Illuminating the progenitors of Type Ia supernovae with supernova rates

Kyle Barbary

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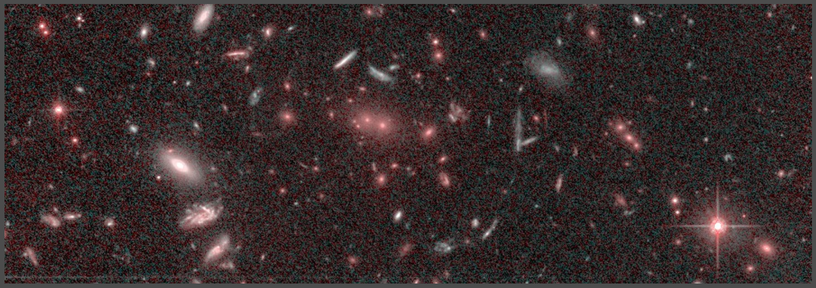
17 January 2012

Outline

- Introduction
- HST Cluster Supernova Survey
  Efficiently finding SNe at the highest redshifts



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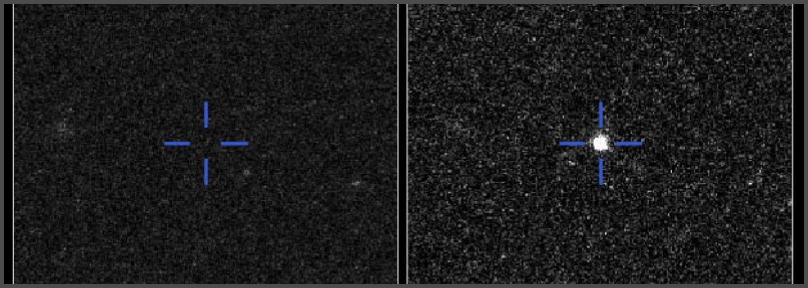
  A surprising discovery in the survey



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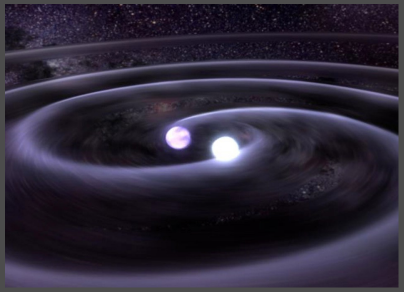
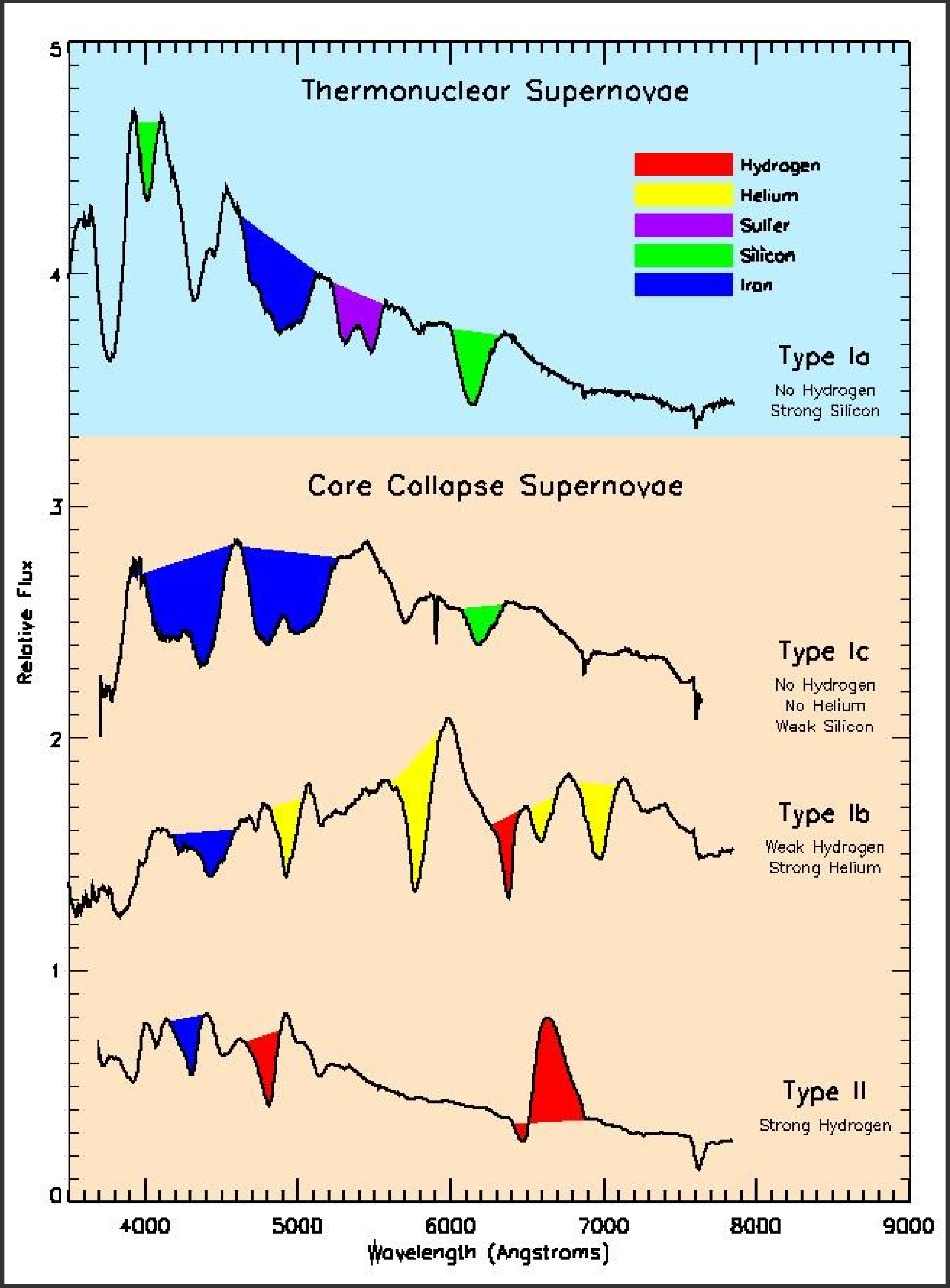
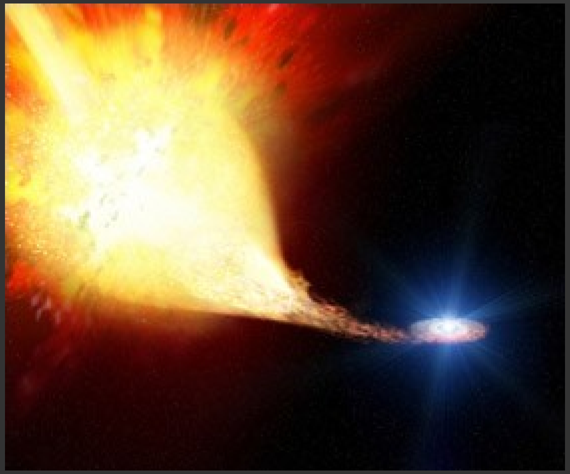
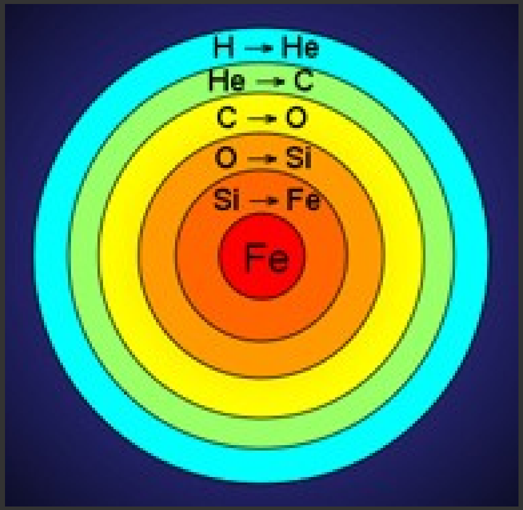


Type Ia supernovae



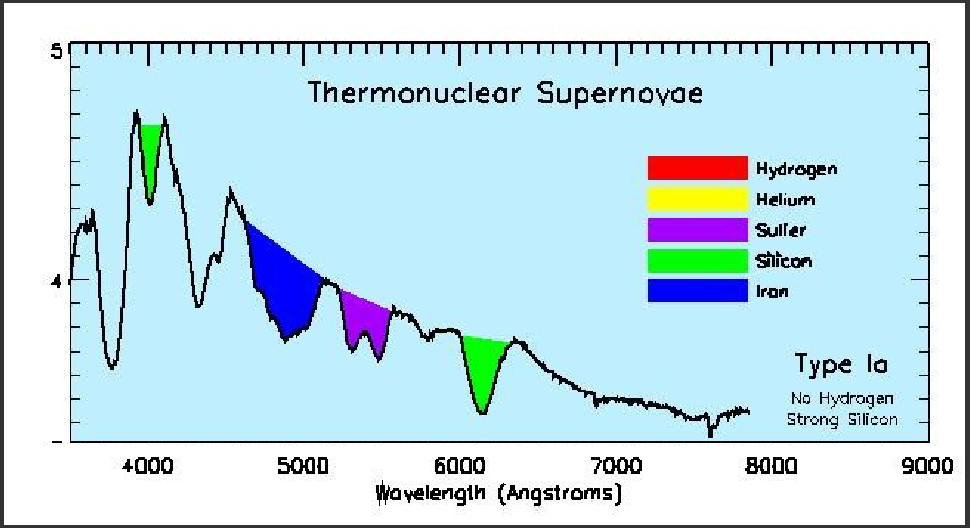


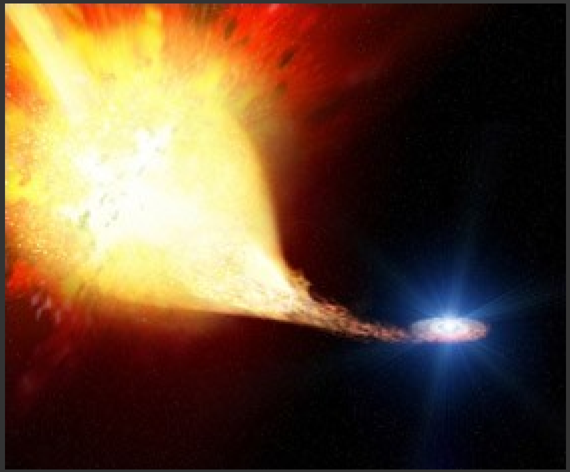
~1.4 $M_{\odot}$ white dwarf



> 8 $M_{\odot}$ star

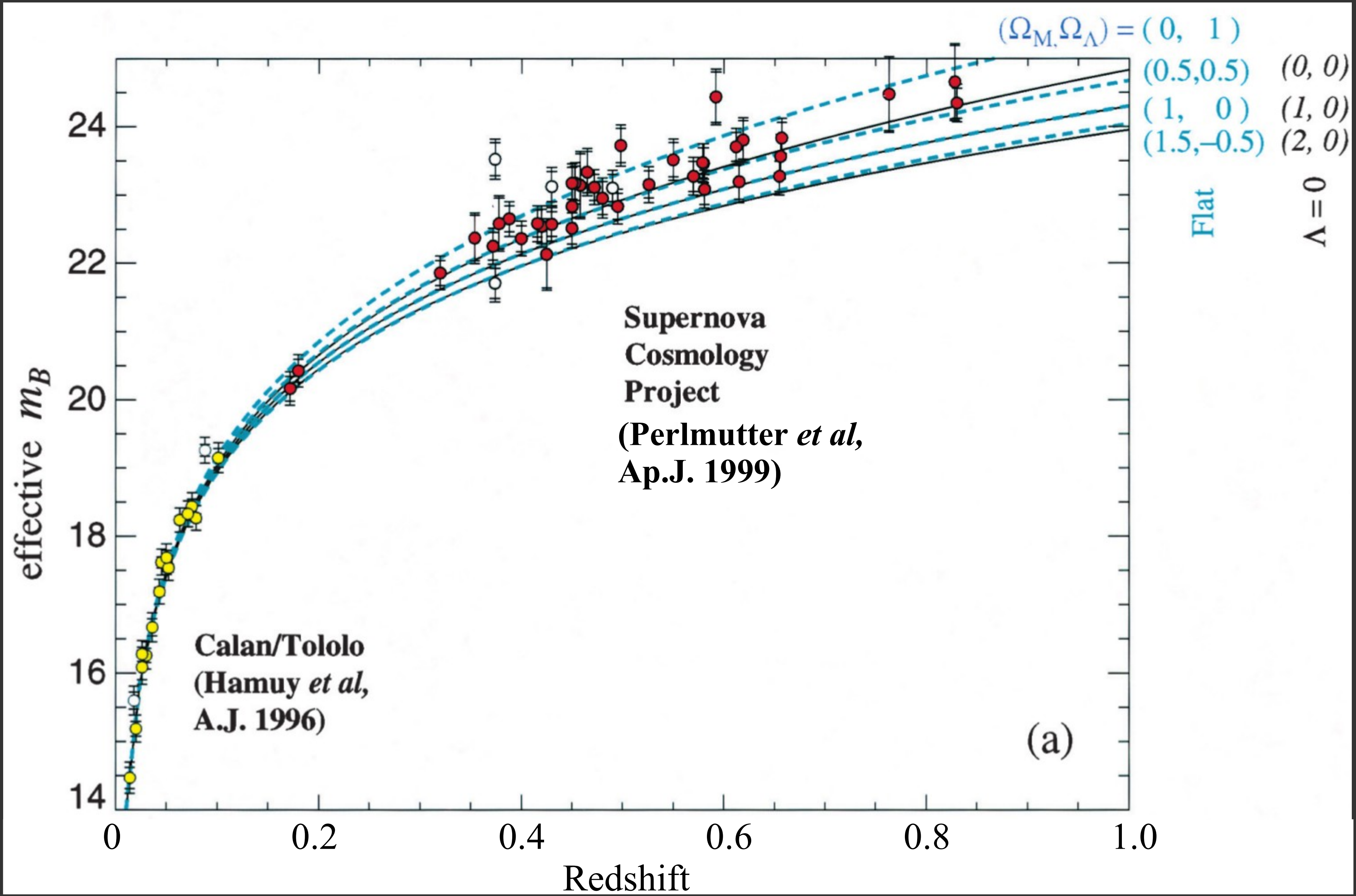
Type Ia supernovae





~1.4 $M_\odot$ white dwarf

Hubble diagram in 1999



2011 Nobel Prize in Physics

Photo: Ariel Zambelich, Copyright © Nobel Media AB

Saul Perlmutter

Photo: Belinda Pratten, Australian National University

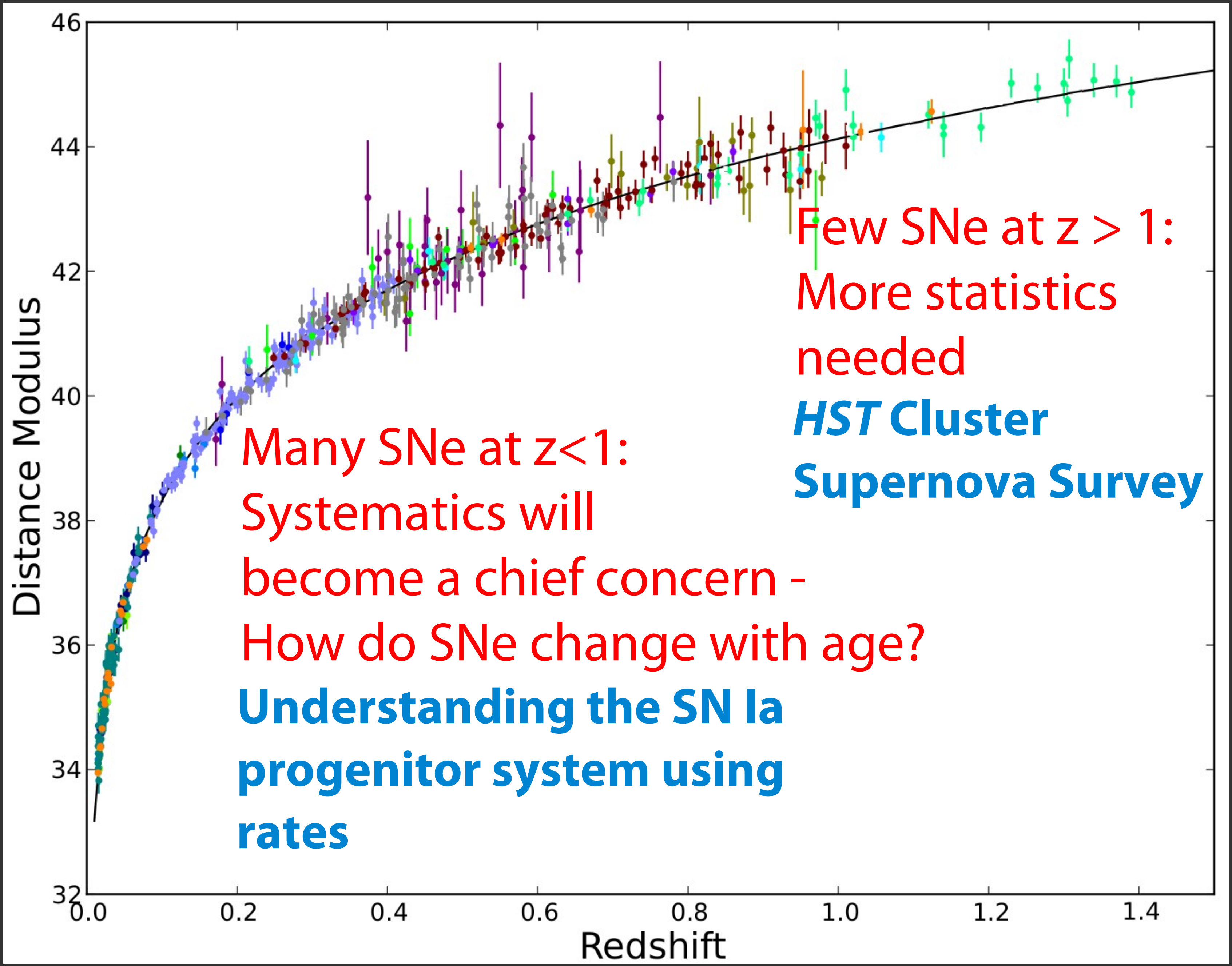
Brian P. Schmidt

Photo: Homewood Photography

Adam G. Riess

"For the discovery of the accelerating expansion of the Universe through observations of distant supernovae"

Hubble diagram today



Many SNe at z<1: Systematics will become a chief concern - How do SNe change with age?

