The Australasian Side of Dark Energy

30 Years of Gravity Research in Australasia: Past Reflections and Future Ambitions
September 2024

Tamara Davis, University of Queensland

Hubble diagram history

1927/9: Discovered expansion

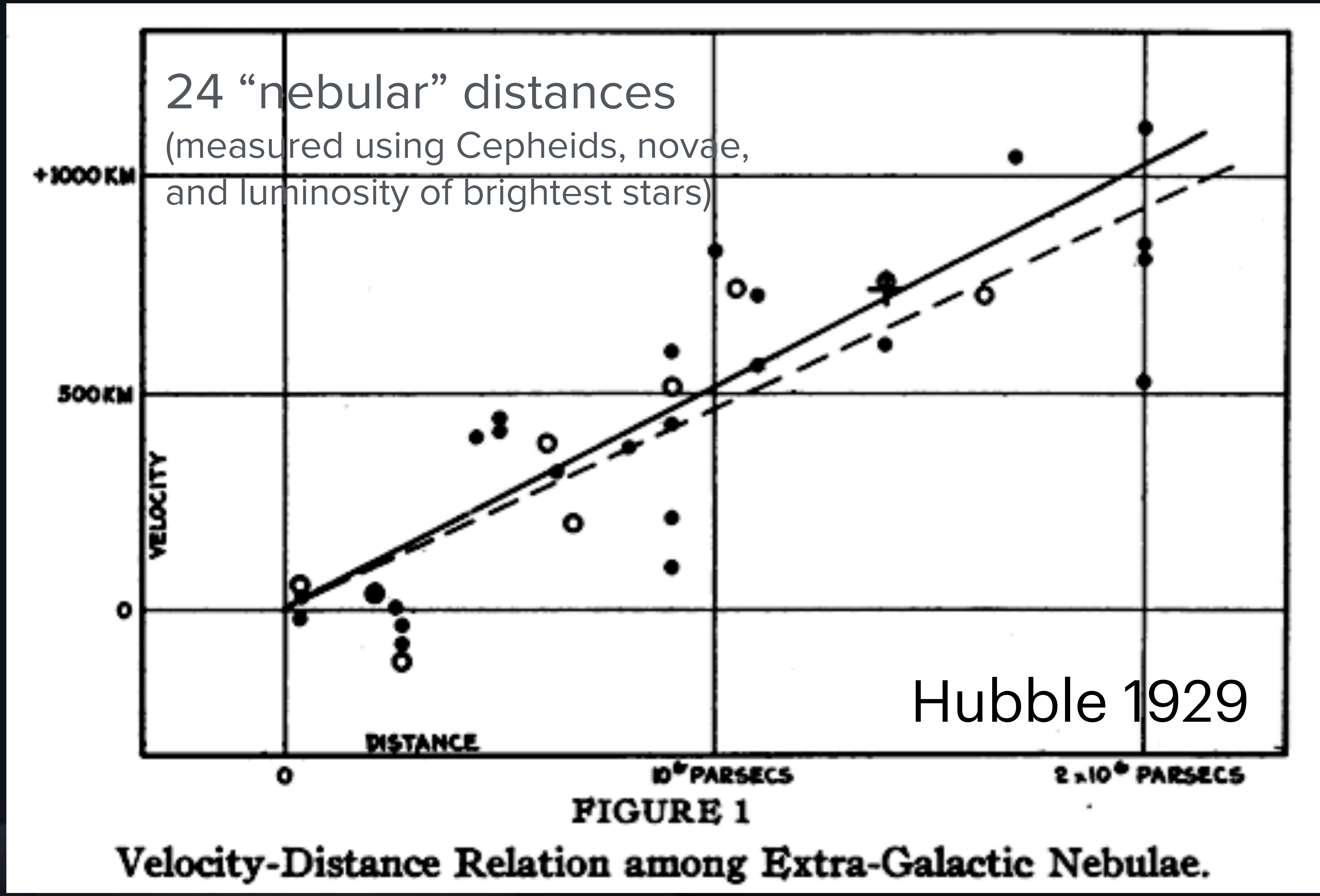
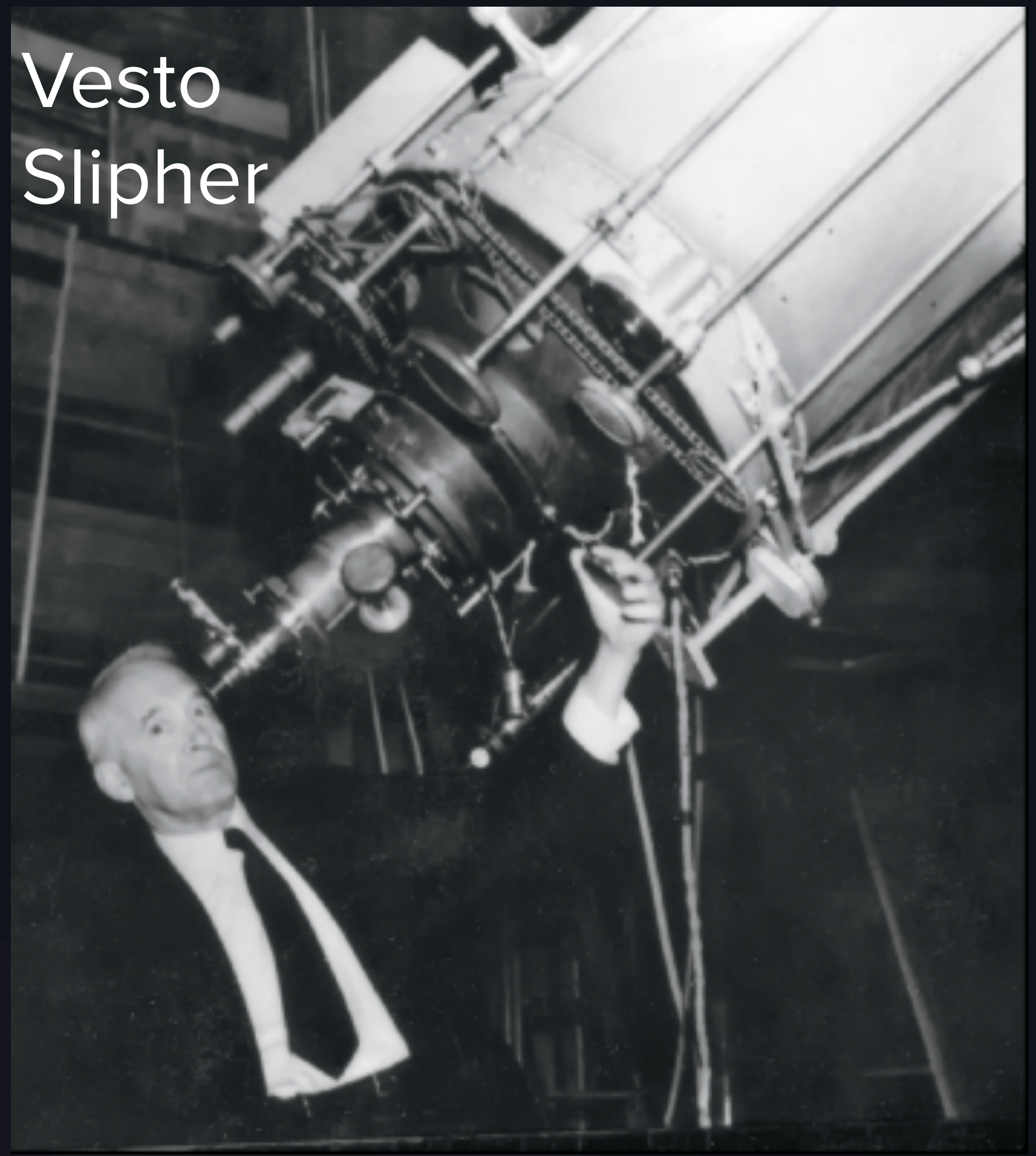
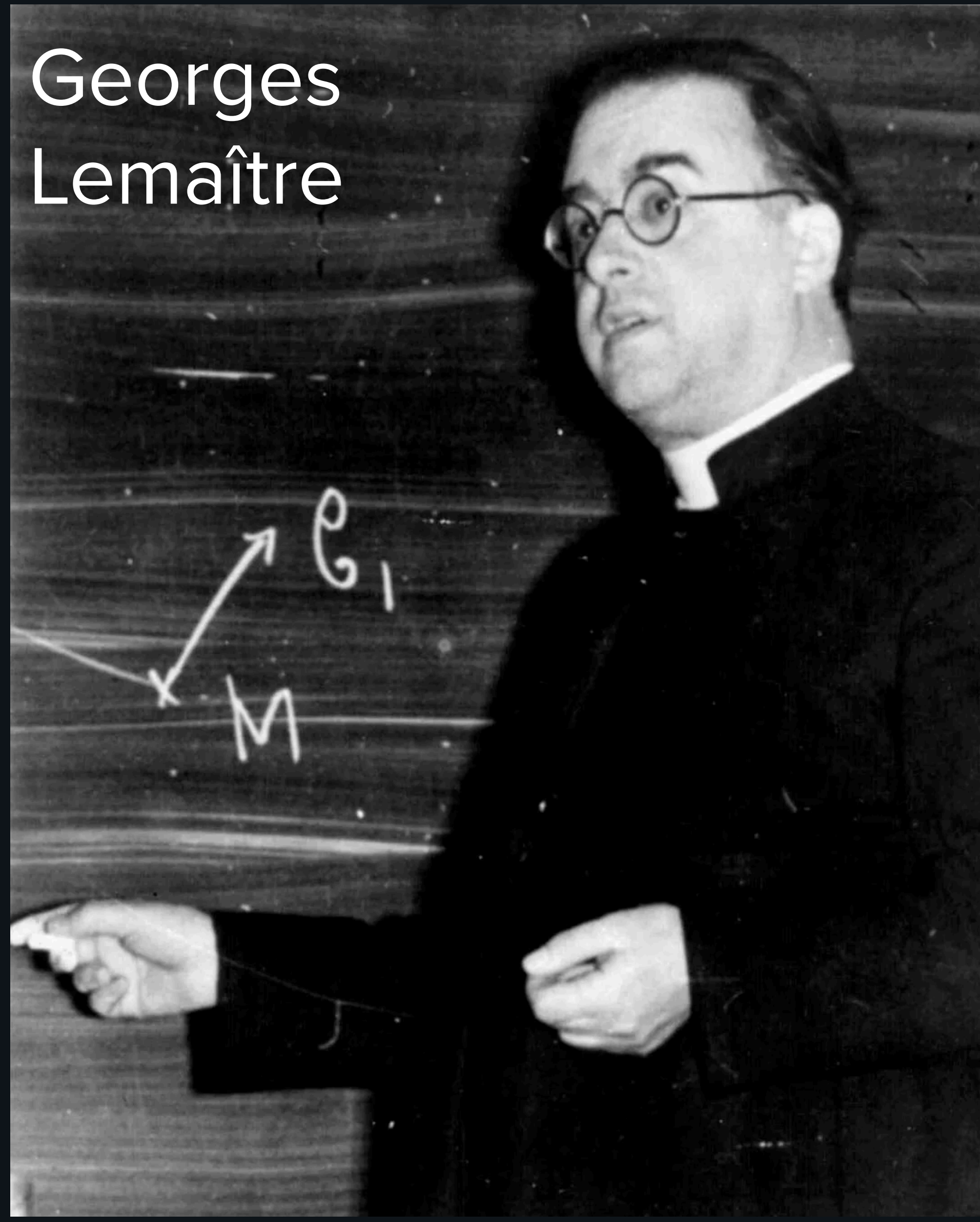


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.



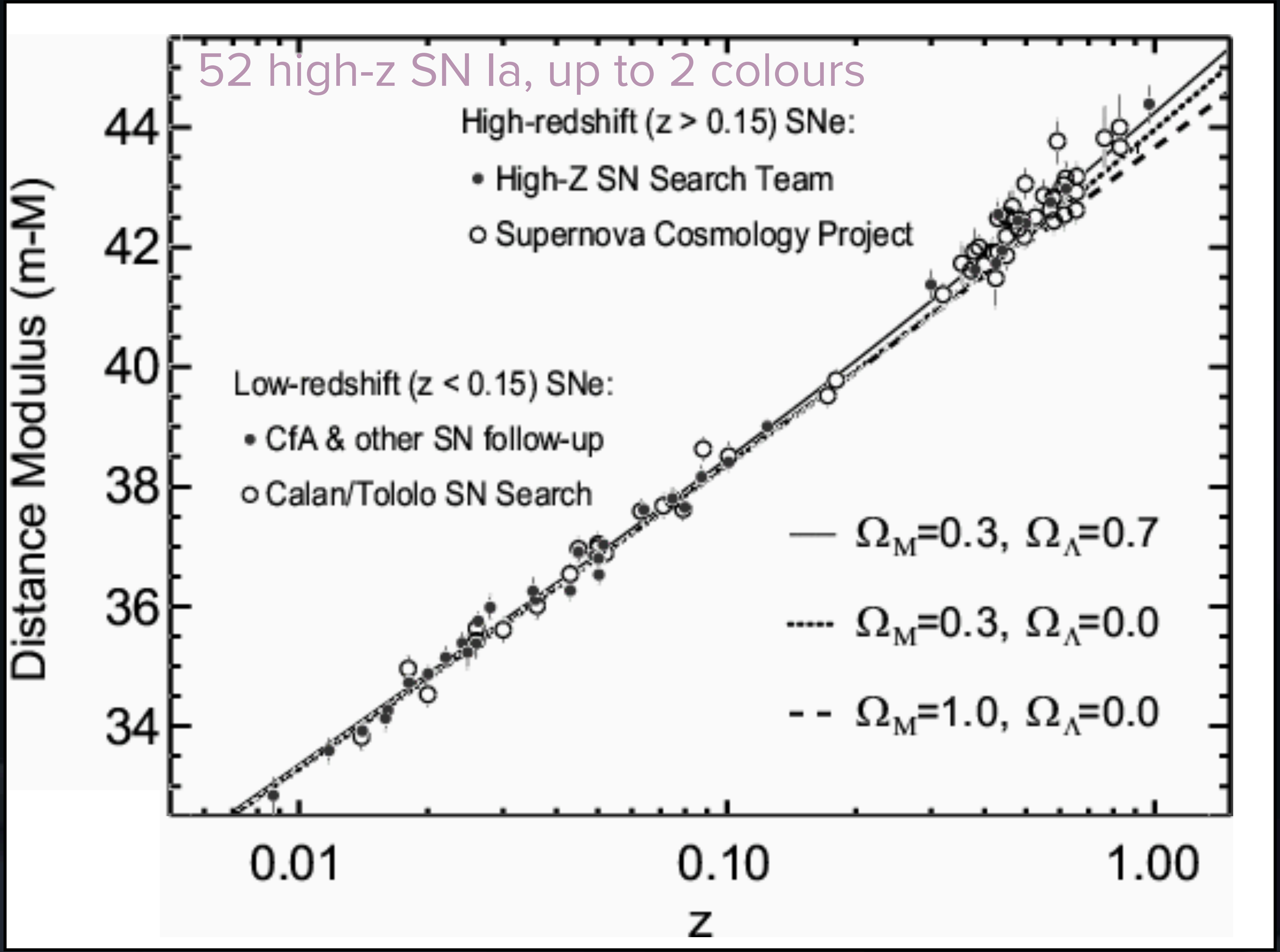


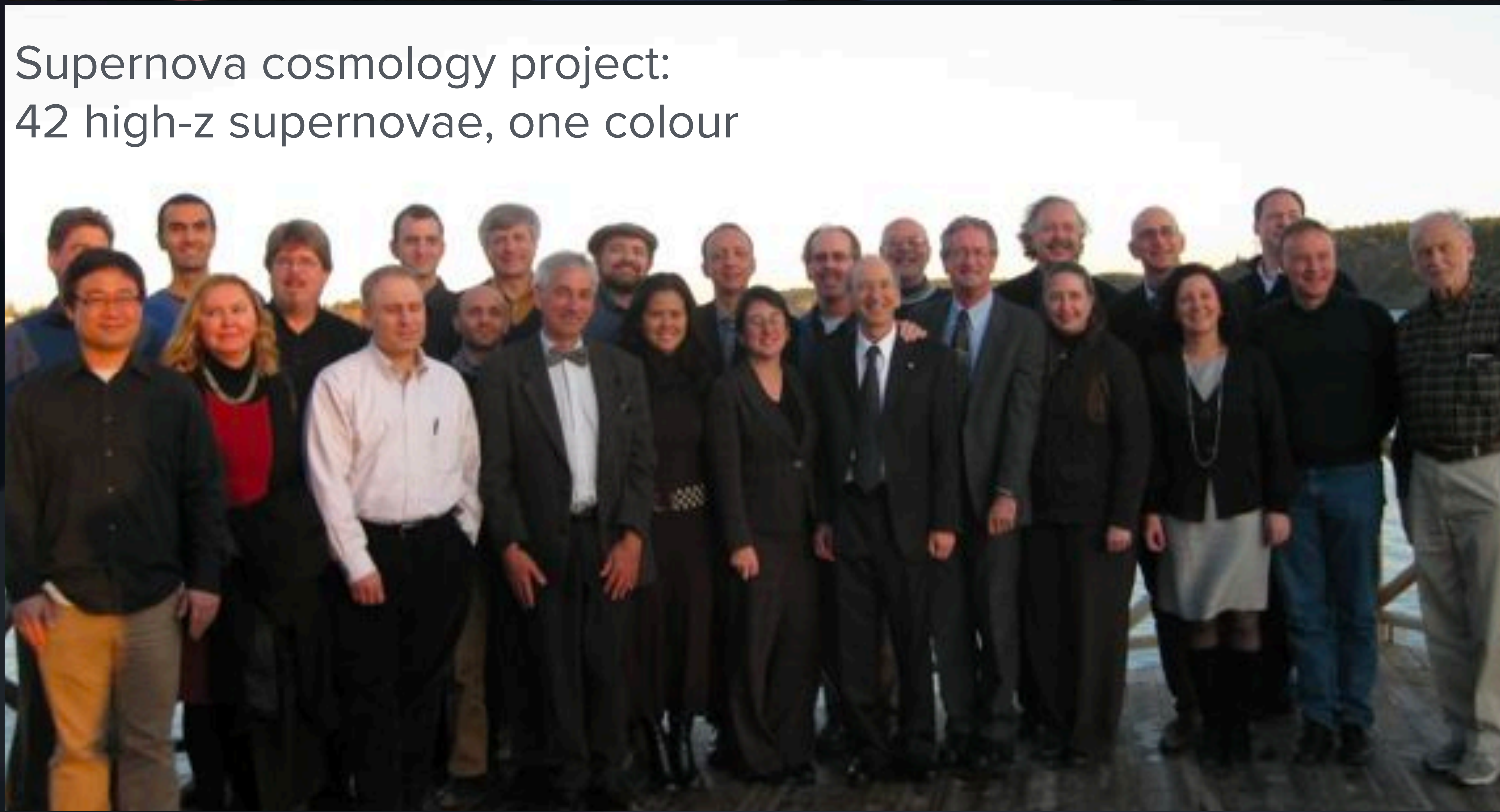
“For such scanty material, so poorly distributed, the results are fairly definite.”

-Hubble 1929

Hubble diagram history

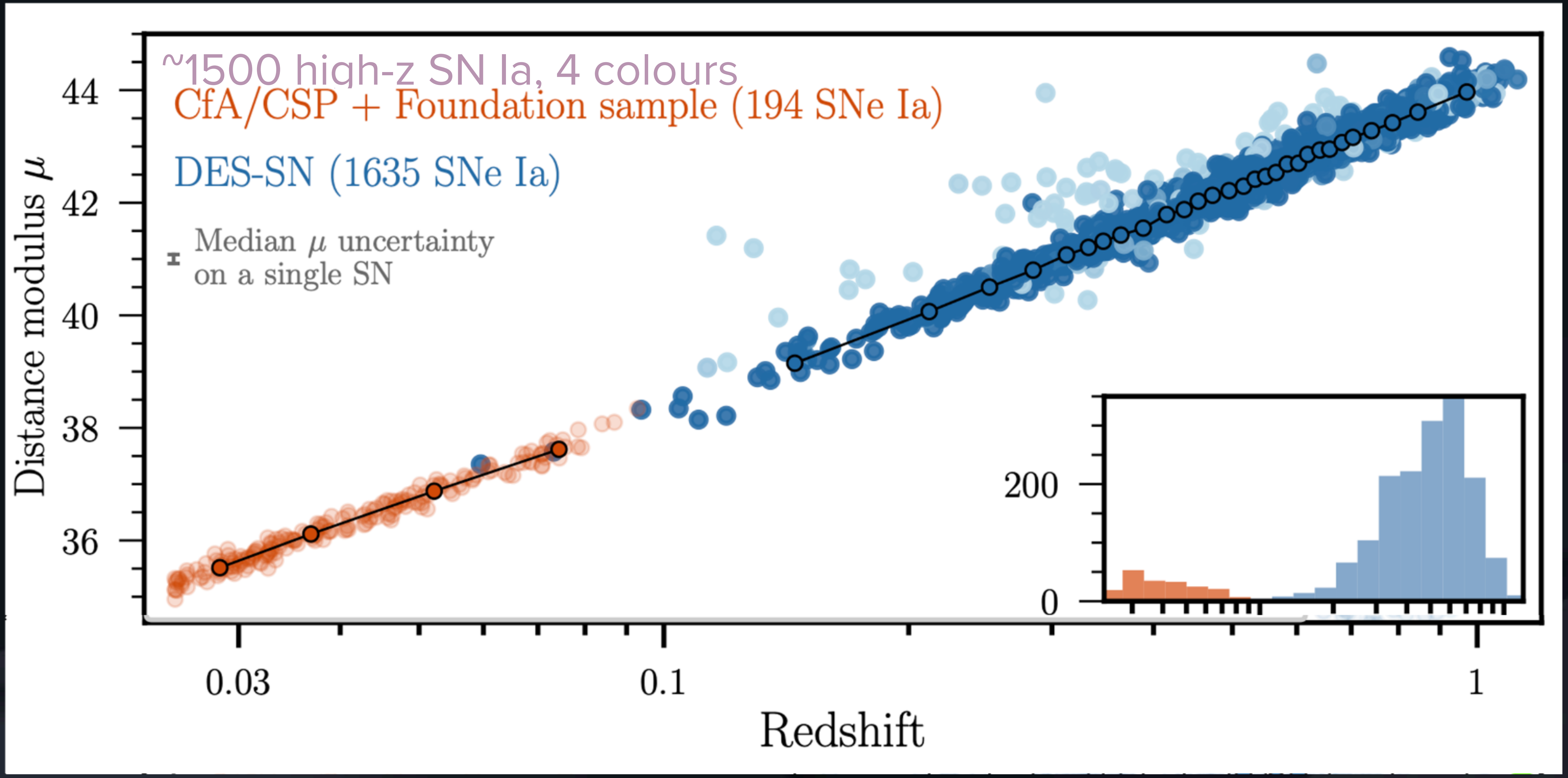
1998/99: Discovered acceleration





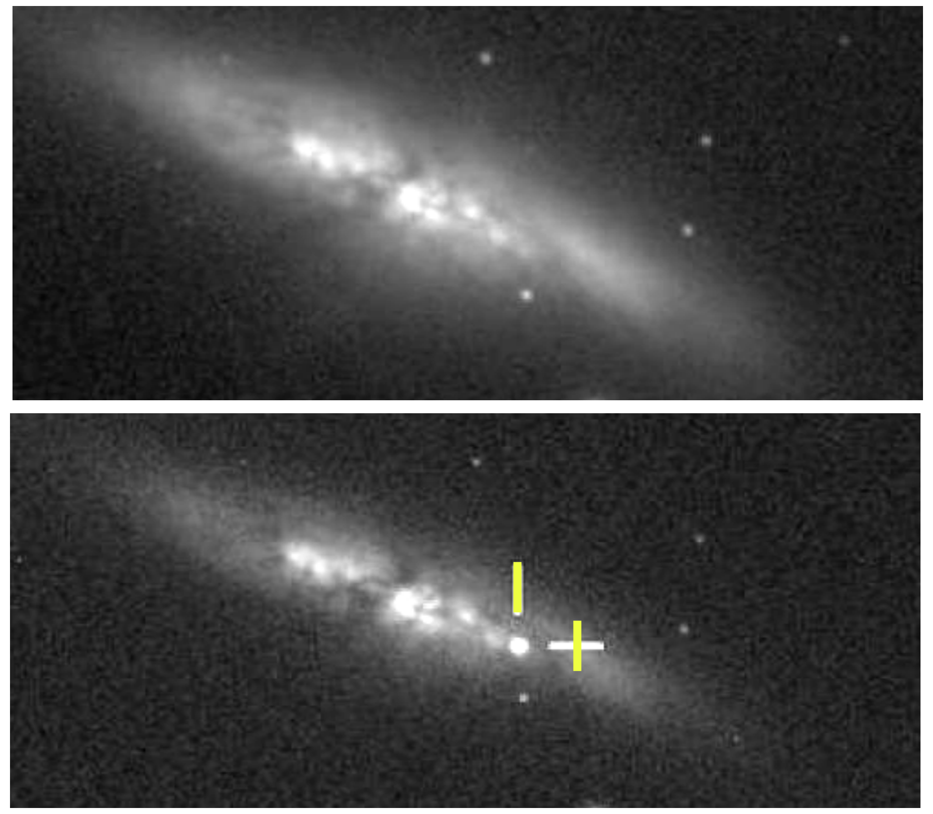
Hubble diagram history

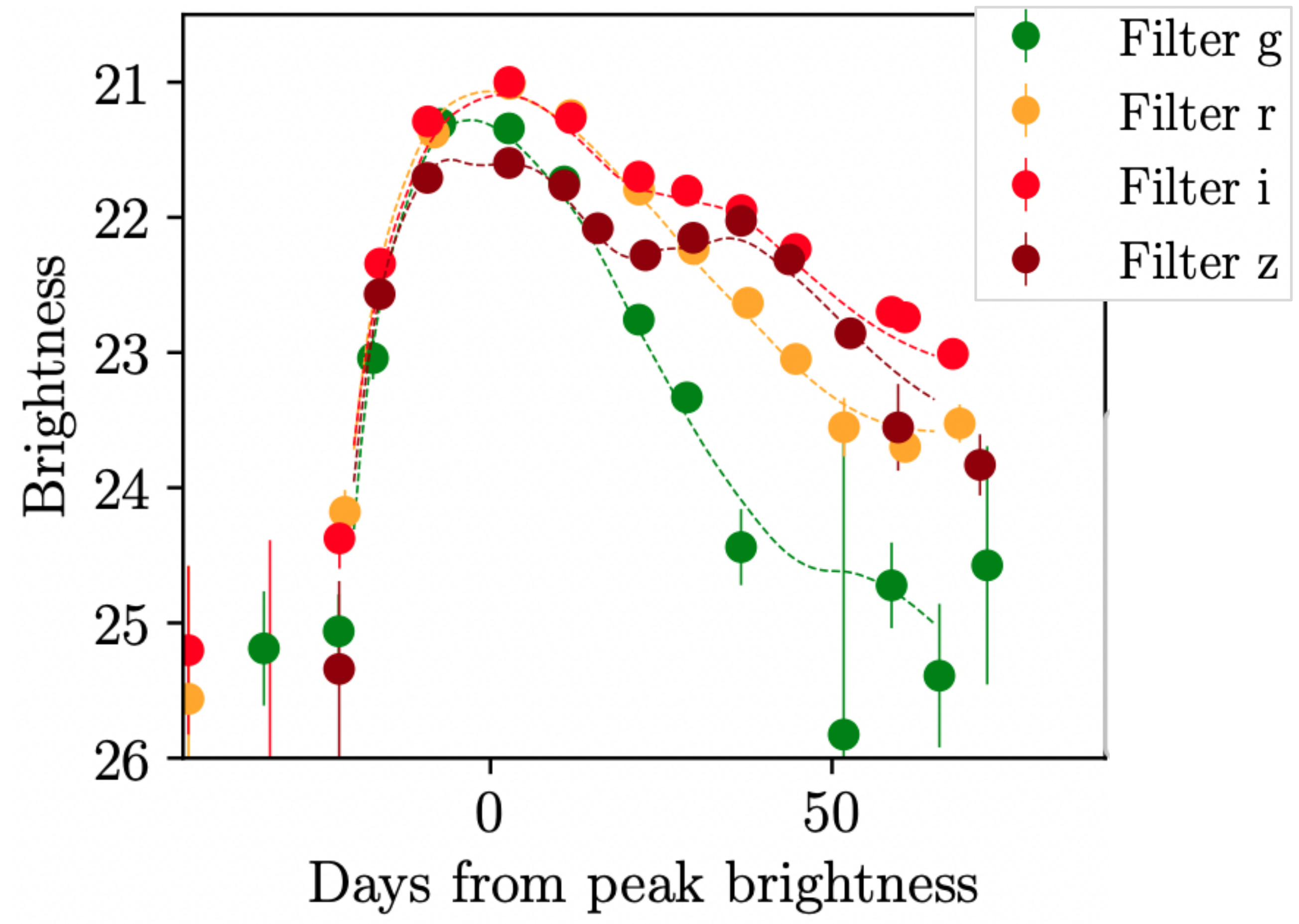
2024: Discovered ....

