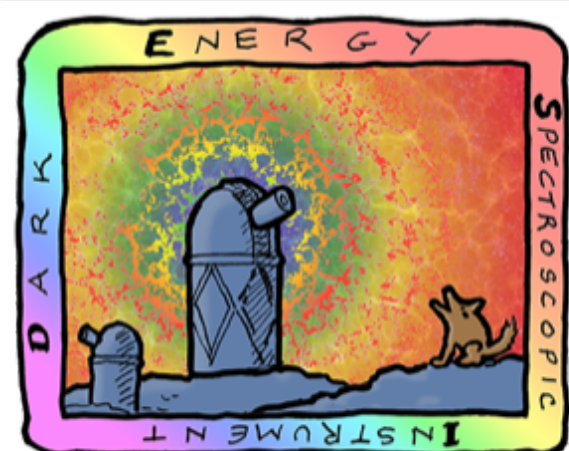


Cosmological results from one year of DESI observations

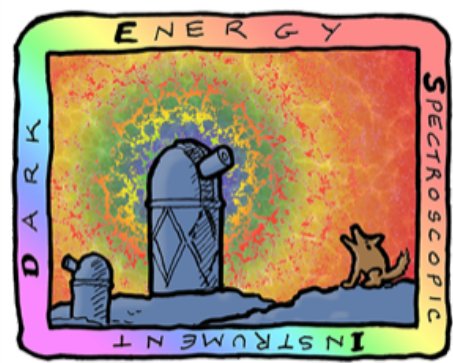
Daide Bianchi
Università degli Studi di Milano



DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

Understanding the Galaxy/Matter Connection in the Era of Large Surveys
Sestri Levante 16/09/2024



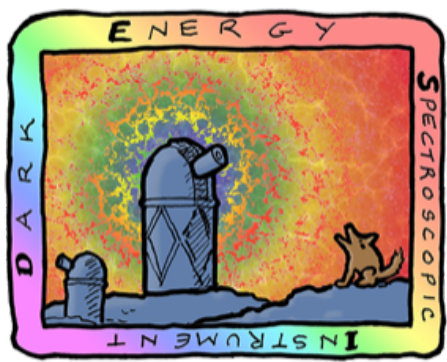
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DESI = Dark Energy Spectroscopic Instrument

Mayall telescope @ Kitt Peak





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DESI survey

Five target classes

40 million redshifts

in 5 years

DESI (2021-2026)

3 million QSOs

Lya $z > 2.1$

Tracers $0.9 < z < 2.1$

16 million ELGs

$0.6 < z < 1.6$

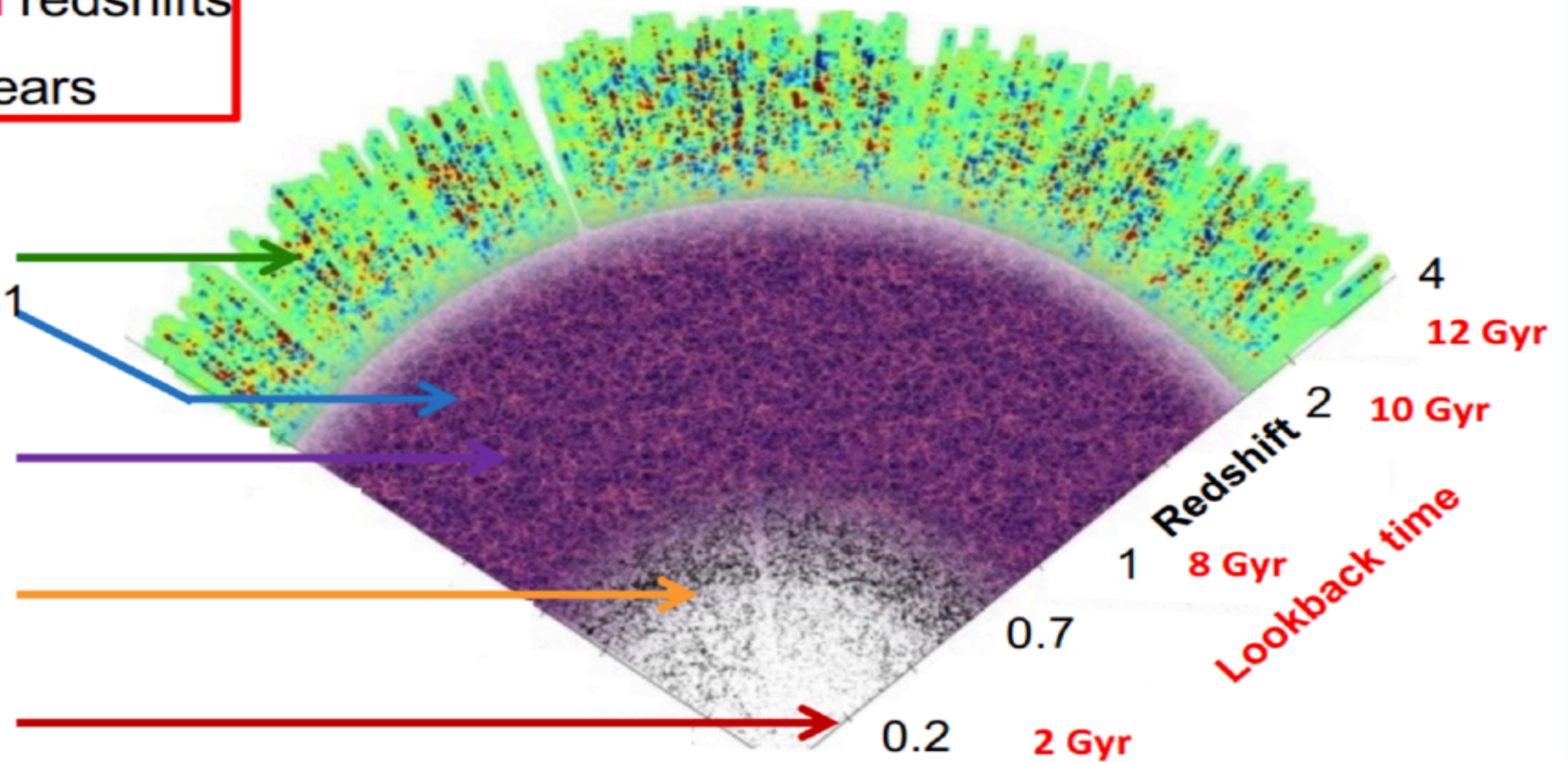
8 million LRGs

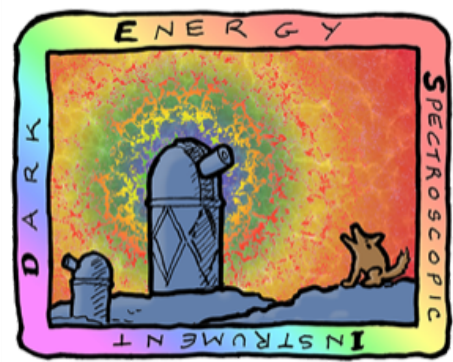
$0.4 < z < 1.0$

13.5 million

Brightest galaxies

$0.0 < z < 0.4$

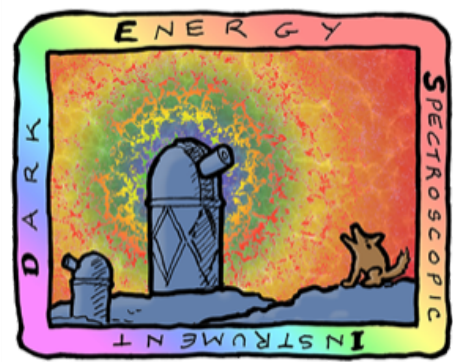




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Why measuring 40M galaxy spectra?



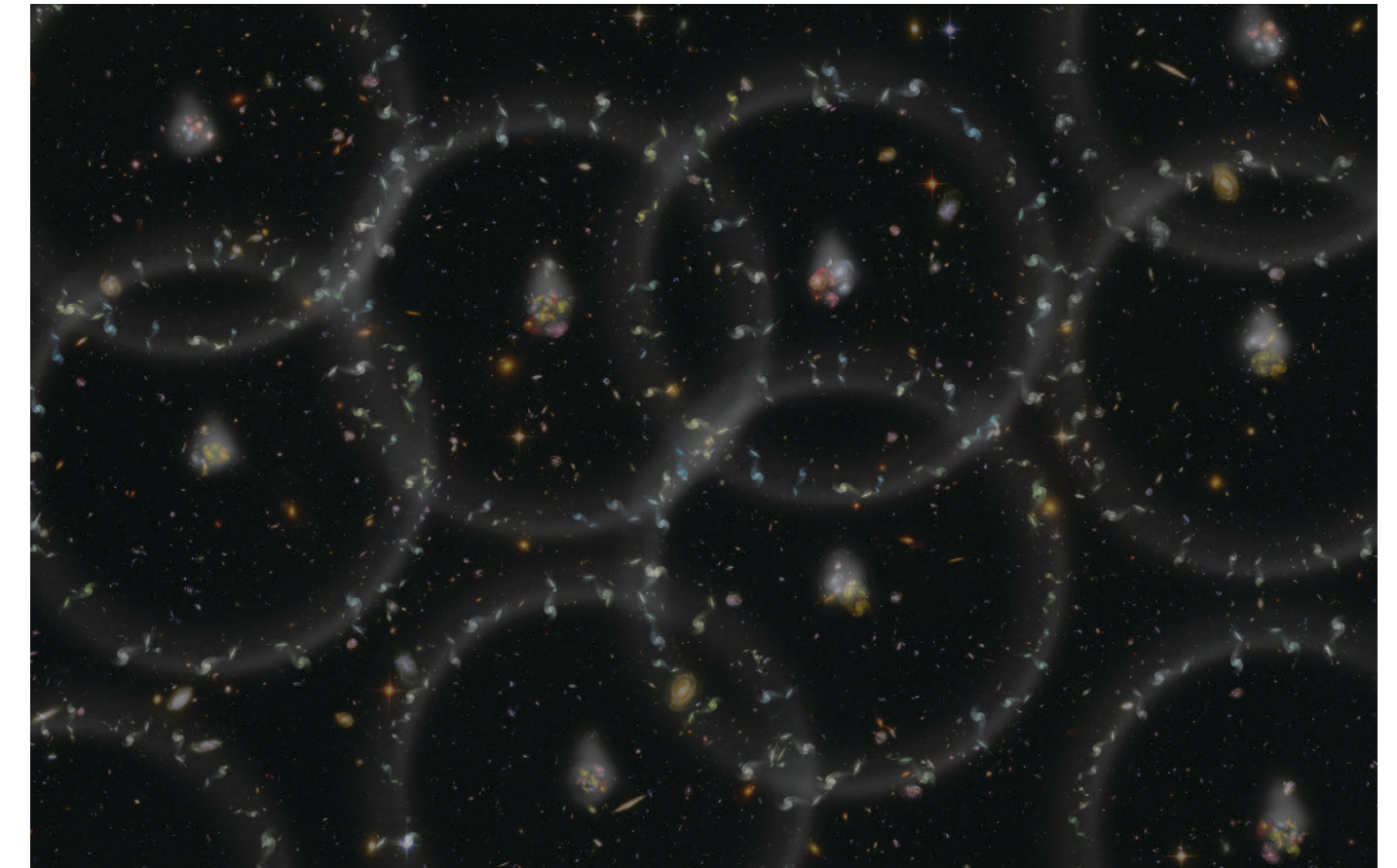
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INSTRUMENT

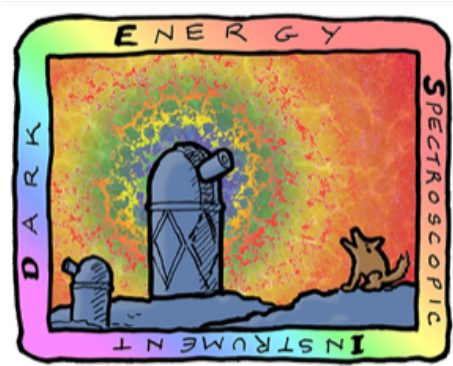
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Why measuring 40M galaxy spectra?

- **Baryon Acoustic Oscillations (BAO)**
 - ▶ Preferred scale in clustering of galaxies
 - ▶ Direct expansion measurement

Artist rendition of BAO





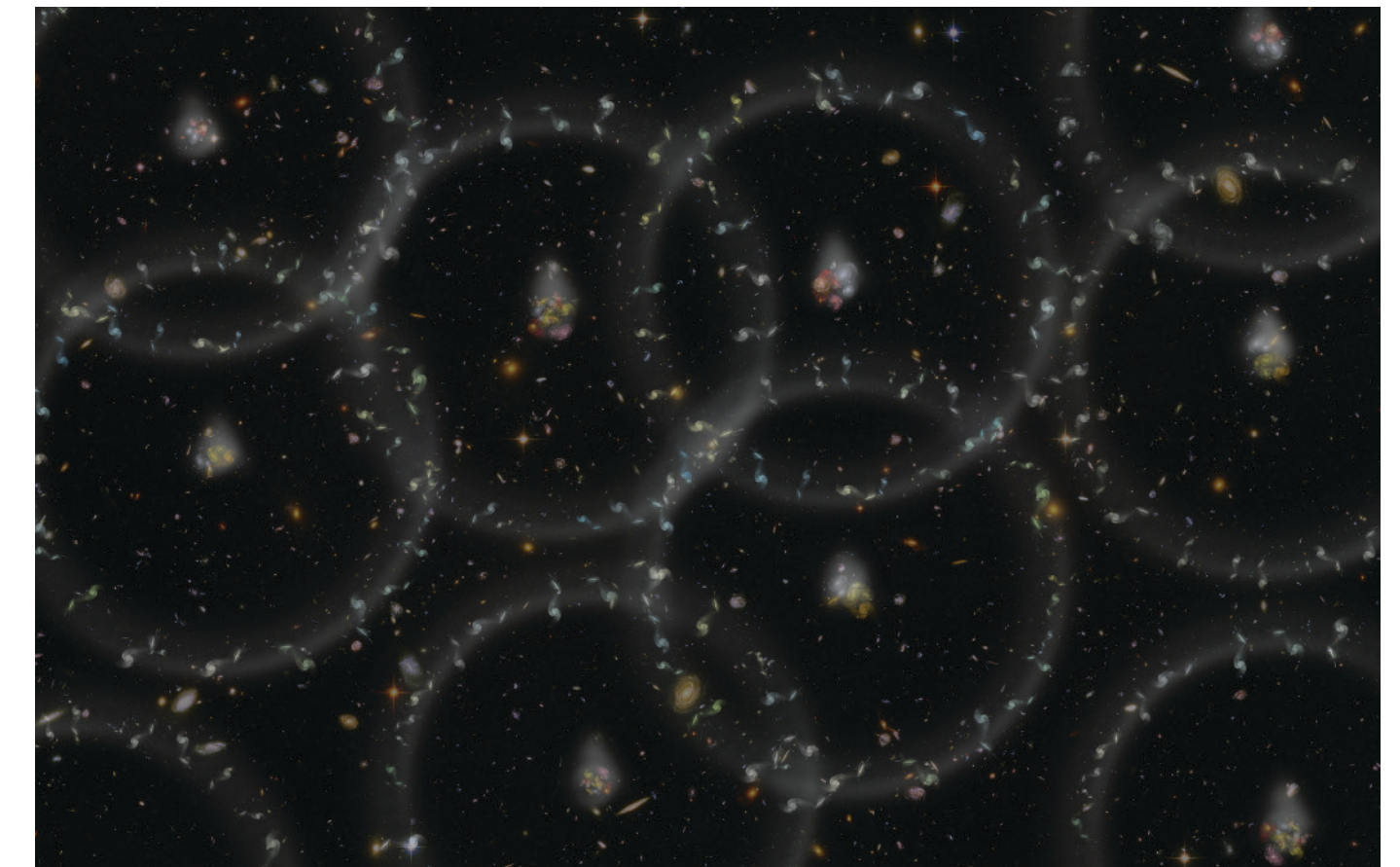
DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

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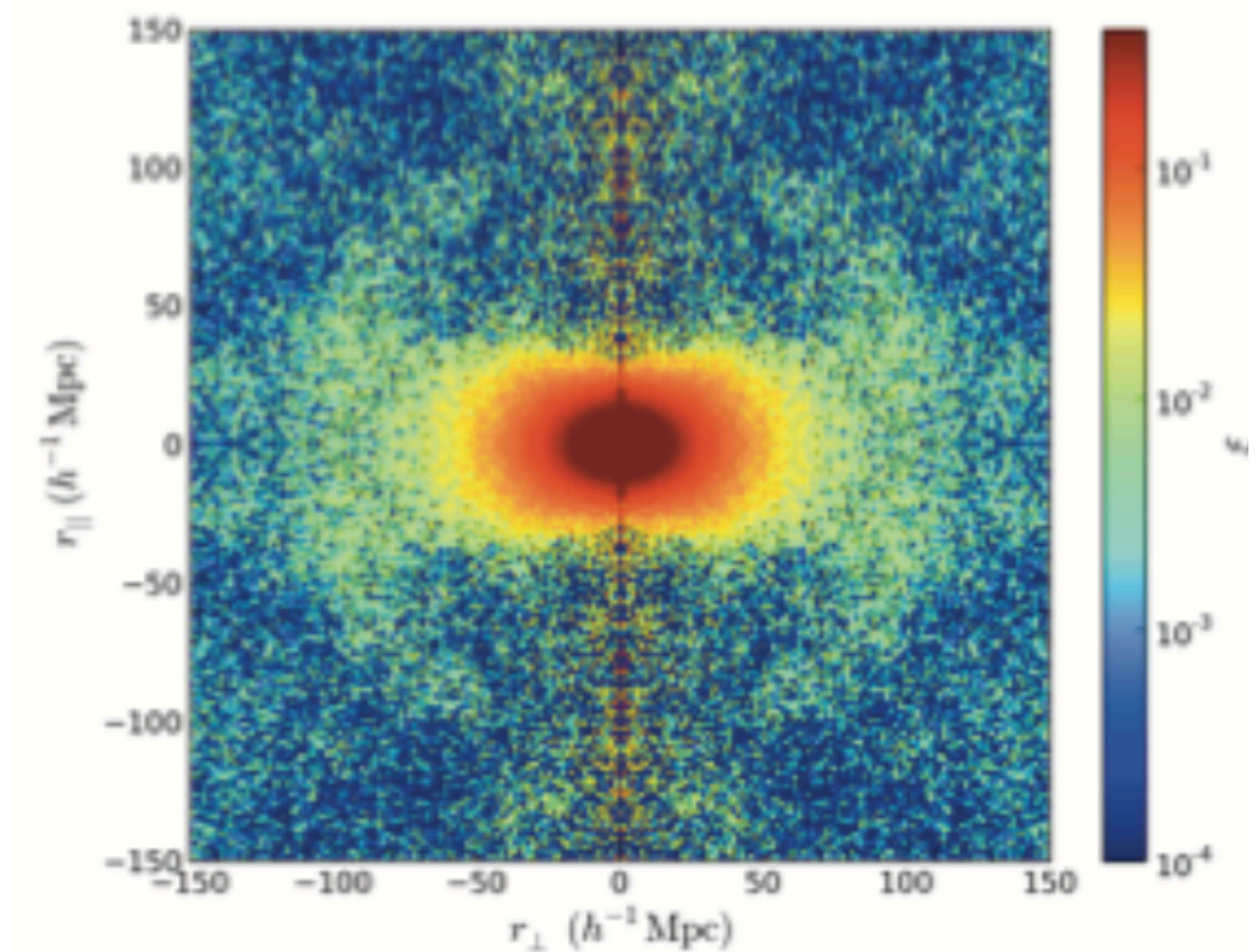
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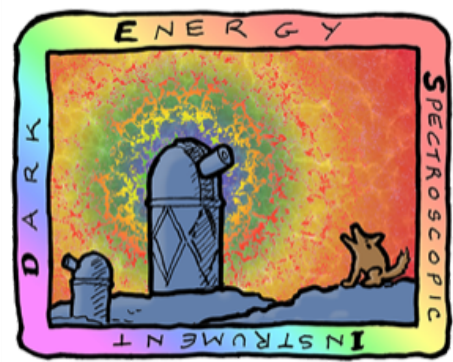
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Galaxy correlation function





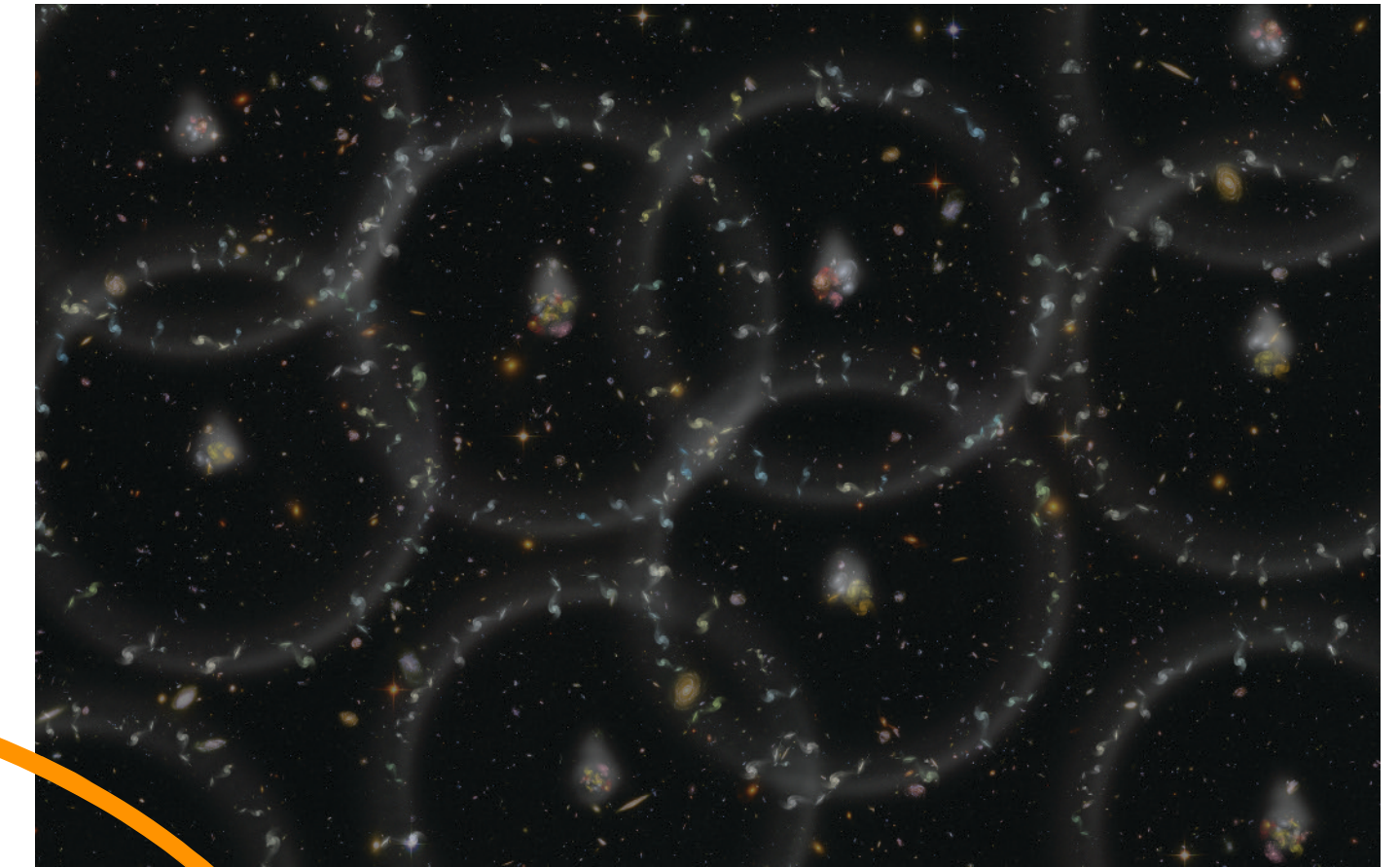
DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

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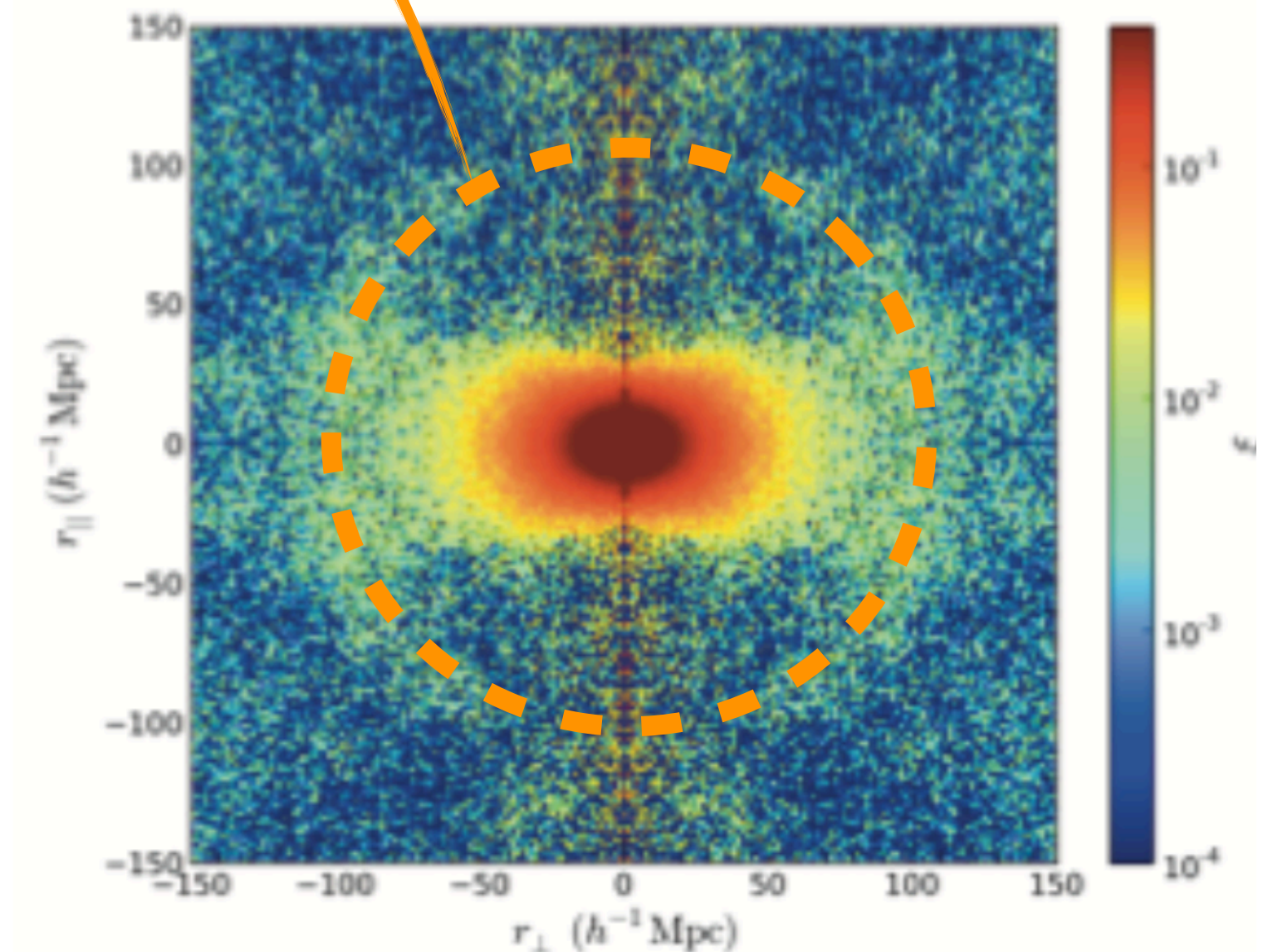
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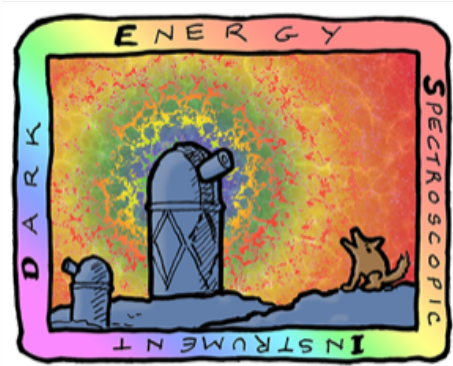
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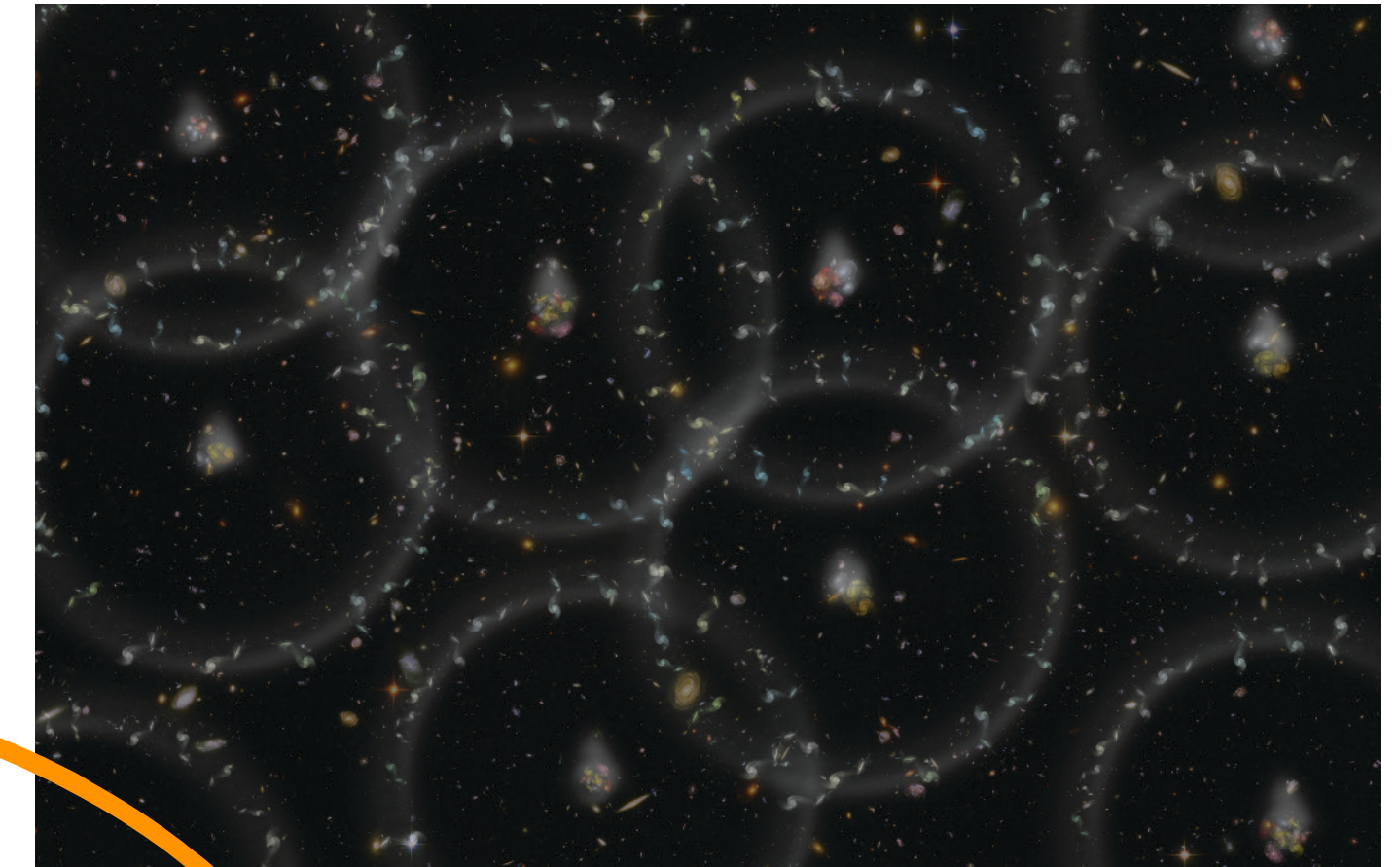
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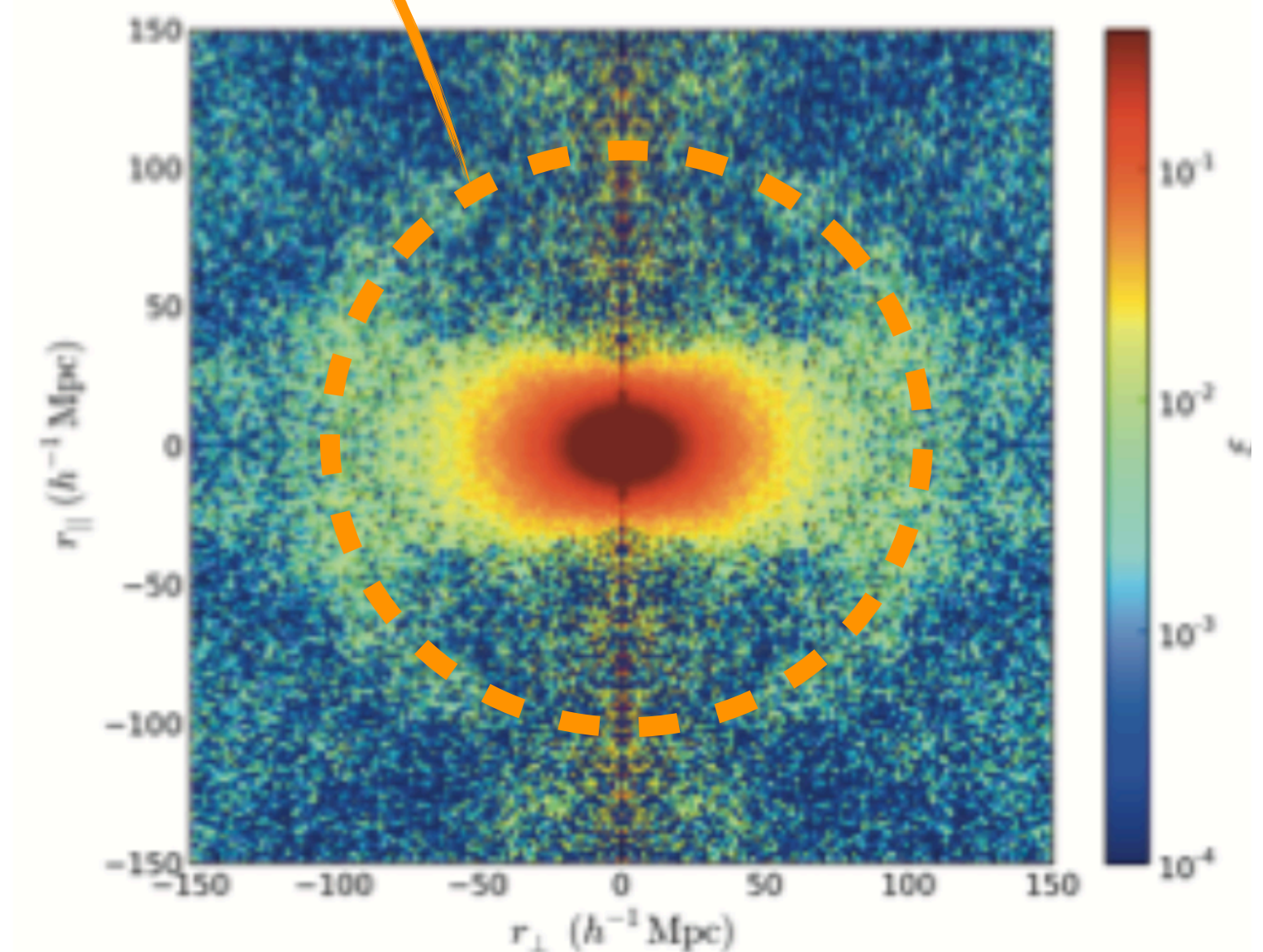
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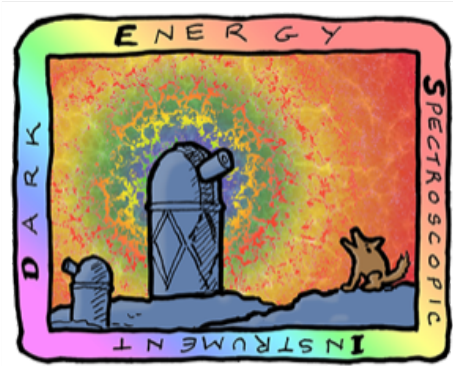
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 - ▶ Growth of structure

Artist rendition of BAO



Galaxy correlation function





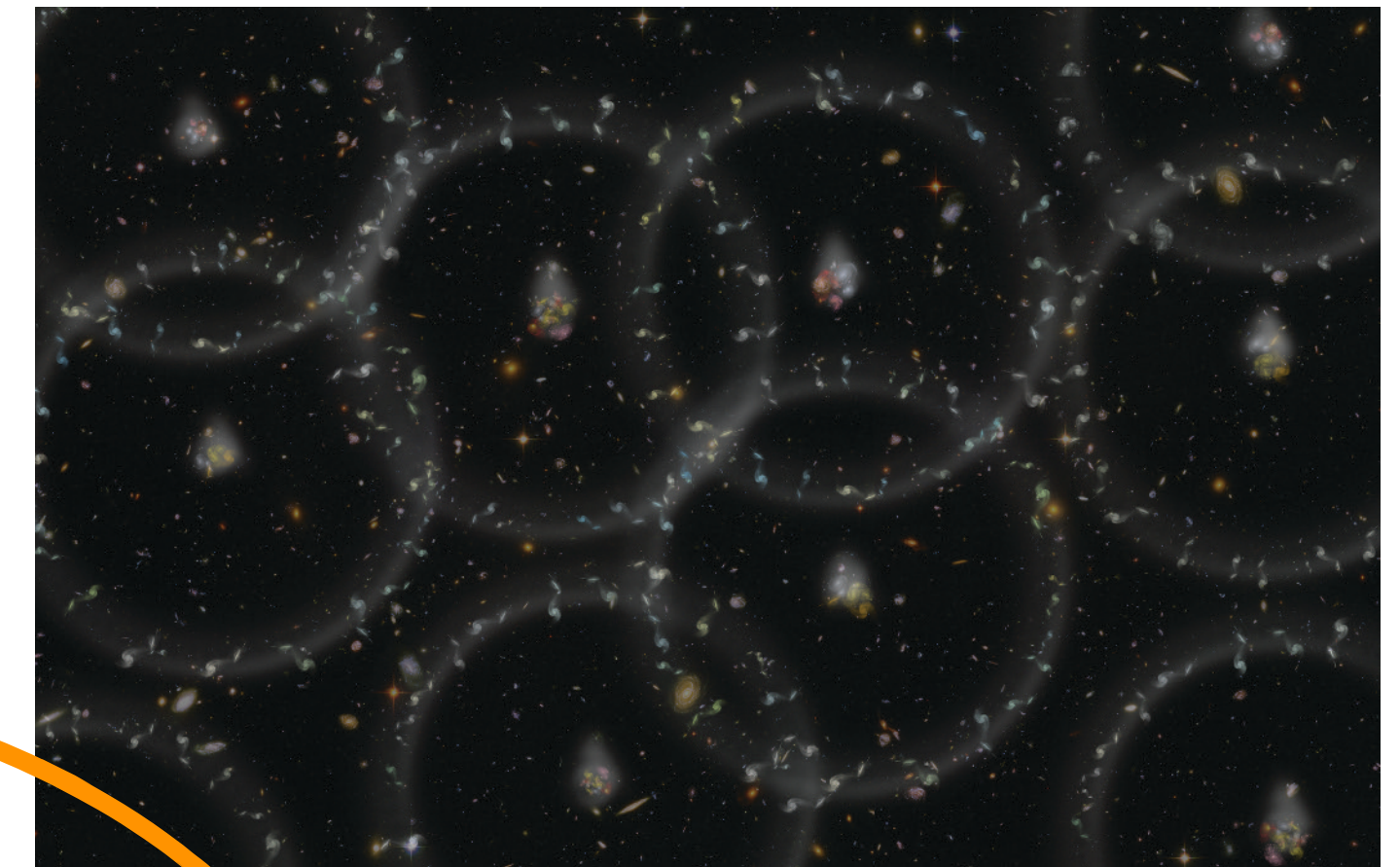
DARK ENERGY
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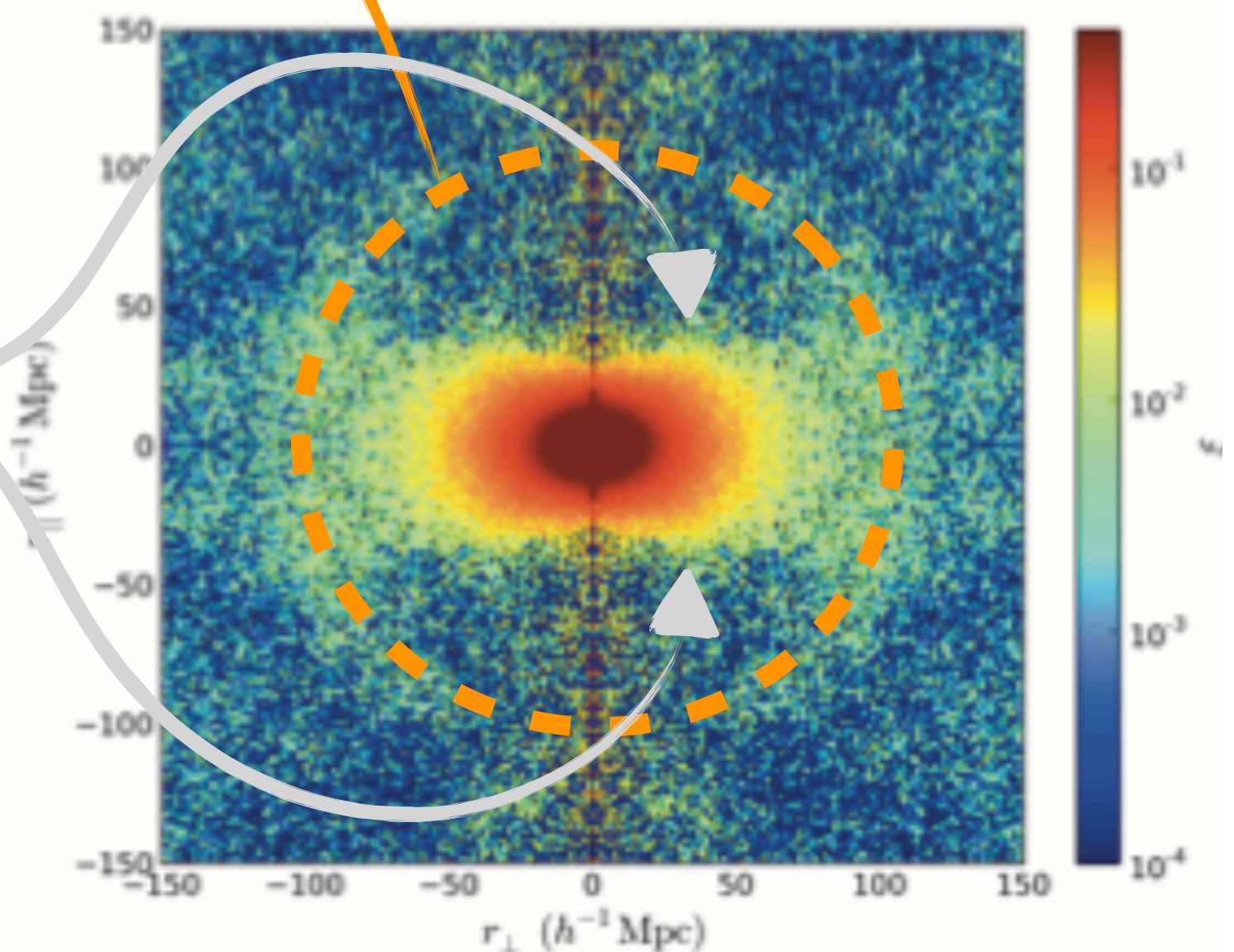
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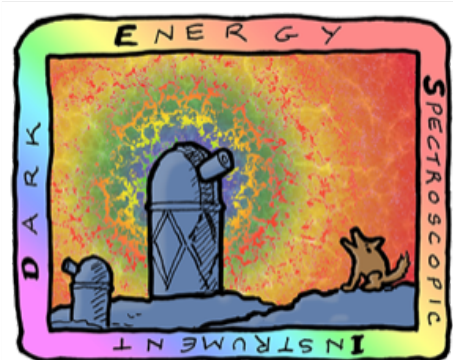
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Galaxy correlation function





DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

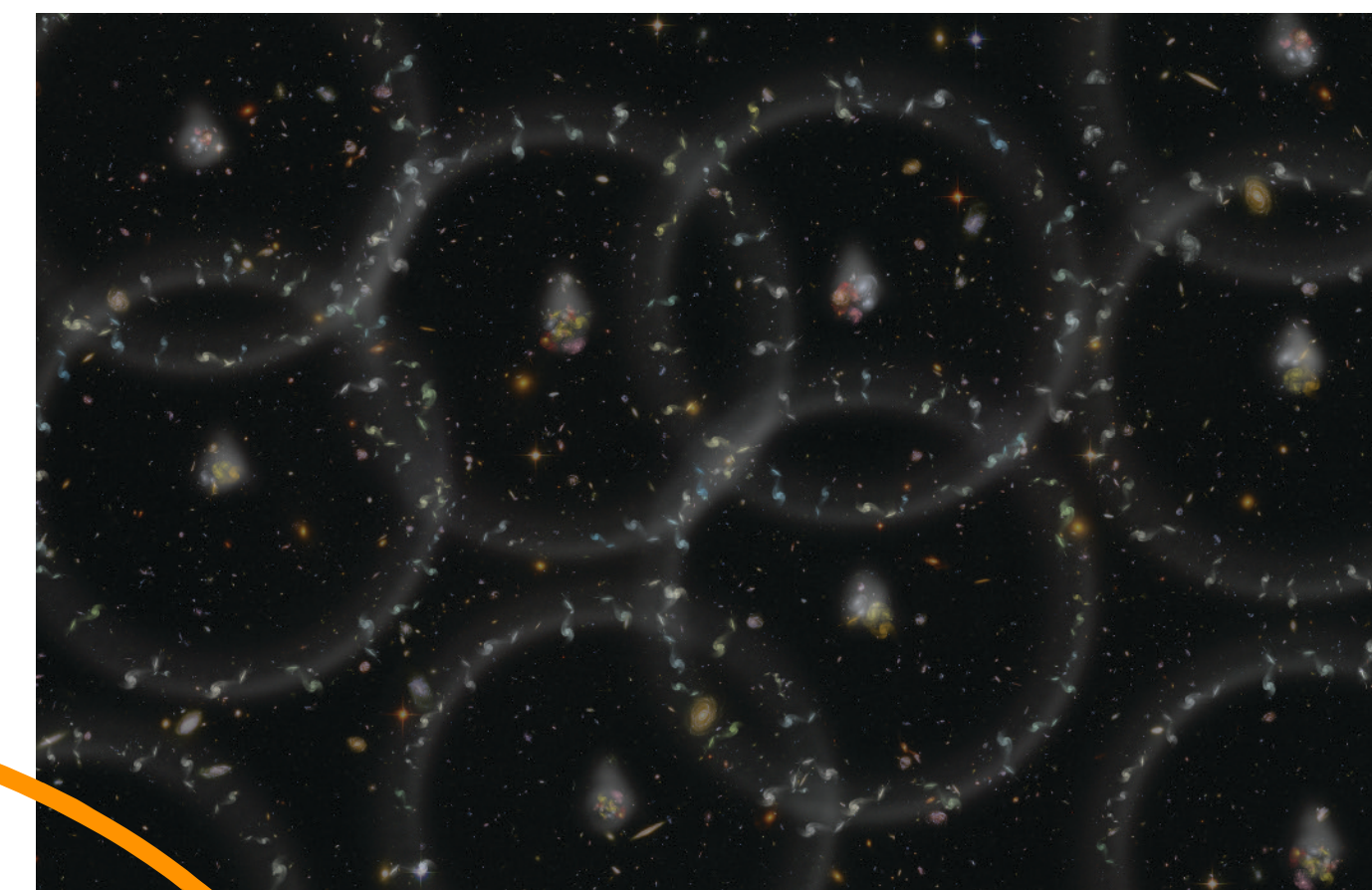
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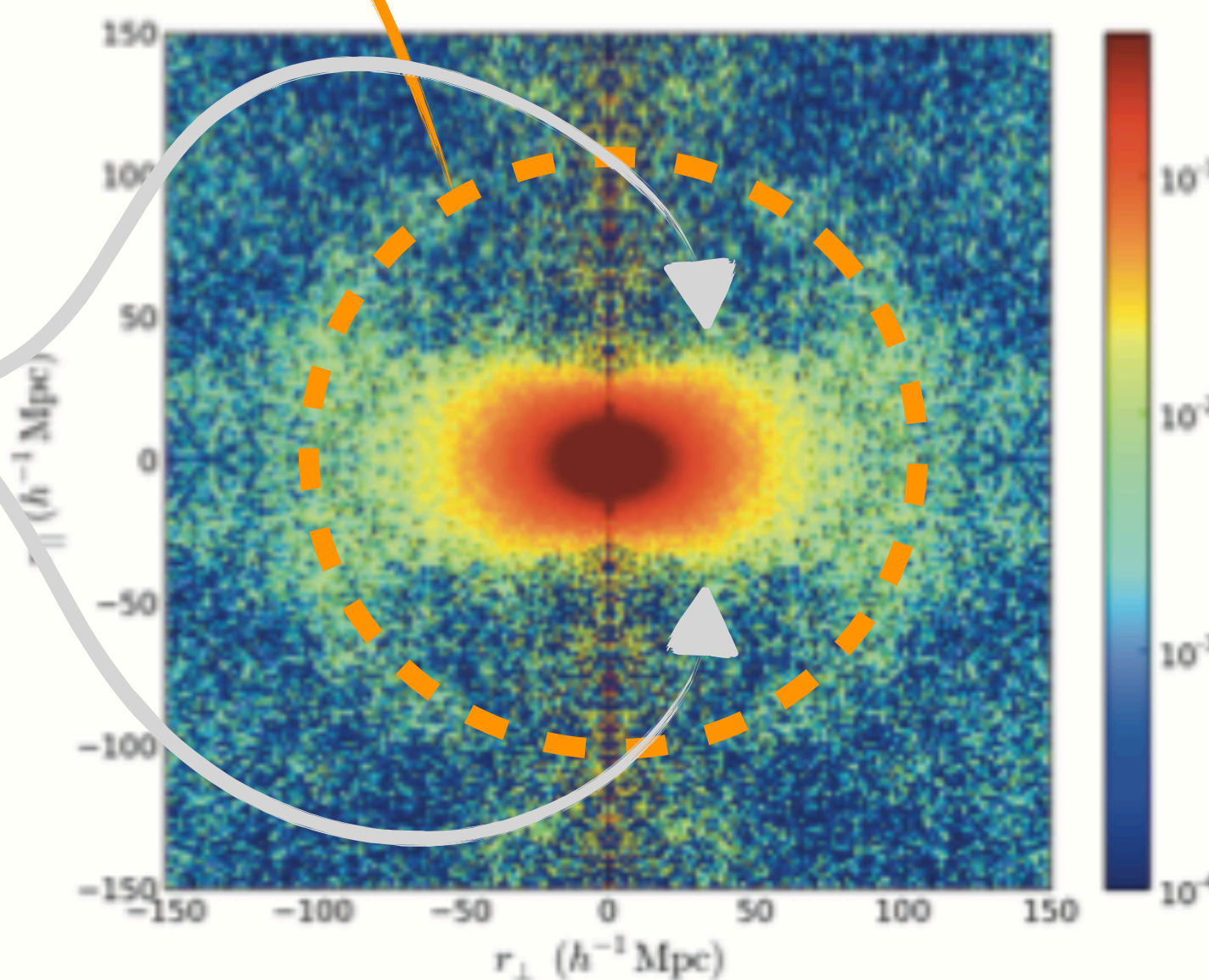
Today's talk

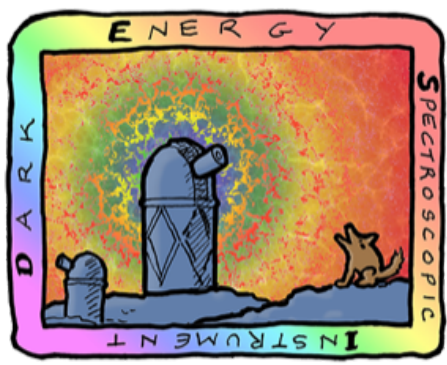
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Galaxy correlation function





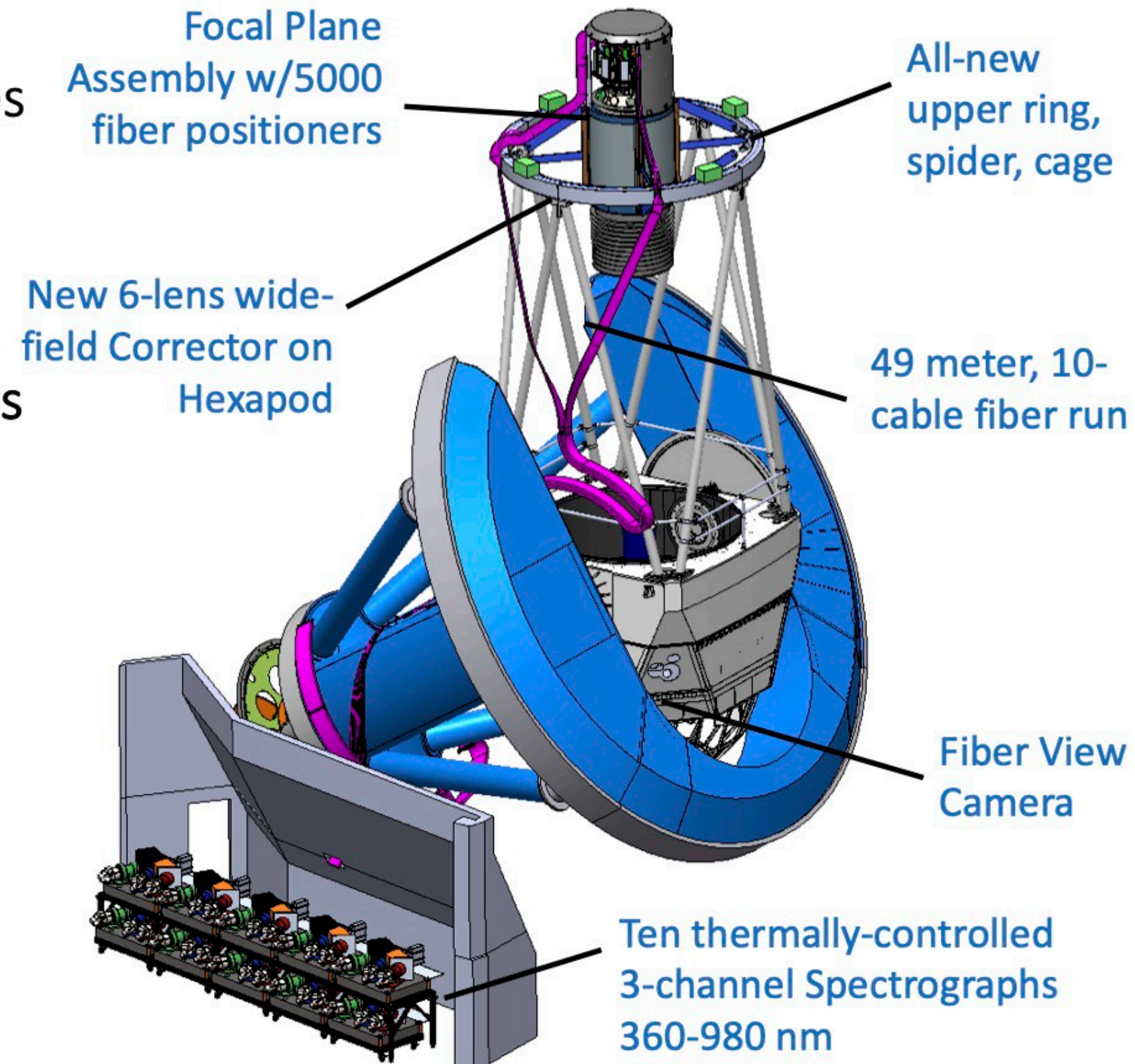
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SPECTROSCOPIC
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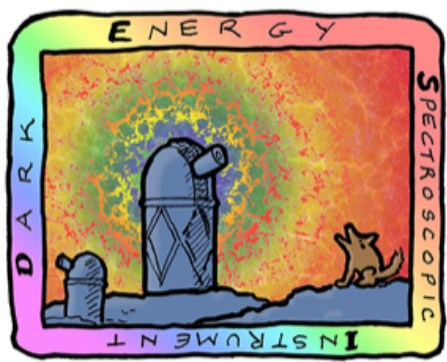
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DESI instrument

DESI by the Numbers

- DESI is a Fiber-fed multi-object spectrograph. It uses robotic control to position optical fibers onto the location of a known galaxy
- 5000 fiber positioner robots on the focal plane
- 8 sq. deg. FOV
- Ten 3-channel spectrographs
- Spectra of 35 million galaxies and quasars over 14,000 deg² in five years





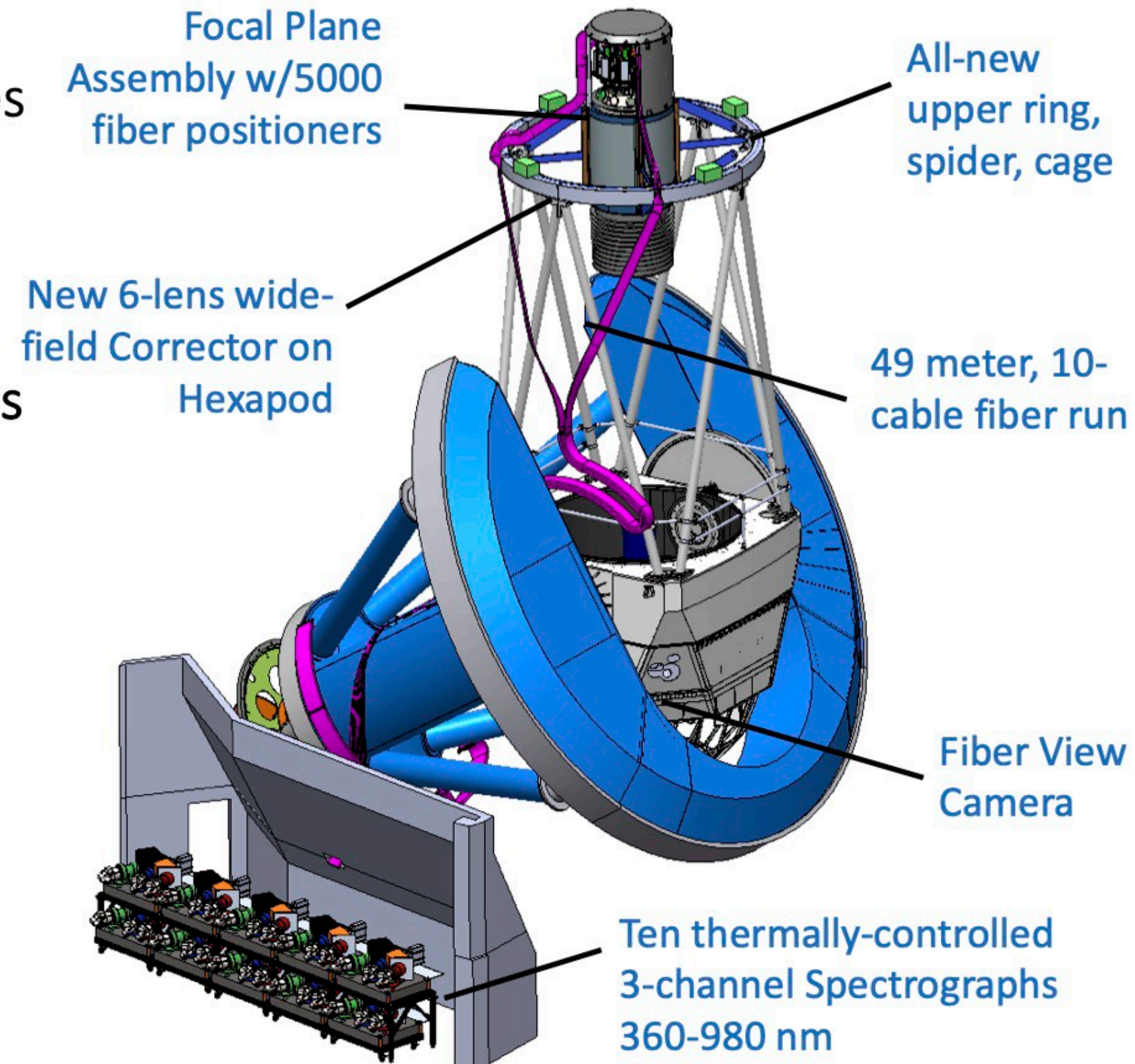
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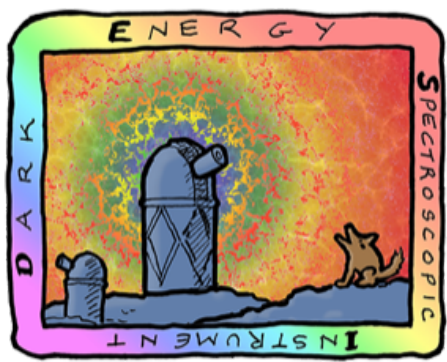
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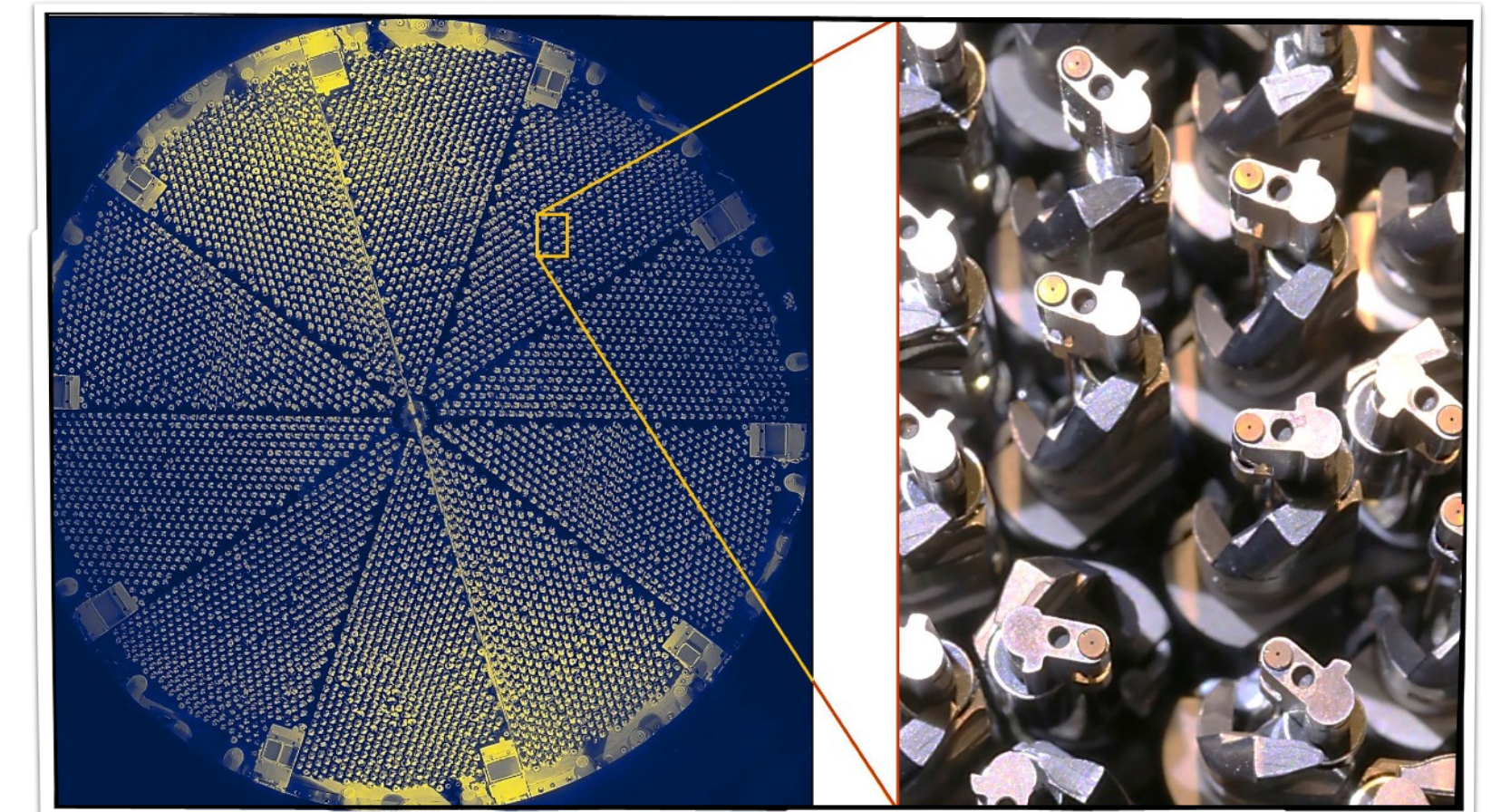
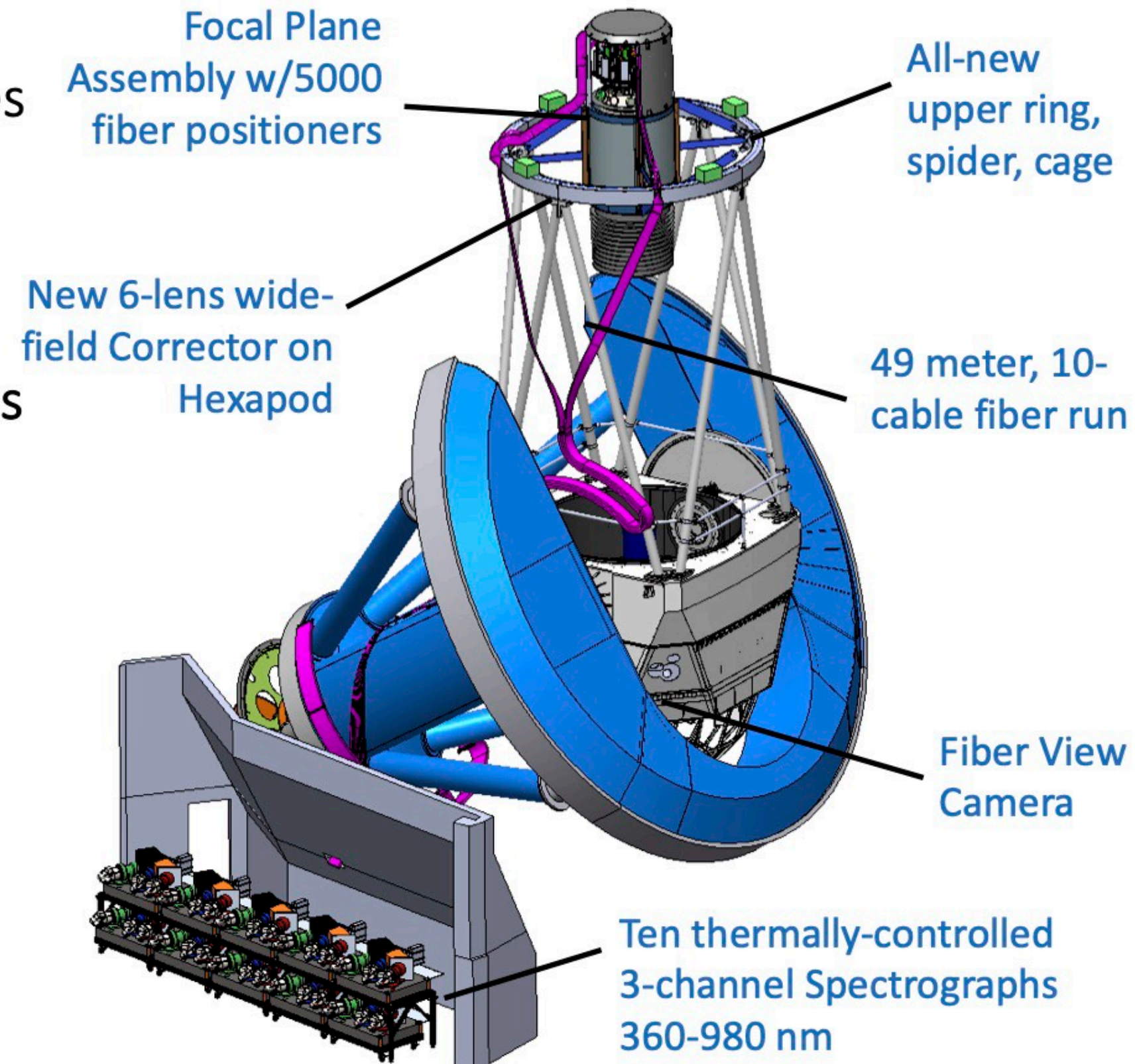
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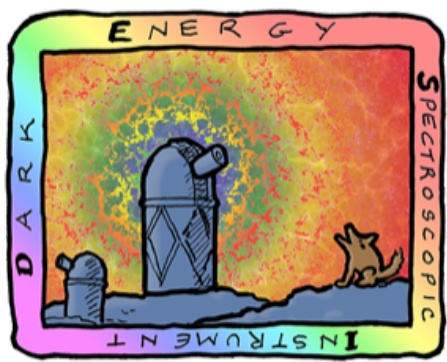
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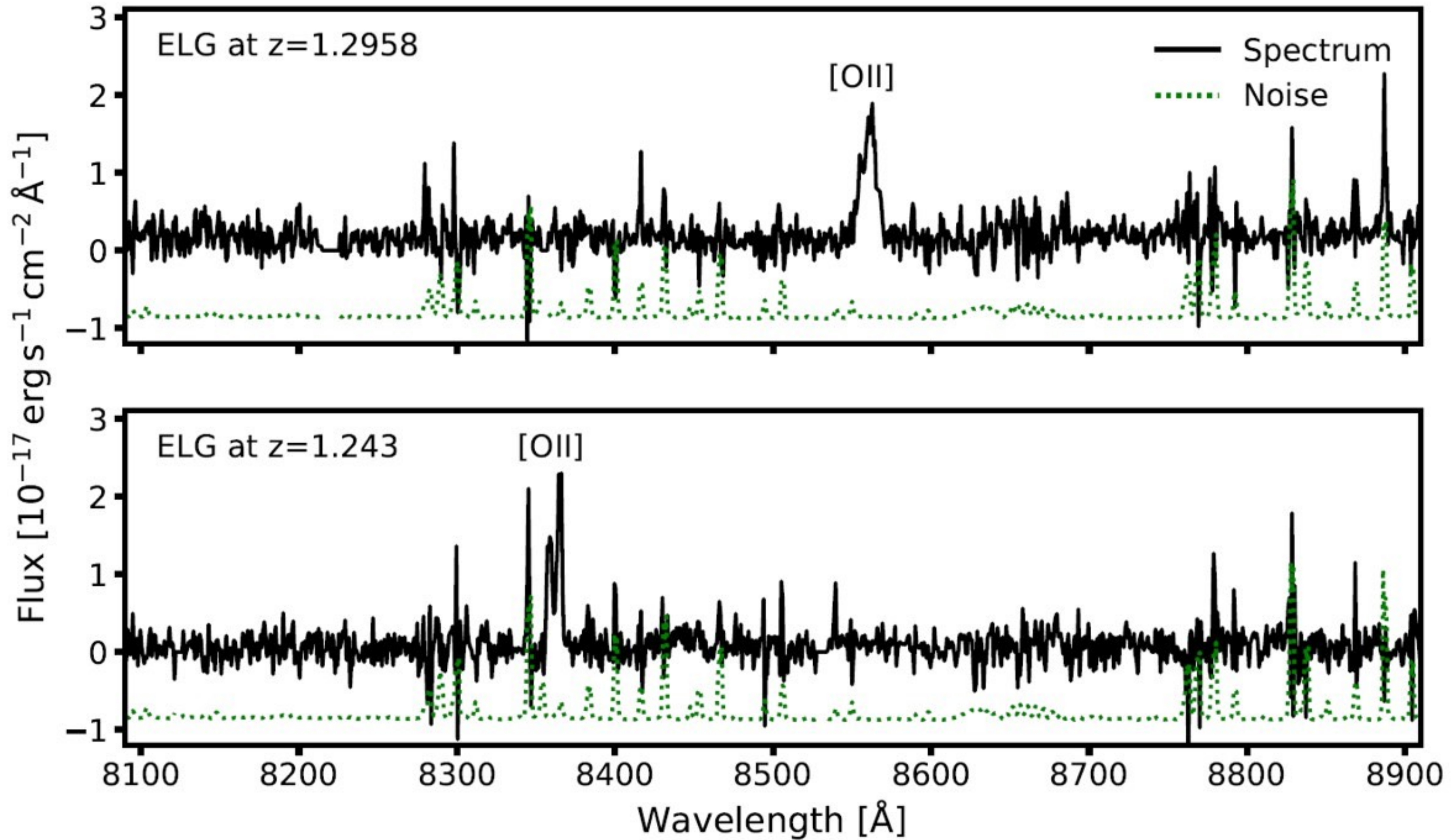


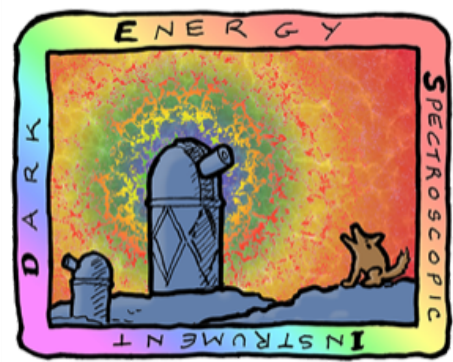


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Spectra

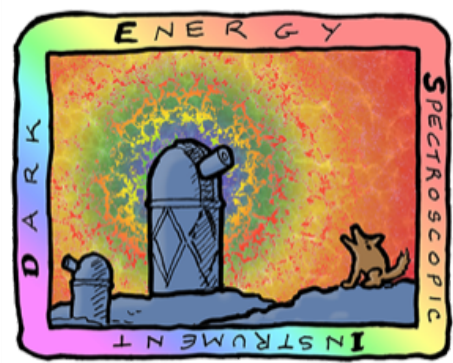




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Data release 1 (DR1)

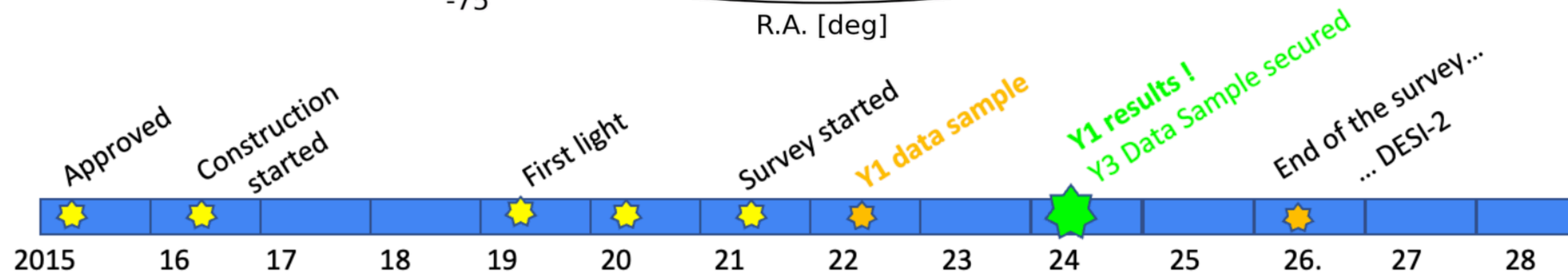
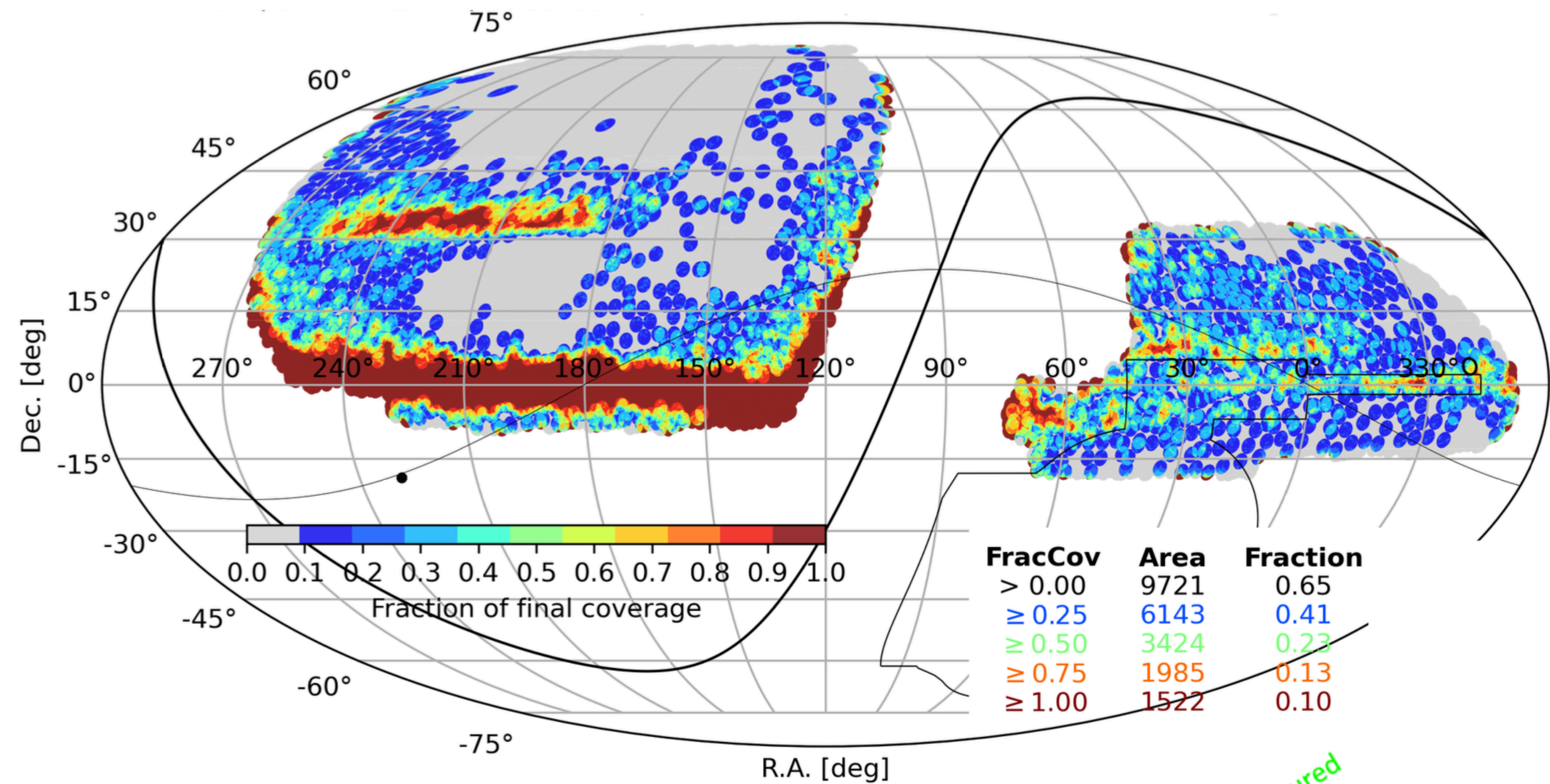


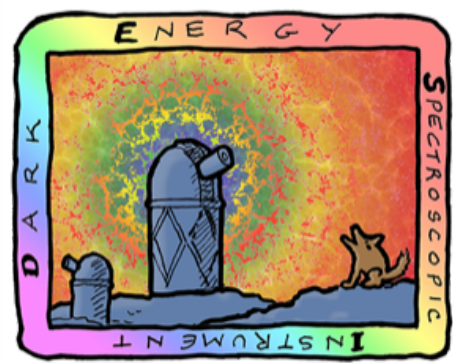
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Sky coverage/completeness

DESI DR1 includes data taken from May 14th (2021) to June 12th (2022)



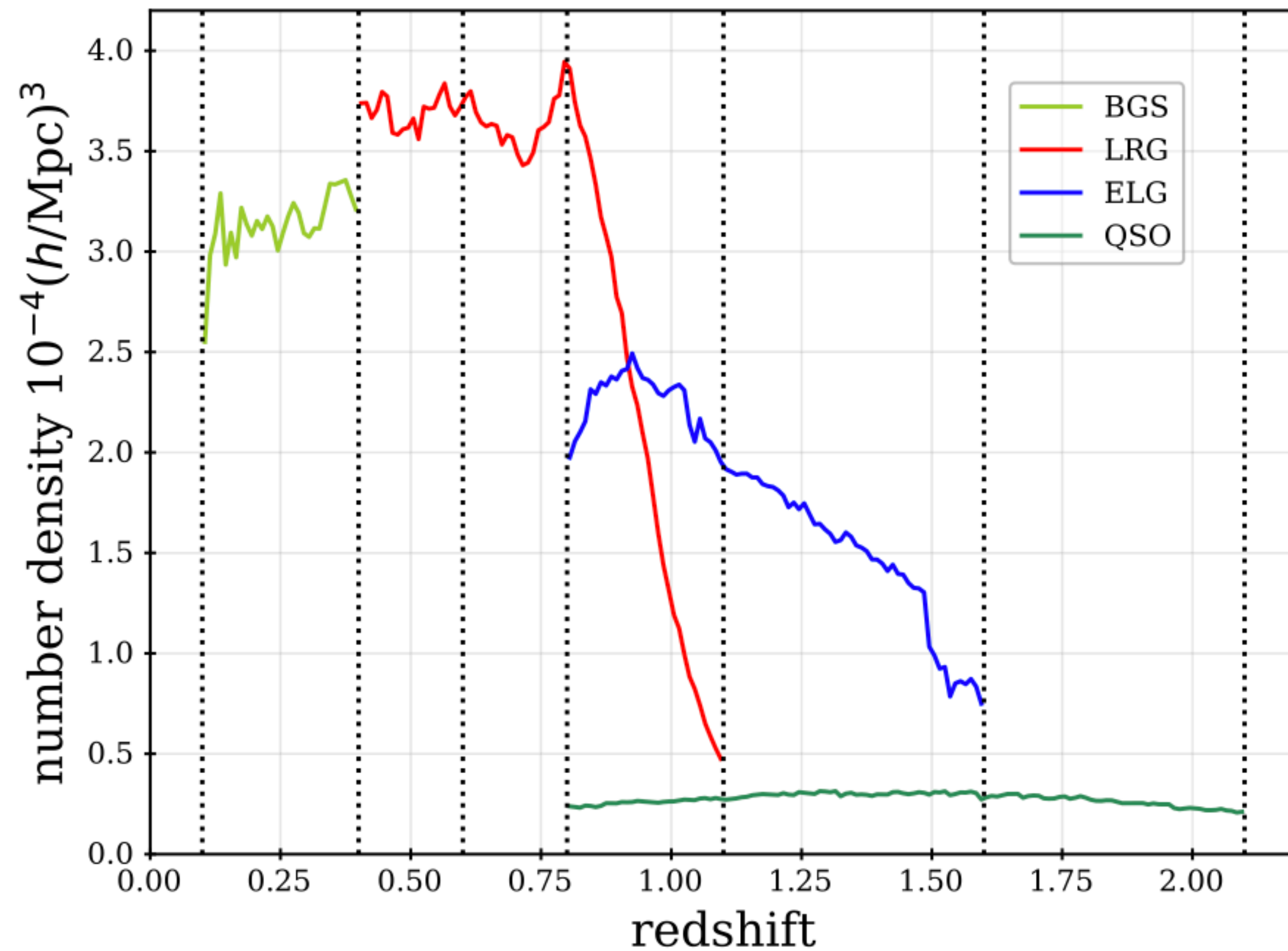


DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

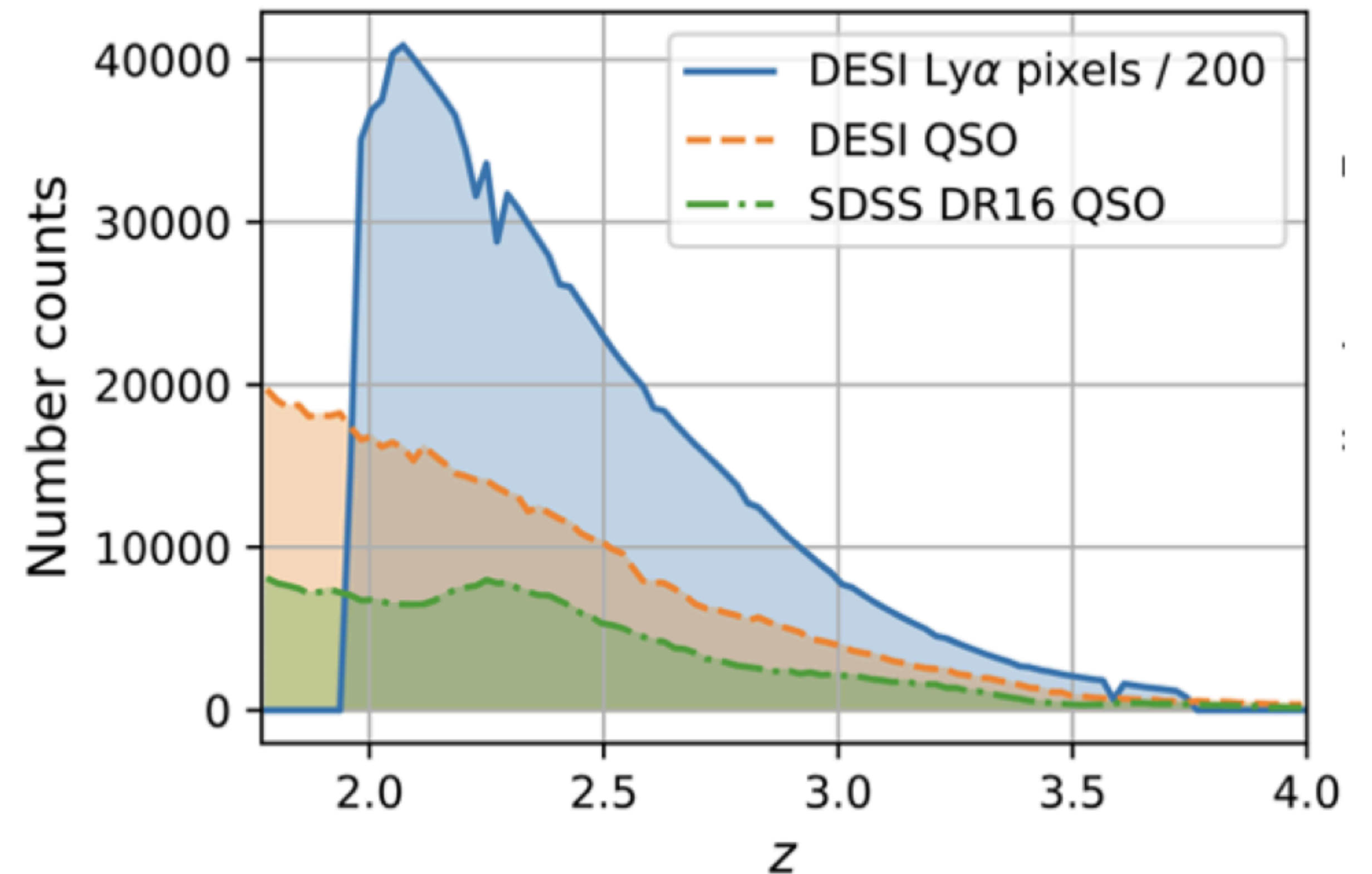
U.S. Department of Energy Office of Science