Understanding the SN Ia progenitor system using rates

Few SNe at z > 1: More statistics needed

***HST* Cluster Supernova Survey**

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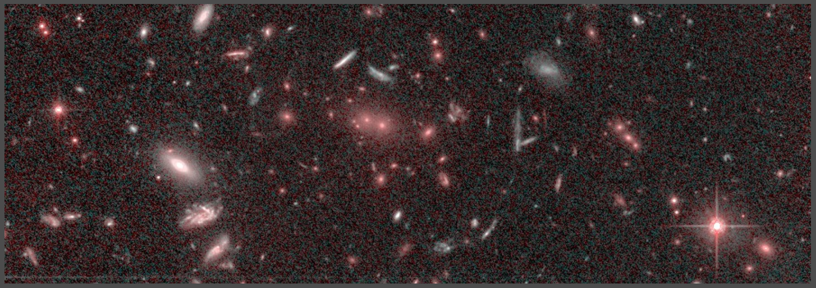

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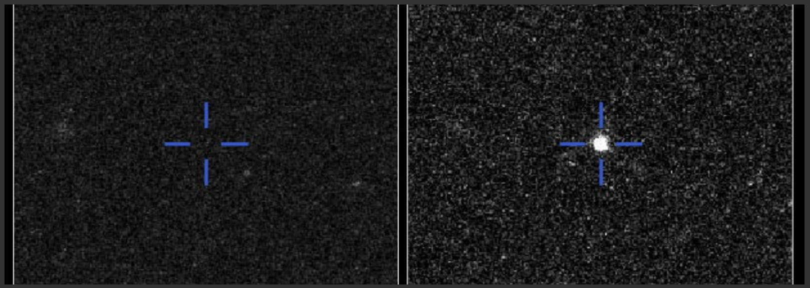

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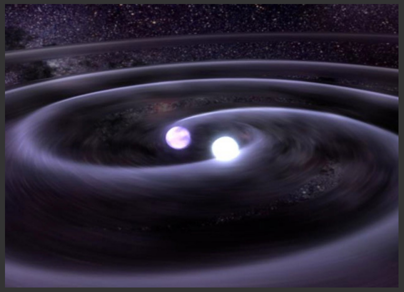
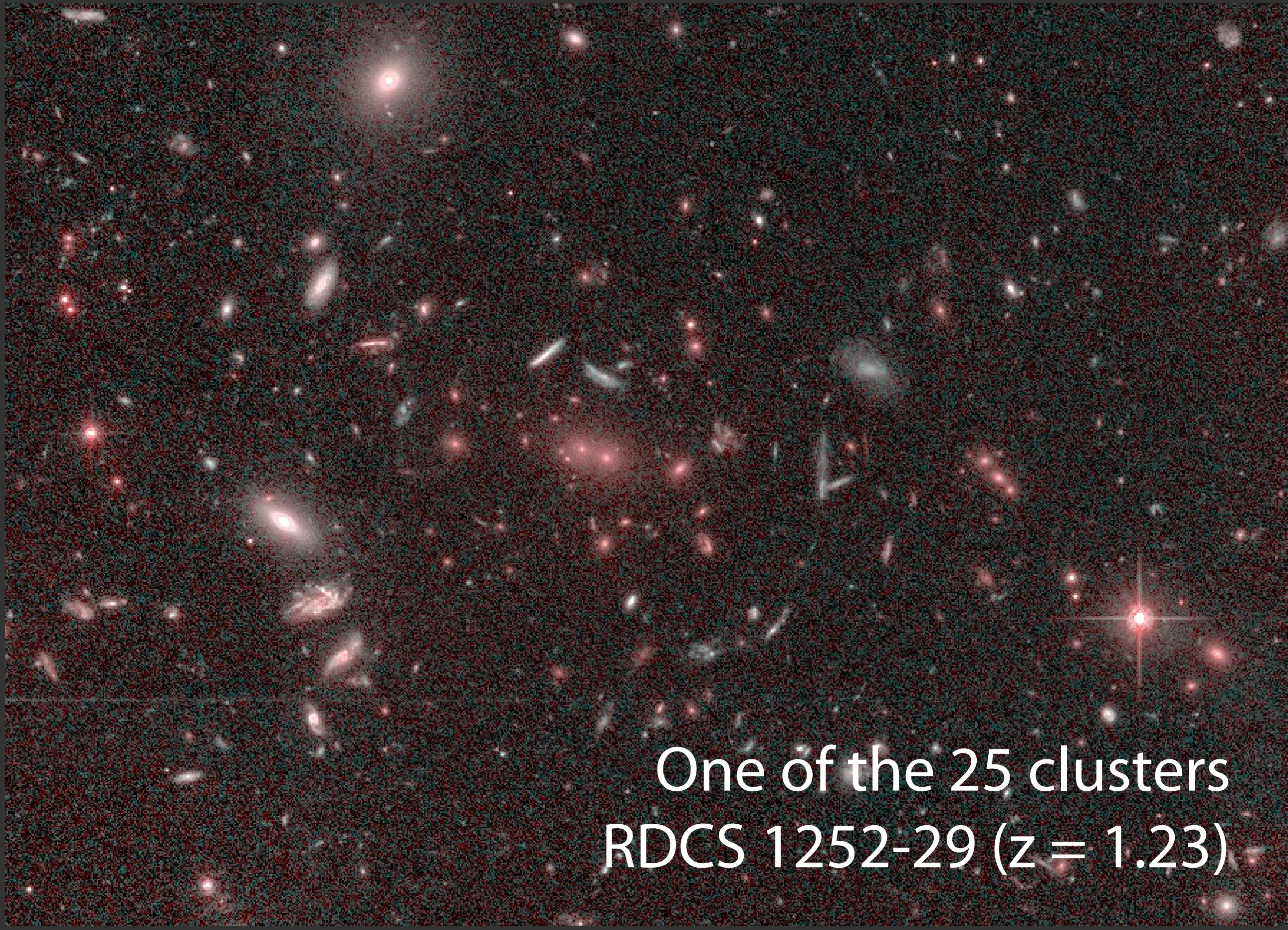


The *HST* Cluster Supernova Survey

Supernova search using the *Hubble Space Telescope* targeting 25 massive clusters at $0.9 < z < 1.5$

Why target clusters?

- Efficient SN discovery with small field of view
- Early-type galaxies: minimal dust



People

Supernova Cosmology Project

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Kyle Barbary
Joshua Meyers
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Nao Suzuki
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Pascal Ripoche
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Mamoru Doi U Tokyo
Tomoki Morokuma U Tokyo
Naoki Yasuda U Tokyo
Marek Kowalski Humboldt U
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Cluster Groups

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Mike Gladders U Chicago
Ben Koester U Chicago
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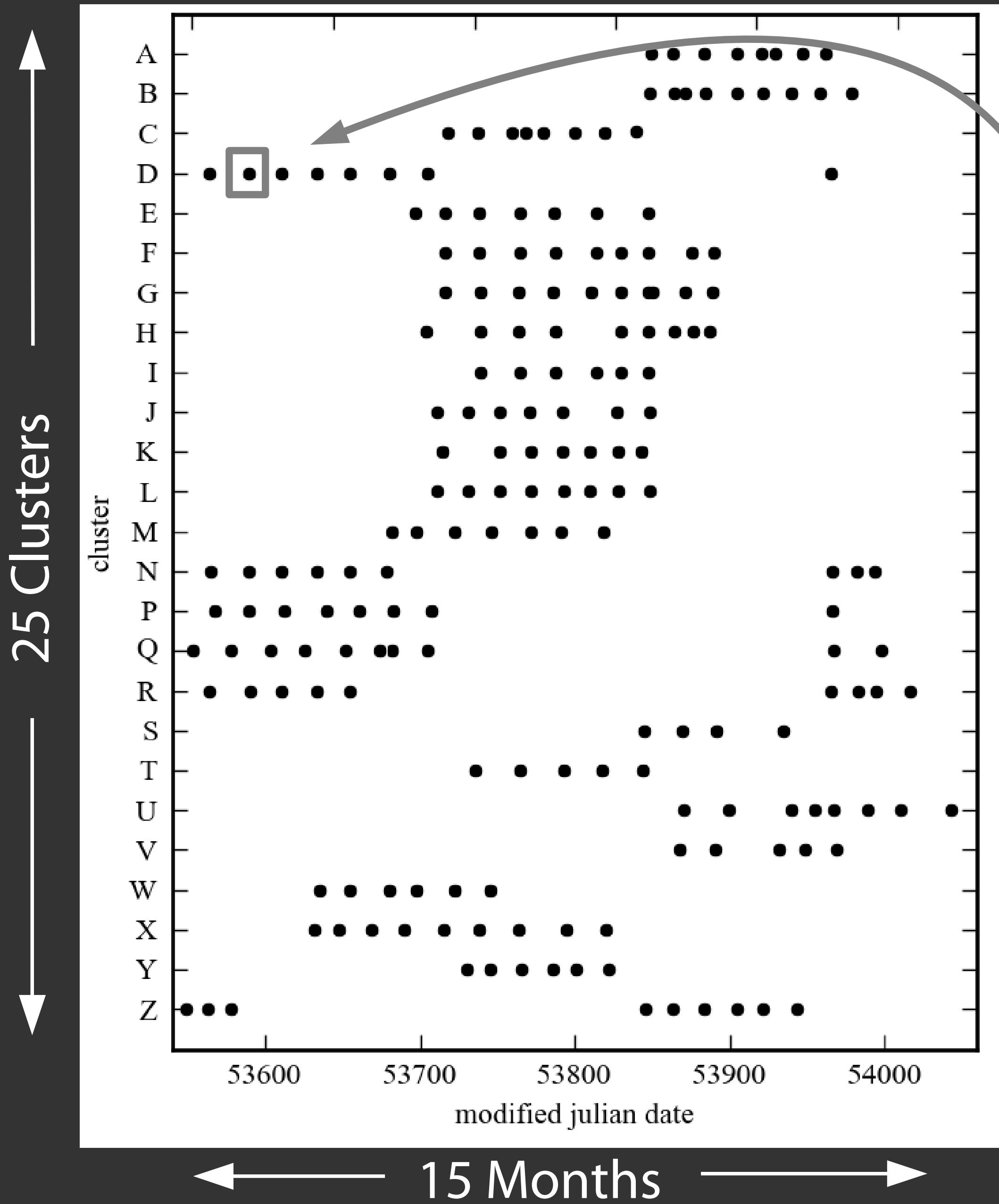
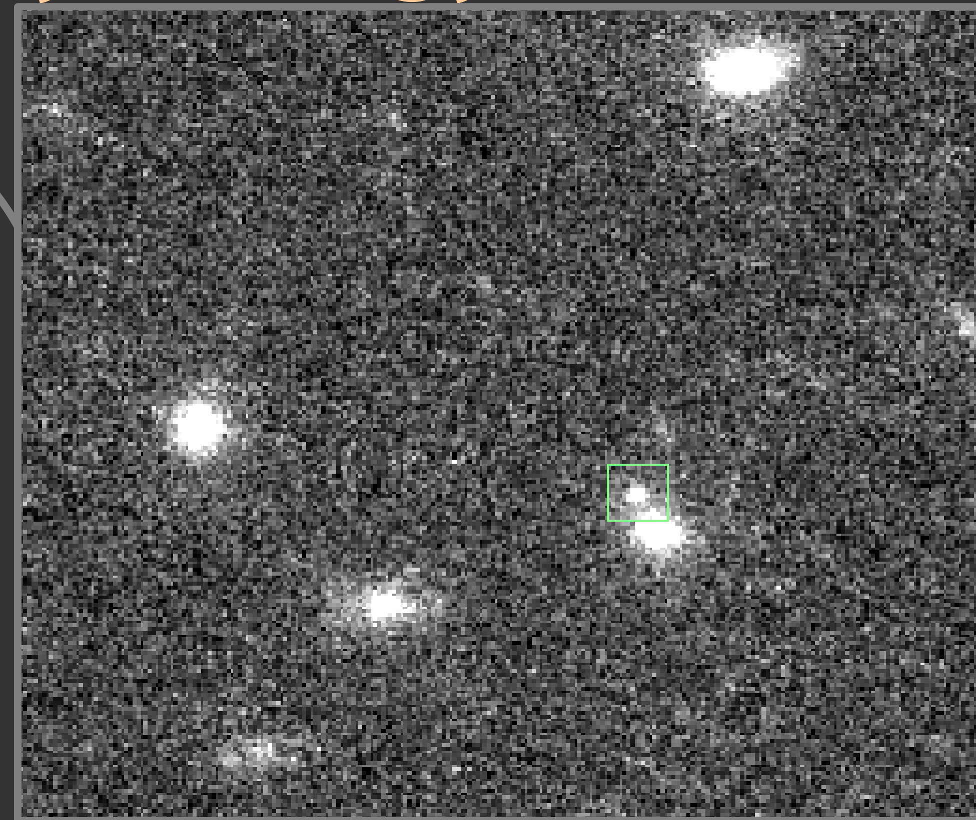
Lori Lubin UC Davis
Adam Stanford UC Davis
Mark Postman STScI
Piero Rosati ESO
Howard Yee U Toronto

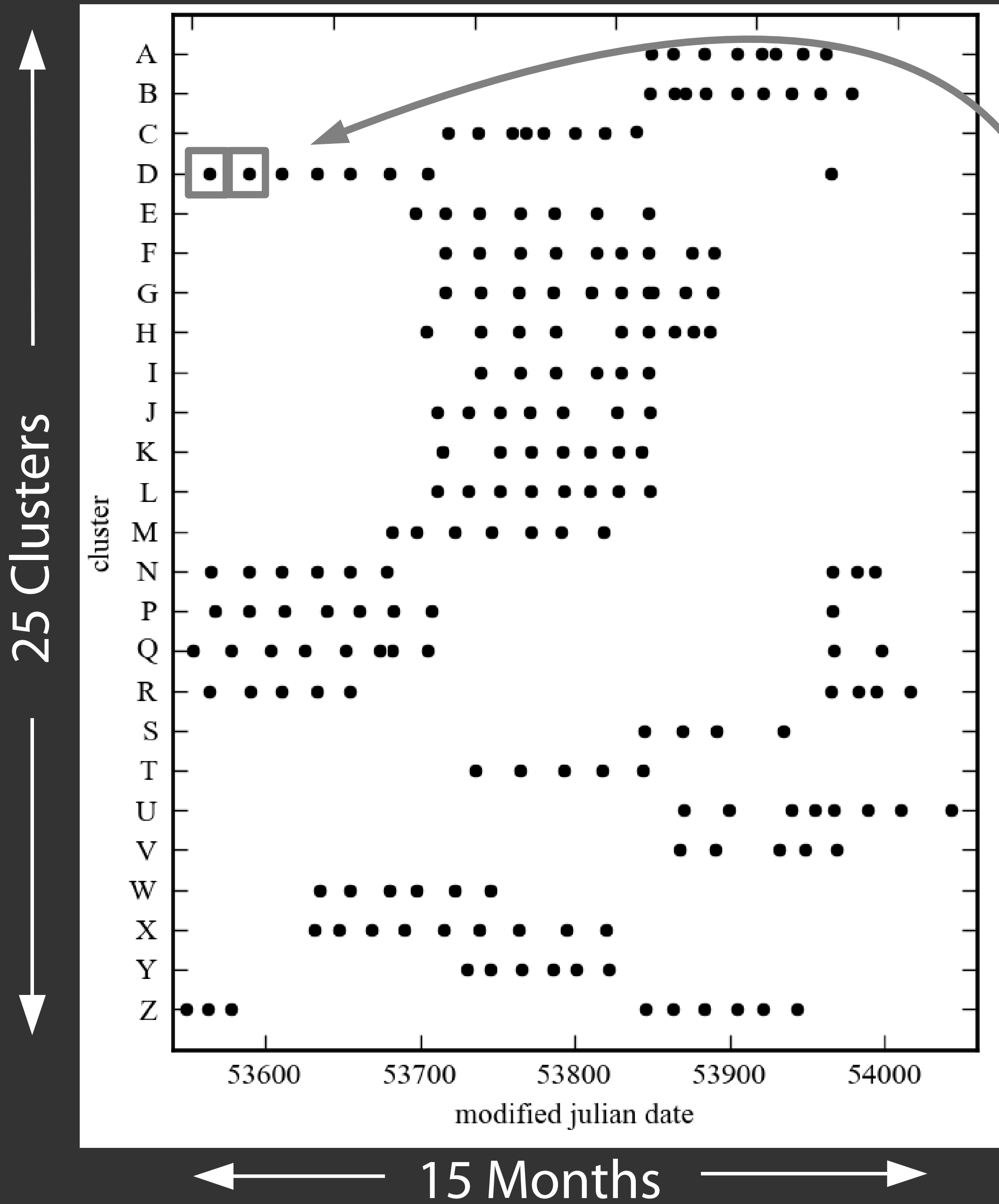
Rolling survey strategy

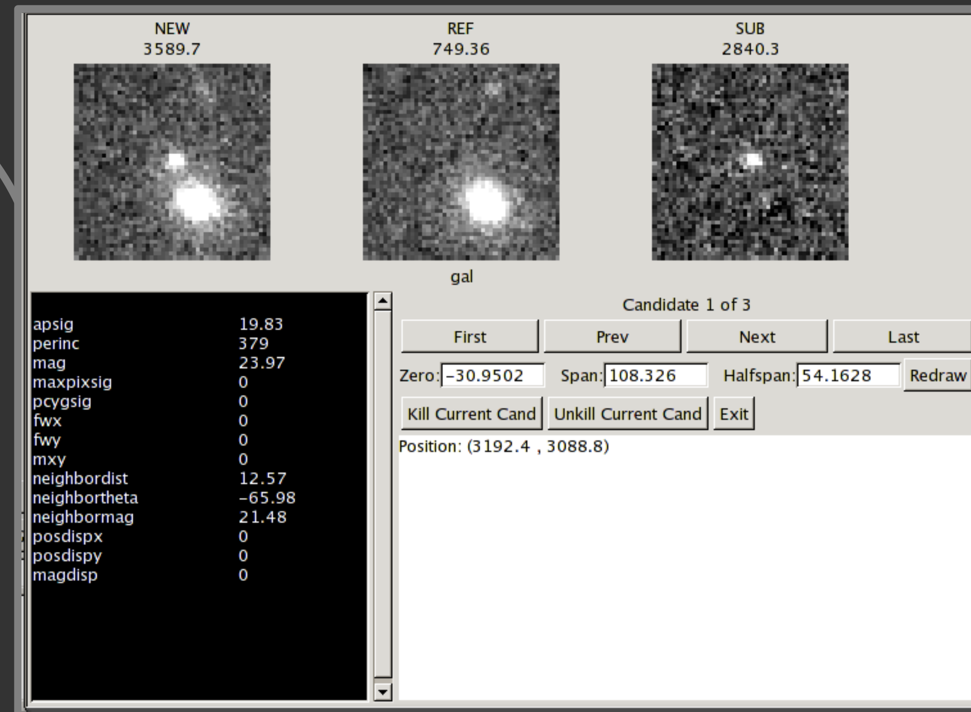




- i and z bands
- Near IR follow-up with NICMOS camera
- Keck, Subaru, VLT used to obtain spectra

