First Results from the Dark Energy Spectroscopic Instrument (DESI)

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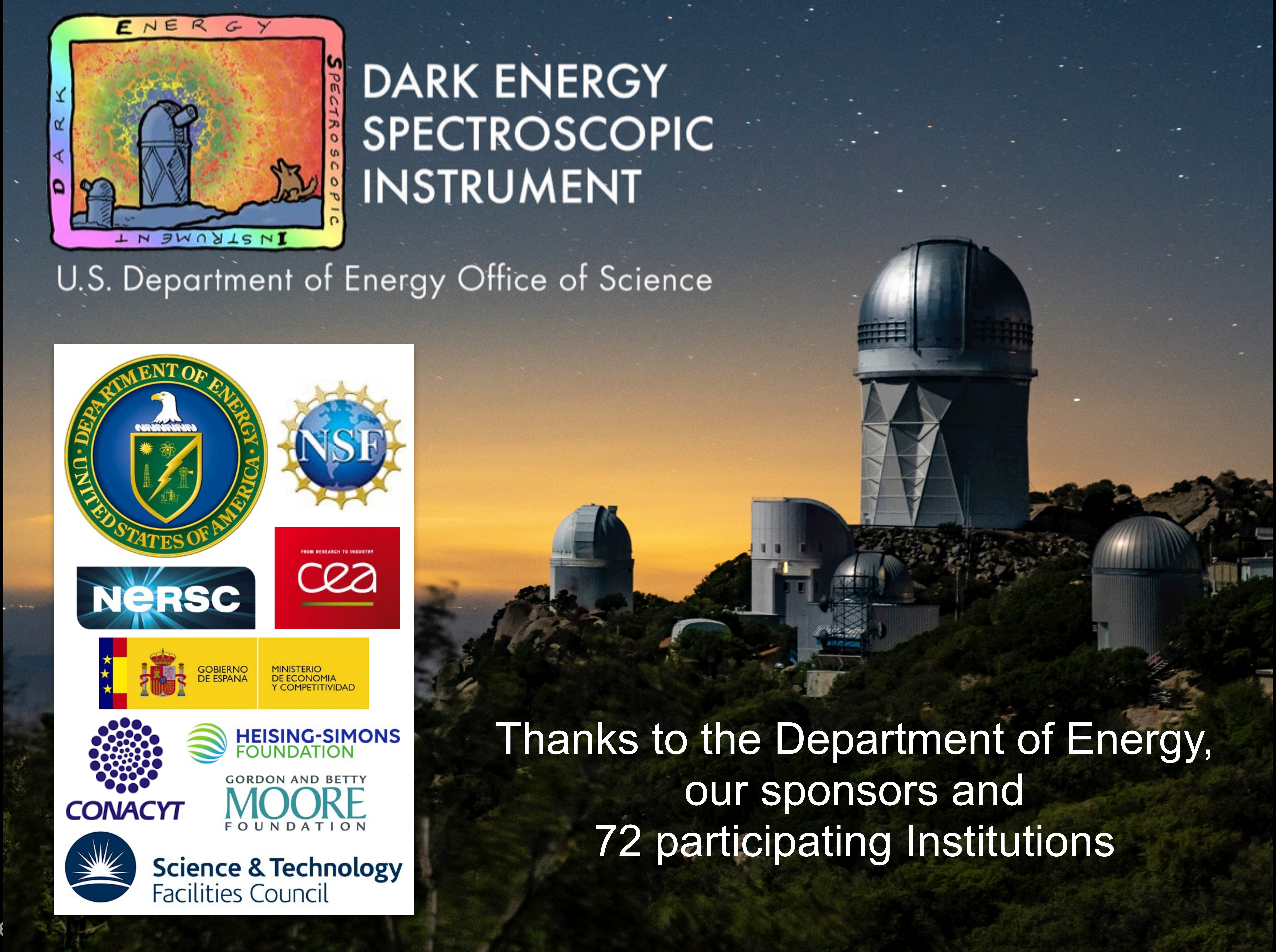
DESI Project Scientist
12 July 2025


DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science
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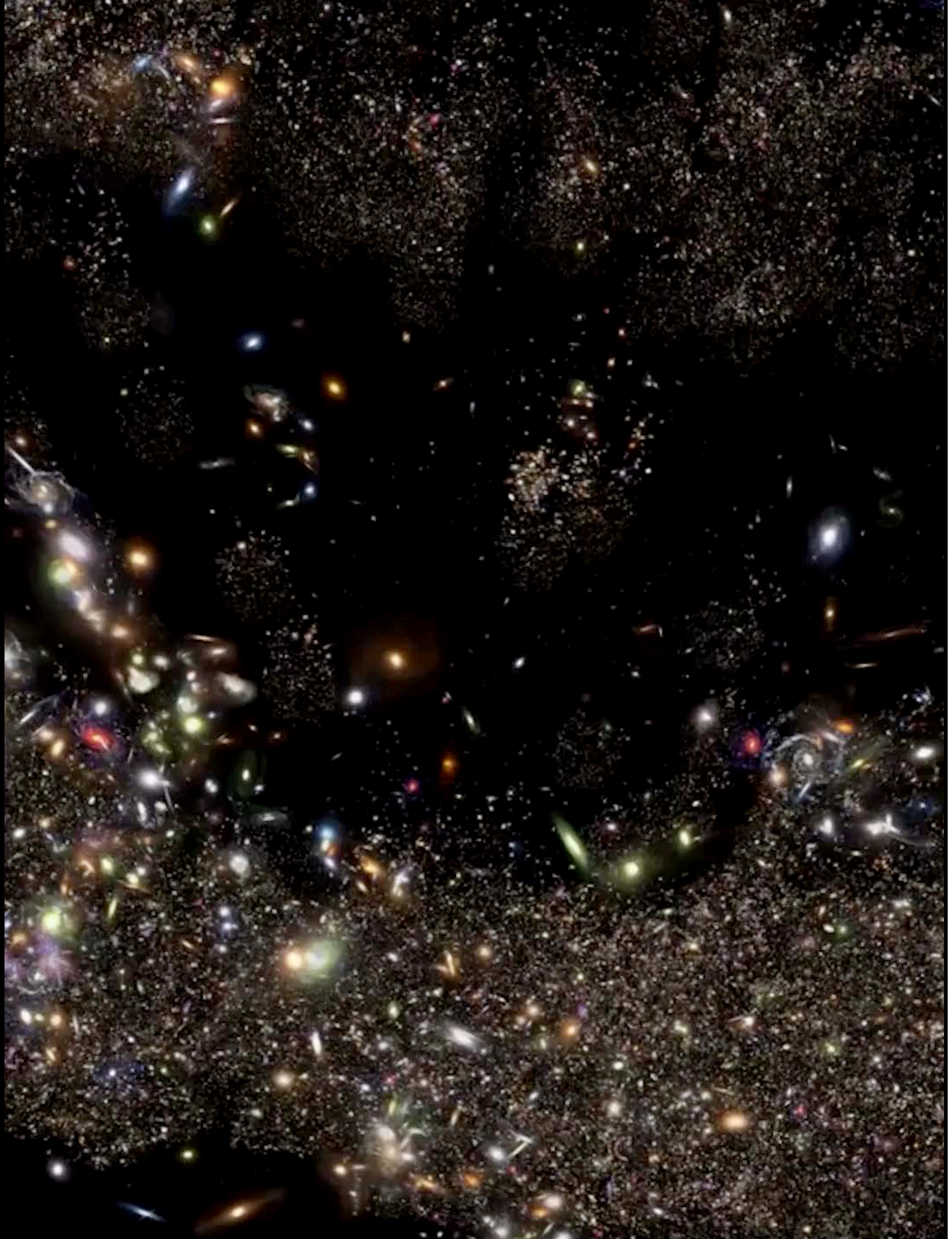


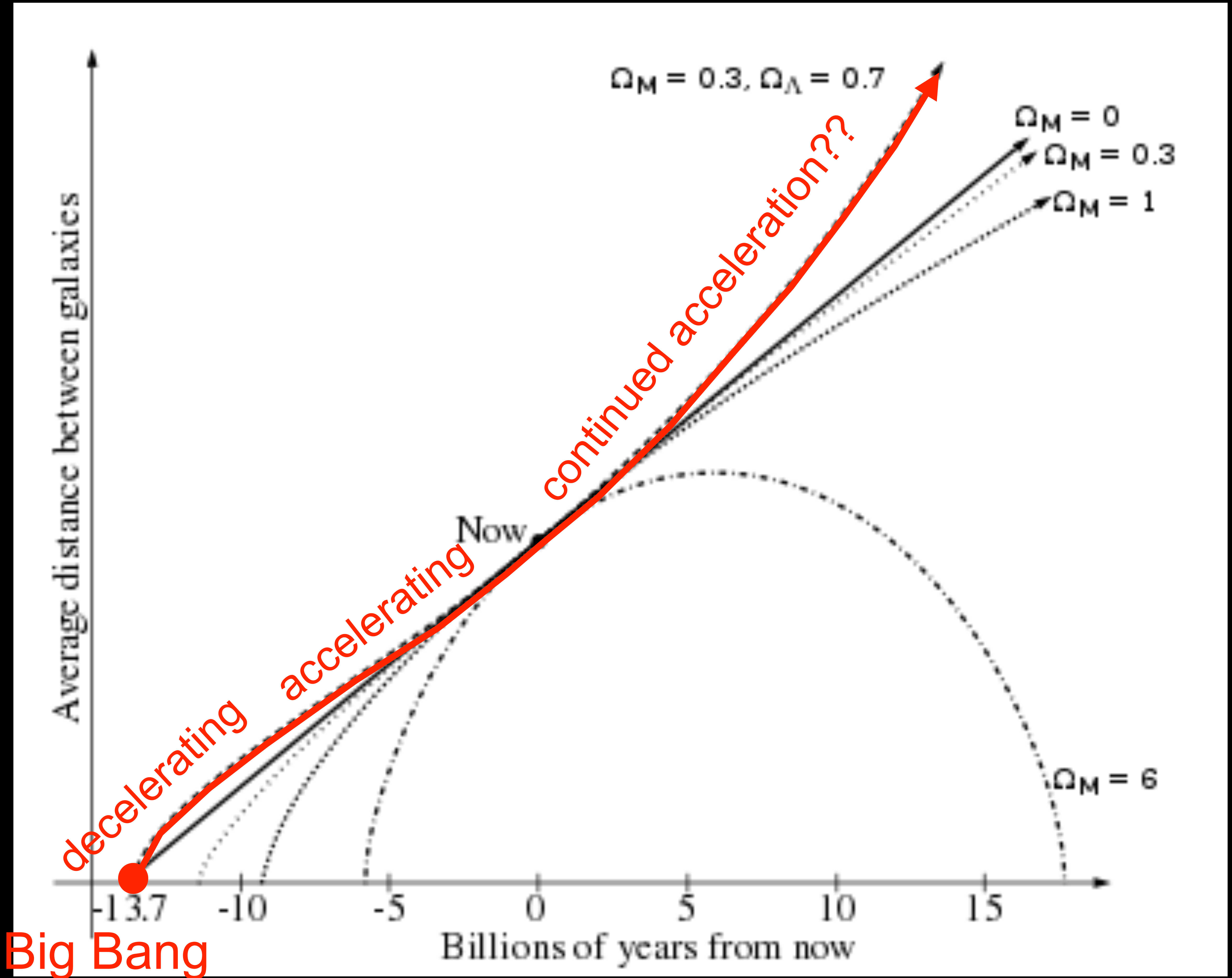
The New York Times
April 4, 2024

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.

What is the Dark Energy Spectroscopic Instrument (DESI)?

- Largest 2-D map of the universe (until Rubin Observatory in the late 2020s)
- Largest 3-D map of the universe
- Dark Energy experiment, measuring Universe's expansion from z=4 → 0



What is a map?


What is a map?
3-D positions of planets, stars, galaxies
3-D velocities
6 dimensions

Maps of the Solar System

Observables:

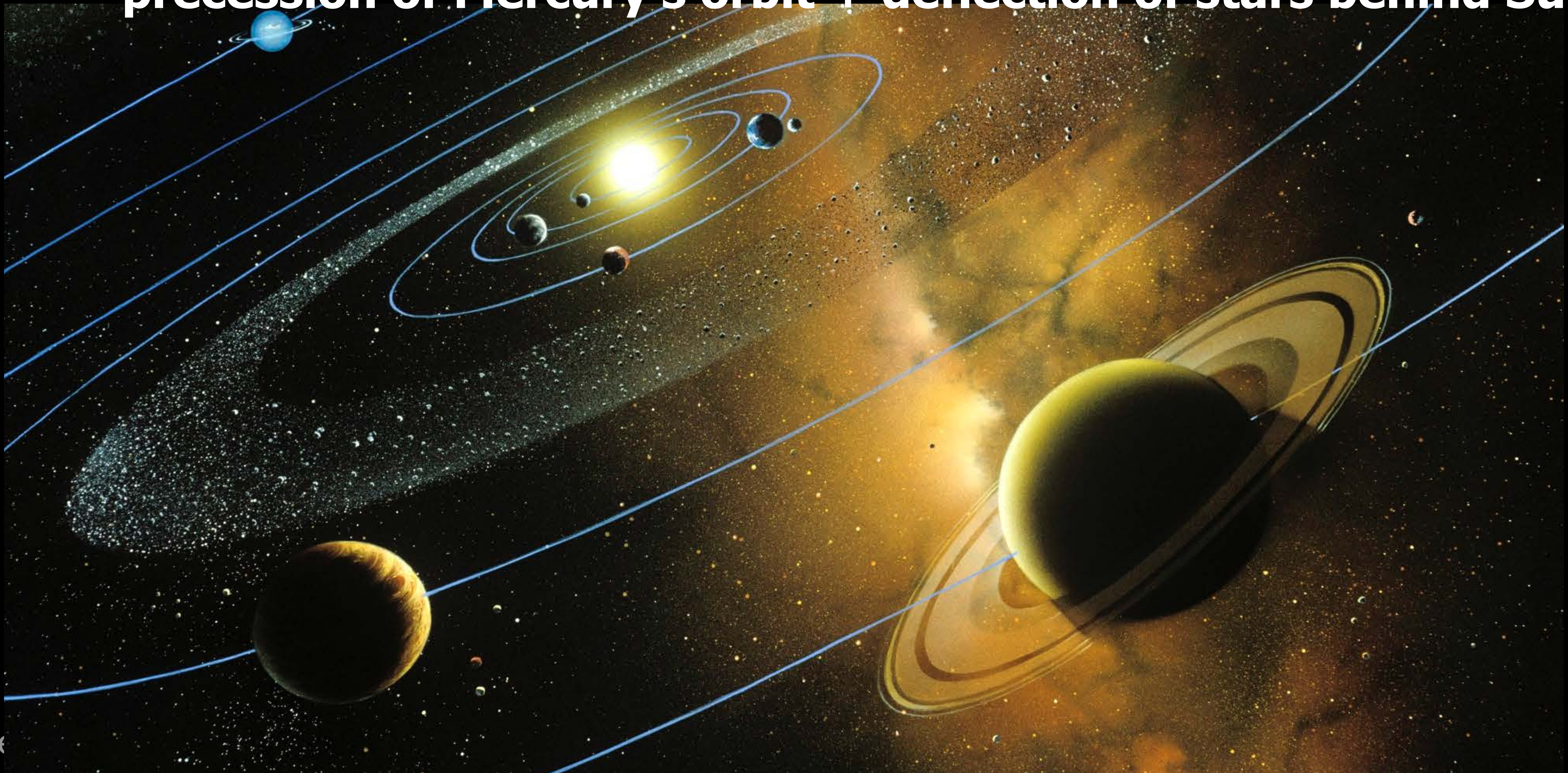
6D information per object: x, y, z, v_x, v_y, v_z
(and in principle $dv_x, dv_y, dv_z, \ldots$)

What do we learn?

- Demand consistency w/ physical laws (gravity)
- Initial conditions, e.g. formation of solar system

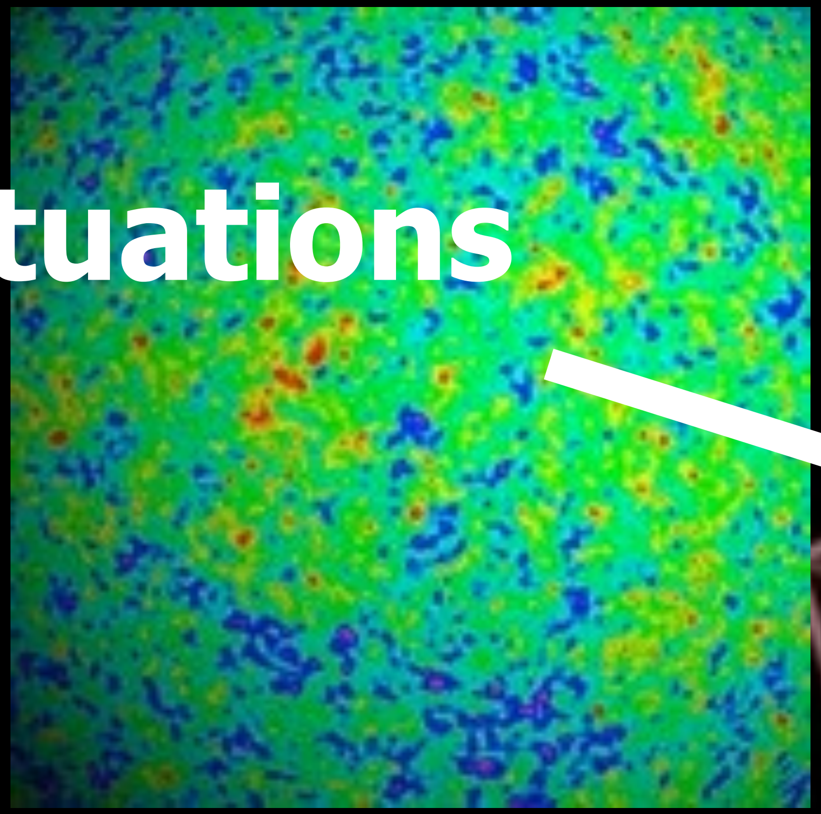
Maps of the solar system

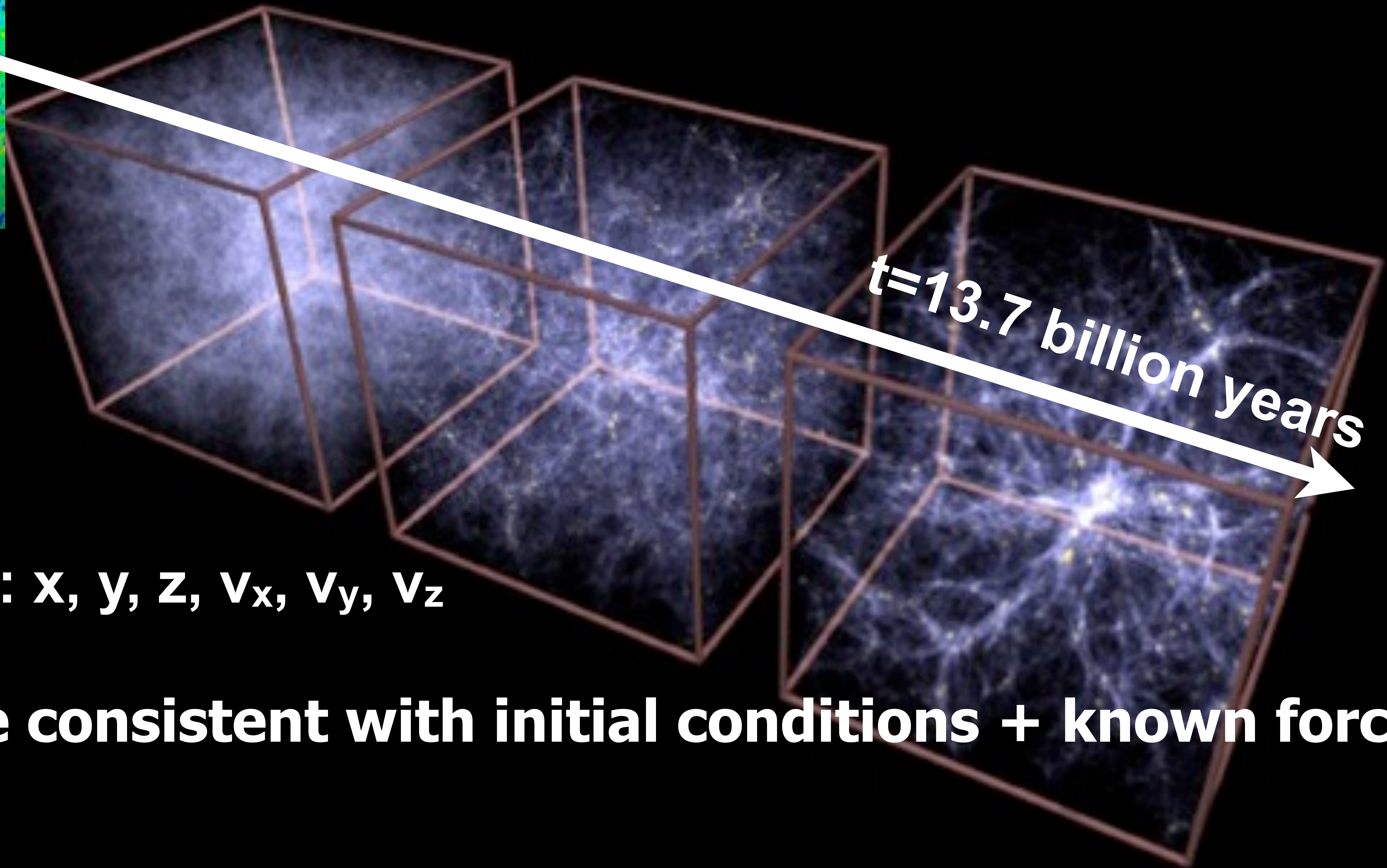
- The speed of light (1676; Jupiter's moons)
- Newton's laws of gravity (1687; planetary orbits)
- Scale of the solar system (1769; Venus transiting Sun)
- Confirmation of Einstein's general relativity (1916, 1919; precession of Mercury's orbit + deflection of stars behind Sun)



Maps of the Universe

$\mathcal{L}$(Our Universe| initial conditions, forces)





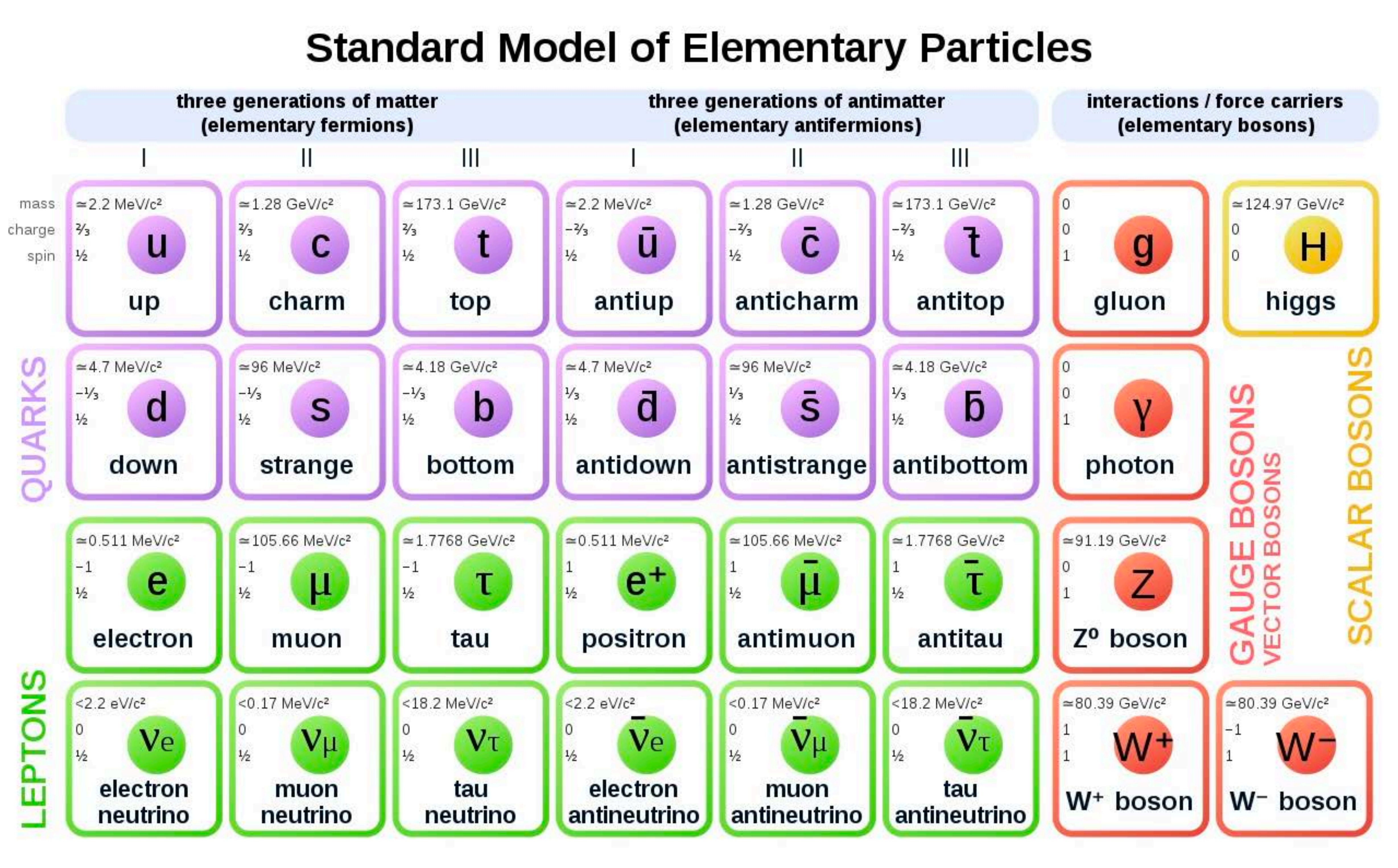
Observables:

6D information per object: x, y, z, v_x, v_y, v_z

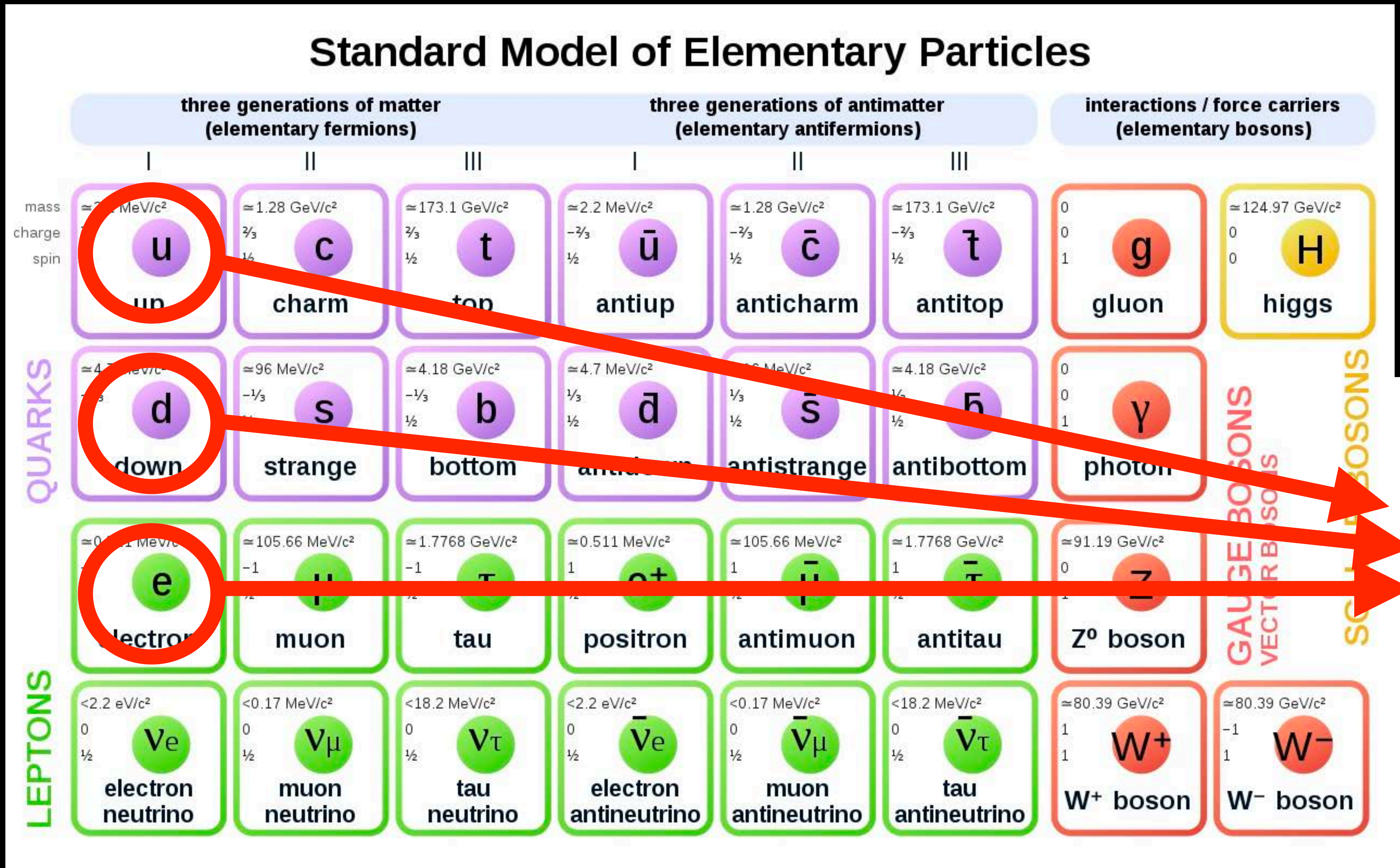
These observables must be consistent with initial conditions + known forces

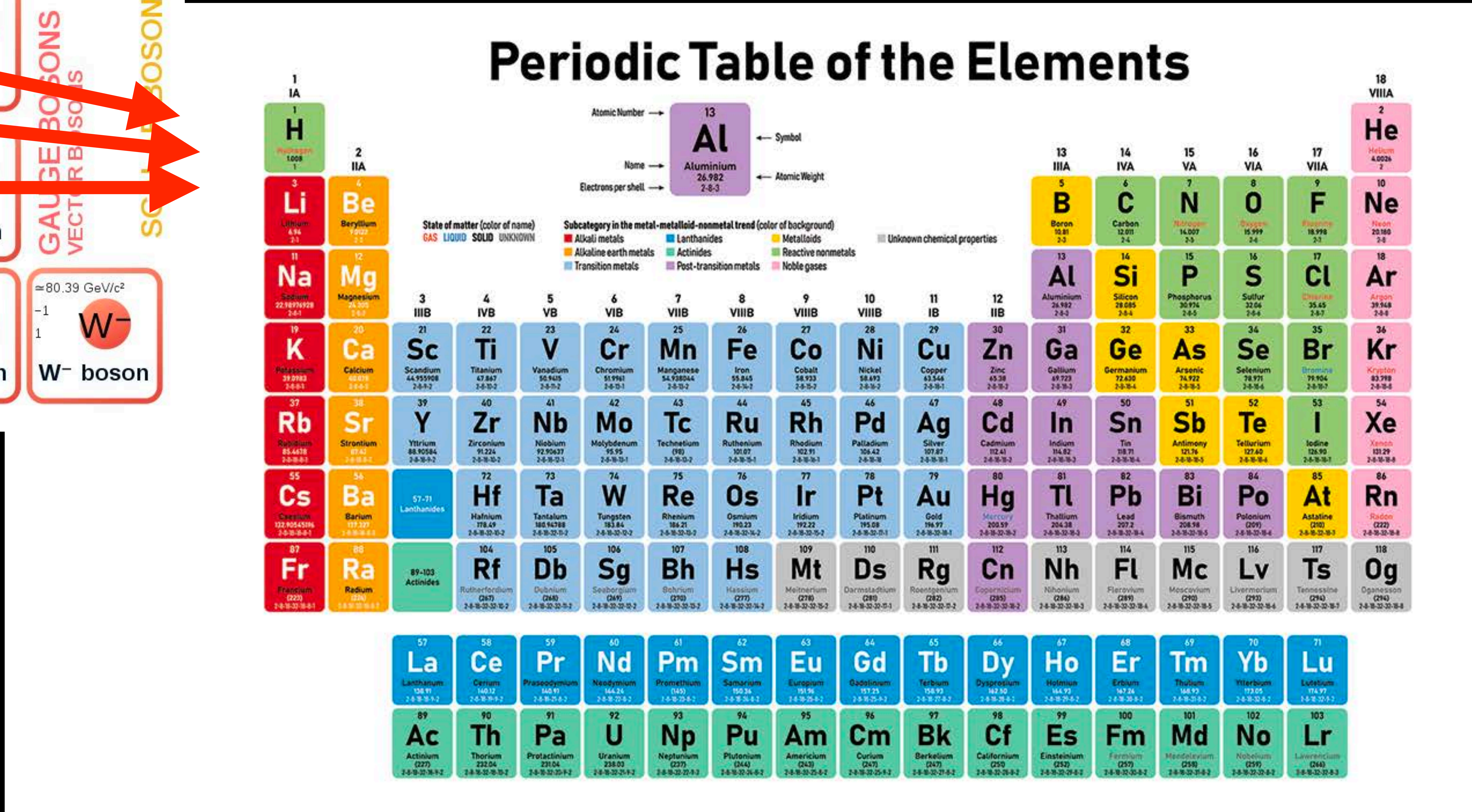
velocities = $\nabla\Phi$

What are the fundamental particles?



What are the fundamental particles?





