Unraveling the Universe
with the Dark Energy Spectroscopic Instrument

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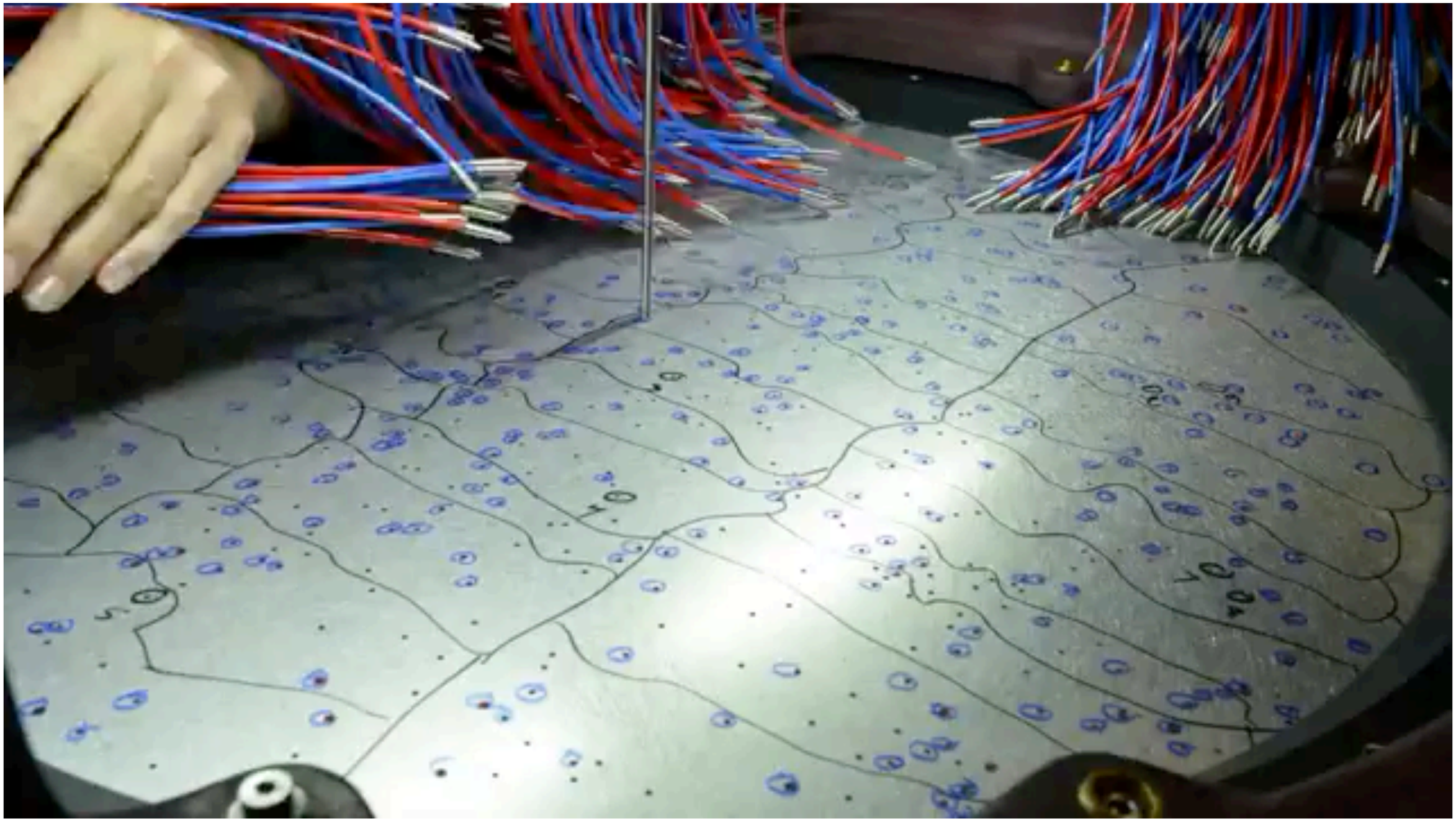
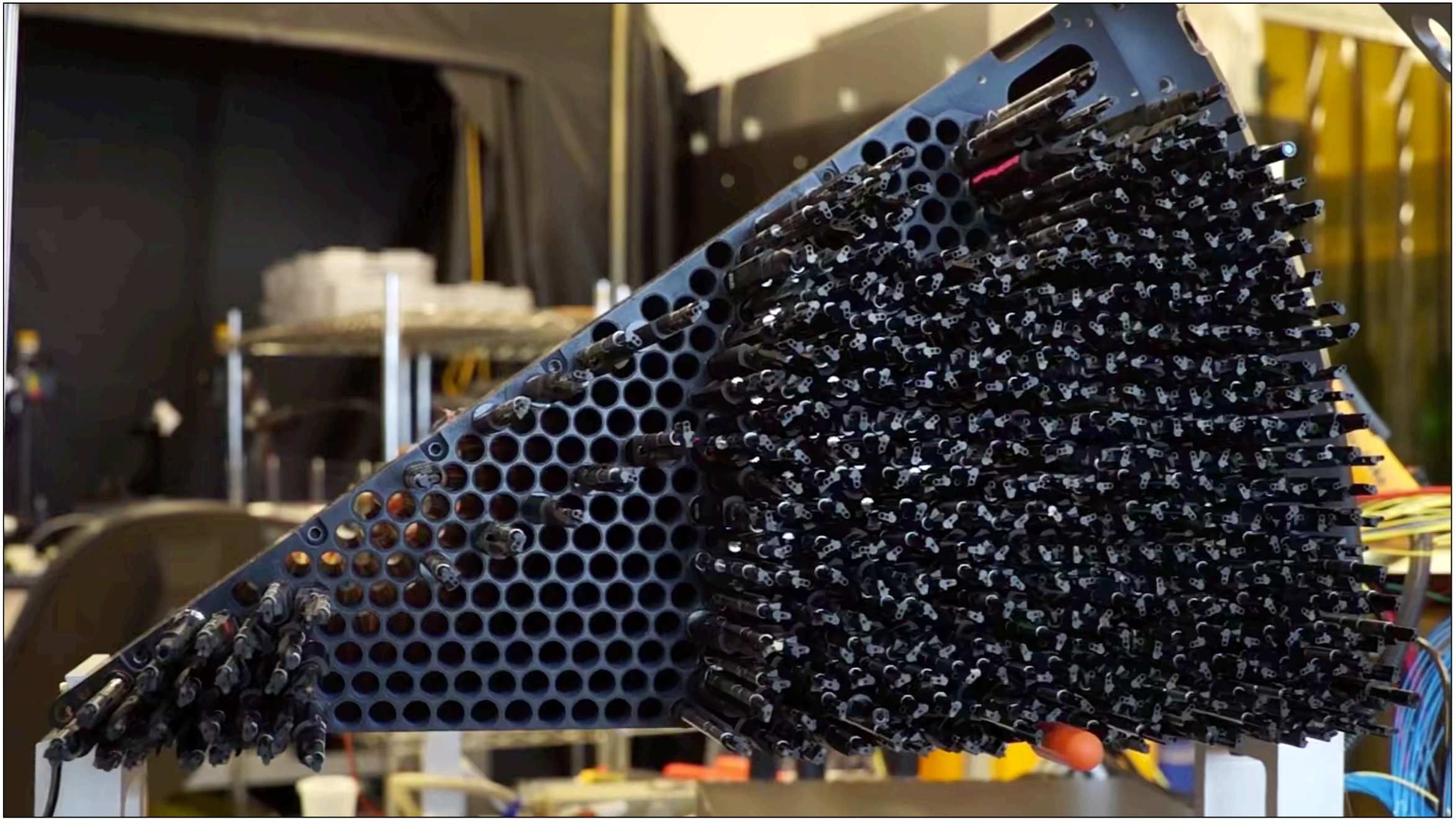
on behalf of the DESI Collaboration

BOSS/eBOSS Plate: 1000 optical fibers (2009-2018)



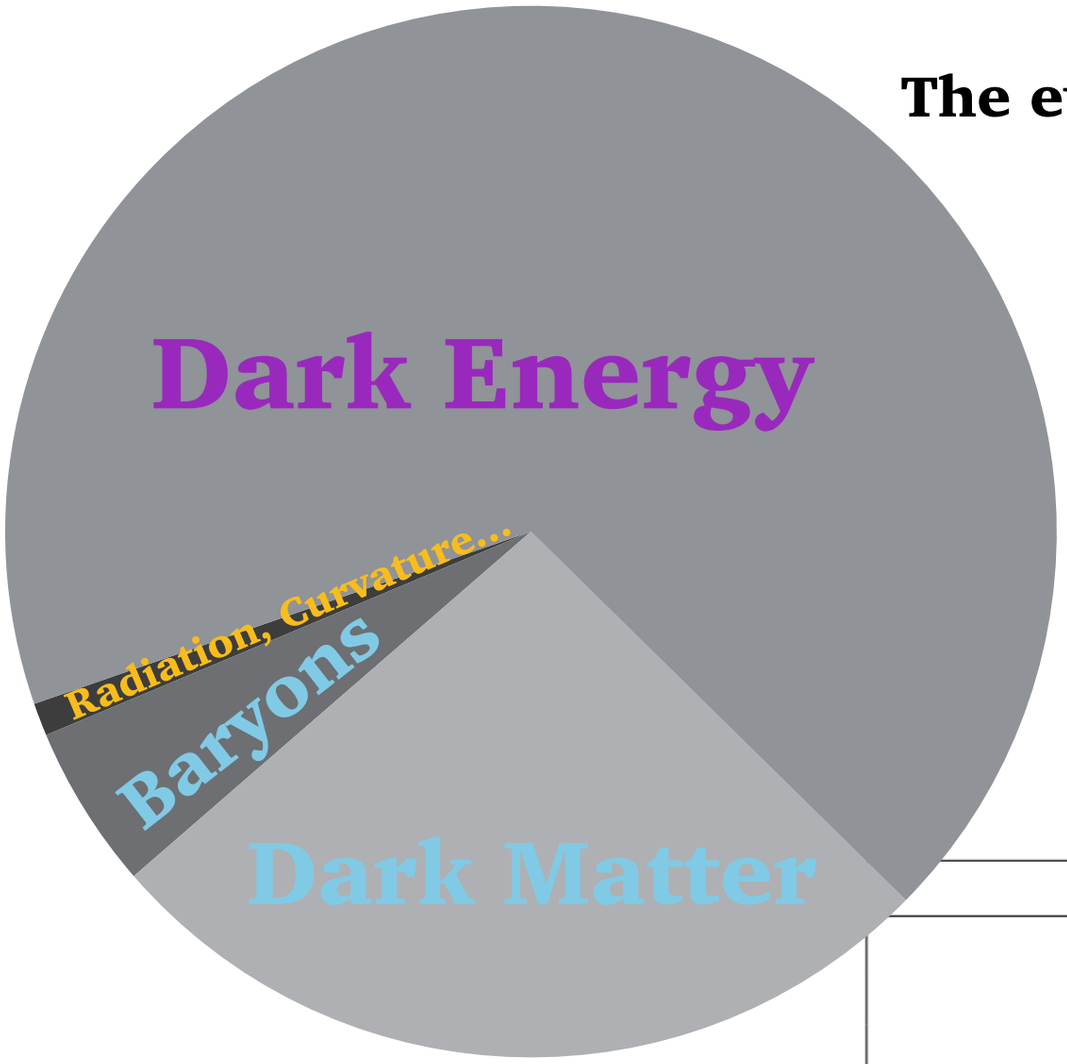
Credit: SDSS-III / Apache Point Observatory

DESI Petal with Fiber Positioners: 500 fibers x 10 petals (now !)



