Cosmic Revelation: Quest for Dark Energy

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International Centre for Theoretical Sciences (ICTS) Colloquium

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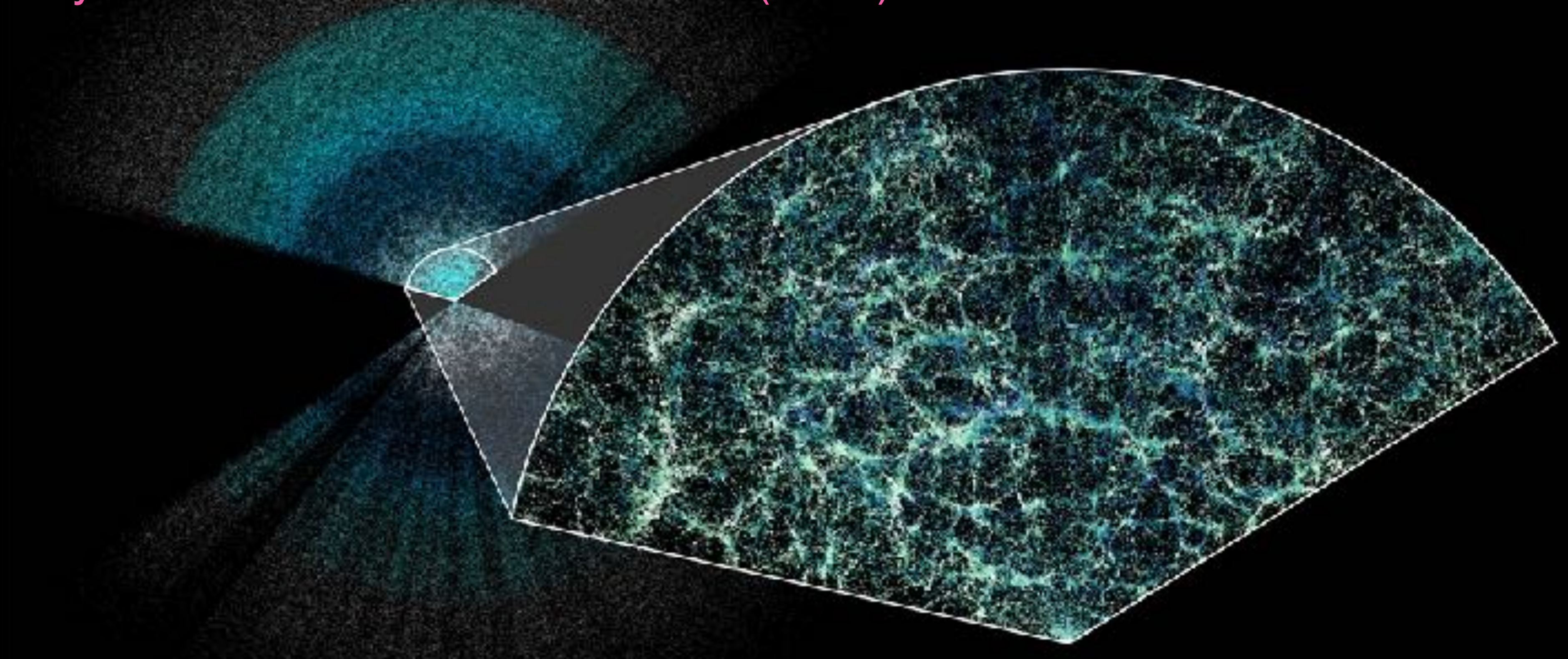
Physics of Universe and Galaxies (PUG) @ TIFR

DARK ENERGY SPECTROSCOPIC INSTRUMENT




DARK ENERGY
SPECTROSCOPIC
INSTRUMENT
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Homogeneous? and Isotropic? Universe

Einstein Field Equation

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}$$

FLRW metric

$$ds^2 = -c^2dt^2 + a^2(t)dX^2$$

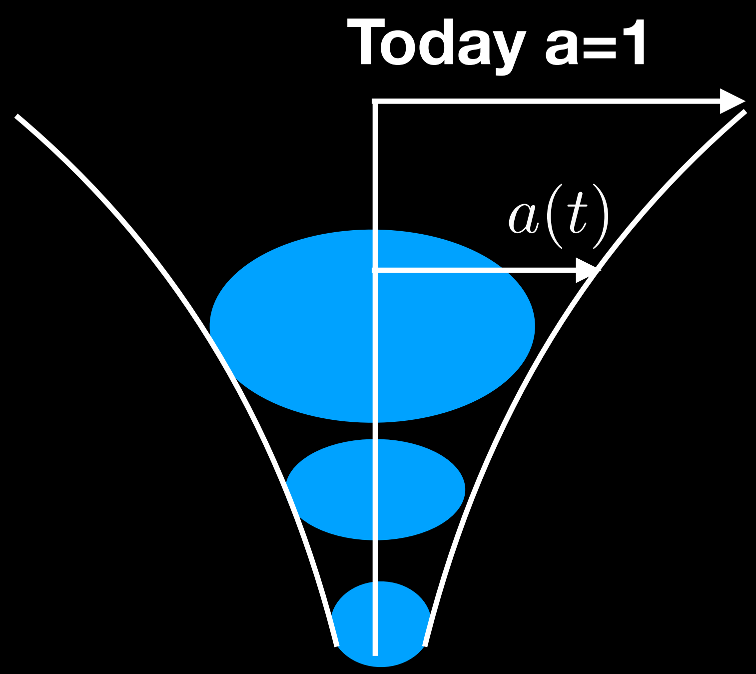
Hubble's rate

$$H(t) = \frac{\dot{a}(t)}{a(t)}$$

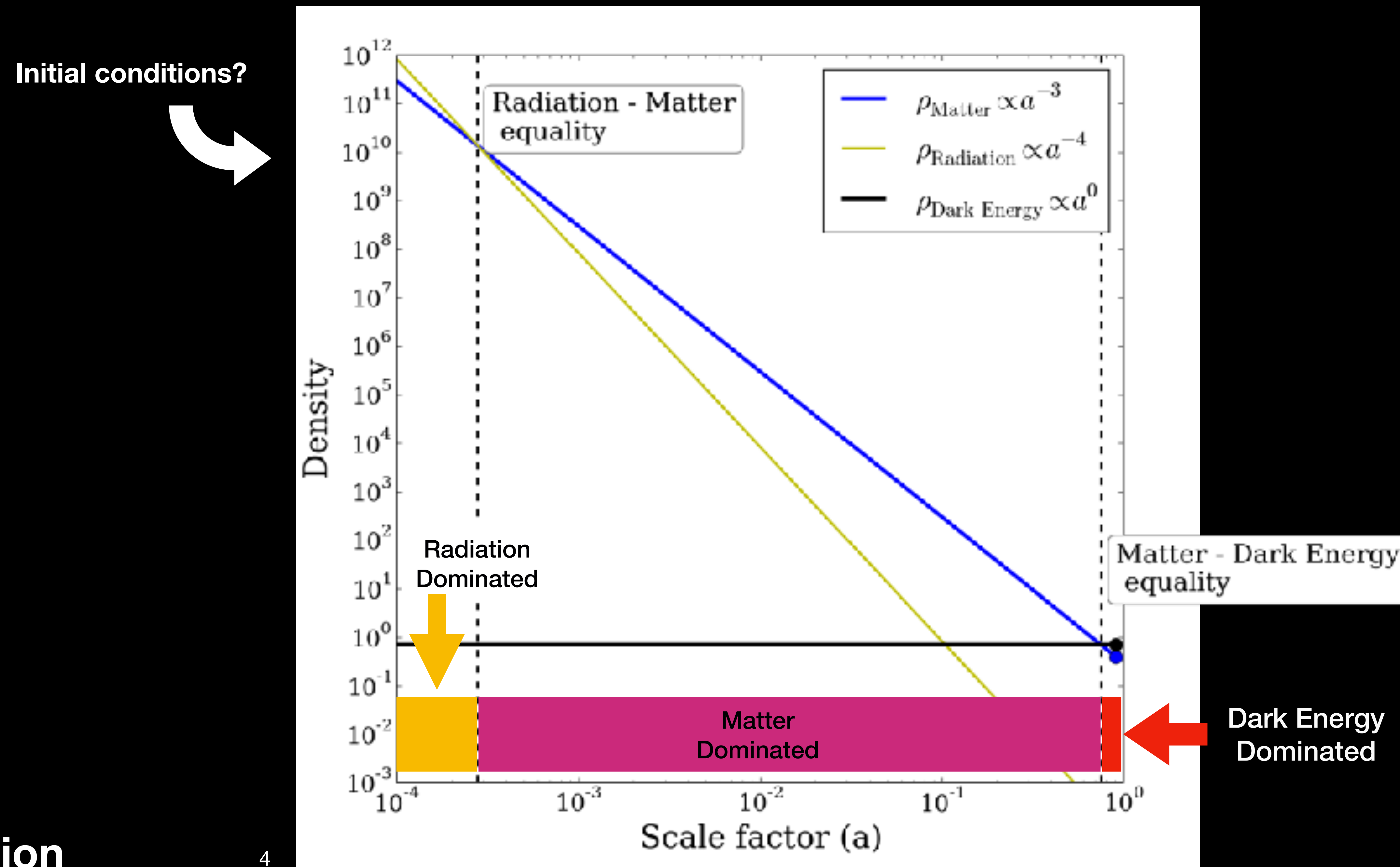
Friedmann equations

$$3\frac{\dot{a}^2}{a^2} = 8\pi G\rho + \Lambda c^2$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$$



Different phases of the universe



Density evolution

$$\rho \propto a^{-3(w+1)}$$

$$w = 0(\text{matter}), w = 1/3(\text{radiation}), w = -1(\text{dark energy})$$

Dark Energy

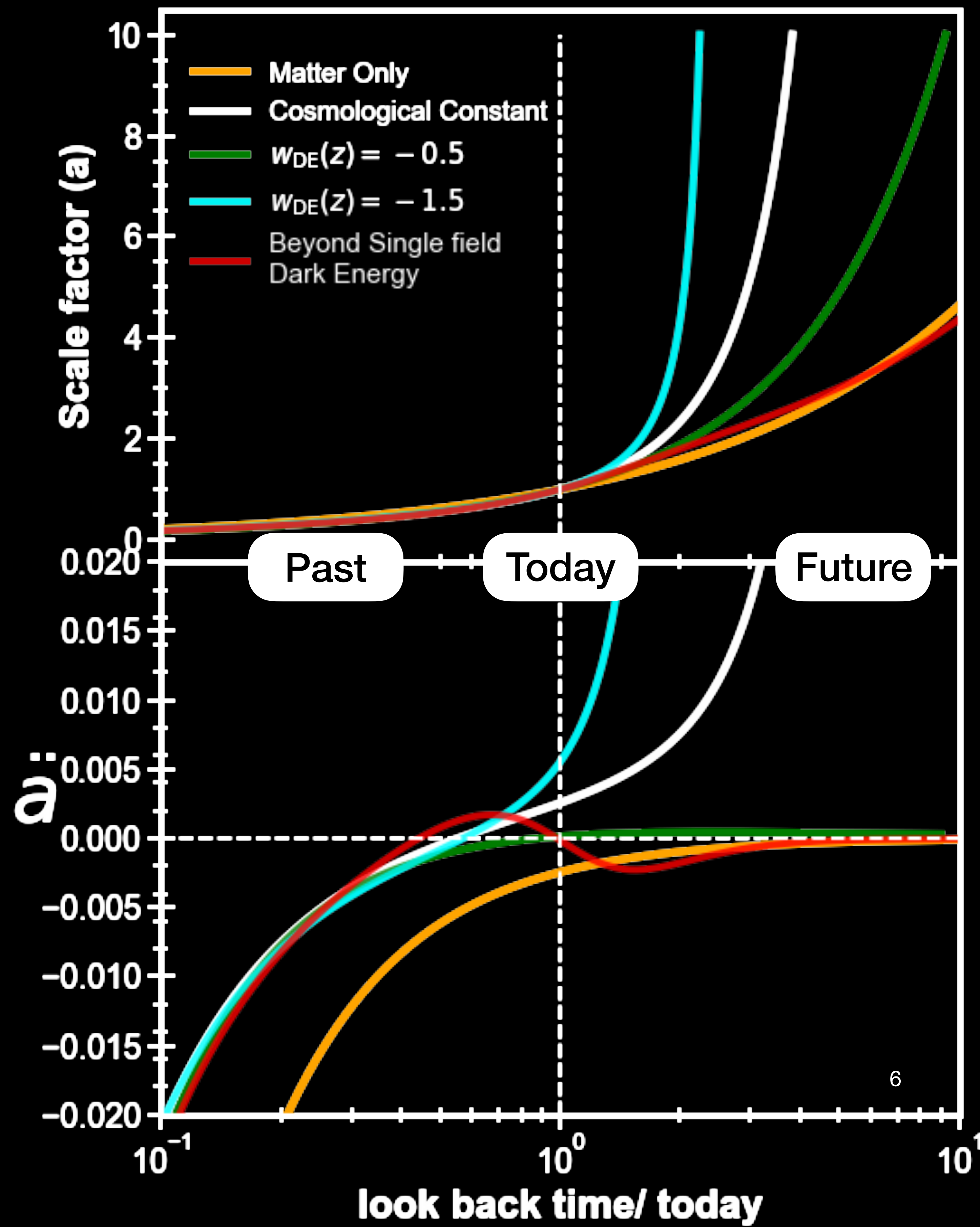
Remarkable properties:

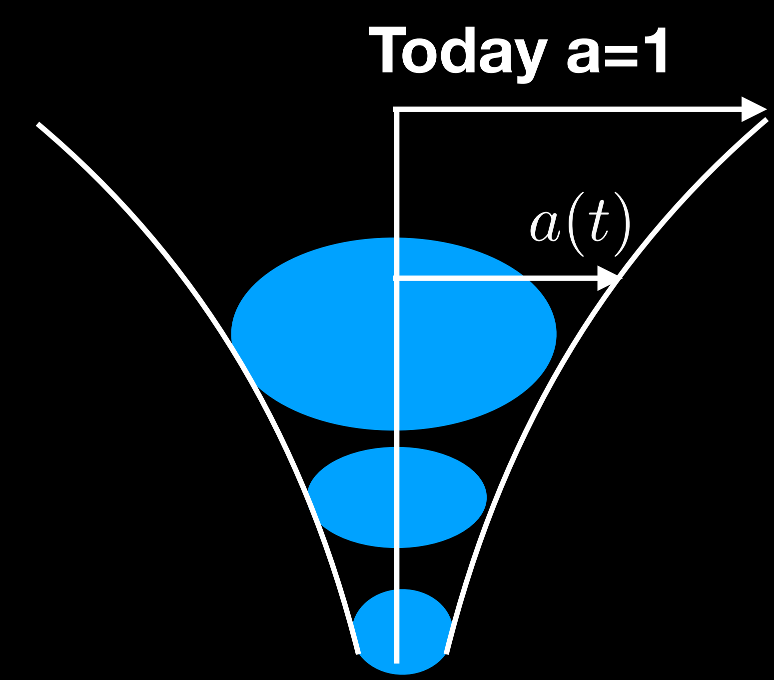
* Pressure must be negative to drive cosmic acceleration
* Consist of 70% of current energy content of the Universe

Equation of state $w_{\rm DE}$ of dark energy is the key:

$$w_{\rm DE}(z) = \frac{p_{\rm DE}(z)}{\rho_{\rm DE}(z)}$$

Cosmological constant?	Modification to General Relativity	Extra dimension String Theory	Multiple scalar fields



