

## Lensed supernovae: past and future

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# Vipava valley in the 10 best places to visit in 2018





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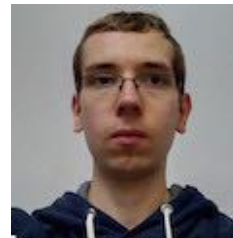
Gašper  
Kuček



Aurora  
Clerici



Marta  
Trini



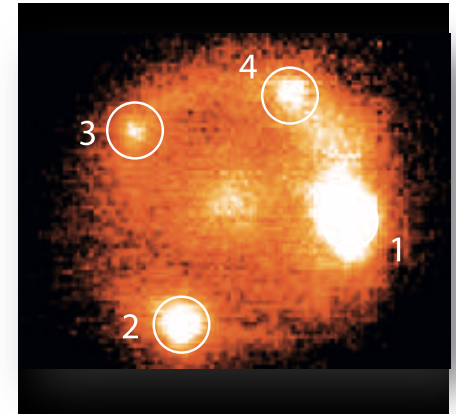
Christopher  
Eckner



Lukas Zehrer



Katja Bricman

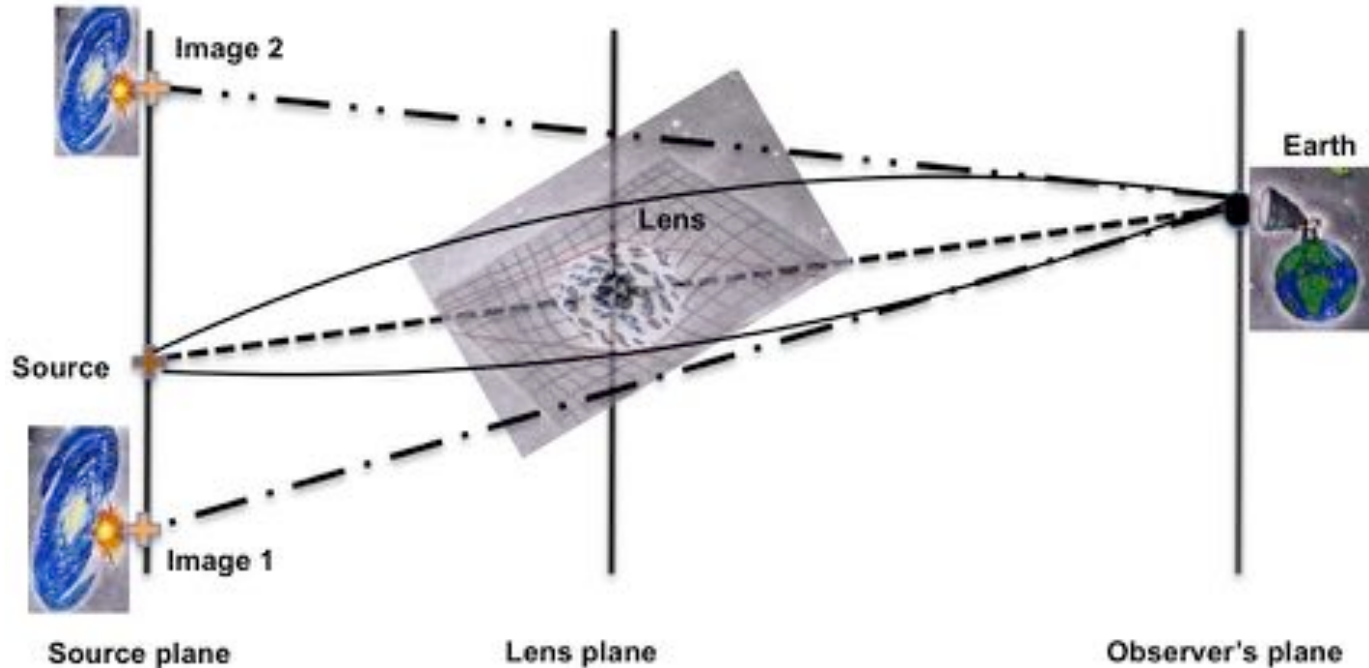


## Lensed supernovae: past and future

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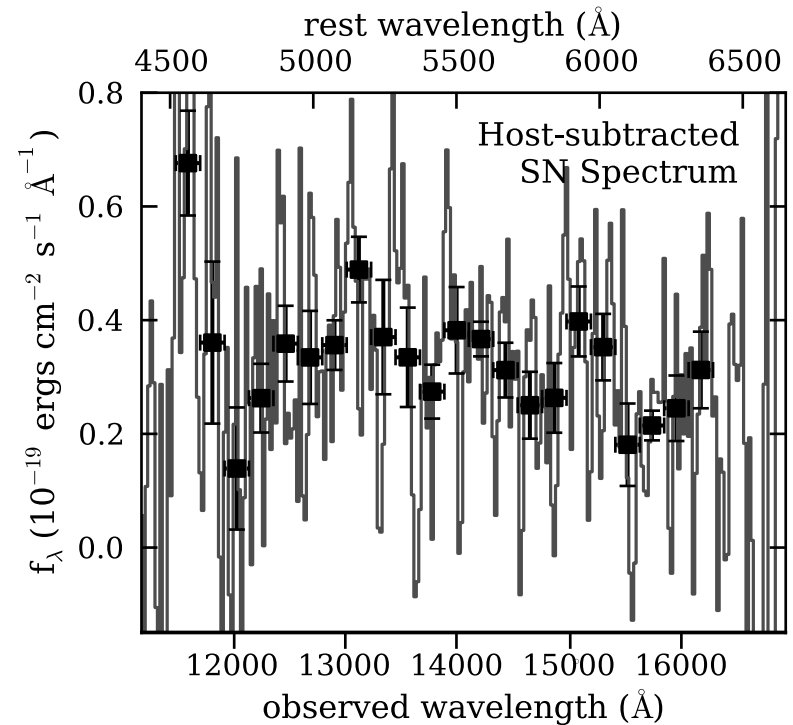
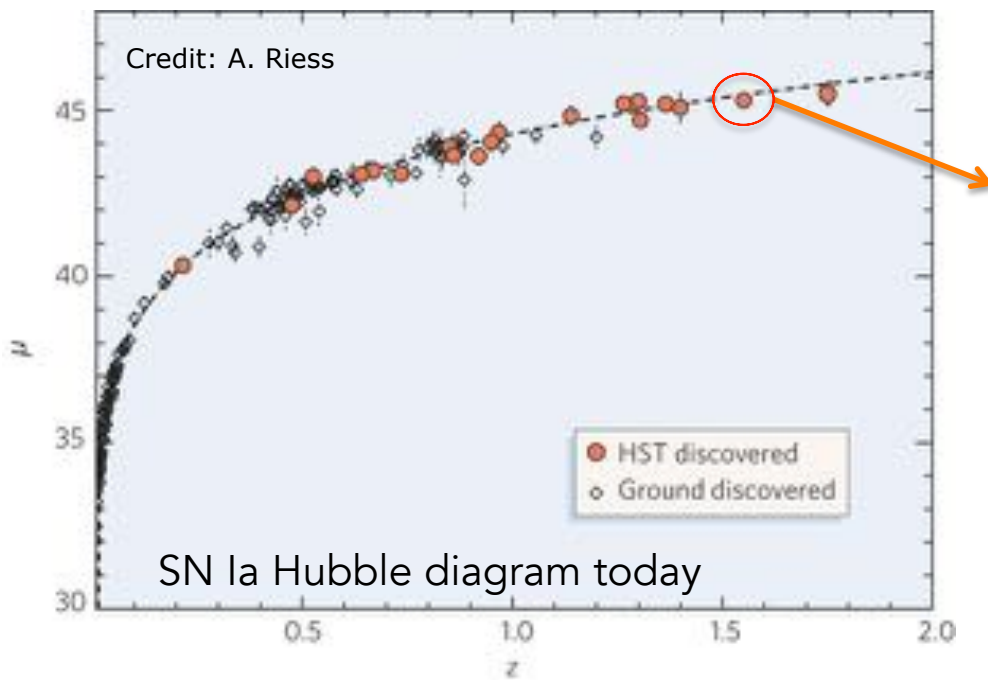
# Strong lensing as a tool for studying the high-redshift universe



- **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)

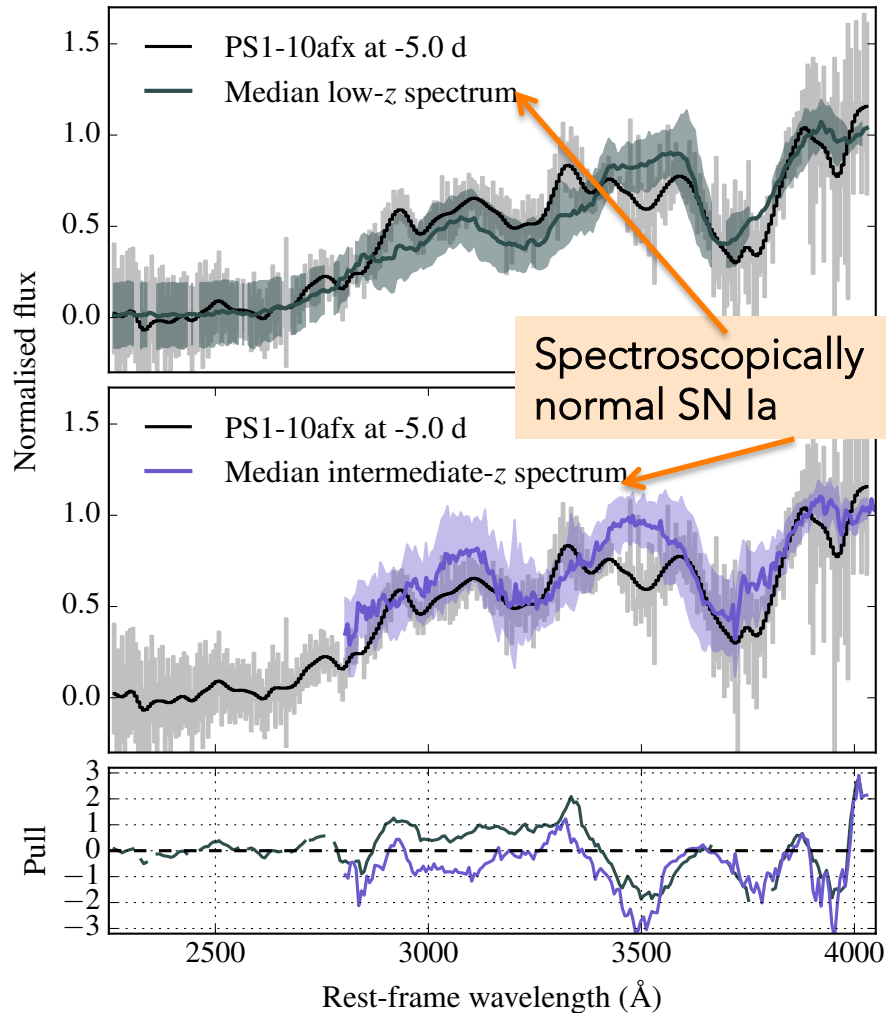
# Evolution in SN Ia properties as possible systematic effect for future surveys