Credit: DESI / LBL

Cosmological Standard Model



The evolution of the Universe is driven by its content.

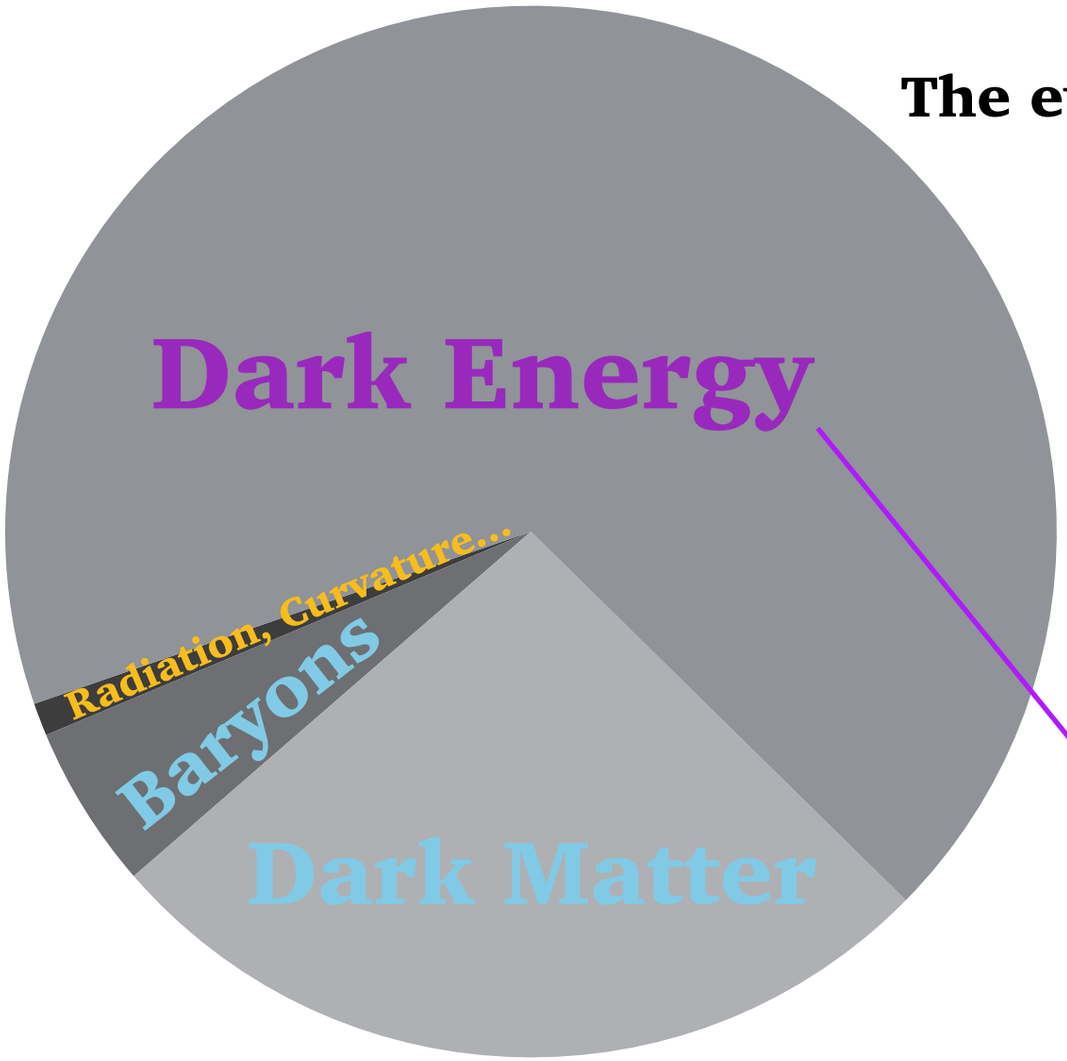
Acceleration of the Expansion of the Universe

↕

Dark Energy dominated era

-Epoch-/Event	Time	Temp. (K)	Energy (eV)	Redshift
Hot Big Bang	-	-	-	-
Inflation	-	-	-	-
Reheating	-	0	-	$\sim 10^{28}$
-Radiation domination era-	**-**	**-**	**-**	**-**
Baryongenesis-Leptogenesis	10^{-4} s	2×10^{12}	2×10^{8}	10^{11}
Primordial Nucleosynthesis	100 s	10^{9}	10^{5}	10^{9}
-Matter domination era-	**100 kyrs**	**9000**	**0.81**	**3400**
Recombination	380 kyrs	3000	0.3	1100
reionization	320 Myrs	120	0.01	20
First galaxies formation	1.3 Gyrs	60	5×10^{-3}	10
-Dark Energy domination era-	**9.4 Gyrs**	**4.8**	$\mathbf{4{\times}10^{-4}}$	**0.75**
Today	15 Gyrs	2.7	2.35×10^{-4}	0

Cosmological Standard Model



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Dark Energy dominated era

Within the context of GR Dark Energy is understood as a macroscopic manifestation of the quantum vacuum energy

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} - \Lambda g_{\mu\nu}$$

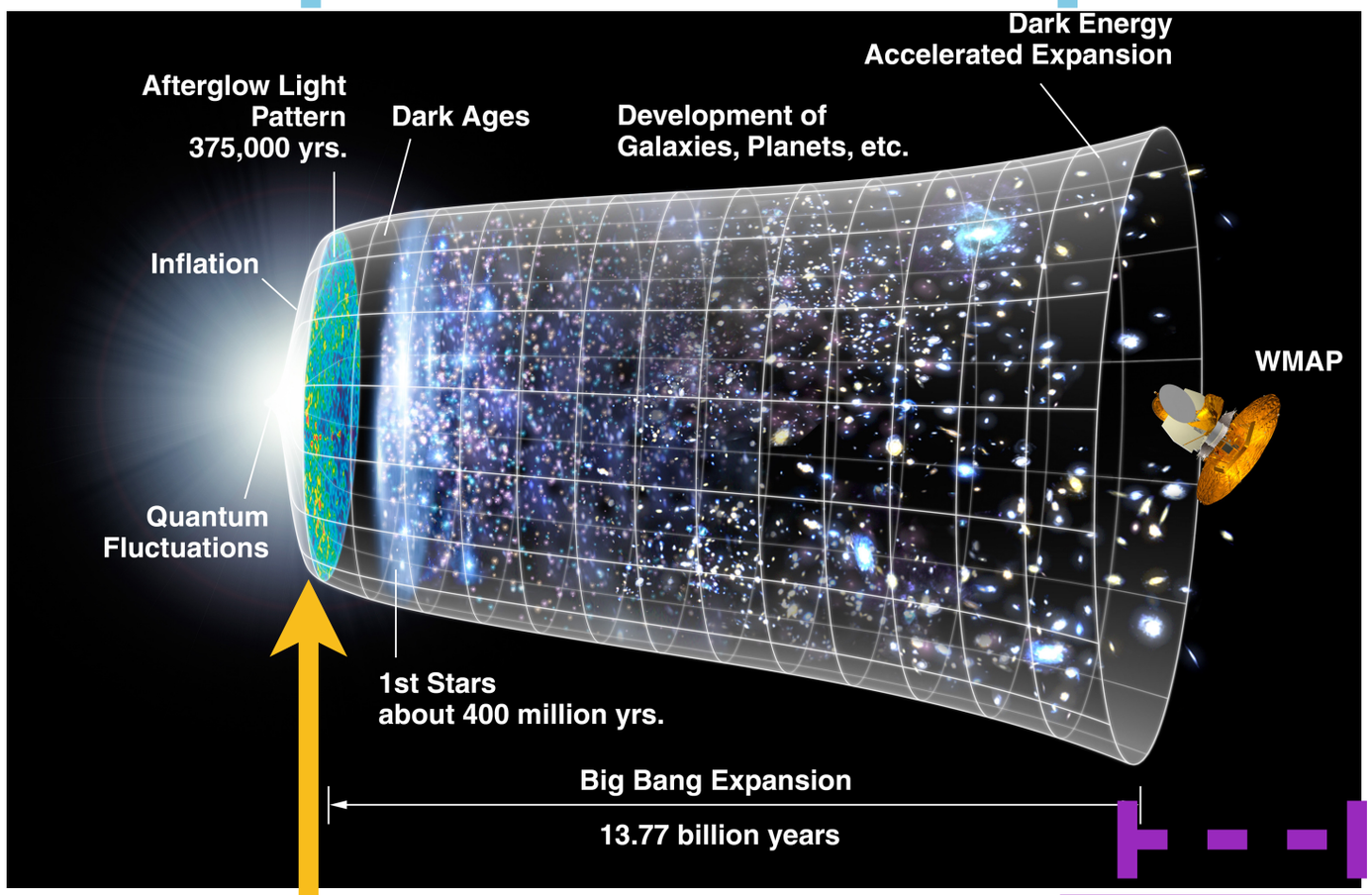
Other alternatives include: Modified Gravity, time evolving DE,…

All these different DE theories —> different expansion rate H(z), and different logarithmic growth of structure factor $f(z)\sigma_8(z)$

Strong constraints on cosmology from measurements at z > 0.75 with Planck, SDSS-III/BOSS (quasars, Lyman-alpha forest)