Rolling survey strategy





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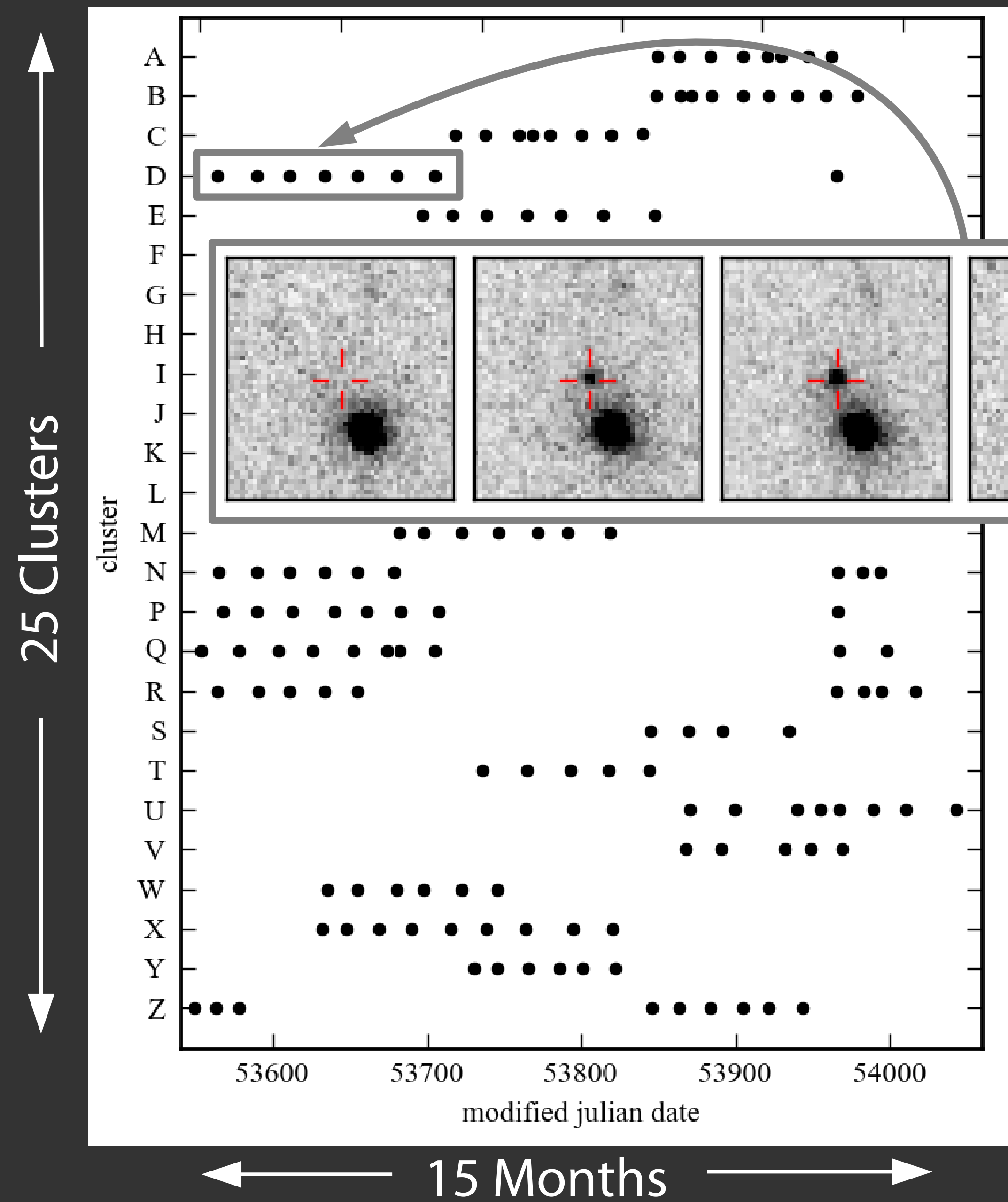

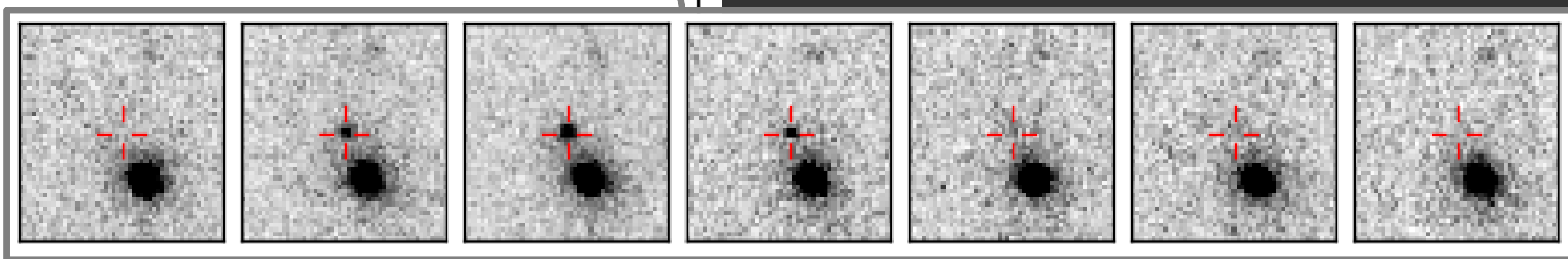

SN SCP05D0 (z = 1.01)

- i and z bands
- Near IR follow-up with NICMOS camera
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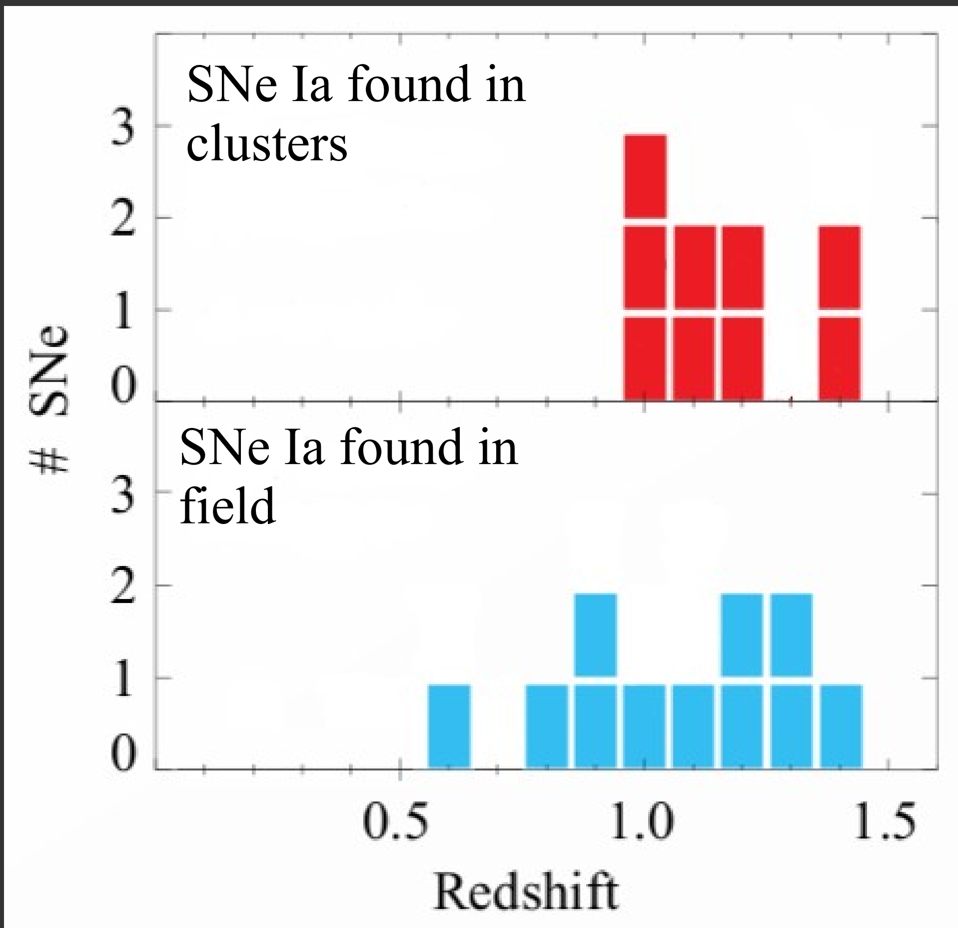
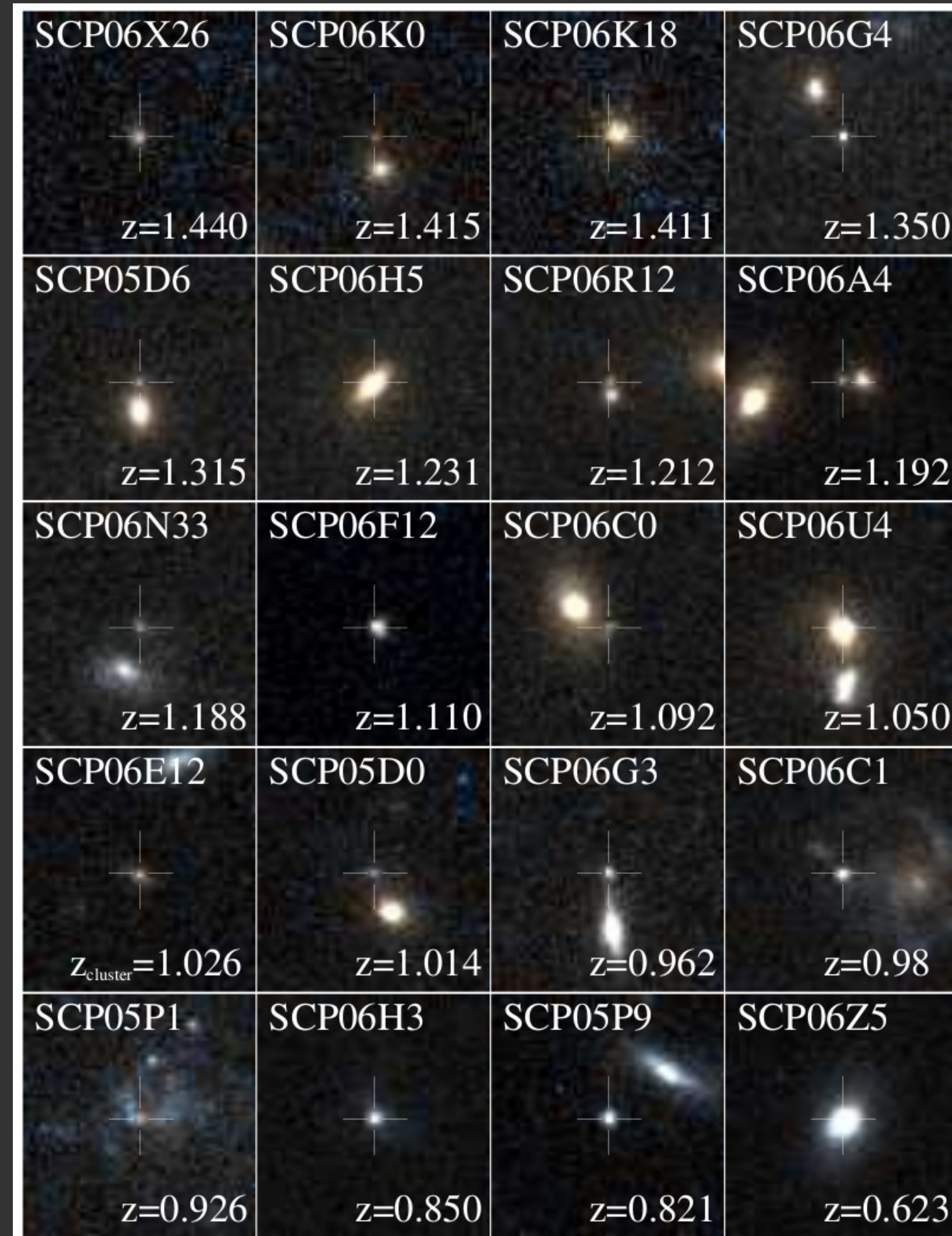
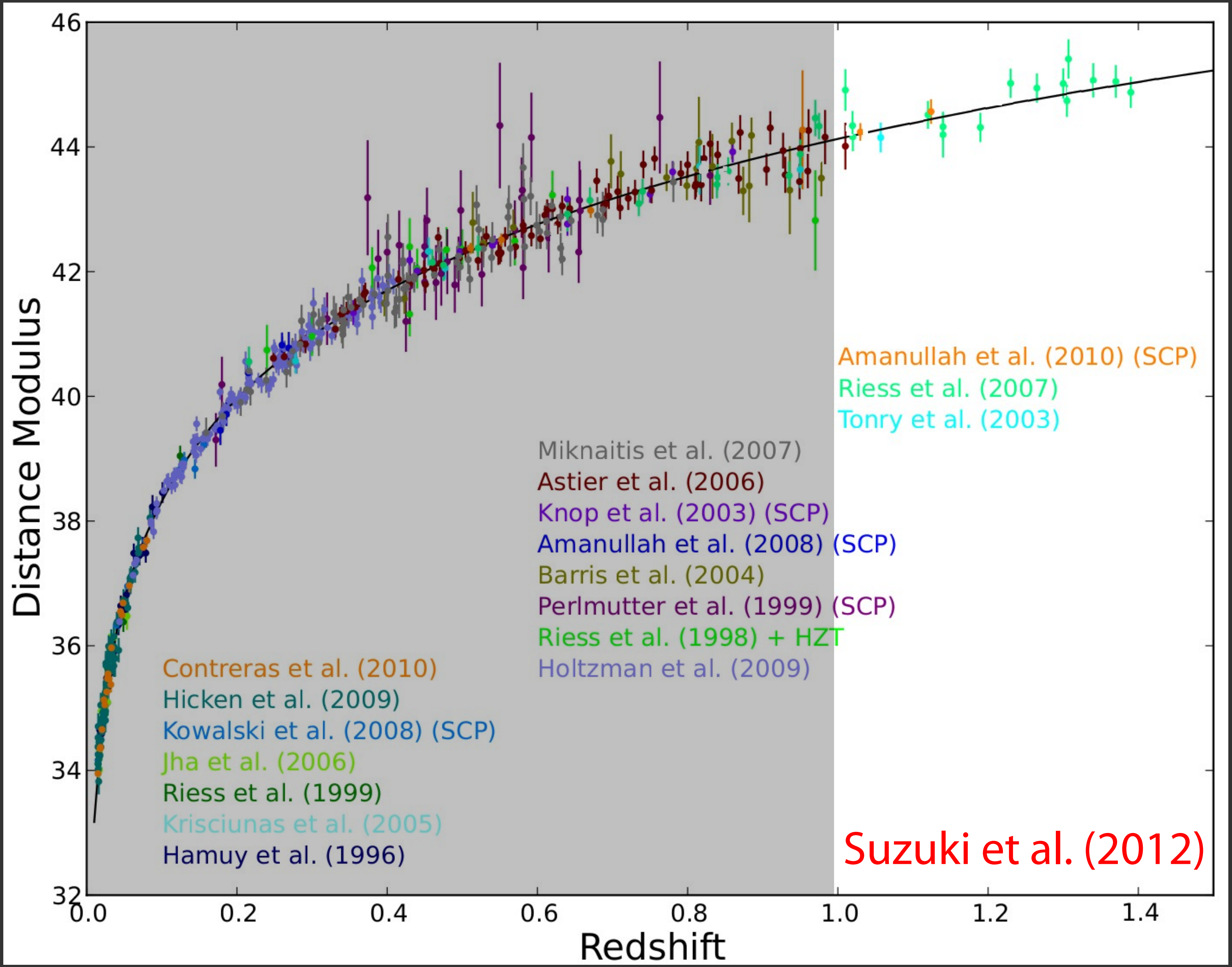
20 new SN Ia discoveries





New Hubble diagram



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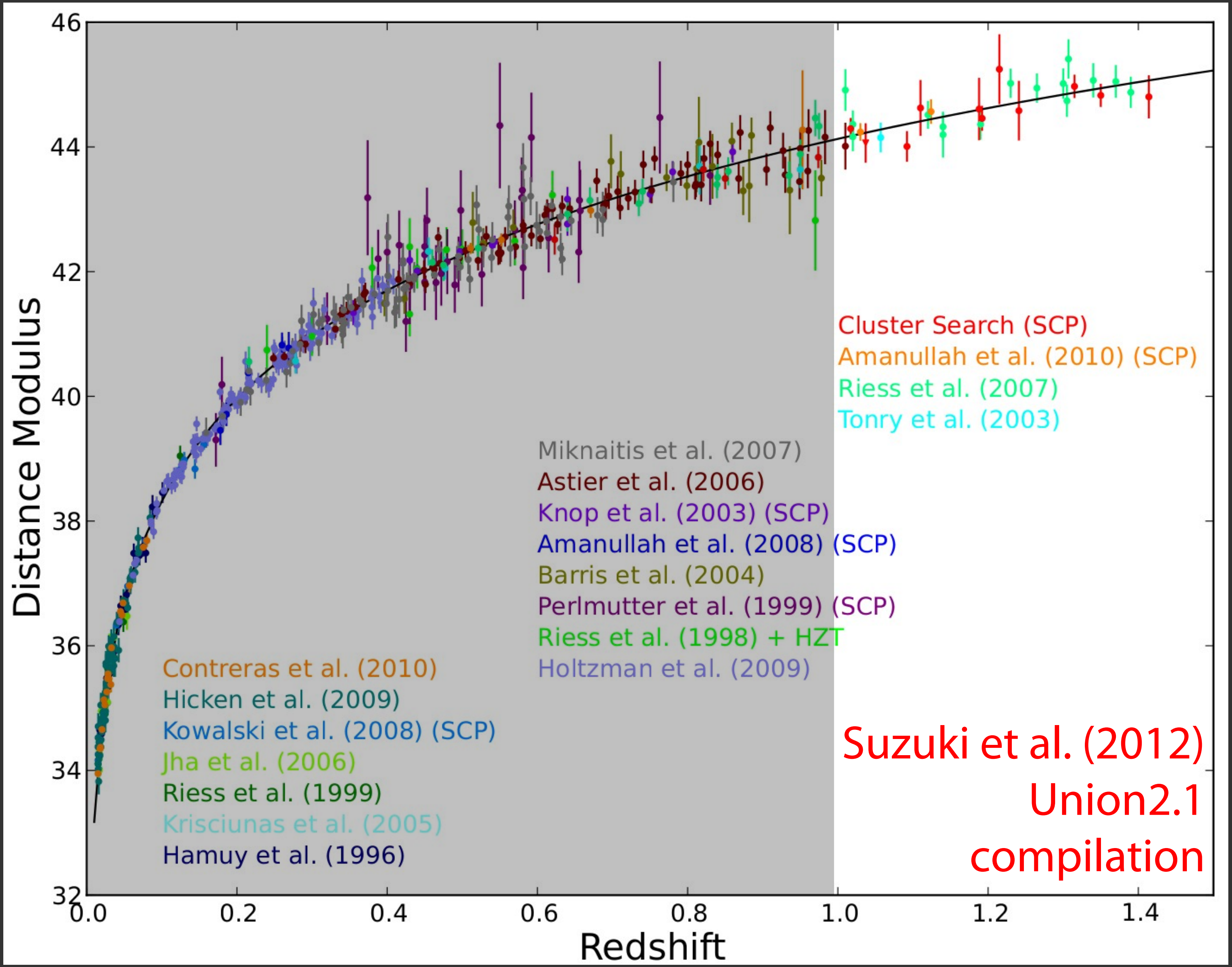

Publications

Rest-Frame R-band Light Curve of a z ~ 1.3 Supernova Obtained with Keck Laser Adaptive Optics
Melbourne et al. 2007, AJ, 133, 2709
SN

The XMM Cluster Survey: The Dynamical State of XMMXCS J2215.9-1738 at z = 1.457
Hilton et al. 2007, ApJ, 670, 1000
CLUSTER

Clusters of Galaxies in the First Half of the Universe from the IRAC Shallow Survey
Eisenhardt et al. 2008 ApJ, 684, 905
CLUSTER

Discovery of an Unusual Optical Transient with the Hubble Space Telescope
Barbary et al. 2009, ApJ, 690, 1358
SN

