How Type Ia supernovae probe large scale structures

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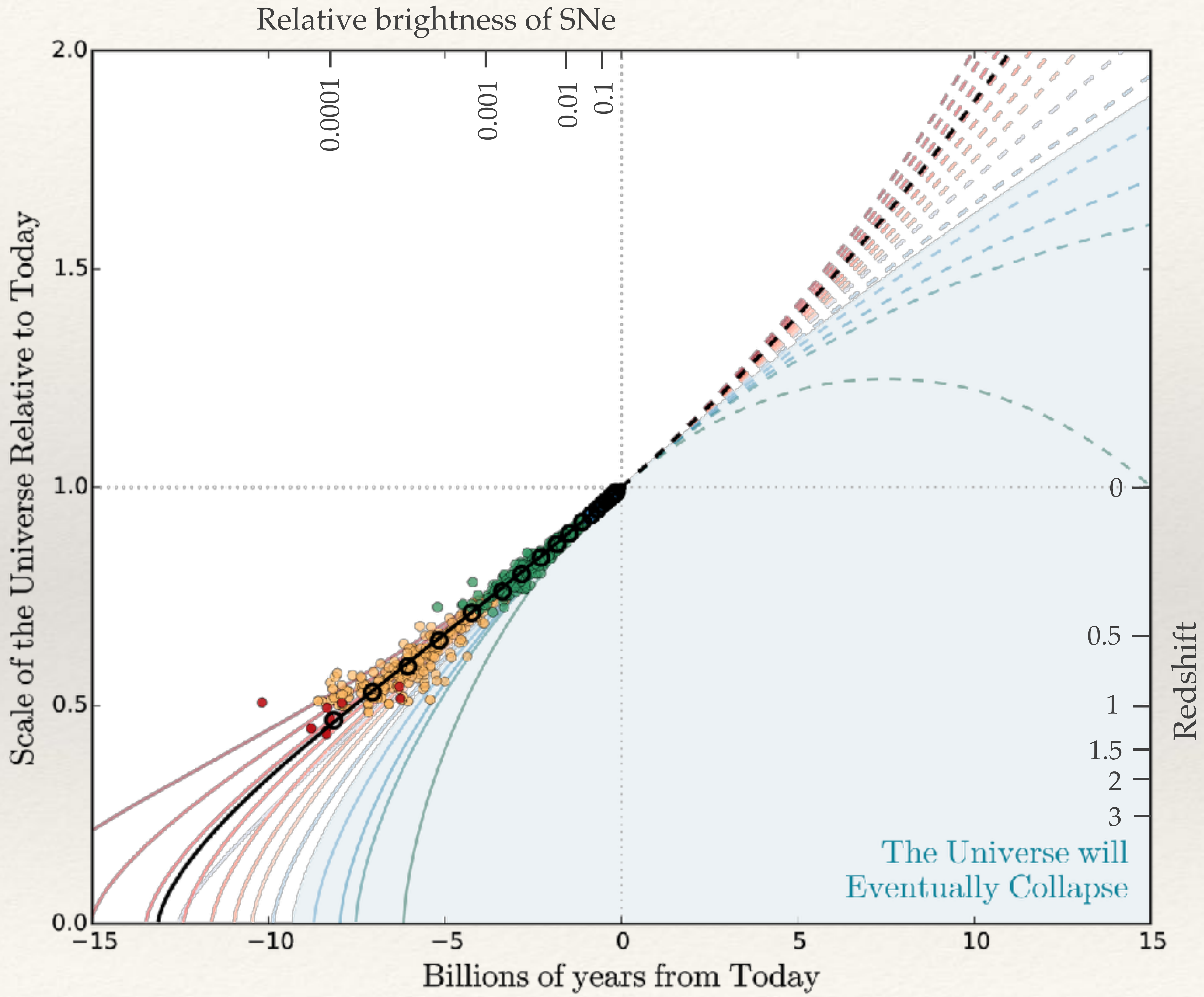
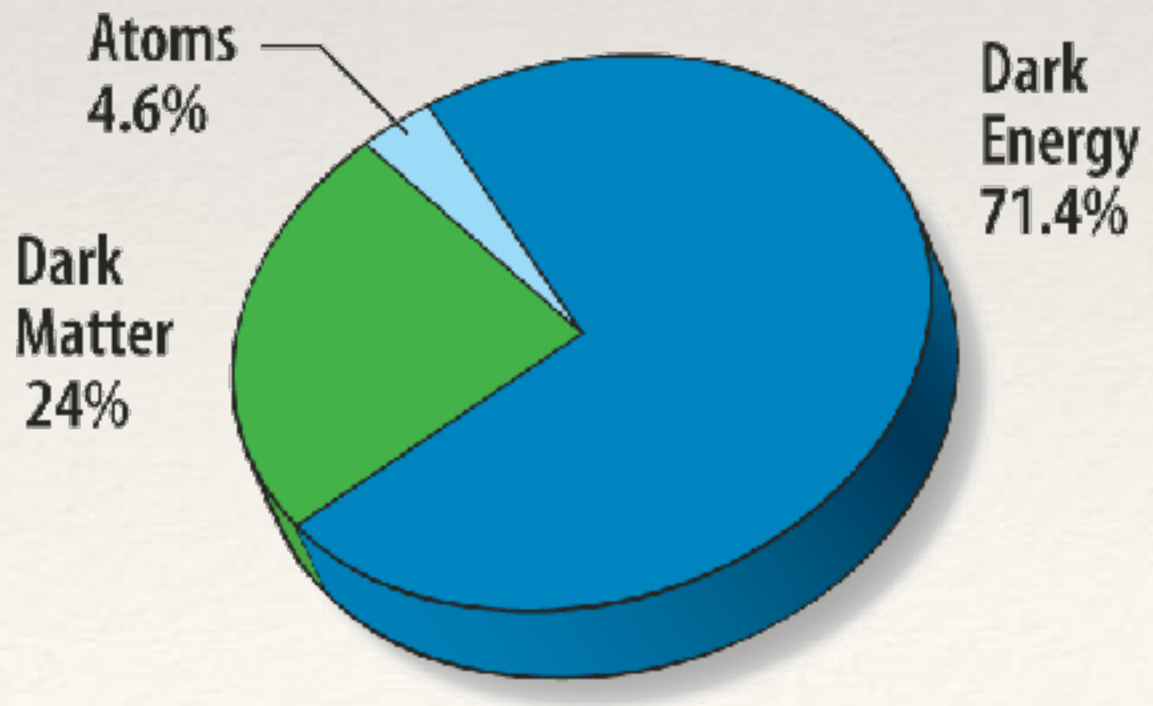
1. **Ia cosmology**
2. **SNe Ia**
3. **ZTF**
4. **AMPEL**
5. **Bulk Flow**

Ia cosmology

SNe Ia cosmology

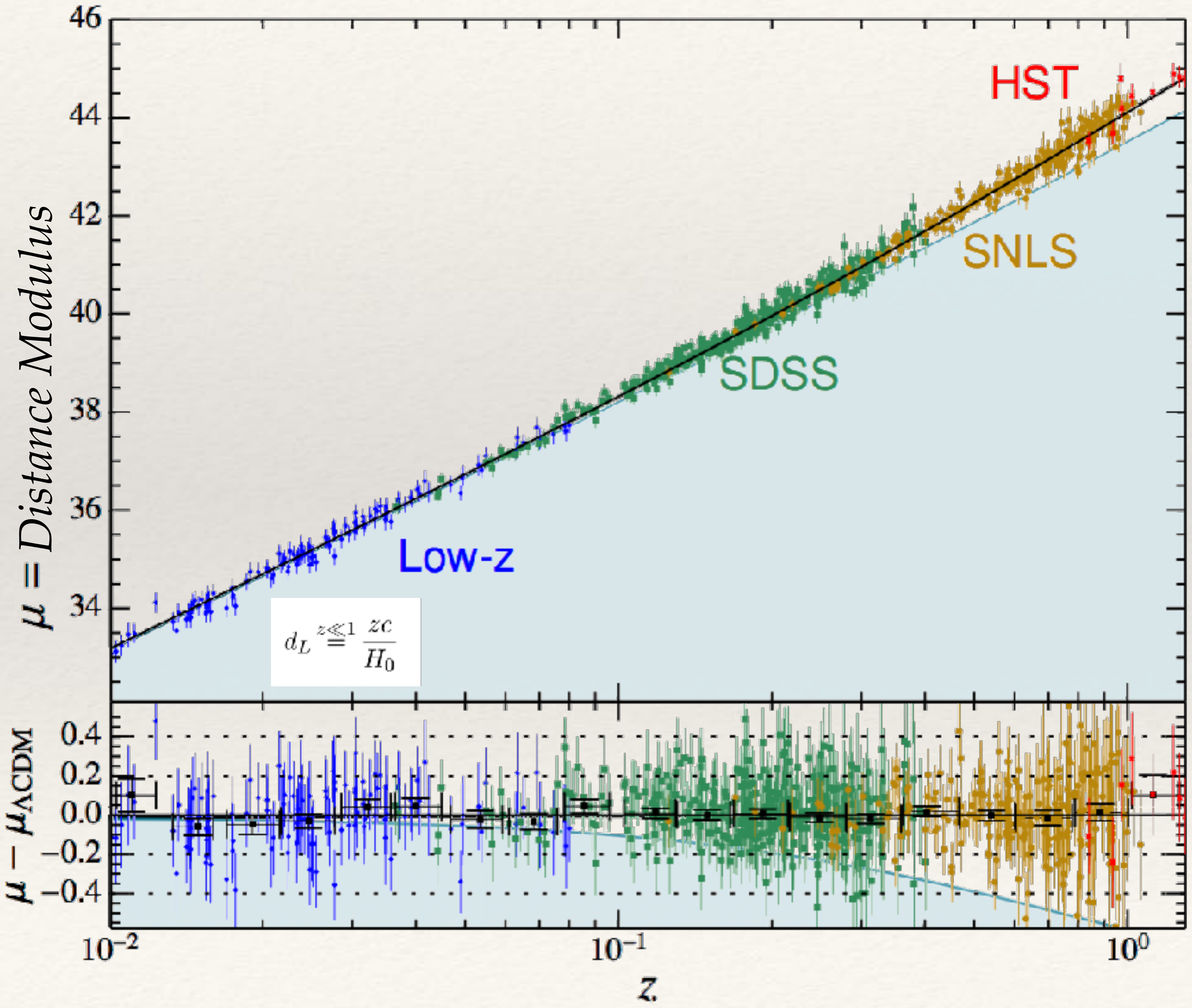




SNe Ia cosmology

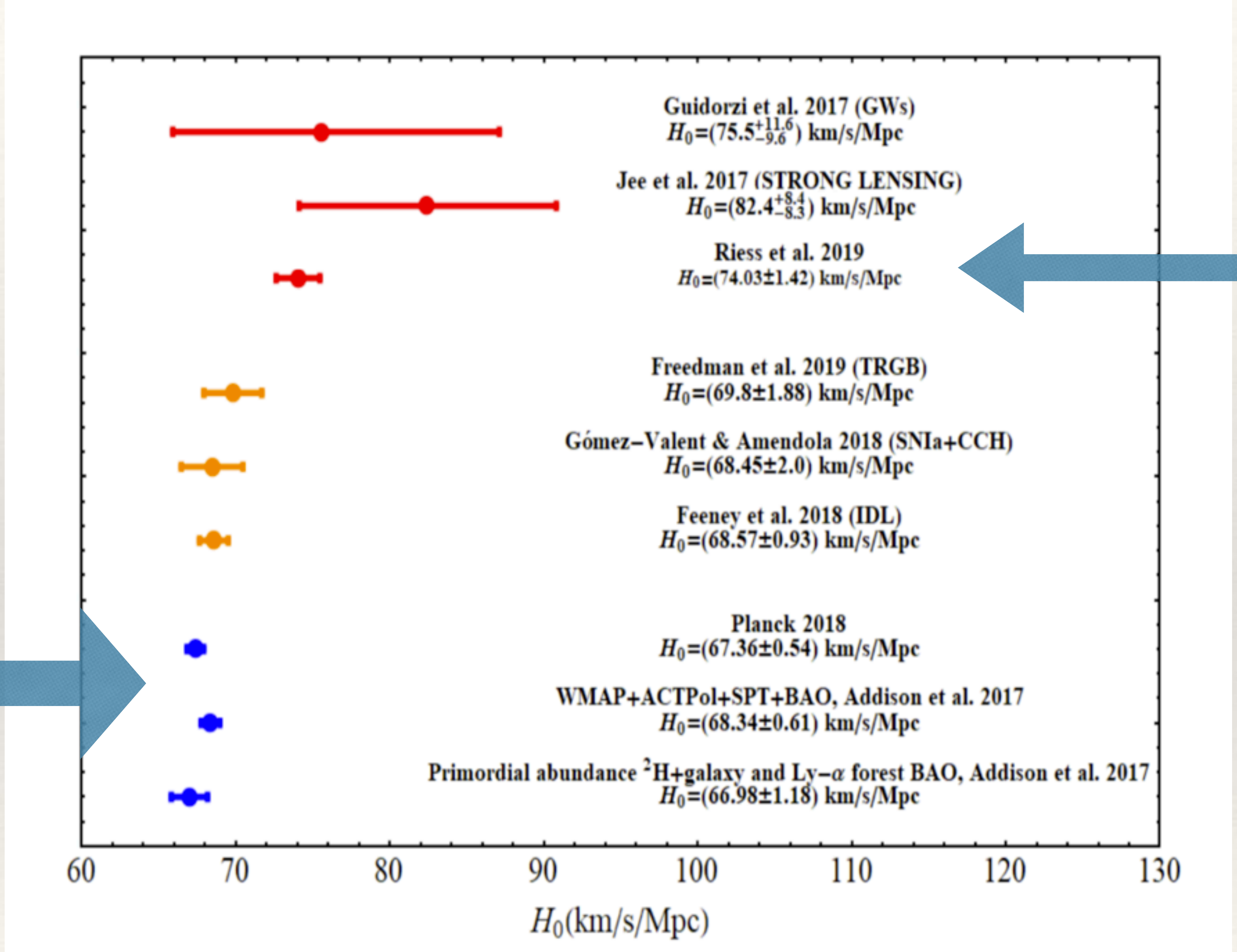
$$d_L(z) = (1+z)\frac{c}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_{r_0}(1+z')^4 + \Omega_{m_0}(1+z')^3 + \Omega_{\Lambda_0}}}$$

(flat universe)



Betoule et al. 2014

ΛCDM concern: H_0

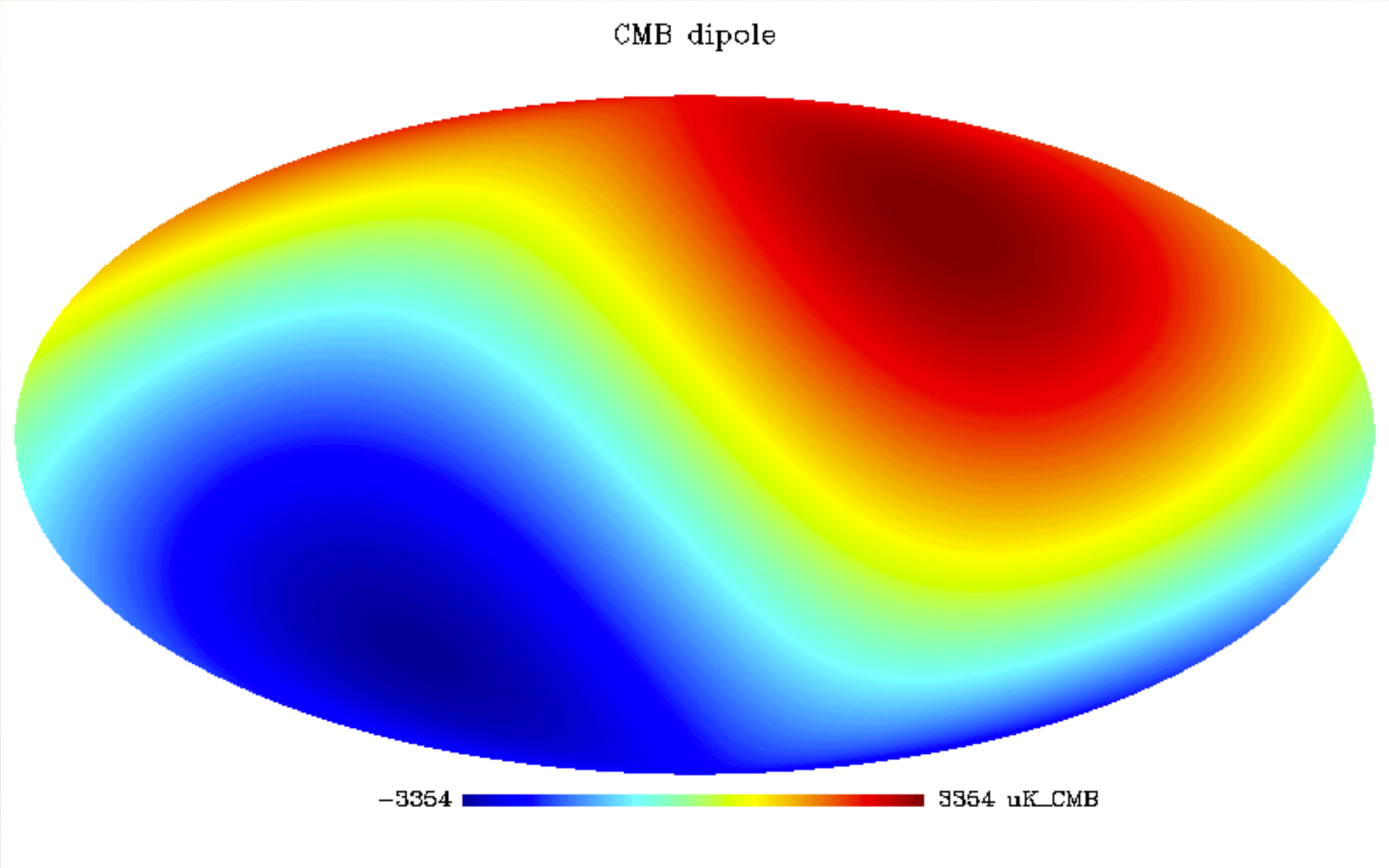


SNe

CMB

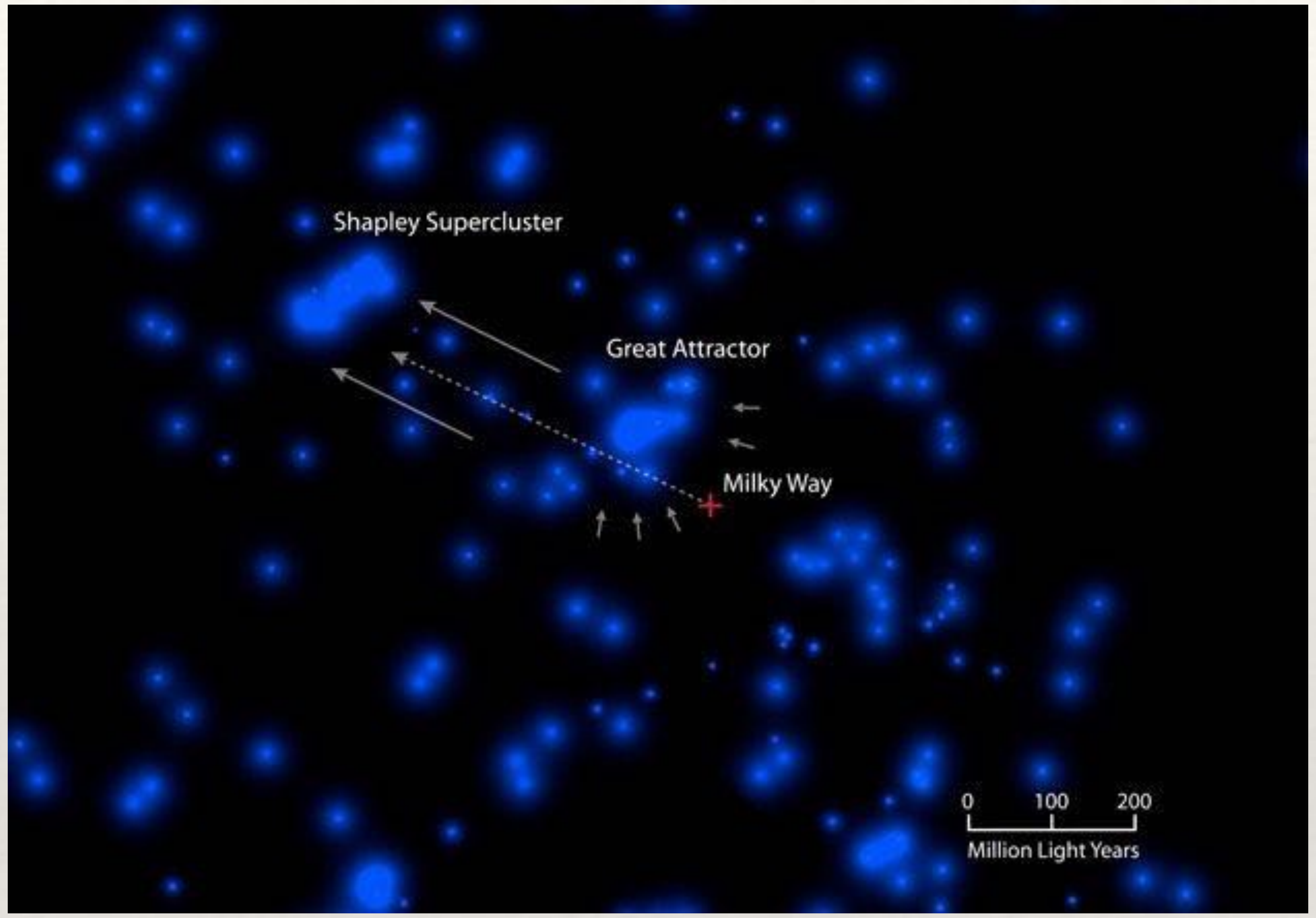
Credit: Gómez-Valent

ΛCDM concern: bulk flow



We move with ~300km/s wrt to CMB frame

ΛCDM concern: bulk flow



In CMB frame, the Local Group moves at ~ 600 km/s, why?

