

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

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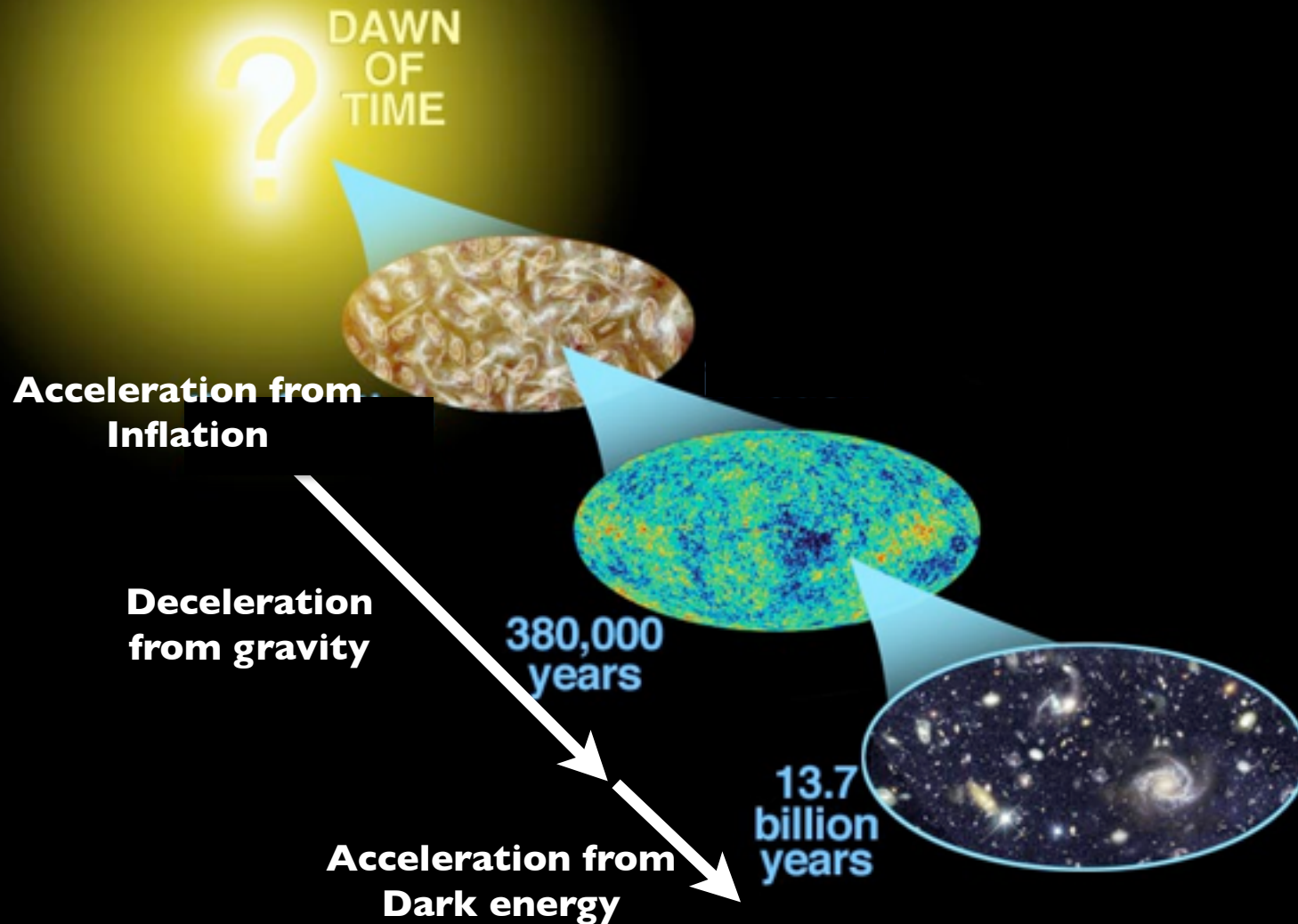
2nd Age of Dark Energy

$t \sim \text{now}$

Phase of accelerating expansion dubbed “dark energy”

Observable at $t > 2$ billion years, possibly dynamic

Timeline of Dark Energy

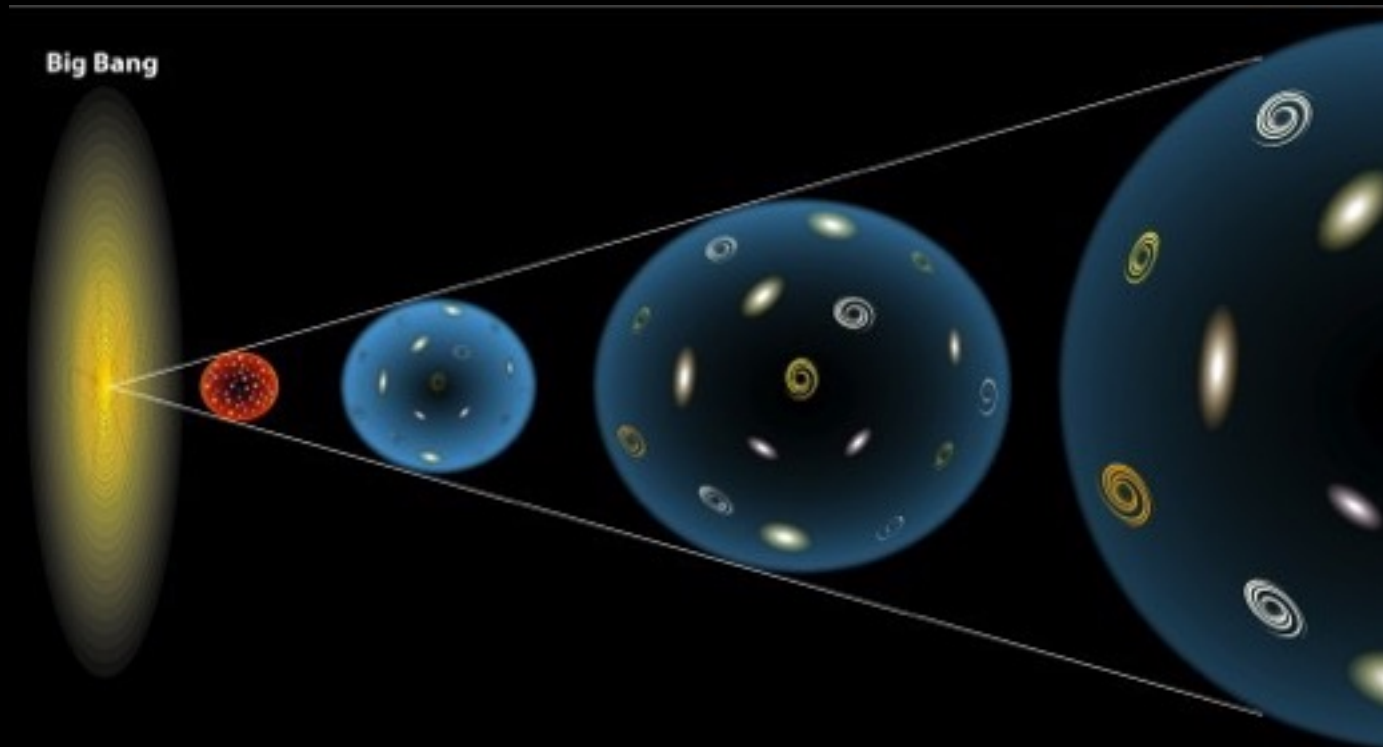


Toolset for Dark Energy are geometrical measures

Measurements that are per-object:
supernovae

Measurements that are statistical:
features + scales in density maps (galaxies, CMB)

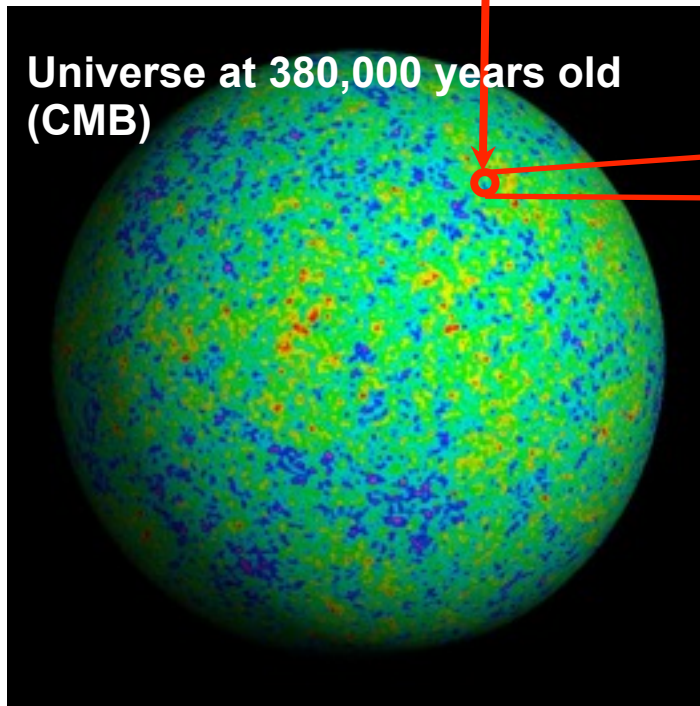
All imply extra volume between us and high redshift