- 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  $\approx 30$  times by a foreground galaxy



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

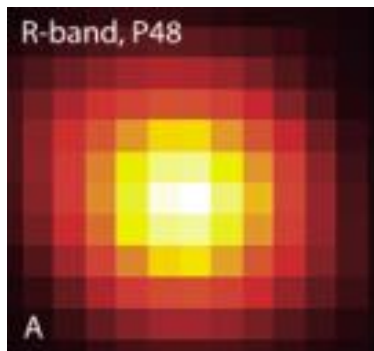
Petrushevskaya et al. 2017

# 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  $z \lesssim 0.1$

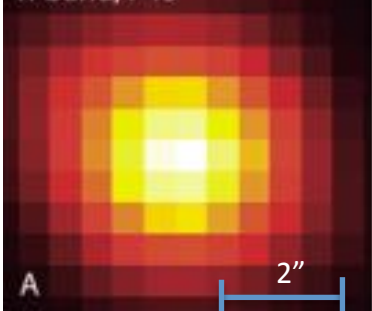


- In October 2016, a supernova was discovered which low-resolution spectrum indicates  $z \approx 0.4$ . Later high-resolution spectrum confirmed SN Ia at  $z = 0.409$ . At the location, known elliptical galaxy at  $z = 0.206$ ...

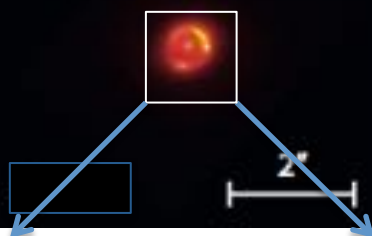
Is it a lensed supernova?

# iPTF16geu the first strongly lensed SN Ia with resolved multiple images

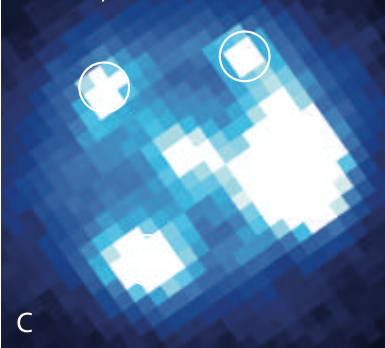
R-band, P48



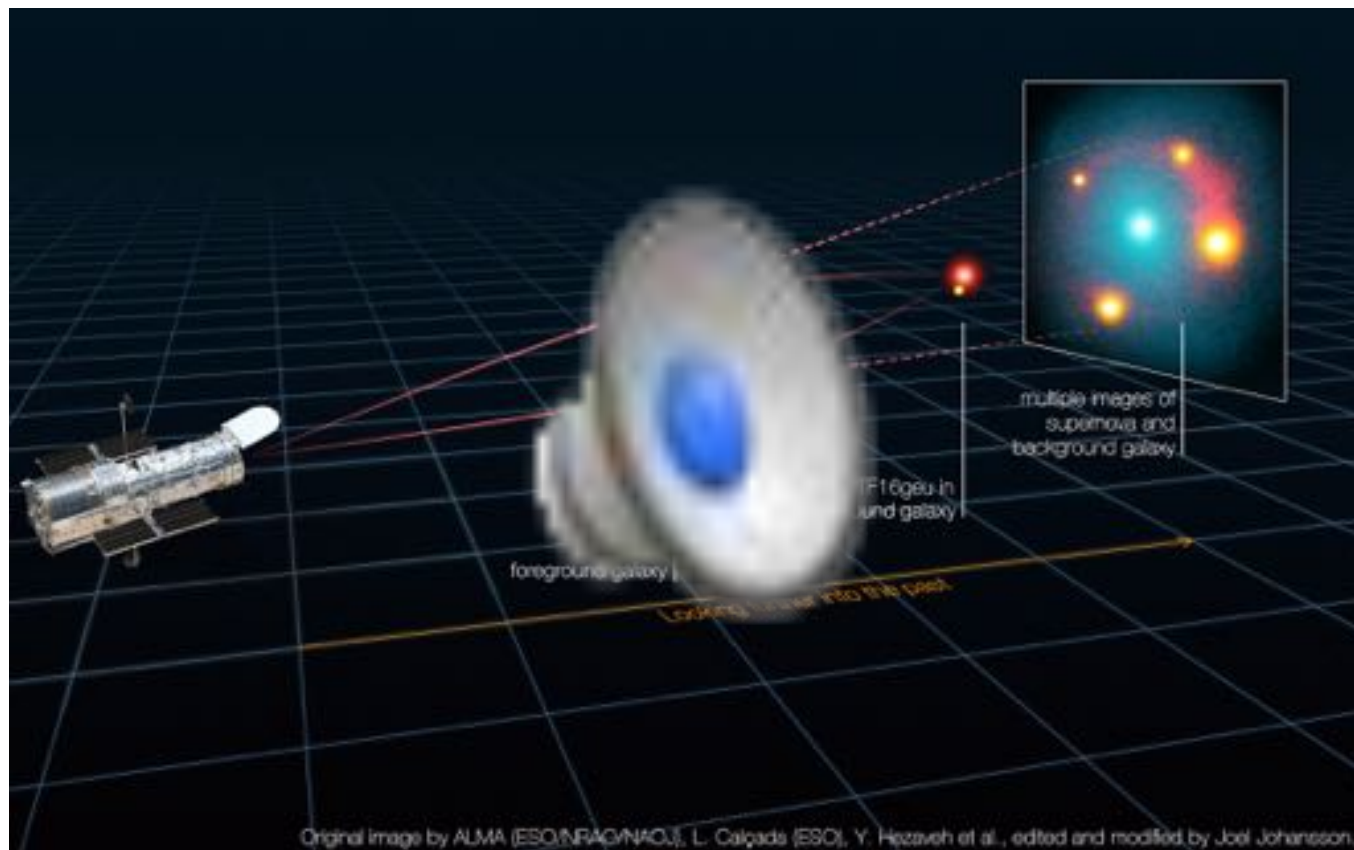
Keck/OSIRIS  
(Laser Guide Star AO)



F814W, HST/WFC3



- 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 !

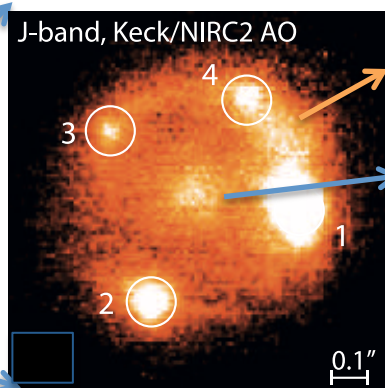
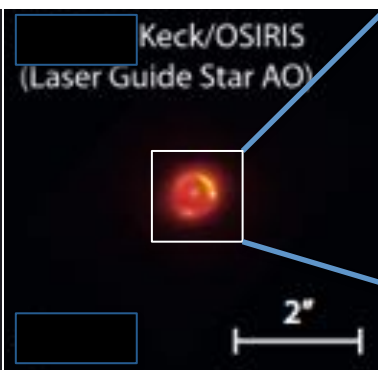
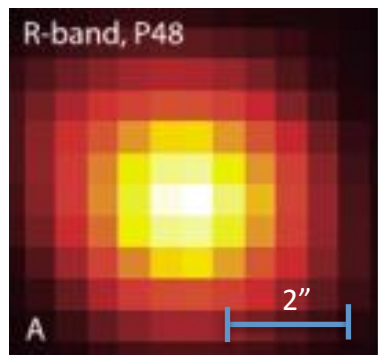




# iPTF16geu the first strongly lensed SN Ia with resolved multiple images

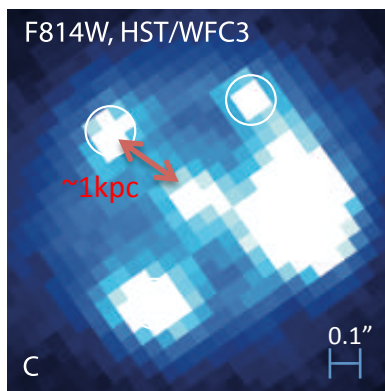
Goobar et al. 2017 Science

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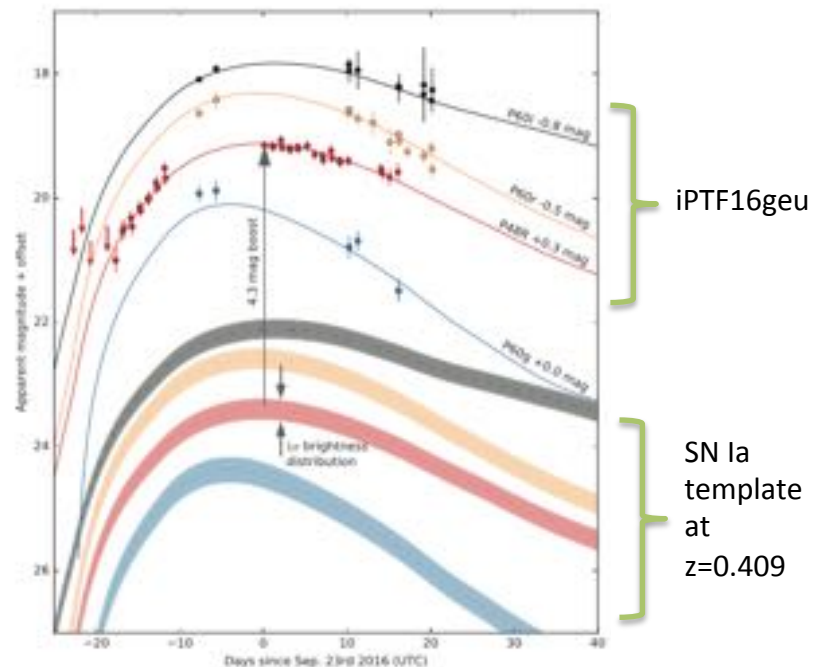


Lensed SN host galaxy

Lensing galaxy



Surprisingly large magnification, most likely also microlensed



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.