Is there a large bulk flow beyond Shapley ? (would break ΛCDM)

SNe Ia

Measurable at cosmological distances

10 Mpc

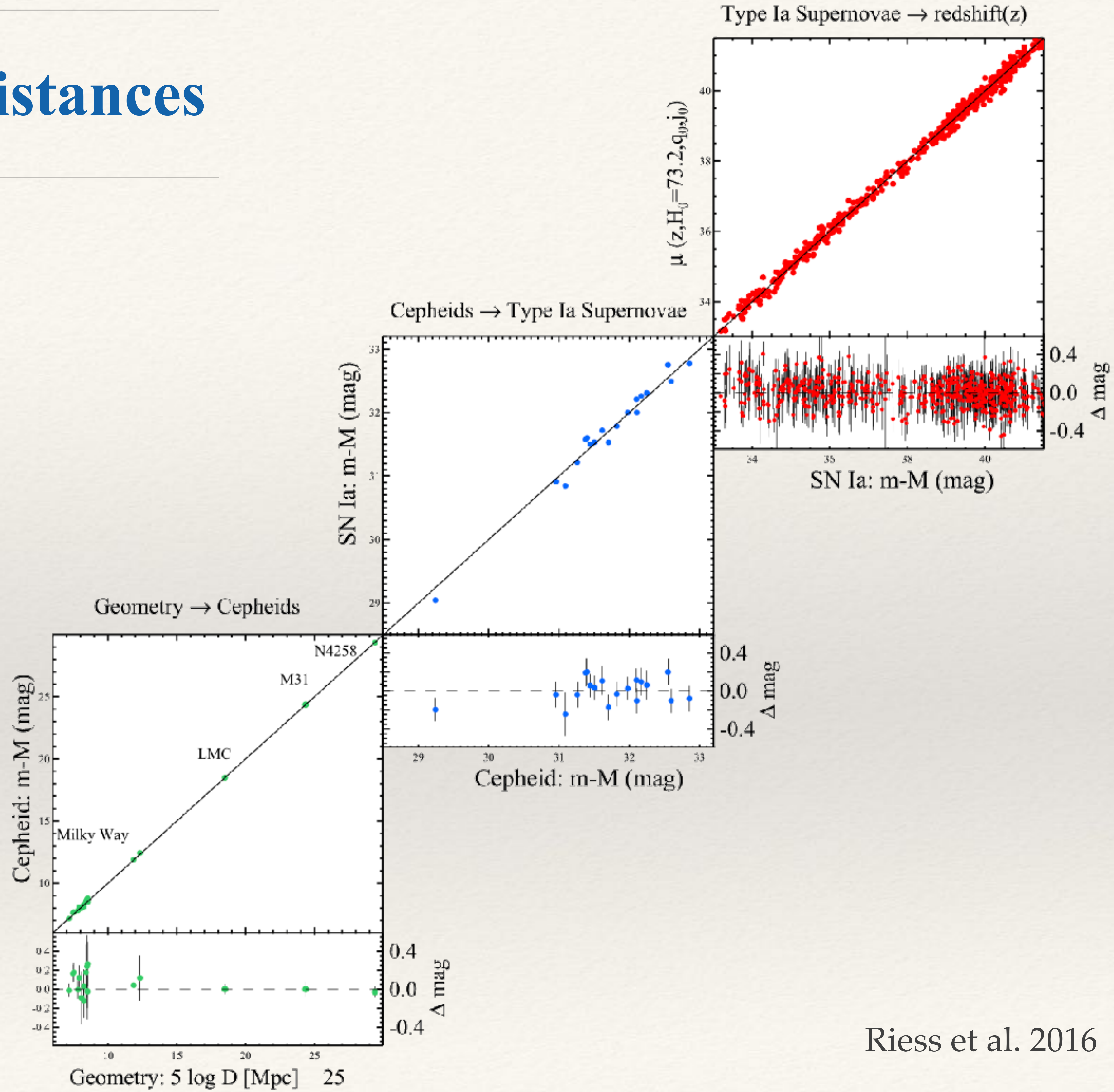
100 Mpc

1 Gpc

Geometrical Distances

Cepheids

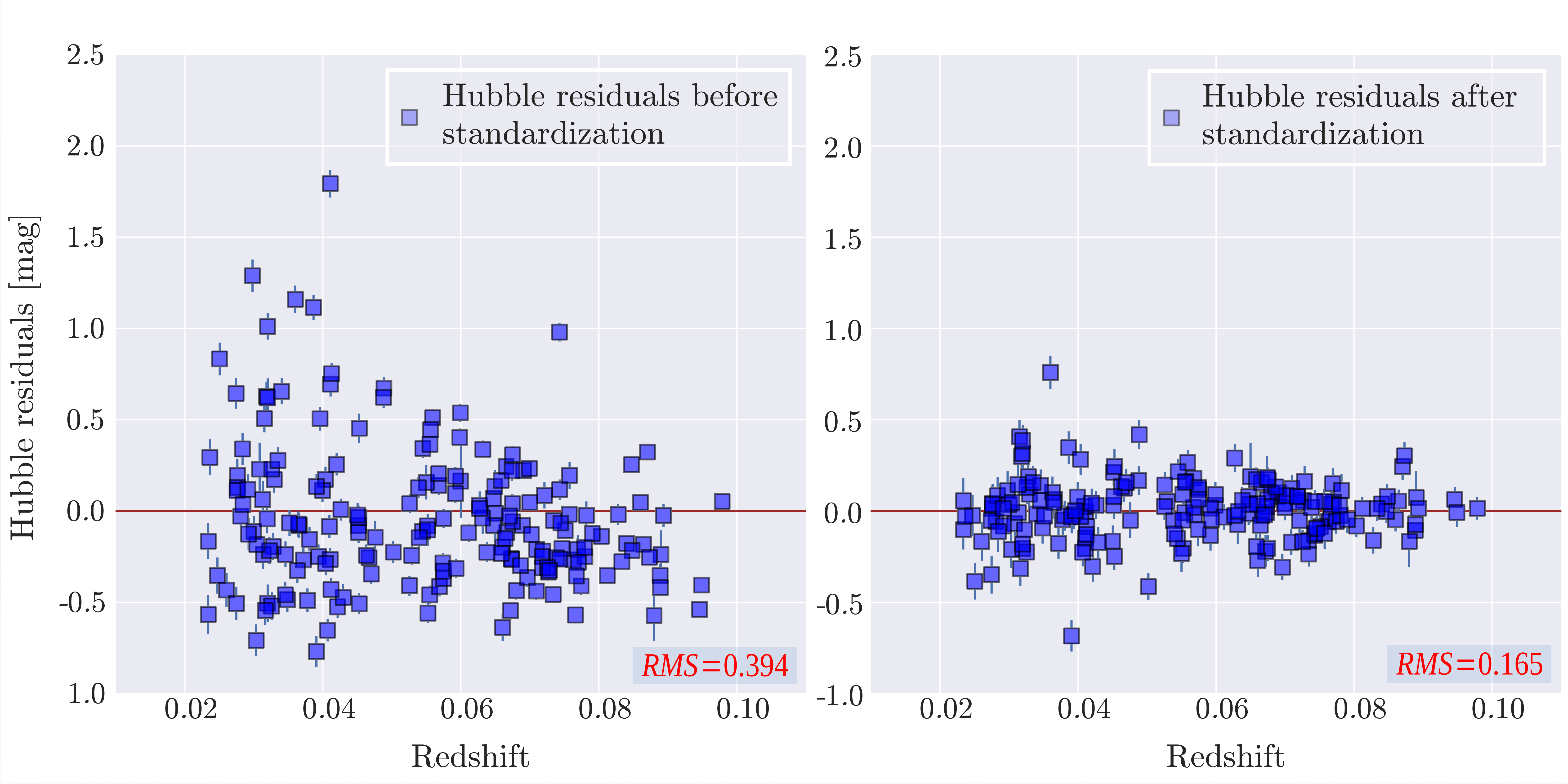
Type Ia Supernovae



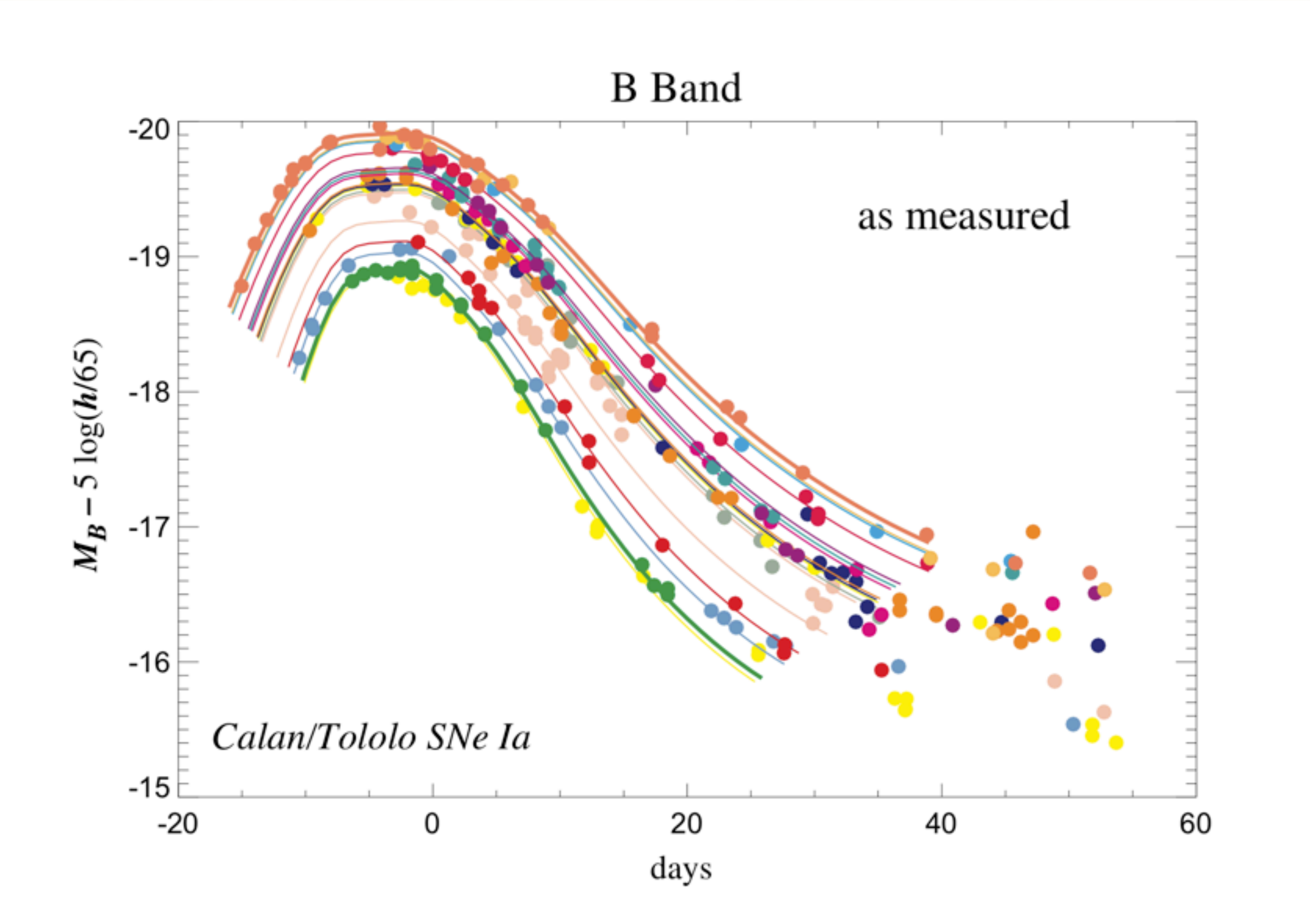
Riess et al. 2016

SNe Ia are standardisable

201 SNe Ia with 0.02 < z < 0.10, measured by *SNfactory*



Stretch



Linear correlation between decline-rate and absolute magnitude (Phillips 1993)

Standardisation

Lightcurve parameters

Peak magnitude in rest-frame B-band — *Stretch* — *Color*

Standardised distance modulus

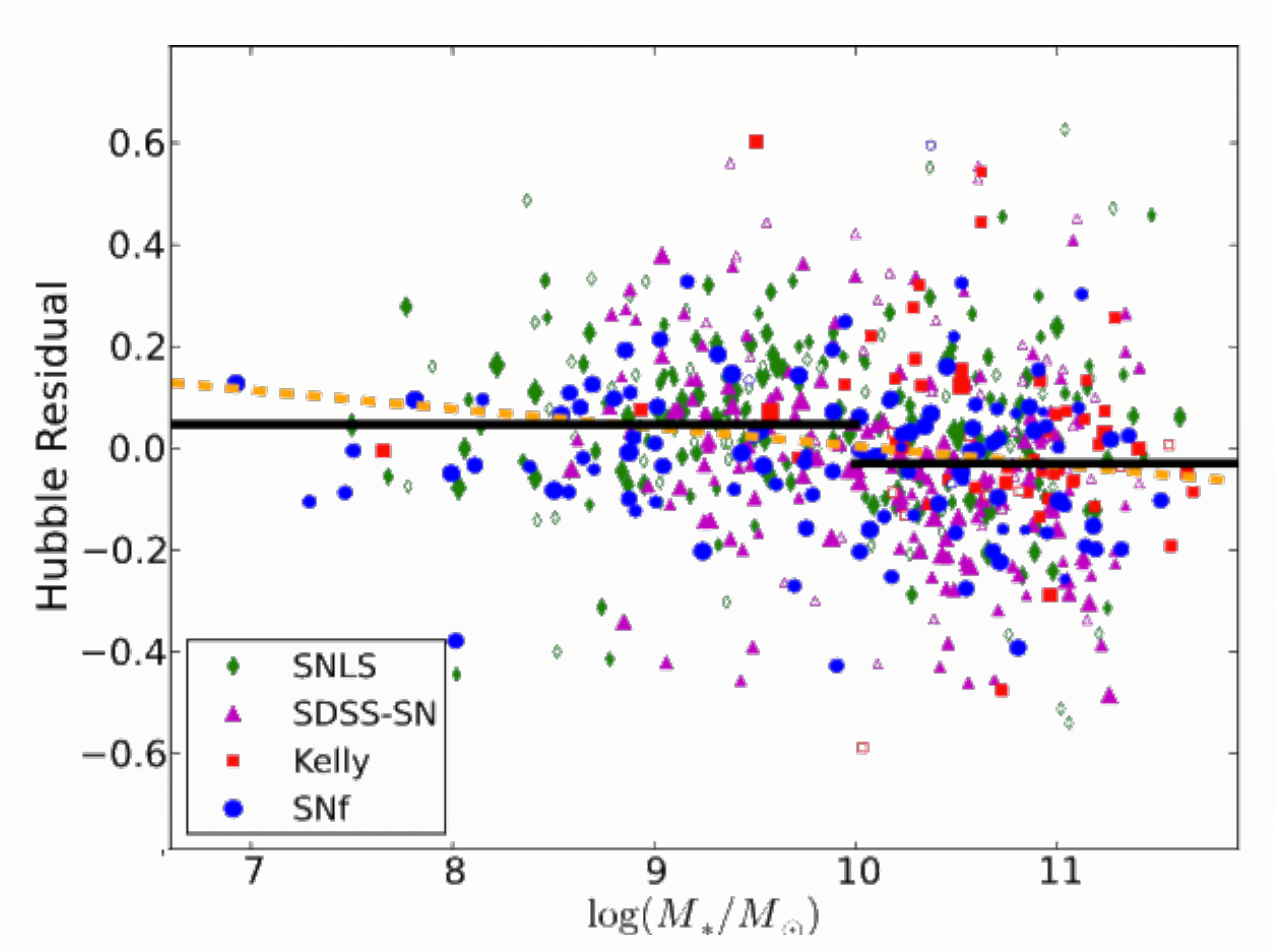
$$\mu = m_B - (M_B - \alpha \times x1 + \beta \times c)$$

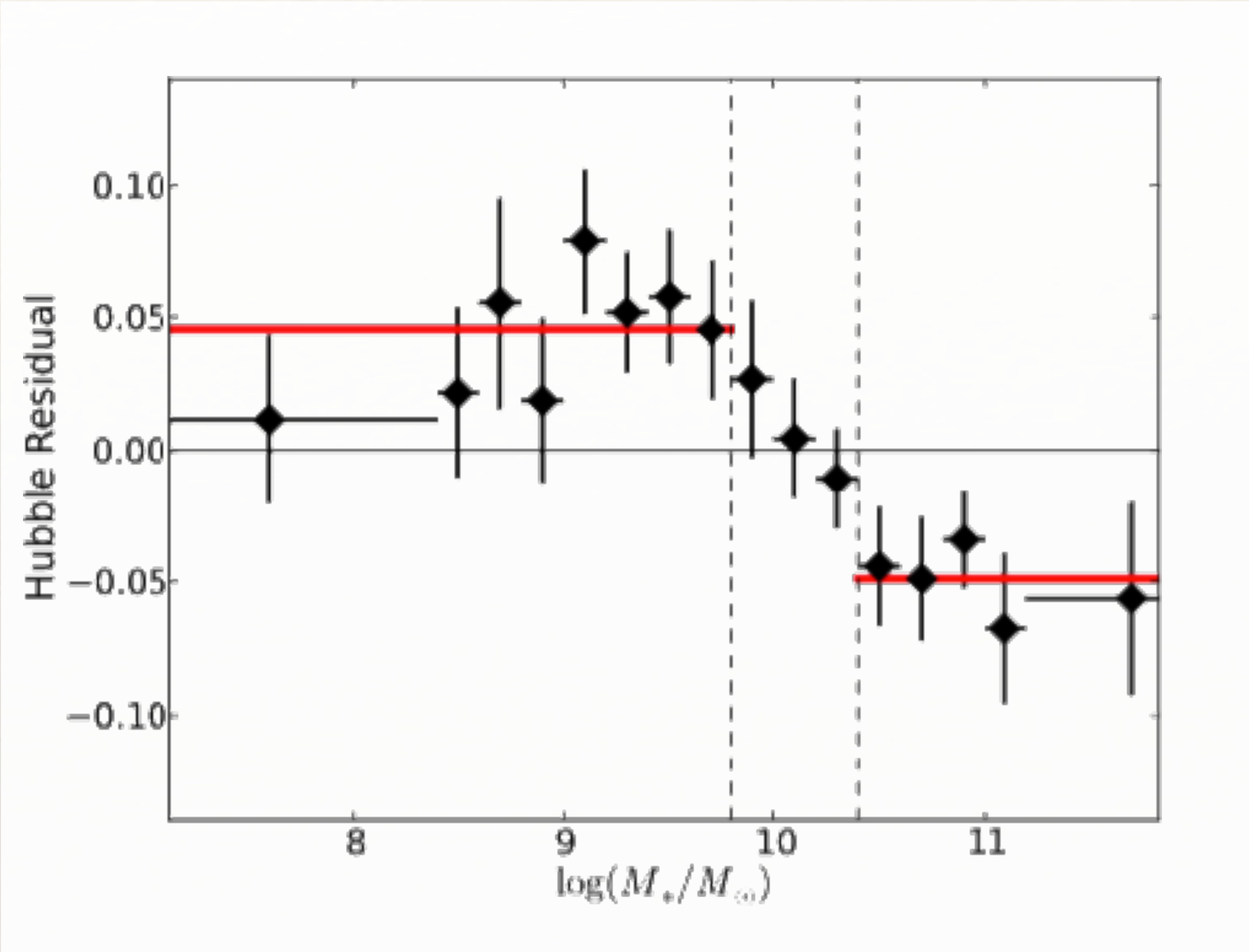
Global fit parameters

So far everything looks good for ZTF data

“Mass step”

Childress et al. 2013





Two populations ?

