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Cosmological constraints on fundamental physics

The AAT and its siblings

AAT



2dF (OzDES)

Blanco



DECam (DES)

Mayall



DESI (DESI)

Let's go...

How we detect dark energy

Hubble diagram cosmology basics

Distance $D = c \int_0^z \frac{dz}{H(z)}$

Speed of light c

Redshift z

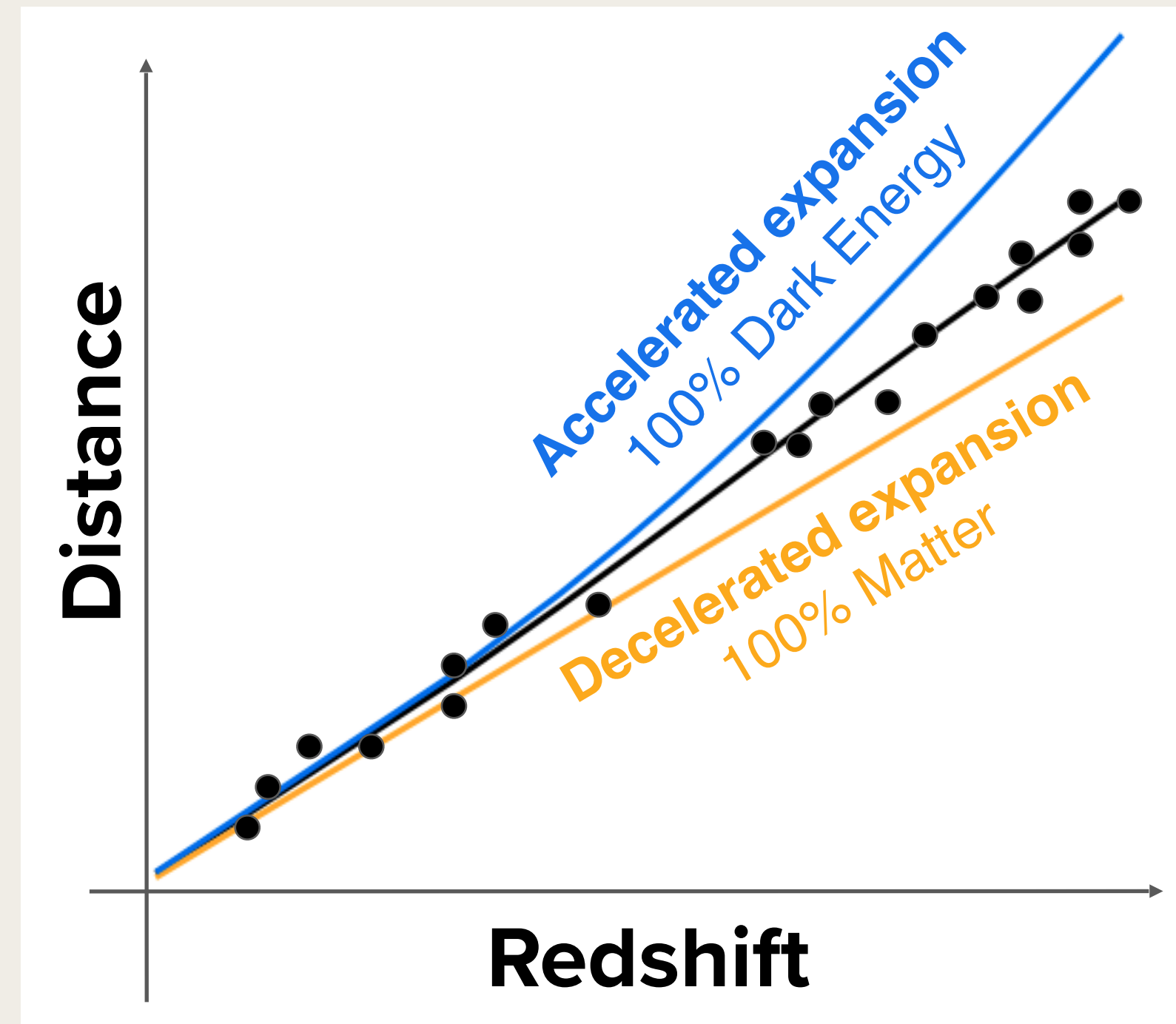
Hubble parameter $H(z)$

$$H(z) = H_0 \sum_i \Omega_i (1+z)^{3(1+w_i)}$$

Hubble constant H_0

Density Ω_i

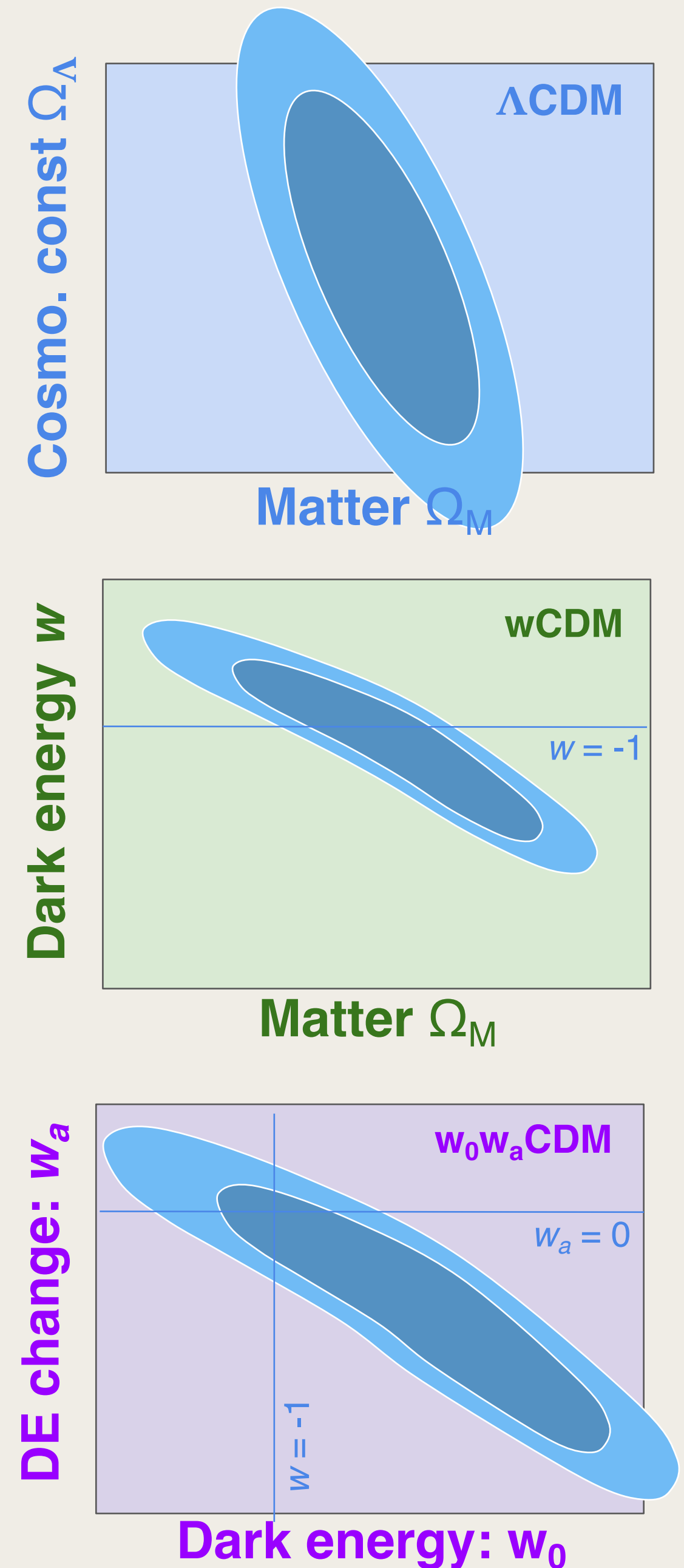
Equation of state w_i



Ω_M = matter density; $w_M = 0$

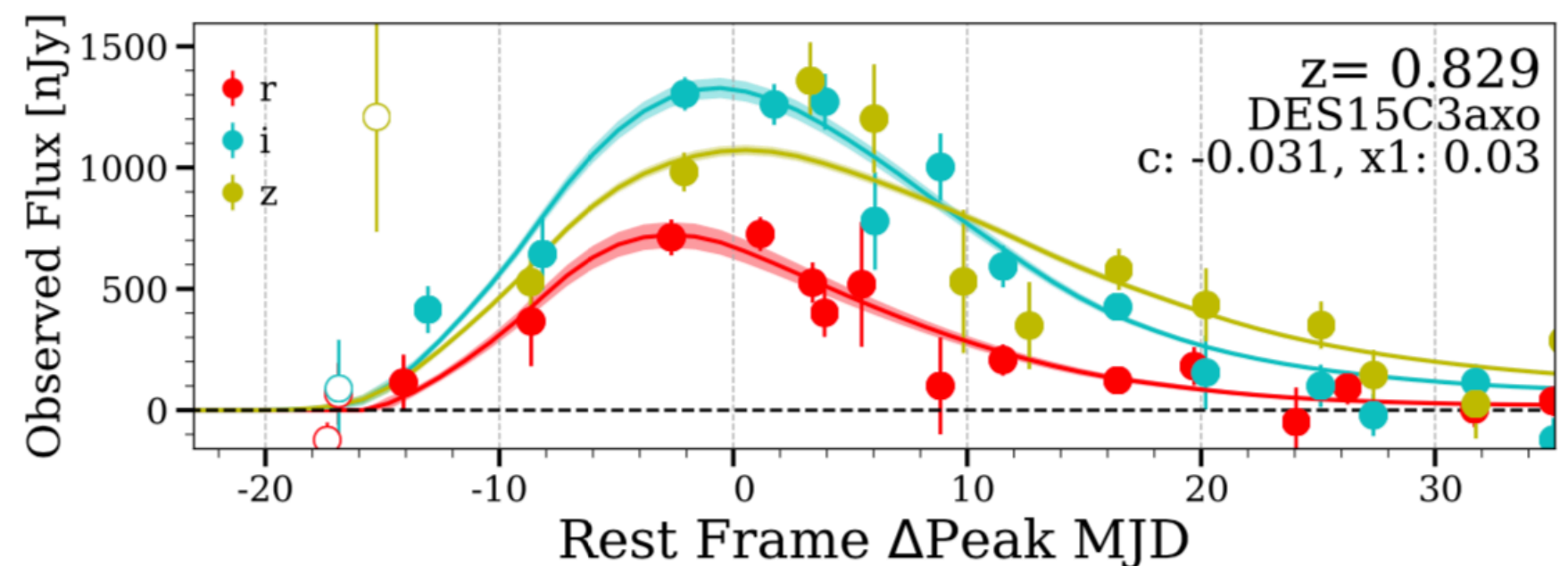
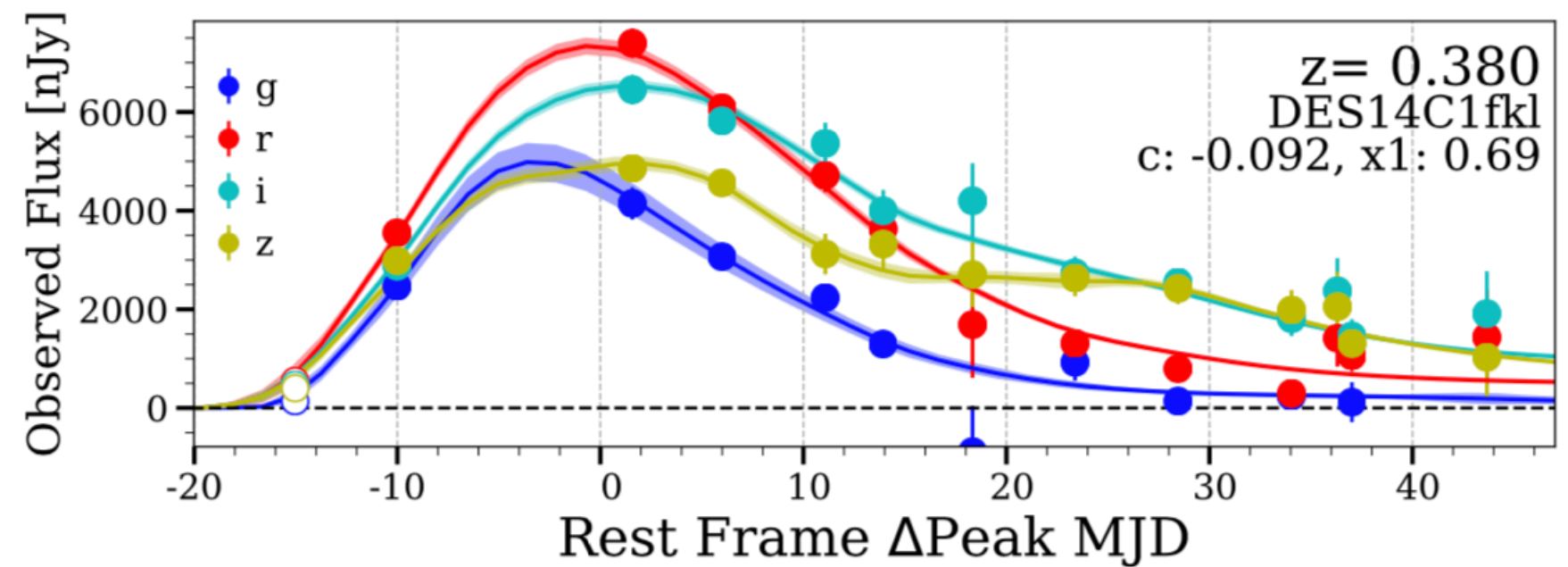
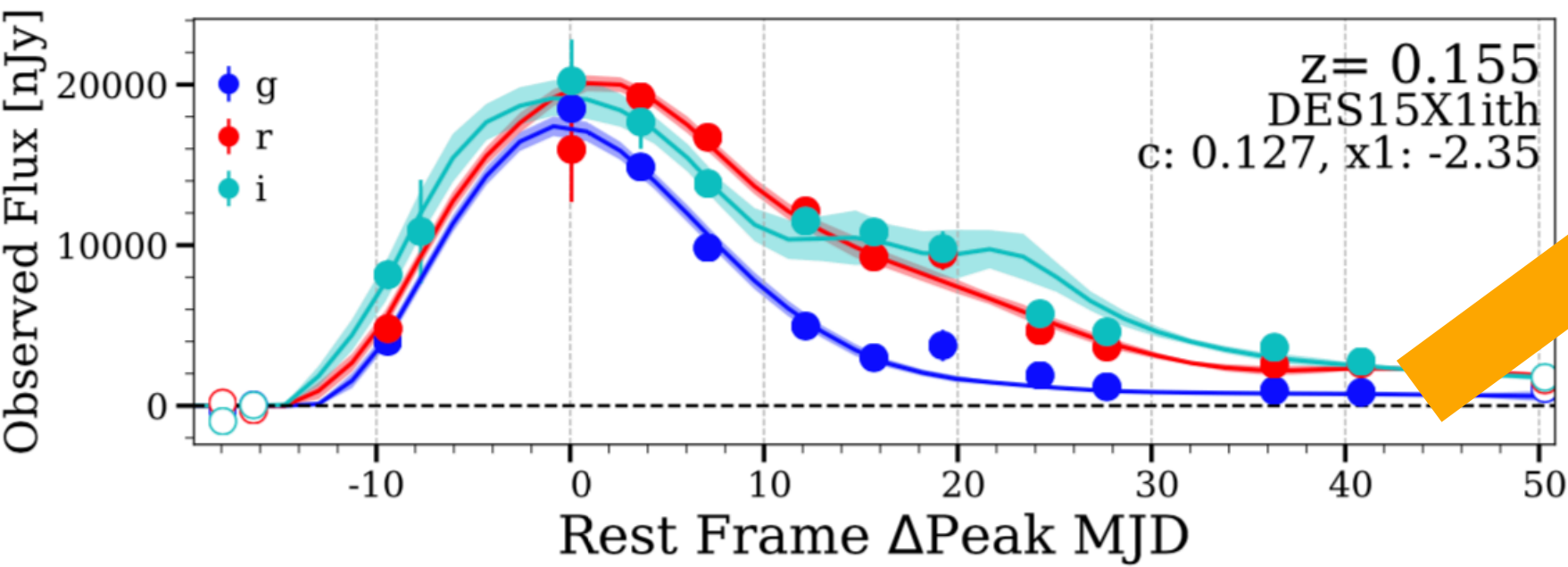
Ω_Λ = dark energy density; $w_\Lambda = -1$ for cosmo. const.

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



Supernova cosmology

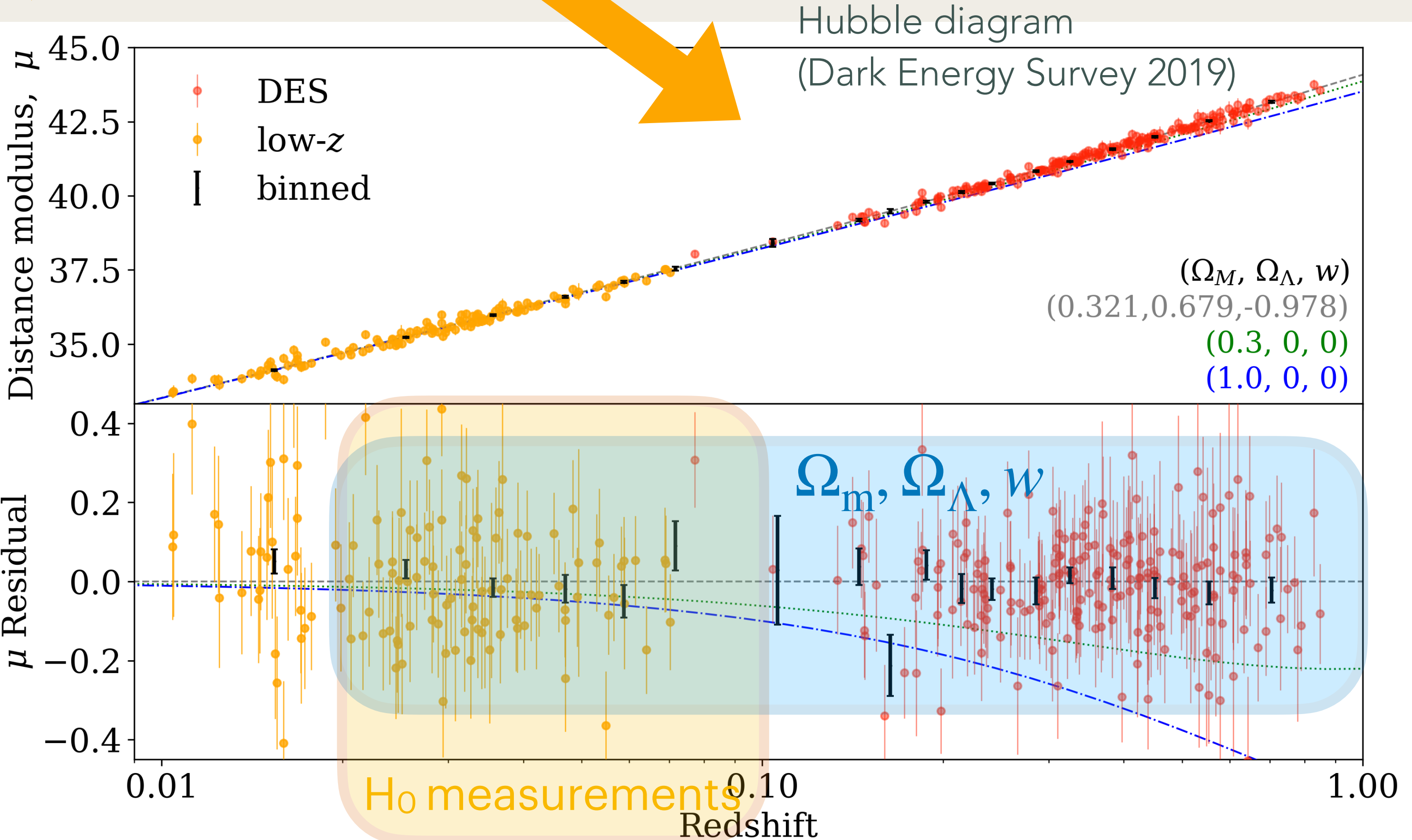
Light curves (Brout et al. DES 2019)



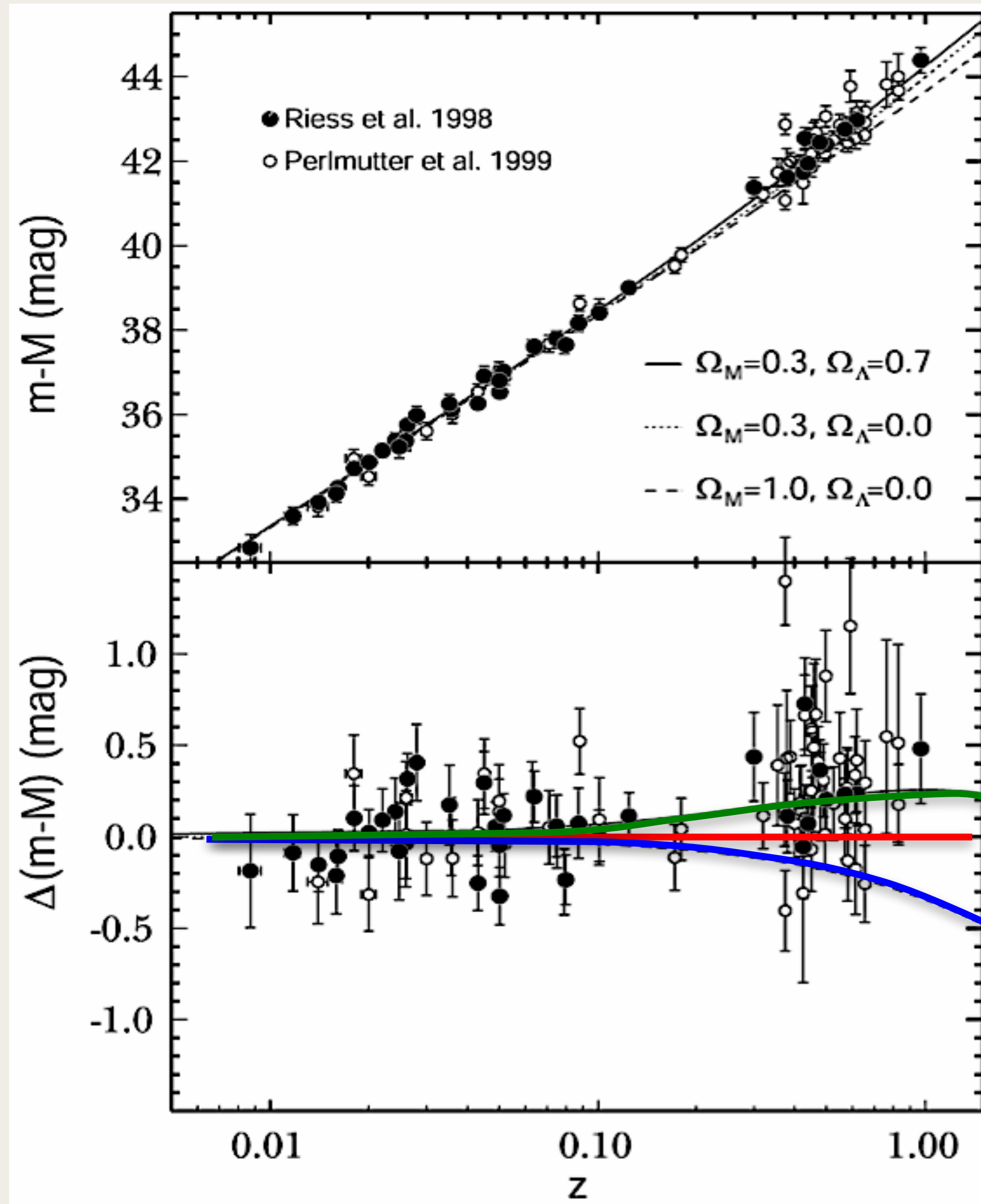
distance modulus: $\mu_B = m_B^* - M_B + \alpha x_1 - \beta C + \gamma G_{\text{host}} + \Delta\mu_{\text{bias}}$

derived from fit to SNIa light curve
can be constrained using cosmo fits

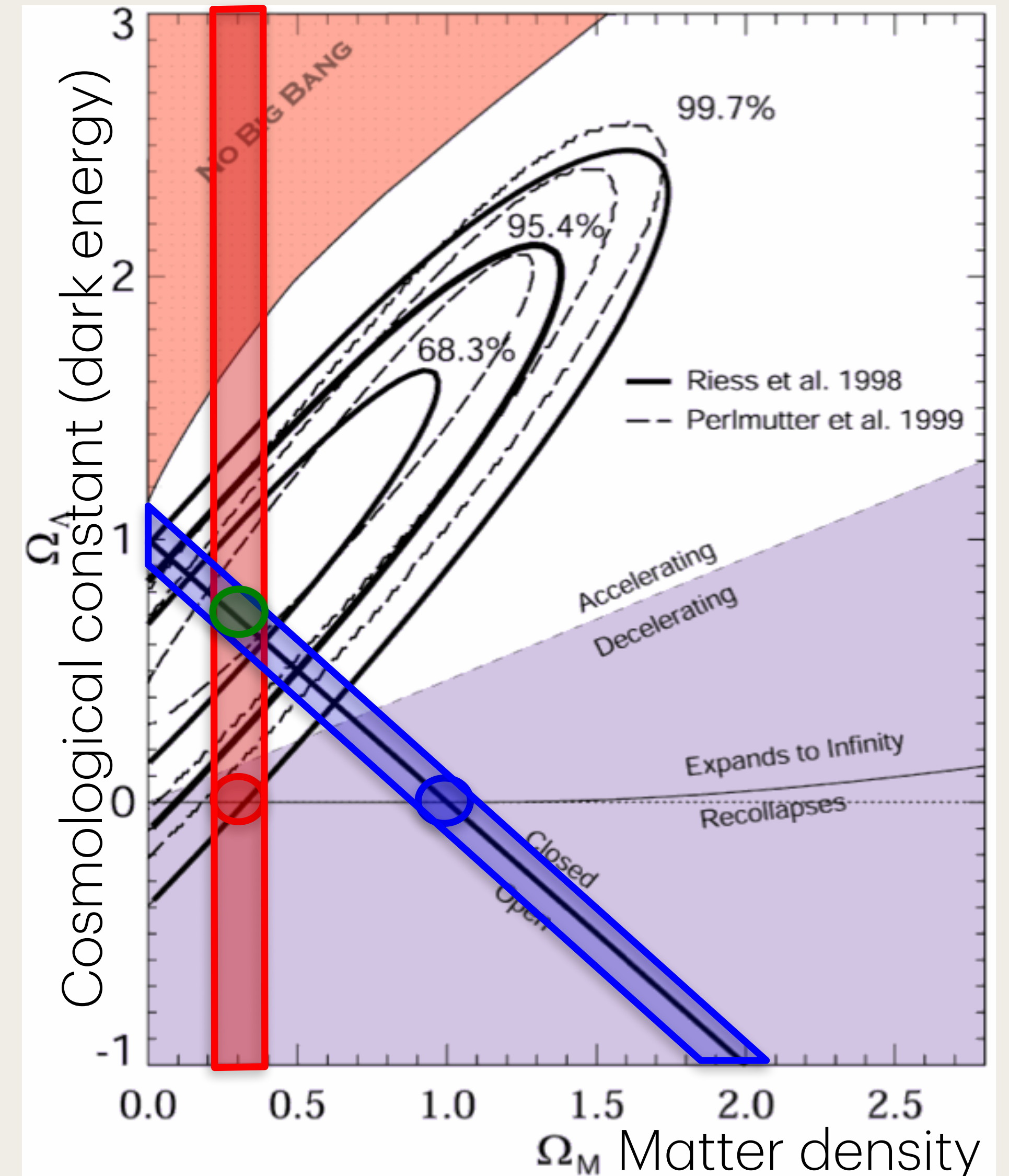
Legend for equation terms:
distance modulus: μ_B
apparent mag: m_B^*
abs mag: M_B
stretch scale: x_1
colour scale: C
host scale: G_{host}
host mass factor: γ
malmquist + selection bias: $\Delta\mu_{\text{bias}}$



Discovery of Acceleration (dark energy)



Everyone's
happy
Observers
Theorists



Perlmutter & Schmidt 2003

An insight into quantum gravity?

Why I find dark
energy
interesting...

Cosmological constant / vacuum energy

Einstein's equation with a cosmological constant:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Can be rearranged to instead have vacuum energy:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} \left(T_{\mu\nu} + T_{\mu\nu}^{(\Lambda)} \right)$$

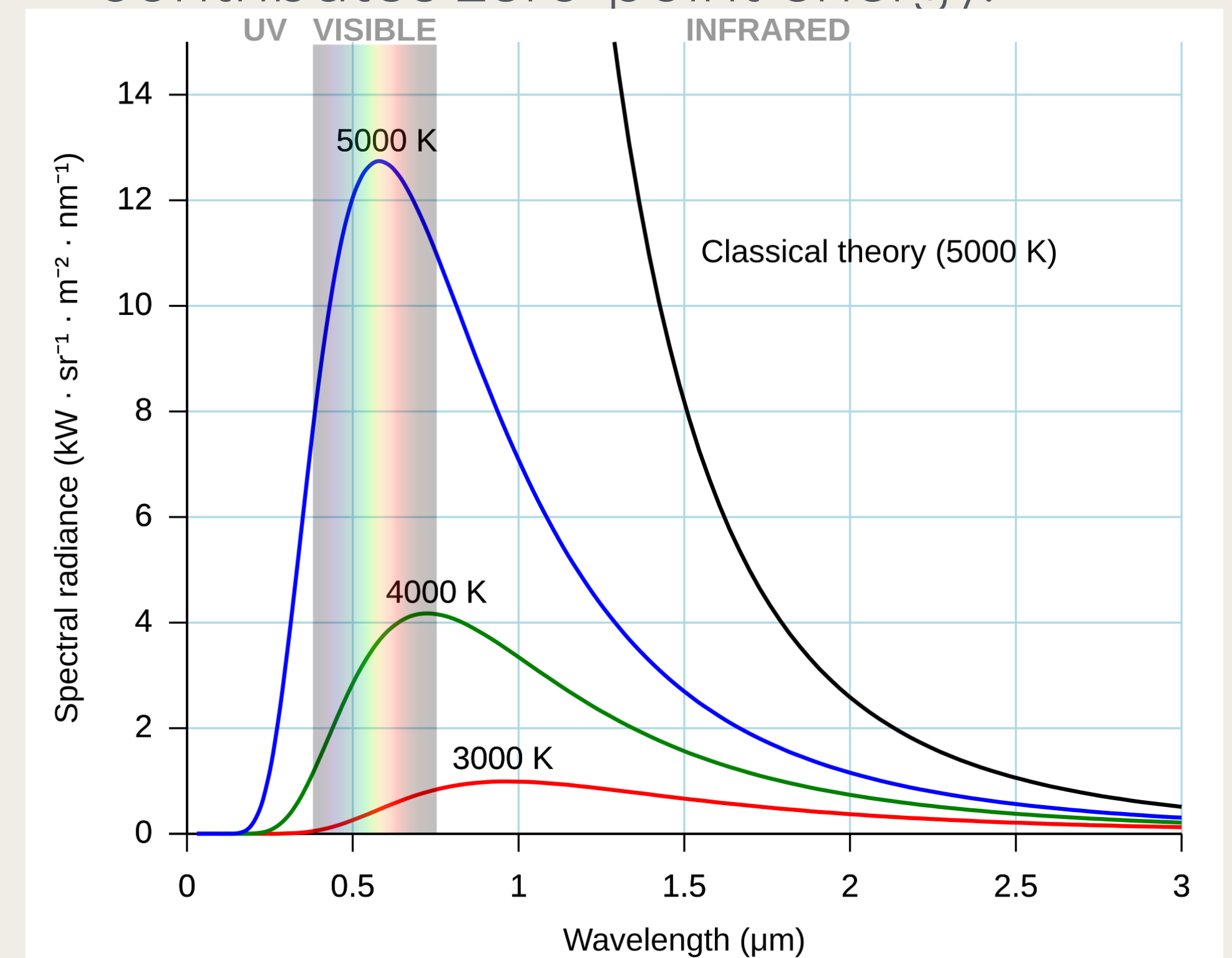
Vacuum energy is predicted by quantum physics,
and mathematically identical to a cosmo. const. when:

$$T_{\mu\nu}^{(\Lambda)} = -\frac{\Lambda c^4}{8\pi G} g_{\mu\nu} \qquad \rho_{\Lambda} = \frac{\Lambda c^2}{8\pi G}$$

With eq. of state: $w \equiv \frac{p_{\Lambda}}{\rho_{\Lambda} c^2} = -1$

So why isn't dark energy solved?

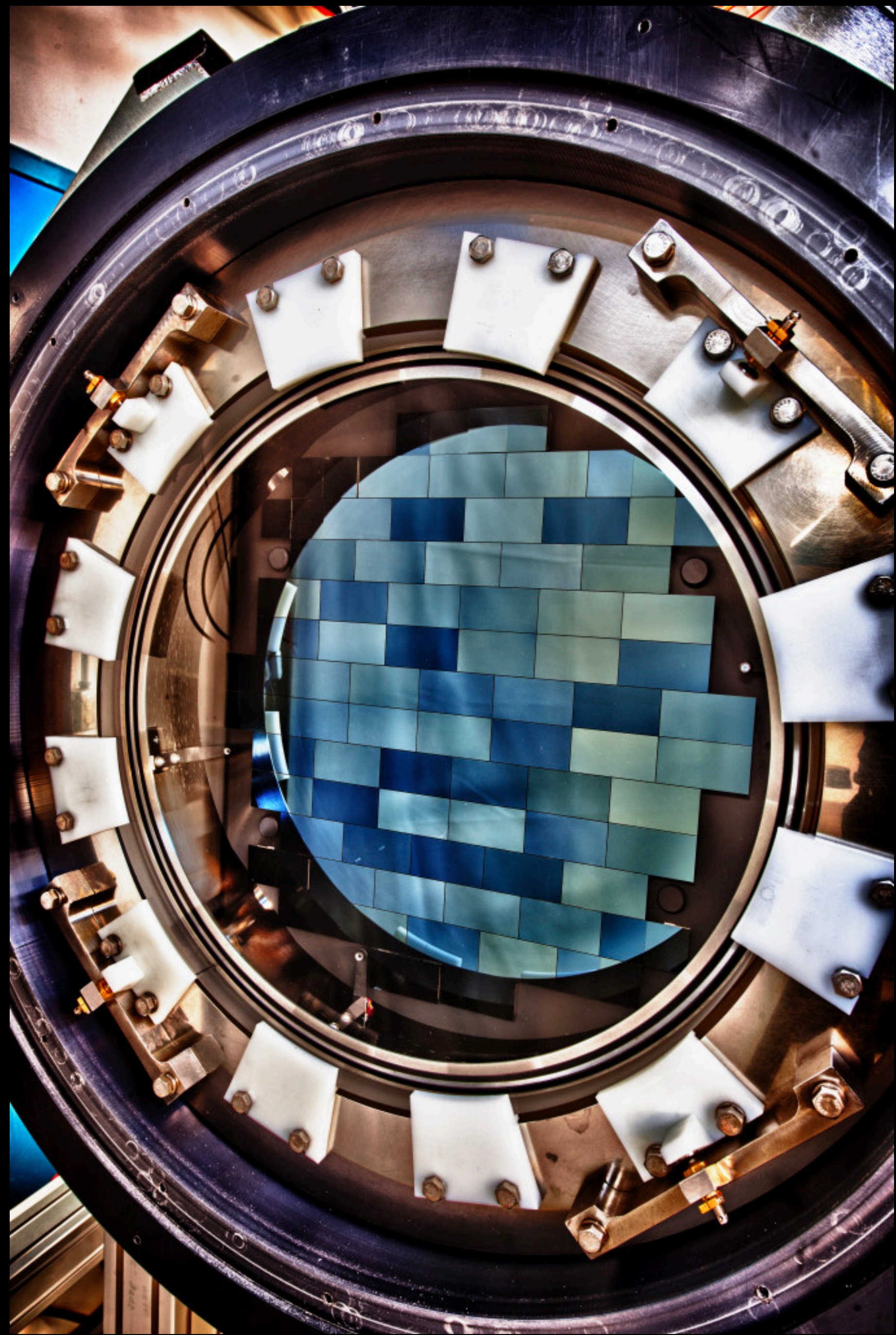
Quantum field theory predicts every mode of every quantum field contributes zero-point energy.



The cosmological constant catastrophe

Let's measure it more precisely...

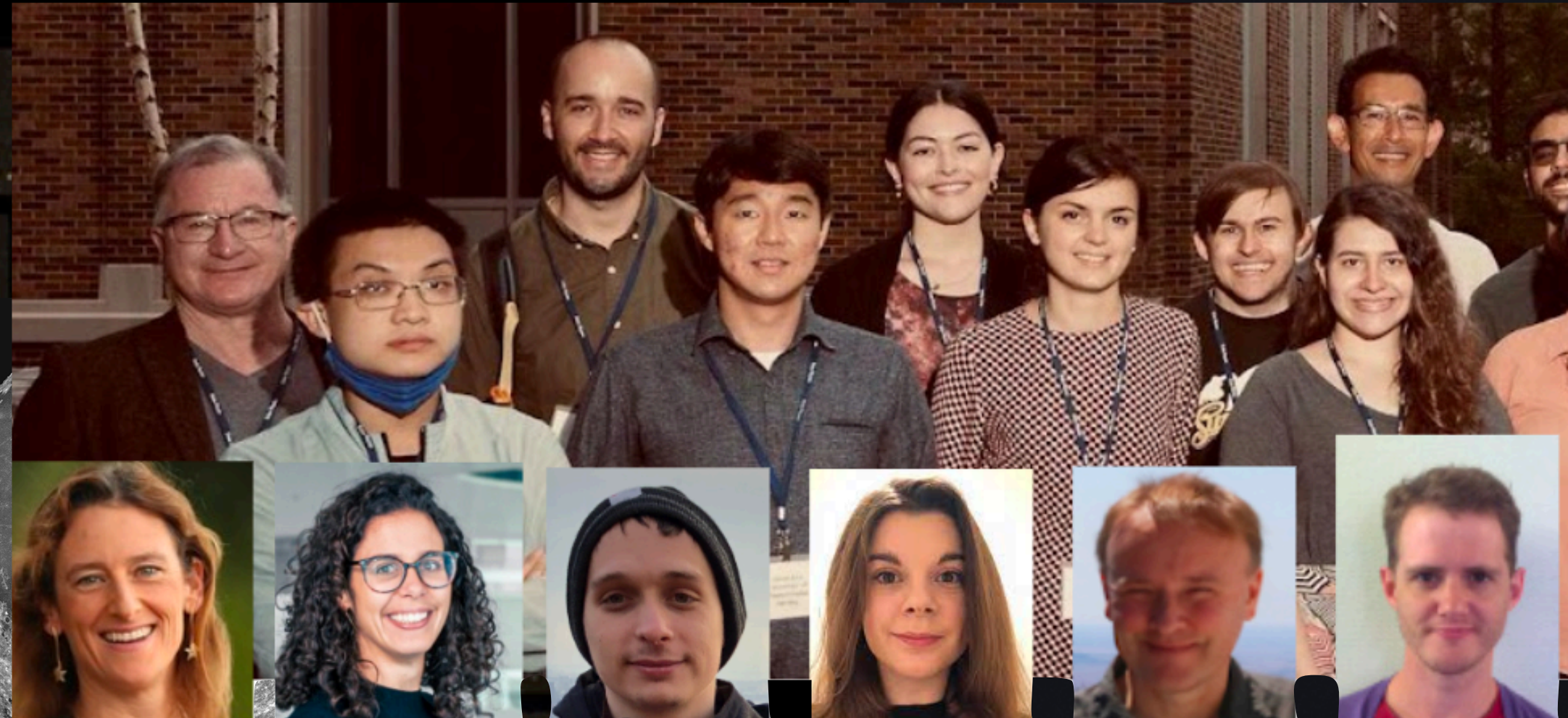
The Dark Energy Survey (DES)



The Dark Energy Survey

570 mega-pixels
10 years designing
6 years observing

Approximately:
▶ 543 million galaxies
▶ 145 million stars
▶ 700,000 asteroids
▶ 20,000 supernovae



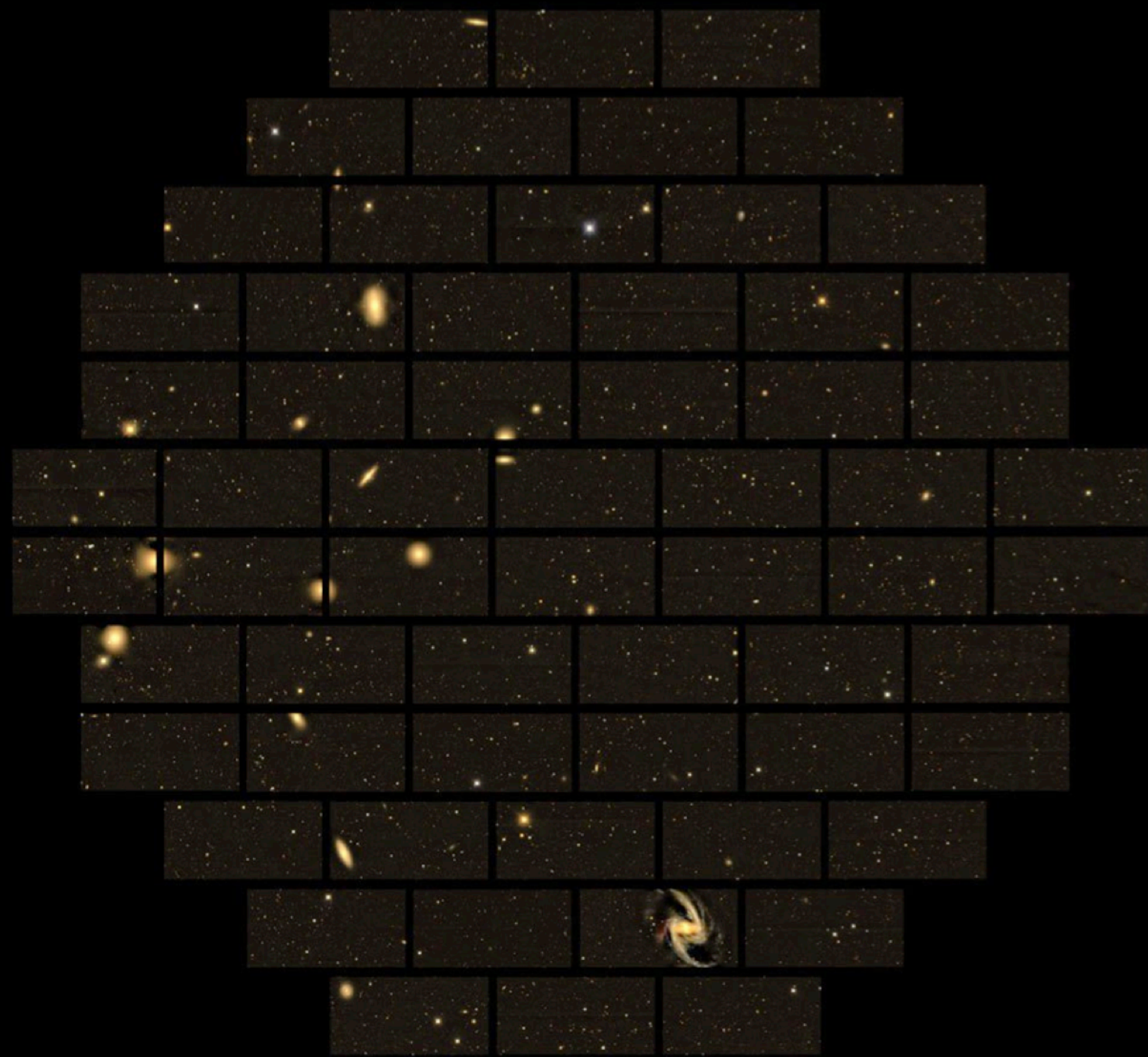
A 2dF night at the Anglo-Australian Telescope



