The State of Dark Energy in 2015

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DPF, 6 Aug 2015

Outline:

1. **Observing inflation + dark energy**
2. **BAO experiments**
3. **CMB experiments**
4. **Future experiments**

Dark Energy

An observational question:
Has the Dark Energy Tooth Fairy come once or twice?

1st Age of Dark Energy

- **$t \sim 10^{-35}$ sec**
- **Phase of accelerating expansion dubbed "inflation"**
- **"Dynamic", because it turned off**
- **Imprinted density fluctuations + grav. waves**

2nd Age of Dark Energy

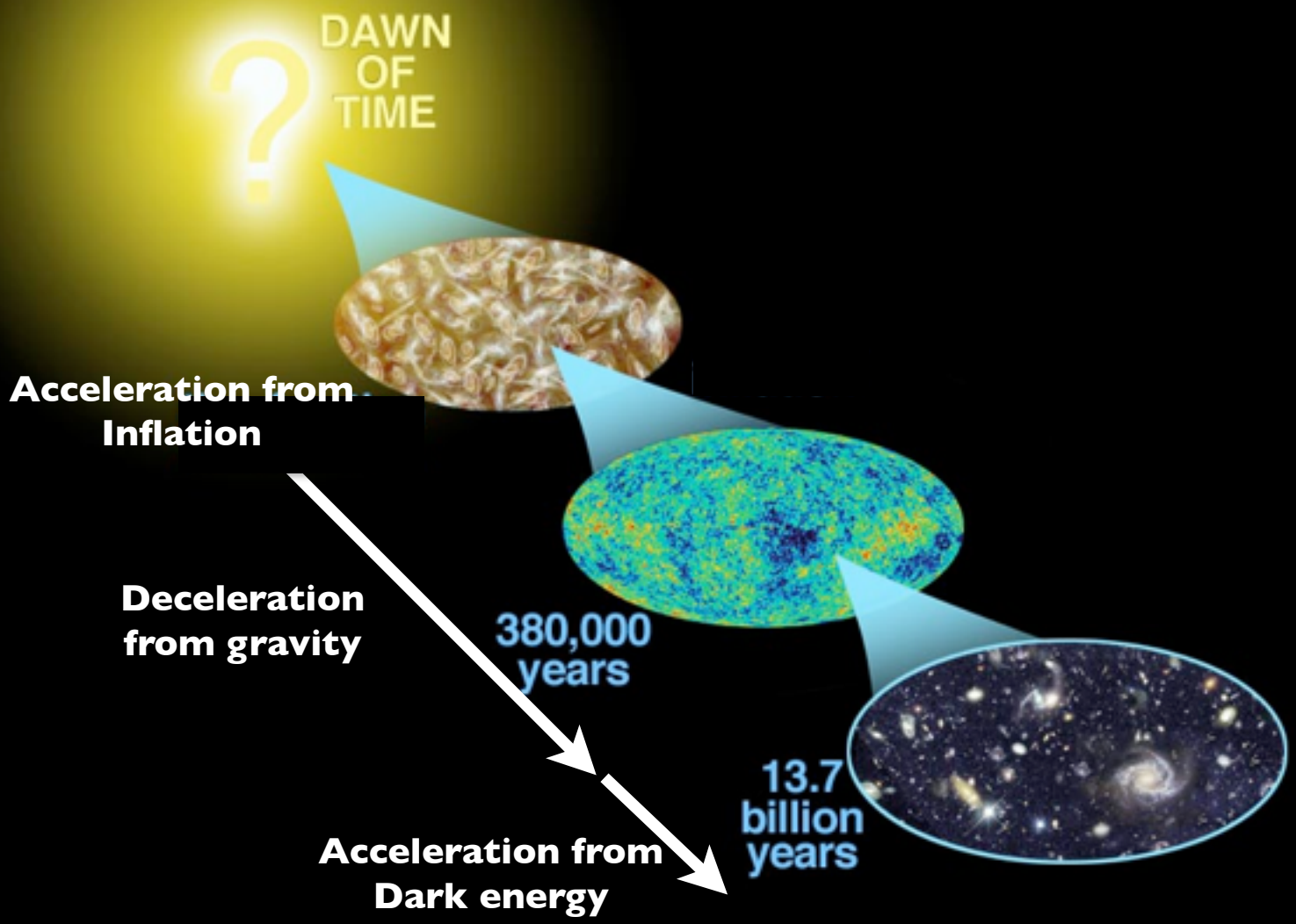
- **t ~ now**
- **Phase of accelerating expansion dubbed "dark energy"**
- **Observable at t > 2 billion years, possibly dynamic**

An observational question:
Has the Dark Energy Tooth Fairy come once or twice?

1st Age of Dark Energy

- **$t \sim 10^{-35}$ sec**
- **Phase of accelerating expansion dubbed "inflation"**
- **"Dynamic", because it turned off**
- **Imprinted density fluctuations + grav. waves**

Timeline of Dark Energy



Toolset for Dark Energy are geometrical measures

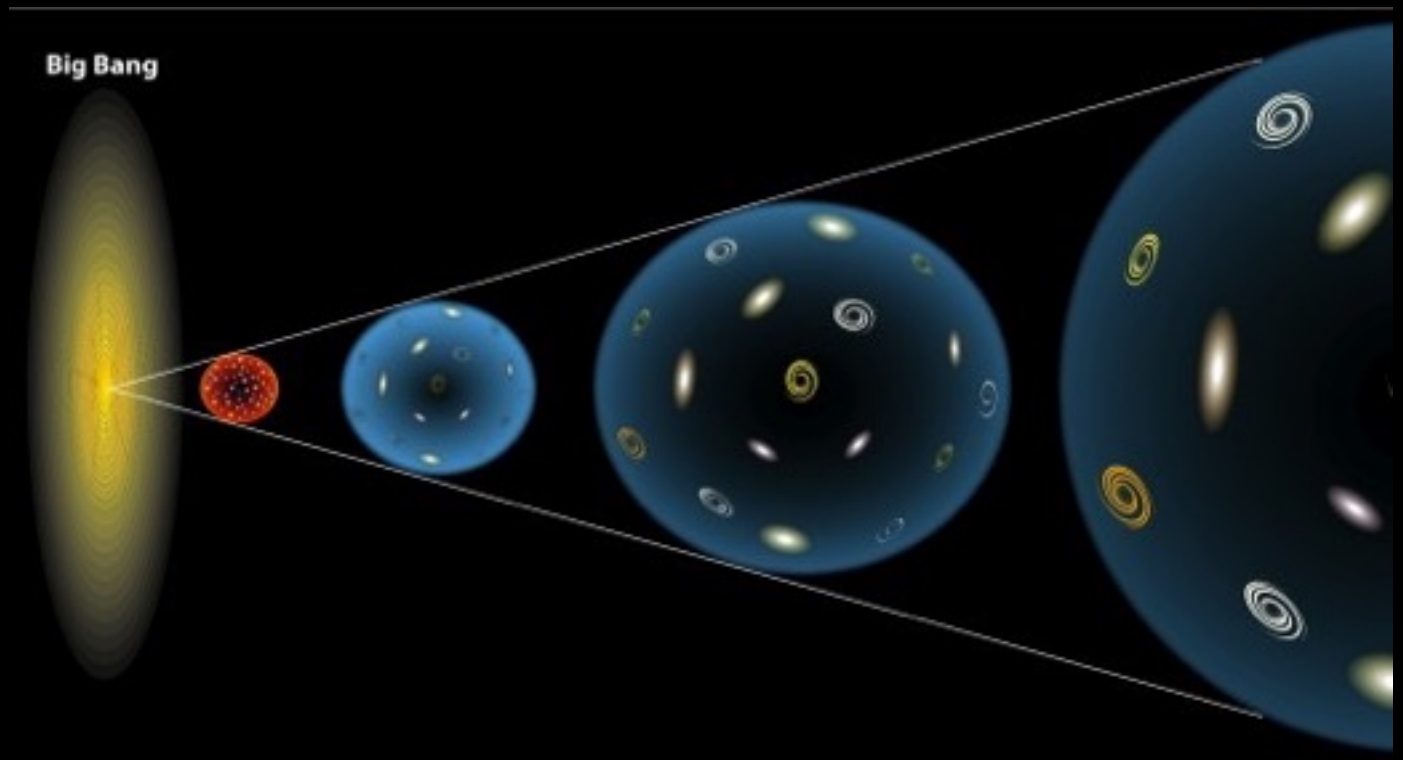
Measurements that are per-object:

supernovae

Measurements that are statistical:

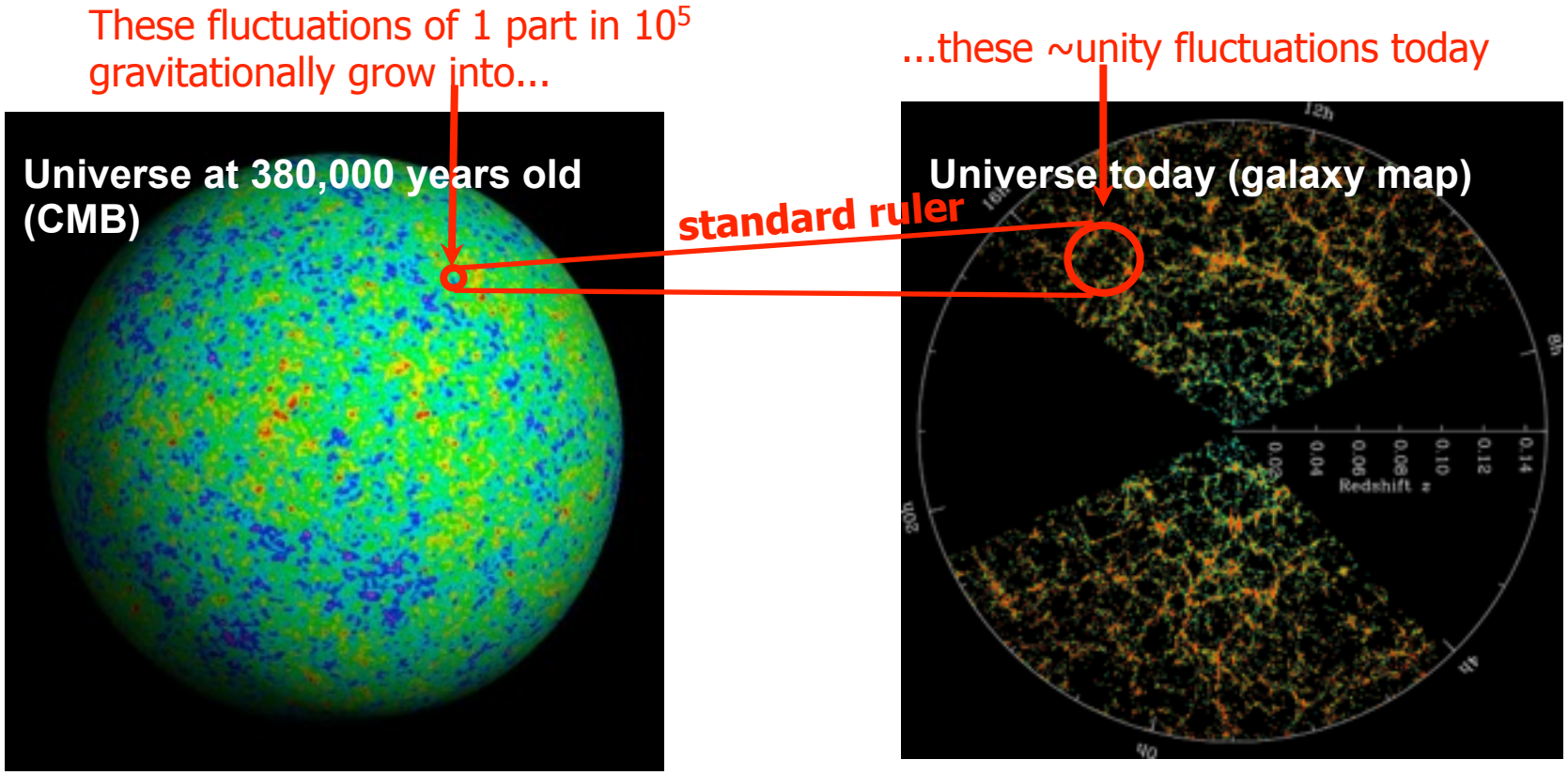
features + scales in density maps (galaxies, CMB)

