Credit: R. Kaehler, T. Abel (KIPAC, SLAC), AMNH

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

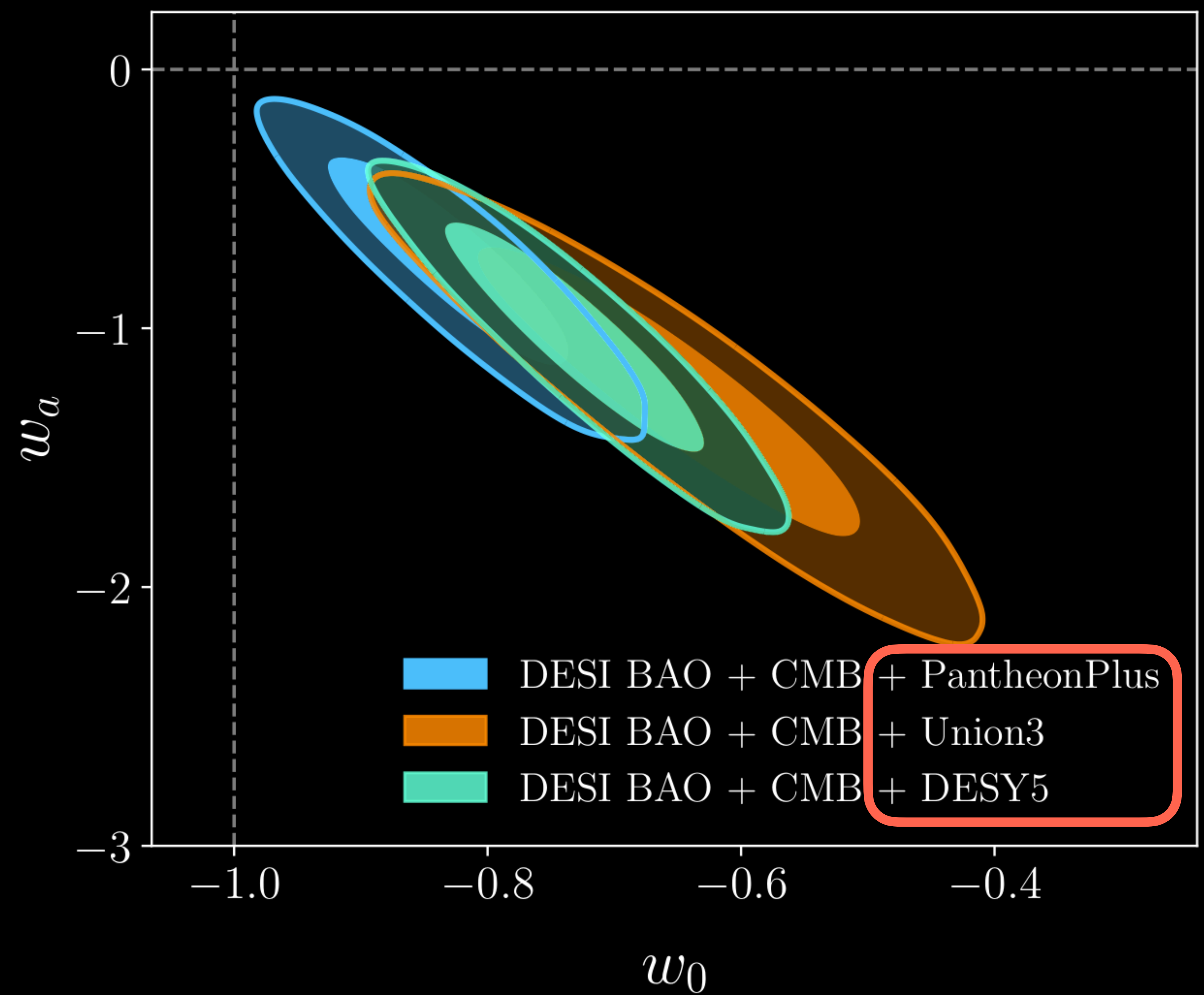
# Supernovae Cosmology in the era of large surveys

Benjamin Racine
CPPM

EDSU tools, Noirmoutier

04/06/2024

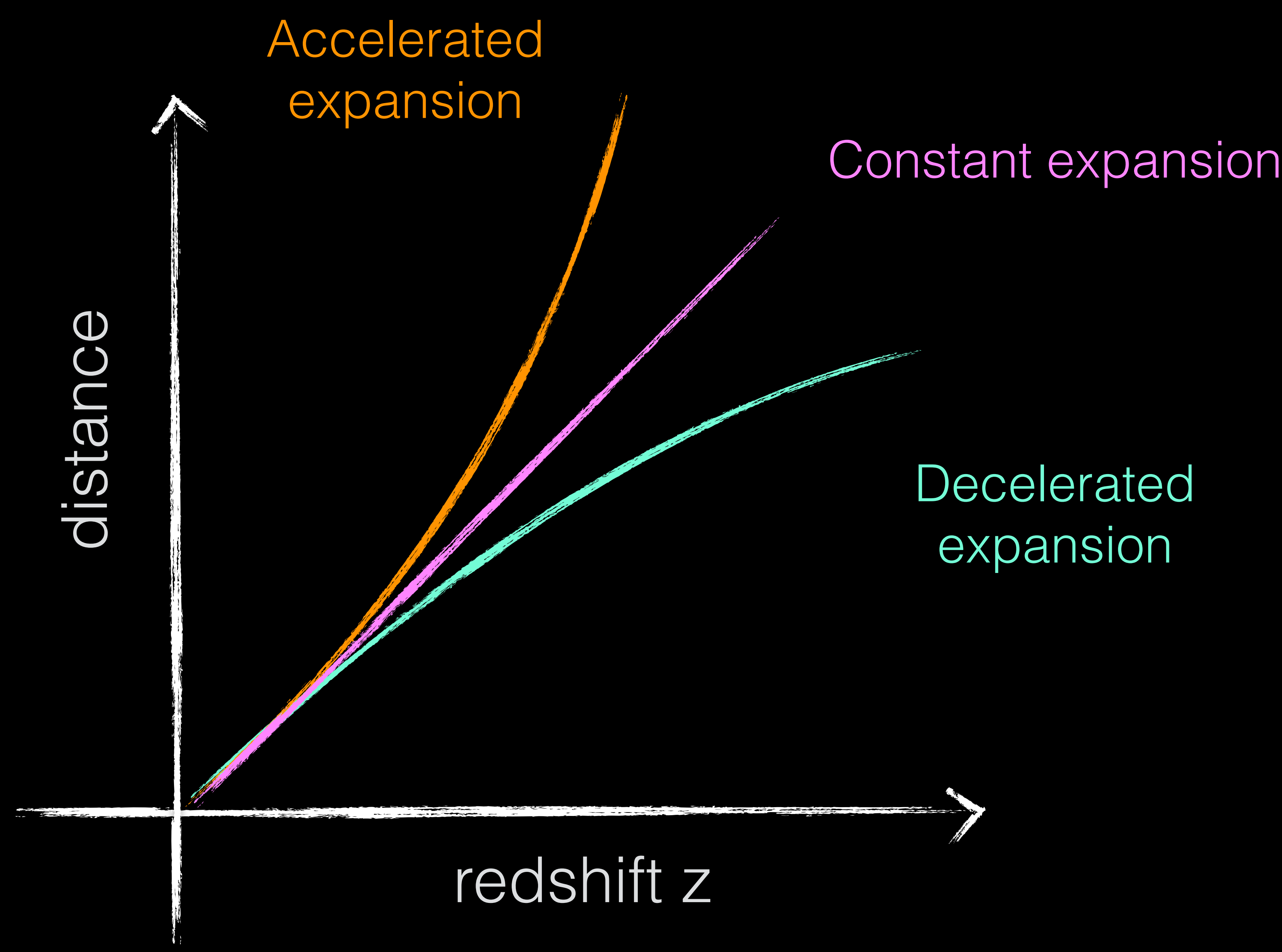
# DESI results




Type 1a Supernovae !

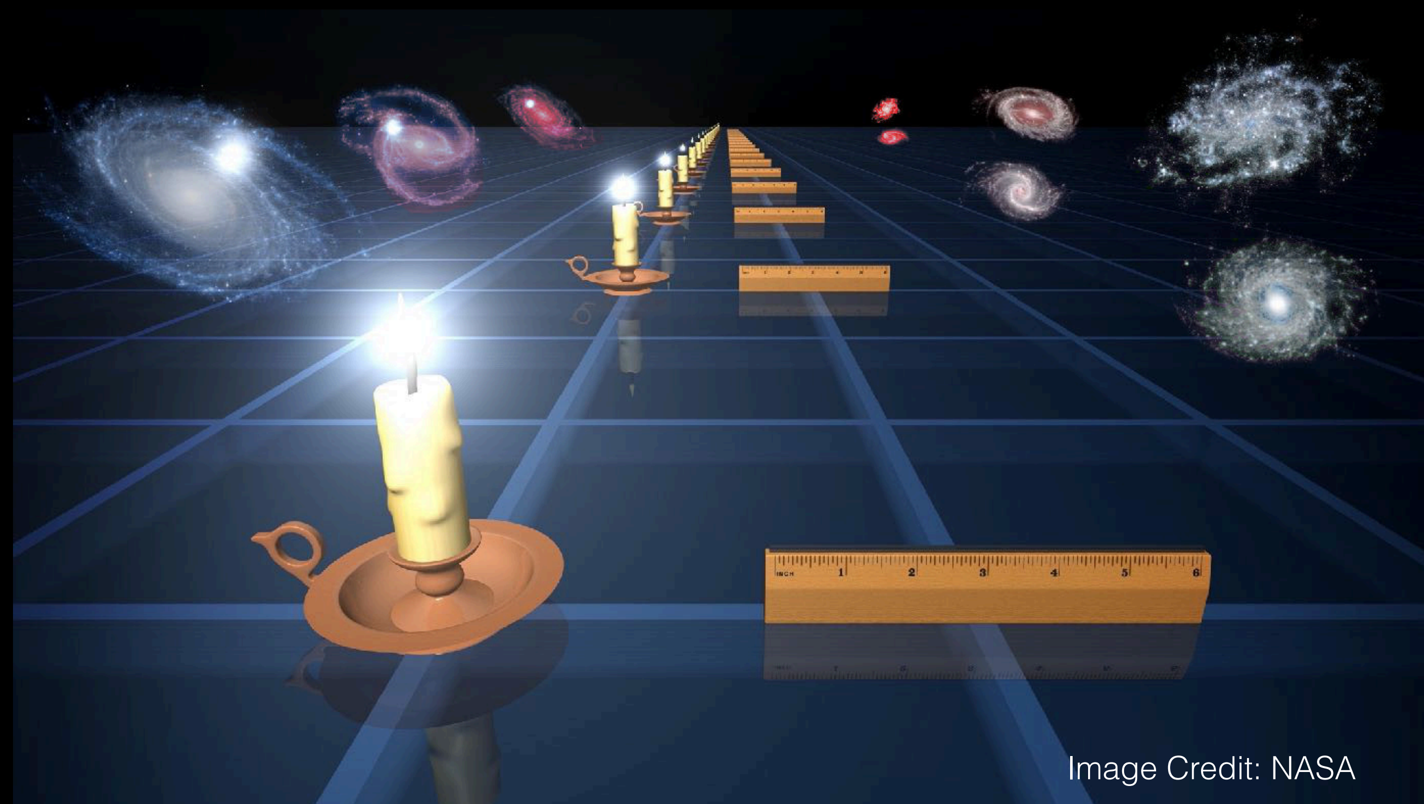
$P = [w_0 + w_a(1 - a)]\rho$ a=scale factor of the Universe

# Measuring the background expansion




Our goal:
Map this expansion as a function of distance

# Measuring the background expansion




*standard candle:*
*know luminosity*
*infer distance*

*standard ruler:*
*know size*
*infer distance*

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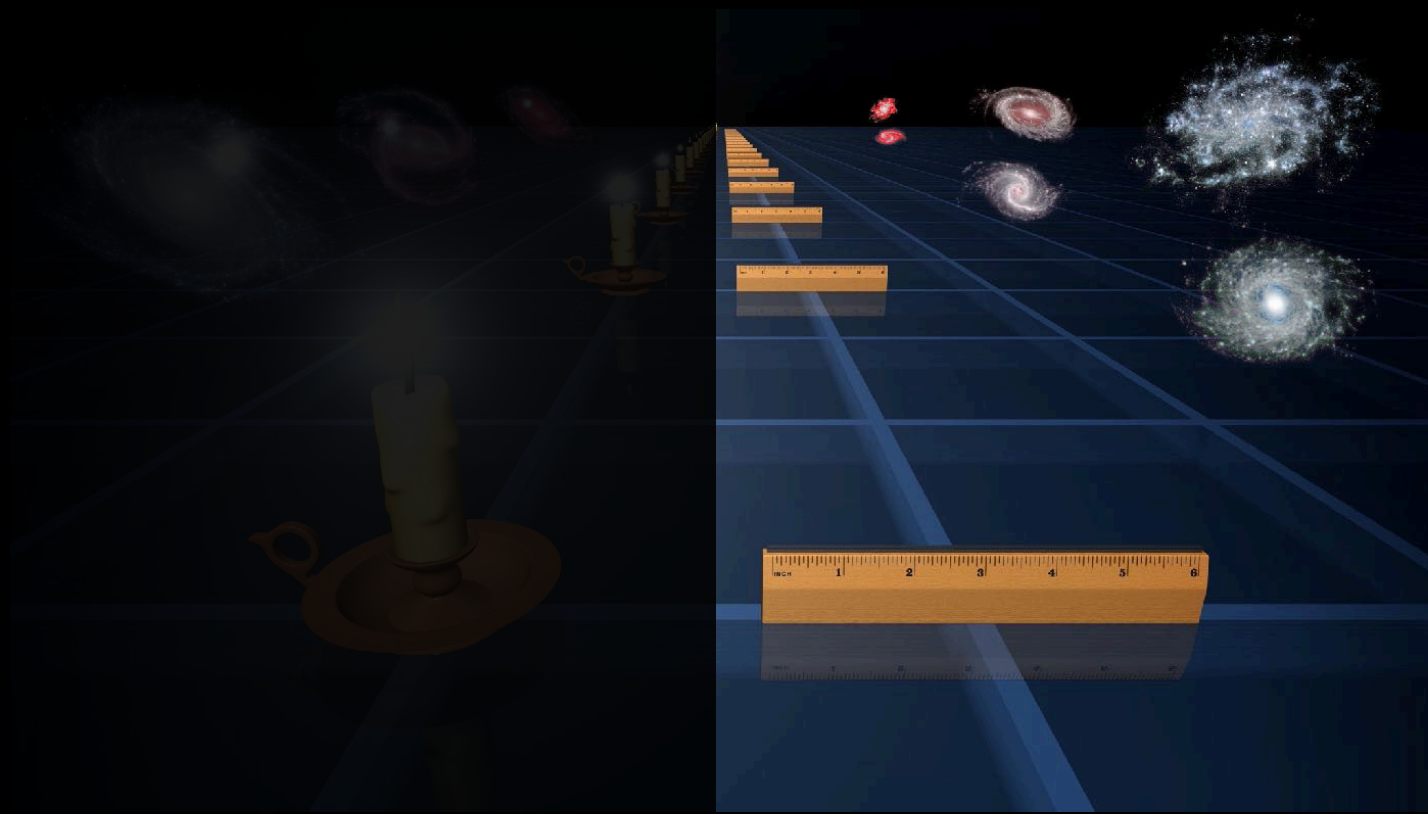
Map this expansion as a function of distance

# Measuring the background expansion



See DESI BAO results by Arnaud de Mattia

*standard candle: know luminosity infer distance*

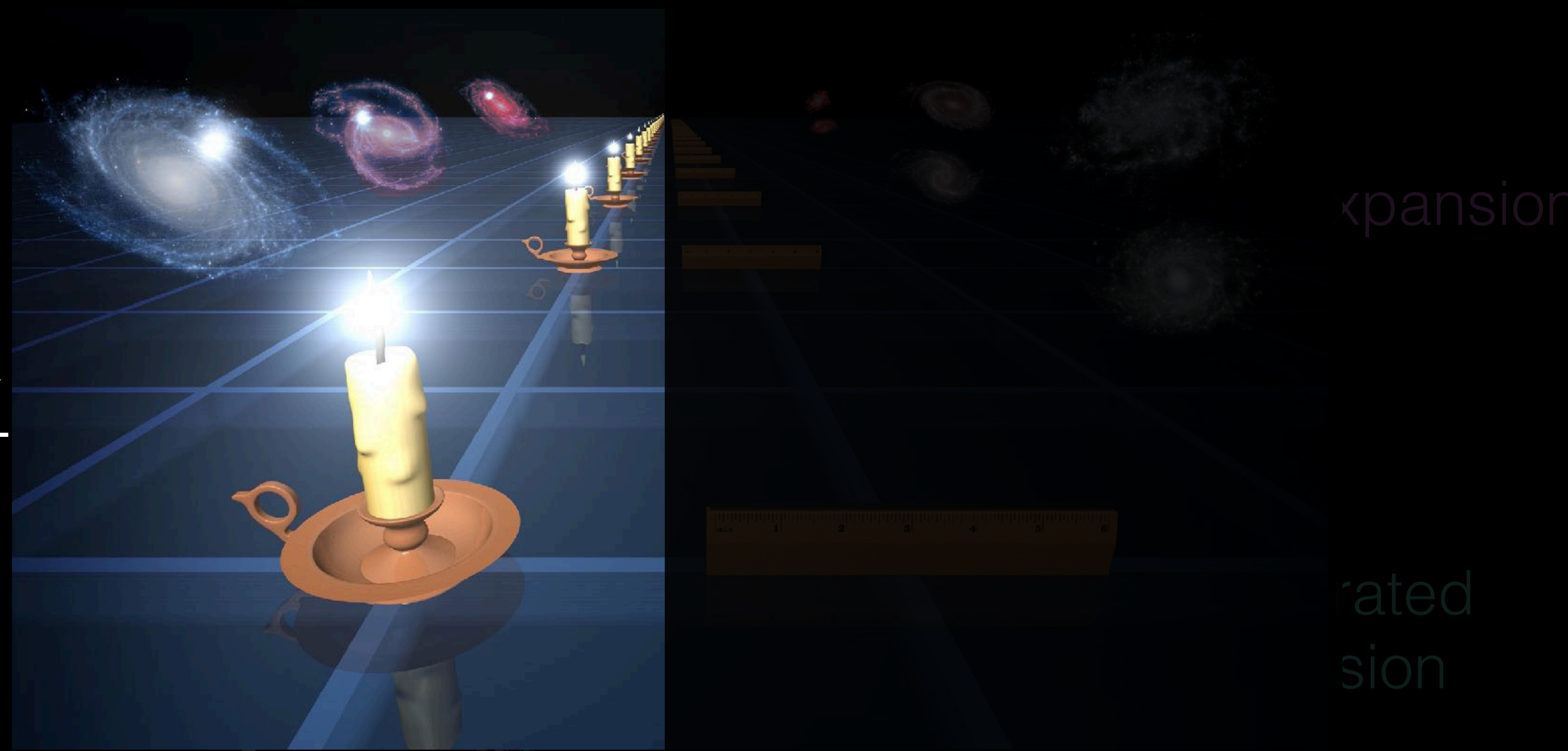
*standard ruler: know size infer distance*

redshift z

Our goal:
Map this expansion as a function of distance

# Measuring the background expansion

$$\text{Flux} = \frac{1}{4\pi}\frac{\text{Luminosity}}{\text{Distance}^2}$$



*standard candle:*
*know luminosity*
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*standard ruler:*
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redshift z

Our goal:
Map this expansion as a function of distance

# Outline

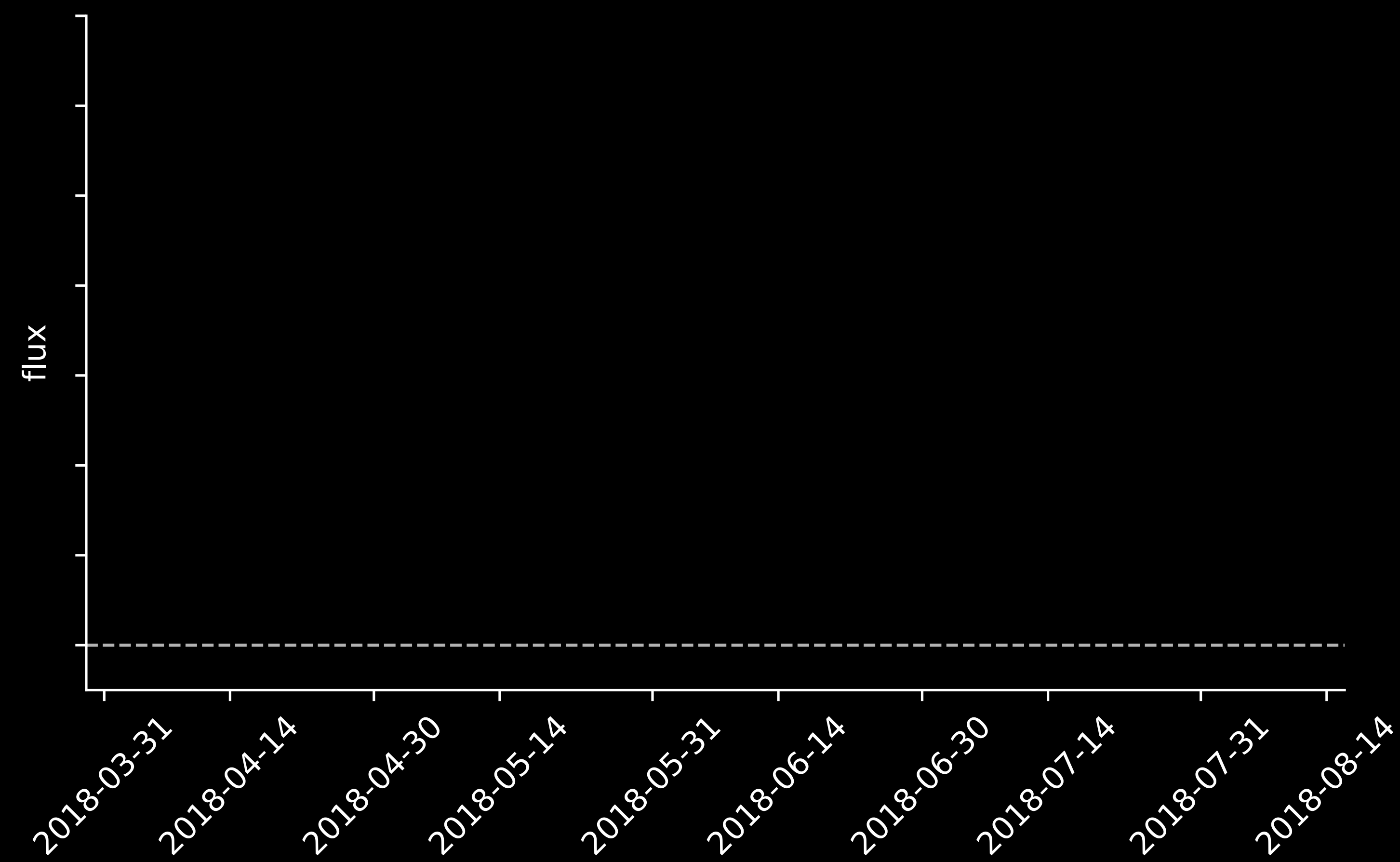
1. Type 1a Supernovae as Standardizable candles

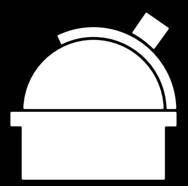
2. Most recent dark energy measurements

3. Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST) and ZTF enter a new era

4. We can probe gravity using SN1a peculiar velocities.

# Type 1a Supernovae



Photo

SN1a: thermonuclear explosion of a white dwarf

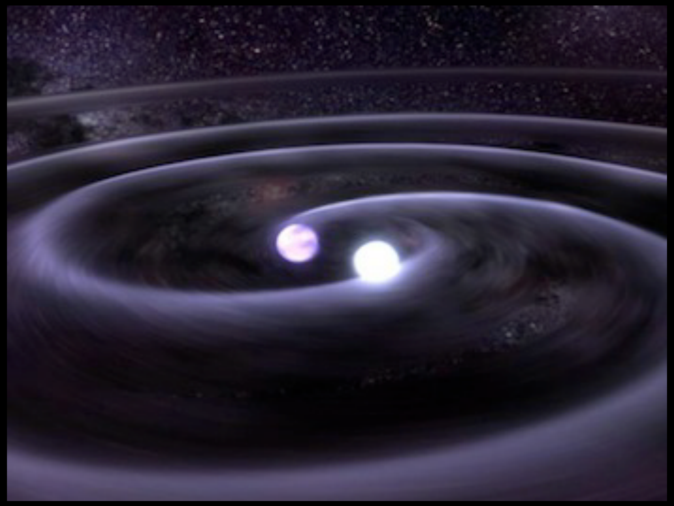


Image Credit: NASA  T. Strohmayer, D. Berry

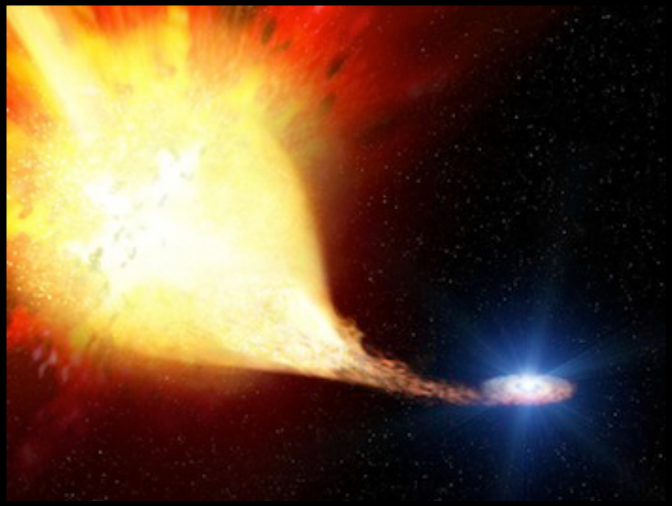


Image Credit: ESA J.R. Maund

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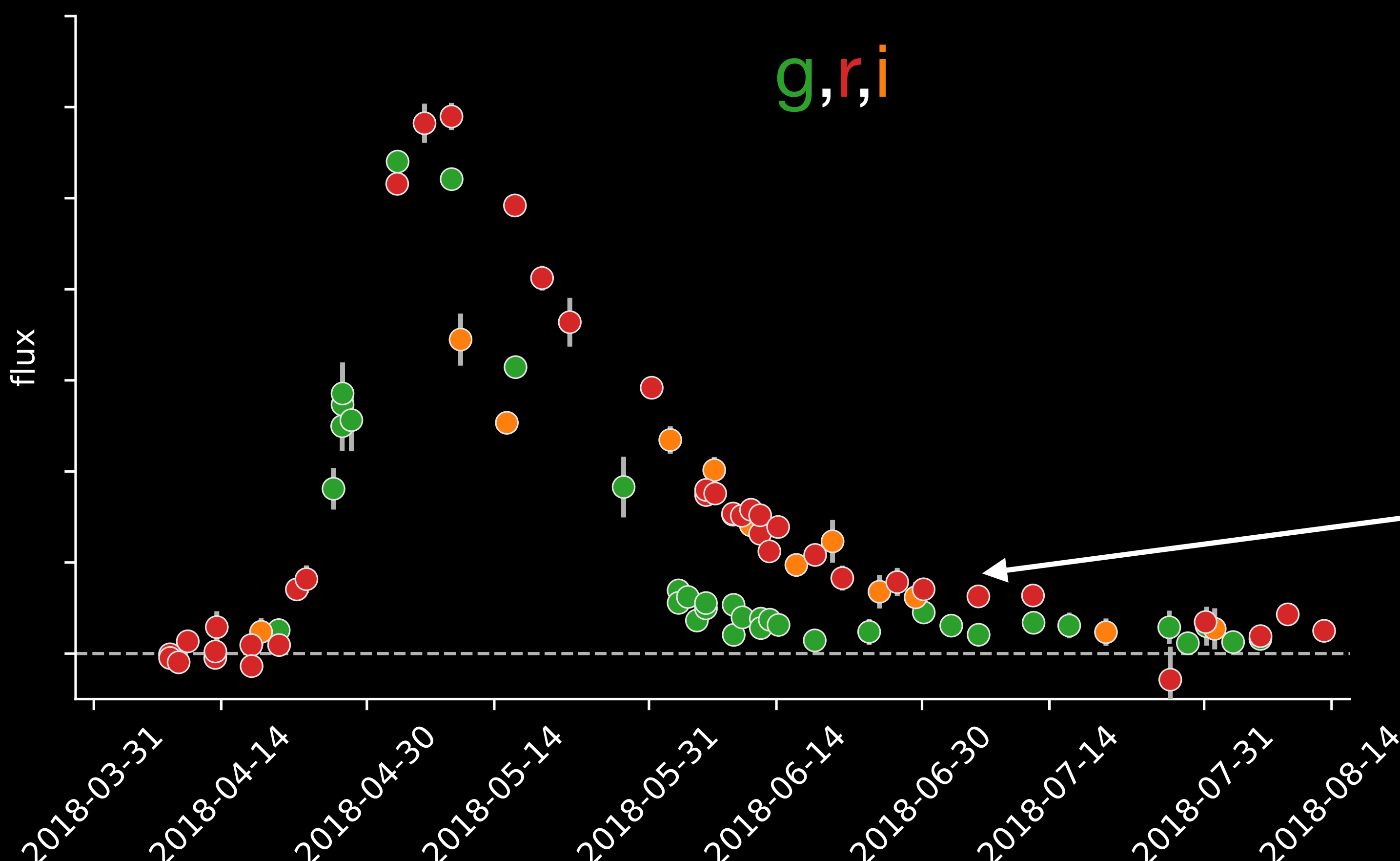


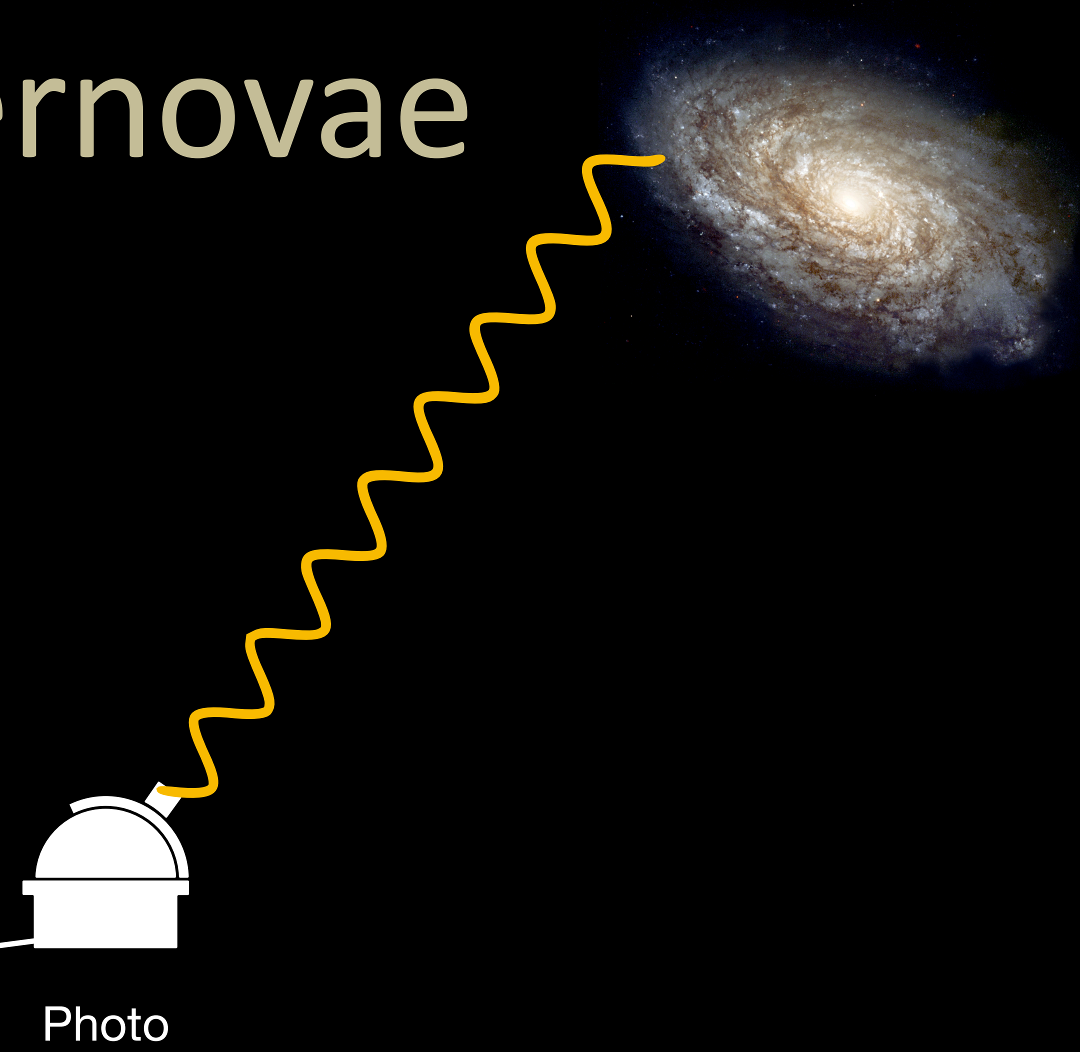


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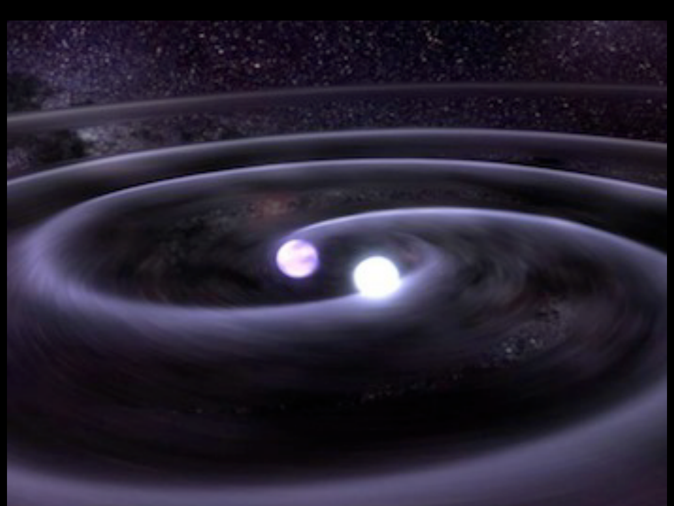
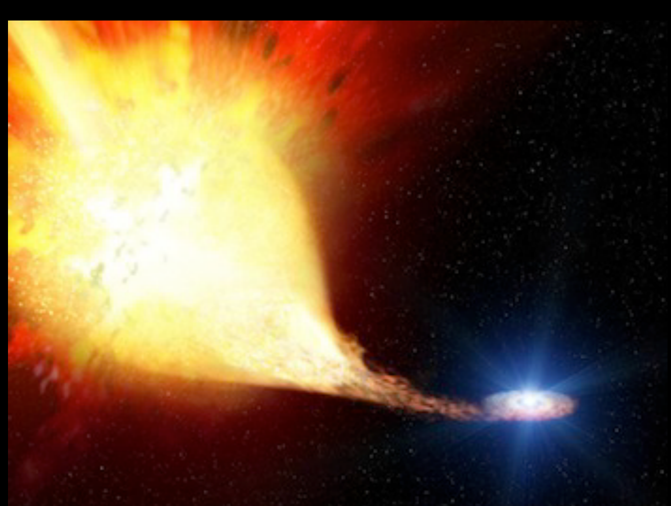


Image Credit: NASA T. Strohmayer, D. Berry



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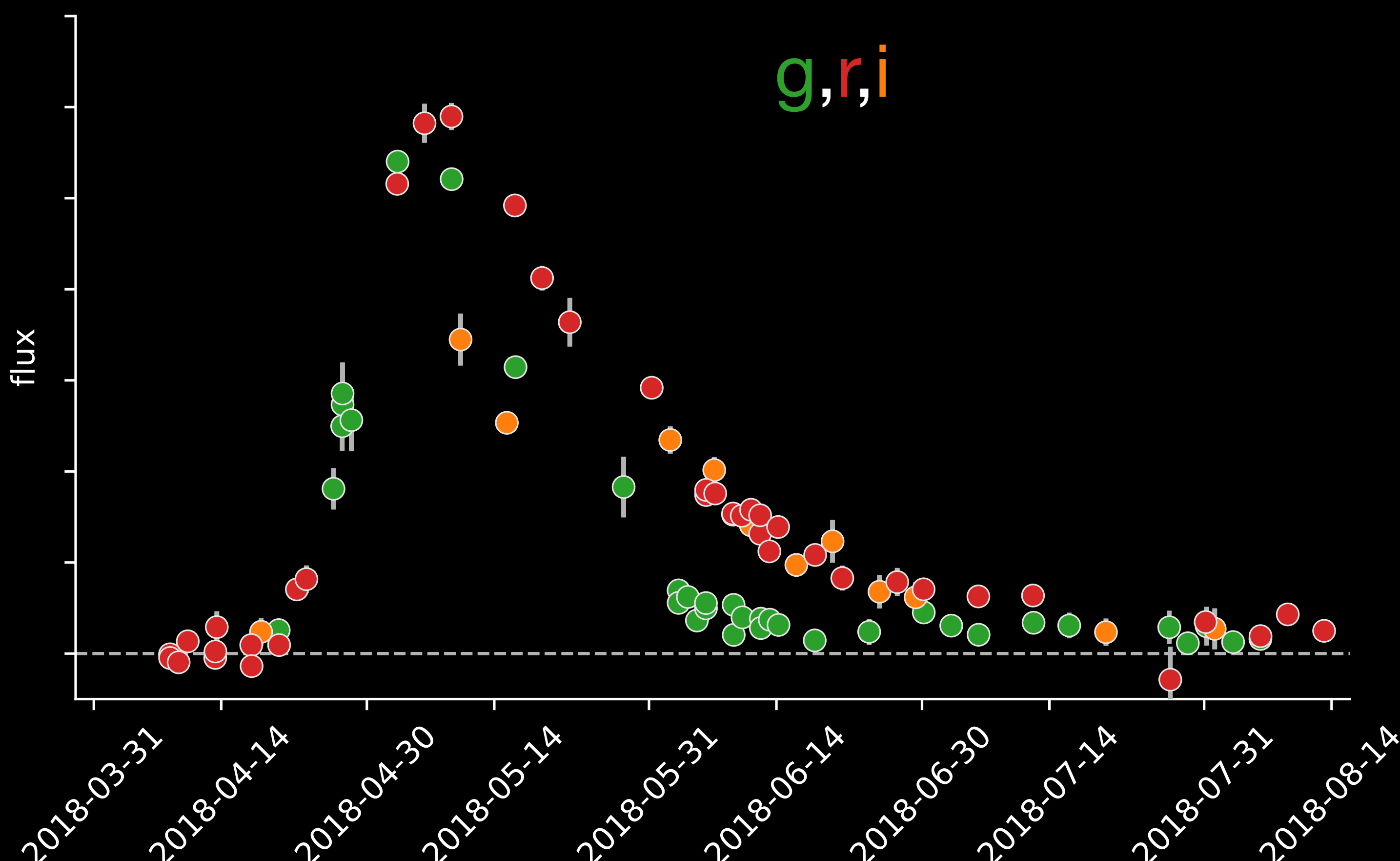