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

SN Ia

Core collapse SNe  
(CC SNe)

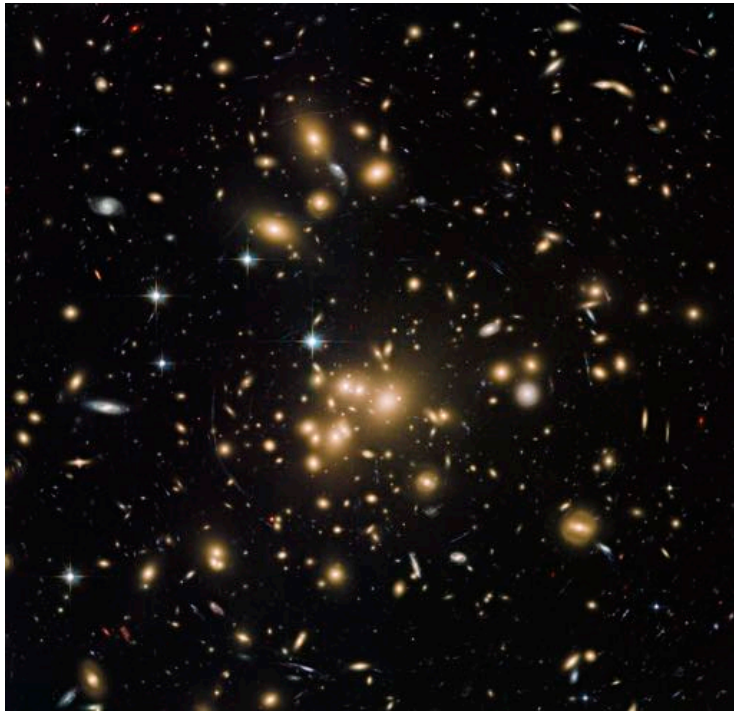
The time delays of multiply- imaged SNe -> measure the Hubble constant

- 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



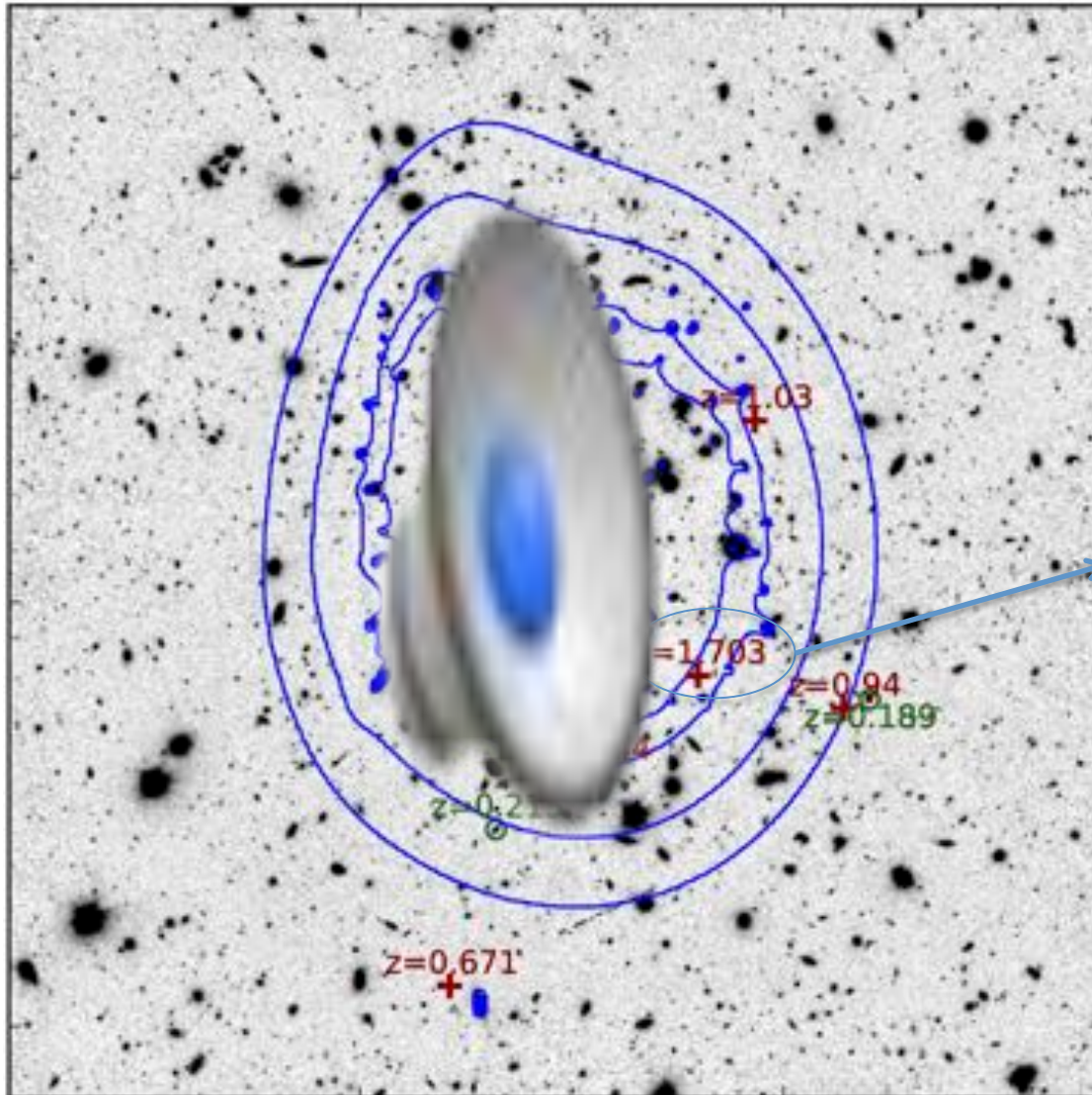
- Abell 1689 at  $z = 0.18$
- 31 epochs over 5 years