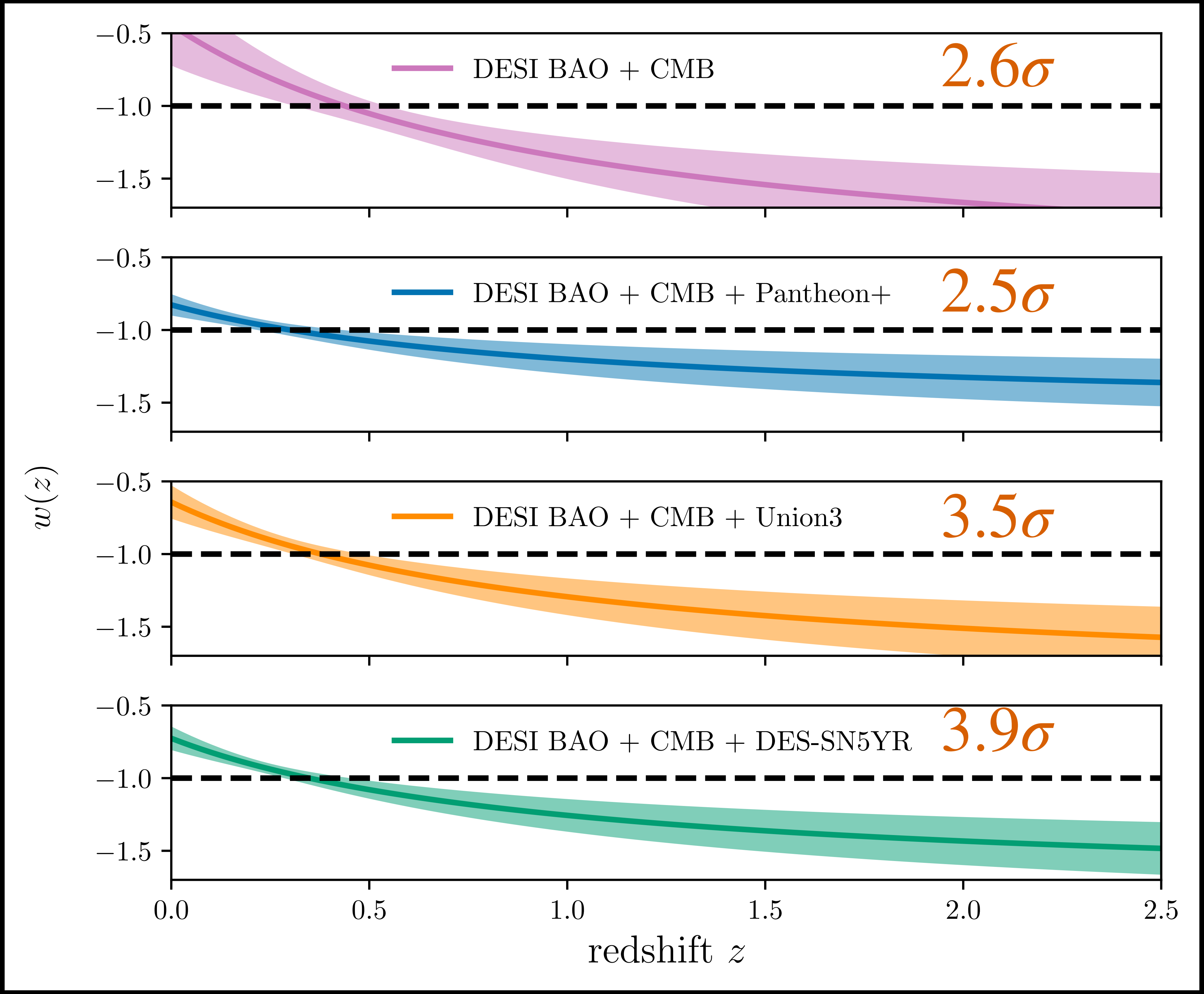


The Expanding Universe

$w_{DE}(z) \geq -1$	Quintessence (additional Scalar field)
$w_{DE}(z) \leq -1$	Phantom: Big Rip, ghost (negative kinetic term)
$w_{DE}(z)$ cross -1	No-Go Theorem with single fluid or scalar field. Quintom

DESI Y1 sample: $w_{\rm DE}(z)$

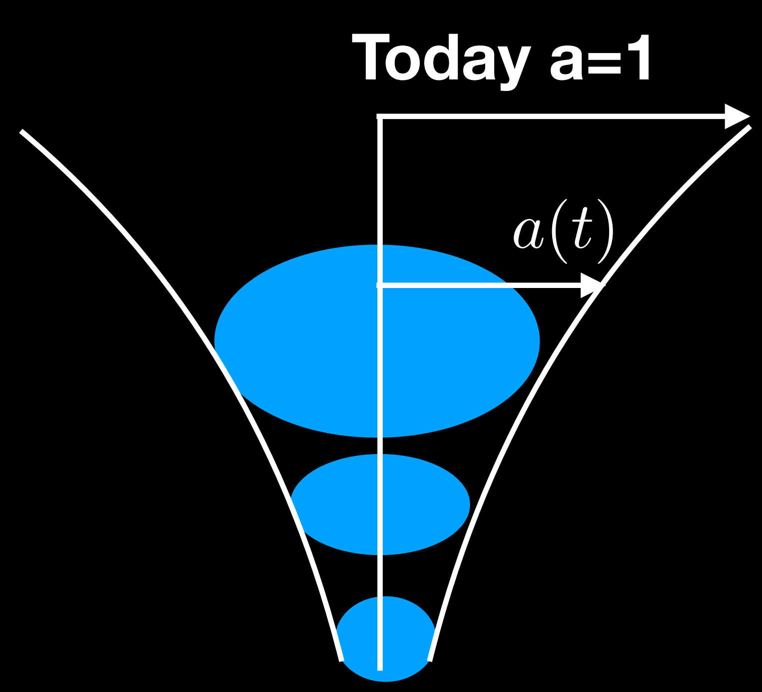
If $w_{\rm DE}$ crossing -1 is confirmed then It will rule out cosmological constant, quintessence, k-essenece and will require two coincidence (that is two additional freedom)



$$w_{\rm DE}(z) = w_0 + (1-a)w_a$$

How would you measure dark energy equation of state?

If we can measure a(t) precisely then that should encode information about content of universe including dark energy equation of state. (And curvature, neutrino mass, etc.)



Spectroscopy can help

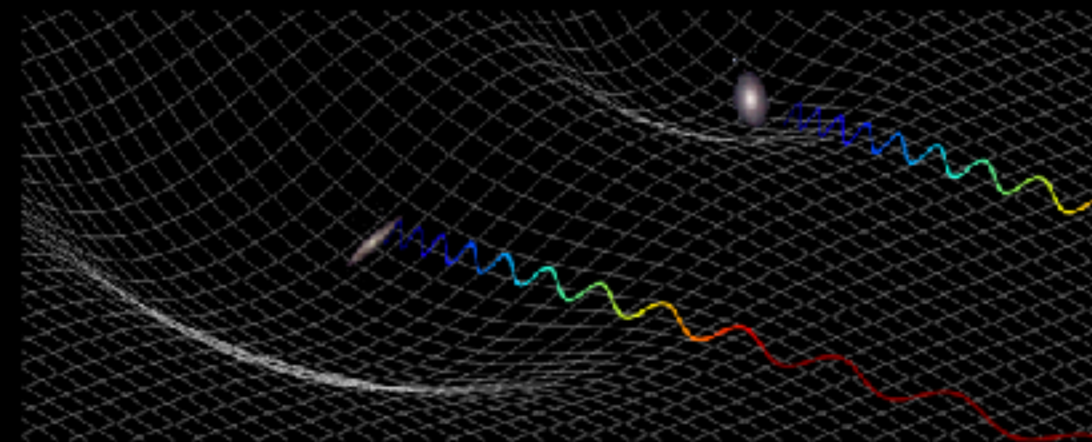
$$\frac{\Delta\lambda}{\lambda_e} = z \leftarrow \text{ (redshift)}$$

$$a(t_e) = \frac{1}{1+z}$$

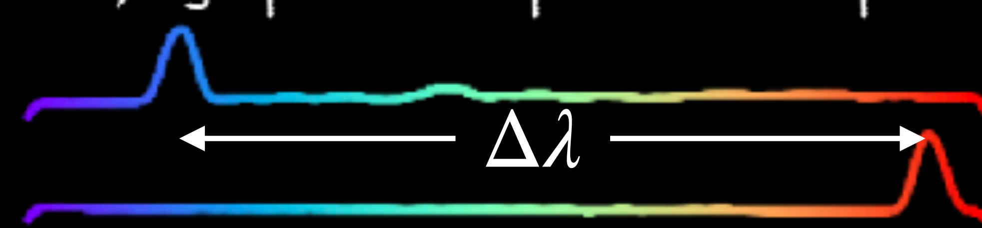
If we can also measure the time of emission then that will give us a measurement of $a(t_e)$

Light waves oscillate at different rates based on their wavelength/colour.

As light traverses the expanding universe, its wavelength gets stretched, shifting colours towards the red end.



Galaxies emit light over a range of wavelengths, creating a unique spectral fingerprint with peaks and dips.



By measuring how much these spectral peaks have redshifted, we can determine how much the light's wavelength stretched.

How about if we can measure proper distance of objects as the function of emission time.

$$d_p(t_0) = c\int_{t_e}^{t_0} \frac{dt}{a(t)}$$

Standard Candle

$$\text{flux} = \frac{L}{4\pi d_L^2}$$

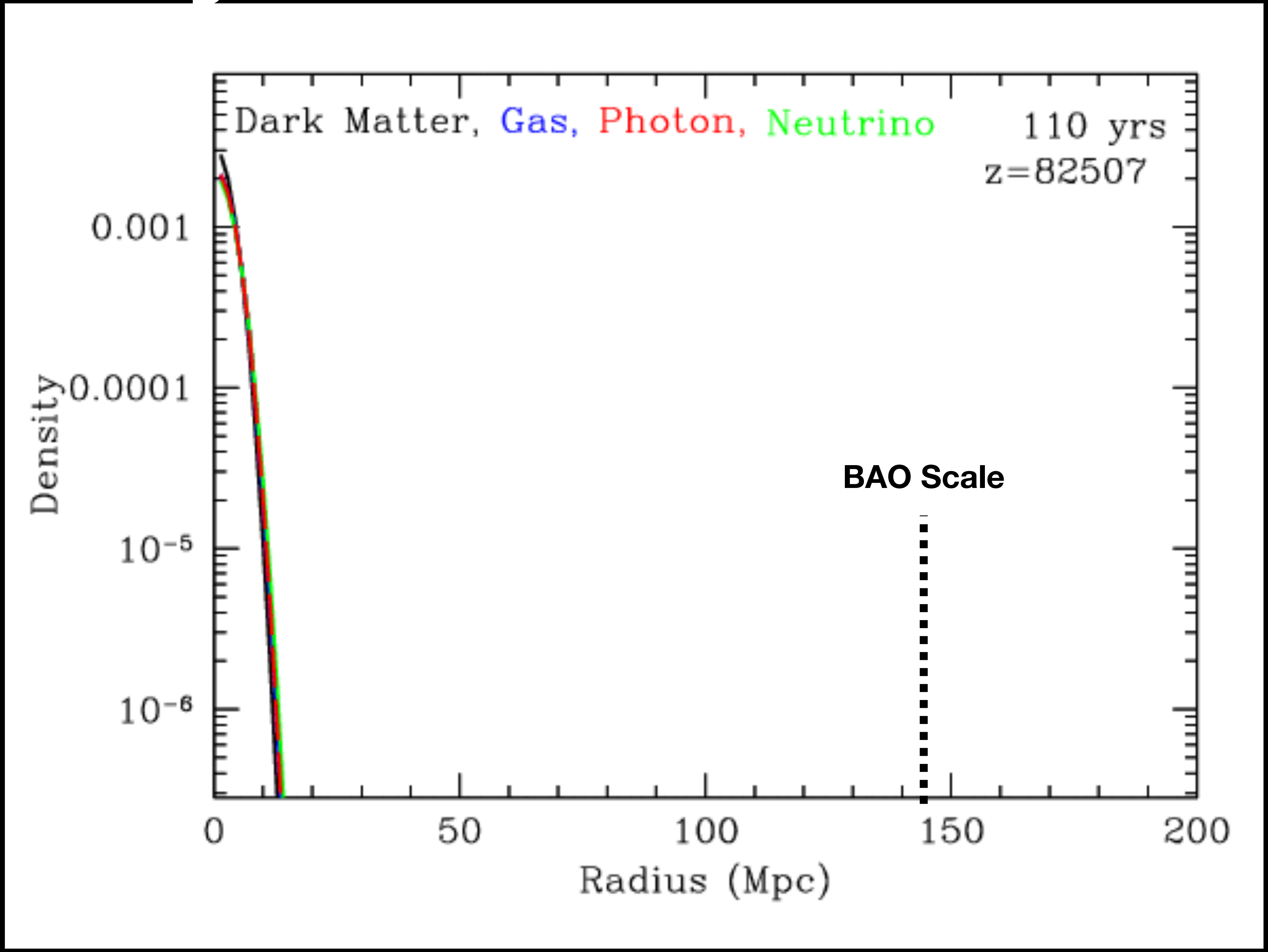
$\downarrow$ Luminosity distance

$$d_L = d_p(t_0)(1+z)$$

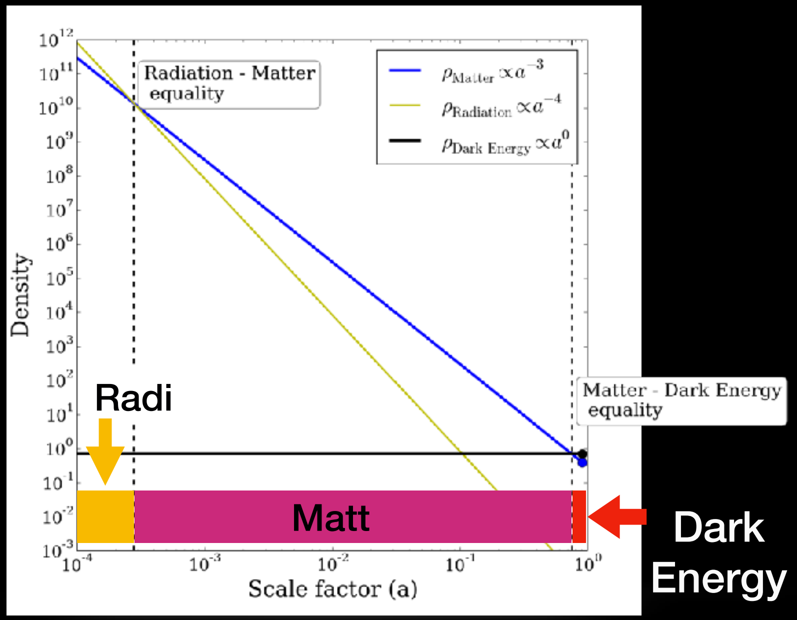
Supernovae cosmology

Standardizeable candle

Baryon Acoustic Oscillation



Animation Credit: Daniel Eisenstein

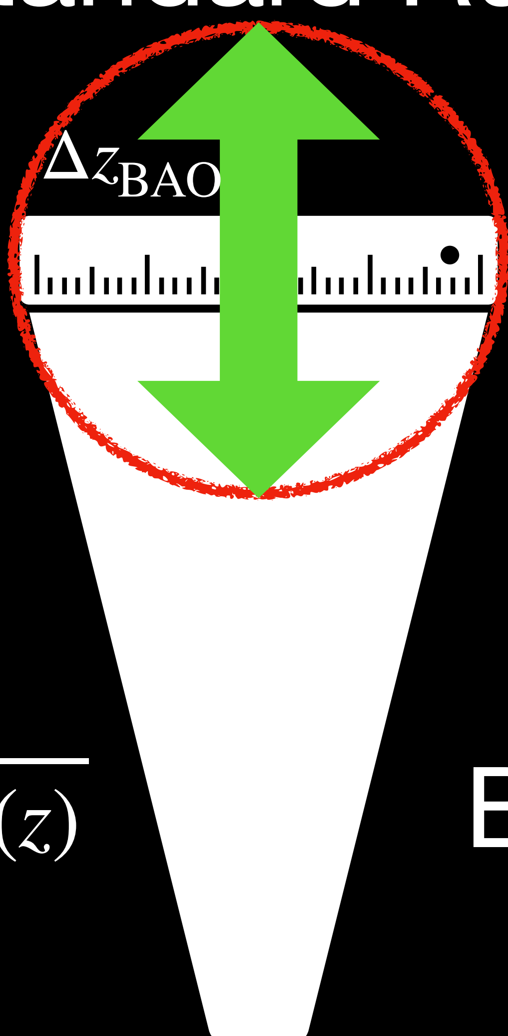


$$r_d = \int_{z_{\rm eq}}^{\infty} \frac{c_s}{H(z)} dz$$

How about if we can measure proper distance of objects as the function of emission time.

