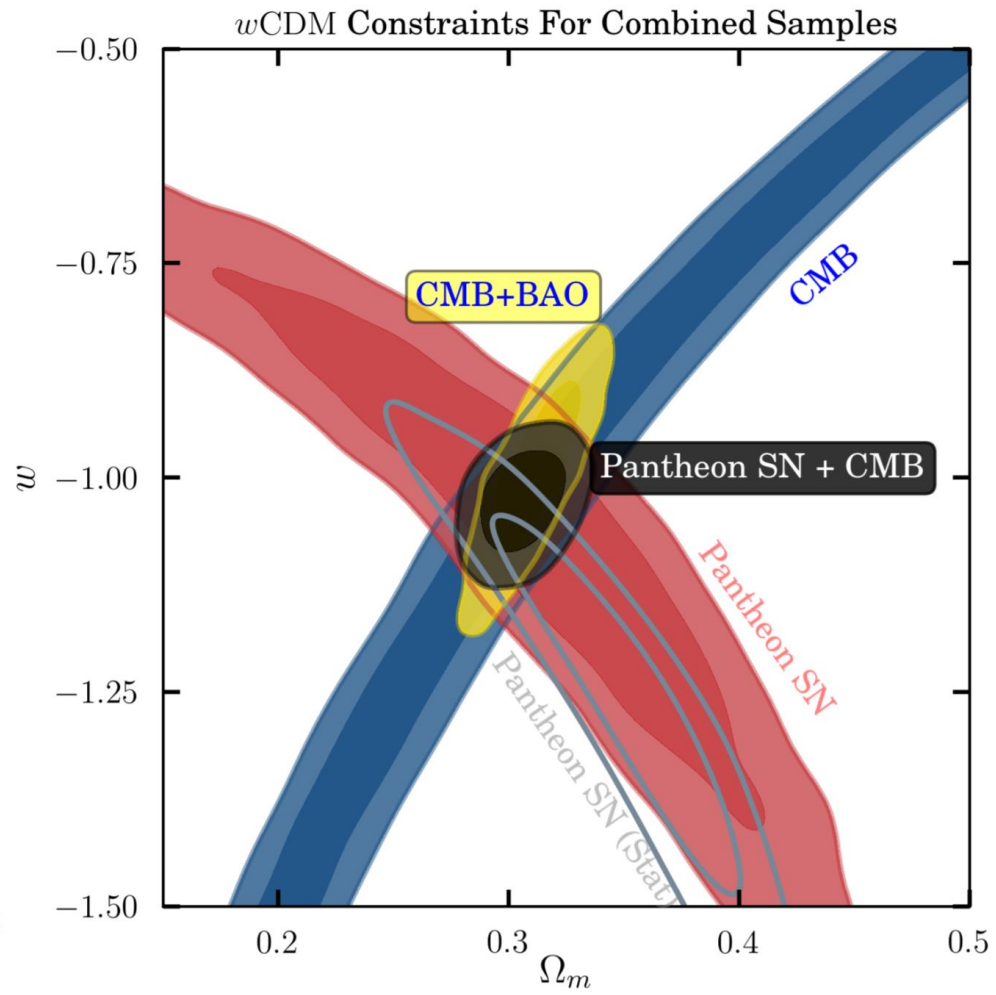
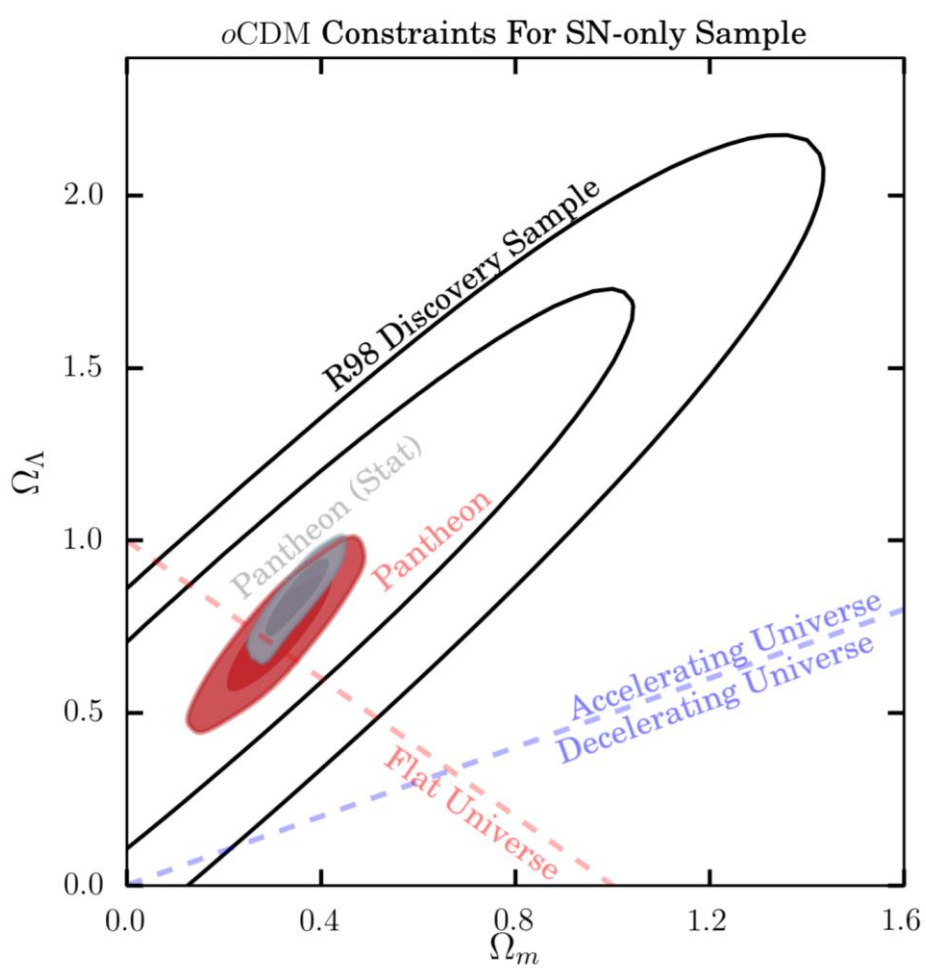
**SNe dimming
with redshift**

**Inhomogeneous
low- z dataset**

**Photometric
error alone
cannot account
for scatter**



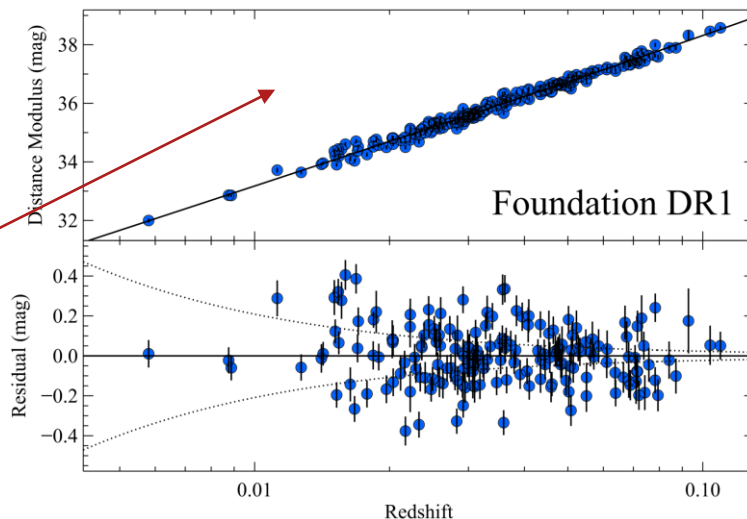
Systematics Need to be Addressed



Systematic Uncertainties

	w shift	σ_w^{synt}	Fraction of $\sigma_w^{(\text{stat})}$
Stat. Uncertainty	+0.000	0.031	1.000
Total Sys Uncertainty	+0.031	0.025	0.814
Calibration			
SALT2 Cal	-0.002	0.014	0.457
Survey Cal	+0.006	0.009	0.285
HST Cal	-0.006	0.006	0.177
Supercal	+0.002	0.003	0.098
SN Modeling			
Selection	+0.010	0.007	0.233
Intrinsic Scatter	+0.019	0.005	0.170
β Evol.	-0.001	0.007	0.238
γ Evol.	-0.002	0.000	0.000
m_{step} Shift	-0.002	0.002	0.064
External			
MW Extinction	+0.010	0.008	0.262
Pec. Vel.	+0.000	0.003	0.103

Scolnic et al. 2017

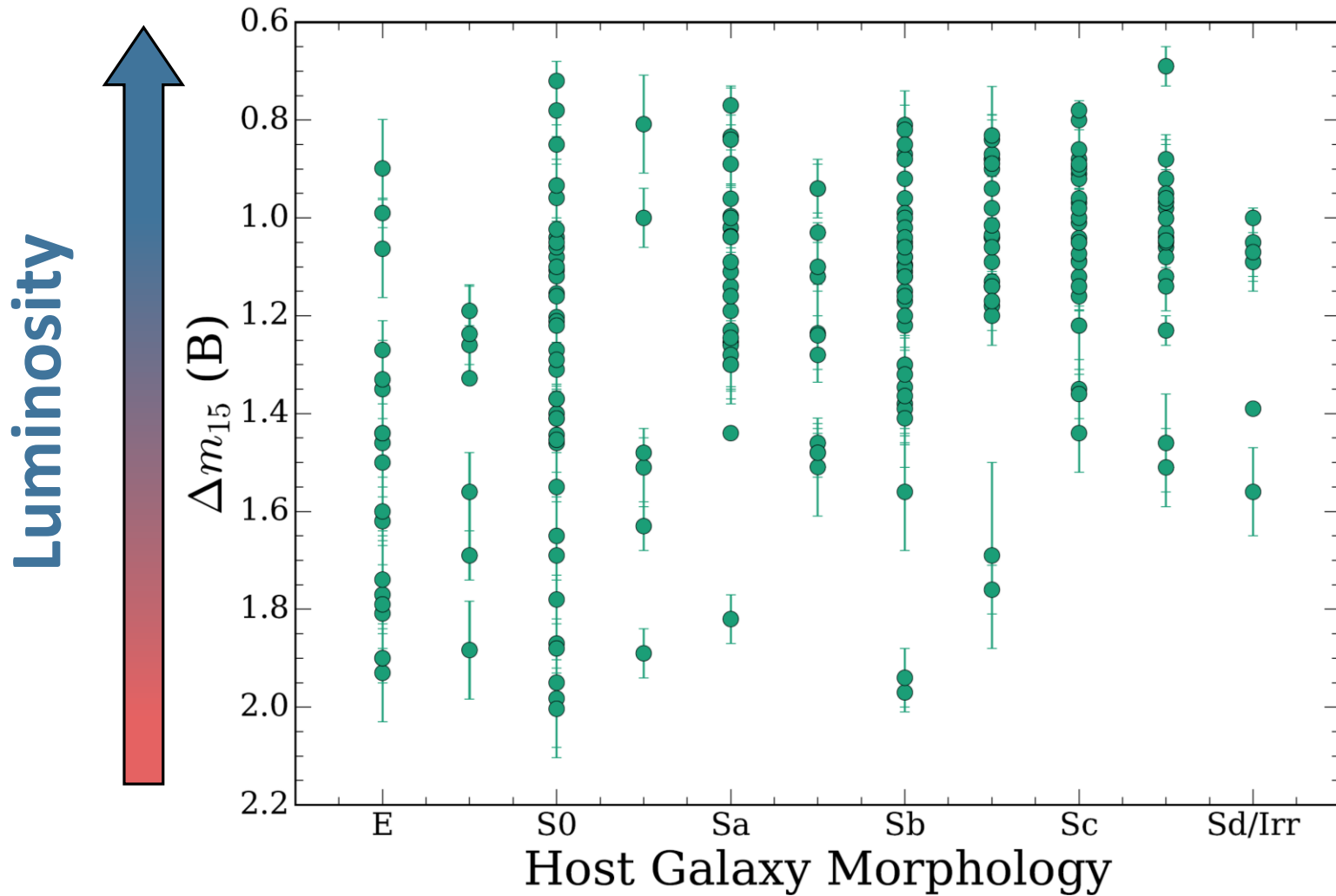


Foley et al. 2018

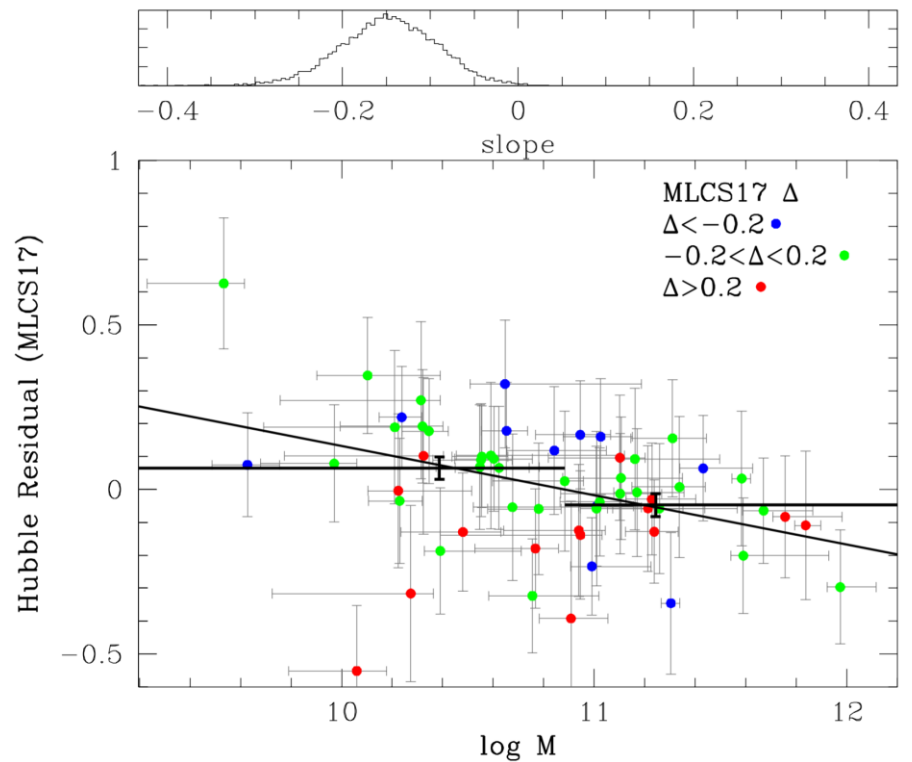
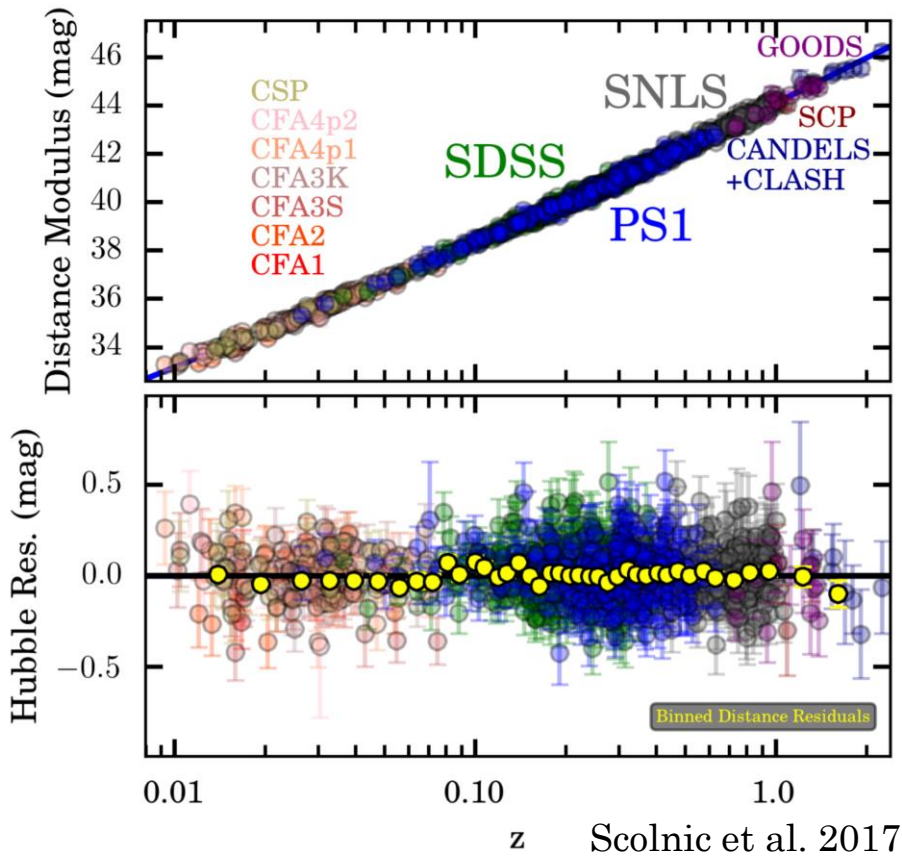
Explosion Physics



Environmental Dependence



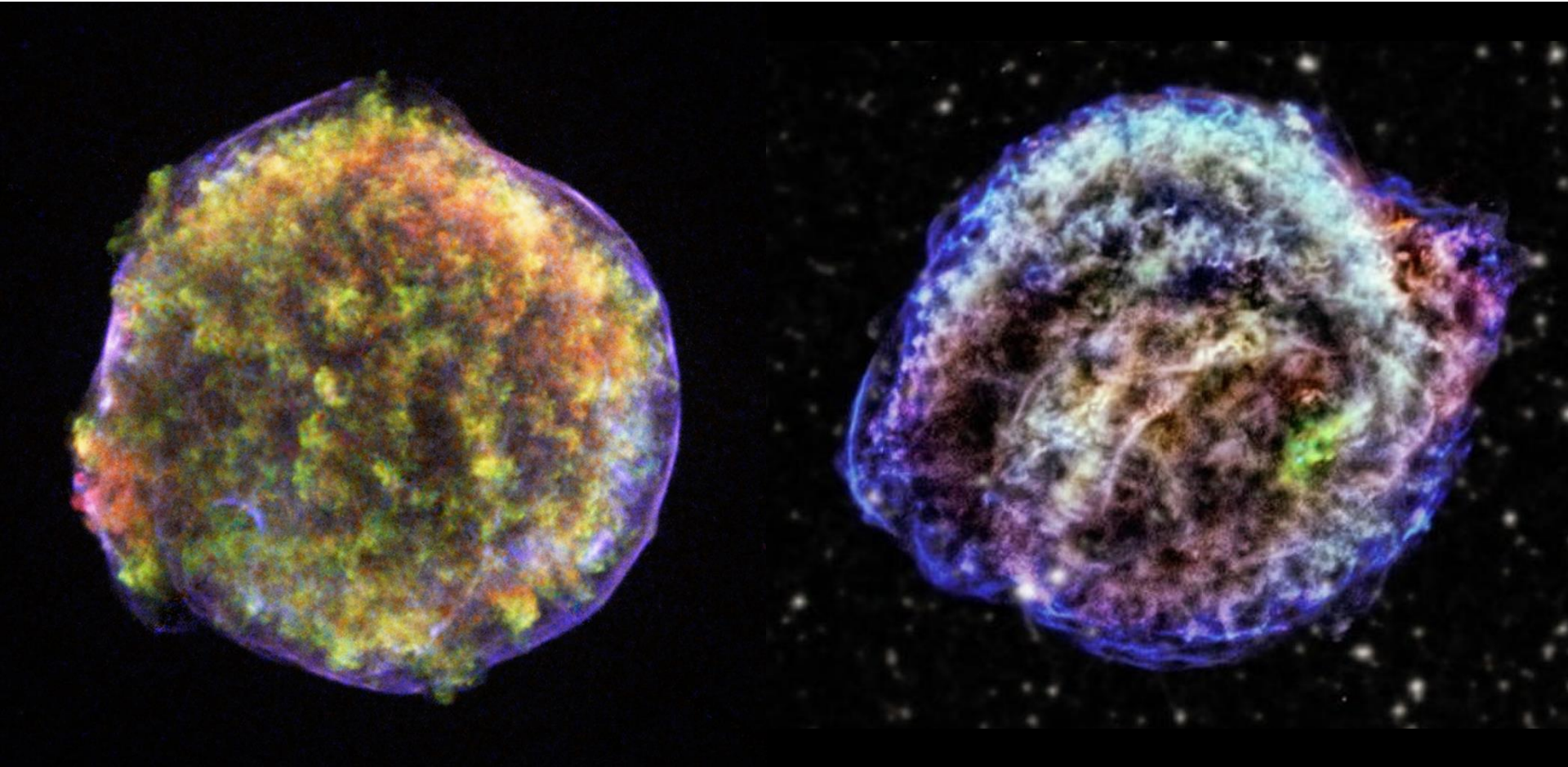
Environmental Dependence



Kelly et al. 2010

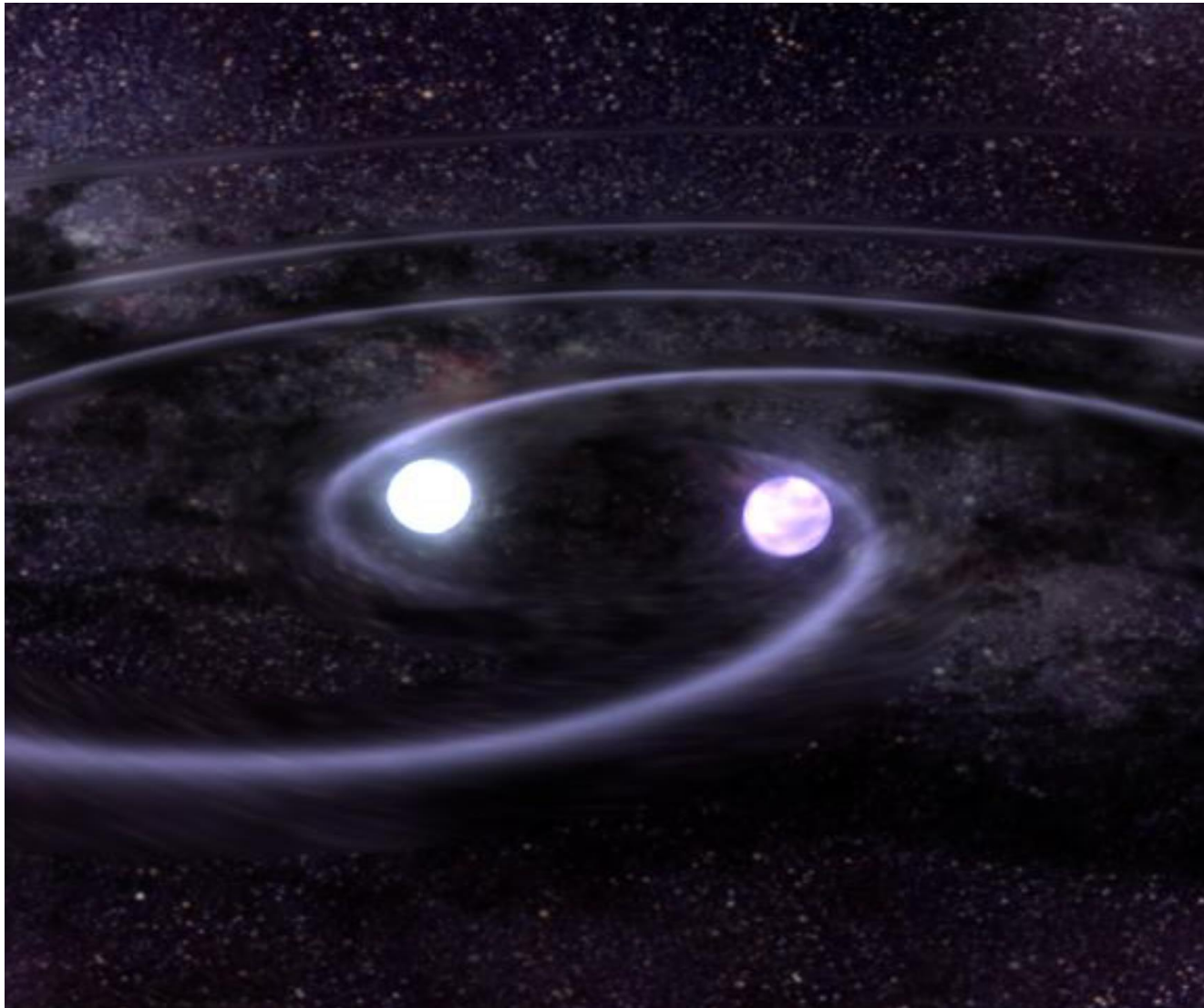


Different Progenitors?





