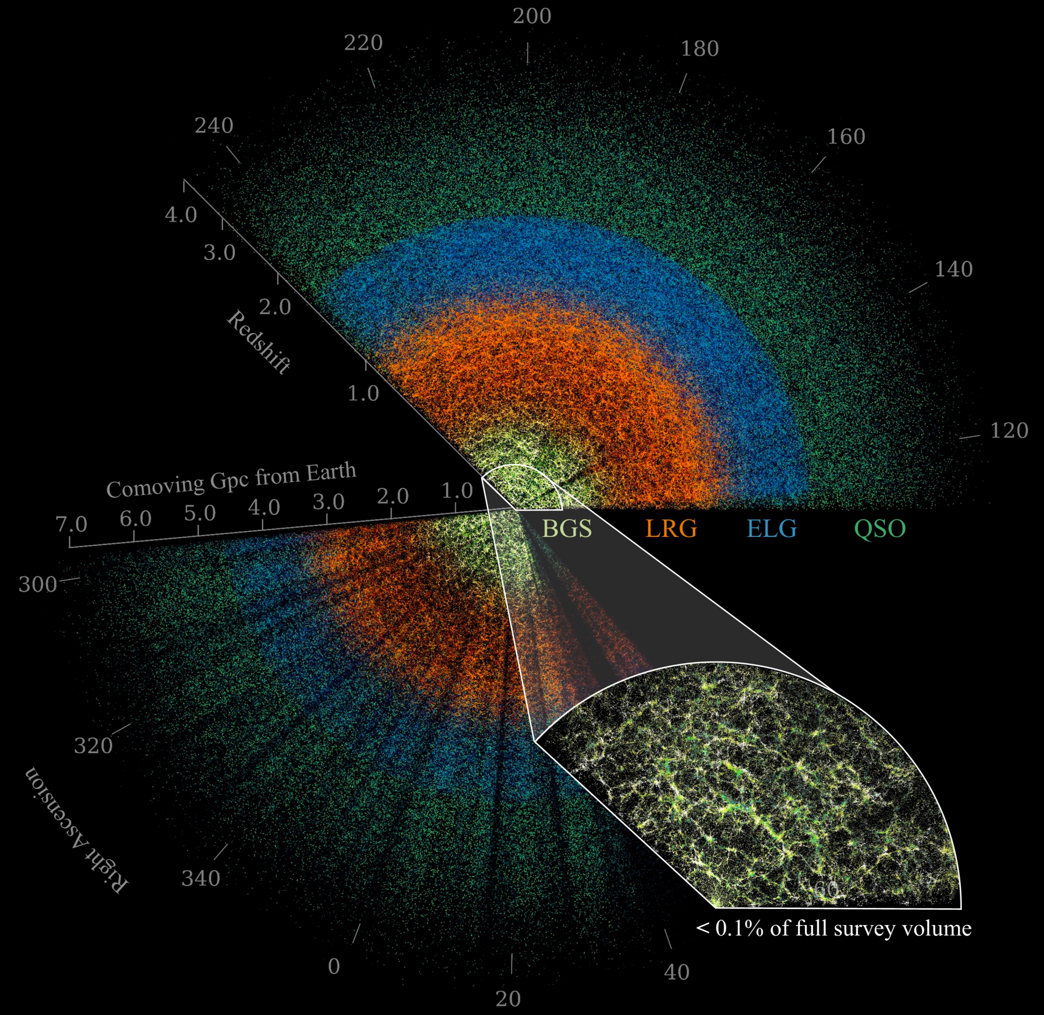
What's the deal with dark energy?

New results from the Dark Energy Spectroscopic Instrument



Chris Blake (Swinburne)

In the news recently …

LE GOÛT DE M
ÉVASION AU JAPON
SUPPLÉMENT

Le Monde

ALGÉRIE, UN « CRIME D'ÉTAT »
DANS LES SECRETS DU FLN

STEPHEN KING
DOUZE NOUVELLES AU NOIR

Supplément
LE MONDE DES LIVRES

VENDREDI 21 MARS 2025 • 81E ANNÉE • Nº 24951 • 3,80 € • FRANCE MÉTROPOLITAINE • WWW.LEMONDE.FR
FONDATEUR : HUBERT BEUVE-MÉRY • DIRECTEUR : JÉRÔME FENOGLIO

Comment l'Europe entend se réarmer en cinq ans

► Les chefs d'Etat et de gouvernement des Vingt-Sept devaient à nouveau échanger sur la défense européenne, jeudi 20 mars, à Bruxelles

► Mercredi, la Commission a dévoilé une note d'intention intitulée « Etre prêt en 2030 », qui détaille les menaces et les moyens pour y répondre

► Bruxelles se propose de faciliter le financement de l'effort de défense par les Etats et de favoriser la réorganisation d'un marché européen fragmenté

► Lors d'un entretien téléphonique, mercredi, Donald Trump et Volodymyr Zelensky se sont accordés sur le principe d'un cessez-le-feu partiel

► La Maison Blanche a infléchi sa position sur les armes et les enfants enlevés, et exprimé des vues sur les actifs énergétiques

PAGES 3 ET 4, ET CHRONIQUE PAGE 27

Economie
Etats-Unis : la Fed anticipe un ralentissement
Les turbulences du début de mandat de Trump amènent la Réserve fédérale à revoir ses prévisions
P. 5, 14 ET TRIBUNE P. 24

Politique
Port du voile dans le sport : vers une interdiction légale
Sous la pression des ministres de l'intérieur et de la justice, l'exécutif soutient un texte sénatorial
PAGE 8

Gaza
L'armée israélienne s'engage au sol
Après la reprise des bombardements, mardi, Israël a réinvesti en partie le corridor de Netzarim
PAGE 6 ET ANALYSE PAGE 26

EXPANSION DE L'UNIVERS
UNE NOUVELLE CARTE DES GALAXIES BOUSCULE LES THÉORIES
Une collaboration internationale de 900 chercheurs constate que la dynamique de l'Univers n'est pas conforme aux prédictions
PAGE 7

La plus grande carte, à ce jour, de l'Univers, diffusée le 19 mars, où chaque point est une galaxie.
COLLABORATION DESI ET KPNO/NOIRLAB/NSF/AURA/R. PROCTOR

Retraites
La CGT se retire de la négociation
L'INCERTITUDE sur l'issue des discussions entre partenaires sociaux sur les retraites est montée d'un cran, mercredi 19 mars, avec l'annonce de la défection de la CGT, qui s'ajoute à celles de Force ouvrière et de l'Union des entreprises de proximité. Pour la secrétaire générale de la confédération, Sophie Binet, François Bayrou a *« trahi sa parole »* en fermant la porte, dimanche, à une baisse de l'âge légal de départ. Les cinq organisations restantes devaient se retrouver, jeudi, pour échanger sur la suite de ce « conclave ».
PAGES 8-9

ÉDITORIAL
LUTTER CONTRE LE NARCOTRAFIC, UN ENJEU VITAL POUR L'ÉTAT DE DROIT
PAGE 27

Russie
Après la fin des aides américaines, l'inquiétude des médias en exil
PAGES 2-3

Tribunes
La conquête coloniale de l'Algérie au regard des historiens
PAGE 25

Covid-19
La pandémie a transformé nos habitudes de consommation
Cinq ans après, la montée en puissance de la vente en ligne s'est confirmée. Dans le tourisme, les activités associées au plein air demeurent appréciées
PAGES 16-17

Etats-Unis
Huntington Beach, laboratoire des MAGA
Capitale du surf, cette cité balnéaire de Californie vit sous tension depuis l'élection d'un conseil municipal 100 % républicain
PAGE 18

Allemagne 4,80 €, Andorre 4,30 €, Autriche 4,50 €, Belgique 4,00 €, Espagne 4,30 €, Grèce 4,20 €, Guadeloupe-Martinique 4,00 €, Italie 4,20 €, Luxembourg 4,20 €, Maroc 32 DH, Pays-Bas 4,60 €, Portugal cont. 4,30 €, La Réunion 4,00 €, Sénégal 2 500 F CFA, Suisse 4,80 CHF, Tunisie 7,10 DT

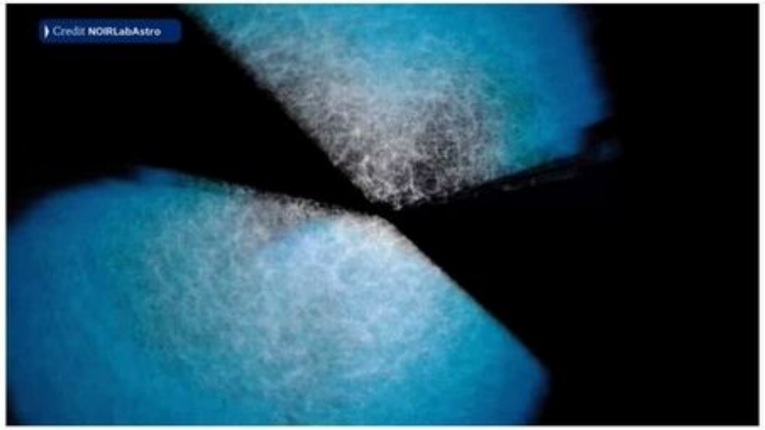
ABC NEWS

SHARE

Largest 3D map of the universe hints dark energy is becoming weaker, challenging models of the cosmos

ABC Science / By Ellen Phiddian

Posted 19h ago



An international research collaboration is creating a 3D map of the universe to see how galaxies have spread and clustered over 11 billion years. Earth is at the centre of the image, and each point in the map is a galaxy.

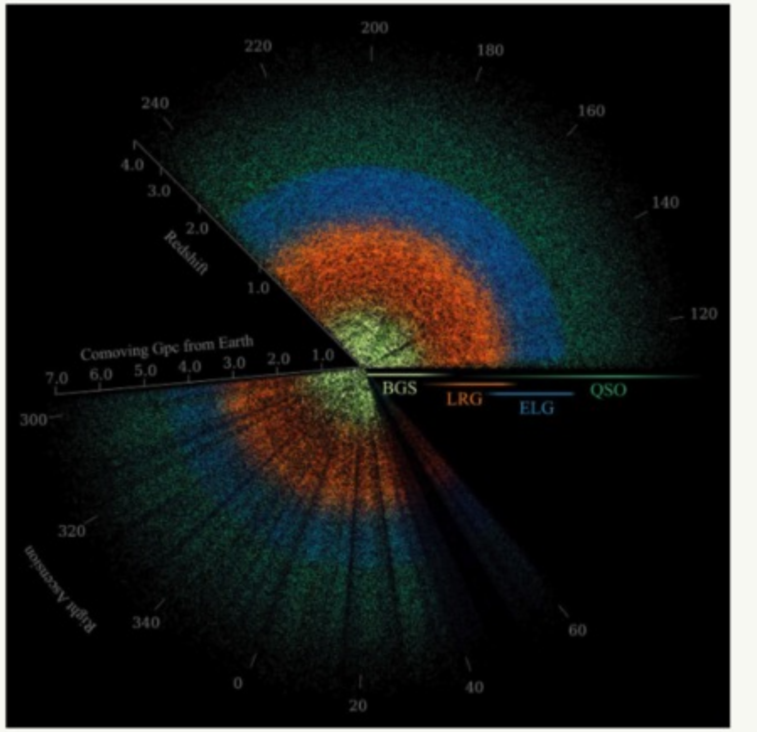
作者：甘晓 来源：中国科学报 发布时间：2025/3/21 18:07:47　　选择字号：小 中 大

全球最大宇宙三维地图发布

国家天文台深度参与

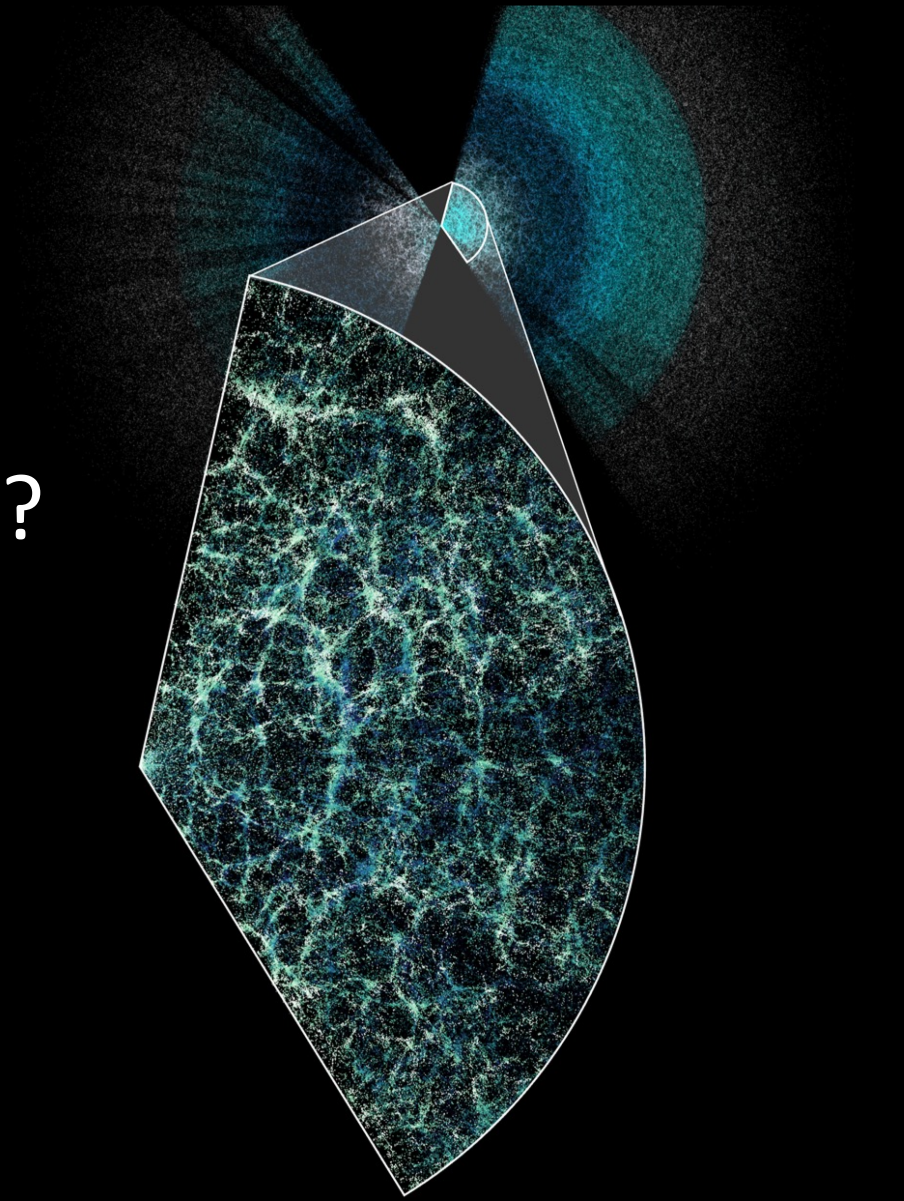
北京时间2025年3月20日，在美国物理学会年会上，由全球70多个科研机构共同组建的暗能量光谱巡天（DESI）合作组向全球发布了关于暗能量的最新研究成果，并同步公开了该项目首年的光谱数据。根据合作组的研究，他们运用前三年收集的数据，结合其他巡天信息，发现暗能量对宇宙膨胀的影响可能随着时间的推移而减弱，这一发现表明有可能存在超出现行宇宙标准模型的新物理。

在此次发布中，DESI合作组还向全球公开了首年观测数据，构建迄今最大的宇宙三维地图，该数据集包含了近1870万个星系、类星体和恒星的信息。其中河外天体数量也是此前所有光谱巡天项目的总和的两倍以上。



Talk outline

- What is DESI?
- Why do we think dark energy exists?
- How does DESI measure dark energy?
- The physics of dark energy
- DESI results
- What does it all mean?



What is DESI*?

*The Dark Energy Spectroscopic Instrument

What is DESI? *(Dark Energy Spectroscopic Instrument)*

A spectroscopic instrument at the Mayall Telescope (Kitt Peak) which can position 5000 optical fibres across an 8 deg^2 field-of-view in $\sim$1 minute

An international collaboration which is conducting a large spectroscopic survey using this instrument between 2021 and 2026 *(... now 4 years in!)*

Our amazing DESI team at Swinburne!

