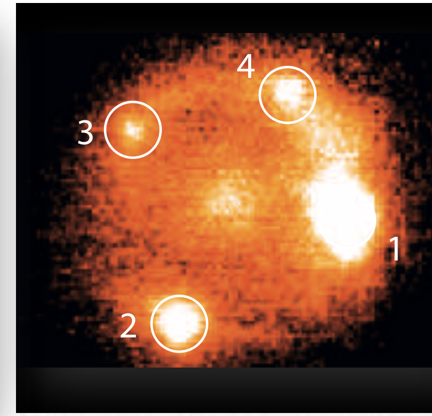


Lensed supernovae: past and future

Tanja Petrushevska
Centre for Astrophysics and Cosmology
University of Nova Gorica, Slovenia

Where is the Center of Astrophysics and Cosmology of the University of Nova Gorica, Slovenia?

Vipava valley in the 10 best places to visit in 2018

Center for Astrophysics and Cosmology
University of Nova Gorica

Prof. Dr.
Danilo
Zavrtanik

Prof. Dr.
Samo
Stanič

Prof. Dr.
Andrej
Filipčič

Prof. Dr.
Andreja
Gomboc

Prof. Dr.
Marko
Zavrtanik

Prof. Dr. Serguei
Vorobiov

Prof. Dr. Gabrijela
Zaharijaš

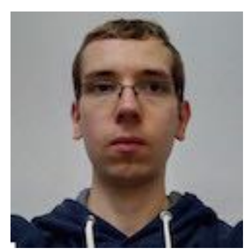
Dr.
Lili Yang

Dr.
Tanja
Petrushevska

Gašper
Kukec

Aurora
Clerici

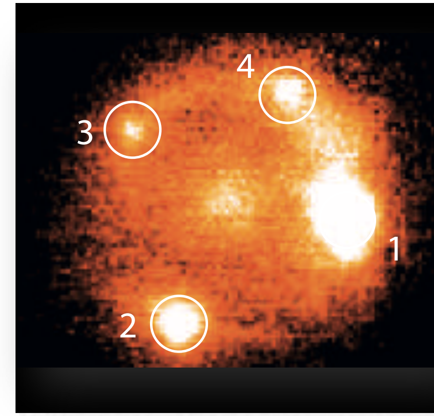
Marta
Trini



Christopher
Eckner

Lukas Zehrer

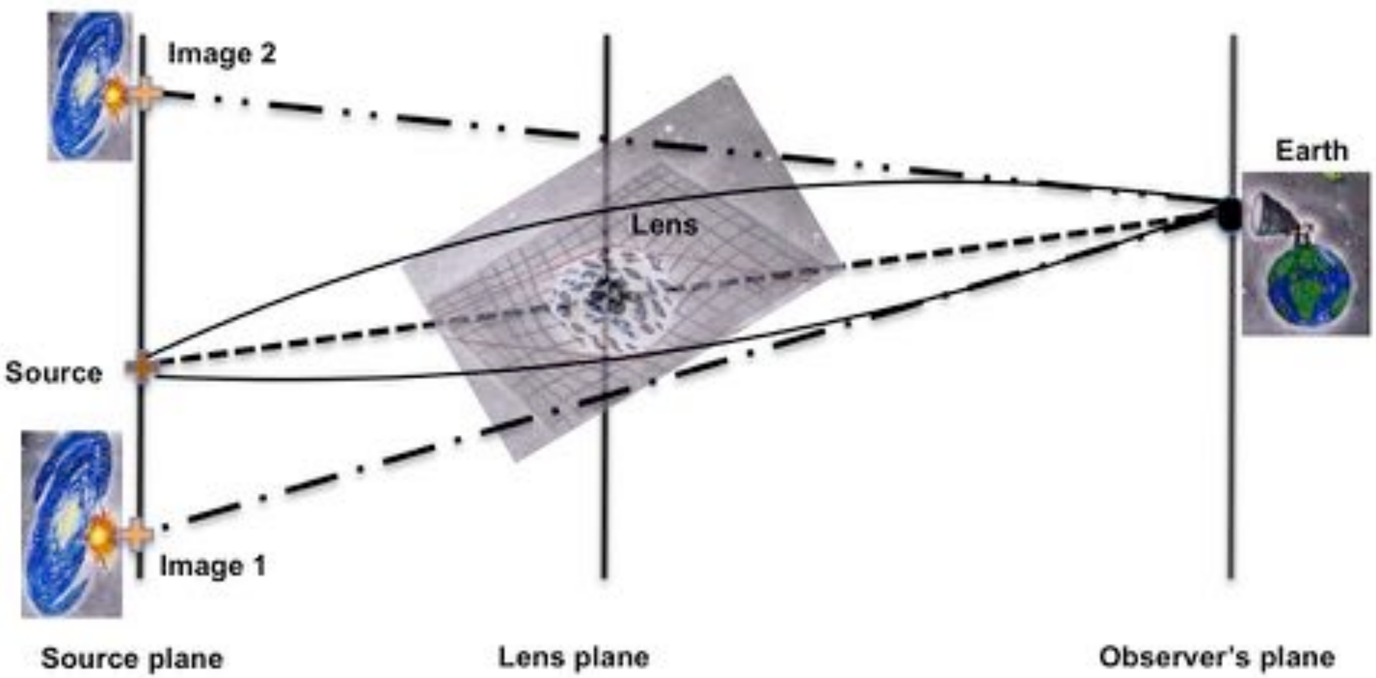
Katja Bricman



Lensed supernovae: past and future

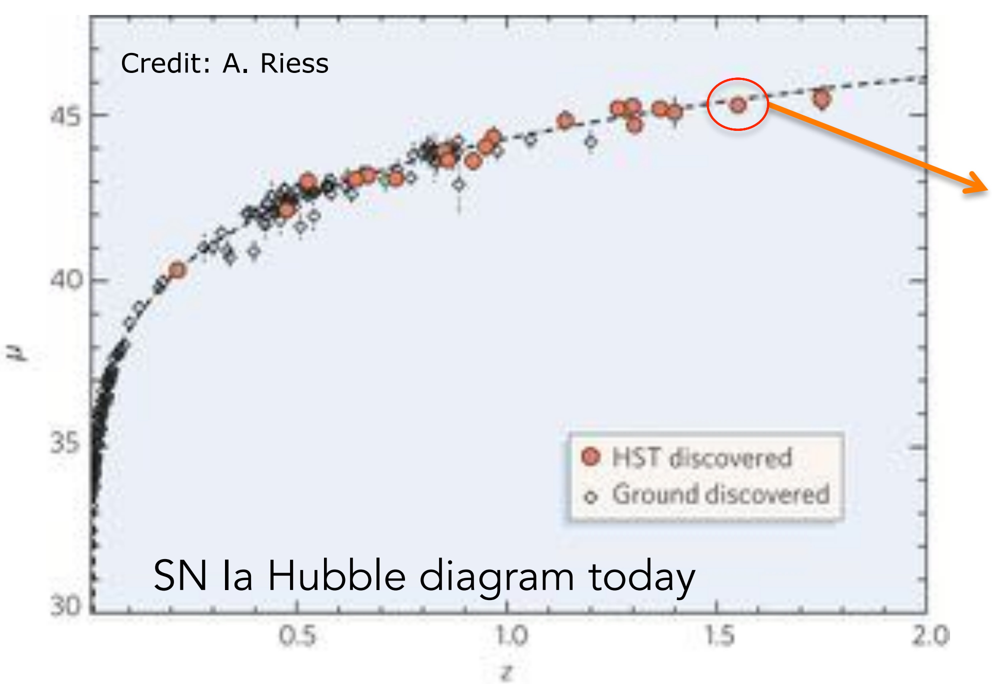
Tanja Petrushevska
Centre for Astrophysics and Cosmology,
University of Nova Gorica, Slovenia

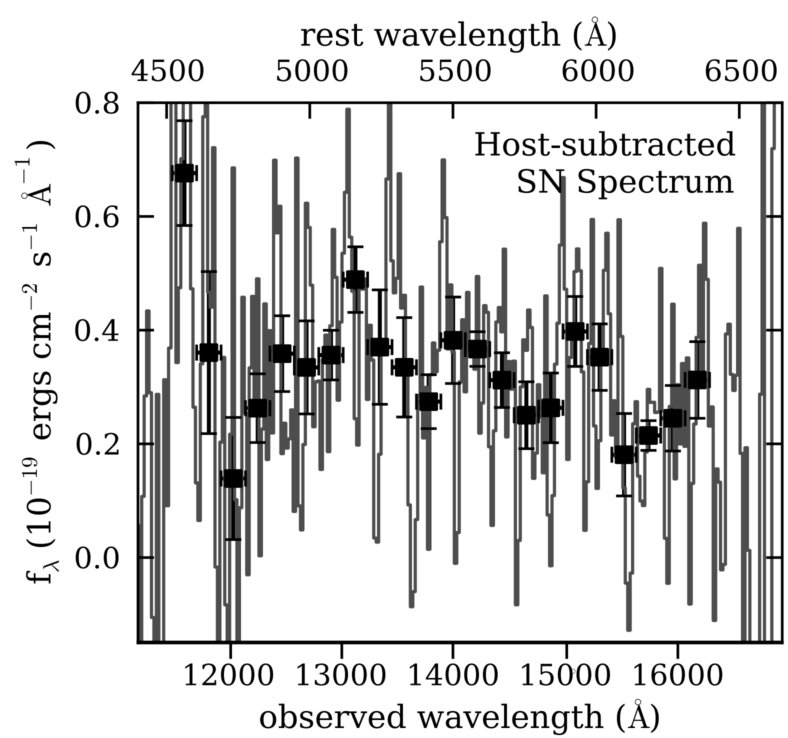
Strong lensing as a tool for studying the high-redshift universe



- **Multiple images**
  - **time delay** between the images depends on cosmology
- **Magnification**
  - observe objects that are otherwise undetectable

At high redshifts, the S/N of spectroscopic data is not enough for a detailed study