Double Degenerate Scenario





Single Degenerate Scenario

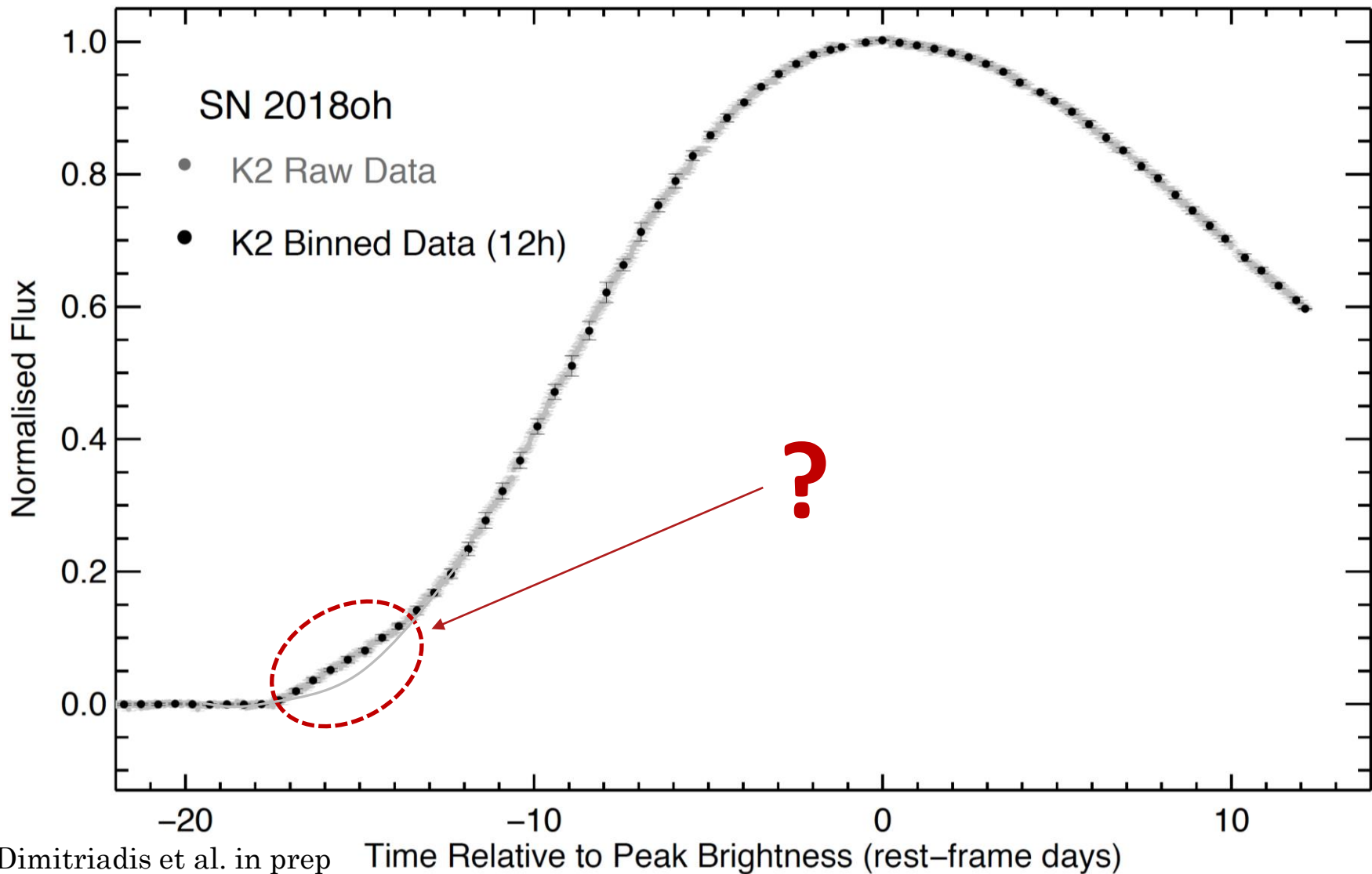


DD Evidence – SN2011fe

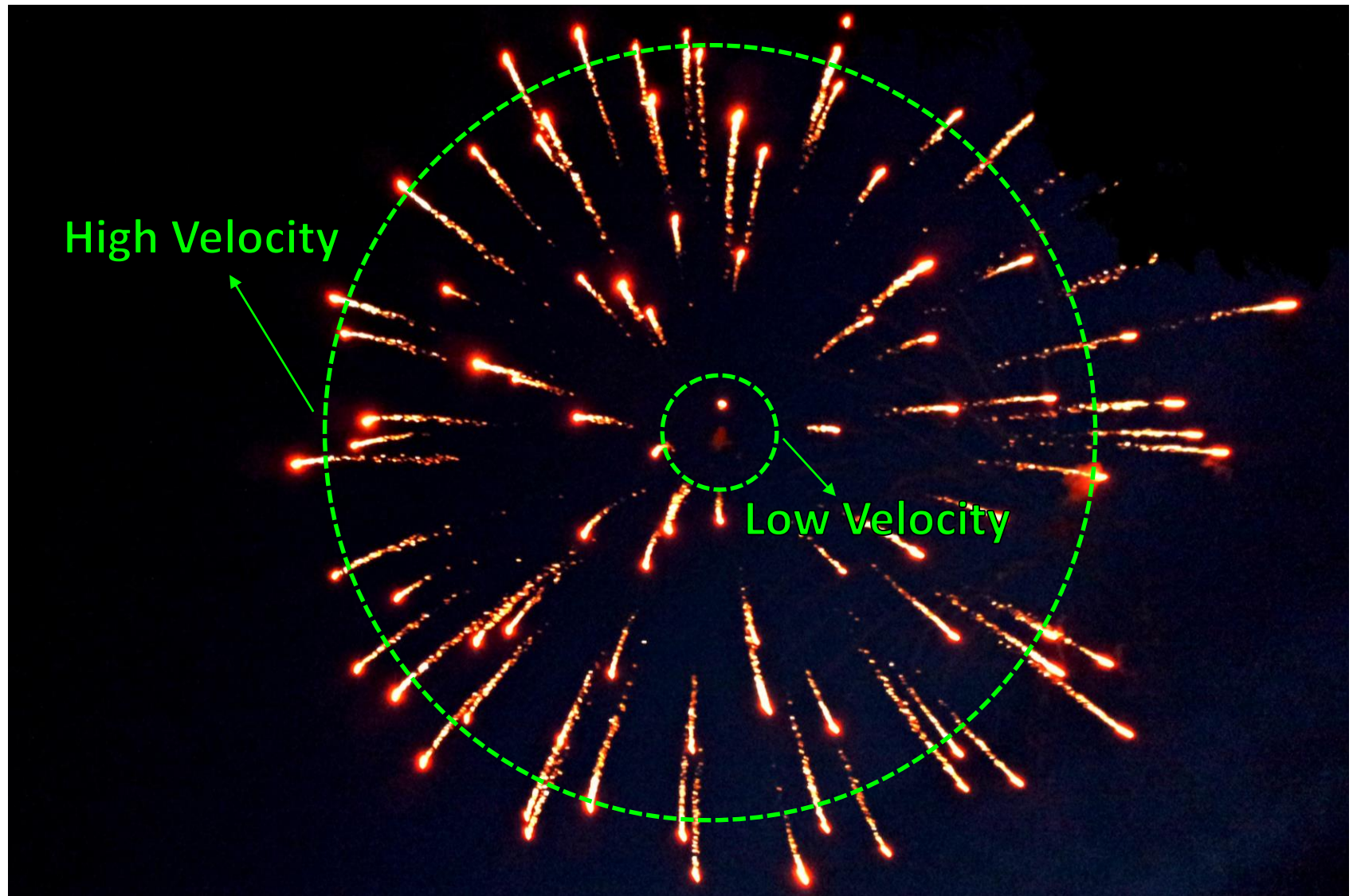


Li et al. 2011

SD Evidence – Early Excess Flux

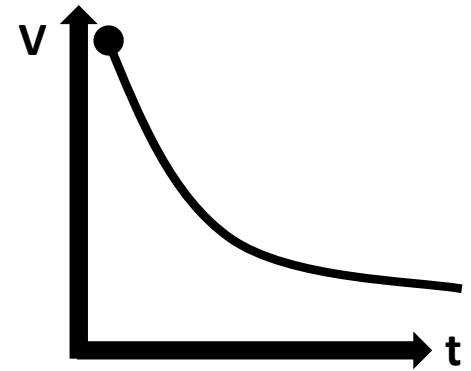
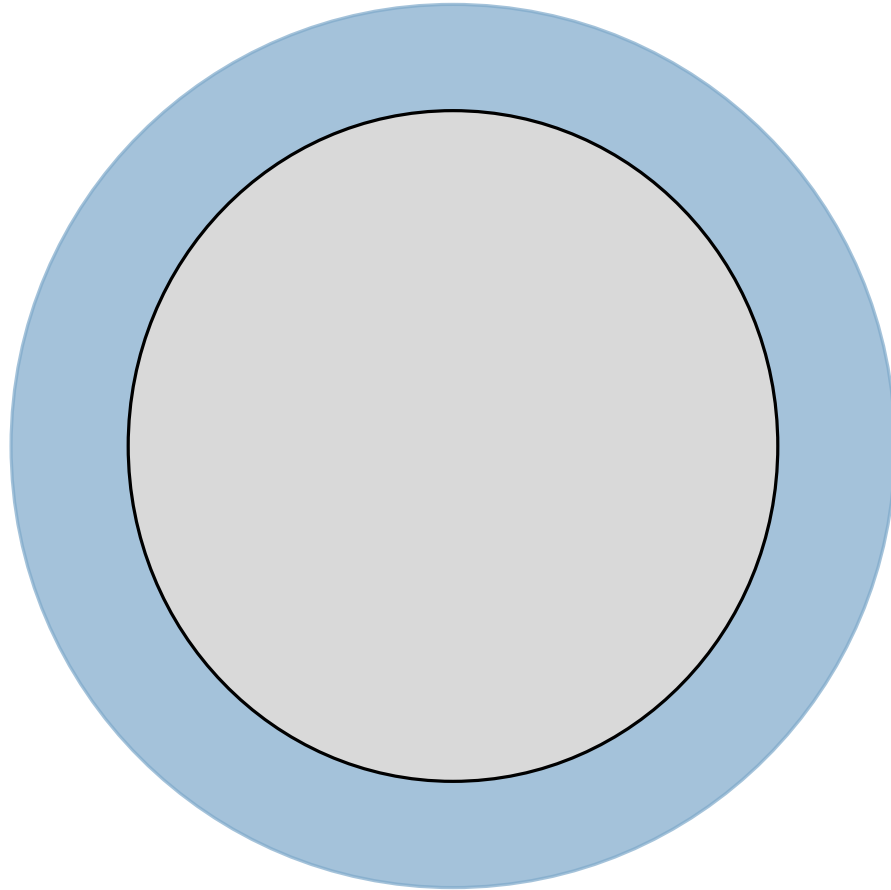


Supernova Explosion





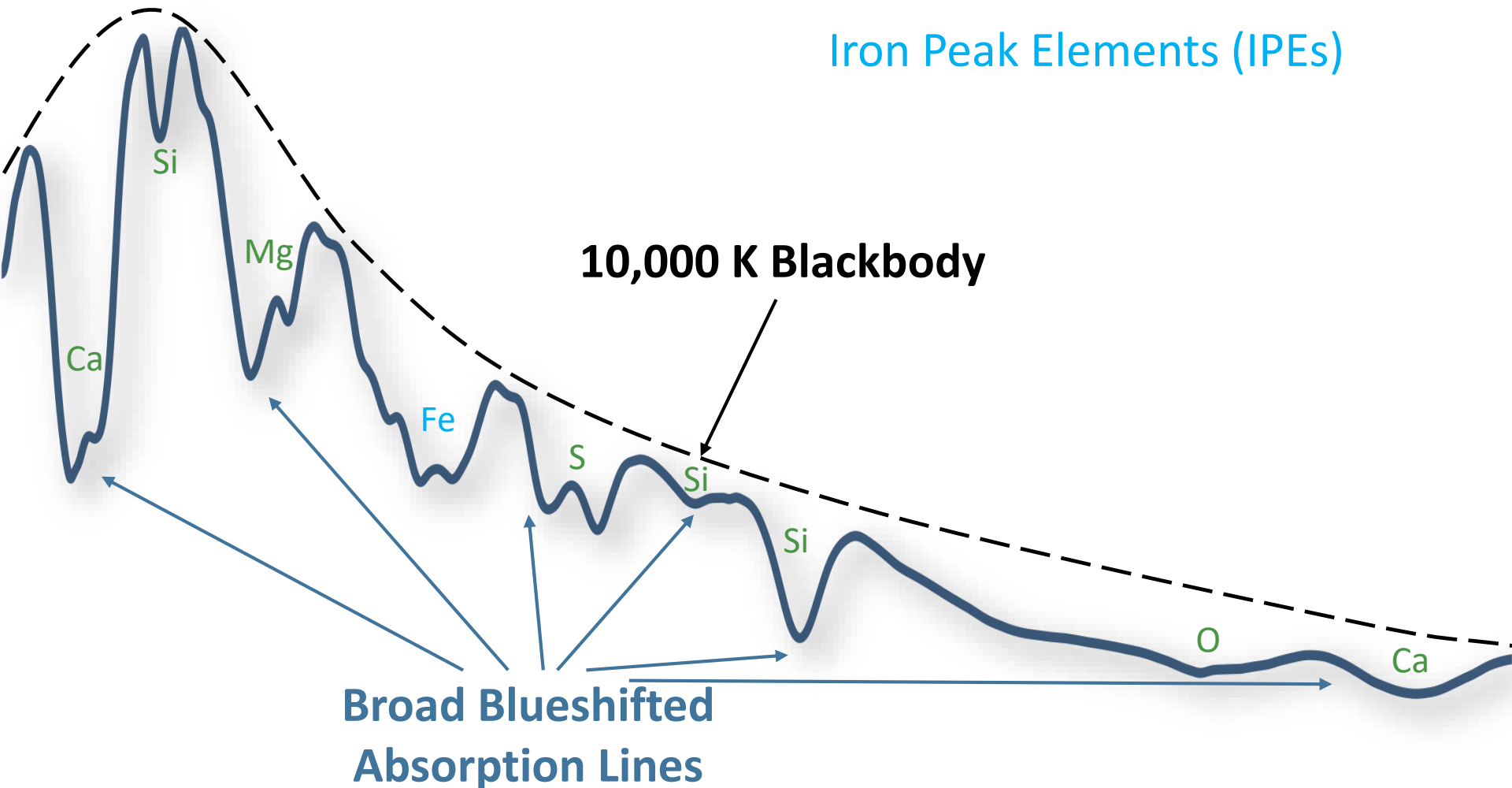
Supernova Explosion



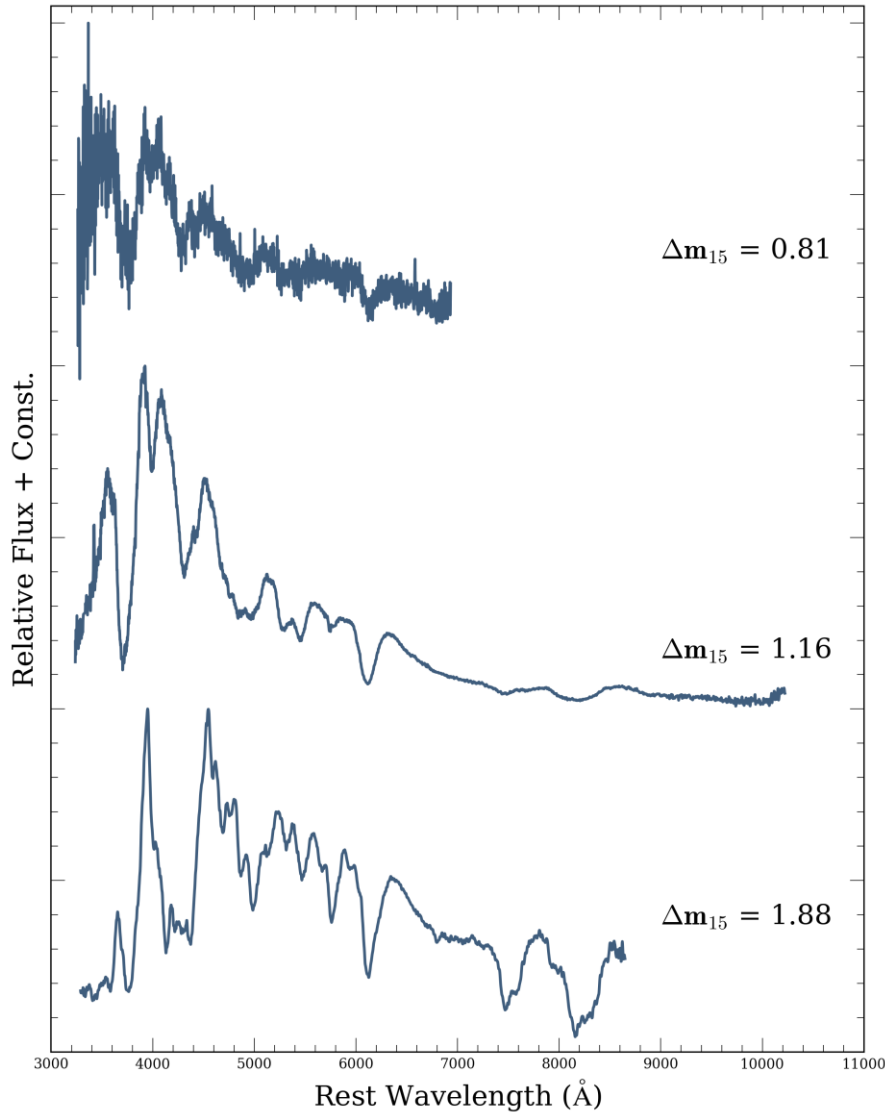
Maximum Light SED

Intermediate Mass Elements (IMEs)

Iron Peak Elements (IPEs)