Ryan Turner

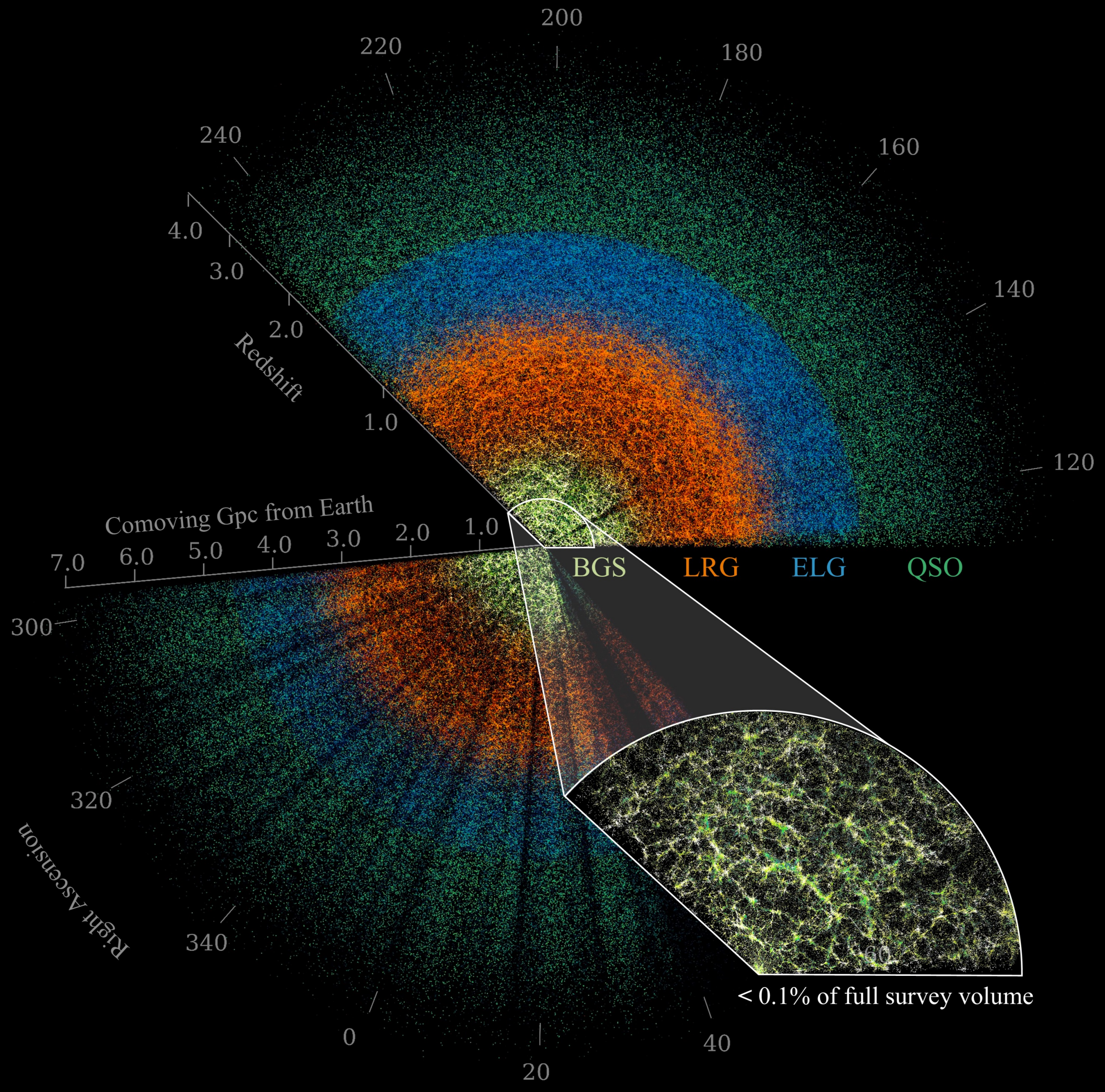
Agne Semenaite

Nimas

Andy Nguyen

Sera Rauhut

What is the DESI survey?



A spectroscopic survey of $14{,}000 \text{ deg}^2$ which plans to measure $\approx$ 60 million redshifts

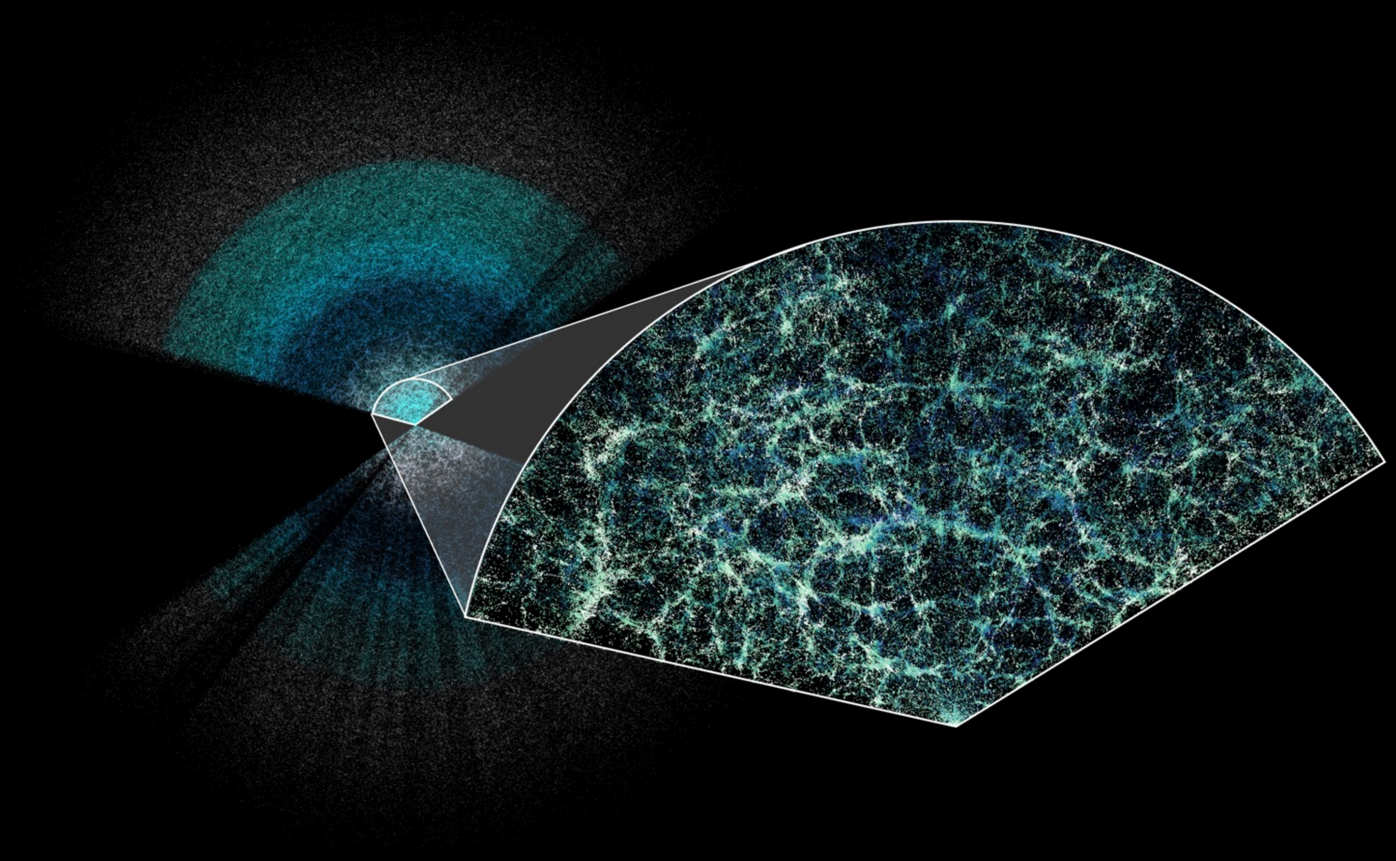
Extragalactic component includes:

- Bright Galaxies (BGS)
- Luminous Red Galaxies (LRG)
- Emission-Line Galaxies (ELG)
- Quasars (QSO)

across redshifts $z < 4$, selected from photometric imaging surveys

What is the science goal of DESI?

Use the large-scale structure of the Universe to test cosmological models for the expansion of the Universe and the growth of cosmic structure



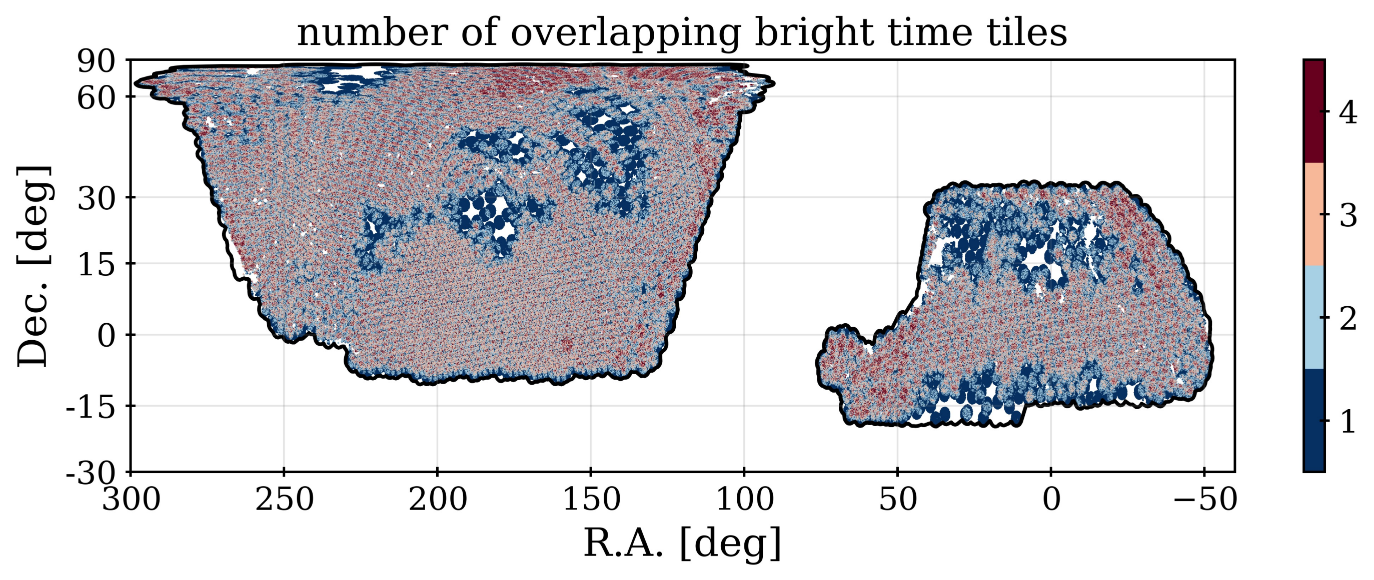
- **Baryon acoustic oscillations**
- Redshift-space distortions
- Galaxy peculiar velocities
- Weak lensing cross-correlations
- CMB cross-correlations

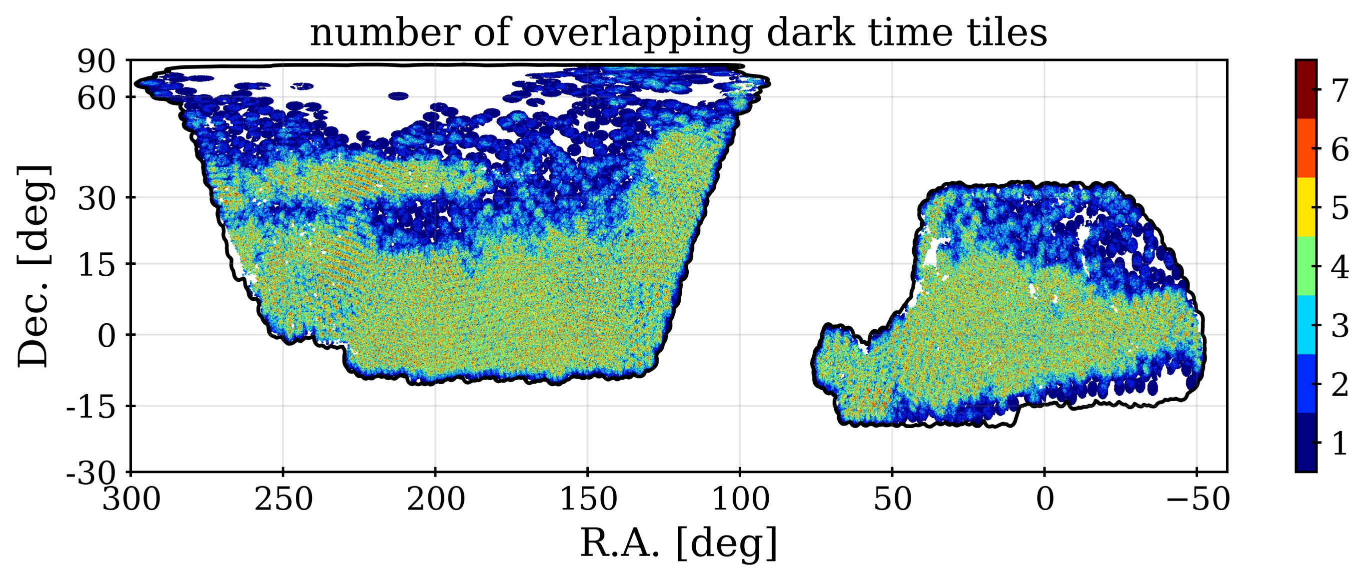
DESI survey coverage

DESI has already observed ≈ 10,000 deg^2 above Dec $= -30°$

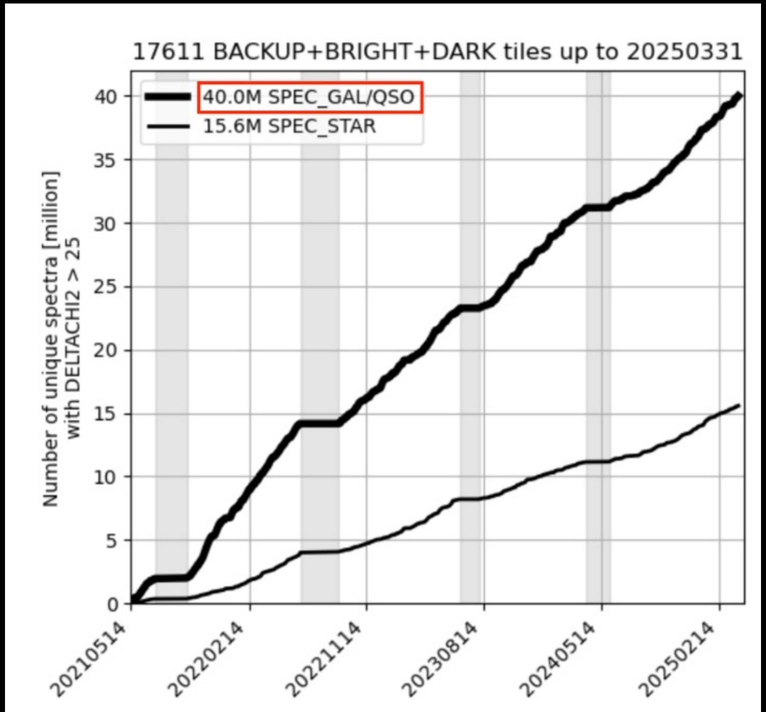
DESI Data Release 1 is publicly available, containing ≈ 20 million redshifts up to and including Year 1 of the survey

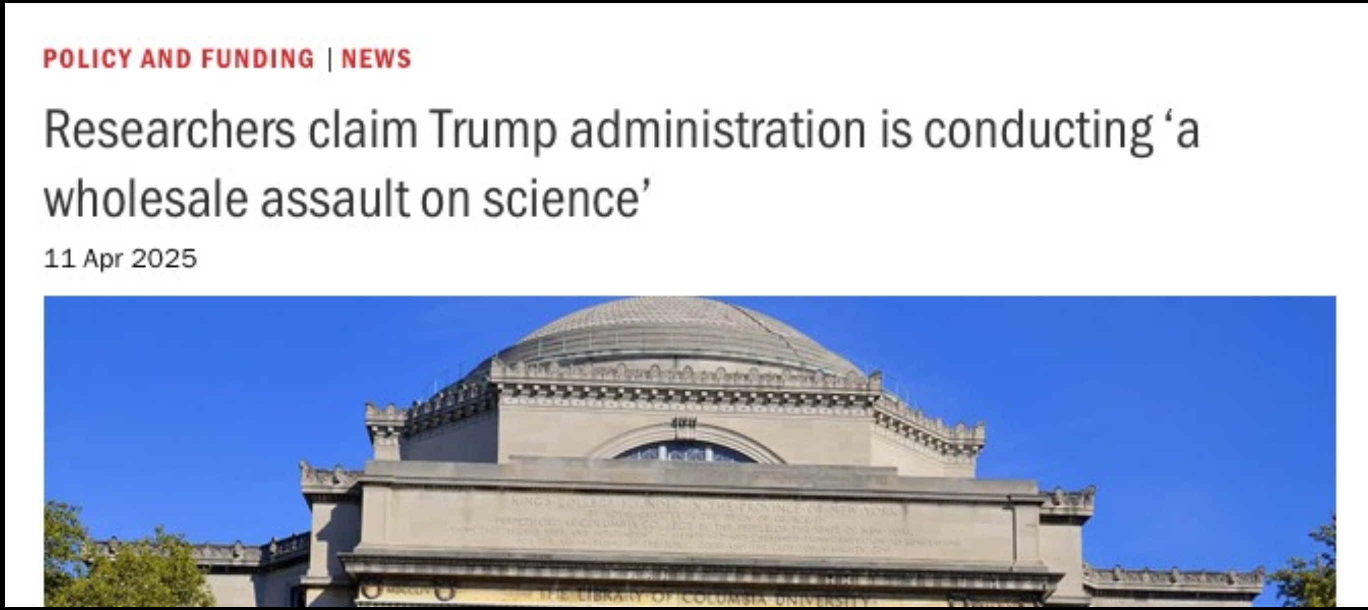
Today I'm going to show you results from the latest DESI samples up to and including Year 3 of the survey





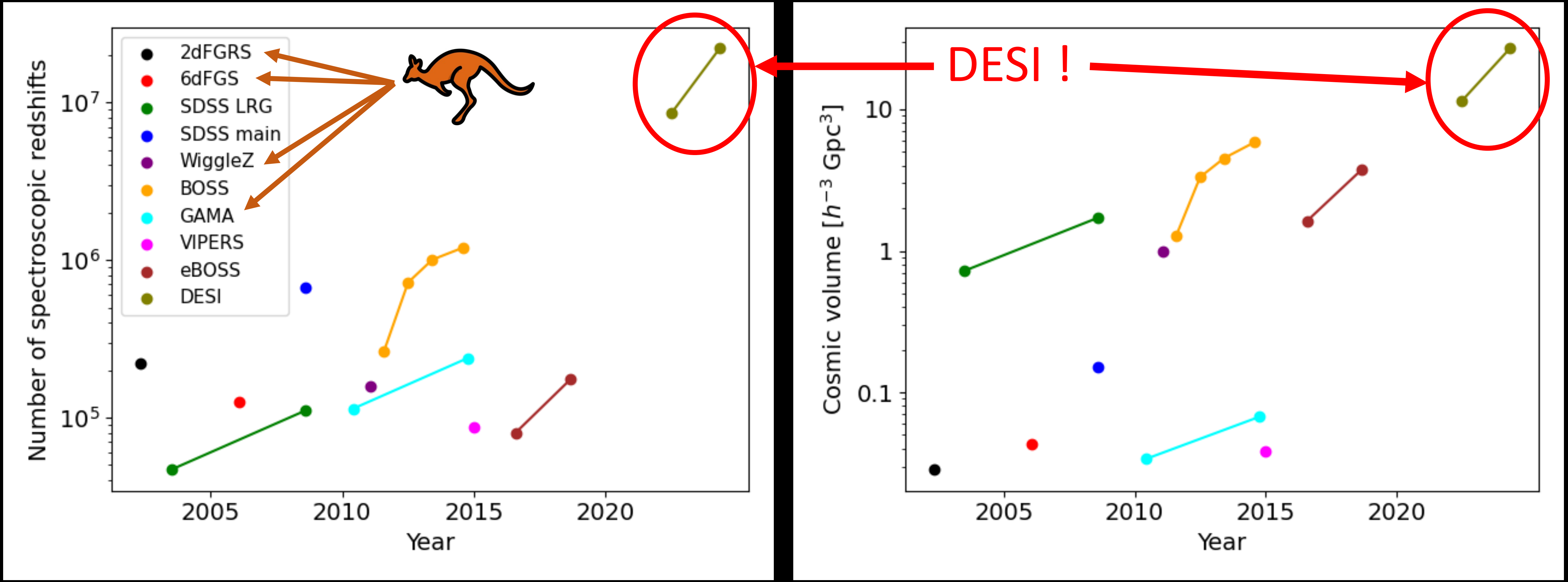
Progress has been amazing, all things considered!





