DESIgning concordant cosmological distances in the age of precision cosmology

David Camarena
Department of Physics and Astronomy
University of New Mexico

August 13, 2025

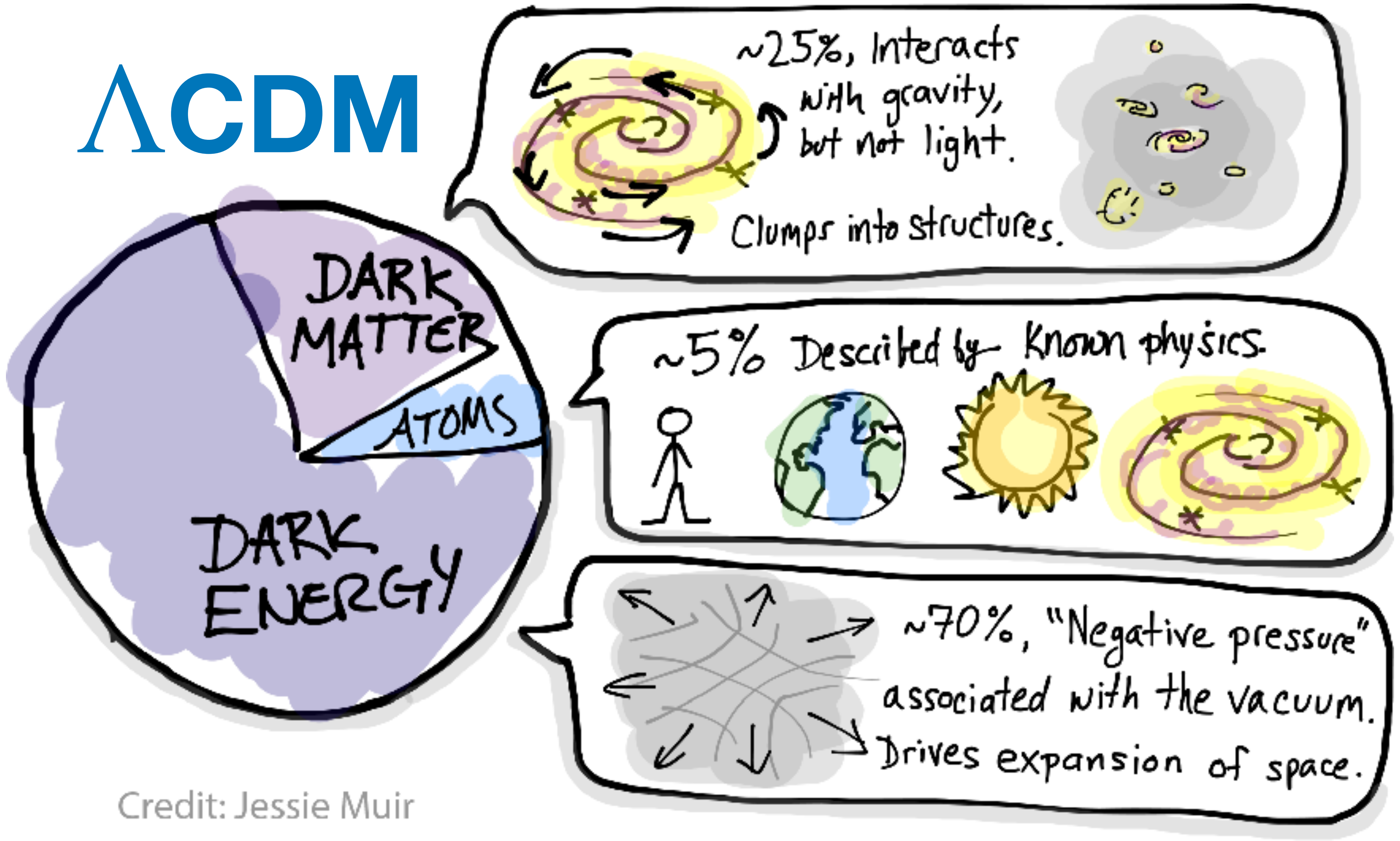
The standard paradigm

- *Theory of gravity:* ***General Relativity***
- *Particles/fields/components and their fundamental inter.:* ***SM + CDM + Cosmological Constant***
- *Geometry/Symmetries:* ***Large-scale inhomogeneity and isotropy***

The standard paradigm

- *Theory of gravity:* ***General Relativity***
- *Particles/fields/components and their fundamental inter.:* ***SM + CDM + Cosmological Constant***
- *Geometry/Symmetries:* ***Large-scale inhomogeneity and isotropy***

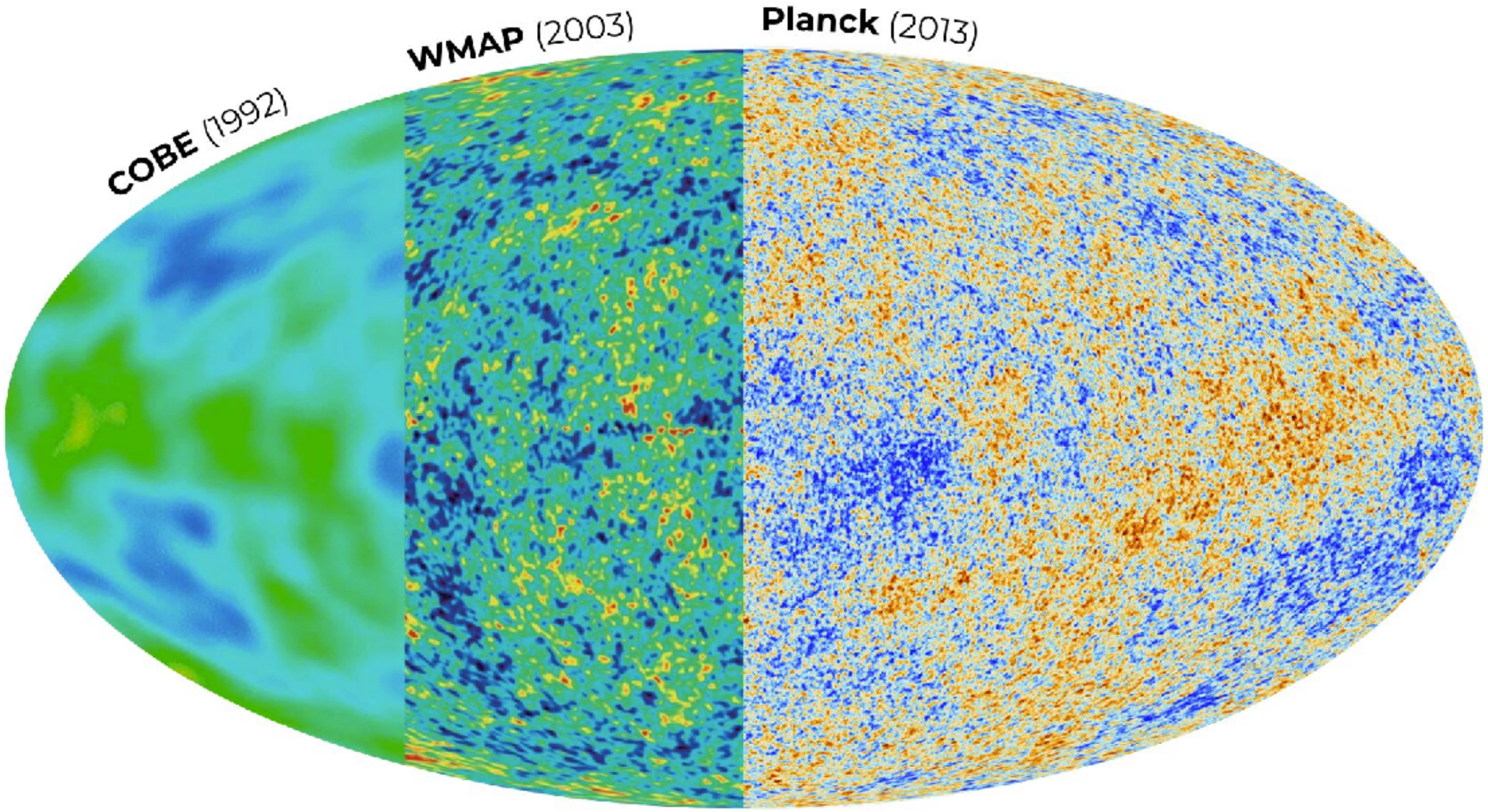
ΛCDM



Credit: Jessie Muir

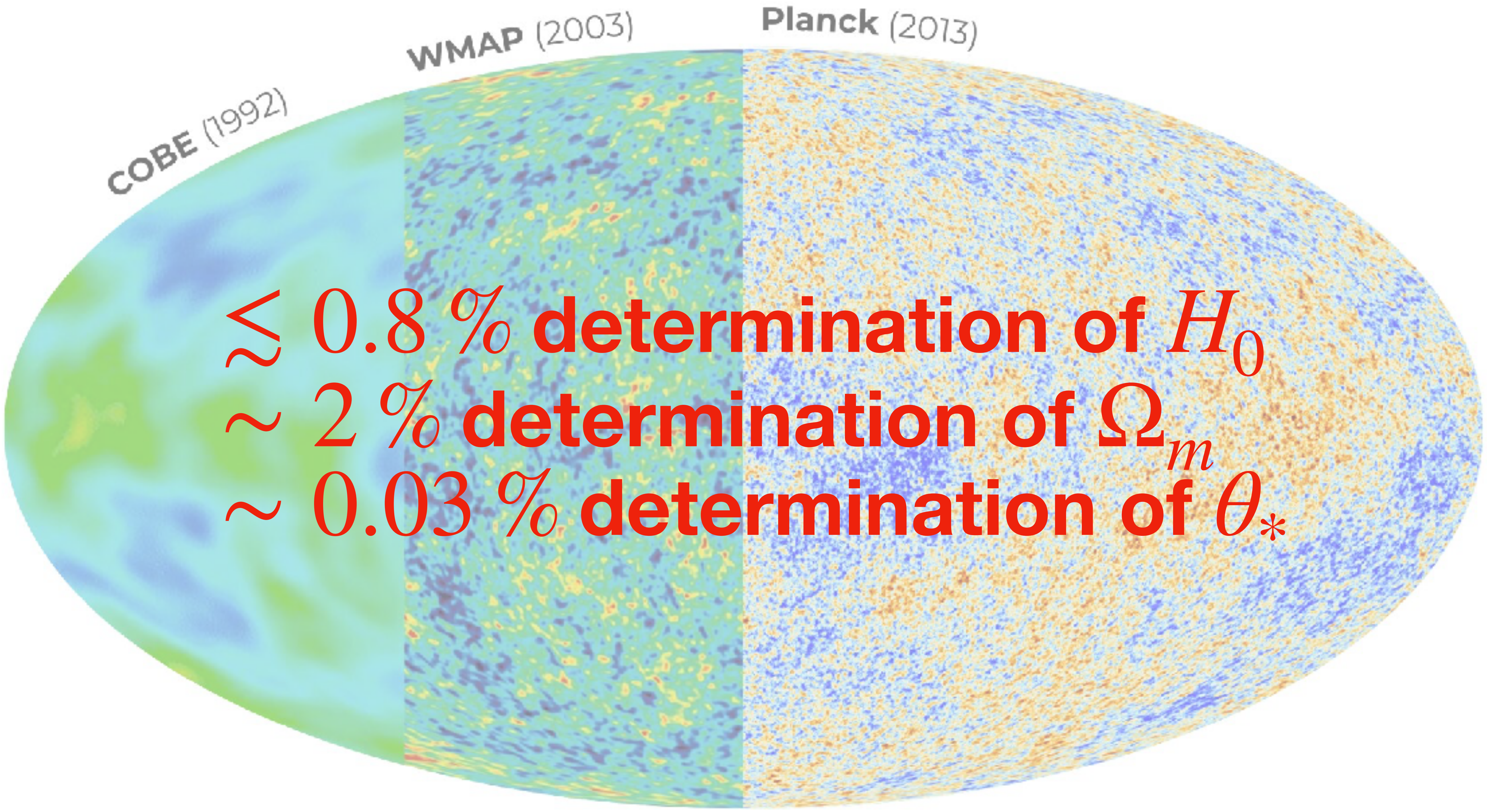
Precision cosmology

Cosmic microwave background observations have been crucial to establish the standard paradigm!



Precision cosmology

Cosmic microwave background observations have been crucial to establish the standard paradigm!

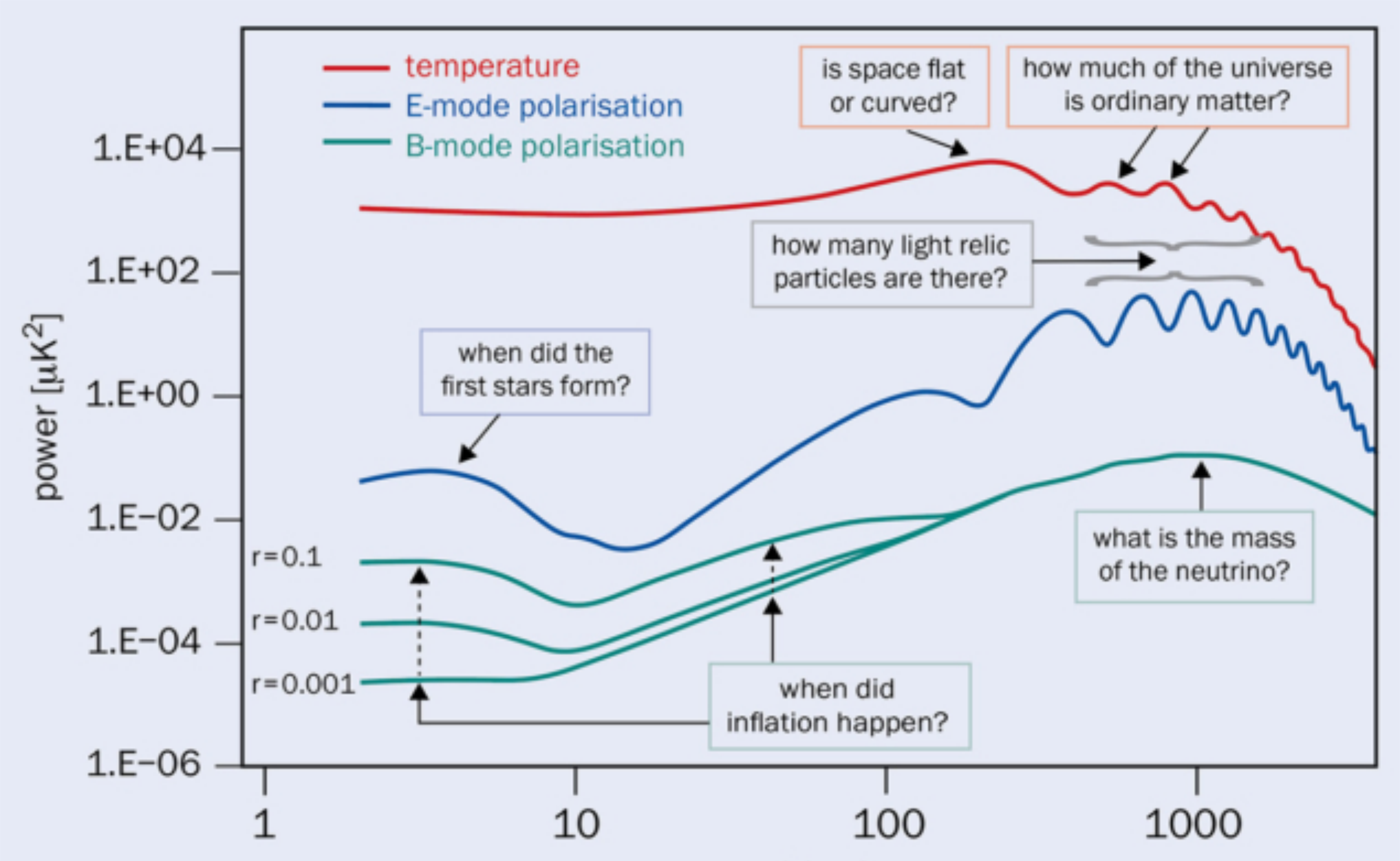


$\lesssim 0.8\,\%$ **determination of** H_0

$\sim 2\,\%$ **determination of** Ω_m

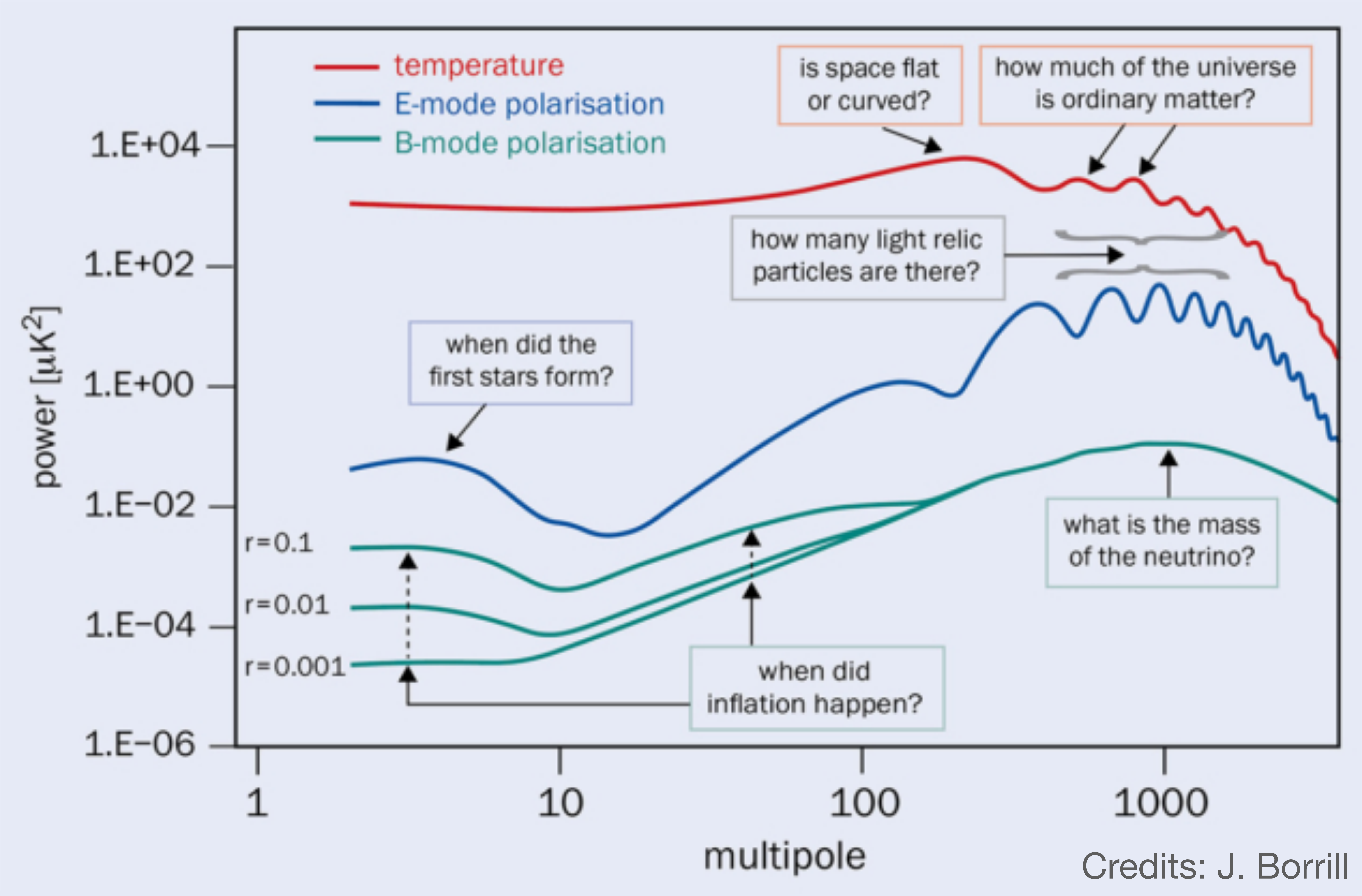
$\sim 0.03\,\%$ **determination of** θ_*

