SN Cosmology

N. Regnault & R. Graziani

and M. Rigault, M. Betoule, 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,

Nature of Dark Energy ?

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

From JLA to the LSST era

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DE equation of state

$$p = w(z) \times \rho$$

Growth of structure

$$f = \Omega_m^{\gamma}$$

(GR predicts γ ~ 0.55)

Peculiar velocity cosmology with type Ia supernovae

R. Graziani[1], M. Rigault[1], N. Regnault[2], Ph. Gris[1], A. Möller[1], P. Antilogus[2], P. Astier[2], M. Betoule[2], S. Bongard[2], M. Briday[3], J. Cohen-Tanugi[4], Y. Copin[3], H. M. Courtois[3], D. Fouchez[5], E. Gangler[1], D. Guinet[3], A. J. Hawken[5], Y.-L. Kim[3], P.-F. Léget[2], J. Neveu[6], Ph. Rosnet[1] E. Nuss[4]

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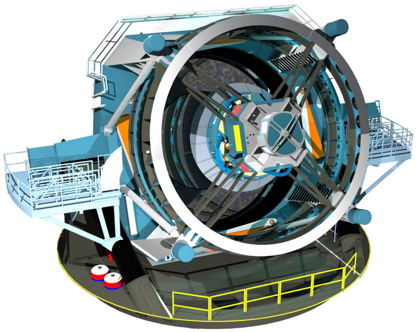
… relying on 3 complementary projects

- **ZTF** **(& ZTF-II)**
  - 2017 - 2020 (-> 2024)
  - 1.2-m, 47 deg^2
  - O(800) SNe @ z < 0.08
  - -> O(3000) SNe
- **Subaru/HSC**
  - 2017 - 2020
  - 8.2-m, 1.8 deg^2
  - O(300) SNe @ z < 1.1
  - ~ 50 SNe @ z < 1.5 **(+HST)**
- **LSST**
  - 2022 - 2032
  - 6.2-m equivalent, 10 deg^2
  - O(3 10^5) SNe @ z < 0.4
  - O(2 10^4) SNe @ z < 1



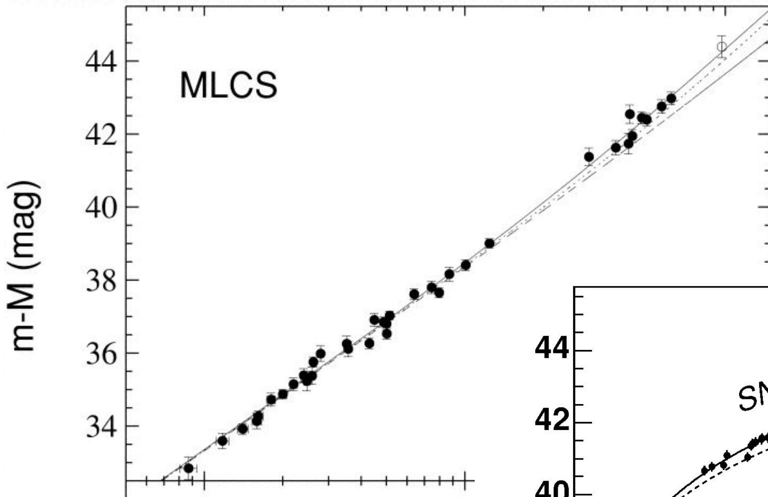
Mapping the expansion history with SNe Ia

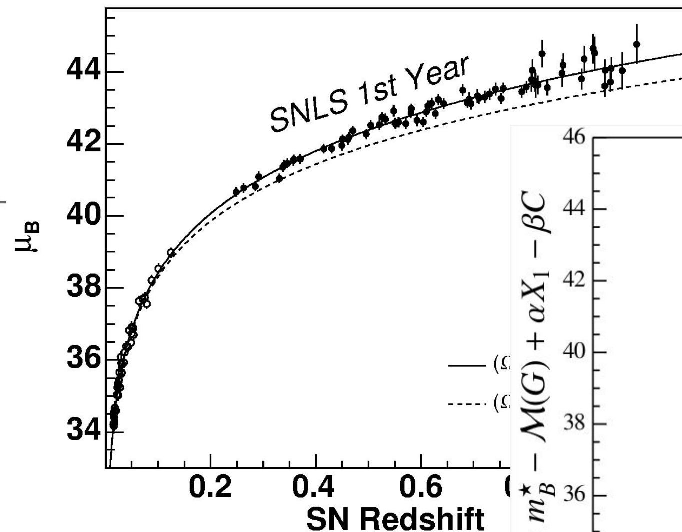
SN Hubble diagram(s)

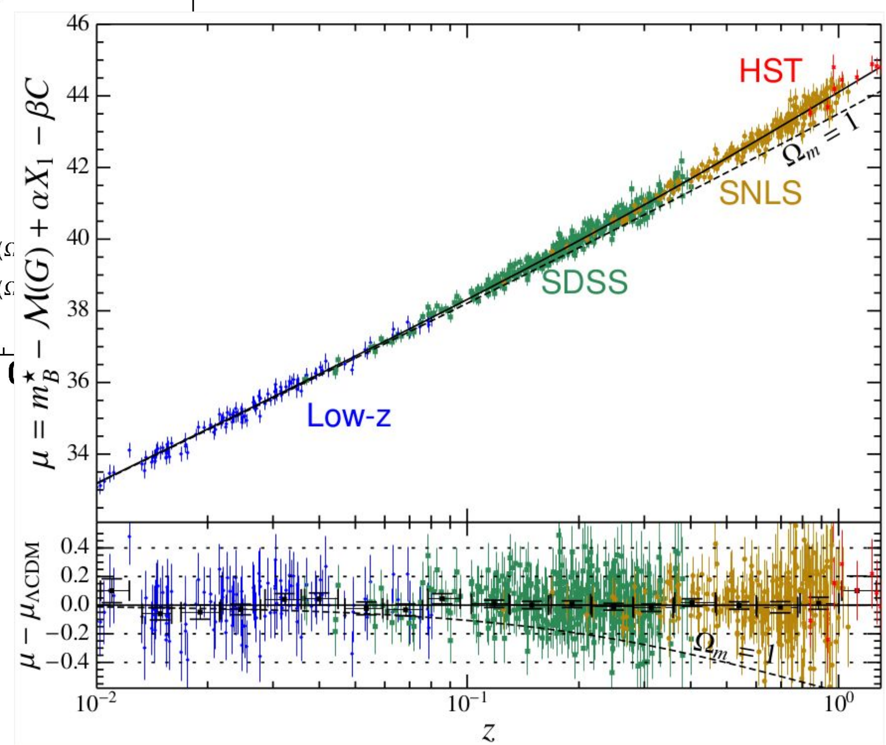
State of the art (still today):
Betoule et al, 2014)

Key ingredients:

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

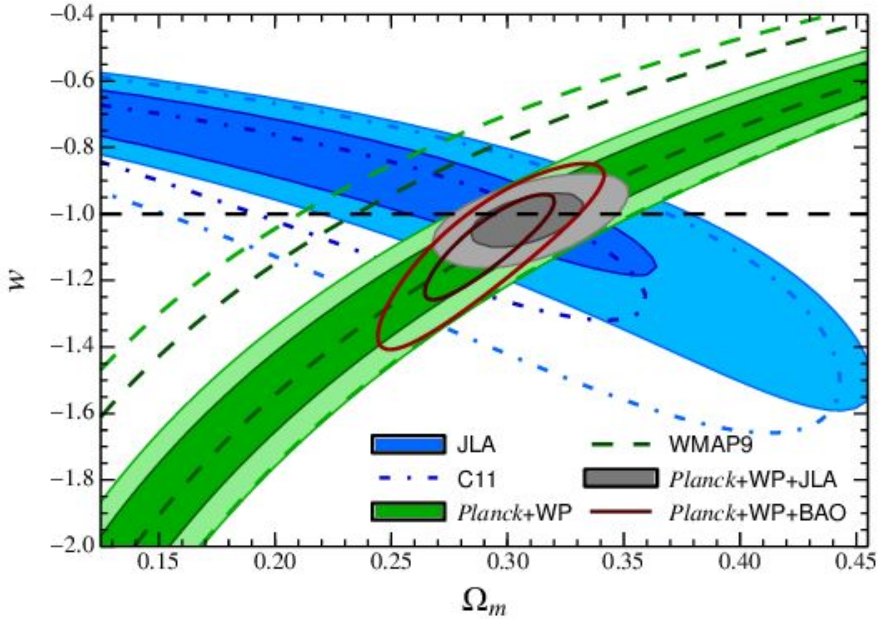


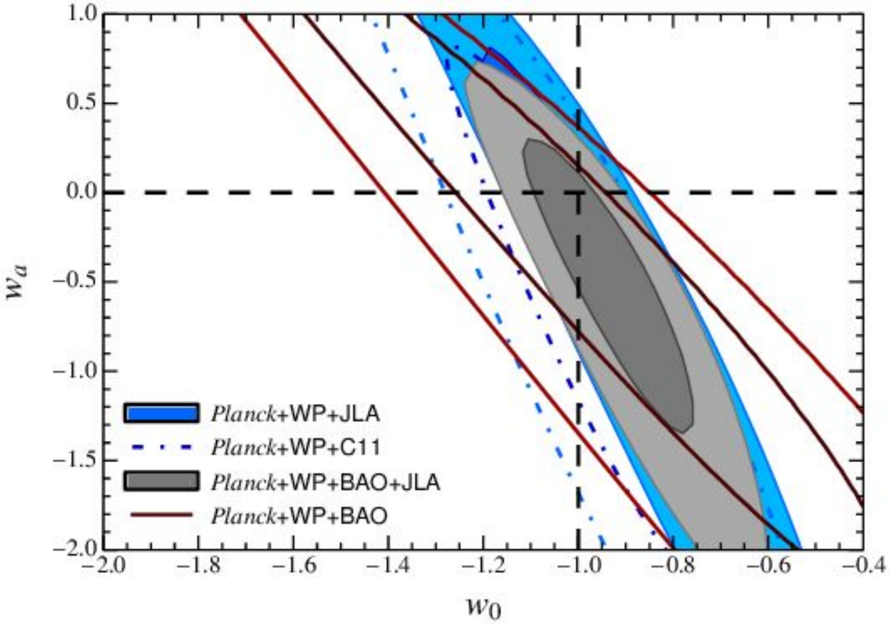




- 1998 : O(50) SNe
- 2005 : O(100) SNe
- 2014 : O(1000) SNe

Joint light curve analysis





Constraints on DE equation of state:

$$p = w \times \rho$$

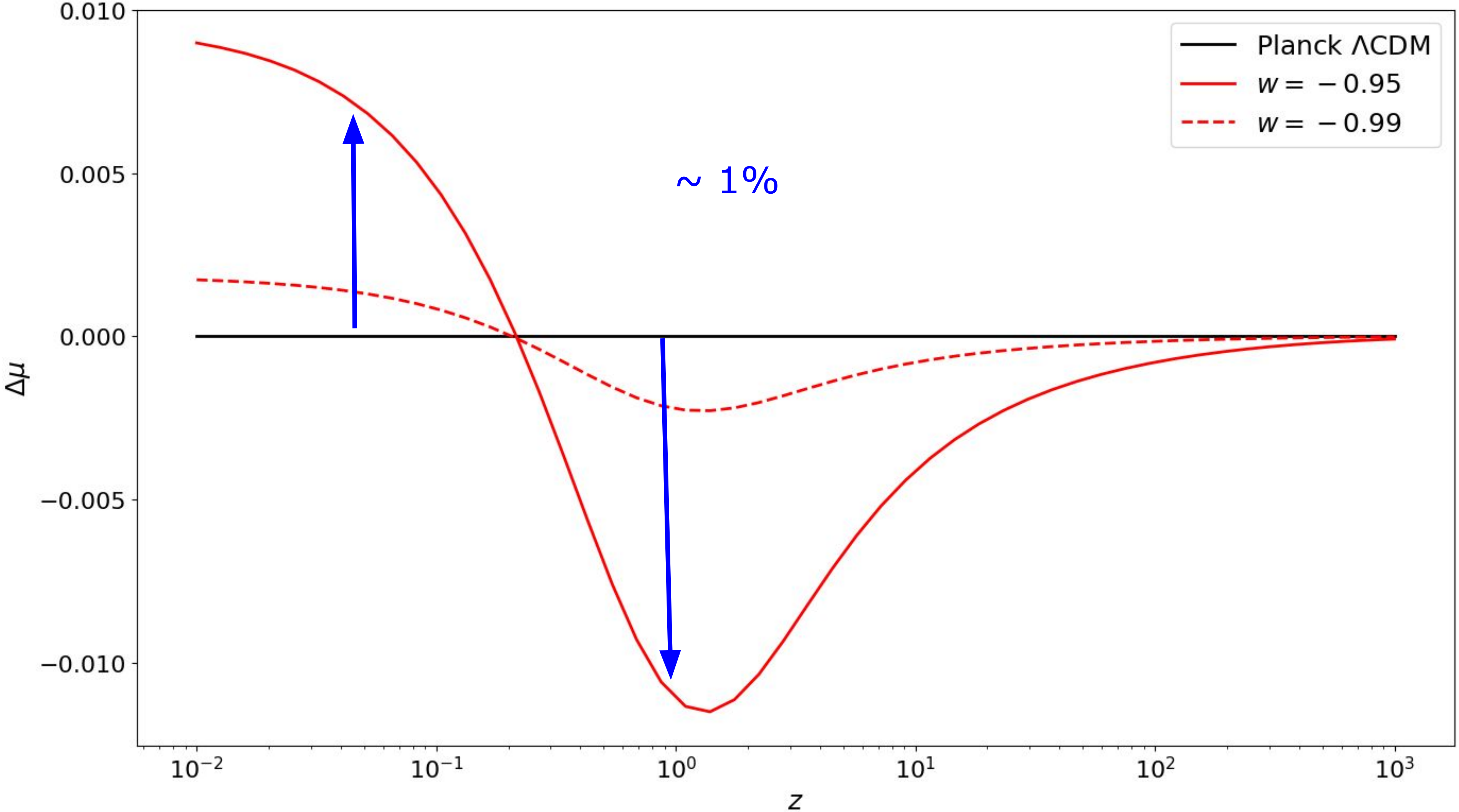
$\sigma(w)$ ~ 0.057 (stat+sys)