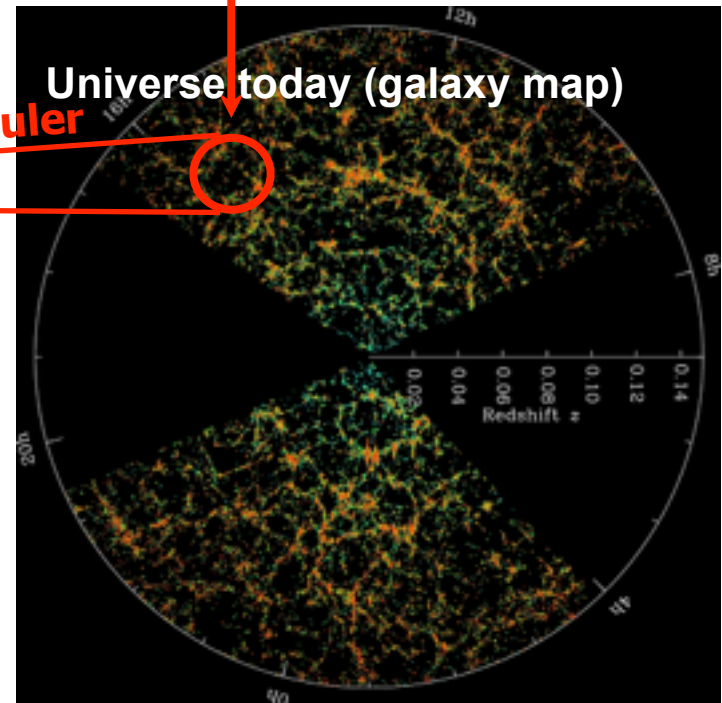
Baryon Acoustic Oscillations (BAO) standard ruler at 147 Mpc

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

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



...these \sim unity fluctuations today



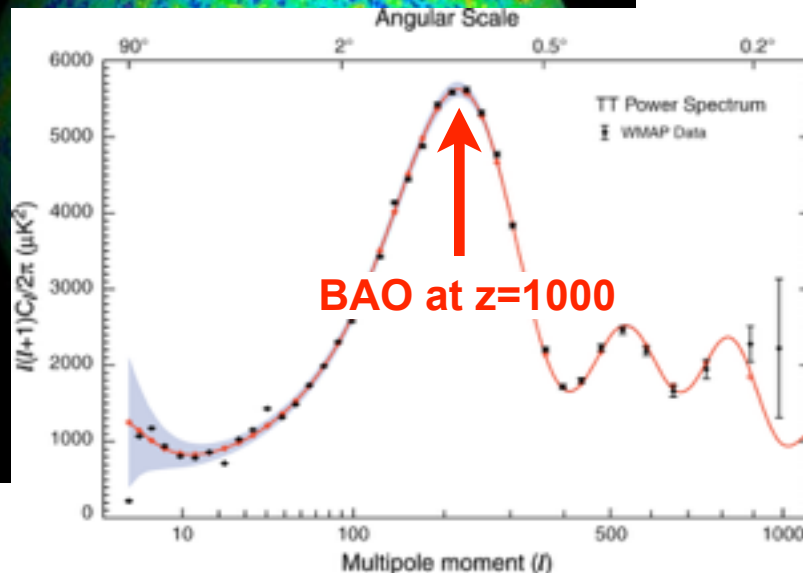
standard ruler

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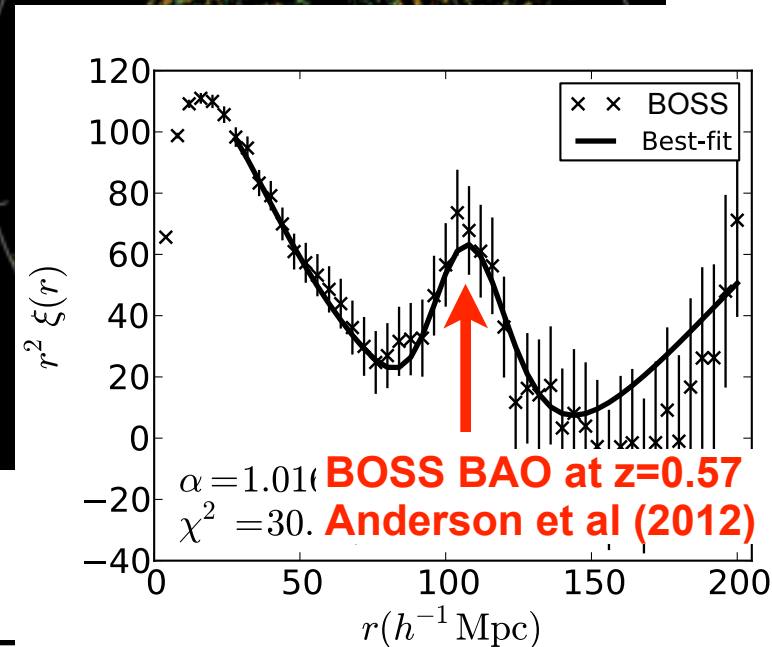
Universe at 380,000 years old
(CMB)



...these \sim unity fluctuations today

Universe today (galaxy map)

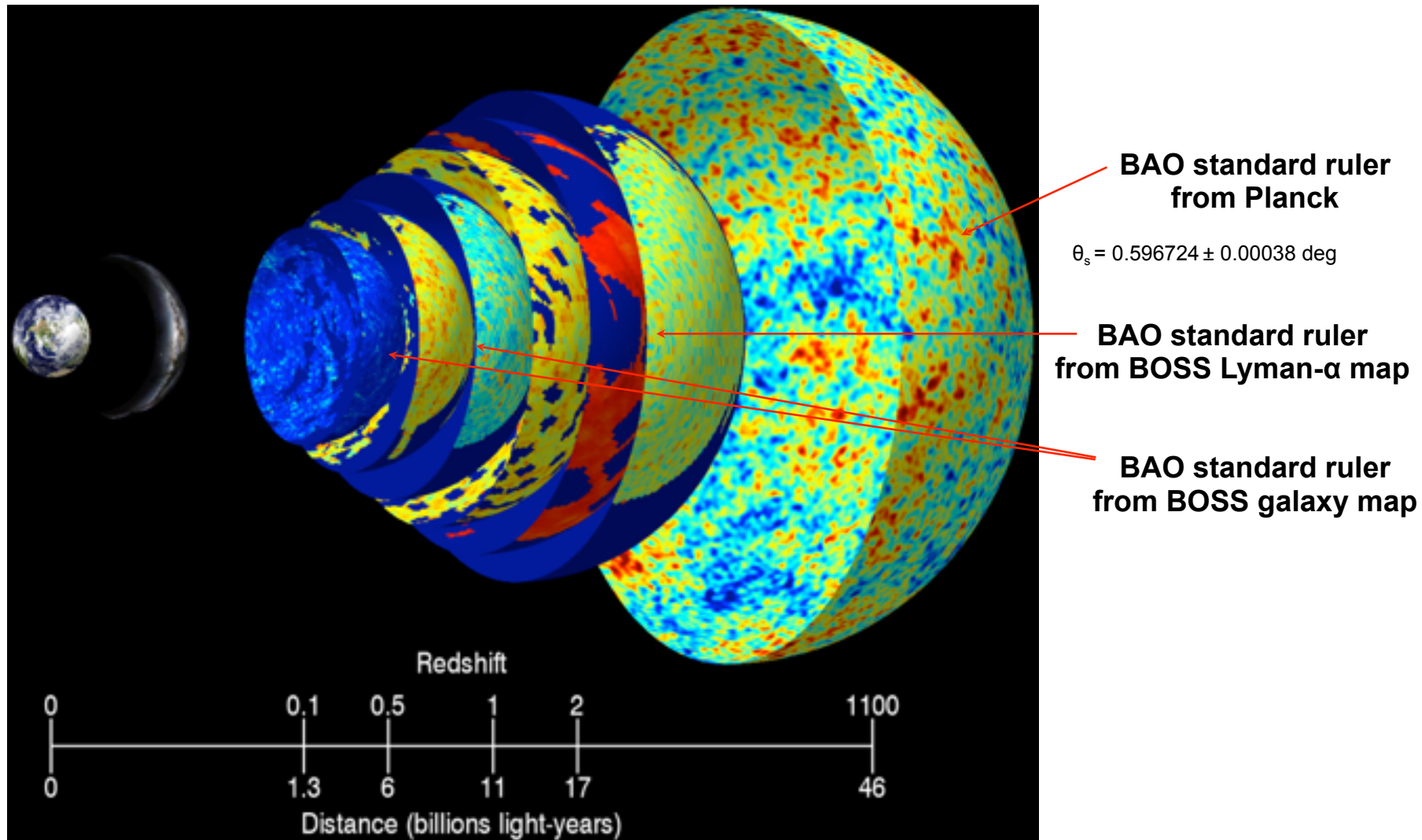
standard ruler



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



Baryon Oscillation Spectroscopic Survey (BOSS)

