Cosmology with Type Ia supernovae and Gravitational Lensing

Suhail Dhawan, on behalf of Cosmology WG

ZTF meeting, Seattle, 05 September 2019

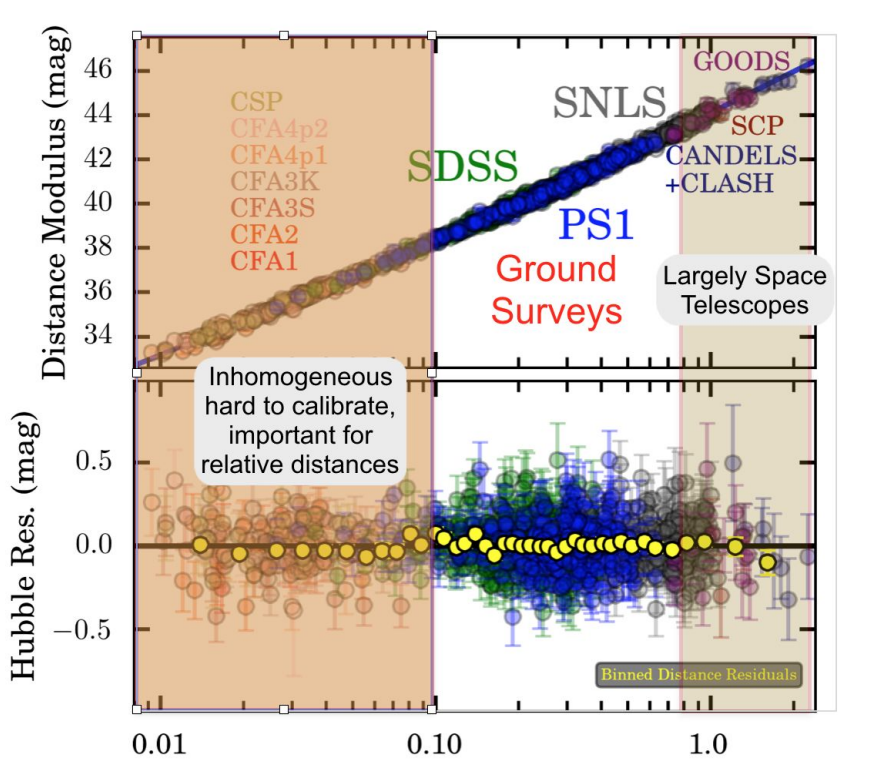
Outline

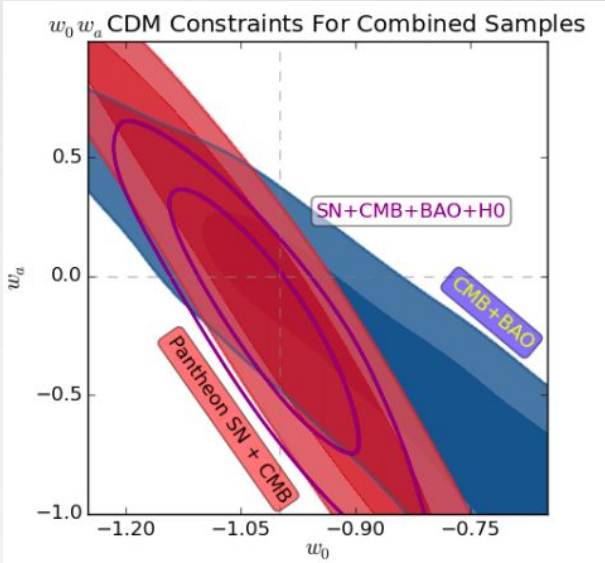
- Motivation for low-z SNe~Ia
  - Expansion history: Dark energy and H_0
  - Growth of structure: Bulk Flows and $f\sigma_8$

- Update on 1.5 year sample
  - Summary statistics and light curve
  - Preliminary Hubble diagram

- Lensed SNe
  - Lessons from iPTF16geu
  - Image stacking for ZTF lensed SNe

SN cosmology: low-z calibration



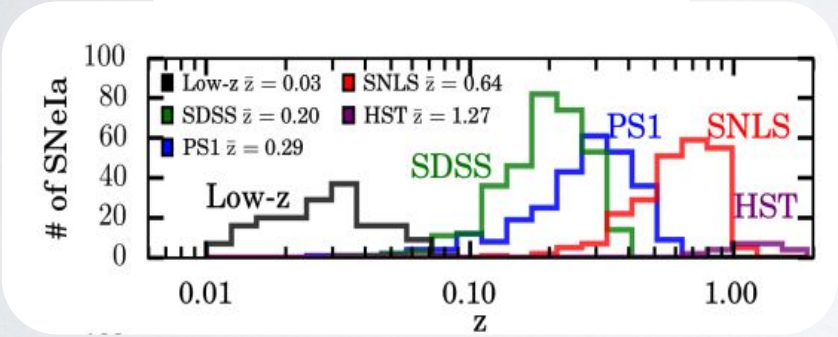


- Heterogeneous low-z sample
- Low-z size << high-z; weighted higher
- ZTF improves upon status quo
  - Homogeneous sample
  - Larger statistics (10 X current)

Low z Anchor : State of the art

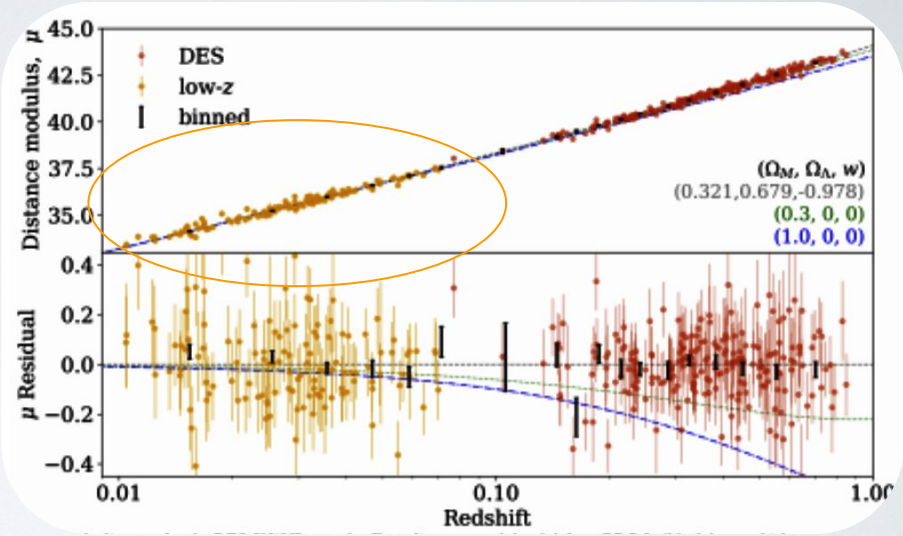
Table 4.

Sample	Number	Mean z
CSP	26	0.024
CFA3	78	0.031
CFA4	41	0.030
CFA1	9	0.024
CFA2	18	0.021
SDSS	335	0.202
PS1	279	0.292



Pantheon Sample (Scolnic et al. 2018)
Total 1048 SNIa

172 SNIa from CFA1, CFA2, CFA3, CFA4, CSP

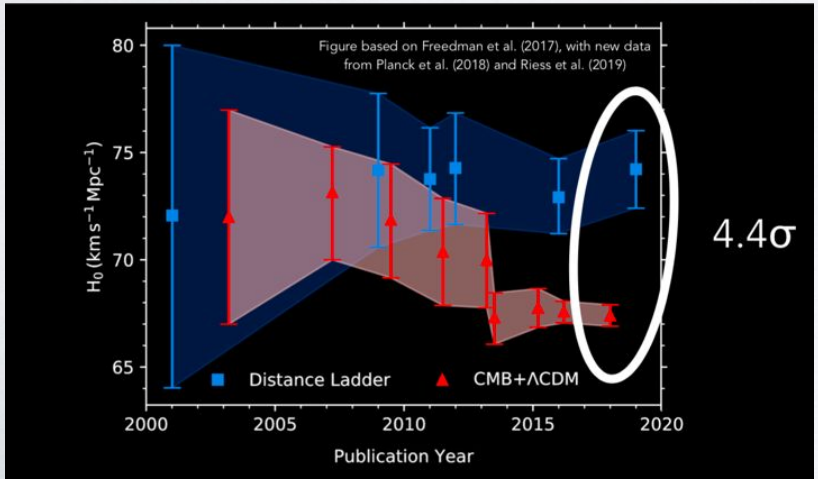


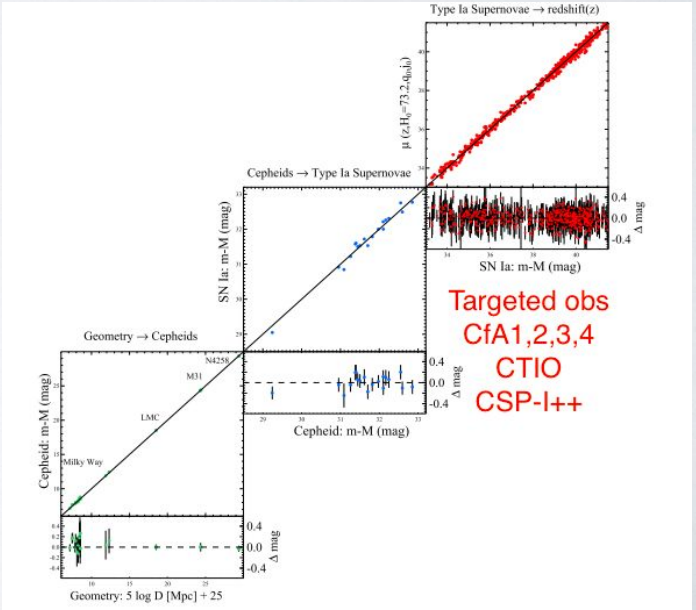
Dark Energy Survey (Abbott et al. 2019)
Total 251 SNIa from DES

122 SNIa from CFA3 CFA4, CSP

Hubble tension: Role of SNe~Ia

- Distance ladder; Cepheid has been tested extensively
- Hubble flow (0.023 < z < 0.15): Heterogenous
  - Several different telescope/instrument combinations
- **Environment bias**: Largest systematic for SNe (Scolnic+ 2019)
- ZTF will be a crucial, untargeted sample

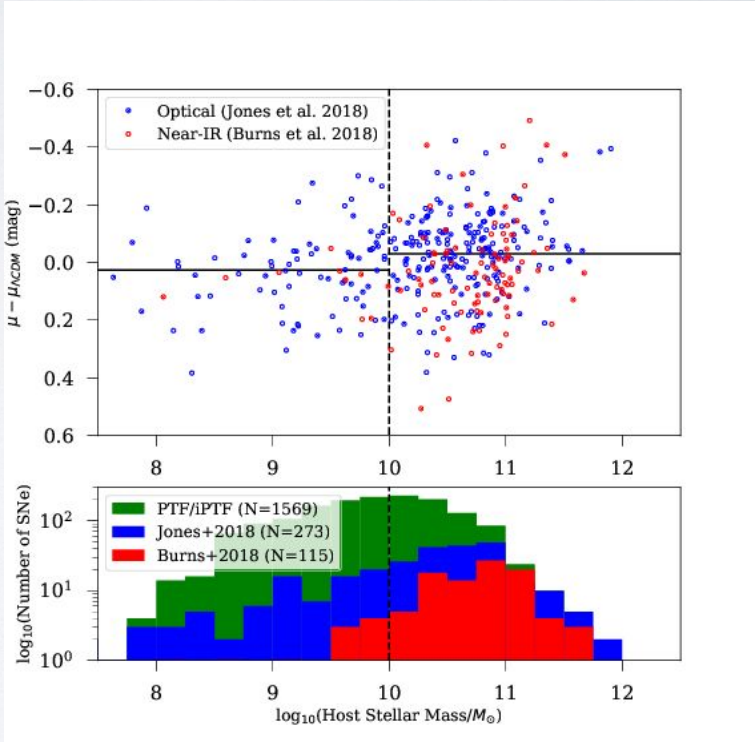




ZTF: A unique sample of SNe Ia

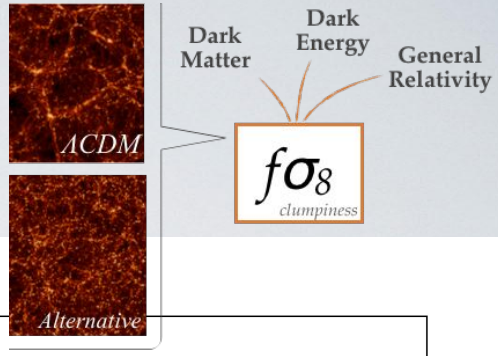
- ZTF is untargeted: Survey all SN Ia host types
  - Unlike, e.g. CSP (red points)
- Important for SN host - H_0 inference
- Cross-check for selection bias
  - Non-uniform Hubble flow sample
  - Even Foundation is follow-up only

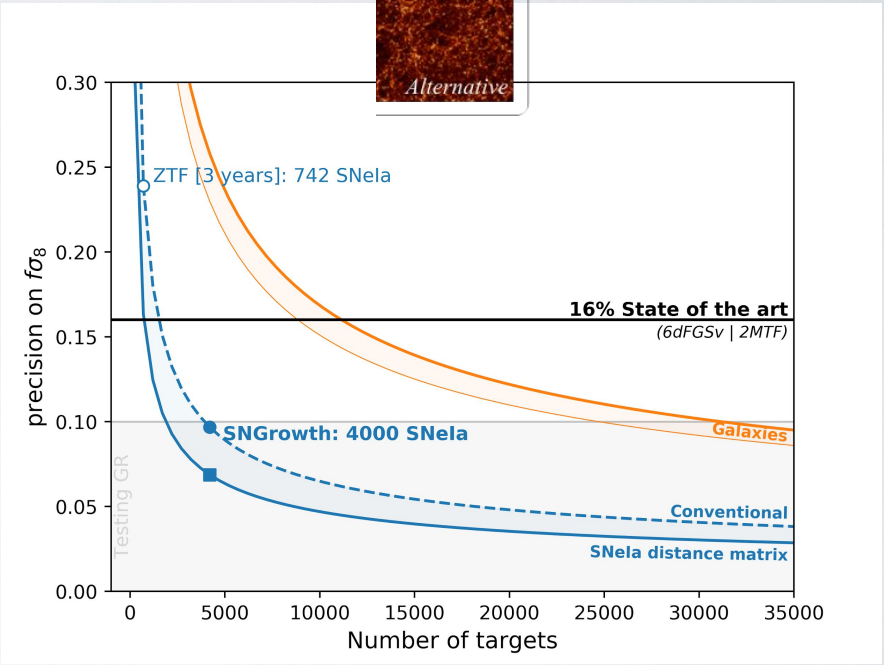
- Complete SN sample
  - Common ZTF goal
  - Photometric classification
- SN environment correlation

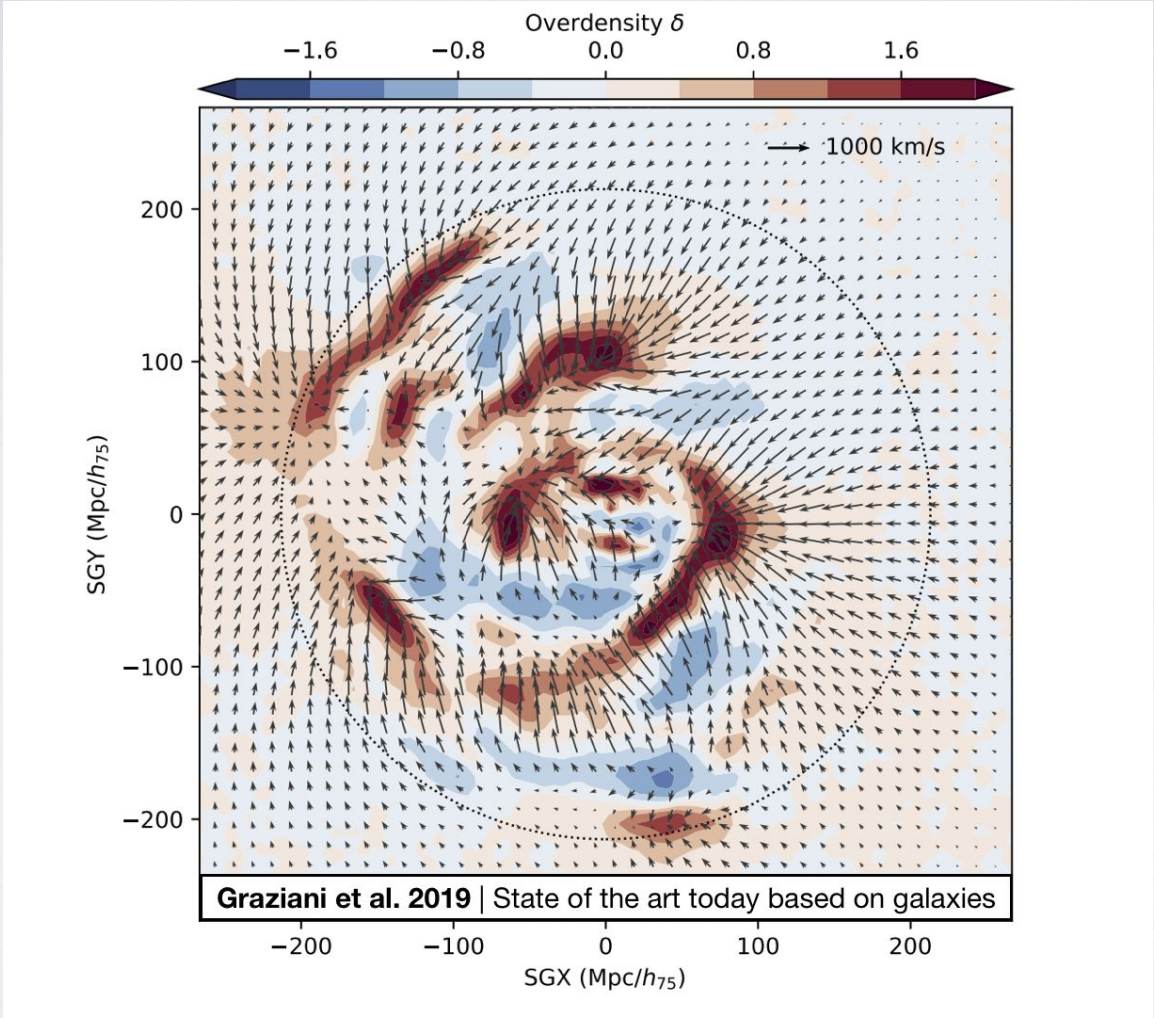


Growth of Structure

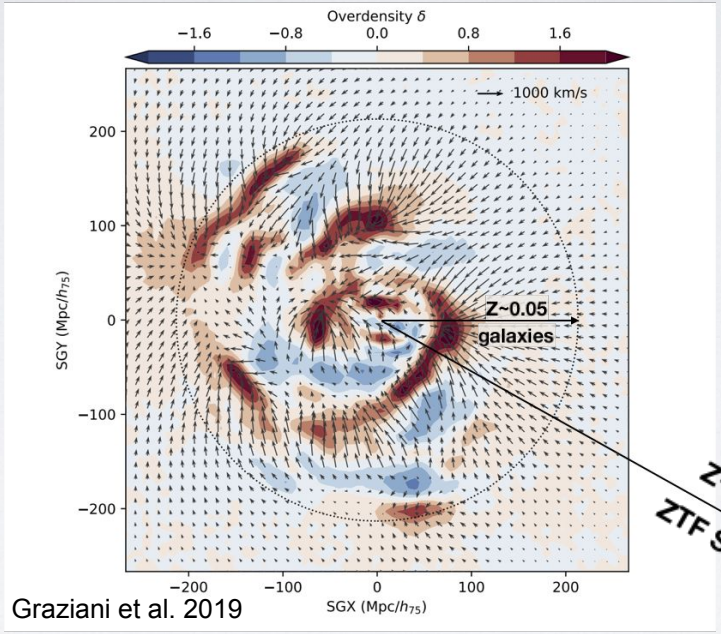
- In addition to distances, we can use peculiar velocities
- Measure growth of structure from velocity correlations
- Independent probe of σ_8 tension
- Require ~1000 SNe (statistically equivalent to ~15000 galaxies)
- Large coherent motion (bulk flow) in ZTF volume could contradict ΛCDM structure formation