All imply extra volume between us and high redshift



Baryon Acoustic Oscillations (BAO) standard ruler at 147 Mpc

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

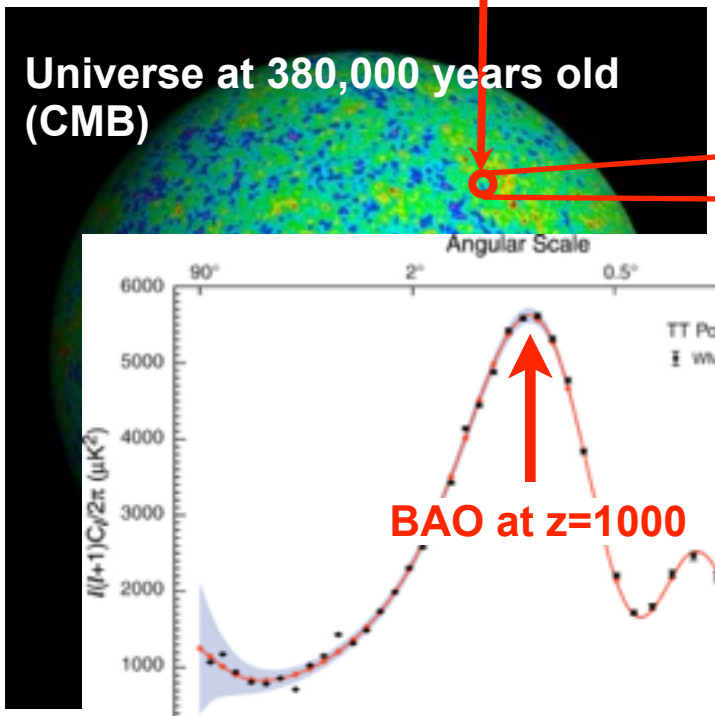


Baryon Acoustic Oscillations (BAO) standard ruler at 147 Mpc

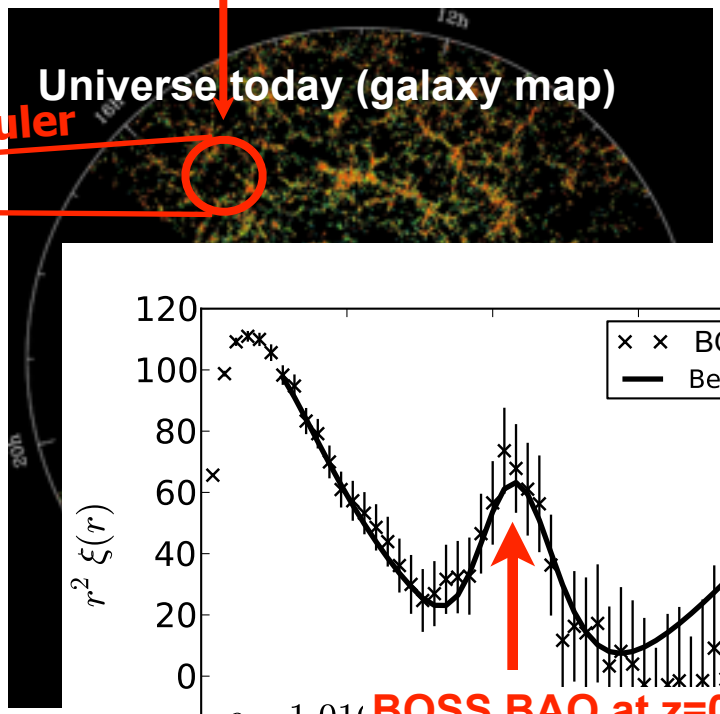
BAO imprinted in the microwave background at z=1100
… and forever more in galaxy maps

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

...these ~unity fluctuations today

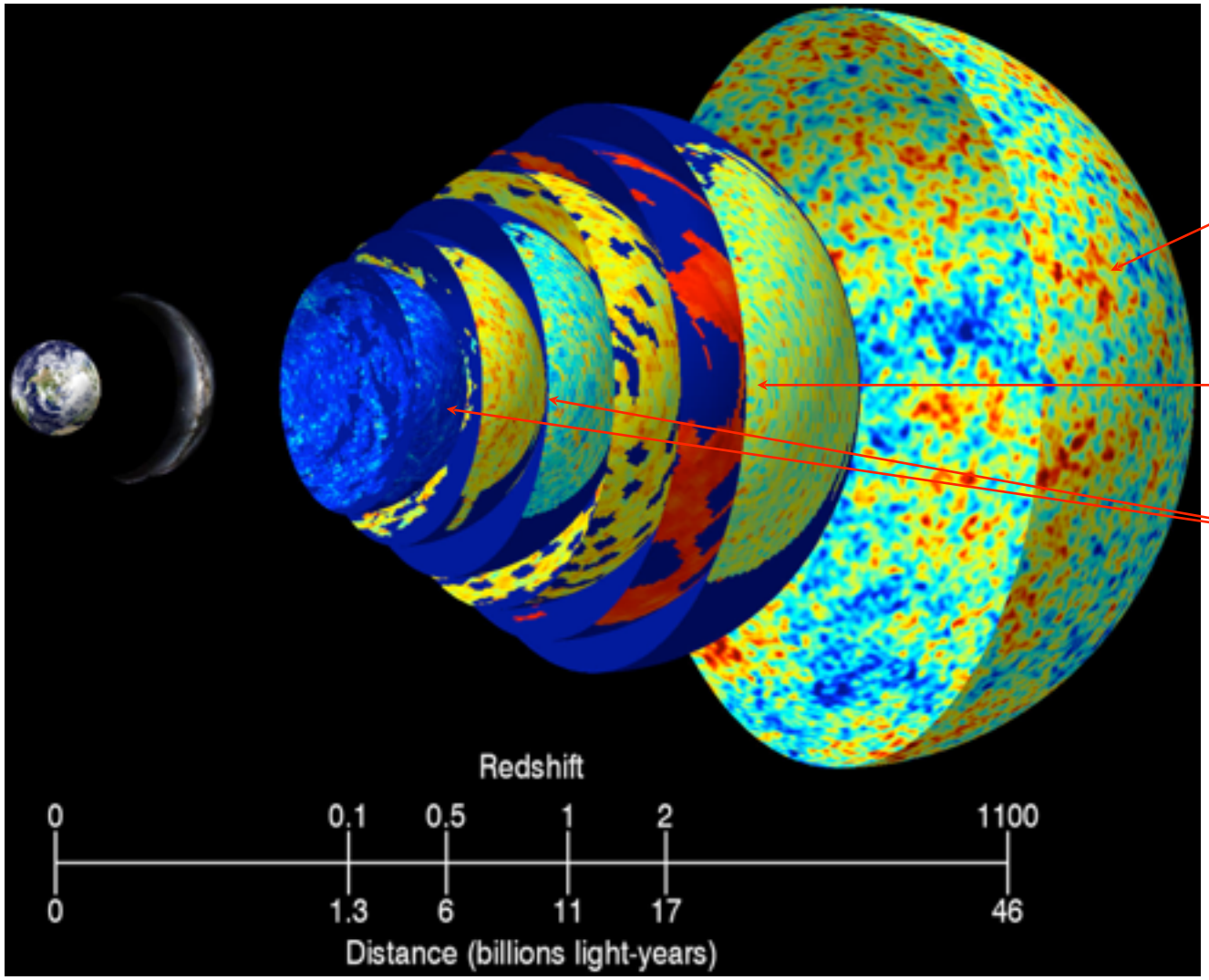


standard ruler



Large volumes required to sample BAO scale at 147 Mpc

3-d maps measure more modes than 2-d maps
Higher redshifts have more volume



BAO standard ruler from Planck

$\theta_s = 0.596724 \pm 0.00038$ deg

BAO standard ruler from BOSS Lyman-α map

BAO standard ruler from BOSS galaxy map

Baryon Oscillation Spectroscopic Survey (BOSS)

Most capable instrument today for mapping the Universe

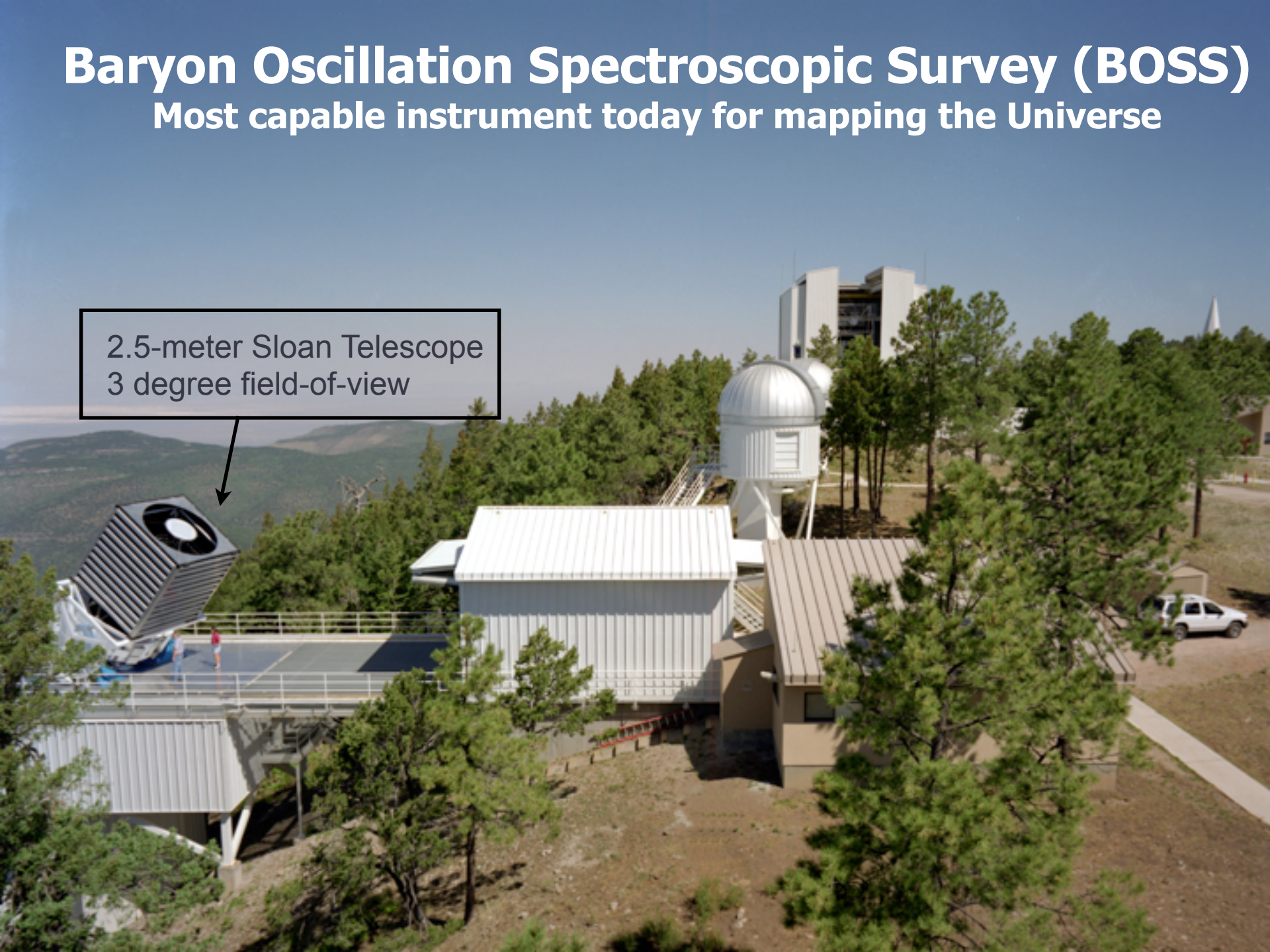


Image sky

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Select targets

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Design plug-plates

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Plug fibers

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Observe!

↓

Spectra + redshifts

↓

Make 3-D maps

↓

Cosmology

Image sky

↓

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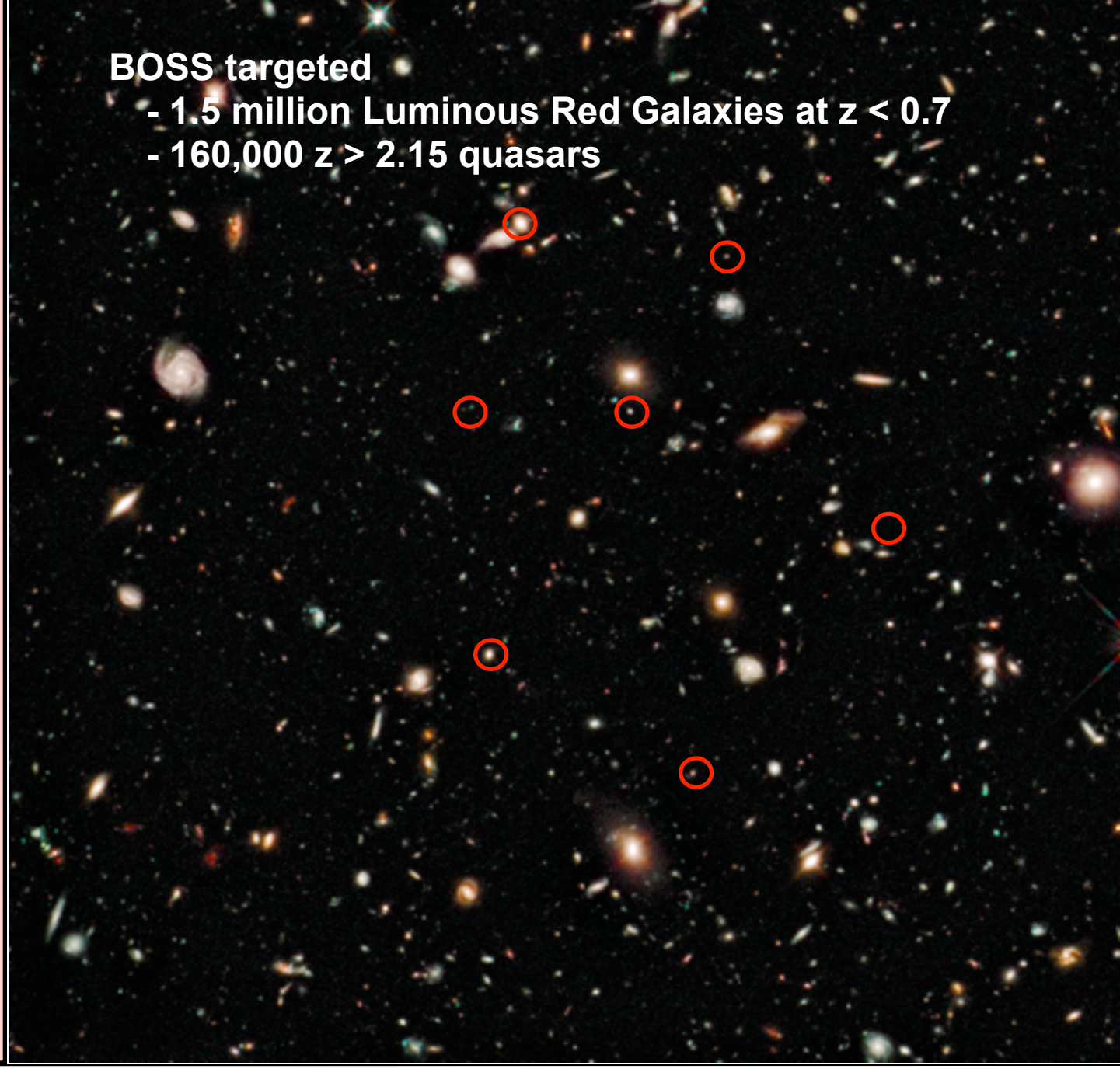
Cosmology