Most capable instrument today for mapping the Universe

2.5-meter Sloan Telescope
3 degree field-of-view

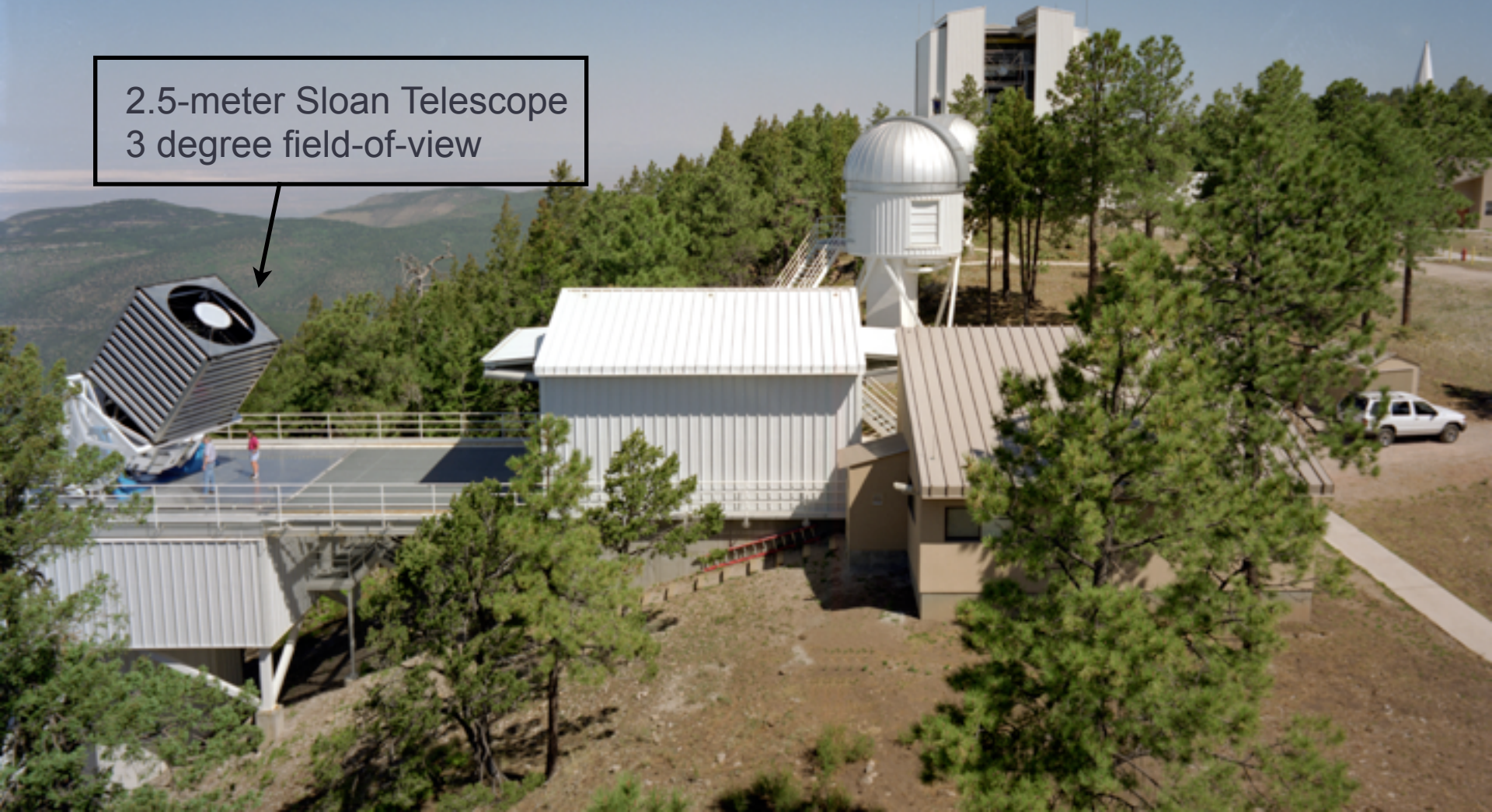


Image sky



Select targets



Design plug-plates



Plug fibers



Observe!



Spectra + redshifts



Make 3-D maps



Cosmology

SDSS-III/BOSS imaging completed in Dec 2009

- 10,400 deg² extragalactic footprint

- 5 filters (ugriz)

