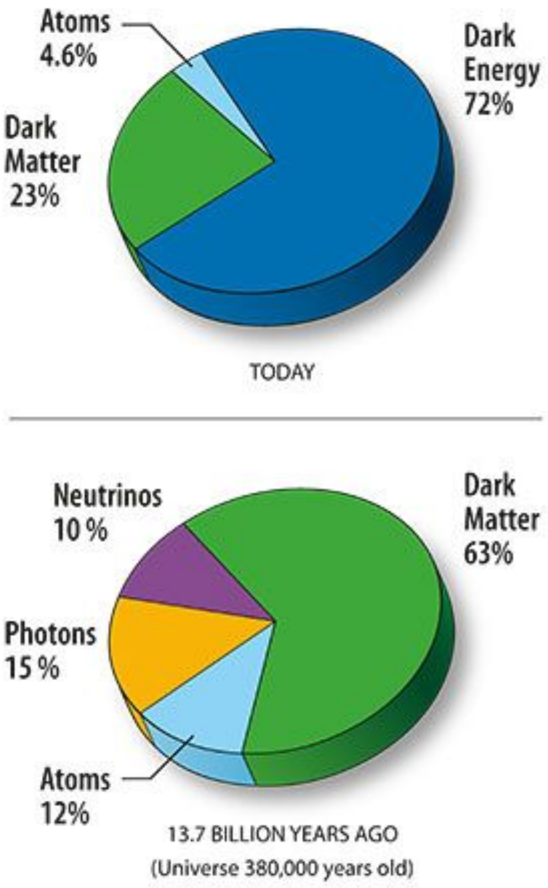
The Dark Universe

Naoki Yasuda (Kavli IPMU) & Nicolas Regnault (LPNHE)

Dark Matter and Dark Energy

- Dark Matter
  - Indicated in 1930’s from the comparison of mass of visible matter and mass estimated from the motion of matters
  - Galaxy’s flat rotation curve …



Credit: [NASA / WMAP]()

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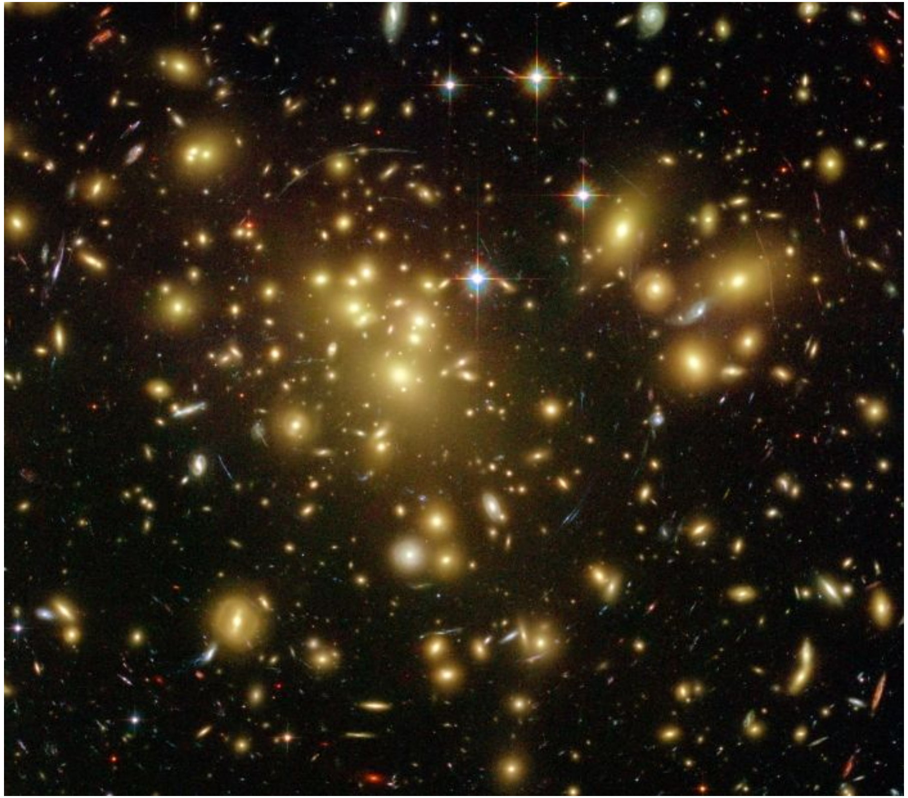
  - Strong gravitational lensing
    - Image of background galaxies are distorted by massive mass.



Credit: *Space Telescope Science Institute*

Dark Matter and Dark Energy

- Dark Matter
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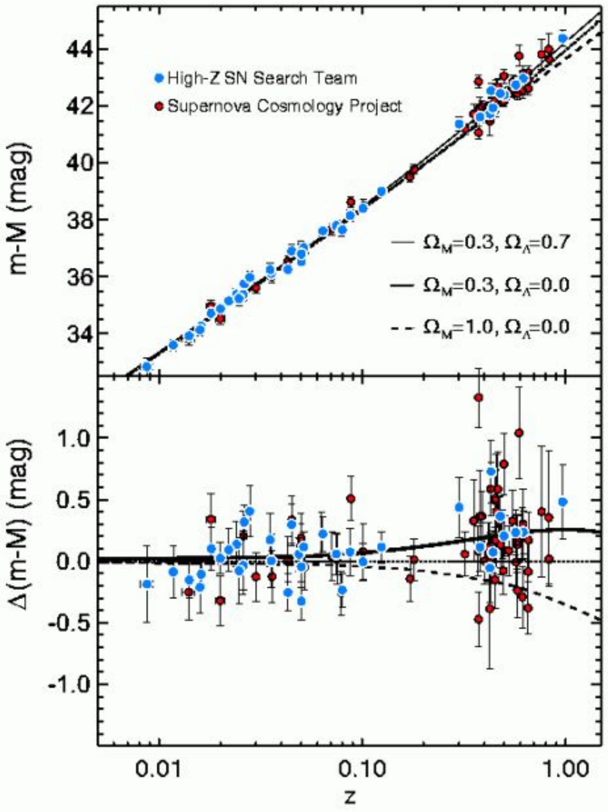
  - Galaxy's flat rotation curve …
  - Strong gravitational lensing
    - Image of background galaxies are distorted by massive mass.
- Dark Energy
  - Accelerated expansion of the Universe revealed by Type Ia Supernova in ~1999
- Nature of both dark components are still unknown.

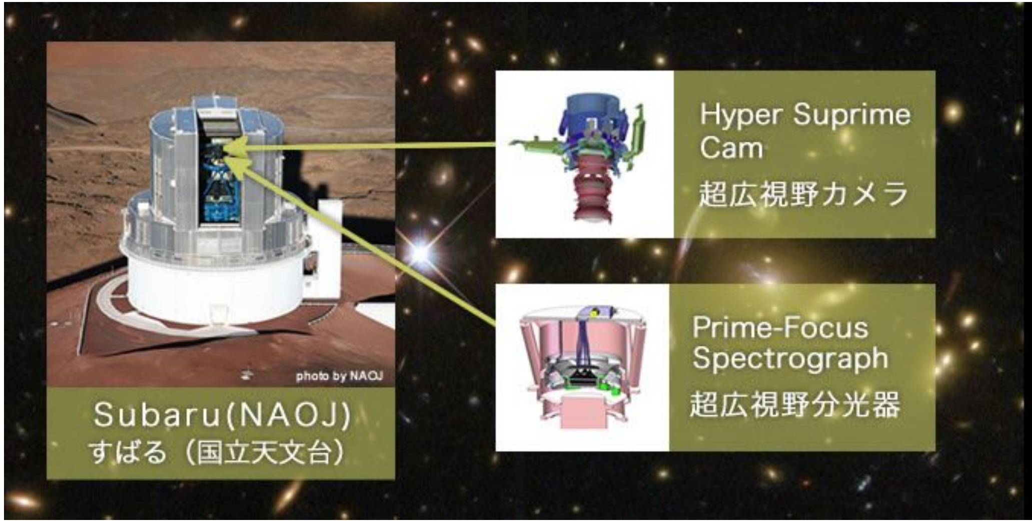


Credit: [High-z supernova search team]

Probe the dark Universe

- Supernova
- Baryonic Acoustic Oscillation
- Galaxy Clutering
- Weak Lensing
- Clusters

- All these probes need wide-field photometric and spectroscopic survey
- Kavli IPMU is leading SuMIRE (Subaru Measurements of Images and Redshifts) project with Hyper Suprime-Cam and Prime Focus Spectrograph on Subaru telescope