$$d_p(t_0) = c\int_{t_e}^{t_0} \frac{dt}{a(t)}$$

Standard Ruler



$\delta\theta_{\rm BAO}$

$$\Delta z_{\rm BAO} = \frac{1}{D_H(z)}$$

$$d_A = \frac{\ell}{\delta\theta_{\rm BAO}}$$

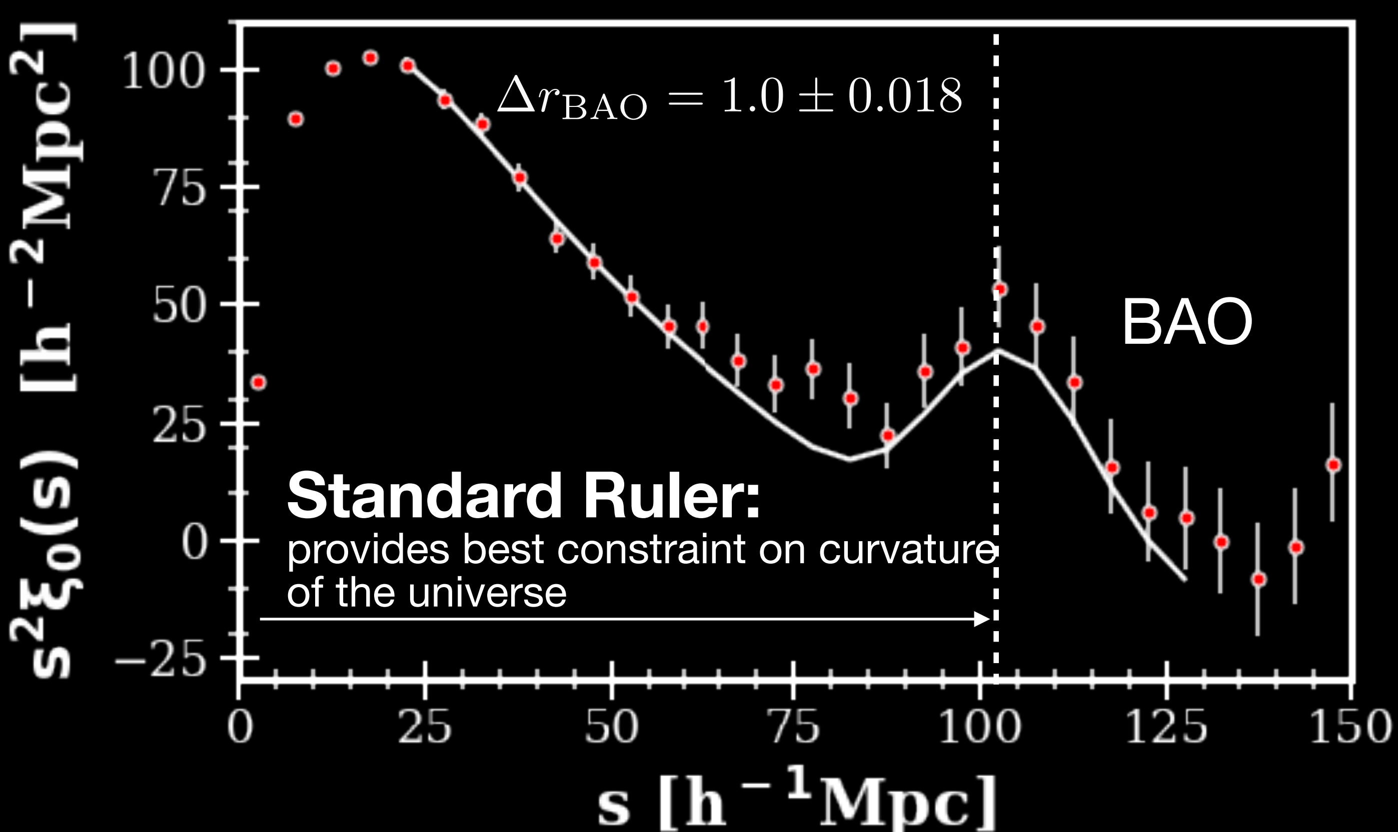
$$(1+z)d_A = d_p(t_0) \;\rightarrow D_M(z)$$

↑ Angular diameter distance

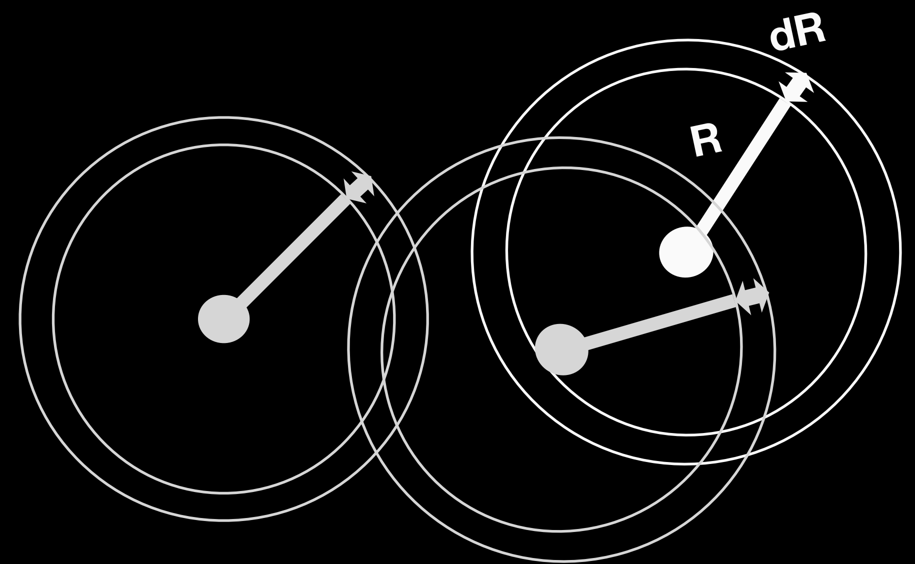
Baryon Acoustic Oscillation (BAO)

$$\frac{D_M(z)}{r_d}, \frac{r_d}{D_H(z)} \qquad D_{\rm V}(z) = \frac{[zD_M^2(z)D_H(z)]^{1/3}}{r_d}$$

Baryon Acoustic Oscillations (BAO)



Measure Correlation Function

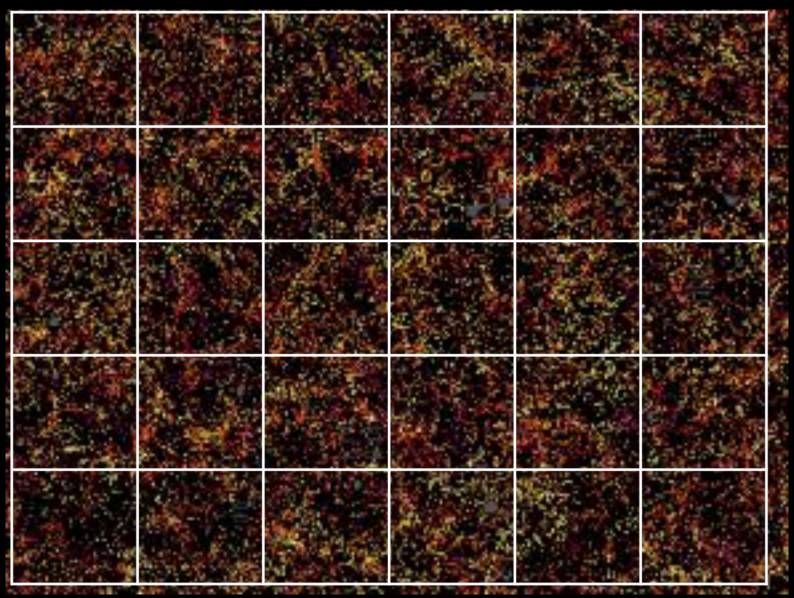


$$\xi(R) = \frac{\mathrm{npair}_{\mathrm{galaxy}}(R)}{\mathrm{npair}_{\mathrm{randoms}}(R)} - 1 \equiv \left\langle \delta(\vec{x})\delta(\vec{x}+\vec{R}) \right\rangle$$

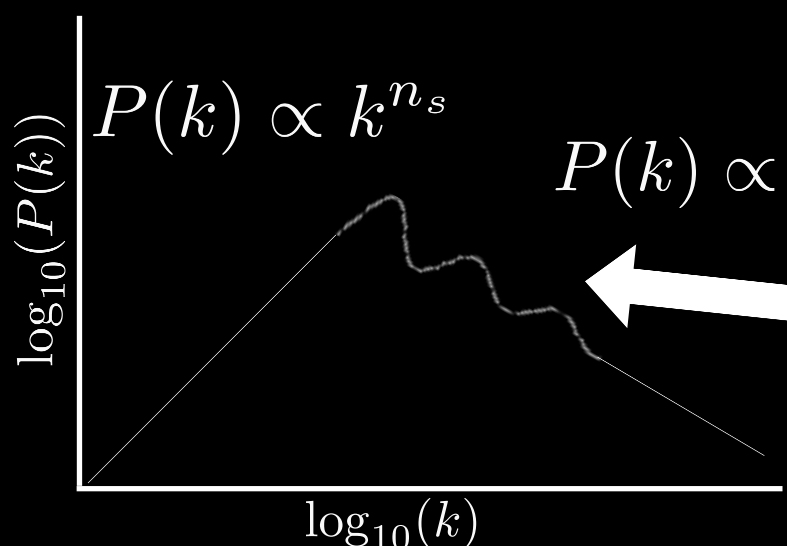
For a sample of galaxy measure their position in the sky (RA,DEC) and spectra to get redshift (z) needed to measure BAO.

BAO in Fourier Space

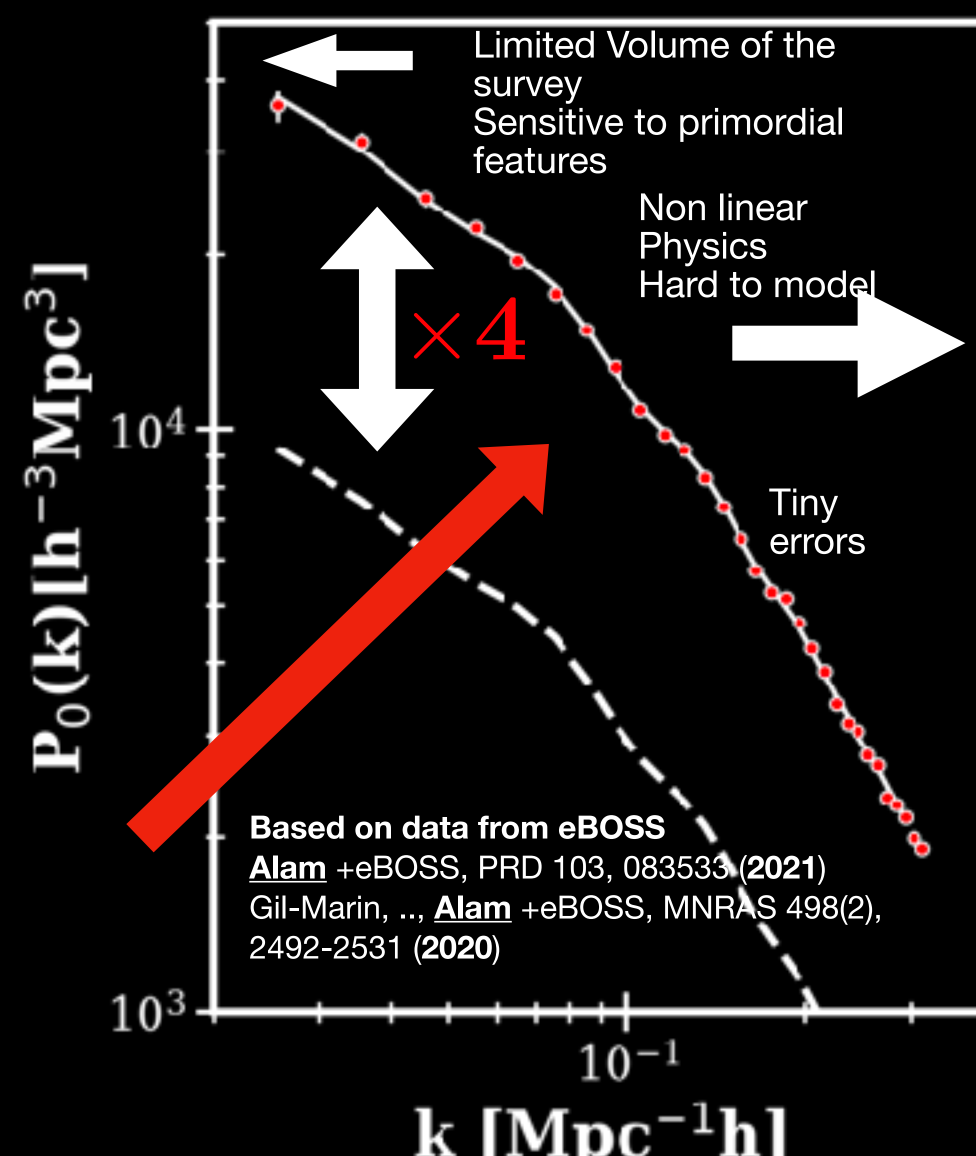
Standard model of Cosmological Structure Formation



$$P(k) = \left\langle \delta(\vec{k})\delta^*(\vec{k}) \right\rangle$$



Baryon Acoustic Oscillation (BAO)



Cosmological constant?

Modification to General Relativity

Extra dimension String Theory

Multiple scalar fields

?

$w_{\rm DE}(z)$ has great implication on the physics of Universe as well as its eventual fate

$a(t)$ is the physical quantity which we can target

$d_p(z)$ proper distance can be measured*. The redshift require spectroscopic measurements.

How to improve the PRECISION of the measurements?

Supernovae
$$d_L(z) = (1+z)d_p(z)$$

BAO $\dfrac{D_M(z)}{r_d}, \dfrac{r_d}{D_H(z)}$

Precision of BAO

It seems natural to measure lots of galaxies spatial location (RA,DEC,z) precisely to make more precise measurement of BAO and hence $w_{\rm DE}(z)$

DESI Legacy Imaging Survey
6+ years of taking imaging of night sky
Detected **1.5 Billion** galaxies and **1.3 Billion** stars (PSF)

But for BAO we need spectra of galaxies.
DESI can take 5000 spectra at a time.

4000 spectra X 8 hrs x 2 (per hour) = 64,000 spectra per night

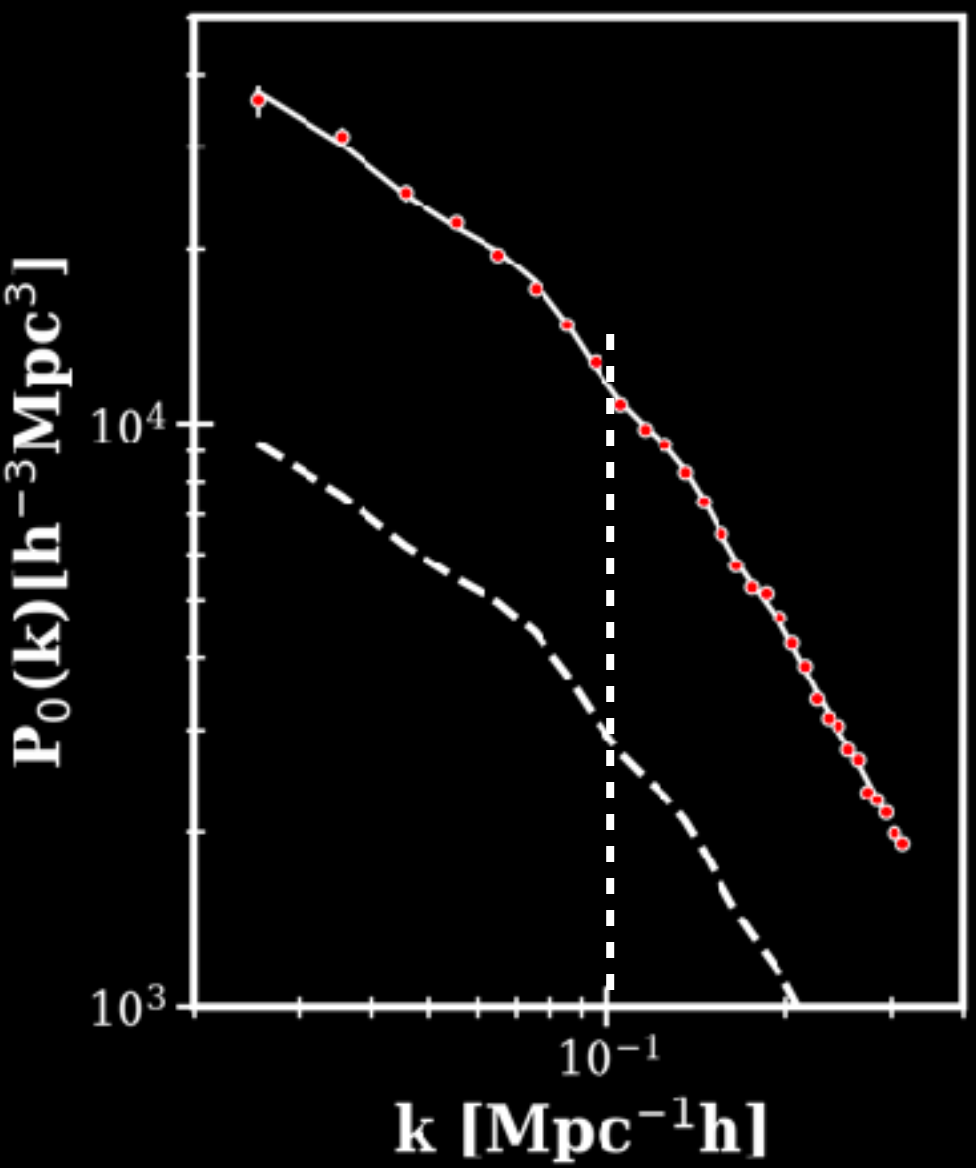
64,000 x 365 days x 5 years x 0.5 efficiency ~ 58 Million galaxies

58 million /1.5 Billion~ **0.04** Fraction of source possible to observe

How to select the **4%** for best cosmological constraint?