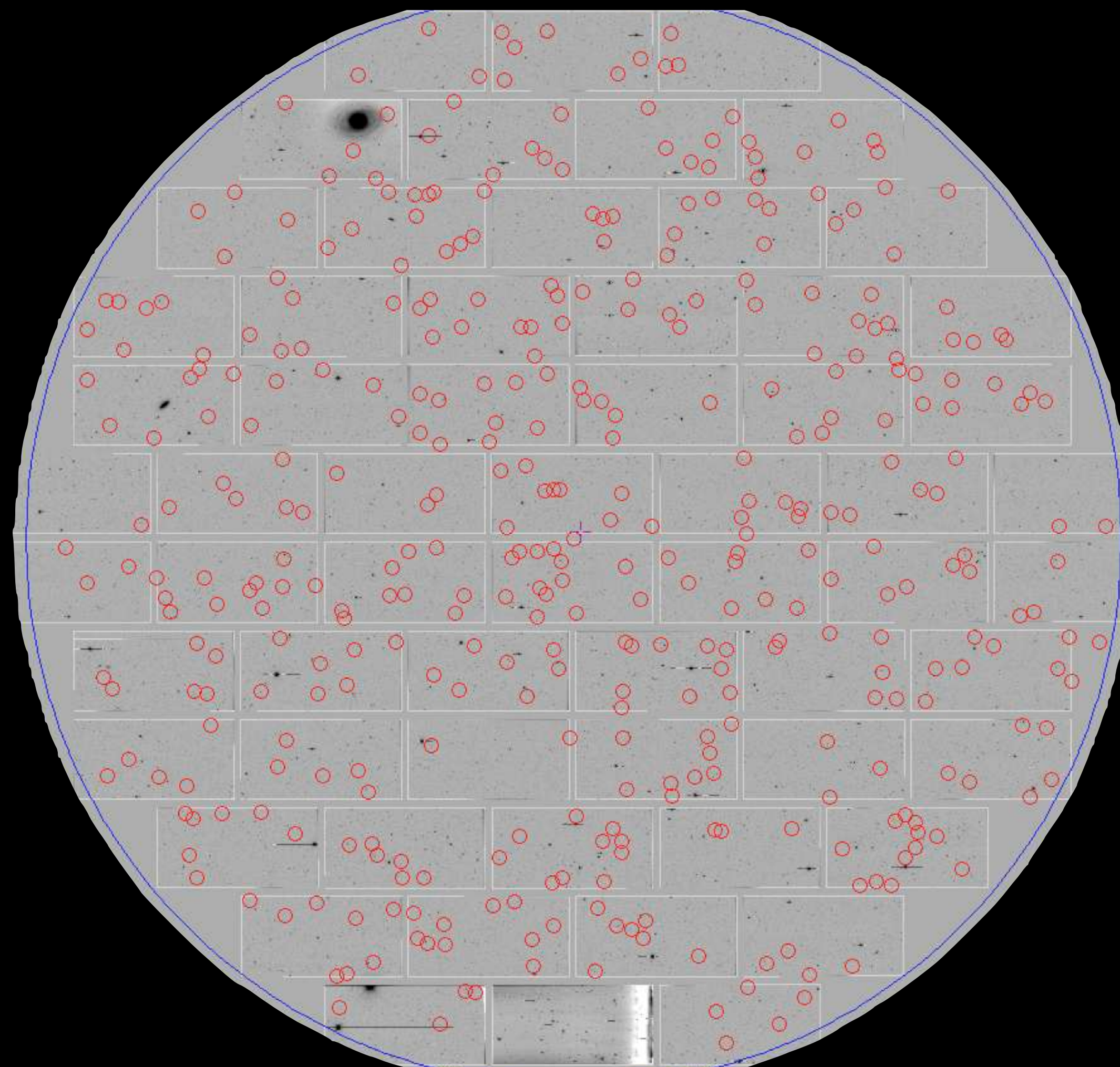
Australian Government

**Department of Industry
Innovation, Science, Research
and Tertiary Education**

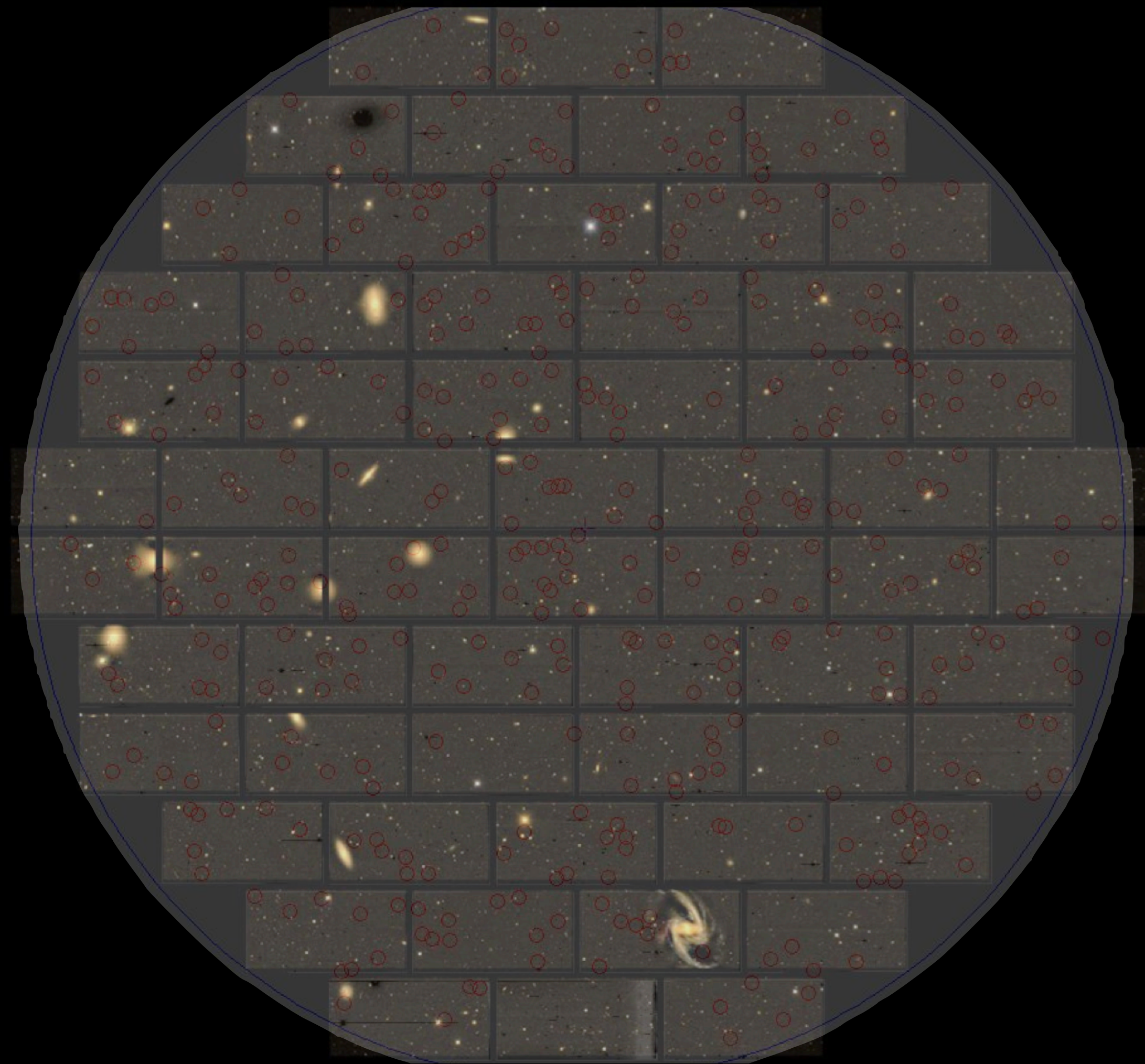




DECam (DES)

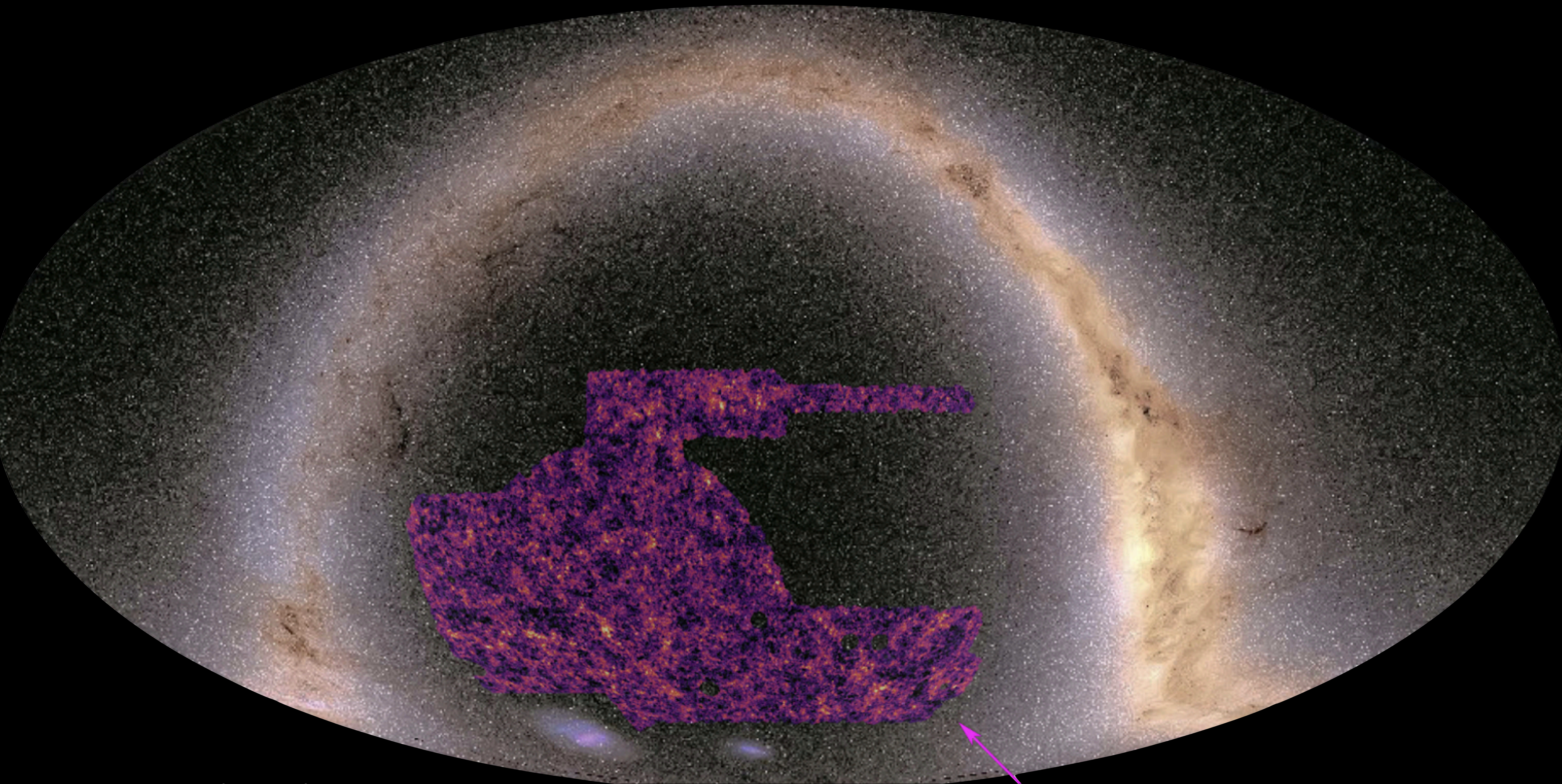


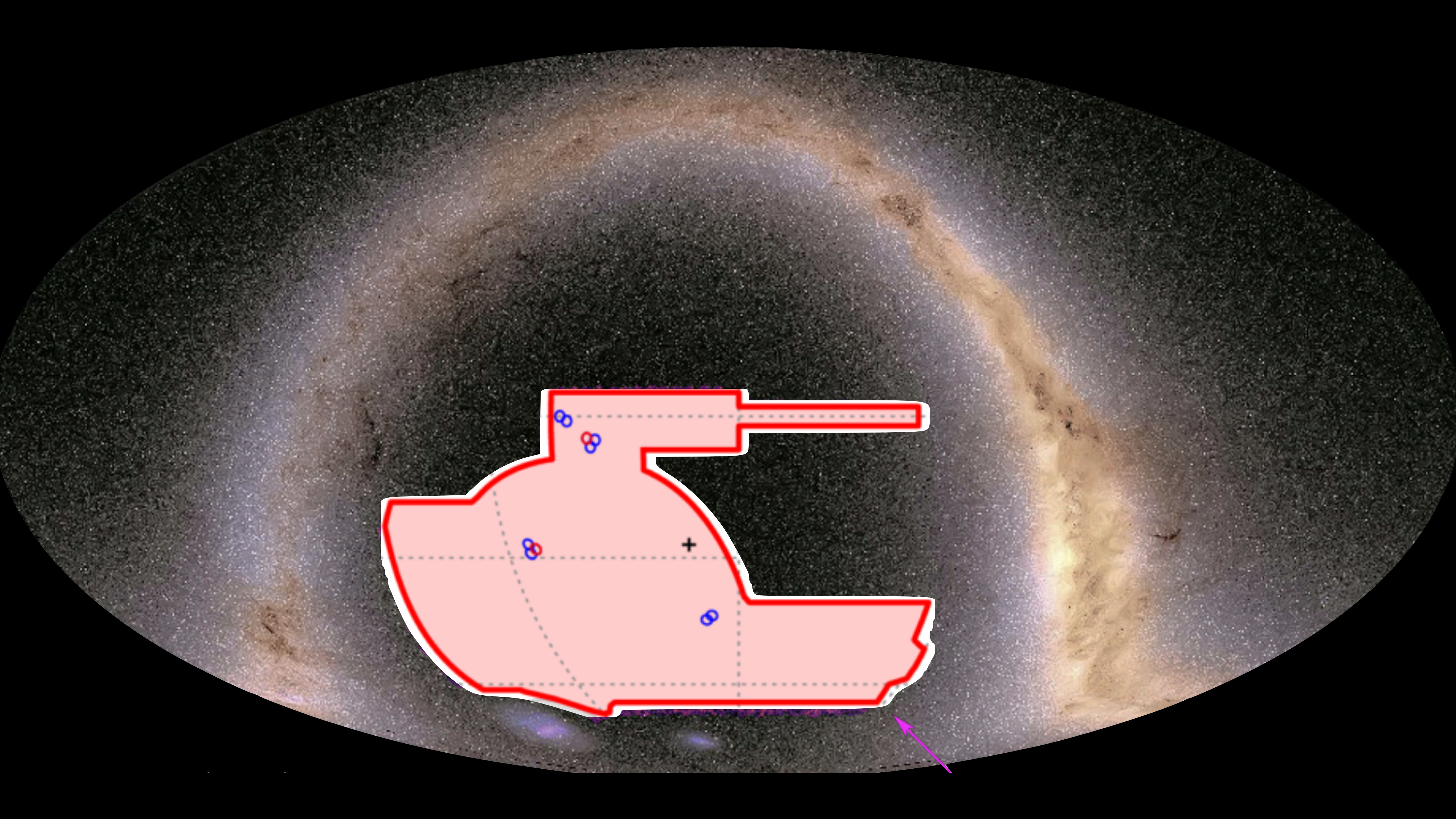
2dF (OzDES)



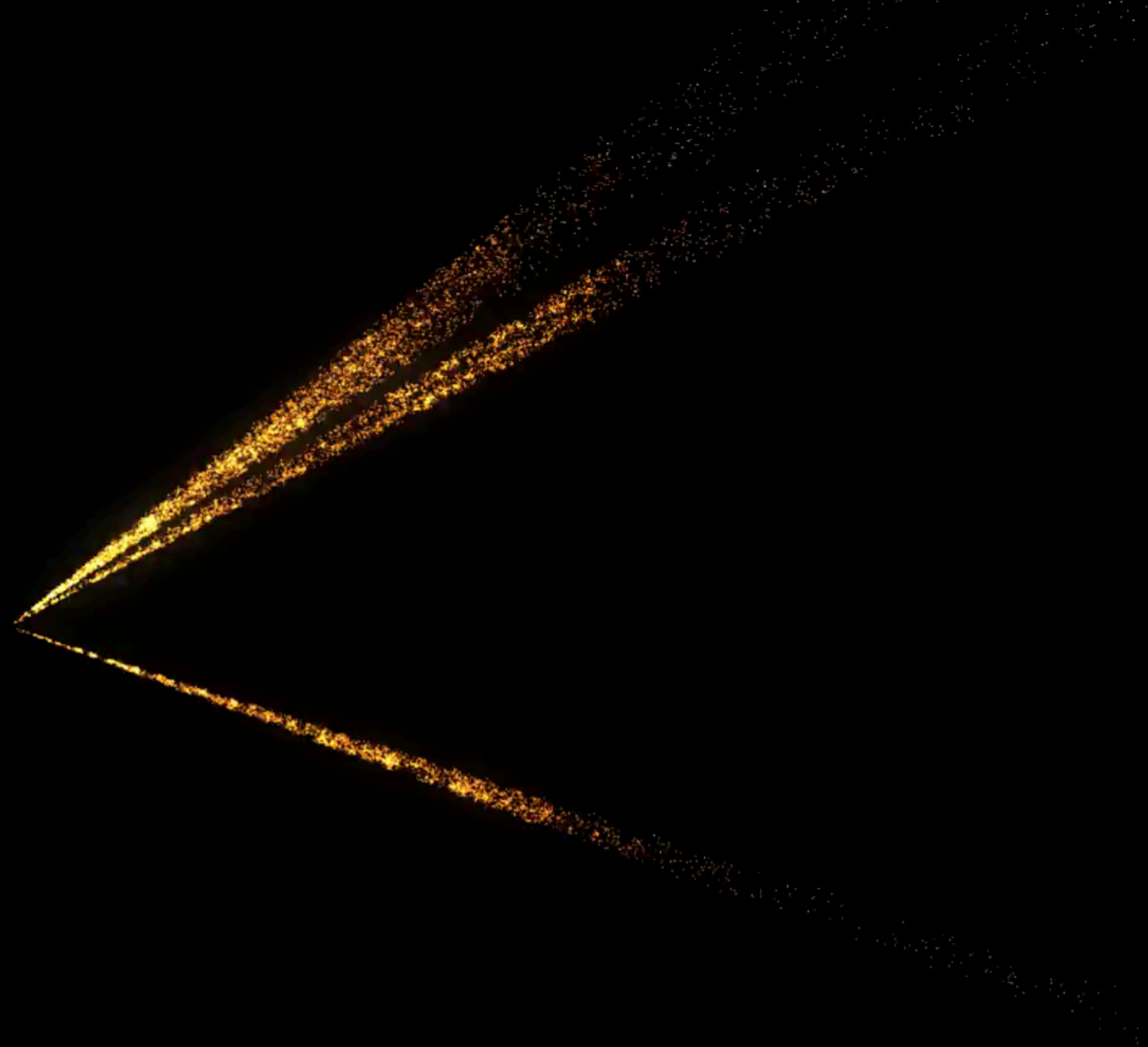
DECam (DES)

2dF (OzDES)





DES supernovae



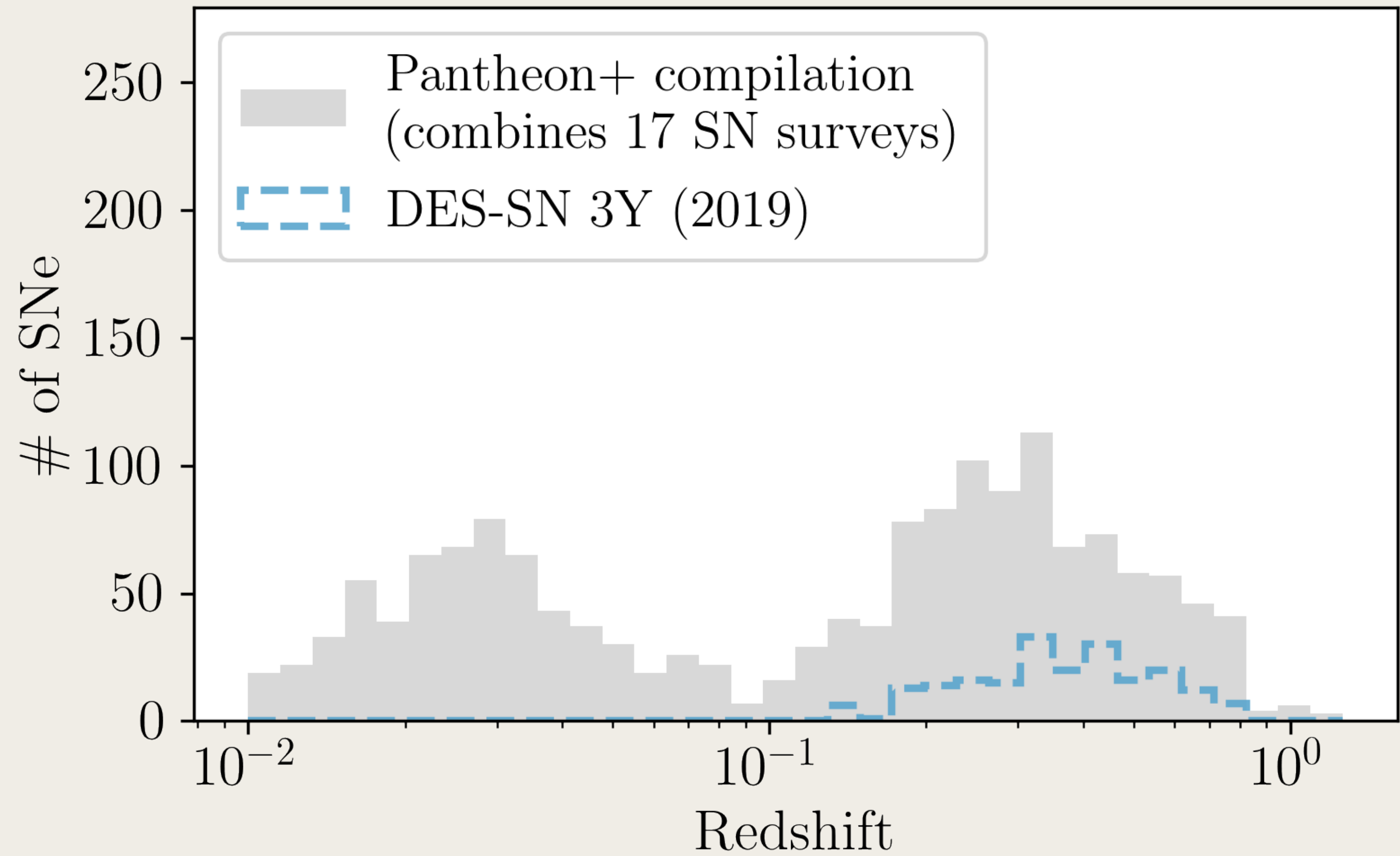
The DES Sample



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

- Approx 1500 new **high-redshift supernovae**
- 80% of SNe Ia ($z > 0.5$)
- Focus: systematics control
- Hints that dark energy may change with time

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



The DES Sample

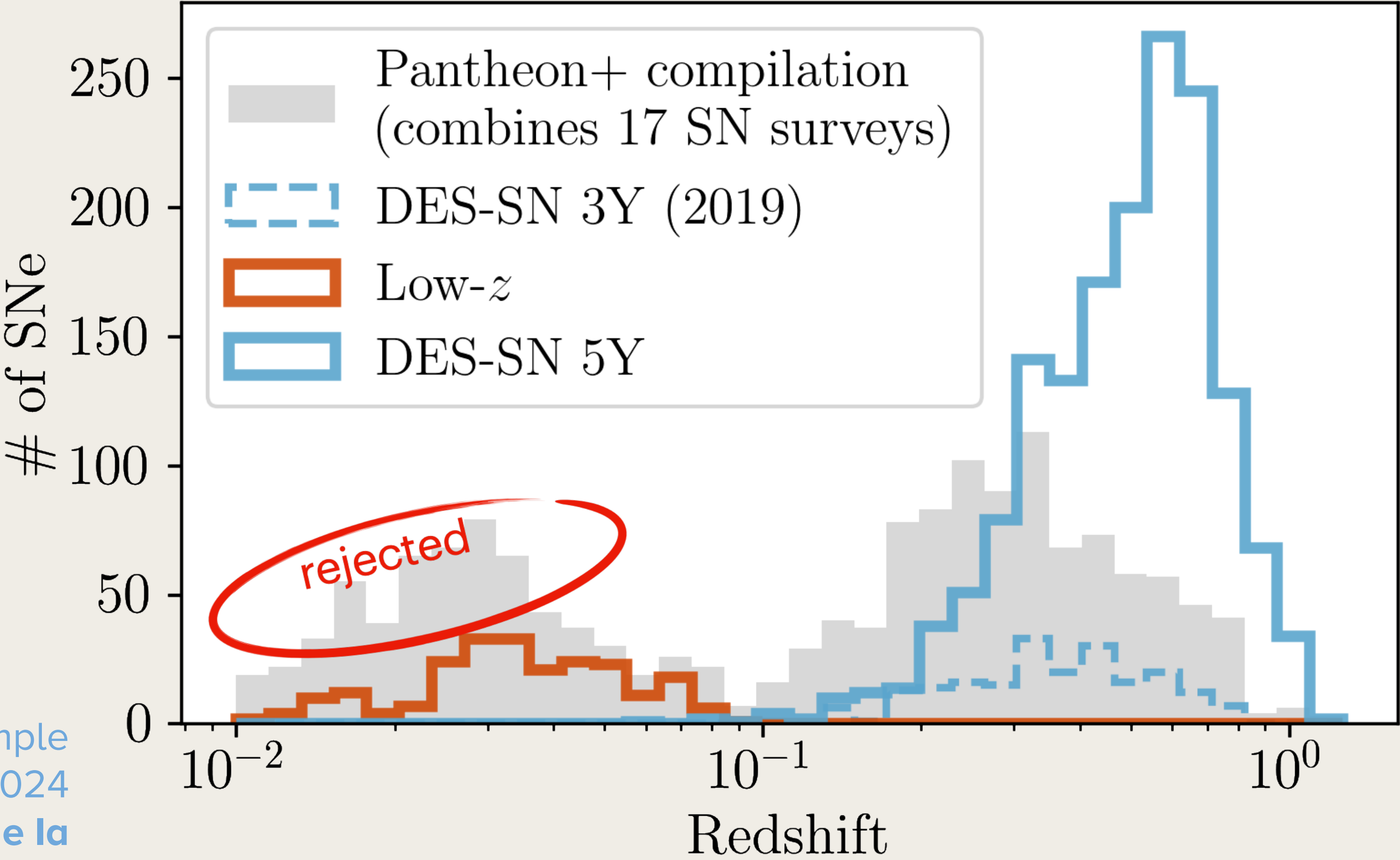


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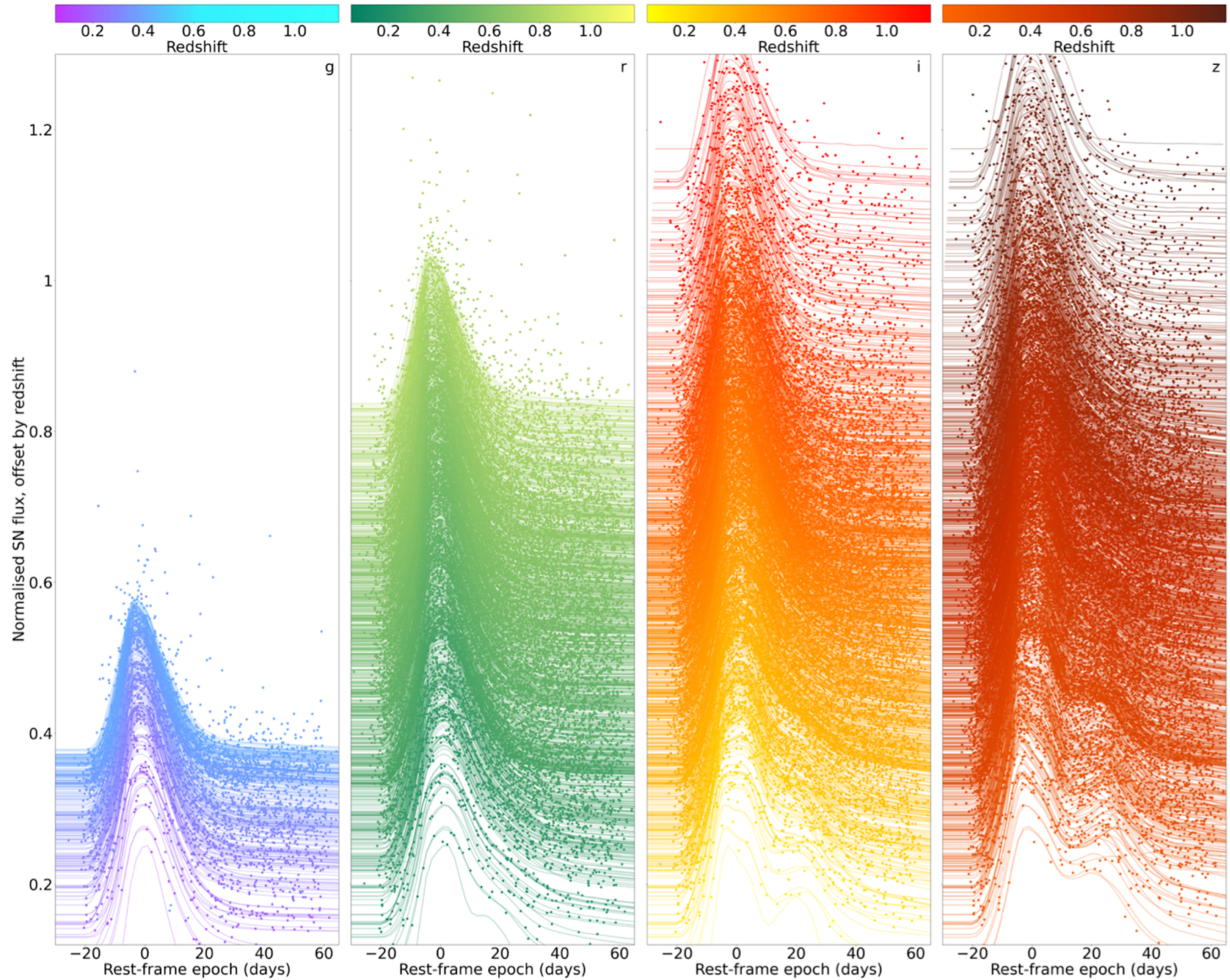
Pantheon+ and **Union** compilations
Brout et al. 2021
Rubin et al. 2024

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



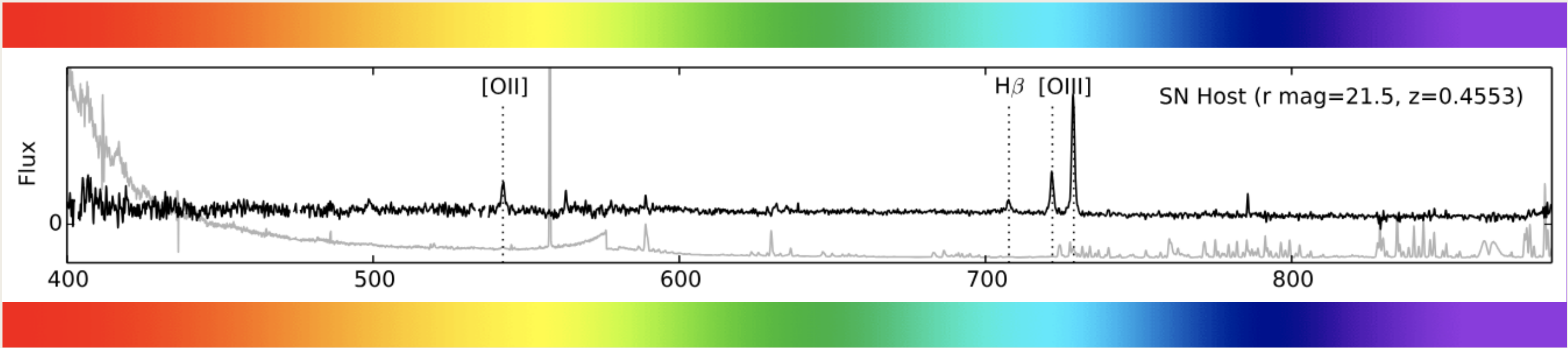
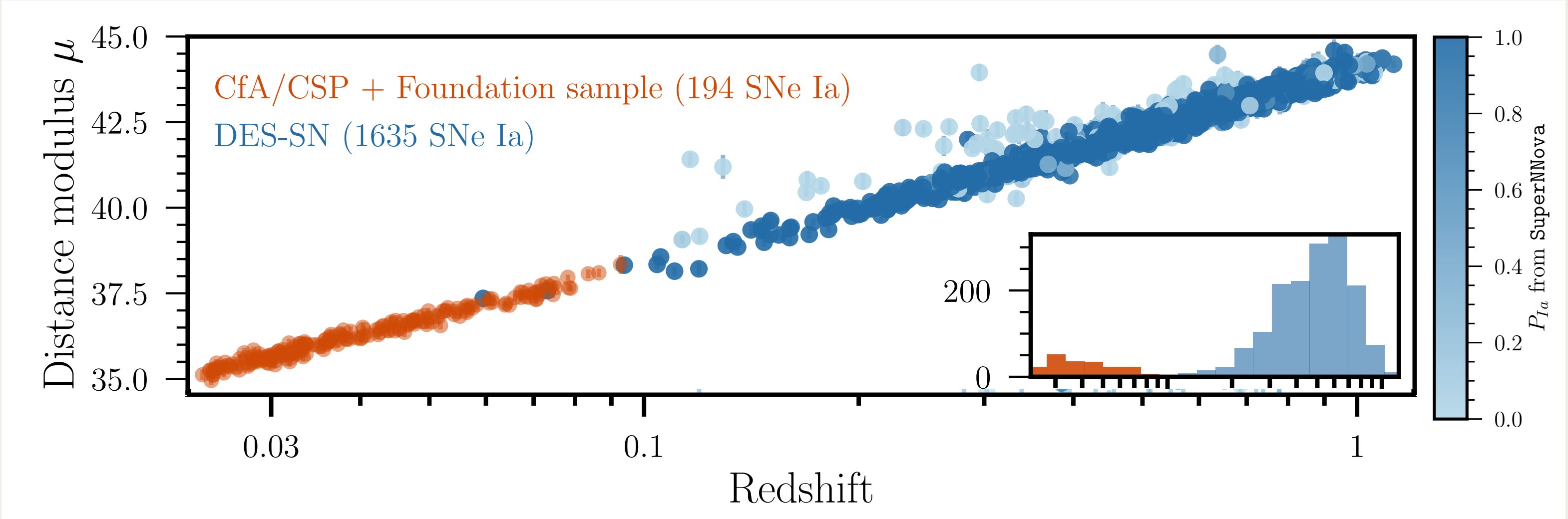
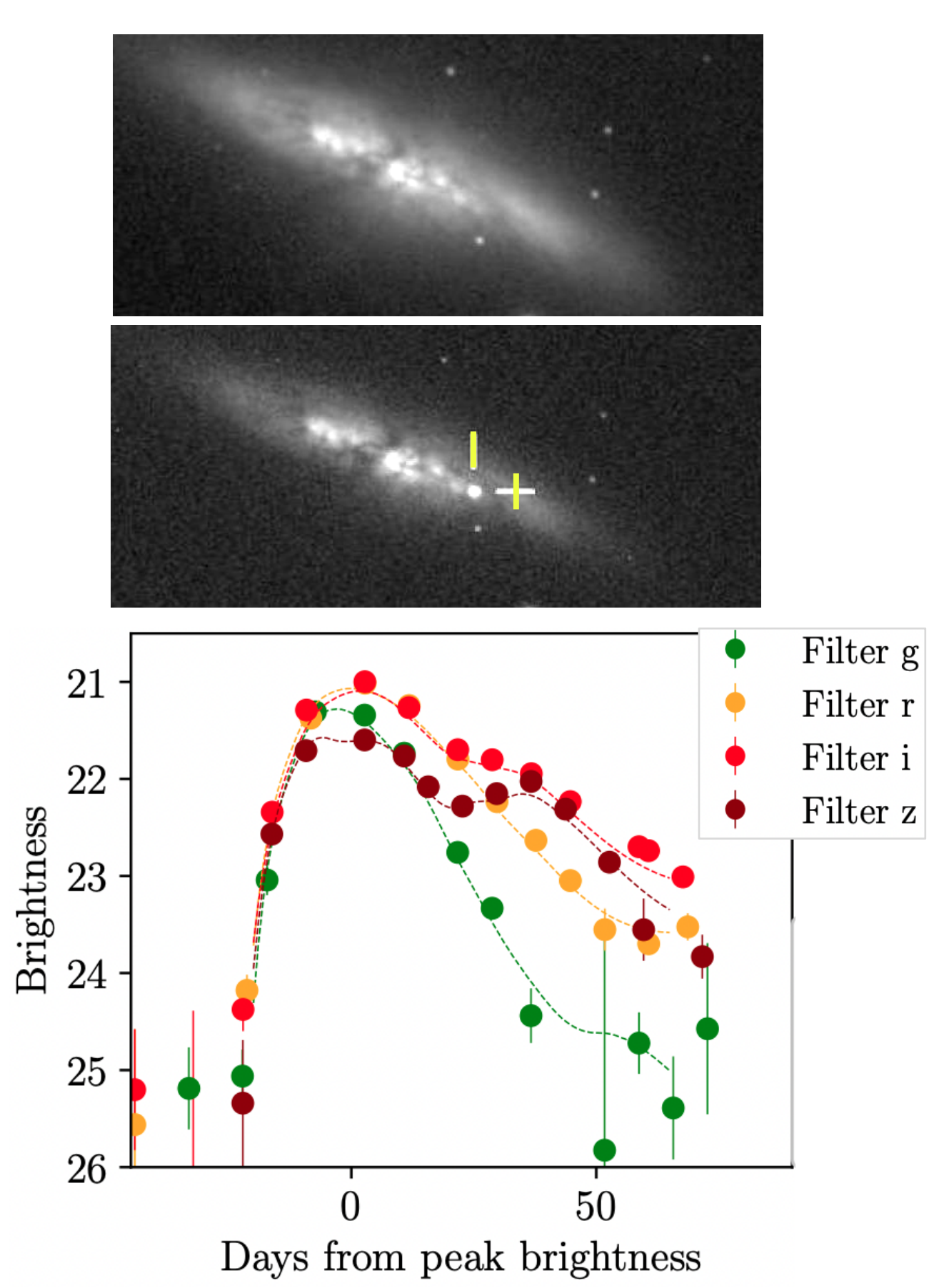
The DES Supernova Light Curves

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



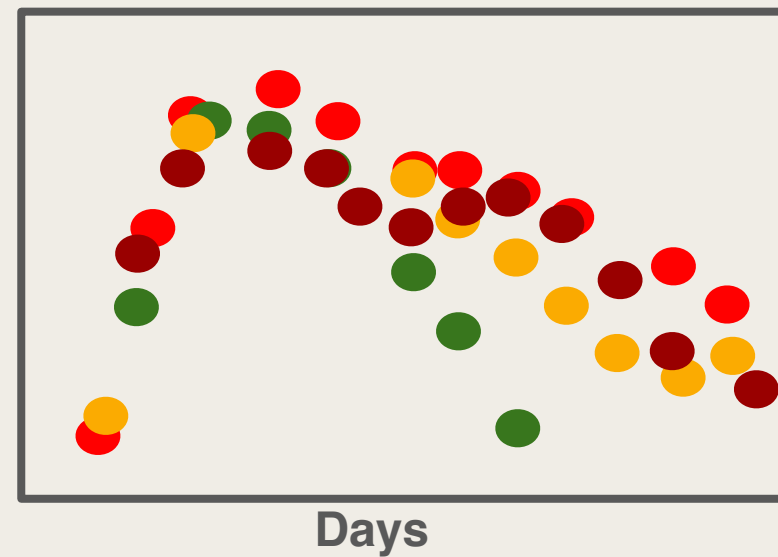
DES Hubble Diagram

Magnitude (DECam)

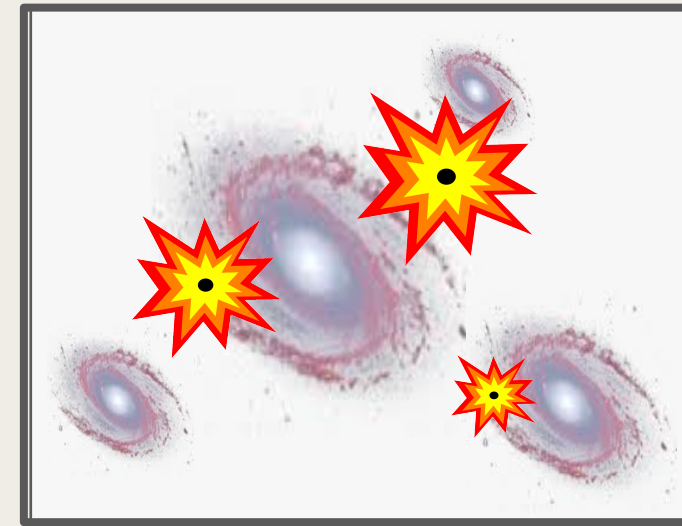


Redshift (AAT)

DES Analysis Details



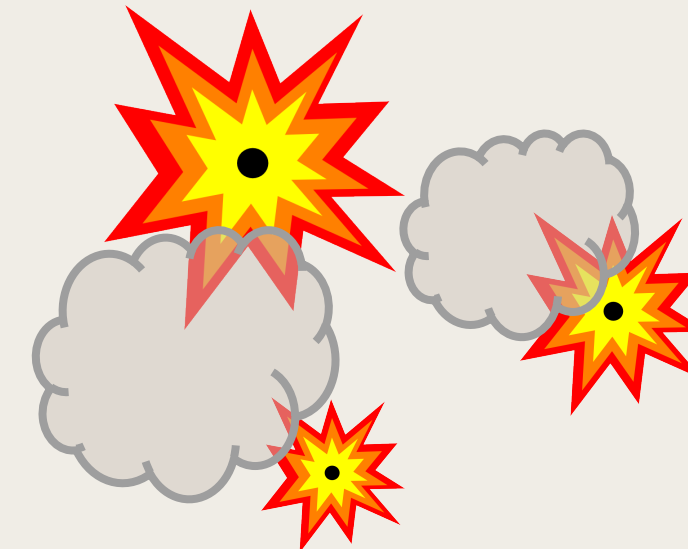
1. Building the Data Set: find SNe, **calibrate** photometry, get host redshifts



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](#)

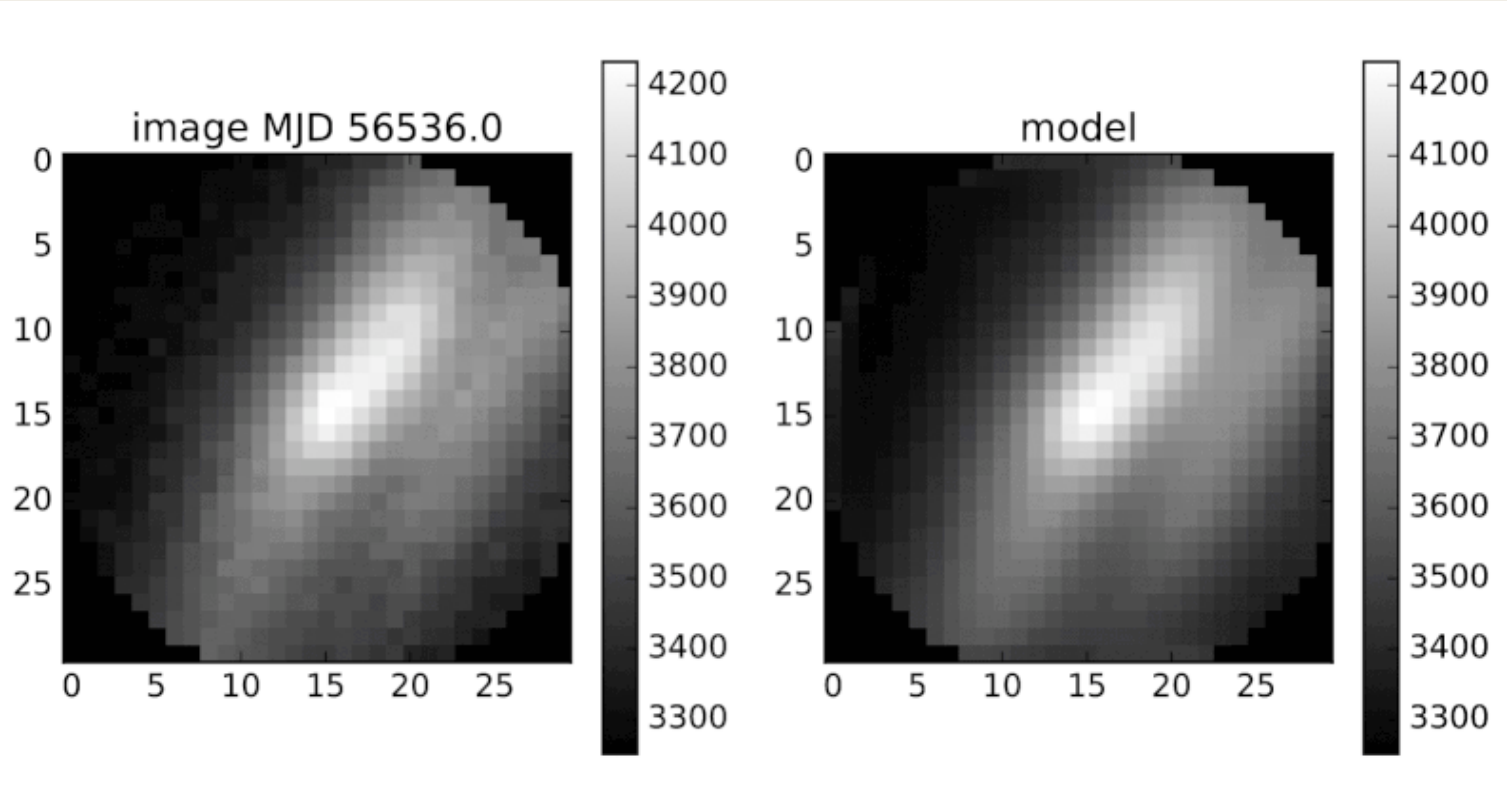
Testing non-standard cosmological models ([Camilleri et al. 2024](#))

DES Analysis Details

Set new standards in multiple areas



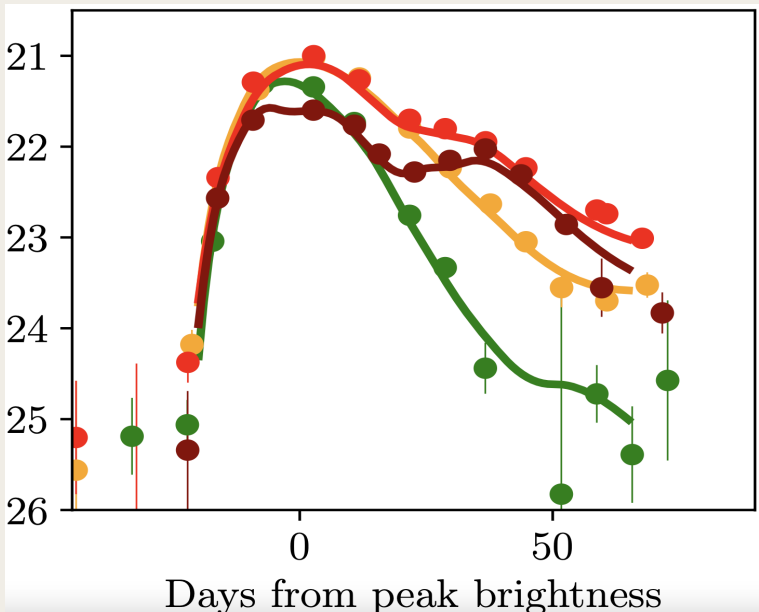
Photometry calibrated to 5mmag accuracy



Dillon Brout et al. 2019



Bruno Sanchez et al. 2024



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

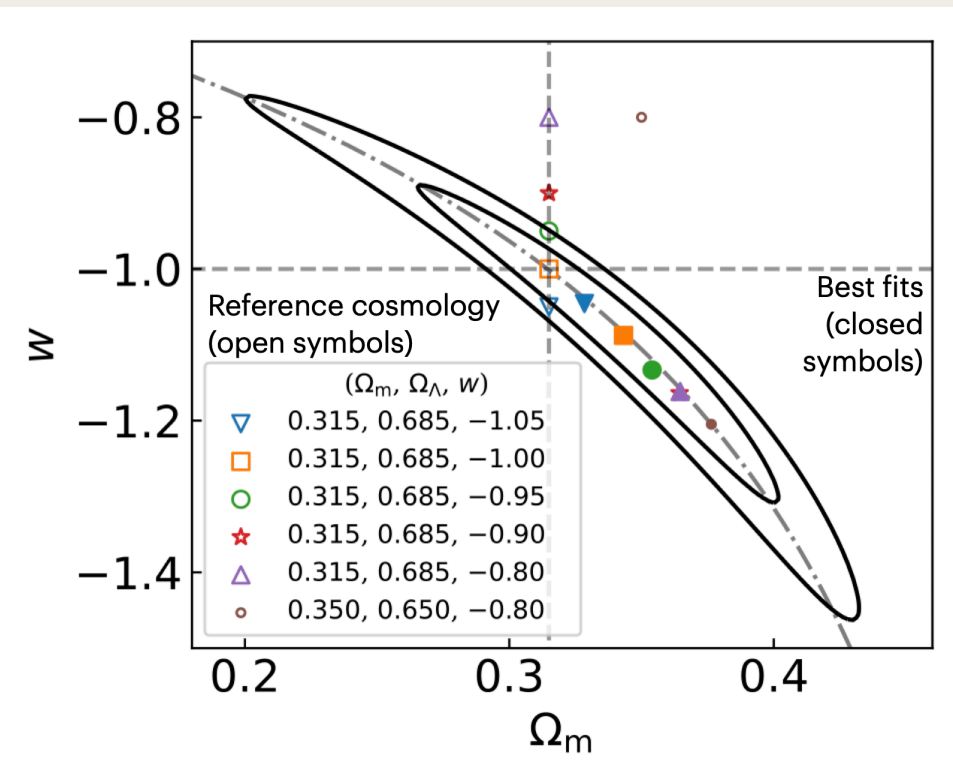
- SALT3 trained on x1.5 larger data
- **SALT3** goes **redder** (where DES has high-quality data)
- Calibration uncertainties incorporated in the light-curve model training as well as the fitting.