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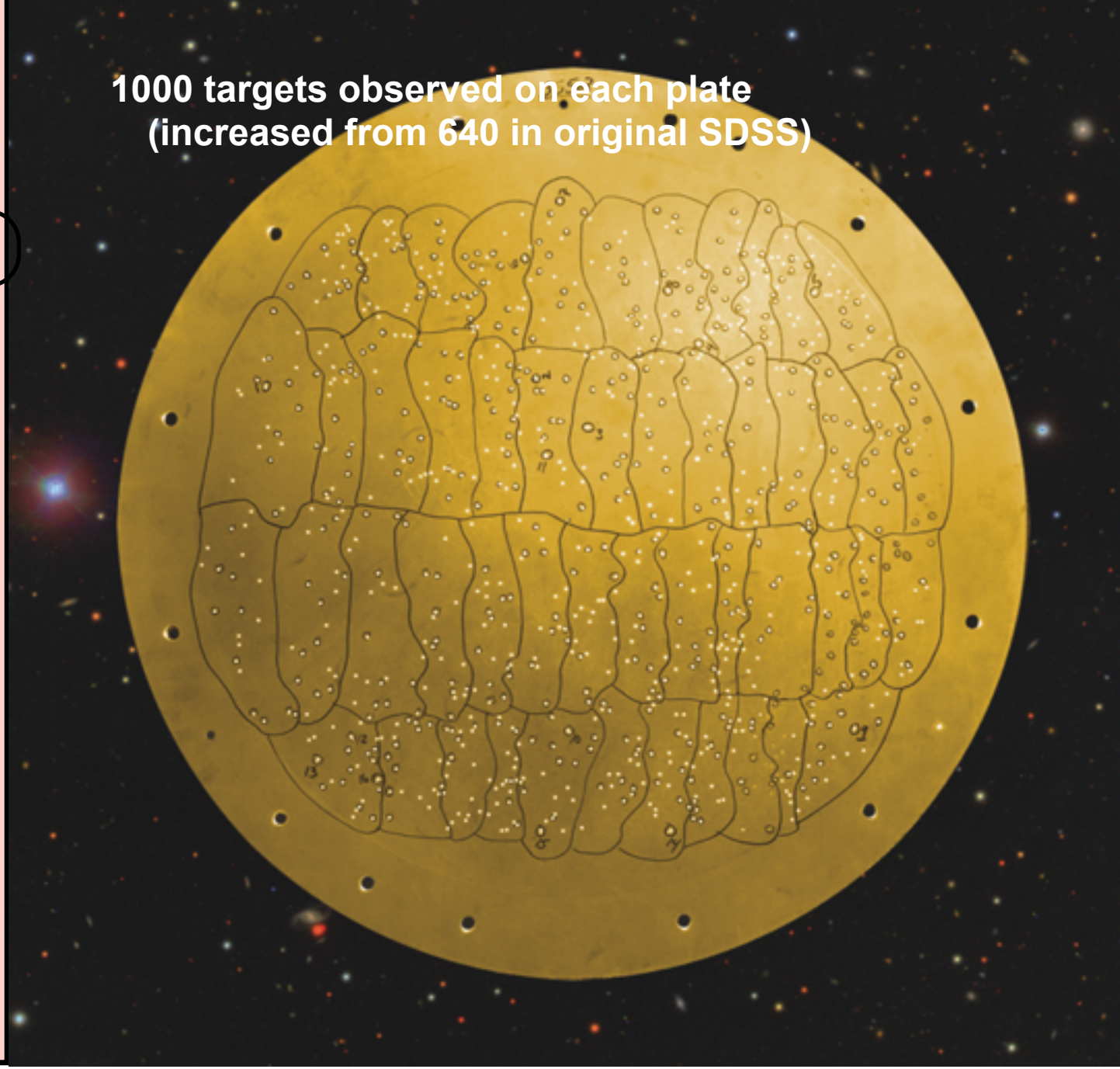

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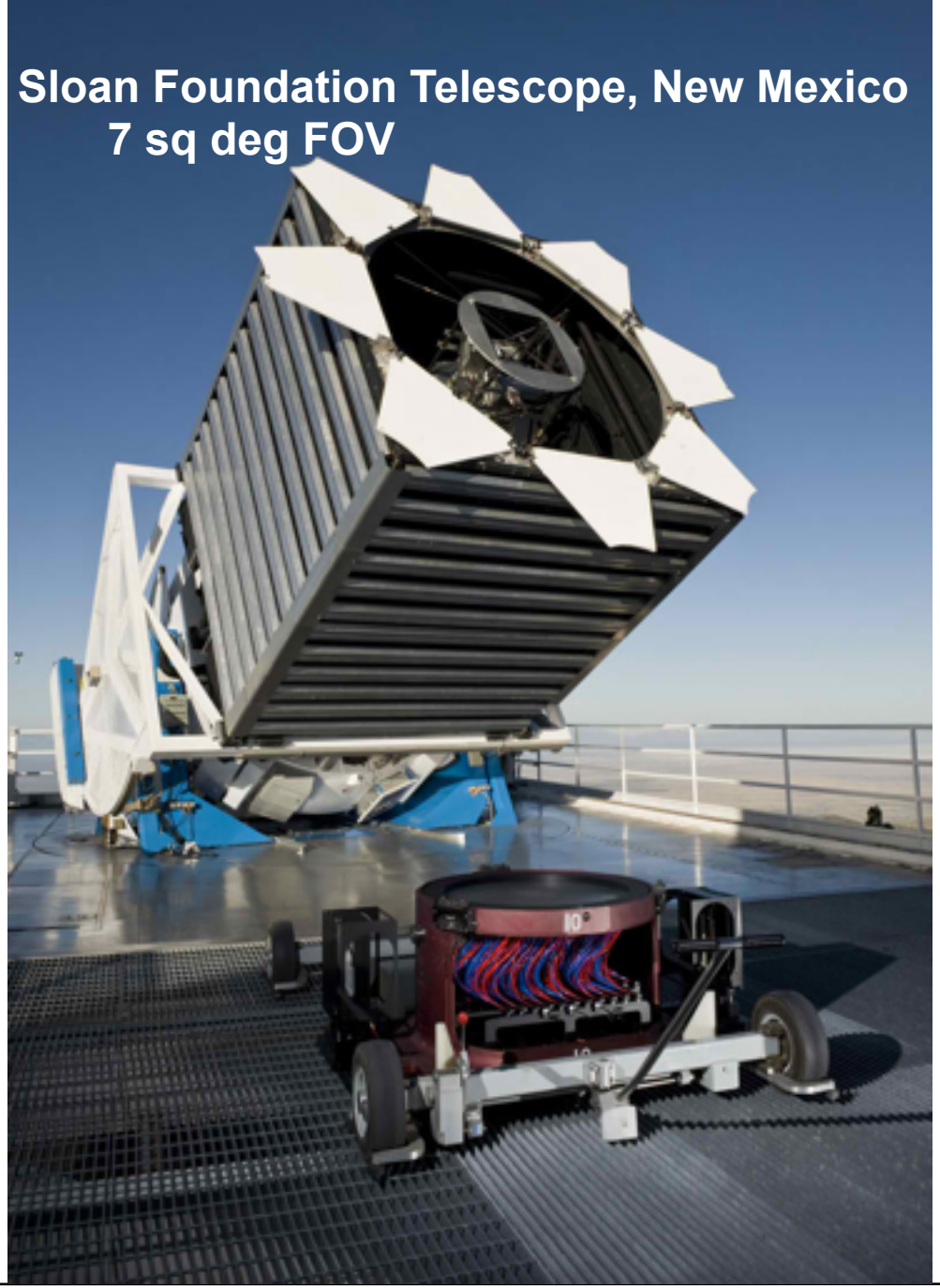
Cosmology



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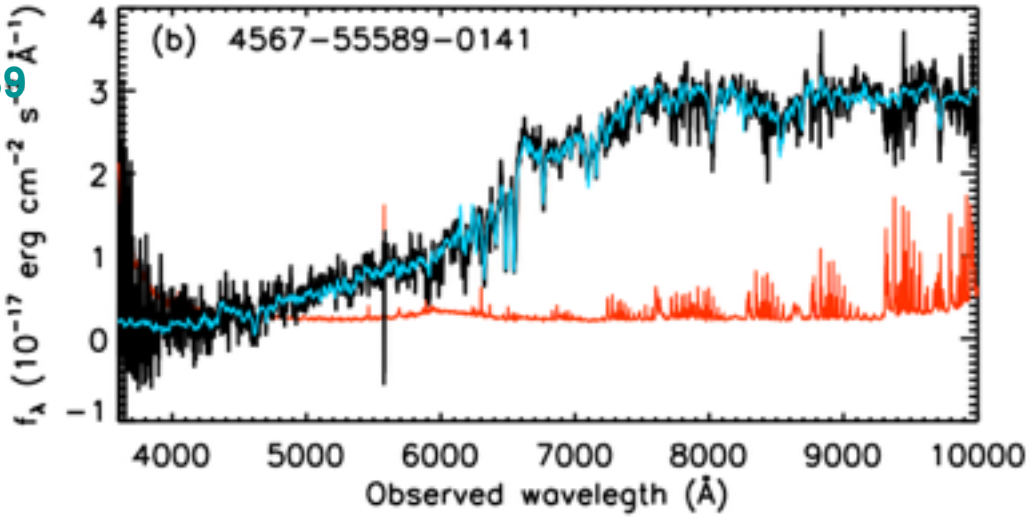
Cosmology

