The SN Hubble diagram

N. Regnault, and M. Betoule, P. Gris, M. Rigault, R. Graziani, P. Antilogus, P. Astier, S. Bongard, Y. Copin, H. M. Courtois, M. Briday, J. Cohen-Tanugi, D. Fouchez, E. Gangler, P. Gris, D. Hardin, A. J. Hawken, Y-L Kim, P-F Leget, L. Le Guillou, A. Moller, J. Neveu, E. Nuss, P. Rosnay, and many others

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Constraints on the Dark Energy equation of state with Type Ia Supernovae

From JLA to the LSST era

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Peculiar velocity cosmology with type Ia supernovae

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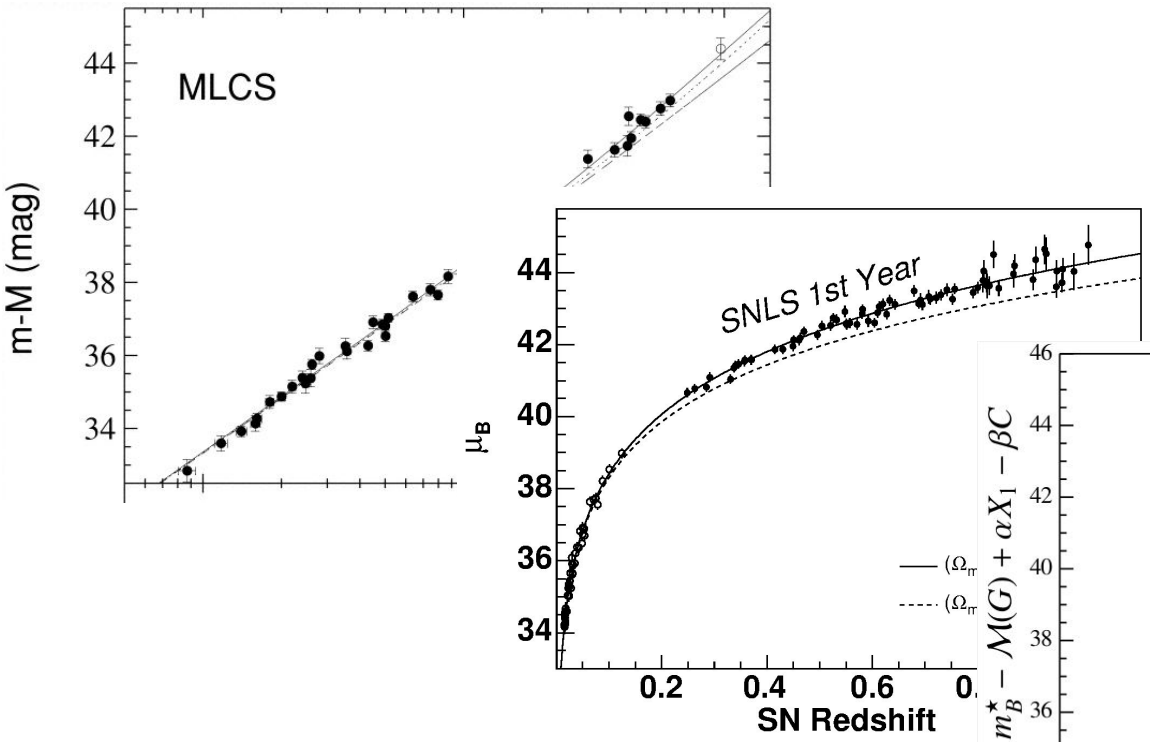
+ Lensing magnification (see talk by PF Leget)

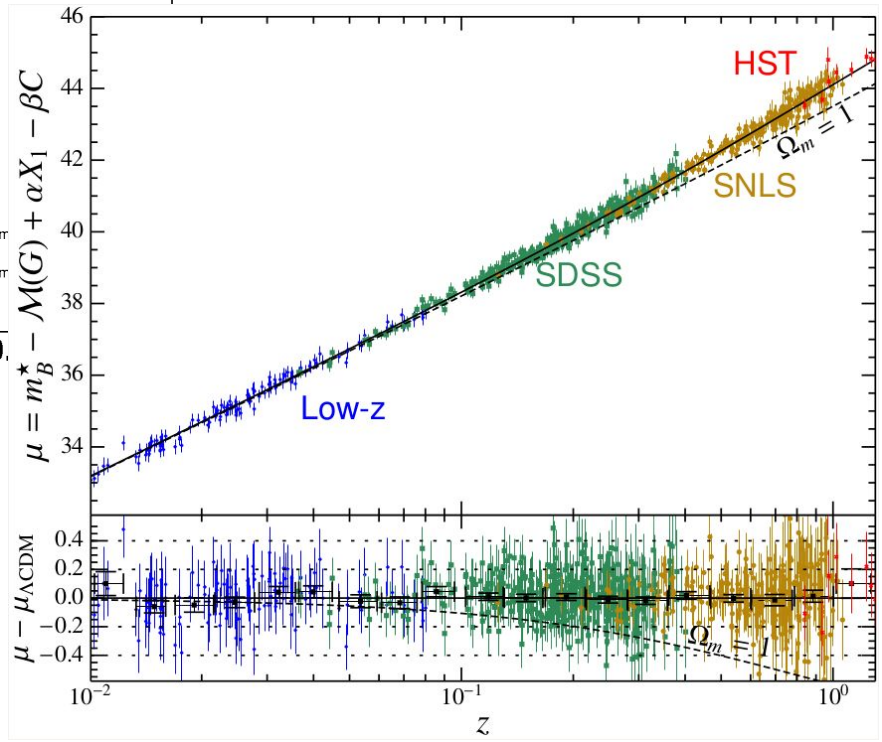
SN Hubble diagram

State of the art (still today):
Betoule et al, 2014)

Key ingredients:

- Standardization
- LC fitter
- Precision photometry
- Calibration
- Calibration
- Calibration...