Georgie Taylor et al. 2022



Patrick Armstrong et al. 2022



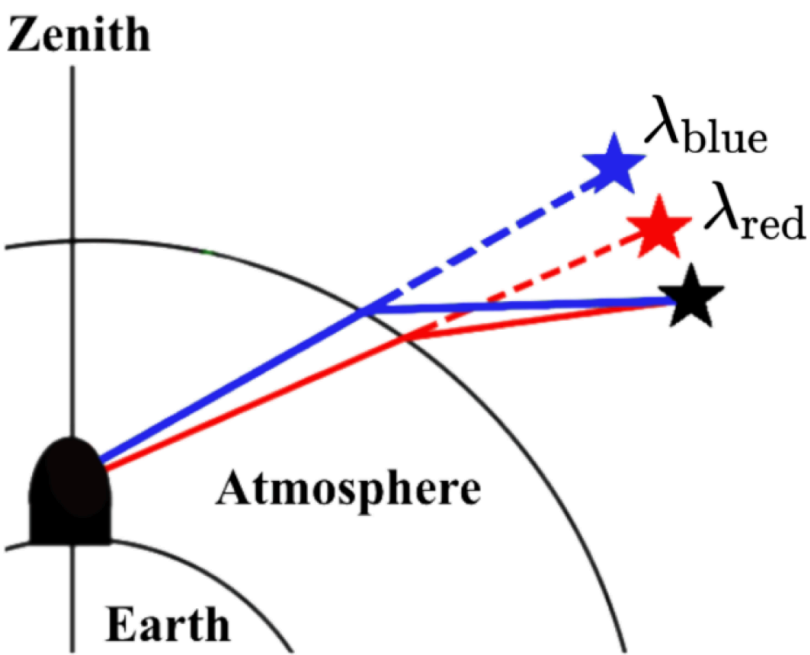
Validated contours, assumptions, and uncertainties

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

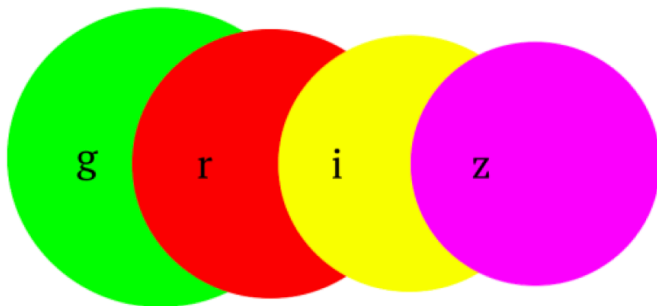


Ryan Camilleri et al. 2024

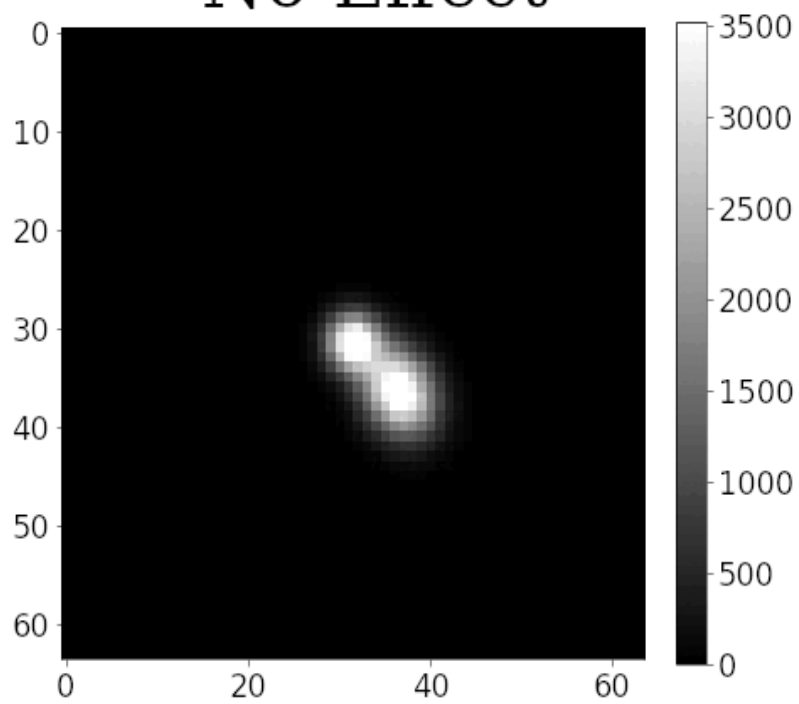
Effect #1: Differential Chromatic Refraction



Effect #2: λ -dependent seeing



No Effect



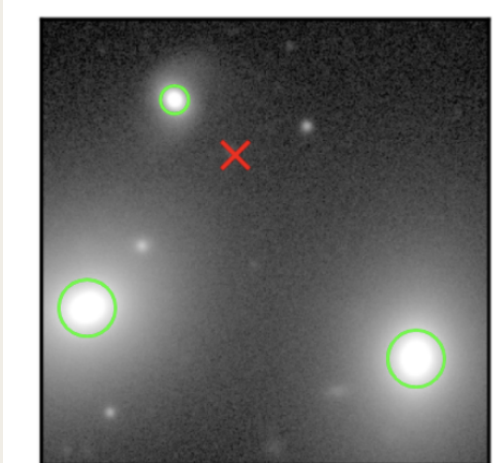
Jason Lee and Maria Acevedo et al. 2022



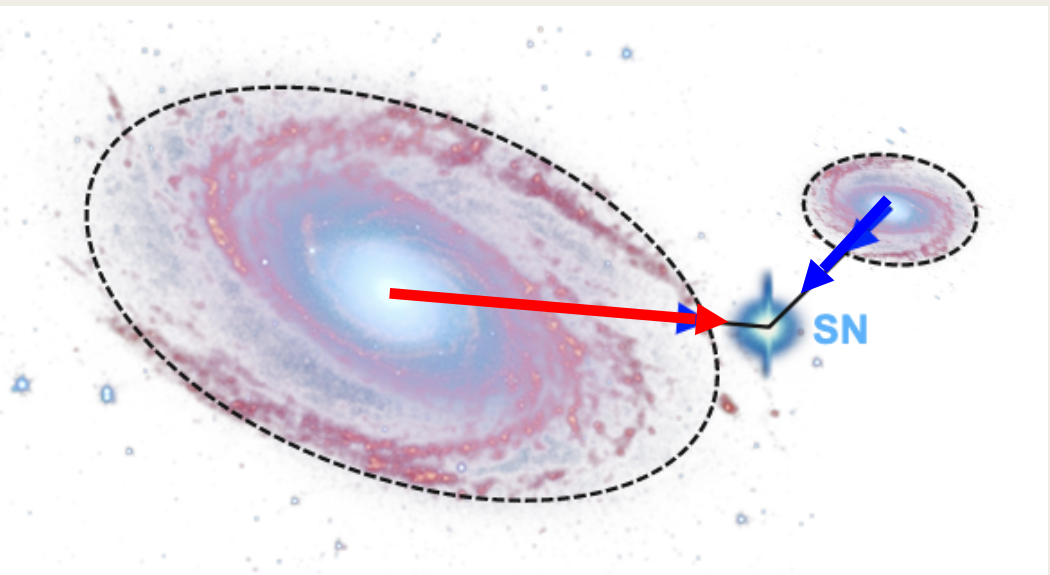
Helen Qu et al. 2023

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)



Brodie Popovic et al. 2021



Phil Wiseman et al. 2022

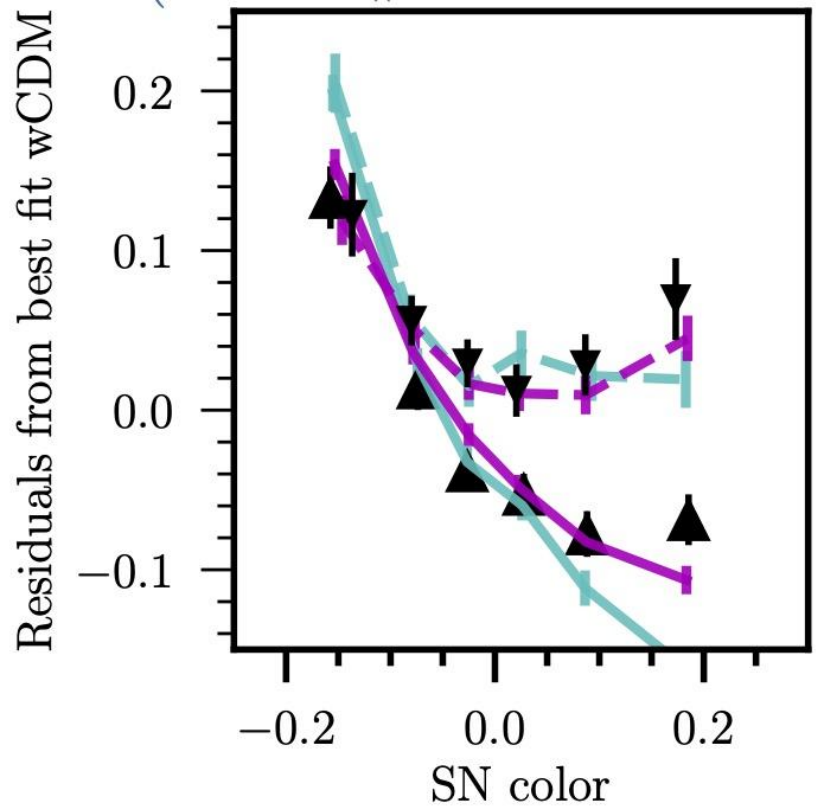
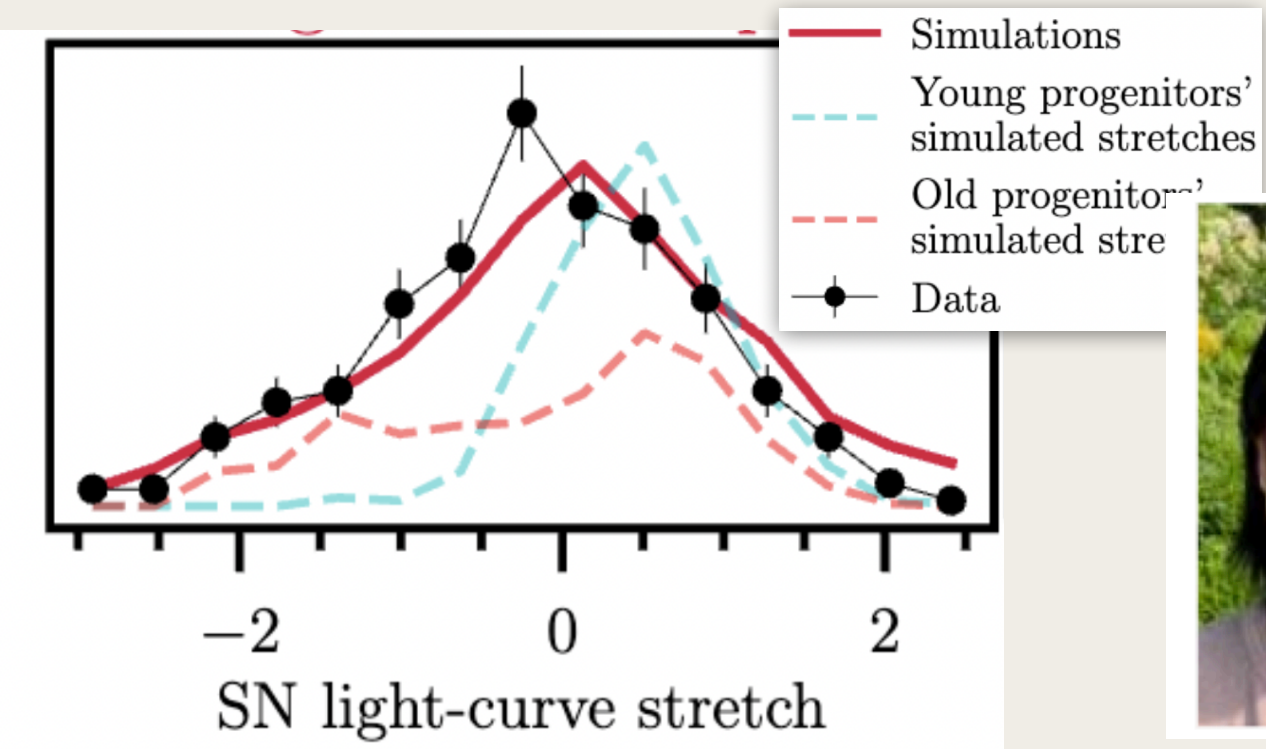
Rebecca Chen et al. 2022

Lisa Kelsey et al. 2021



Modelling SN progenitors & dust extinction

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



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

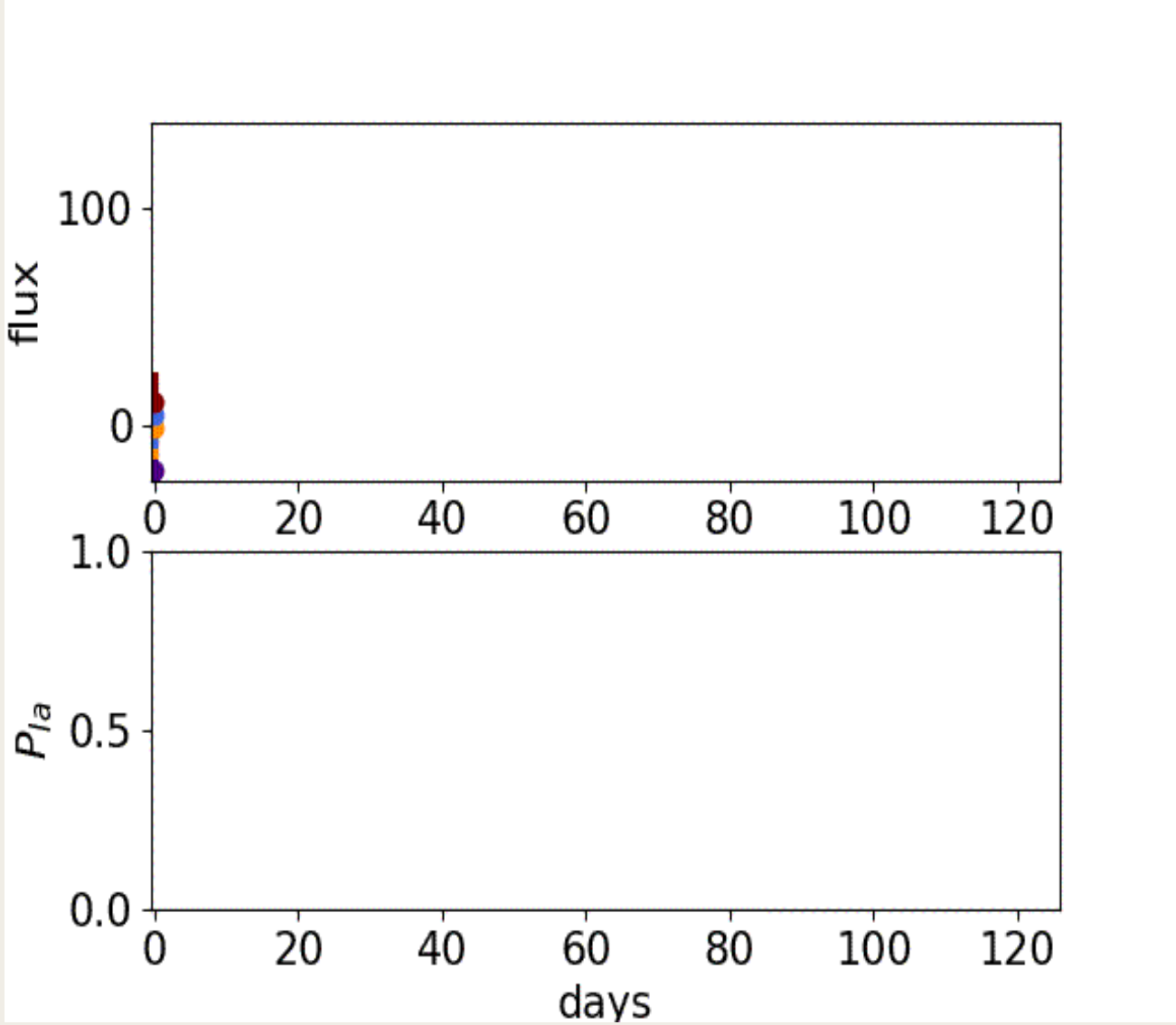


Maria Vincenzi

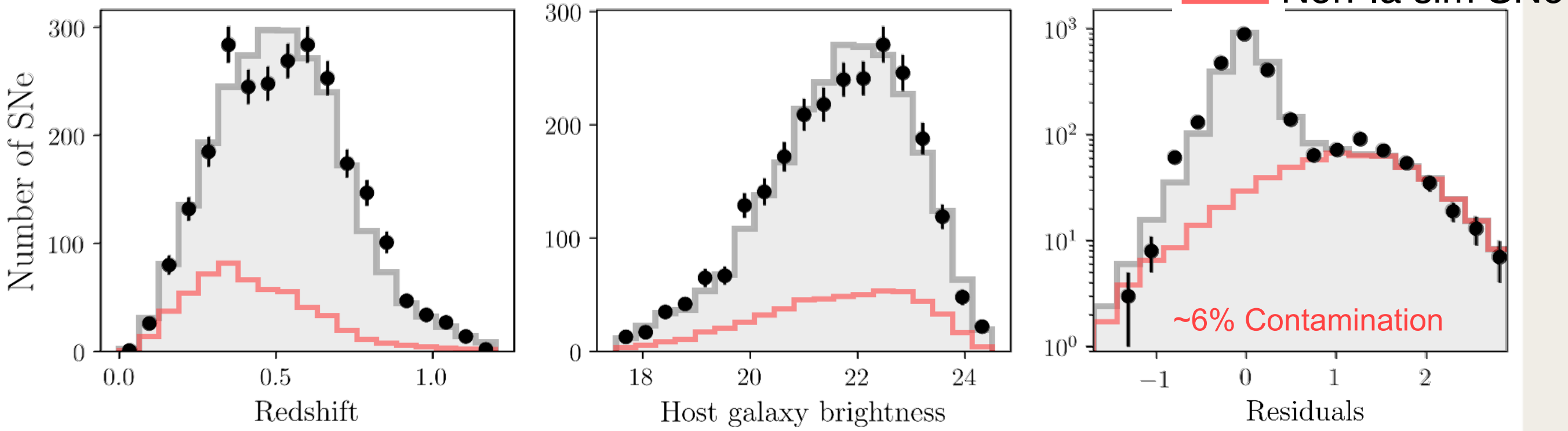
Photometric classification

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

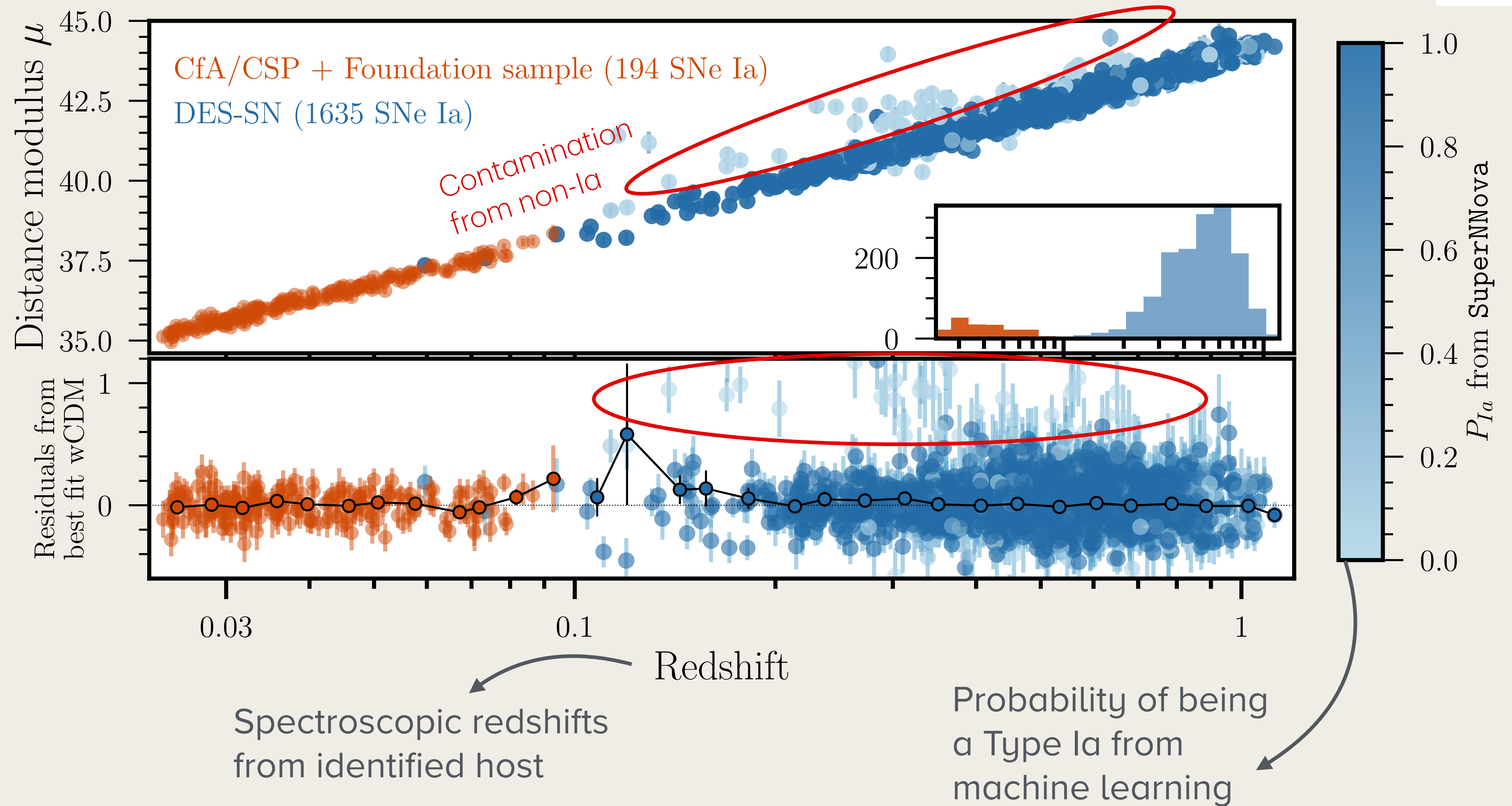
Classifiers **perform remarkably well:**
>98.5% purity
>99.0% efficiency



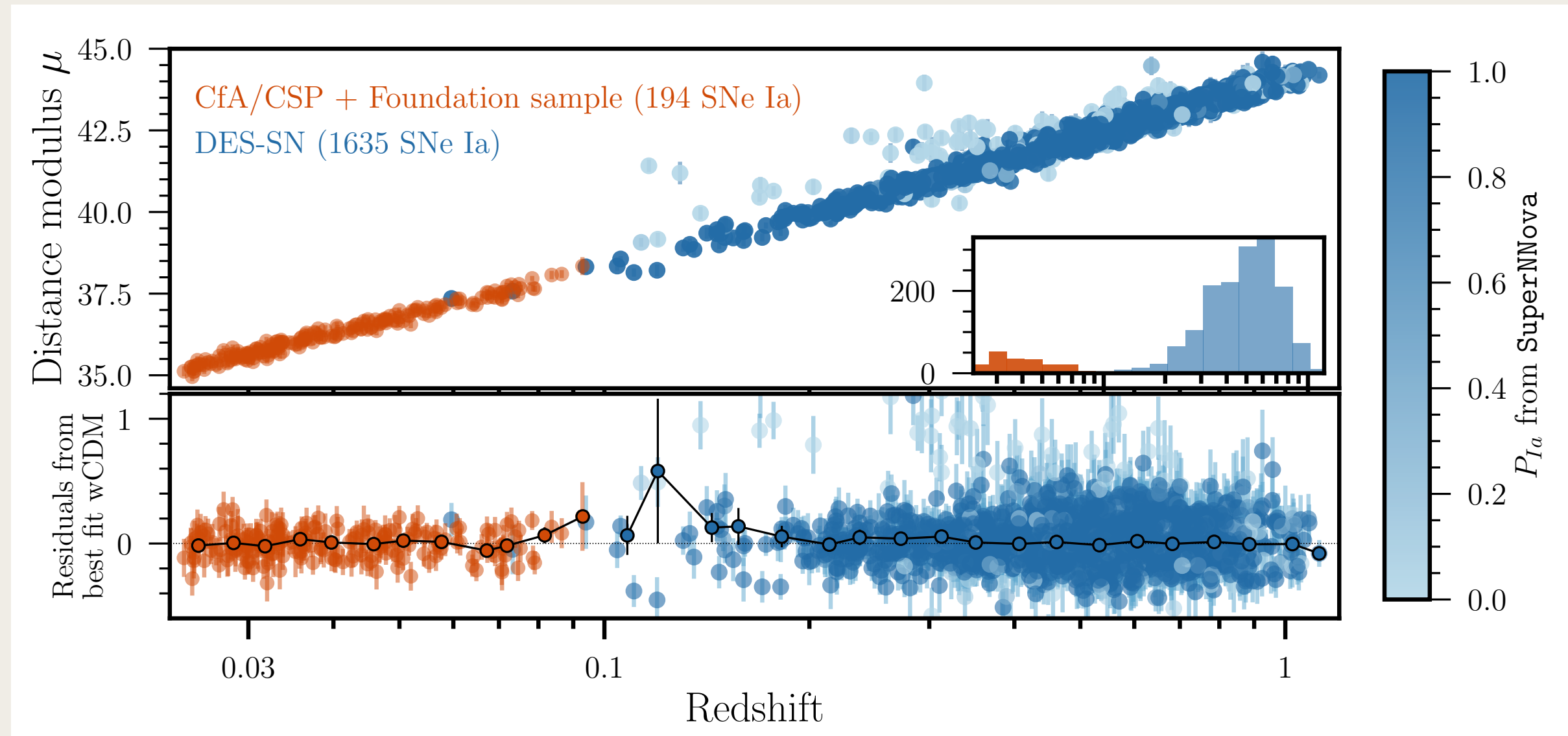
Sims:from first principles... to real data:



The DES Hubble Diagram



DES SN Cosmology Results: Λ CDM



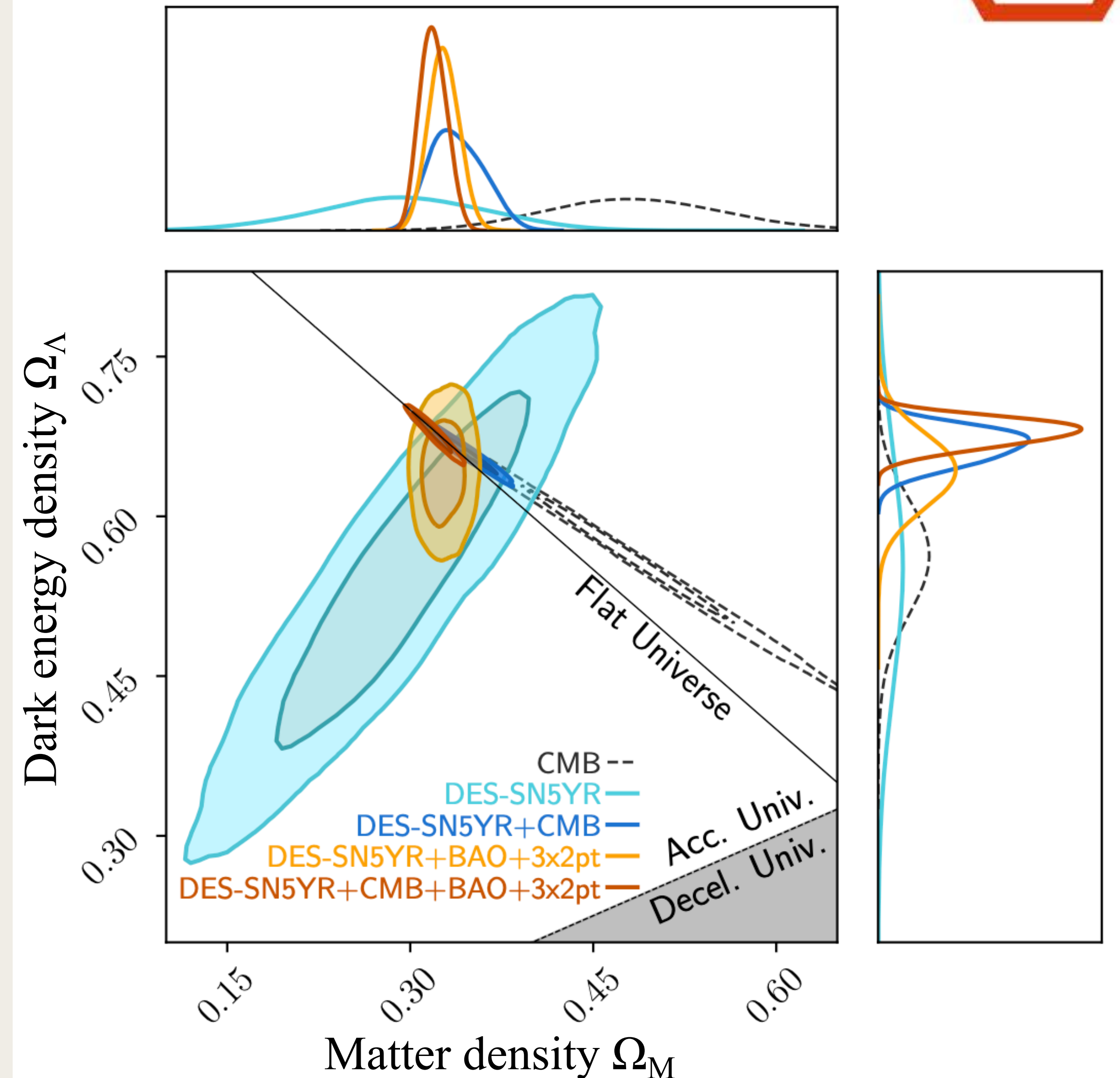
DES-SN alone $\Omega_M = 0.291^{+0.063}_{-0.065}$

$\Omega_k = 0.16 \pm 0.16$

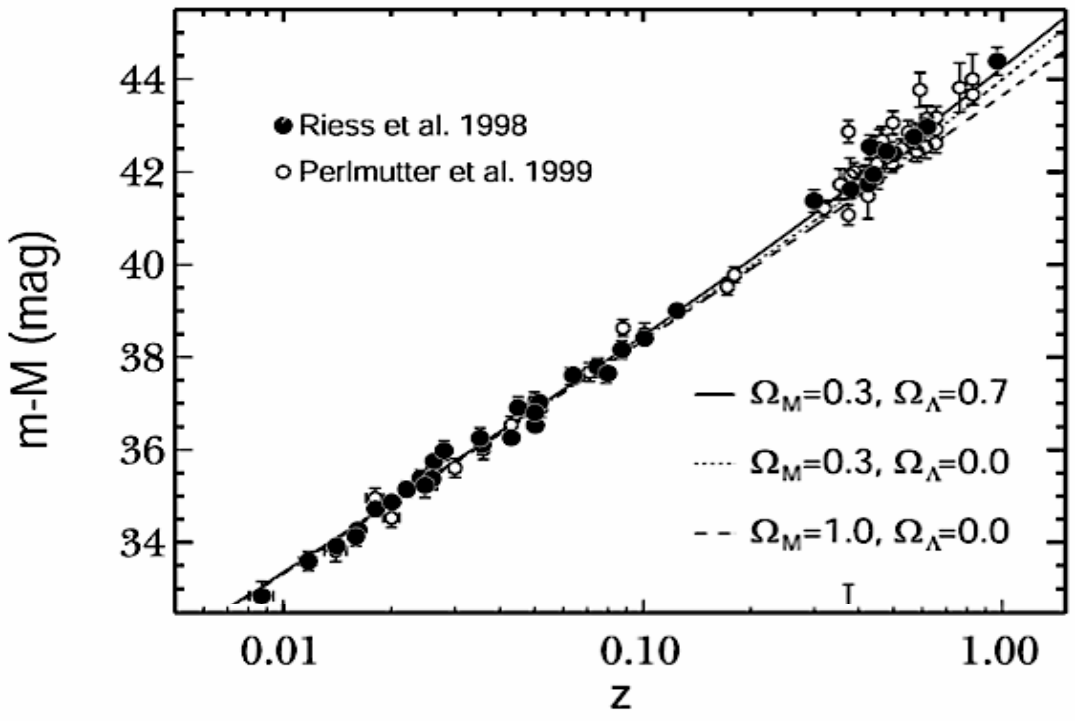
DES5YR + CMB + BAO + 3x2pt

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

$\Omega_k = 0.010 \pm 0.005$



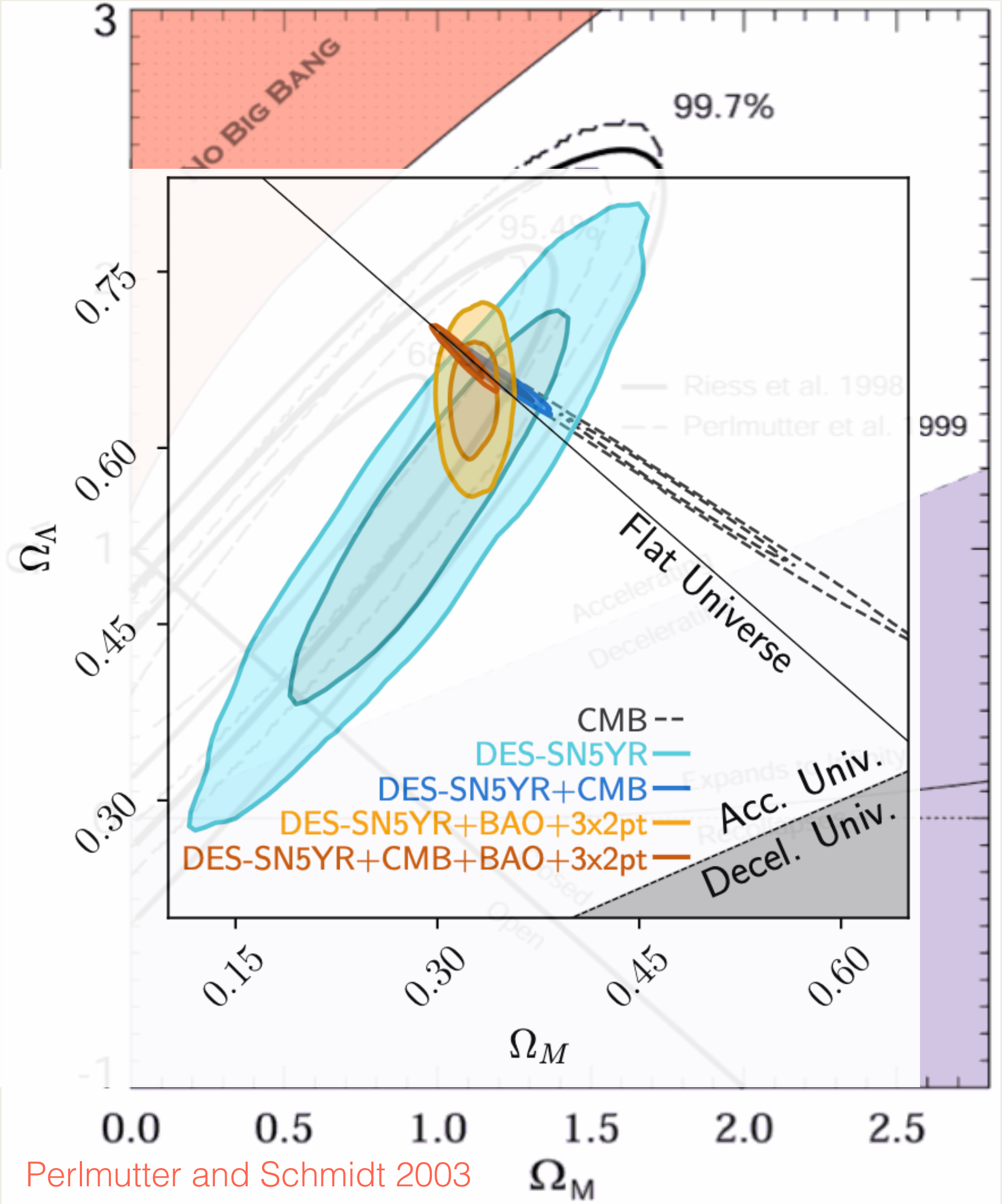
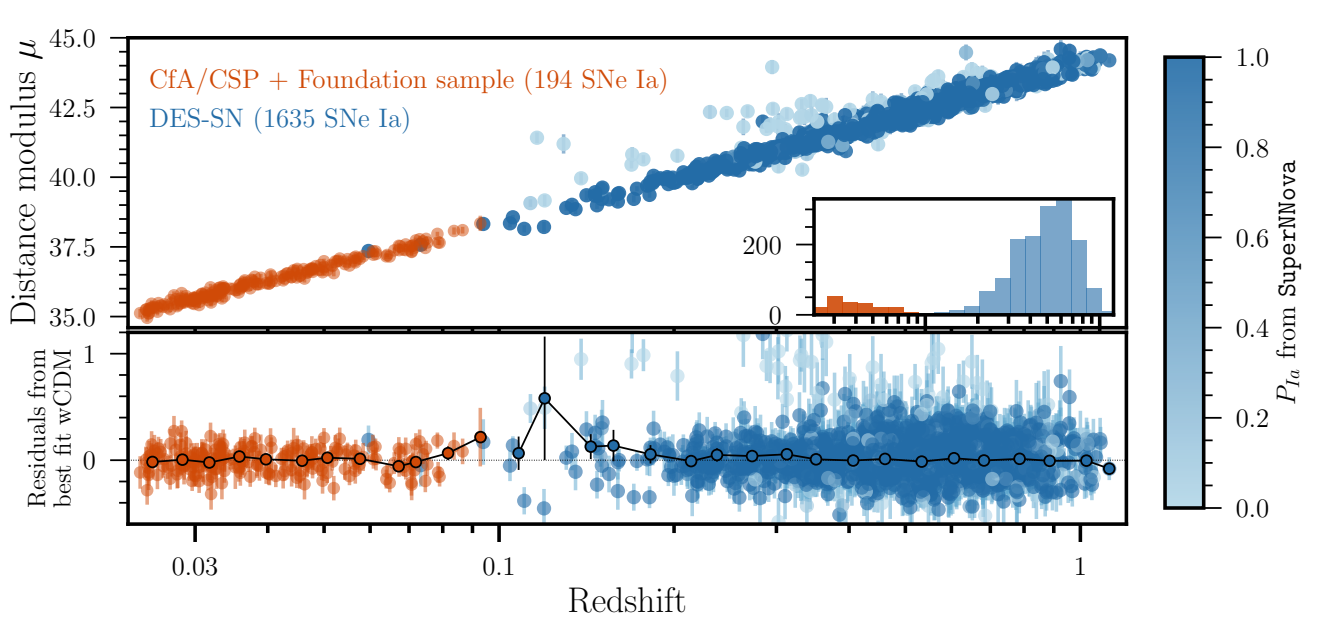
How far have we come?



~50 SN in ≤ 2 colours

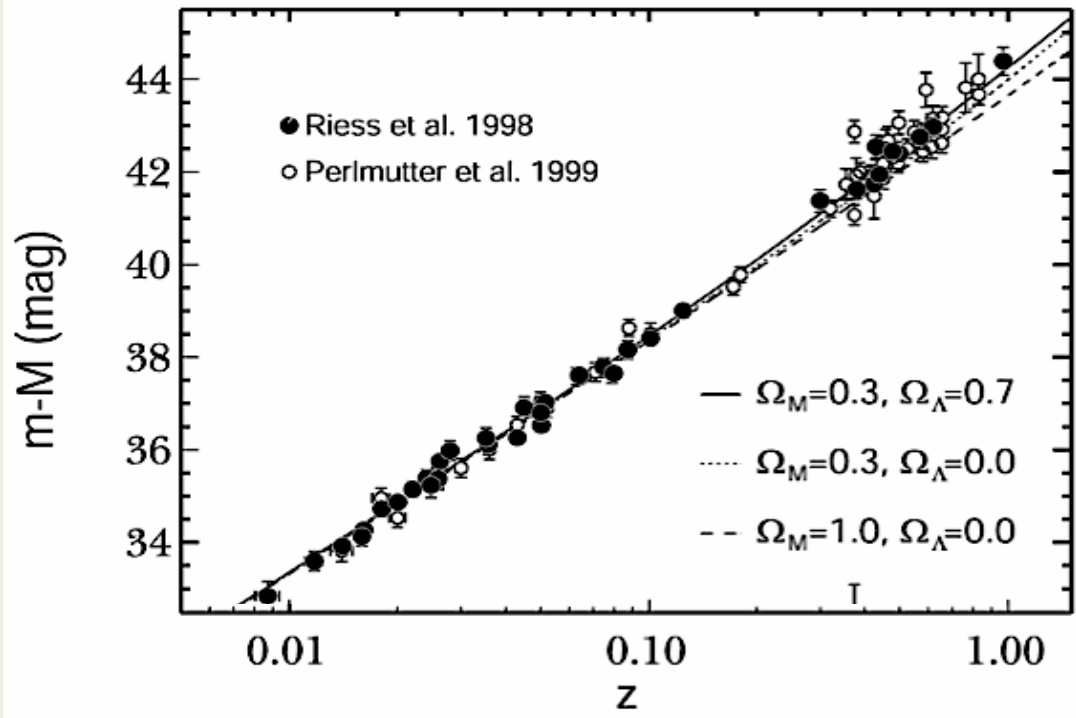


~1500 SN in 4 colours
(plus better calibration, models, etc...)