Spectroscopic Diversity



Individual Spectra

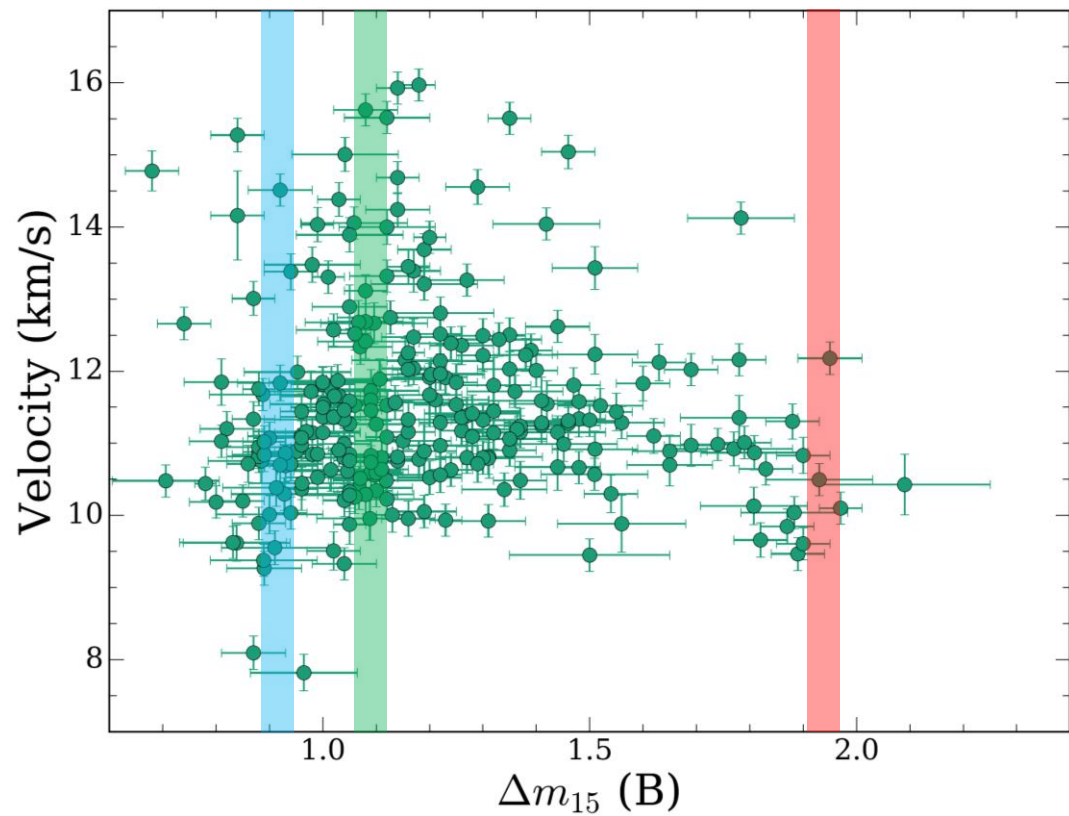
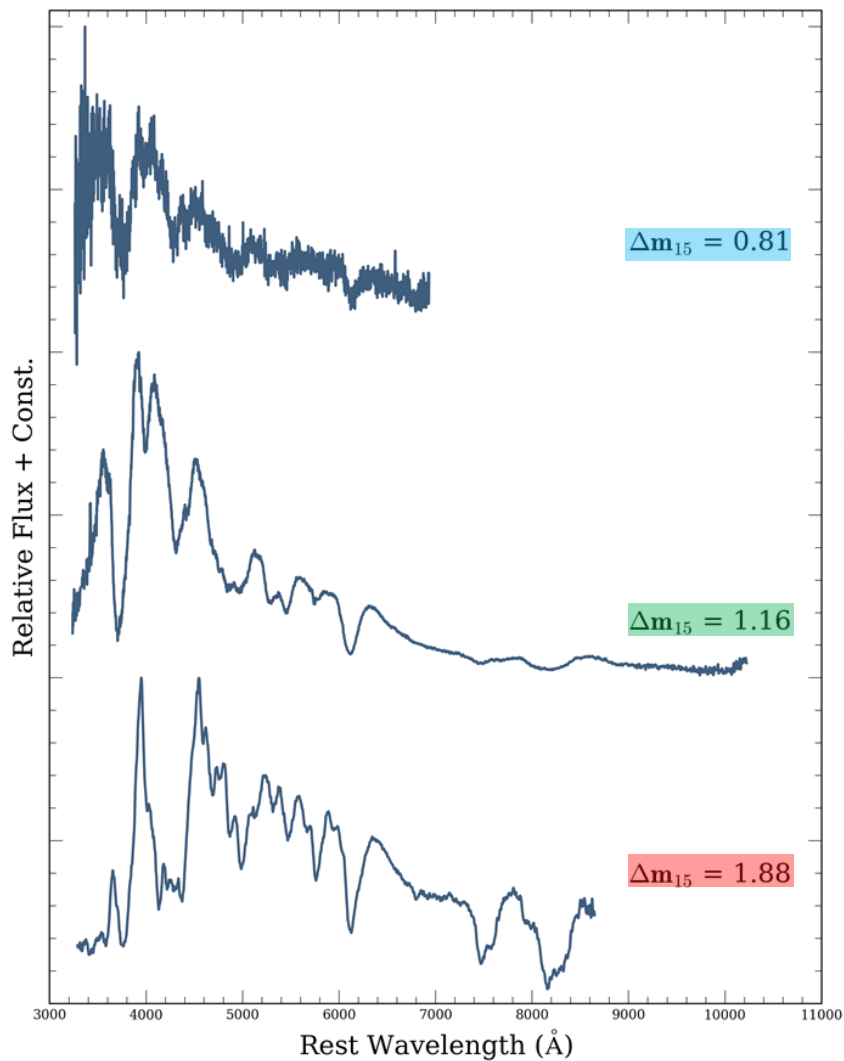
Heterogeneous

Signal

Wavelength Coverage

Spectral Features

No Correlation with Velocity

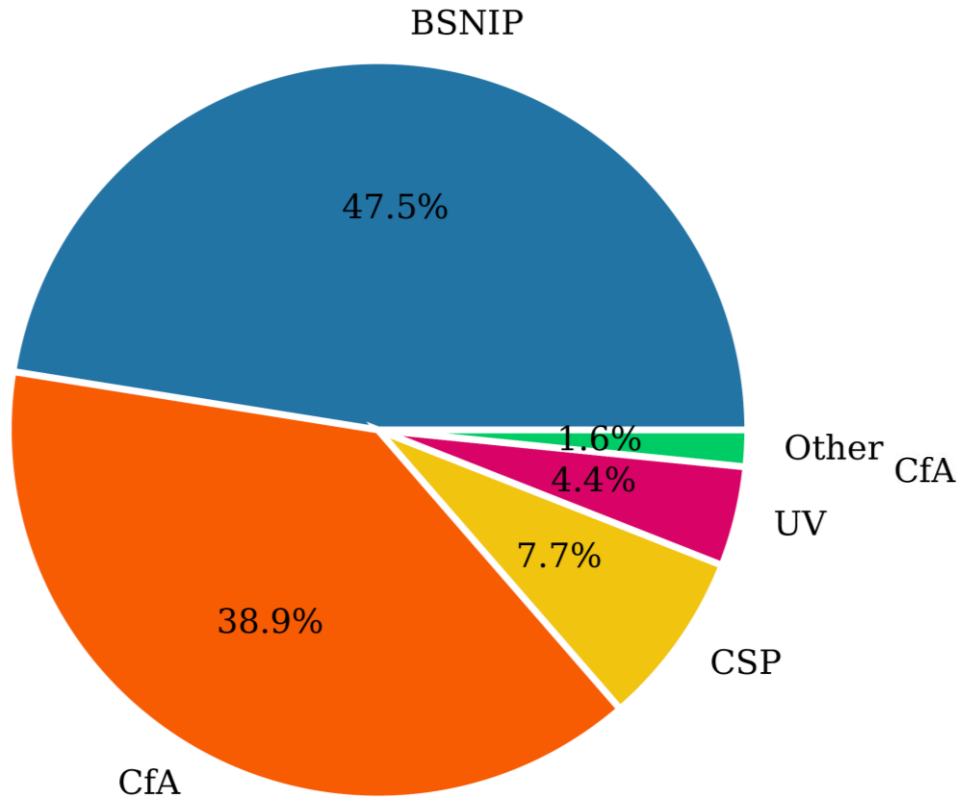


SN Ia Relational Database

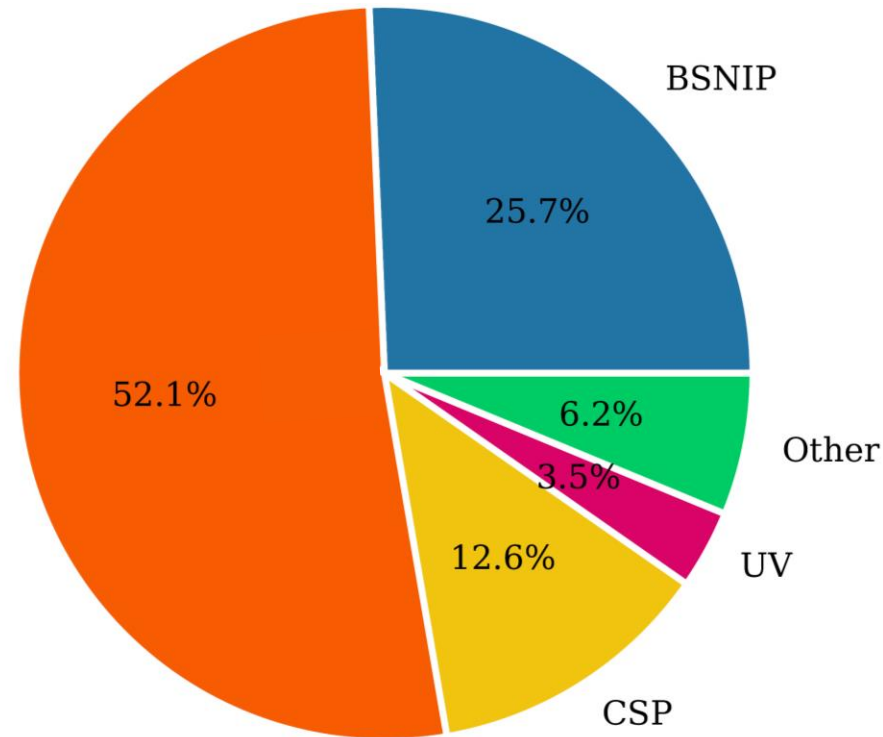
Siebert et al. in prep

*Contrived acronym pending

N = 784 SNe

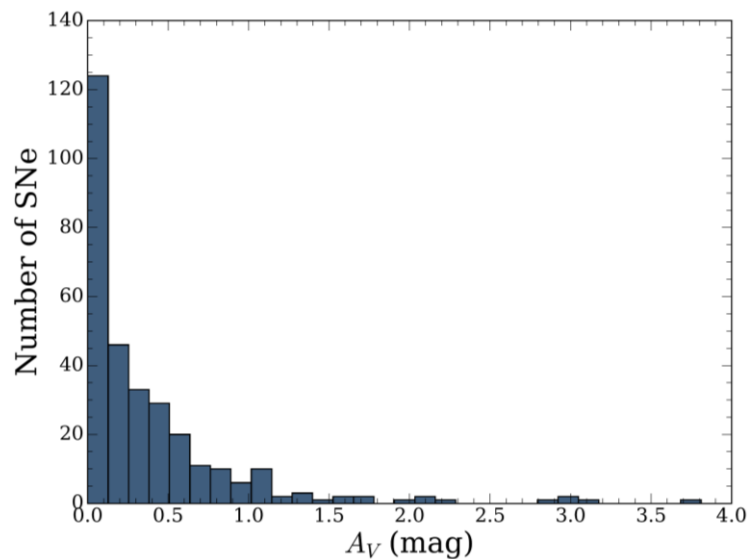
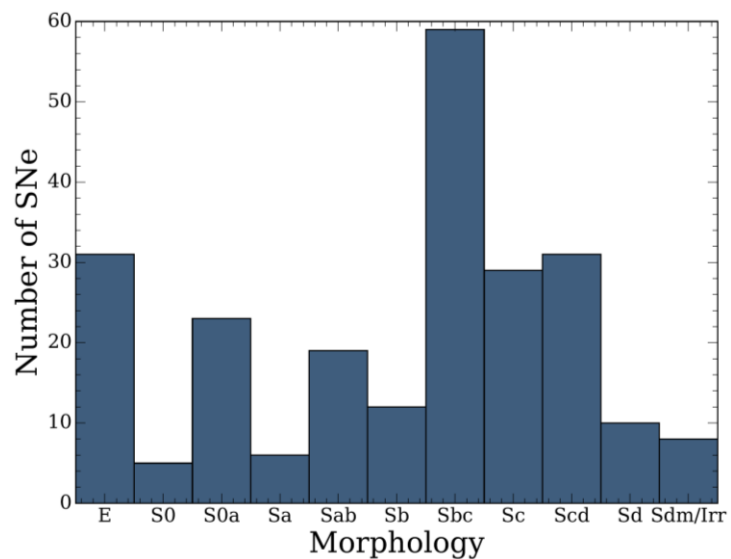
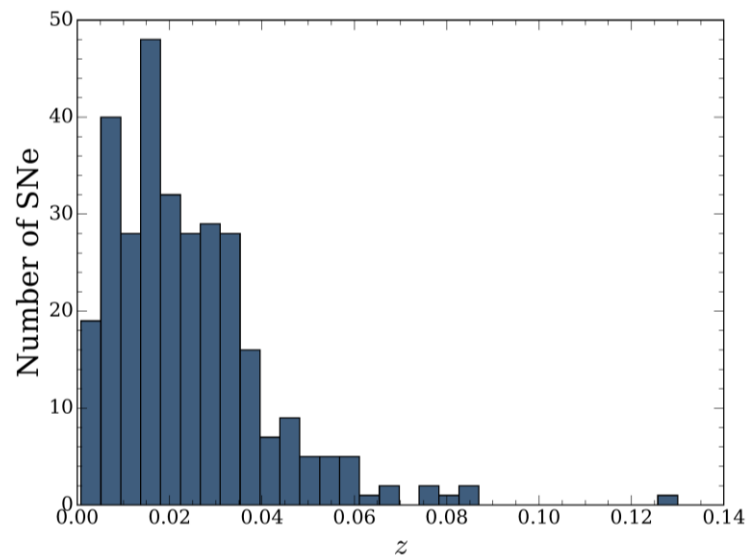
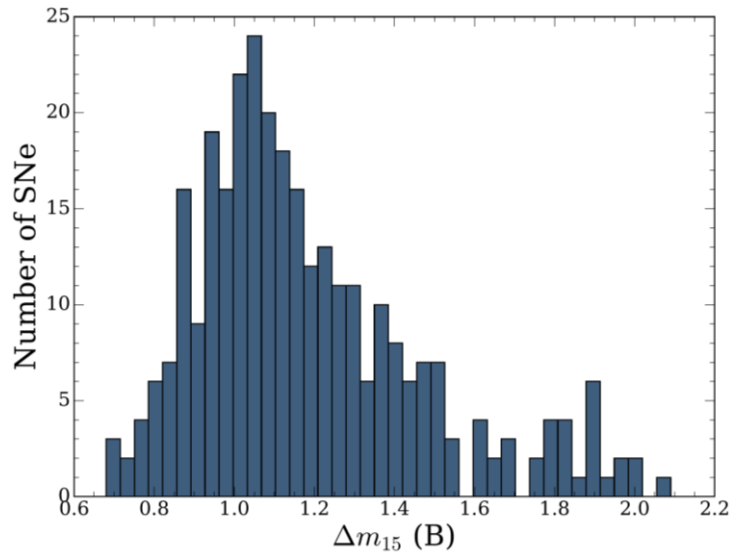


4972 Spectra



Metadata

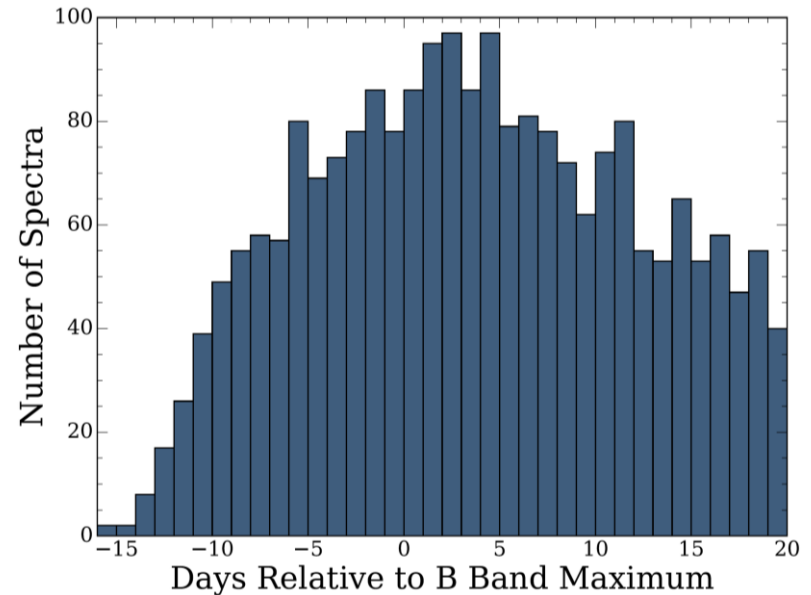
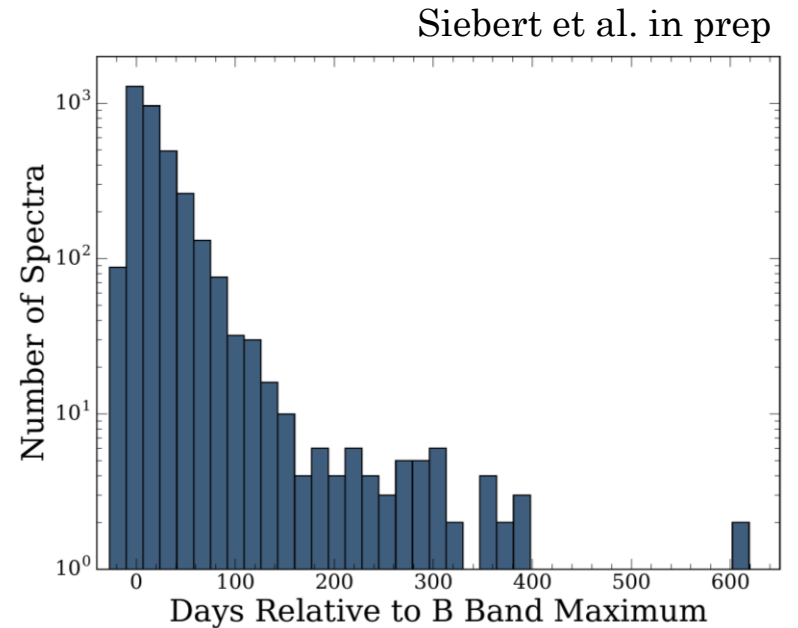
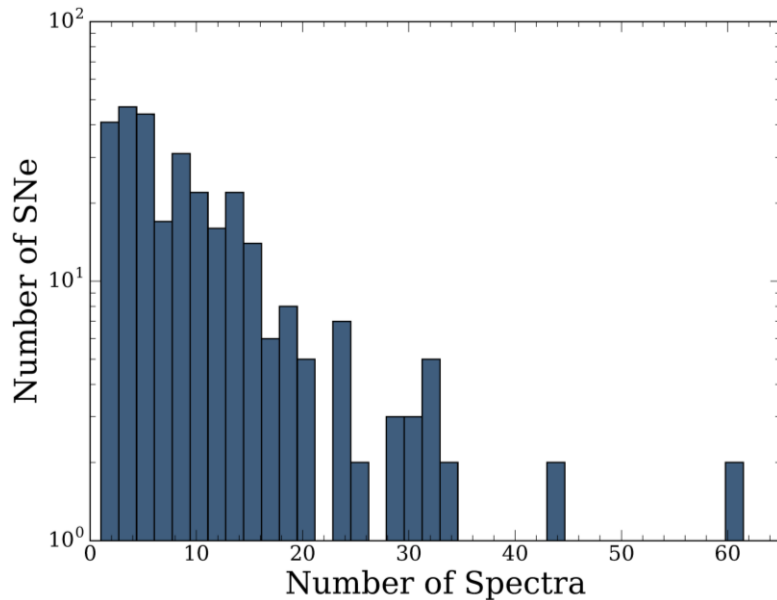
Siebert et al. in prep



Demographics

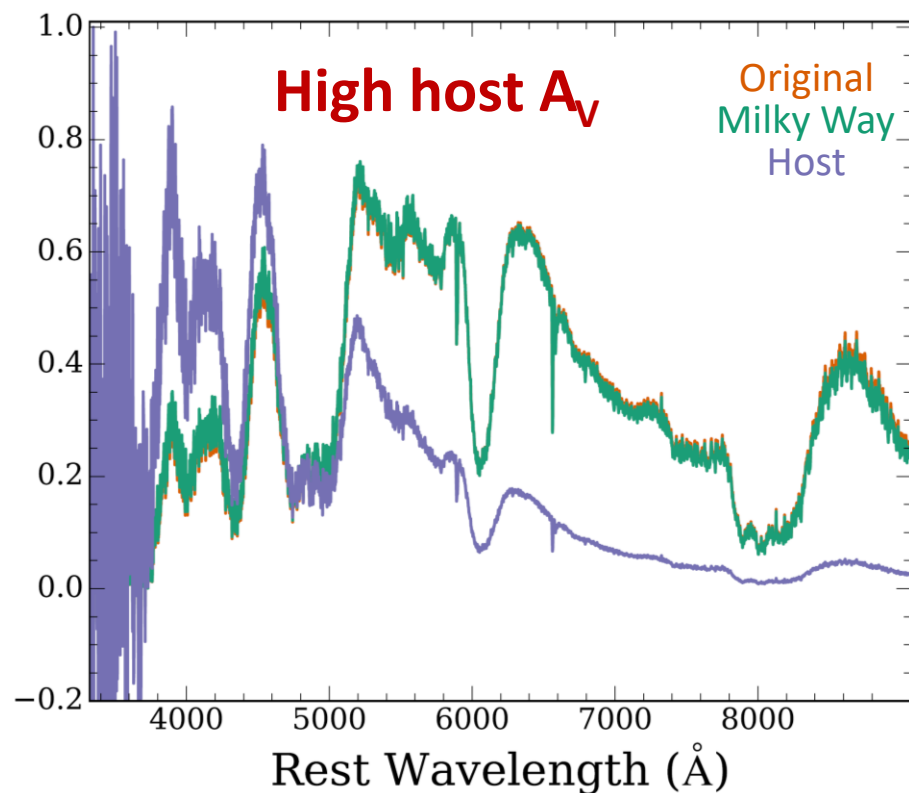
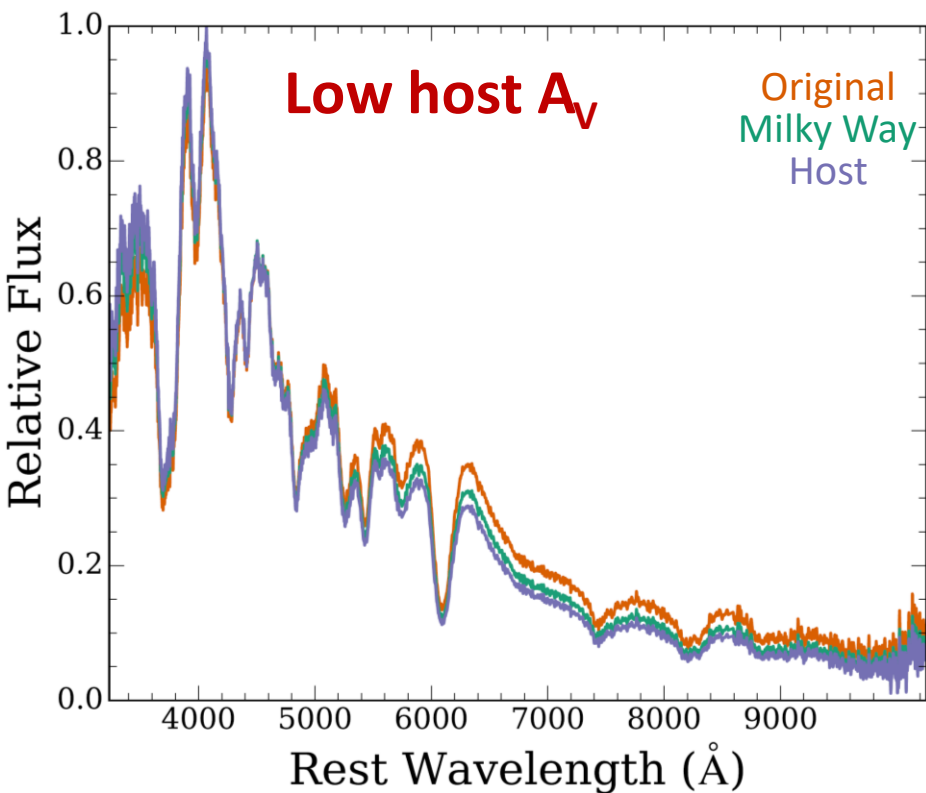
- Subsample requirements
 - Phase estimate
 - Host extinction estimate from light curve fit