Matter Dominated

+ SDSS-III/BOSS (galaxies) at z < 0.7



Percent level precision

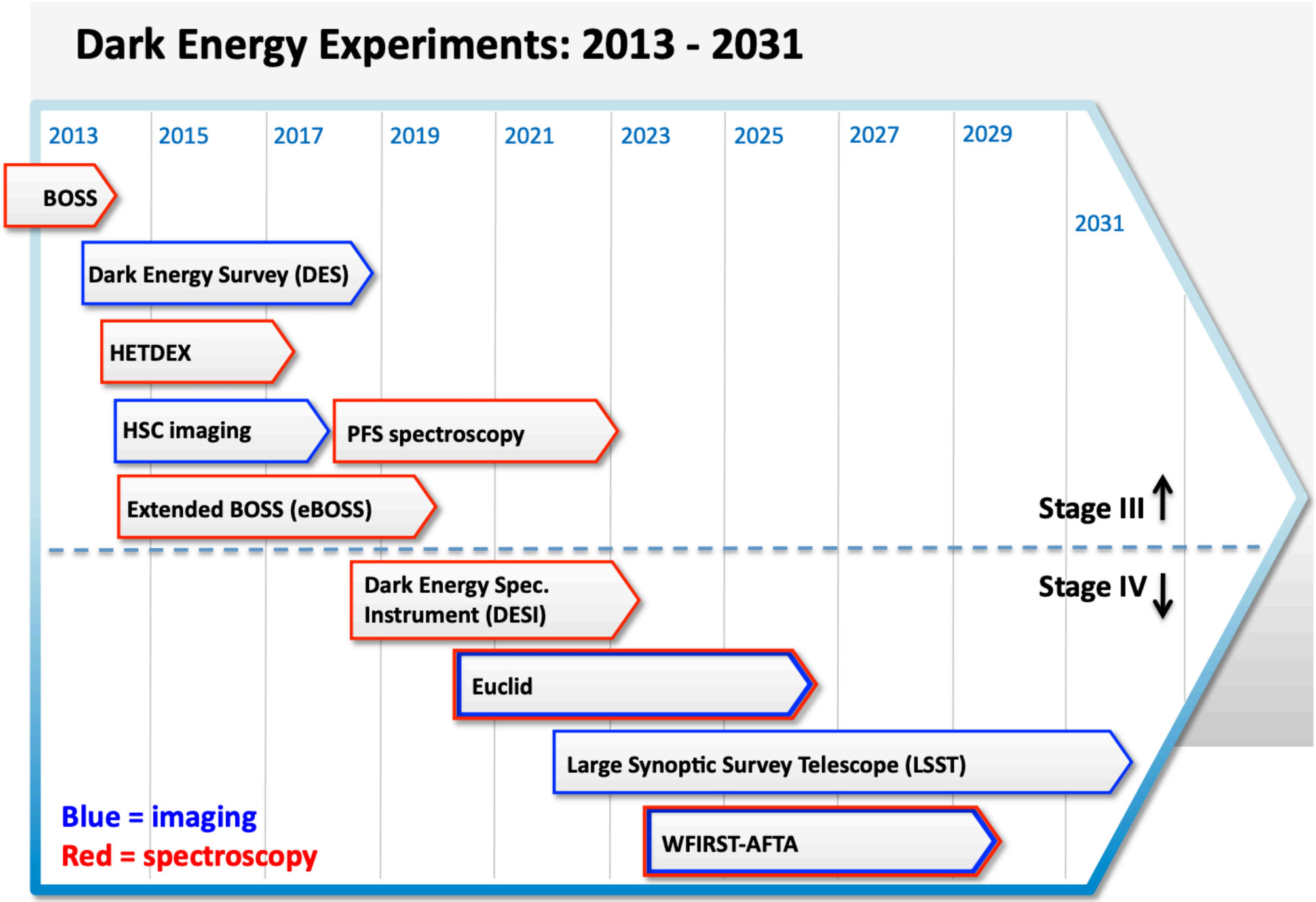
Radiation Dominated

Dark Energy Dominated

DESI (right now!)

Sub-percent level precision

Dark Energy Program (US Centric)



Key Goal: Achieve a Stage IV Dark Energy Experiment

Figure of Merit 10x better than Stage II
Figure of Merit 3x Stage III.

How to do this with minimum cost and maximum science?

Maximize the volume surveyed: 14,000 sq. deg. survey (baseline)

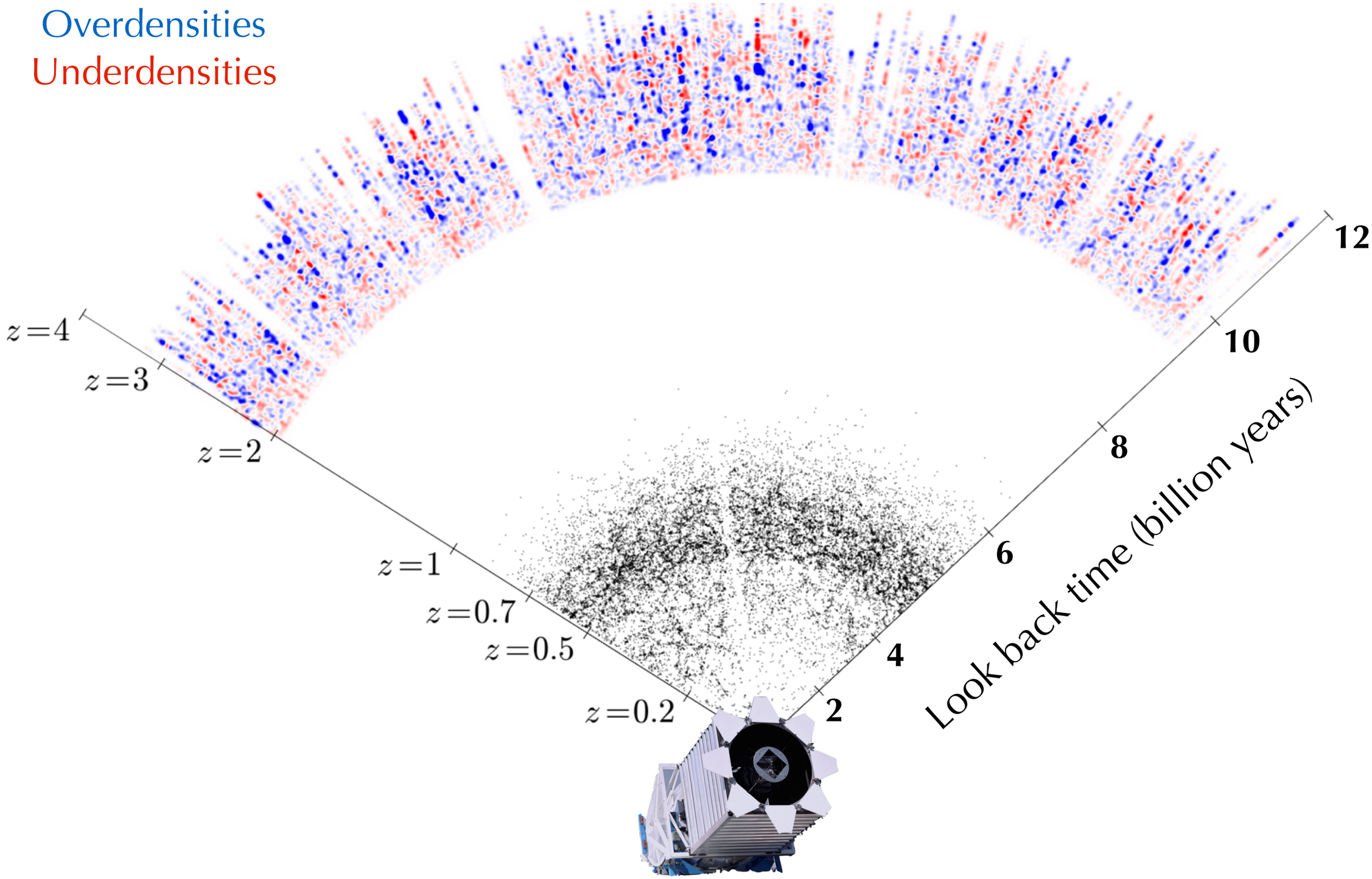
Sample the density field with high enough fidelity

Mapping the Universe with SDSS-III

Early 2010s

SDSS ~$2h^{-3}Gpc^3$ ⇨ BOSS ~$6h^{-3}Gpc^3$

Overdensities
Underdensities



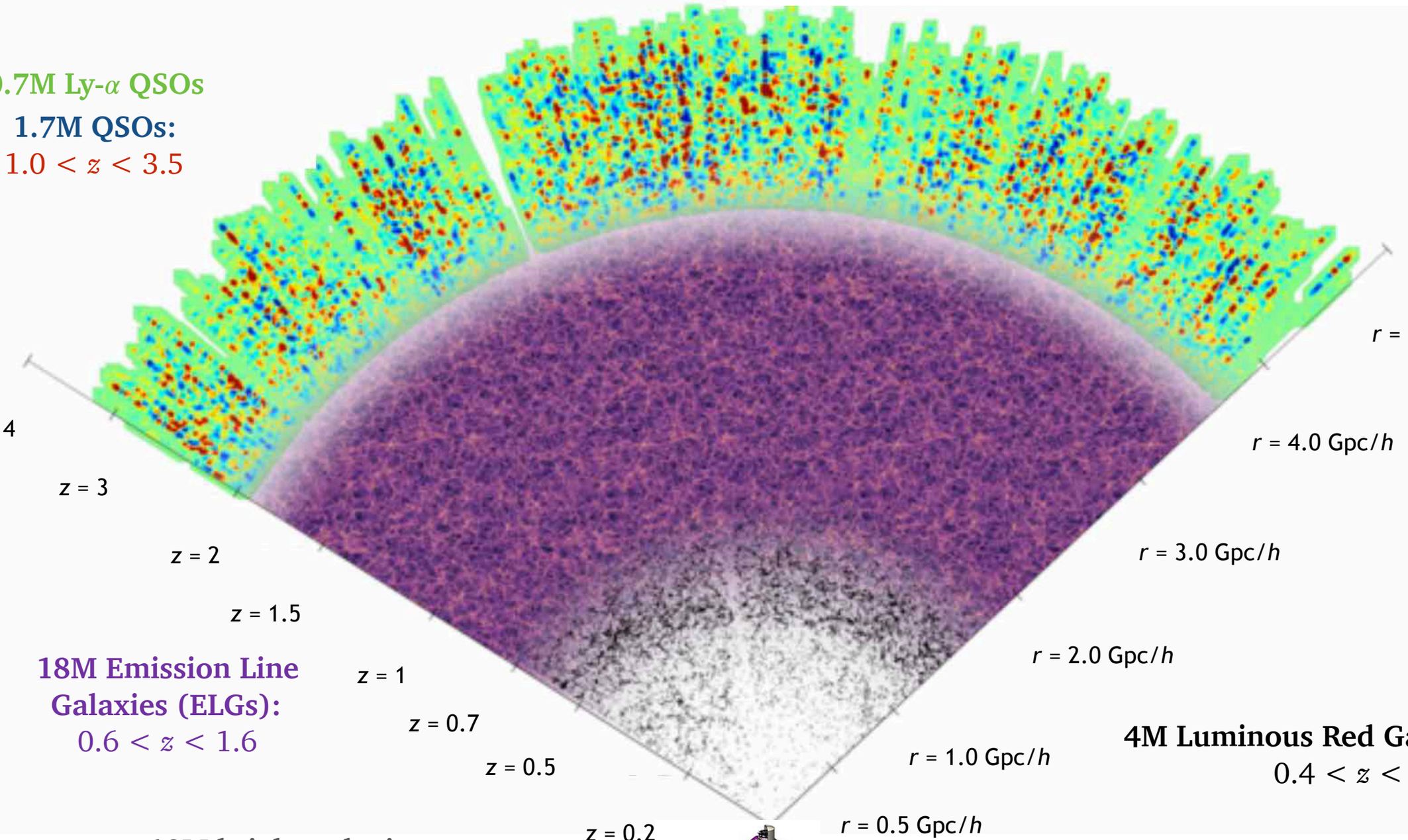
DESI Survey: 35M redshifts in 5 years

Early 2020s

BOSS ~6h^{-3}Gpc^3 ⇨ DESI 50h^{-3}Gpc^3

0.7M Ly-α QSOs

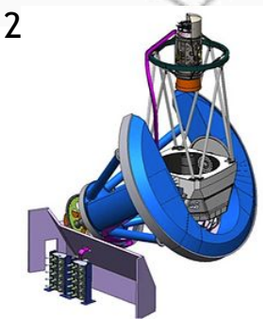
1.7M QSOs:
$1.0 < z < 3.5$



18M Emission Line Galaxies (ELGs):
$0.6 < z < 1.6$

4M Luminous Red Galaxies (LRGs)
$0.4 < z < 1.0$

10M bright galaxies
$r < 19.5,\ z < 0.4$



Milky Way Survey: ~10M stars

Key Goal: Achieve a Stage IV Dark Energy Experiment

Figure of Merit 10x better than Stage II
Figure of Merit 3x Stage III.