Precision of BAO

$$\mathrm{SNR} \approx \frac{P_i}{\sqrt{C_{ii}}} \quad \leftarrow 10^3 - 10^4\,(k \approx 0.1)$$



For Gaussian Random Field

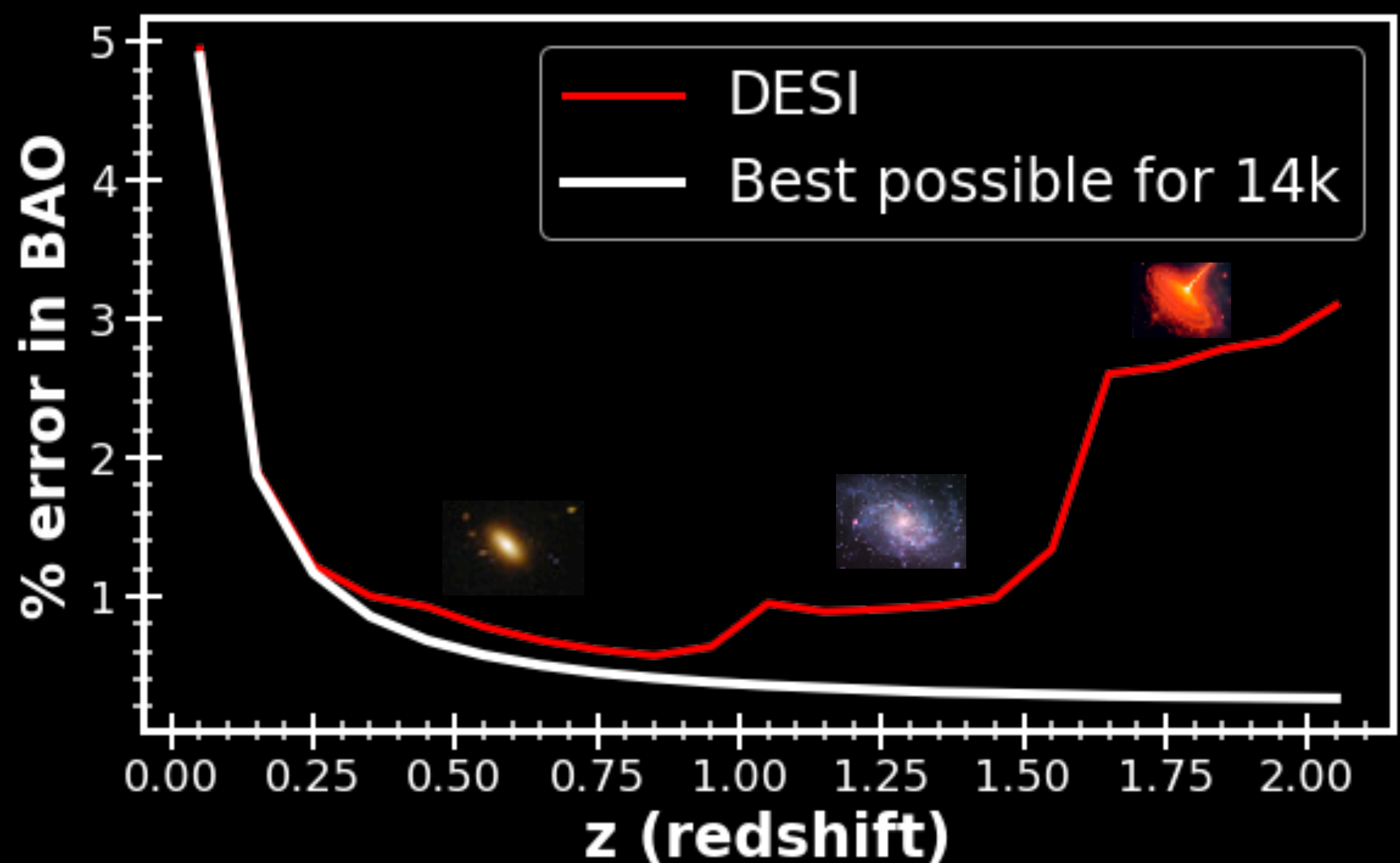
$$C_{ij} = \frac{(2\pi)^3}{V} \frac{(P_i + \frac{1}{n})^2}{2\pi k_i^2 \delta k} \delta_{ij}$$

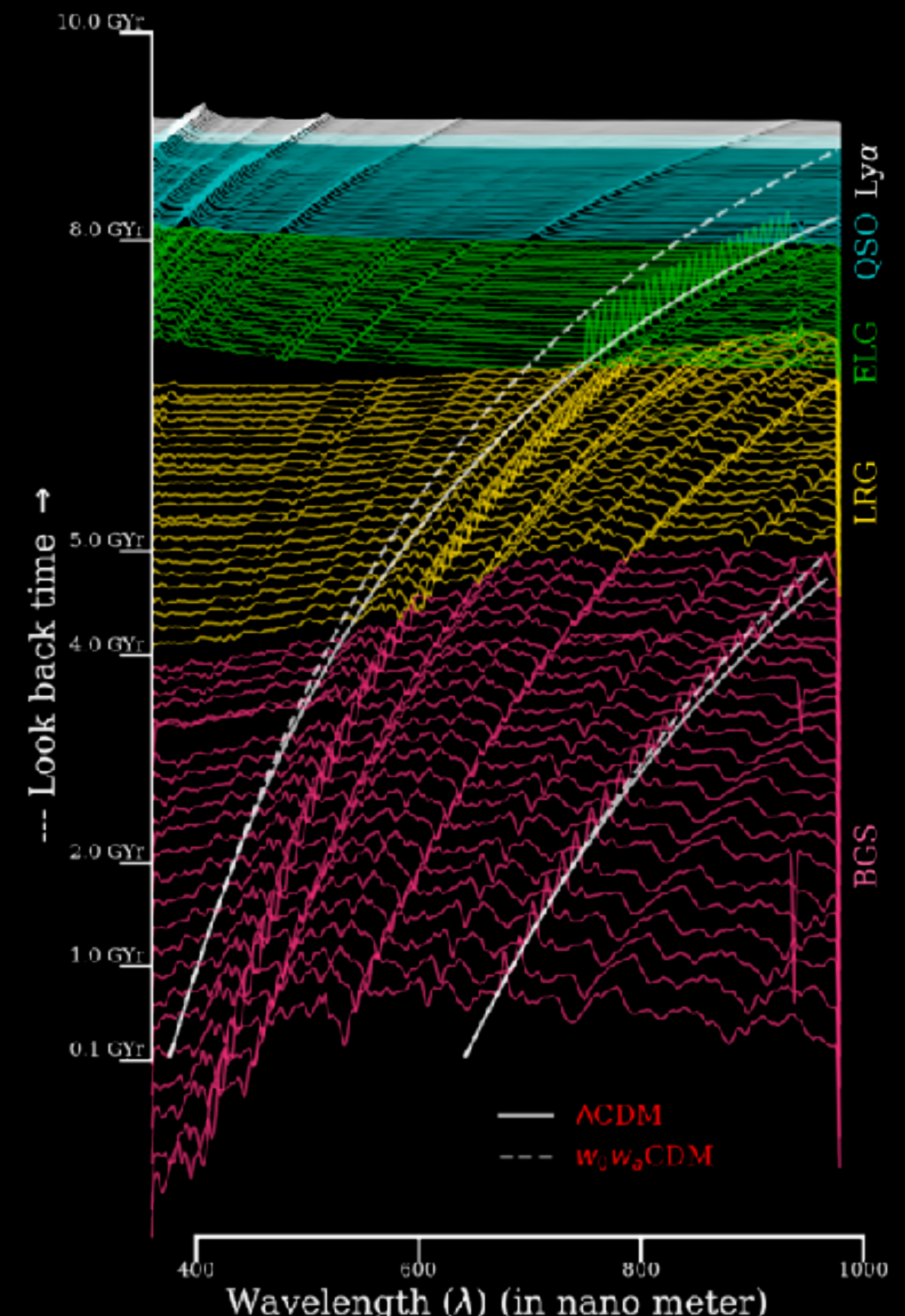
$\uparrow \approx \sigma_k^2$ want to minimize

To keep sampling (shot) noise sub-dominant

$$\frac{1}{n} < P_i \implies n > \frac{1}{P_i} > 10^{-3} - 10^{-4} [\mathrm{Mpc/h}]^{-3}$$

Precision of BAO





To keep sampling (shot) noise sub-dominant

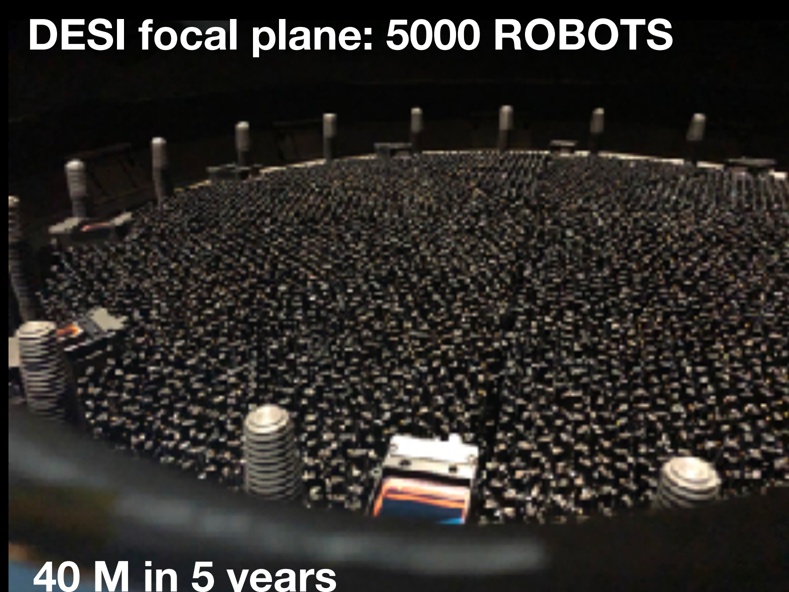
$$\frac{1}{n} < P_i \implies n > \frac{1}{P_i} > 10^{-3} - 10^{-4}$$

Dark Energy Spectroscopy Instrument (DESI)

Ongoing from 2021-2026 (5 year program), overall cost~150 M $ (~1300 crore INR)

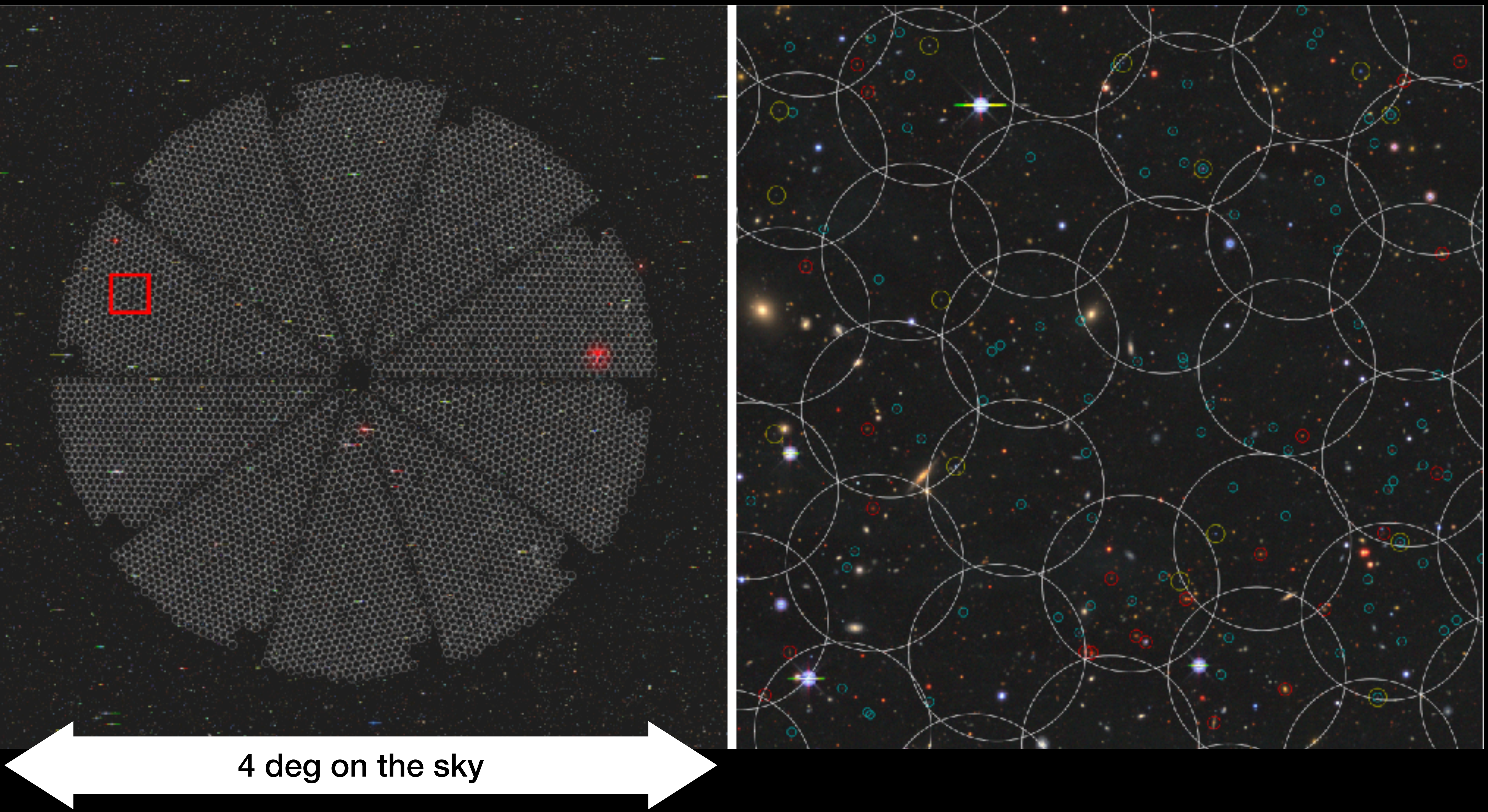
SDSS focal plane: HUMAN

DESI focal plane: 5000 ROBOTS



- 2021-2026 (5 years, Ongoing since May 2021)
- Instrument performs excellently (3 years of data collected on-April 2024)
- **40 million** Galaxy Spectra by the end of 5 years

DESI Focal plane (ideal for unclustered universe)

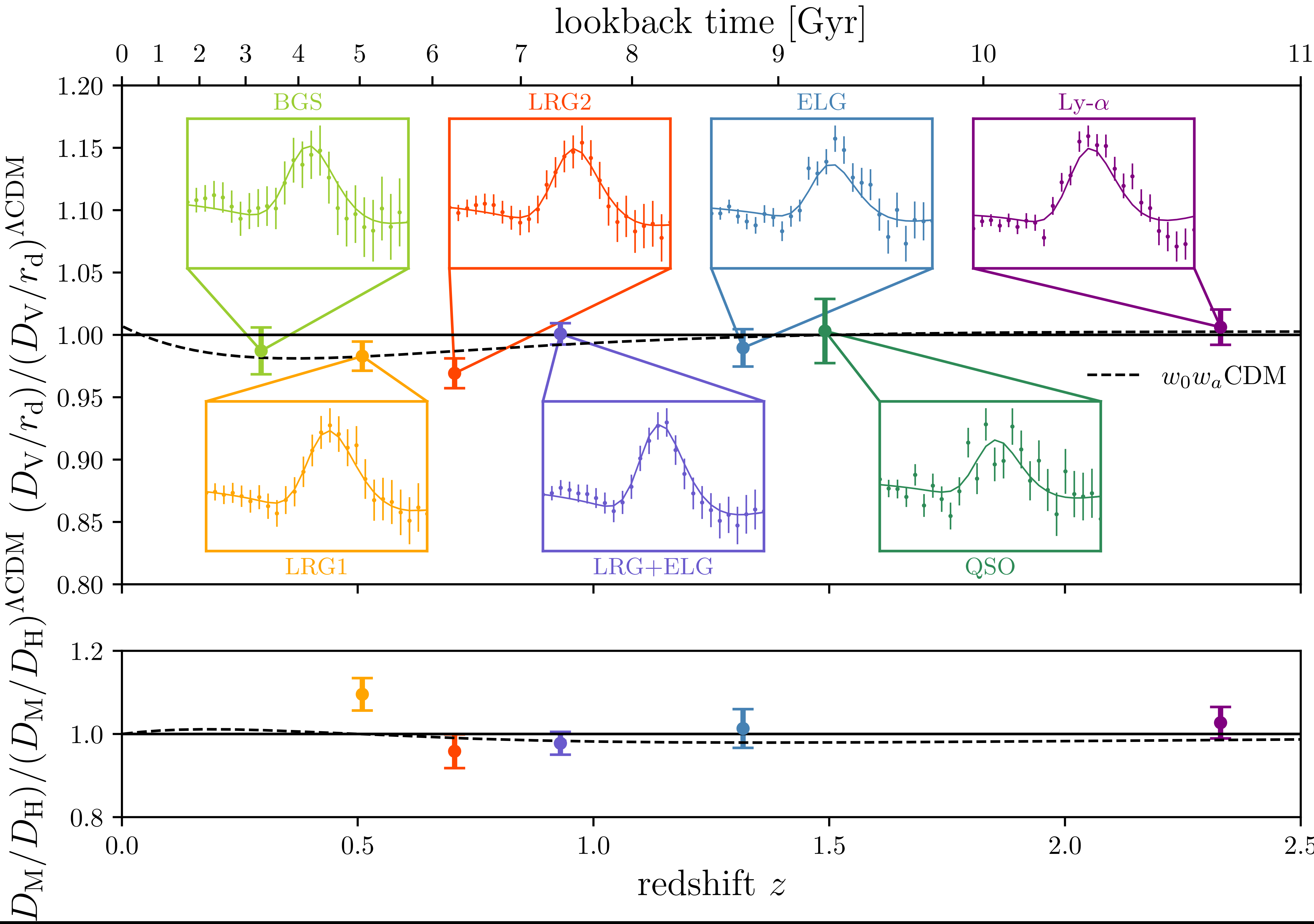


DESI Legacy Imaging Survey
6+ years of imaging using 3 telescope covering 18000 deg^2
with 1.5 Billion galaxy

Build DESI Instrument with 5000 optical fibres
10+ years of designing, 600 crore INR , 700 + team members