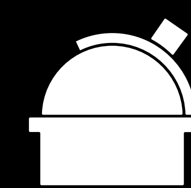

Photo

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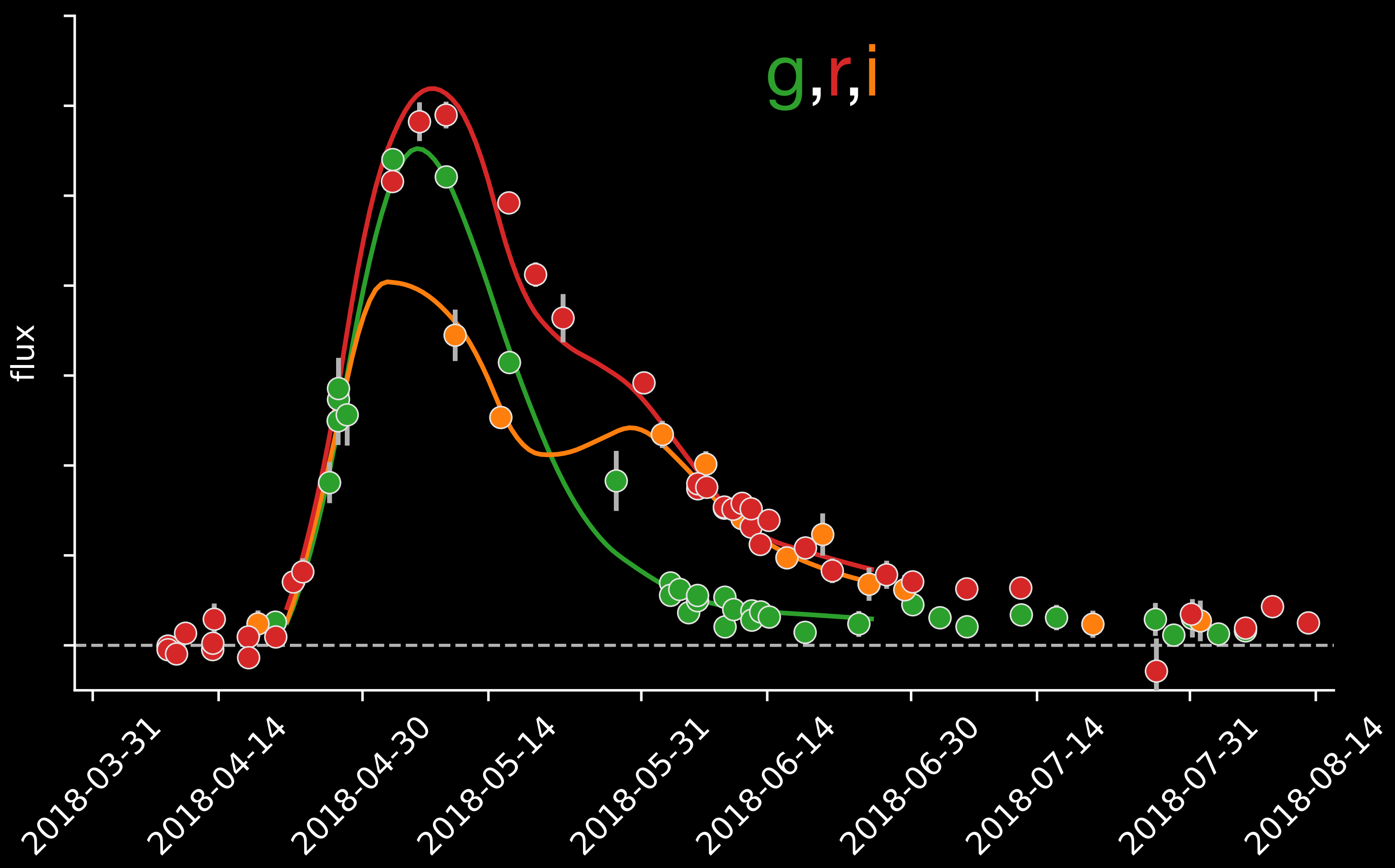
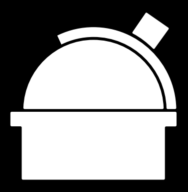
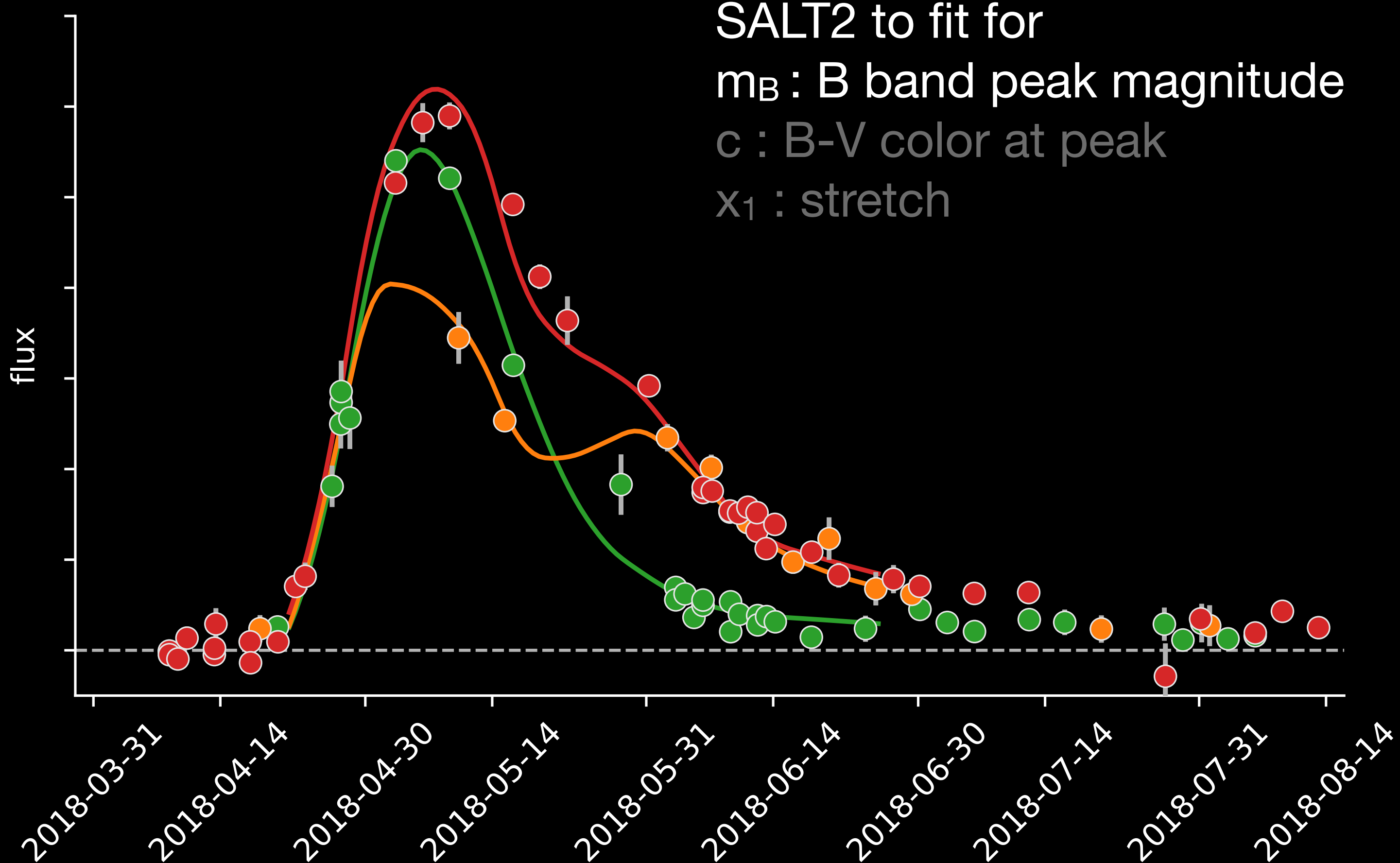
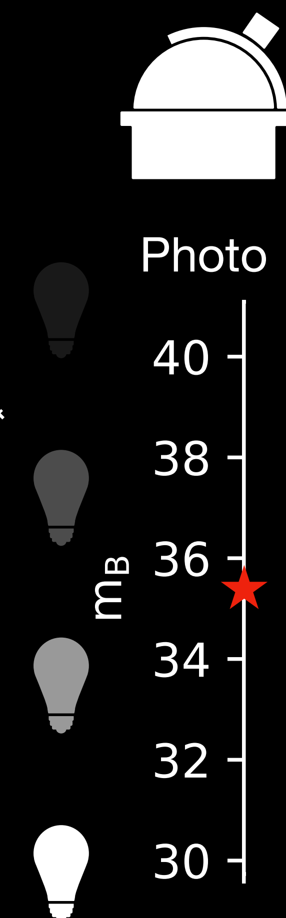


# Type 1a Supernovae

SALT2 to fit for
$m_B$ : B band peak magnitude
c : B-V color at peak
$x_1$ : stretch



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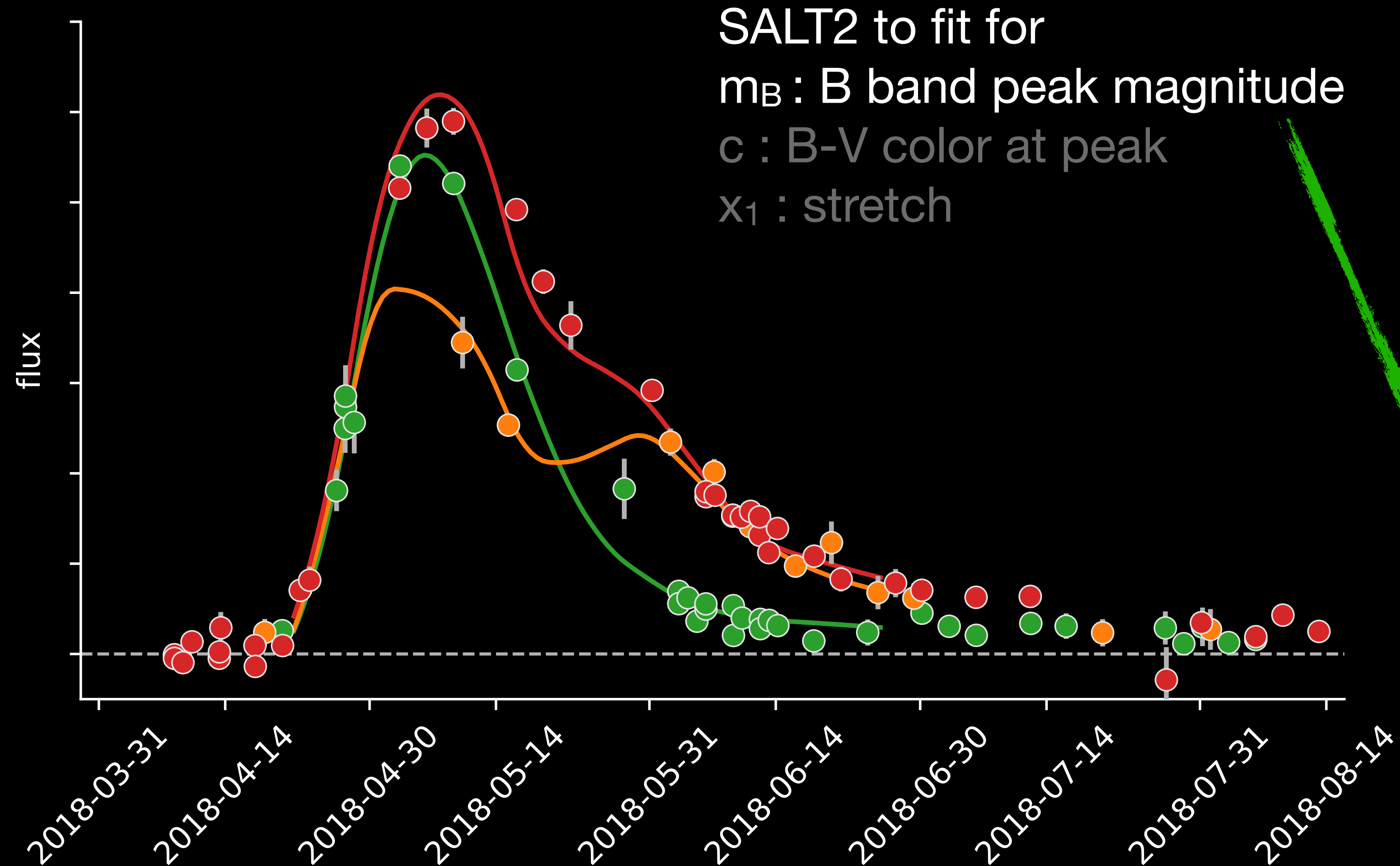


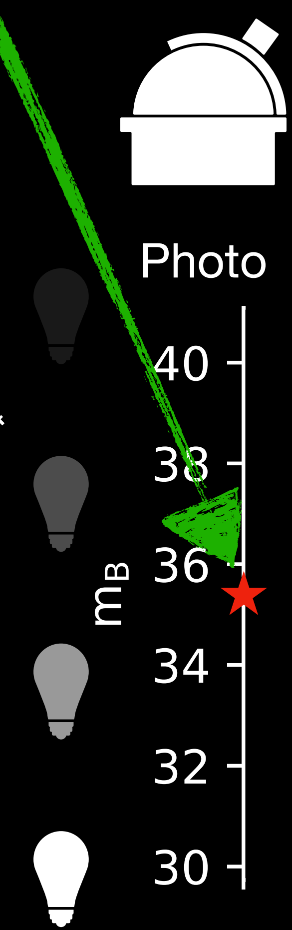

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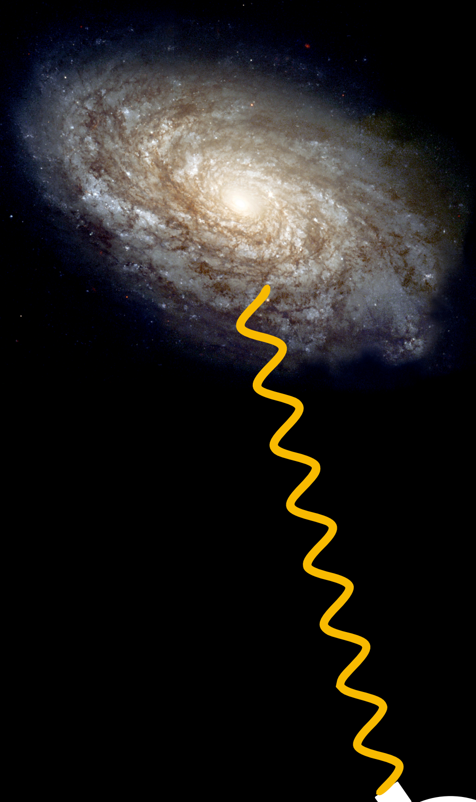

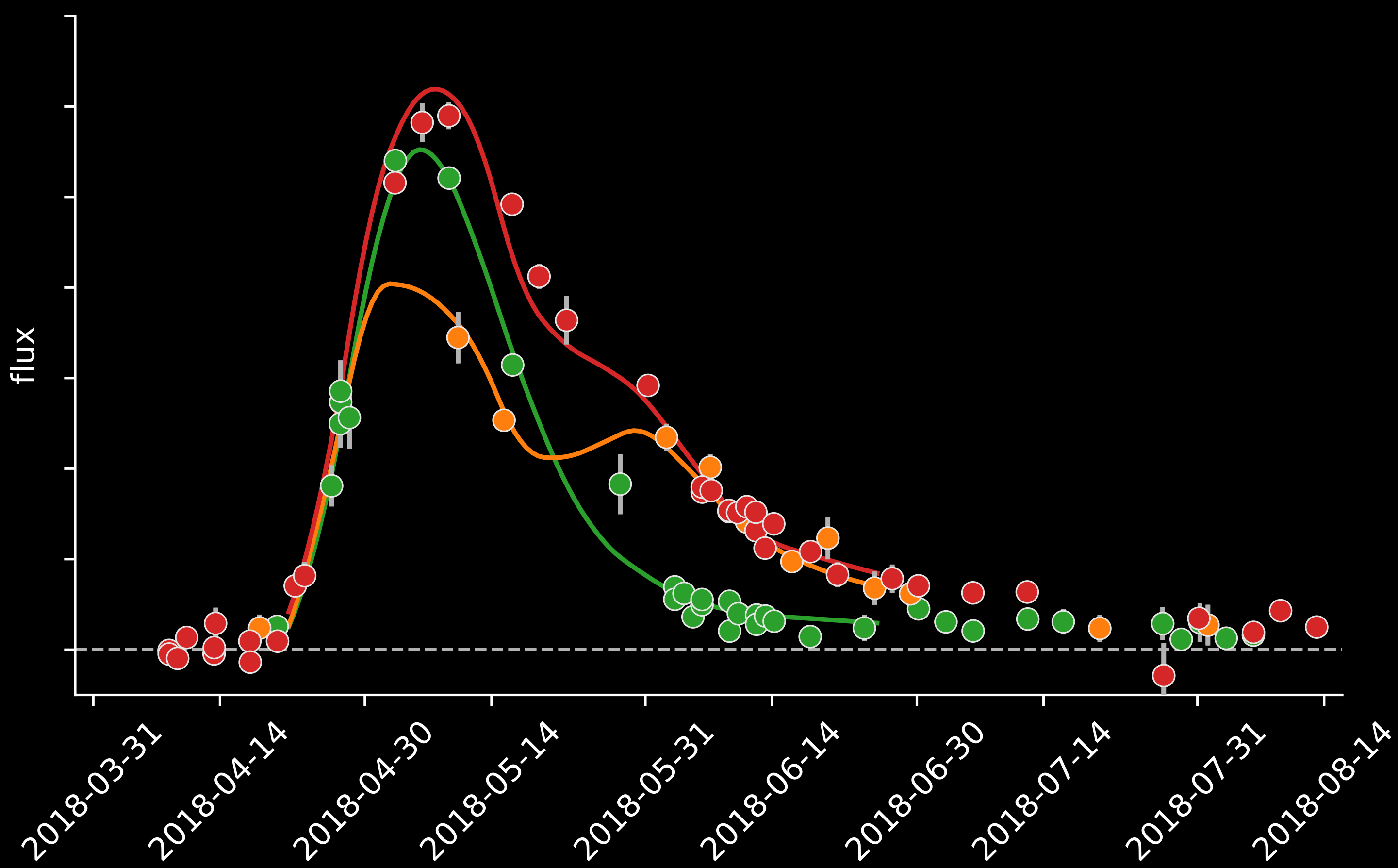


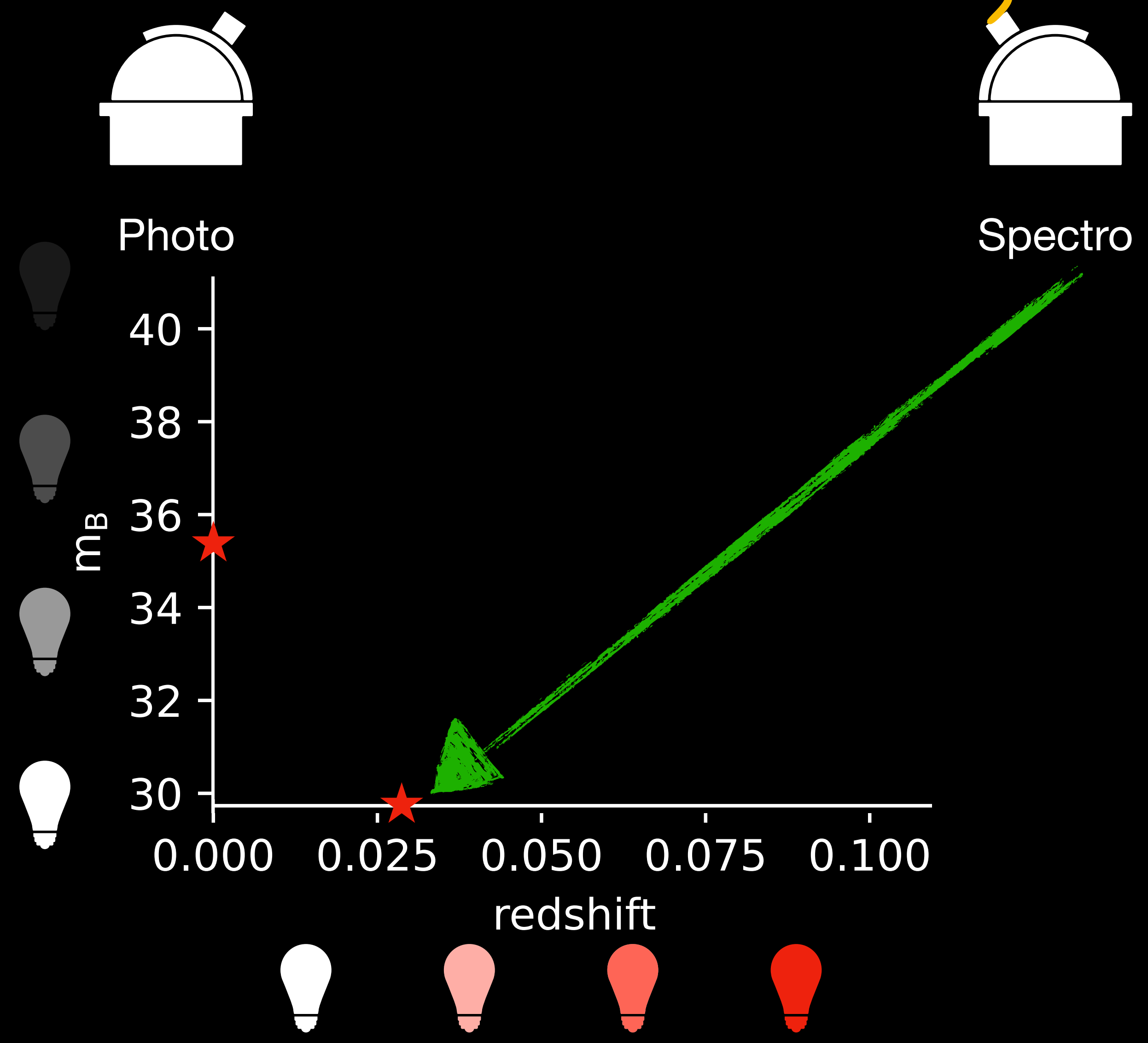

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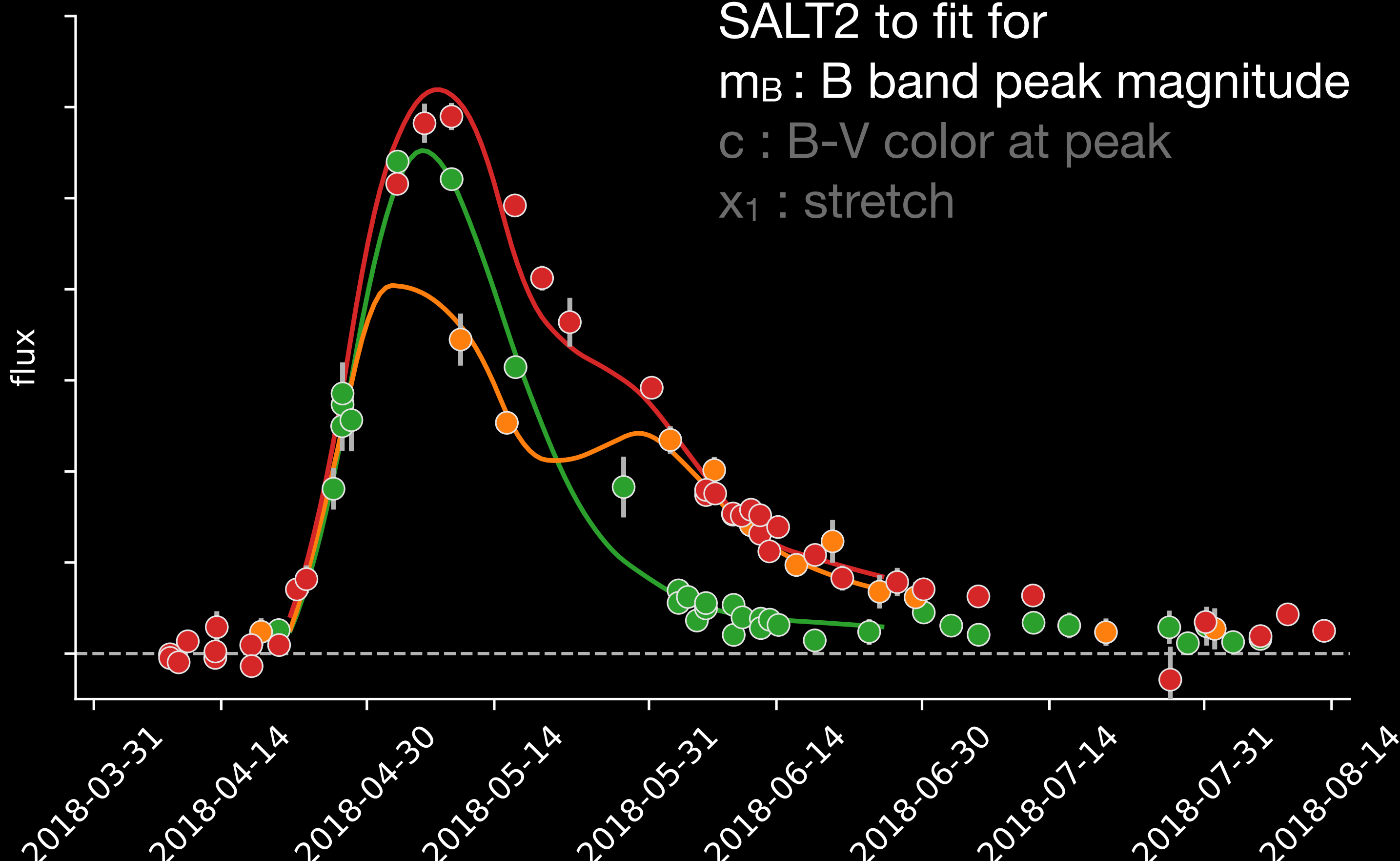


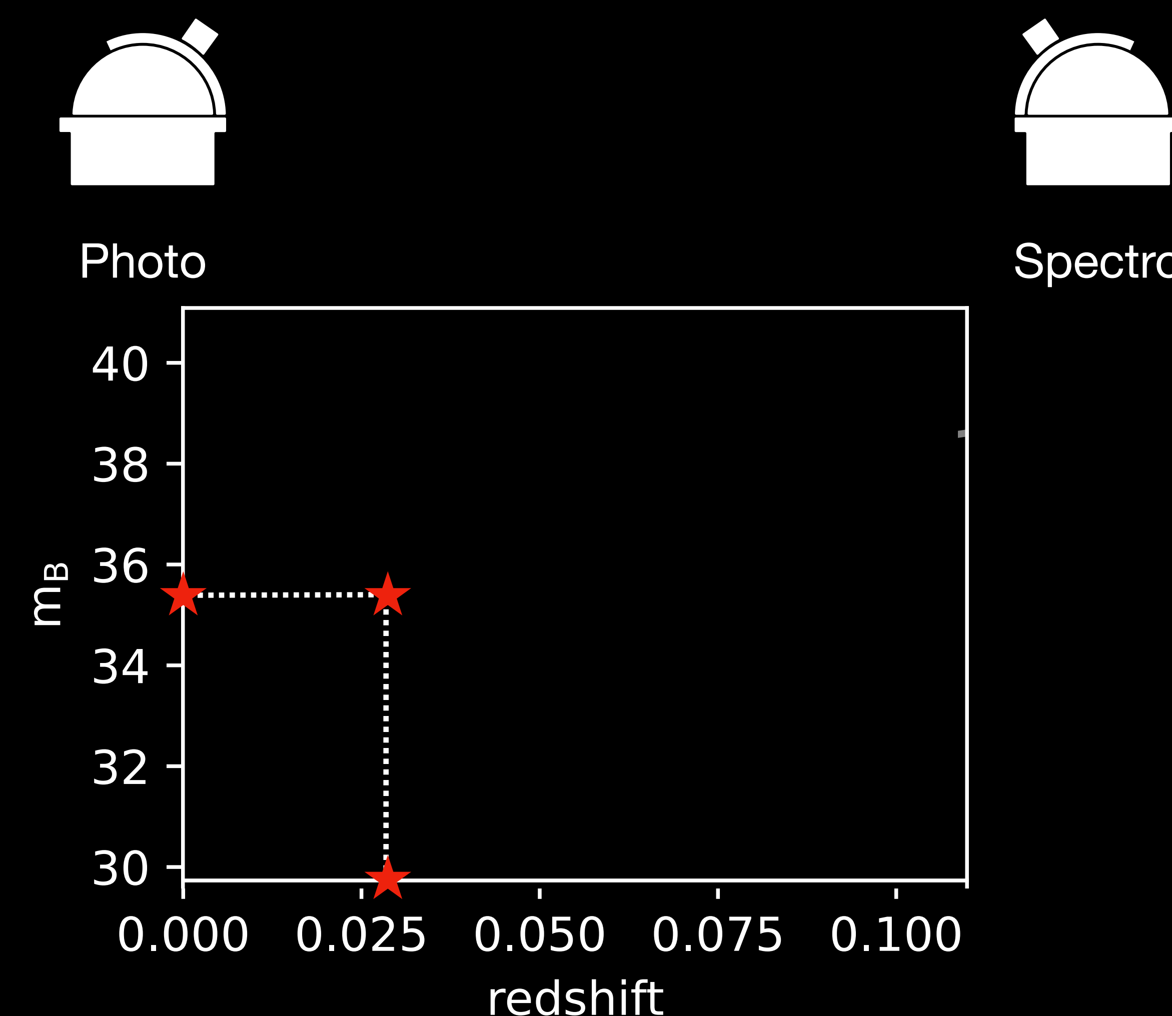

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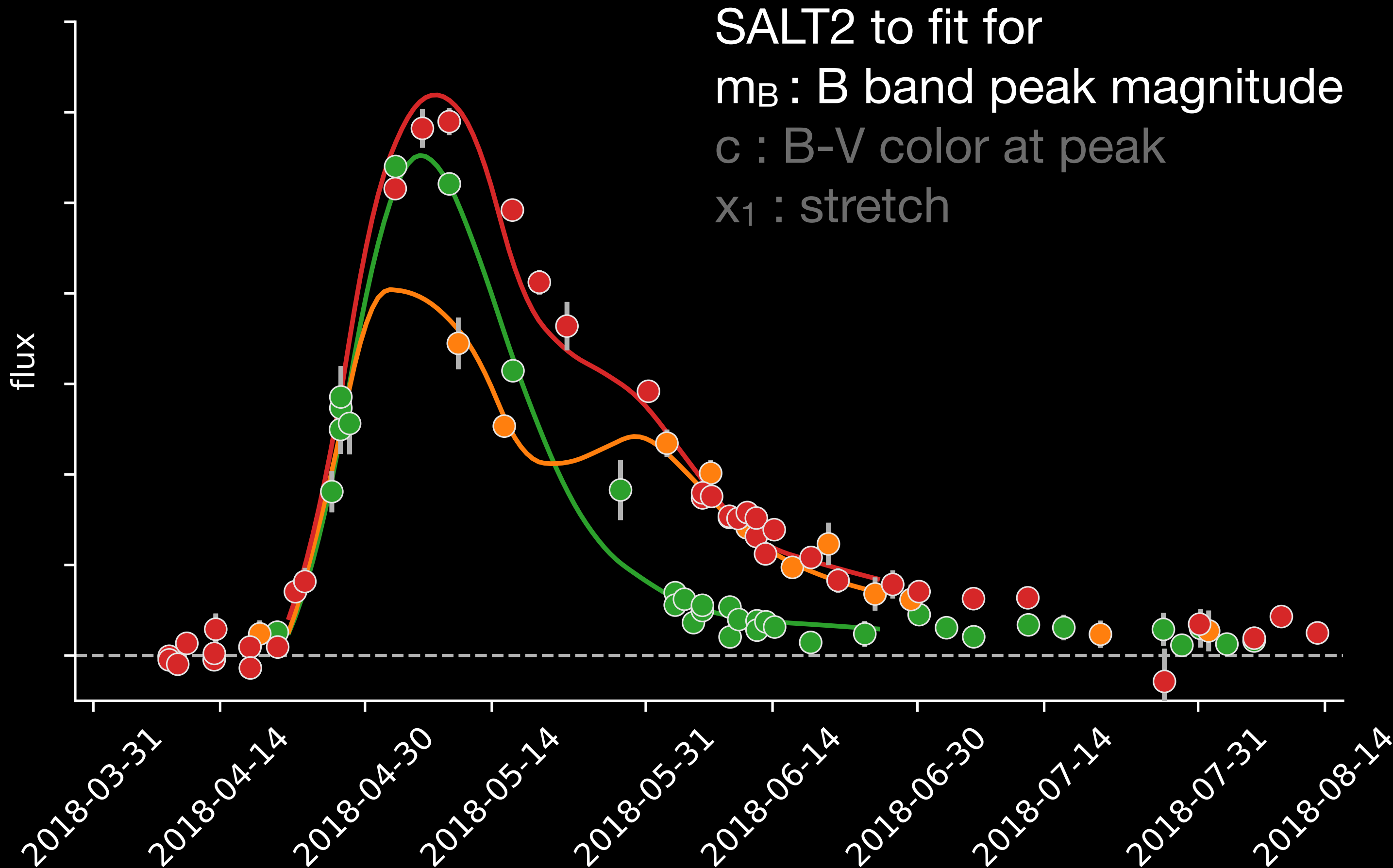


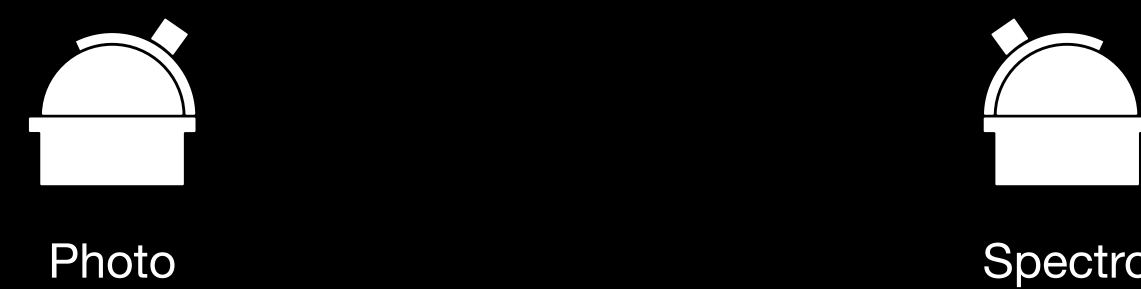


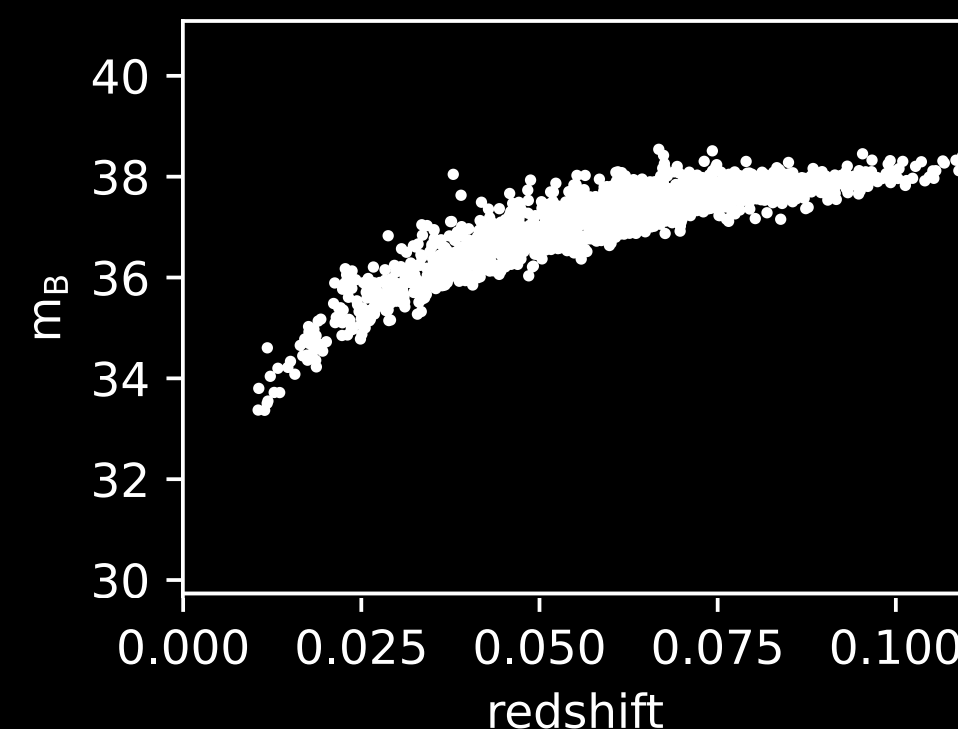

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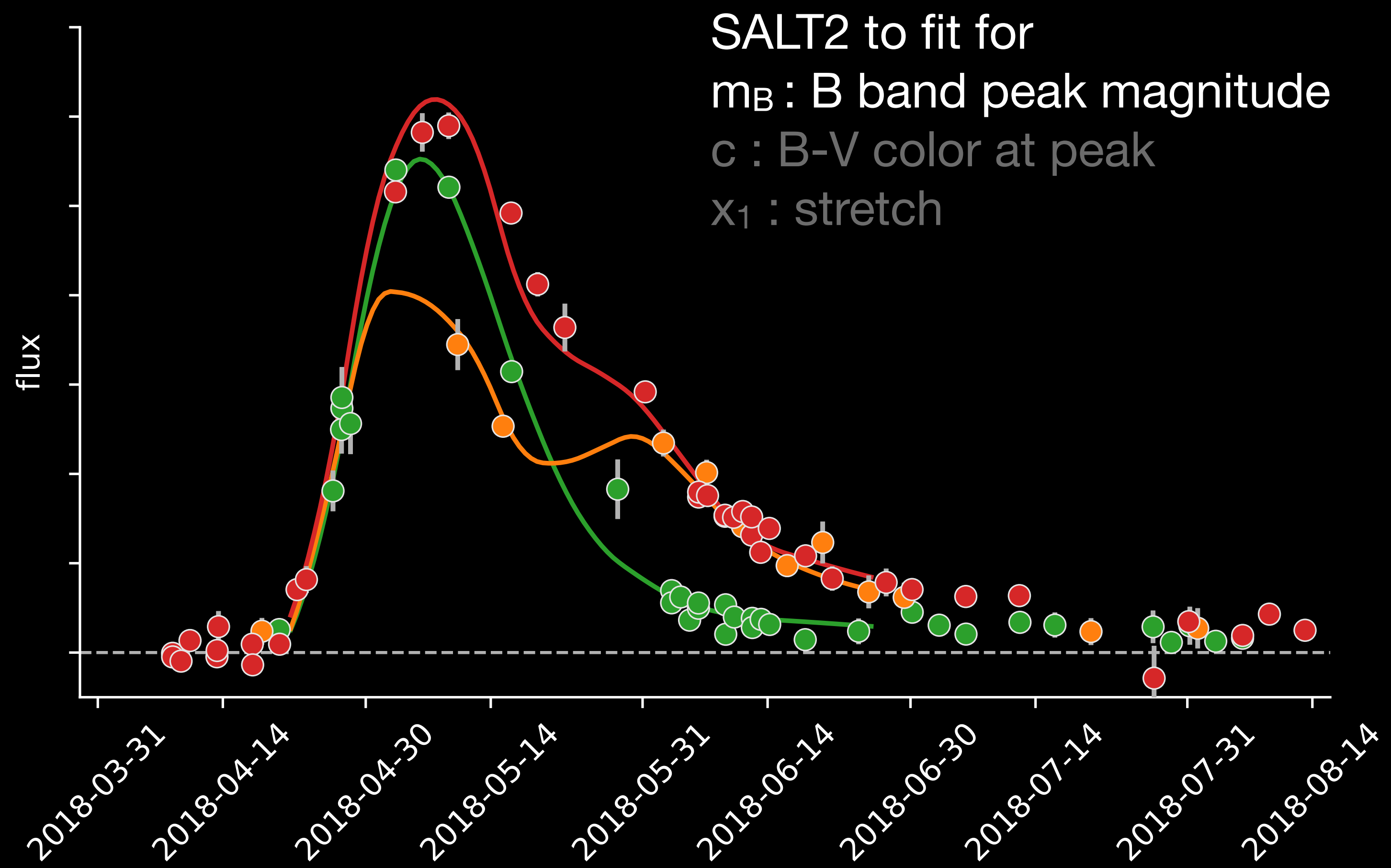


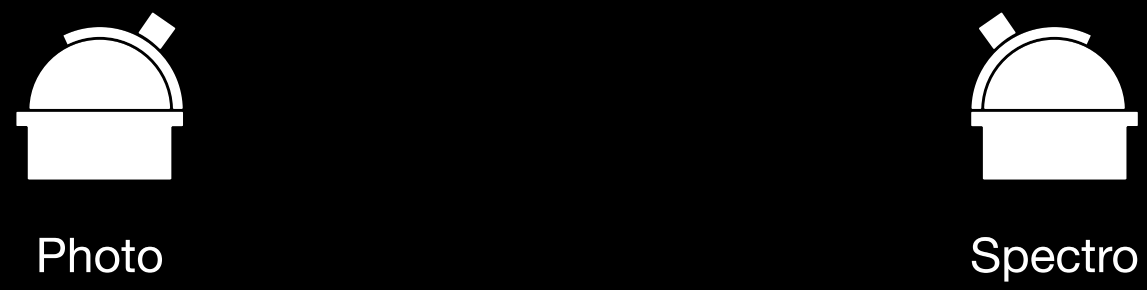


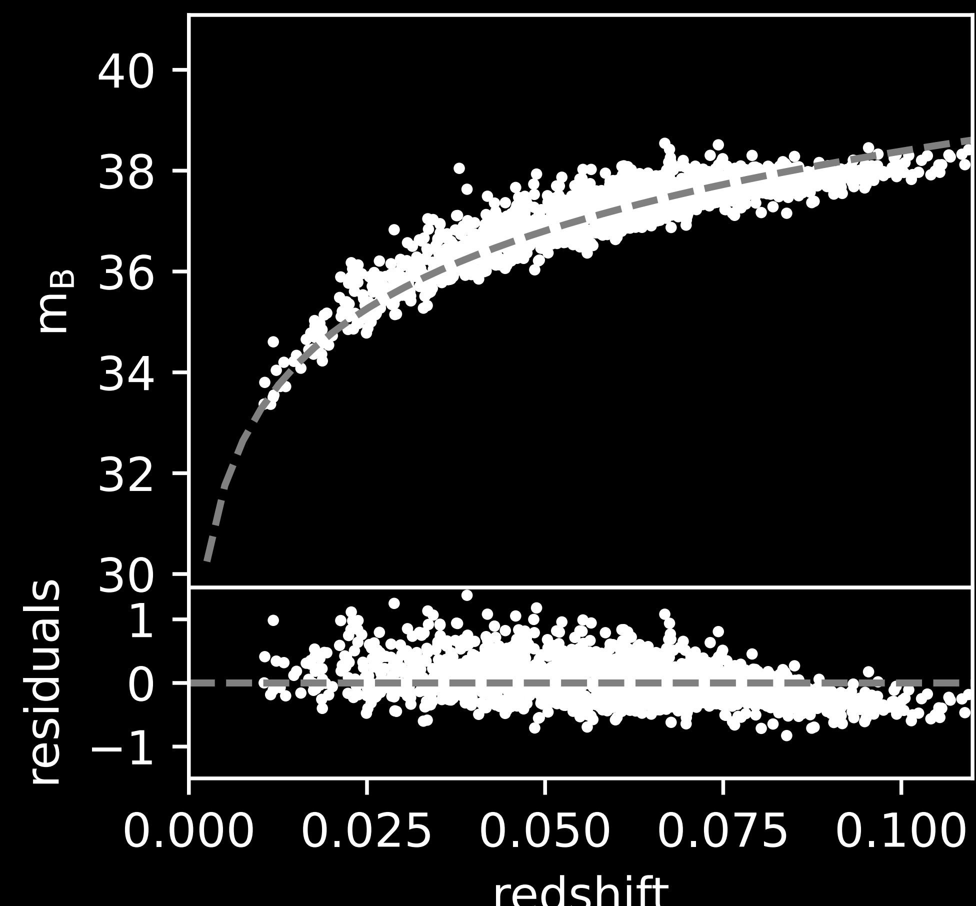

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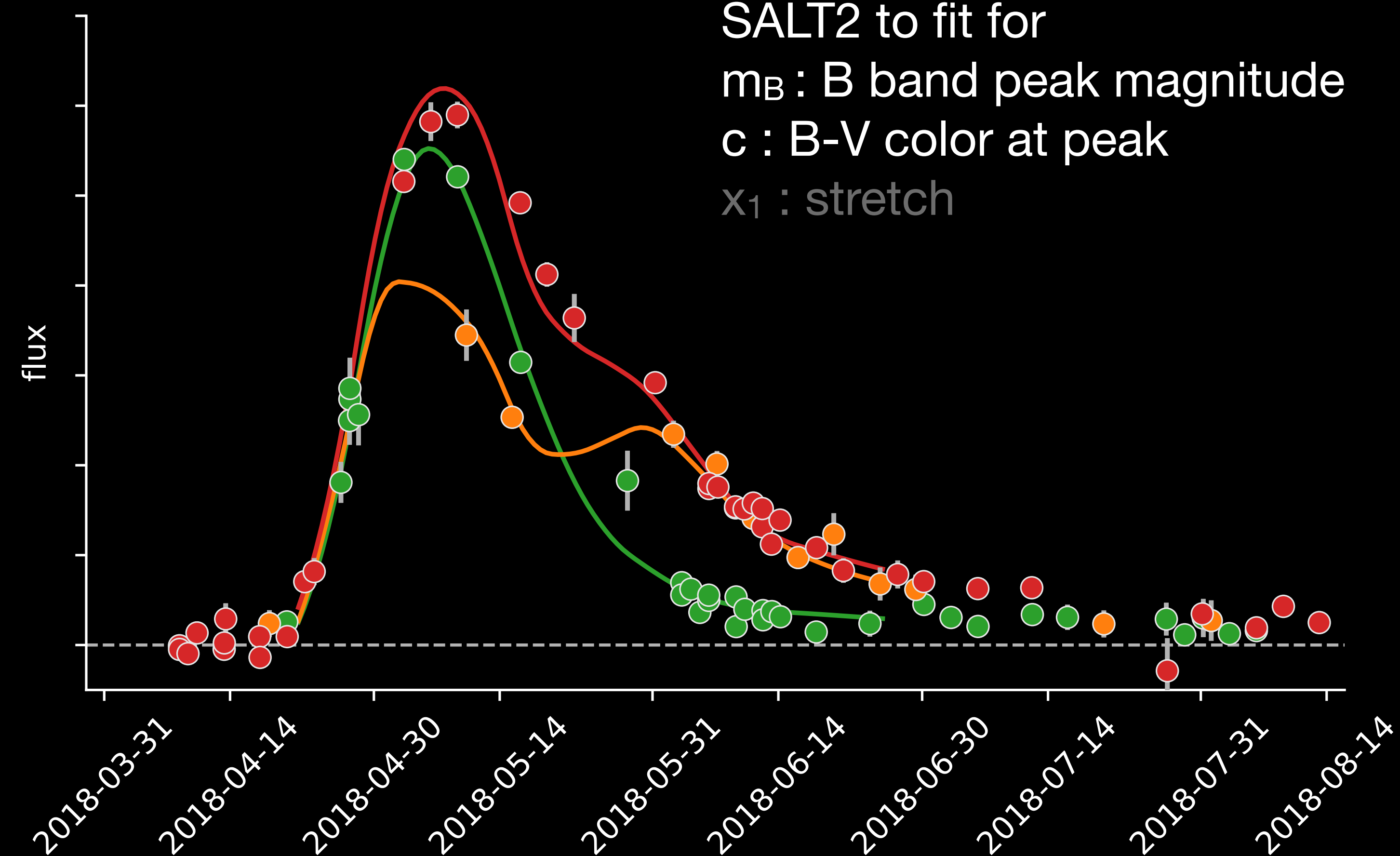
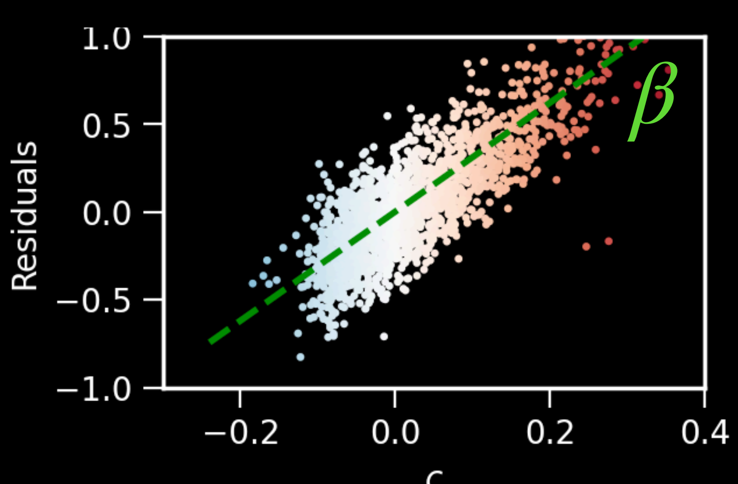
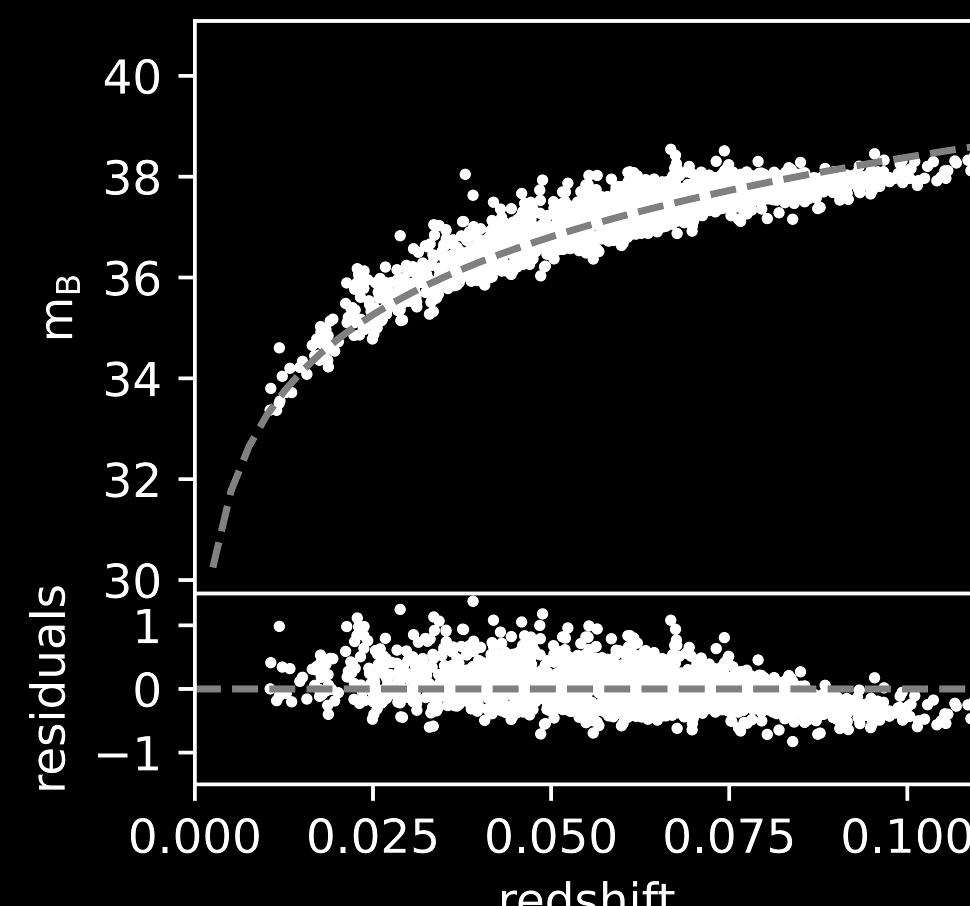