The XMM Cluster Survey: Galaxy Morphologies and the Color-Magnitude Relation in XMMXCS J2215.9-1738 at z = 1.46
Hilton et al. 2009, ApJ, 697, 436
CLUSTER

Multiwavelength observations of a rich galaxy cluster at z = 1: The HST/ACS colour-magnitude diagram
Santos et al. 2009, A&A, 501, 49
CLUSTER

Multi-wavelength study of XMMU J2235.3-2557: the most massive galaxy cluster at z > 1
Rosati et al. 2009, A&A, 508, 583
CLUSTER

HST Weak-Lensing Study of the Galaxy Cluster XMMU J2235.3-2557 at z = 1.4: A Surprisingly Massive Galaxy Cluster when the Universe is One-Third of its Current Age
Jee et al. 2009 ApJ, 704, 672
CLUSTER

HST Discovery of a z=3.9 Multiply Imaged Galaxy Behind the Complex Cluster Lens WARPS J1415+36 at z=1.026
Huang et al. 2009, ApJL, 707, 12
CLUSTER

An Intensive HST Survey for z > 1 Supernovae by Targeting Galaxy Clusters
Dawson et al. 2009, AJ, 138, 1271
SN

Subaru FOCAS Spectroscopic Observations for High-Redshift Supernovae
Morokuma et al. 2010, PASJ, 62, 19
SN

The HST Cluster Supernova Survey: II. The SN Ia Rate in High-Redshift Galaxy Clusters
Barbary et al., 2012, ApJ, 745, 31
SN

The HST Cluster Supernova Survey: III. Correlated Properties of Type Ia Supernovae and Their Hosts
Meyers et al., 2012, ApJ, in press
SN

The HST Cluster Supernova Survey: IV. NICMOS Calibration for Faint Sources Using Red Cluster Galaxies
Ripoche et al., Submitted to ApJ
SN

The HST Cluster Supernova Survey: V. Improving Dark Energy Constraints Above z=1 and Building an Early-Type-Hosted Supernova Sample
Suzuki et al., 2012, ApJ, in press
SN

The HST Cluster Supernova Survey: VI. High-Redshift Volumetric SN Ia Rates
Barbary et al., 2012, ApJ, 745, 32
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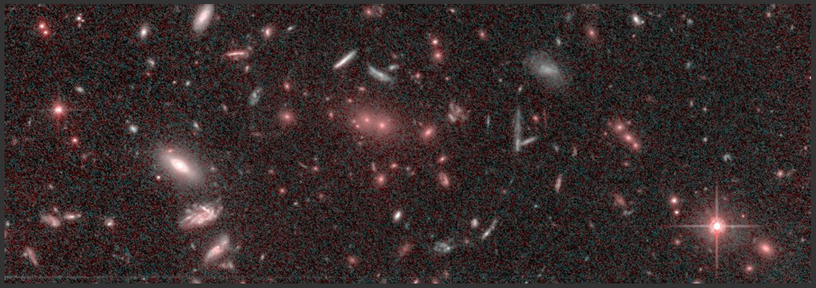

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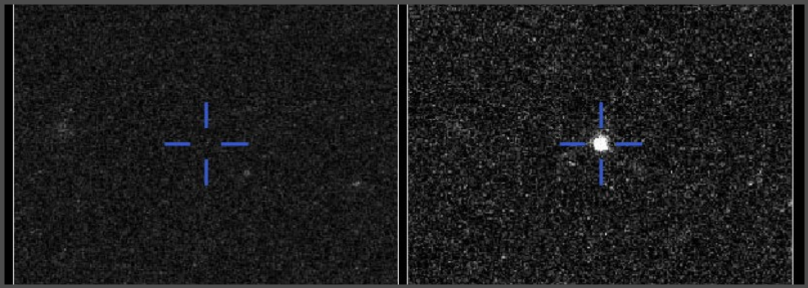

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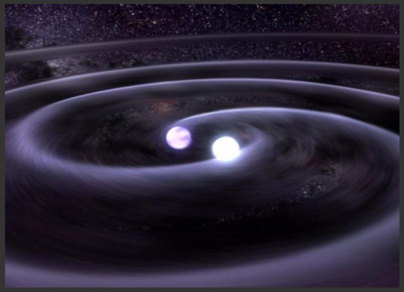
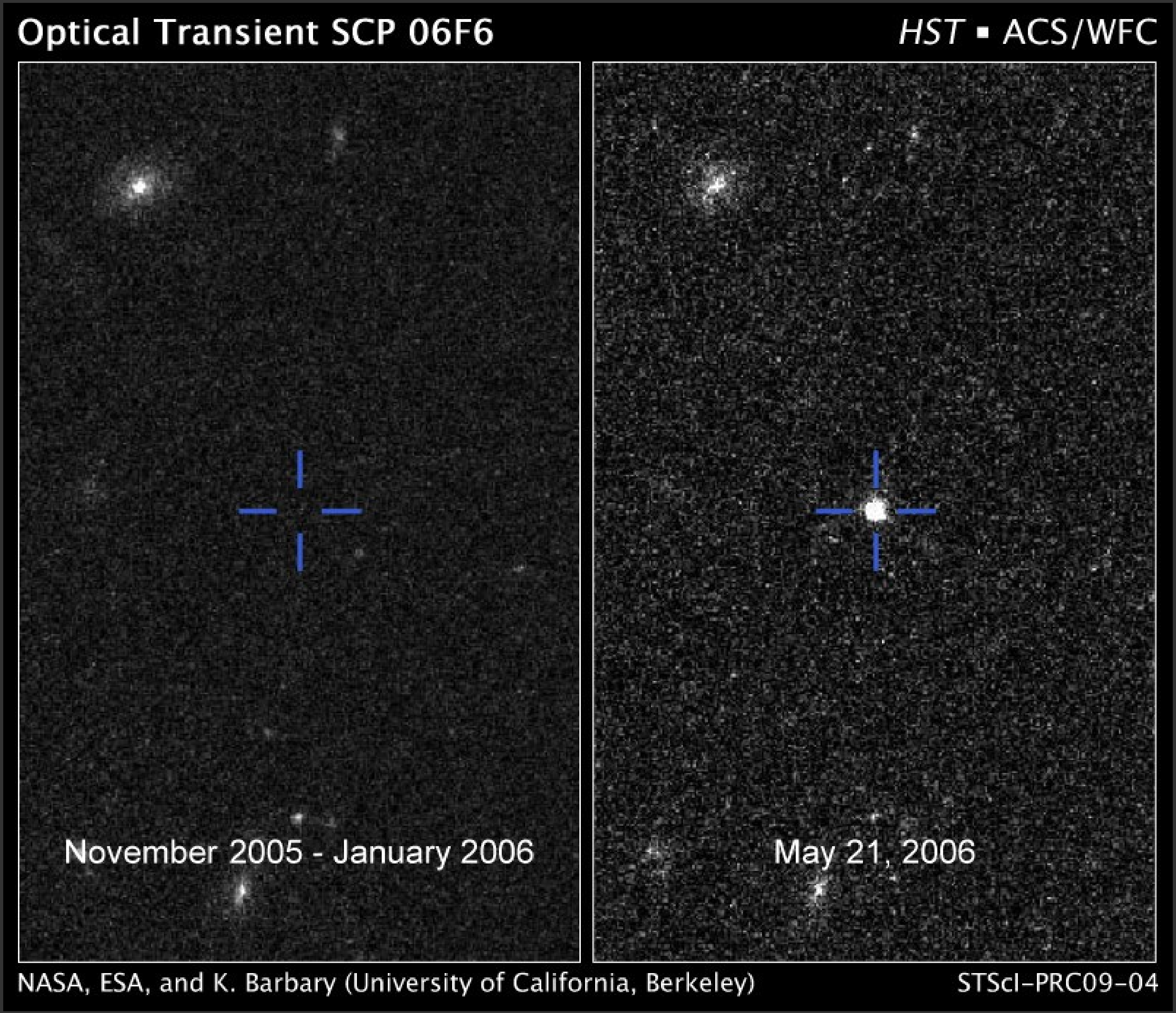
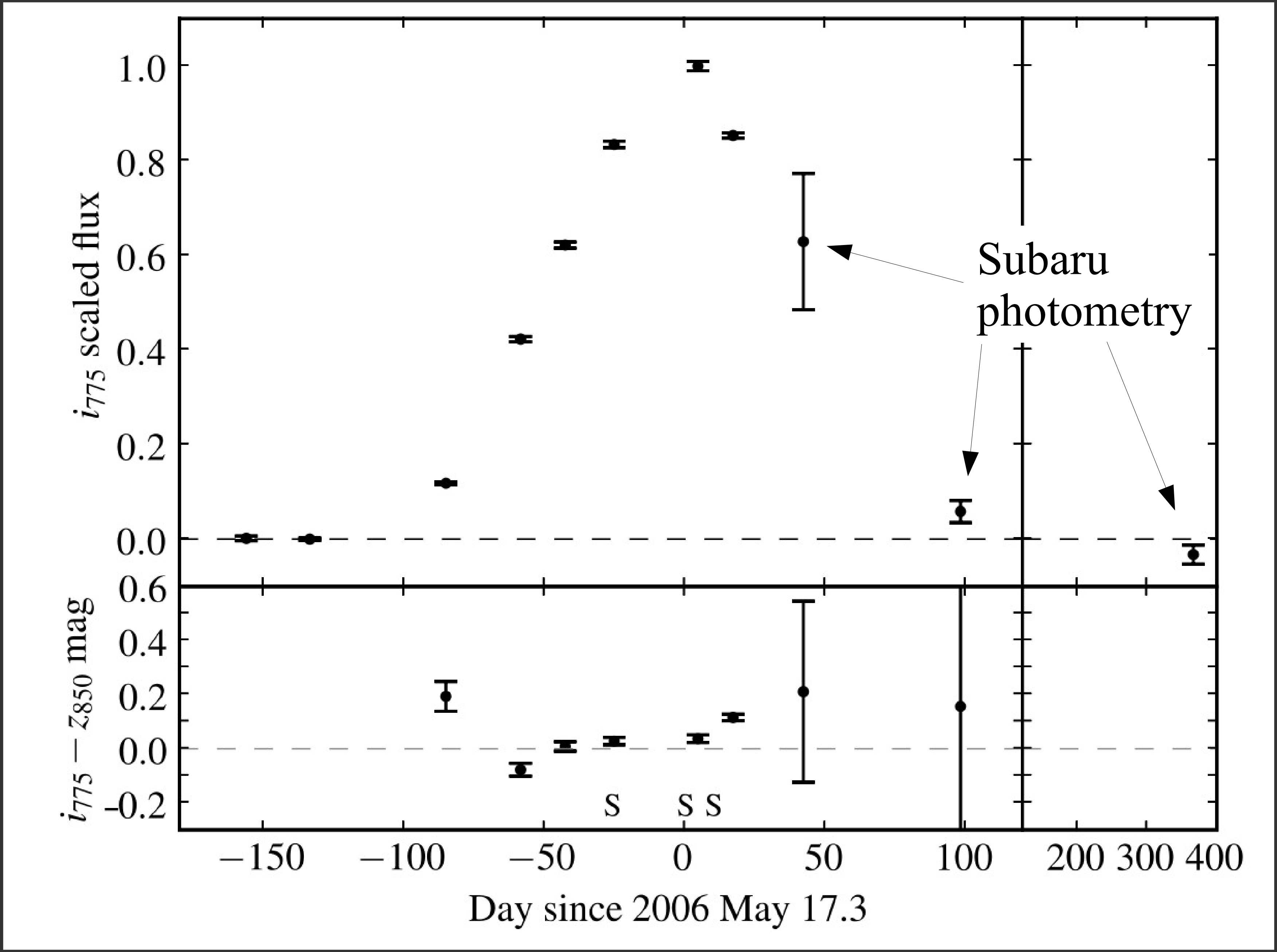




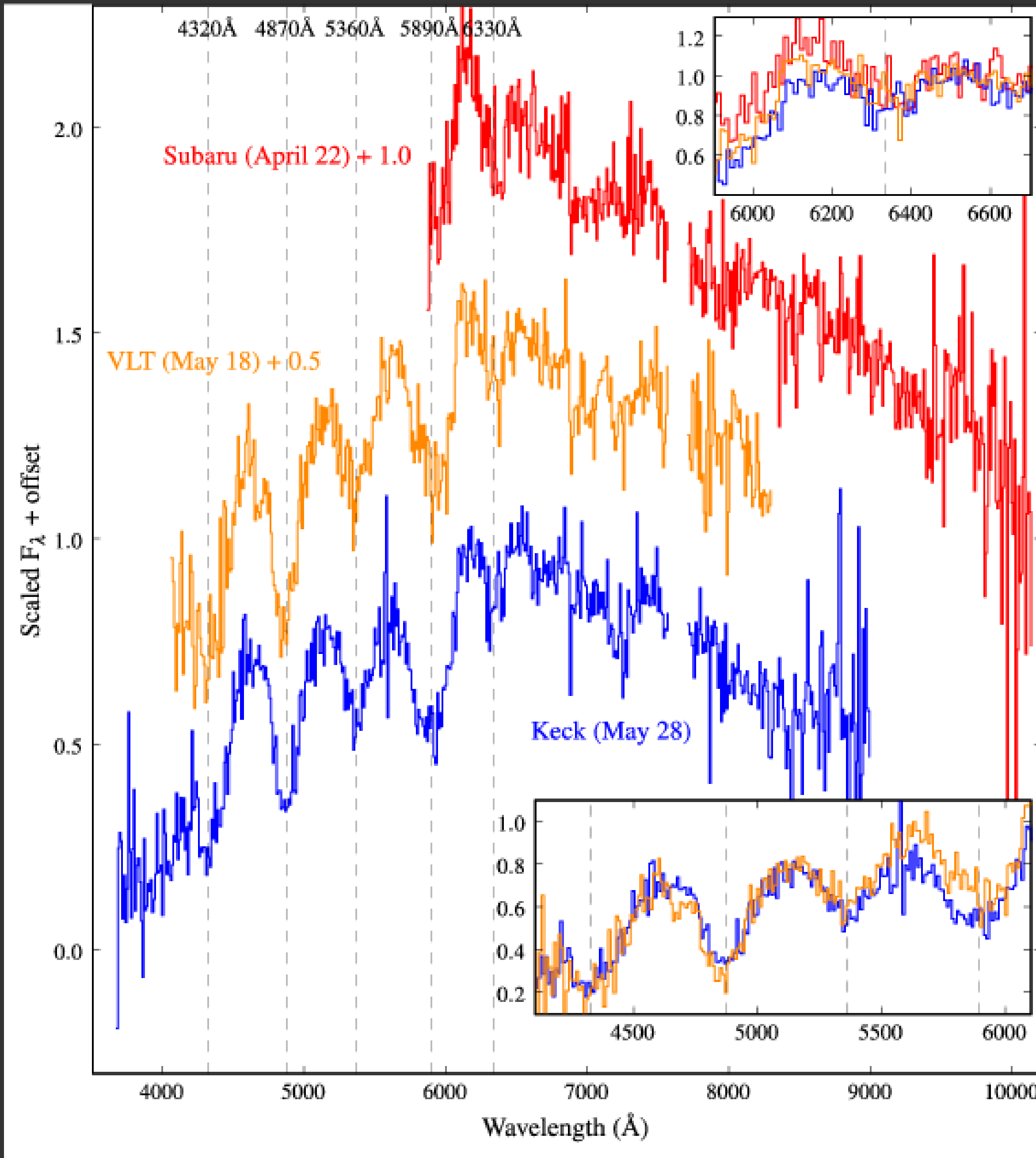
Optical Transient SCP 06F6
HST ▪ ACS/WFC
November 2005 - January 2006
May 21, 2006
NASA, ESA, and K. Barbary (University of California, Berkeley)
STScI-PRC09-04

SN SCP06F6: 100+ day rise time



Barbary et al. (2009)

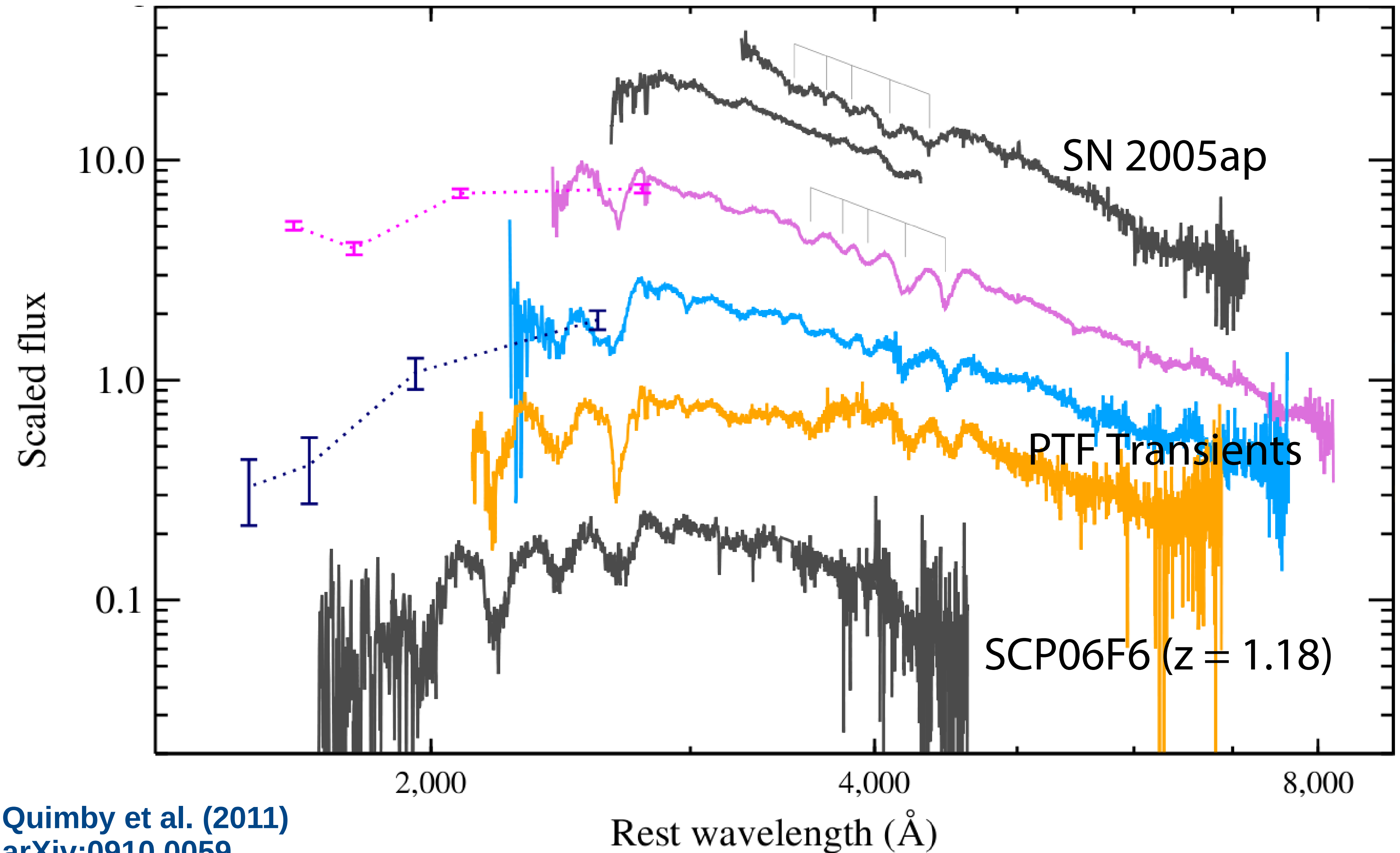
SCP06F6: Unusual spectrum



Barbary et al. (2009)