Overdensity δ
−1.6
−0.8
0.0
0.8
1.6
1000 km/s
200
100
0
−100
−200
SGY (Mpc/h_{75})
Graziani et al. 2019 | State of the art today based on galaxies
−200
−100
0
100
200
SGX (Mpc/h_{75})

1 SNIa has statistical power of ≥15 galaxies

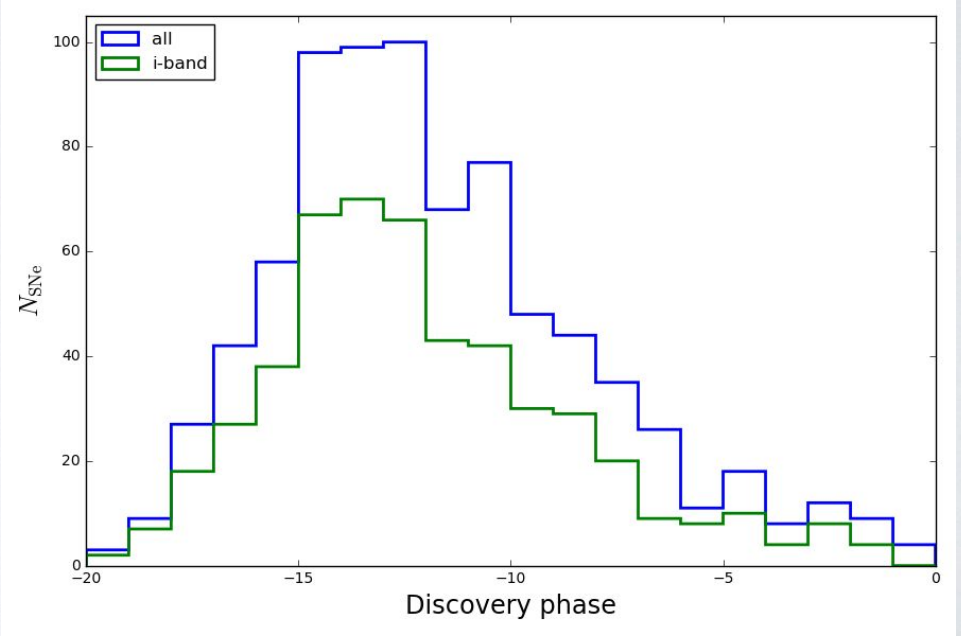


Graziani et al. 2019

Updates with ZTF data

Science with Early Discovery

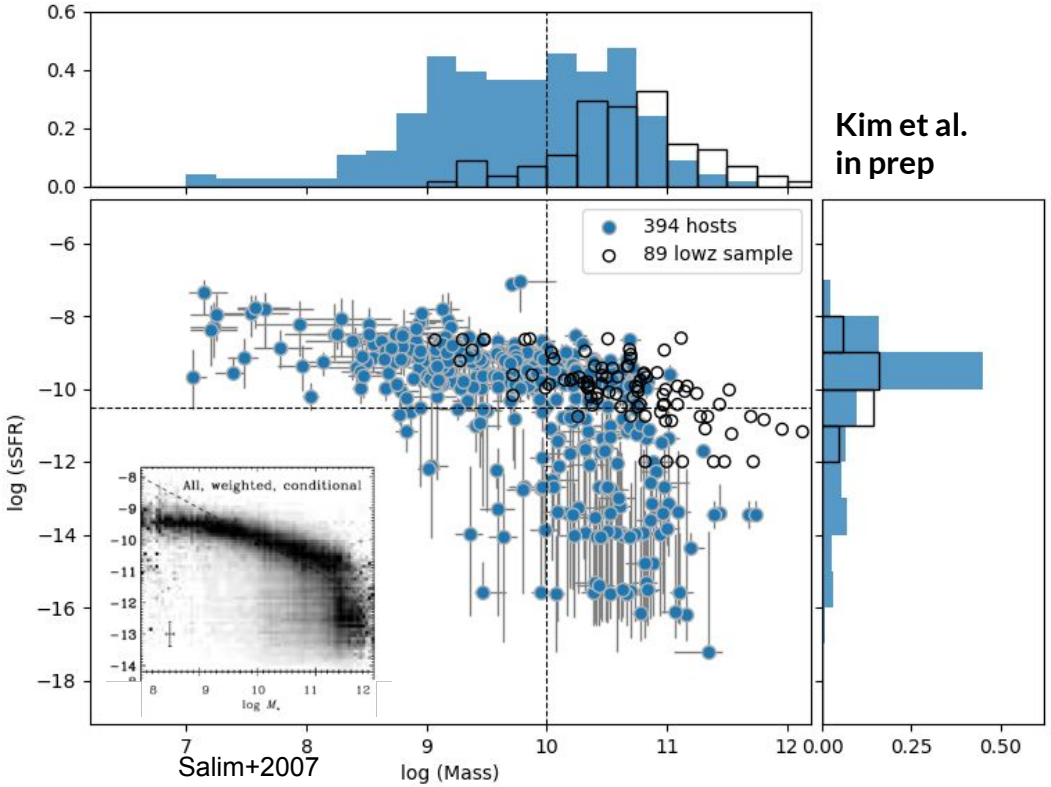
- Unique among cosmology samples, almost all SNe Ia were discovered more than a week before peak
  - Can use early lightcurve to estimate probability of transient being SN Ia.
  - Standardization by separate rise and fall time can improve standardization (see Hayden et al. 2019)



Discovery phases for SNe Ia. Credits: U. Feindt

ZTF SN Ia Hosts | Preliminary

- Host properties => impact DE/H0 constraints
- Underlying cause unknown
  - Different dust properties?
  - Intrinsic 56Ni difference?
- SDSS ugriz photometry fitted
  - LePHARE for fitting 394 hosts
  - Pan-STARRS to increase sample
- Symmetric distribution in mass
  - Low-z data is asymmetric (e.g. Kim et al. 2019)
  - Important to test selection effects



Kim et al. in prep

Salim+2007
(~50,000 galaxies at z~0.1)

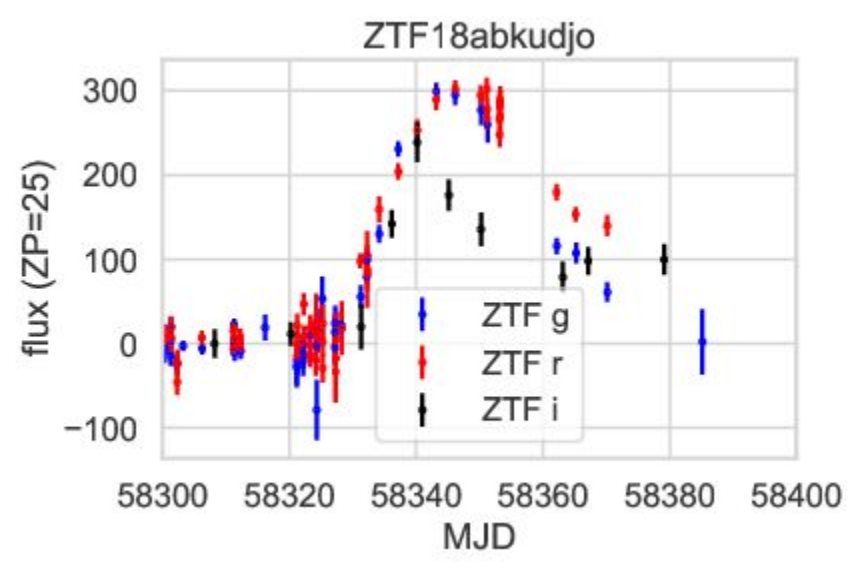
Photometry

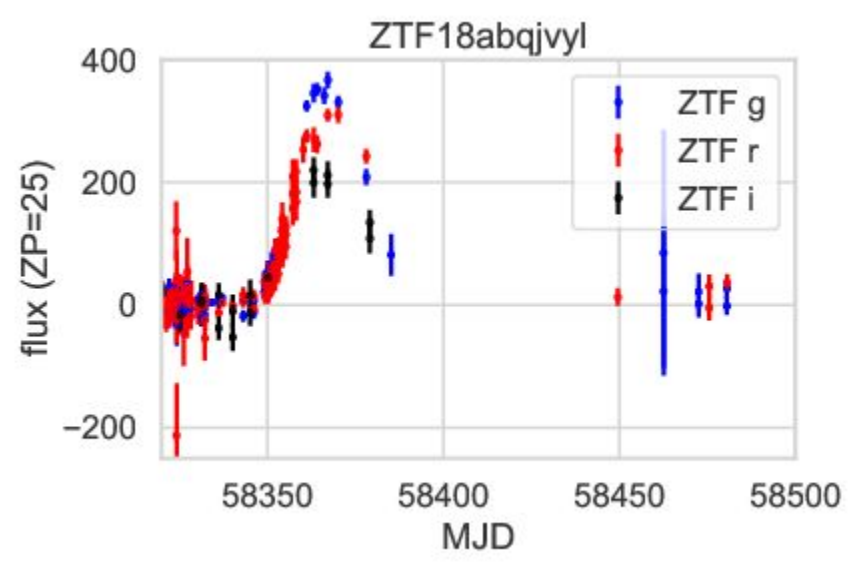
- Cosmology impact and legacy tied to photometry systematics
- Show that a sequence of potential effects are subdominant:
  - Readout, flatfield, extraction, subtraction etc
- Requires repeated data reprocessing, not possible currently
  - Long term solution required. Parallel pipeline?
  - **Necessary:** Having a tool ***we*** could use to reprocess data
  - **Urgent:** re-doing (i) reference images having SN light.
- Yr 1 cosmology papers might use post-processing corrections
  - No path to demonstrate photometric quality for these

Year 1 SNIa base sample

- ZTF SNIa fulfilling basic lightcurve quality cuts
  - Not considered “cosmology” yet
  - 479 SNe in total (314 with i-band)
- Size determined by:
  - Reference reprocessing and i-band lightcurves
  - Host galaxy redshifts (e.g. DESI SV)
- To be used for a series of papers

Year 1 SNIa lightcurves

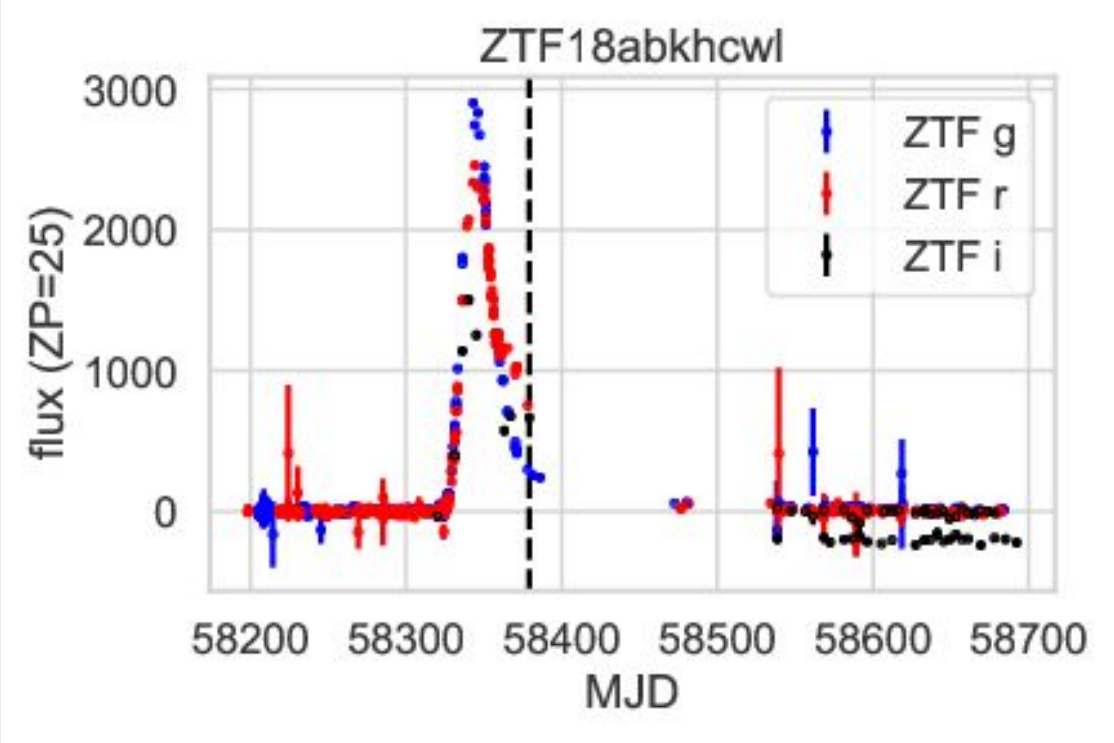




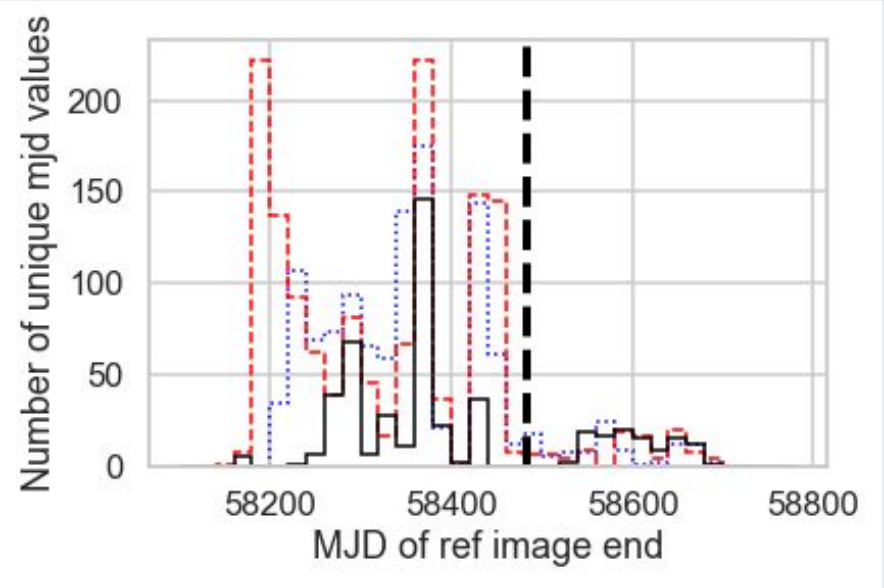
MSIP+i-band

High-cadence

SN in i-band reference



SN in reference



Times of last image used in reference images

SNIa with good references in different bands

Criteria	*Number of SN*
In sample	*1056*
Good references in at least one band	*964*
Good references in g band	*843*
Good references in r band	*931*
Good references in i band	*336*

Good references : images in references taken at least 30 days before SN peak (SALT t0).