Marginal constraints on a varying equation of state

$$p = w_a(1-a) + w_0$$

DETF FoM ~ 15

This is a precision measurement...



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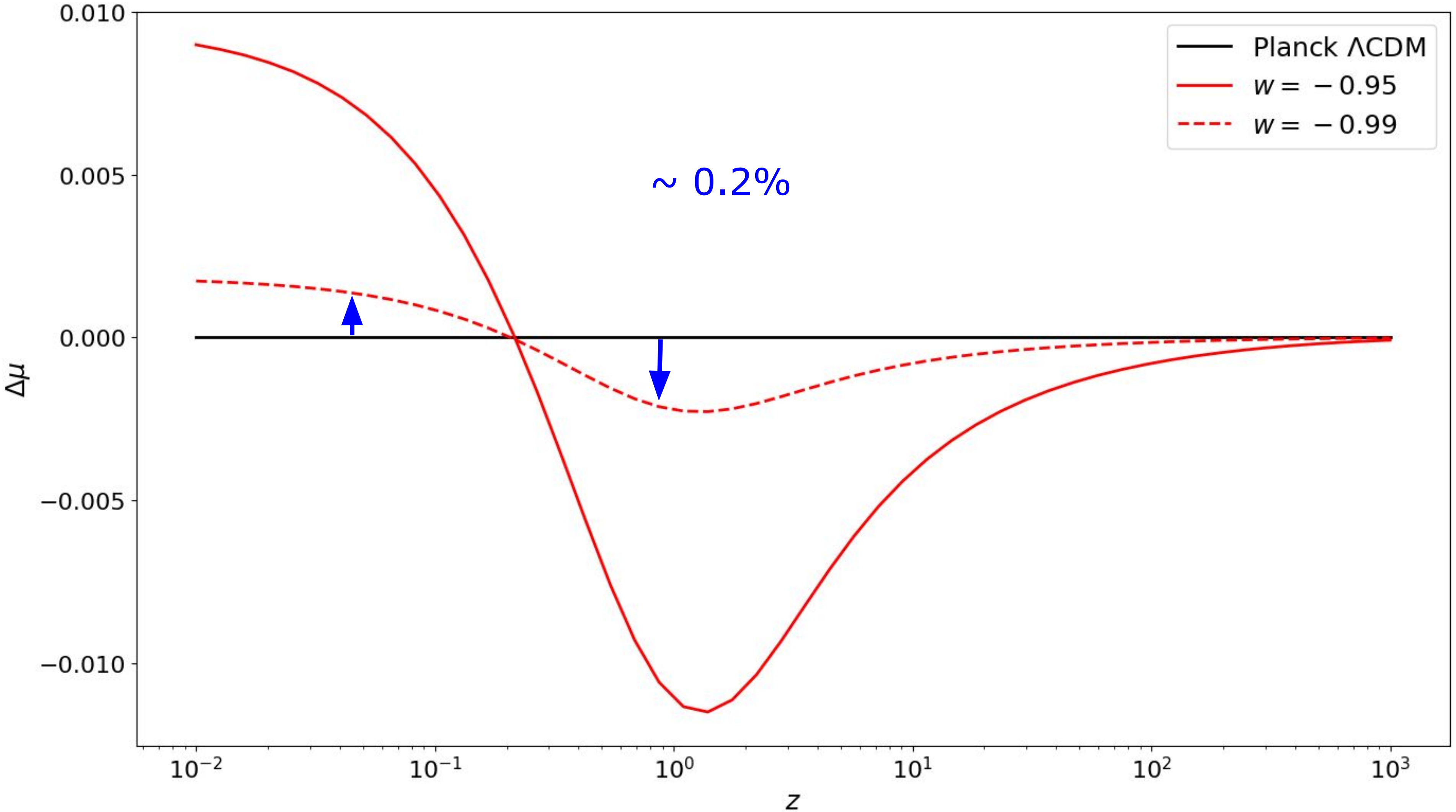

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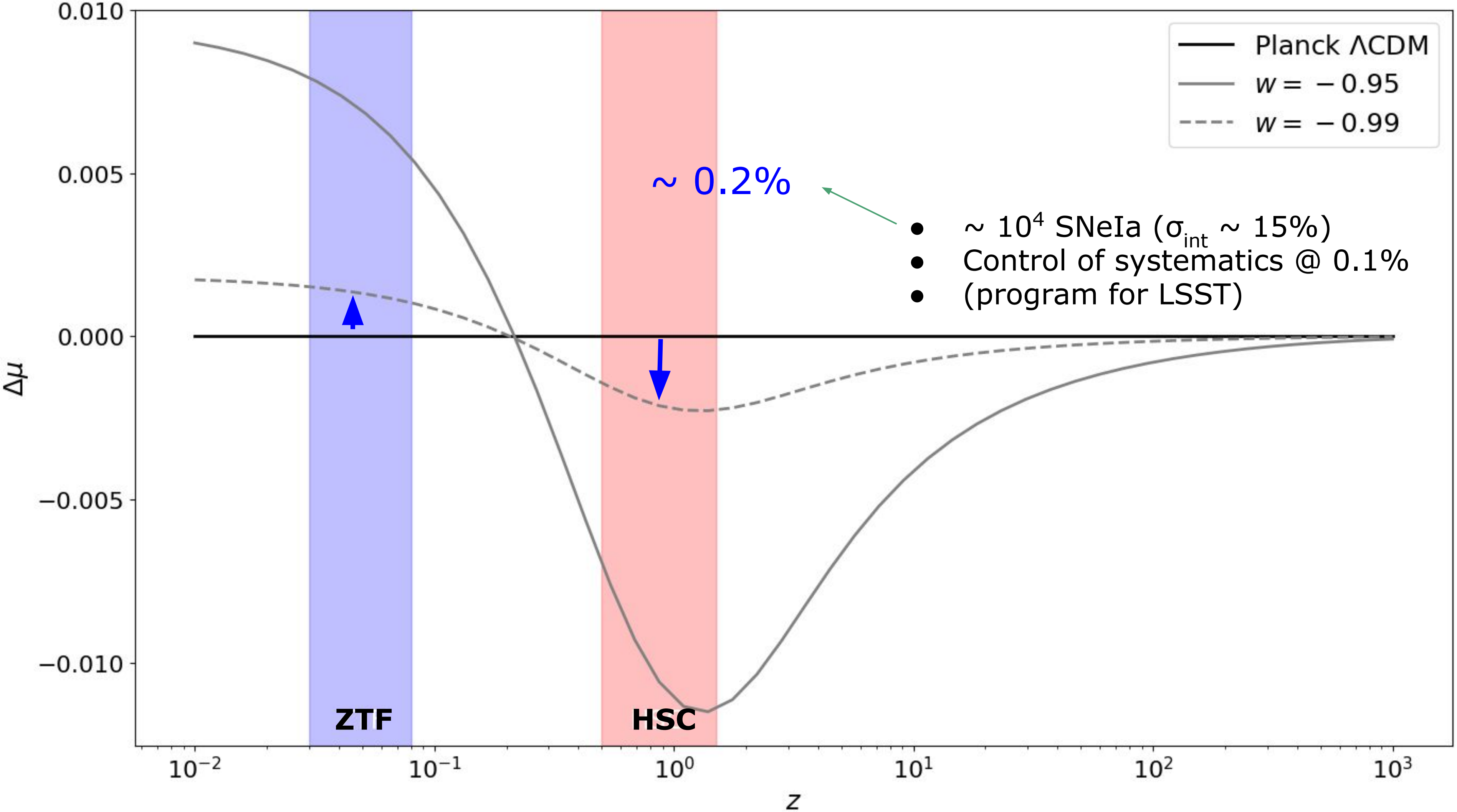
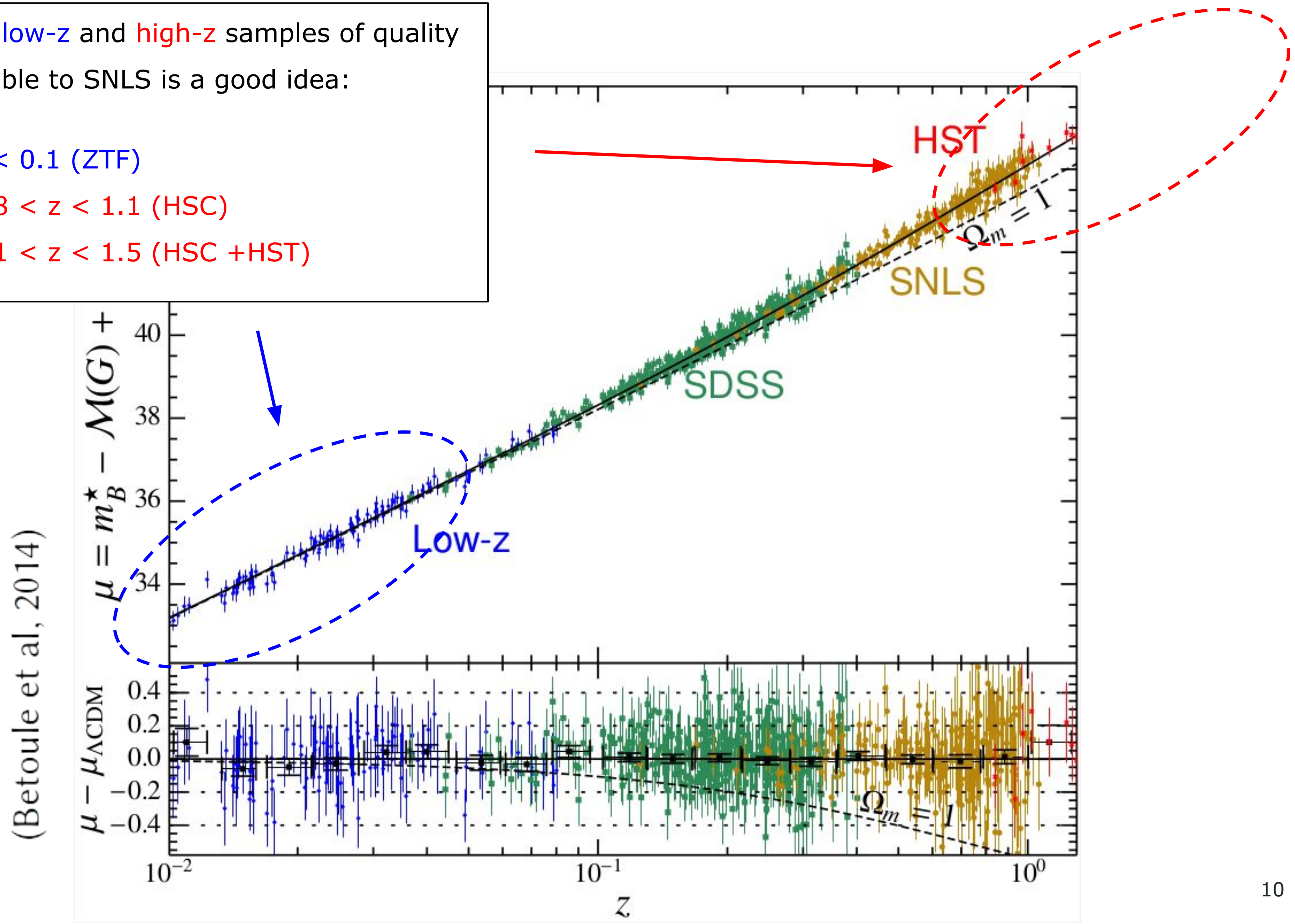