Brief history of spec-z surveys

DESI has assembled the largest sample of extragalactic redshifts, exceeding previous surveys by an order of magnitude in number and cosmic volume



Why do we think dark energy exists?

Why do we think dark energy exists?

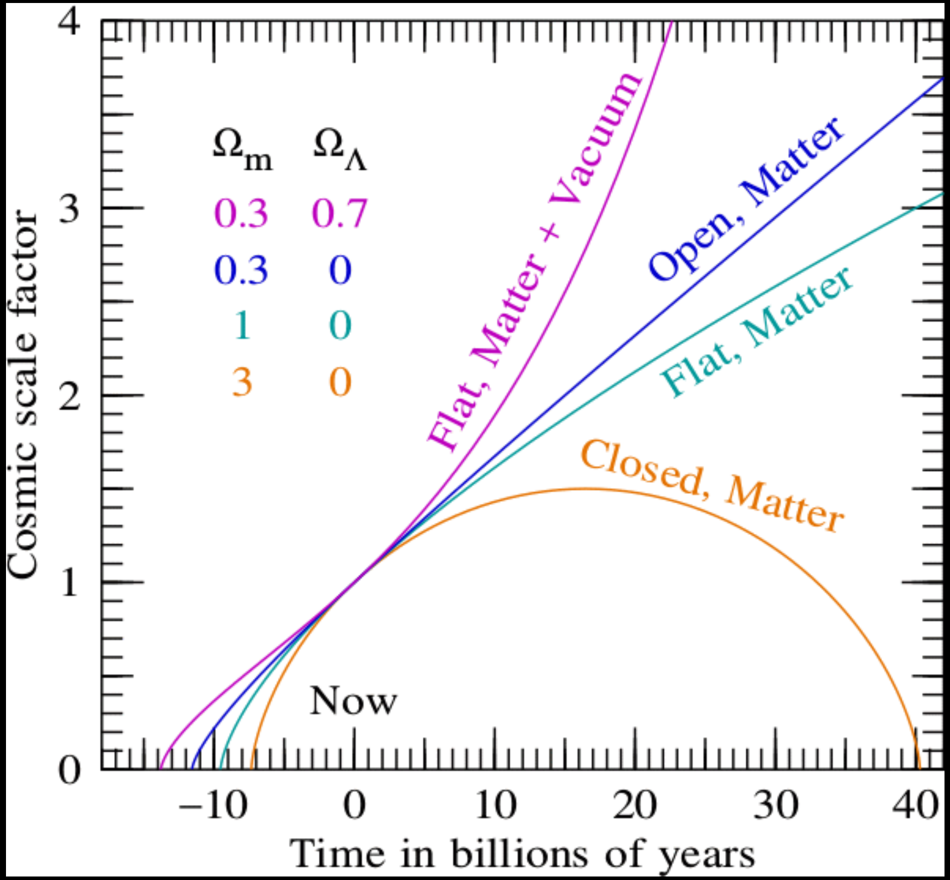
Cosmology class 1: the contents of the Universe determine its expansion!

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2 = \frac{8\pi G\rho(t)}{3}$$

Expansion of the Universe as described by scale factor $a(t)$

Hubble parameter $H(t)$

Contents of the Universe as described by density $\rho(t)$



Why do we think dark energy exists?

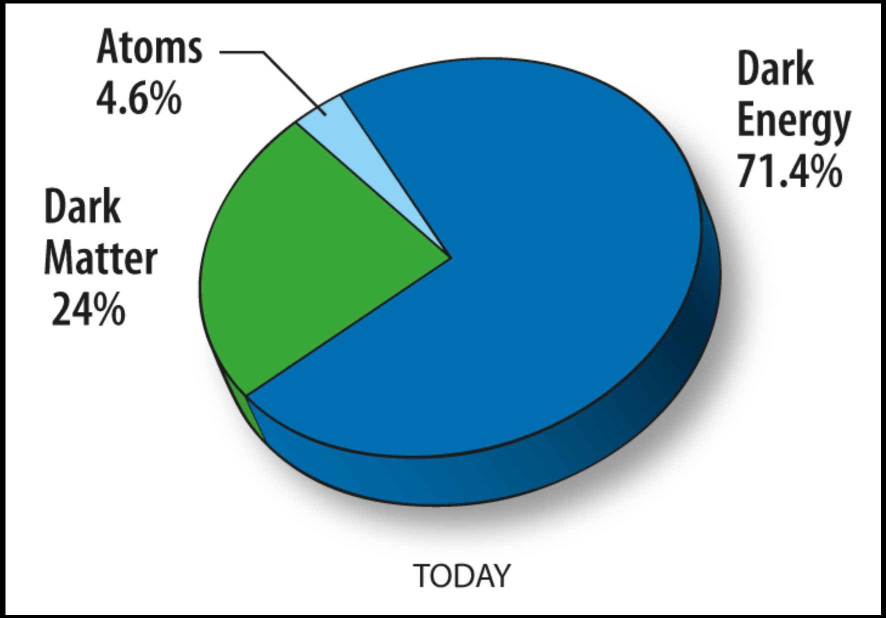
Cosmology class 2: the expansion determines the distance-redshift relation!

$$r(z) = \int_0^z \frac{c\, dz'}{H(z')}$$

Comoving radial coordinate of a source with redshift z

Integral of the Hubble parameter over the light path

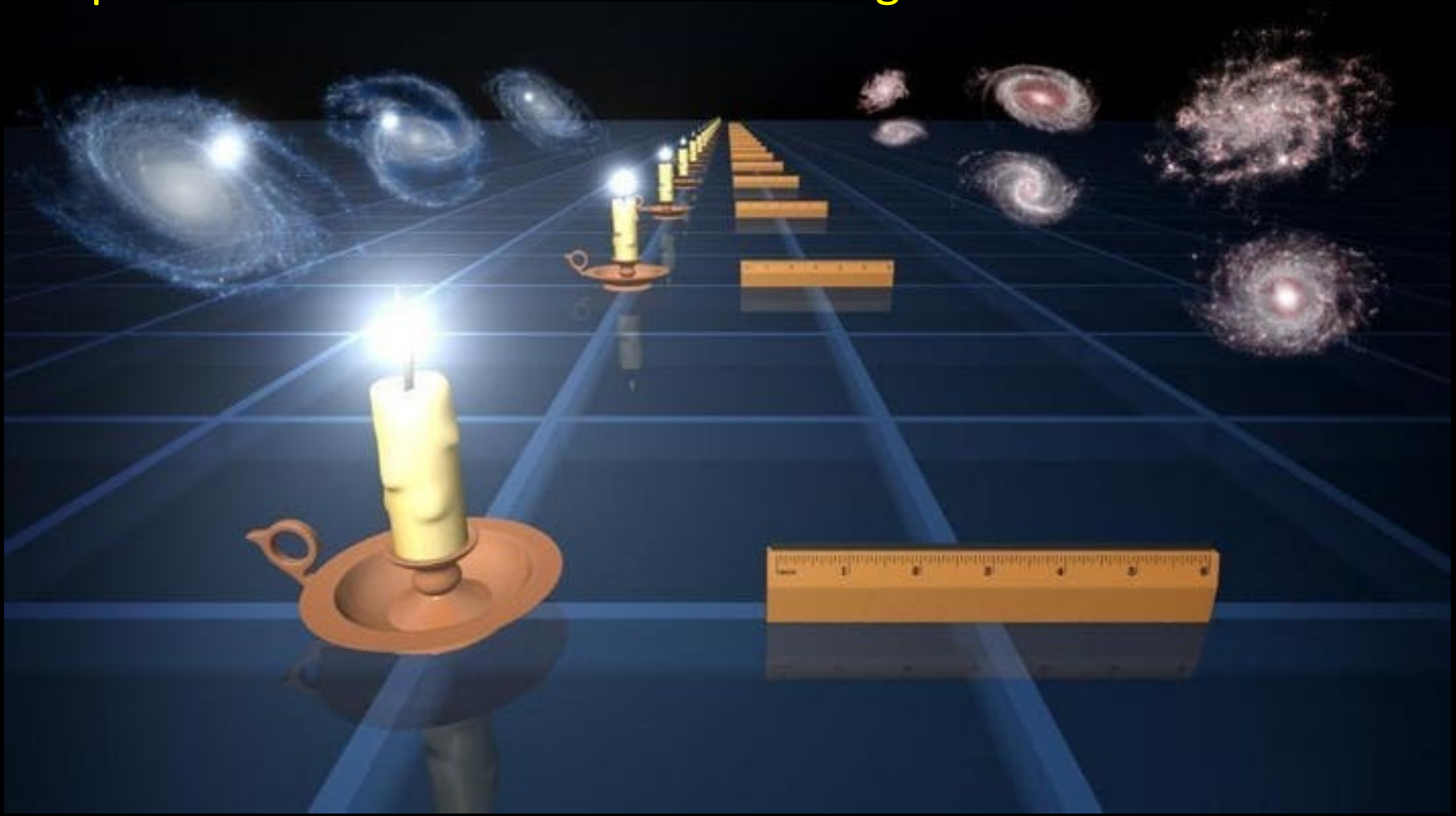
Mapping the distance-redshift relation measures the contents!



Cosmological observations cannot be described by applying General Relativity to a homogeneous and isotropic Universe containing only matter

Why do we think dark energy exists?

We map the distance-redshift relation using standard candles and rulers!



So, what could dark energy be?

Our leading model for dark energy is the **cosmological constant Λ** *(constant density)*

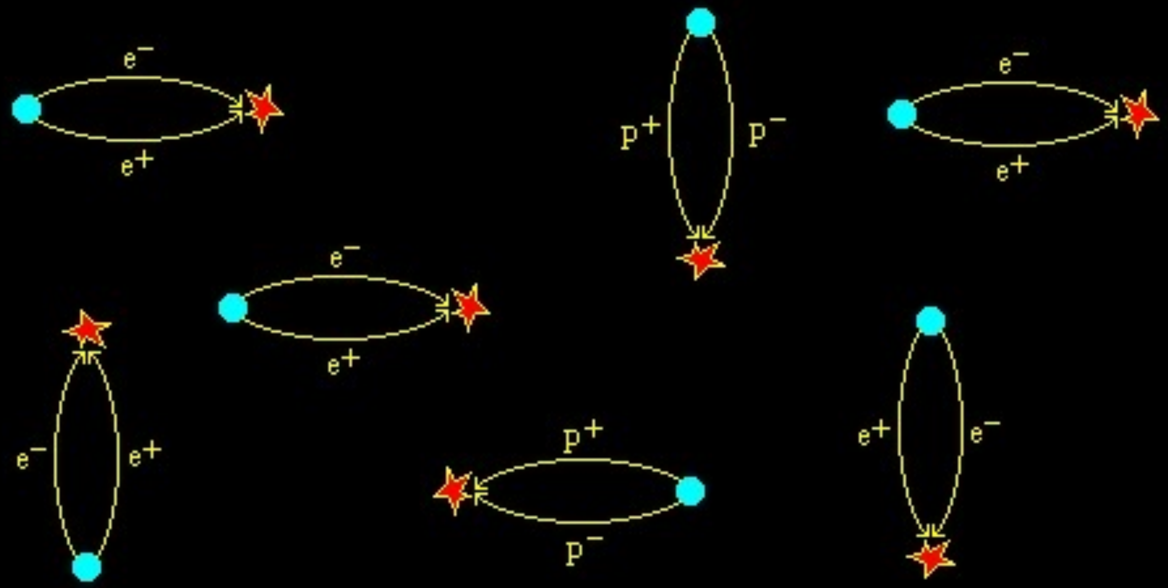
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho_m}{3} + \frac{\Lambda c^2}{3}$$

Astronomer view: **Empirical evidence**

It has kind-of worked so far

Physicist view: **Theoretical inevitability**

The Heisenberg uncertainty principle allows particle-antiparticle pairs to appear and disappear. *The vacuum is not "empty space" but contains a constant energy associated with these "virtual particles".*



The problem with Λ

Quantum theory allows us to estimate ρ_{vacuum}. Unfortunately, these estimates disagree with observations by many tens of orders of magnitude!

Quintessence	Chaplygin gas	Phantom models
Dark energy - dark matter interaction	Extra-dimensional models	Modified gravity
Holographic models	Oscillating models	Scalar-tensor models

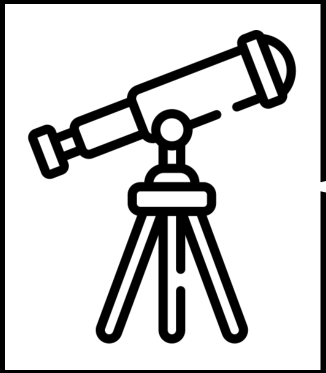
We want to distinguish between these models!

How does DESI measure dark energy?

What are baryon acoustic oscillations?

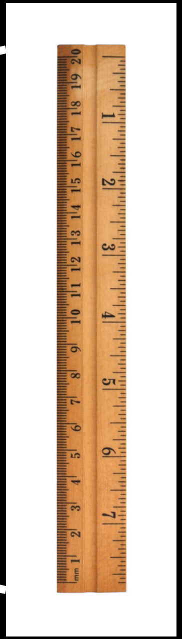
Baryon acoustic oscillations (BAOs) are a **cosmological standard ruler** that can be used to measure cosmic distances and expansion across a range of redshifts

Observer



$$\Delta\theta = \frac{s}{D_A(z)}$$

Measure angular extent



Object at redshift z with known comoving size s

Measure redshift extent

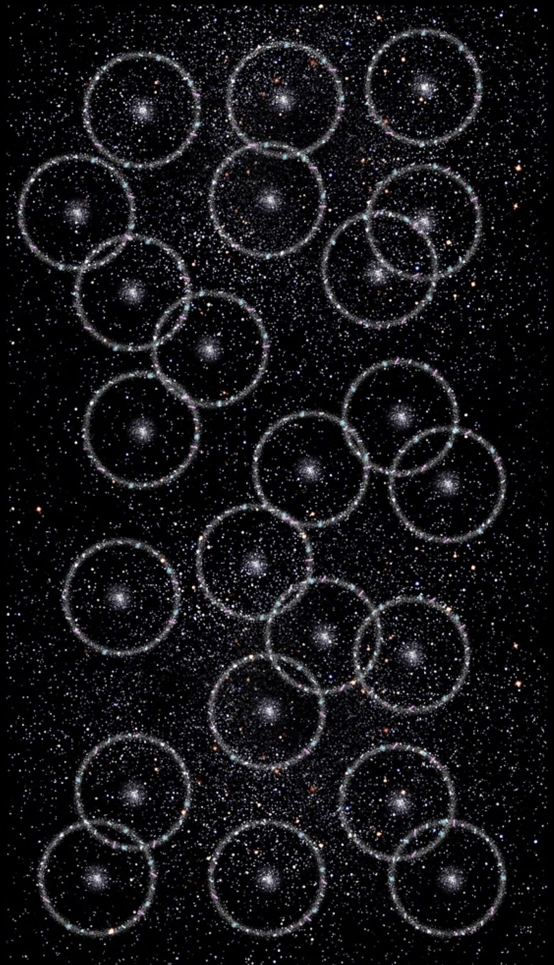
Δz

$$\Delta z = \frac{s\,H(z)}{c}$$

Result: measurements of $D_A(z)/s$ and $cH^{-1}(z)/s$ at a series of redshifts z

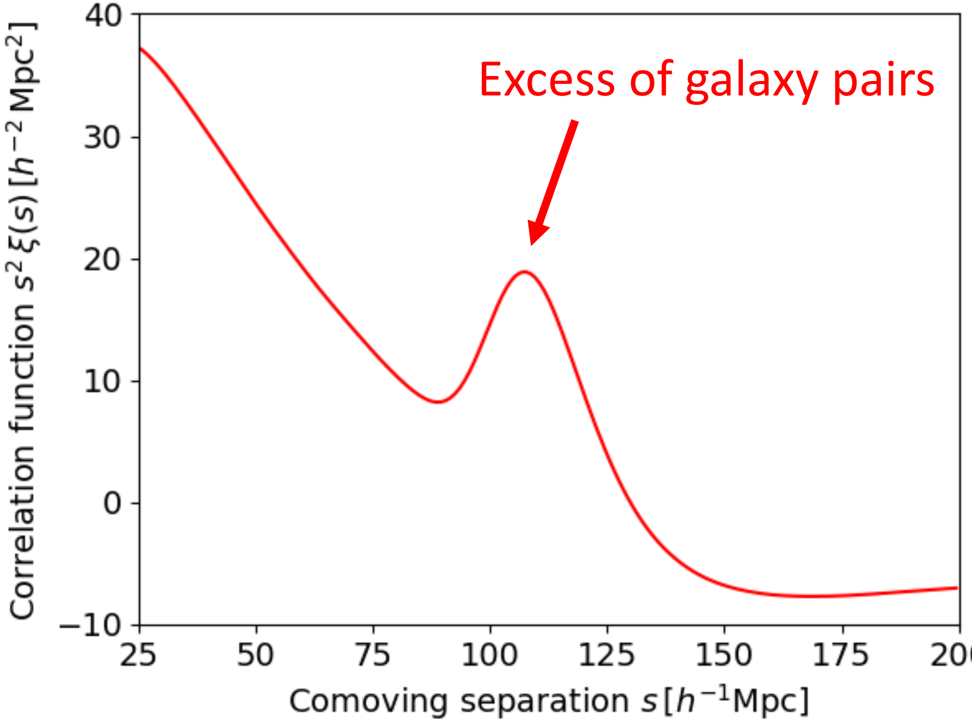
What are baryon acoustic oscillations?