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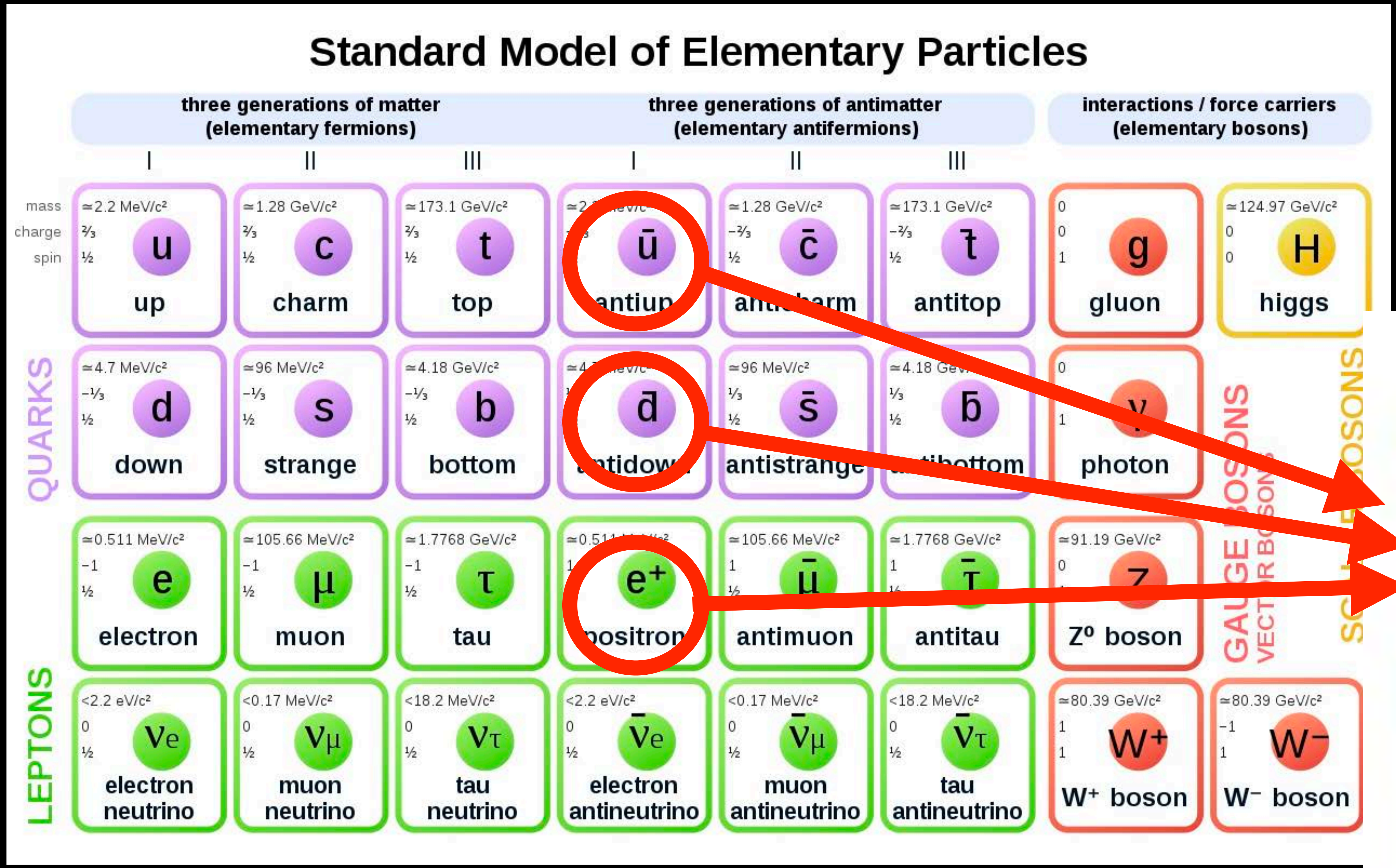
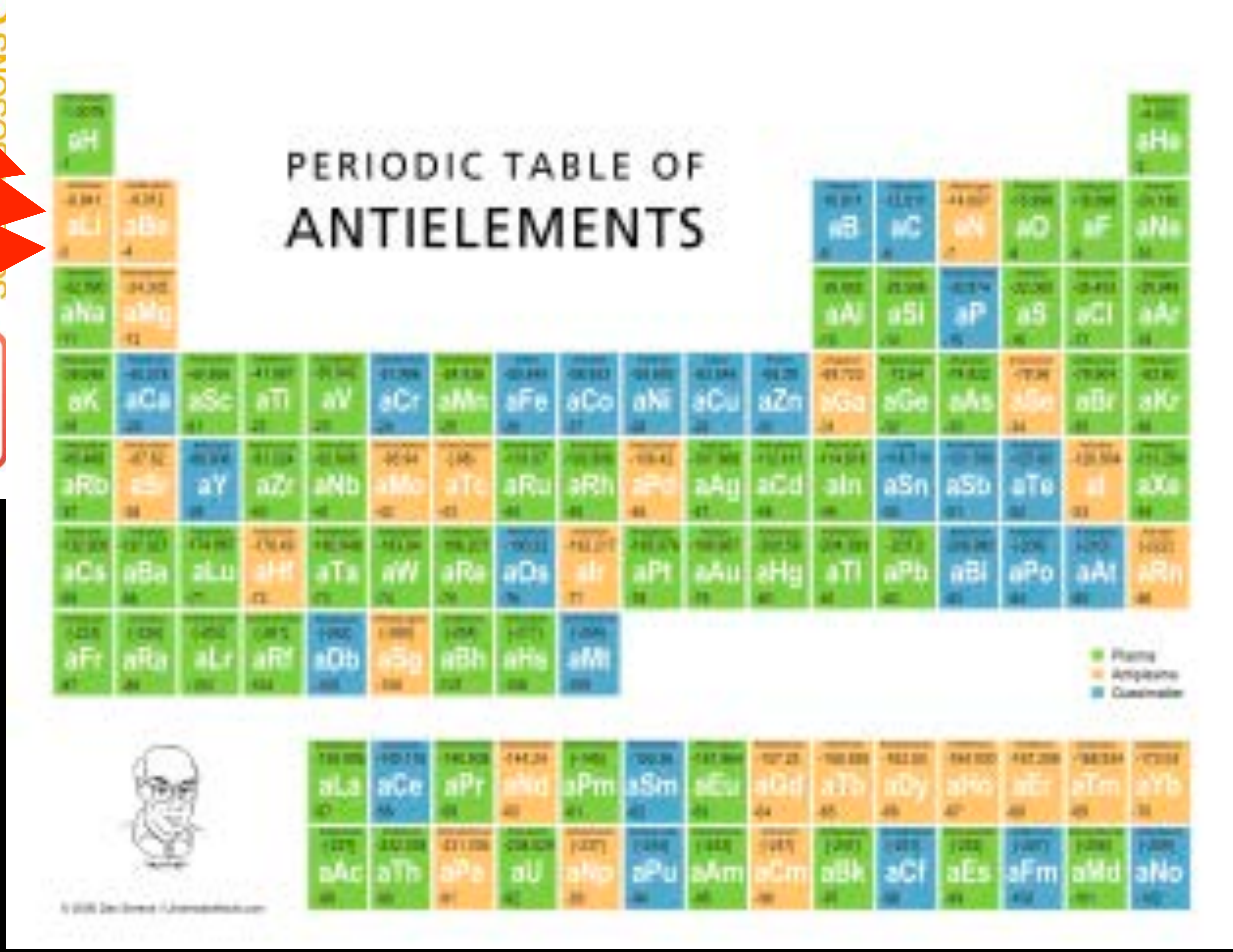
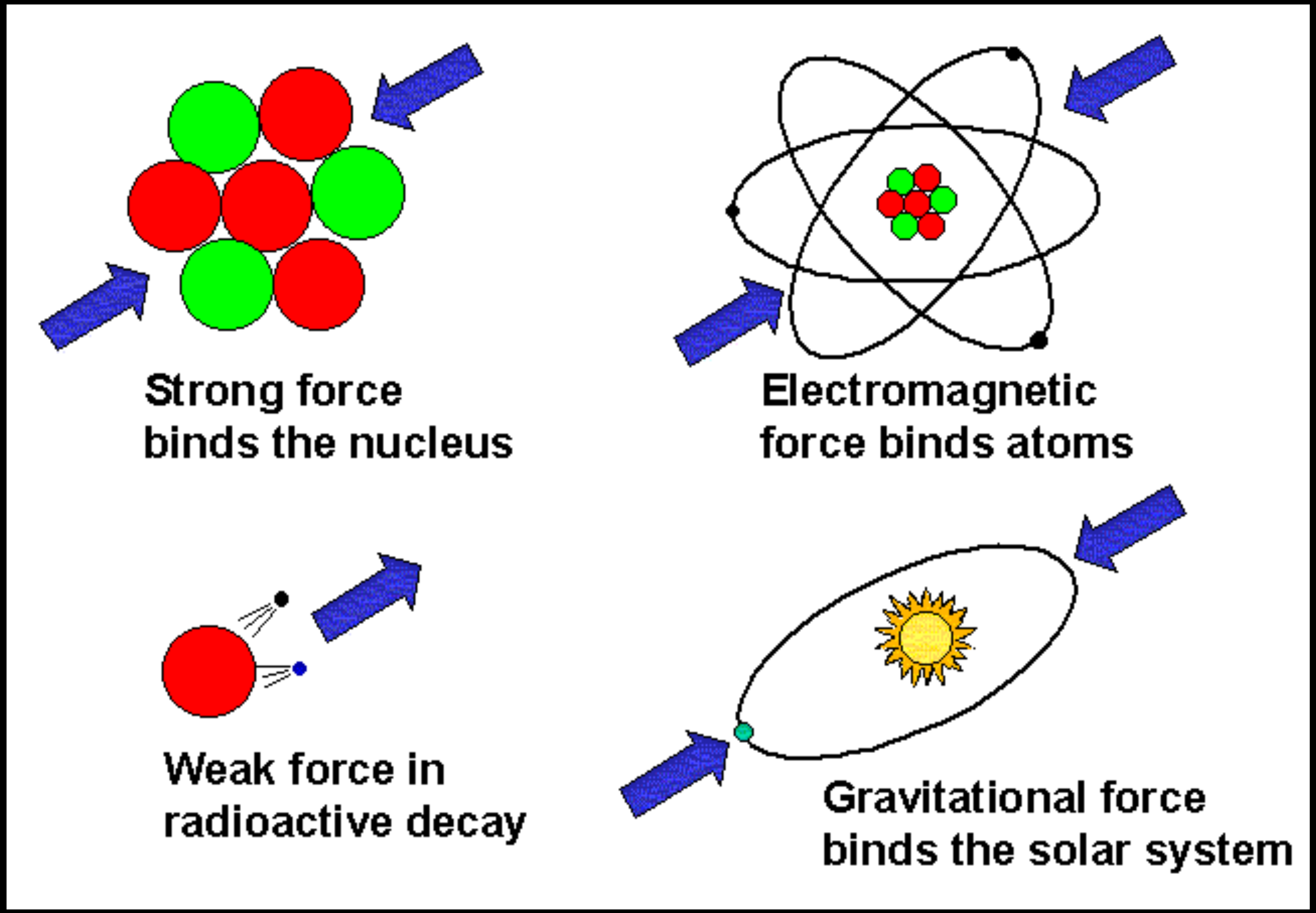


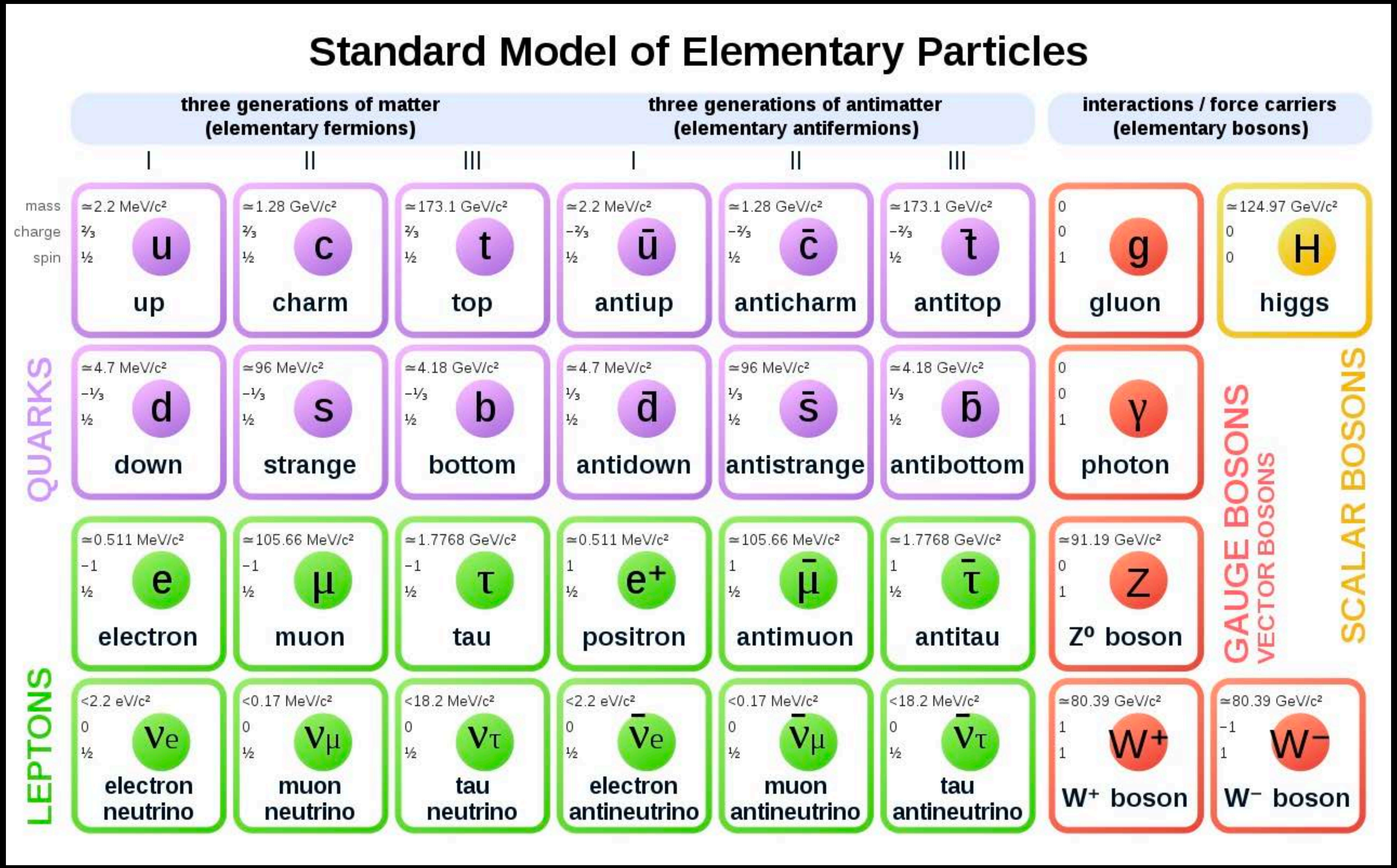


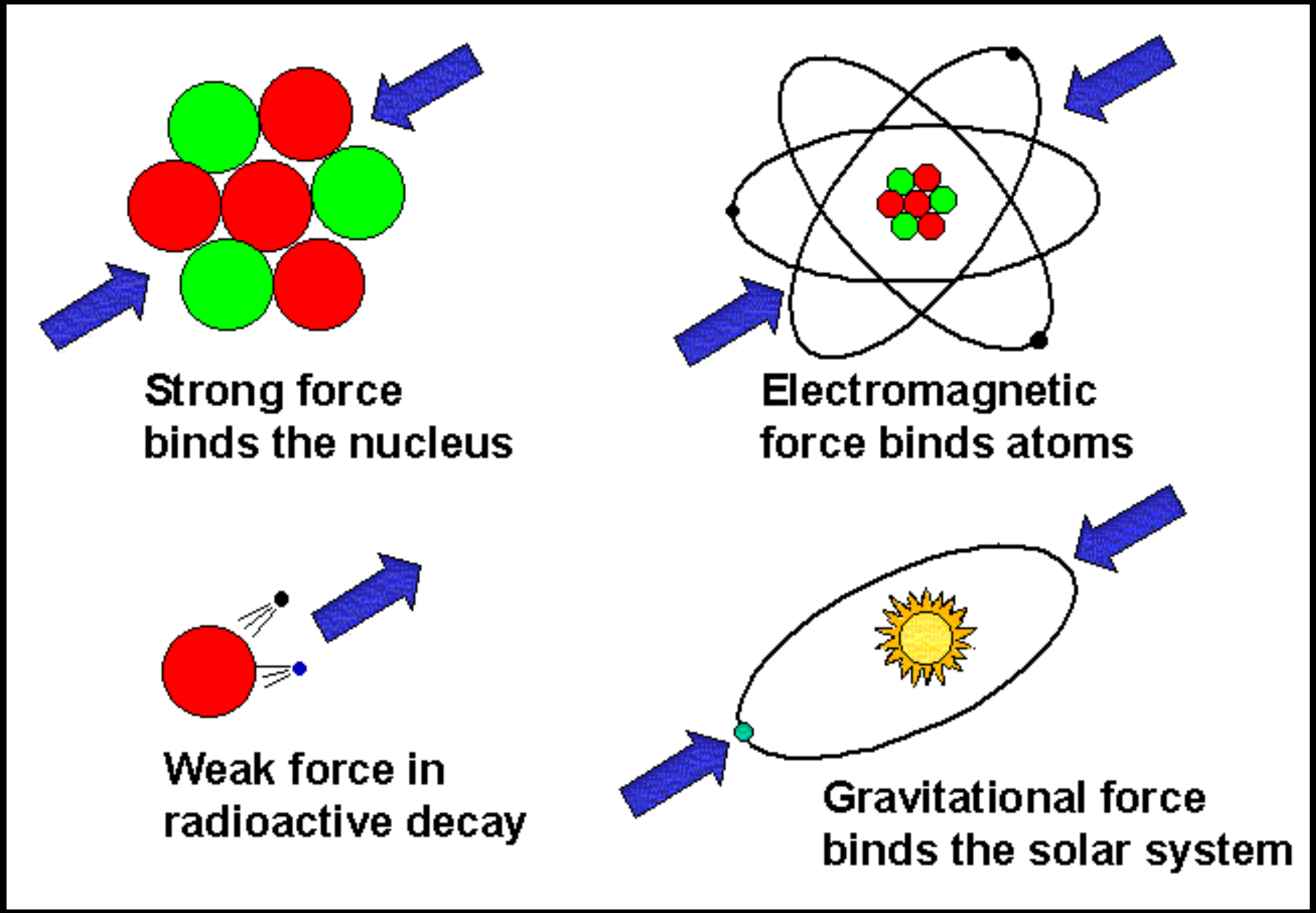
What are the fundamental forces?

The 4 known forces



This is the “standard model” of physics … supposed to explain everything

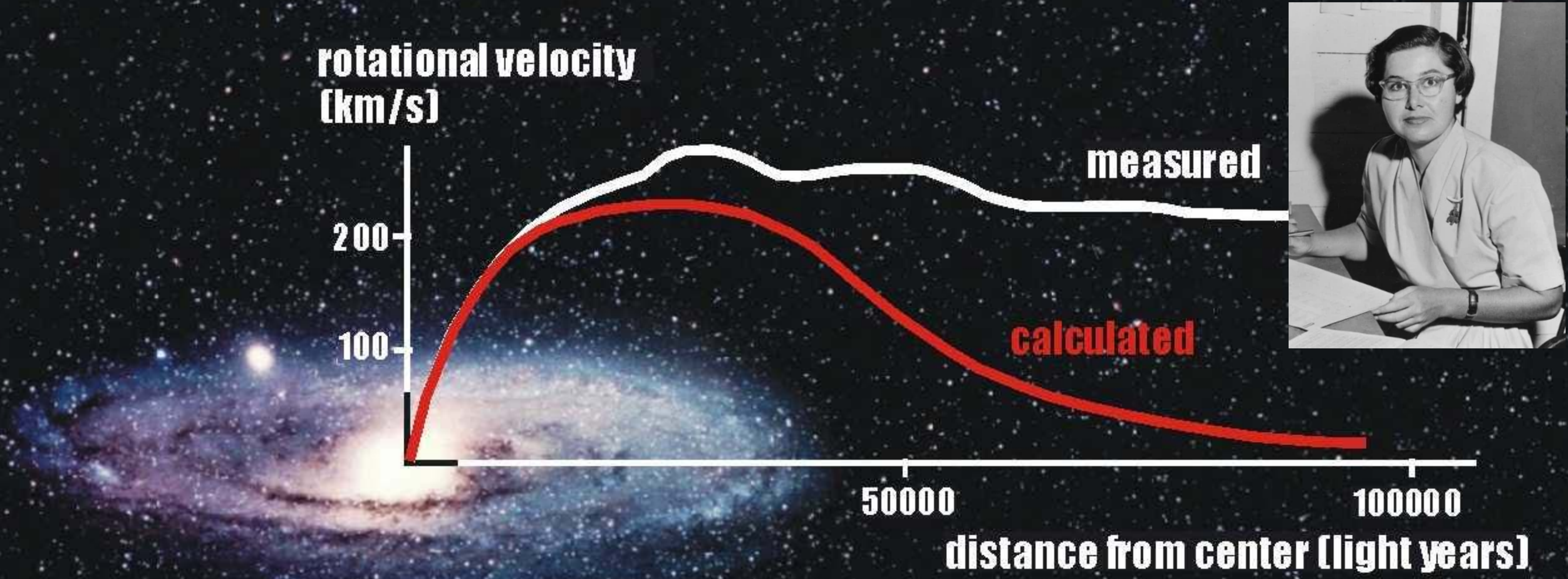




Cosmic maps are not consistent with the known fundamental particles + forces

Dark Matter is most of the mass in the universe

Vera Rubin discovery in the 1970s, explains why galaxies gravitationally bound (oops — no Nobel Prize)



Dark matter not yet found with “direct” searches

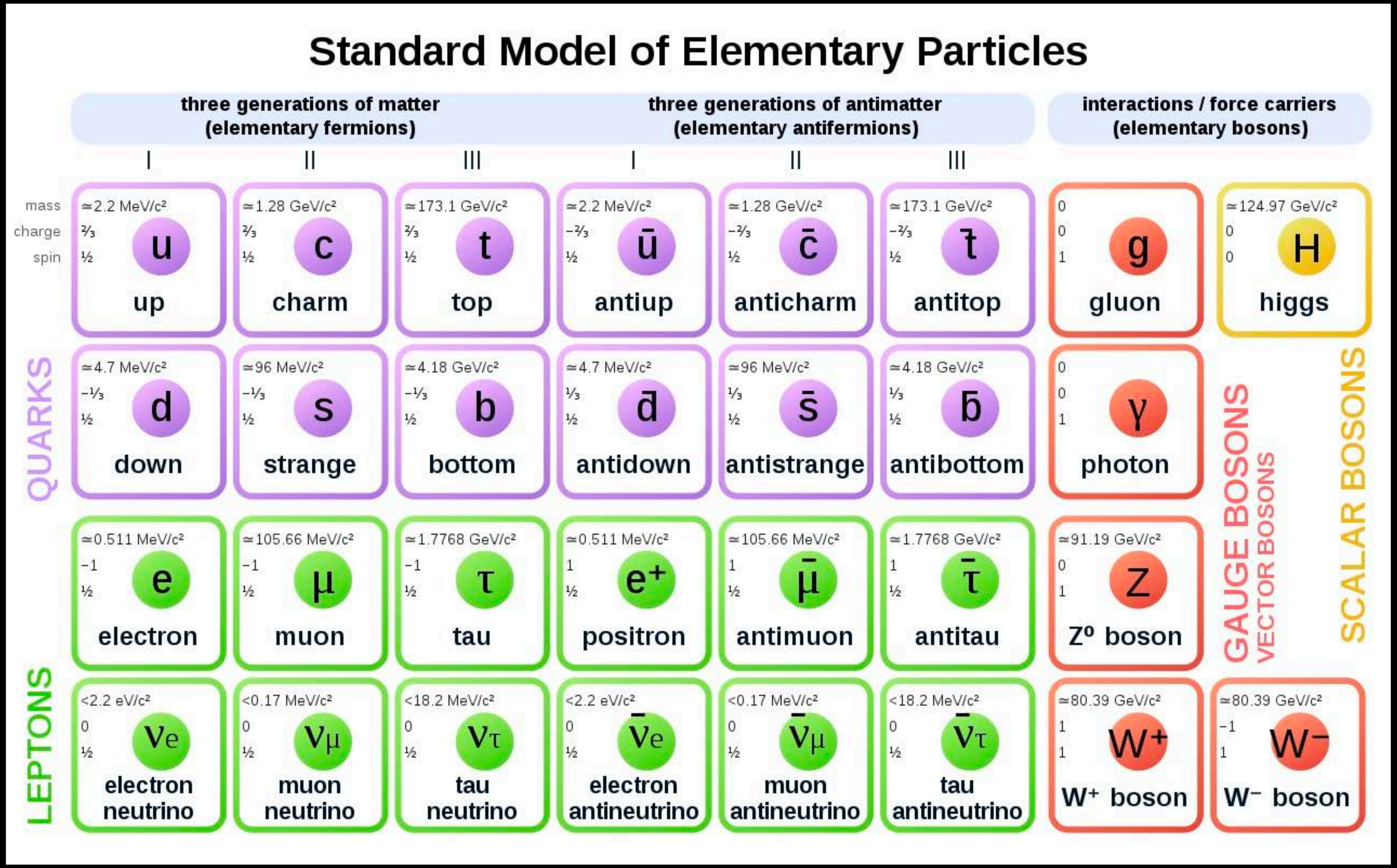
Lux-Zeplin experiment, 7 tons liquid Xenon 1 mile underground

We can now map where the dark dark matter is gravitationally

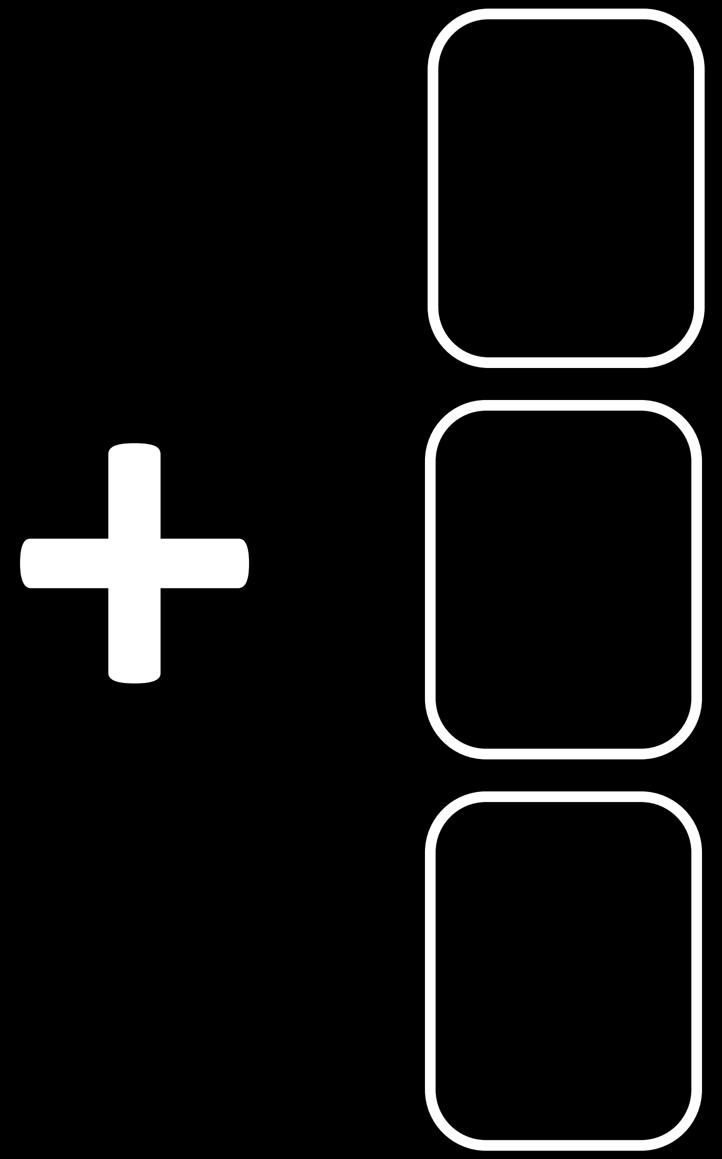
… and we know it's not made of normal matter (baryons)

What are the fundamental particles?

Known particles

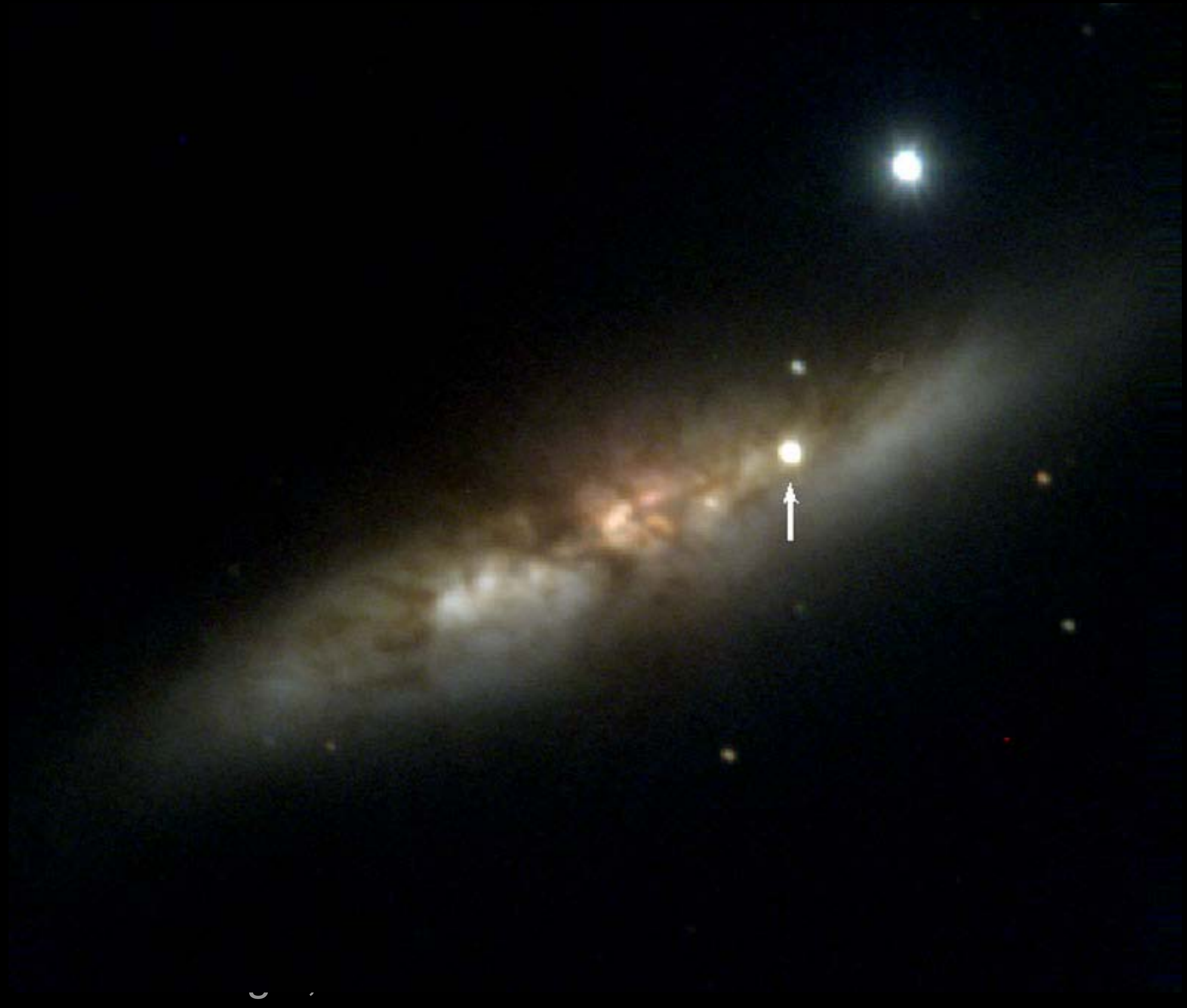


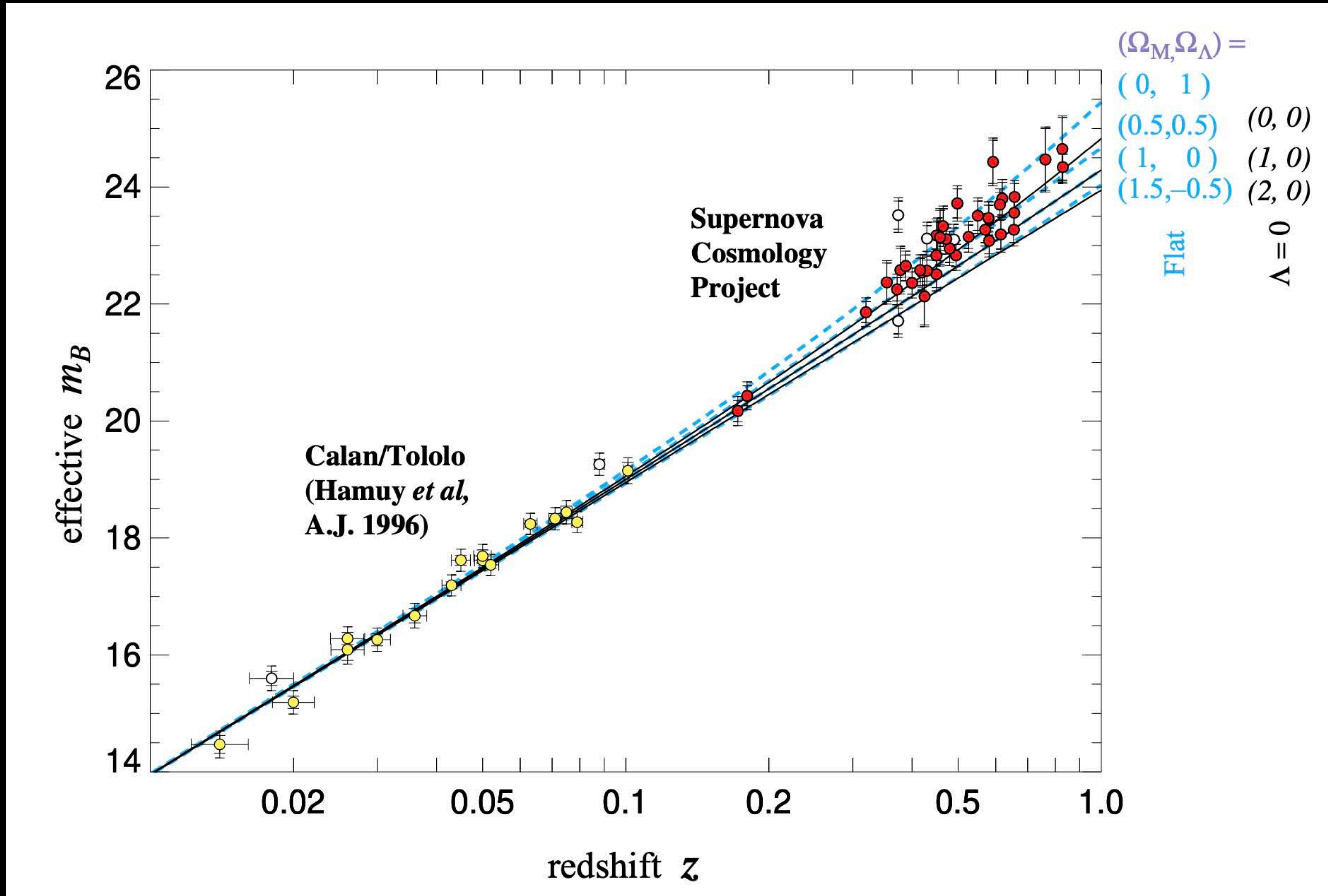
Dark Matter



<u>Dark Energy</u> is most of the mass-energy of the universe

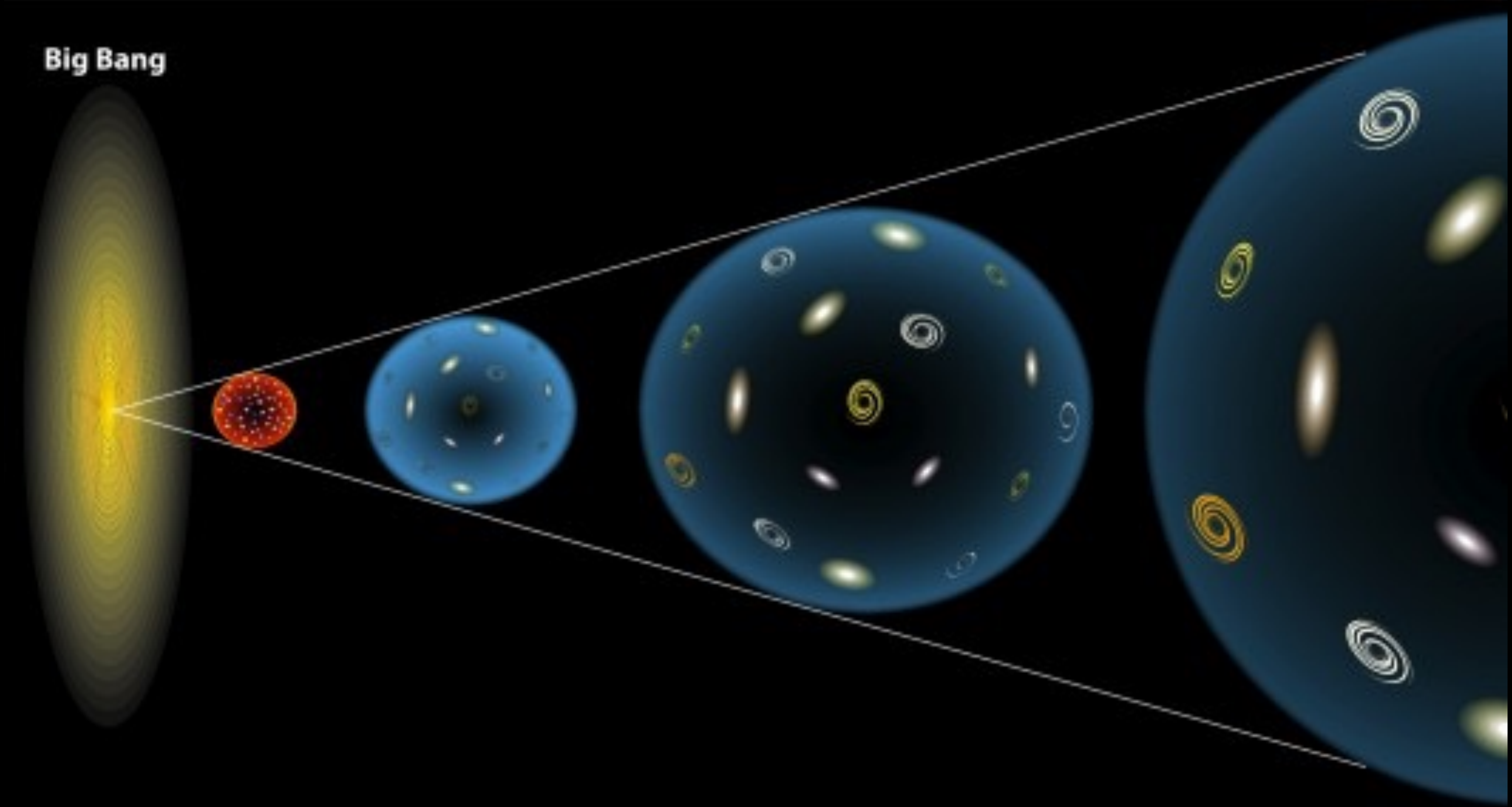
Discovered in 1998
Distant supernova explosions are too faint
(Nobel Prize for Perlmutter, Schmidt, Reiss in 2011)





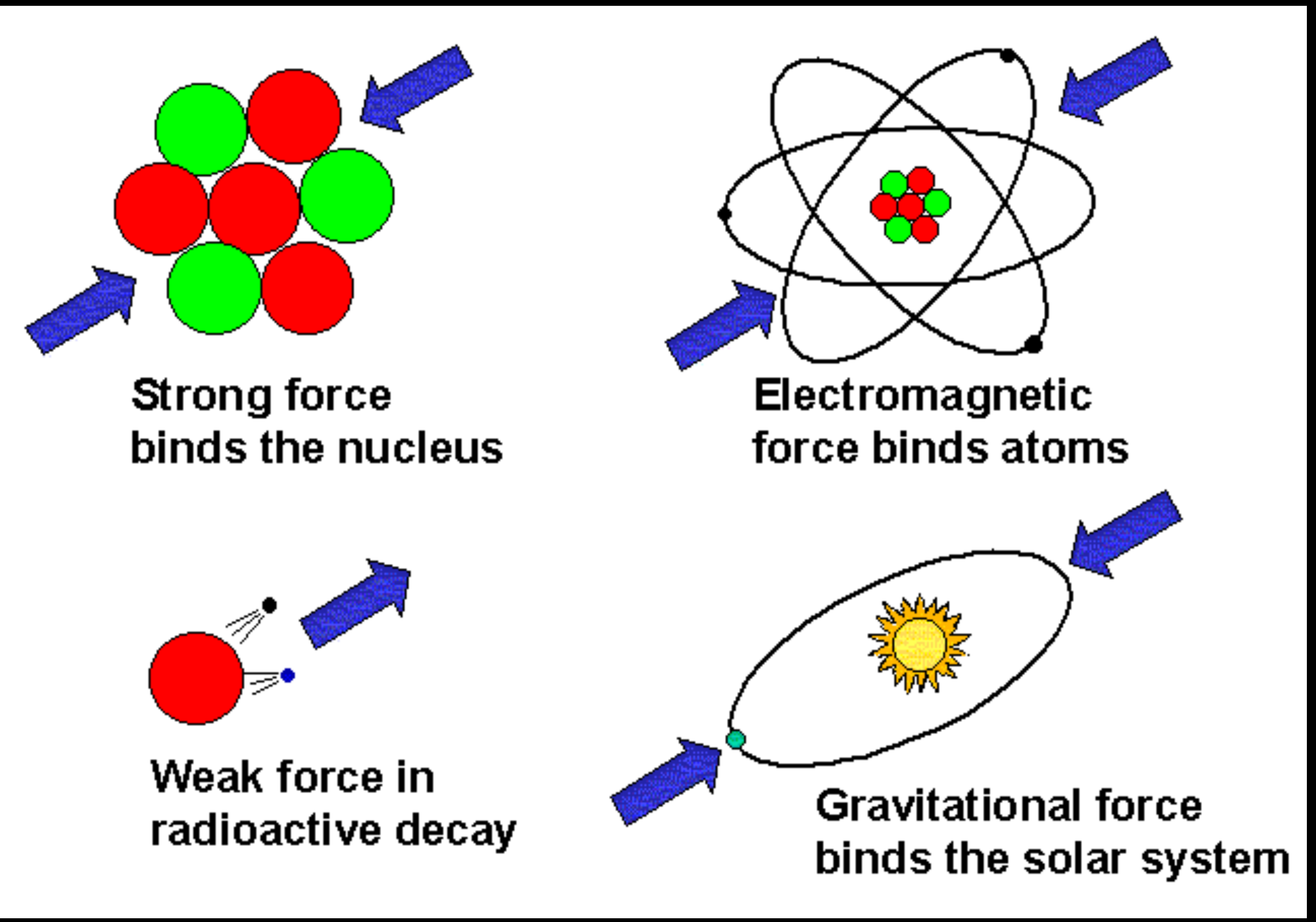
What is Dark Energy?