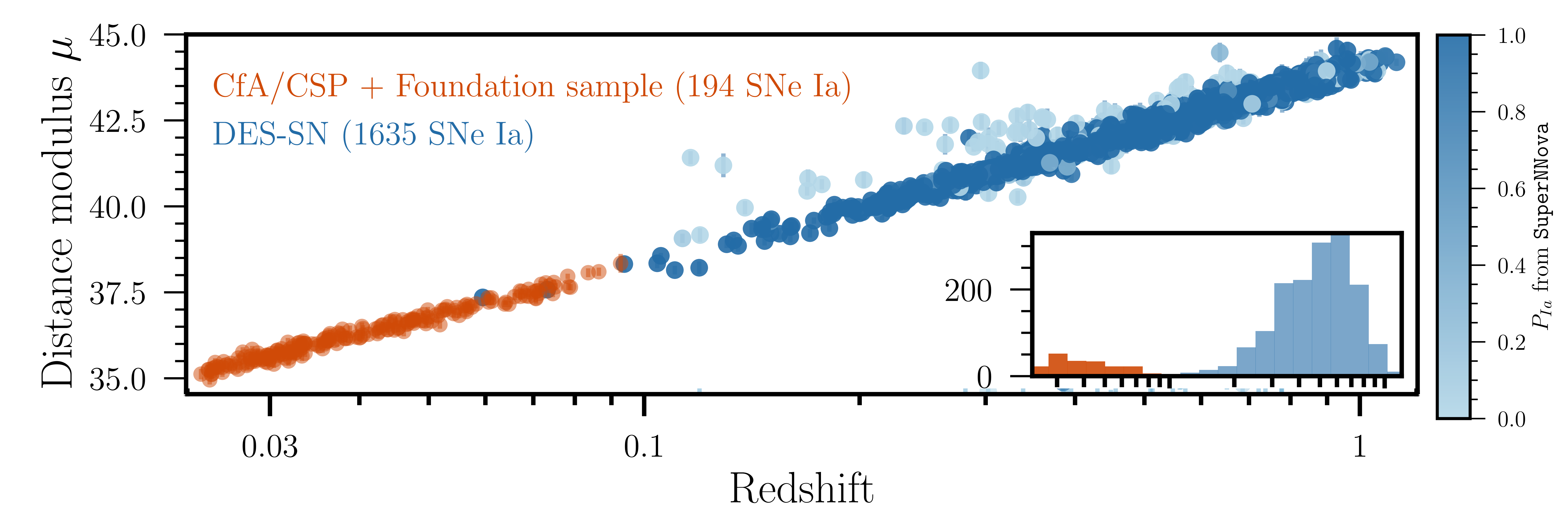


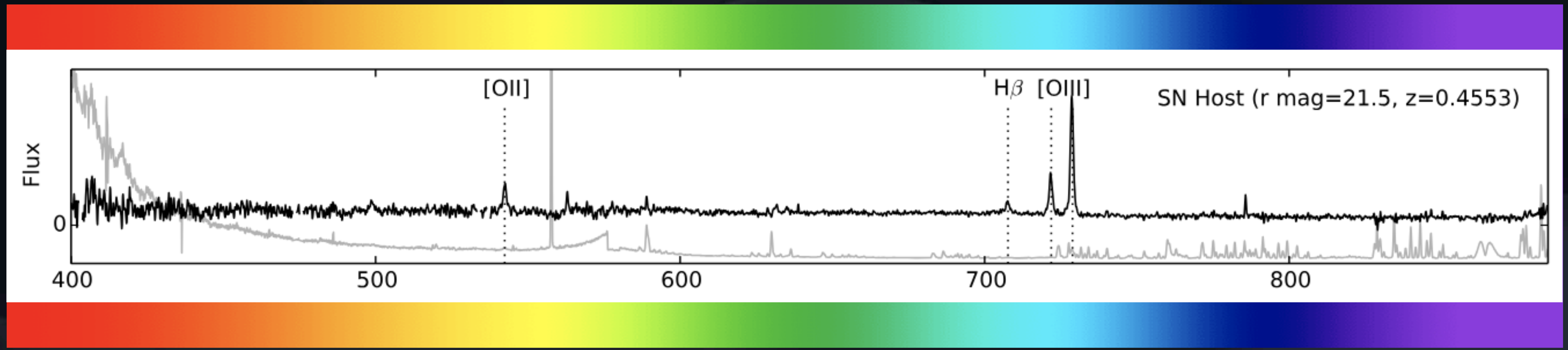
Hubble diagram basics

Distance measure



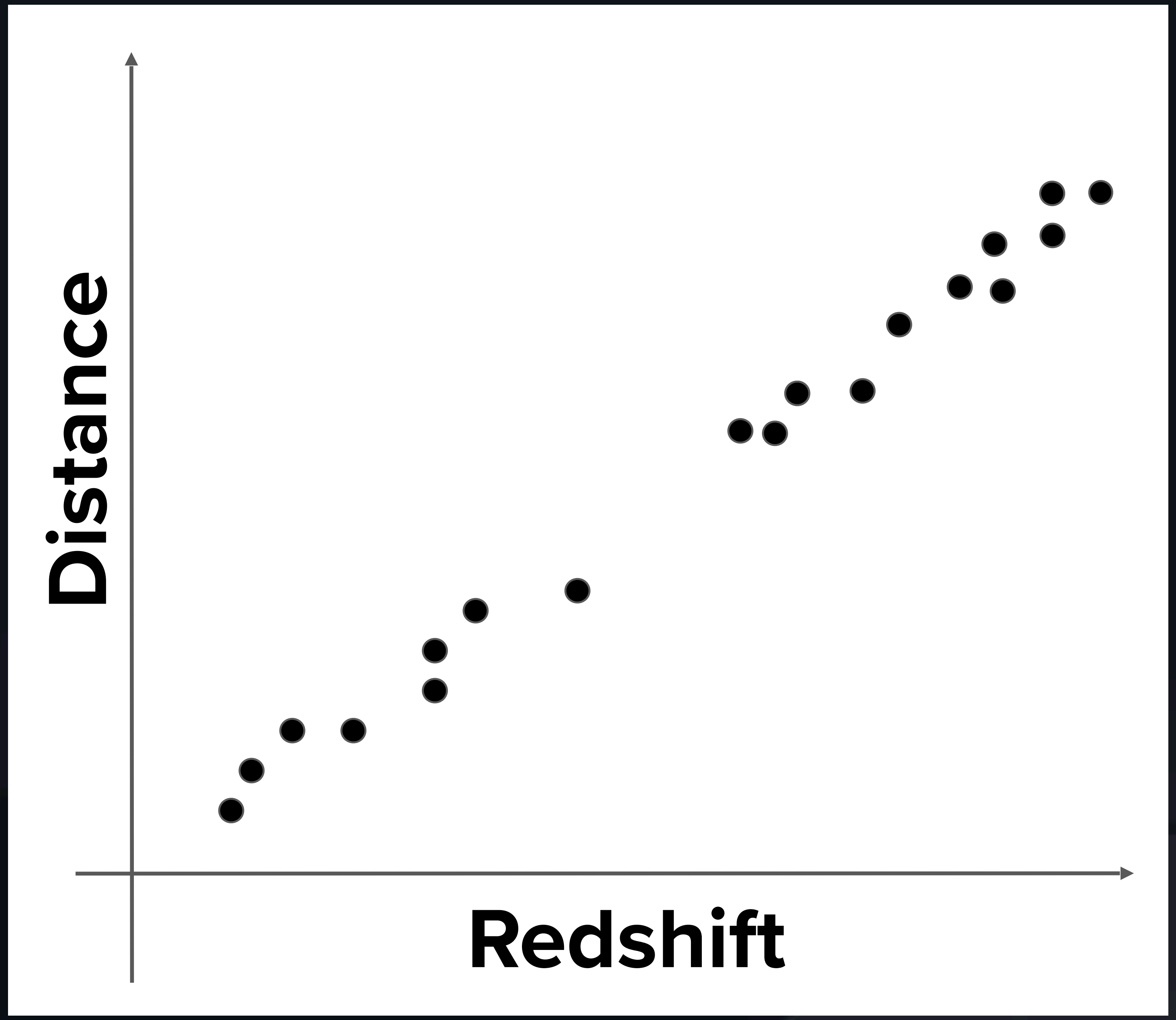




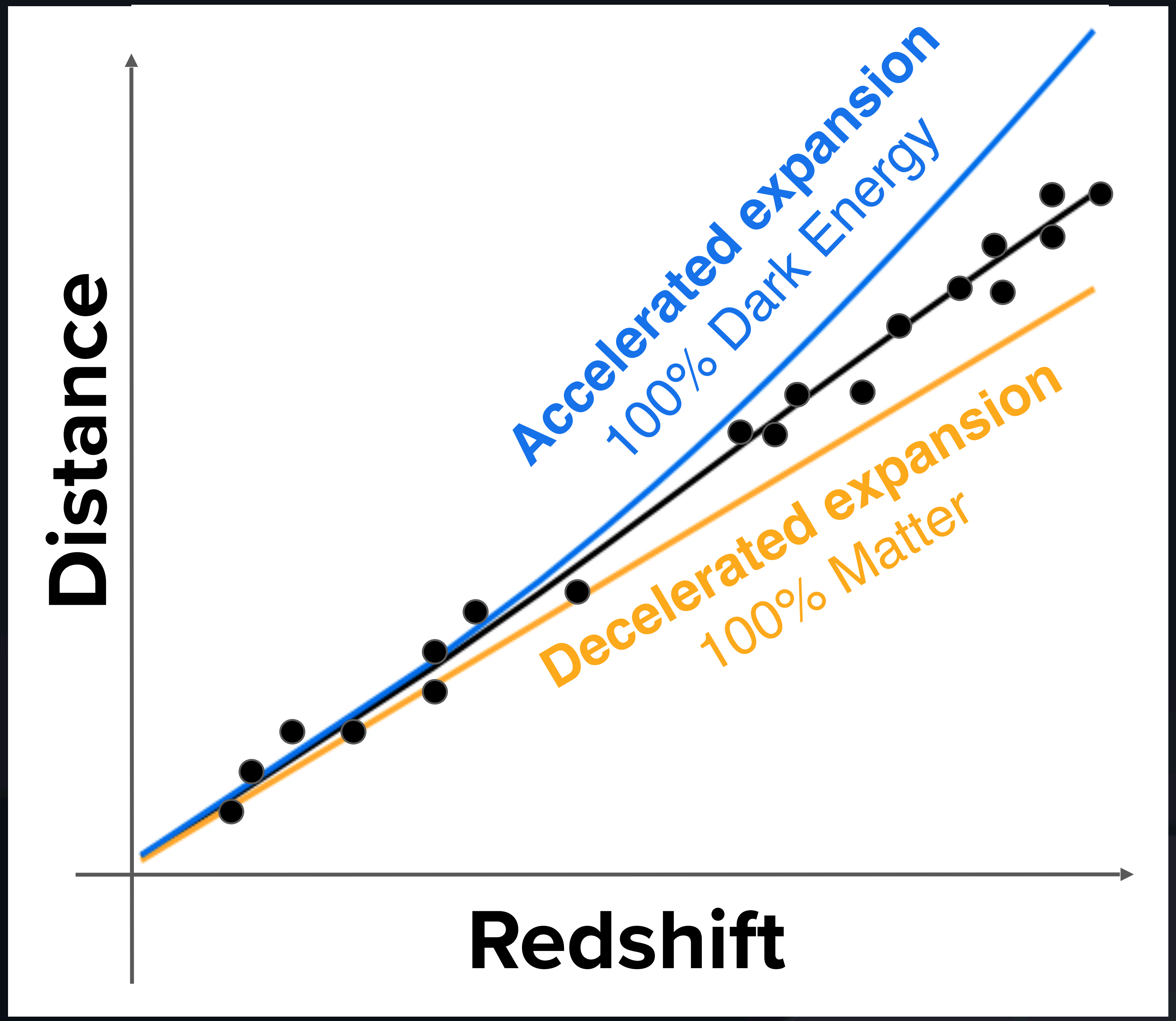


Redshift

Hubble diagram basics

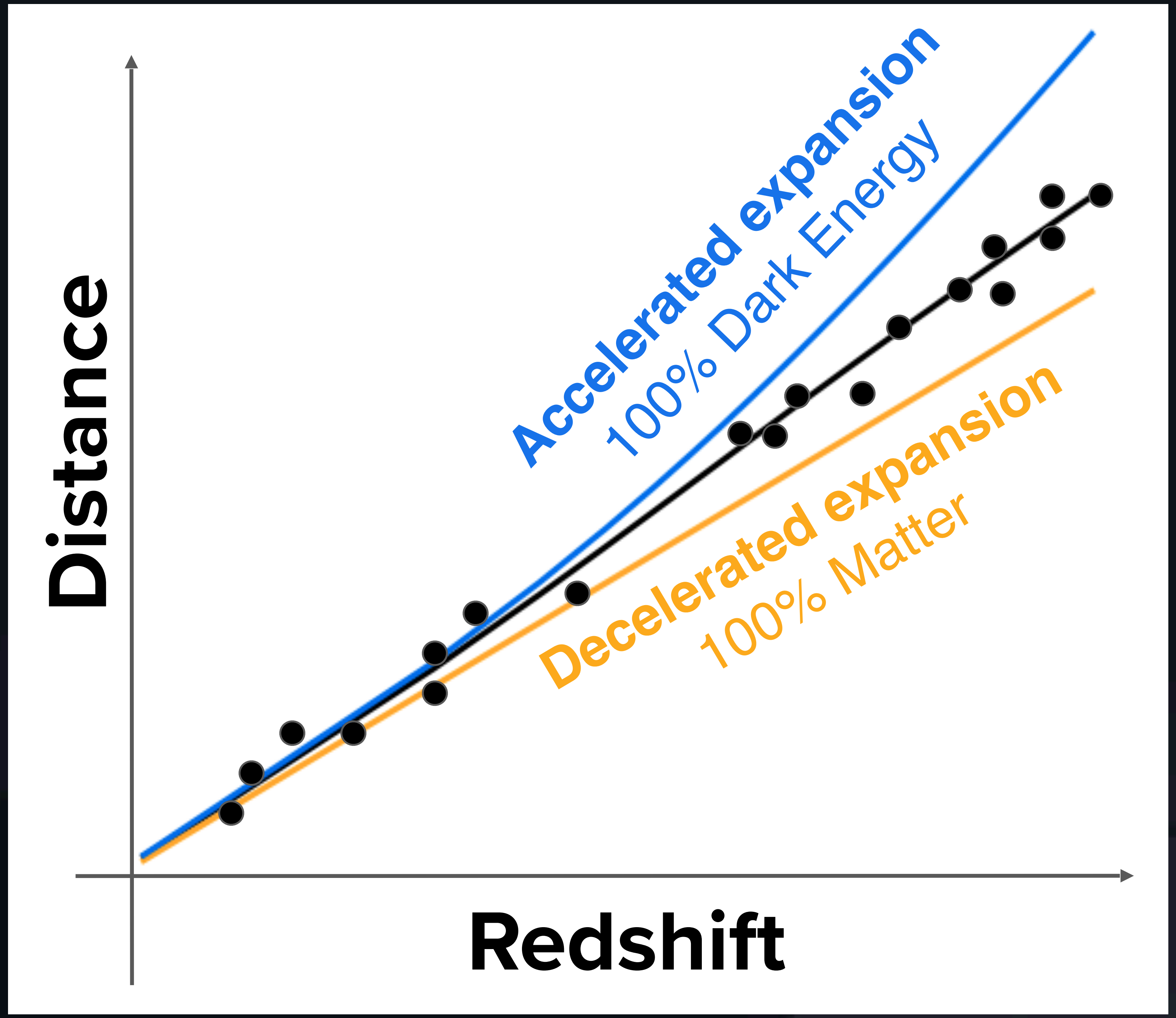


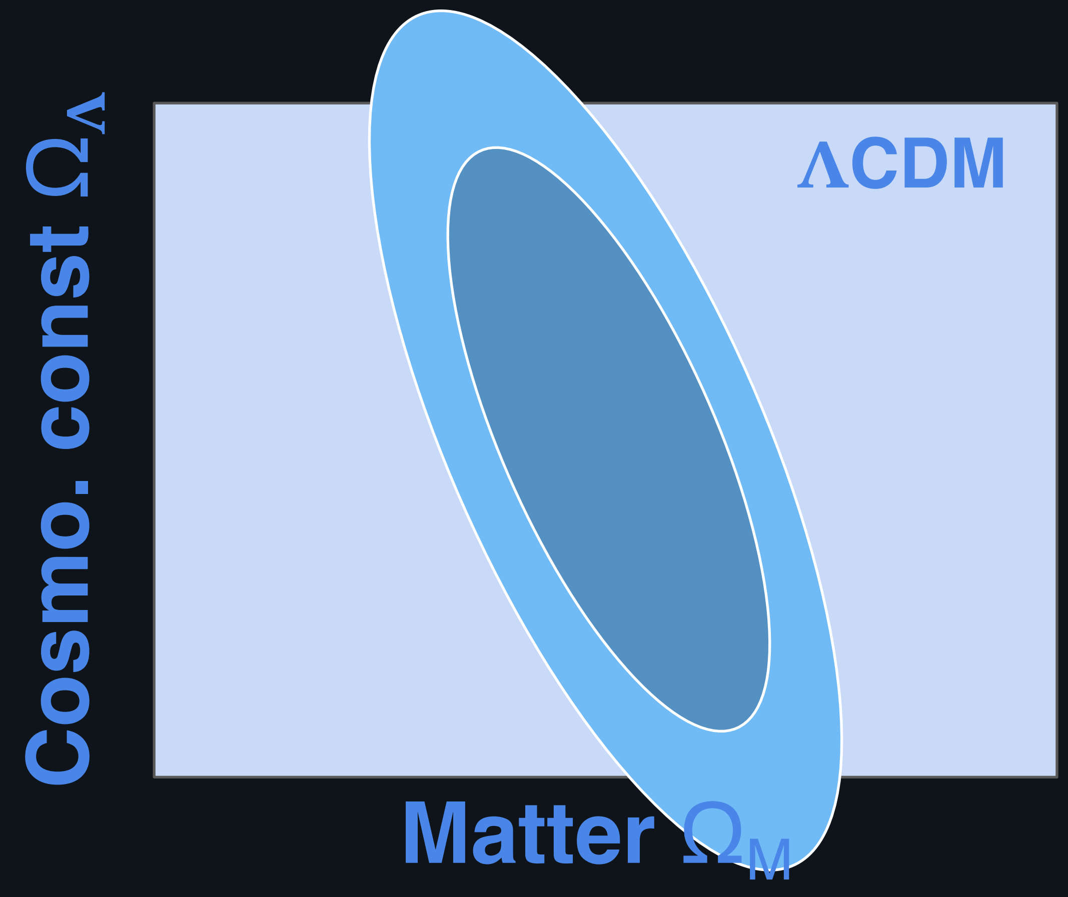
Hubble diagram basics

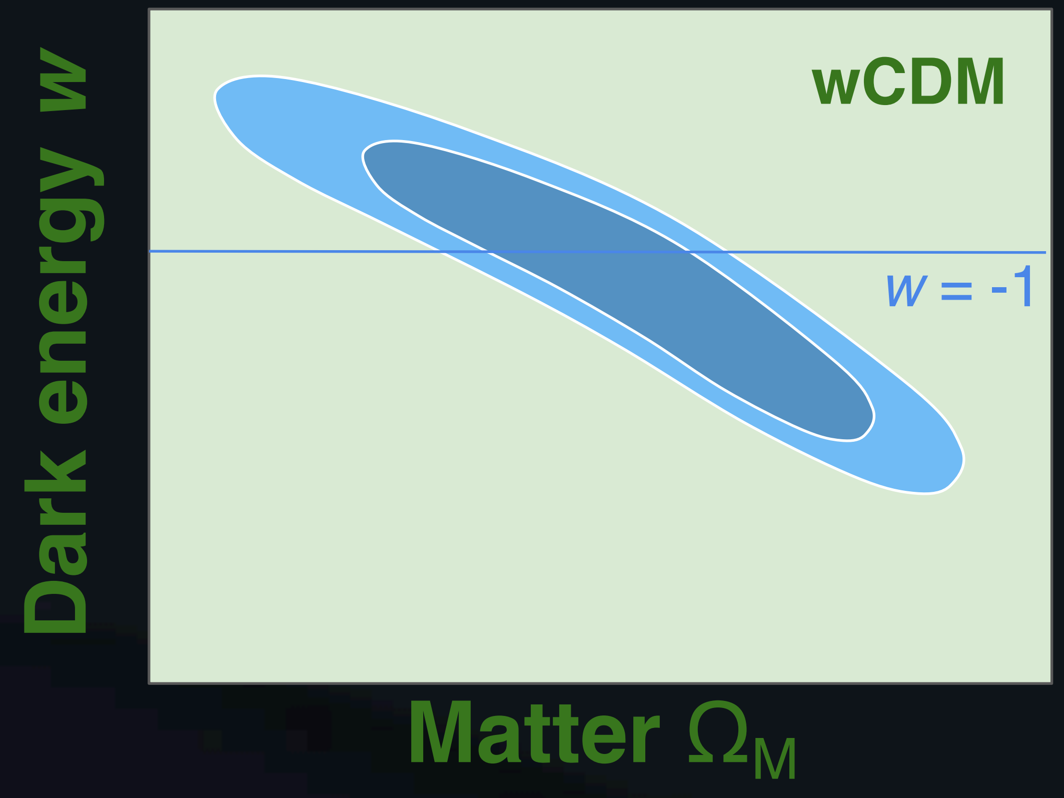


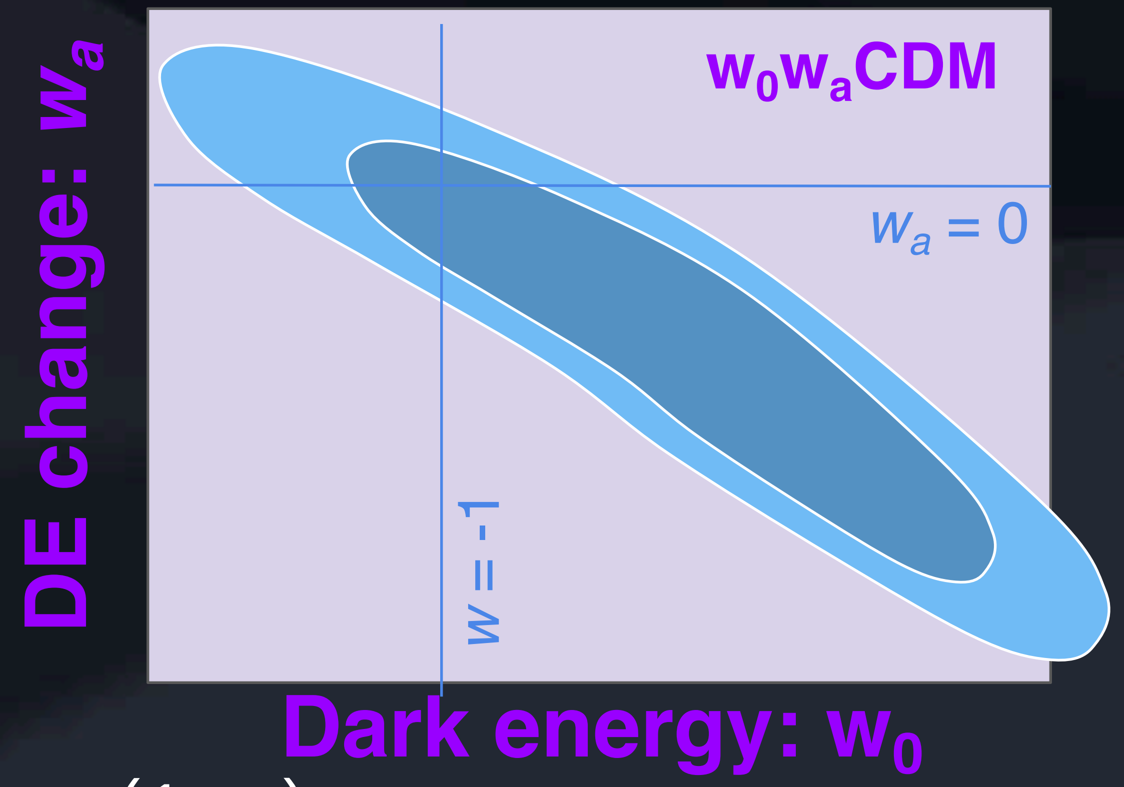
Hubble diagram basics

$$D_L = (1+z)\frac{c}{H_0}\int_0^z \frac{dz}{E(z)}$$







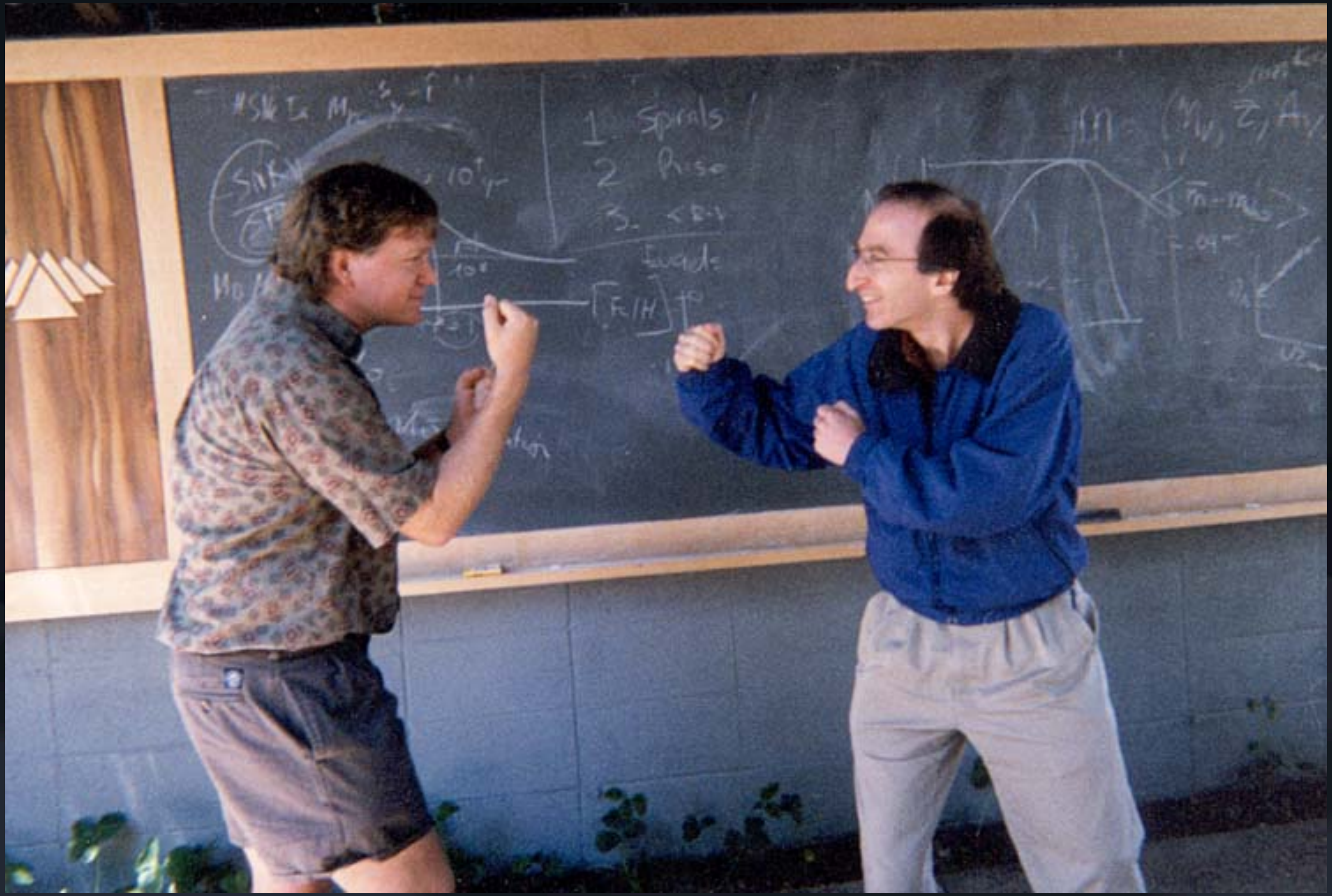


Cosmological Model	Friedmann Equation: $\mathbf{E(z) = H(z)/H_0} =$	Fit Parameters Θ
Flat-ΛCDM	$[\Omega_M(1+z)^3 + (1-\Omega_M)]^{1/2}$	Ω_M
ΛCDM	$[\Omega_M(1+z)^3 + \Omega_\Lambda + (1-\Omega_M-\Omega_\Lambda)(1+z)^2]^{1/2}$	Ω_M, Ω_Λ
Flat-wCDM	$\left[\Omega_M(1+z)^3 + (1-\Omega_M)(1+z)^{3(1+w)}\right]^{1/2}$	Ω_M, w
Flat-w_0w_aCDM	$\left[\Omega_M(1+z)^3 + (1-\Omega_M)(1+z)^{3(1+w_0+w_a)}e^{-3w_a z/(1+z)}\right]^{1/2}$	Ω_M, w_0, w_a

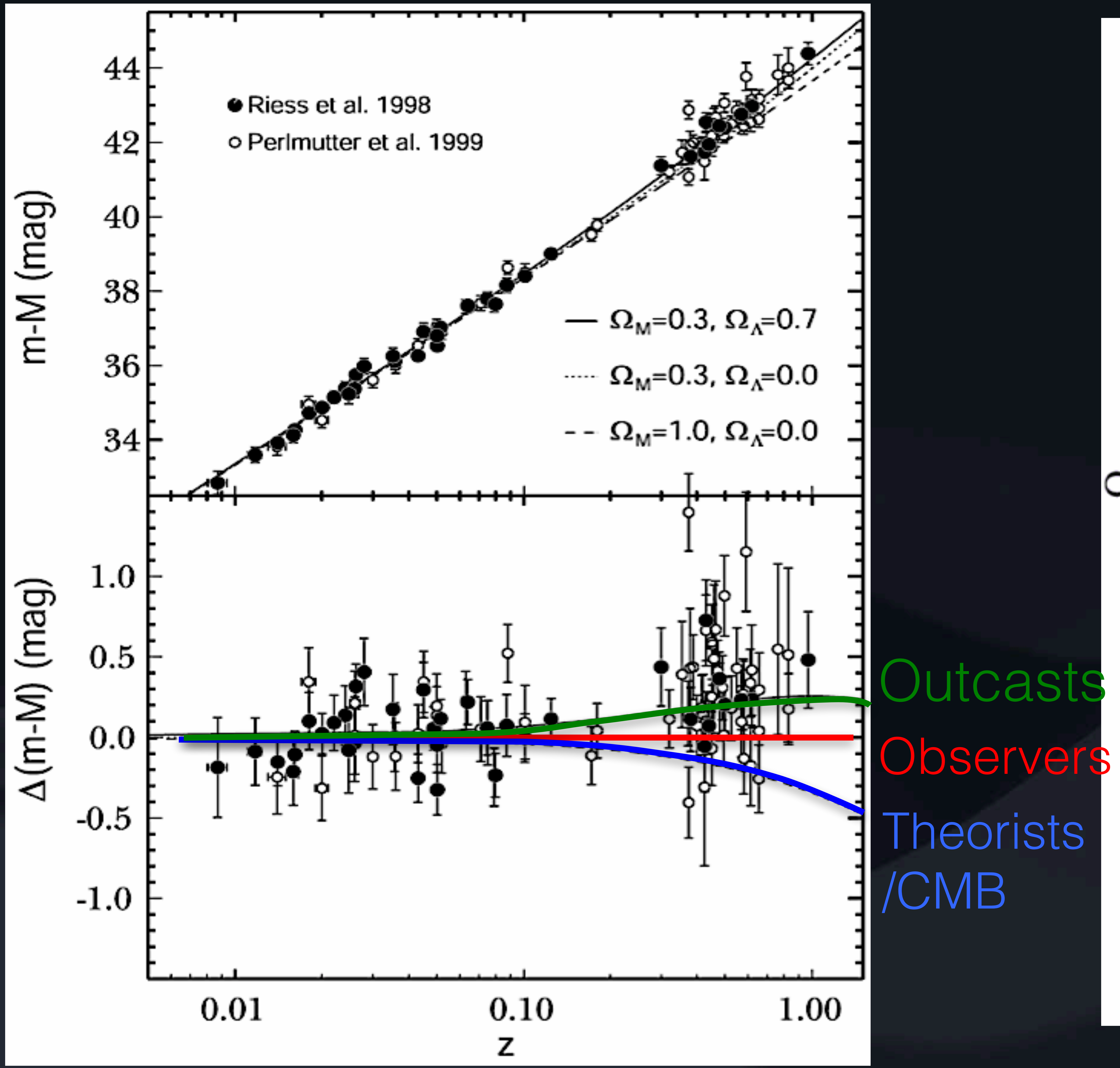
$w = w_0 + w_a(1-a)$

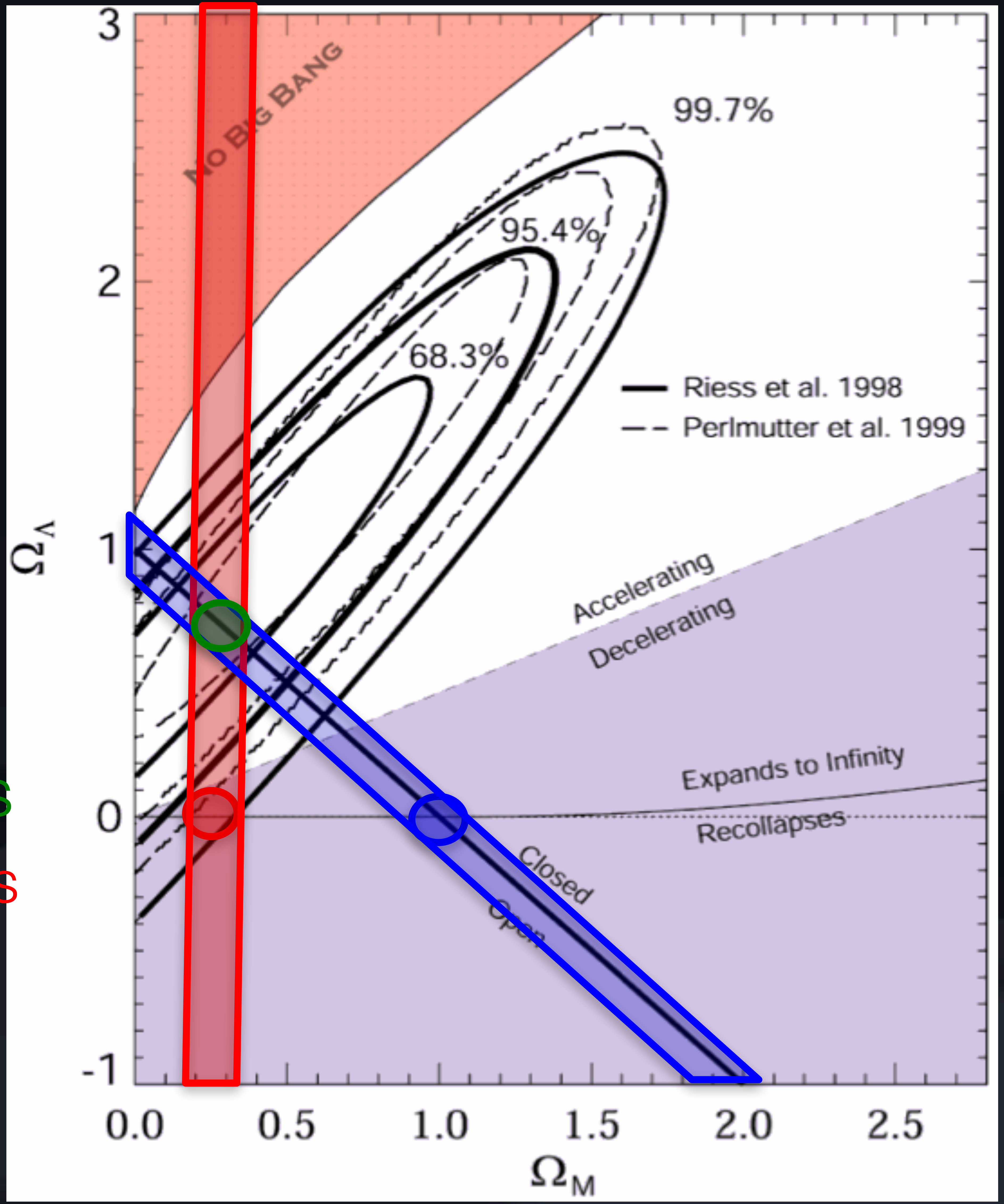
Discovery of Acceleration

(i.e. Discovery of Dark Energy)



Discovery of Acceleration (dark energy)





Perlmutter & Schmidt 2003

Fertile Ground

Solved several big problems in cosmology

AGE

NUMBER

MASS

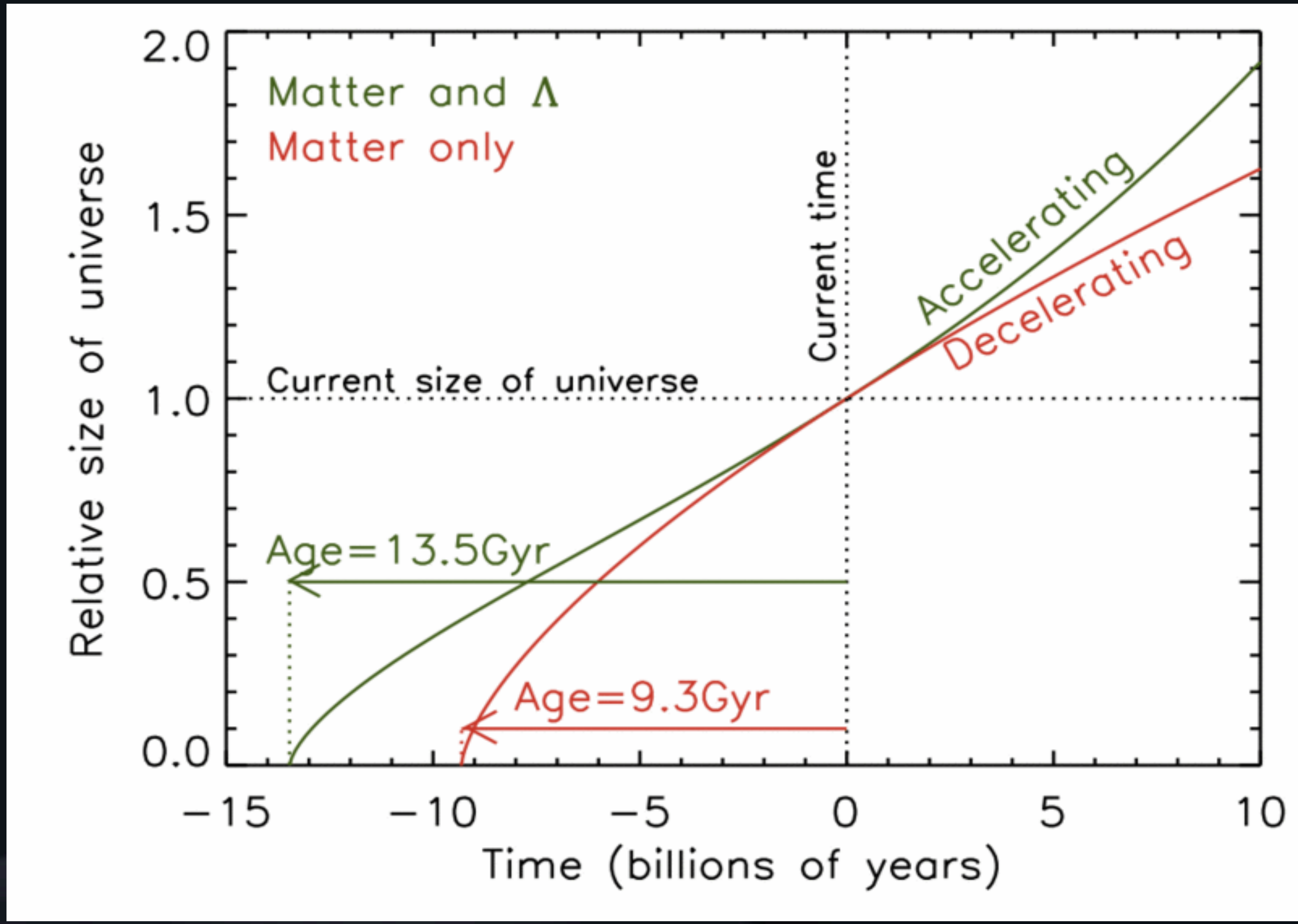
(Some stars were older than the universe.)

(There were too many galaxies at large distances.)

(The amount of matter didn't add up.)

Solved several big problems in cosmology

AGE



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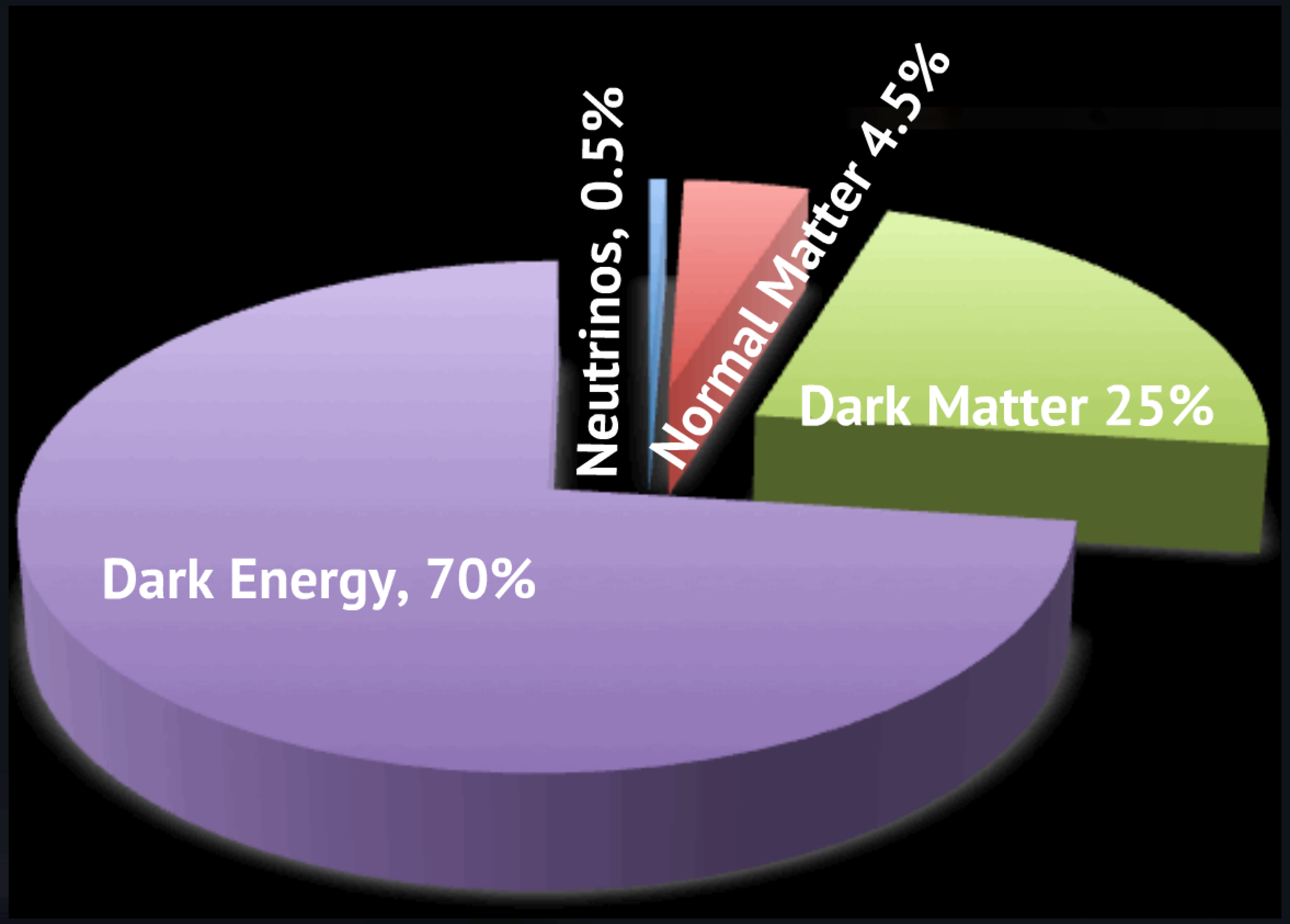


(The amount of matter didn't add up.)

Galaxy counts: Dark energy 80% (published 1990)

The cosmological constant and cold dark matter

G. Efstathiou, W. J. Sutherland & S. J. Maddox

Department of Physics, University of Oxford, Oxford OX1 3RH, UK

THE cold dark matter (CDM) model[1–4] for the formation distribution of galaxies in a universe with exactly the crit density is theoretically appealing and has proved to be dura but recent work[5–8] suggests that there is more cosmological st ture on very large scales ($l > 10\ h^{-1}$ Mpc, where h is the Hul constant H_0 in units of 100 km s^{-1} Mpc^{-1}) than simple vers of the CDM theory predict. We argue here that the successe the CDM theory can be retained and the new observat accommodated in a spatially flat cosmology in which as muc 80% of the critical density is provided by a positive cosmological constant, which is dynamically equivalent to endowing the vacuum with a non-zero energy density. In such a universe, expansion was dominated by CDM until a recent epoch, but is now governed by the cosmological constant. As well as explaining large-scale structure, a cosmological constant can account for the lack of fluctuations in the microwave background and the large number of certain kinds of object found at high redshift.

NATURE · VOL 348 · 20/27 DECEMBER 1990

FIG. 1 The dots show estimates of the angular correlation function $w(\theta)$ for galaxies in the APM galaxy survey (see ref. 5 for details). These estimates have been scaled to the depth of the Lick galaxy catalogue where 1° corresponds to a spatial scale of $\sim 5h^{-1}$ Mpc. The dotted line shows the predictions of the $\Omega = 1$ CDM model (from ref. 5). The thin solid and dashed lines show the results of the linear theory for $\Omega_0 = 0.2$ scale-invariant CDM models with $h = 1$ and 0.75, respectively. The thick solid line shows N-body results for $\Omega = 0.2$ and $h = 0.9$; the flattening of this curve at angular scales $\lesssim 0.1°$ is an artefact of the resolution of the computer code, but the excess between 0.1° and 1° is real (see Fig. 2).

THE ASTROPHYSICAL JOURNAL, 444:15–20, 1995 May 1

INTERPRETATION OF THE FAINT GALAXY NUMBER COUNTS IN THE K BAND

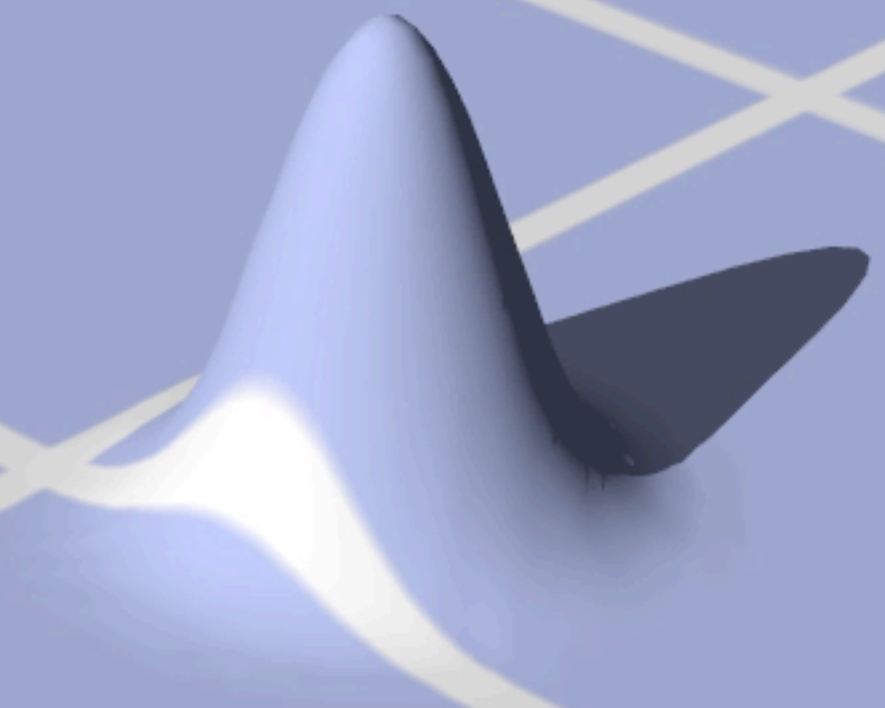
YUZURU YOSHII[1,2,3] AND BRUCE A. PETERSON[2,3]
Received 1994 February 28; accepted 1994 November 7

ABSTRACT

Number counts of K(2.2 μm)-selected galaxies reaching to $K = 23$ mag are compared to model predictions which take into account the selection bias against high-redshift galaxies inherent in the methods used to detect faint galaxy images. Using a standard model for galaxy luminosity evolution with a constant comoving density of galaxies, we find that these number count data favor a flat, low-density $\Omega_0 \sim 0.2$ universe with a nonzero cosmological constant. We argue that the agreement with the model predictions for a low-density universe considerably diminishes any need to introduce a hypothetical population to explain the excess galaxies found in deep blue surveys.

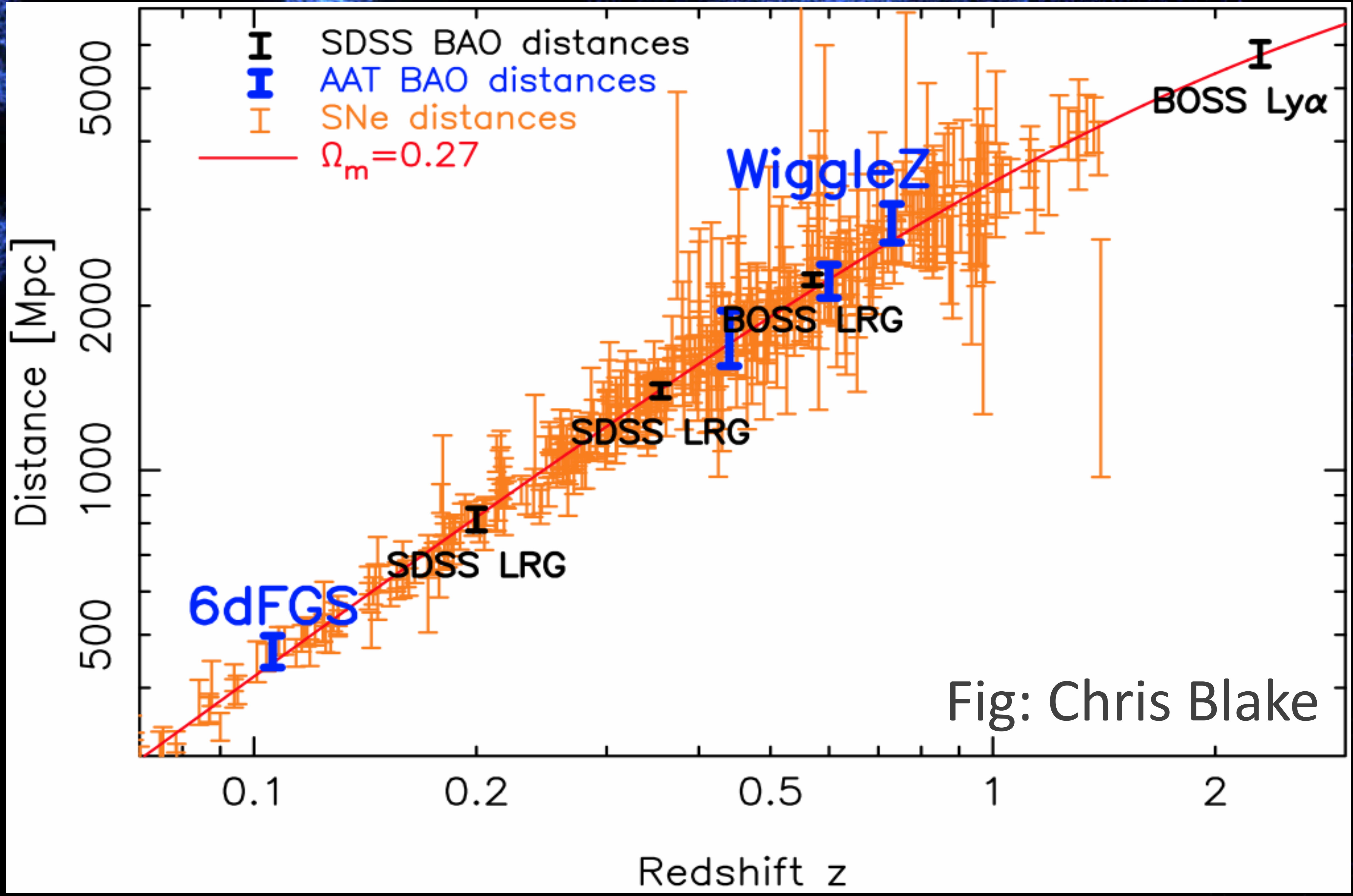
Confirmation of Acceleration

Independent technique
Baryon Acoustic Oscillations (BAO)



Confirmation of Acceleration

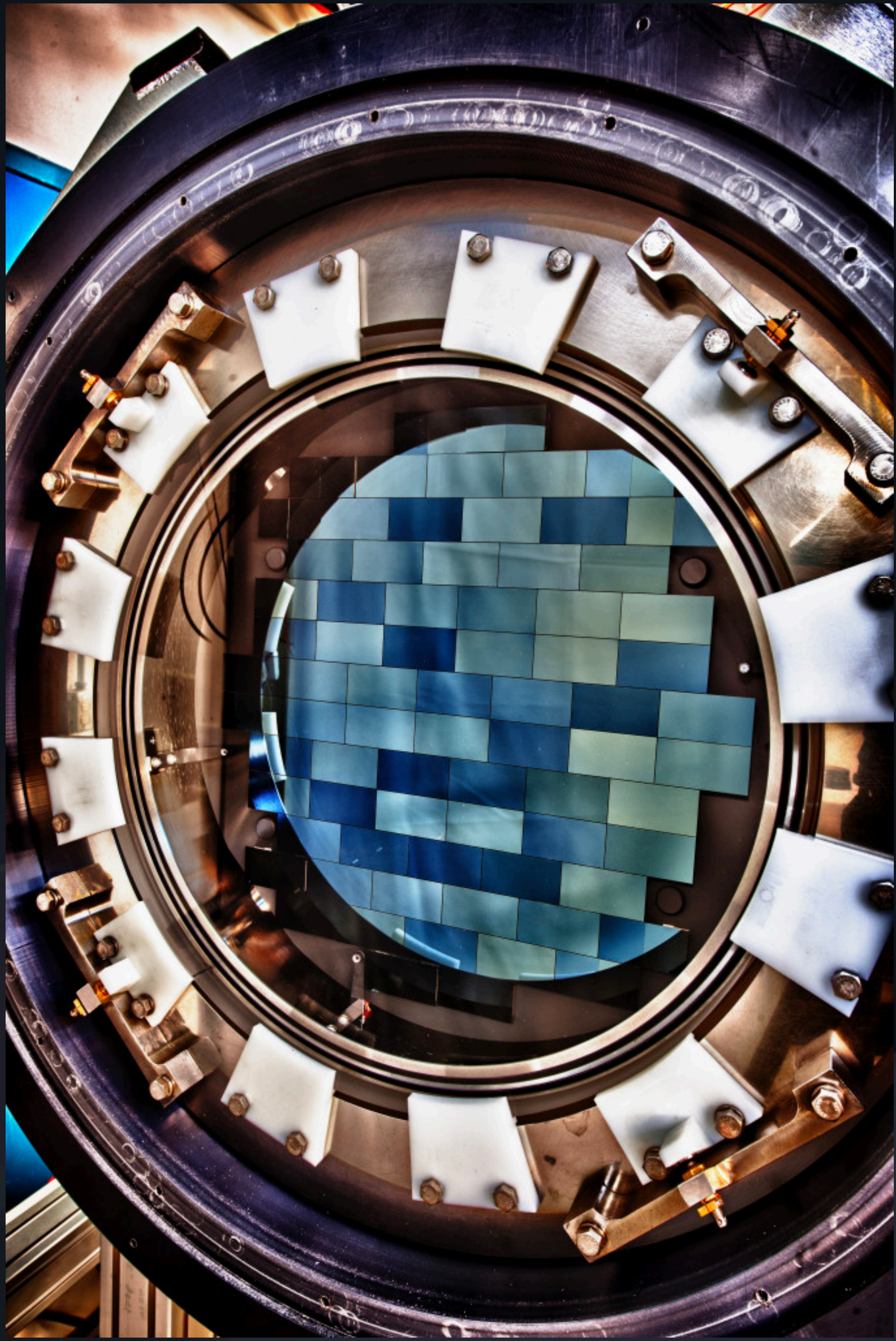
WiggleZ BAO (2011)



What could dark energy be?

Let’s measure it more precisely.