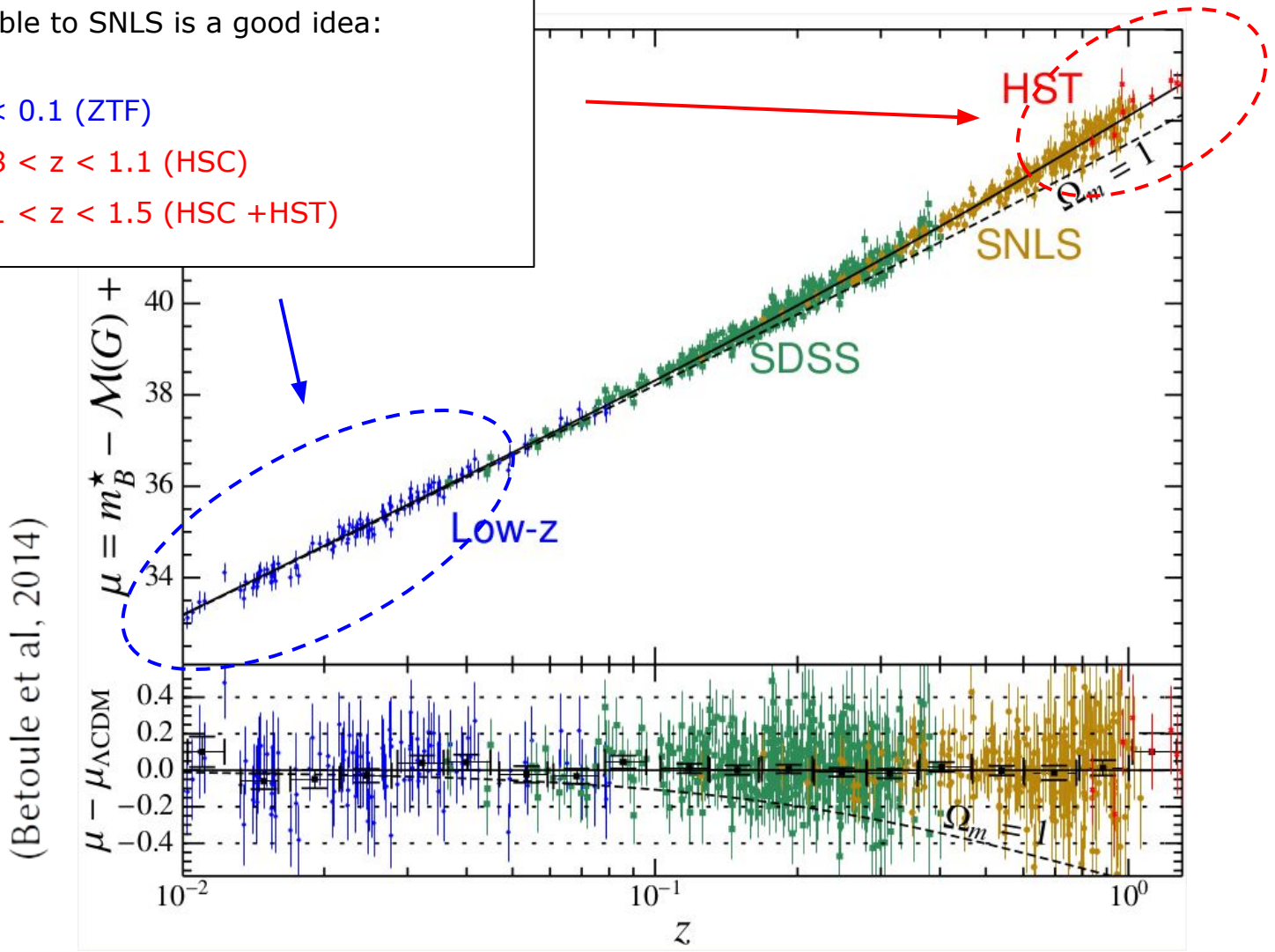


- 1998 : O(50) SNe
- 2005 : O(100) SNe
- 2014 : O(1000) SNe

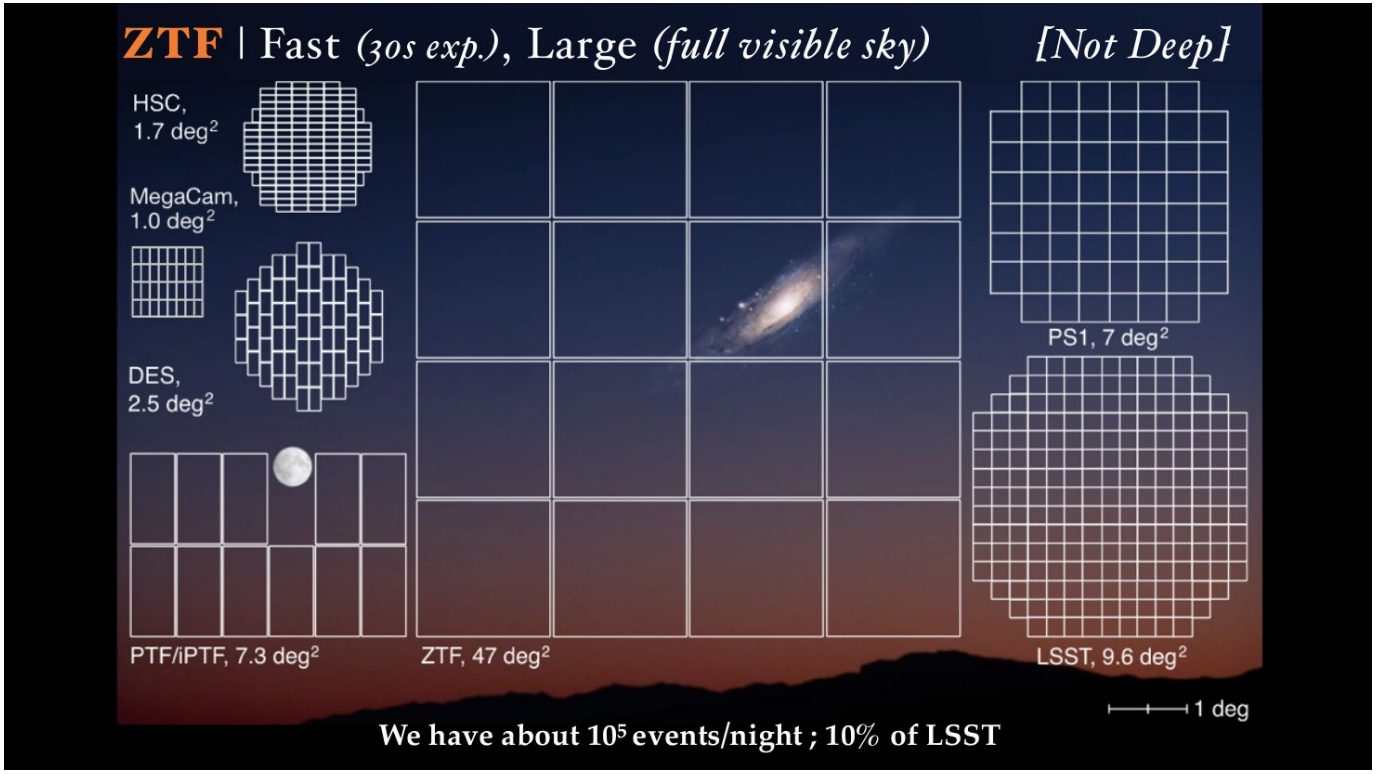
Under-constrained regions

To build low-z and high-z samples of quality comparable to SNLS is a good idea:

- z < 0.1 (ZTF)
- 0.8 < z < 1.1 (HSC)
- 1.1 < z < 1.5 (HSC +HST)

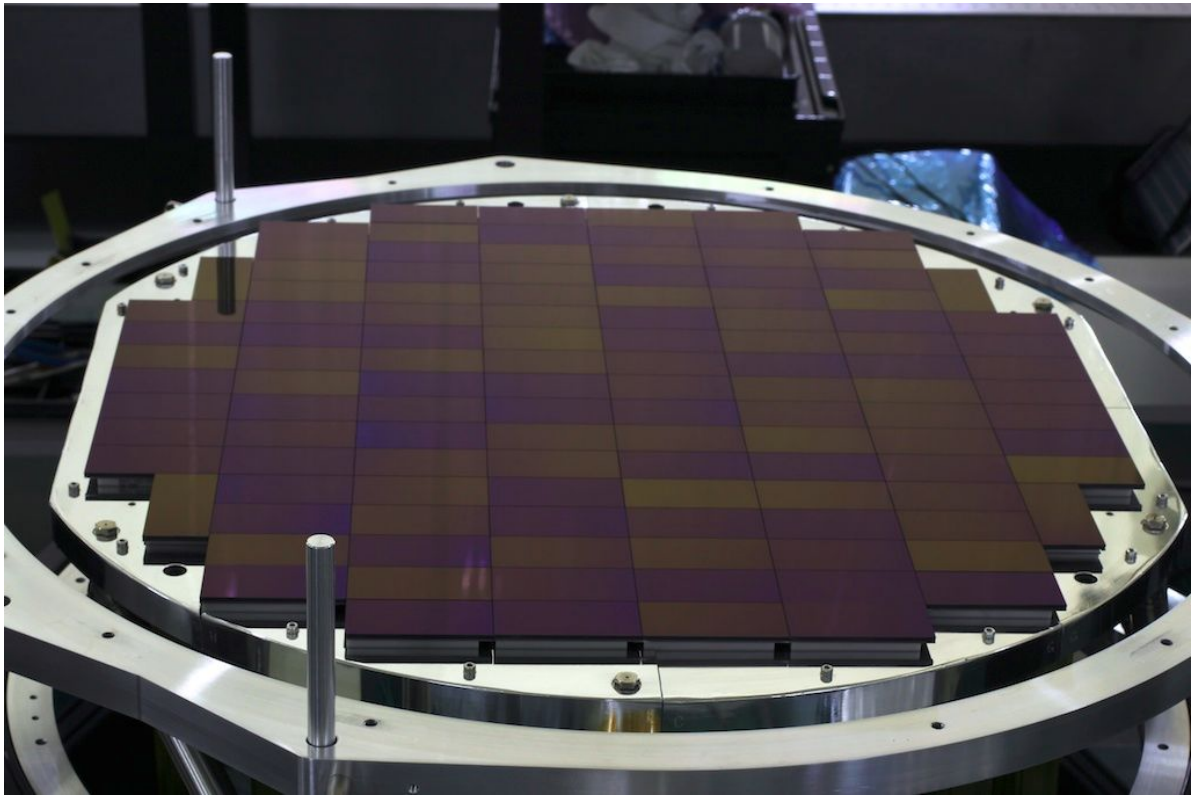


ZTF



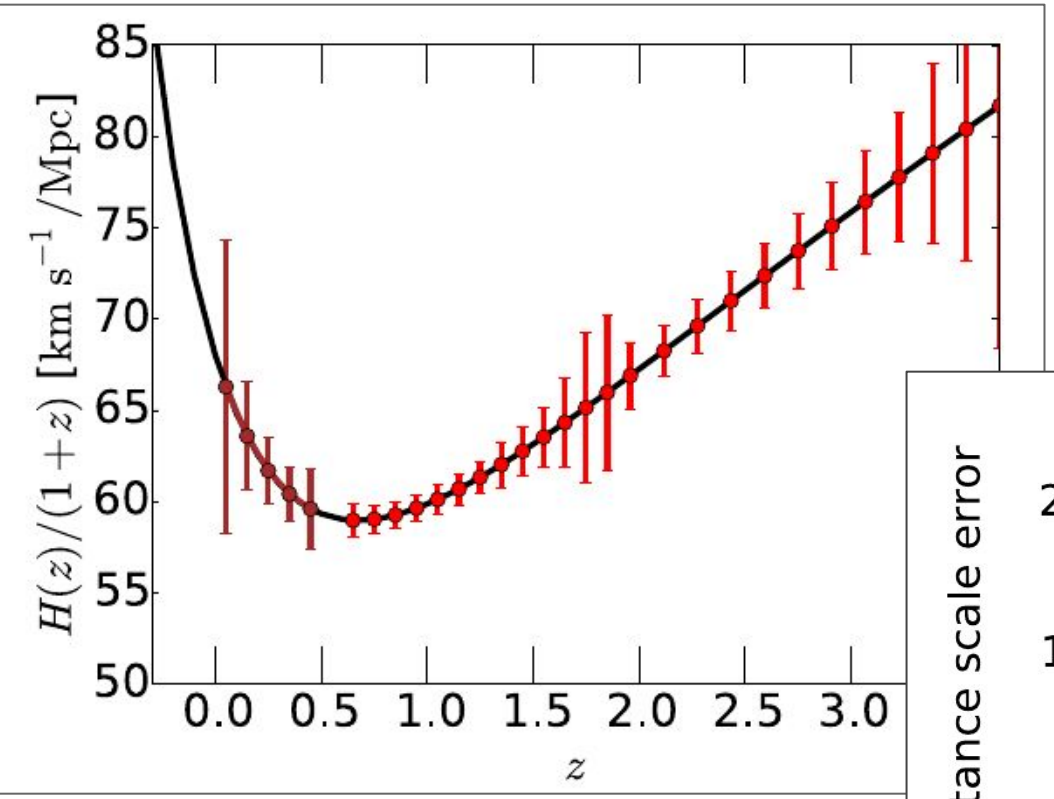
- O(1000) SNe up to z < 0.1
- 4-day cadence (g,r) + 6 day cadence (i-band, private)
- 10% of sample with a higher cadence (1 day ?)

Subaru Strategic Program



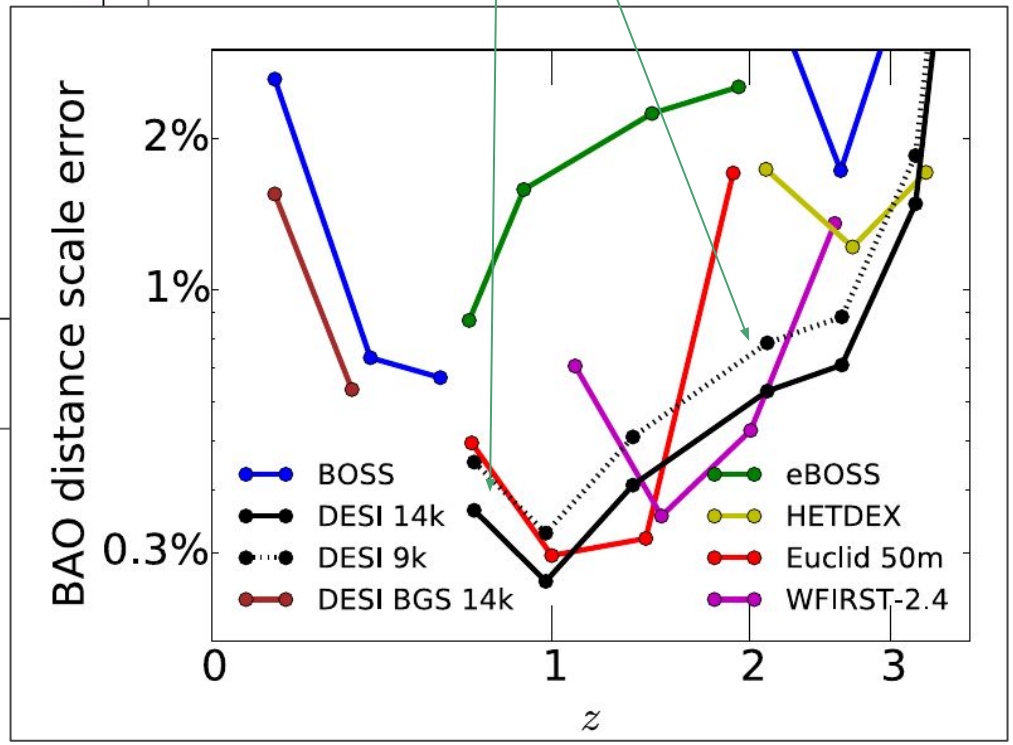
- 1.8 deg^2 camera
- 116 CCD à haute résistivité
- Télescope Subaru (8.2-m)

Around ~ 2025 ...