How to do this with minimum cost and maximum science?

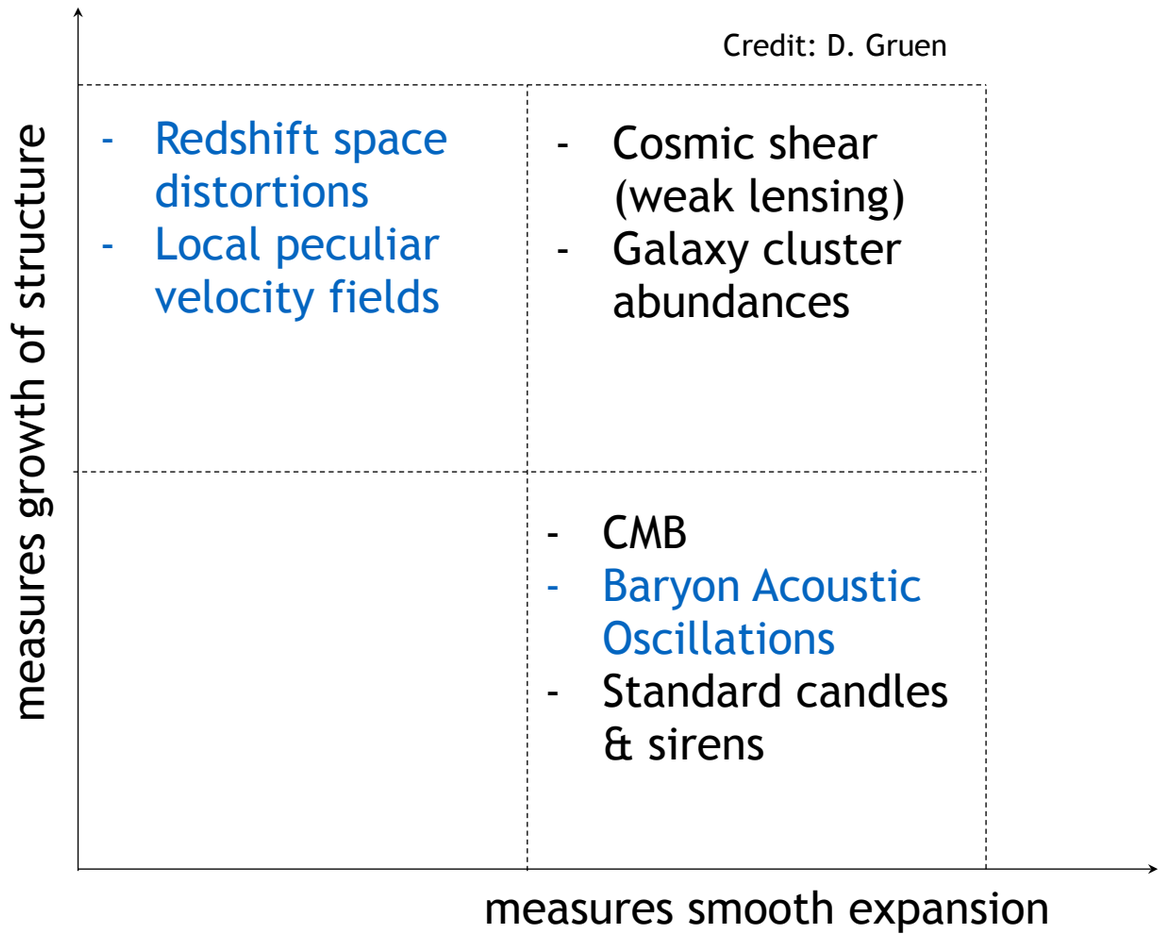
Use robust techniques:

Baryon Acoustic Oscillations (BAO)

Redshift Space Distortions (RSD)

DESI will do both in one survey

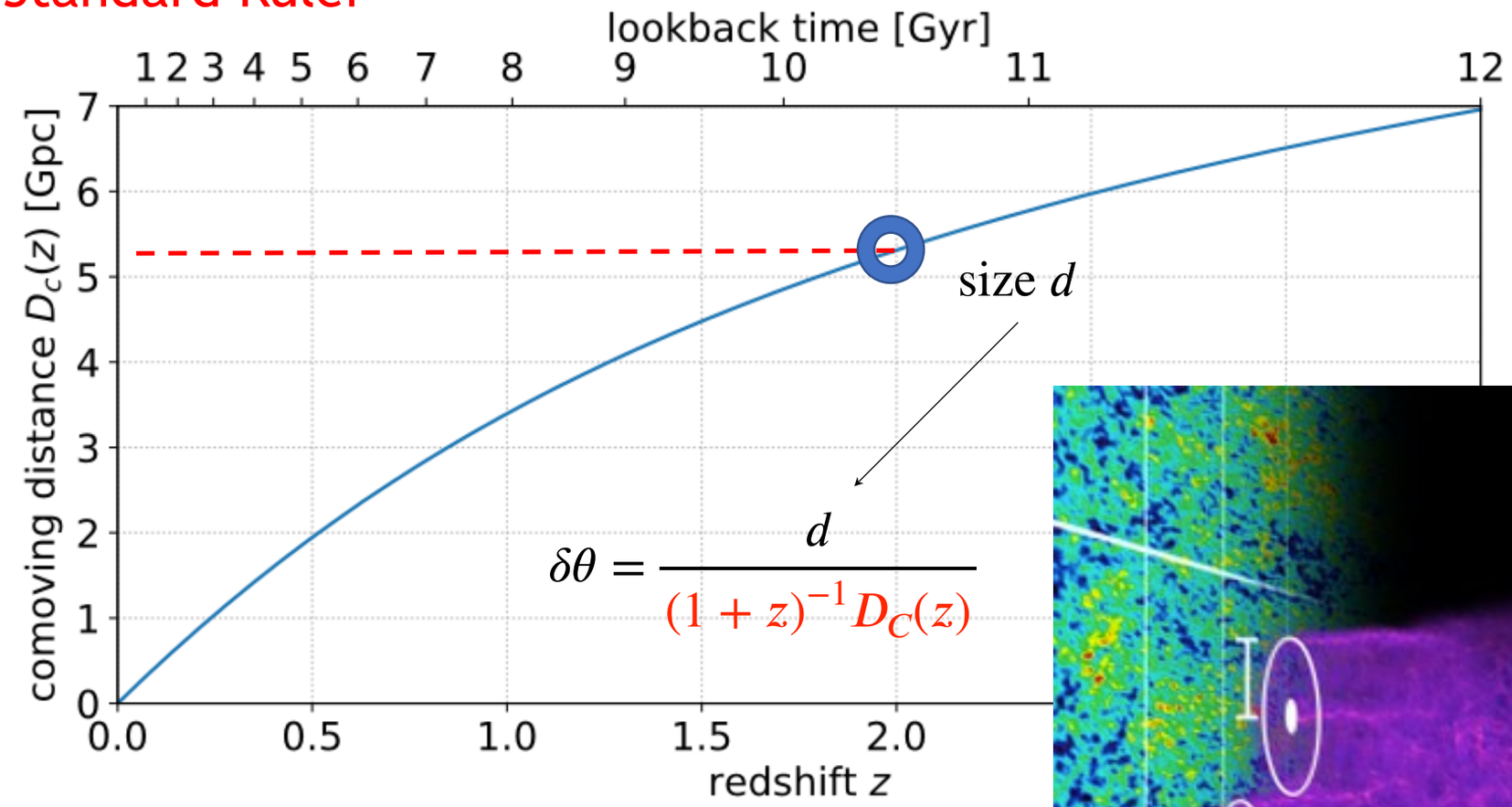
Important:
many observational probes with different (and often complementary) systematic uncertainties.

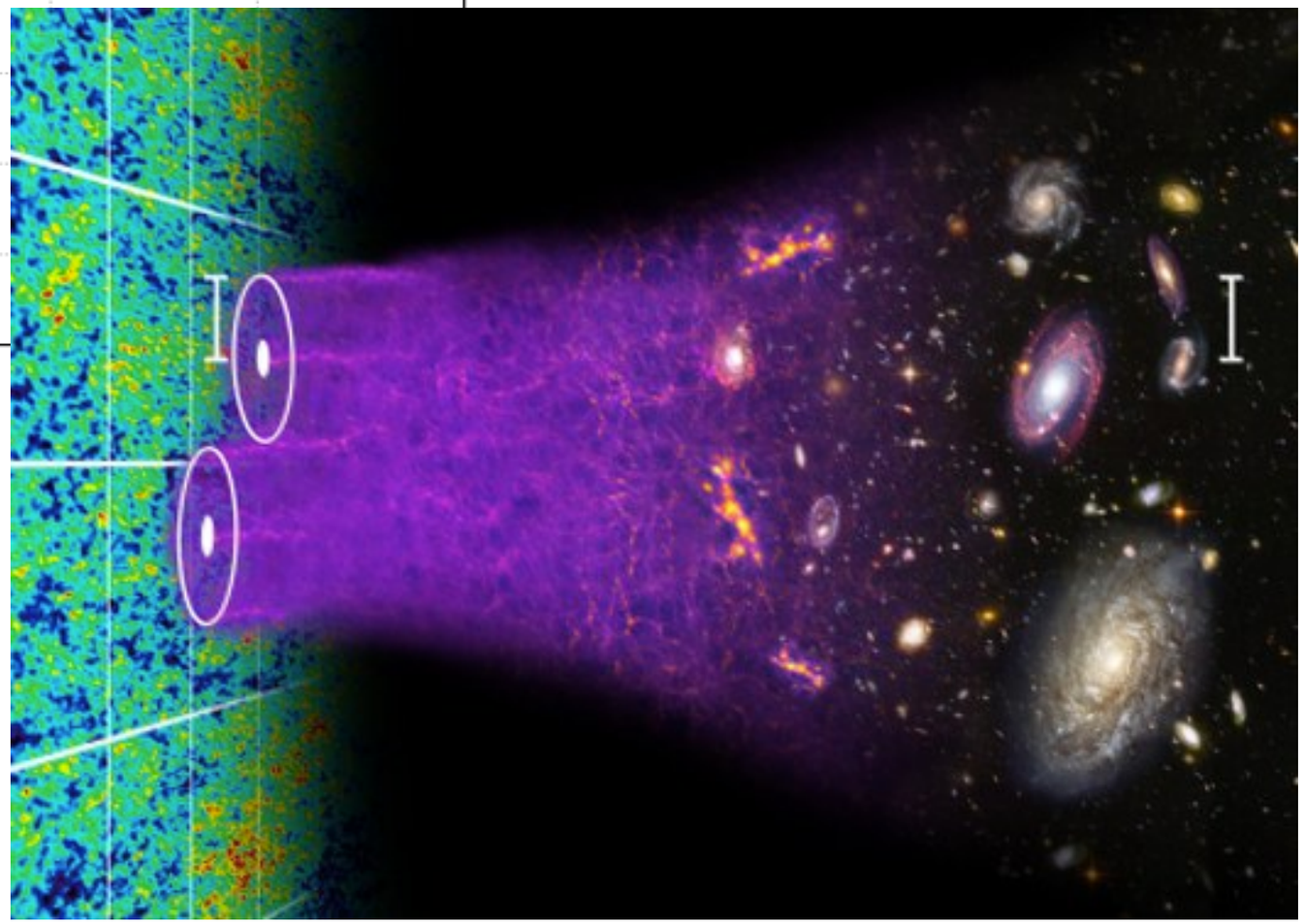


Dark Energy Part I: the Hubble Expansion Observable: Baryon Acoustic Oscillation (BAO)