The Dark Energy Survey
(DES)



The Dark Energy Survey

570 mega-pixels
10 years designing
6 years observing

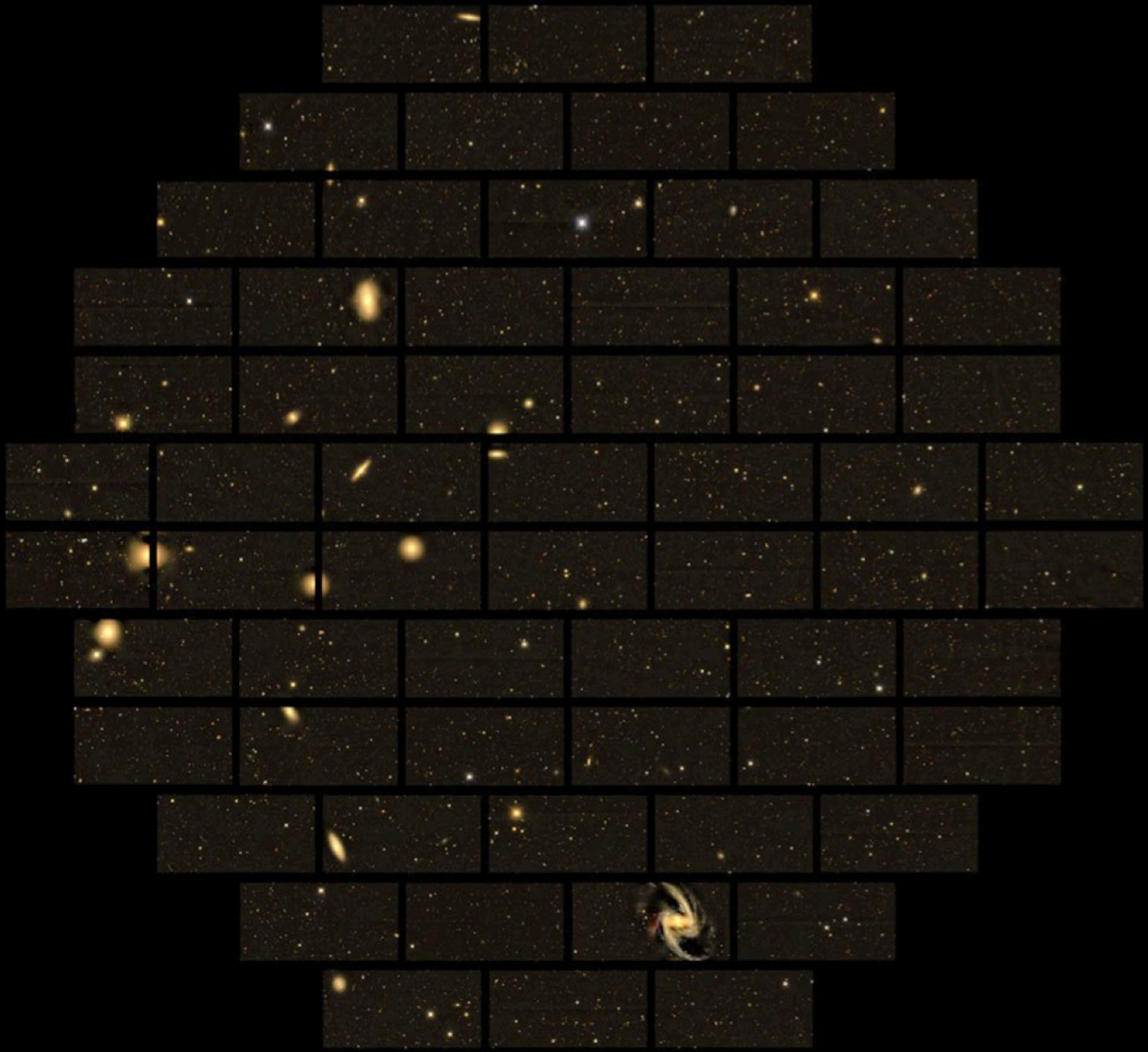
Approximately:
- 543 million galaxies
- 145 million stars
- 700,000 asteroids
- 10,000 supernovae

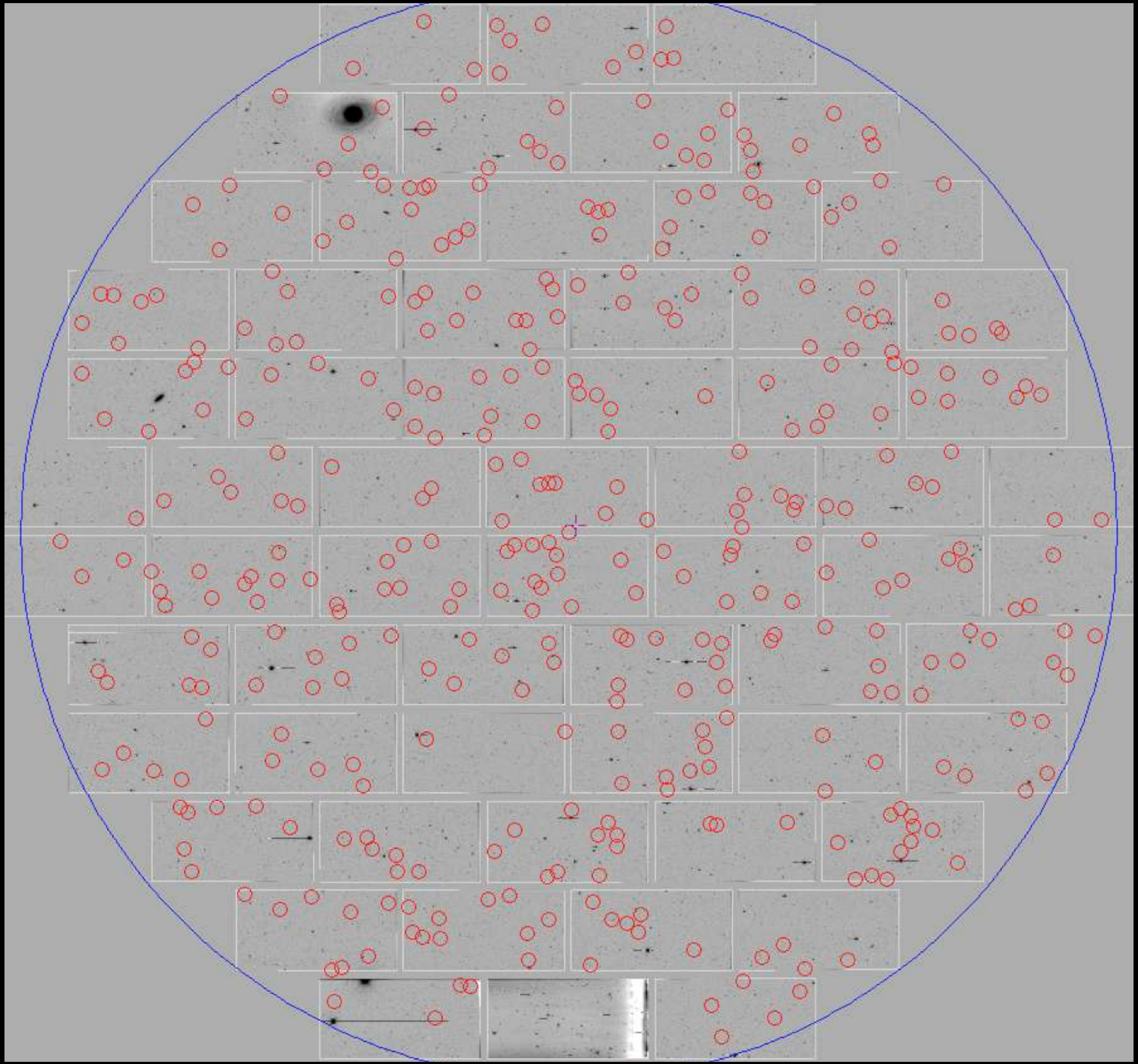
A 2dF night at the Anglo-Australian Telescope

Australian Government

Department of Industry
Innovation, Science, Research
and Tertiary Education

by Ángel López-Sánchez

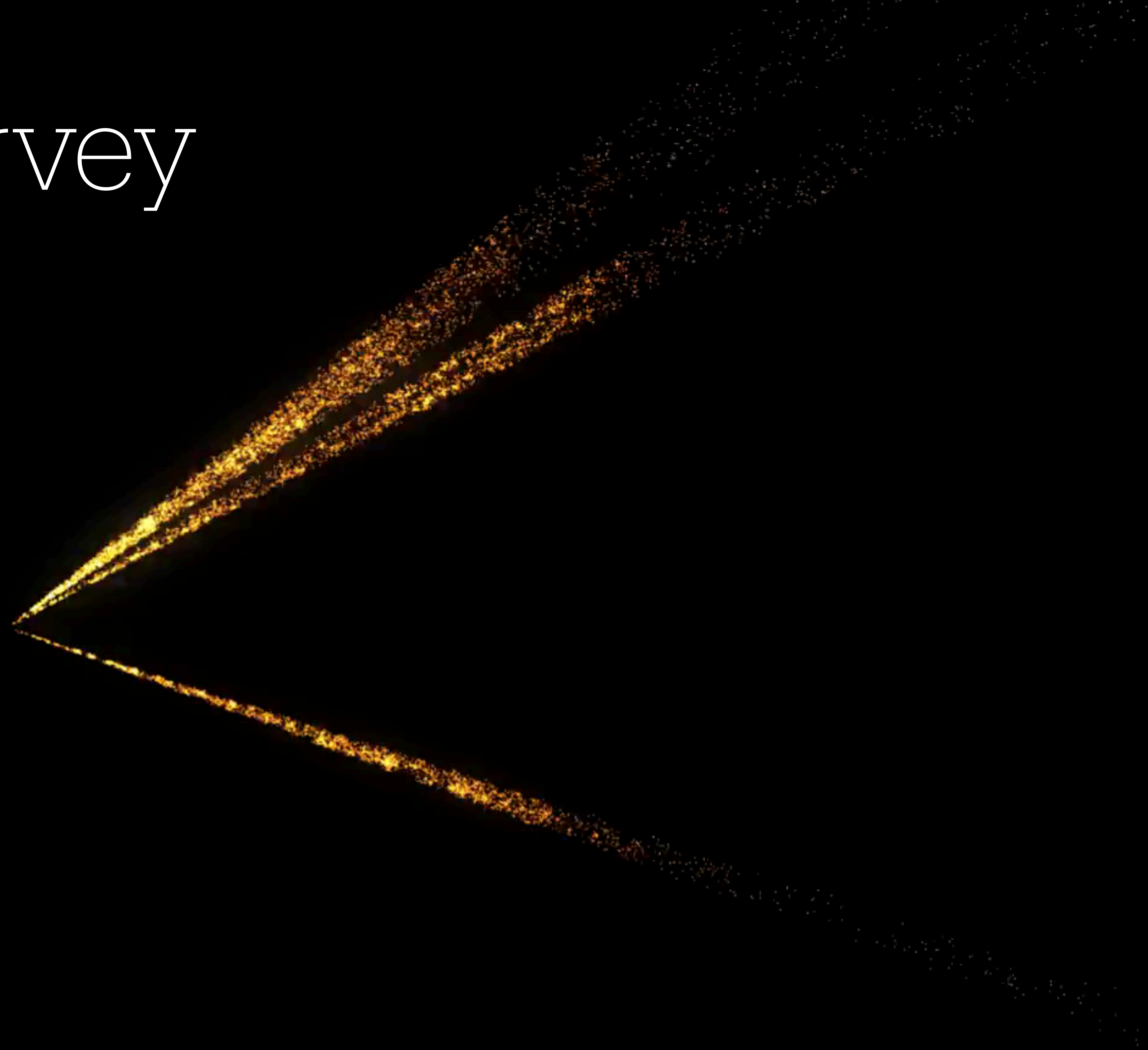




The Dark Energy Survey

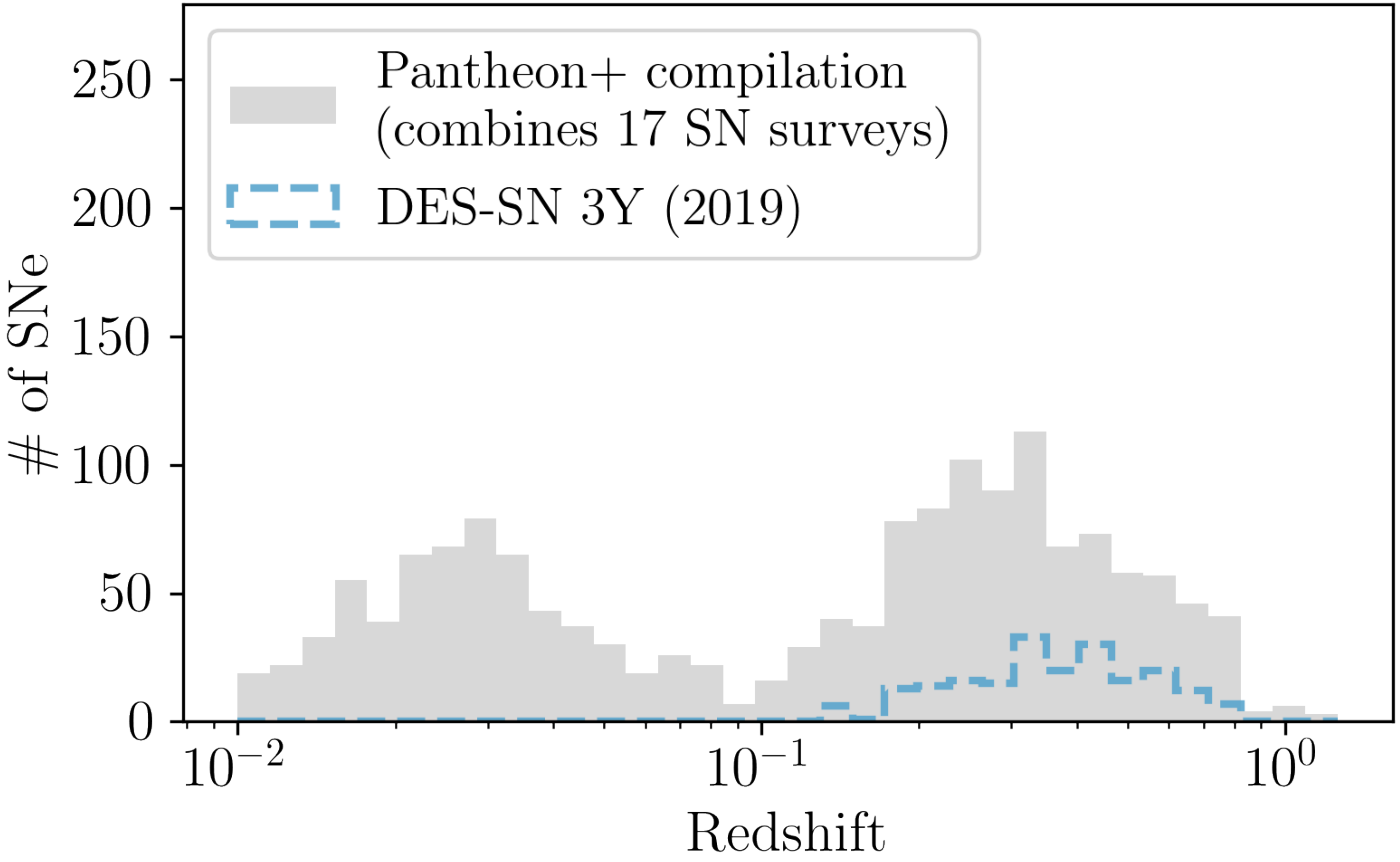
The Dark Energy Survey

(DES)



The DES Sample

The **largest** and **deepest** SN sample from a **single telescope** ever compiled



Pantheon+ and **Union** compilations
Brout et al. 2021
Rubin et al. 2024

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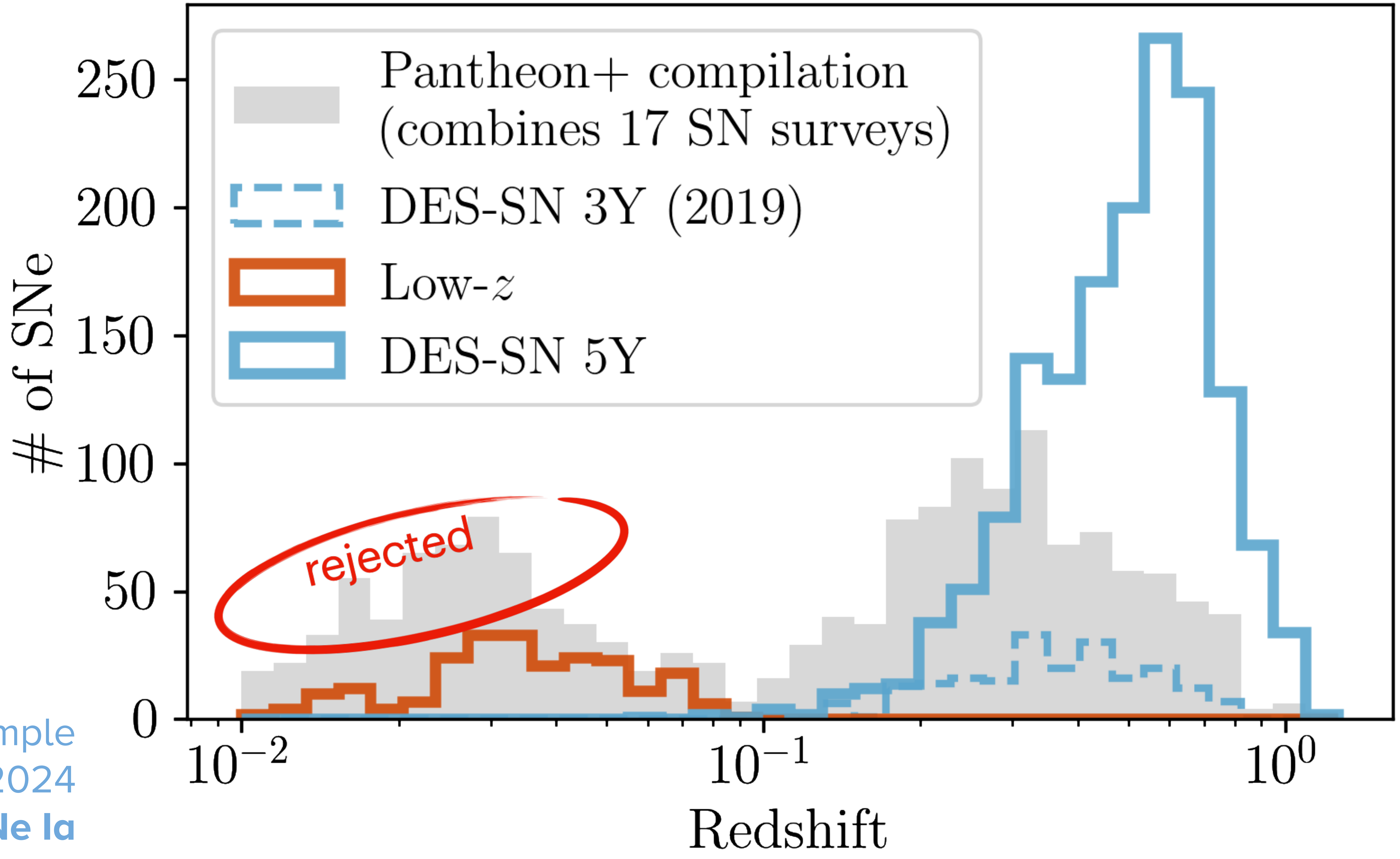
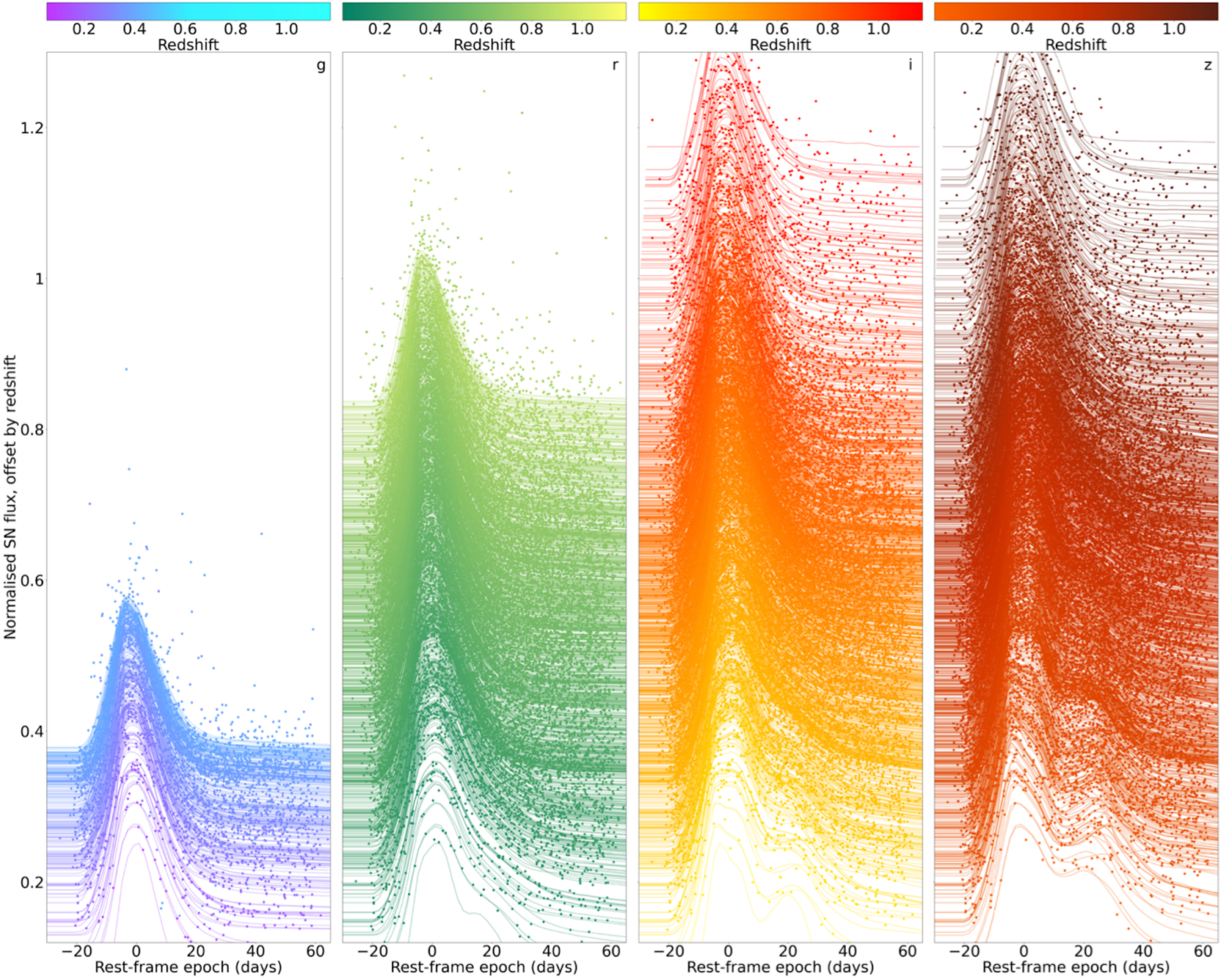


Pantheon+ and **Union** compilations
Brout et al. 2021
Rubin et al. 2024

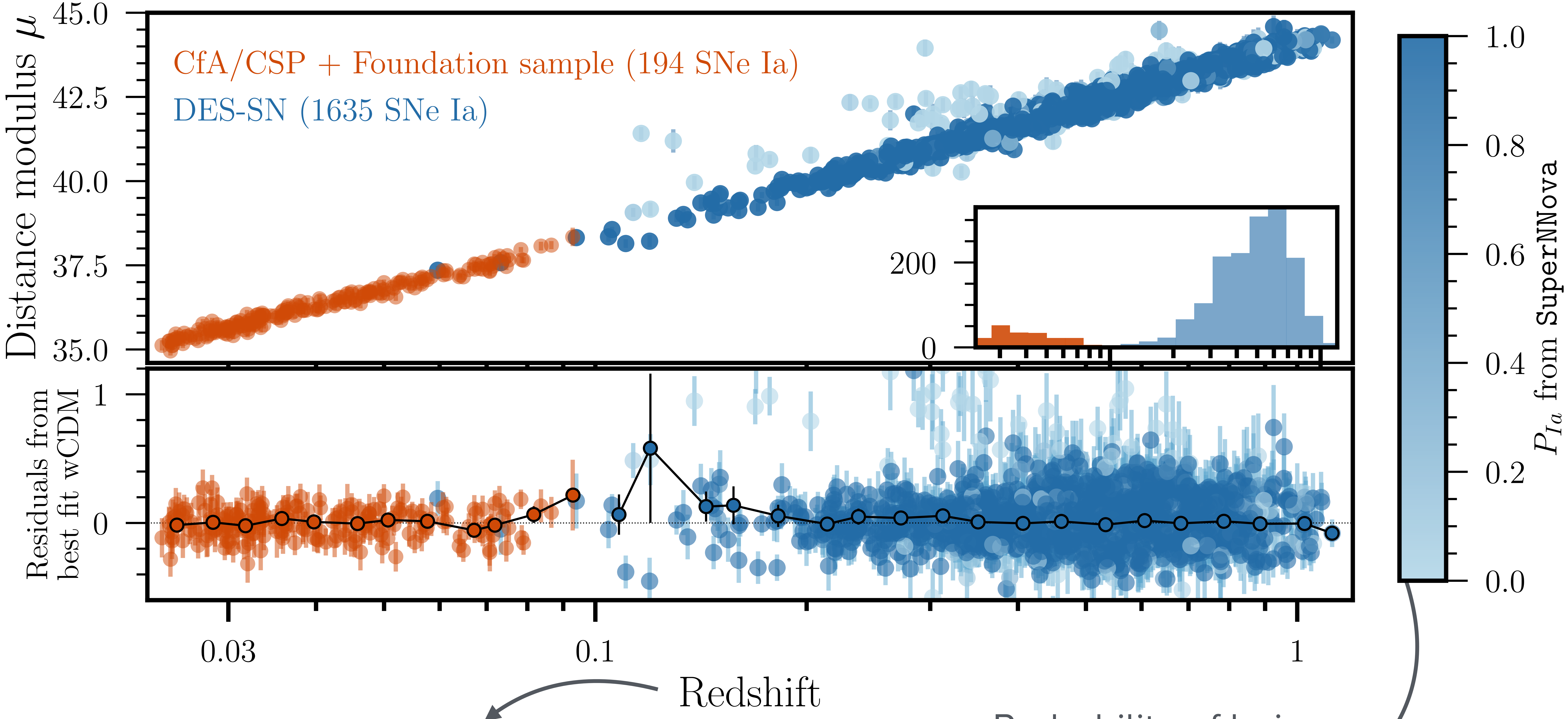
DES-SN5YR sample
DES 2024
Approx 1500 new SNe Ia
Photometrically classified

The DES Supernova Light Curves

All of our SN Ia light curves (offset by redshift)



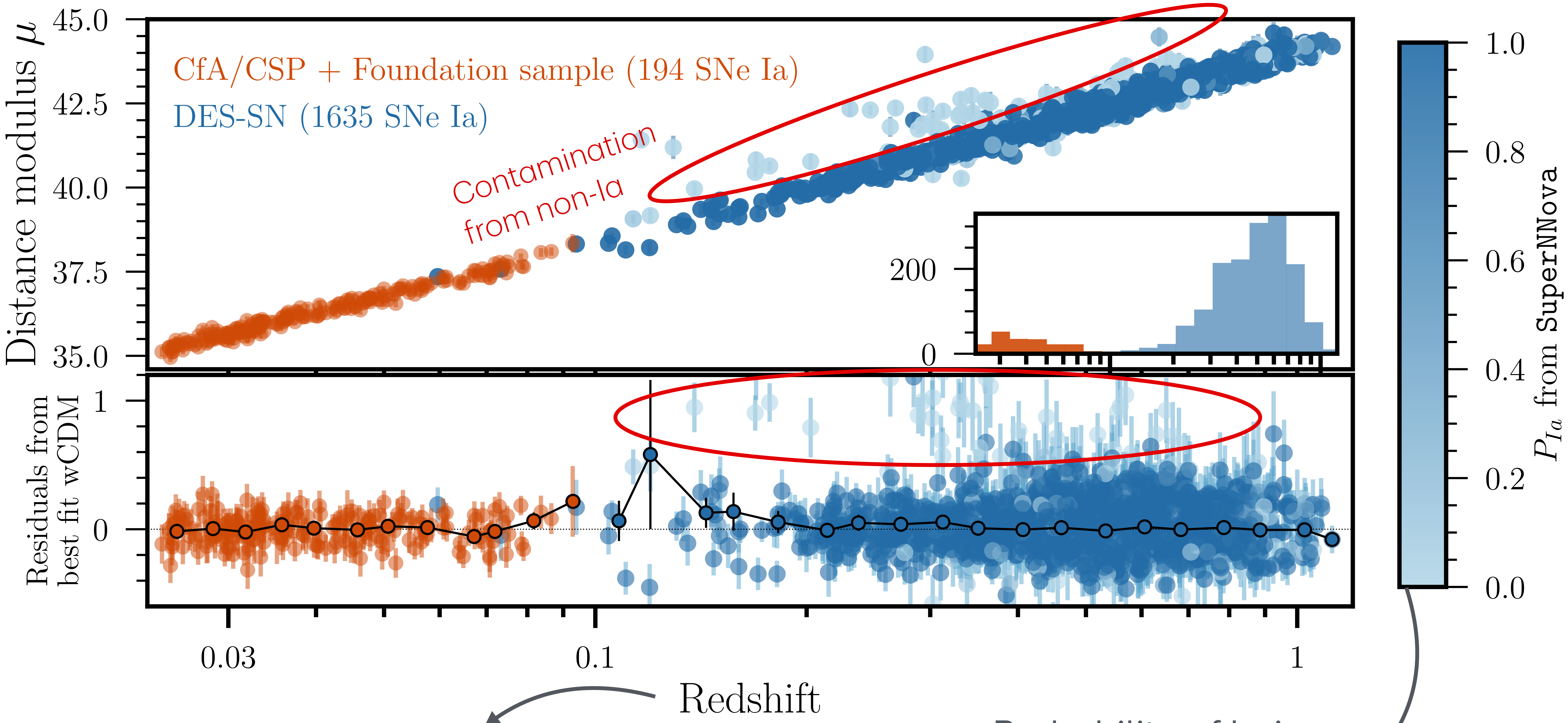
The DES Hubble Diagram



Spectroscopic redshifts from identified host

Probability of being a Type Ia from machine learning

The DES Hubble Diagram



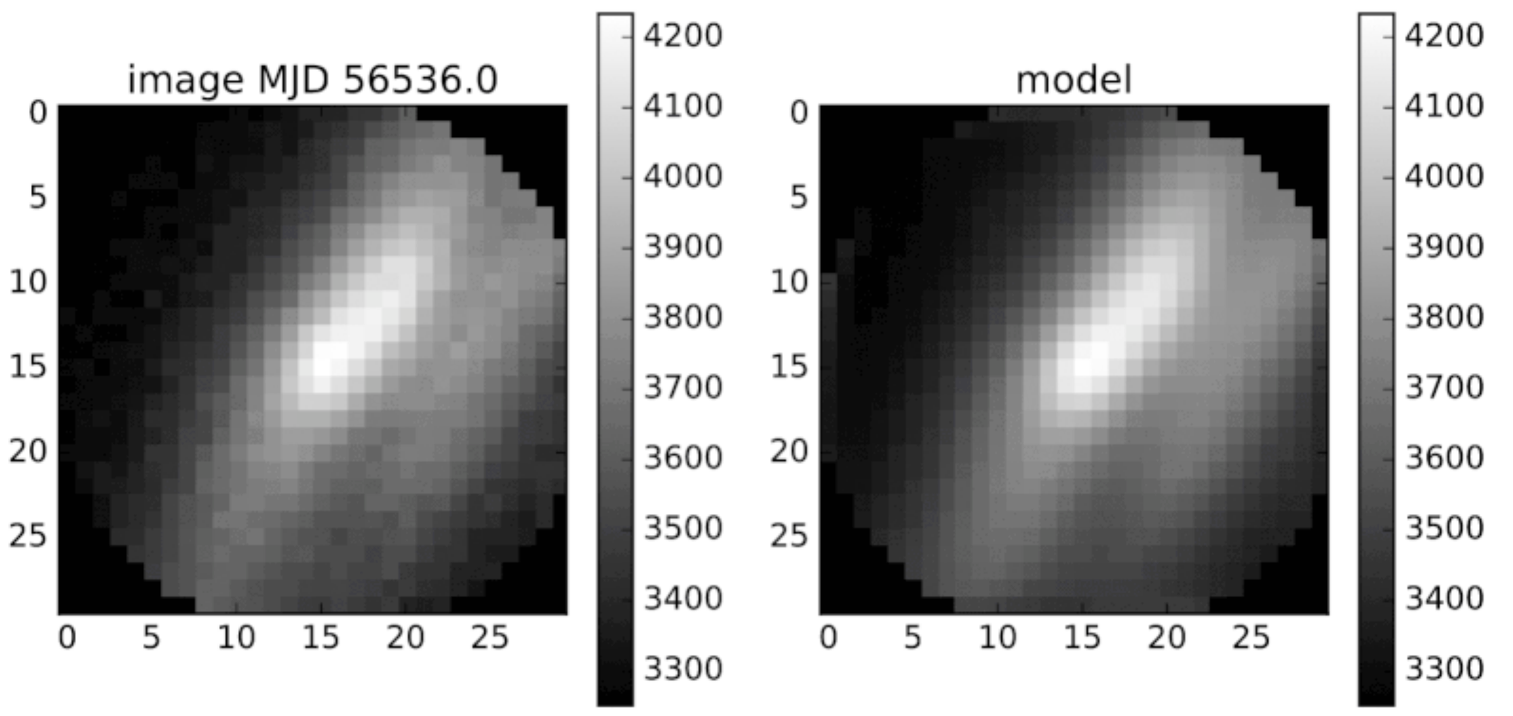
Spectroscopic redshifts from identified host

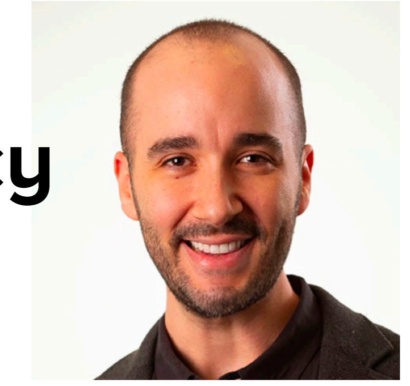
Probability of being a Type Ia from machine learning

DES Analysis Details

Set new standards in multiple areas

Photometry calibrated to 5mmag accuracy

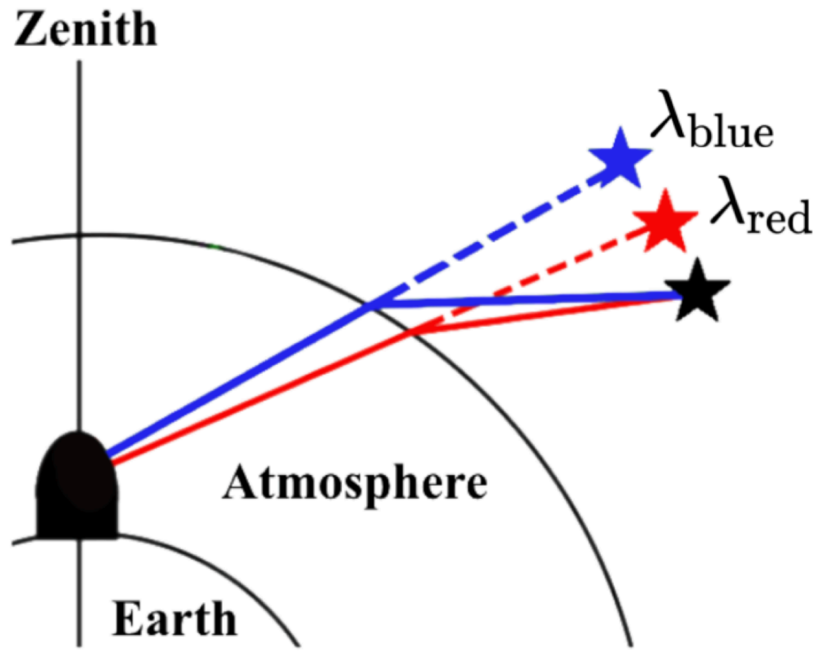




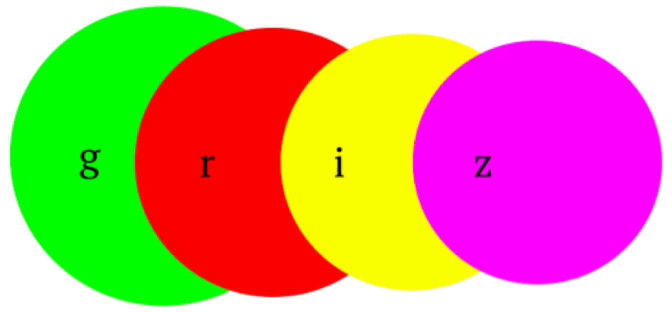
Dillon Brout et al. 2019

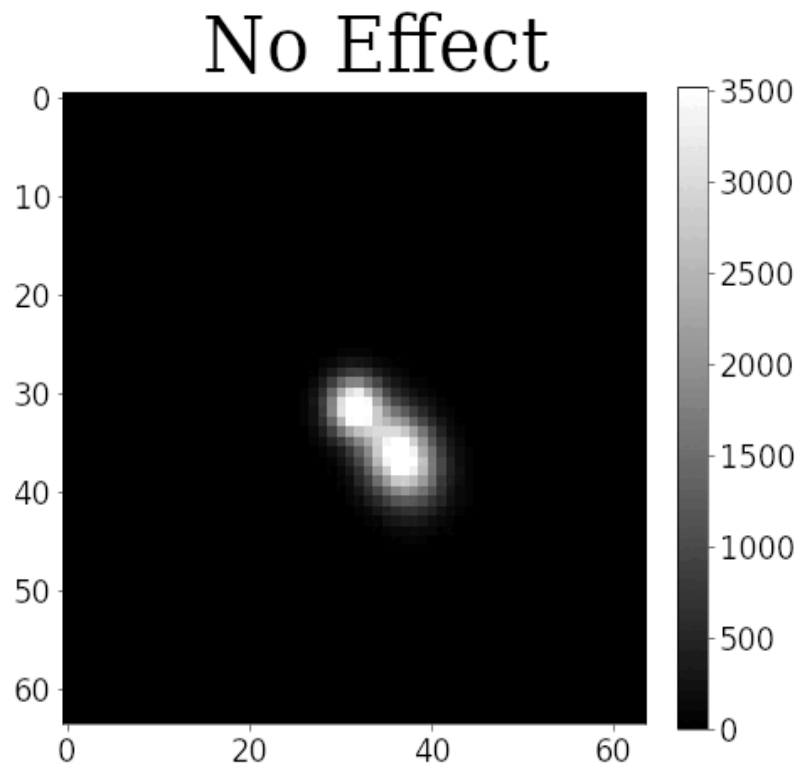
Bruno Sanchez et al. 2024

Effect #1:Differential Chromatic Refraction

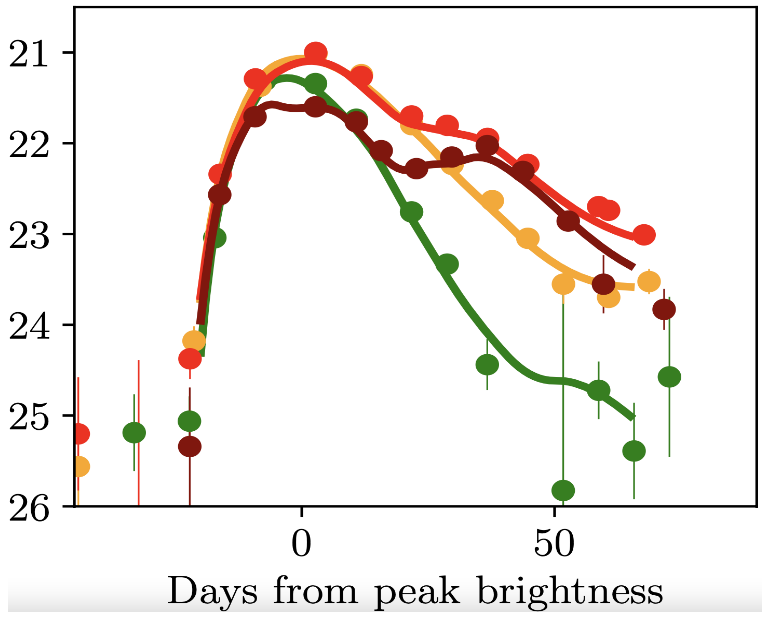


Effect #2: λ-dependent seeing





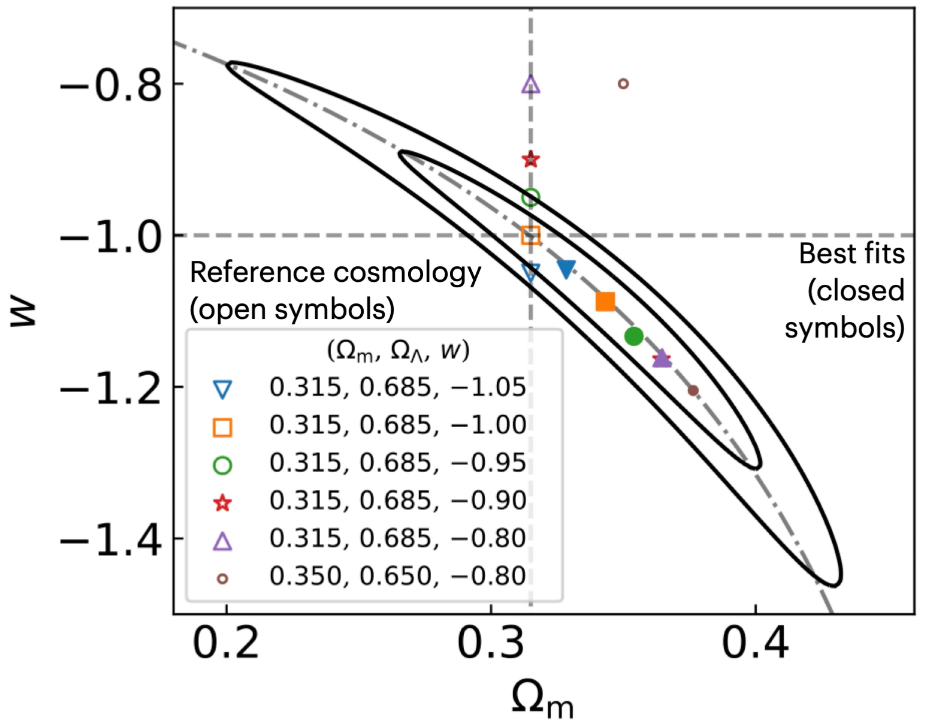
Jason Lee and Maria Acevedo et al. 2022



The first SN Ia cosmological analysis to use a new light-curve model: SALT3

- SALT3 trained on x1.5 larger data
- SALT3 goes redder (where DES has high-quality data)
- Calibration uncertainties incorporated in the light-curve model training as well as the fitting.

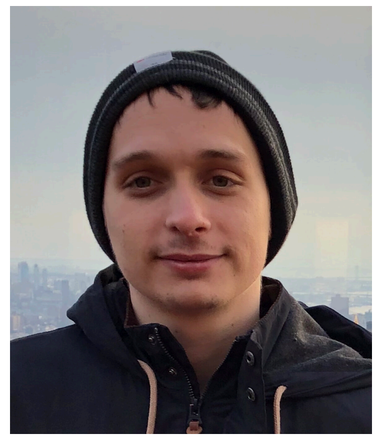
Georgie Taylor et al. 2022



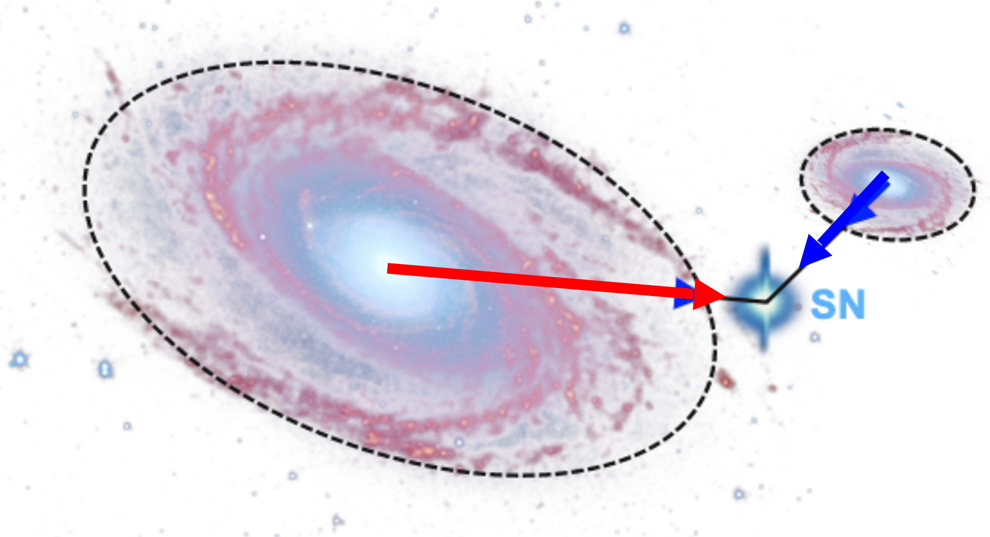
Validated contours, assumptions, and uncertainties

- Only weak dependence on simulation cosmology
- Contour sizes are accurate (including at the extremes)

Patrick Armstrong et al. 2022

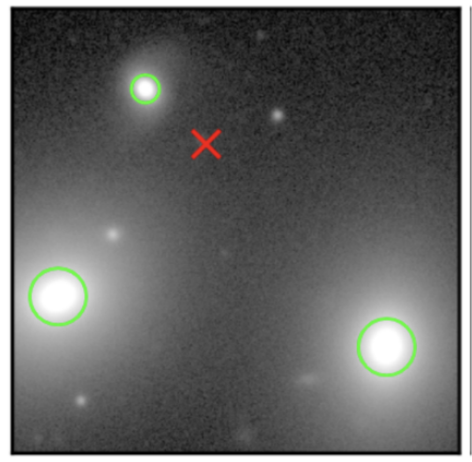


Ryan Camilleri et al. 2024



Deep dive on host galaxy associations

- Host Mismatch systematics are less than 10% of total error budget.