Fully automated spectral reductions

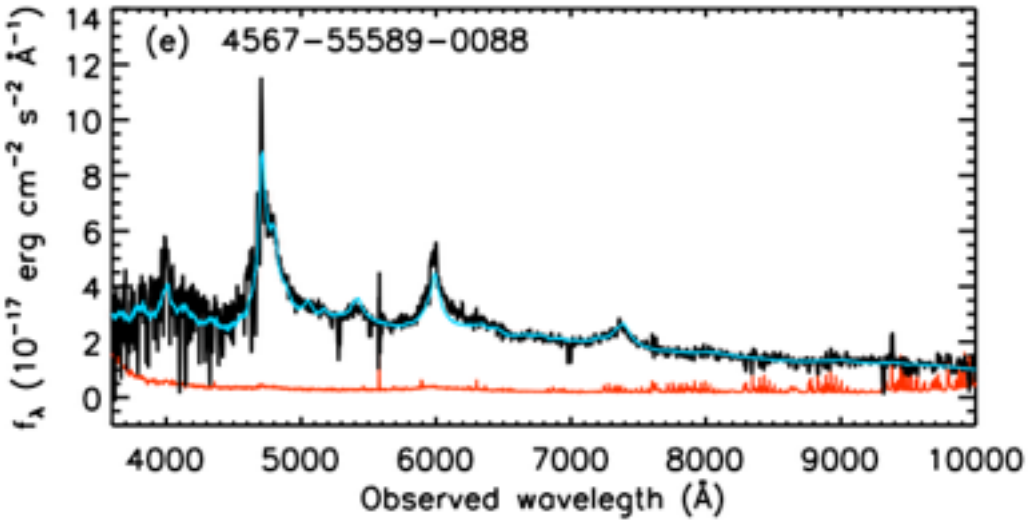
360-1000 nm coverage for all targets

Automated classifications, >98% for galaxies

Example:
Galaxy at z=0.6489



Example:
QSO at z=2.873



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Spectra + redshifts

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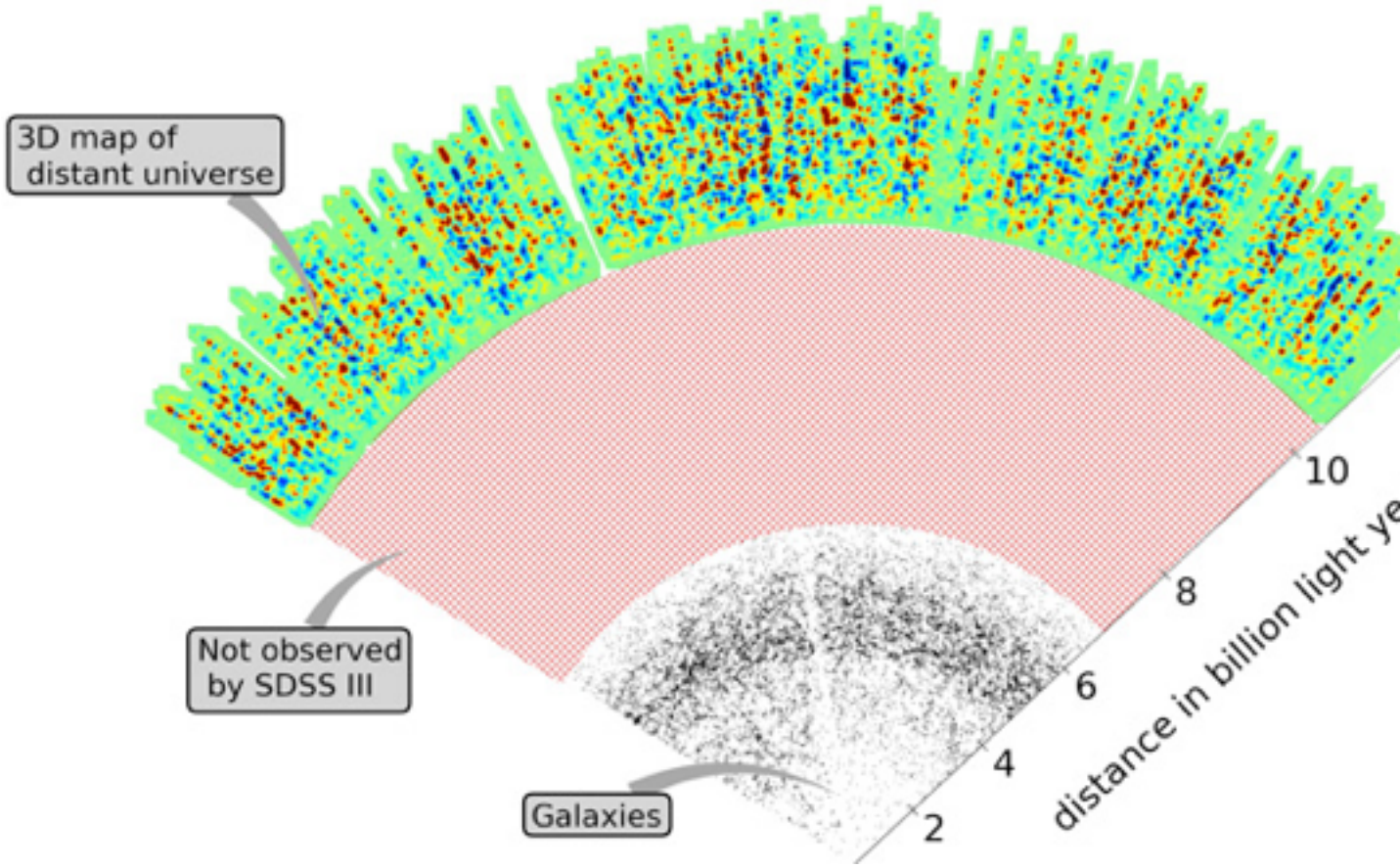
Cosmology

BOSS completed main survey, April 2014
1.5 million galaxies + 160,000 Lyman-alpha quasars



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Spectra + redshifts

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Make 3-D maps

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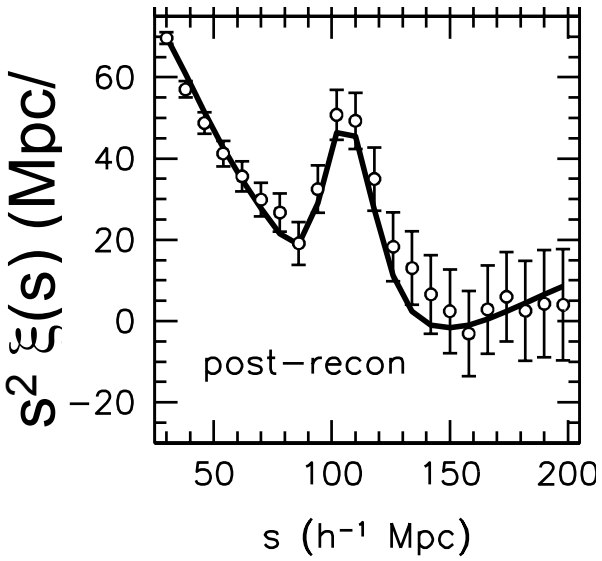
Cosmology

Four distinct BAO measures in BOSS Data Release 11

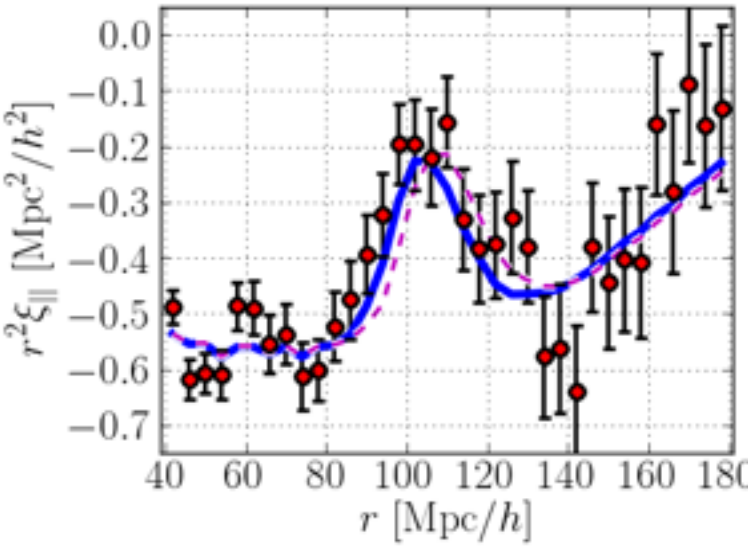
- **LOWZ galaxies at z=0.32**
- **CMASS galaxies at z=0.57**
- **Lyman-alpha forest auto-correlation at z=2.3**
- **Lyman-alpha + Quasar cross-correlation at z=2.3**

z=0.57



Anderson et al.

z=2.3



Delubac et al. (2014)

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Spectra + redshifts

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Make 3-D maps

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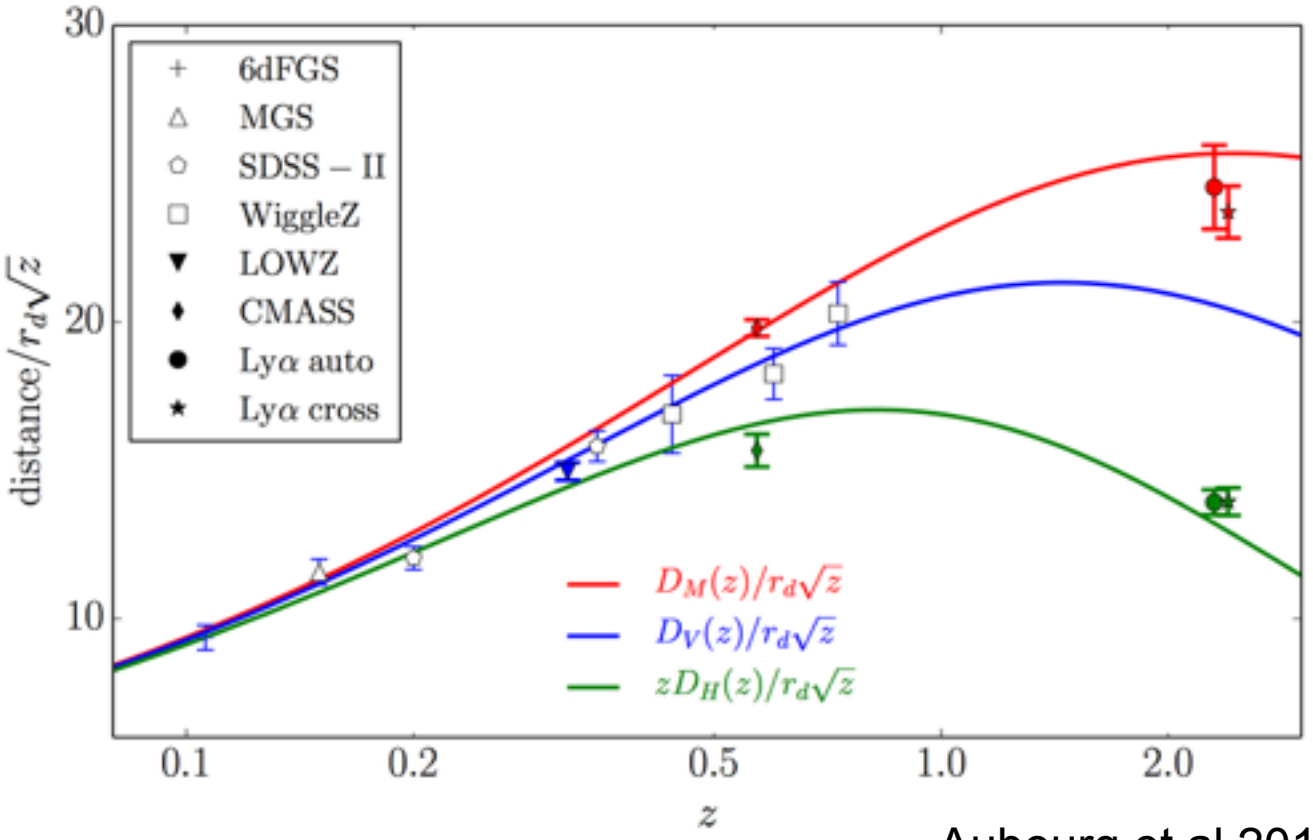
Cosmology

BAO as a ruler measures the expansion history, even with no physical scale

BAO measured near its cosmic variance limit at z=0 → z=0.7
Future improvement can only be ~2X better there
BAO at z > 0.7 nowhere near cosmic variance limit



Aubourg et al 2014

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Spectra + redshifts

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Make 3-D maps

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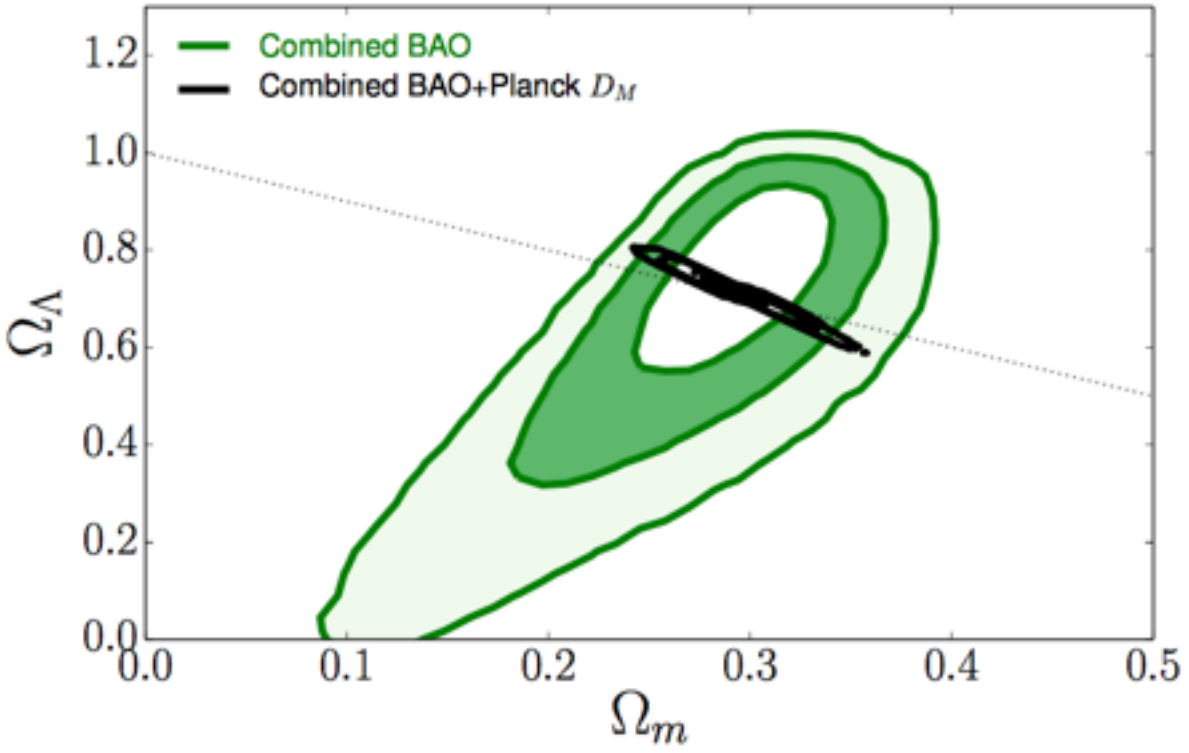
Cosmology

Dark energy is needed to explain galaxy+quasar BAO

Angular acoustic scale of the CMB is put on the same system with simple assumptions about recombination era