Physics of the CMB



Credits: J. Borrill

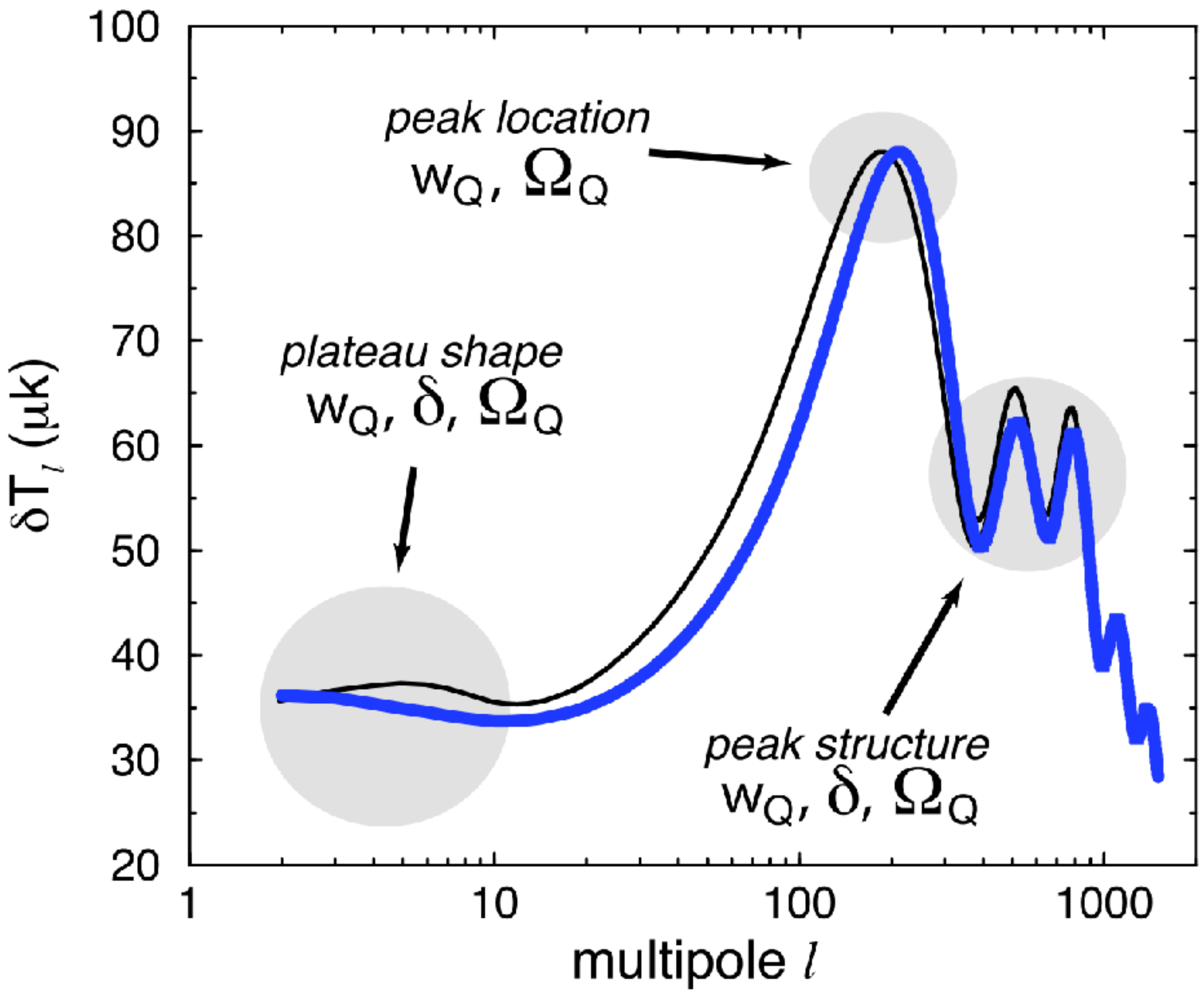
Physics of the CMB



For instance, what can CMB tells us about the nature of Dark Energy?

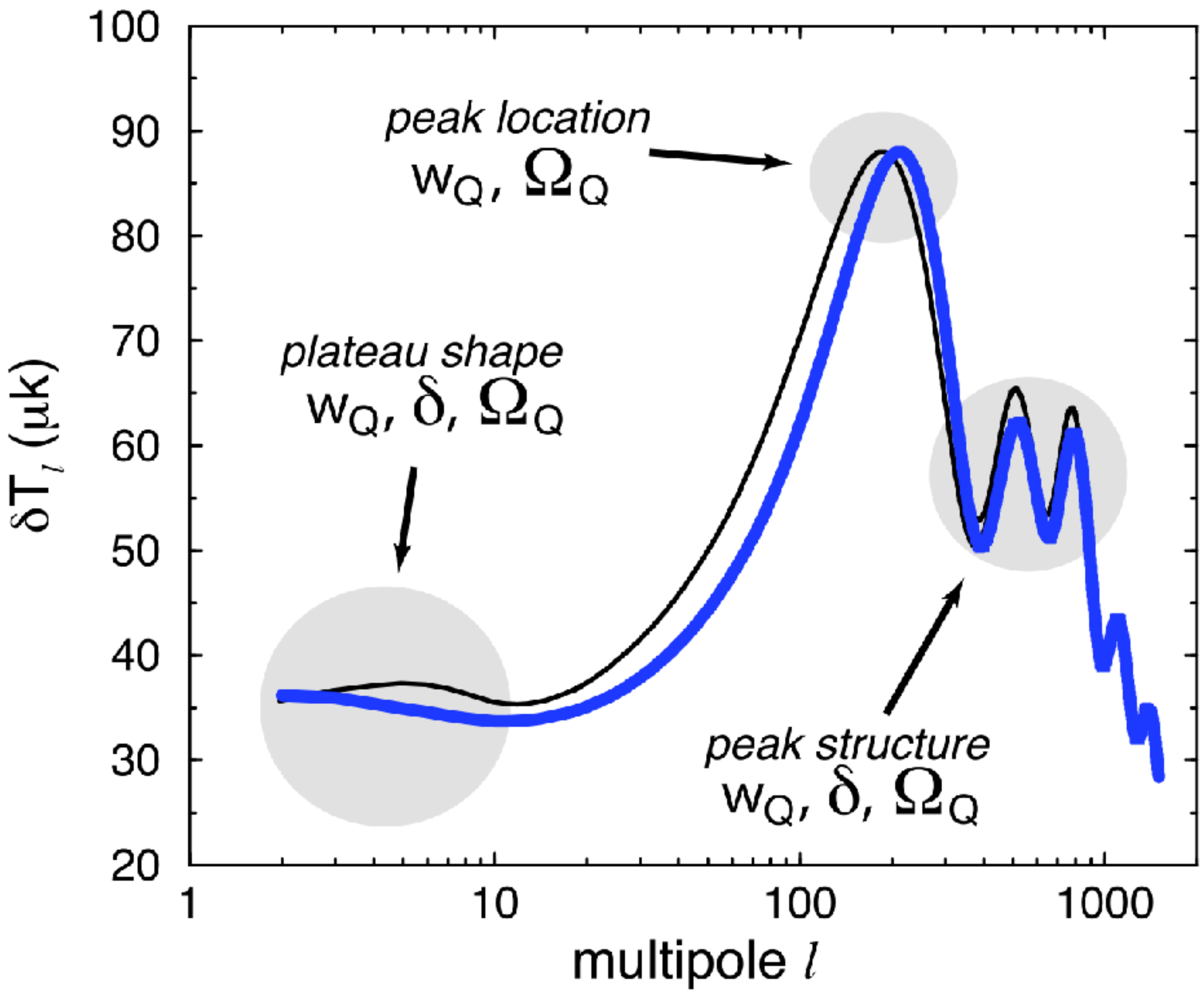
Dark energy imprints in the CMB

Caldwell and Kamionkowski, arXiv:0903.0866



Dark energy imprints in the CMB

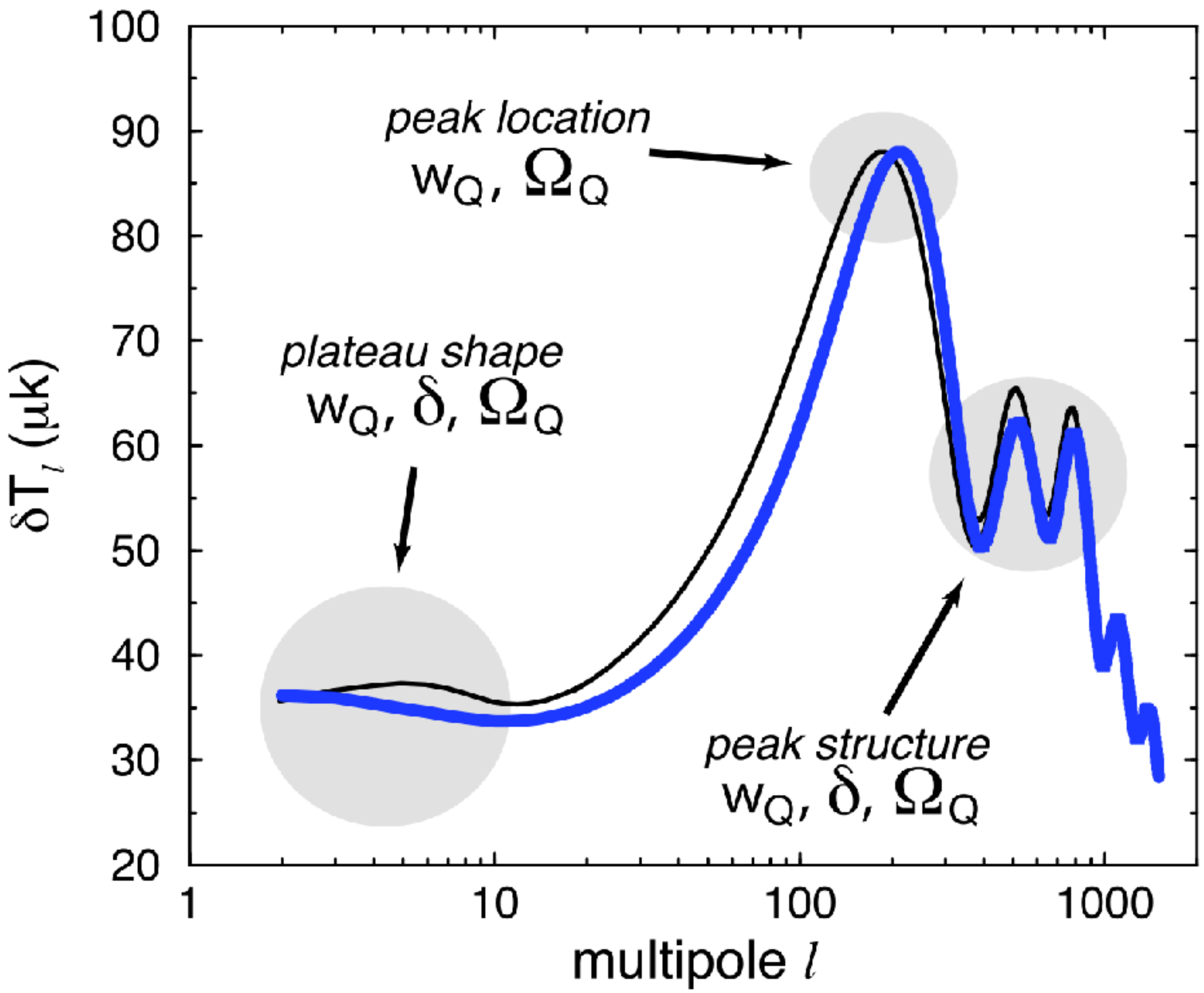
Caldwell and Kamionkowski, arXiv:0903.0866

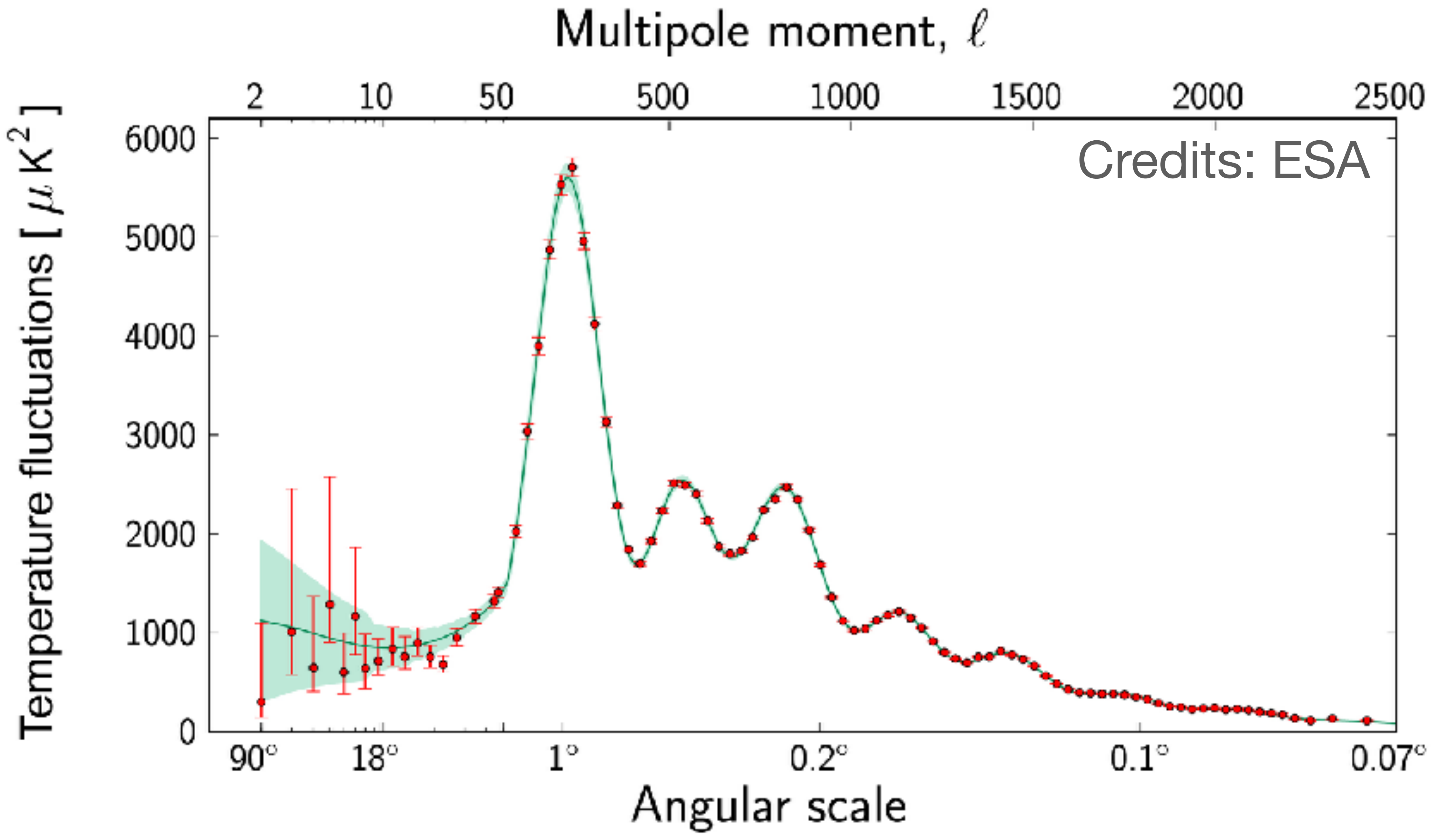


- *Large scales (low ℓ): comic variance dominated*
- *Acoustic peak: sensitive to expansion rate at $z \gtrsim 10$*
- *Acoustic peak structure: when abundant at early times*

Dark energy imprints in the CMB

Caldwell and Kamionkowski, arXiv:0903.0866





- *Large scales (low ℓ): comic variance dominated*
- *Acoustic peak: sensitive to expansion rate at* $z \gtrsim 10$
- *Acoustic peak structure: when abundant at early times*

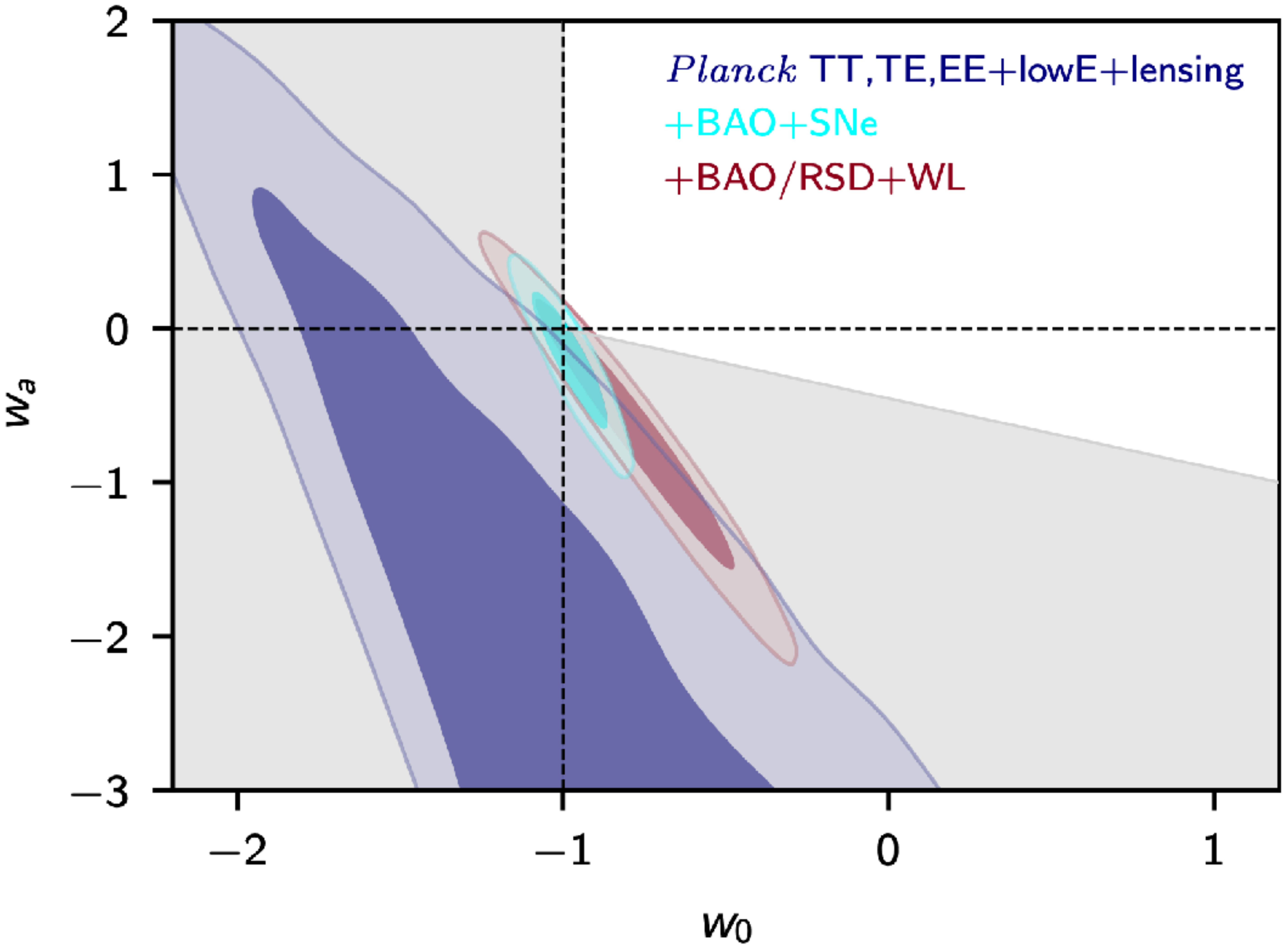
What can CMB tells us about the nature of Dark Energy?

However…

$$w(a) = p/\rho$$

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

Planck 2018, arXiv:1807.06209



What can CMB tells us about the nature of Dark Energy?