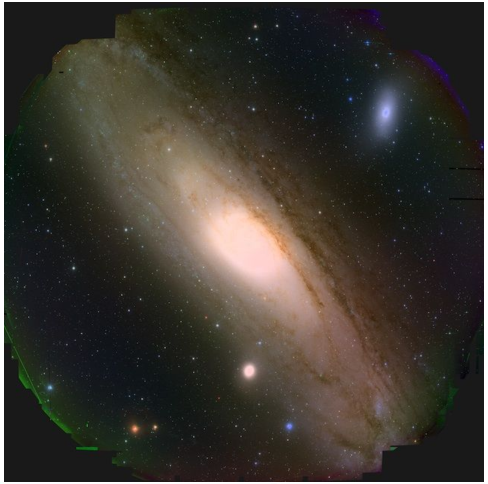


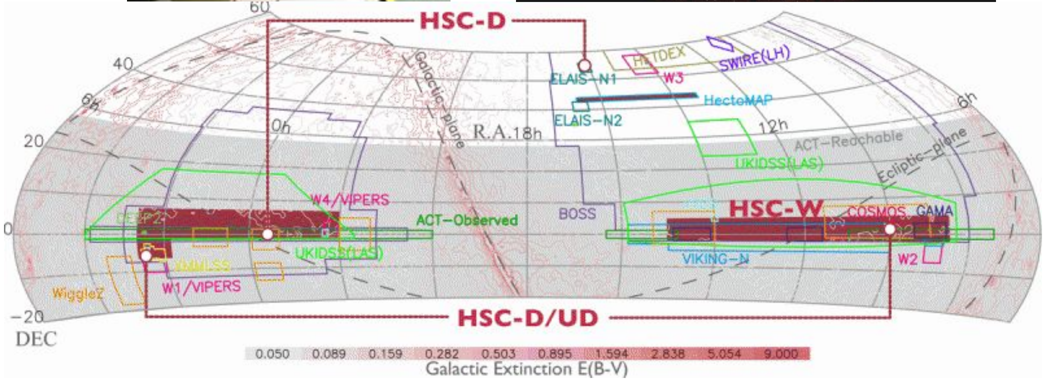
Credit: [SuMIRe Project]

Hyper Superime-Cam

- Wide field imaging camera
- 116 CCD sensors are covering the area of 1.5 degrees in diameter

- In operation from 2014
- Now conducting Subaru Strategic Program spending 330 nights.



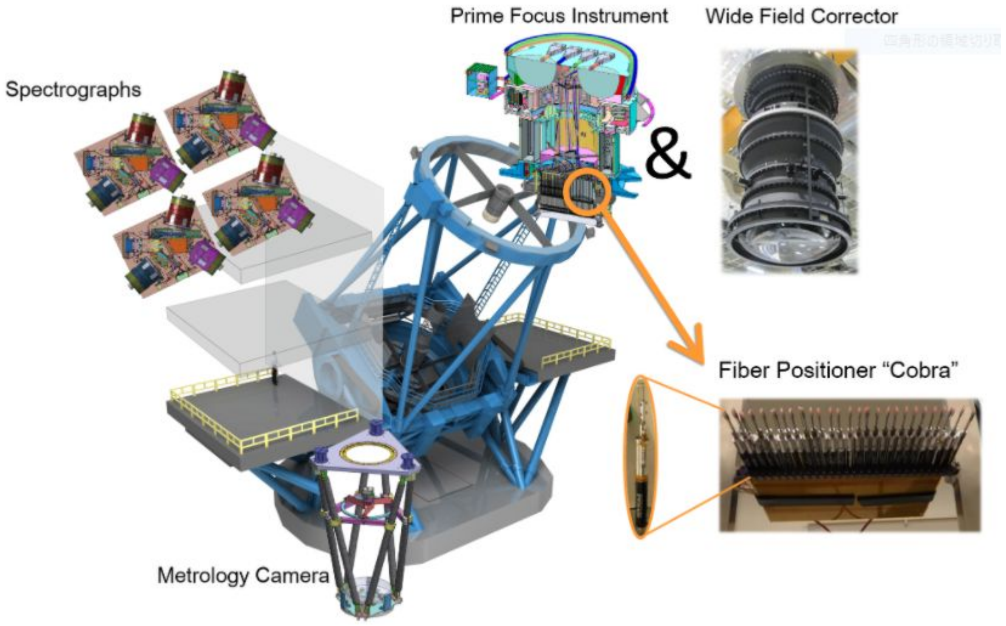


Credit: HSC-SSP

Prime Focus Spectrograph

- Wide-field multi-object spectrograph
- Simultaneous spectroscopic observation of ~2400 objects
- Cover the wide range of wavelengths, [380, 1260]nm

- Massive spectroscopic survey will start from 2023



Credit: [PFS Project]

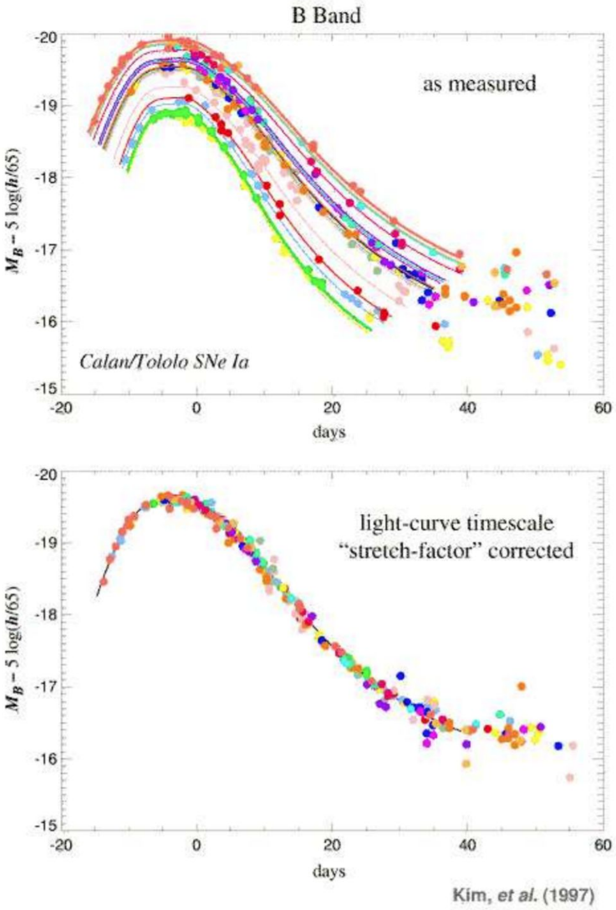
On-going collaboration between Kavli IPMU and LPNHE

- LPNHE team has expertise of supernova observation and data analysis based on the CFHT (4m telescope) SuperNova Legacy Survey in the last decade
- Kavli IPMU is conducting HSC-SSP survey with Subaru (8m telescope)

- We have been collaborating on Supernova Cosmology project from 2014
- This collaboration will lead to the next generation big survey of the Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST)