One standard ruler from z=1100 → z=0.1



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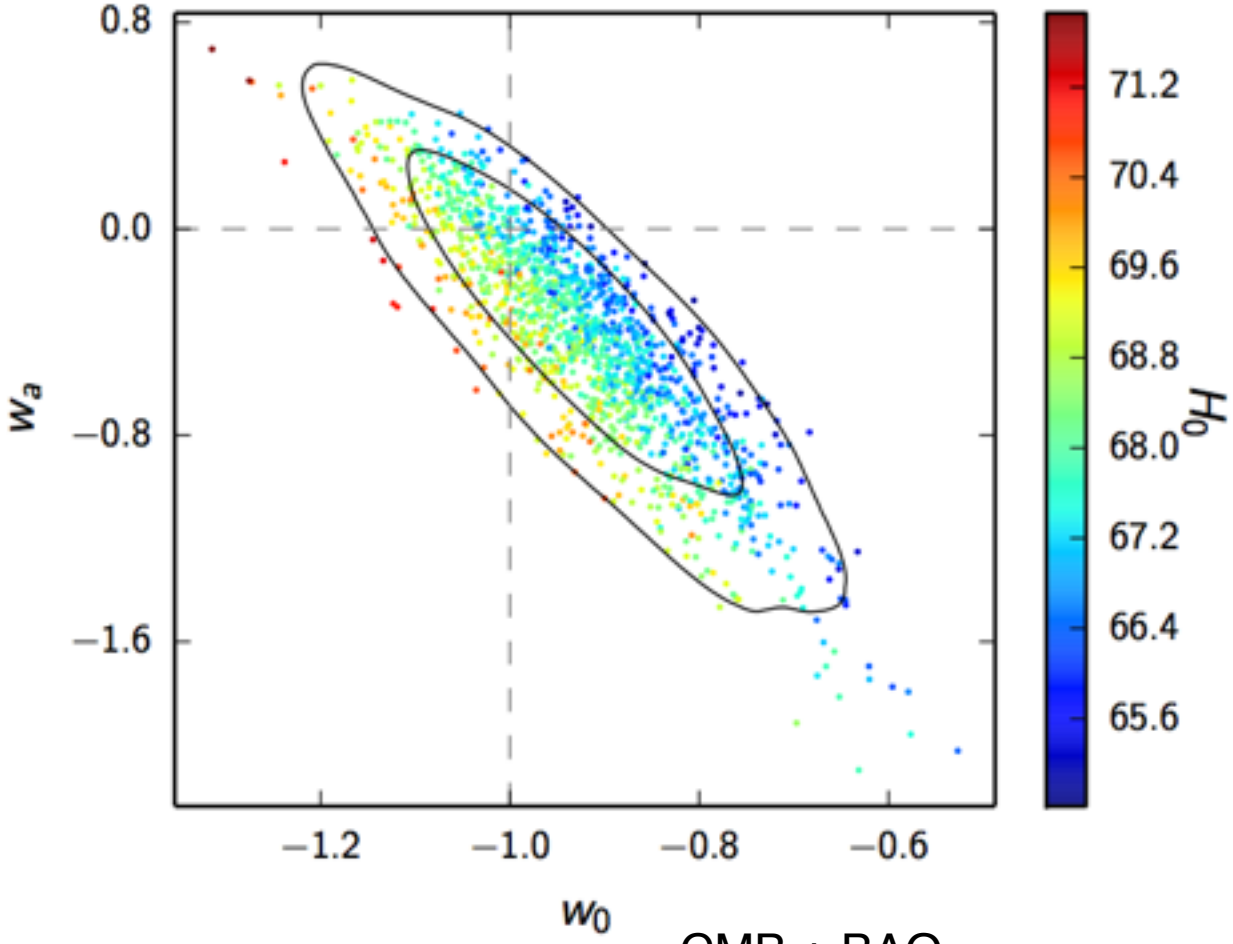
Cosmology

Dark energy need not be dynamic to explain the data today

w_0=-1, w_a=0, equivalent to a cosmological constant

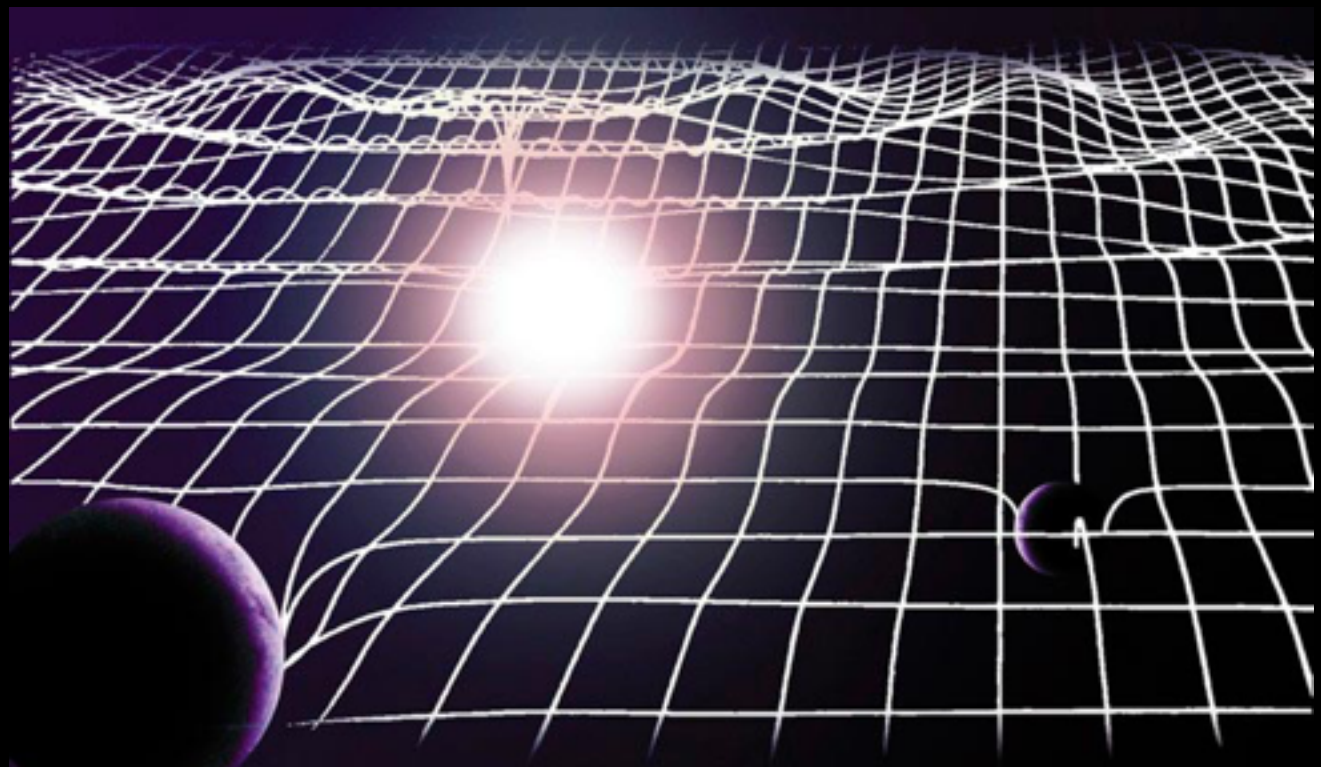


CMB + BAO
Planck Collaboration 2015

Inflation

Toolset for Inflation?

- **Matter fluctuations**
  - **Primordial fluctuation power spectrum (n_s)**
  - **Non-gaussianities**
  - **Flatness (Ω_K)**
- **Gravitational wave background**
  - **Direct measure of grav. waves**
  - **Imprinted grav. waves as B-modes in CMB**

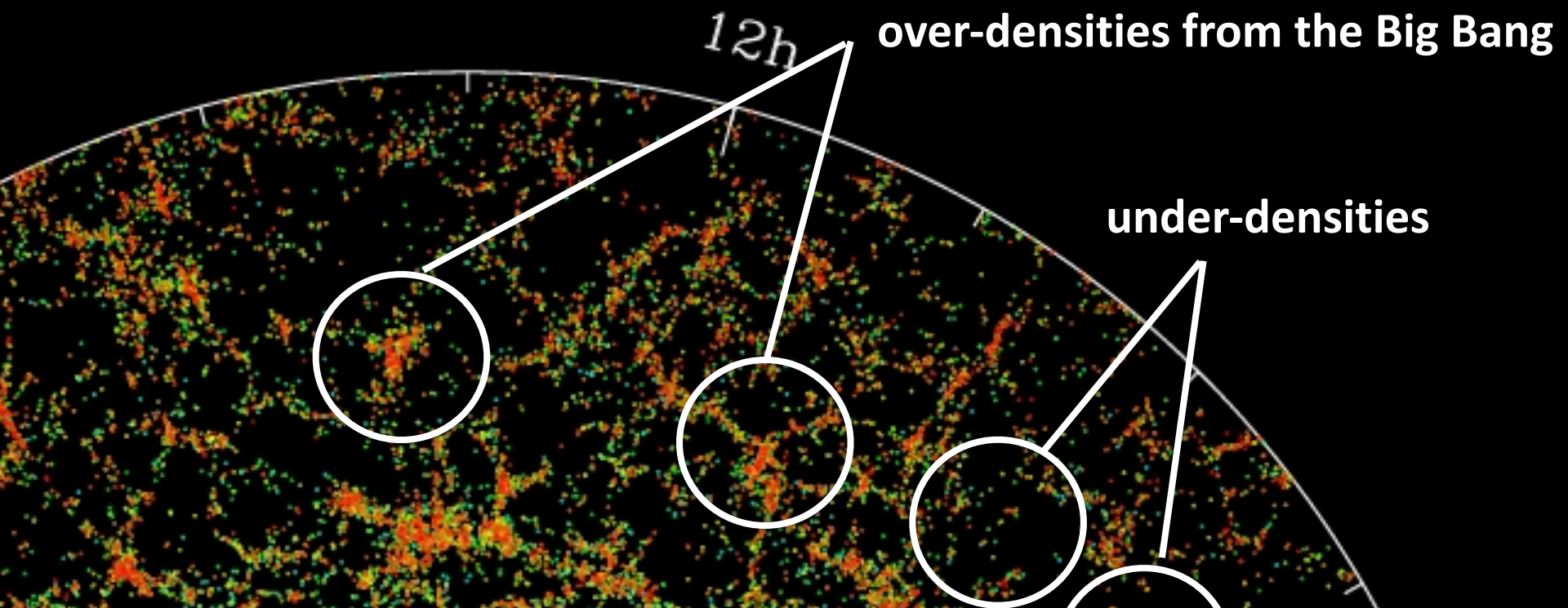


Most inflation-era measures are upper limits

- Spatial curvature (Ω_K) is flat to <0.5%

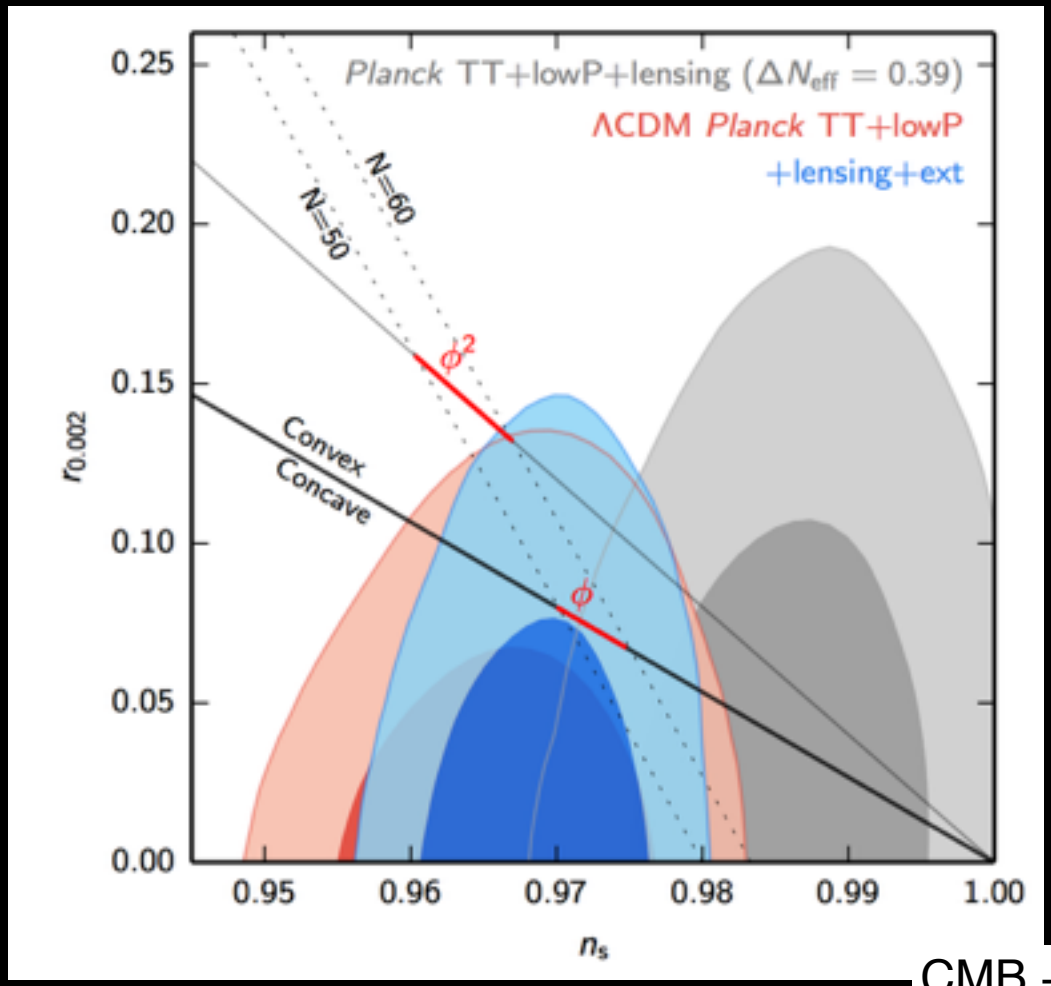
- Non-gaussianities (f_{NL}) are not detected

- Primordial fluctuations are adiabatic (growing mode), not isocurvature



At least one inflation-era measure is measured!