1% photometric precision

Camera is now retired at the Smithsonian

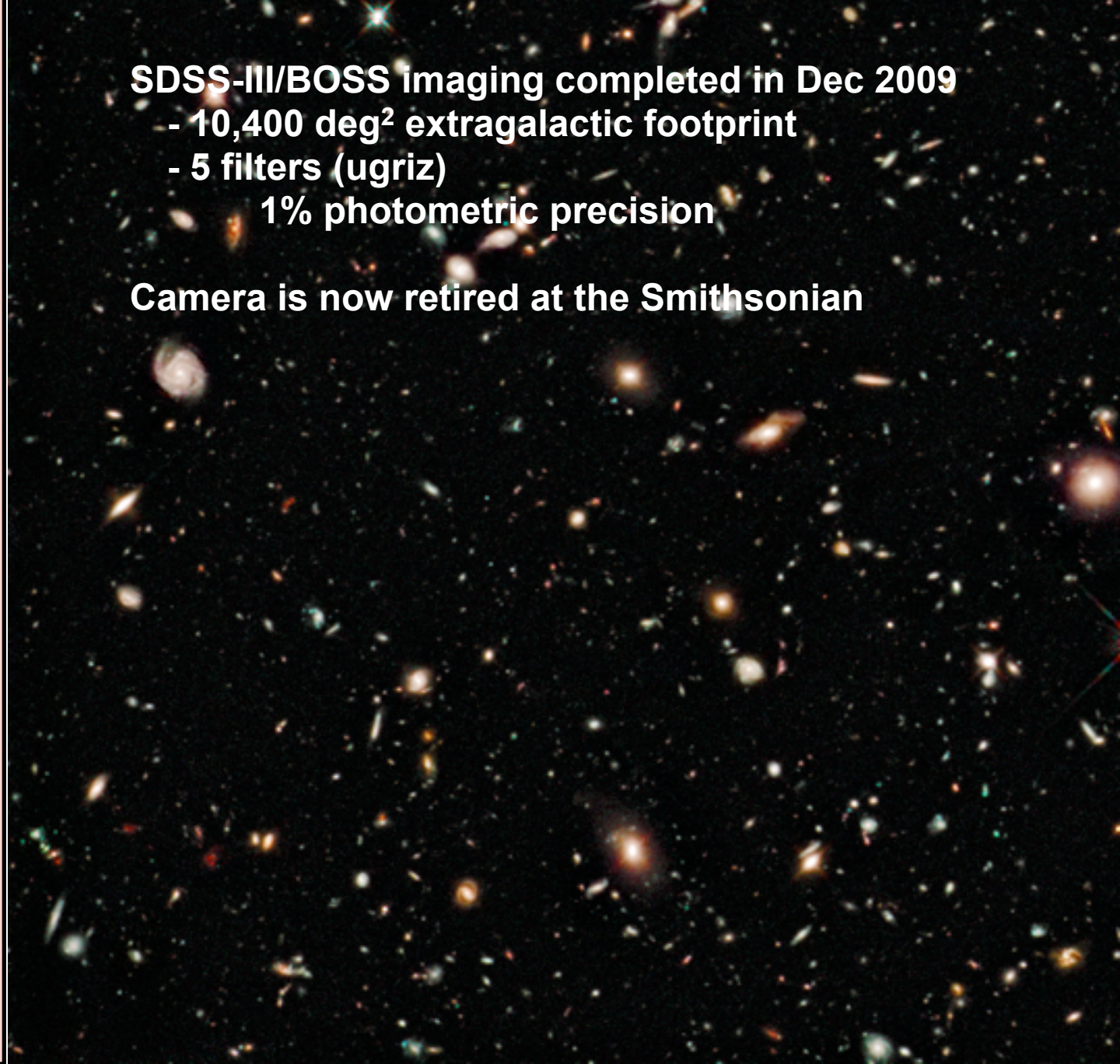


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Spectra + redshifts

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Cosmology

BOSS targeted

- 1.5 million Luminous Red Galaxies at $z < 0.7$
- 160,000 $z > 2.15$ quasars



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Cosmology

**1000 targets observed on each plate
(increased from 640 in original SDSS)**

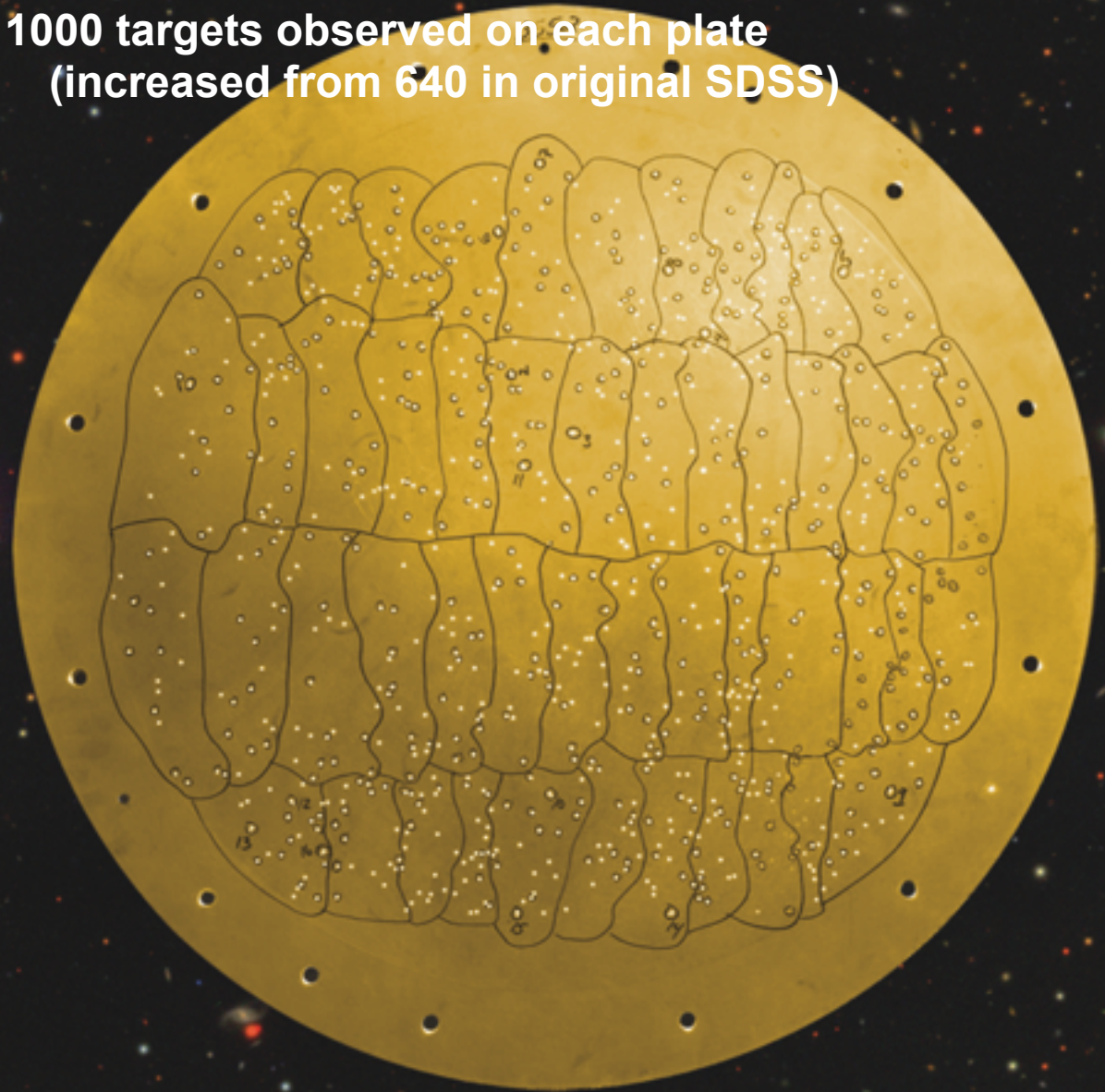


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Cosmology

Sloan Foundation Telescope, New Mexico
7 sq deg FOV

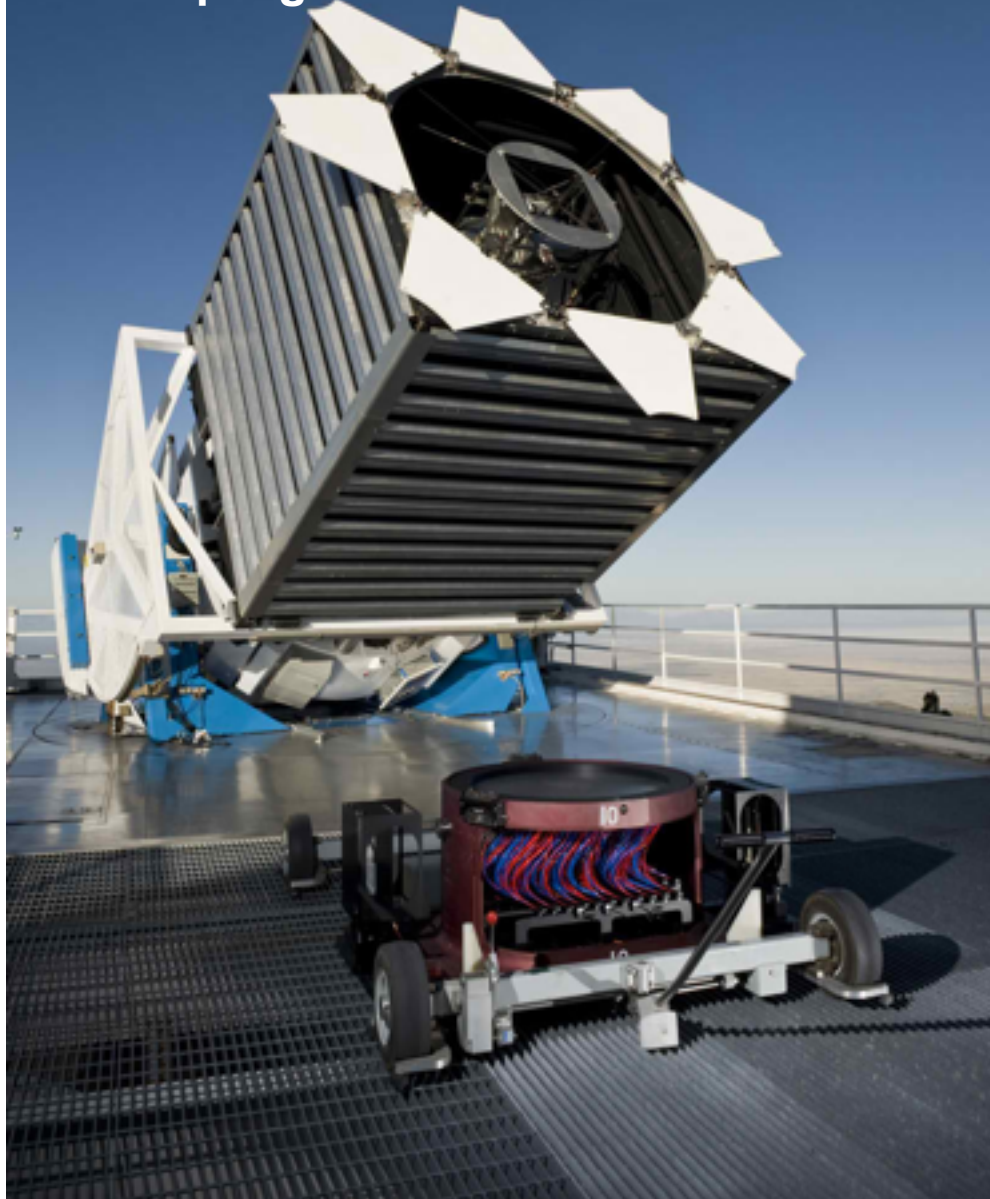
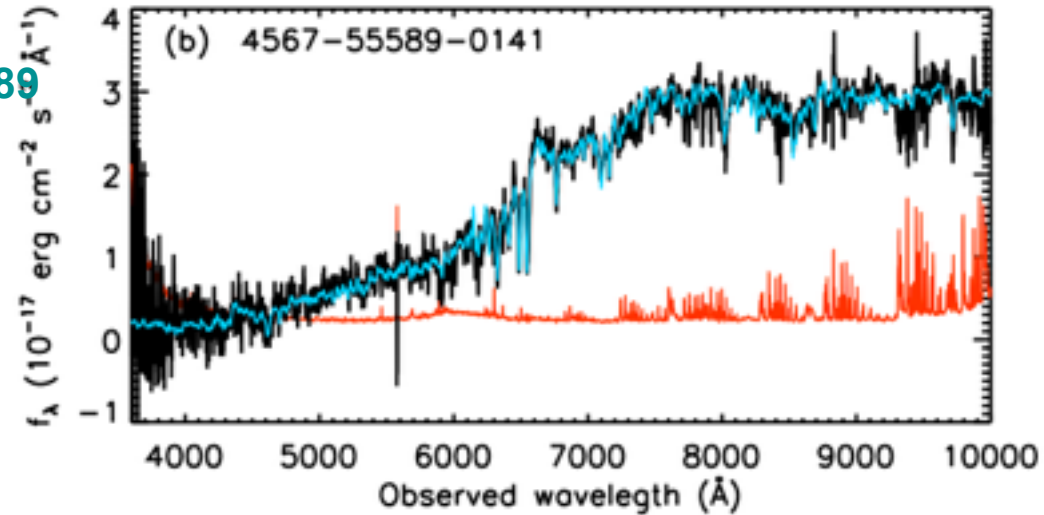


Image sky
↓
Select targets
↓
Design plug-plates
↓
Plug fibers
↓
Observe!
↓
Spectra + redshifts
↓
Make 3-D maps
↓
Cosmology