Helen Qu et al. 2023

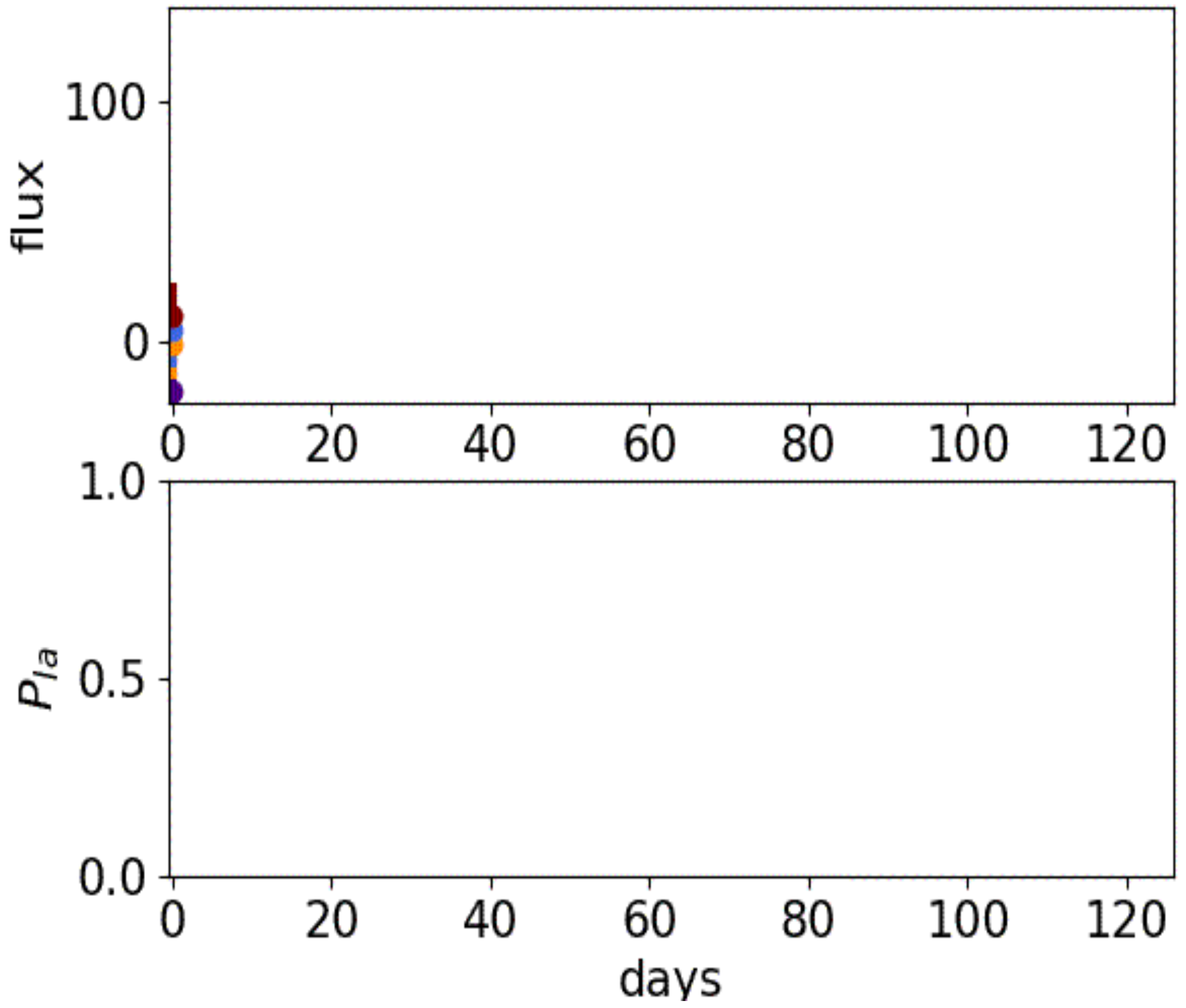
DES Analysis Details

Set new standards in multiple areas

SuperNNova (Anais Moller et al. 2019)

SCONE (Helen Qu et al 2019)

SNIRF (Kovacs & Kuhlmann)



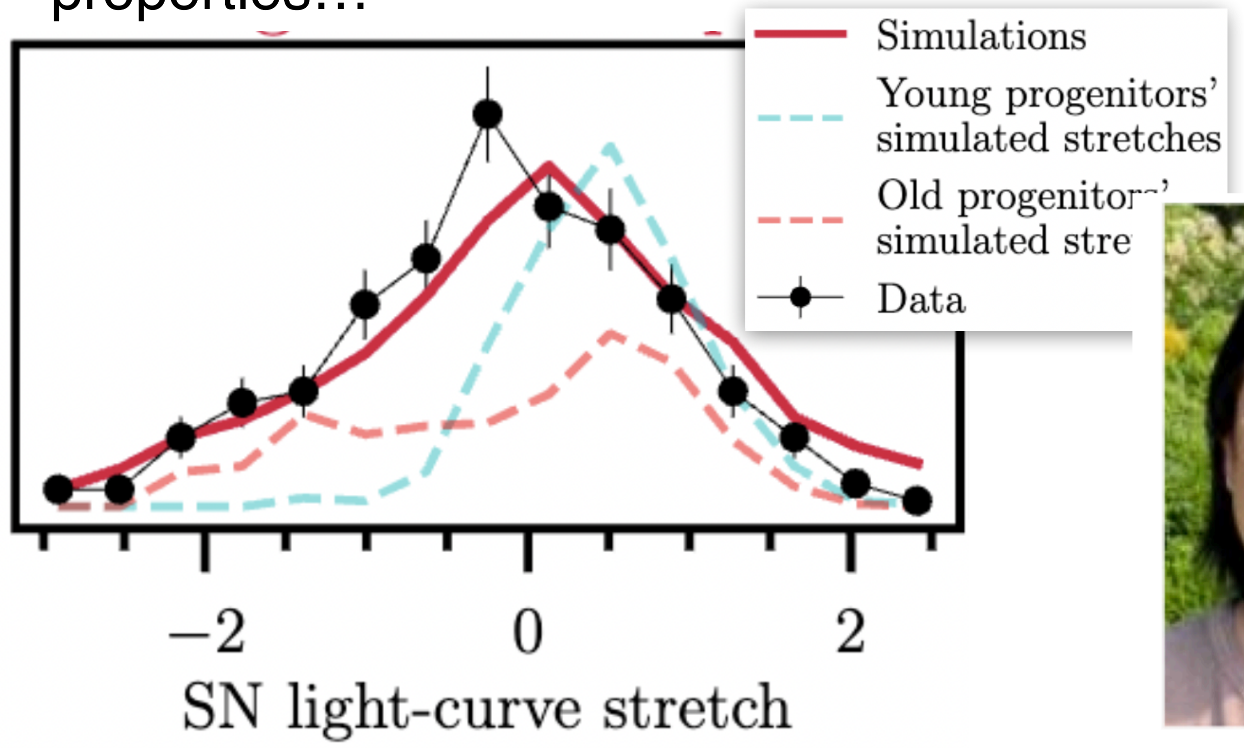
Photometric classification

- **Three** SN classification algorithms
- **Seven** non-Ia simulation variants (for independent train/test)

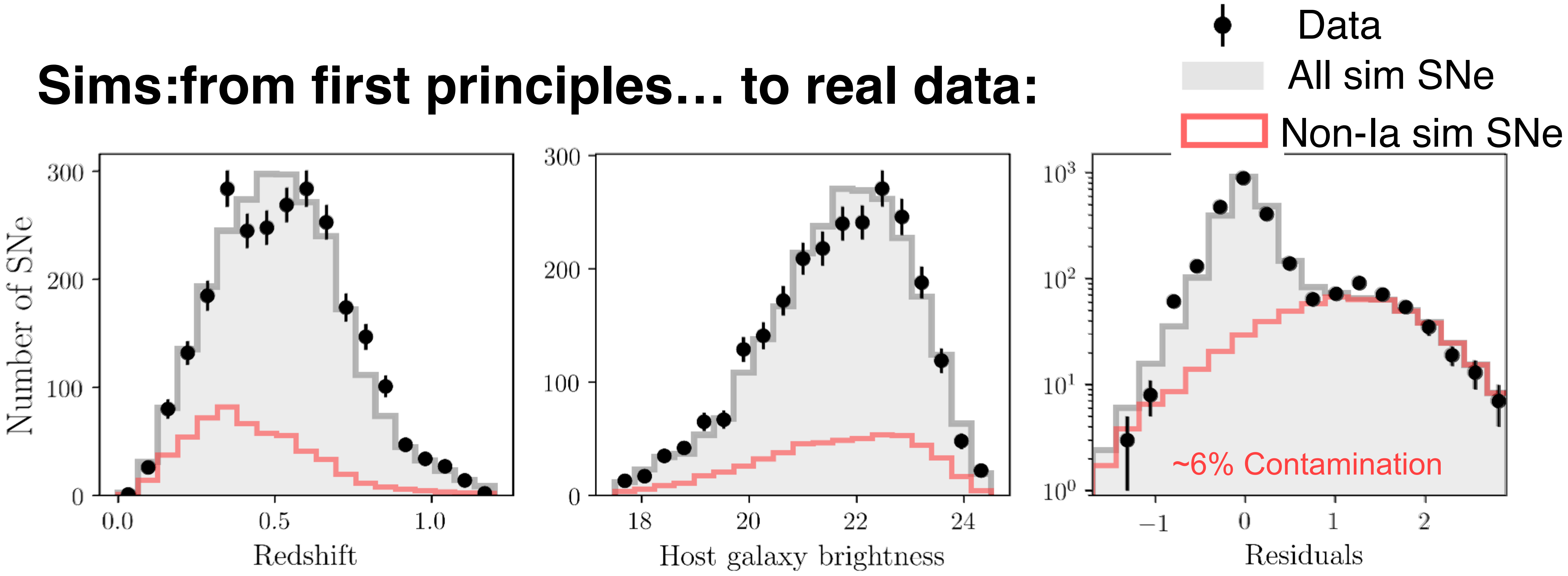
Classifiers **perform remarkably well:**
>98.5% purity
>99.0% efficiency

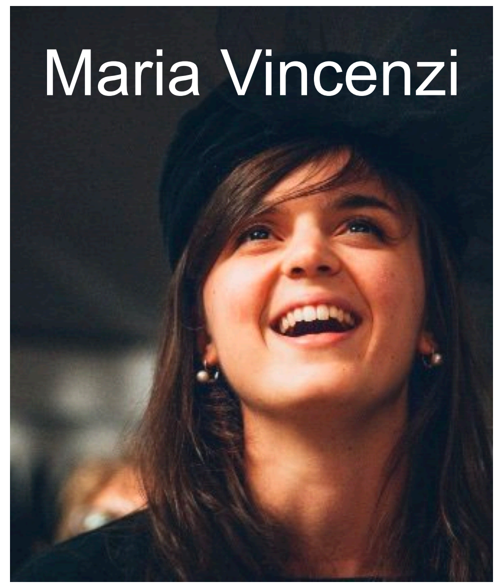
Modelling SN progenitors & dust extinction

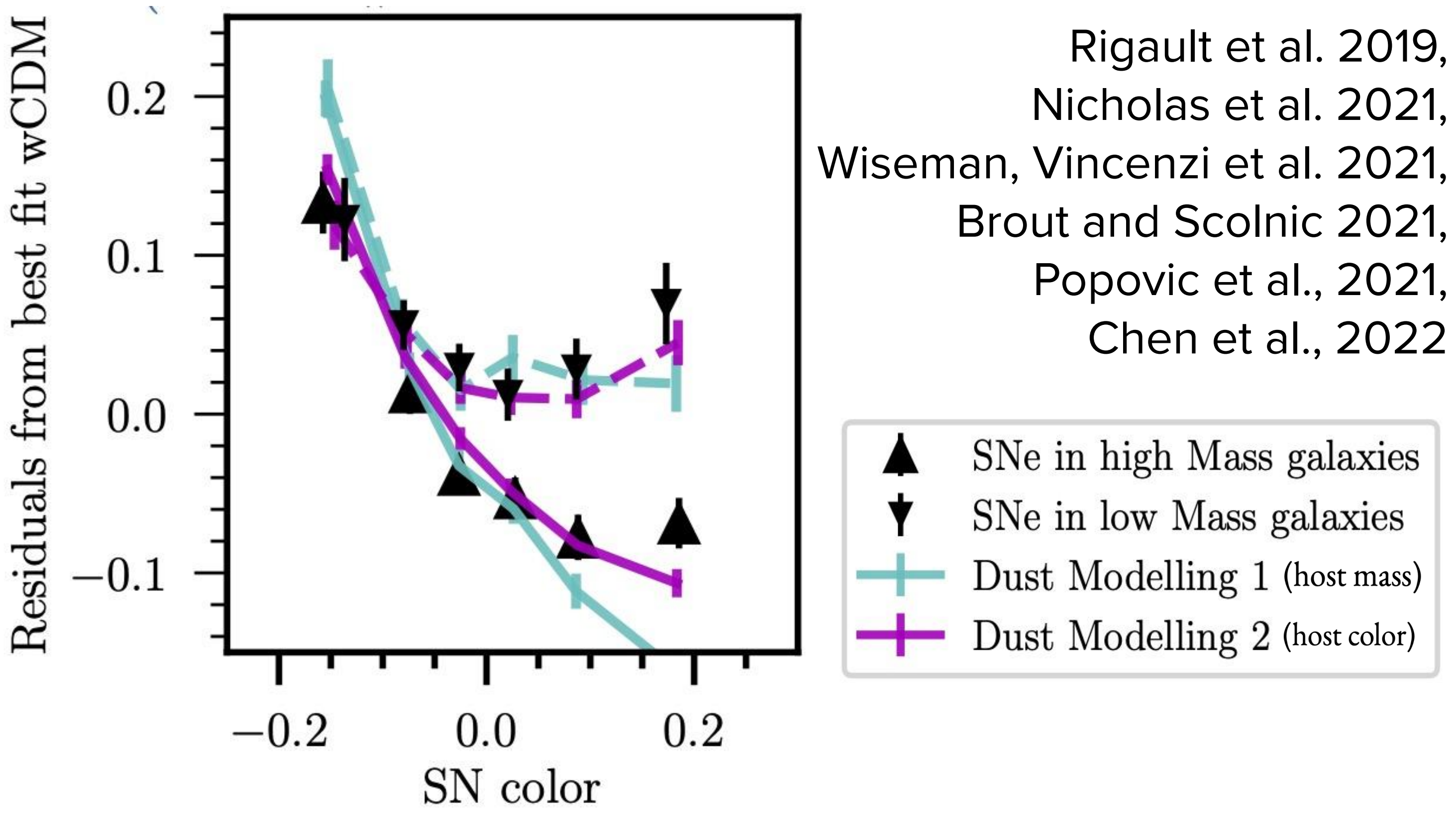
- Intrinsic origin: Modelling correlations between SN age / SN host / SN stretch
- Extrinsic origin: Modelling dust properties…



Sims:from first principles… to real data:

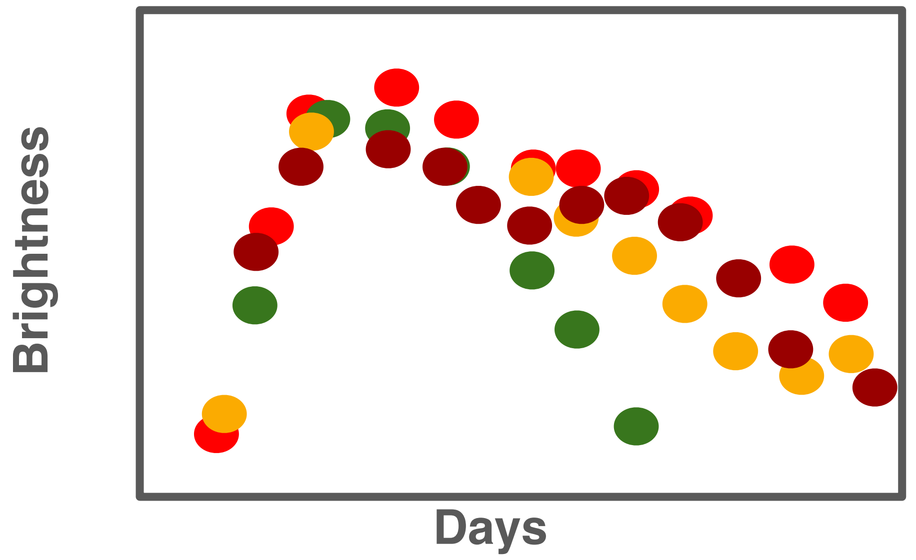


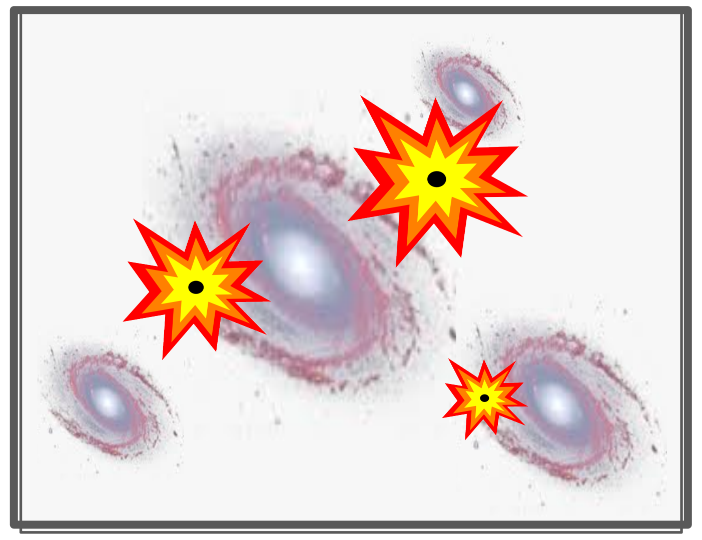


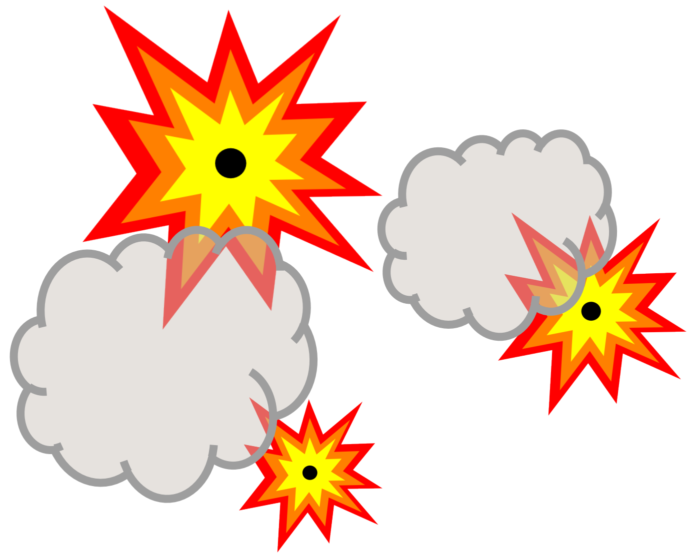


Rigault et al. 2019,
Nicholas et al. 2021,
Wiseman, Vincenzi et al. 2021,
Brout and Scolnic 2021,
Popovic et al., 2021,
Chen et al., 2022

DES Analysis Details







1. Building the Data Set: find SNe, **calibrate** photometry, get host redshifts

2. Simulating DES-SN5YR: samples that looks like the *observed* sample

3. Classify SNe Ia: Machine Learning

4. Modelling: SN dust, progenitors, physics

DES-SN5YR analysis overview

Data:
- Calibration (Burke et al. 2018, Brout et al. 2022, Rykoff et al. 2023)
- SN photometry (Brout et al. 2019, Sanchez et al. 2024)
- SN spectroscopy (Smith et al. 2020a)
- DCR and chrom (Lasker et al. 2018, Lee&Acevedo et al. 2023)
- Host galaxy redshifts and properties (Lidman et al. 2020, Carr et al. 2021, Wiseman et al. 2020/2021, Kelsey et al. 2023)

Simulations:
- Survey selection effects (Kessler et al. 2019a, Vincenzi et al. 2020)
- SN Ia intrinsic and dust properties (Brout&Scolnic 2021, Popovic et al. 2021a/b, Wiseman et al. 2022) and rates (Wiseman et al. 2021)
- Contamination (Vincenzi et al. 2019/2020, Kessler et al. 2019b)

Analysis:

Pipeline and Overview (Hinton et al. 2020, Vincenzi et al. 2024)
- Light-curve fitting (Taylor et al. 2023)
- SN classification (Möller & de Boissière 2020, Qu et al. 2021, Vincenzi et al. 2021, Moller et al. 2022)
- "BEAMS" and bias corrections (Kessler & Scolnic 2017), unbinning the SN Hubble diagram (Brout et al. 2020, Kessler et al. 2023)
- Effects of host galaxy mismatch (Qu et al. 2023)
- Cosmological contour validation (Armstrong et al. 2023)

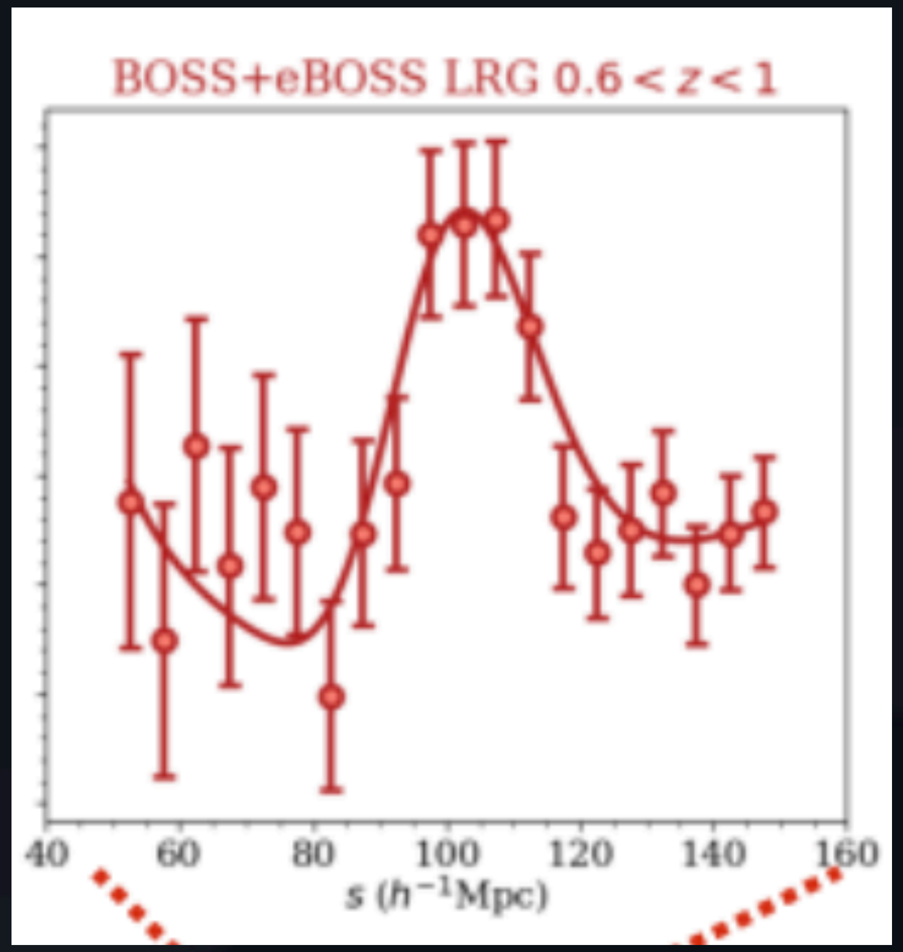
Cosmological results: DES Collaboration 2024

Testing non-standard cosmological models (Camilleri et al. 2024)

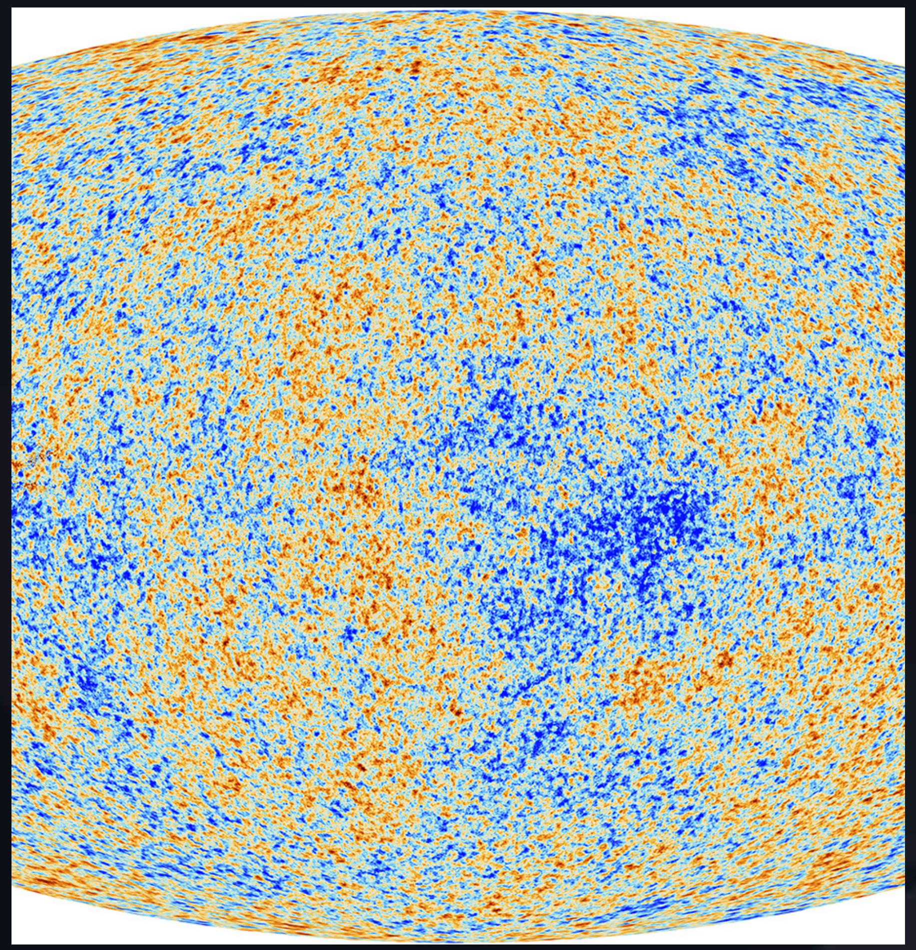
DES SN Cosmology Results

Combine with three probes

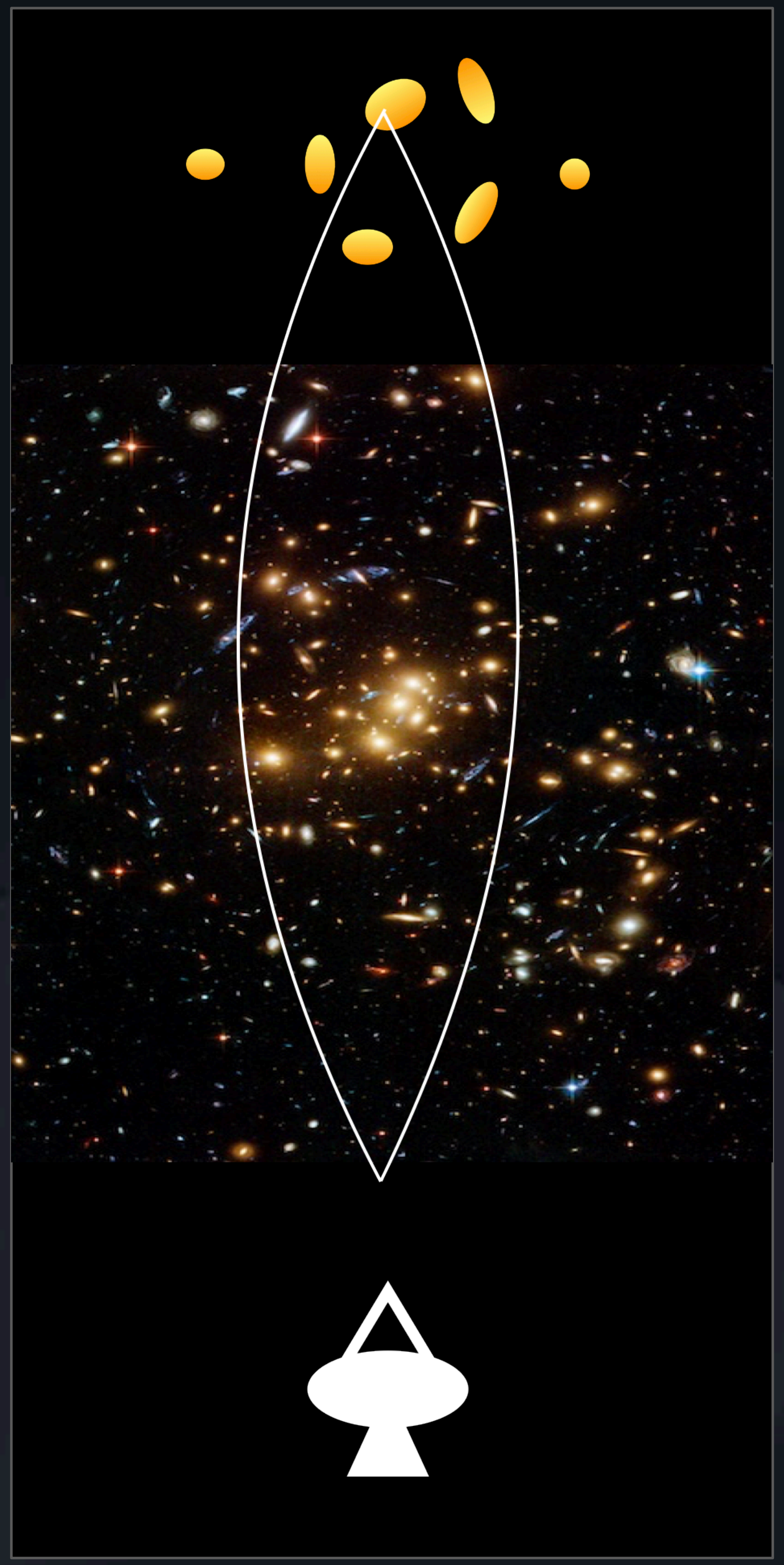
Baryon Acoustic Oscillations (BAO from SDSS)



Cosmic Microwave Background (CMB from Planck)



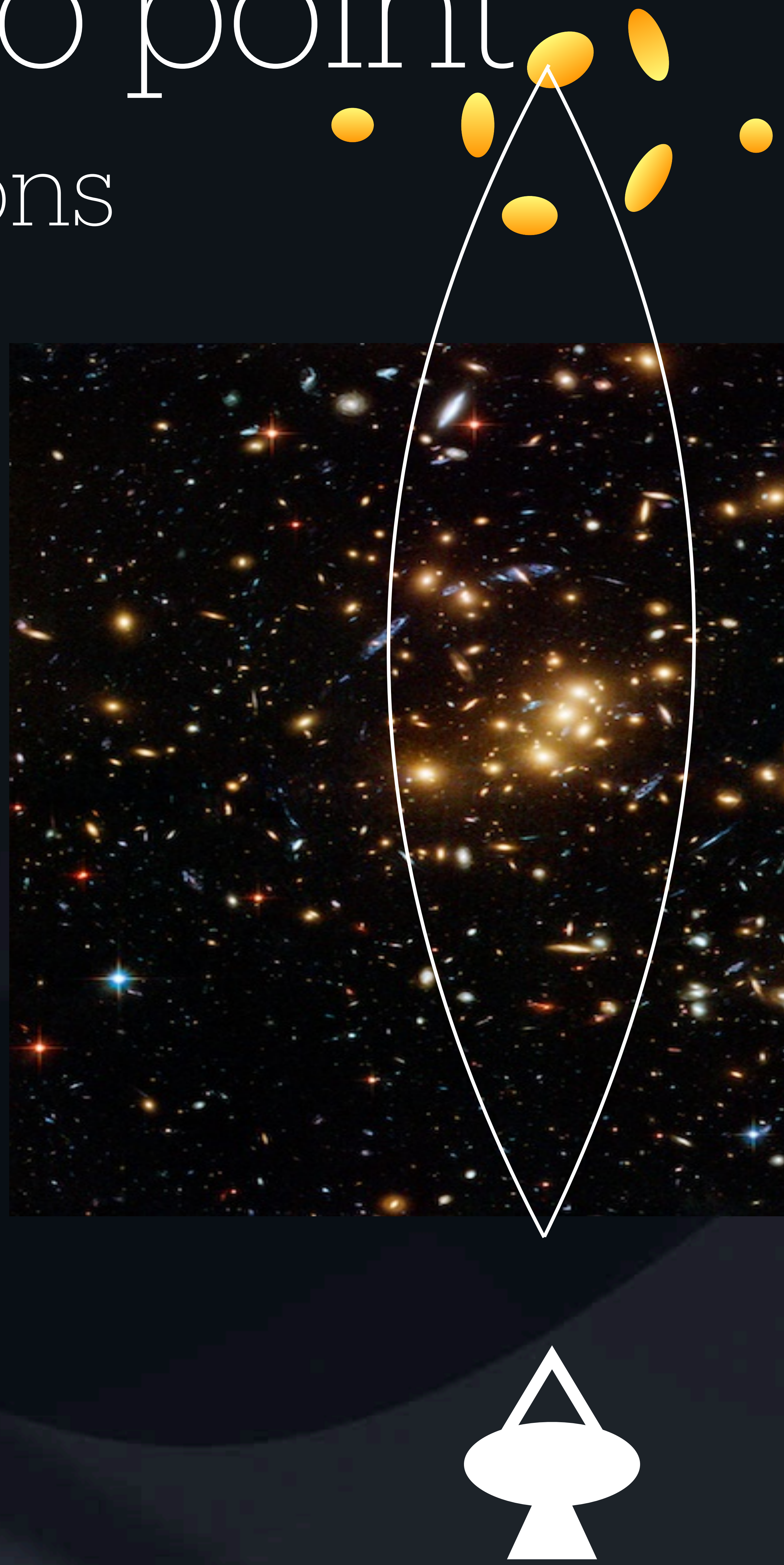
Two by three-point correlations (3x2pt from DES)



Alam et al. 2021; Planck 2020; DES 2023

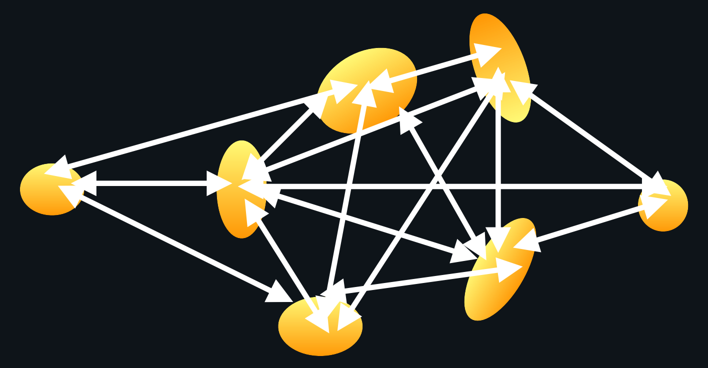
"Three by two point"

3 two-point correlations



“Three by two point”