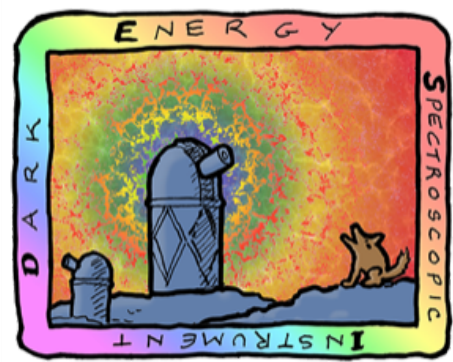
Redshift distribution

5.7 million unique redshifts at $z < 2.1$



... and $> 420,000$ Lyman- α QSOs at $z > 2.1$

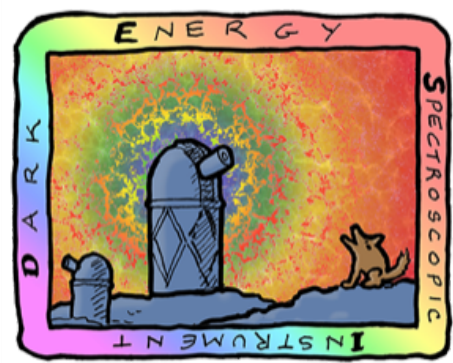




DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

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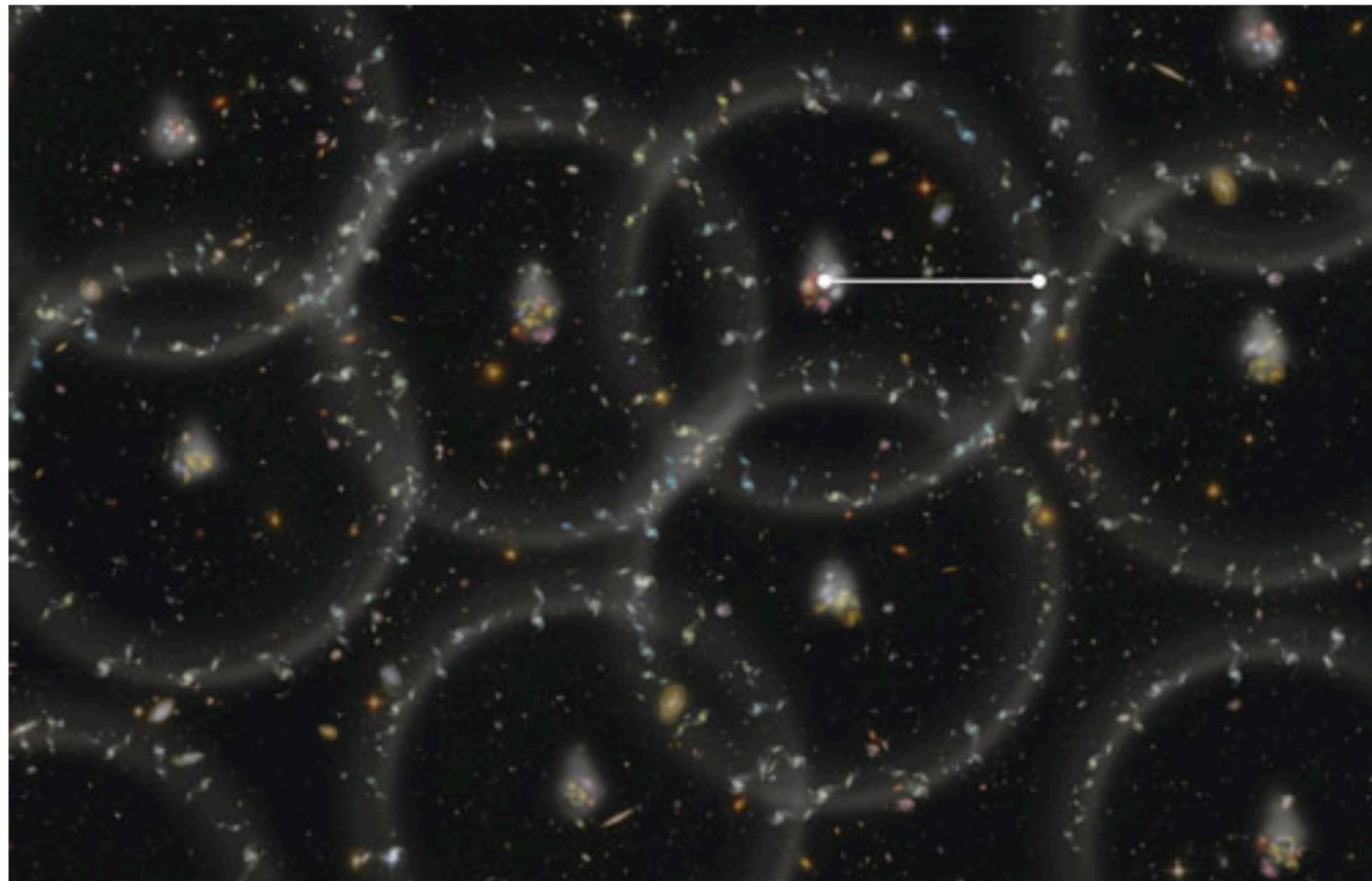
Baryon acoustic oscillations (BAO)

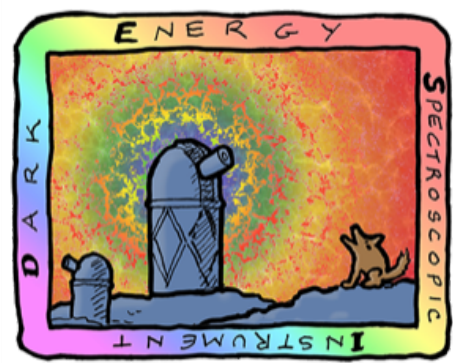


DARK ENERGY
SPECTROSCOPIC
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Baryon Acoustic Oscillations (BAO)

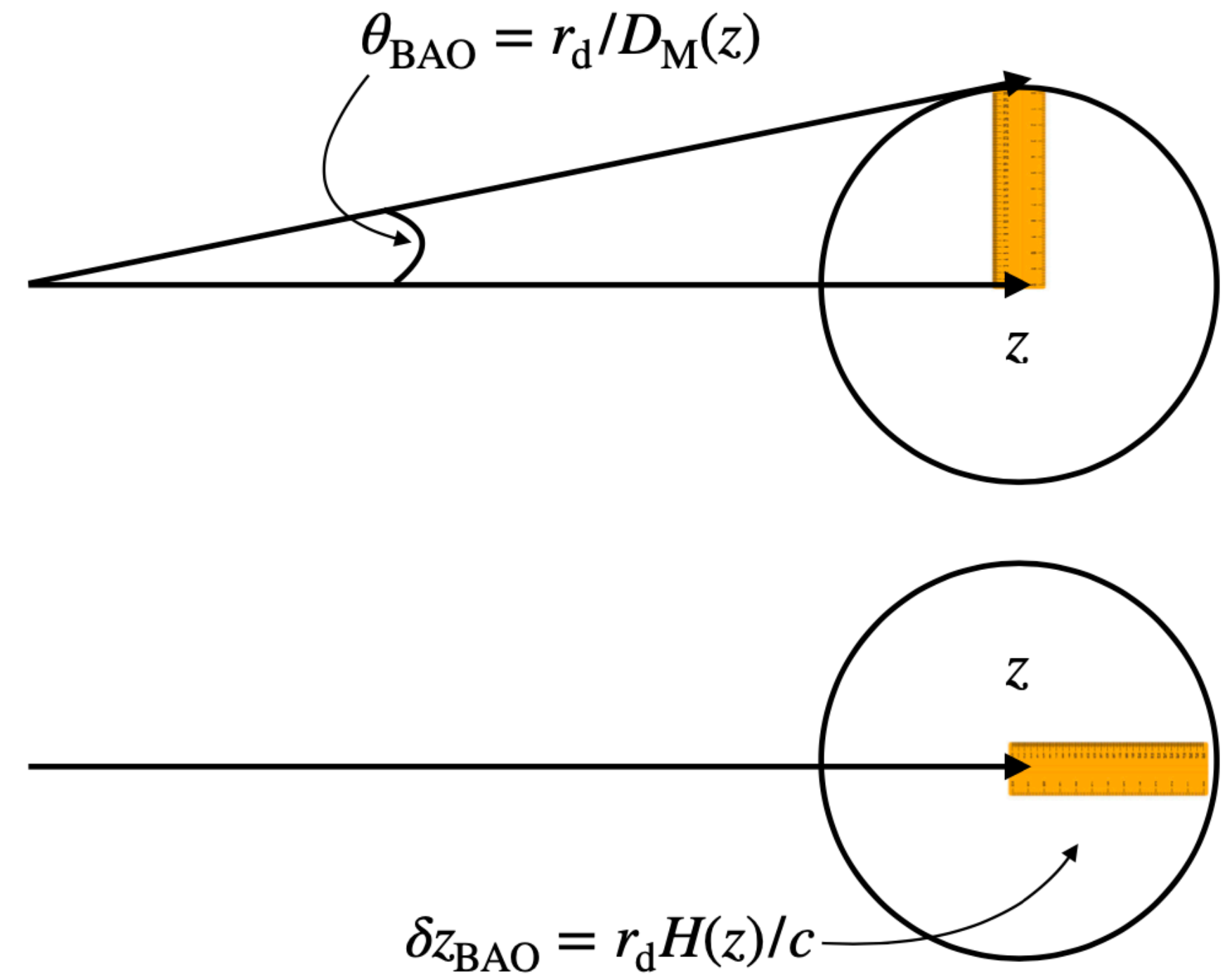
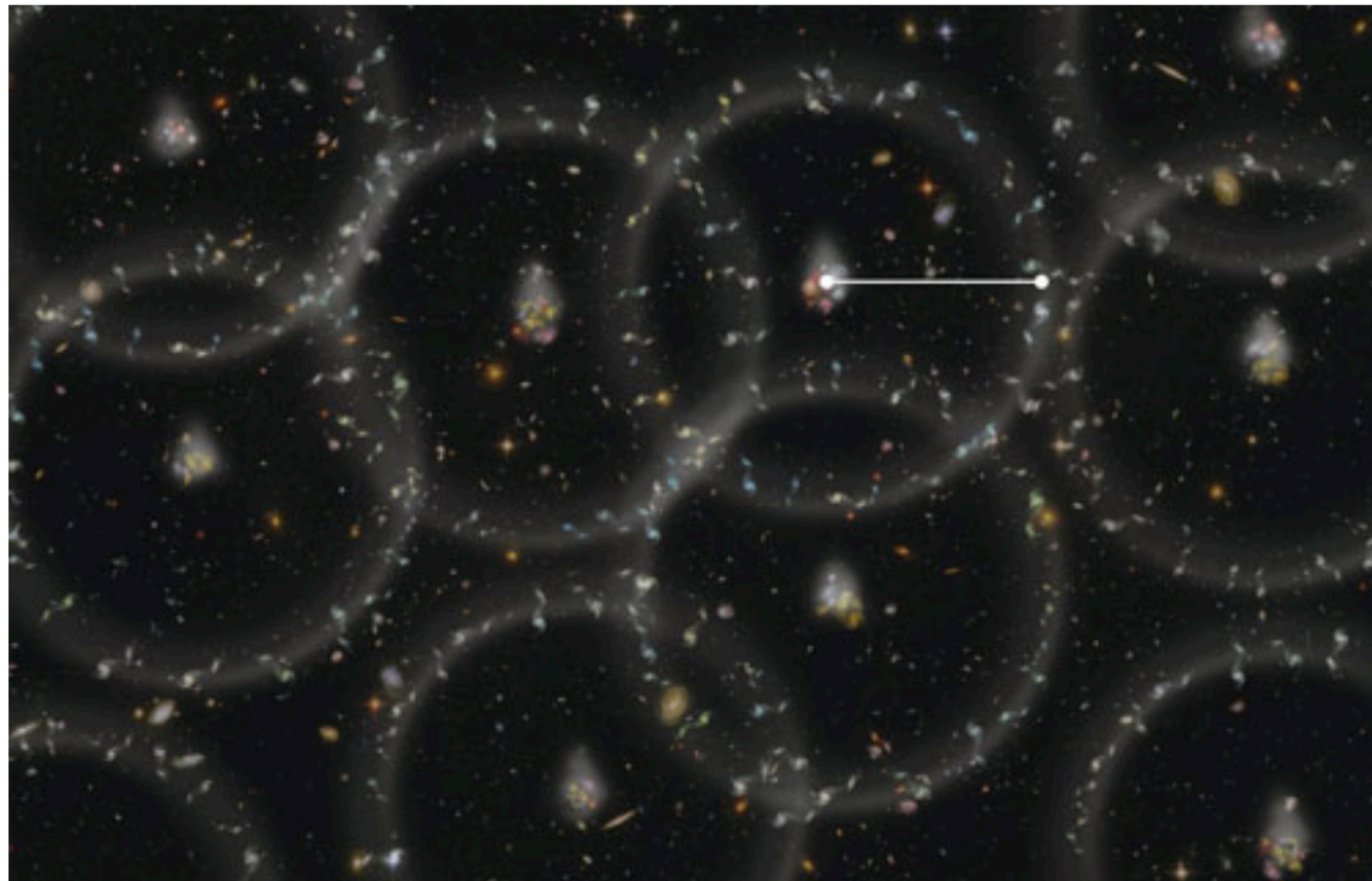




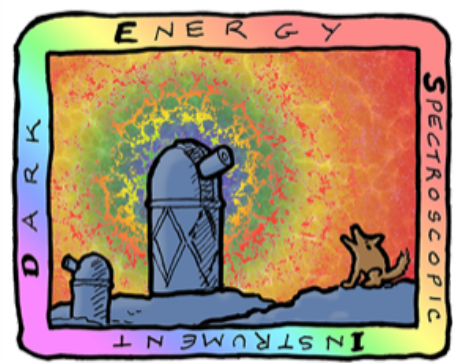
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Baryon Acoustic Oscillations (BAO)



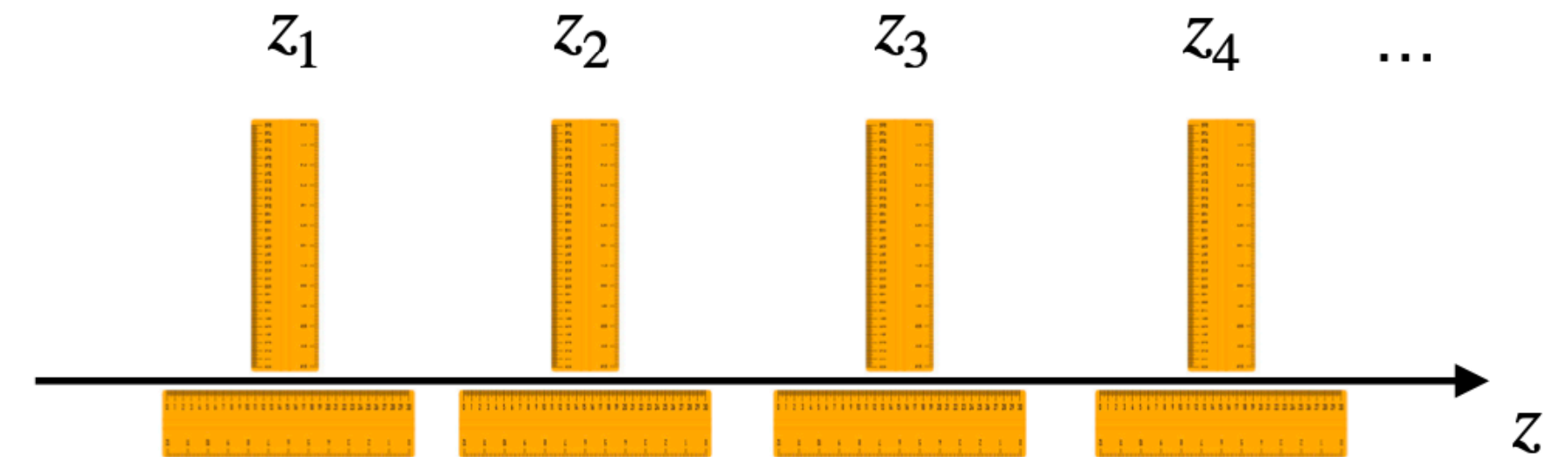
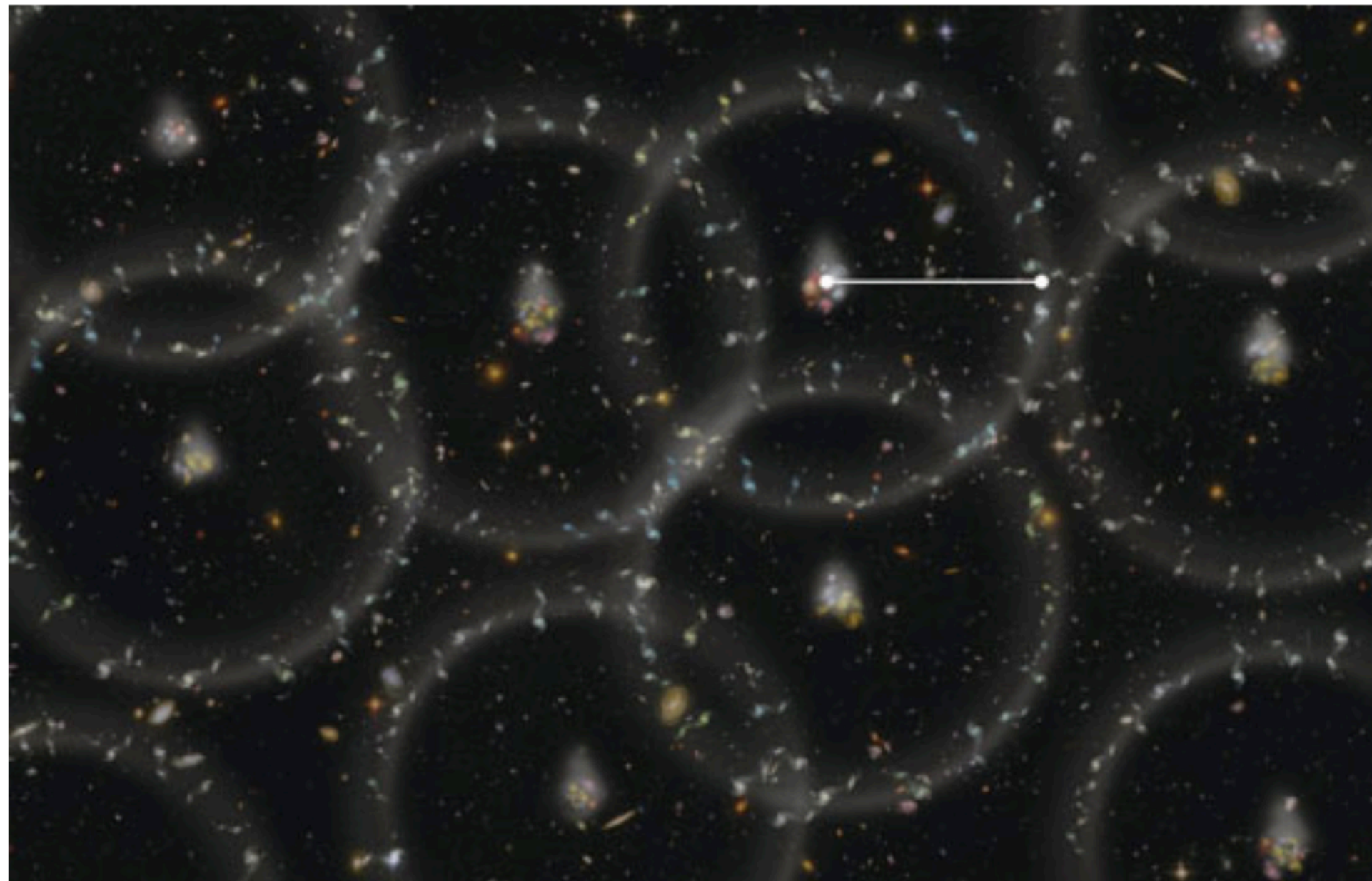
$D_M(z)$ and $H(z)$ encode the expansion history of the Universe



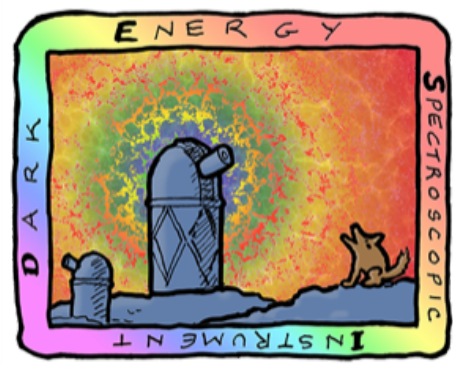
DARK ENERGY
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Baryon Acoustic Oscillations (BAO)



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SPECTROSCOPIC
INSTRUMENT

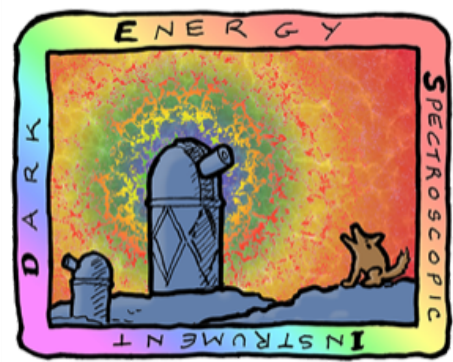
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BAO scaling parameters

2 different compressions for the BAO information

1

2



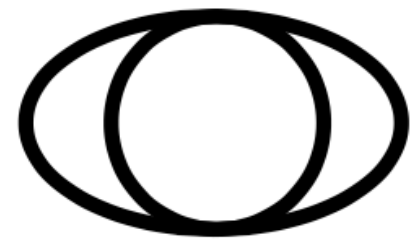
DARK ENERGY
SPECTROSCOPIC
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BAO scaling parameters

2 different compressions for the BAO information

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$$\alpha_{\perp} = \frac{D_M}{r_d} \frac{r_d^{\text{fid}}}{D_M^{\text{fid}}}$$

and

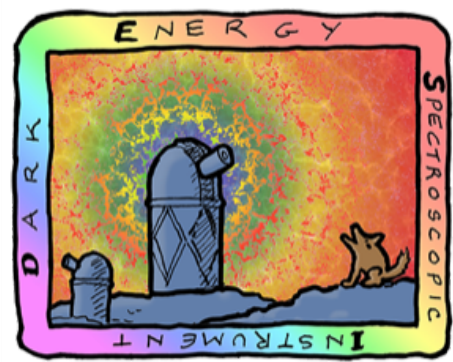
$$\alpha_{\parallel} = \frac{D_H}{r_d} \frac{r_d^{\text{fid}}}{D_H^{\text{fid}}}$$



perpendicular std ruler size

line-of-sight std ruler size

2



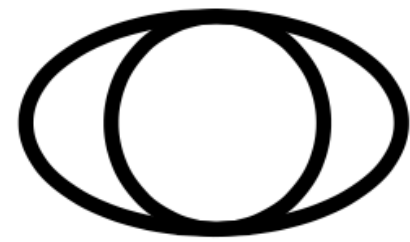
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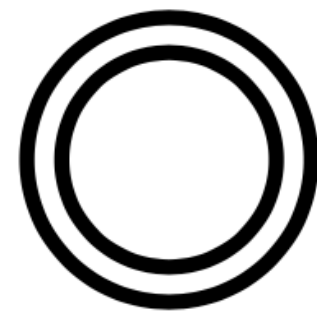
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perpendicular std ruler size

line-of-sight std ruler size

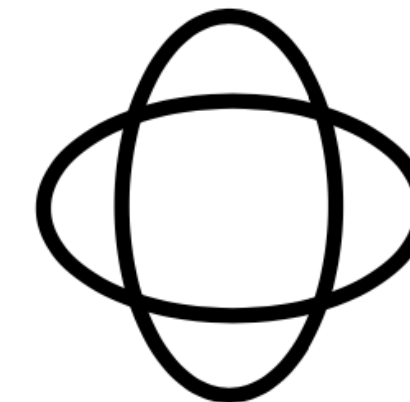
2



$$\alpha_{\text{iso}} = \left(\alpha_{\perp}^2 \alpha_{\parallel} \right)^{1/3}$$

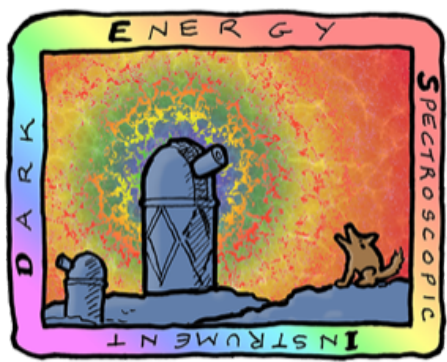
and

$$\alpha_{\text{AP}} = \frac{D_H}{D_M} \frac{D_M^{\text{fid}}}{D_H^{\text{fid}}}$$



overall scale of std ruler

anisotropy of std ruler



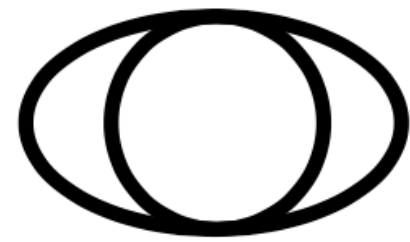
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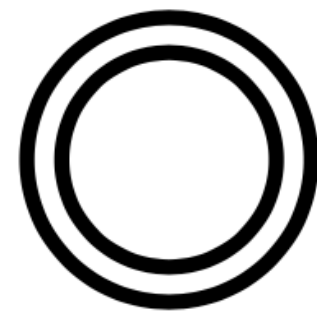
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perpendicular std ruler size

line-of-sight std ruler size

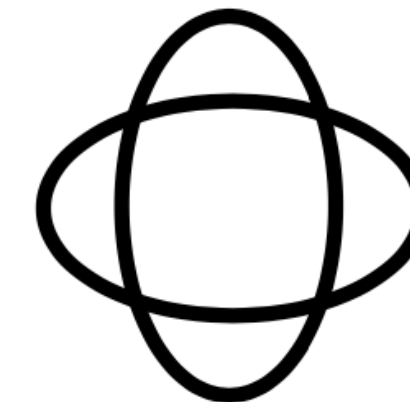
2



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and

$$\alpha_{\text{AP}} = \frac{D_H}{D_M} \frac{D_M^{\text{fid}}}{D_H^{\text{fid}}}$$

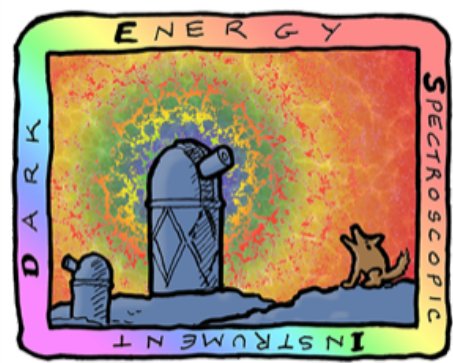


overall scale of std ruler

anisotropy of std ruler

or

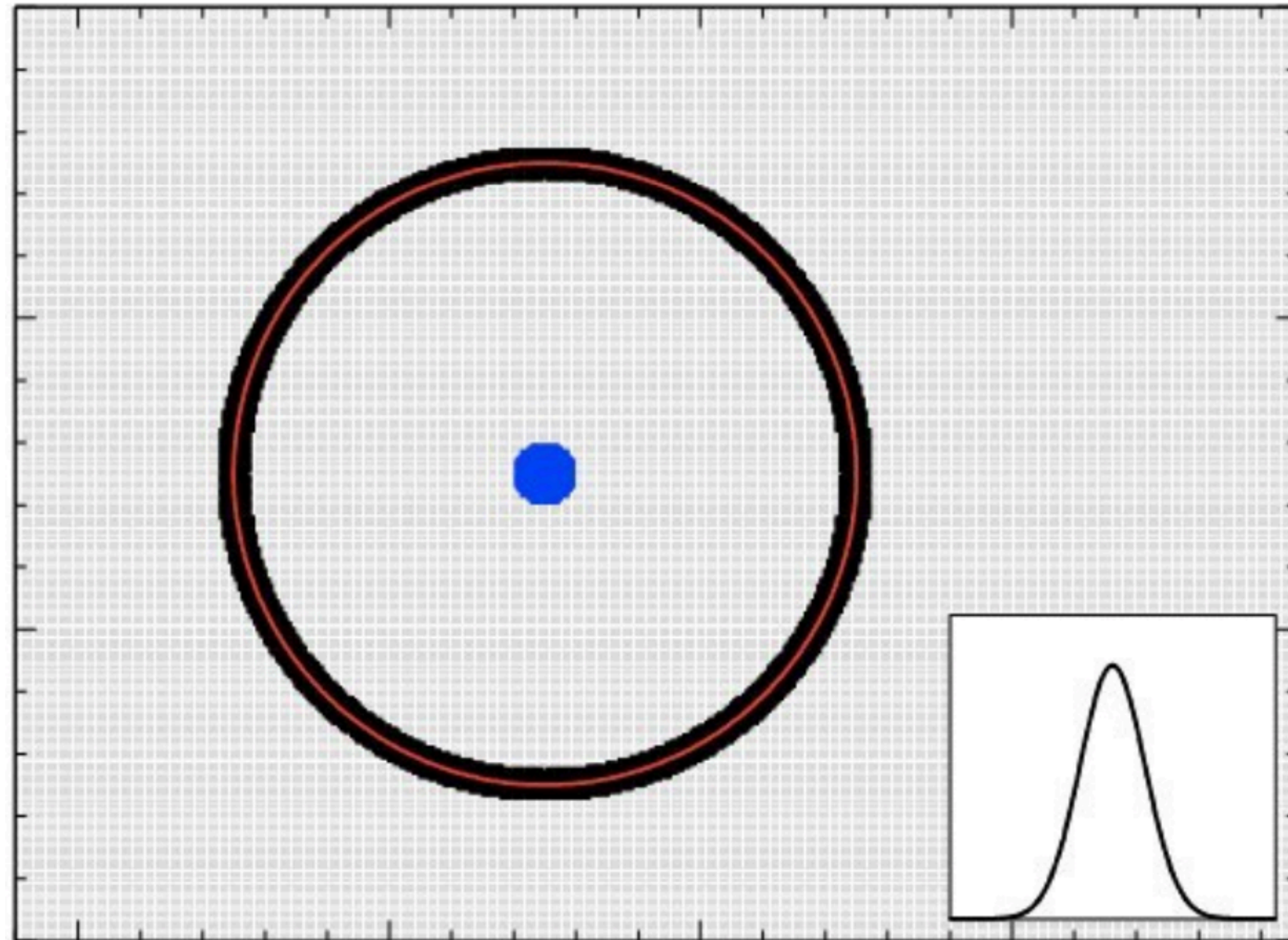
$$\text{just } \alpha_{\text{iso}} = \left(\alpha_{\perp}^2 \alpha_{\parallel} \right)^{1/3} \text{ (if SNR is low)}$$



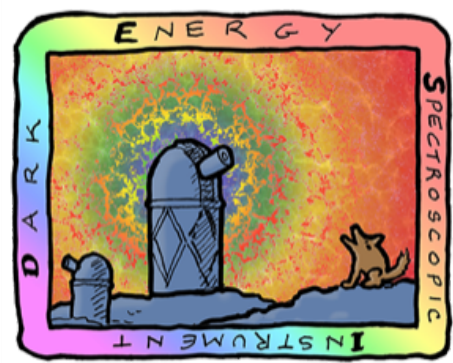
DARK ENERGY
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BAO reconstruction



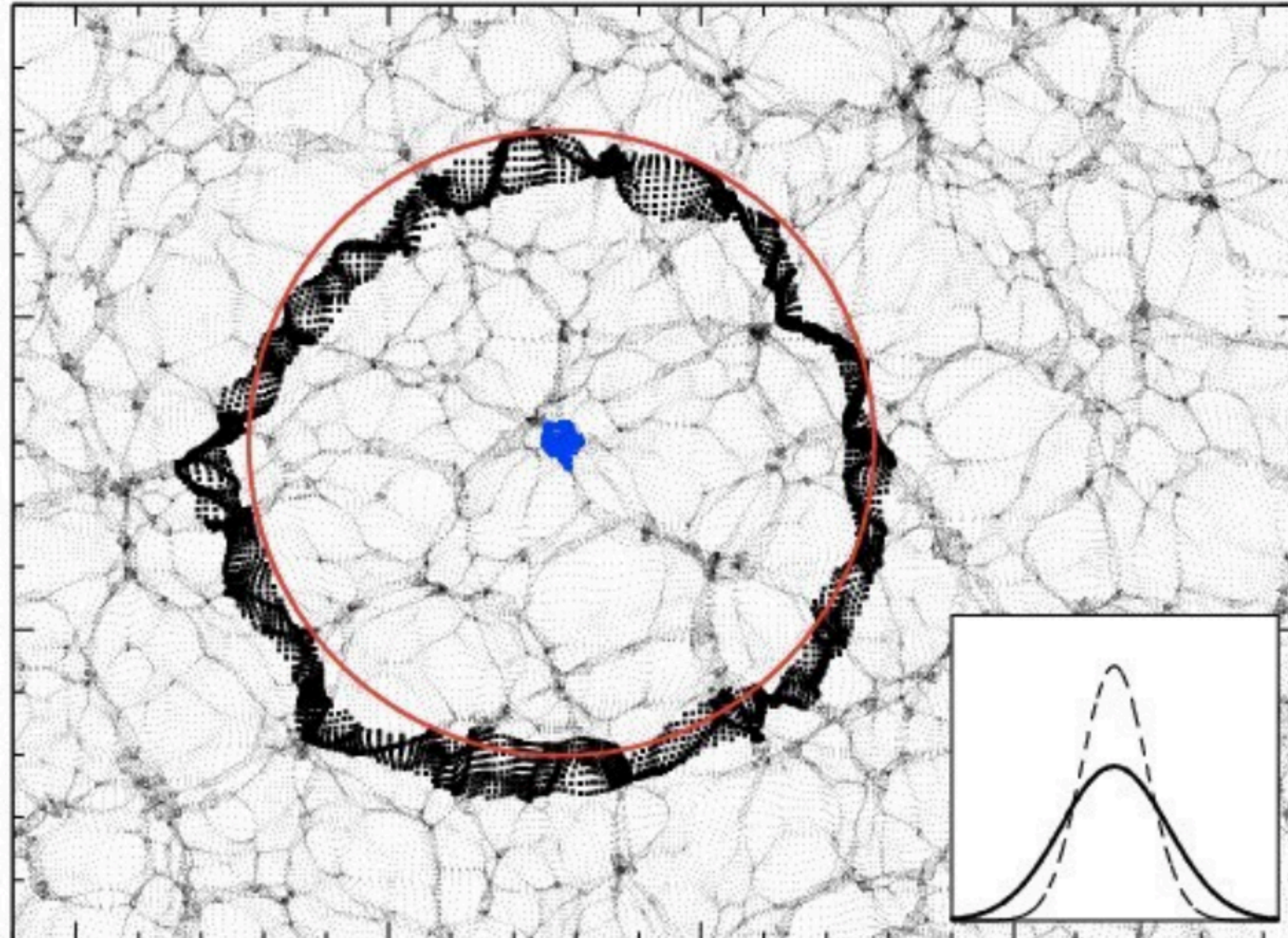
Eisenstein+ 2008,
Padmanabhan+ 2012



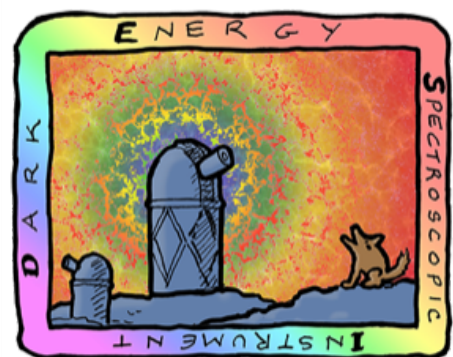
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BAO reconstruction



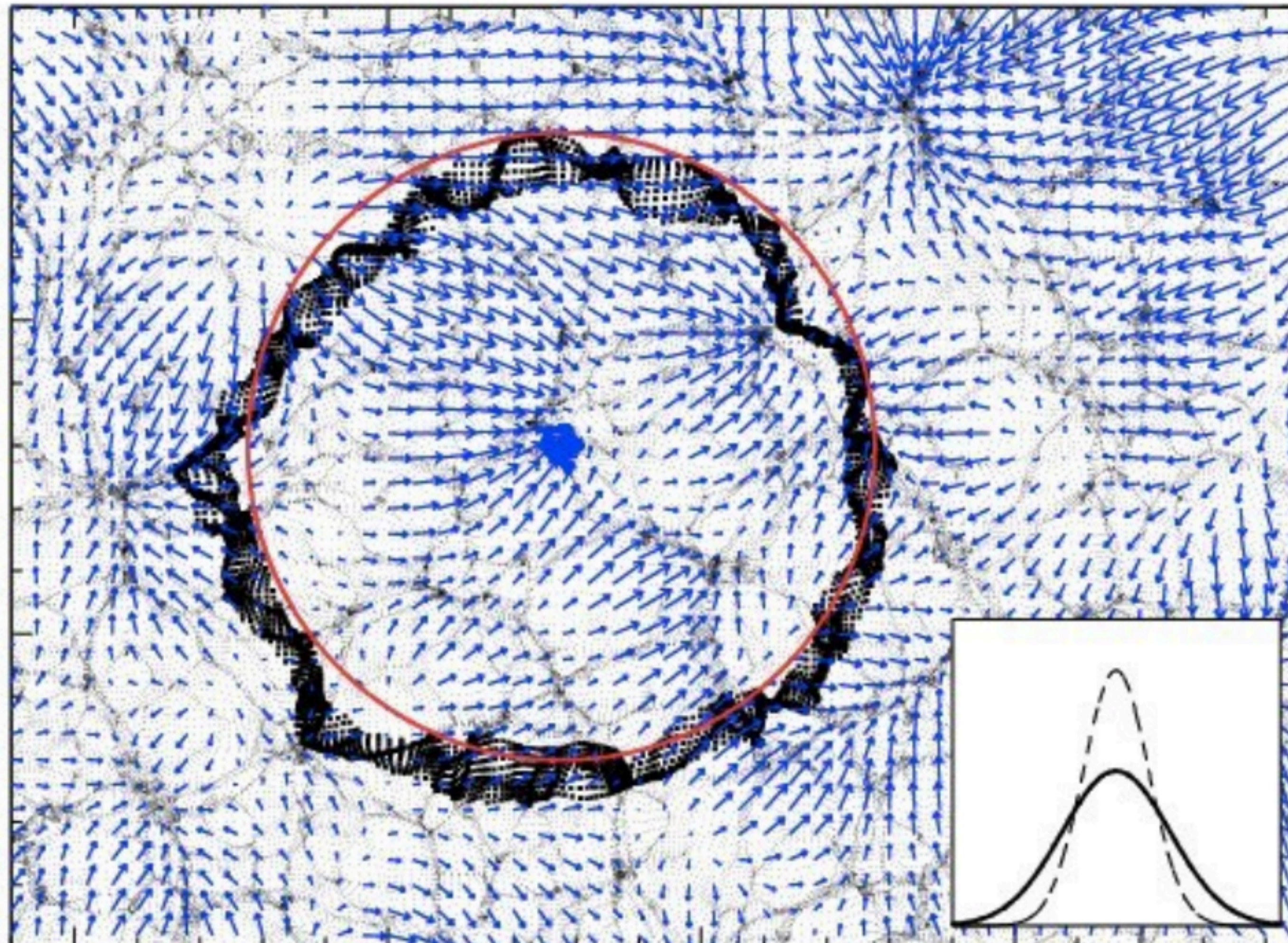
Eisenstein+ 2008,
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DARK ENERGY
SPECTROSCOPIC
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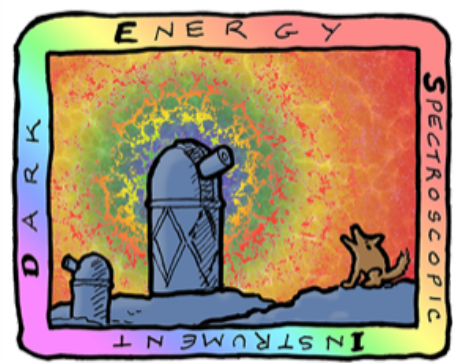
U.S. Department of Energy Office of Science

BAO reconstruction



**Zeldovich
displacement
Field**

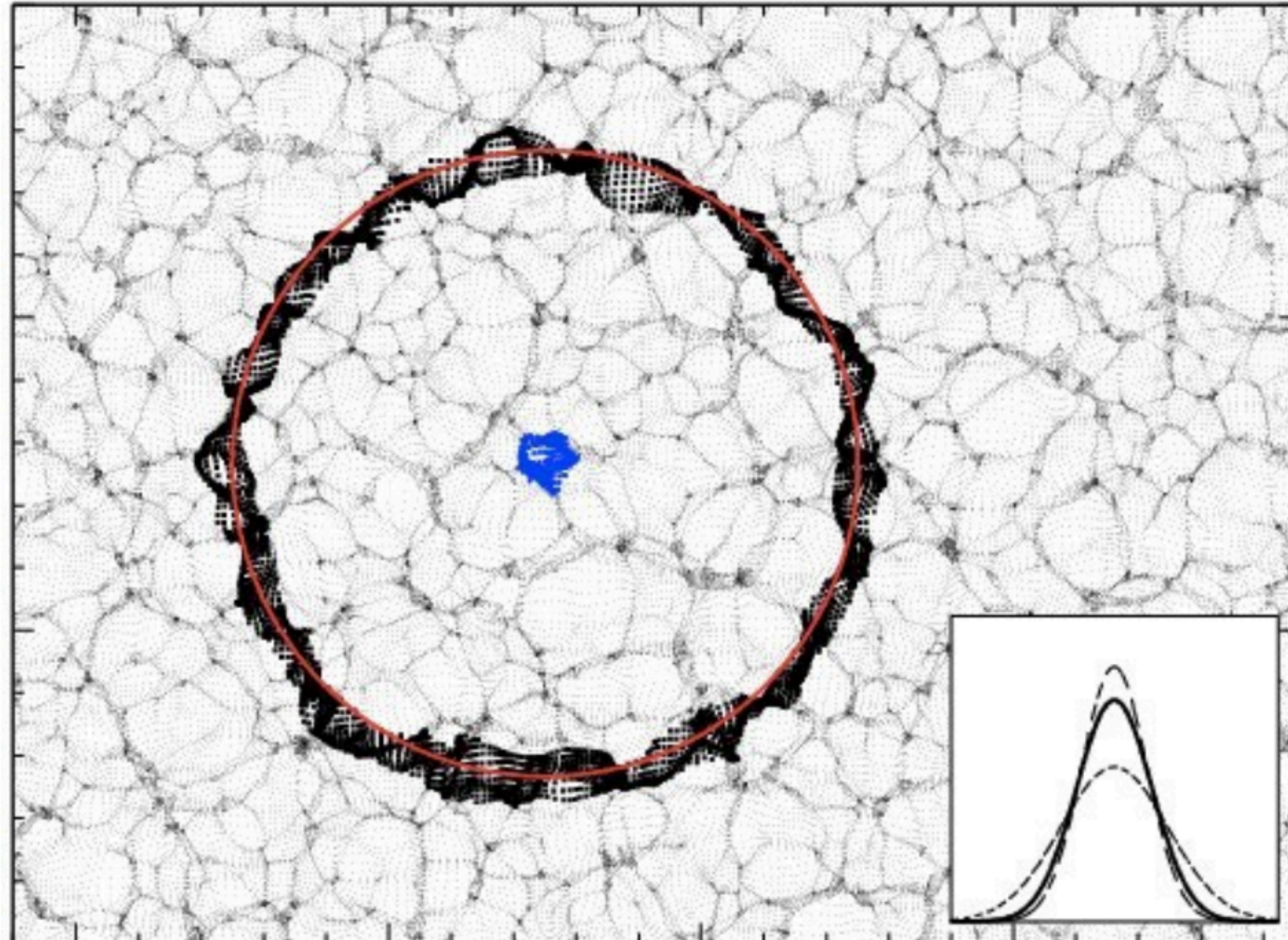
Eisenstein+ 2008,
Padmanabhan+ 2012



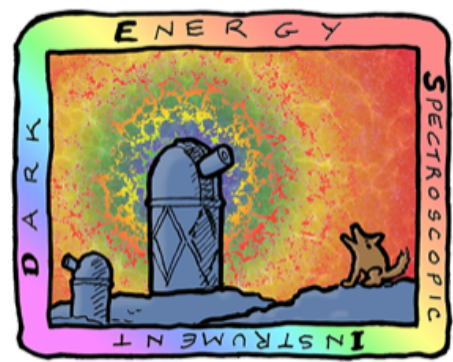
DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

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BAO reconstruction



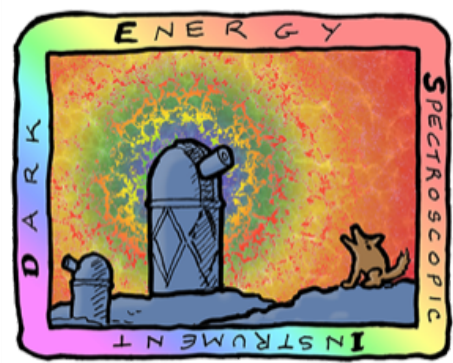
Eisenstein+ 2008,
Padmanabhan+ 2012



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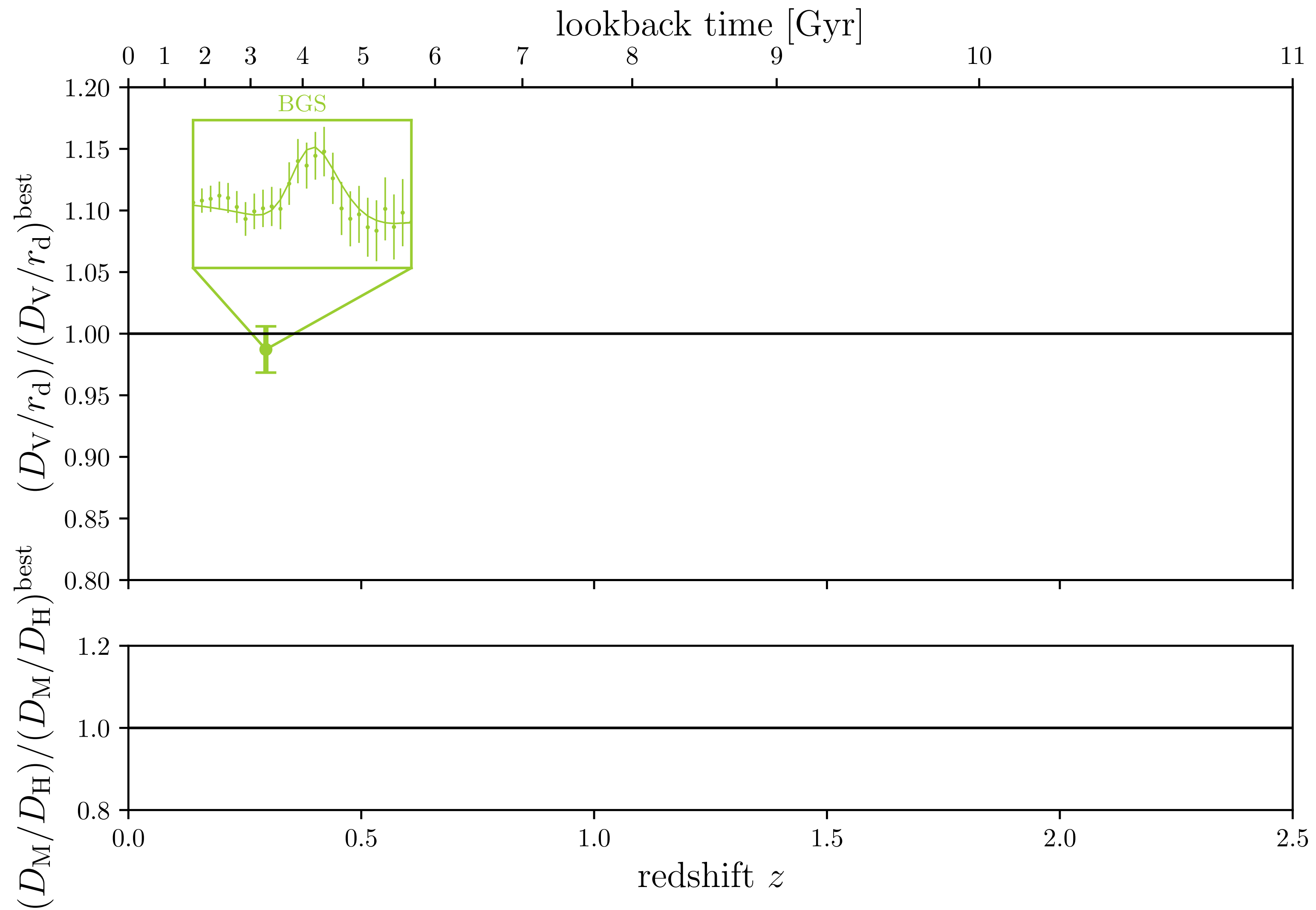
Cosmological results