Preliminary Hubble diagram

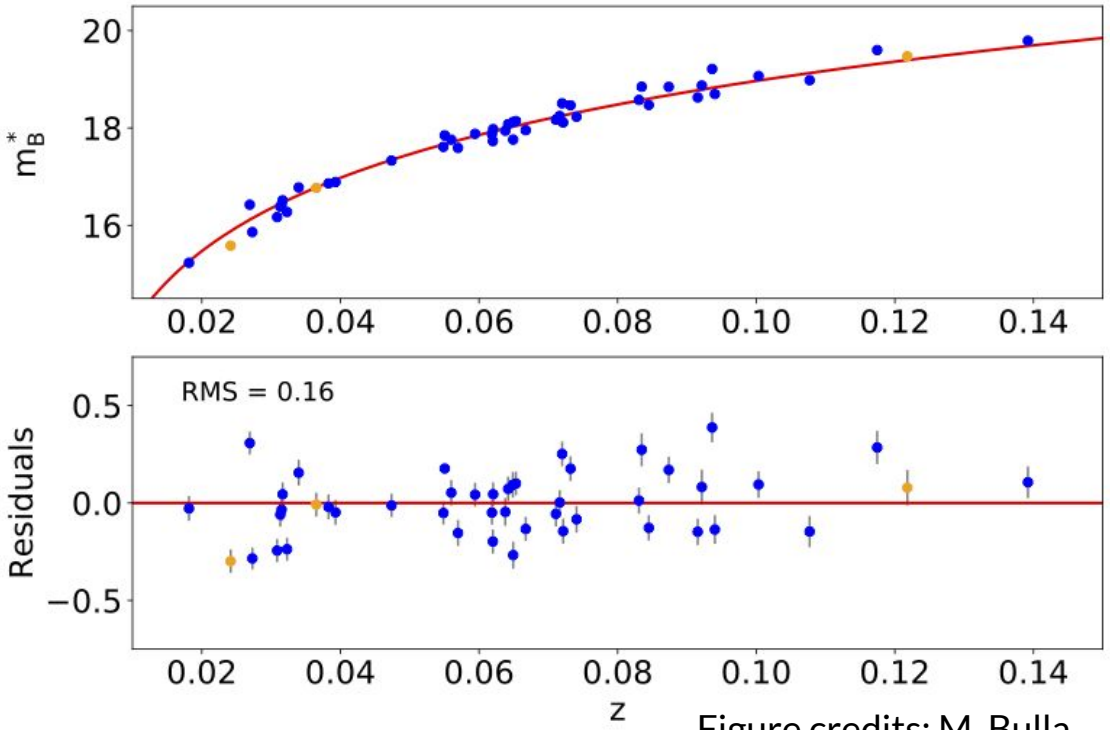


Figure credits: M. Bulla

- Early discovery
  - Gold sample (Yao et al., submitted)
- Limited by host-z
- Scatter high
  - ~ 0.12 mag known

Year 1 spectra: SEDm

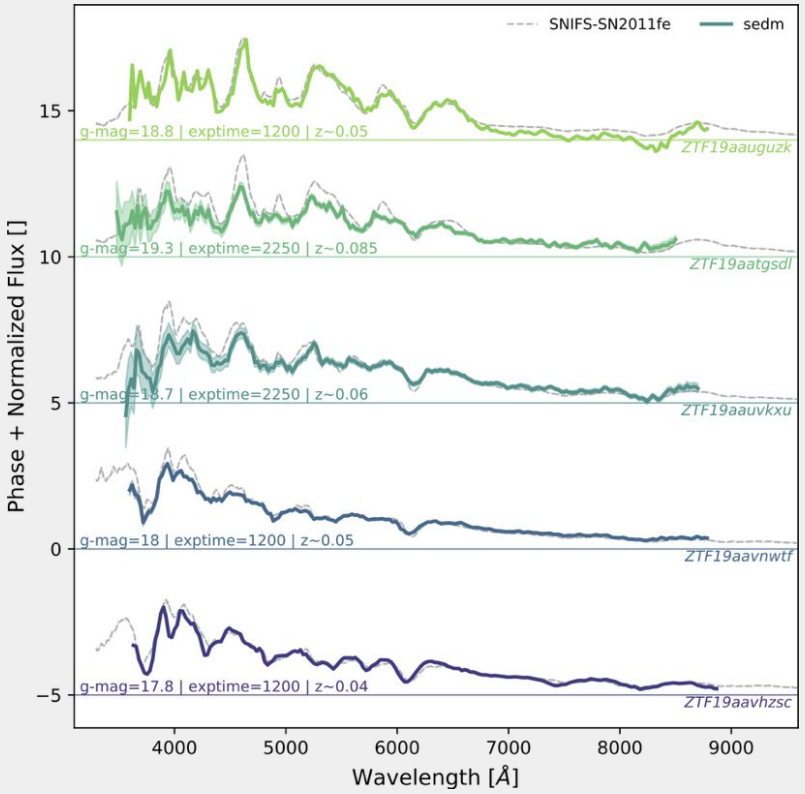
Type Ia Spectral analysis:

- Typing/subtyping
- Spectral evolution w phase
- Correlation spectral features
  - Host
  - LC

SEDm (mainly) *+ any other spectra*

[cross WG analysis: SEDm & Cosmo & SN & RCF]

SNeIa of June 1 2019 (random day)

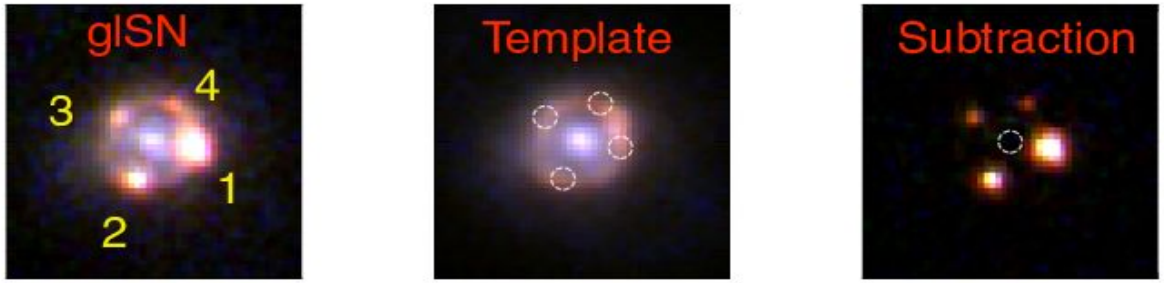


Rigault et al. in prep

iPTF16geu: First resolved lensed SN Ia

- Short time-delays (~ 1 day)
- Resolved photometry begin late (> 2 weeks after max)
- Extremely high magnification (> 65 times)
- Evidence for microlensing

Dhawan et al. 2019, submitted; Figure credits: Joel Johansson



Lensed SNe with ZTF

- H_0 from time-delays (3-4% per object)
  - ZTF is expected to **discover** a few lensed SNe per year
  - **Resolved (A.O)** follow-up required; have VLT/Gemini time for optical/NIR

Simulation by Danny Goldstein

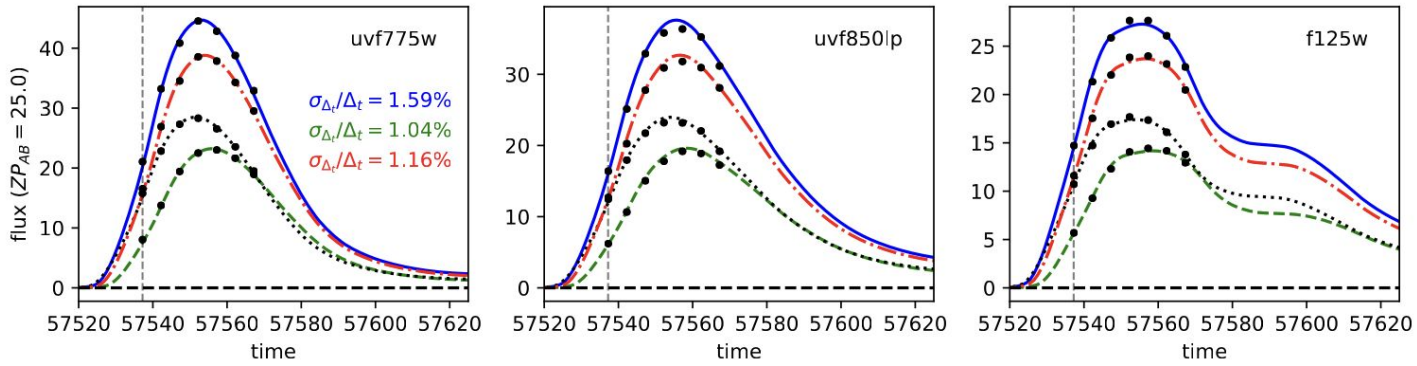
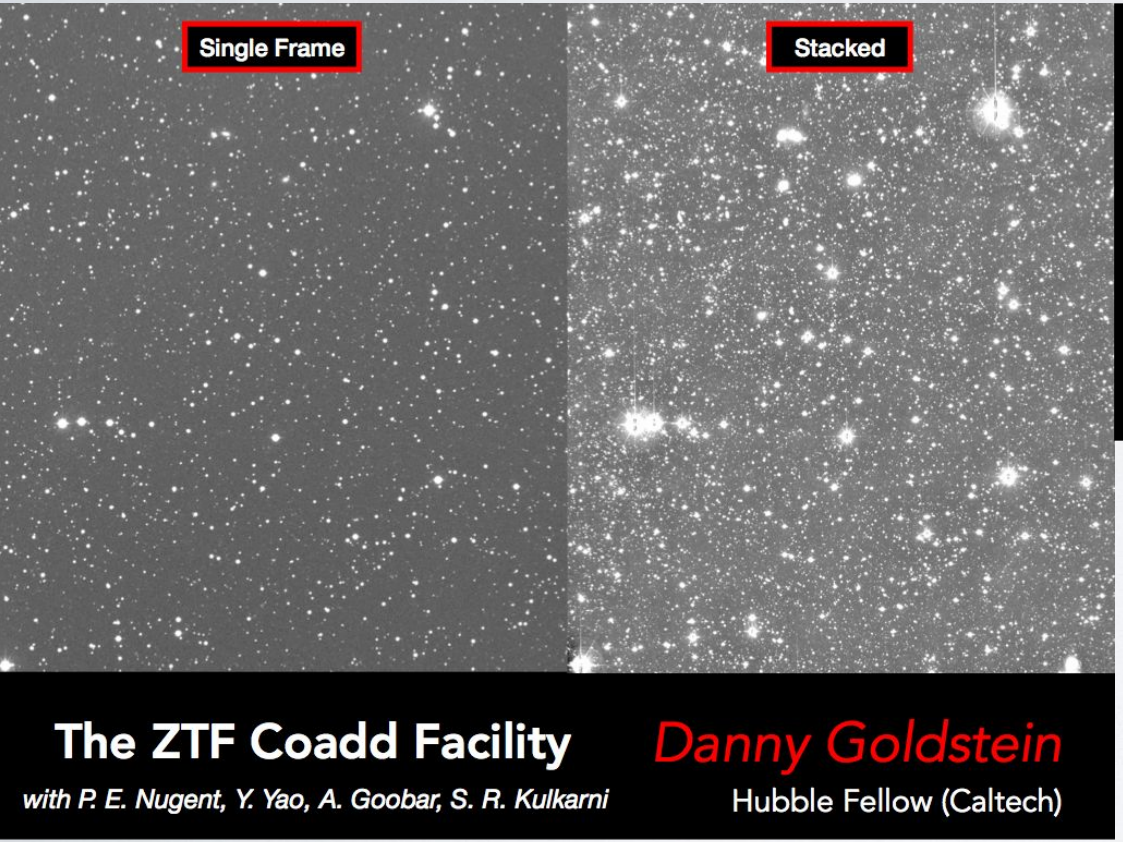
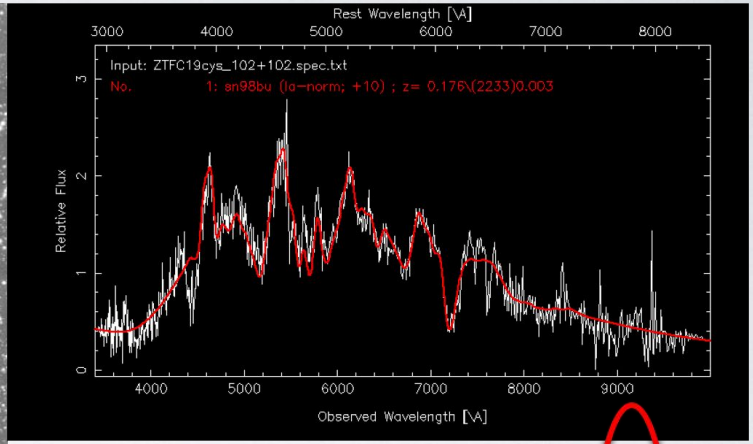
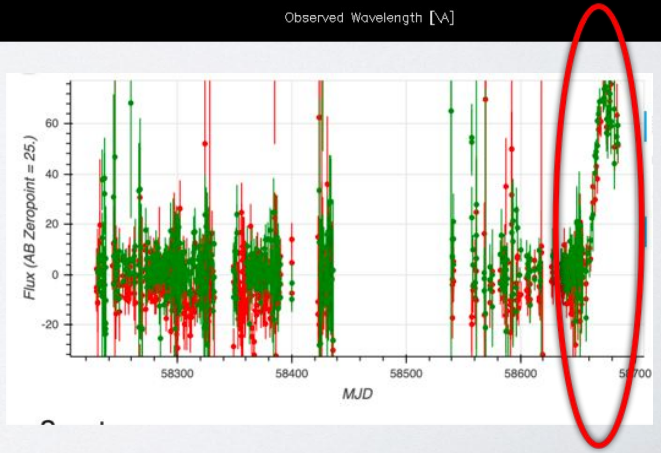


Image Stack: lensed and high-z SNe







Paper plans

Expansion history:

- Low-z anchor (Goobar)
- SEDM SNeIa (Rigault)
- SN selection: Impact on H_0 (Dhawan)
- Properties of complete SN samples (Nicolas, Biswas, Kim)
  - Lightcurve properties
  - Host properties

Growth of structure:

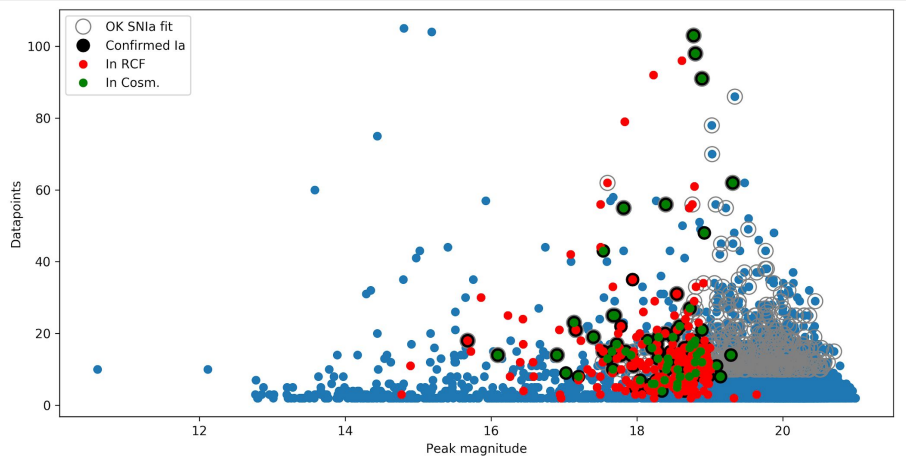
- Bulk flow, directional H_0 (Brinnel, Amenouche)
- Amplitude of fixed power spectrum (Brinnel)
- Combining SN velocities and densities for cosmology (Graziani)
- Void dispersion (Nordin)
- ZTF Phase II and LSST outlook (Graziani)

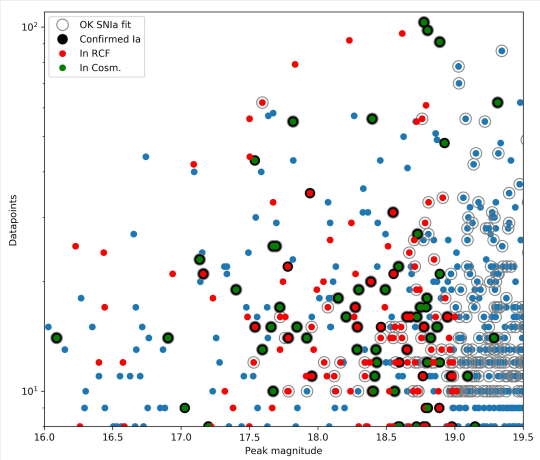
Summary and Outlook

- ZTF: Ideal sample for completeness/testing biases
- Early discovery: New standardization procedures
- Untargeted survey
  - Test of SN environment systematics
- Year 1 SEDm spectra study
- Preliminary Hubble diagram
  - Understand systematics better from calibration
- iPTF16geu: Extremely high magnification
  - Lensed SNe to measure H_0
  - Image stack improves distance X 2

Unbiased SN sample

Comparison with AMPEL alert rerun. Here last month:

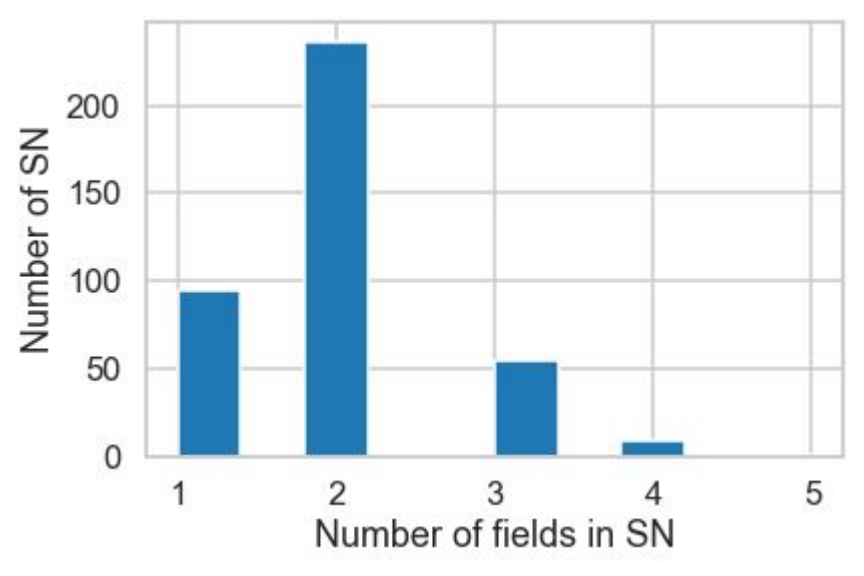


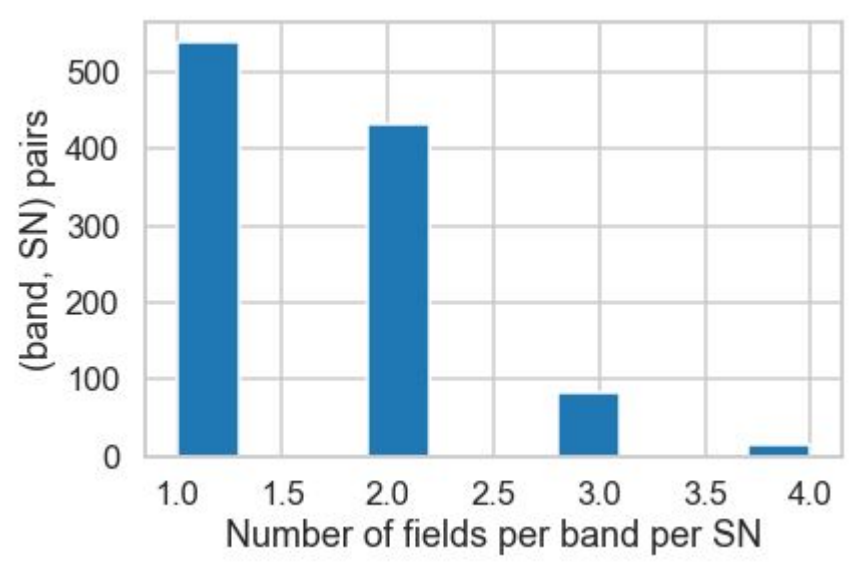


We find:

- Bright transients with SN like lightcurves not in RCF/Cosm.
- Fainter transients that are compatible w. SNe
- Potential photo-SN for DESI SV sample

Yr1 SNIa lightcurves





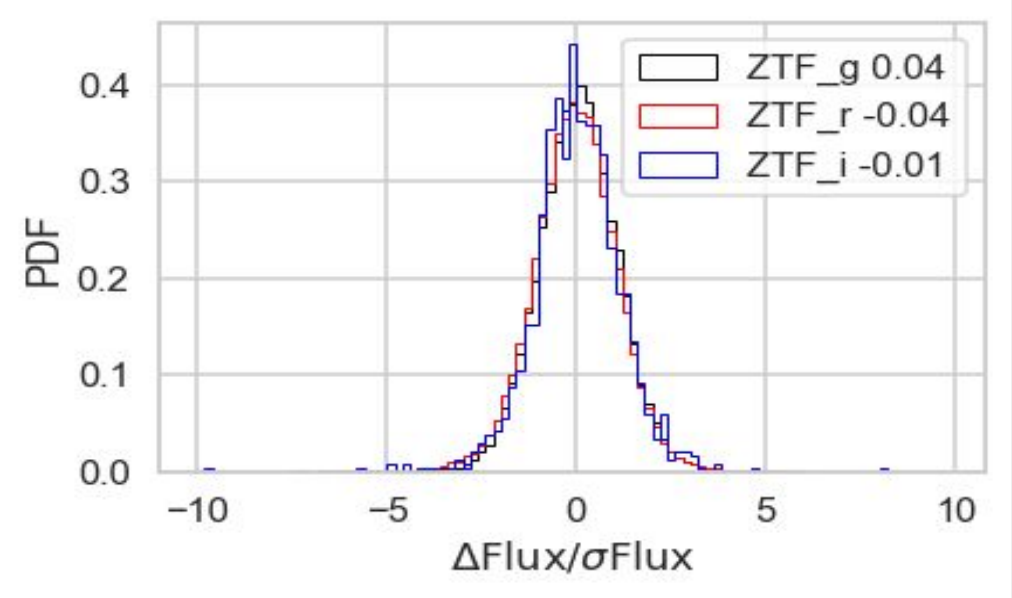
Year 1 spectra: Other sources

- SNIFS @ UH88 for MSIP targets
  ~ 20 nights with ~ 10 SNe

- ePESSTO time

- DESI for host galaxy redshifts

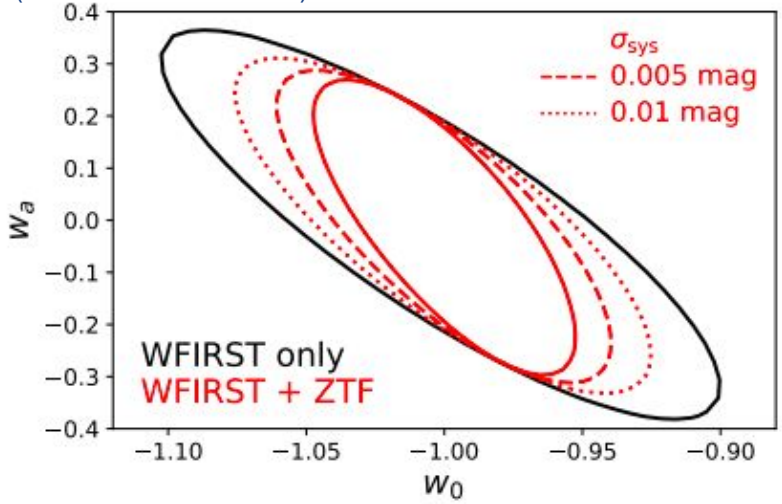
Yr1 SNIa lightcurves



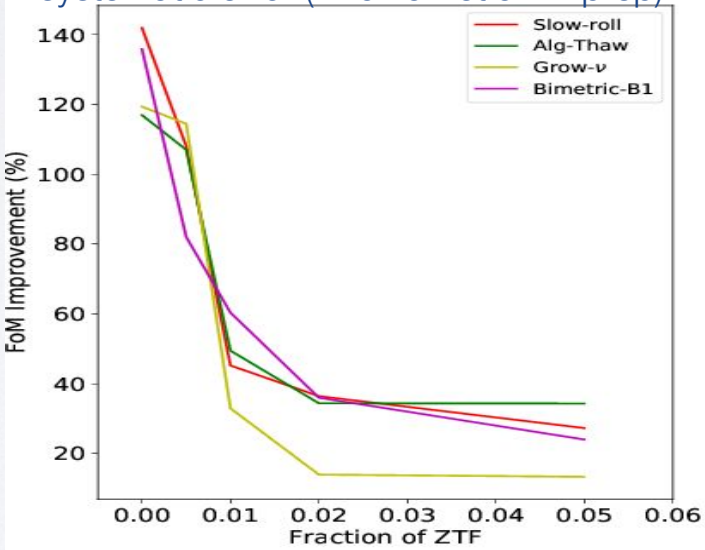
On epochs before 30 days preceding SALT t0

Calibration systematics: Impact on cosmology

Role of systematics in constraining dark energy (Feindt et al. 2019)



Exotic dark energy models versus systematic error (Dhawan et al. in prep)



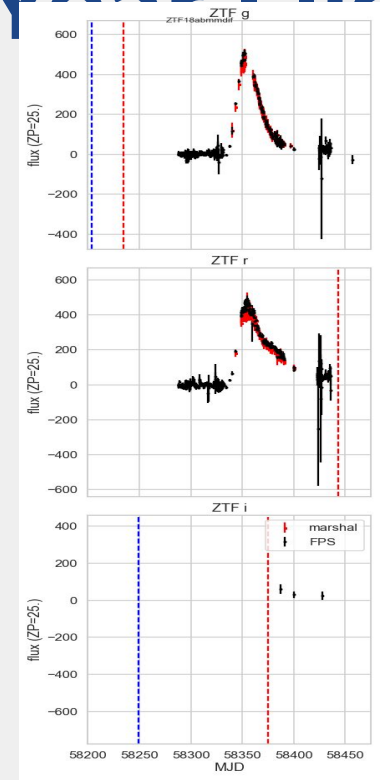
Paper plans II

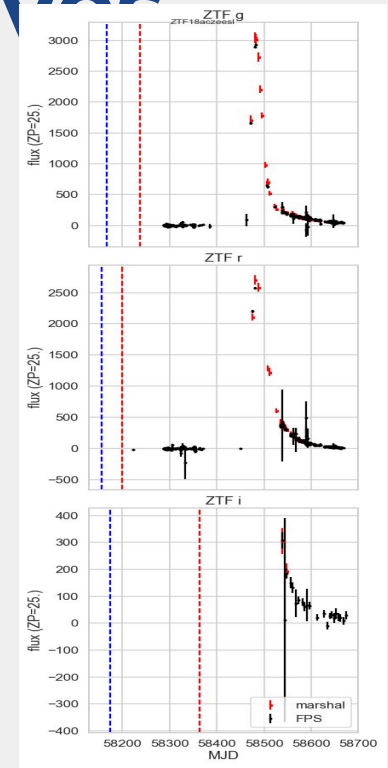
- Low-z anchor (Goobar)
- SEDM SNeIa (Rigault, see slide 12)
- Hubble parameter (Dhawan)
- Properties of complete SN samples (Nicolas, Biswas, Kim)
  - Lightcurve properties
  - Host properties

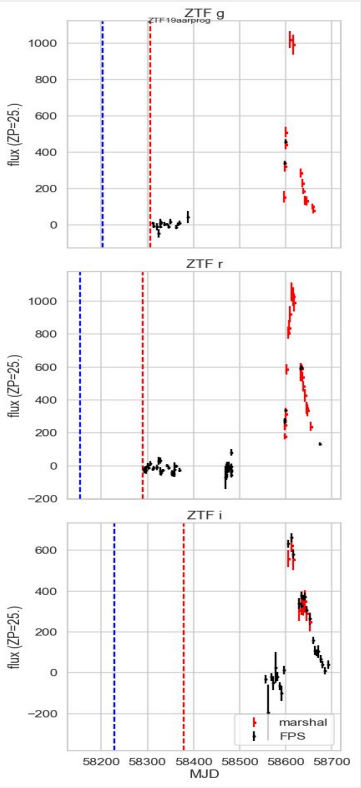
[Do we have some preliminary sample plot to use??]

[MR: Y.L Kim is going one.]

Year Light curves







Plans for the coming year

Outline

1. ZTF Legacy Surveys (BTS, CLU)
2. Early Observations of SNe (Ia, CC)
3. SN Ia Cosmology
4. Unusual CC SNe (Stockholm, Weizmann)

SN Ia Cosmology

BTS (Bright Transient Survey)

We are successfully classifying (almost) every bright (m<18.5) supernova in the Palomar sky!

Most productive SN survey ever (per TNS statistics)

Statistical samples of every SN type from "normal" to exotic.

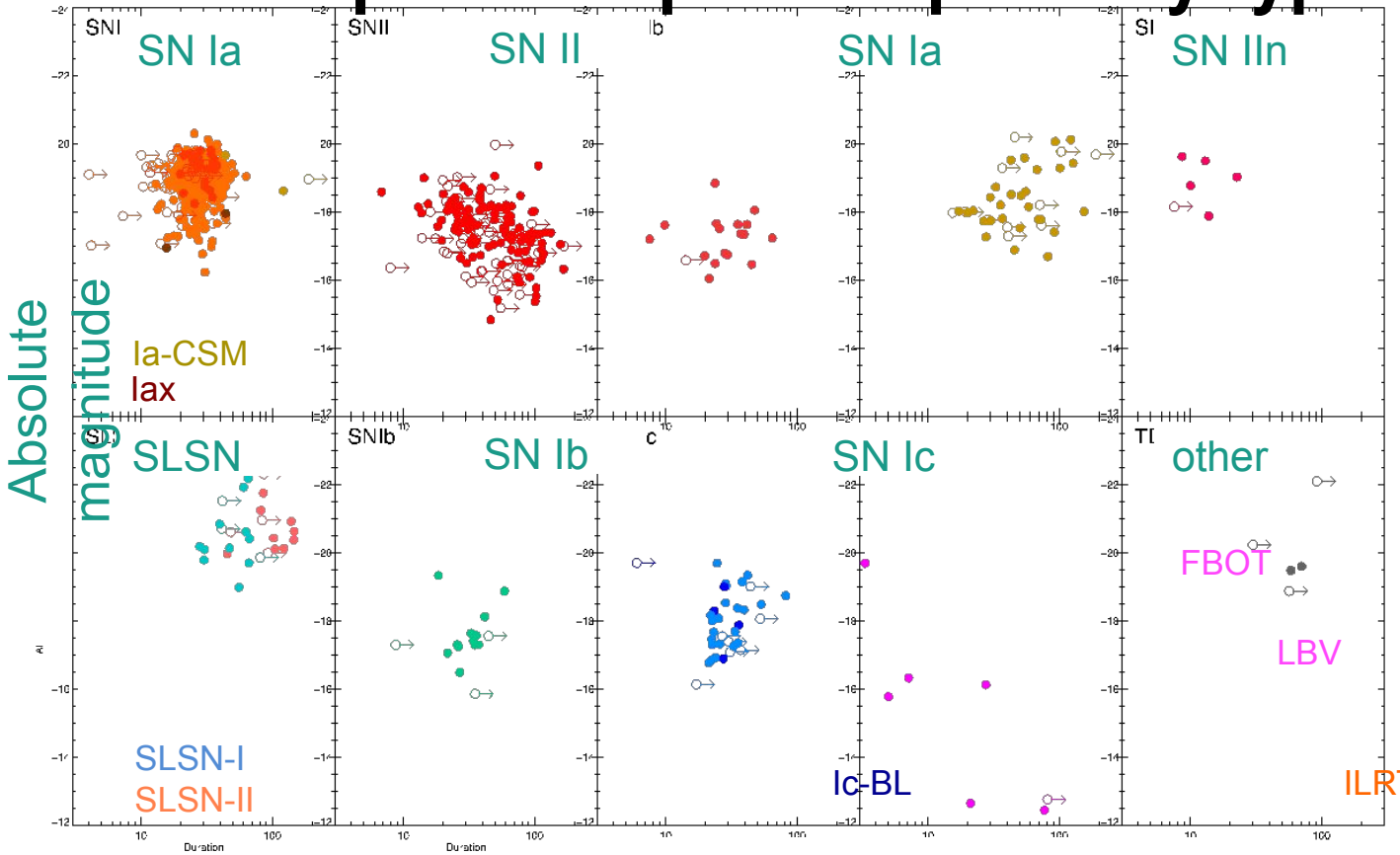
Mag limit	# SNe	% classified
17	116	99.1 %
17.5	207	99.0 %
18	397	96 %
18.5	**743**	**93 %**
19	1234	82 %

(considers events with good light curve coverage and SN-like rise and fall times)

786 SNe Ia (3 Ia-CSM, 2 Ia-x)
243 SNe II (19 IIb, 40 IIn, 13 SLSN-IIn)
65 SNe Ib/c (7 Ibn, 9 Ic-BL, 15 SLSN-Ic)
6 TDE (2 "hyperluminous")
7 "other" (1 FBOT, 3 LBV, 1 ILRT, 1 Ca-rich)

First-year sample paper and galaxy-catalog redshift completeness study (Fremling, Miller et al.) is approaching completion.

BTS: Supernova phase space by type

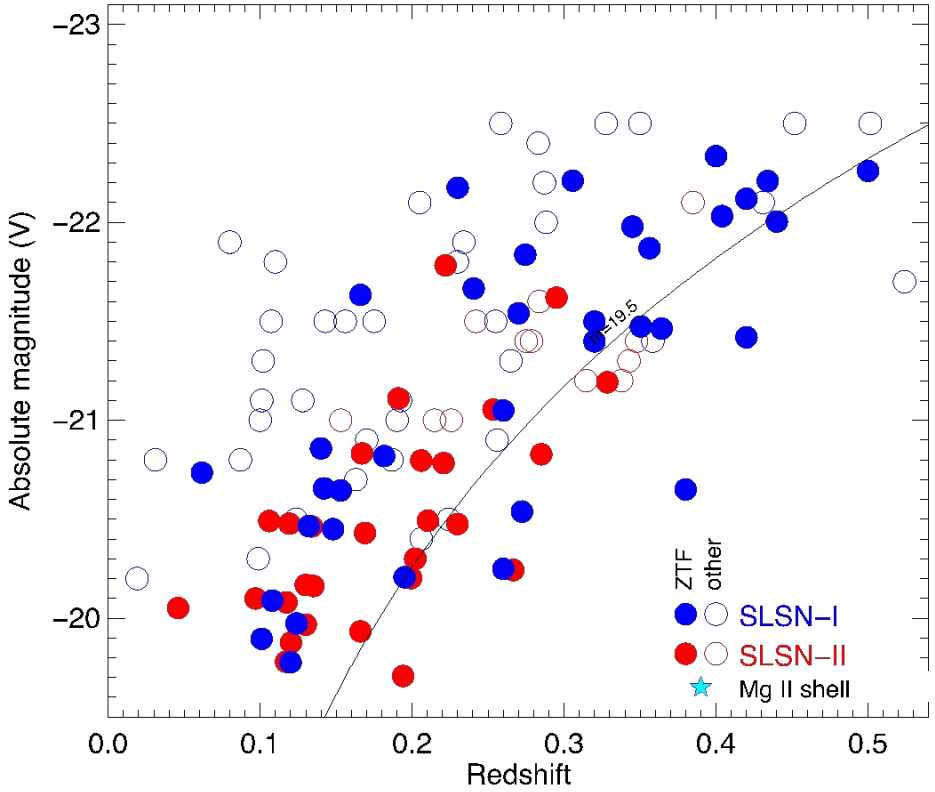


ZTF Legacy Surveys:

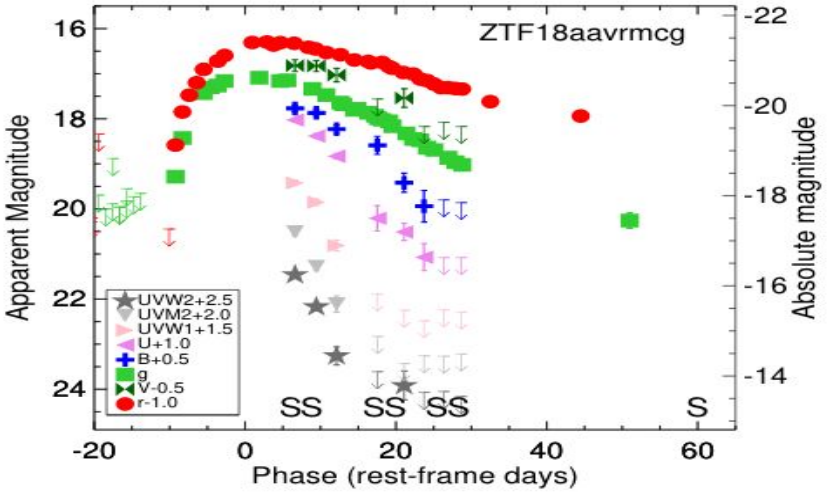
Bright Transient Survey (BTS)