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 $z=2.873$

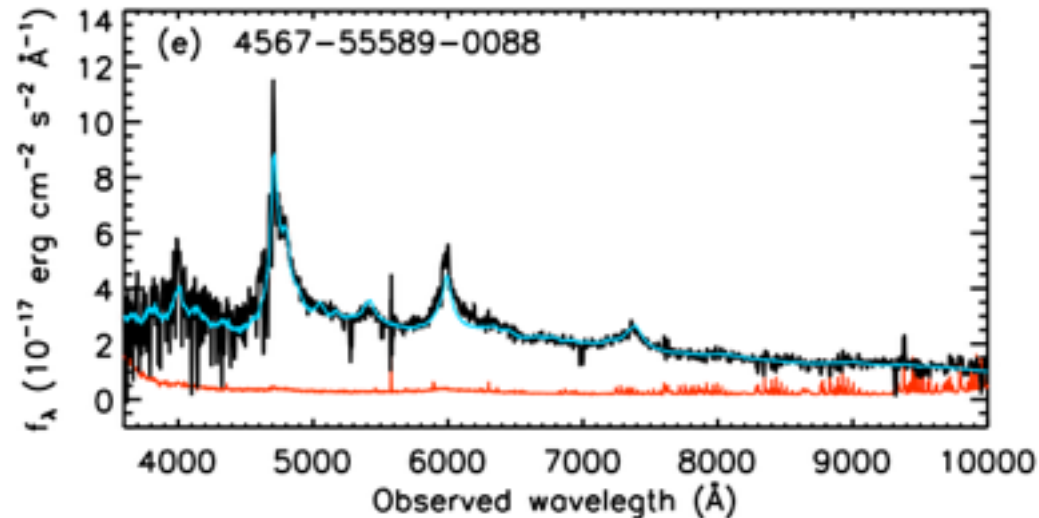


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Spectra + redshifts



Make 3-D maps



Cosmology

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

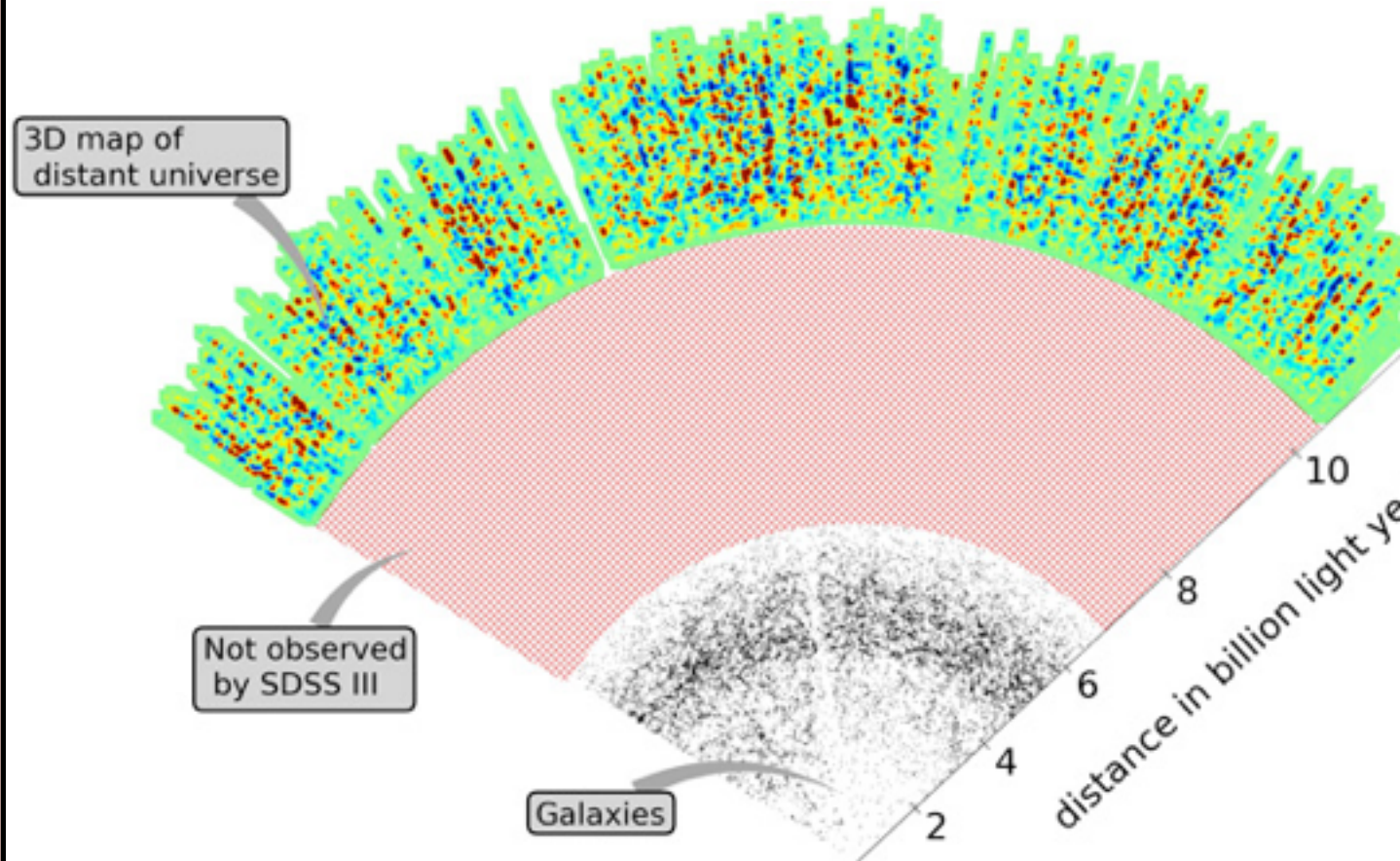


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Spectra + redshifts



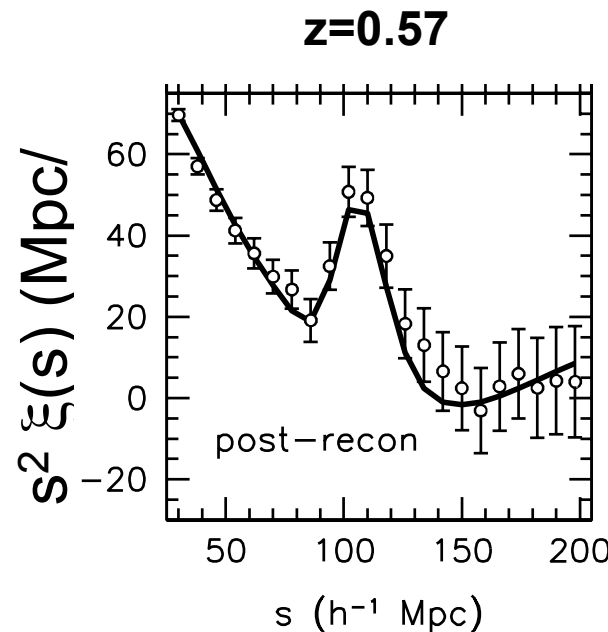
Make 3-D maps



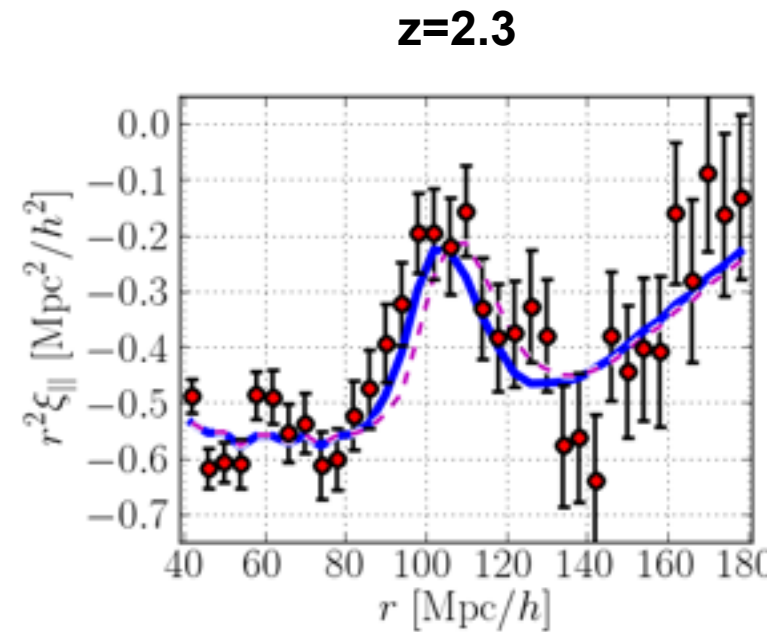
Cosmology

Four distinct BAO measures in BOSS Data Release 11

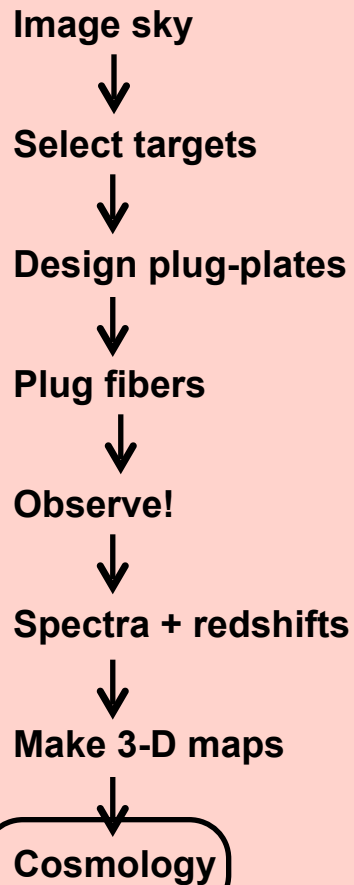
- LOWZ galaxies at $z=0.32$
- CMASS galaxies at $z=0.57$
- Lyman-alpha forest auto-correlation at $z=2.3$
- Lyman-alpha + Quasar cross-correlation at $z=2.3$



Anderson et al.

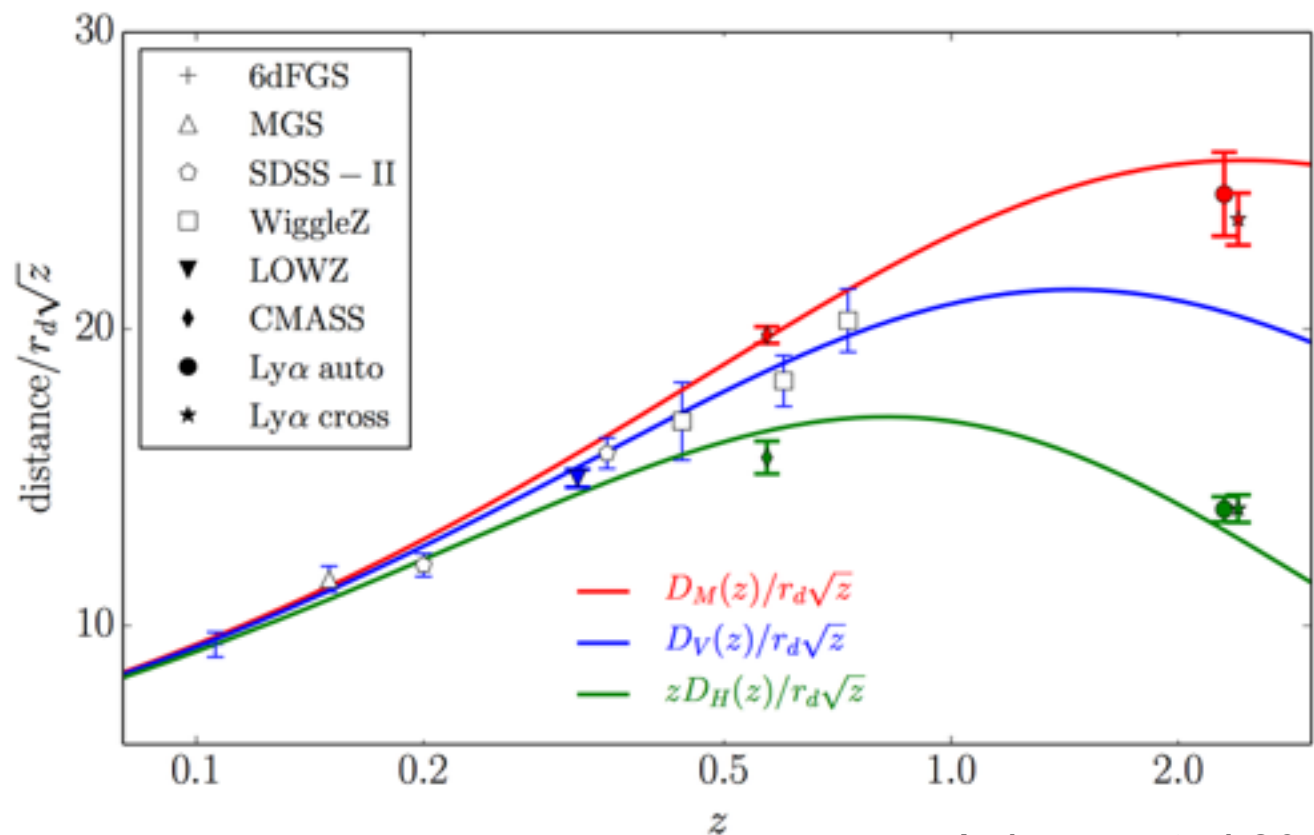


Delubac et al. (2014)