DESI BAO Hubble diagram

Independent redshift bins

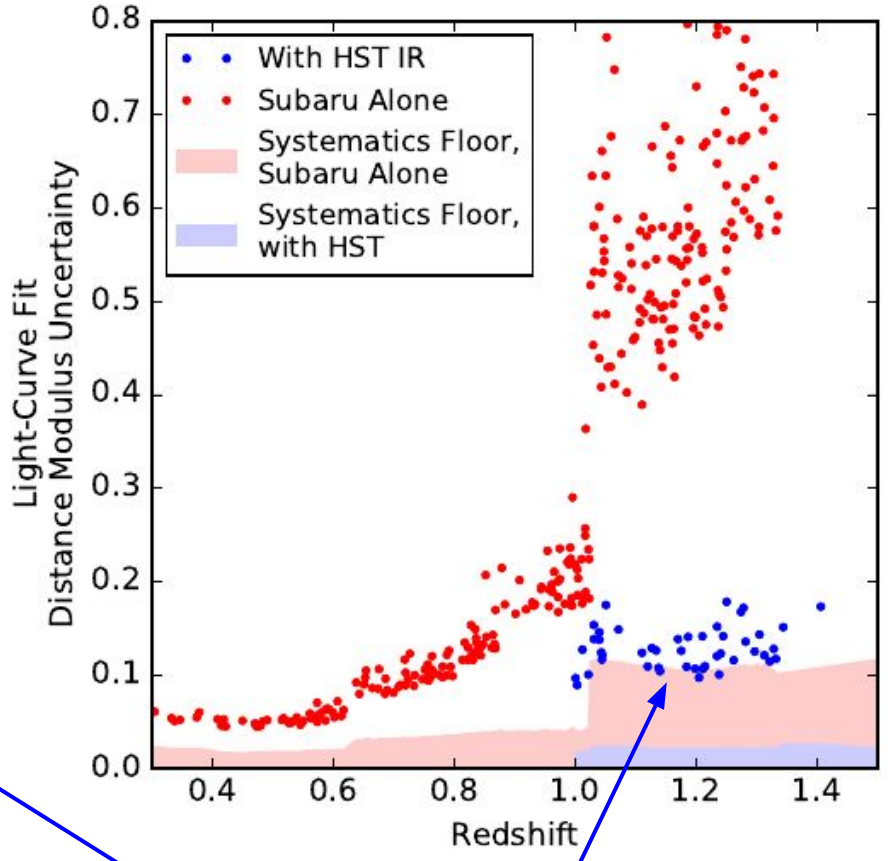


SN Hubble diagram ?

- Type Ia supernovae are a
  - *statistically efficient*
  - *mature*
  - probe of the expansion history
- With ground based observations only, can cover: $0.05 < z < 1$
- With additional IR observations, can cover: $1 < z < 1.5$
- Can we build a strategy, to get a LSST SN Hubble diagram
  - in 2 years of observations (2023, 2024)
  - with a constraining power (w_0, w_a) equivalent to that of DESI ?

How can we go beyond z ~ 1 ?

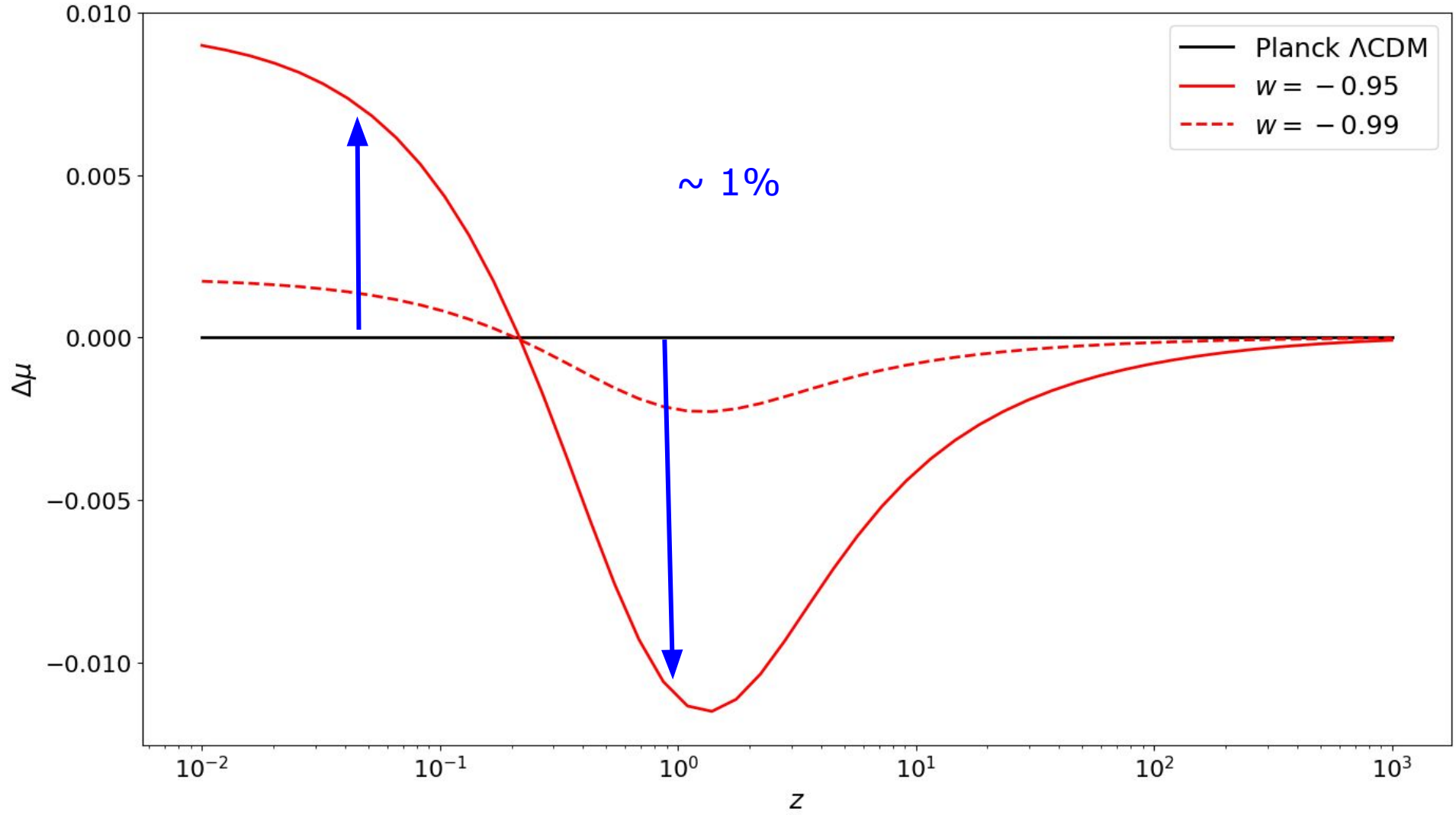
- Currently being explored with the combination of Subaru/HSC and HST
- Ground base observations alone can measure distances up to z<1.1
- Beyond that, we need IR photometry (e.g. HST observations)



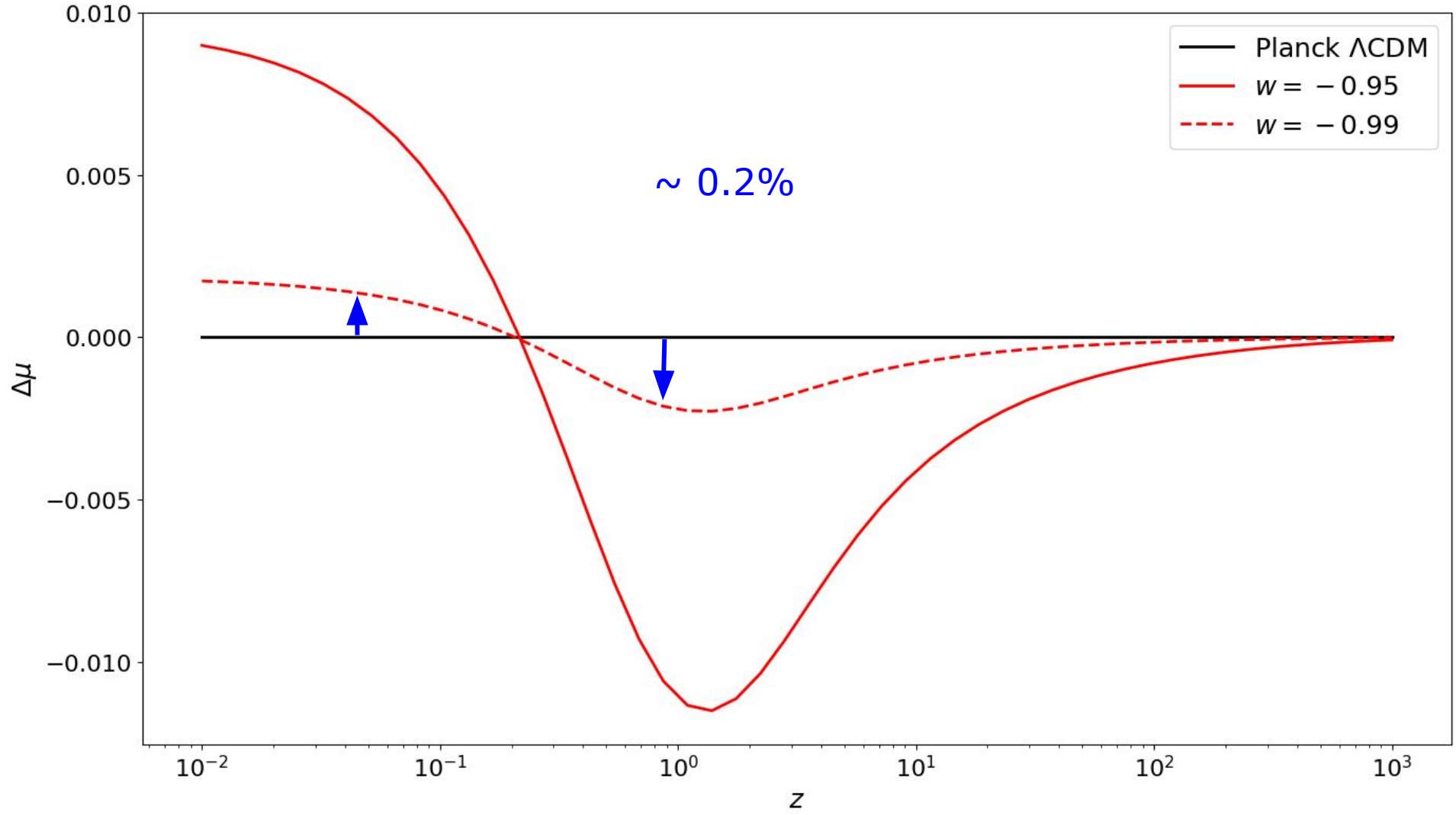
With one single HST visit (2 orbits per SN), One can measure a distance

Poor man's version of (Astier et al, 2014)
But seems to work pretty well !