Third parameter

Lightcurve parameters

Environmental parameters

Peak magnitude in rest-frame B-band

Stretch

Color

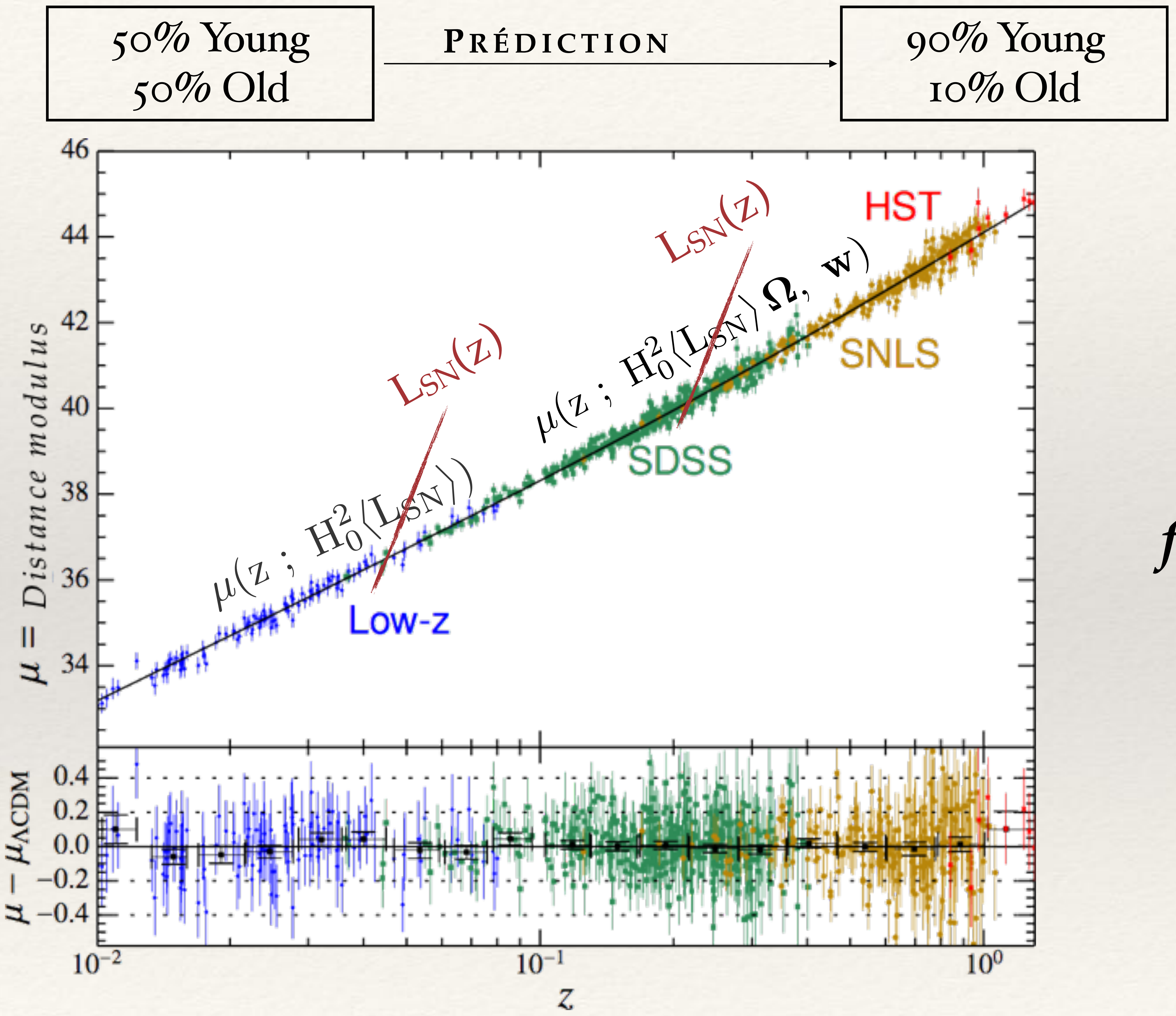
Standardised distance modulus

$$\mu = m_B - (M_B - \alpha \times x1 + \beta \times c)$$

$$M_B = \begin{cases} M_B & \text{if} \quad X < X_{\text{lim}} \\ M_B + \Delta M_B & \text{if} \quad X > X_{\text{lim}} \end{cases}$$

Global fit parameters

Environments evolve



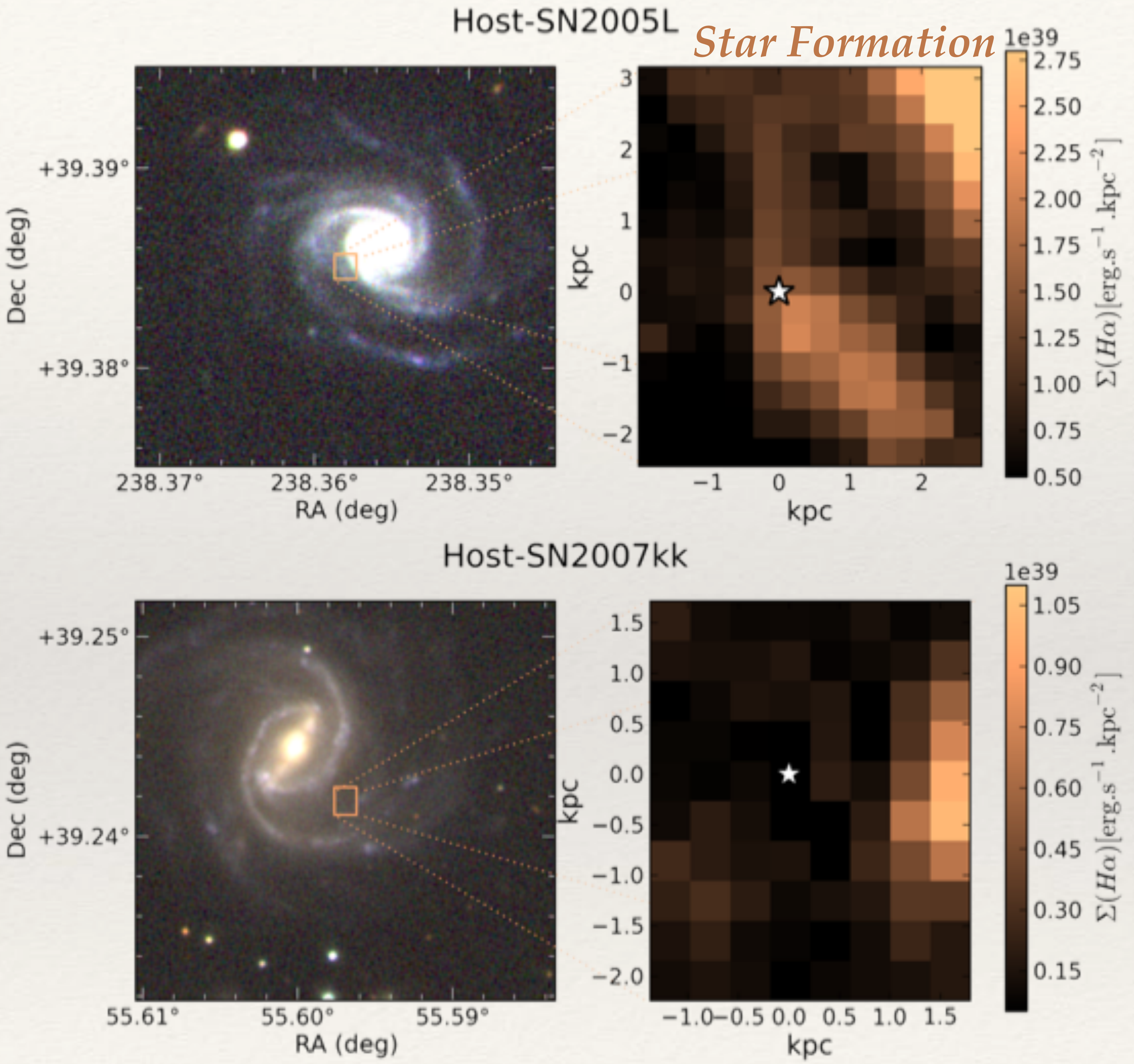
Galaxies are more star forming at higher redshift

Local perspective

Rigault et al. 2013

GLOBAL

Spiral, Star Forming, host galaxies



LOCAL

Star Formation

—

Young Stars

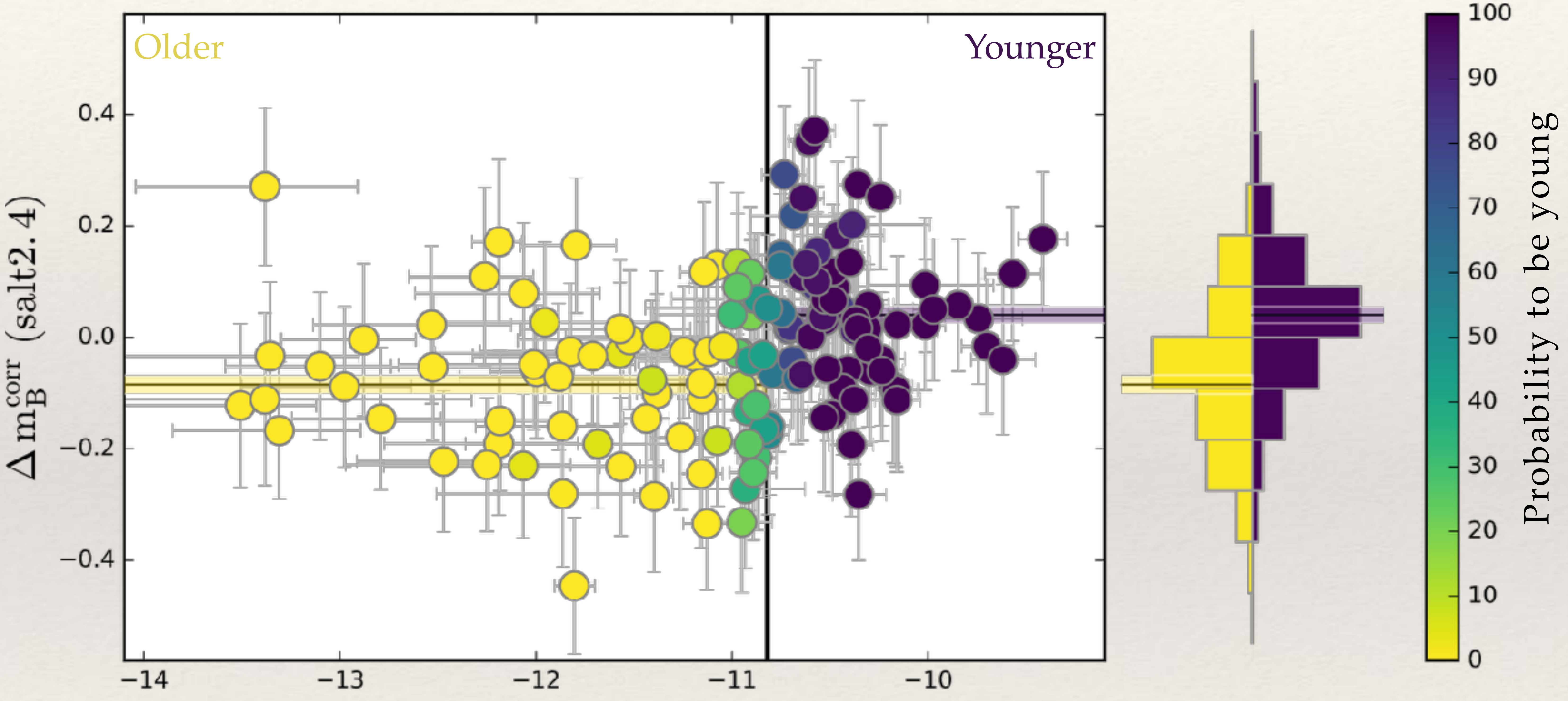
No Star Formation

—

Older Stars

"Age step"

non-zero at ~6σ level | Δ_Y = 0.16 ± 0.03

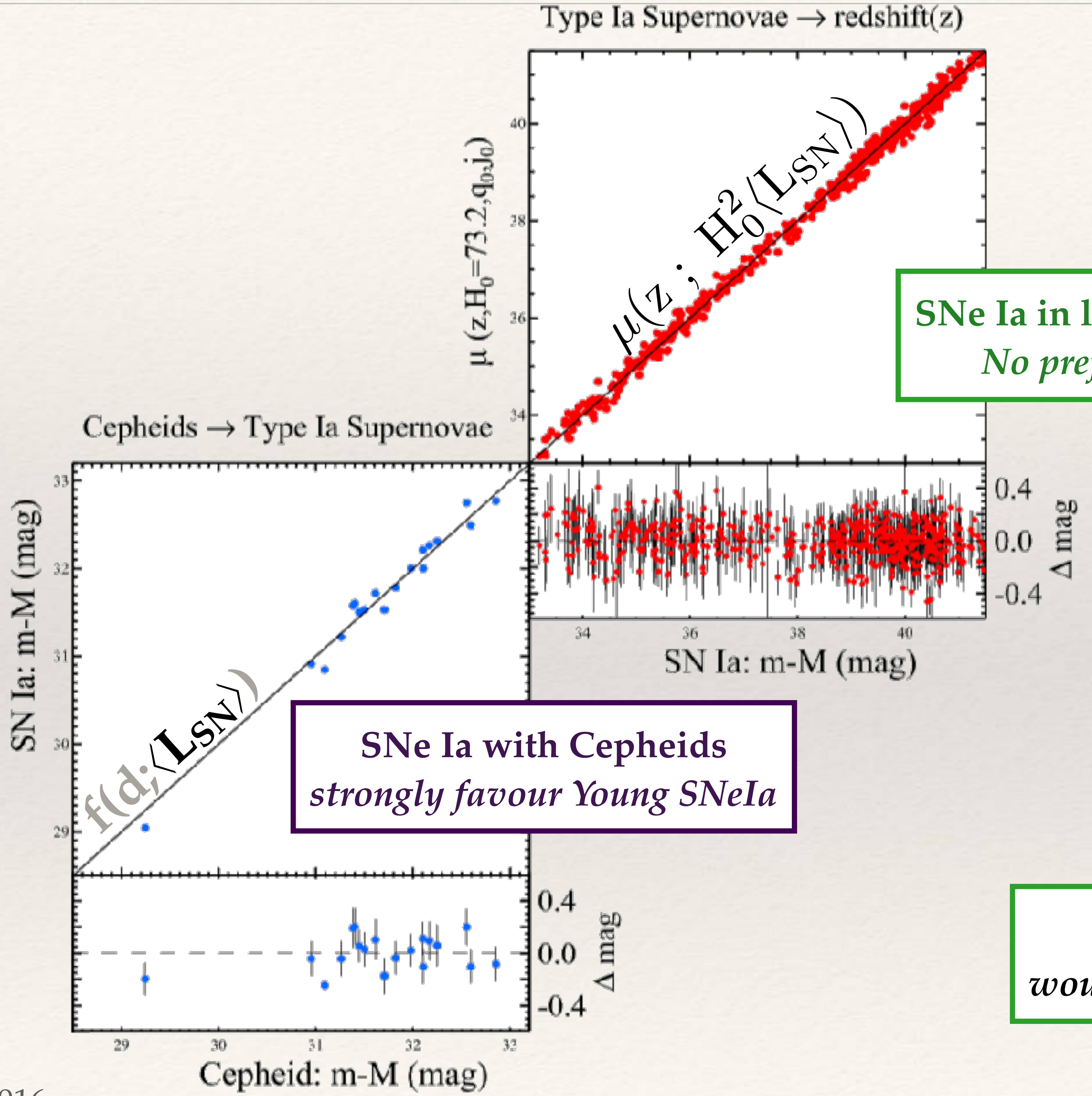


SNeIa Luminosity
with respect to average

local Star formation rate / *local* stellar mass

Fraction of young star at the SN location

ΛCDM concerns: H_0



SNe Ia in local universe
No preferred age

SNe Ia with Cepheids
strongly favour Young SNeIa

Riess et al. 2016

Rigault 2018

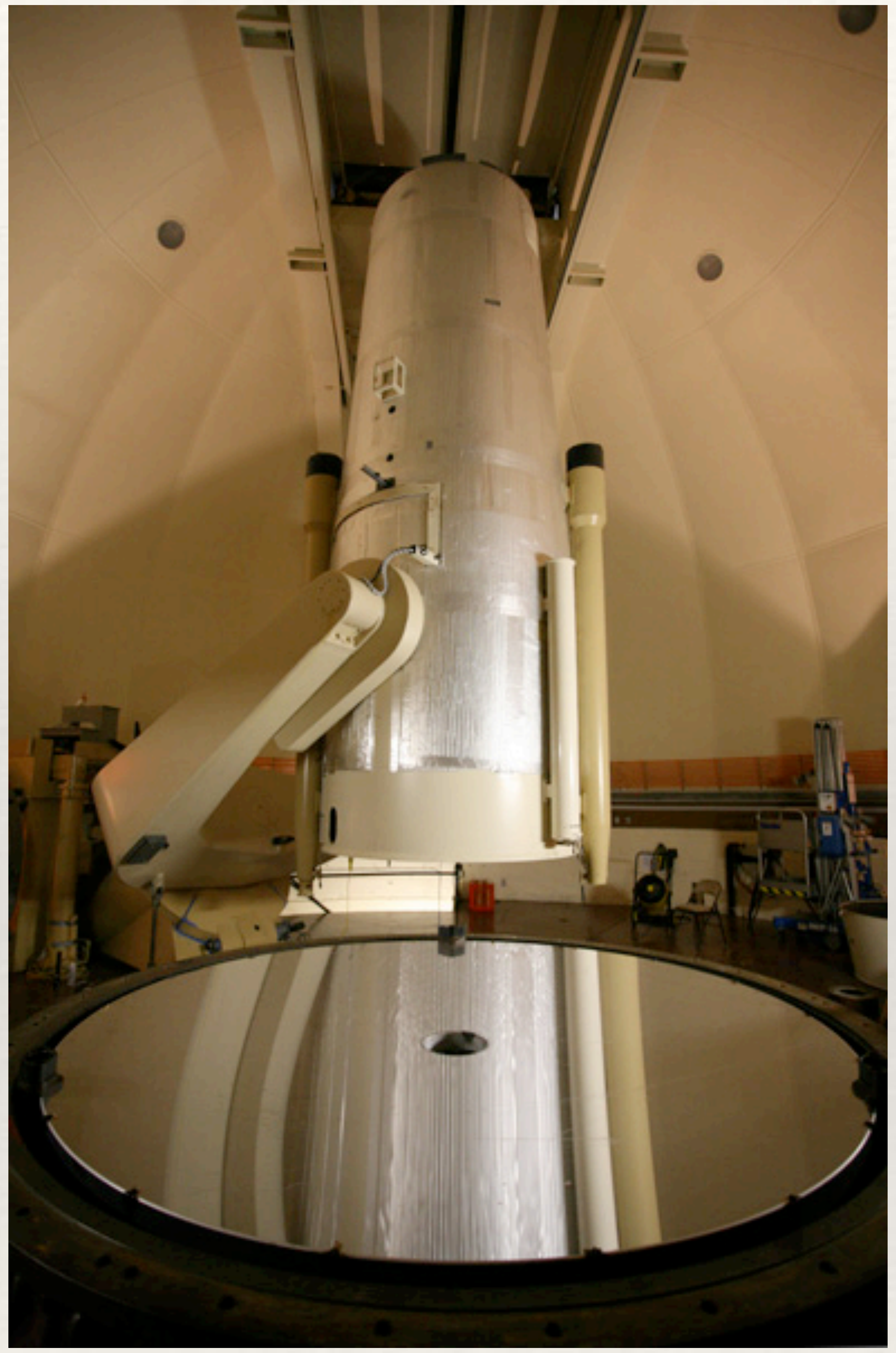
Up to 3% bias on H_0
would reduce H_0 down to ~71.5 km/s/Mpc