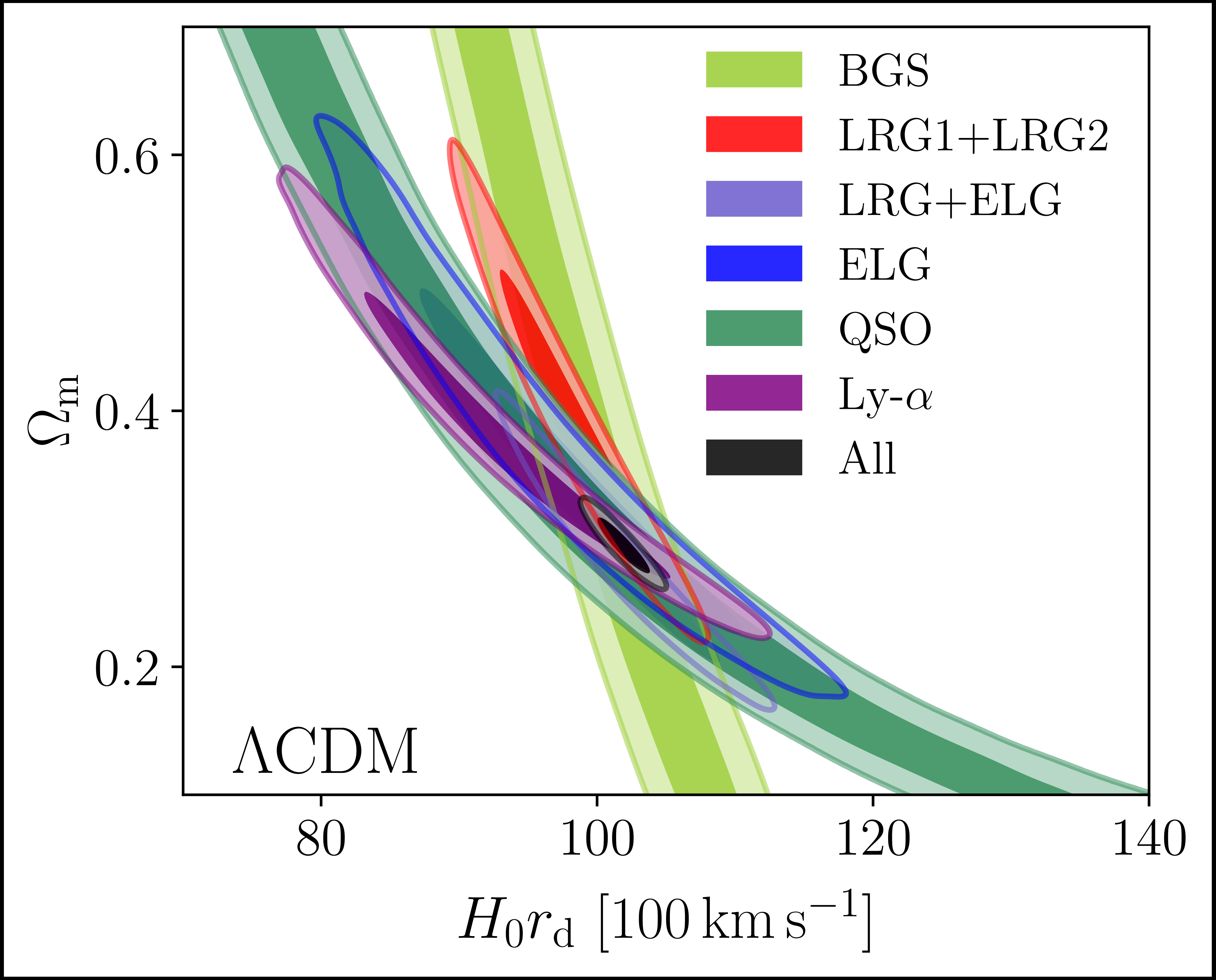
Select objects to obtain best cosmology
Based on n*P~1 and 30 minutes of observing time on DESI select objects for spectroscopy

Observed ~6 million extra galactic objects in Y1, spend 100 times more computing on estimating errors and 1000 times more computing on tracking non-idealities of Instrument.



lookback time [Gyr]
0 1 2 3 4 5 6 7 8 9 10 11
BGS
LRG2
ELG
Ly-α
LRG1
LRG+ELG
QSO
$w_0 w_a$CDM
$(D_V/r_d)/(D_V/r_d)^{\Lambda CDM}$
1.20 1.15 1.10 1.05 1.00 0.95 0.90 0.85 0.80
$(D_M/D_H)/(D_M/D_H)^{\Lambda CDM}$
1.2 1.0 0.8
0.0 0.5 1.0 1.5 2.0 2.5
redshift z