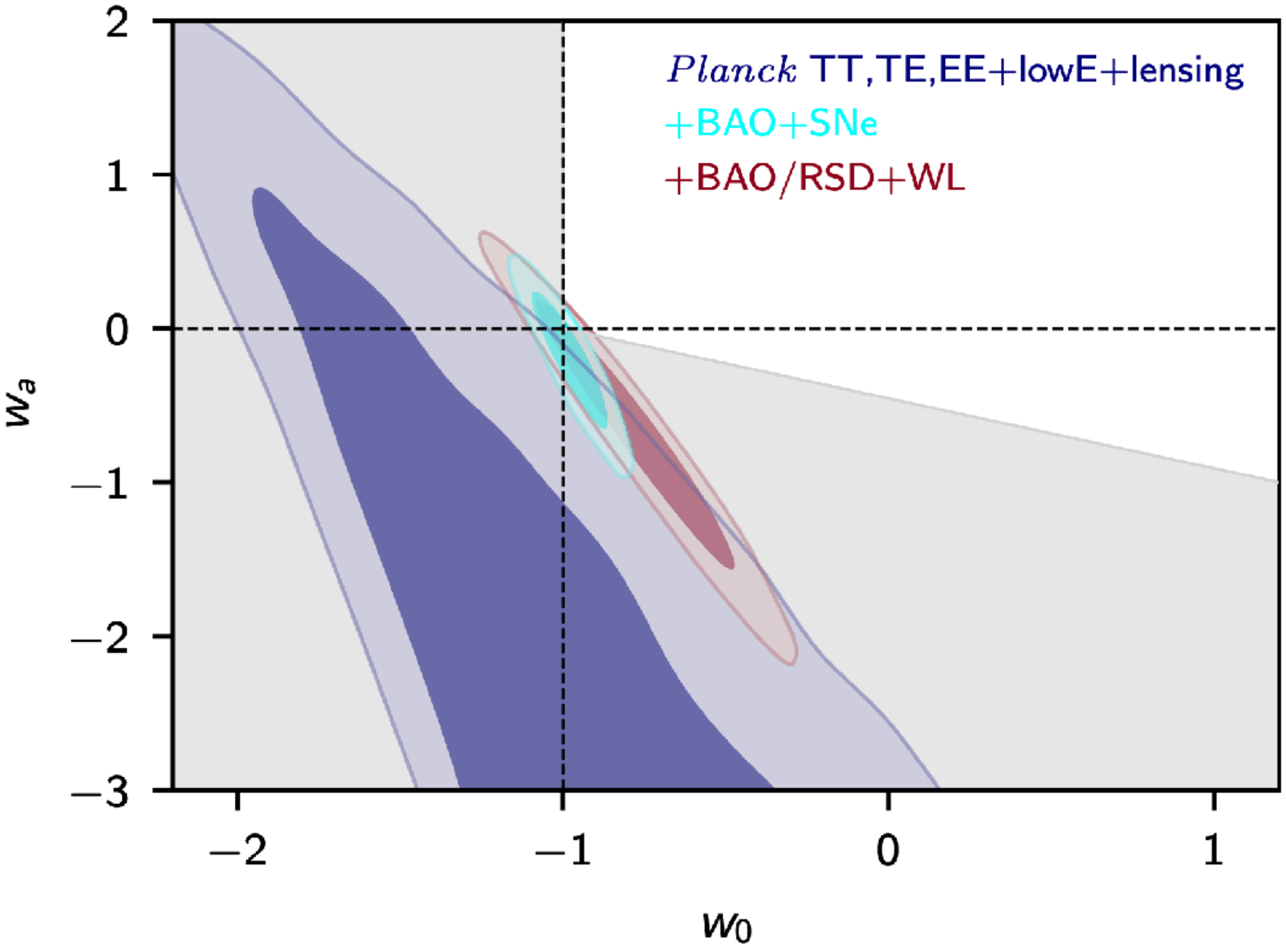
However…

$$w(a) = p/\rho$$

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

DE imprints in the CMB mainly reflect changes in the expansion history of the Universe!

Planck 2018, arXiv:1807.06209

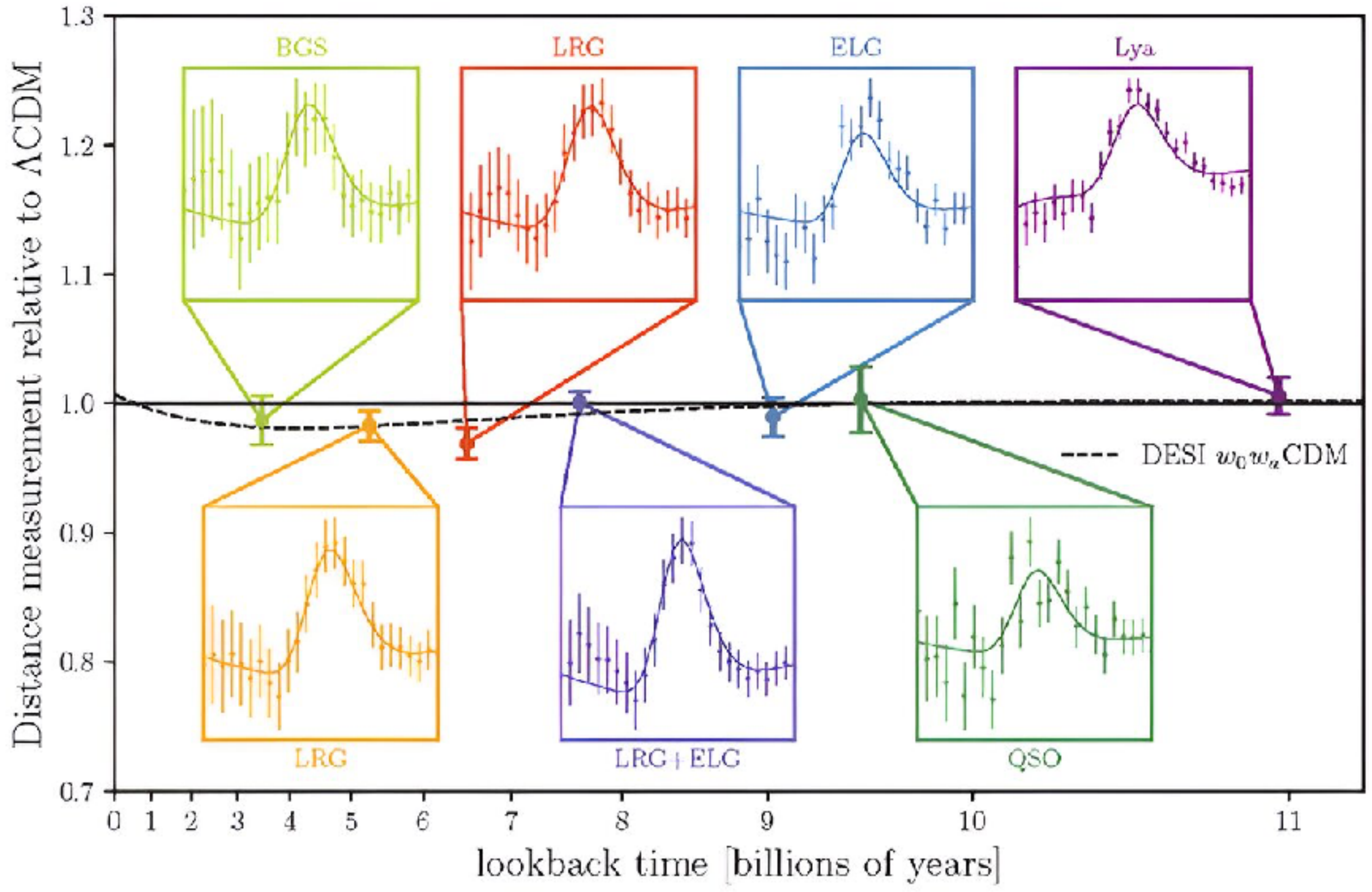


Cosmological distances

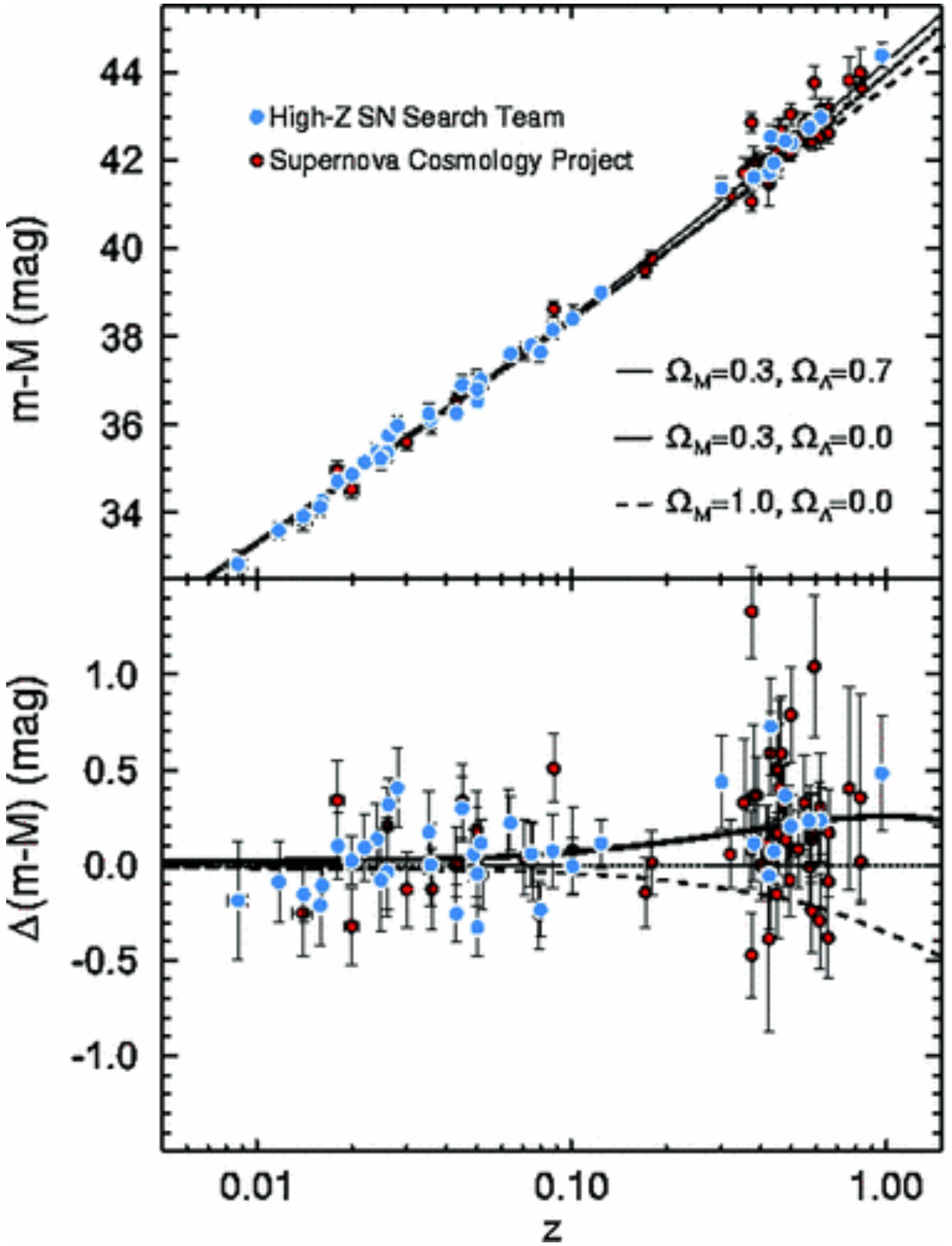
Precise measurements of the expansion history will key to advance (or challenge) the standard paradigm!

$H(z)$, distance-redshift relation

Credits: Arnaud de Mattia/DESI collaboration



Perlmutter and Schmidt, astro-ph/0303428



Summary

1. *Baryonic acoustic oscillations*
2. *DESI measurements*
3. *Discordant distances in the* Λ*CDM picture*
4. *Evidence for evolving dark energy*
5. *Pitfalls of the CPL parametrization - tomorrow*

Baryonic acoustic oscillations

Before recombination photons and baryons behave as a single fluid.

Dark matter, collisionless and cold, clusters to form overdense regions.

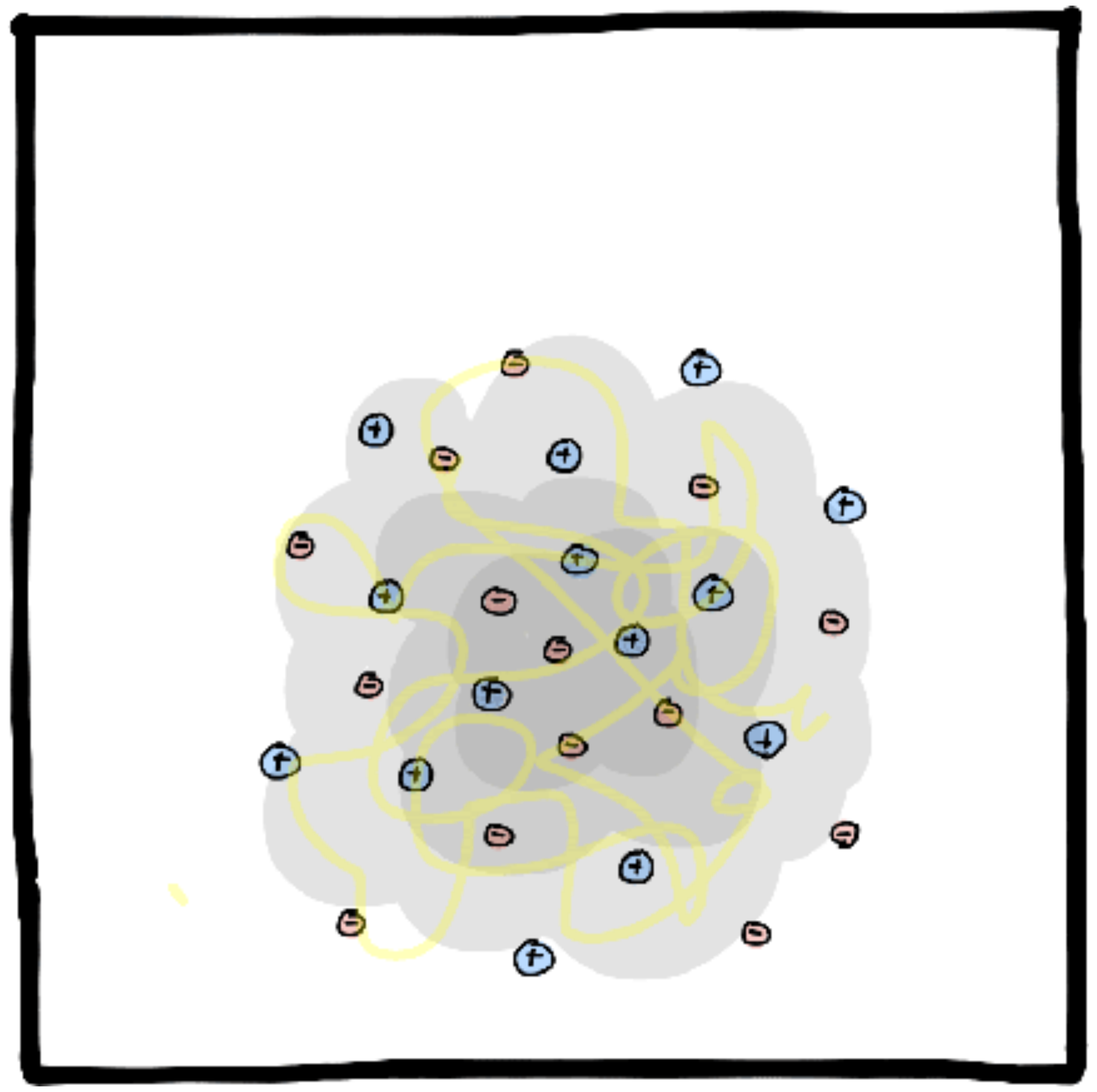
Credits: Daniel Eisenstein

Baryonic acoustic oscillations

Before recombination **photons** and **baryons** behave as a single fluid.

Dark matter, collisionless and cold, clusters to form overdense regions.

The **photon**-**baryon** fluid oscillates due to the competing forces of gravity pulling it into the overdensity, and radiation pressure pushing out when the fluid gets compressed.