3 two-point correlations

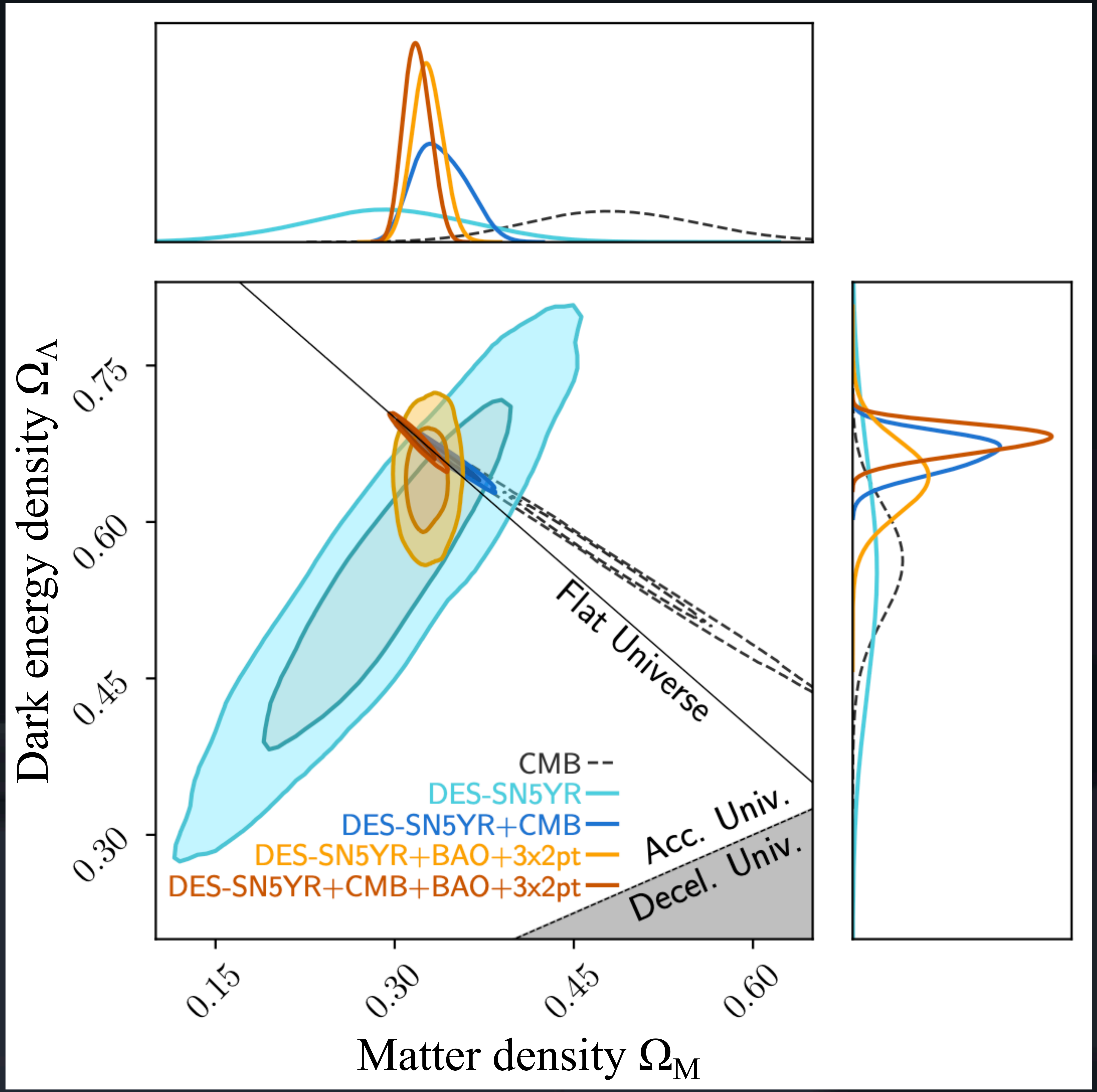


galaxy-galaxy

galaxy-lens

lens-lens

DES SN Cosmology Results: ΛCDM



DES-SN alone

$$\Omega_M = 0.291^{+0.063}_{-0.065}$$

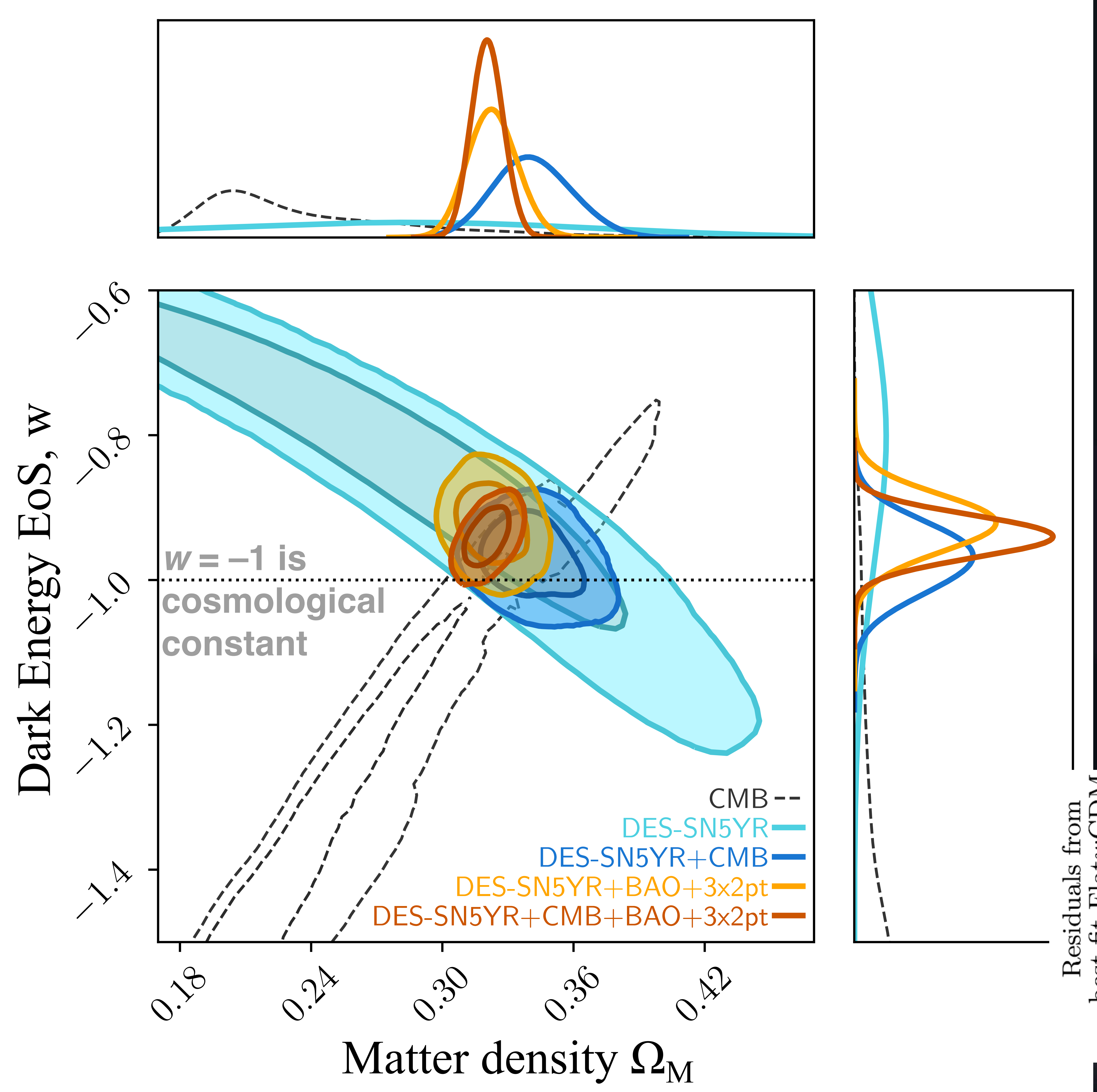
$$\Omega_k = 0.16 \pm 0.16$$

DES5YR + CMB + BAO + 3x2pt

$$\Omega_M = 0.327^{+0.026}_{-0.032}$$

$$\Omega_k = 0.010 \pm 0.005$$

DES SN Cosmology Results: ΛCDM

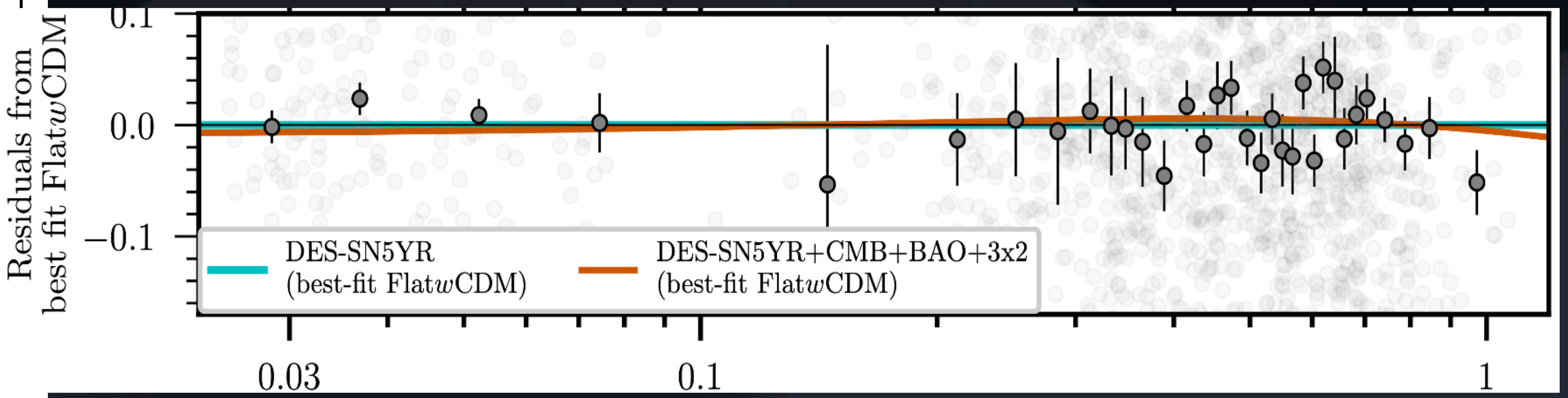


DES-SN alone

$w = -0.80^{+0.14}_{-0.16}$

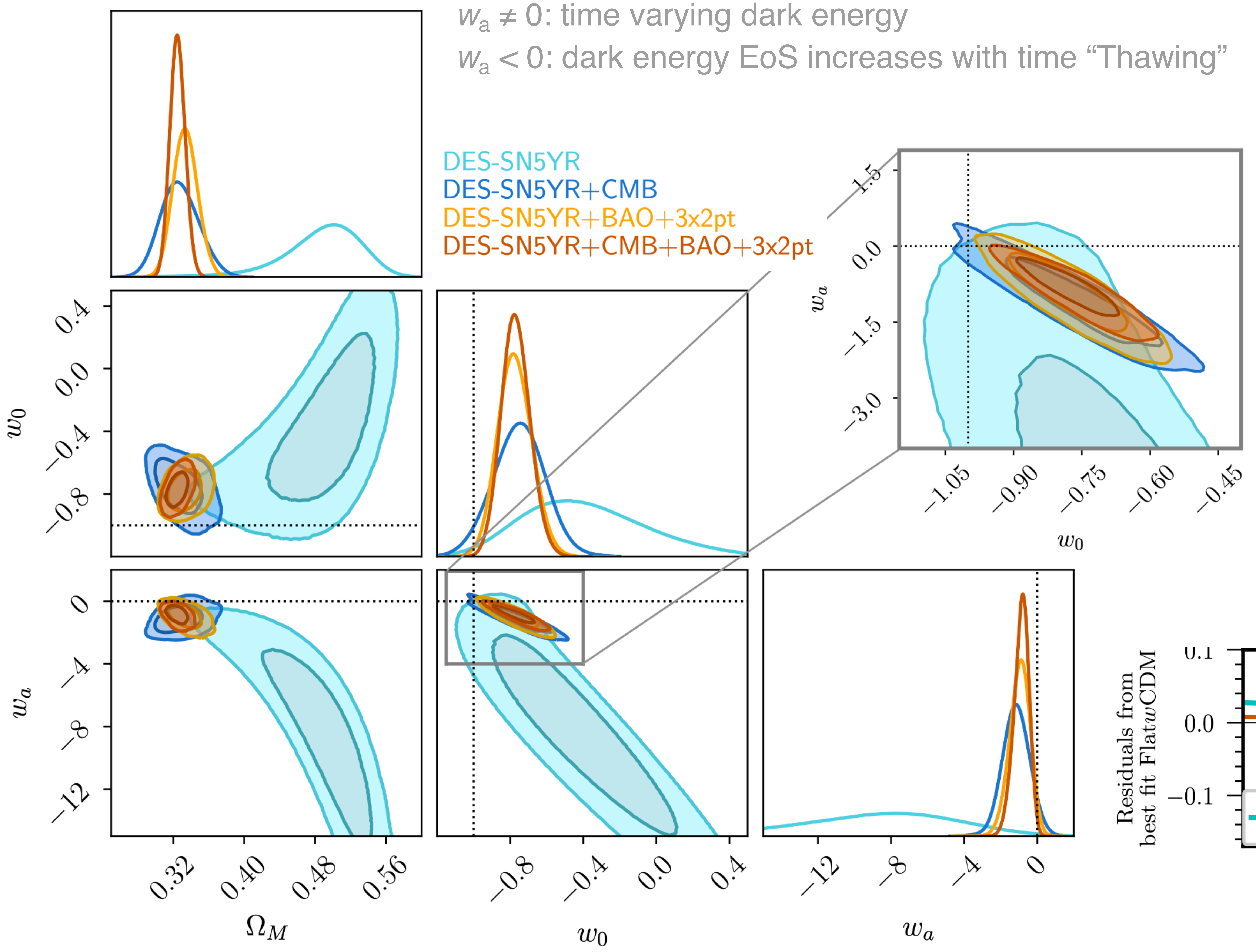
DES5YR + CMB + BAO + 3x2pt

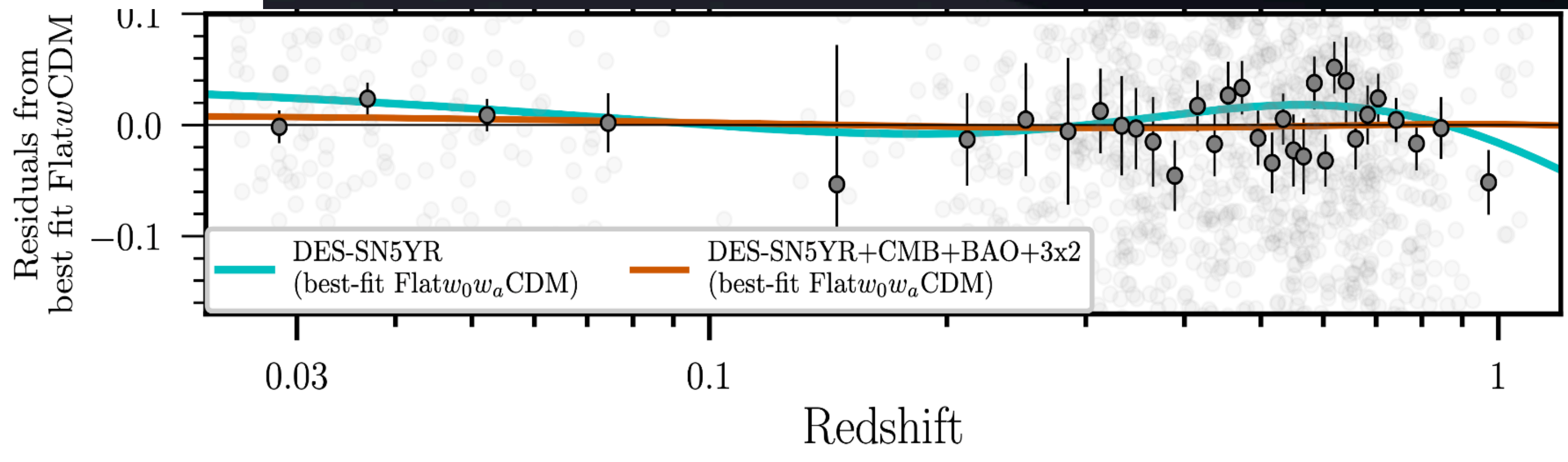
$w = 0.941 \pm 0.026$



DES SN Cosmology Results: ΛCDM

$w_a \neq 0$: time varying dark energy
$w_a < 0$: dark energy EoS increases with time “Thawing”





DES-SN alone

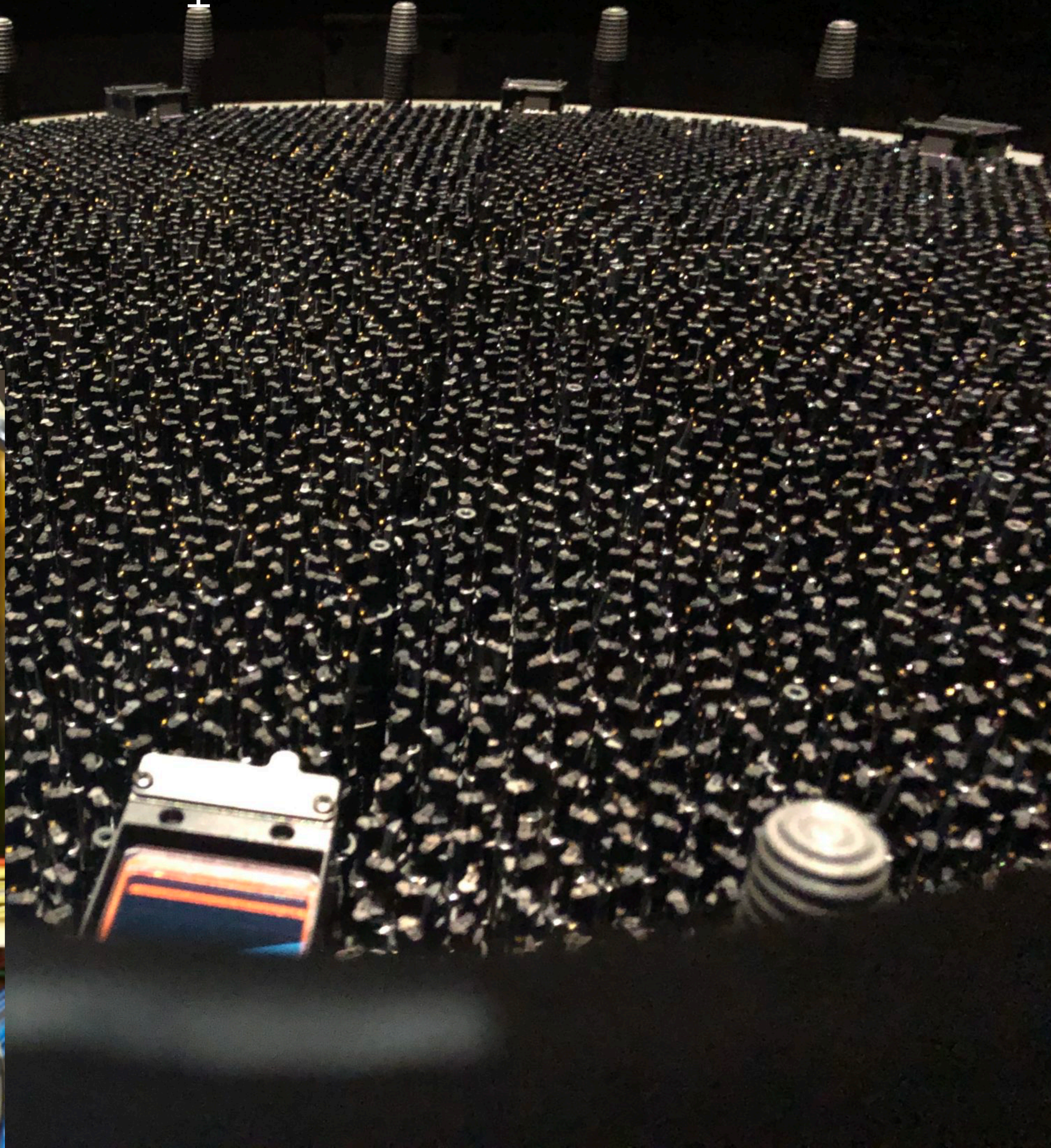
$w_a = -8.8^{+3.7}_{-4.5}$ (>2σ less than 0)

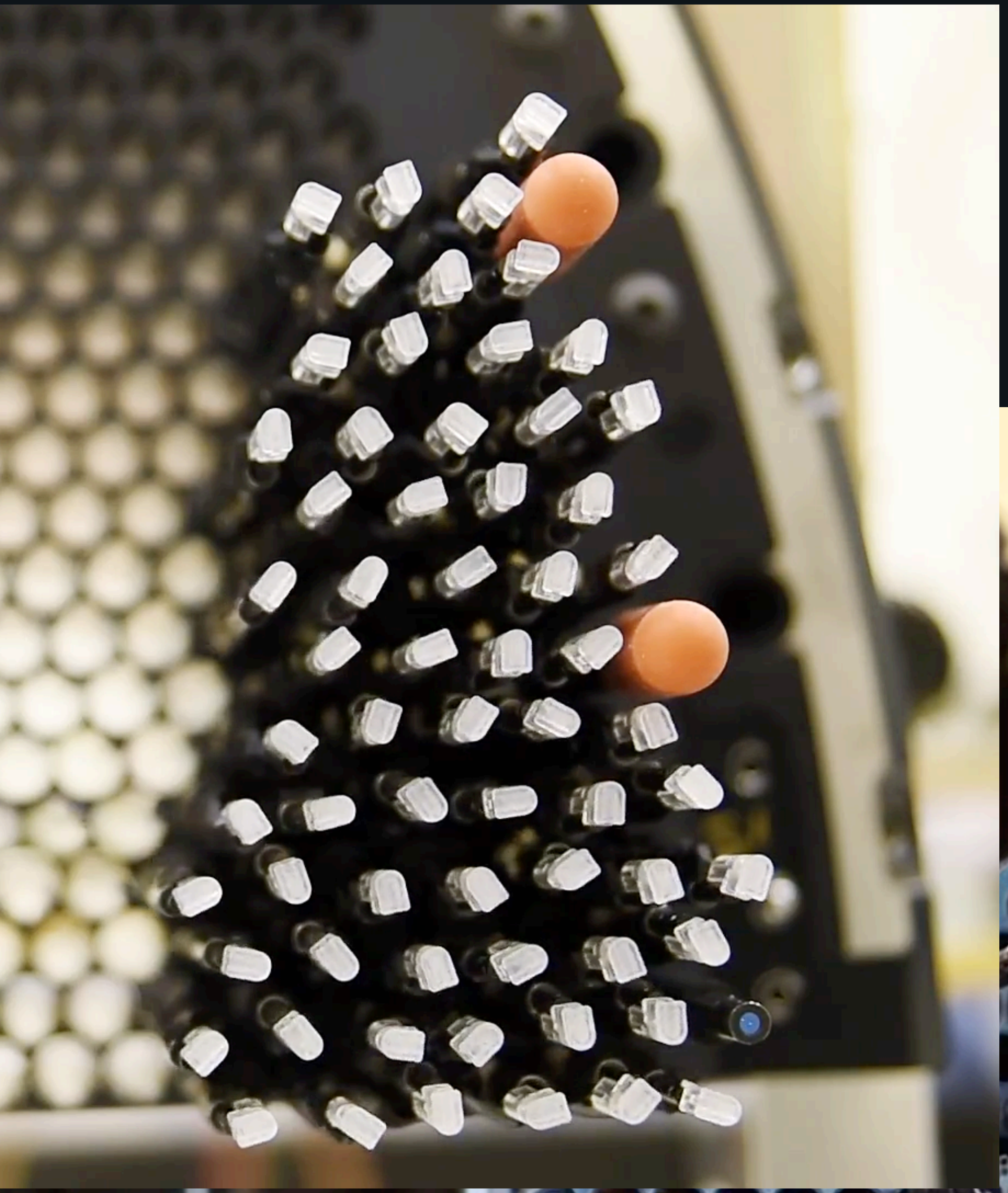
DES5YR + CMB + BAO + 3x2pt

$w_a = -0.83^{+0.33}_{-0.42}$ (>2 less than 0)

The Dark Energy Spectroscopic Instrument

DESI (different to DES!)



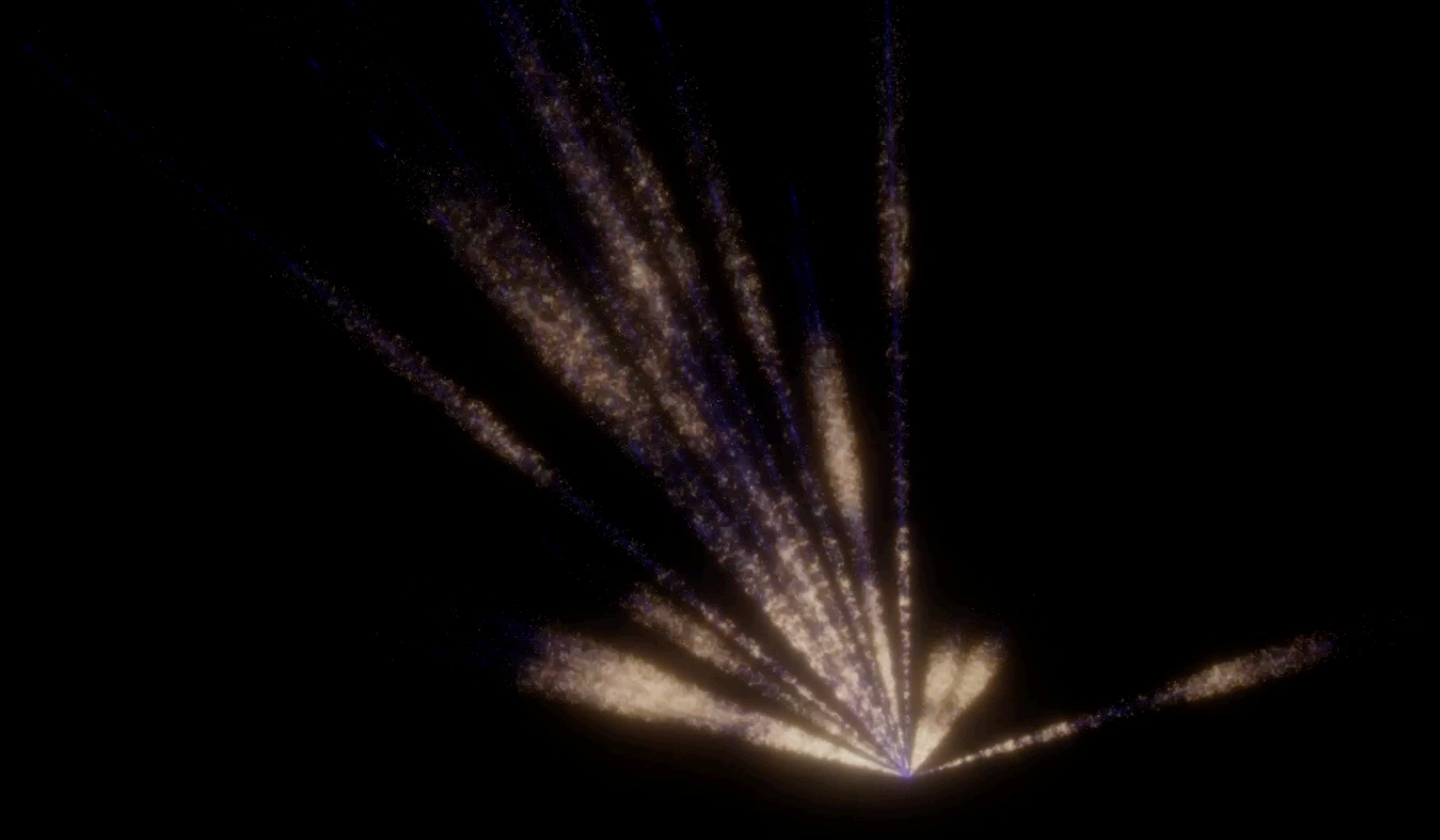


From: www.legacysurvey.org --- check it out yourself!

From: www.legacysurvey.org --- check it out yourself!

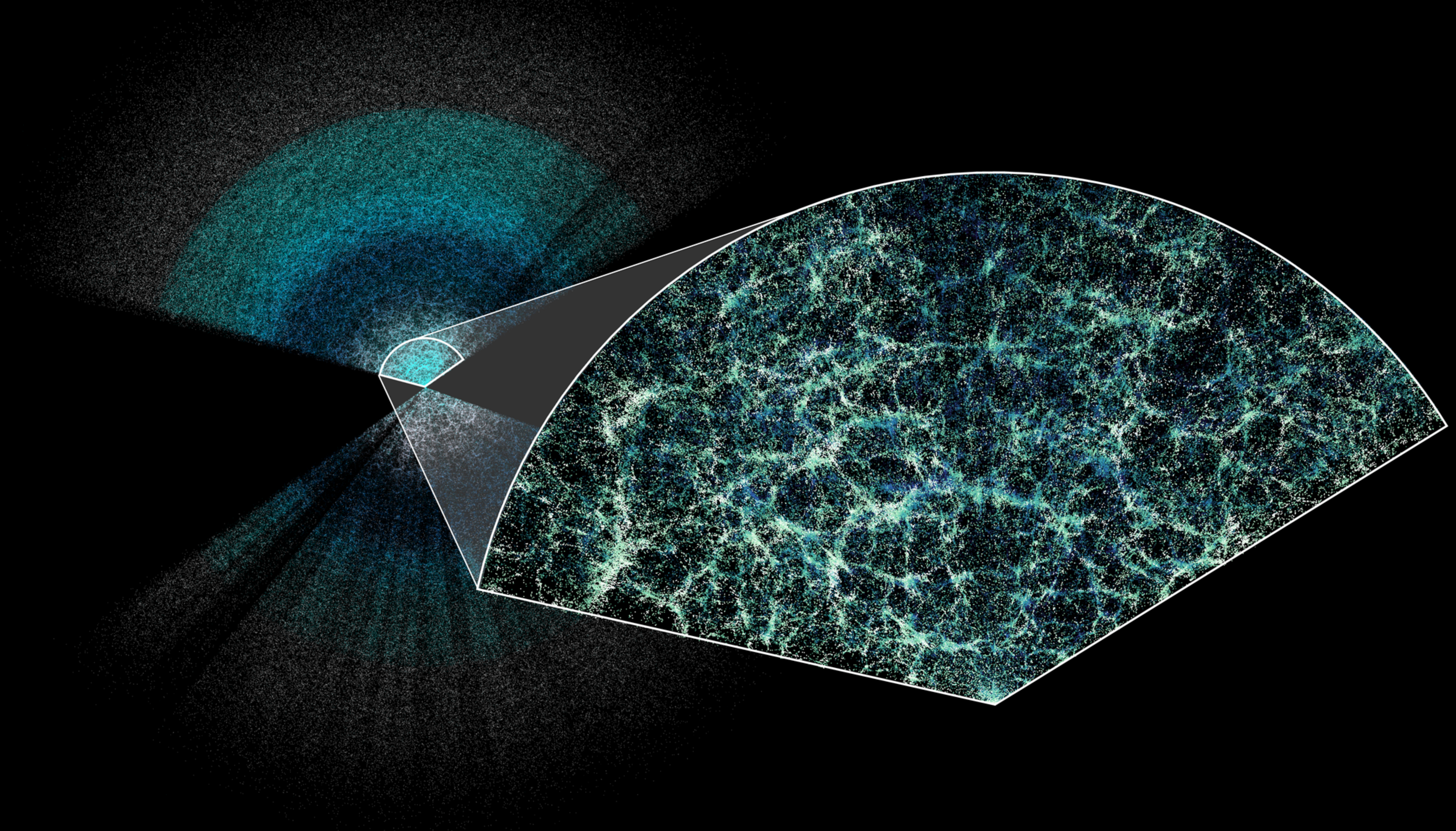
DESI focal plane

DESI FIRST DATA RELEASE - 2 MILLION OBJECTS!



DESI Early Data Release: 1% Survey

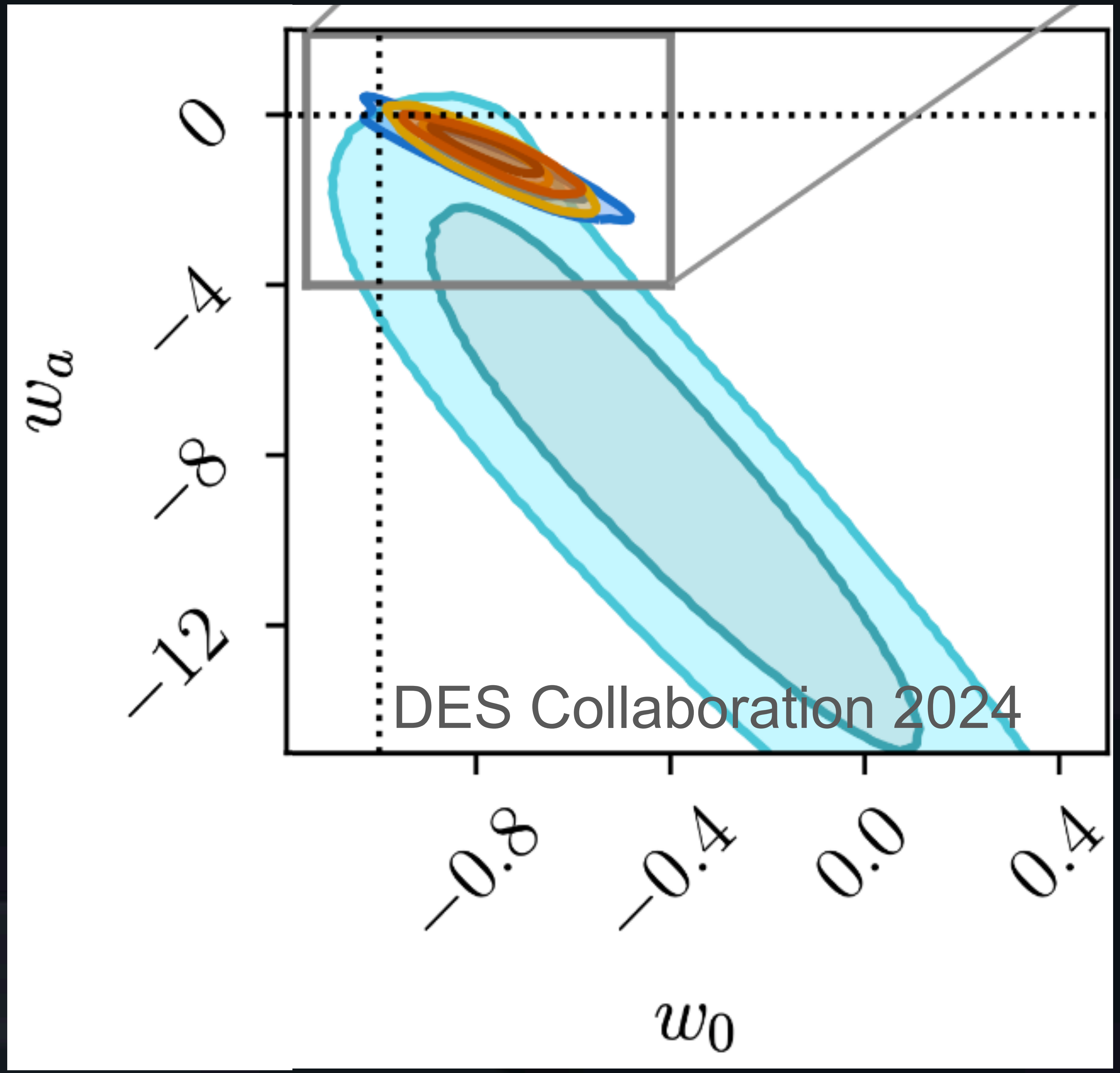
DESI SUPPORTS DES

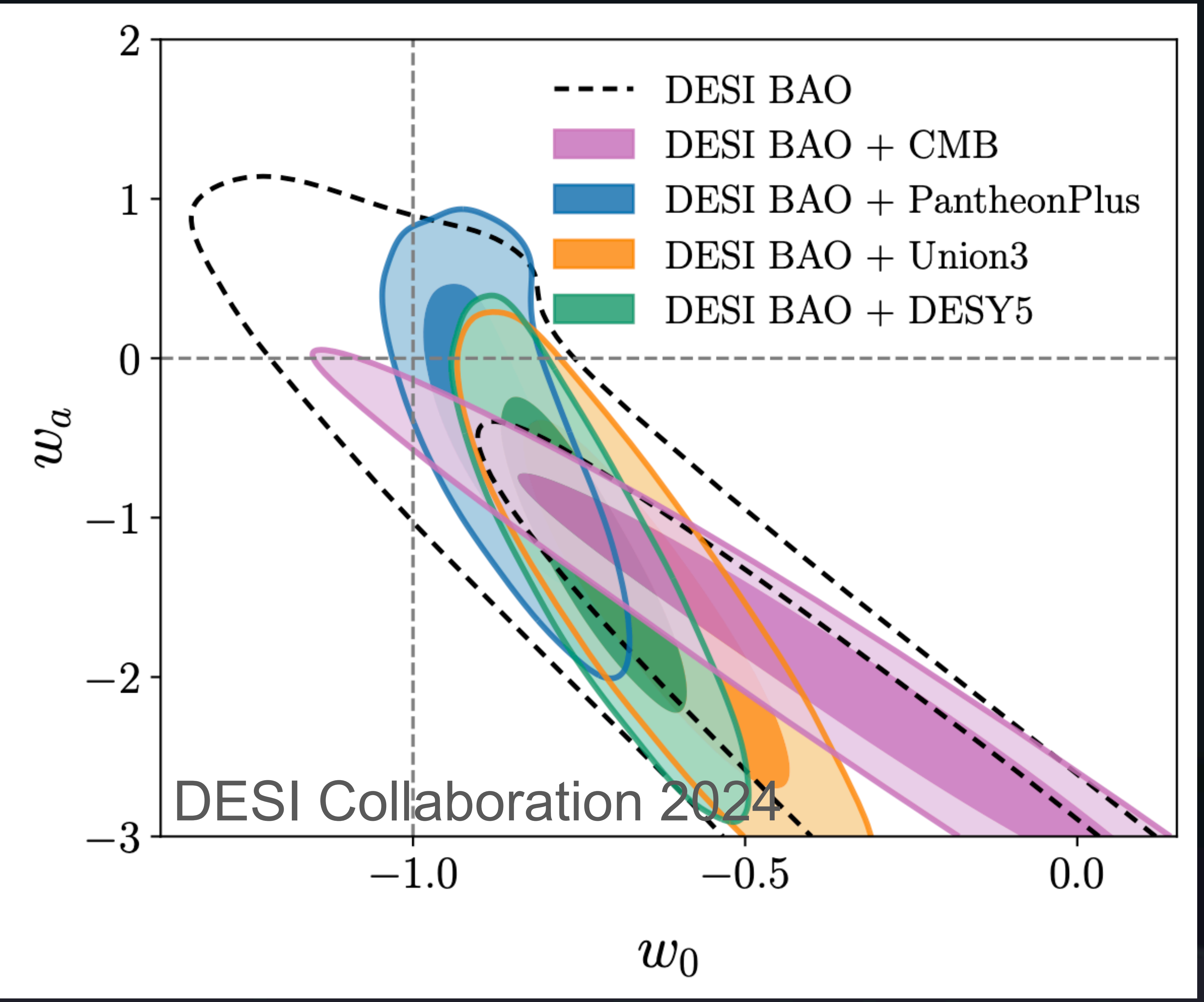


Already mapped more than 10 million galaxies

April 2024: DESI supports DES!

DESI finds similar result for w_a





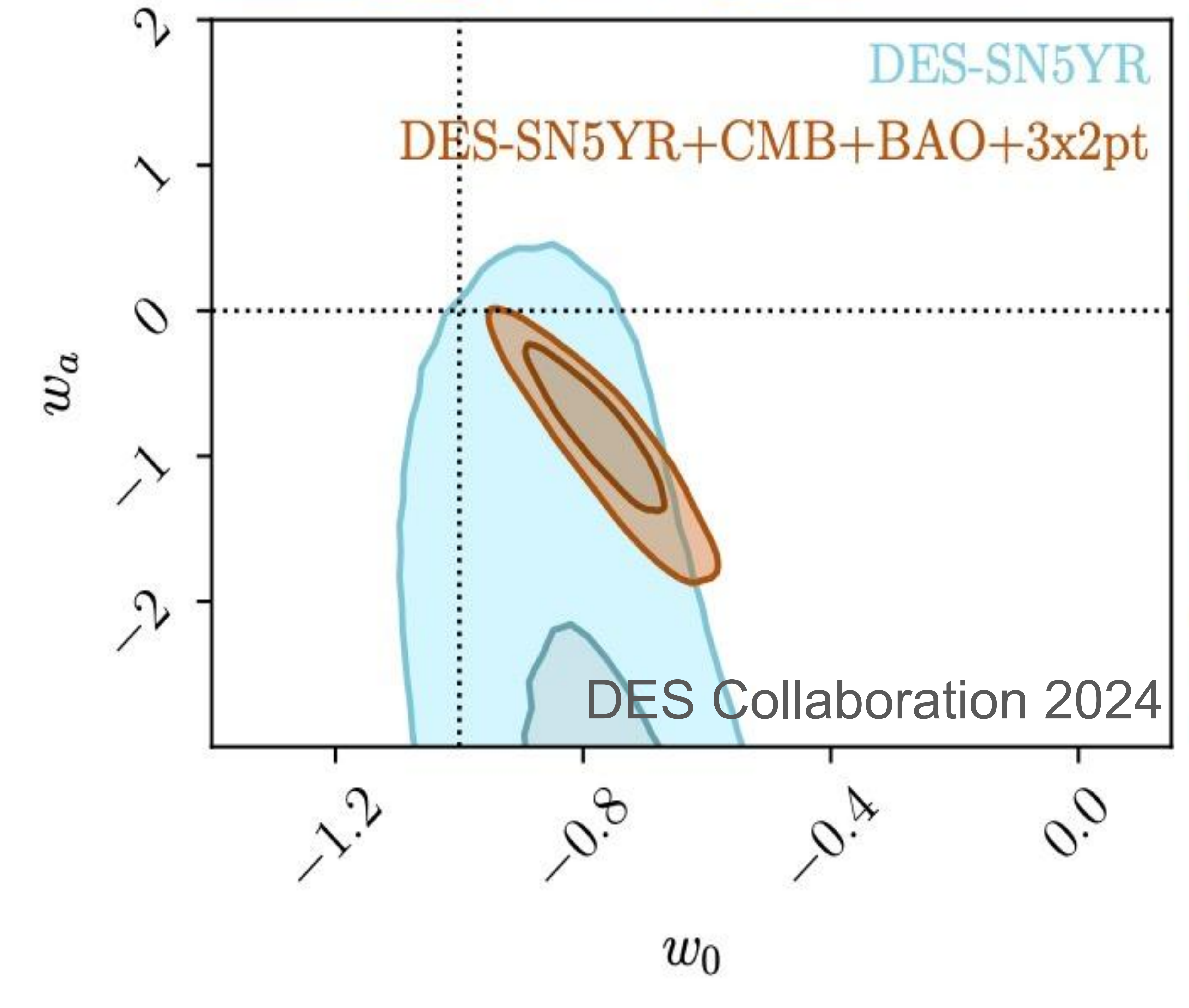
DES: $w_a = -8.8^{+3.7}_{-4.5}$

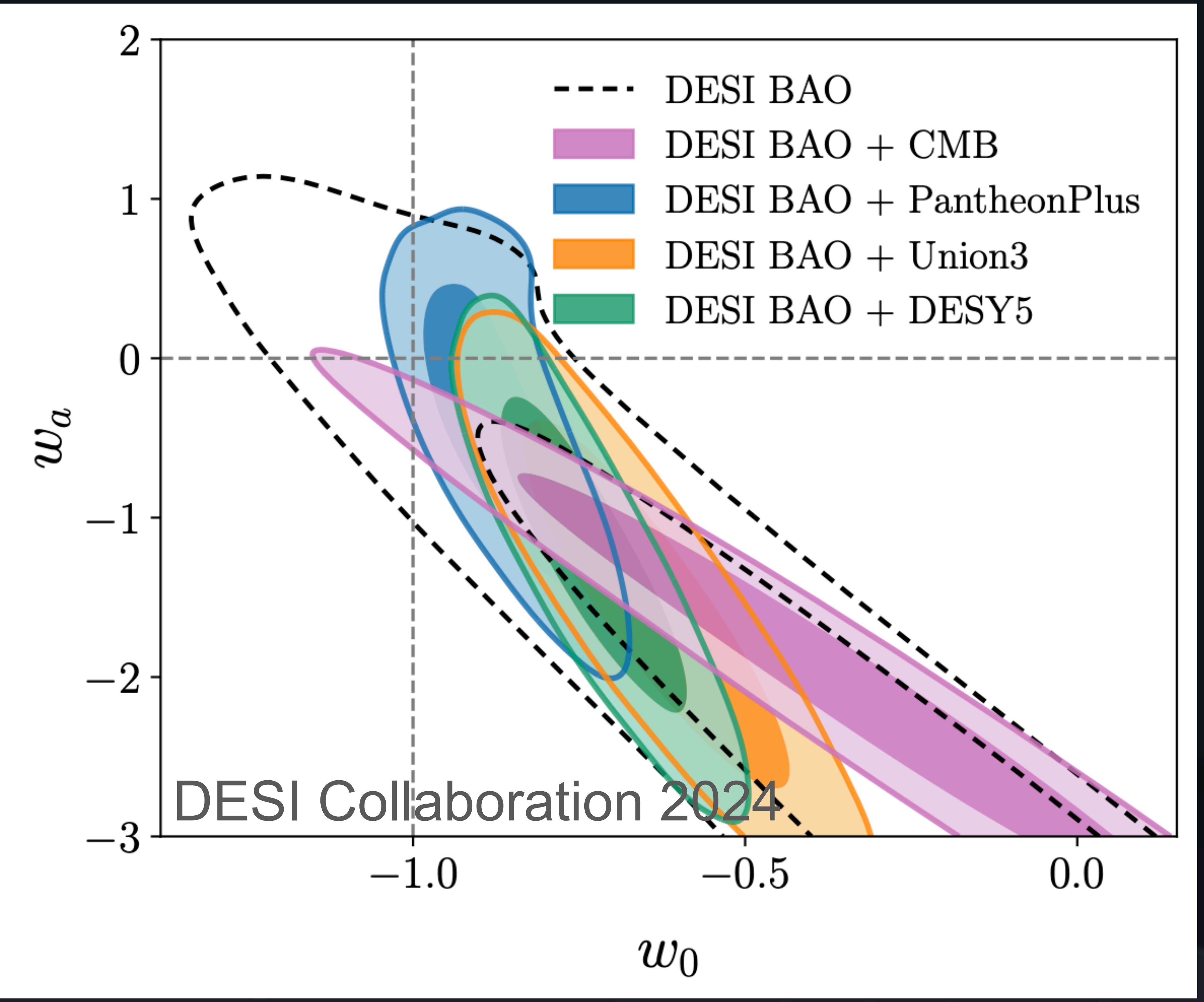
DESI: $w_a < -1.32$

DES+DESI+CMB: $w_a = -1.05^{+0.31}_{-0.27}$ **(>3 less than 0)**

April 2024: DESI supports DES!

DESI finds similar result for w_a





DES: $w_a = -8.8^{+3.7}_{-4.5}$

DESI: $w_a < -1.32$

DES+DESI+CMB: $w_a = -1.05^{+0.31}_{-0.27}$ **(>3 less than 0)**

The New York Times

Argh! I hate these kinds of headlines!!

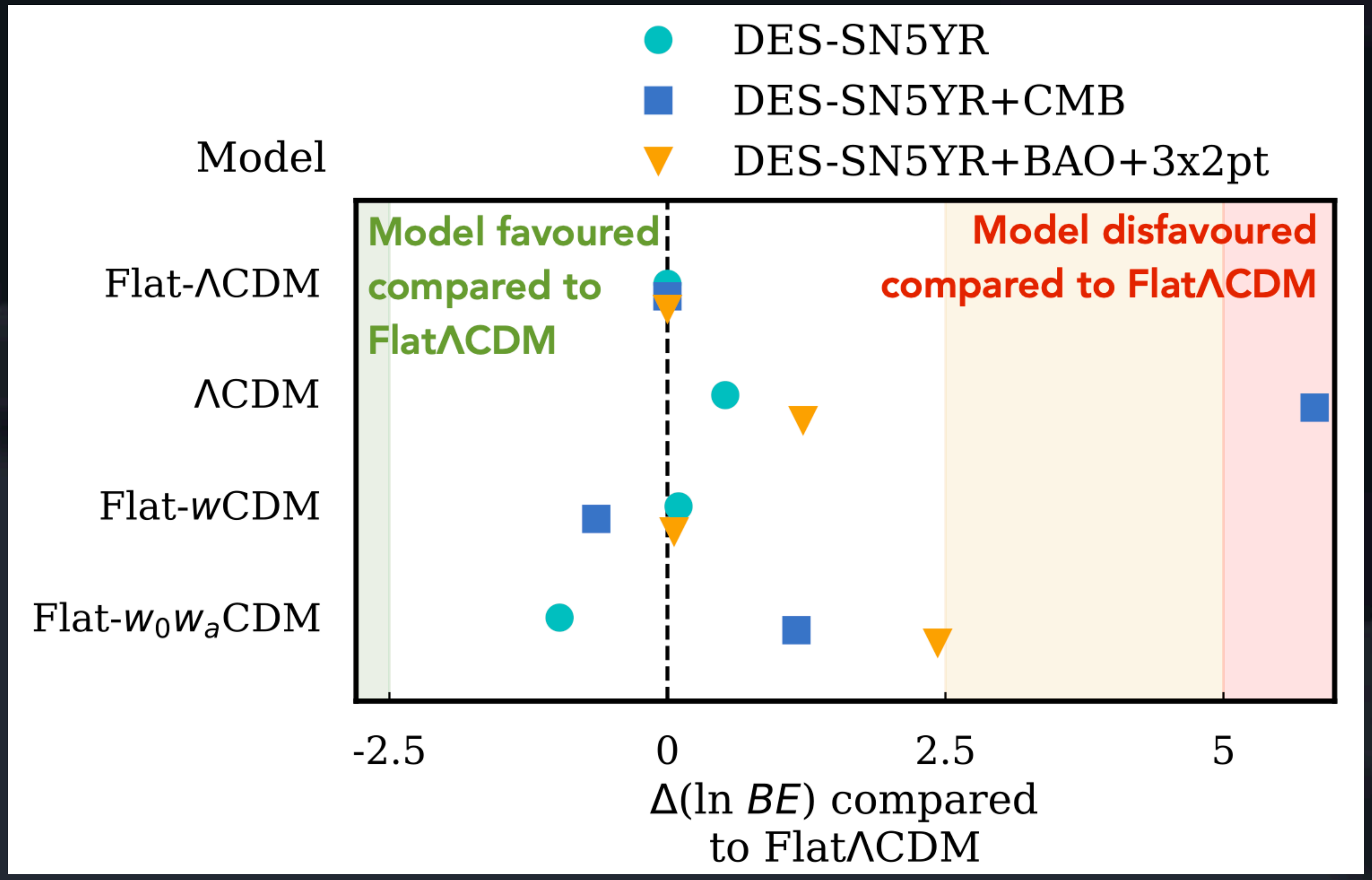
A Tantalizing 'Hint' That Astronomers Got Dark Energy All Wrong

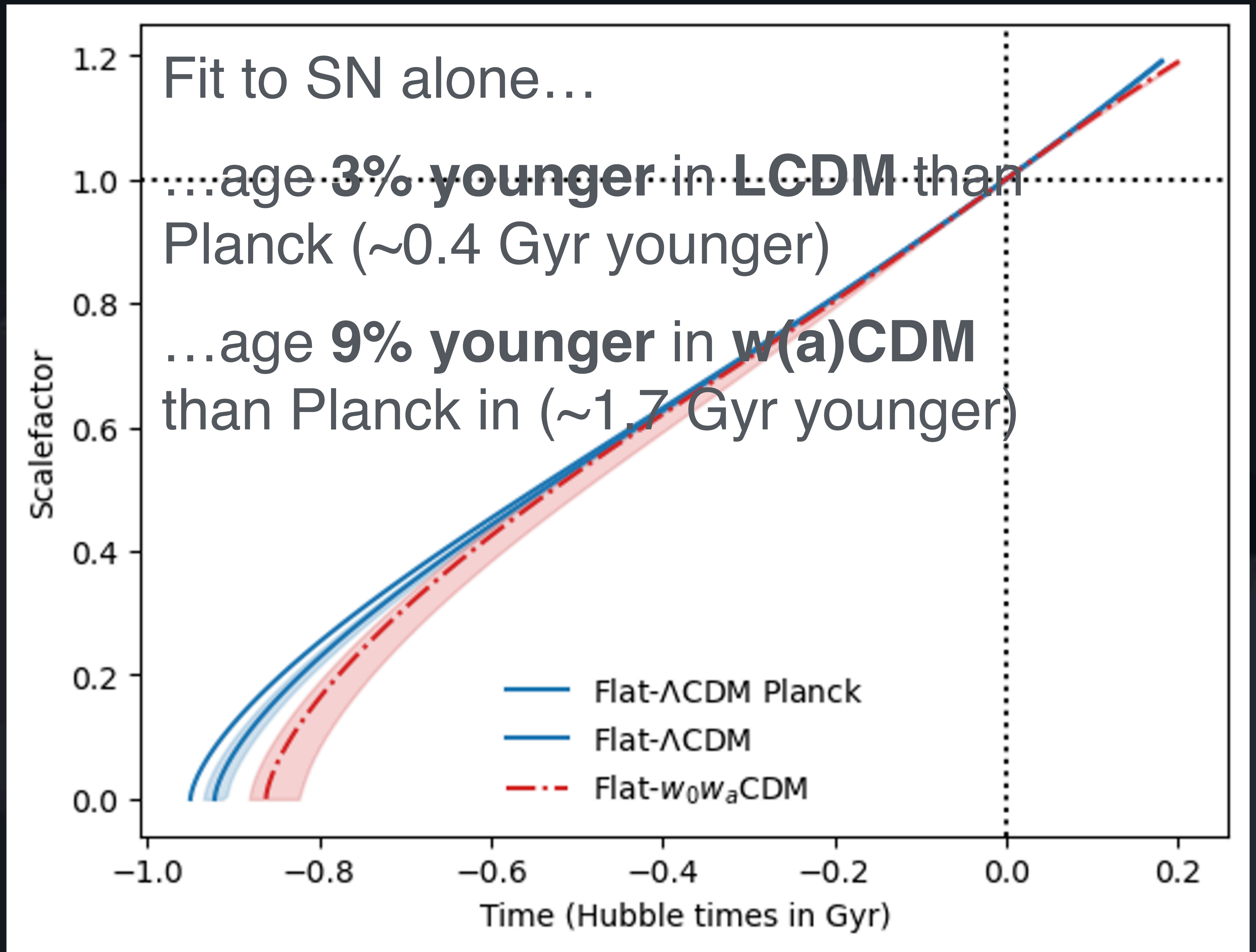
Scientists may have discovered a major flaw in their understanding of that mysterious cosmic force. That could be good news for the fate of the universe.