Baryon acoustic oscillations are not a physical object but a statistical feature in the pattern with which galaxies cluster together



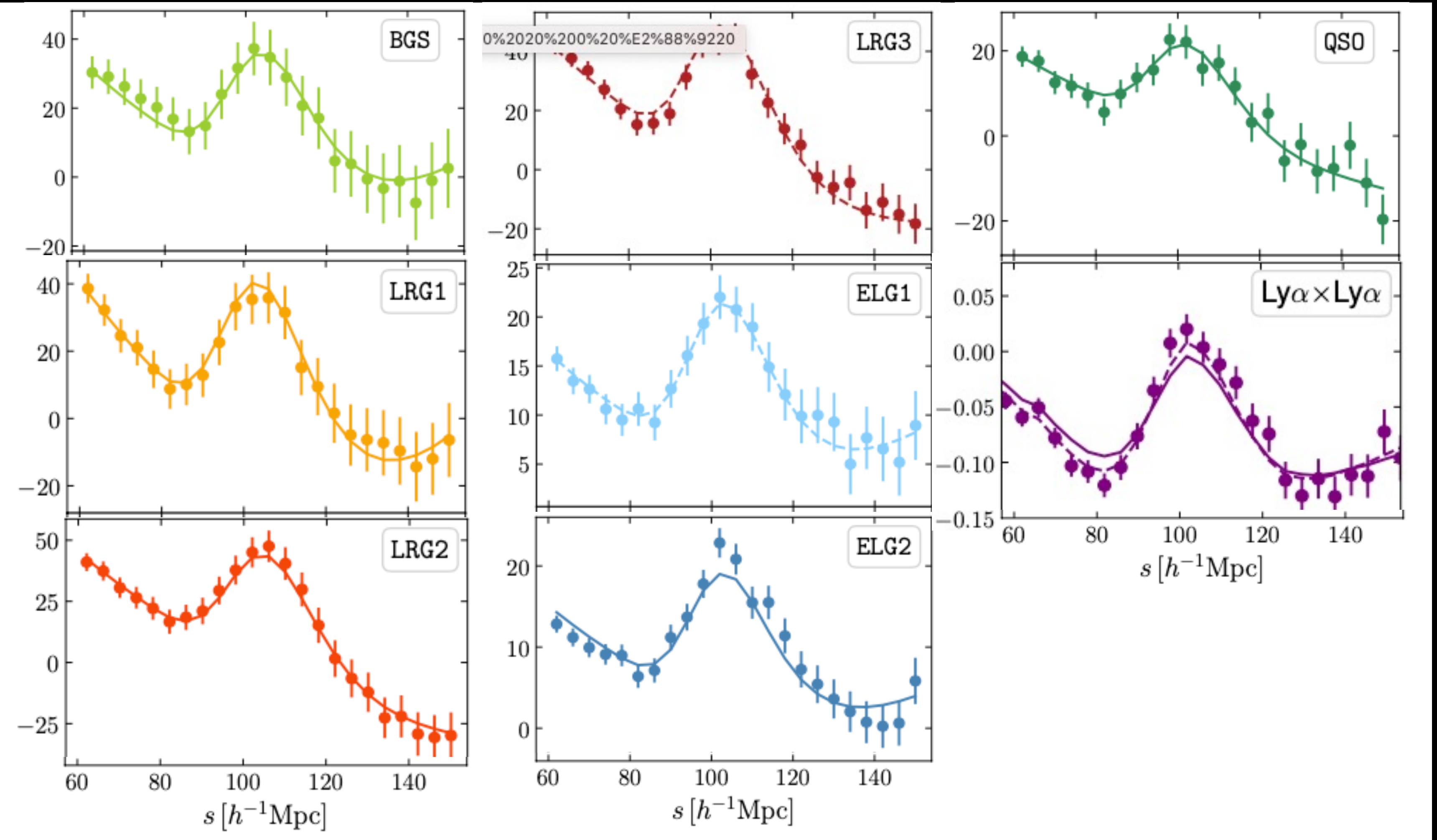
Galaxies prefer to form in both the densest regions of the Universe, and in spherical shells of radius $\approx 100\ h^{-1}\mathrm{Mpc}$ around those dense regions

The pattern is quantified using the galaxy correlation function …

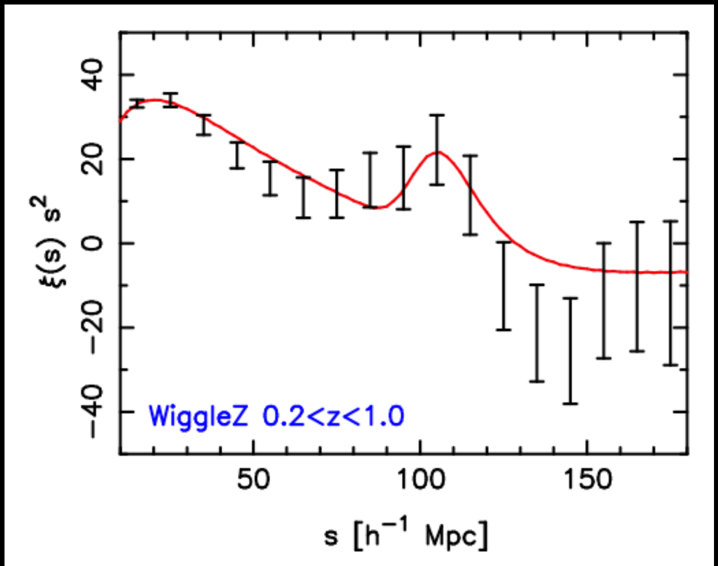


These measurements from DESI look amazing!

DESI has provided the most accurate correlation measurements from which the peak can be determined



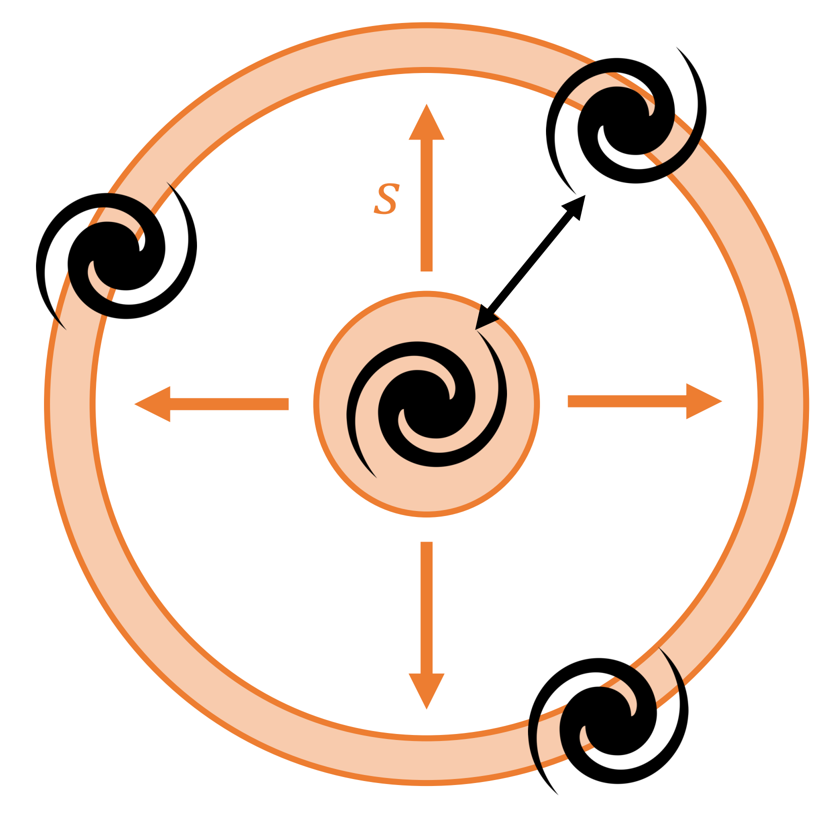
Our work at the AAT 15 years ago!



It’s annoying when 4 years of work can be repeated in 1 week ☺

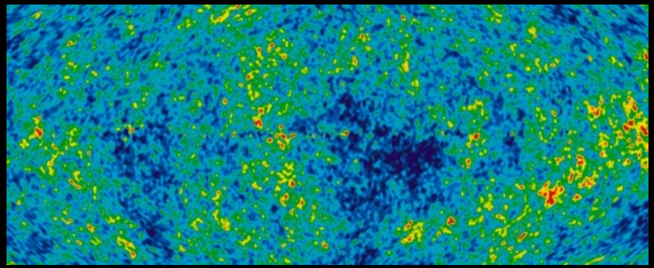
Why?? Why is this acoustic peak appearing?

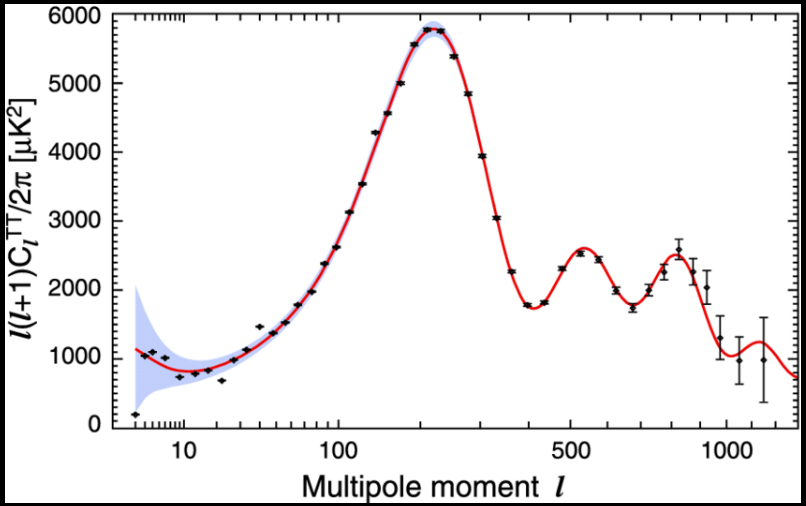
Baryon acoustic oscillations are the **sound waves** from the early Universe imprinted in the **distribution of baryons** in the late Universe



1. Dark matter clump in the early Universe attracts the photon-baryon gas
2. Gas is compressed, launching outward sound waves
3. Sound waves travel a distance *s* until recombination, which breaks photon-baryon coupling
4. Baryon overdensity frozen-in at radius *s*

We see these same sound waves imprinted in the CMB photons!





The preferred scale s is known from CMB physics

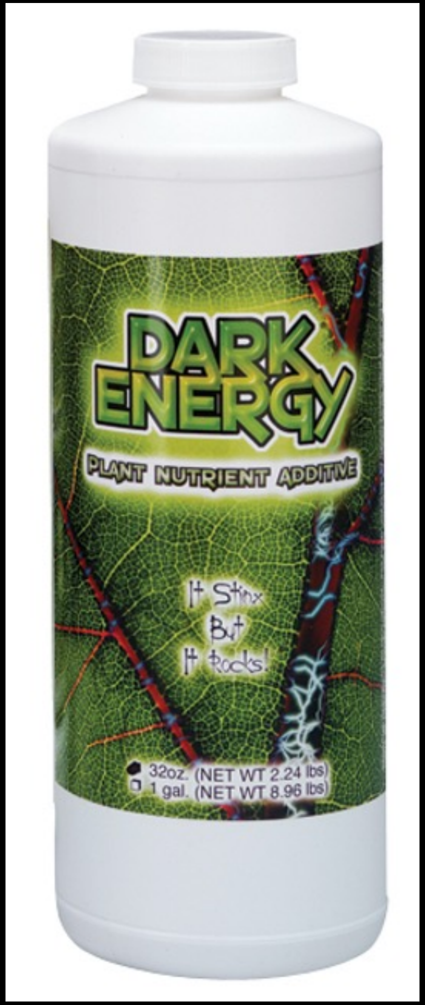
The physics of dark energy

How should we think about dark energy?

Let's consider some common phrases associated with dark energy:

Accelerating expansion

Negative pressure



"Repulsive gravity"

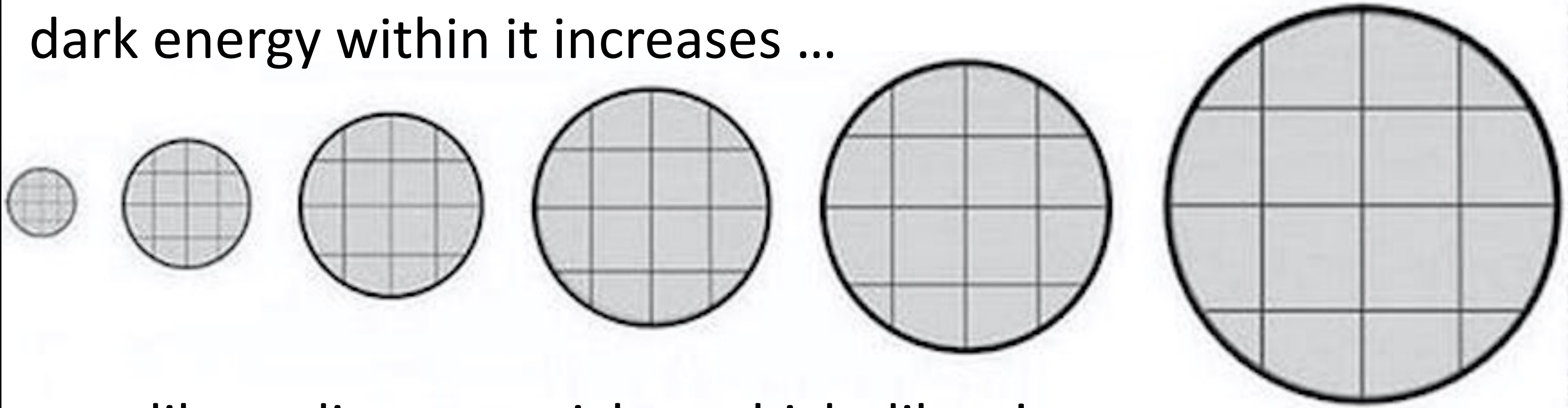
$w = -1$

??????????
Why does dark energy have such weird properties? And what's the best analogy for it?

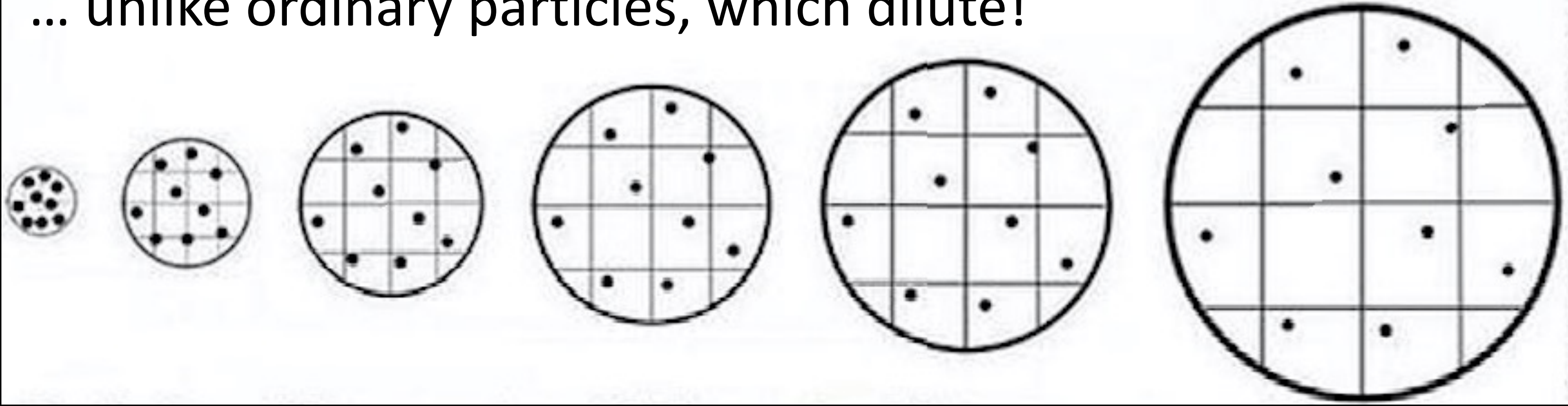
How should we think about dark energy?