Perlmutter and Schmidt 2003

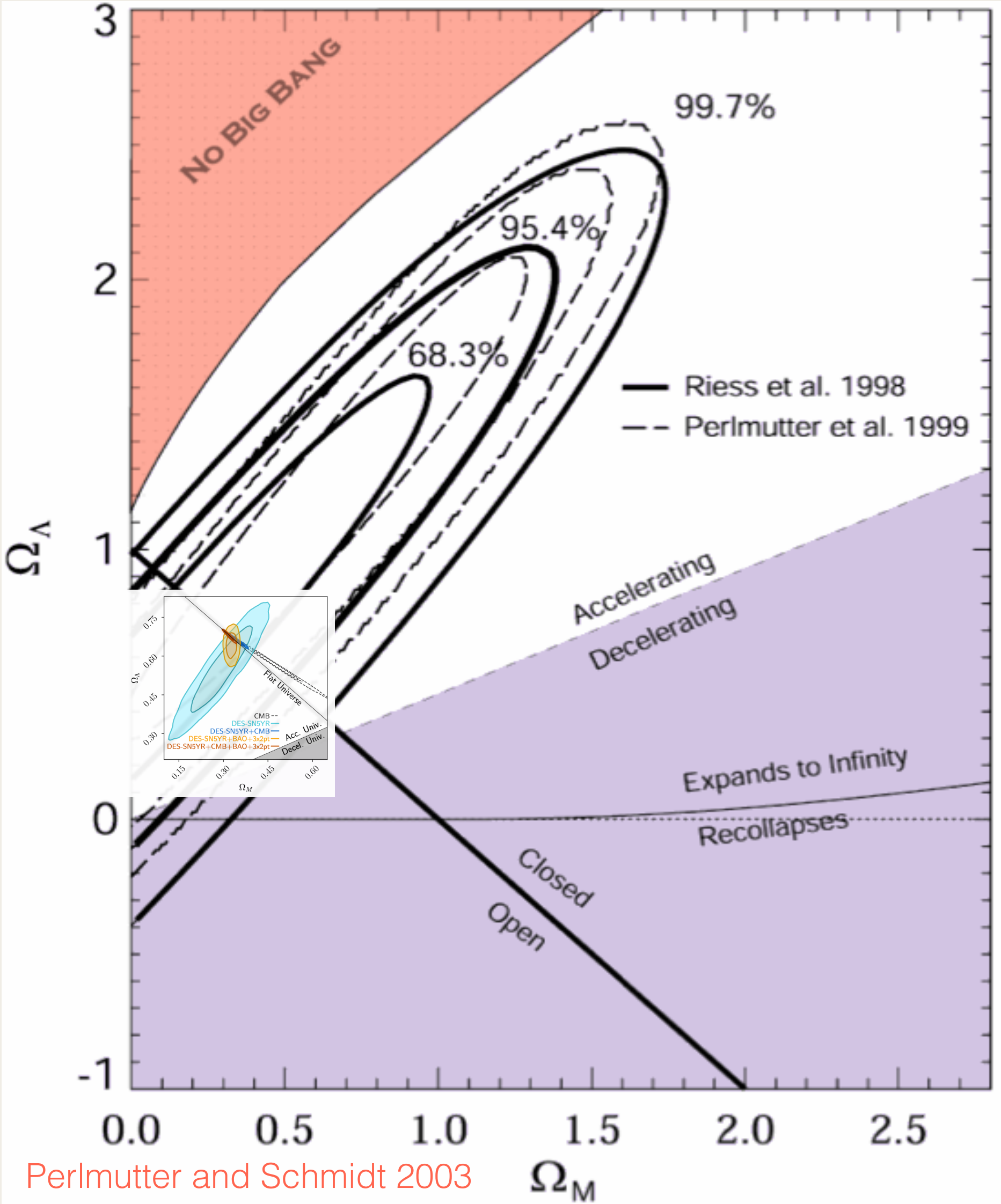
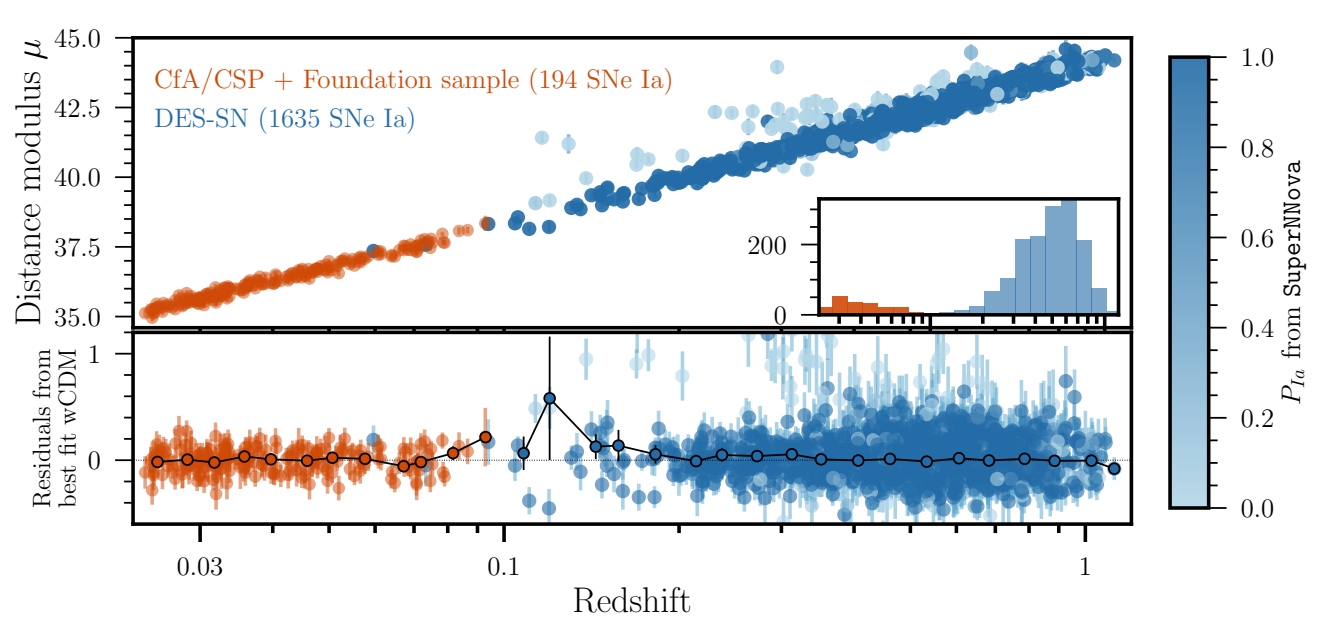
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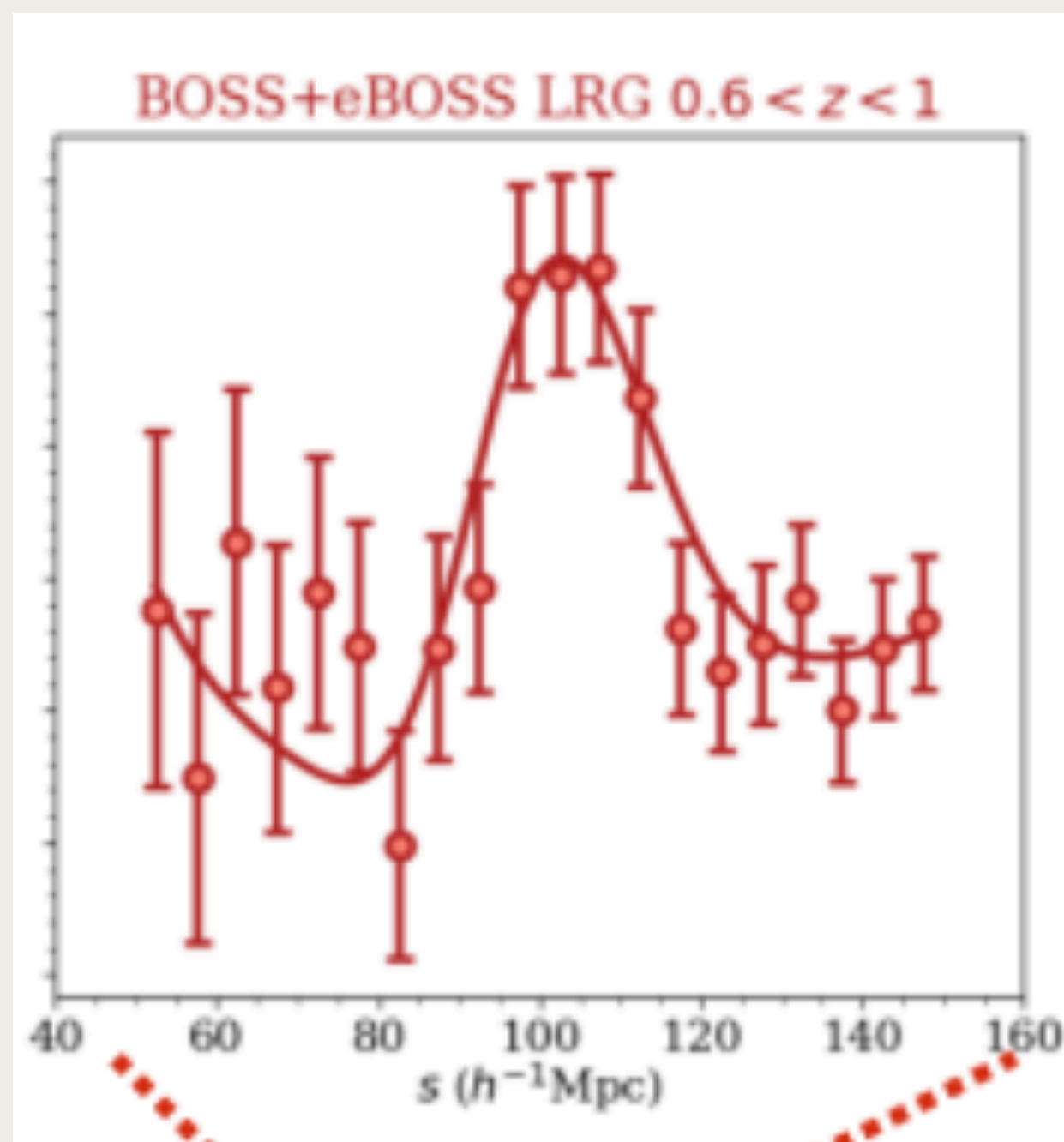


Perlmutter and Schmidt 2003

DES SN Cosmology Results

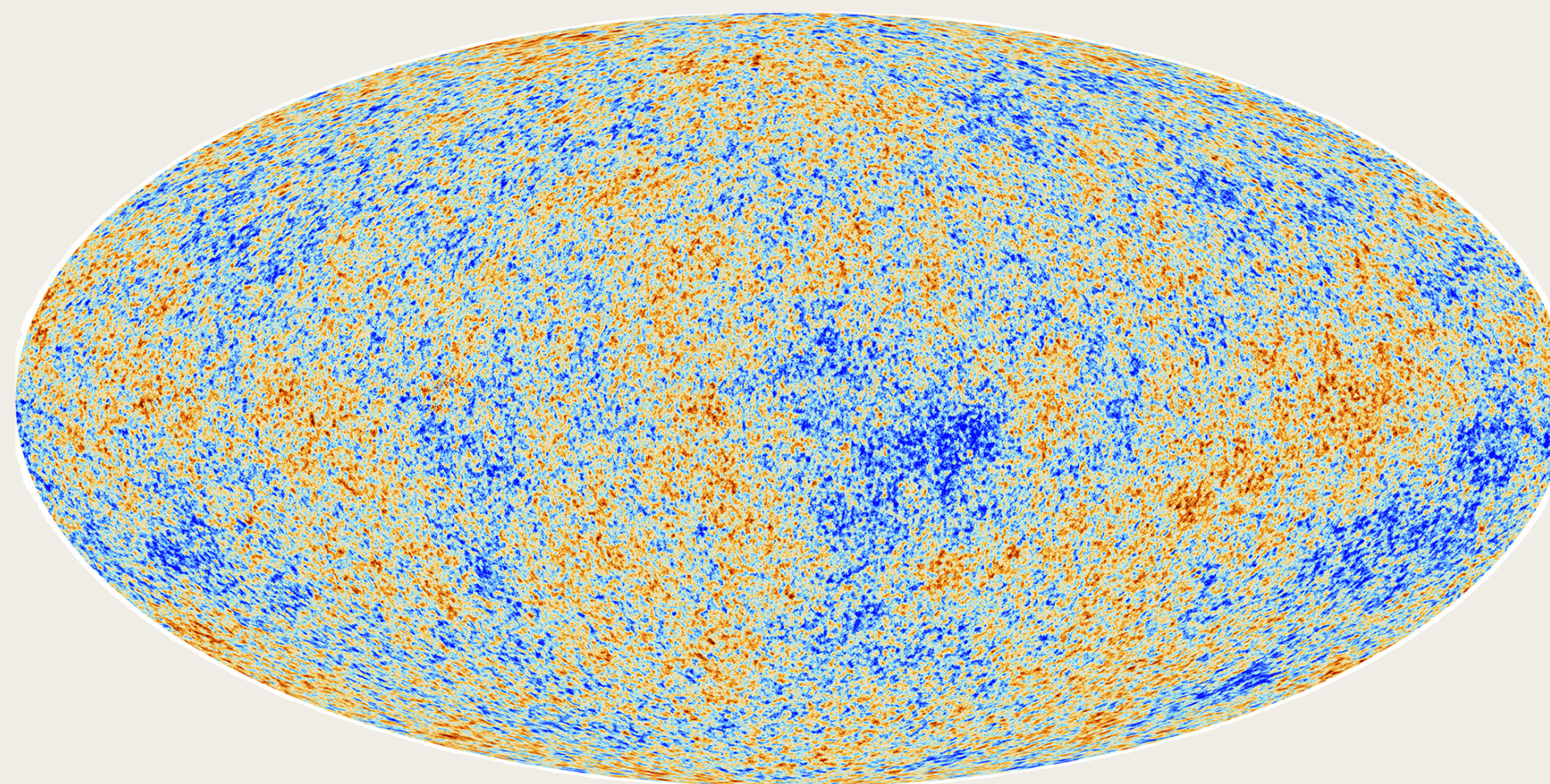


Baryon Acoustic
Oscillations
(BAO from SDSS)



Alam et al. 2021;

Cosmic Microwave
Background
(CMB from Planck)



Planck 2020;

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

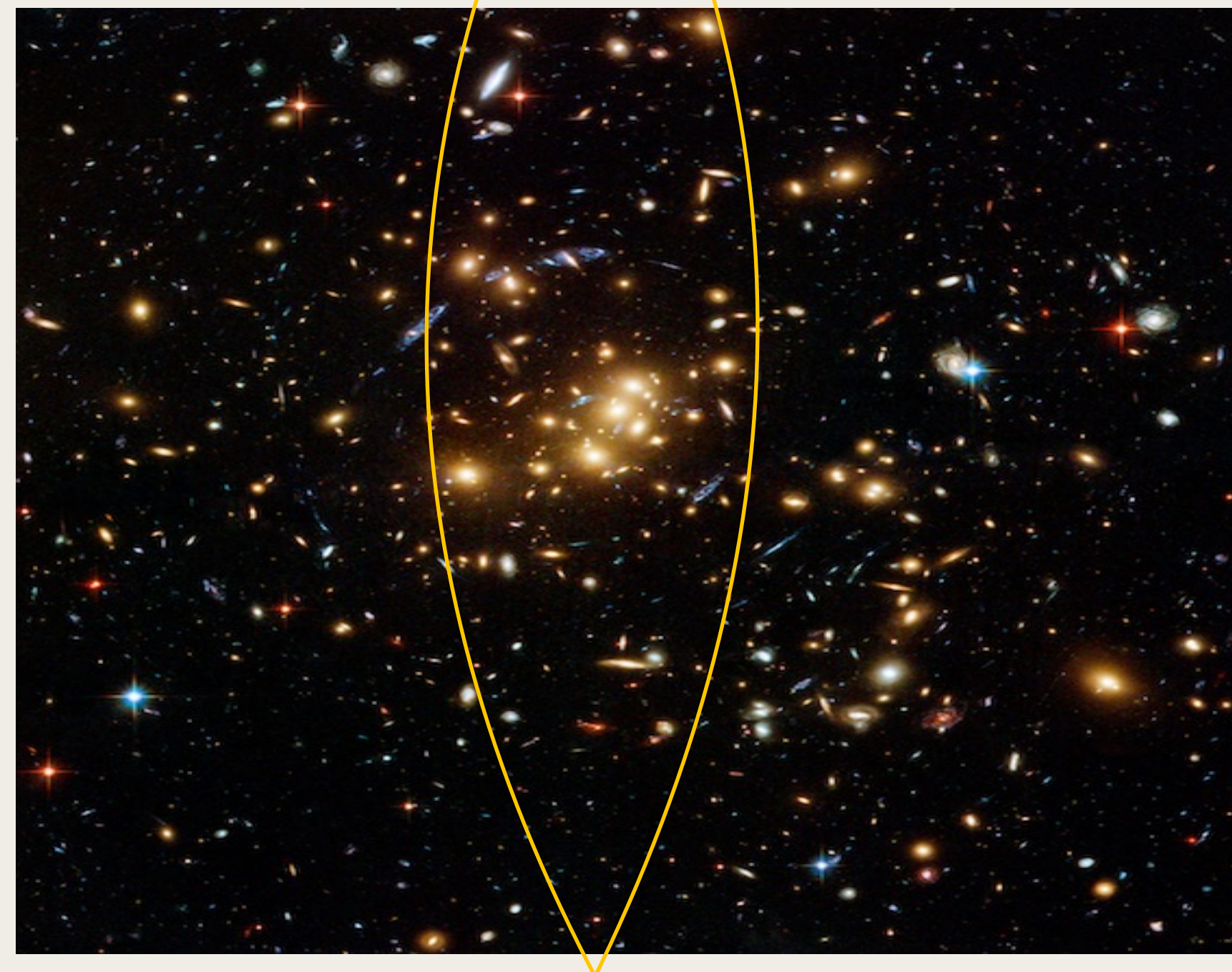


DES 2023



Three by two-point (3x2pt)

Three two-point correlations
calculated simultaneously.



Three by two-point (3x2pt)

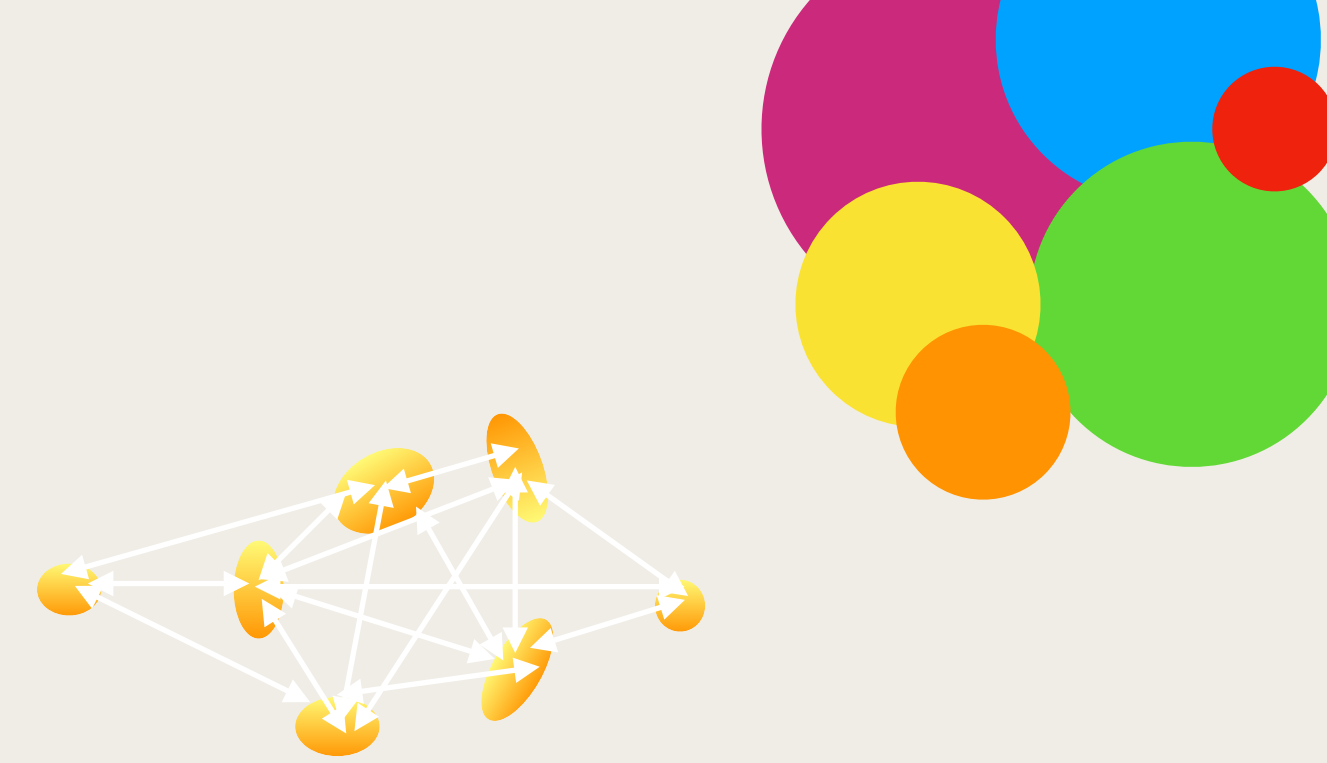
Three two-point correlations
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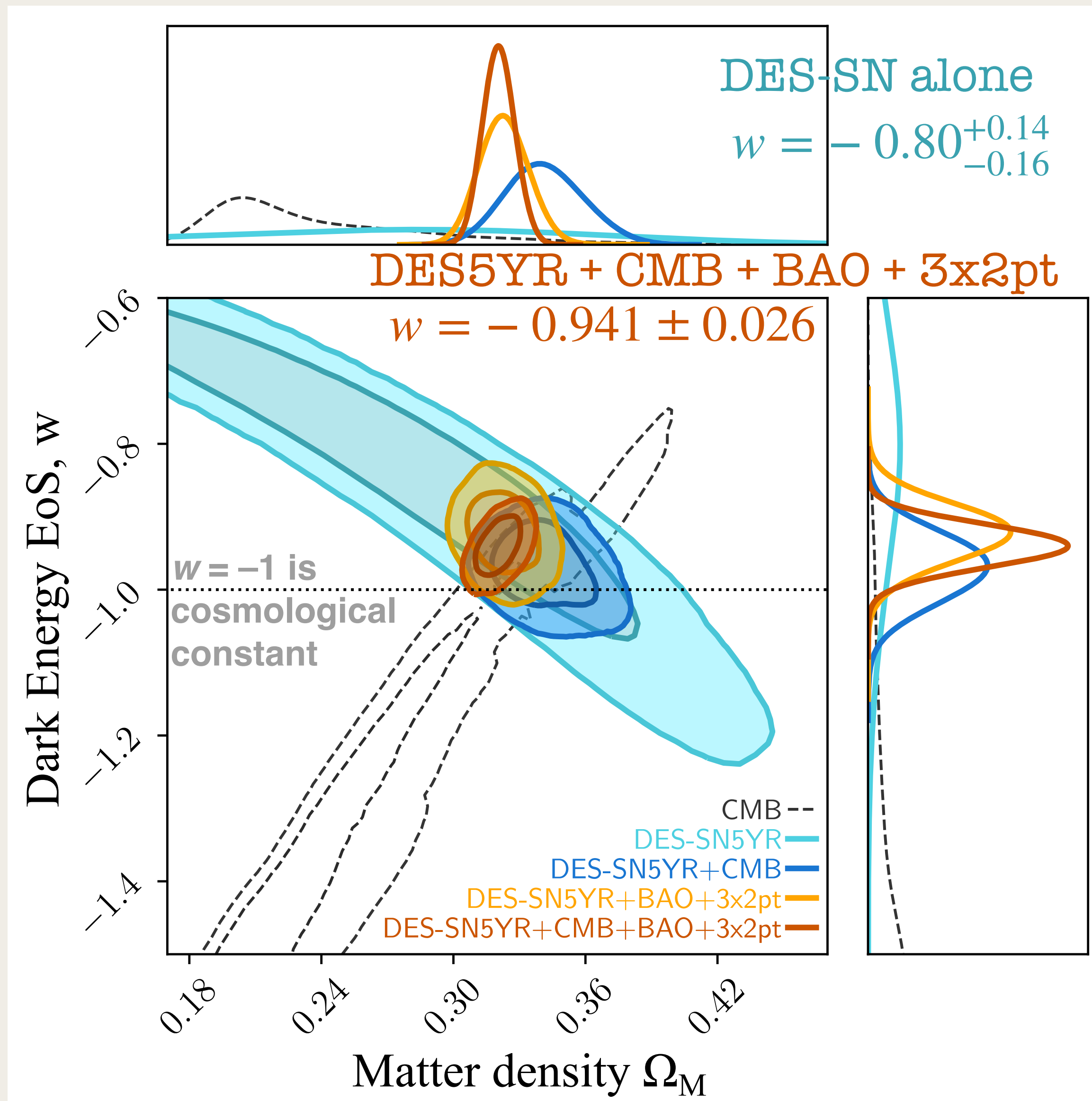
galaxy-galaxy

galaxy-lens

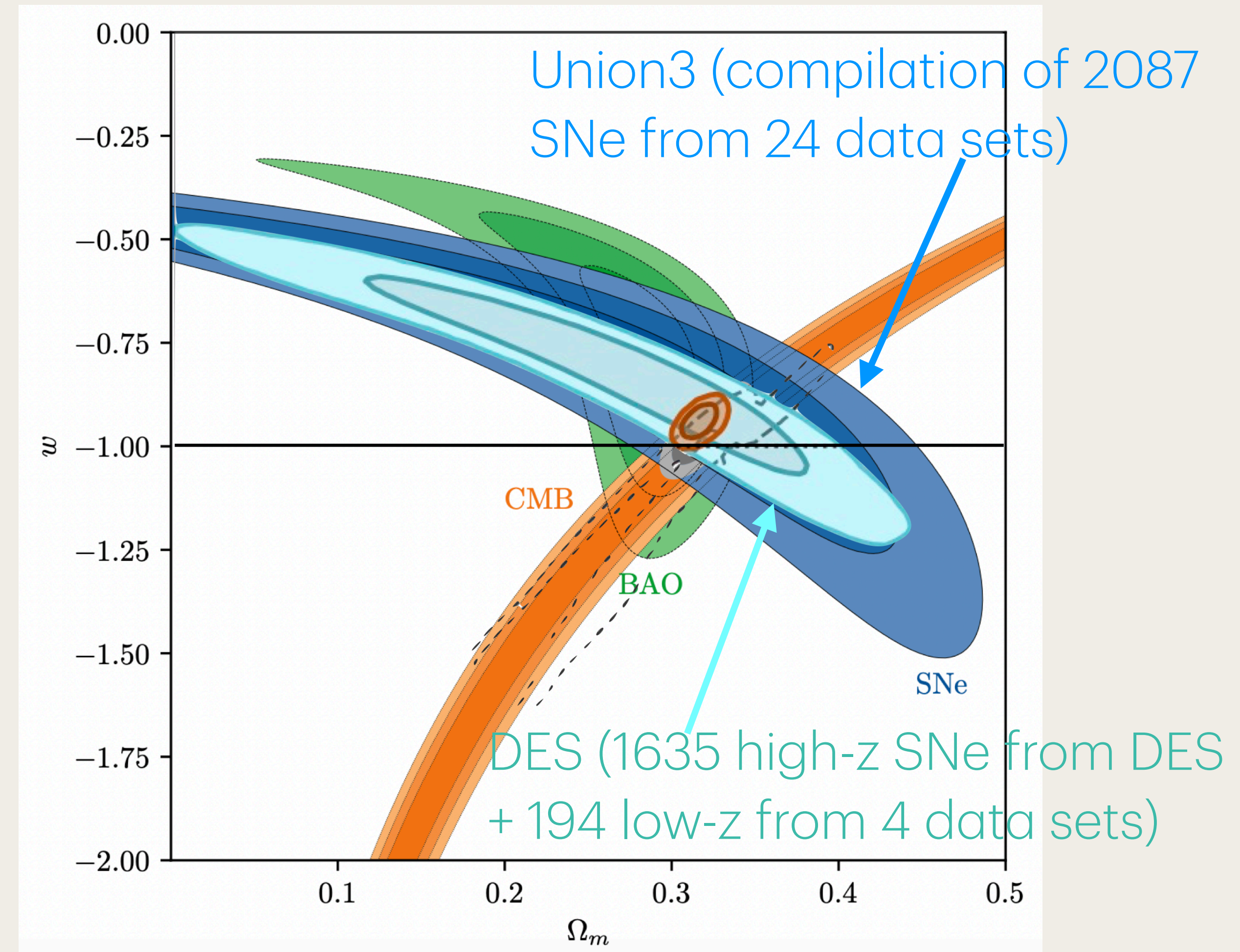
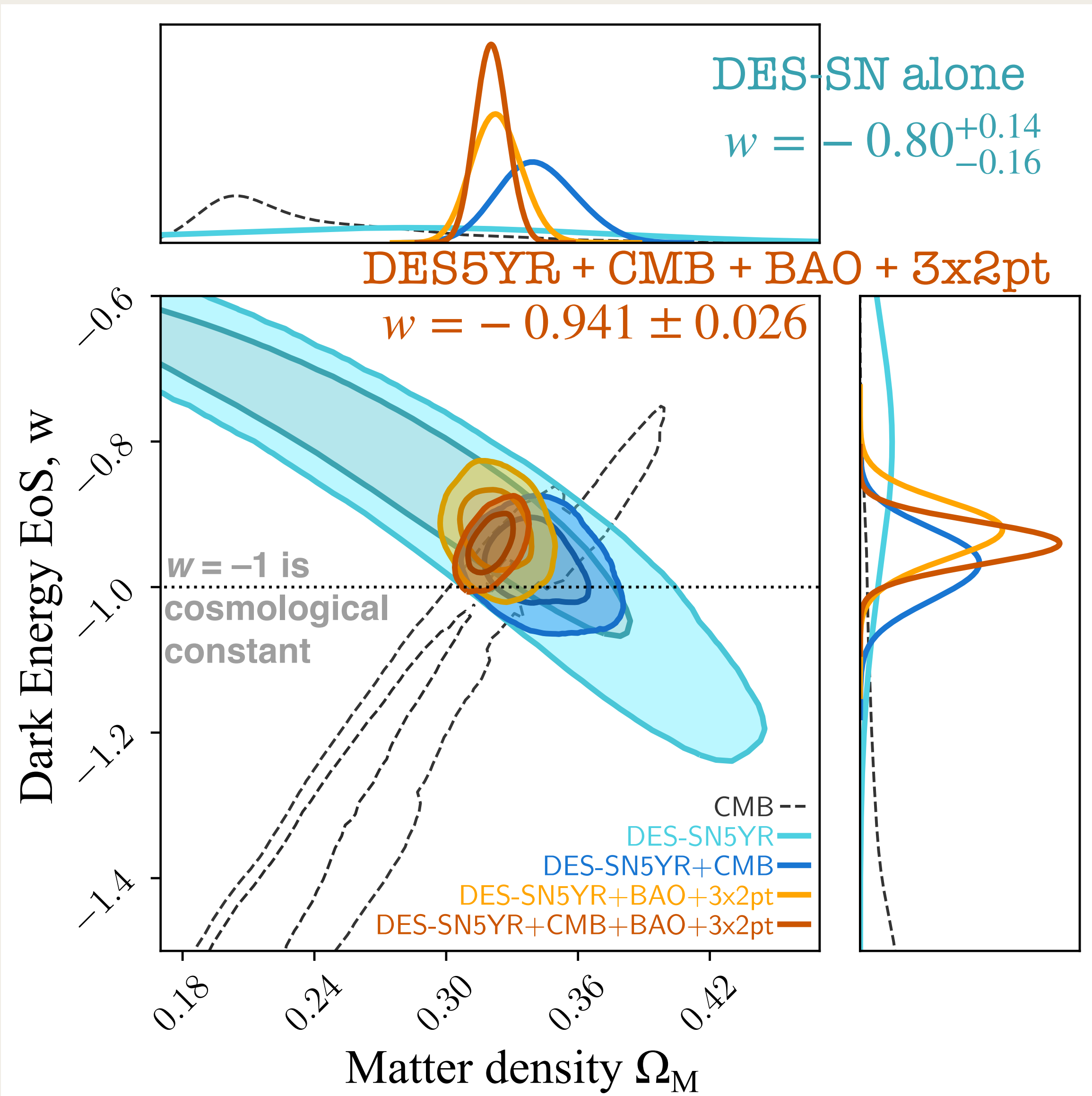
lens-lens



DES SN Cosmology Results: wCDM



Supernova data sets agree



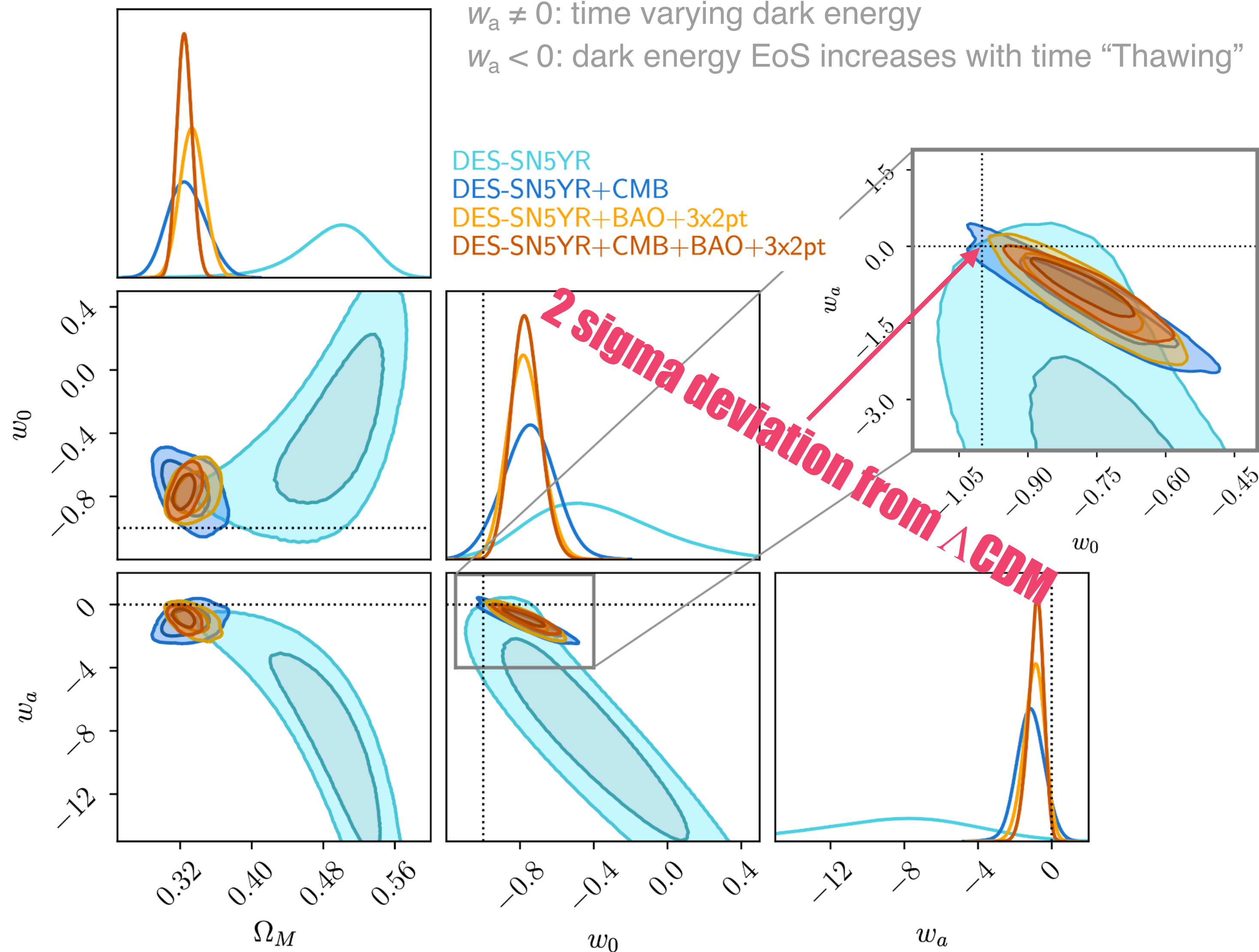
DES SN Cosmology Results: w_0w_a CDM



$$W=W_0+W_a(1-a)$$

$w_a \neq 0$: time varying dark energy

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



DES-SN alone

$$w_a = -8.8^{+3.7}_{-4.5} \quad (>2\sigma \text{ less than } 0)$$

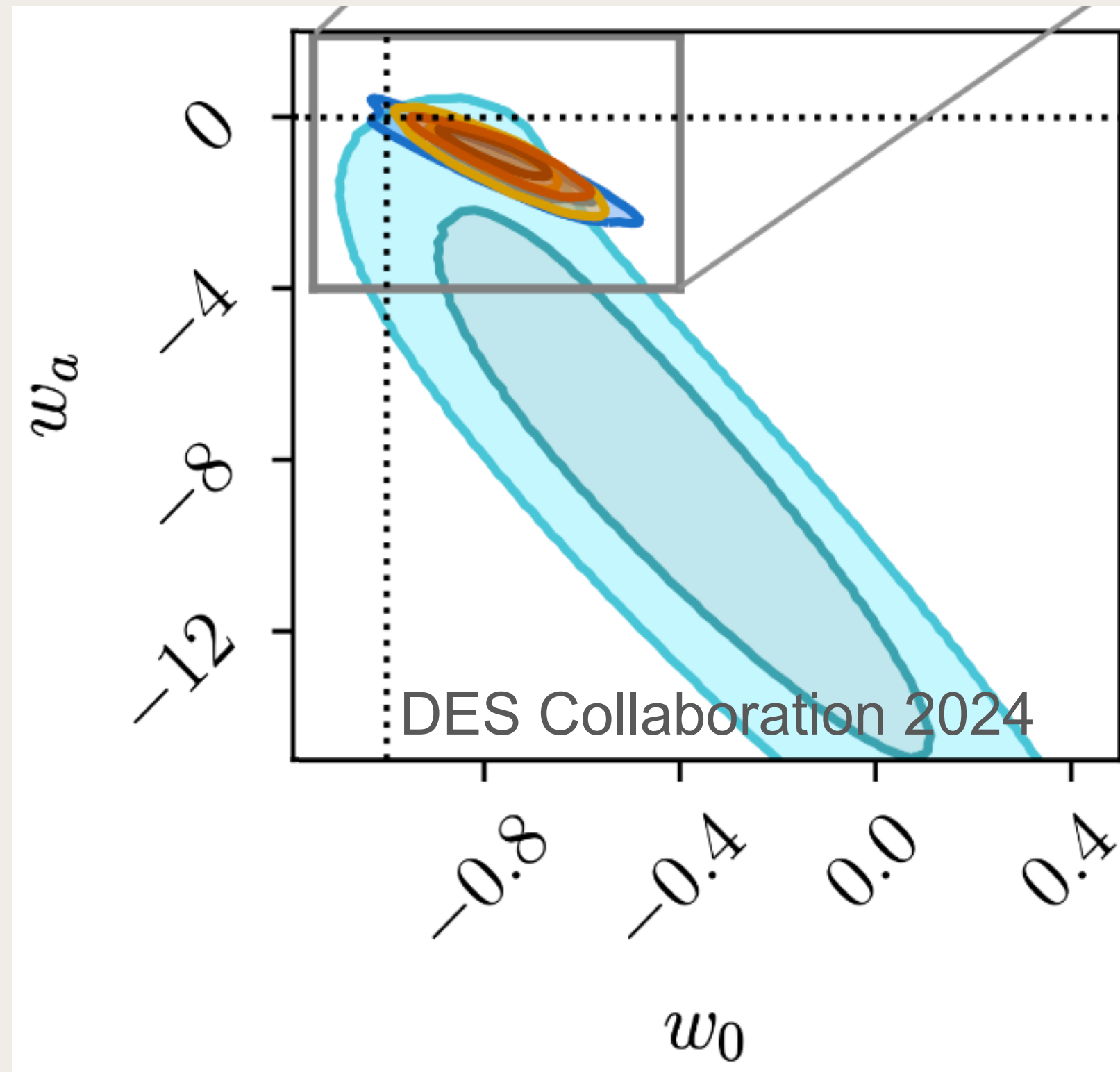
DES5YR + CMB + BAO + 3x2pt

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

Pre-DESI

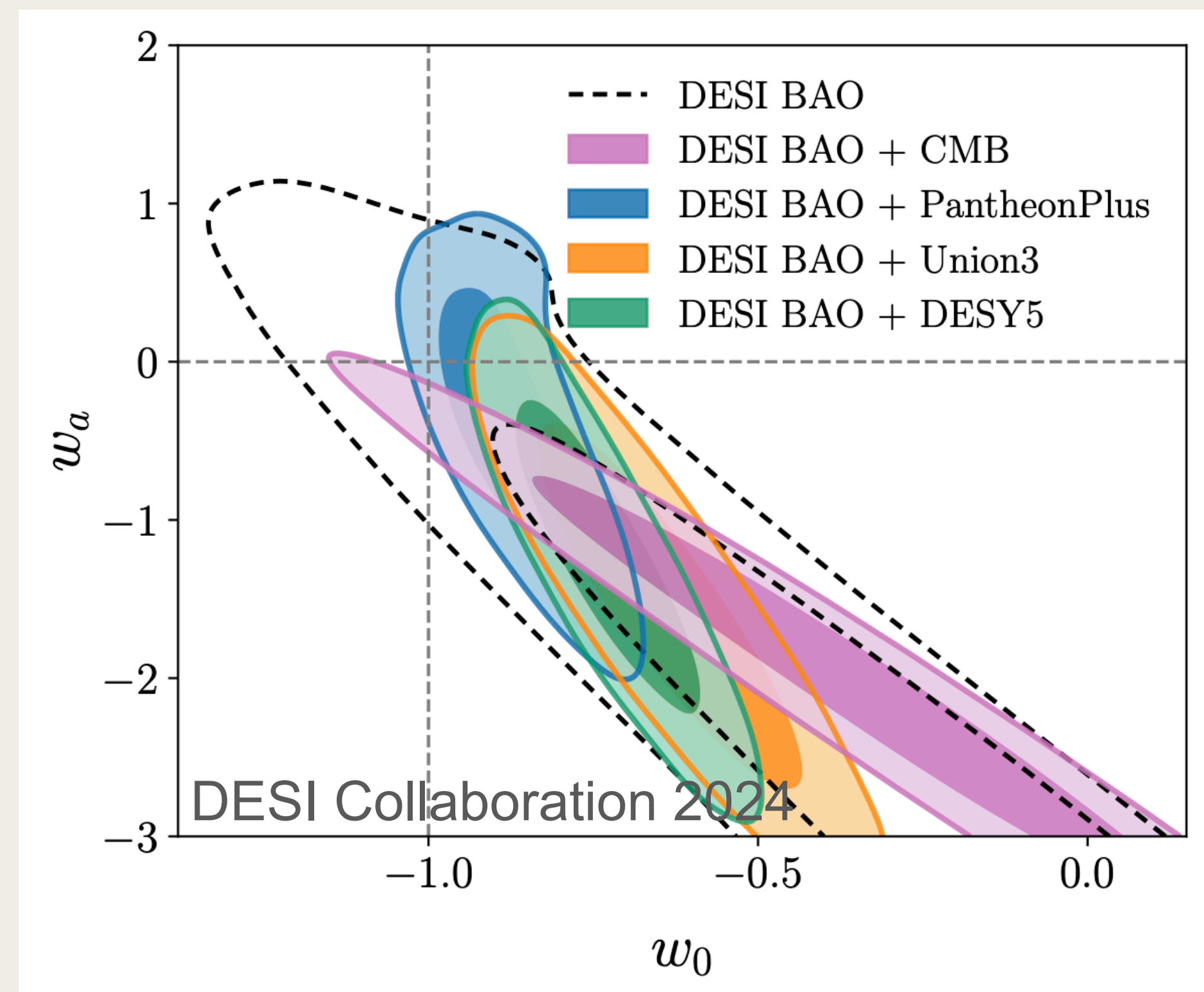
April 2024: DESI finds similar result to DES!

DES:



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

DESI:

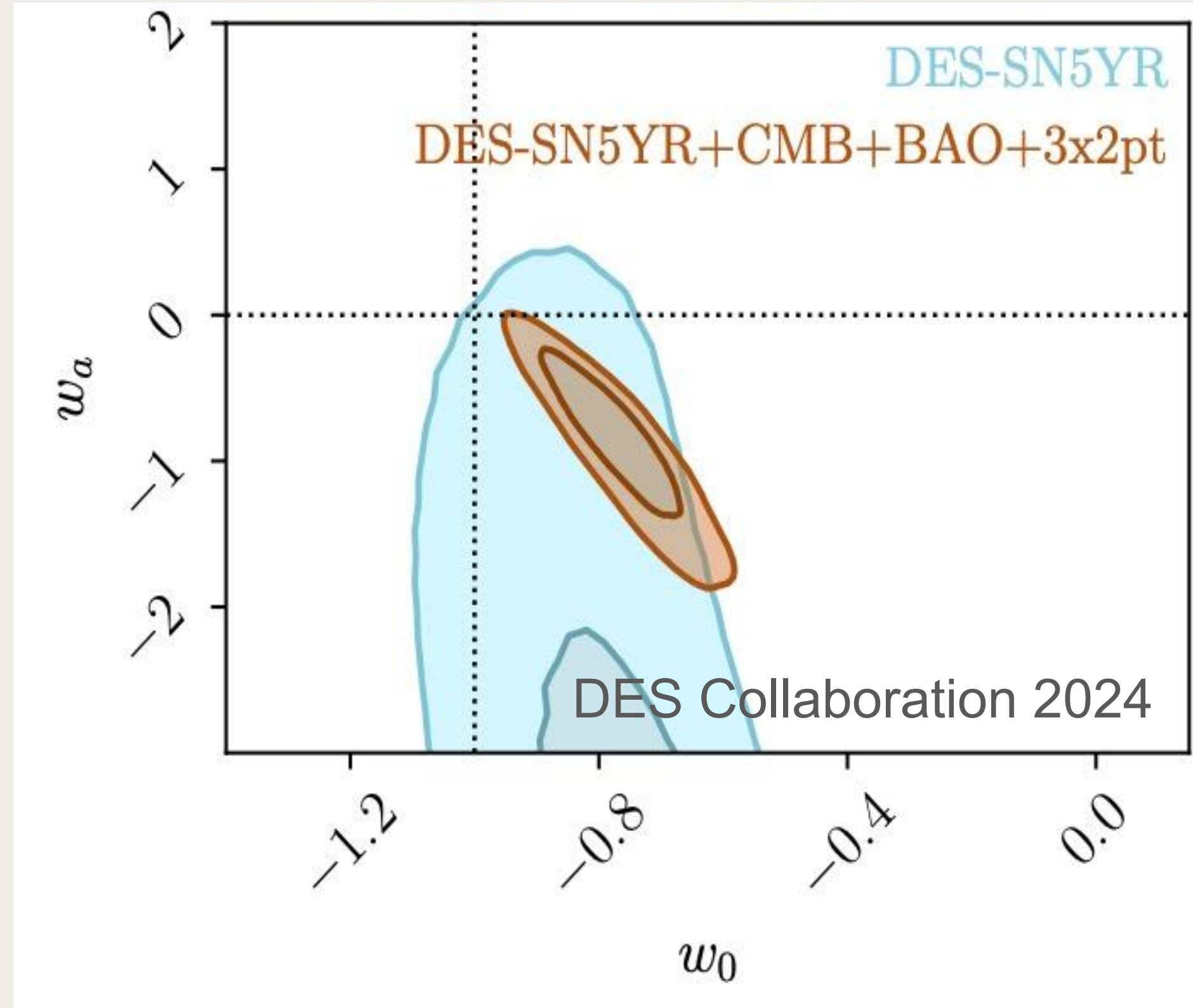


$$w_a < -1.32$$

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

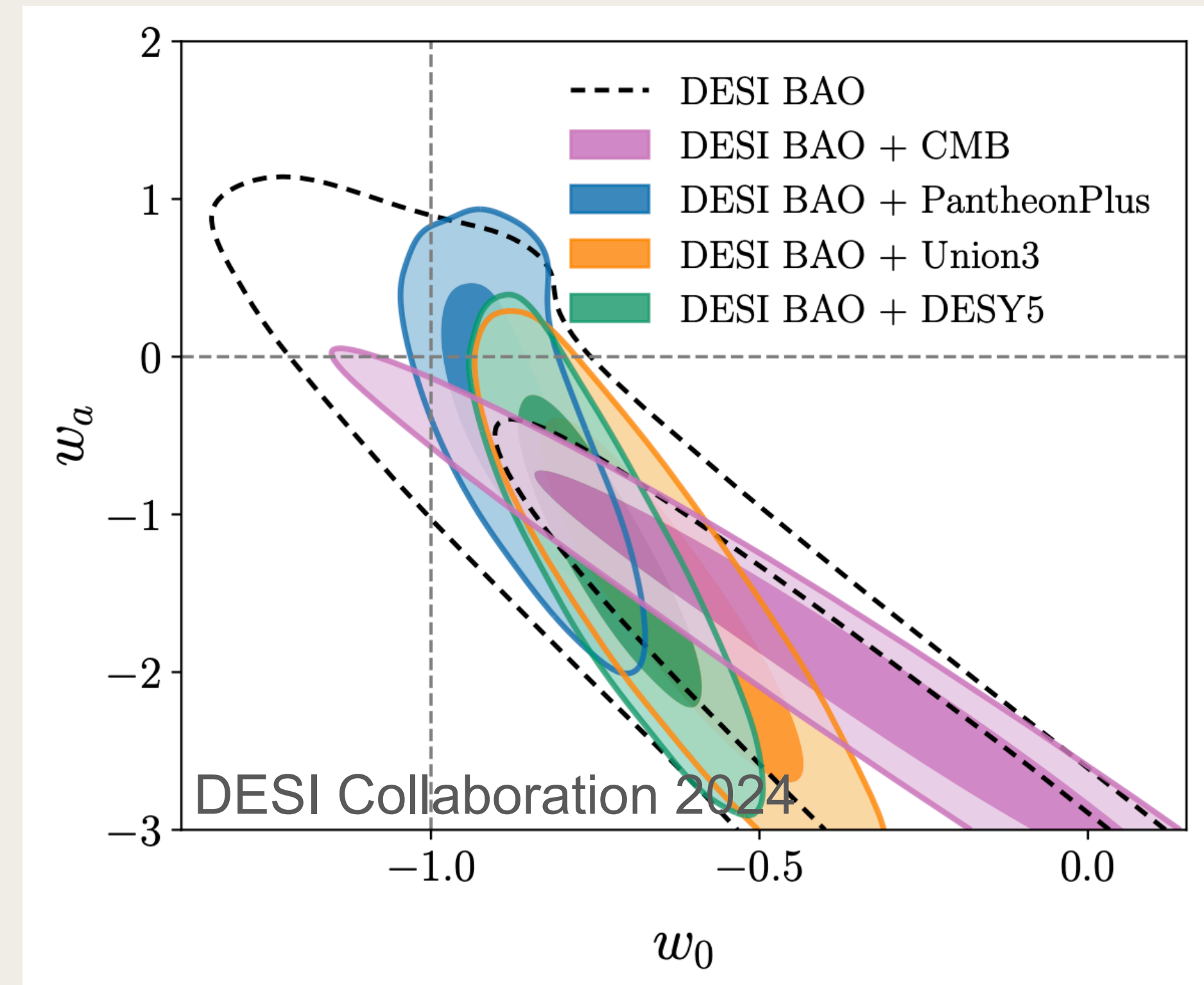
April 2024: DESI finds similar result to DES!