Too much "space" between us + distant galaxies
Apparent force accelerating expansion of universe



The Fundamental Forces

The 4 known forces



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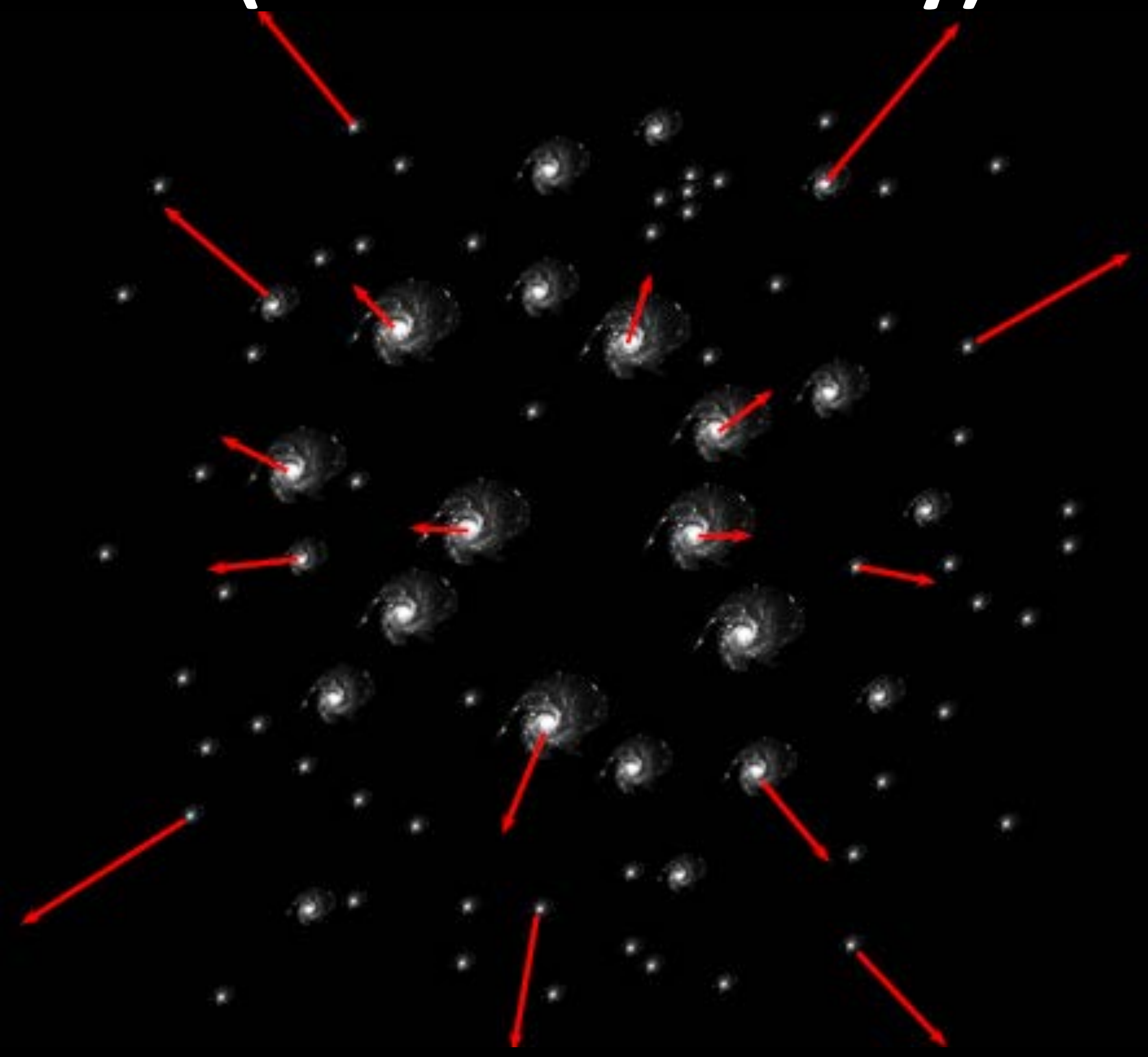
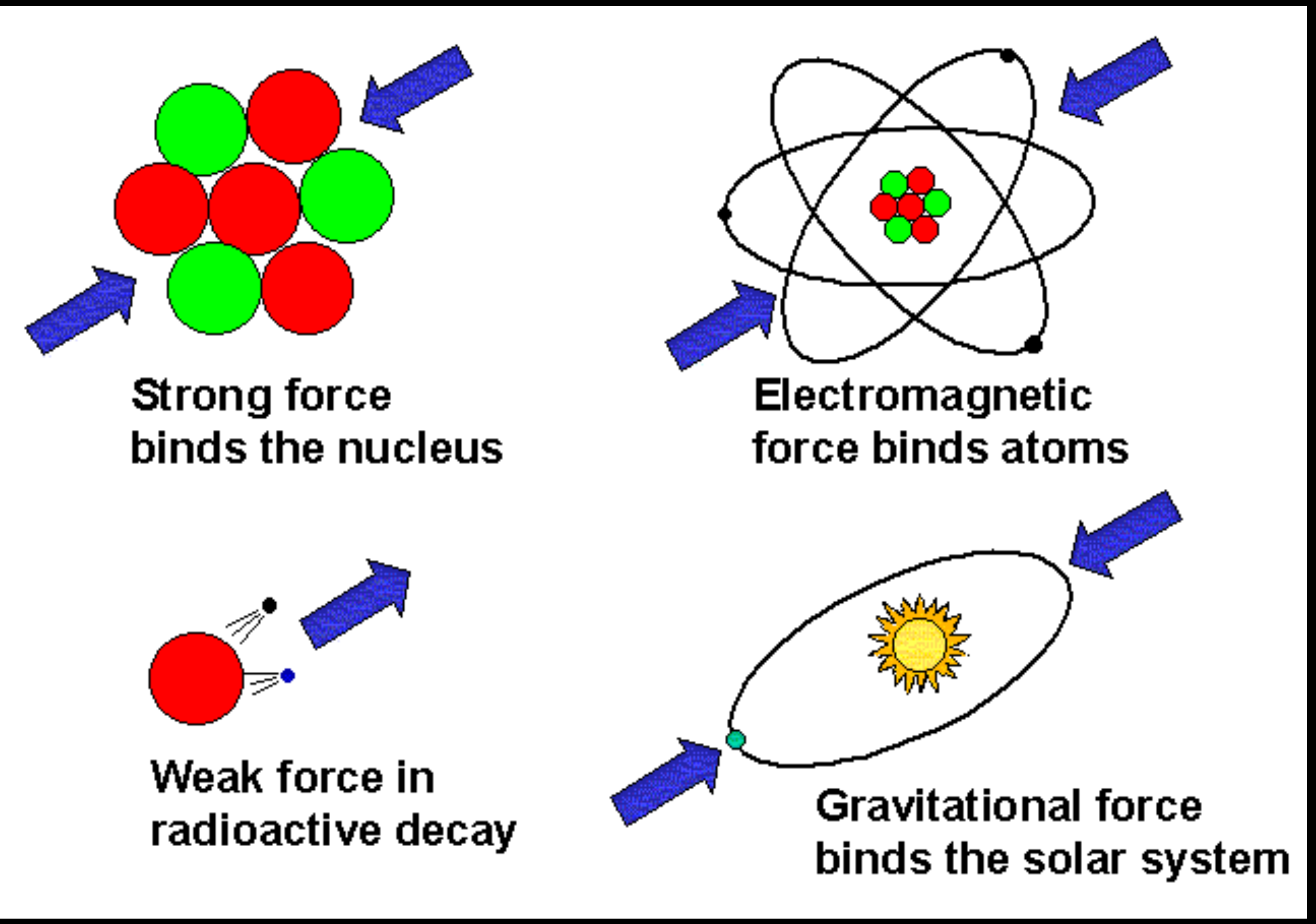
Dark energy
(dominates today)



The Fundamental Forces

The 4 known forces



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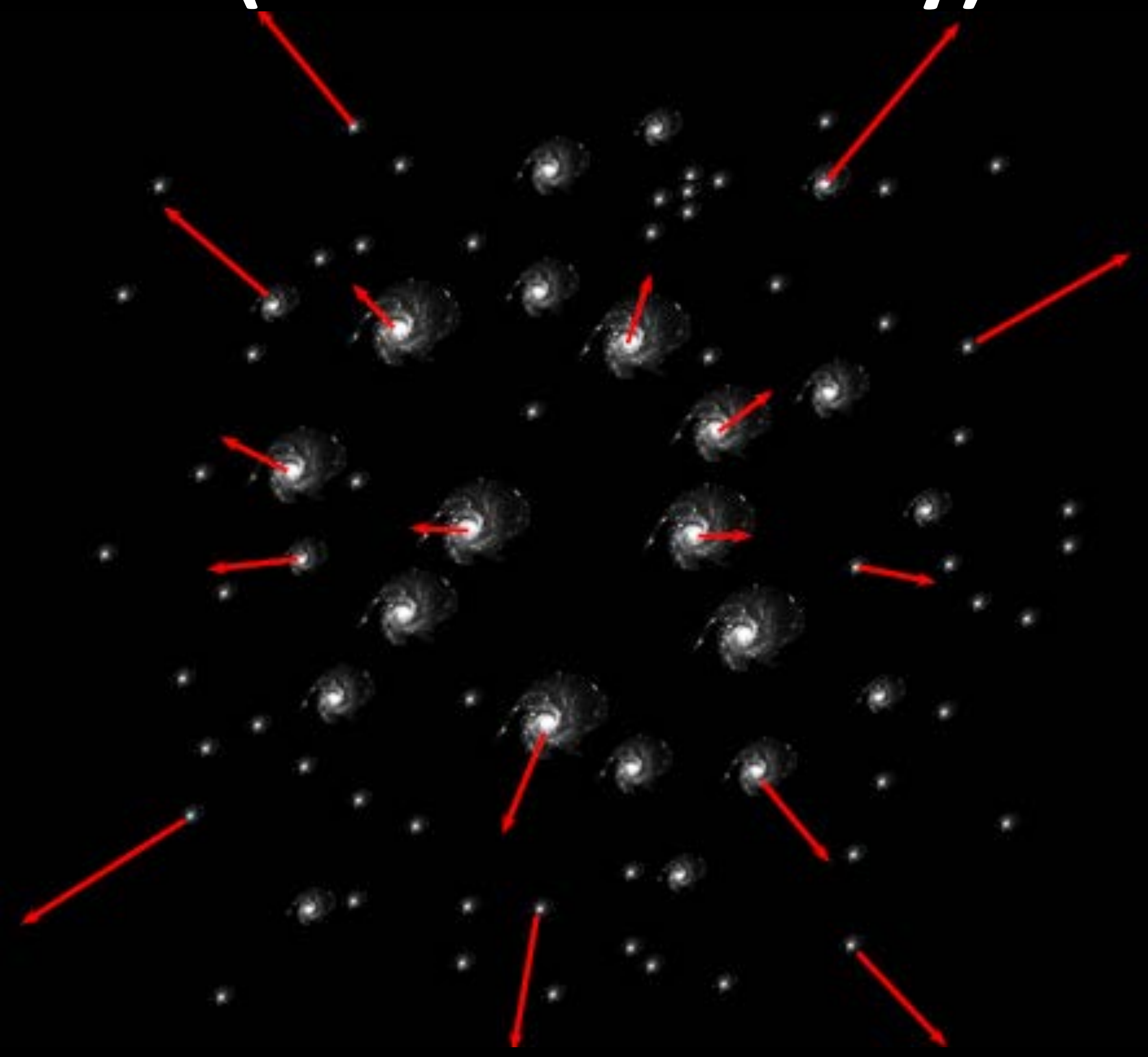

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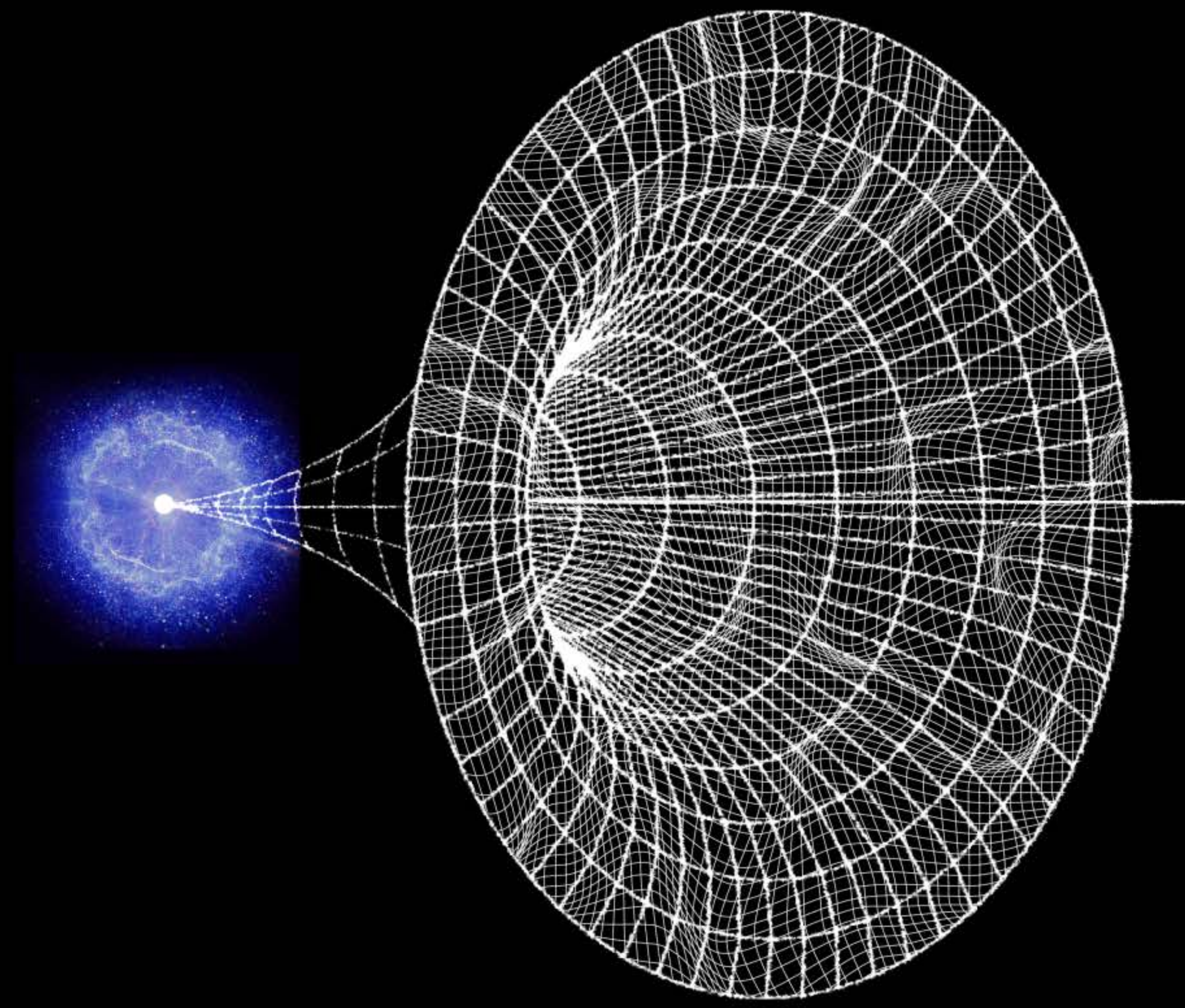
Inflation (<1 sec after Big Bang)



Most of the Universe's energy density is Dark Energy

Dark Energy is a component in the universe that can enter Einstein's equations of gravity like a cosmic fluid with a negative equation of state

$$w \equiv \frac{p_{de}}{c^2 \rho_{de}}$$

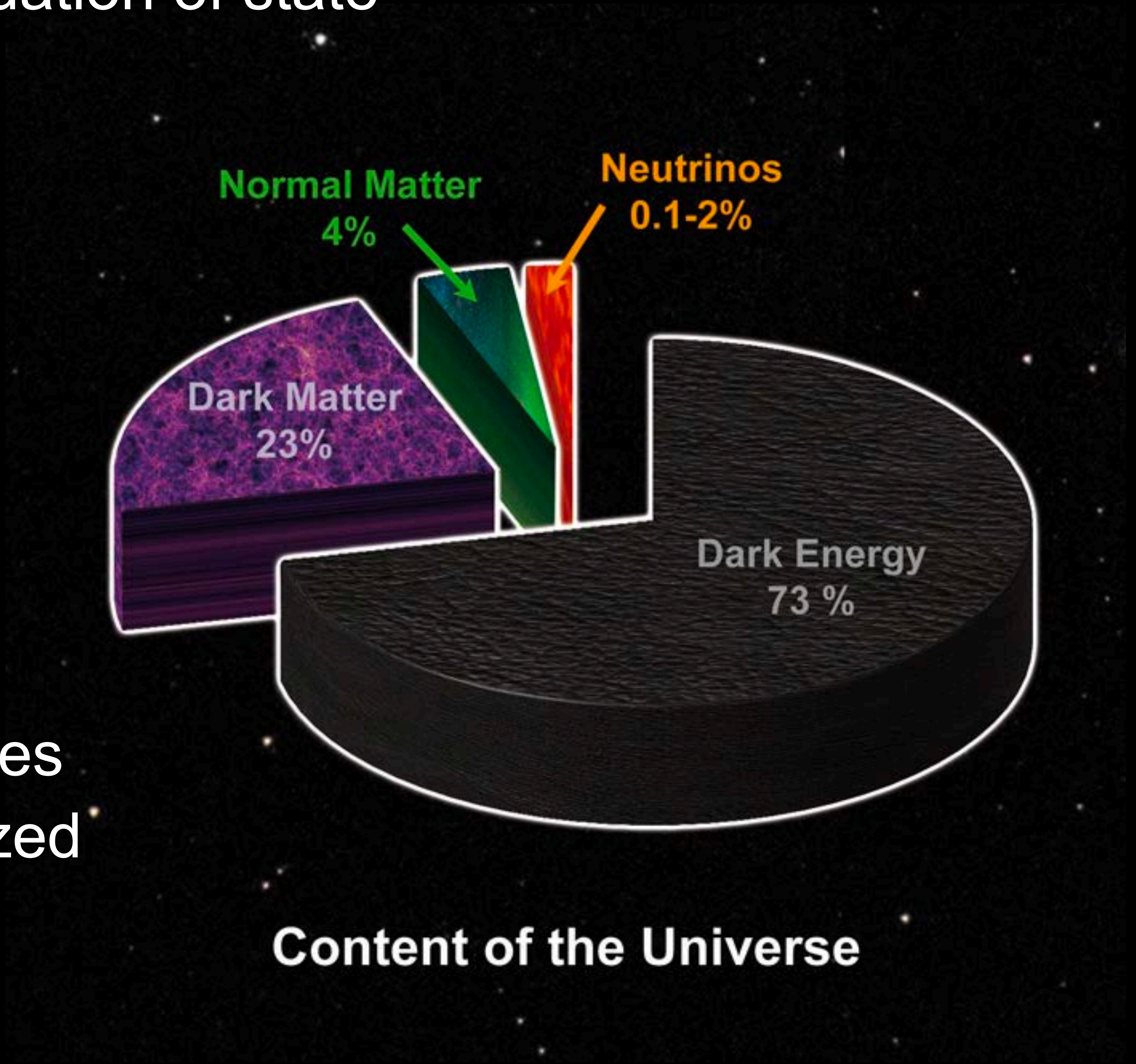
Negative w < -1/3 gives an accelerating expansion

$$\frac{\ddot{a}}{a} = -4\pi G \rho_{de} \left(\frac{1}{3} + w \right)$$

Dark Energy candidates can have slightly different w values

Dark Energy may be dynamic, conventionally parameterized by the scale factor a:

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



Mapping the Universe

Maps are never simply x,y,z

DESI maps in angular coordinates (**α**,**δ**) + redshift (z)


Maps are never simply x,y,z
gravity erases initial conditions on small (non-linear) scales
DESI maps in angular coordinates (α,δ) + redshift (z)
z= distance + gravity-induced velocity
TNG50

Mapping the Universe: Point maps vs. Statistical maps

Galaxies are not a good standard ruler!

$$d_A(z) = \frac{c}{\sqrt{|\Omega_{\mathrm{k},0}|}\,H_0(1+z)} \cdot S_k\left(H_0\sqrt{|\Omega_{\mathrm{k},0}|}\int_0^z \frac{dz}{H(z)}\right)$$

…though they have been proposed over the years as “standard-izable”, (dating back to Carl Wirtz in 1924), as have galaxy clusters…

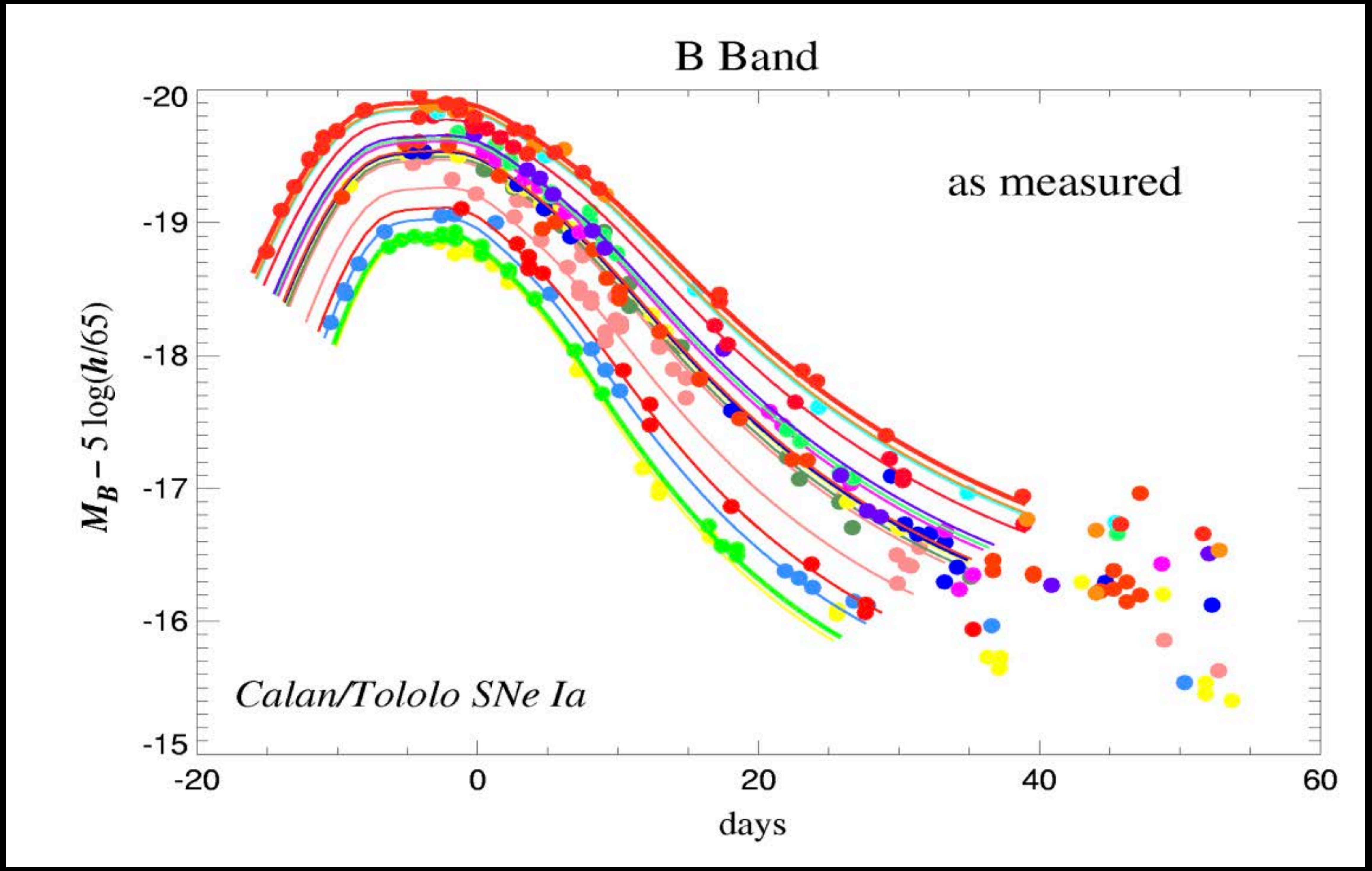
Mapping the Universe: Point maps vs. Statistical maps

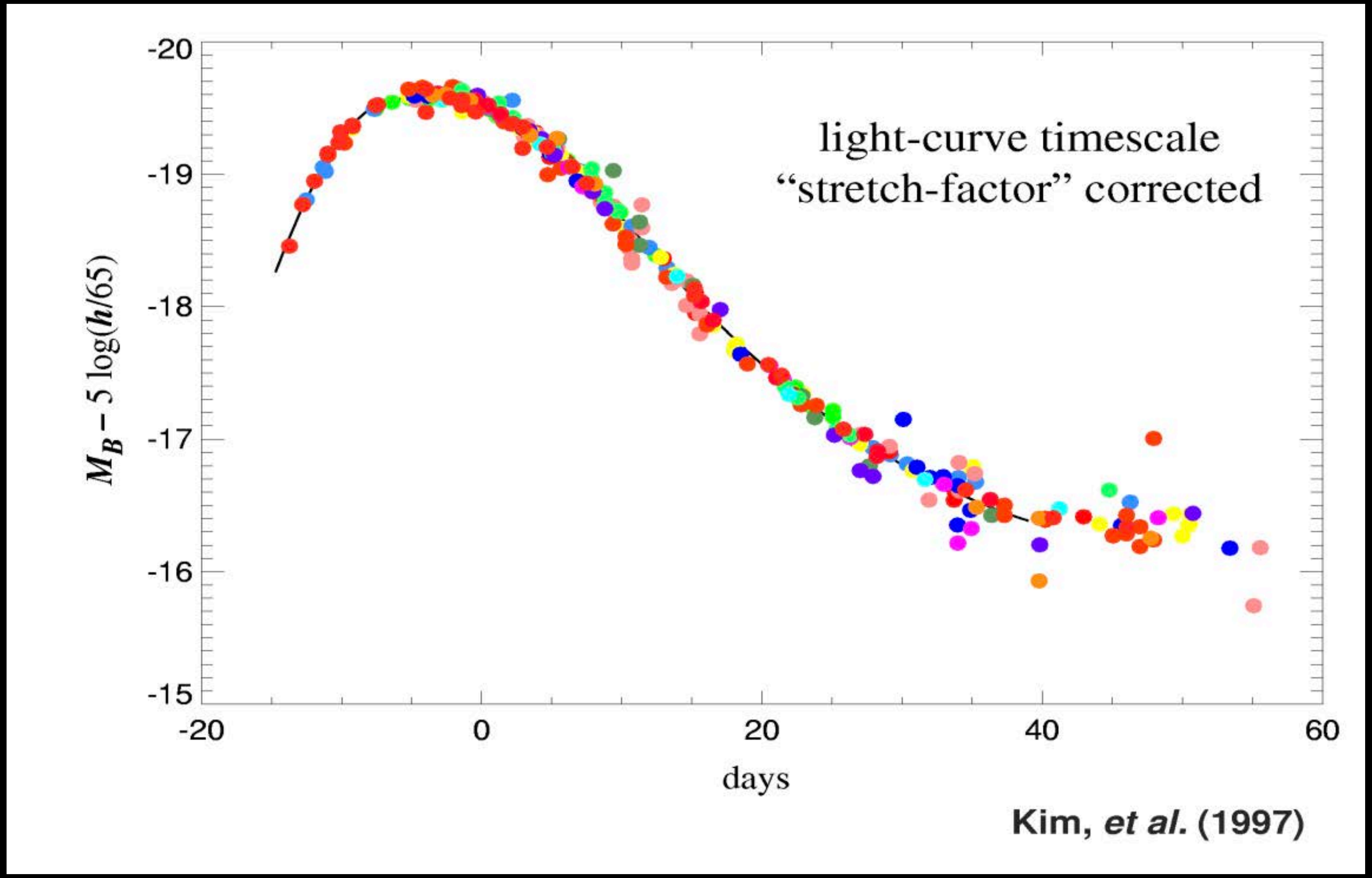
Supernovae are an excellent "standard-izable" candle in intrinsic luminosity

$$d_\mathrm{L} = \frac{r_1}{a} = (1+z)\,r_1 = (1+z)^2 \cdot d_\mathrm{A}$$

Absolute mag
Apparent mag

$$\underset{\text{Absolute mag}}{M} - \underset{\text{Apparent mag}}{m} = 2.5 \log \left(\frac{d_{\mathrm{L},0}}{d_\mathrm{L}}\right)^2 = 5 \log \left(\frac{d_{\mathrm{L},0}}{d_\mathrm{L}}\right)$$