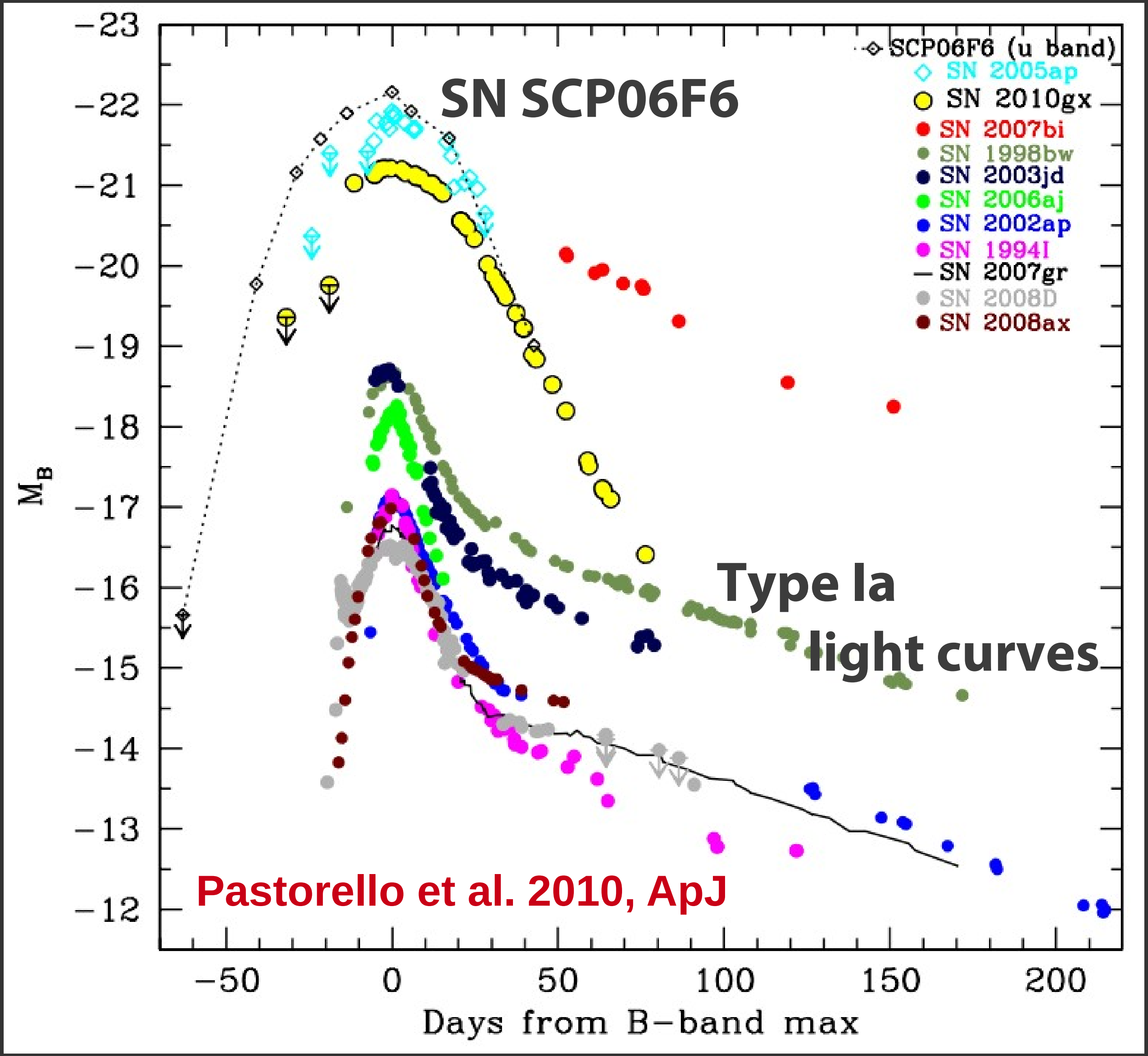
- Best matched to C_2 DQ white dwarfs?
- Microlensing?
- Likely not galactic.
- Did we really find something new with a 0.04 sq deg field-of-view?
- Needed to identify lines for a redshift: more examples needed

Matches in Palomar Transient Factory



Quimby et al. (2011)
arXiv:0910.0059

New class of rare "superluminous SN"



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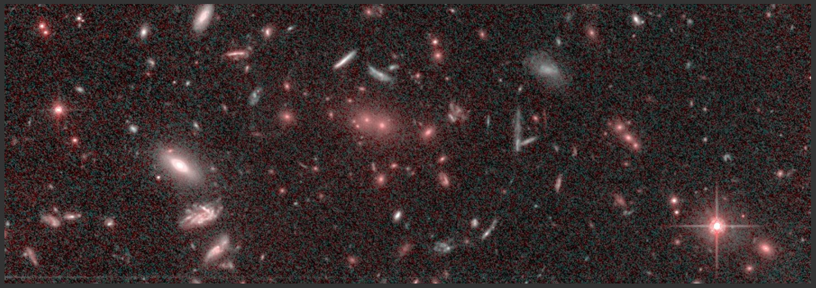

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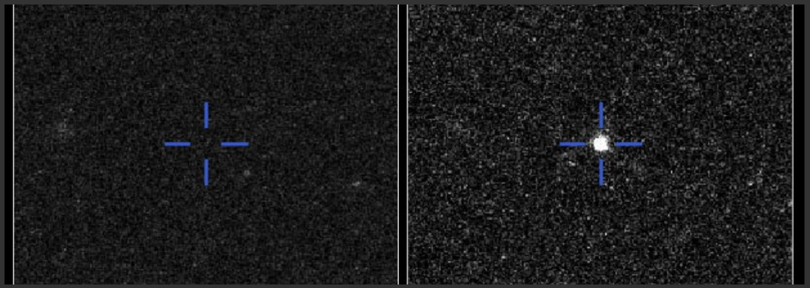

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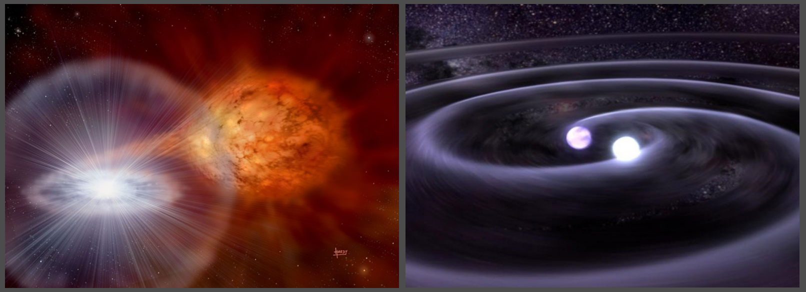

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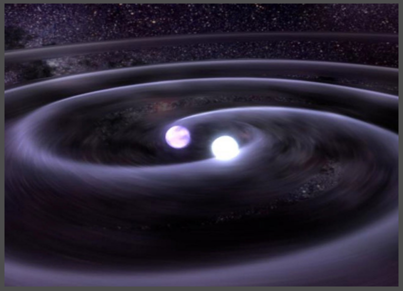
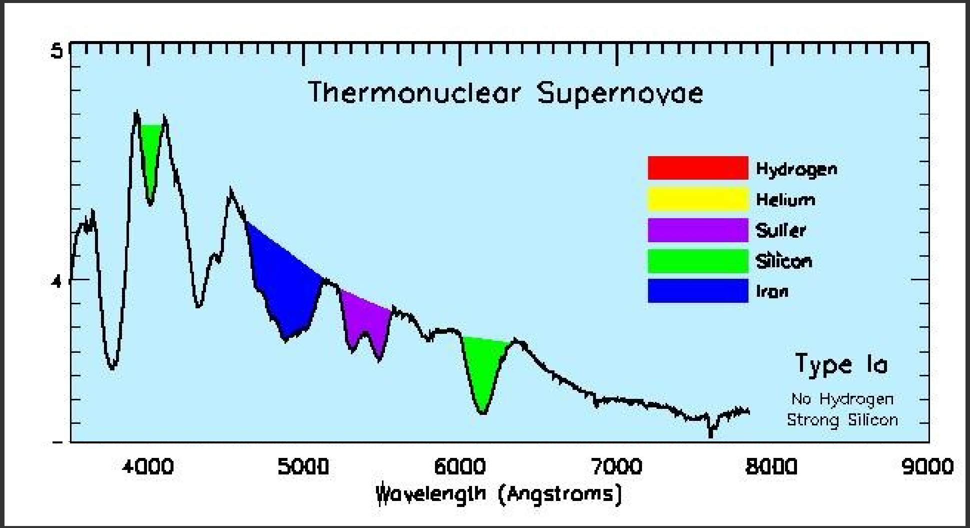


  - What I mean by “progenitor system”
  - How one can study it using SN rates
  - SN Ia rate in clusters

SNe Ia: knowns and unknowns



- ~1.4 $M_{\odot}$ C-O white dwarf
  spectrum matches; uniform luminosity
- Binary system
  mechanism for mass transfer
- **What is the companion?**
  How does the system evolve with time?

Two main classes of progenitor models

Non-degenerate companion:

- Red giant star
- Main sequence star

(Whelan & Iben 1973)

Degenerate companion:

- White dwarf

(Iben & Tutukov 1984)

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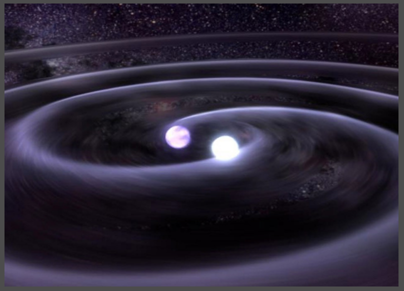

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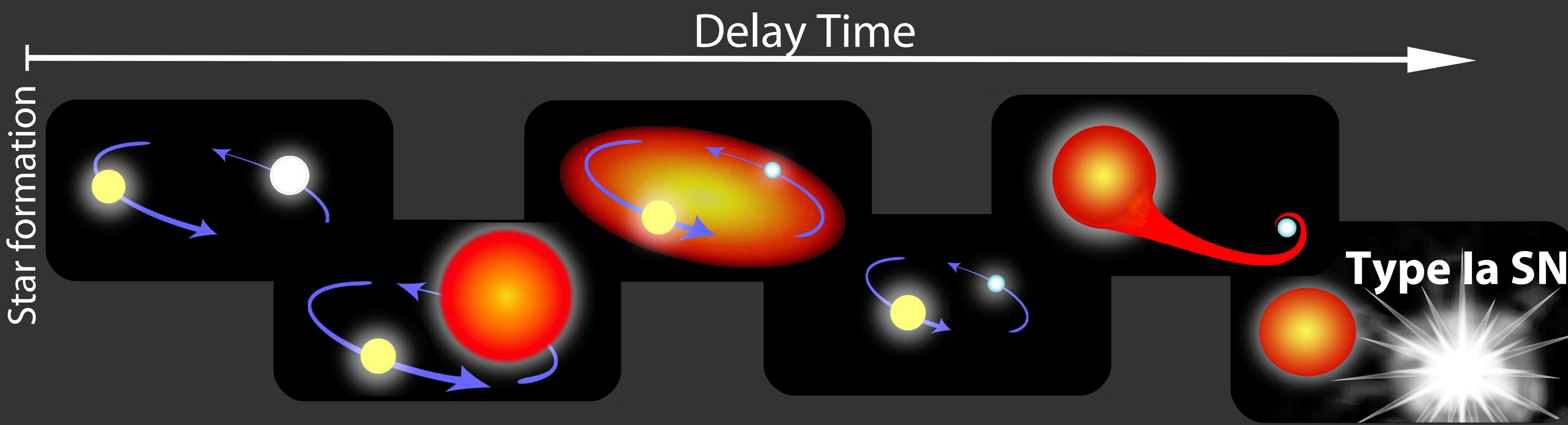
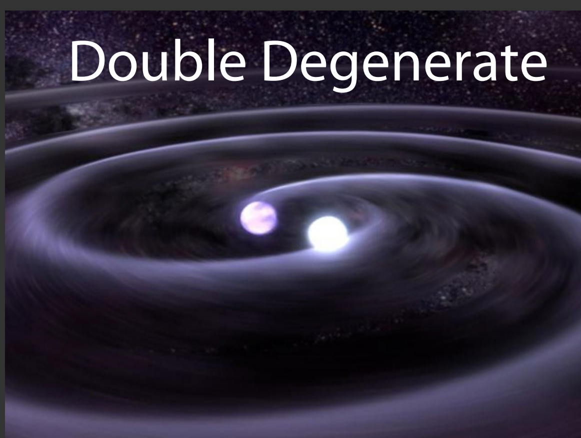
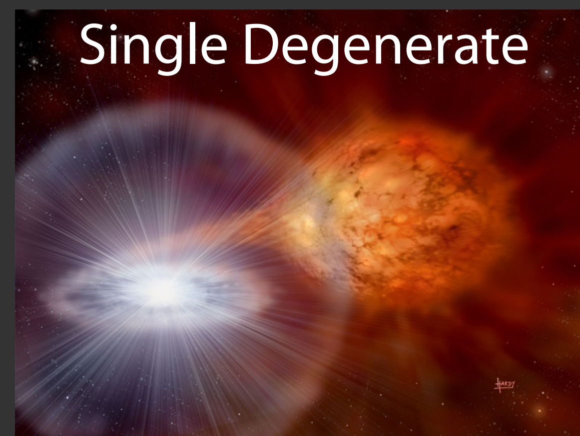
Distinguishing the progenitor using rates





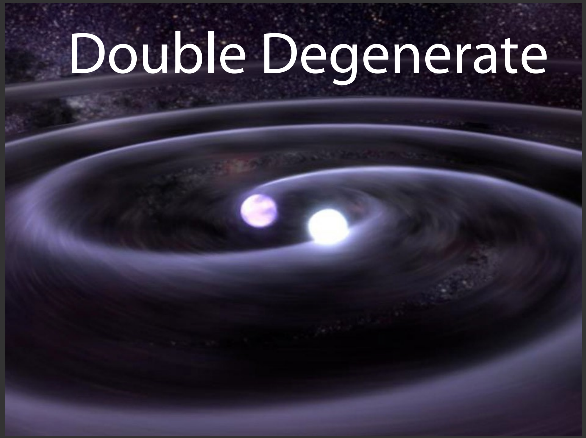
Delay governed by timescale for gravitational radiation



Delay governed by evolution of secondary star

Delay Time Distribution (DTD): SN rate following an ideal burst of star formation

Back of the envelope calculation



Delay governed by timescale for gravitational radiation

$$t \sim a^4$$

Time for orbit to decay (known from GR)

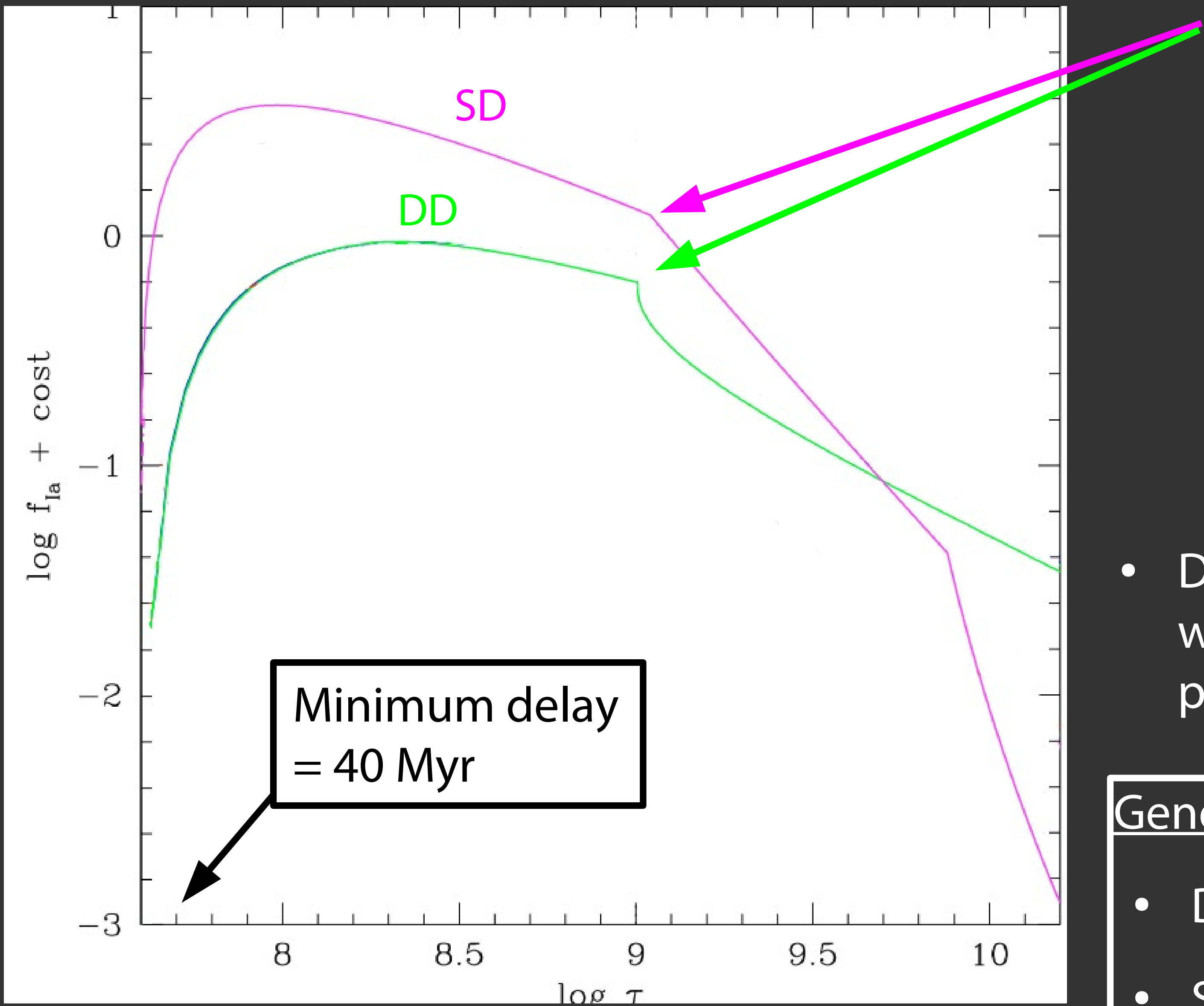
$$\frac{dN}{da} \sim a^{\epsilon}$$

Distribution of initial separations

$$\frac{dN}{dt} = \frac{dN}{da}\frac{da}{dt} \sim t^{(\epsilon-3)/4}$$

$$\mathrm{DTD} \sim t^{-1}$$

Detailed DTD calculations



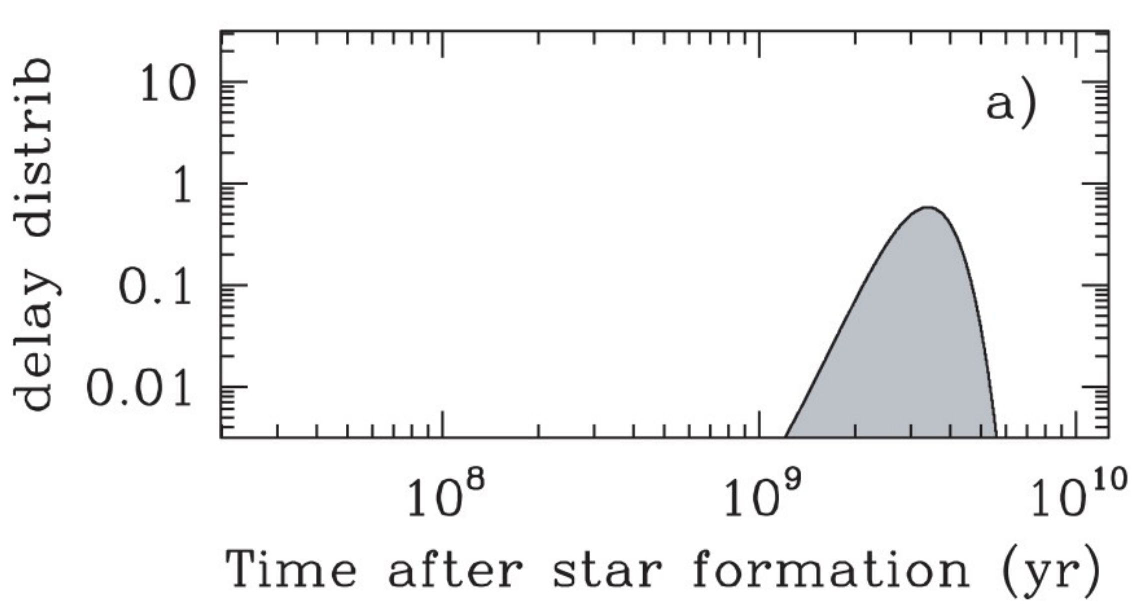
Greggio (2005)