- ~ 10^4 SNeIa (σ_{int} ~ 15%)
- Control of systematics @ 0.1%
- (program for LSST)

Under-constrained regions

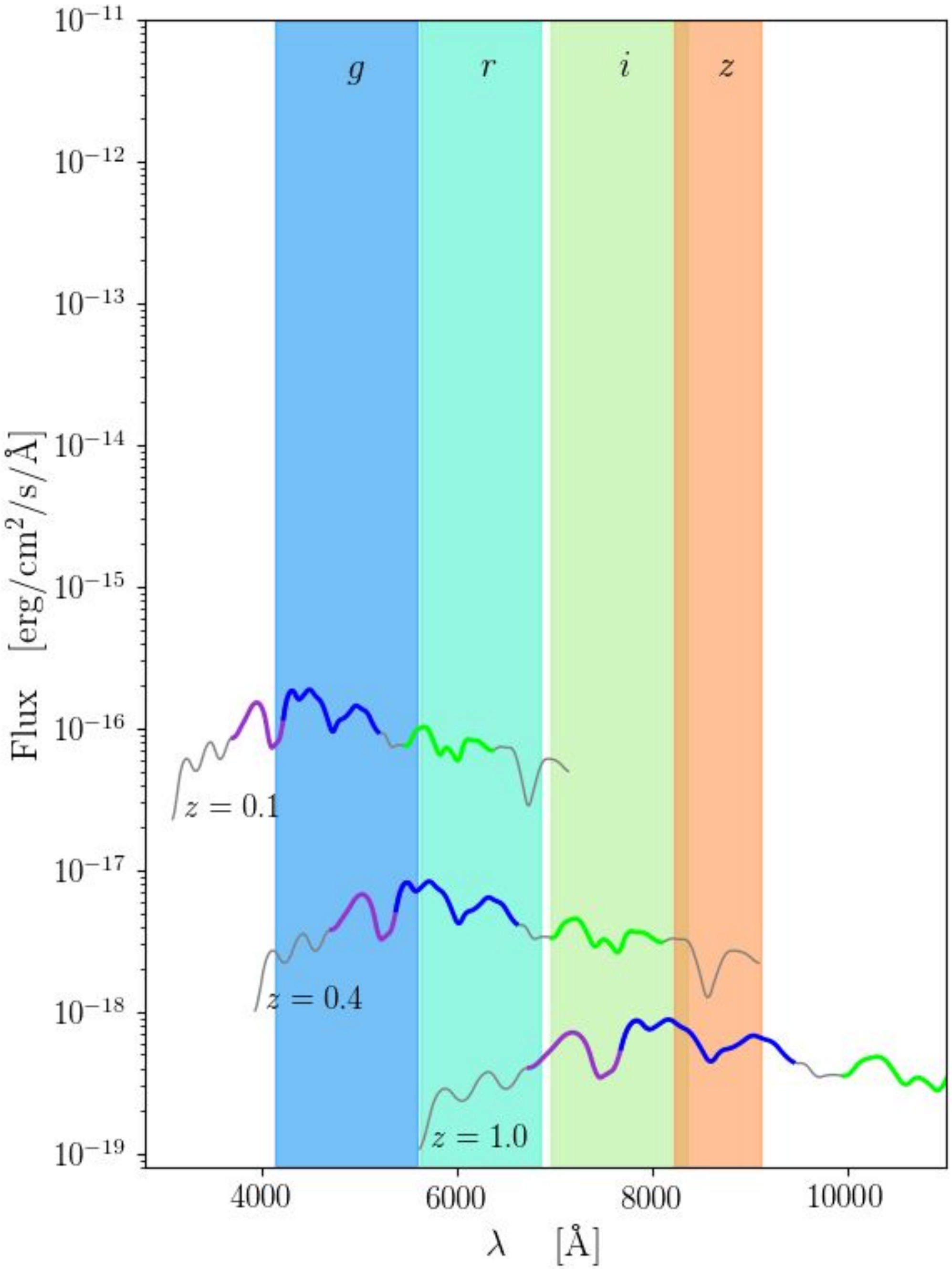
To build low-z and high-z samples of quality comparable to SNLS is a good idea:

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



Roadmap

- Subaru/HSC + ZTF have the potential to produce the best measurement of *w* by 2021
  - just because they sample the right redshift range
  - great prefiguration of LSST analysis
- LSST can deliver the $O(10^4)$ low- and high-z SNe needed to measure *w* at ~ 1%
- Key ingredient
  - Photometric calibration (target ~ 0.1%)
- Bonus
  - Ground - space complementarity to extend redshift range



Survey calibration

Distances to low-z SNe rely on blue bands (g,r)

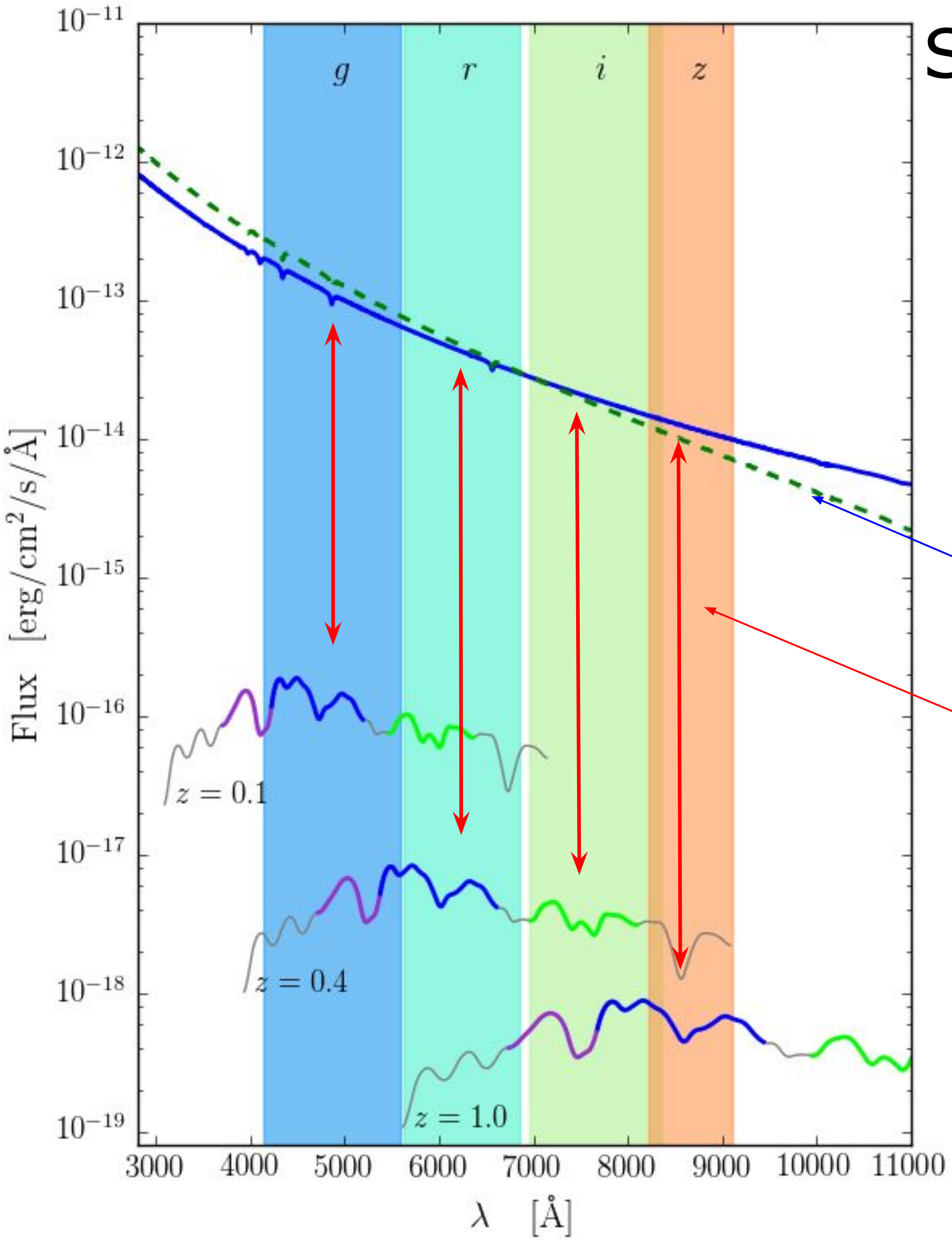
Distances to high-z SNe rely on red band (i,z)

Critical calibration ingredients:

- relative (band-to-band) flux calibration
- positions of filter cut-on/cut-off

Calibration errors affect

- SN magnitudes
- SN empirical model
- -> SN distances (x2)



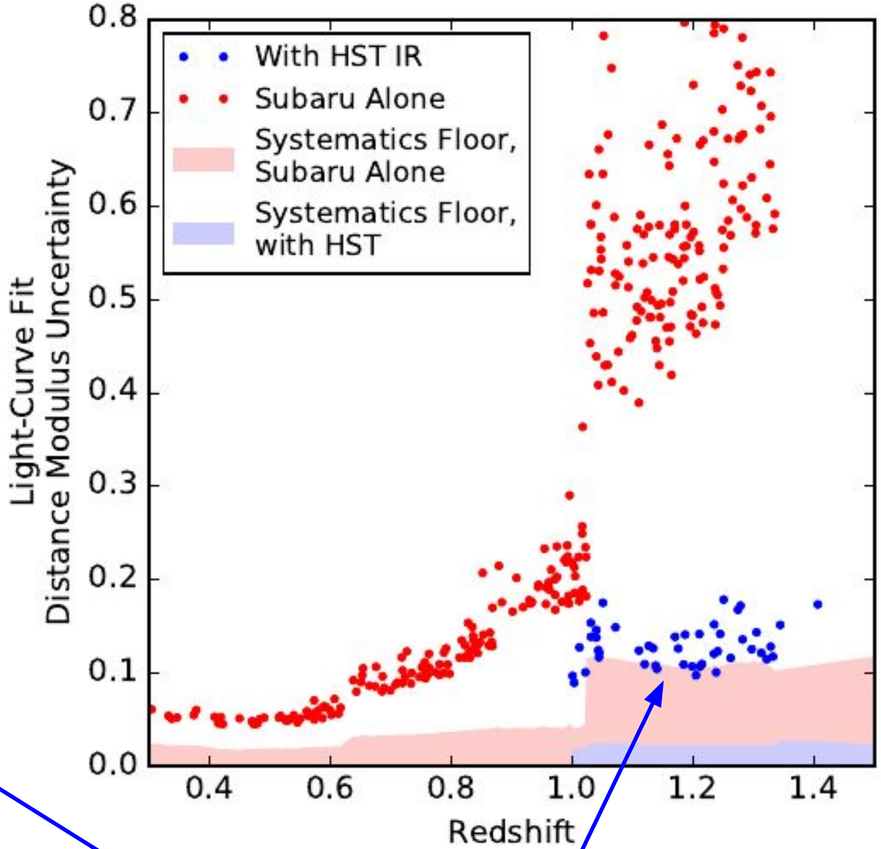
Survey calibration

- Relative flux calibration
  - Primary flux reference
  - Flux metrology chain

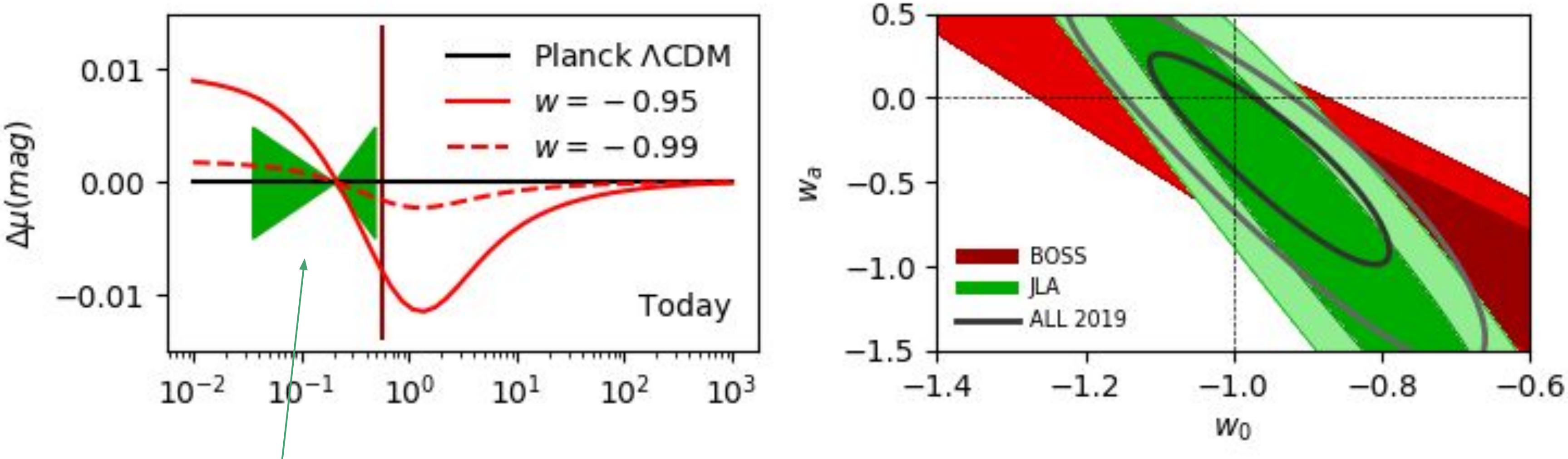
$$\varphi_{\mathrm{SN},b}[\gamma/\mathrm{s}] = \frac{\varphi_{\mathrm{SN},b}[\mathrm{ADU/s}]}{\varphi_{\mathrm{WD},b}[\mathrm{ADU/s}]} \times \varphi_{\mathrm{WD},b}[\gamma/\mathrm{s}]$$