Photo

Spectro



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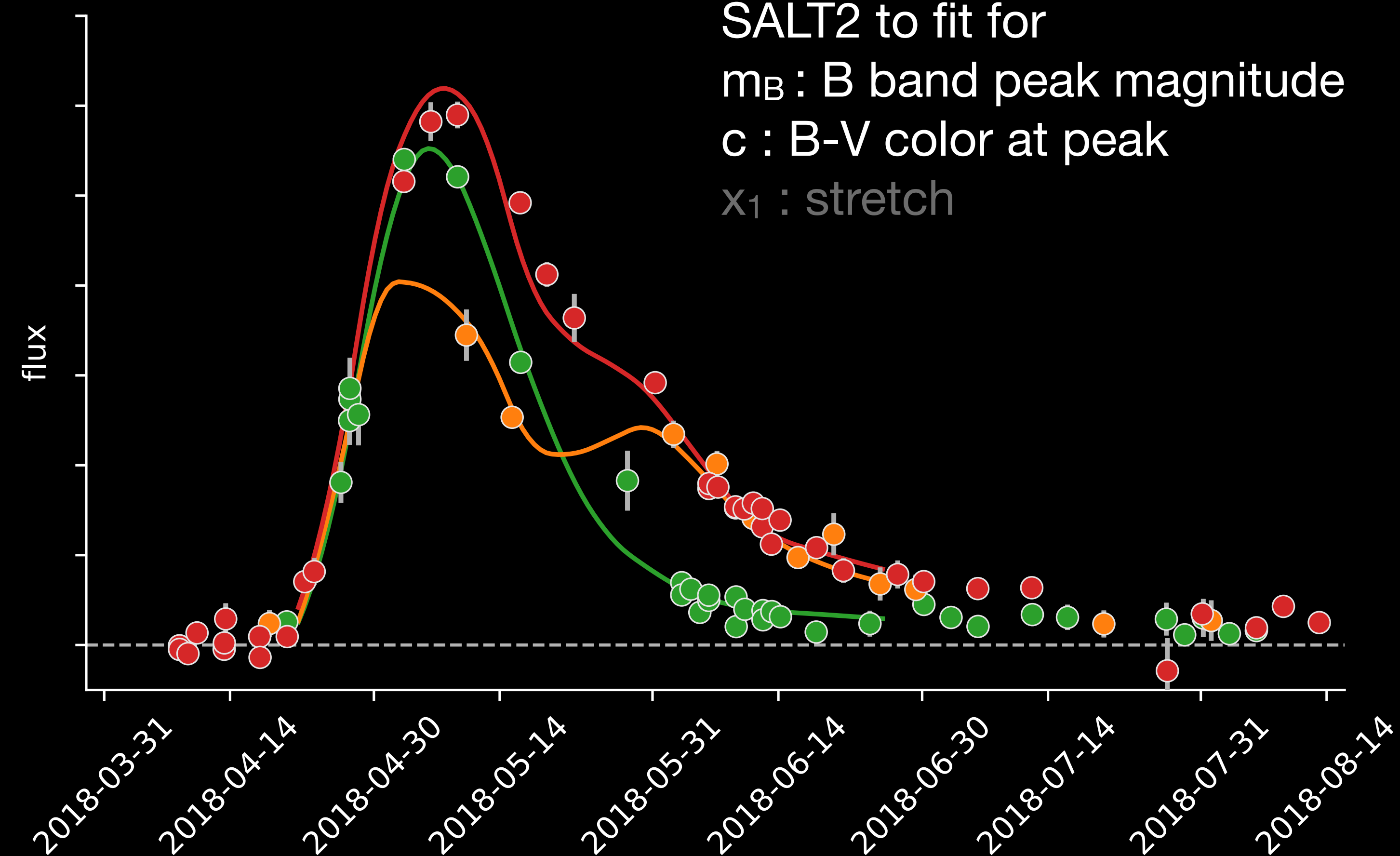
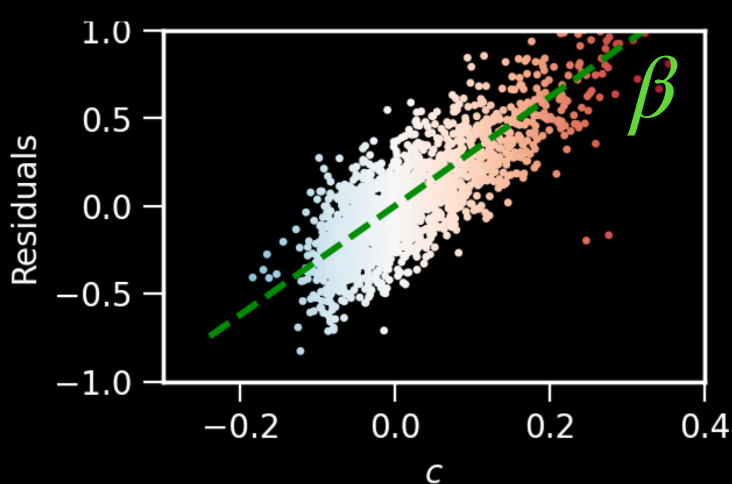
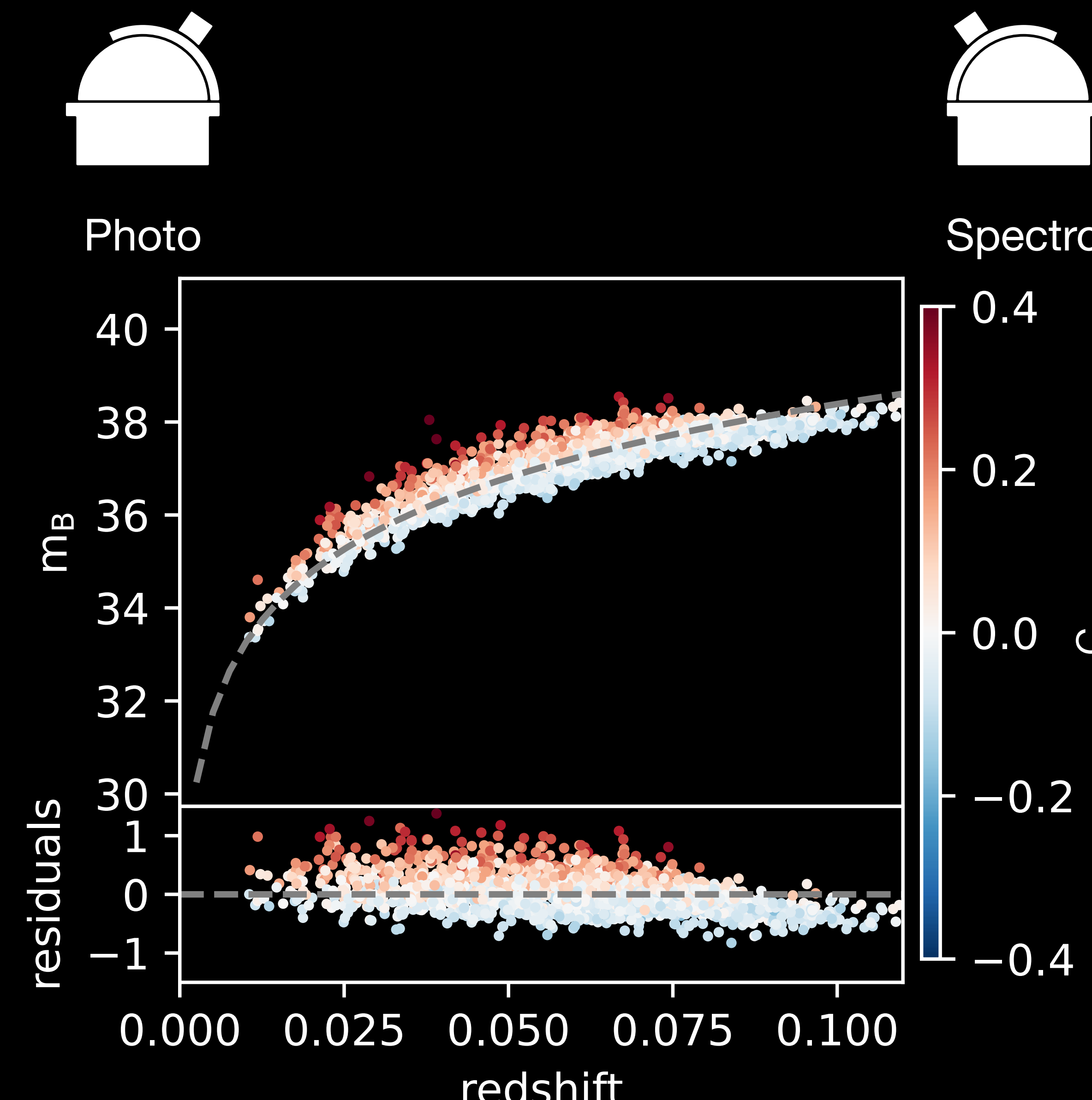



Redder —> fainter



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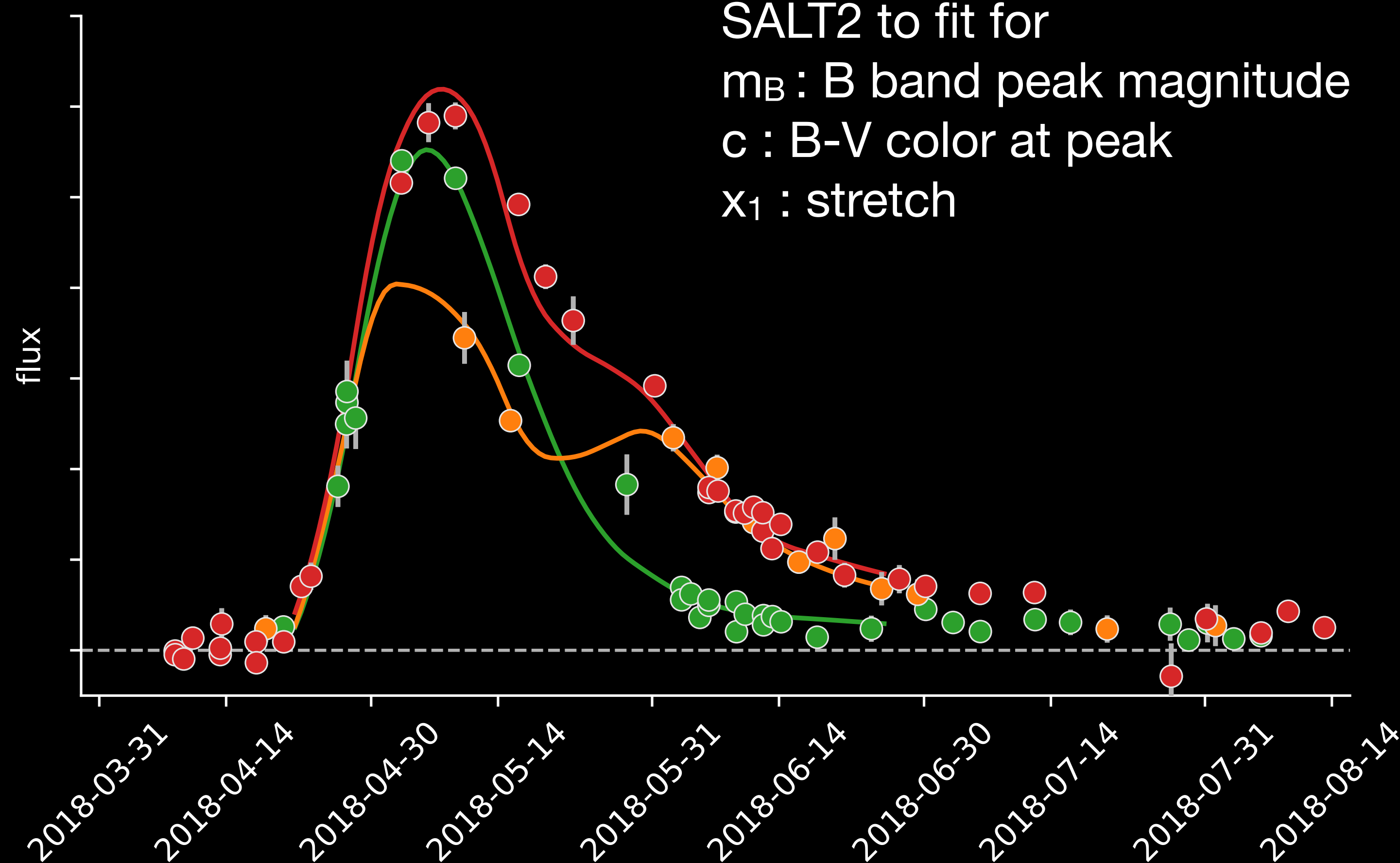


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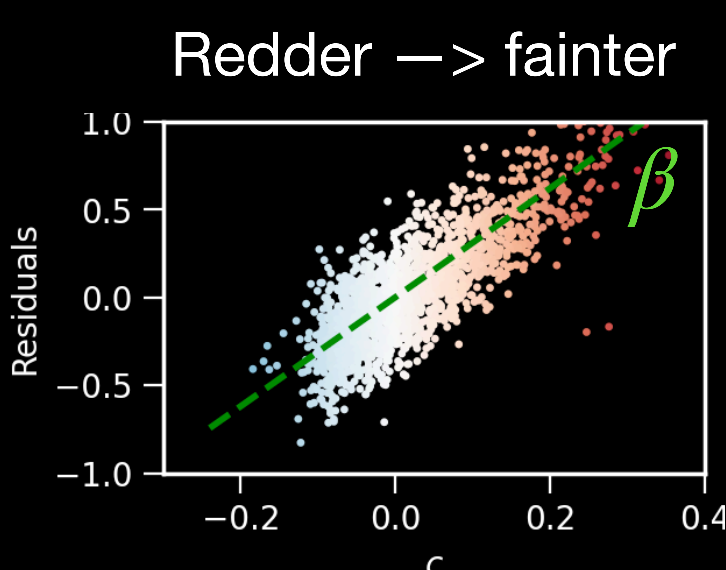


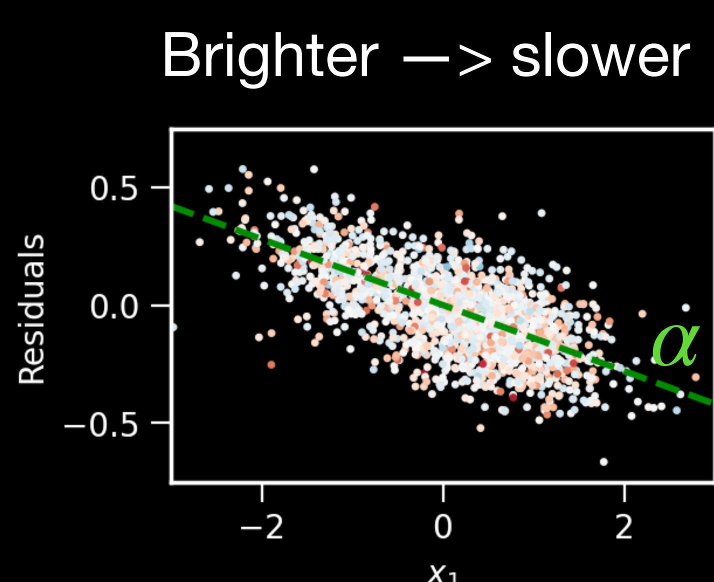


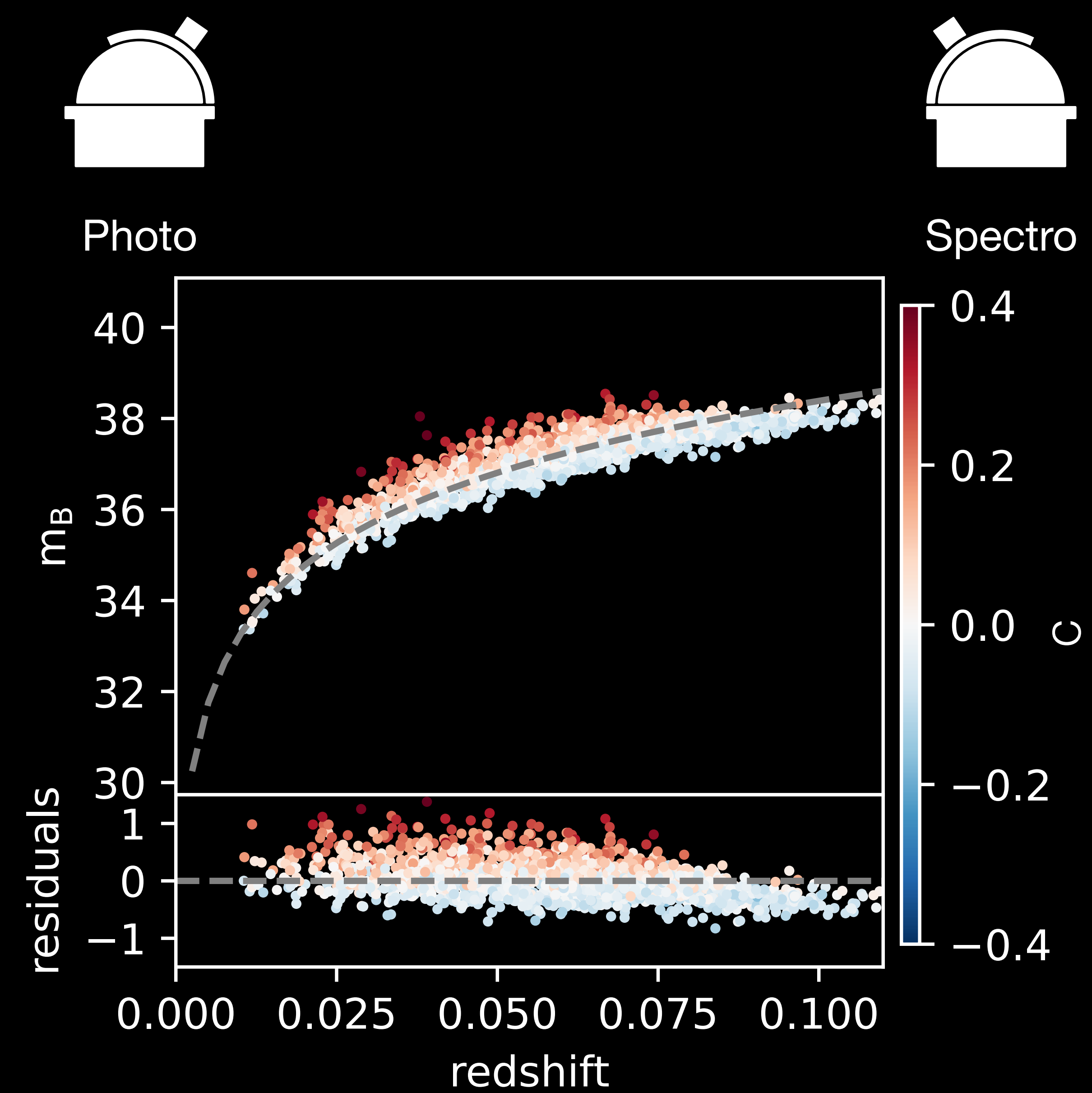

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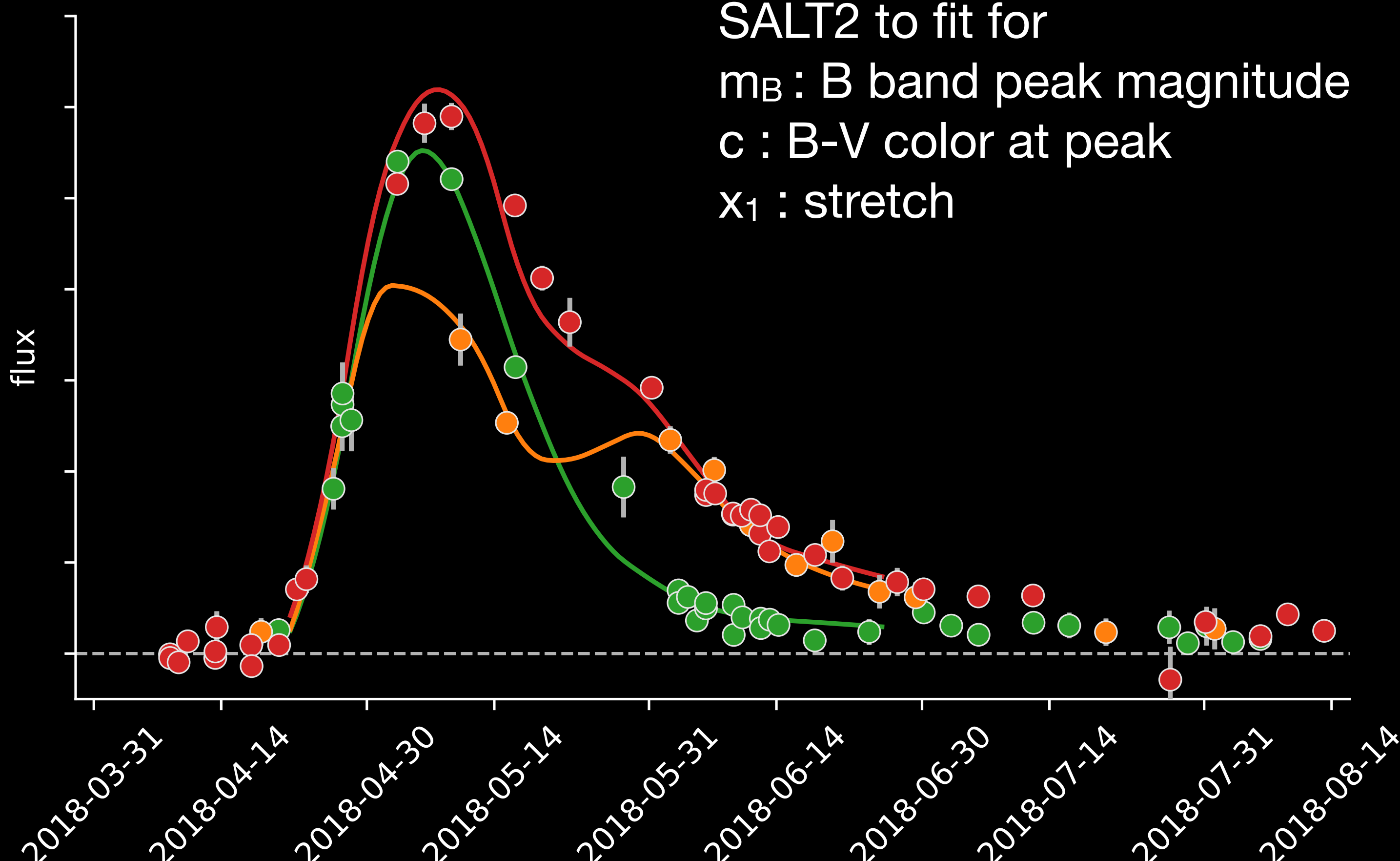


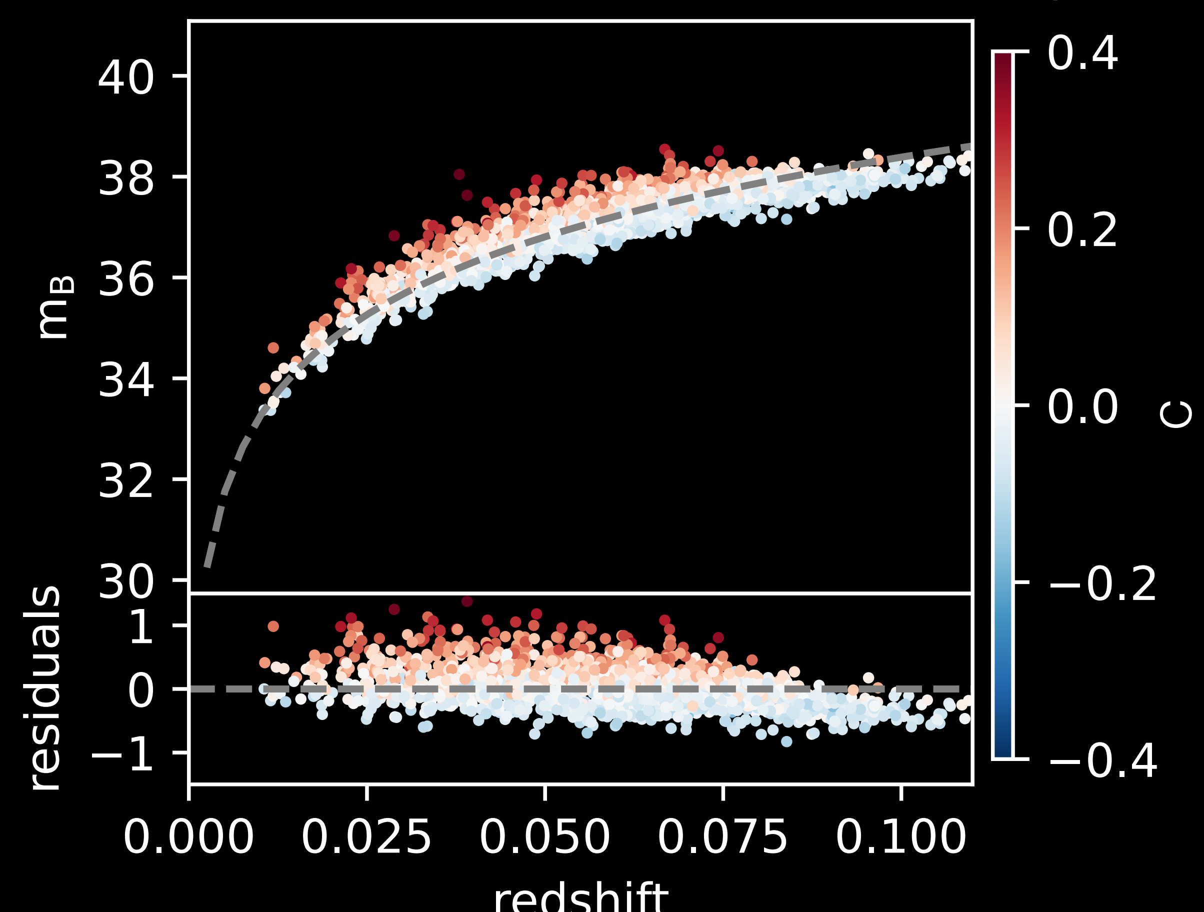

Redder —> fainter

Brighter —> slower

From ~40% dispersion…

Photo

Spectro



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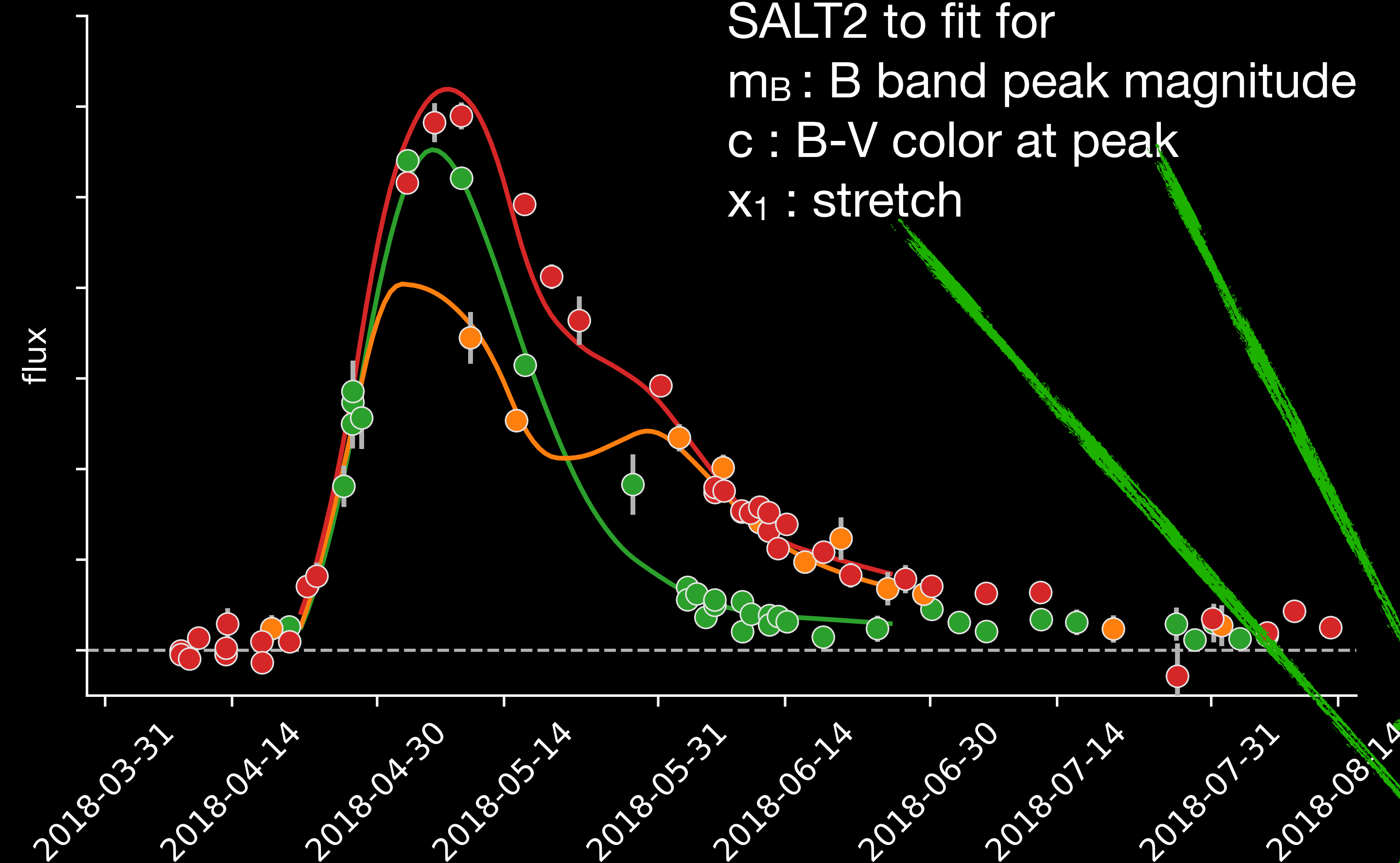


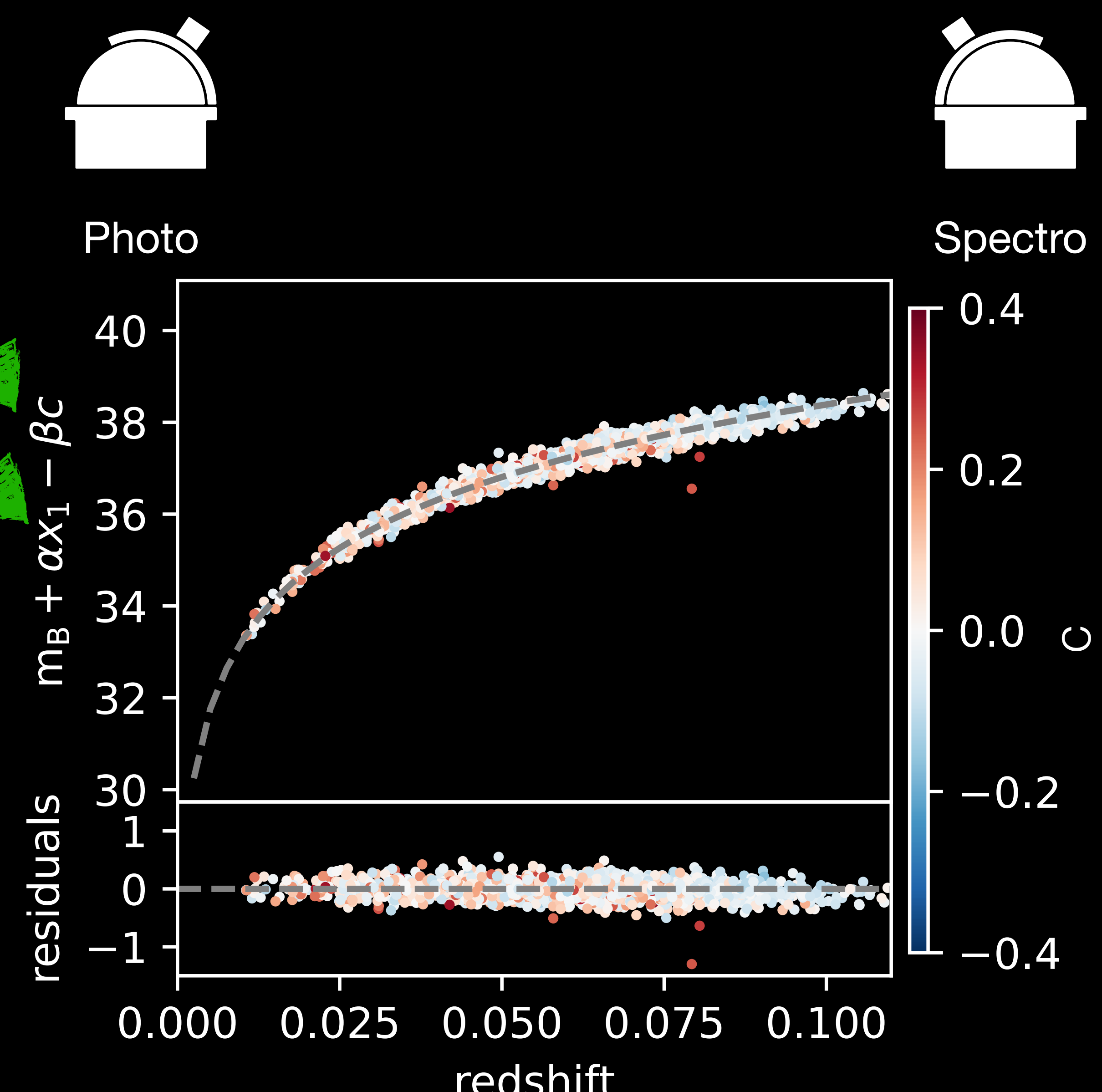


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From ~40% dispersion…

to ~15% using empirical correction (Tripp 1998)

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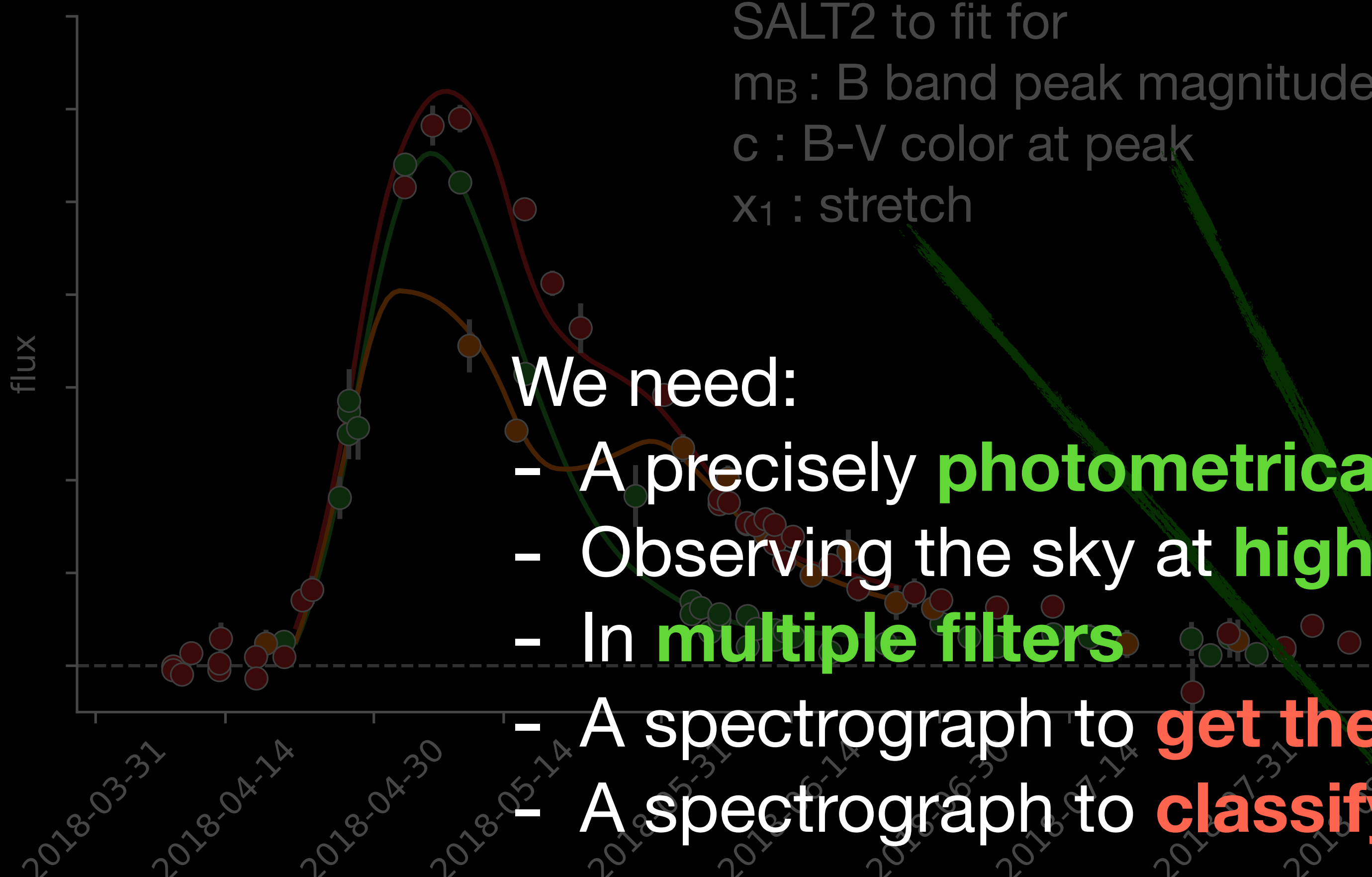
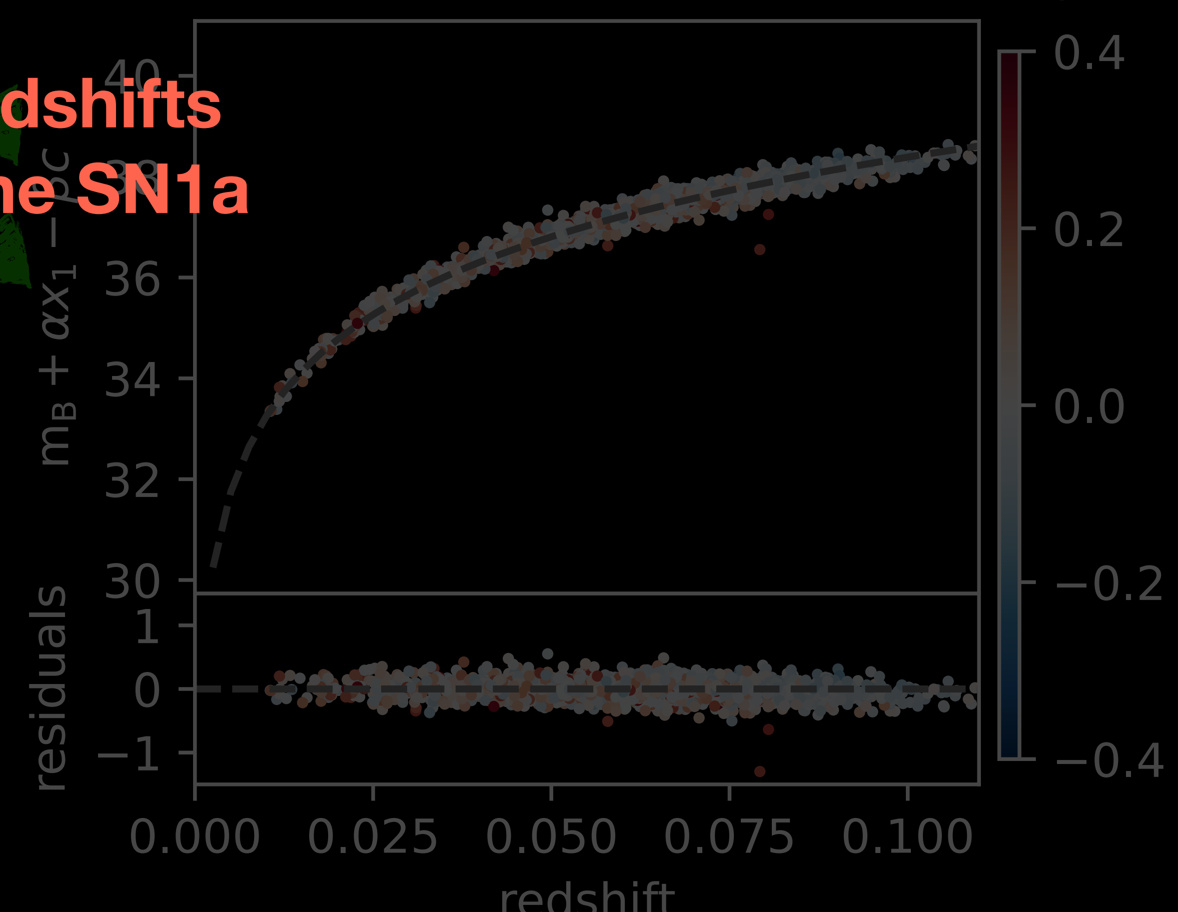