- Different groups come up with different results, particularly for SD model

Generic predictions at t > 1 Gyr

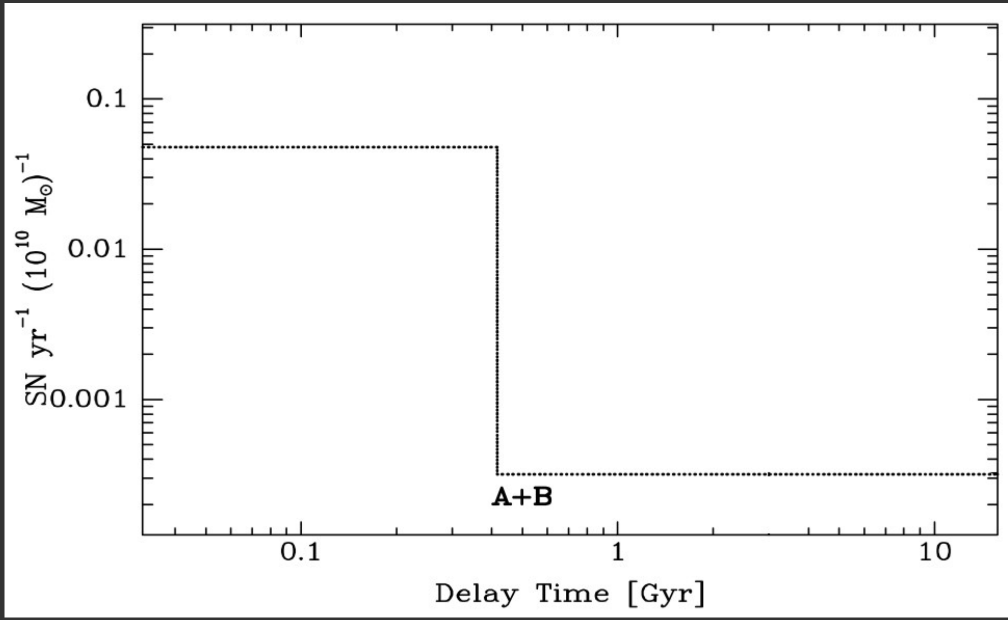
- DD: close to t^{-1} ($t^{-0.75} - t^{-1.25}$)
- SD: t^{-2} or steeper

Observed DTDs



Dahlen et al. (2004), Strolger et al. (2004)

- Measuring the DTD is difficult!
  galaxies are made up of a large mix of stellar ages



Mannucci et al. (2005),
Scannapieco & Bildsten (2005)

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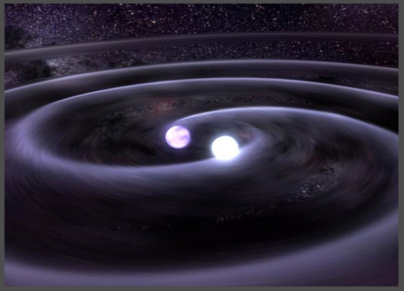

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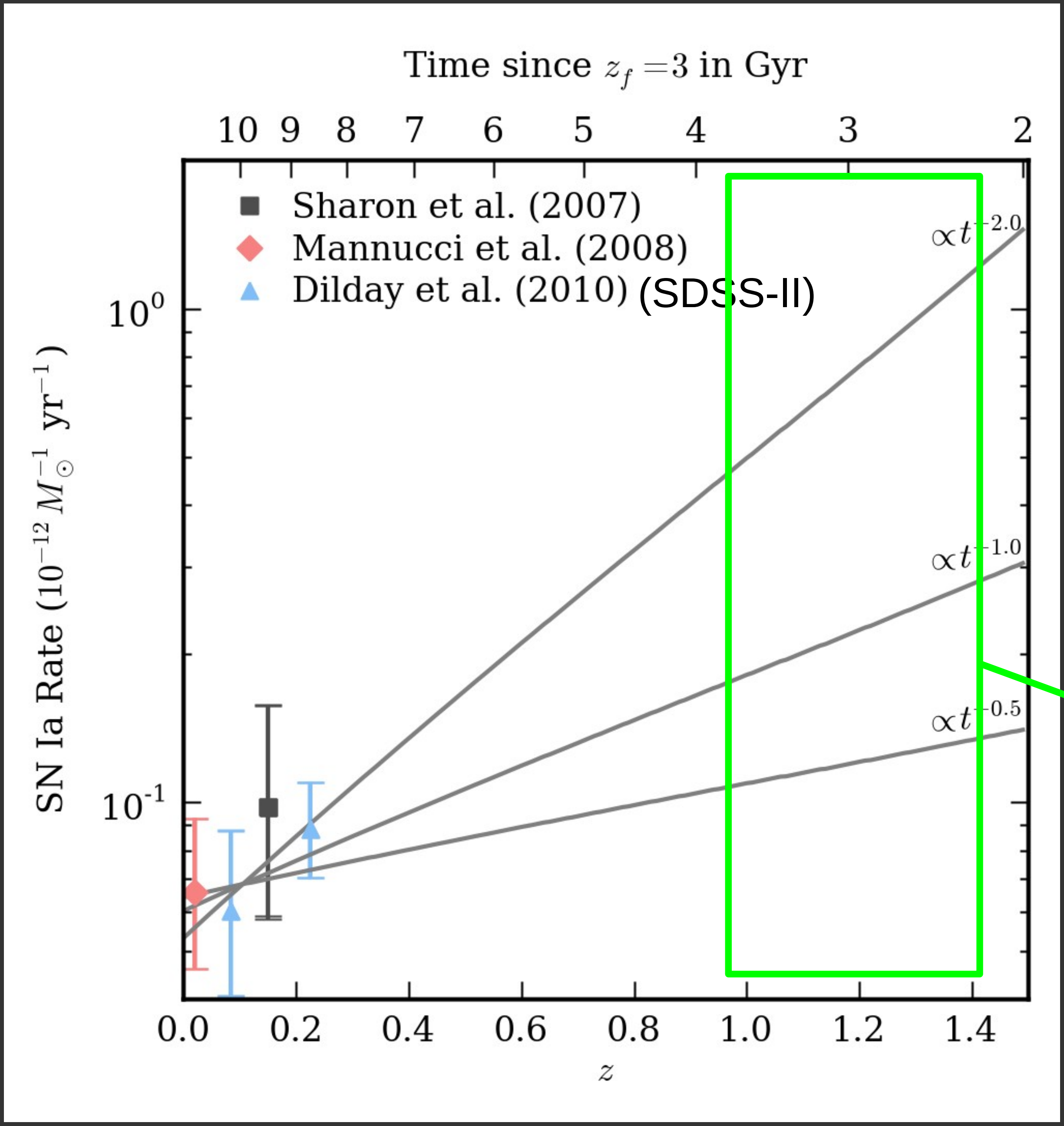
Clusters dominated by passive galaxies



- Star formation occurred at high redshift
- SN Ia rate in clusters dominated by old stars

Rate Calculation

of cluster SNe Ia

$$\mathcal{R} = \frac{N_{\mathrm{SN\ Ia}}}{\sum_j T_j L_j}$$

cluster luminosity

Effective observing time

Rate Calculation

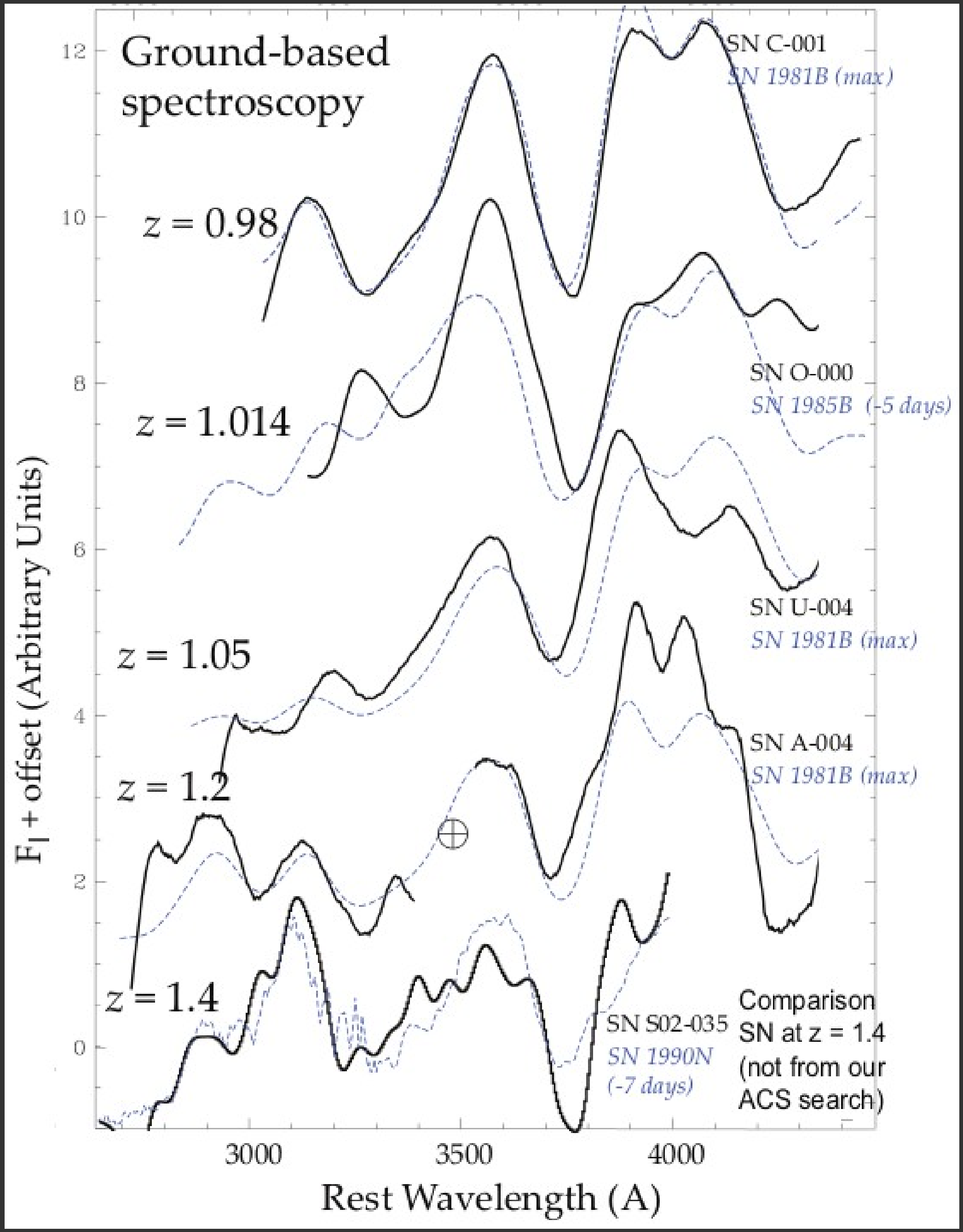
$$\mathcal{R} = \frac{N_{\mathrm{SN\ Ia}}}{\sum_j T_j L_j}$$

# of cluster SNe Ia

- *Is SN candidate in cluster?*
  27/30 of SN candidates have host-galaxy redshifts
- *Is candidate a Type Ia*
  Combination of methods used for typing

Typing

- 7 spectroscopically-confirmed (3 in cluster)

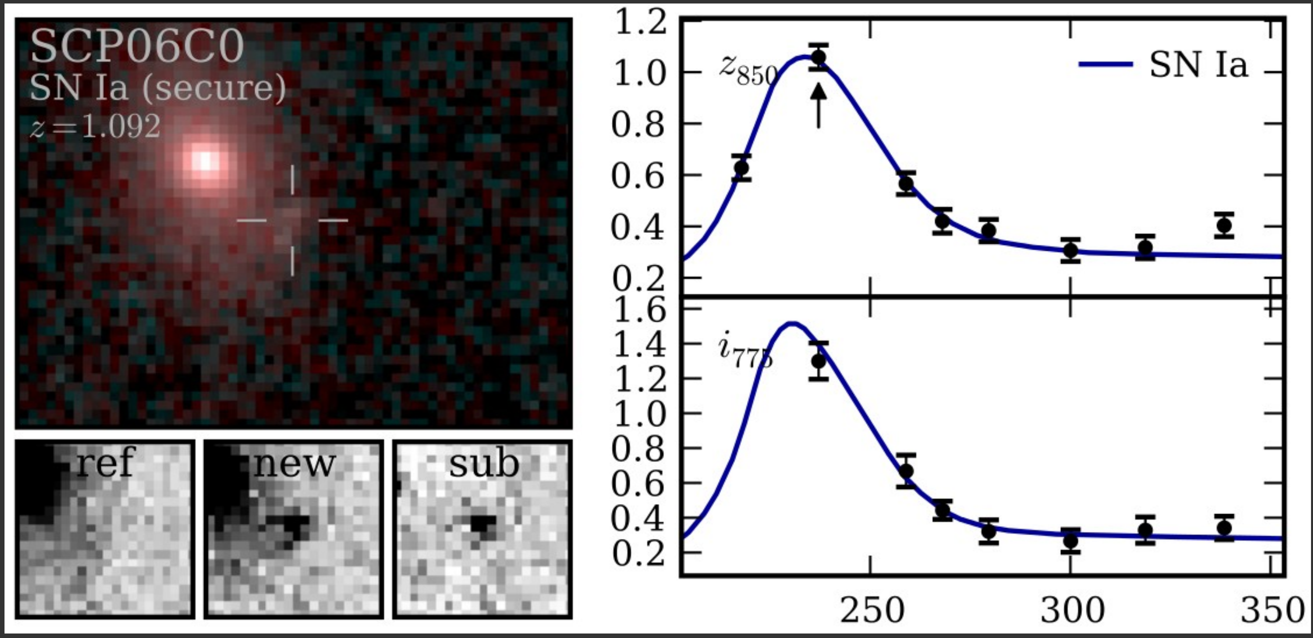


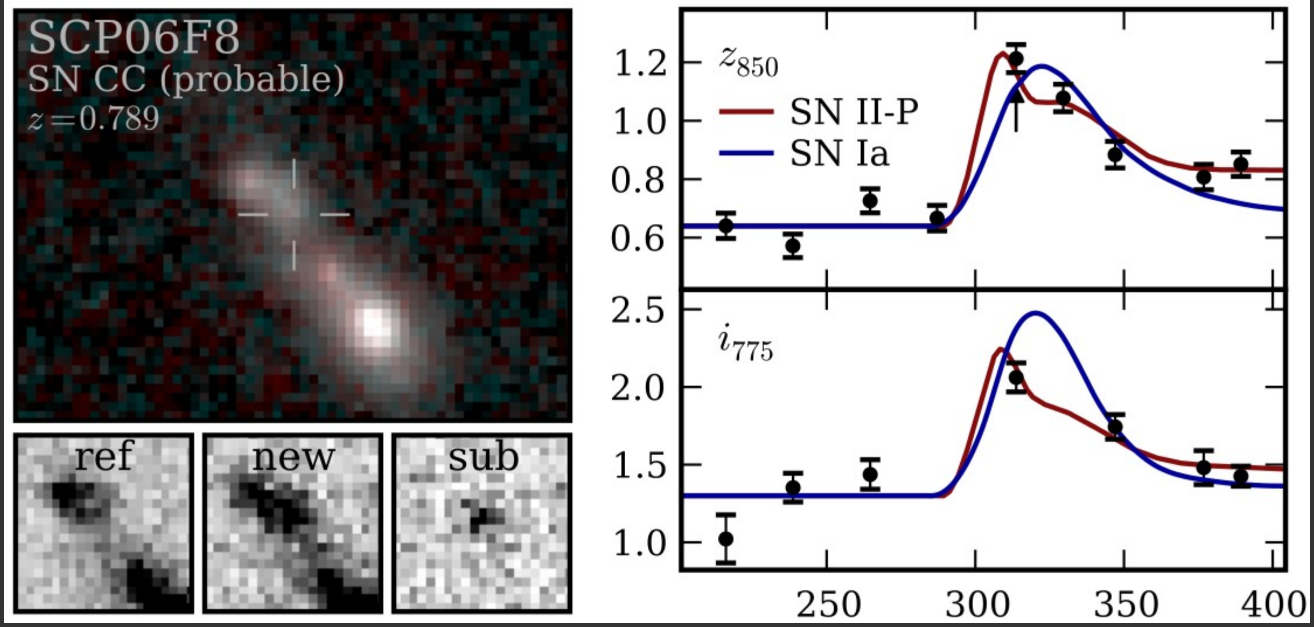
Typing

- 7 spectroscopically-confirmed
- 5 Early-type host + light-curve typing

- 12 “secure” Type Ia
- 5 “probable” Type Ia
- 3 “plausible” Type Ia

- 10 Core-collapse





Rate Calculation

$$\mathcal{R} = \frac{N_{\mathrm{SN\ Ia}}}{\sum_j T_j L_j}$$

# of cluster SNe Ia

- *<u>Is SN candidate in cluster?</u>*
  27/30 of SN candidates have host-galaxy redshifts