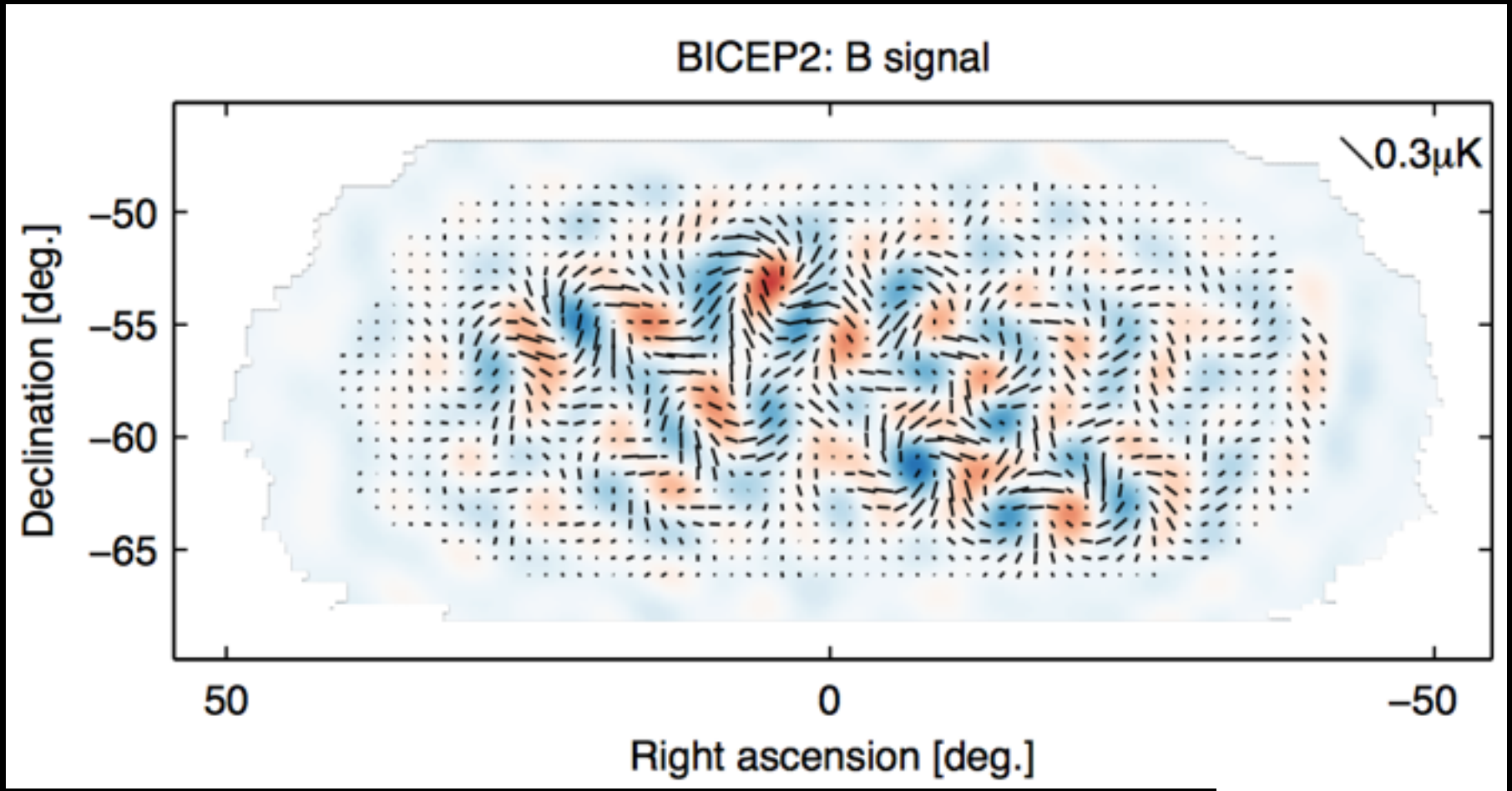
Primordial fluctuation spectrum (n_s) is not scale-free



CMB + BAO
Planck Collaboration 2015

At least one inflation-era measure was incorrect

Indirect measure of grav. waves imprinted on CMB B-modes

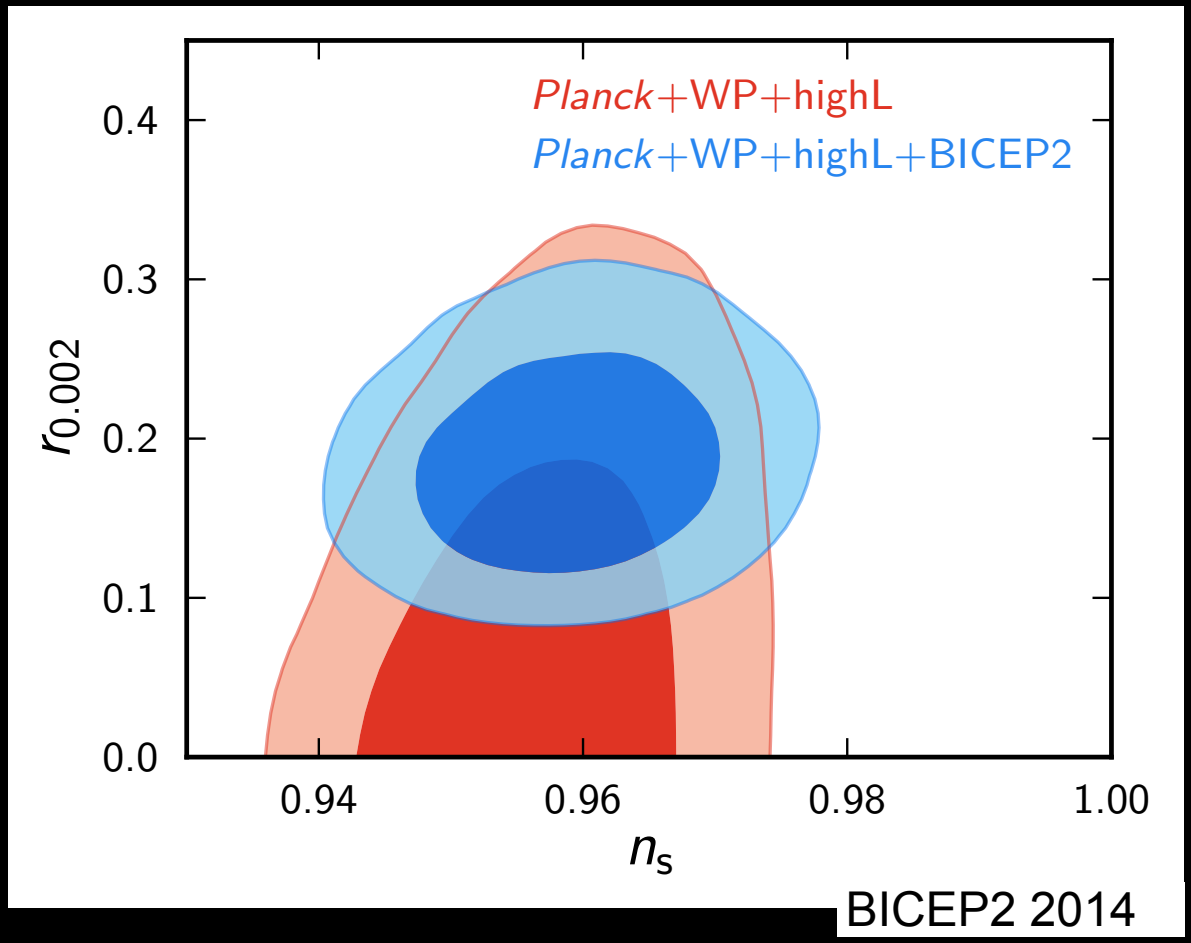


BICEP2 2014

At least one inflation-era measure was incorrect

The signal was real

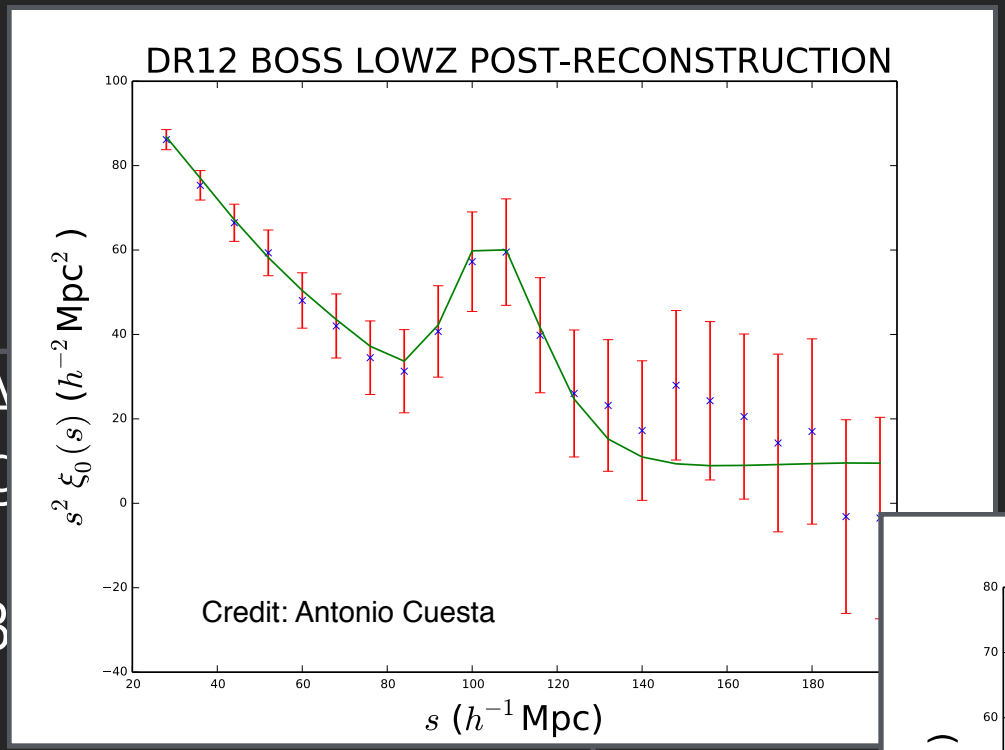
- **Sourced from dust in the Milky Way**
- **Mis-interpreted as grav. waves imprinted upon CMB**



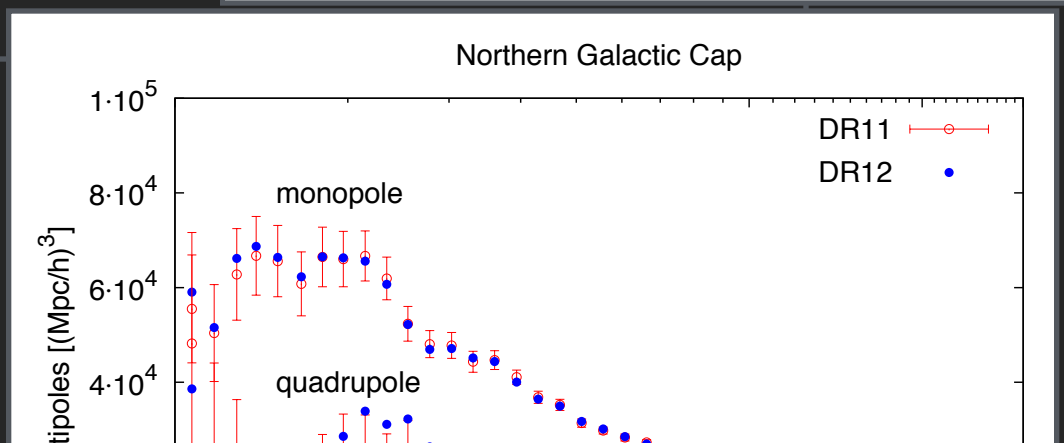
Future Experiments

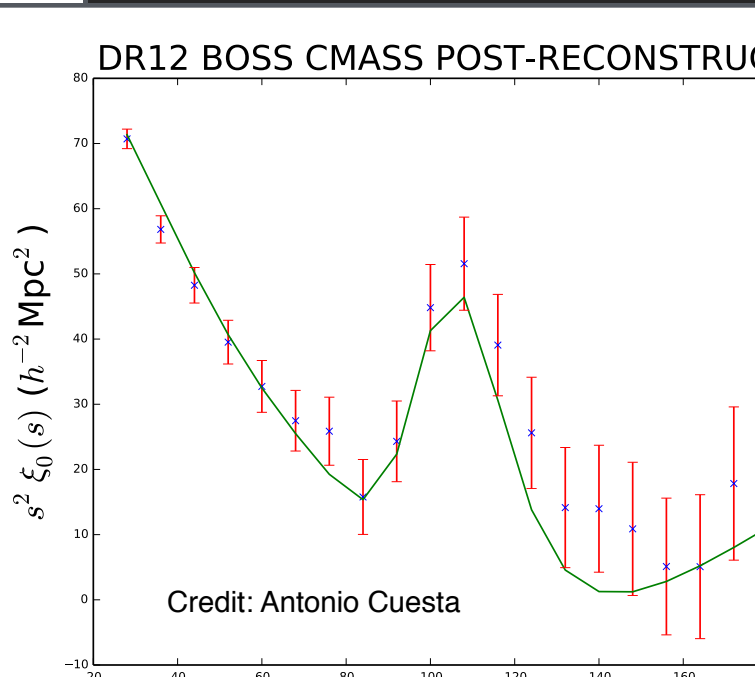
DR12…coming soon

- 2D BA
  Config
- joint B



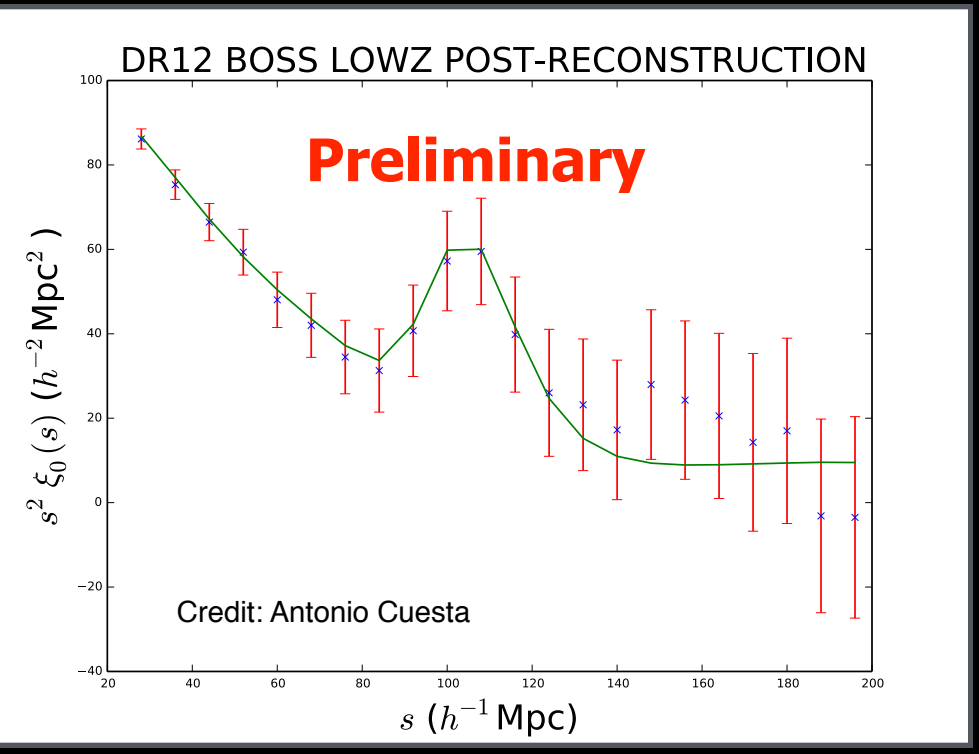
!Preliminary!