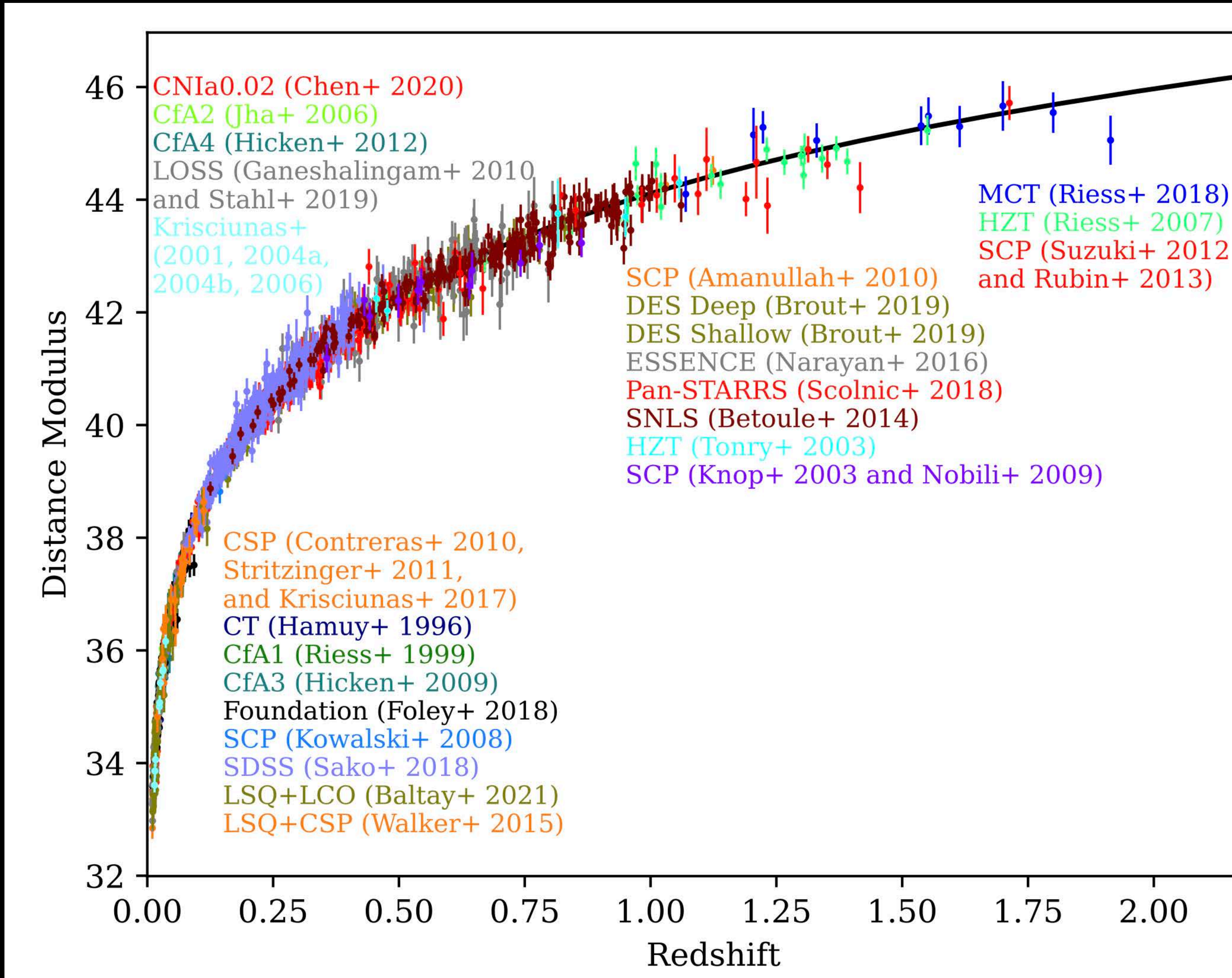


Mapping the Universe: Point maps vs. Statistical maps

Supernovae are an excellent "standard-izable" candle in intrinsic luminosity

Large compilations of supernova samples recently published

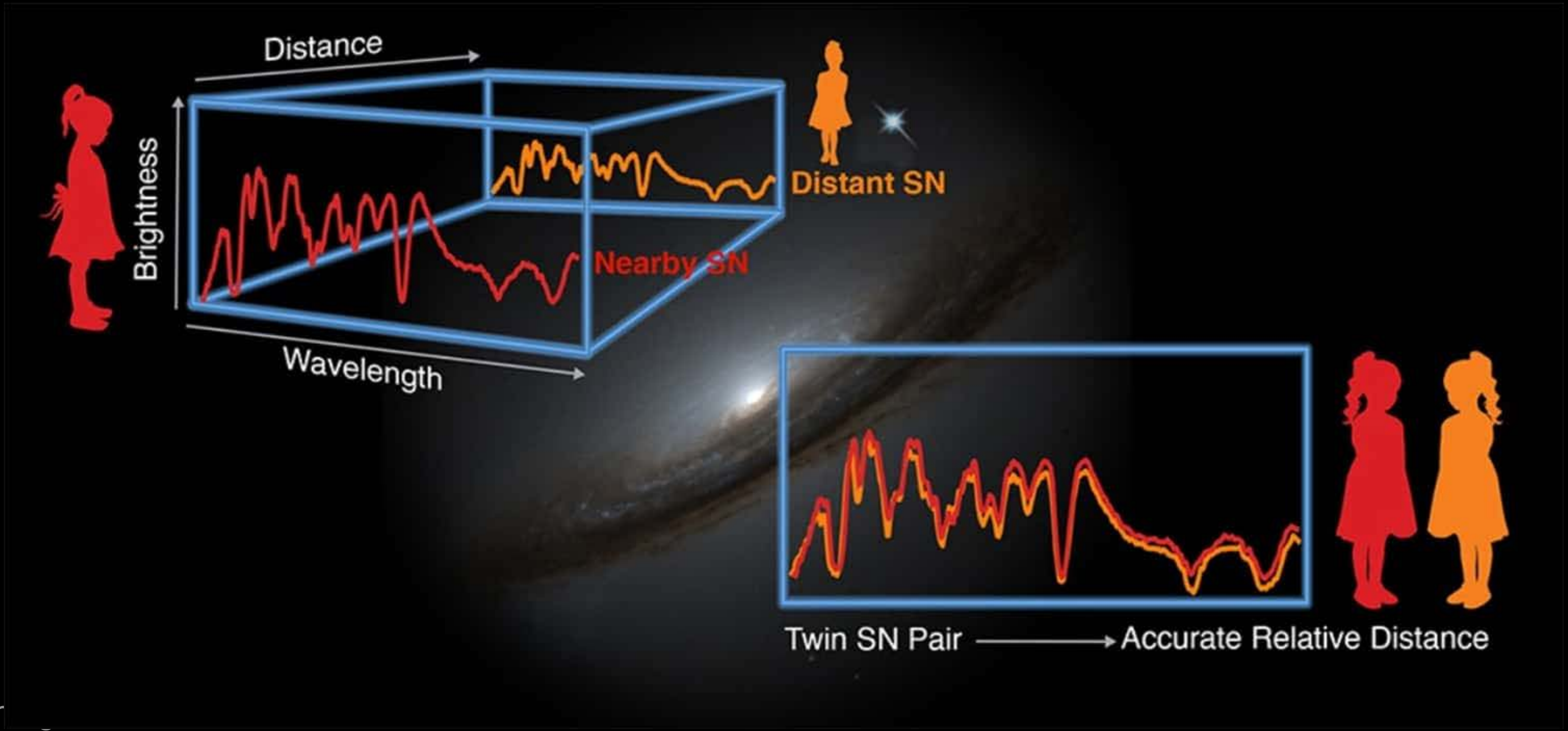
- Pantheon+(Scolnic+ 2022)
- Dark Energy Survey(DES-SN5YR 2023)
- Union 3 -> Unity (Rubin+ 2024)



Mapping the Universe: Point maps vs. Statistical maps

Supernovae are an excellent "standard-izable" candle in intrinsic luminosity

Supernova "twinning" can double the accuracy of each supernova distance



Mapping the Universe: Point maps vs. Statistical maps

Supernovae are an excellent "standard-izable" candle in intrinsic luminosity

Next generation of supernova projects starting

- Zwicky Transient Factory (0.6 Gpix)
- La Silla Schmidt Southern Survey (0.3 Gpix)
- Vera Rubin Observatory (3 Gpix)

Promised improvements with

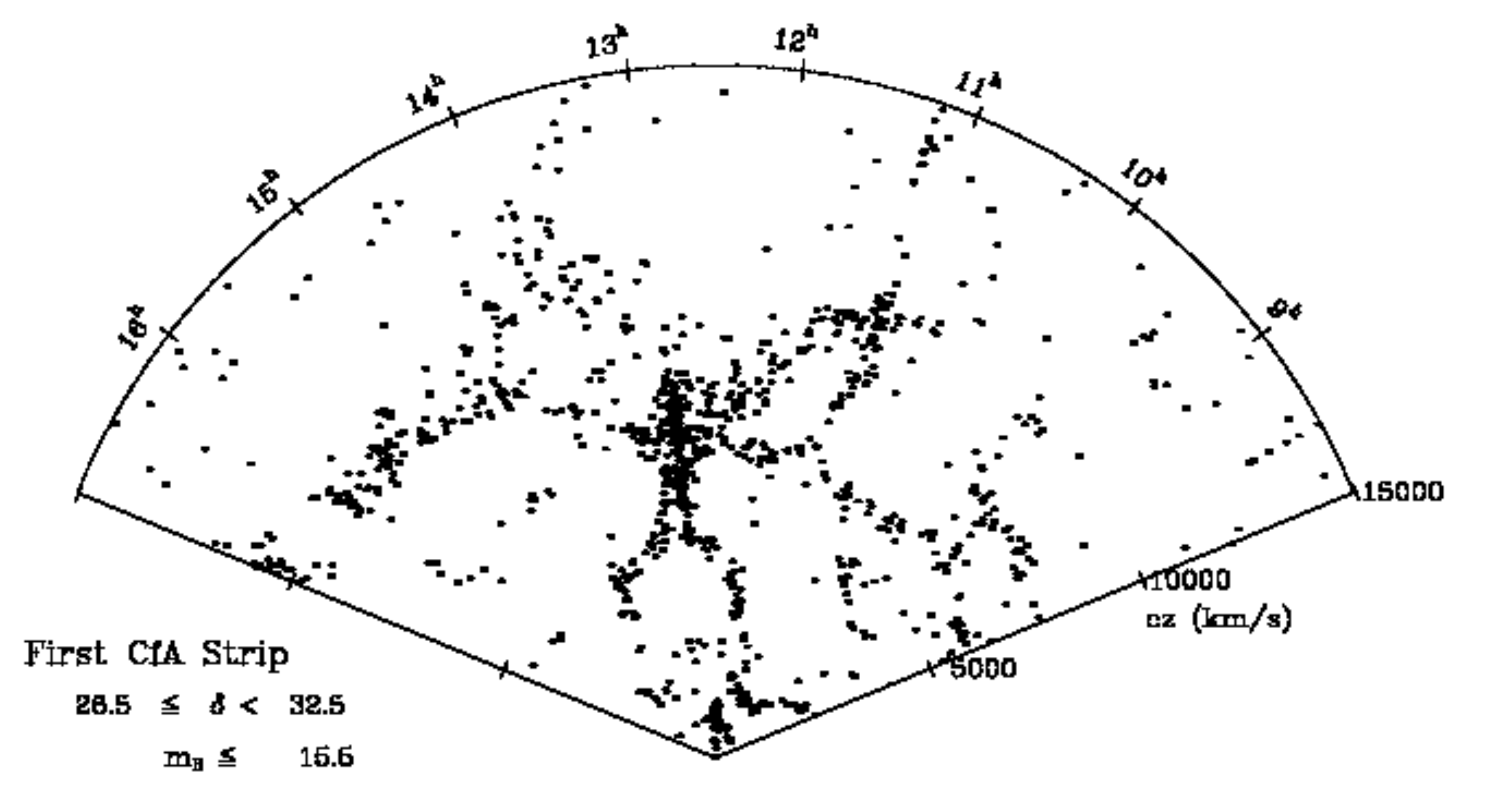
- more statistics (millions!)
- improved flux calibration

Mapping the Universe: Point maps vs. Statistical maps

The beginning of redshift surveys for 3-dimensional maps in 1983

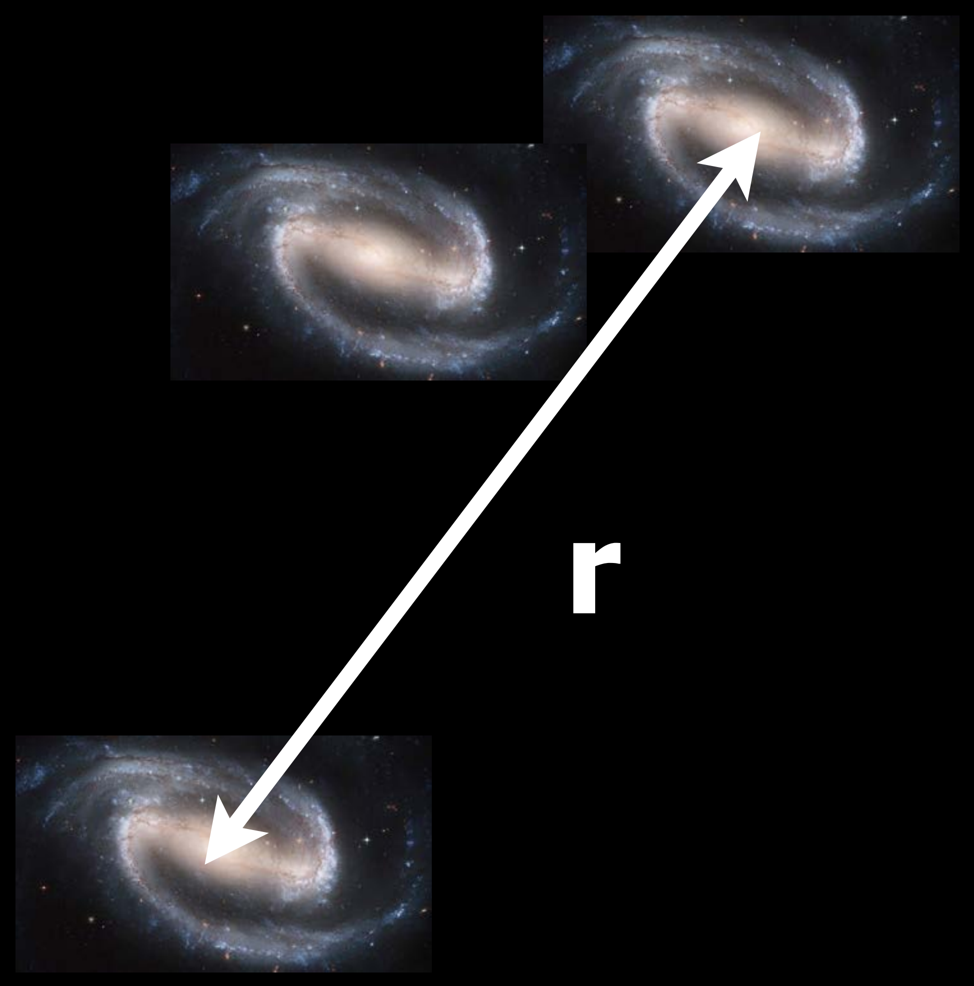
The "Z machine" (now in the Smithsonian)
Redshifted 2401 galaxies… 1 galaxy at a time…

the famous "stick man"



Huchra, Davis, Latham 1983

The start of measuring statistics of the clustering of galaxies with the 2-point function == excess probability of galaxies at each r



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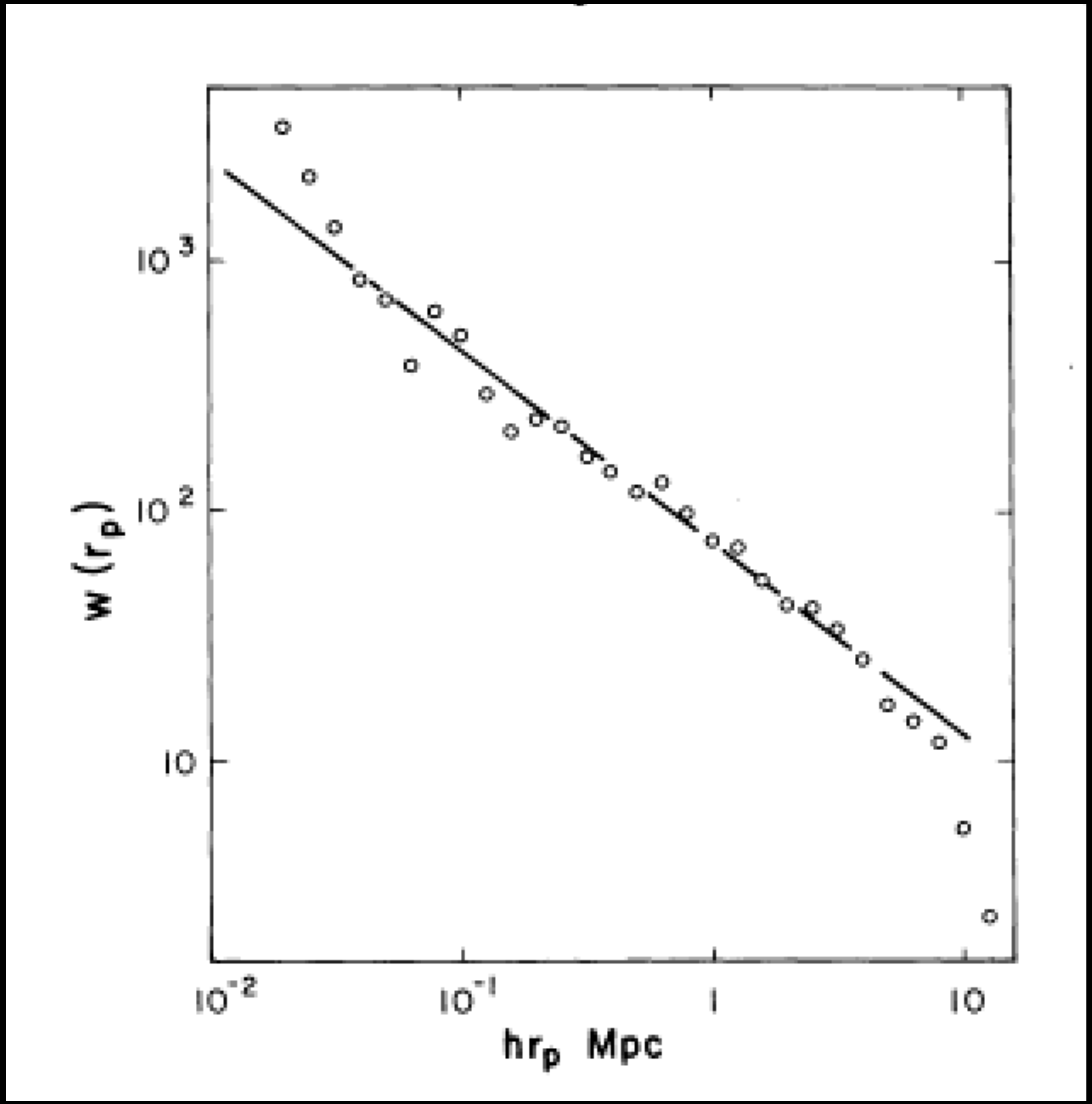
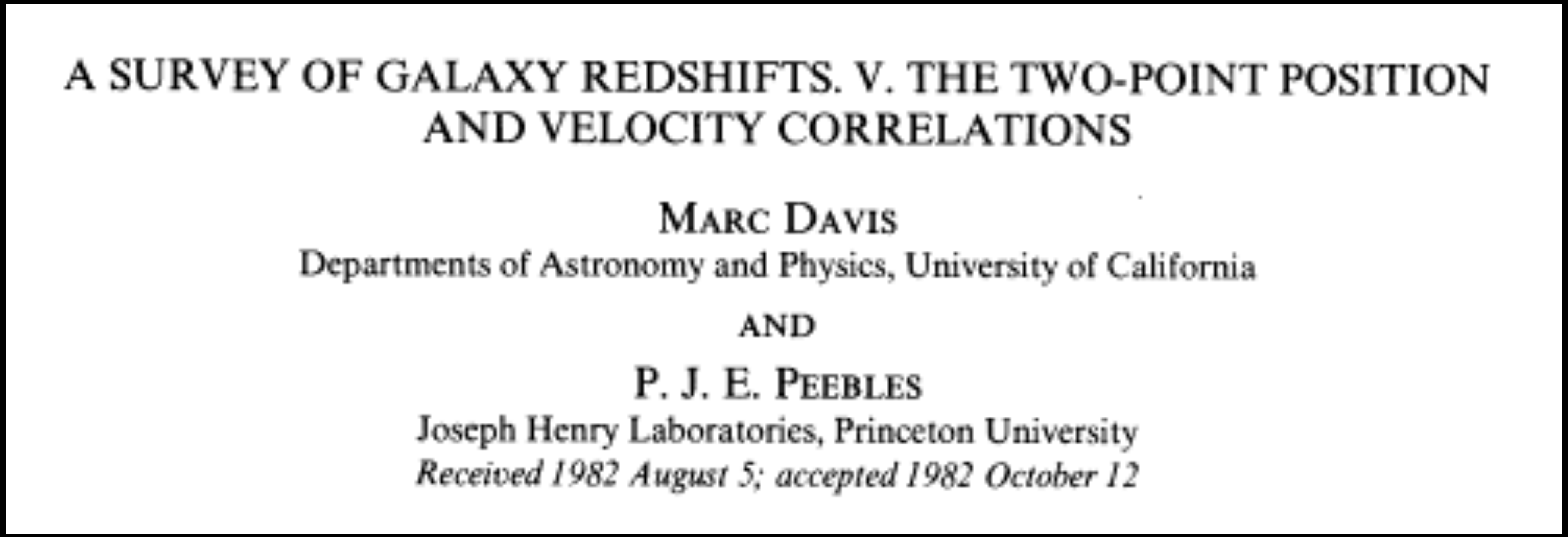




A SURVEY OF GALAXY REDSHIFTS. V. THE TWO-POINT POSITION AND VELOCITY CORRELATIONS

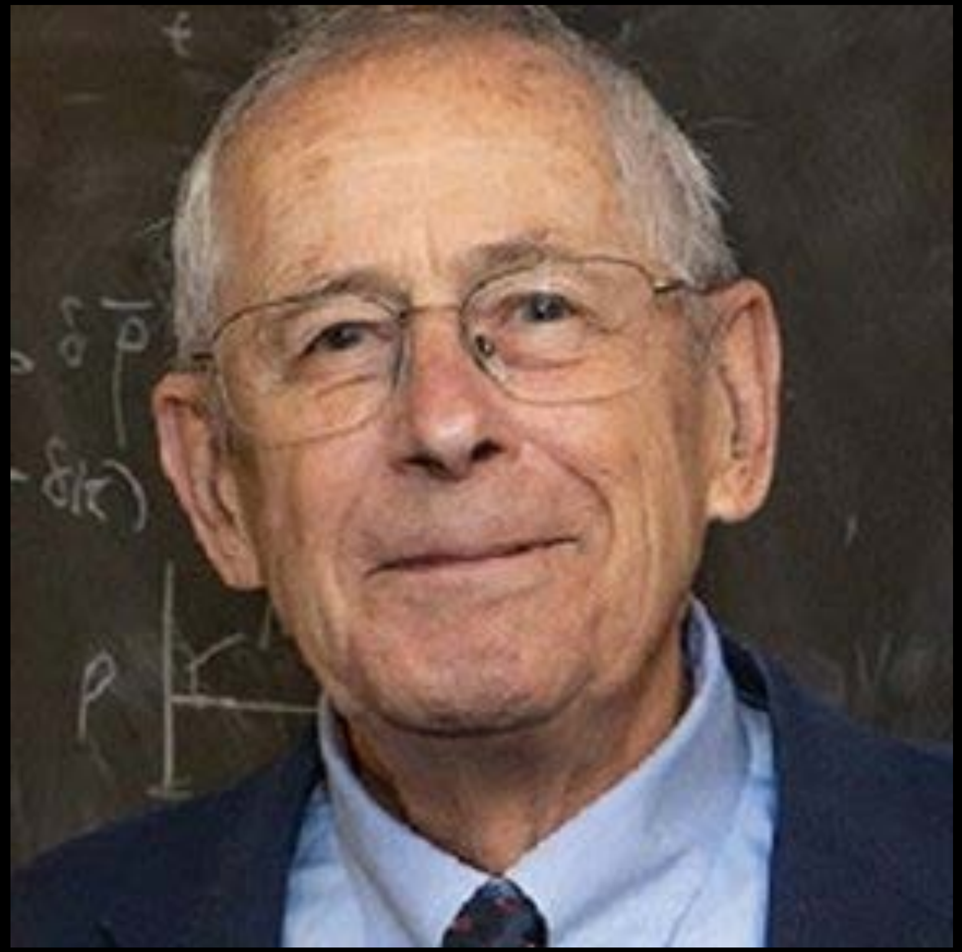
MARC DAVIS
Departments of Astronomy and Physics, University of California

AND

P. J. E. PEEBLES
Joseph Henry Laboratories, Princeton University

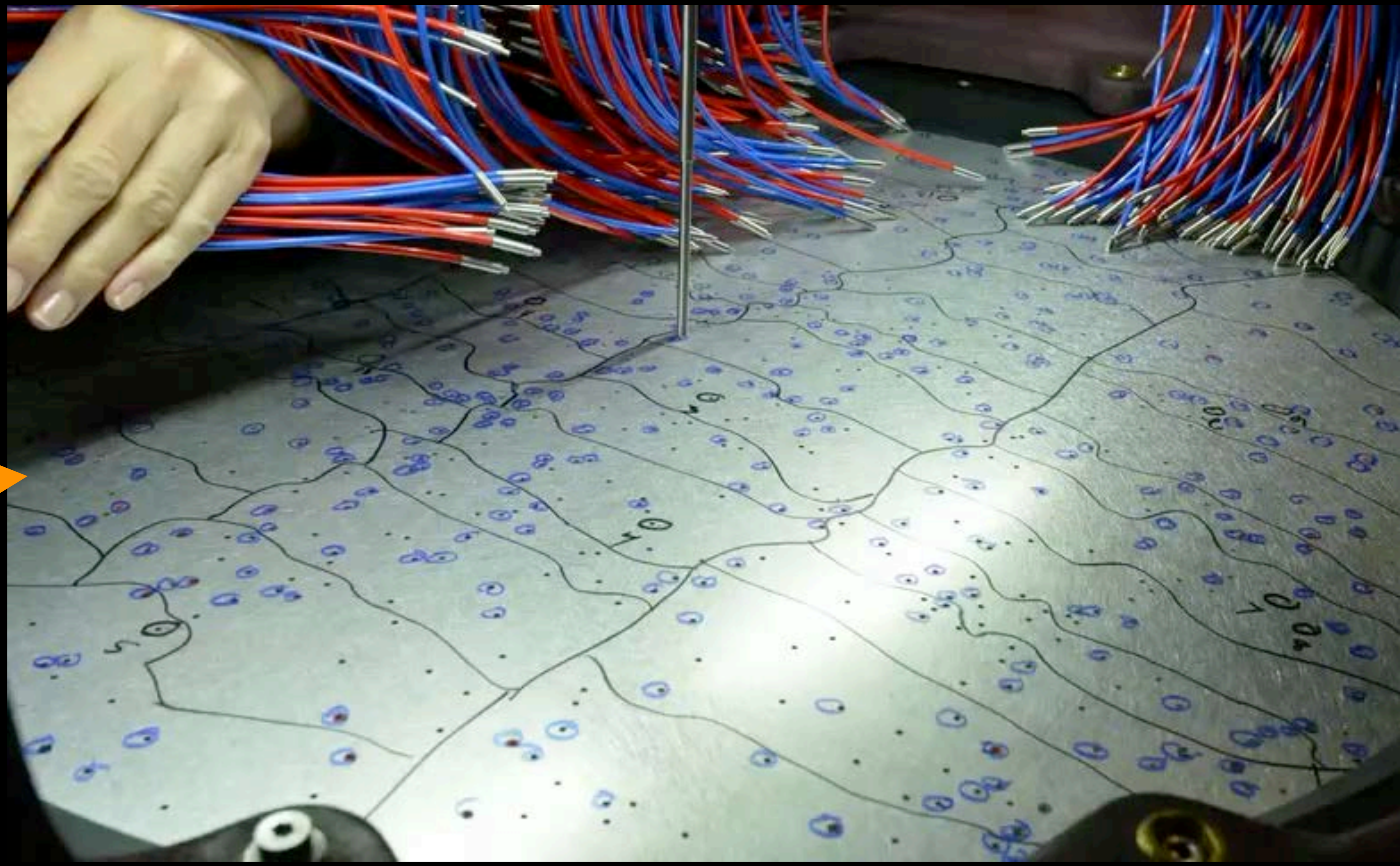
Received 1982 August 5; accepted 1982 October 12

2019 Nobel Prize for "contributions to for our understanding of the evolution of the universe"



Sloan Digital Sky Survey (SDSS)

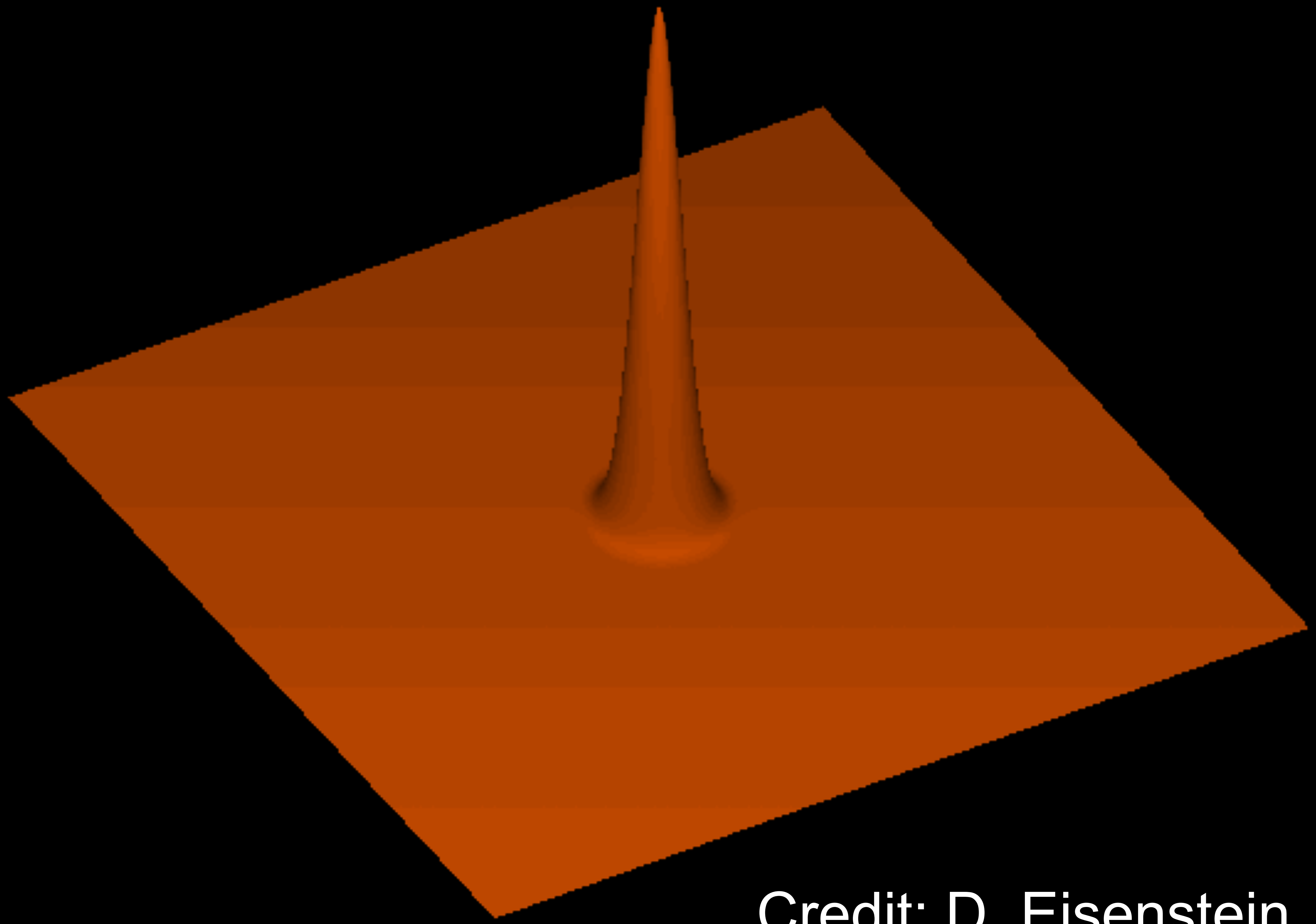
Multiplexing with fiber optic cables to observe 640 galaxies simultaneously
… later upgraded to 1000 … up to 9000 galaxies/night



SDSS — the first 3-dimensional map to make a good movie with 1 million galaxies

Baryon Acoustic Oscillations (BAO) provide a standard ruler at 147 Mpc

BAO imprinted in the microwave background at z=1100
… and forever more in galaxy maps



Credit: D. Eisenstein

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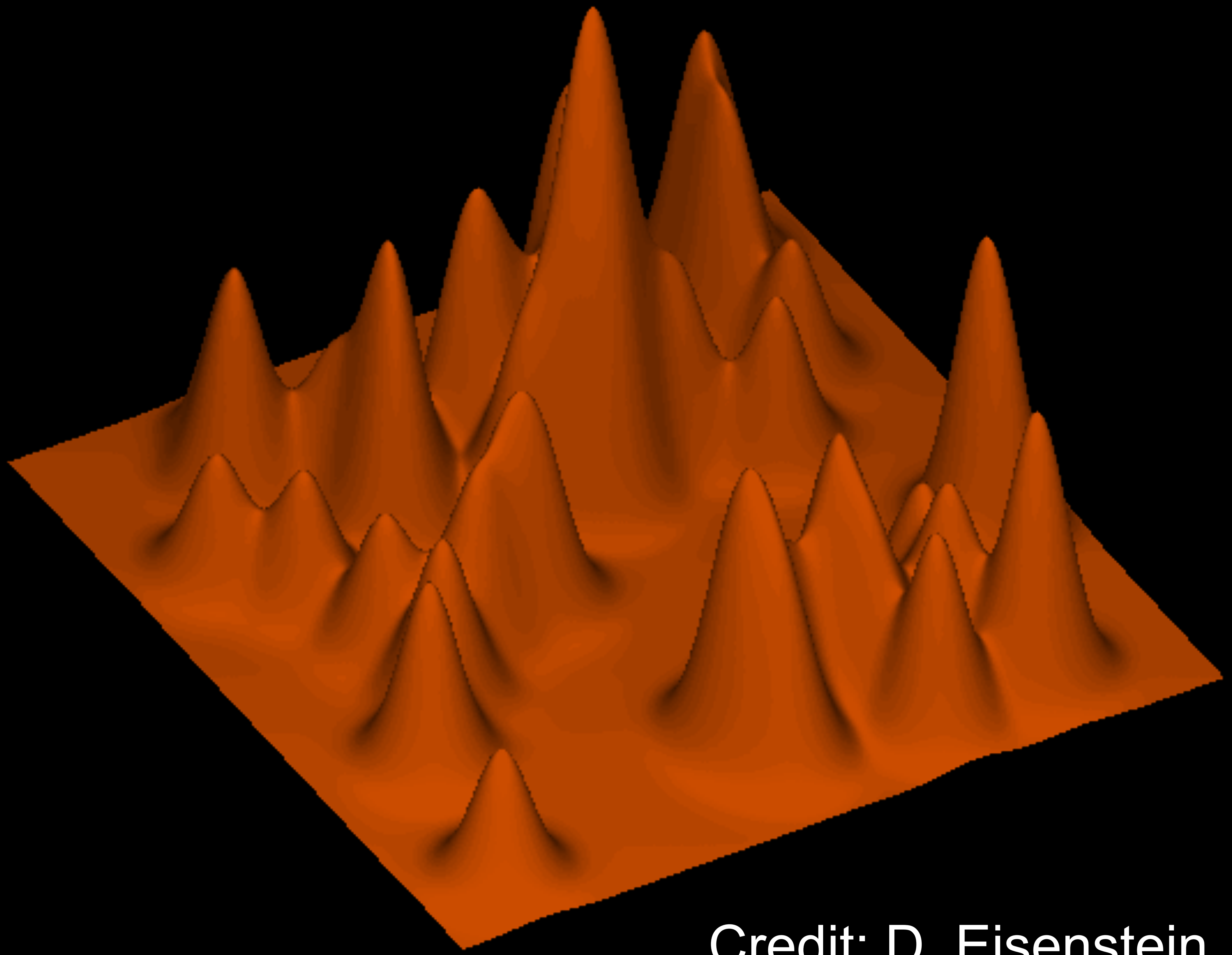