ZTF

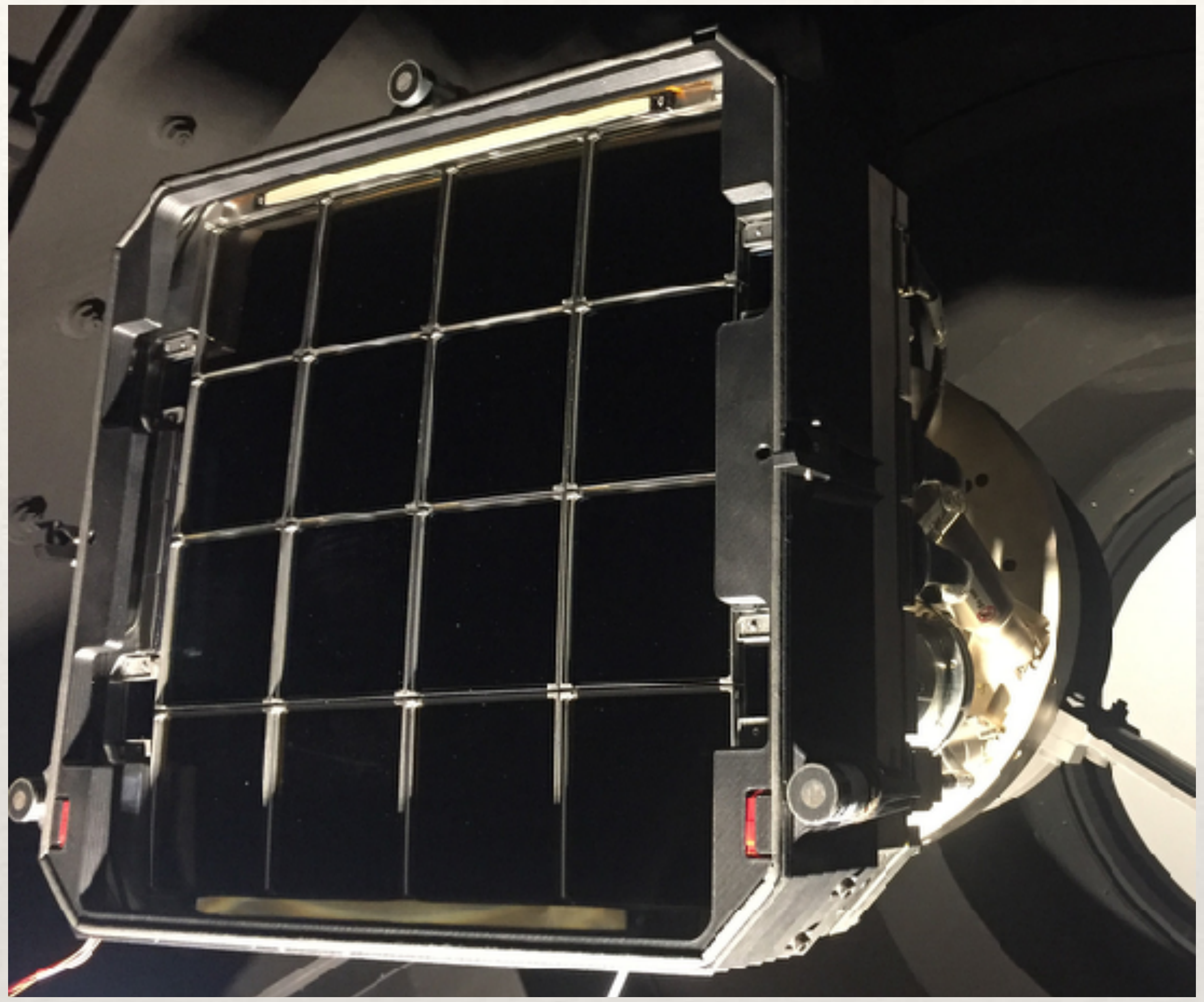
Zwicky Transient Facility

Palomar

Zwicky Transient Facility



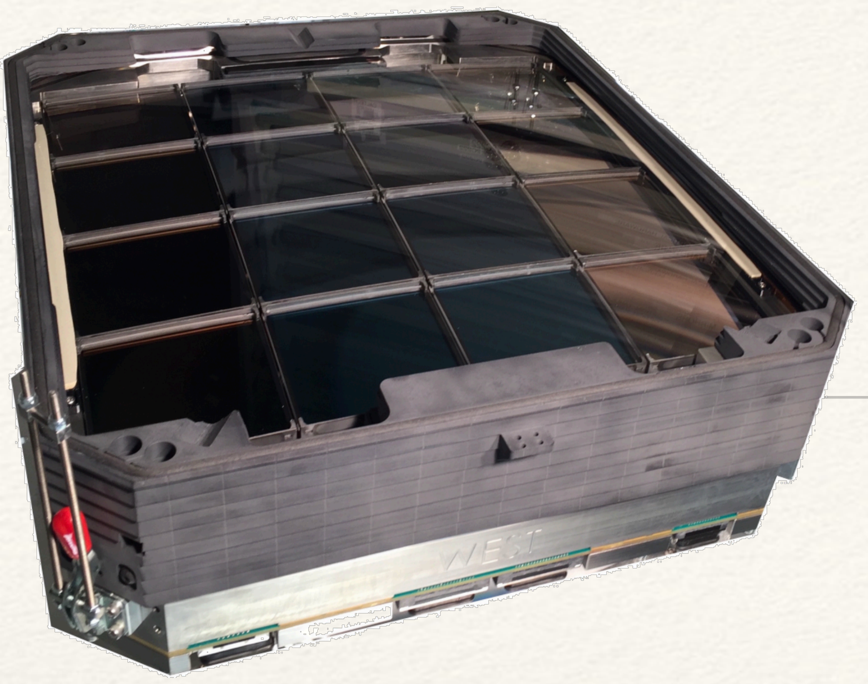
48” mirror



576 megapixels

Shutter at DESY

The focal plane is so big that the shutter blades would obstruct much of the beam, so the shutter is instead at the entrance to the telescope. It opens in just 340 ms and applies only a few grams of reaction force to the telescope



The Camera

KEY INFORMATION

47 square degree field
(on 2 grids ; 1 main + extra)

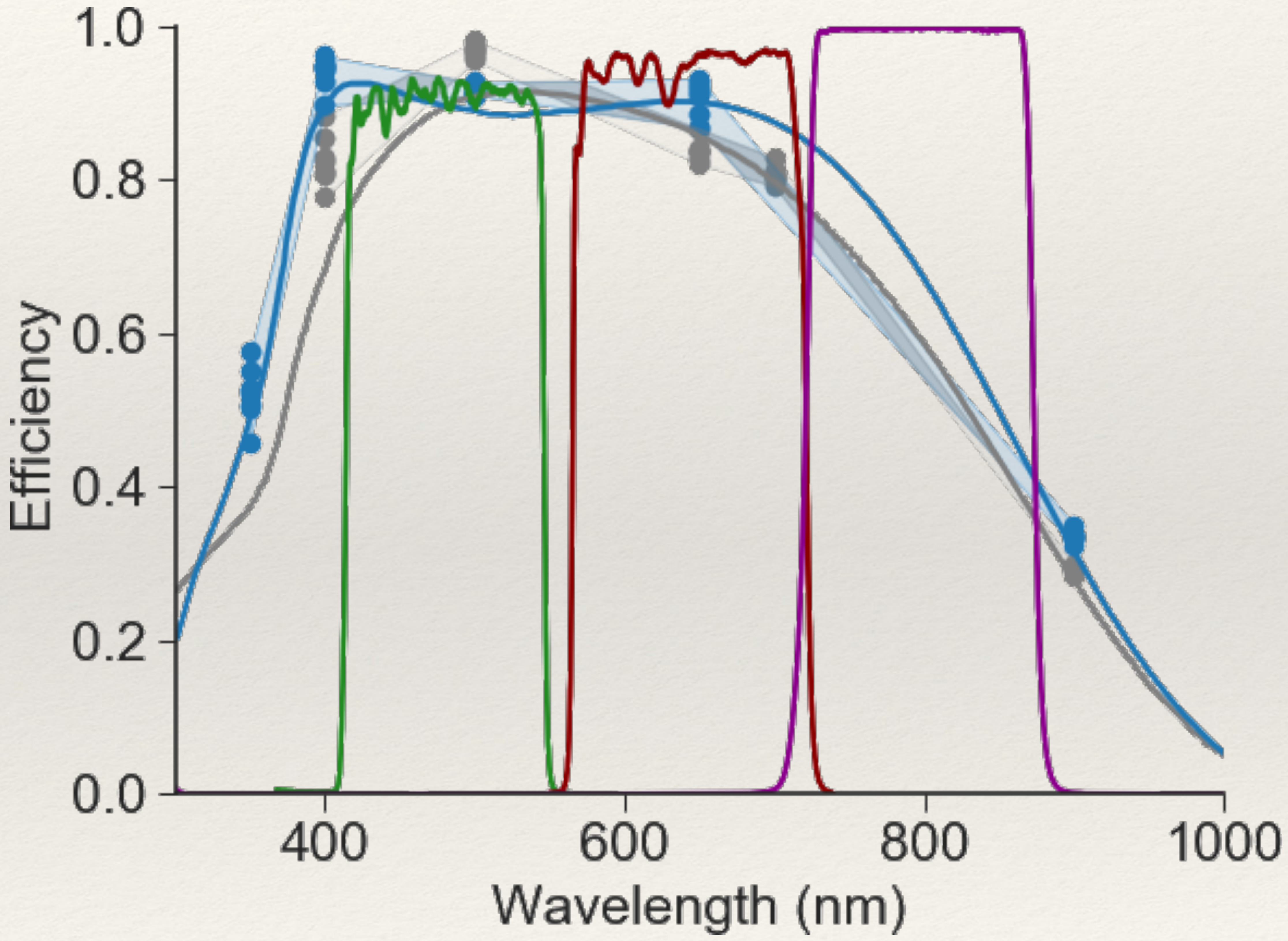
16 E2V 6k x 6k CCDs
(2 different coatings)

1 Pixel ~ 1 arcsec
(typical seeing ~2arcsec)

30s exposure + 15s slew

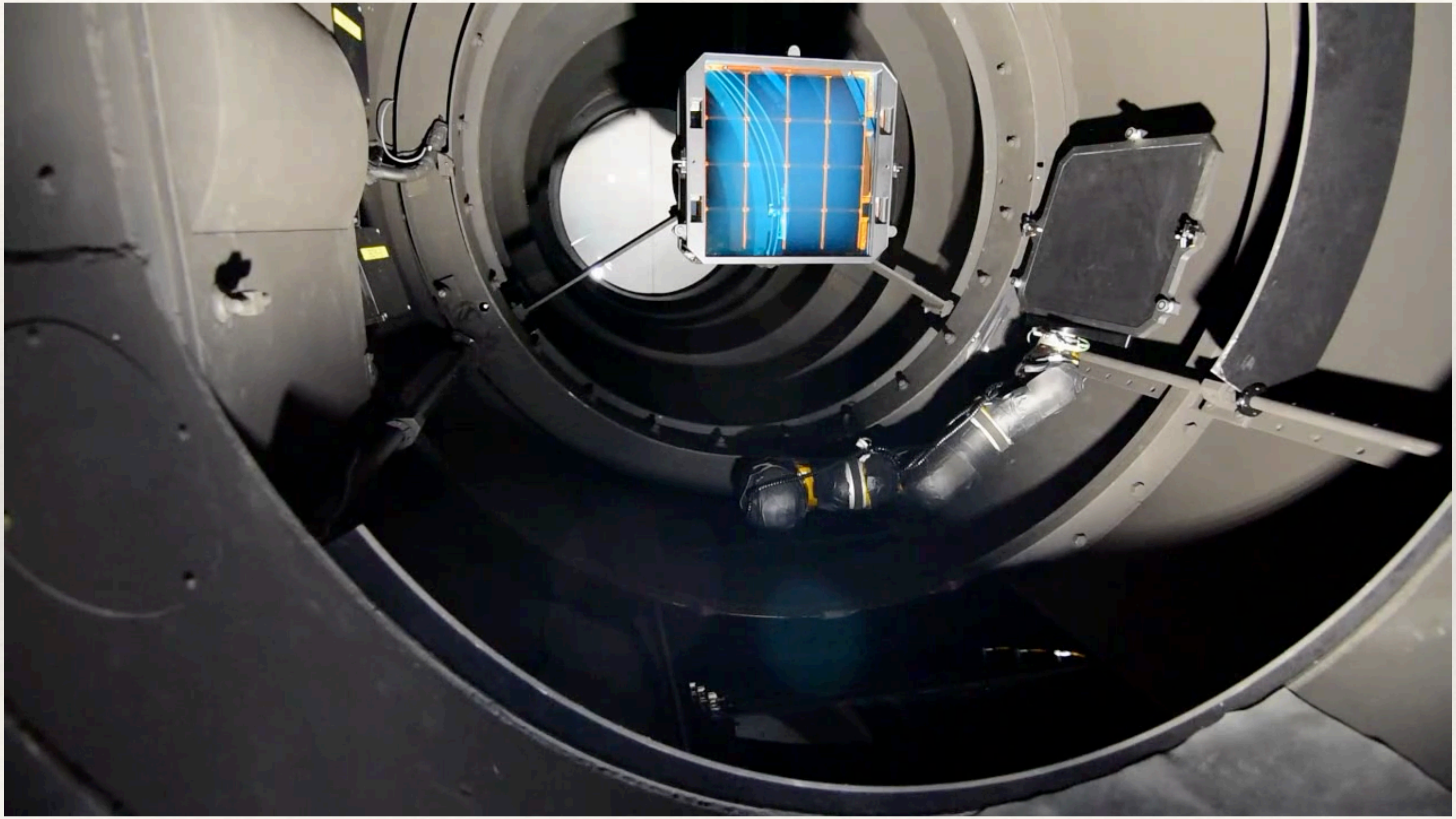
~20.5 mag (5σ) per exposure
(slightly better in R)