"As Biden would say, it's a B.F.D.," said Adam Riess, an astronomer at Johns Hopkins University and the Space Telescope Science Institute in Baltimore. He shared the 2011 Nobel Prize in Physics with two other astronomers for the discovery of dark energy, but was not involved in this new study. "**It may be the first real clue we have gotten about the nature of dark energy in 25 years,**" he said.

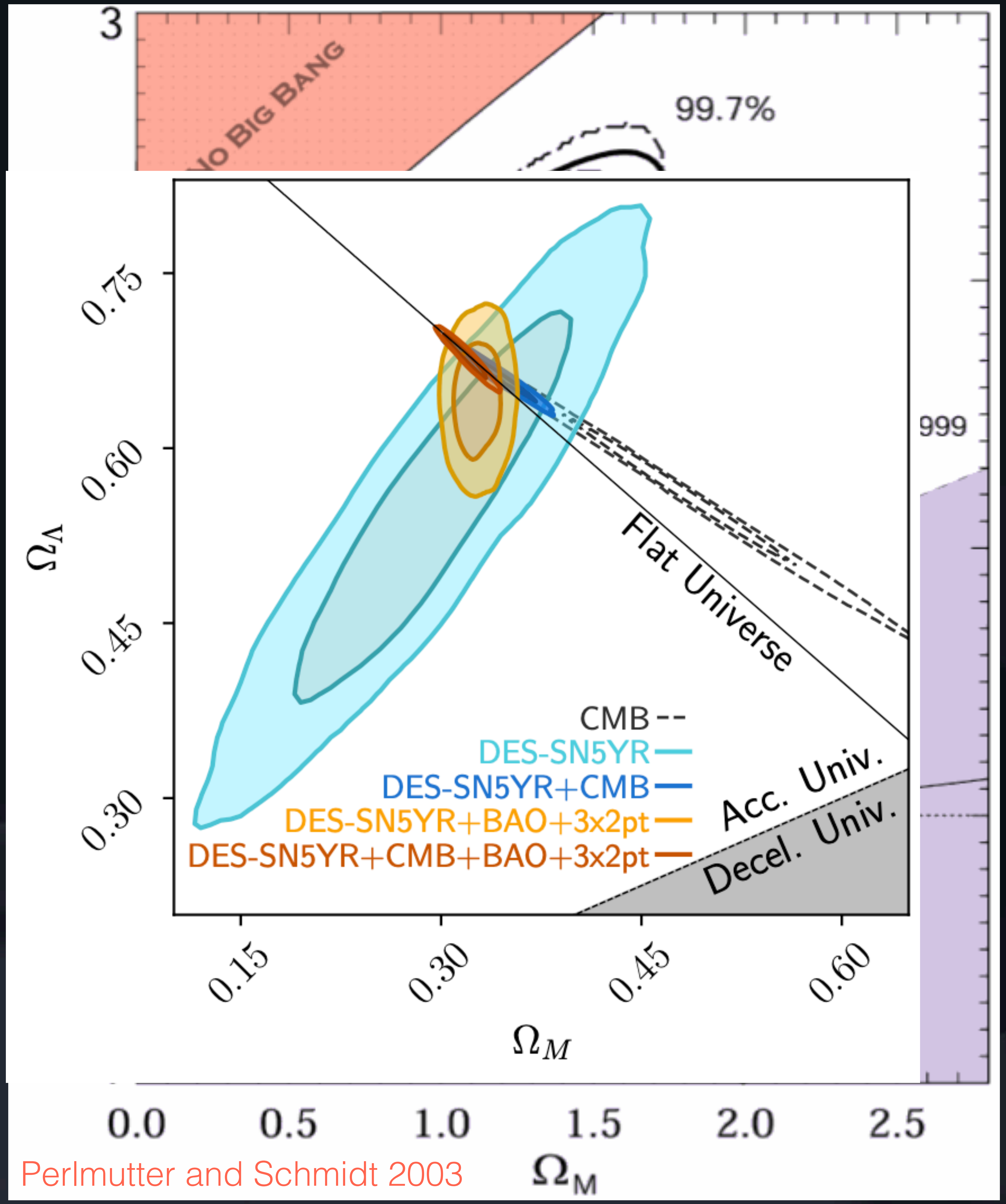
The Big Questions

- Is the Universe accelerating? **Yes!**
- Is dark energy a cosmological constant? **Maybe…** (but it's not the best fit)
- How old is the Universe? **Slightly younger than we thought?**
- Does this solve the Hubble Tension? **No.**



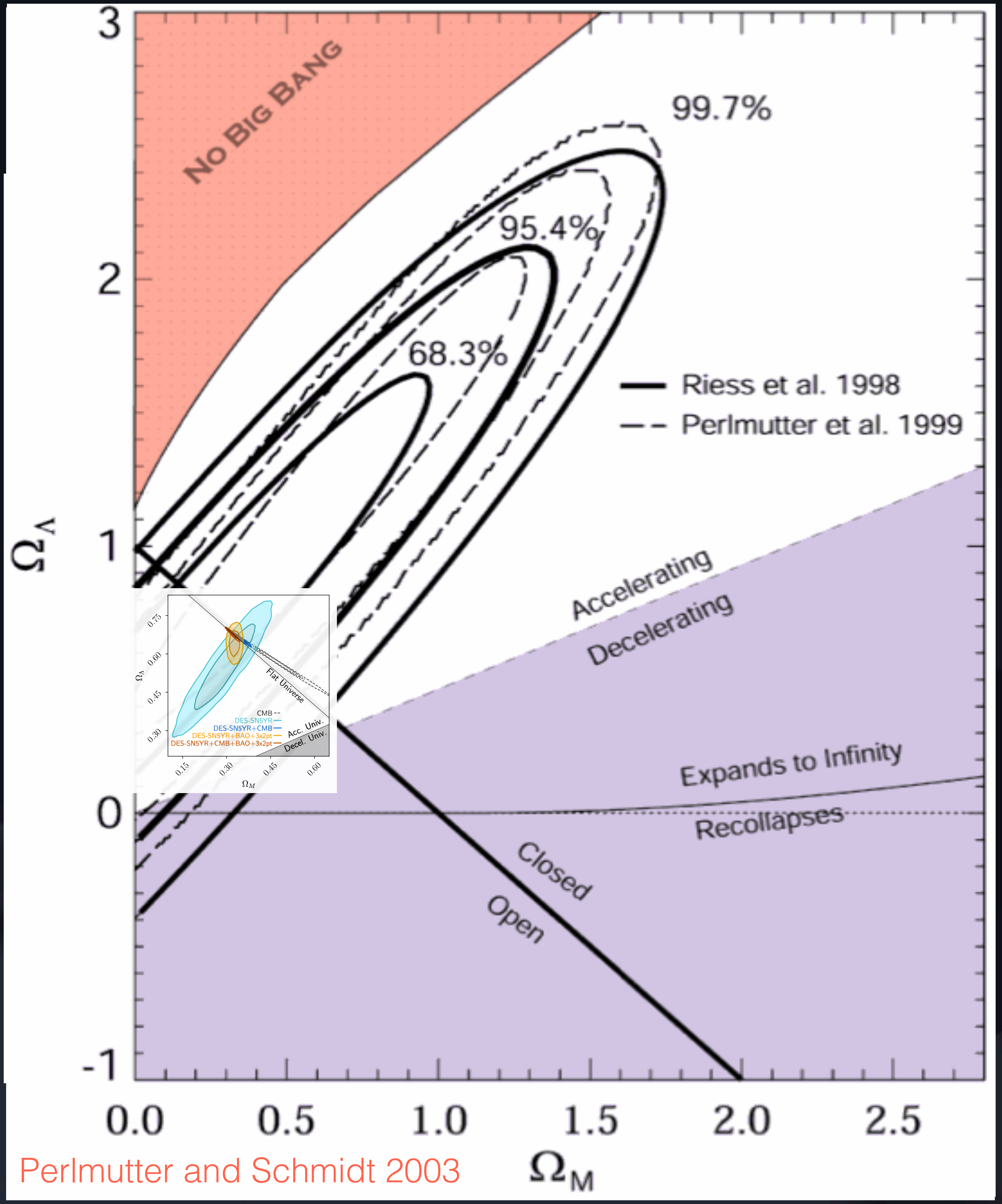


How far have we come?

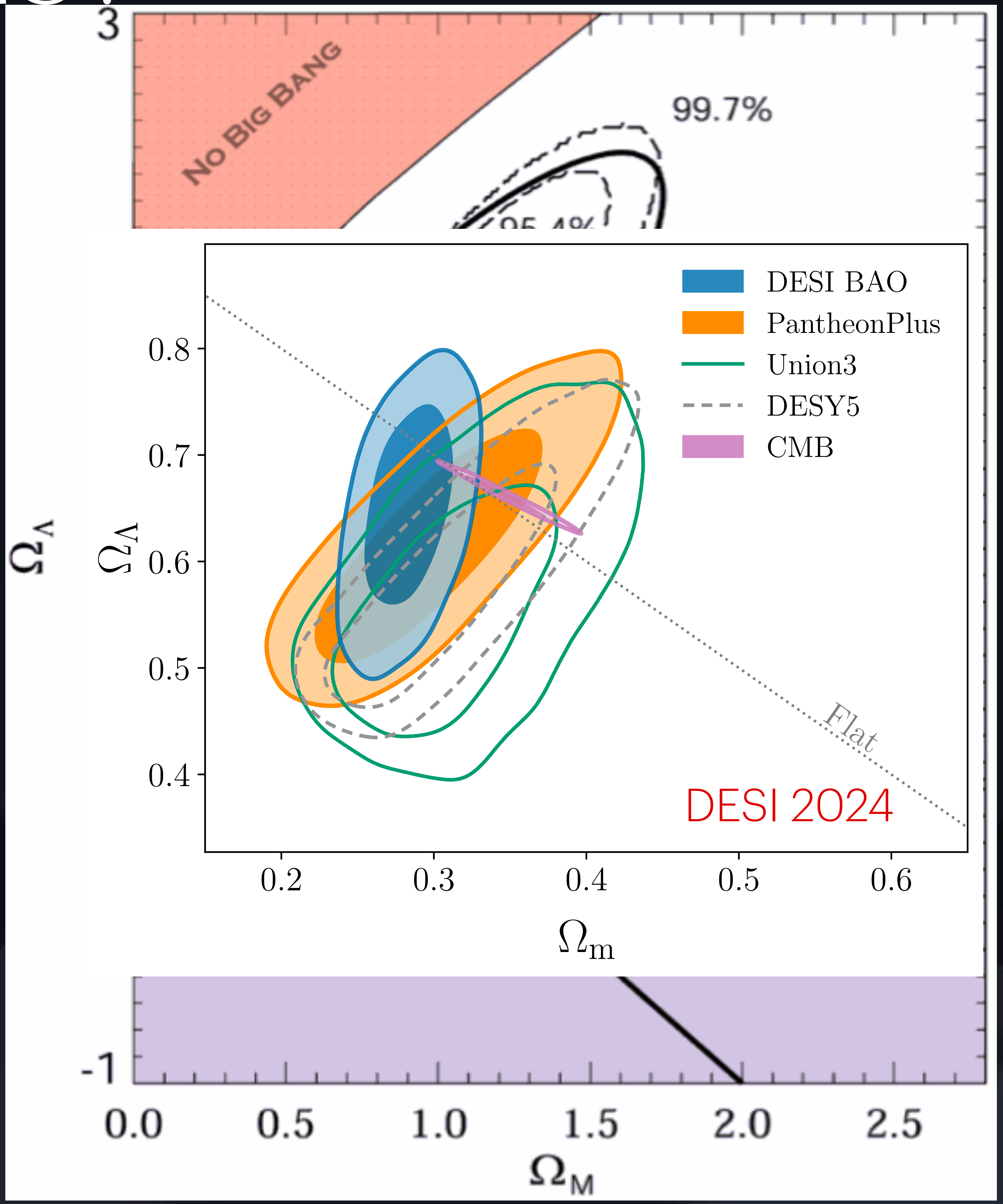


Perlmutter and Schmidt 2003

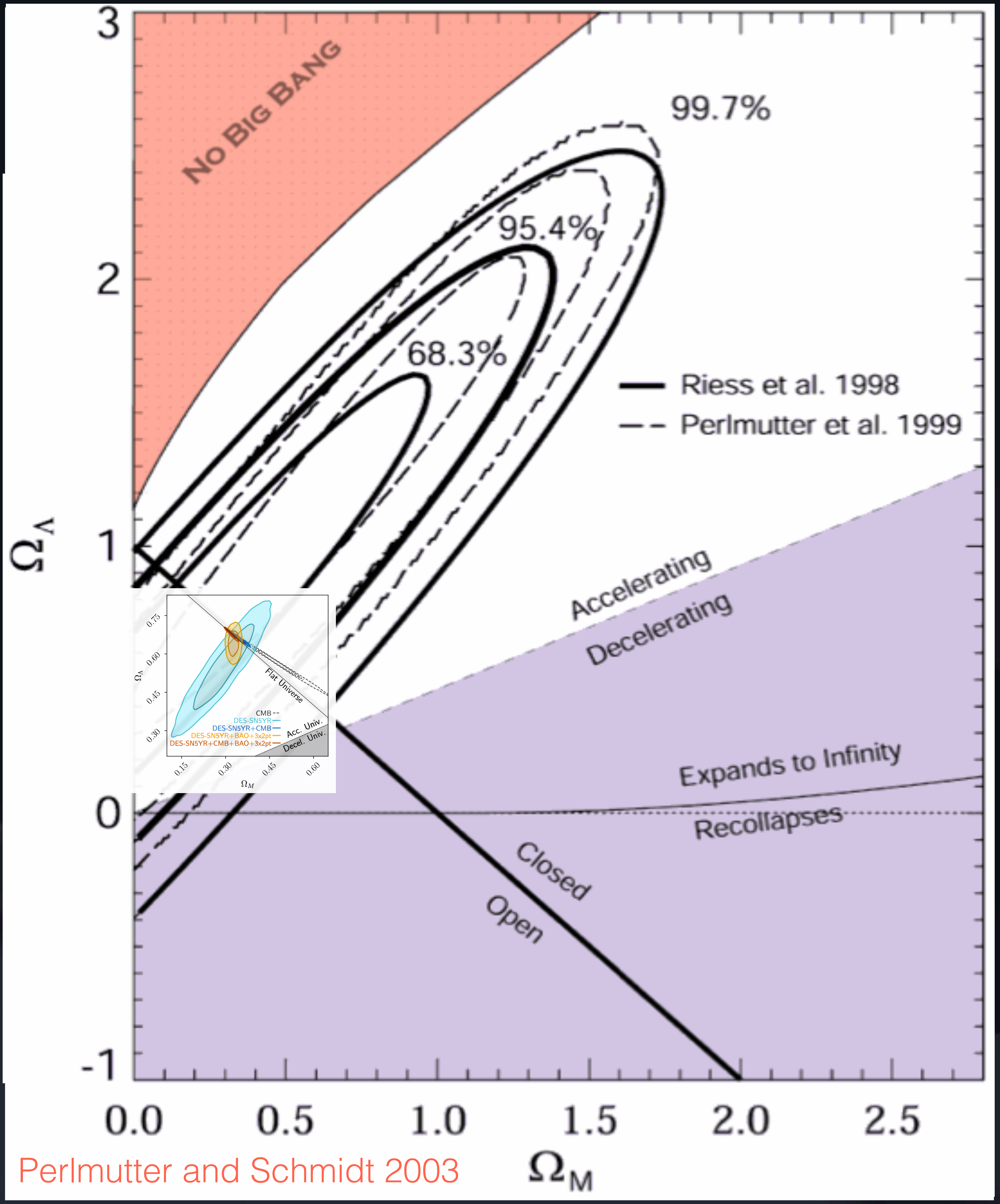
How far have we come?



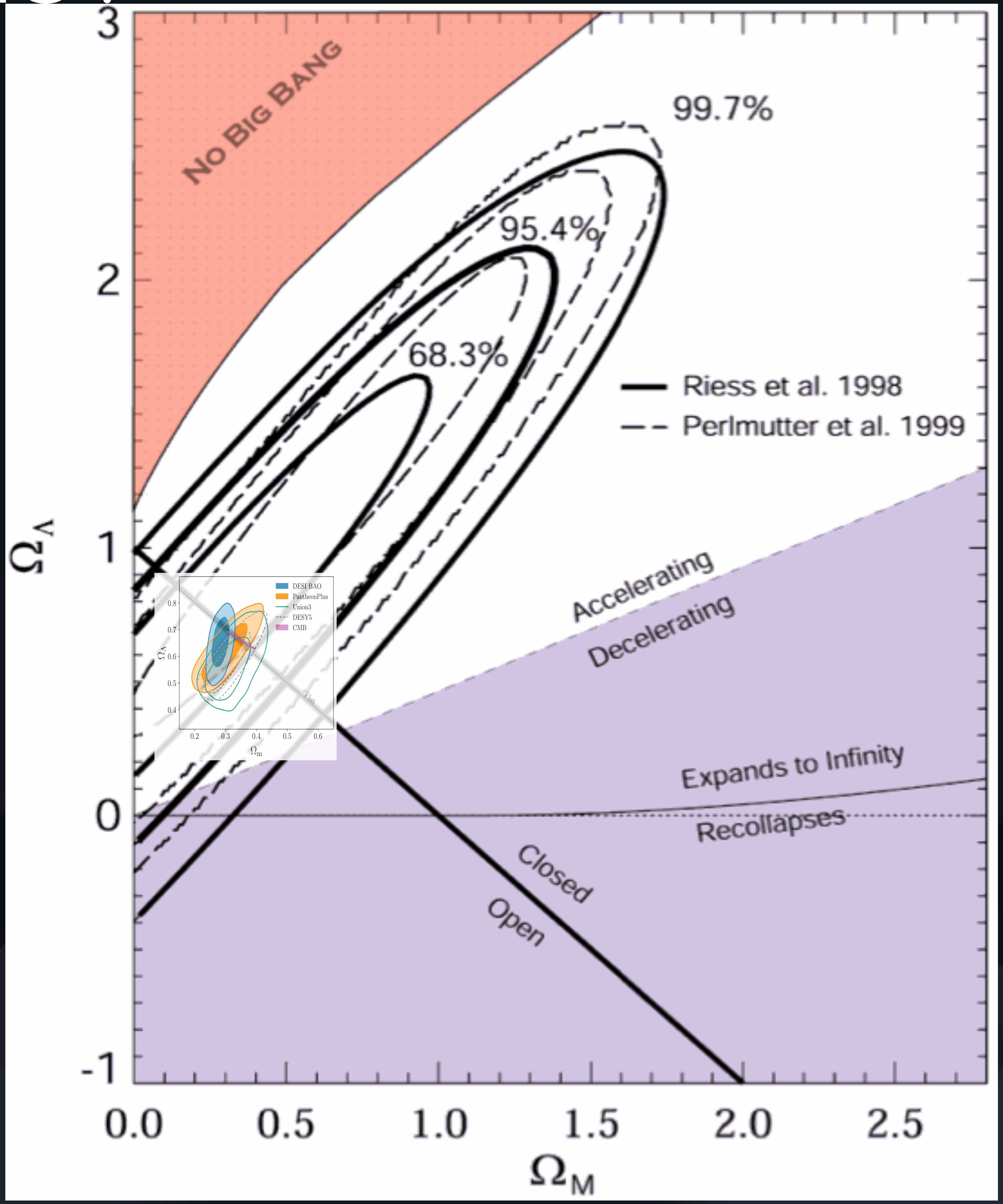
Perlmutter and Schmidt 2003



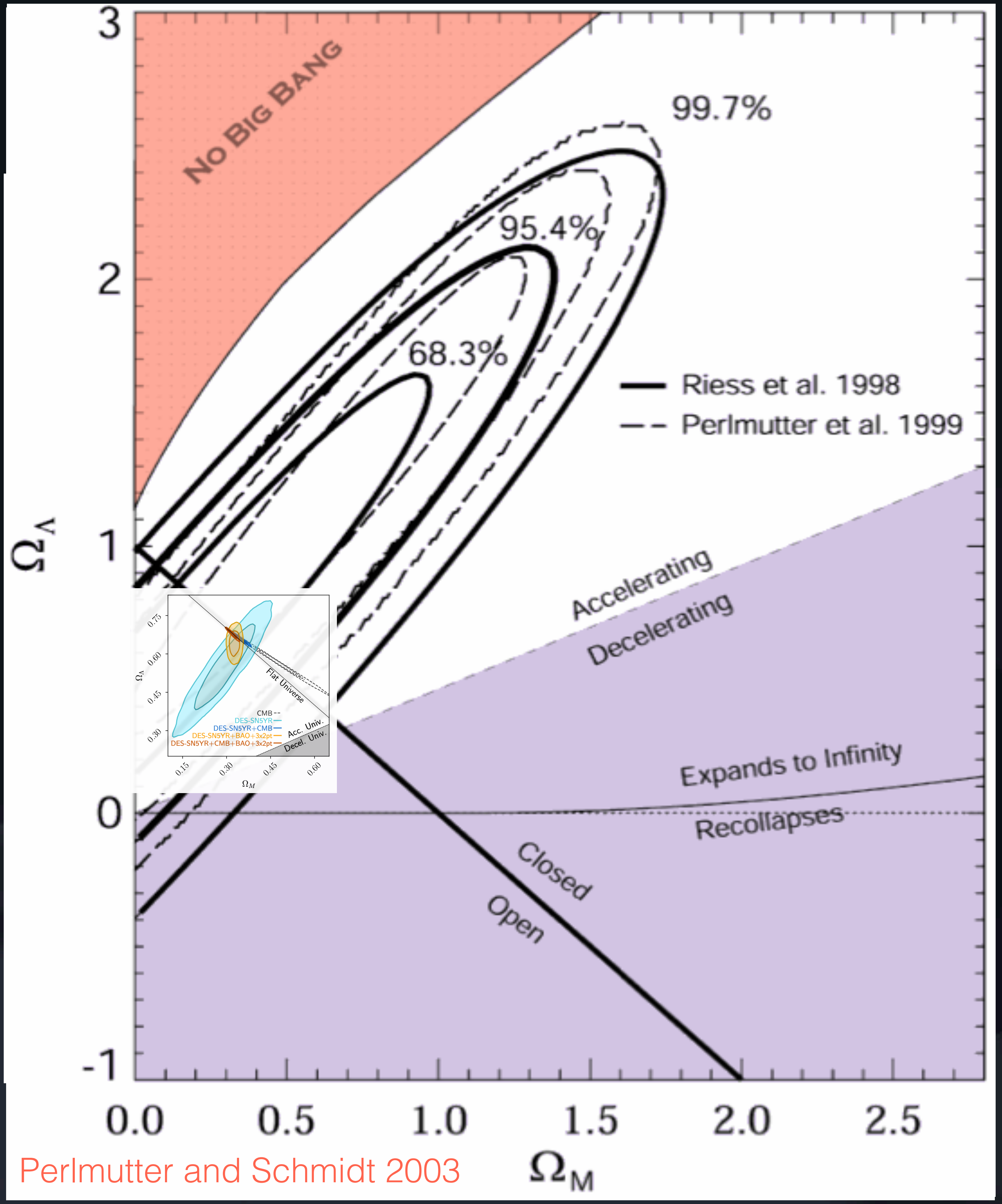
How far have we come?



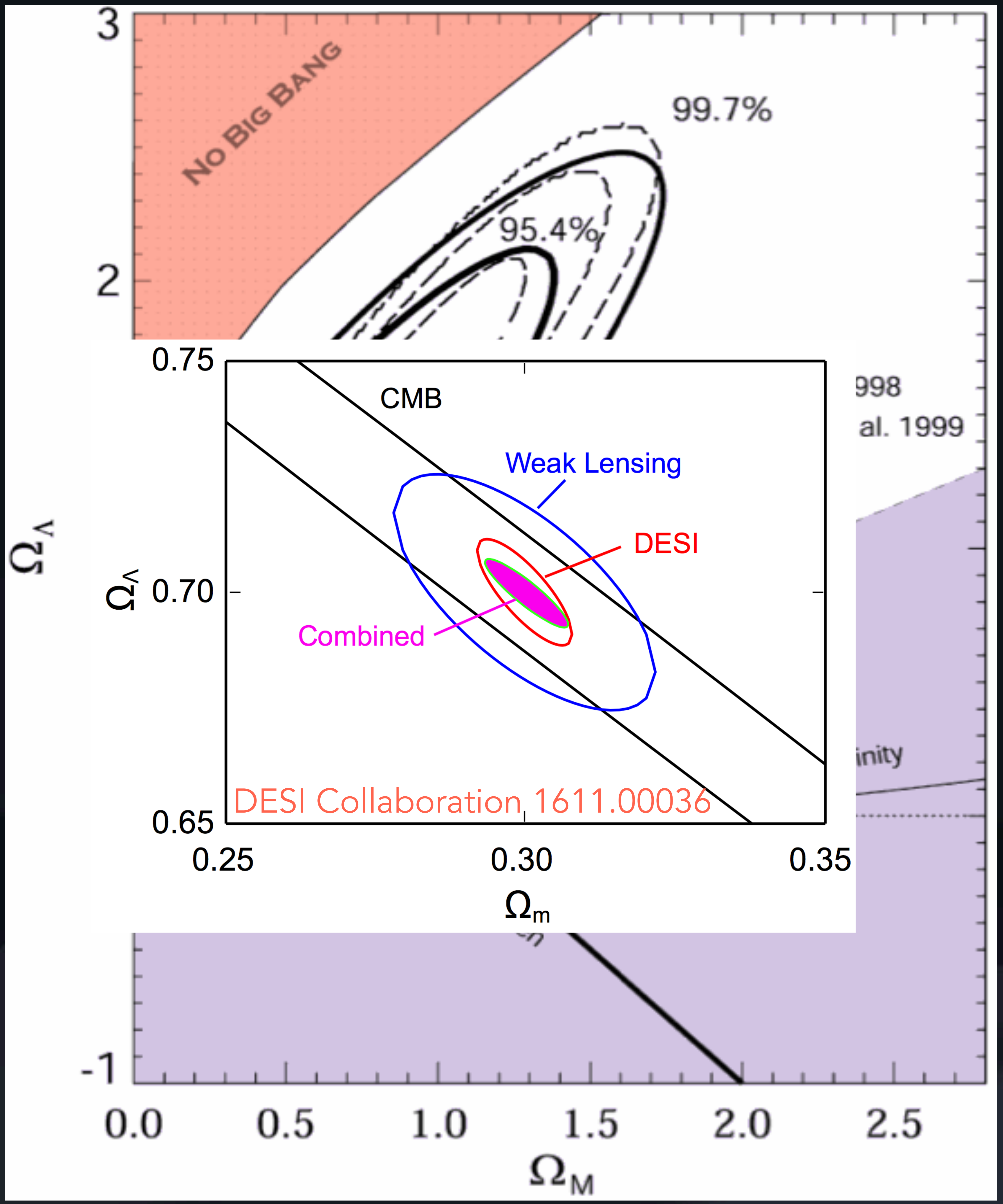
Perlmutter and Schmidt 2003



How far will we go?

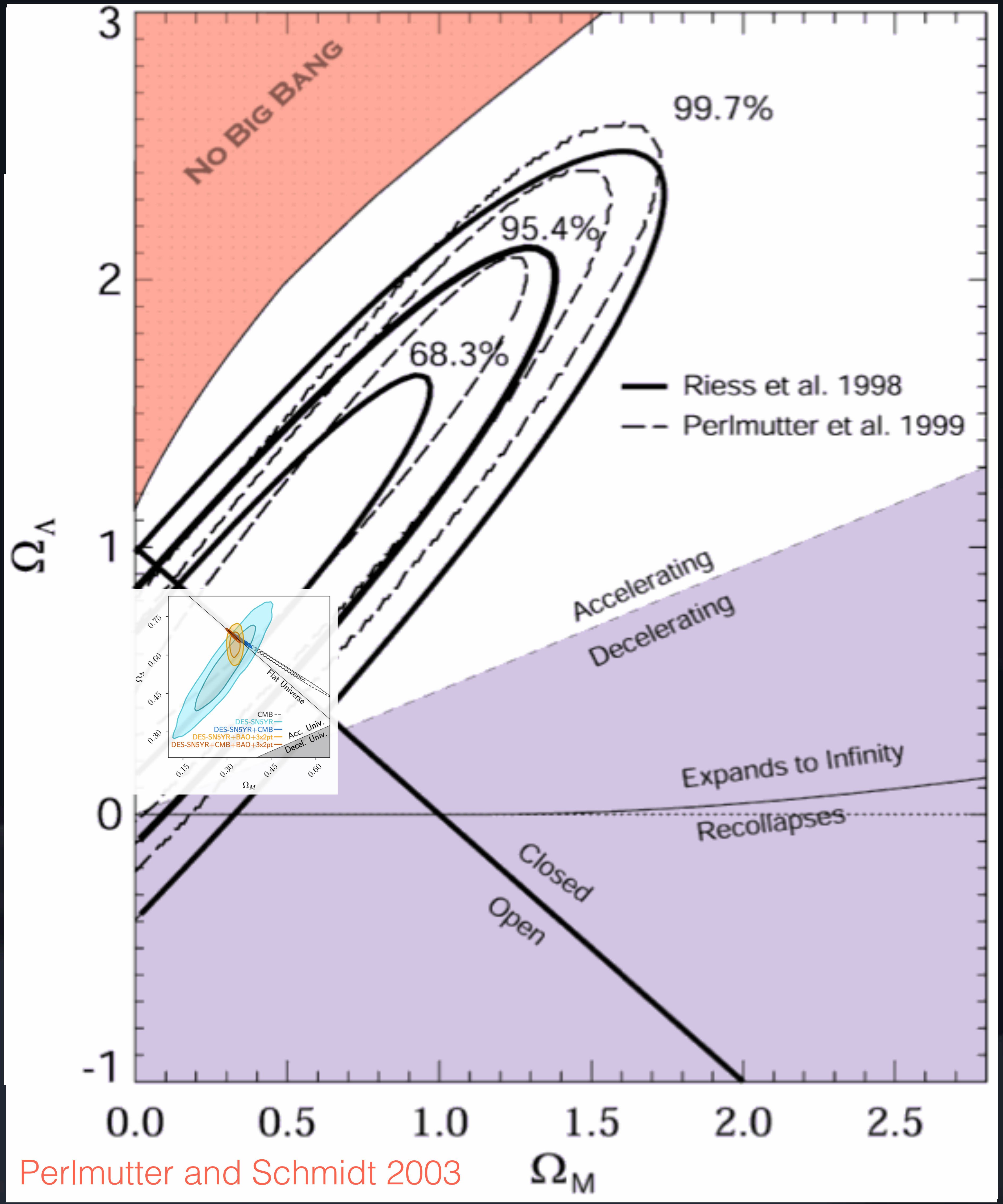


Perlmutter and Schmidt 2003

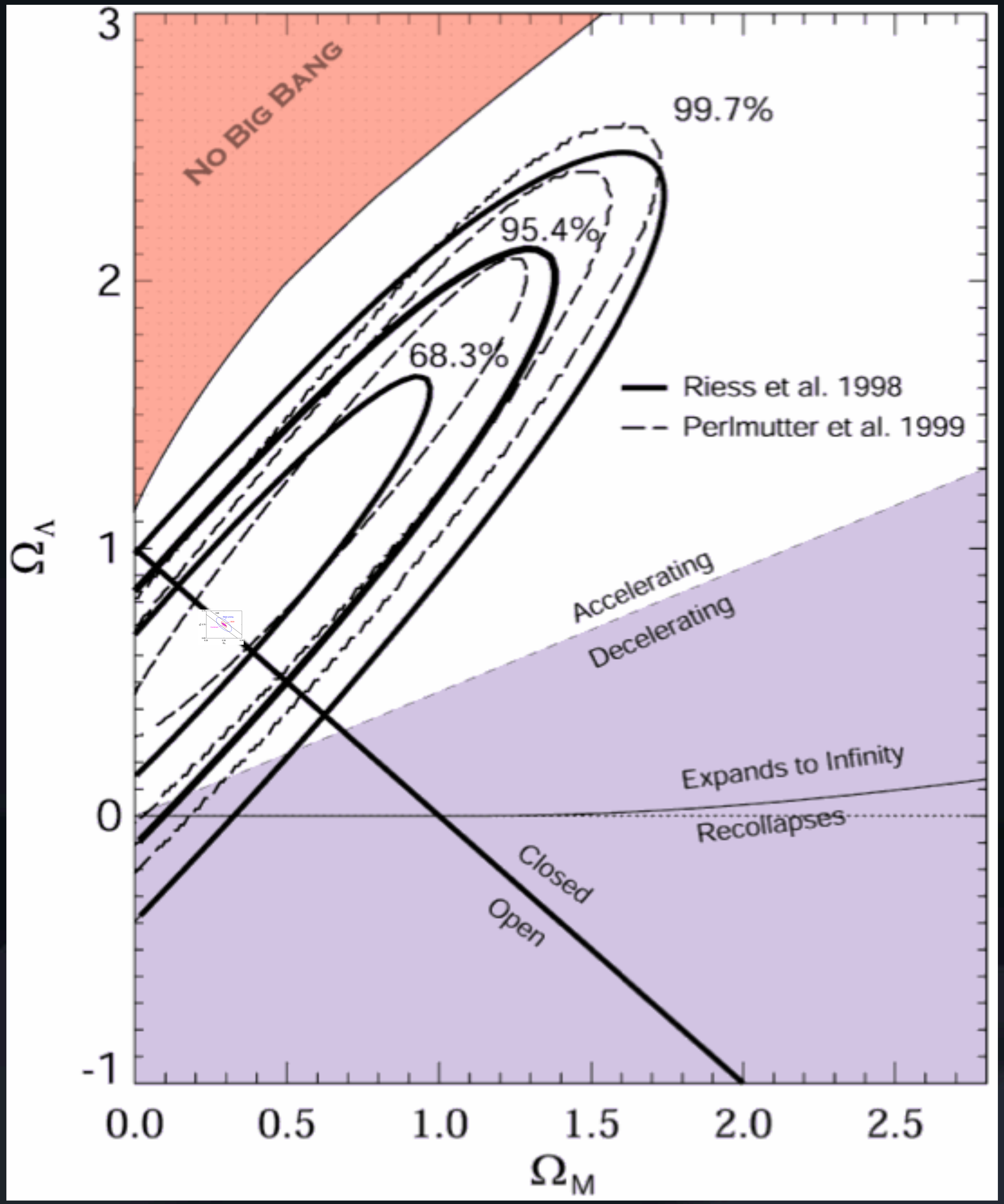


DESI Collaboration 1611.00036

How far will we go?



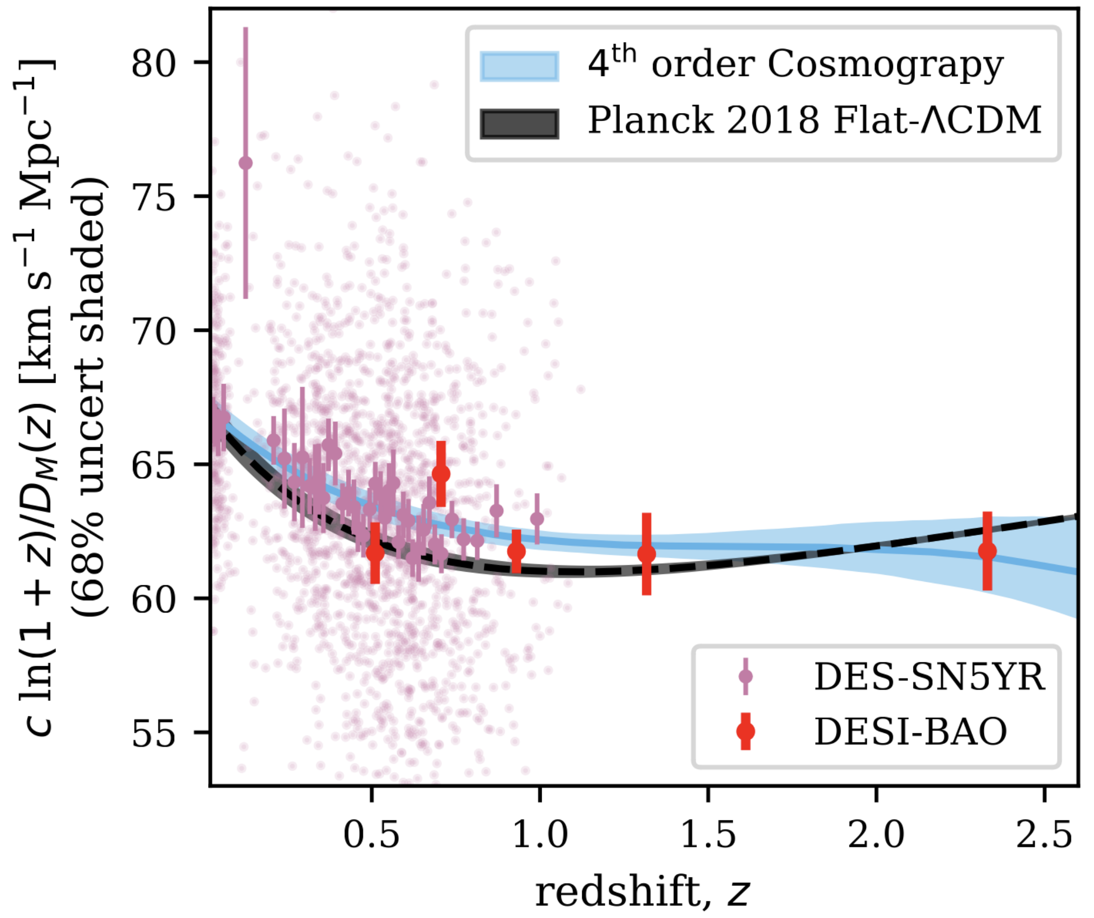
Perlmutter and Schmidt 2003



But that's not all!