Credit: Jesse Muir

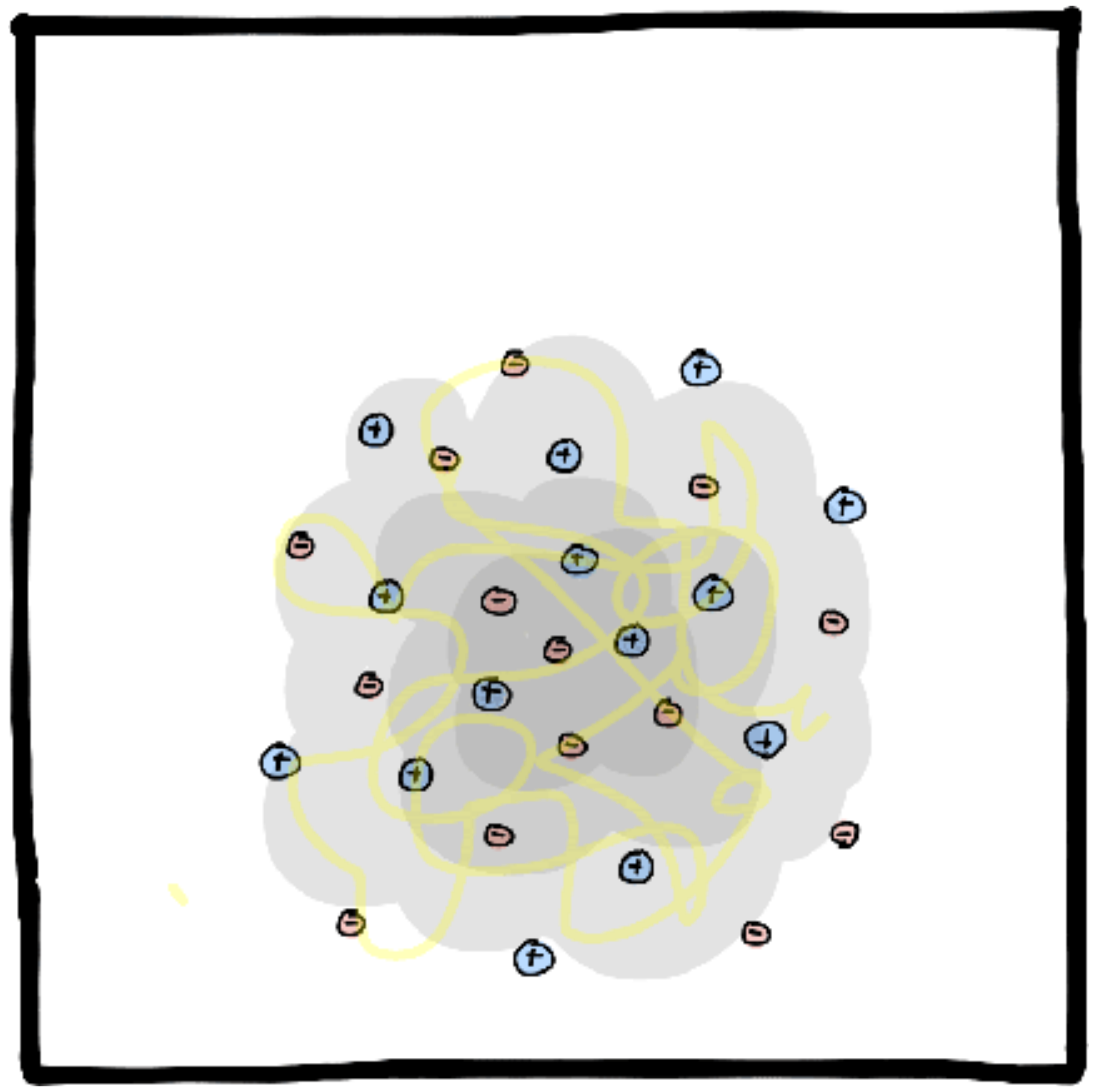
Credits: Daniel Eisenstein

Baryonic acoustic oscillations

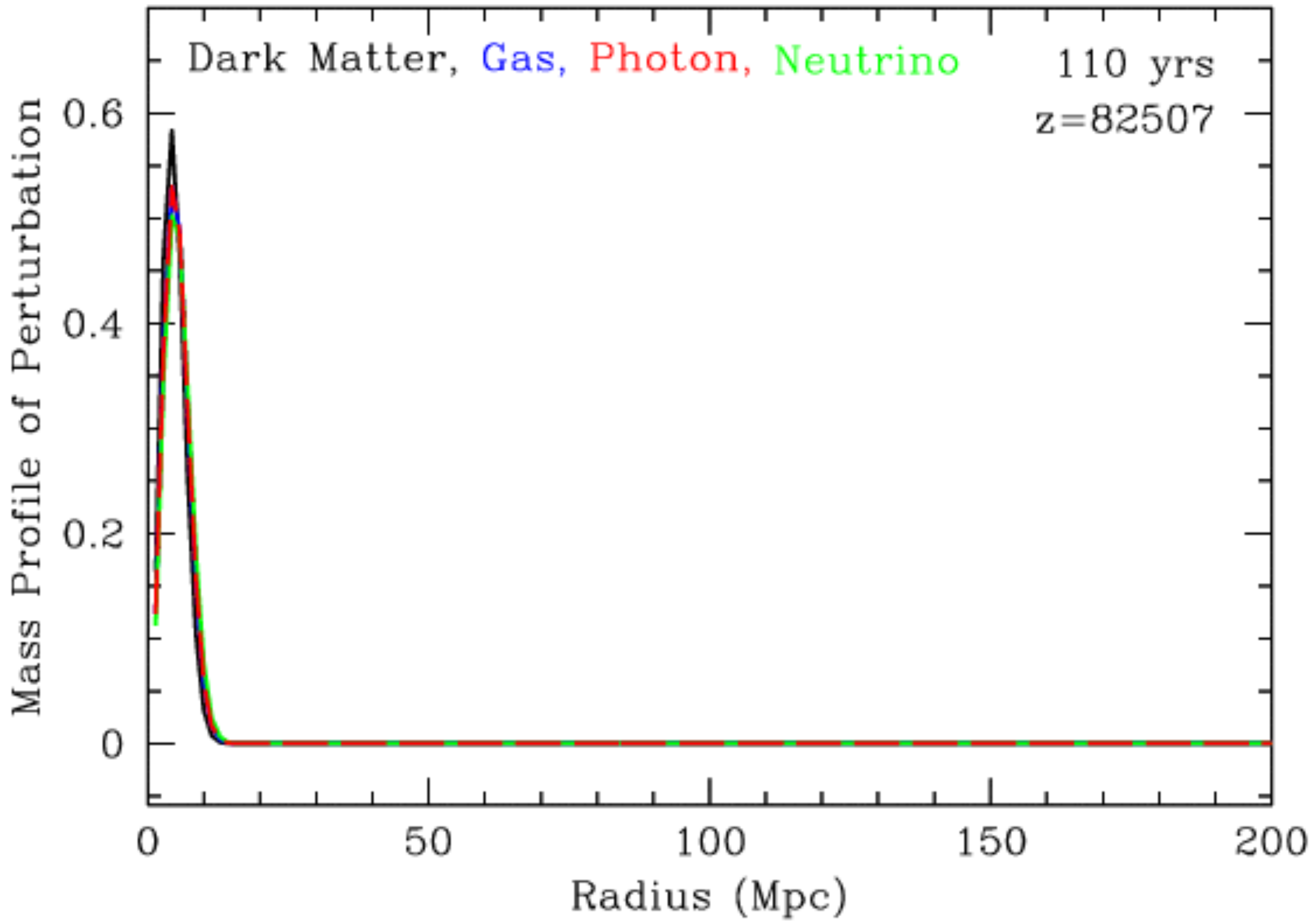
Before recombination **photons** and **baryons** behave as a single fluid.

Dark matter, collisionless and cold, clusters to form overdense regions.

The **photon**-**baryon** fluid oscillates due to the competing forces of gravity pulling it into the overdensity, and radiation pressure pushing out when the fluid gets compressed.

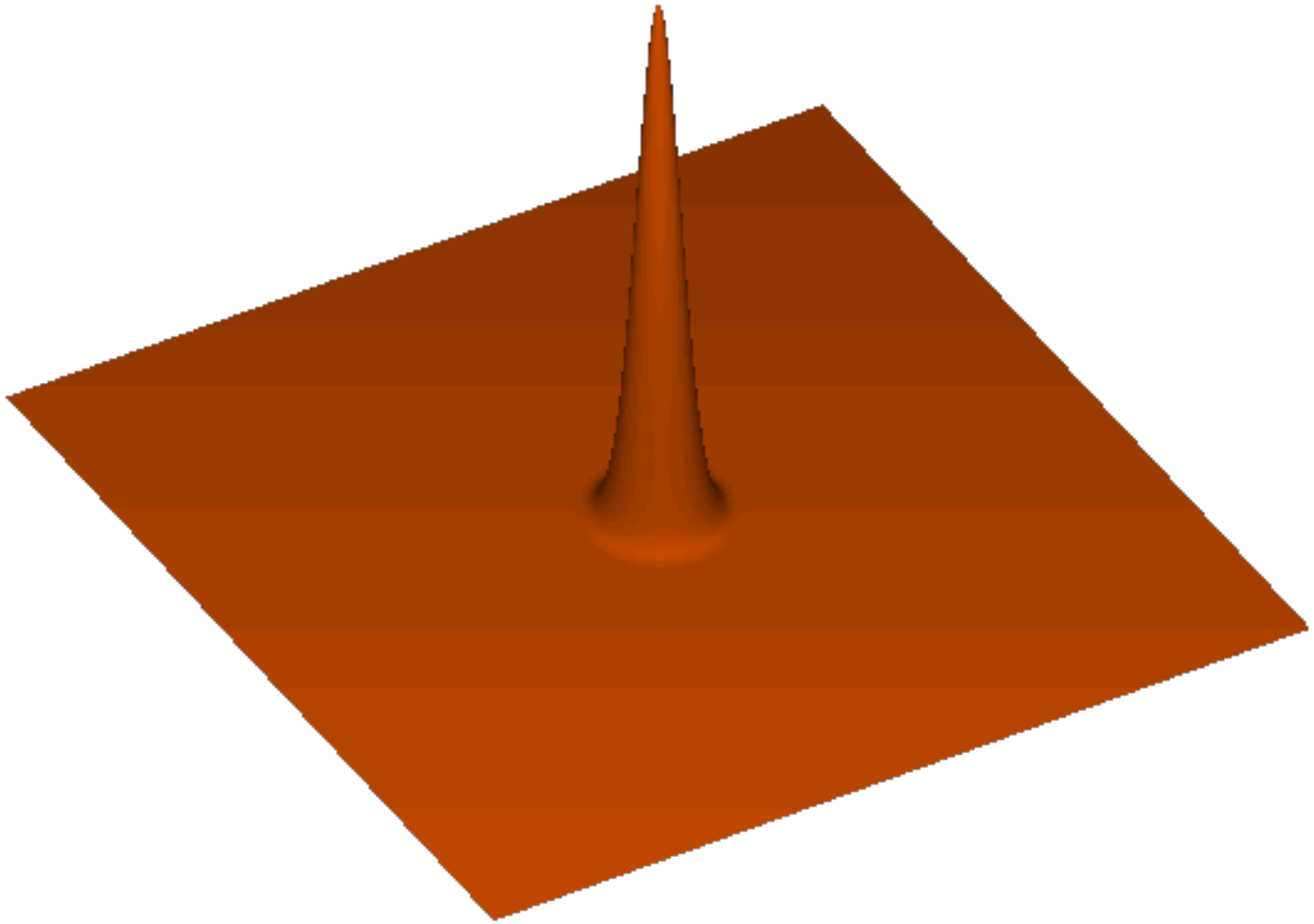


Credit: Jesse Muir



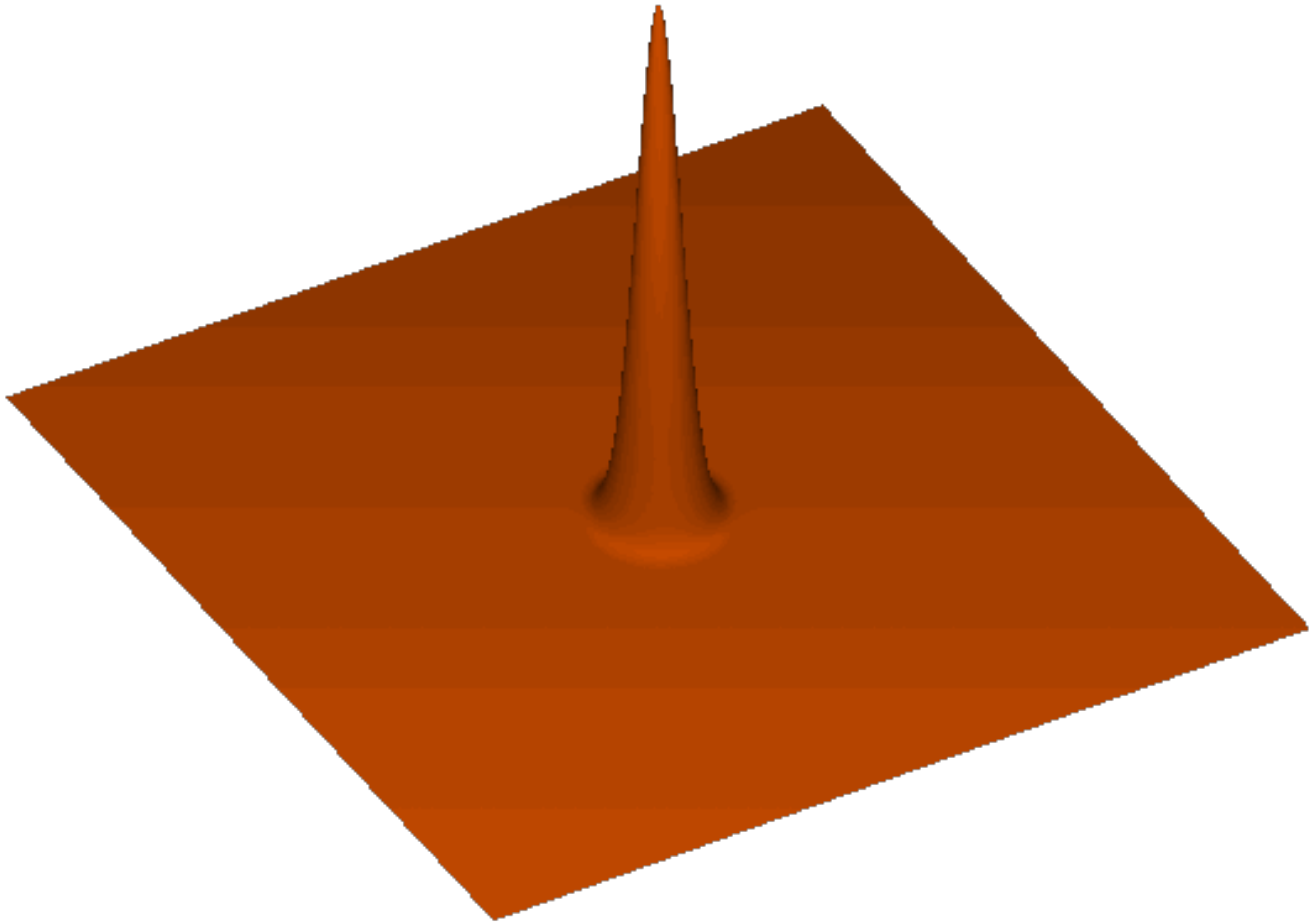
Credits: Daniel Eisenstein

Baryonic acoustic oscillations



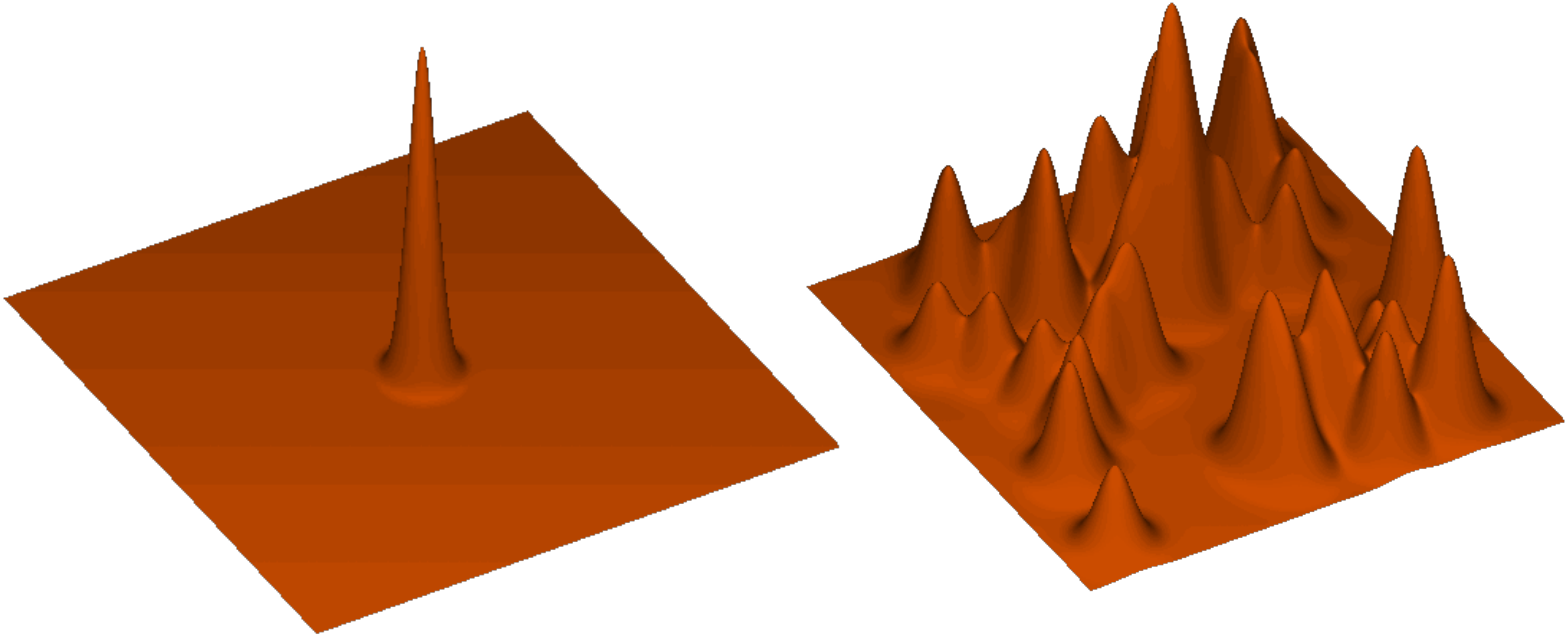
Credits: Daniel Eisenstein

Baryonic acoustic oscillations



Credits: Daniel Eisenstein

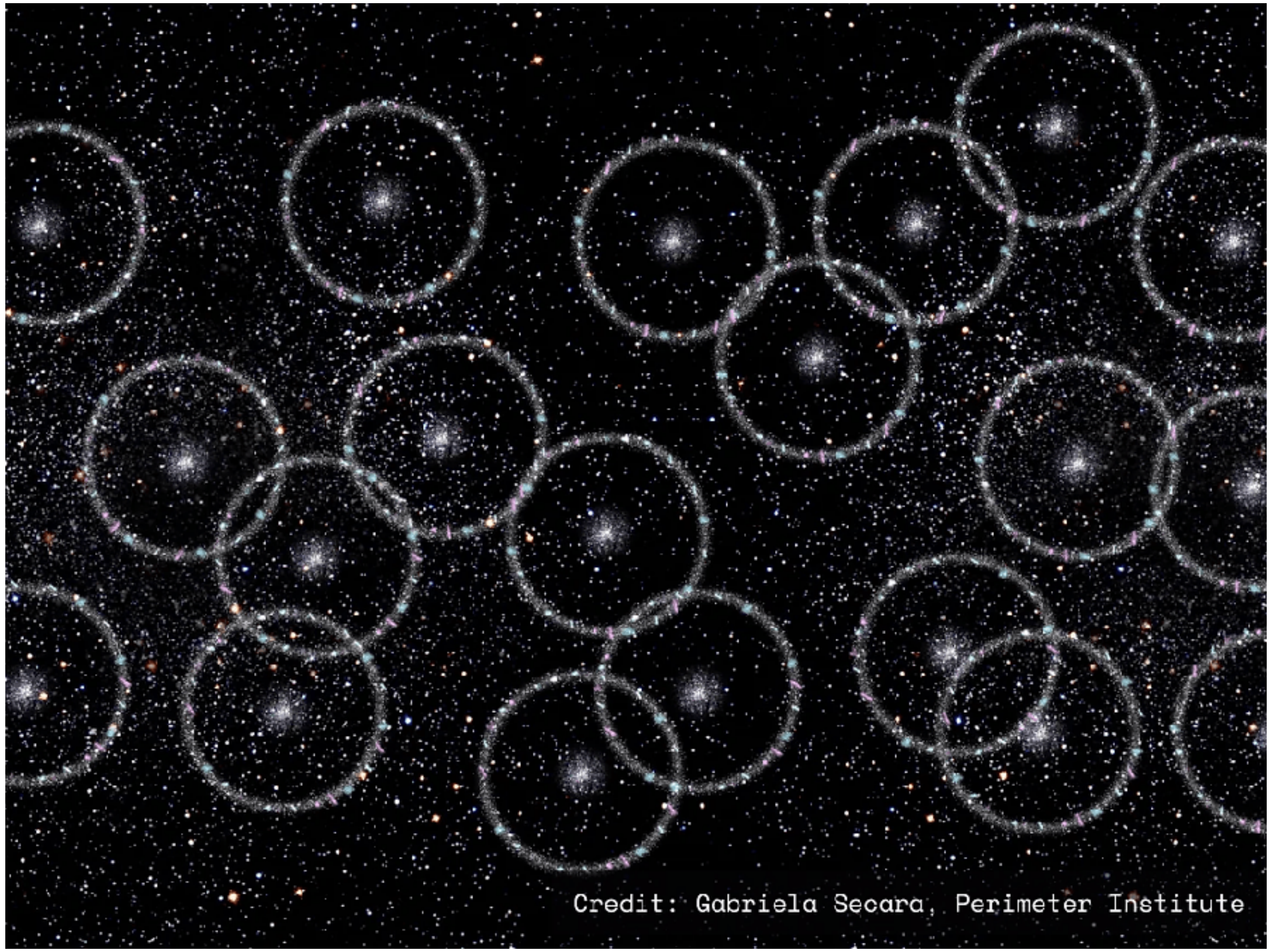
Baryonic acoustic oscillations



Credits: Daniel Eisenstein

Baryonic acoustic oscillations

The baryonic acoustic oscillations (BAO) imprint a characteristic scale on matter clustering.