DES:



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

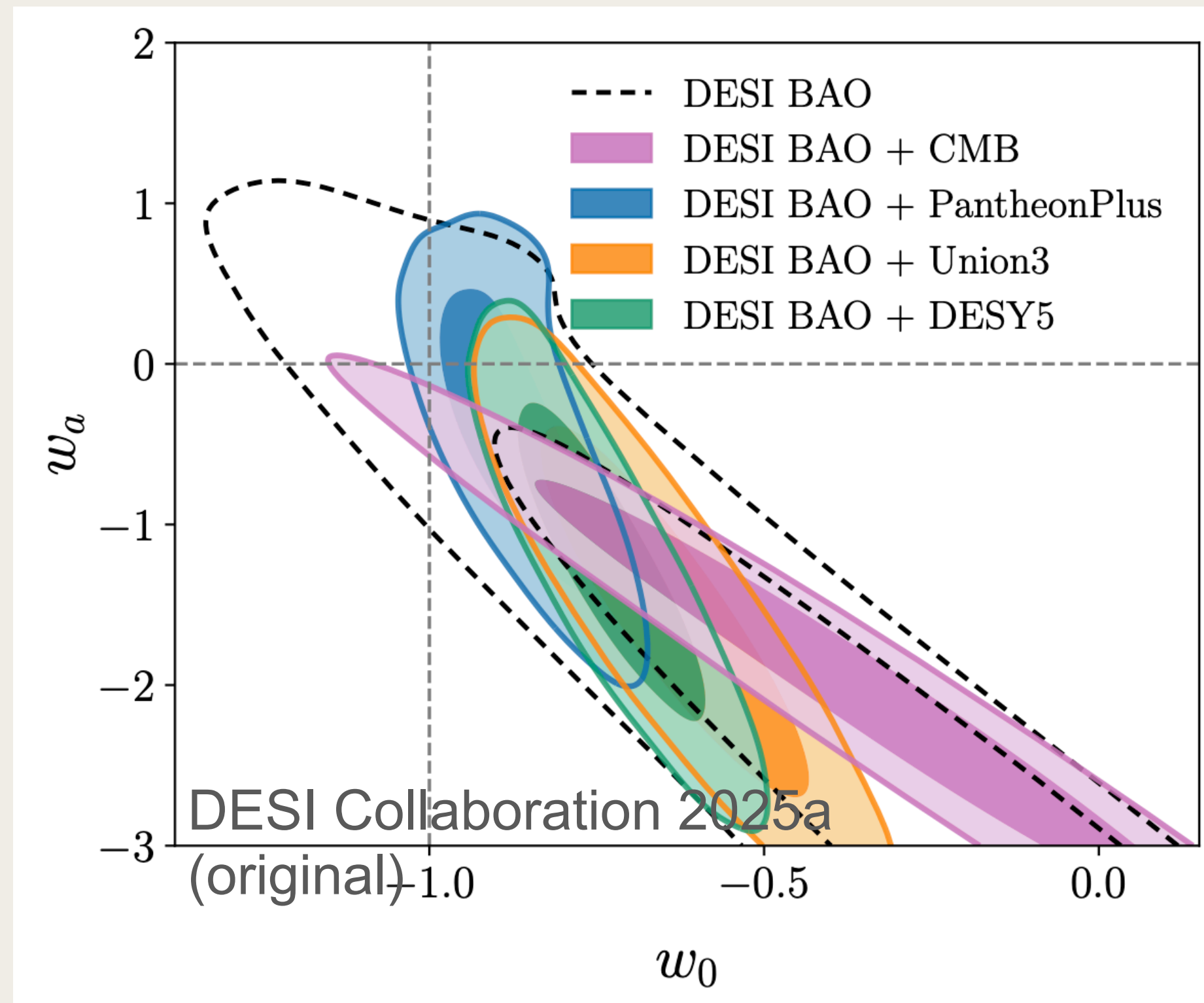
DESI:



$$w_a < -1.32$$

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

April 2025: DESI update

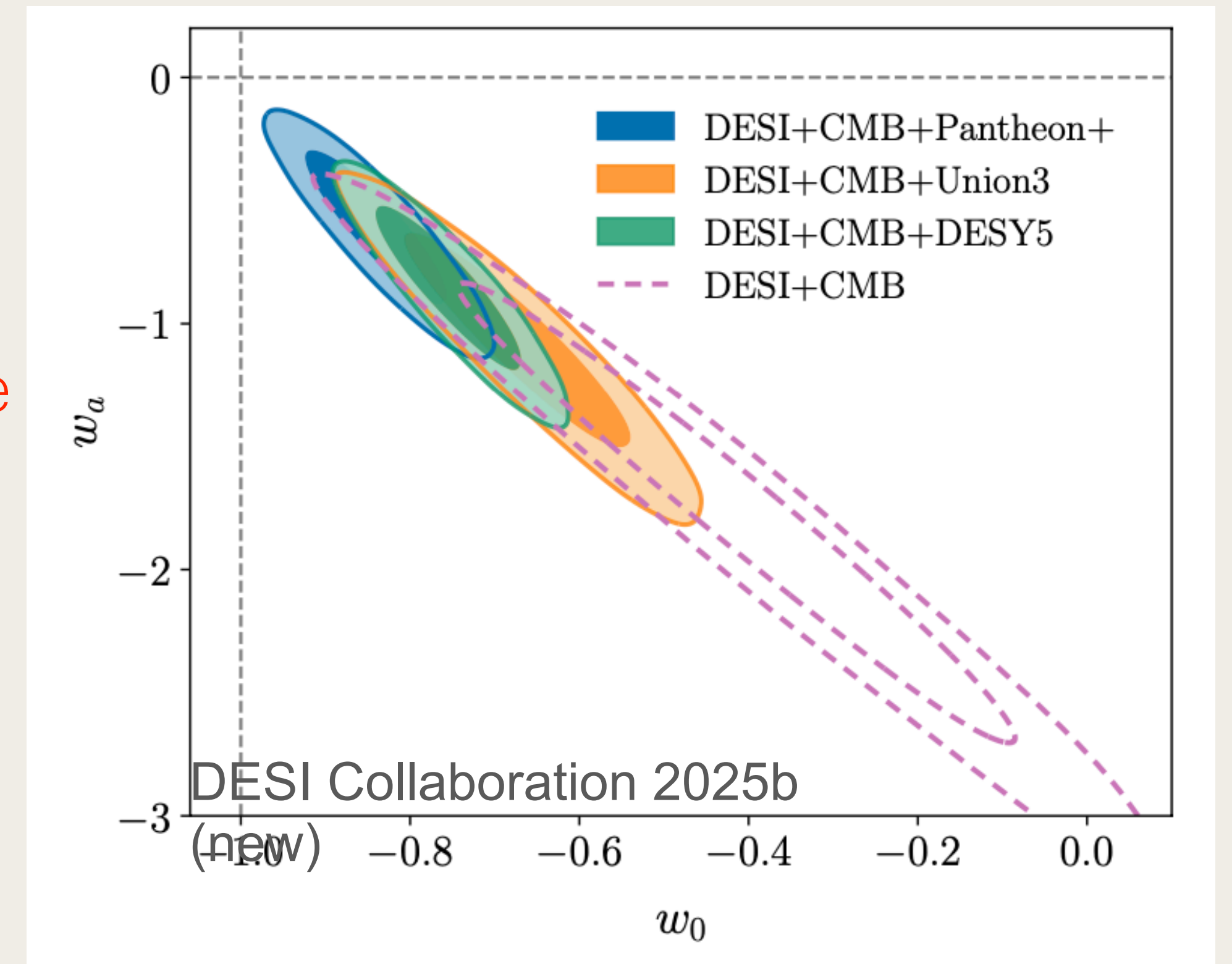


DESI: $w_a < -1.32$

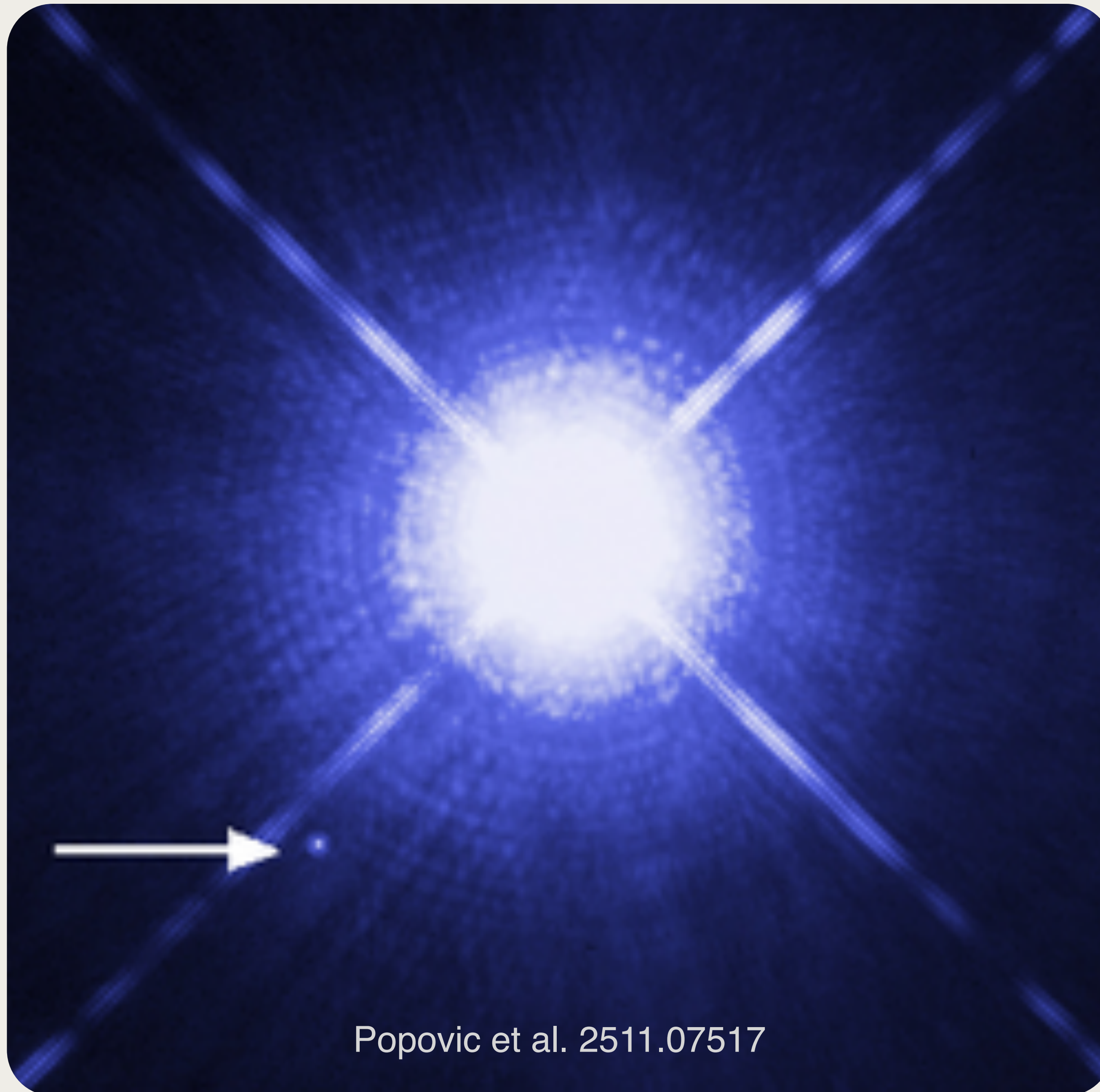
DESI Y1+CMB+DES: $w_a = -1.05^{+0.31}_{-0.27}$ (>3 sigma less than 0)

DESI Y3+CMB+DES: $w_a = -0.86^{+0.23}_{-0.20}$ (>3 sigma less than 0)

Note,
colours are
not the
same!



DESI: $w_a < -1.34$



DES-Dovekie



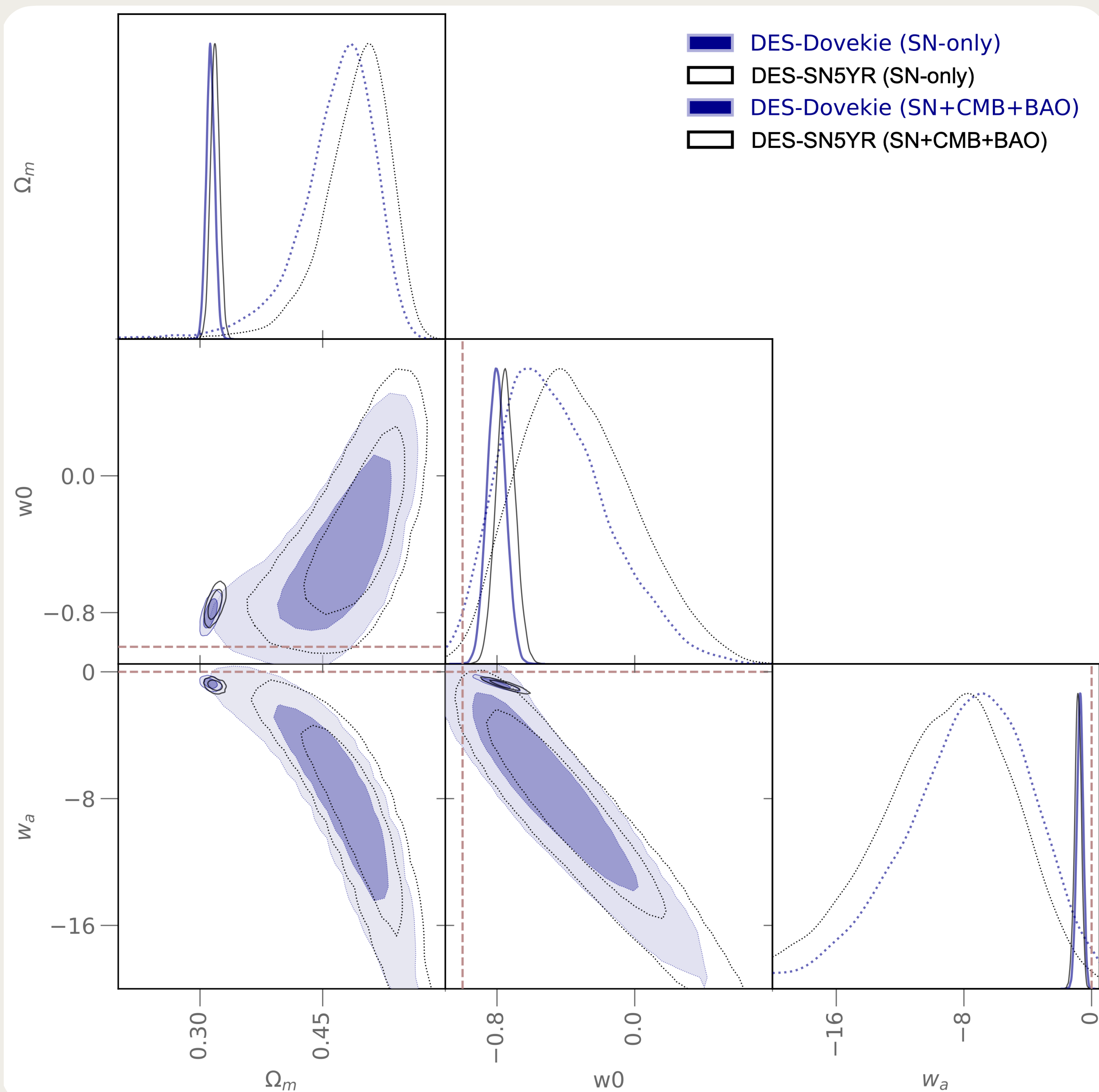
New cross-calibration available for SNe!

Improve photometric cross-calibration between DES and low-*z* supernovae:

- Utilise **new white dwarf** measurements
- Use **Gaia spectroscopy** to better model filter transmission
- Improve **SALT training** and error models

Meanwhile also fixed two poor approximations:

1. The approx to the **host galaxy colour law**
2. A bug that slightly under-weighted the **calibration uncertainties**

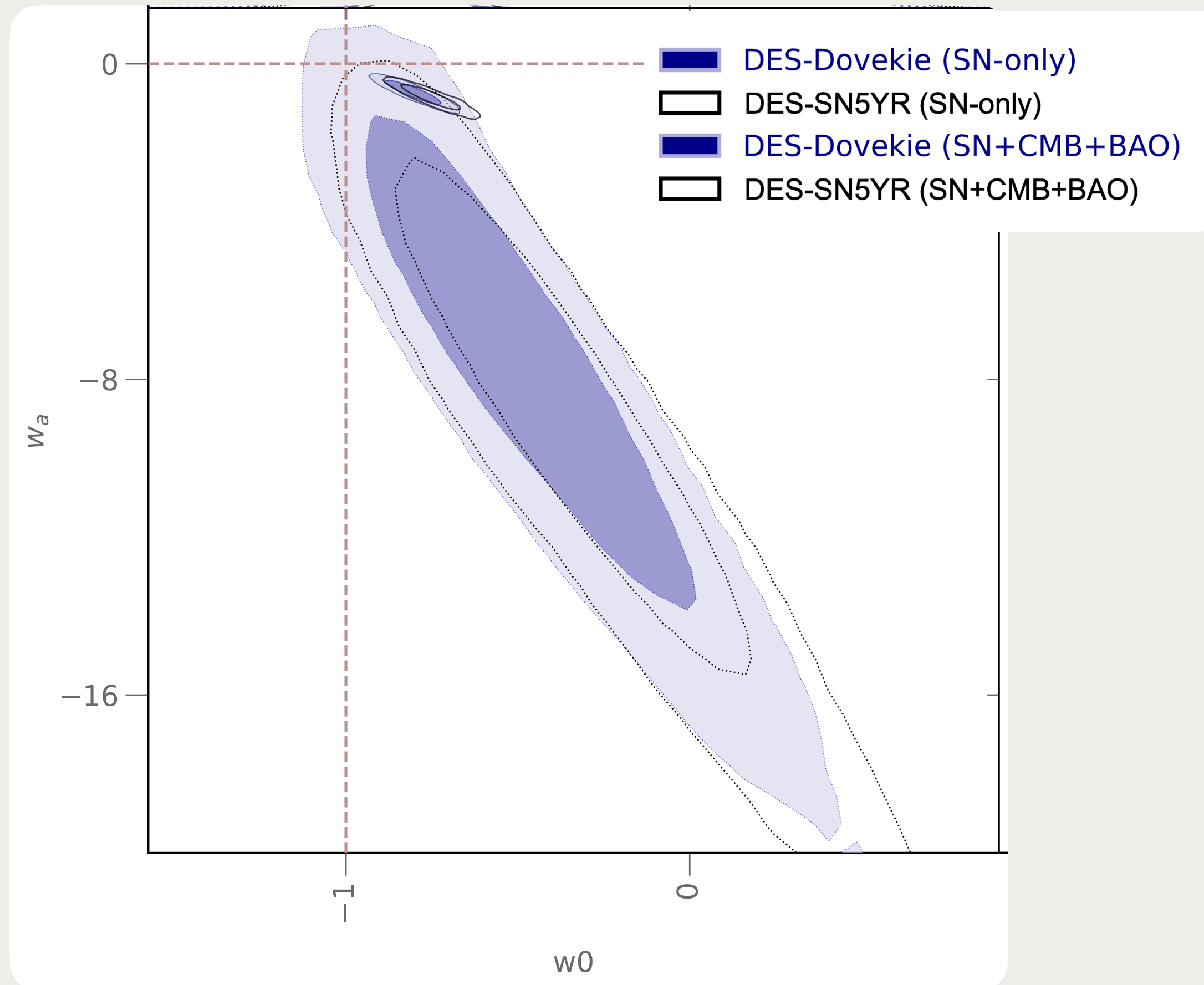


DES-Dovekie

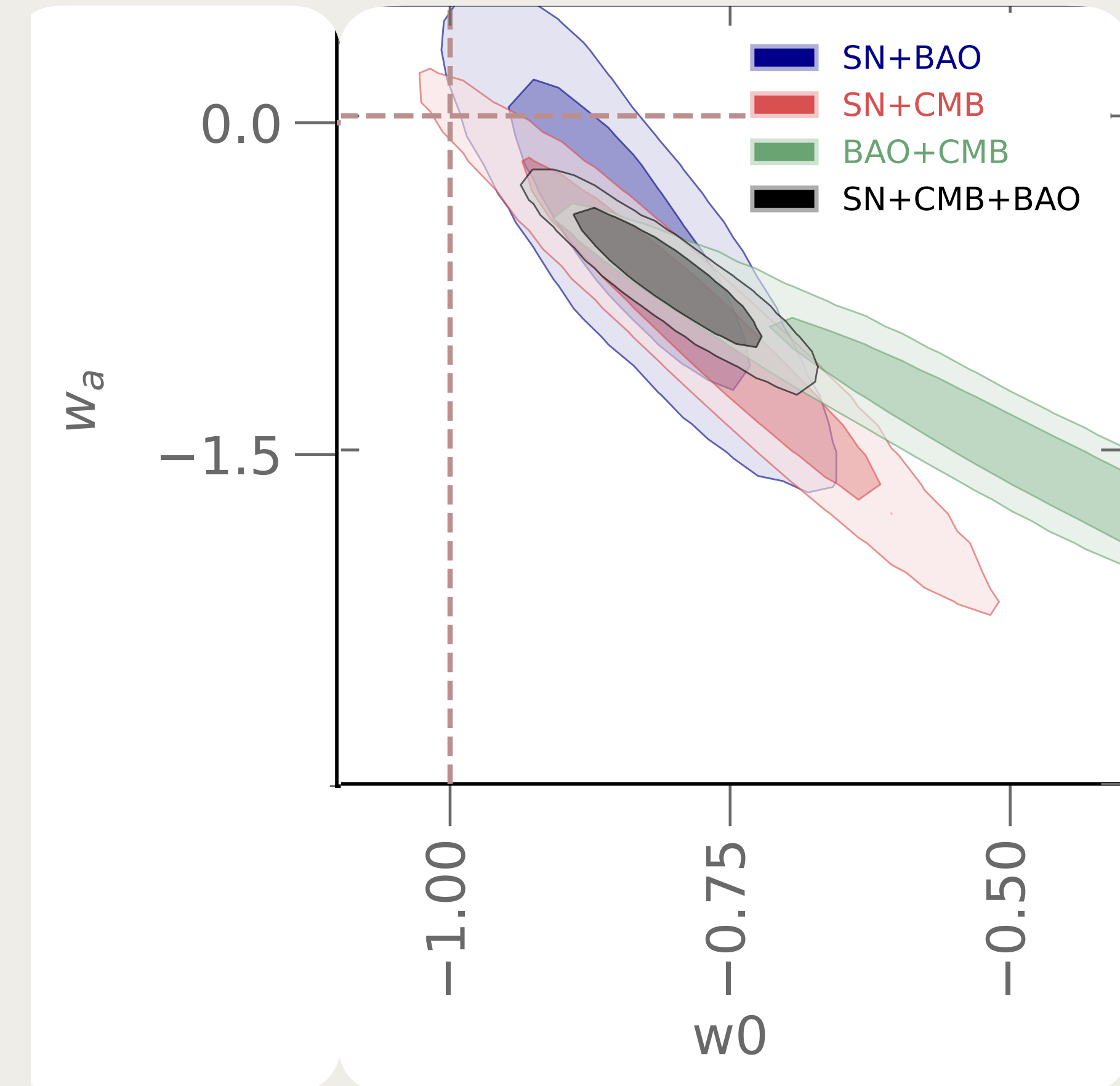
$< 1\sigma$ shifts c.f. original DES analysis
(slightly lower Ω_M)

When combined with other probes, see a
decrease in significance of $w_a < 0$
(from 4.2σ to 3.2σ)

DES-Dovekie

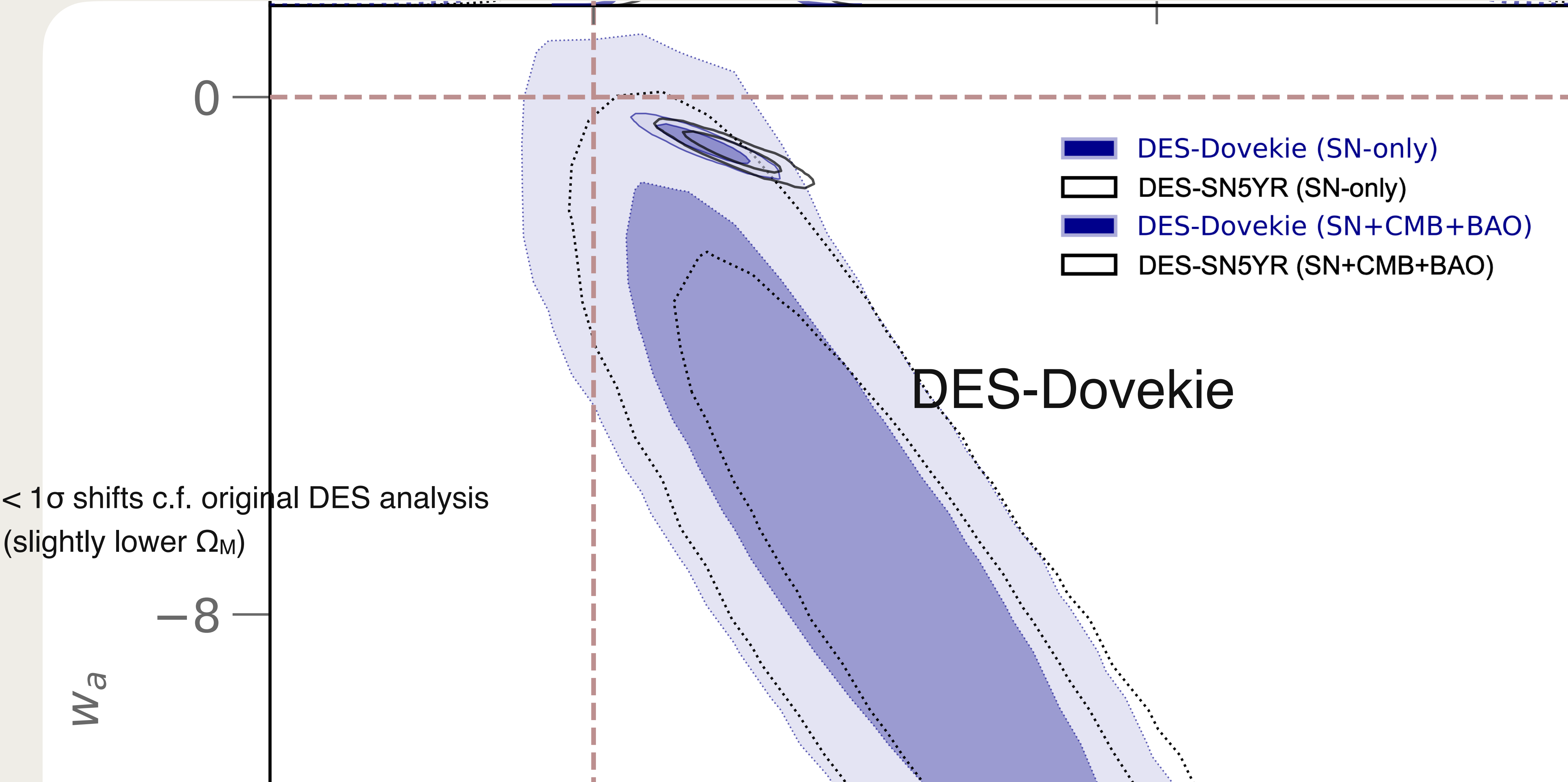


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When combined with other probes, see a
decrease in significance of $w_a < 0$
(from 4.2σ to 3.2σ)

DES-Dovekie



Criticisms and debate

See Paul Shah's talk tomorrow!

Scrutiny of supernova results

George effects

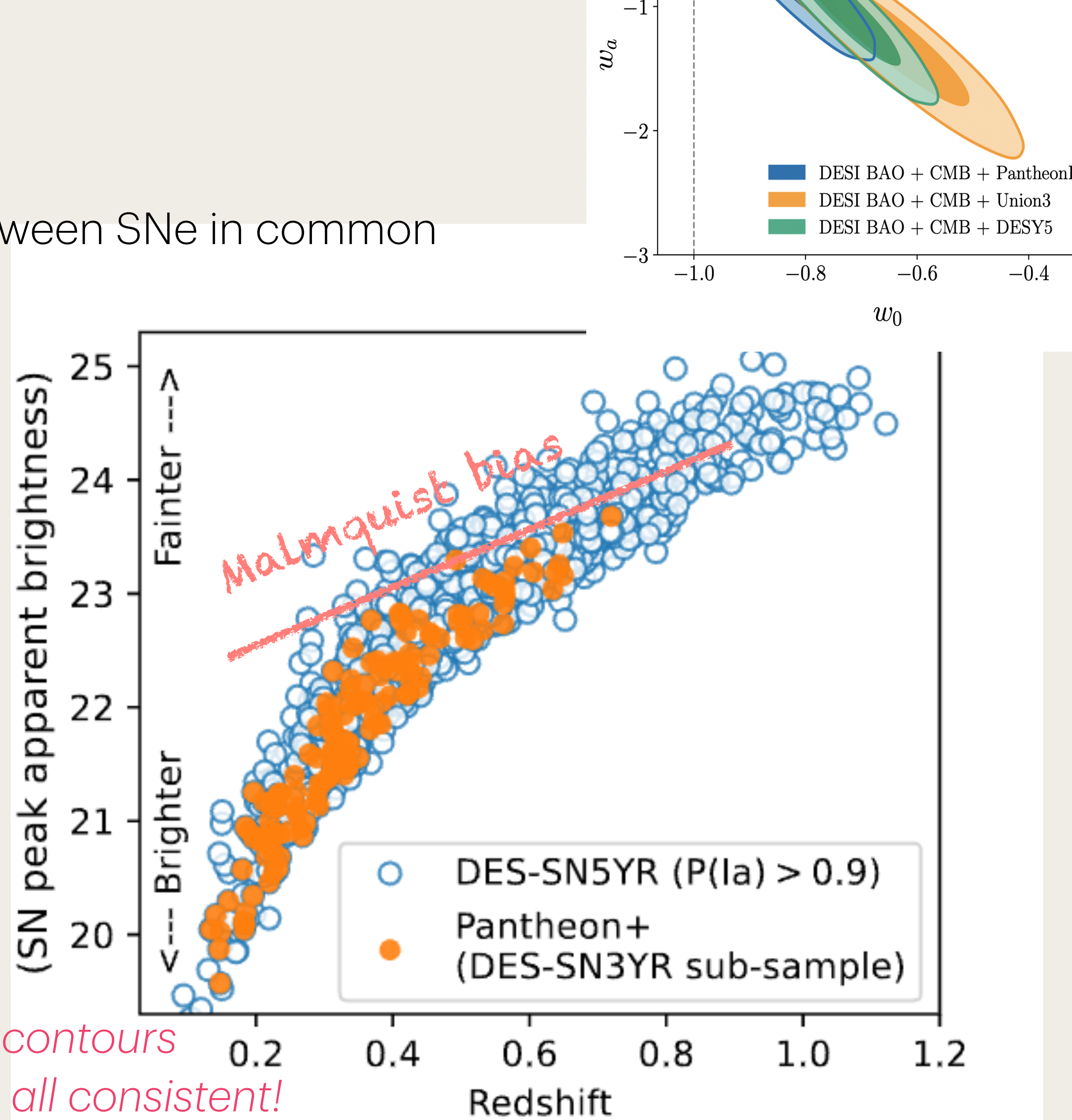
Efstathiou 2024 noticed shift of 0.042 mag between SNe in common between Pantheon+ and DES

Reasons:

- Improved intrinsic scatter model thanks to four colours to high-z (0.008 mag)
- Deeper imaging in DES gives better host masses (0.010 mag)
- DES much more complete, therefore smaller bias corrections (0.016 mag)

And even with these changes, and new data, the contours between Pantheon+, DES-SN5YR, and Union3 are all consistent!

You expect scatter in observations — and they all overlap at the 1 sigma level.

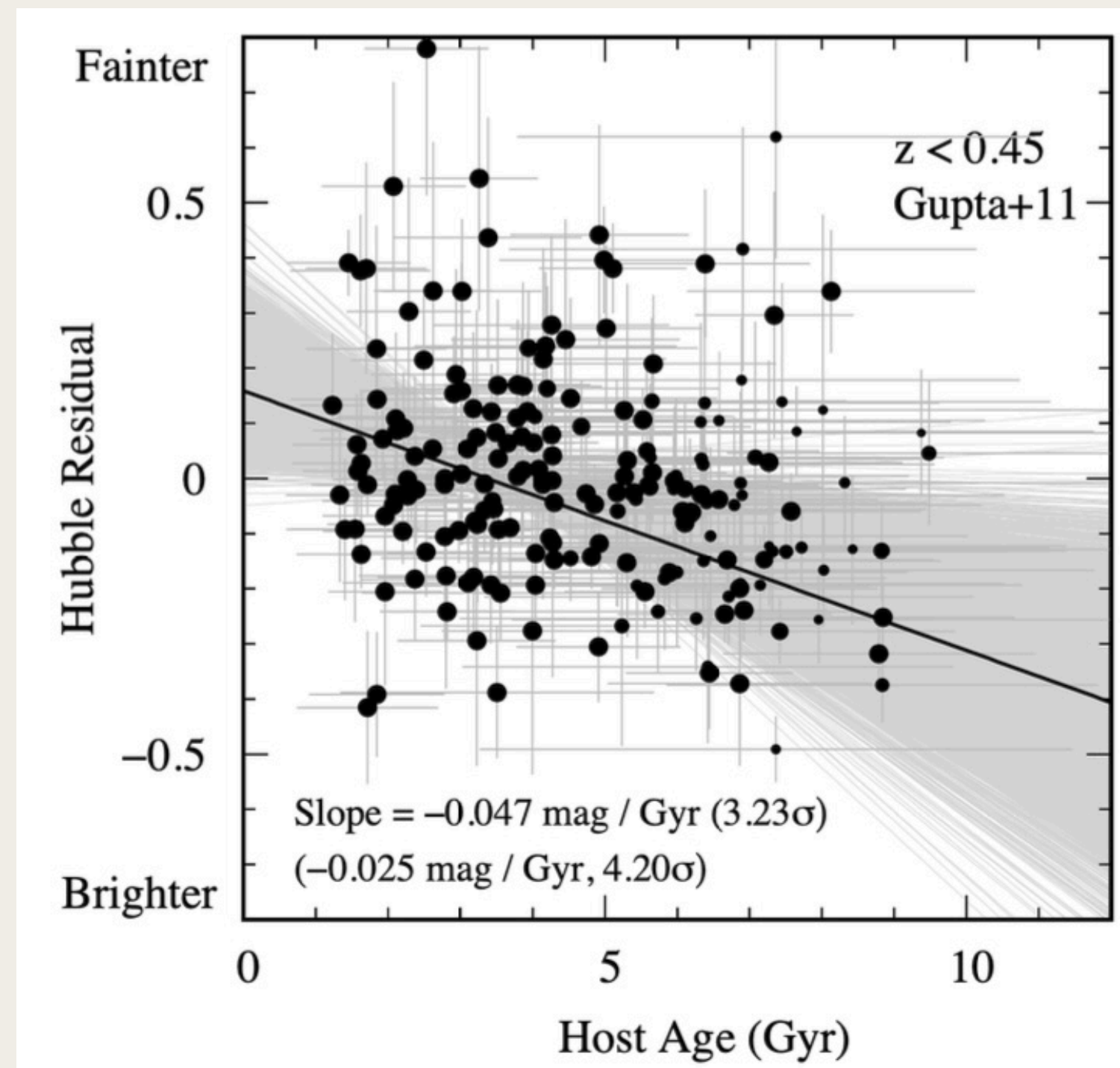


Son effects

Strong Progenitor Age-bias in Supernova Cosmology. II. Alignment with DESI BAO and Signs of a Non-Accelerating Universe

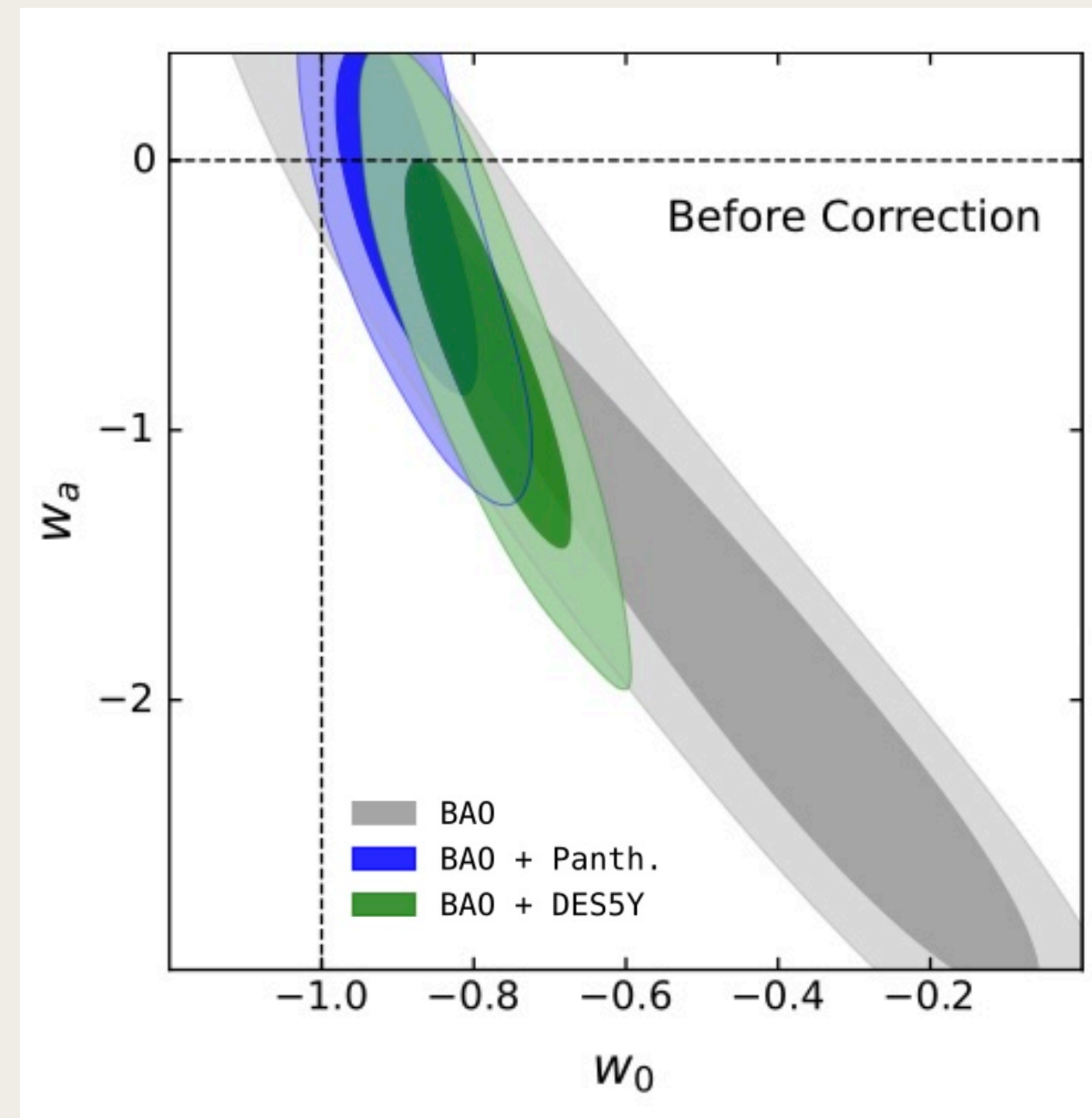
Junhyuk Son,[★] Young-Wook Lee,[†] Chul Chung,[‡] Seunghyun Park and Hyejeon Cho
Department of Astronomy & Center for Galaxy Evolution Research, Yonsei University, Seoul 03722, Republic of Korea

Hubble residuals correlate with
galaxy age (well known).

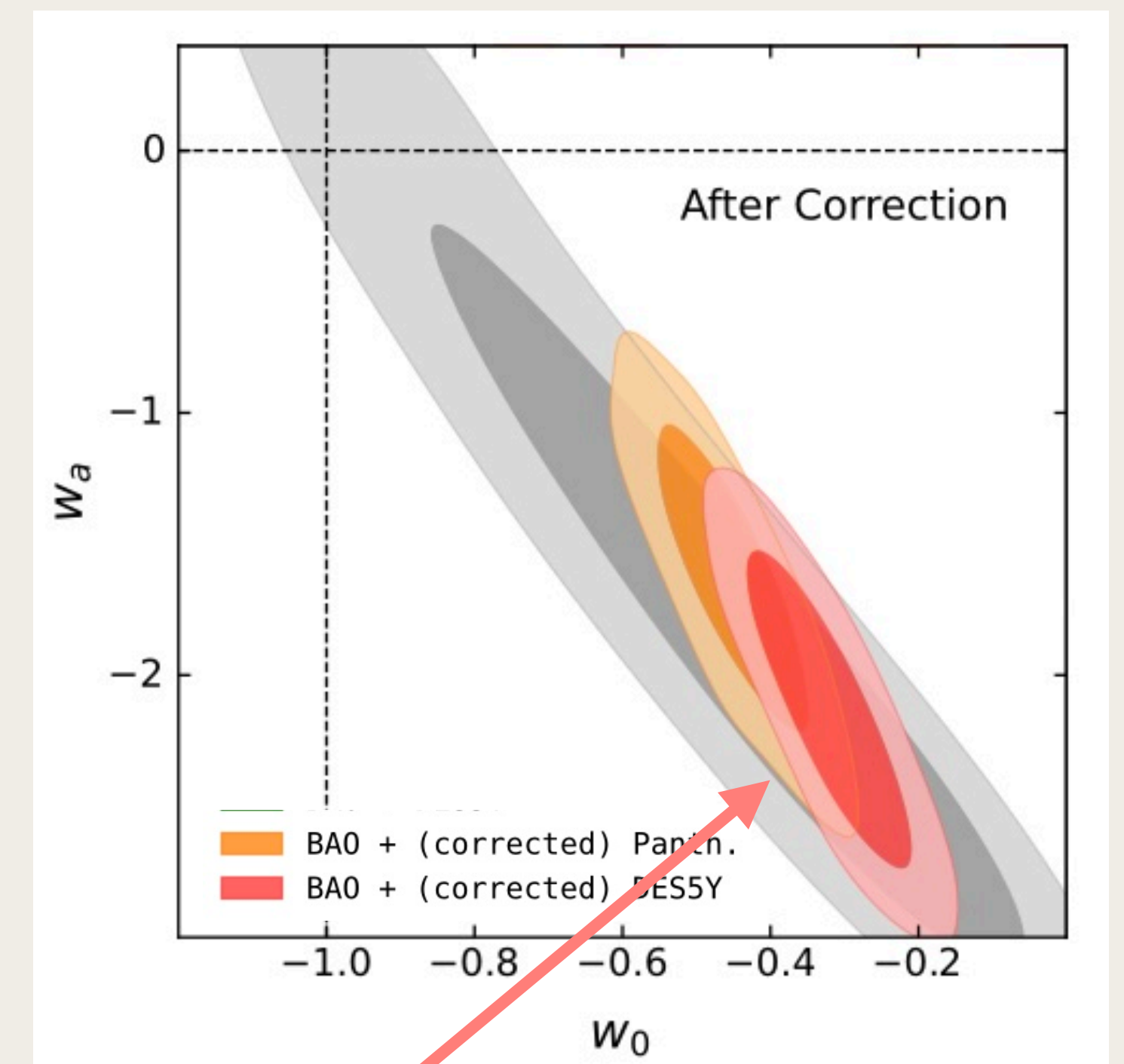


Attempts to correct this....