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



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

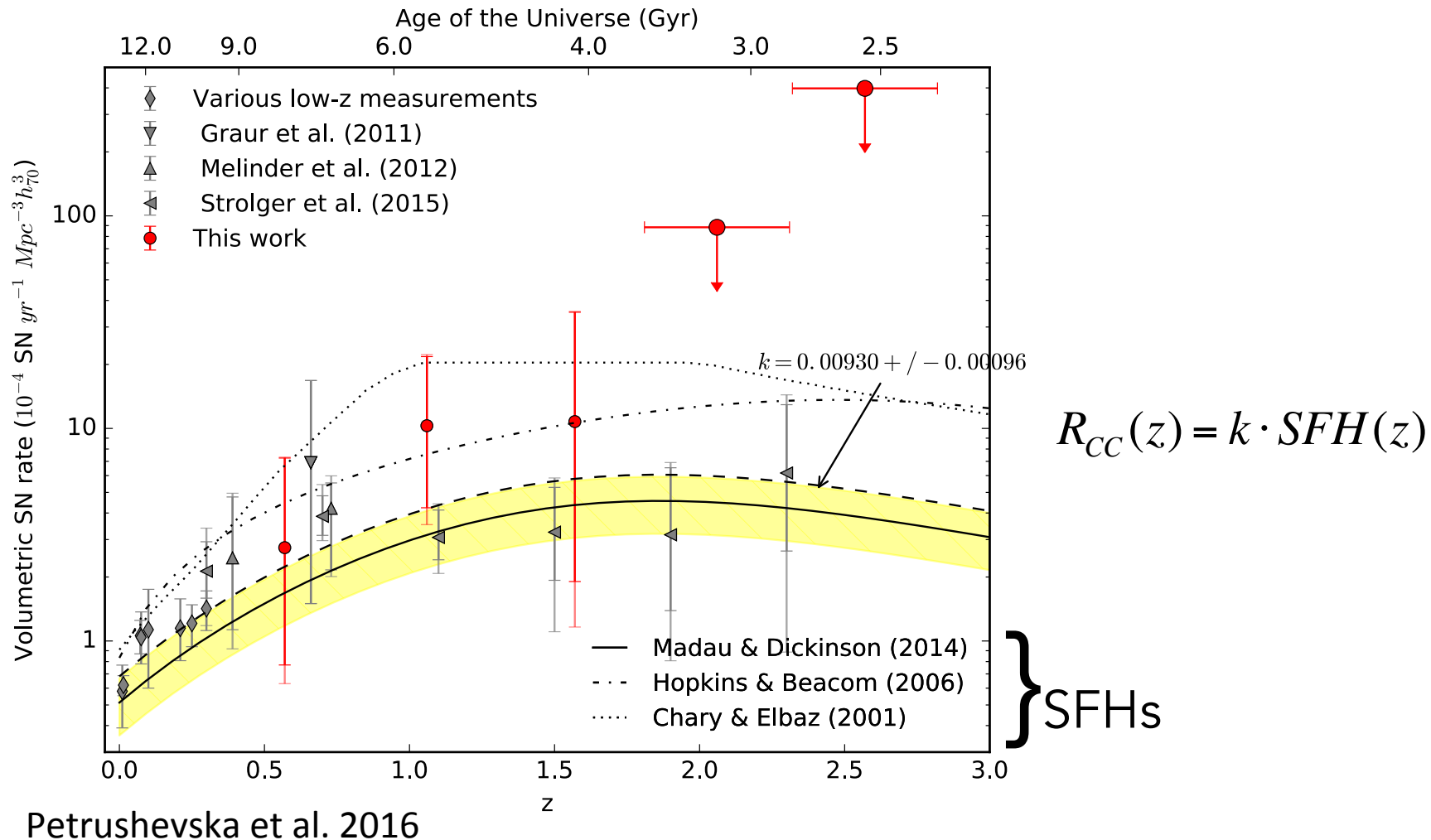


SNe Ia  
CC SNe

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

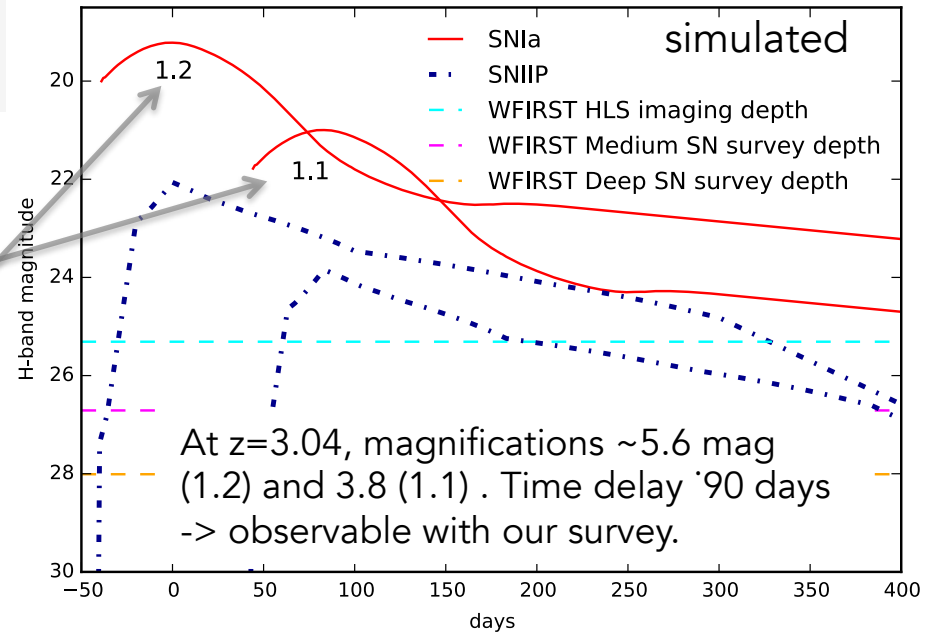
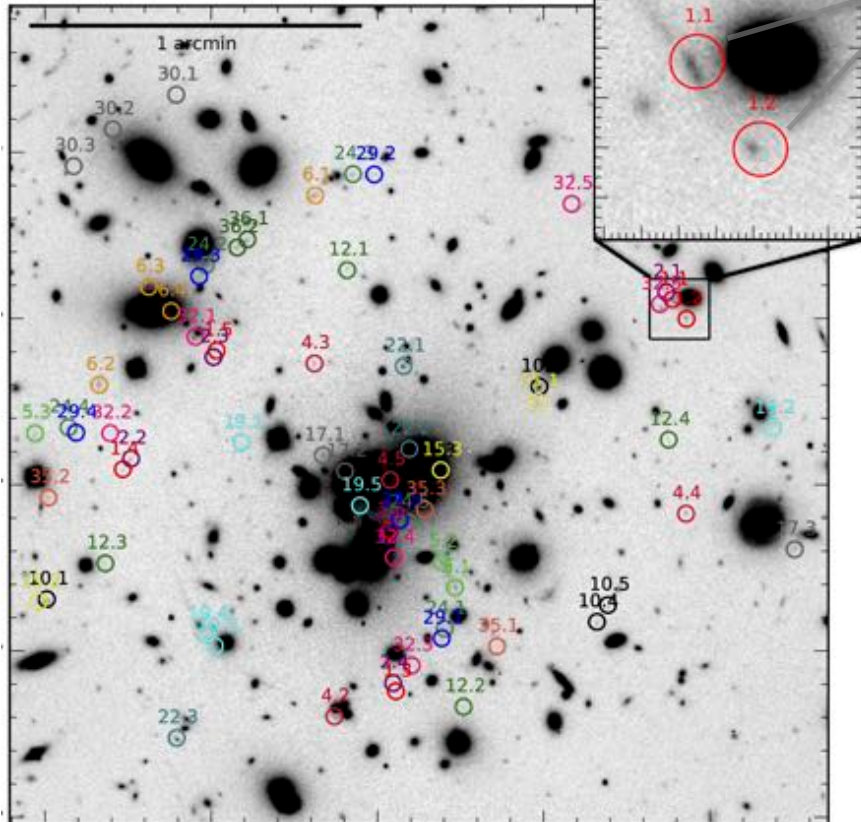
# Volumetric CC SN rates

+ comparison with the star formation history



# 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  | $0.7 < z < 6$ |

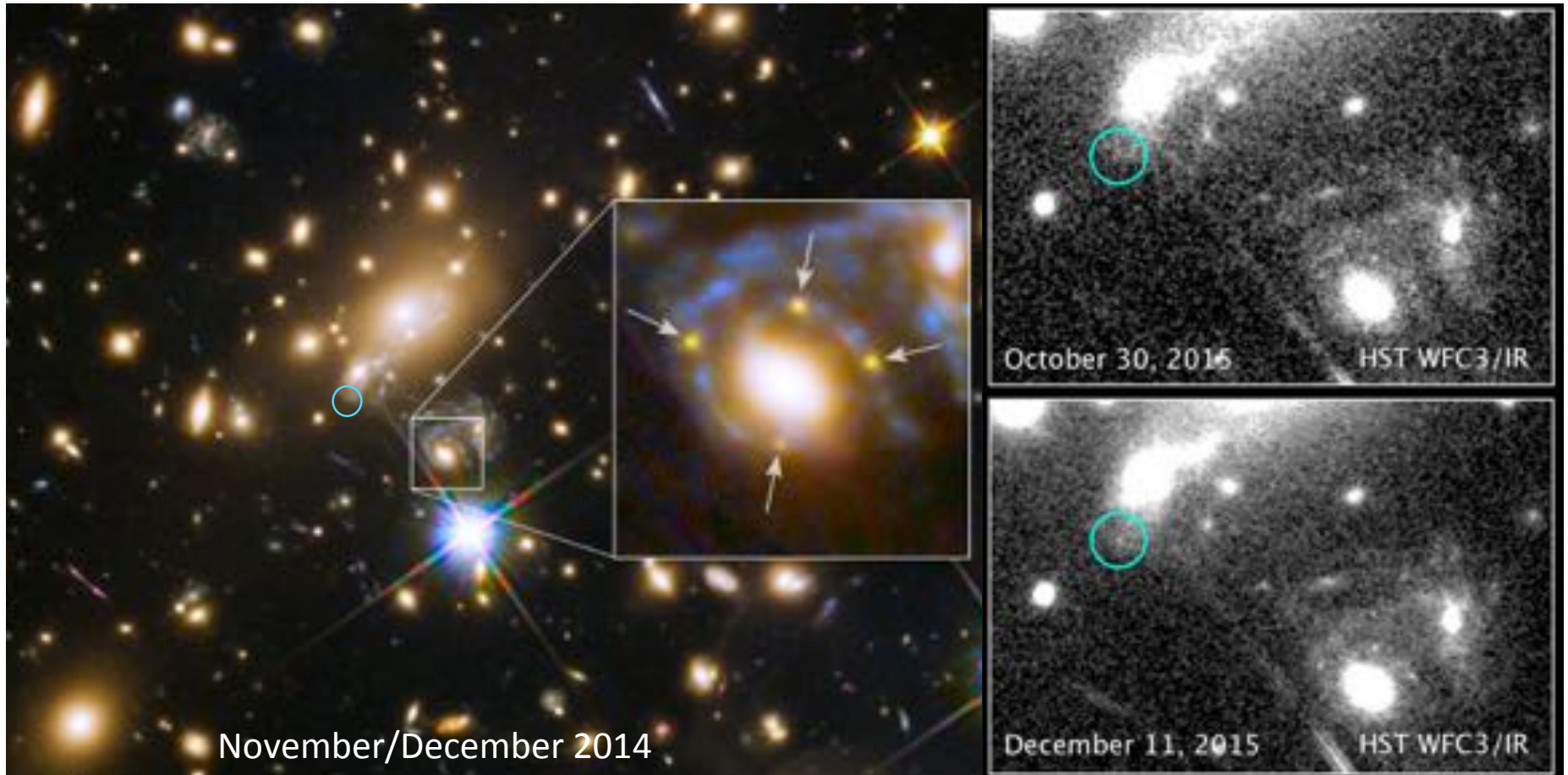


- We did not find any SNe in the multiply lensed galaxies
- The expected SNe for our surveys in these galaxies was  $\sim 0.6$  SNe.

Petrushevskaya 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 $N_{\text{SNe}}$ 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:  $N_{\text{SNe}} \sim 0.7$  with JWST
- Increasing the number of epochs does not increase  $N_{\text{SNe}}$  significantly