3 FILTERS | G, R, I

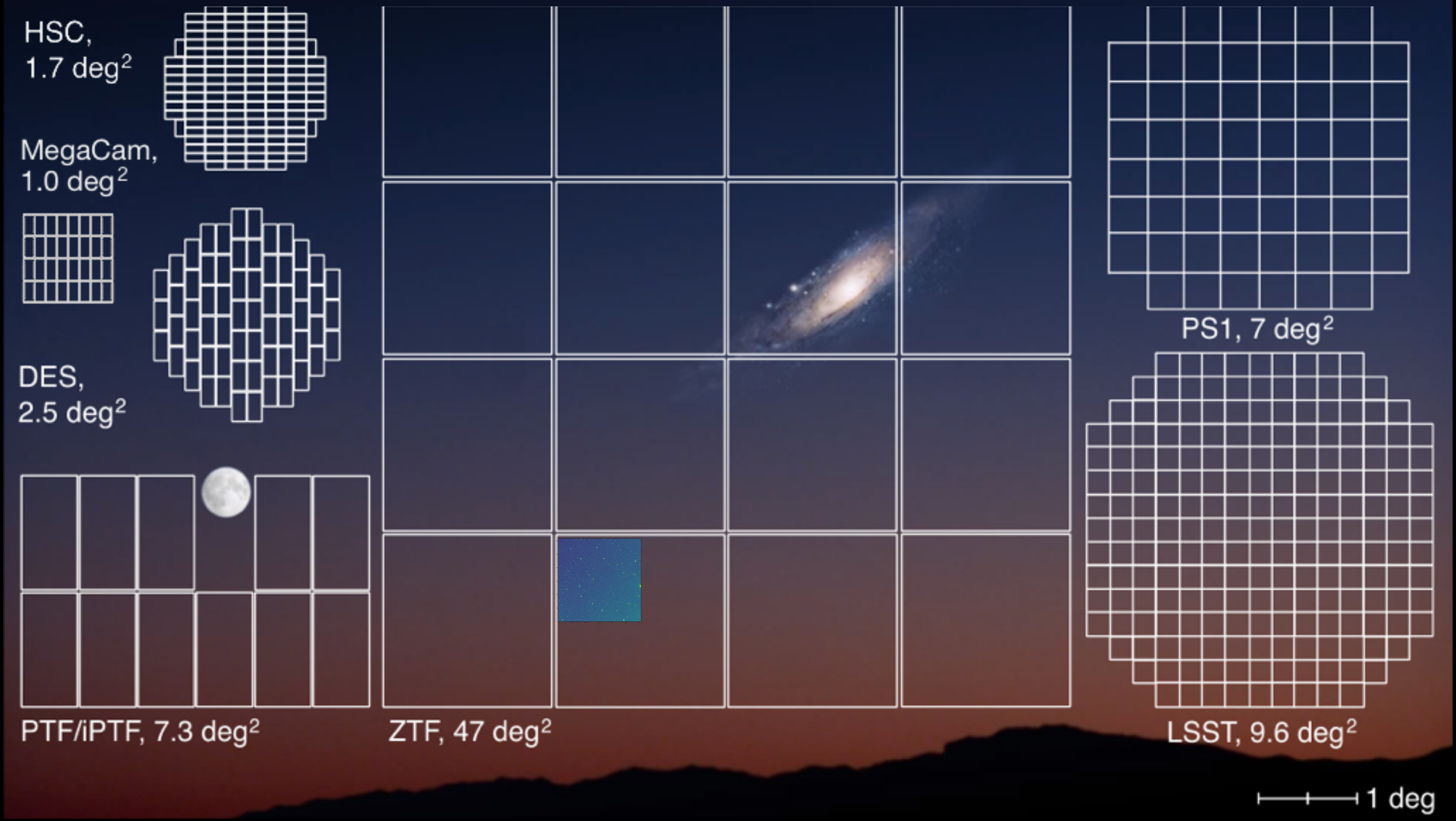


ZTF = 3 750 square degrees/hour

Robotic arm in action

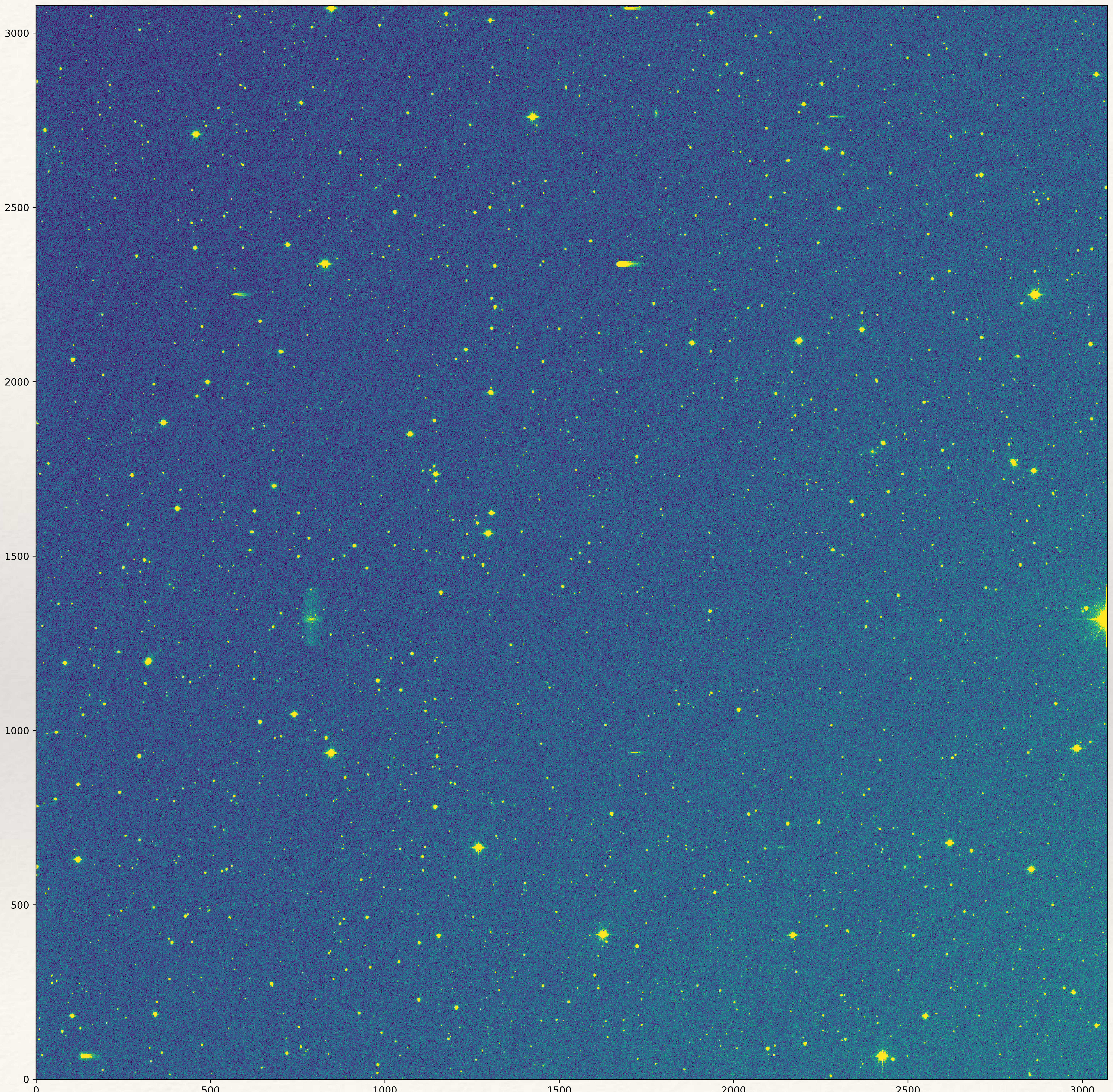


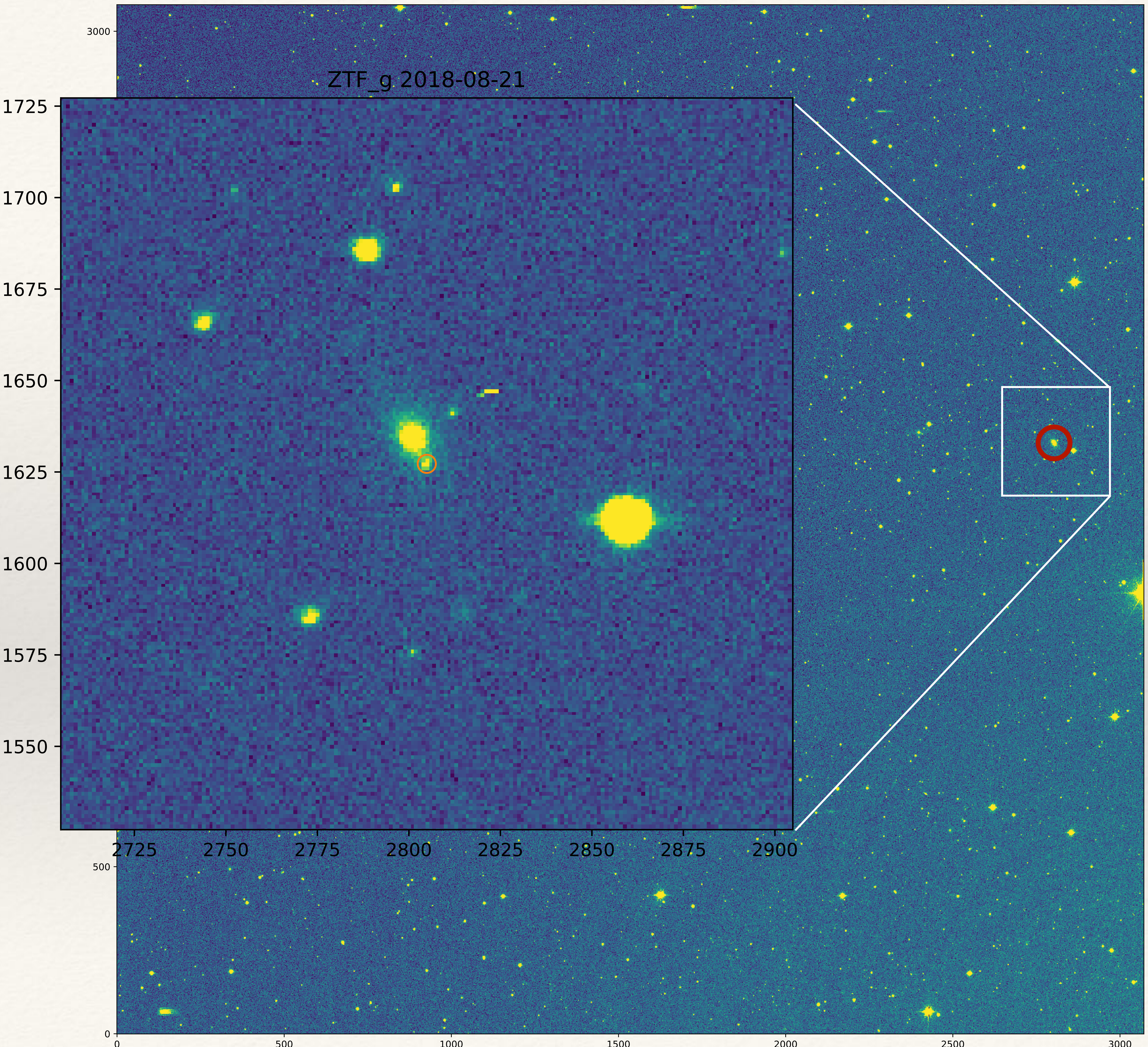
Field of view



ZTF | 2018-2021+ | ~2000 SNeIa z<0.1 — LSST | 2022-2032 | 200 000 SNeIa<0.3

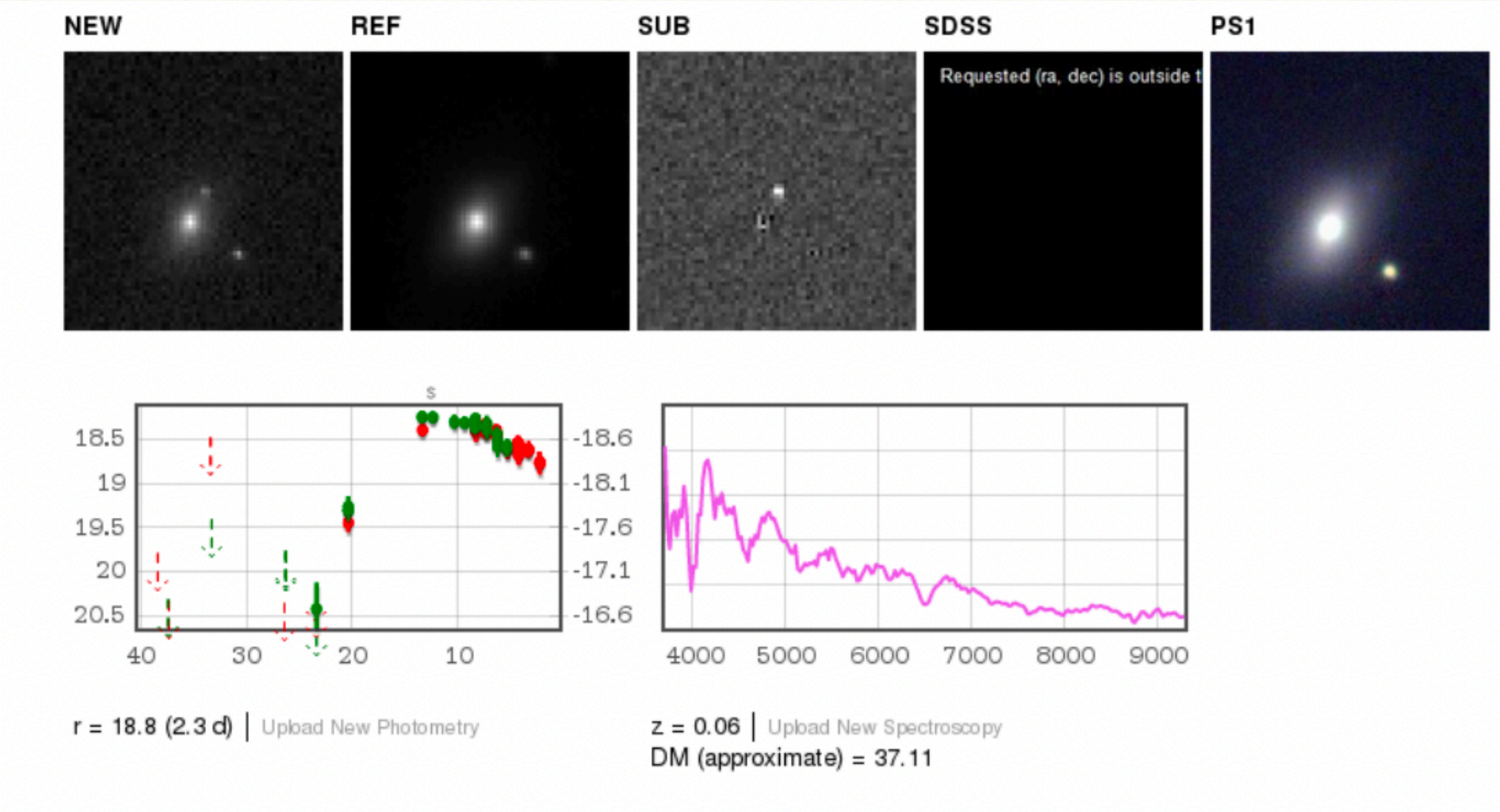
+WFIRST (space telescope 2030+ ~1000 SNeIa z>1)


0
500
1000
1500
2000
2500
3000

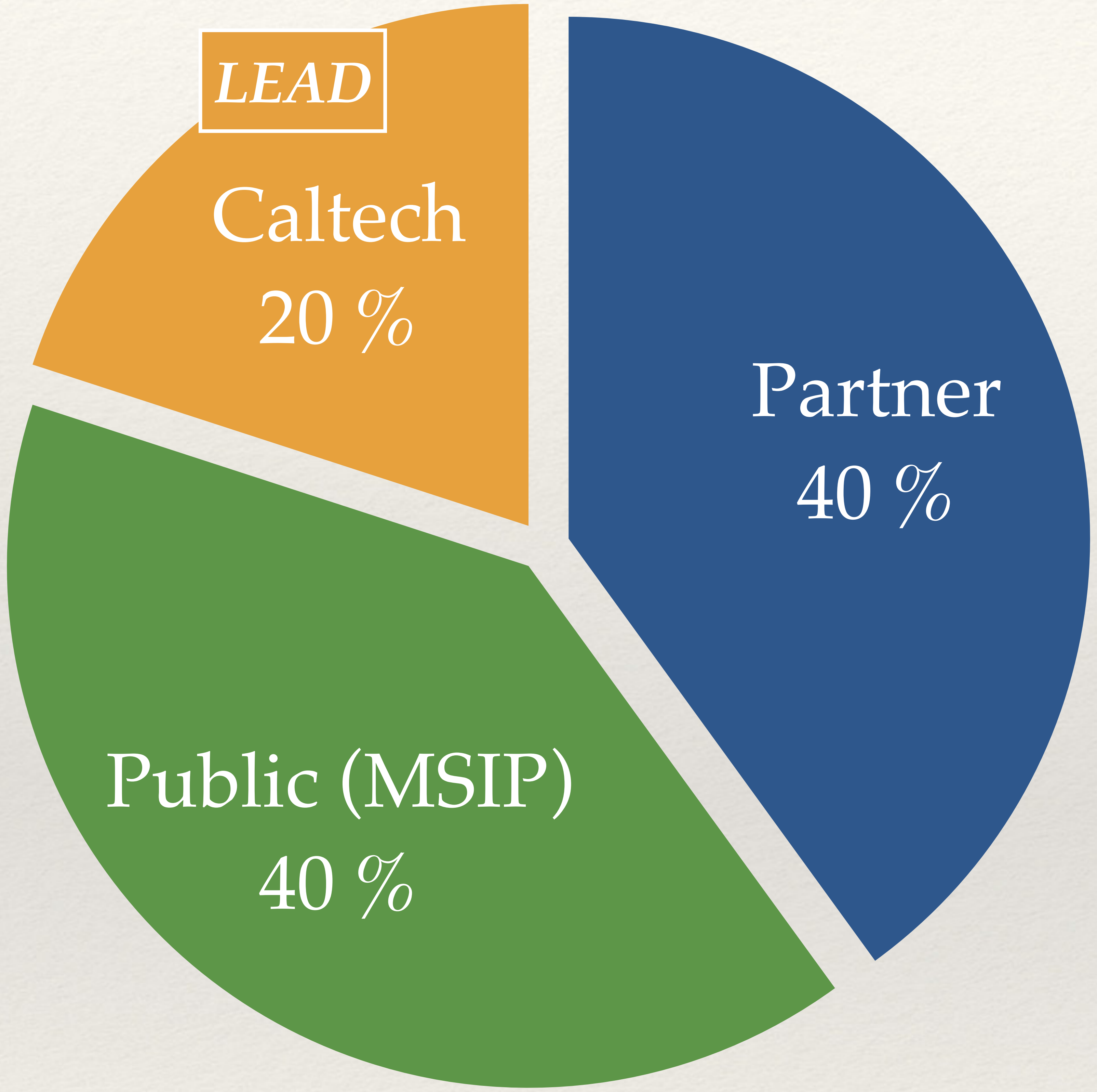


ZTF_g 2018-08-21
1725
1700
1675
1650
1625
1600
1575
1550
2725
2750
2775
2800
2825
2850
2875
2900
3000
500
0
0
500
1000
1500
2000
2500
3000

ZTF18abltaxf - z~0.07 SNe Ia



ZTF data



PUBLIC SURVEY "MSIP"

2 Filters (g, r)

6400 sqdeg every 3 days
(in both bands!)

Alerts public right away
(all transients discovered within MSIP)

+ Galactic plane
(August mainly)

PARTNERSHIP & CALTECH

High cadence fields (g,r)
(4x the same field every night)

Third filter mapping MSIP
(4 days cadence ; For Cosmology mainly)

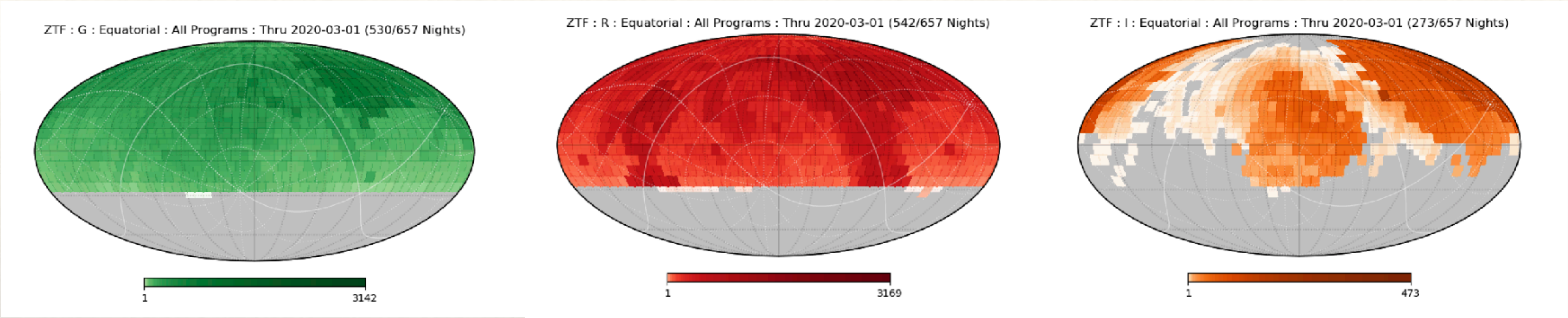
ToO | GW, Neutrino, GRB

Galactic Plane + M31
(Mainly August)

Data Access |
- **MSIP**: Alert, public right away | Pixels 6 month embargo
- **Partner+**: Alert, not public | Pixels 18 month embargo

Alert | **Kafka stream hosted by UW**
i.e. the LSST stream

Zwicky Transient Facility



Observing the full visible extra-galactic sky in half a night

DR5:

~24.8 million single-exposure images

~153,000 co-added images accompanying source catalog files containing

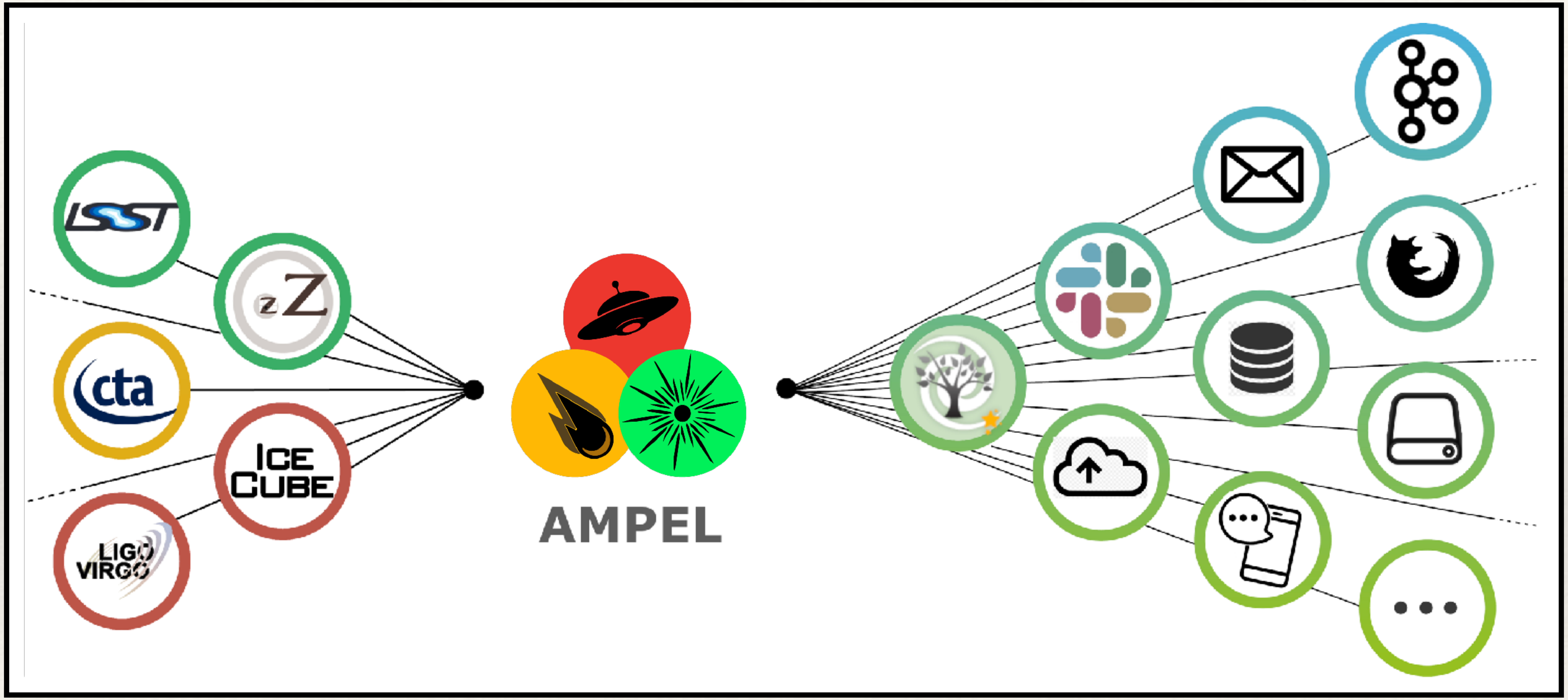
~350 billion source detections extracted from those images

~3.6 billion lightcurves constructed from the single-exposure extractions

Up to 500 000 alerts / night

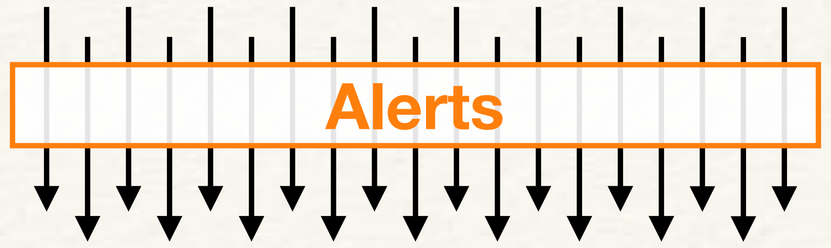
AMPEL

AMPEL system



AMPEL | Process Flow

Nordin et al. 2019



T0

FILTER

Which alerts are potentially interesting?

T1

CORRELATE

Only relevant for multi-messenger science

T2

AUGMENT

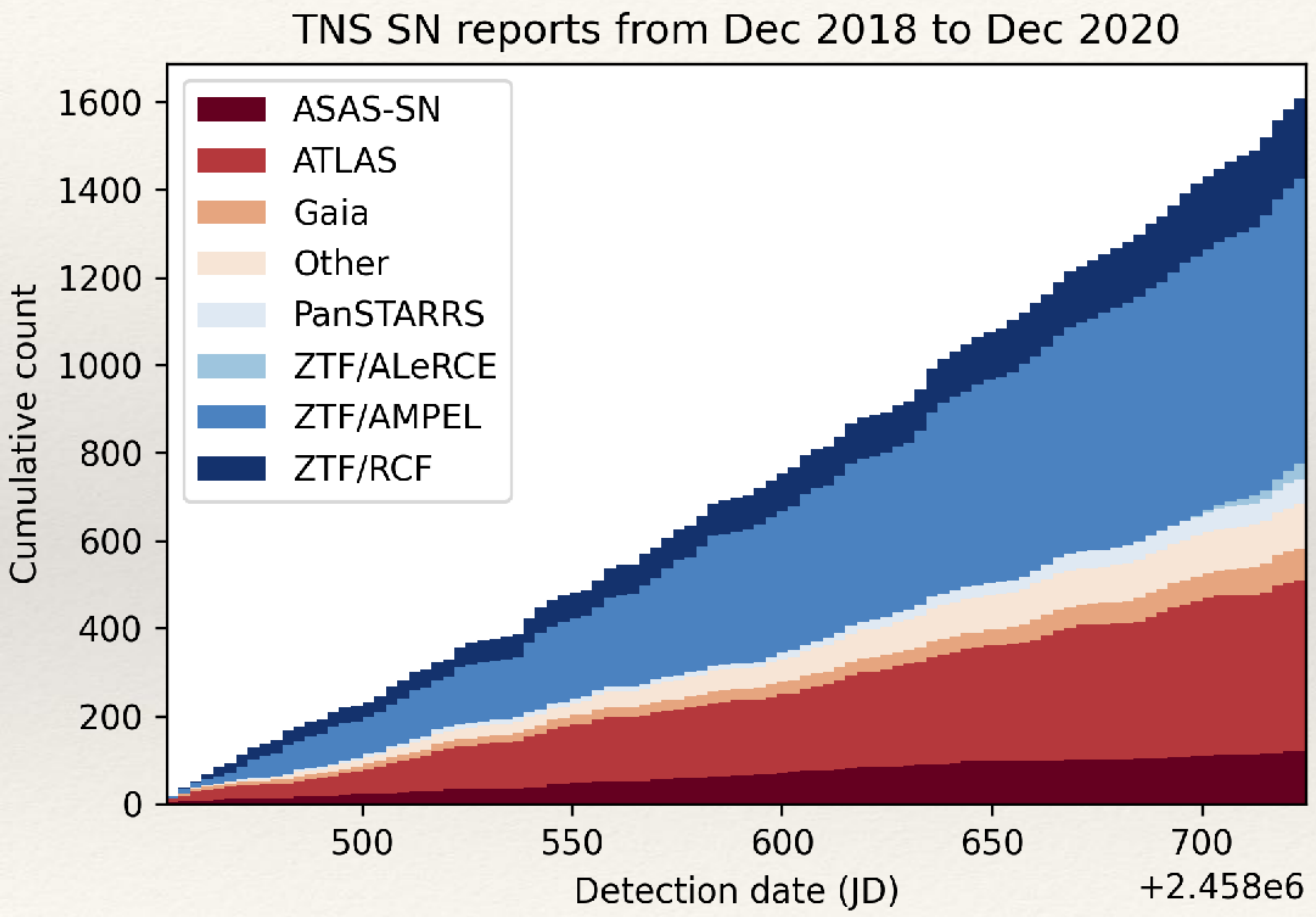
Evaluate/derive transient properties

T3

REACT

What reaction to trigger ?