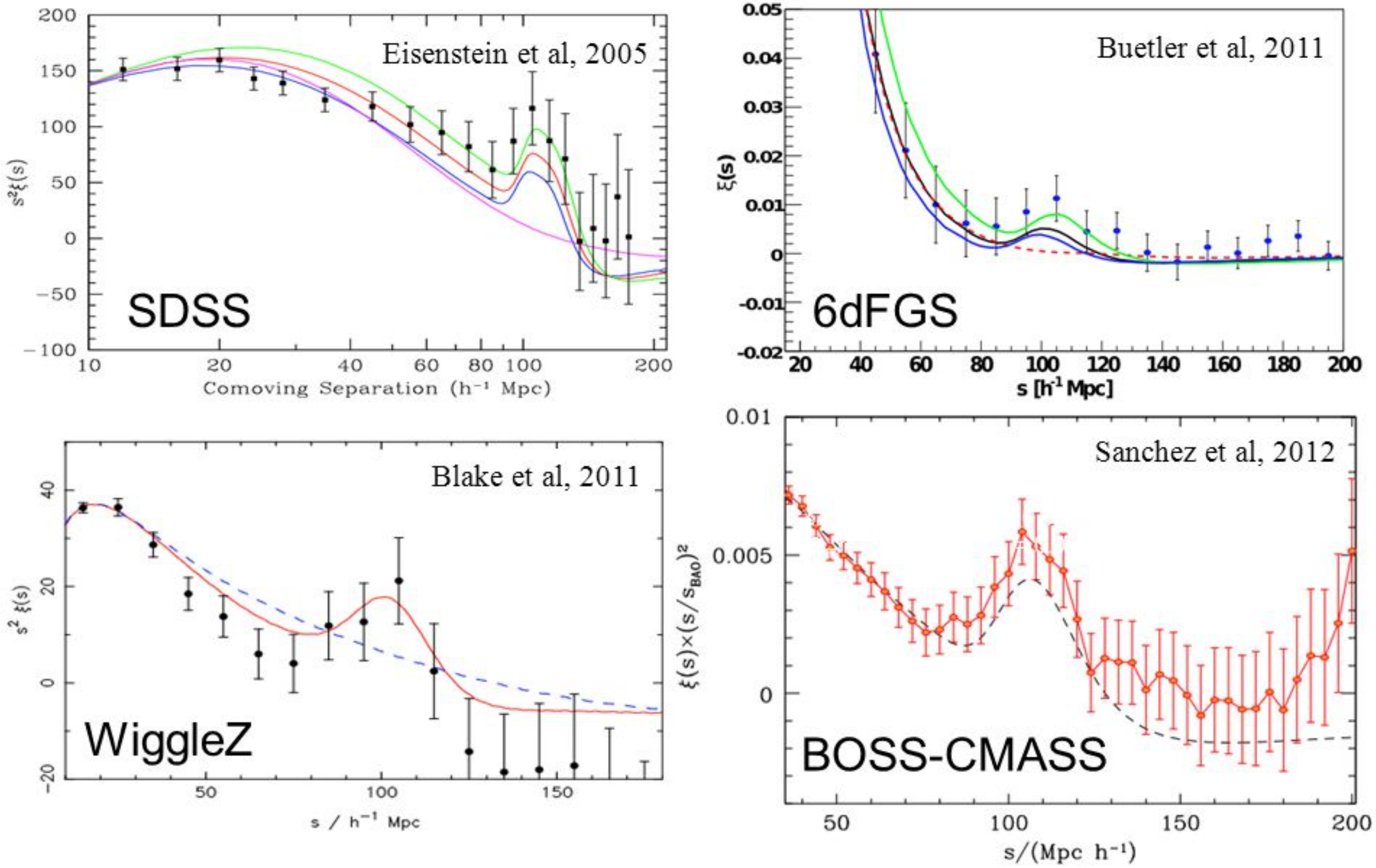


There is an exceed of probability of finding a pair of galaxies separated the BAO radio.

Baryonic acoustic oscillations

2-pt correlation function features a "bump" at the characteristic BAO scale ($r \approx 150\ \mathrm{Mpc}$)

Detected in galaxy correlations!

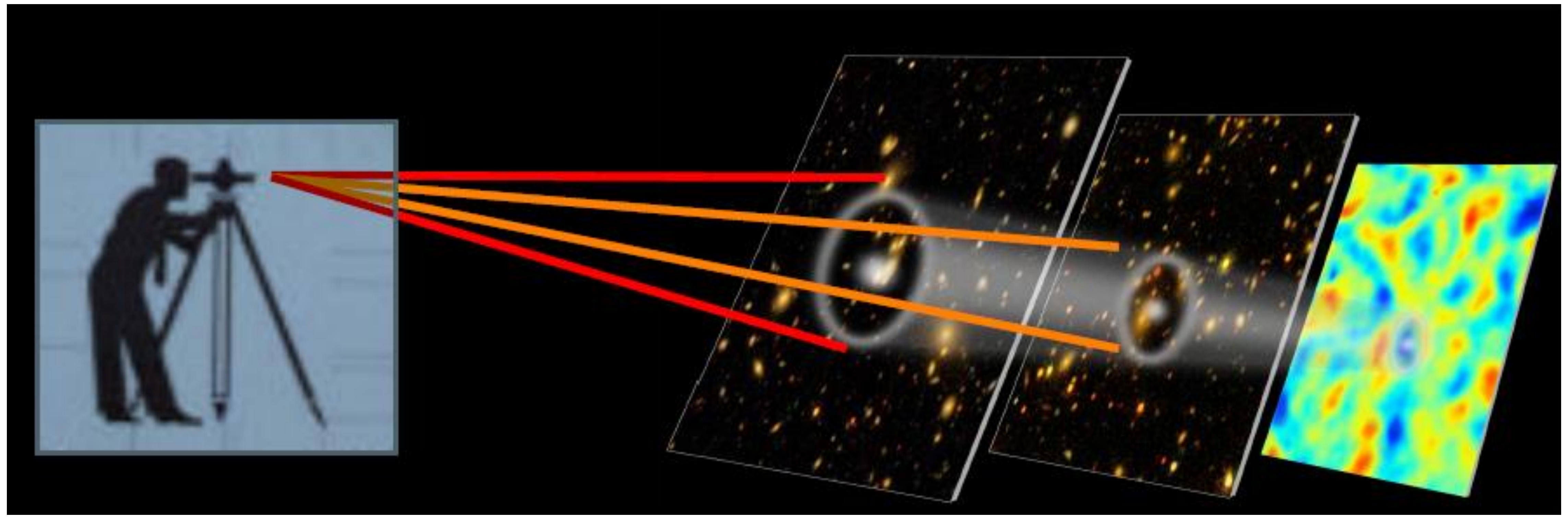


Baryonic acoustic oscillations

Credits: Eusebio Sanchez

Why is this interesting?

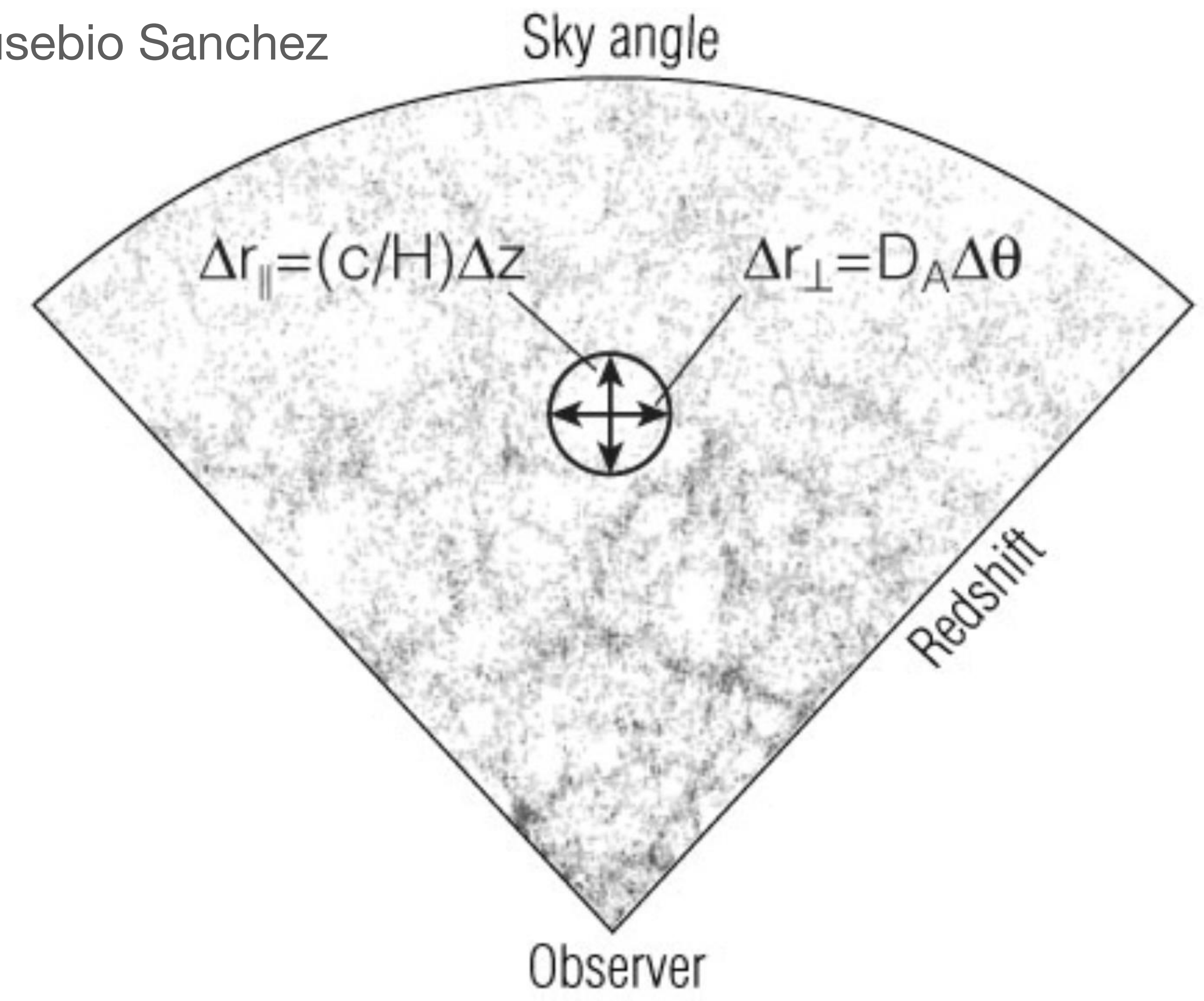
- BAO are a standard ruler
- We can study cosmic expansion history using it



- In a galaxy redshift survey, we can measure this along and across the line of sight → Yields $H(z)$ and $D_A(z)$!
- Measuring the acoustic peaks across redshift gives a purely *geometrical measurement of cosmological distance*.
- It is a *robust method*. Not very sensitive to systematic errors.
- However, the peaks are weak in amplitude and are only available on large scales. *Require huge survey volumes.*

Baryonic acoustic oscillations

Credits: Eusebio Sanchez



Simultaneous measurement of:

- *Distance-redshift relation*
- *Direct measurements of the expansion history*

Measuring 2 distances with standard rulers:

Angular diameter distance → $D_A(z; \Omega_M, \Omega_B, \Omega_\Lambda, w\ldots)$

Expansion rate (along the LoS) → $H\,(z; \Omega_M, \Omega_B, \Omega_\Lambda, w\ldots)$

Different sensitivity and systematic errors

Baryonic acoustic oscillations

GALAXY REDSHIFT SURVEYS

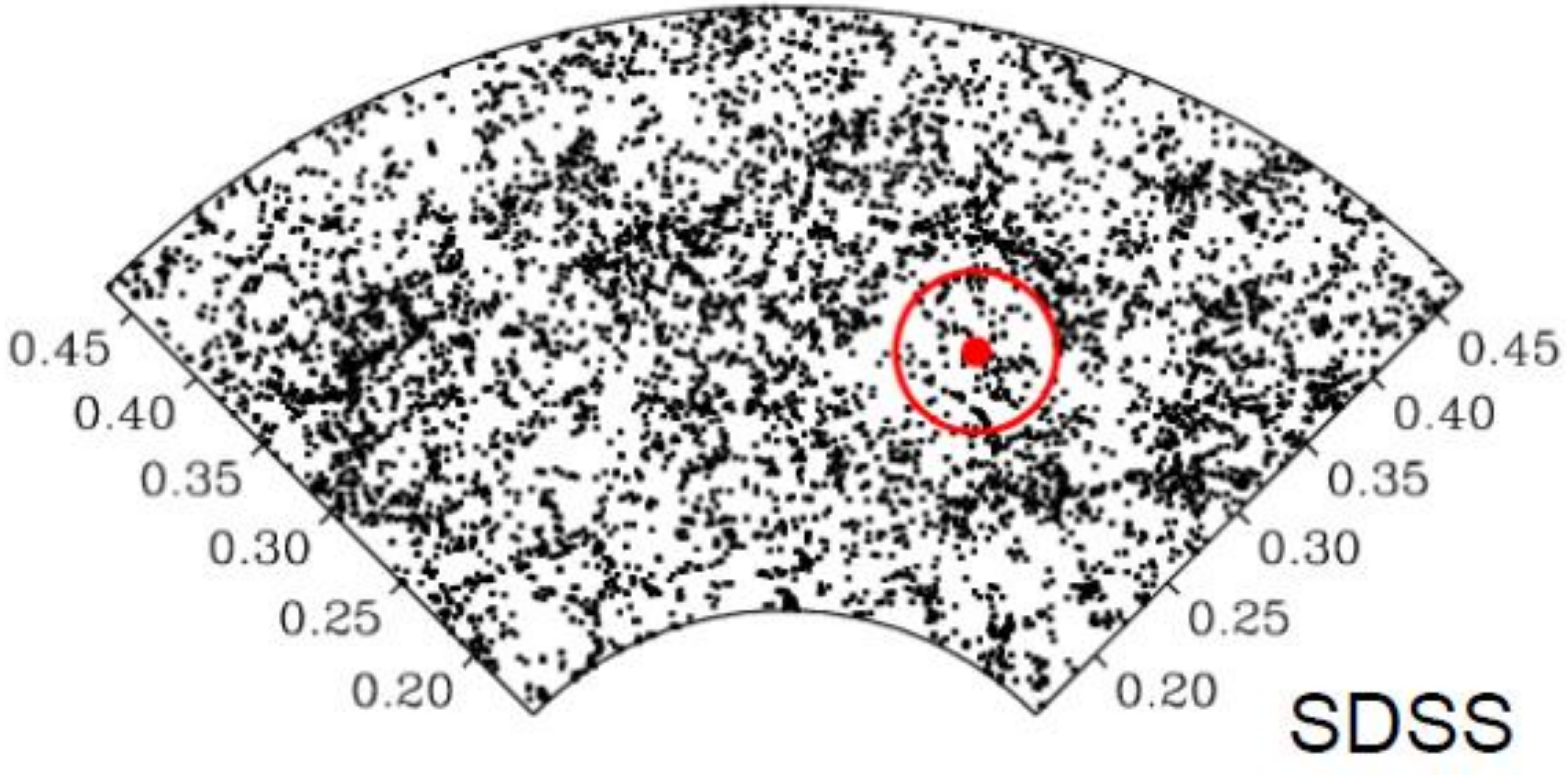
Redshift surveys are the main way of measuring the 3D clustering of matter

But there are some complications:

- *Non-linear structure formation*
- *Bias (light does not trace mass)*
- *Redshift space distortions*

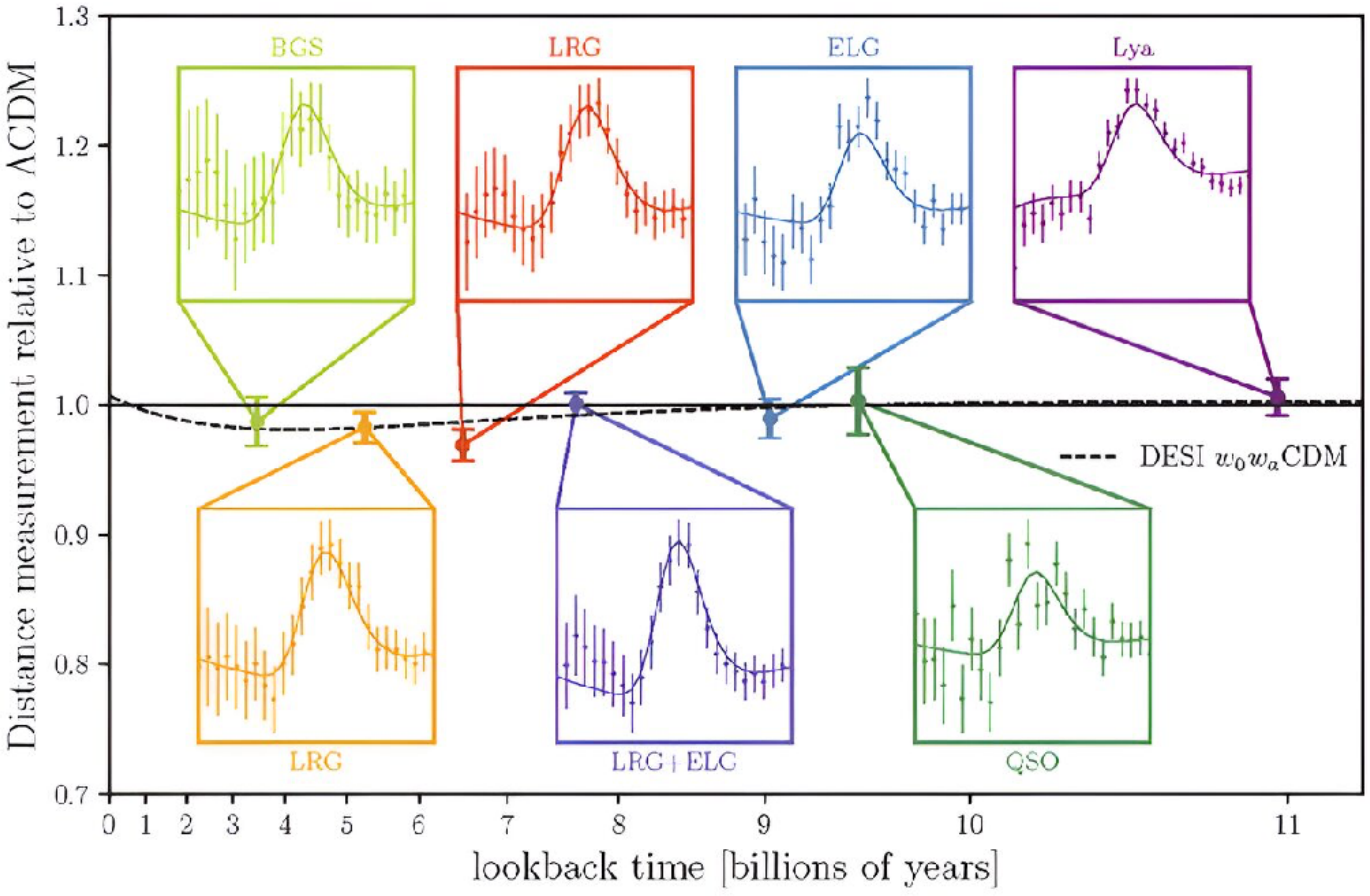
Credits: Eusebio Sanchez

All these effects partially degrade the BAO peak, but systematics are small because BAO is a very large scale