Before "correction"



After "correction"

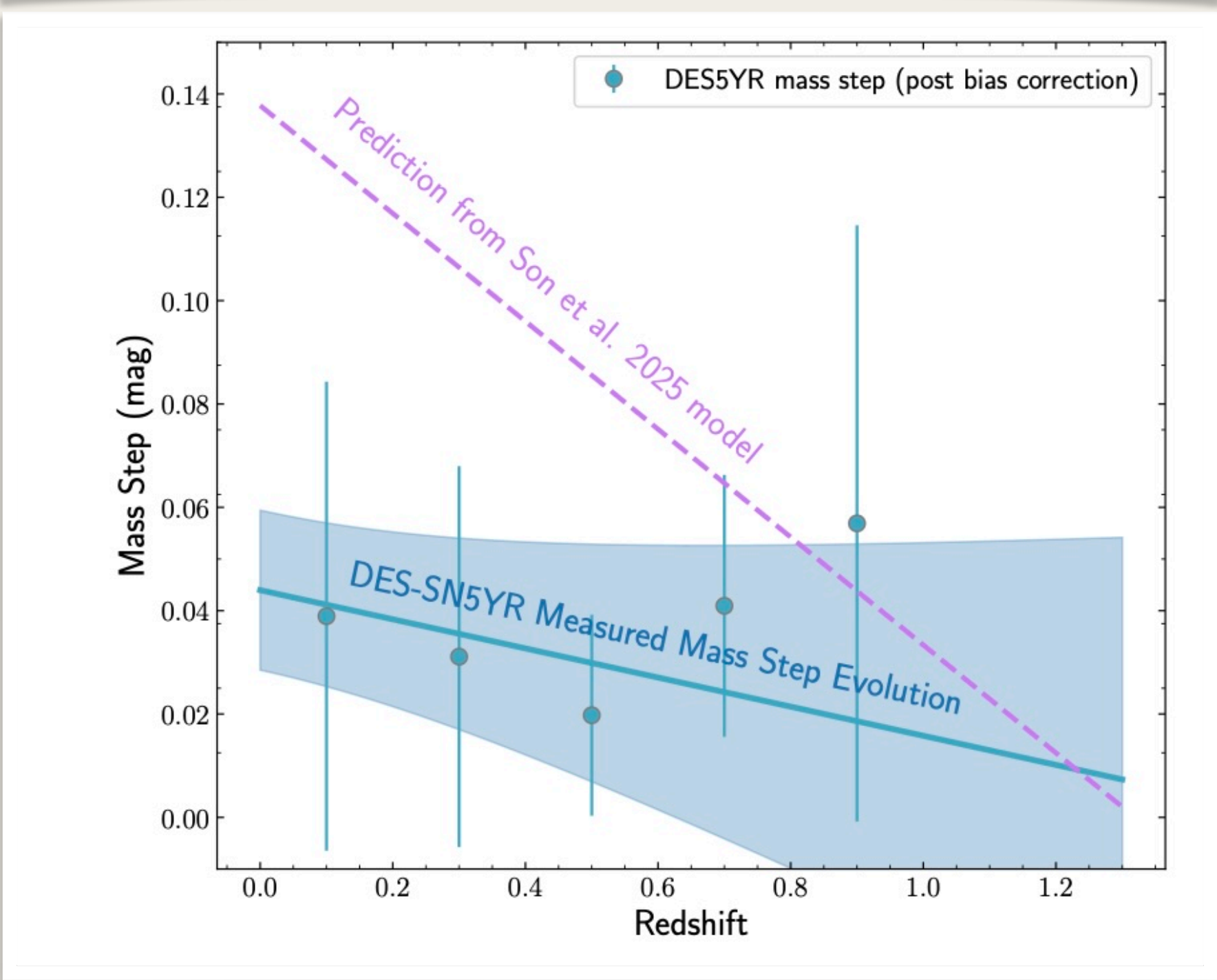
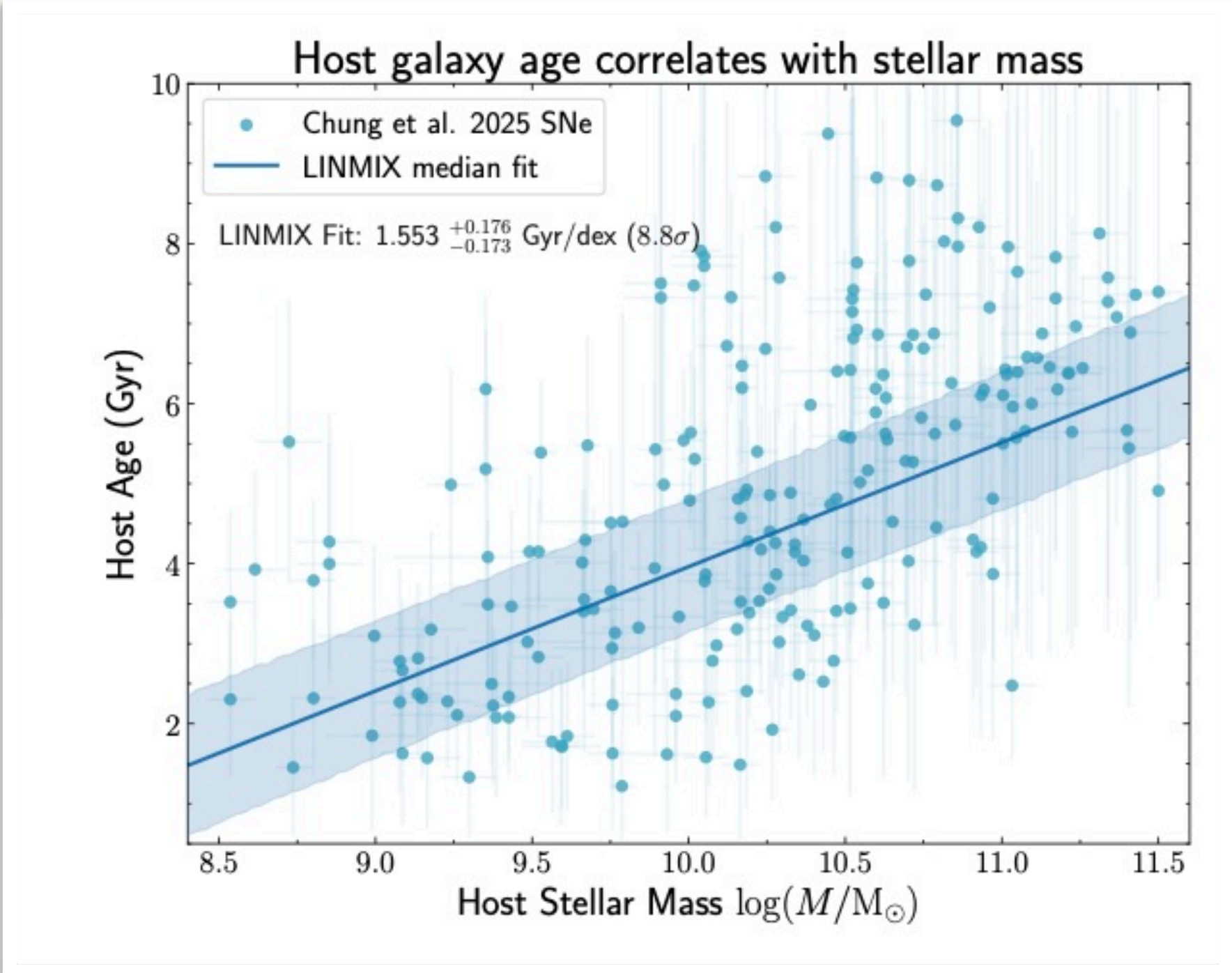


Finds much greater discrepancy with Λ CDM

Son effects

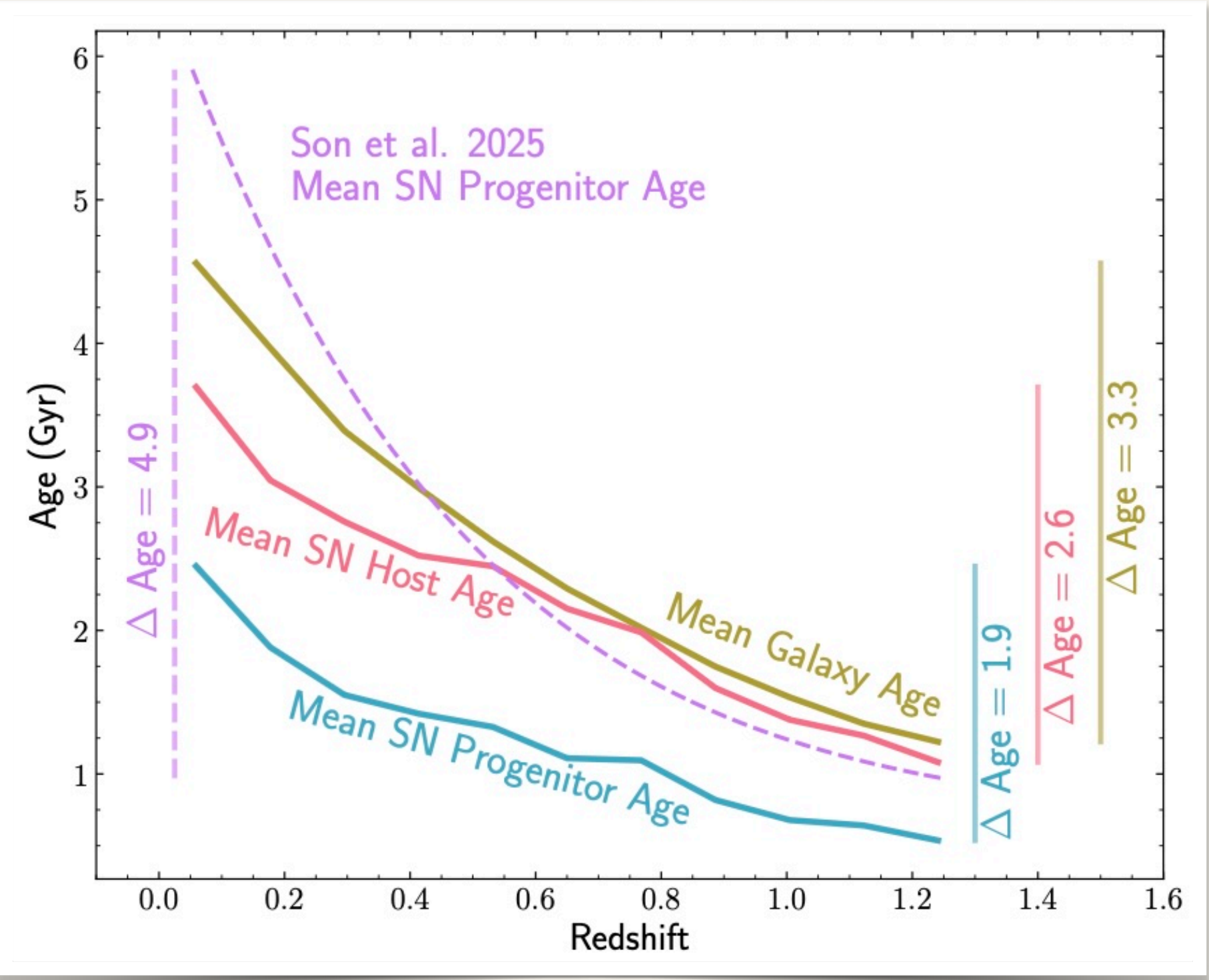
Explanation:

- They **omit the host-galaxy mass correlation** (reinstating it finds no additional trend with galaxy age)
- They **predict strong redshift evolution of the host mass effect** (but DES measured evolution and found it consistent with zero)
- They **confuse host galaxy age with supernova progenitor age**, (thus overestimating the progenitor age evolution by a factor of 3-5).



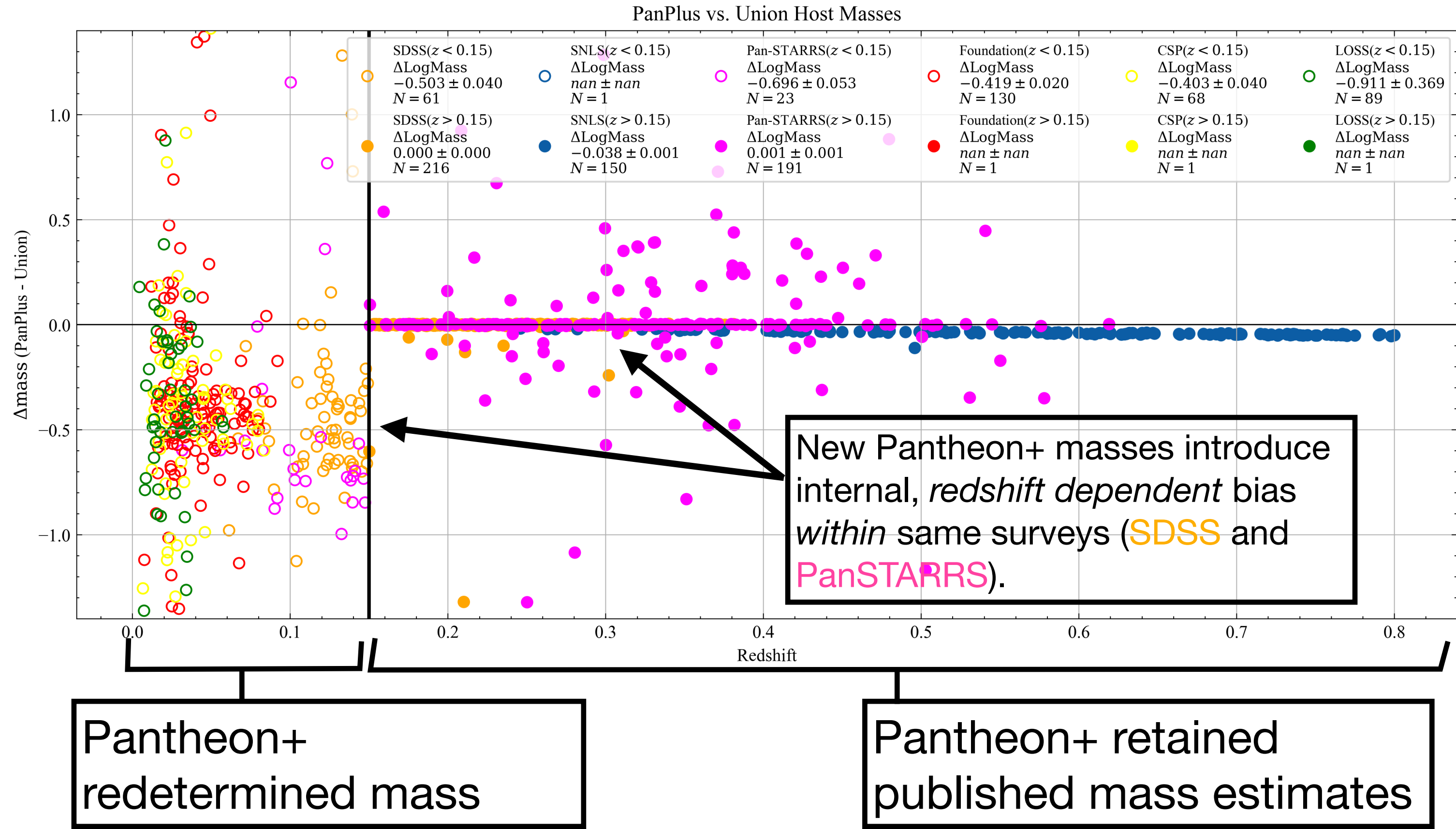
Still Accelerating: Type Ia supernova cosmology is robust to host galaxy age evolution

Phil Wiseman^{1*}, Brodie Popovic¹, Mark Sullivan¹, Adam G. Riess^{2,3}, Dan Scolnic⁴, Rebecca C. Chen^{5,6,7}, Tamara M. Davis⁸, Lluís Galbany^{9,10}, Isobel M. Hook¹¹, Saurabh W. Jha¹², Lisa Kelsey¹³, Yukei S. Murakami³, Mickaël Rigault¹⁴, Benjamin M. Rose¹⁵, Brian Schmidt¹⁶, Mat Smith¹¹, Maria Vincenzi¹⁷



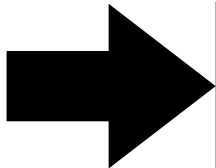
A. Discrepancies and Inconsistencies in Pantheon+ Systematic, redshift dependent bias in host mass estimates

- 0.5 dex systematic bias in Pantheon+ masses estimated to $z < 0.15$ SN host galaxies.
- Destroys internal self-consistency within and across SN surveys.
- This is the *exact same* discrepancy Efstathiou commented on between Pantheon+ and DES SNe. However, he claimed the DES SN distances were biased, but the reality is the *reverse*.
- That is, the new masses estimated by Pantheon+ to $z < 0.15$ hosts have introduced an artificial redshift evolution that both suppresses the signal for evolving dark energy and biases their H_0 to higher values.
- This mass bias results in a 0.02 mag bias in the low redshift SN bin, which accounts for half the suppression of evolving dark energy and is equal to 2/3 of the Pantheon+SH0ES *total* uncertainty on H_0

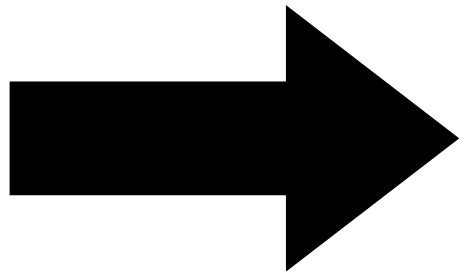
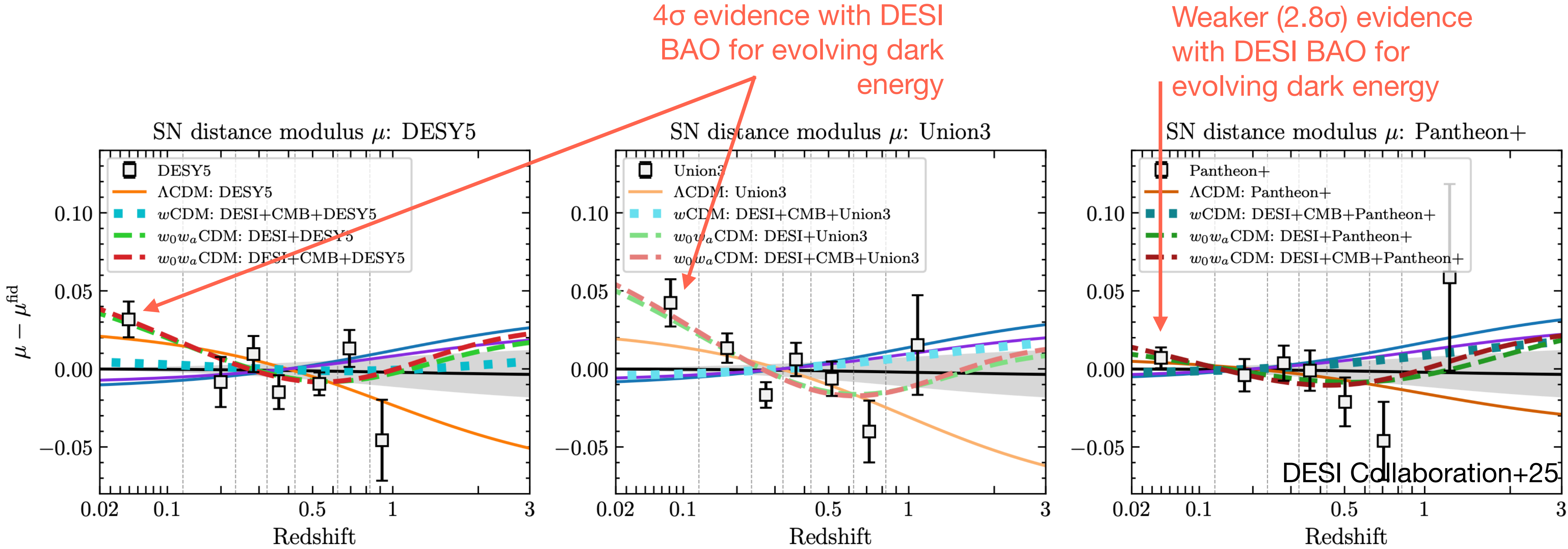


A. Discrepancies and Inconsistencies in Pantheon+

Inconsistent with DES-SN5YR and Union3 at low redshift

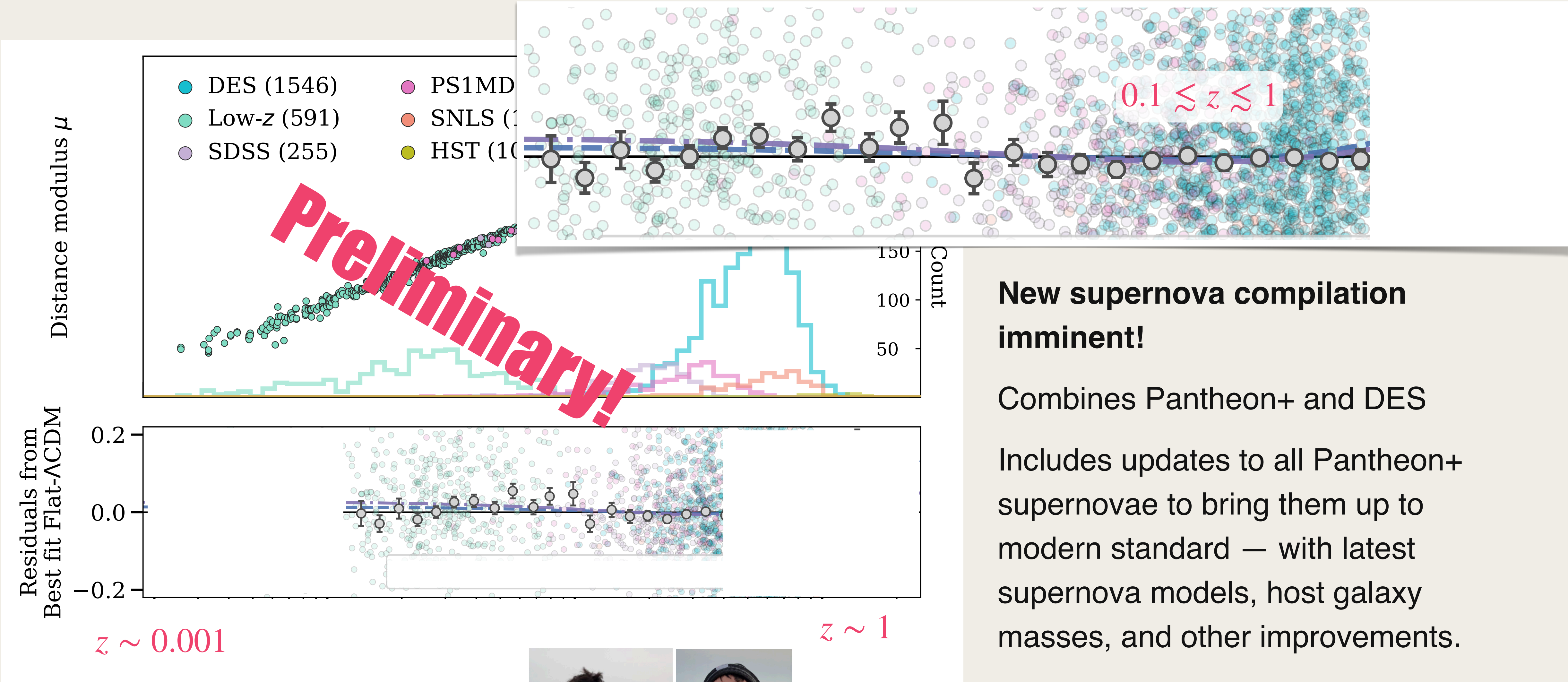


A systematic bias of 0.5 dex in the host masses that Pantheon+ determined for $z < 0.15$ hosts explains $\sim$ half (0.02 mag) of this difference!



This same low redshift bin is what determines the value of the Hubble Constant, i.e., $H(z = 0)$. Need independent check on Pantheon+ H_0

Unite: New data compilation imminent!!!



New supernova compilation imminent!

Combines Pantheon+ and DES

Includes updates to all Pantheon+ supernovae to bring them up to modern standard — with latest supernova models, host galaxy masses, and other improvements.

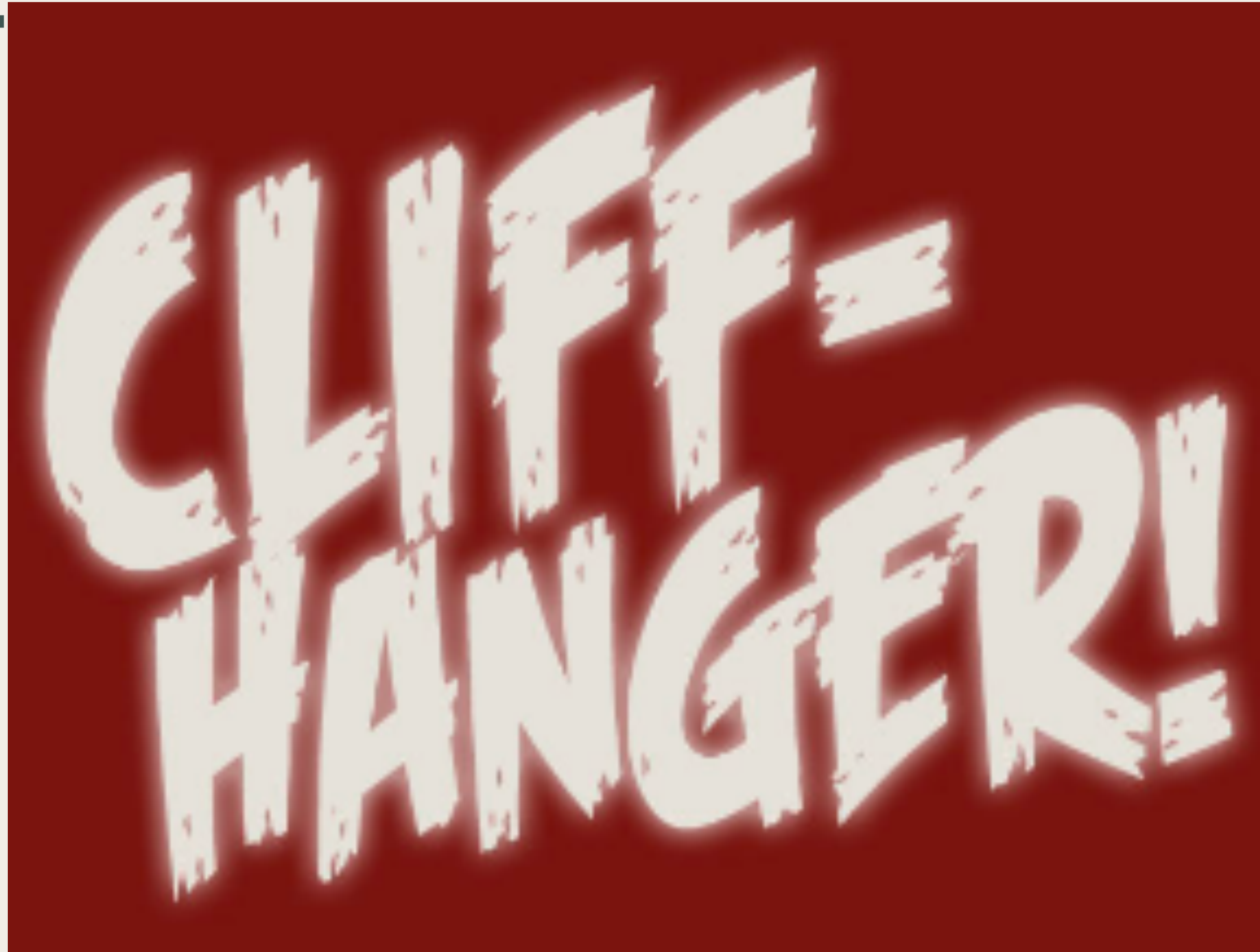
Lee et al. in prep: Host galaxy masses
Camilleri et al. in prep: Cosmology results



>2800 SNe!

The Result.

Lee et al. in prep: Host galaxy masses
Camilleri et al. in prep: Cosmology results



... tune in next time to find out
whether dark energy is constant
or whether dark energy changes with time



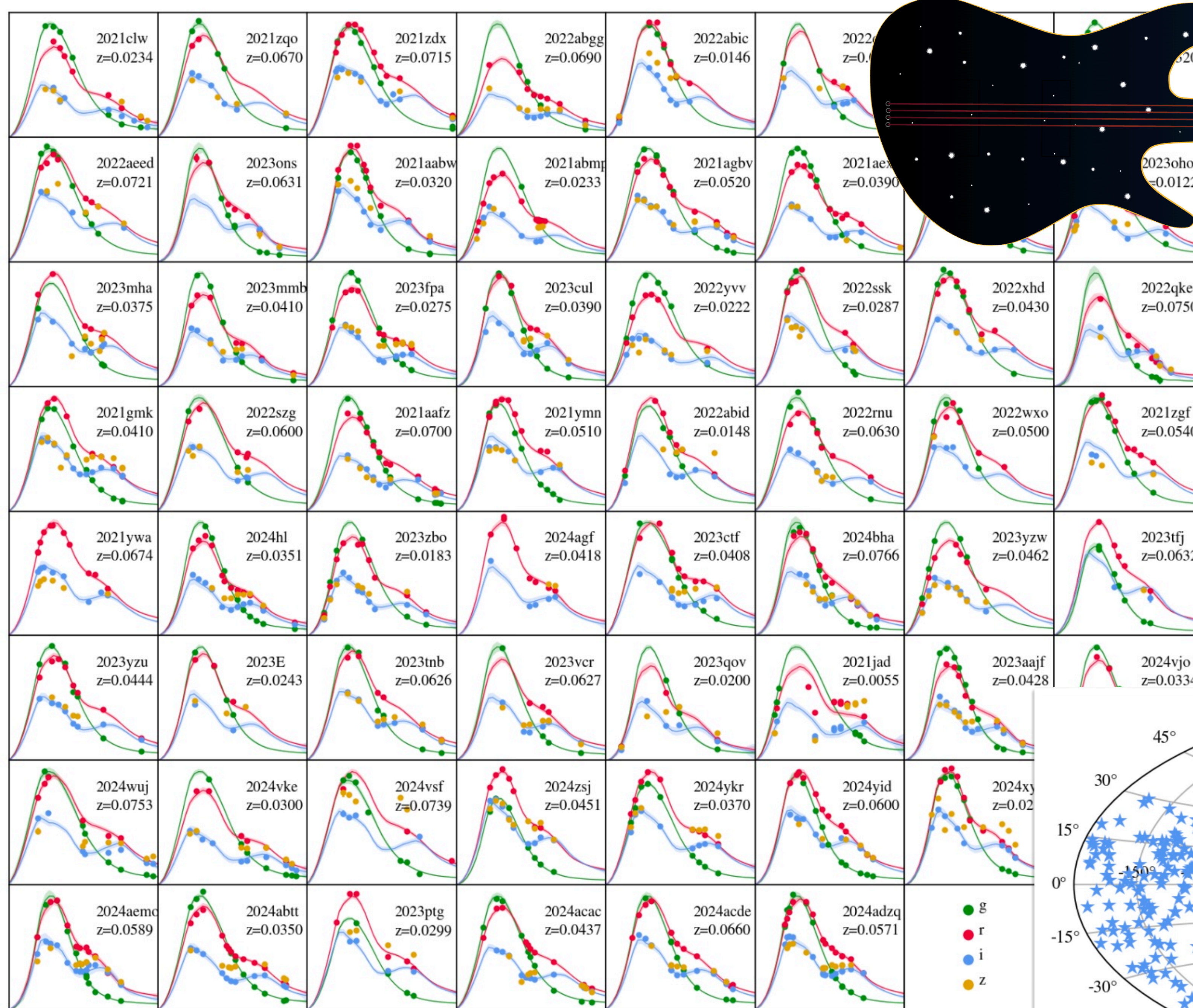
DEBass

New low-redshift supernova sample on its way!

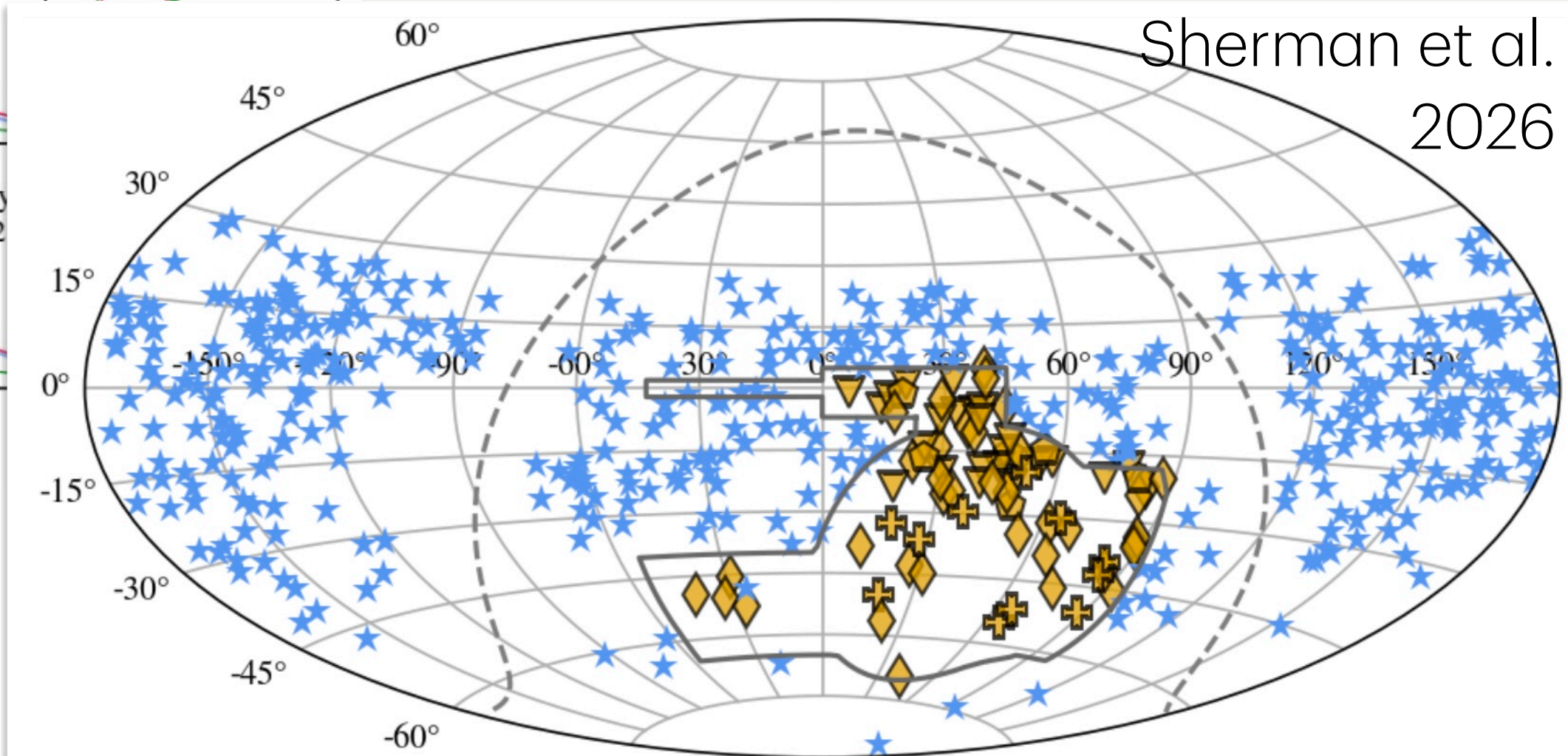
The Dark Energy Bedrock All-Sky Supernova Program

Approximately 400 low-z supernovae with DECam already ready to go

Flux



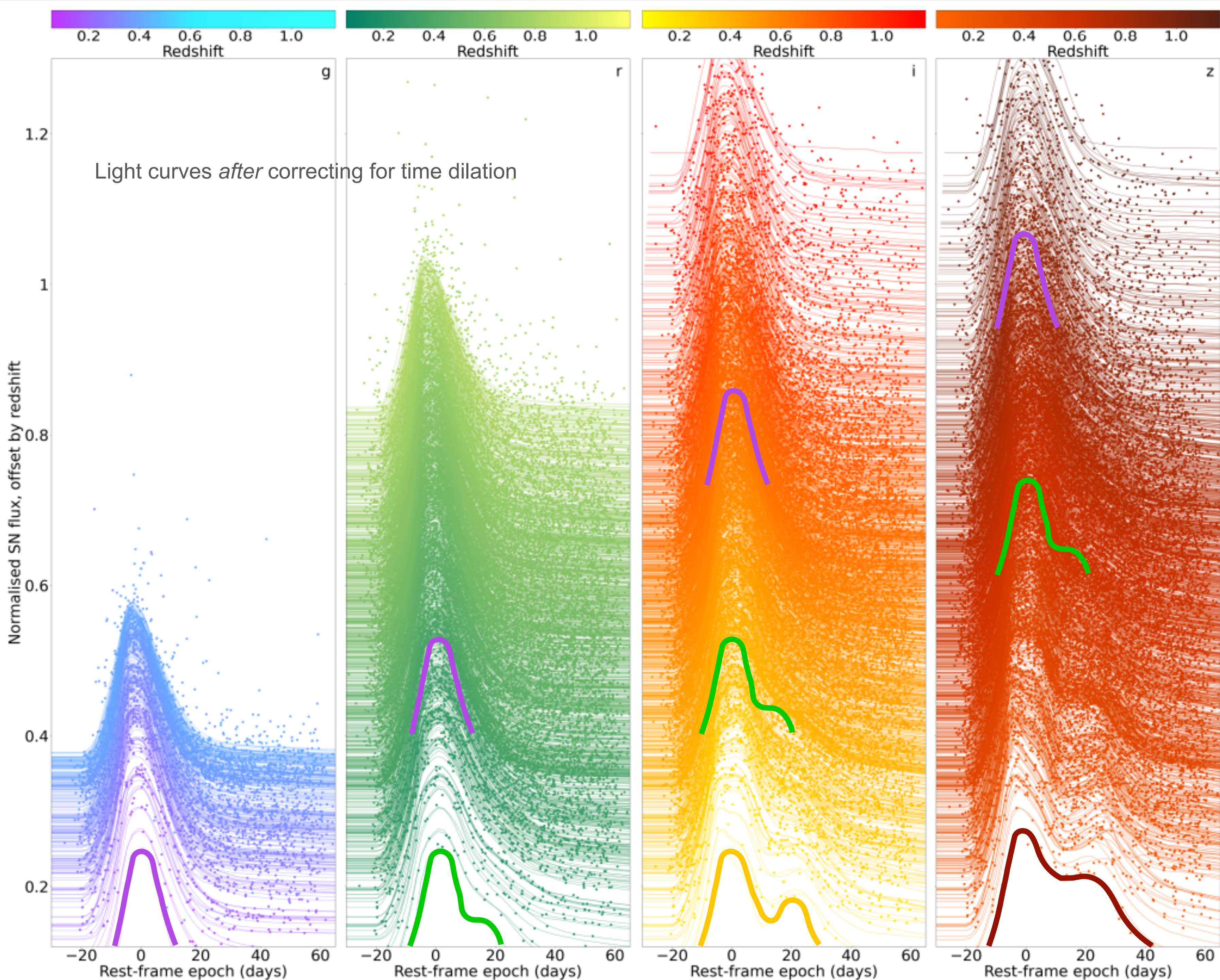
Δ MJD from Peak



Sherman et al.
2026

Slow supernovae!

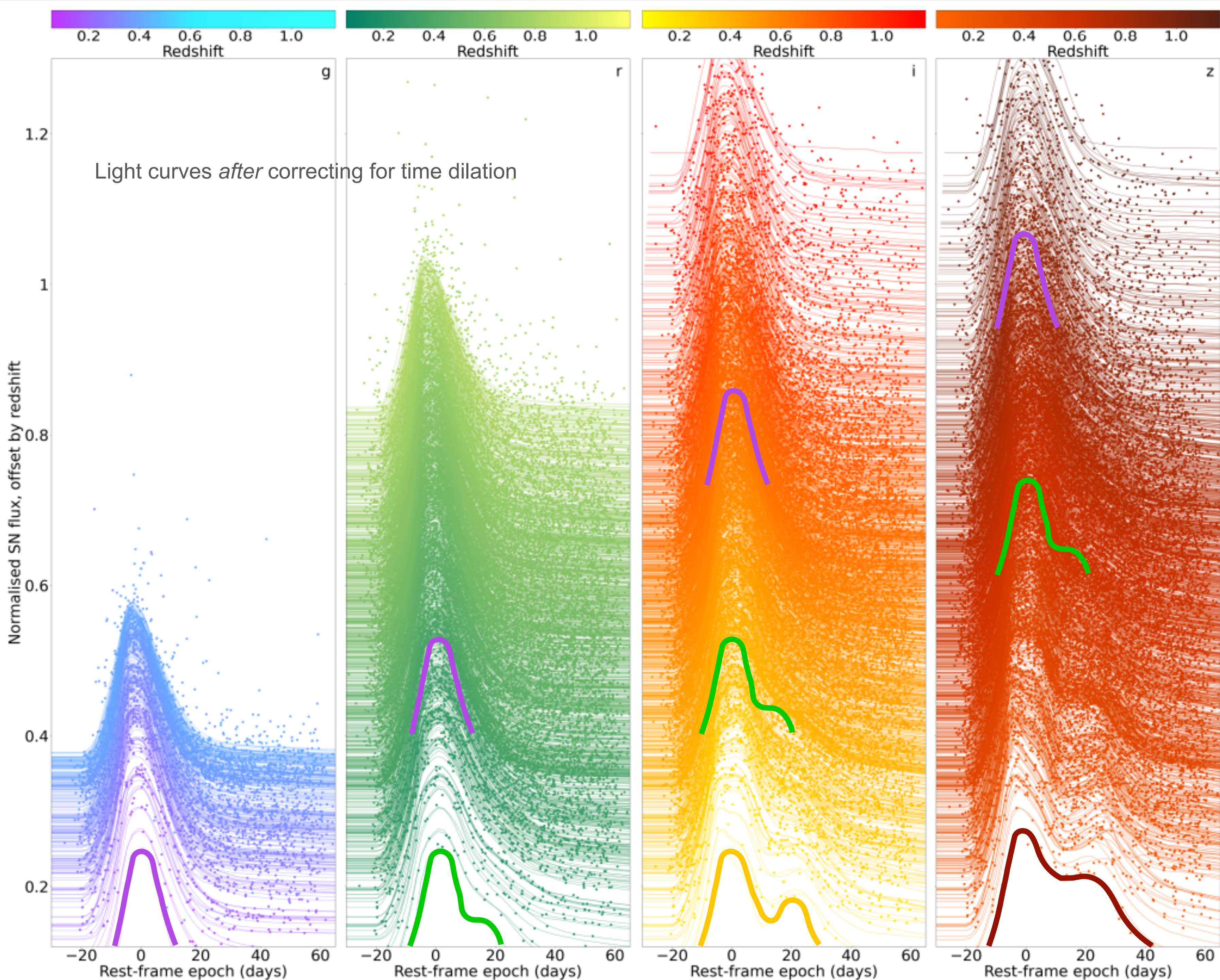
DES:
Time Dilation



Time dilation

Expect observed duration to be $(1+z)$ times the original duration

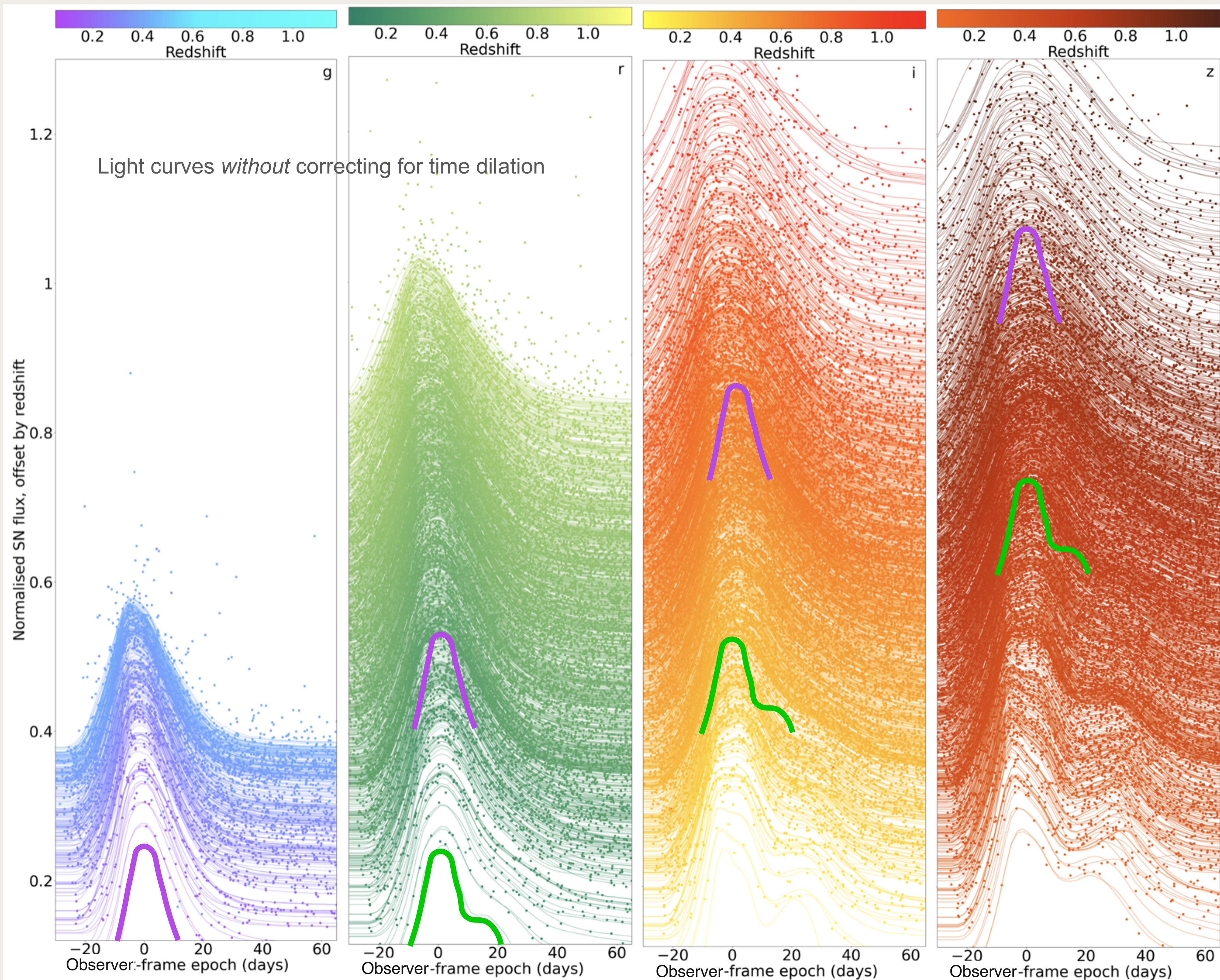




Time dilation

Expect observed duration to be $(1+z)$ times the original duration





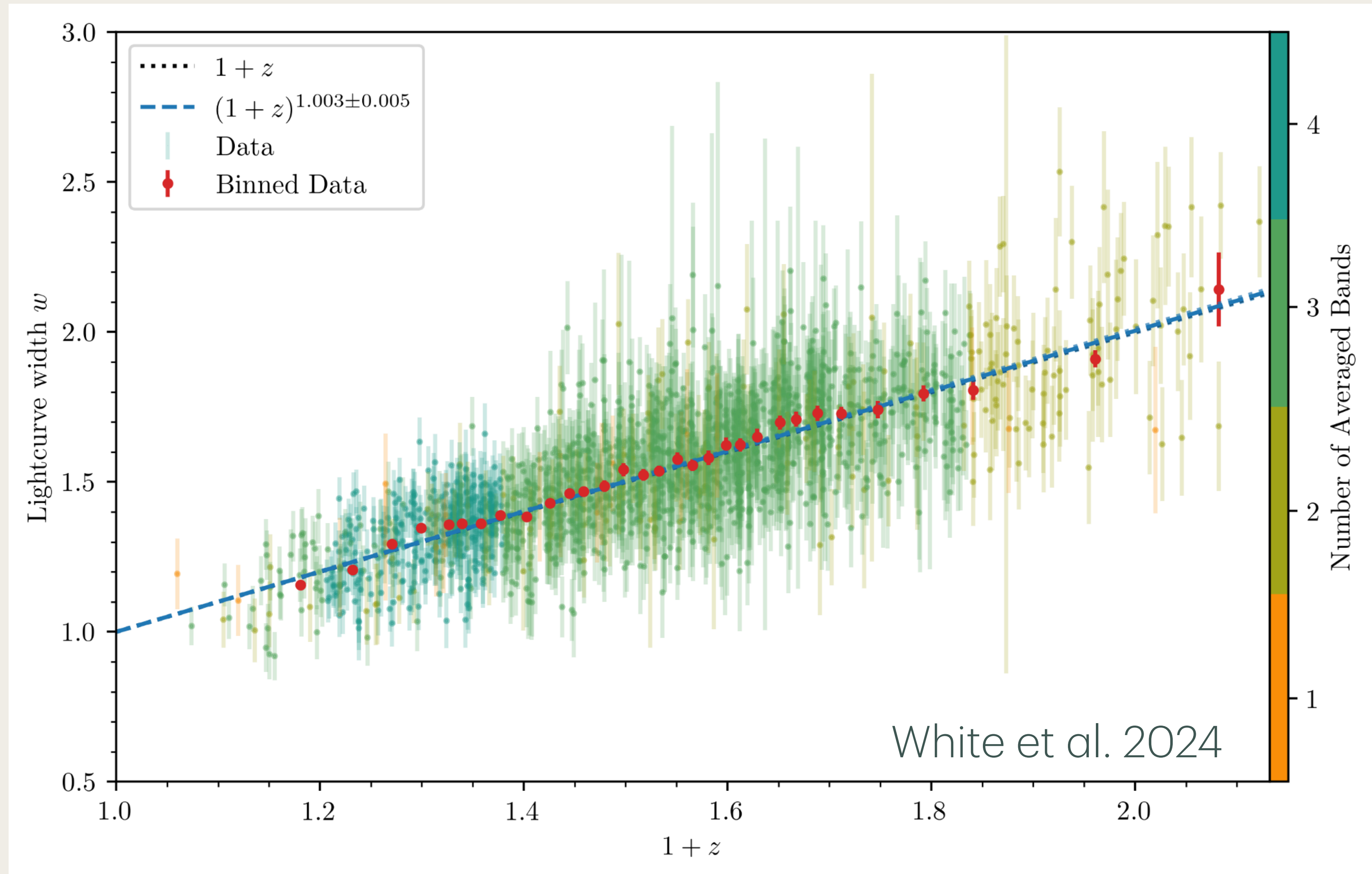
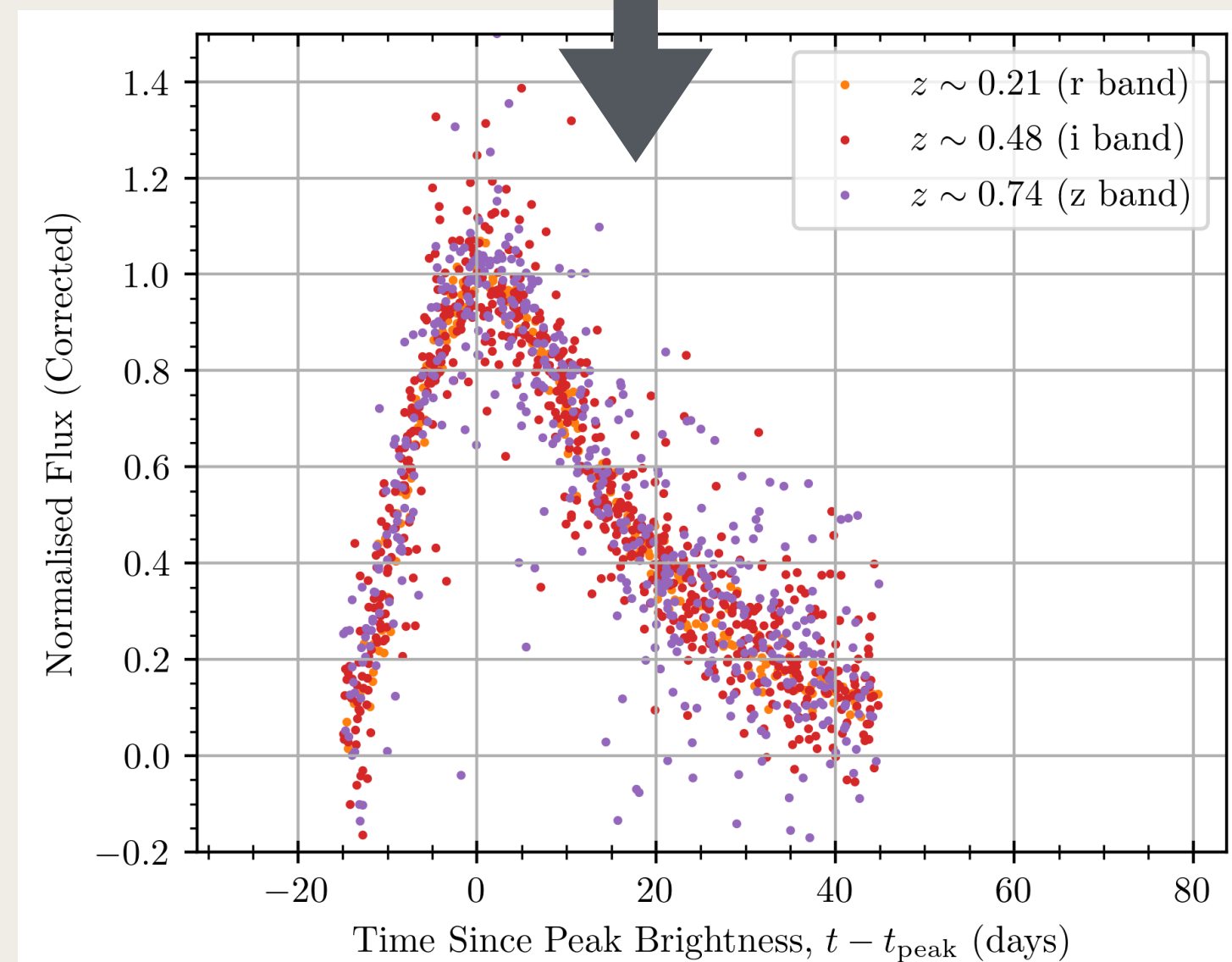
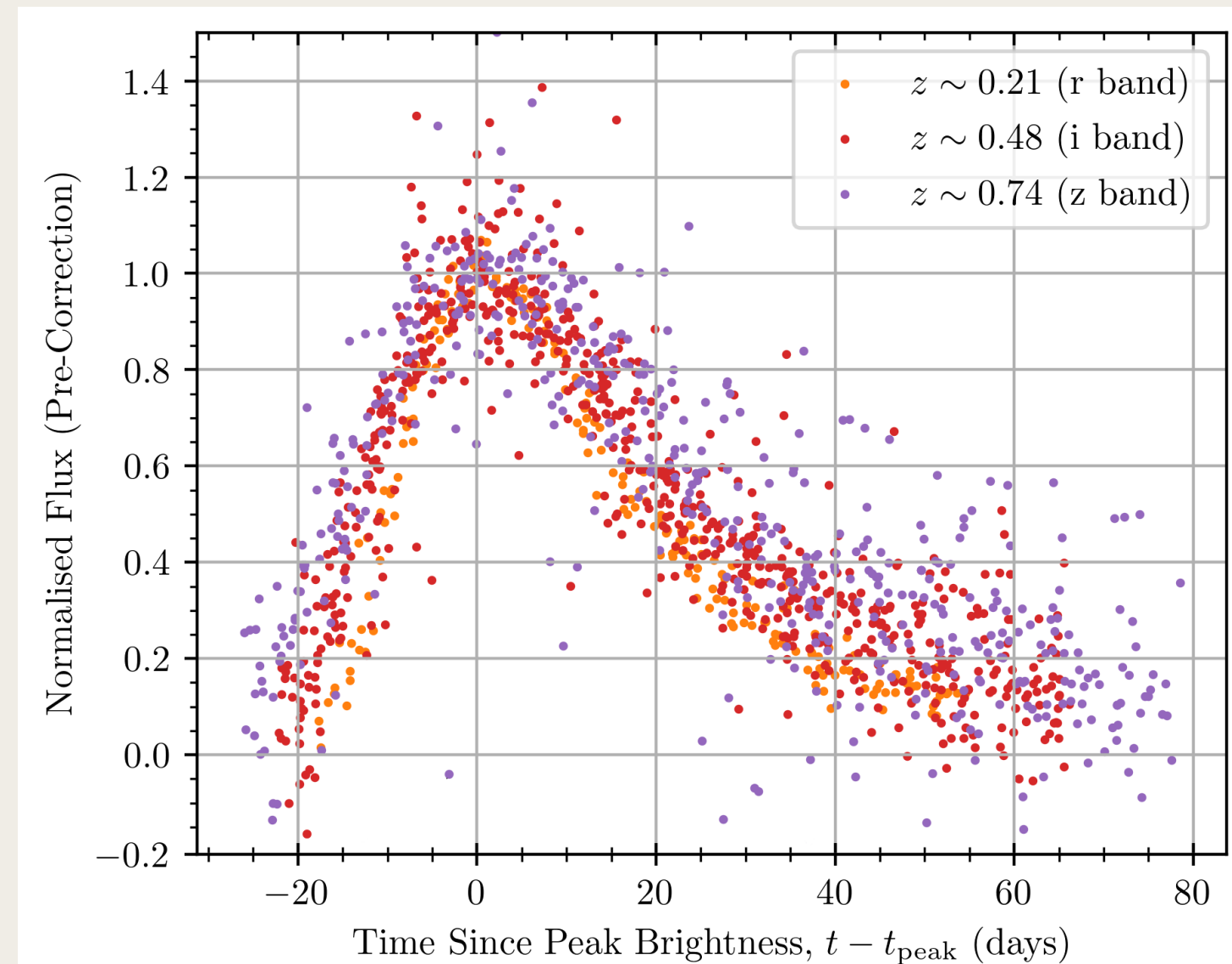
Time dilation