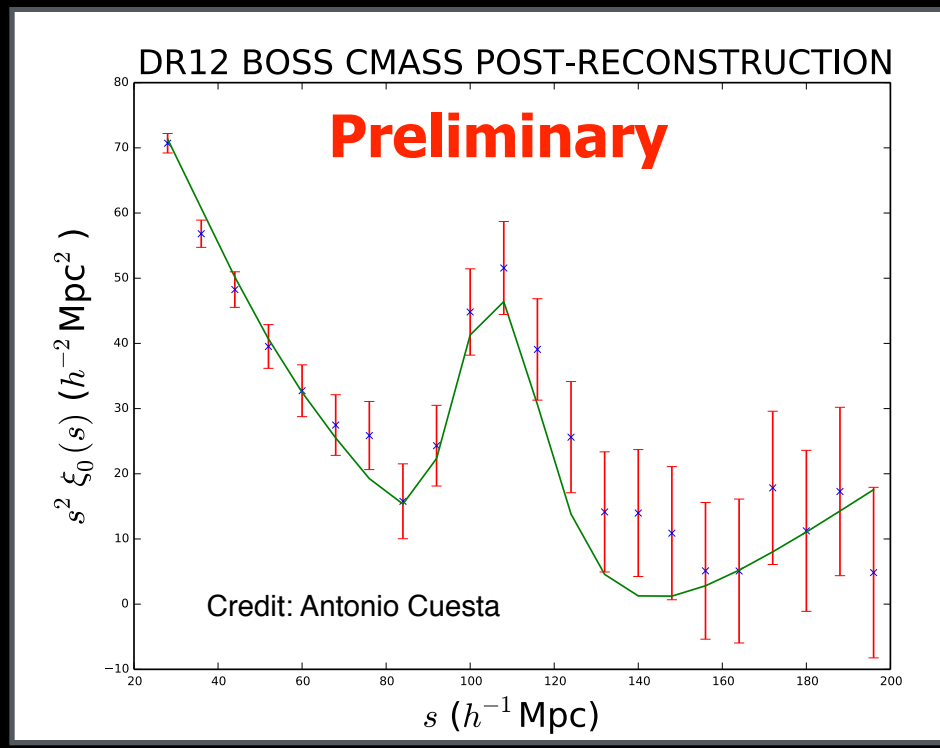




Final results from BOSS in prep.

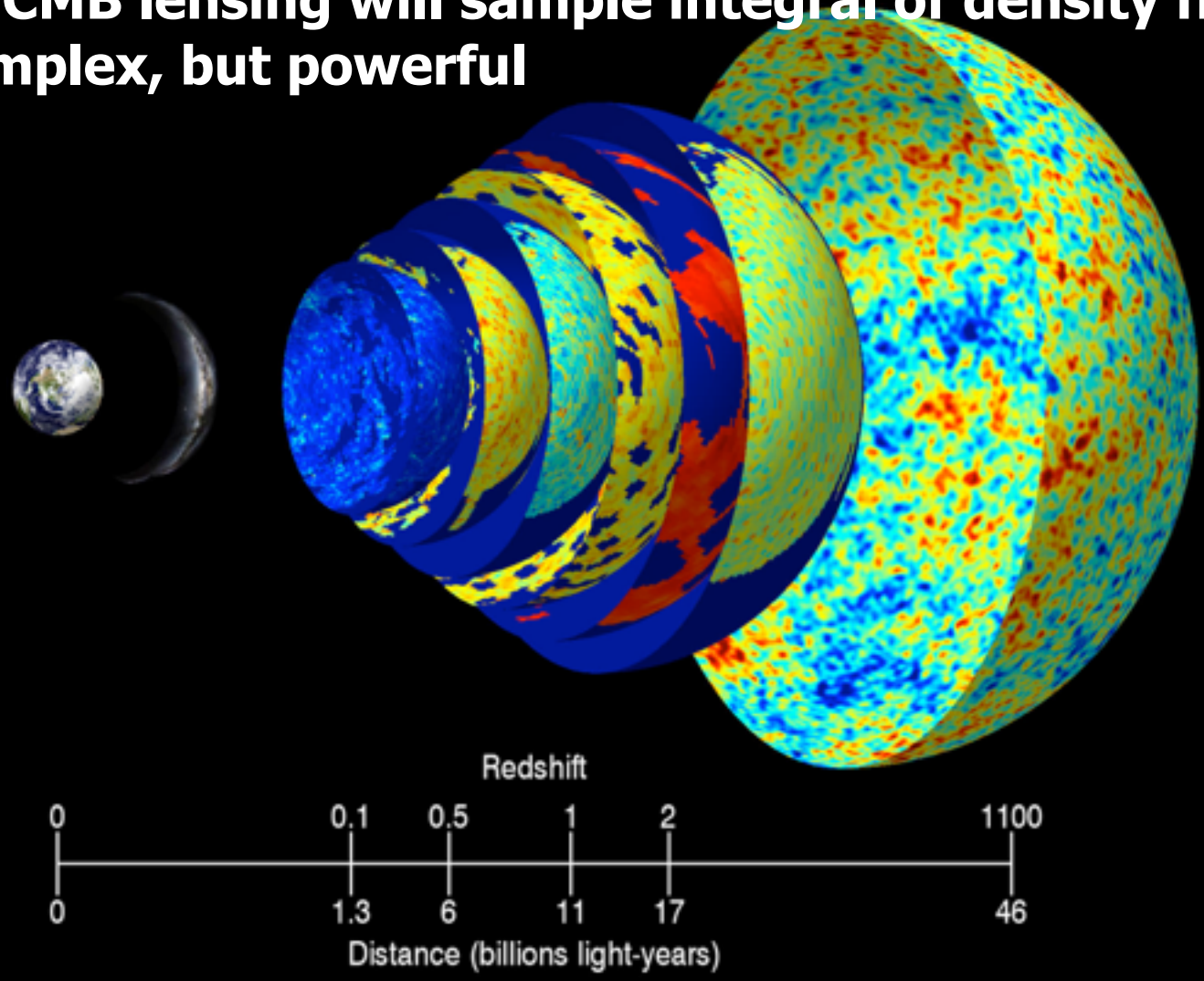
Uses final Data Release 12, which was made public Jan 2015





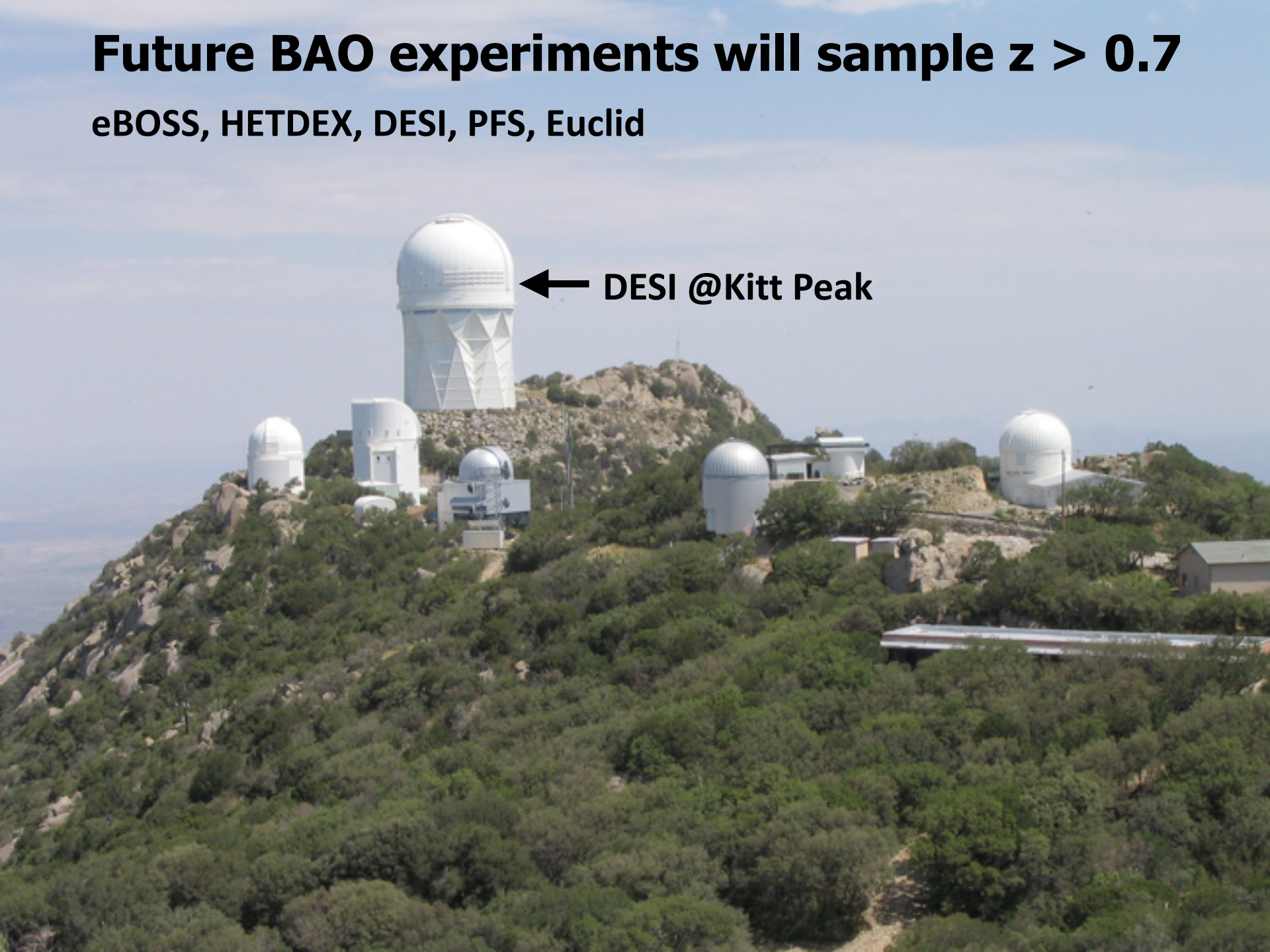
Statistical power increases with # of modes

Cosmic variance limit for BAO only reached at z<0.7 & z=1100
More modes at smaller scales
Galaxy + CMB lensing will sample integral of density fields
-> Complex, but powerful