Bonus: ground - space complementarity

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



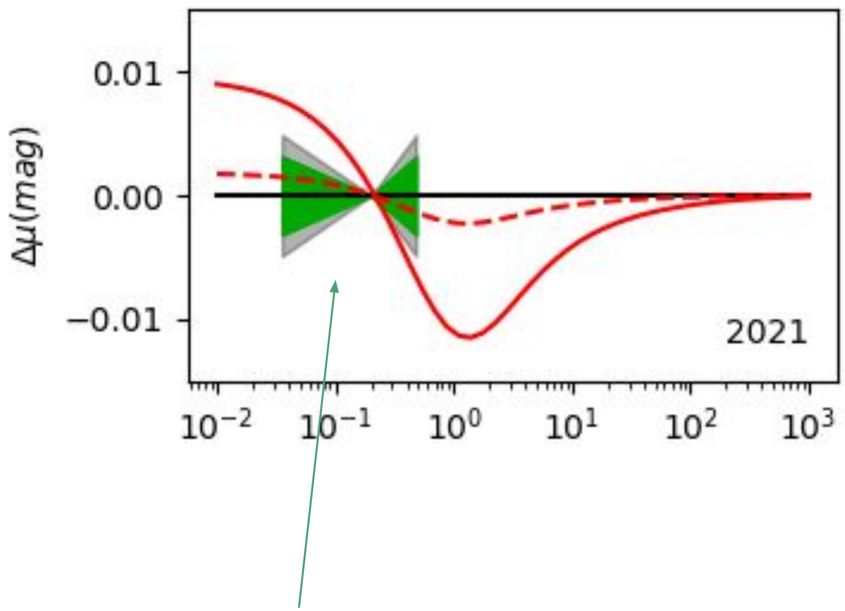
(w,wa) constraints as of today

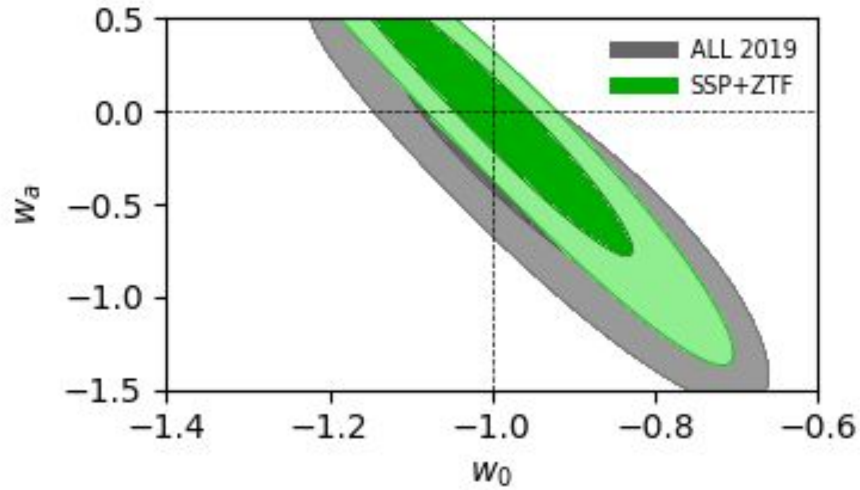


Uncertainty on μ(highz) - μ(lowz)

Regnault, Betoule, Hazenberg et al

Expected (w,wa) constraints in 2021



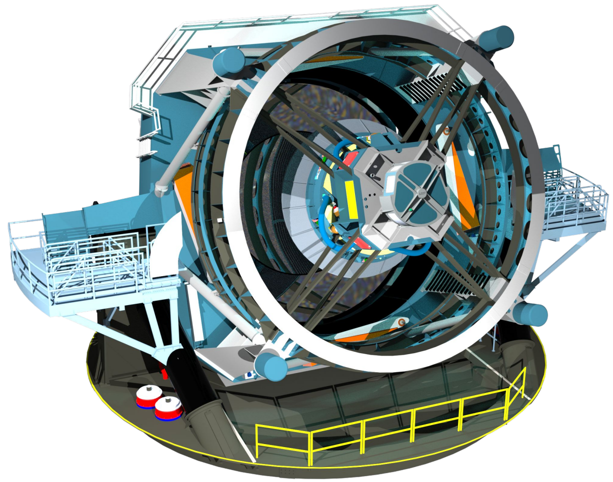


Uncertainty on μ(highz) - μ(lowz)

FoM ~ 50

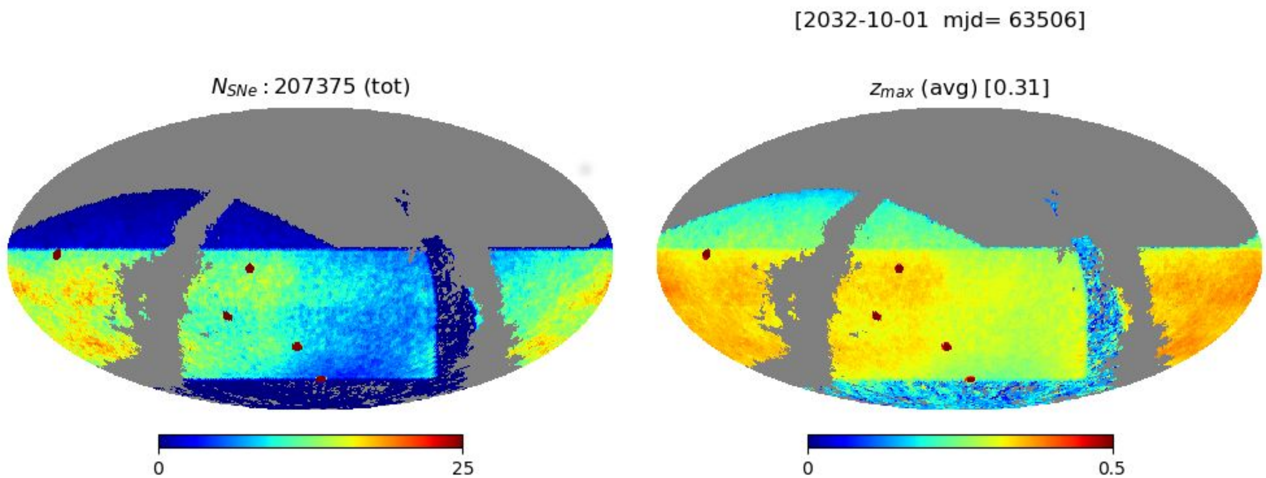
First 2 years of LSST + Some IR from space

Euclid or HST



- $O(10^5)$ well sampled nearby SNe Ia
- up to z ~ 0.3
- in the Wide Fast Deep footprint

- $O(10^4)$ well sampled distant SNe Ia
- up to z ~ 1
- in the Deep drilling fields



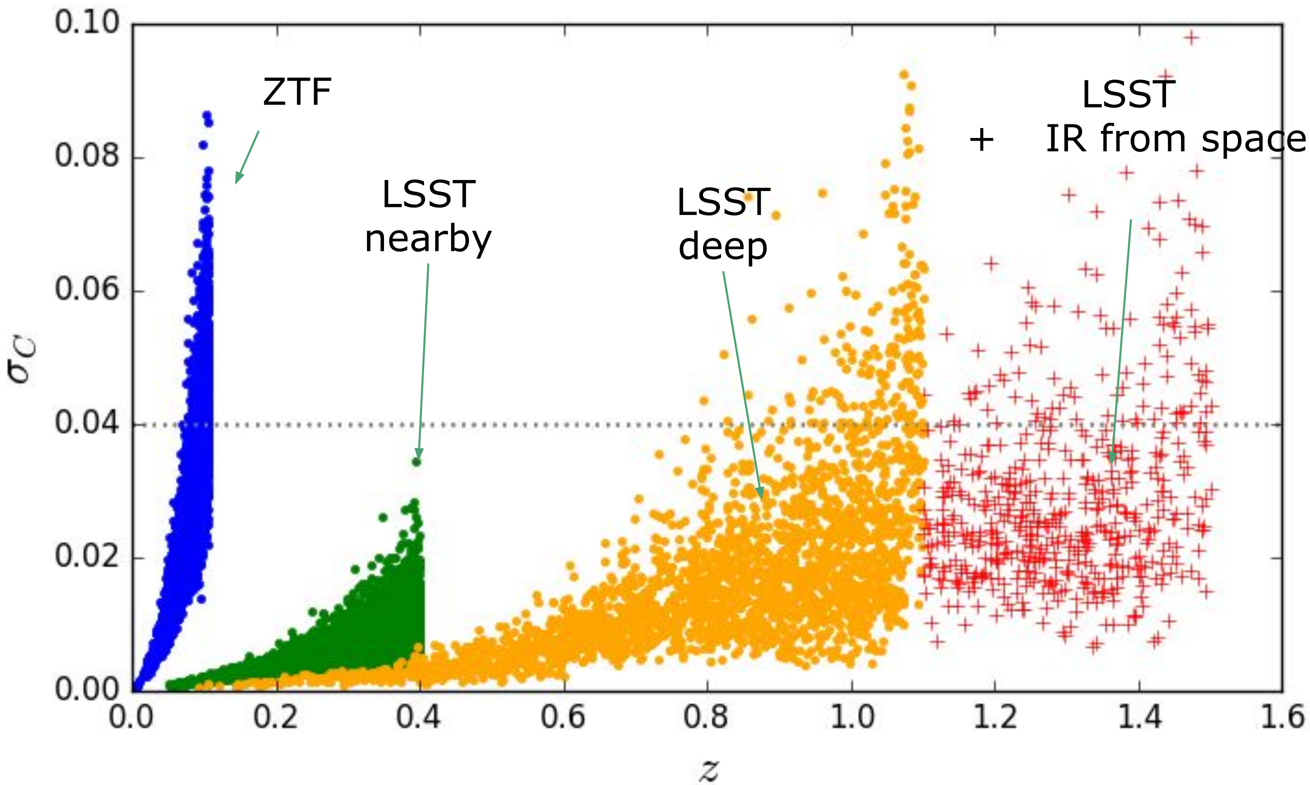
Density of SNe

Redshift limit

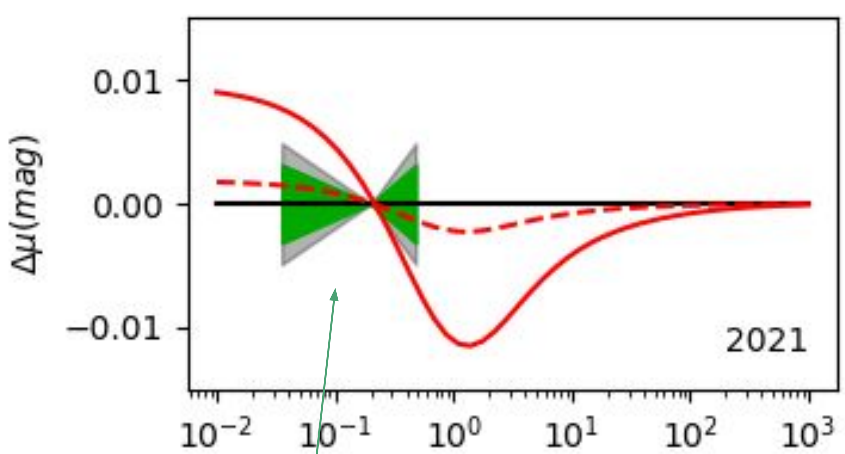
First 2 years of LSST + Some IR from space