Expect observed duration to be $(1+z)$ times the original duration



Time dilation measured

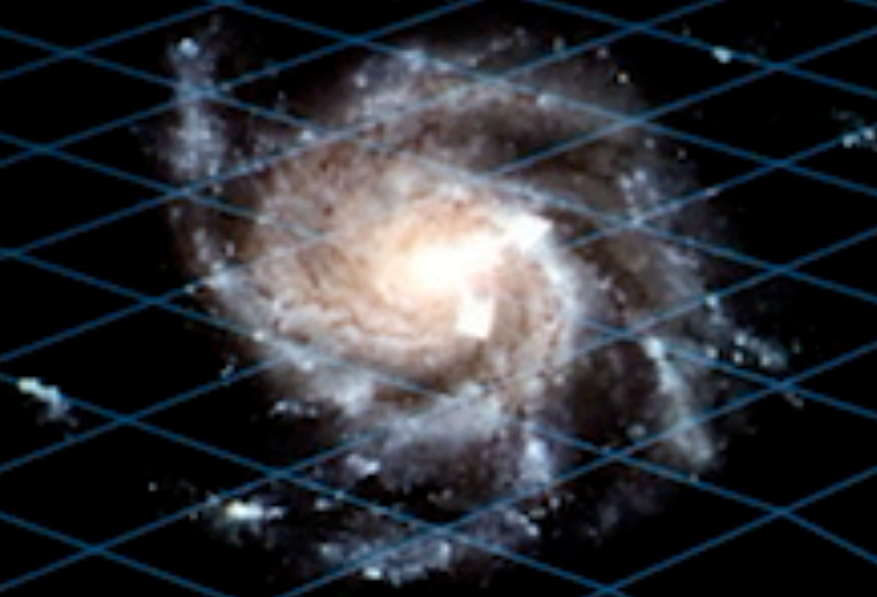
- 1.. Time dilation is obvious in the data (and bigger than the width-luminosity relation).
2. If you assume time dilation it gives evidence that the population of SN we see at high- z are the same as at low- z .



Growth of structure

DES:
Supernova lensing
magnification

Gravitational Lensing (strong)



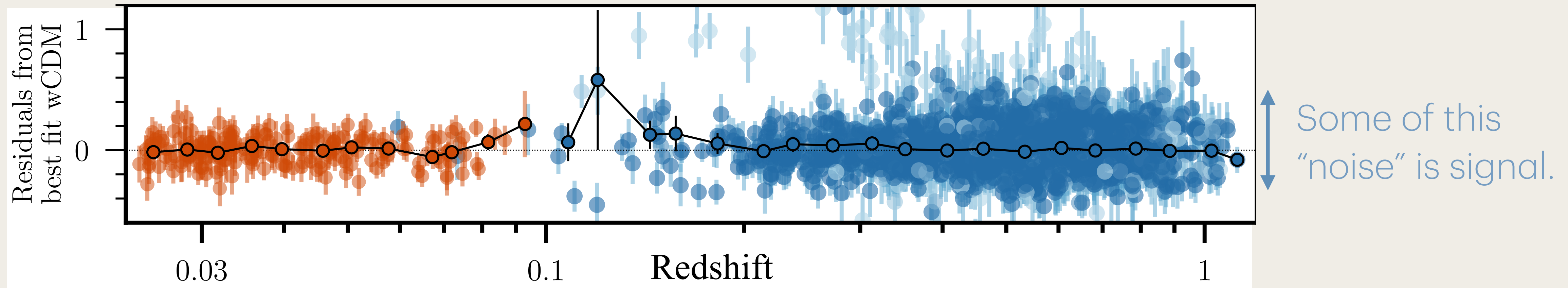
Galaxy Cluster

Gravitational Lensing (weak)

Galaxies

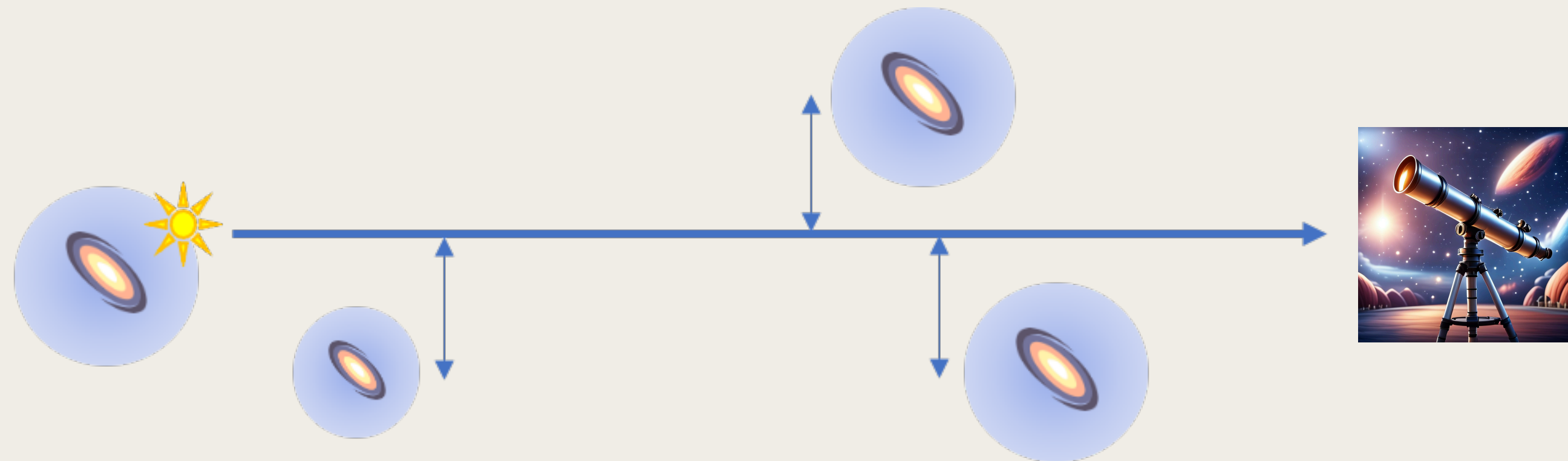


Supernova lensing magnification



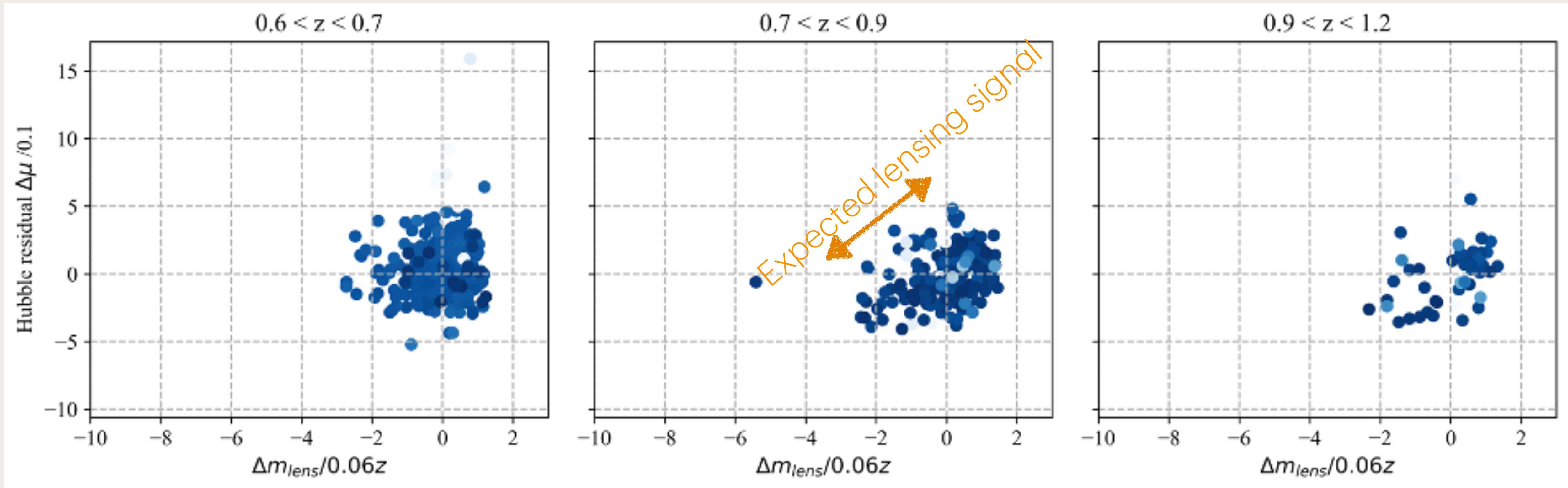
The magnification is weak: $\sim 2.5\%$ at $z = 0.5$
SN Ia are intrinsically diverse by $\sim 10\%$

Correlate Hubble diagram residuals with foreground density



Paul Shah et al.
[arXiv:2406.05047](https://arxiv.org/abs/2406.05047)

Supernova lensing magnification



Detected weak lensing magnification of SNe at $>5 \sigma$ for the first time

Can correct luminosity distances for lensing.

Moves Λ CDM *slightly* closer to Λ CDM: $\Delta\Omega_M = +0.036$, $\Delta w = -0.056$

Supernova lensing magnification

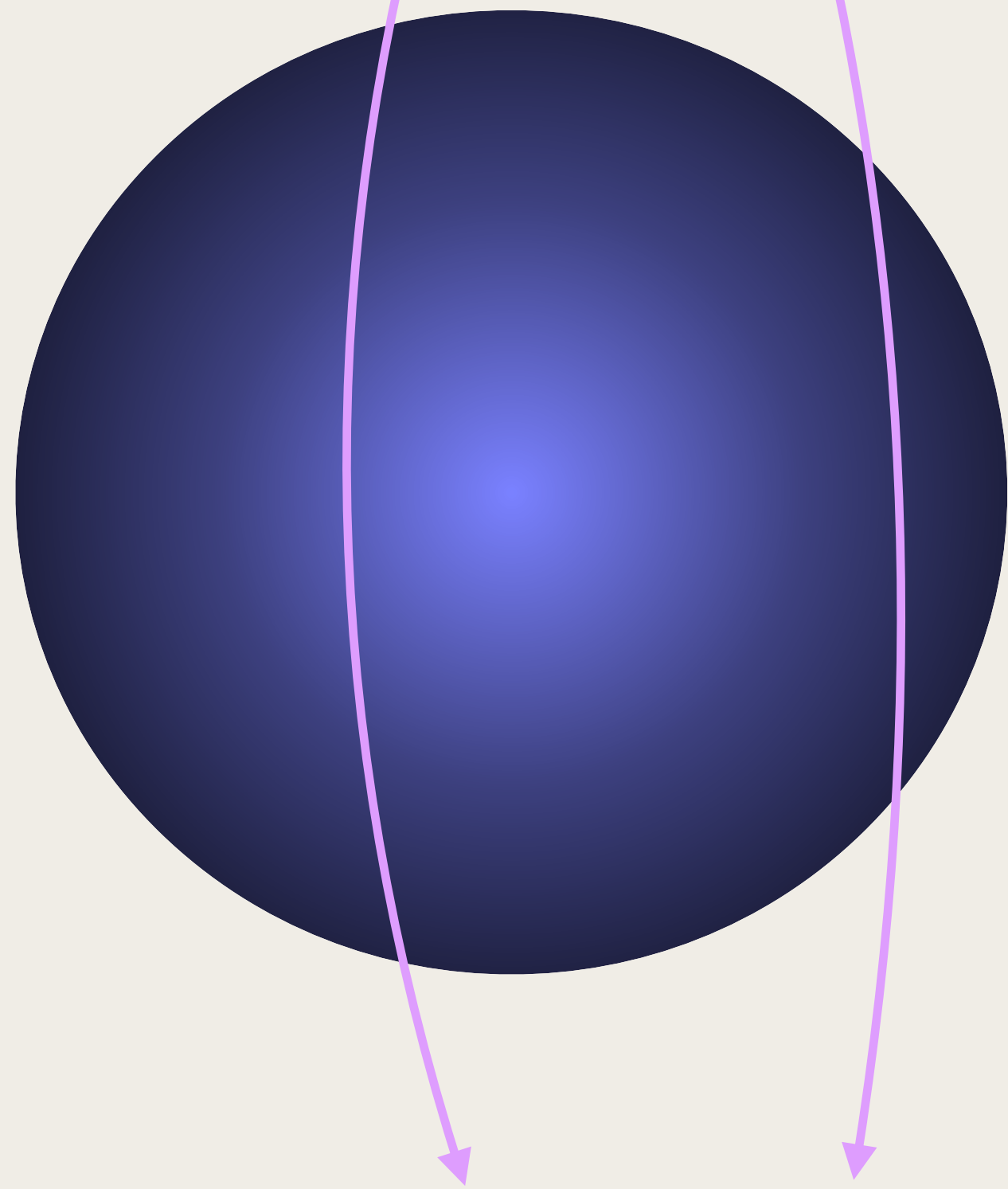
Constrain **shape of dark matter halos** (consistent with NFW profile) 2406.05047

Constrain **amount of dark matter in compact objects** ($< 12\%$) 2410.07956

Constrain **small-scale power spectrum** ($k > 1 \text{ h/Mpc}$) 2501.19117



*Paul Shah et al.
2024, 2025a,b*



Smooth = small dispersion

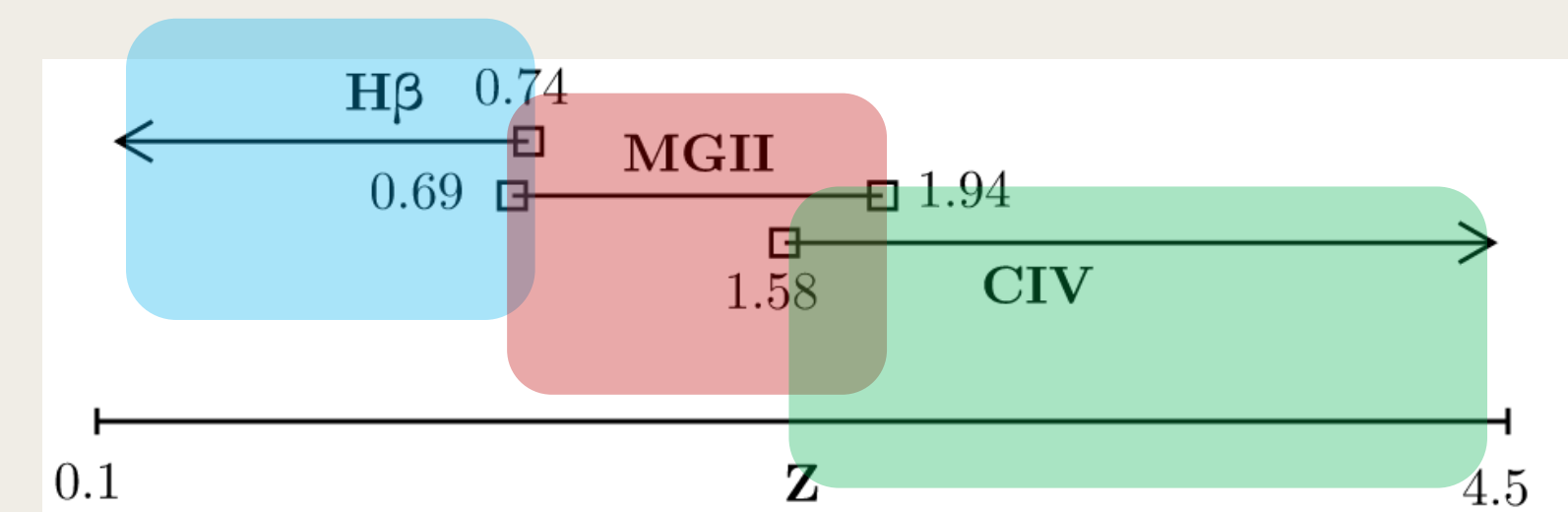
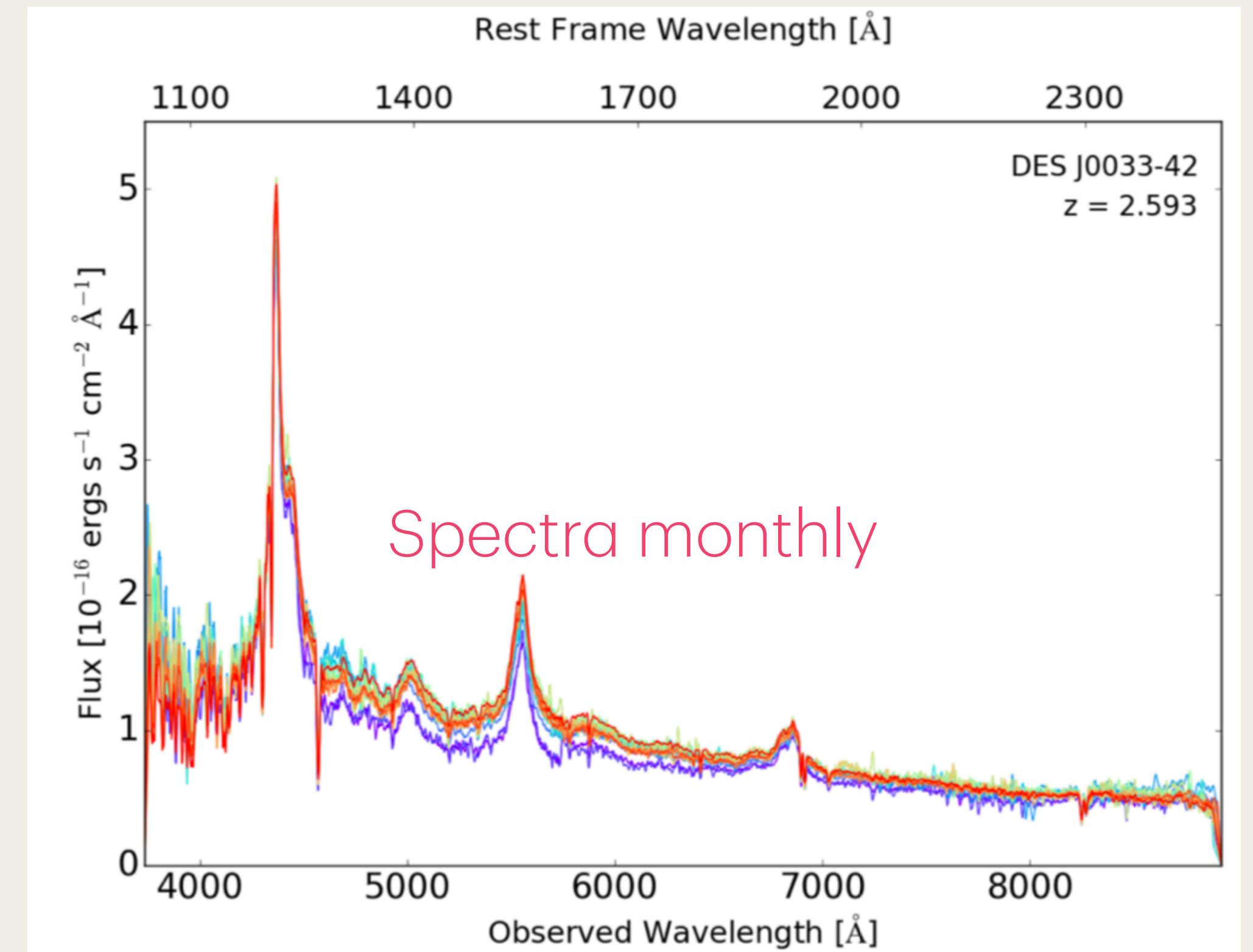
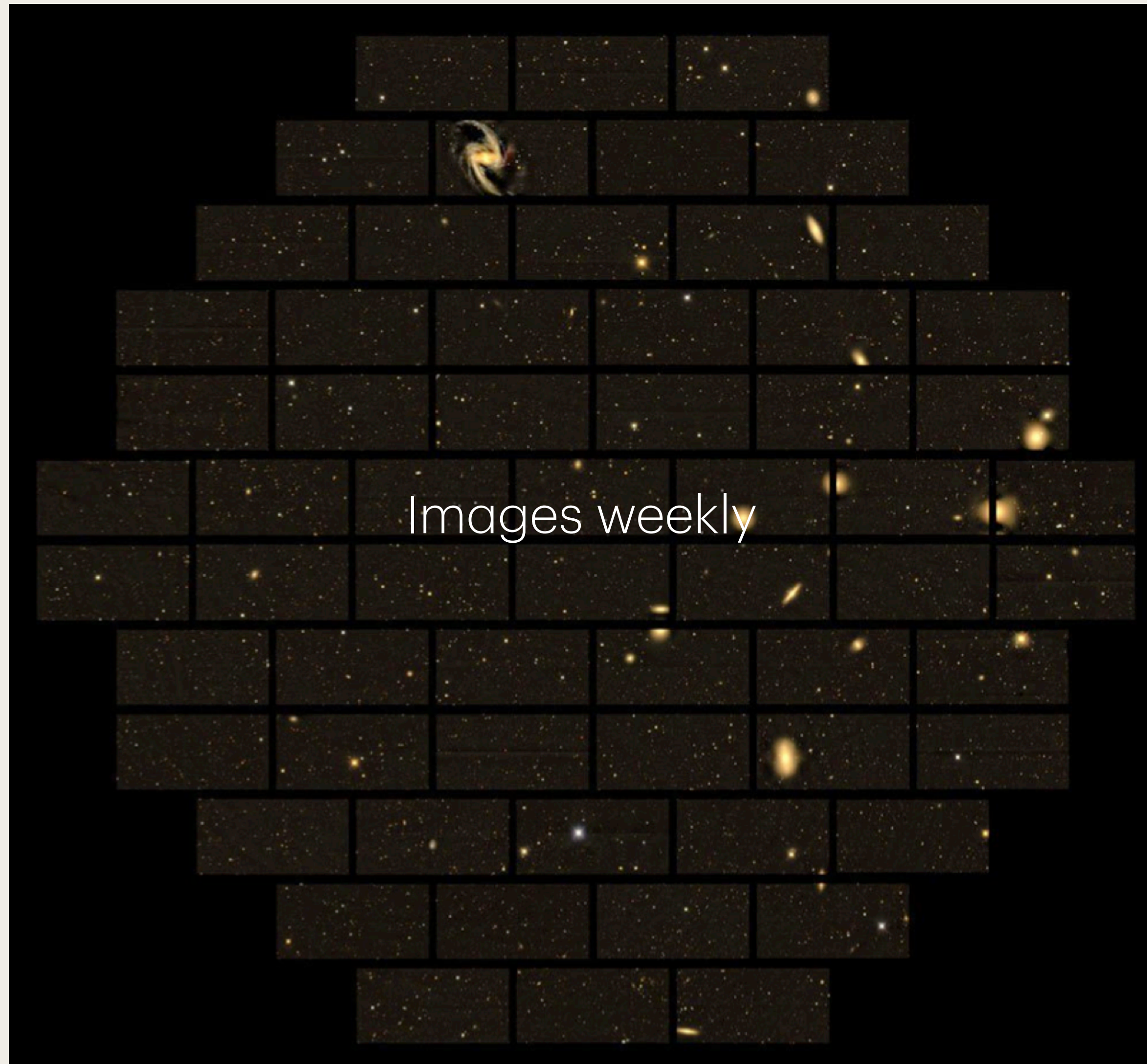


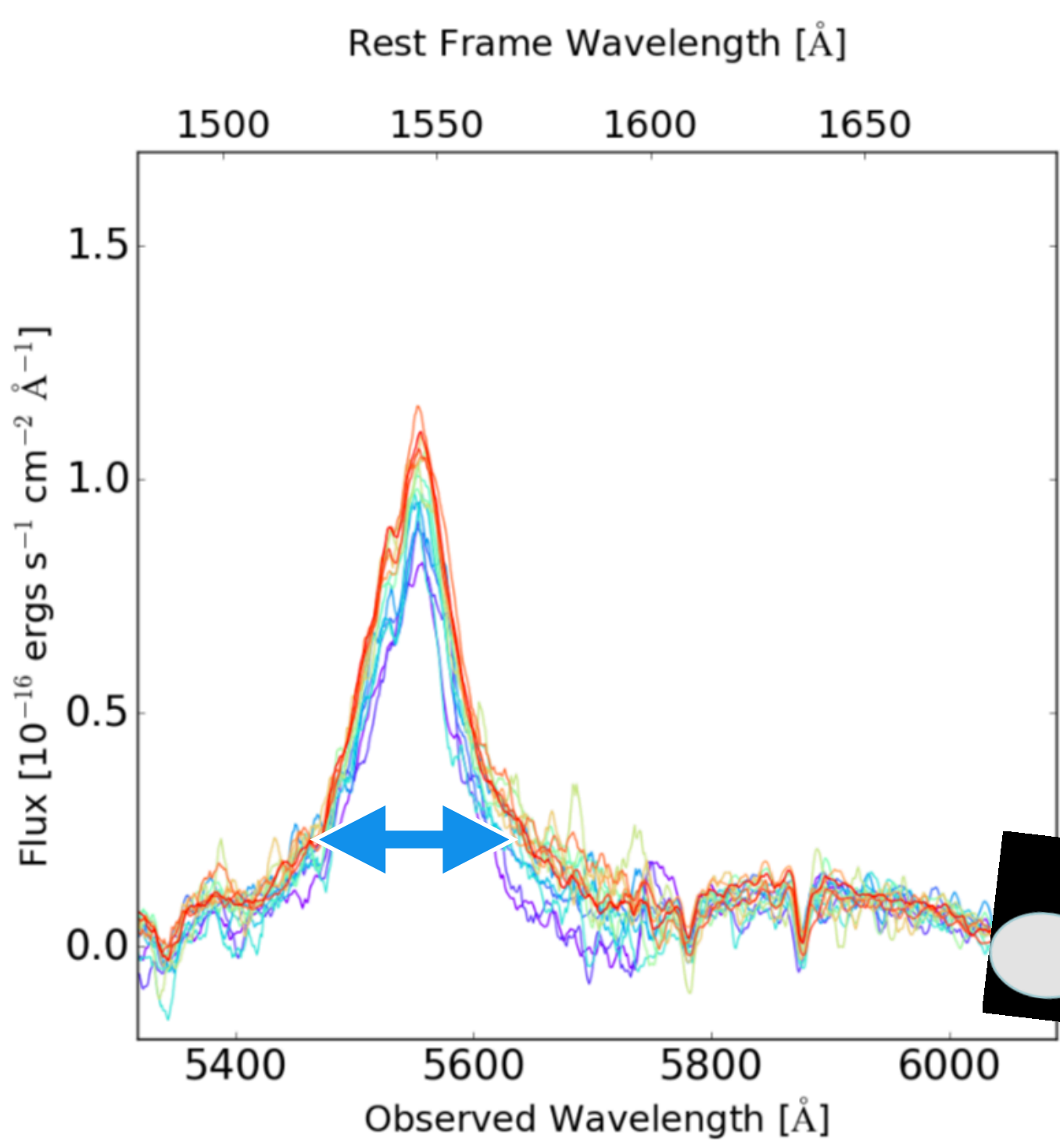
Compact objects = large dispersion

AGN Reverberation Mapping

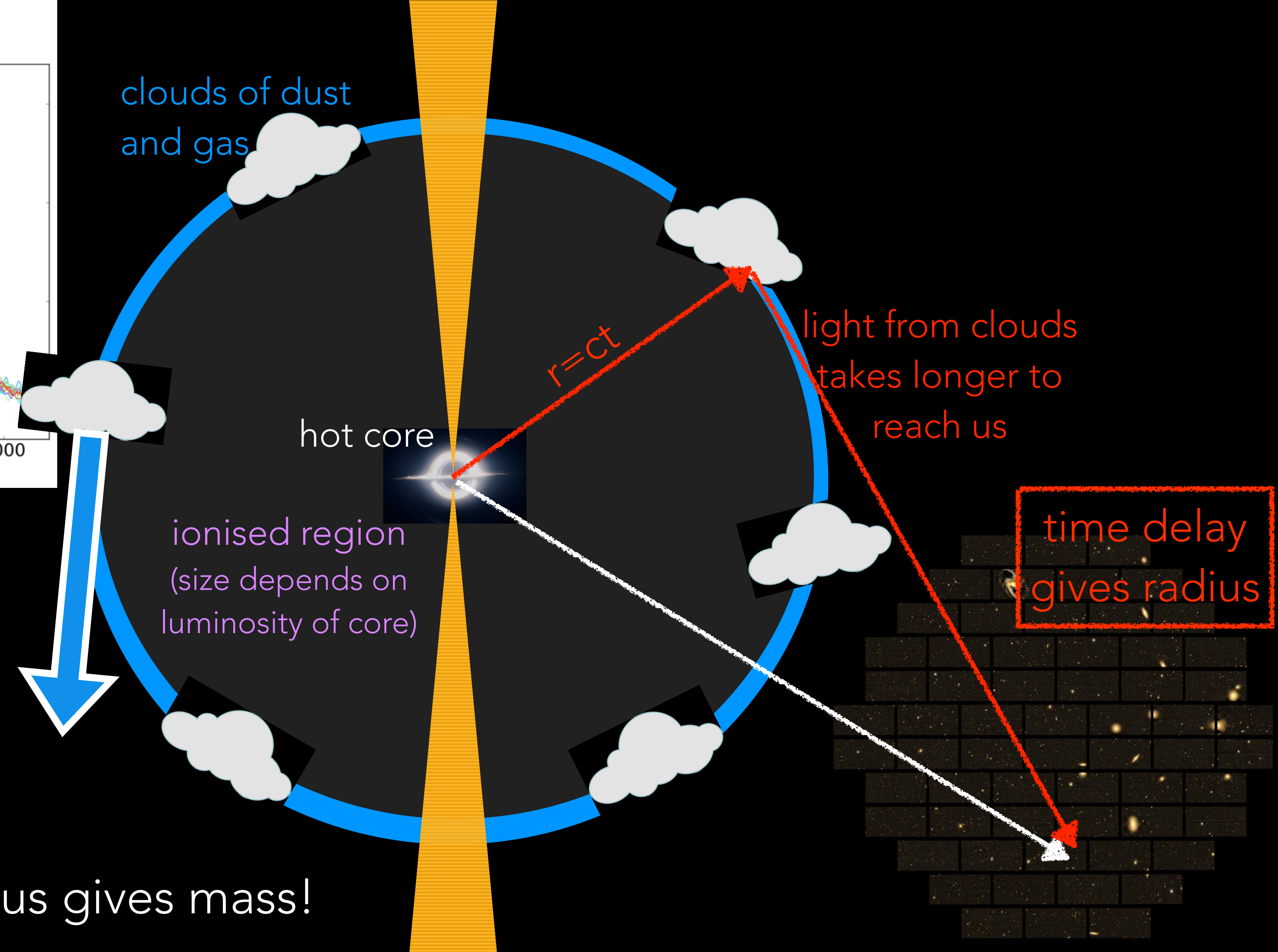
DES: Weighing Black Holes

Observing black holes



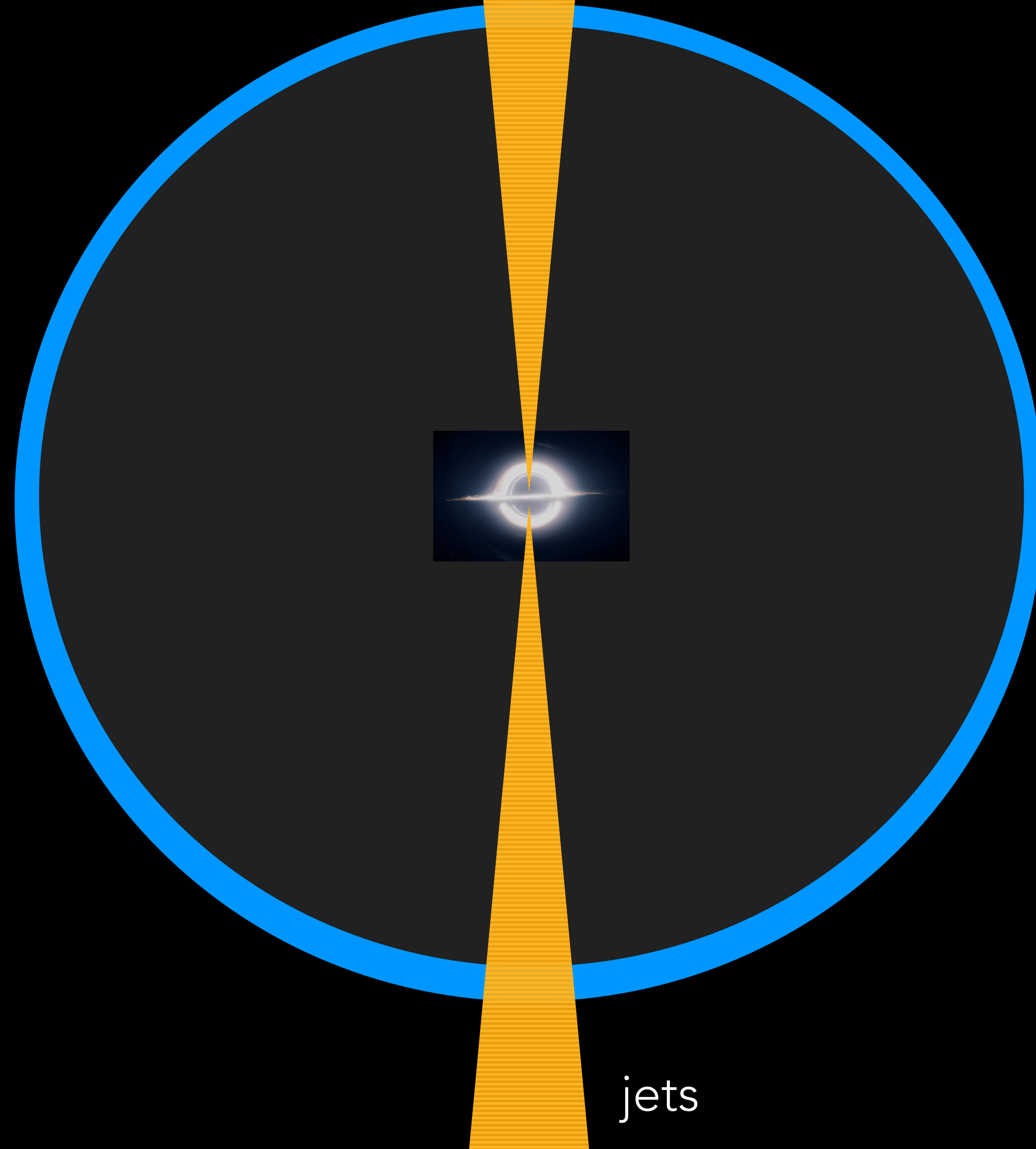


line widths
give velocity



velocity and radius gives mass!

MEASURING BLACK HOLE MASS



jets

Core of Galaxy NGC 4261

JAMES WEBB SPACE TELESCOPE

CIRCINUS GALAXY

ESO 97-G13

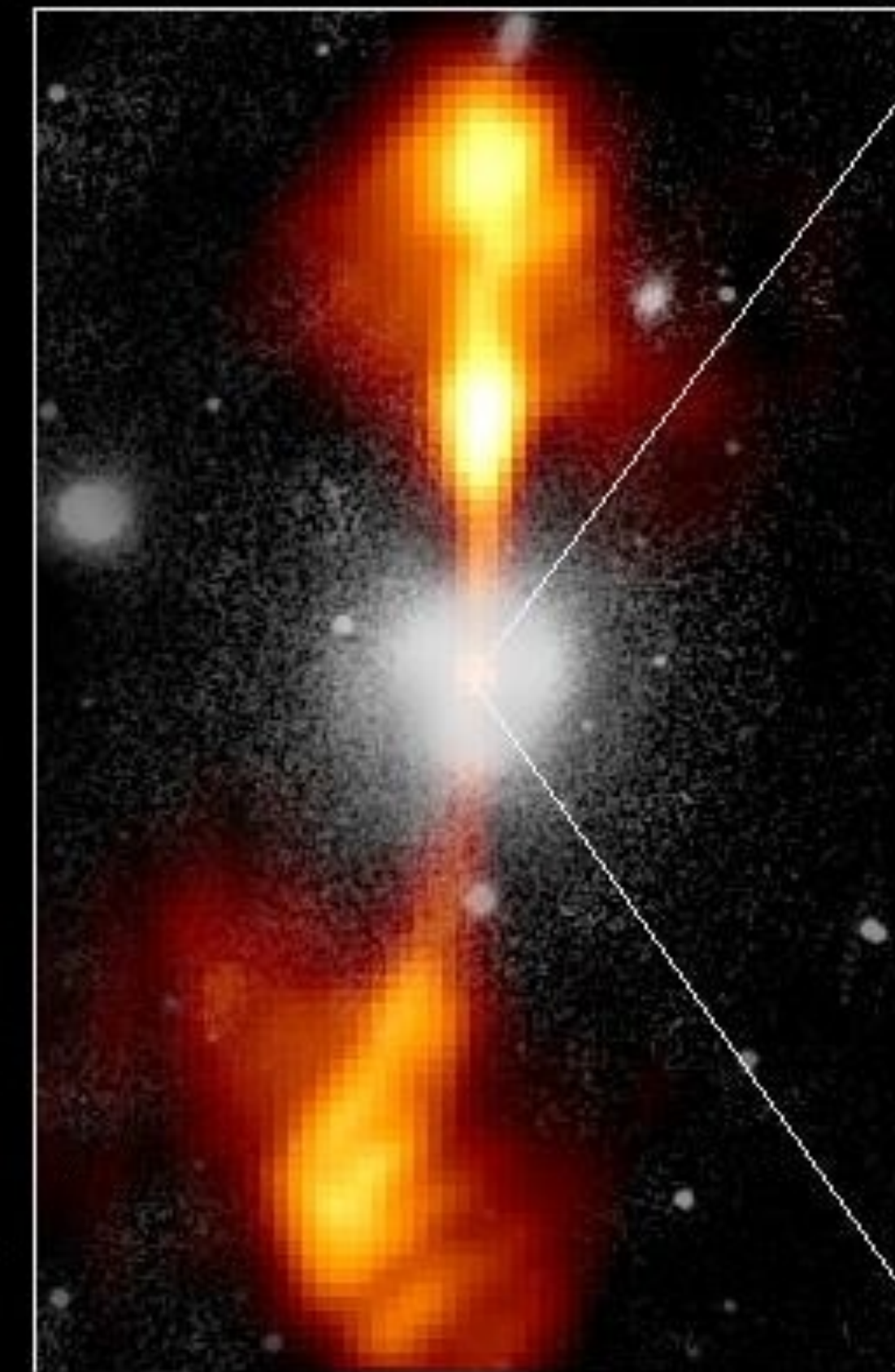
Hubble Space Telescope

Wide Field / Planetary Camera

$z=0$ Hubble

Ground-Based Optical/Radio Image

HST Image of a Gas and Dust



380 Arc Seconds
88,000 LIGHT-YEARS



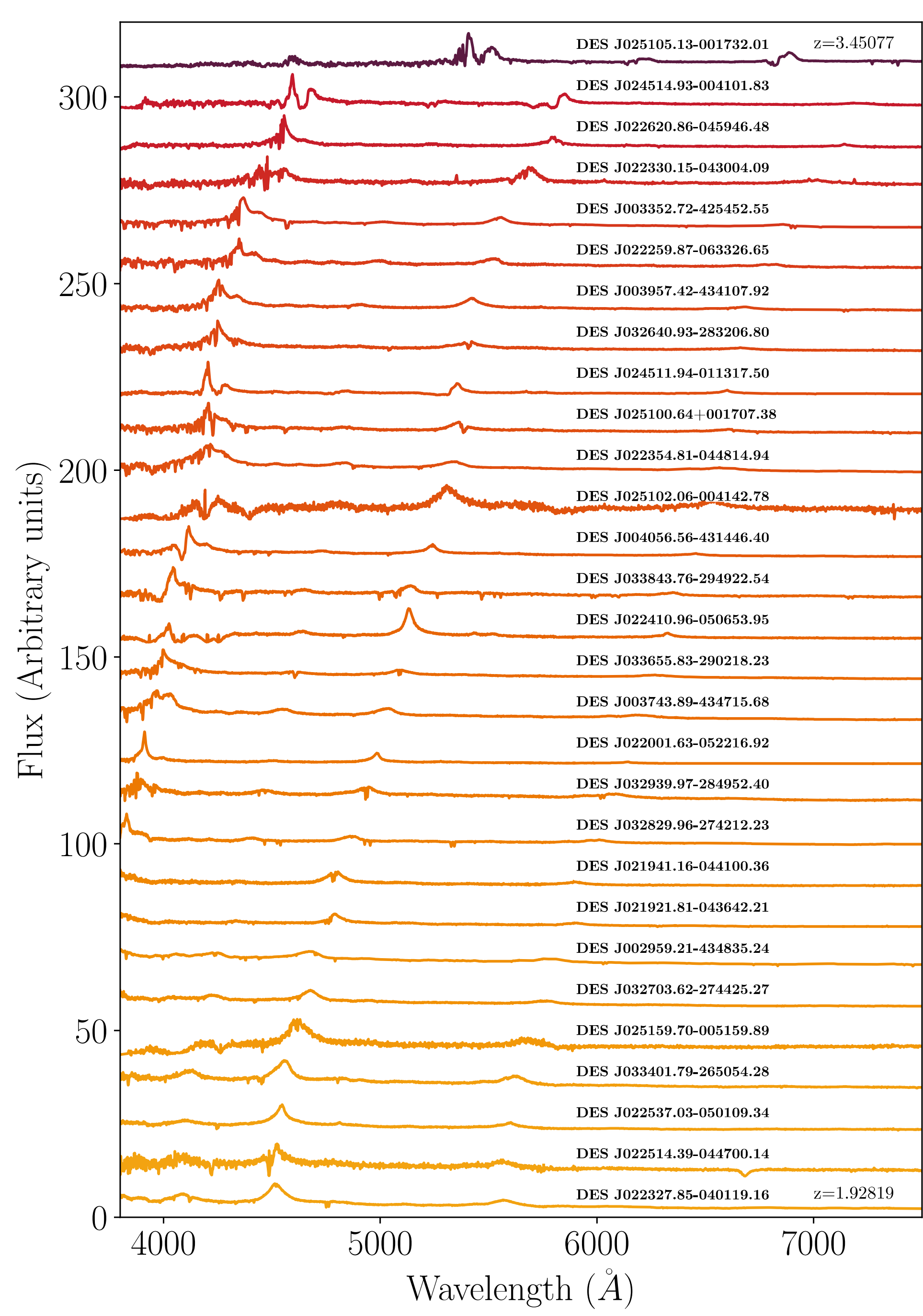
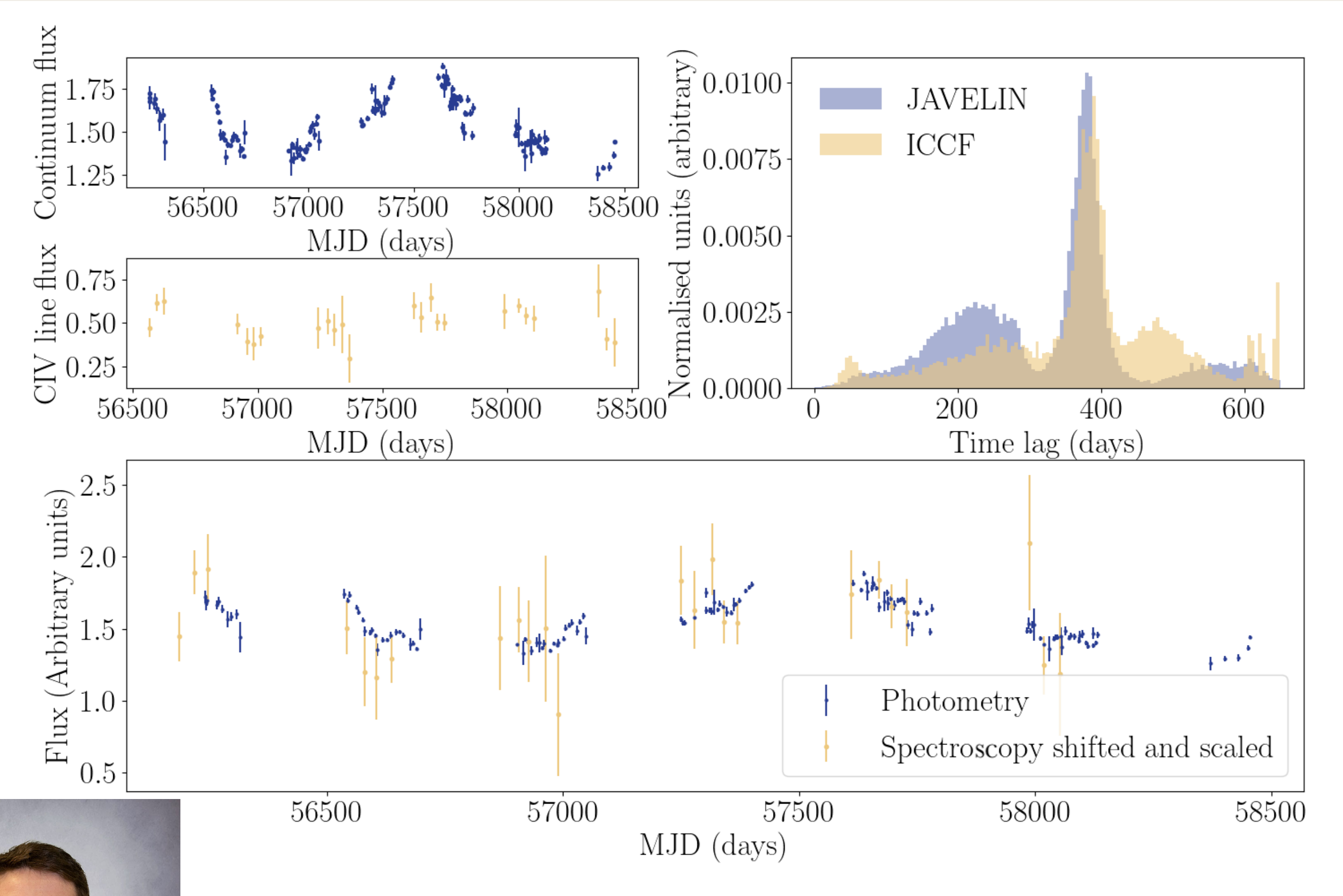
With time delays we can resolve more
i.e. what's happening in the center