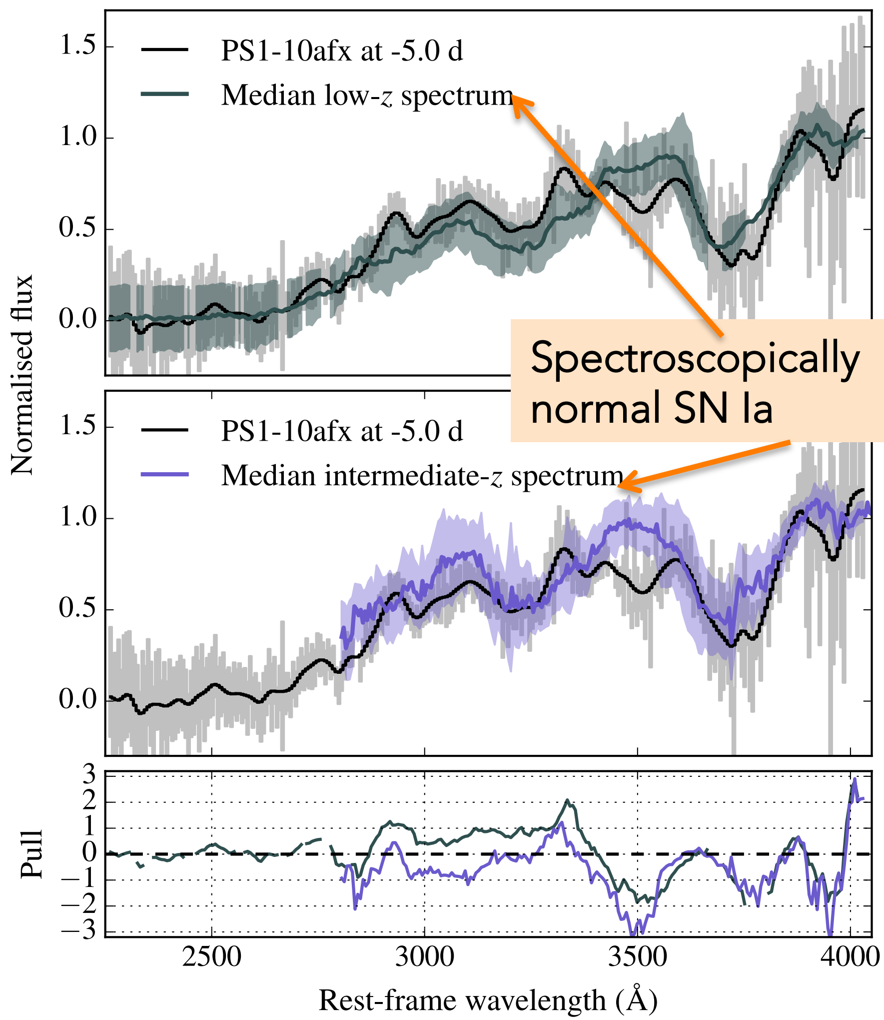
(Rodney et al. 2012)

Evolution in SN Ia properties as possible systematic effect for future surveys

- From the Hubble diagram, cosmological measurements are made possible under the assumptions that SNe Ia are the same type of objects at high and low redshift.
- In the future, with increased precision measurements, deviation from this assumption could bias the measurements.
- The method to test this, is to compare spectra of objects at high redshift with those at low redshift.

Testing for redshift evolution of SNe Ia using the strongly lensed PS1-10afx at $z = 1.4$

PS1-10afx was a SN Ia magnified ≈30 times by a foreground galaxy

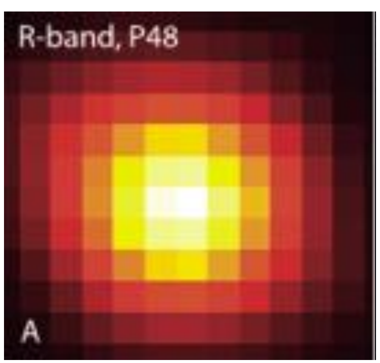


Comparisons of median spectra constructed from normal SNe Ia at low and intermediate redshift show to PS1-10afx show no signs of significant spectral evolution

Petrushevska et al. 2017

The discovery of iPTF16geu

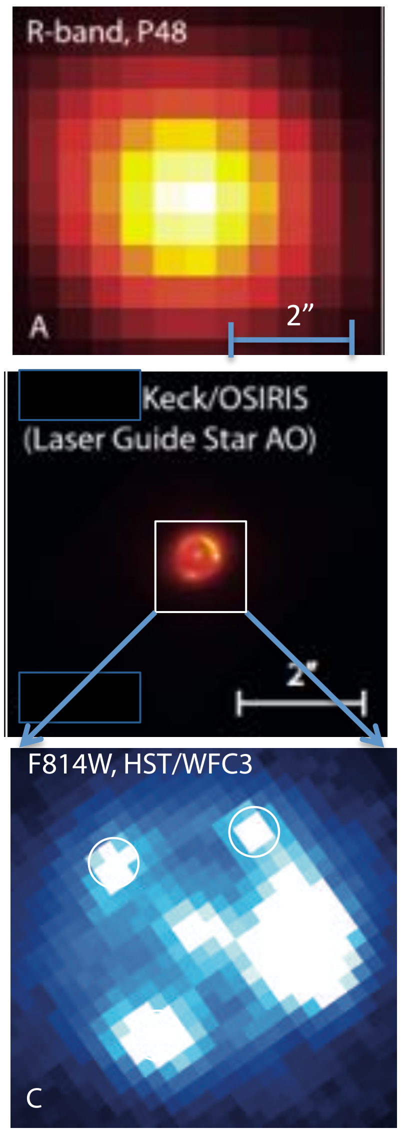
From 2013 to March 2017, The intermediate Palomar Transient Factory (iPTF) was a fully-automated, wide-field survey for systematic exploration of the optical transient sky.
-> Very efficient in finding **nearby** supernovae up to $z \lesssim 0.1$



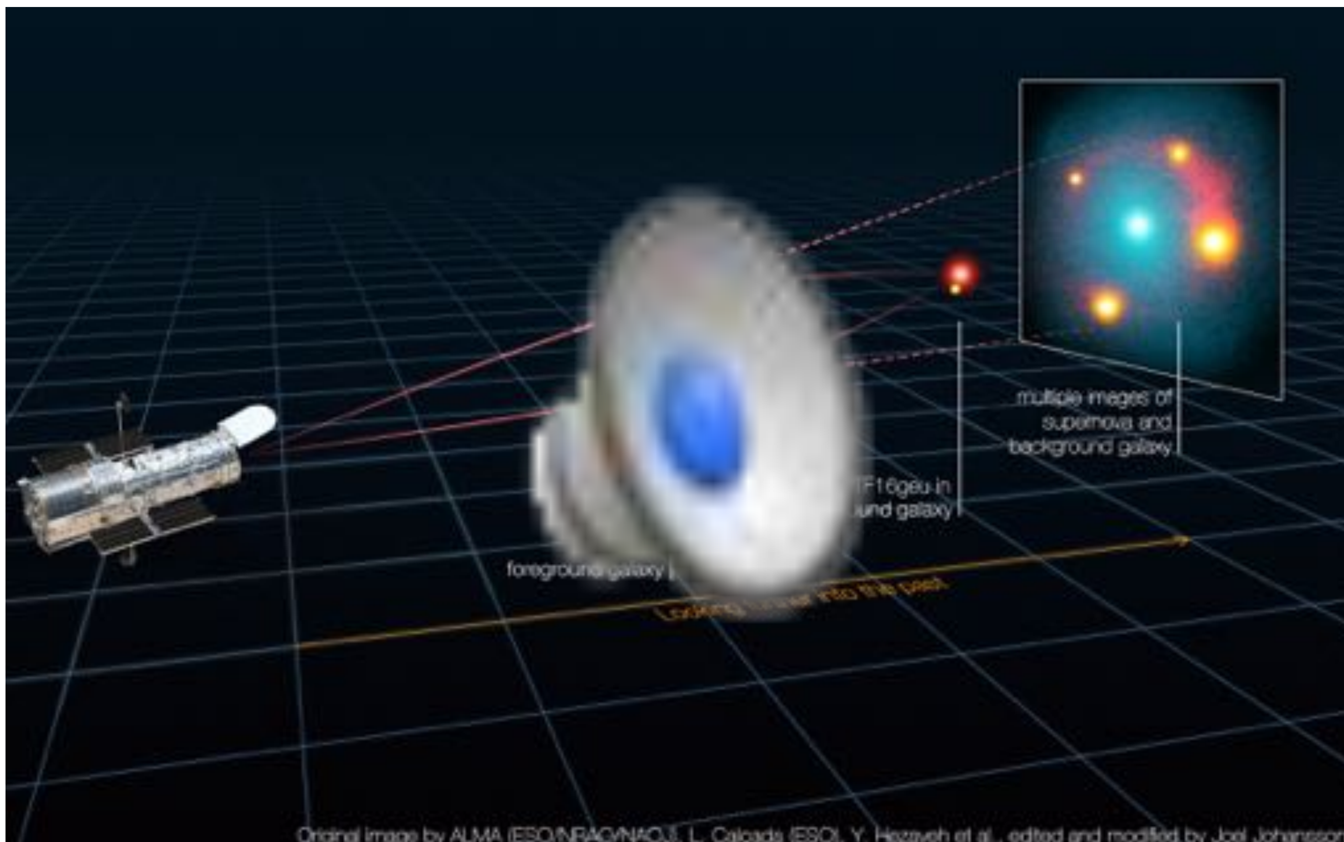
- In October 2016, a supernova was discovered which low-resolution spectrum indicates $z \approx 0.4$. Later high-resolution spectrum confirmed SN Ia at $z=0.409$. At the location, known elliptical galaxy at $z=0.206$…

Is it a lensed supernova?

iPTF16geu the first strongly lensed SN Ia with resolved multiple images



- iPTF image resolution of 2” could not resolve the possible multiple images (as in the case for PS1-10afx).
- Timely follow-up observations with high-resolution ground facilities with adaptive optics and HST confirmed the suspicion !