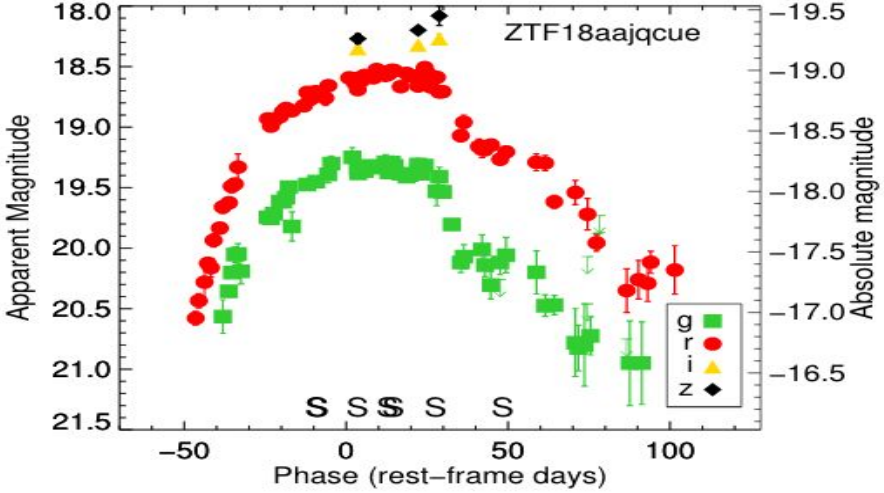
Census of the Local Universe (CLU)

SLSNe: 73 and counting



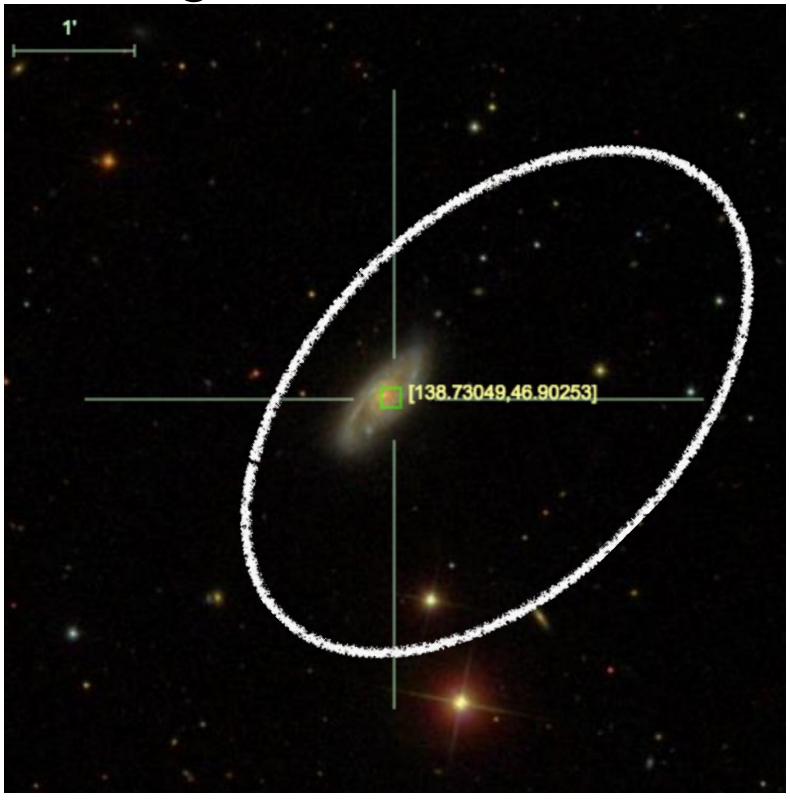
SLSN diversity: fast event, red/dusty event



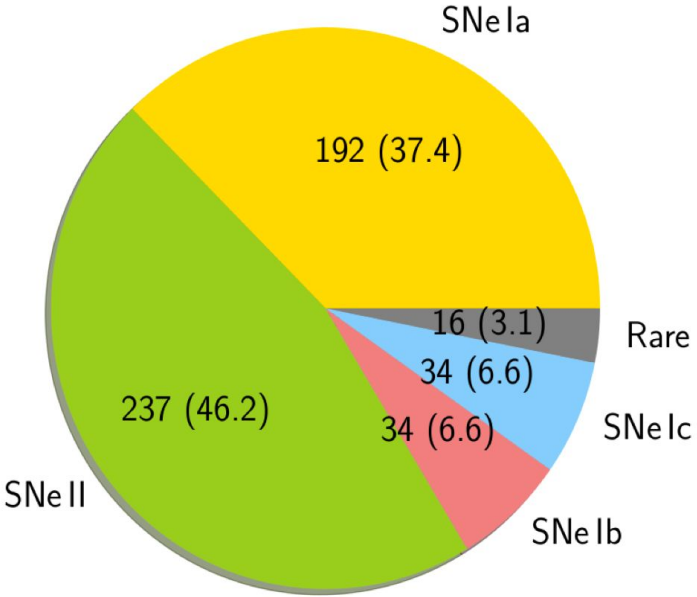


Census of the local universe (CLU)

A systematic, volume-limited experiment to find transients coincident with galaxies in the local universe (< 200 Mpc)

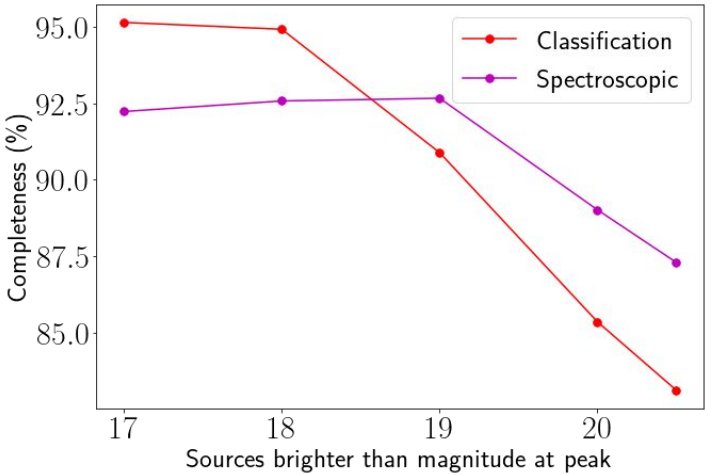


CLU Classifications

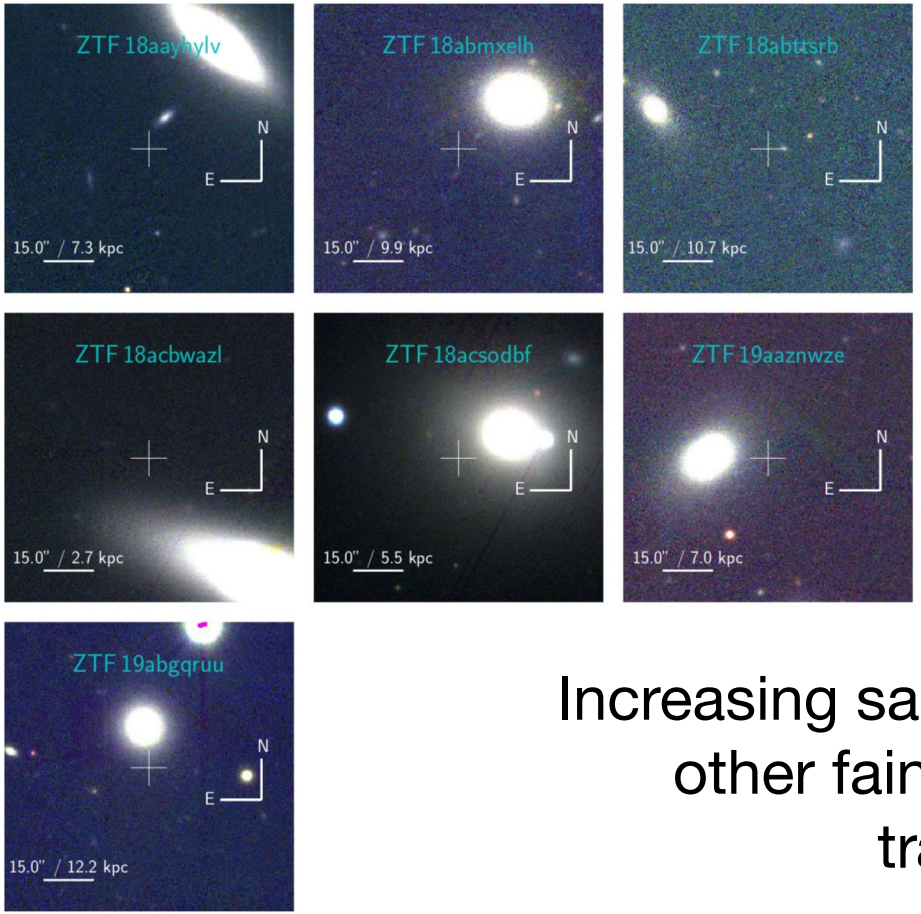


Classification completeness > 85% down to 20.5 mag

Limited by moon phase and targets found too close to sun

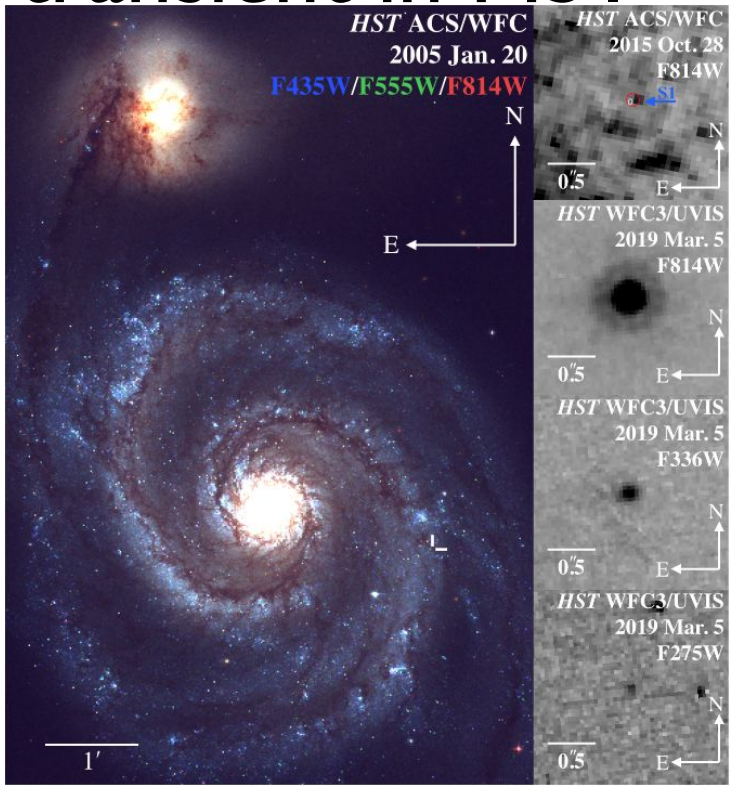


Faint and fast transients



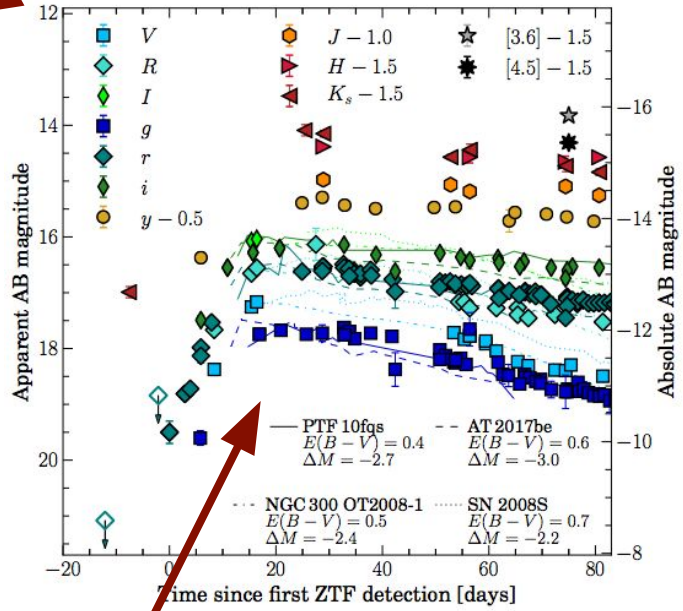
Increasing sample of Ca-rich and other faint / fast evolving transients

ZTF19aadyppr: An intermediate-luminosity red transient in M51



Jencson+ 2019, *ApJL*, 880, 20

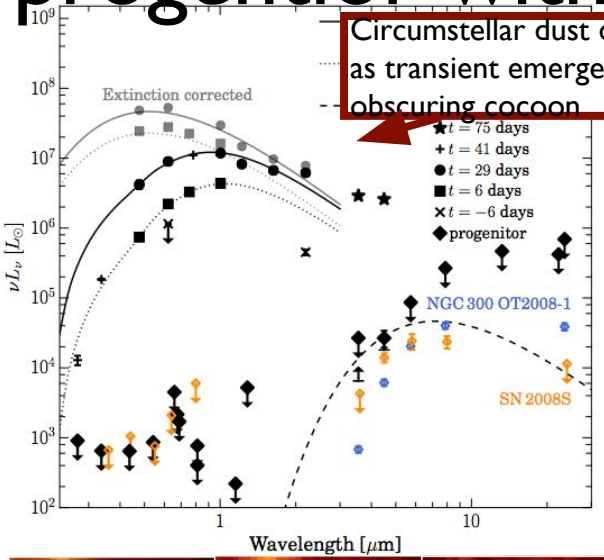
No candidate progentior star in archival HST imaging

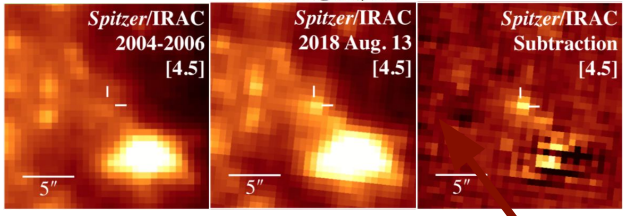


Early detections show slow rise and color evolution to the blue

Direct identification of self-obscured, IR-variable progentior with *Spitzer*.

Circumstellar dust destruction as transient emerges from obscuring cocoon

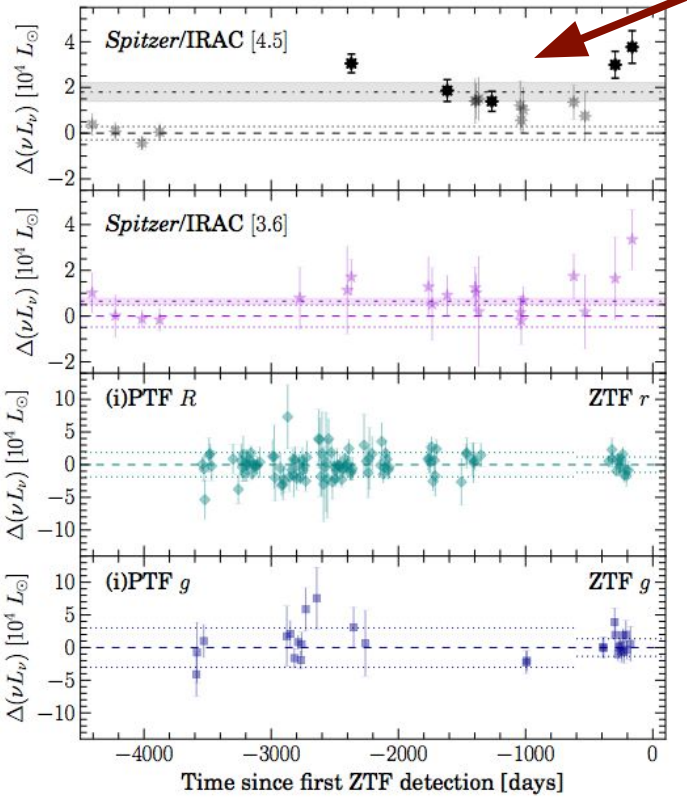




IR progentior star showing variability in pre-explosion *Spitzer*

Jencson+ 2019, *ApJL*, 880, 20

IR pre-explosion brightening episodes



No pre-explosion variability in optical

Early Observations of Supernovae:

Ia and Core-Collapse

Automated discovery and follow-up

Previous low-z SNe Ia samples

Sample	# SNe Ia	Time span	Redshift range	Early fraction ★	# ops nights	Bands
SDSS-II	**327**	2005-2007	0.037–0.4	33%	9	*ugriz*
CfA3	185	2011-2008	0.005–0.085	5%	12	*BVRIr'i'*
CfA4	94	2006-2011	0.055—0.073	5%	16	*(u'U)BVr'i'*
LOSS	165	1998-2008	0.002—0.095	19%	21	*BVRI*
CSP-I	134	2004-2009	0.0037-0.0835	10%	28	*uBgVriYJH*
CSP-II	214	2011-2015	0.004-0.137	10%	25	*uBgVriYJH*
PTF/iPTF	265	2009-2014	0.0007—0.409	65%	**35**	*R*
Foundation-I	225	2015—2017	0.004—0.11	10%	7	*grizy*
TESS-2018	18	2018	0.0163—0.09	**89%**	20	*I*

★ The fraction of SNe with first detection prior to 10 days before maximum light

ZTF & Previous low-z SNe Ia samples

Yao (2019, submitted)