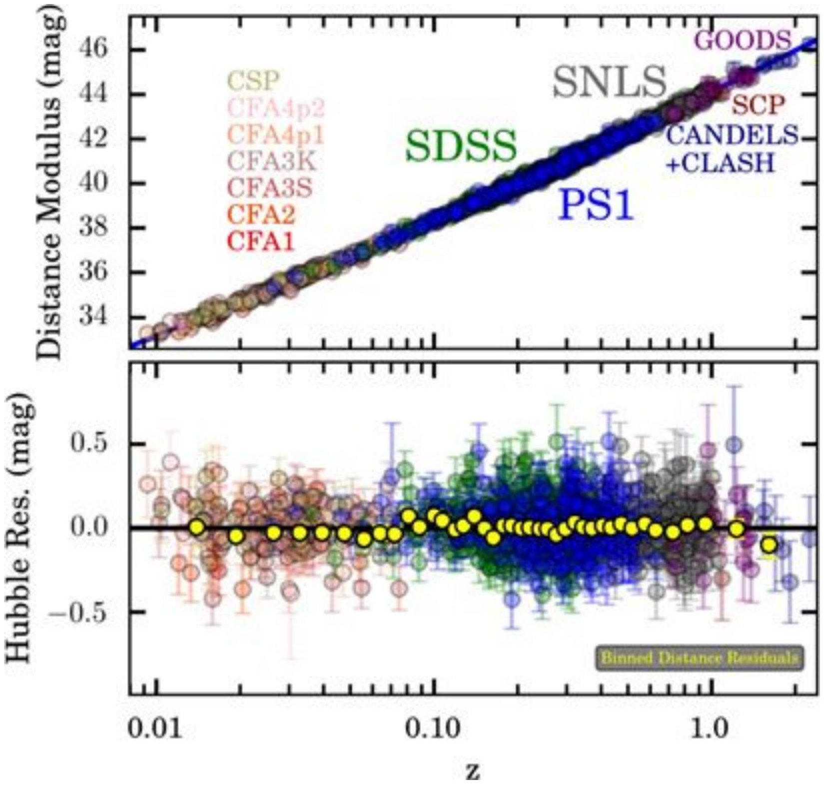
Type Ia Supernova

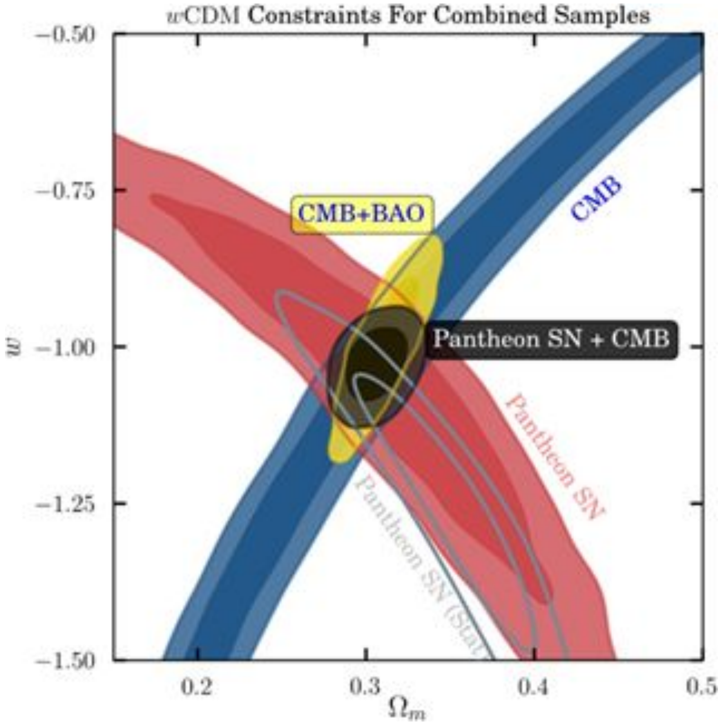
- Thermonuclear explosion of white dwarfs
- Chandrasekhar mass limit of 1.44 $M_{\odot}$
- Standardizable candle with a light curve shape parameter
- Bright enough (M_B~-19) to reach cosmological distance (z~1)



SN Ia cosmology

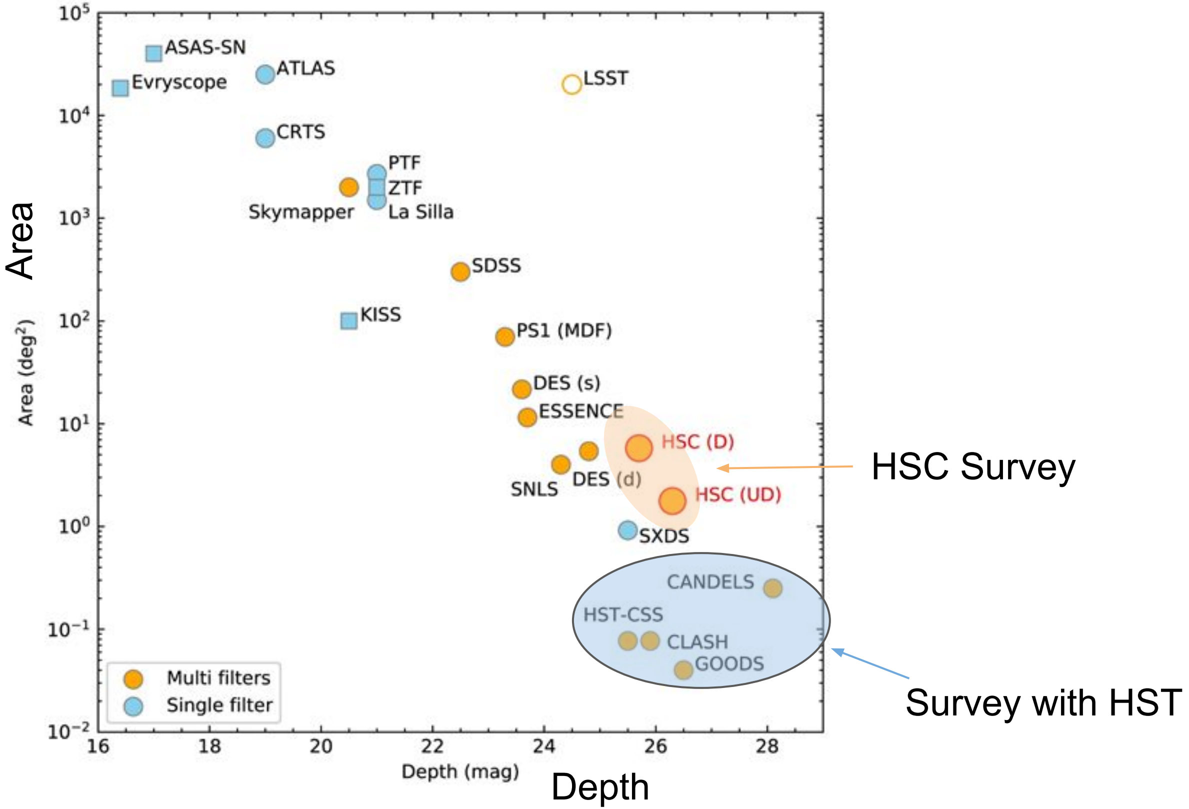
Scolnic et al. 2018 (ApJ, 859, 101)





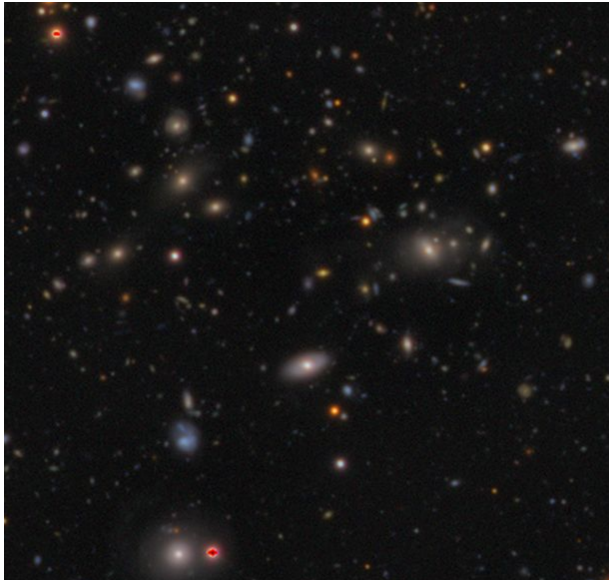
Only a few tens of SNe Ia at z > 1 detected by HST
HSC can play an important role at this redshift range to constrain time variability of dark energy

HSC SSP Transient Survey



HSC (8.2m from ground) vs HST (2.4m from space)

- Depth is comparable but field of view is much larger (~1000x) for HSC

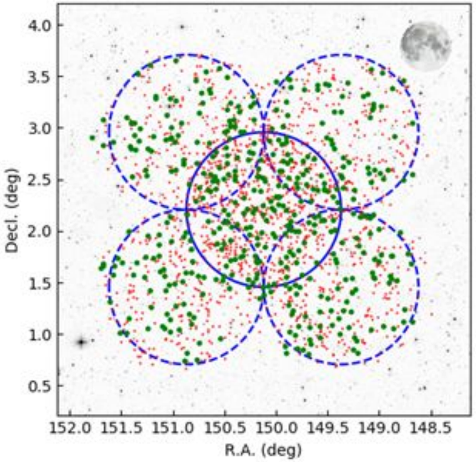


HSC

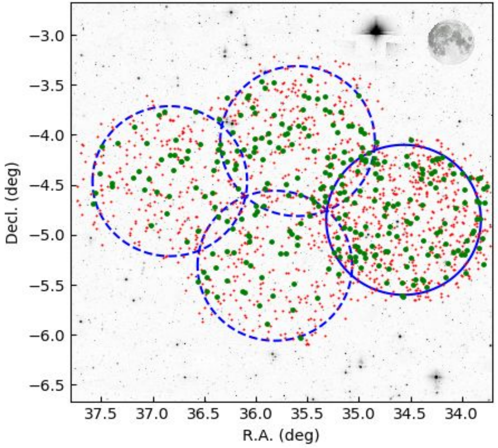
HST

HSC SSP Transient Survey

- 1st season -- COSMOS
- Nov. 2016 -- Apr. 2017
- 1,824 SN candidates
- 433 SN Ia candidates
  - 163 at z > 1