Measuring the Hubble Expansion

Standard Ruler

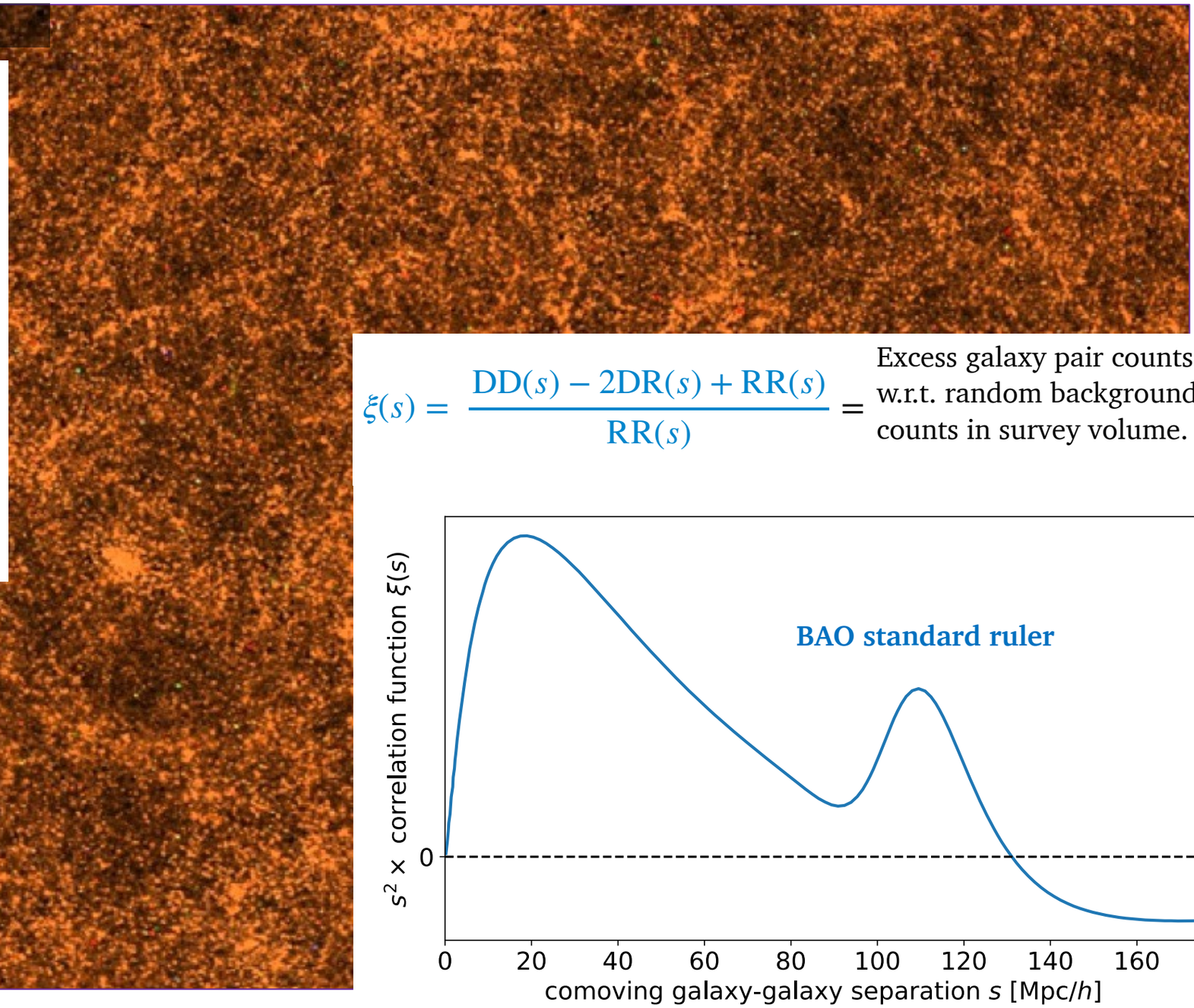


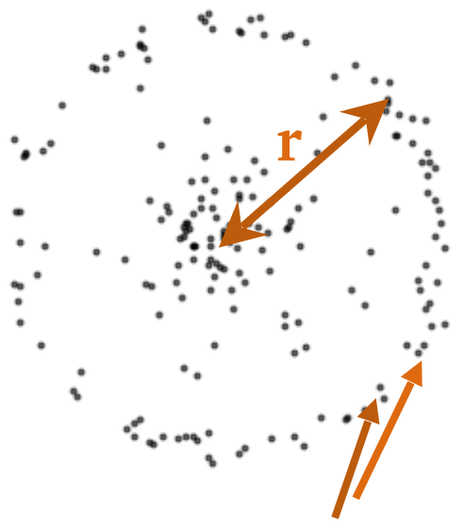


Credit: D. Kirkby, SDSS-III

Mapping the density field

Credit: SDSS III Collaboration, Aihara+ 2011



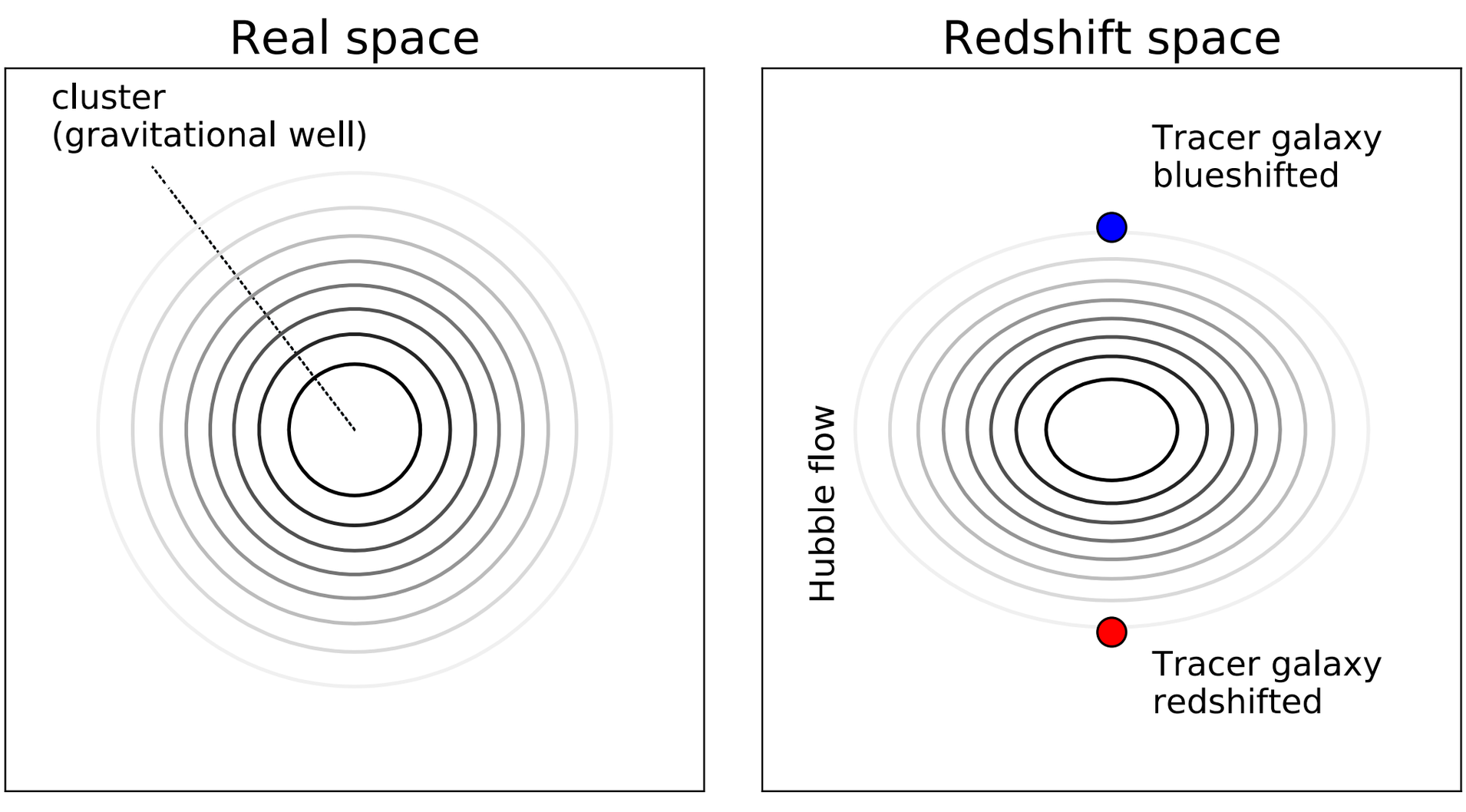


Tracer galaxy "test particles"