Sample	# SNe Ia	Time span	Redshift range	Early fraction	# ops nights	Bands
SDSS-II	327	2005-2007	0.037–0.4	33%	9	*ugriz*
CfA3	185	2011-2008	0.005–0.085	5%	12	*BVRIr'i'*
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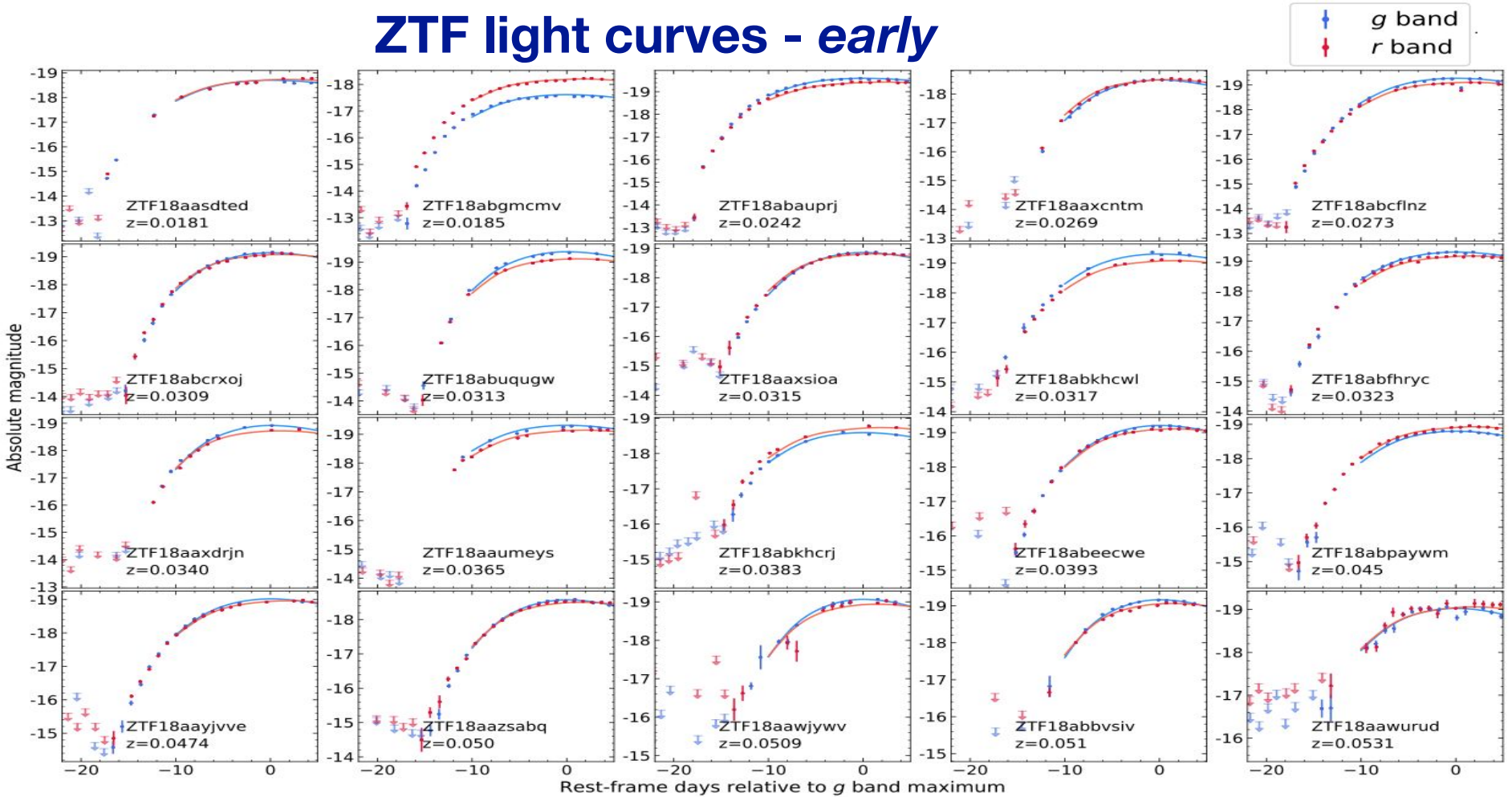
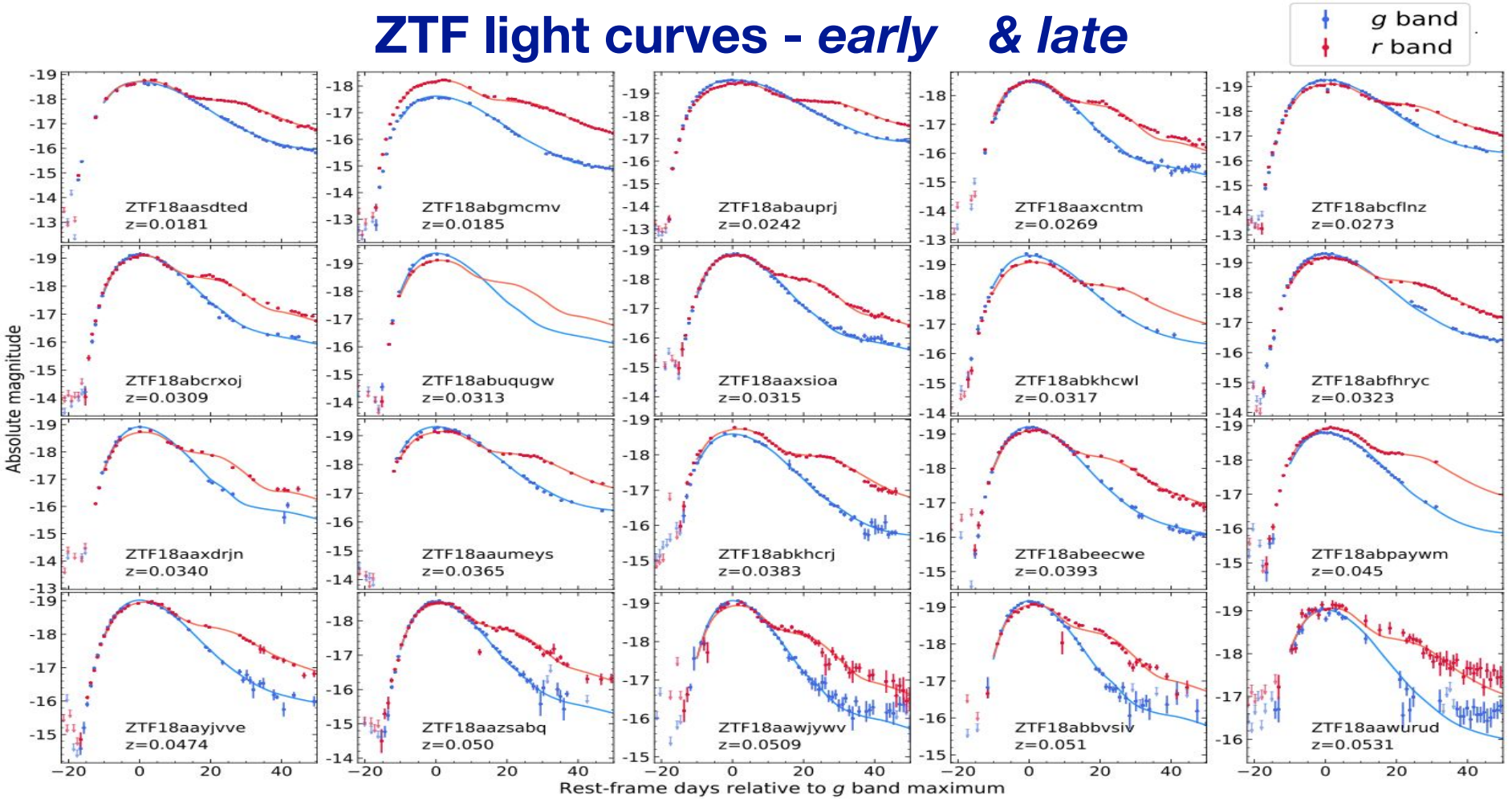
Foundation-I	225	2015—2017	0.004—0.11	10%	7	*grizy*
TESS-2018	18	2018	0.0163—0.09	**89%**	20	*I*
ZTF-2018	127	2018	0.0182—0.0164	**100%**	**43**	*gr*

ZTF light curves - *early*



Yao (2019, submitted)

ZTF light curves - *early* & *late*

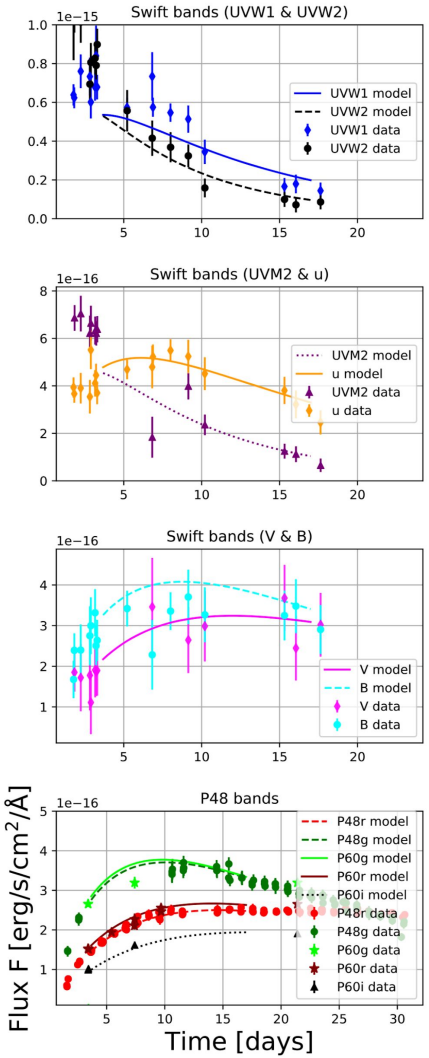


Yao (2019, submitted)

Early LC modeling

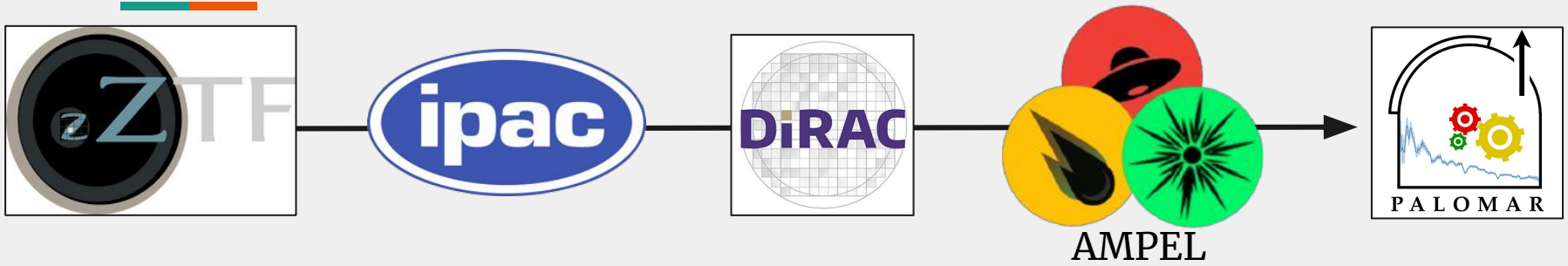
- ~~2018fif~~ (ZTF18abokyfk) was discovered close to first light and followed up by SWIFT
- It is a good candidate for testing shock cooling models (Sapir & Waxman 2017)
- The main challenge: the temporal validity window of these models depends on the parameters of the models!
- the progenitor of SN2018fif was a large red supergiant, with a radius of $R=1174\ ^{+208}_{-81}$ solar radii, and an ejected mass of $M=5.6\ ^{+9.1}_{-1}$ solar masses. Larger than previously modeld object.
- The code SOPRANOS will become available to the community on October 15 and is available now upon requests.

Soumagnac et al. 2019 (submitted to ApJ)

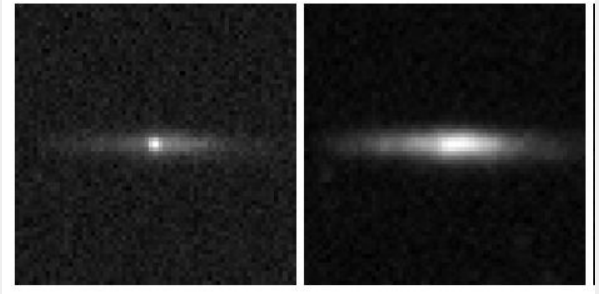


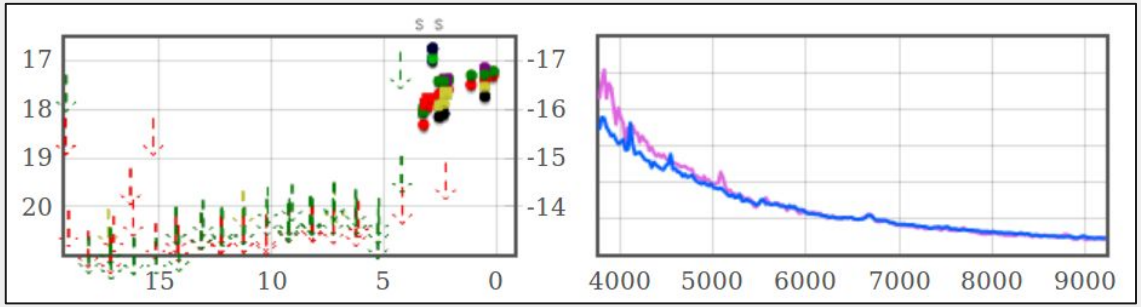
ZTF19abqhobb

First fully autonomous optical transient follow-up



Young SNII w. flash features at z=0.01815





AmpelRapid

Developments coming after first trigger:

- Faster follow-up.
  First trigger revealed delays both at AMPEL and SEDM. (~2h)
- Better Growth Marshal integration.
  AMPEL SEDM triggers not automatically visible.
- Gradually relaxed trigger requirements.
  In next phase from ~1/month to ~1/week
- Improved integration with InfantSN program.
  Alerting scanners of “almost” automatic triggers.

From Stockholm:

Stripped-envelope core-collapse supernovae

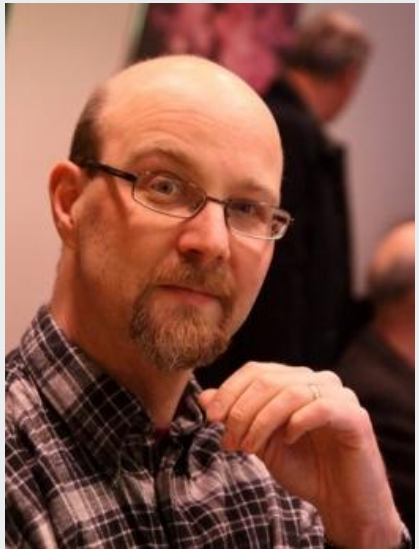
Sorry we could not come!









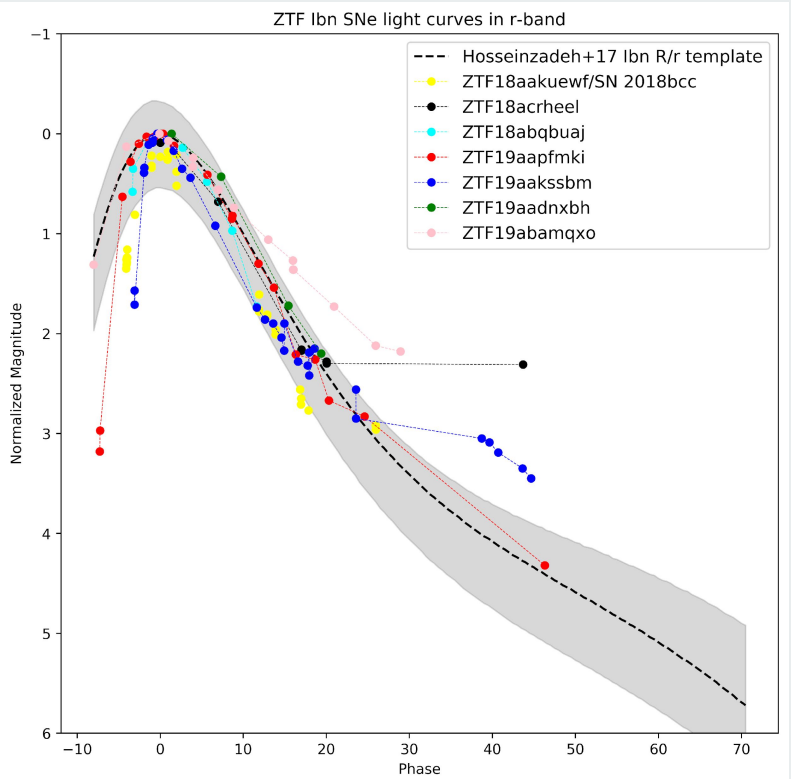


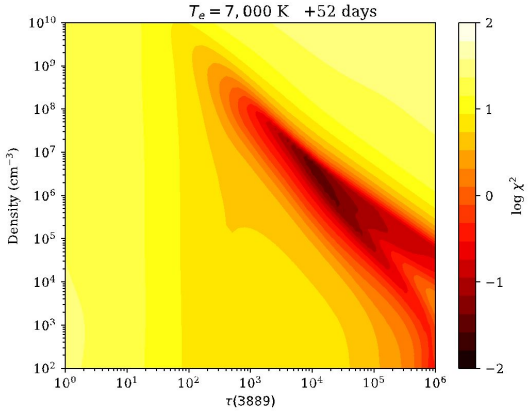

Four examples

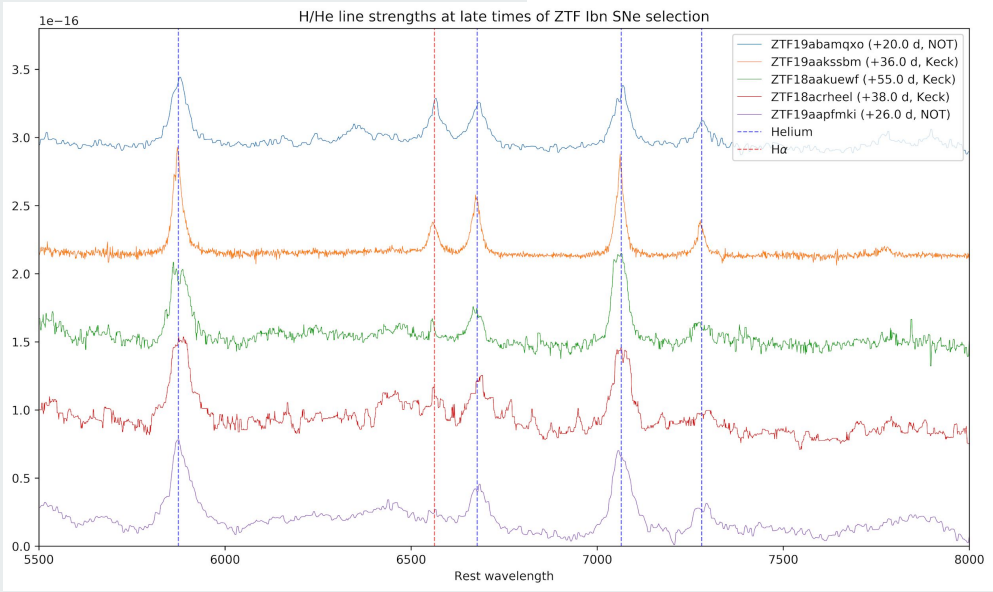
- Supernovae Type Ibn – A detailed study of SN2018bcc (Emir) and a full ZTF sample (Erik)
- Rise times of SNe Type Ic, a ZTF sample (Cristina & master student Patrik Moquist)
- A SN Ic with a weird spectral sequence (Leonardo)
- Another SN Ic with the funniest light curve (Cristina)