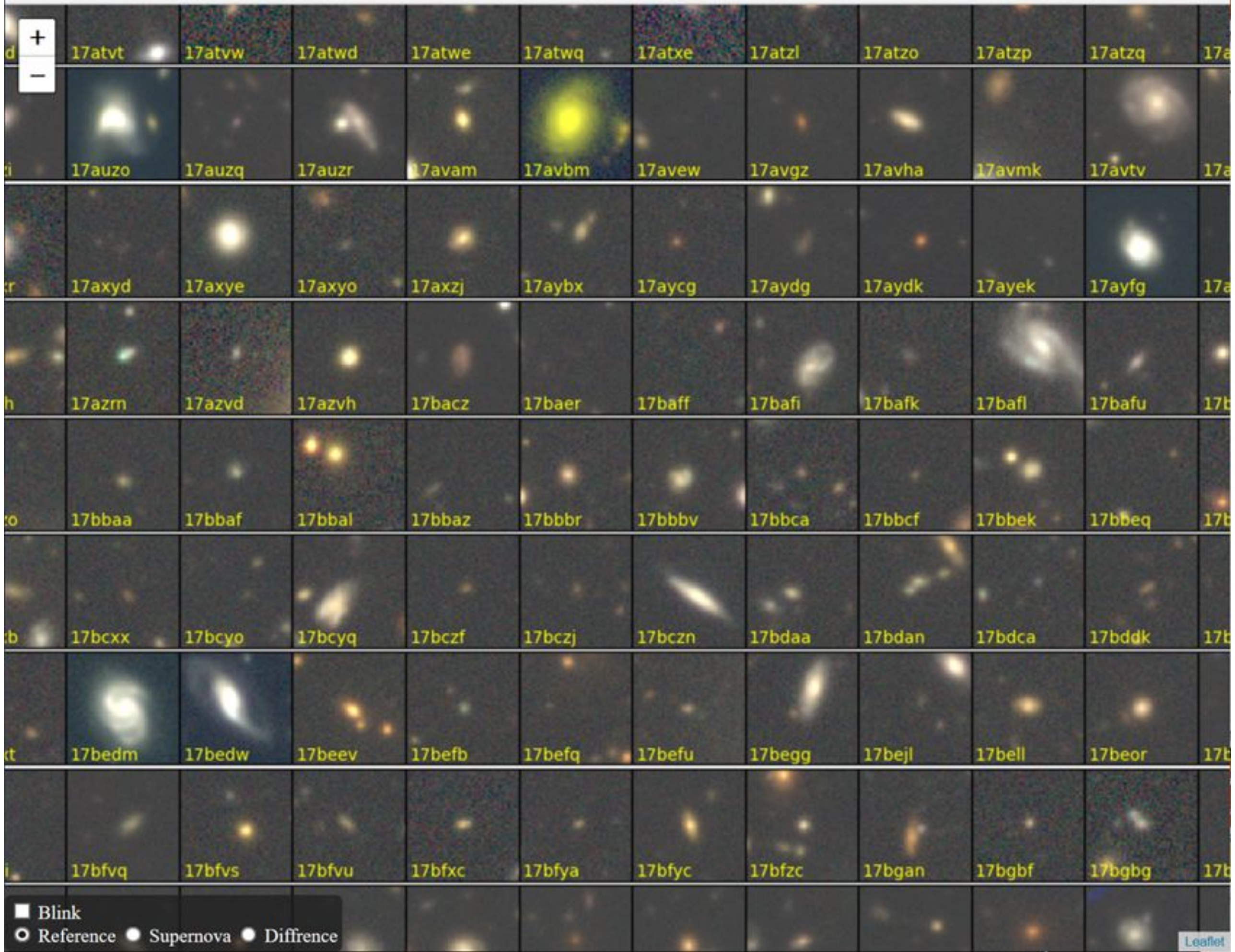


- 2nd season -- SXDS
- Sep. 2019 -- Feb. 2020
- 1,537 SN candidates
- 294 SN Ia candidates
  - 96 at z > 1



Reference

https://web.ipmu.jp/press/201905-HSC-SSP/HSC_SNimages/



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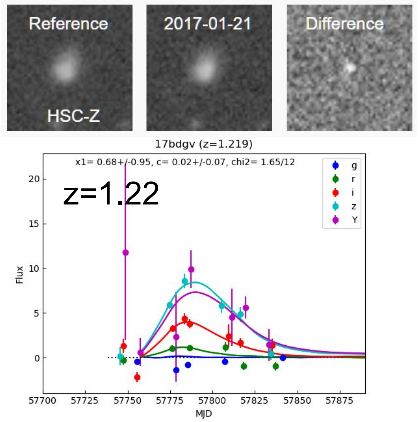
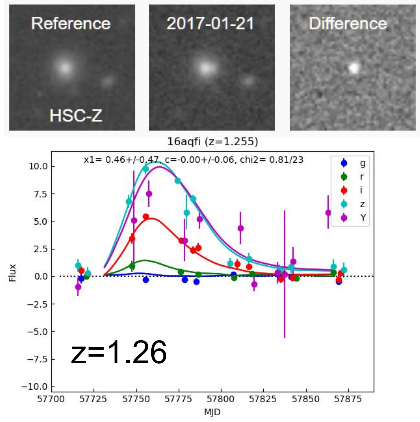
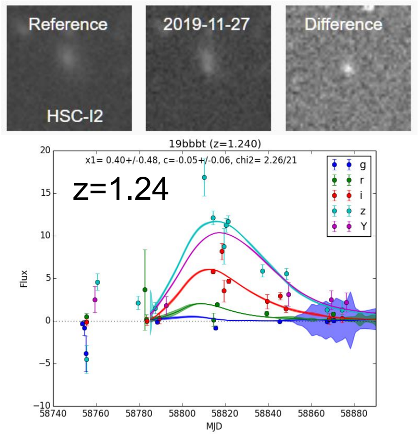
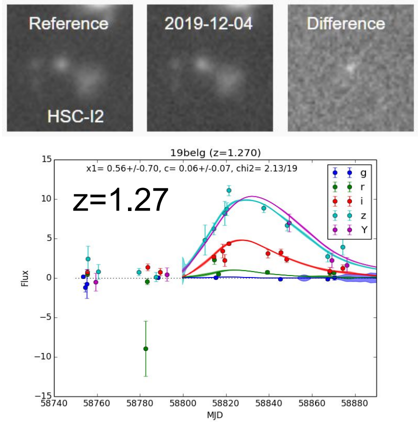
With SN

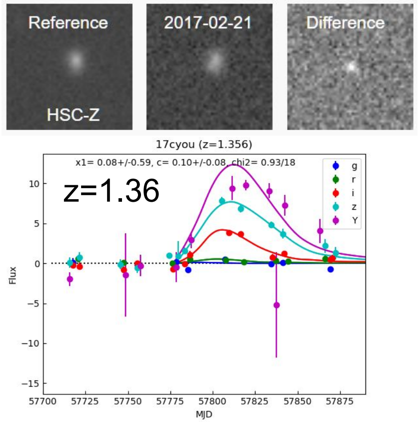
HSC SSP Transient Survey

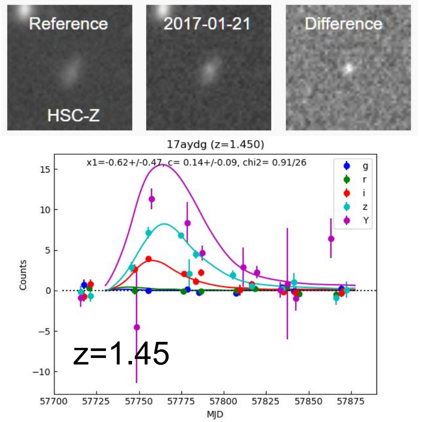


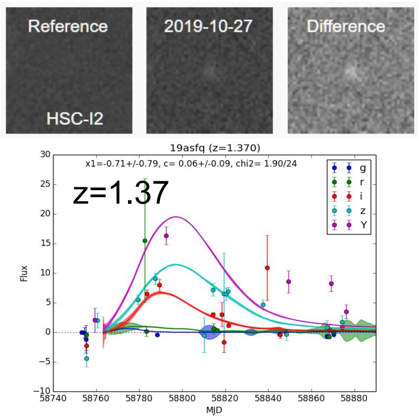


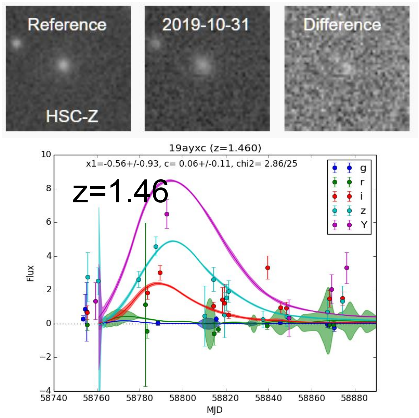












Tasks towards SN Ia cosmology

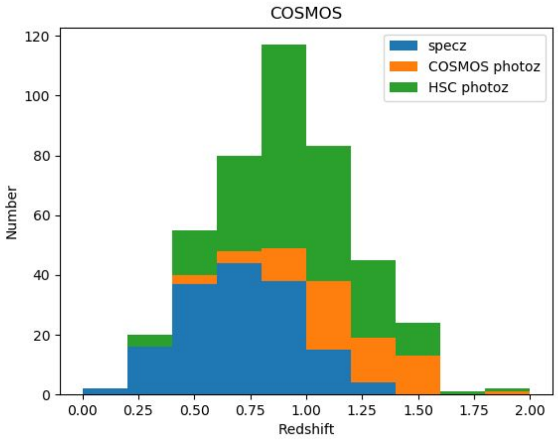
- Observation : Completed

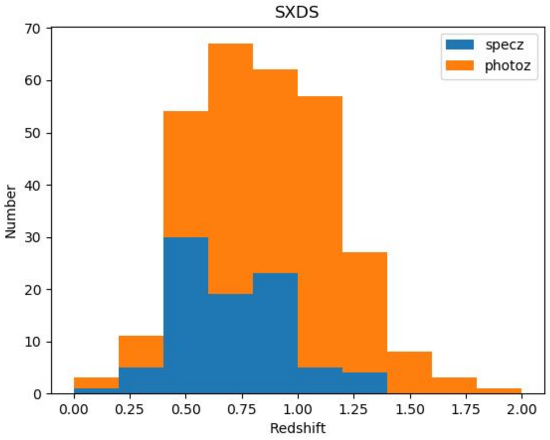
- Measurement of host redshift
- Photometric calibration
- SN photometry
- HST photometry