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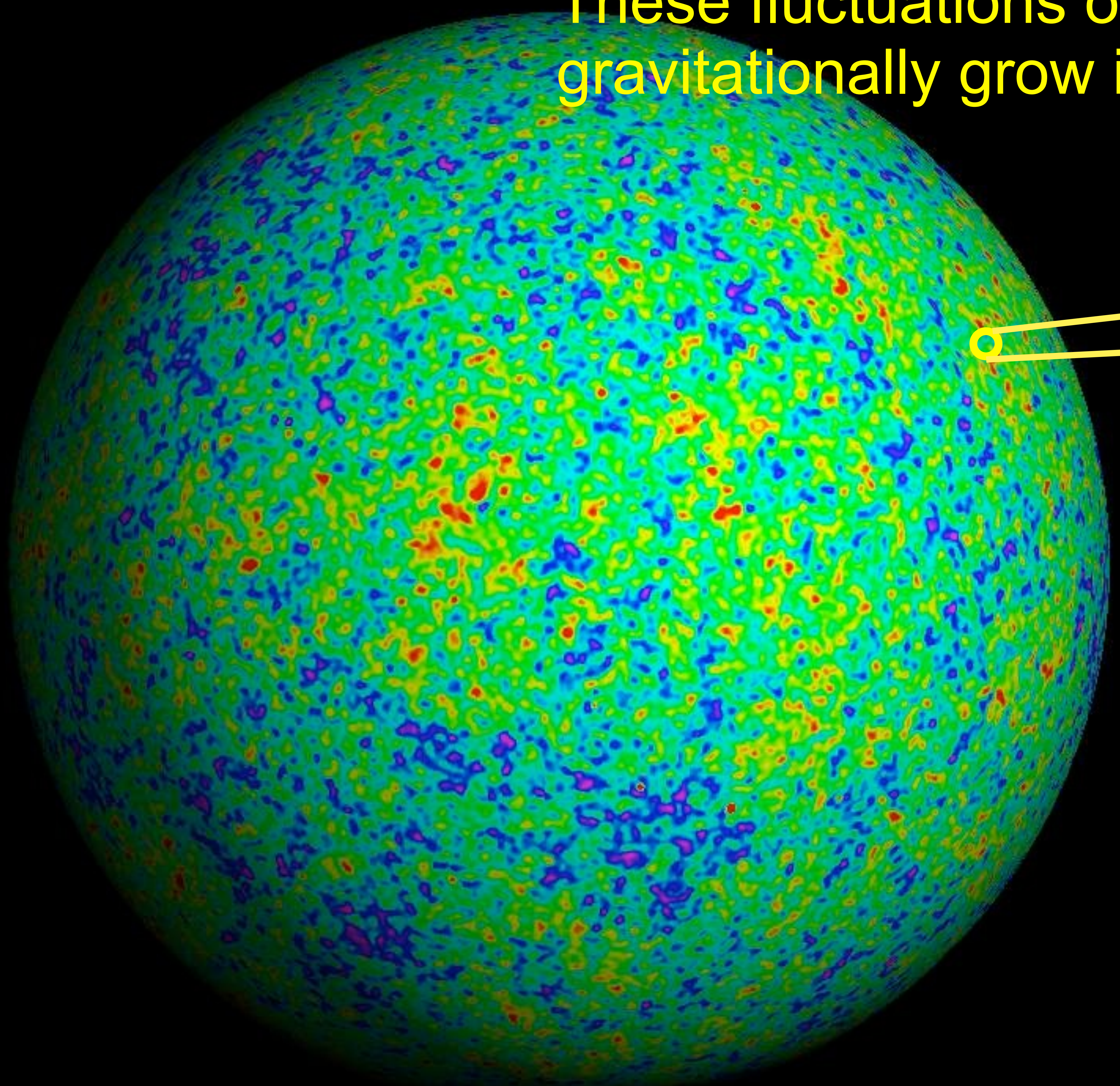
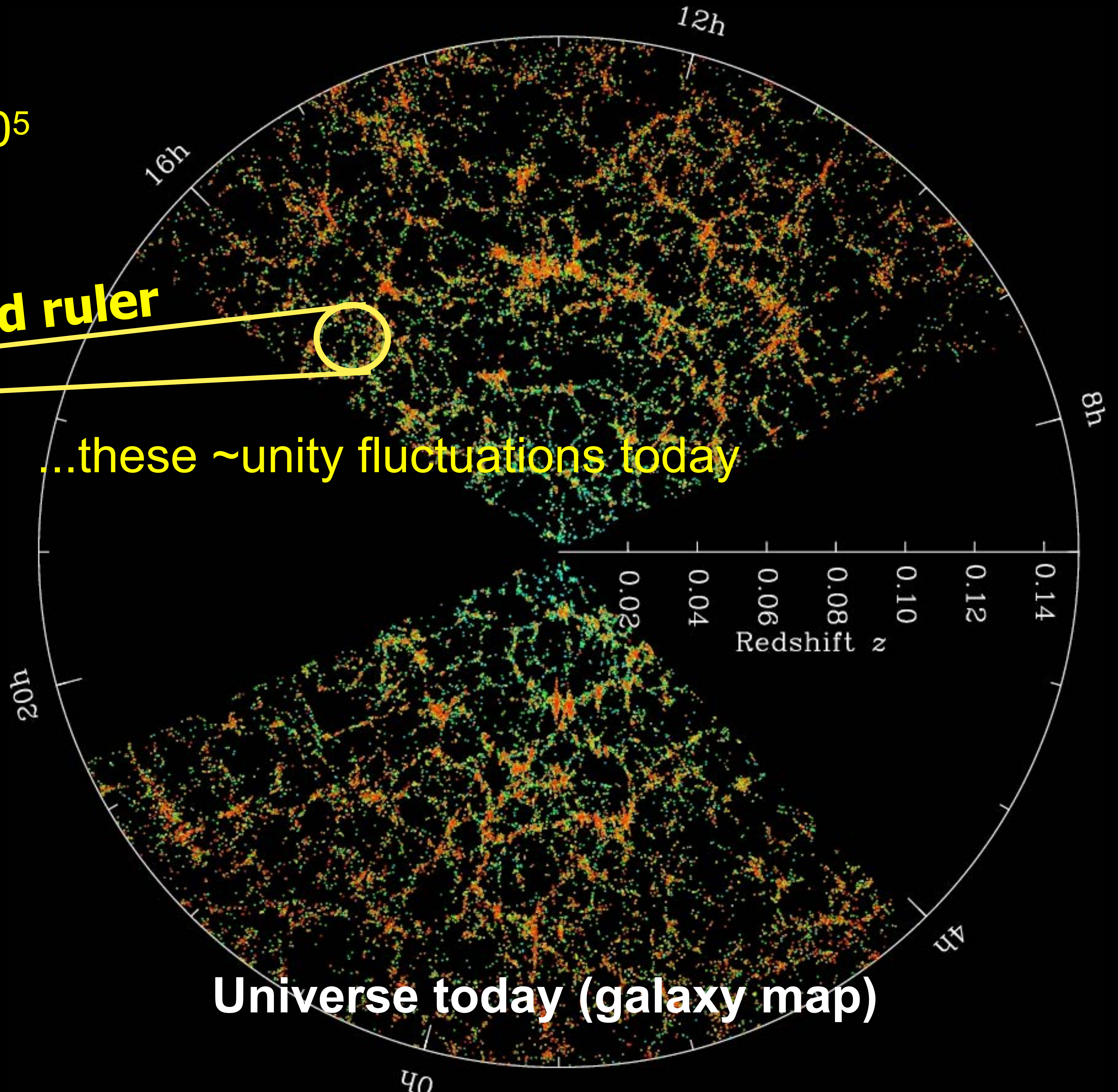




Universe at 380,000 years old (CMB)

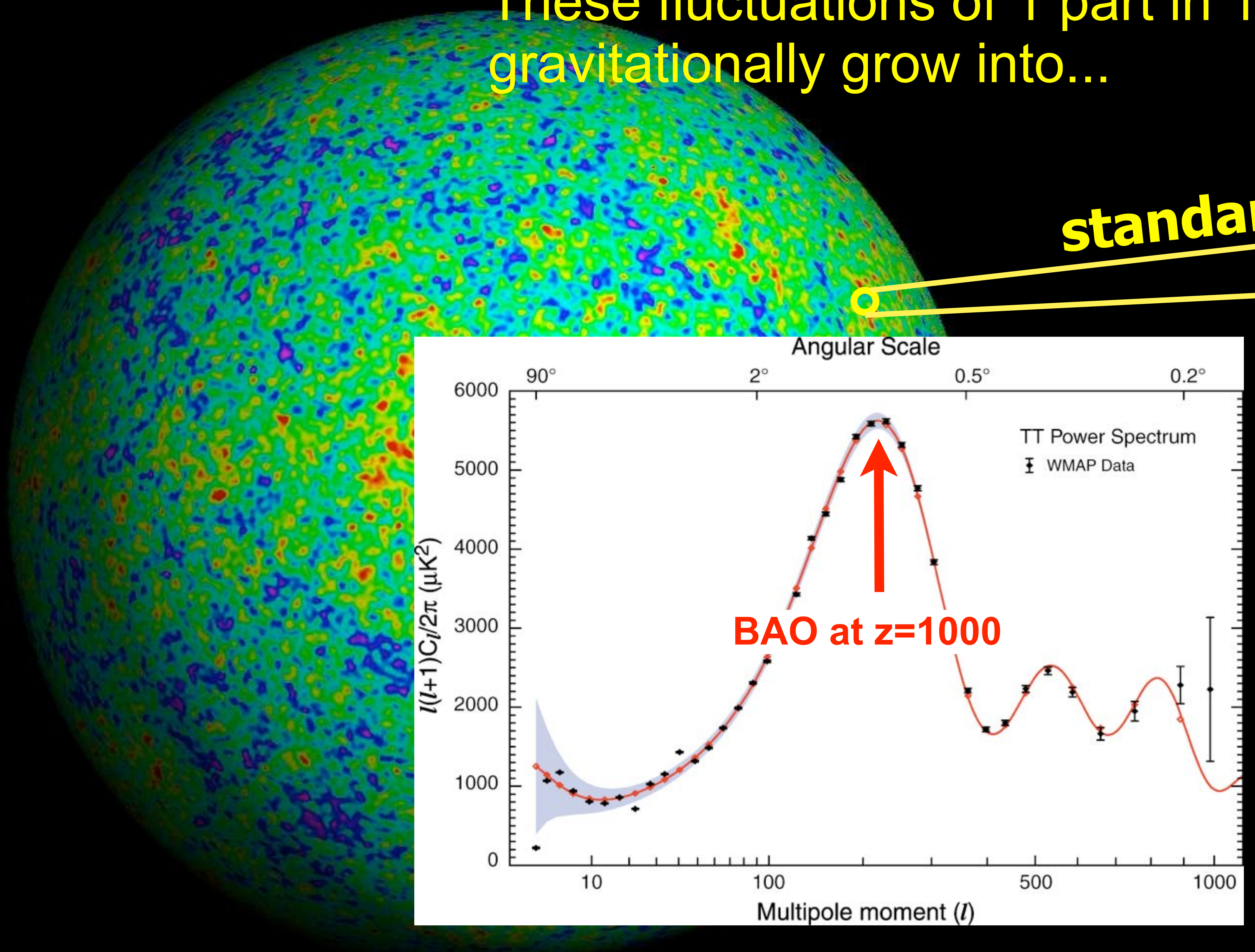
Universe today (galaxy map)

Baryon Acoustic Oscillations (BAO) provide a standard ruler at 147 Mpc

BAO imprinted in the microwave background at z=1100
… and forever more in galaxy maps

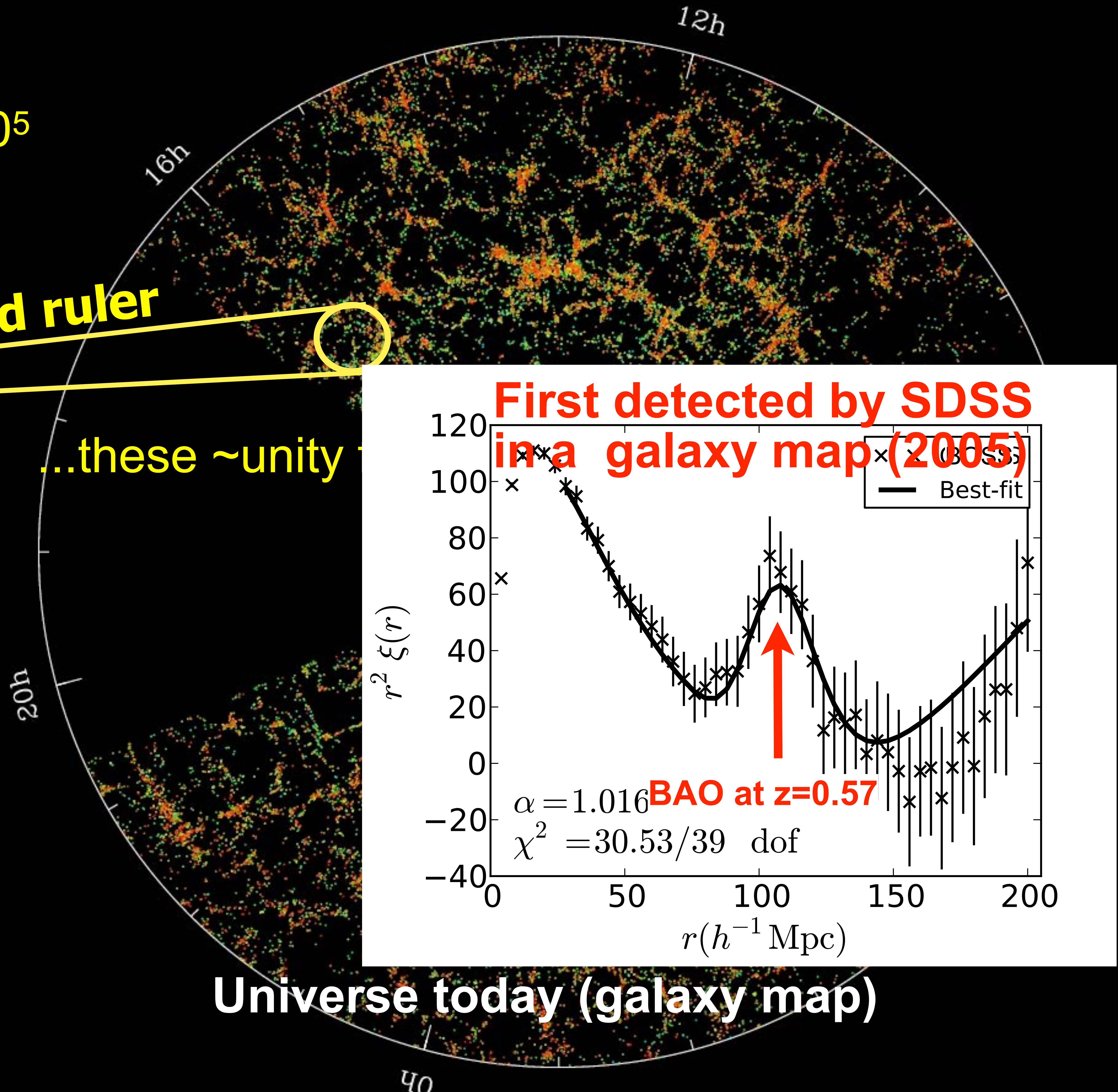
These fluctuations of 1 part in 10^5
gravitationally grow into...

standard ruler



Universe at 380,000 years old (CMB)

...these ~unity



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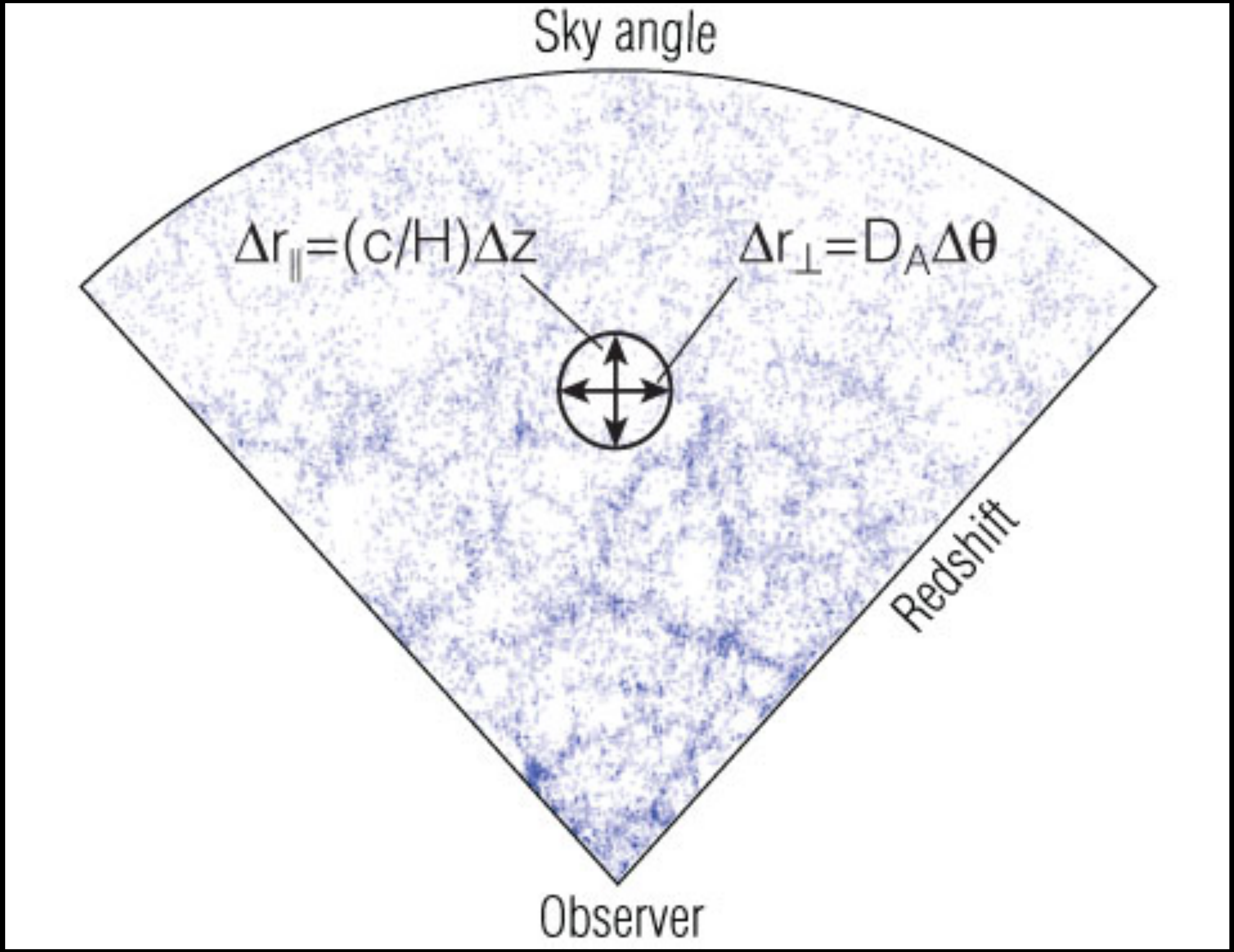


Galaxy maps give us two measures:
along the line of sight, H(z),
+ perpenticular to the line-of-sight, $D_A(z)$

$$H(z) = \sqrt{\Omega_M(1+z)^3 + (1-\Omega_M-\Omega_\Lambda)(1+z)^2 + \Omega_\Lambda}\,, \tag{2.4}$$

$$d_A(z) = \begin{cases} (-K)^{-1/2}\sinh\left[(-K)^{1/2}\chi(z)\right] & K<0\,, \\ \chi(z) & K=0\,, \\ K^{-1/2}\sin\left[K^{1/2}\chi(z)\right] & K>0\,, \end{cases} \tag{2.5}$$

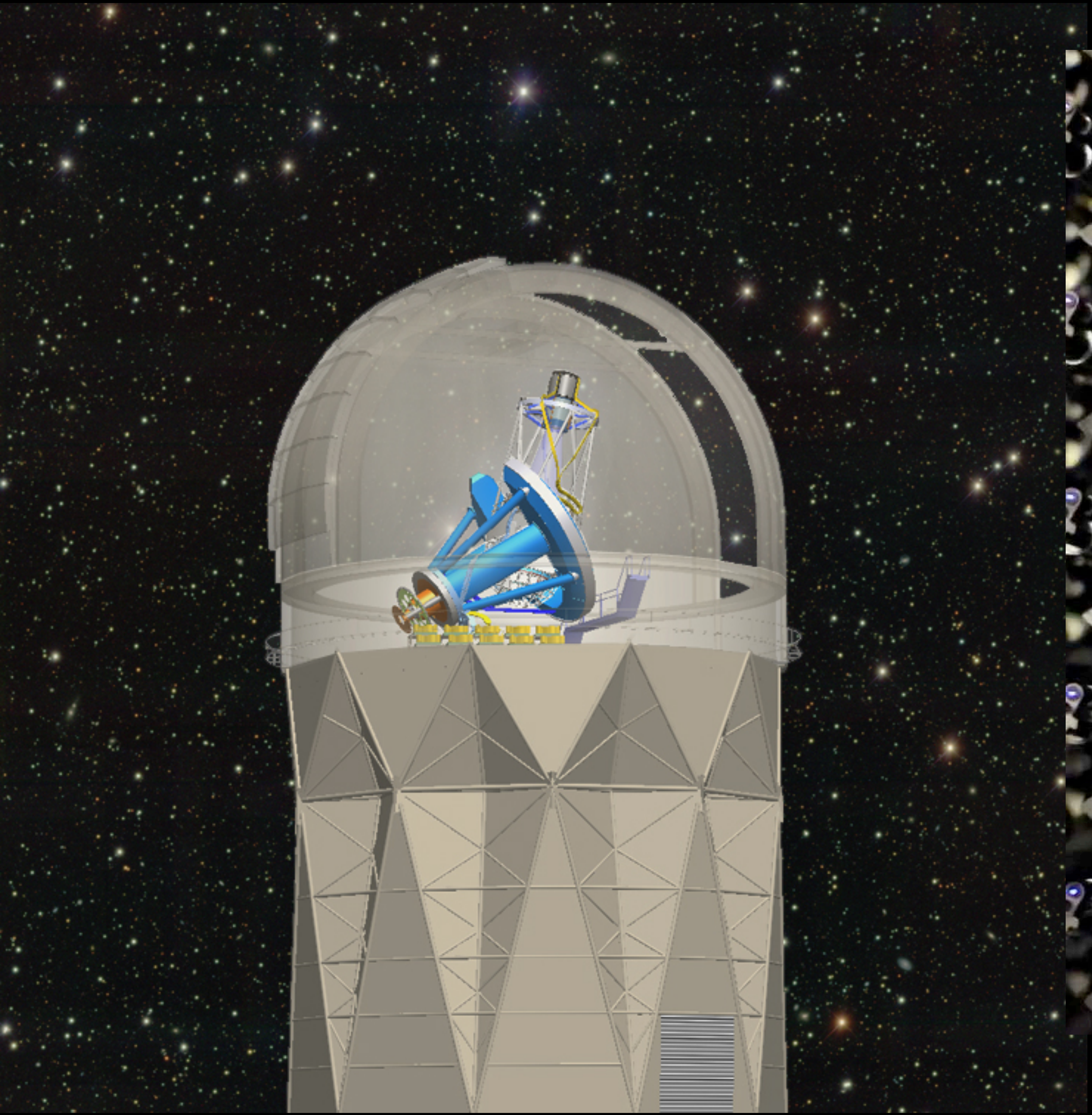
where

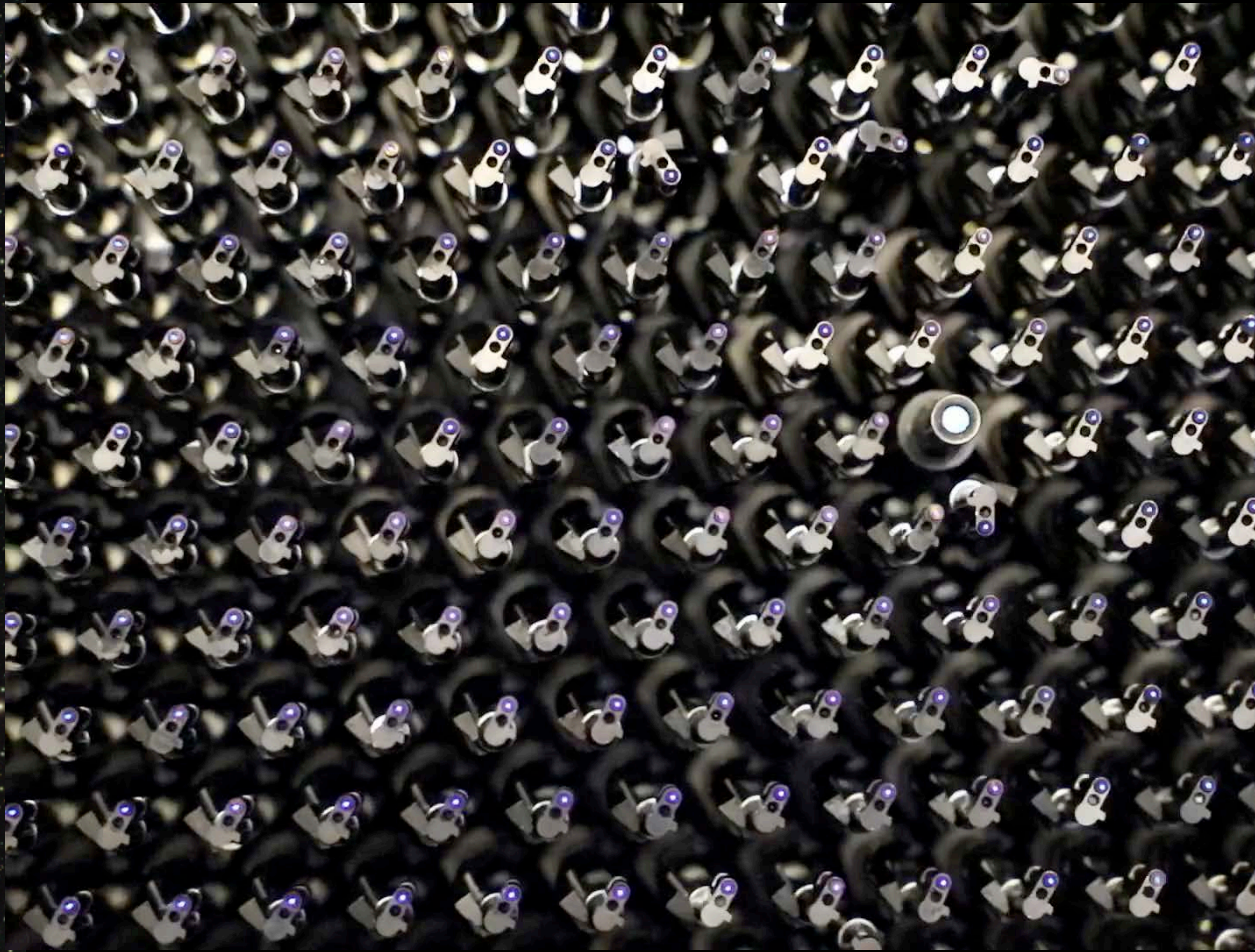
$$K = 1-\Omega_M-\Omega_\Lambda, \qquad \chi(z) = \int_0^z \frac{dz'}{H(z')} \tag{2.6}$$


"Baryon Acoustic Oscillations"
150 Mpc = 450 million light years
Derived map with dark energy
(artist rendition)


"Baryon Acoustic Oscillations"
150 Mpc = 450 million light years
Derived map **without** dark energy
(artist rendition)

Dark Energy Spectroscopic Instrument (DESI), 2021-2028
multiplexed with 5000 optical fibers on a robotic focal plane



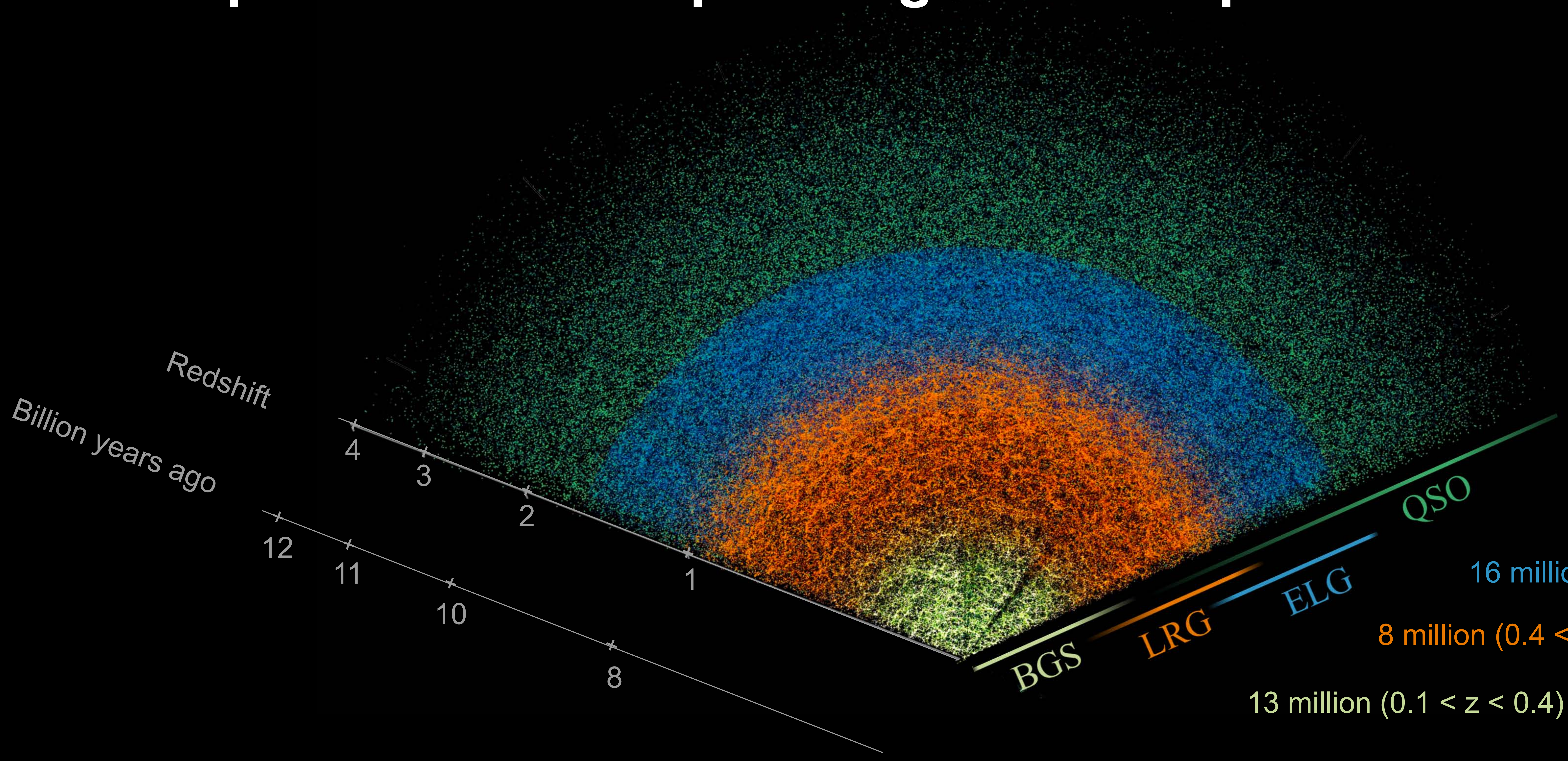


DESI — a much bigger map with 42 million galaxies… and counting…

Credit: David Kirkby

DESI year 1 results published in April 2024, DESI year 3 results published in March 2025, based upon several samples of galaxies + quasars

+10 million stars



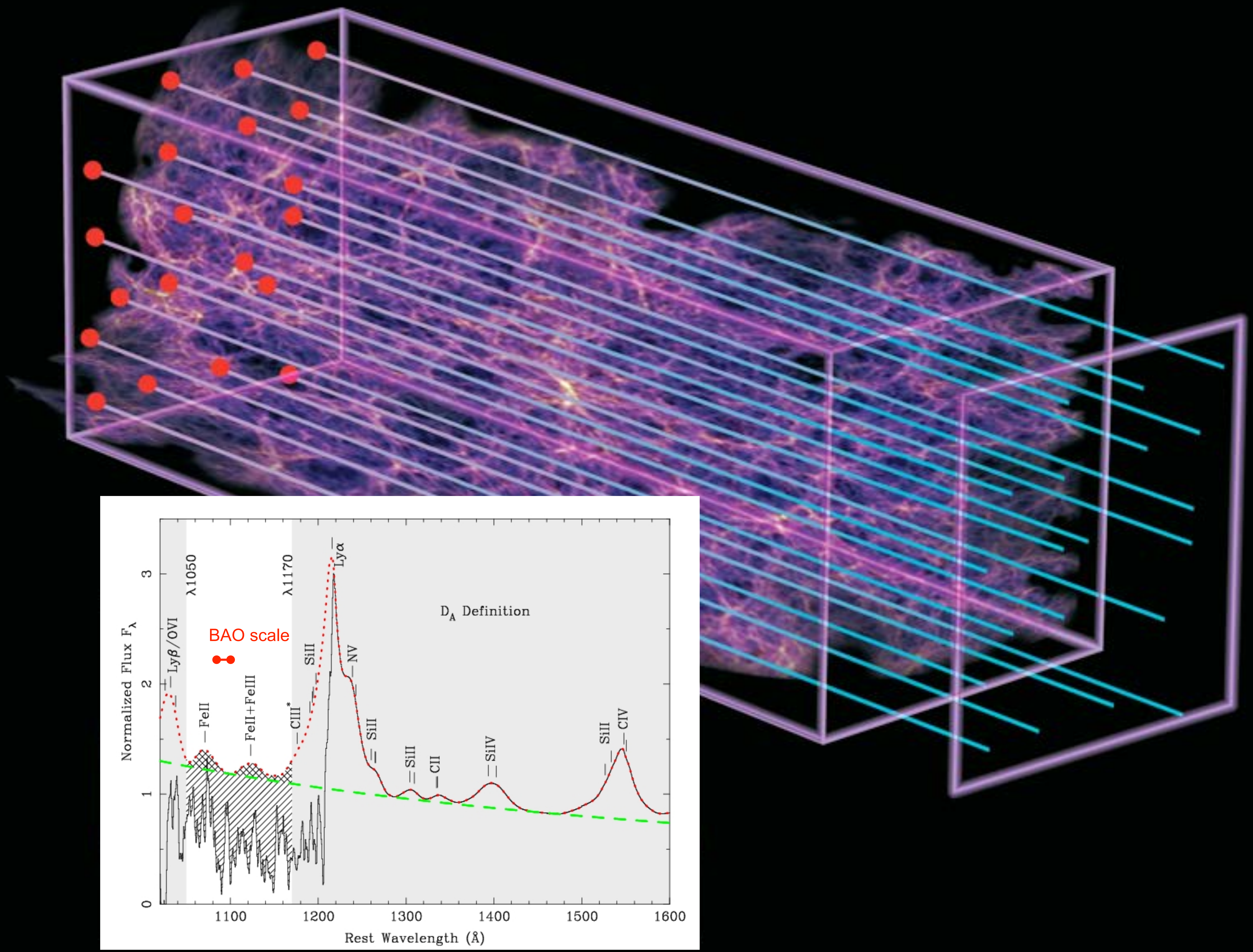
3 million (1.0 < z < 4.0) *SDSS: 0.5M*

16 million (0.6 < z < 1.6) *SDSS: 0.2M*

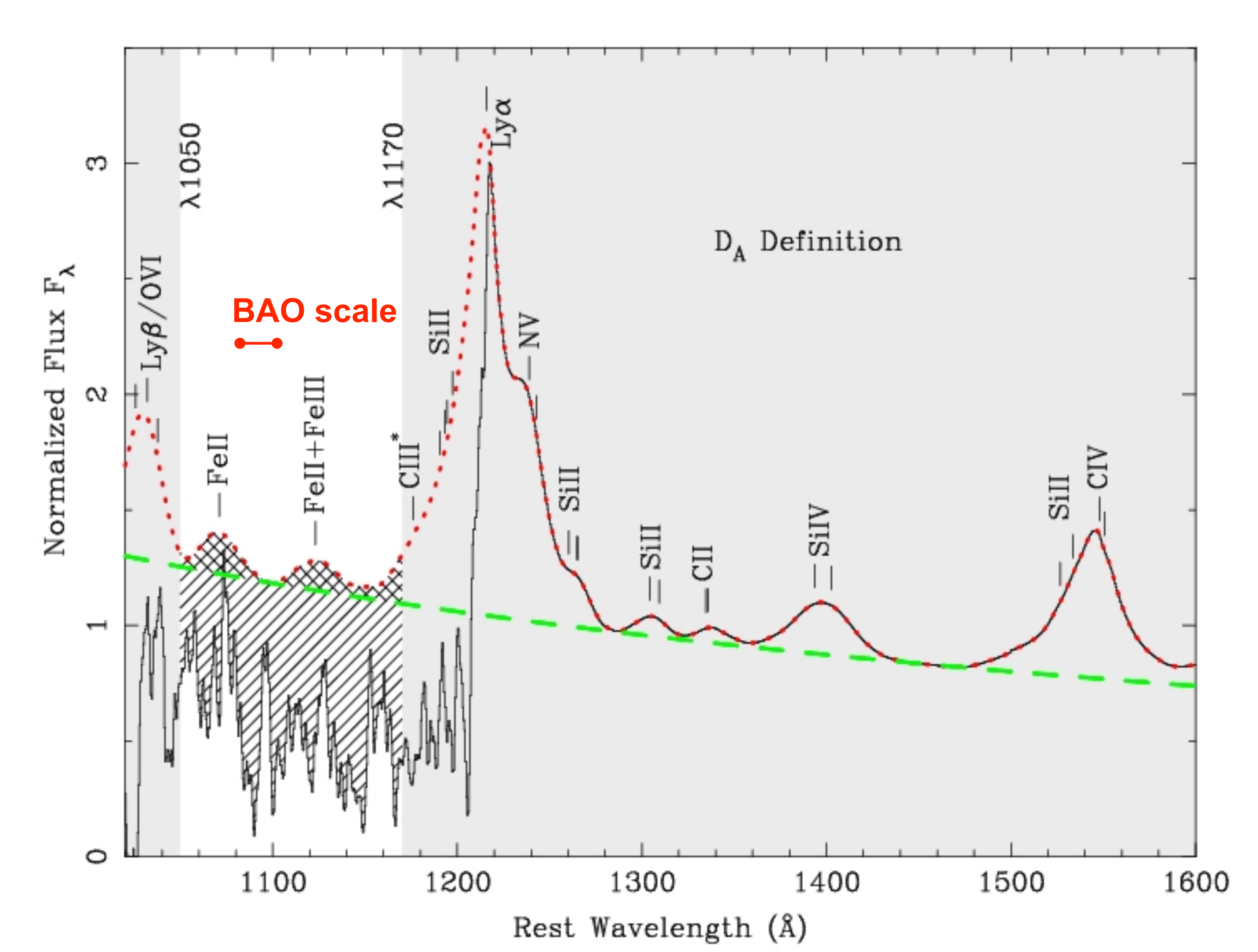
8 million (0.4 < z < 1.0) *SDSS: 1M*

13 million (0.1 < z < 0.4) *SDSS: 0.6M*

Quasars at z > 2.1 used as a back-light for the Lyman-alpha forest



Quasars at z > 2.1 used as a back-light for the Lyman-alpha forest



$$P_{\text{raw}}(\mathbf{k}) = \left[P_F(\mathbf{k}) + n^{-1} P_F^{1\text{D}}(k_\parallel)\right] W^2\left(k_\parallel R\right) + P_N^{\text{eff}}$$