N = 308 SNe 3453 Spectra



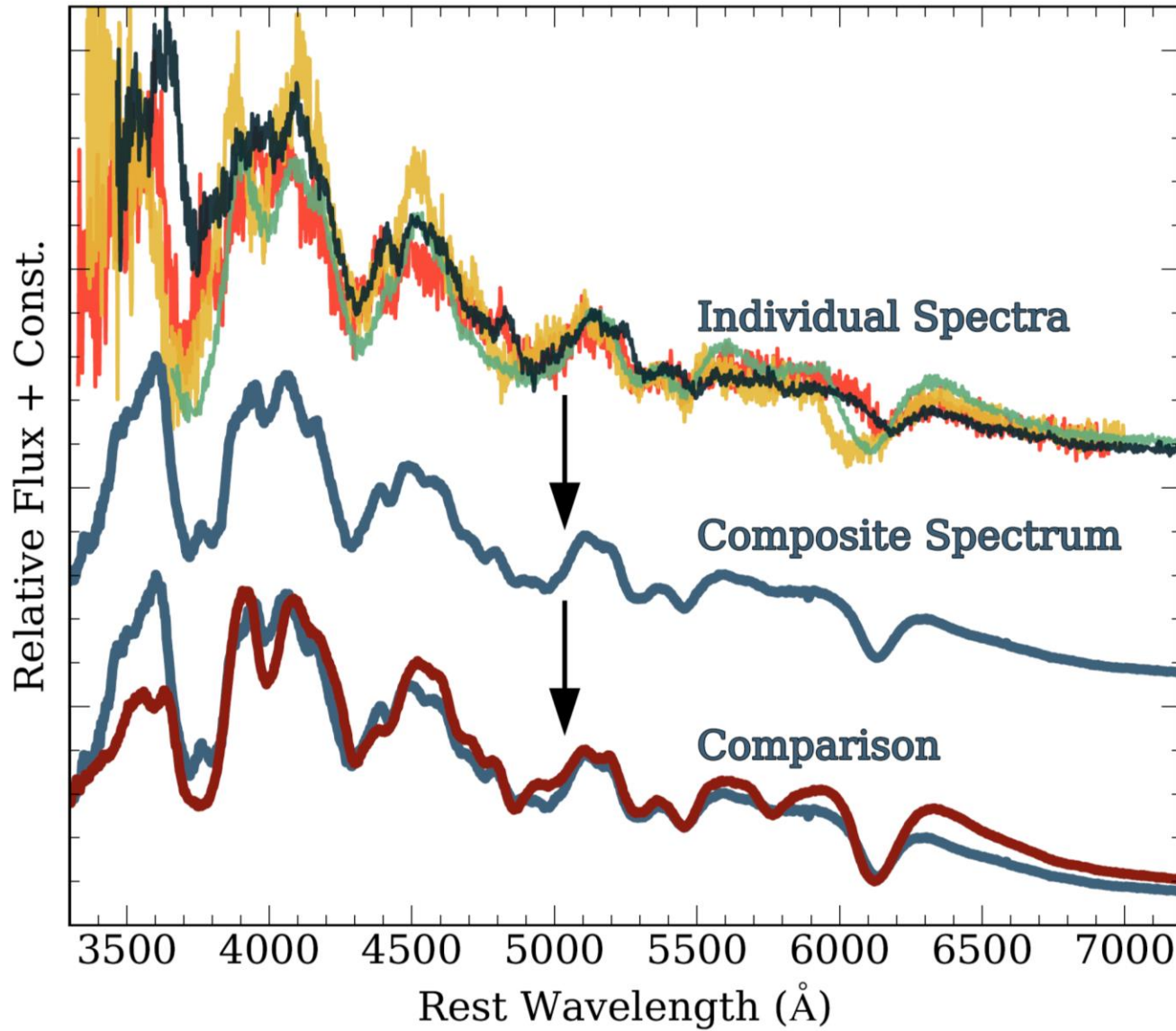
Reddening Corrections

Siebert et al. in prep



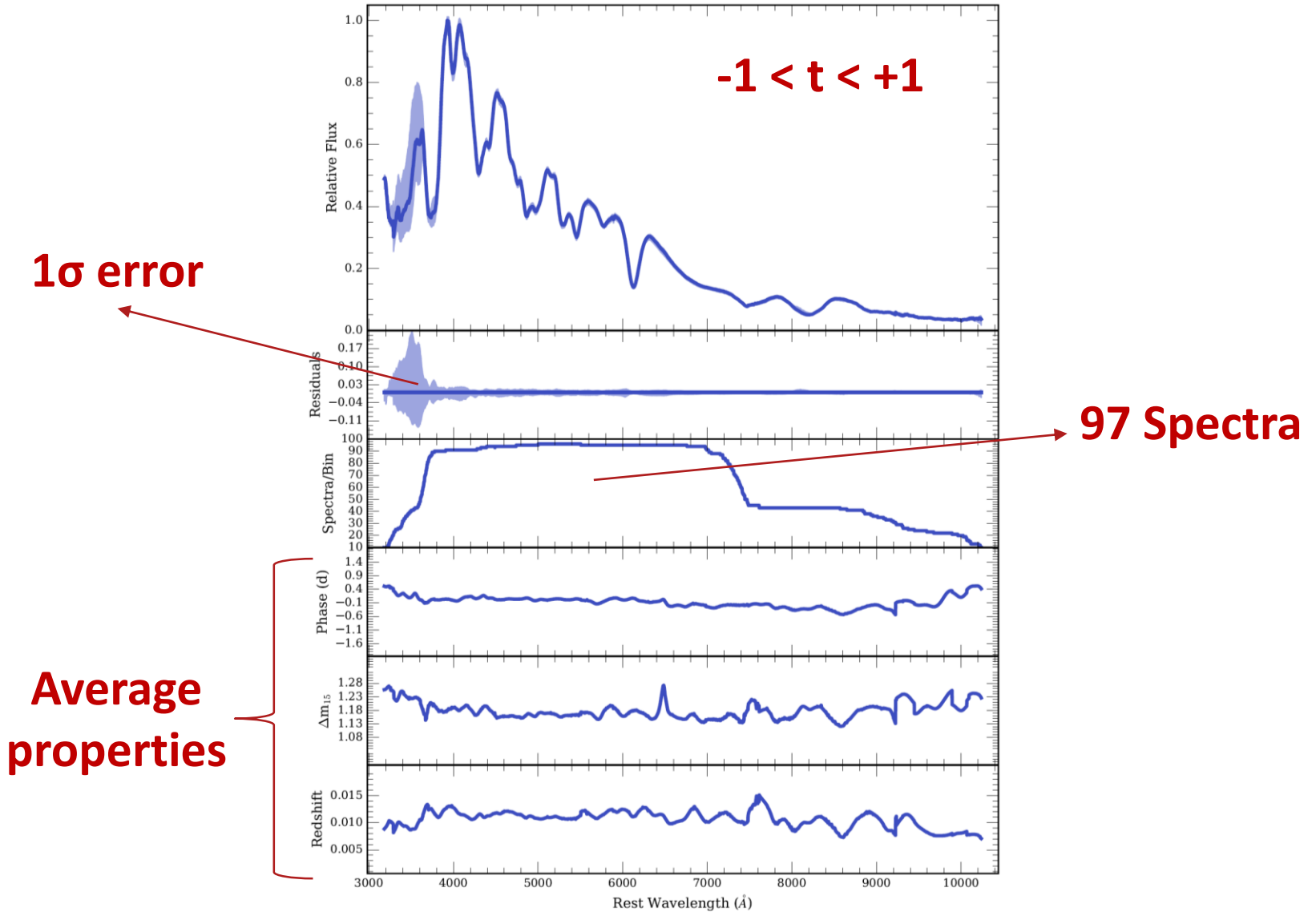
Composite Spectra

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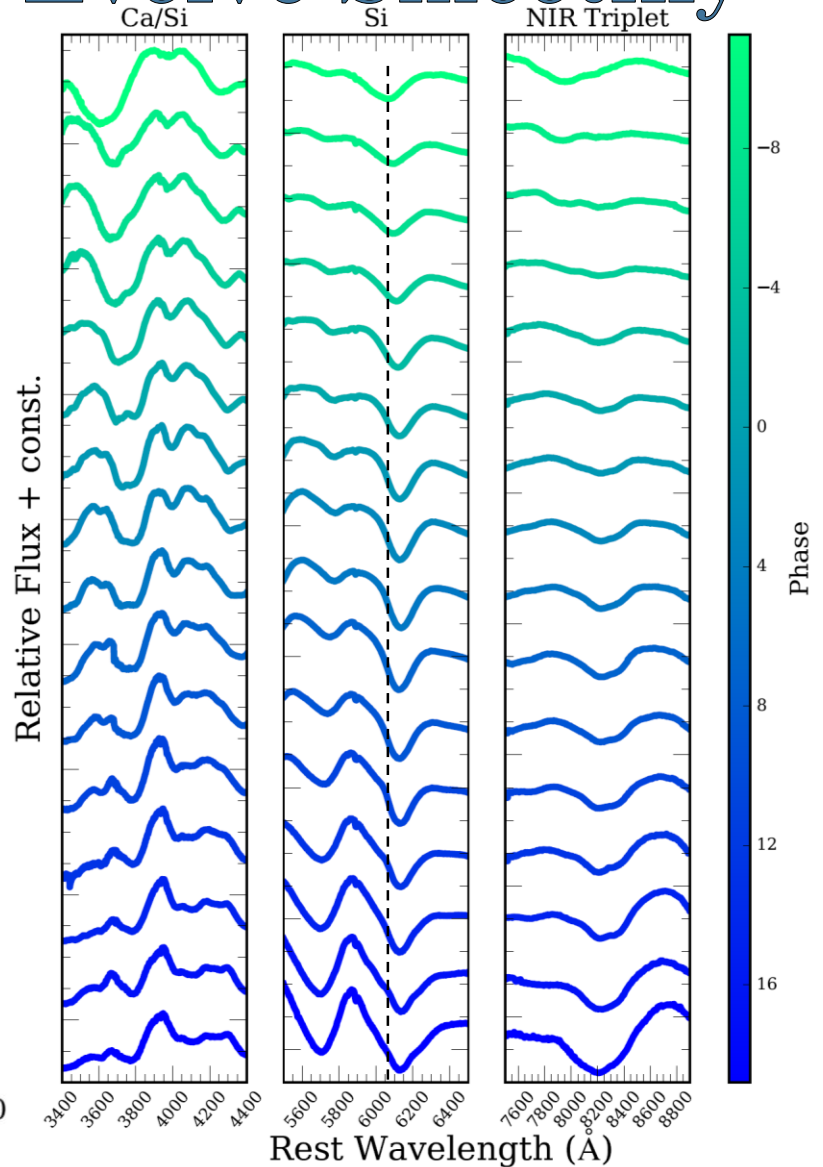
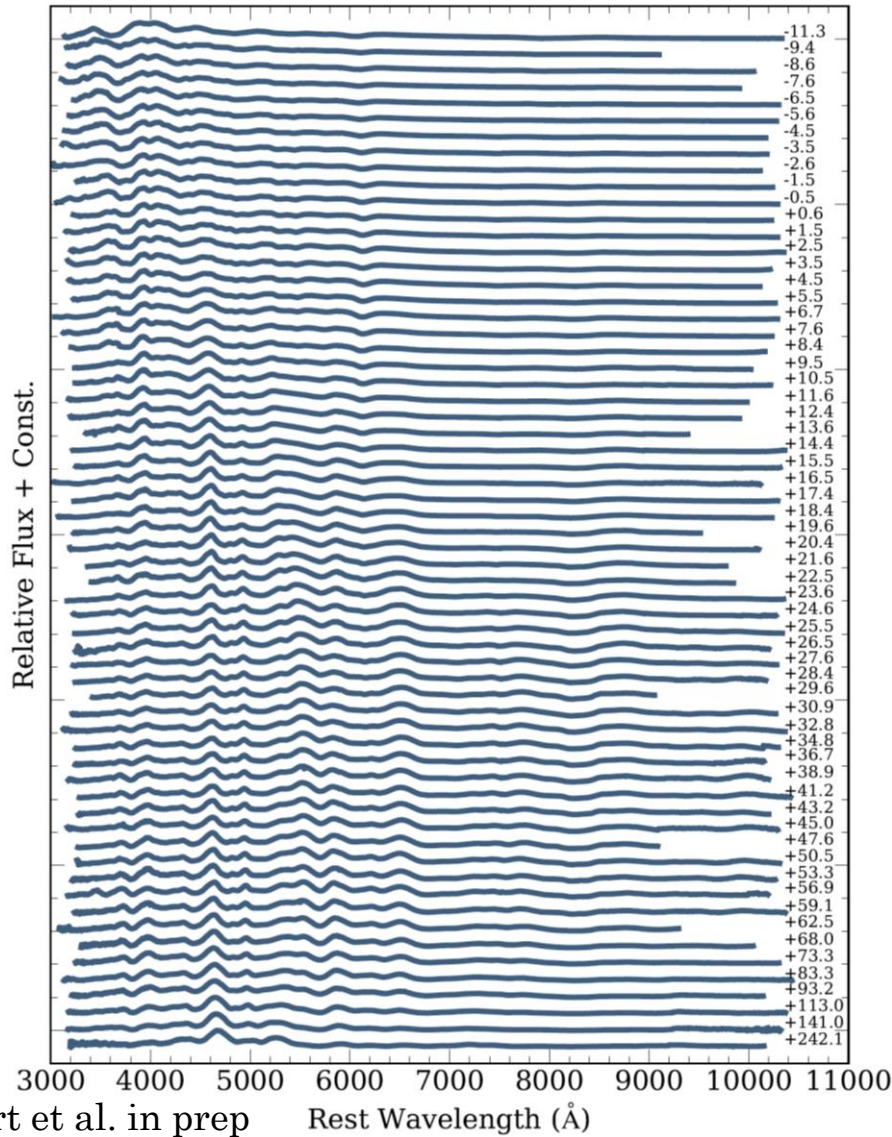


Composite Spectra

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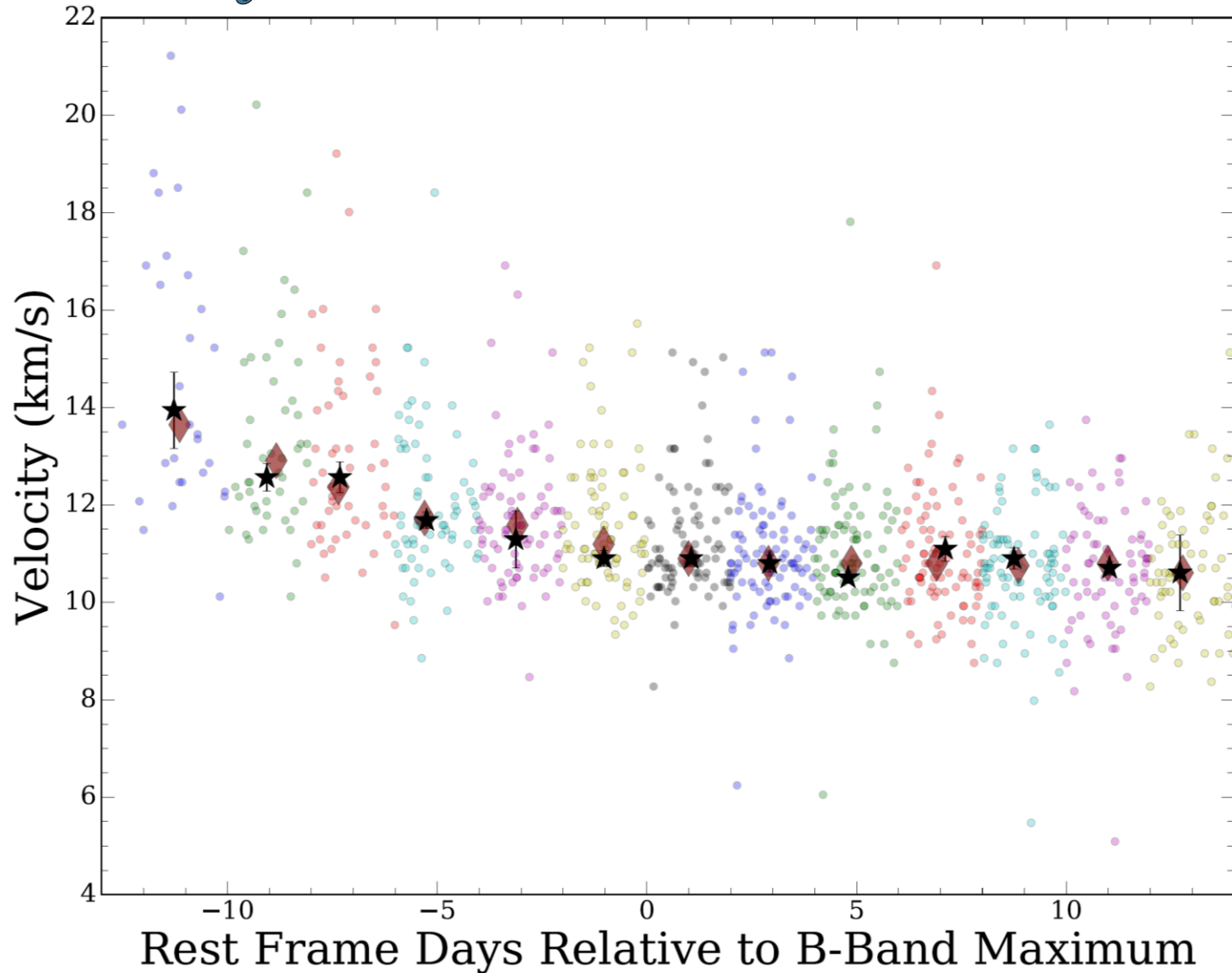