- SN Ia cosmology

Measurement of host redshift

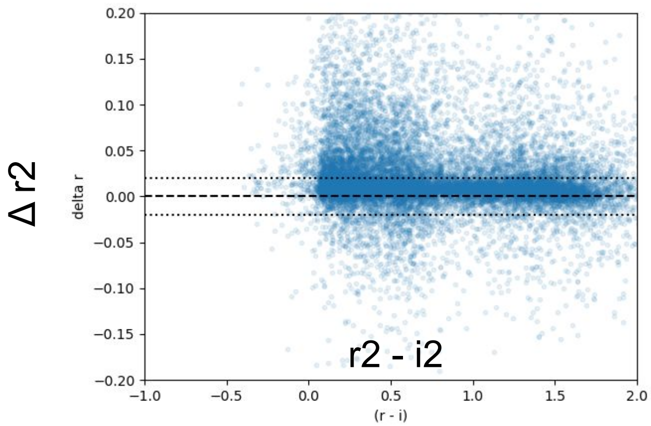
- Redshift of host galaxies should be observed for cosmology
- AAOmega, Subaru, VLT, Keck, Gemini observations are on-going
  - AAOmega (Australia) can reach up to z~0.8 effectively
  - 8-10m telescopes are needed beyond that
- Each season we can get only 20-30 redshifts
- Still ~480 (~220@z>1) Ia candidates need to be observed

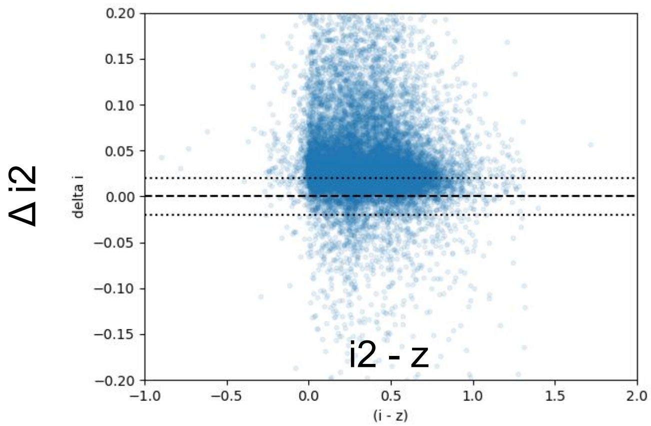




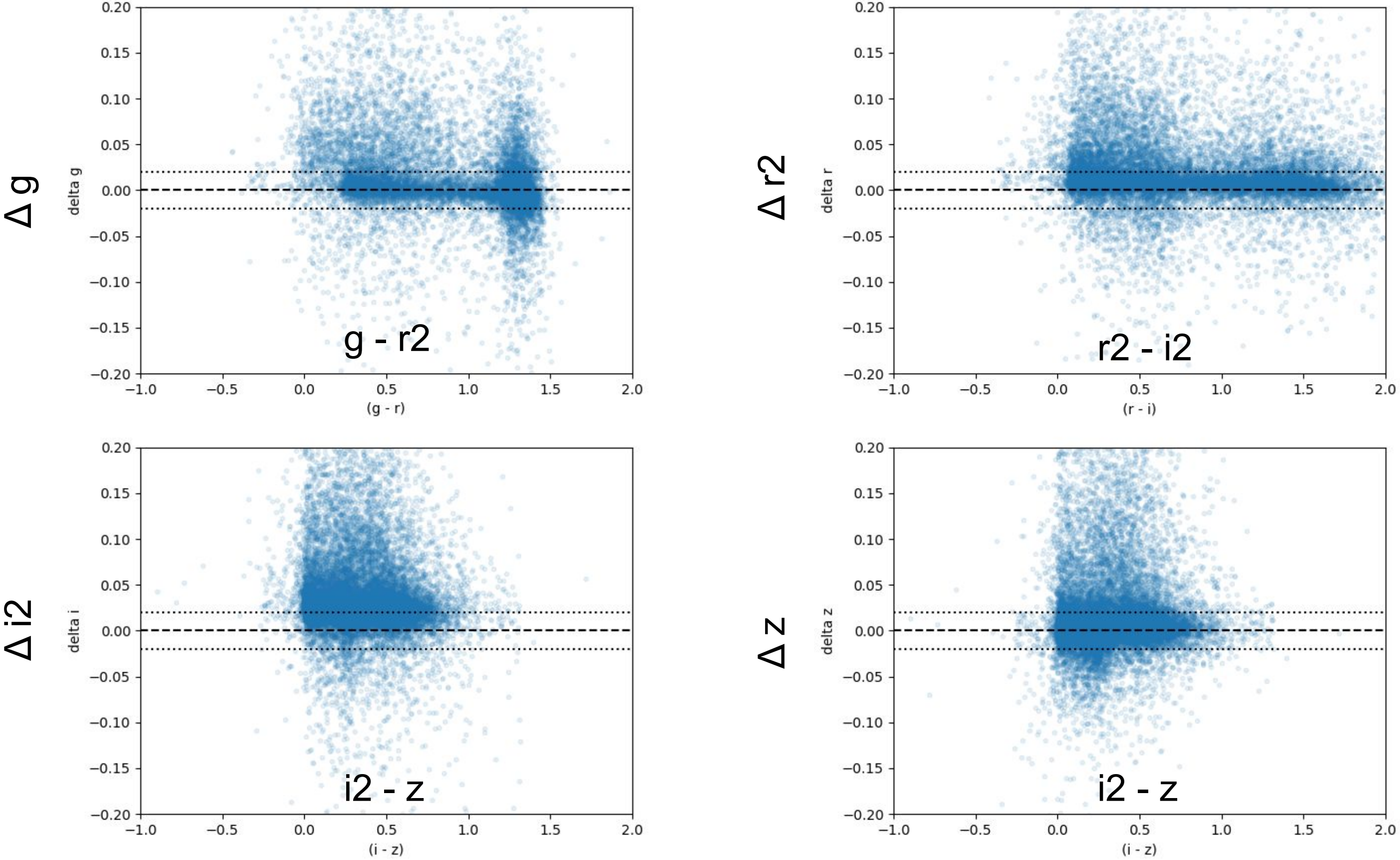
Photometric calibration

- Data processing with two pipelines
  - HSC pipeline based on LSST Data Management
  - Pipeline developed for SNLS + updated characterizations of sensors
- Calibration
  - HSC -> Pan-STARRS1 -> Primary flux standard stars (HST CALSPEC)
  - SNLS -> Tertiary standards -> Primary flux standard stars (HST CALSPEC)
- Comparison of tertiary stars
  - 1% / 2% offsets for r2- and i2-band, g- and z-band look fine