Ideal 3D power (perfectly sampled)

Sampling noise
n=surface density of lines of sight
(analogous to galaxy shot noise)

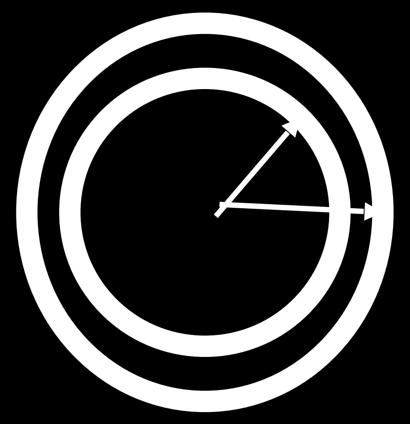
Resolution

Detector noise

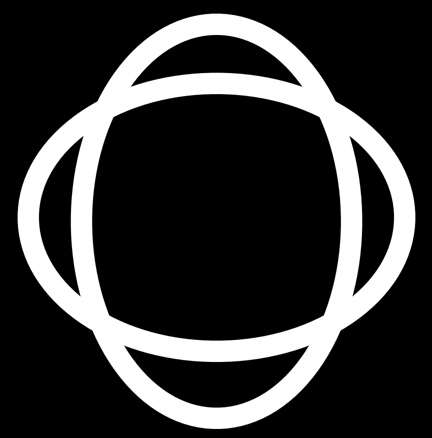
DESI analyses were all conducted blinded

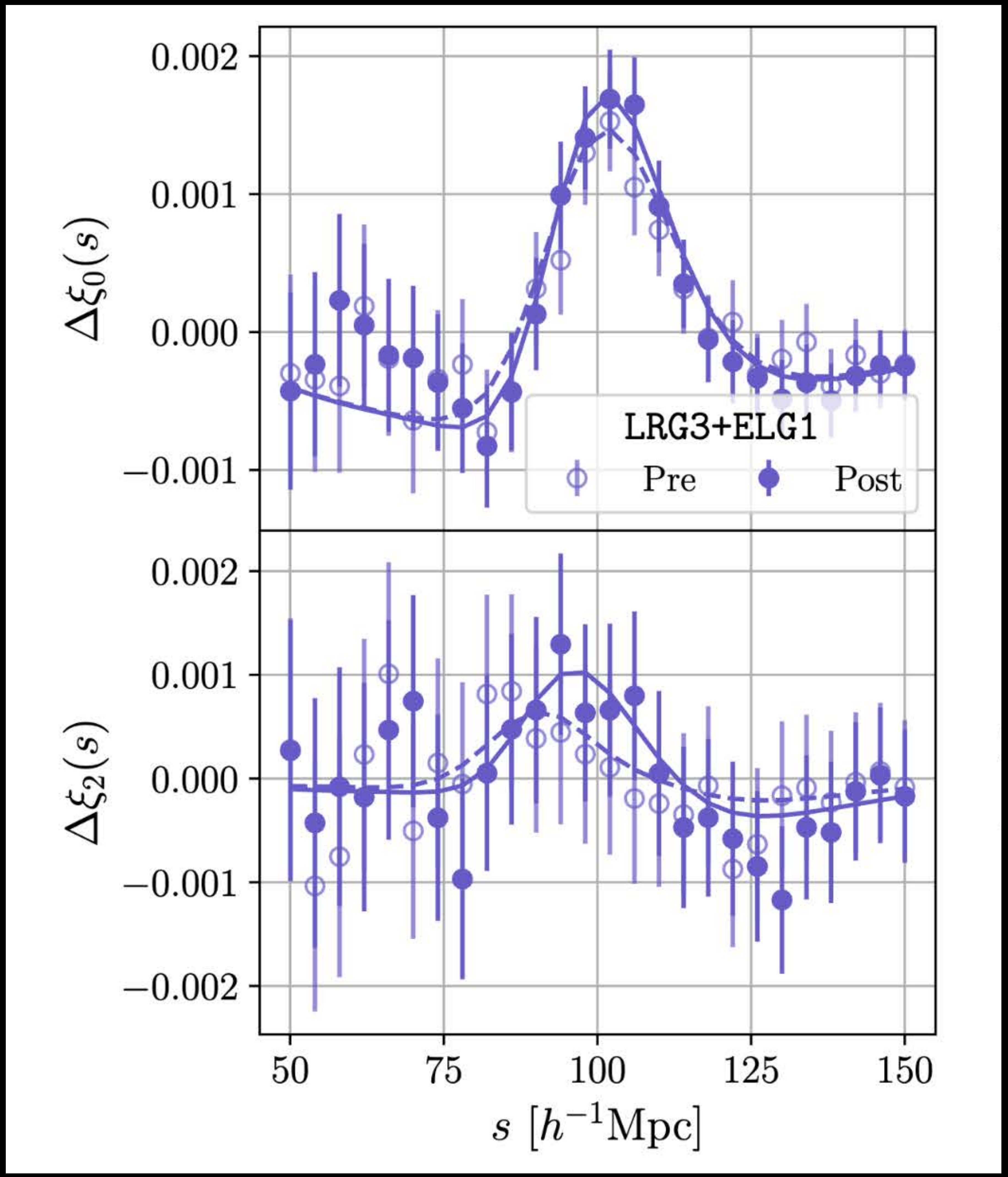
BAO feature well-measured in 7 samples at 7 redshifts

Overall BAO size

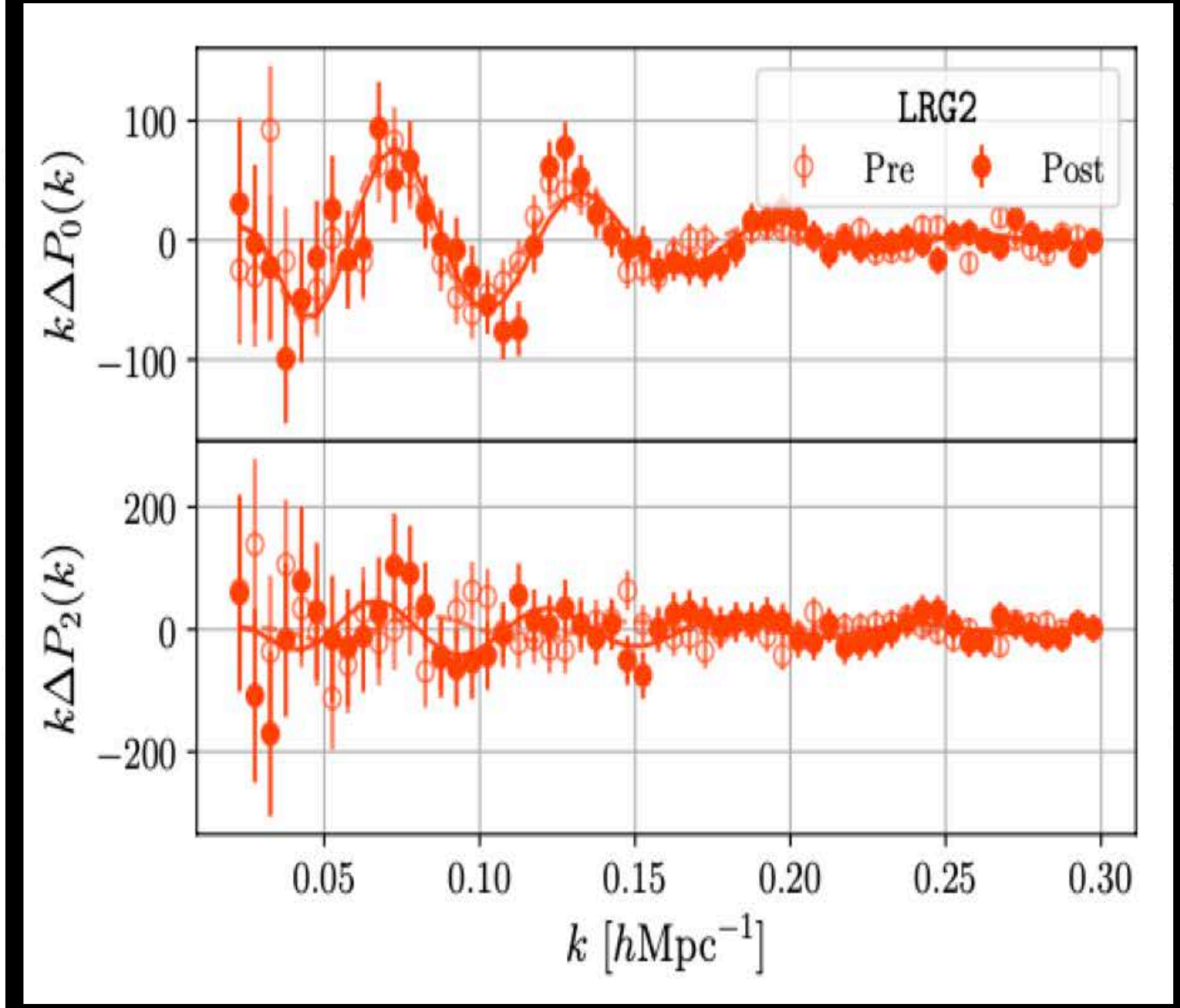


BAO anisotropy





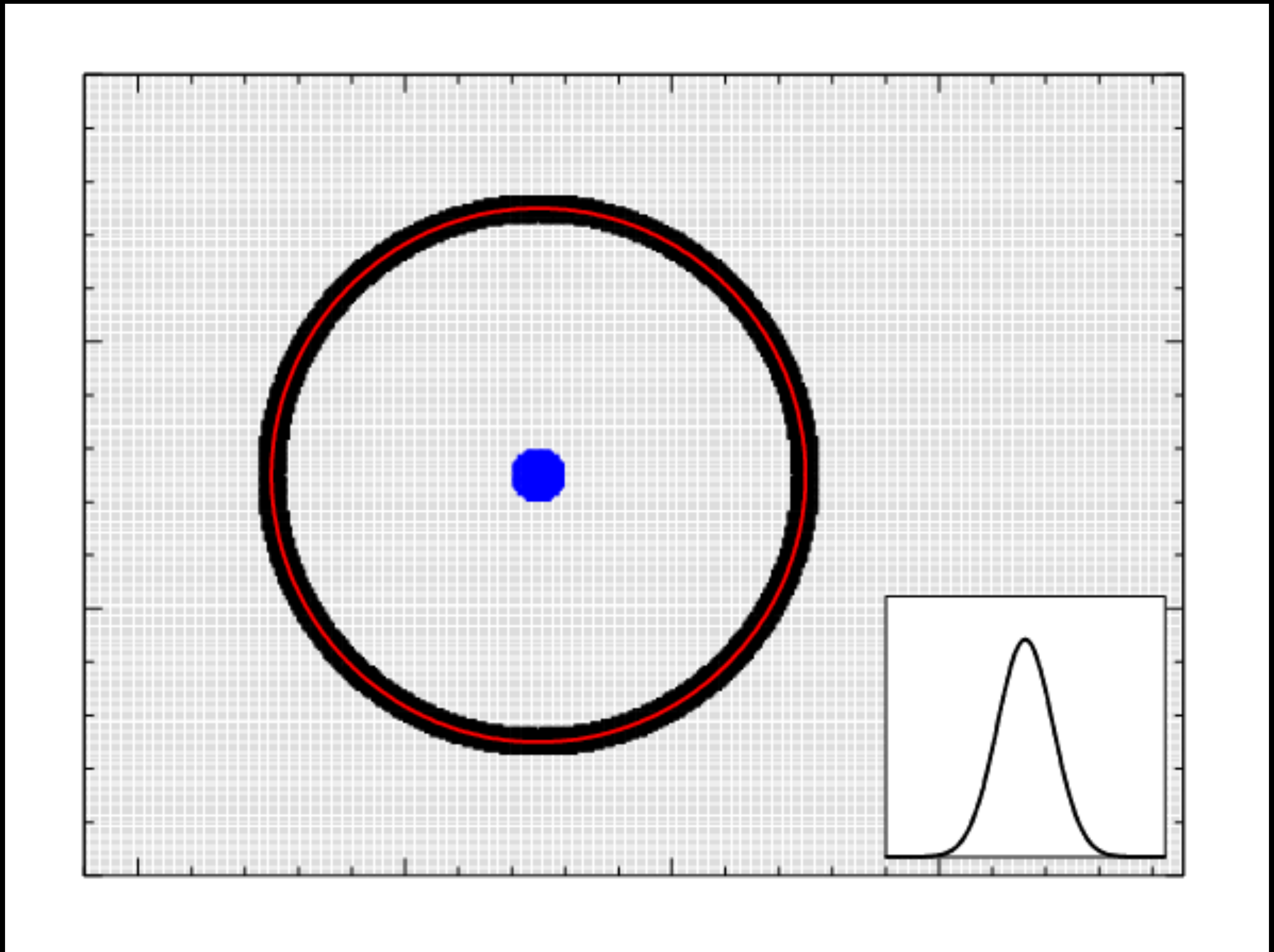
configuration space



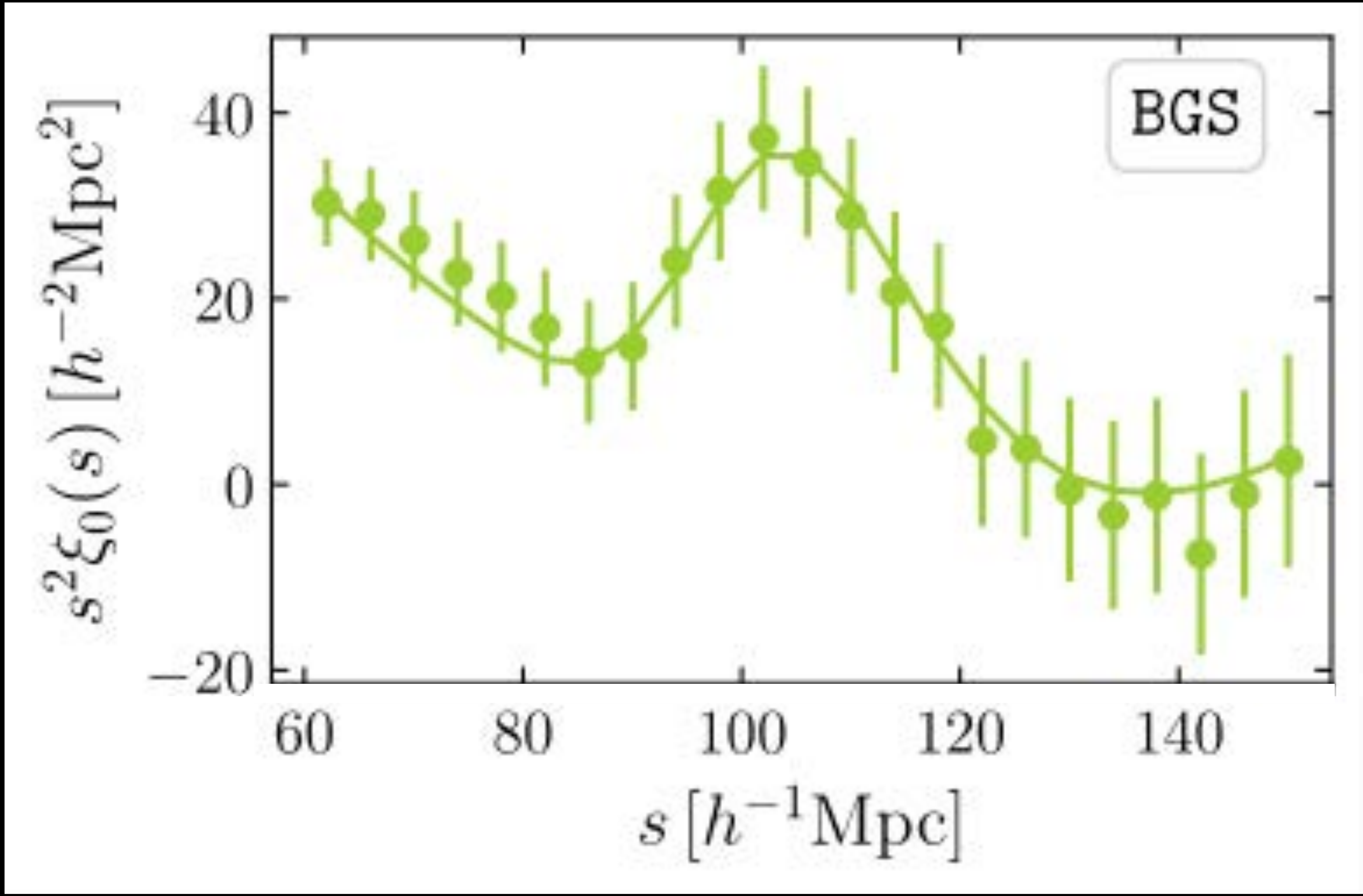
Fourier space

DESI analyses were all conducted blinded

Most of the maps underwent some “reconstruction”
to remove some of the non-linear gravitational growth