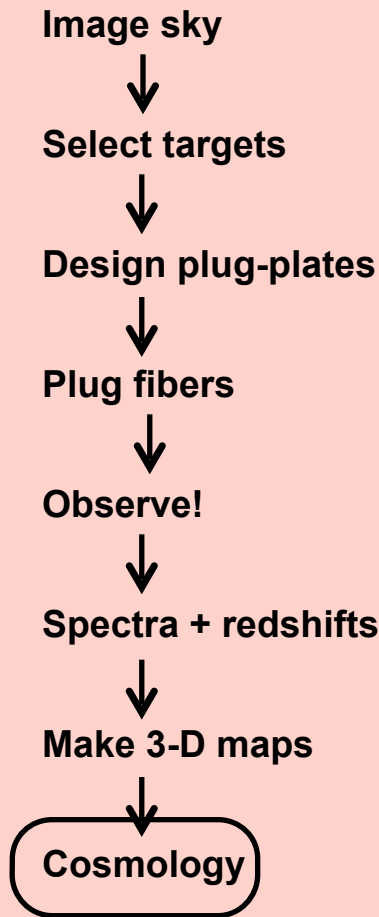


**BAO as a ruler measures the expansion history,
even with no physical scale**

**BAO measured near its cosmic variance limit at $z=0 \rightarrow z=0.7$
Future improvement can only be $\sim 2X$ better there
BAO at $z > 0.7$ nowhere near cosmic variance limit**



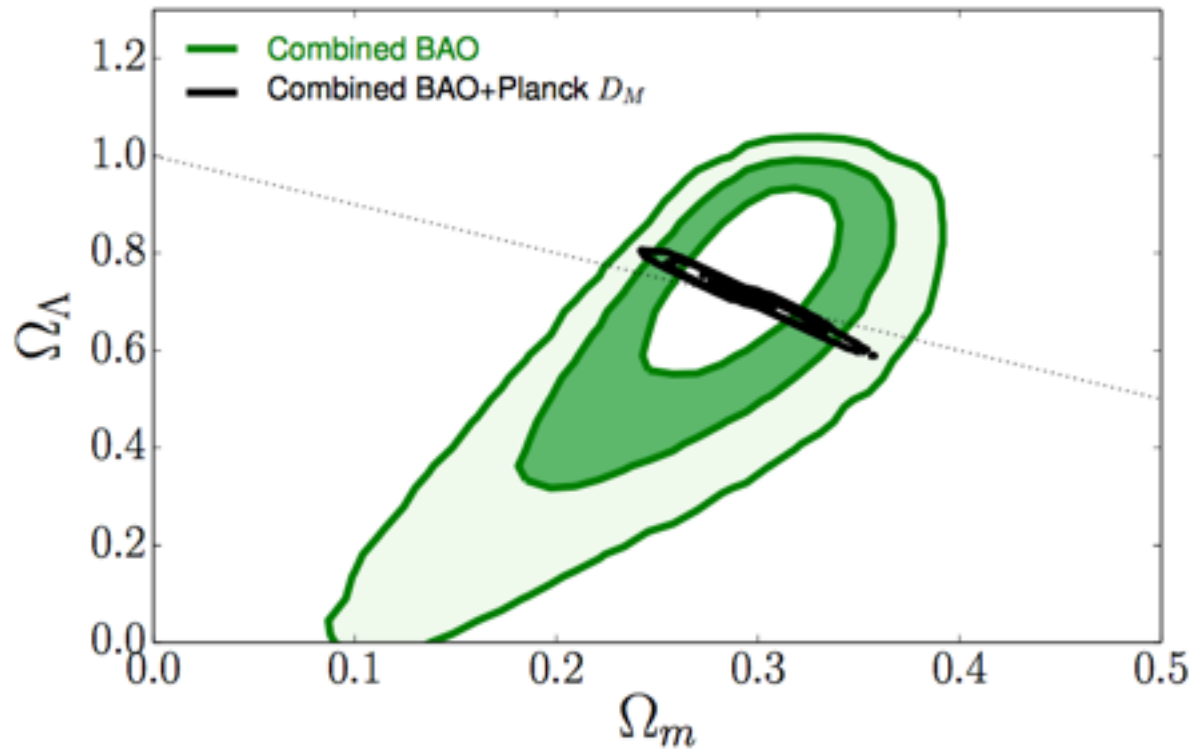
Aubourg et al 2014



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 $z=1100 \rightarrow z=0.1$



Aubourg et al 2014

Image sky



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Plug fibers



Observe!



Spectra + redshifts



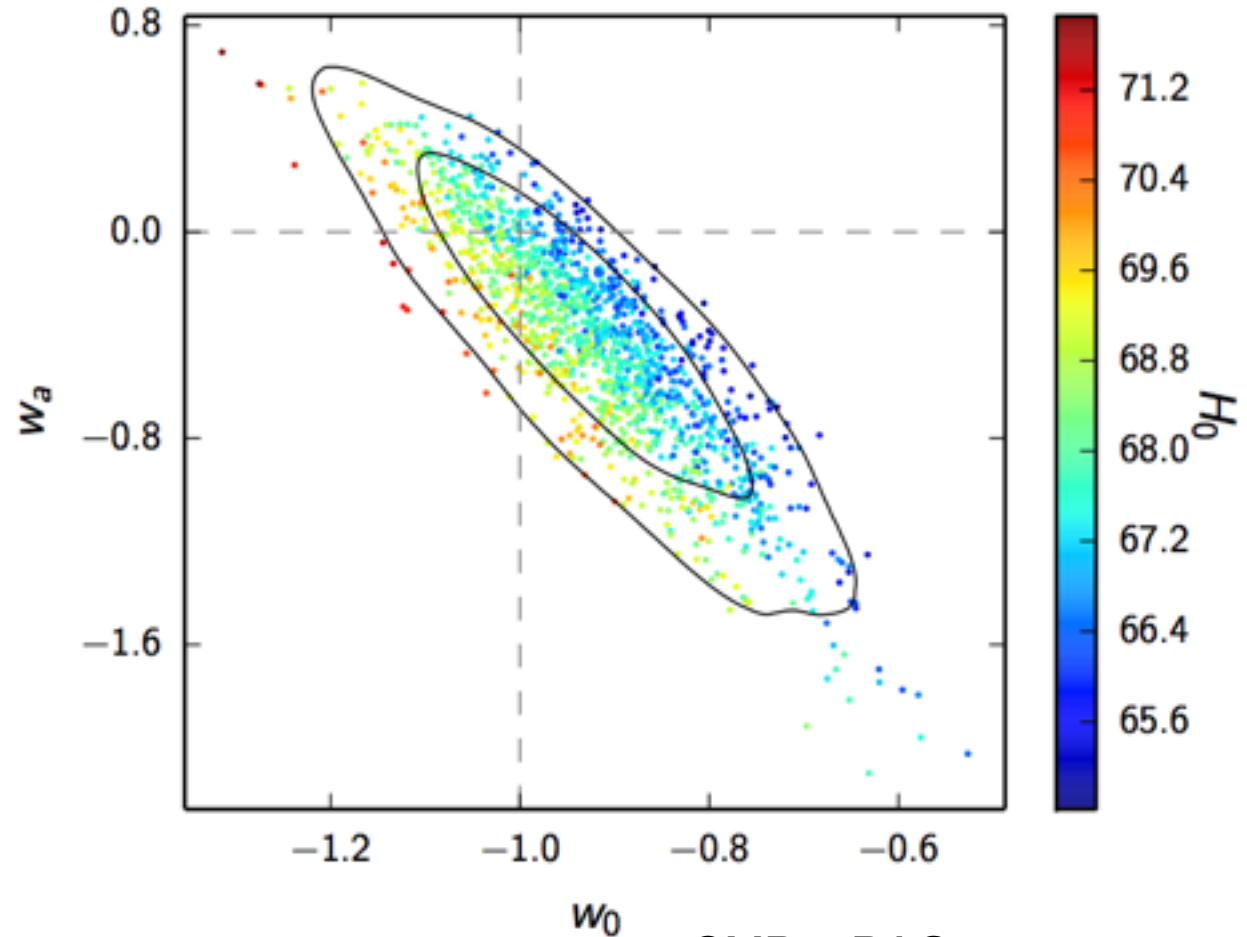
Make 3-D maps



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)

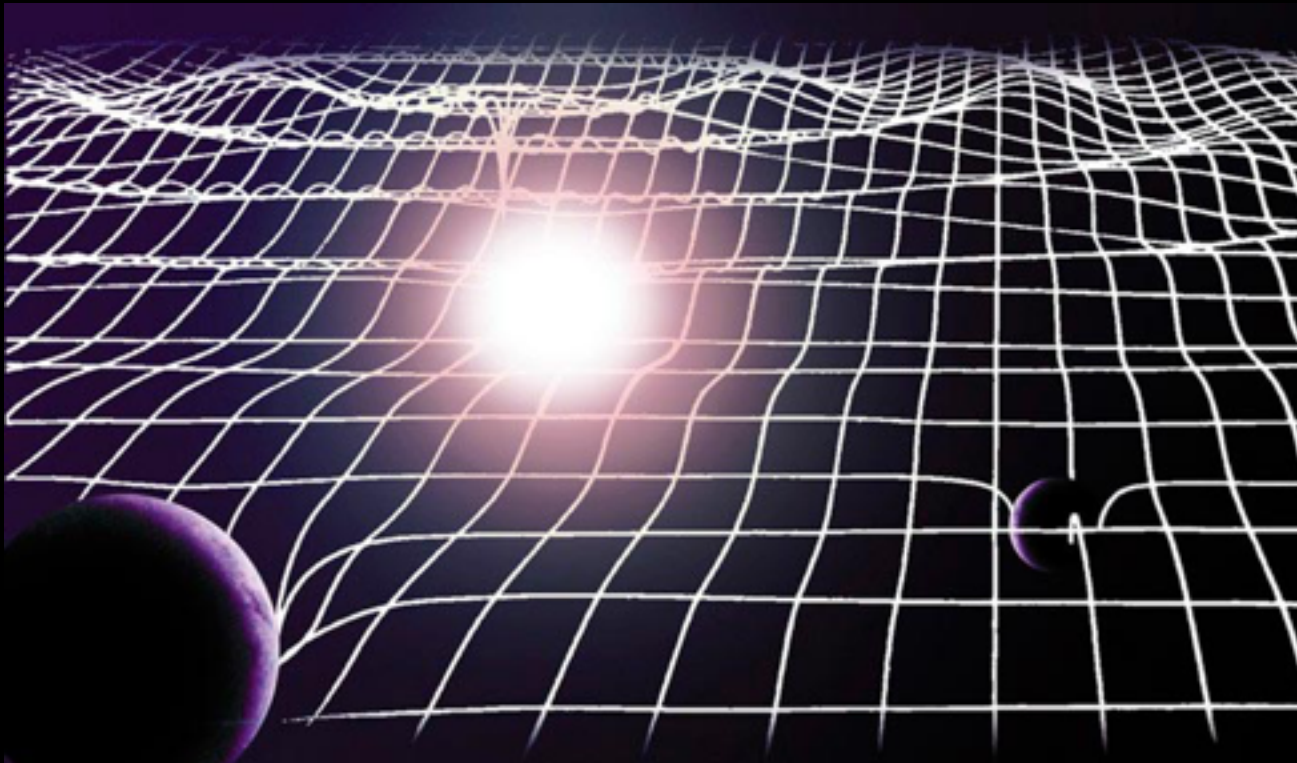
Non-gaussianities

Flatness (Ω_k)