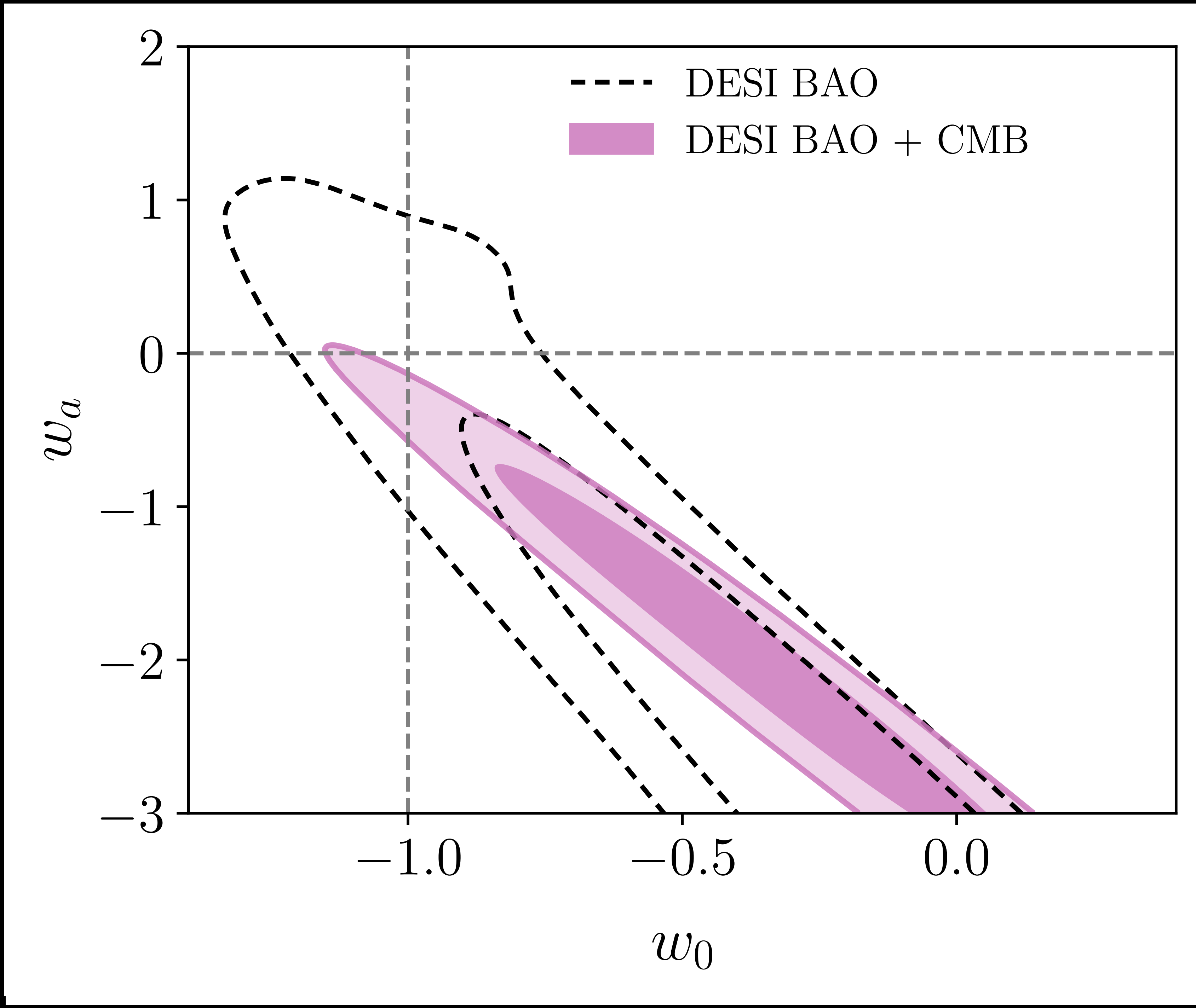
LCDM



$$\Omega_m = 0.295 \pm 0.015 \ (5.1\%)$$

$$H_0 r_d = 101.8 \pm 1.3 [100 \mathrm{km\,s^{-1}}]$$

Dark Energy



$w_0 = -0.45^{+0.34}_{-0.21},\ w_a = -1.79^{+0.48}_{-1.00}$

2.6σ

$$w_{\mathrm{DE}}(z) = w_0 + (1 - a)w_a$$

Dark Energy

$w_0 = -0.827 \pm -0.063,\ w_a = -0.75^{+0.29}_{-0.25}$

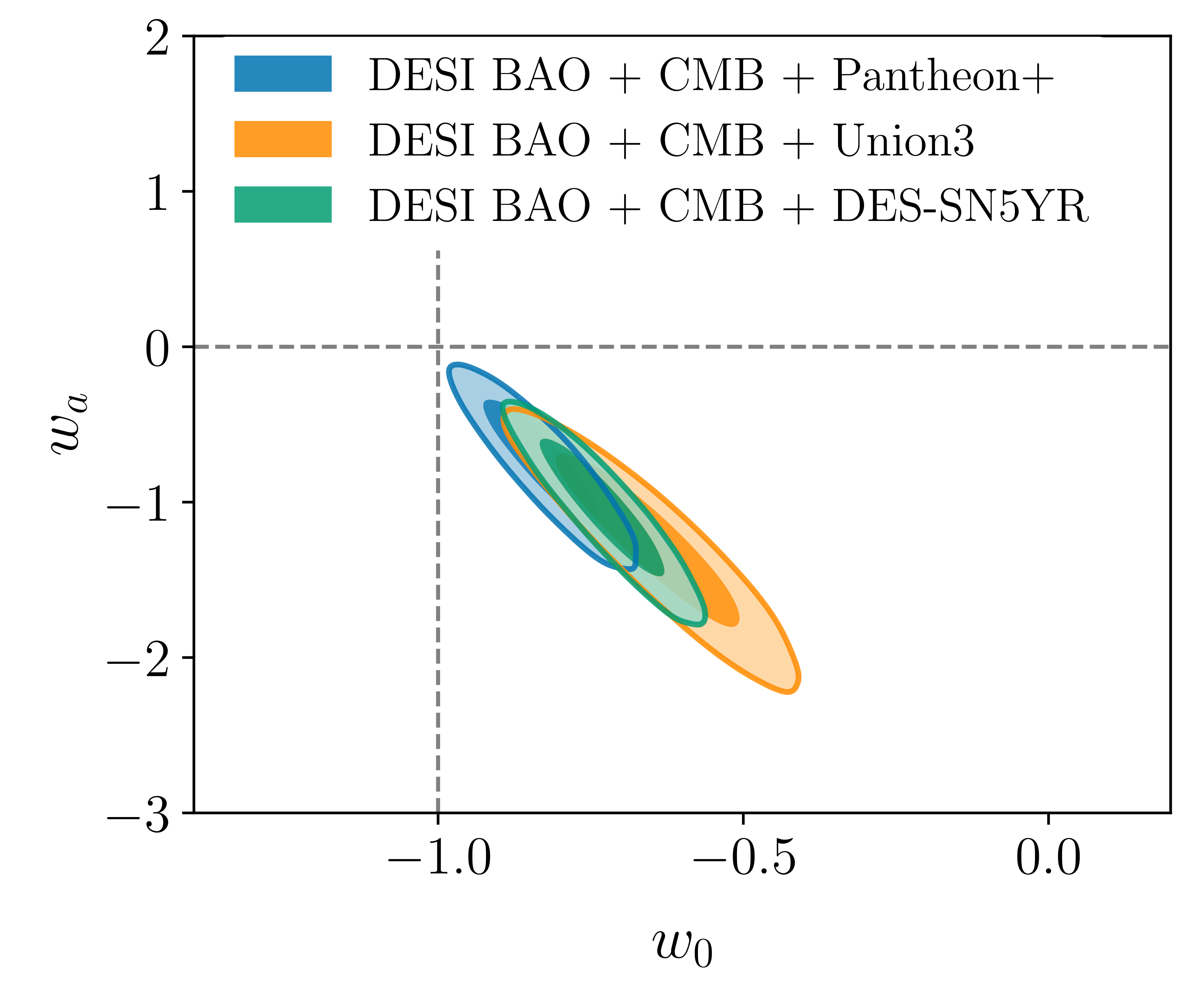
2.5σ

$w_0 = -0.827 \pm -0.063,\ w_a = -0.75^{+0.29}_{-0.25}$

3.5σ

$w_0 = -0.727 \pm -0.067,\ w_a = -1.05^{+0.31}_{-0.27}$

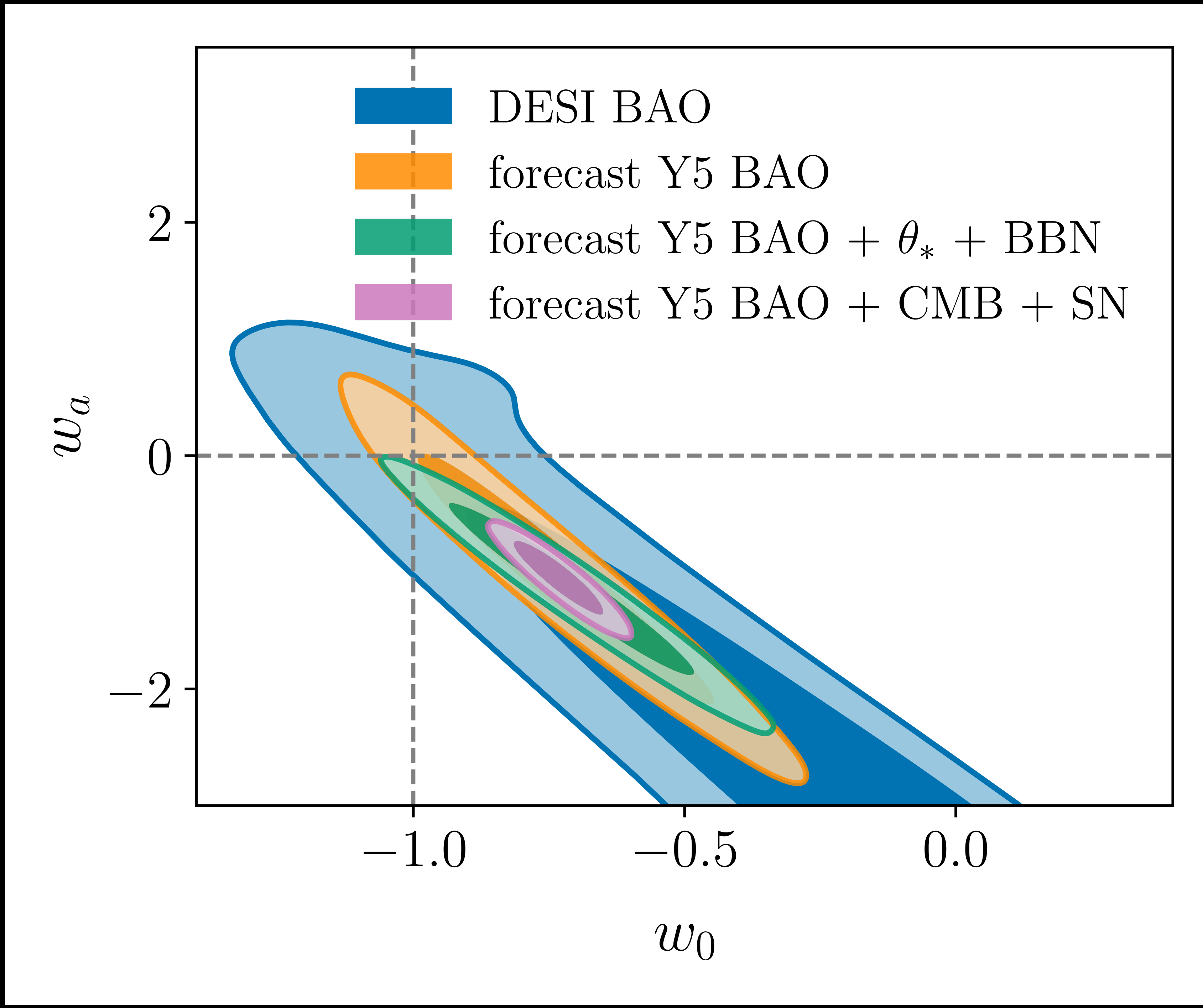
3.9σ



$$w_{\mathrm{DE}}(z) = w_0 + (1-a)w_a$$

Dark Energy

Data by 2026 and analysis soon after



$$w_{\mathrm{DE}}(z) = w_0 + (1 - a)w_a$$

Beyond Dark Energy

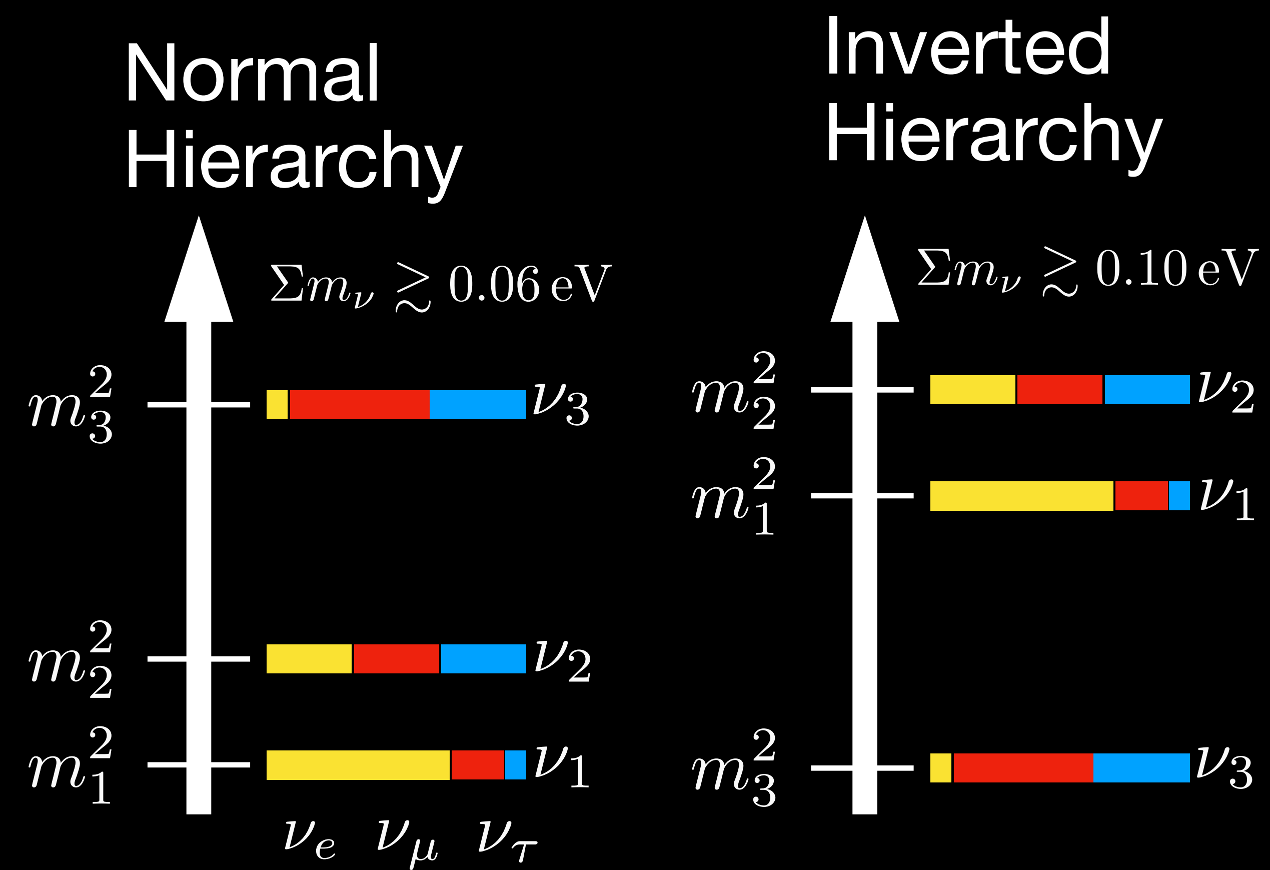
LSS can provide precise measurements of the sum of neutrino masses

Neutrino Oscillation experiments

Gonzalez-Garcia JHEP 1411:052, 2014

$$\Delta m^2_{21} = (0.0086 \pm 0.0011 \mathrm{eV})^2$$ Solar

$$\Delta m^2_{3\ell} = (0.05 \pm 0.0005 \mathrm{eV})^2$$ Atmospheric



Neutrinos and Cosmology : Geometry

- Radiation matter equality with neutrino

$$\rho_b(a_{\rm eq}) + \rho_c(a_{\rm eq}) = \rho_\gamma(a_{eq}) + \rho_\nu(a_{\rm eq})$$

- Changing sound horizon

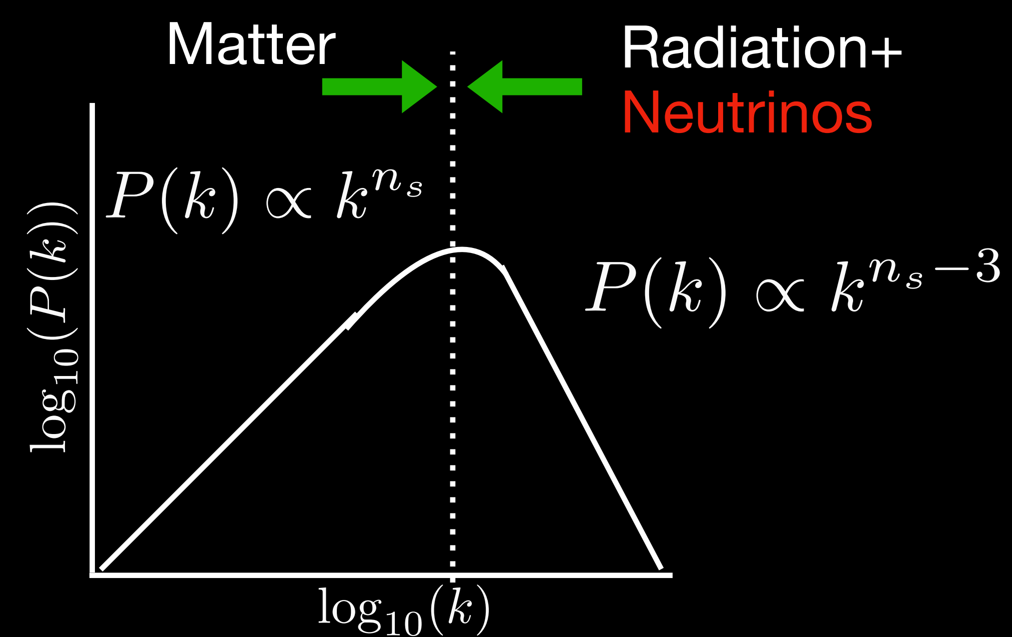
$$r_d = \int_{z_{\rm eq}}^{\infty} \frac{c_s}{H(z)} dz$$

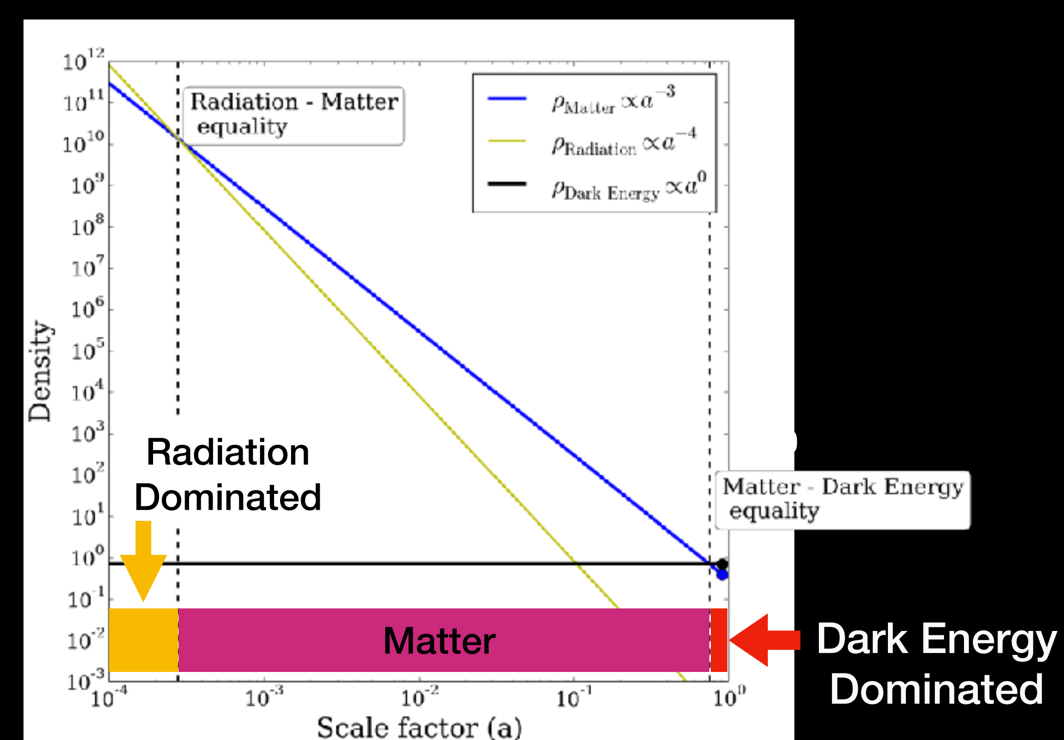
$$\left(\frac{H}{H_0}\right)^2 = \Omega_m a^{-3} + (\Omega_\gamma + \Omega_\nu) a^{-4} + \Omega_\Lambda$$

- This will affect BAO measurements

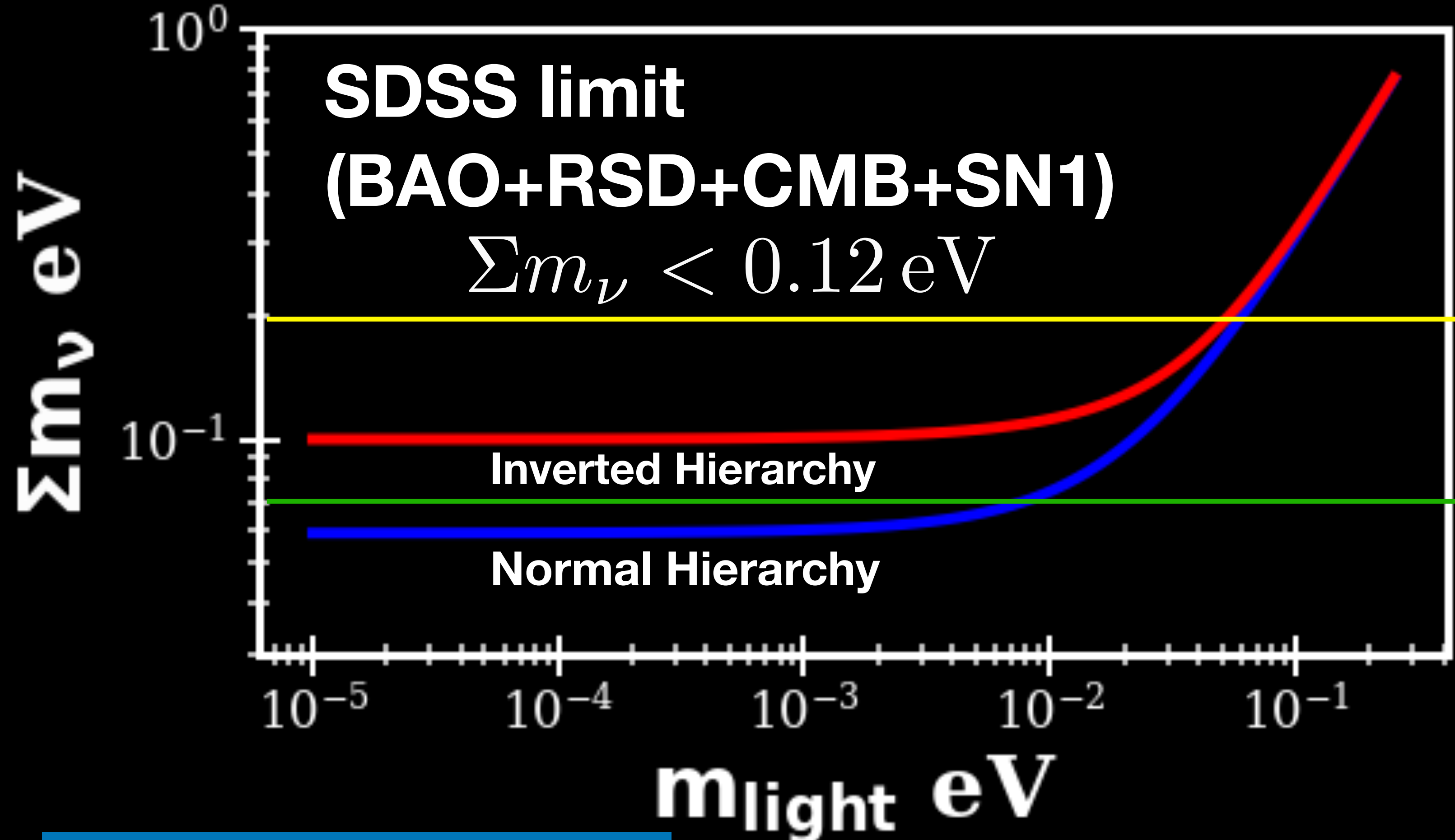
$$D_M/r_d \qquad D_H/r_d$$

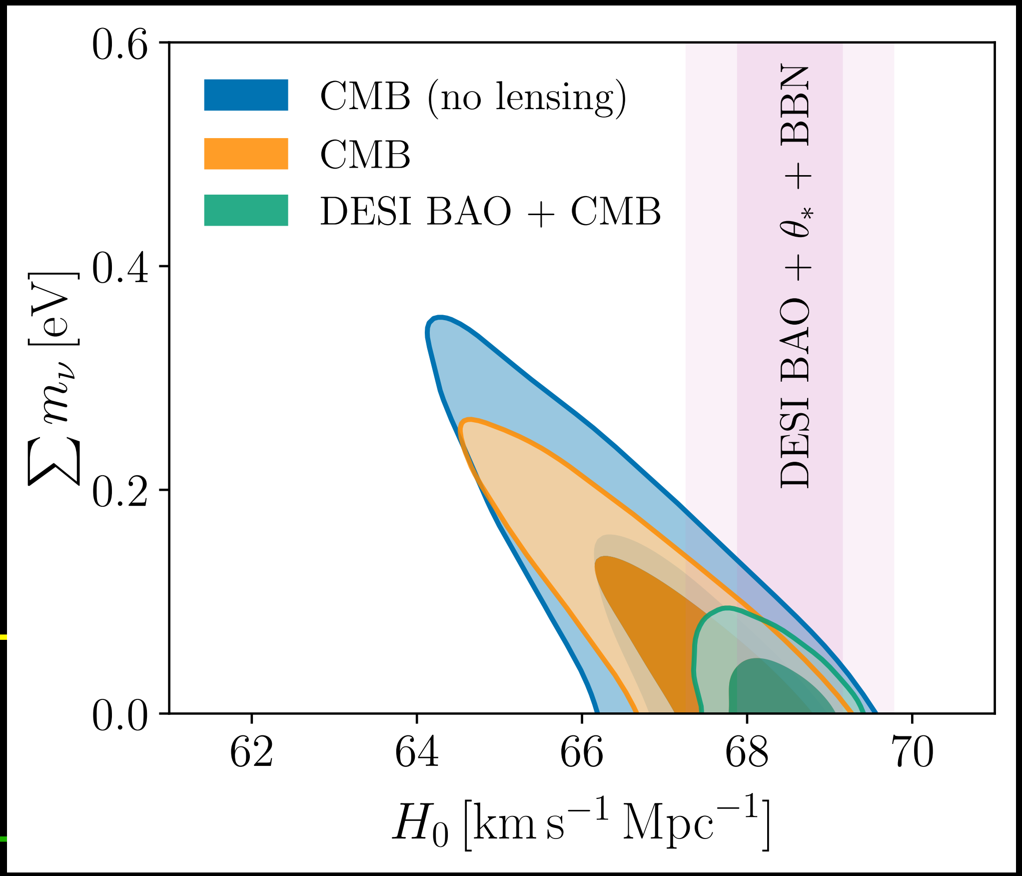
*Neutrinos also affect He abundance (BBN) in the universe. But I will not discuss it in this talk for brevity.