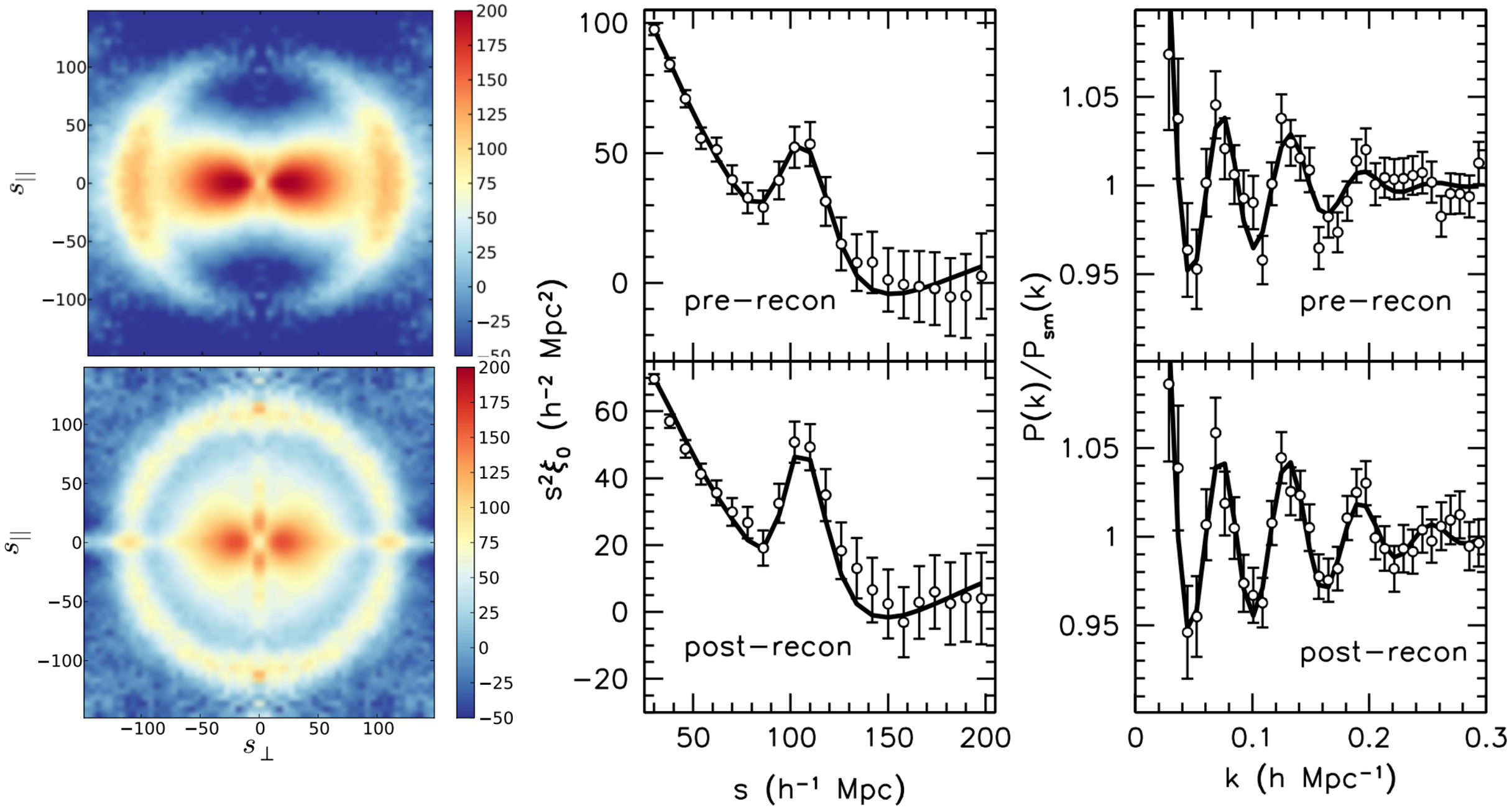
$$\xi(s) = \frac{\mathrm{DD}(s) - 2\mathrm{DR}(s) + \mathrm{RR}(s)}{\mathrm{RR}(s)} =$$ Excess galaxy pair counts in data w.r.t. random background pair counts in survey volume.

Systematics : Redshift Space Distortions

- Tracer galaxies are gravitationally attracted to clusters (peculiar motion).
- In redshift space, clusters appear squashed and voids appear stretched along the line of sight.
- Redshift space distortions (RSDs) create artificial anisotropy in the BAO.



BAO after Reconstruction (BOSS DR11)



Credit: Padmanabhan+ 2012

Dark Energy Part II: Growth of Structure Observable: Redshift Space Distortion (RSD)

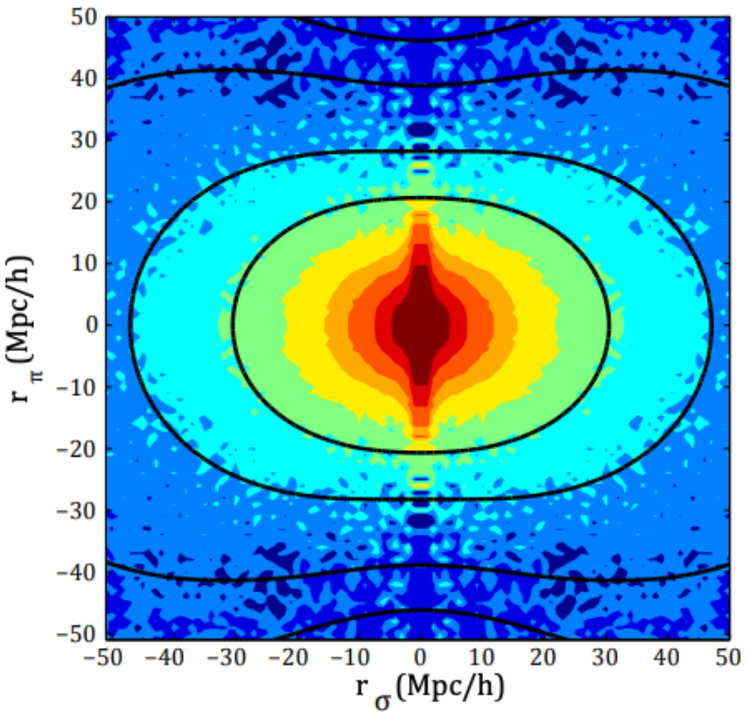
Growth of Structure information contained in RSD

- RSD must be removed to study the BAO standard ruler, but they are extremely useful in their own right!
- The anisotropy produced by RSD constrains $f\sigma_8$, where f is the growth rate of structure and σ_8 is the normalized amplitude of mass fluctuations.
- Growth index predicted by GR, as such measuring $f\sigma_8$ allows to test theories of gravity

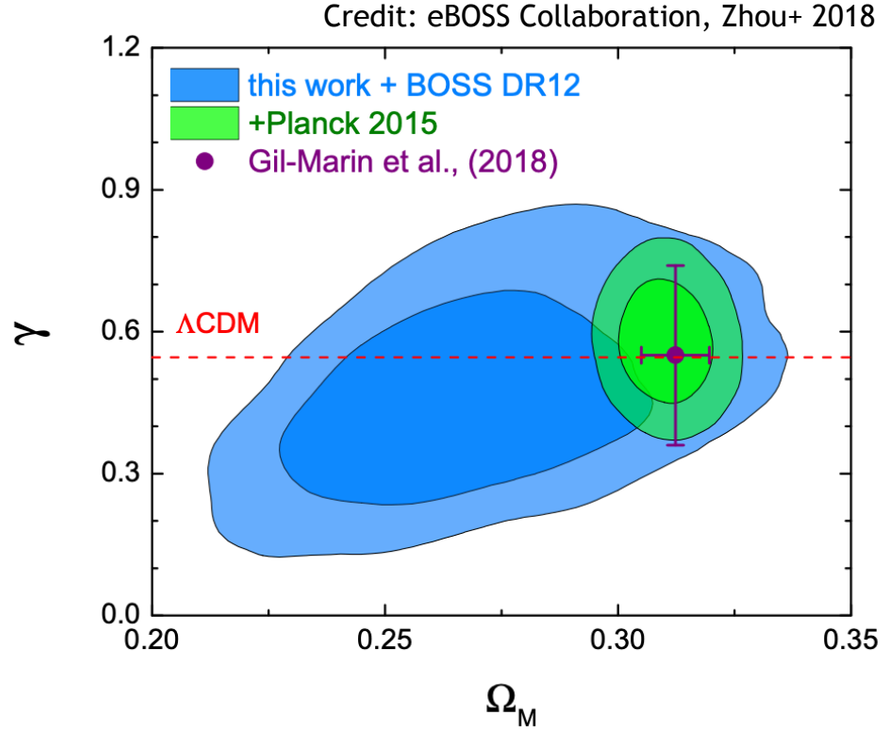
$$f(z) \approx \Omega_m(z)^{\gamma}$$

Growth rate of structure — Matter density — Growth index

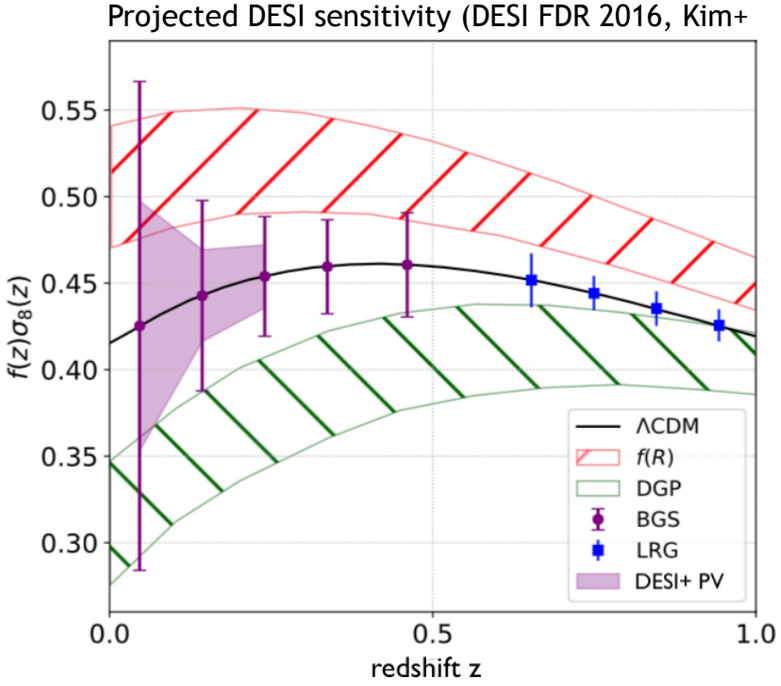
Credit: BOSS Collaboration, Alam+ 2017



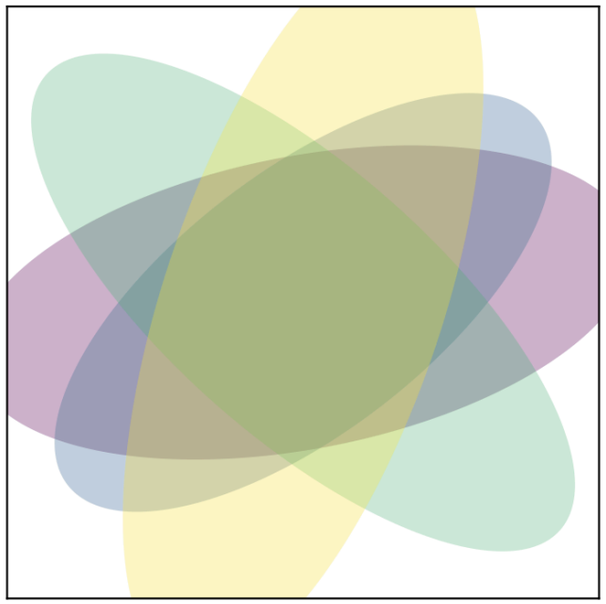
Credit: eBOSS Collaboration, Zhou+ 2018

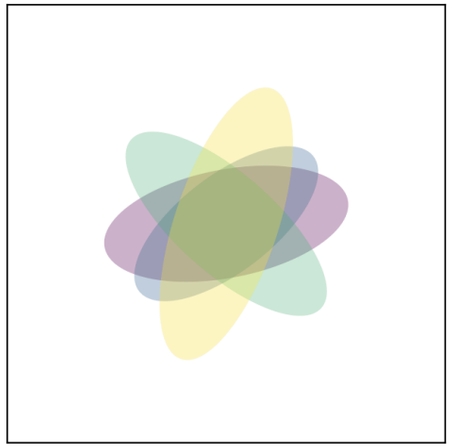


Projected DESI sensitivity (DESI FDR 2016, Kim+



Testing LCDM: the next 5 years





Confirmation

New systematics ?