iPTF16geu the first strongly lensed SN Ia with resolved multiple images

Goobar et al. 2017 Science

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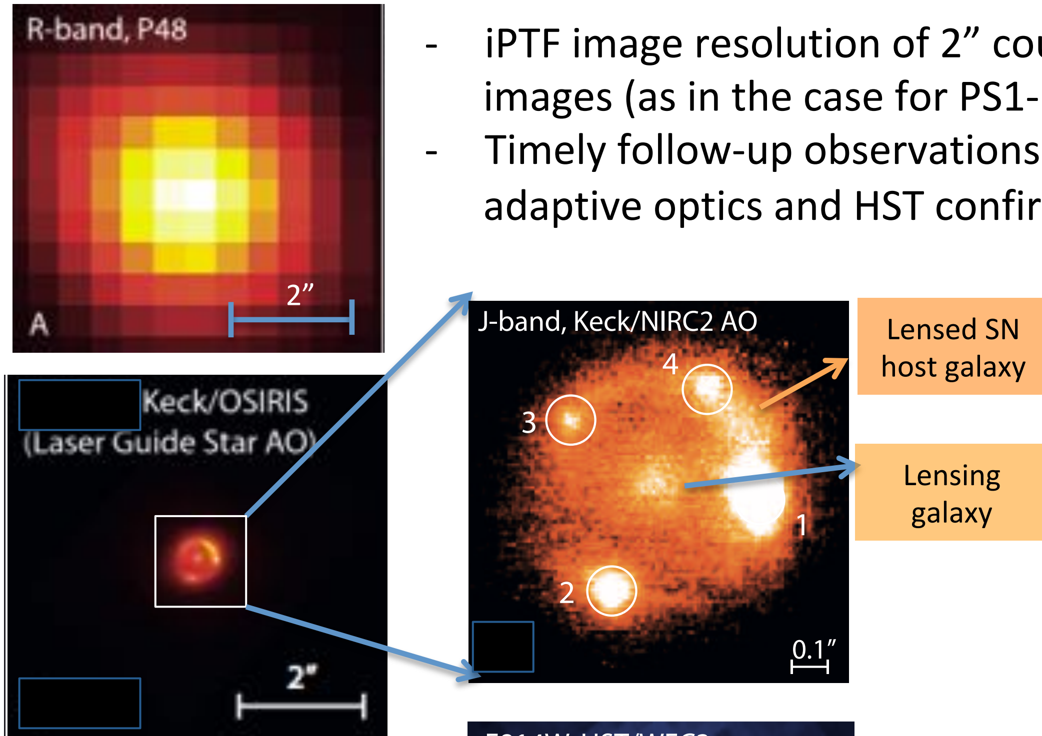
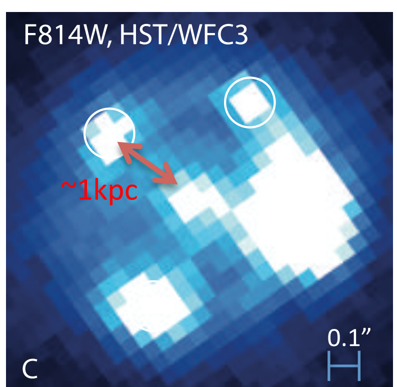
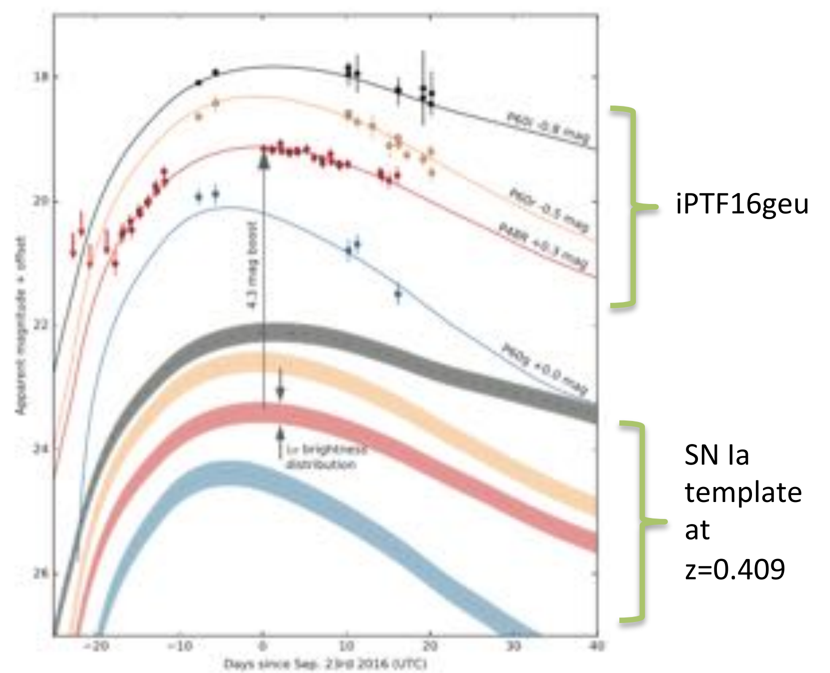






Light curves of the SN shows that that is was magnified ~ **52** times by the foreground galaxy at z=0.206. The estimated time delays are <24 hrs, which makes them hard to measure.

Surprisingly large magnification, most likely also microlensed

Galaxy clusters as gravitational telescopes can be used to search for high-redshift SNe

SN Ia

Core collapse SNe (CC SNe)

The time delays of multiply- imaged SNe -> measure the Hubble constant

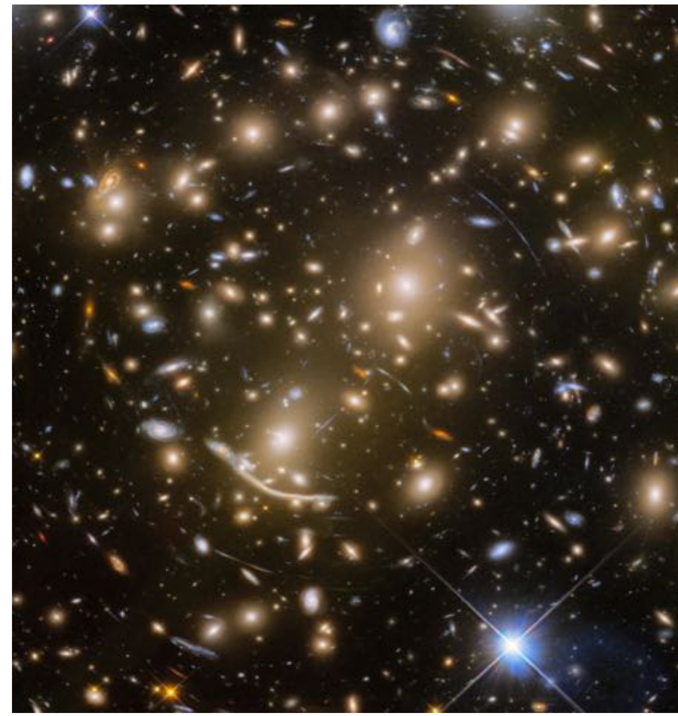
- Their magnification can be estimated directly -> **test the lensing model** which suffers from degeneracies

- CC SNe are explosion of short-lived stars
- their volumetric rates are directly related to the cosmic star formation history (SFH)
- Lensing magnification -> allows studies at high redshifts where they are hard to find

Ground-based near-infrared surveys to search for lensed SNe

NIR surveys in J band

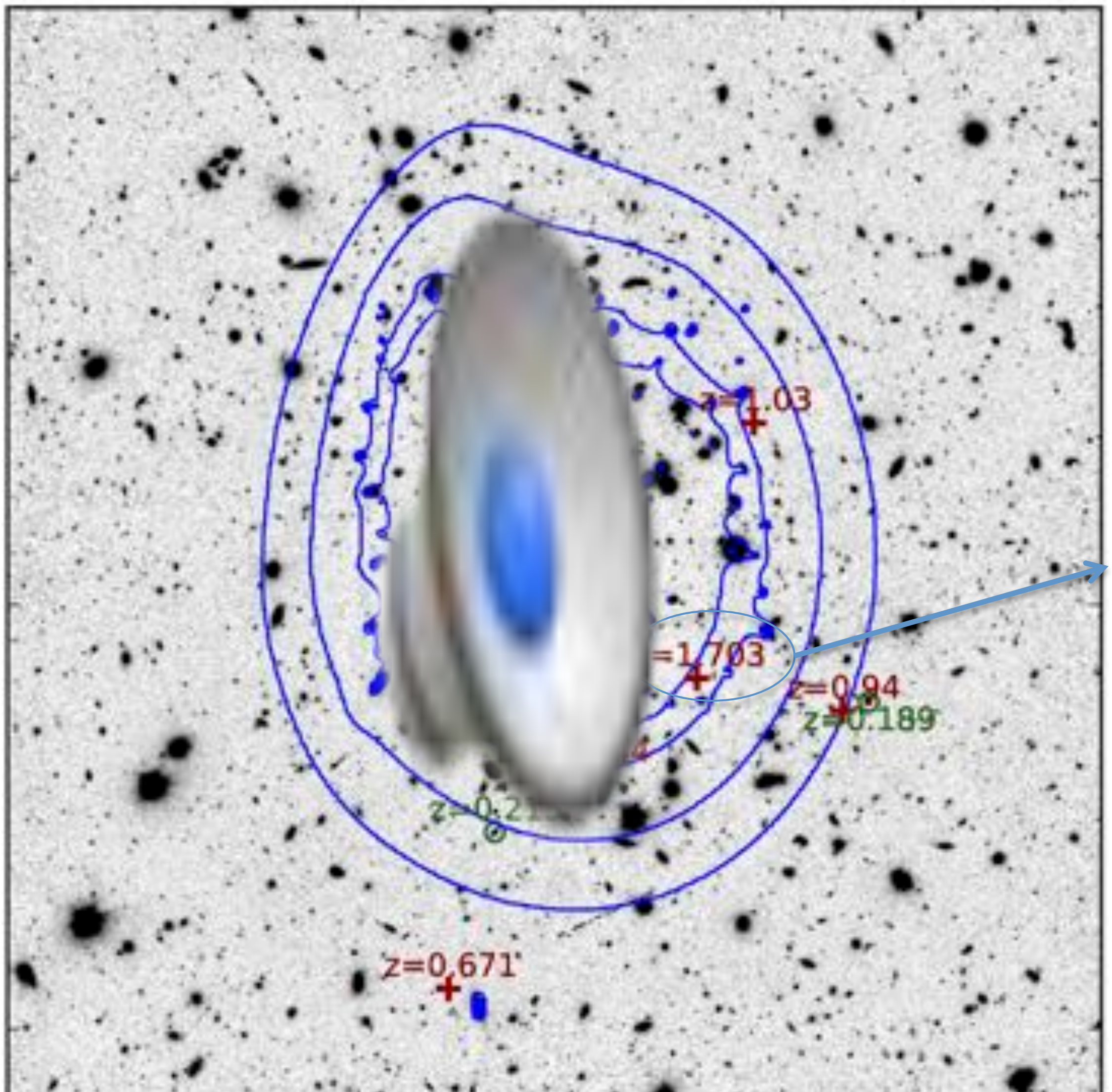
- Abell 1689 at z = 0.18
- 31 epochs over 5 years



- Abell 370 at z=0.35
- 15 epochs over 2 years

Petrushevska et al. 2016, 2018

5 high-z SNe (core-collapse) with significant magnification (1.33-4.29)