SNe Ibn

Stripped envelope supernovae with narrow Helium lines

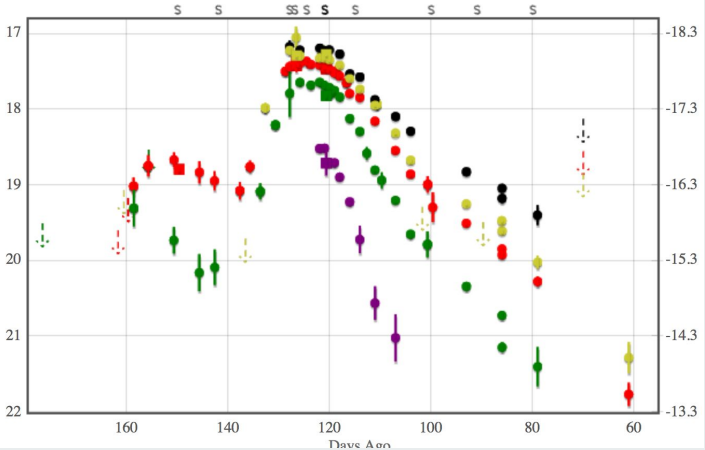


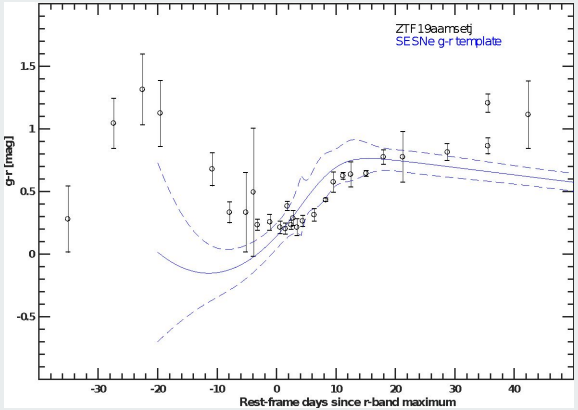




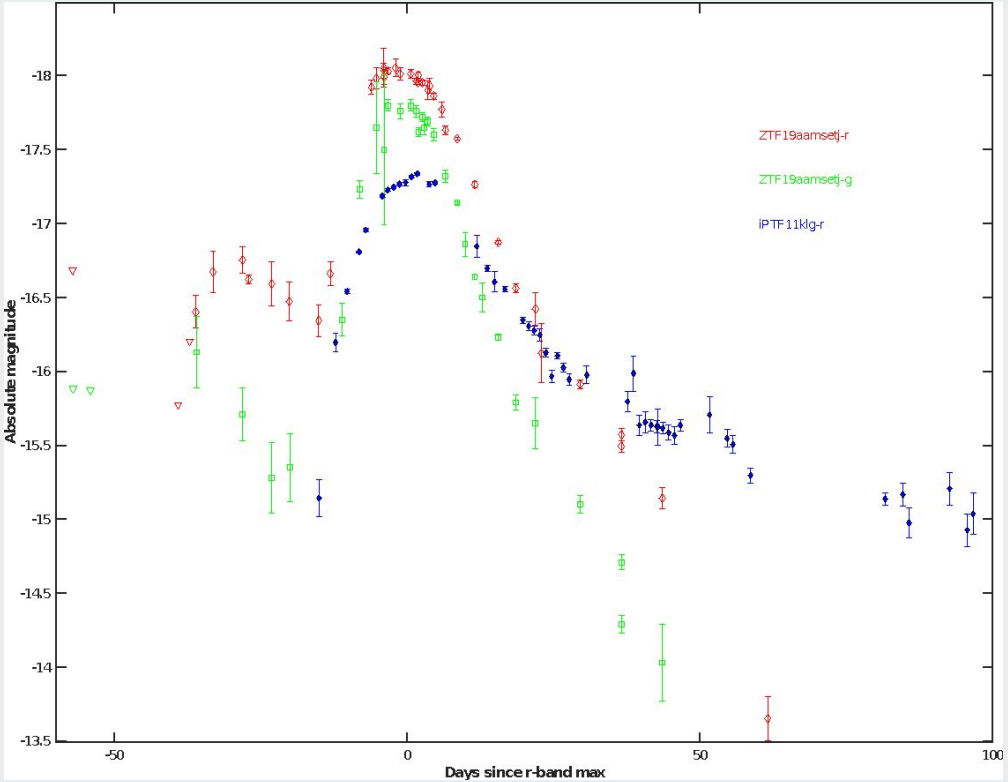
ZTF19aamsetj SN Ic

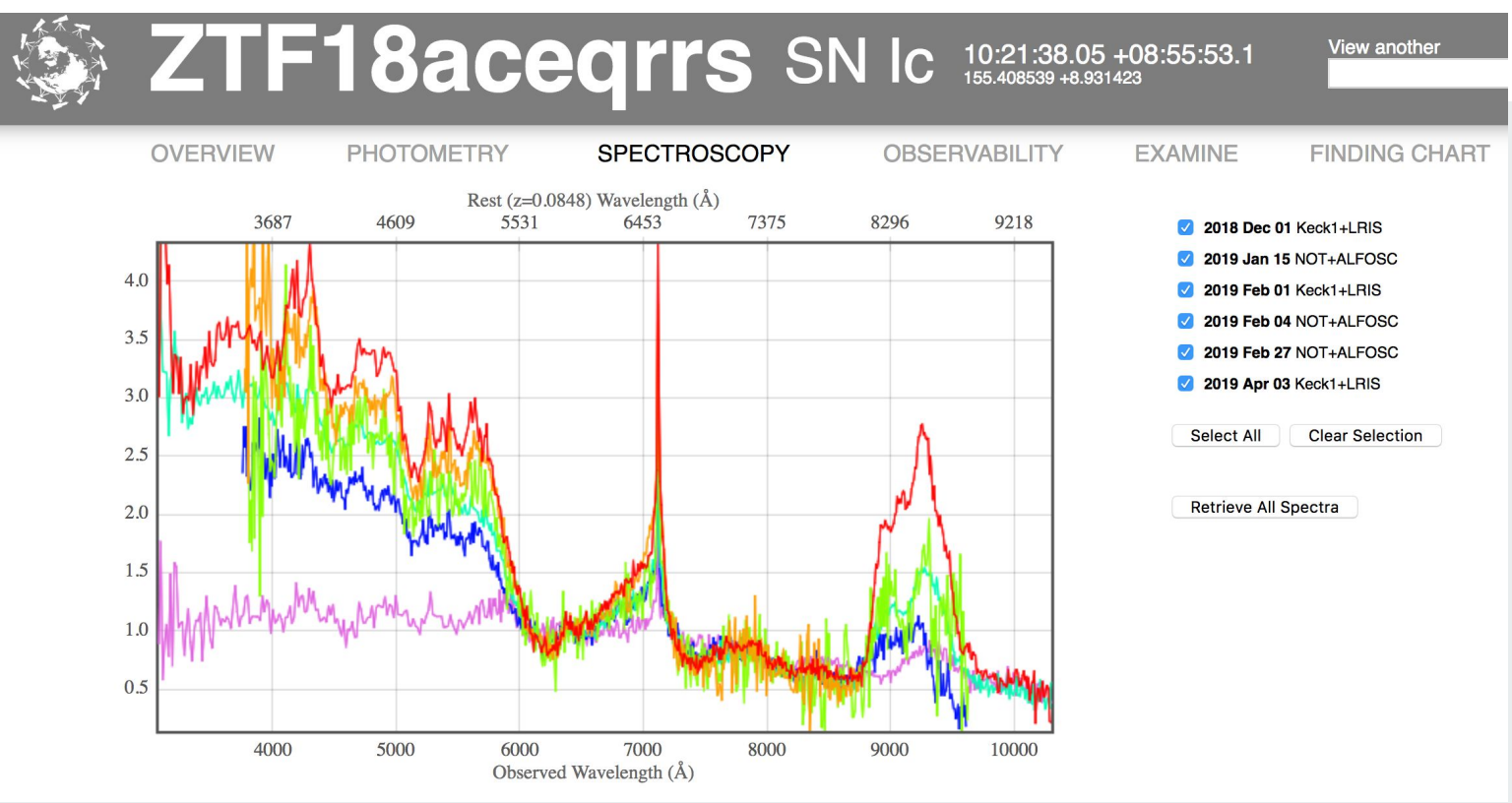
OVERVIEW PHOTOMETRY SPECTROSCOPY OBSERVAE



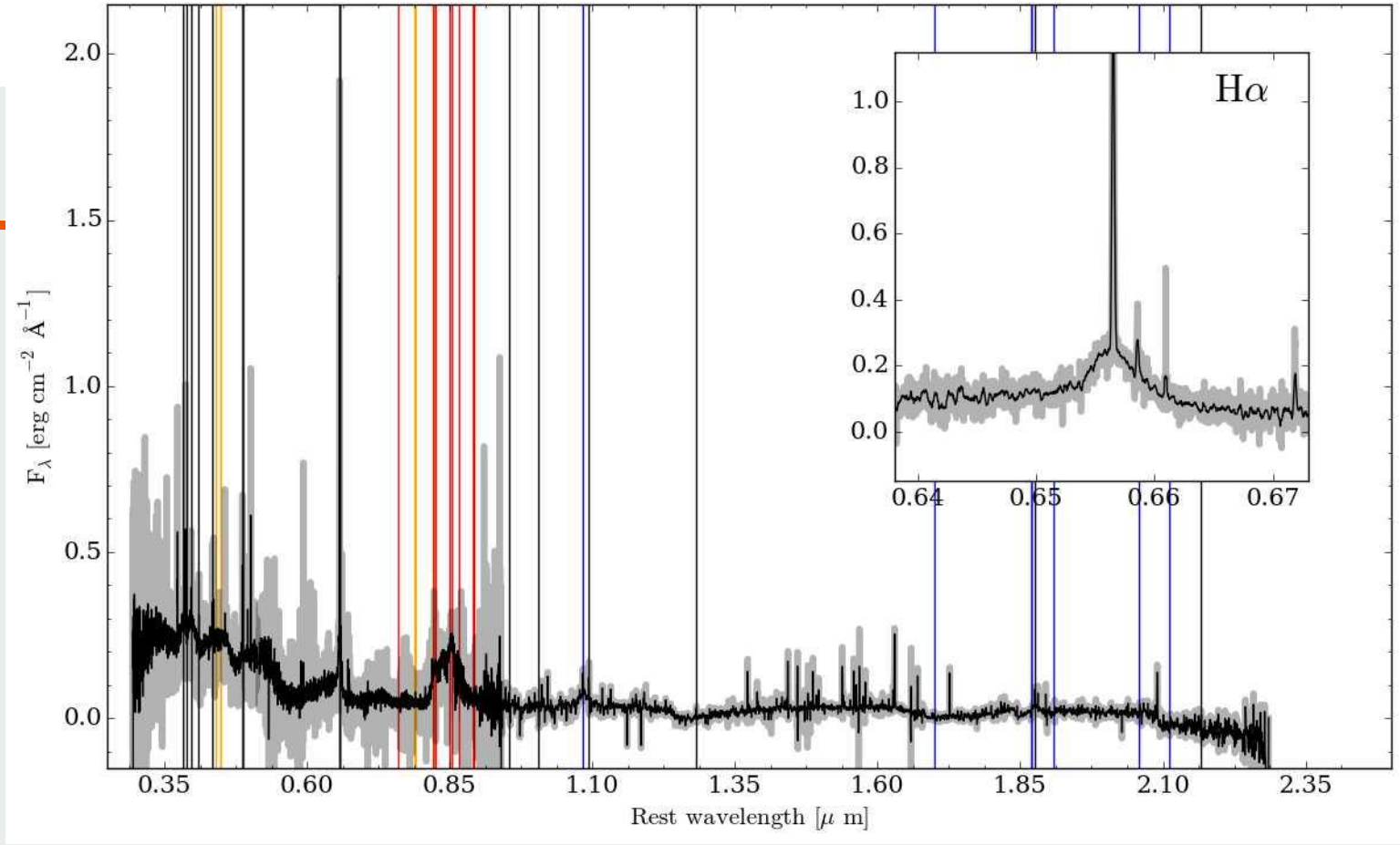


Weird LC SN

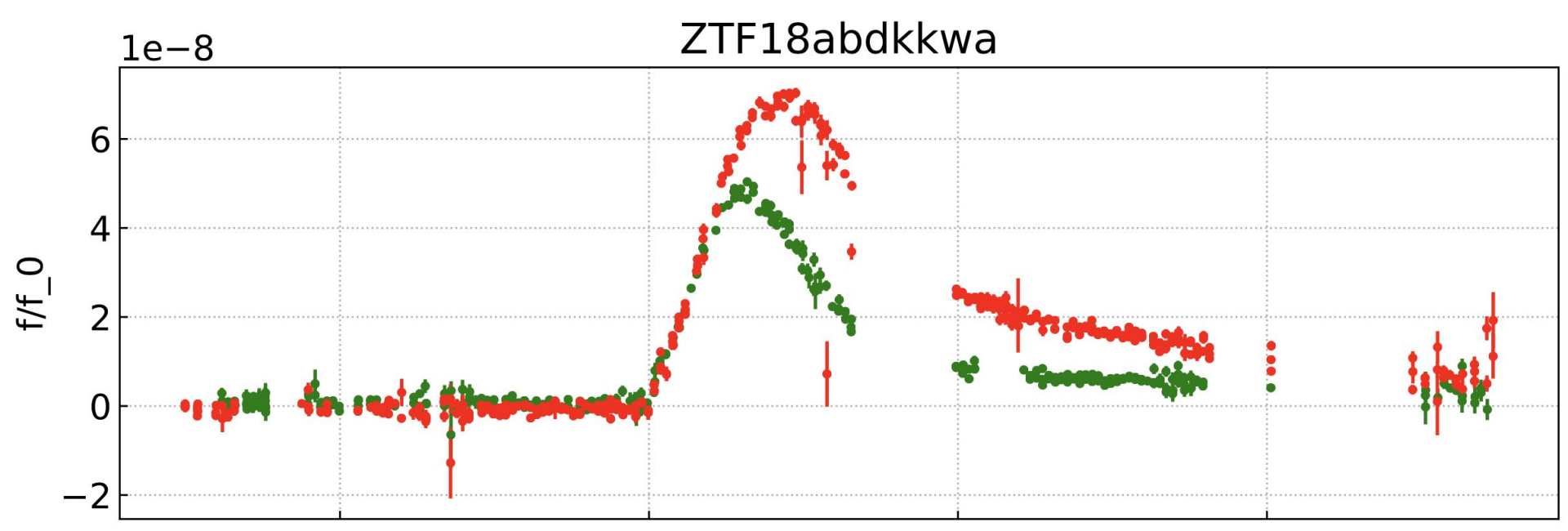




Another strange Ic(?). Spectra get bluer with time!