Composite Spectra Evolve Smoothly



Velocity Evolution

Siebert et al. in prep

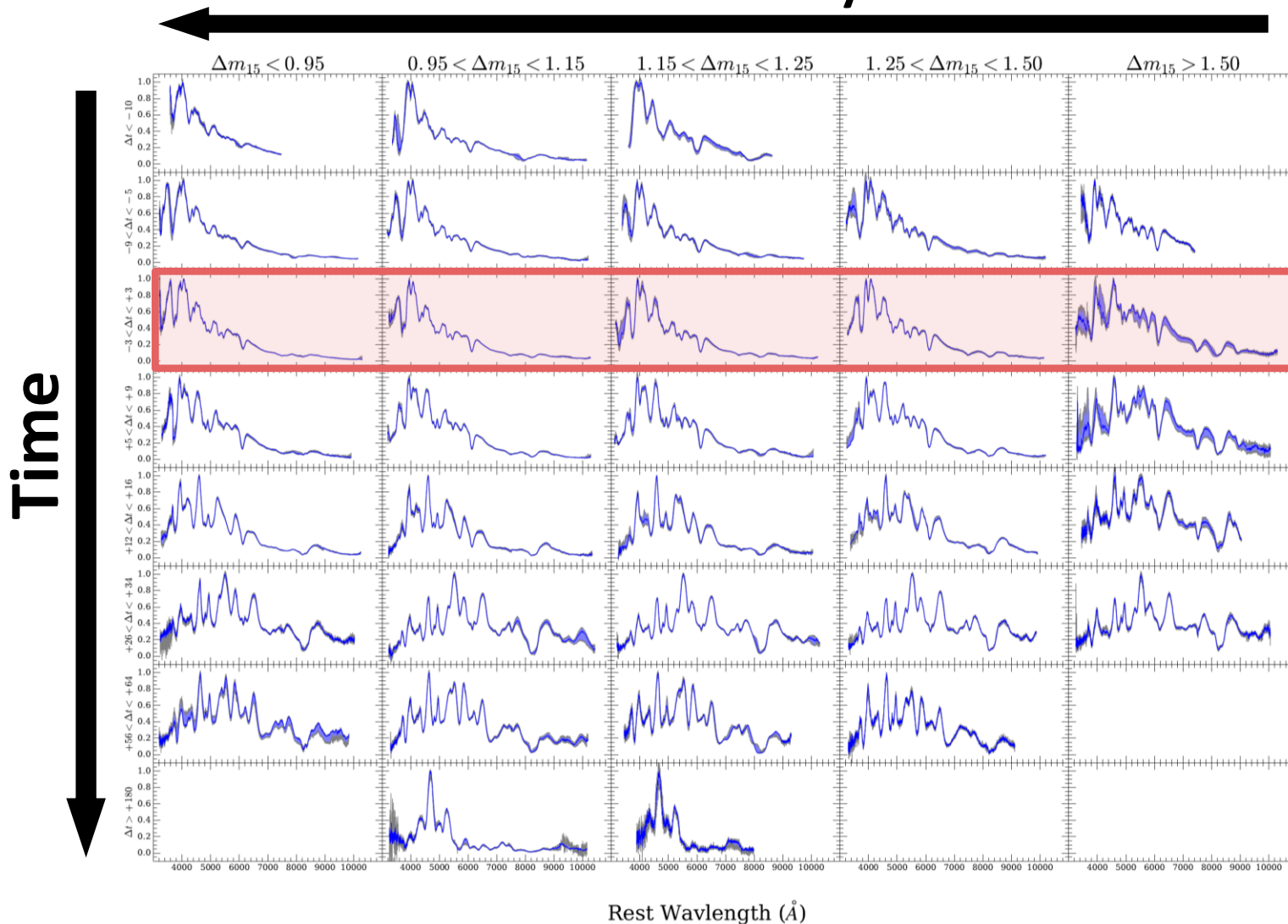


Parameter Hyperspace

Luminosity

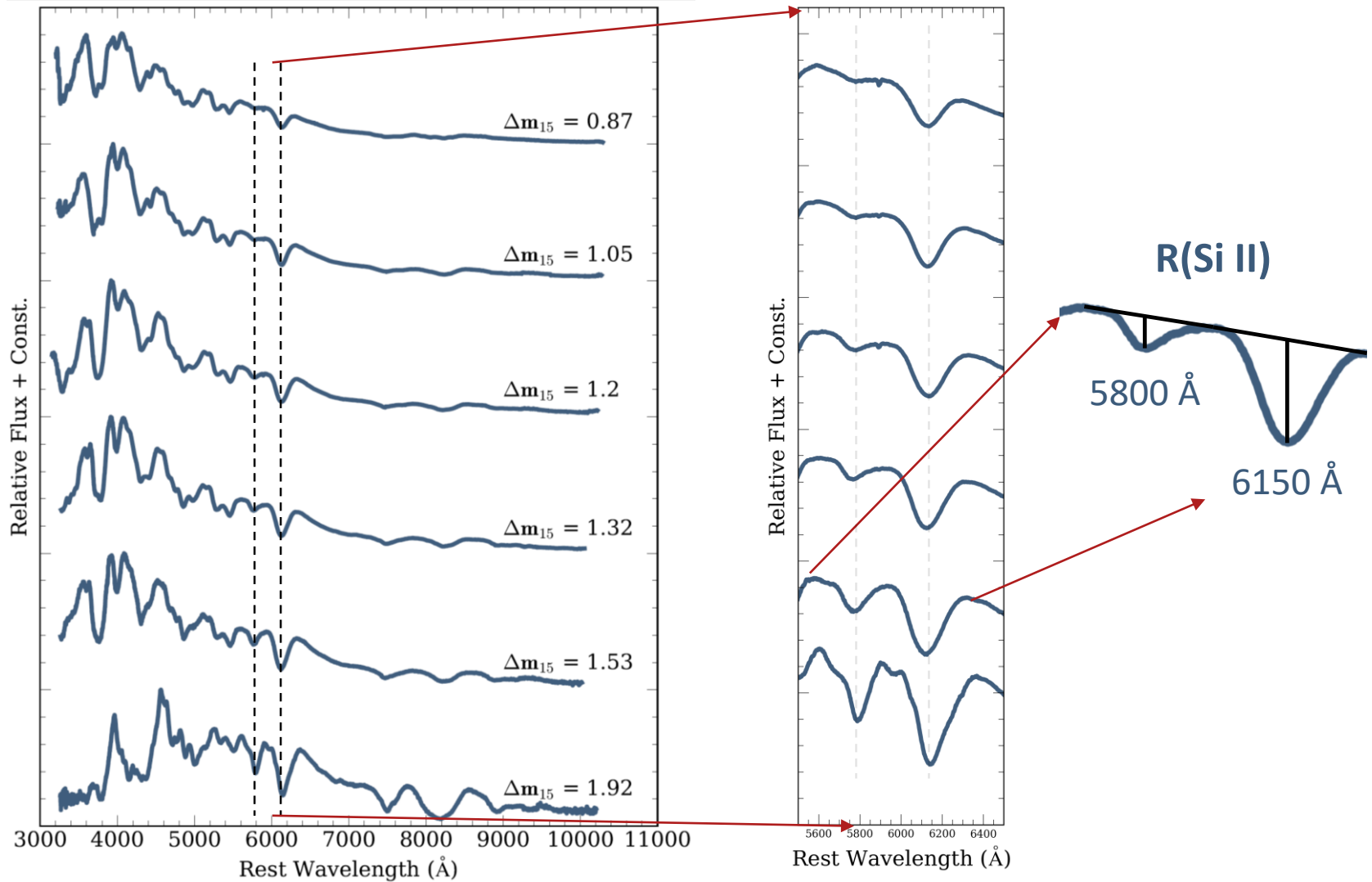


Siebert et al. in prep



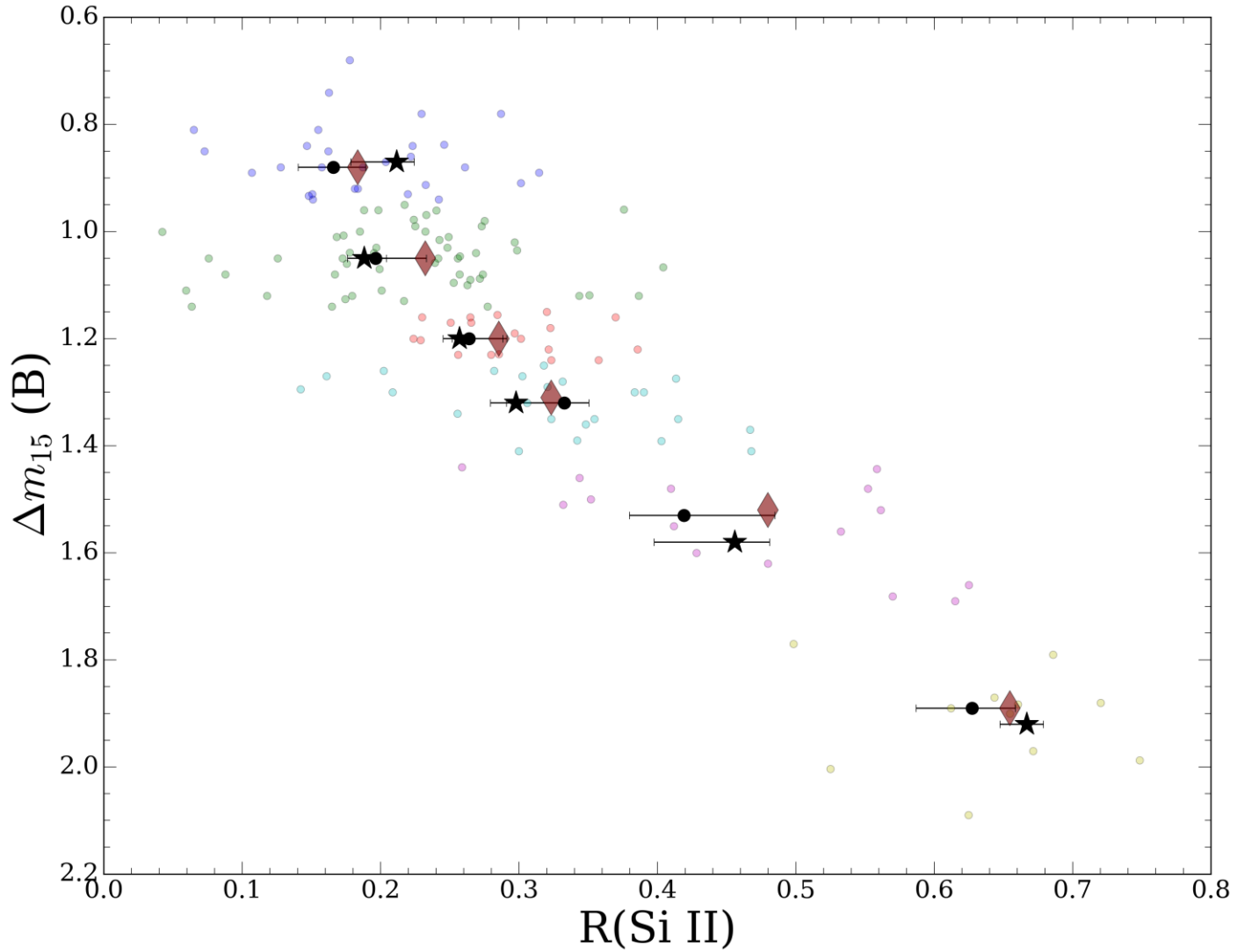
Light Curve Shape – Δm_{15}

Siebert et al. in prep



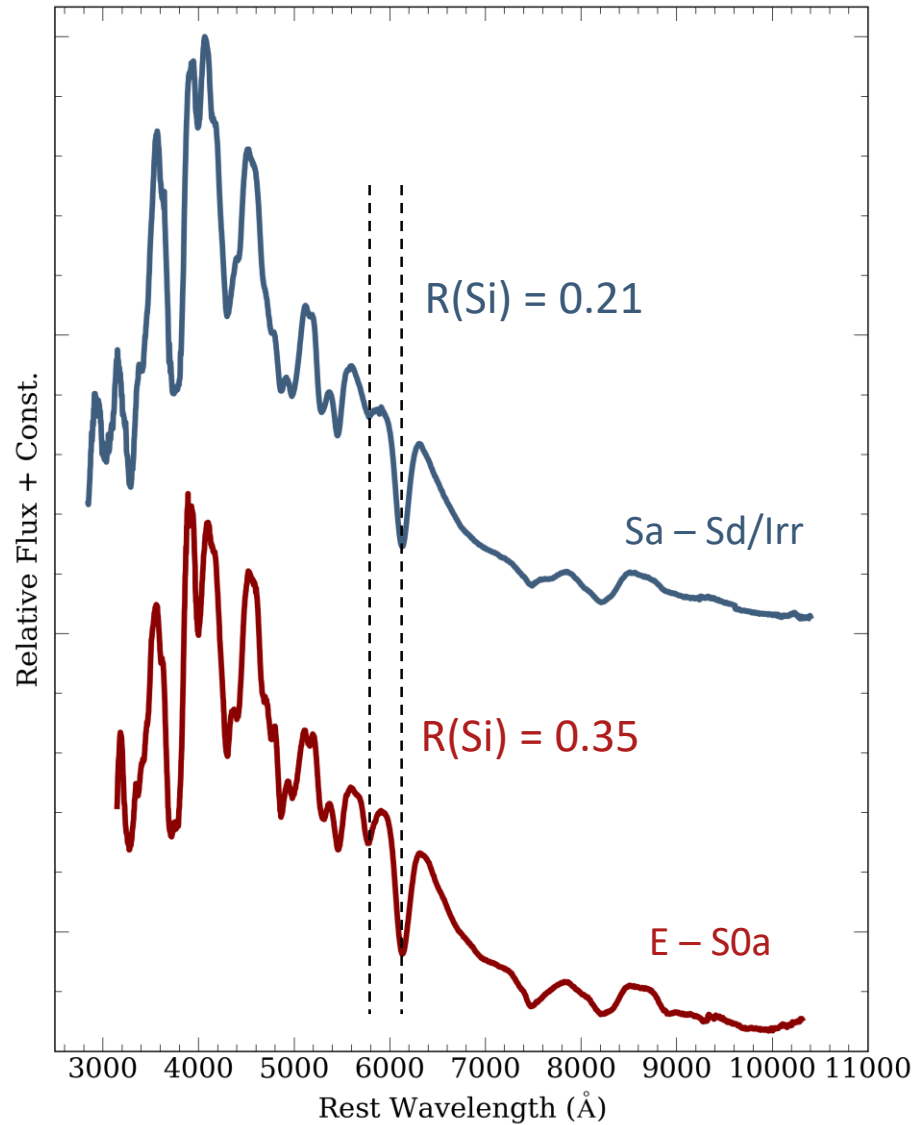
Silicon Ratio – R(Si II)

Siebert et al. in prep



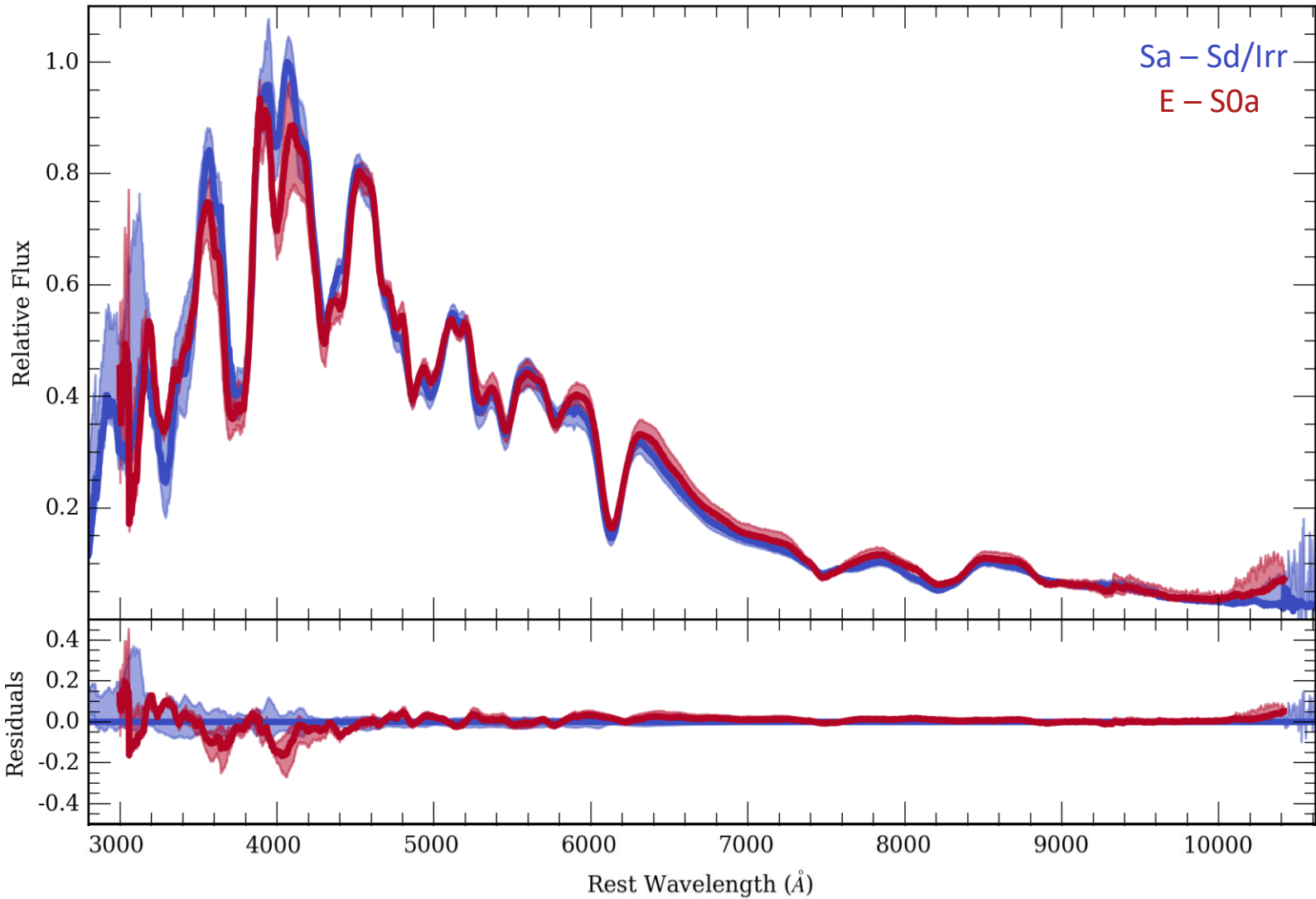
Host Galaxy Morphology

Siebert et al. in prep

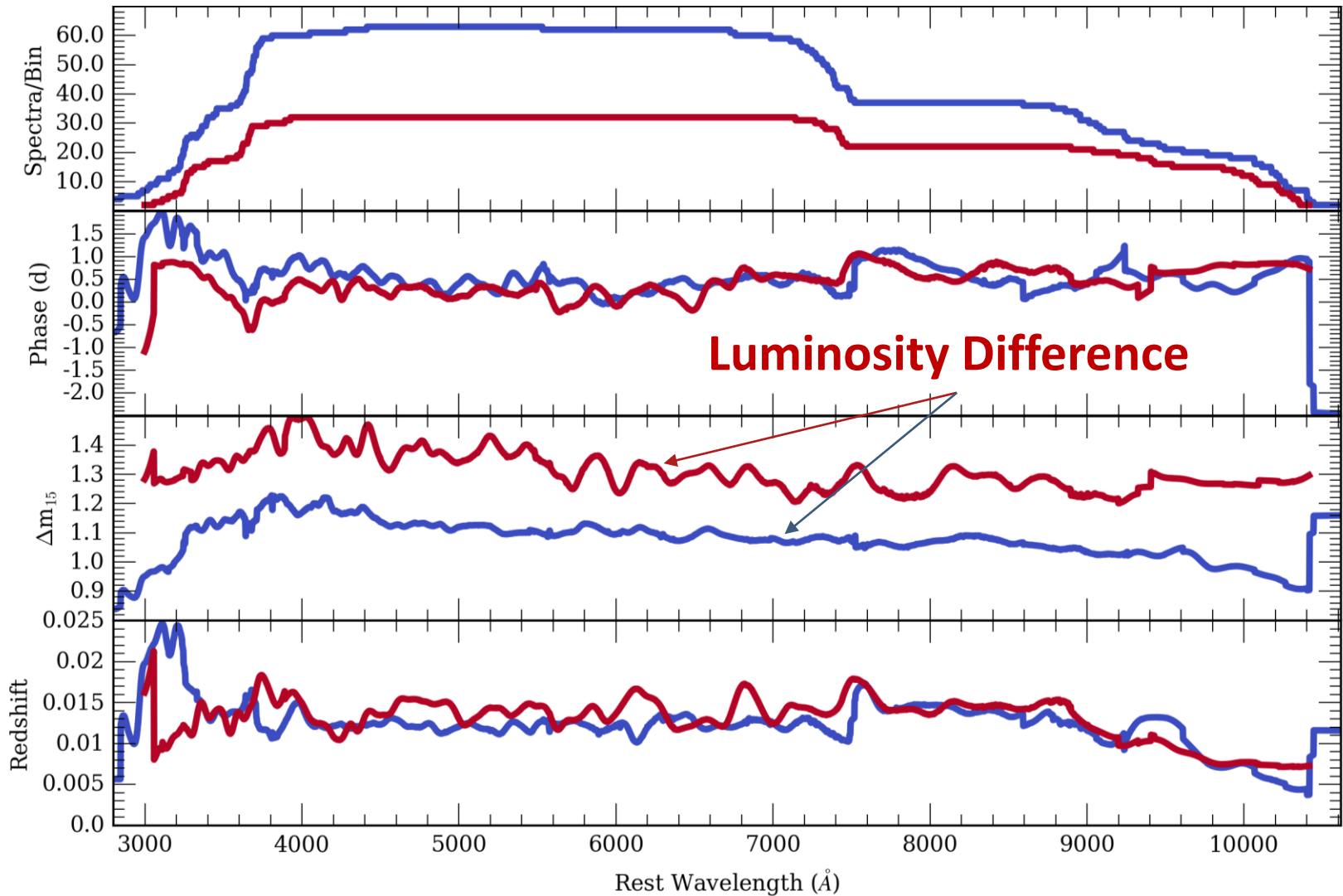


Host Galaxy Morphology

Siebert et al. in prep

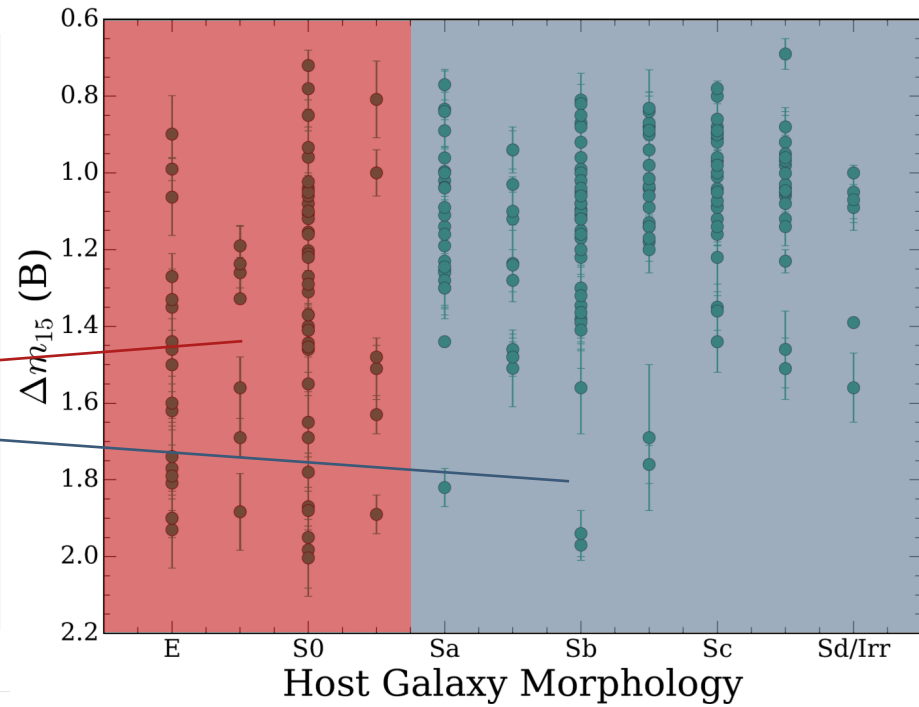
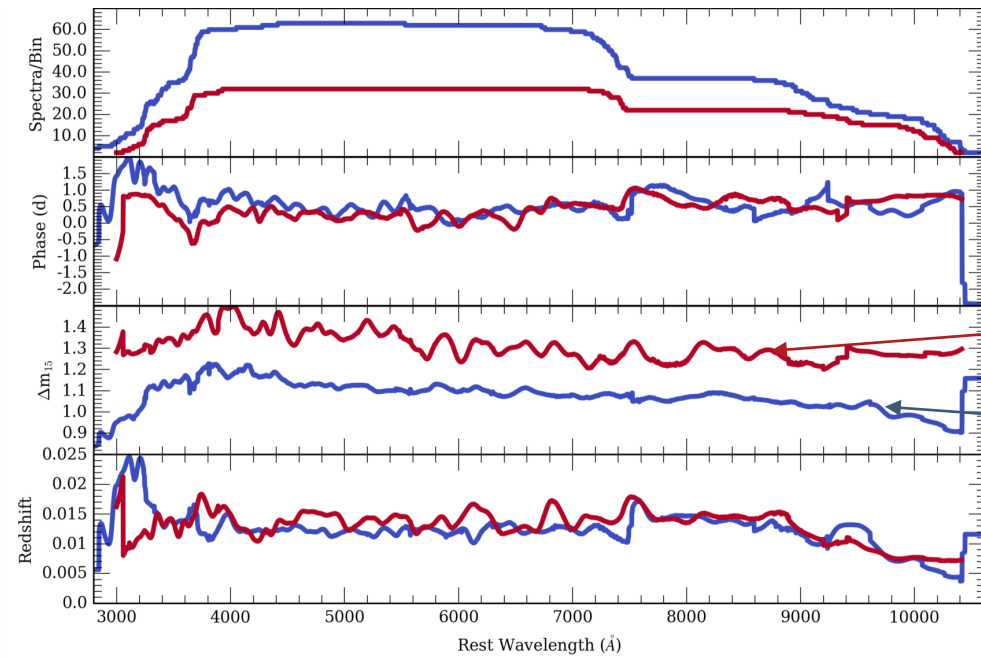