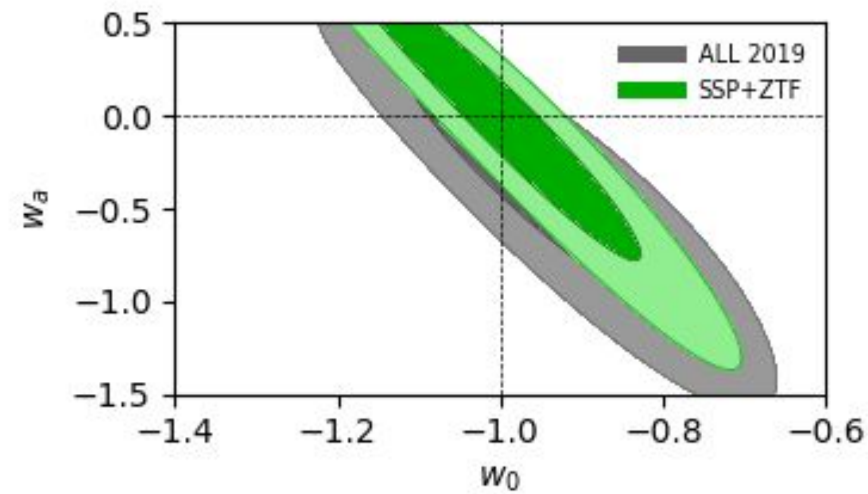
Euclid or HST

Proxy for distance quality (uncertainty on SN color)



Expected (w,wa) constraints in 2021

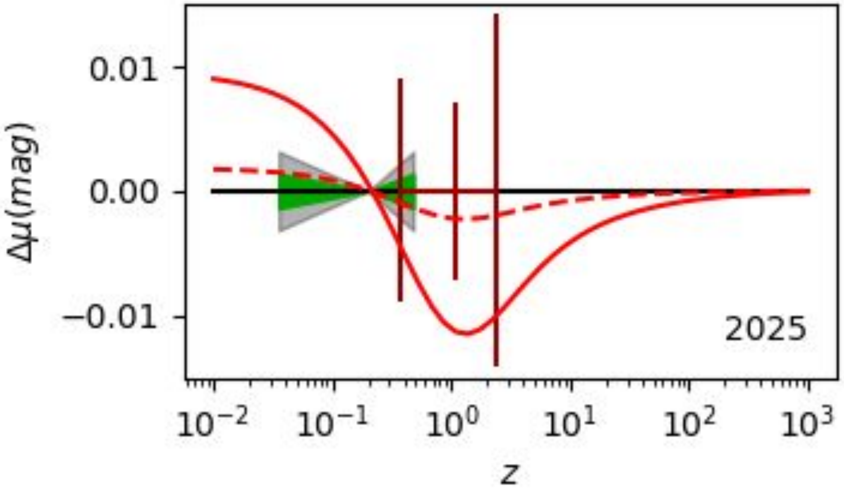


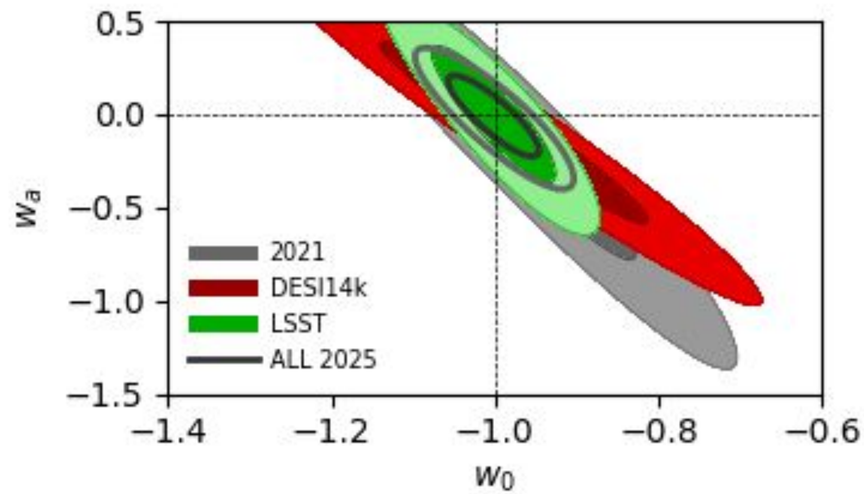


Uncertainty on μ(highz) - μ(lowz)