Constraints on Neutrino mass





DESI BAO + CMB

$\Sigma m_\nu < 0.072$

Prior dependent

$\Sigma m_\nu < 0.113$ for $> 0.059\,\mathrm{eV}$

$\Sigma m_\nu < 0.145$ for $> 0.1\,\mathrm{eV}$

Model dependent

$\Sigma m_\nu < 0.195$ for $w_0 w_a$CDM

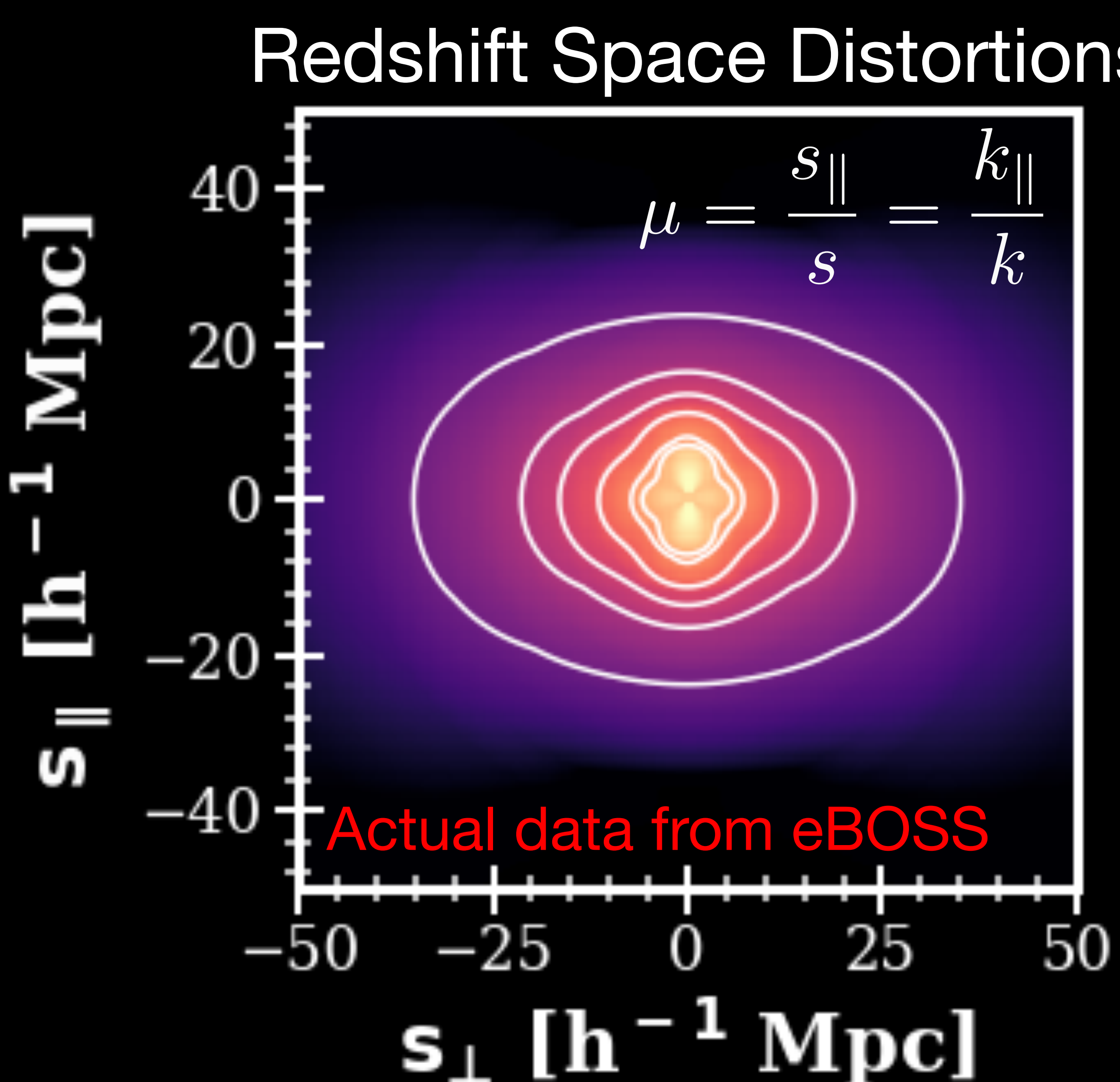
DESI 5 year data (2026)

$\sigma_{\Sigma m_\nu} = 0.02\,\mathrm{eV}$

$*\ \Lambda$CDM

Beyond BAO science

Redshift Space Distortions (RSD)



σ_8

$$P_s^g(k,\mu) \overset{*}{=} P_m(k)(b + f\mu^2)^2$$

$$f_{\mathrm{gravity}}(a,k) = \frac{\partial \ln(\delta(a,k))}{\partial \ln(a)}$$ Test of gravity

$$f_{\mathrm{GR}}(a) \approx \Omega_m(a)^{0.55} \qquad \Lambda CDM$$

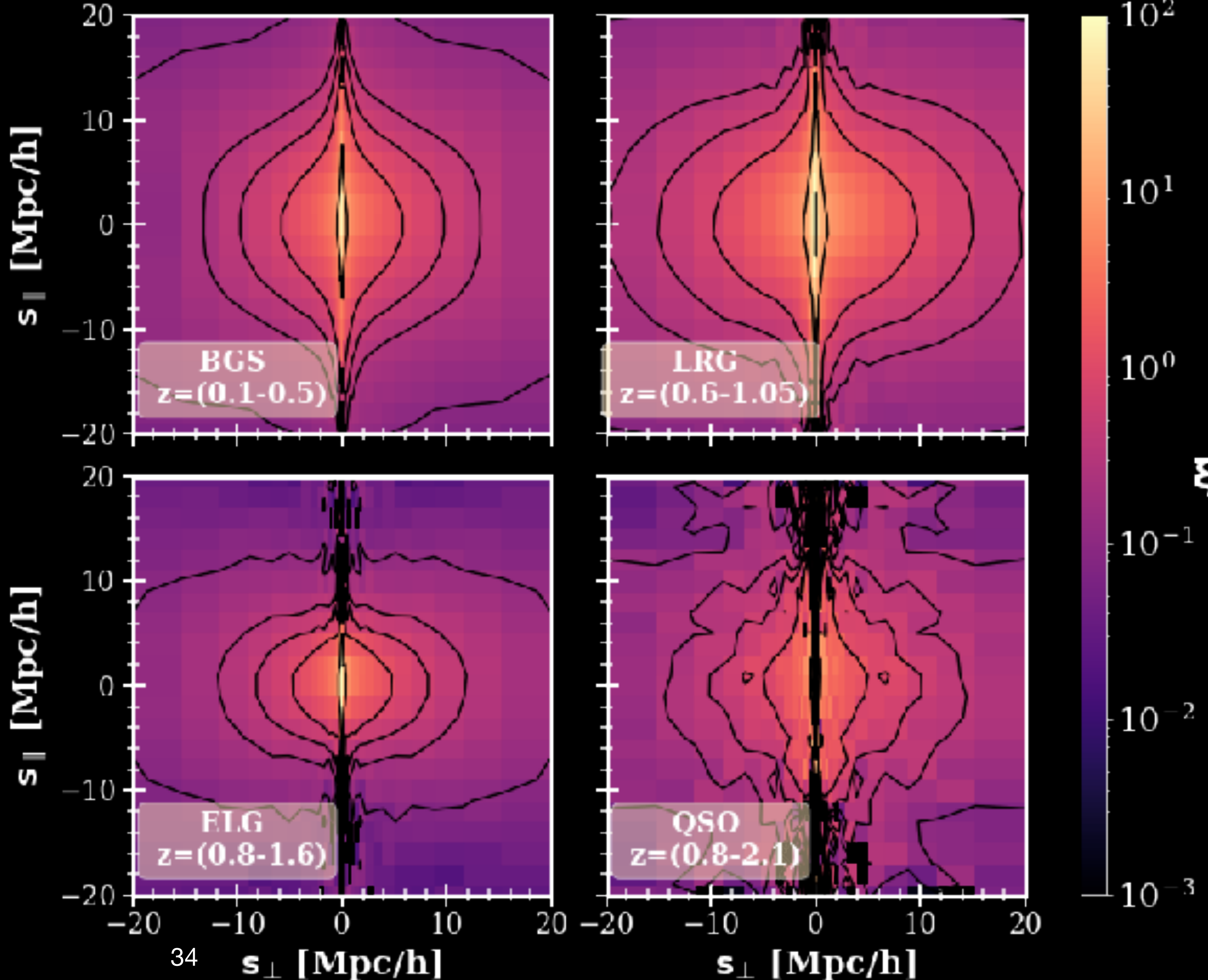
*Full equations are much more involved and cannot be written in such simple closed form

Wang L., Steinhardt P. J., 1998, AJ, 508, 483

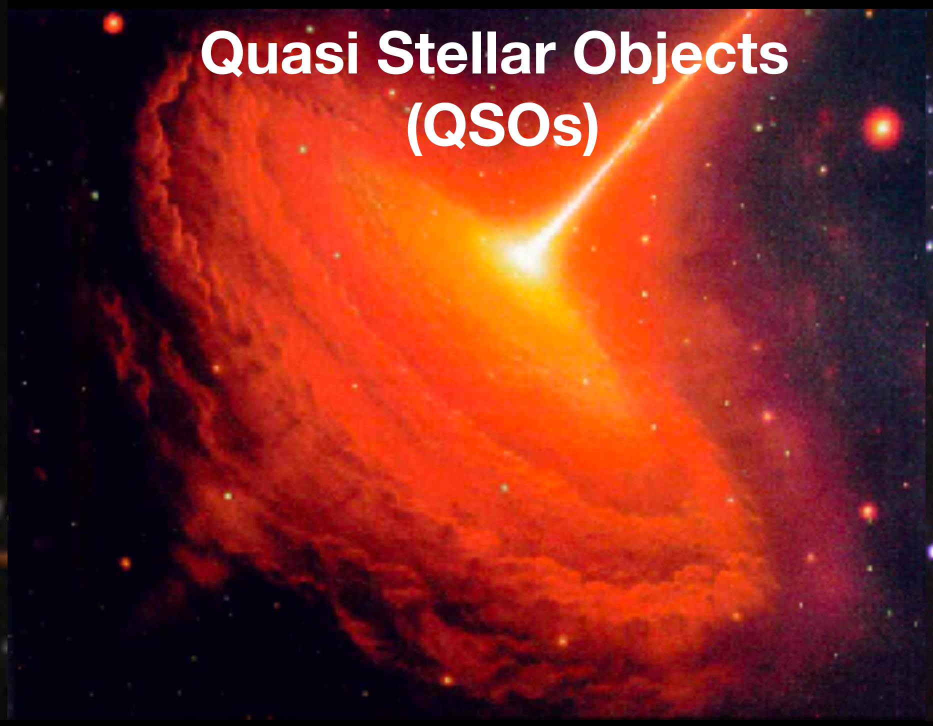
One month of DESI data

Cosmological Onions

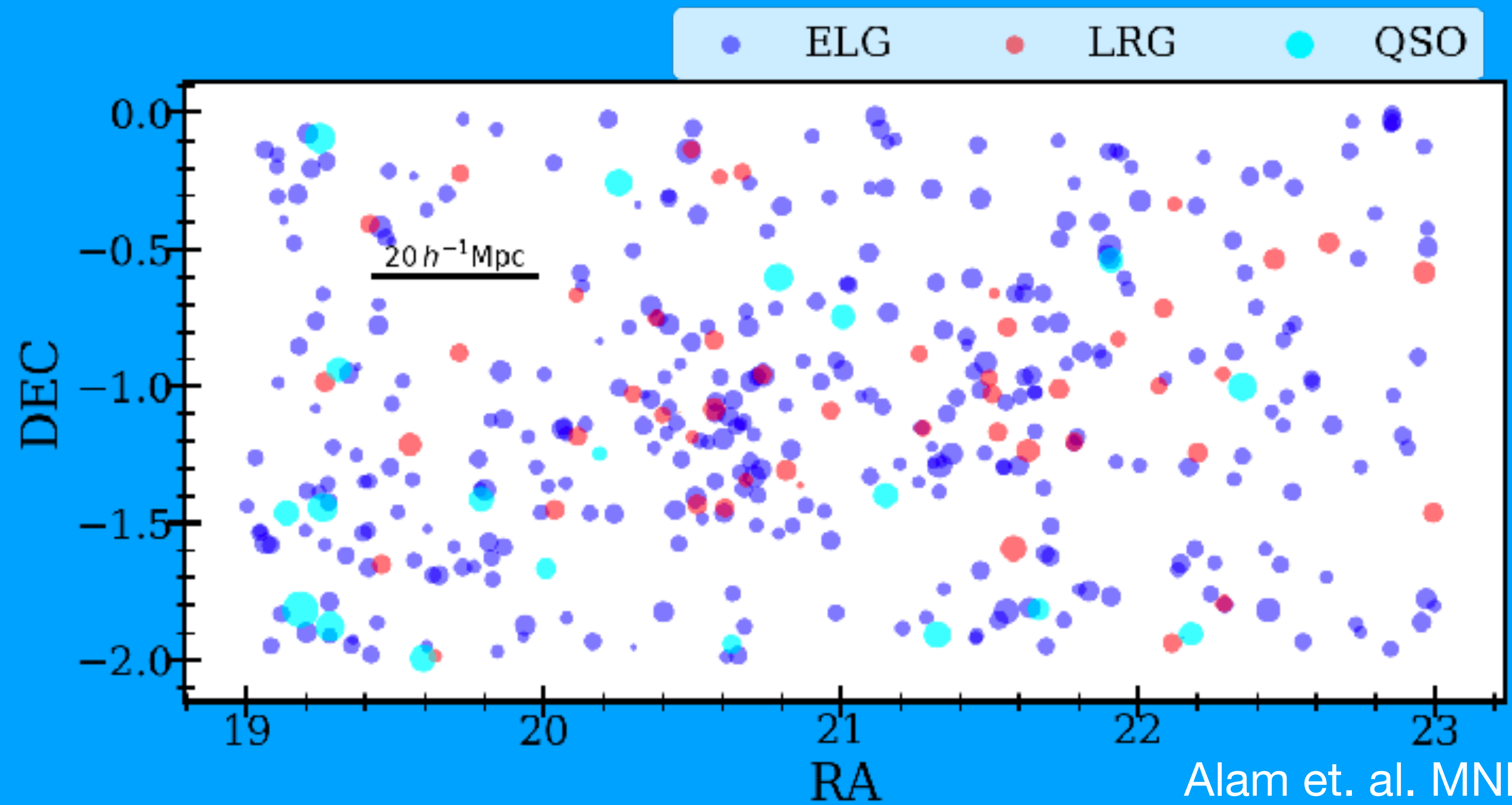
Previous surveys took years to produce such quality measurements



Analysis of DESI Y1 sample for RSD is expected to be released soon. Still Blinded!