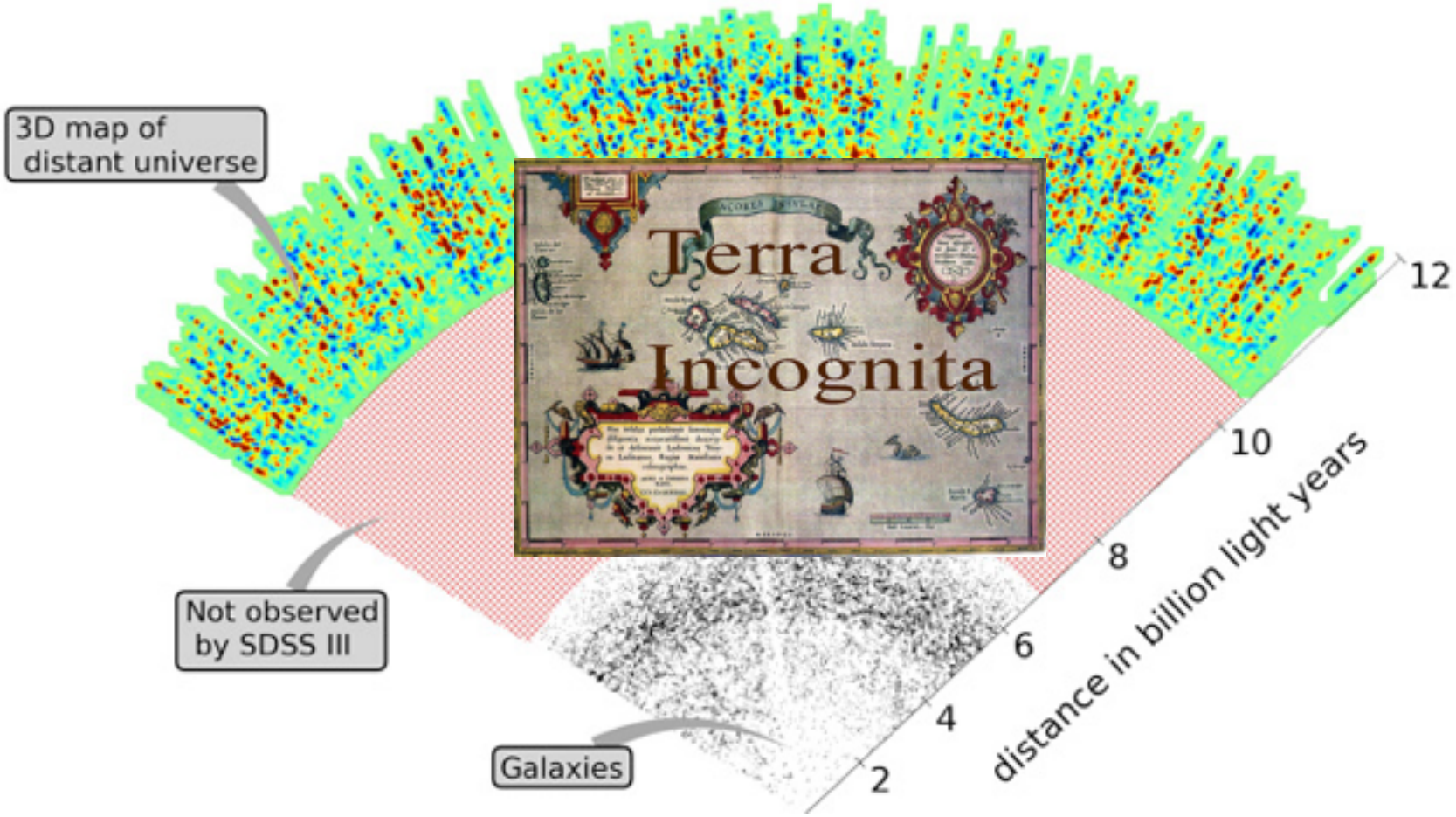


Future BAO experiments will sample z > 0.7

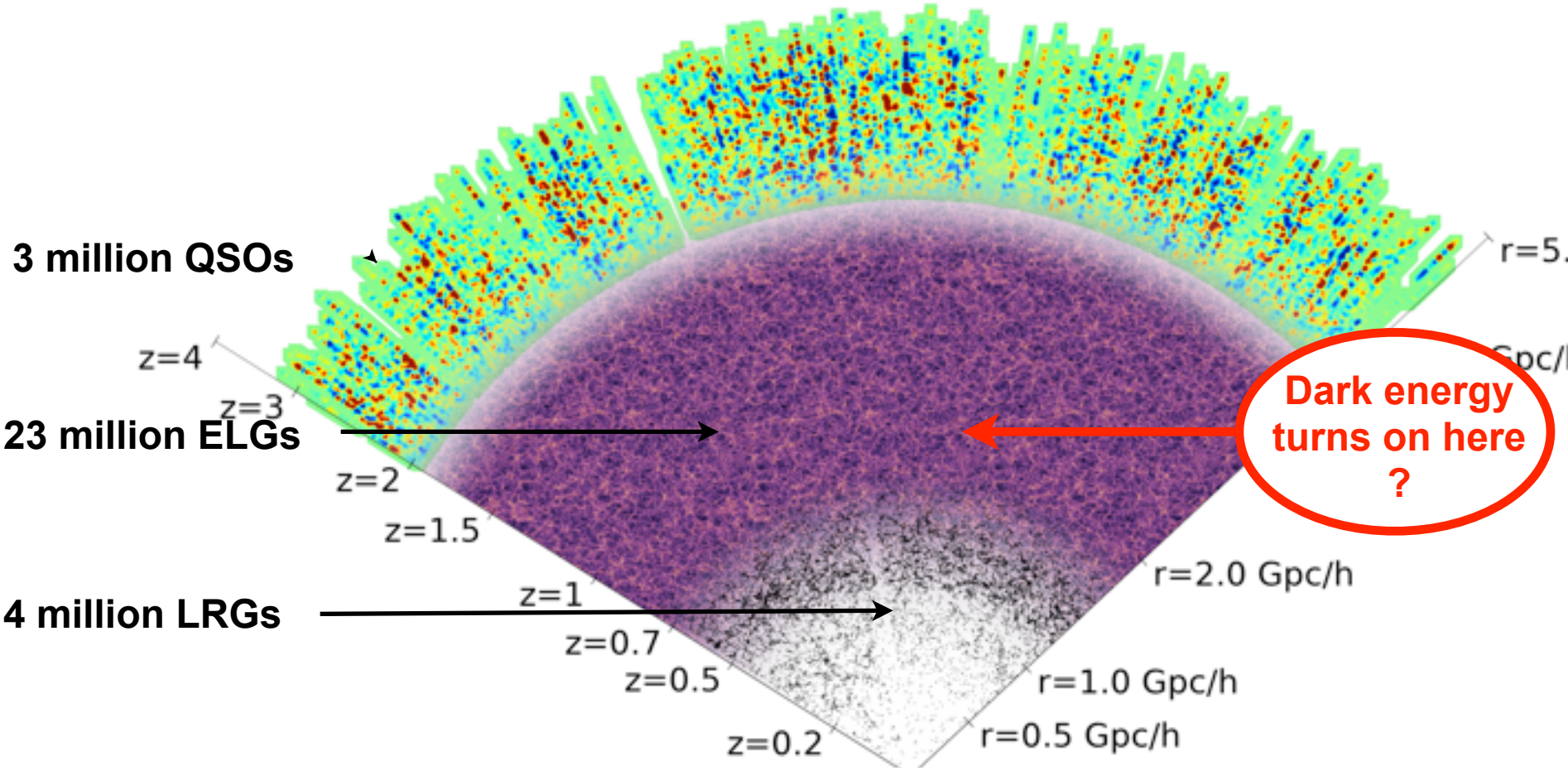
eBOSS, HETDEX, DESI, PFS, Euclid



BOSS sampled a volume of 5 $h^{-3}Gpc^3$

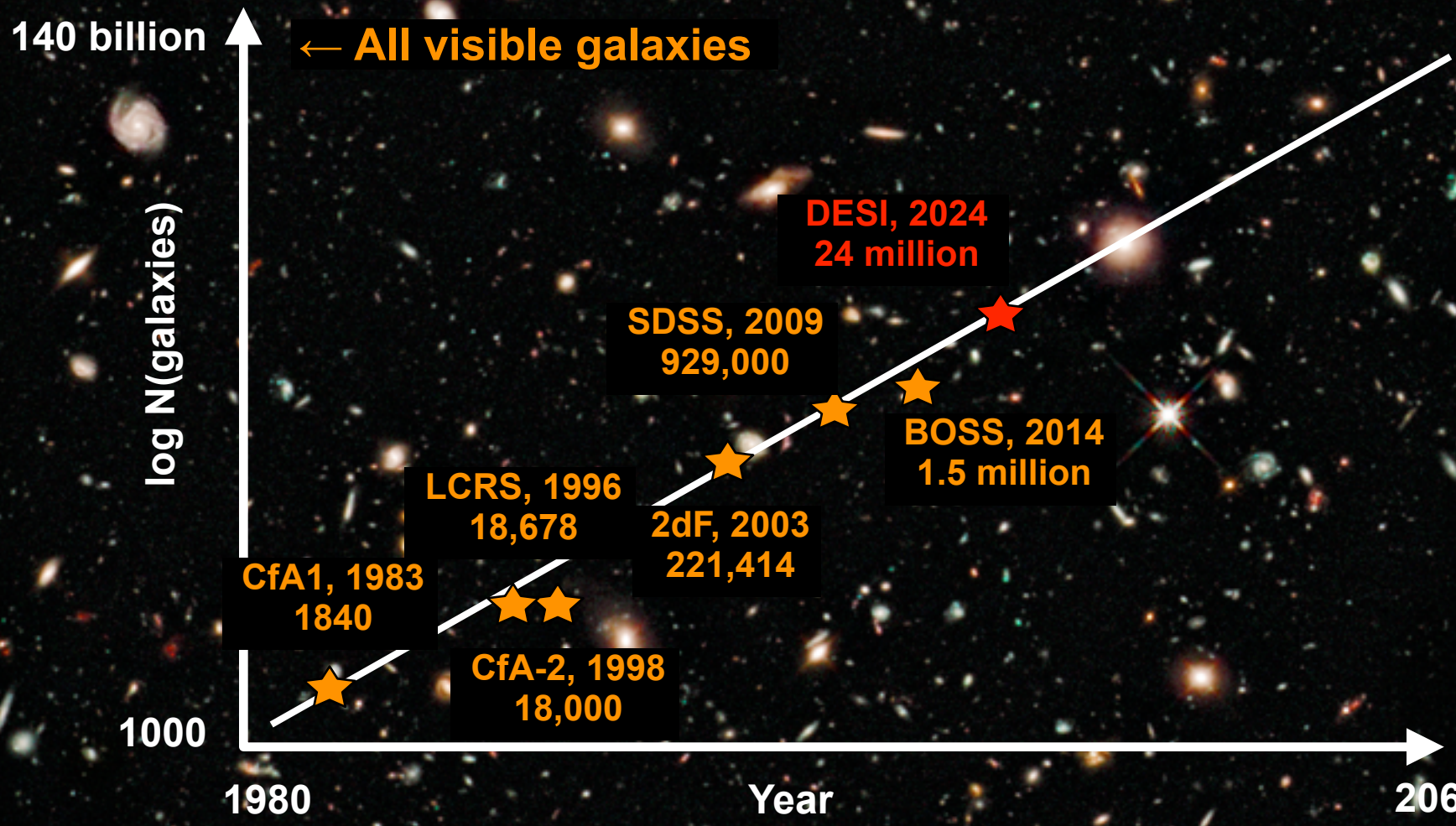


DESI will sample a volume >50 $h^{-3}Gpc^3$



Redshift surveys increasing exponentially in size

Large enough for BAO starting in 2005



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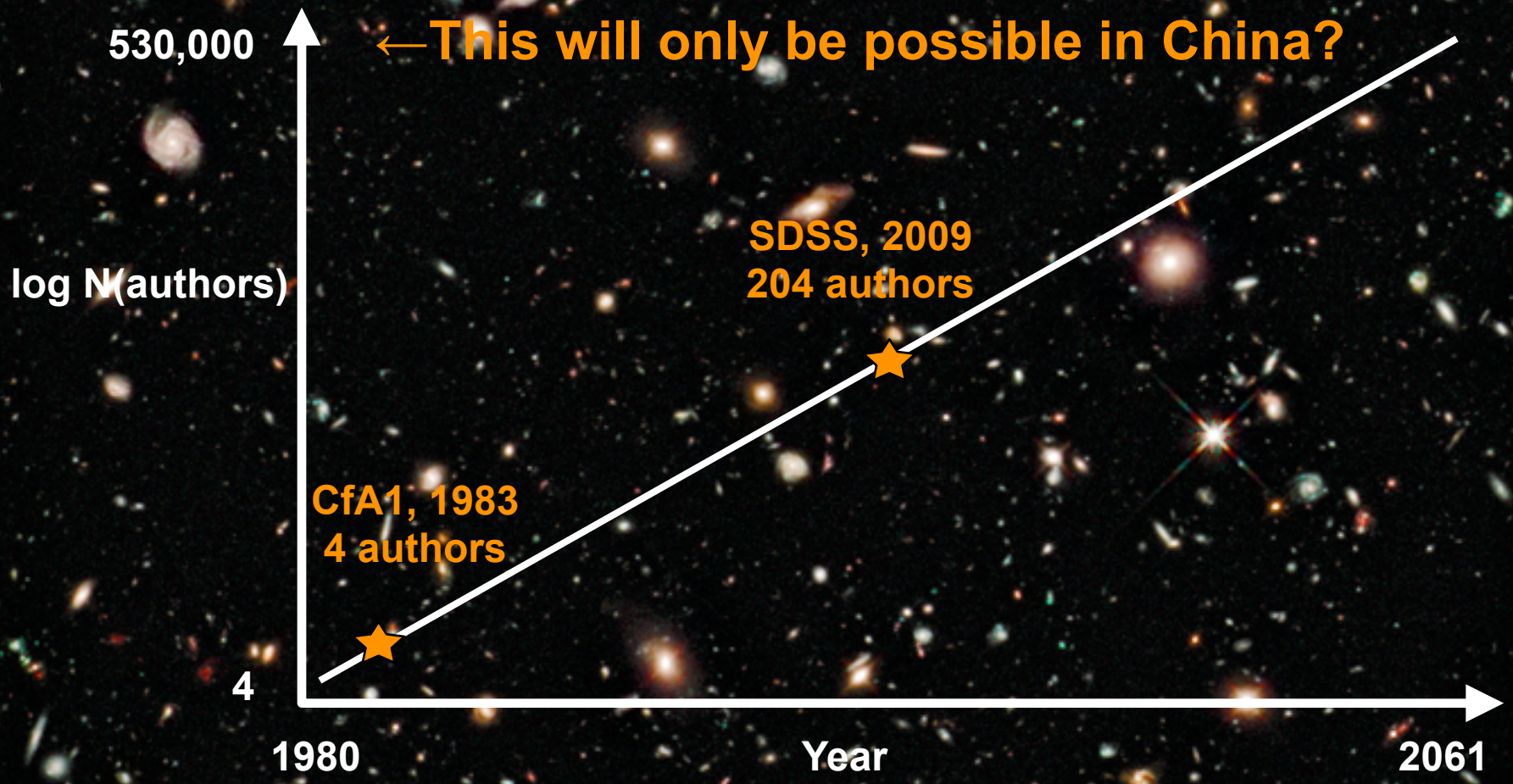

Future CMB experiments racing to detect B-modes

BICEP2/Keck/BICEP3, ACTPol, SPTPol, Polarbear/Simons Array
SPIDER, EBEX

Summary

- BAO measured expansion history from z=0.1->1100
- Dark energy consistent with a cosmological constant
- Future experiments will be dramatically larger, esp. at z>0.7

- Inflation-era primordial fluctuations definitively measured, and not scale-free
- Inflation era non-gaussianities not detected
- No detection yet of primordial gravitational waves, but future CMB B-mode experiments racing to measure