We need:

- A precisely **photometrically calibrated** telescope
- Observing the sky at **high cadence**
- In **multiple filters**
- A spectrograph to **get the redshifts**
- A spectrograph to **classify the SN1a**


Redder —> fainter

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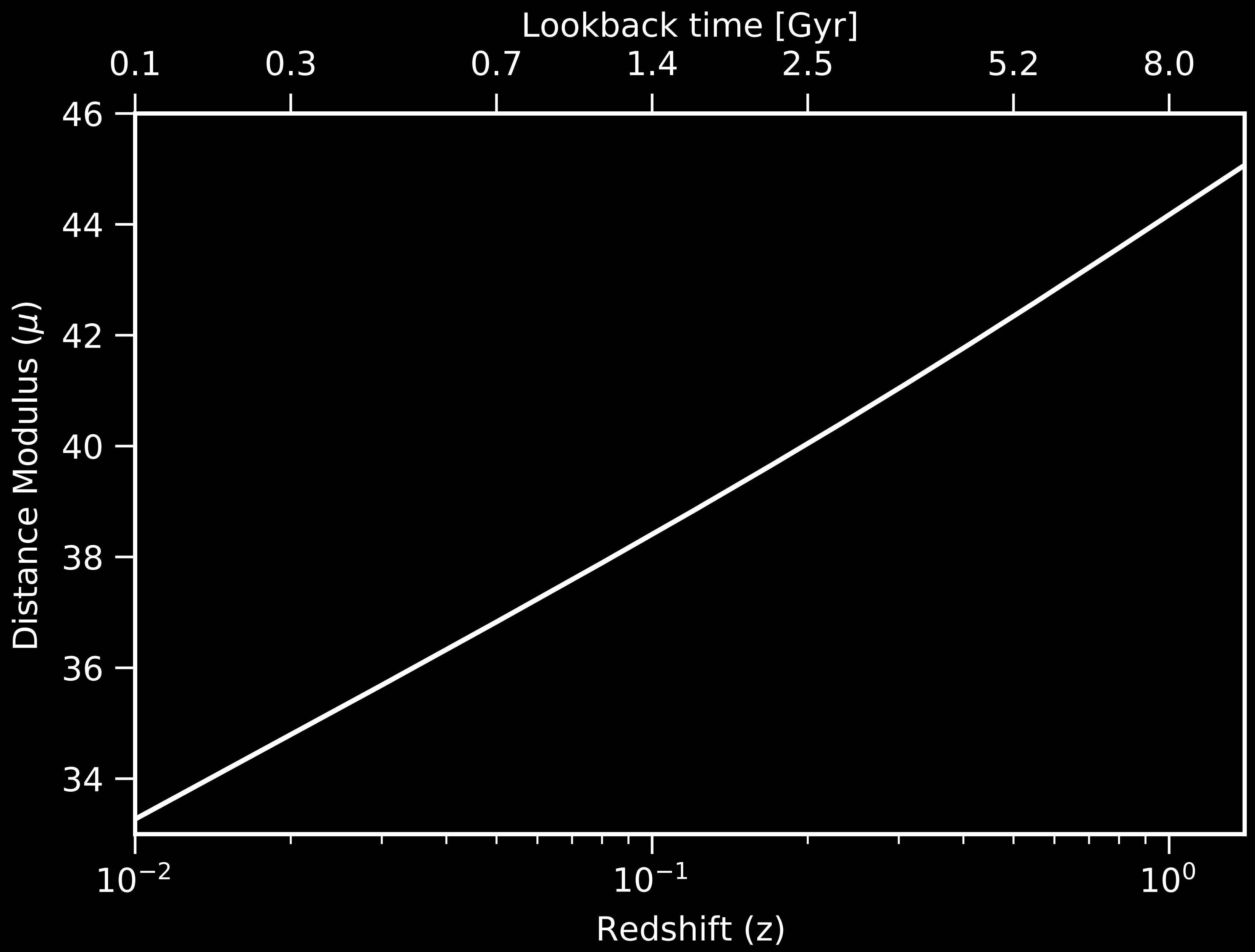
# Hubble Diagram



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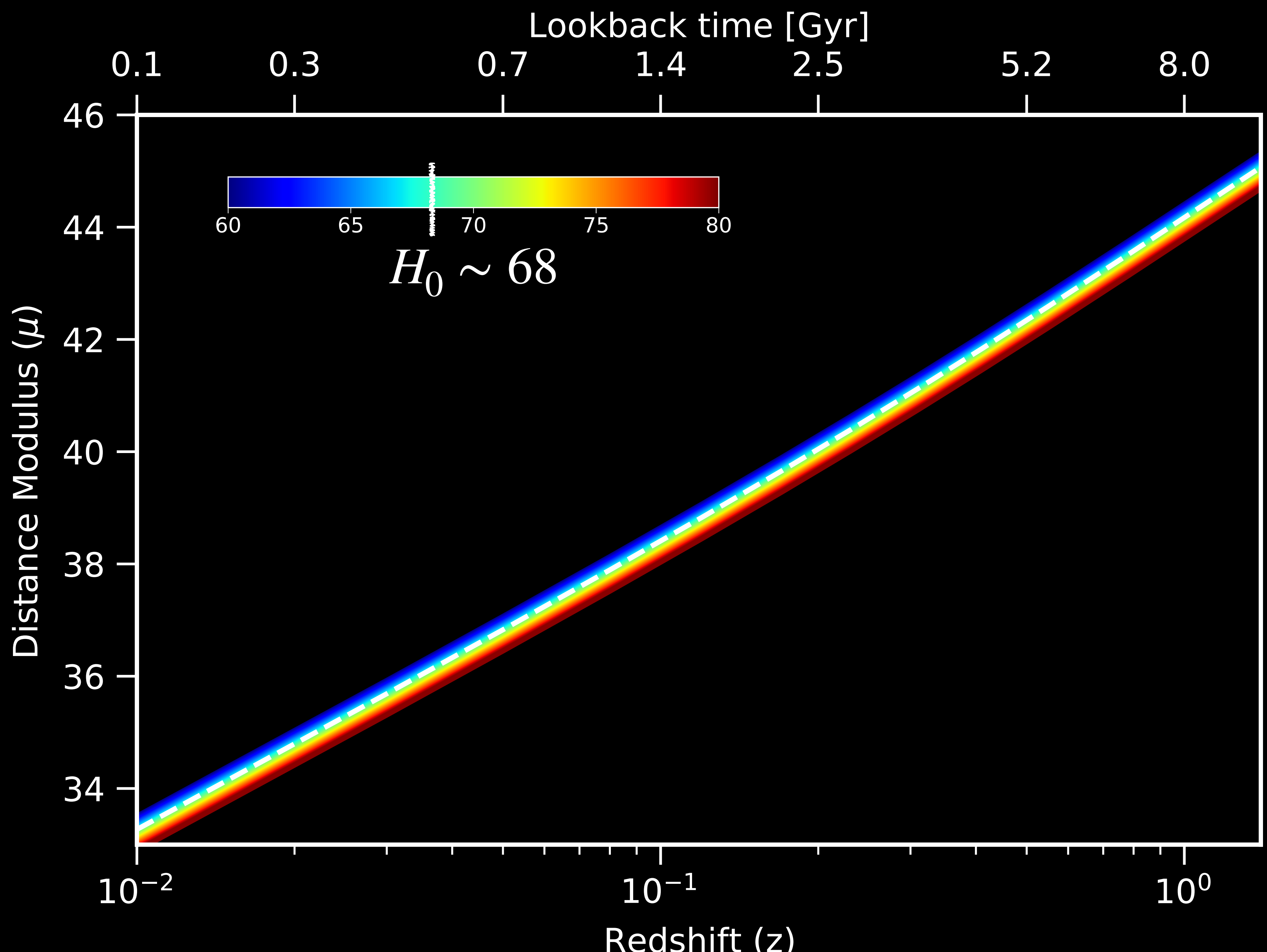


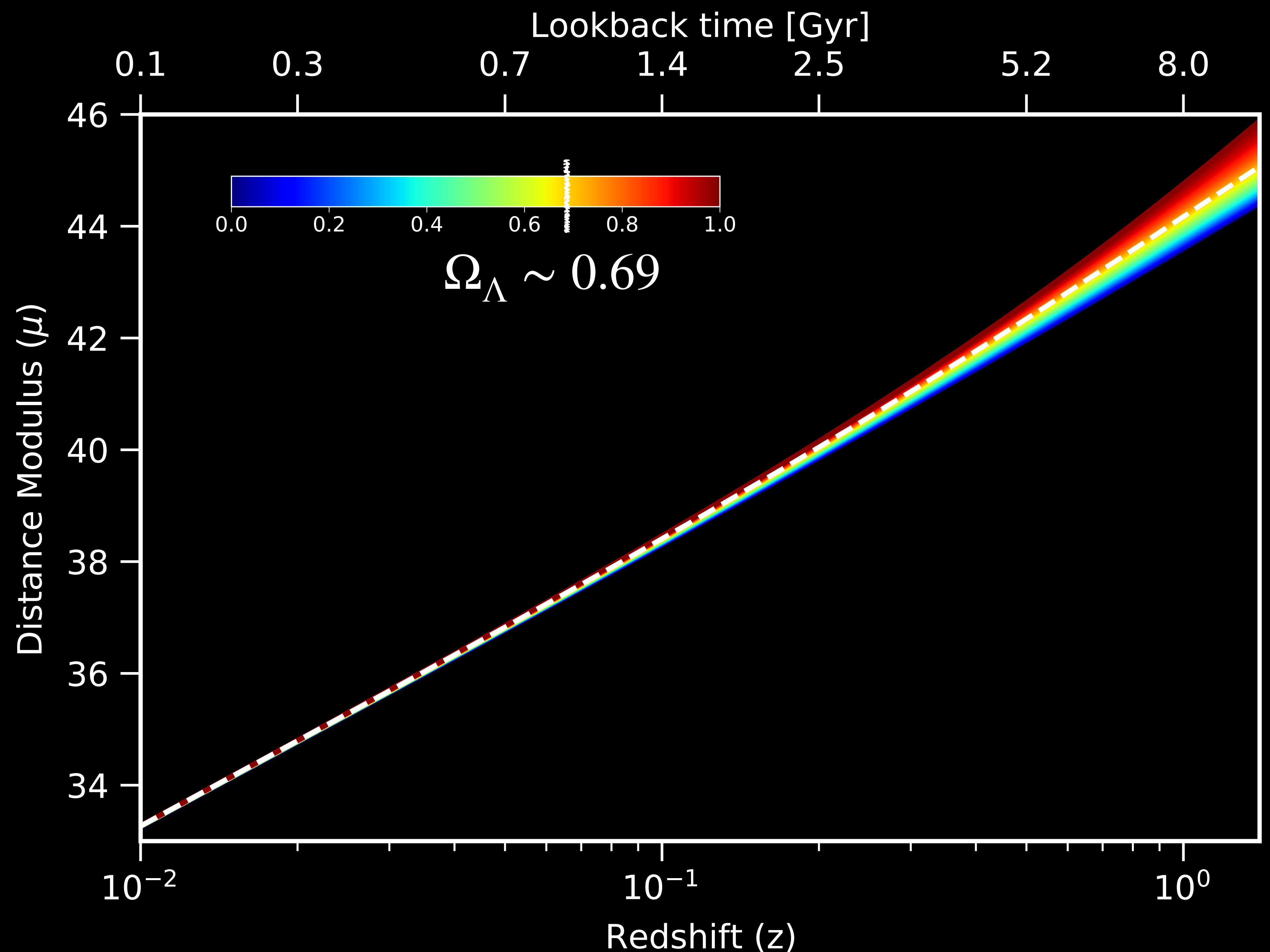

Measure current expansion $H_0$

Requires "Anchoring" (Cepheids, TRGB)

Study Dark Energy

Requires Low & high redshifts

# Hubble Diagram




Measure current expansion $H_0$

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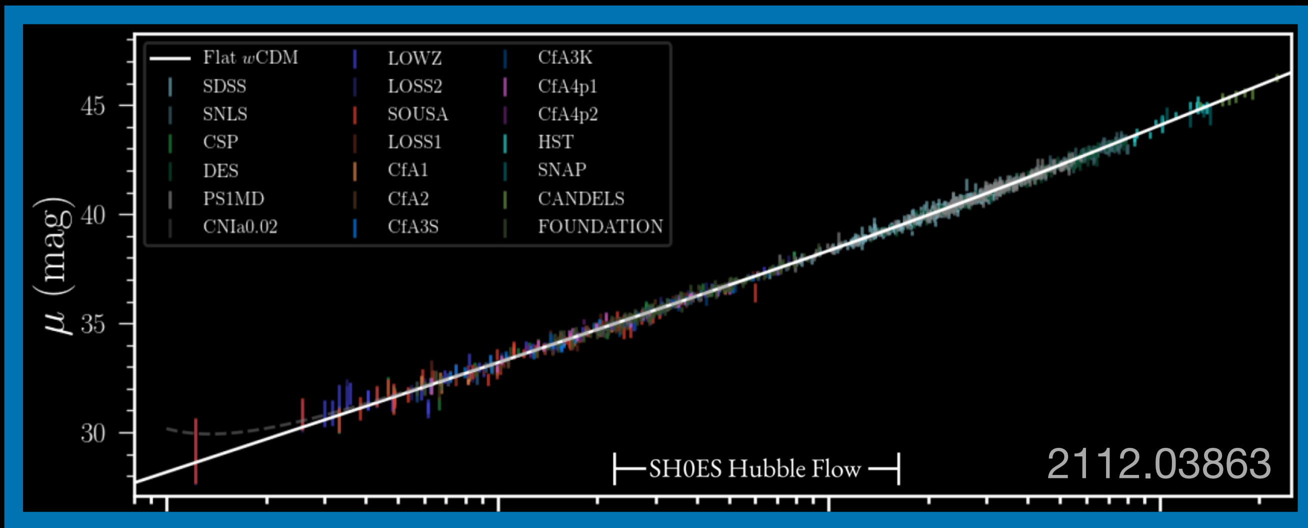
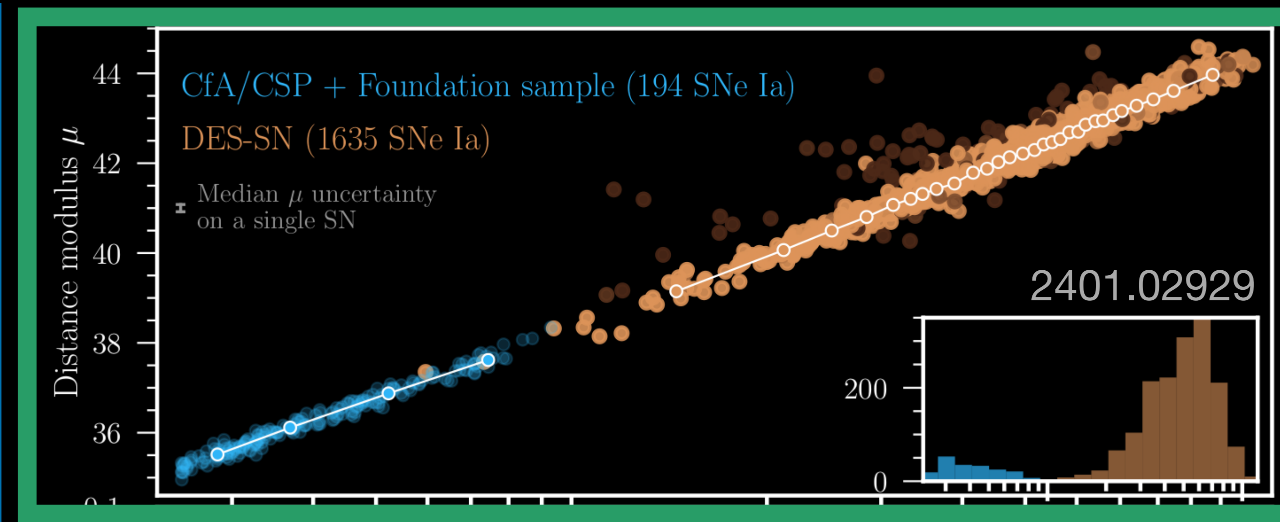
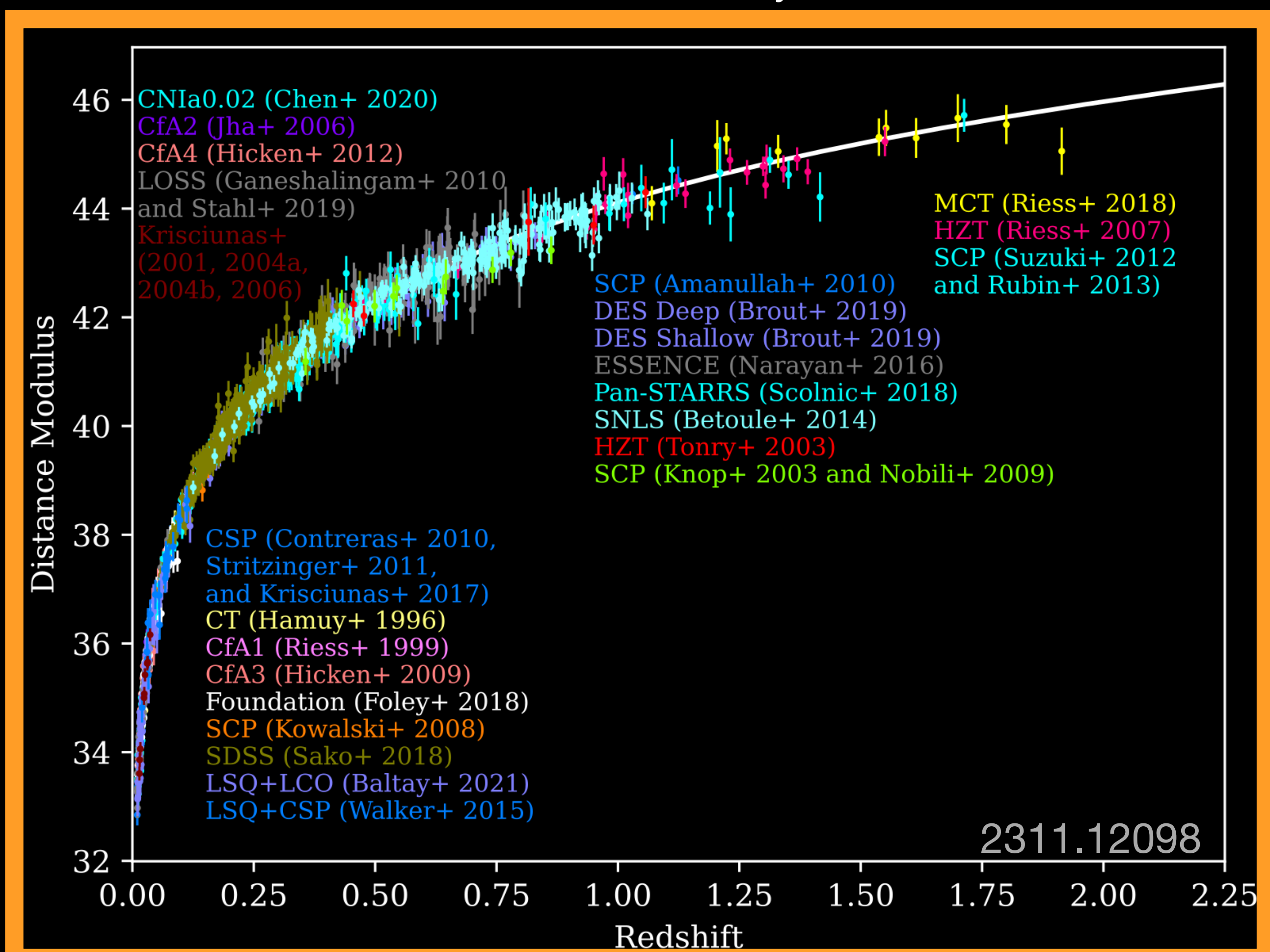
Pantheon+: 1701 SN (1550 distinct) 20 surveys intercalibrated

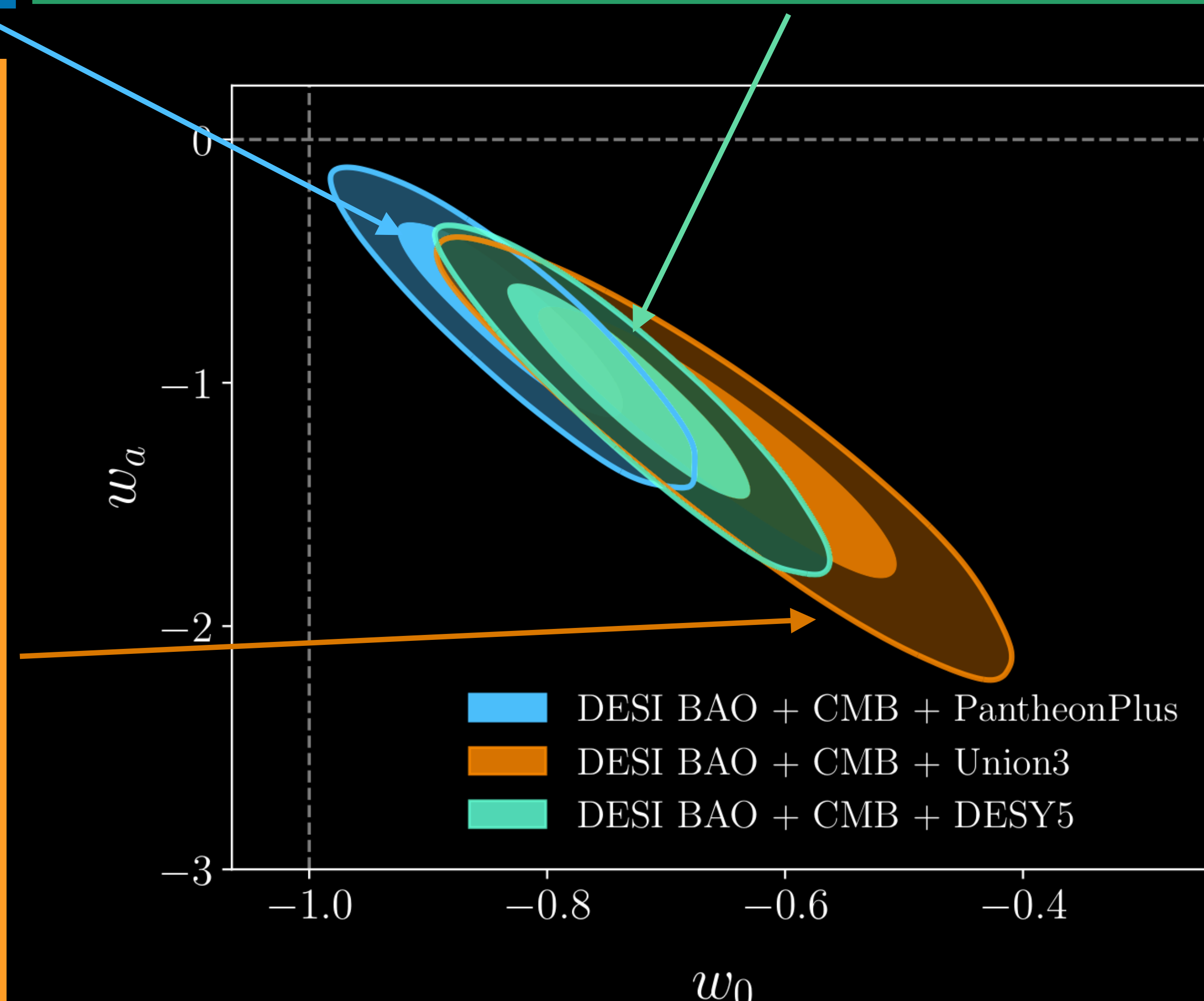



DES 5yr : 1829 SN from 5 surveys intercalibrated

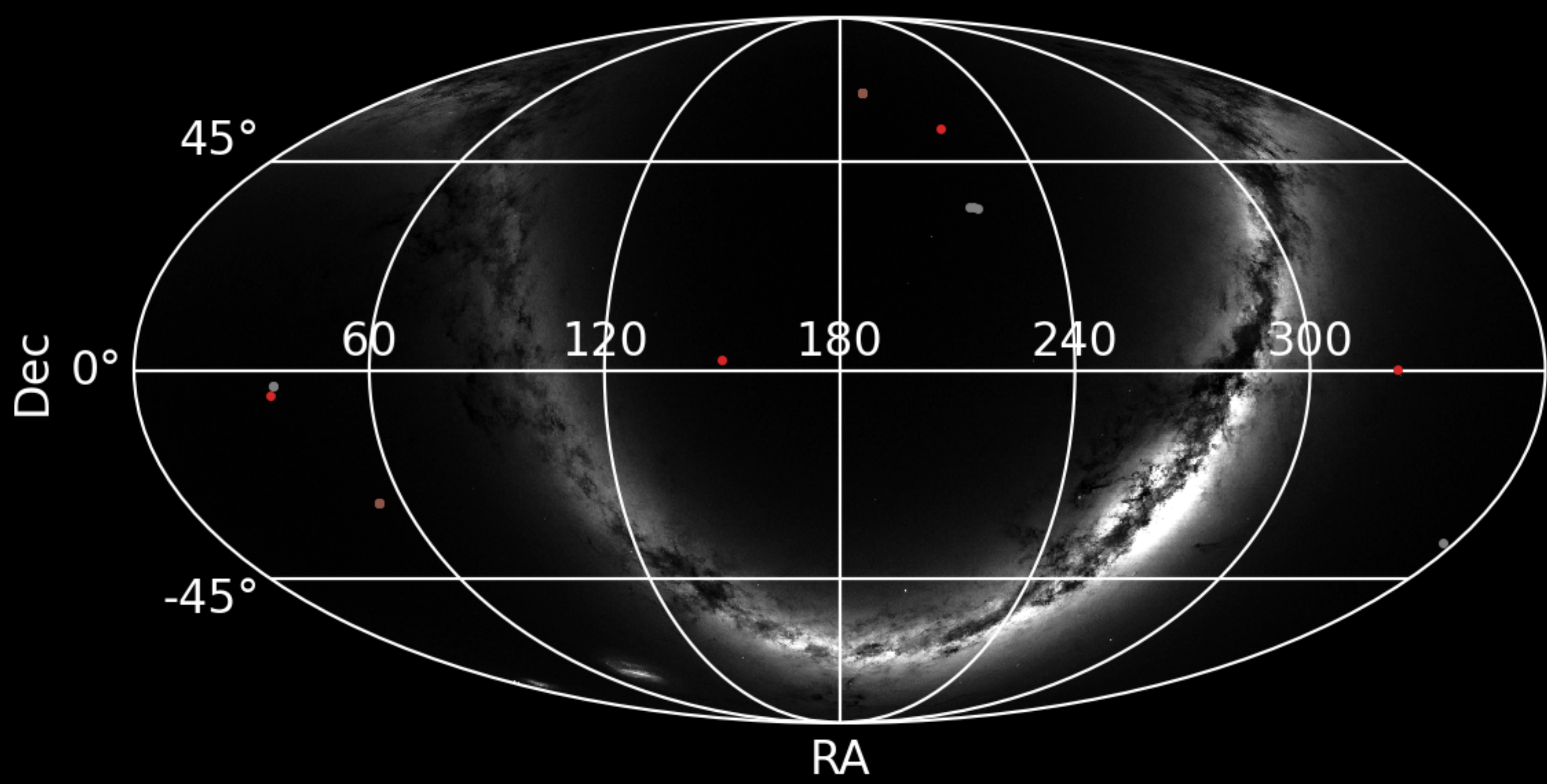


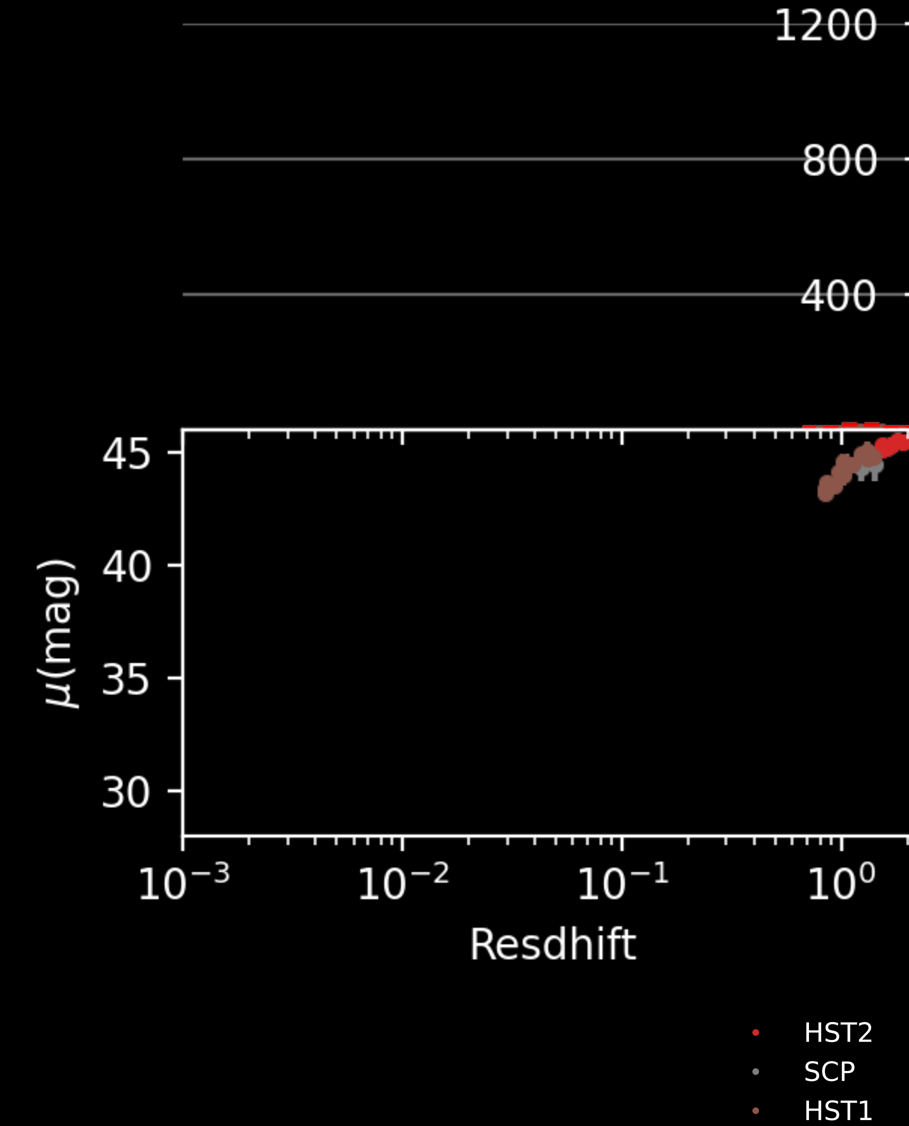

Union3: 2000 SN from 24 surveys intercalibrated

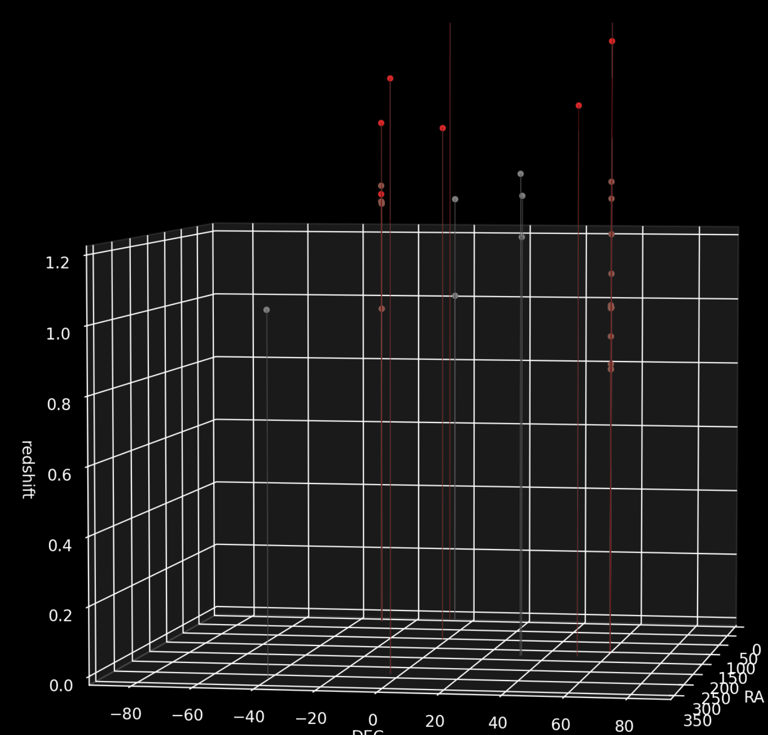



All the modern compilations of Supernovae use a **low-z sample of O(100) SN** coming from **many different telescopes**

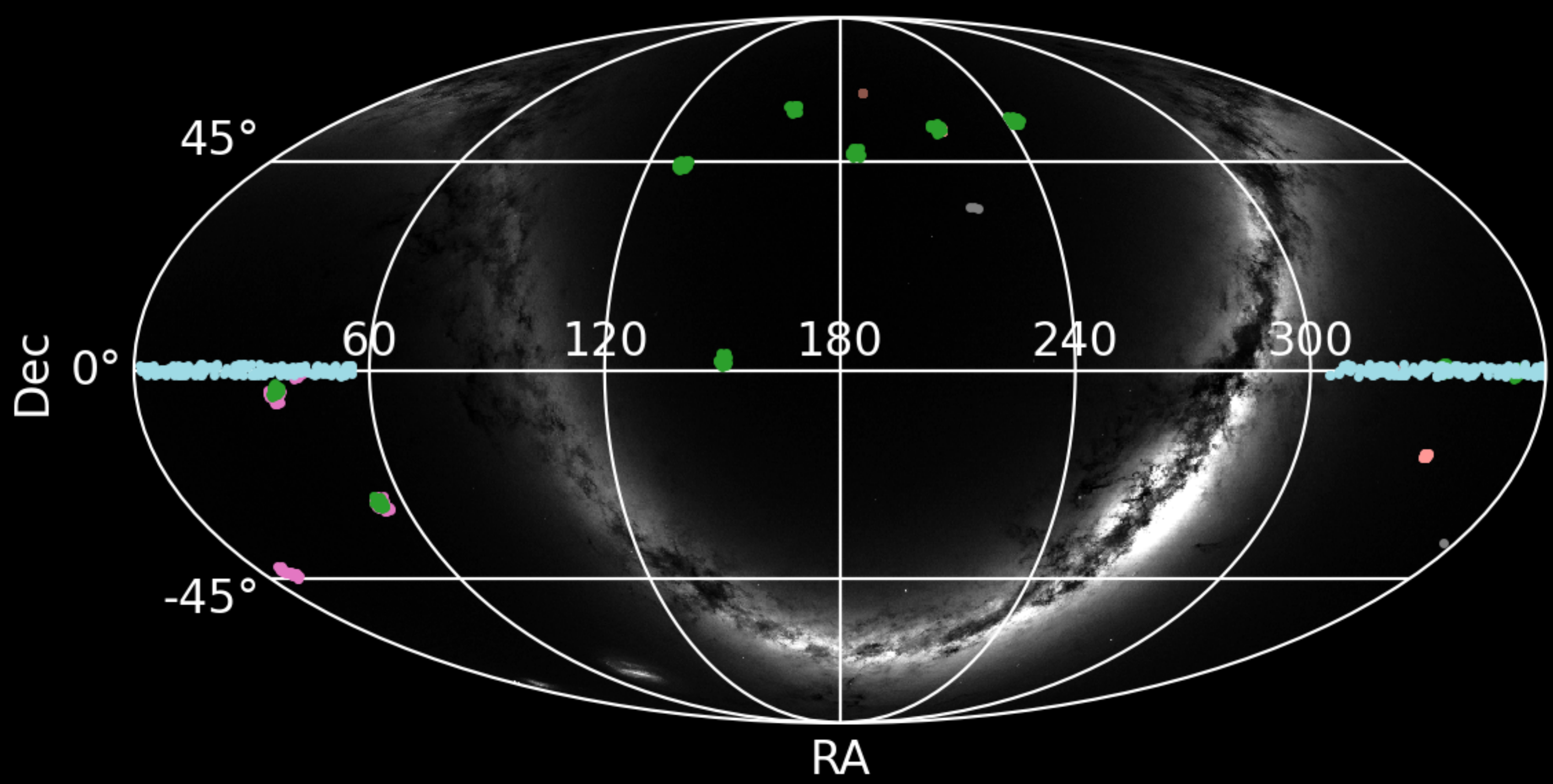


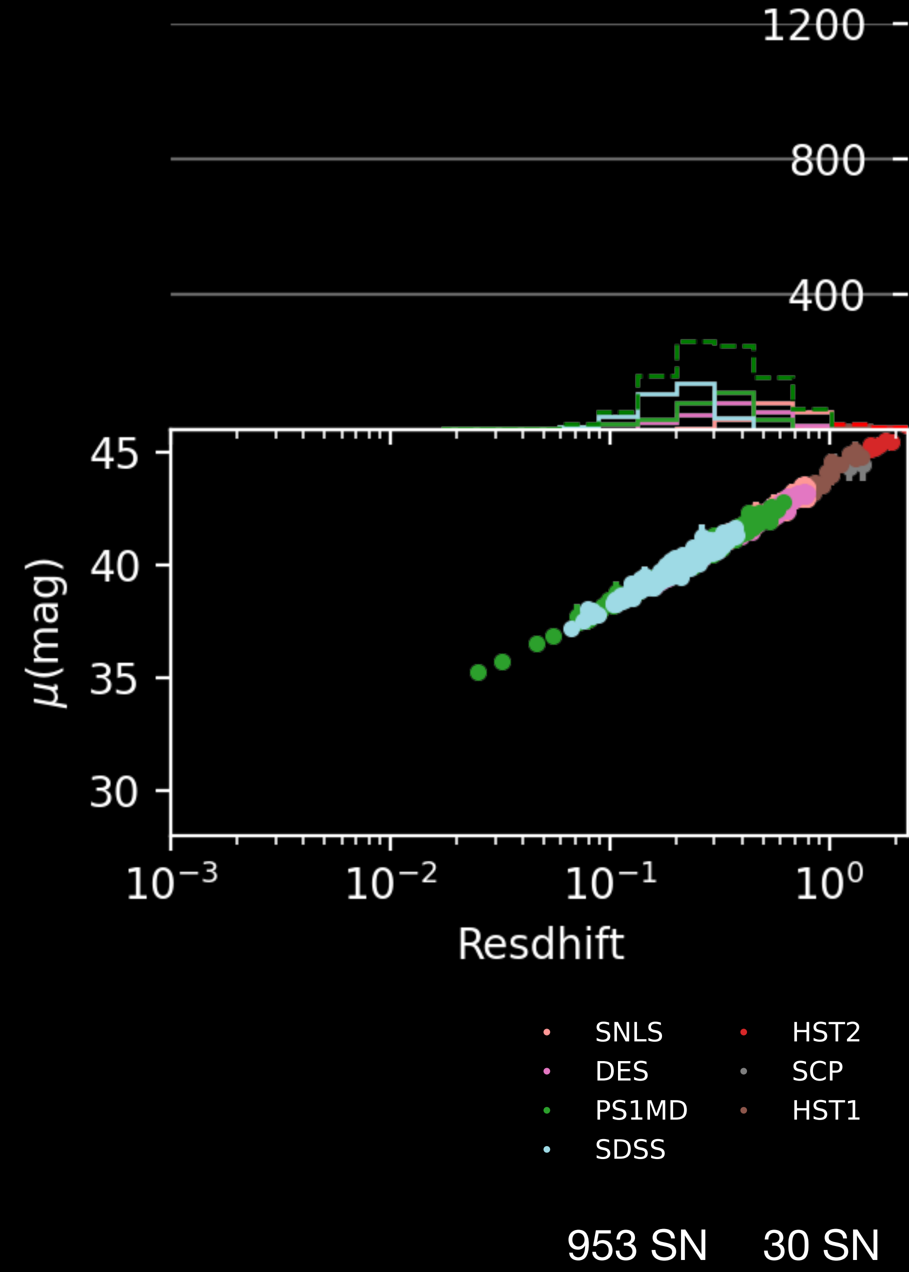



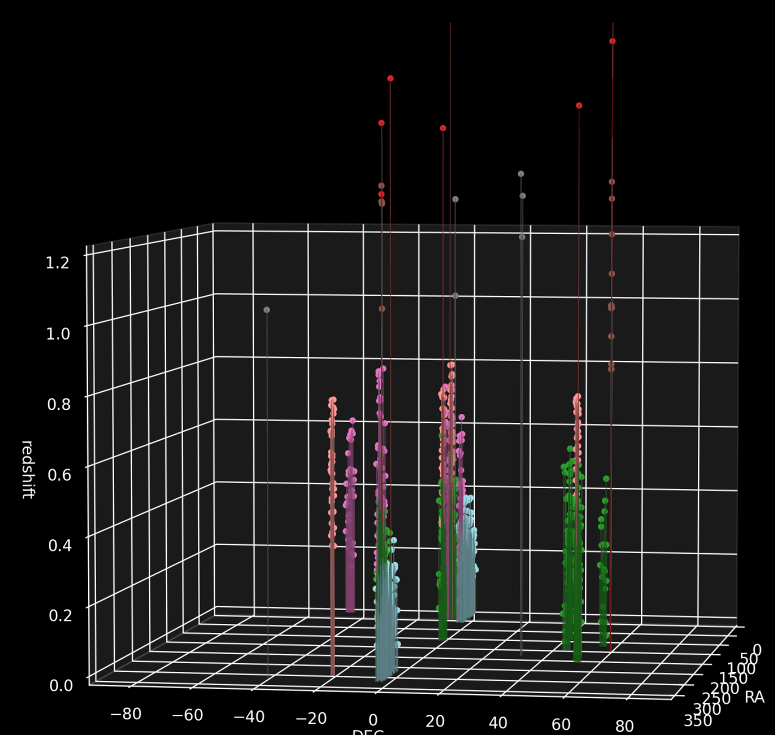




30 SN

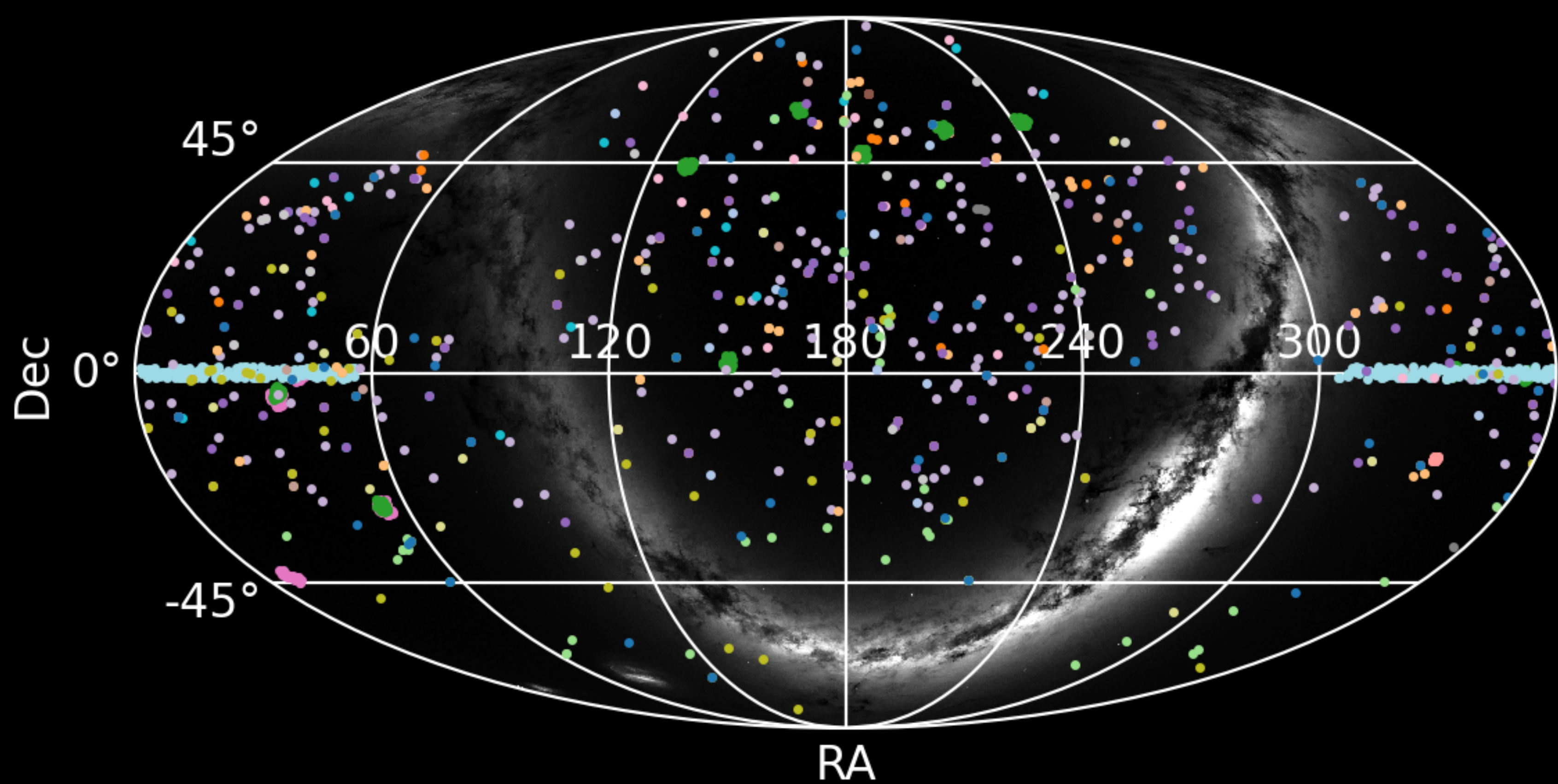
Pantheon+: 1701 SN (1550 distinct) 20 surveys intercalibrated