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

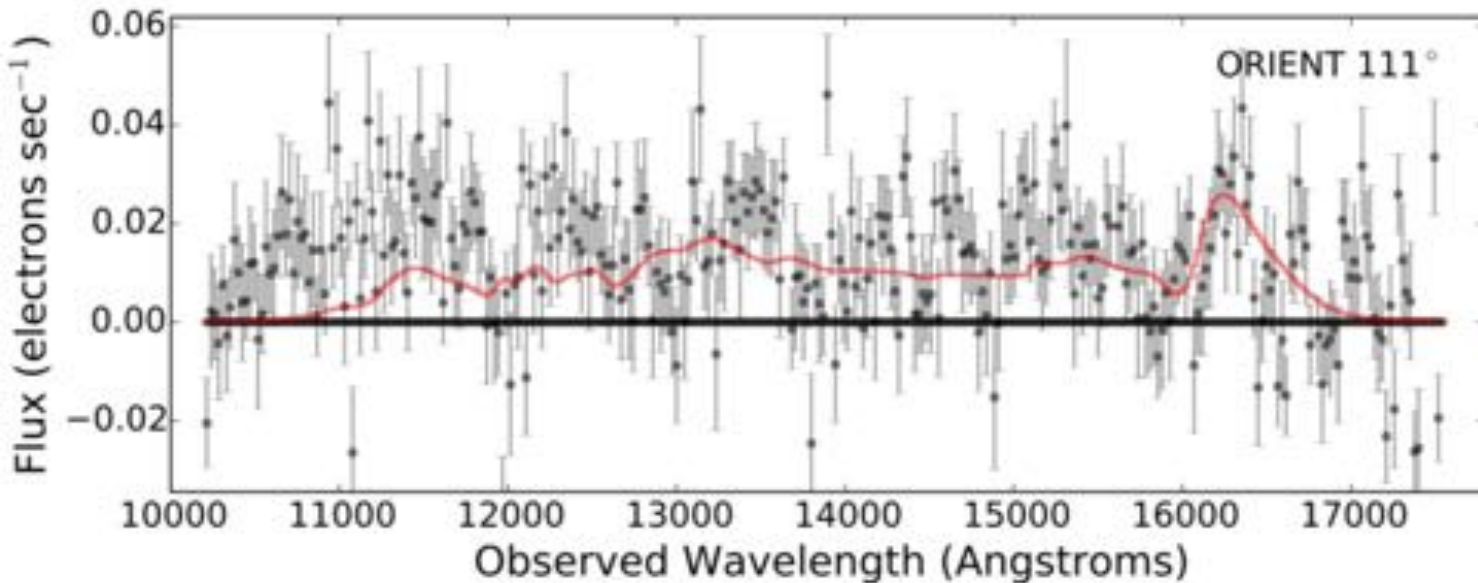
4 visits in 1 year with F150W (exposure time 1 hour)  
27.5 mag  $5\sigma$  (3-4 mag deeper than Keck-AO!)



| Cluster    | $N_{cc}$   | $N_{Ia}$     | $z_{max}$ | $N_{gal}$ |
|------------|------------|--------------|-----------|-----------|
| 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        |



# High redshift SNe will need NIR spectroscopy



SN Refsdal  
@  $z = 1.49$

Kelly et al. 2016

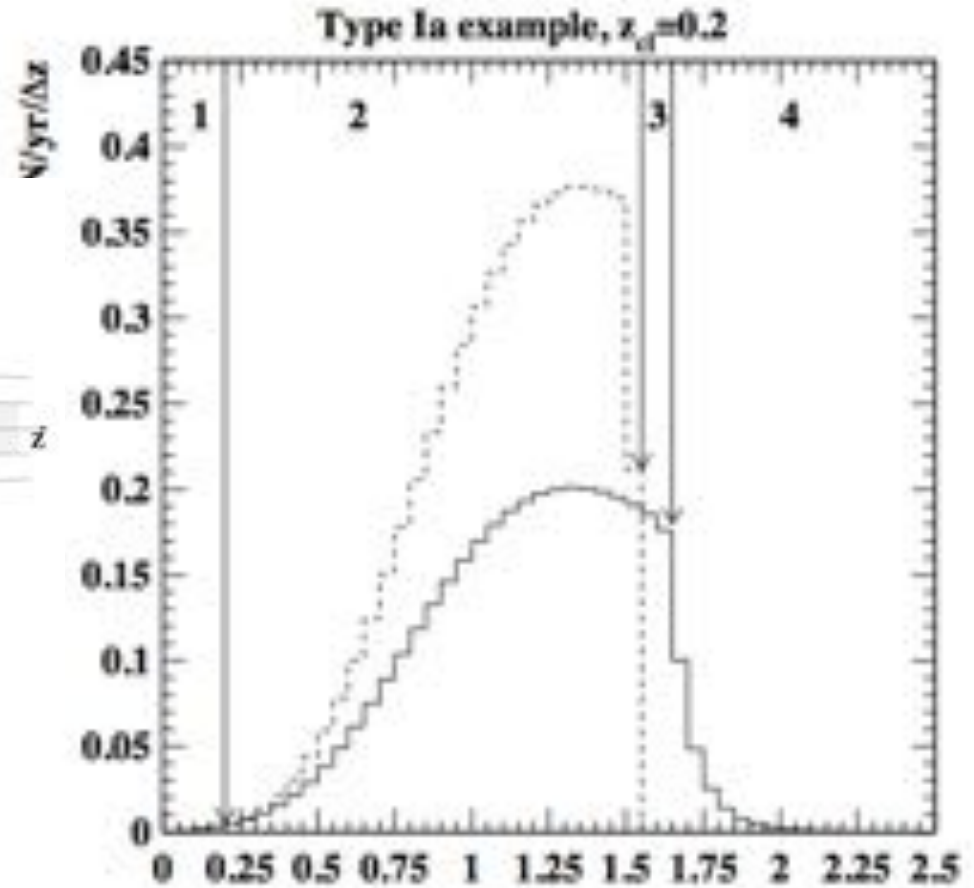
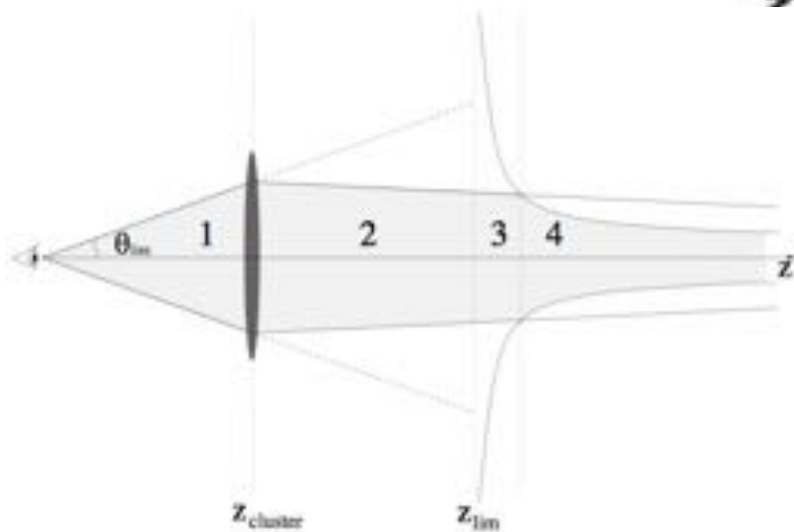
=> Here is where ELT, GMT and TMT will be needed



# 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)



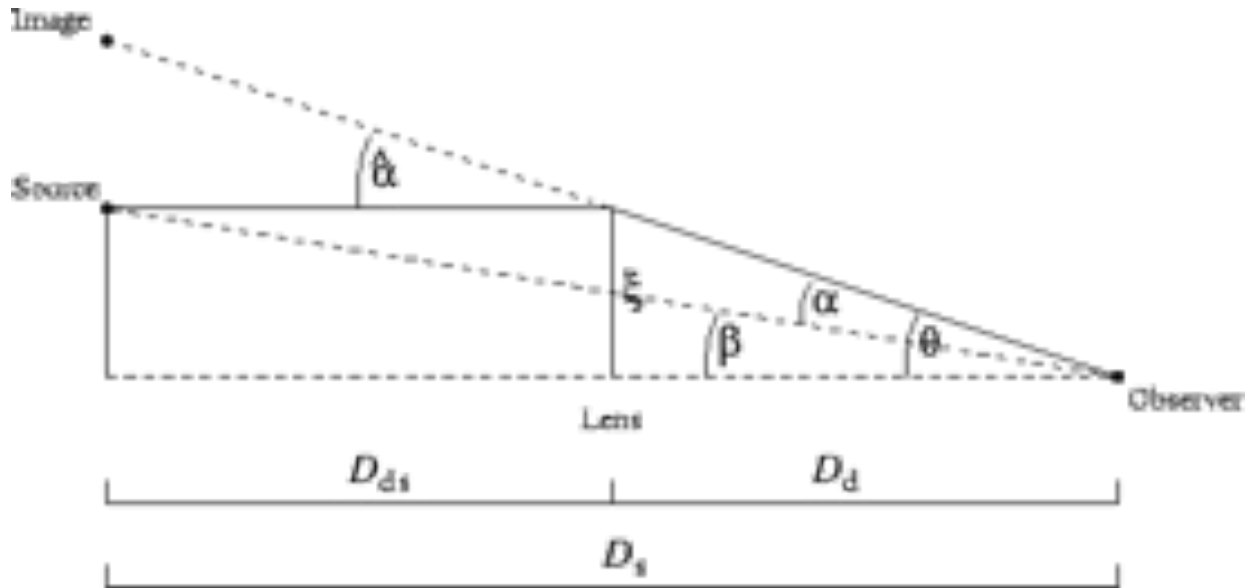


# Galaxy clusters as gravitational telescopes

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)