FoM ~ 50

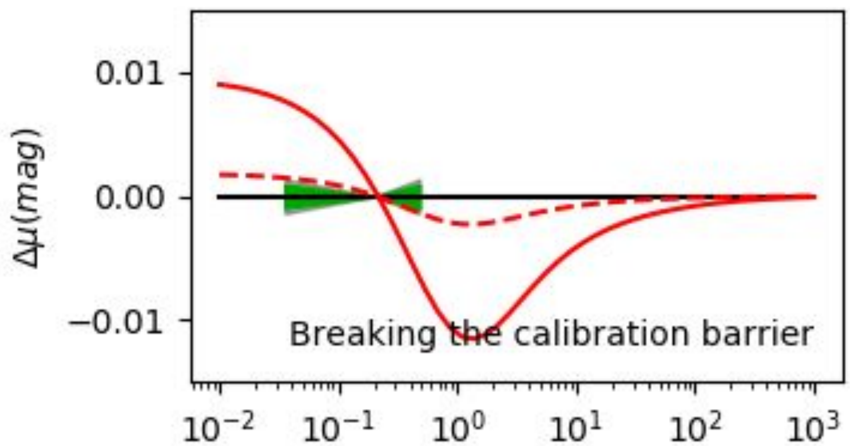
With two years of LSST + IR from space

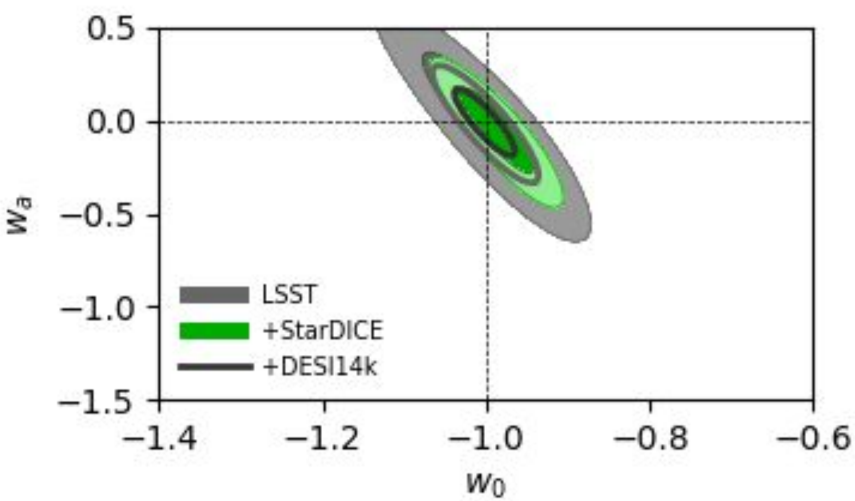




FoM ~ 150

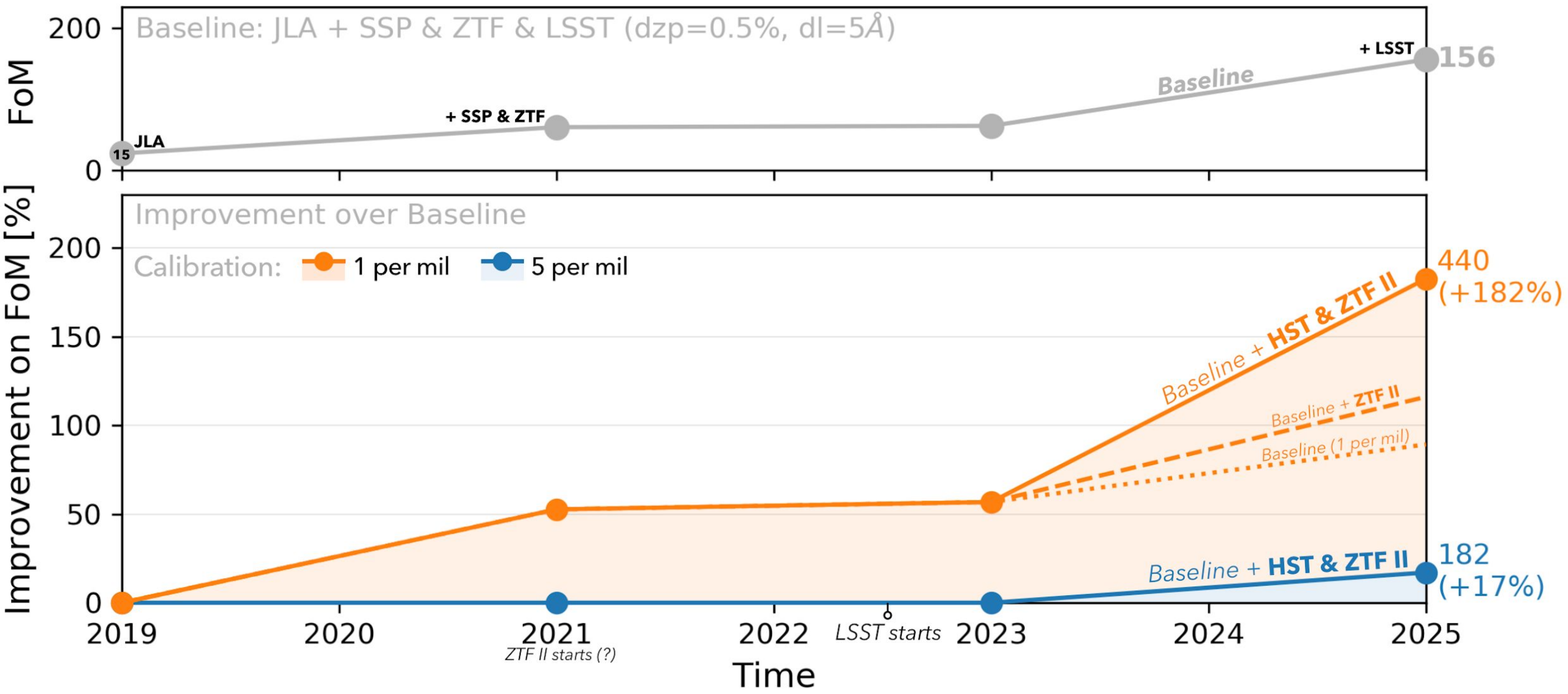
With calibration at the 0.1% level





FoM ~ 450

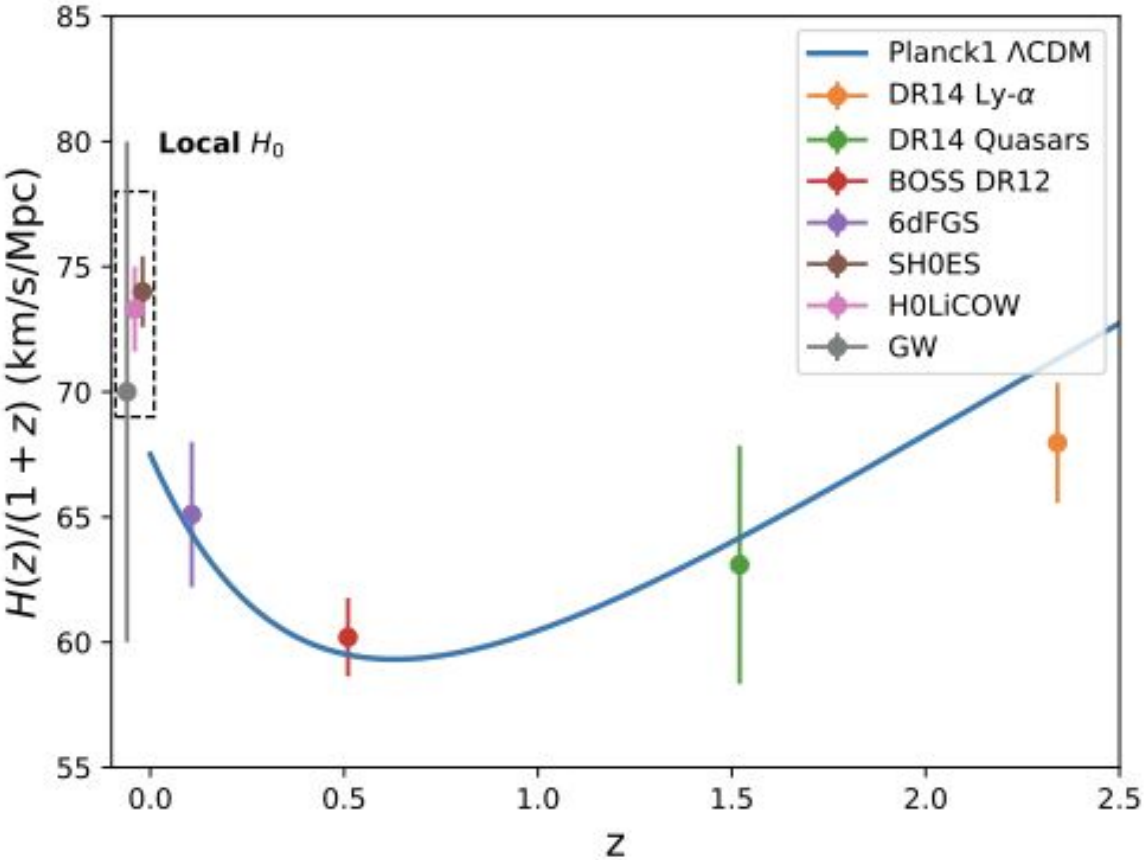
Timeline



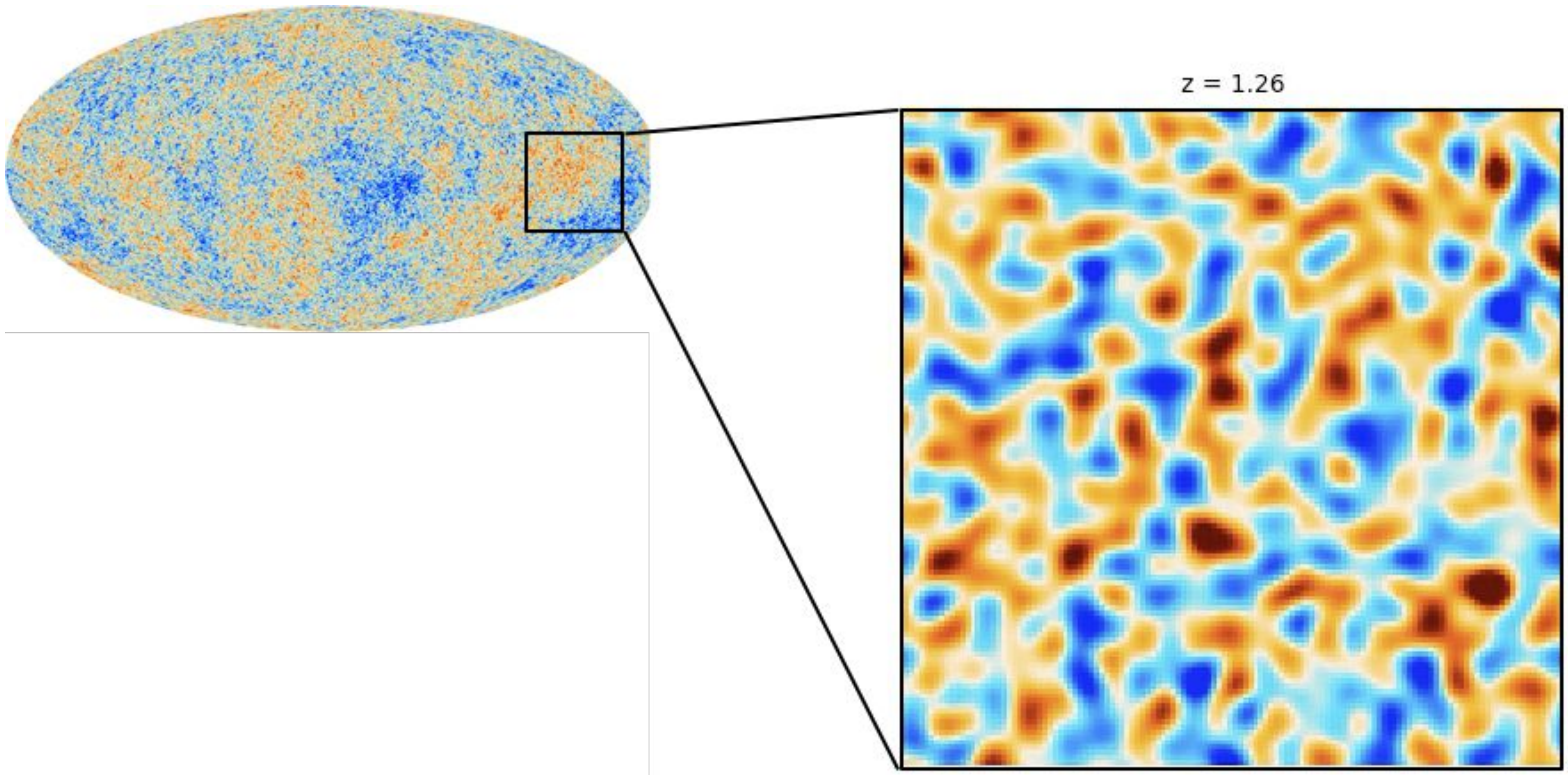
Regnault, Rigault, Hazenberg, Betoule et al

Cosmology with peculiar velocities

The CMB predicts the expansion law...



Linear growth of structures



$$\delta(t) = \delta_0 D(z)$$

We can’t directly probe D(z) because of the galaxy bias

Linear growth of structures

$$\frac{d\rho}{dt} + \vec{\nabla} \cdot \vec{v} = 0$$

↓

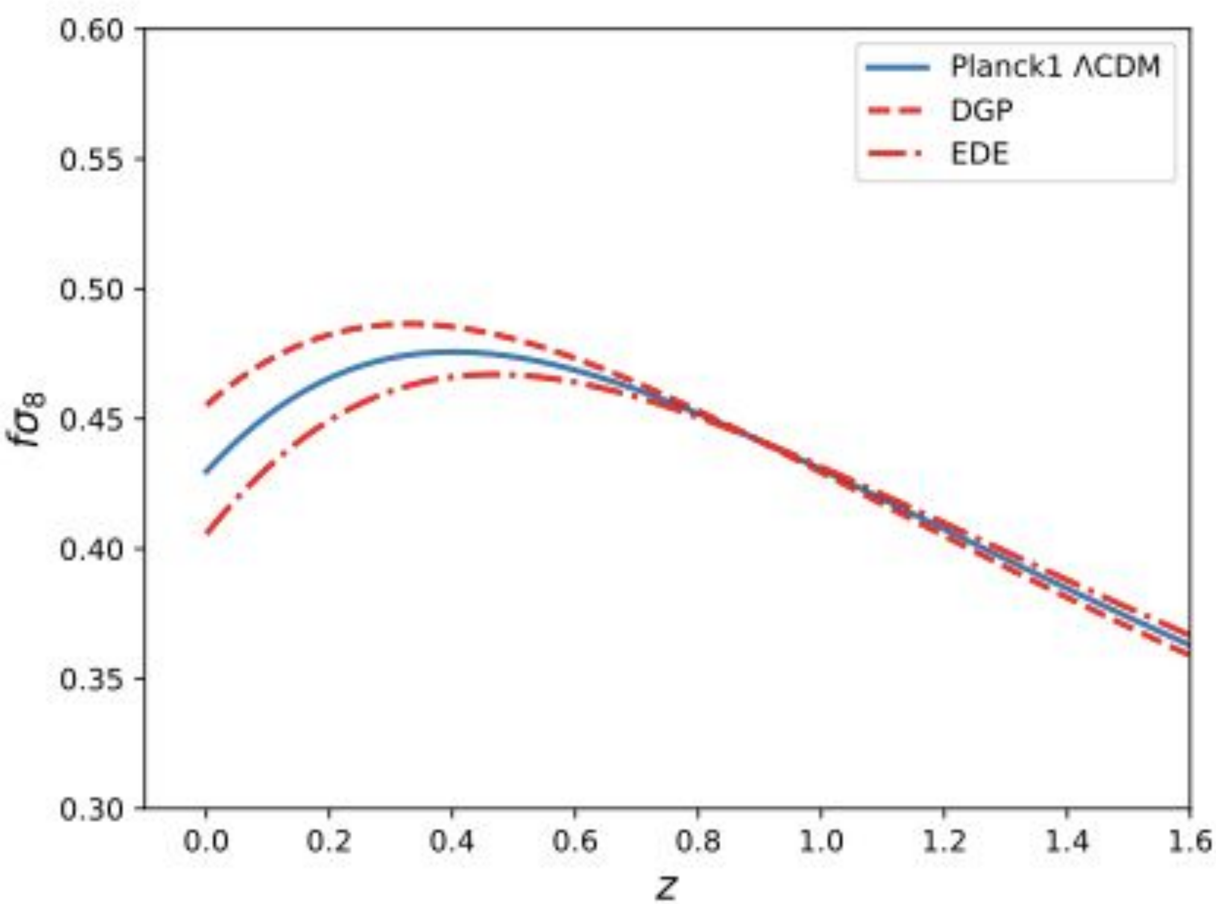
$$\vec{\nabla} \cdot \vec{v} \propto \frac{d\ln D}{d\ln a} D(z)\delta_0$$

↓

$$\vec{\nabla} \cdot \vec{v} \propto f D \delta_0$$

(also called $f\sigma_8$)

Growth factor evolution : $f = \Omega_m(z)^\gamma$



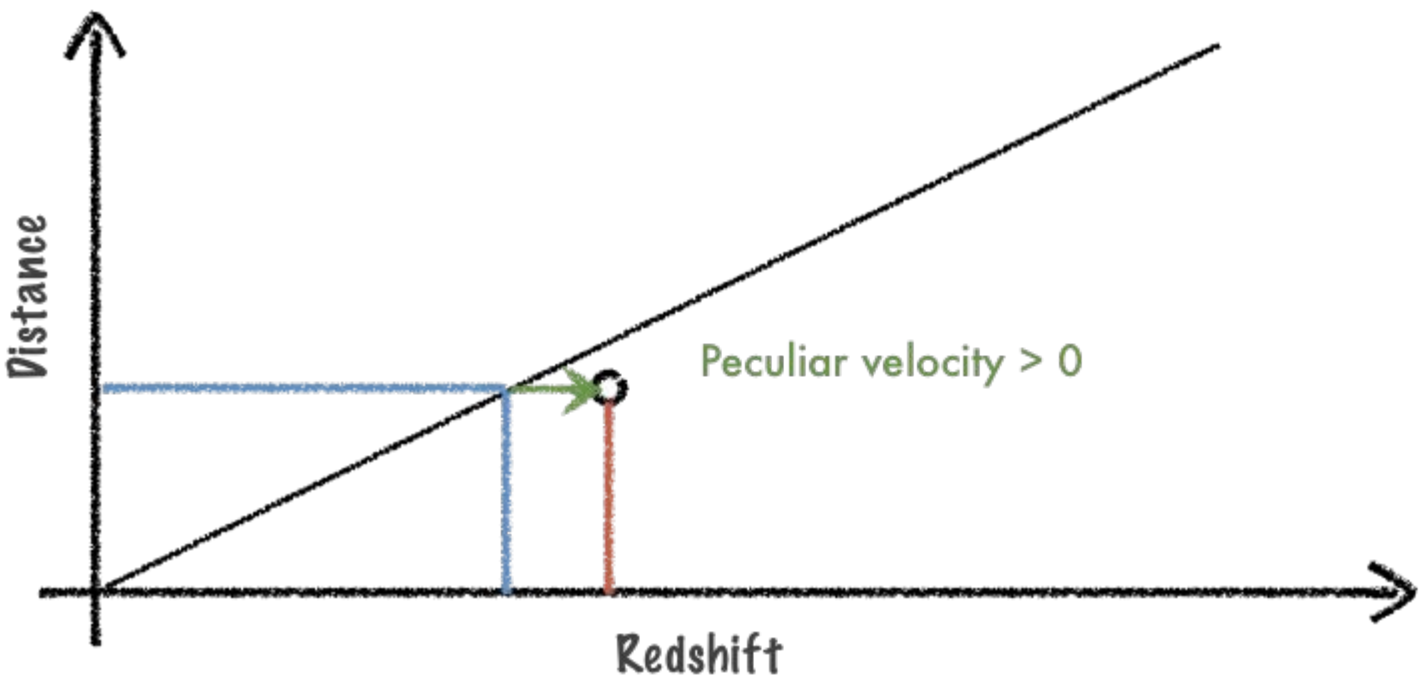
How to measure the growth rate?