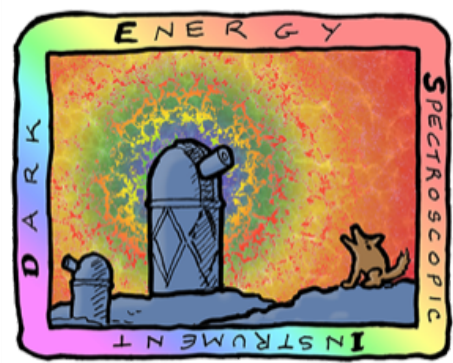


DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

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BAO scale

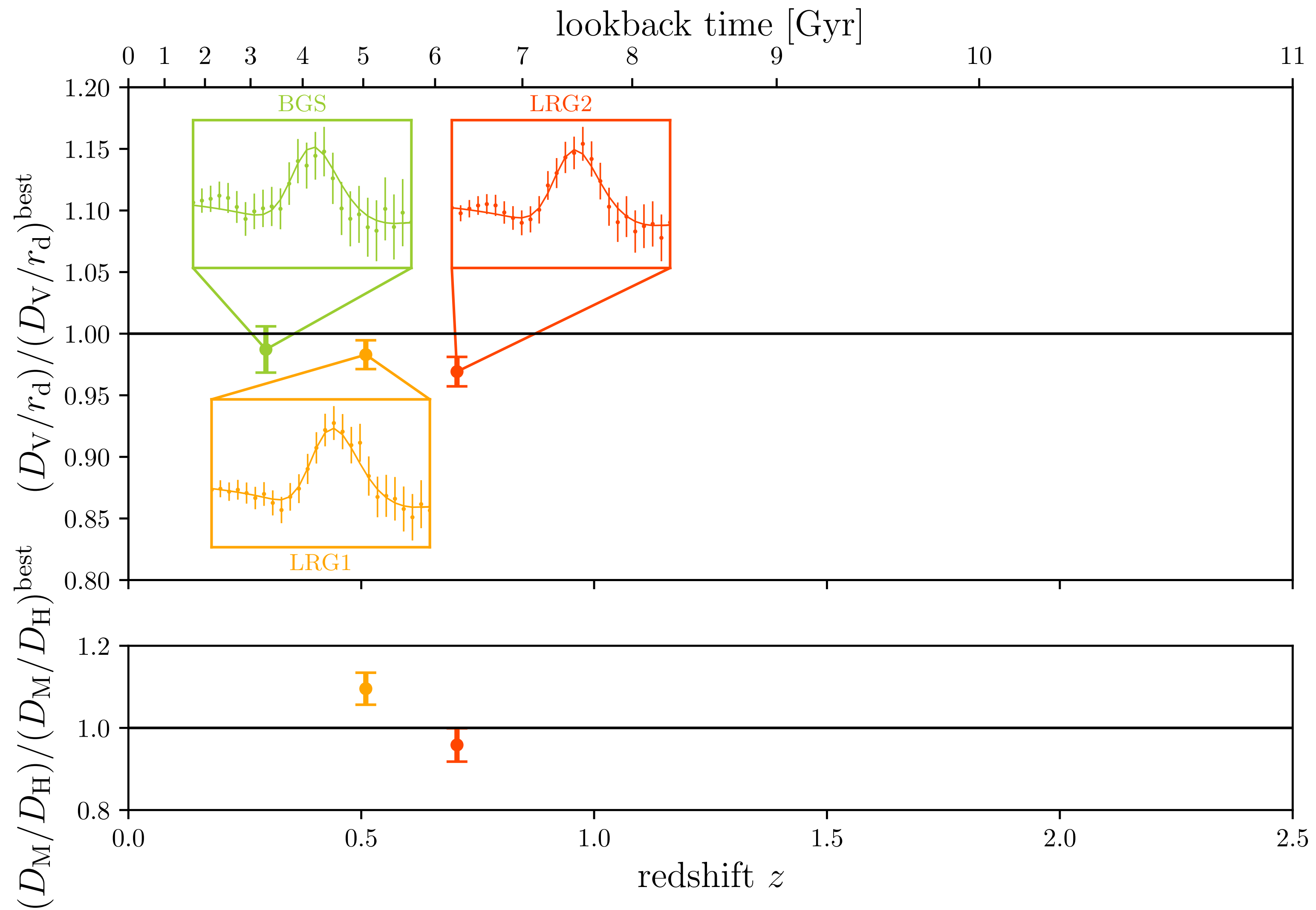


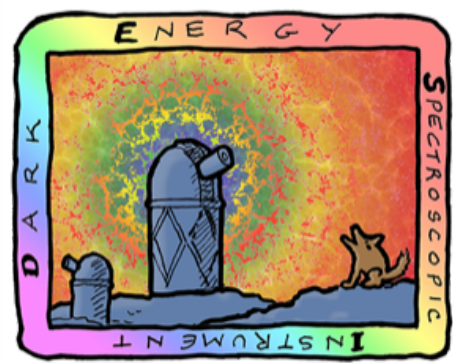


DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

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BAO scale

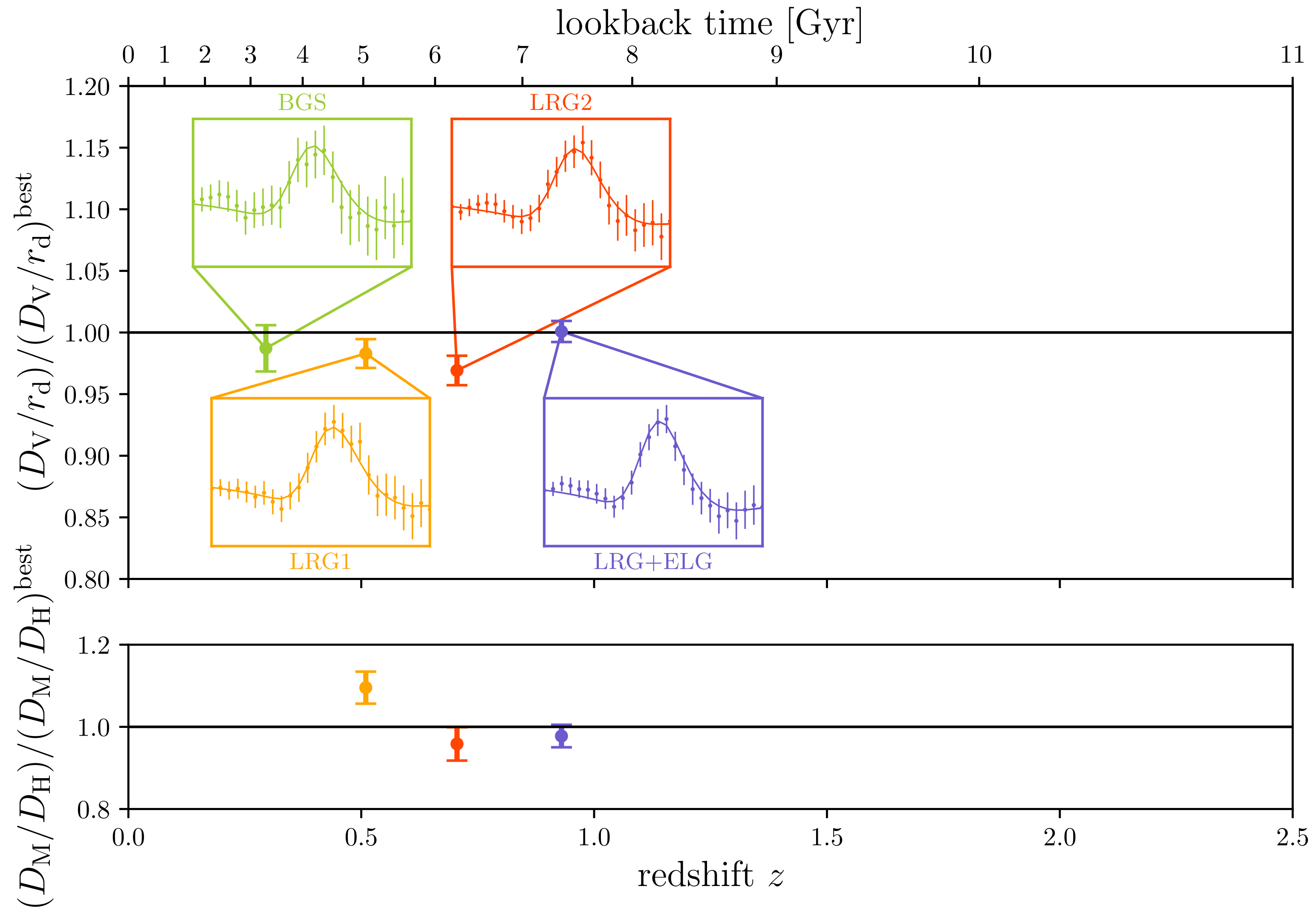


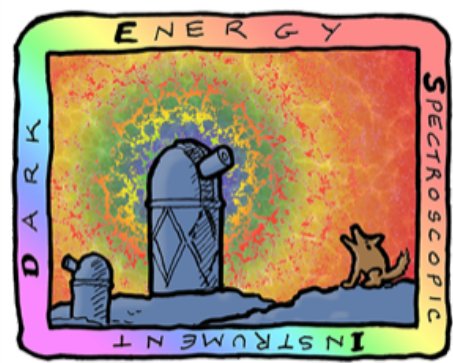


DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

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BAO scale

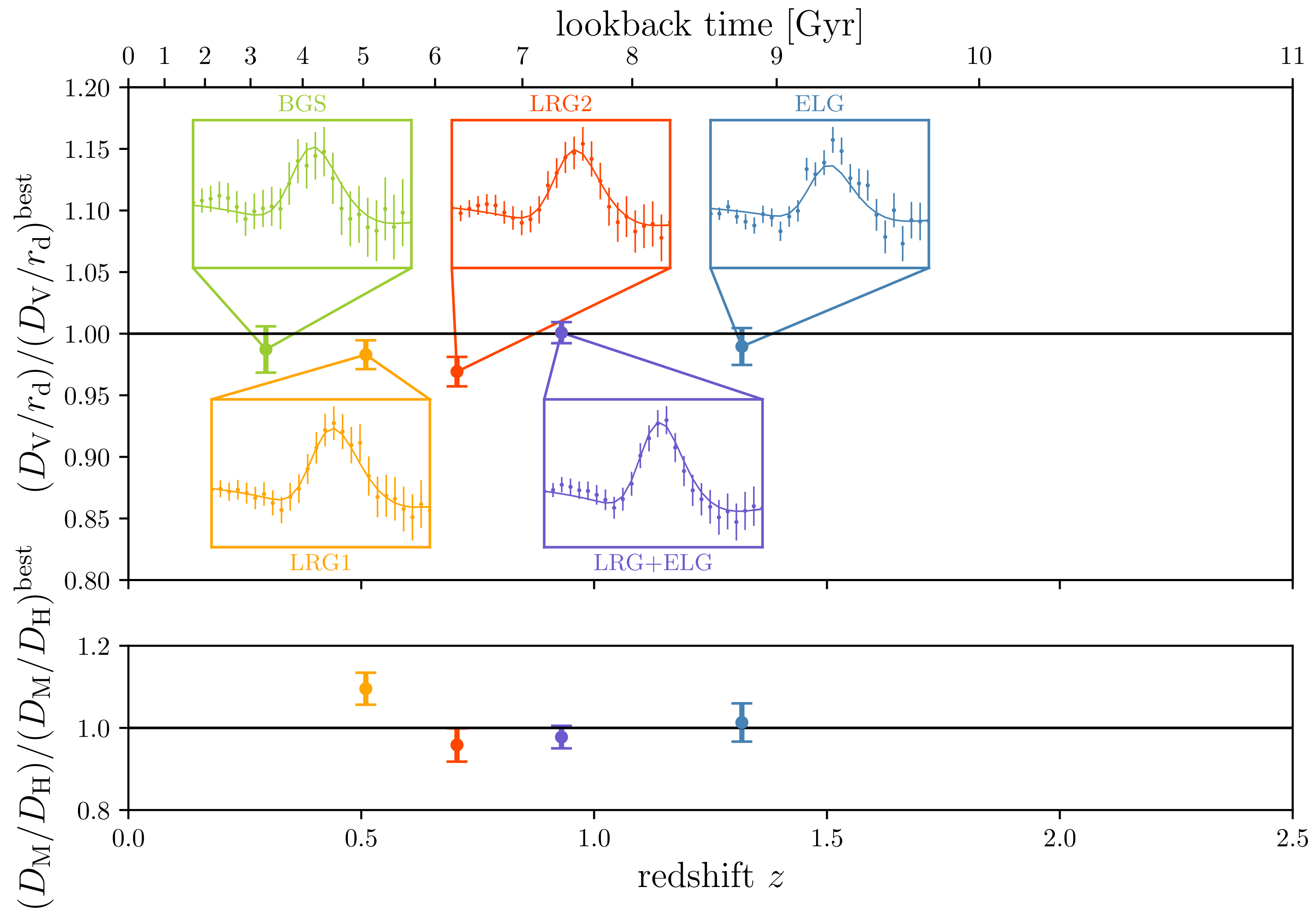


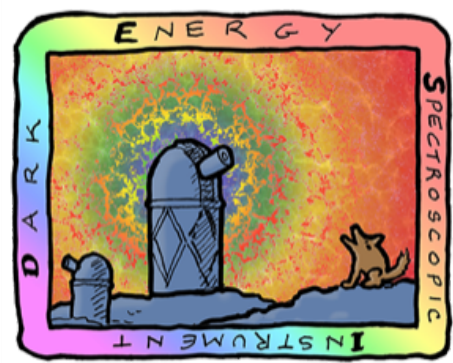


DARK ENERGY
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INSTRUMENT

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BAO scale

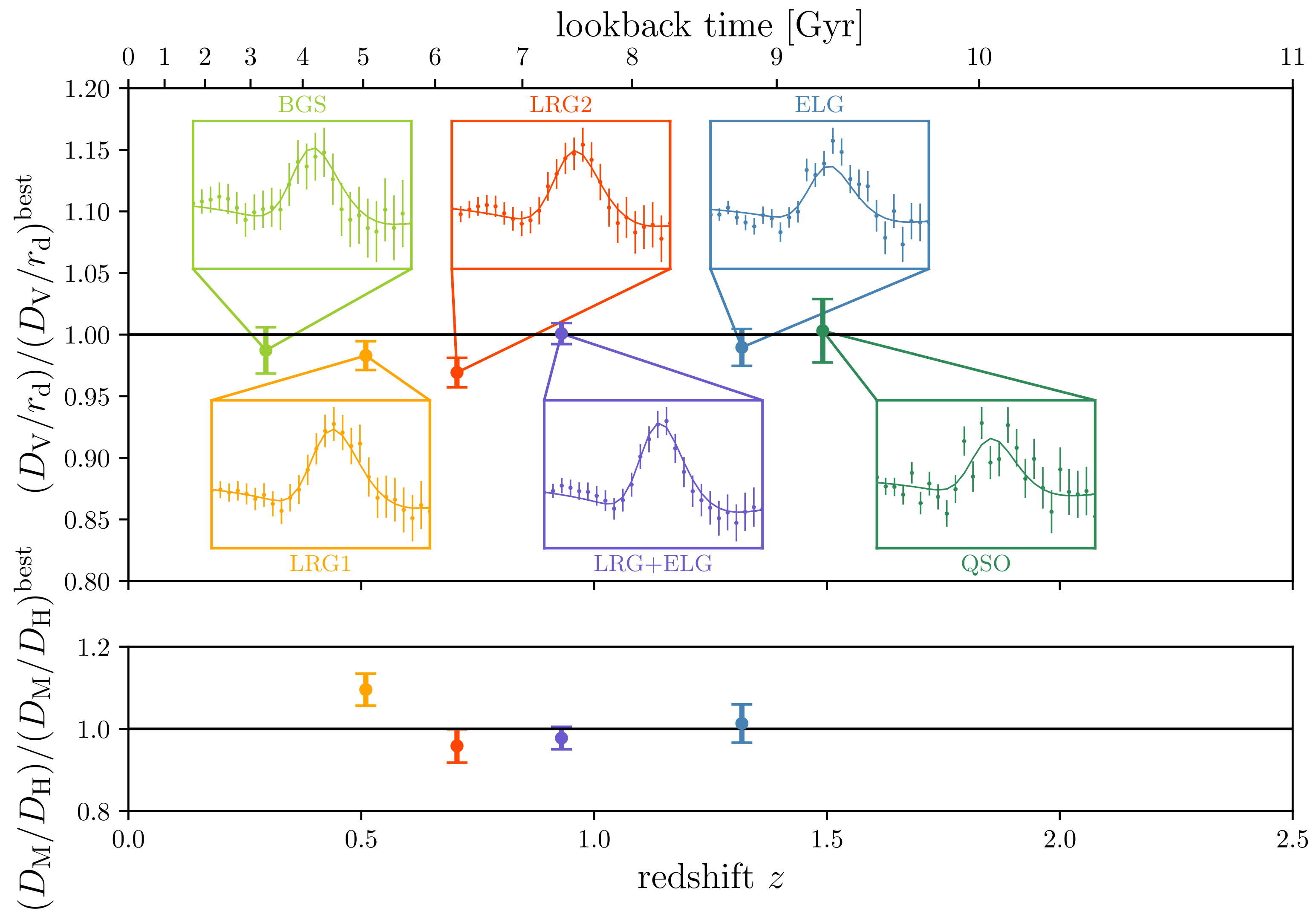


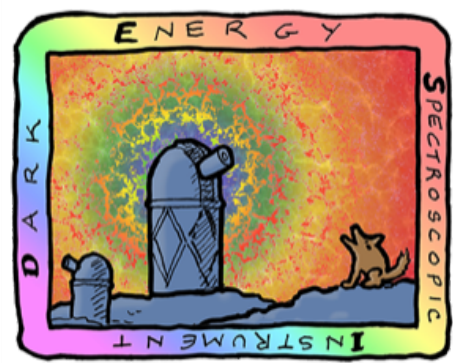


DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

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BAO scale

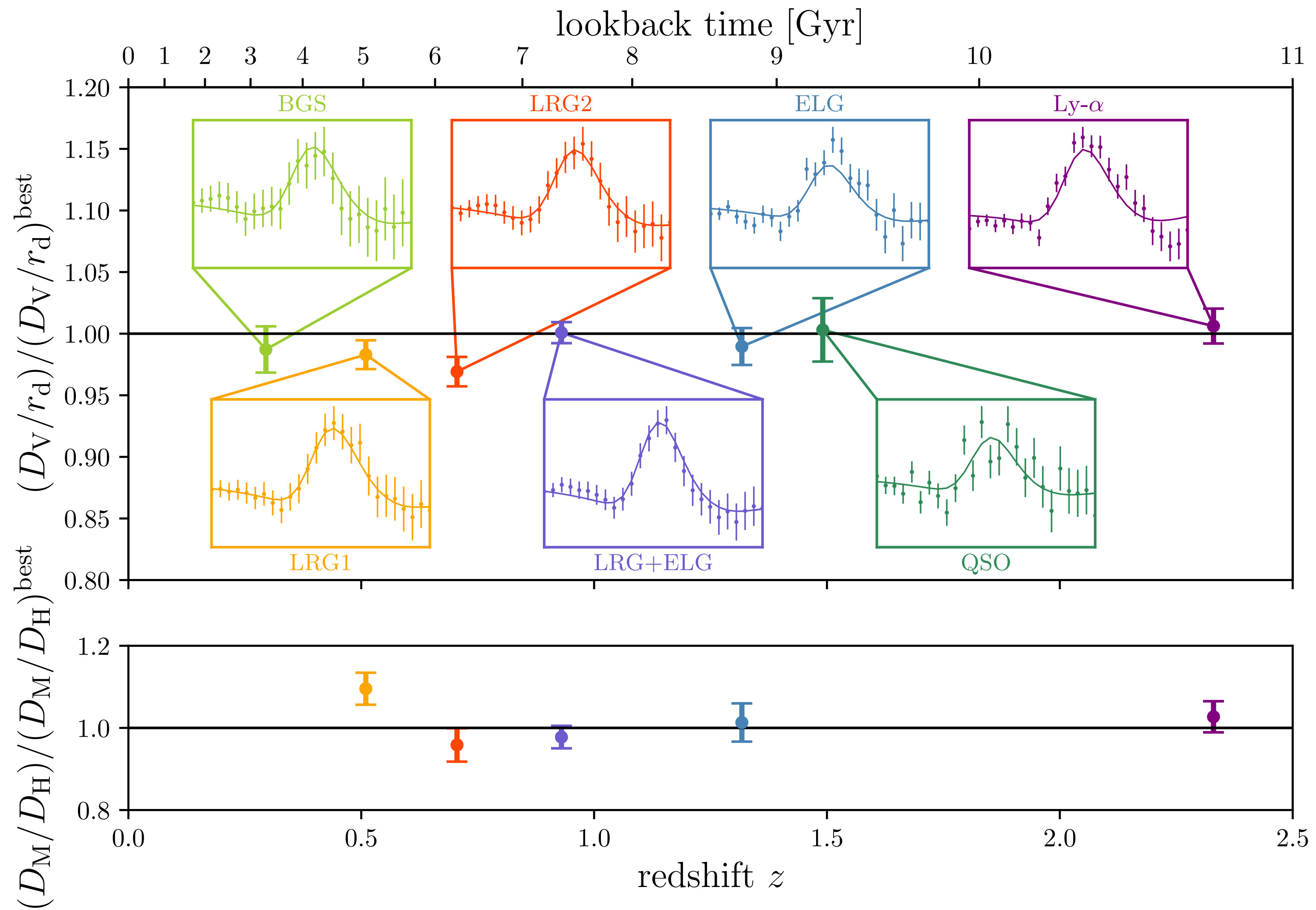


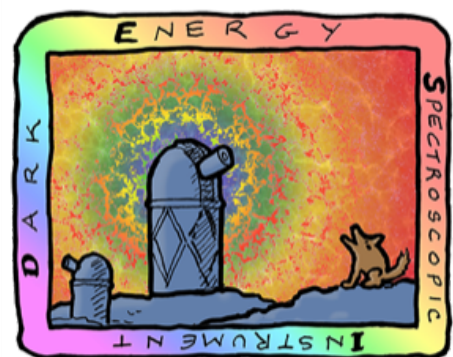


DARK ENERGY
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INSTRUMENT

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BAO scale

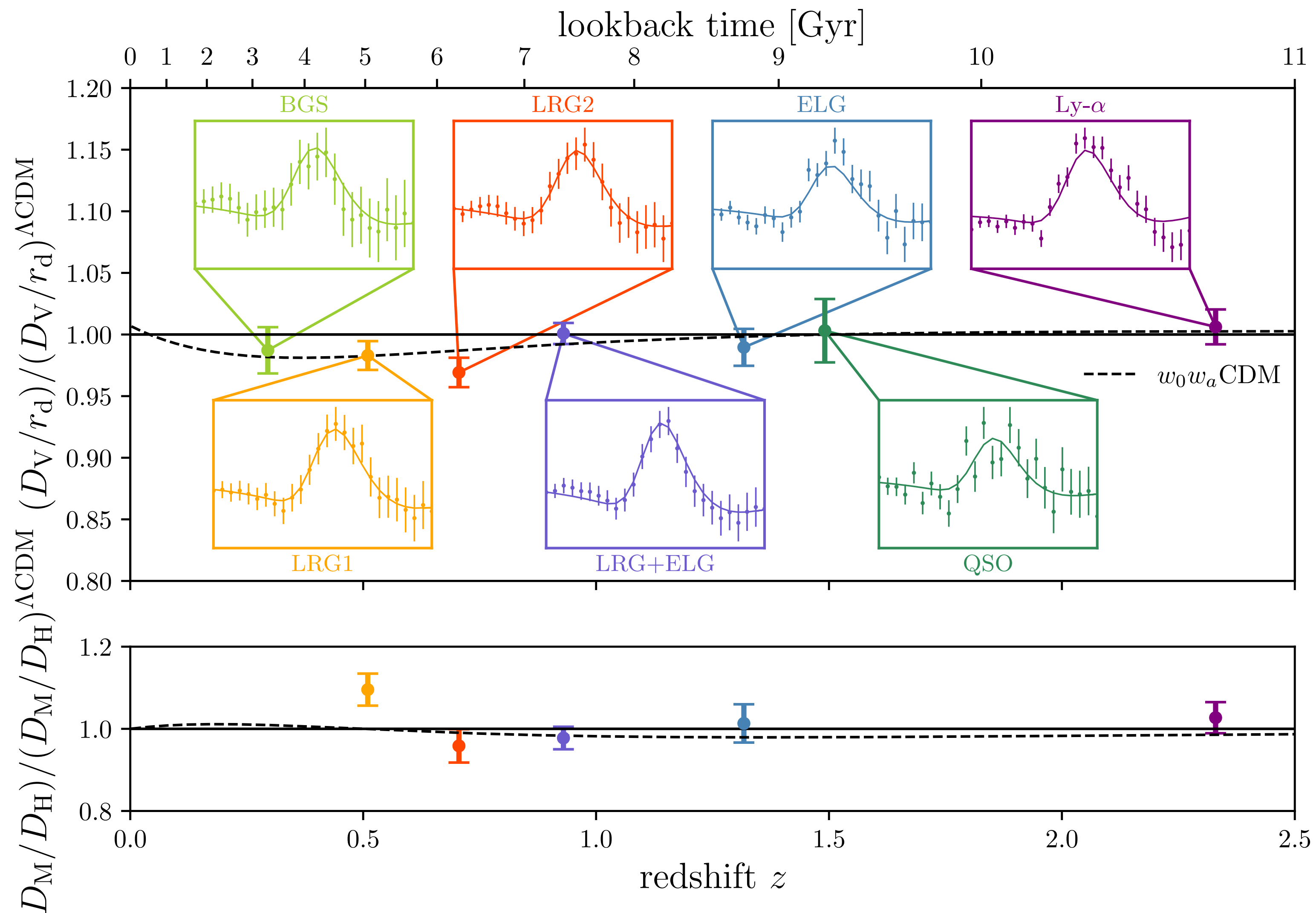


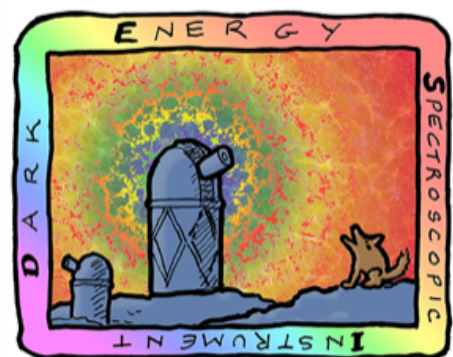


DARK ENERGY
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BAO scale





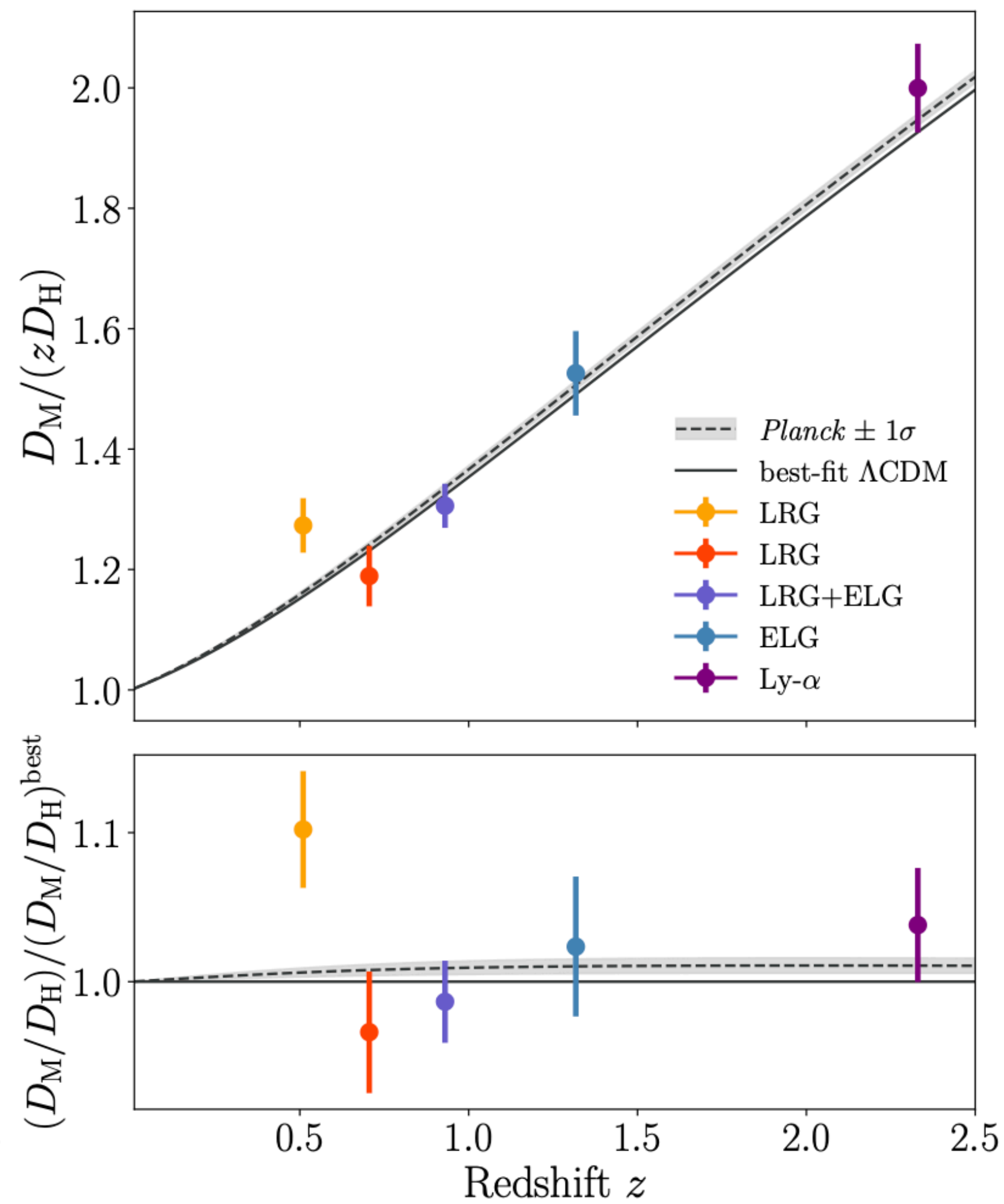
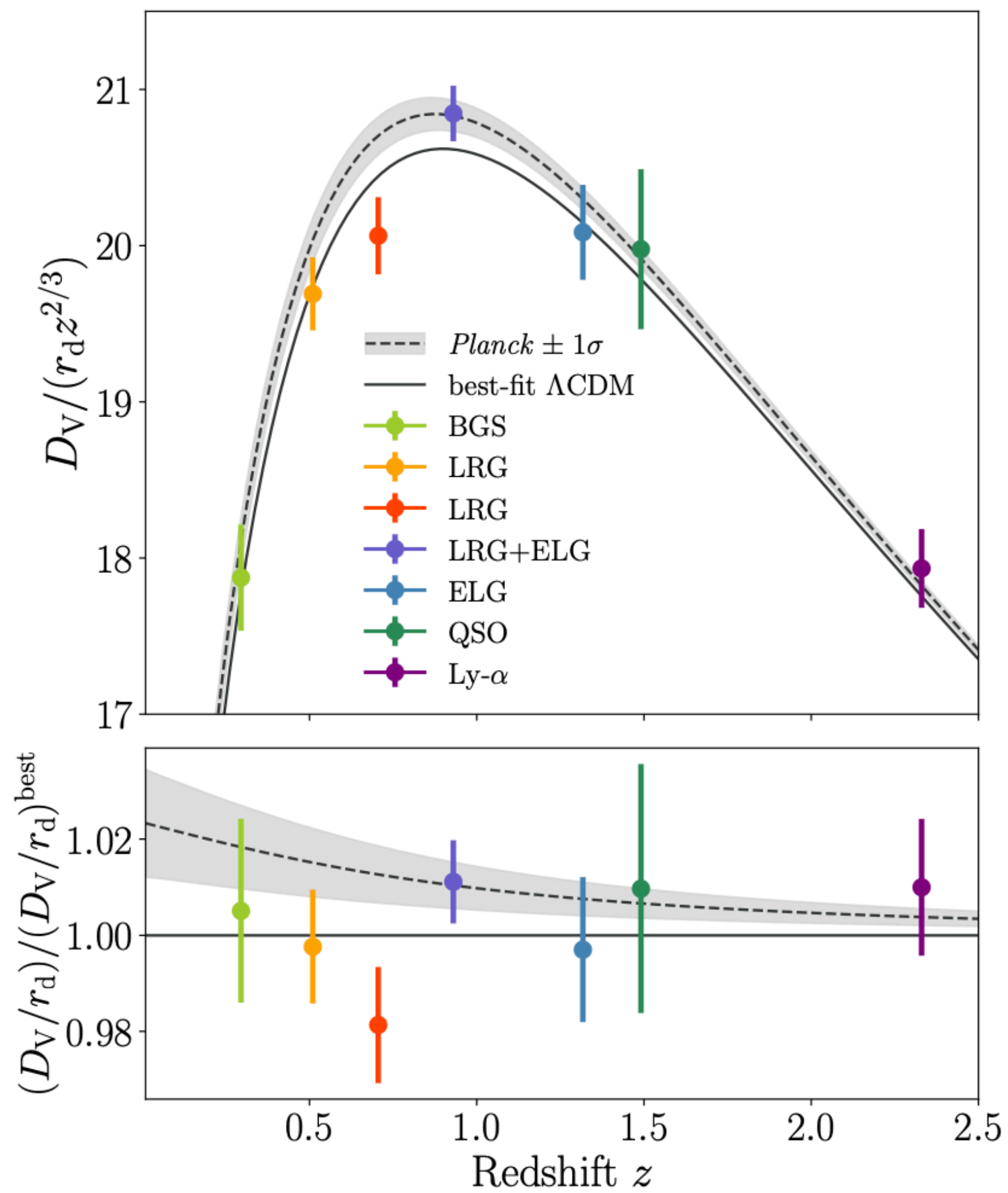
DARK ENERGY
SPECTROSCOPIC
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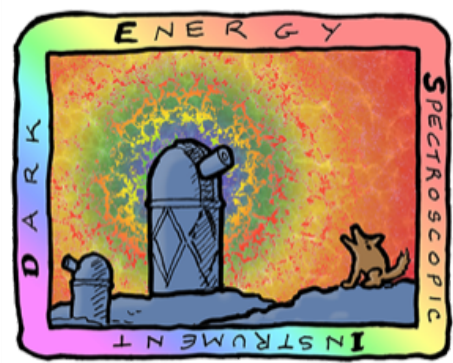
BAO scale



Overall size



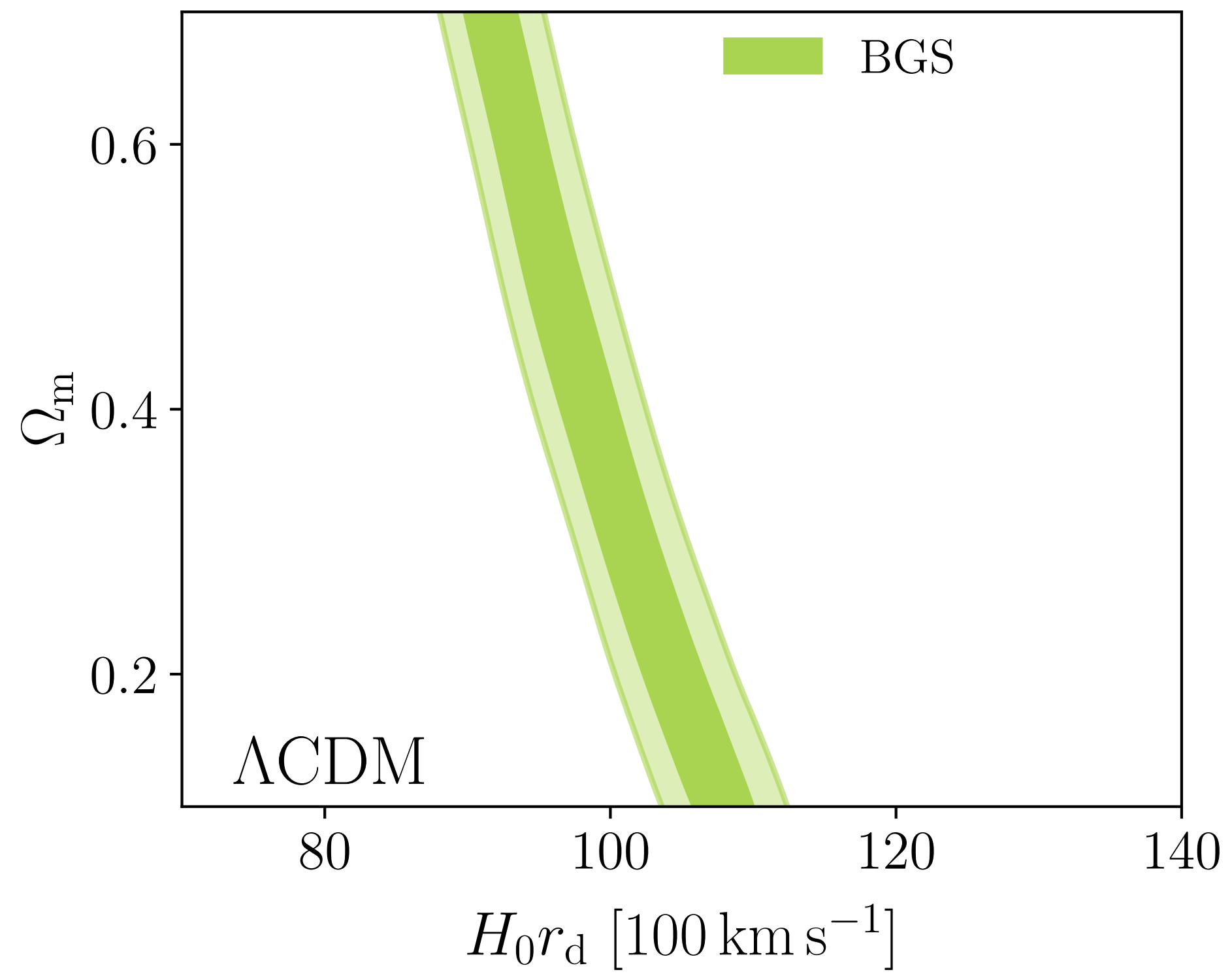
Anisotropy

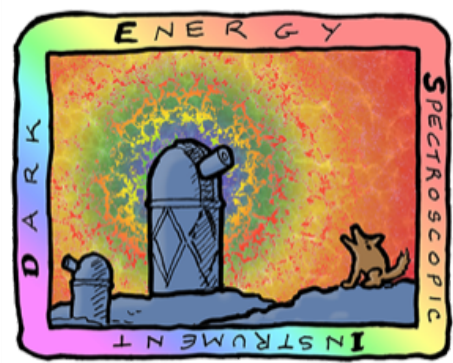


DARK ENERGY
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Cosmological parameters