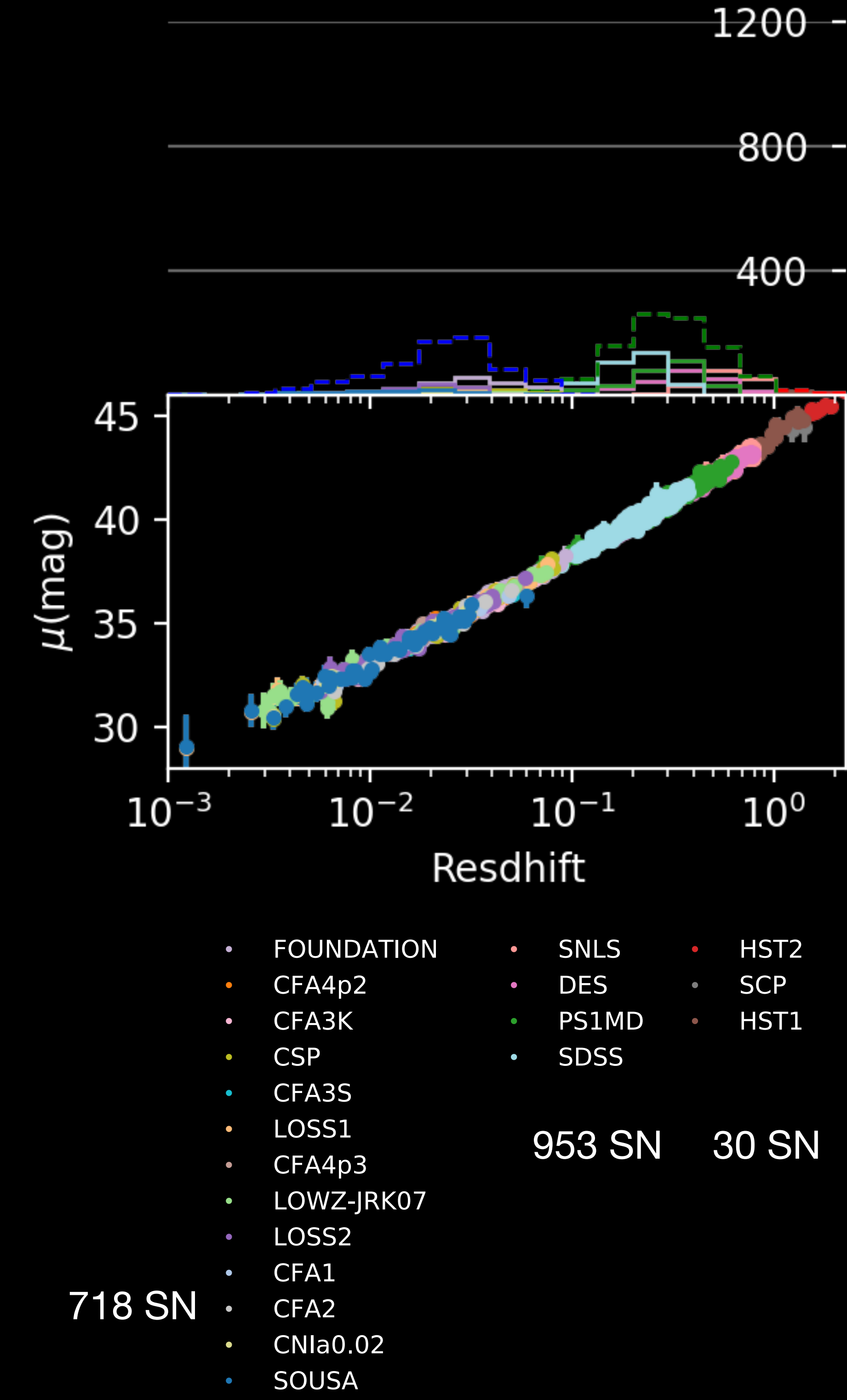


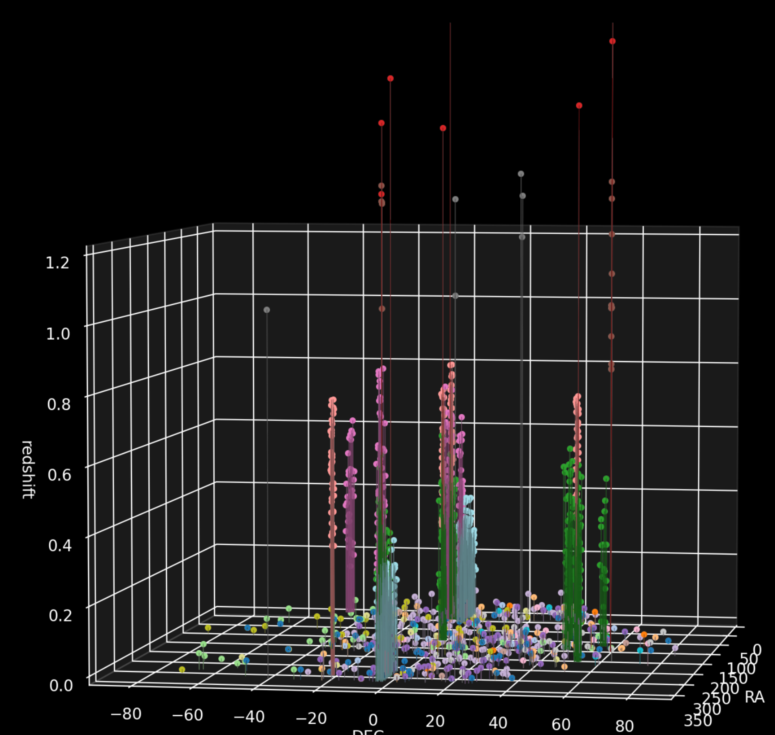




Pantheon+: 1701 SN (1550 distinct) 20 surveys intercalibrated



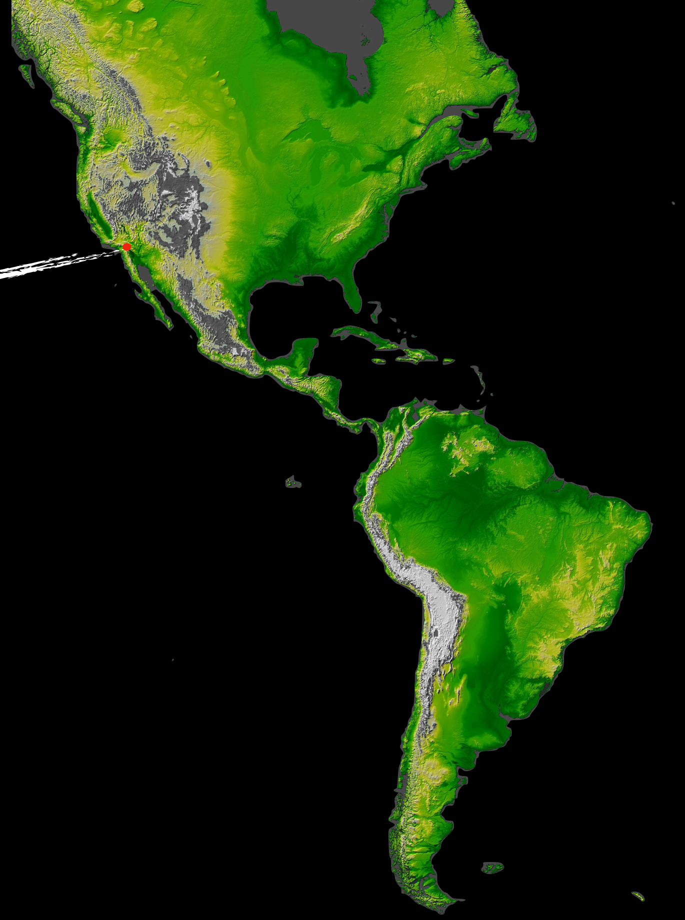




Pantheon+: 1701 SN (1550 distinct) 20 surveys intercalibrated

# Zwicky Transient Facility

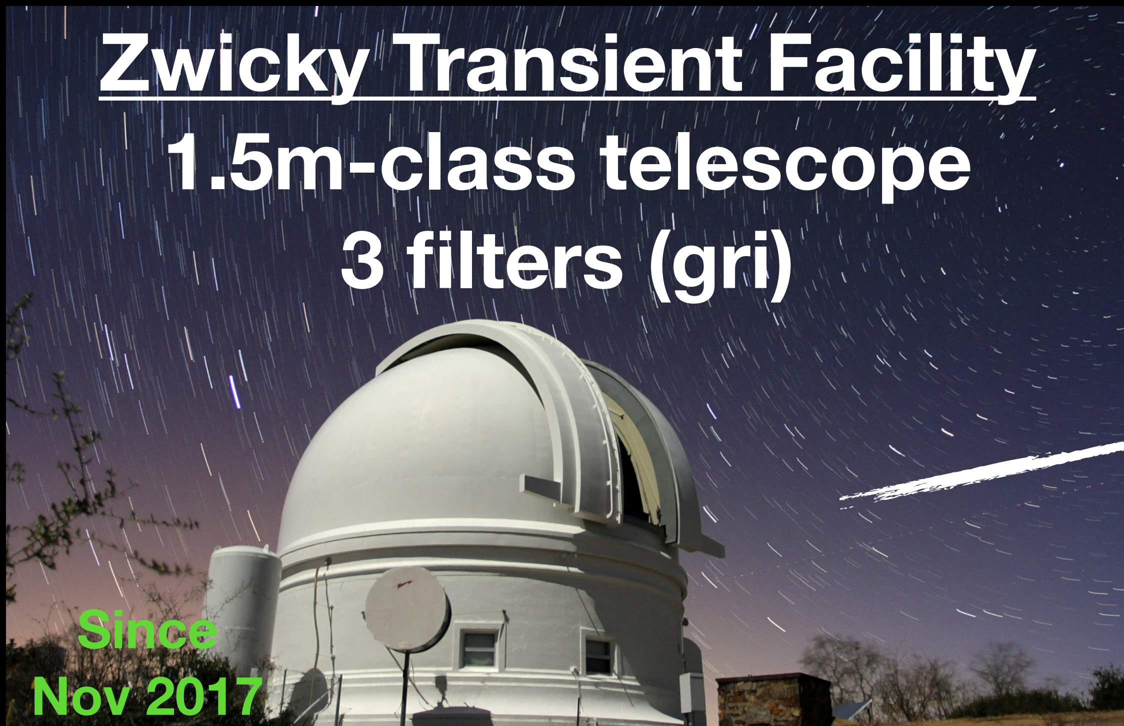
**1.5m-class telescope**

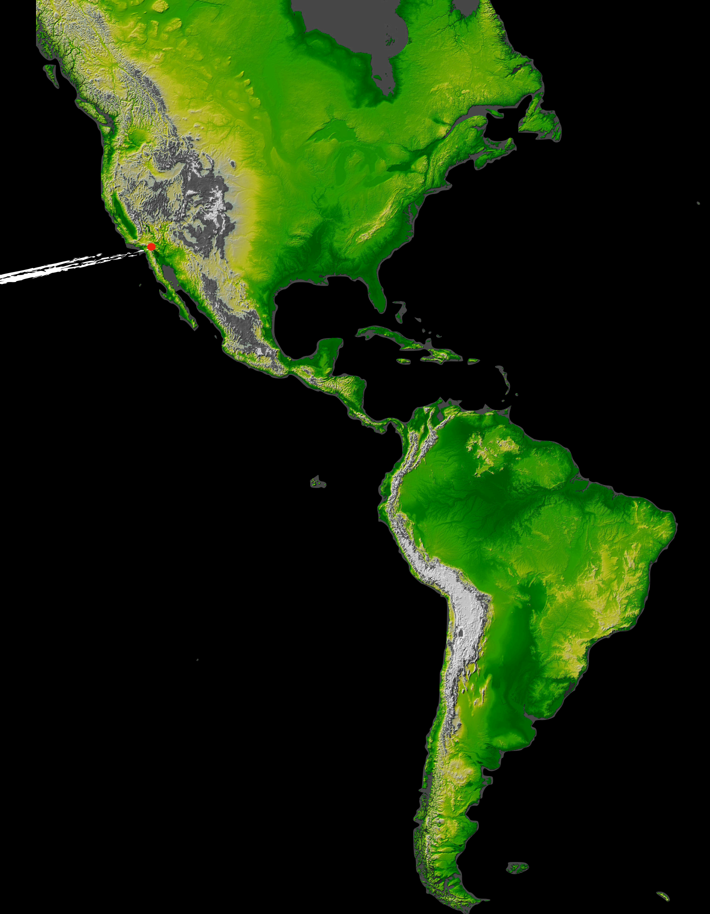
**3 filters (gri)**

+ a dedicated spectro

—> complete up to z ~ 0.06



+ a dedicated spectro
—> complete up to z ~ 0.06

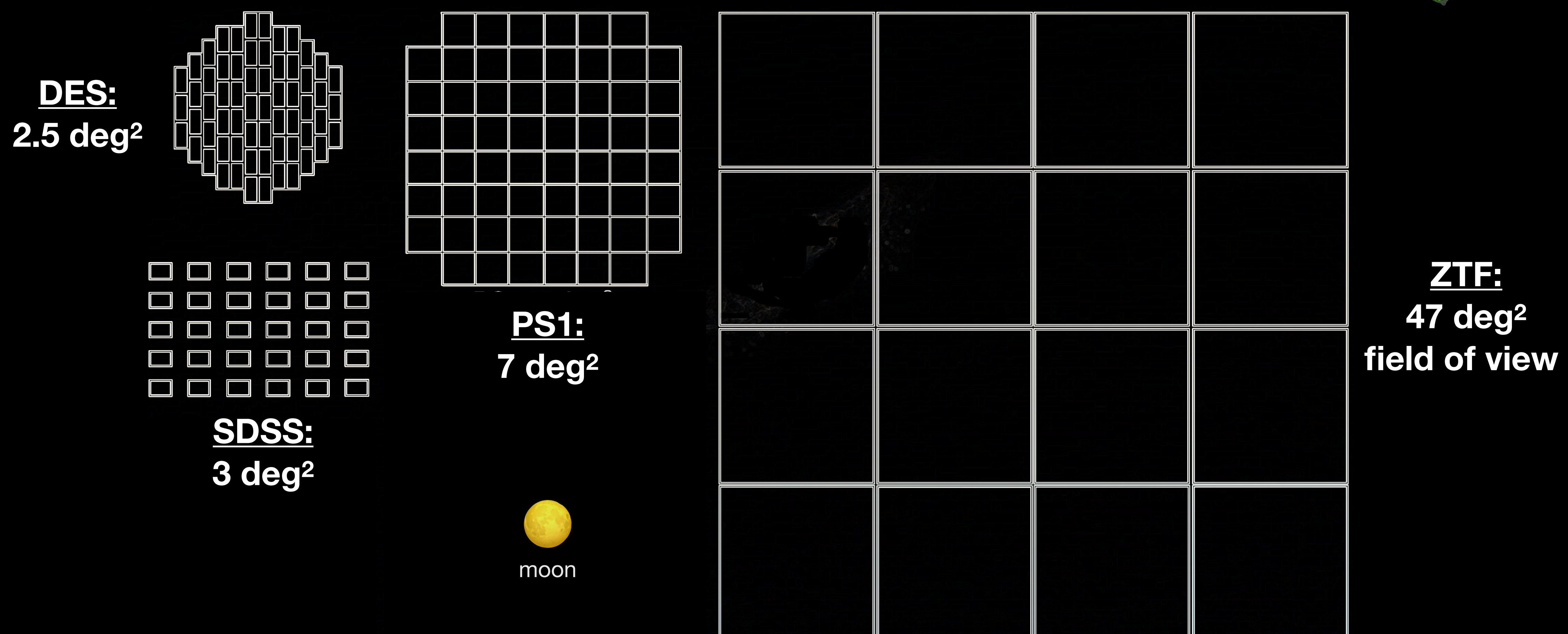
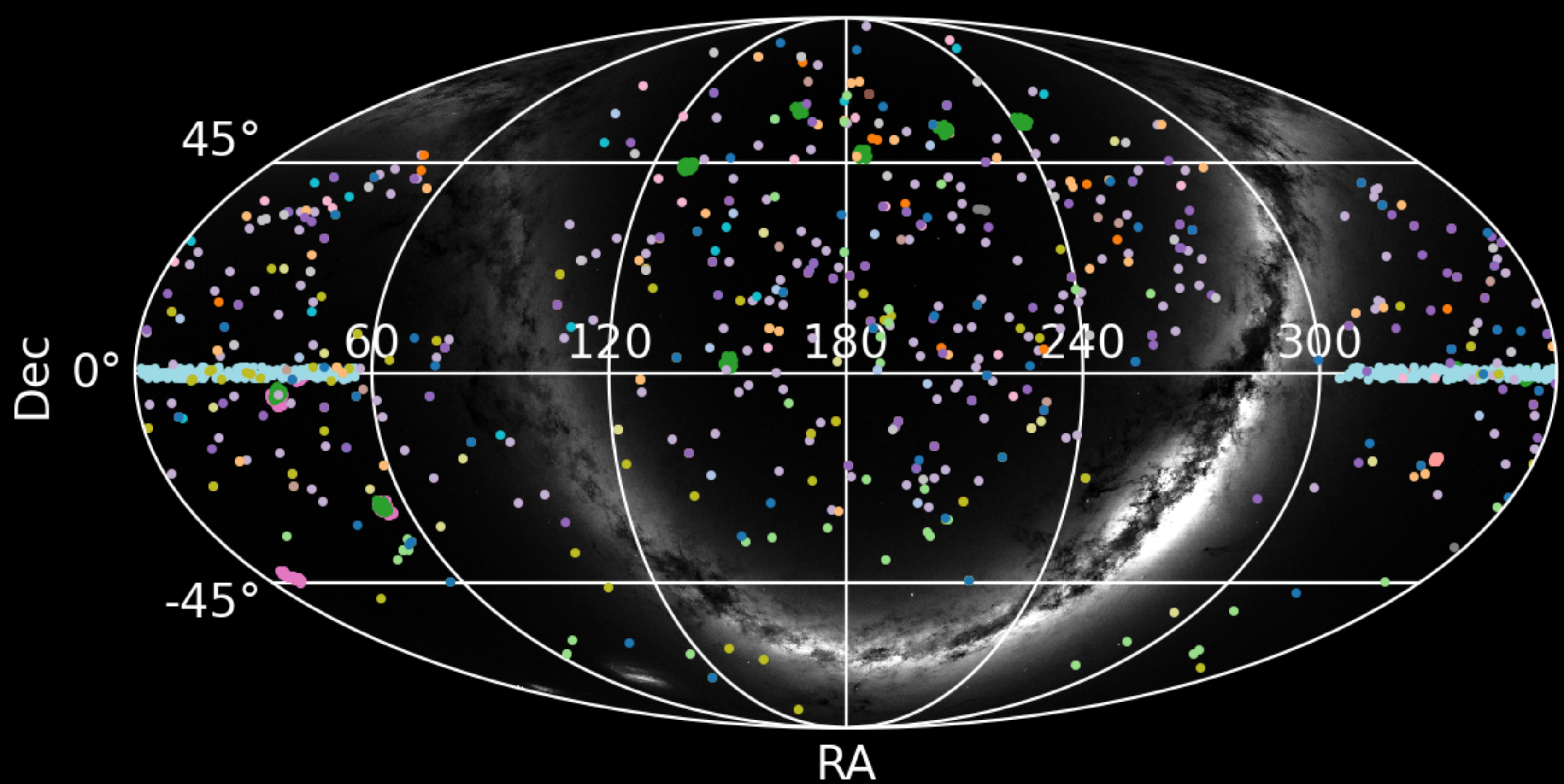
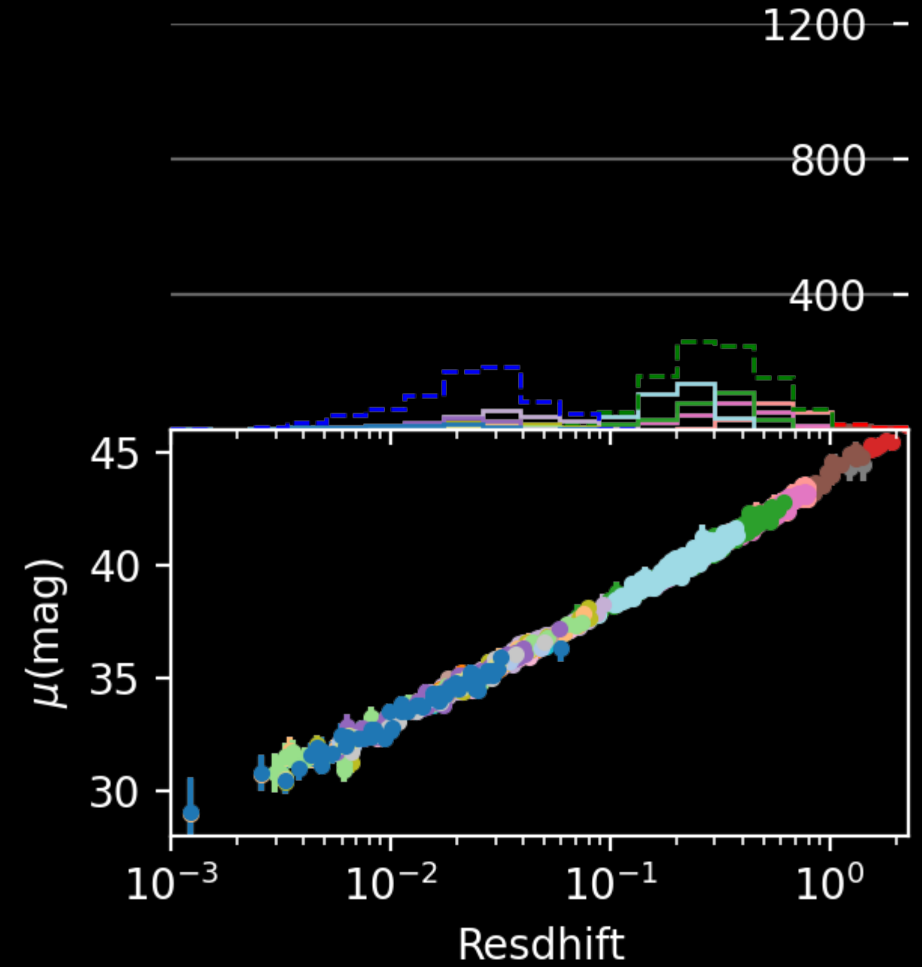
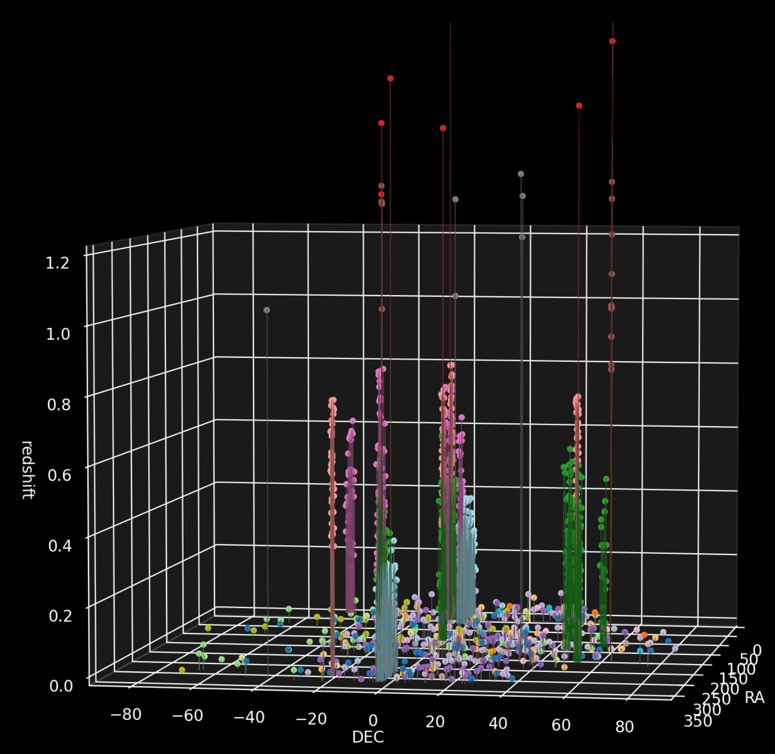