Dark energy is a substance smoothly filling the Universe, that **doesn't dilute** as the Universe expands

As a volume of space expands, the amount of dark energy within it increases …



… unlike ordinary particles, which dilute!



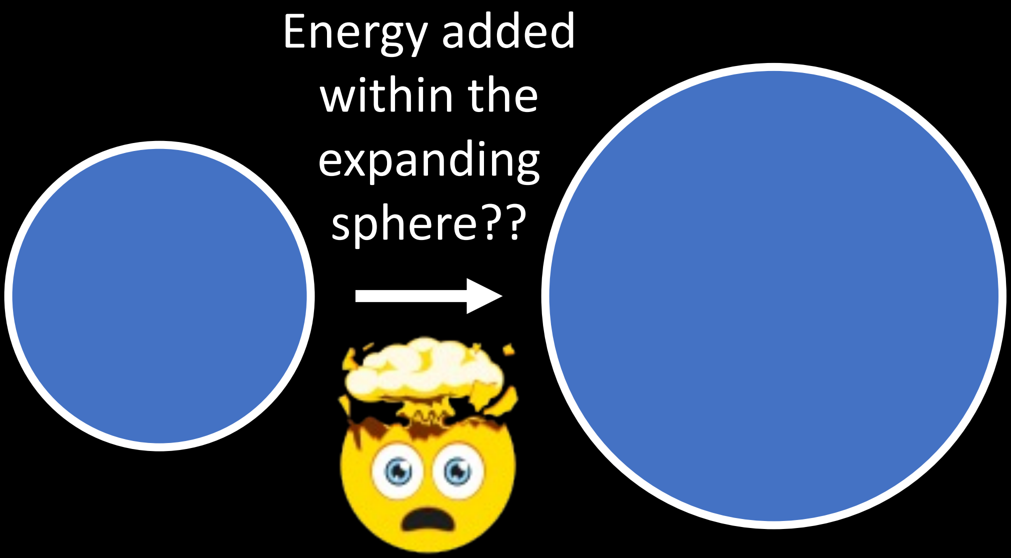
Dark energy is hence something associated with "**space**" rather than with "**particles**"

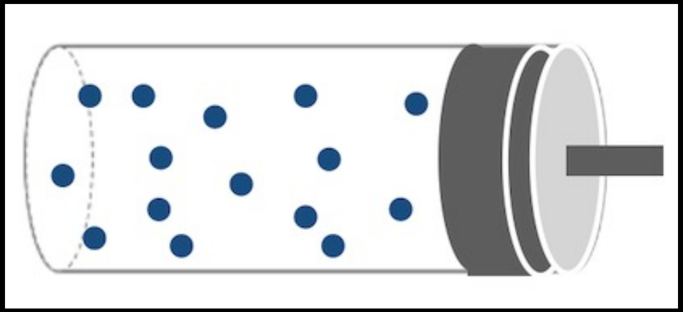
Dark energy **comes to dominate** the Universe as the other components dilute

Fun fact: a sphere of 100 parsec radius would contain dark energy equal to the rest mass of the Sun!

How should we think about dark energy?

The fact that dark energy doesn’t dilute as space expands leads to some **weird properties** when we apply the laws of physics!





- We understand stuff like this using the **1st law of thermodynamics!**
- A volume of gas **loses energy** (cools) as it expands, by doing work on the surroundings through the positive pressure it exerts
- A volume of dark energy **gains energy** as it expands, hence is receiving work from the surroundings, such that the *pressure it exerts is negative !! Aaargh!*

What is “$w = -1$”?

Substances can be characterized by their equation of state,
the ratio of the pressure they exert to their energy density, $w = P/\rho c^2$

The 1st law of thermodynamics provides a direct relation between the pressure of a substance in the expanding Universe, and how its energy dilutes away:

$$\text{If} \quad \rho \propto a^n, \quad \text{then} \quad w = -1 - \frac{n}{3}$$

For normal matter, $n = -3$ and hence $w = 0$ (pressureless)

For cosmological constant, if $n = 0$ then $w = -1$

How should we think about dark energy?

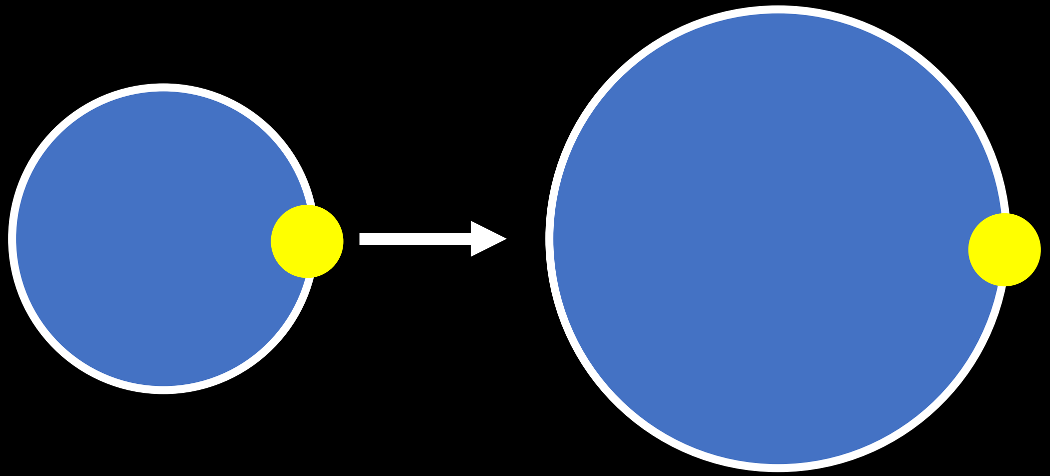
Let's meet some more **weird properties** which come from the fact that dark energy doesn't dilute as space expands!

"Accelerating expansion??"

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho(t)}{3}$$

A constant $\rho(t)$ means a constant value of $\dot{a}/a$, so as a increases, so does $\dot{a}$! Hence, the **expansion is accelerating** $(\ddot{a} > 0)$

Gravitational effect?



As the mass inside increases, the particle becomes **more tightly bound** !

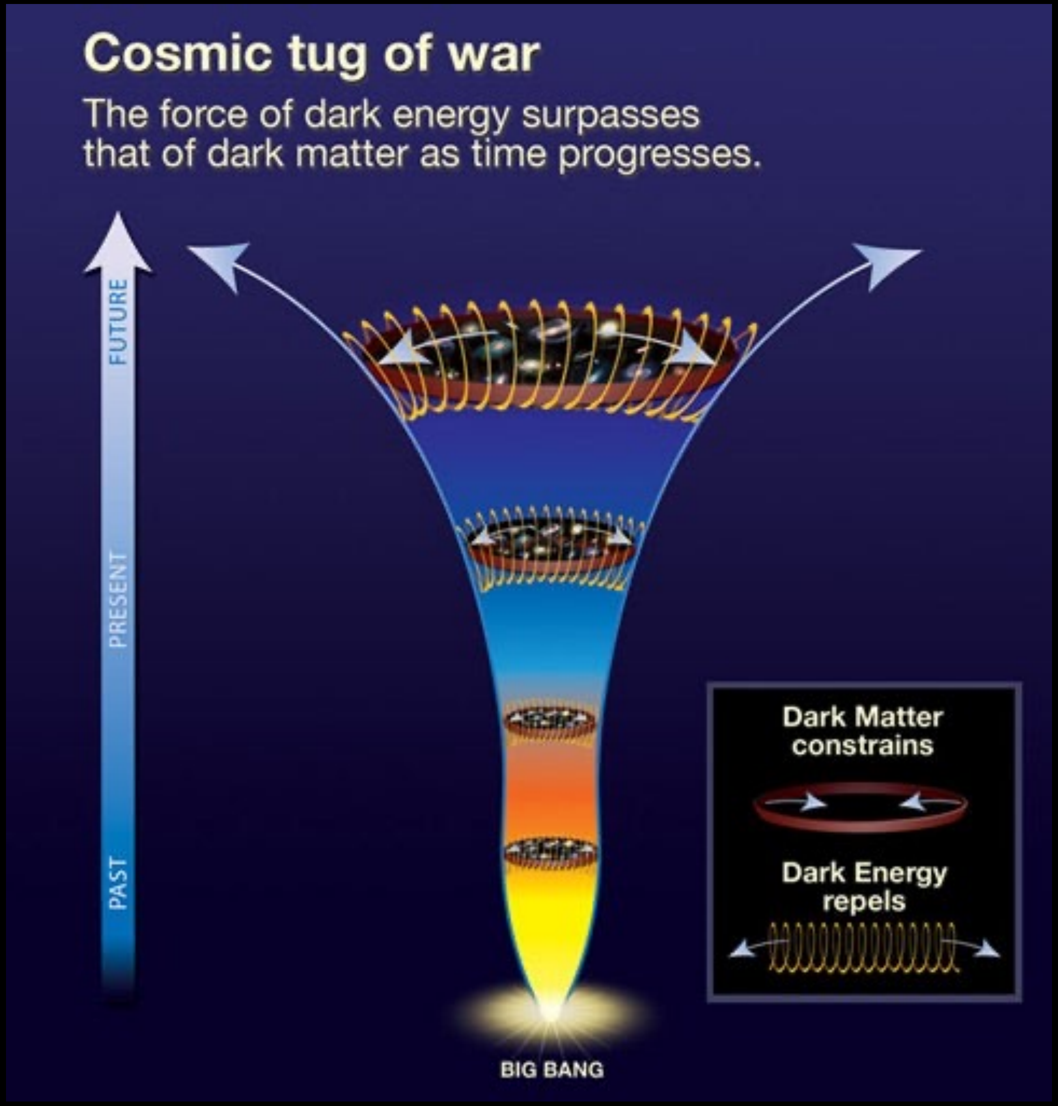
So, how should we think about dark energy?

Dark energy is a "**repulsive force**"? –
No, the force is gravity. Dark energy is a substance!

Dark energy is an "**anti-gravity**"? –
No, normal gravity.

Dark energy is a "**negative pressure**"? –
Technically yes, but that's a hard phrase to understand. Doesn't pressure push outwards? Wouldn't negative pressure pull inwards? Aargh!

Dark energy is like "**coiled springs**"? –
I like this analogy, because it conveys that as space expands, the energy within this volume increases



How to make progress?

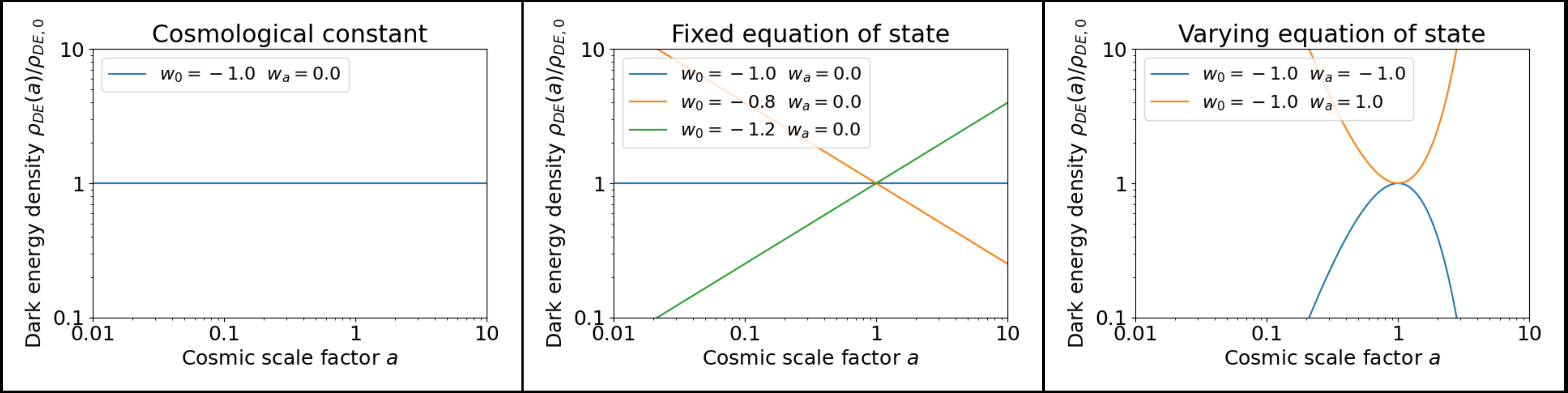
Let's try fitting a general model as a function of scale factor (time) $a(t)$:

"constant term" ($w_0 = -1$ for Λ)

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

"evolving term" ($w_a = 0$ for Λ)

Although this equation doesn't itself come from a physical model, it's a flexible parametrization matching a range of models that are physically motivated



“Phantom” dark energy

Dark energy with the property $w < -1$ at some time is called a phantom.
Theorists have particular difficulties modelling phantoms!

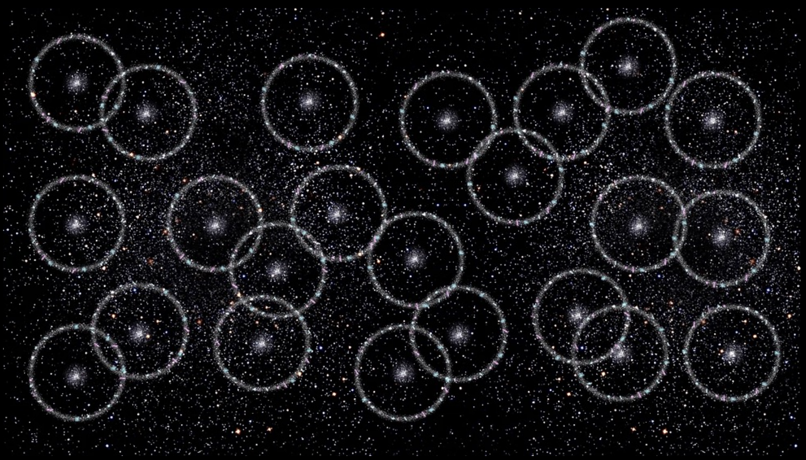
- Since $\rho \propto a^{-3(1+w)}$, then if $w < -1$ the density is increasing with time as space expands
- Acceleration exponentially increasing, heading for “Big Rip” scenario if sustained!
- Violates the “Null Energy Condition” satisfied by any conventional physics description

Now I am finally getting to the …

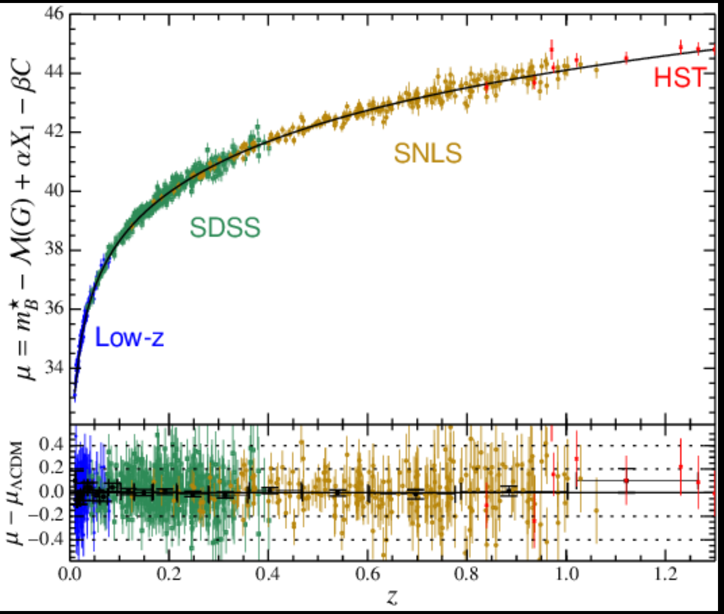
DESI results!