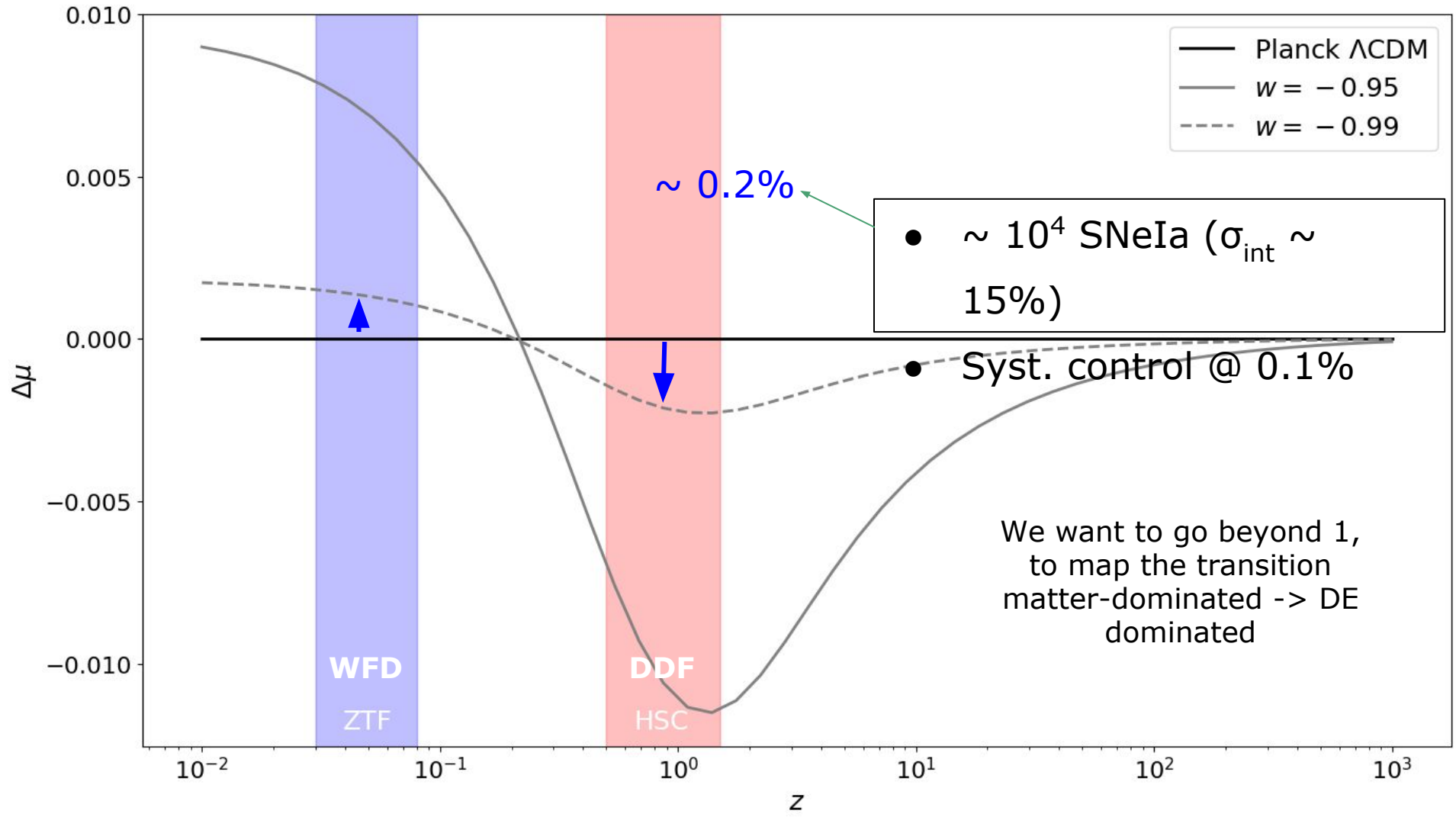
This is a precision measurement ...



This is a precision measurement...



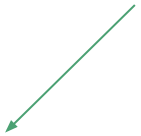
This is a precision measurement...



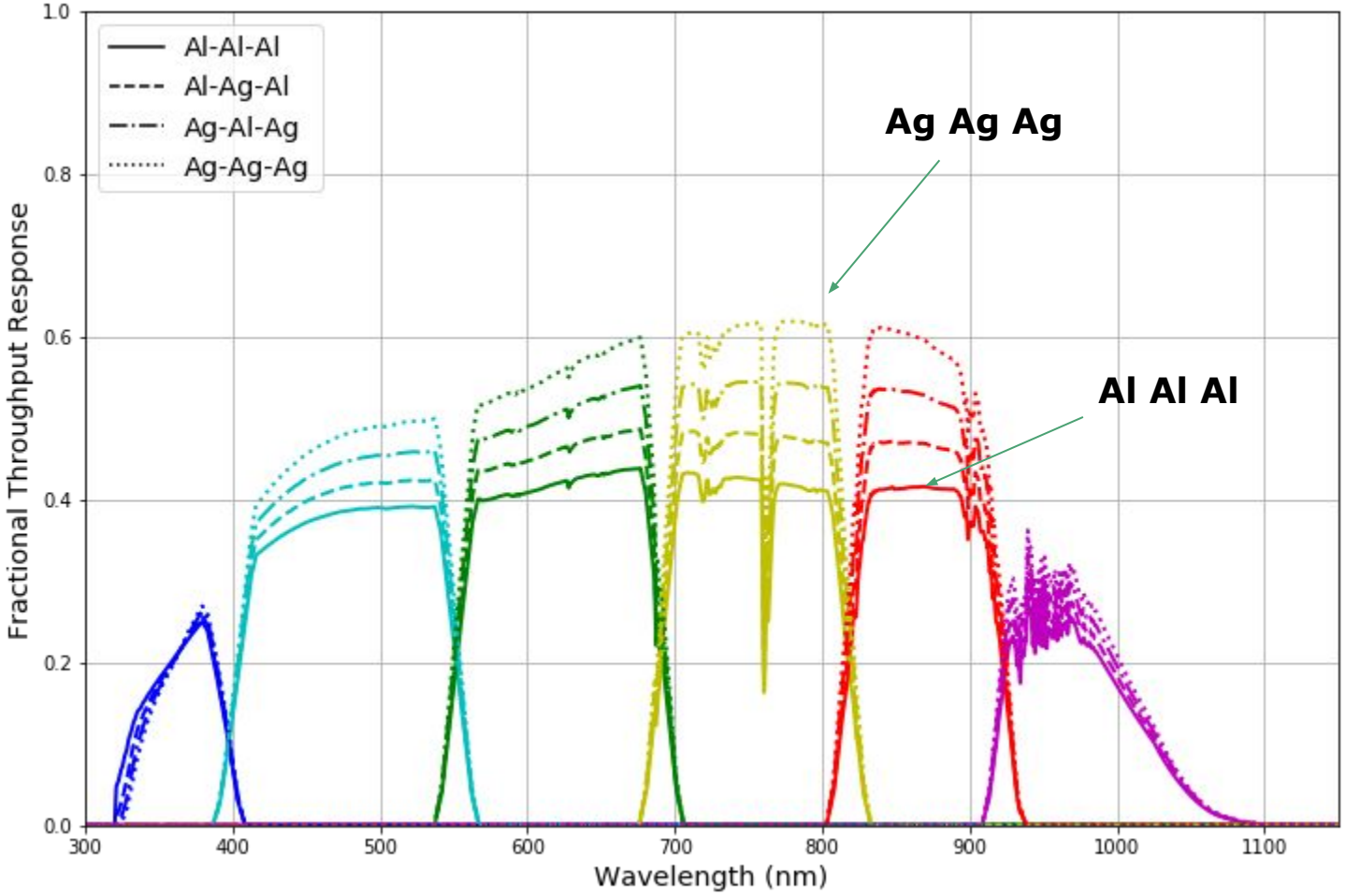
Ingredients for competitive cosmological constraints

- O(10^4) well sampled SNe in the WFD
  - (easy, most cadences can deliver that)
- O(10^4) well sampled SNe in the DDF
  - Can get O(3000) SNe in 2 years on 2 DDF pointings
  - Need a deeper cadence than baseline (7% obs time)
- IR from space to extend the redshift lever arm up to z ~ 1.5
- A plan to get ~ 10^4 host galaxy redshifts up to z ~ 1.5
  - The only spectrograph that can do that is PFS
  - -> focus on equatorial DDF's
- A calibration at the 0.1% - level
  - StarDICE, SCALA et al + control of DM photometry @ 0.1%

Depends on mirror coatings



Al versus Ag mirror coatings



What can we get by ~ 2025 ?