Supermassive Black hole growth

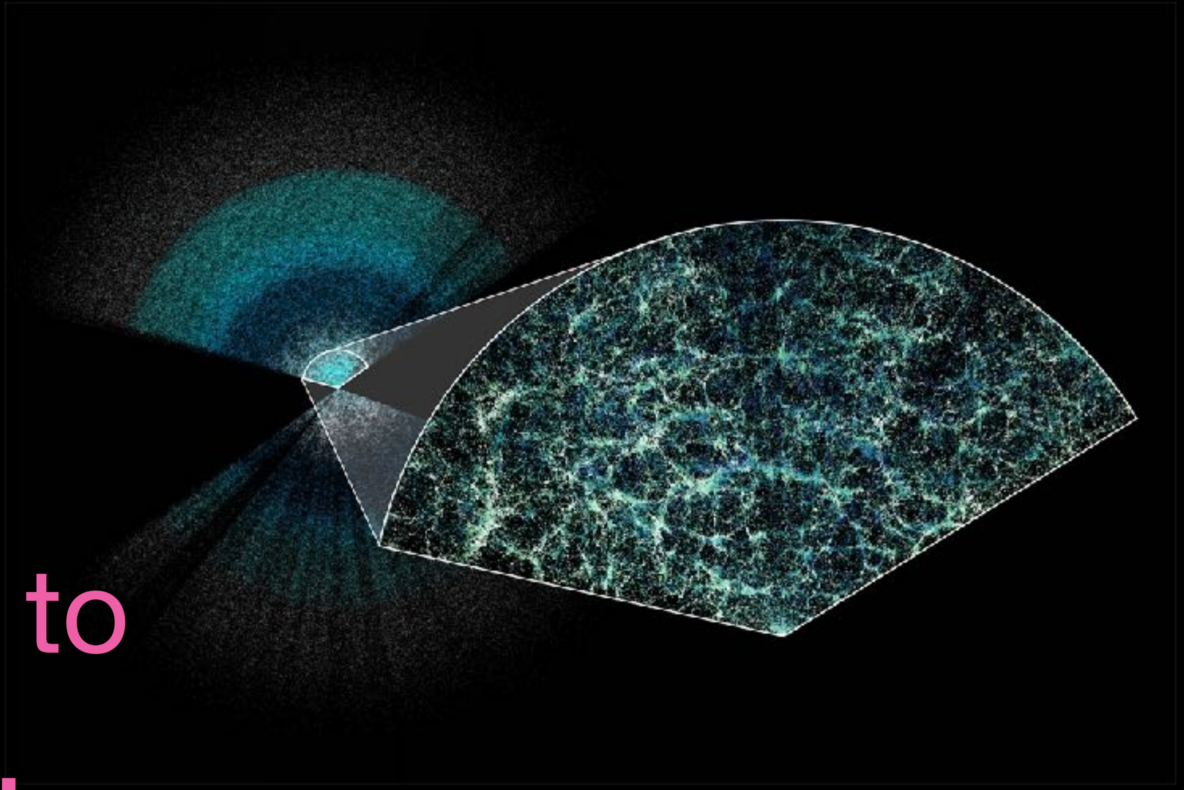


Alam et. al. MNRAS 504(1), 2021

Unprecedented data / space for discovery

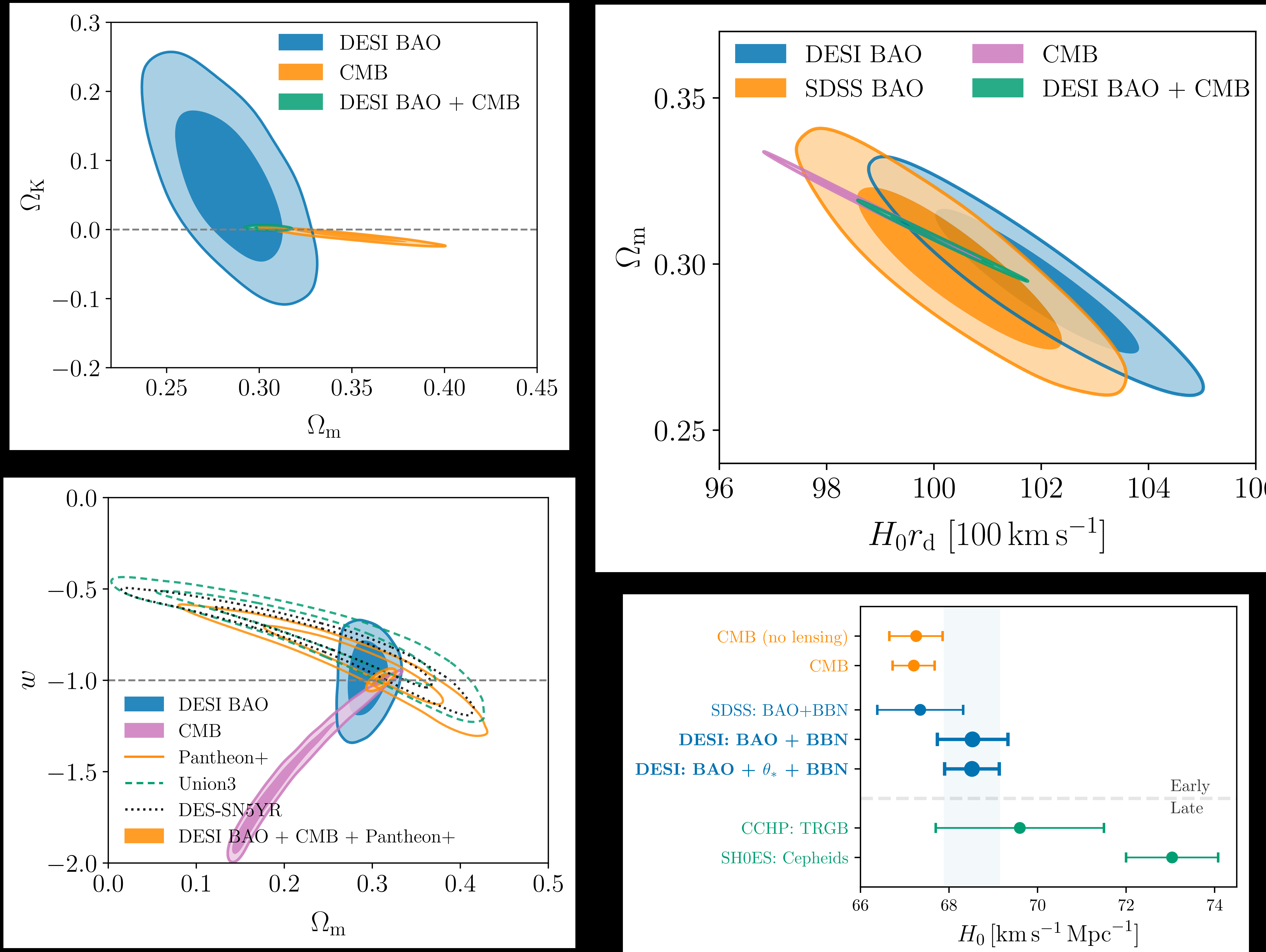
- Relativistic effects (such as gravitational redshift, relativistic beaming)
- Boundaries of dark matter haloes
- Constrain models of dark matter interactions
- Life cycle of galaxies
- Beyond gaussian terms in the initial conditions of the Universe

Conclusions

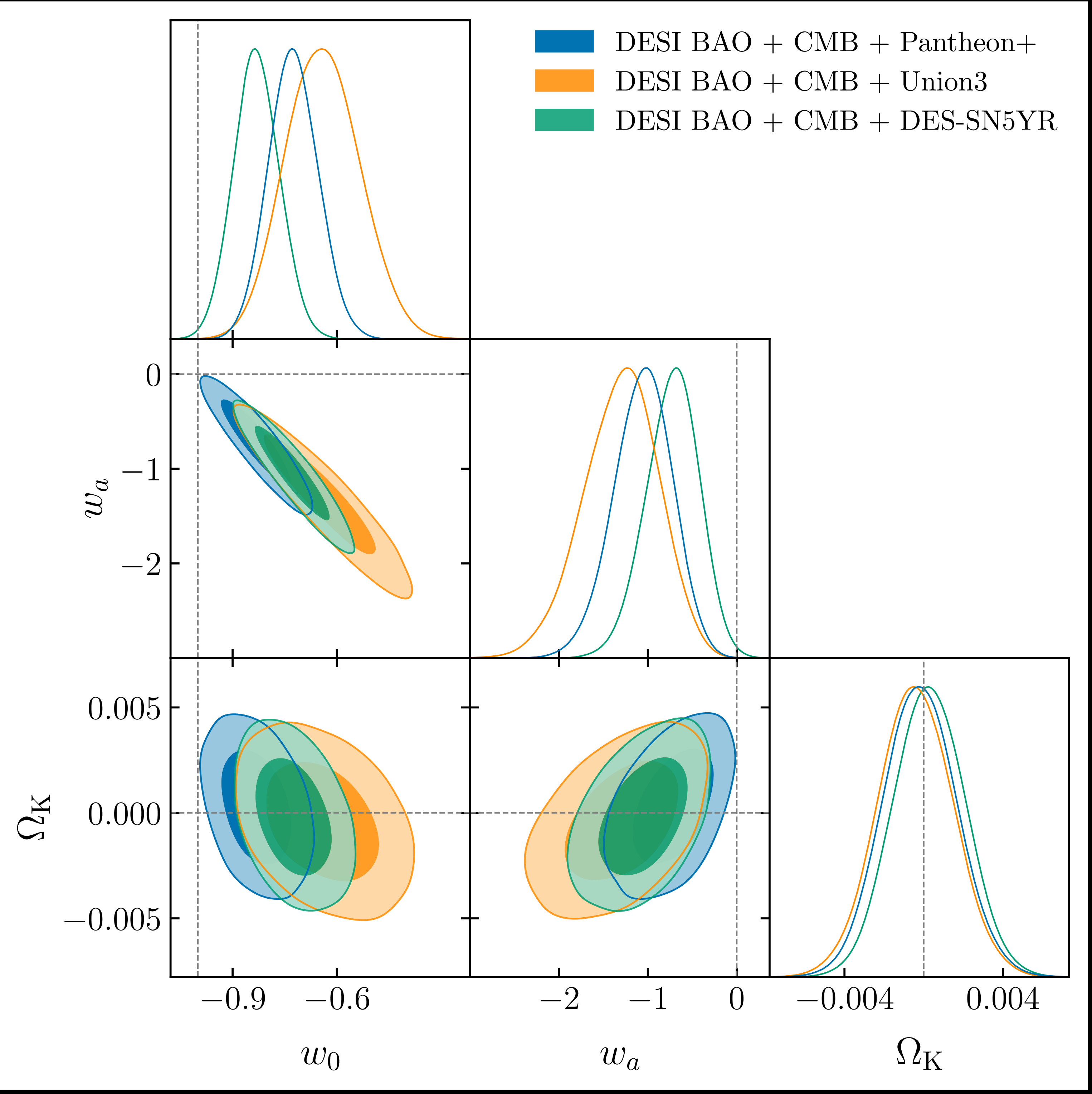


Take away: This map is amazing and hold the key to huge number of treasures. Go explore!

- Results from ~ 6 Million spectra is out and data will be released within a year
- Dark Energy may not be cosmological constant. May even need a second coincidence.
- Upper limit on Neutrino mass improved, but need to wait for more interesting results with 5 years of DESI data.
- Most of the details in the map created by DESI is not yet studied and hence this will serve as a treasure for interesting investigations about the cosmos.



DESI BAO
CMB
DESI BAO + CMB
Ω_K
Ω_m
0.3
0.2
0.1
0.0
−0.1
−0.2
0.25
0.30
0.35
0.40
0.45
DESI BAO
SDSS BAO
CMB
DESI BAO + CMB
Ω_m
0.35
0.30
0.25
96
98
100
102
104
106
$H_0 r_d$ [100 km s^{-1}]
DESI BAO
CMB
Pantheon+
Union3
DES-SN5YR
DESI BAO + CMB + Pantheon+
w
0.0
−0.5
−1.0
−1.5
−2.0
0.0
0.1
0.2
0.3
0.4
0.5
Ω_m
CMB (no lensing)
CMB
SDSS: BAO+BBN
DESI: BAO + BBN
DESI: BAO + θ_* + BBN
Early
Late
CCHP: TRGB
SH0ES: Cepheids
66
68
70
72
74
H_0 [km s^{-1} Mpc^{-1}]


DESI BAO + CMB + Pantheon+
DESI BAO + CMB + Union3
DESI BAO + CMB + DES-SN5YR
w_a
Ω_K
0
−1
−2
0.005
0.000
−0.005
−0.9
−0.6
w_0
−2
−1
0
w_a
−0.004
0.004
Ω_K

Sample (numbers and volume)

tracer	redshift	N_{tracer}	z_{eff}	$D_{\mathrm{M}}/r_{\mathrm{d}}$	$D_{\mathrm{H}}/r_{\mathrm{d}}$	r or $D_{\mathrm{V}}/r_{\mathrm{d}}$	V_{eff} (Gpc^3)
BGS	$0.1 - 0.4$	300,017	0.295	—	—	7.93 ± 0.15	1.7
LRG1	$0.4 - 0.6$	506,905	0.510	13.62 ± 0.25	20.98 ± 0.61	-0.445	2.6
LRG2	$0.6 - 0.8$	771,875	0.706	16.85 ± 0.32	20.08 ± 0.60	-0.420	4.0
LRG3+ELG1	$0.8 - 1.1$	1,876,164	0.930	21.71 ± 0.28	17.88 ± 0.35	-0.389	6.5
ELG2	$1.1 - 1.6$	1,415,687	1.317	27.79 ± 0.69	13.82 ± 0.42	-0.444	2.7
QSO	$0.8 - 2.1$	856,652	1.491	—	—	26.07 ± 0.67	1.5
Lya QSO	$1.77 - 4.16$	709,565	2.330	39.71 ± 0.94	8.52 ± 0.17	-0.477	—

Table 1. Statistics for the DESI samples used for the DESI DR1 BAO measurements used in this paper. For each tracer and redshift range we quote the number of objects (N_{tracer}), the effective redshift (z_{eff}) and effective volume (V_{eff}). Note that for each sample we measure either both $D_{\mathrm{M}}/r_{\mathrm{d}}$ and $D_{\mathrm{H}}/r_{\mathrm{d}}$, which are correlated with a coefficient r, or $D_{\mathrm{V}}/r_{\mathrm{d}}$. Redshift bins are non-overlapping, except for the shot-noise-dominated measurements that use QSO (both as tracers and for Lyα forest).

Posterior

model/dataset	Ω_m	H_0 $[\mathrm{km\,s^{-1}\,Mpc^{-1}}]$	$10^3\Omega_\mathrm{K}$	w or w_0	w_a
Flat ΛCDM					
DESI	0.295 ± 0.015	—	—	—	—
DESI+BBN	0.295 ± 0.015	68.53 ± 0.80	—	—	—
DESI+BBN+θ_*	0.2948 ± 0.0074	68.52 ± 0.62	—	—	—
DESI+CMB	0.3069 ± 0.0050	67.97 ± 0.38	—	—	–
ΛCDM+Ω_K					
DESI	0.284 ± 0.020	—	65^{+68}_{-78}	—	—
DESI+BBN+θ_*	0.296 ± 0.014	68.52 ± 0.69	$0.3^{+4.8}_{-5.4}$	—	—
DESI+CMB	0.3049 ± 0.0051	68.51 ± 0.52	2.4 ± 1.6	—	—
wCDM					
DESI	0.293 ± 0.015	—	—	$-0.99^{+0.15}_{-0.13}$	—
DESI+BBN+θ_*	0.295 ± 0.014	$68.6^{+1.8}_{-2.1}$	—	$-1.002^{+0.091}_{-0.080}$	—
DESI+CMB	0.281 ± 0.013	$71.3^{+1.5}_{-1.8}$	—	$-1.122^{+0.062}_{-0.054}$	—
DESI+CMB+Panth.	0.3095 ± 0.0069	67.74 ± 0.71	—	-0.997 ± 0.025	—
DESI+CMB+Union3	0.3095 ± 0.0083	67.76 ± 0.90	—	-0.997 ± 0.032	—
DESI+CMB+DESY5	0.3169 ± 0.0065	66.92 ± 0.64	—	-0.967 ± 0.024	—
w_0w_aCDM					
DESI	$0.344^{+0.047}_{-0.026}$	—	—	$-0.55^{+0.39}_{-0.21}$	< -1.32
DESI+BBN+θ_*	$0.338^{+0.039}_{-0.029}$	$65.0^{+2.3}_{-3.6}$	—	$-0.53^{+0.42}_{-0.22}$	< -1.08
DESI+CMB	$0.344^{+0.032}_{-0.027}$	$64.7^{+2.2}_{-3.3}$	—	$-0.45^{+0.34}_{-0.21}$	$-1.79^{+0.48}_{-1.0}$
DESI+CMB+Panth.	0.3085 ± 0.0068	68.03 ± 0.72	—	-0.827 ± 0.063	$-0.75^{+0.29}_{-0.25}$
DESI+CMB+Union3	0.3230 ± 0.0095	66.53 ± 0.94	—	-0.65 ± 0.10	$-1.27^{+0.40}_{-0.34}$
DESI+CMB+DESY5	0.3160 ± 0.0065	67.24 ± 0.66	—	-0.727 ± 0.067	$-1.05^{+0.31}_{-0.27}$
w_0w_aCDM+Ω_K					
DESI	0.313 ± 0.049	—	87^{+100}_{-85}	$-0.70^{+0.49}_{-0.25}$	< -1.21
DESI+BBN+θ_*	$0.346^{+0.042}_{-0.024}$	$65.8^{+2.6}_{-3.5}$	$5.9^{+9.1}_{-6.9}$	$-0.52^{+0.38}_{-0.19}$	< -1.44
DESI+CMB	$0.347^{+0.031}_{-0.025}$	$64.3^{+2.0}_{-3.2}$	-0.9 ± 2	$-0.41^{+0.33}_{-0.18}$	< -1.61
DESI+CMB+Panth.	0.3084 ± 0.0067	68.06 ± 0.74	0.3 ± 1.8	-0.831 ± 0.056	$-0.73^{+0.32}_{-0.28}$
DESI+CMB+Union3	$0.3233^{+0.0089}_{-0.010}$	66.45 ± 0.98	-0.4 ± 1.9	-0.64 ± 0.11	$-1.30^{+0.45}_{-0.39}$
DESI+CMB+DESY5	0.3163 ± 0.0065	67.19 ± 0.69	-0.2 ± 1.9	-0.725 ± 0.071	$-1.06^{+0.35}_{-0.31}$

Posterior with Neutrino

model / dataset	$\Omega_{\rm m}$	H_0 [km s^{-1} Mpc^{-1}]	Σm_ν [eV]	$N_{\rm eff}$
ΛCDM+$\sum m_\nu$				
DESI+CMB	0.3037 ± 0.0053	68.27 ± 0.42	< 0.072	—
ΛCDM+$N_{\rm eff}$				
DESI+CMB	0.3058 ± 0.0060	68.3 ± 1.1	—	3.10 ± 0.17
wCDM+$\sum m_\nu$				
DESI+CMB	0.282 ± 0.013	$71.1^{+1.5}_{-1.8}$	< 0.123	—
DESI+CMB+Panth.	0.3081 ± 0.0067	67.81 ± 0.69	< 0.079	—
DESI+CMB+Union3	0.3090 ± 0.0082	67.72 ± 0.88	< 0.078	—
DESI+CMB+DESY5	0.3152 ± 0.0065	67.01 ± 0.64	< 0.073	—
wCDM+$N_{\rm eff}$				
DESI+CMB	0.281 ± 0.013	$71.0^{+1.6}_{-1.8}$	—	2.97 ± 0.18
DESI+CMB+Panth.	0.3090 ± 0.0068	67.9 ± 1.1	—	3.07 ± 0.18
DESI+CMB+Union3	0.3097 ± 0.0084	67.8 ± 1.2	—	3.06 ± 0.18
DESI+CMB+DESY5	0.3163 ± 0.0067	67.2 ± 1.1	—	3.09 ± 0.18
w_0w_aCDM+$\sum m_\nu$				
DESI+CMB	$0.344^{+0.032}_{-0.026}$	$64.7^{+2.1}_{-3.2}$	< 0.195	
DESI+CMB+Panth.	0.3081 ± 0.0069	68.07 ± 0.72	< 0.155	—
DESI+CMB+Union3	0.3240 ± 0.0098	66.48 ± 0.94	< 0.185	—
DESI+CMB+DESY5	0.3165 ± 0.0069	67.22 ± 0.66	< 0.177	—
w_0w_aCDM+$N_{\rm eff}$				
DESI+CMB	$0.346^{+0.032}_{-0.026}$	$63.9^{+2.2}_{-3.3}$	—	2.89 ± 0.17
DESI+CMB+Panth.	0.3093 ± 0.0069	67.5 ± 1.1	—	2.93 ± 0.18
DESI+CMB+Union3	0.3245 ± 0.0098	65.9 ± 1.3	—	2.91 ± 0.18
DESI+CMB+DESY5	0.3172 ± 0.0067	66.6 ± 1.1	—	2.92 ± 0.18