$z_{\text{lens}}$  ↓

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

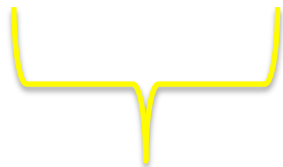


Ia

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

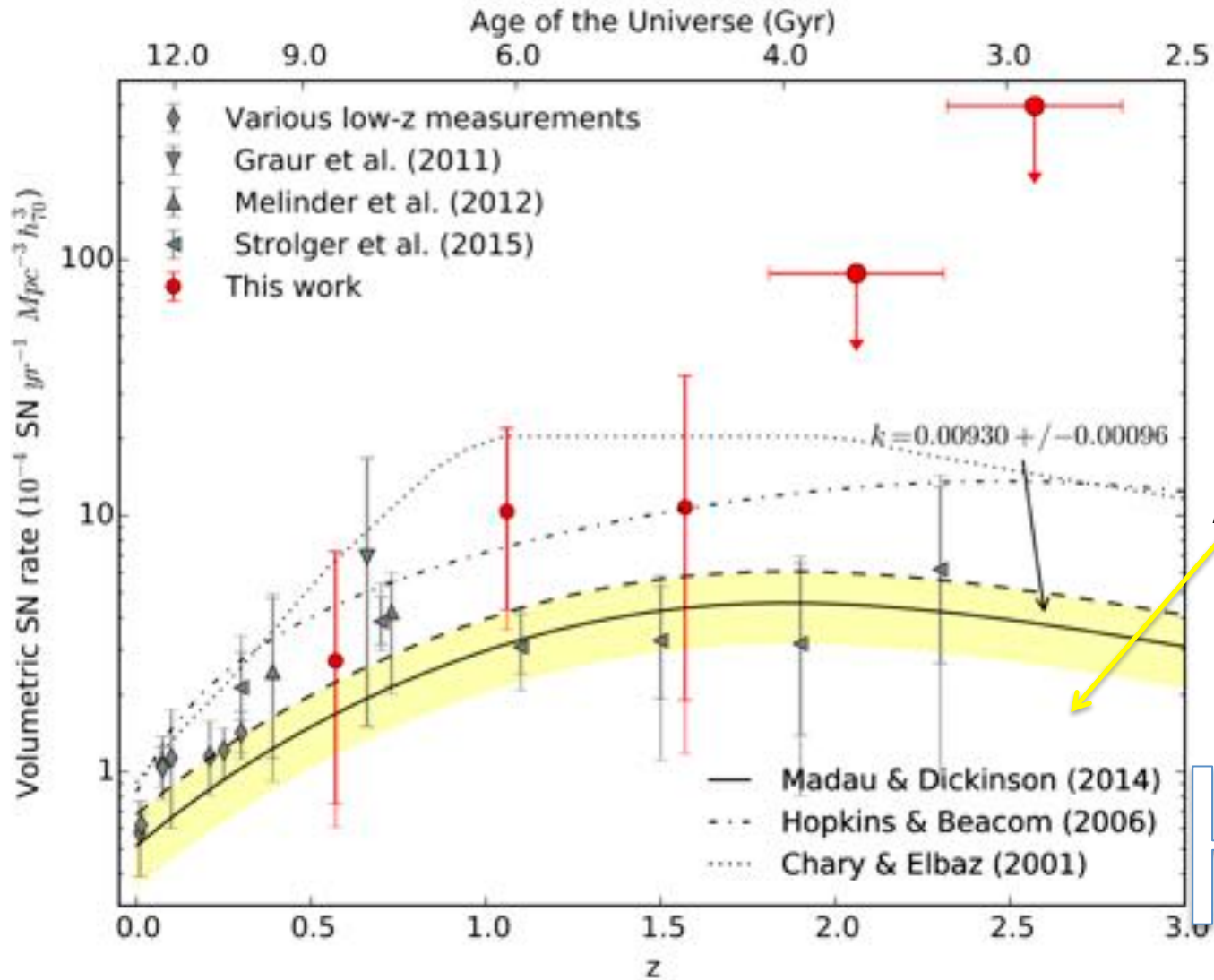
IIn

Found only in star forming galaxies

Short-lived star -> Core collapse SN

# Volumetric CC SN rates

+ comparison with the Star formation history (Paper I)



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

With

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

if Salpeter IMF

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

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

→ SFHs

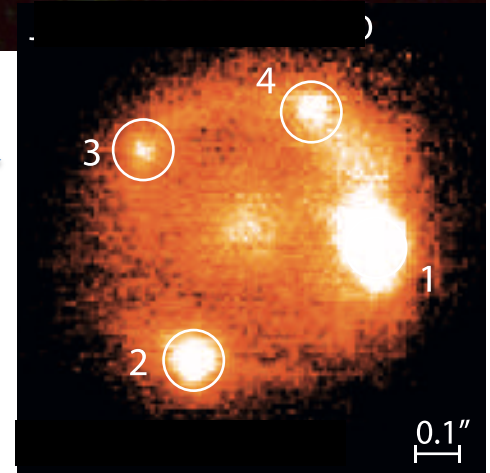


# Strong lensing by galaxies and galaxy clusters

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

~arcsec for a galaxy lens,

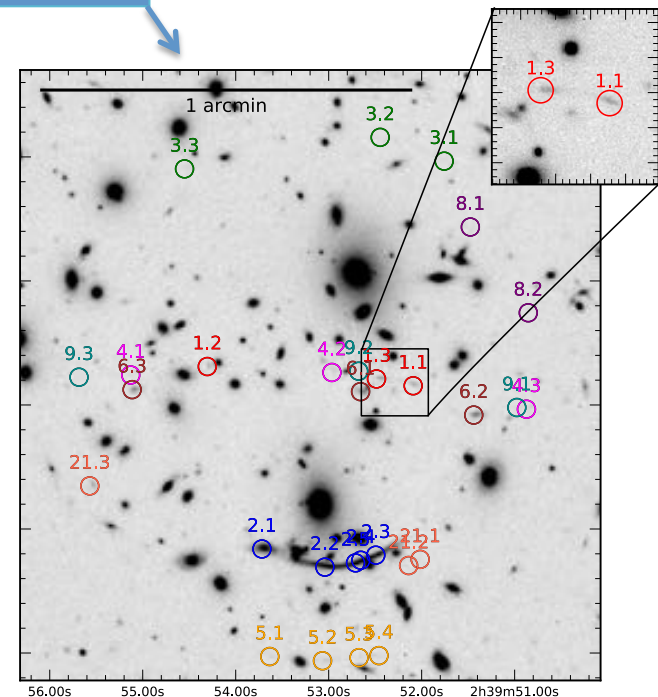
~arcmin for a galaxy cluster lens



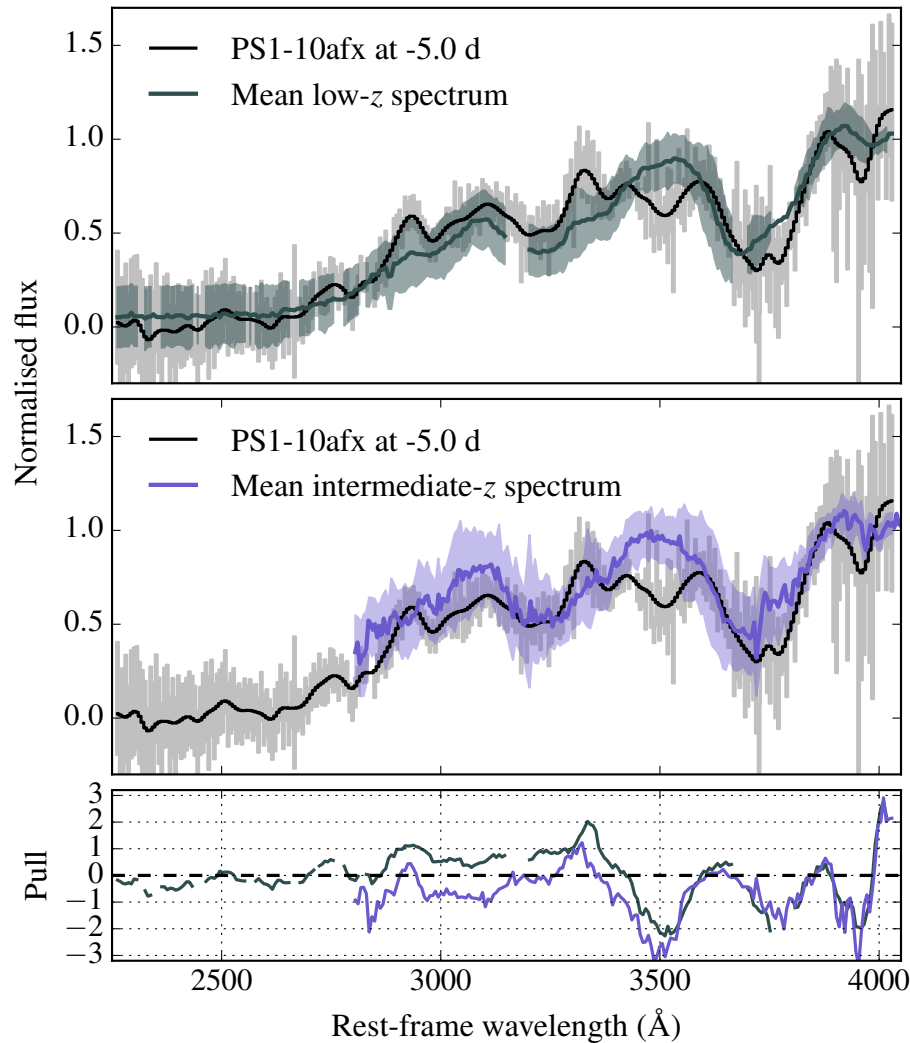
**Magnification** of the flux of the background sources

Strong lensing

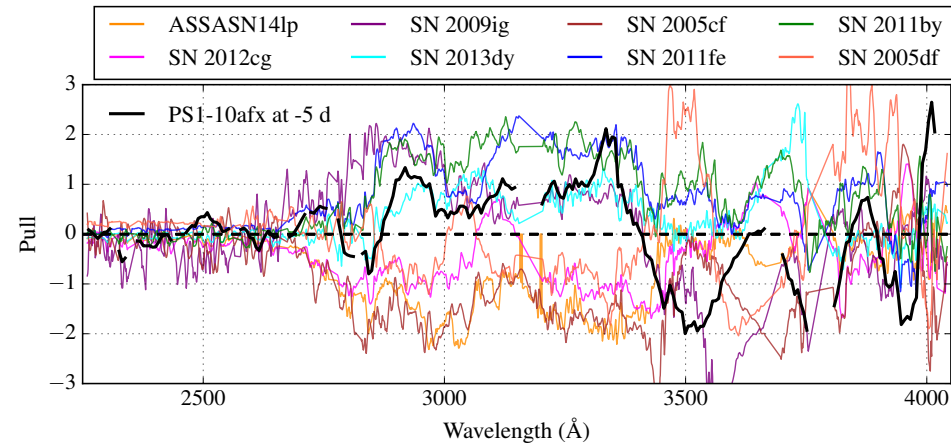
**Multiple images** of the background sources