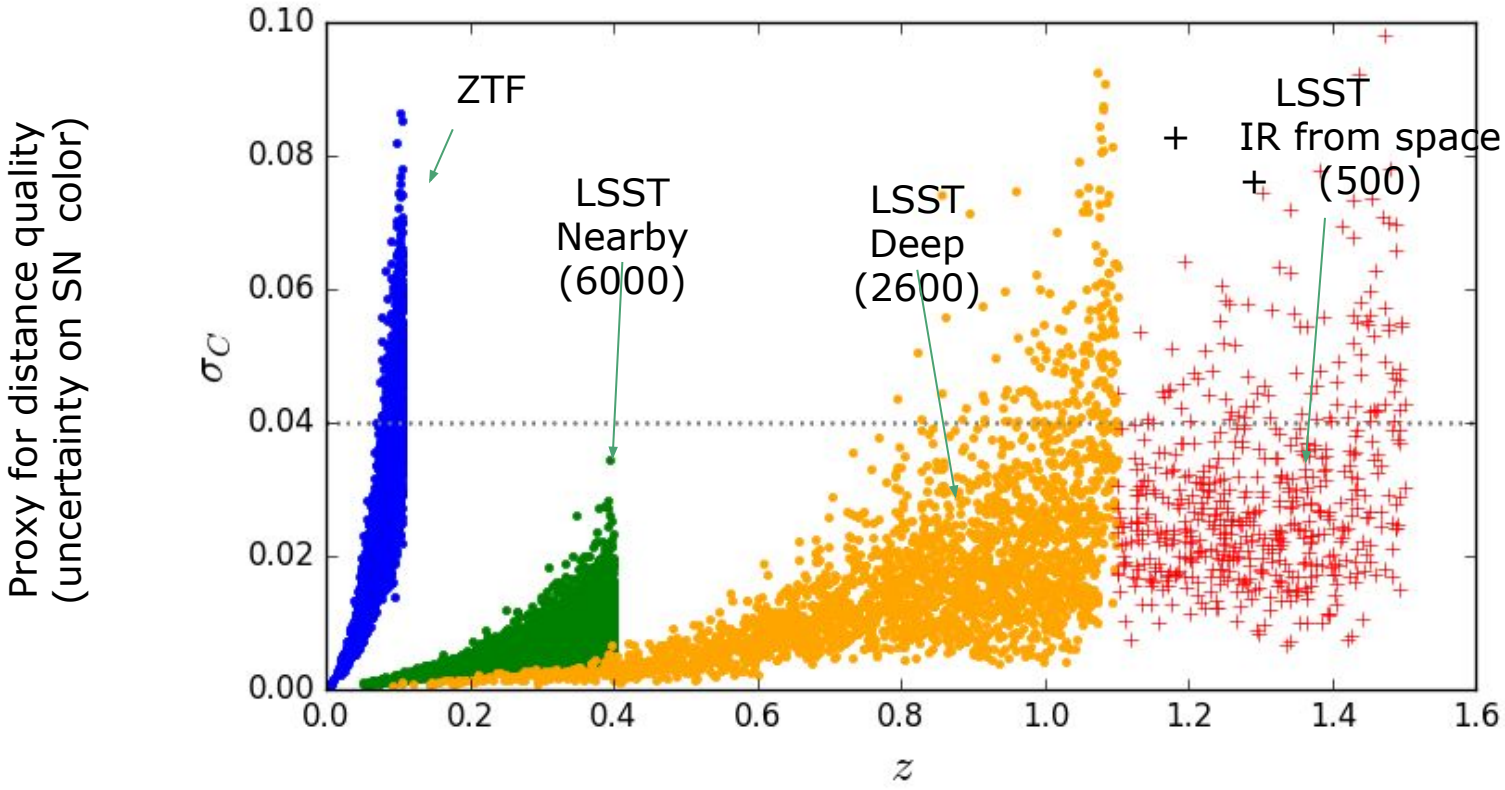
- Easy to get O(10^4) nearby SNe
  - Most WFD cadences are now able to deliver that
  - ~ 1000 deg^2 during 2 years
  - 30-s exposures and a 4-day cadence give us enough SNR up to z ~ 0.3
- Regarding the DDF's, we need
  - a deeper cadence w.r.t. baseline
  - to focus on 2 fields during 2 years
  - e.g. 4 day cadence, with

7% of observing time during 2 years

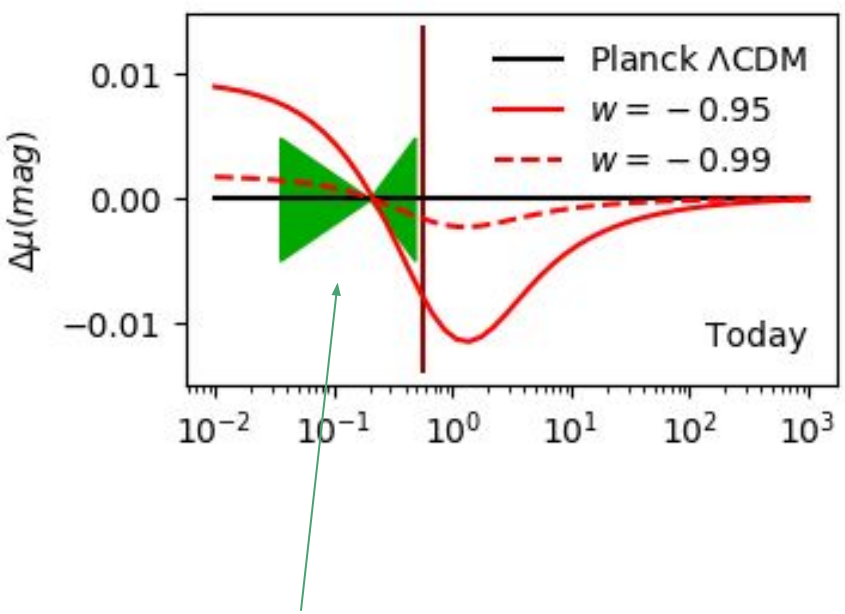
	g	***r***	***i***	***z***	***y***	
deep	2 x 30	20 x 30	80 x 30	80 x 30	?	1.5 hr
baseline	2 x 30	4 x 30	8 x 30	25 x 30	4 x 30	0.3 hr

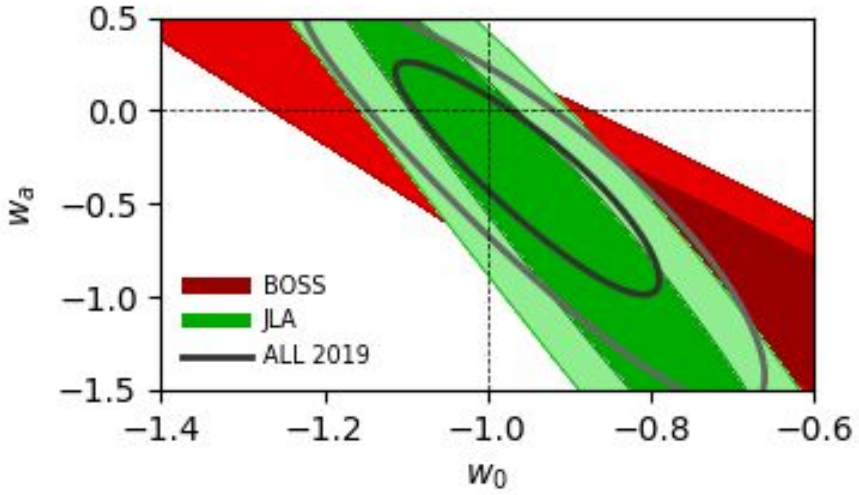
First 2 years of LSST + Some IR from space

(Euclid or HST)



(w,wa) constraints as of today

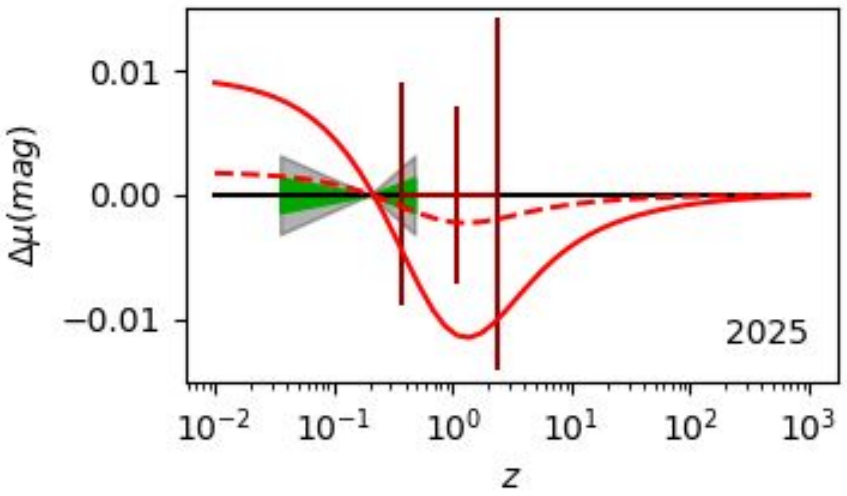


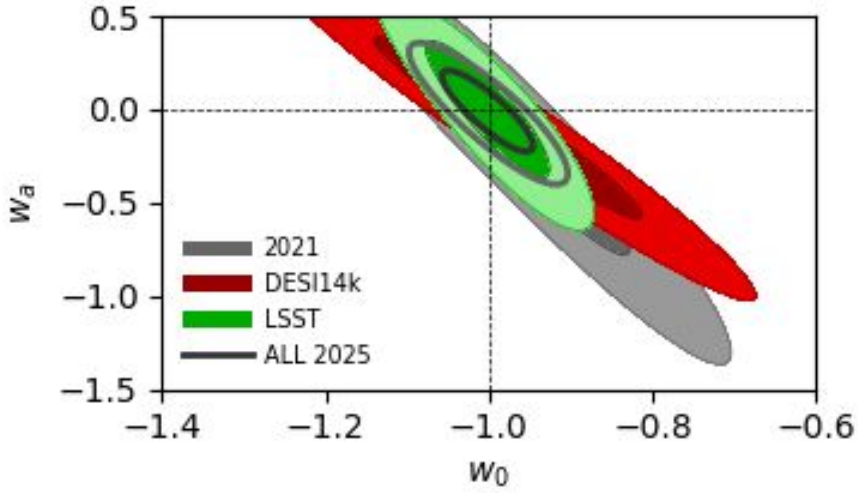


Uncertainty on μ(highz) - μ(lowz) (subtracting common mode from calibration)