Gravitational wave background

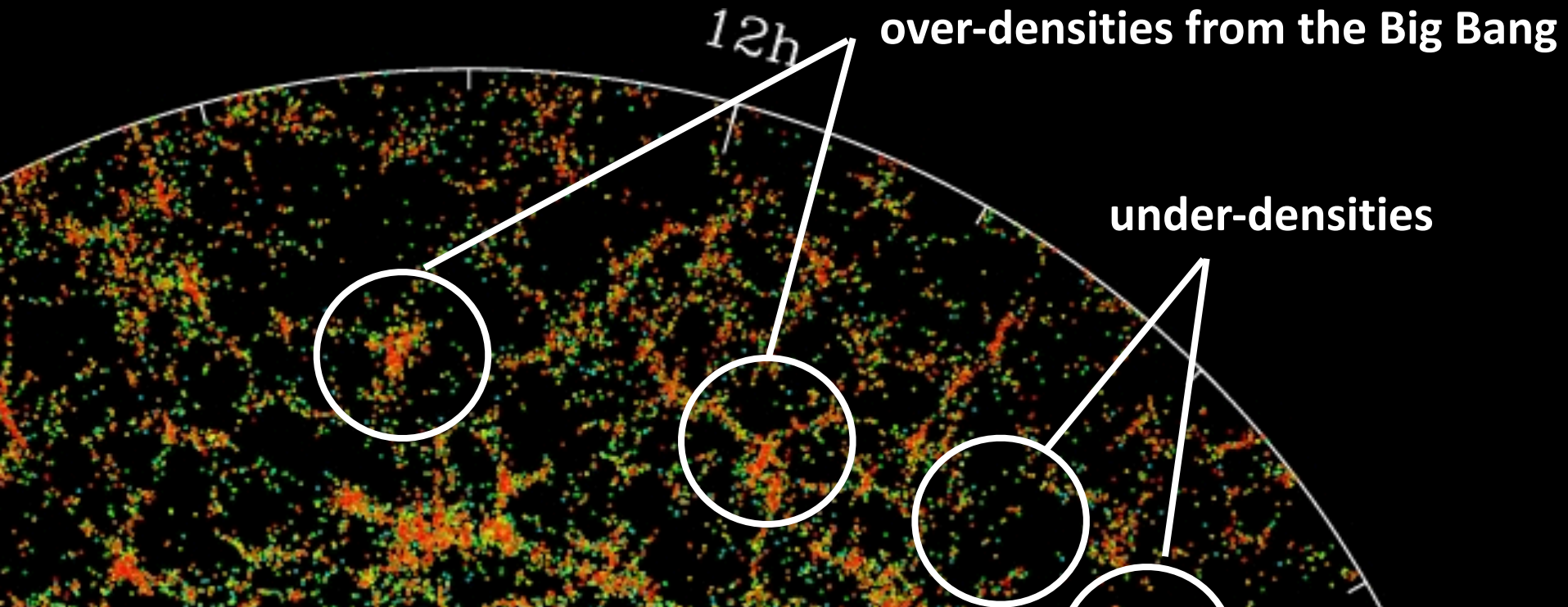
Direct measure of grav. waves

Imprinted grav. waves as B-modes in CMB



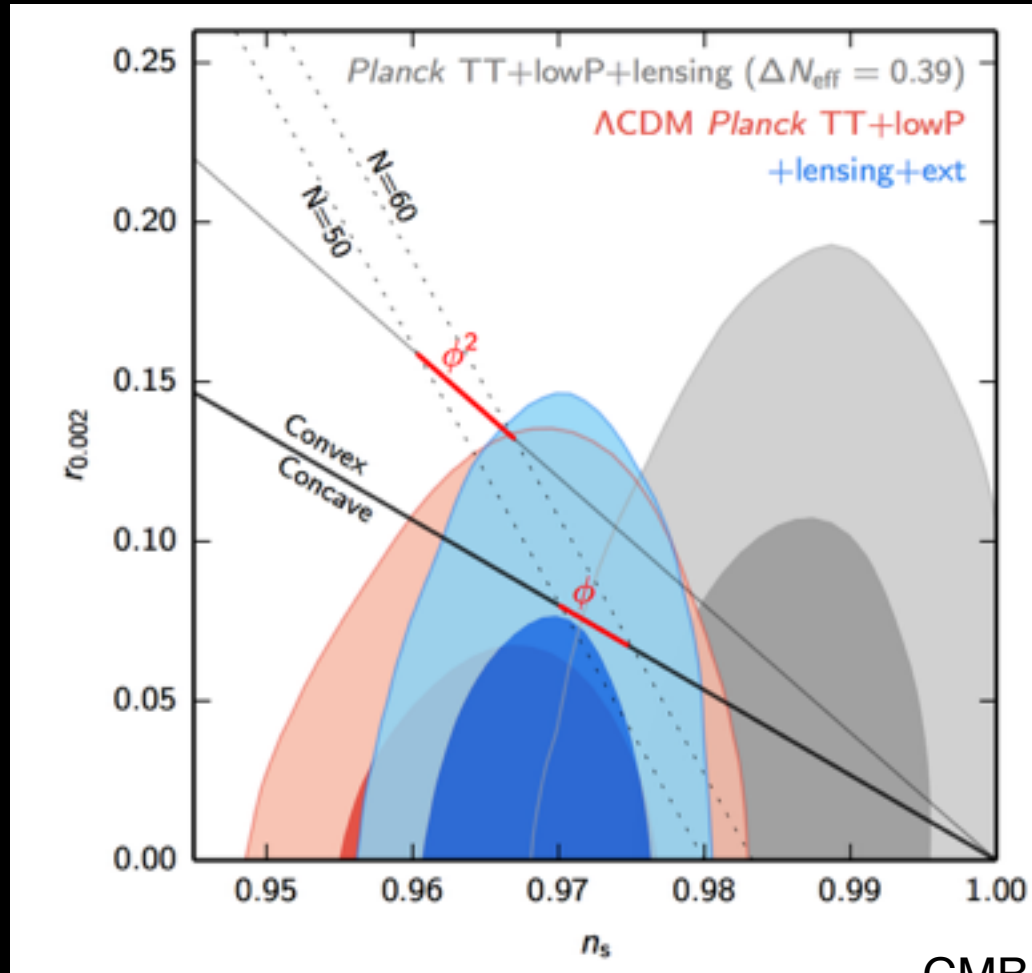
Most inflation-era measures are upper limits

- 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!

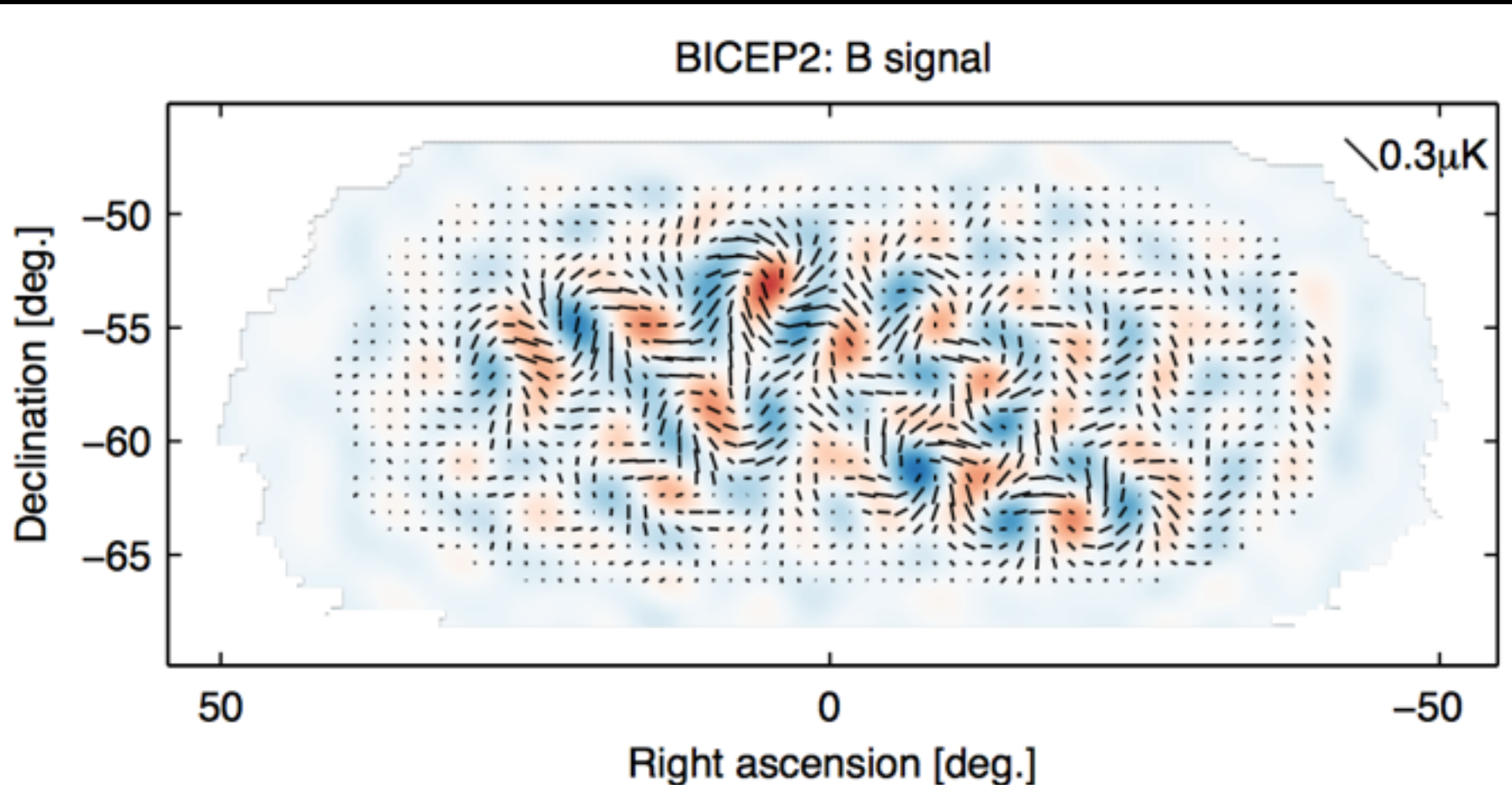
Primordial fluctuation spectrum (n_s) is not scale-free