Dark Energy Spectroscopic Instrument measurements

Credits: Arnaud de Mattia/DESI collaboration



DESI Collaboration, arXiv:2503.14738

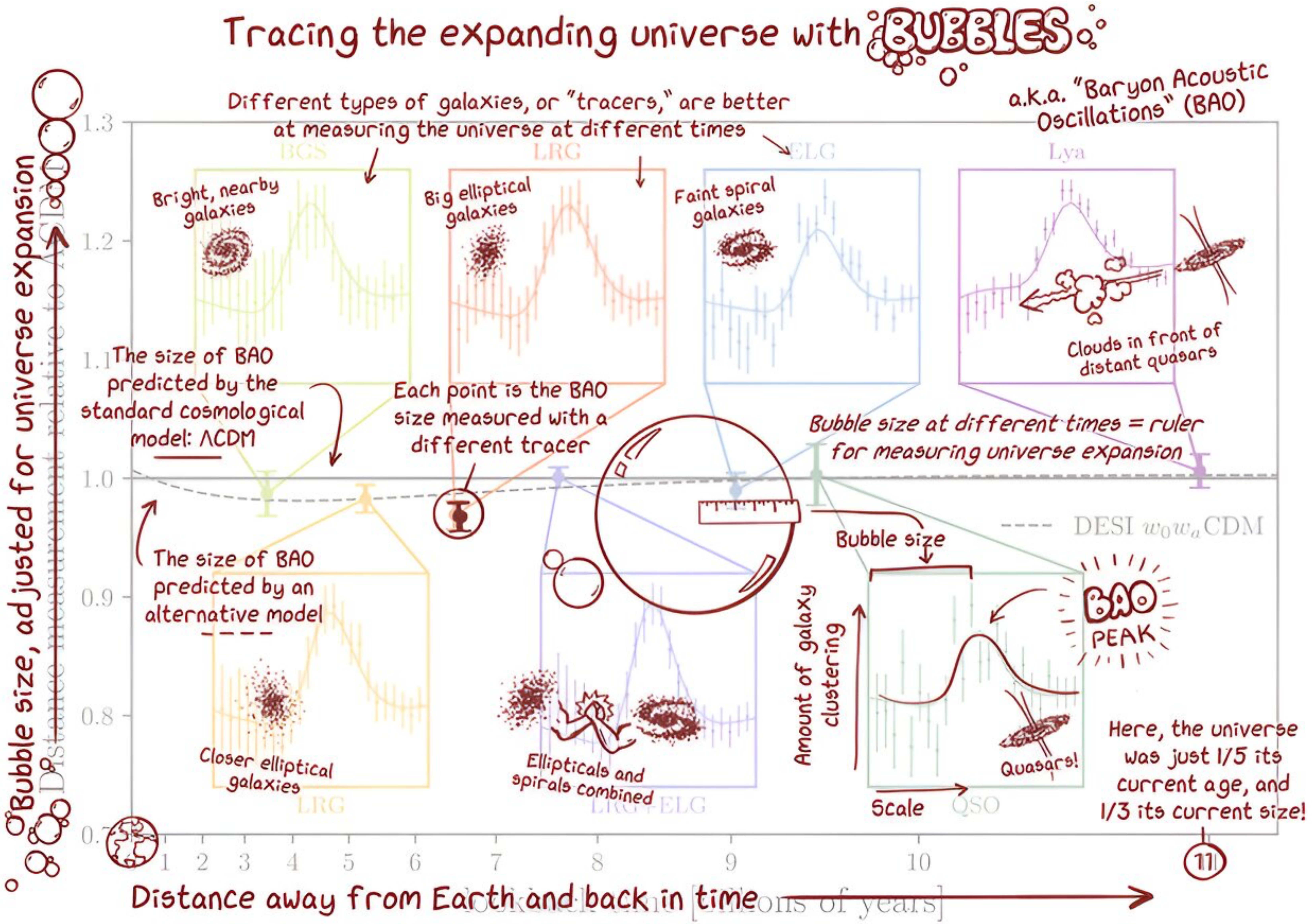
Tracer	Redshift range	N_{tracer}	V_{eff} (Gpc^3)
BGS	0.1 – 0.4	1,188,526	3.8
LRG1	0.4 – 0.6	1,052,151	4.9
LRG2	0.6 – 0.8	1,613,562	7.6
LRG3+ELG1	0.8 – 1.1	4,540,343	14.8
ELG2	1.1 – 1.6	3,797,271	8.3
QSO	0.8 – 2.1	1,461,588	2.7
Lyα	1.8 – 4.2	1,289,874	—
LRG3	0.8 – 1.1	1,802,770	9.8
ELG1	0.8 – 1.1	2,737,573	5.8

In a flat Universe:

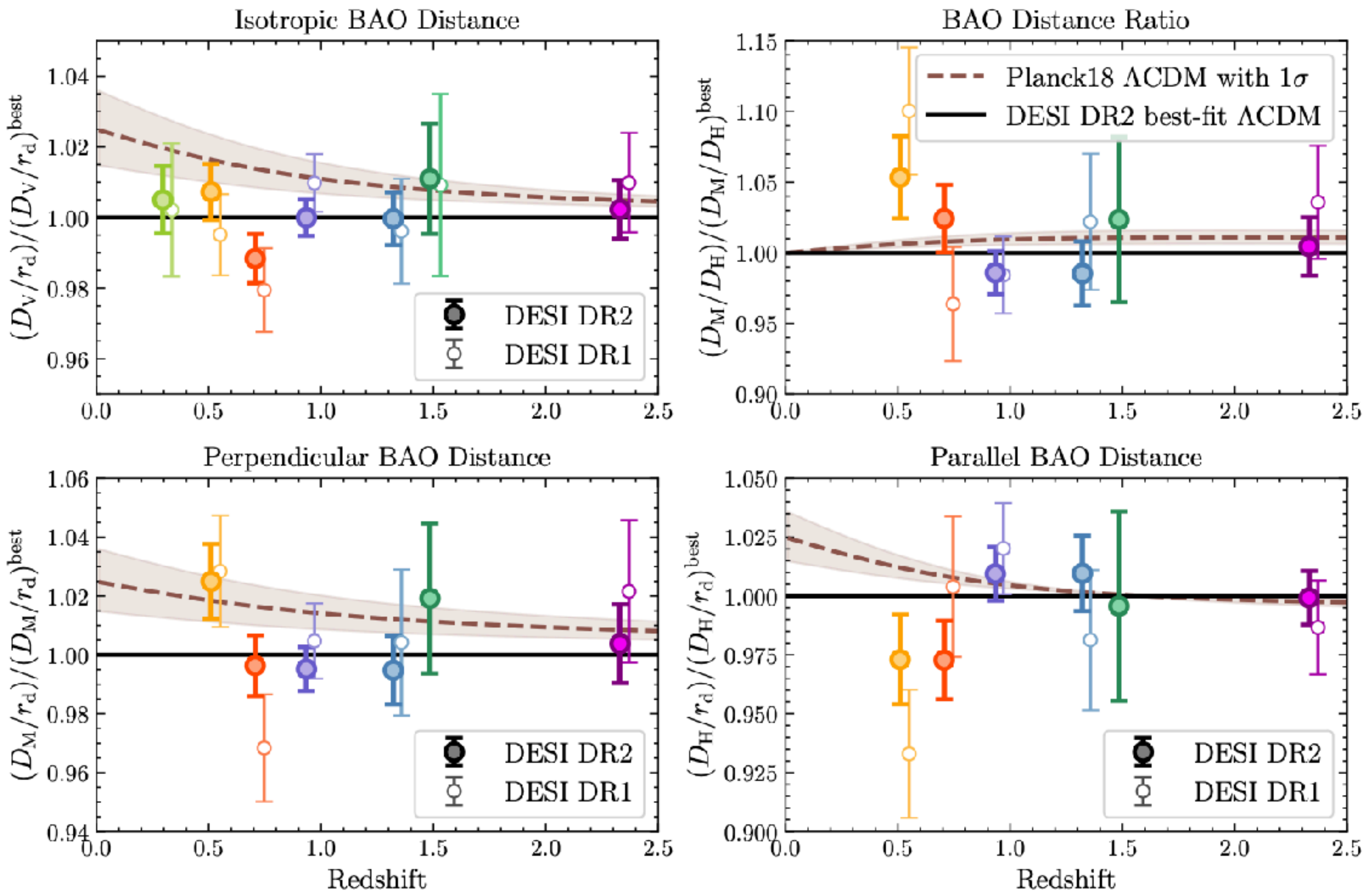
$$D_{\mathrm{M}}(z) = \frac{c}{H_0}\int_0^z \frac{dz'}{H(z')/H_0}$$

$$D_{\mathrm{H}}(z) = \frac{c}{H(z)}$$

Dark Energy Spectroscopic Instrument measurements

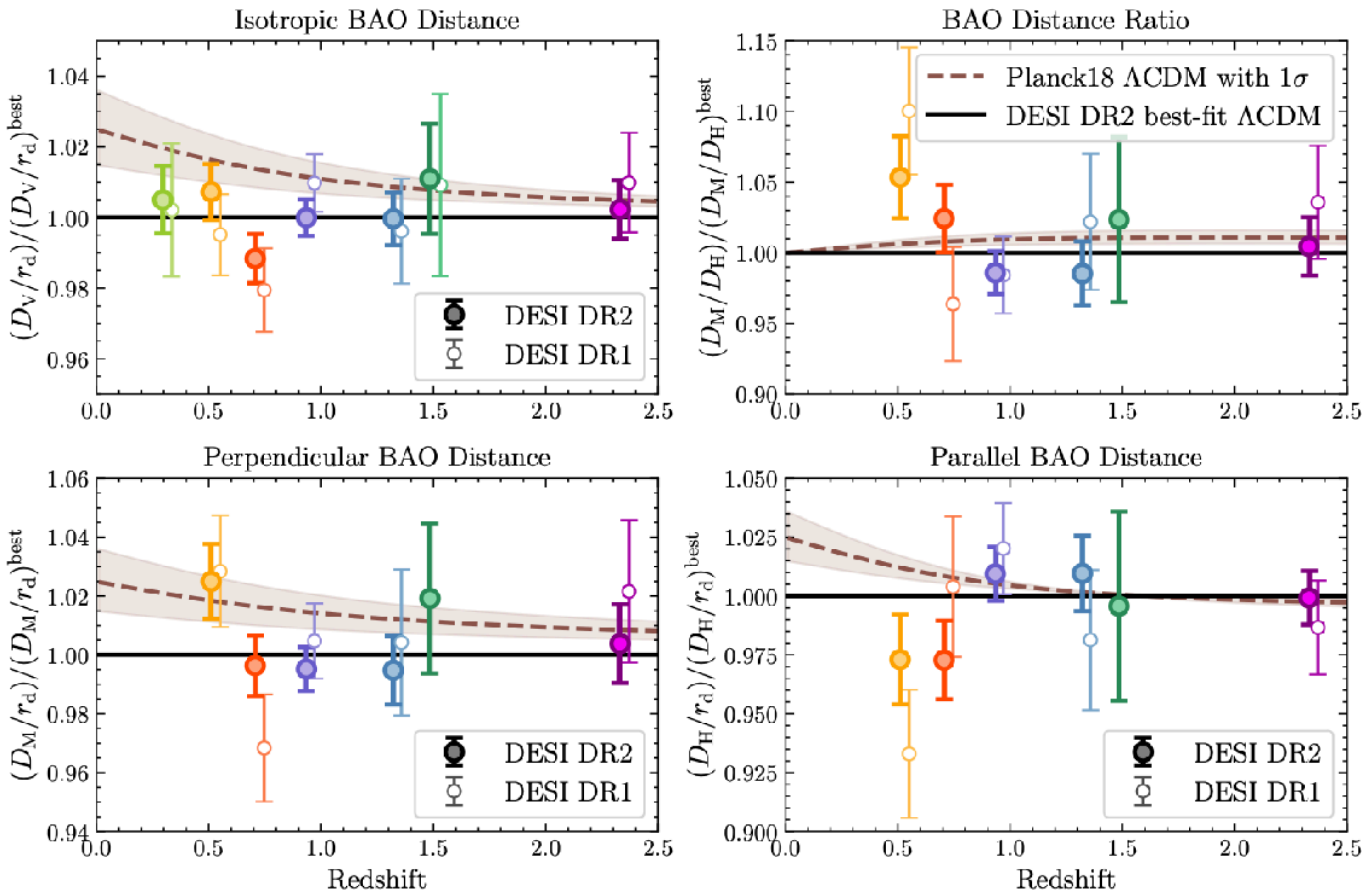


DESI vs CMB

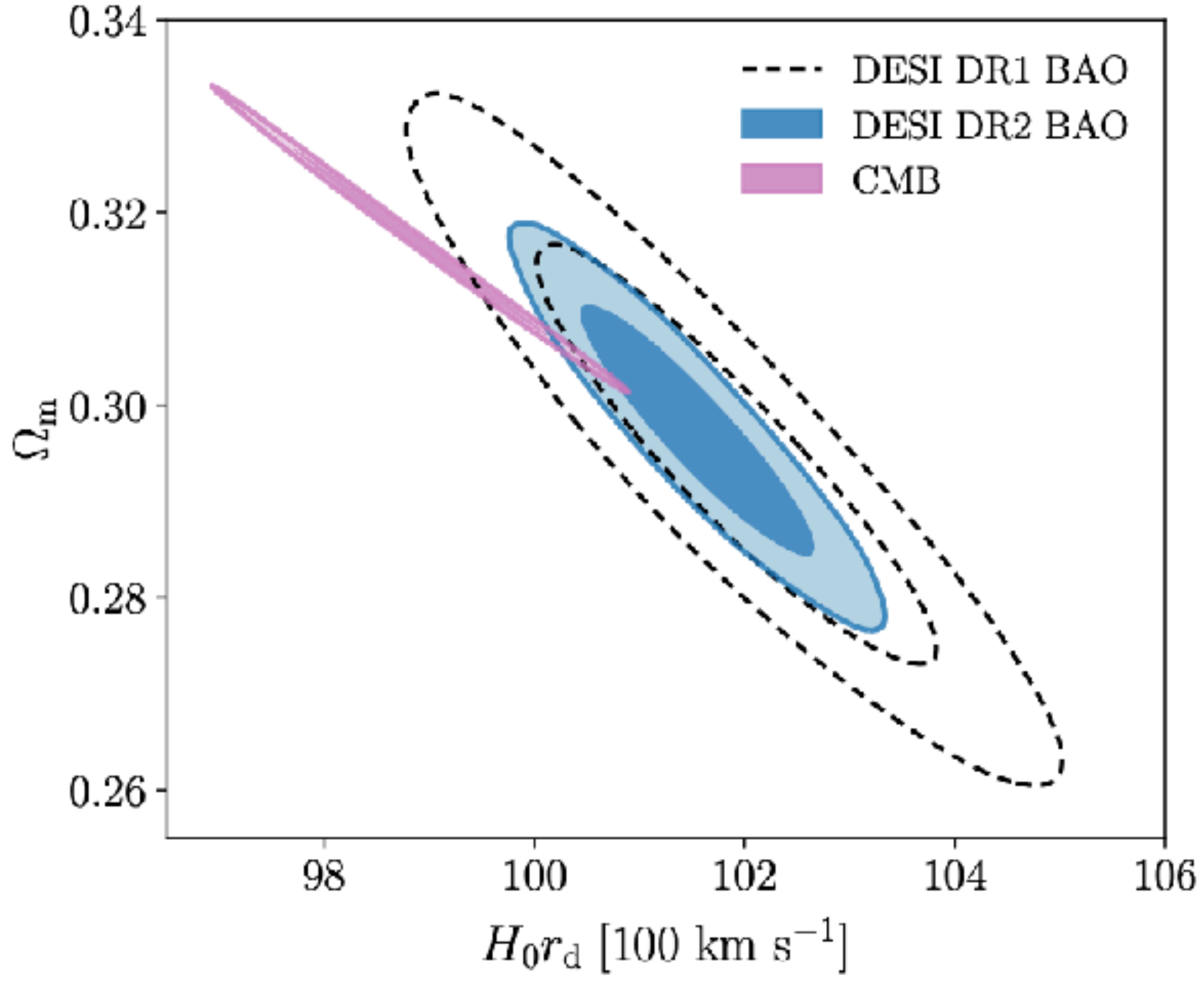


Isotropic BAO Distance
BAO Distance Ratio
Perpendicular BAO Distance
Parallel BAO Distance
$(D_V/r_d)/(D_V/r_d)^{best}$
$(D_M/D_H)/(D_M/D_H)^{best}$
$(D_M/r_d)/(D_M/r_d)^{best}$
$(D_H/r_d)/(D_H/r_d)^{best}$
Planck18 ΛCDM with 1σ
DESI DR2 best-fit ΛCDM
DESI DR2
DESI DR1
Redshift

DESI vs CMB



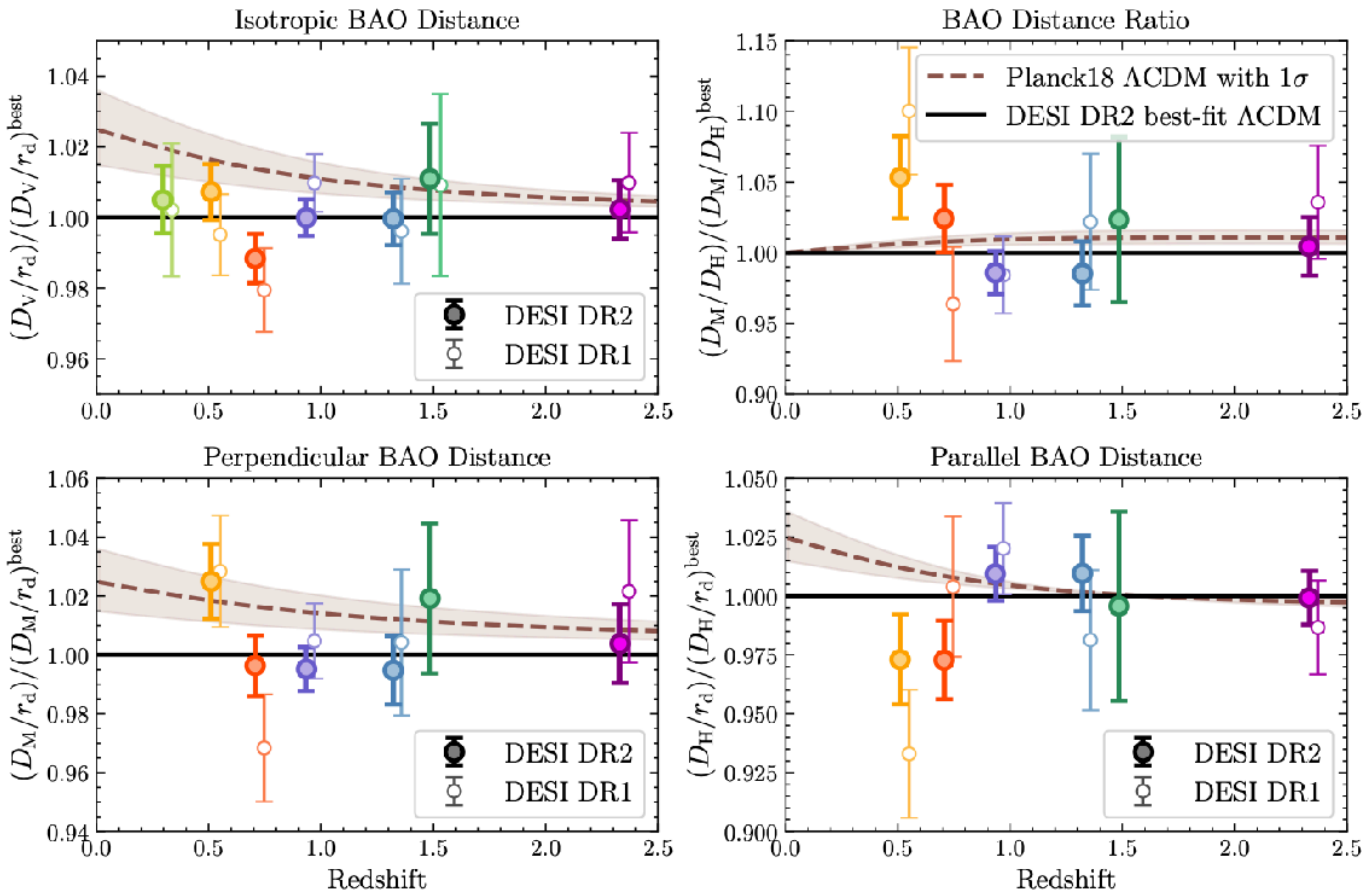
Isotropic BAO Distance
BAO Distance Ratio
Perpendicular BAO Distance
Parallel BAO Distance
$(D_V/r_d)/(D_V/r_d)^{\rm best}$
$(D_M/D_H)/(D_M/D_H)^{\rm best}$
$(D_M/r_d)/(D_M/r_d)^{\rm best}$
$(D_H/r_d)/(D_H/r_d)^{\rm best}$
Planck18 ΛCDM with 1σ
DESI DR2 best-fit ΛCDM
DESI DR2
DESI DR1
Redshift