New physics ?

Credit: D. Kirkby

Requirements & Predictions

DESI Science Requirements

- Measure the distance scale from BAO:

  0.28% precision from $0 < z < 1.1$

  0.39% precision from $1.1 < z < 1.9$

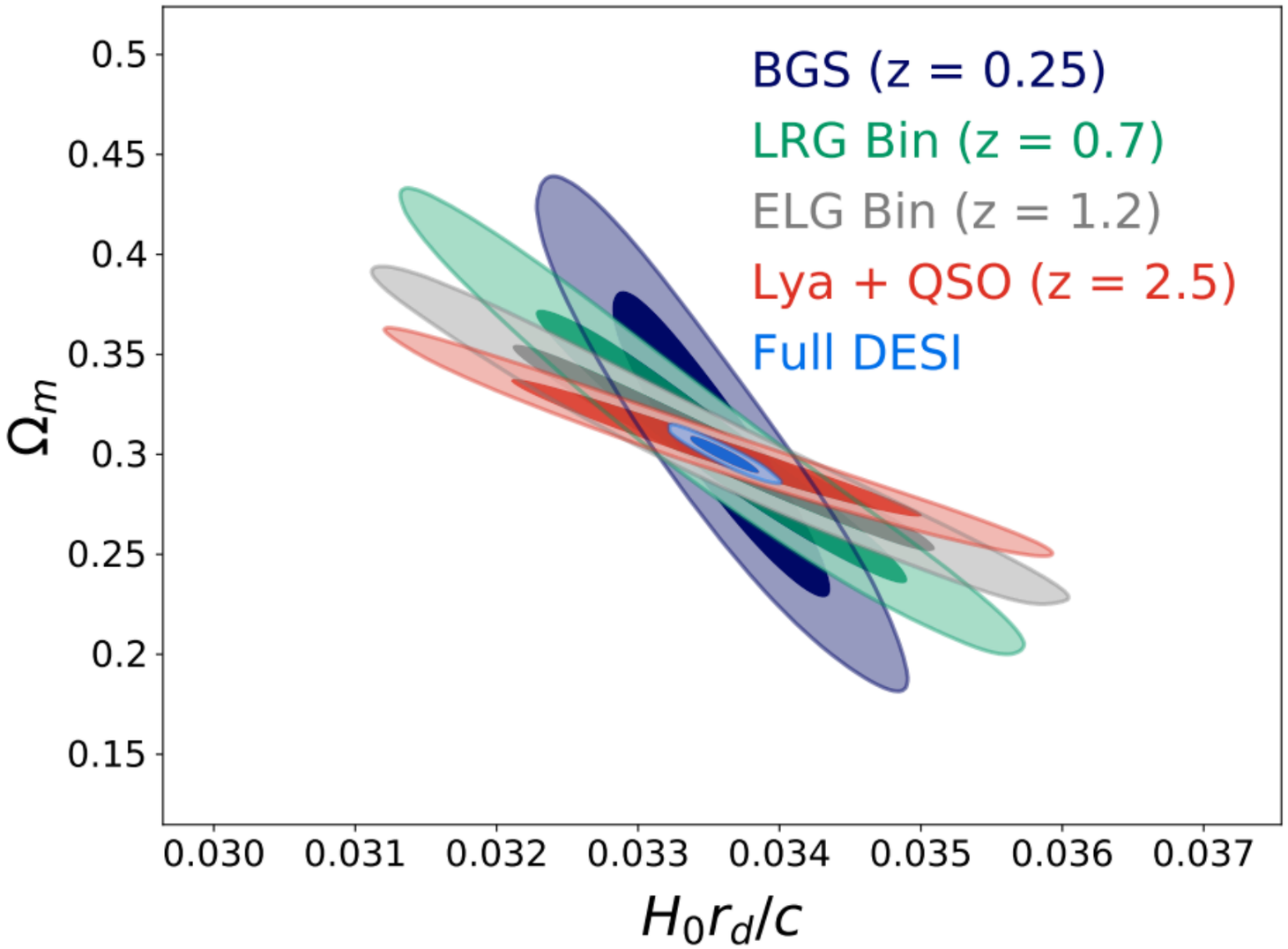
- Measure the Hubble Parameter to 1.05% at $1.9 < z < 3.7$ from BAO

- Galaxy survey at $z < 1.5$ should be capable of separately determining $D_A(z)$ and $H(z)$ from BAO

  systematic errors from instrument and observational effects must not exceed 0.16% for D_A and 0.26% for H

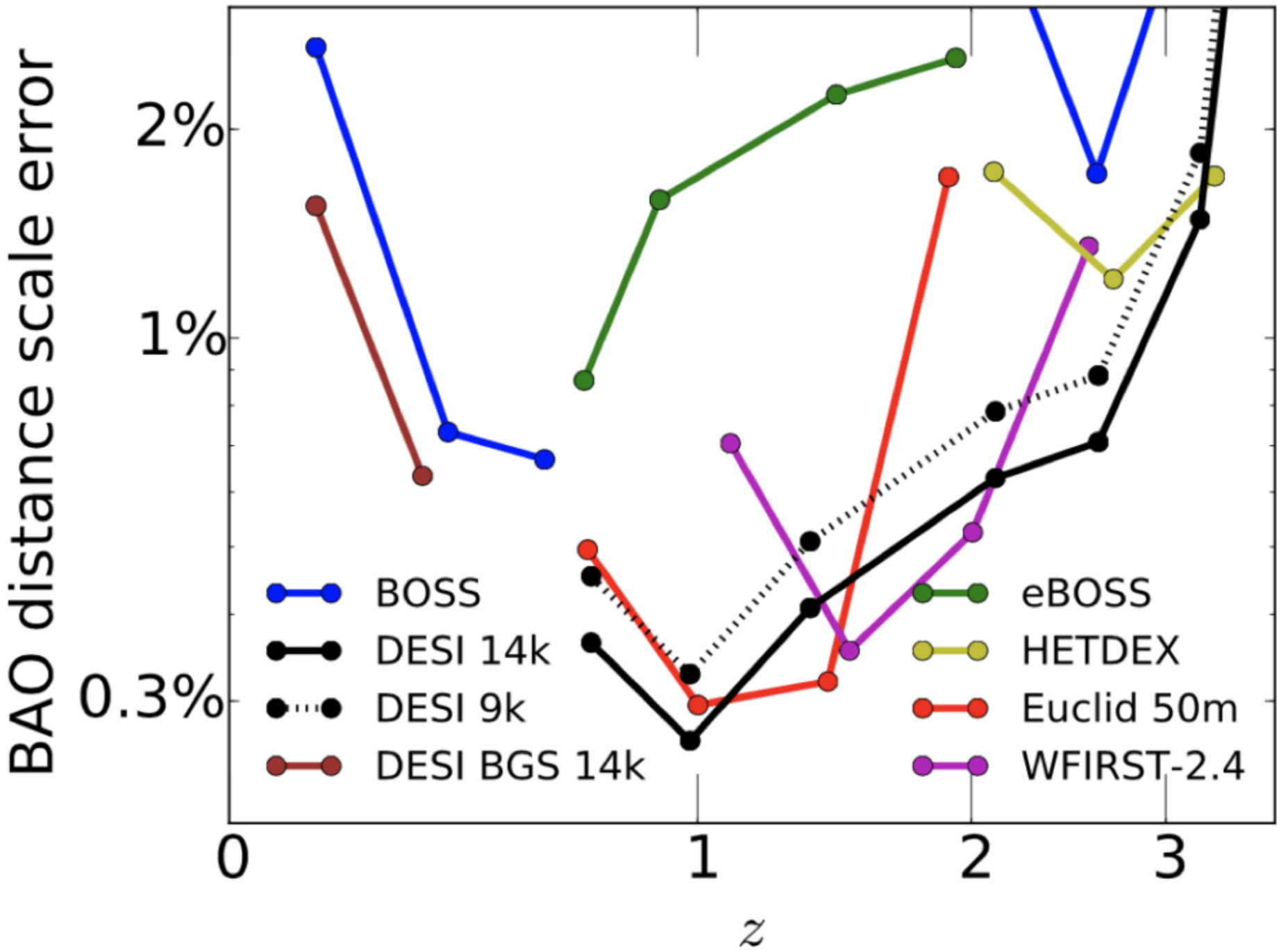
H0 Sensitivity Forecast for DESI

Expect much tighter contours in the Ω_m-H_0 plane with DESI due to 10x higher statistics.



Credit: Cucei+ 2019

BAO Distance Error for DESI



Additional Science Goals

DESI Science "Bonus"

These goals do not drive the survey design or science requirements, but are achievable using the baseline survey !