Host Galaxy Morphology



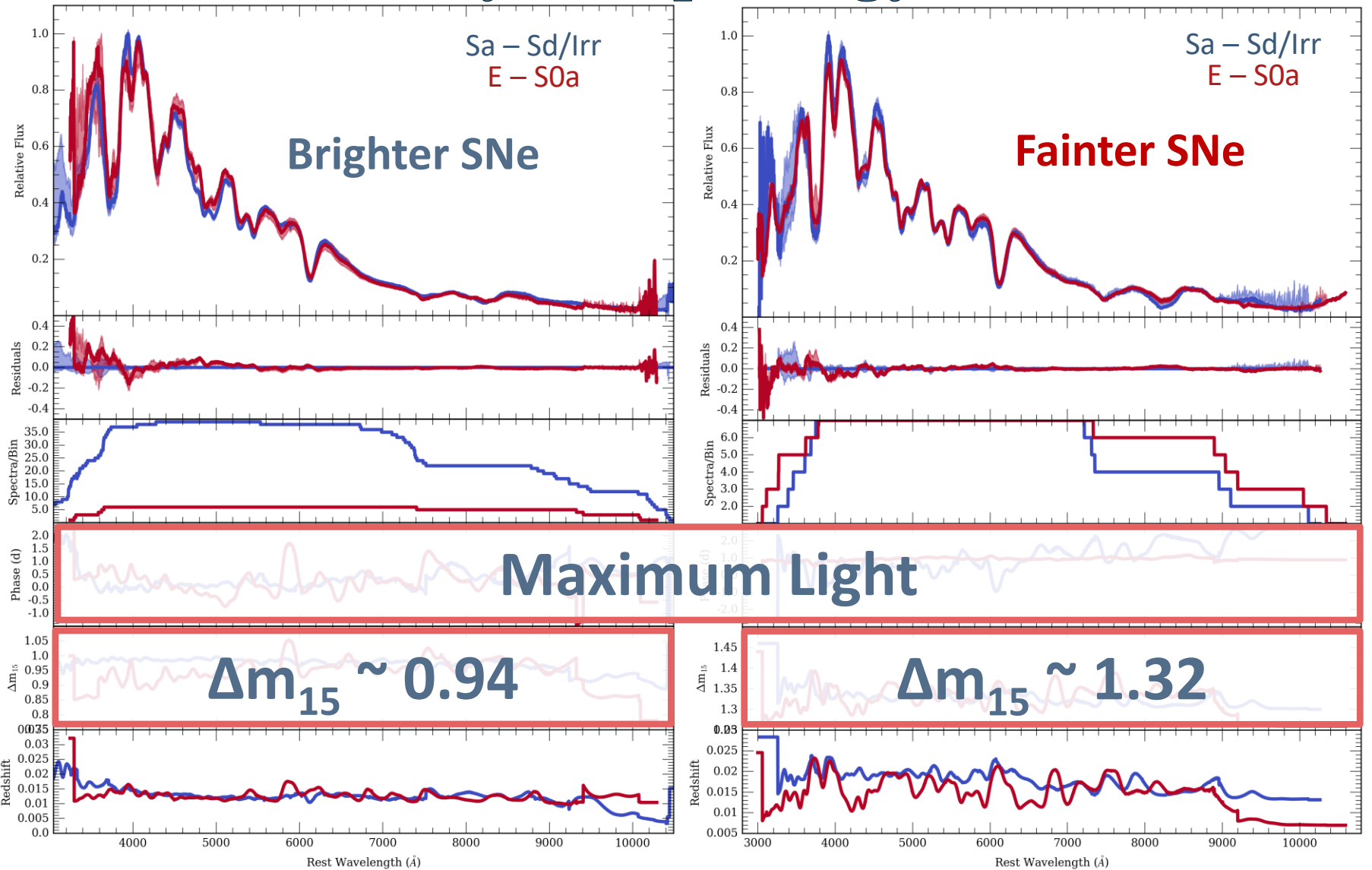
Host Galaxy Morphology

Siebert et al. in prep



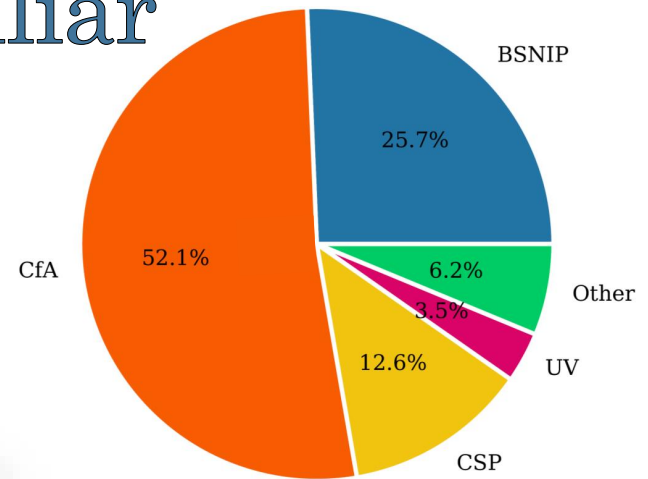
Host Galaxy Morphology

Siebert et al. in prep

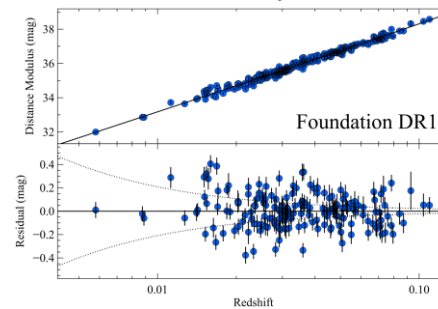


Conclusions – The Familiar

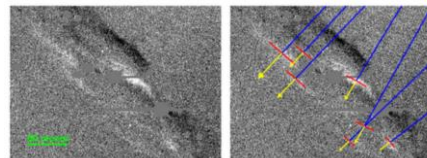
- Open source relational database for SNe Ia
 - Large amount of useful metadata
- Composite spectra are useful tools
 - Reproduce known correlations
- Investigate more parameters
 - Hubble residuals, velocity, color, carbon presence, etc.
- Add more data
 - Foundation sample
 - Other transient classes
- Sub-classification
- Light echoes



Foley et al. 2018

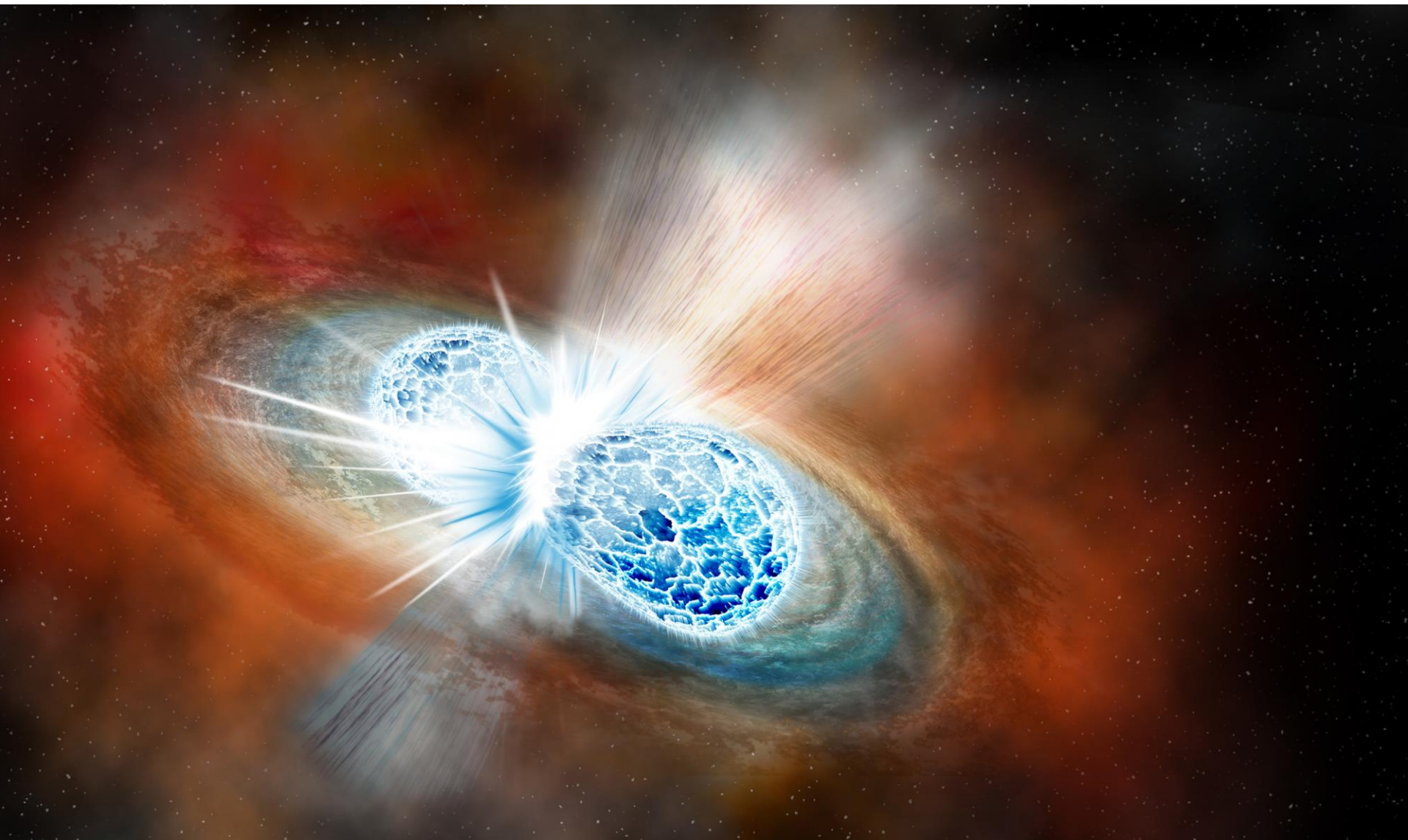


Rest et al. 2014





The Exotic

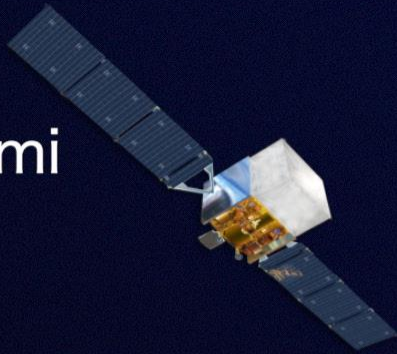




Coincident GW/GRB Trigger

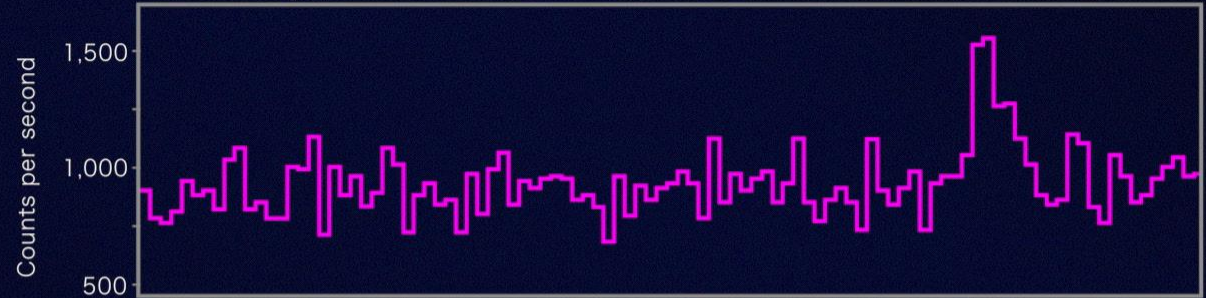
Abbott et al. 2017

Fermi



Gamma rays, 50 to 300 keV

GRB 170817A

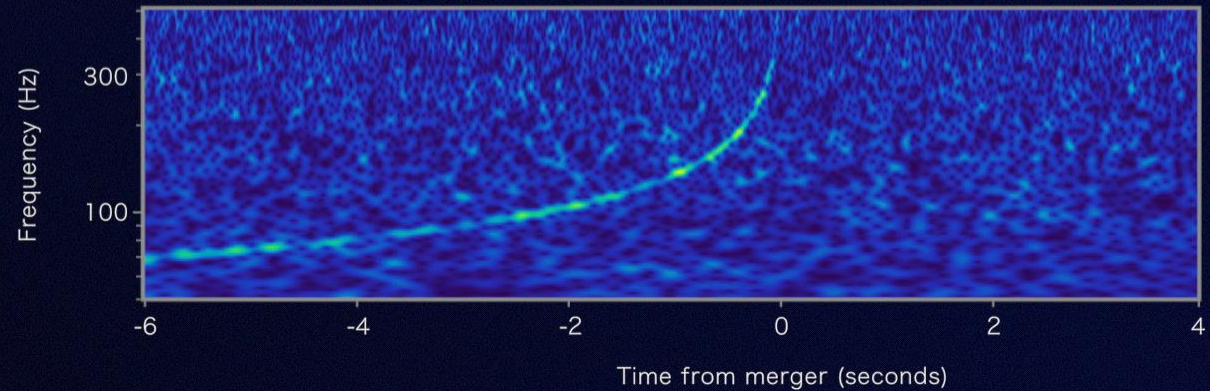


LIGO



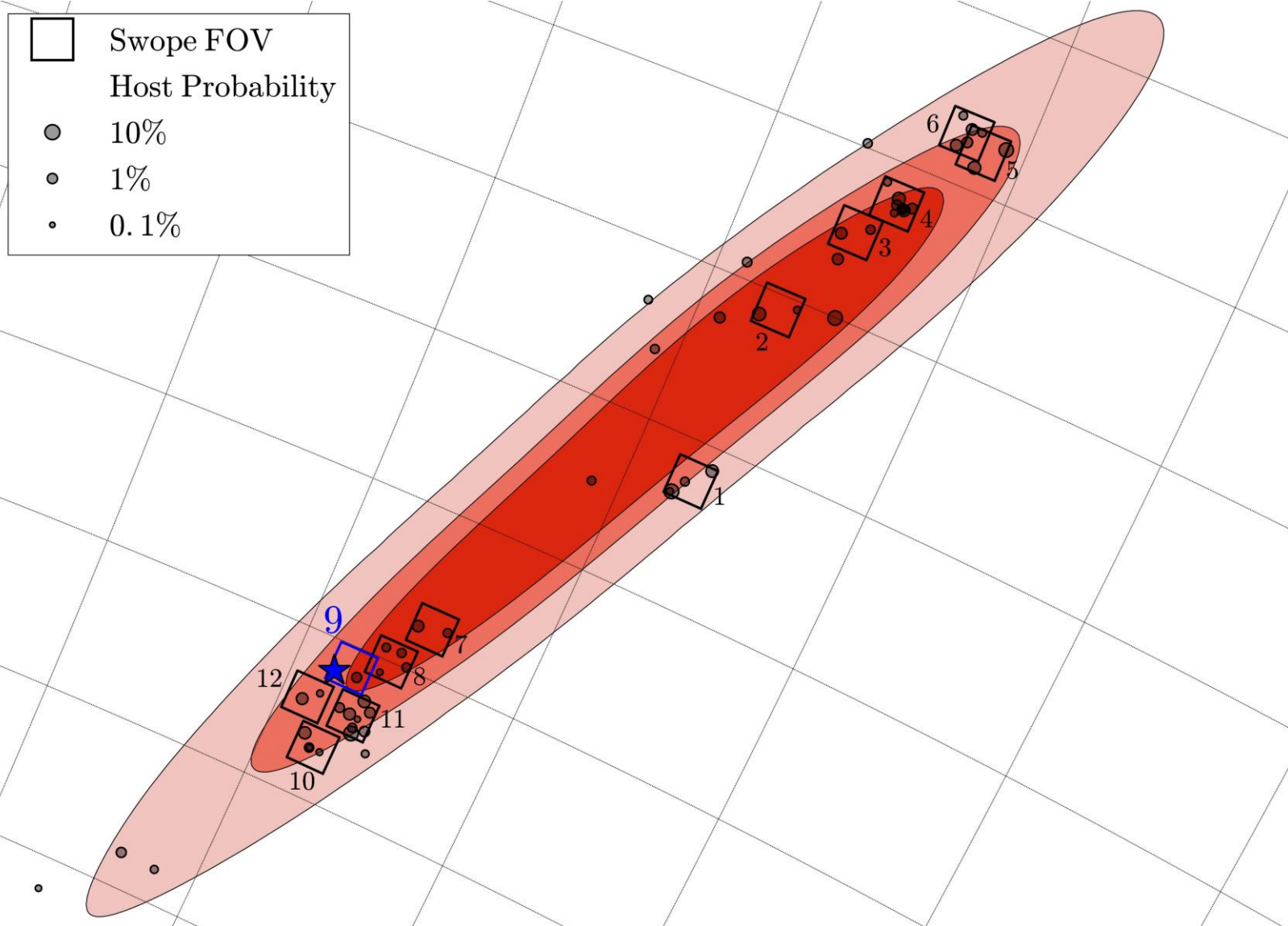
Gravitational-wave strain

GW170817



Counterpart Discovery

Coulter et al. 2017



Counterpart Discovery



NGC 4993



April 28, 2017

Hubble Space Telescope

SSS17a



August 17, 2017

Swope & Magellan Telescopes



Multi-Messenger Astrophysics Begins



2017

BREAKTHROUGH *of the* YEAR

gw170817

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2	2017ApJ...848L..13A Abbott, B. P., Abbott, R., Abbott, T. D., Acernese, F., Ackley, K., Adams, C., Adams, T., Adesso, P., Adhikari, R. X., Adya, V. B., and 1146 coauthors	95.260 Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A	10/2017	A E E X R C S U
3	2017ApJ...848L..12A Abbott, B. P., Abbott, R., Abbott, T. D., Acernese, F., Ackley, K., Adams, C., Adams, T., Adesso, P., Adhikari, R. X., Adya, V. B., and 3967 coauthors	95.260 Multi-messenger Observations of a Binary Neutron Star Merger	10/2017	A E E X D R C S U
4	2017PhRvL.119g1302C Creminelli, Paolo; Vernizzi, Filippo	91.840 Dark Energy after GW170817 and GRB170817A	12/2017	A E X R C U
5	2017Sci...358.1556C Coulter, D. A., Foley, R. J., Kilpatrick, C. D., Drout, M. R., Piro, A. L., Shappee, B. J., Siebert, M. R., Simon, J. D., Ulloa, N., Kasen, D., and 7 coauthors	91.380 Swope Supernova Survey 2017a (SSS17a), the optical counterpart to a gravitational wave source	12/2017	A E E X D R C S U
6	2017arXiv:171005903M Mena Ezquerra, Jose; Zomalacáregui, Miguel	90.620 Dark Energy after GW170817: dead ends and the road ahead	10/2017	A X R C U
7	2017ApJ...848L..13S Savchenko, V., Ferrigno, C., Koulikers, E., Bazzano, A., Bozzo, E., Brandt, S., Chenevez, J., Courvoisier, T. J.-L., Duthil, R., Domingo, A., and 15 coauthors	89.960 INTEGRAL Detection of the First Prompt Gamma-Ray Signal Coincident with the Gravitational-wave Event GW170817	10/2017	A E E X R C S U
8	2017Natur.551..747T Troja, E., Piro, L., van Eerten, H., Wollaeger, R. T., Im, M. I., Fox, O. D., Butler, N. R., Cenko, S. B., Sakamoto, T., Fryer, C. L., and 24 coauthors	89.800 The X-ray counterpart to the gravitational-wave event GW170817	11/2017	A E X D R C S U
9	2017ApJ...848L..11C Covverthwaite, P. S.; Berger, E.; Villar, V. A.; Metzger, B. D.; Nicholl, M.; Chornock, R.; Blanchard, P. K.; Fong, W.; Margutti, R.; Soares-Santos, M., and 134 coauthors	89.470 The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO-Virgo GW170817. II. UV, Optical, and Near-infrared Light Curves and Comparison to Kilonova Models	10/2017	A E E X D R C S U
10	2017Natur.551..85A Abbott, B. P., Abbott, R., Abbott, T. D., Acernese, F., Ackley, K., Adams, C., Adams, T., Adesso, P., Adhikari, R. X., Adya, V. B., and 1304 coauthors	89.300 A gravitational-wave standard siren measurement of the Hubble constant	11/2017	A E X D R C S U
11	2017Natur.551..67P Plan, E., D'Avanzo, P., Benetti, S., Branchesi, M., Brocato, E., Campana, S., Cappellaro, E., Covino, S., DElia, V., Fynbo, J. P. U., and 74 coauthors	88.940 Spectroscopic identification of r-process nucleosynthesis in a double neutron-star merger	11/2017	A E X D R C S U
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14	2017Natur.551..75S Smart, S. J.; Chen, Y.			
15				
16				
17				
18	2017ApJ...848L..21A Alexander, K. D.; Berger, E.; Fong, W.; Williams, P. K. G.; Gouzouris, C.; Margutti, R.; Metzger, B. D.; Aman, J.; Blanchard, P. K.; Chornock, R.; Covverthwaite, P. S.; Eftekhari, T.; Fong, W.; Gouzouris, C.; Hotokezaka, K.; Jha, Saurabh W.; Reichart, Daniel E.; Haislip, Joshua; Koopmanov, Vladimir	87.690 The Discovery of the Electromagnetic Counterpart of GW170817: Kilonova AT 2017gfo/ DLT17k	10/2017	A E E X R C S U
19	2017ApJ...848L..24V Valent, Stefano; David, Sand, J.; Yang, Sheng; Cappellaro, Enrico; Tartaglia, Leonardo; Corsi, Alessandra; Jha, Saurabh W.; Reichart, Daniel E.; Haislip, Joshua; Koopmanov, Vladimir	87.580 The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO-Virgo GW170817. VI. Radio Constraints on a Relativistic Jet and Predictions for Late-time Emission from the Kilonova Ejects	10/2017	A E E X D R C S U
20	2017ApJ...848L..21A Alexander, K. D.; Berger, E.; Fong, W.; Williams, P. K. G.; Gouzouris, C.; Margutti, R.; Metzger, B. D.; Aman, J.; Blanchard, P. K.; Chornock, R.; Covverthwaite, P. S.; Eftekhari, T.; Fong, W.; Gouzouris, C.; Hotokezaka, K.; Jha, Saurabh W.; Reichart, Daniel E.; Haislip, Joshua; Koopmanov, Vladimir	87.580 The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO-Virgo GW170817. VI. Radio Constraints on a Relativistic Jet and Predictions for Late-time Emission from the Kilonova Ejects	10/2017	A E E X D R C S U
21	2017ApJ...848L..24V Valent, Stefano; David, Sand, J.; Yang, Sheng; Cappellaro, Enrico; Tartaglia, Leonardo; Corsi, Alessandra; Jha, Saurabh W.; Reichart, Daniel E.; Haislip, Joshua; Koopmanov, Vladimir	87.580 The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO-Virgo GW170817. VI. Radio Constraints on a Relativistic Jet and Predictions for Late-time Emission from the Kilonova Ejects	10/2017	A E E X D R C S U
22	2017ApJ...848L..19C Chornock, R.; Berger, E.; Kasen, D.; Covverthwaite, P. S.; Nicholl, M.; Villar, V. A.; Alexander, K. D.; Blanchard, P. K.; Eftekhari, T.; Fong, W., and 22 coauthors	87.450 The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO-Virgo GW170817. III. Optical and UV Spectra of a Blue Polar Ejecta	10/2017	A E E X D R C S U
23	2017ApJ...848L..18N Nicholl, M.; Berger, E.; Kasen, D.; Metzger, B. D.; Elias, J.; Briceño, C.; Alexander, K. D.; Blanchard, P. K.; Chornock, R.; Covverthwaite, P. S., and 24 coauthors	87.450 The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO-Virgo GW170817. III. Optical and UV Spectra of a Blue Polar Ejecta	10/2017	A E E X D R C S U
24	2017ApJ...848L..16S Soares-Santos, M.; Holz, D. E.; Annis, J.; Chornock, R.; Hesser, K.; Berger, E.; Brout, D.; Chen, H.-Y.; Kessler, R.; Sako, M., and 138 coauthors	87.450 The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO-Virgo GW170817. I. Discovery of the Optical Counterpart Using the Dark Energy Camera	10/2017	A E E X R C S U
25	2018arXiv:180102669Z Lyman, J. D.; Lamb, G. P.; Levian, A. J.; Mandel, I.; Tanvir, N. R.; Kobayashi, S.; Gompertz, B.; Hjorth, J.; Fruchter, A. S.; Kangas, T., and 26 coauthors	87.330 The optical afterglow of the short gamma-ray burst associated with GW170817	01/2018	A X R C U
26	2017arXiv:171005931M Metzger, Brian D.	87.330 Welcome to the Multi-Messenger Era! Lessons from a Neutron Star Merger and the Landscape Ahead	10/2017	A X R C U
27	2017PhRvL.119g1303S Sakstein, Jeremy; Jam, Bhuvanesh	87.210 Implications of the Neutron Star Merger GW170817 for Cosmological Scalar-Tensor Theories	12/2017	A E X R C U
28	2018Natur.554..207M Mooley, K. P.; Nakar, E.; Hotokezaka, K.; Hallinan, G.; Corsi, A.; Frail, D. A.; Hotokezaka, K.; Murphy, T.; Lenc, E.; Kaplan, D. L., and 15 coauthors	86.670 A mildly relativistic wide-angle outflow in the neutron-star merger event GW170817	02/2018	A E X R C U
29	2017Natur.551..89K Kasen, Daniel; Metzger, Brian; Barnes, Jennifer; Quataert, Eliot; Ramirez-Ruiz, Enric	86.670 Origin of the heavy elements in binary neutron-star mergers from a gravitational-wave event	11/2017	A E X R C S U
30	2017Sci...358.1559K Kasliwal, M. M.; Nakar, E.; Singer, L. P.; Kaplan, D. L.; Cook, D. O.; Van Sistine, A.; Lau, R. M.; Fremming, C.; Gottlieb, O.; Jencson, J. E., and 71 coauthors	86.380 Illuminating gravitational waves: A concordant picture of photons from a neutron star merger	12/2017	A E E X D R C S U
31	2017ApJ...848L..23H Haggard, Daryl; Nyika, Melania; Ruan, Jot; Kalogera, Vicky; Cenko, S. Bradley; Evans, Phil; Kennea, Jamie A.	86.230 A Deep Chandra X-Ray Study of Neutron Star Coalescence GW170817	10/2017	A E E X D R C S U
32	2017Sci...358.1579H Hallinan, G.; Corsi, A.; Mooley, K. P.; Hotokezaka, K.; Nakar, E.; Kasliwal, M. M.; Kaplan, D. L.; Frail, D. A.; Myers, S. T.; Murphy, T., and 23 coauthors	85.910 A radio counterpart to a neutron star merger	12/2017	A E E X R C S U
33	2017Sci...358.1561E Evans, P. A.; Cenko, S. B.; Kennea, J. A.; Emery, S. W. K.; Koza, N. P. M.; Korobkin, O.; Wollaeger, R. T.; Fryer, C. L.; Maden, K. K.; Harrison, F. A., and 49 coauthors	85.910 Swift and NuSTAR observations of GW170817: Detection of a blue kilonova	12/2017	A E E X R C S U