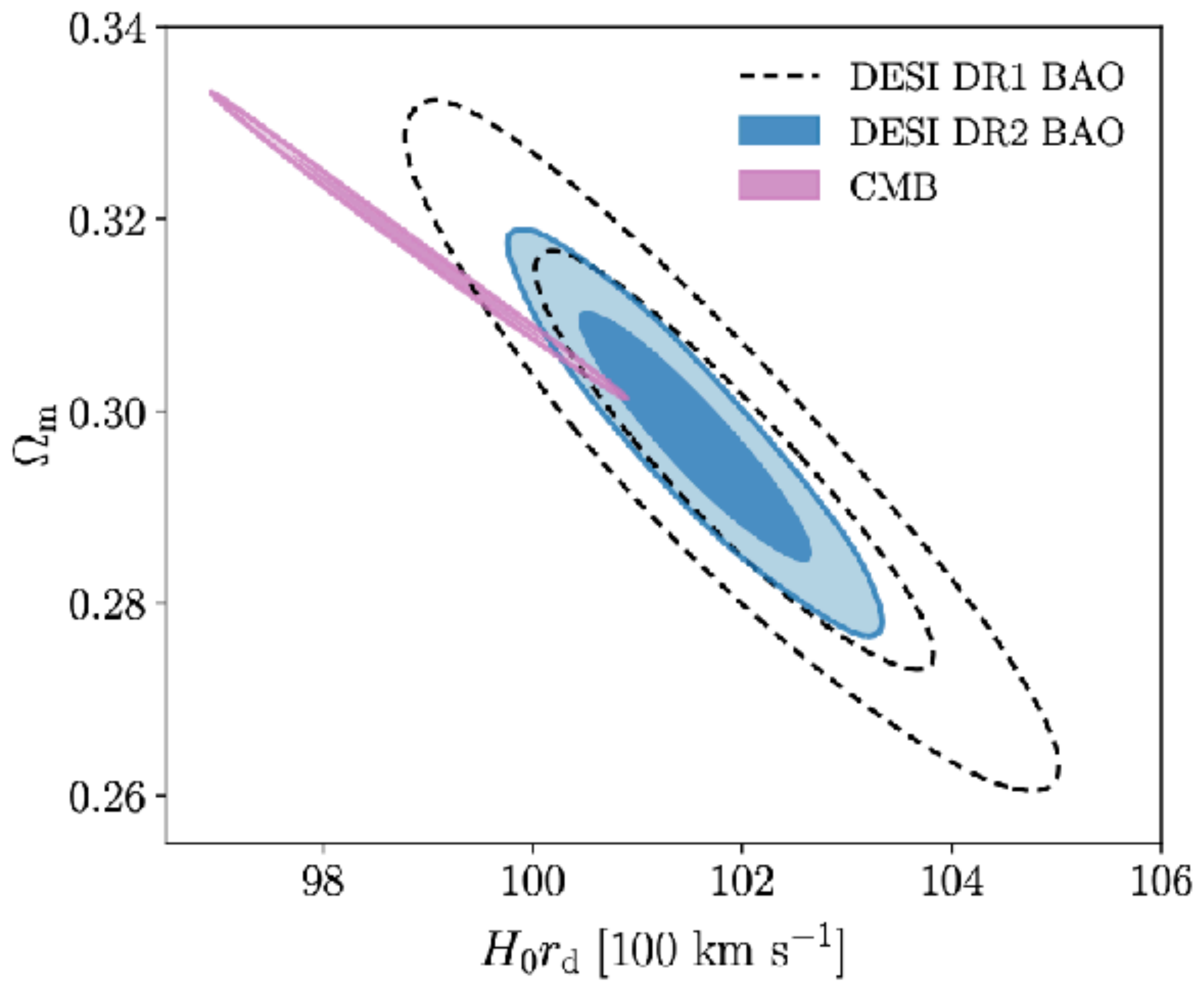


DESI DR1 BAO
DESI DR2 BAO
CMB
Ω_m
$H_0 r_d$ [100 km s^{-1}]

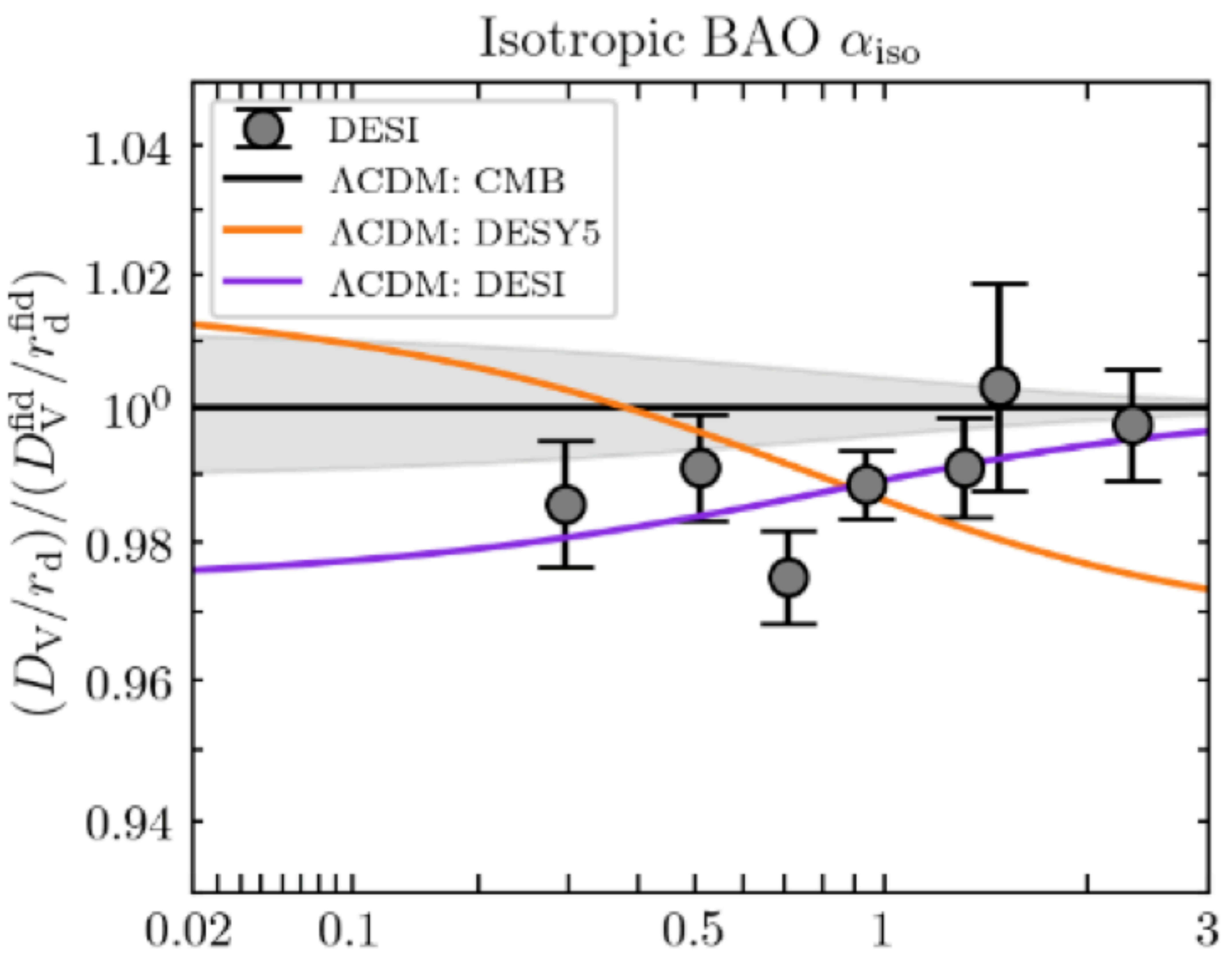
DESI vs CMB

DESI measurements are in 2.3σ tension with CMB predictions for ΛCDM!





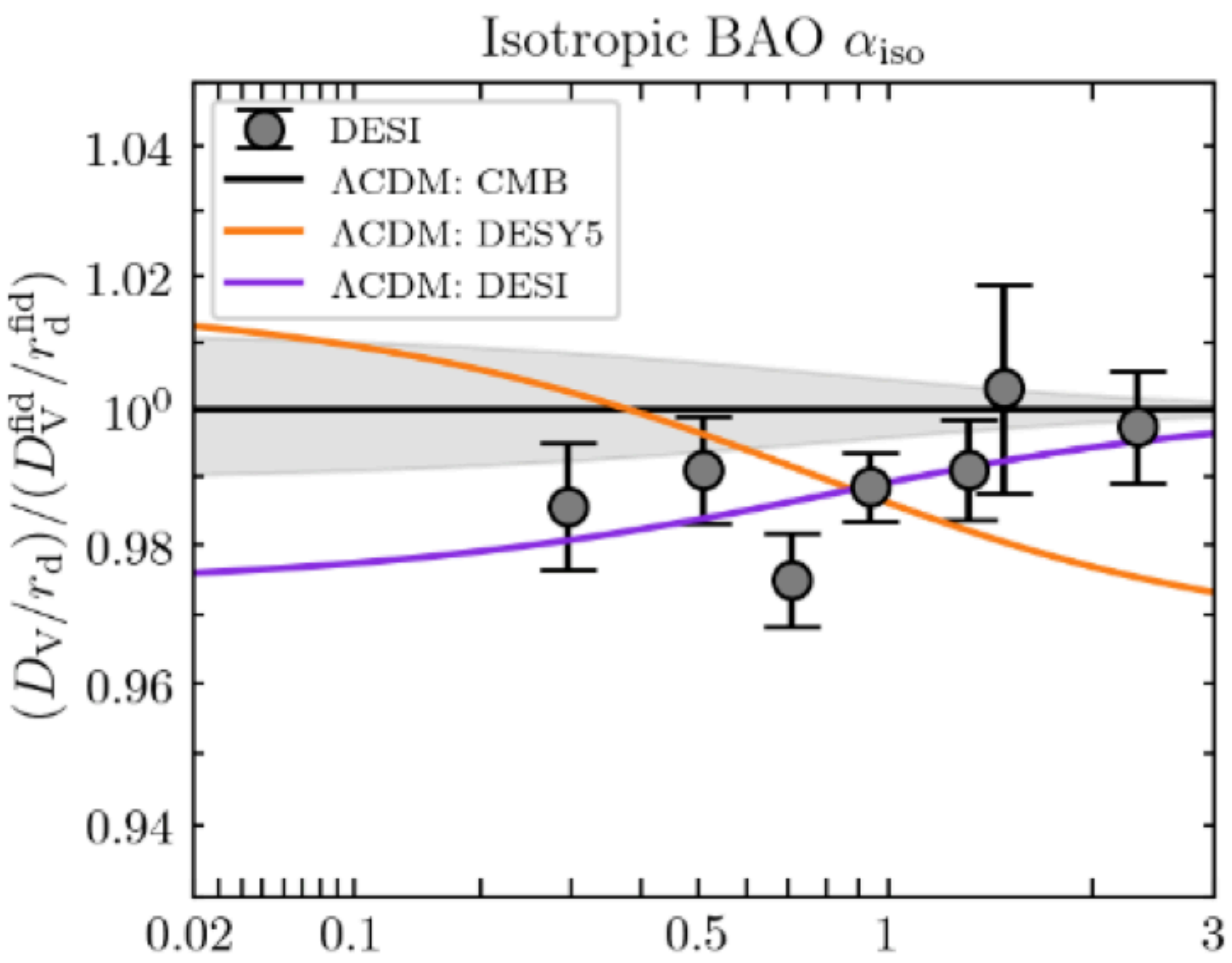
DESI vs Supernovae



Credits: Kyle Dawson

DESI vs Supernovae

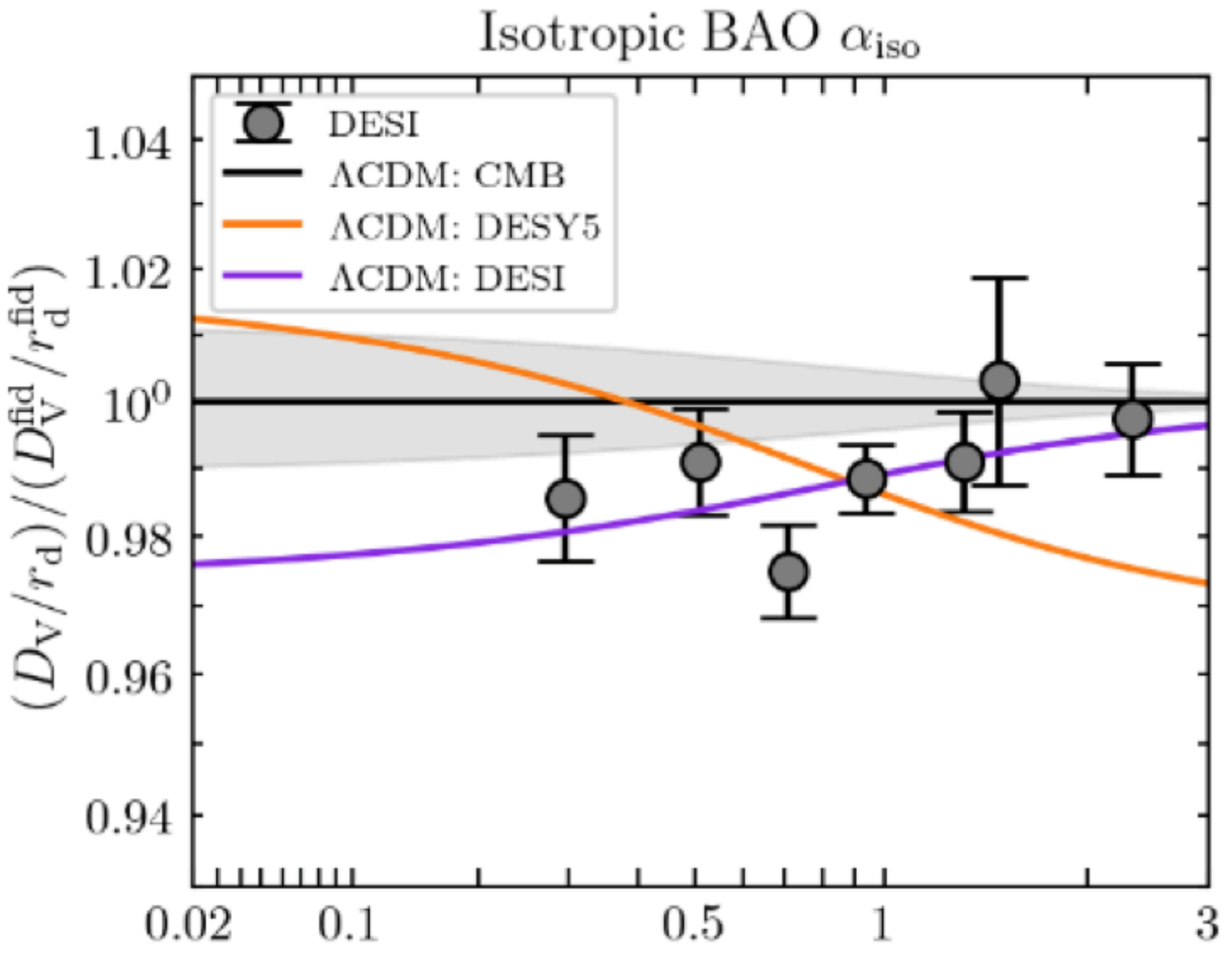
ΛCDM fails to simultaneously fit BAO and SNe distances!

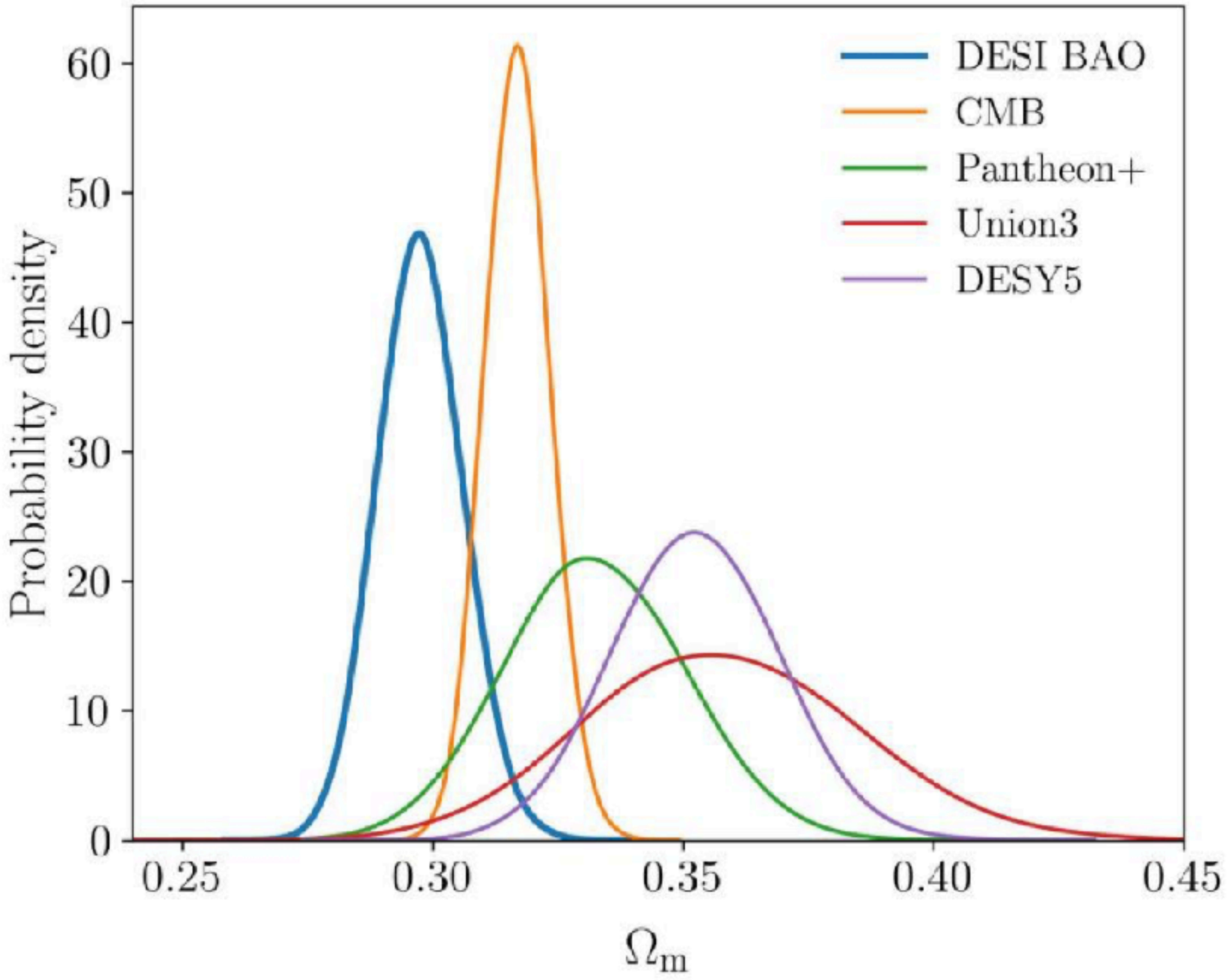


Credits: Kyle Dawson

DESI vs Supernovae

ΛCDM fails to simultaneously fit BAO and SNe distances!