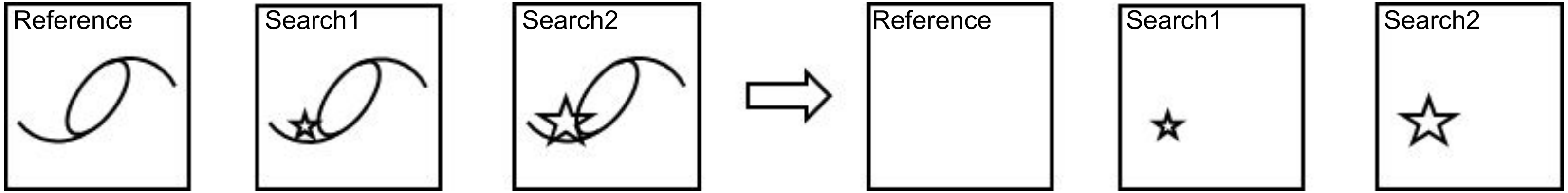


Comparison of tertiary stars



SN photometry

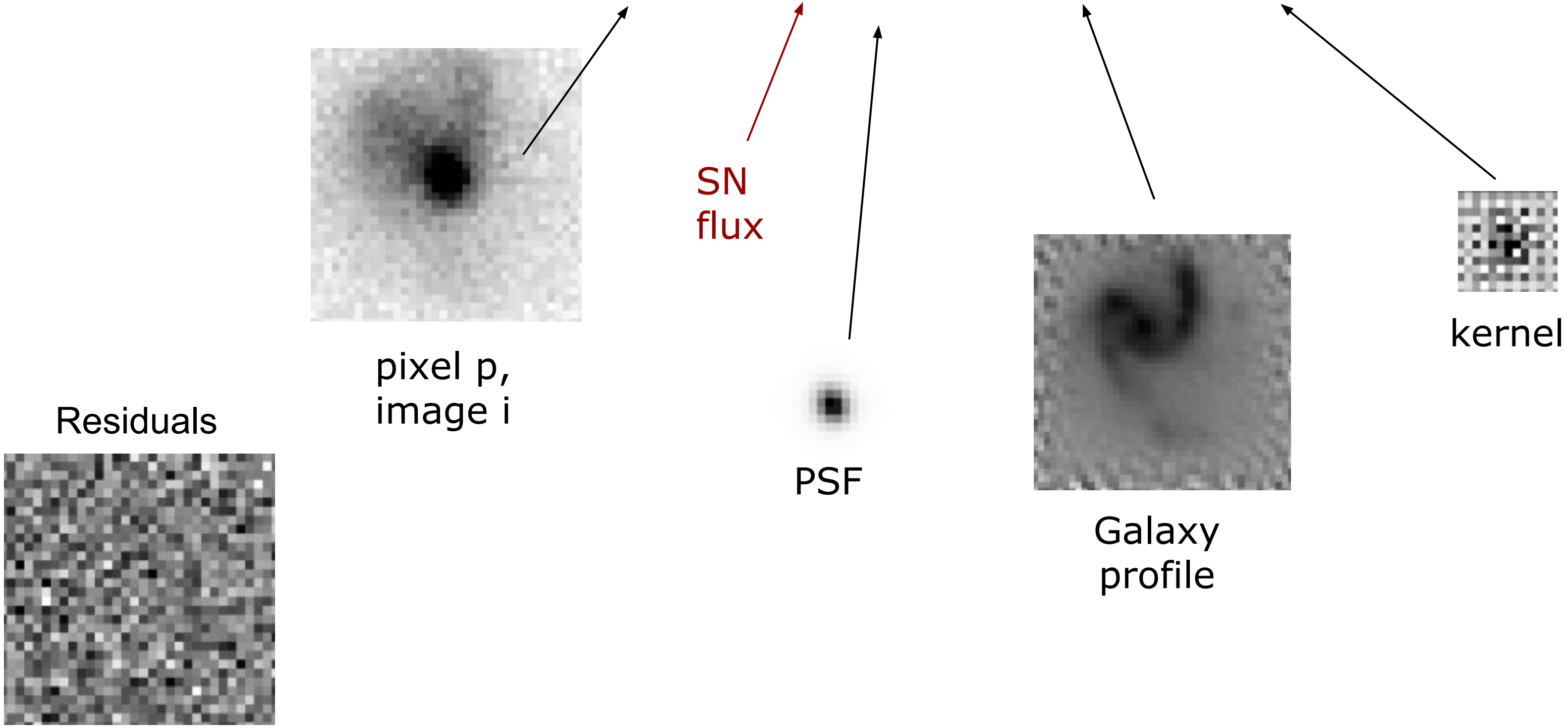
- Standard photometry (Japanese team)



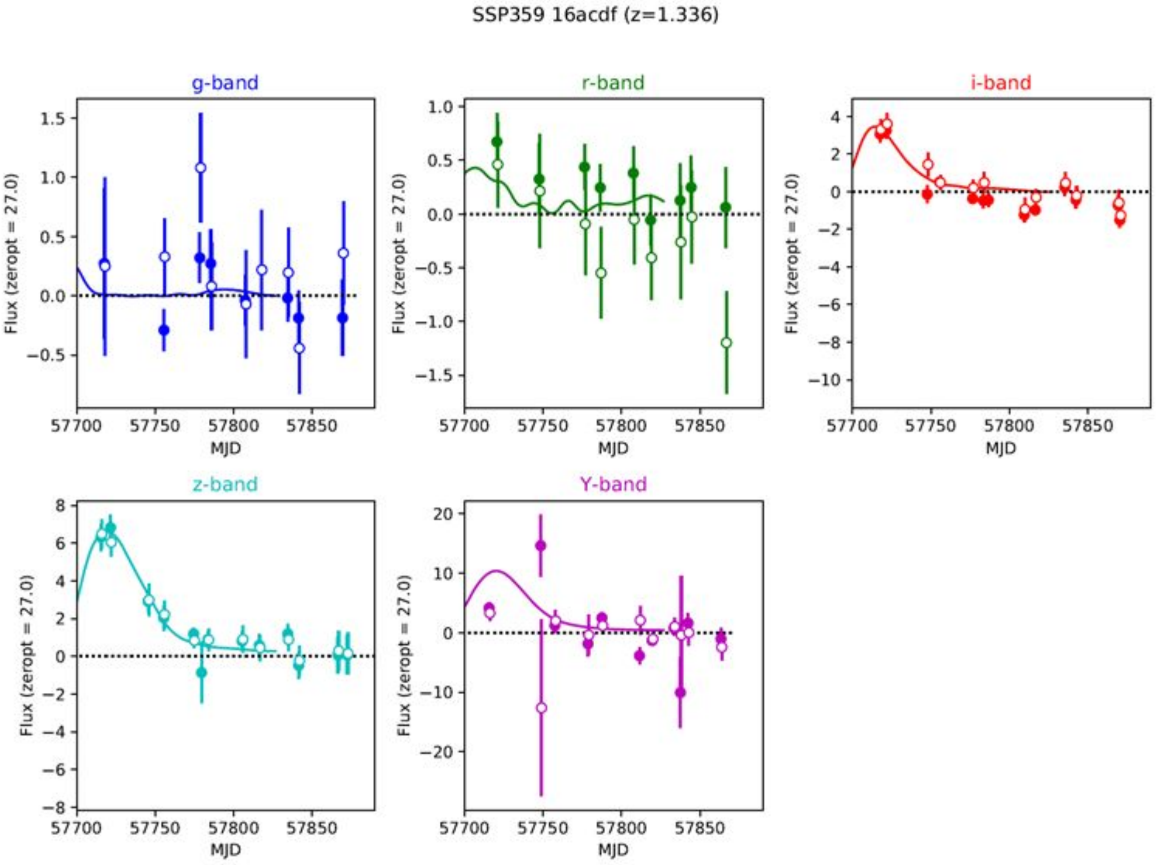
  - Subtract reference image and photometry on difference images
- Scene modeling photometry (French team)
  - Simultaneous fit of constant background and variable SN brightness using known PSF model
  - No need for re-sampling and convolution
  - Developed for SDSS/SNLS

Scene modeling photometry

$$I_{ip} = f_i\ \phi_i + \mathrm{Gal} \otimes K_i + \ldots$$



Comparison of SN photometry (filled : J, open : F)