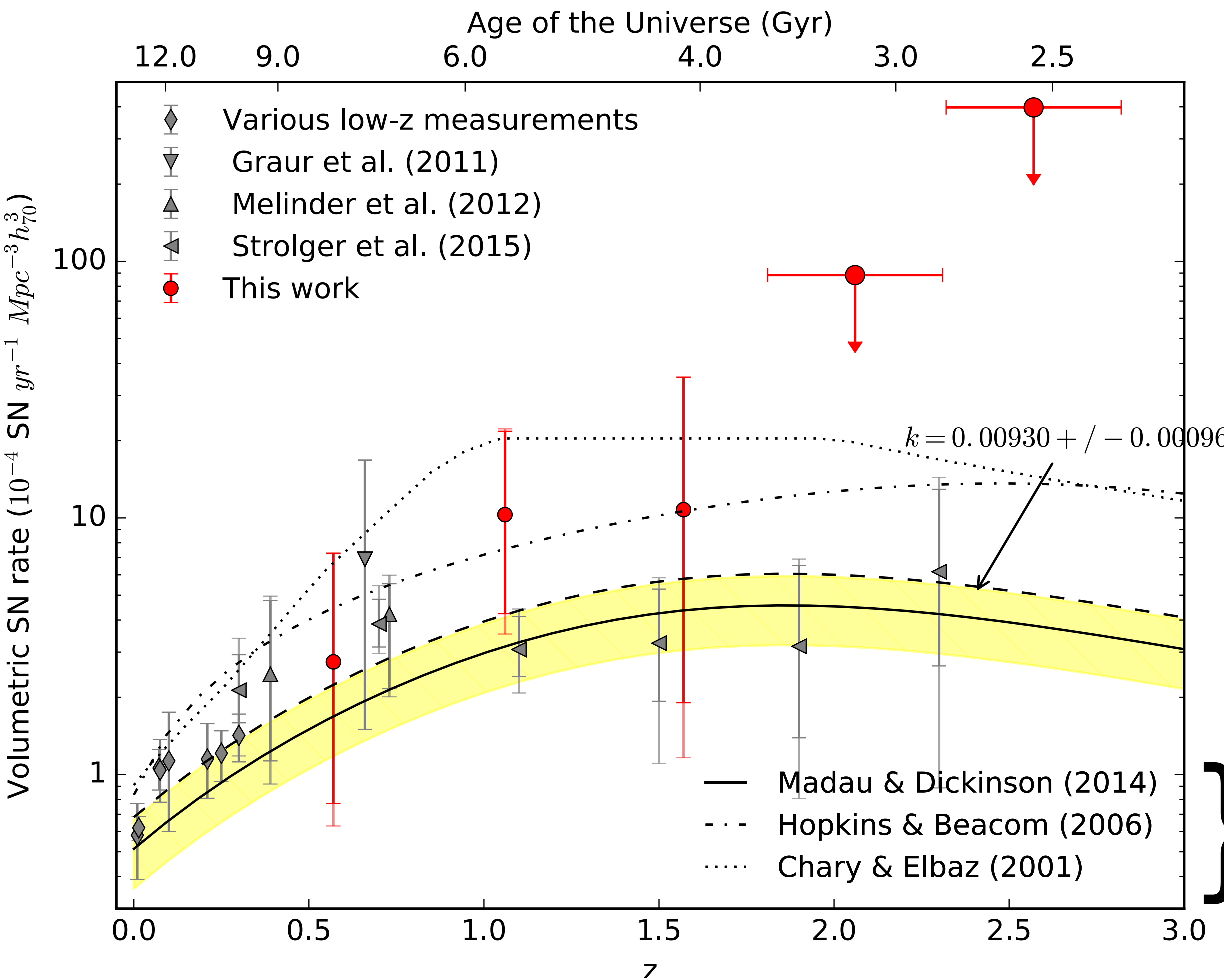


SNe Ia
CC SNe

One of the highest-z CC SN ever discovered at the time, magnified ~4.3 times from the galaxy cluster

Volumetric CC SN rates

+ comparison with the star formation history



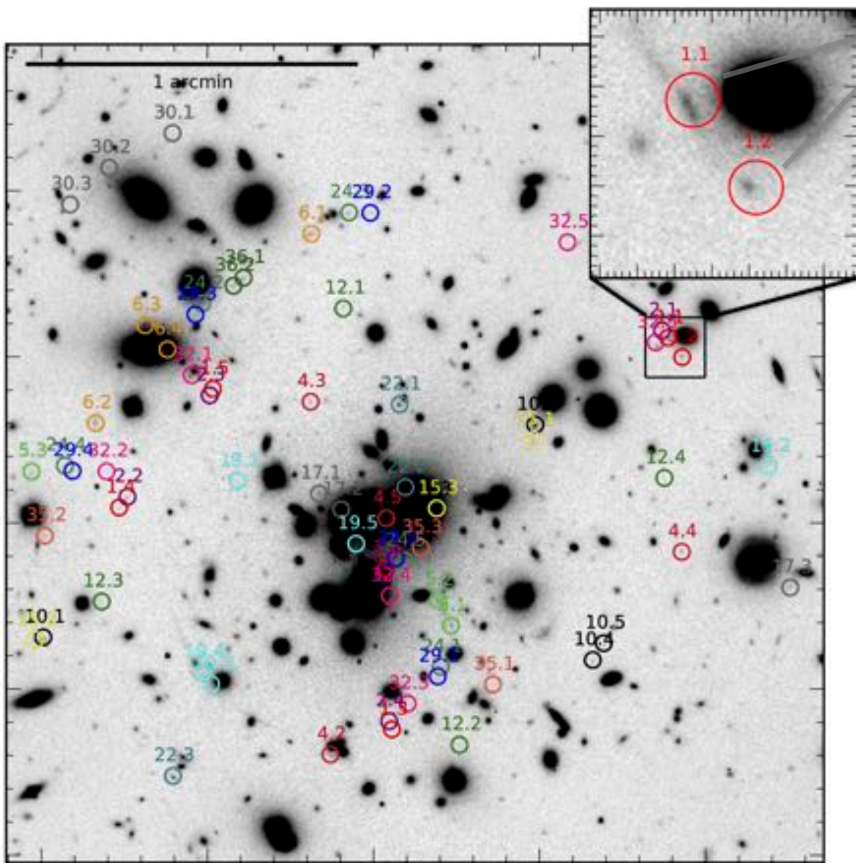
$$R_{CC}(z) = k \cdot SFH(z)$$

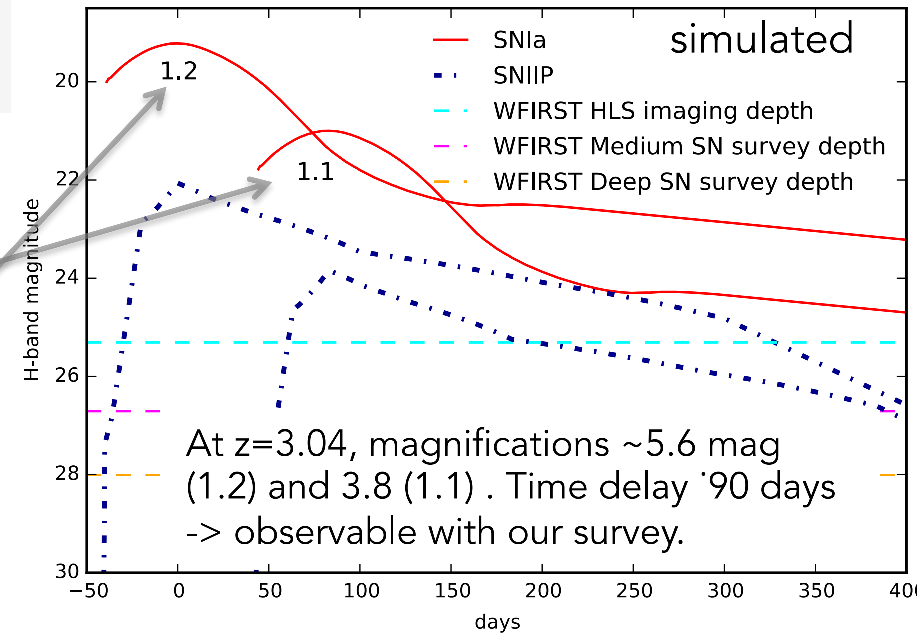
} SFHs

Petrushevska et al. 2016

Search for SNe in strongly lensed galaxies with multiple images

Cluster	Background source galaxies	Total number of multiple images of galaxies	Redshift
A1689	34	125	1<z<5
A370	21	67	0.7<z<6

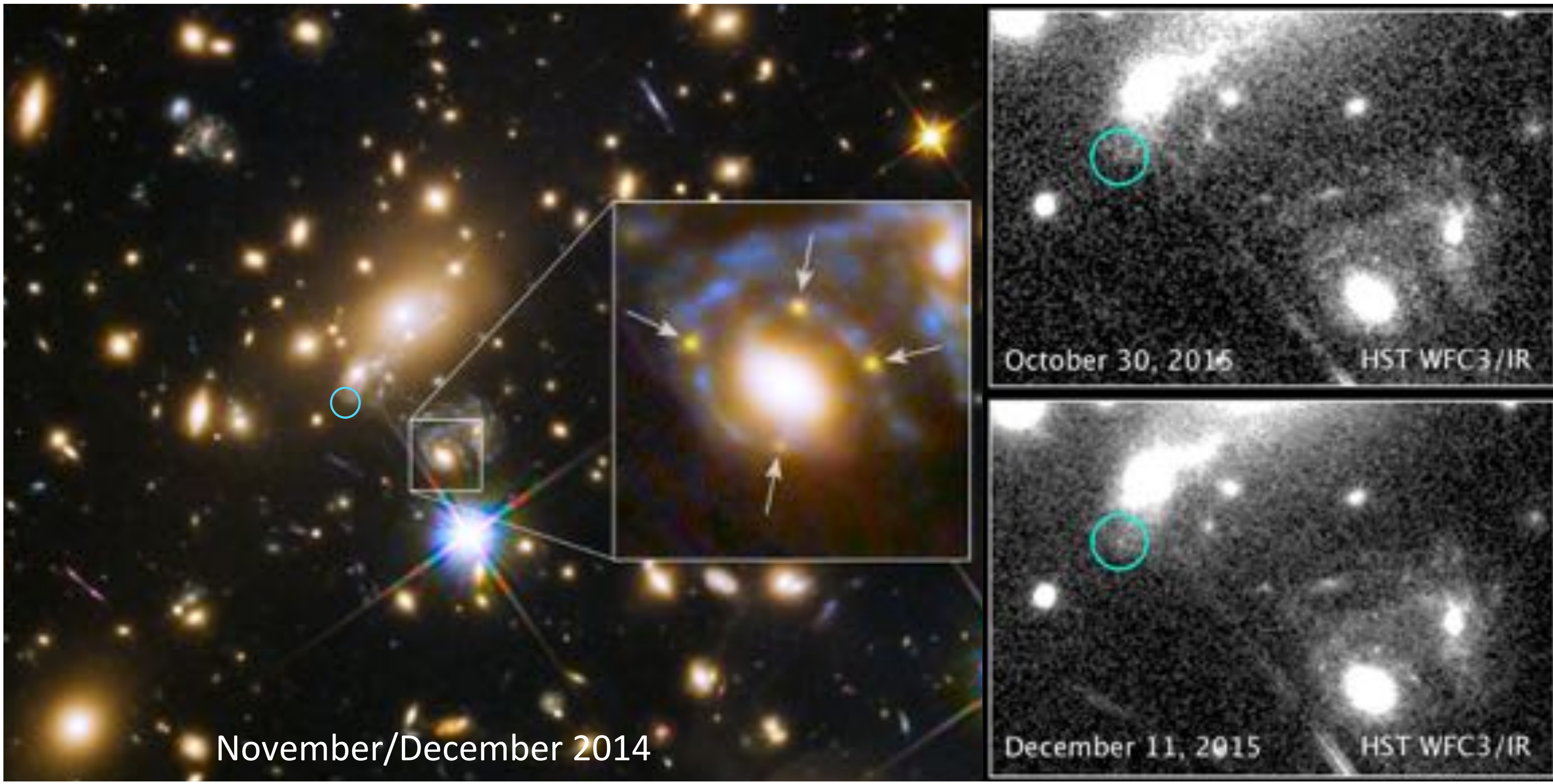




- We did not find any SNe in the multiply lensed galaxies
- The expected SNe for our surveys in these galaxies was ~0.6 SNe.