Recapping on the data …

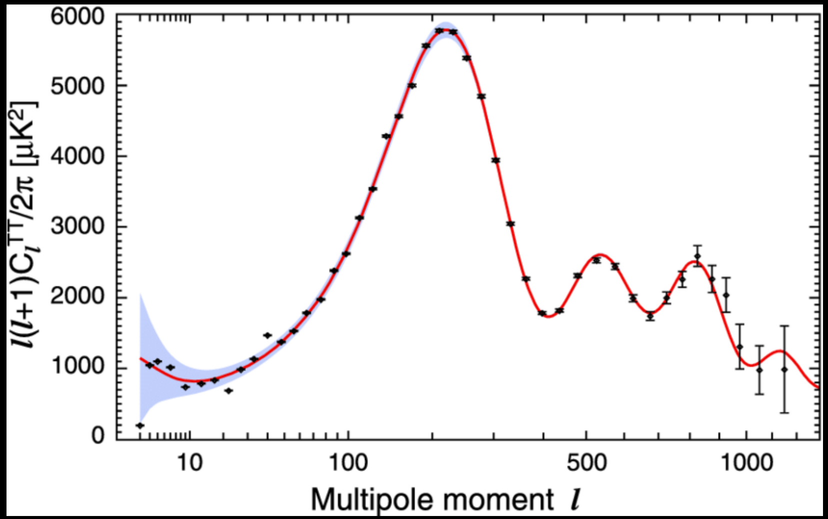
Baryon acoustic oscillations: measure $D_A(z)/s$ and $H^{-1}(z)/s$ by standard ruler technique for $z < 3$



Supernovae: measure $H_0 D_L(z)$ by standard candle technique for $z < 1$



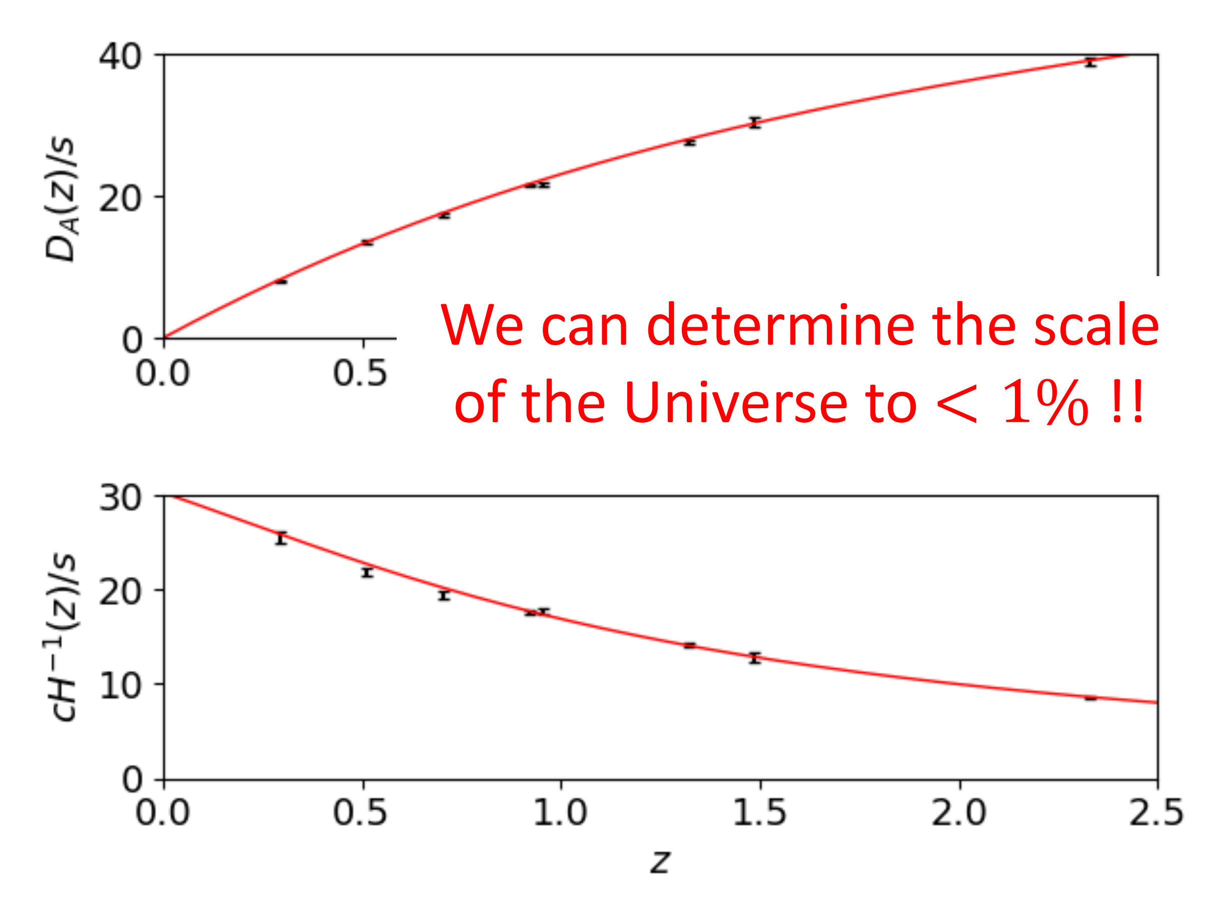
CMB: calibrate s and measure $D_A(z = 1100)$ through angular position of 1st acoustic peak

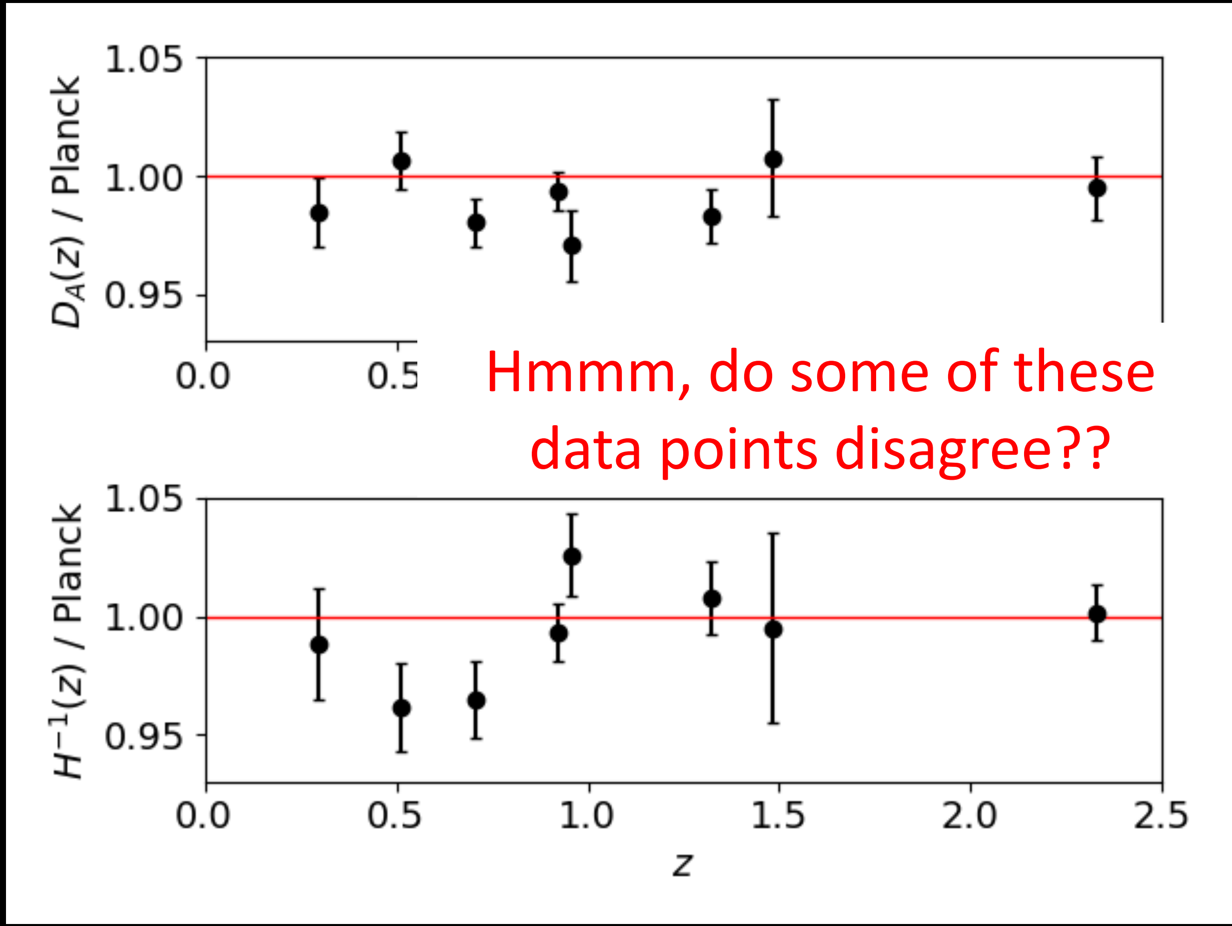


These quantities all have different dependences on w_0 and w_a which help break degeneracies and improve the measurements

Measurements from DESI

Here are the DESI distance and expansion rate measurements from the galaxy types across redshift, compared to the ΛCDM prediction

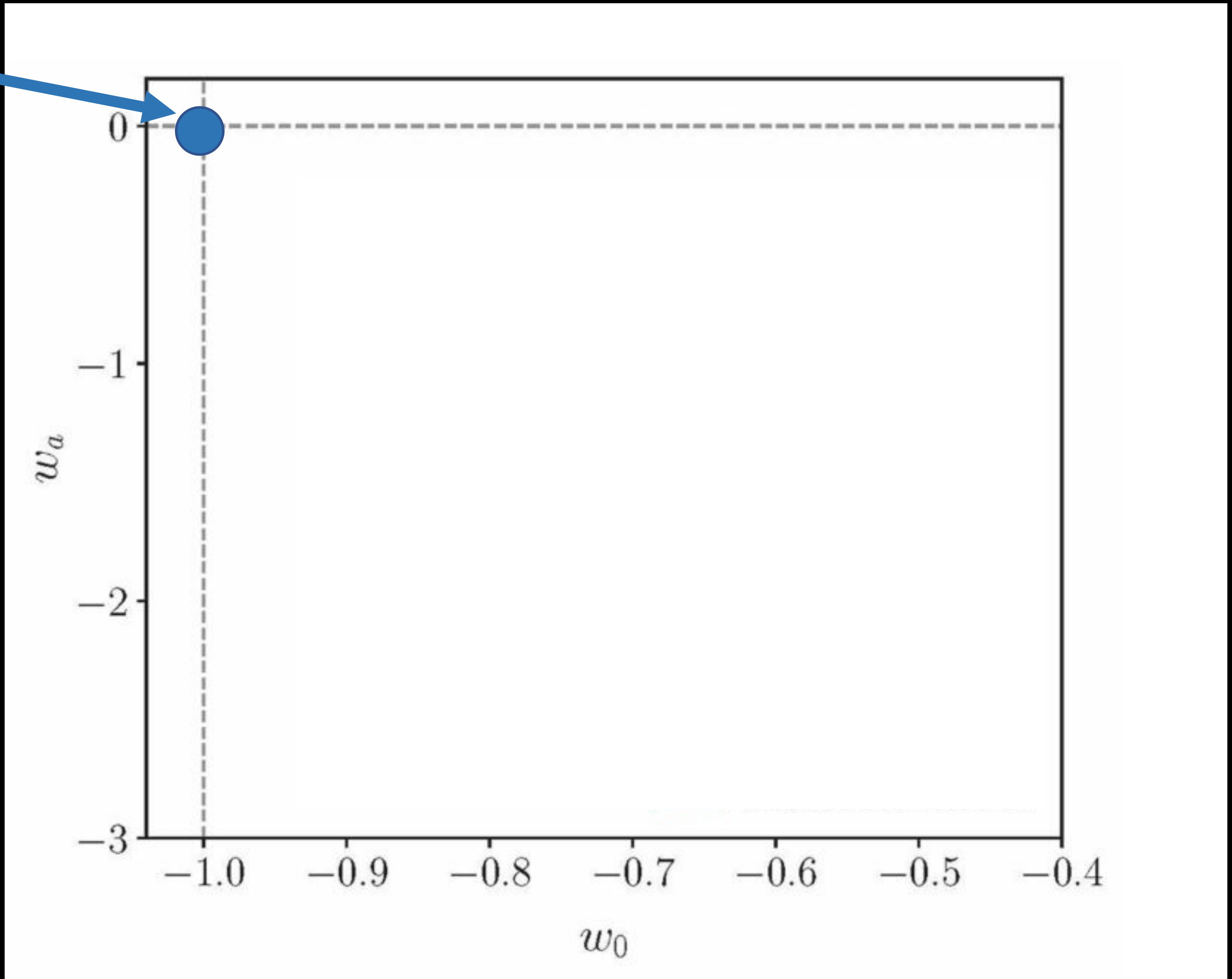




Statistics to the rescue!

What are the dark energy parameters $w(a) = w_0 + w_a(1 - a)$?

The standard model of dark energy (constant energy density)



Dark energy results

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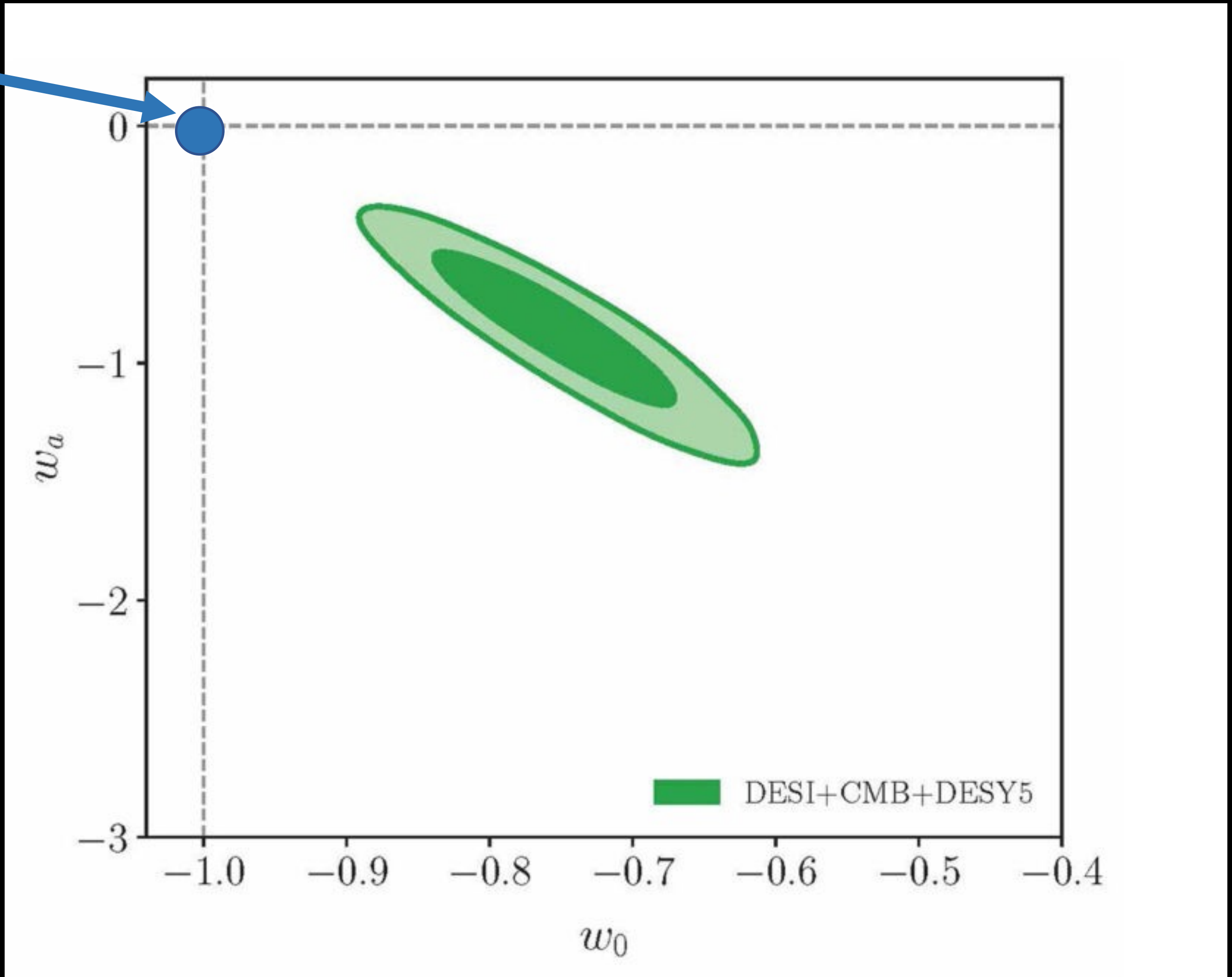
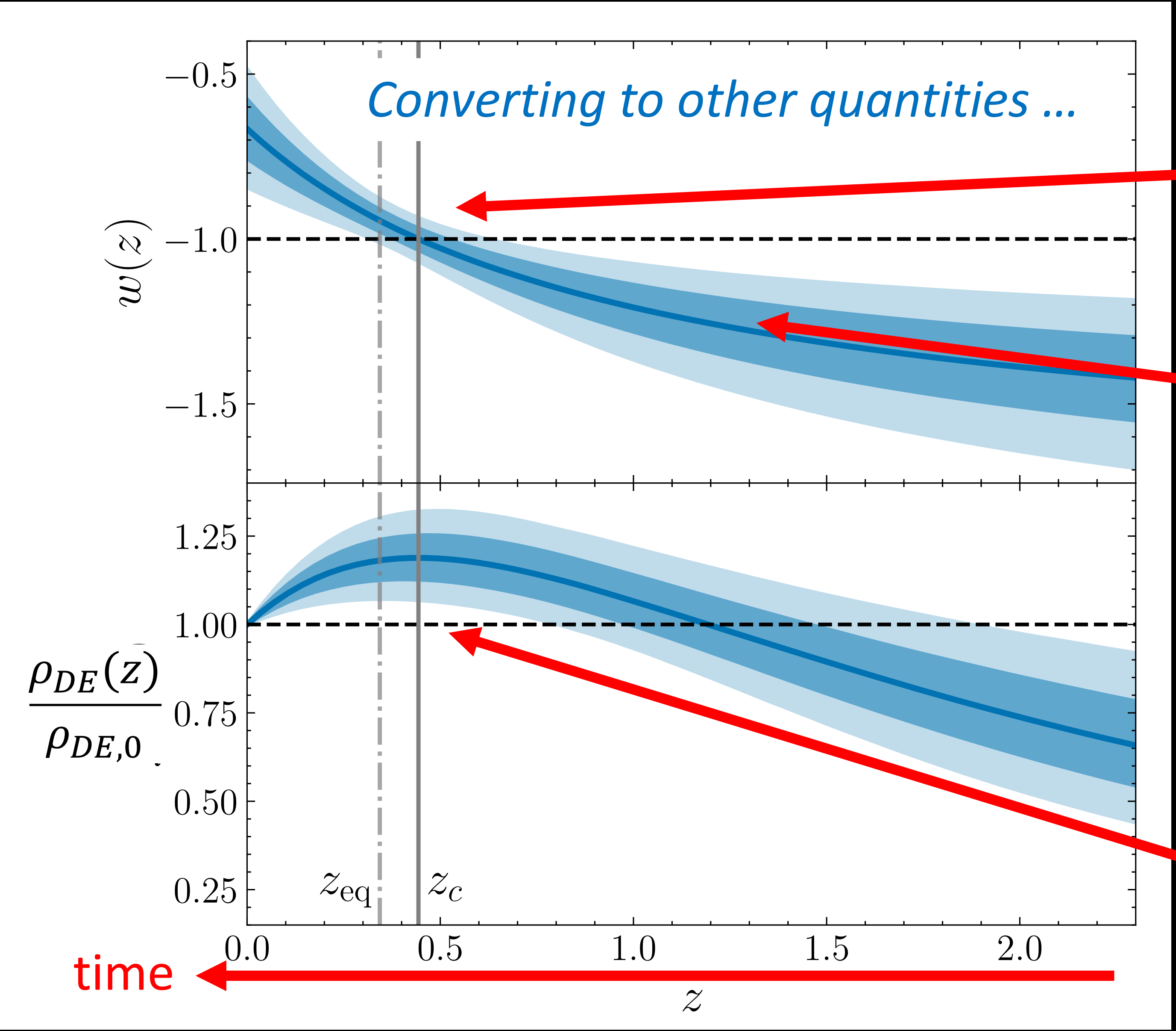