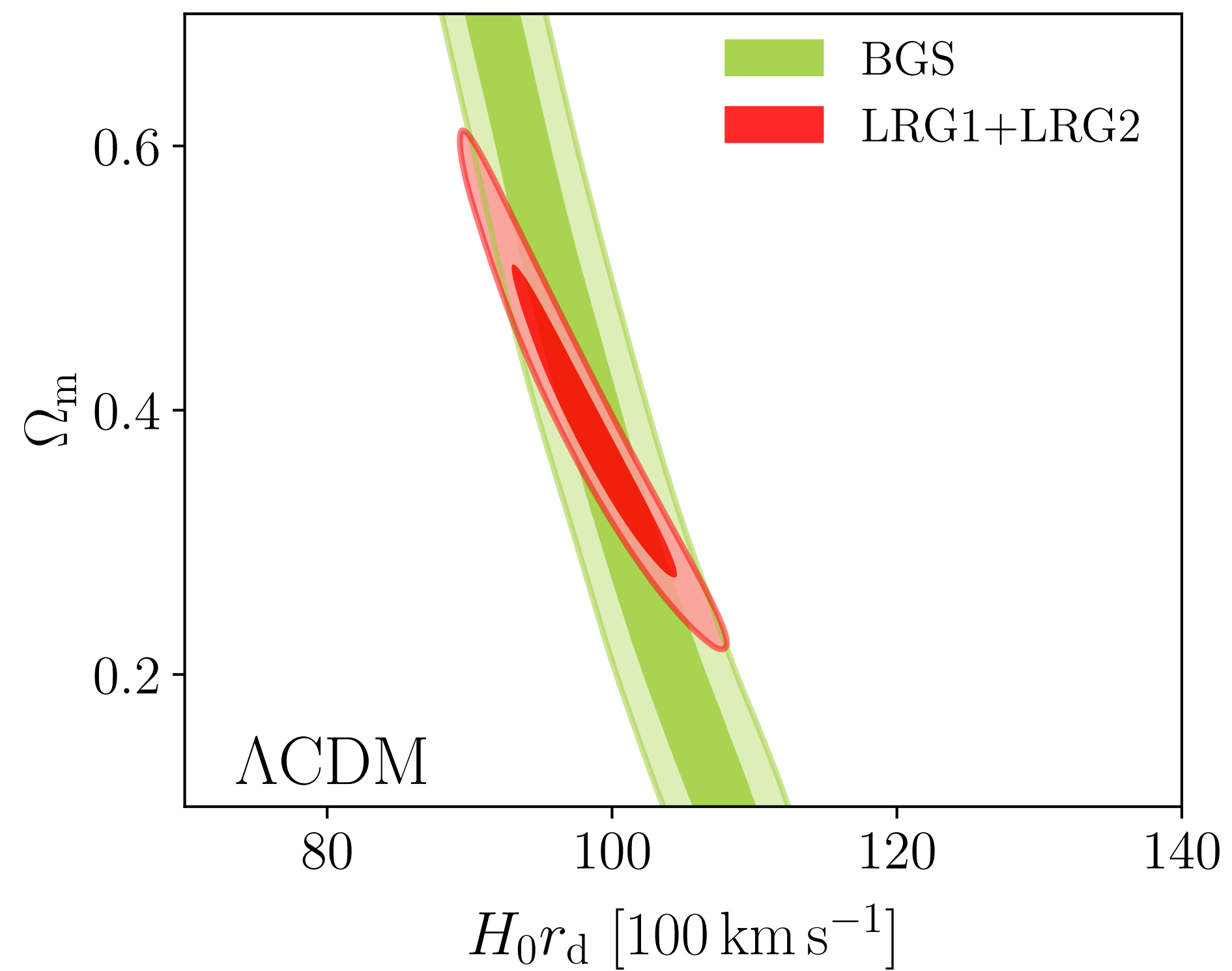


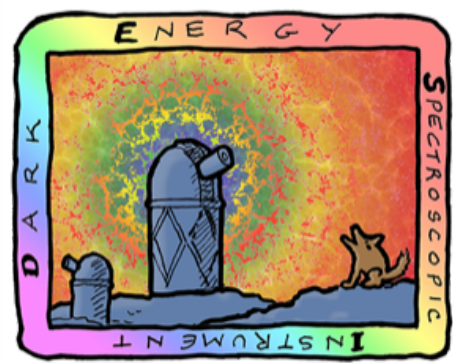


DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

Cosmological parameters

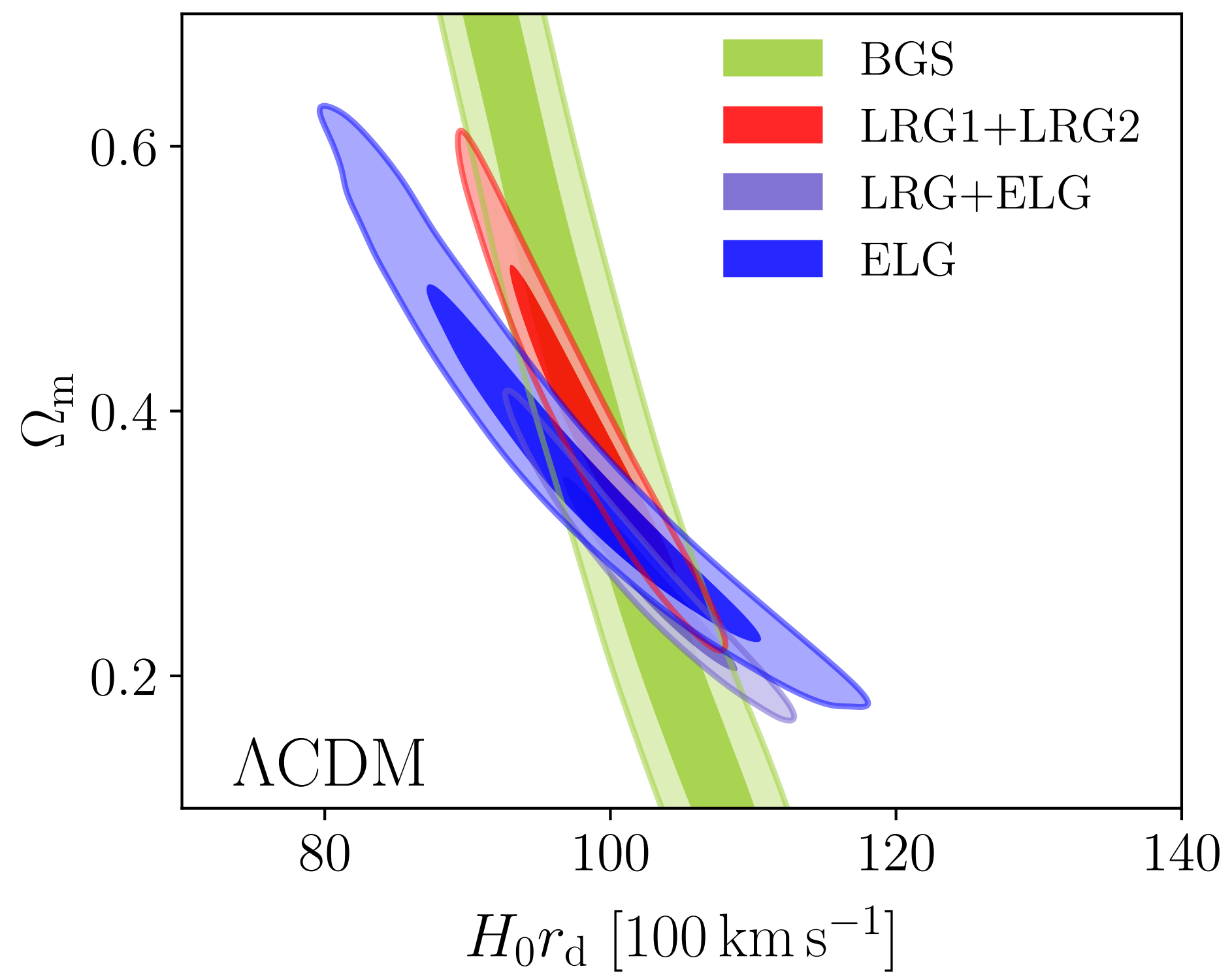


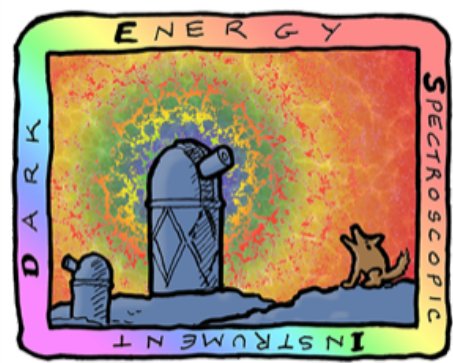


DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

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Cosmological parameters

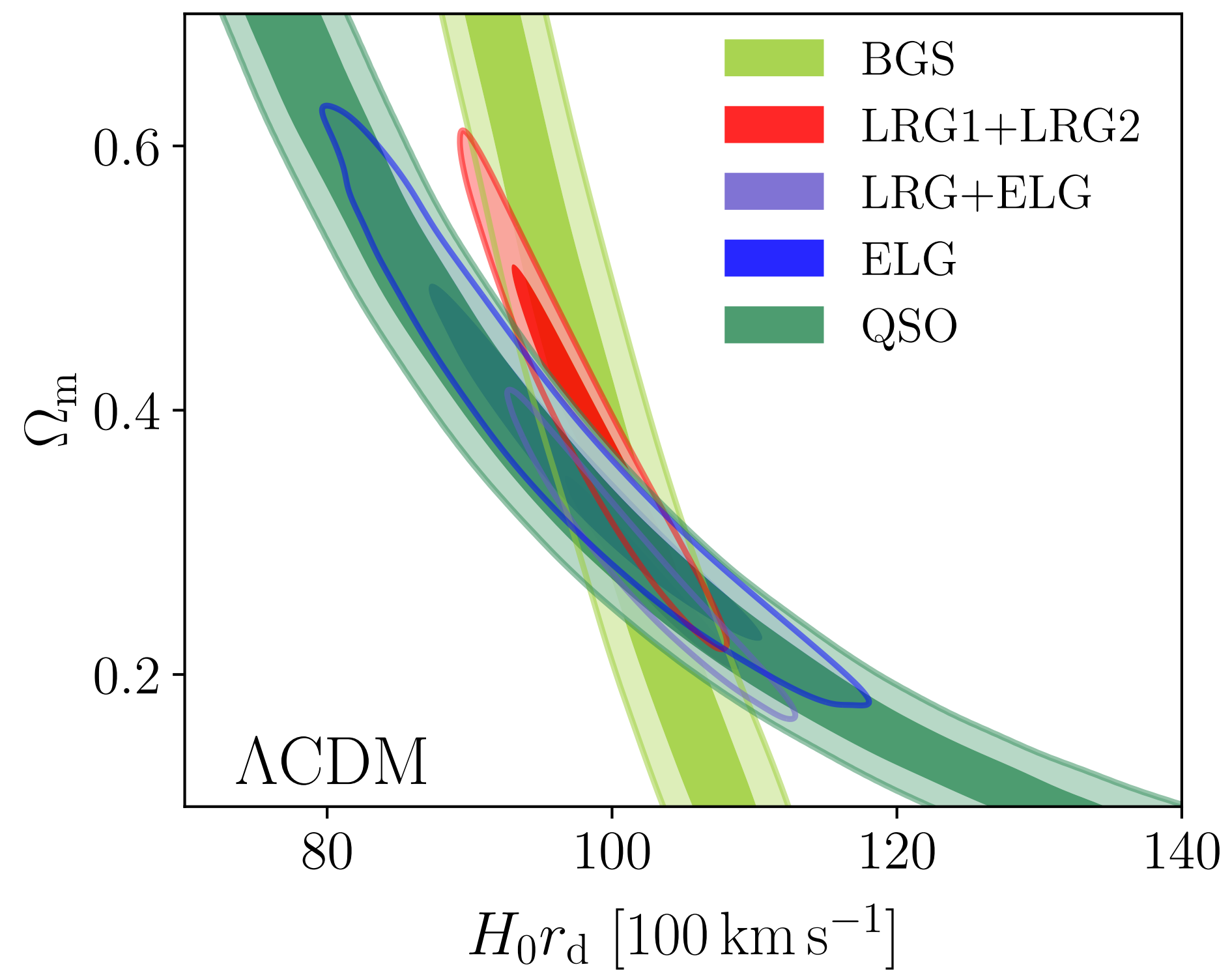


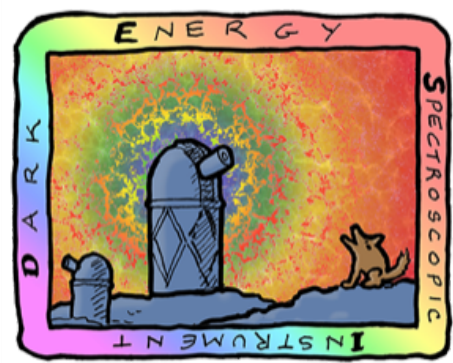


DARK ENERGY
SPECTROSCOPIC
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Cosmological parameters

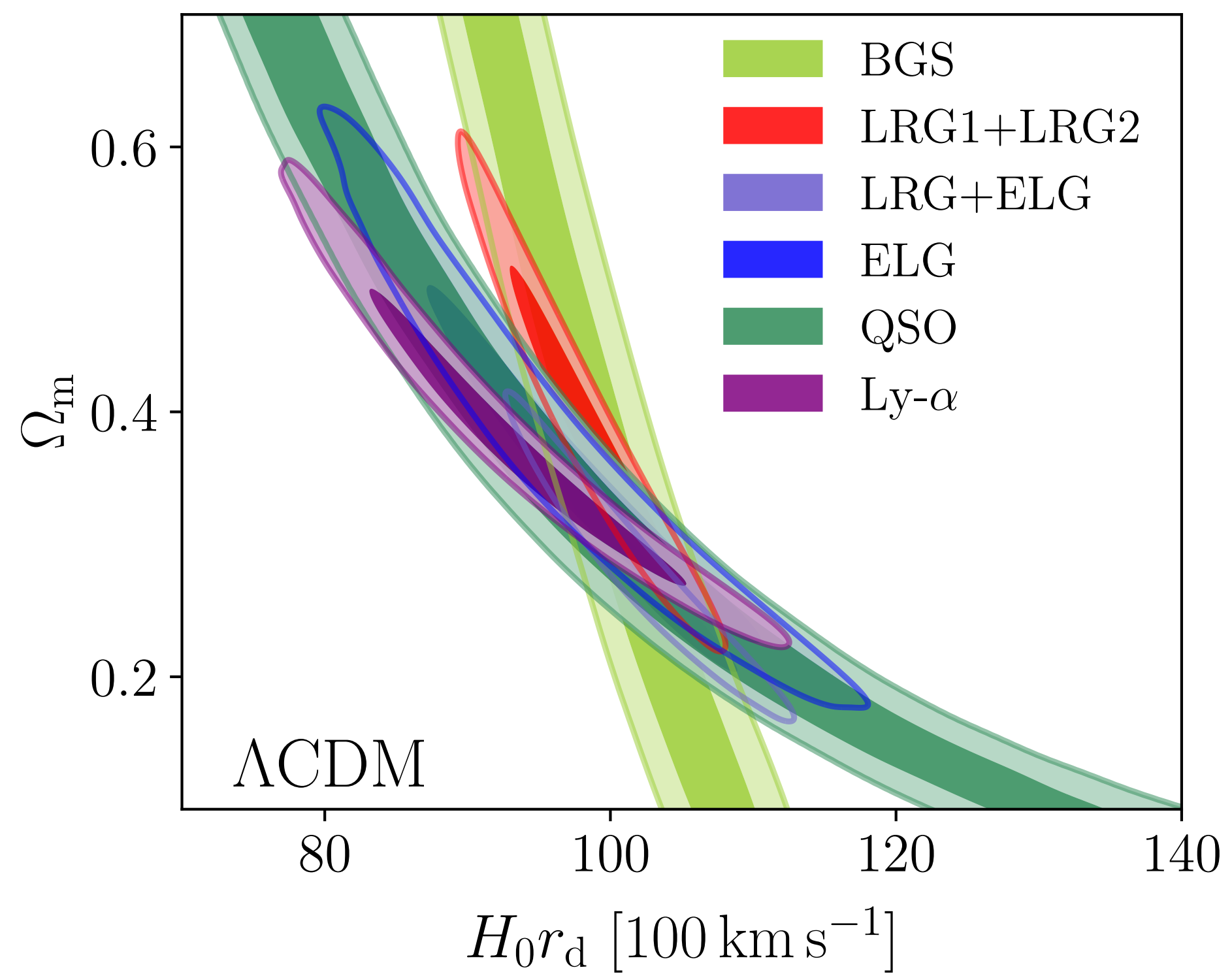


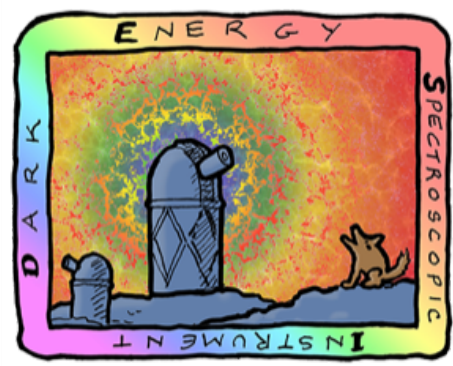


DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

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Cosmological parameters

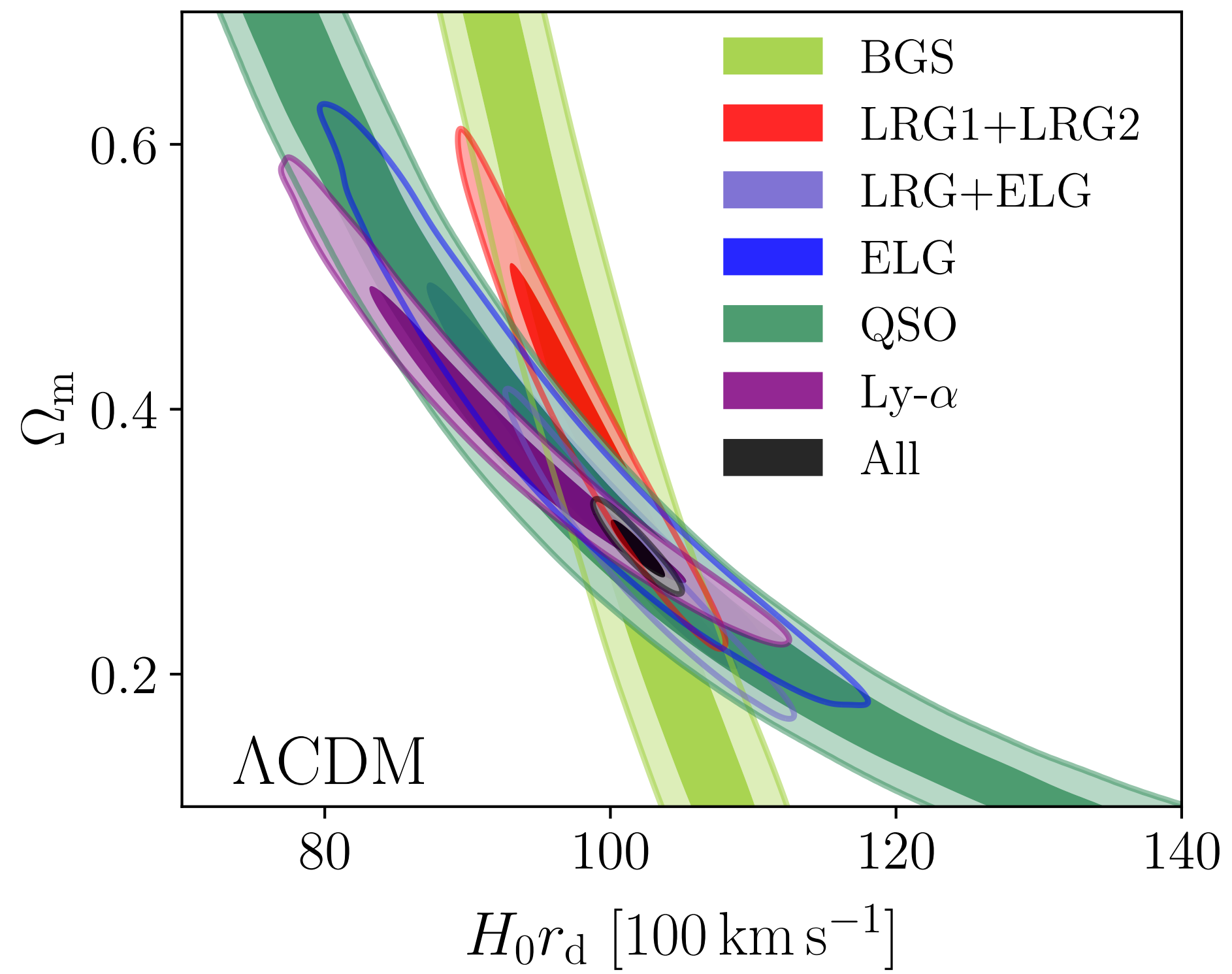


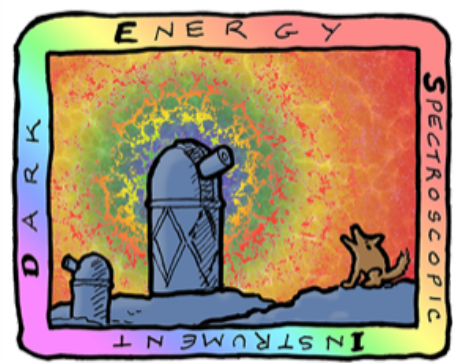


DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

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Cosmological parameters

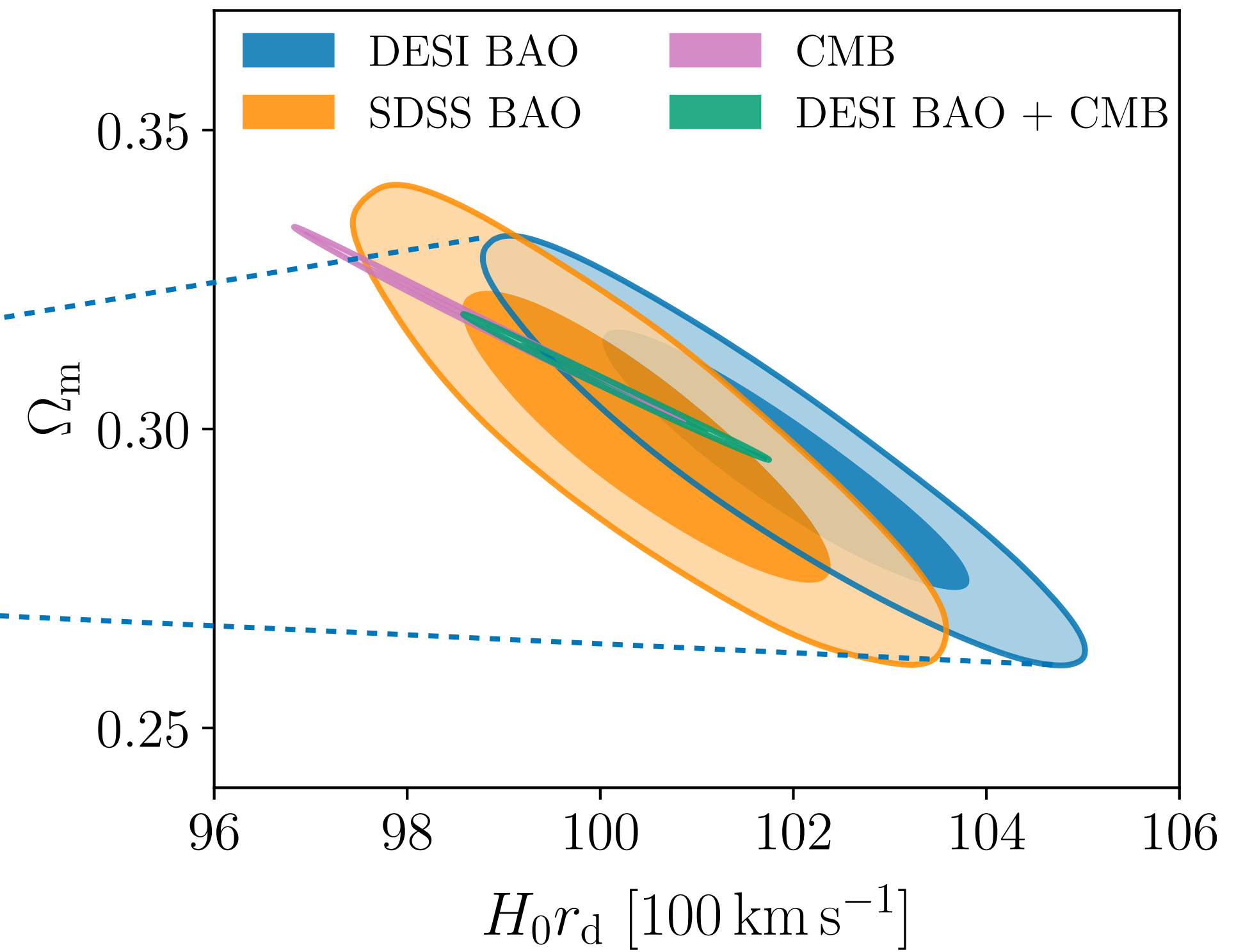
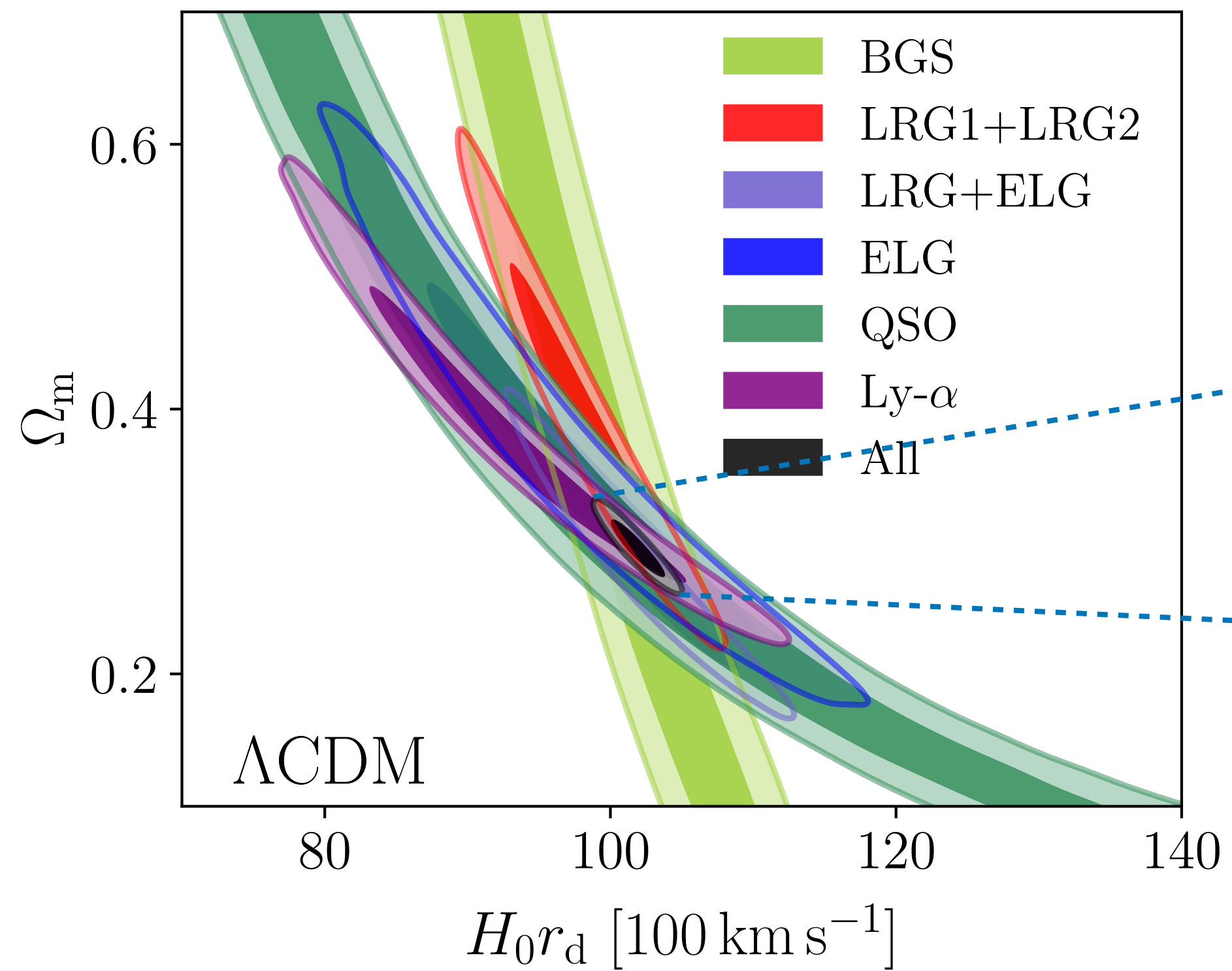


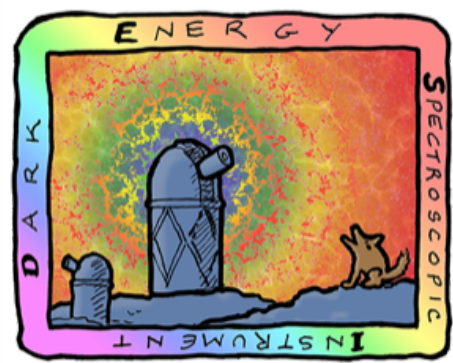


DARK ENERGY
SPECTROSCOPIC
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Cosmological parameters

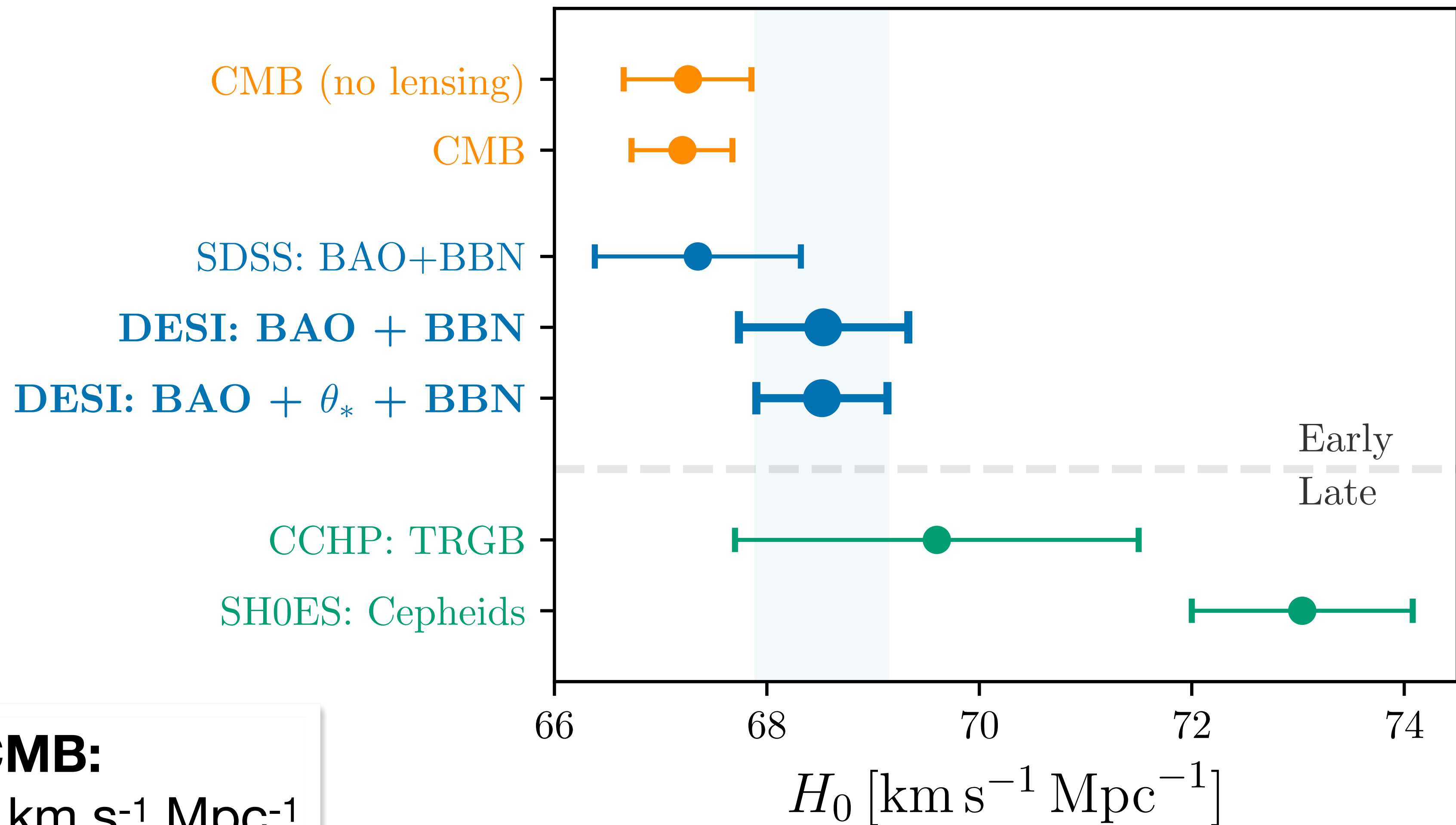




DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

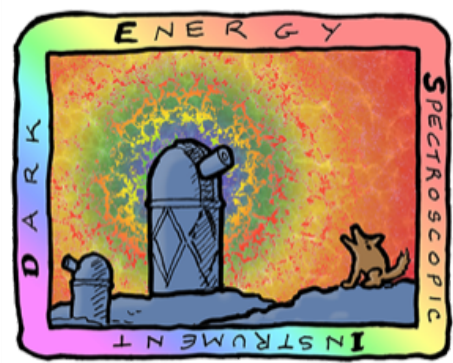
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Hubble tension



DESI + CMB:

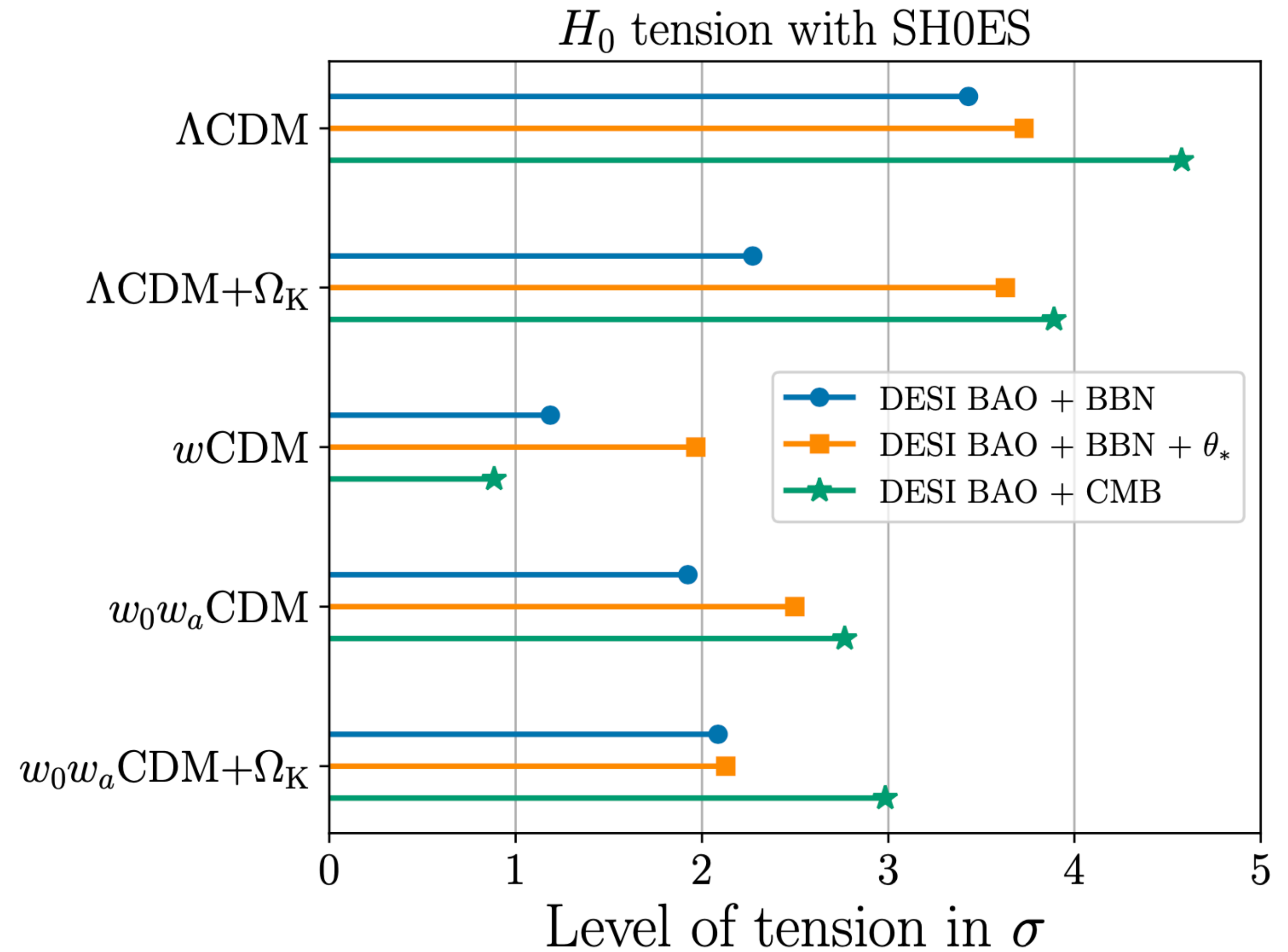
$$H_0 = 67.97 \pm 0.38 \text{ km s}^{-1} \text{ Mpc}^{-1}$$



DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

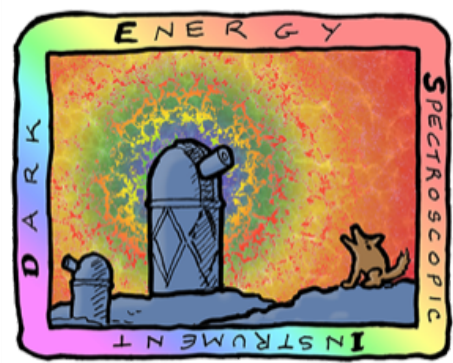
U.S. Department of Energy Office of Science

Hubble tension



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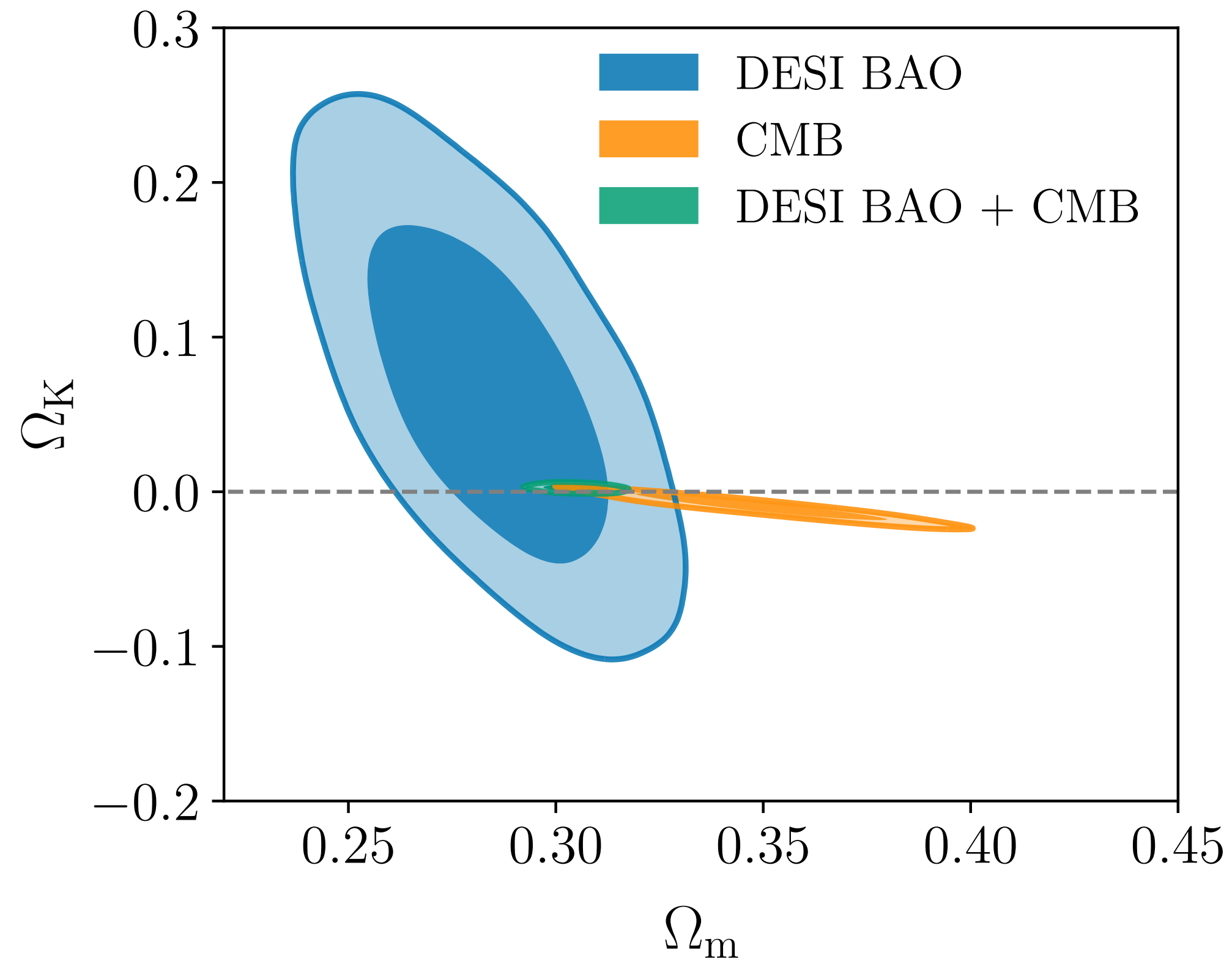


DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

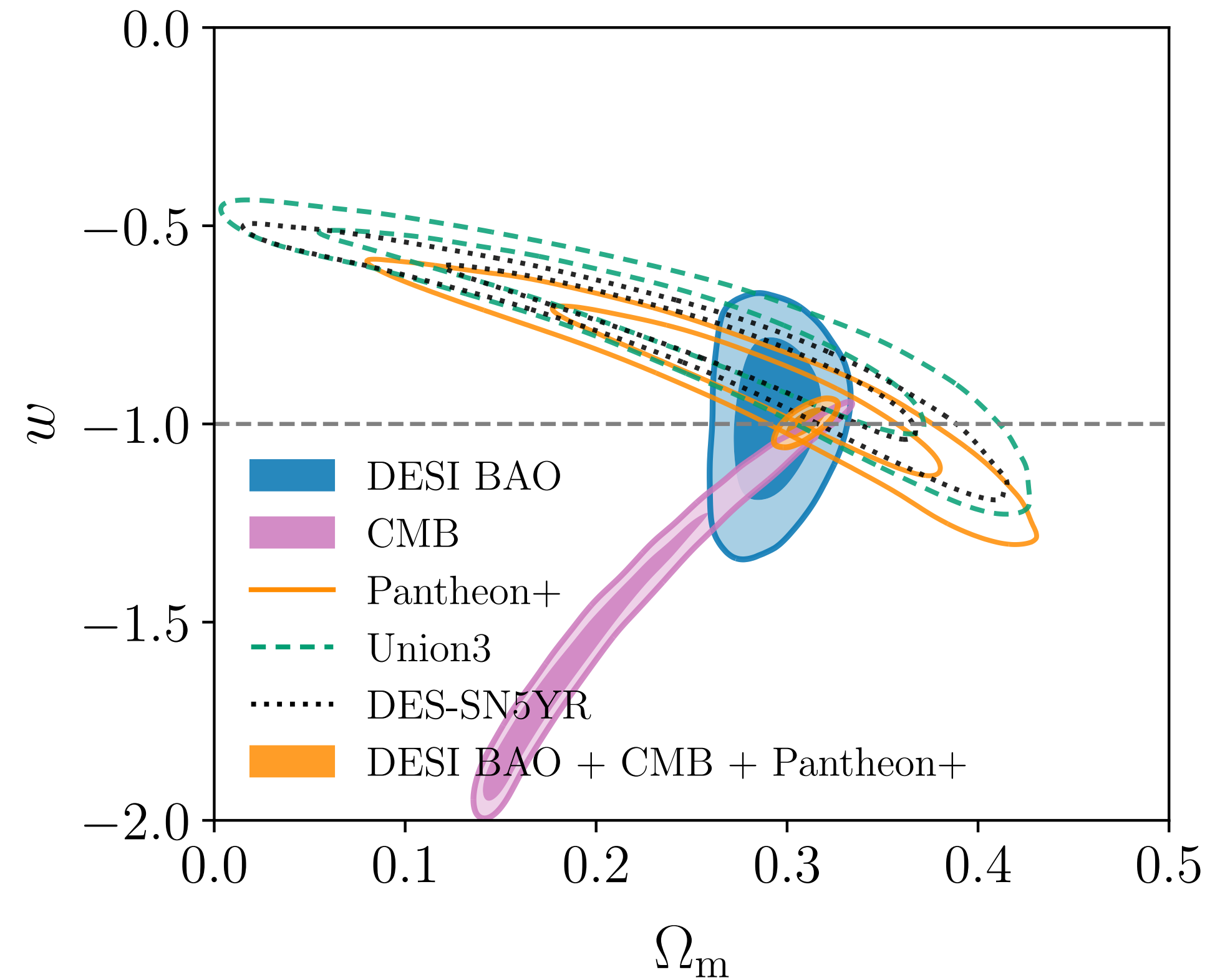
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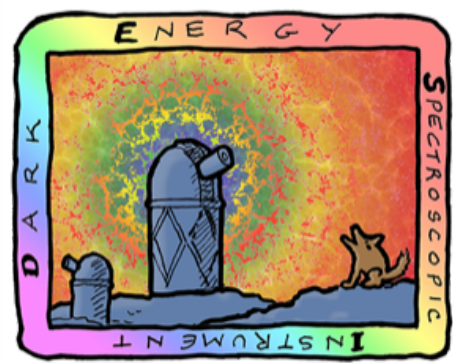
More cosmological parameters

Curvature



dark energy $w = \text{const}$



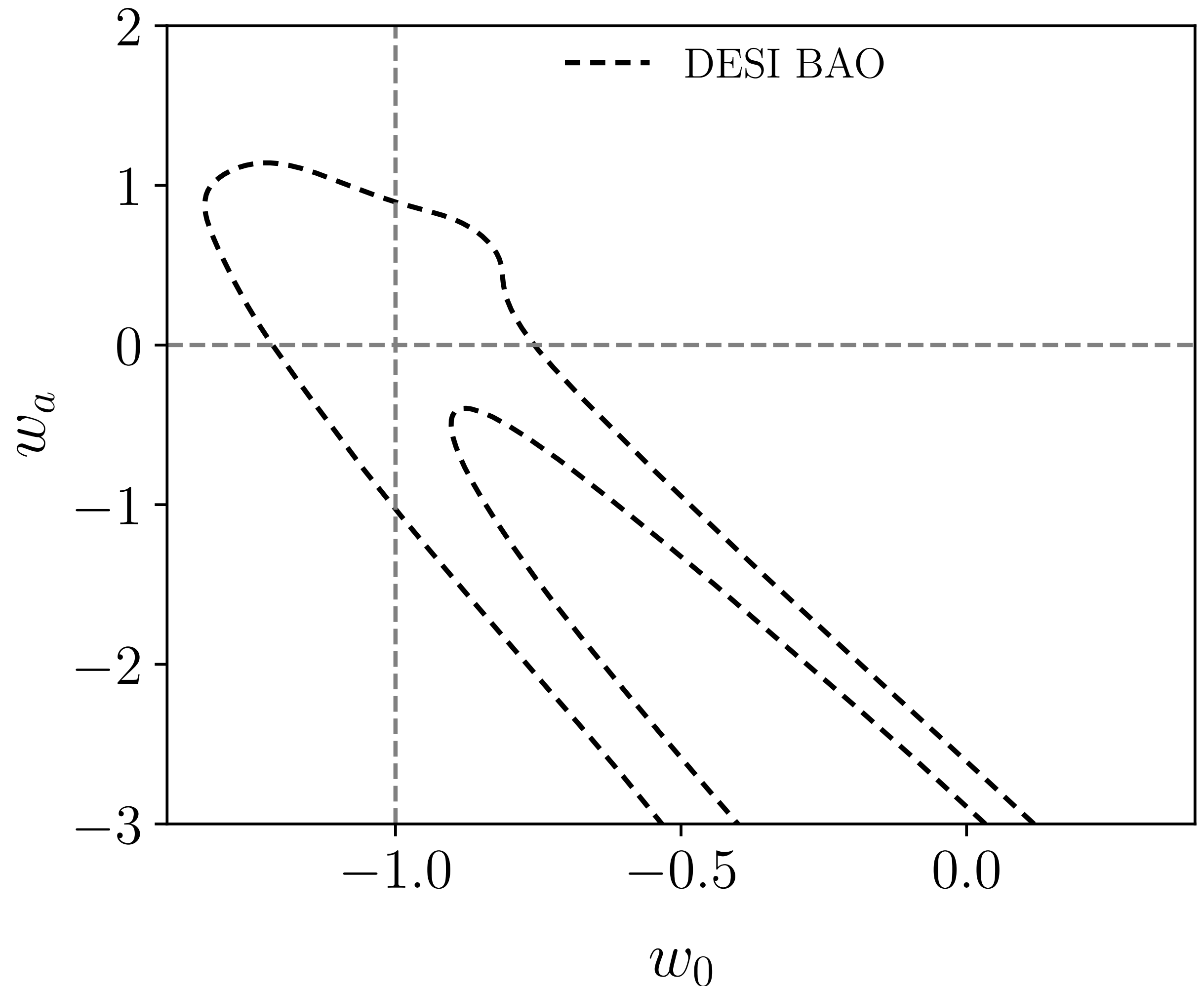


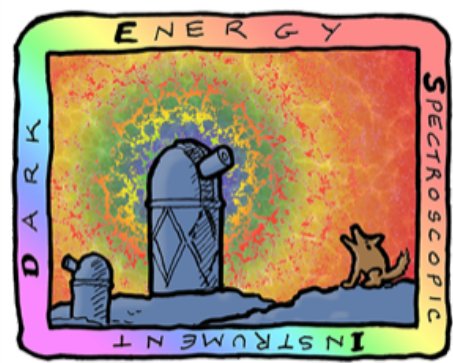
DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