Petrushevska et al. 2016, 2018

The reappearance of SN Refsdal behind the galaxy cluster



Kelly et al. 2015, Treu et al. 2016

Expected SNe in strongly lensed galaxies with multiple images for upcoming surveys

Towards A1689

Survey/filter	**Duration** (yrs)	**Total N_{SNe} from galaxies with multiple images**
LSST/z	10	~2
WFIRST/H	2	~2
JWST/F150W	5	~6

- If A370 is used, the numbers are lower: N_{SNe}~ 0.7 with JWST
- Increasing the number of epochs does not increase N_{SNe} significantly

Petrushevska et al. 2016, 2018

Expected SNe in strongly lensed galaxies with multiple images for JWST in one year

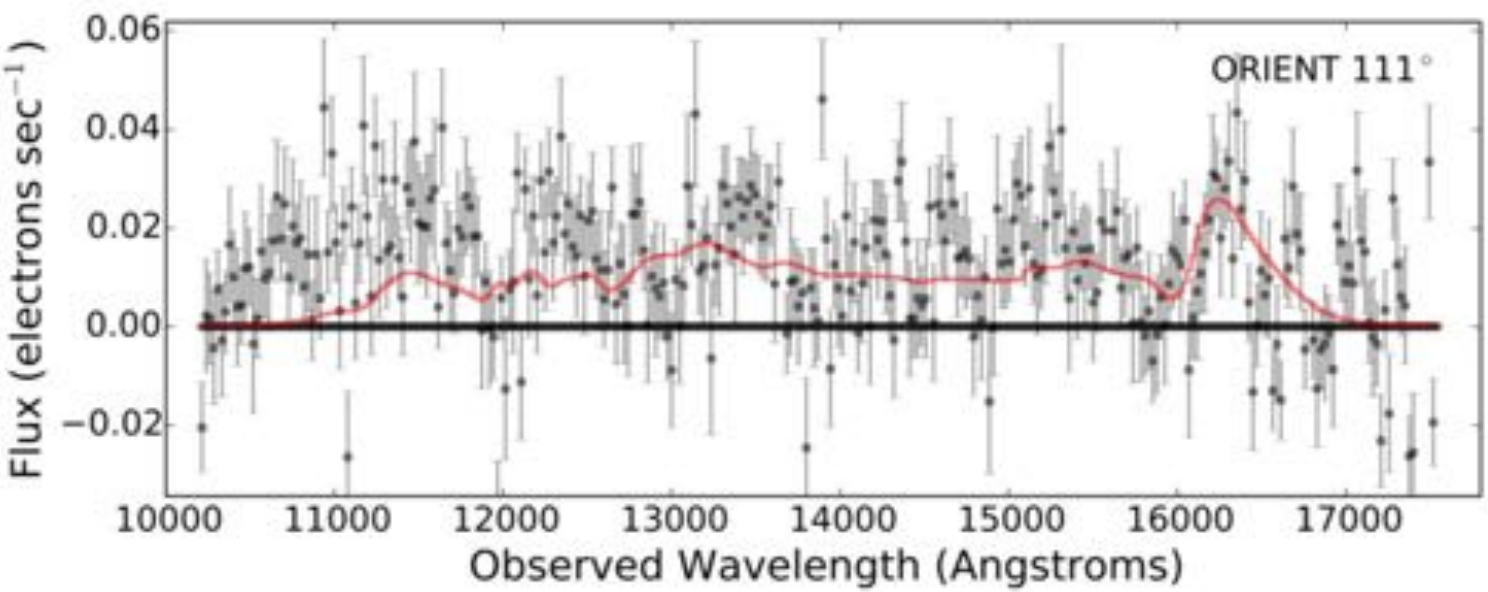
4 visits in 1 year with F150W (exposure time 1 hour)

27.5 mag 5**σ** (3-4 mag deeper than Keck-AO!)

Cluster	N_{CC}	N_{Ia}	z_{max}	Ng_{al}
A2744	0.06(0.04)	0.006(0.004)	3.98	40
AS1063	0.12(0.06)	0.008(0.004)	3.61	42
MACSJ1149	0.08(0.02)	0.005(0.001)	3.70	24
MACSJ04416	0.24(0.07)	0.016(0.005)	3.87	67
MACSJ0717	0.12(0.07)	0.007(0.004)	2.96	20
A370	0.3(0.1)	0.02(0.01)	3.77	47
A1689	1.0(0.5)	0.14(0.07)	3.05	66

Petrushevska et al. in prep

High redshift SNe will need NIR spectroscopy

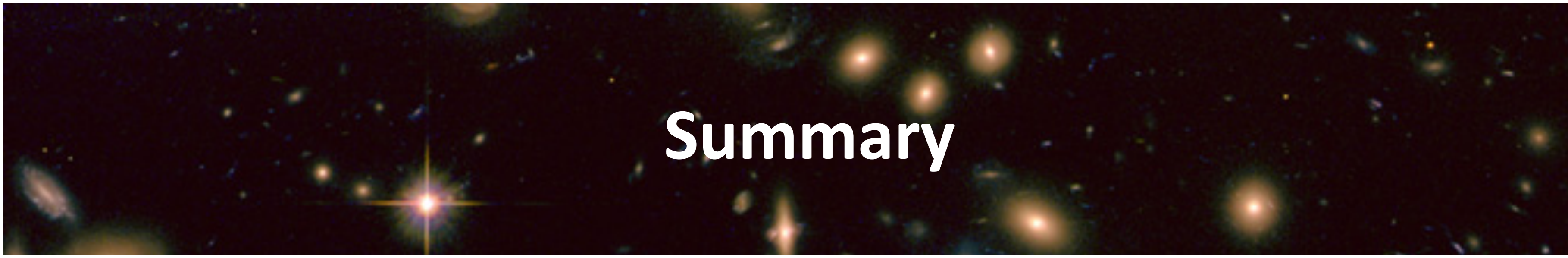


SN Refsdal
@ z = 1.49

Kelly et al. 2016

=> Here is where ELT, GMT and TMT will be needed

Summary



- Massive galaxies and galaxy clusters act as a lens allowing to study SNe at high redshift, that otherwise would remain undetected.

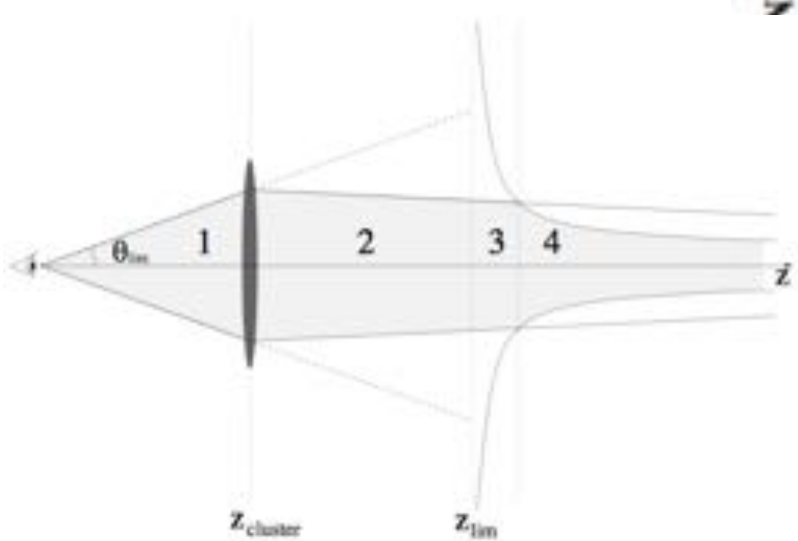
  - PAST

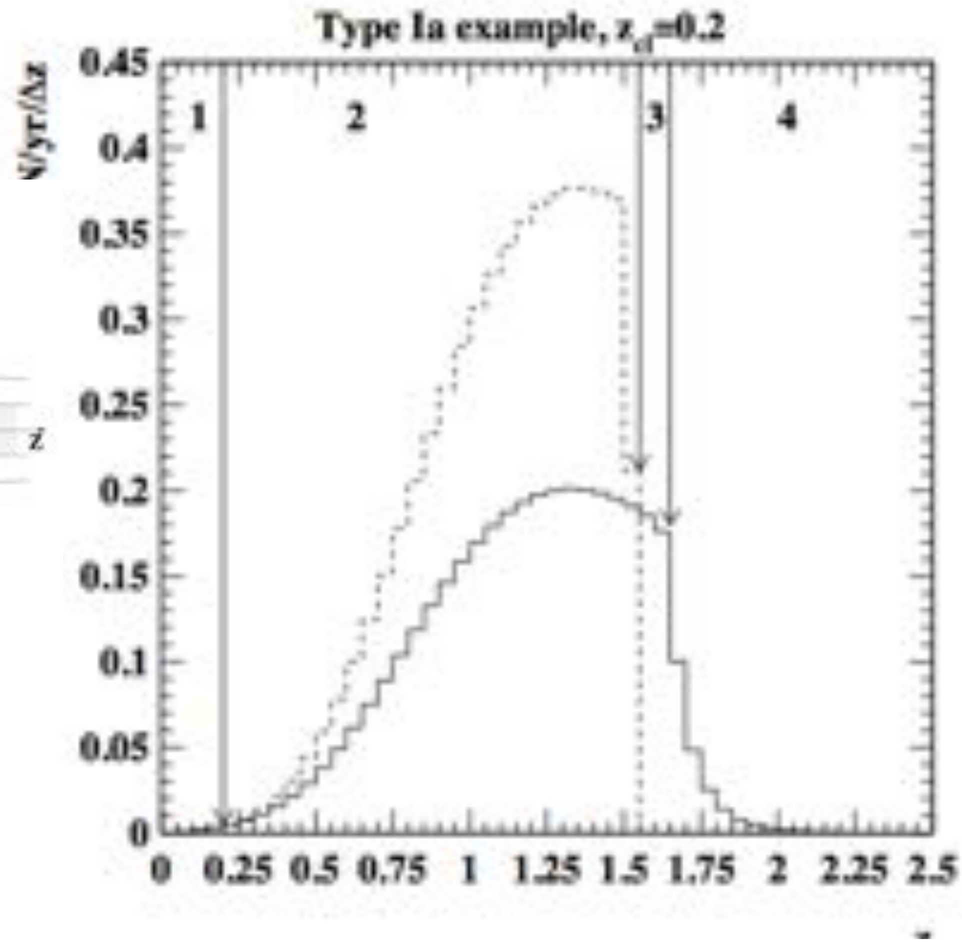
- Magnified SN Ia PS1-10afx at z=1.4 shows no signs of redshift evolution that can threaten the use of distant SNe Ia for cosmology in future wide-field SN surveys.
- We performed systematic ground-based NIR search for lensed SNe behind the gravitational telescopes, A1689 and A370. We discovered highly magnified CC SNe at very high-z. We also measured volumetric CC SN rates in agreement with HST surveys results and latest SFH.