Data favour evolving equation of state of dark energy

The significance of rejection of ΛCDM is 4.2σ in this case (< 1 in 10,000 by chance)

Dark energy results

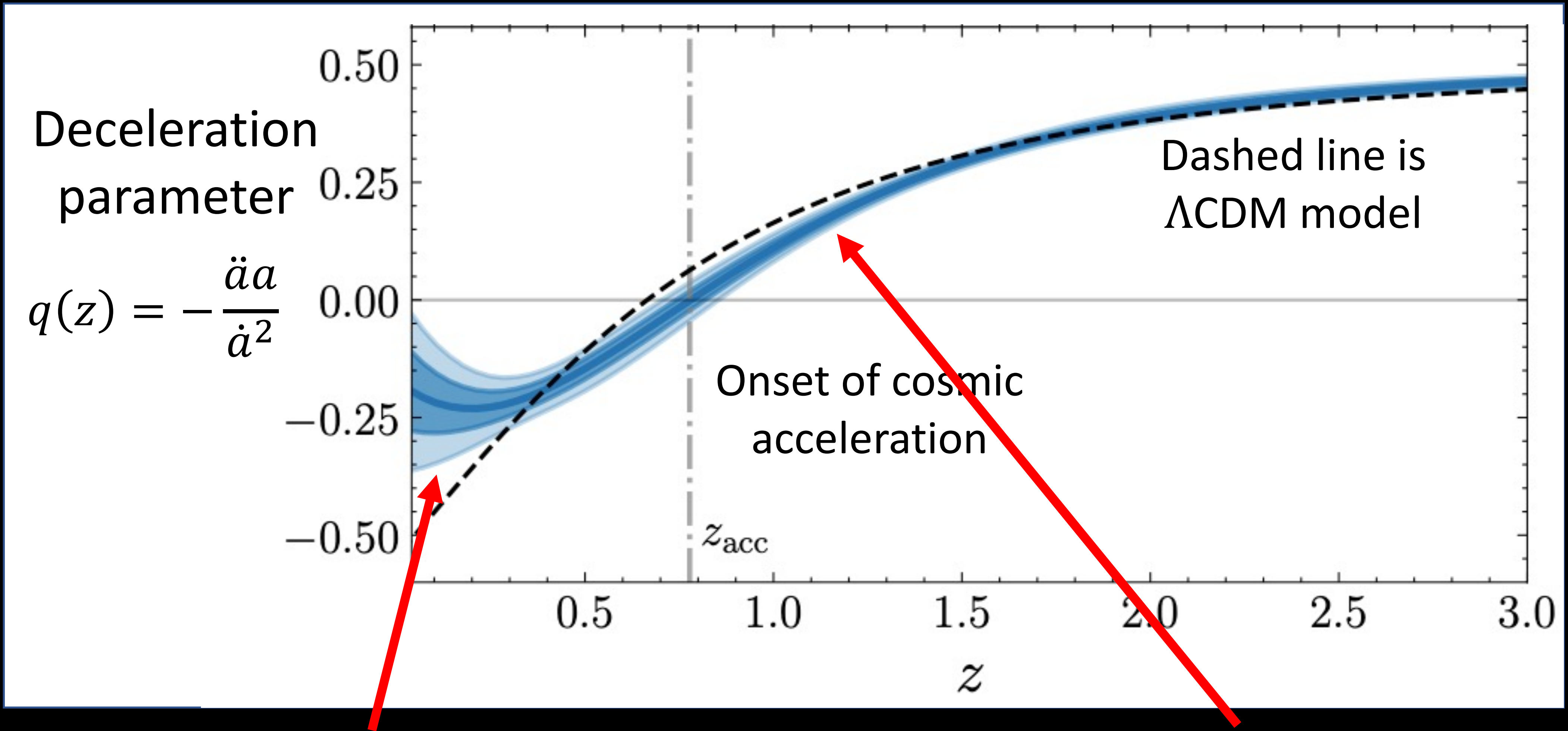


Phantom crossing!

Dark energy behaves as phantom??

Dark energy density peaks in the past and is now “weakening”

DESI results



Acceleration appears smaller than expected in today's Universe

Acceleration appears larger than expected in the past

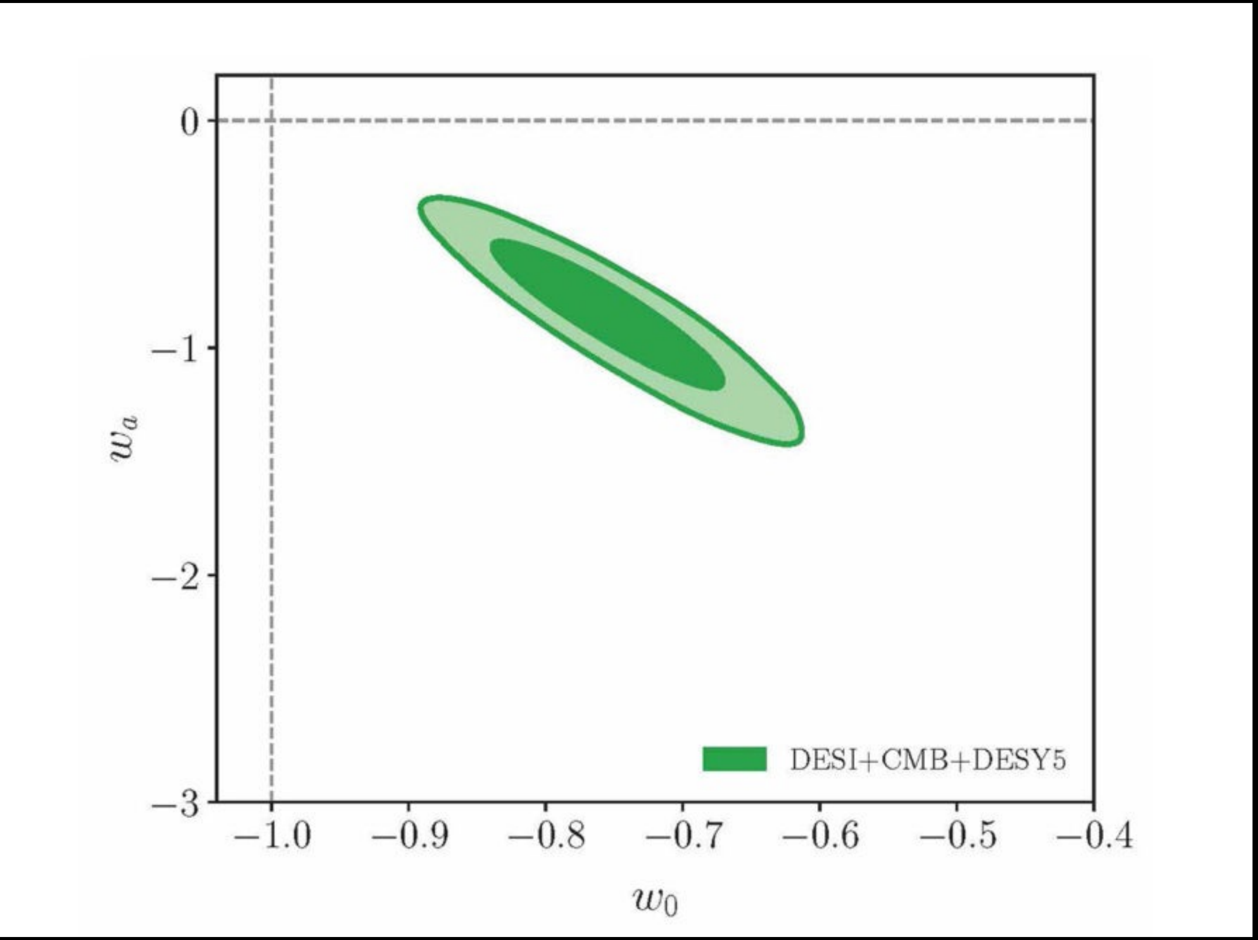
What does it all mean?

Have we disproven the ΛCDM model??

Not yet!

We have a suggestive result, but the statistical significance is still $< 5\sigma$

The result relies on DESI, SNe and CMB data, all of which will continue to be analysed



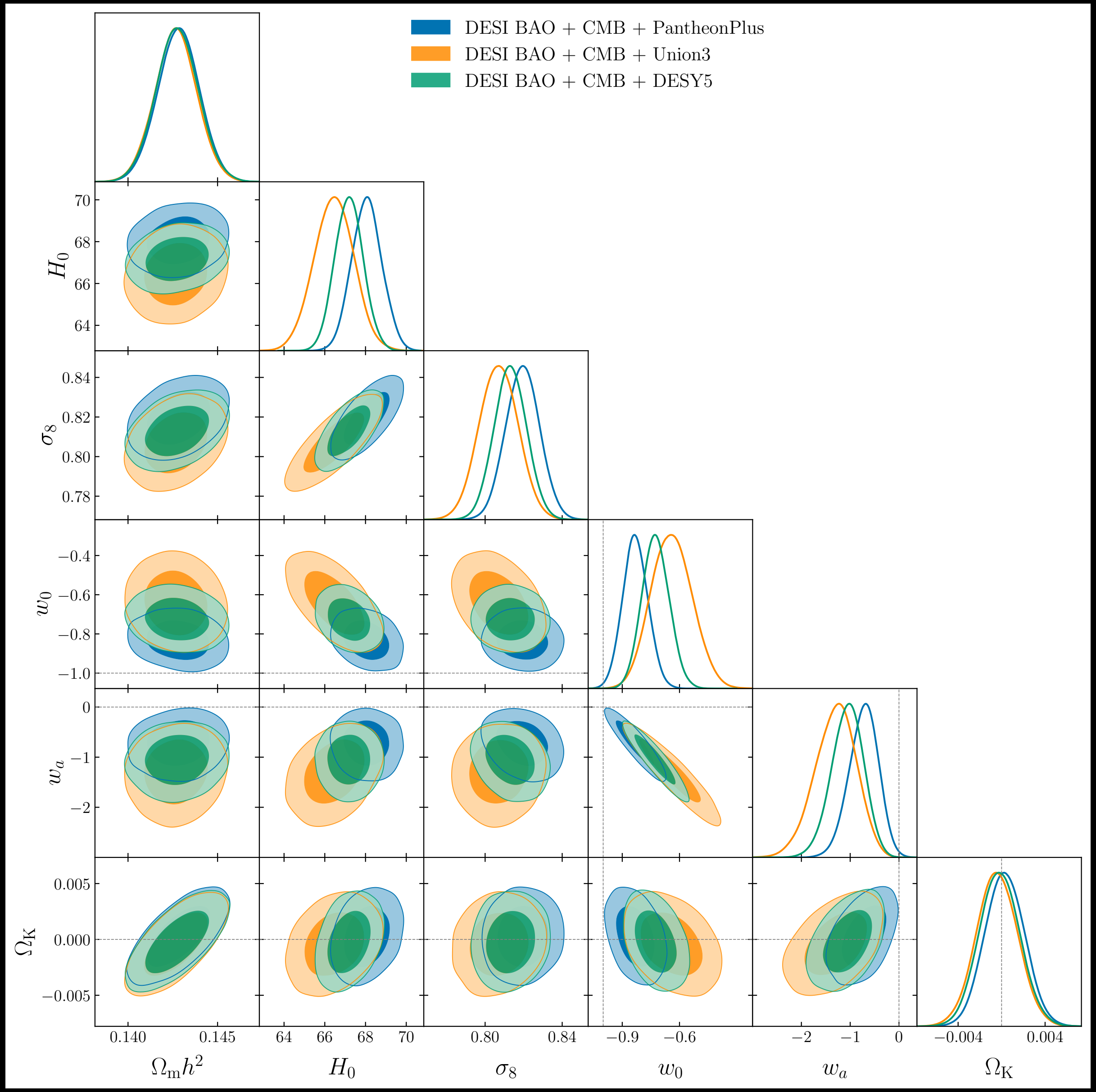
Does evolving dark energy affect the Hubble tension?

Unfortunately, no!

The Hubble tension remains, even after fitting evolving dark energy models

$$H_0 = 66.7 \pm 0.6 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

Now we have another cosmological tension !?!



What's next … more DESI!

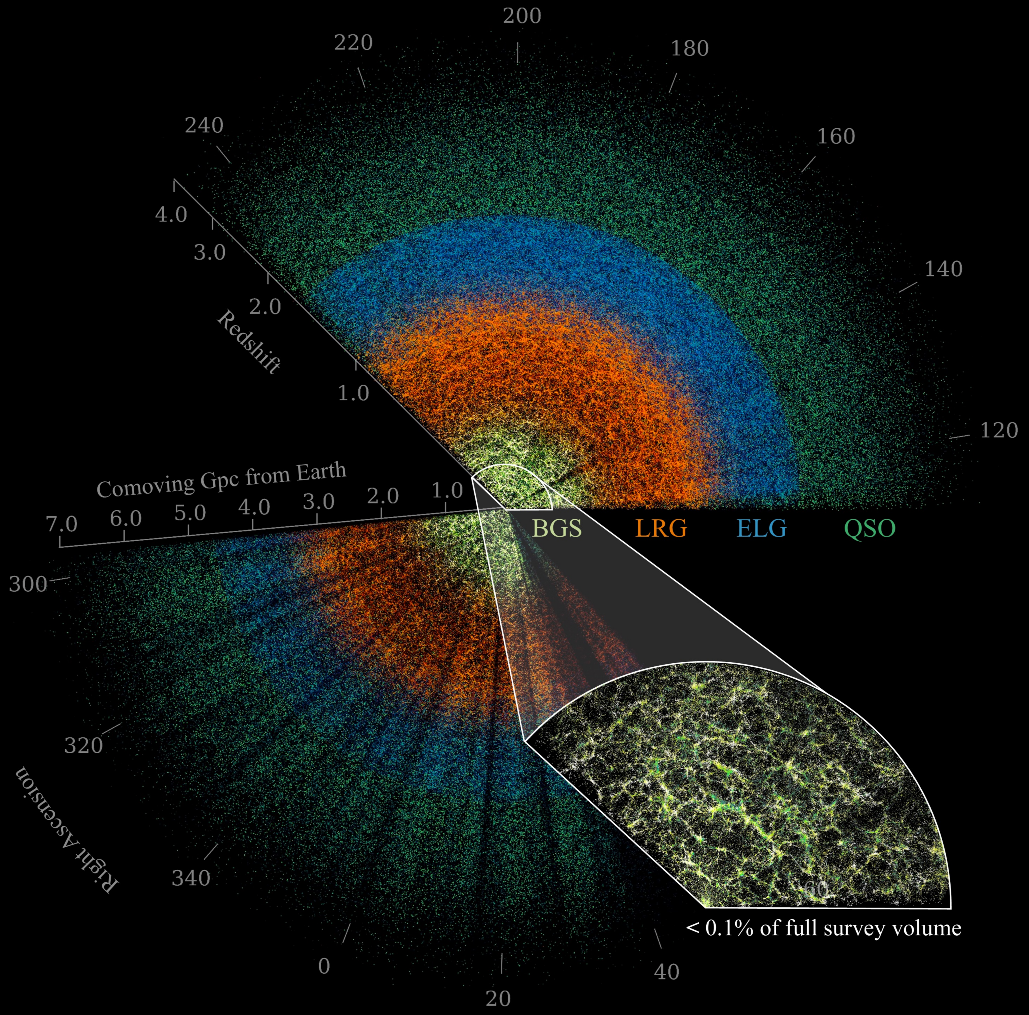
DESI has at least two more years of data to analyse … *will they reinforce these hints of dark energy behaviour?*

We are using DESI for many other cosmological analyses including *weak gravitational lensing* and *galaxy peculiar velocities*

Whatever emerges, DESI is providing one of the key cosmological datasets of this decade!

What's the deal with dark energy?