# 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 that PS1-10afx shows no signs of significant spectral evolution

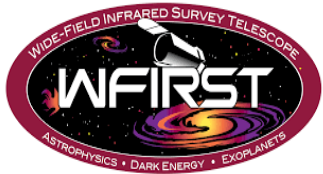


# Expected SNe in strongly lensed galaxies with multiple images for upcoming surveys

Towards A1689



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

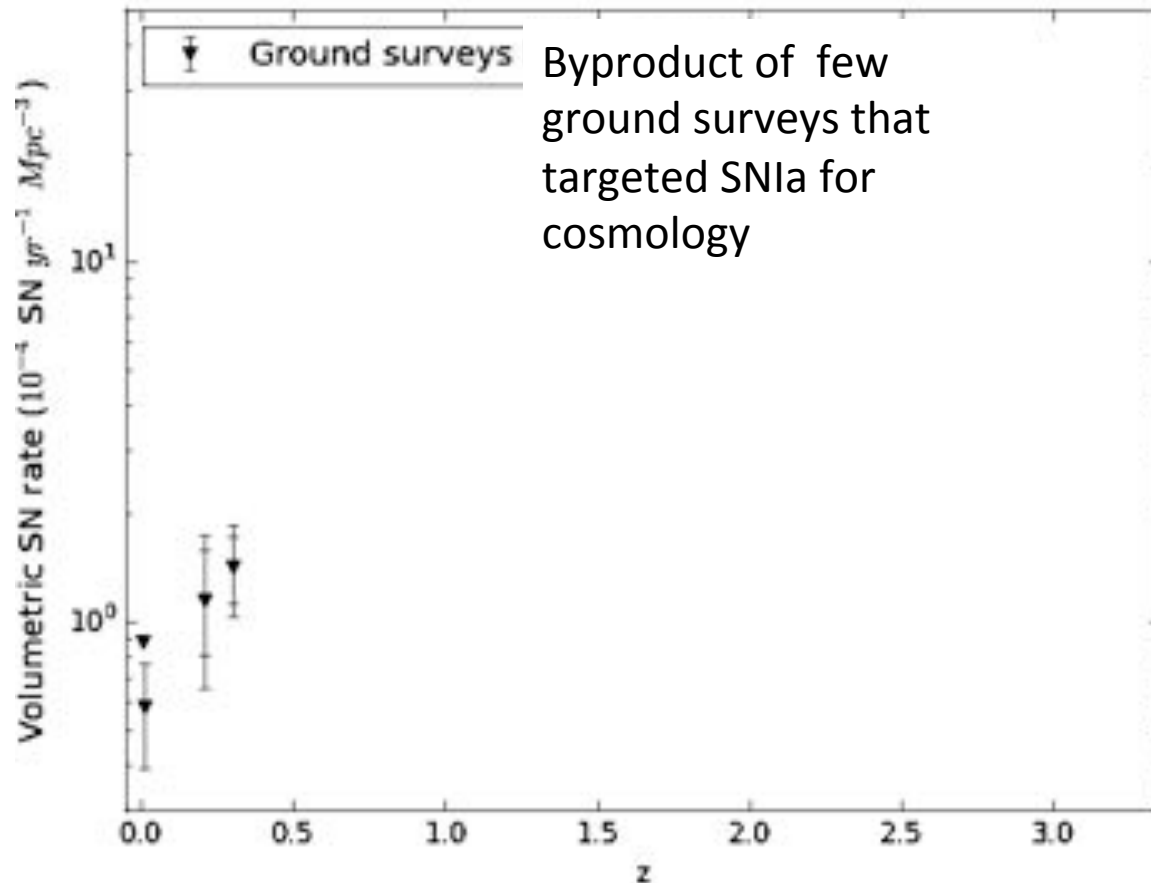


- If A370 is used, the numbers are much lower:  $N_{cc} \sim 0.7$  and  $N_{Ia} \sim 0.05$  with JWST
- Increasing the number of epochs does not increase  $N_{SNe}$  significantly