  - FUTURE

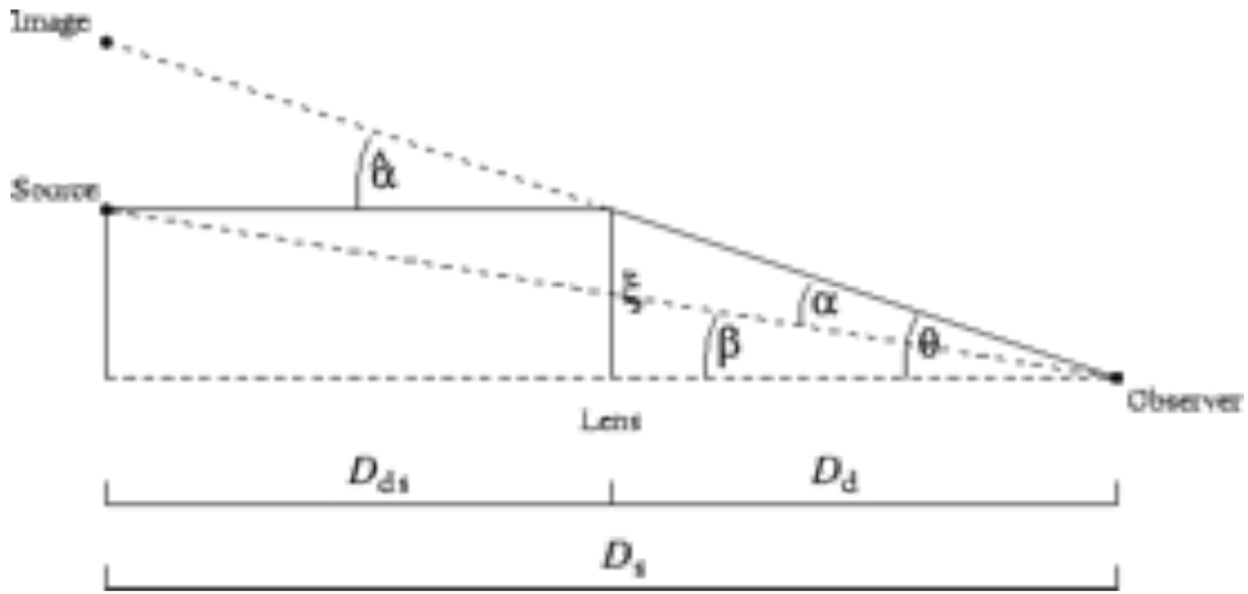
- Upcoming ground and space telescopes offer prospects of finding multiply-lensed SN with measurable time delays. ELT can help with the spectroscopy of very high-z lensed SNe.

Gr.Tel. tunnel vision: G&G (2003)





Galaxy clusters as gravitational telescopes



Lensed SNIa + assumed cosmology ->
Test the magnification maps of the galaxy cluster lensing model

Possibility of multiple images of SN with time delays

The time delays from could be used to measure the Hubble constant

Refsdal (1964)

z_{lens}

Lens potential.

$$D \equiv \frac{D_L D_S}{D_{LS}} \propto H_0^{-1}$$

Supernova observables – spectra

No Hydrogen

Type I

Silicon

No Silicon

Ia

Si @6150Å

Ib

Ic

Found in all type of galaxies

Long-lived star as a progenitor

Hydrogen

Type II

Light curve decay after maximum

Narrow emission lines present

IIL

Linear

IIP

Plateau

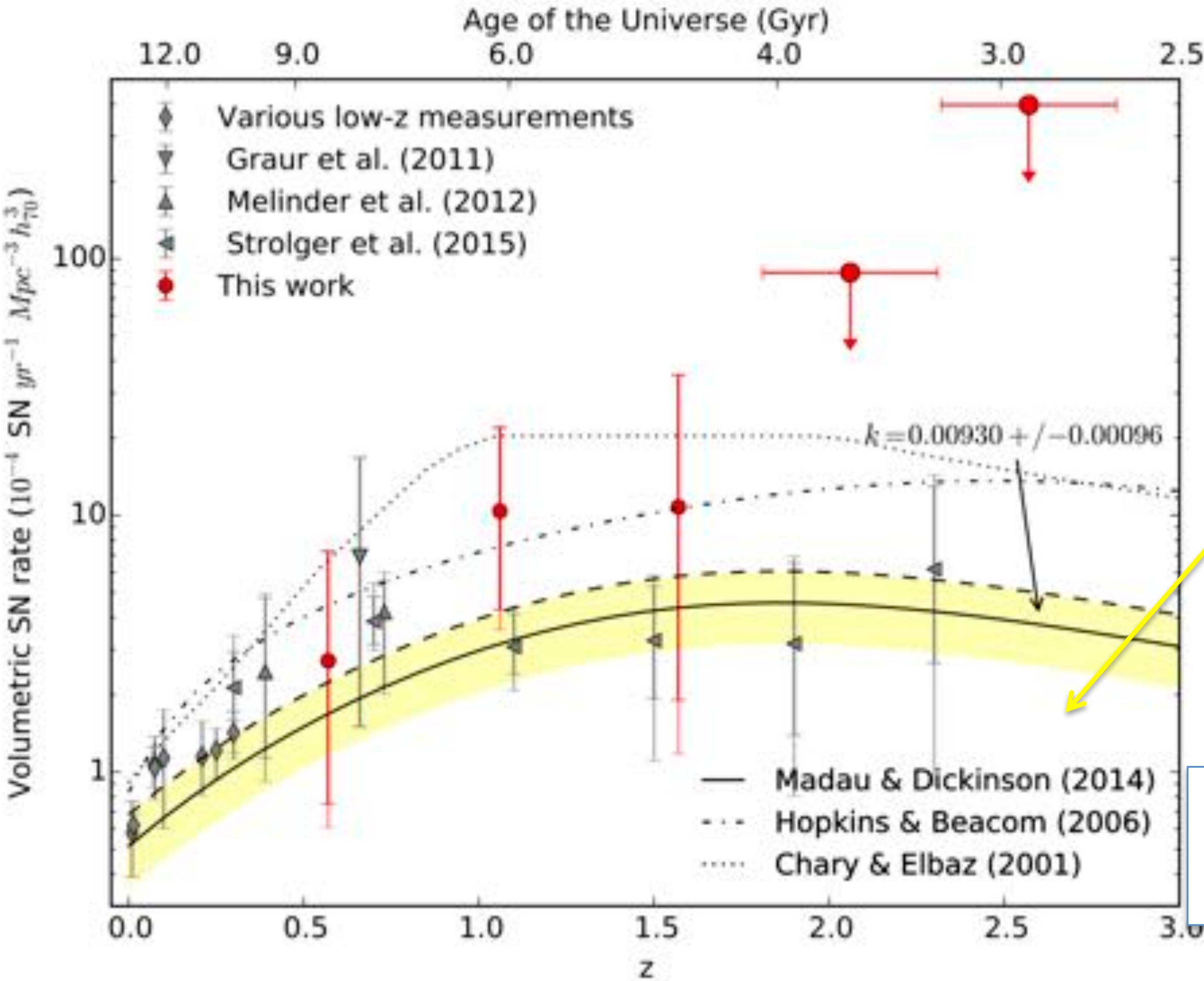
IIn

Found only in star forming galaxies

Short-lived star- > Core collapse SN

Volumetric CC SN rates

+ comparison with the Star formation history (Paper I)



$$R_{CC}(z) = k \cdot SFH(z)$$

With

$$k = 0.007 M_{\odot}^{-1}$$

if Salpeter IMF

$$m_{up} = 50 M_{\odot}$$

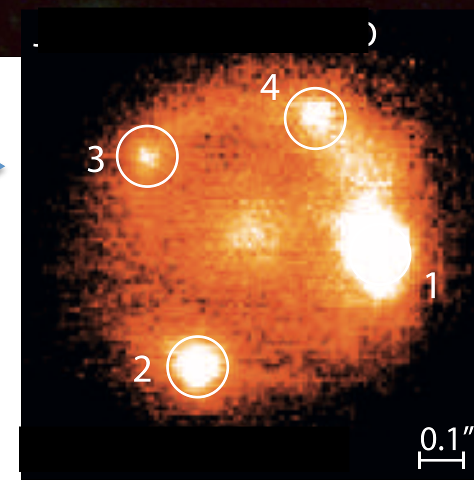
$$m_{low} = 8 M_{\odot}$$

SFHs

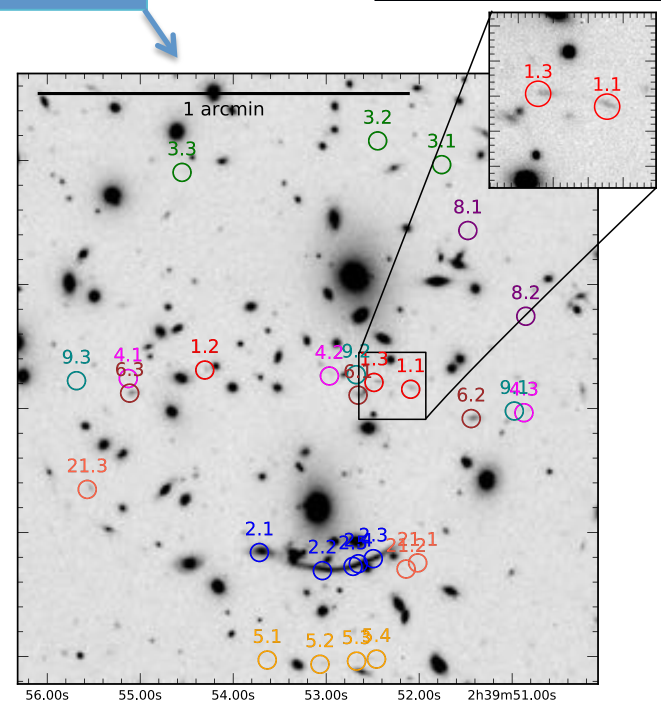
Strong lensing by galaxies and galaxy clusters