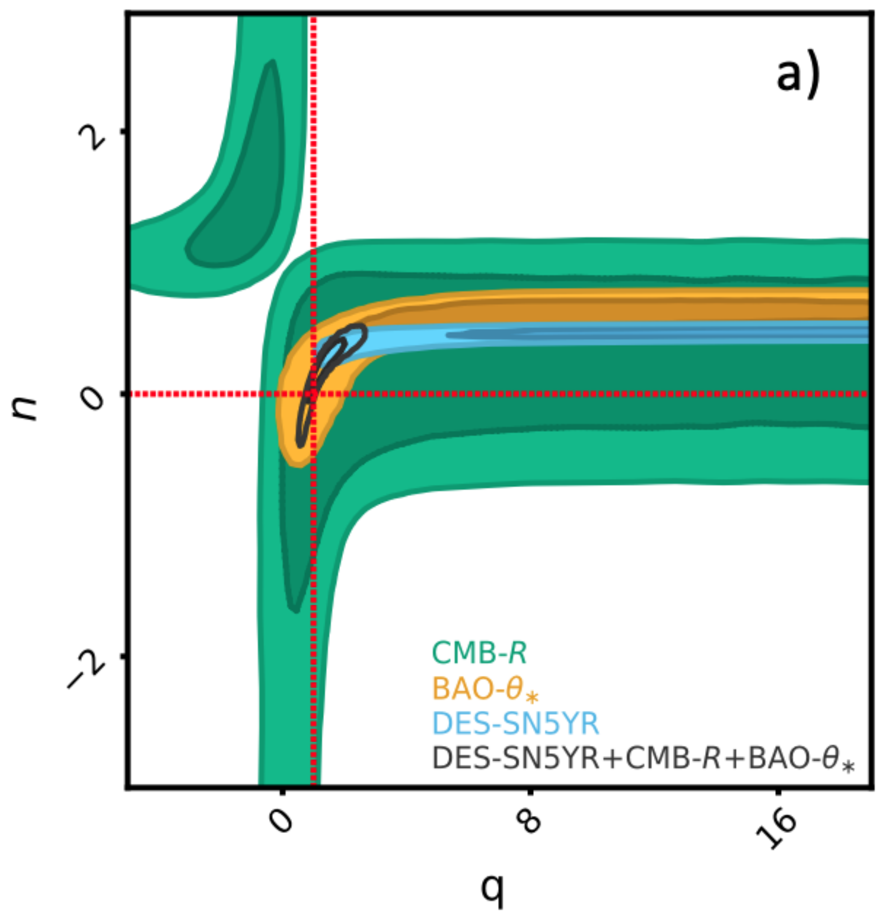
Inverse distance ladder

(we do measure H_0 after all)



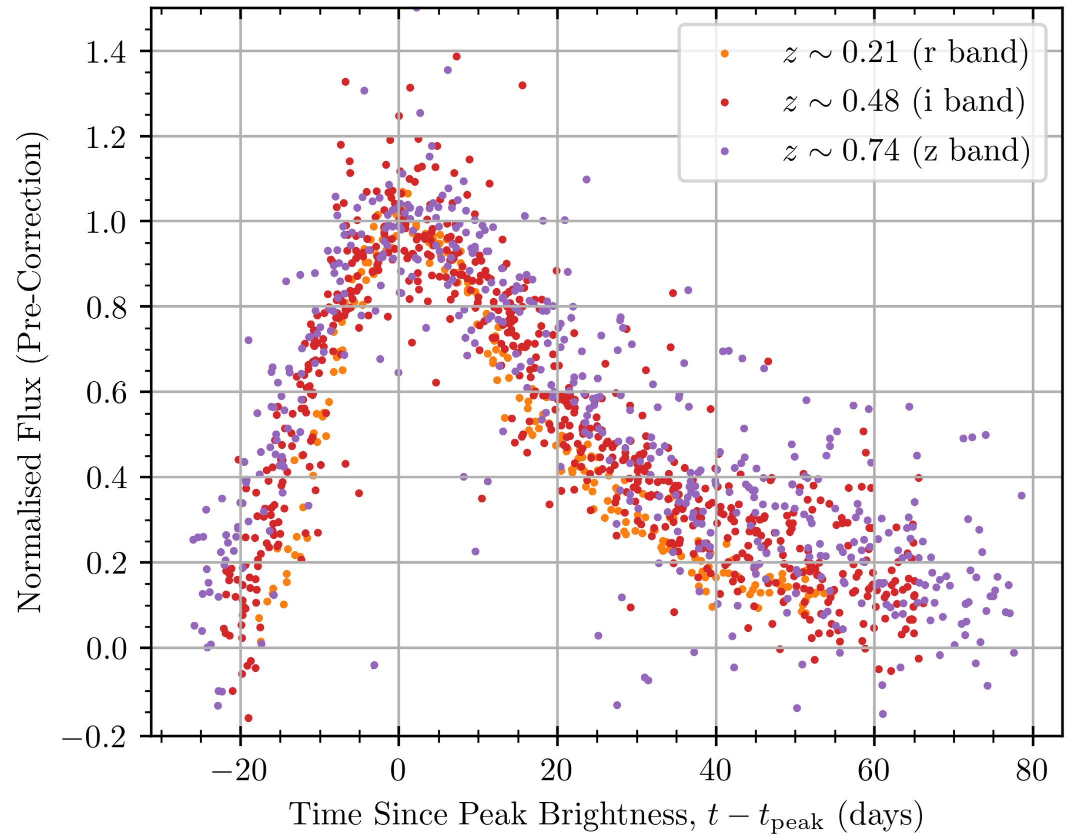
Ryan Camilleri et al.
arXiv:2406.05049

Exotic models



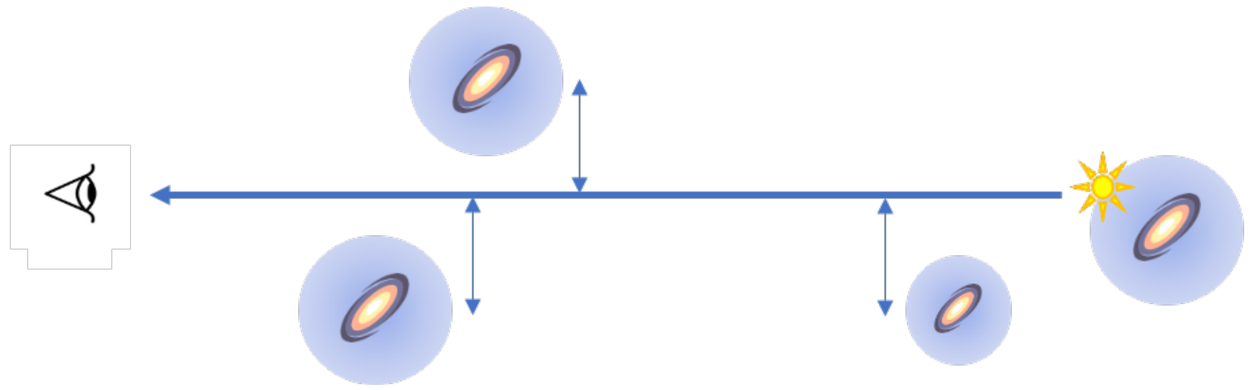
Ryan Camilleri et al.
arXiv:2406.05048

Time dilation



Ryan White et al.
arXiv:2406.05050

Gravitational lensing *magnification*

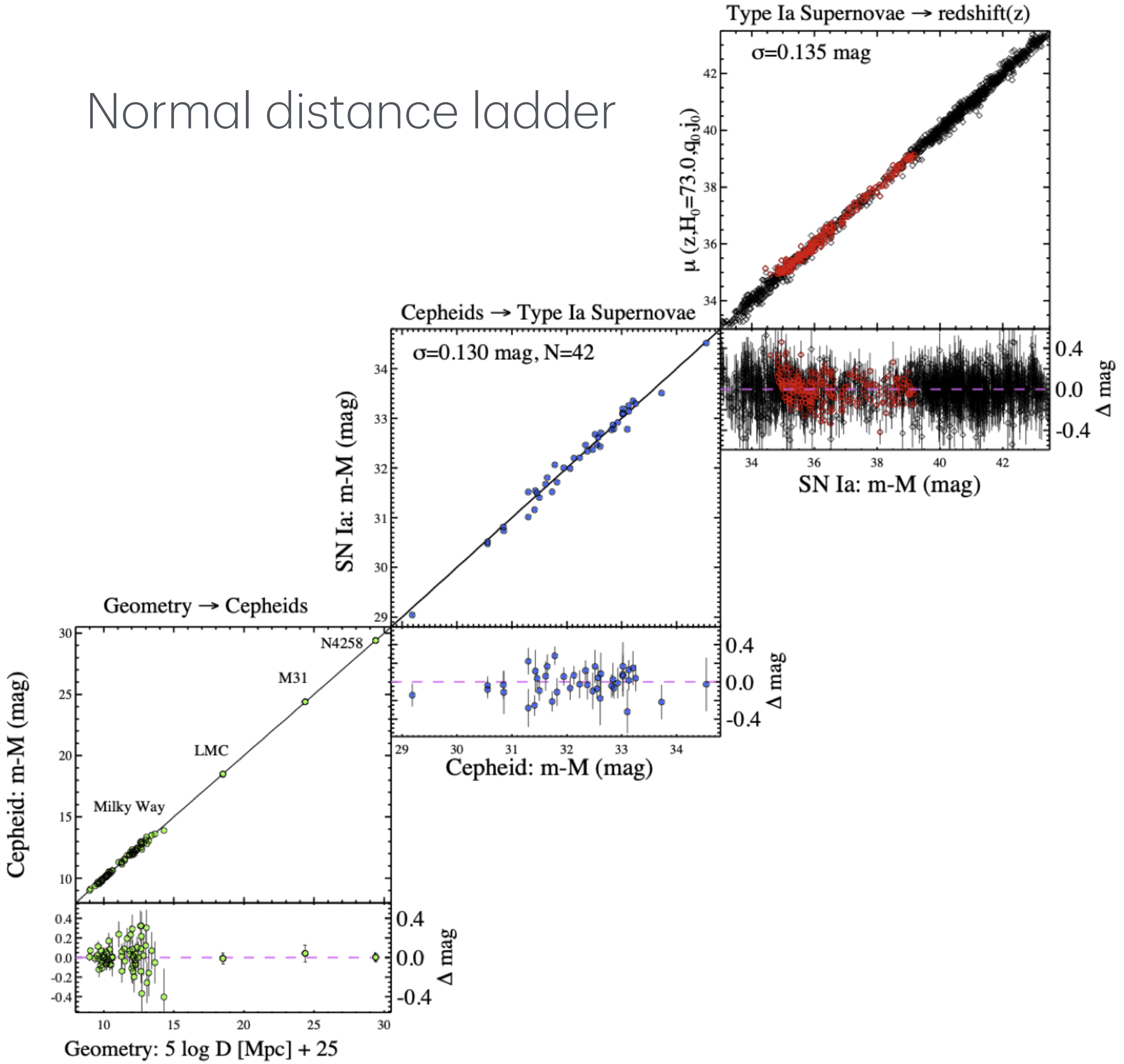


Paul Shah et al.
arXiv:2406.05047

Inverse Distance Ladder

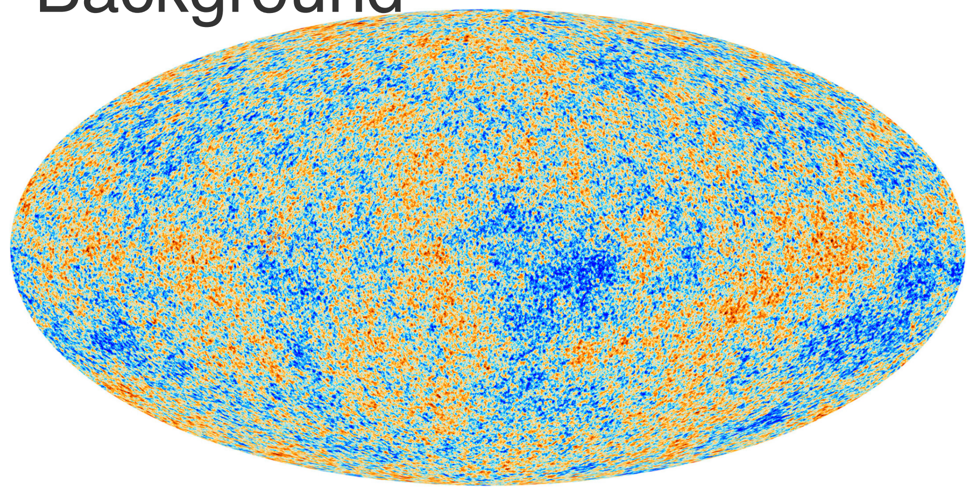
Camilleri et al. arXiv:2406.05049

Normal distance ladder



Inverse distance ladder

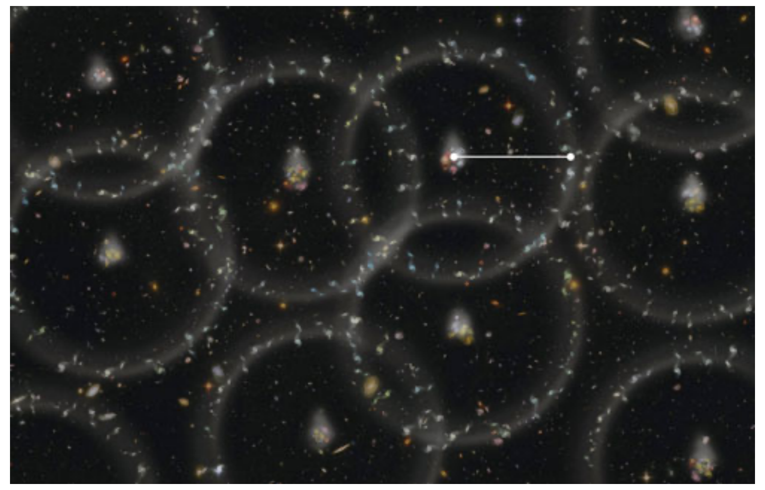
Start at the Cosmic Microwave Background



z >1000

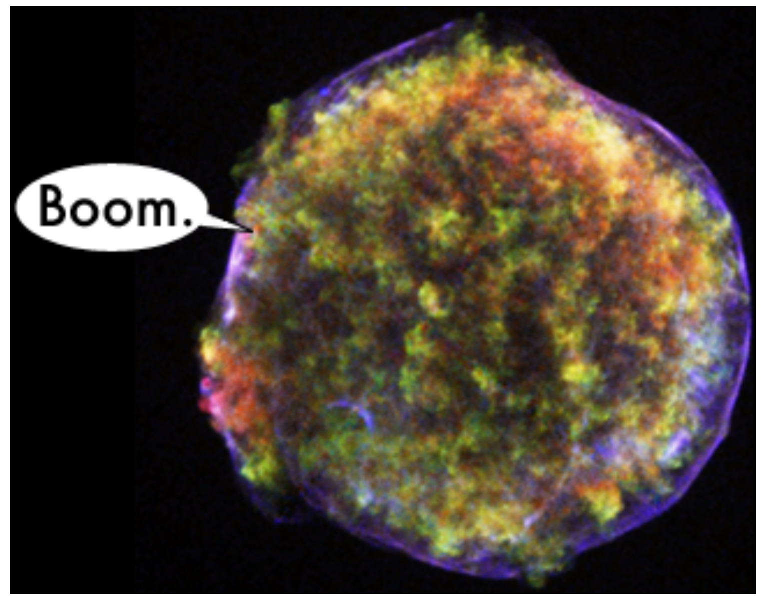
$\mathbf{r_d}$

Sound horizon scale sets the scale of the Baryon Acoustic Oscillations (BAO)



2.330 > z > 0.295

The BAO then break the H_0 - M_B degeneracy of the SN

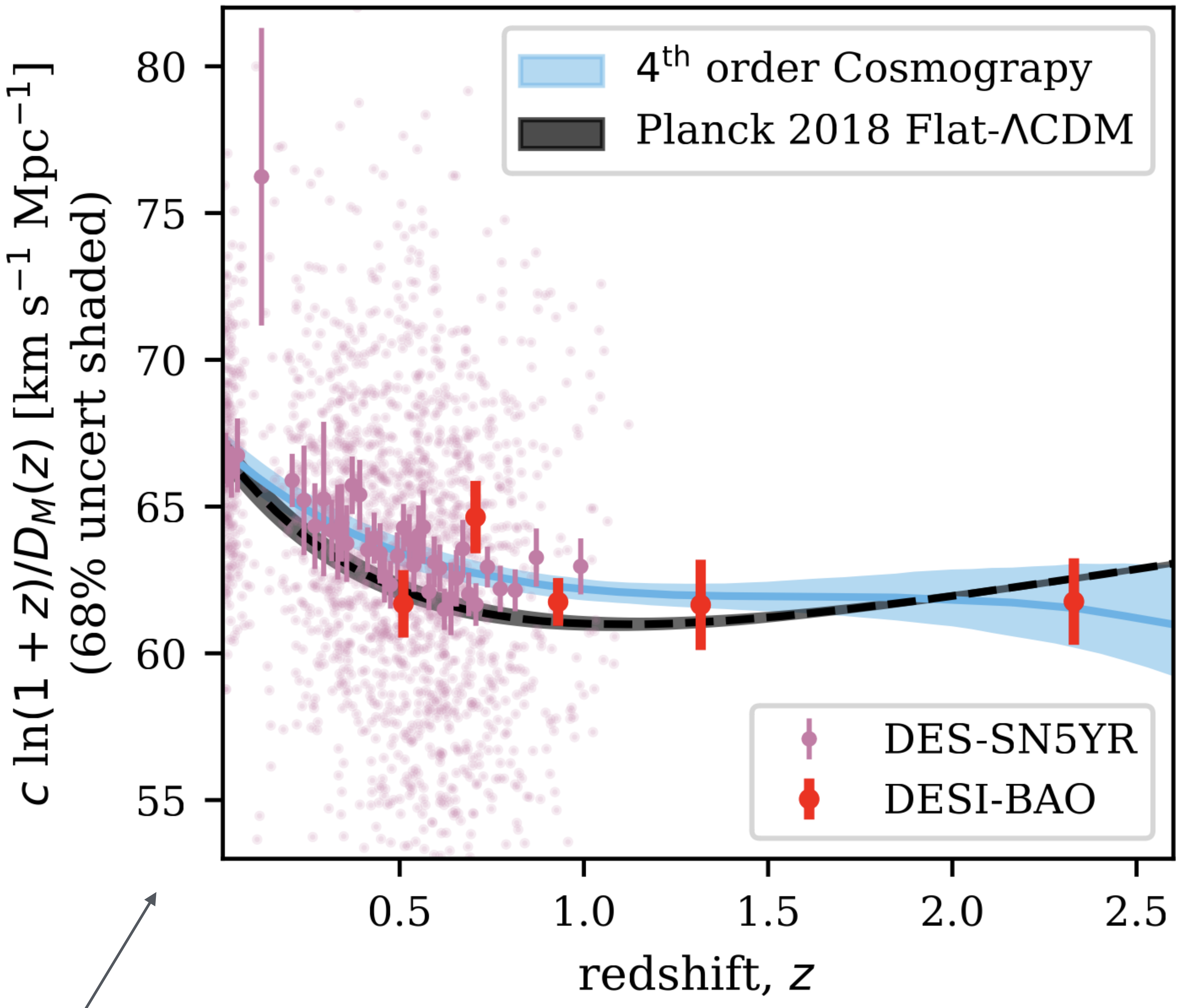


1.15 > z > 0.025

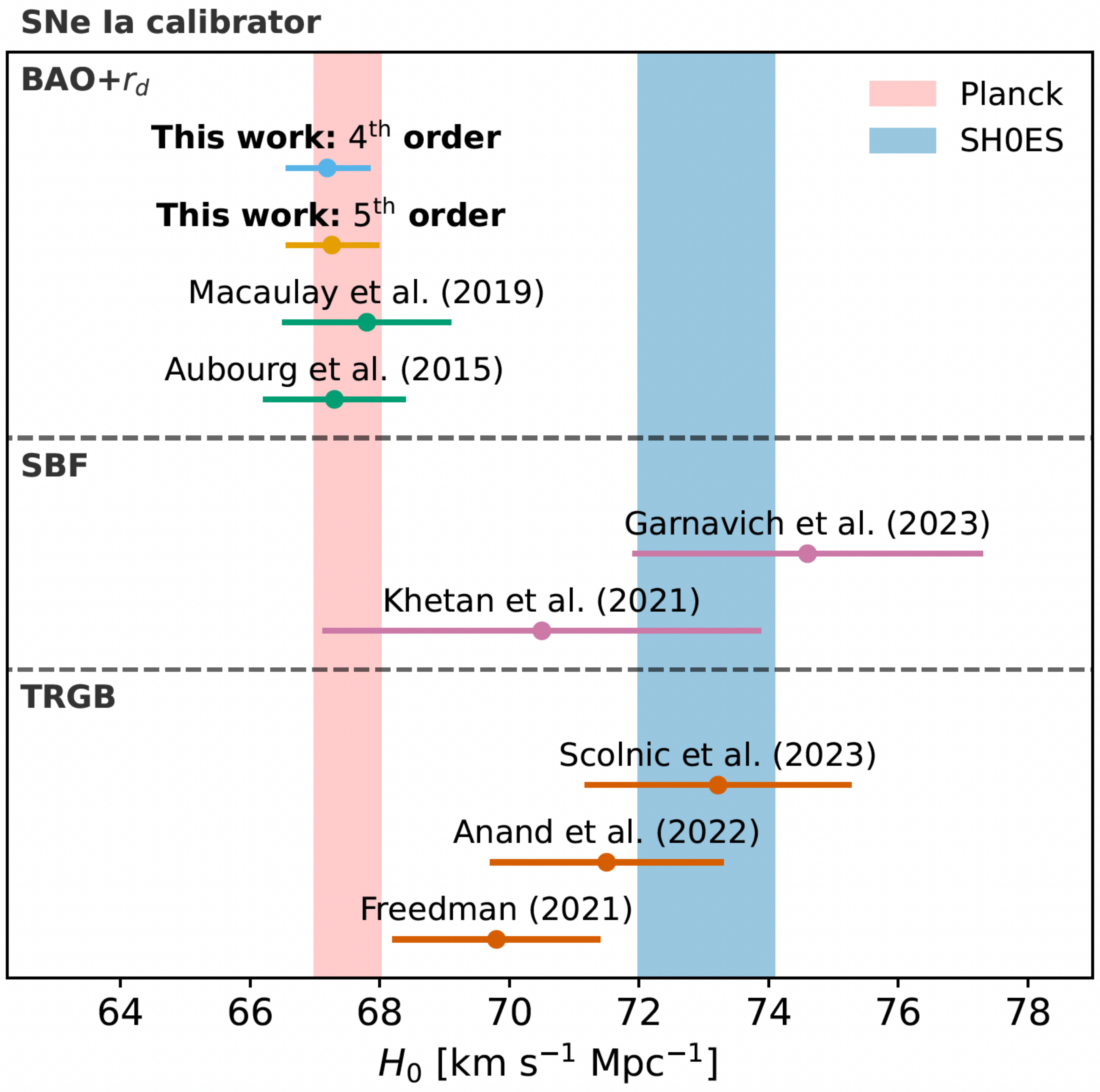
Inverse Distance Ladder

Camilleri et al. arXiv:2406.05049

$$H_0 = 67.19^{+0.66}_{-0.64} \text{ km s}^{-1} \text{ Mpc}^{-1}$$

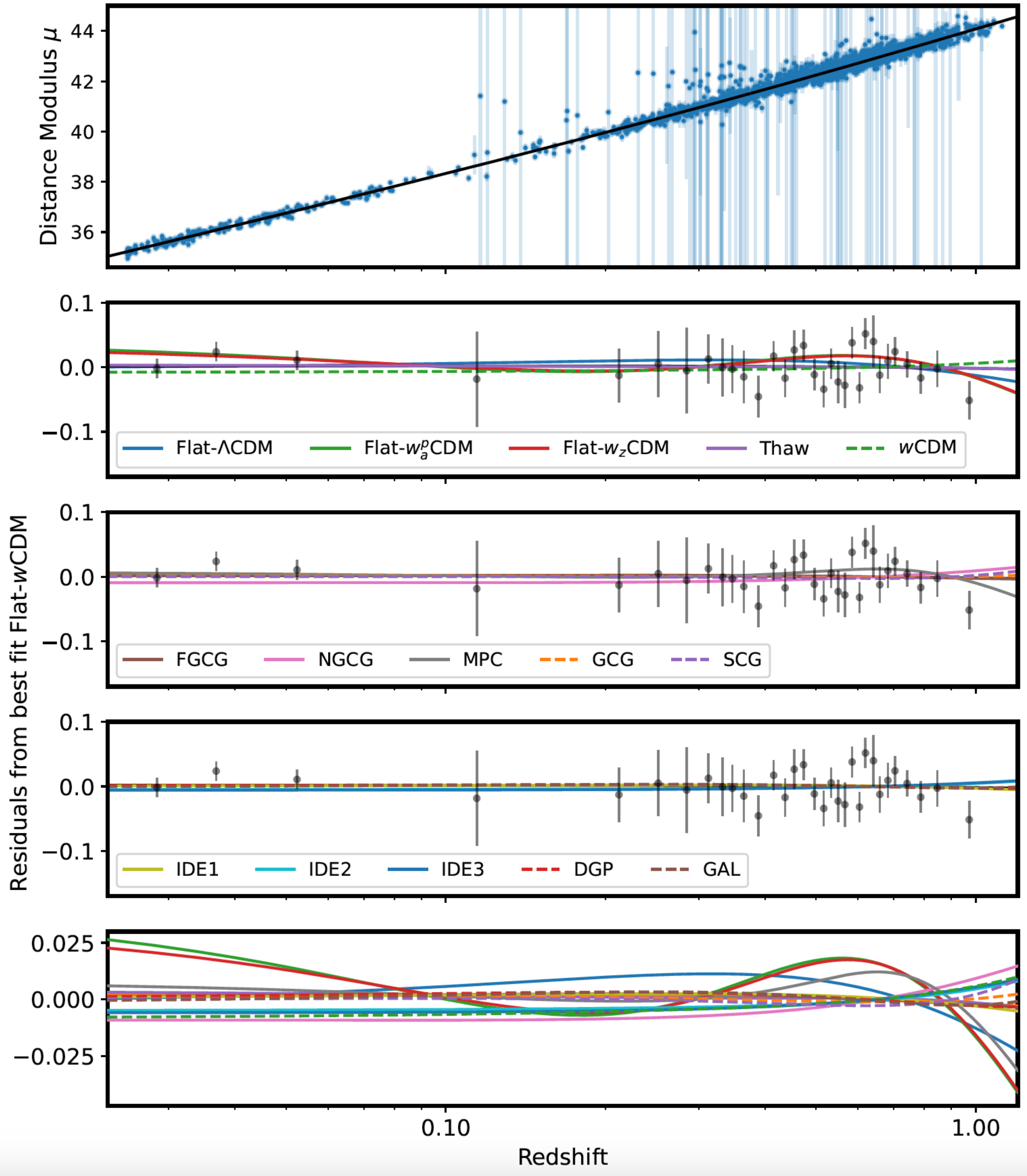


Intercept shows H_0



Camilleri et al. arXiv:2406.05048

Exotic Cosmological Models



	DES-SN5YR				DES-SN5YR + CMB-R + BAO-θ_*		
Model	$\frac{1}{2}\Delta$AIC	$\Delta \ln S$	χ^2/dof	Model	$\frac{1}{2}\Delta$AIC	$\Delta \ln S$	χ^2/dof
Cosmography - Third Order	−0.9	−1.37	1641 / 1733 = 0.947				
Cosmography - Fourth Order	−3.6	−4.39	1633 / 1732 = 0.943				
Flat-ΛCDM						0.0	1665 / 1749 = 0.952
ΛCDM						−0.10	1664 / 1747 = 0.952
wCDM						−3.64	1655 / 1747 = 0.947
Flat-w_0w_zCDM						−4.16	1655 / 1747 = 0.947
Flat-w_a^pCDM						−4.17	1655 / 1747 = 0.947
Thaw						−4.60	1655 / 1747 = 0.947
SCG						138.03	1940 / 1748 = 1.110
FGCG						−3.94	1657 / 1748 = 0.948
GCG						−3.71	1656 / 1747 = 0.948
NGCG						−4.08	1655 / 1747 = 0.947
MPC						−3.94	1655 / 1747 = 0.947
IDE1						−3.70	1656 / 1747 = 0.948
IDE2						−3.75	1656 / 1747 = 0.948
IDE3						−3.82	1655 / 1747 = 0.947
DGP						31.11	1726 / 1748 = 0.988
GAL						72.10	1808 / 1748 = 1.035
	DES-SN5YR$_{\text{cut}}$				DES-SN5YR$_{\text{cut}}$ + BAO-$\theta_{*\perp}$		
Flat-ΛCDM	0.0	0.0	1616 / 1665 = 0.970	Flat-ΛCDM	0.0	0.0	1624 / 1672 = 0.972
Timescape	−1.7	−1.72	1612 / 1665 = 0.968	Timescape	6.3	6.17	1637 / 1672 = 0.979

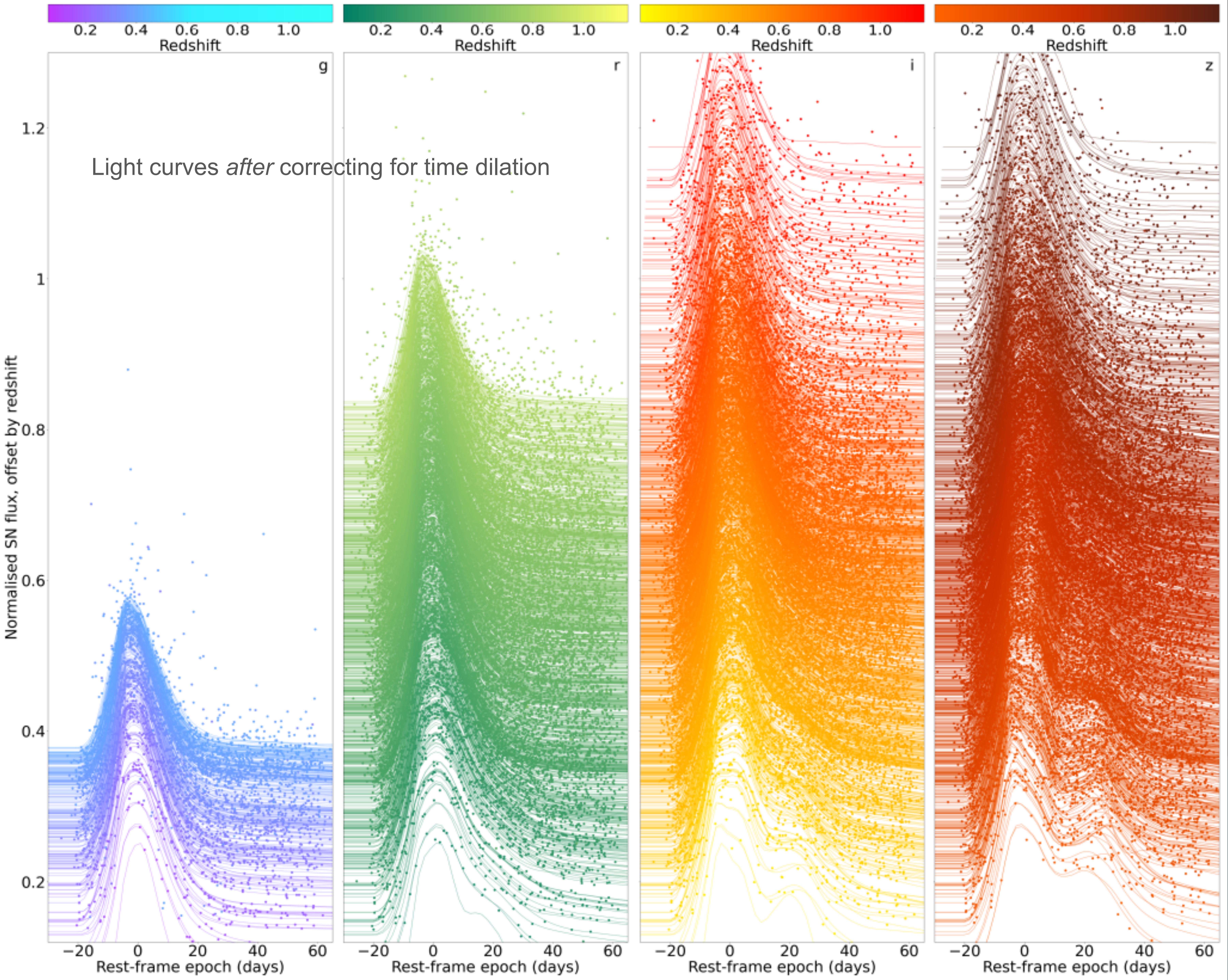
Flat generalised Chaplygin gas

Flat thawing scalar field

Flat time-varying dark energy

- No *strong* evidence for or against Flat-ΛCDM
- DES-SN alone: 3 models moderately preferred over Flat-ΛCDM
- DES-SN + CMB + BAO: 11 (of 15) models moderately preferred over Flat-ΛCDM

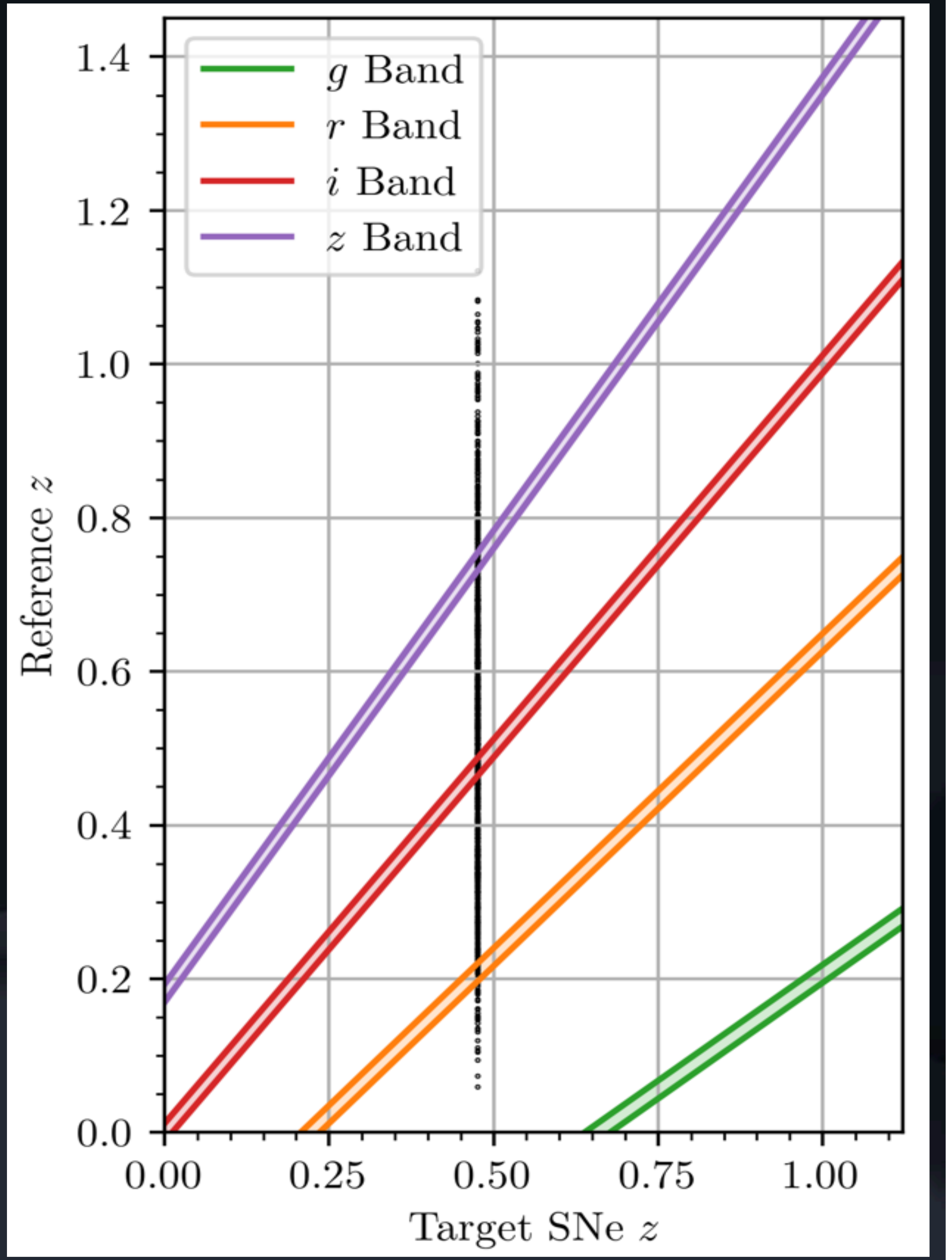
Time Dilation



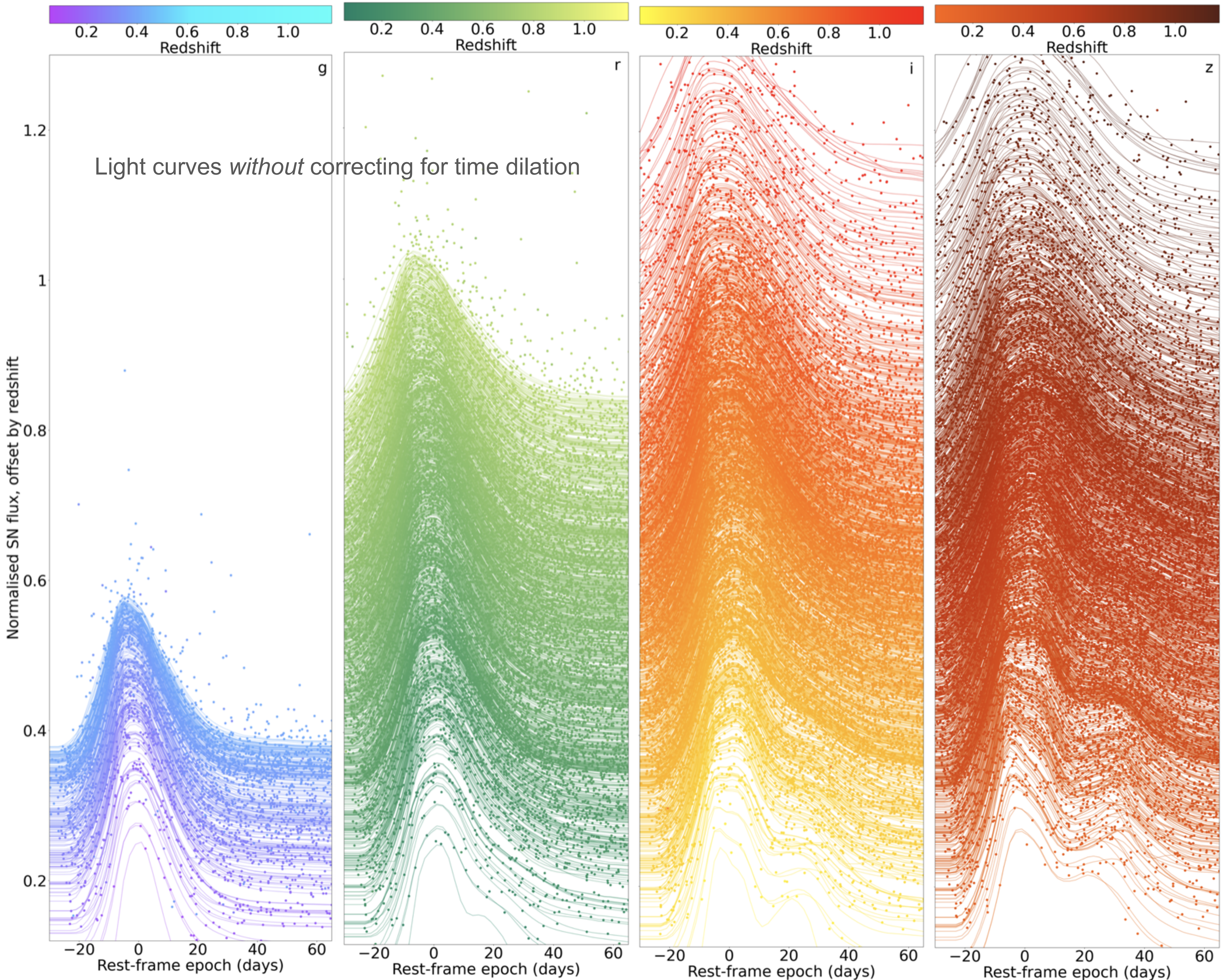
White et al. arXiv:2406.05050

Time Dilation

Pick light curves sampling the same colours

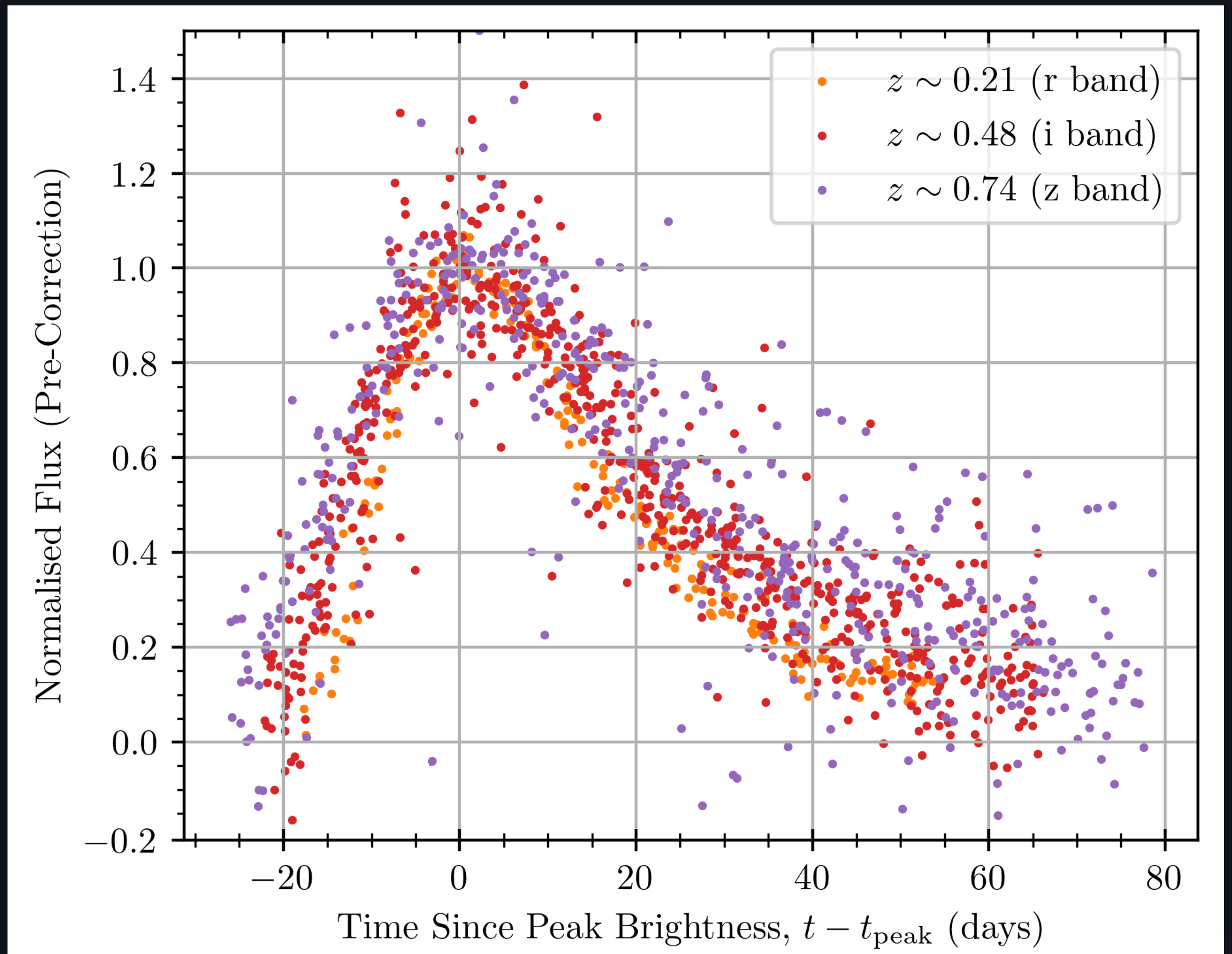


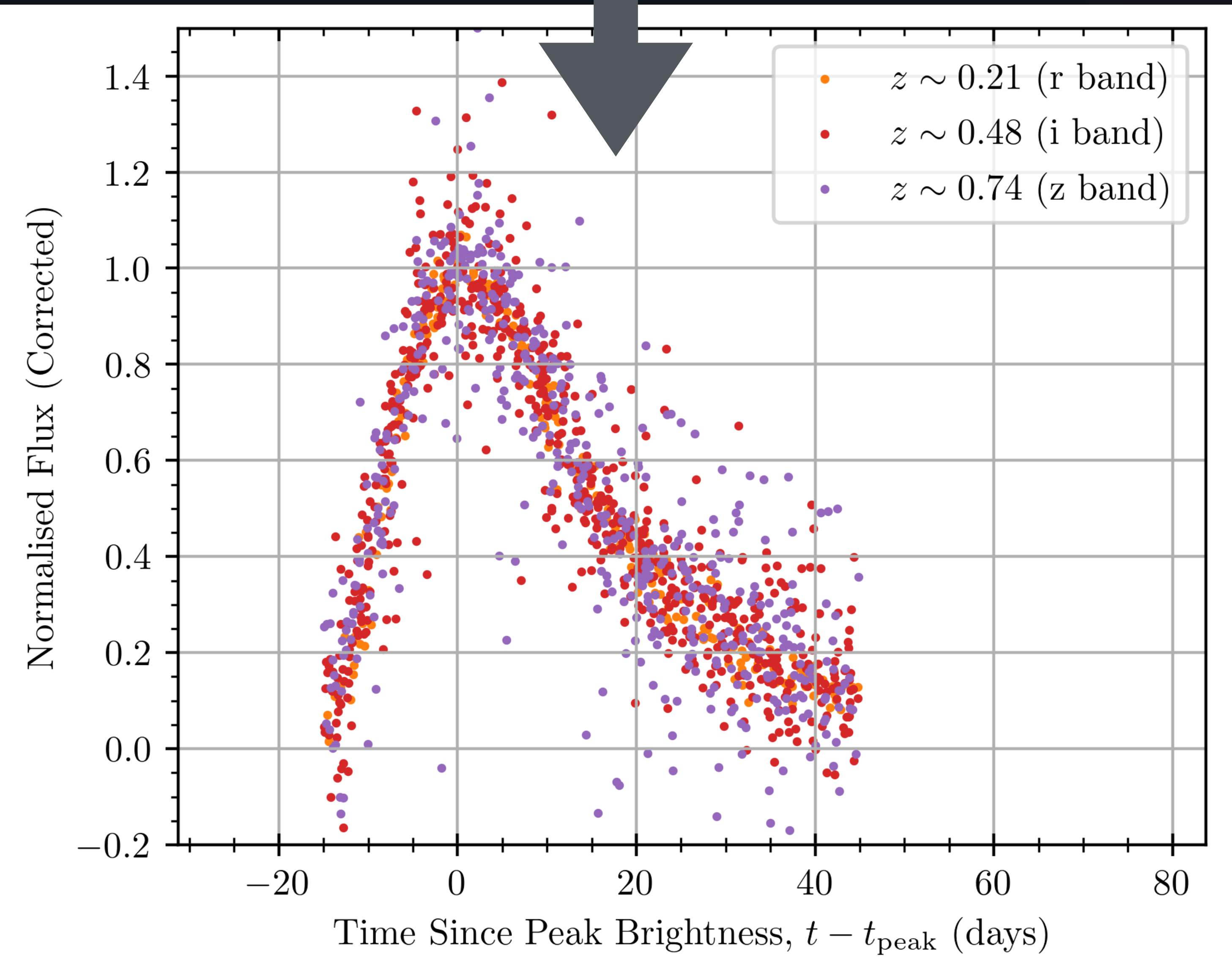
White et al. arXiv:2406.05050

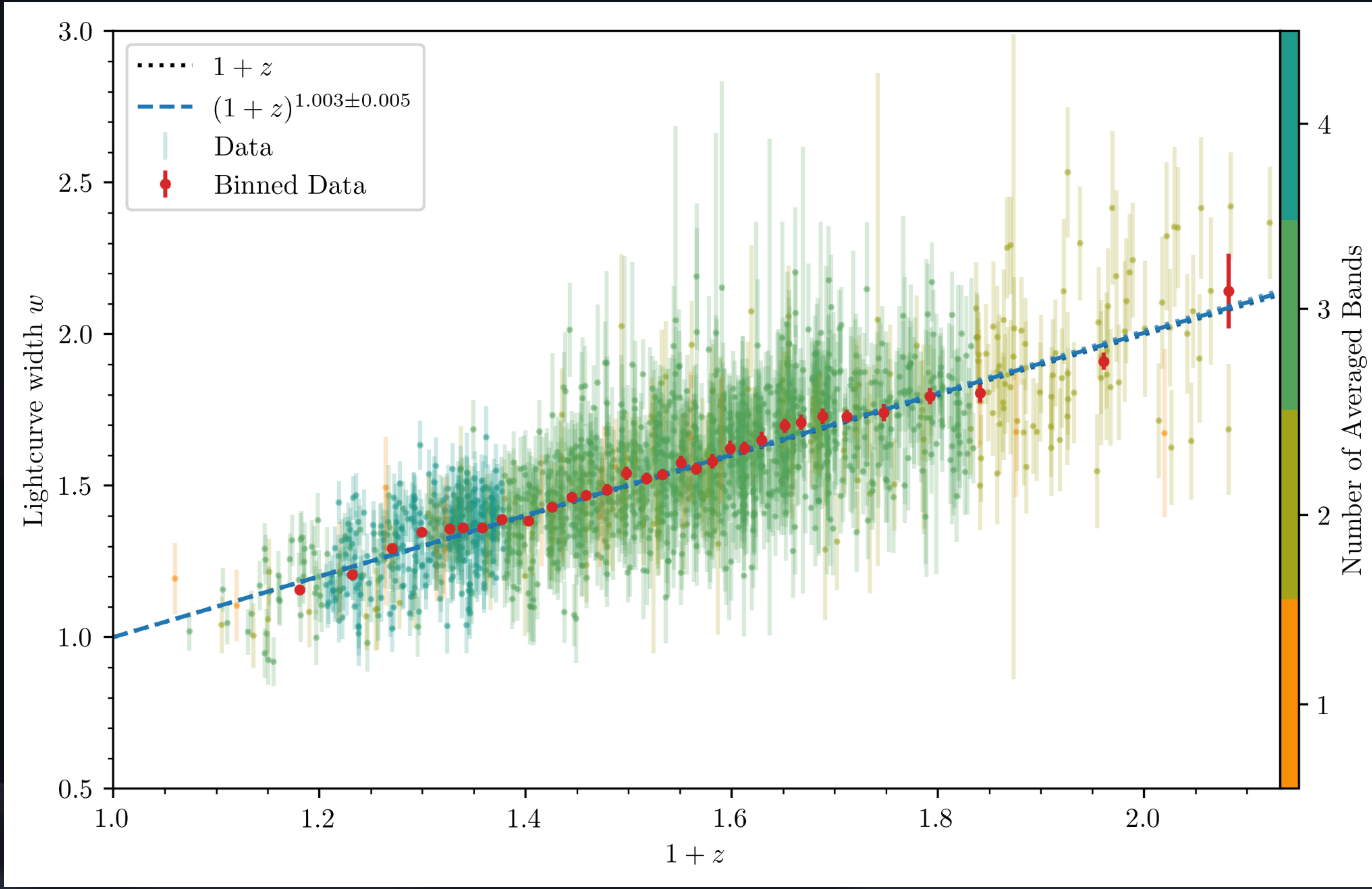


Time Dilation

White et al. arXiv:2406.05050







The Future

Gravitational waves “rule”