Regnault, Betoule, Hazenberg et al

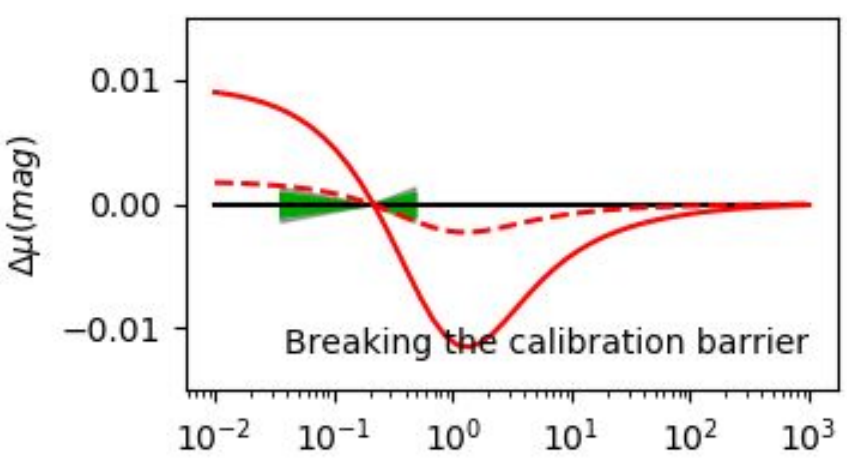
With two years of LSST + IR from space

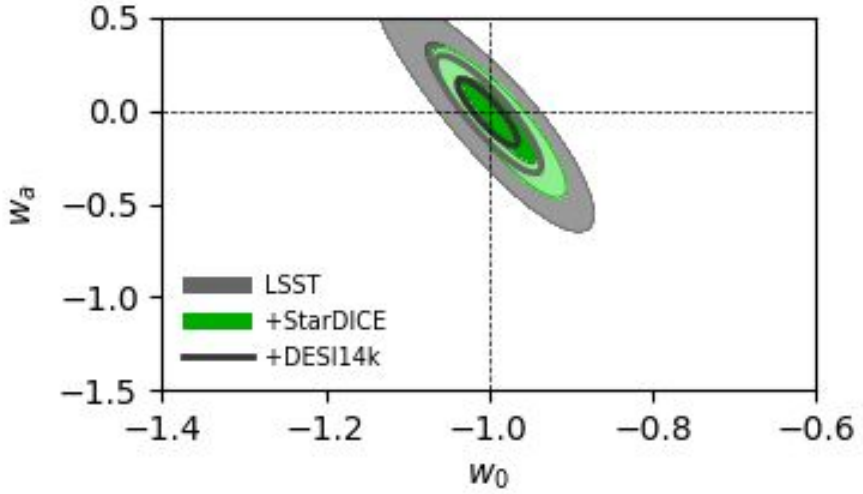




FoM ~ 150

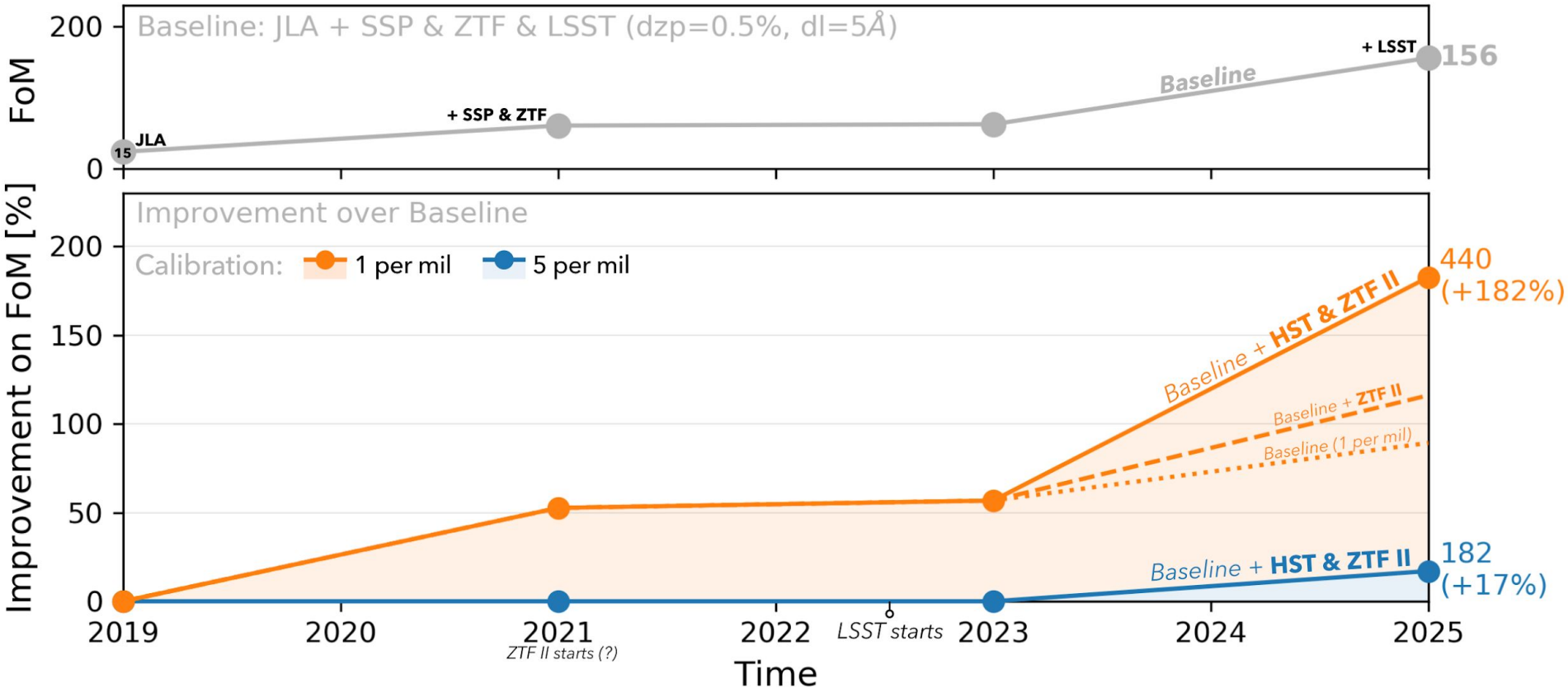
With calibration at the 0.1% level





FoM ~ 450

Timeline



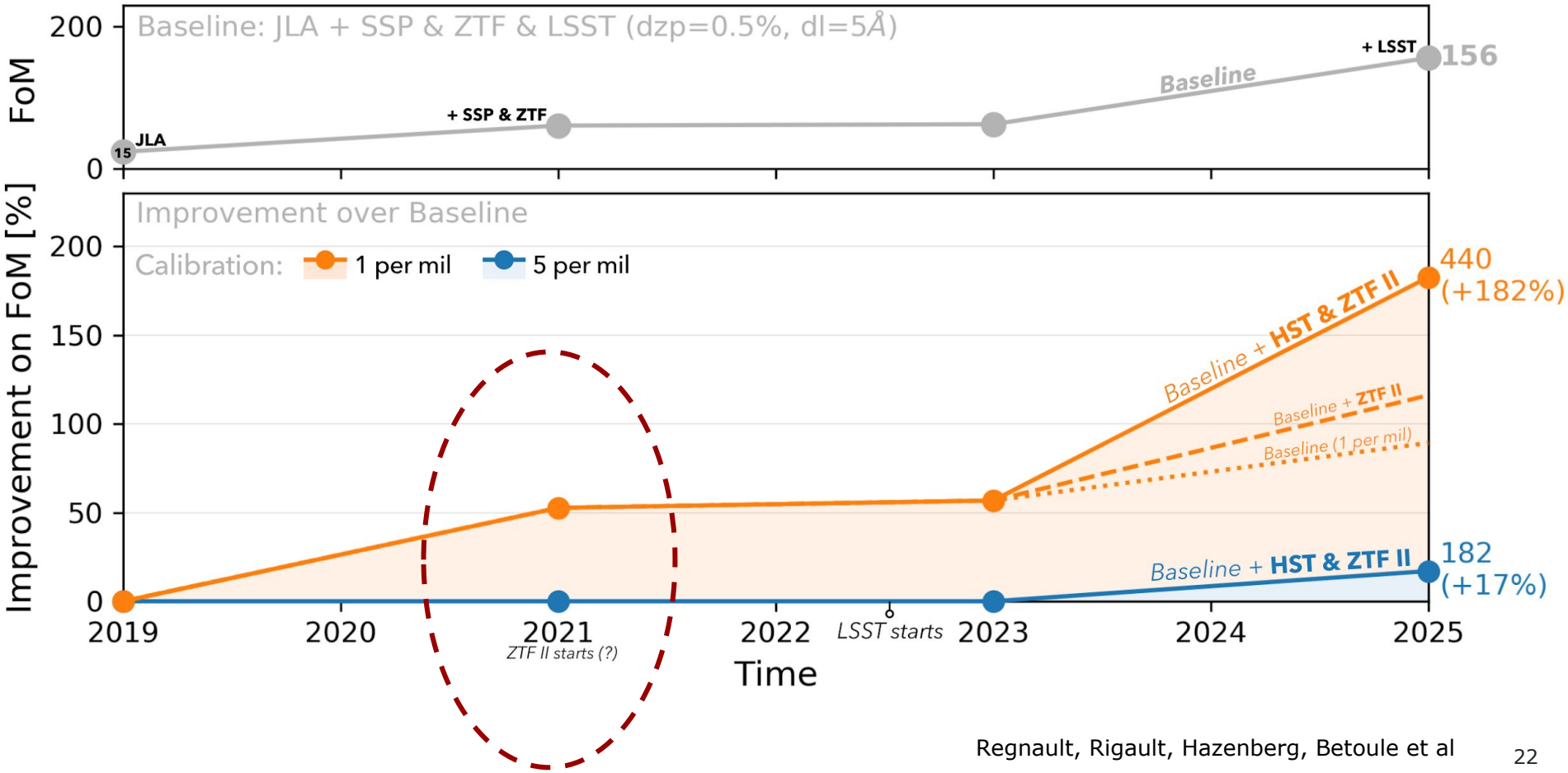
Regnault, Rigault, Hazenberg, Betoule et al

Conclusion

- LSST has the potential to produce the best constraints on a varying DE equation of state *by 2025*
- Are we ready to
  - Define projects that are
    - shorter than the duration of the full project
    - designed to get early science
  - Request a deeper, *more expensive* cadence on at least two *equatorial* DDF's for the first 2 years ? (and relax these constraints in the following years)
  - Support a large HST proposal to complement the follow-up of the most distant SNe.