Massive galaxies and galaxy clusters act as lens. The **deflection angles** are

~arcsec for a galaxy lens,



~arcmin for a galaxy cluster lens

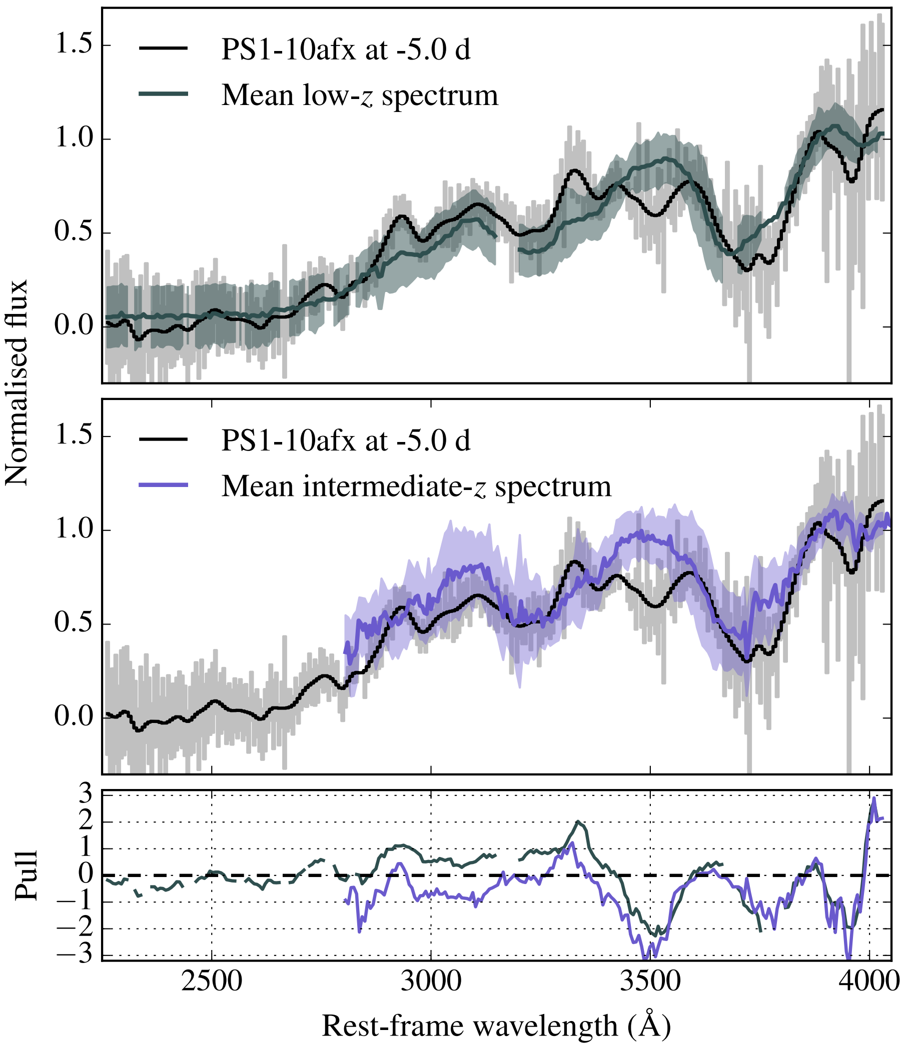


Strong lensing

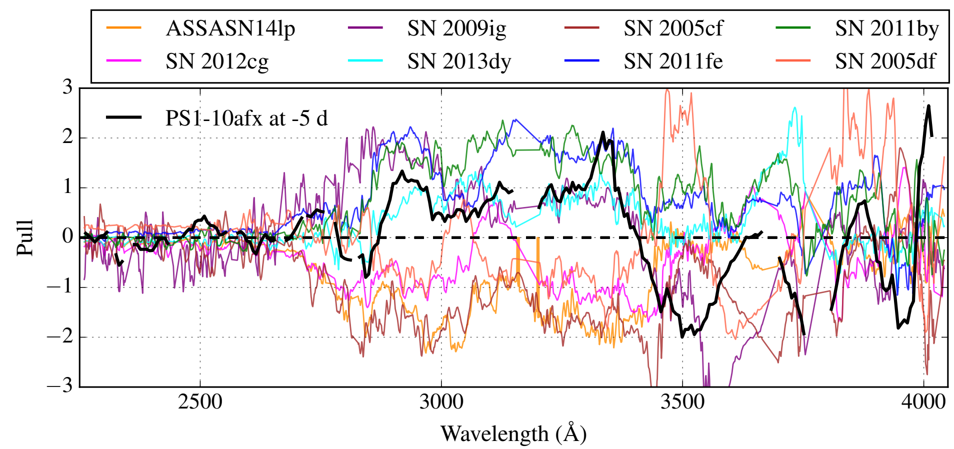
Magnification of the flux of the background sources

Multiple images of the background sources

Testing for redshift evolution of SNe Ia using the strongly lensed PS1-10afx at z = 1.4 (Paper III)



Comparisons of median spectra constructed from normal SNe Ia at low and intermediate redshift show to PS1-10afx show no signs of significant spectral evolution



Expected SNe in strongly lensed galaxies with multiple images for upcoming surveys

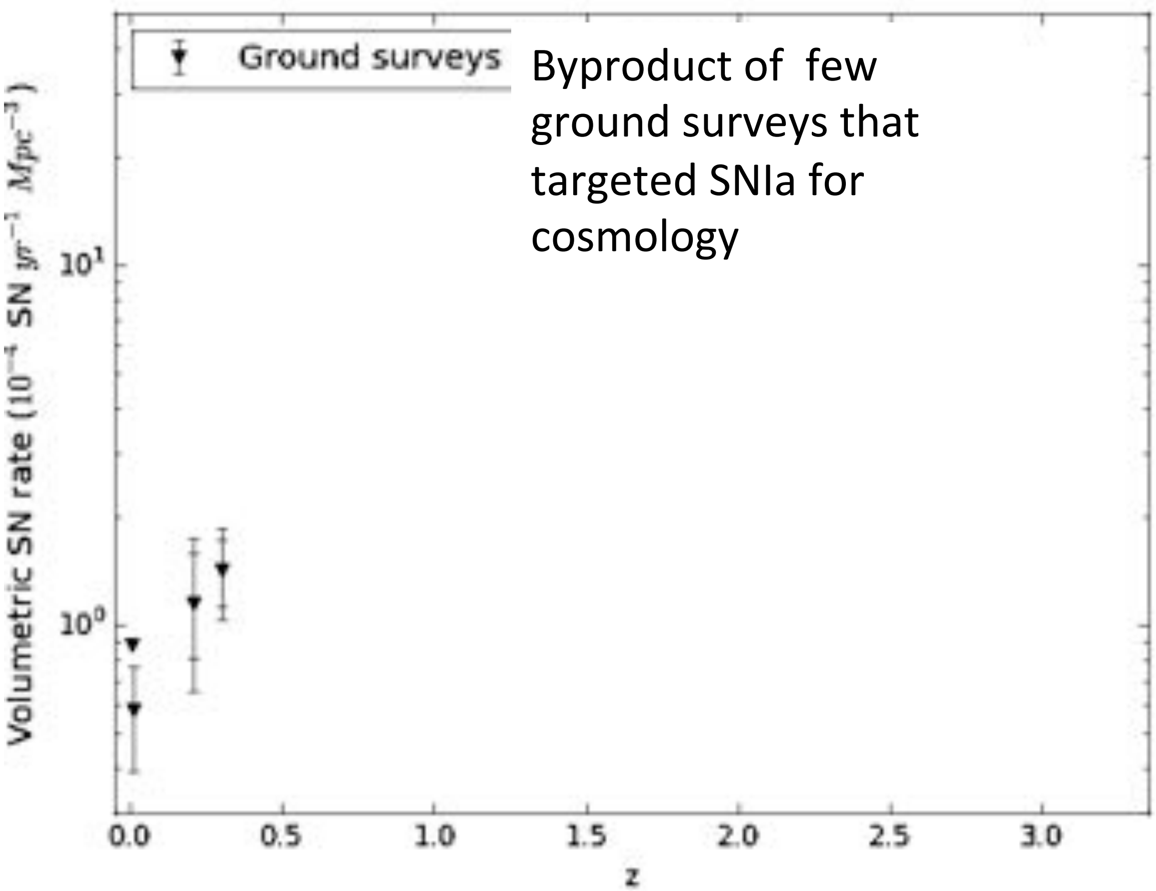
Towards A1689

Survey/filter	**Depth** (mag)	**Duration** (yrs)	**Epochs** (1/yr)	**Cadence** (days)	N_{CC}	N_{Ia}
LSST/i	24.0	10	7	30	0.18±0.09	0.21±0.17
LSST/i	25.0	10	7	30	0.38±0.18	0.26±0.20
LSST/z	22.76	10	7	30	1.14±0.61	0.68±0.40
WFIRST/H	28.01	2	3	30	1.74±0.82	0.17±0.08
JWST/F115W	27.5	5	4	30	2.5±1.2	0.5±0.2
JWST/F150W	27.5	5	4	30	5.4±2.6	0.6±0.3
JWST/F115W	27.5	5	12	30	4.4±2.1	0.7±0.4
JWST/F150W	27.5	5	12	30	7.7±3.6	0.7±0.4

- If A370 is used, the numbers are much lower: N_{cc}~ 0.7 and N_{Ia}~ 0.05 with JWST
- Increasing the number of epochs does not increase N_{SNe} significantly

Measuring core collapse Supernova rates

Before 2010

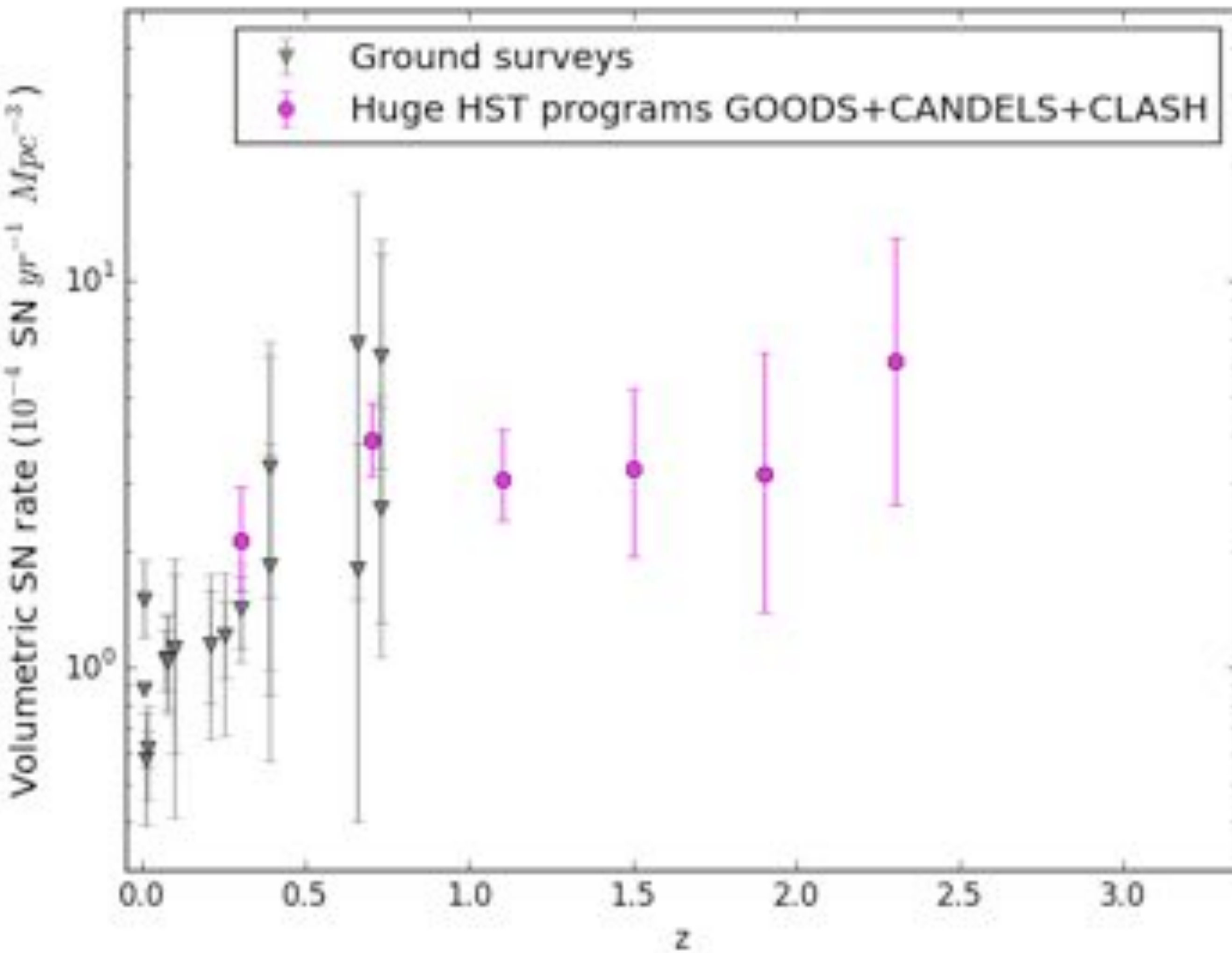


Byproduct of few ground surveys that targeted SNIa for cosmology

Unlike SNIa, CC SN rates have been measured poorly for long time for several reasons:

- CC SNe are on average intrinsically fainter than SNIa
- CC SNe explode often in dusty environments
- At high-z, SN light shifts from optical to NIR where atmosphere is trouble

Measuring core collapse Supernova rates



More than 1000 HST orbits

(Strolger et al. 2015)

Core collapse Supernova rates and Cosmic Star formation history

CC SN rate

Simple relation

$$R_{CC}(z) = k \cdot \psi(z)$$

Cosmic SFH

Core collapse Supernova rates and Cosmic Star formation history

Simple relation

$$R_{CC}(z) = k \cdot \psi(z)$$

CC SN rate → $R_{CC}(z)$

k → Fraction of stars that end up as CC SN progenitors per unit mass

$\psi(z)$ → Cosmic SFH

$$k \equiv \frac{\int_{m_{\min}}^{m_{\max}} IMF(m)dm}{\int_{0.1M_\odot}^{125M_\odot} m \cdot IMF(m)\, dm}$$

Core collapse Supernova rates and Cosmic Star formation history

CC SN rate

Simple relation

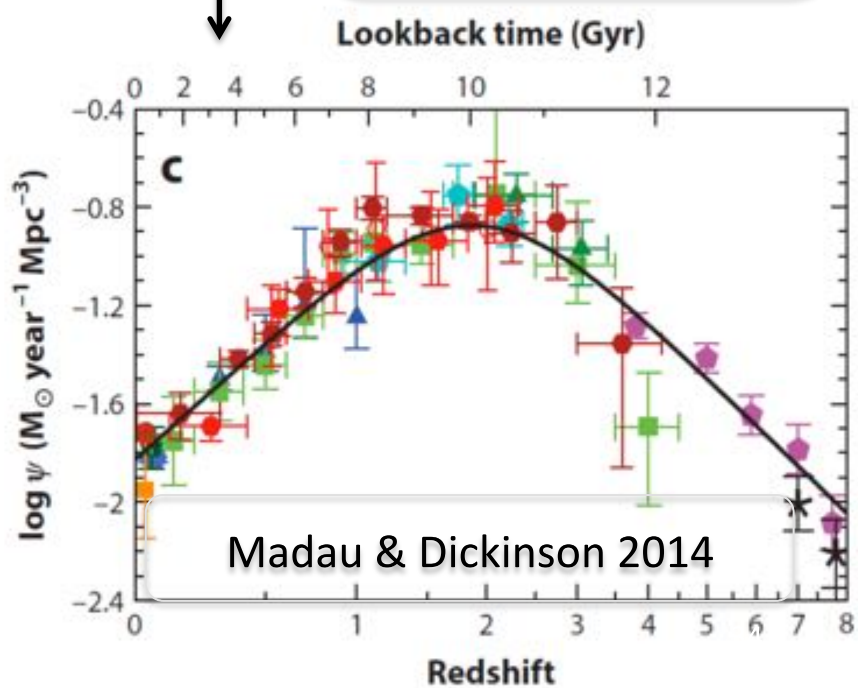
$$R_{CC}(z) = k \cdot \psi(z)$$

Number of CC SN progenitors

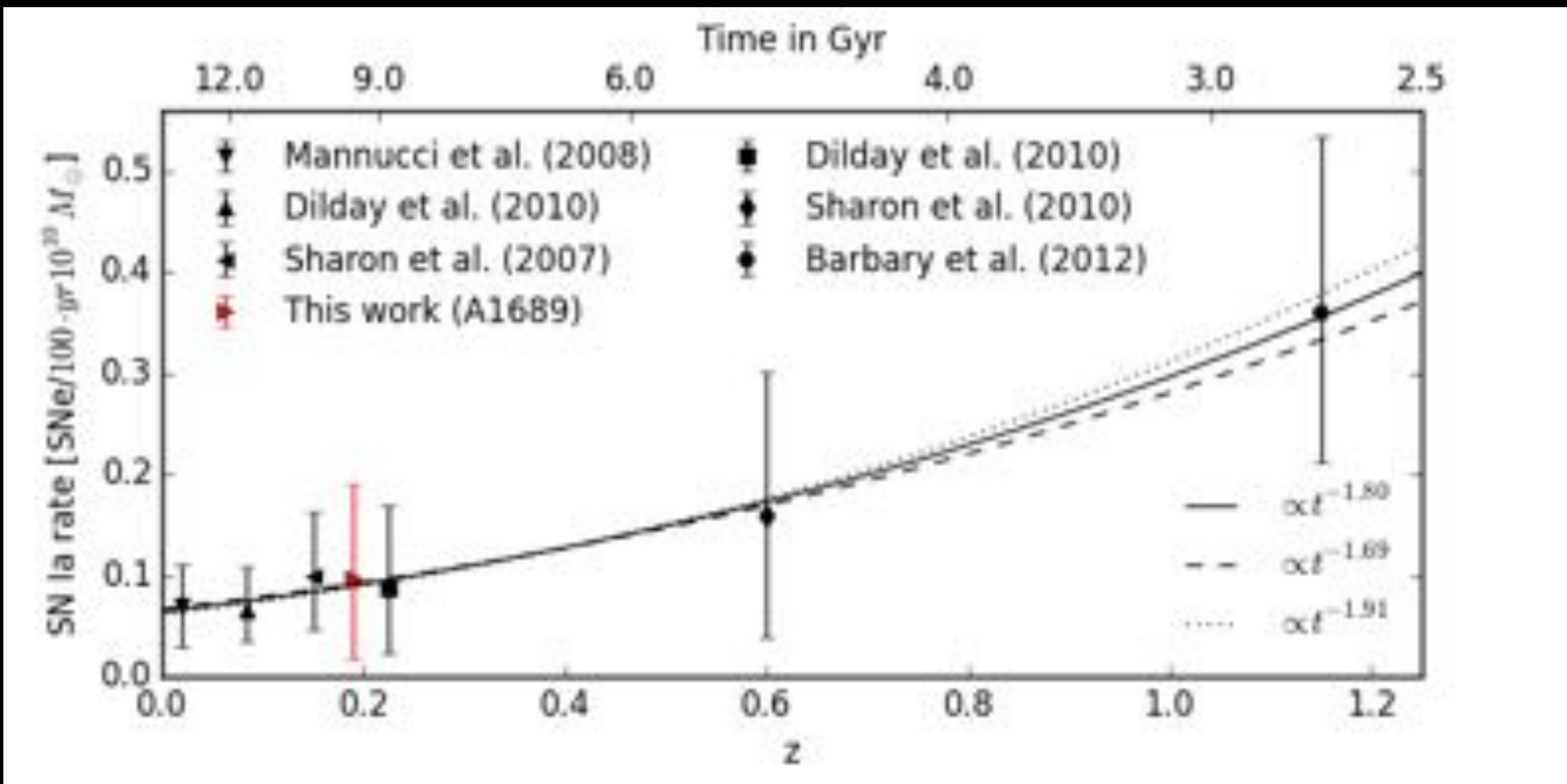
Cosmic SFH

There are several methods for measuring the SFR. For a long time there was not a consistent picture…

$$k \equiv \frac{\int_{m_{\min}}^{m_{\max}} IMF(m)dm}{\int_{0.1M_{\odot}}^{125M_{\odot}} m \cdot IMF(m)\,dm}$$

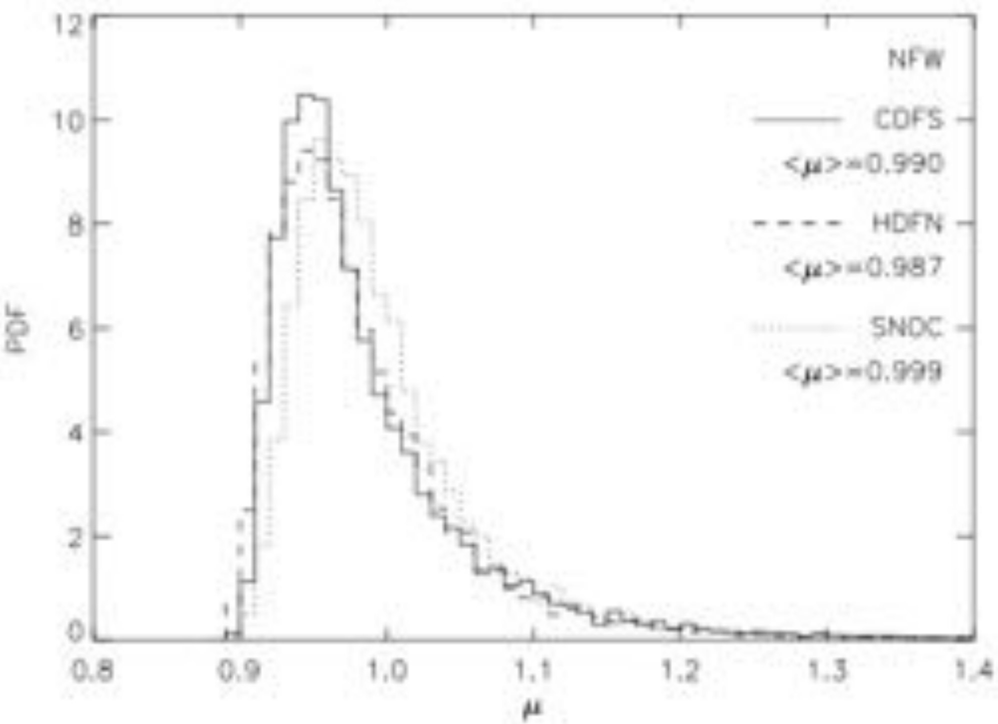


3 Cluster SNe Ia → Cluster SNIa rates



Paper I

Gravitational lensing as systematic effect in SN Ia cosmology



The magnification factors computed for a large number of LOS to sources at redshift, say z=1.5.
Model is NFW halos

- Since flux is conserved, the average flux from a number of standard candles at random positions, all at the same redshift, is expected to be the same as the flux from one single standard candle in a homogeneous universe. Gravitational lensing should not lead to any bias, if the average flux is used as distance indicator.
- Gravitational lensing could lead to selection bias in a magnitude limited survey. A selection bias would affect the value of the average flux.