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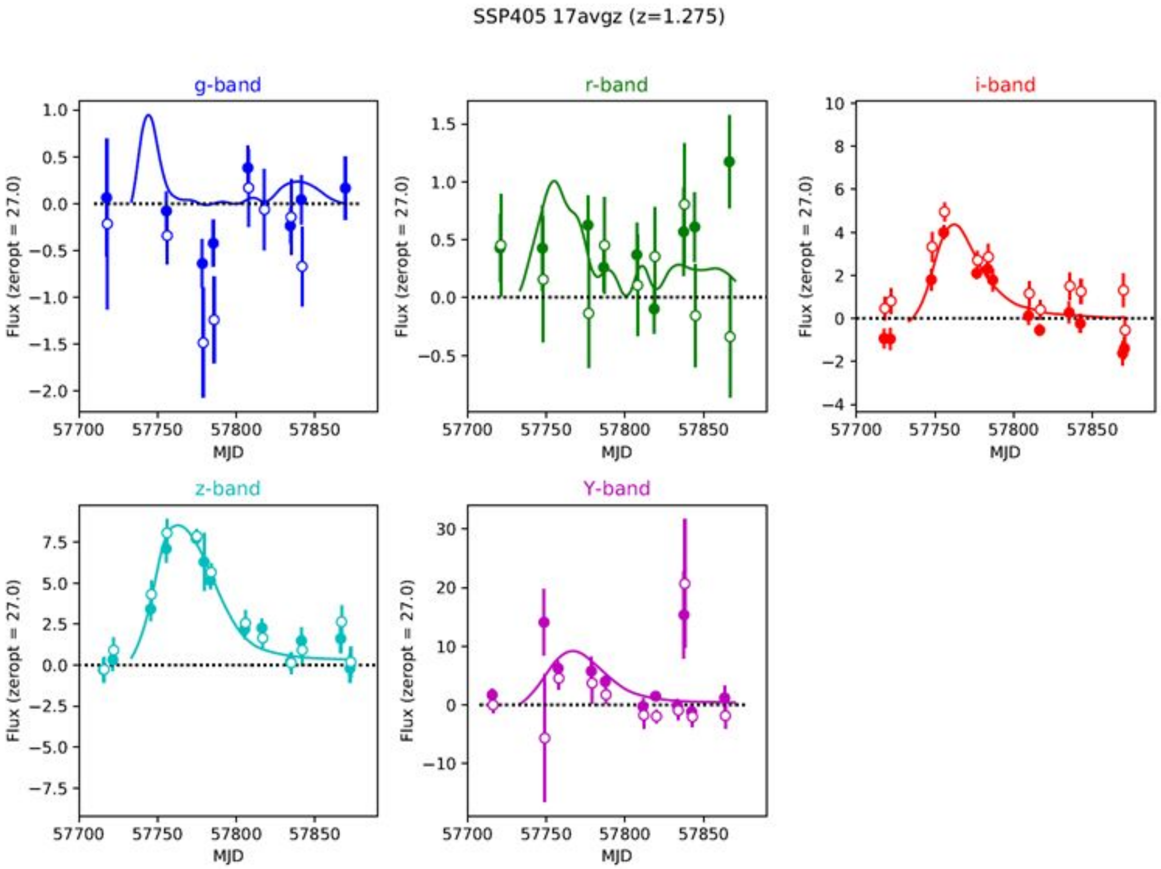

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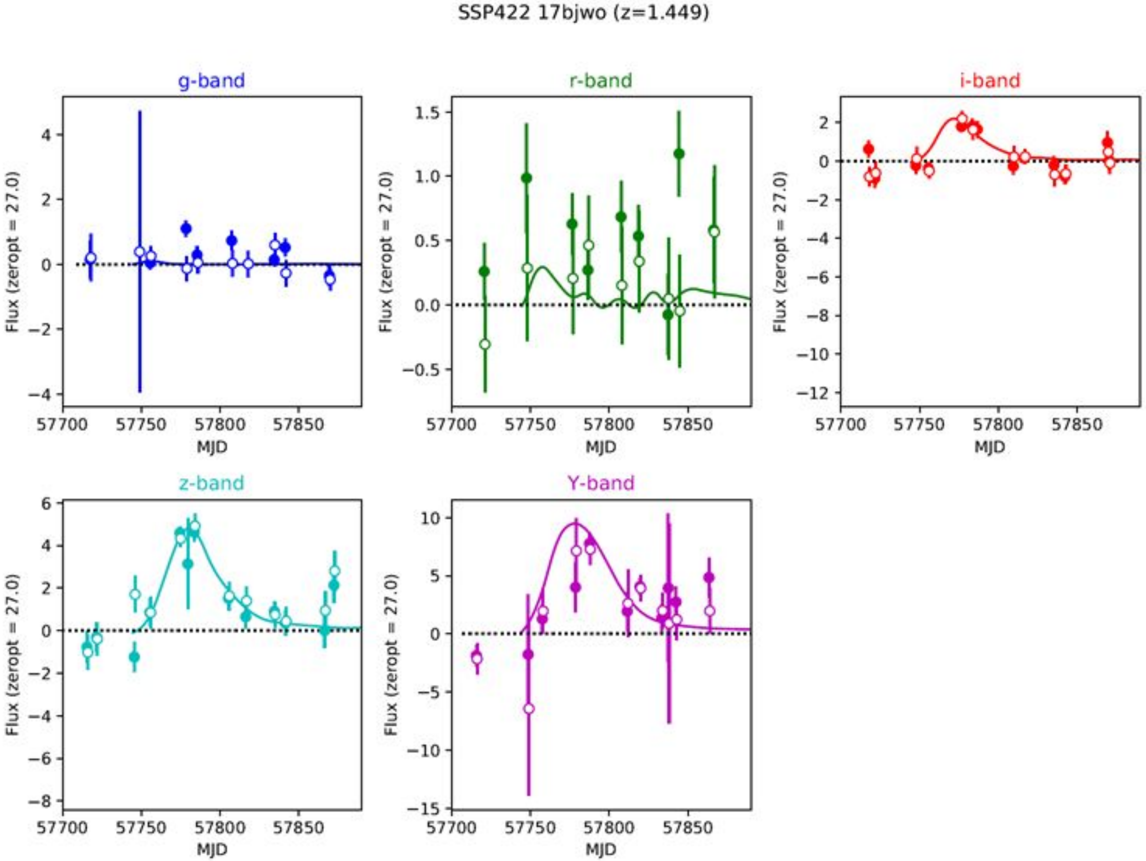
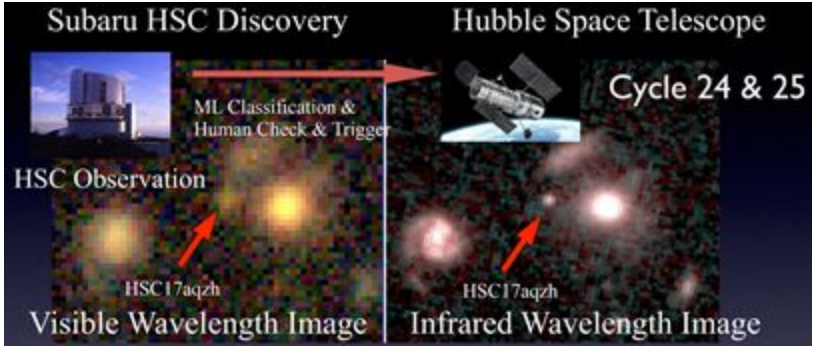
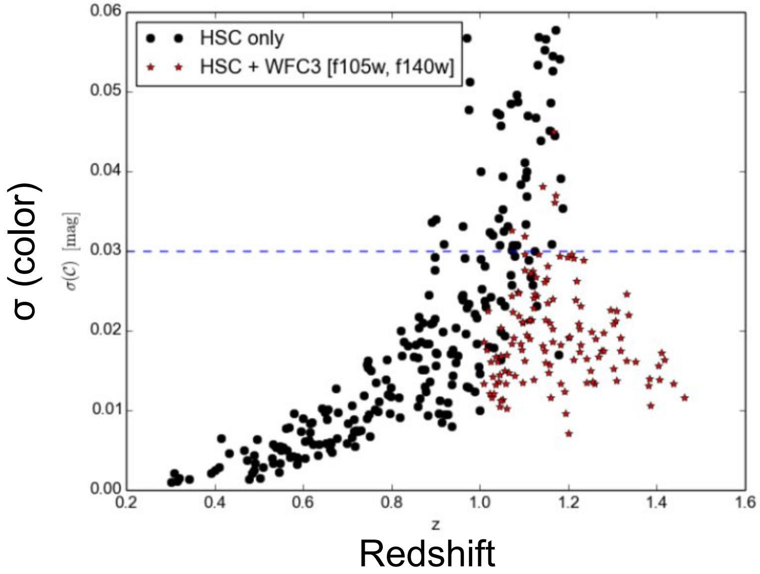


Two measurements look consistent. Need more check.