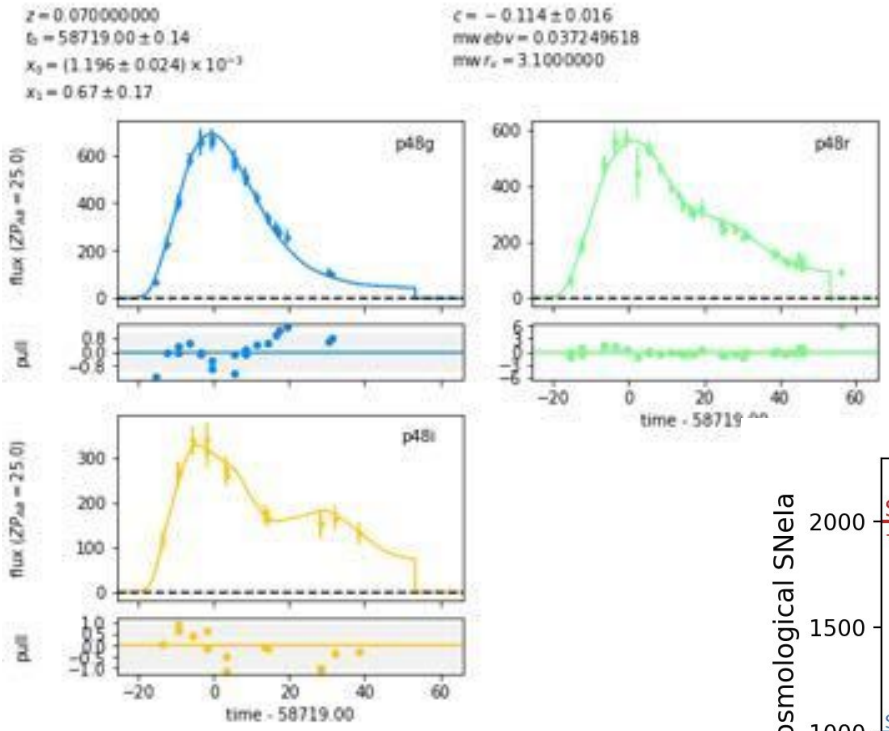
(Mirror coating has an impact here)