- *<u>Is candidate a Type Ia?</u>*
  Combination of methods used for typing

8 ± 1 Cluster SNe Ia

Rate Calculation

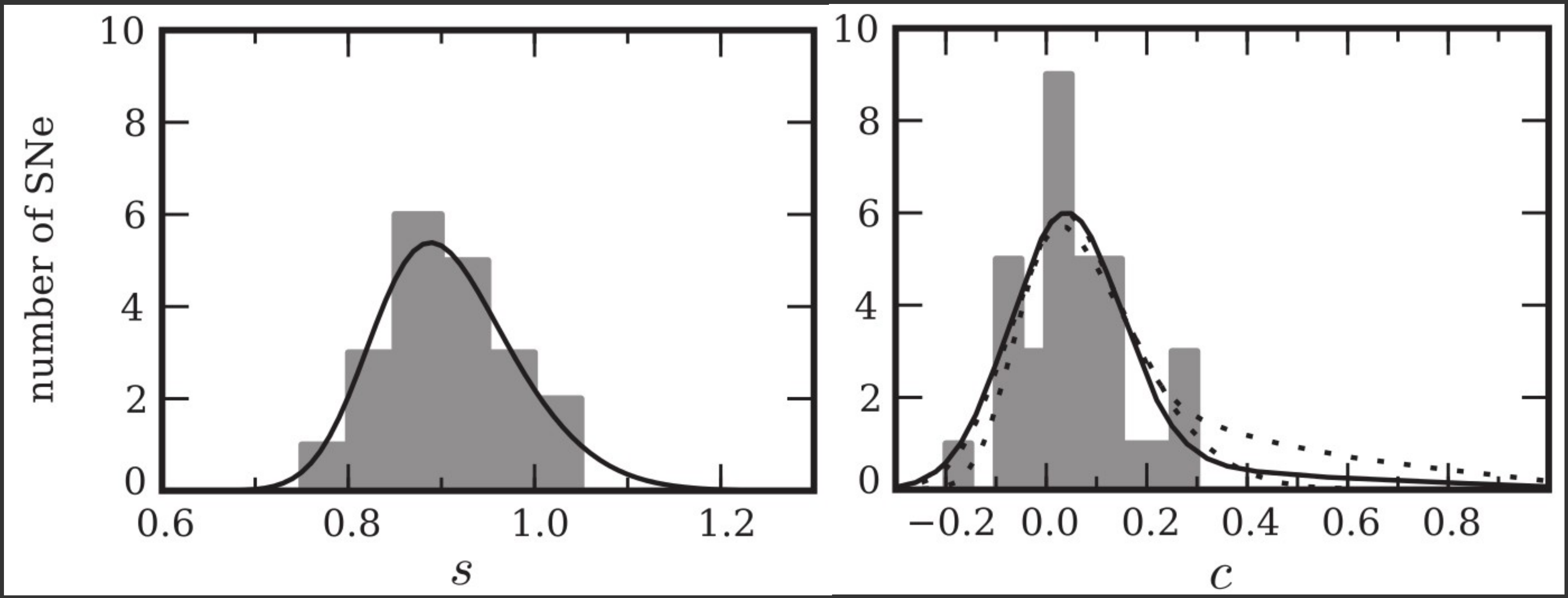
$$\mathcal{R} = \frac{N_{\mathrm{SN\ Ia}}}{\sum_j T_j L_j}$$

Effective observing time
= time x efficiency

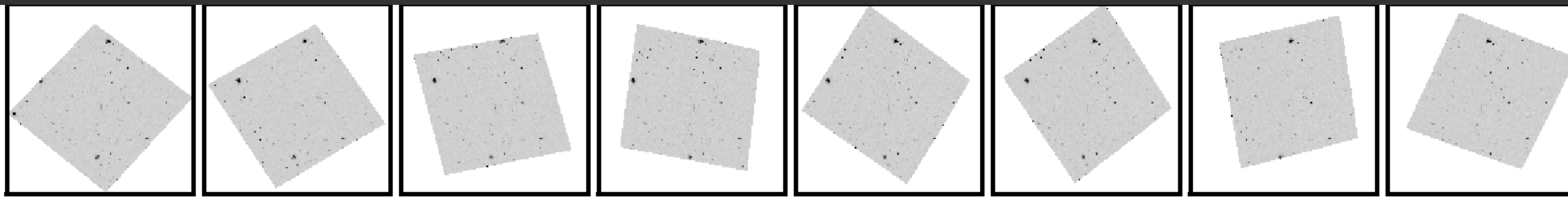
Effective observing time

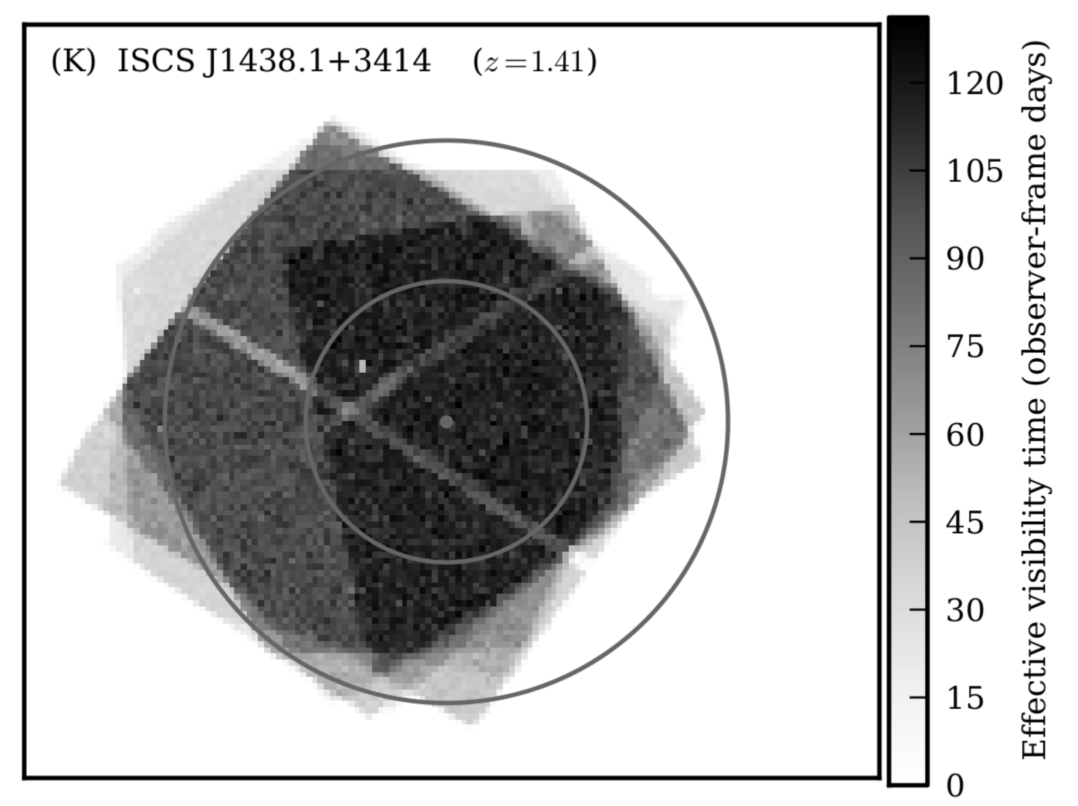
- Monte Carlo simulation:
  simulated Type Ia light curves placed on actual survey data
- Distribution of properties mimic observed distributions

$$M_B = -19.31 - \alpha(s-1) + \beta c$$



Effective observing time





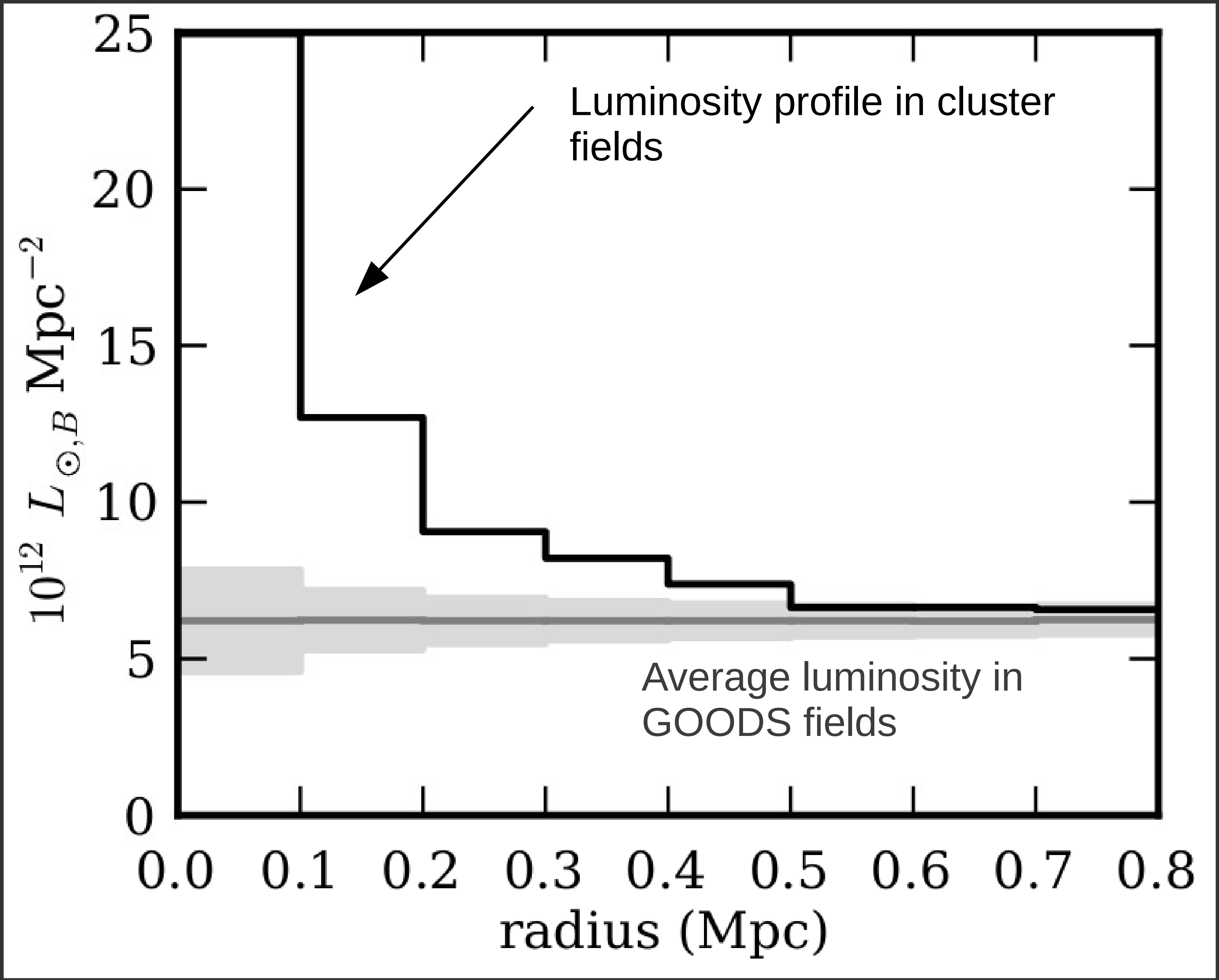
Rate Calculation

$$\mathcal{R} = \frac{N_{\mathrm{SN\ Ia}}}{\sum_j T_j L_j}$$

cluster luminosity

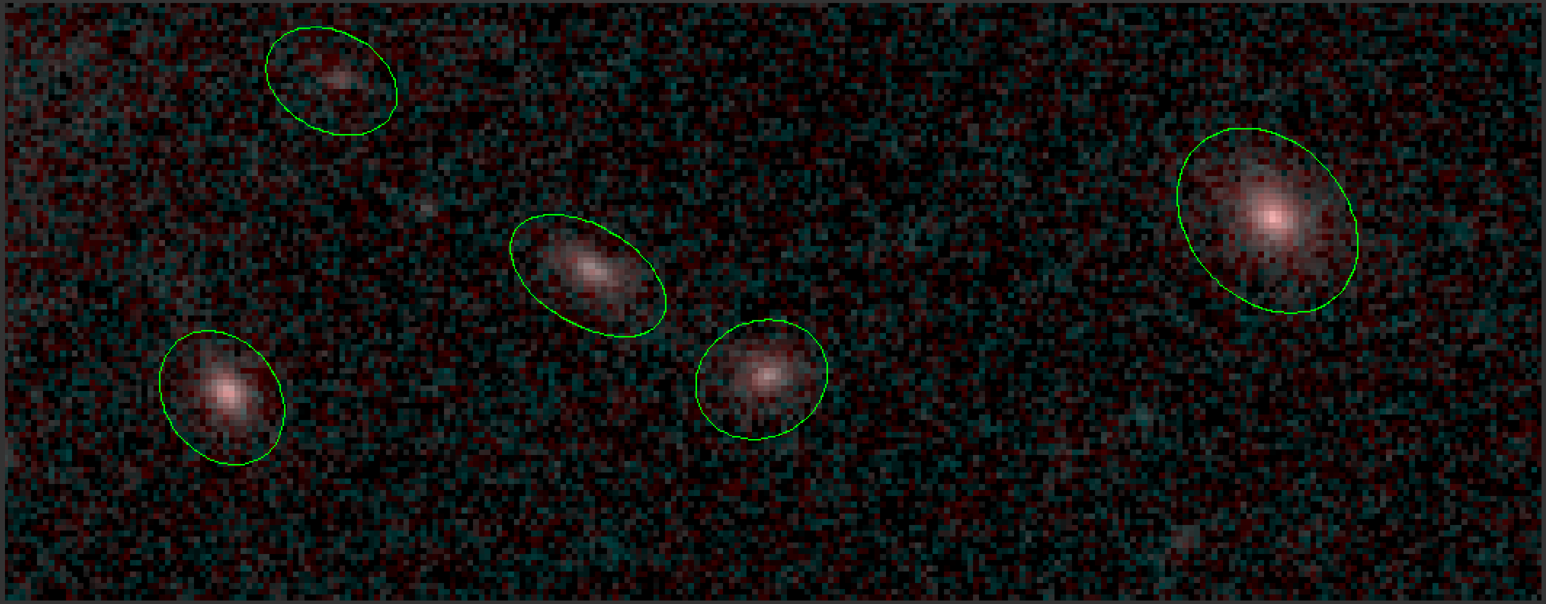
Cluster luminosities

- <u>Strategy</u>: sum up light from all galaxies in field, subtract background



Cluster luminosities

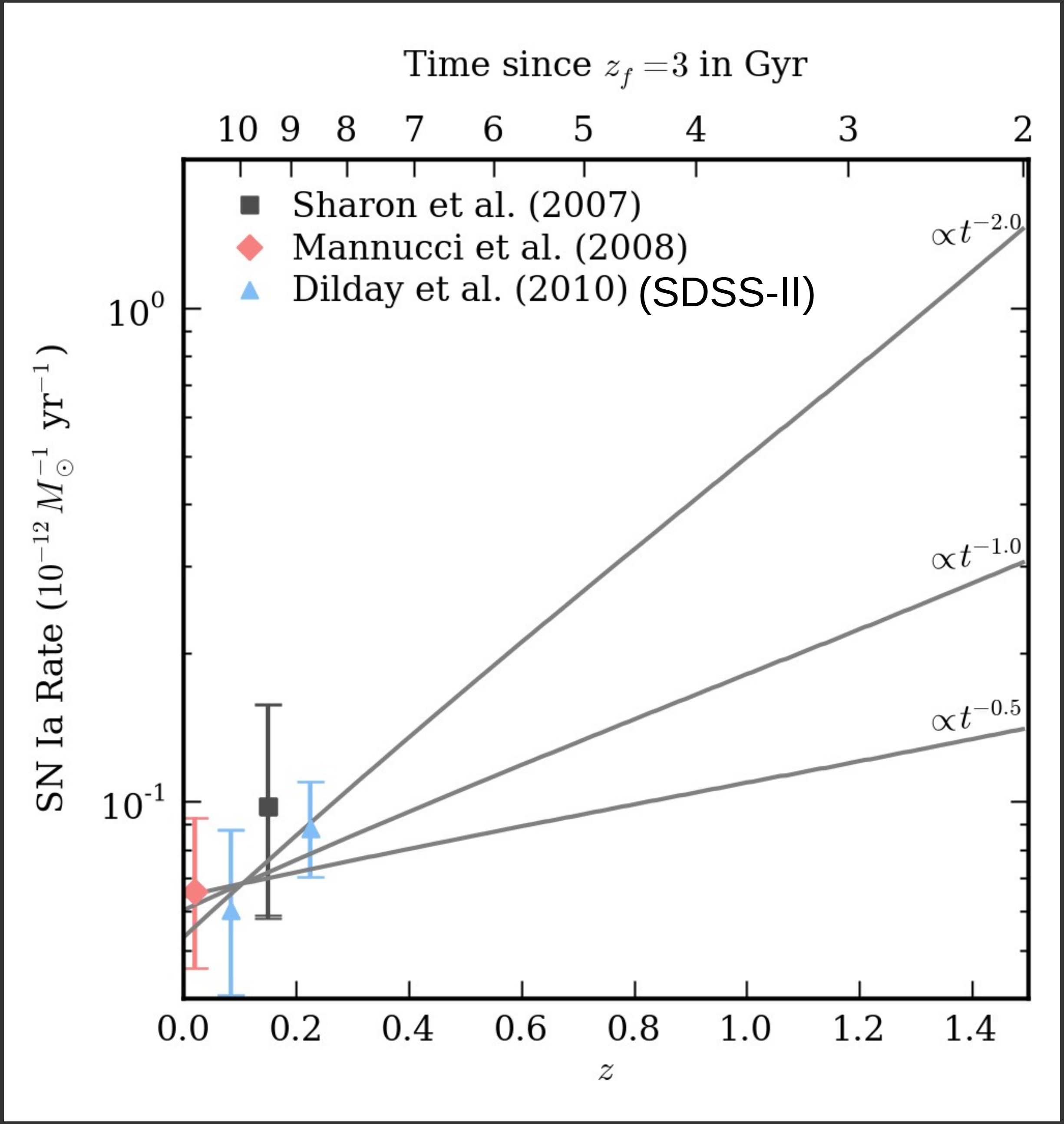
- Account for luminosity from faint galaxies below detection threshold (~5% correction)
- Account for luminosity outside apertures (~20% correction)