BILLIONS AND BILLIONS MORE!

IC COUNTERPART

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SSS17A

H. LEE,⁵ A. L. PIRO,⁶
ST,^{7,8} C. ROJAS-BRAVO,¹

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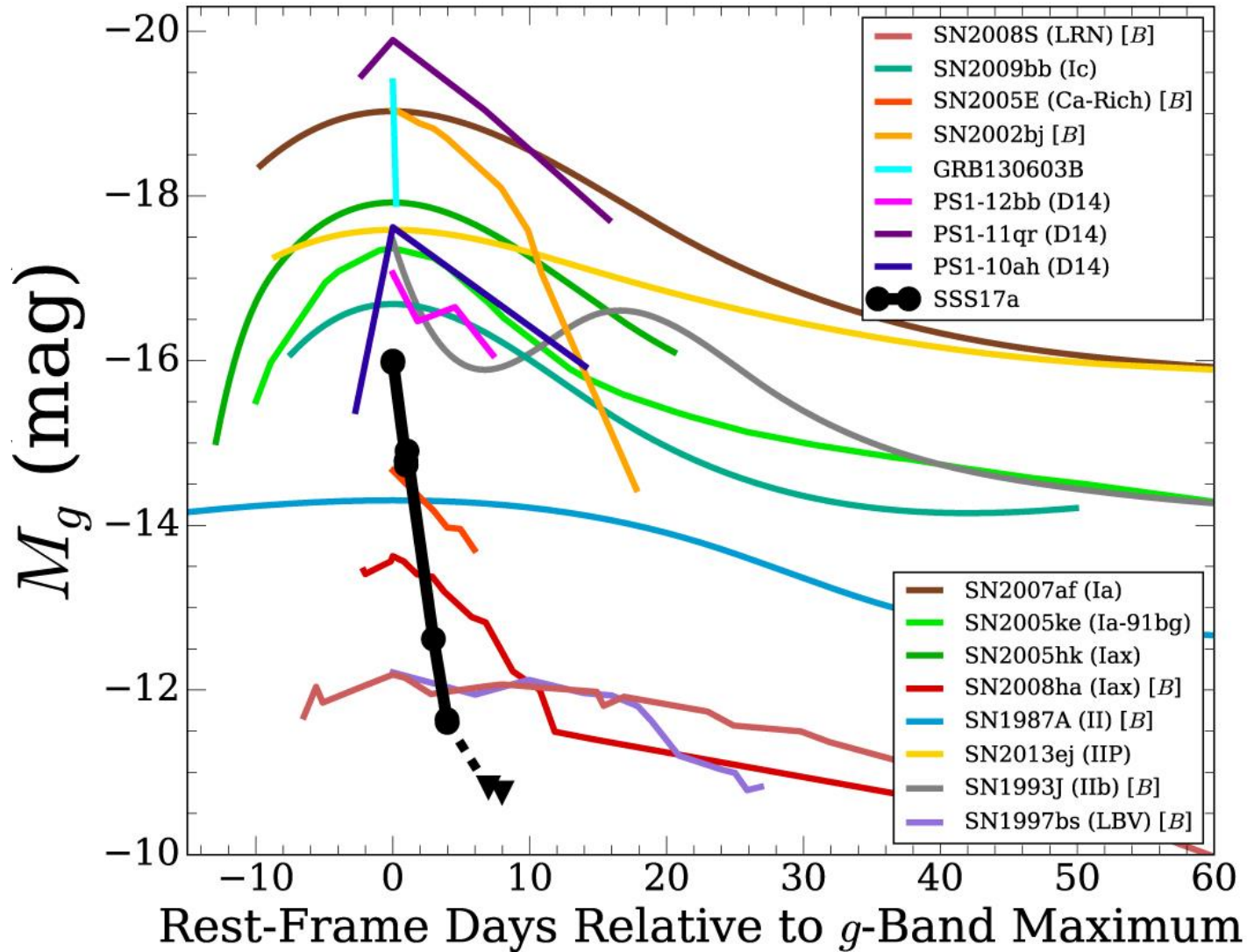
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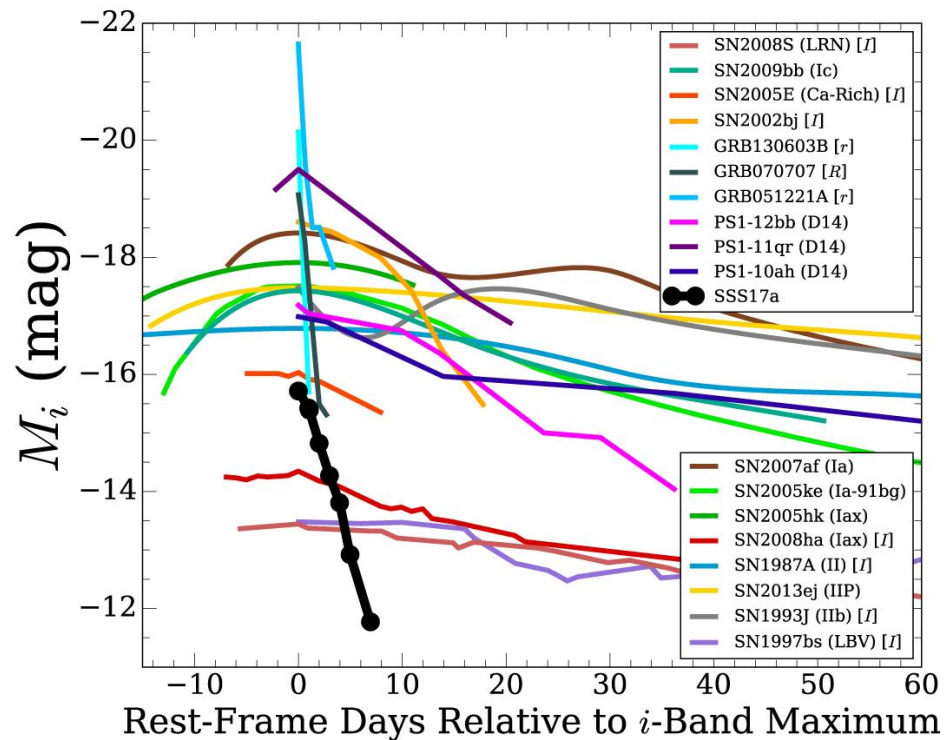
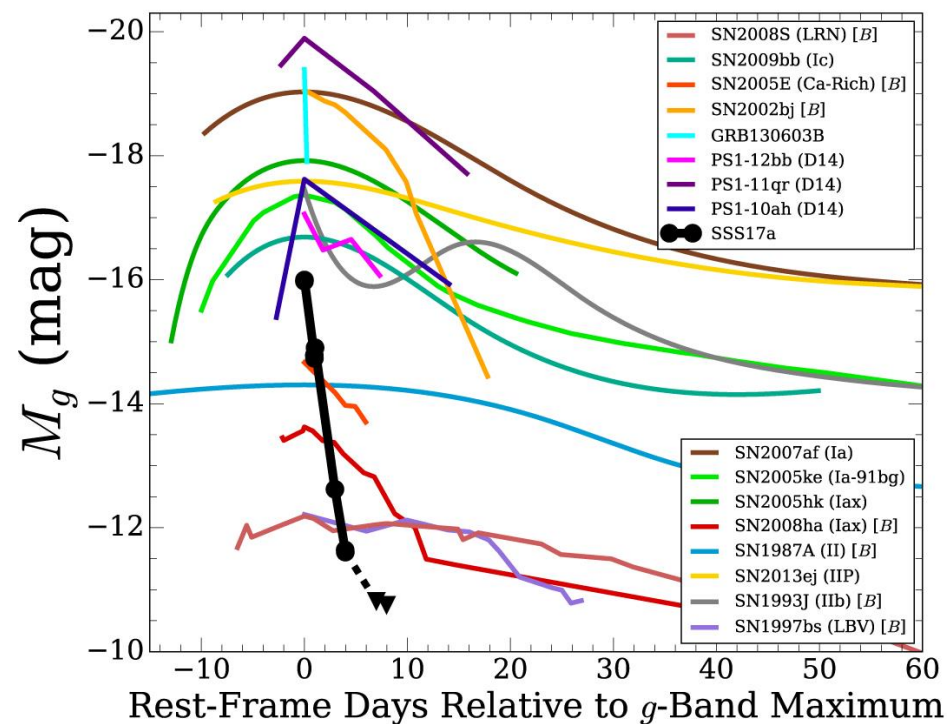
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Light Curve



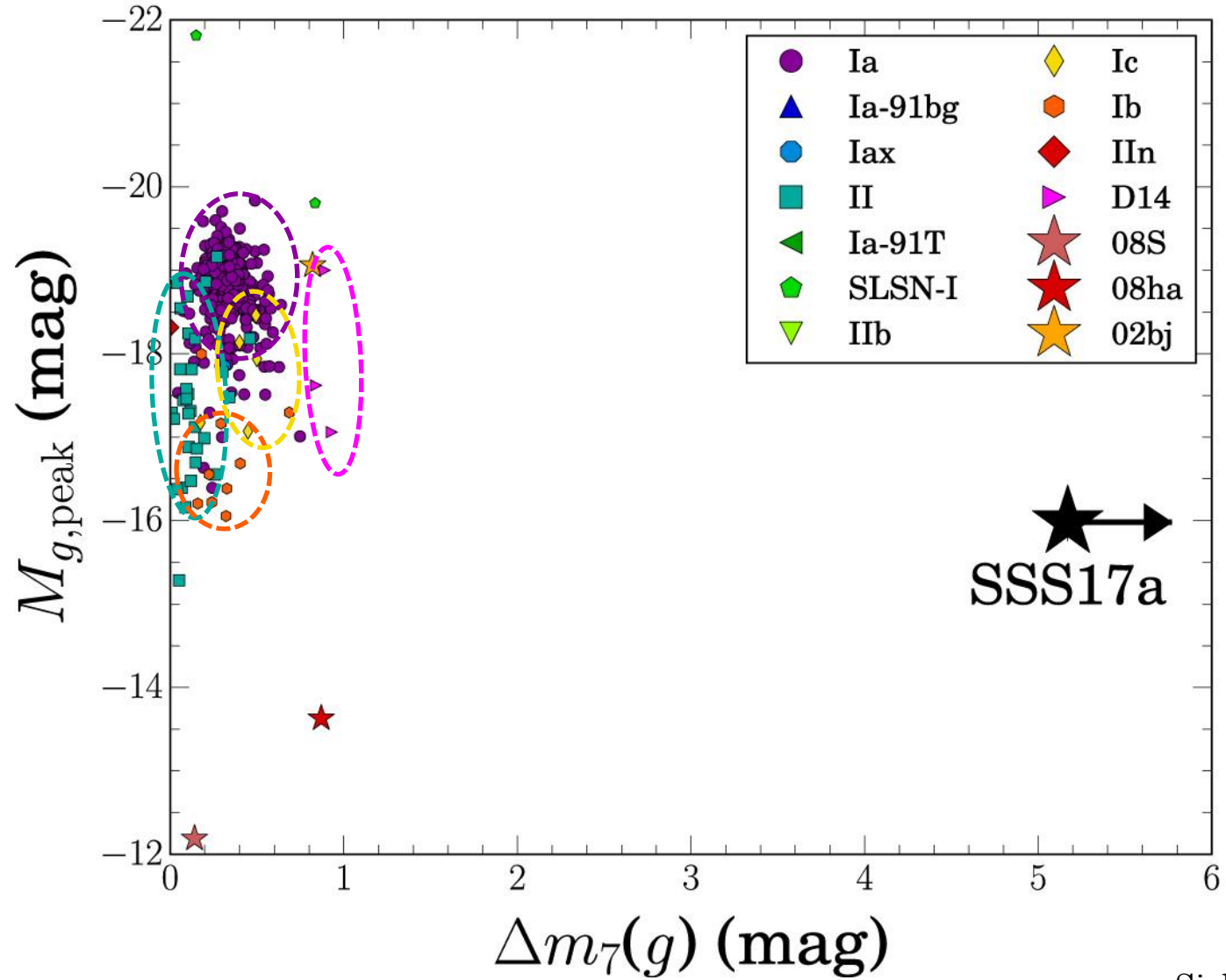


Light Curve

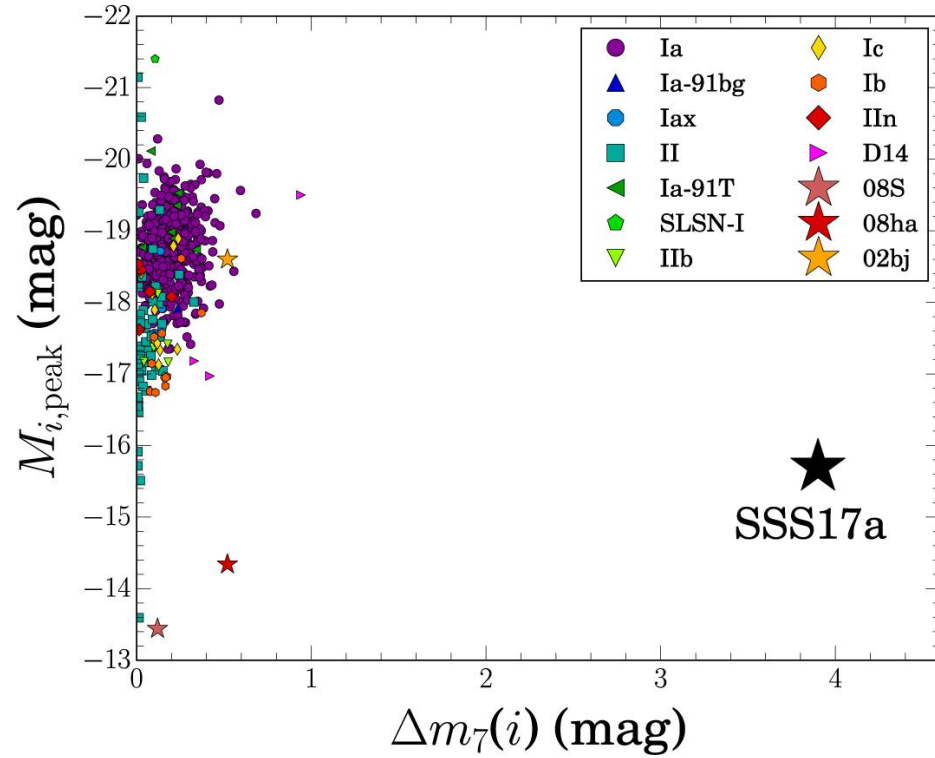
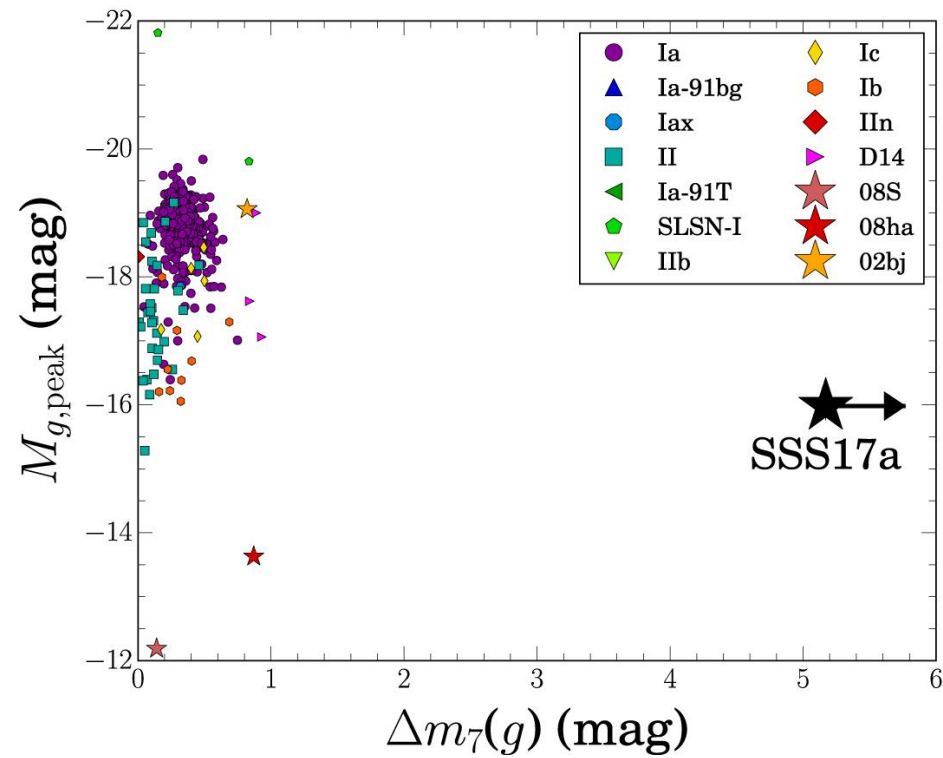