Radial peculiar velocity

Cosmological redshift

$$1 + z = (1 + \bar{z})\left(1 + \frac{v^r}{c}\right)$$

Observed redshift



How to measure the growth rate? Ex : RSD

$$1 + z = (1 + \bar{z}) \left(1 + \frac{v^r}{c}\right)$$

(1) Measure redshifts

$P^s(k)$

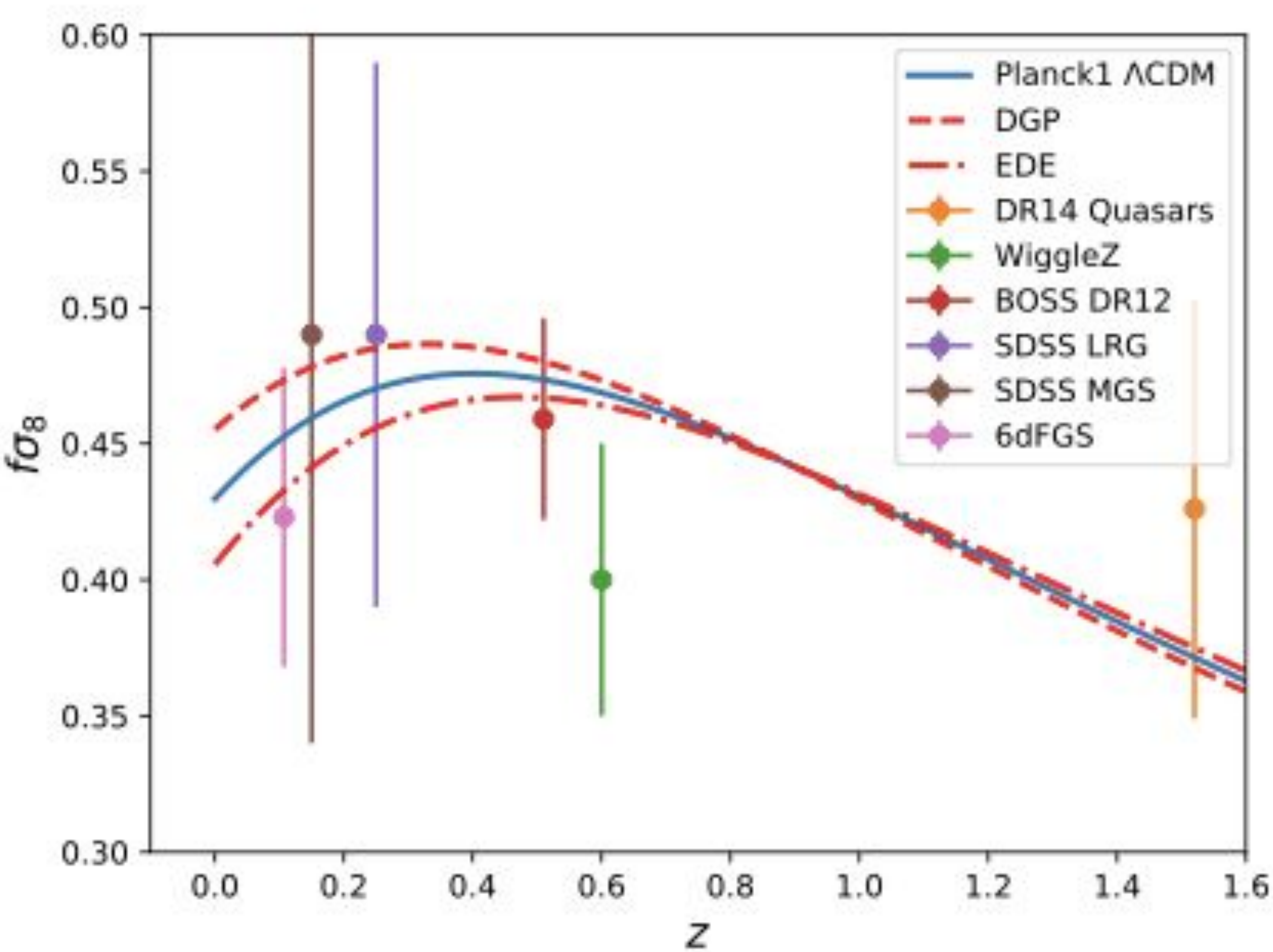
(2) Assume a statistical distribution for the distances

$P(k)$

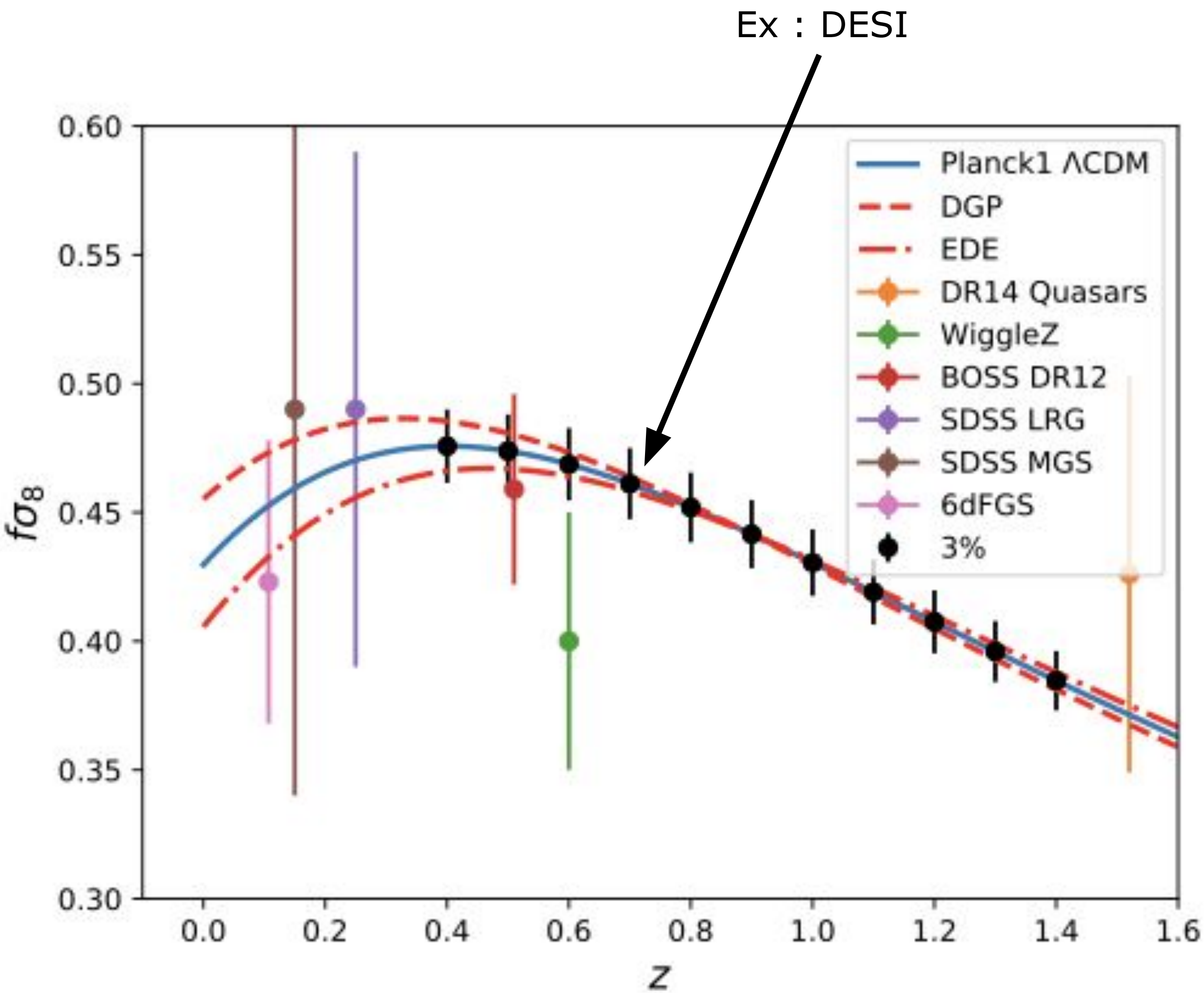
(3) Deduce the statistical distribution for the peculiar velocities

$f\sigma_8$

Growth factor evolution : $f = \Omega_m(z)^\gamma$



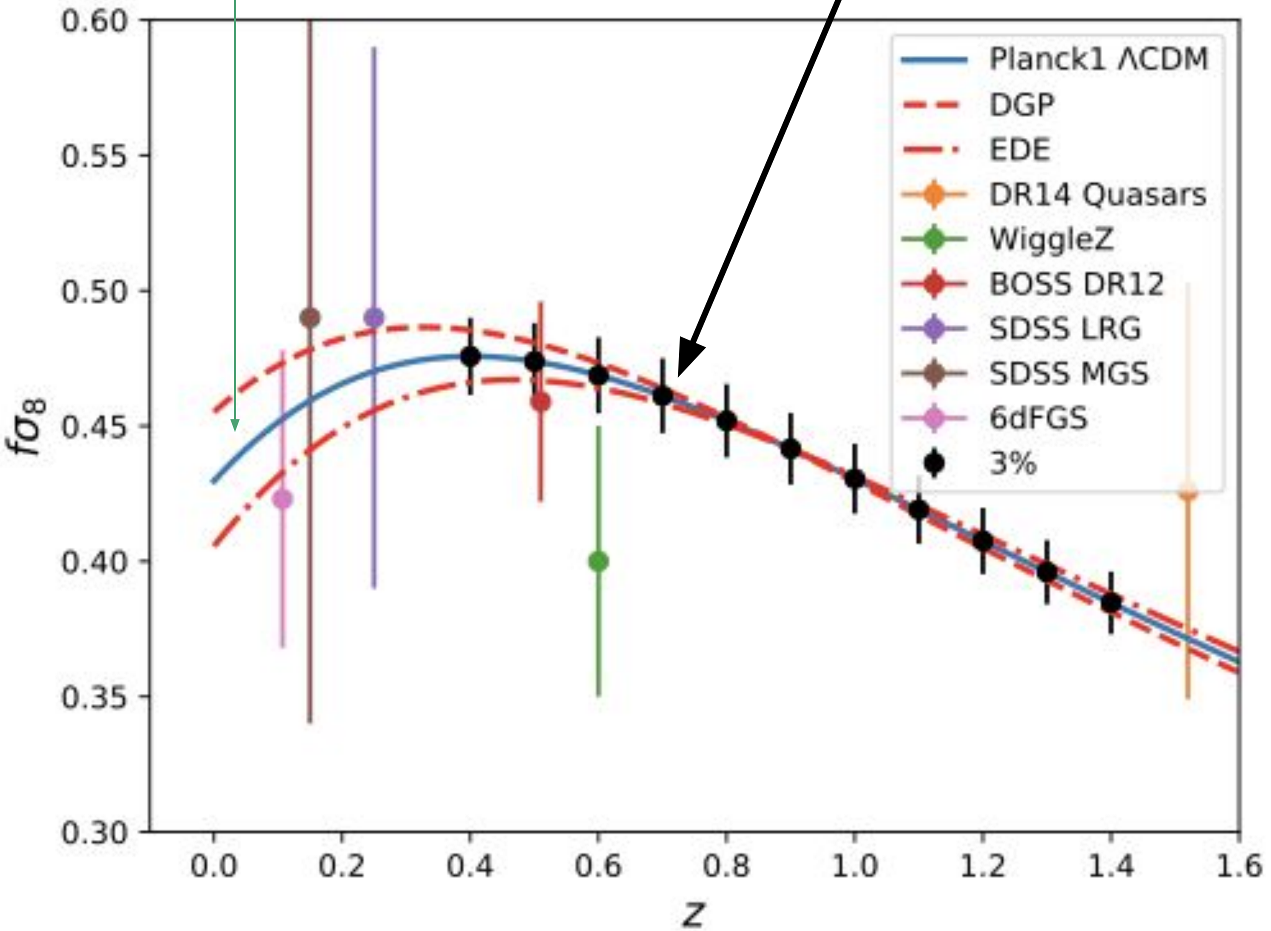
Growth factor evolution : $f = \Omega_m(z)^\gamma$