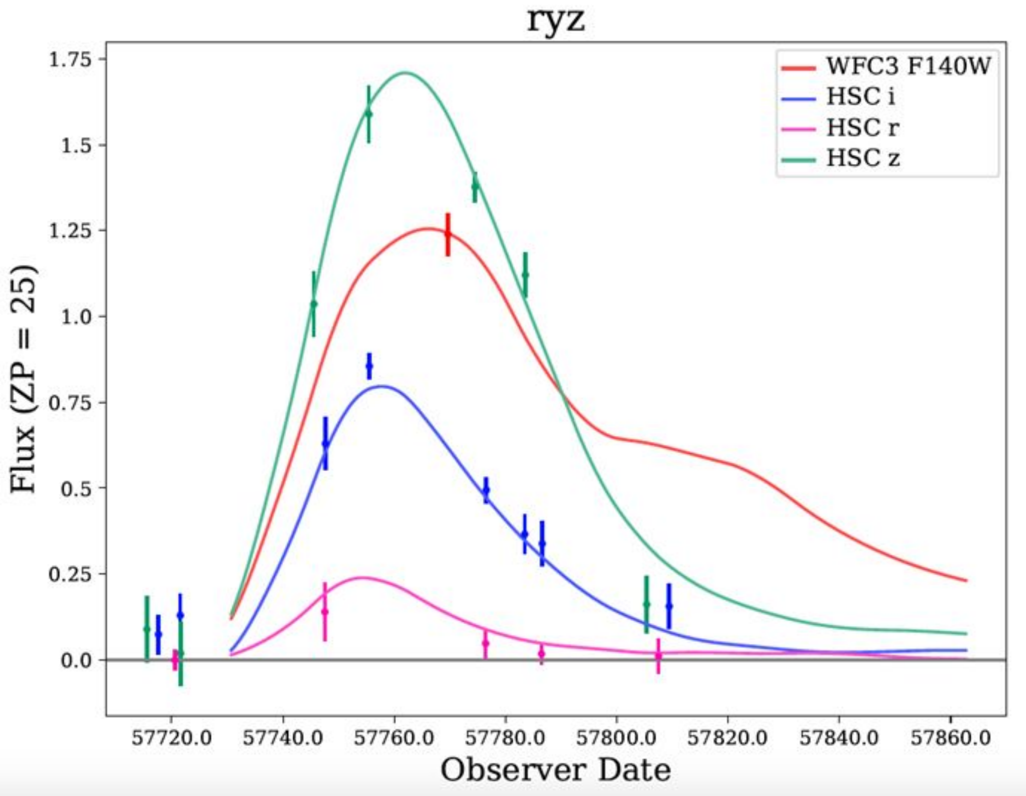
HST follow-up photometry

- HST proposal by N. Suzuki (Kavli IPMU) has been accepted
- 26 SNe Ia candidates for COSMOS and 10 for SXDS has been observed by HST/WFC3 (F105W/F140W)
- Get accurate rest-frame optical color
- Reference images has been taken for COSMOS candidates
- Need to get final photometry for SXDS candidates





HST follow-up photometry



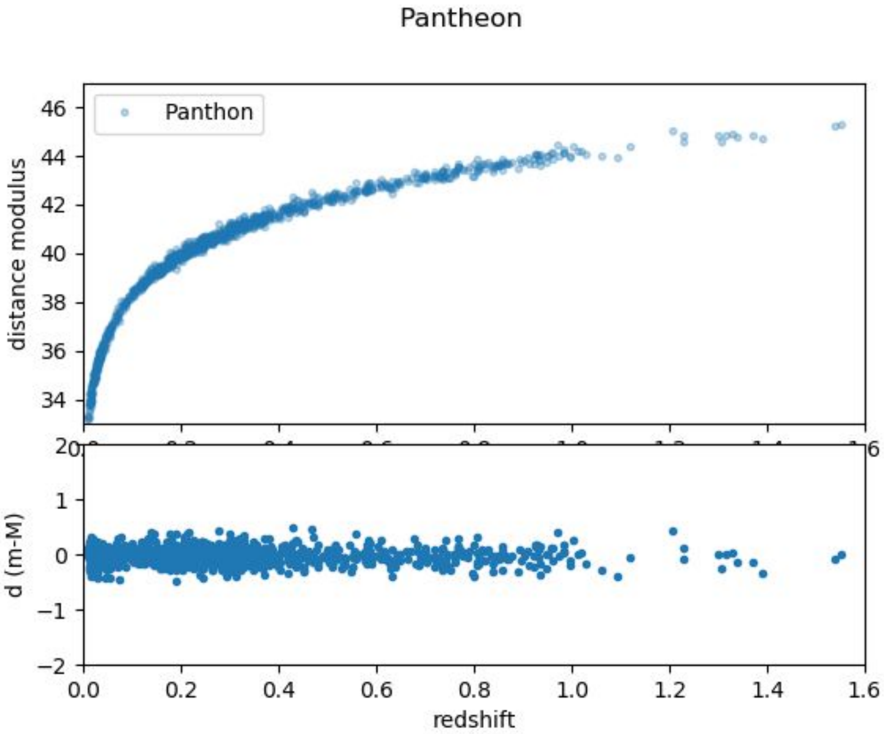
Tasks towards SN Ia cosmology

- Observation : Completed

- Measurement of host redshift : On progress but need more effort
- Photometric calibration : On progress
- SN photometry : On progress
- HST photometry : Need reference for SXDS

- SN Ia cosmology : Need more effort

Hubble diagram



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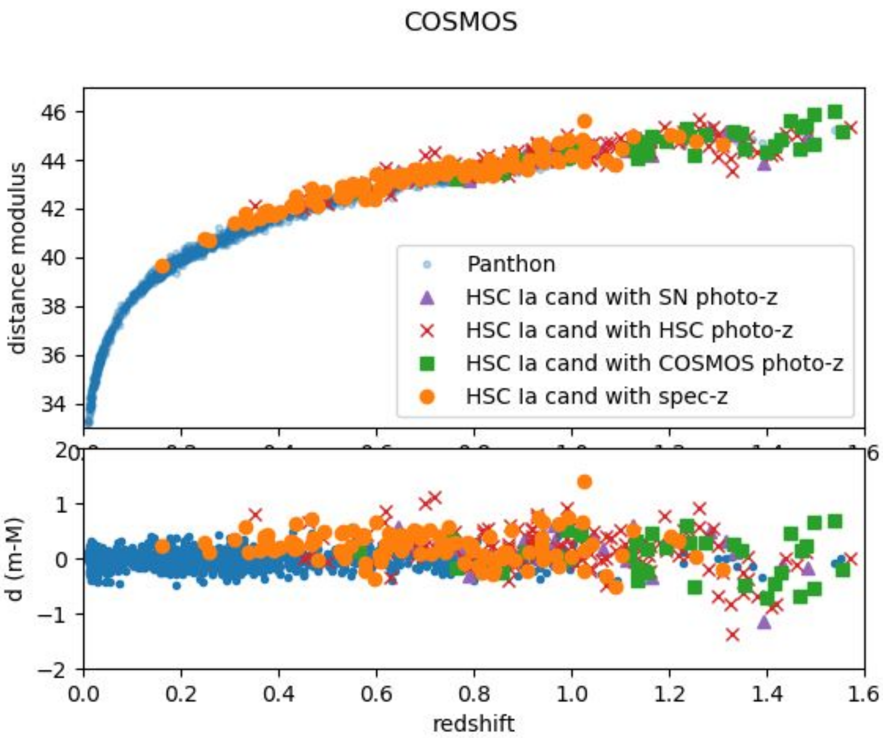

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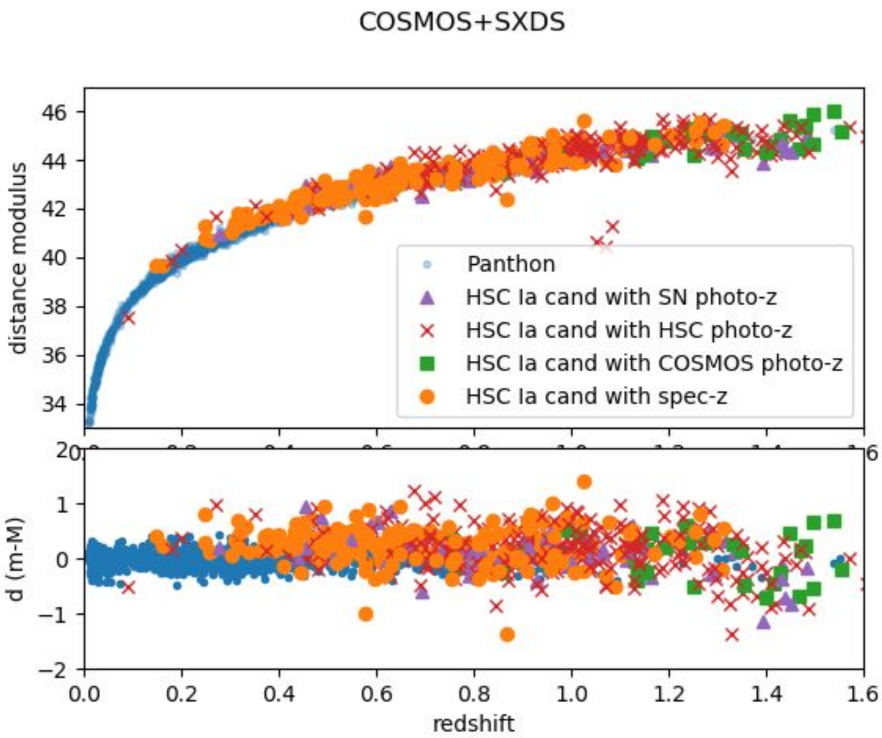

Summary

- HSC SSP Transient Survey identified large number of SN Ia candidates usable for cosmology
  - HSC is more powerful than HST and LSST
- Collaboration for SN Ia cosmology is on-going
  - Measuring host-galaxy redshifts
  - Photometric calibration
  - Detailed photometry
- Result of cosmological constraint will be a primary goal of the current collaboration in a few years
- Next step : LSST
  - Subaru/PFS is the only instrument able to gather the redshifts for the distant LSST SNe.
  - Japan has submitted a in-kind contribution proposal to join LSST. Now under reviewing.