Siebert et al. 2017

Decline Rate

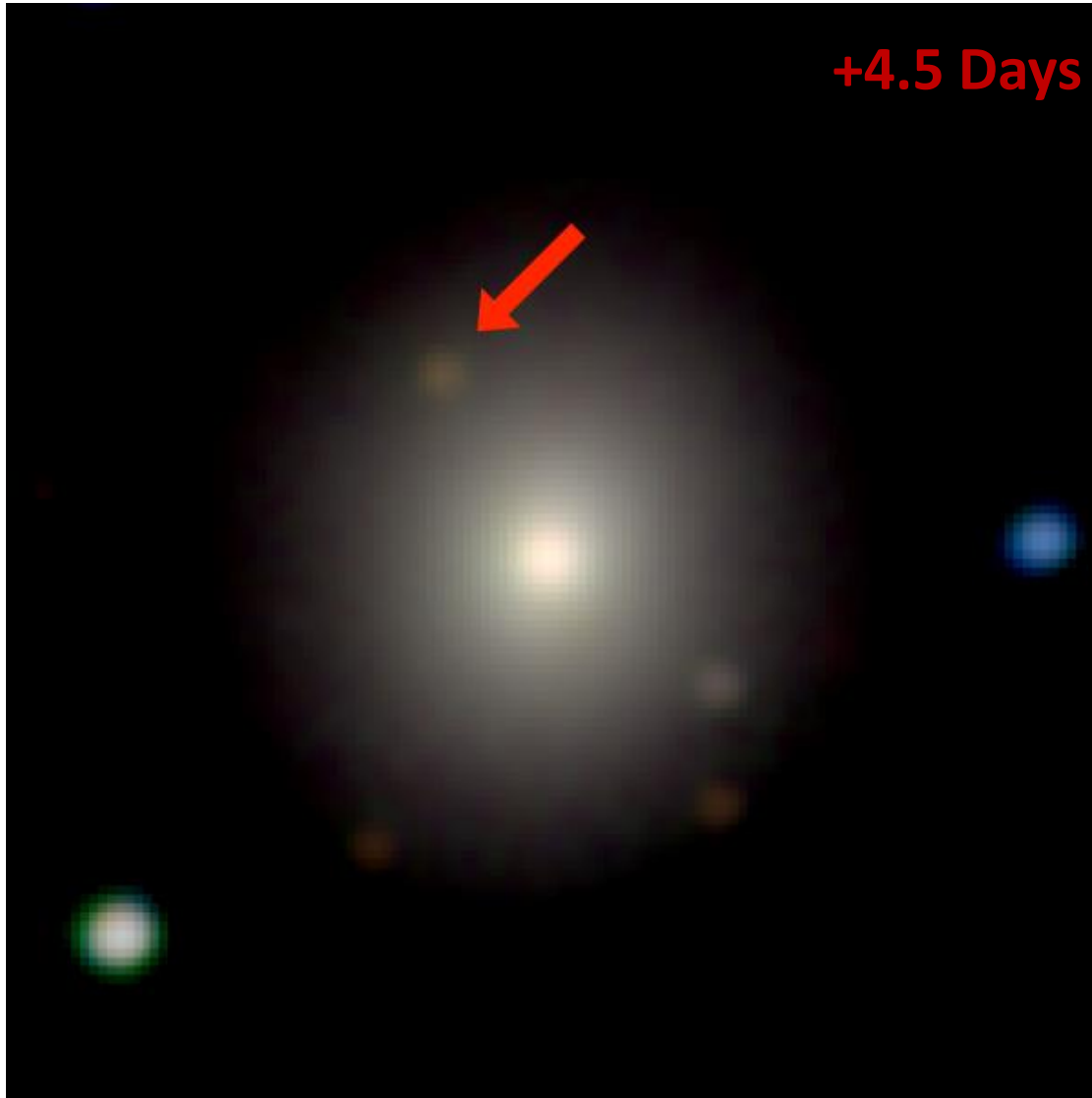


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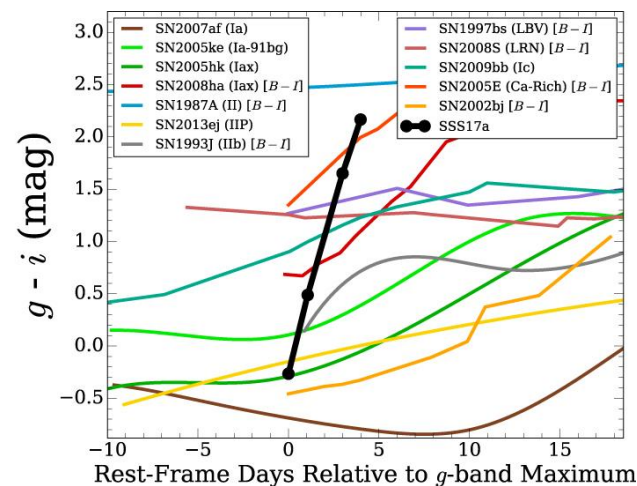
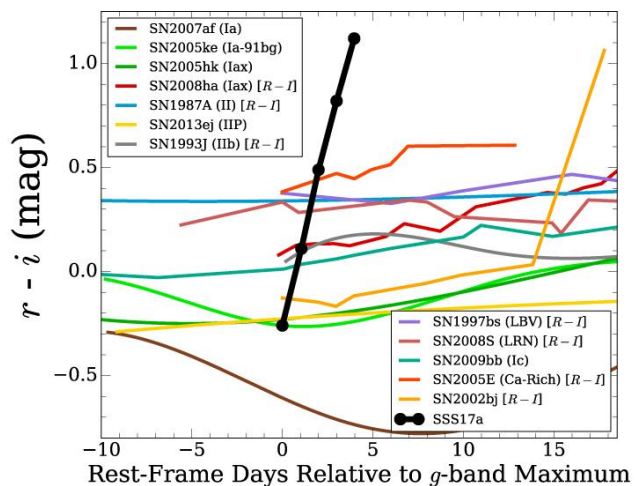
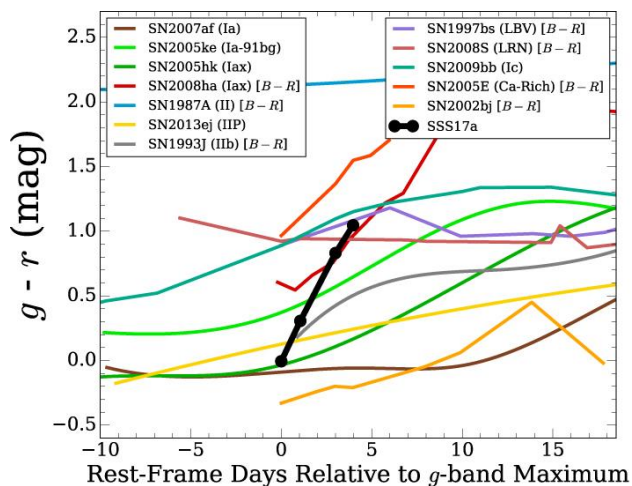
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Color Evolution





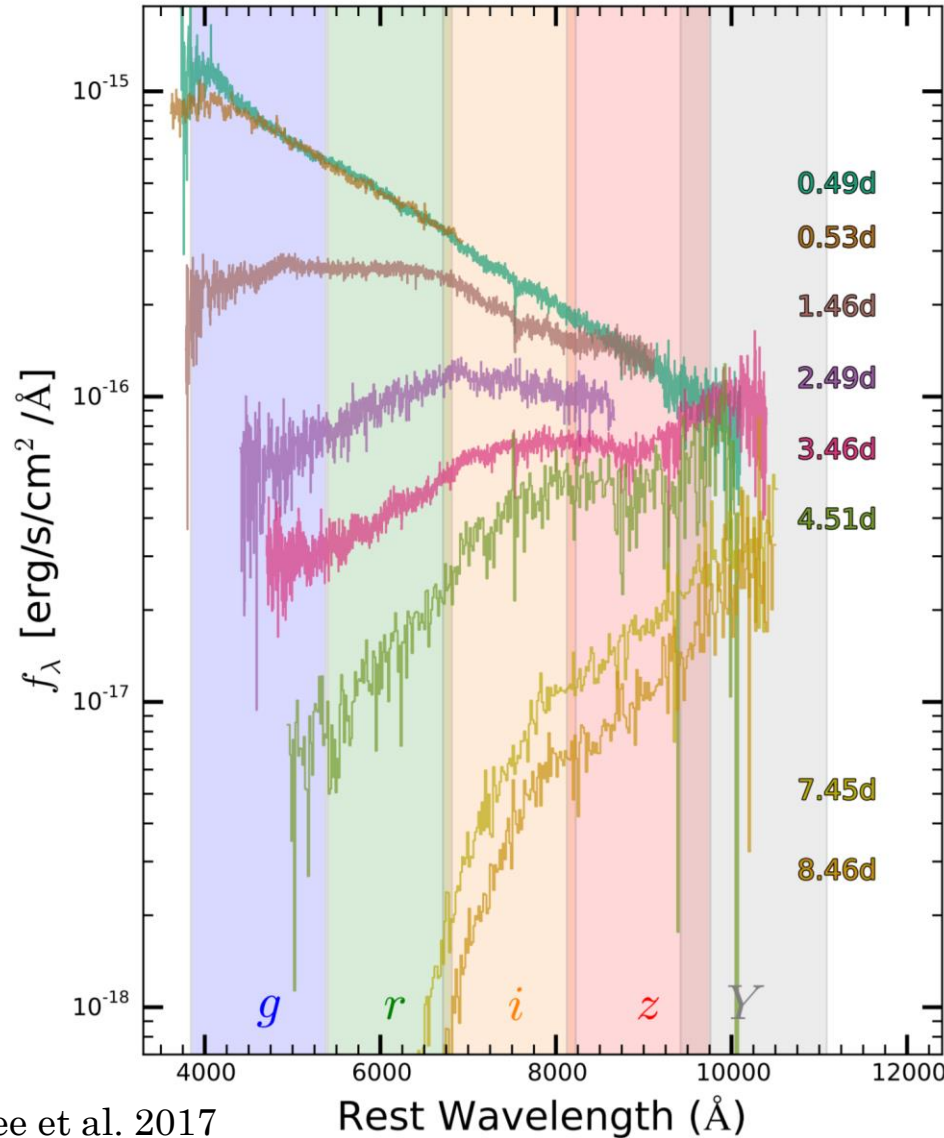
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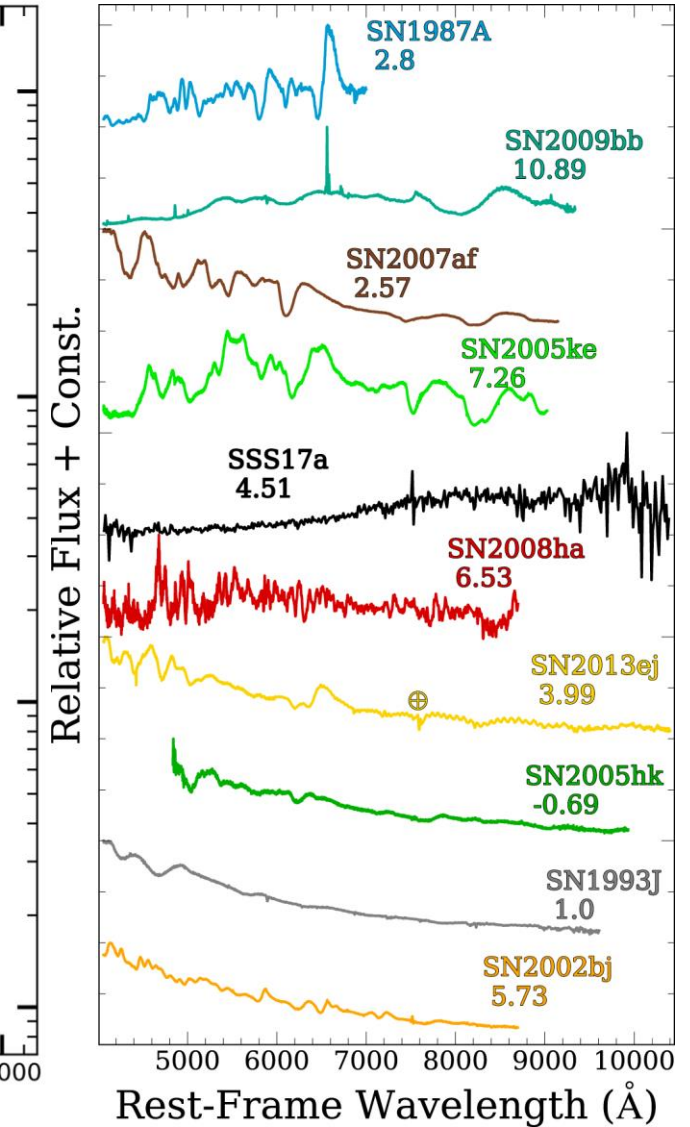
Siebert et al. 2017

Spectroscopic Evolution

Siebert et al. 2017



Shappee et al. 2017





Fraction of SSS17a-like Transients

How constraining are past SN surveys?

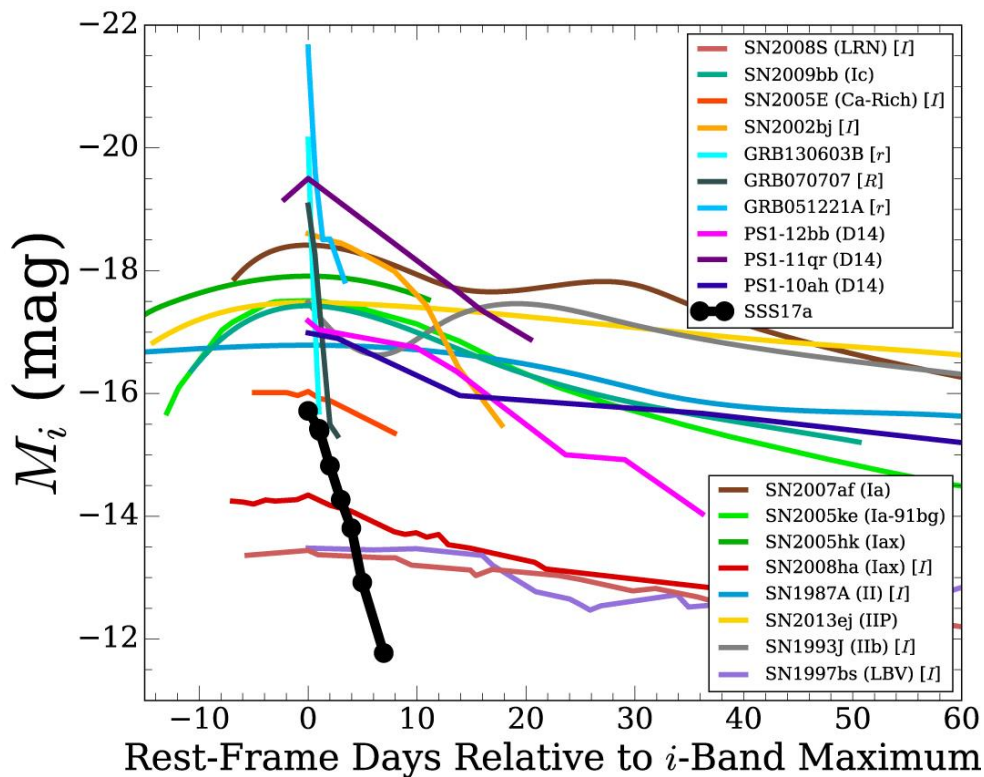
Need 2 detections

~15 Mpc

58 SNe since 2008

Difficulty of observing

$$f_{\text{SSS17a}} \leq 0.16 * \text{total SN rate} \\ \text{(90\% confidence)}$$



Siebert et al. 2017



Chance of Coincidence

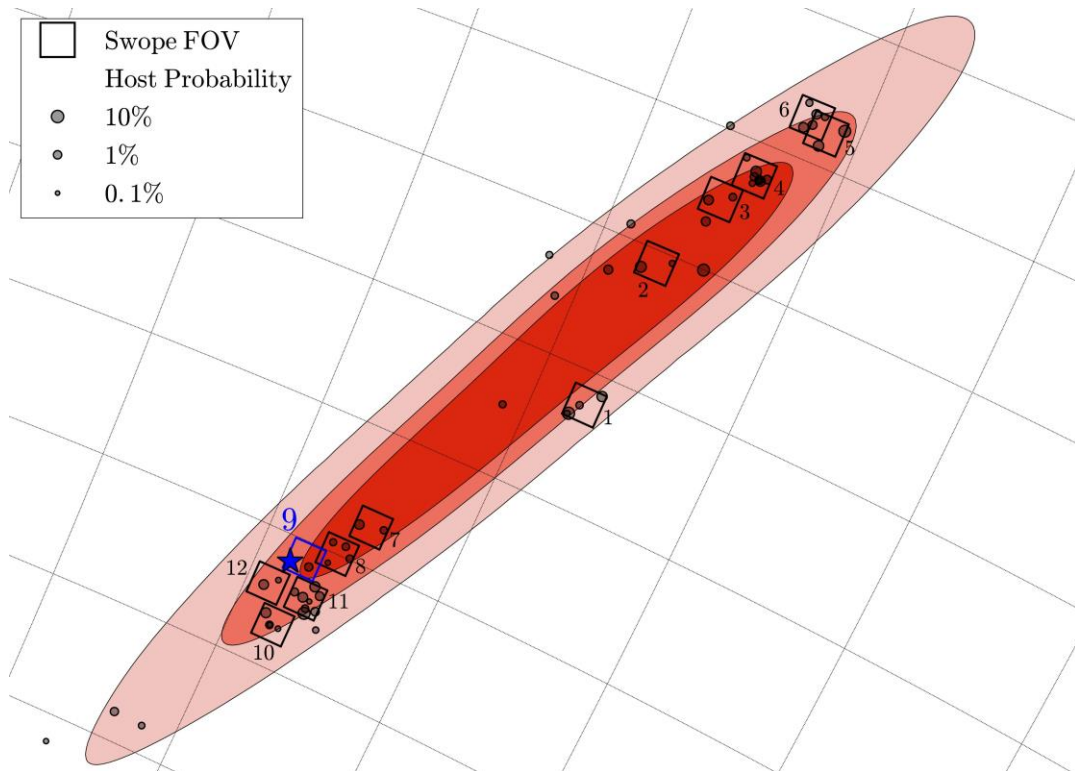
Coulter et al. 2017

40 ± 7 Mpc in 31 deg^2

RLVC $\sim 0.01 \text{ SNe yr}^{-1}$

$t_{\text{nd}} \sim 2$ days

$$P_{\text{chance}} \leq f_{\text{SSS17a}} \times R_{\text{LVC}} \times t_{\text{nd}} \leq 9 \times 10^{-6} \text{ at } 90\% \text{ confidence}$$





Rate of SSS17a-like transients

LVC

$$1.5^{+3.2}_{-1.2} \times 10^3 \text{ Gpc}^{-3} \text{ yr}^{-1}$$

$$0.018^{+0.038}_{-0.014} \text{ per century in the MW}$$

**Rate of “SSS17a-like”
events**

$$\leq 1.6 \times 10^4 \text{ Gpc}^{-3} \text{ yr}^{-1}$$

$$\leq 0.19 \text{ per century in the MW}$$

r-process in the Milky Way

$$m_{r-p} \approx 0.06 M_{\odot} \text{ per “SSS17a-like event”} \quad \text{Kilpatrick et al. 2017}$$

$$M_{r-p} = 1.1^{+2.3}_{-0.9} \times 10^5 M_{\odot}$$

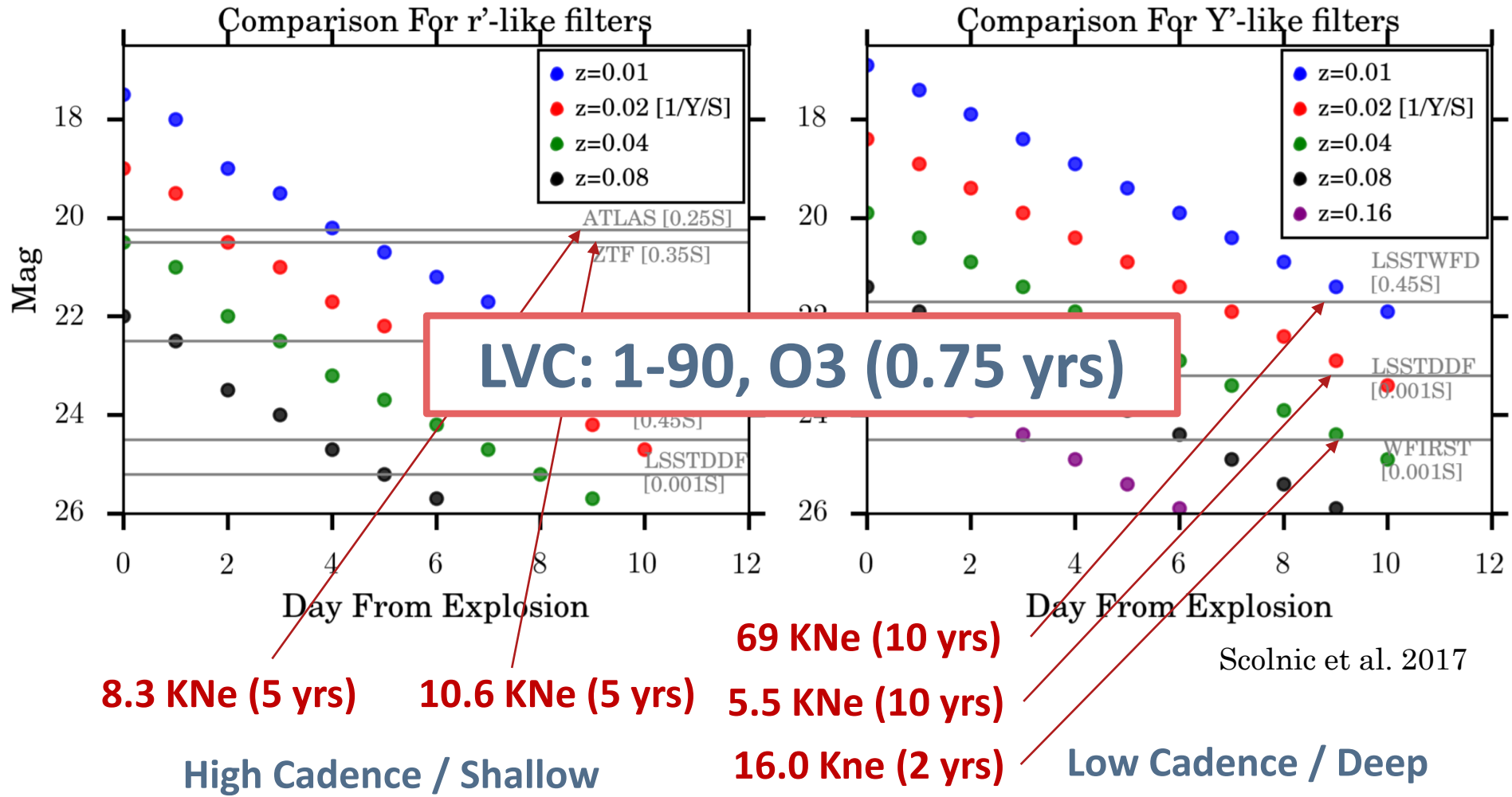
$$M_{r-p} \leq 1.1 \times 10^6 M_{\odot}$$

$$M_{r-p} \approx 10^4 M_{\odot}$$

Kafle et al. 2014

Grevesse et al. 2007

Future Independent Survey Design



Conclusions – The Exotic

- SSS17a has extremely unique optical properties
 - Rapidly fades and reddens
- Rate of events like these must be $< 16\%$ total SN rate
- Probability of chance coincidence is extremely low
- Independent surveys must have high cadence in redder bands