Growth factor evolution : $f = \Omega_m(z)^\gamma$

Goal : <5% at z = 0.1

Ex : DESI



How to measure the growth rate? Ex : SNe

$$1 + z = (1 + \bar{z})(1 + \frac{v^r}{c})$$

(1) Measure redshifts

(2) Measure distances with SNeIa

(3) Deduce the statistical properties of velocities

SNeIa sample both the velocity and overdensity field

$$\vec{\nabla} \cdot \vec{v} \propto f D \delta_0$$

Peculiar velocity of SNe

Spatial distribution of SNe

$$\langle vv \rangle \propto (f(z)D(z))^2$$

$$\langle nn \rangle \propto (b_{SN} D(z))^2$$

$$\langle vn \rangle \propto f(z) b_{SN} D^2(z)$$

"3x2 pt"

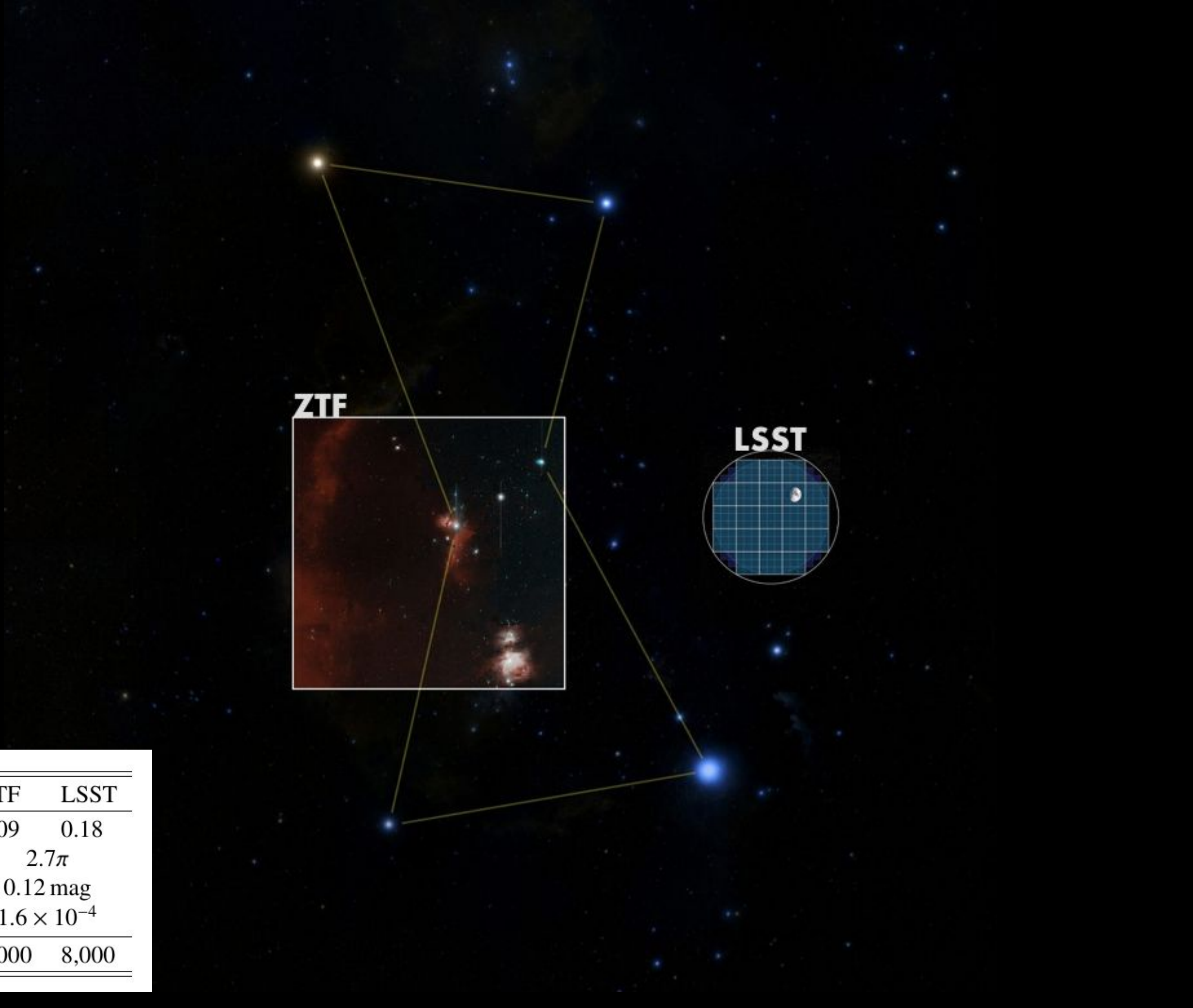
What do we need ?

- All-sky observation of SNe
- Spectroscopic redshifts
- Known sample selection
- Statistics

What do we need ?

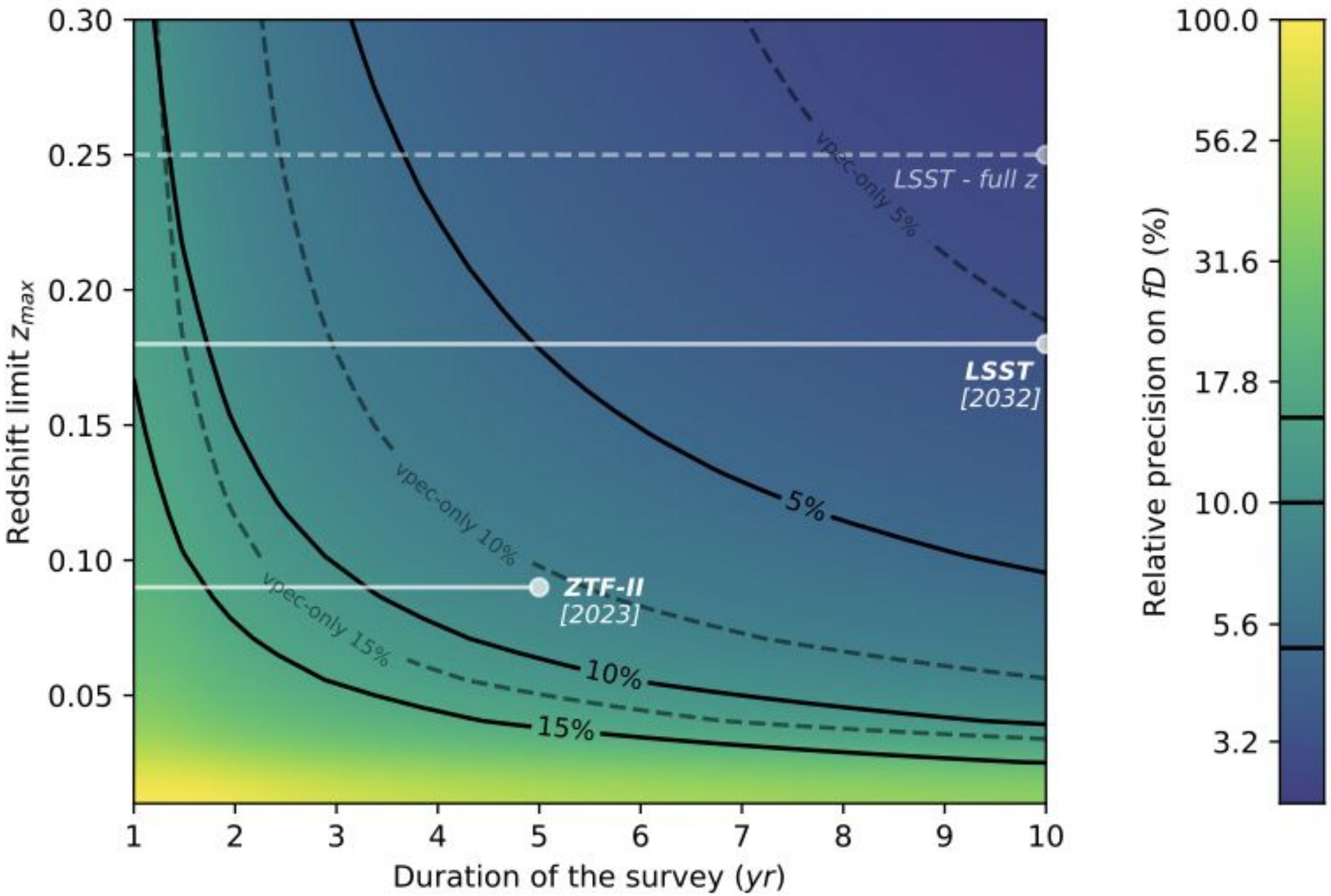
- All-sky observation of SNe
- Spectroscopic redshifts
- Known sample selection
- Statistics

→ **ZTF + LSST**

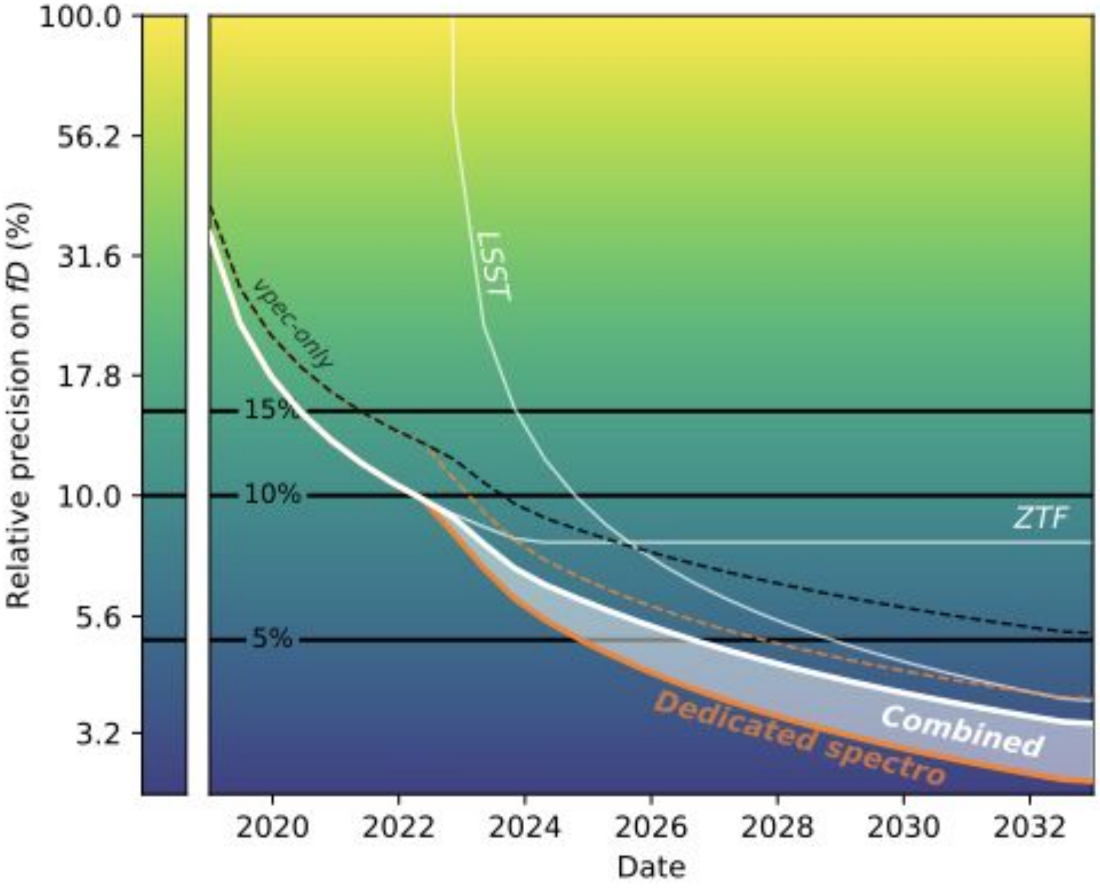


Param	ZTF	LSST
z_{max}	0.09	0.18
Ω	2.7π	
σ_M	0.12 mag	
σ_z	1.6×10^{-4}	
N_{SN}/yr	1,000	8,000

Forecasts LSST - ZTF



Timeline



100.0
56.2
31.6
17.8
10.0
5.6
3.2
Relative precision on fD (%)
15%
10%
5%
vpec-only
LSST
ZTF
Combined
Dedicated spectro
2020
2022
2024
2026
2028
2030
2032
Date

Conclusion

- Roadmap towards:
  - Measurement of varying Dark Energy EoS by 2025
    - FoM ~ 150 attainable
    - FoM > 400 possible with additional synergies
  - Measurement of $f\sigma_8$ at ~ 5% by 2025
  - Early LSST science !
- Great complementarity between Subaru/HSC and ZTF/ZTF-II
- Synergies with external surveys / instruments are essential
  - IR from space (HST, Euclid deep fields are shallow)
  - PFS@Subaru for redshift of distant SNe
  - 4MOST + DESI + others for redshifts of nearby LSST SNe
  - Dedicated spectroscopy effort needed for peculiar velocities