Figure adapted from Joel Johansson




- FOUNDATION
- CFA4p2
- CFA3K
- CSP
- CFA3S
- LOSS1
- CFA4p3
- LOWZ-JRK07
- LOSS2
- CFA1
- CFA2
- CNIa0.02
- SOUSA

718 SN

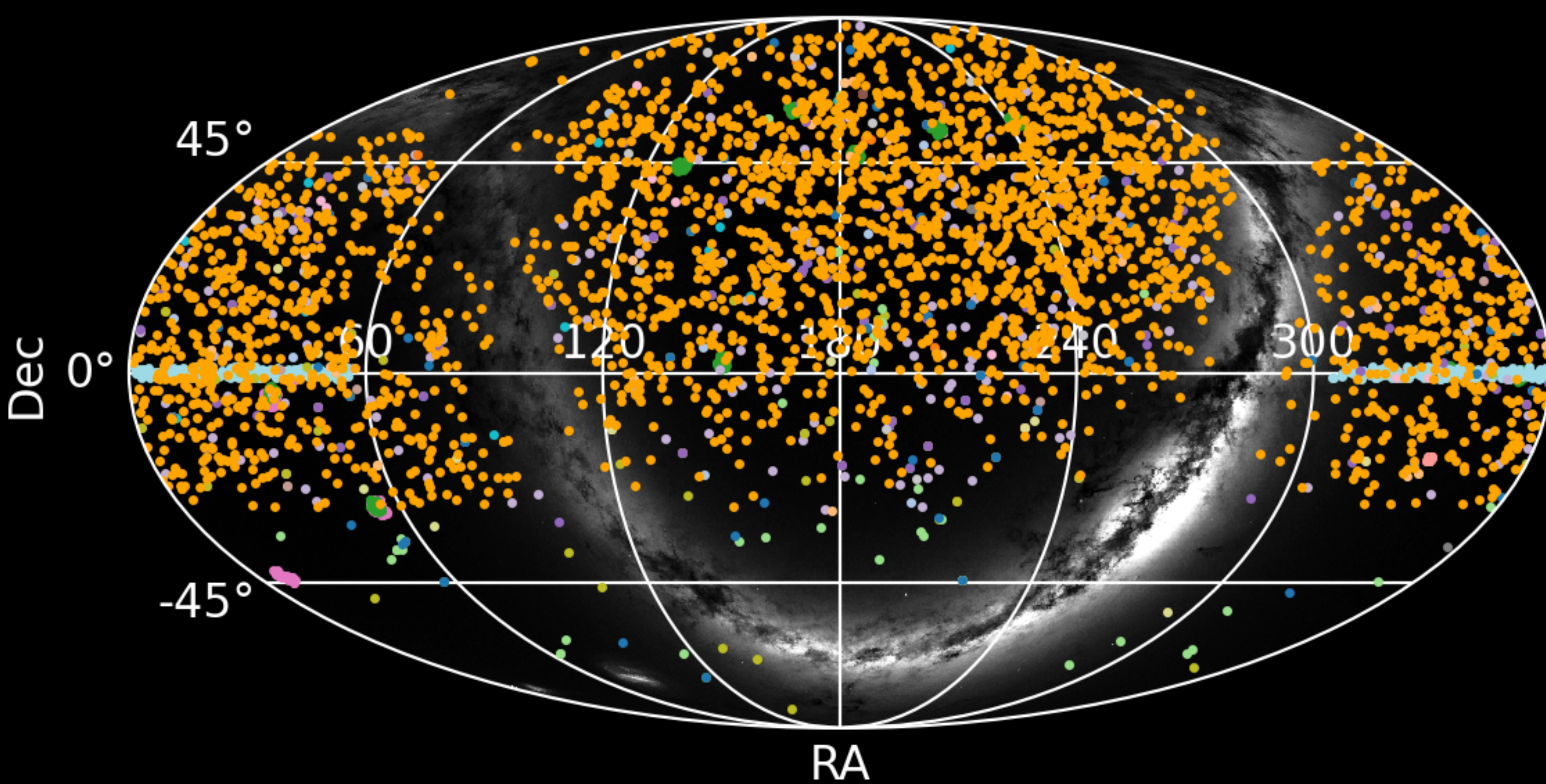
- SNLS
- DES
- PS1MD
- SDSS

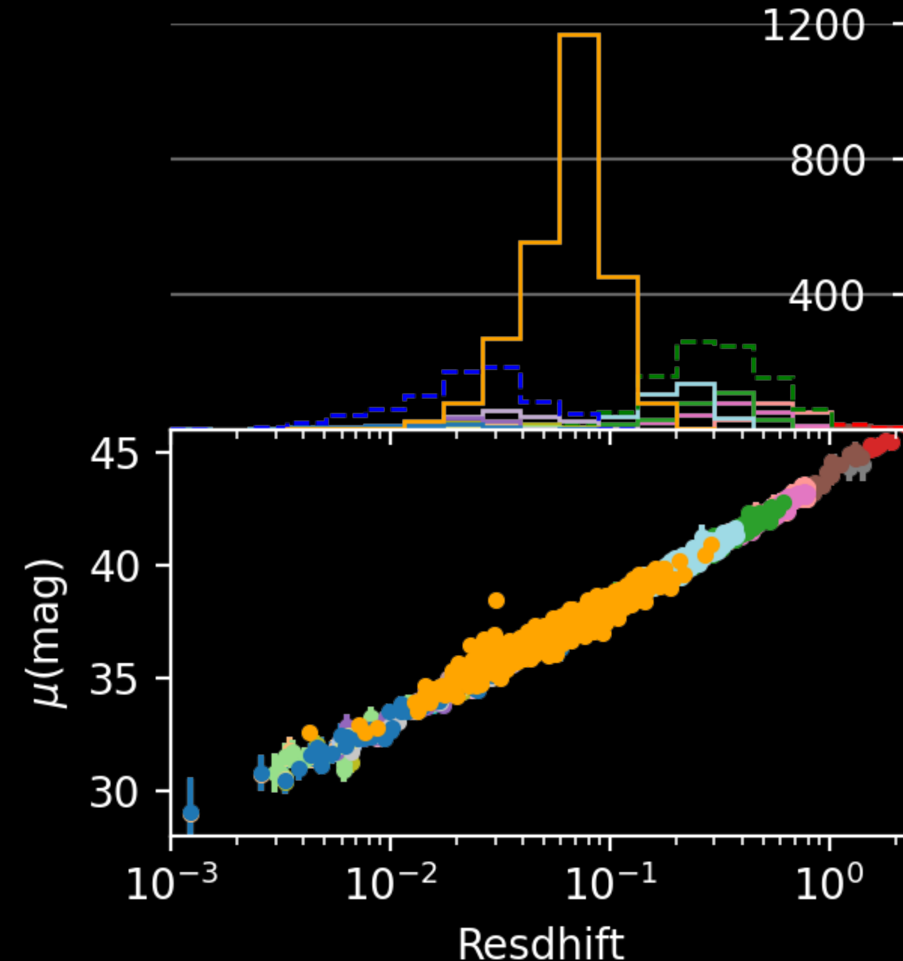
953 SN

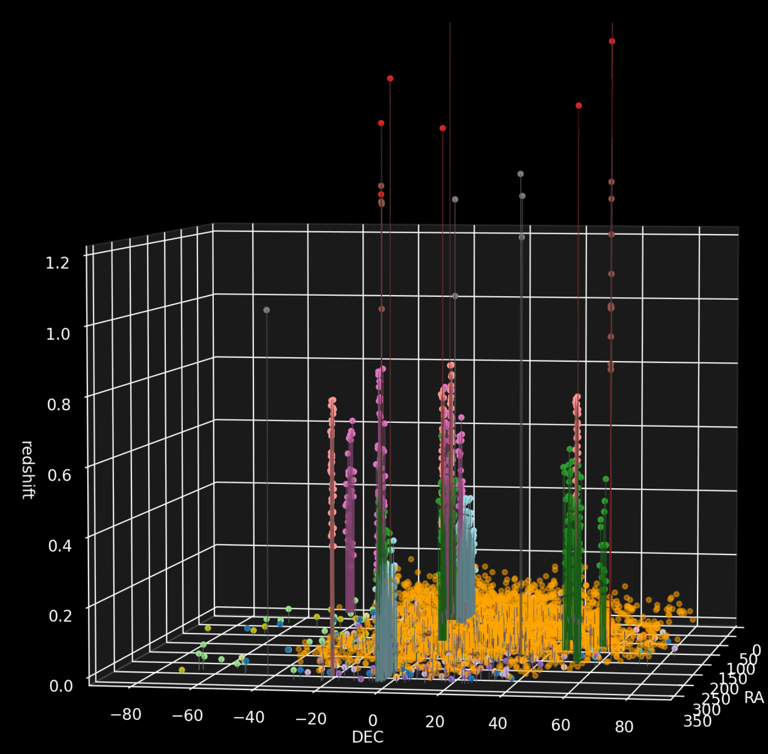
- HST2
- SCP
- HST1

30 SN

# ZTF DR2: ~ 2,000 SN at low redshift (~5000 at the end of ZTF)



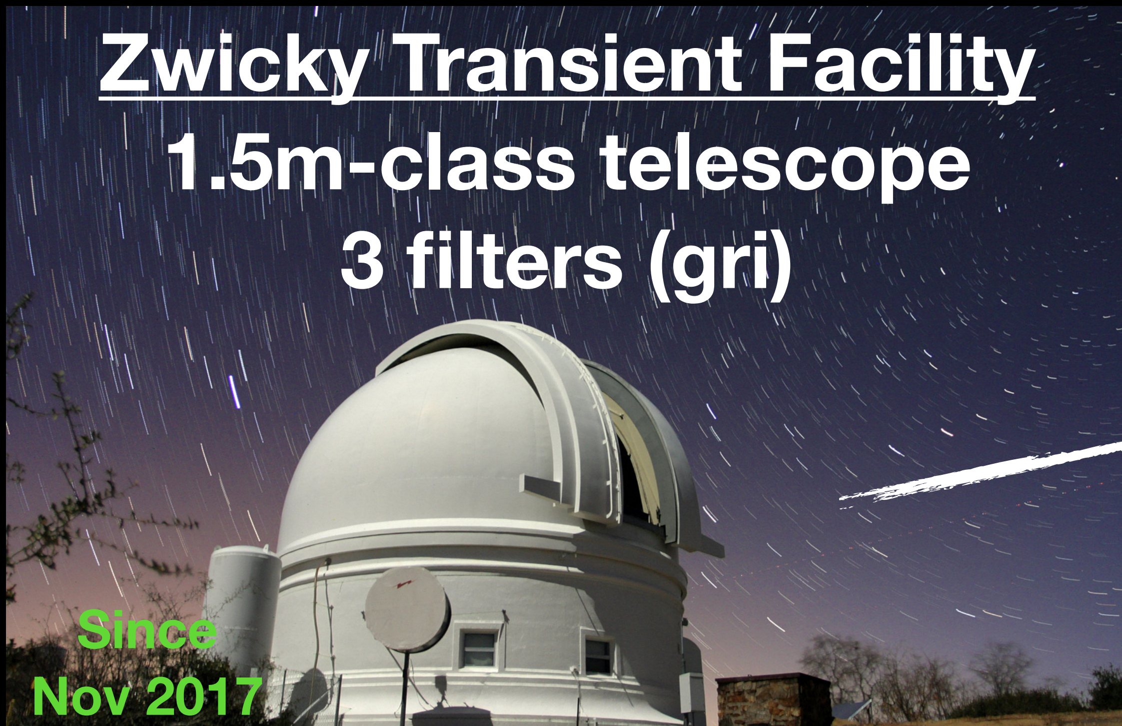



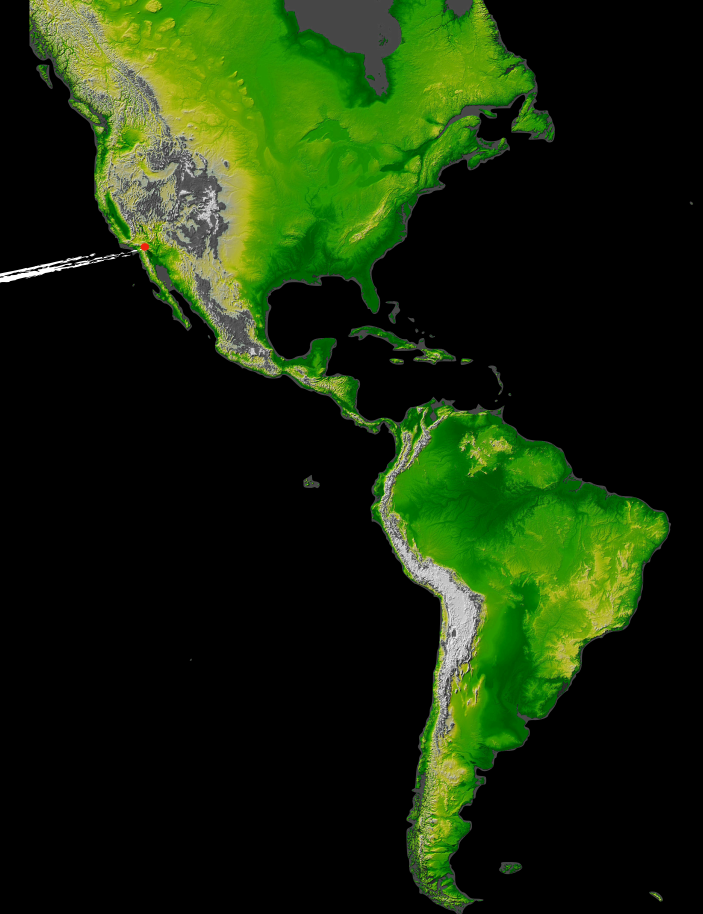



953 SN 30 SN

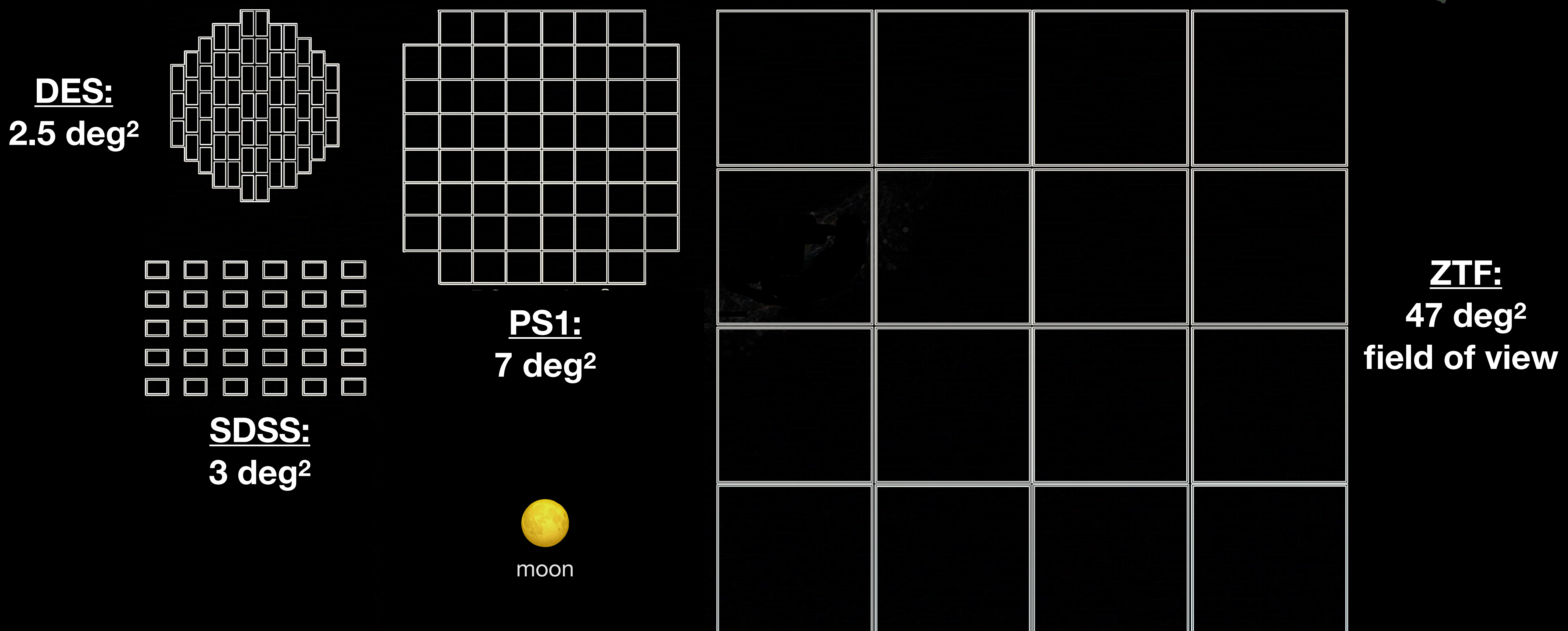
718 SN

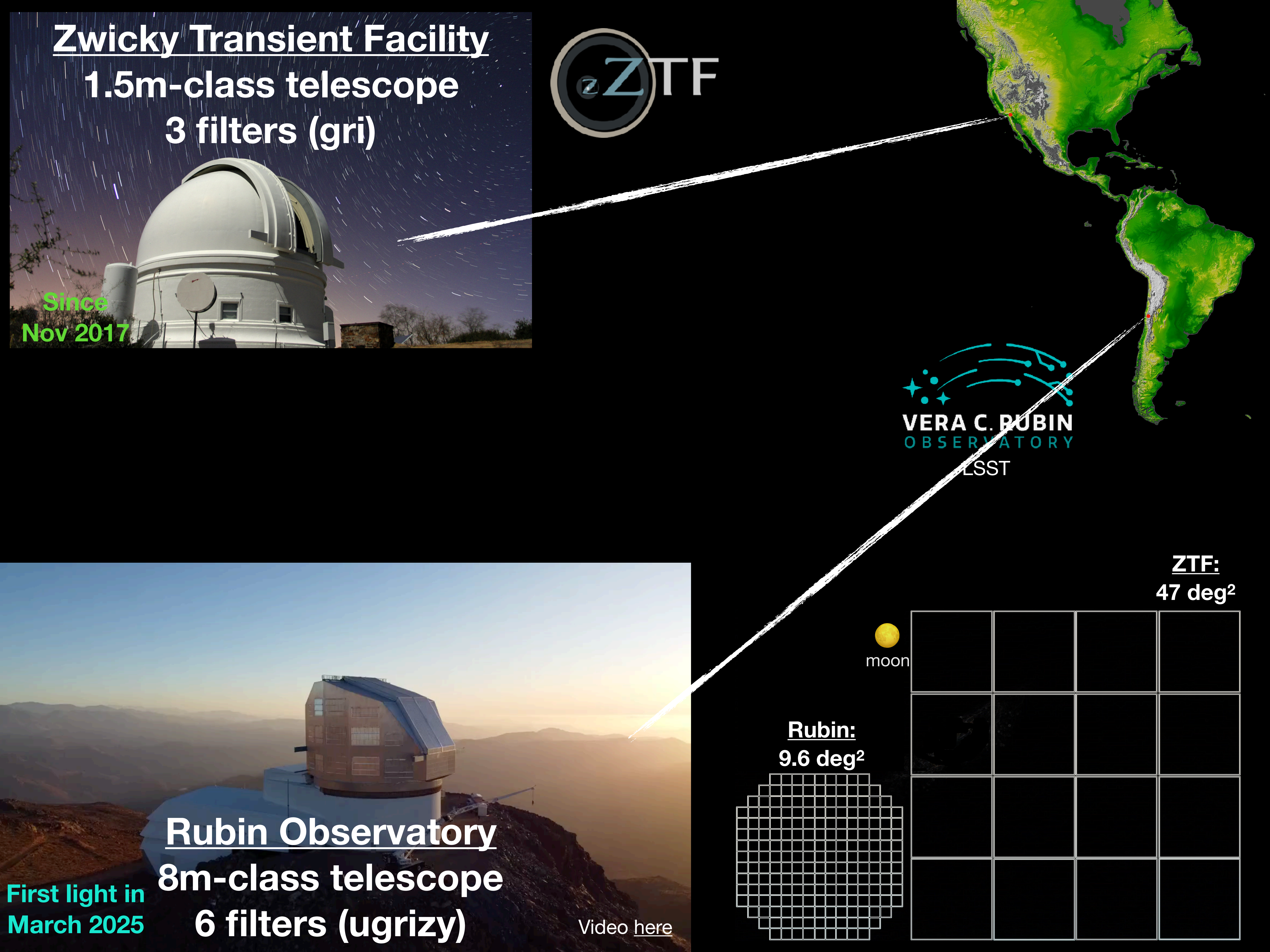



ZTF

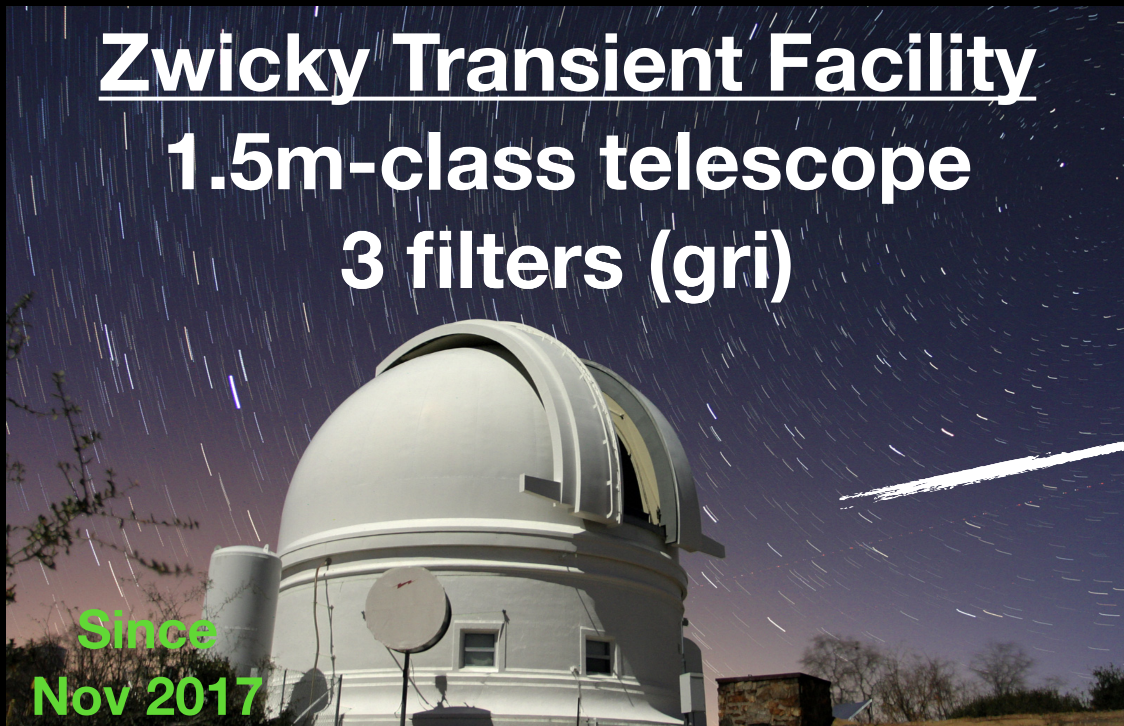


+ a dedicated spectro
—> complete up to z ~ 0.06





Zwicky Transient Facility
1.5m-class telescope
3 filters (gri)
Since
Nov 2017
ZTF
VERA C. RUBIN
OBSERVATORY
LSST
ZTF:
47 deg²
moon
Rubin:
9.6 deg²
Rubin Observatory
8m-class telescope
6 filters (ugrizy)
First light in
March 2025
Video here



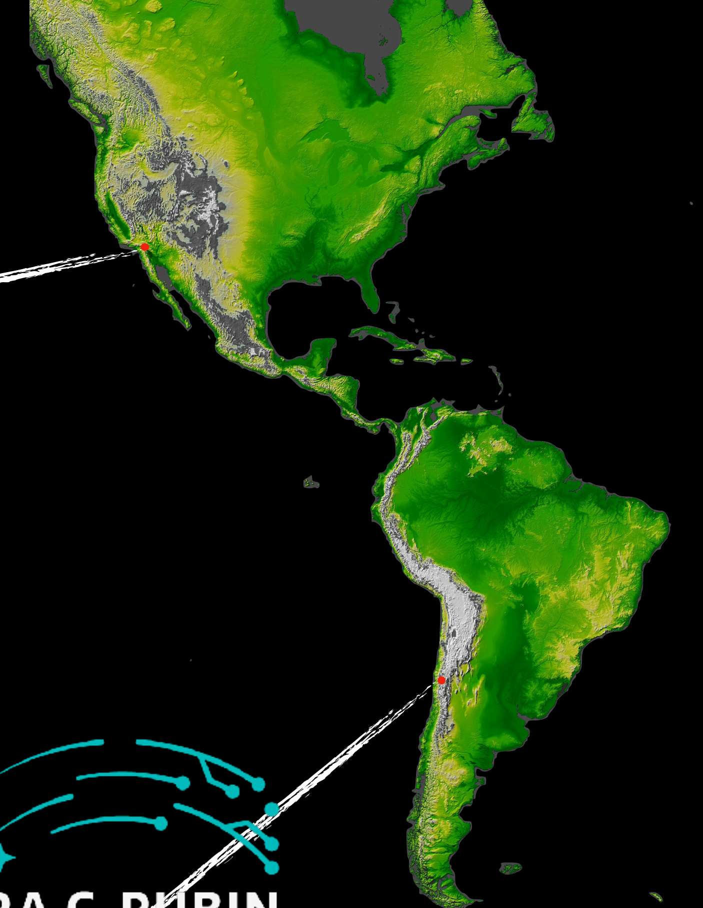
## Zwicky Transient Facility

**1.5m-class telescope**

**3 filters (gri)**

**Since Nov 2017**

ZTF



VERA C. RUBIN OBSERVATORY

LSST

## Rubin Observatory

**8m-class telescope**

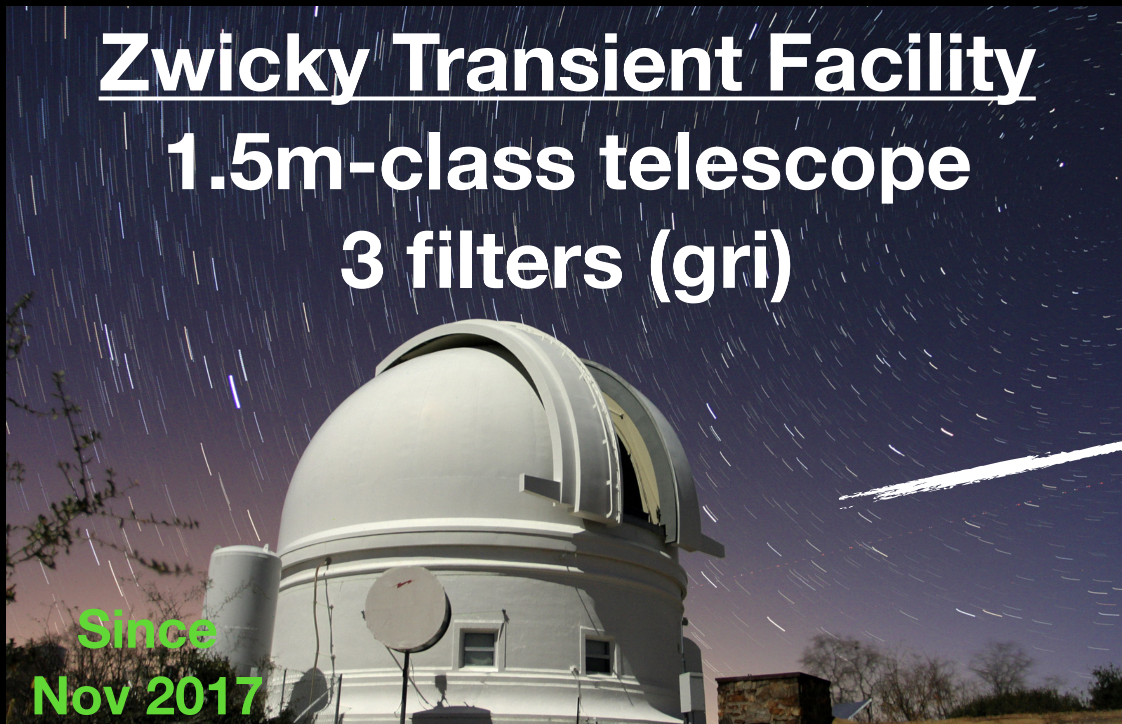
**6 filters (ugrizy)**

**First light in March 2025**

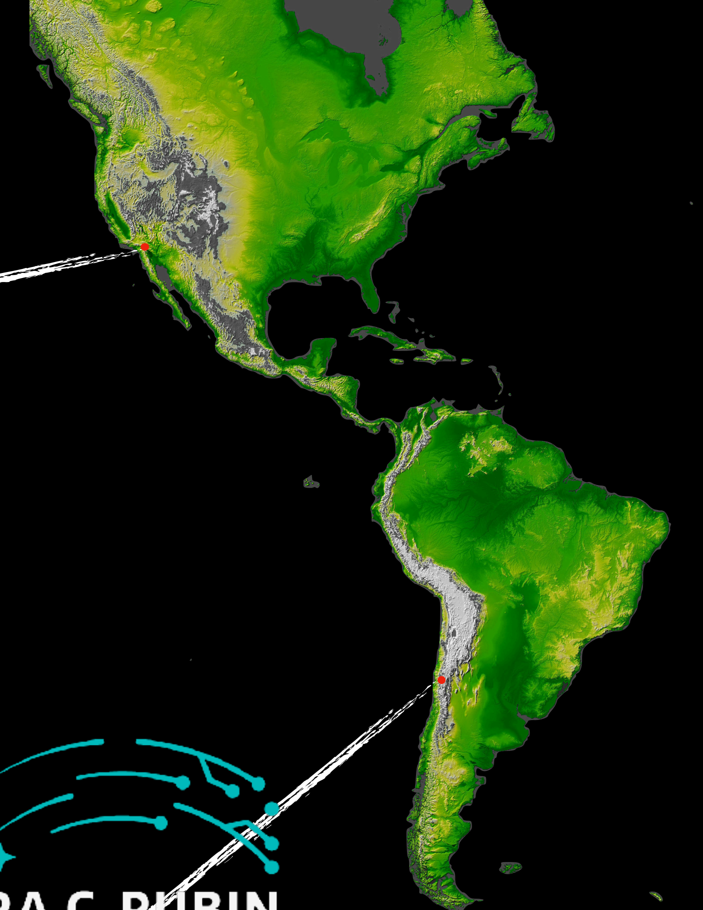
Video here

**World's Largest Camera**

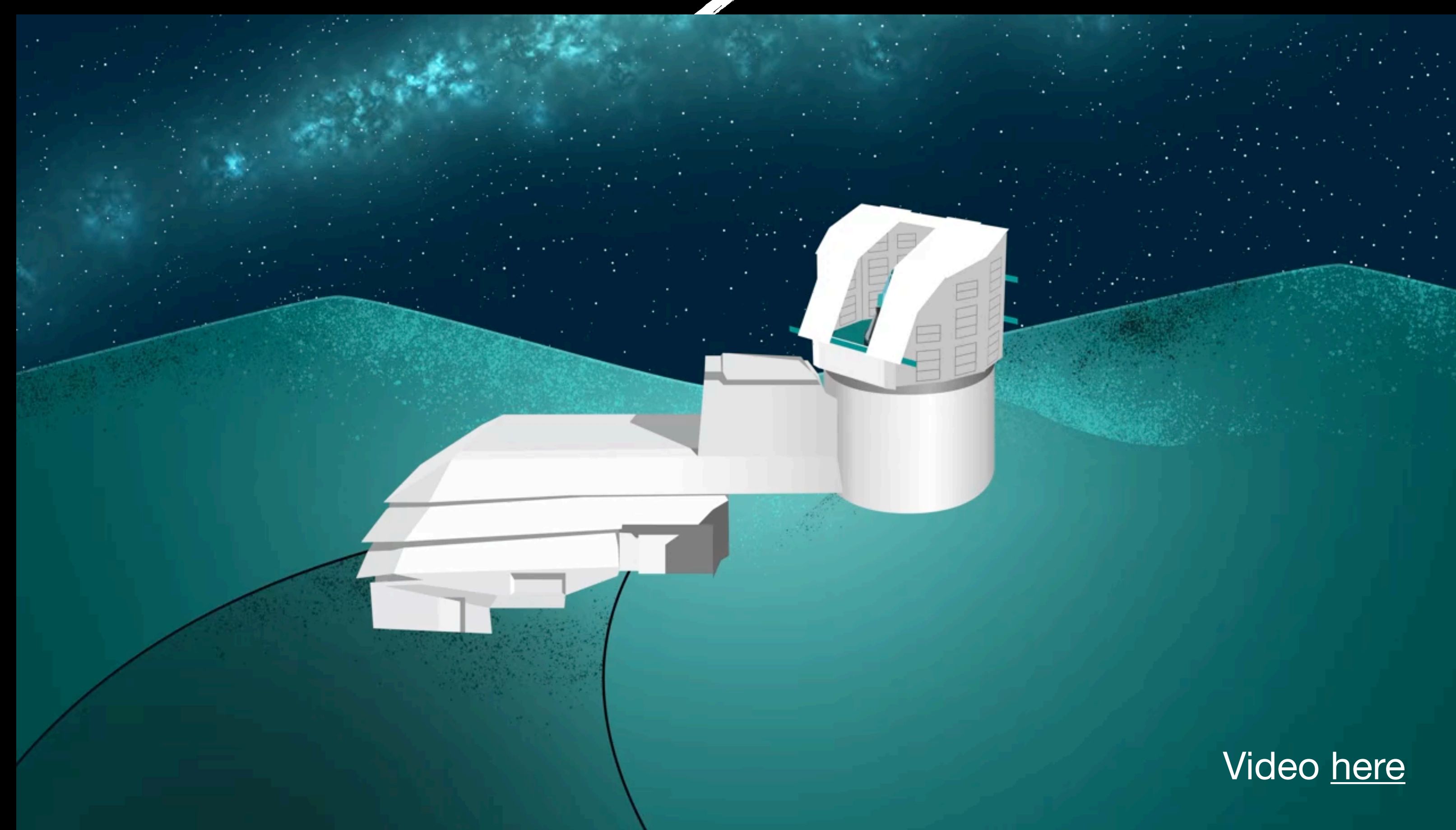
**Now at summit**




ZTF



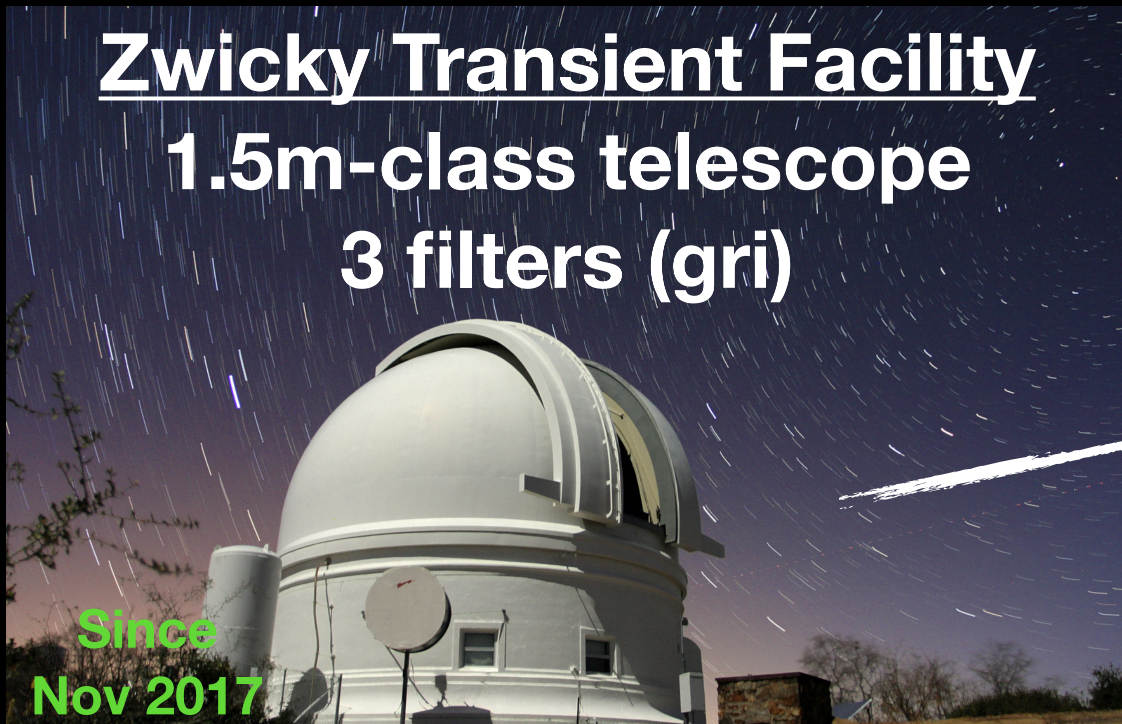
VERA C. RUBIN
OBSERVATORY
LSST



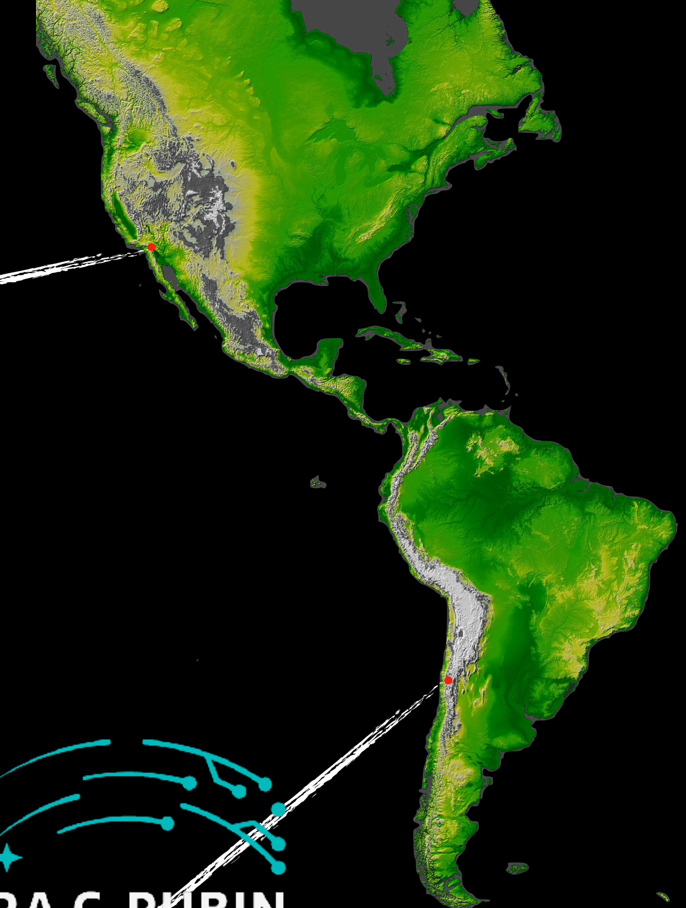

**Rubin Observatory**

**8m-class telescope**

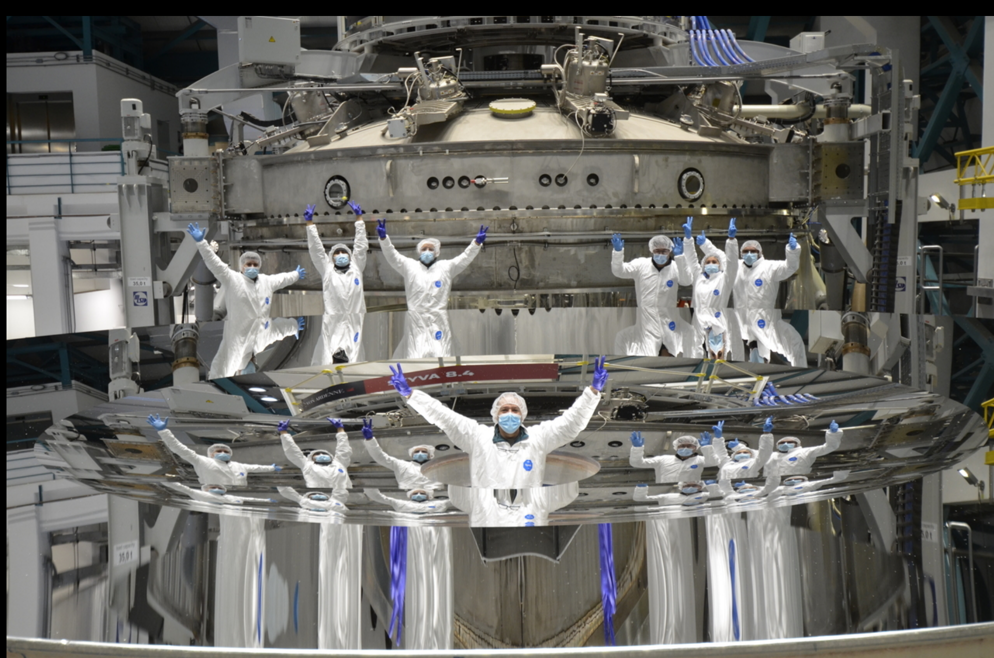
**6 filters (ugrizy)**



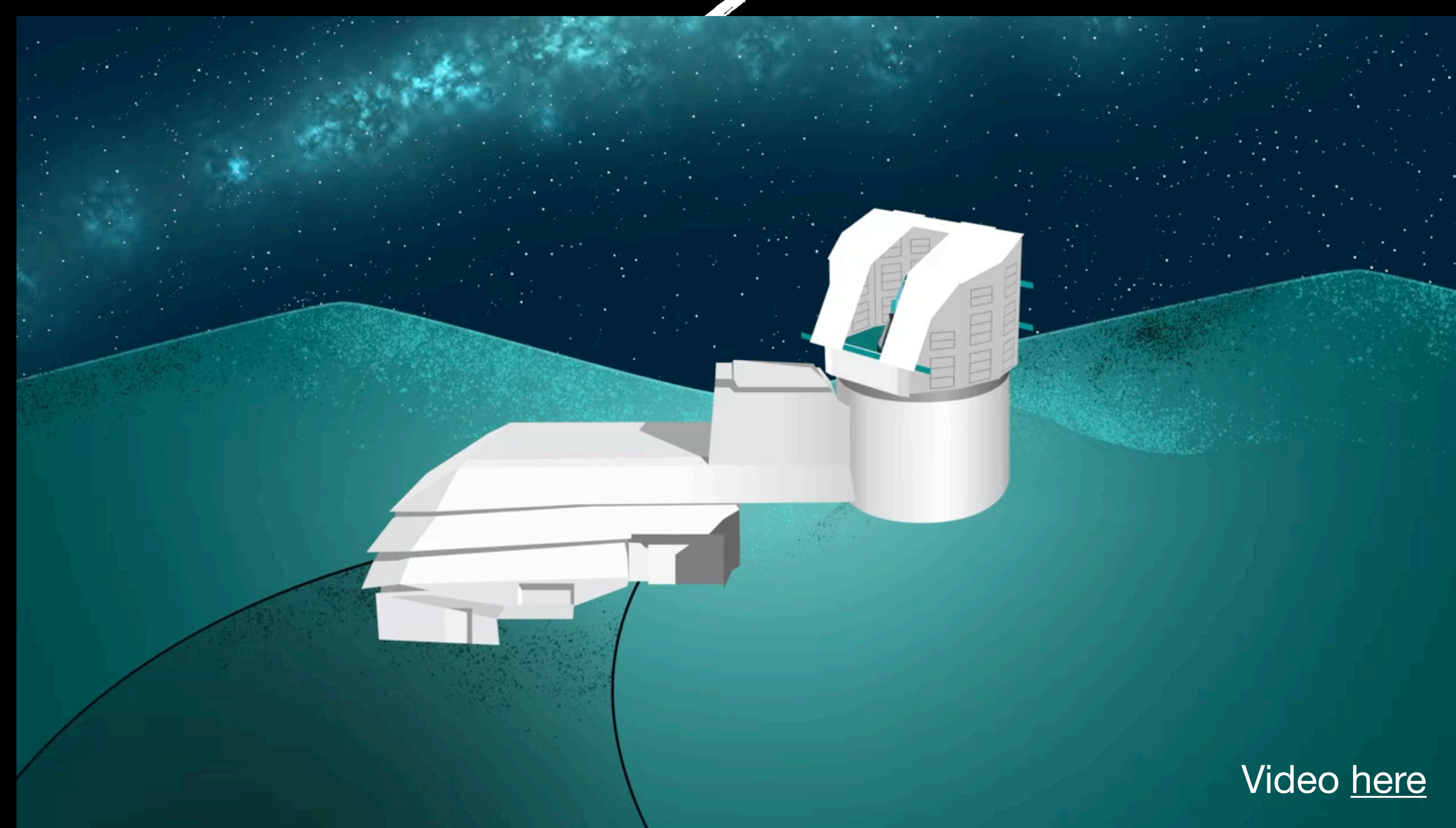

ZTF



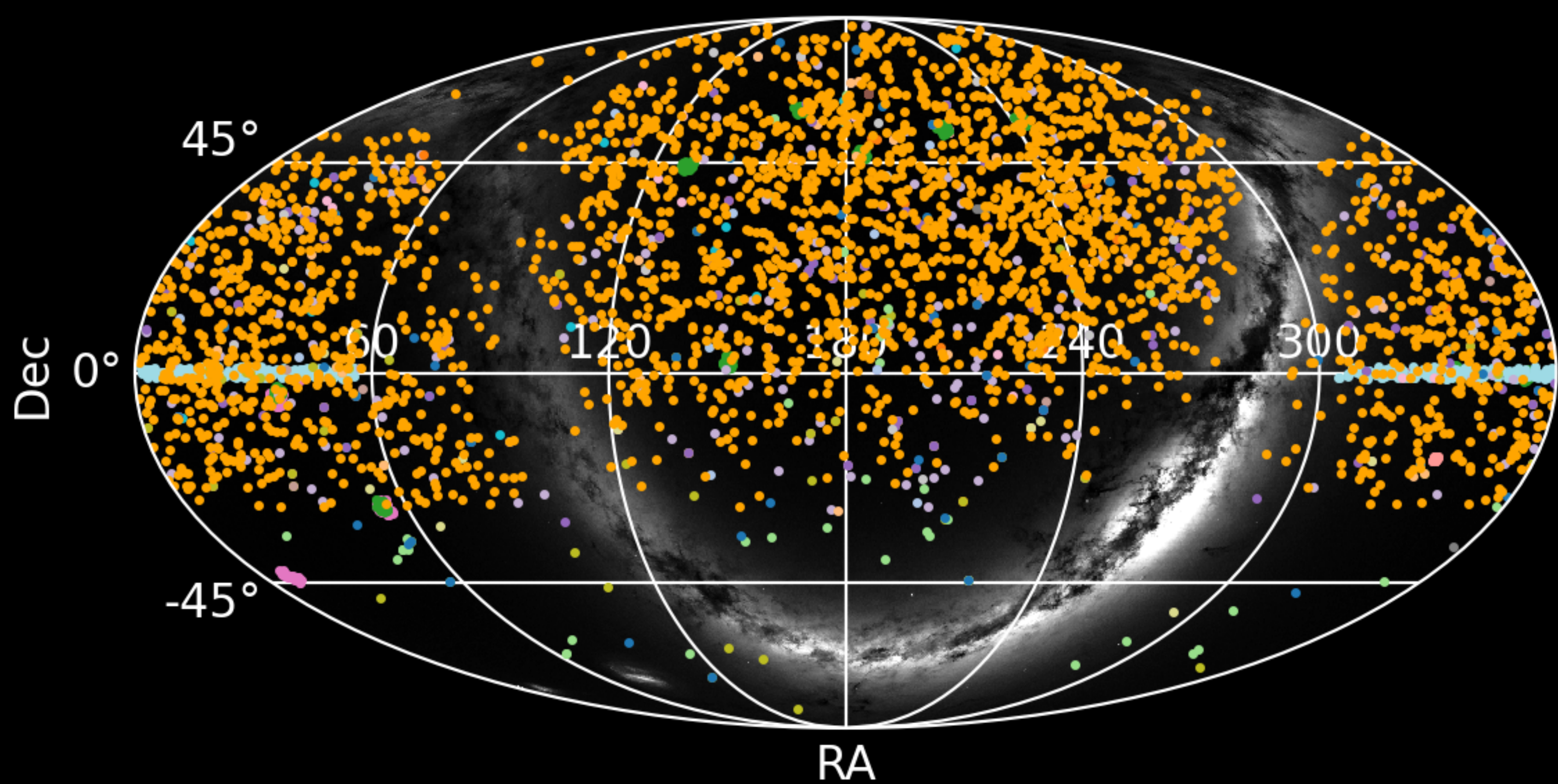
VERA C. RUBIN
OBSERVATORY
LSST

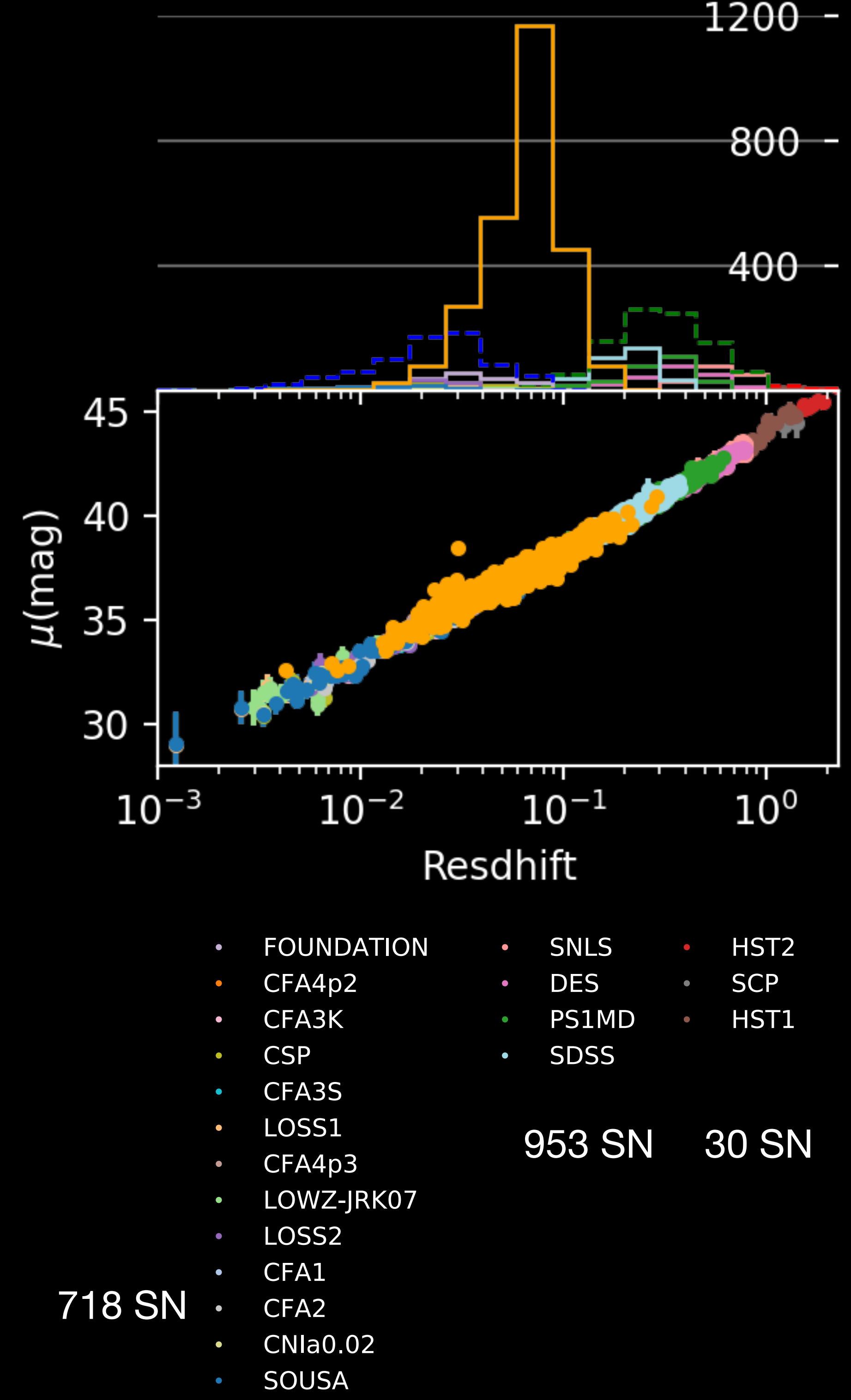


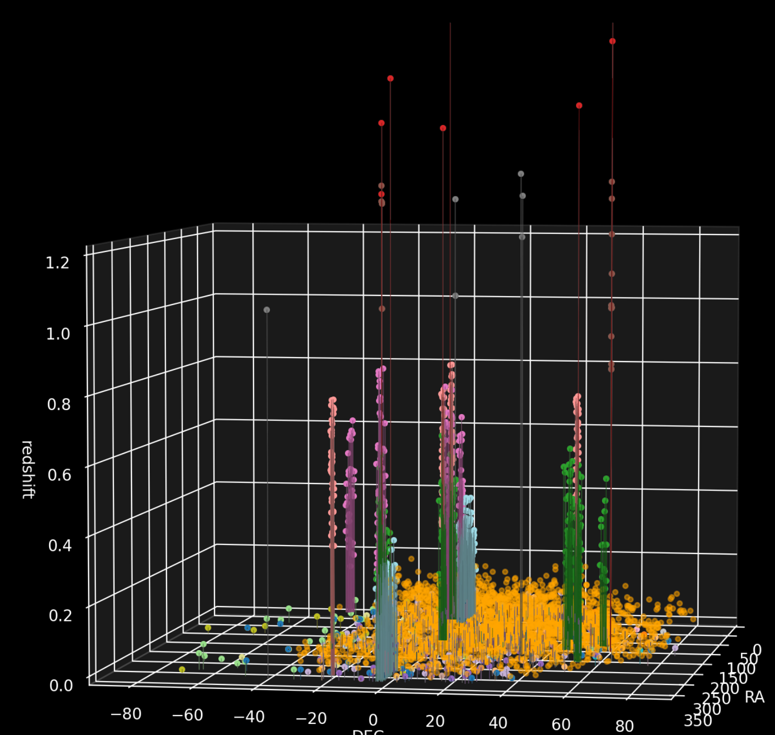
## Rubin Observatory
8m-class telescope
6 filters (ugrizy)