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Time-dependent dark energy

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



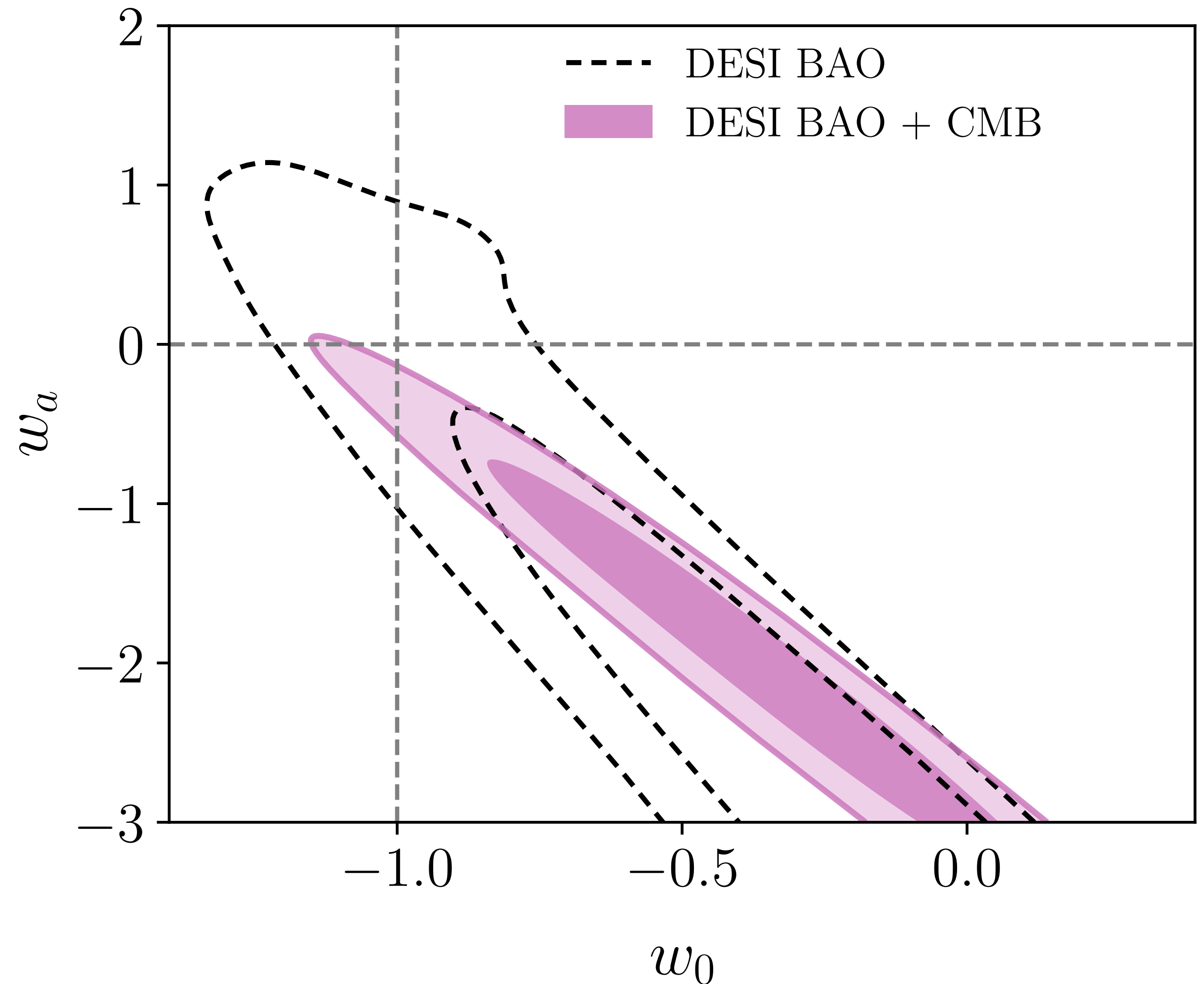


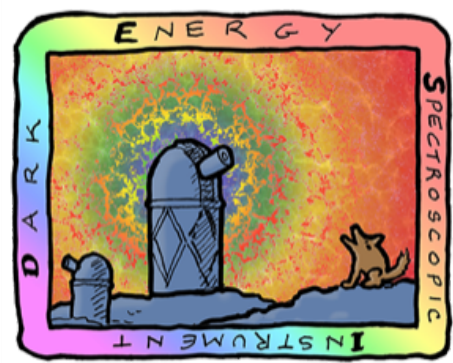
DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

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Time-dependent dark energy

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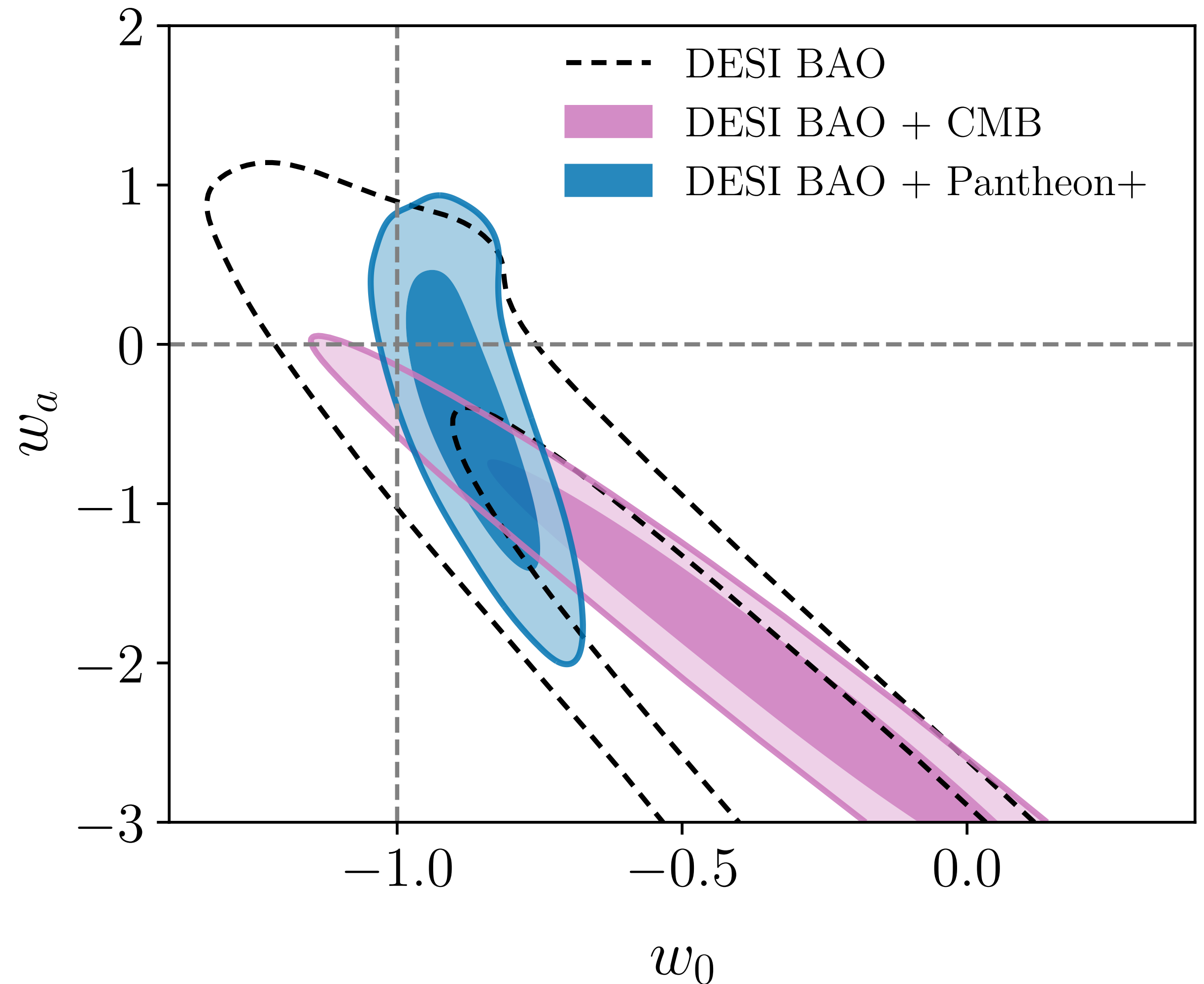


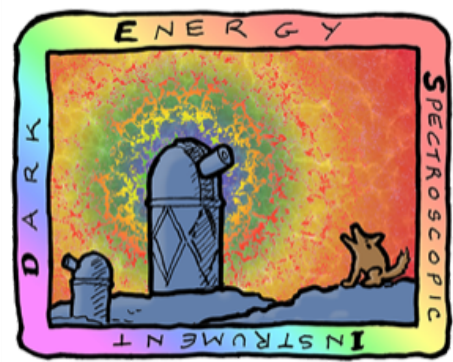
DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

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Time-dependent dark energy

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



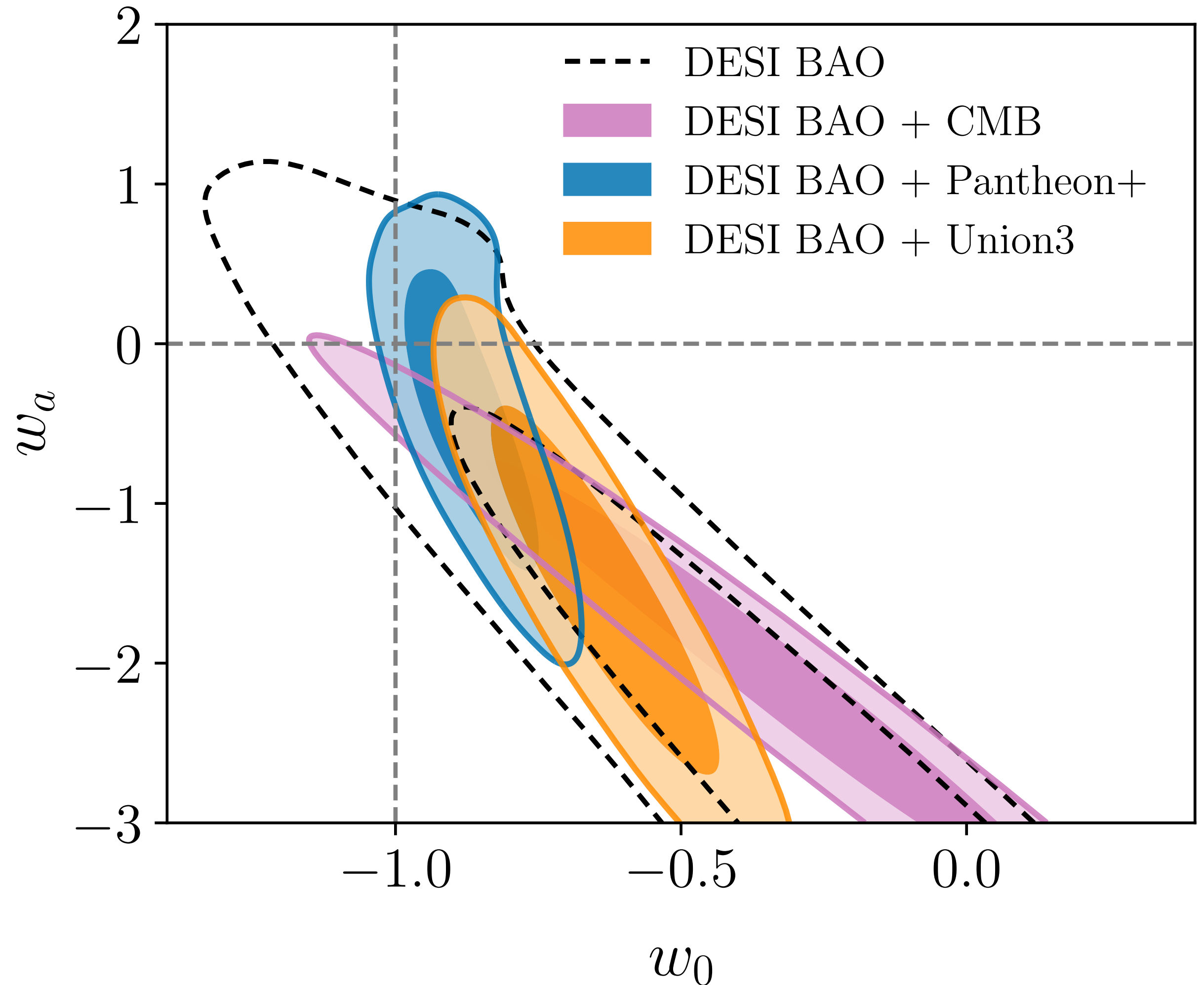


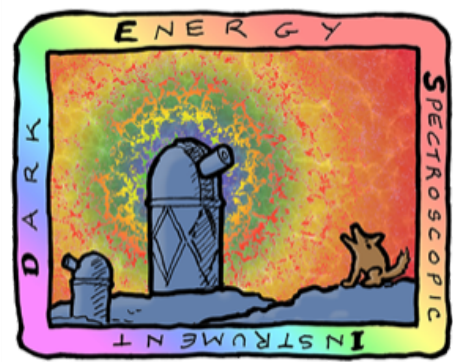
DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

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Time-dependent dark energy

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



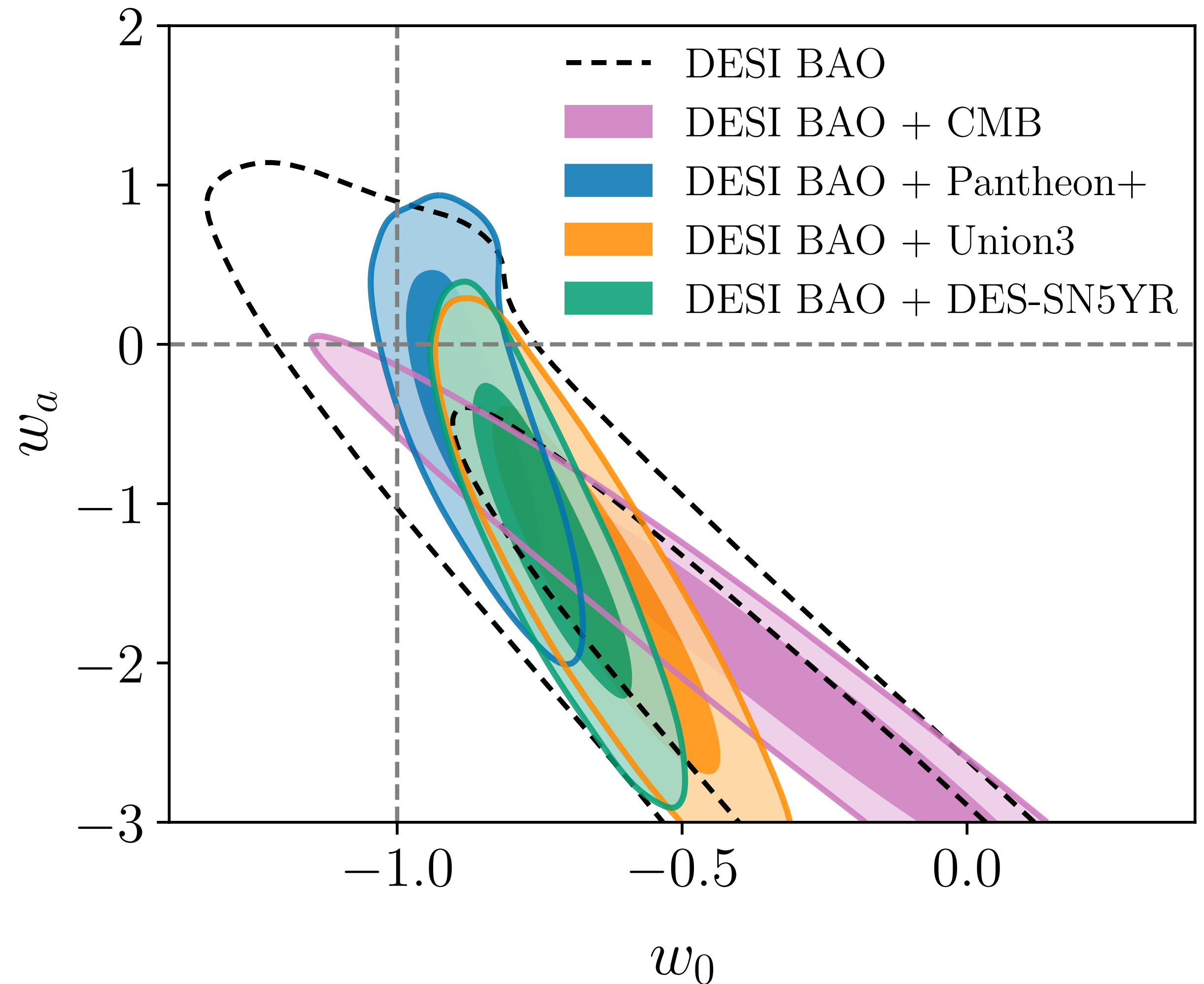


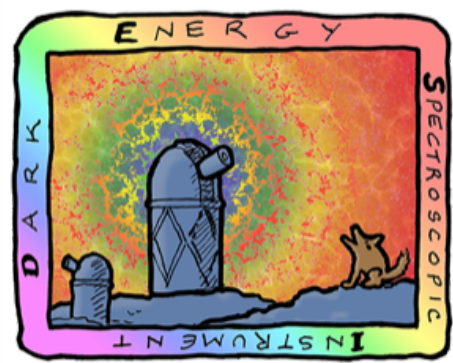
DARK ENERGY
SPECTROSCOPIC
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Time-dependent dark energy

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





DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

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Time-dependent dark energy

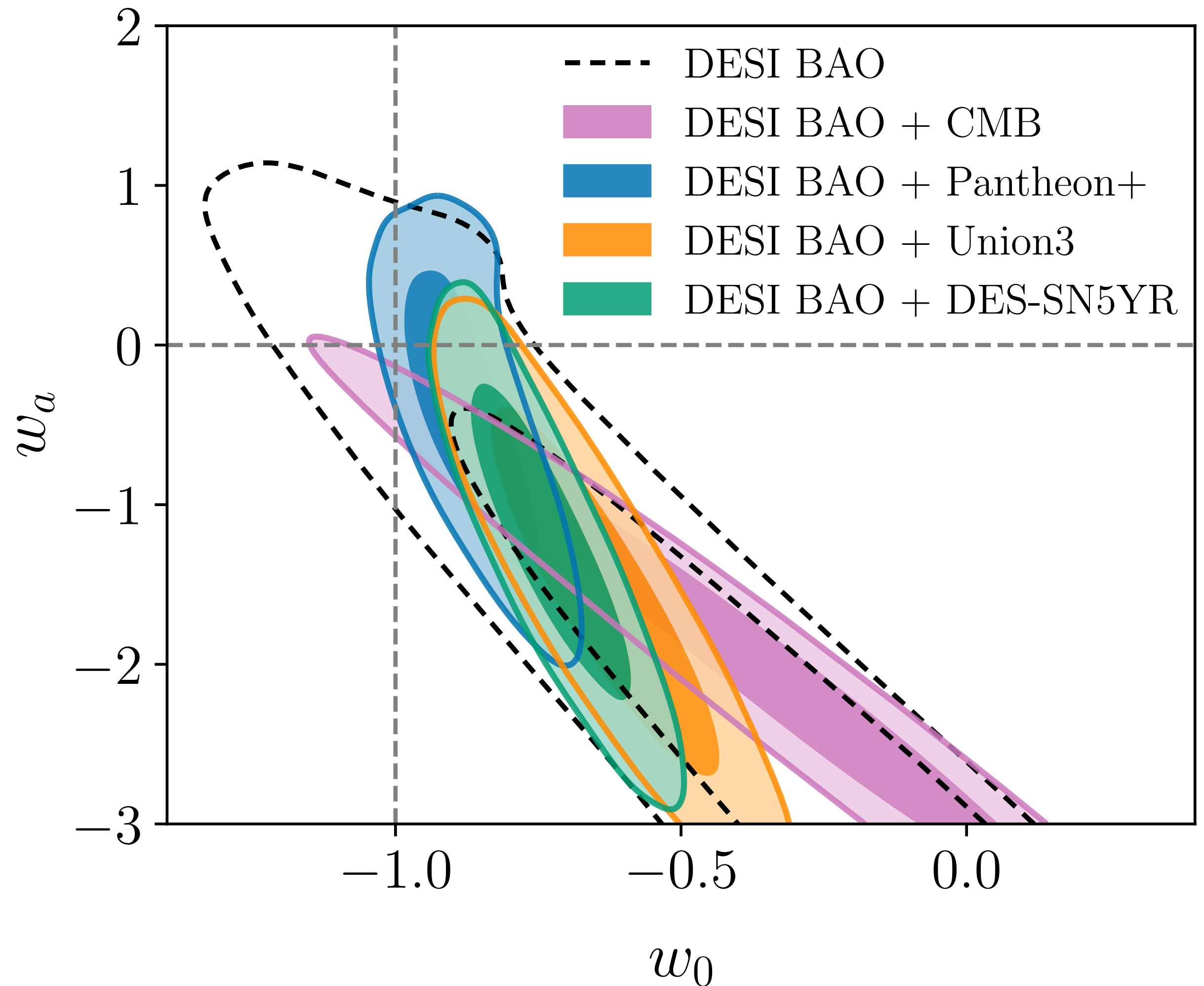
$$w(a) = w_0 + w_a(1 - a)$$

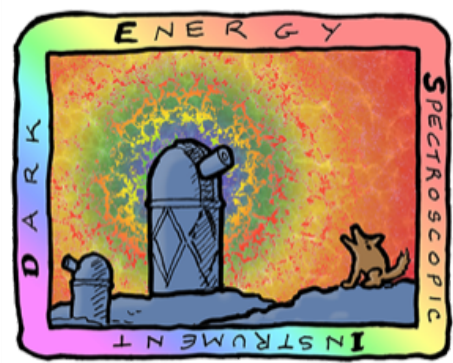
Levels of tension with Λ CDM:

DESI BAO + CMB +

- Pantheon+: 2.5σ
- Union3: 3.5σ
- DES-SN5YR: 3.9σ

Hints of “thawing” dark energy

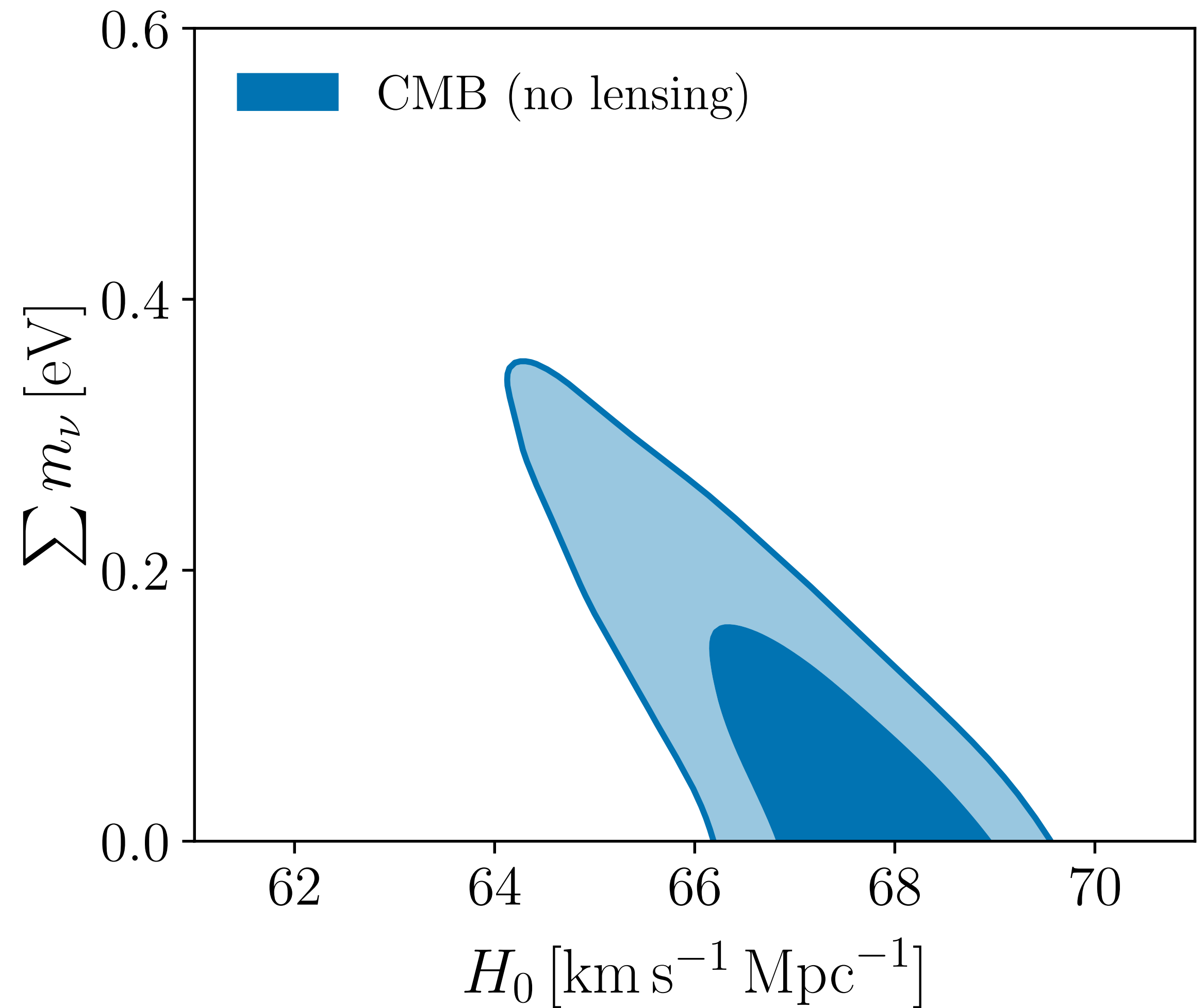


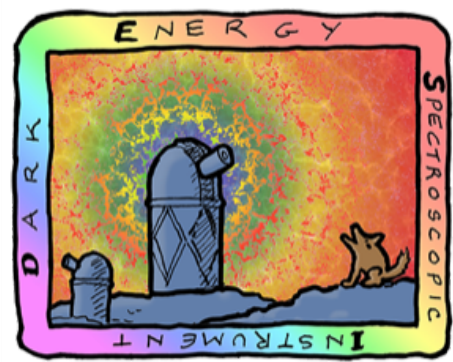


DARK ENERGY
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Neutrino mass

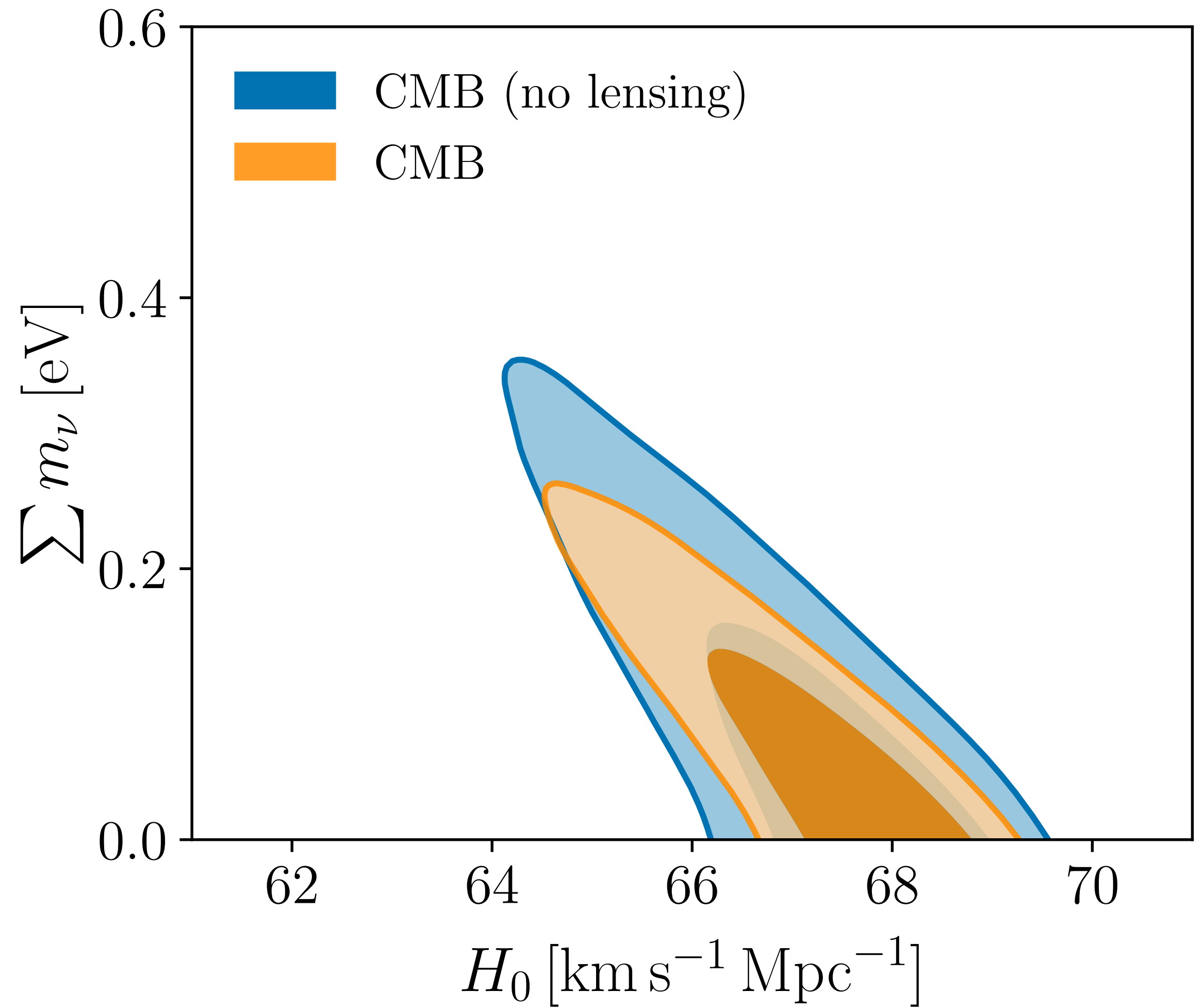


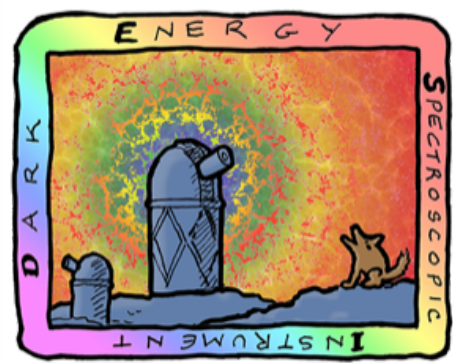


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SPECTROSCOPIC
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Neutrino mass





DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

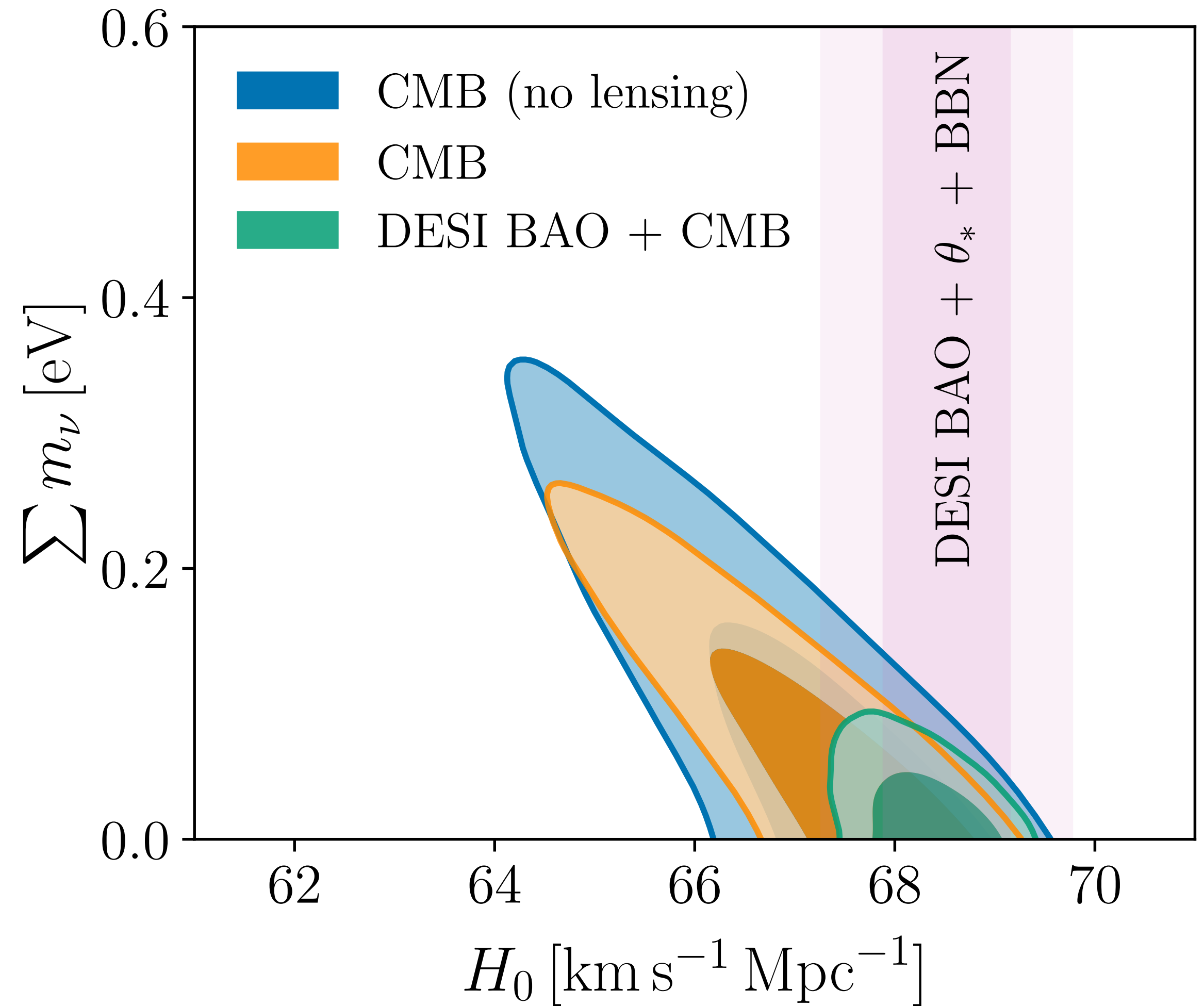
U.S. Department of Energy Office of Science

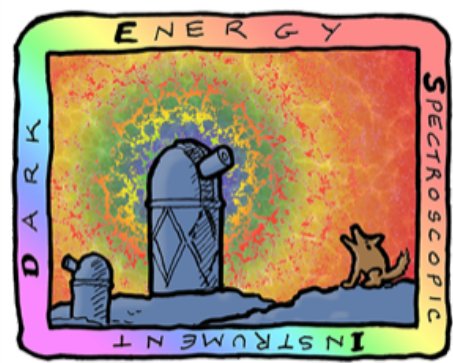
Neutrino mass

BAO break the $H_0 - \Sigma m_\nu$
degeneracy

DESI + CMB:

$\Sigma m_\nu < 0.73$ eV (95%)





DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

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Neutrino mass

BAO break the $H_0 - \Sigma m_\nu$
degeneracy

DESI + CMB:

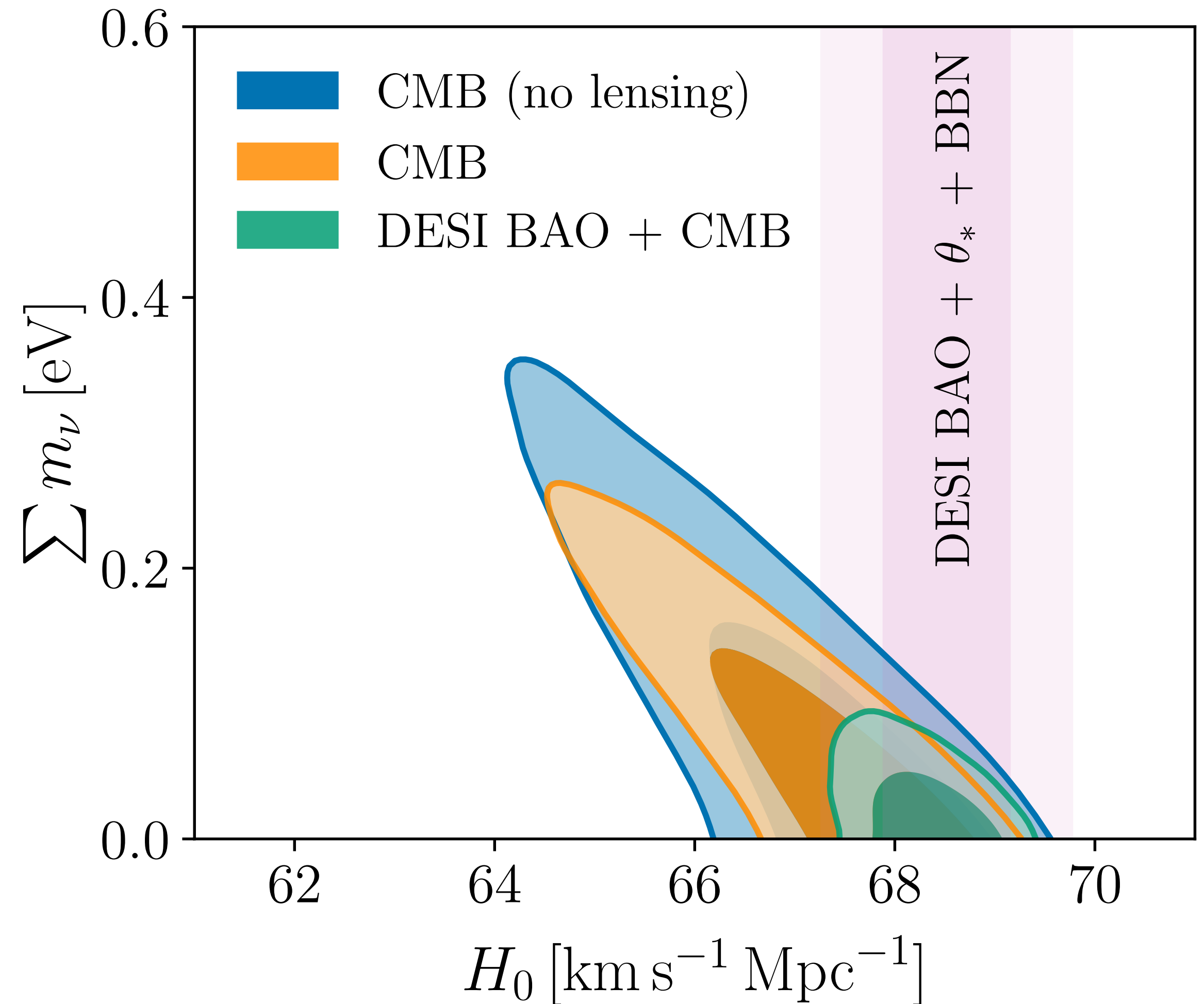
$\Sigma m_\nu < 0.73$ eV (95%)

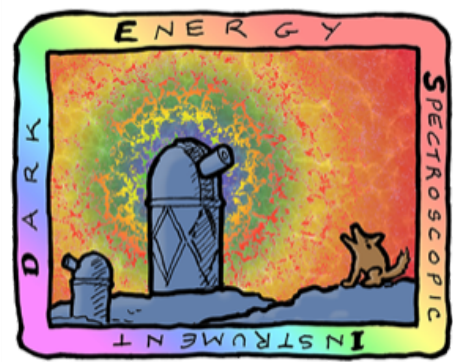
But this limit is
background dependent

Allowing for $w(a)$:

$\Sigma m_\nu < 0.195$ eV (95%)

Also prior dependent





DARK ENERGY
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INSTRUMENT

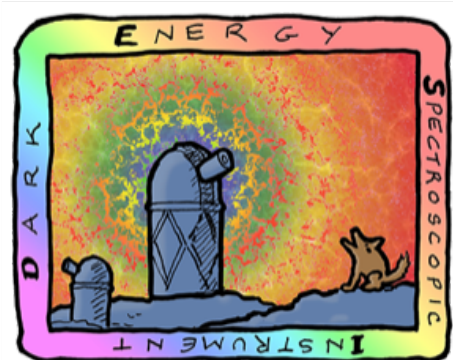
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Summary

- Already the most precise BAO measurements ever
- DESI BAO + external priors give 1% precision on H_0
- Consistent with CMB in flat Λ CDM
- Stringent upper bound on neutrino mass (background dependent)
- Hints of time-dependent dark energy equation of state?
- Papers at <https://data.desi.lbl.gov/doc/papers/>

Coming soon:

- Full-shape DR1
- BAO DR2



DARK ENERGY
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Test of systematics effects

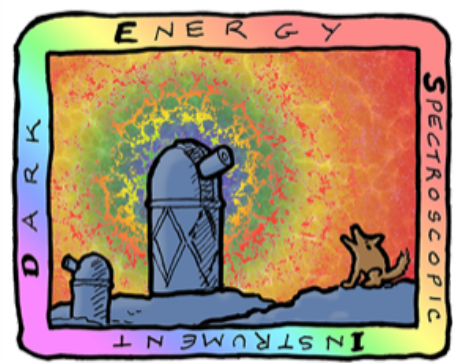
No BAO error detected for:

- observational effects in data (imaging, fiber assignment etc)
- reconstruction algorithm
- covariance matrix construction

Systematics errors \ll statistical for:

- incomplete theory modelling
- choice of fiducial cosmology
- galaxy-halo (HOD) model uncertainties

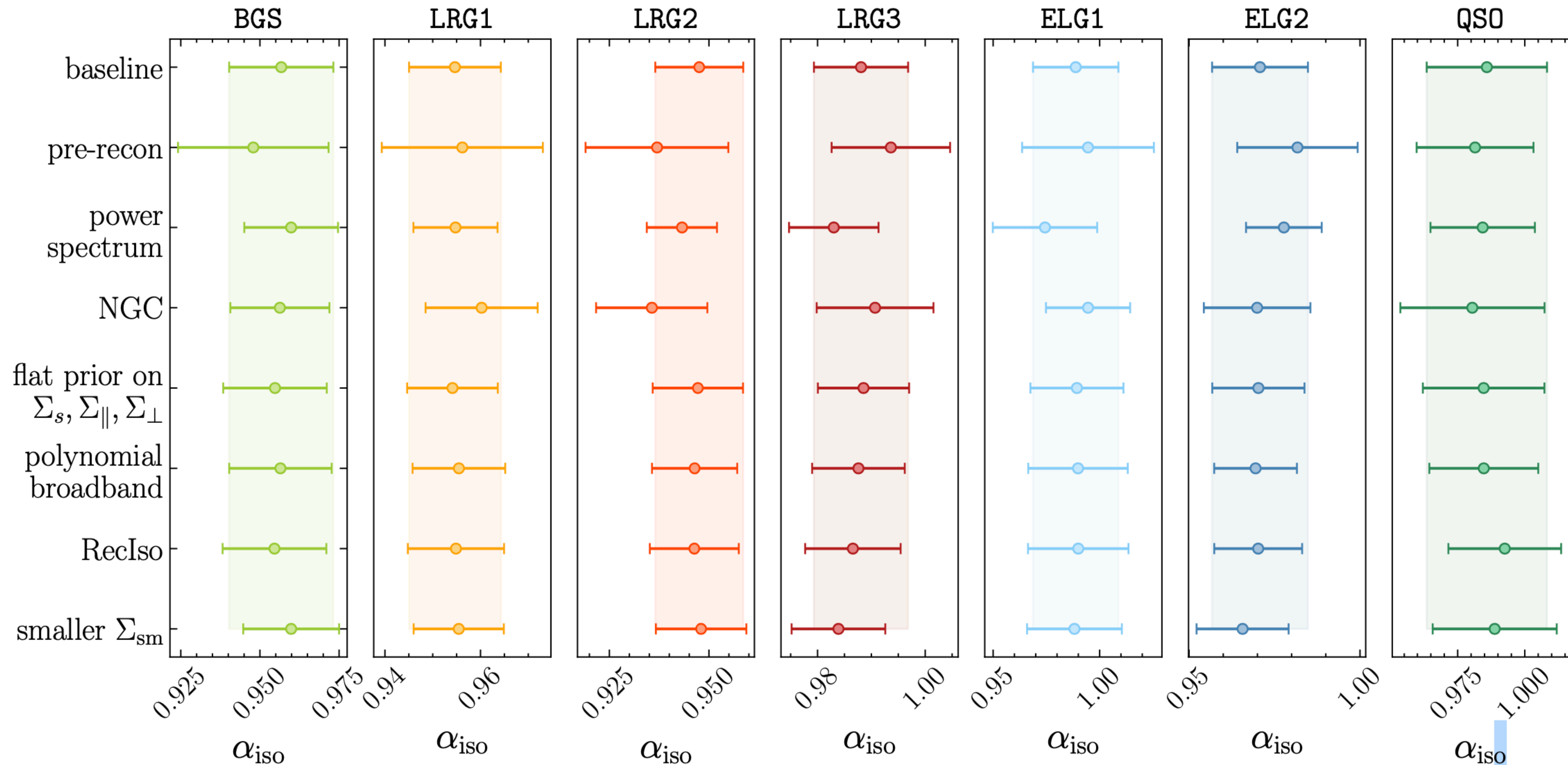
Max. effect: $\sigma_{\text{stat}} = 1.05\sigma_{\text{stat}}$