STANDARD CANDLES / SIRENS

Supernovae

THE DARK ENERGY SURVEY

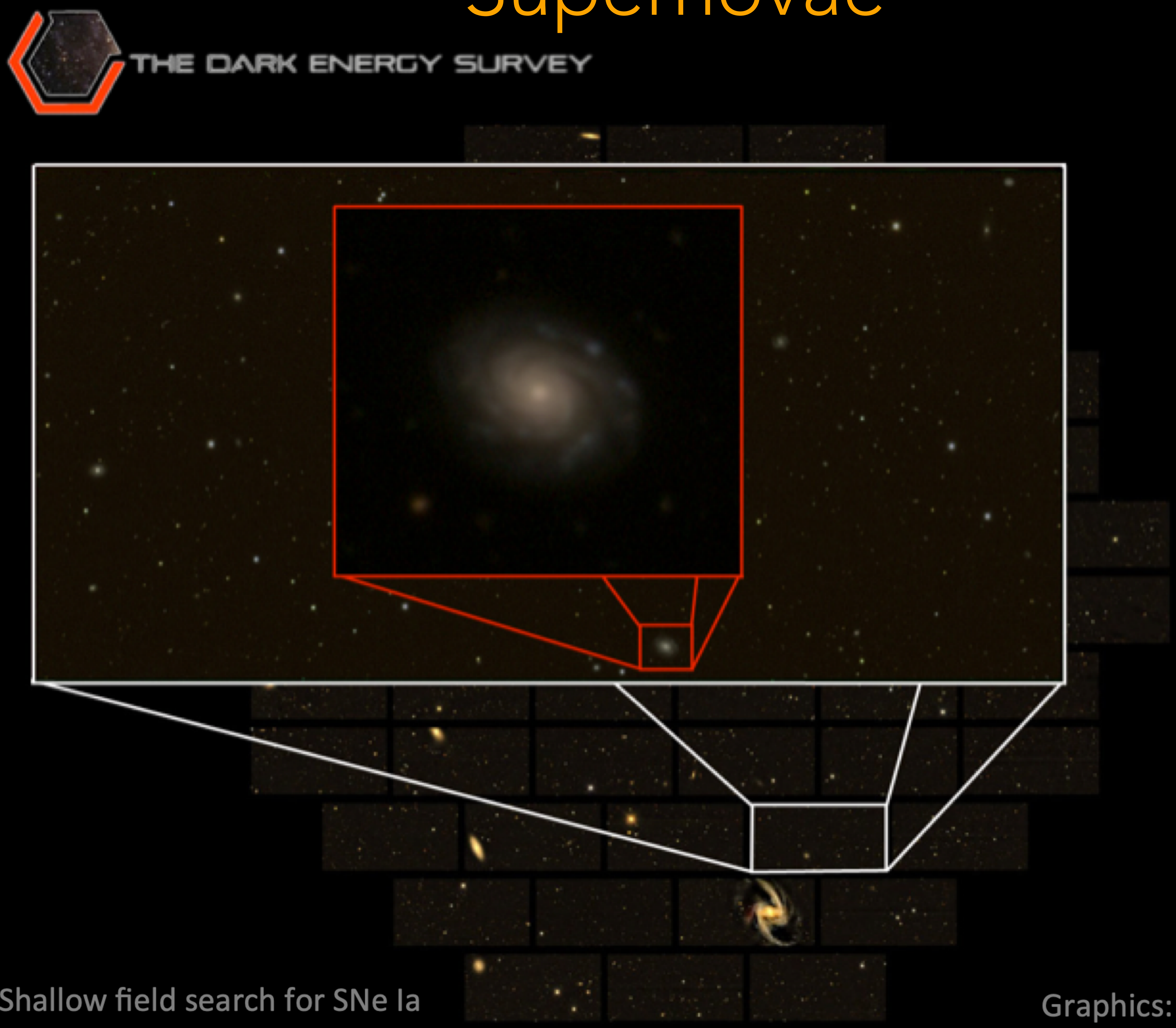
Shallow field search for SNe Ia

Gravitational Waves

Graphics: C. D'Andrea

STANDARD CANDLES / SIRENS

Supernovae



Shallow field search for SNe Ia

Graphics: C. D'Andrea

Gravitational Waves

STANDARD CANDLES / SIRENS

Supernovae

Shallow field search for SNe Ia

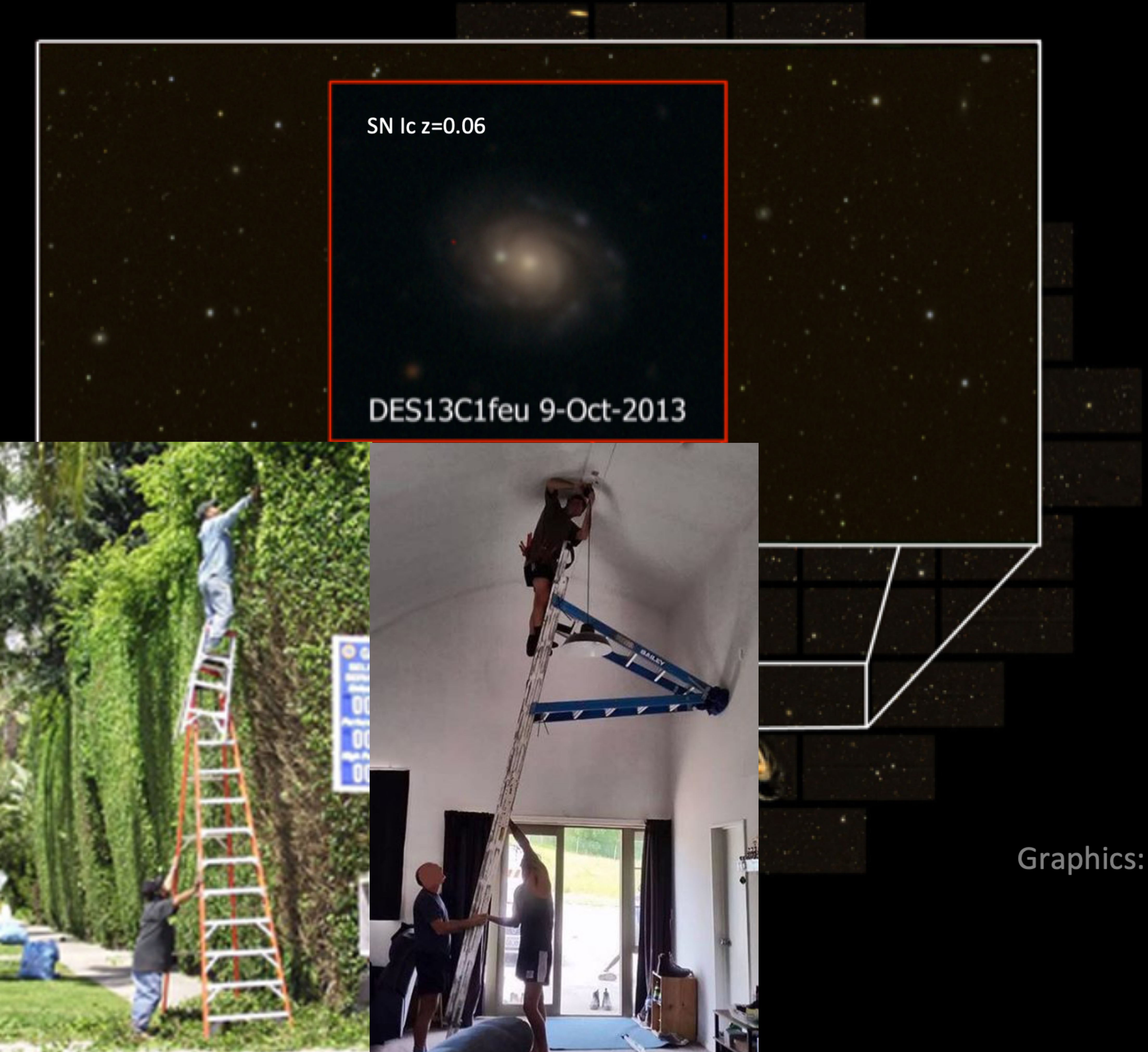
Graphics: C. D'Andrea

Gravitational Waves

STANDARD CANDLES

Supernovae

THE DARK ENERGY SURVEY



Graphics: C. D'Andrea

Gravitational Waves

GRAVITATIONAL WAVES

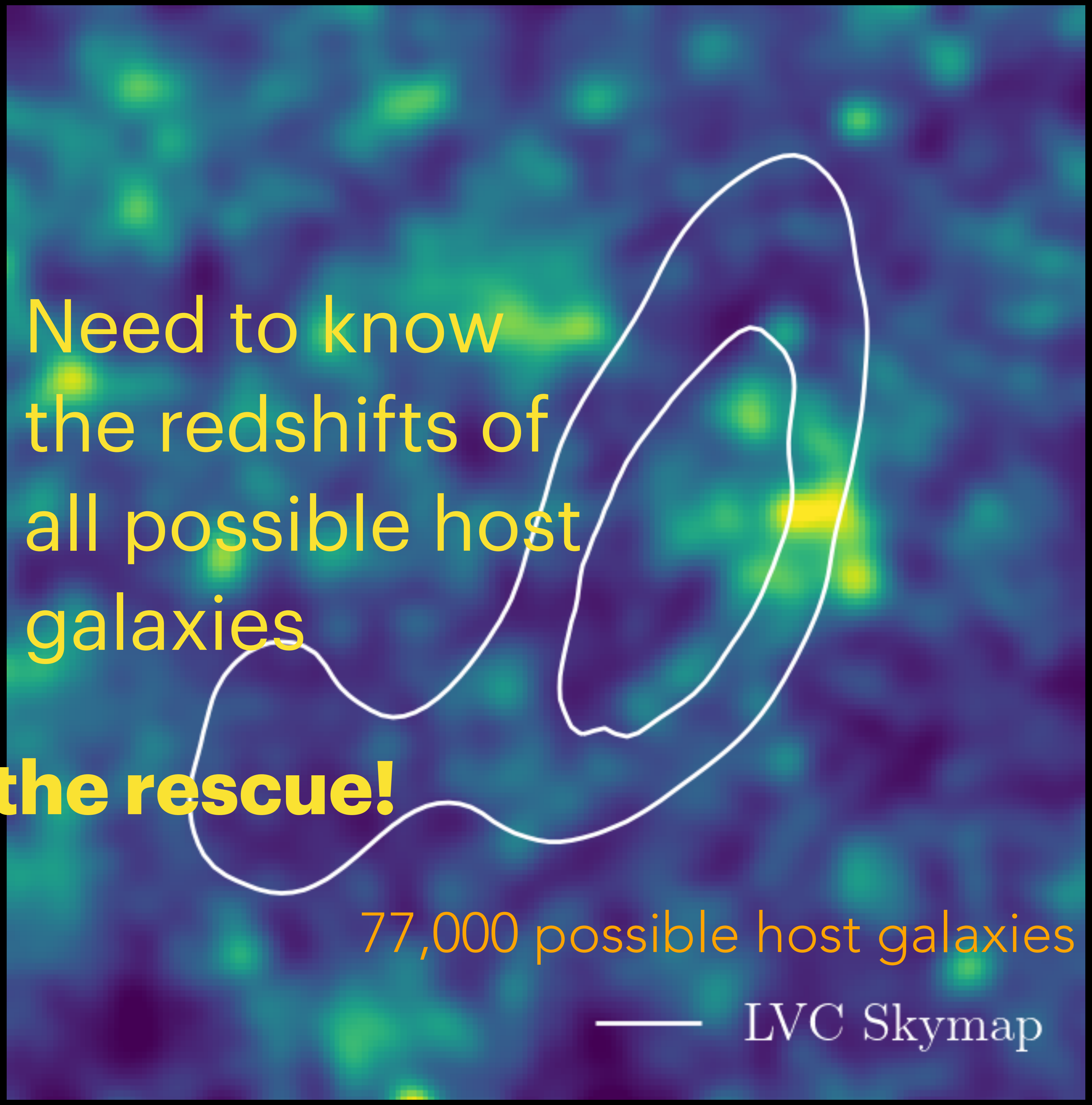
Bright sirens

Need to know the peculiar velocity

Known host galaxy

Soares-Santos +DES 2017

Dark sirens



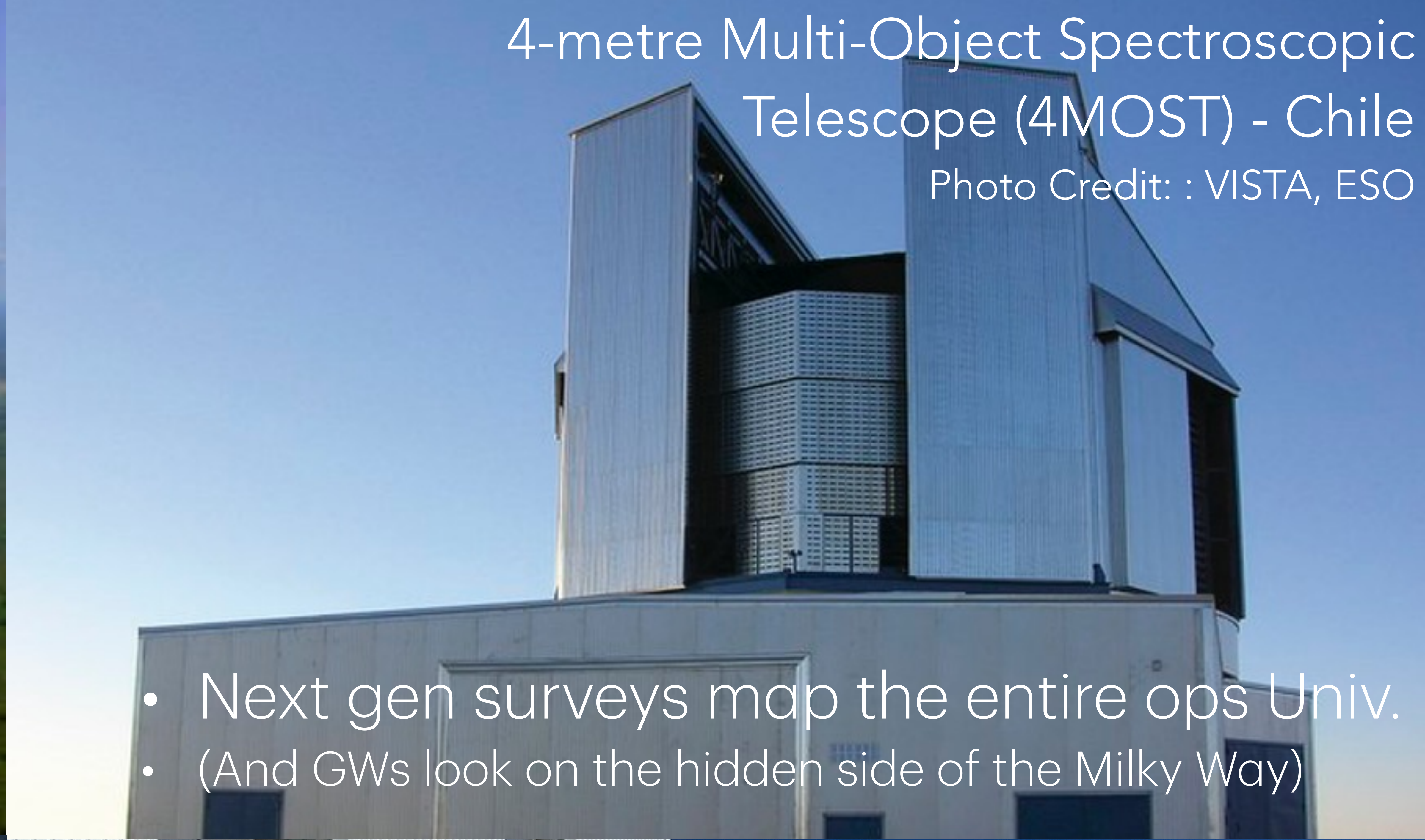
Need to know the redshifts of all possible host galaxies

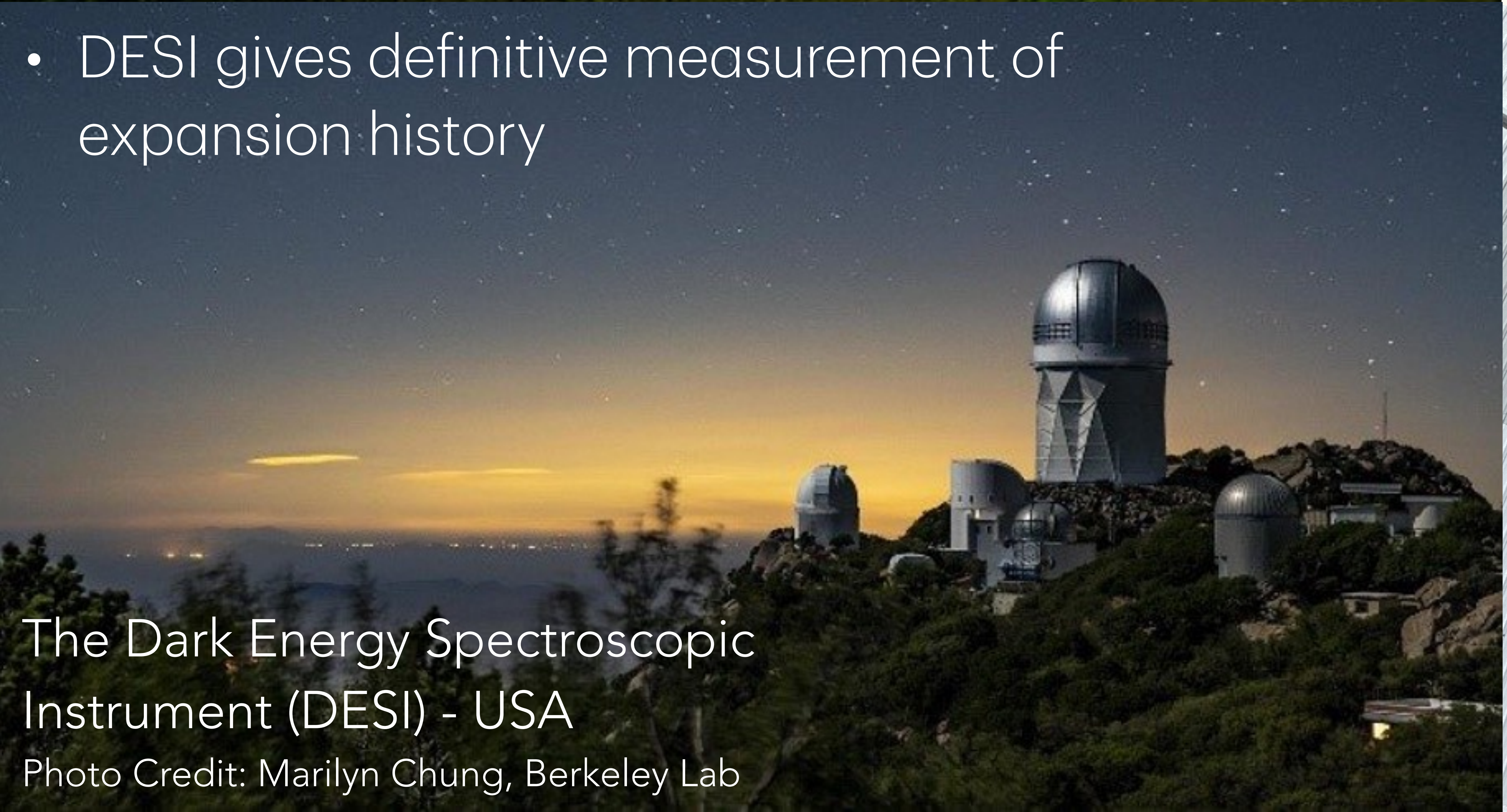
Many possible host galaxies

Soares-Santos +DES 2019

Galaxy surveys to the rescue!


LIGO / VIRGO / KAGRA
Gravitational Wave Detectors
• Gravitational waves replace SNe as "gold standard" standard candles


4-metre Multi-Object Spectroscopic Telescope (4MOST) - Chile
Photo Credit: : VISTA, ESO
• Next gen surveys map the entire ops Univ.
• (And GWs look on the hidden side of the Milky Way)

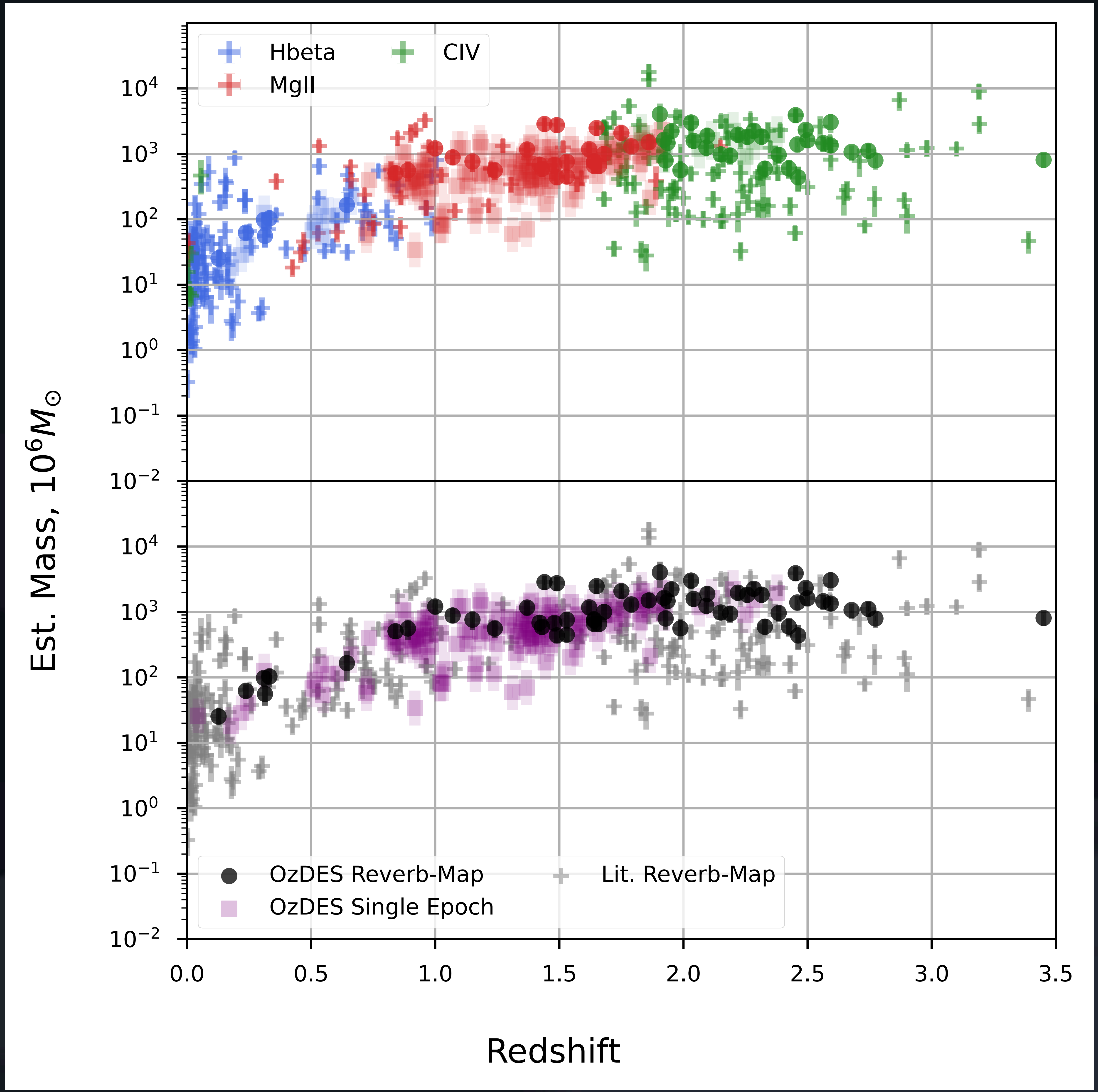

• DESI gives definitive measurement of expansion history
The Dark Energy Spectroscopic Instrument (DESI) - USA
Photo Credit: Marilyn Chung, Berkeley Lab


• Rubin LSST makes movie of the sky
Vera C. Rubin Observatory
Photo Credit: Me

First stars formed
Universe 3 billion years old
Half the age of the Universe
Solar system formed
Redshift
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Comoving Distance (Gpc)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

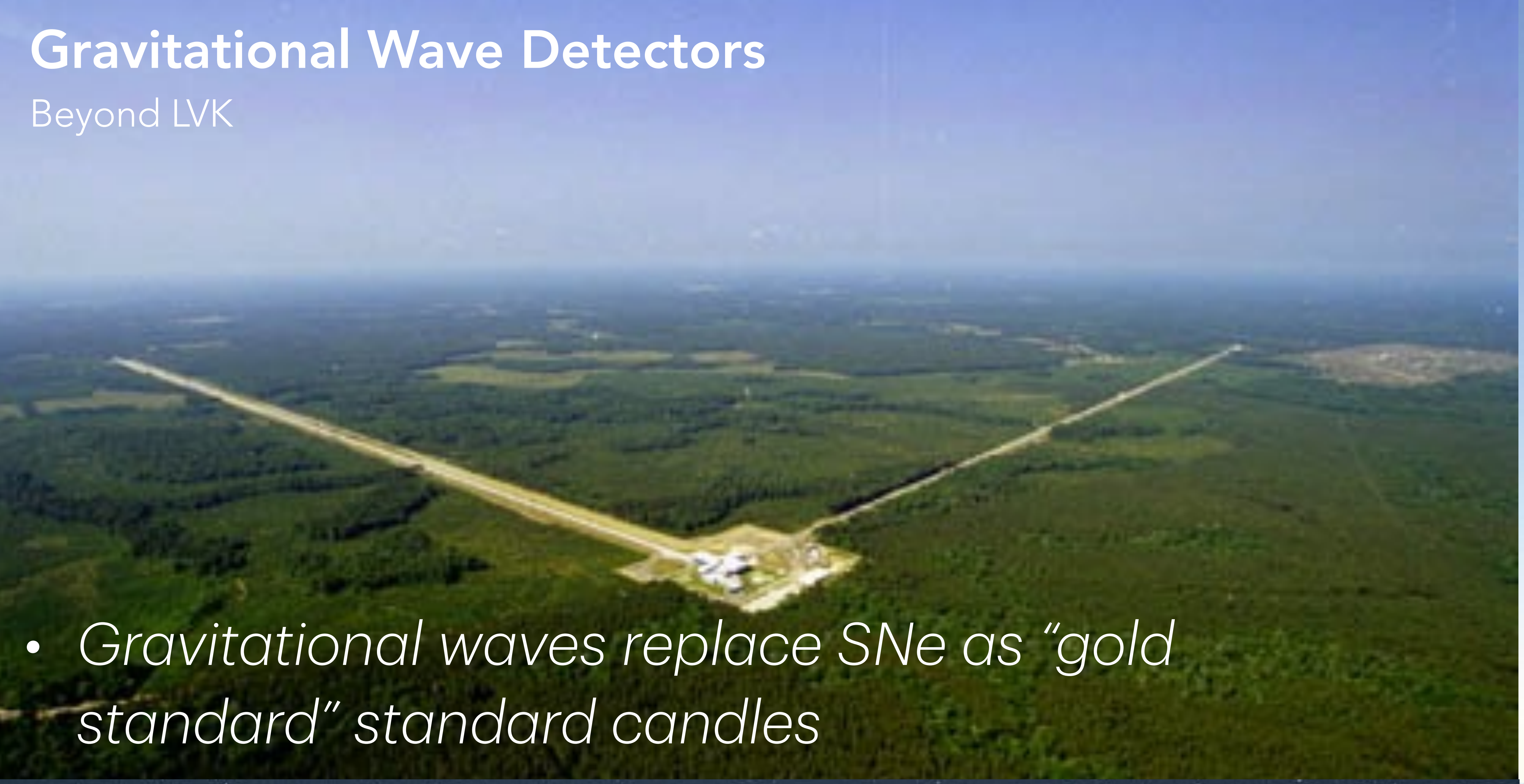
Weighing supermassive black holes

AGN Reveberation Mapping



Gravitational Wave Detectors

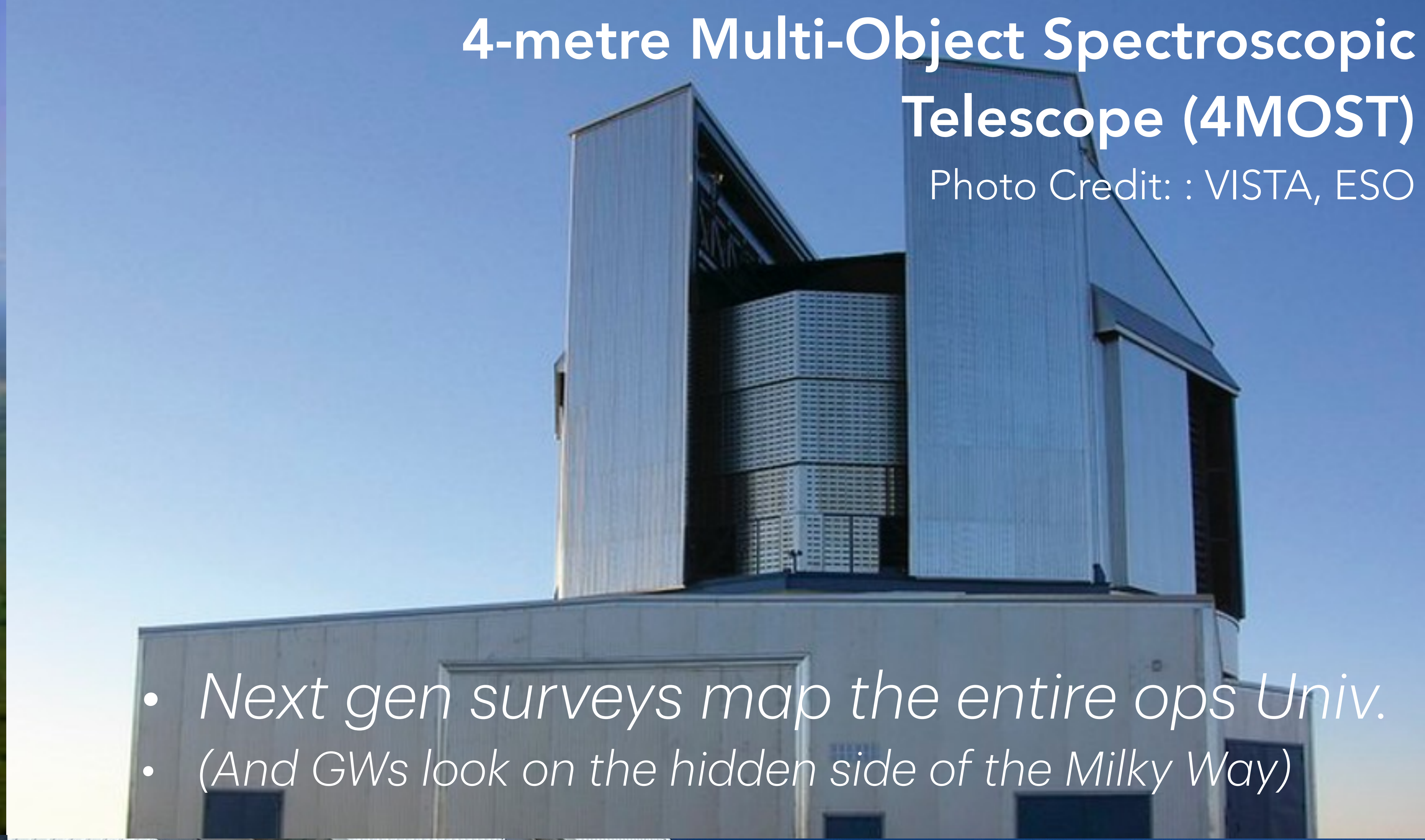
Beyond LVK



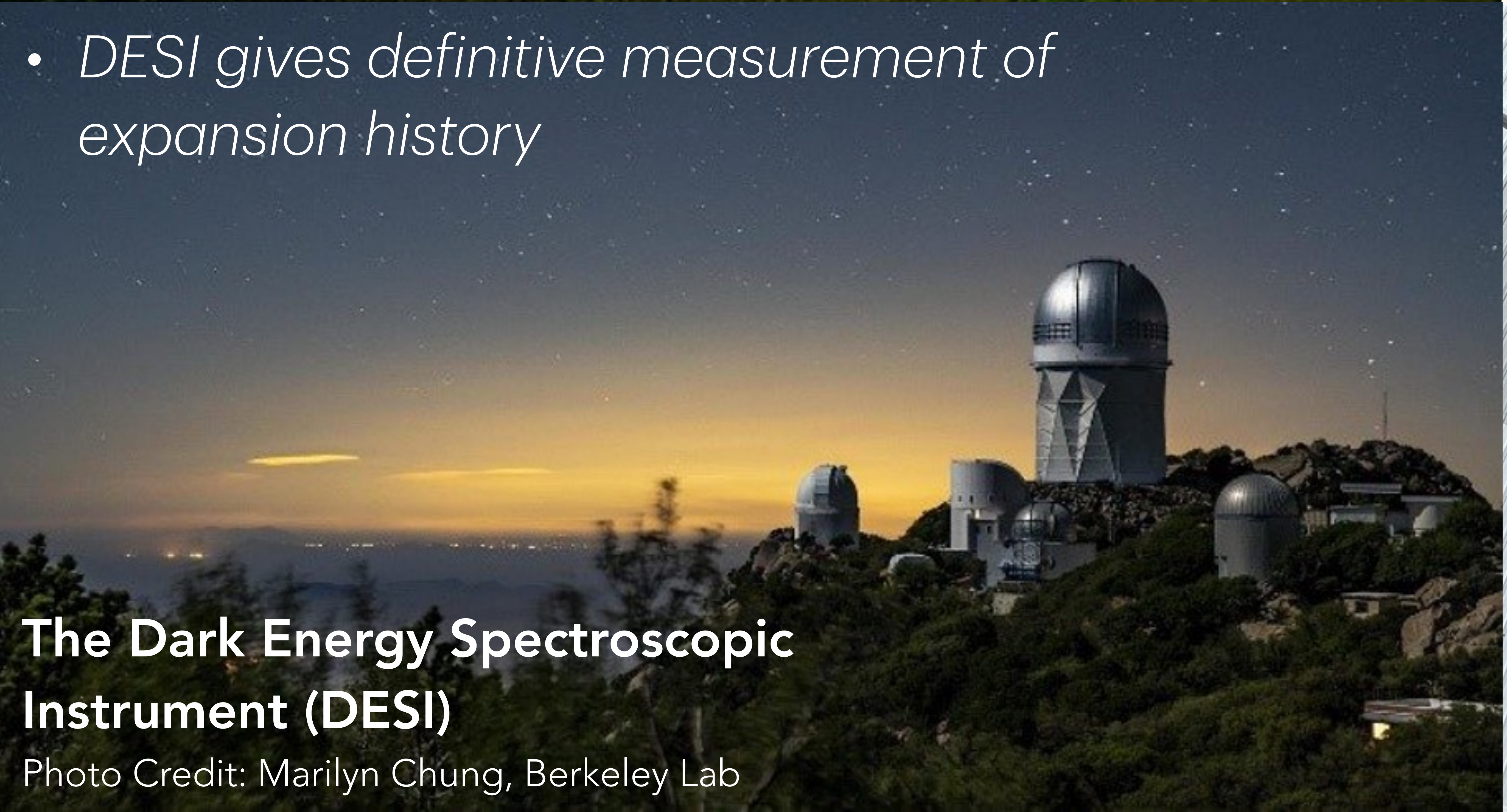
- *Gravitational waves replace SNe as "gold standard" standard candles*

4-metre Multi-Object Spectroscopic Telescope (4MOST)

Photo Credit: : VISTA, ESO



- *Next gen surveys map the entire ops Univ.*
- *(And GWs look on the hidden side of the Milky Way)*



- *DESI gives definitive measurement of expansion history*

The Dark Energy Spectroscopic Instrument (DESI)

Photo Credit: Marilyn Chung, Berkeley Lab

- *Rubin LSST makes movie of the sky*

Vera C. Rubin Observatory

Photo Credit: Me

Dark Energy Survey SN Cosmology Final Results

- Summary:
  - DES-SN5YR is the largest and deepest single-telescope SN sample to date
  - Excellent control of selection effects and contamination
  - Found hints that dark energy may vary.

- Future Work:
  - Analyse DES-SN5YR using the Bayesian Hierarchical Method UNITY
  - Updating the Low-z sample (ZTF, DEBASS)
  - DES+SDSS+PanSTARRS: a Hubble diagram of 3550 SNe Ia
  - fully independent from Pantheon+ and Union3.
  - Working on the next generation of SN samples...

DES Collaboration 2024

Key paper 2401.0292

Vincenzi et al. 2401.02945

Bonus science

Shah et al. 2406.05047

Camilleri et al. 2406.05048

Camilleri et al. 2406.05049

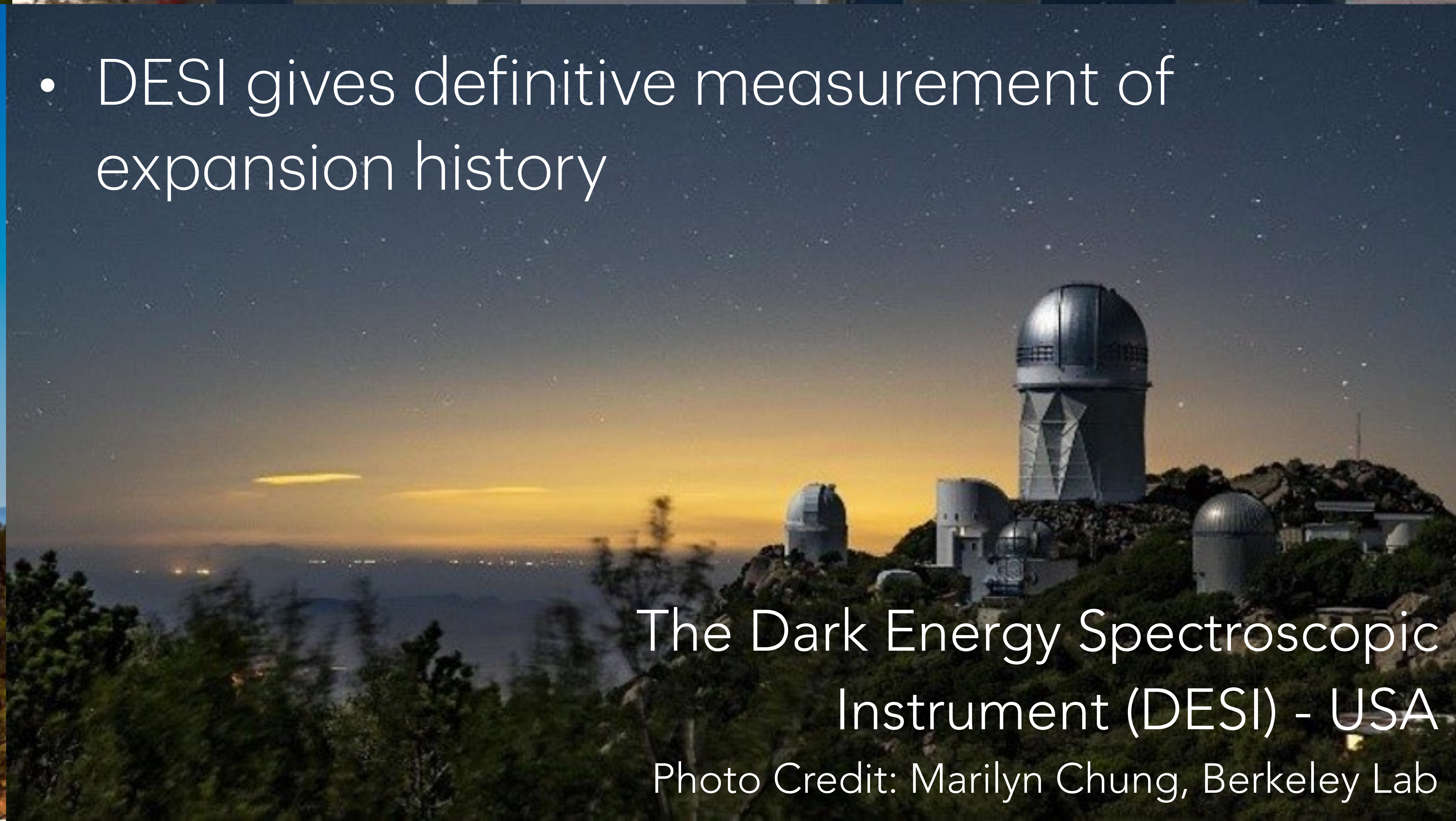
White et al. 2406.05050

Popovic et al. 2406.05051


LIGO / VIRGO / KAGRA
Gravitational Wave Detectors
• Gravitational waves replace SNe as "gold standard" standard candles


4-metre Multi-Object Spectroscopic Telescope (4MOST) - Chile
Photo Credit: : VISTA, ESO
• Next generation of surveys map the entire observable Universe (incl. GWs look on the hidden side of the Milky Way)


• Rubin LSST makes movie of the sky
Vera C. Rubin Observatory
Photo Credit: Me


• DESI gives definitive measurement of expansion history
The Dark Energy Spectroscopic Instrument (DESI) - USA
Photo Credit: Marilyn Chung, Berkeley Lab


Vera C. Rubin Observatory
8.4m mirror.
3200 Mpixels.
40x full moon.
Whole sky
every 3 nights.
500 PB of images
7 trillion images of
37 billion sources
See on
ABC Catalyst!

Bonus tests

Cutting low-z and high-z