SNe reported by AMPEL



AMPEL | Cosmology

T0

ADD

Add confirmed Ia from TNS

T1

CORRELATE

Only relevant for multi-messenger science

T2

AUGMENT

Get host redshift, compute lightcurve template

T3

SYNTHESISE

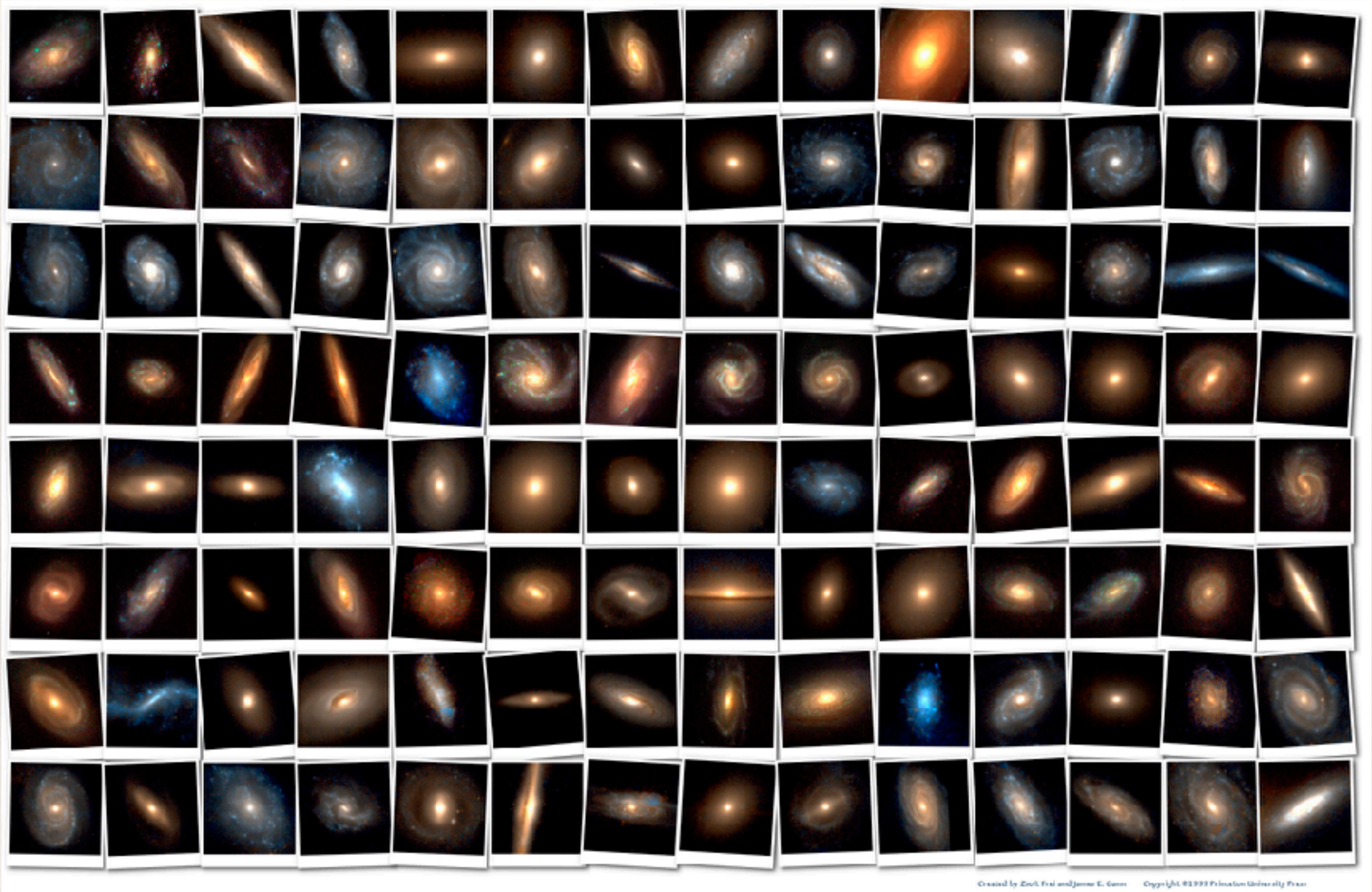
Fit α and β, standardise, fit dipole

ZTF cosmology sample

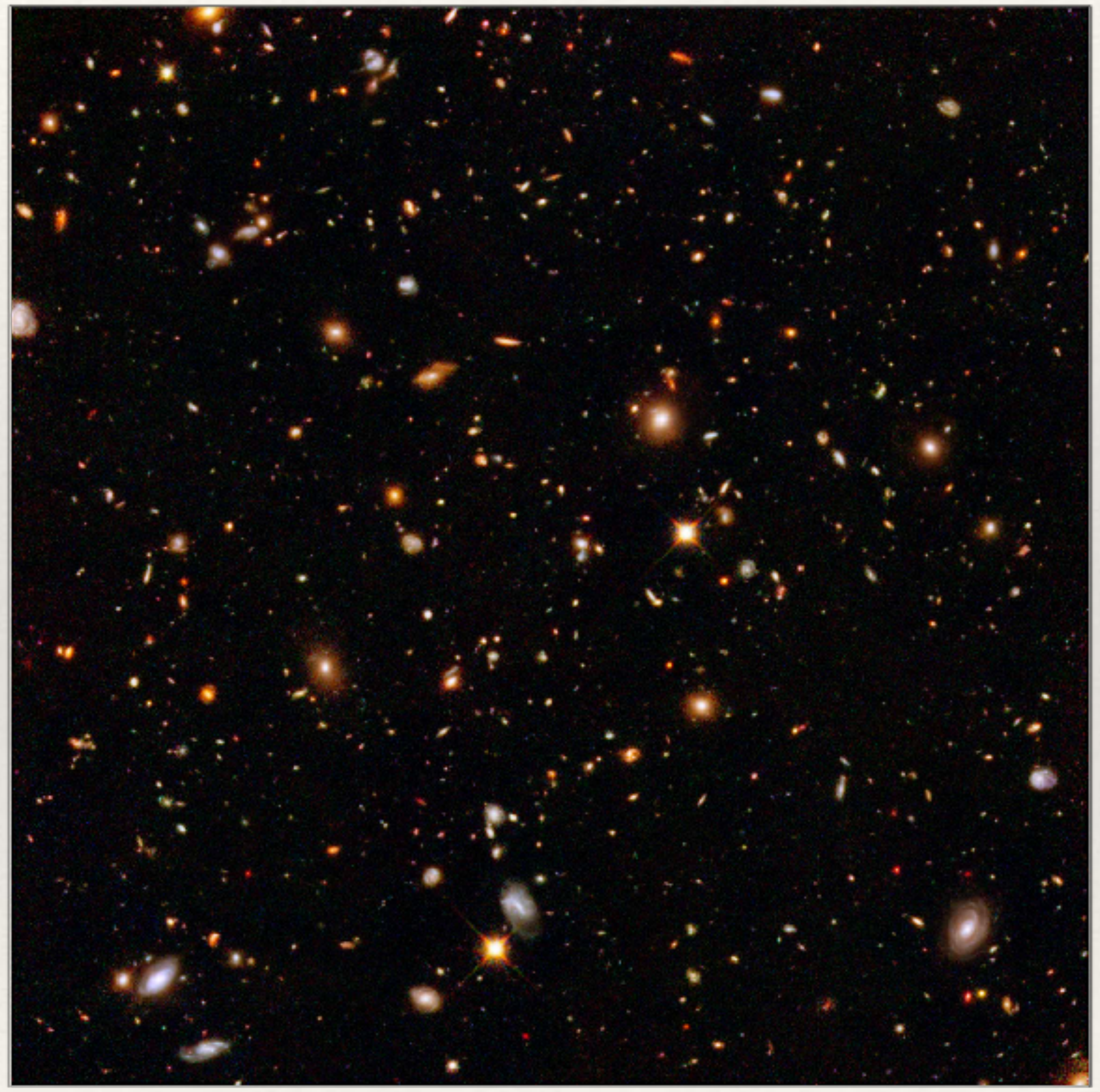
UNDISCLOSED

Un-targeted sample

Targeted Surveys

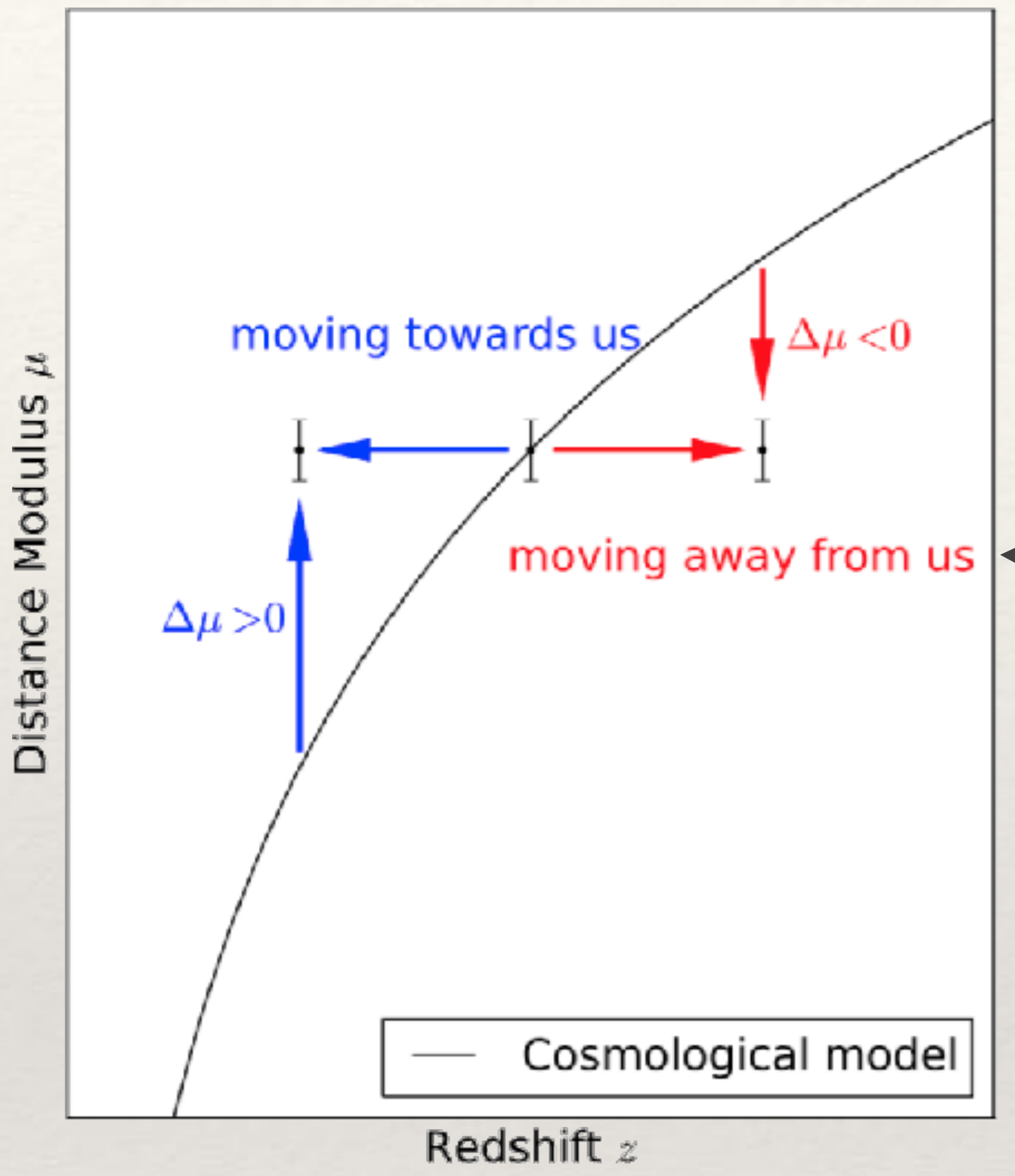


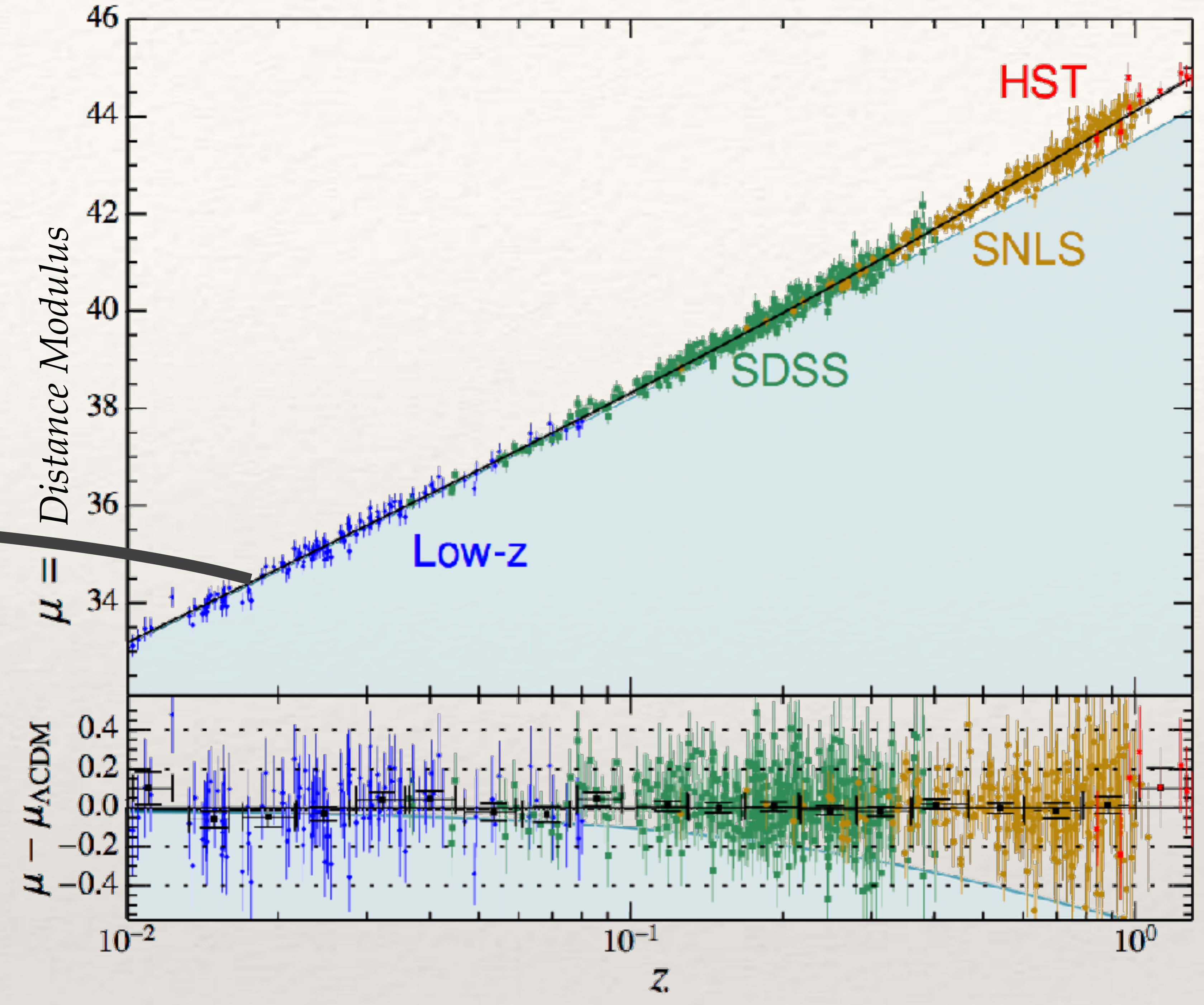
Un-targeted Surveys



Bulk Flow

Bulk Flow





Dipole velocity model (Bonvin et al. 2006)

$$\tilde{d}_{\mathrm{L}}(z,\vec{n},\vec{v}_{\mathrm{d}}) = d_{\mathrm{L}}(z) + \frac{(1+z)^2}{H(z)}\vec{n}\cdot\vec{v}_{\mathrm{d}}$$

Isotropic universe

Effect of Bulk flow

$$\chi^2 = \sum_i \frac{\left|\mu_i - 5\log\left(\tilde{d}_{\mathrm{L}}(z_i,\vec{n}_i,\vec{v}_{\mathrm{d}})/10\mathrm{pc}\right)\right|^2}{\sigma_i^2}$$

Minimize χ^2 to find velocity

Dipole fit

UNDISCLOSED

Perspectives

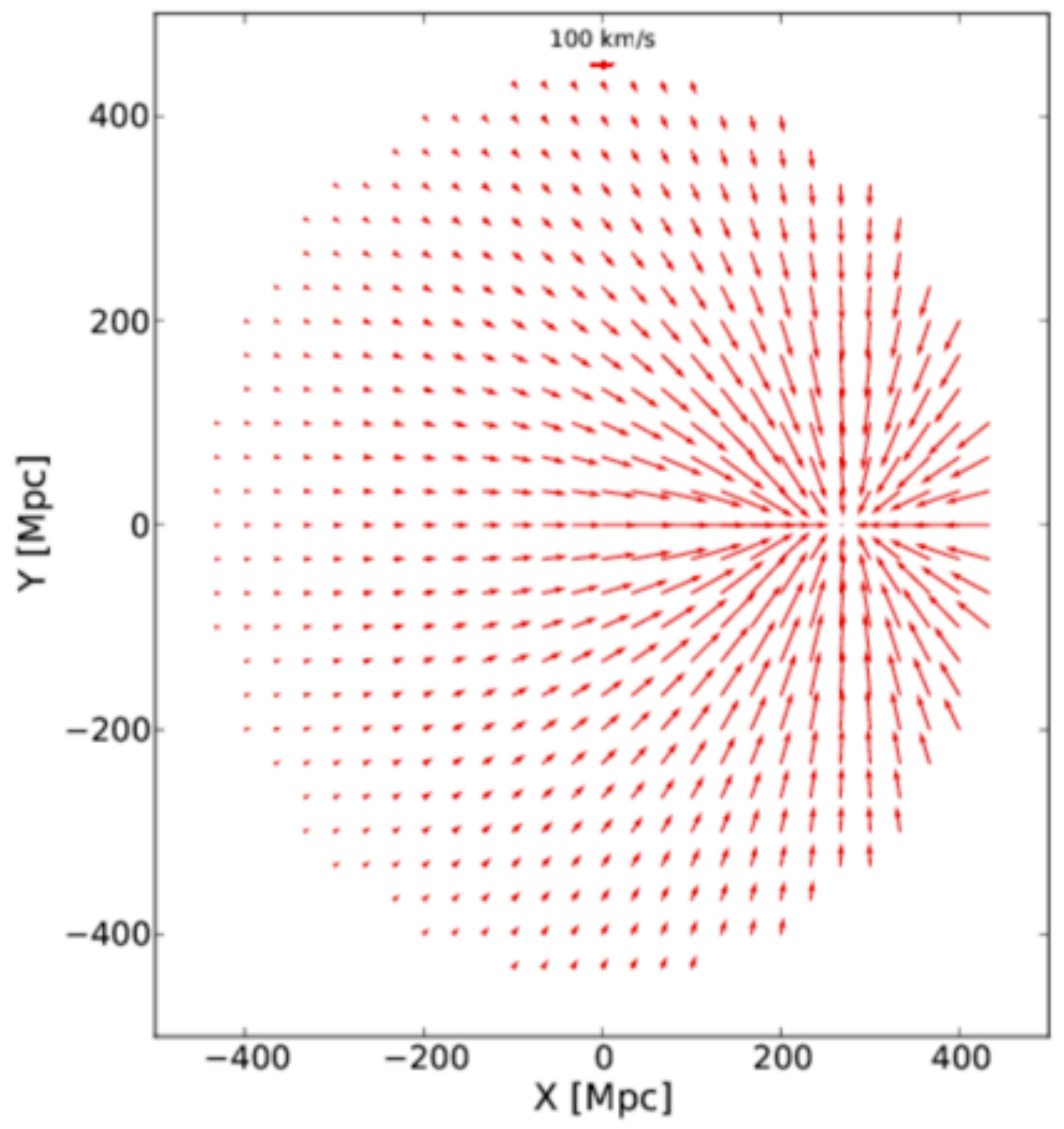
Shear Model

Credit: Uli Feindt

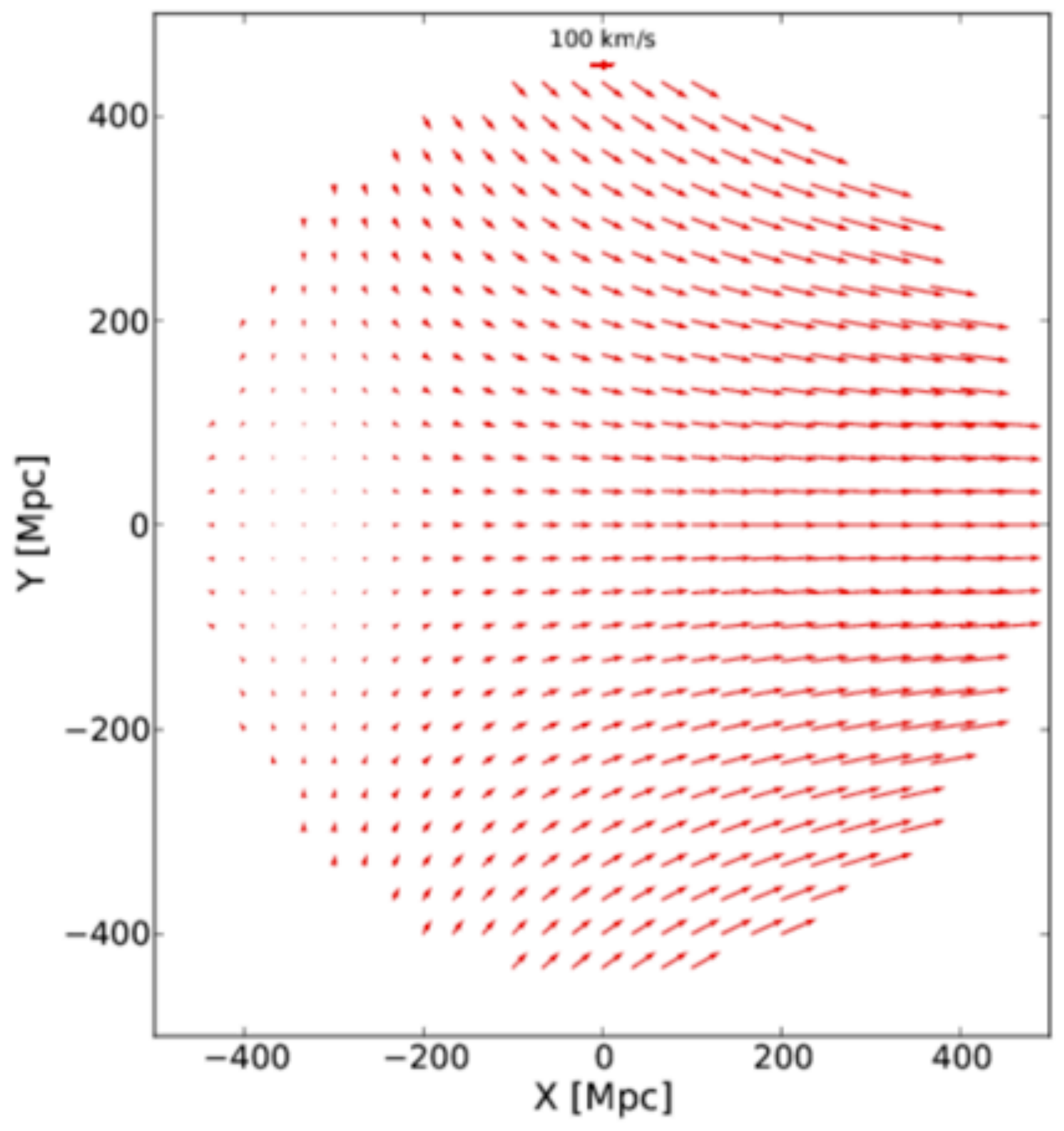
Velocity tidal field:

- Adds 6 new parameters (1 monopole, 5 quadrupole/shear)
- Can estimate distance to attractor as convergence of velocity lines