# Measuring core collapse Supernova rates

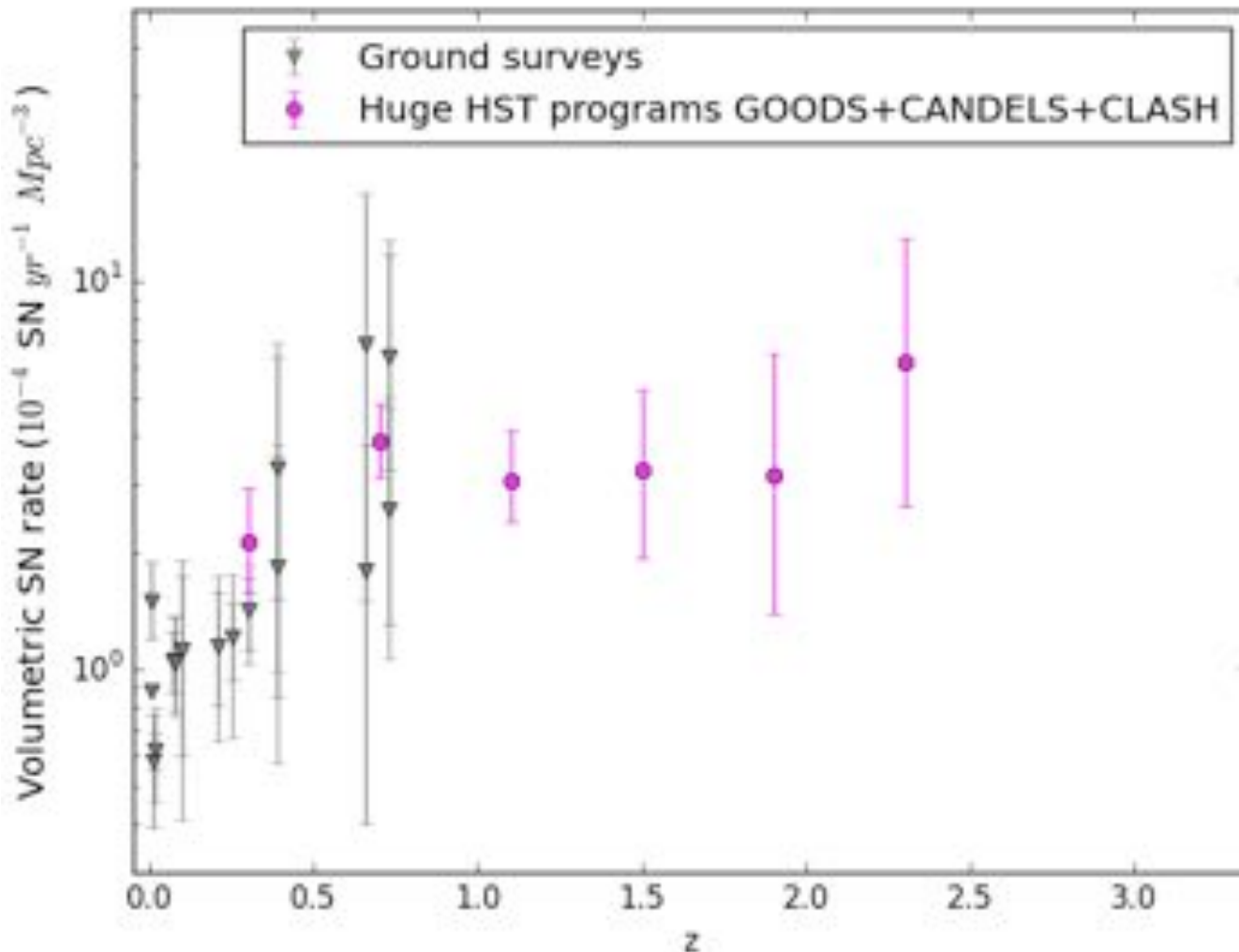
Before 2010



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

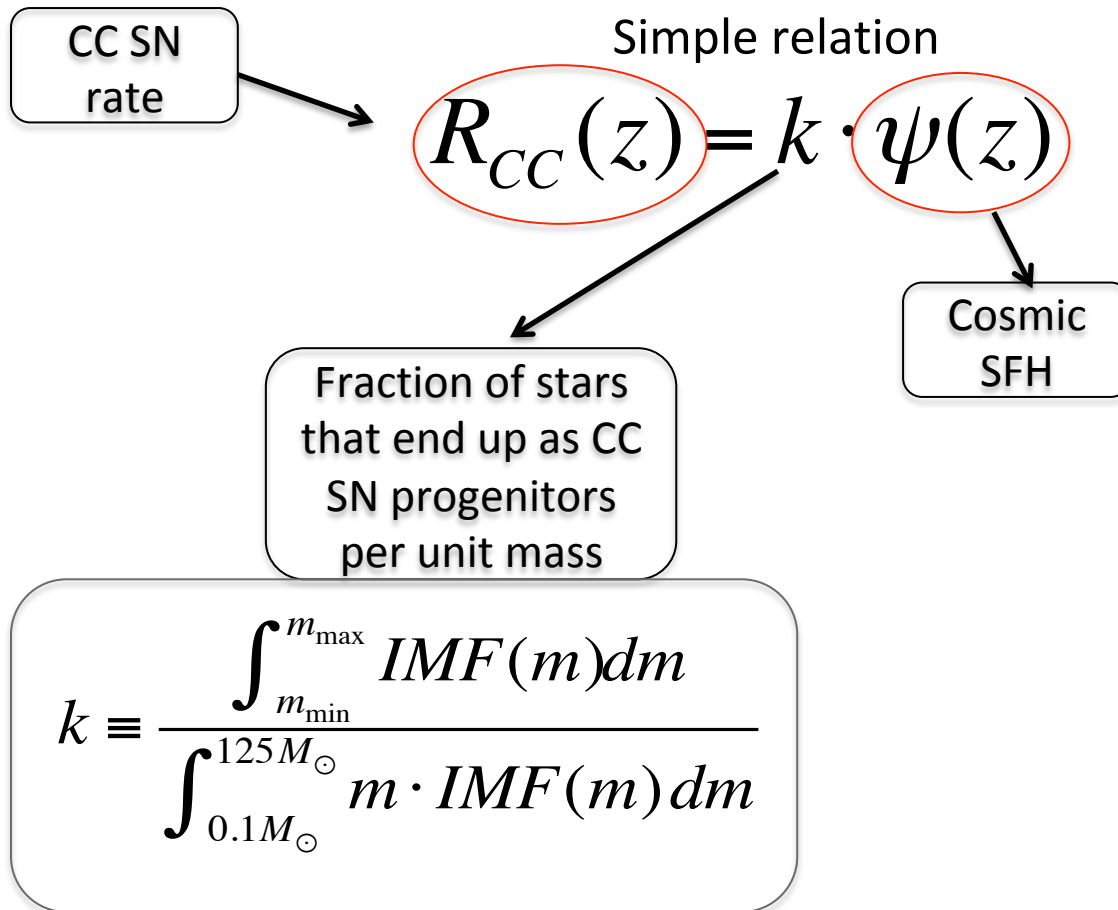
Simple relation

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

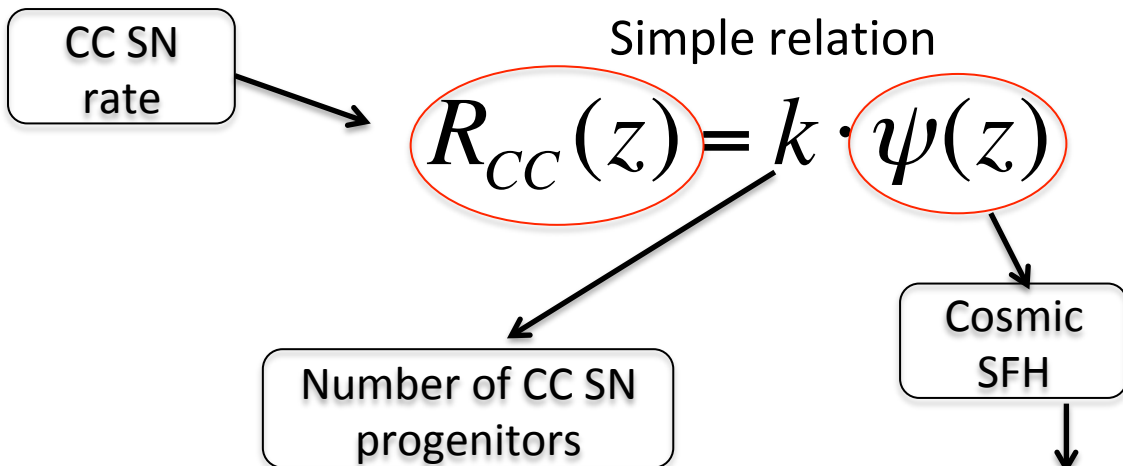
Cosmic  
SFH



# Core collapse Supernova rates and Cosmic Star formation history

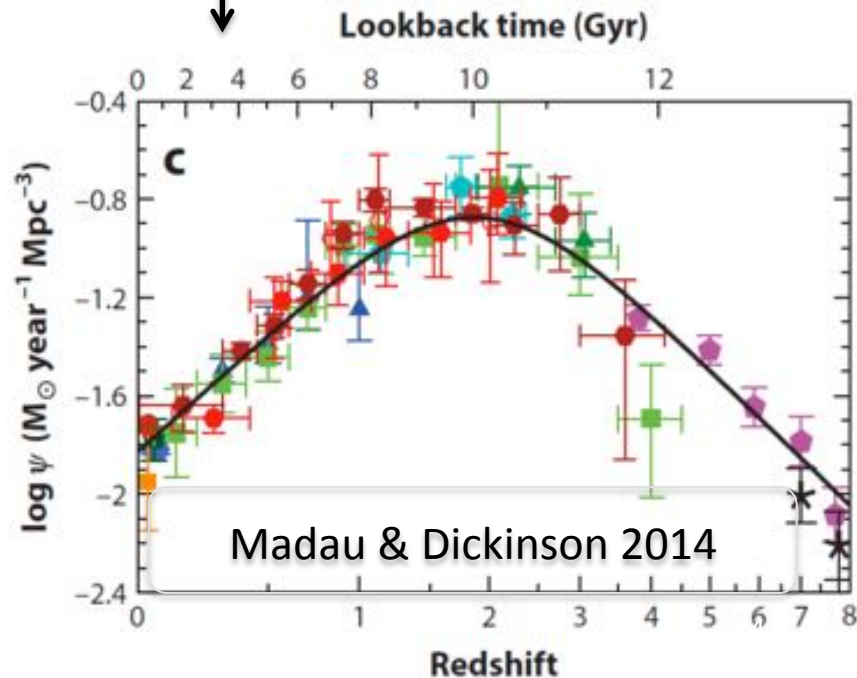


# Core collapse Supernova rates and Cosmic Star formation history

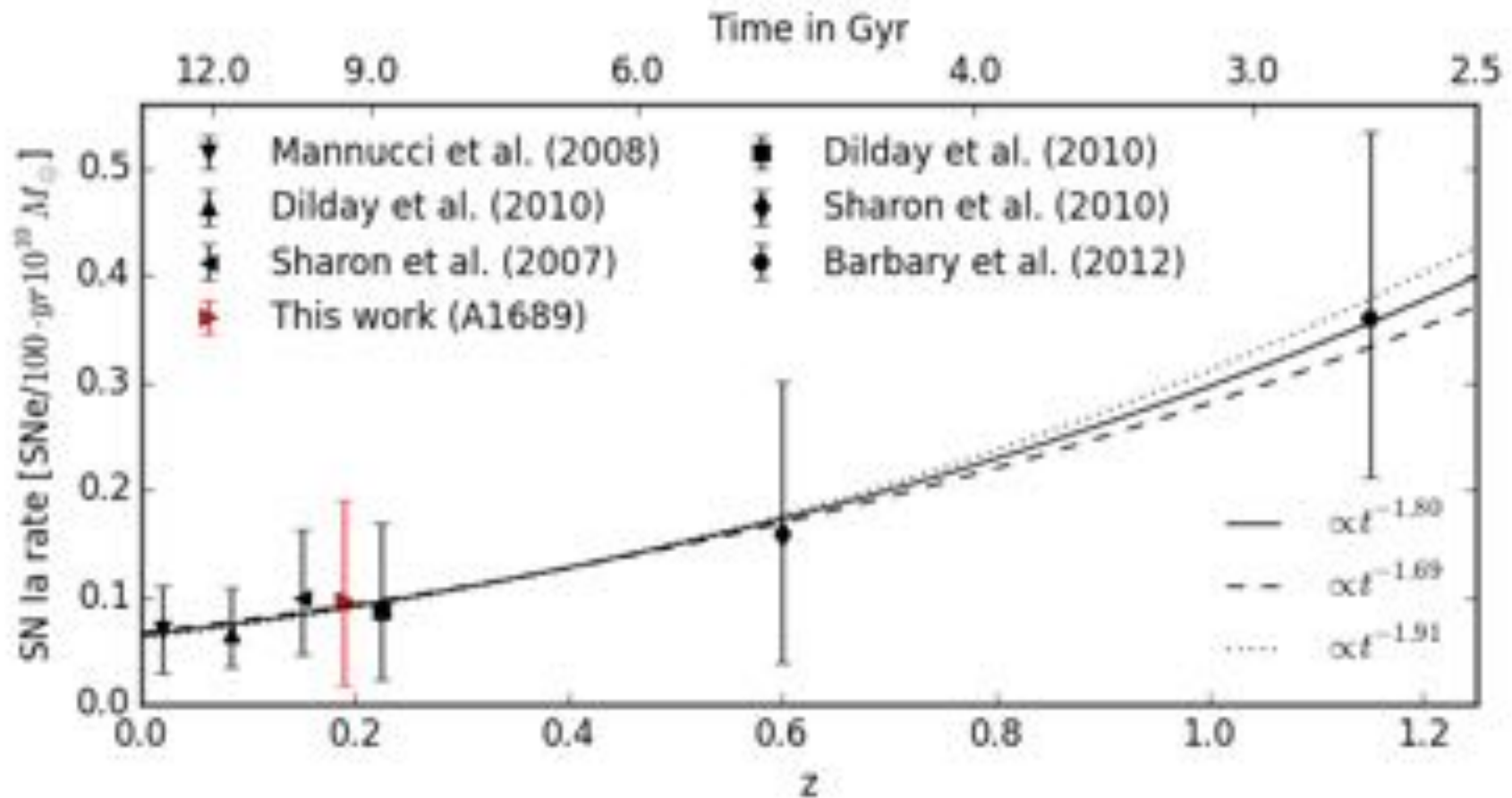


There are several methods for measuring the SFR. For a long time there was not a consistent picture...

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

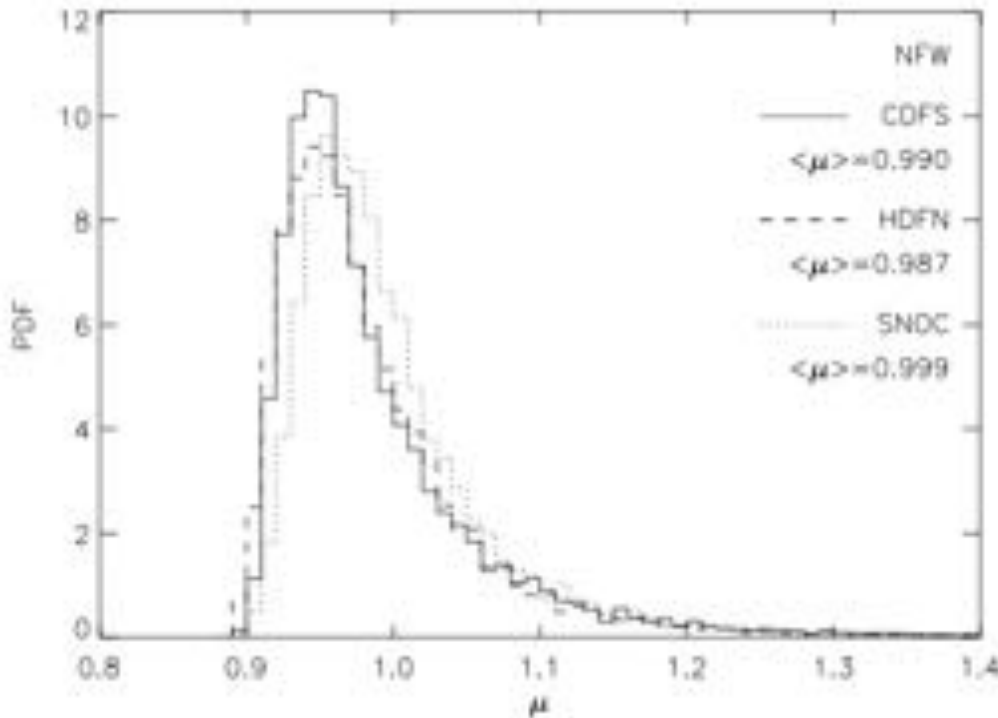


# 3 Cluster SNe Ia $\longrightarrow$ Cluster SNIa rates





# Gravitational lensing as systematic effect in SN Ia cosmology



- 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

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