Sources of Uncertainty

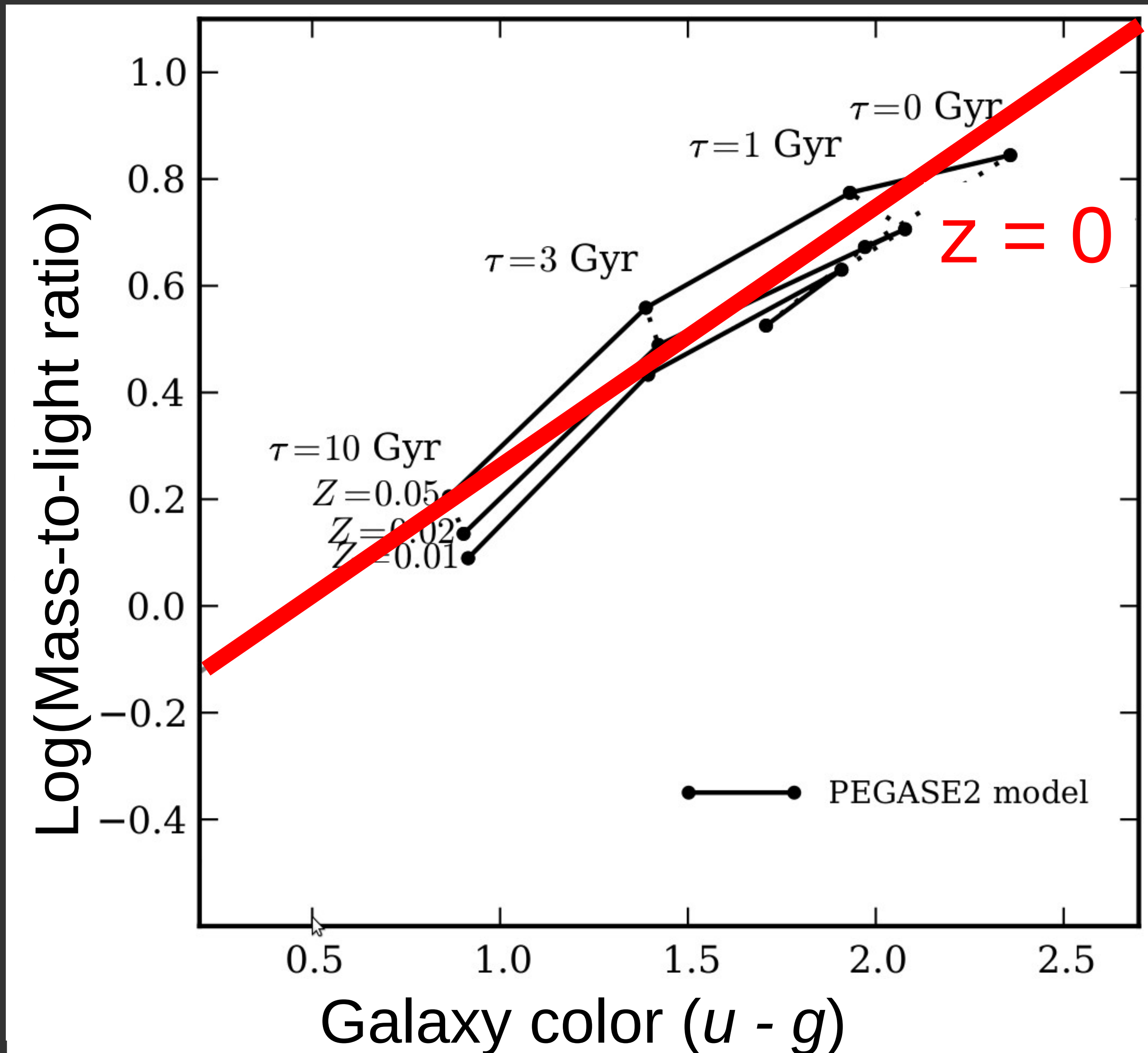
Source of error	(%)
	Statistical
Poisson	$^{+40}_{-32}$
Luminosity (stat)	± 12
Luminosity (cosmic var.)	± 16
Total statistical	$^{+45}_{-38}$
	Systematic
SN type classification	± 13
Control time: varying M_B	$^{+8}_{-6}$
Control time: dust distribution	$^{+10}_{-2}$
Luminosity: MAG_AUTO corr.	± 7
Luminosity: K-correction	± 3
Luminosity: Faint galaxy corr.	$^{+4}_{-9}$
Luminosity: $r > 0.6(0.8)$ Mpc	± 4
Total systematic	$^{+20}_{-19}$
Total statistical + systematic	$^{+49}_{-42}$

Clusters rates normalized by stellar mass

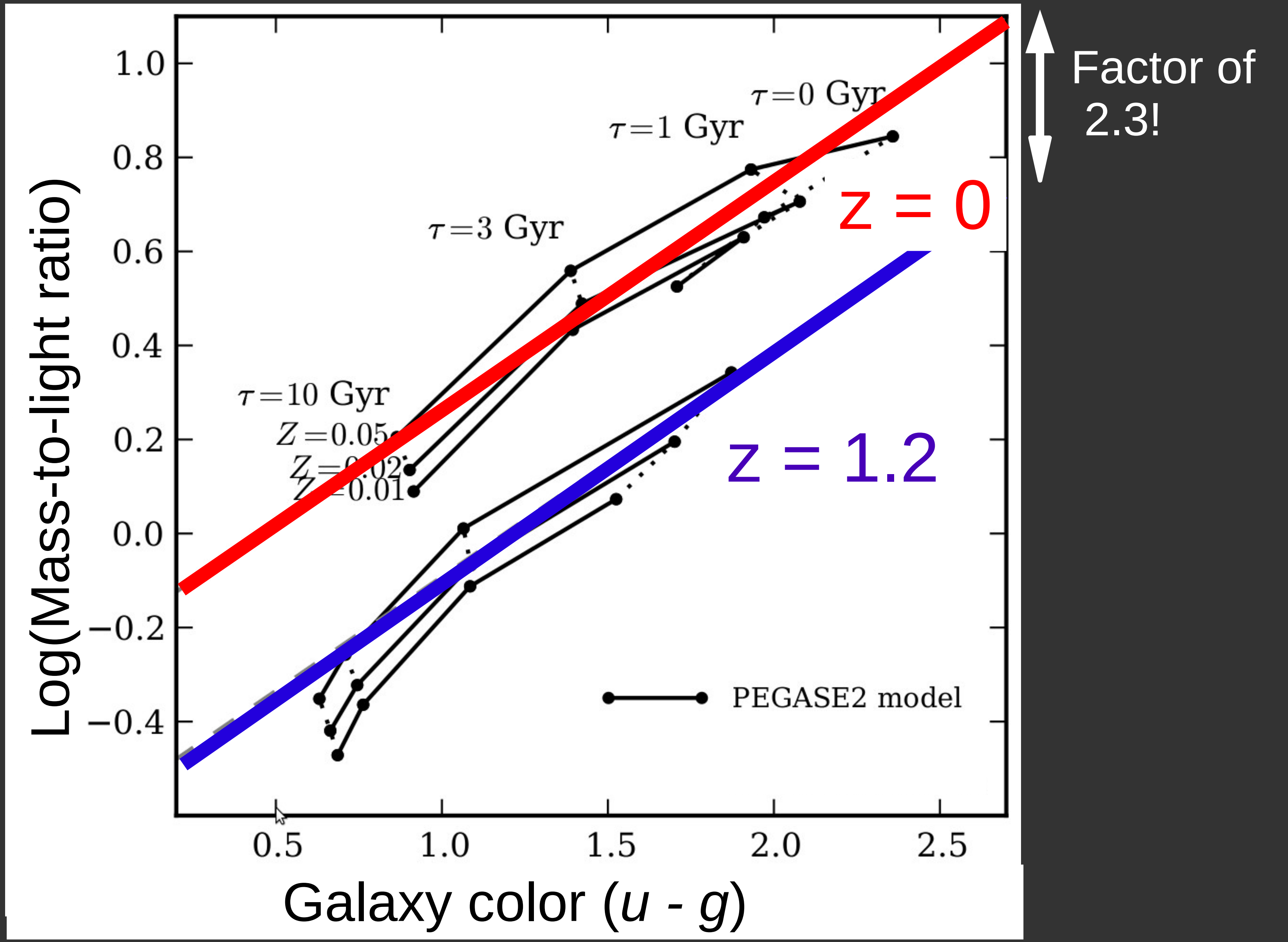


- Want to normalize result by total stars formed, not stellar luminosity
- Important to be consistent with low-z rates

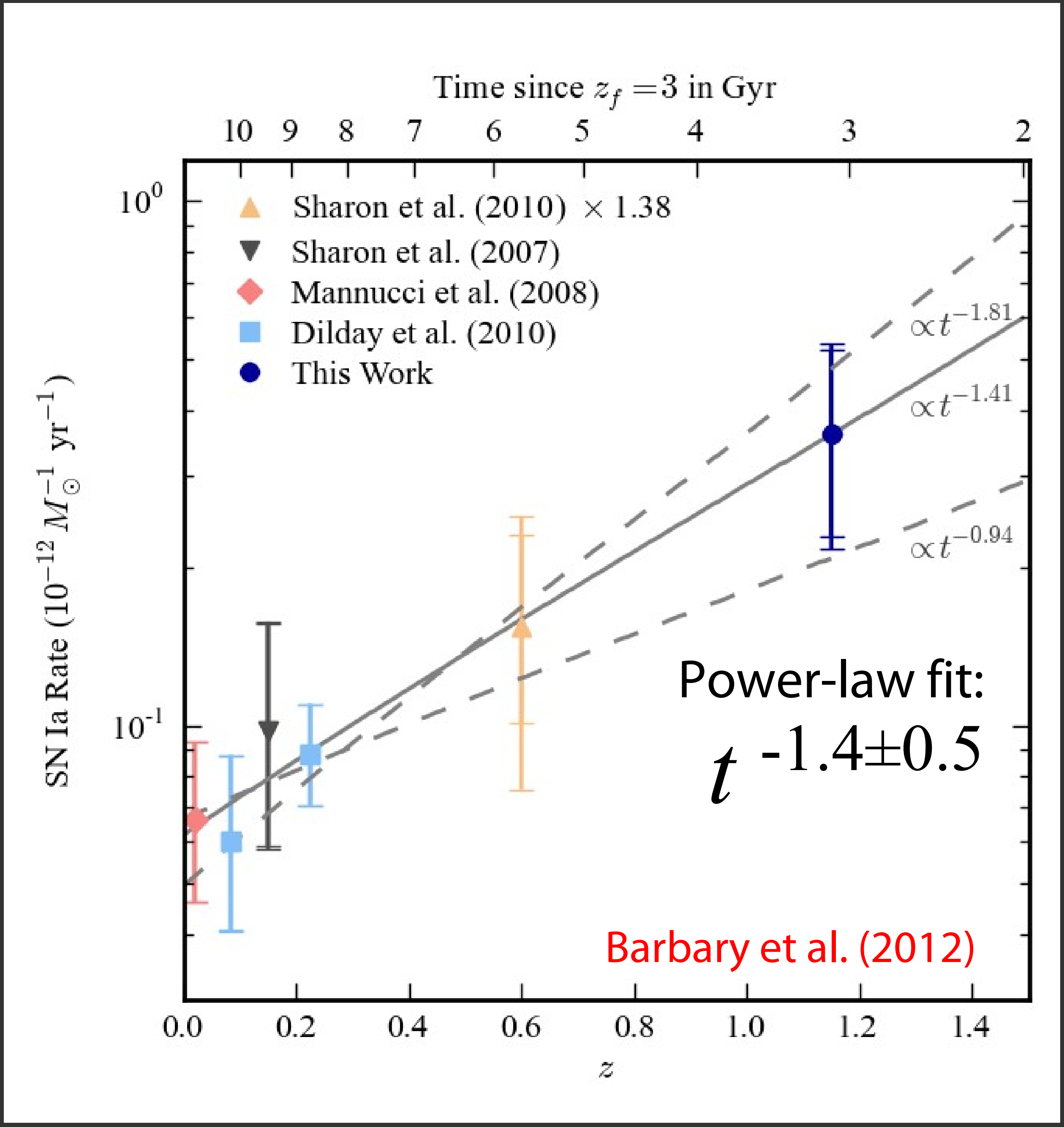
Consistent Mass-to-Light Ratio



Consistent Mass-to-Light Ratio



Results

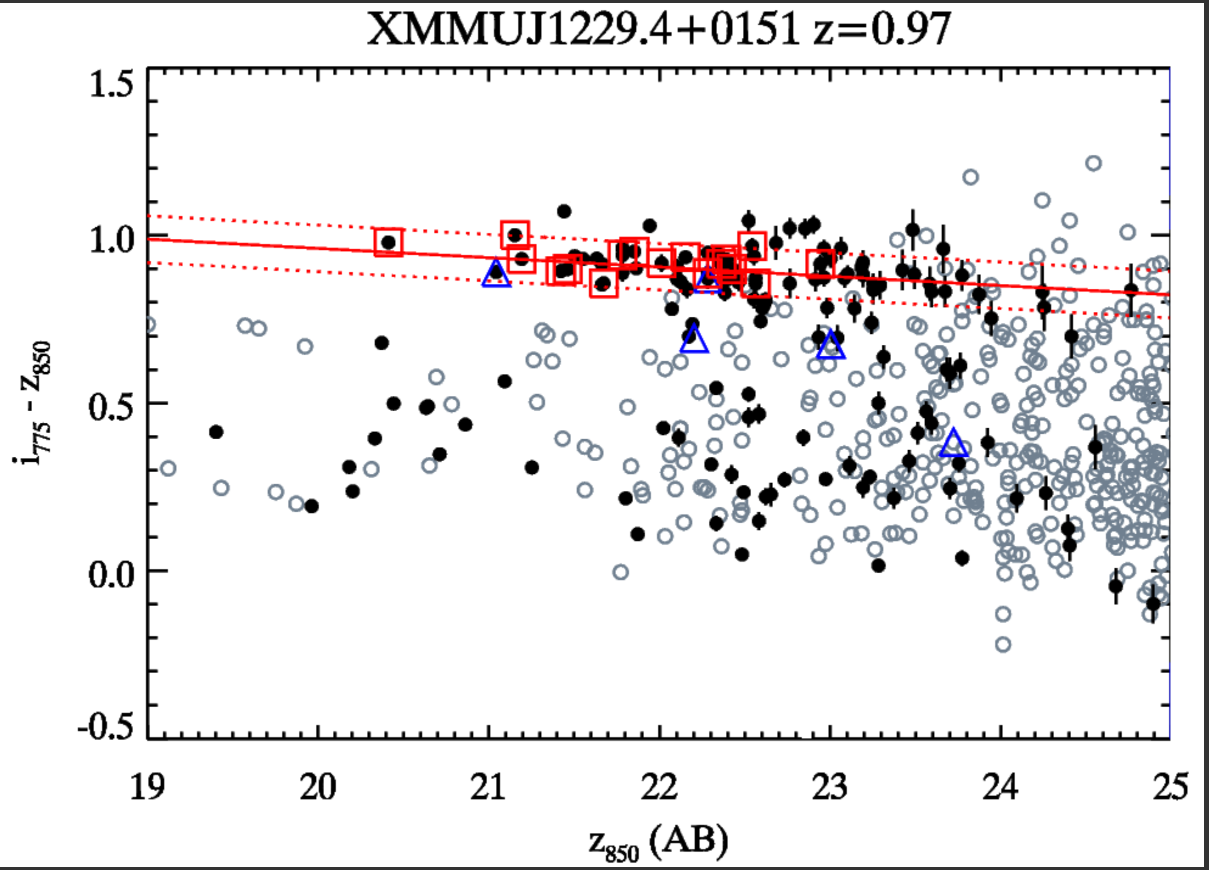


- Factor of 5±2 increase over low-redshift rate

Generic predictions

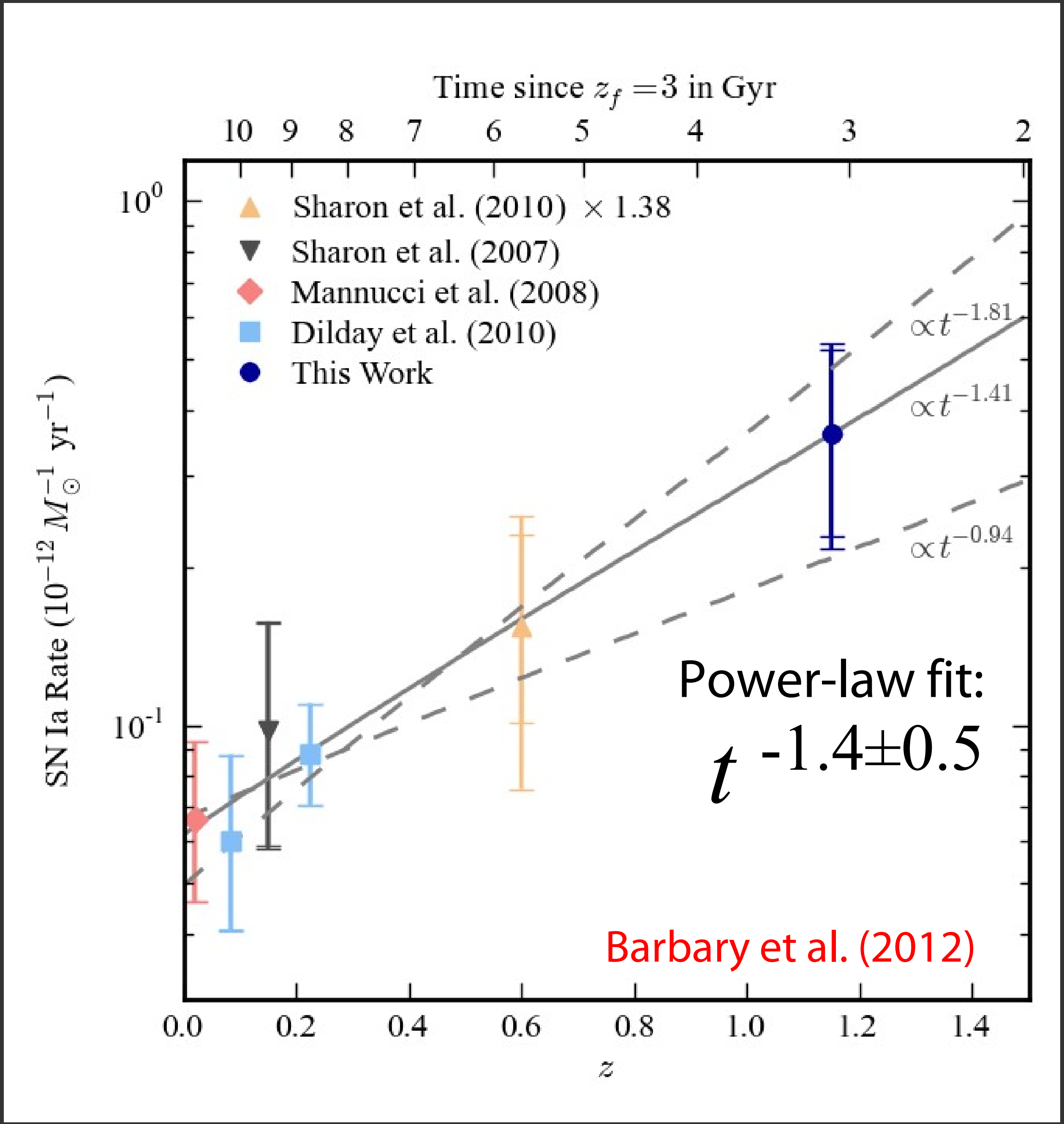
- DD: close to t^{-1} ($t^{-0.75} - t^{-1.25}$)
- SD: t^{-2} or steeper at t > 1 Gyr

Cross-check: red-sequence-only rate



	# SN Ia	Denom	Rate
All galaxies	8±1	22.41	0.36
Red-sequence galaxies	6.5±0.5	17.61	0.37
Red early-type galaxies	6	11.77	0.51

Cross-check: star formation redshift



$z_f = 2.5$: $t^{-1.3}$

$z_f = 3$: $t^{-1.4}$

$z_f = 4$: $t^{-1.55}$

Generic predictions at t > 1 Gyr

- DD: close to t^{-1} ($t^{-0.75}$ – $t^{-1.25}$)
- SD: t^{-2} or steeper

Conclusions

- Cluster rates are now constraining the DTD at late times
- Other measurements (young ellipticals, LOSS rates, magellenic clouds) agree at shorter delay times
- Getting a consistent picture of the SN Ia progenitor from SN rates!