17 Arc Seconds
400 LIGHT-YEARS



OzDES CIV spectra

OzDES monitored 771 AGN in Hbeta, MgII, & CIV



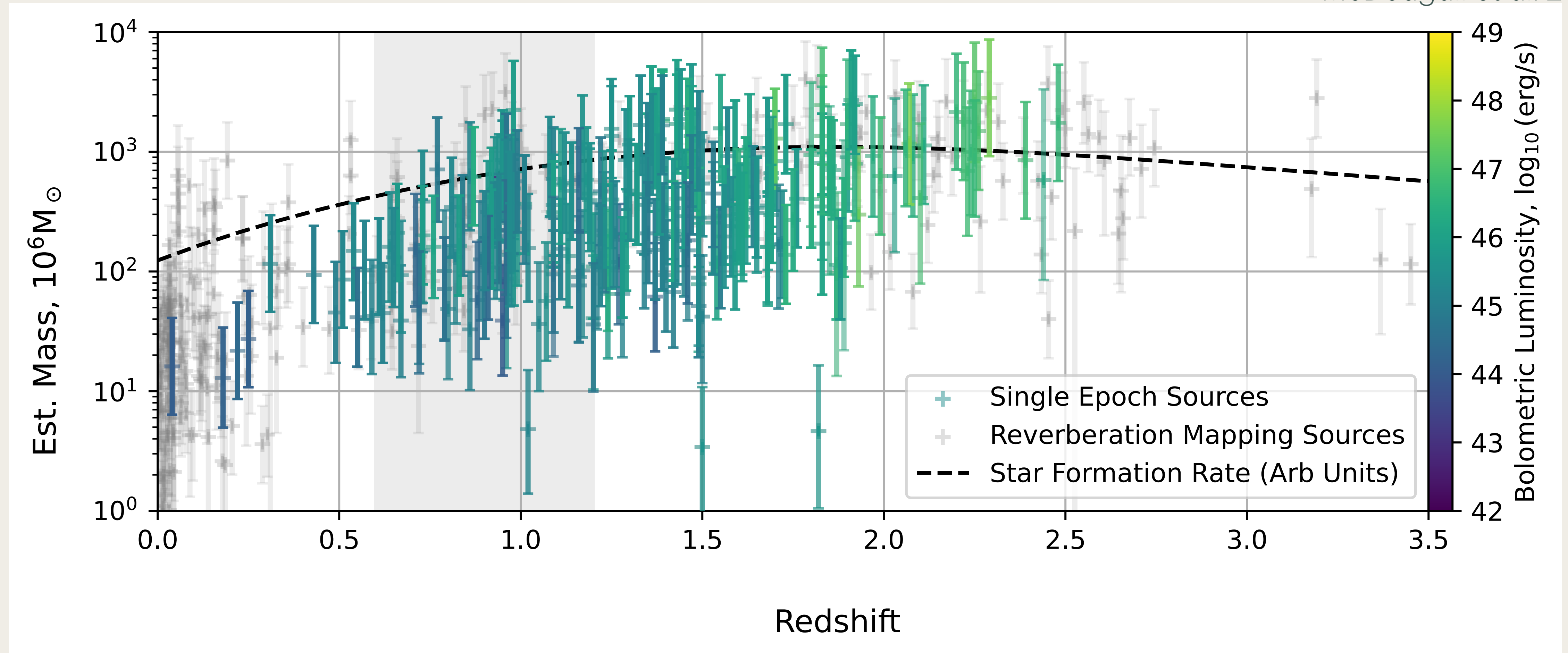
Penton et al. 2026

Black hole masses

Yes, there were big black holes early!



McDougall et al. 2026



Final thoughts

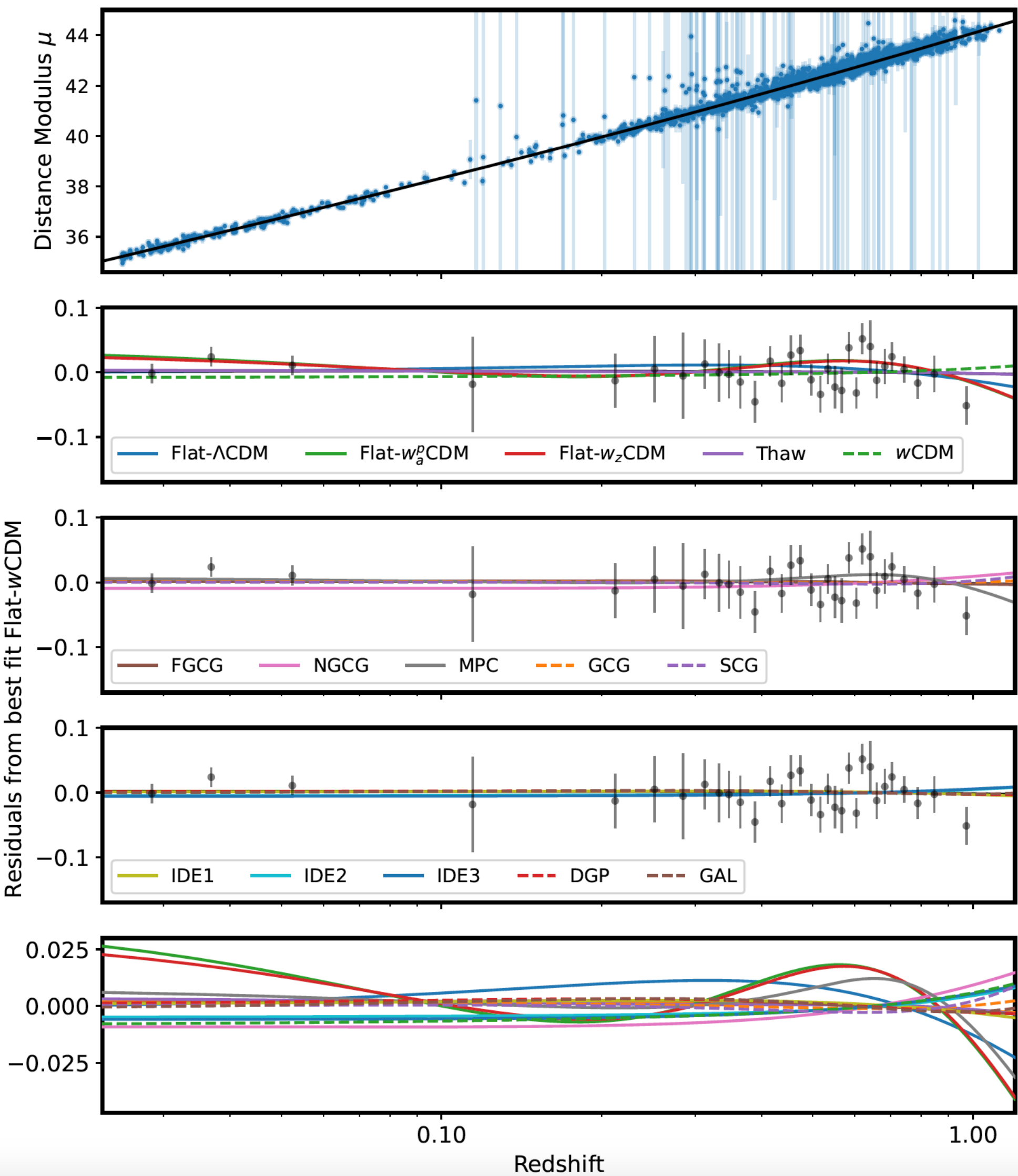
Is dark energy time-
varying?



Is dark energy time varying?

$w(a)$ is not the only option. It should be considered evidence that a more complex model may be required, not that $w(a)$ is the right model.

Exotic Cosmological Models



Model	DES-SN5YR			Model	DES-SN5YR + CMB-R + BAO- θ_*		
	$\frac{1}{2}\Delta\text{AIC}$	$\Delta\ln S$	χ^2/dof		$\frac{1}{2}\Delta\text{AIC}$	$\Delta\ln S$	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- Λ CDM					0.0		1665 / 1749 = 0.952
Λ CDM					-0.10		1664 / 1747 = 0.952
wCDM					-3.64		1655 / 1747 = 0.947
Flat- w_0w_z CDM					-4.16		1655 / 1747 = 0.947
Flat- w_a^p CDM					-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


Flat generalised Chaplygin gas


Flat thawing scalar field


Flat time-varying dark energy

DES-SN5YR _{cut}				DES-SN5YR _{cut} + BAO- $\theta_{* \perp}$			
Flat- Λ CDM	0.0	0.0	1616 / 1665 = 0.970	Flat- Λ CDM	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

No *strong* evidence for or against Flat- Λ CDM

DES-SN alone: 3 models moderately preferred over Flat- Λ CDM

DES-SN + CMB + BAO: 11 (of 15) models moderately preferred over Flat- Λ CDM



Is dark energy time varying?

$w(a)$ is not the only option. It should be considered evidence that a more complex model may be required, not that $w(a)$ is the right model.

In the 1990s there was already **fertile ground** for a cosmological constant, in the form of a H_0 tension, age tension, and galaxy number counts tension. All were fixed by dark energy.

1990s... several big problems in cosmology

AGE



(Some stars were older than the universe.)

NUMBER



(There were too many galaxies at large distances.)

MASS

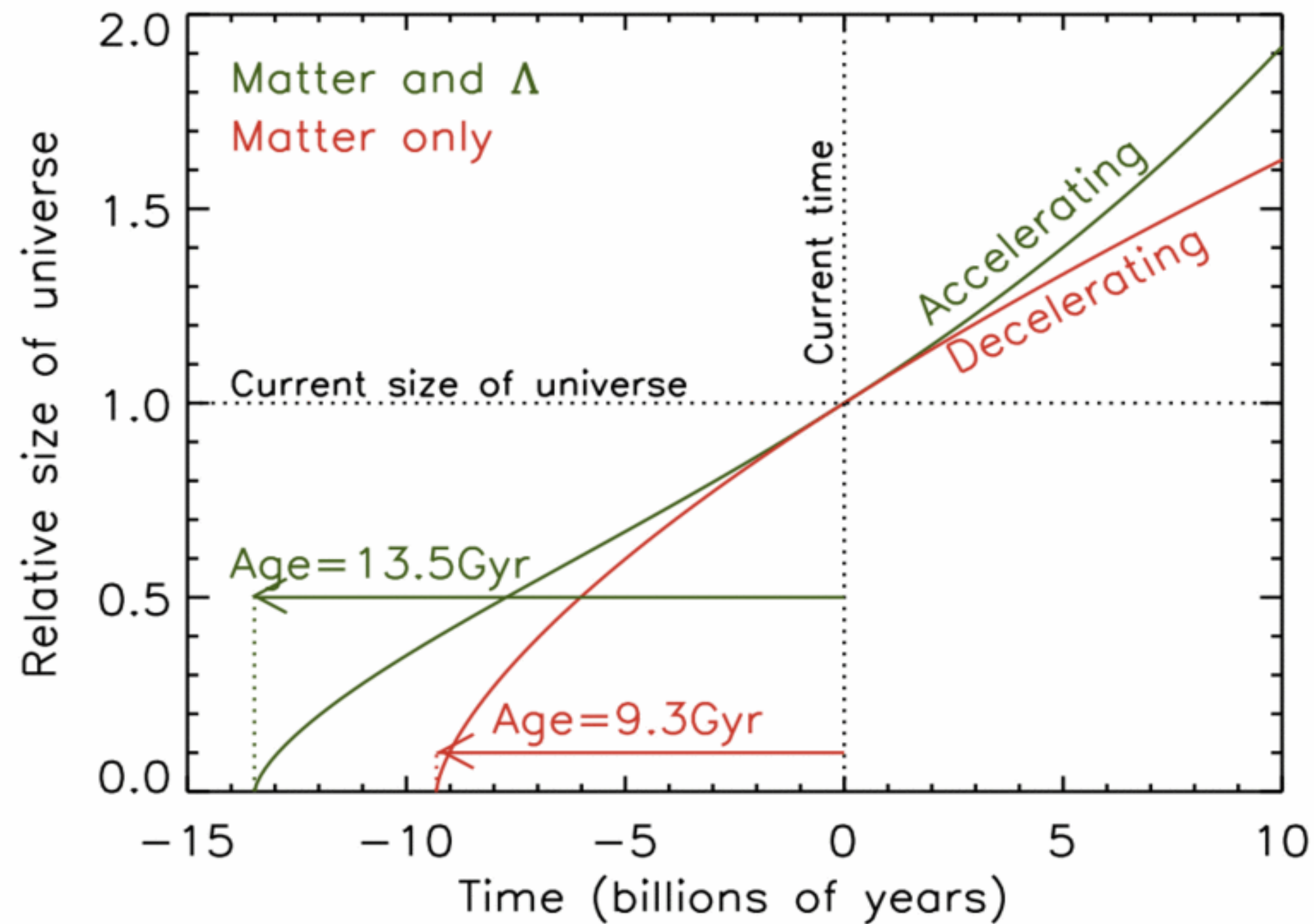


(The amount of matter didn't add up.)

1990s... several big problems in cosmology

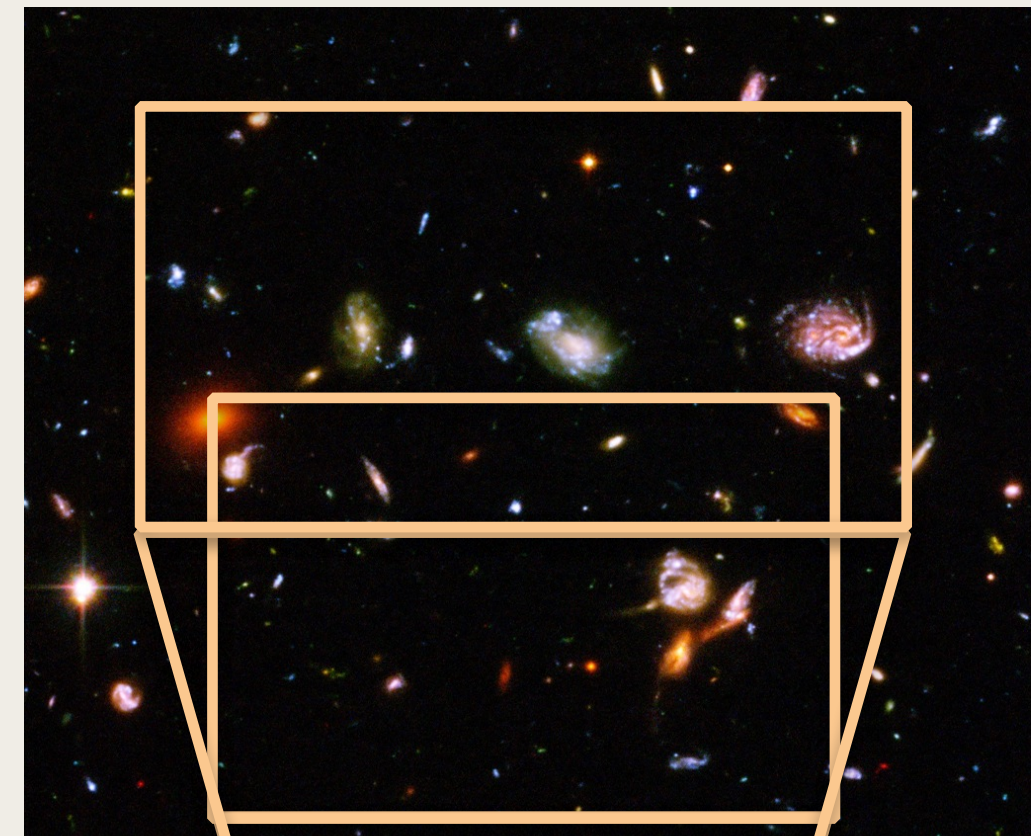
All solved by dark energy

AGE



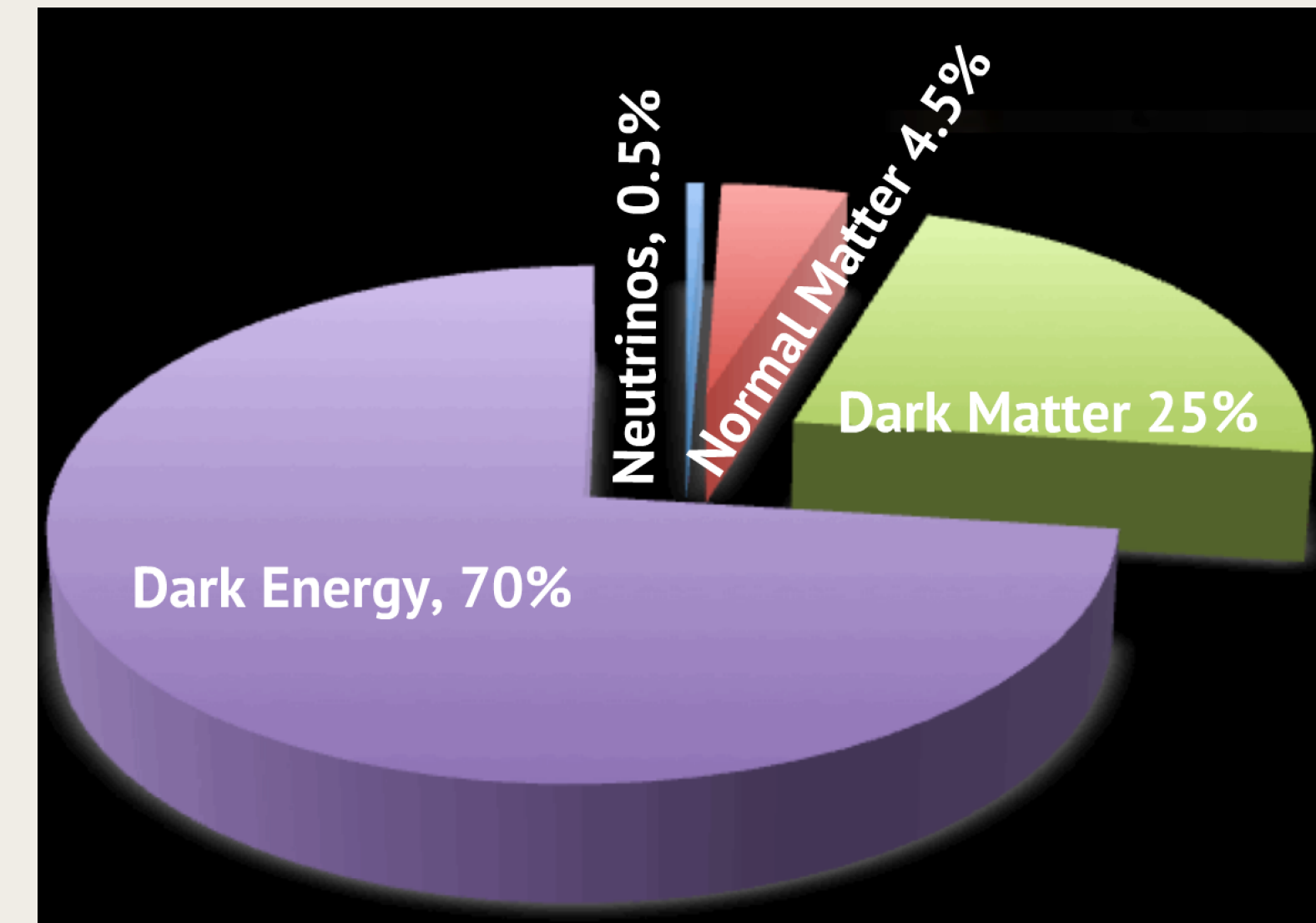
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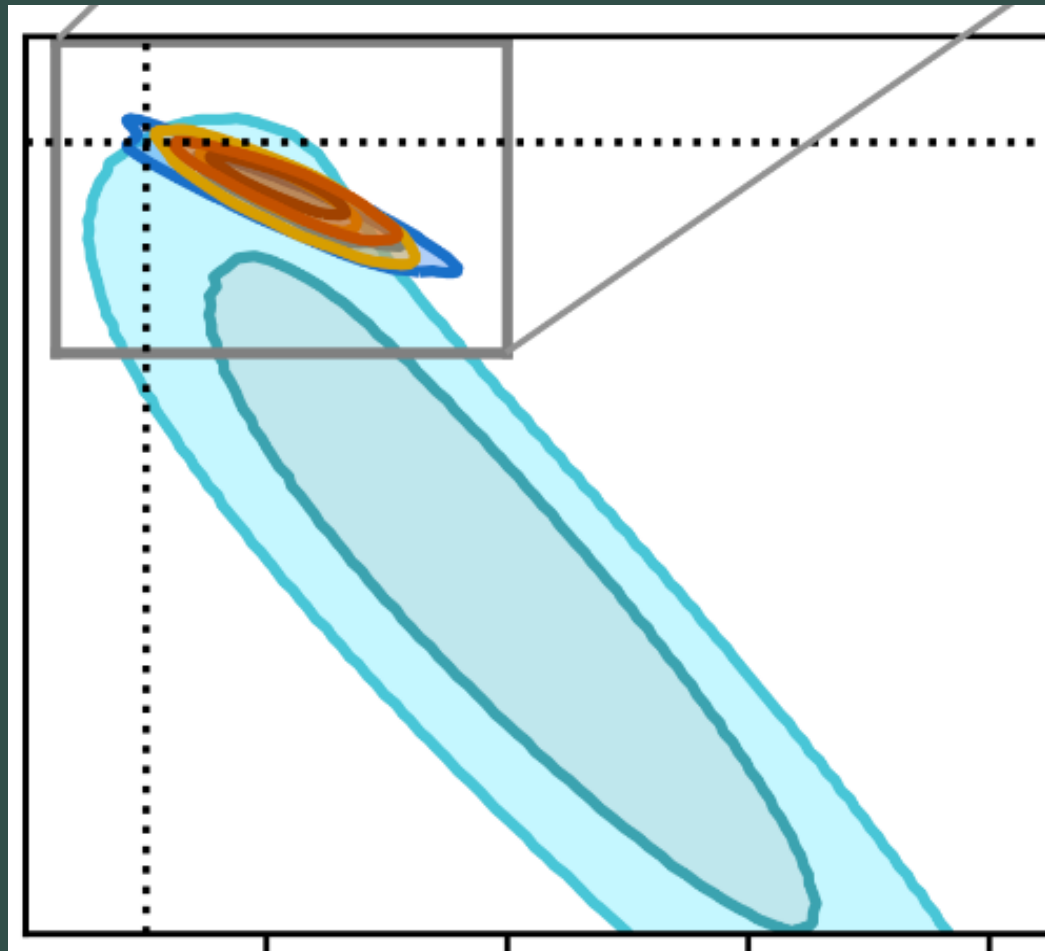
$w(a)$ is not the only option. It should be considered evidence that a more complex model may be required, not that $w(a)$ is the right model.

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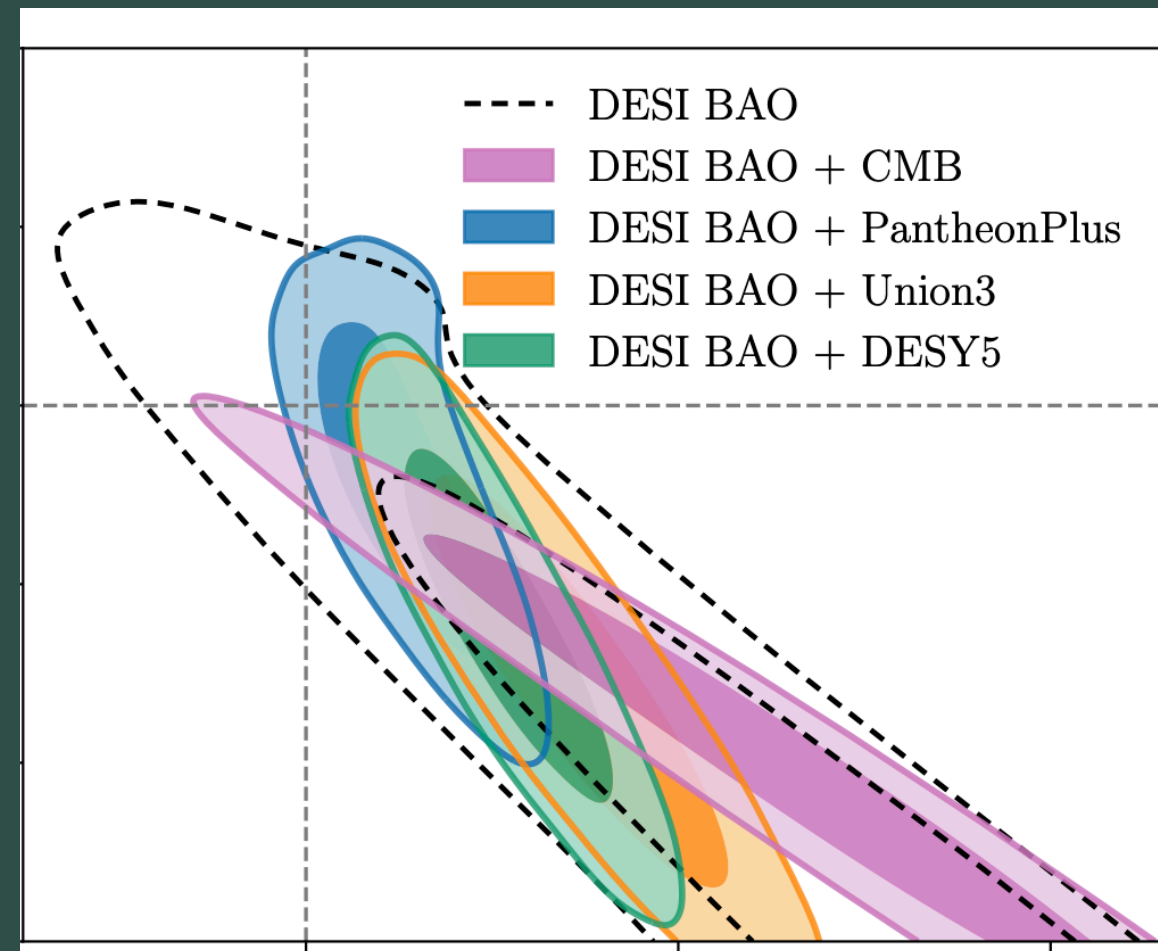
Now there are also tensions, but **none are easily fixed by a $w(a)$ model** with these best fit parameters.

Time varying dark energy?

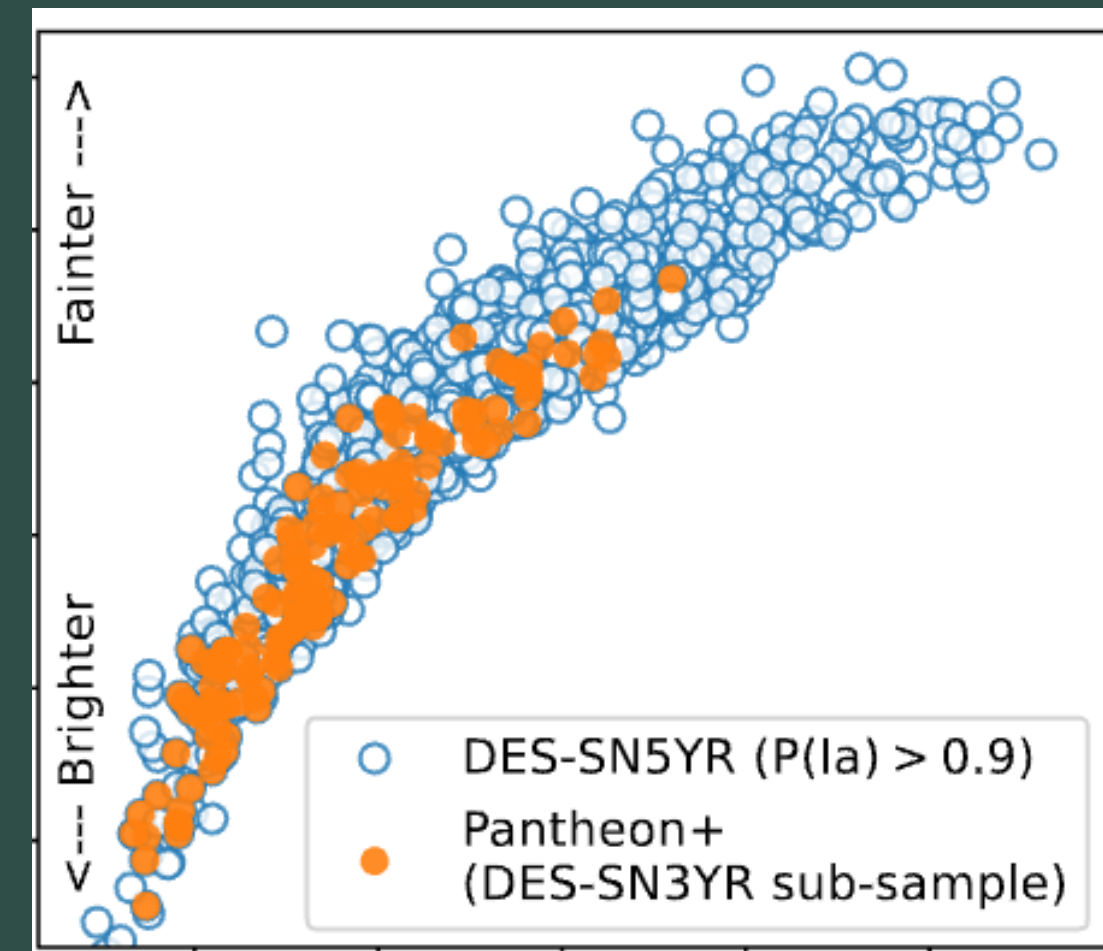
Dark Energy Survey w(a)



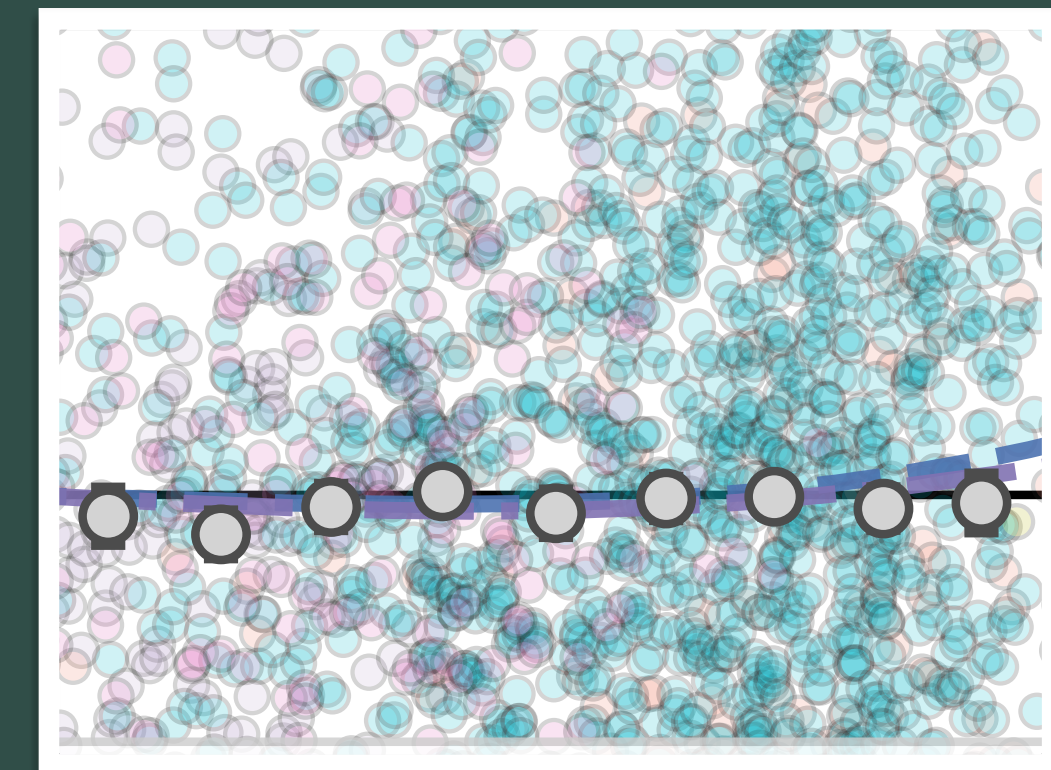
Dark Energy Spec. Inst. w(a)



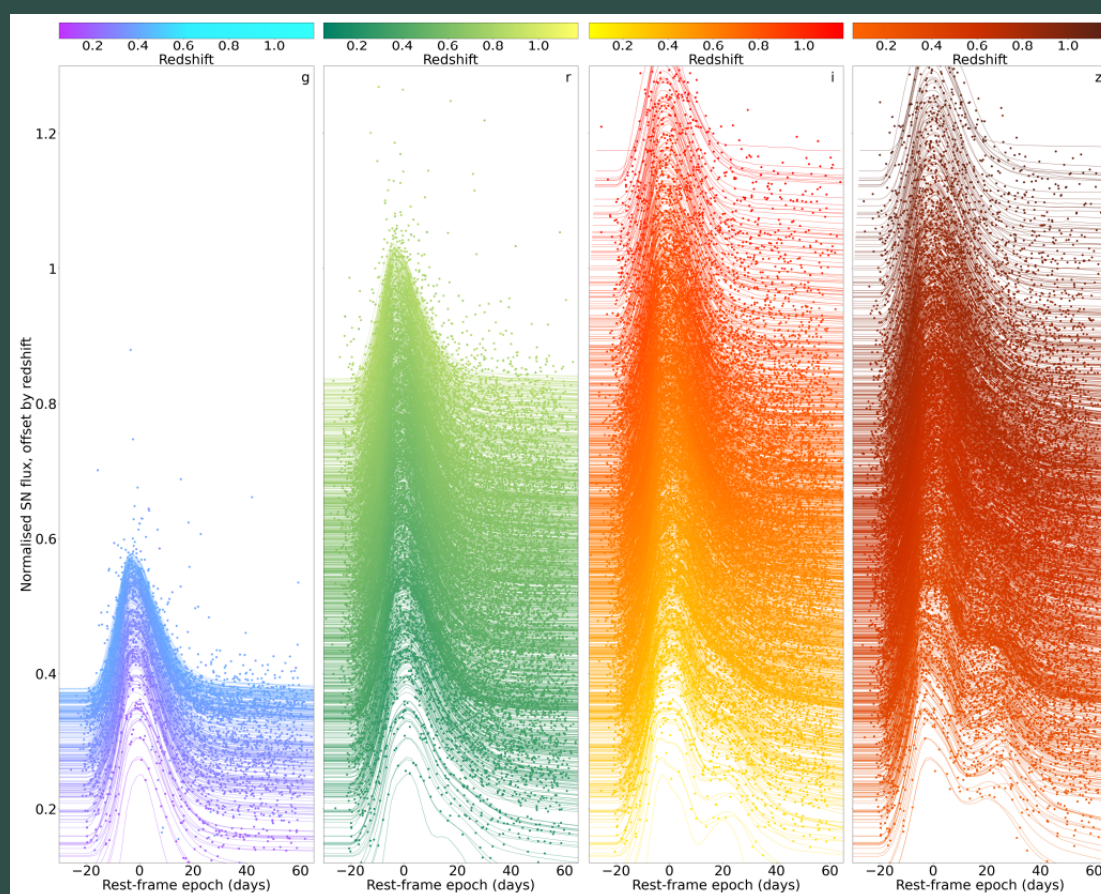
Scrutiny



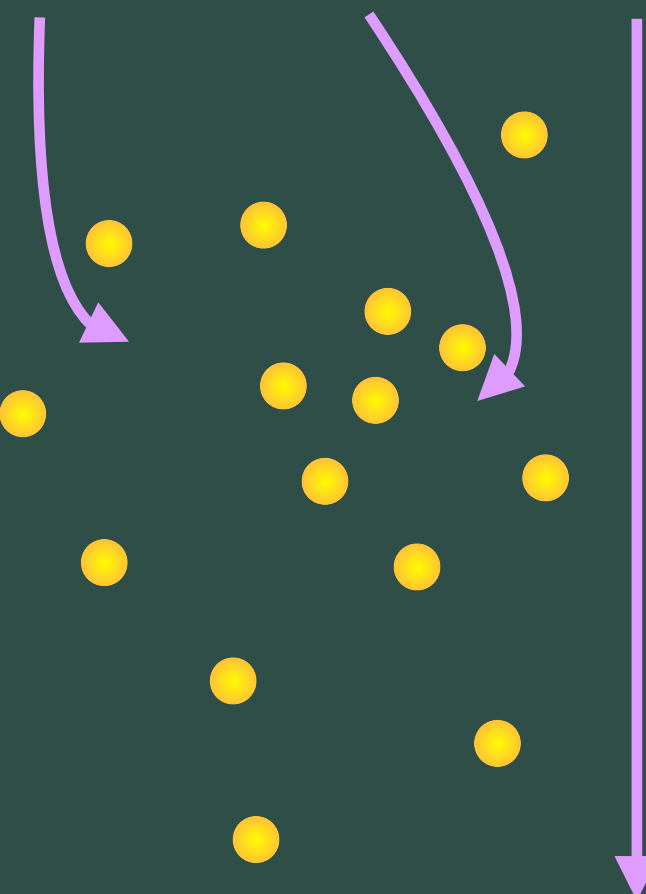
“Unite” imminent



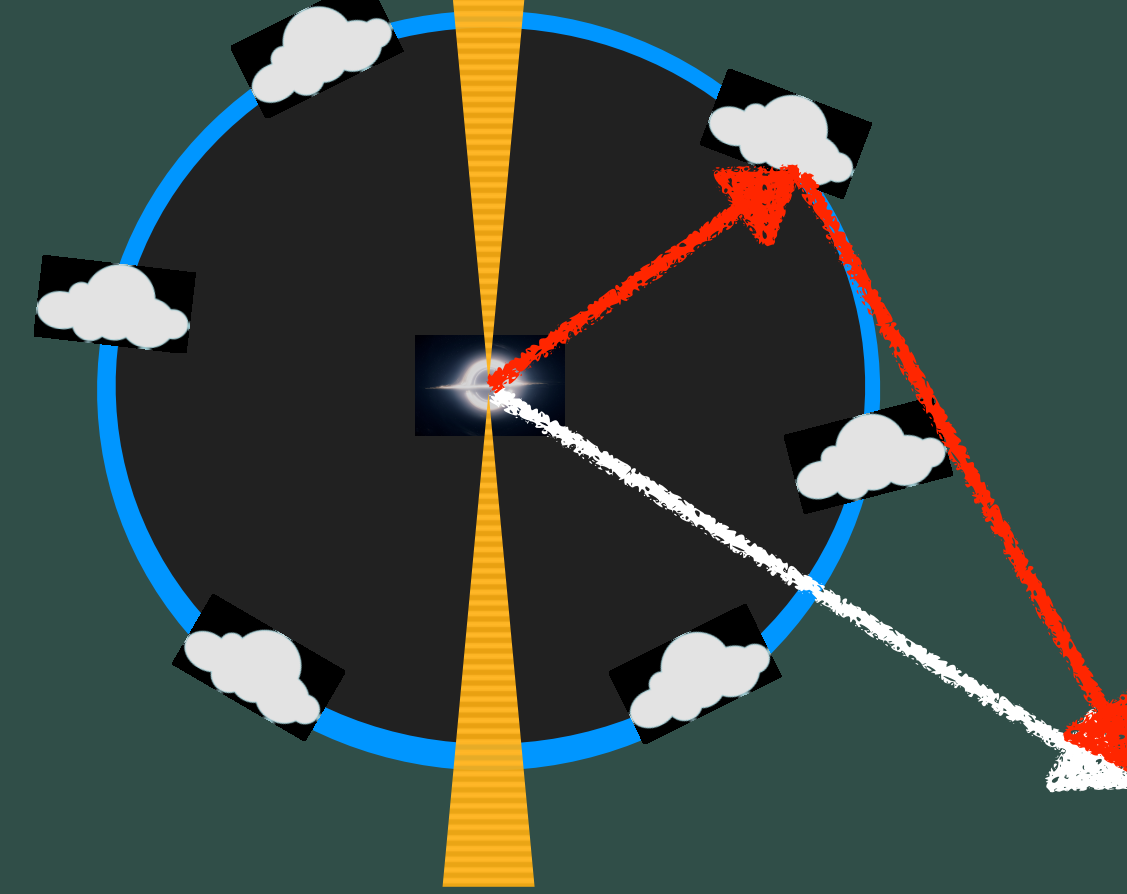
Time Dilation



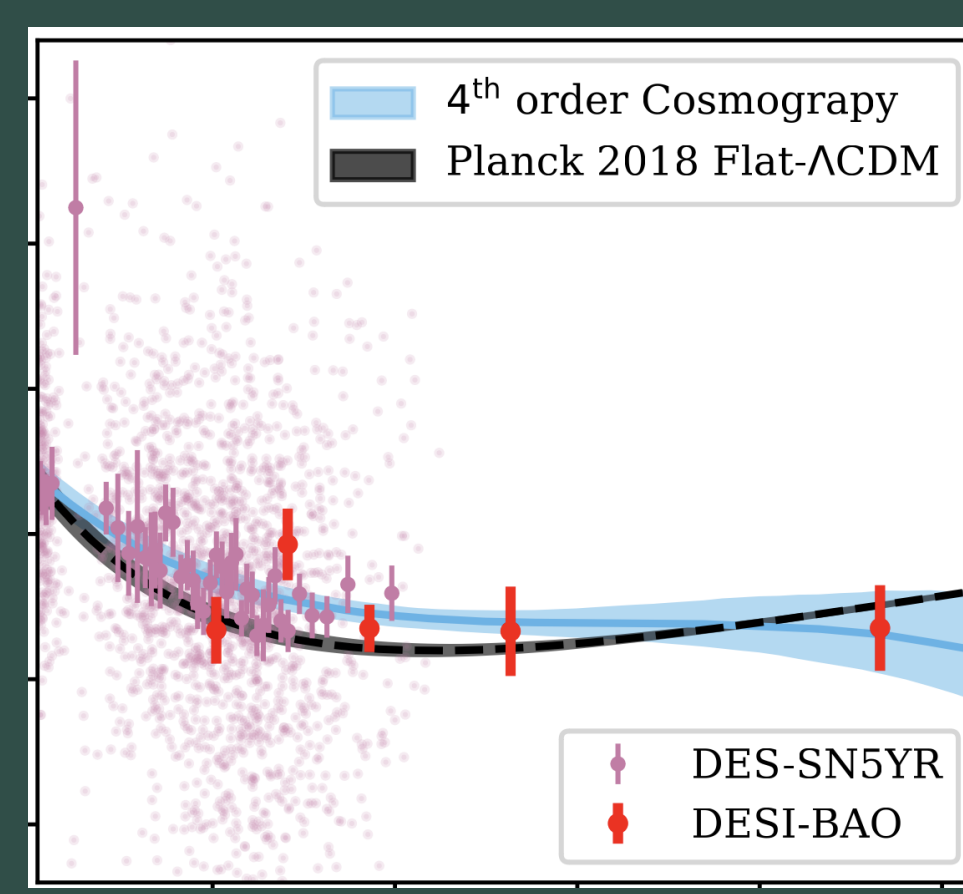
Supernova lensing



Reverberation mapping



Inverse dist. ladder



Side quests!