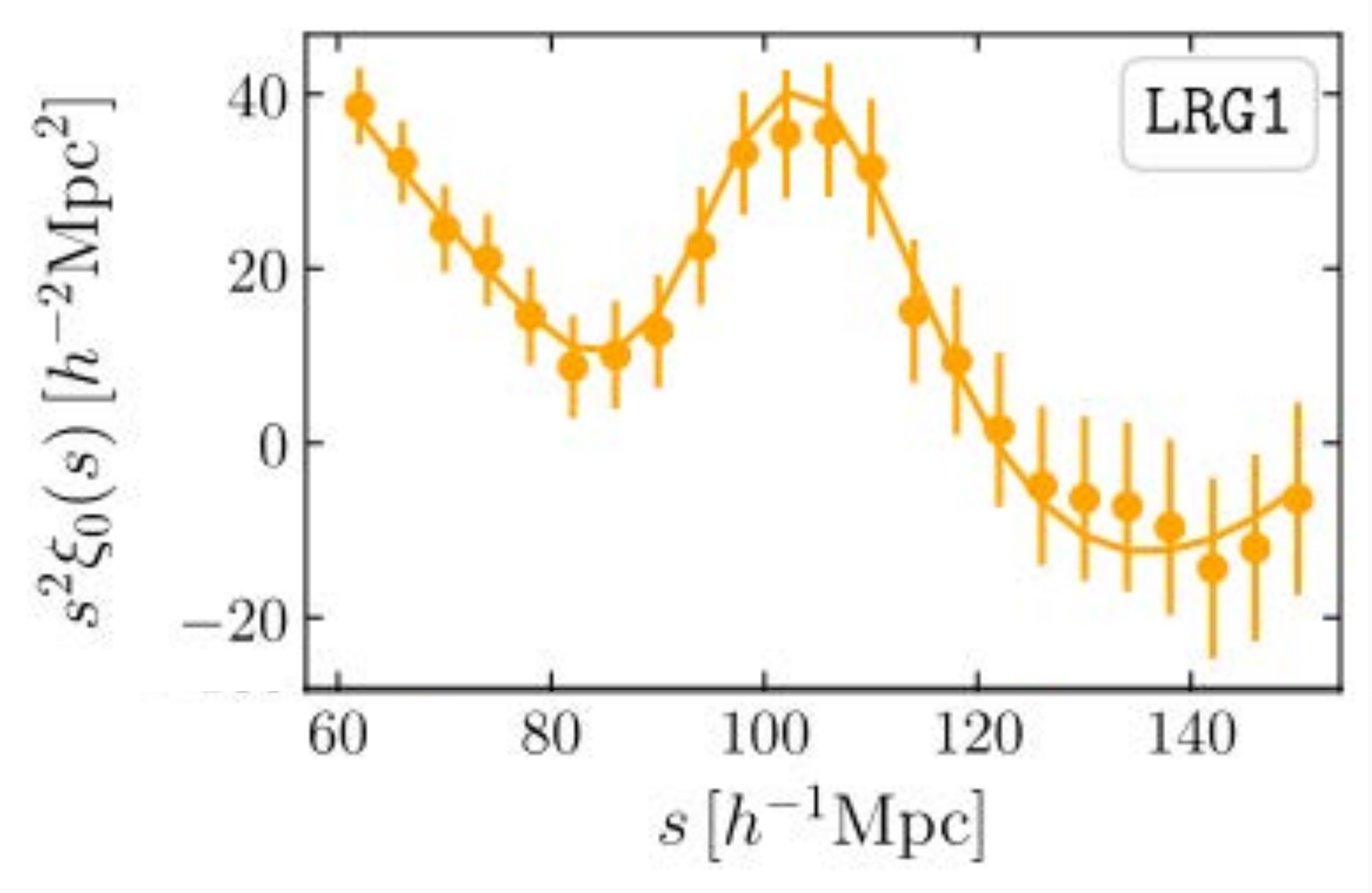


Bright Galaxy Sample, z<0.4, 0.9% distance



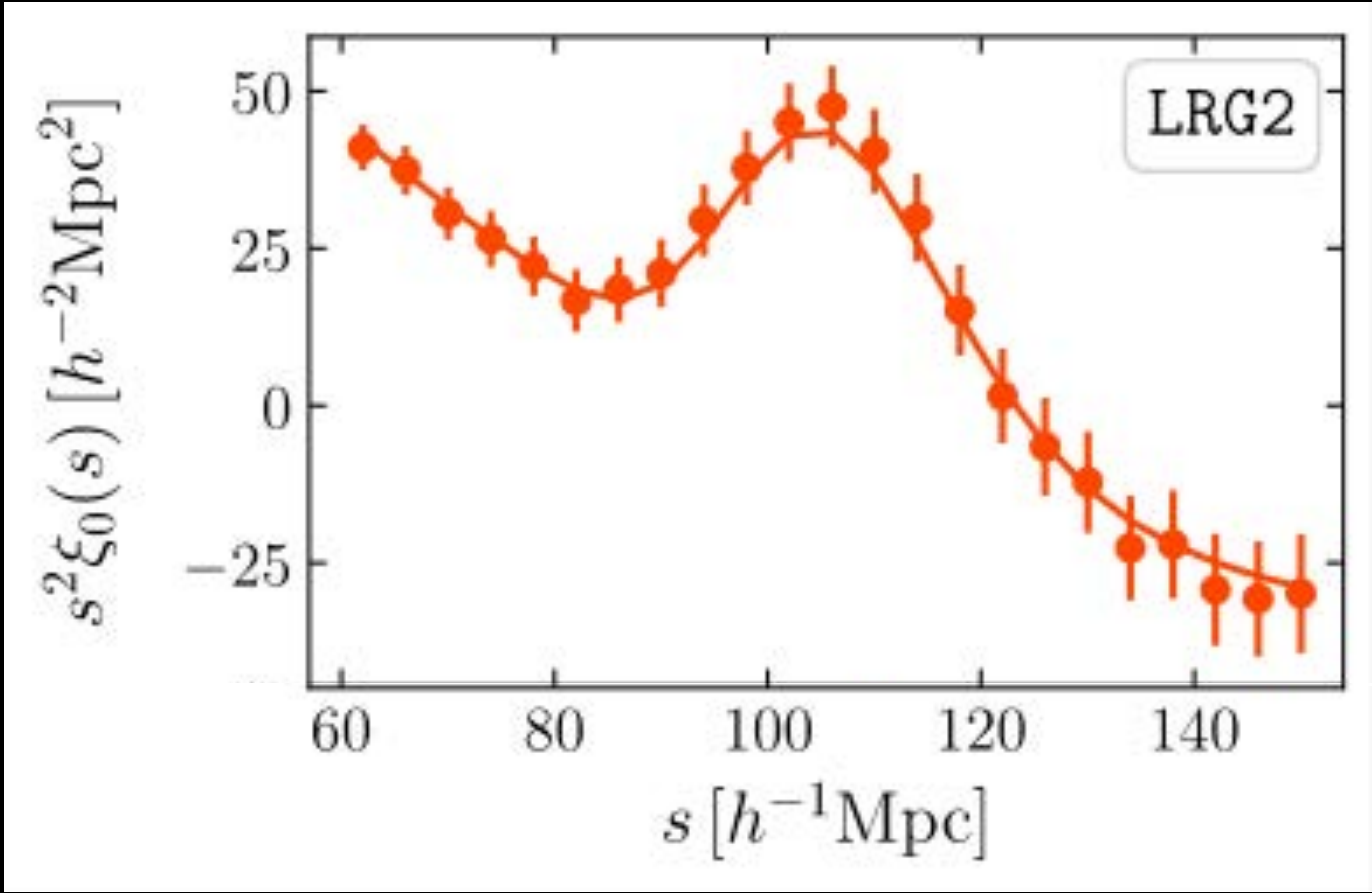
DESI Collaboration; arXiv:2503.14738

Luminous Red Galaxies, 0.4<z<0.6, 0.8% distance



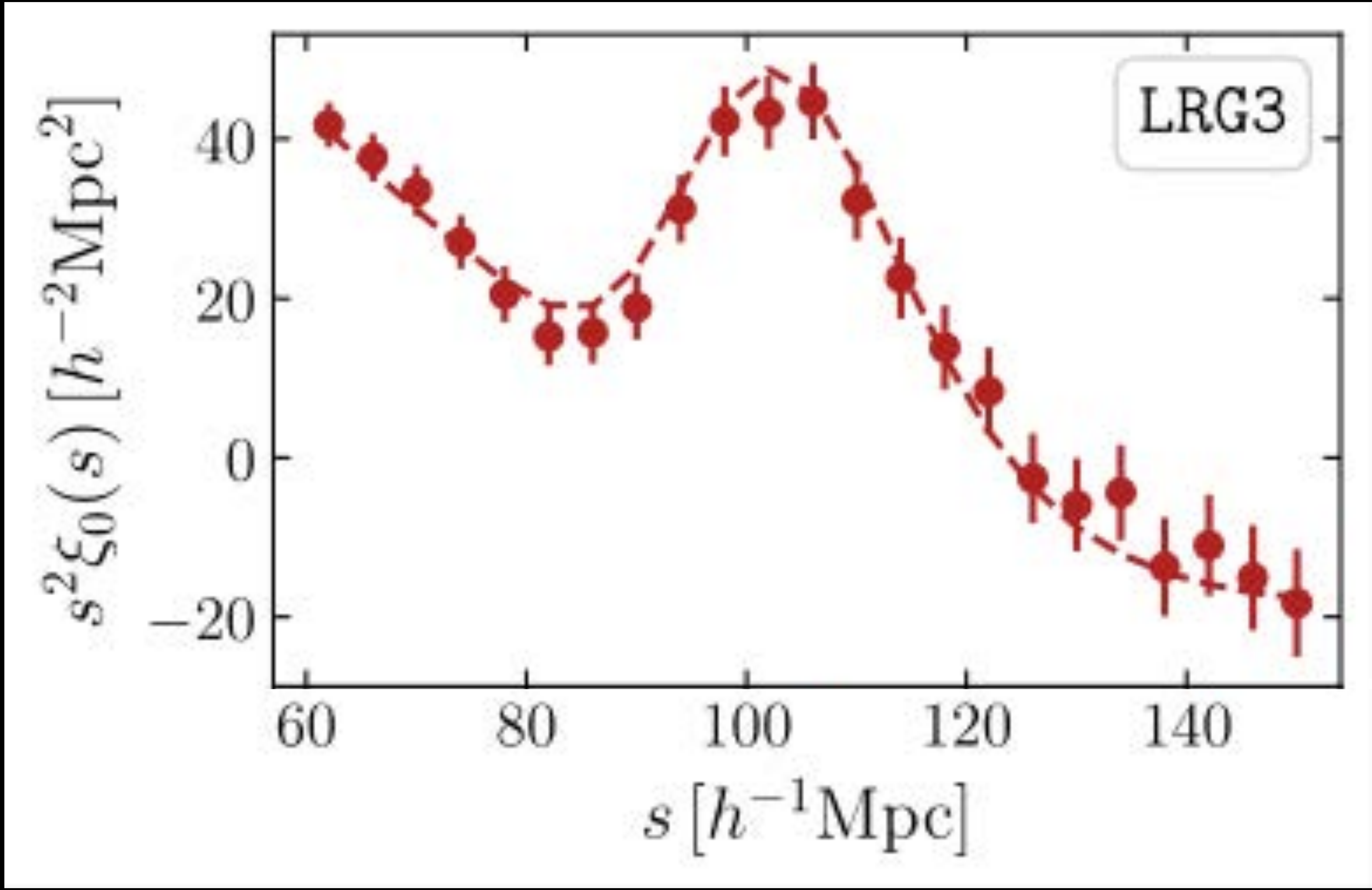
DESI Collaboration; arXiv:2503.14738

Luminous Red Galaxies, 0.6<z<0.8, 0.7% distance



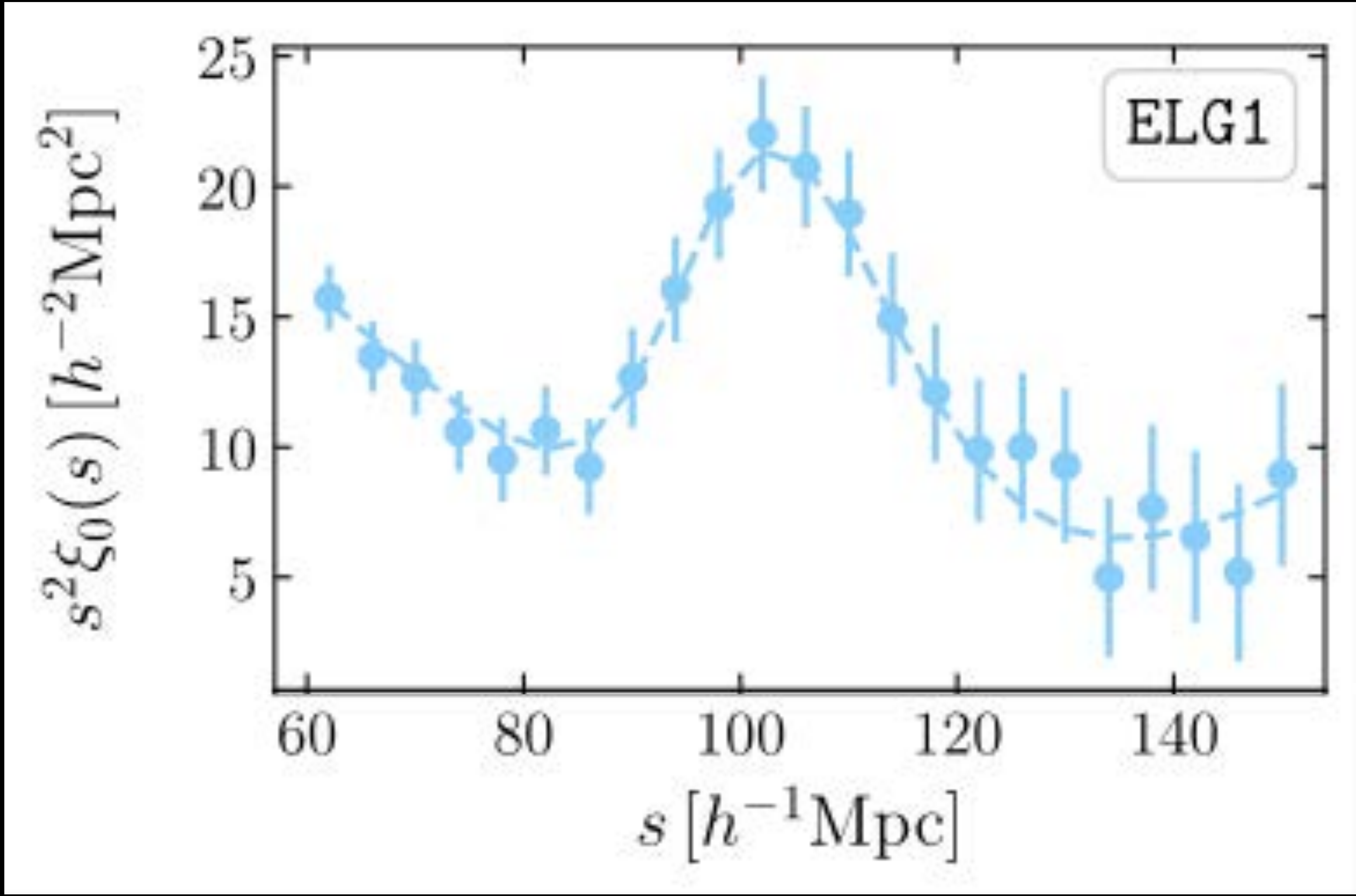
DESI Collaboration; arXiv:2503.14738

Luminous Red Galaxies, 0.8<z<1.1, 0.5% distance



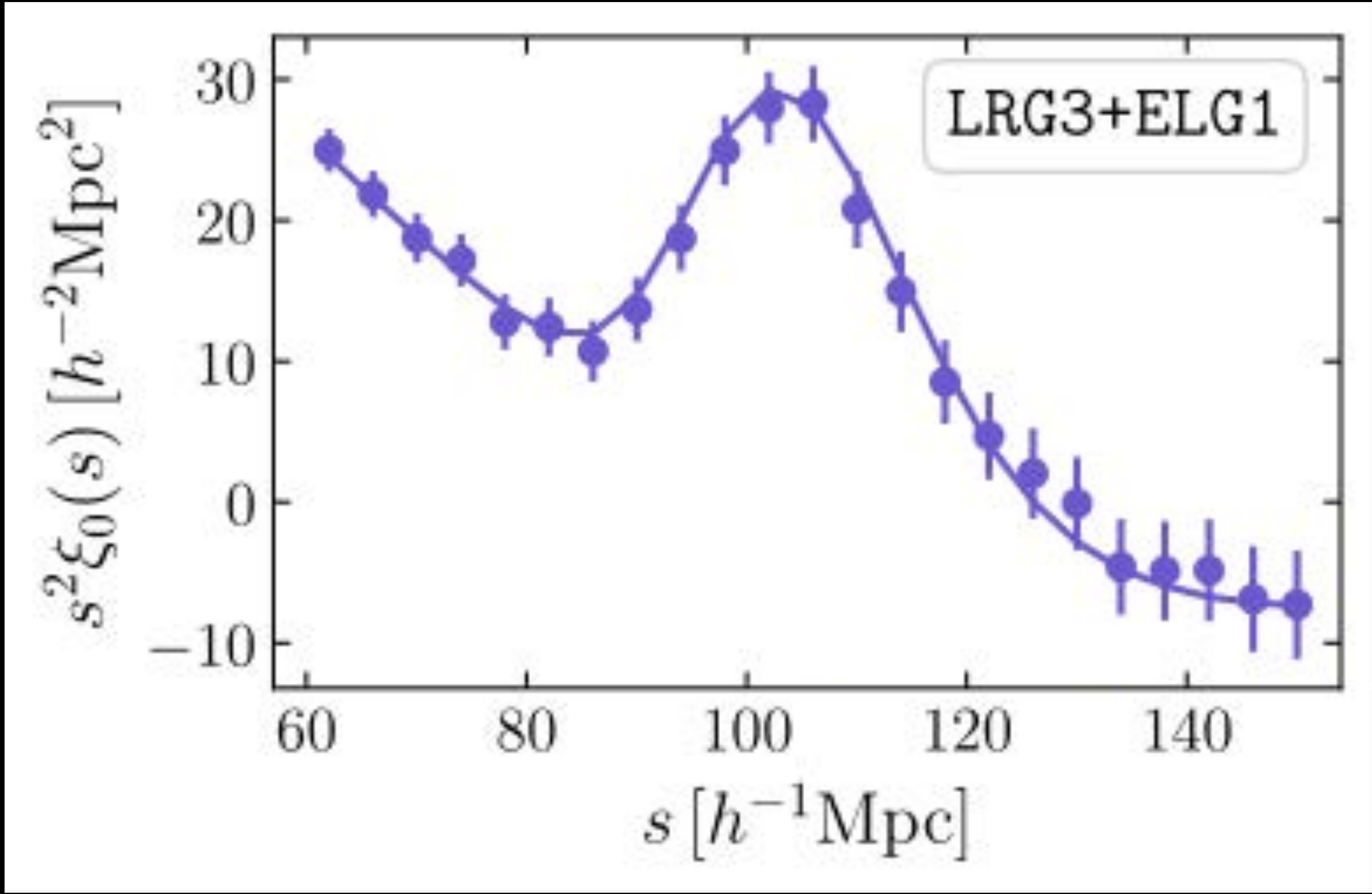
DESI Collaboration; arXiv:2503.14738

Emission Line Galaxies, 0.8<z<1.1, 0.9% distance



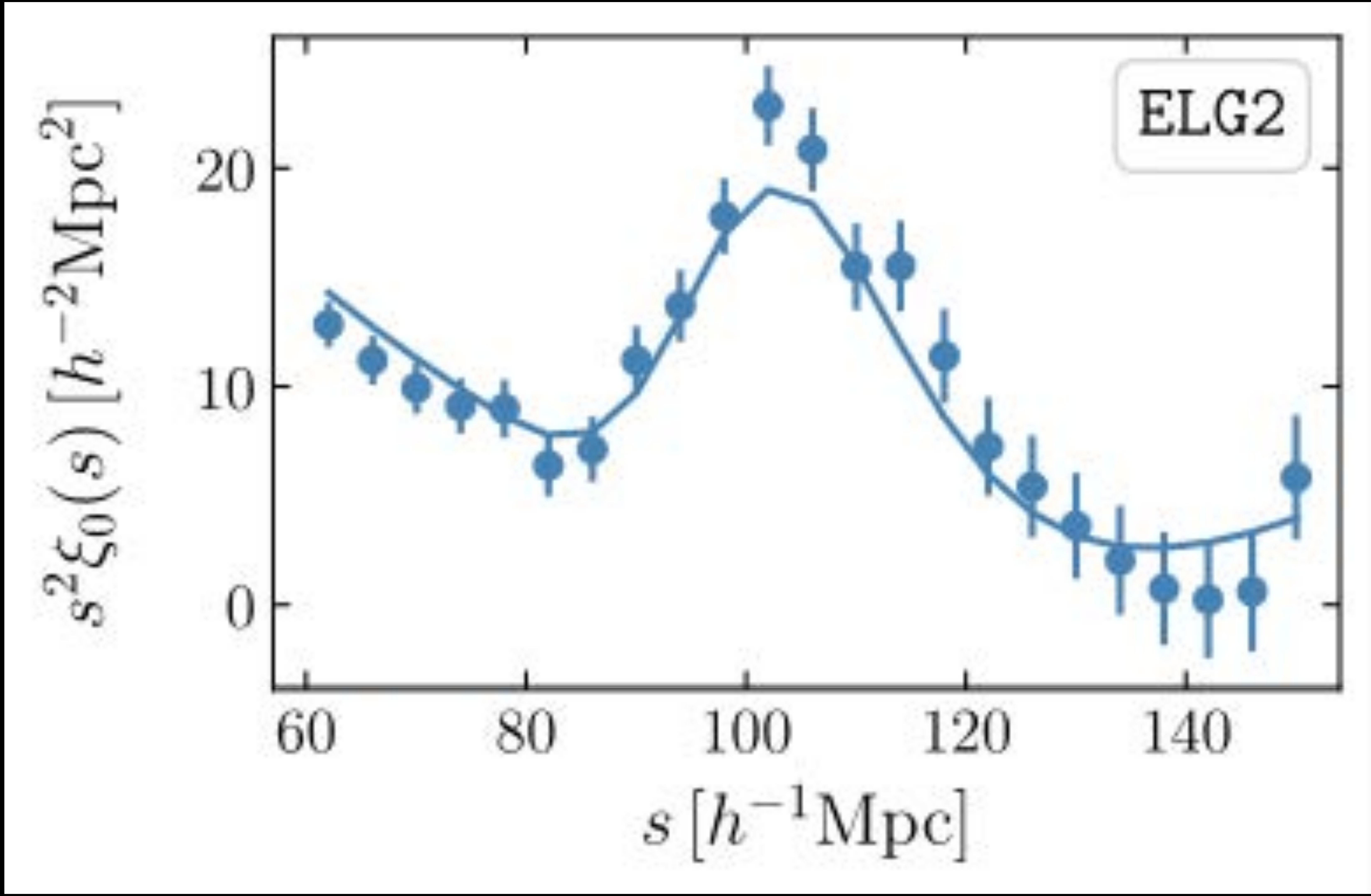
DESI Collaboration; arXiv:2503.14738

LRG3 + ELG1, 0.8<z<1.1, 0.5% distance



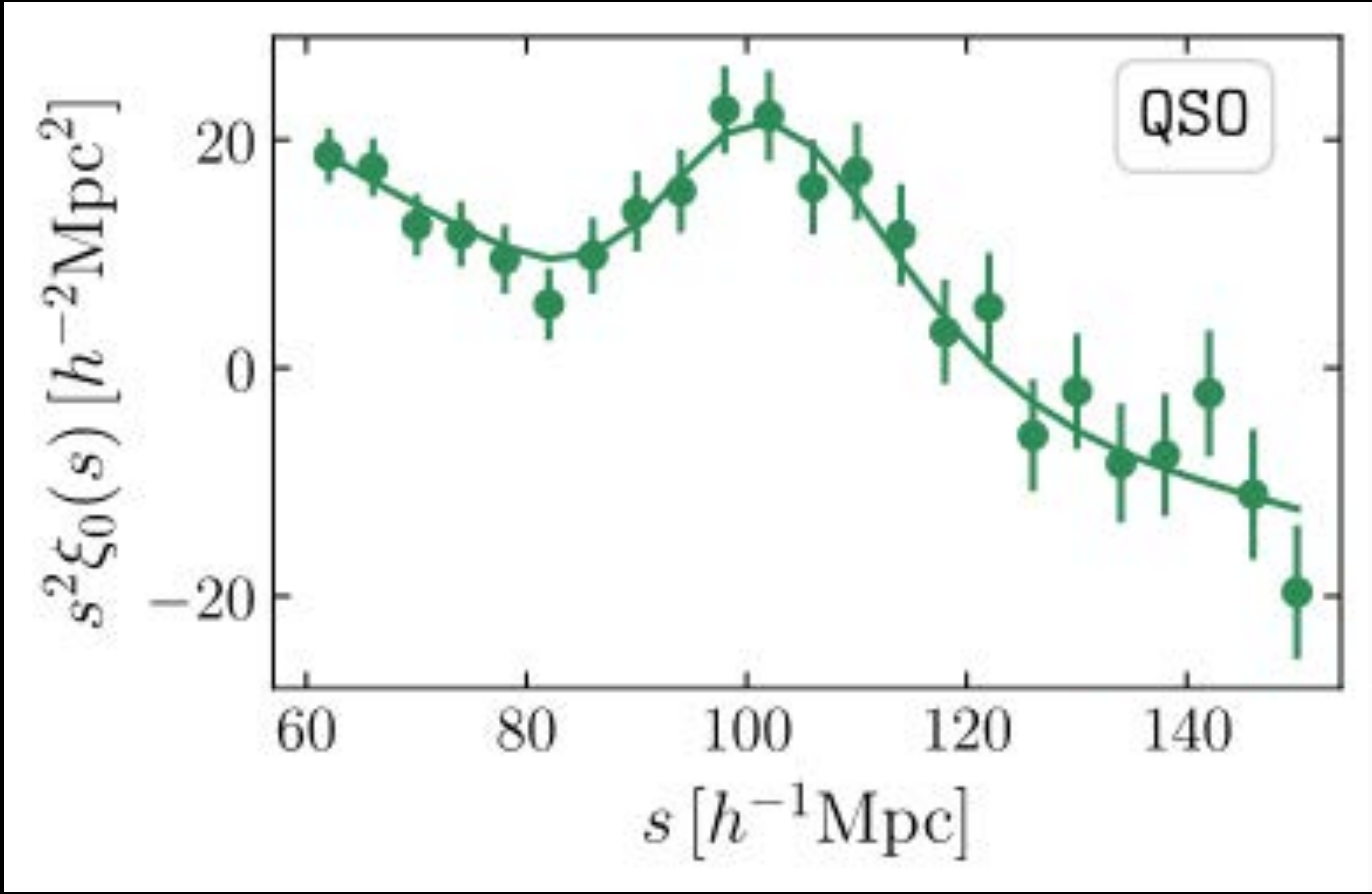
DESI Collaboration; arXiv:2503.14738

Emission Line Galaxies, 1.1<z<1.6, 0.7% distance



DESI Collaboration; arXiv:2503.14738

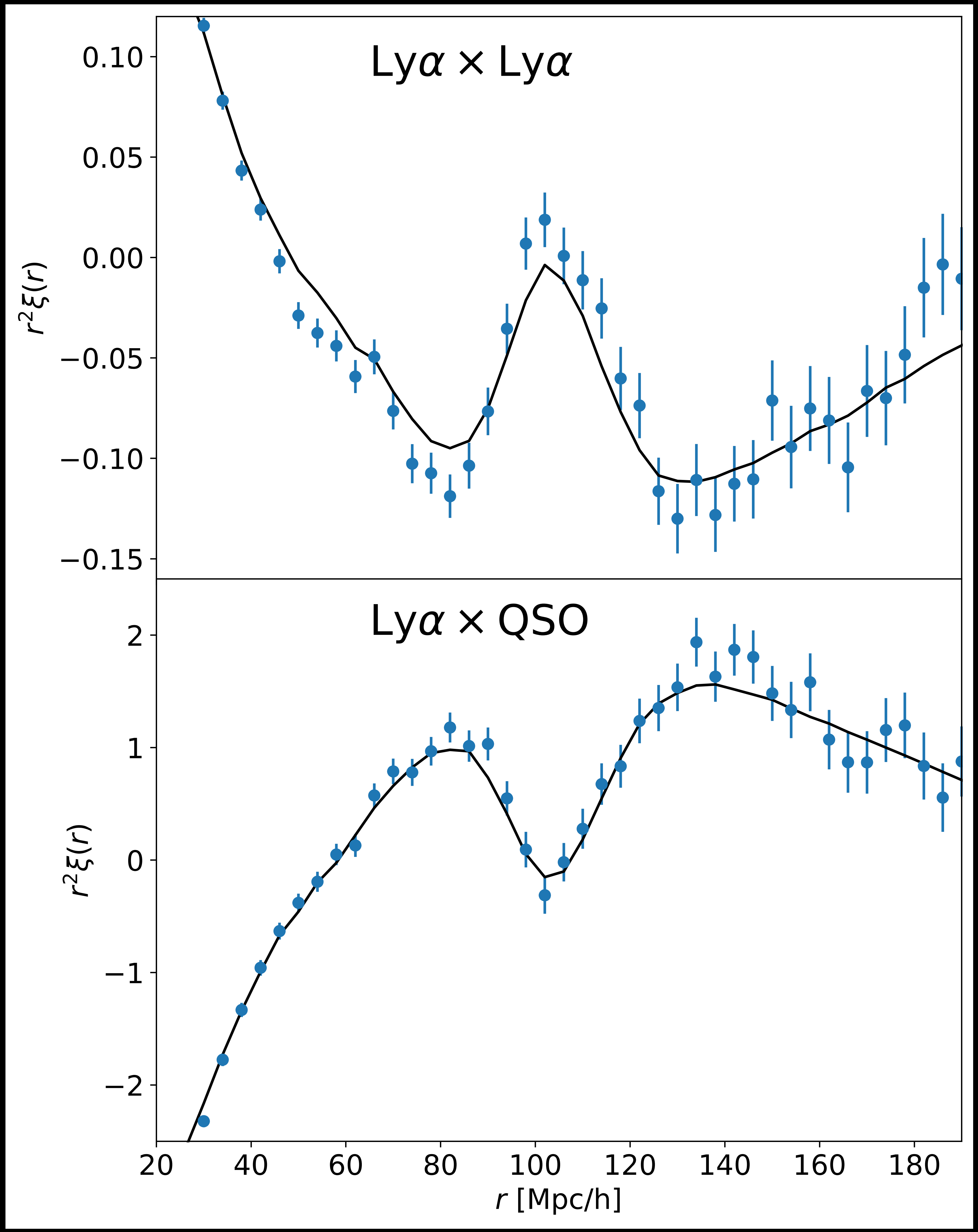
QSOs, 0.8<z<2.1, 1.5% distance



DESI Collaboration; arXiv:2503.14738

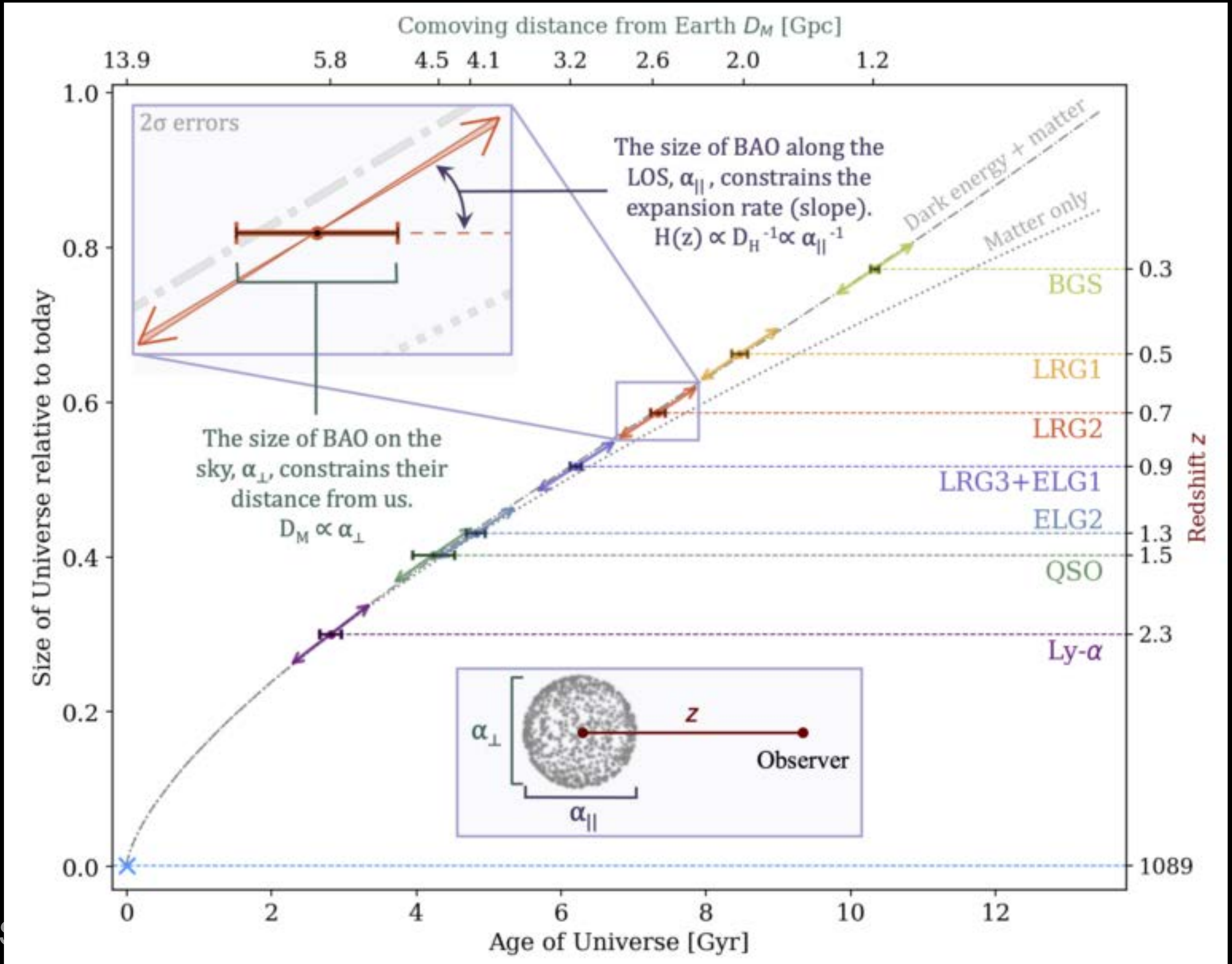
QSO Lyman-alpha forest, z=2.3, 0.65% distance

- Neutral hydrogen in the intergalactic medium leaves a distinctive signature in the spectrum of quasars
- Measure the density along the line of sight to each quasar, producing a 3-d map of neutral gas
- BAO peak 1.1% precision along LOS
- BAO peak 1.3% precision perpendicular

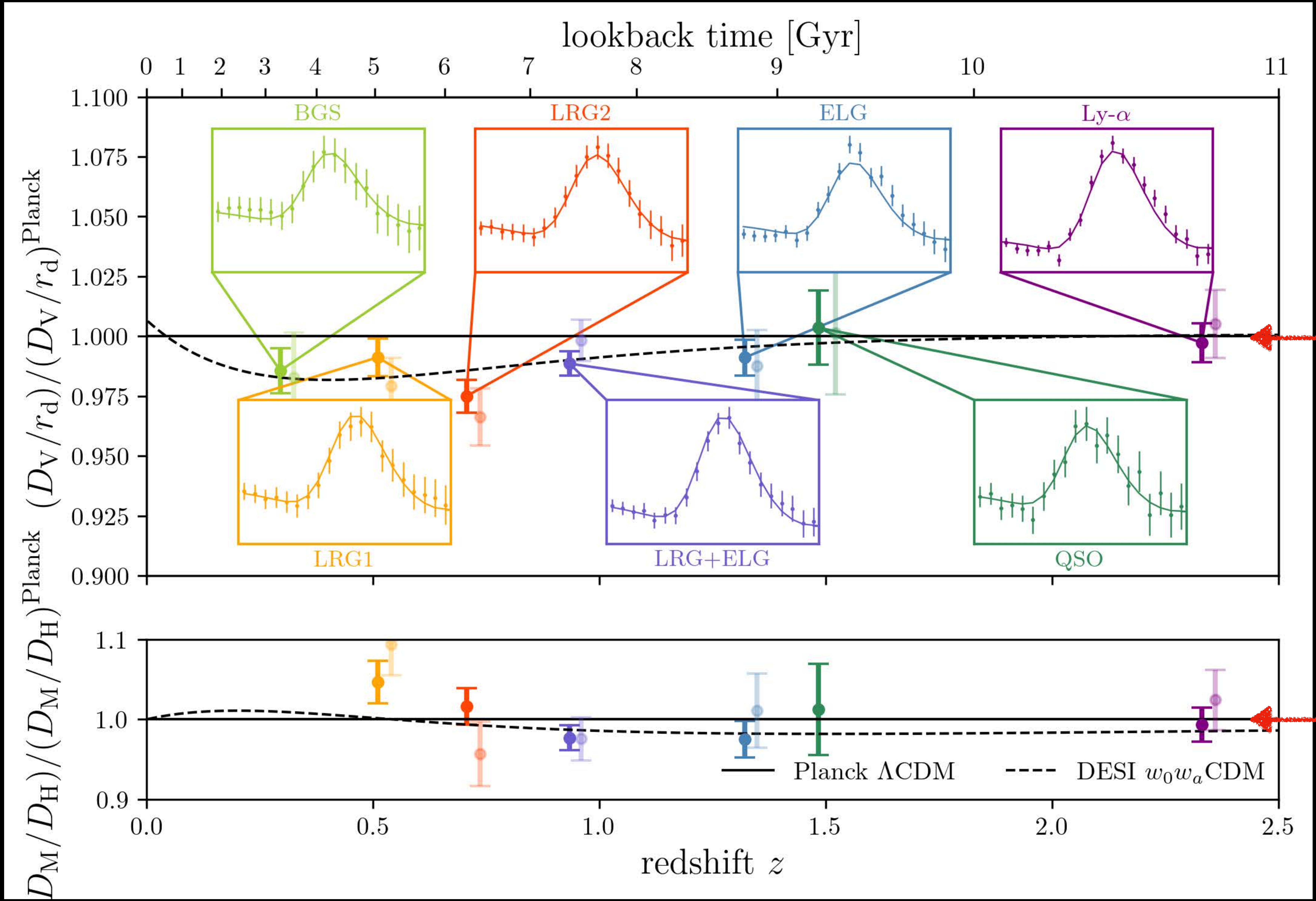


DESI Collaboration; arXiv:2503.14739

DESI gives a very precise history of the scale of the universe



DESI DR2 results: Aggregate precision on BAO scale 0.3%



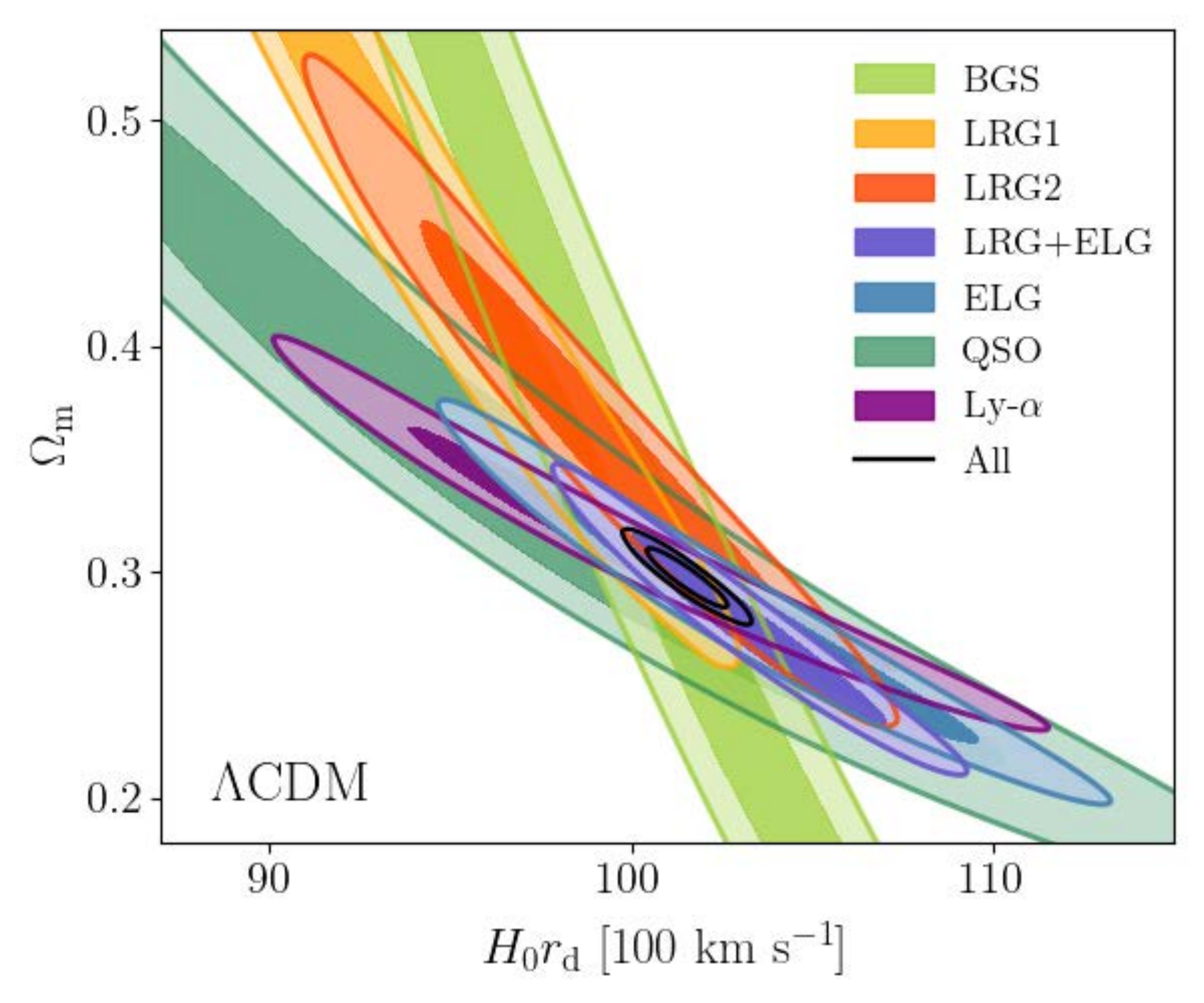
Best-fit cosmology prior to DESI

Best-fit cosmology prior to DESI

Interpretation in context of Lambda-CDM (ΛCDM) model

DESI galaxies at different redshifts are compatible and complementary

- Taking the acoustic scale as uncalibrated, the measurement of the acoustic peak at z=0 would measure H_0r_d
- Measuring at non-zero redshift gives some Ω_m dependence
- Contours are bounded because we measure D_A and H at each redshift



DESI Collaboration; arXiv:2503.14738

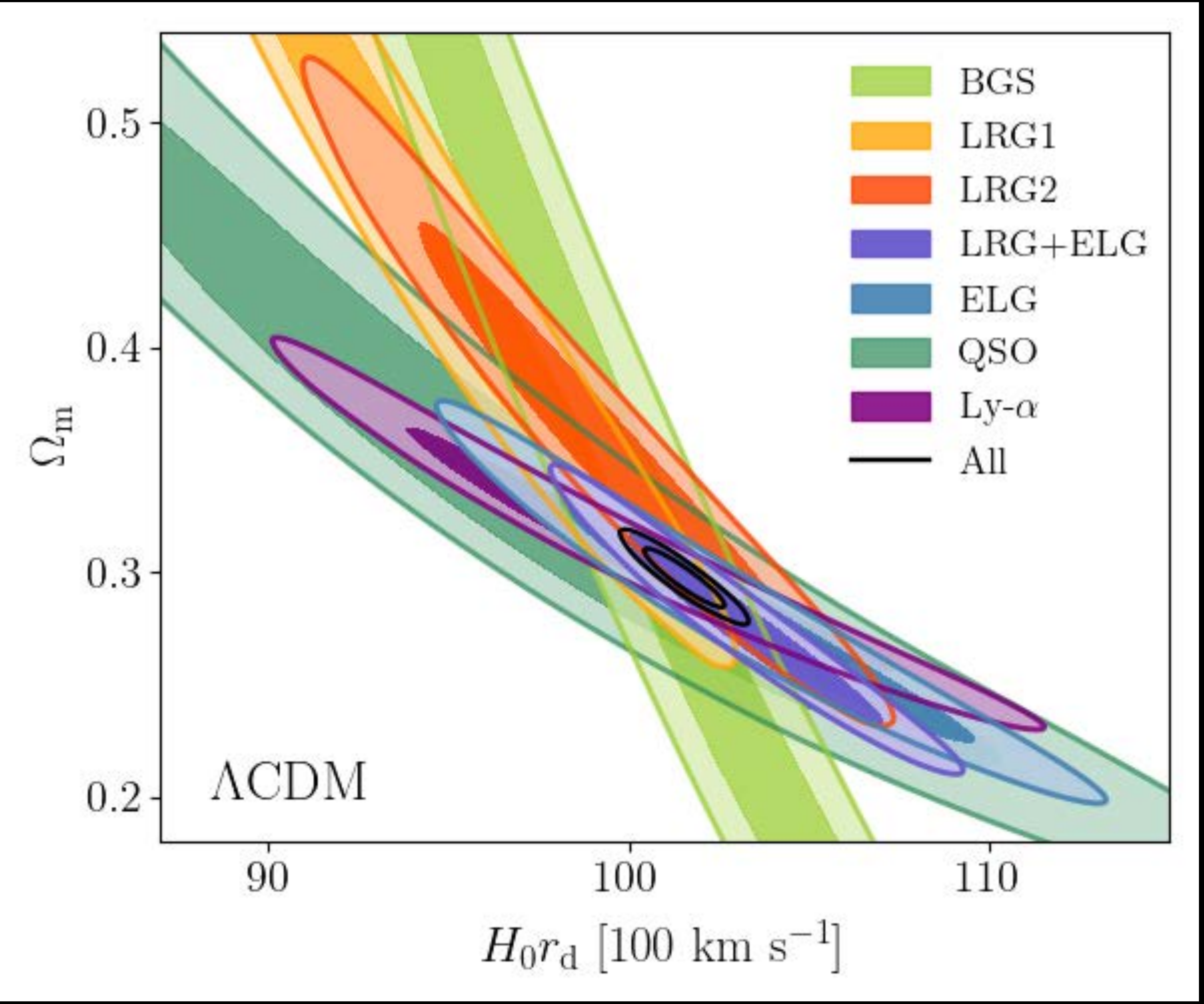
Interpretation in context of Lambda-CDM (ΛCDM) model

DESI galaxies at different redshifts are compatible and complementary

DESI BAO gives:

Matter density of the Universe measured to 2.9%
$\Omega_m = 0.298 \pm 0.0086$

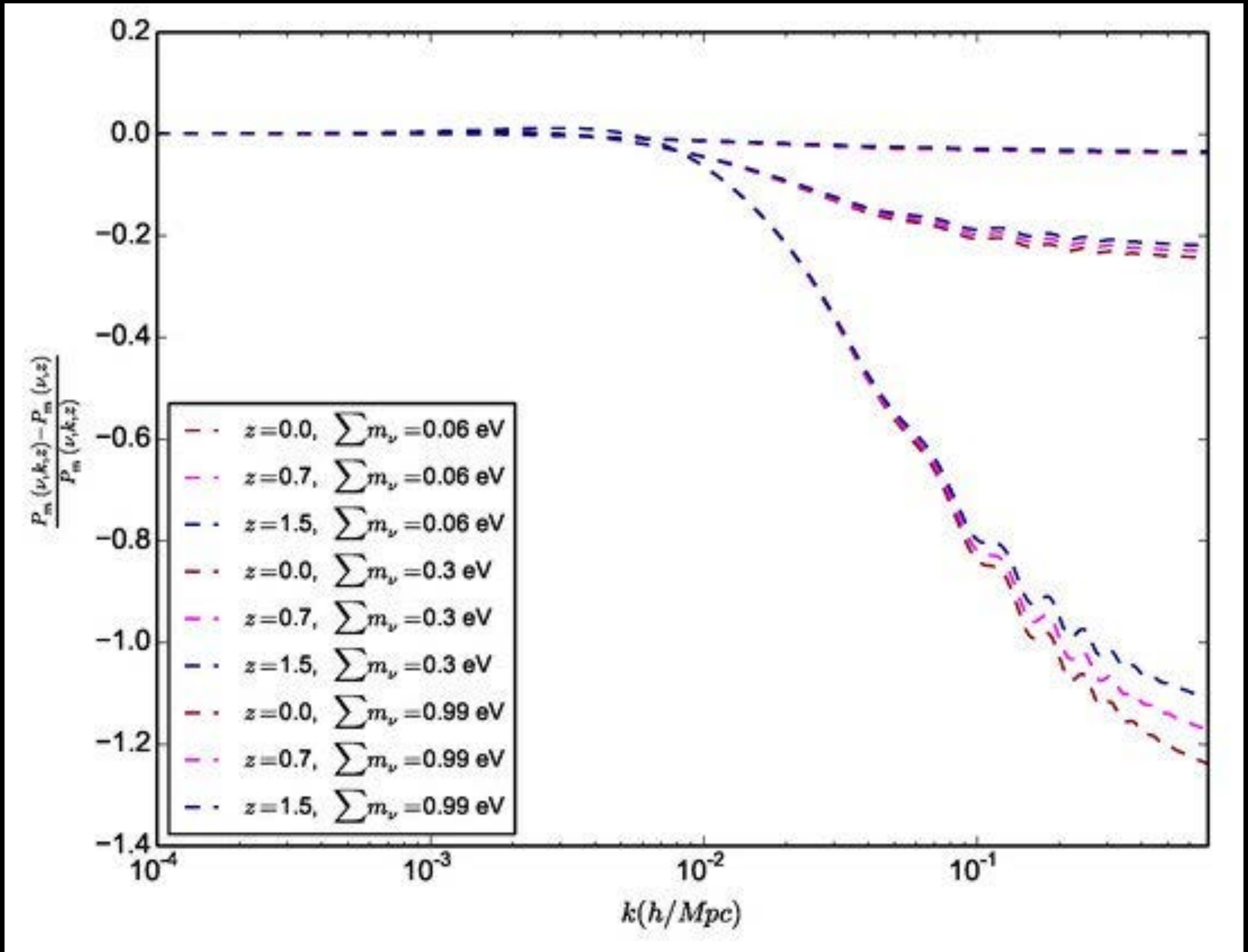
Hubble constant X sound horizon measured to 0.7%
$H_0 r_d = (101.54 \pm 0.73)$ [10^2 km s^{-1}]



DESI Collaboration; arXiv:2503.14738

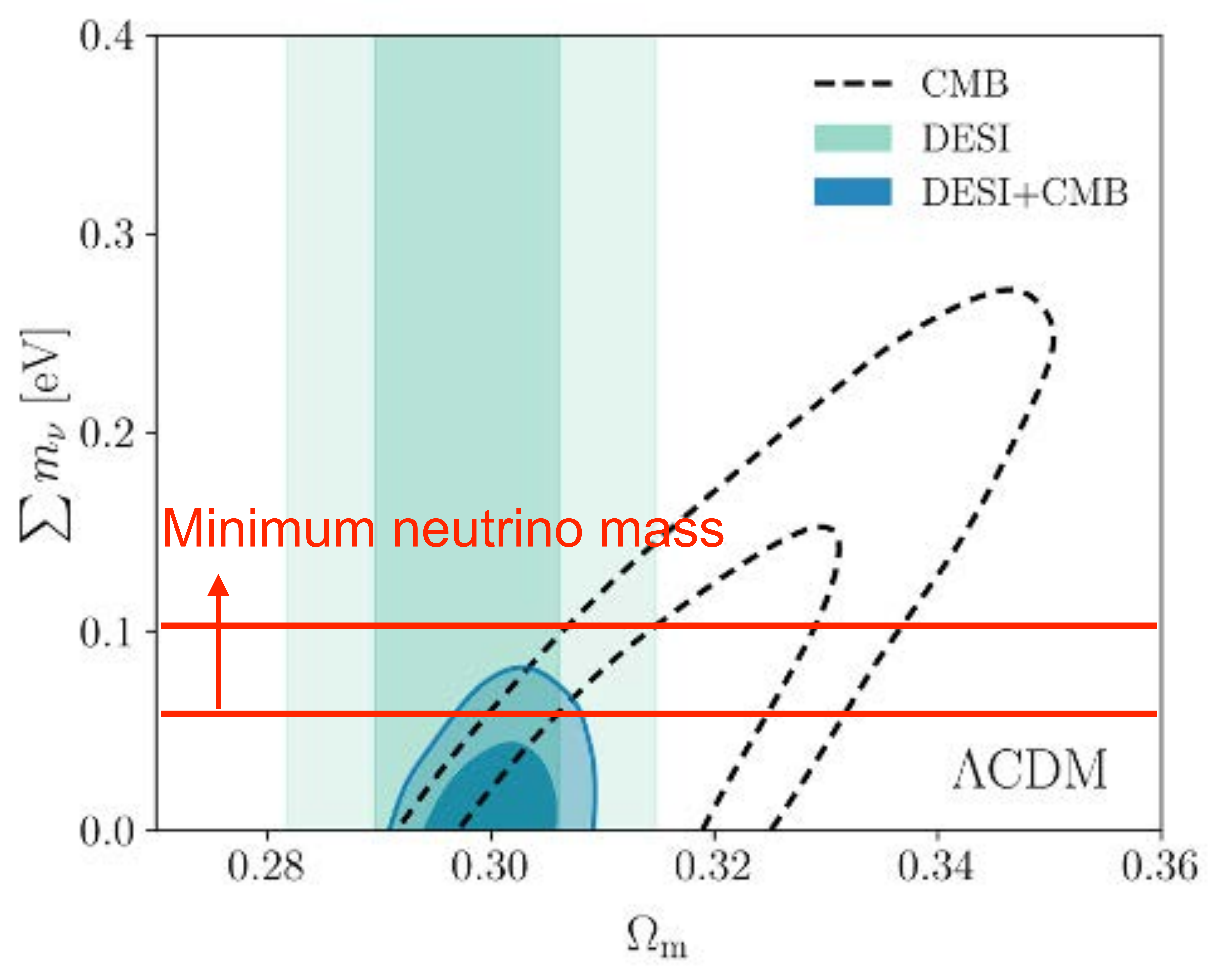
Constraints on neutrino mass in flat ΛCDM model

Neutrino mass both shifts the position of the last scattering surface (CMB peaks + BAO) and suppresses the growth of structure.
This analysis consideres only the former…



Constraints on neutrino mass in flat ΛCDM model

DESI breaks parameter degeneracies in the CMB to further limit the sum of neutrino masses
… but those limits substantially relaxed if Dark Energy is dynamic