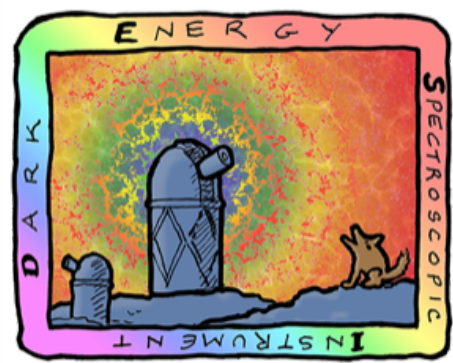


DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

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Test of systematics effects

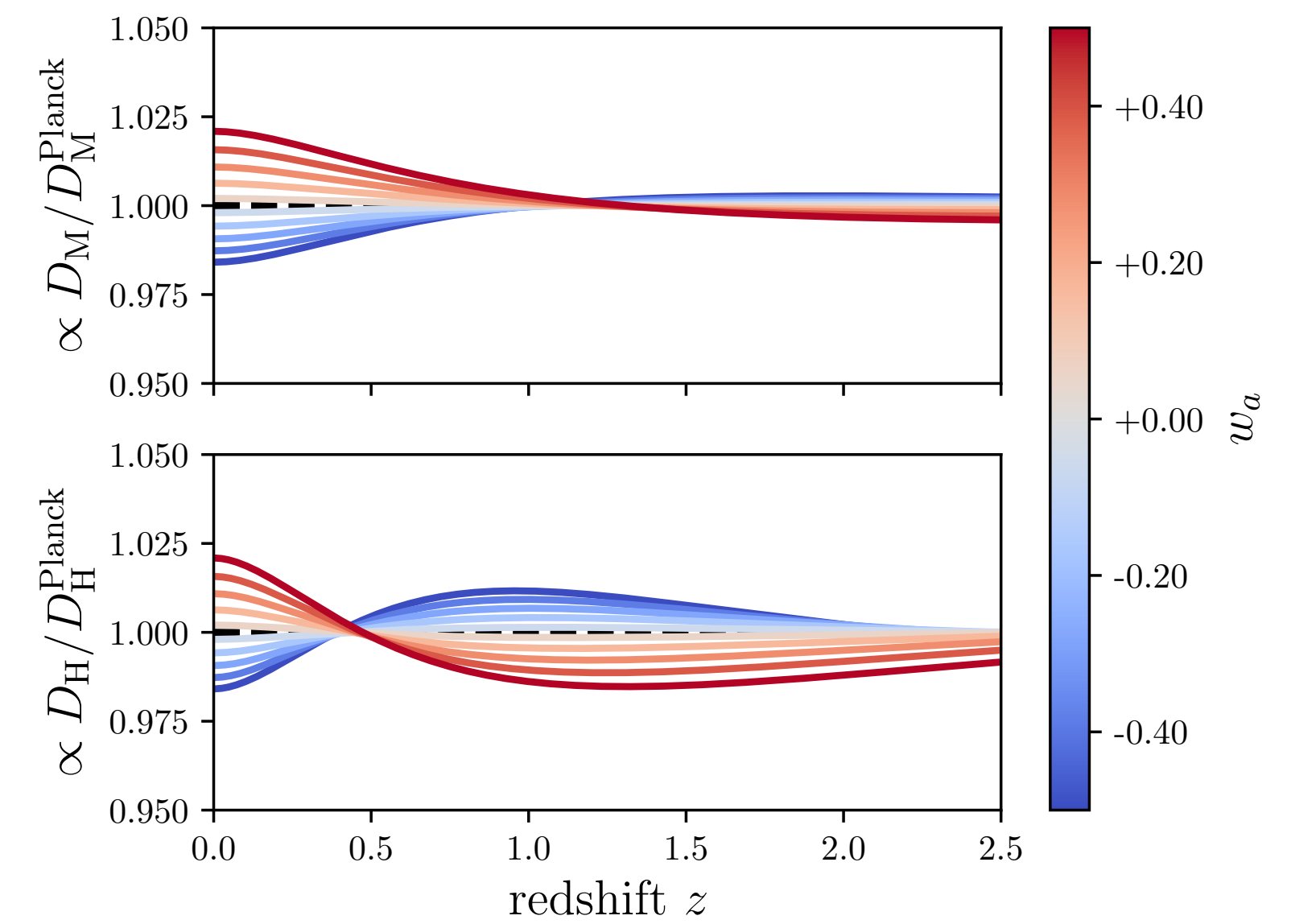
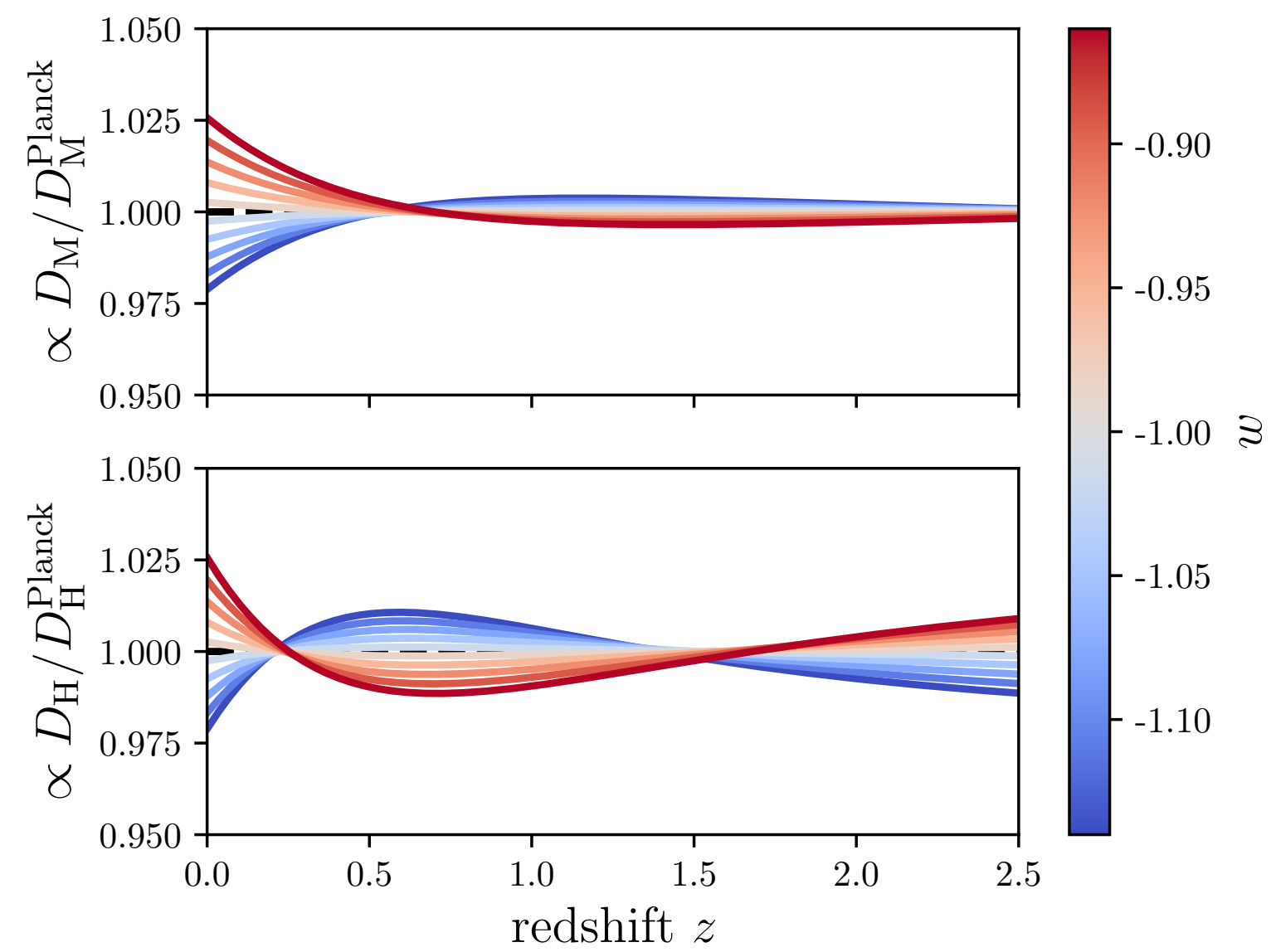
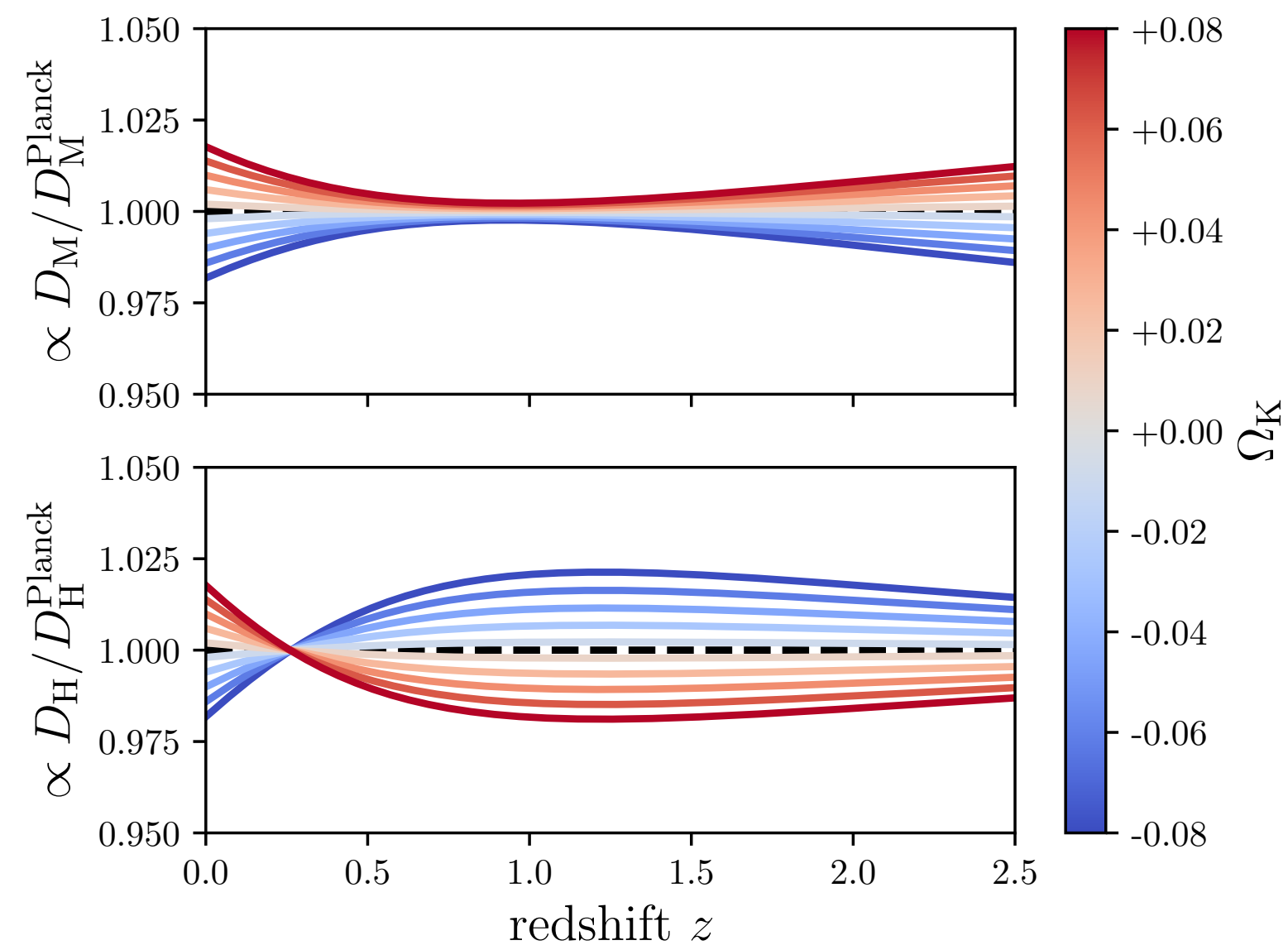


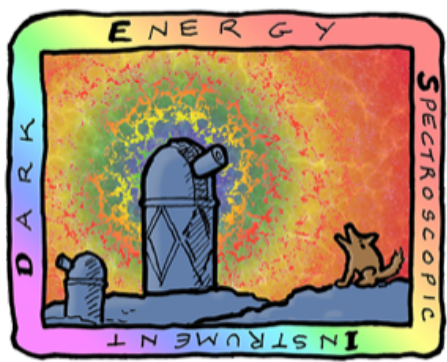


DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

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BAO evolution for different cosmo params

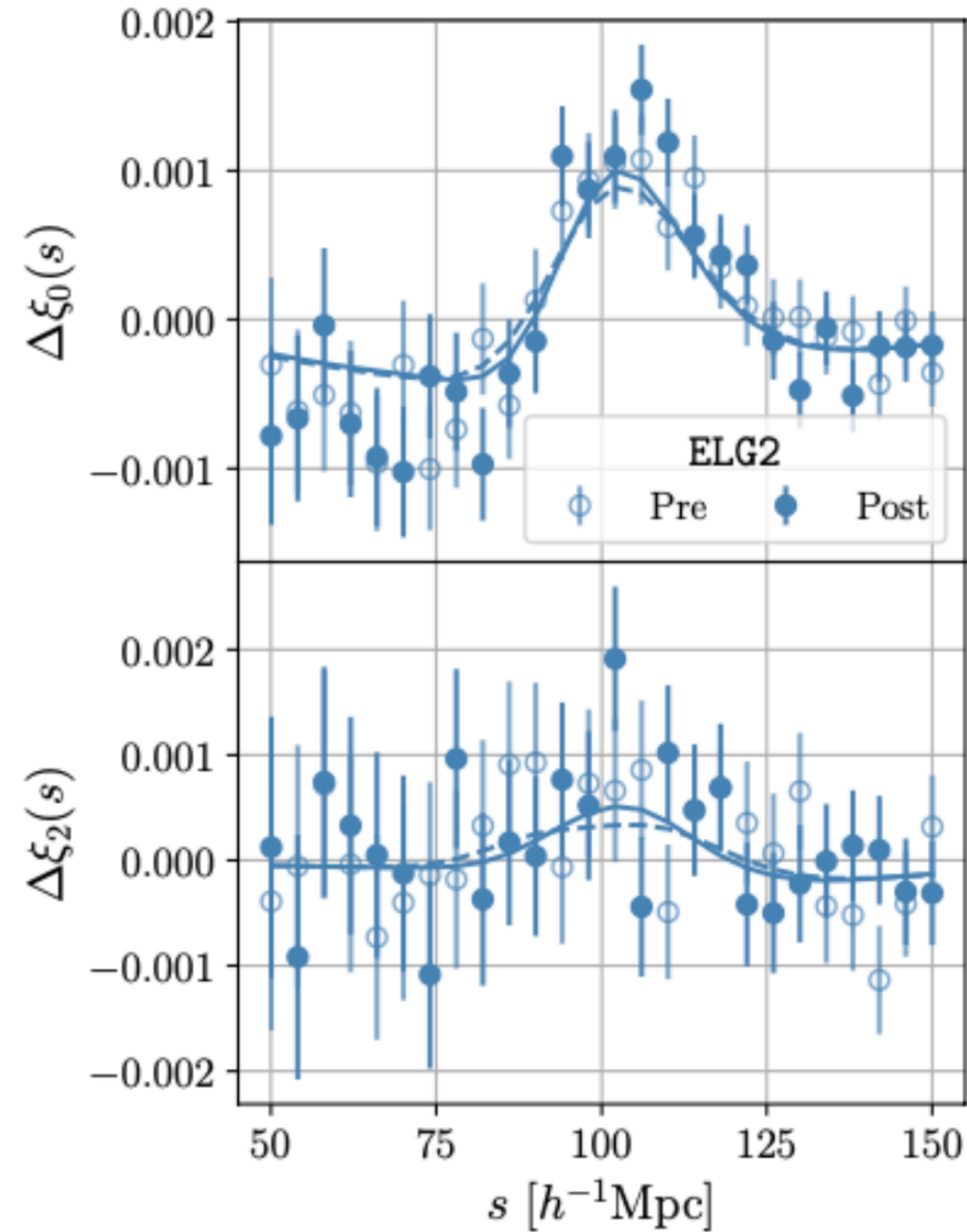
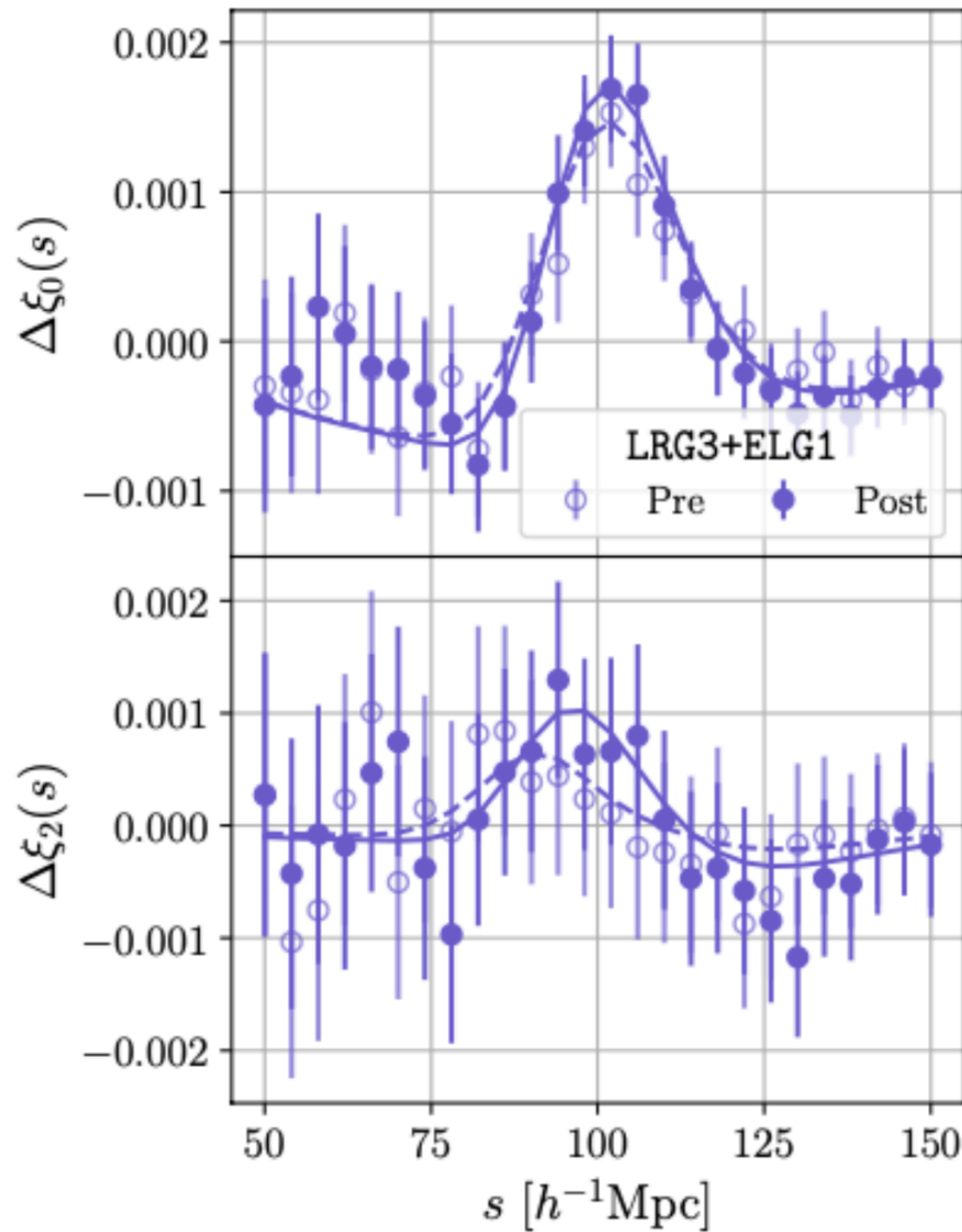


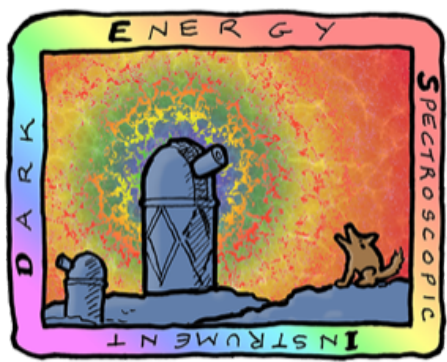


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DESI BAO (correlation function)

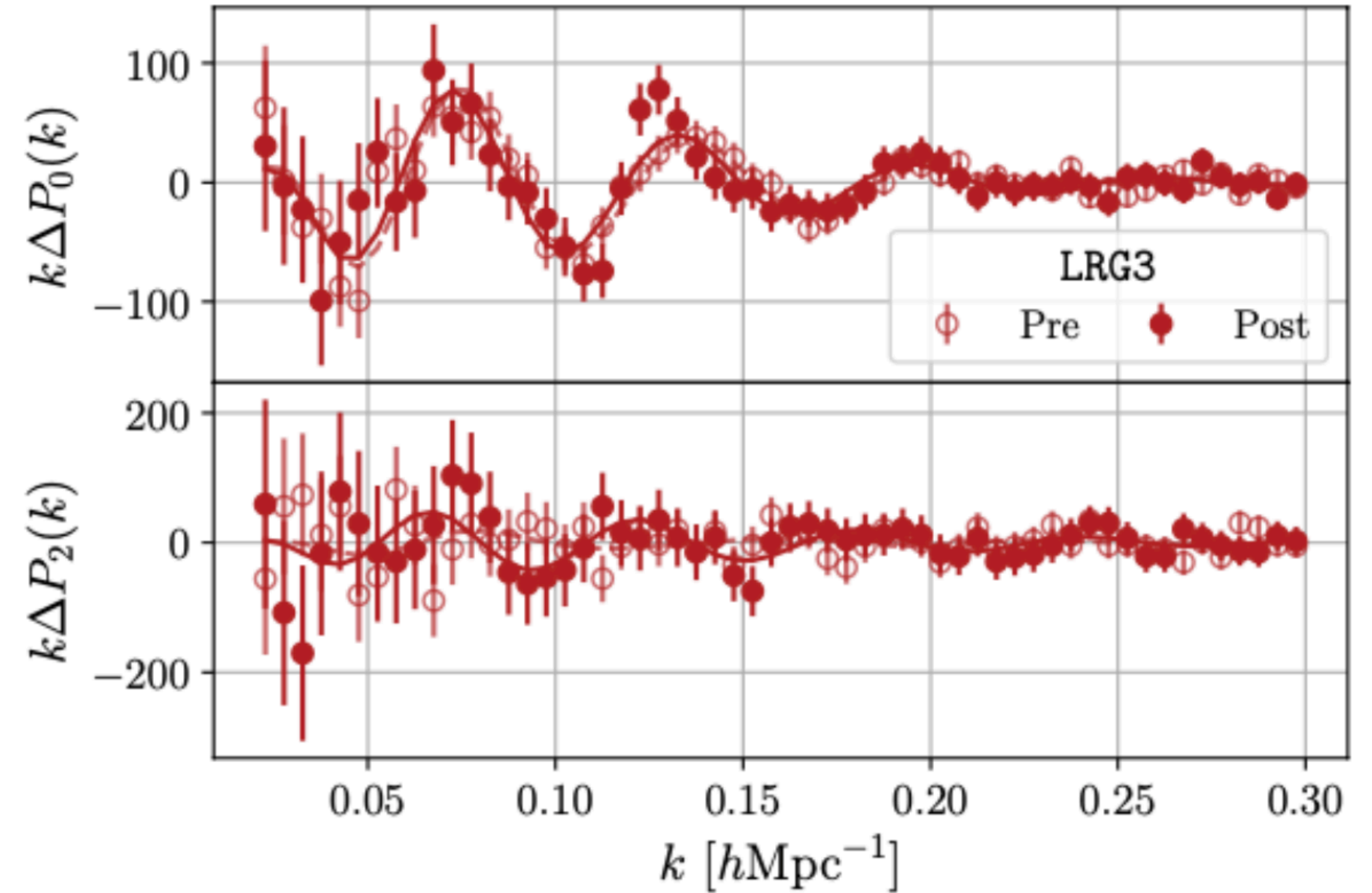
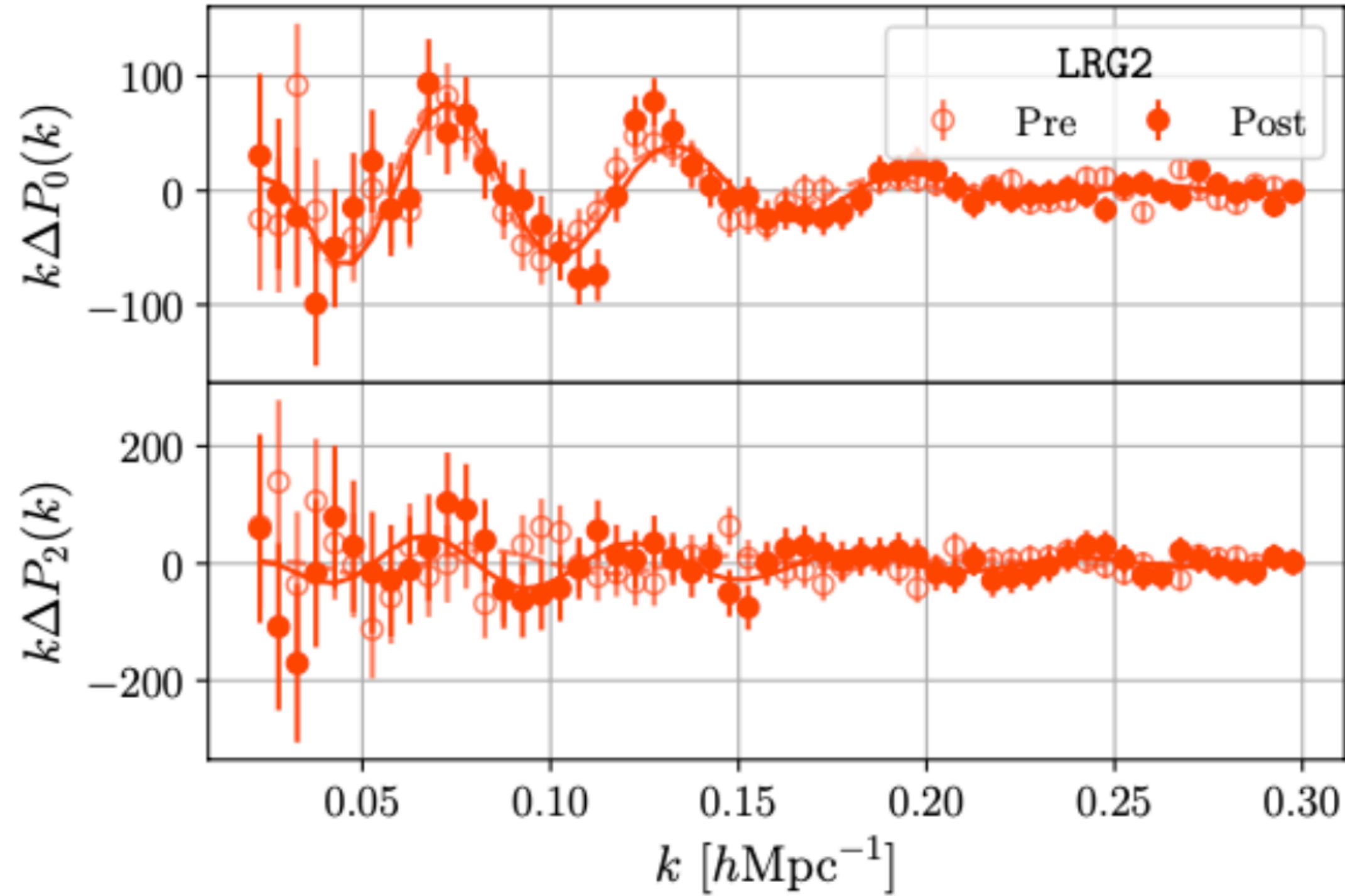


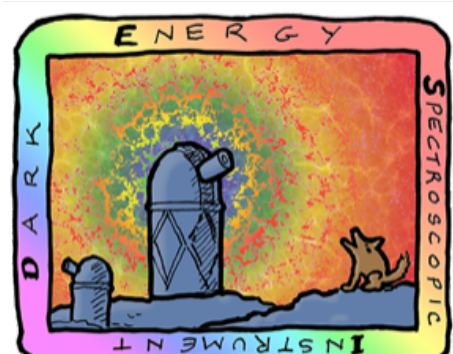


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DESI BAO (power spectrum)



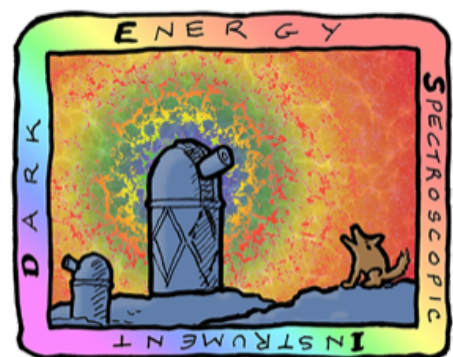


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DESI targets

Galaxy type	Redshift range	Bands used	Targets per deg ²	Exposures per deg ²	Good z 's per deg ²	Baseline sample
LRG	0.4–1.0	$r, z, W1$	350	580	285	4.0 M
ELG	0.6–1.6	g, r, z	2400	1870	1220	17.1 M
QSO (tracers)	< 2.1	$g, r, z, W1, W2$	170	170	120	1.7 M
QSO ($\text{Ly-}\alpha$)	> 2.1	$g, r, z, W1, W2$	90	250	50	0.7 M
Total in dark time			3010	2870	1675	23.6 M
BGS	0.05–0.4	r	700	700	700	9.8 M
Total in bright time			700	700	700	9.8 M



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DESI spectrograph

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10 Multi-Object Spectrographs:

- 360 - 980 nm range over 3 channels
- Resolution: 2000 (blue) – 5500 (NIR)
- 500 fibers per spectrograph
- 4kx4k CCDs, 60s readout

Stable PSF

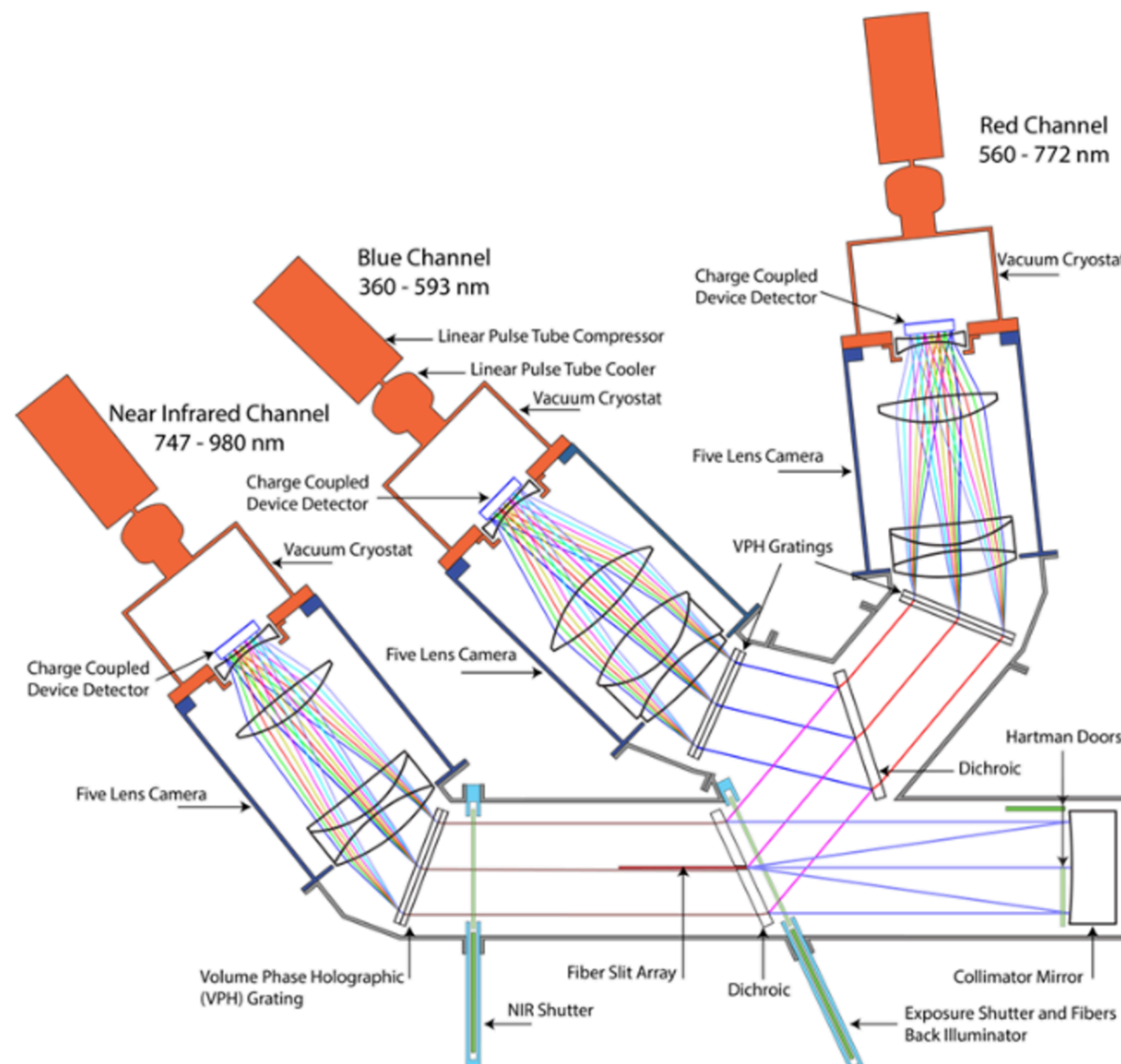
better than 1 % over many days

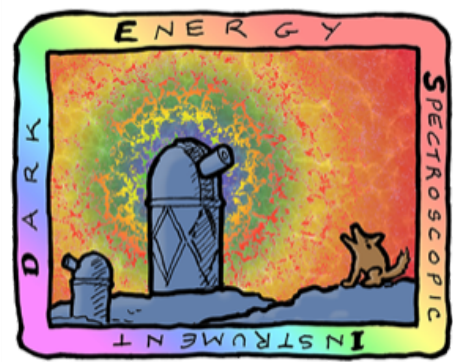
Low Read out noise

~ 3 e-

Throughput of optical chain is excellent

~40% at 700 nm (total)

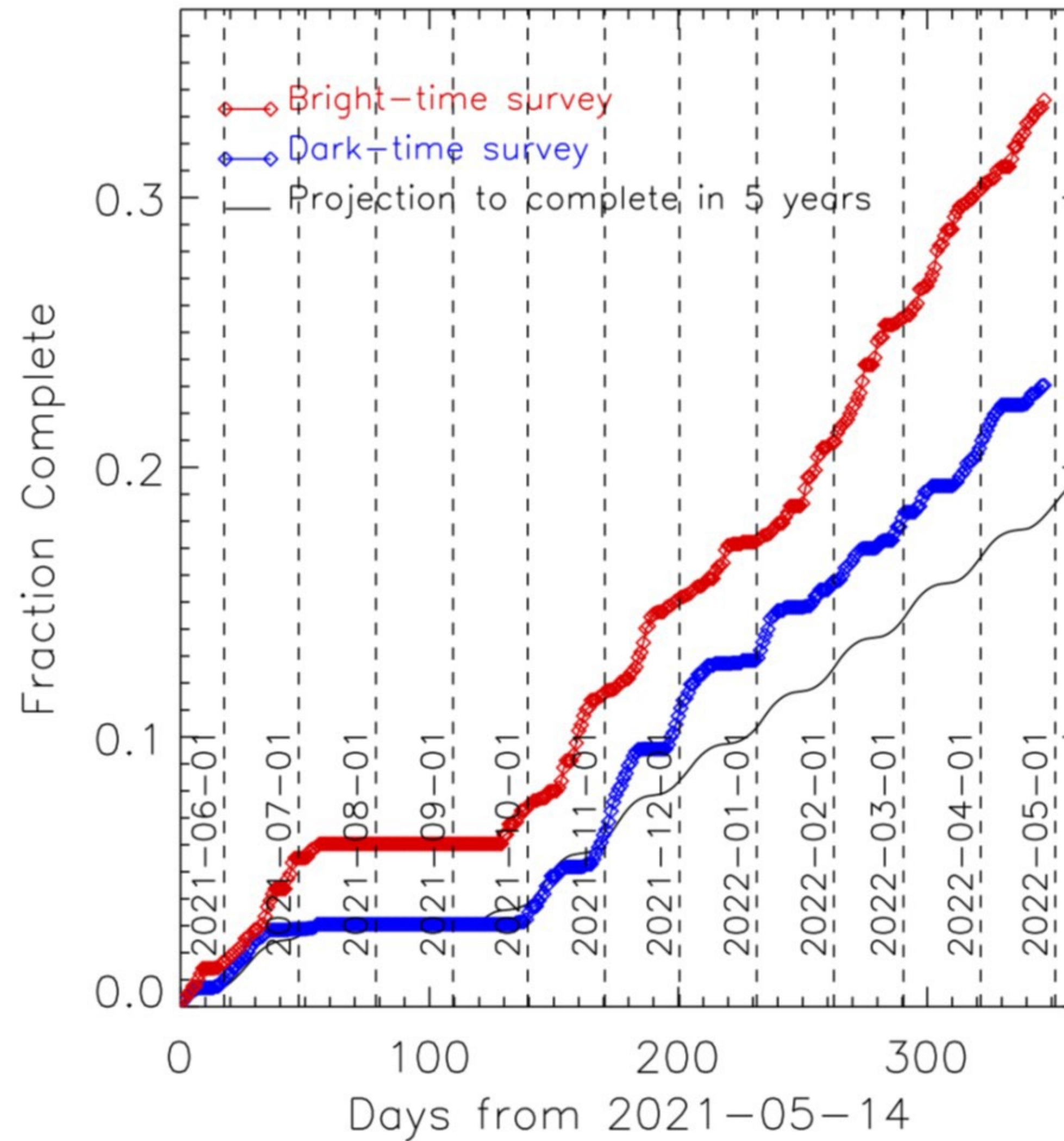


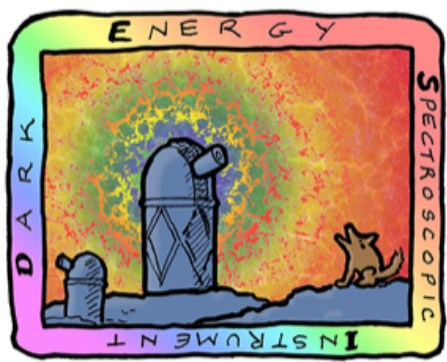


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DR1 survey speed

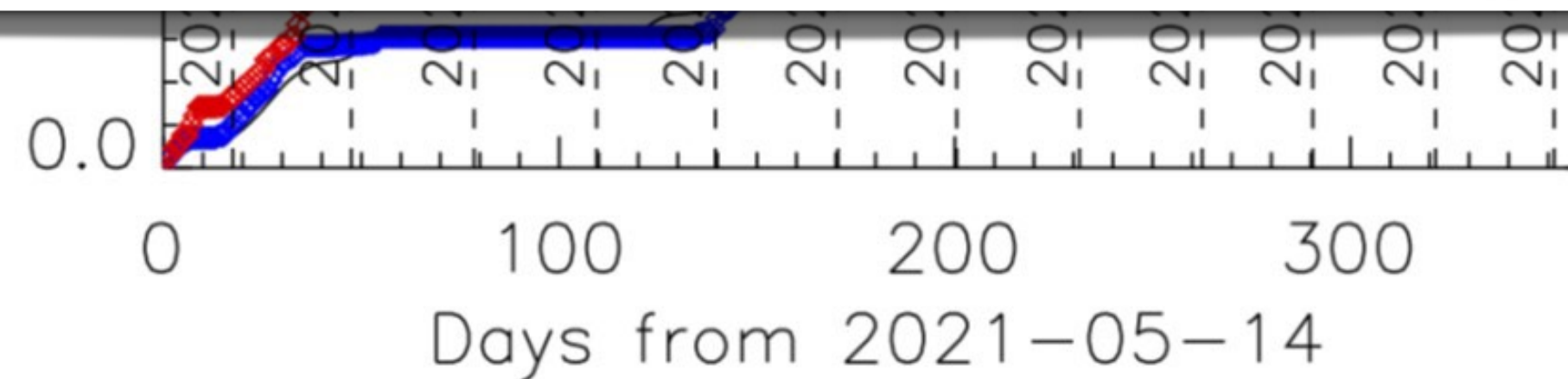
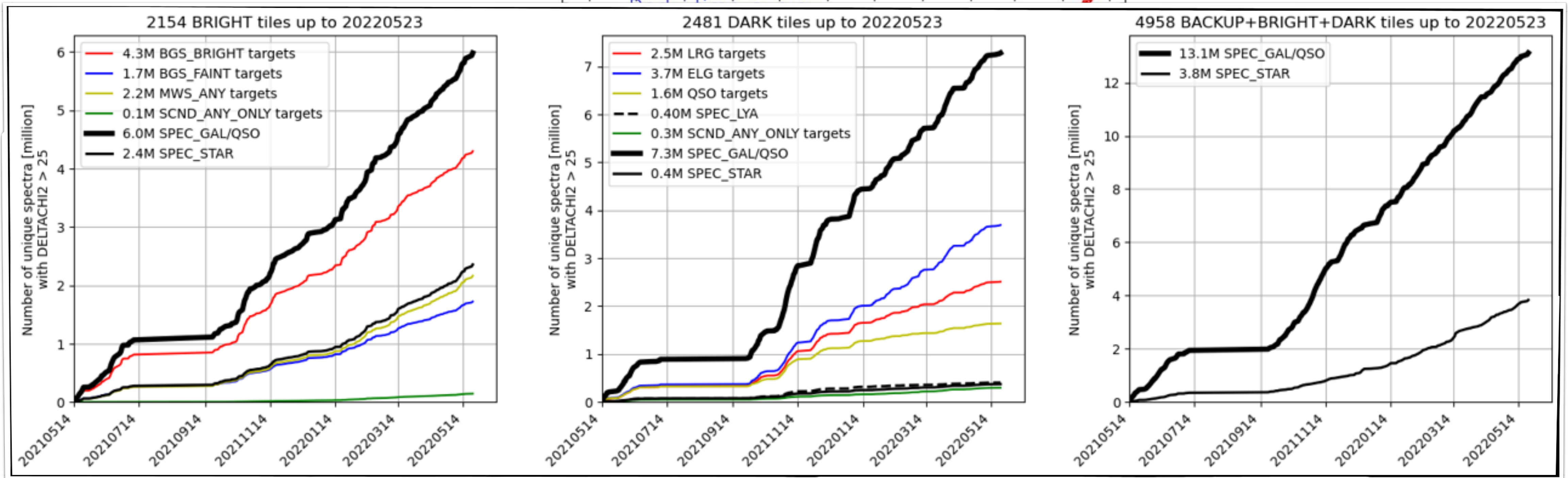
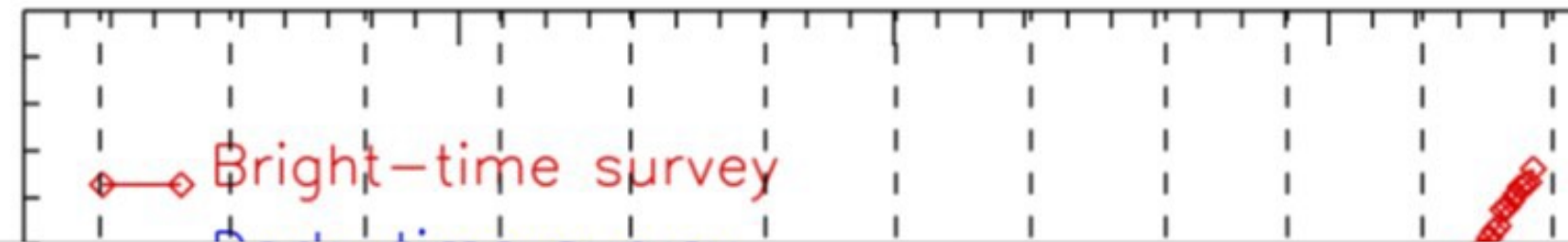