Timeline

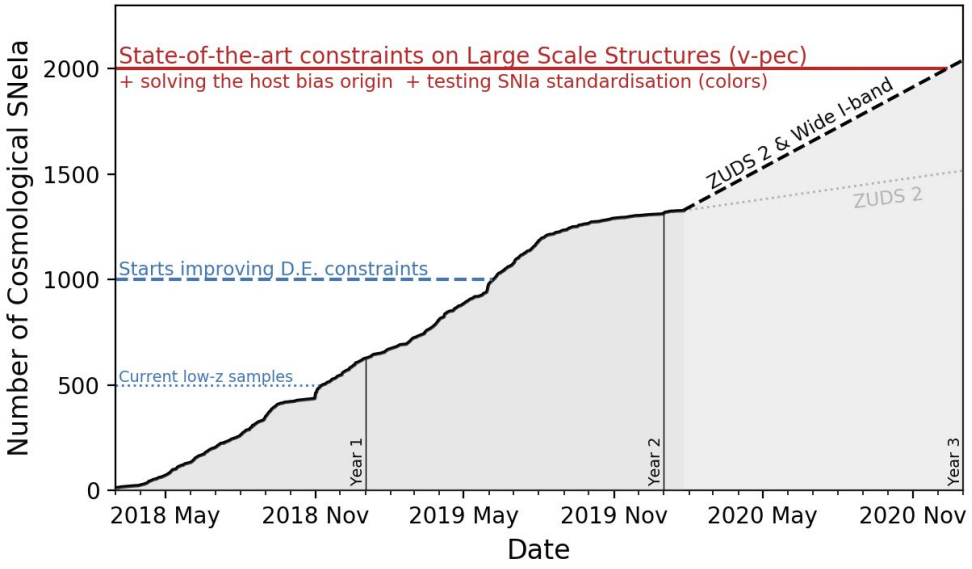


Regnault, Rigault, Hazenberg, Betoule et al

ZTF dataset

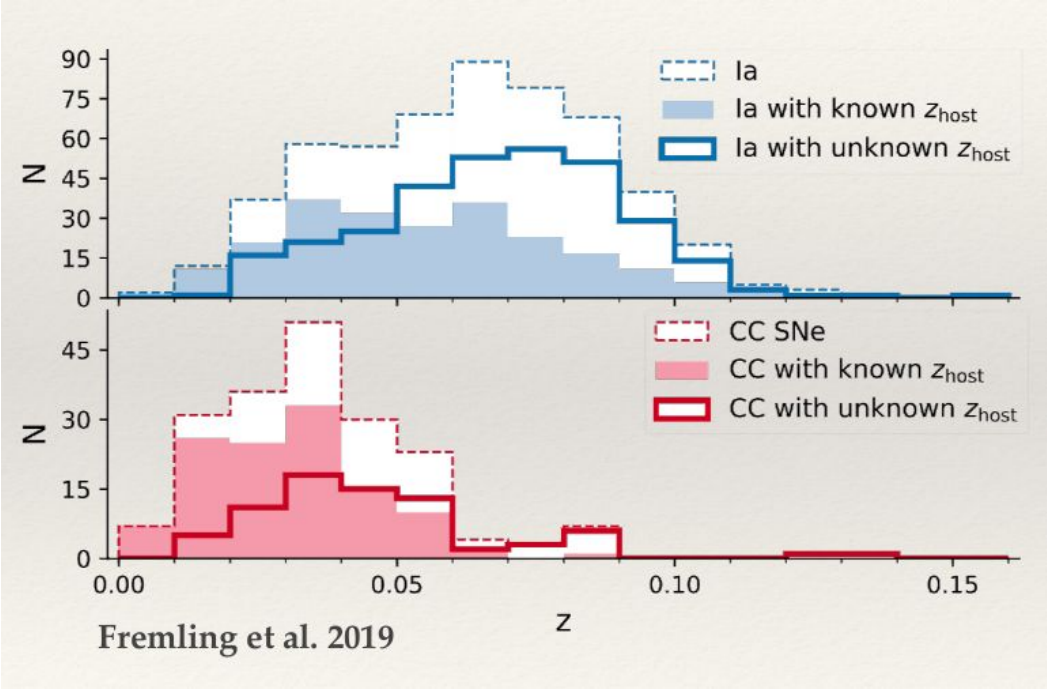


"Typical" light curves



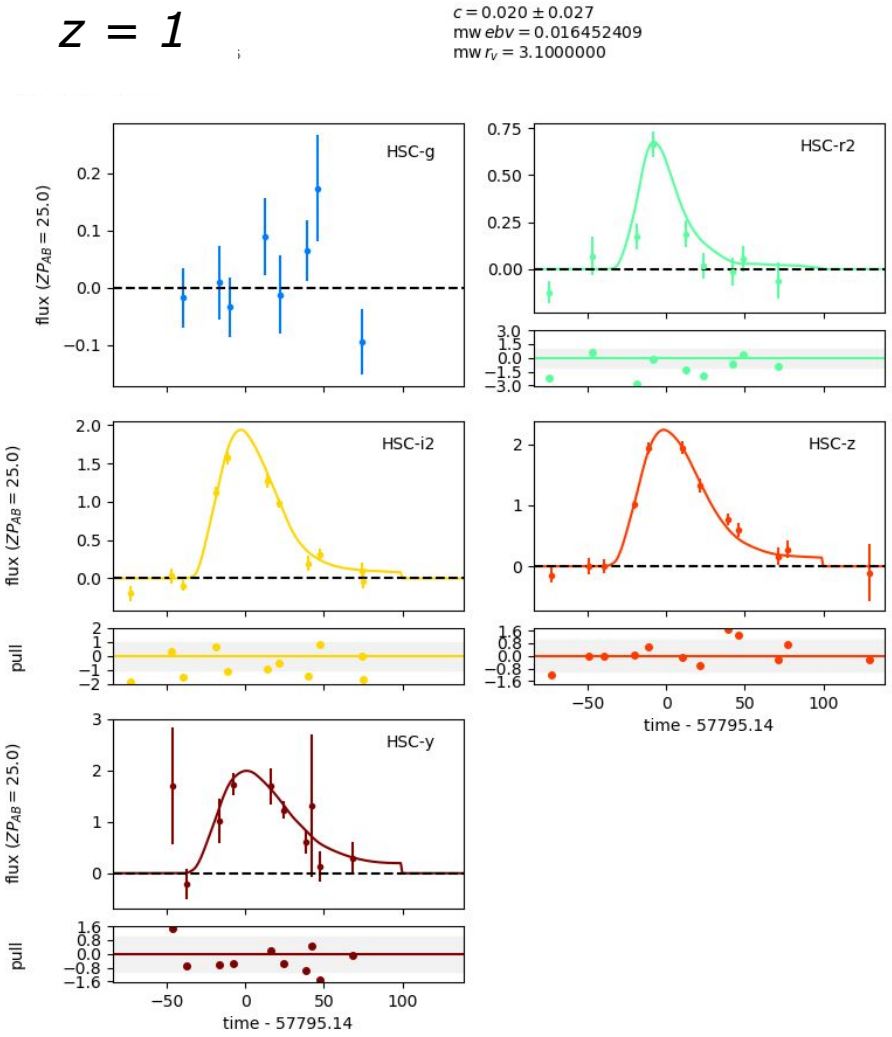
ZTF dataset

All transients are typed (SED machine)
All redshifts will be obtained from DESI

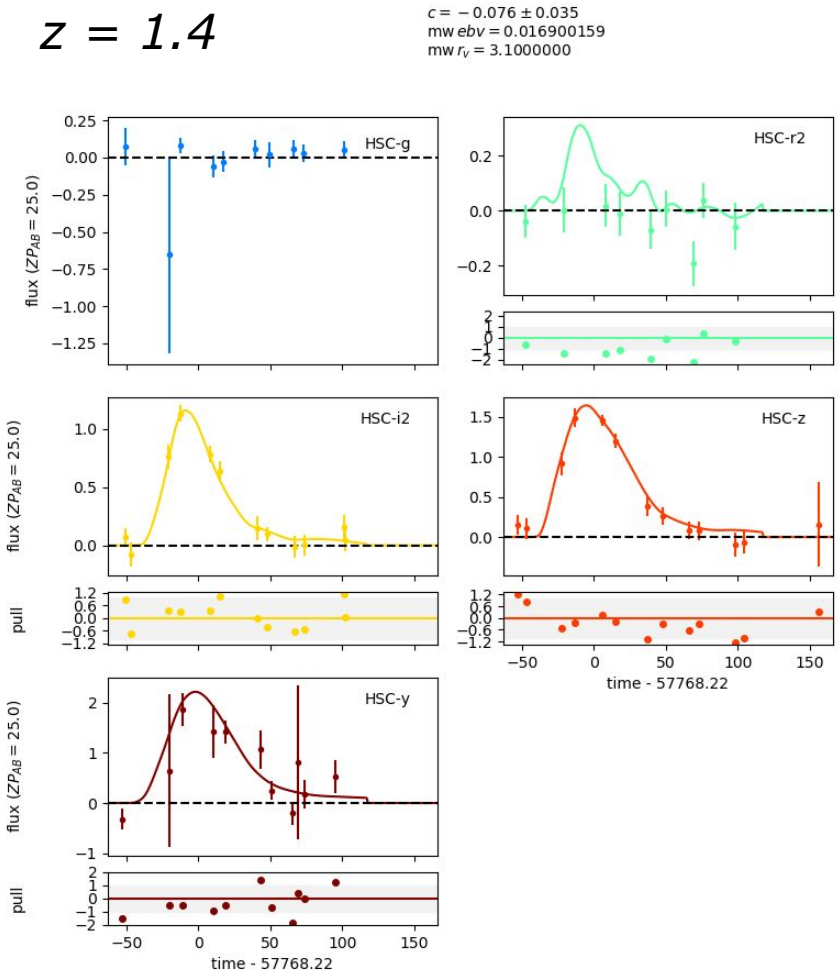


Subaru/HSC dataset : great light curves

z = 1



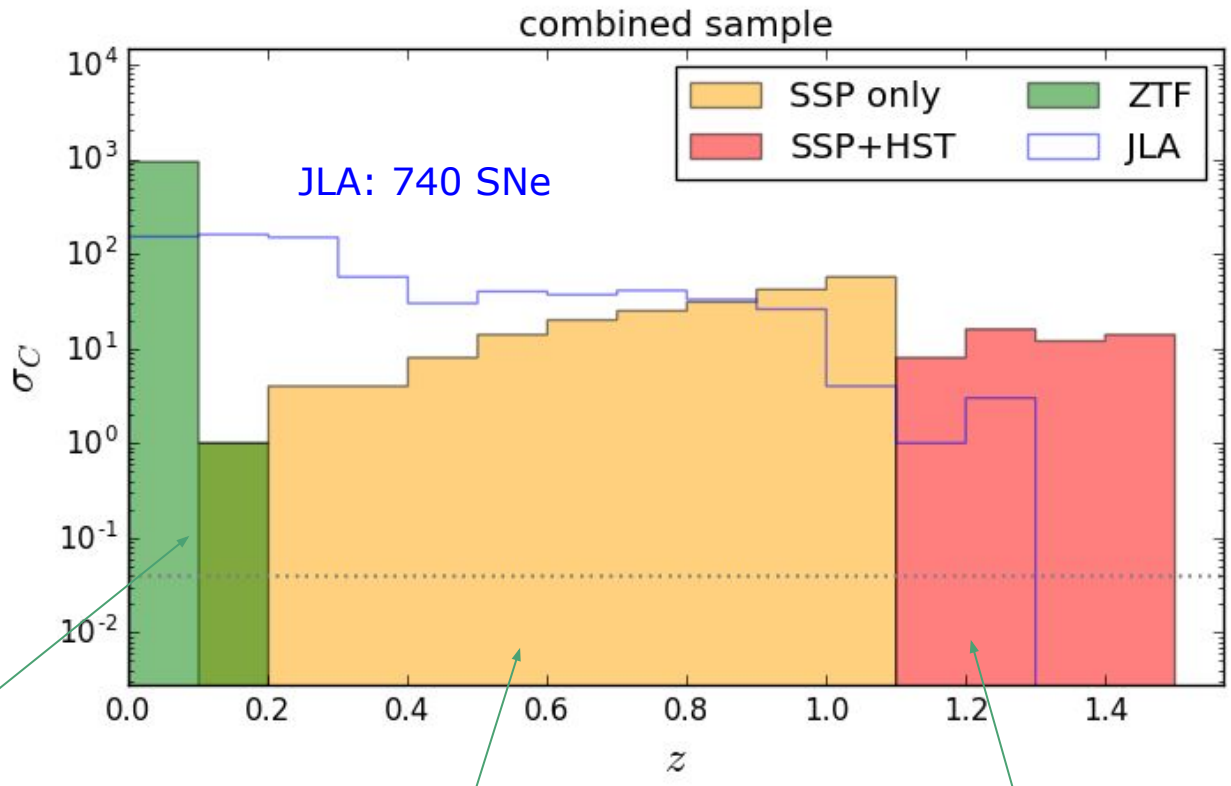
z = 1.4



Subaru / HSC dataset

- Two seasons on disk
  - COSMOS (2017)
  - XMM (2019-2020)
- O(100) redshifts
- Effort to get the remaining redshifts from:
  - AAT (4-m)
  - 8-m telescopes (VLT, Subaru, Keck)
  - PFS (2021)
- Will rely on photometric identification

A look at the JLA+ZTF+HSC/HST SN sample

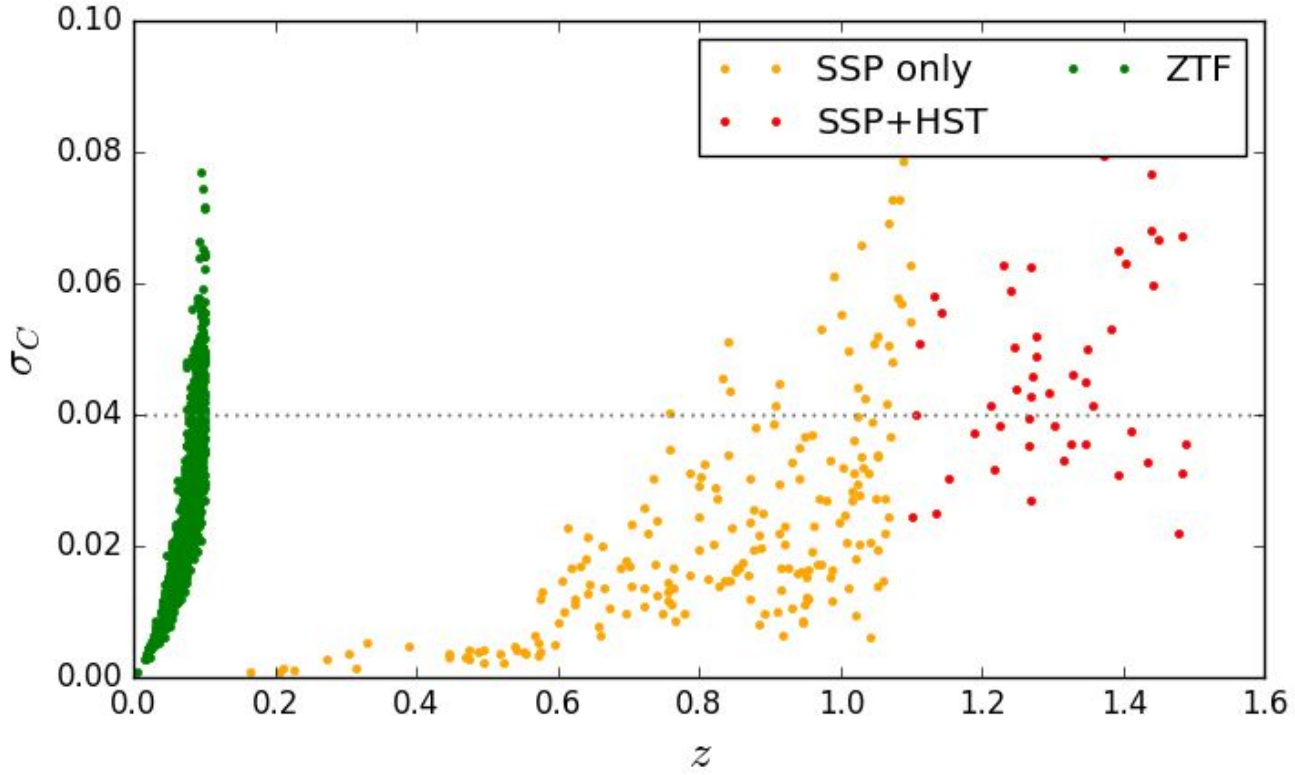


O(800)

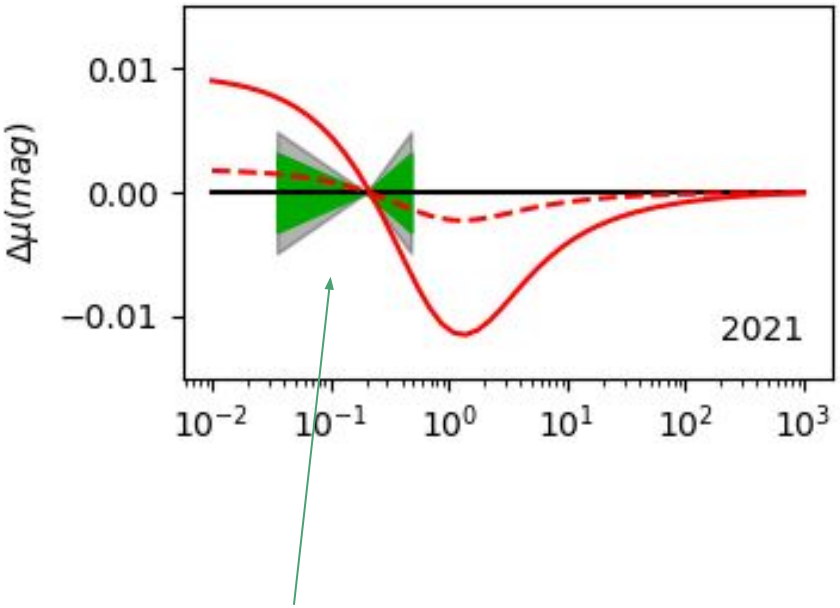
O(250)

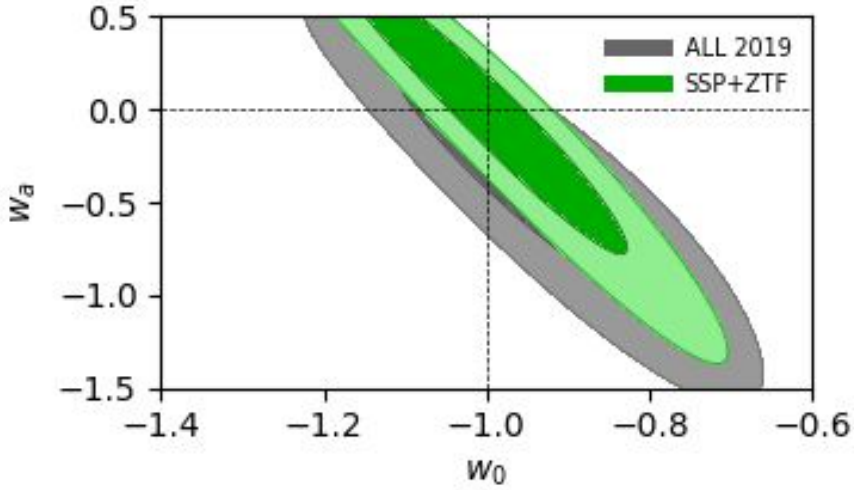
~50

A look at the JLA+ZTF+HSC/HST SN sample



Expected constraints before LSST first light





Uncertainty on μ(highz) - μ(lowz)

FoM ~ 50

Ingredients -> combined Hubble diagram

- Understand the instruments / sensors
  - Instrument linearity
  - Brighter-fatter & other sensor effects
- SN photometry
  - SNLS scene modeling code
  - Other codes (DM stack ?)
  - New developments (PSF, sky subtraction, …)
- Calibration
  - Primary flux references : starDICE
  - Filter metrology : CBP / traveling CBP)
  - Inter calibrate Subaru/HSC <-> ZTF <-> JLA/SNLS5
- SN empirical model
  - Sugar / SALT+ / ....
- SN photometric identification
  - ZTF : great training sample
  - Subaru / HSC : relies on SN photometric identification

Conclusion

- 2 years of ZTF data is public
- 2+ years of HSC data is public
- Lots of expertise in this room
  - *Unique opportunity to confront real data*
  - *To write method papers*