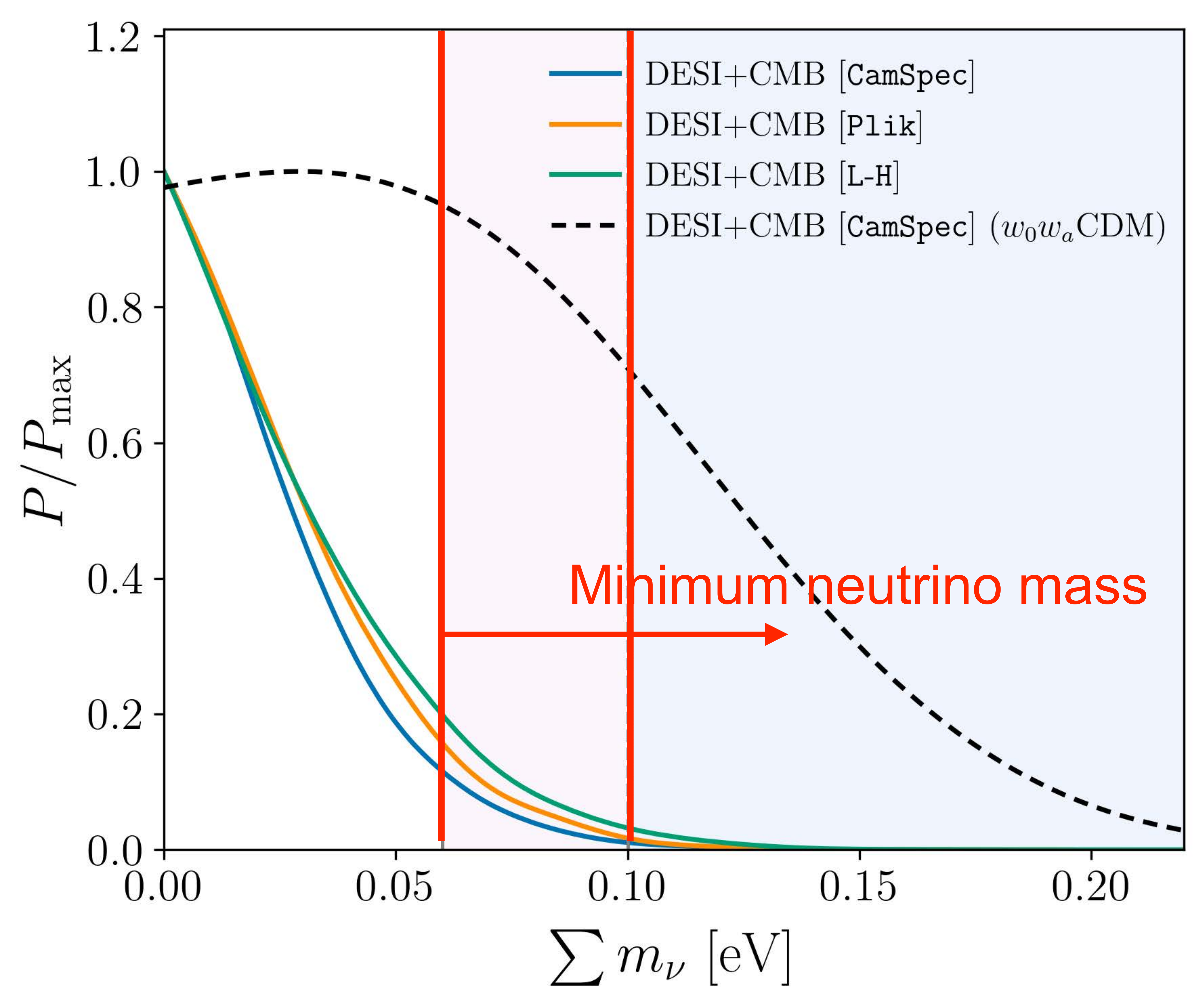
In ΛCDM model:
$\Sigma m_\nu < 0.064$ eV (95%)

In $w_0 w_a$CDM:
$\Sigma m_\nu < 0.163$ eV (95%)

Constraints are model and prior dependent

Constraints on neutrino mass in flat ΛCDM model

DESI breaks parameter degeneracies in the CMB to further limit the sum of neutrino masses
… but those limits substantially relaxed if Dark Energy is dynamic



In ΛCDM model:
$\Sigma m_\nu < 0.064$ eV (95%)

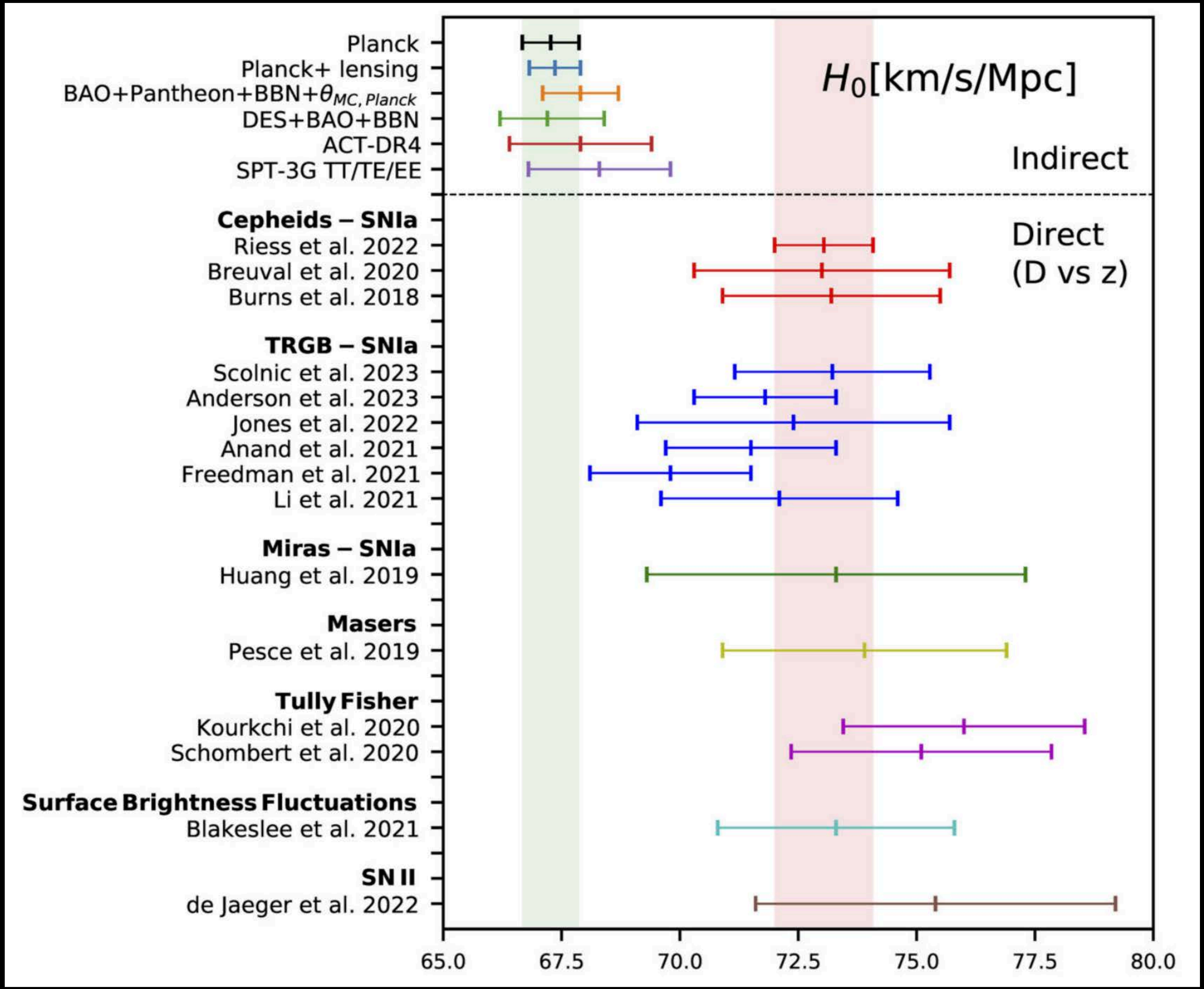
In w_0w_aCDM:
$\Sigma m_\nu < 0.163$ eV (95%)

Constraints are model and prior dependent

But we know neutrinos have mass!!

DESI in the context of the "Hubble tension controversy"

DESI BAO is consistent with previous results, however late-time measures of the Hubble expansion are still "in tension"

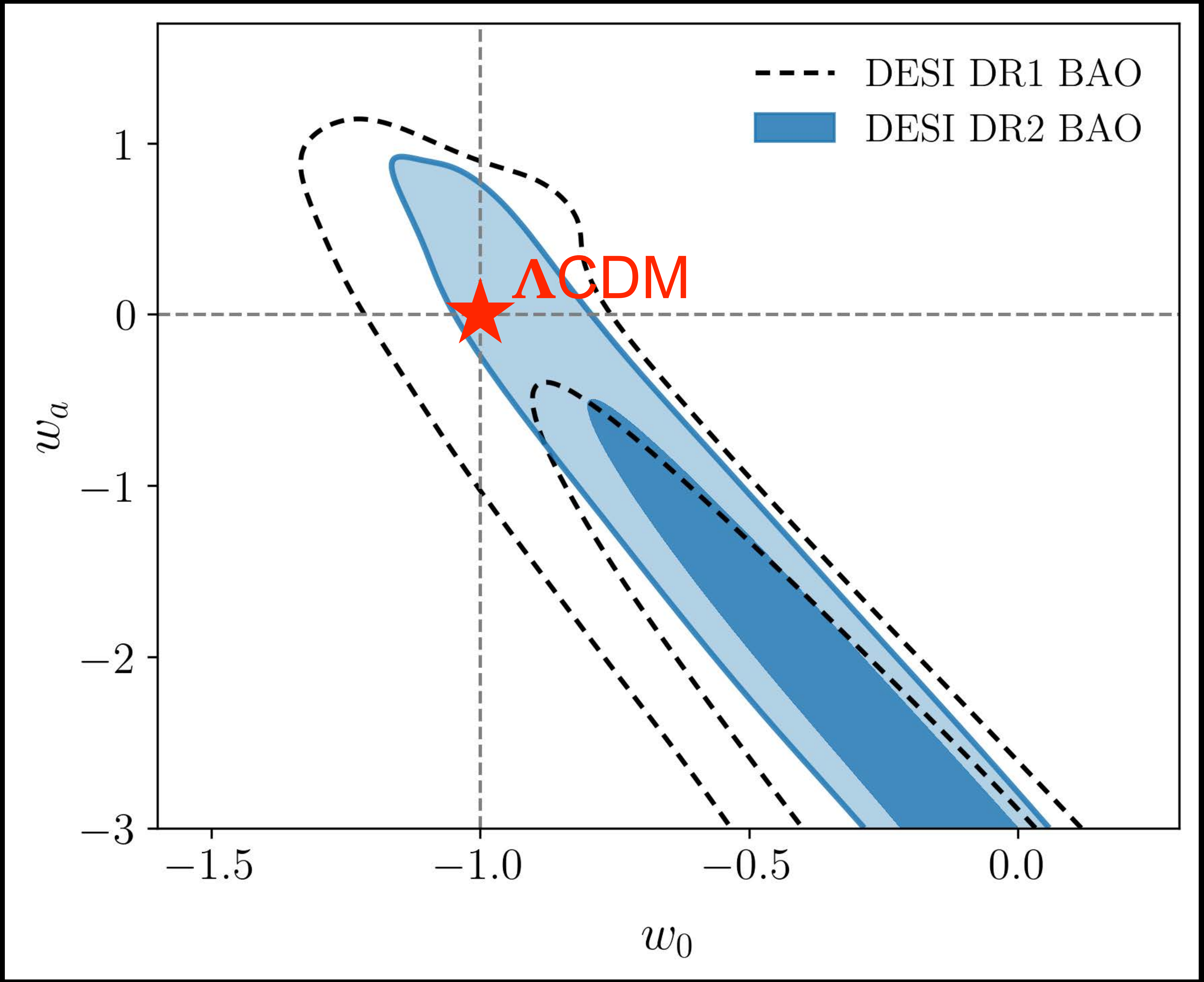


DESI + BBN constraints on physical baryon density, $\Omega_b h^2$, breaks the H_0 r_d degeneracy:

H_0 = (68.51 ± 0.58) km s^{-1} Mpc^{-1}
in 5.4$\boldsymbol{\sigma}$ tension with SH0ES

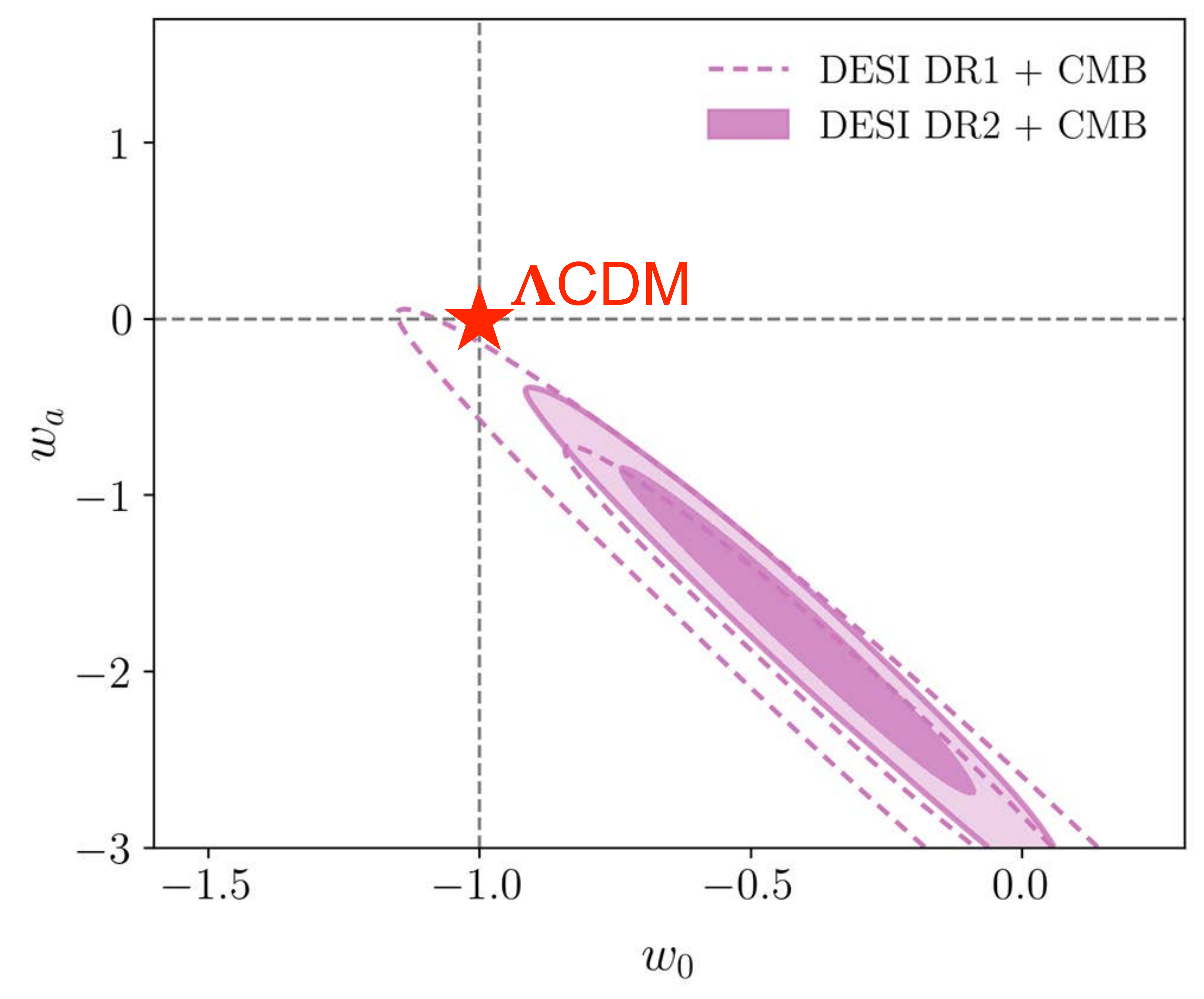
Either the nearby distance scale is wrong by 7% (15% in flux!!) or the sound horizon is actually 7% shorter than we infer!!??

DESI results alone consistent with ΛCDM (non-evolving dark energy)



DESI DR2 within 2-σ of ΛCDM

DESI results alone consistent with ΛCDM (non-evolving dark energy)

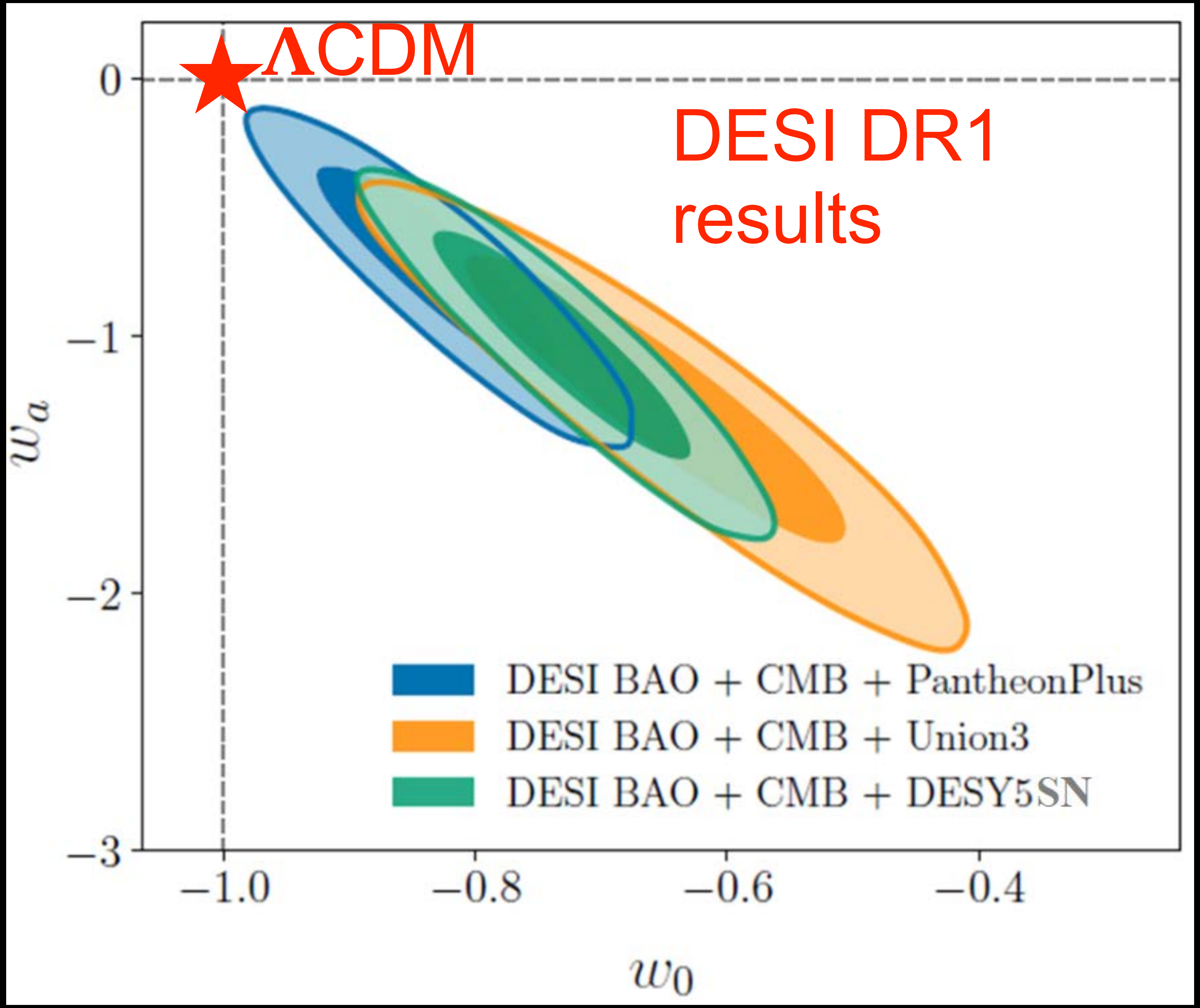


$$w(a) = w_0 + (1- a)\, w_a$$

DESI DR2 + CMB prefers evolving dark energy by 3.1-σ

(+0.5σ compared to DESI DR1)

Dark Energy with a time-varying equation of state w_0w_aCDM appears to fit the data better than ΛCDM when including supernova data



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

Combining DESI+CMB+Supernova increased preference for $w_0 > -1$ and $w_a < 0$

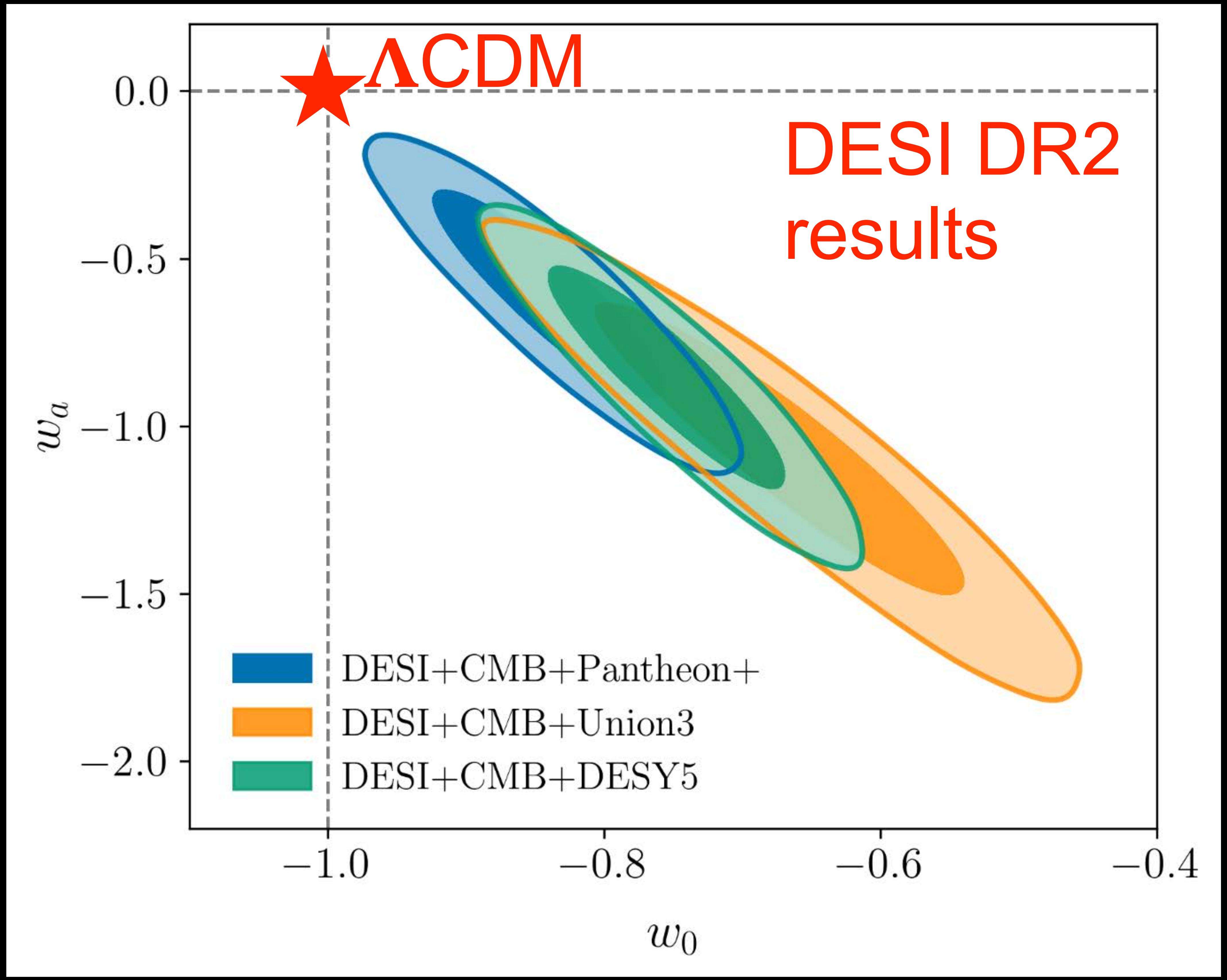
DESI+CMB+PantheonPlus: 2.5σ

DESI+CMB+Union3: 3.5σ

DESI+CMB+DESY5 SN: 3.9σ

Are we seeing first hints for a time-varying w(a) rather than ΛCDM?

Dark Energy with a time-varying equation of state w_0w_aCDM appears to fit the data better than ΛCDM when including supernova data



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

Combining DESI+CMB+Supernova increased preference for $w_0 > -1$ and $w_a < 0$

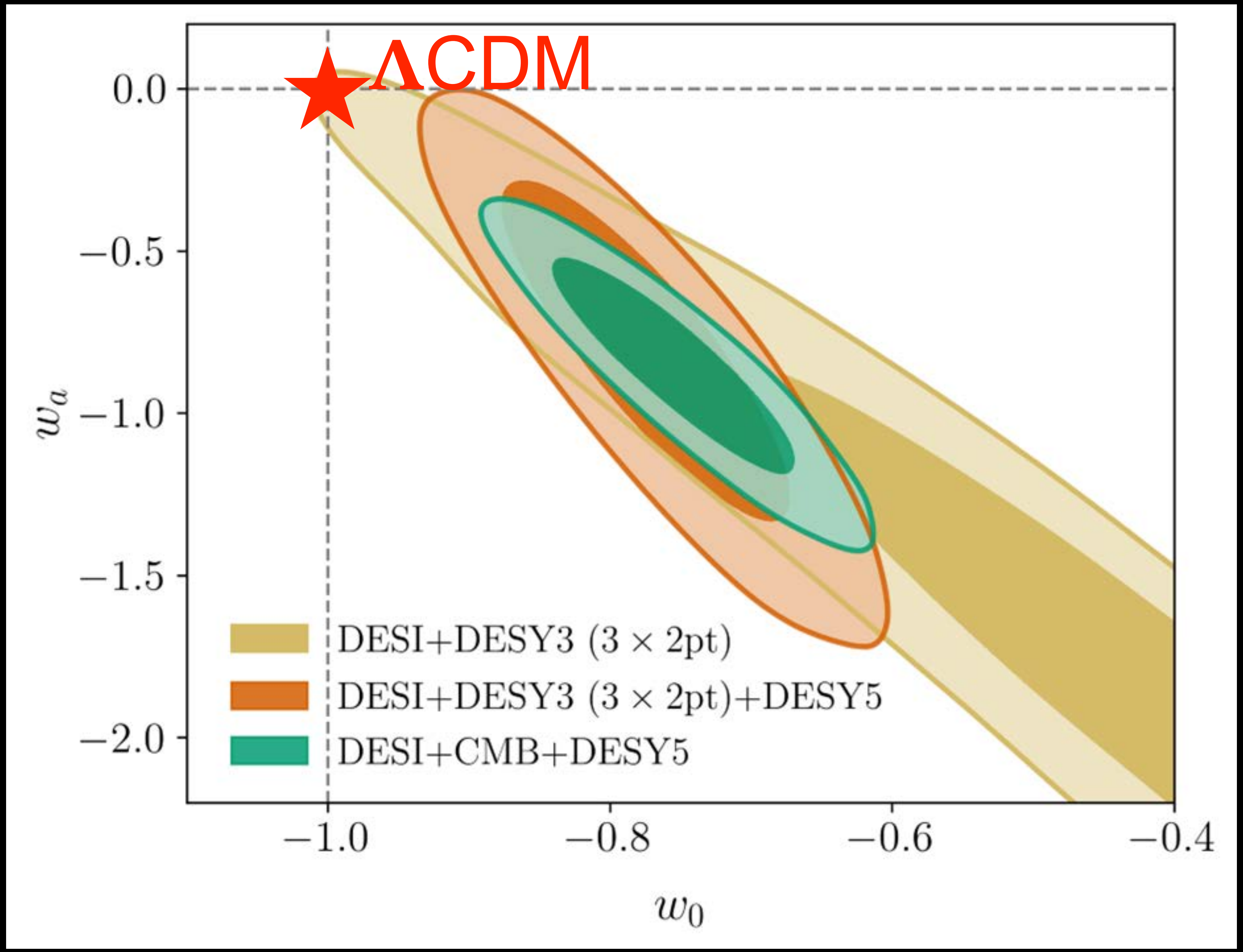
DESI+CMB+PantheonPlus: 2.8σ

DESI+CMB+Union3: 3.8σ

DESI+CMB+DESY5 SN: 4.2σ

Are we seeing first hints for a time-varying w(a) rather than ΛCDM?

Dark Energy with a time-varying equation of state $w_0 w_a$CDM still preferred when using low-redshift probes otherthan supernovae



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

Replacing CMB with DESY3 3x2pt
(weak lensing + galaxy clustering)

DESI + DESY3 (3x2pt) ==> 2.2σ

DESI + DESY3 (3x2pt) + DESY5 ==> 3.3σ

Are we seeing first hints for a time-varying w(a) rather than ΛCDM?

Evolving dark energy

The best-fit LCDM model in DESI+CMB doesn't match the trend in the SNe — would need an 0.05 mag shift

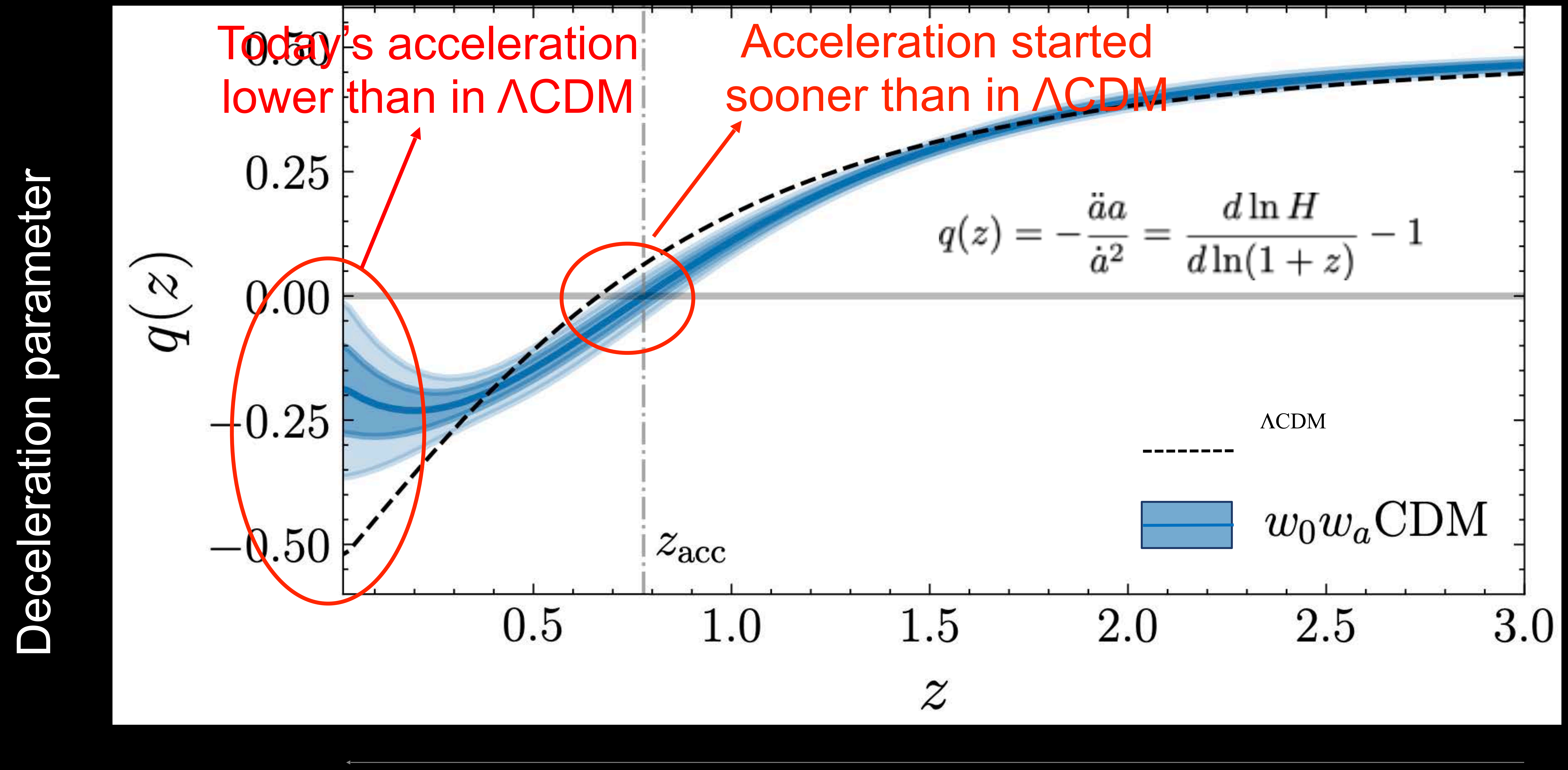
Evolving dark energy

A model of a constant w doesn't help…

Evolving dark energy

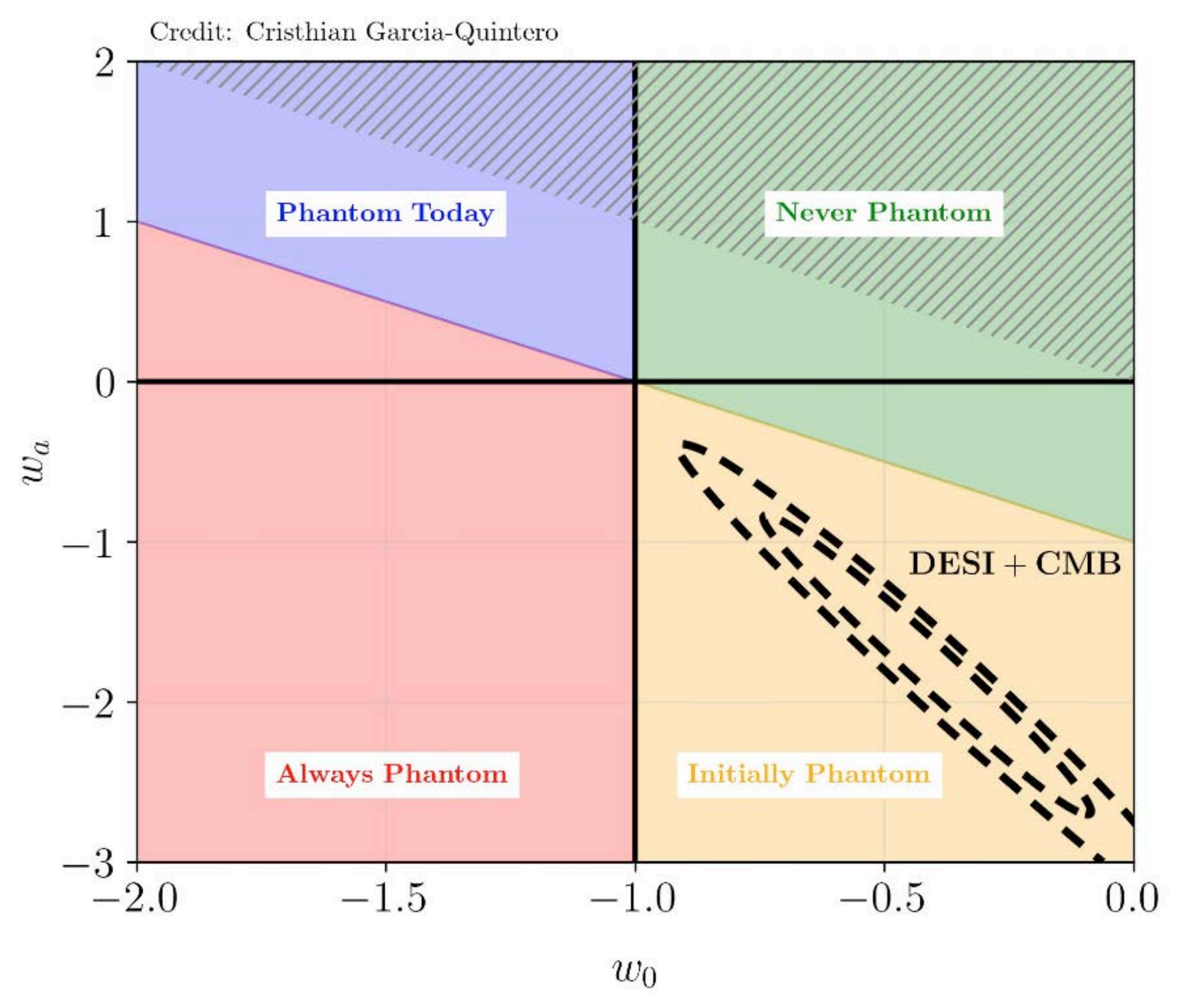
…But a model with w_0,w_a is able to bend to steer through the tensions…

Apparent weakening of dark energy today when combining DESI + CMB + supernovae



Weakening dark energy today

Ask the theorists what this means… they're writing ~3 papers/day…



Conclusions?

DESI has released the most precise BAO measurements

DESI in mild tension with Planck (2.3σ) and SN (~2σ) when interpreted in ΛCDM

Evidence for evolving dark energy (increased by 0.3σ since DESI DR1)

- 3.1σ (DESI+CMB)
- 2.8σ – 4.2σ (DESI+CMB+SN)

Tightest bound on Σm_ν

- Growing tension with neutrino oscillations in ΛCDM
- Tension reduced if evolving dark energy

Eagerly awaiting more data !!