Credits: Kyle Dawson

Evidence for evolving dark energy

At low redshift, distance-redshift relation relies on

$$\frac{H^2(z)}{H_0^2} \approx \Omega_m(1+z)^3 + (1-\Omega_m)$$

As observed cosmological distances points to a departure from the ΛCDM paradigm, a natural and possible solution arise when considering a time-evolving dark energy.

$$\frac{H^2(z)}{H_0^2} \approx \Omega_m(1+z)^3 + \Omega_{de}\frac{\rho_{de}(z)}{\rho_{de,0}}$$

$$\frac{\rho_{de}(z)}{\rho_{de,0}} = \exp\left[3\int_0^z [1+w(z')]\frac{dz'}{(1+z')}\right]$$

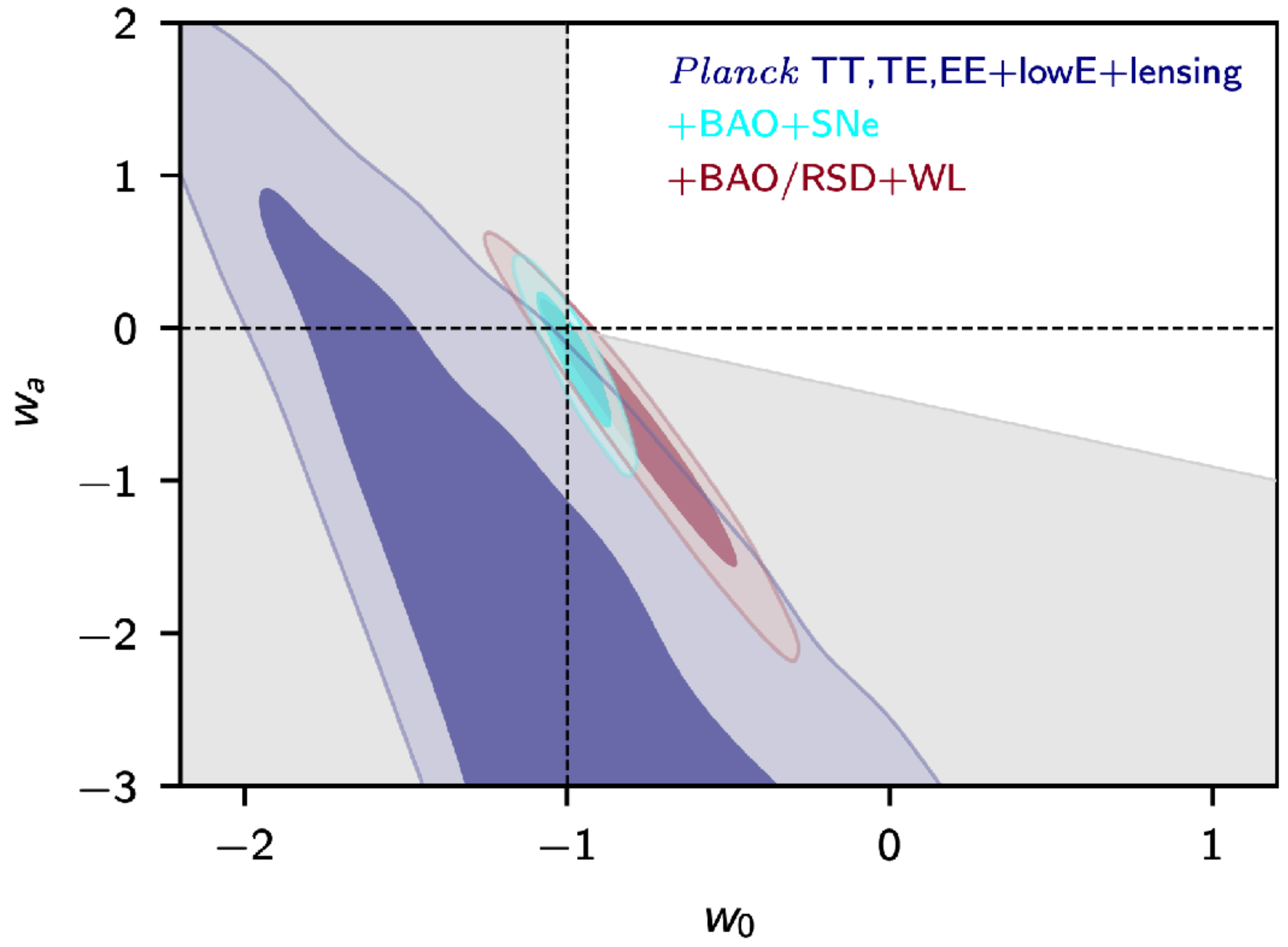
DESI analysis adopts the so-called CPL parametrization, for which $w(z) = w_0 + w_a\frac{z}{(1+z)}$

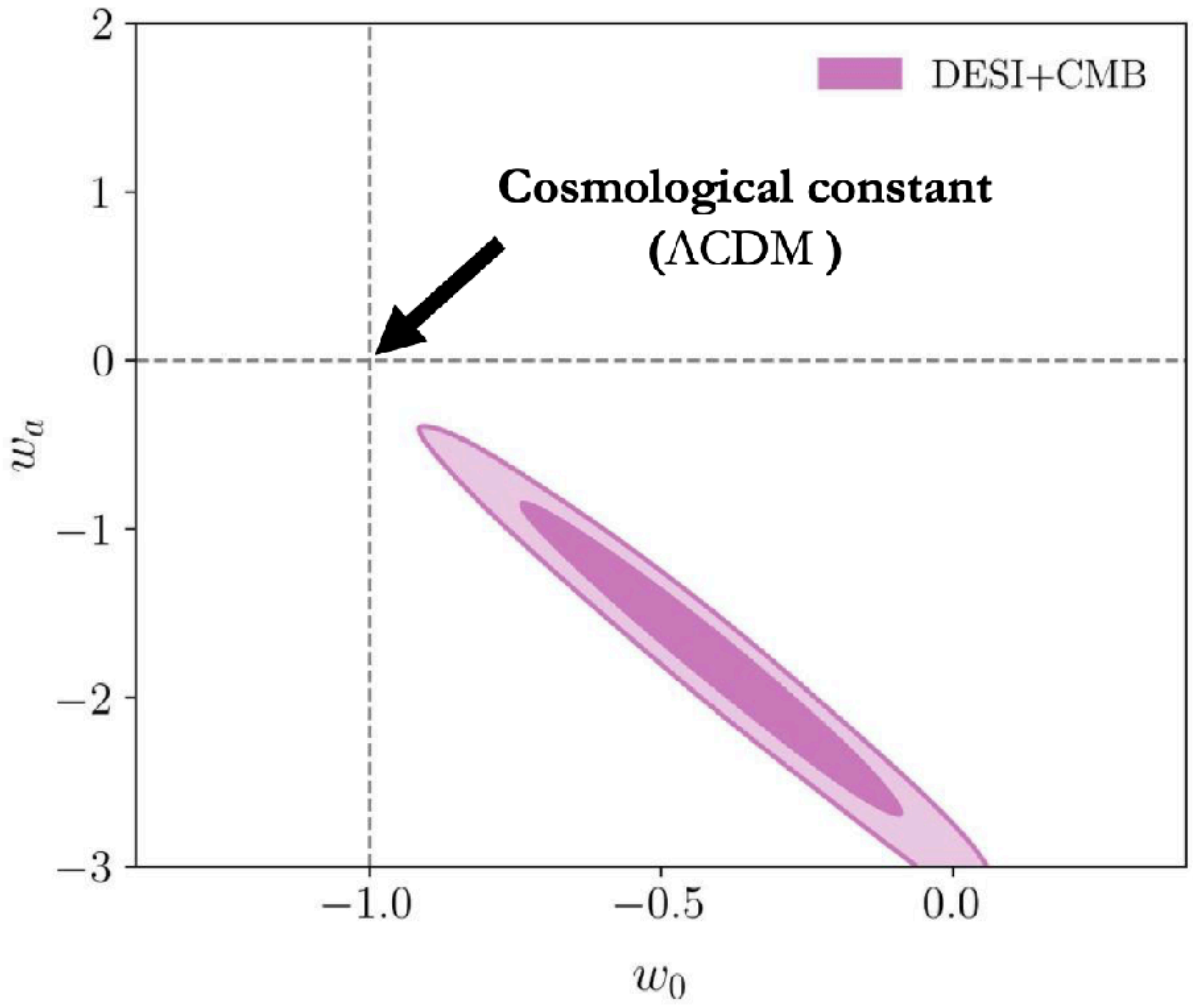
Evidence for evolving dark energy

Credits: Kyle Dawson

3.1σ preference for evolving dark energy from when adding CMB to DESI BAO

$$\left.\begin{aligned} w_0 &= -0.42 \pm 0.21 \\ w_a &= -1.75 \pm 0.58 \end{aligned}\right\} \text{DESI+CMB}$$





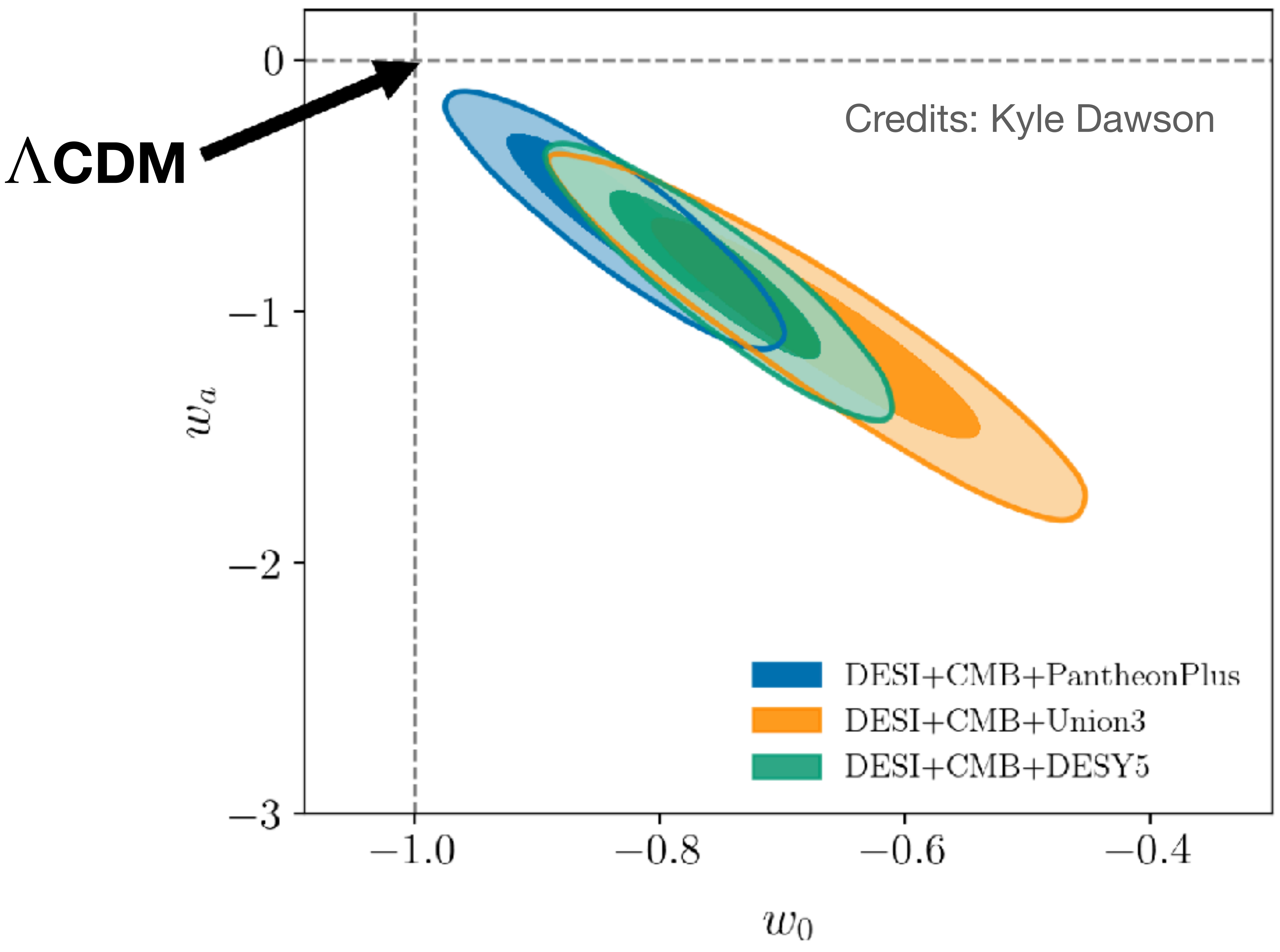
Dynamical DE restore consistency between BAO and CMB!

Evidence for evolving dark energy

Preference for evolving dark energy increases (or even decreases) when adding SNe to CMB and DESI BAO

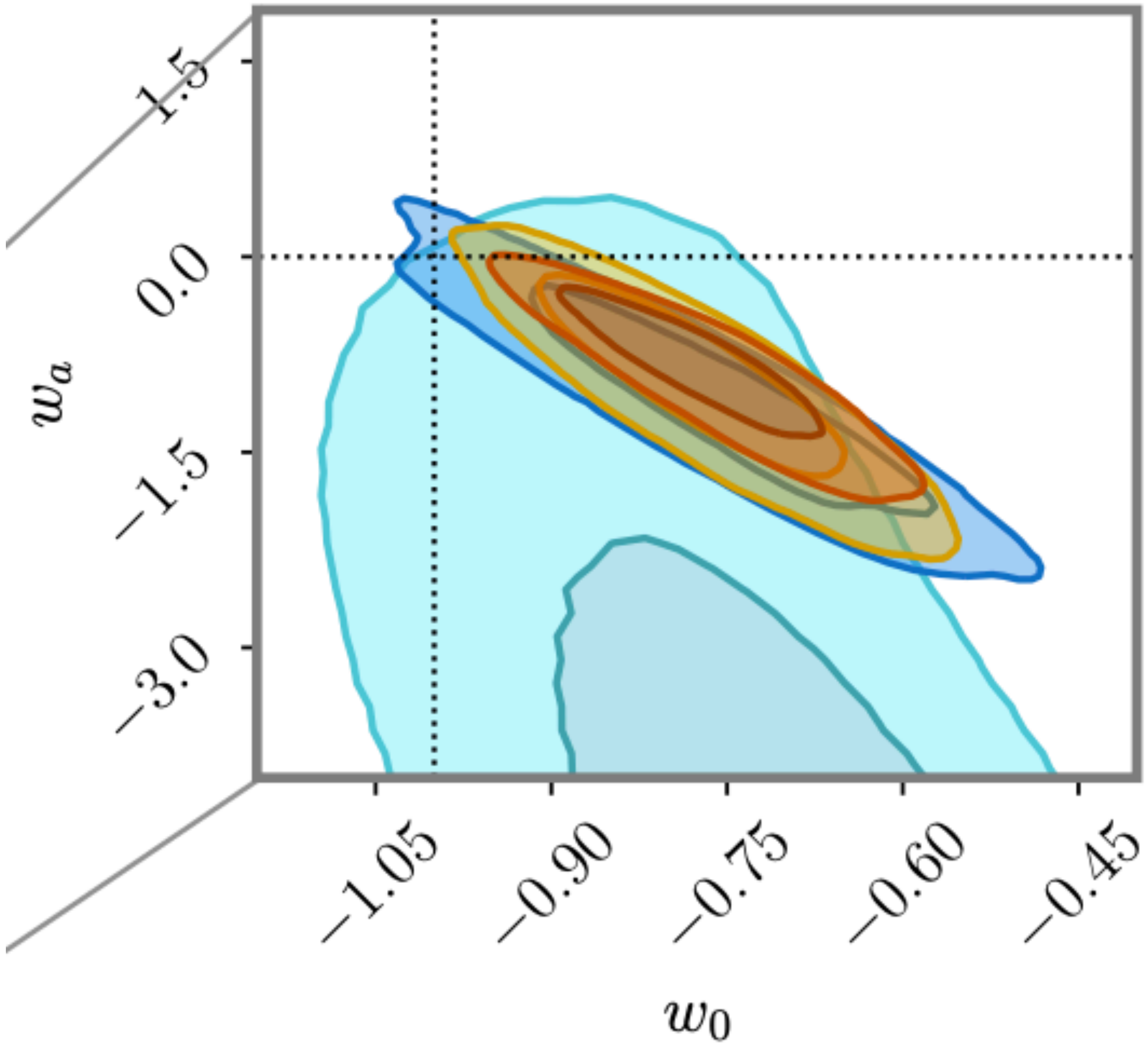
- **DESI+CMB+Pantheon+: 2.8σ**
- **DESI+CMB+Union3: 3.8σ**
- **DESI+CMB+DESY5: 4.2σ**

Significance varies with SNe analysis methodology

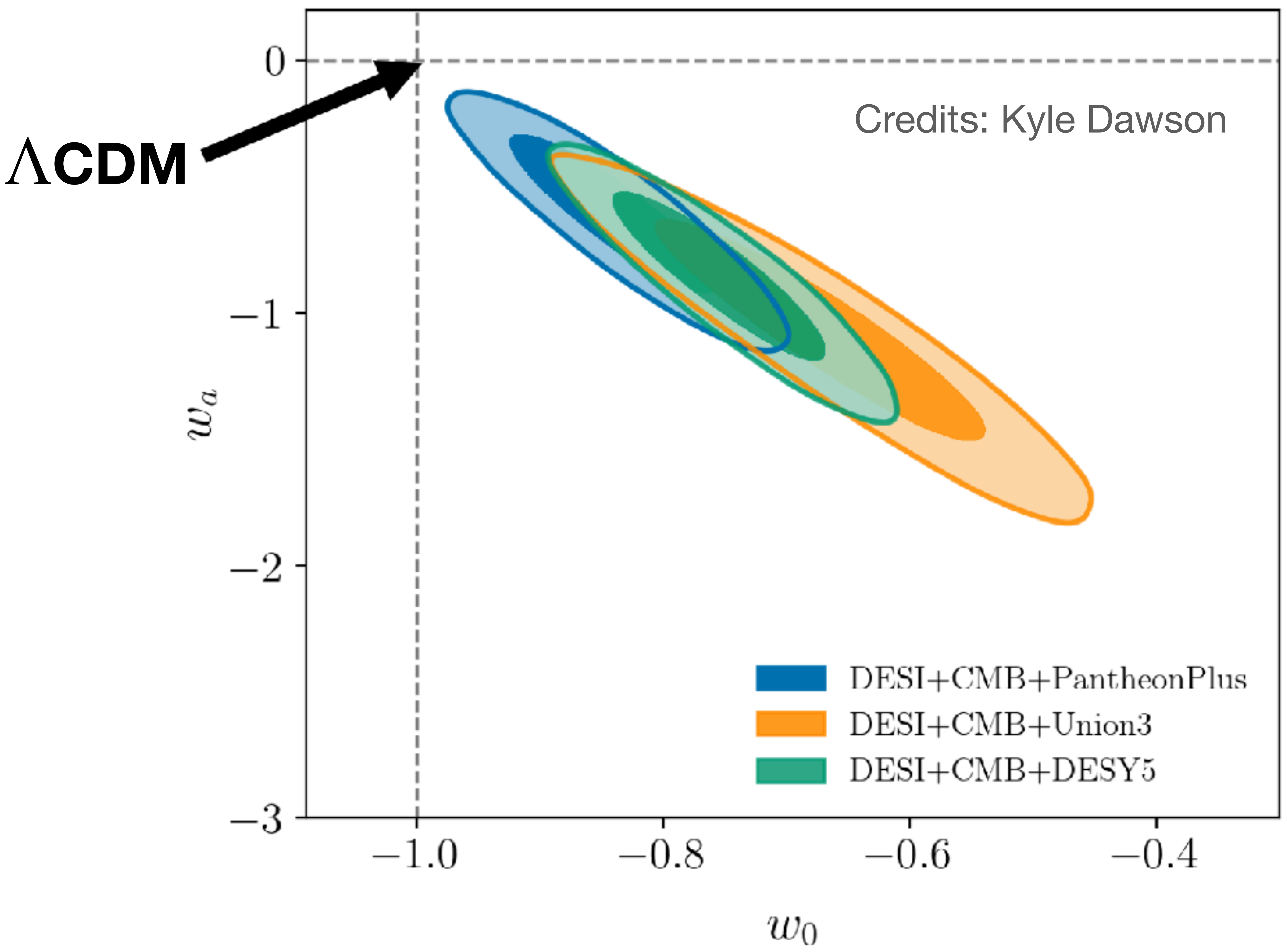


Evidence for evolving dark energy

Dynamical DE arises consistent with both SNe and BAO distances!



DES collaboration, arXiv:2401.02929



Evidence for evolving dark energy

Time-evolving dark energy offers flexibility to simultaneously achieve good fits to all three datasets!