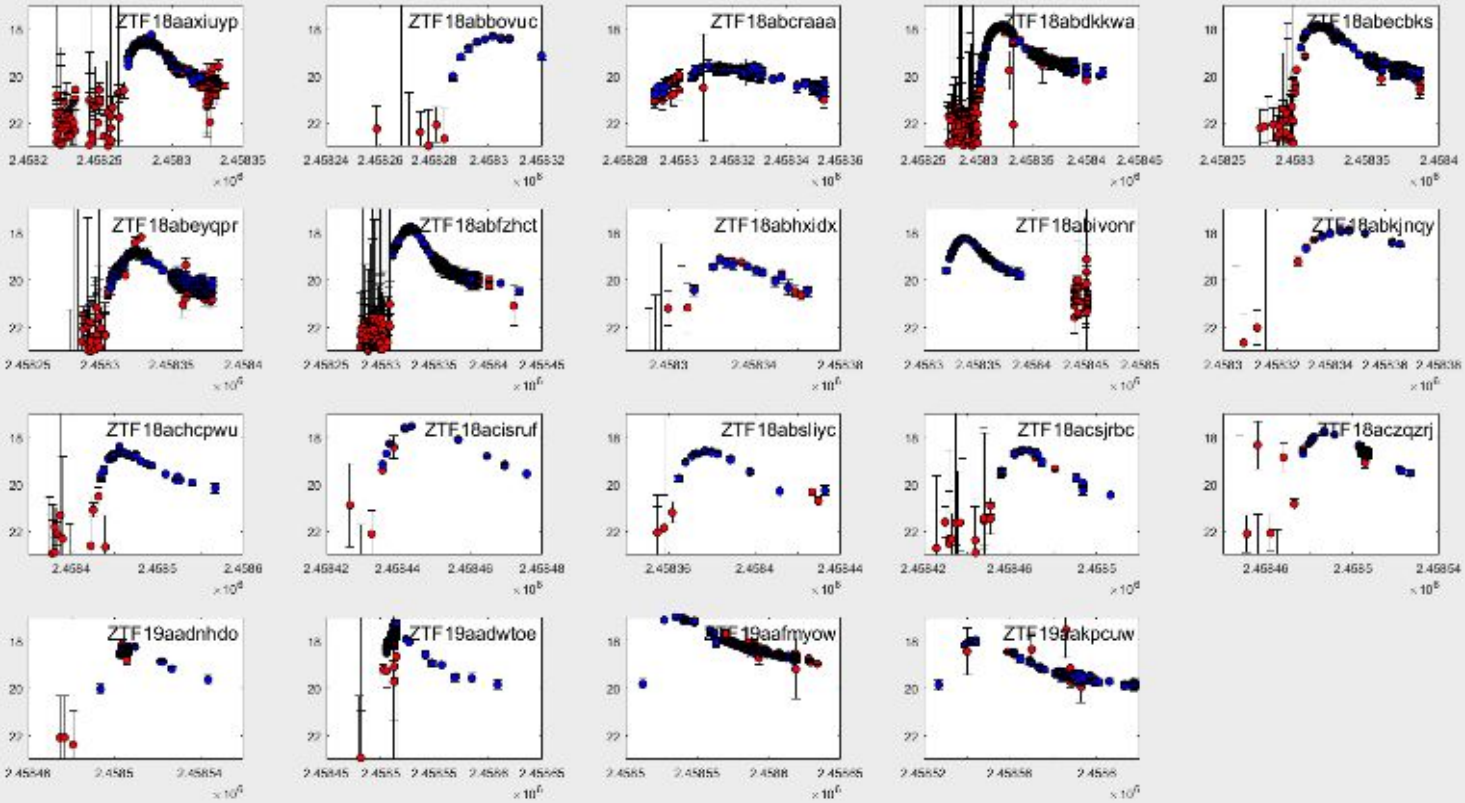


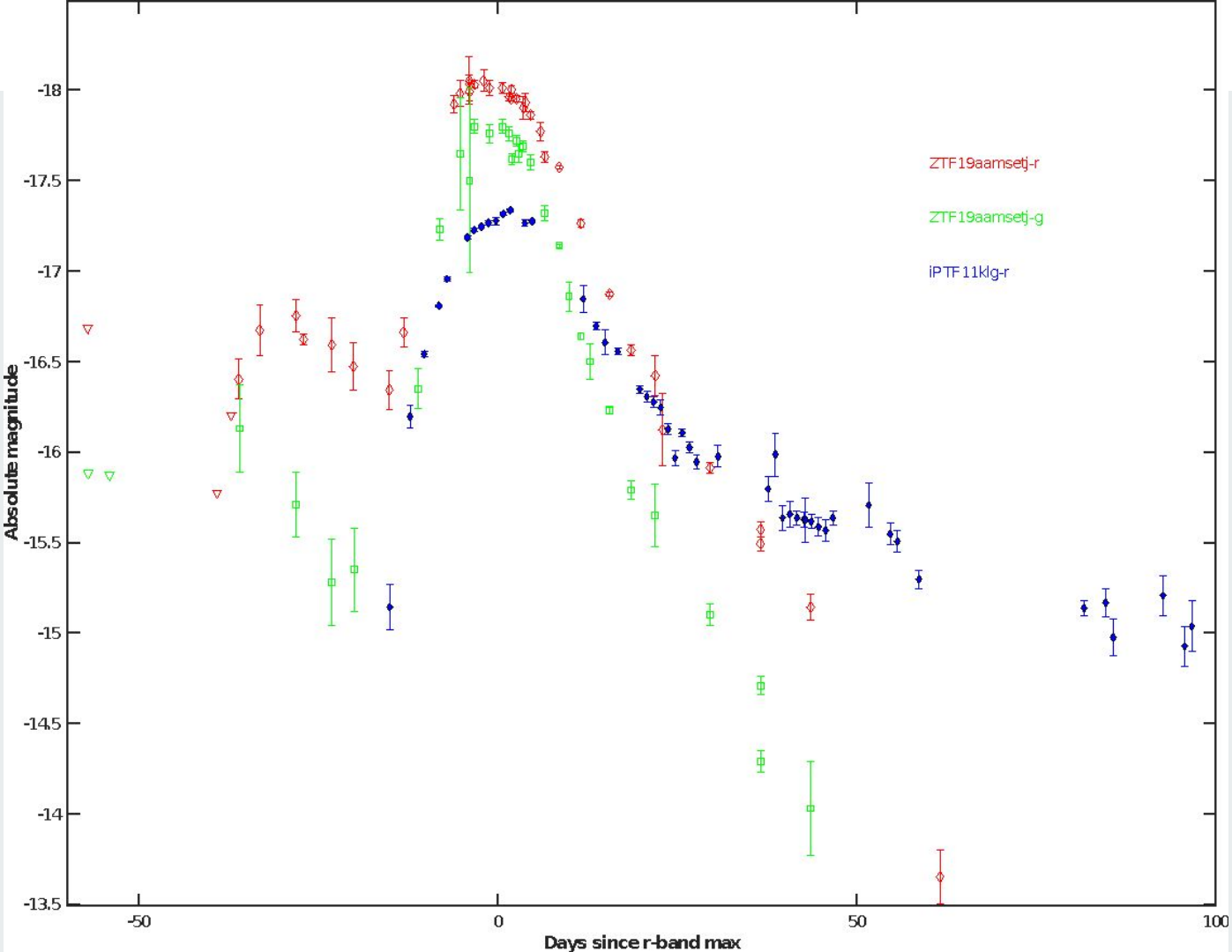
X shooter spectrum from VLT of qqr, 3000-22000 Å

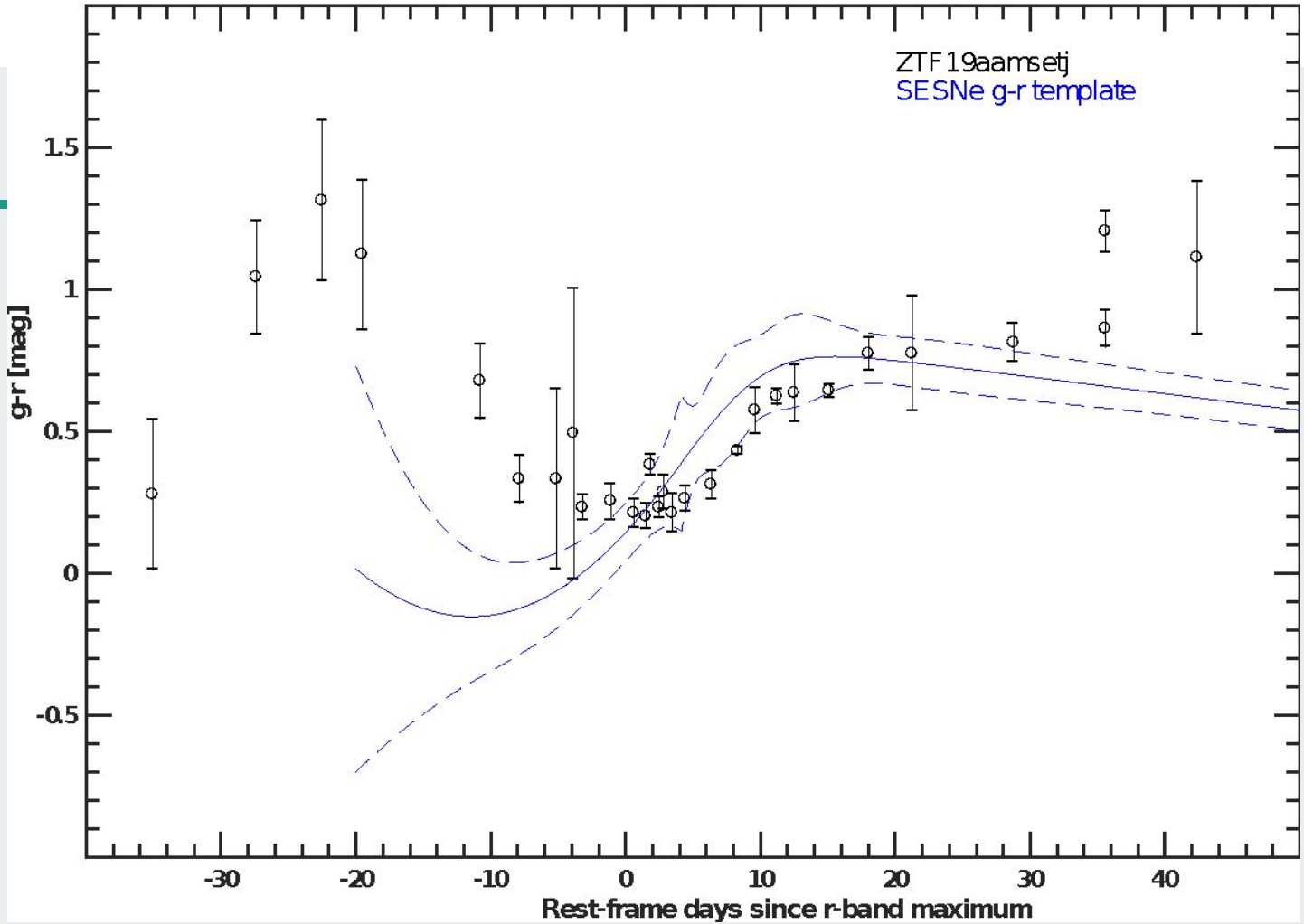


SN Ic rise time study

Rise times, explosion dates, peak mags, rise shape…. For a ZTF sample


ZTF18aaxiuyp
ZTF18abbovuc
ZTF18abcraaa
ZTF18abdkkwa
ZTF18abecbks
ZTF18abeyqpr
ZTF18abfzhct
ZTF18abhxidx
ZTF18abivonr
ZTF18abkjnqy
ZTF18achcpwu
ZTF18acisruf
ZTF18absliyc
ZTF18acsjrbc
ZTF18aczqzrj
ZTF19aadnhdo
ZTF19aadwtoe
ZTF19aafmyow
ZTF19aakpcuw


ZTF19aamsetj-r
ZTF19aamsetj-g
iPTF11klg-r
Absolute magnitude
Days since r-band max
-18
-17.5
-17
-16.5
-16
-15.5
-15
-14.5
-14
-13.5
-50
0
50
100

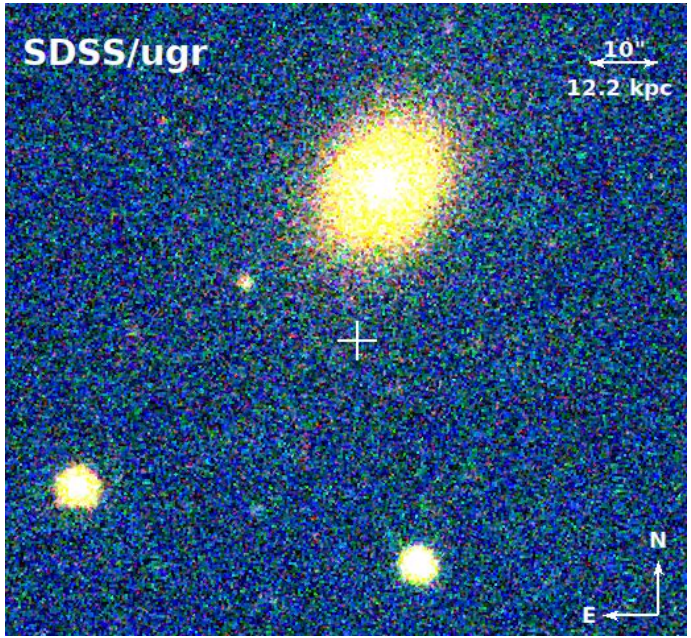

ZTF19aamsetj
SESNe g-r template
g-r [mag]
1.5
1
0.5
0
-0.5
-30
-20
-10
0
10
20
30
40
Rest-frame days since r-band maximum

From Weizmann:

Unusual core-collapse SNe

CCSNe in Elliptical Hosts

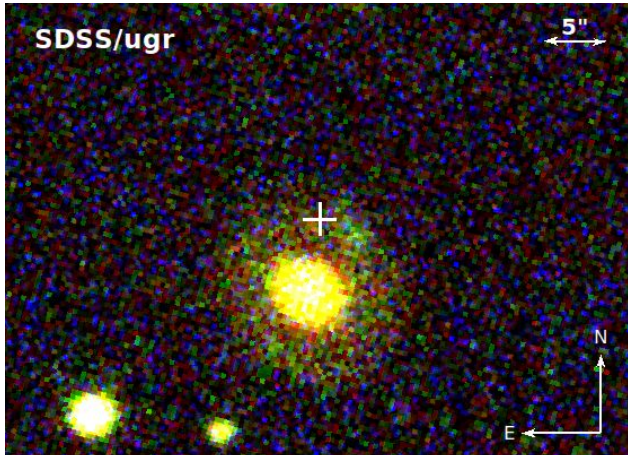
- Motivated by the study of PTF16hil, a Type II at the outskirts of an elliptical host, and with strong limits on any underlying host.
- These are rare cases, since elliptical galaxies are old environments with low SFR.
- Other cases in the past include Abell399 11 19 0 (Type II), and PS-12sk (Type Ibn)

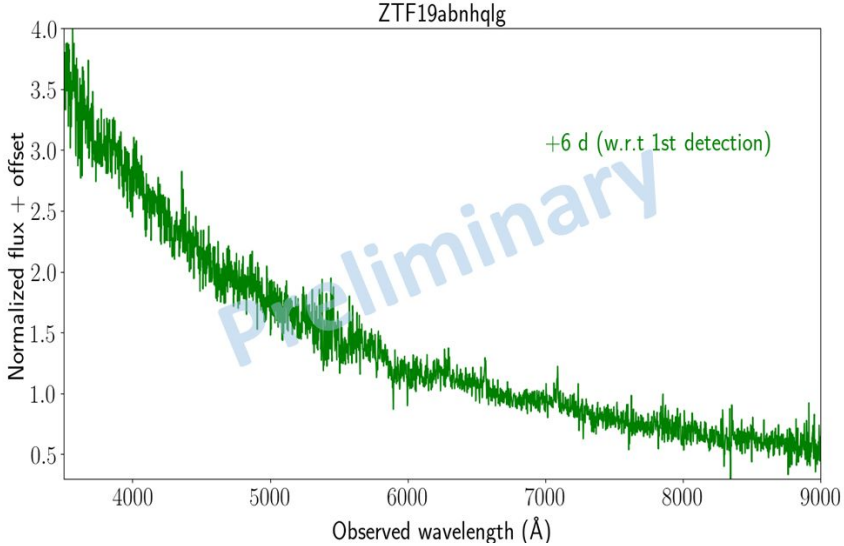


Irani et al. 2019

CCSNe in Elliptical Hosts

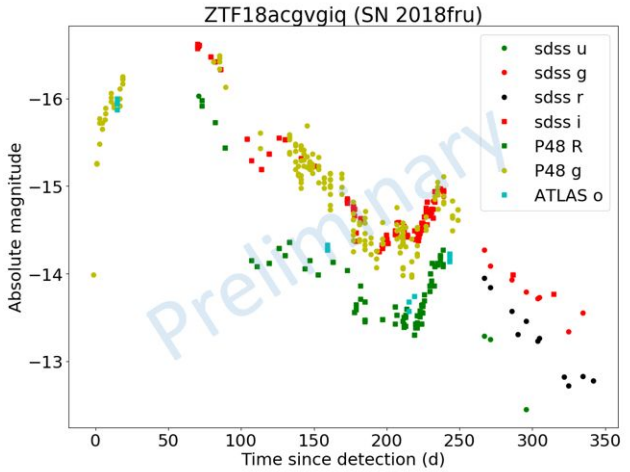
- We are currently attempting to systematically study such events
- Hosts can be separated into
  - Those with residual SF
  - Non SF hosts
- First candidate in ZTF confirmed (ZTF19abnhqlg) – showing a hot continuum (so not Ia!).

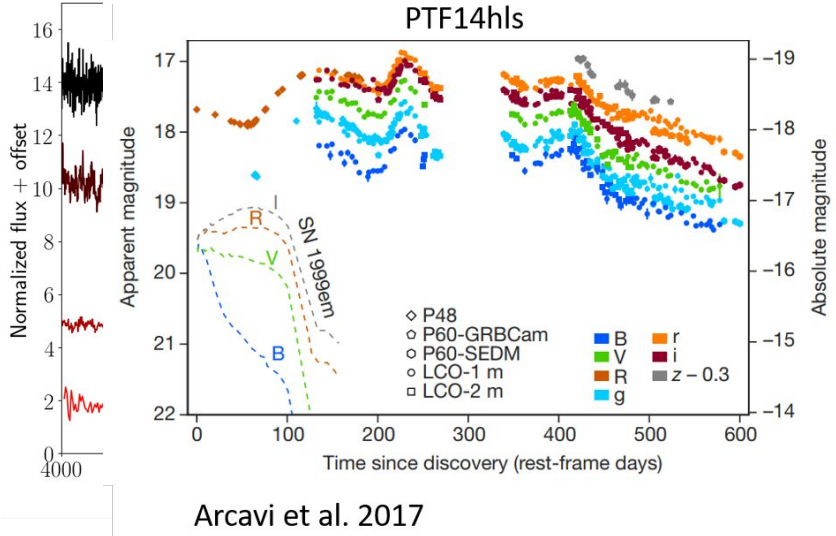




ZTF18acgvgiq (SN 2018fru)

- A Type II with a multi-peaked light curve
- Long lasting (about a year)
- Non trivial color evolution
- Slow evolving spectrum
- Reminiscent of PTF14hls



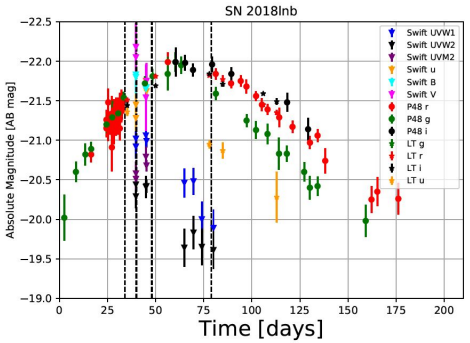


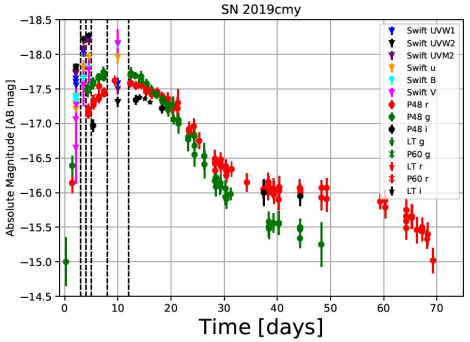
Arcavi et al. 2017

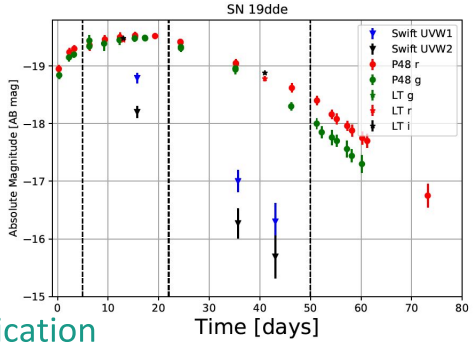
SNe IIn

- We performed the the first Ultra-Violet (UV) survey of type IIn supernovae (SNe IIn)
- 12 SNe IIn discovered and observed with ZTF+Swift
- UV can tell a lot about the physical mecanisms at stake + better estimate of bolometric luminosity
- Here we used the sample to constrain the geometry of the CSM (link to the progenitor!)

- **Results**: at least 35% of SNe Iin show evidence for aspherical CSM! (conservative lower limit)







Soumagnac et al. 2019 (on its way to the publication