Spherical attractor



Dipole + Shear

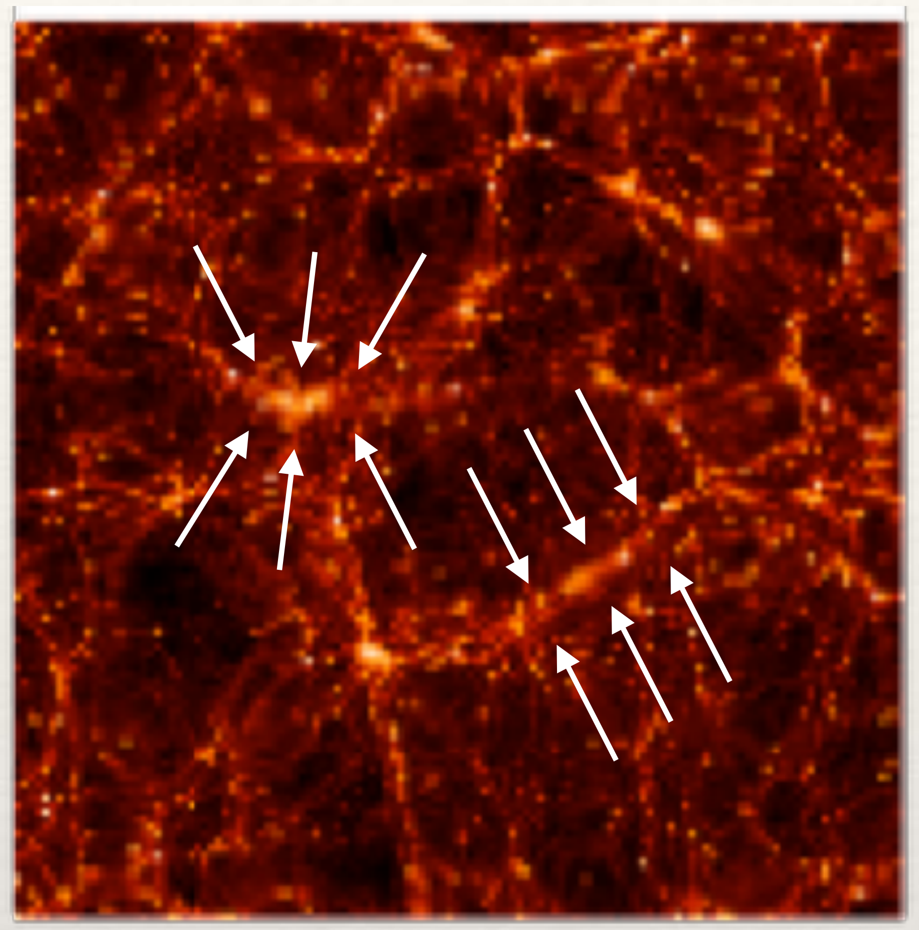


Growth of structure

Simulated local universes

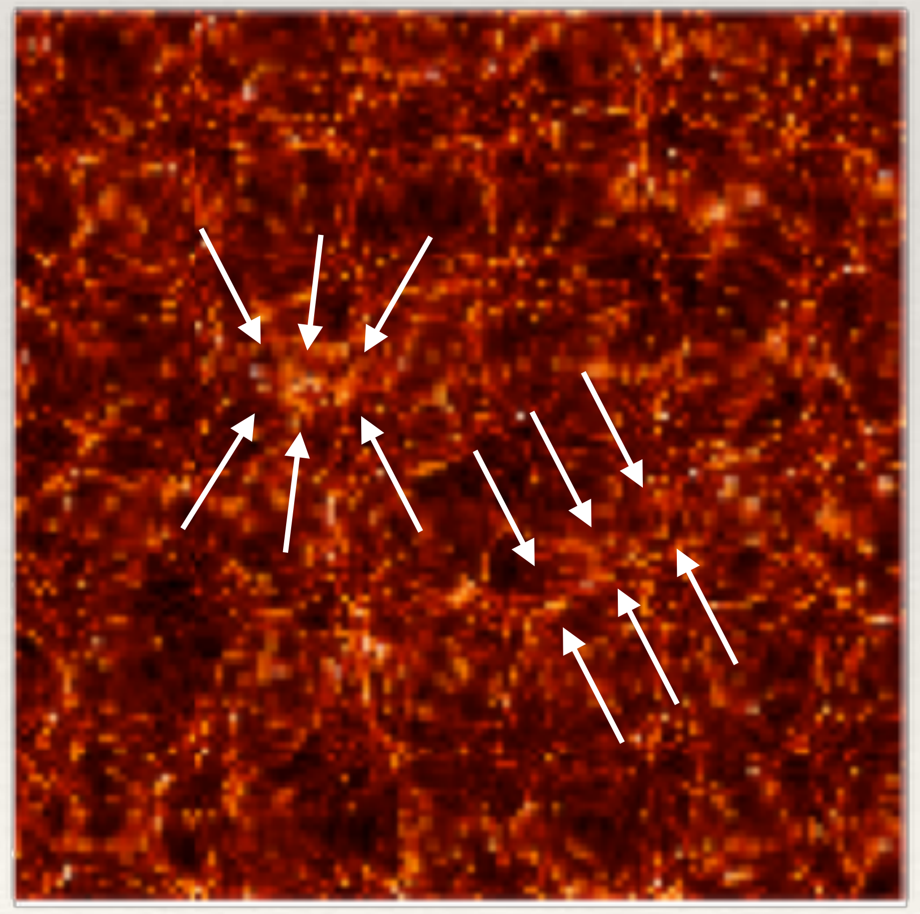
$\Lambda CDM + GR$

$f\sigma_8 = 0.42$

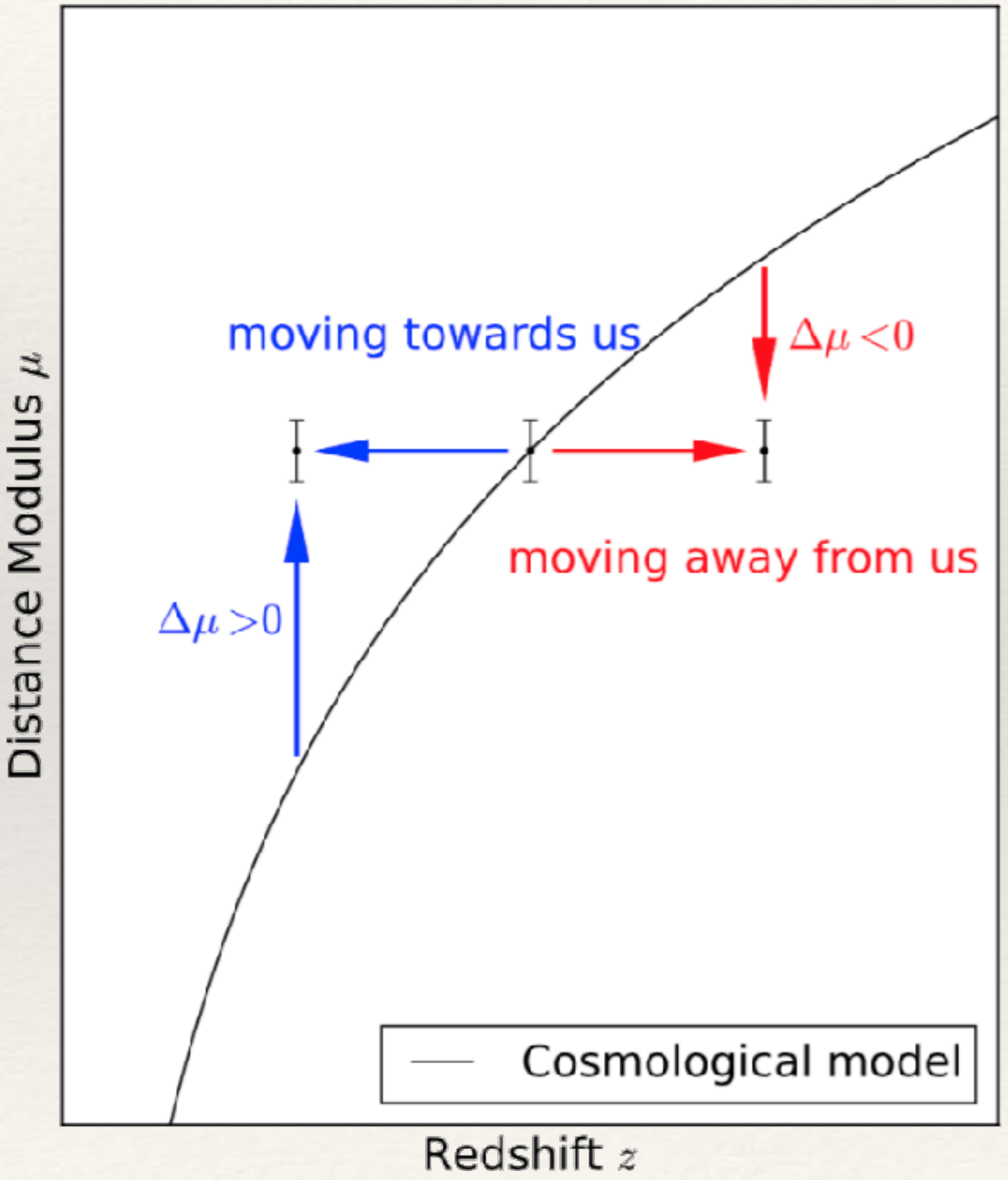


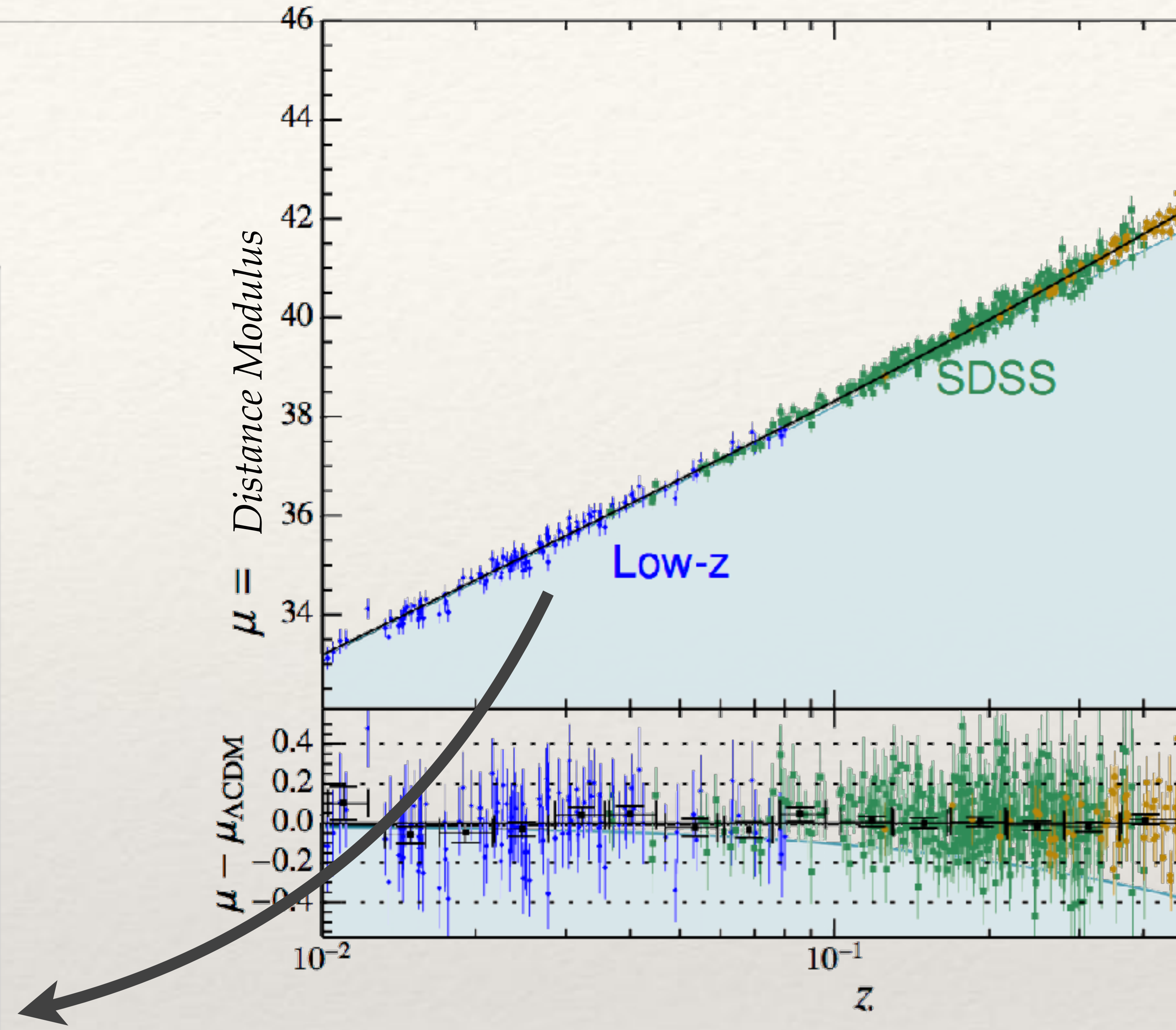
$CDM + GR$

$f\sigma_8 = 1$



Huterer et al., 2013



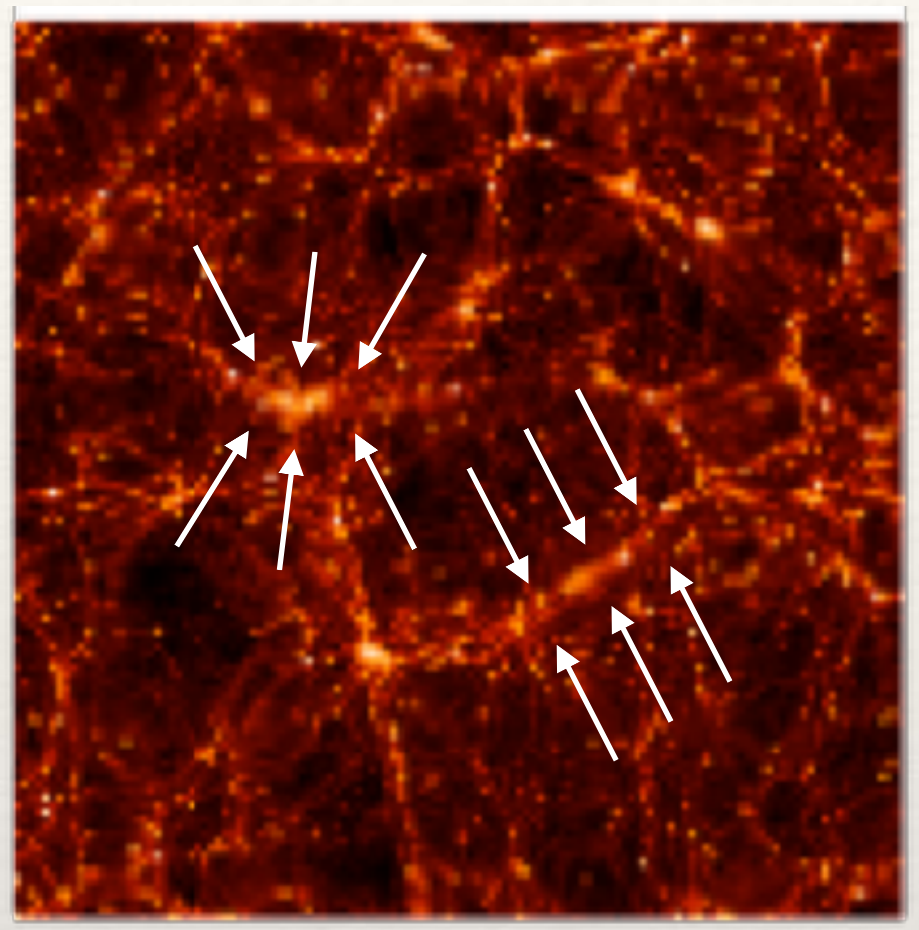


Growth of structures

Simulated local universes

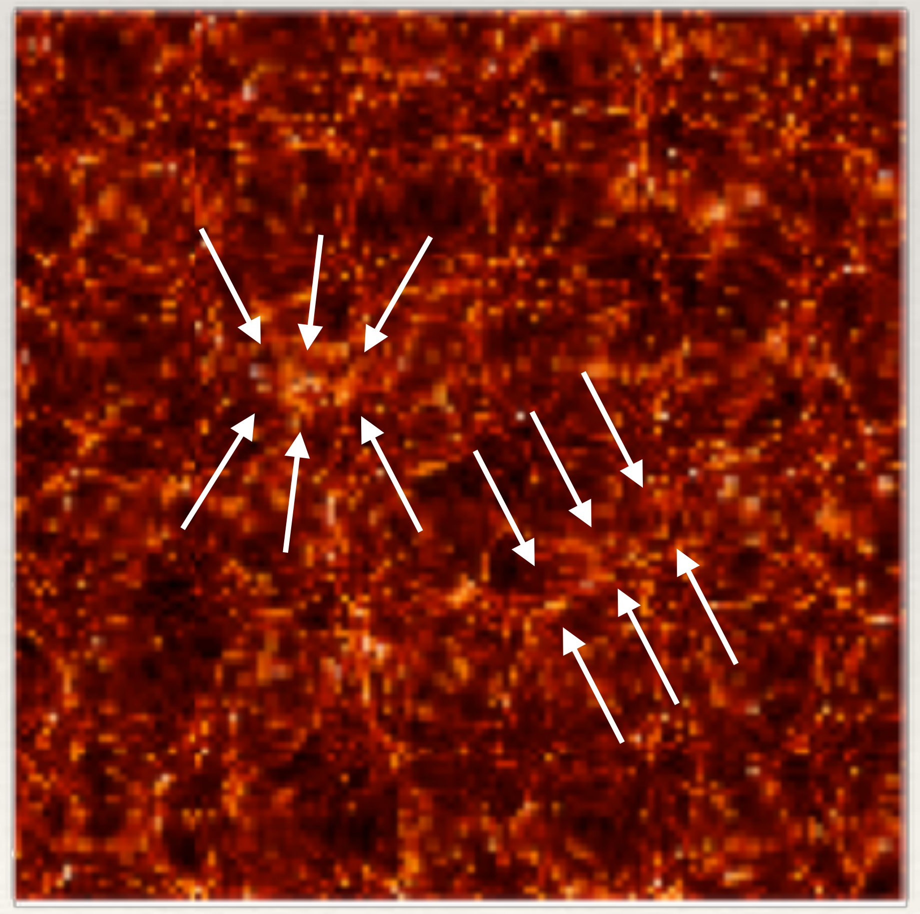
$\Lambda CDM + GR$

$f\sigma_8 = 0.42$



$CDM + GR$

$f\sigma_8 = 1$



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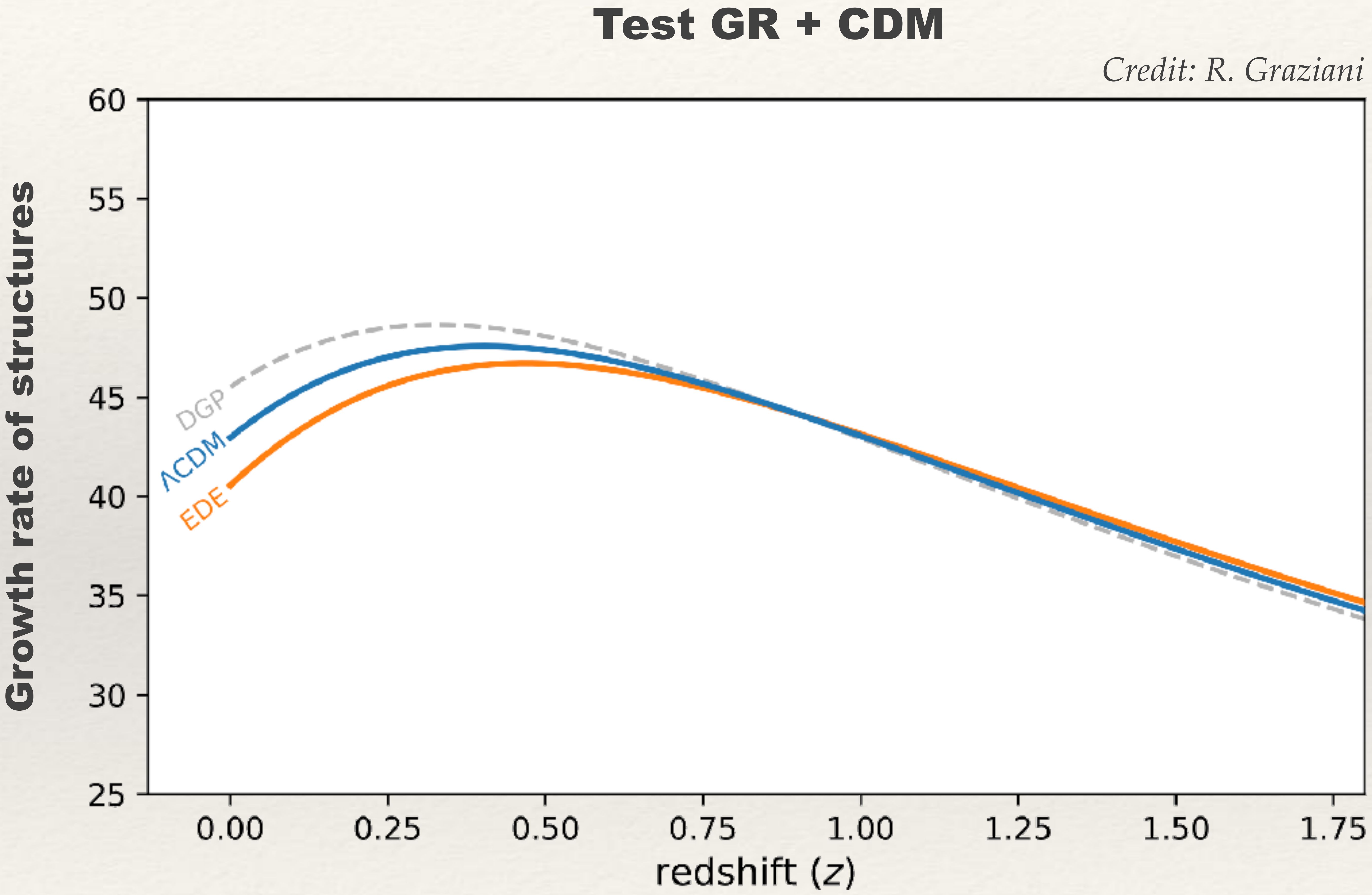
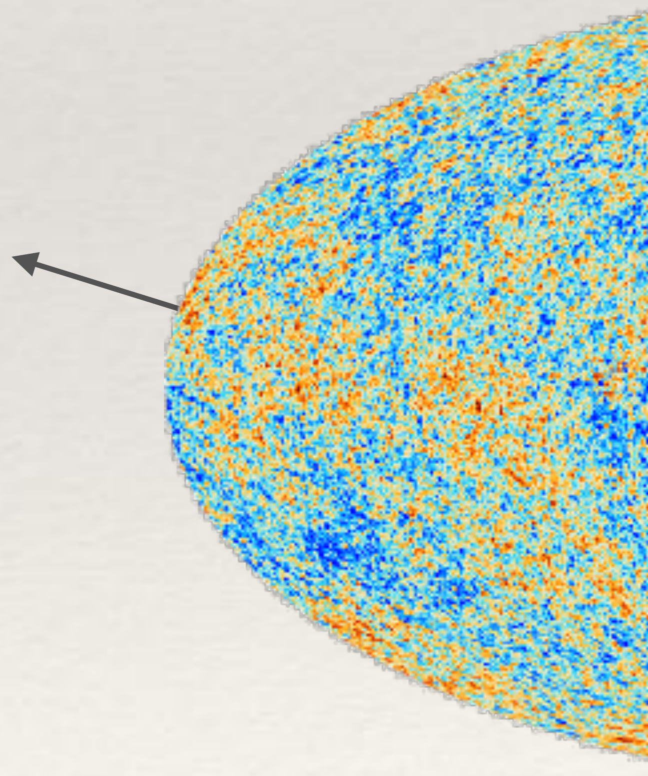
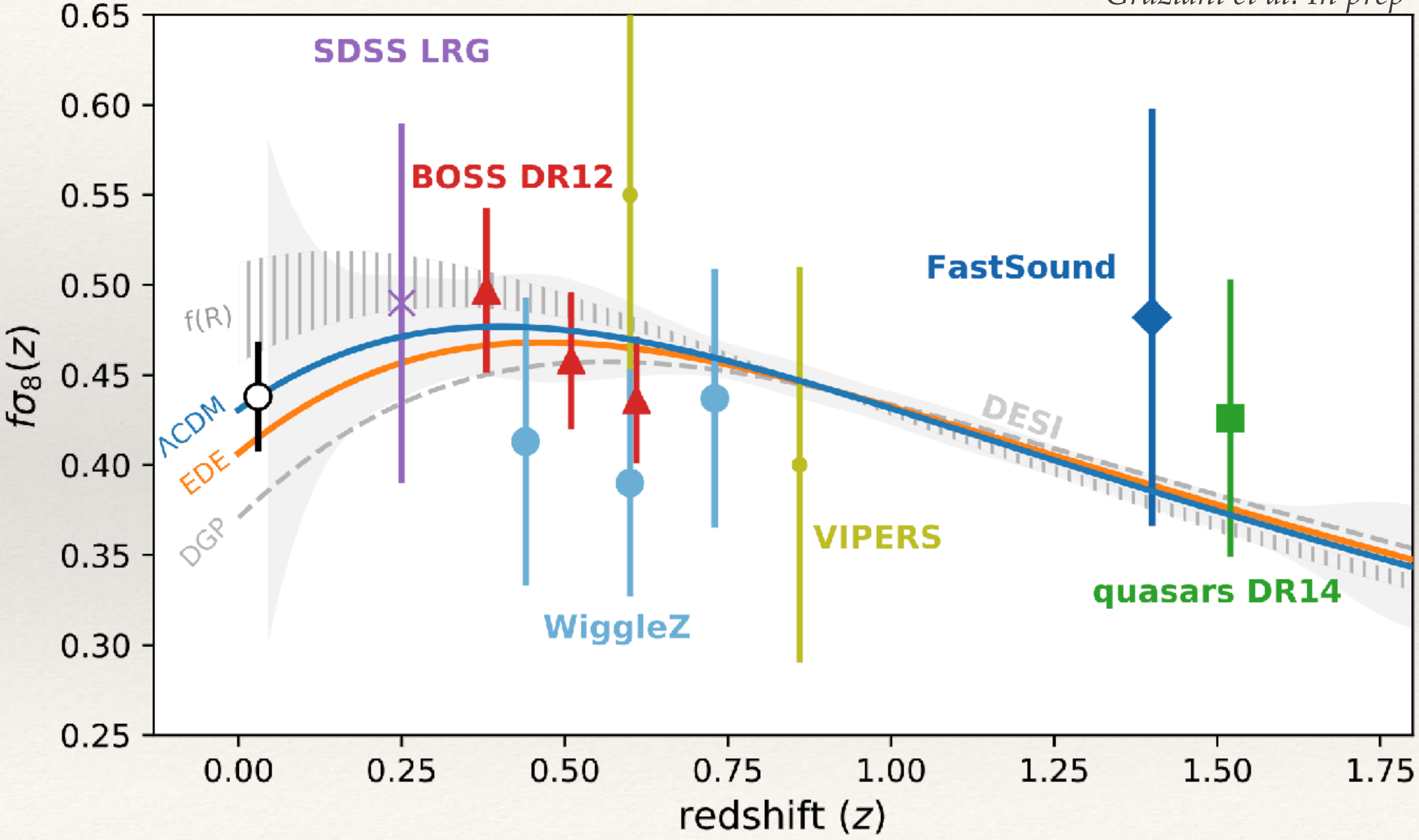




$z \sim 1100$

Peculiar Velocities | *Testing General Relativity*

Graziani et al. In prep



Thank you