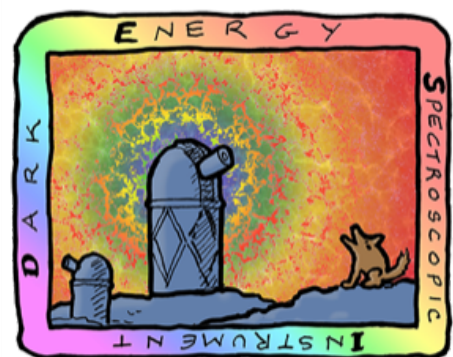


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DR1 survey speed

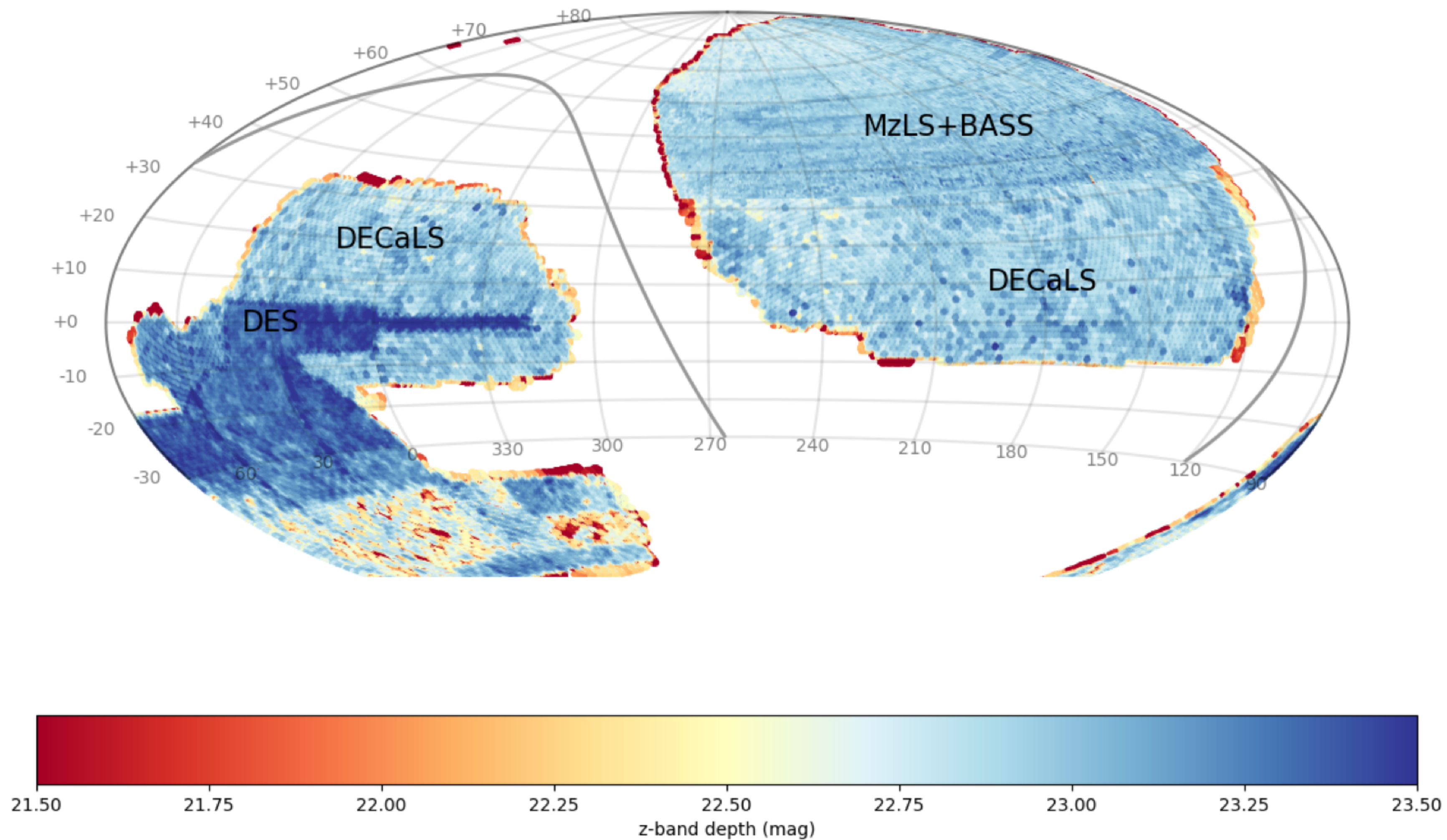


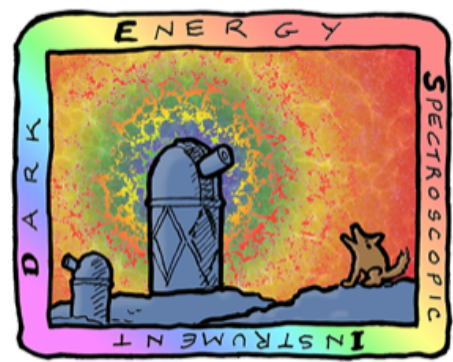


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Parent (imaging) surveys

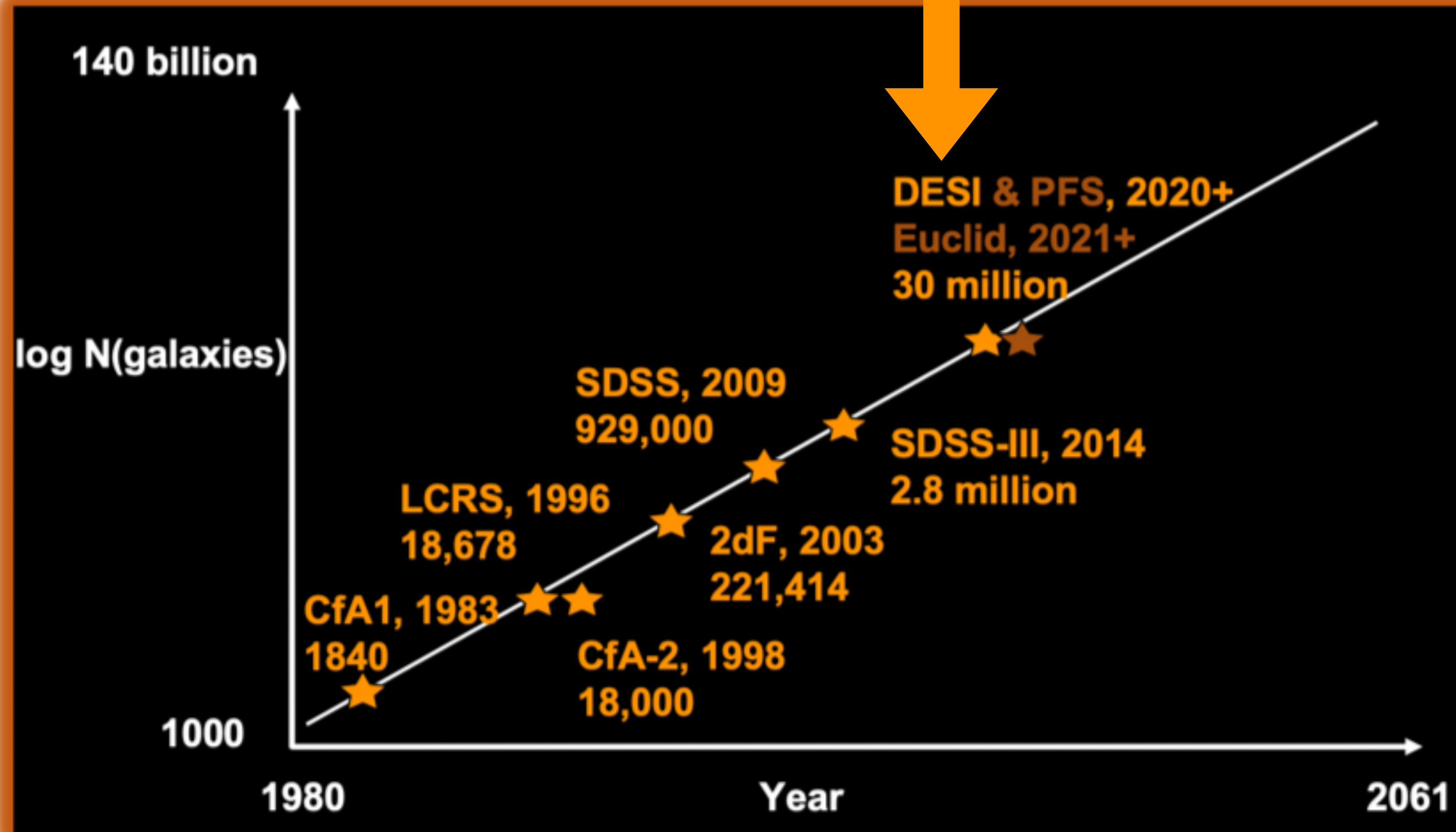


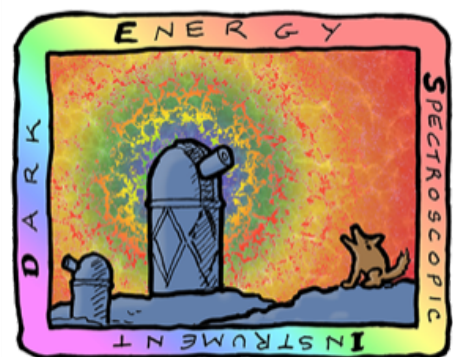


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Evolution of spectroscopic surveys

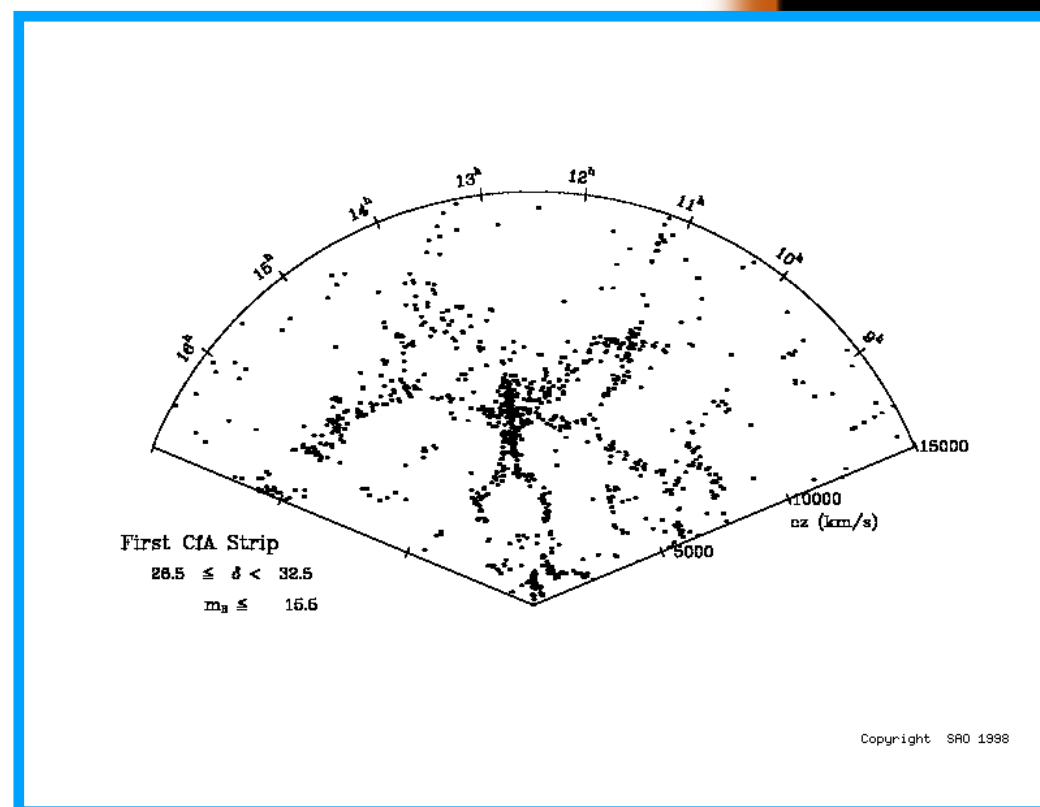
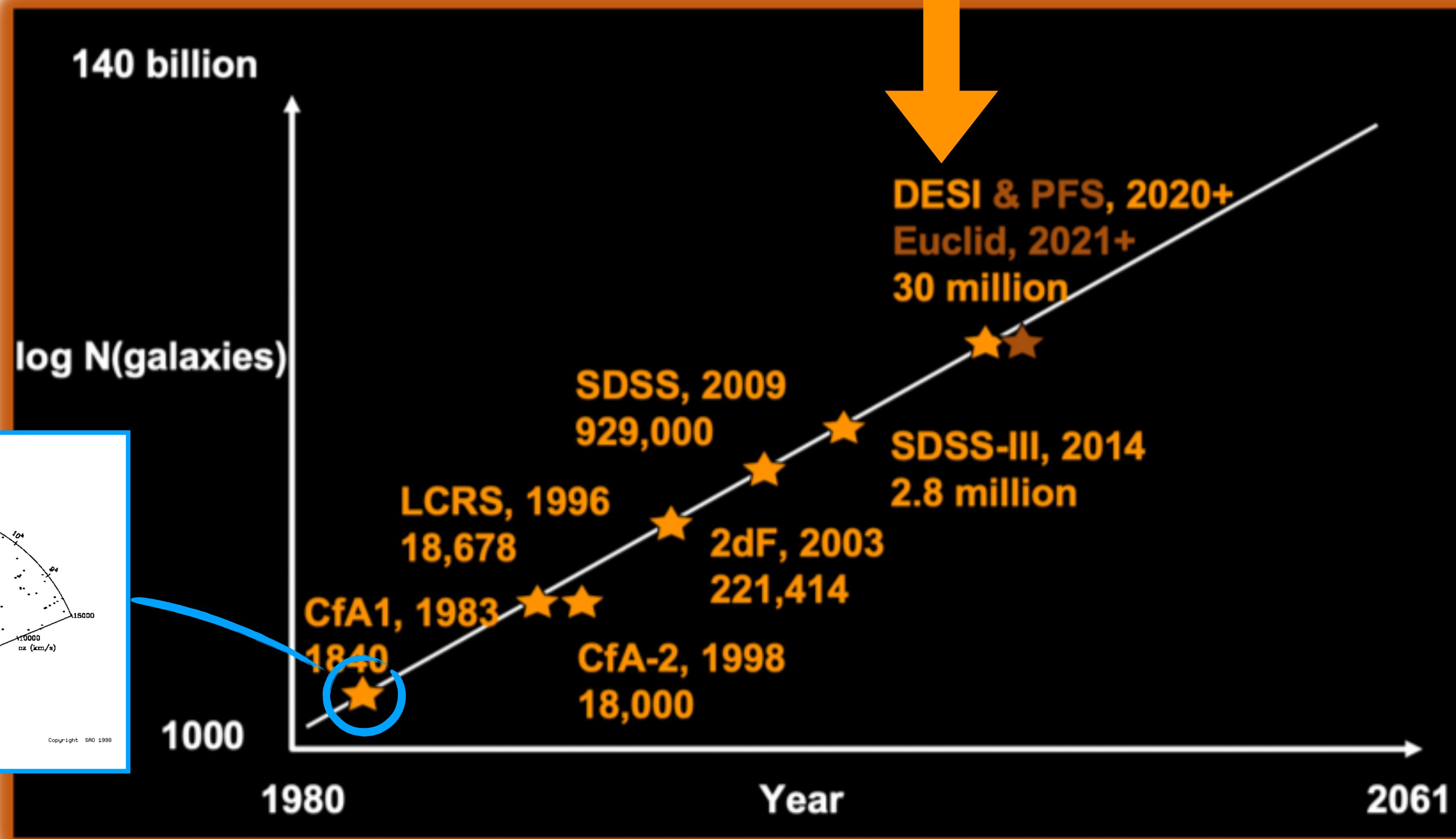


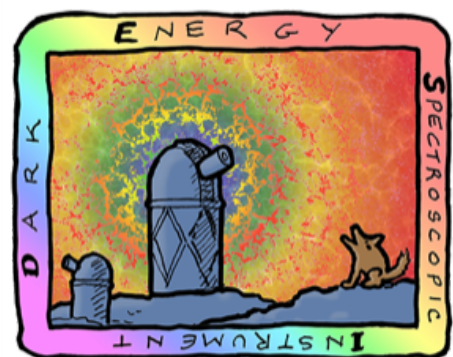


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Evolution of spectroscopic surveys

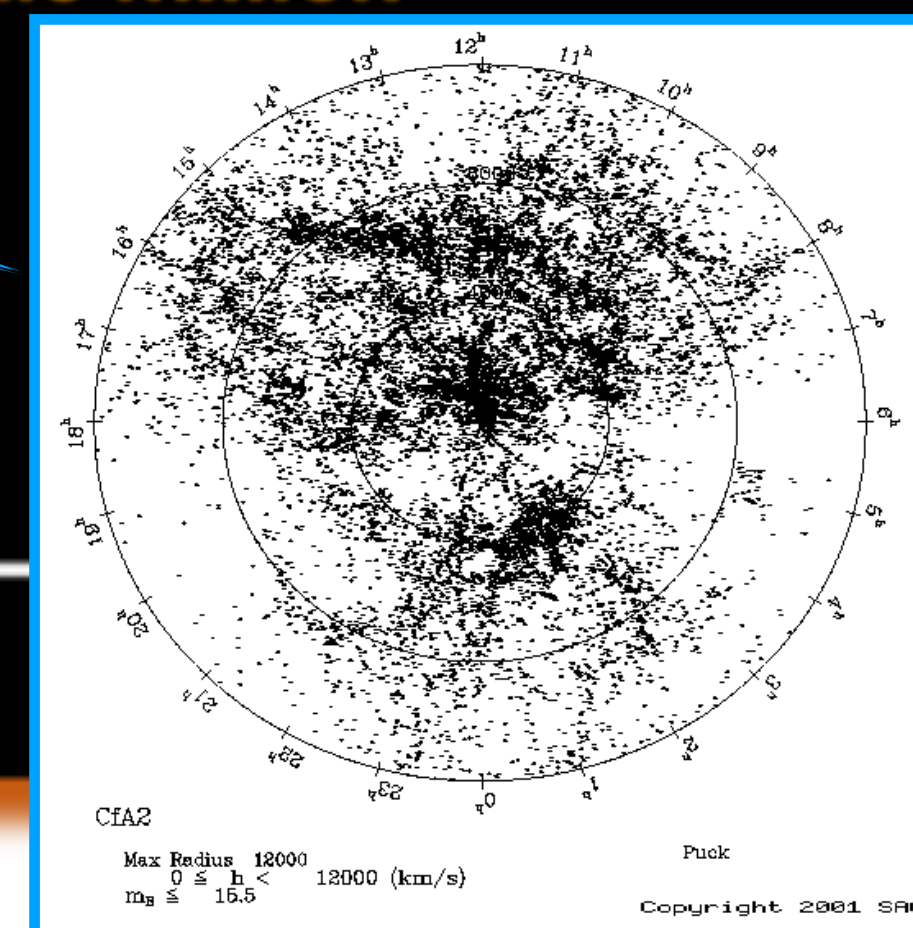
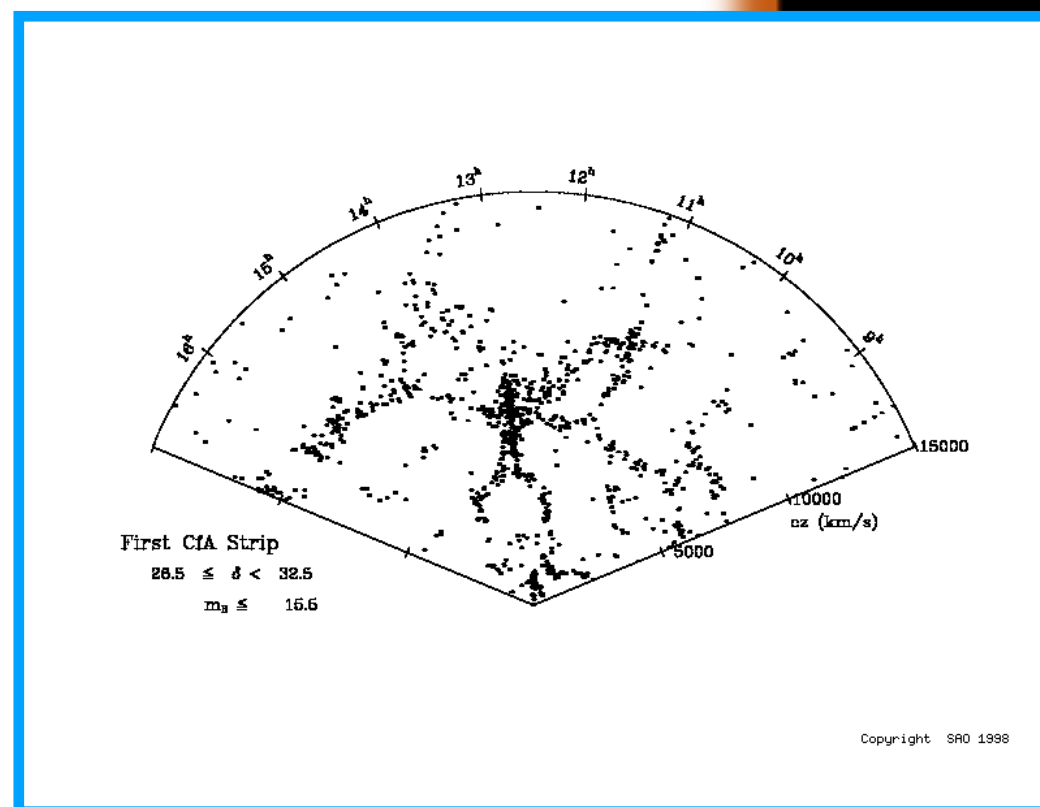
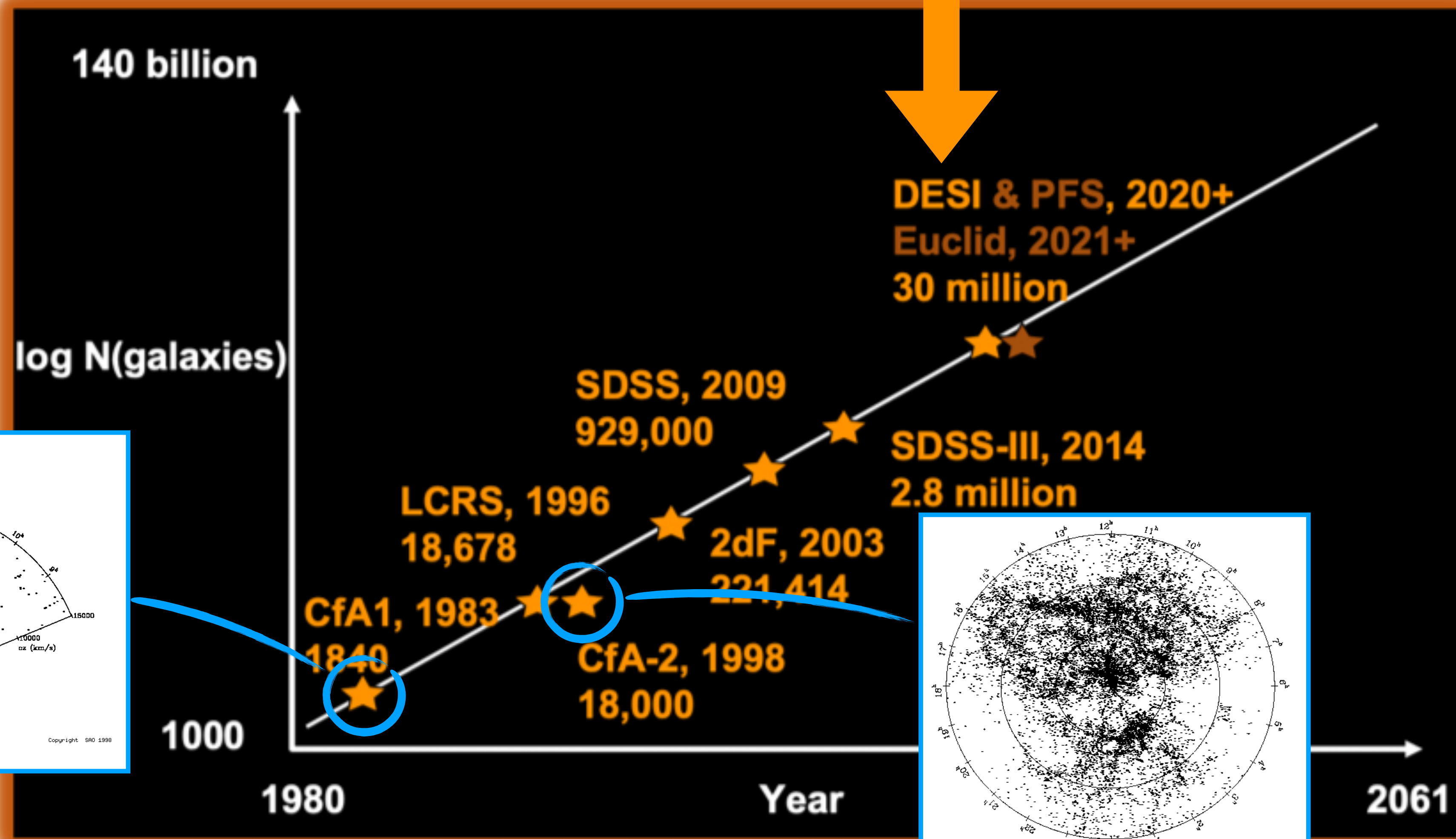


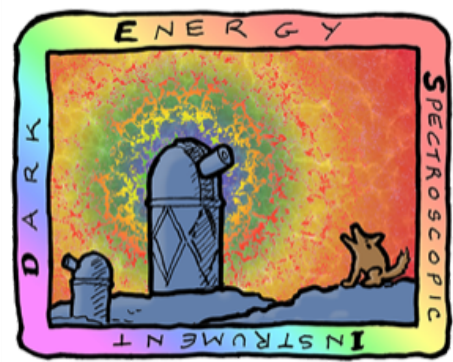


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Evolution of spectroscopic surveys

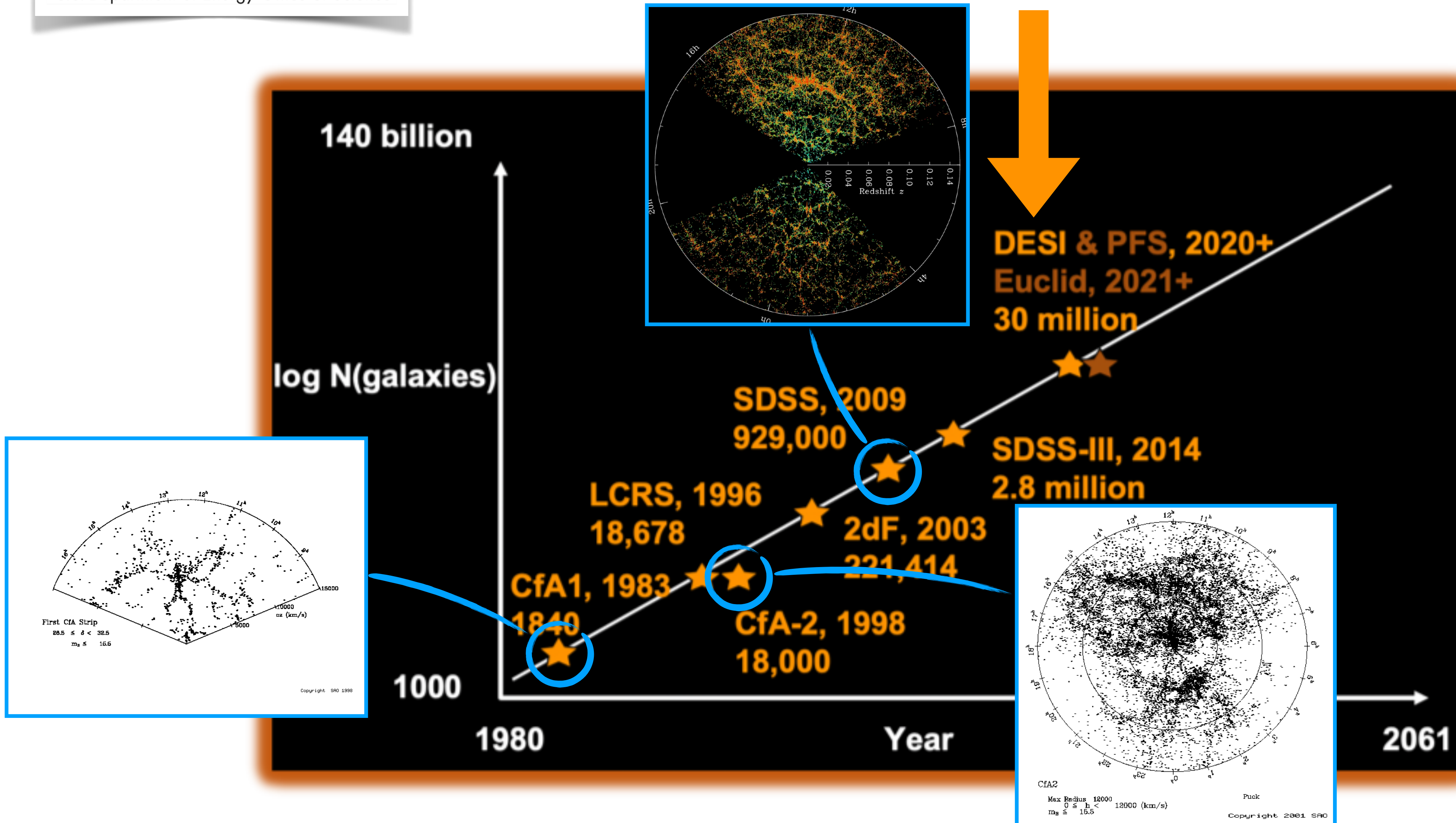


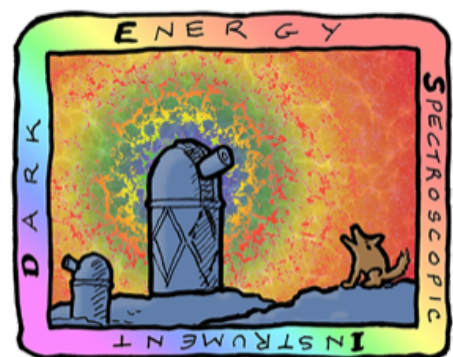


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Evolution of spectroscopic surveys

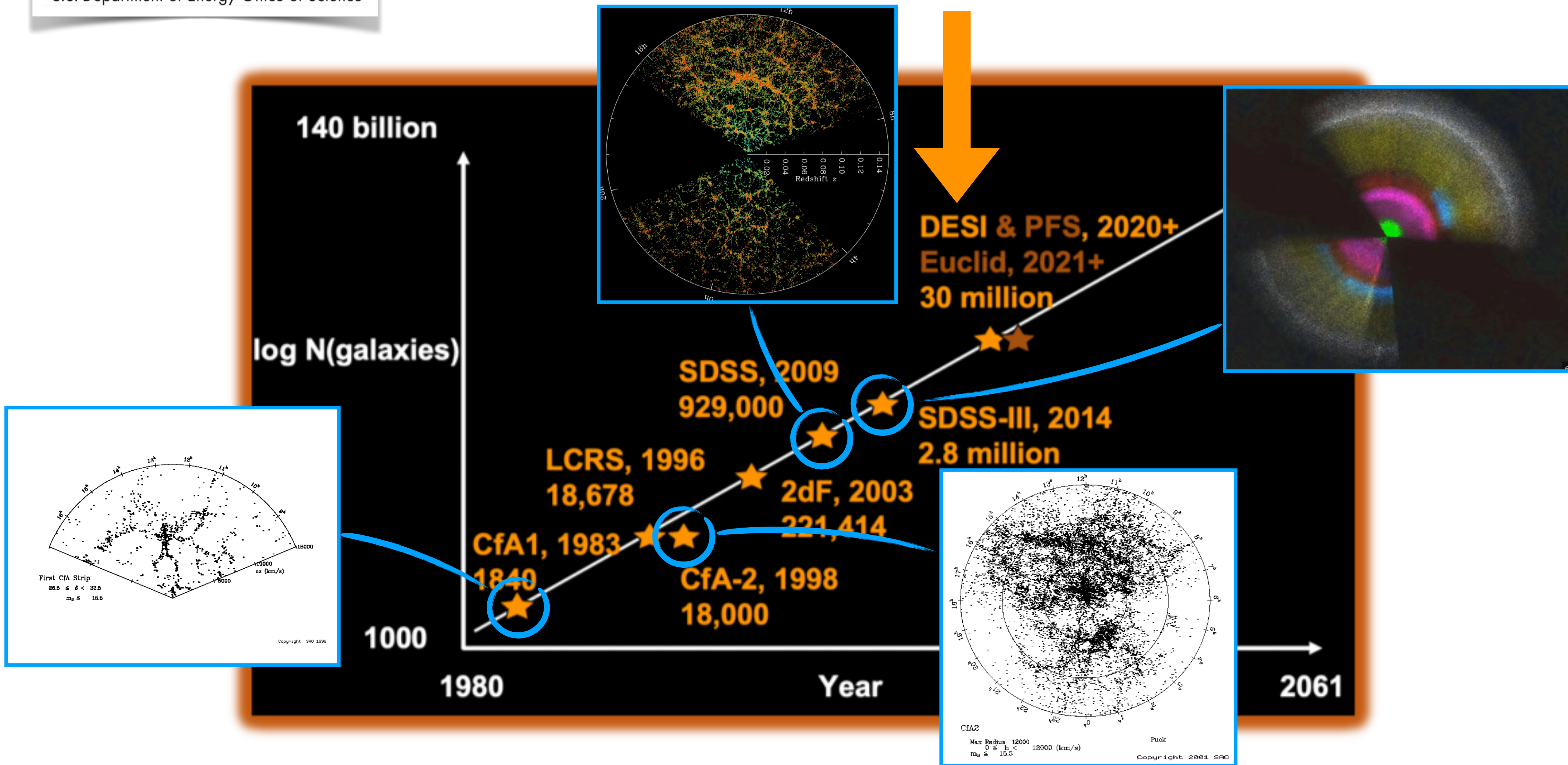


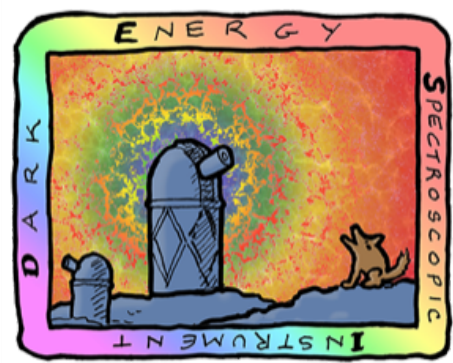


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Evolution of spectroscopic surveys





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RSD in Fourier space with varying line of sight

$$P_\ell(k) = \frac{(2\ell + 1)}{I} \int \frac{d\Omega_k}{4\pi} \left[\int d^3r_1 \int d^3r_2 F(\mathbf{r}_1)F(\mathbf{r}_2)e^{i\mathbf{k}\cdot(\mathbf{r}_1-\mathbf{r}_2)} \mathcal{L}_\ell(\hat{\mathbf{k}} \cdot \hat{\boldsymbol{\eta}}) - S(\mathbf{k}) \right]$$

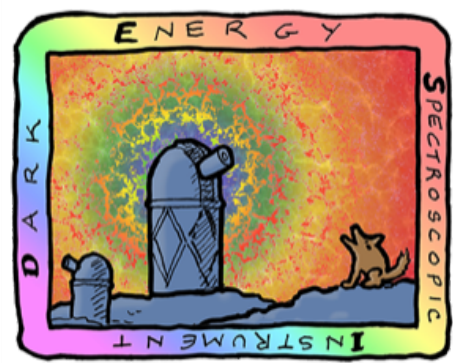
Legendre polynomials
Line of sight
Shot noise

$$F(\mathbf{r}) = n(\mathbf{r}) - \alpha n_s(\mathbf{r})$$

Yamamoto 2005

$$P_\ell(k) = \frac{(2\ell + 1)}{I} \int \frac{d\Omega_k}{4\pi} \left\{ \left[\int d^3r_1 F(\mathbf{r}_1)e^{i\mathbf{k}\cdot\mathbf{r}_1} \right] \left[\int d^3r_2 F(\mathbf{r}_2)e^{-i\mathbf{k}\cdot\mathbf{r}_2} \mathcal{L}_\ell(\hat{\mathbf{k}} \cdot \hat{\mathbf{r}}_2) \right] - S_\ell(\mathbf{k}) \right\}$$

with further manipulation (DB et al. 2015)
 this term can be evaluated via FFTs
 (see also Scoccimarro 2015, Hand et al. 2017)



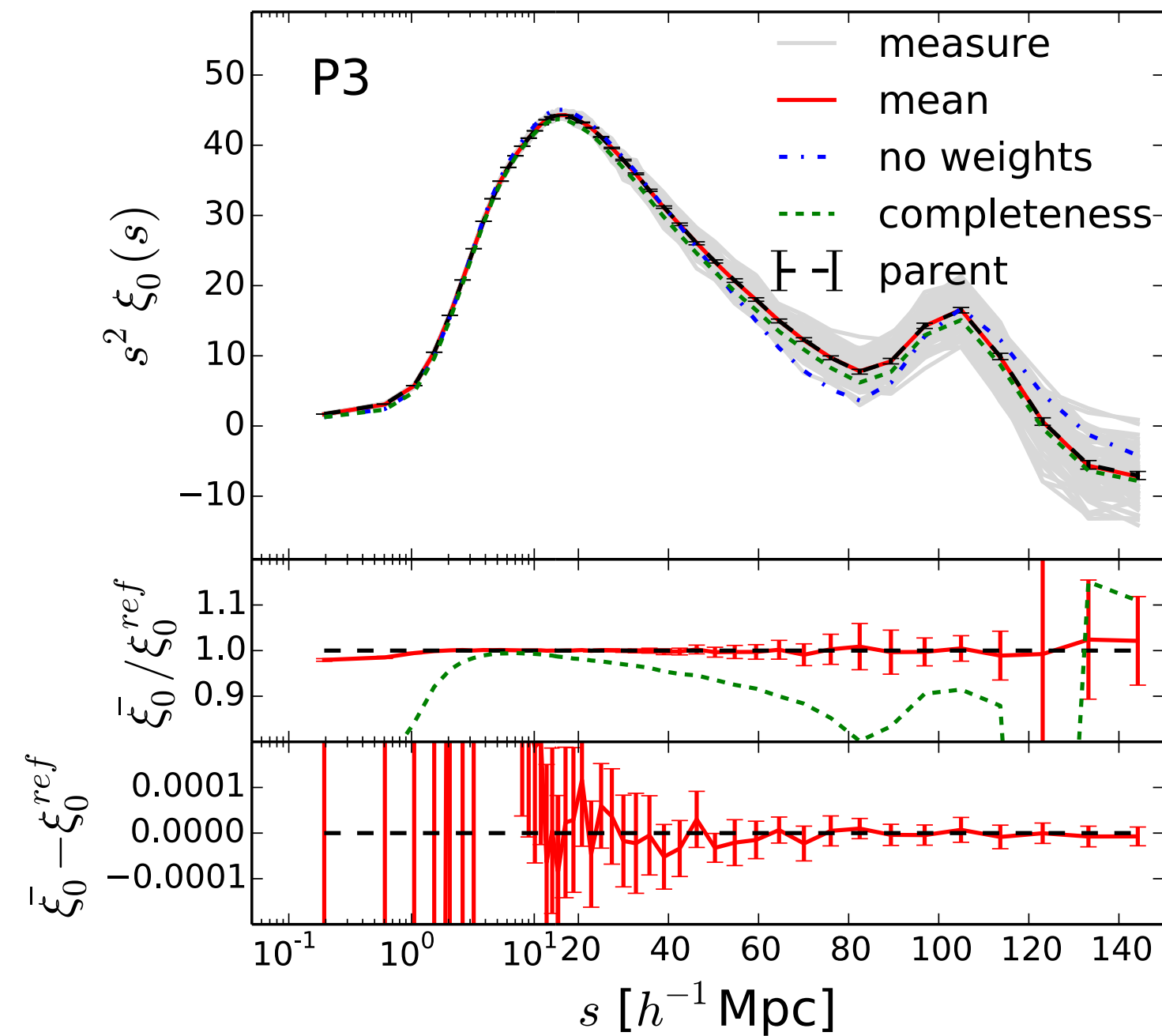
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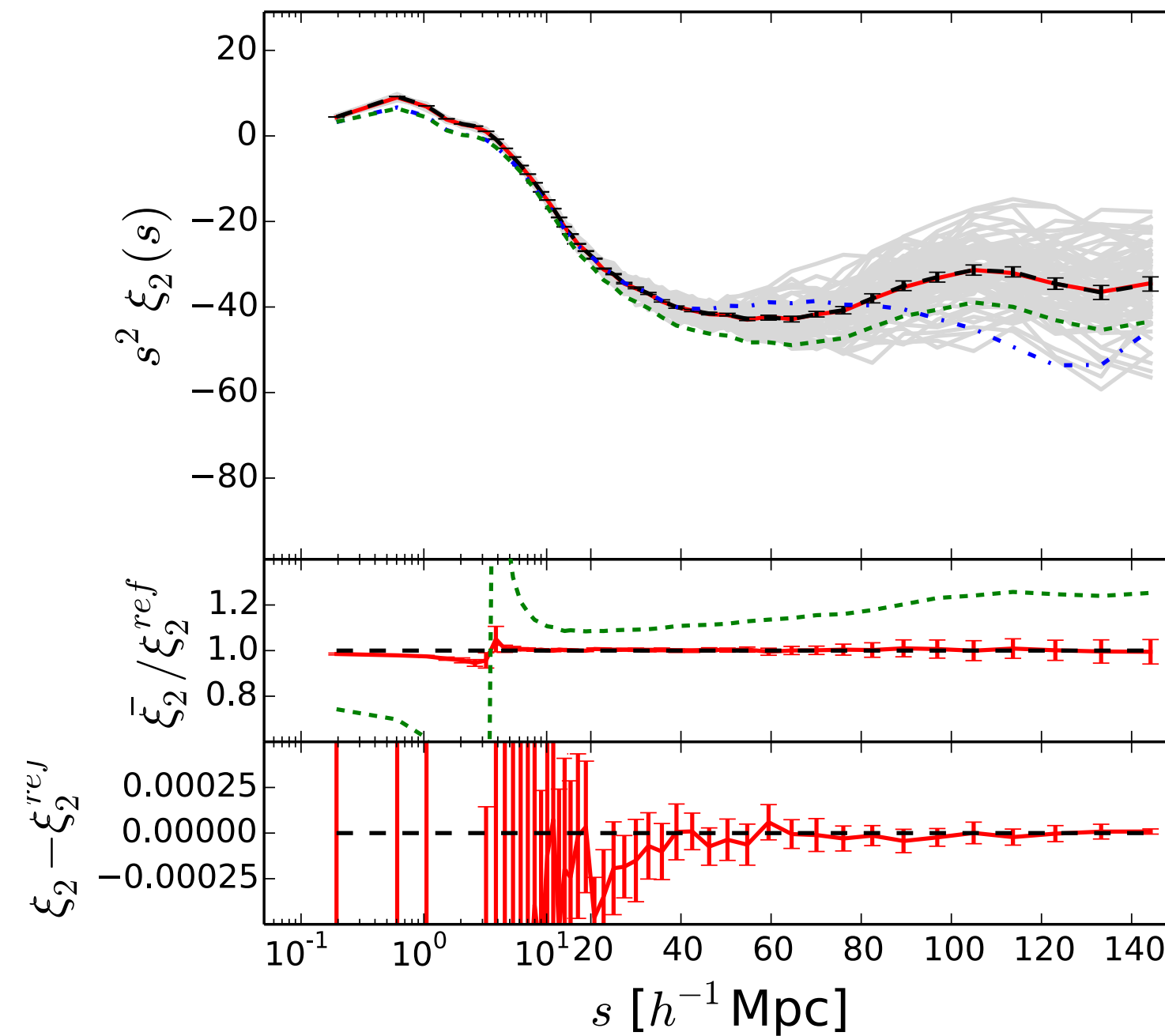
Missing observation: inverse-probability weights

DESI mocks, completeness = 67%

Monopole



Quadrupole



Hexadecapole