- Gravitational growth

  measure the growth factor to < 1% at 0.5 < z < 1.4

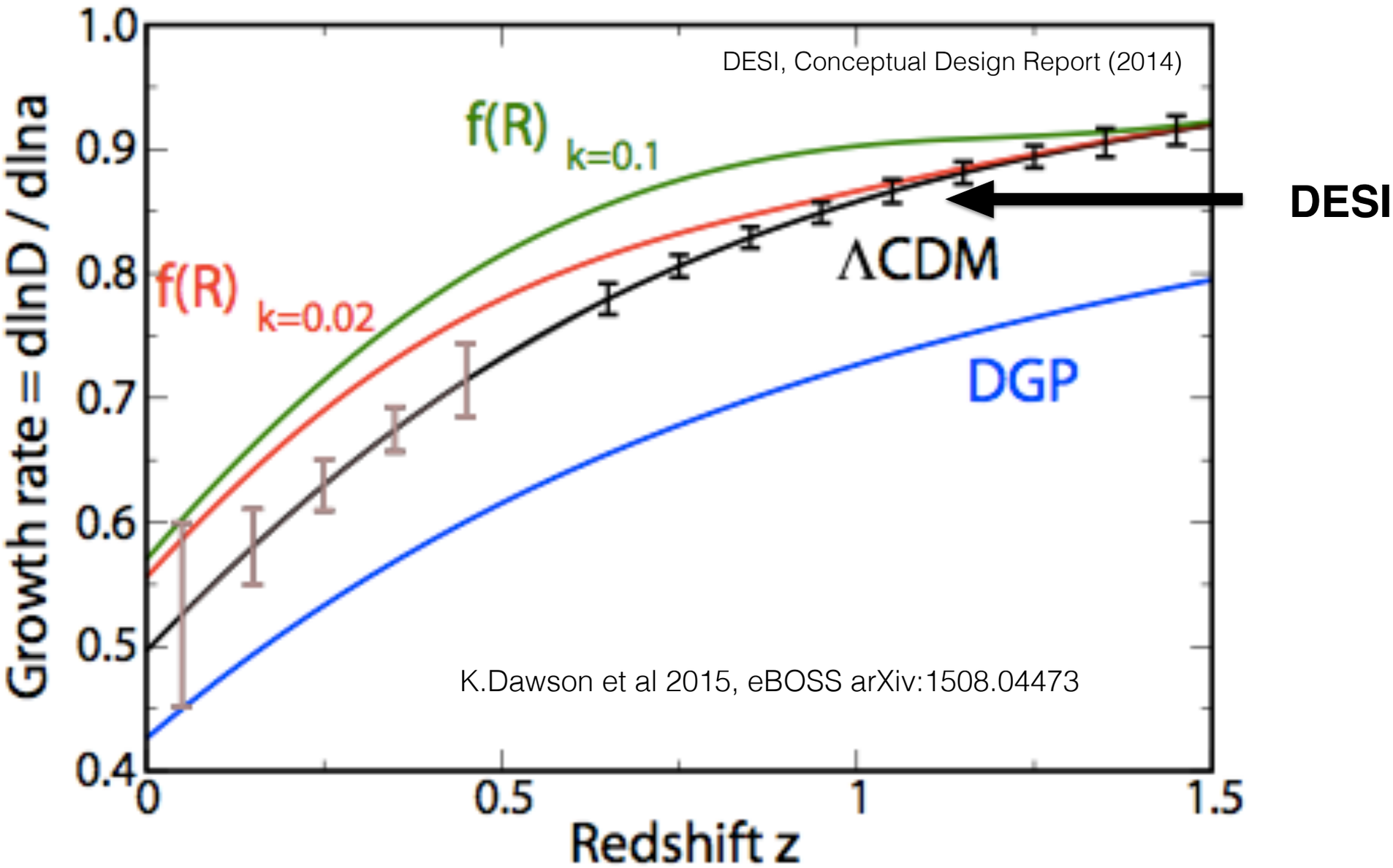
  using Redshift Space Distortions

- Inflation

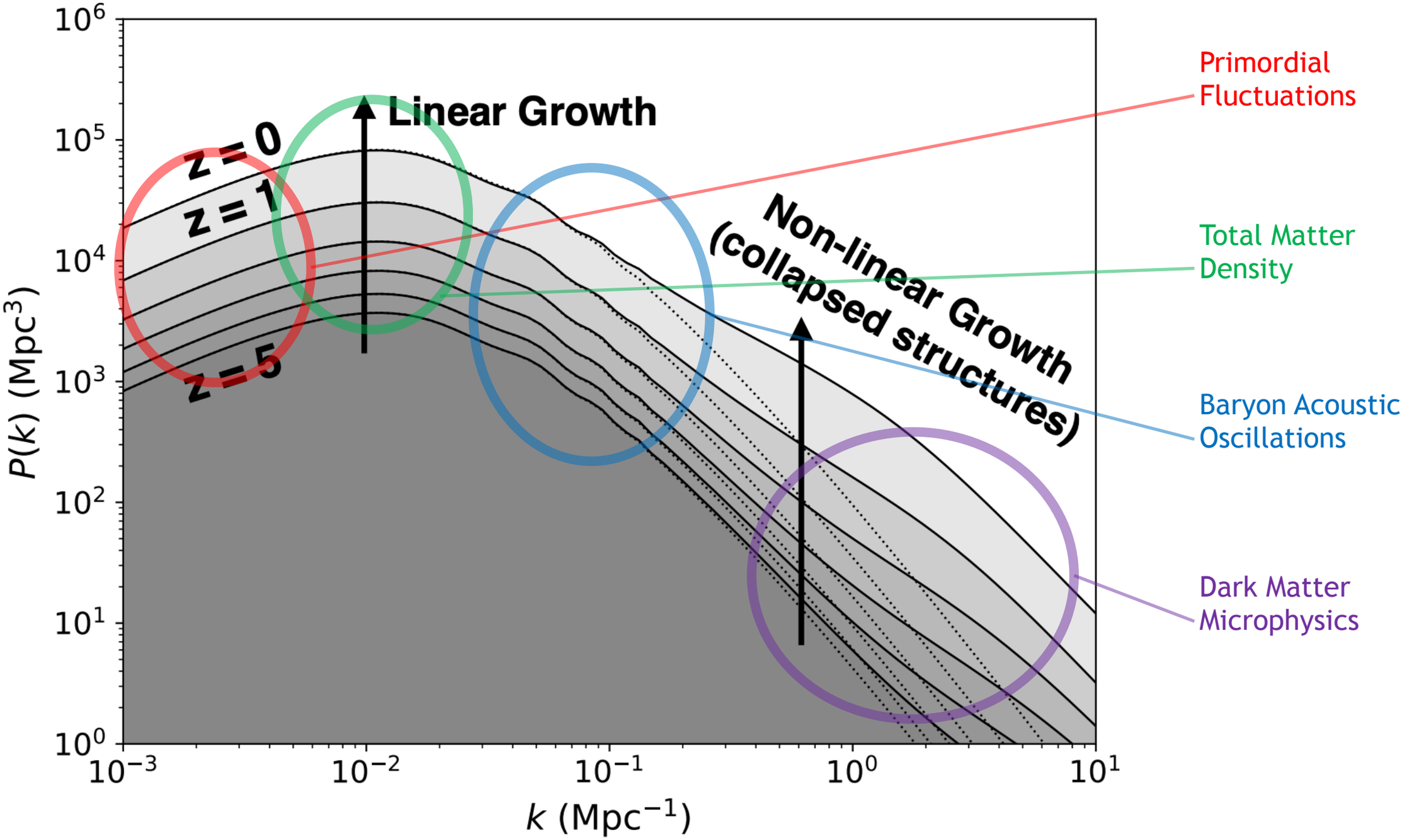
  constrain the spectral index of primordial perturbations

  and its running to < 0.4%

DESI Growth Rate Forecast

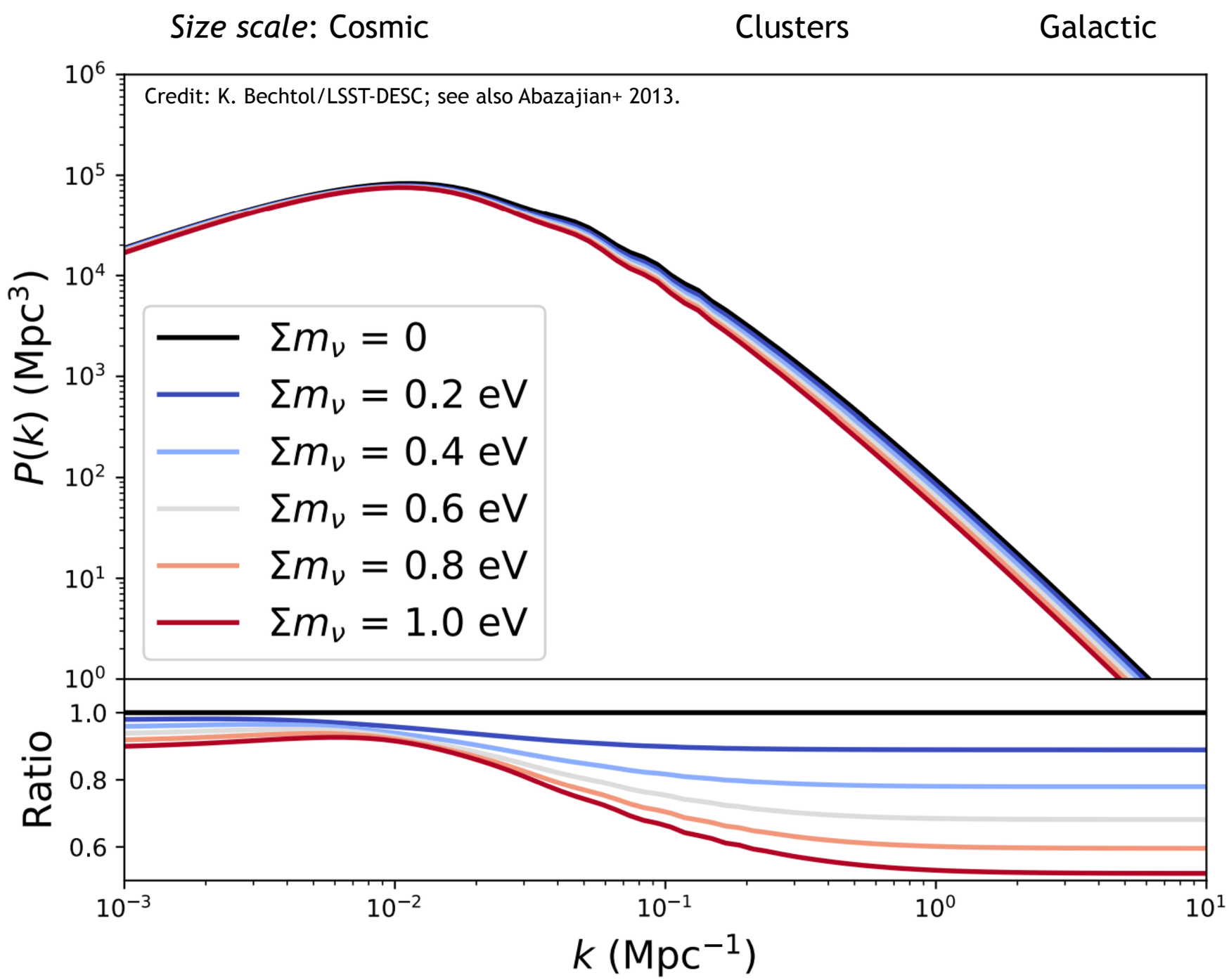


Information encoded in the Power Spectrum



Credit: K. Bechtol/LSST-DESC

Information encoded in the Power Spectrum: Neutrino Mass



Massive neutrinos suppress formation of structure at small size scales.

Neutrinos escape from small grav. potential wells ("free streaming").

If Ω_ν is a bigger component of Ω_m then small-scale structure is suppressed.

=> Strongest constraints on neutrino mass come from 1D Power Spectrum of the Lyman-Alpha Forest (+ Planck)

Palanque-Delabrouille (2015)
Chabanier (2019)

Timeline

FALL 2019: START OF COMMISSIONING

SPRING 2020 : SURVEY VERIFICATION

FALL 2020: START OF THE 5 YEAR SURVEY

Final remarks

- The DESI Collaboration is actively preparing for survey operations and science analysis.
- Large collaboration with rich experience in cosmology and survey astronomy.
- Working groups have developed detailed plans to achieve their science objectives and are now working to carry those out.
- Survey Validation is starting only in a few months… Excitement is palpable!

DESI Collaboration Meeting July 2019

Conclusion

“For the past 13 years, we've had a simple model of how dark energy works. But the truth is, we only have a little bit of data, and we're just beginning to explore the times when dark energy turned on. If there are surprises lurking out there, we expect to find them.”

–DAVID SCHLEGEL*

*co-PI of the DECals, Project Scientist of DESI