# ZTF DR2: ~ 2,000 SN at low redshift (~5000 at the end of ZTF)

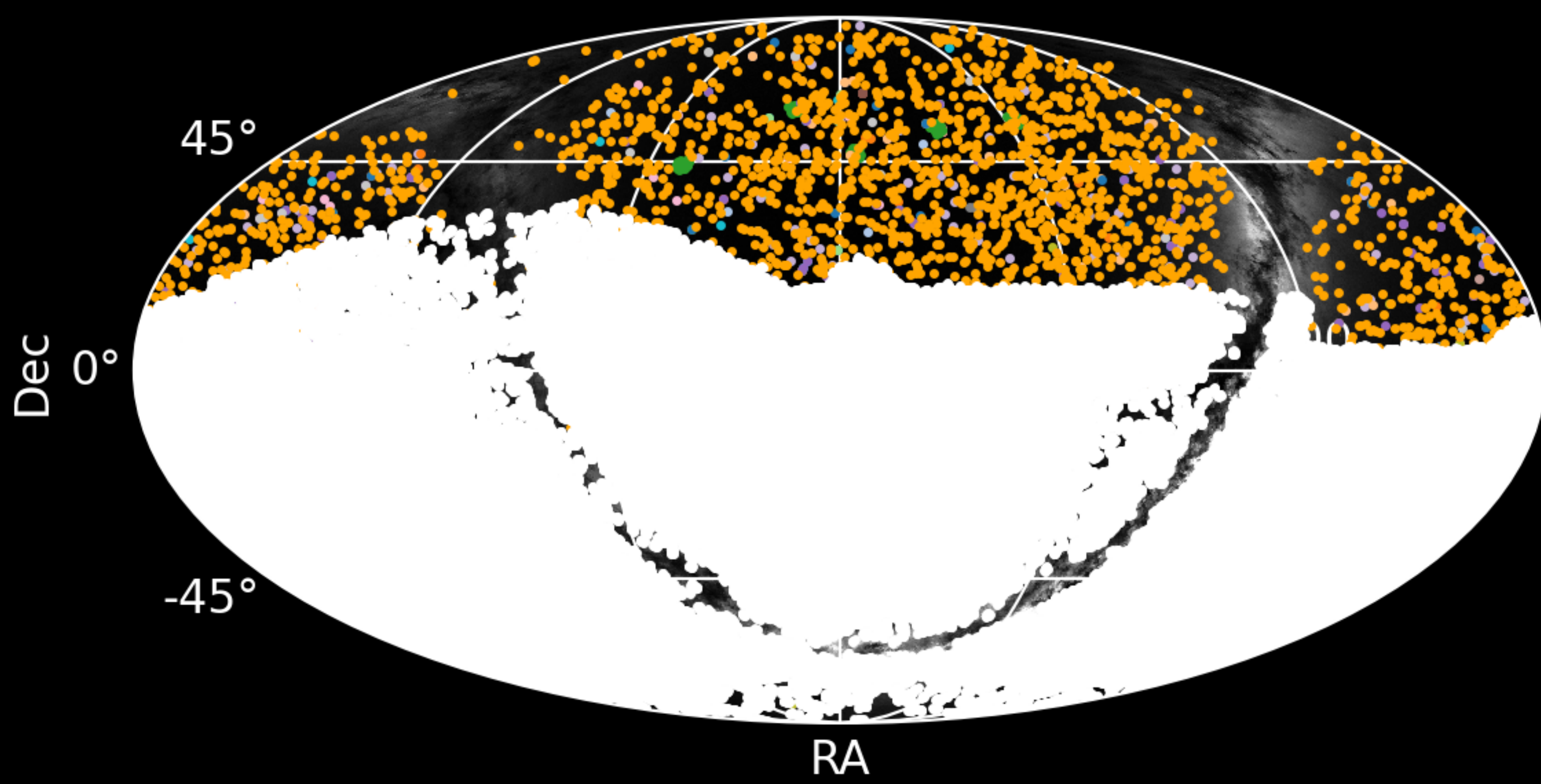


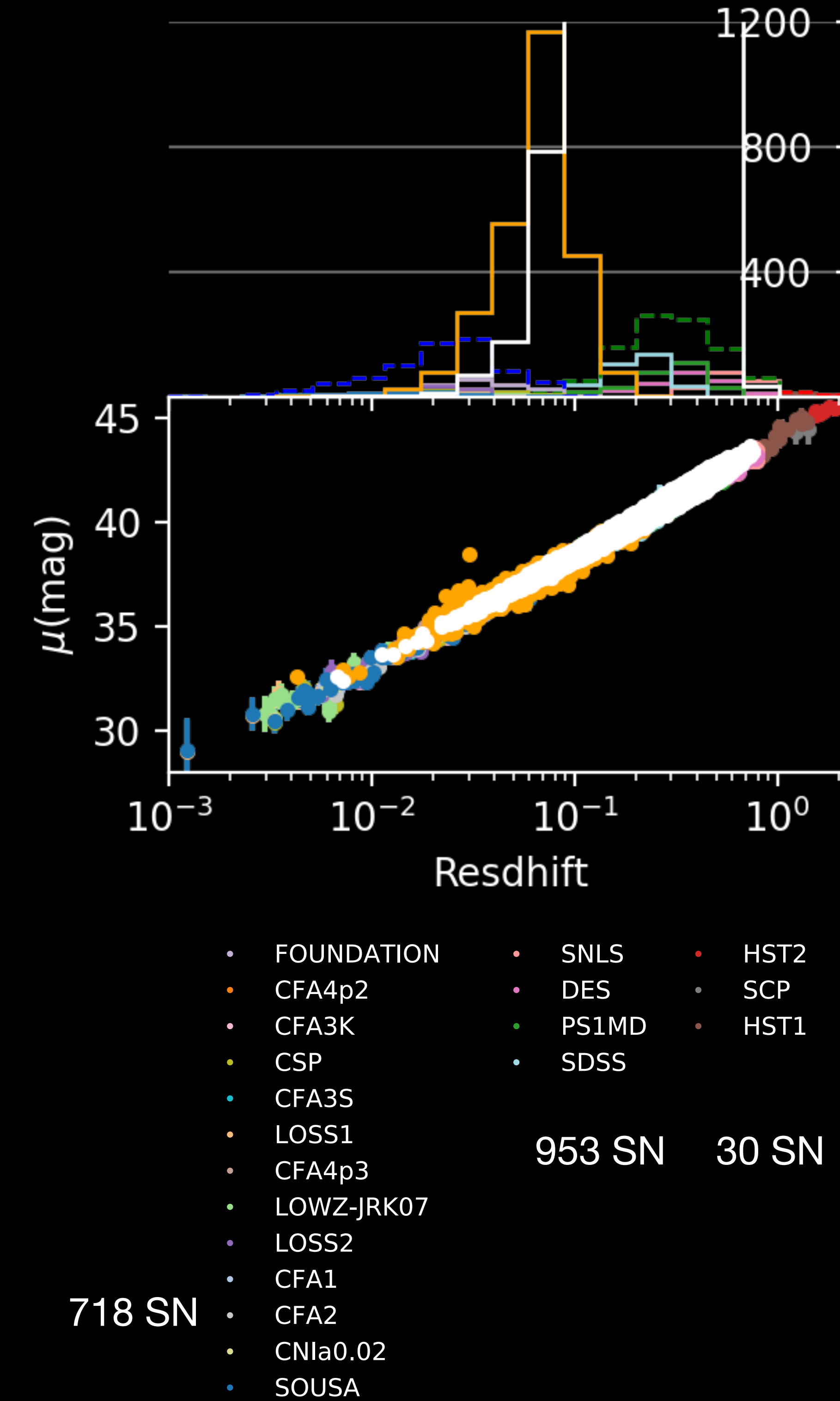



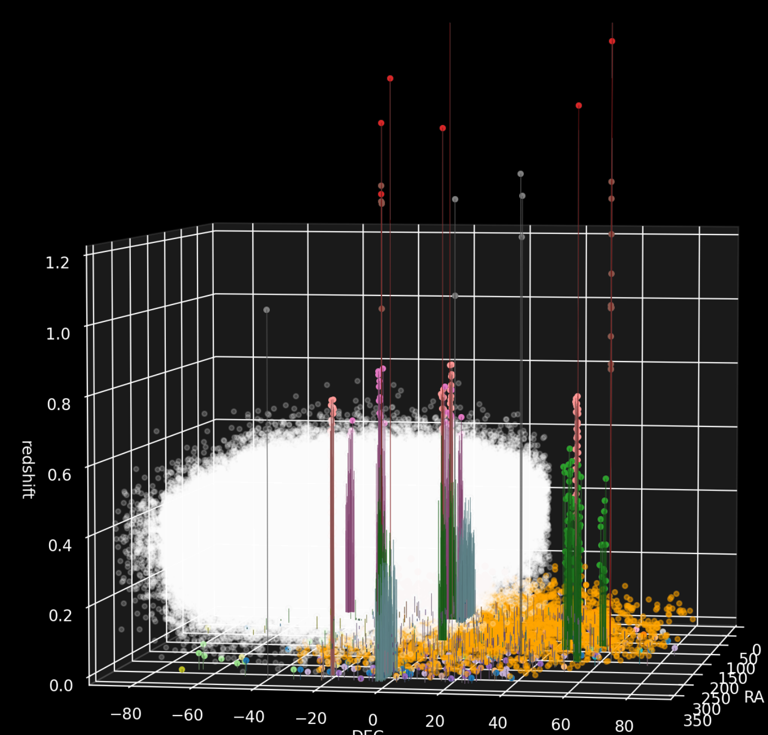



ZTF DR2: ~ 2,000 SN at low redshift (~5000 at the end of ZTF)

LSST wide-fast-deep: ~ 1,000,000 SN at intermediate redshift



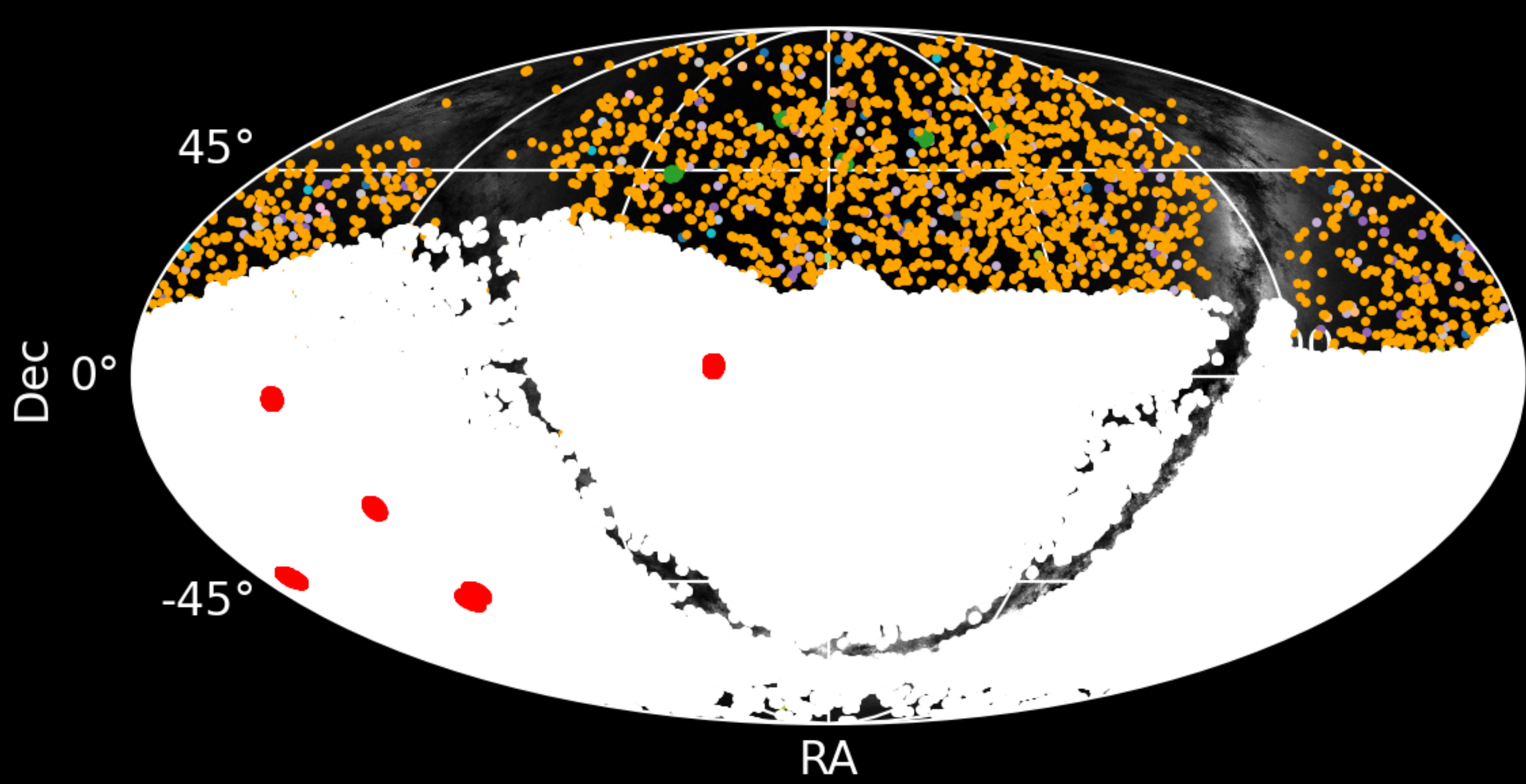
ZTF DR2: ~ 2,000 SN at low redshift (~5000 at the end of ZTF)

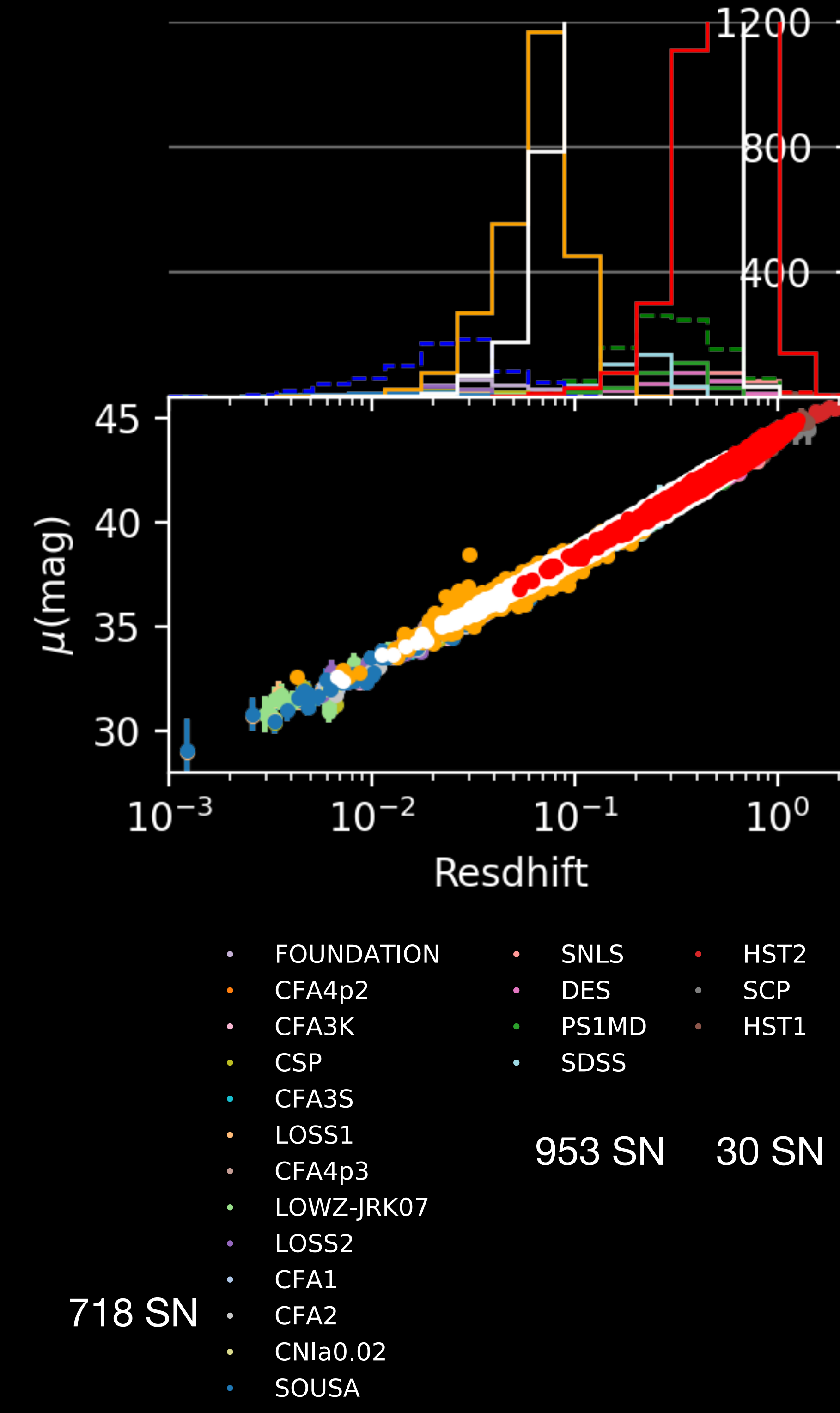
LSST wide-fast-deep: ~ 1,000,000 SN at intermediate redshift

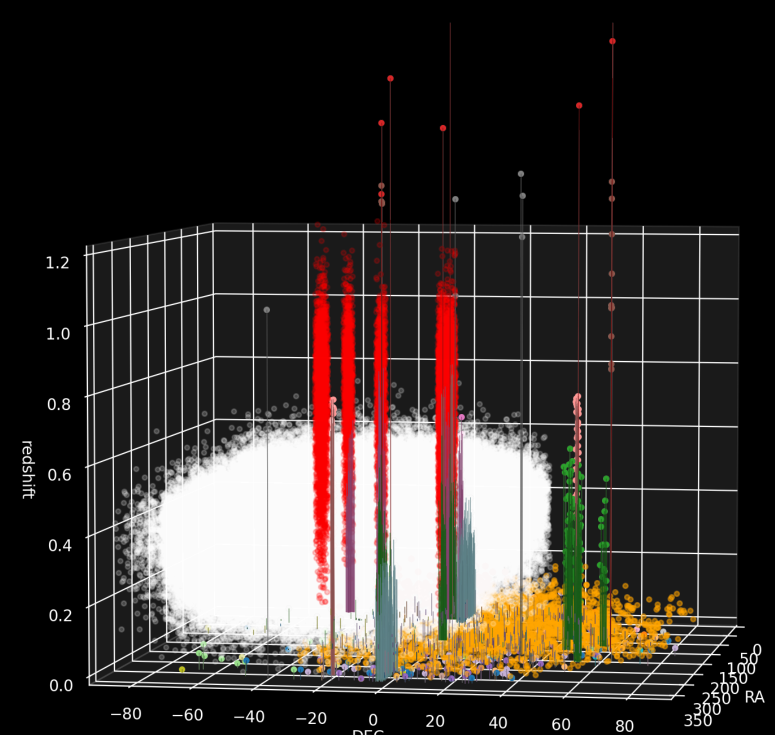
LSST deep-drilling: ~ 10,000 SN at high redshift

ZTF

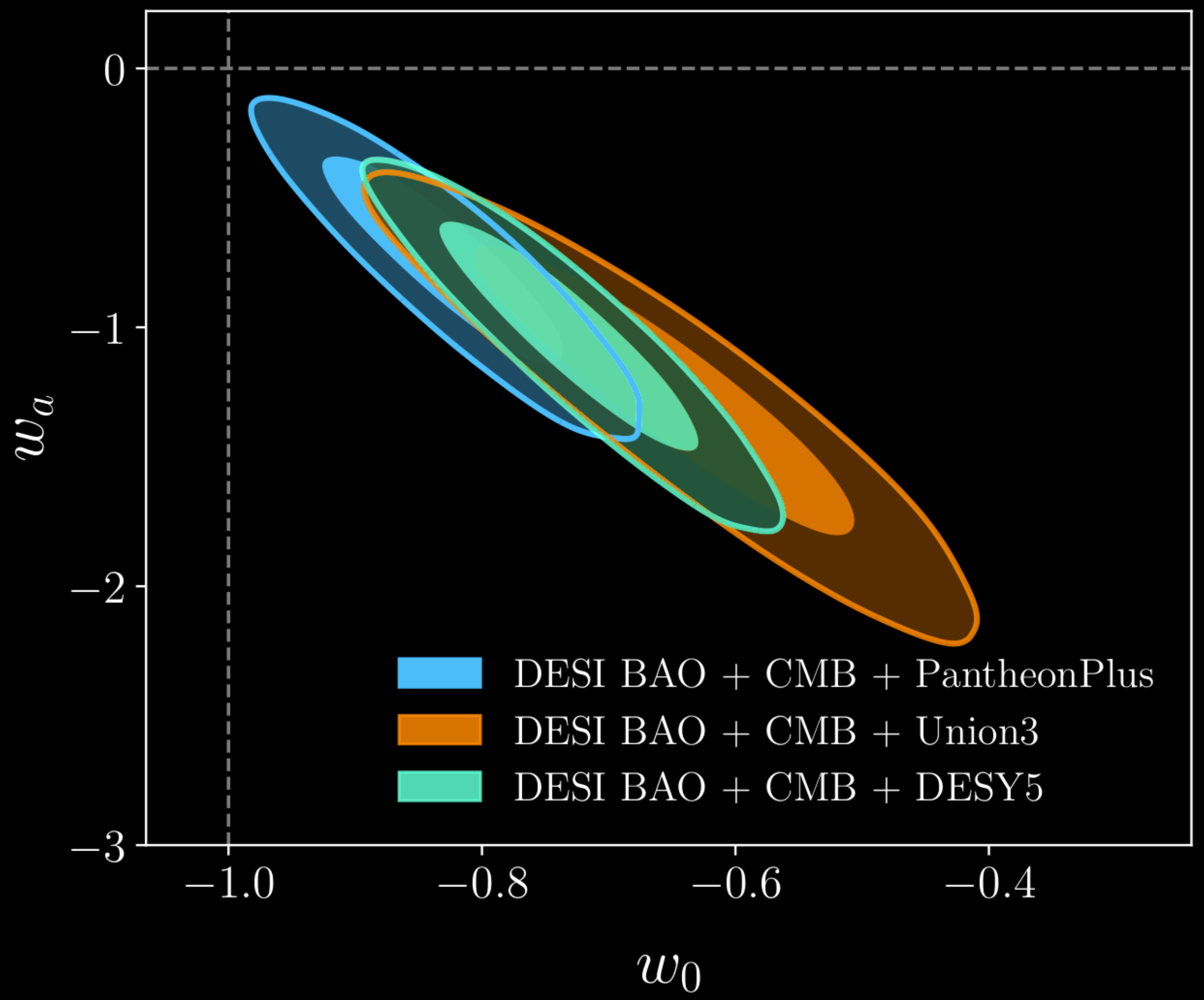
VERA C. RUBIN OBSERVATORY



# Current constraints



# LSST will reduce area by ~20

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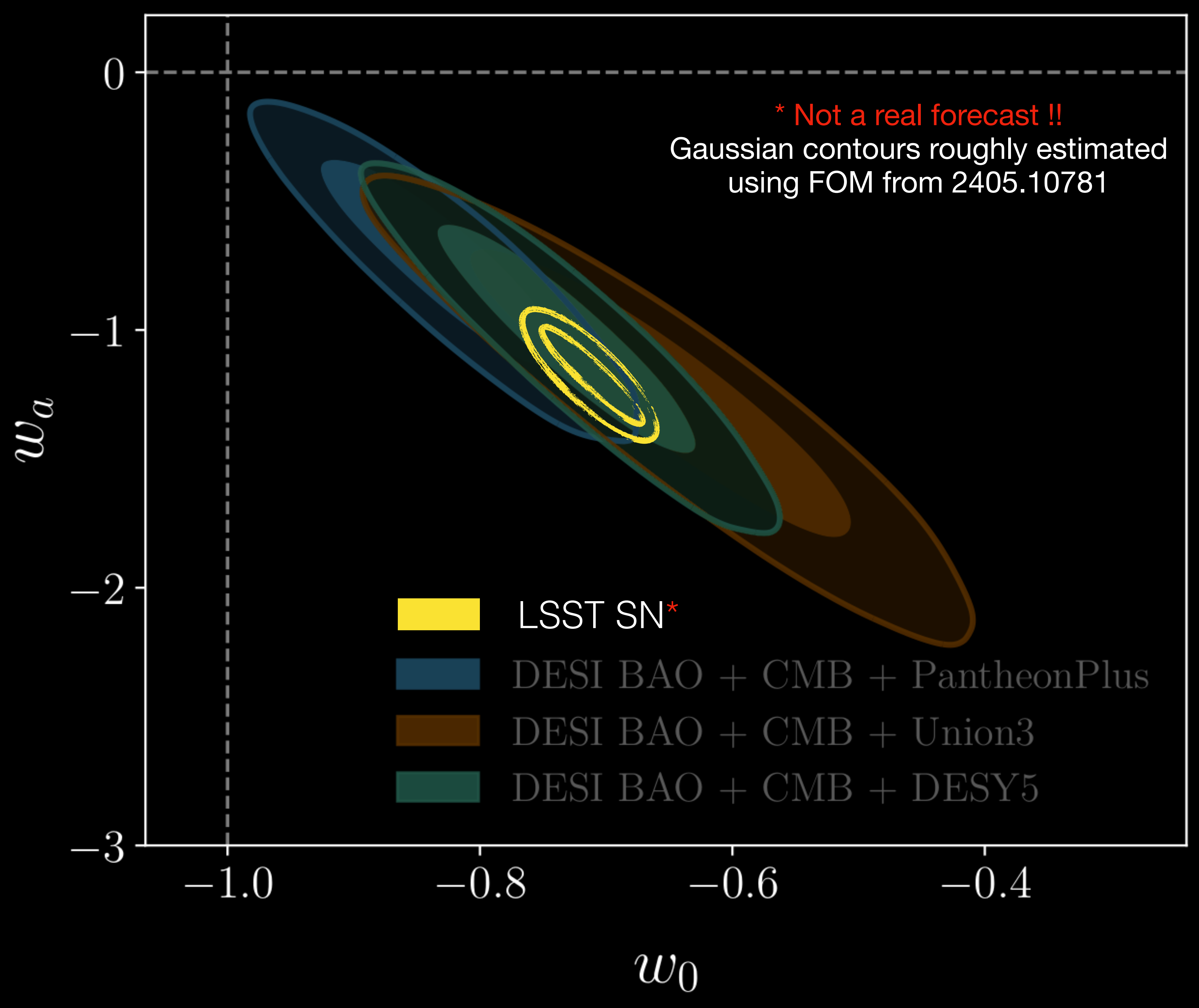
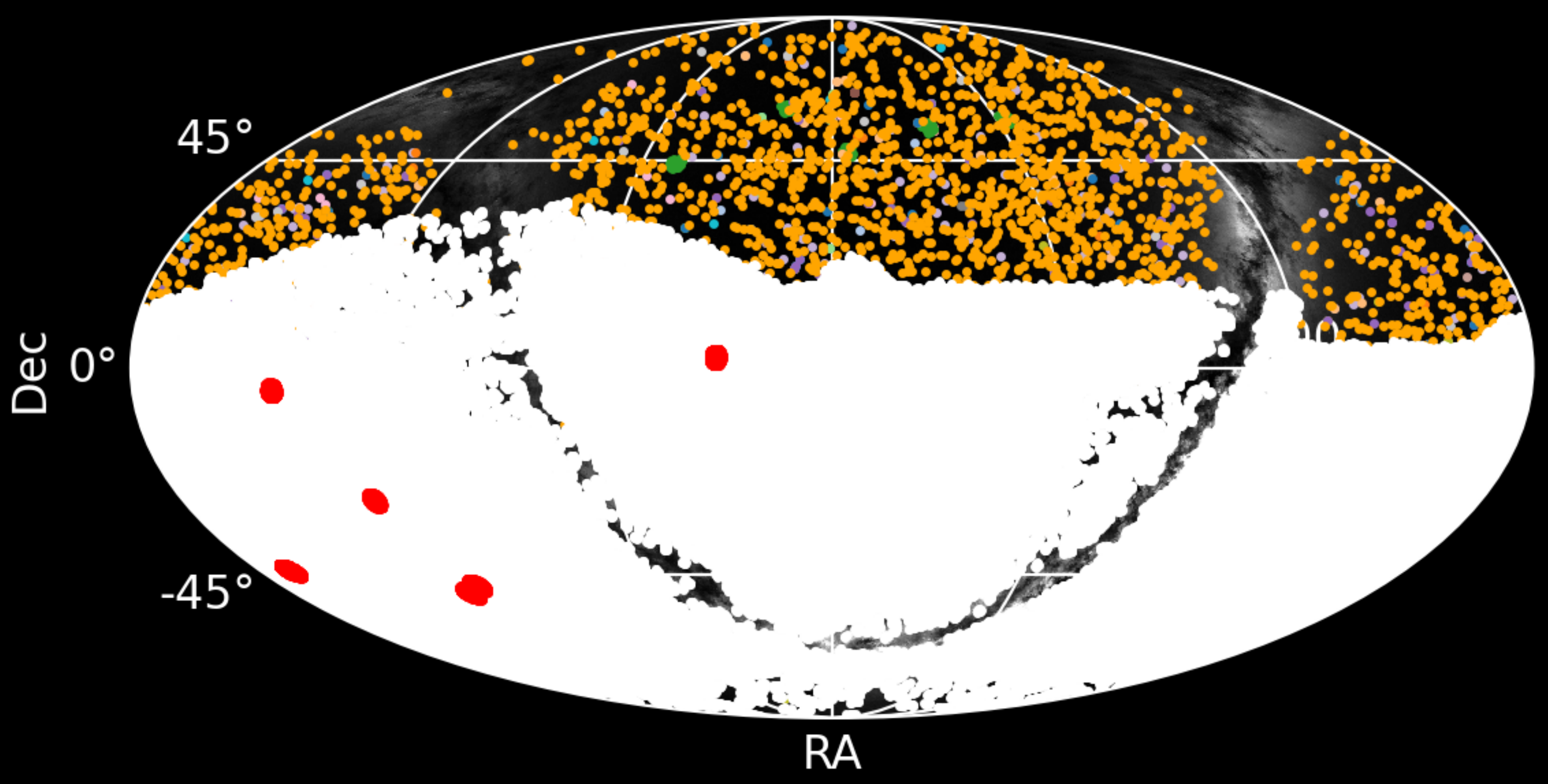
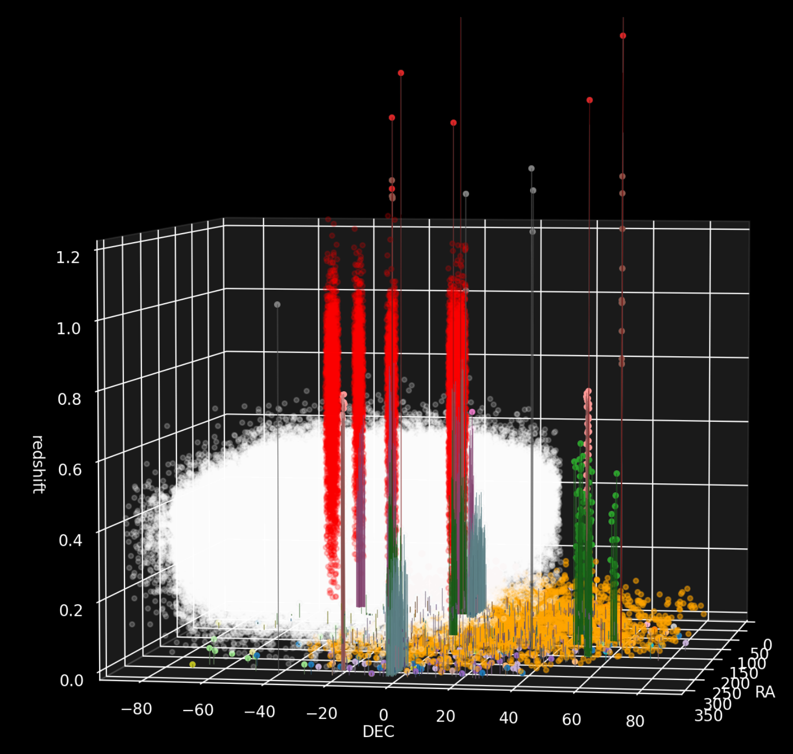
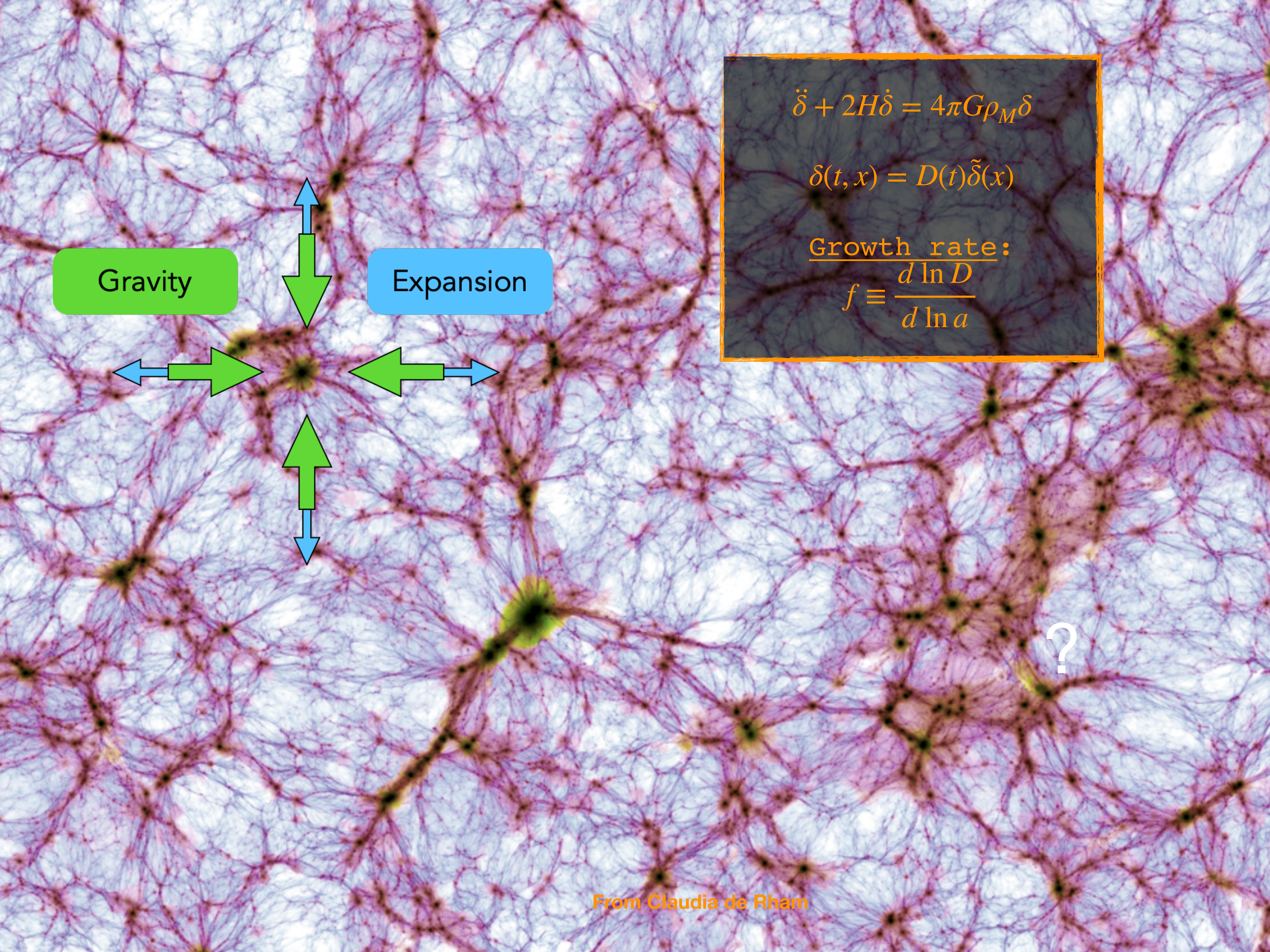


ZTF DR2
LSST wide-fast-deep
LSST deep-drilling




Full sky coverage:
We will be able to measure the isotropy of the expansion, it’s acceleration, etc



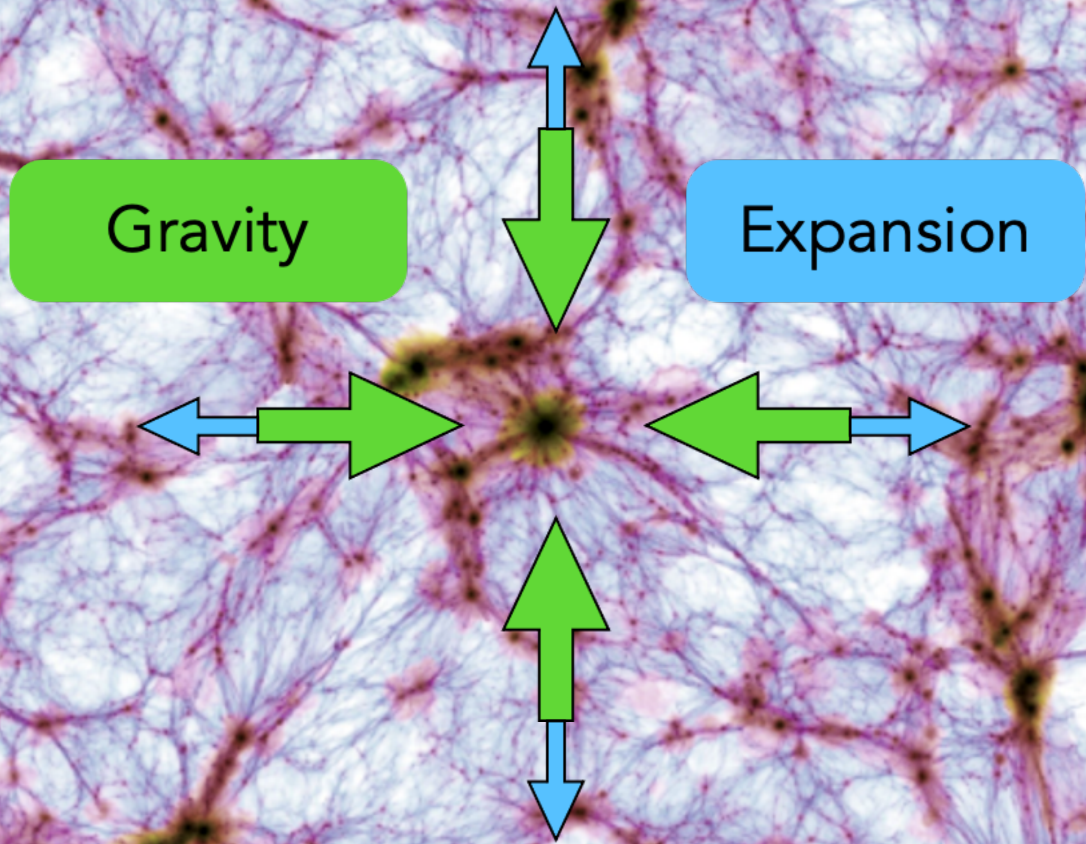

$$\ddot{\delta} + 2H\dot{\delta} = 4\pi G \rho_M \delta$$

$$\delta(t, x) = D(t)\tilde{\delta}(x)$$

Growth rate:

$$f \equiv \frac{d \ln D}{d \ln a}$$

From Claudia de Rham




$$\ddot{\delta} + 2H\dot{\delta} = 4\pi G \rho_M \delta$$

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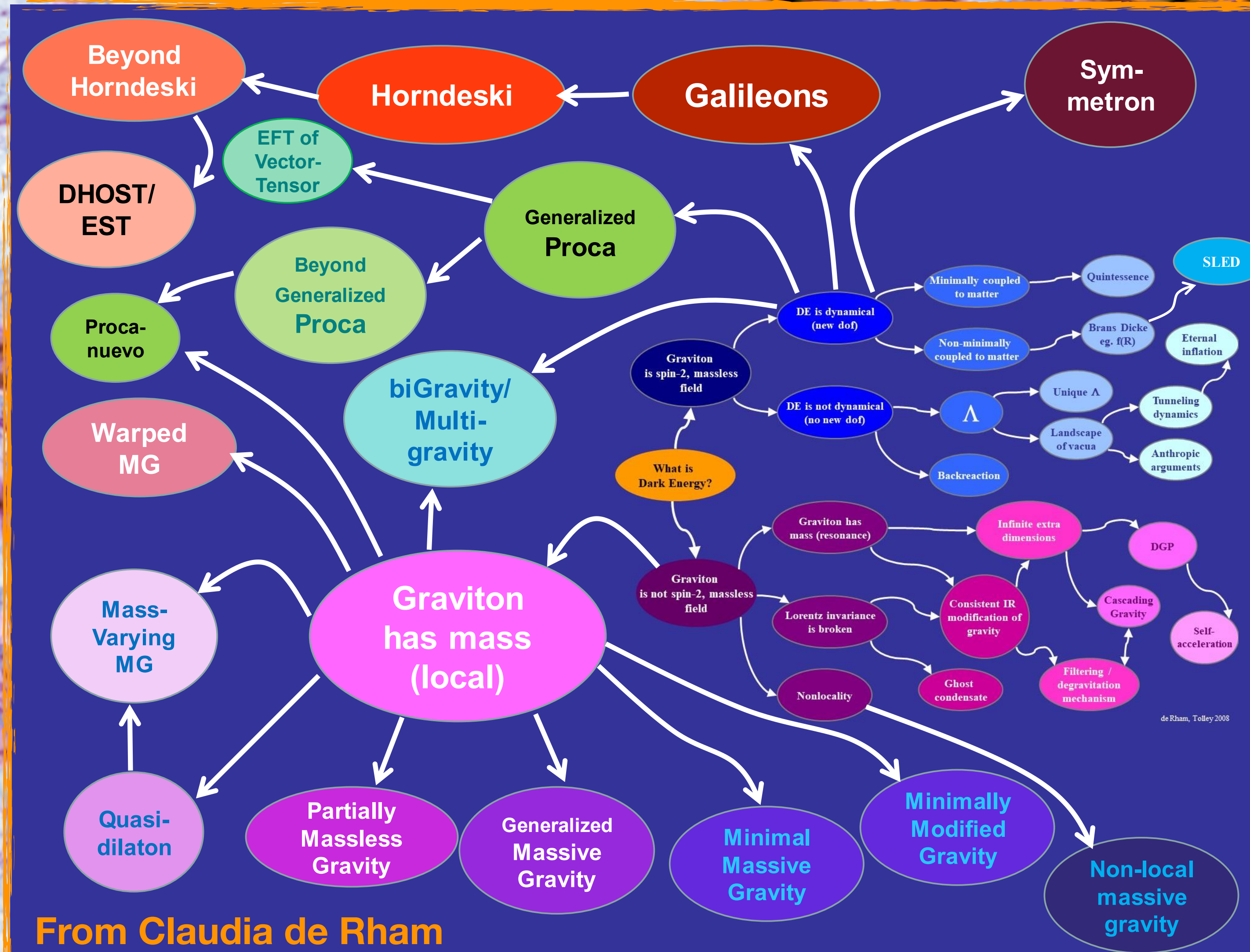
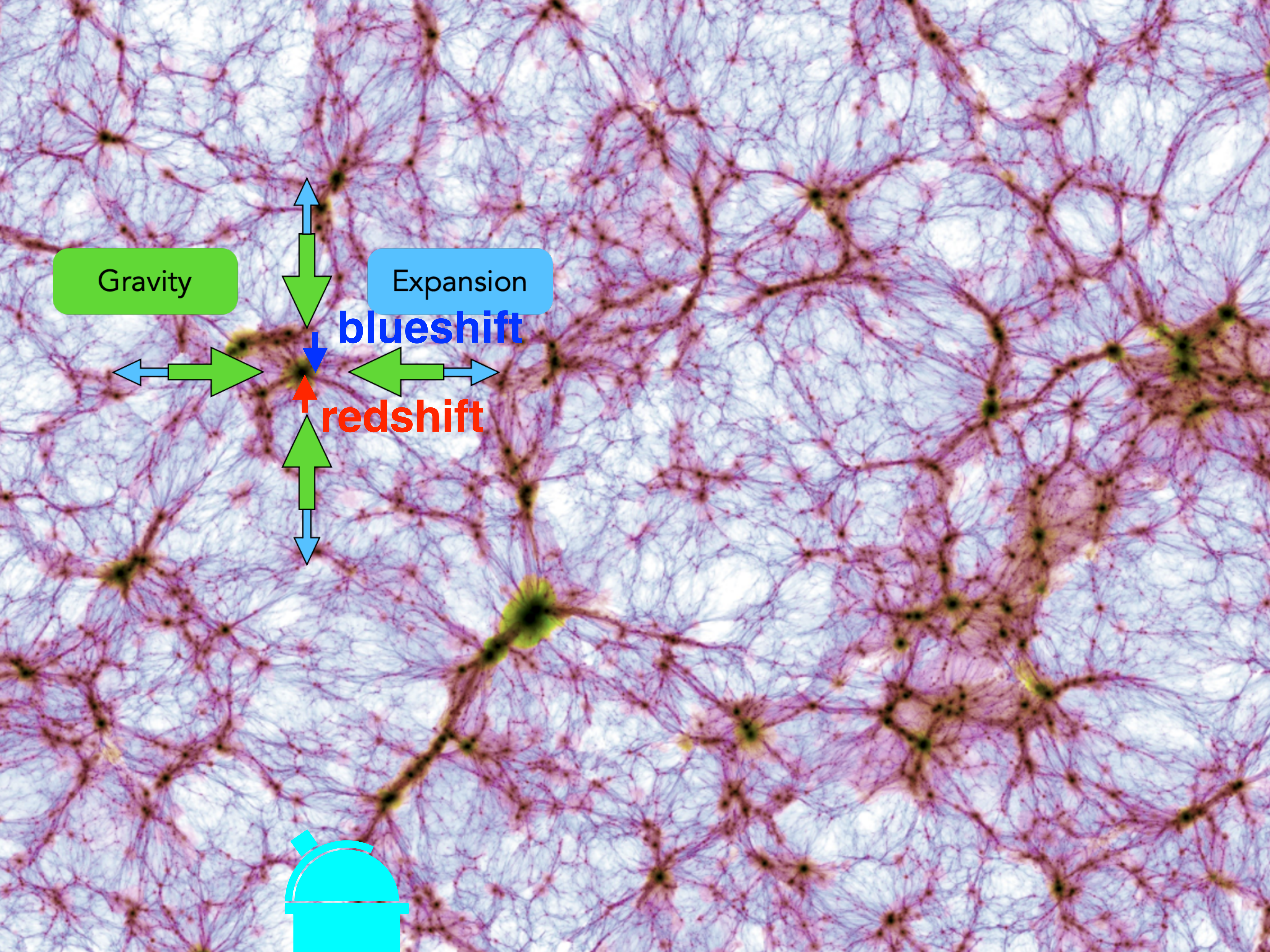
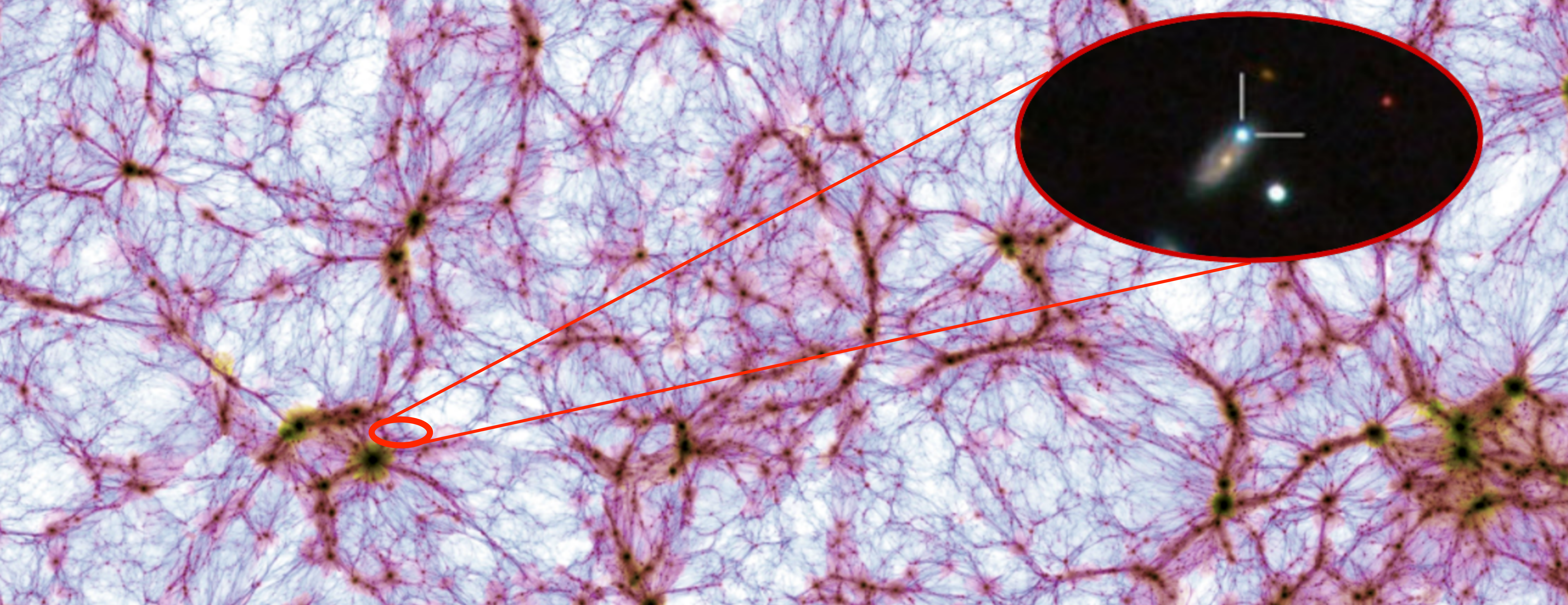
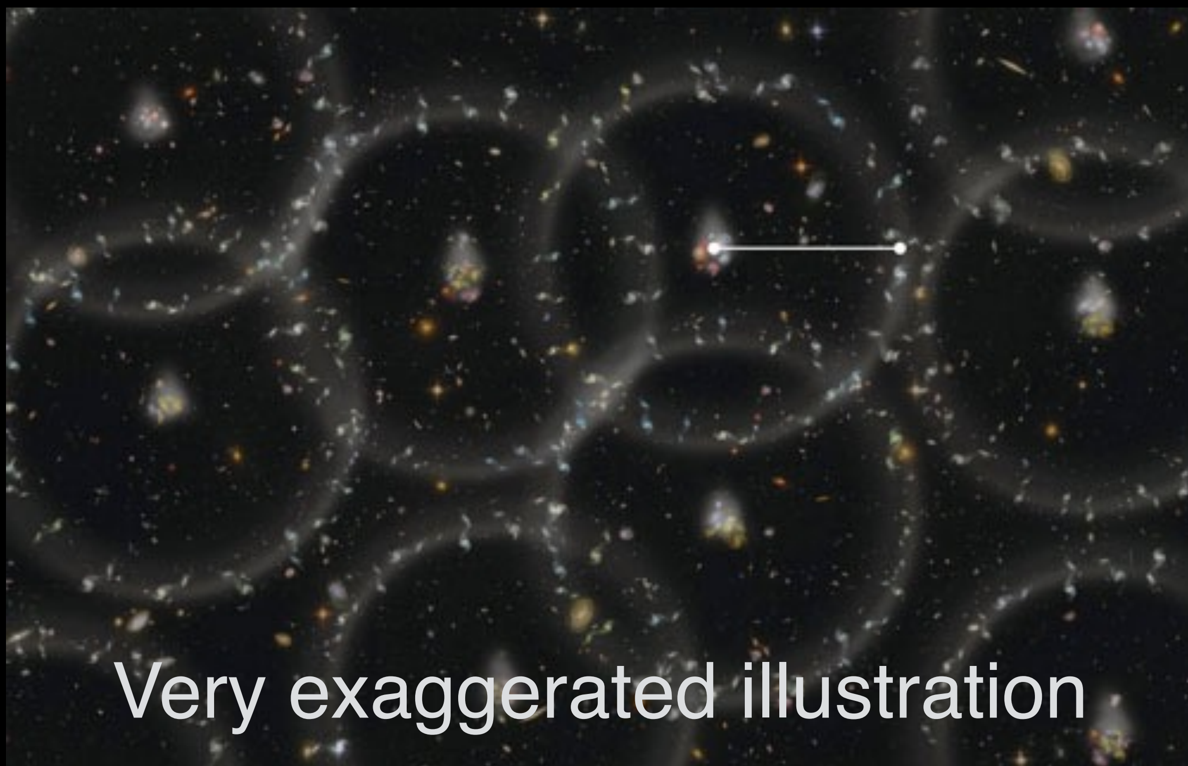


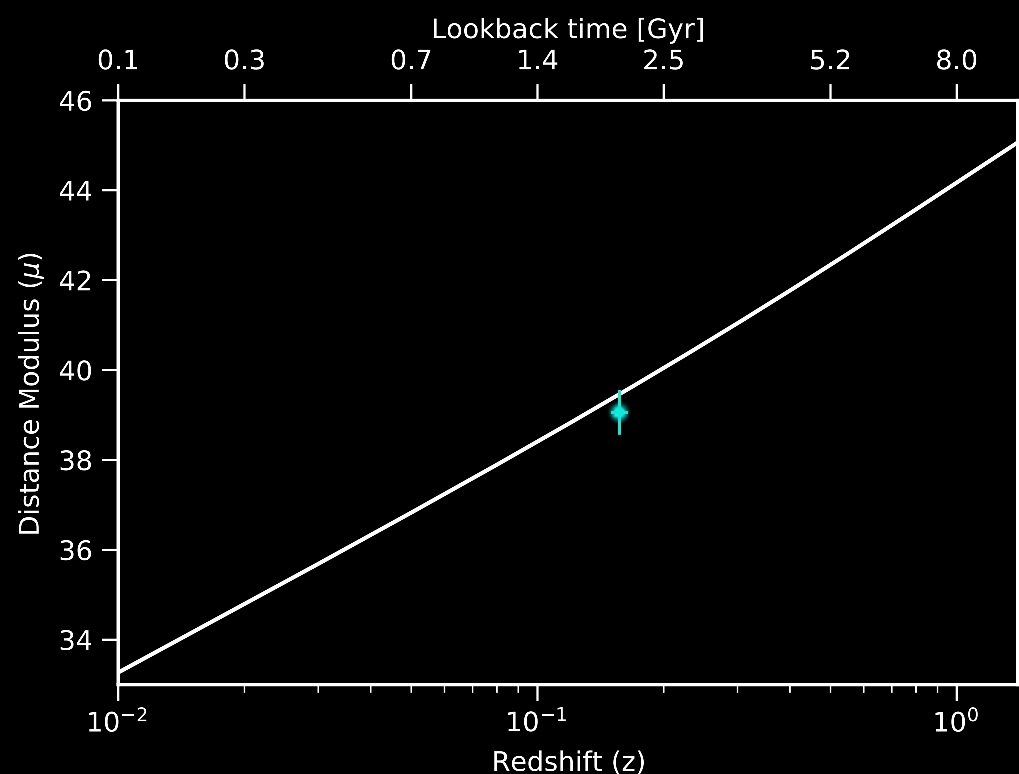

Gravity
Expansion
blueshift
redshift

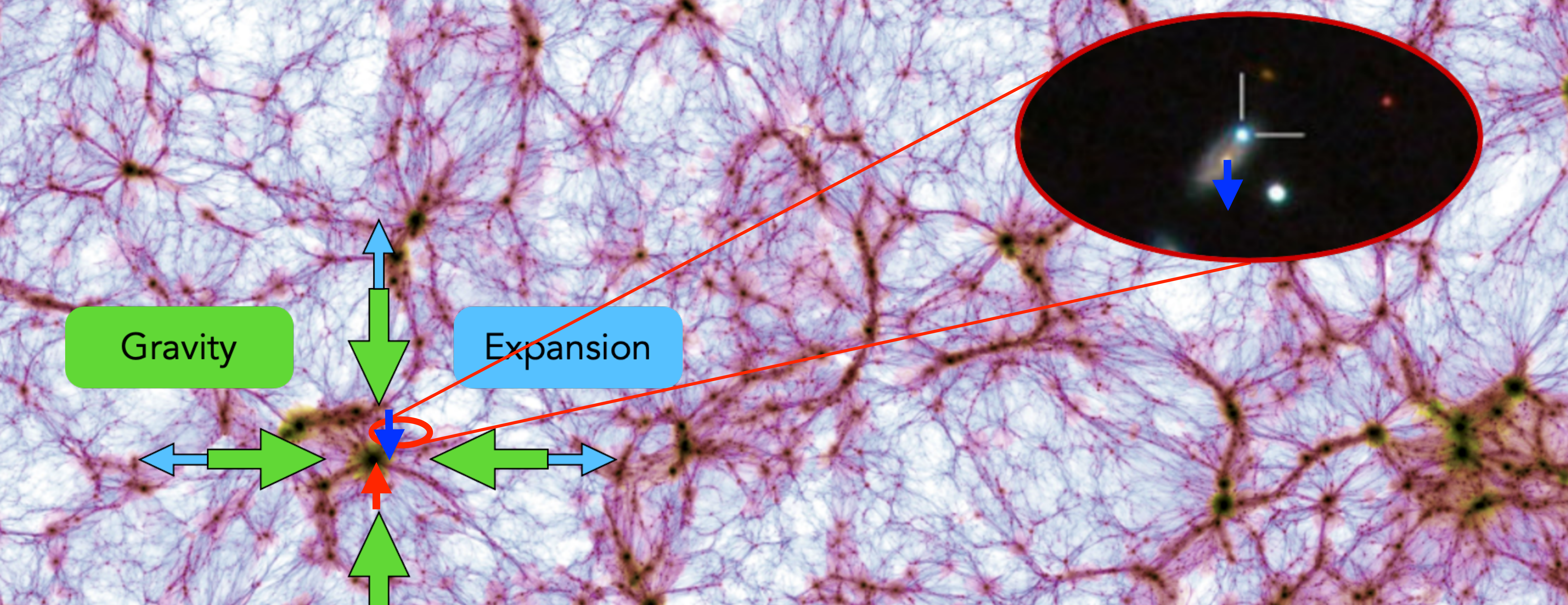


## Galaxy clustering




## SN1a Hubble diagram

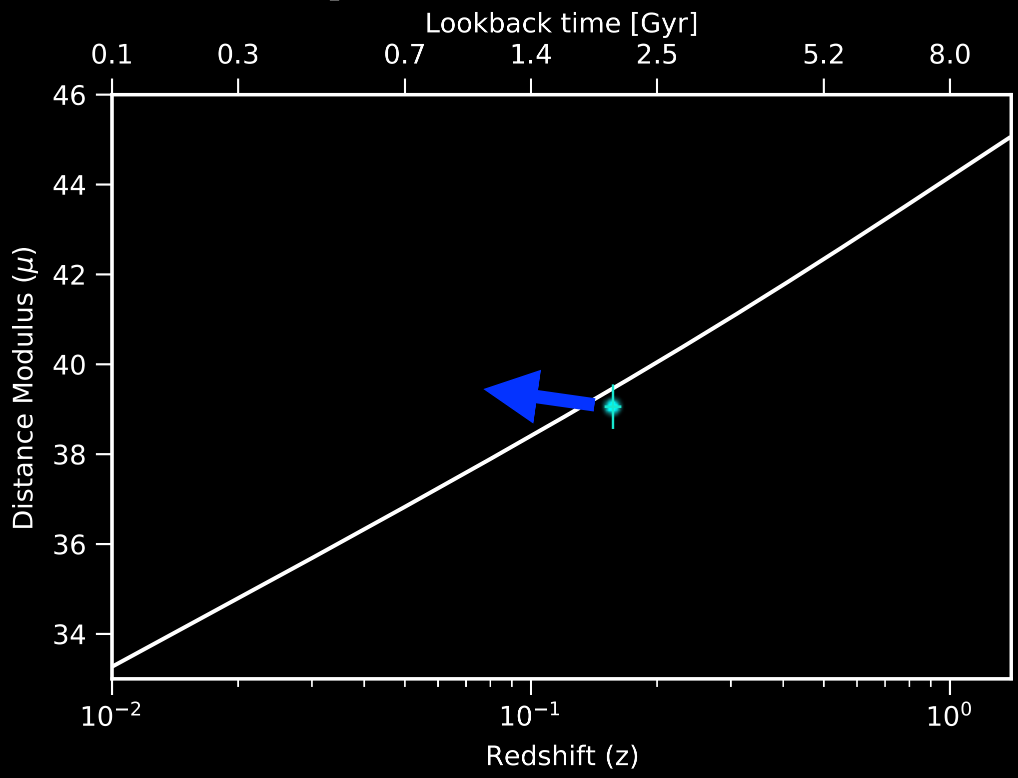




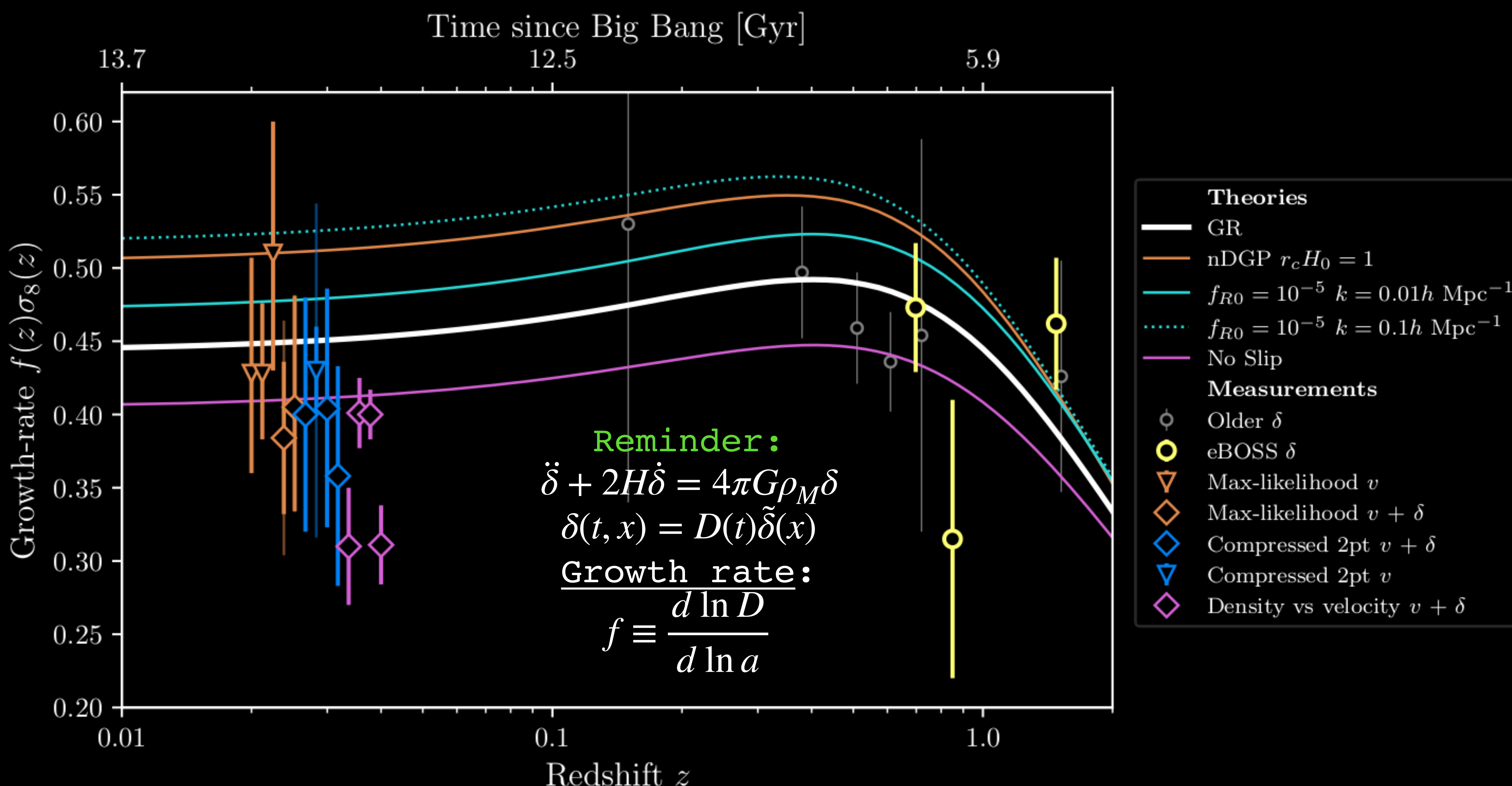

## Galaxy clustering

In observed « redshift space », we get distortions: **RSD**

## SN1a Hubble diagram with peculiar velocities



# Previous measurements




Reminder:

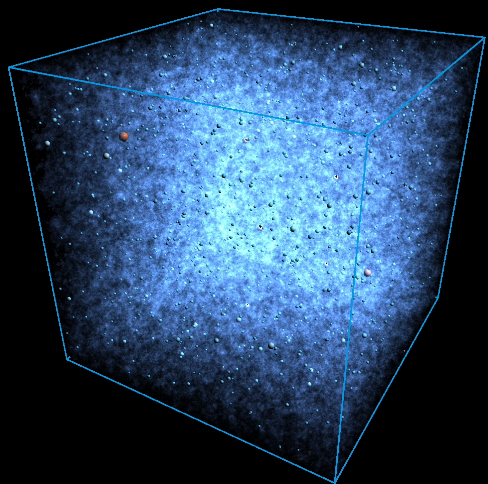
$$\ddot{\delta} + 2H\dot{\delta} = 4\pi G \rho_M \delta$$

$$\delta(t, x) = D(t)\tilde{\delta}(x)$$

Growth rate:

$$f \equiv \frac{d \ln D}{d \ln a}$$

Plot adapted from Julian Bautista



N-Body simulation
(Outerrim, 1904.11970)

SNSIM
survey simulator

ZTF

Or

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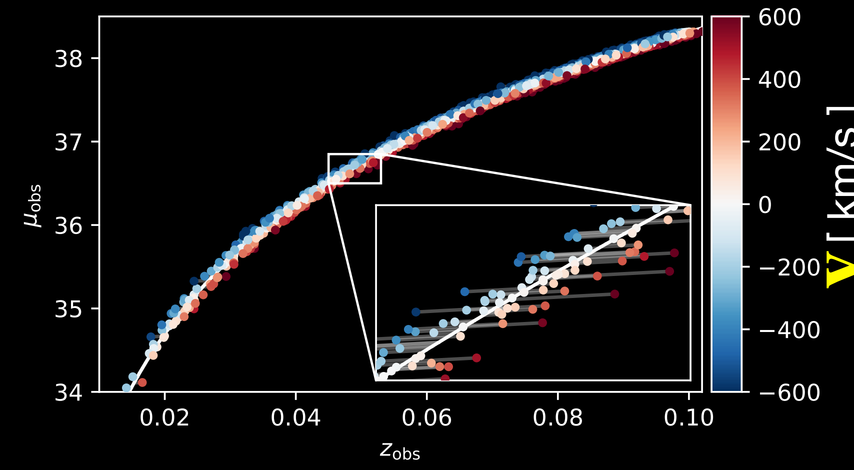
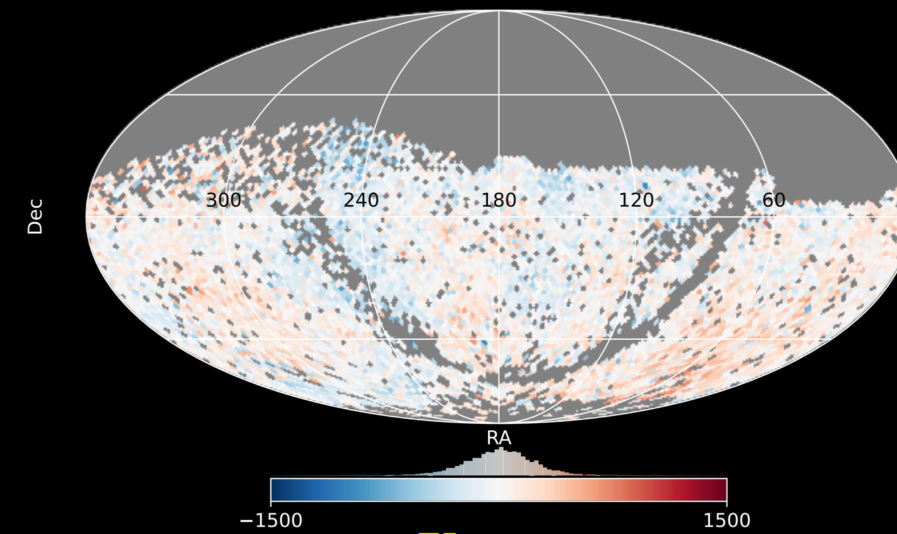
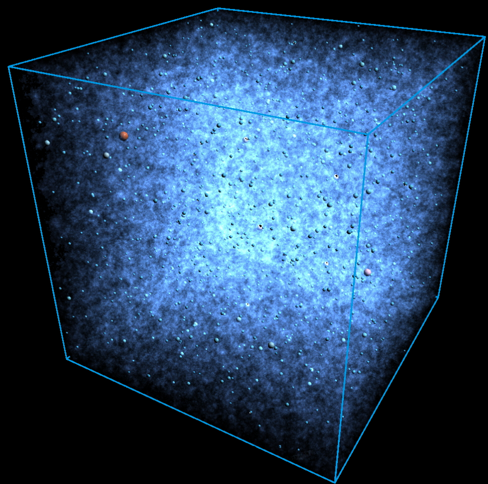
OBSERVATORY
LSST



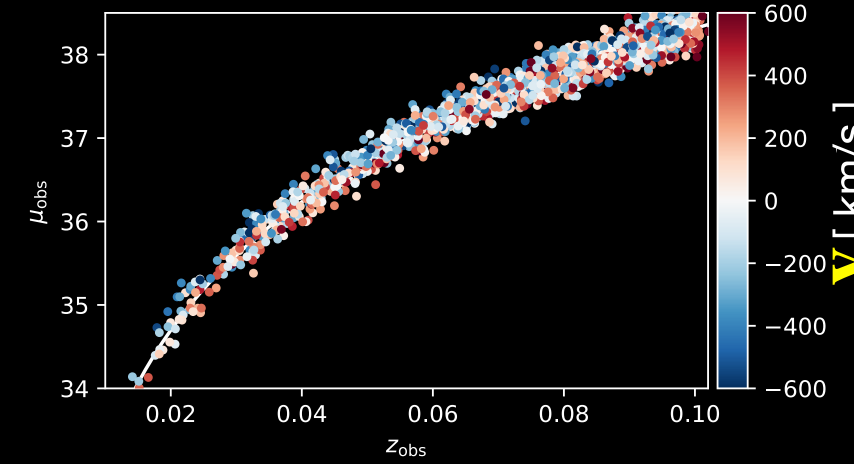



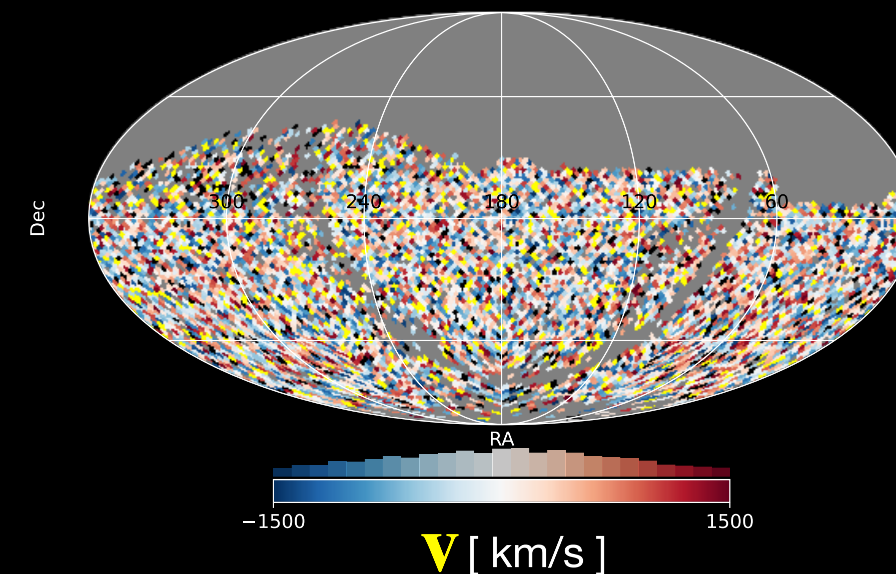


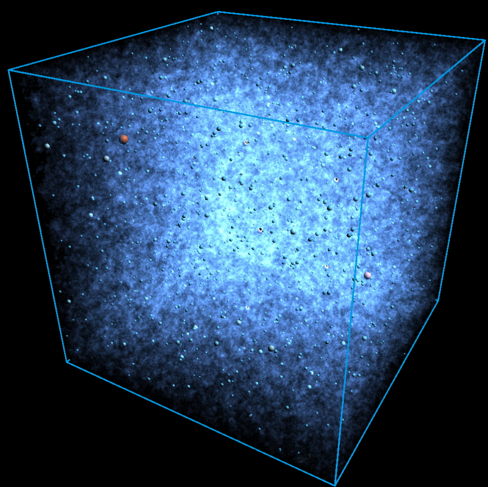
N-Body simulation
(Outerrim, 1904.11970)

Or

LSST



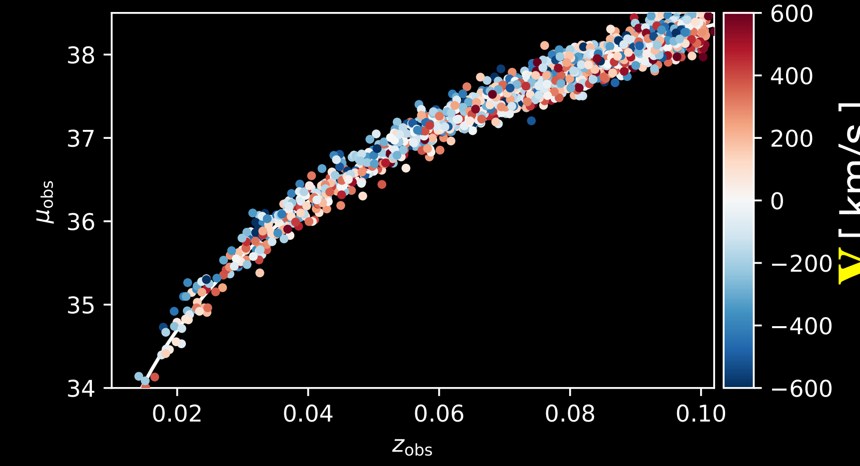



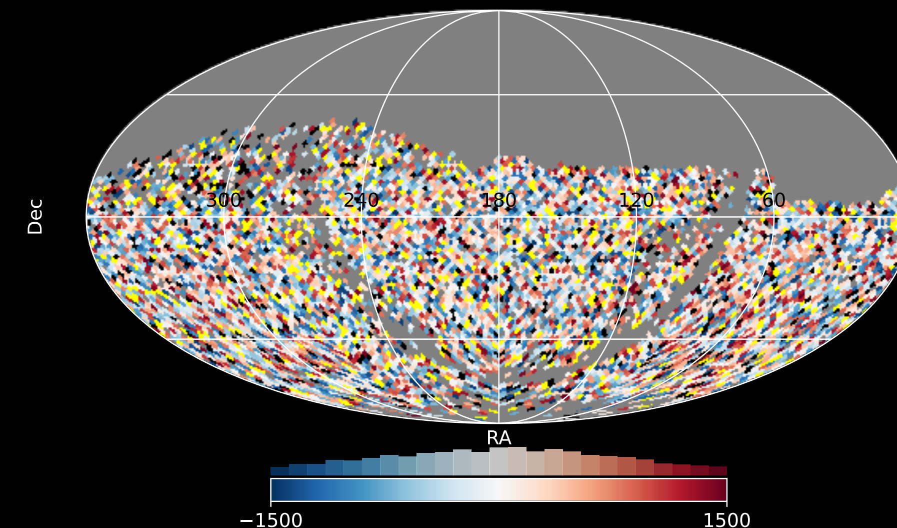


N-Body simulation
(Outerrim, 1904.11970)

SNSIM survey simulator

ZTF Or VERA C. RUBIN OBSERVATORY LSST




**V** [ km/s ]

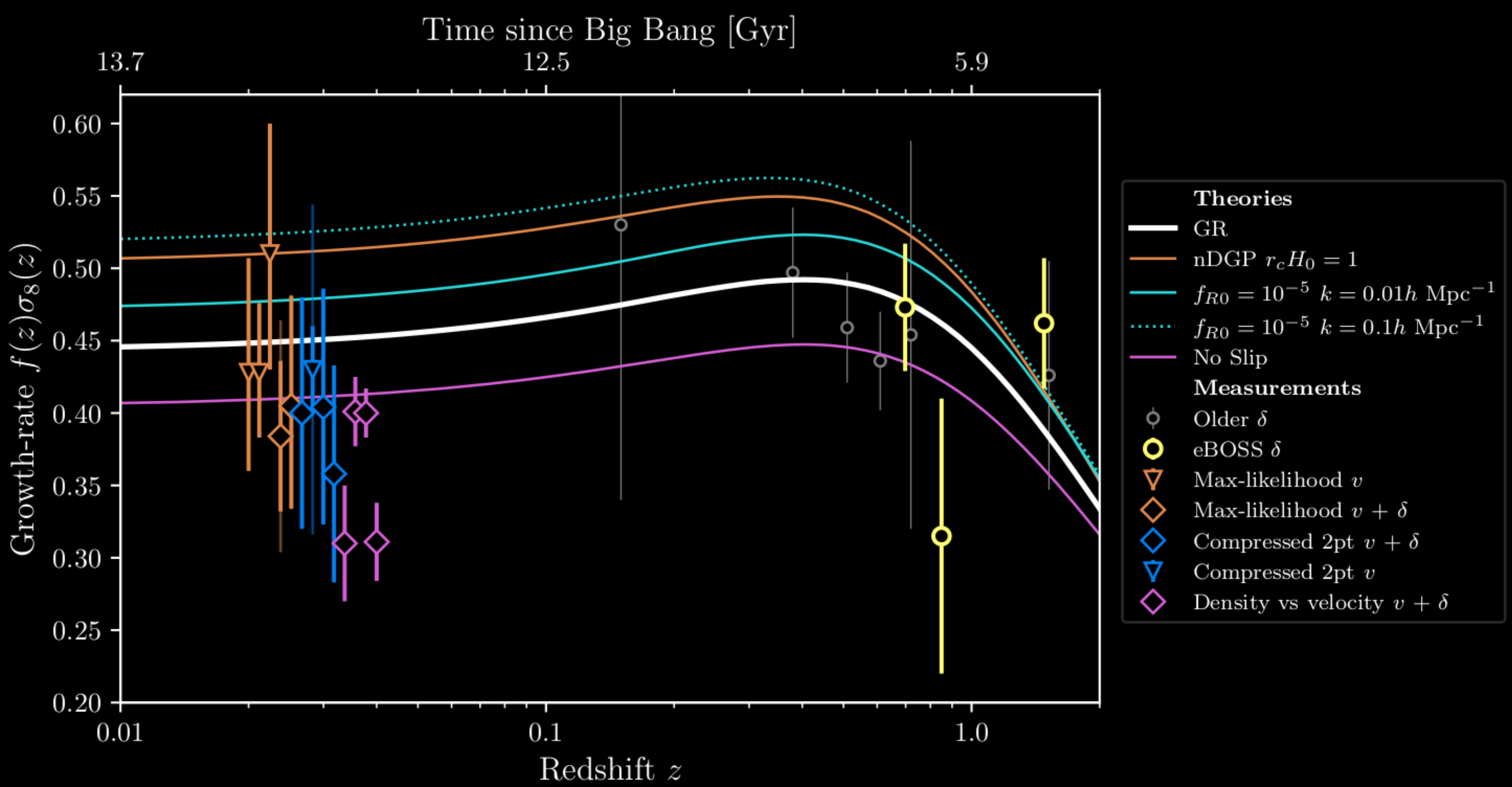
Maximum Likelihood analysis :

$$\mathscr{L}(\theta) = \frac{1}{\sqrt{(2\pi)^n \det(C(\theta))}} e^{-\frac{1}{2}\mathbf{v}^T C(\theta)^{-1}\mathbf{v}}$$

$C(\theta)$ modelled with velocity power spectrum

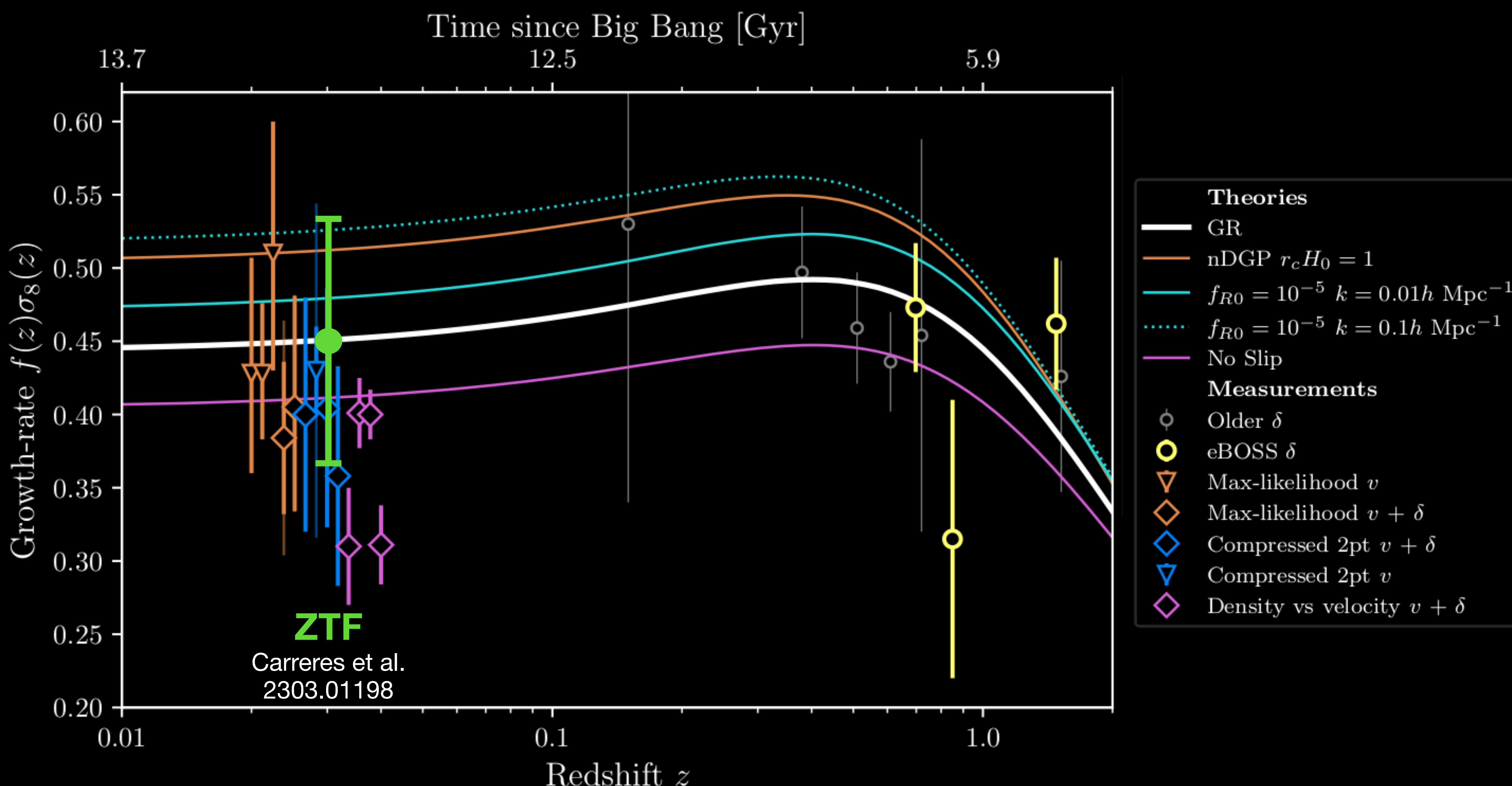
$\theta$ : growth of structure $f\sigma_8$ + nuisance parameters

# Previous measurements

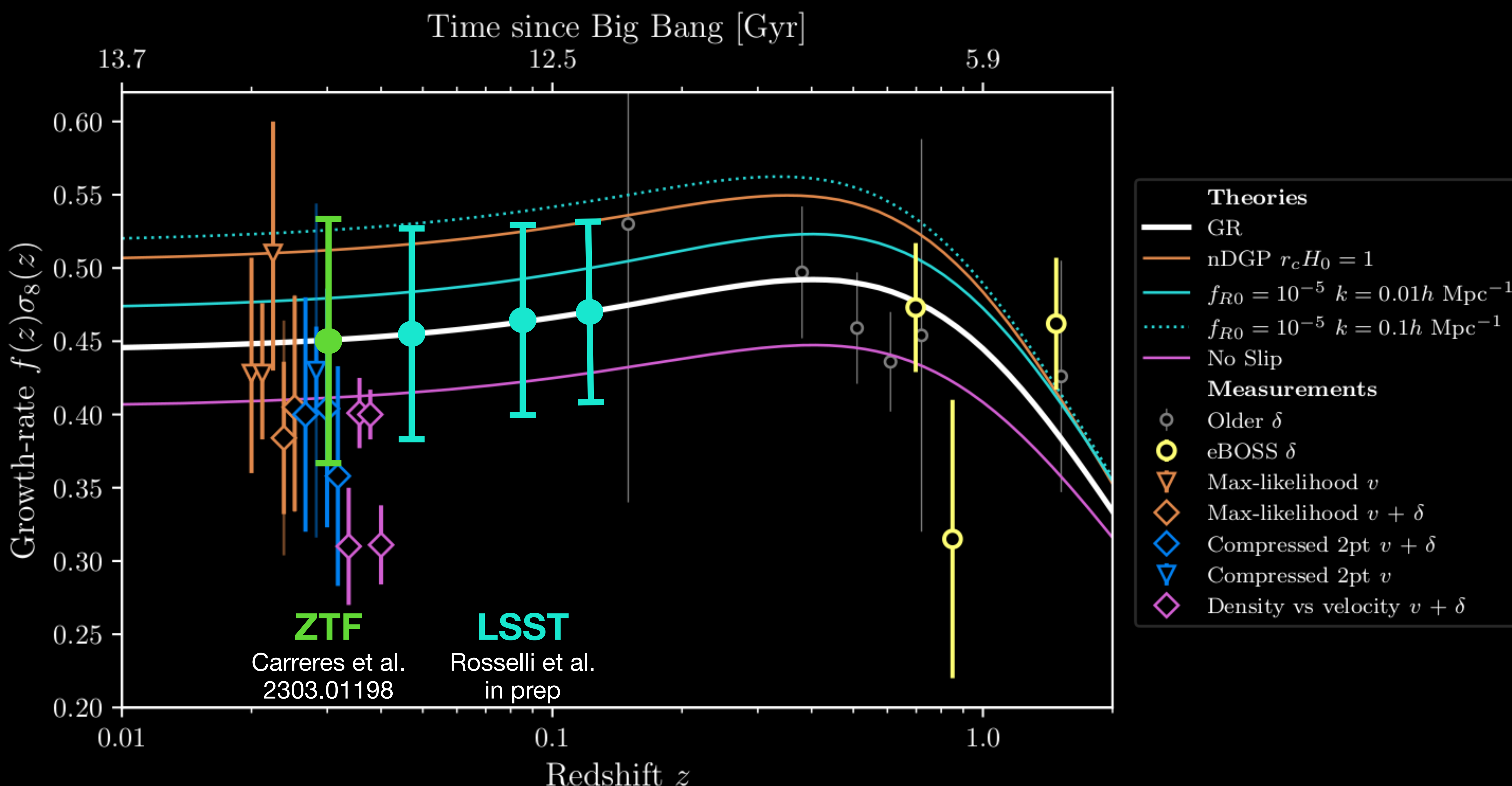



Plot adapted from Julian Bautista

# Forecast for ZTF



# Forecast for ZTF and LSST



# Conclusion

- Supernovae Cosmology will enter a new era with ZTF and LSST

- Supernovae alone will constrain dark energy better than all current data
- The full sky coverage will allow test of the isotropy
- We will be able to study gravity via the peculiar velocities of Supernovae

- This will require a lot of effort on the calibration of the surveys