New results from the Dark Energy Spectroscopic Instrument



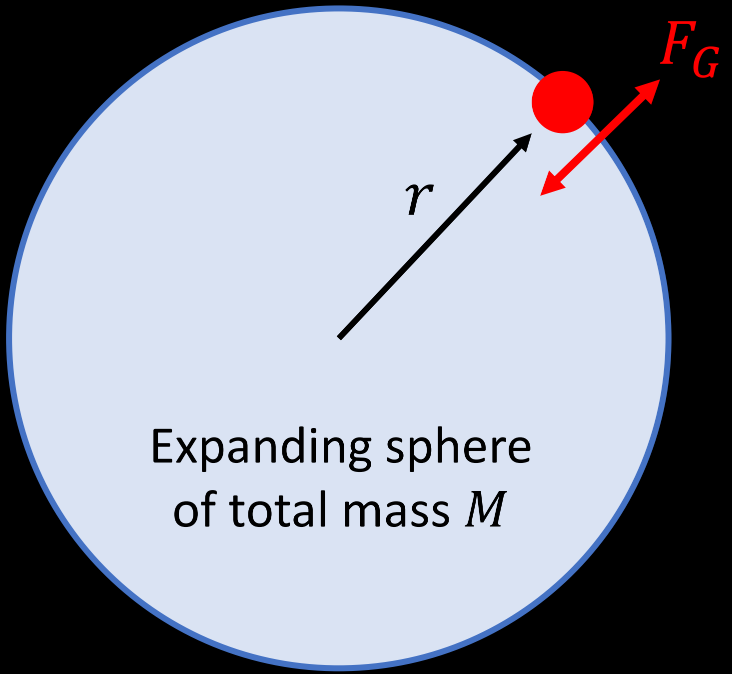
Chris Blake (Swinburne)

Bonus slides

Why "repulsive gravity"?

Normal matter slows expansion due to attractive gravity. Does accelerating expansion mean repulsive gravity? Let's try a Newtonian analogy!!

Consider a particle of mass m on the edge of an expanding sphere, that feels a gravitational force F_G

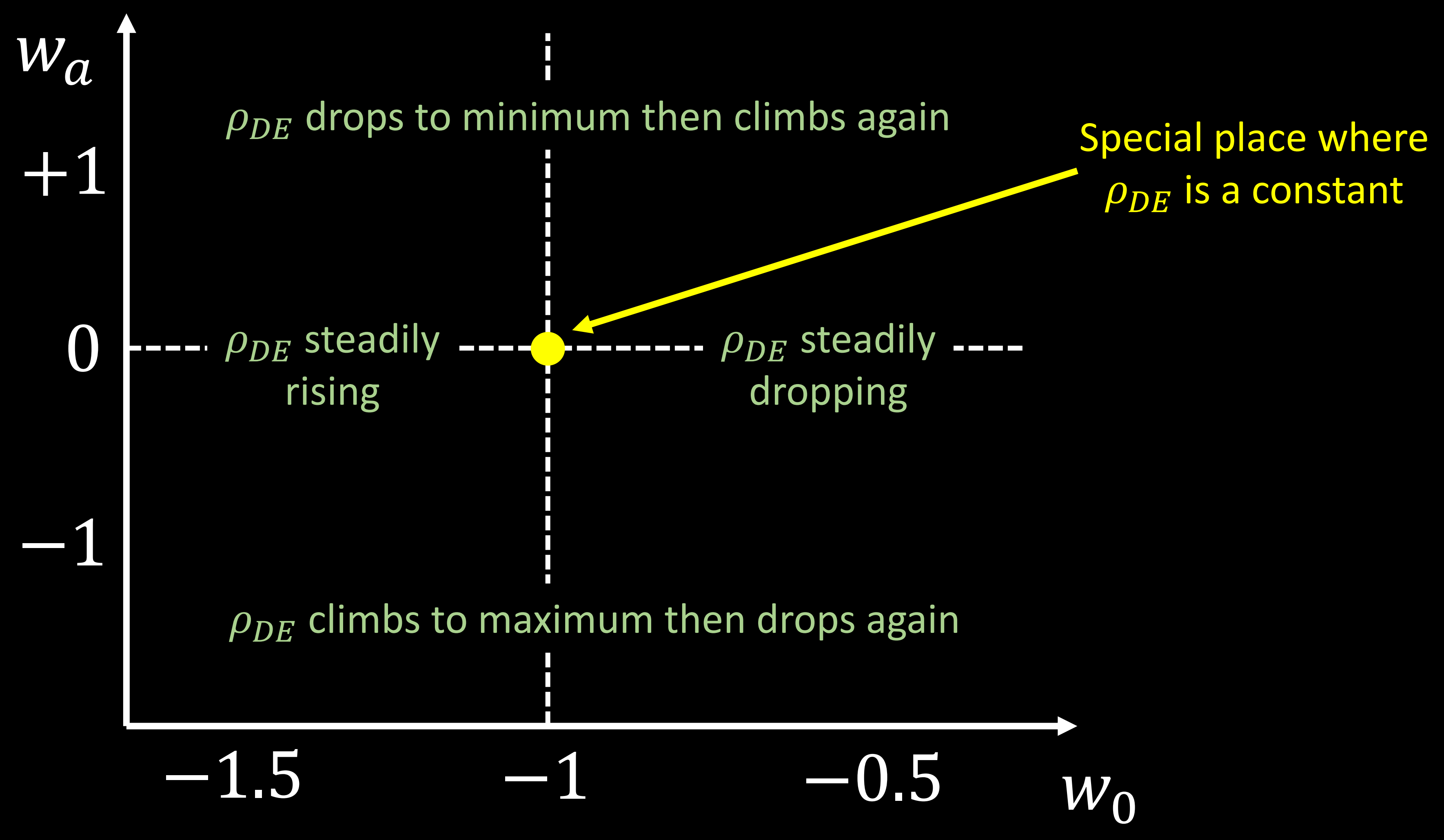


The particle feels a gravitational force from the mass enclosed by the sphere, $F_G = \frac{GMm}{r^2}$

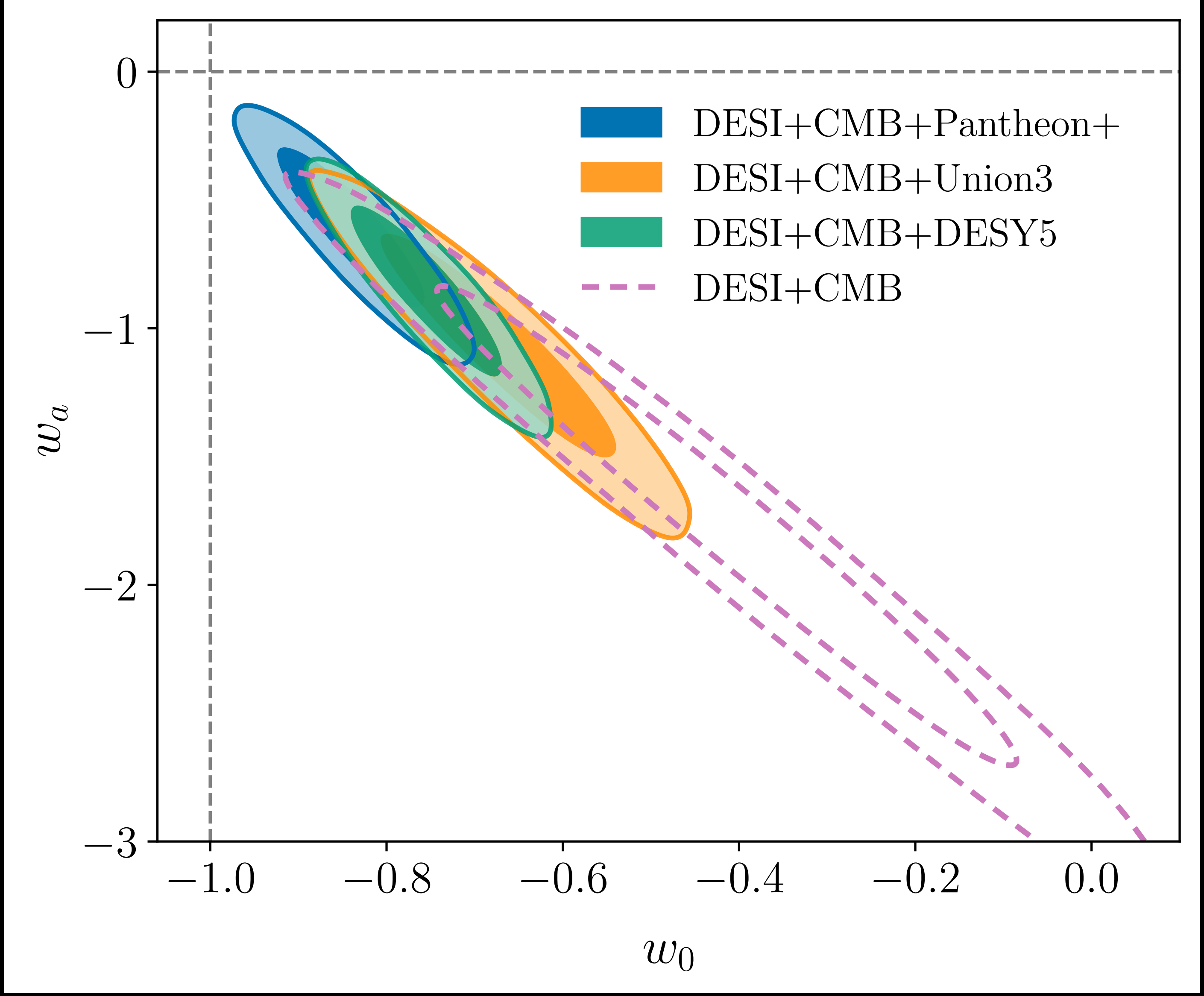
For normal matter, M stays constant as the sphere expands, so $F_G \propto \frac{1}{r^2}$, and the particle becomes less tightly bound (inward force)

For dark energy, $M \propto r^3$ as the sphere expands, so $F_G \propto r$, and the particle becomes more tightly bound (outward force)

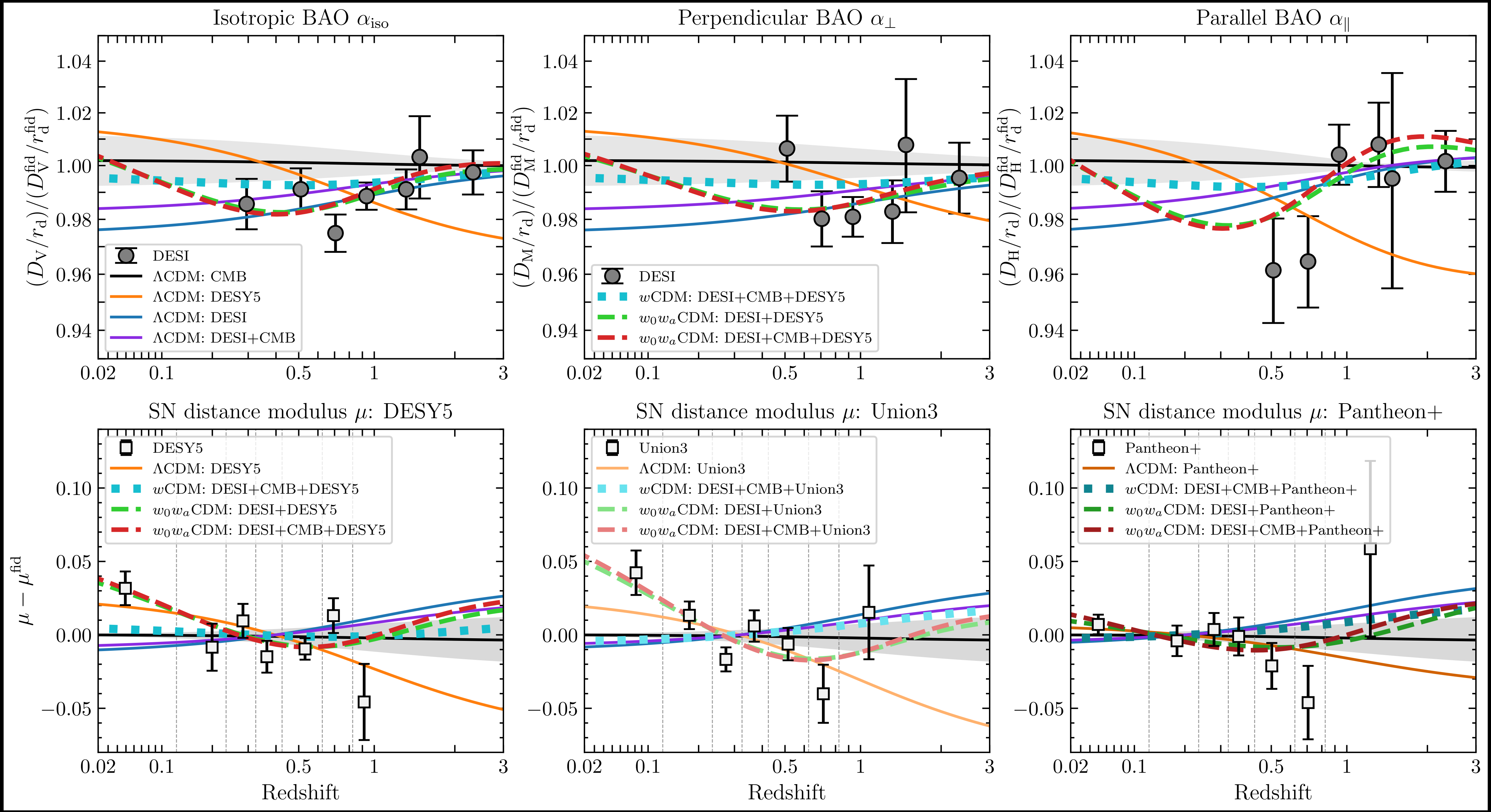
Evolving dark energy



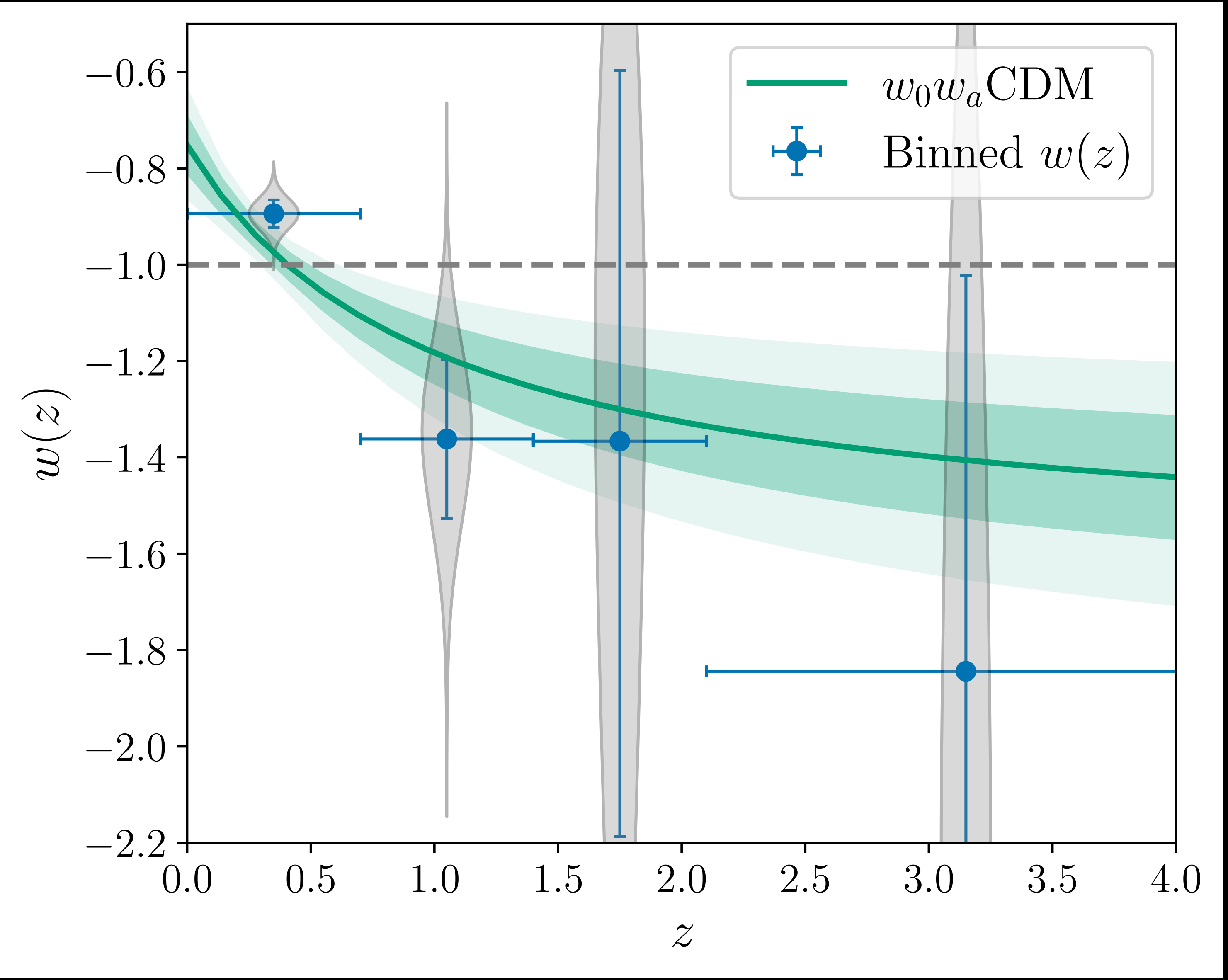
Results are similar for different SNe surveys



Does evolving dark energy improve the distance fit?



Stepwise fit for $w(z)$



Weird Ω_m tension under ΛCDM