CMB + BAO
Planck Collaboration 2015

At least one inflation-era measure was incorrect

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

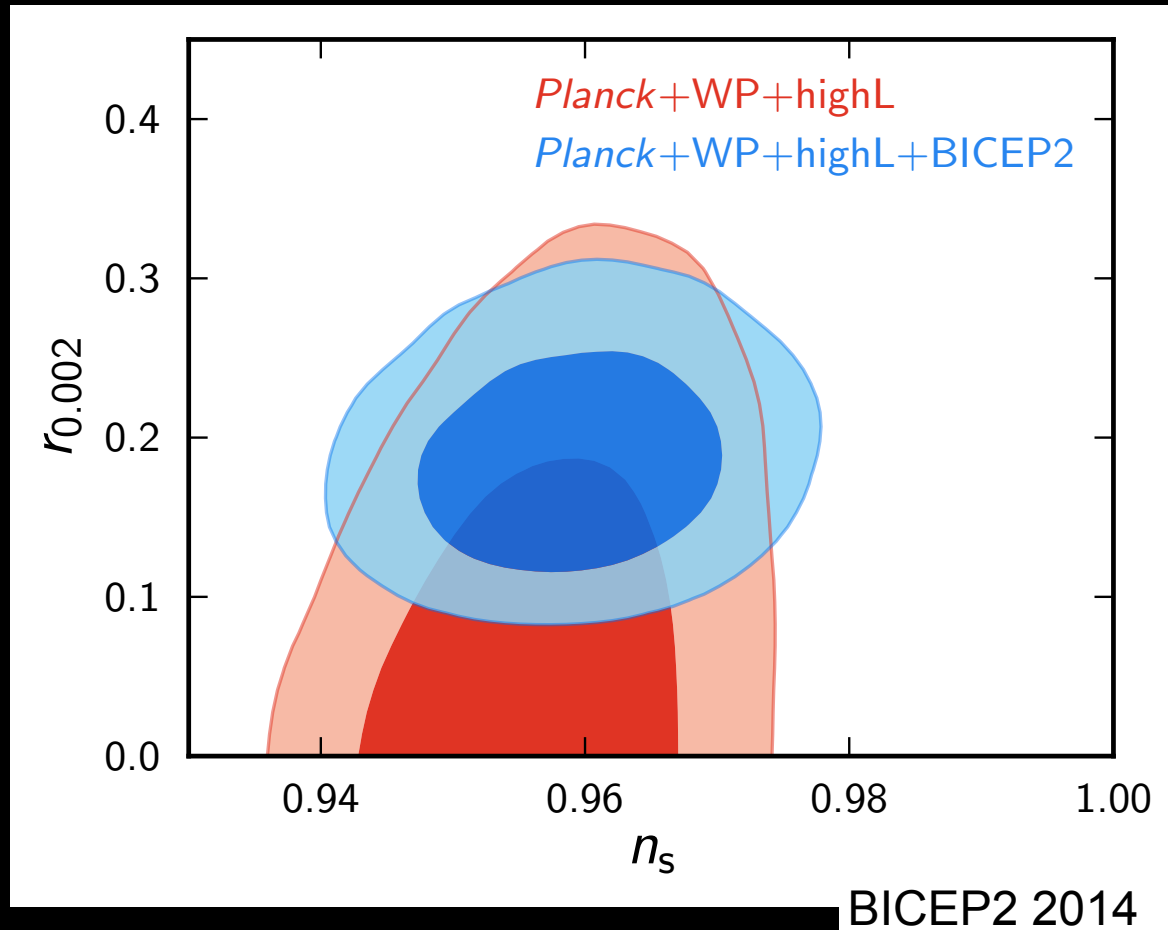


At least one inflation-era measure was incorrect

The signal was real

Sourced from dust in the Milky Way

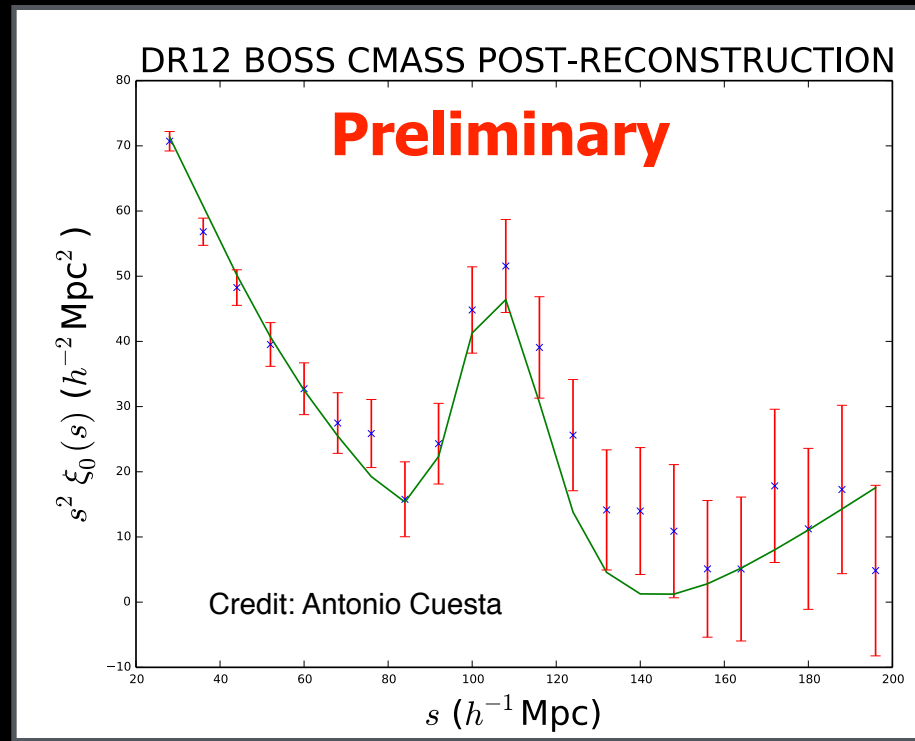
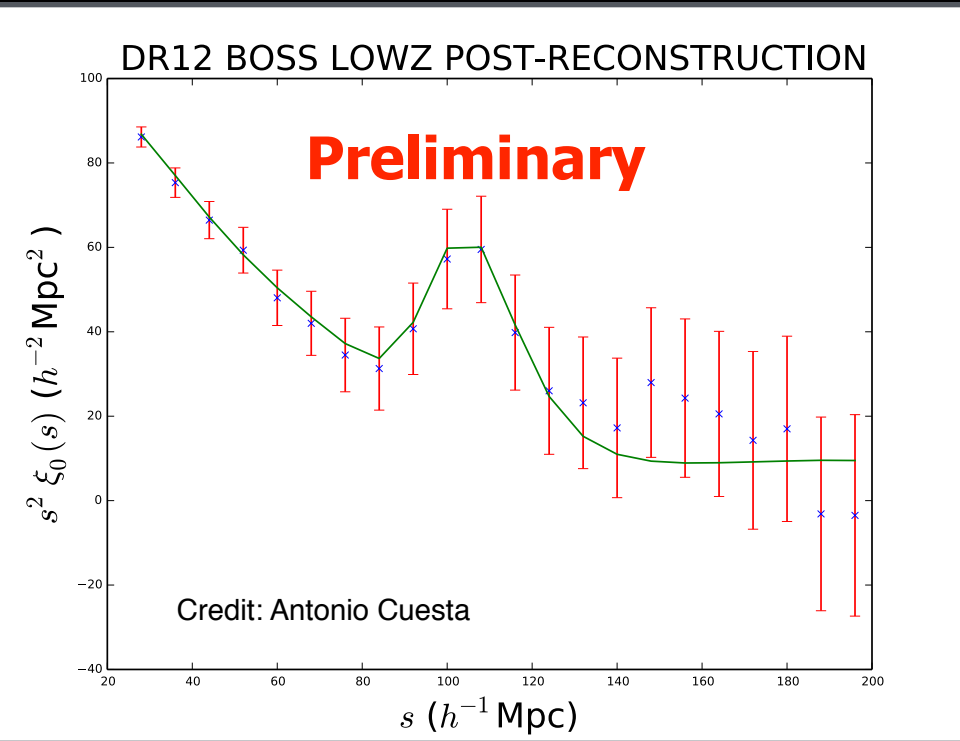
Mis-interpreted as grav. waves imprinted upon CMB



Future Experiments

Final results from BOSS in prep.

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



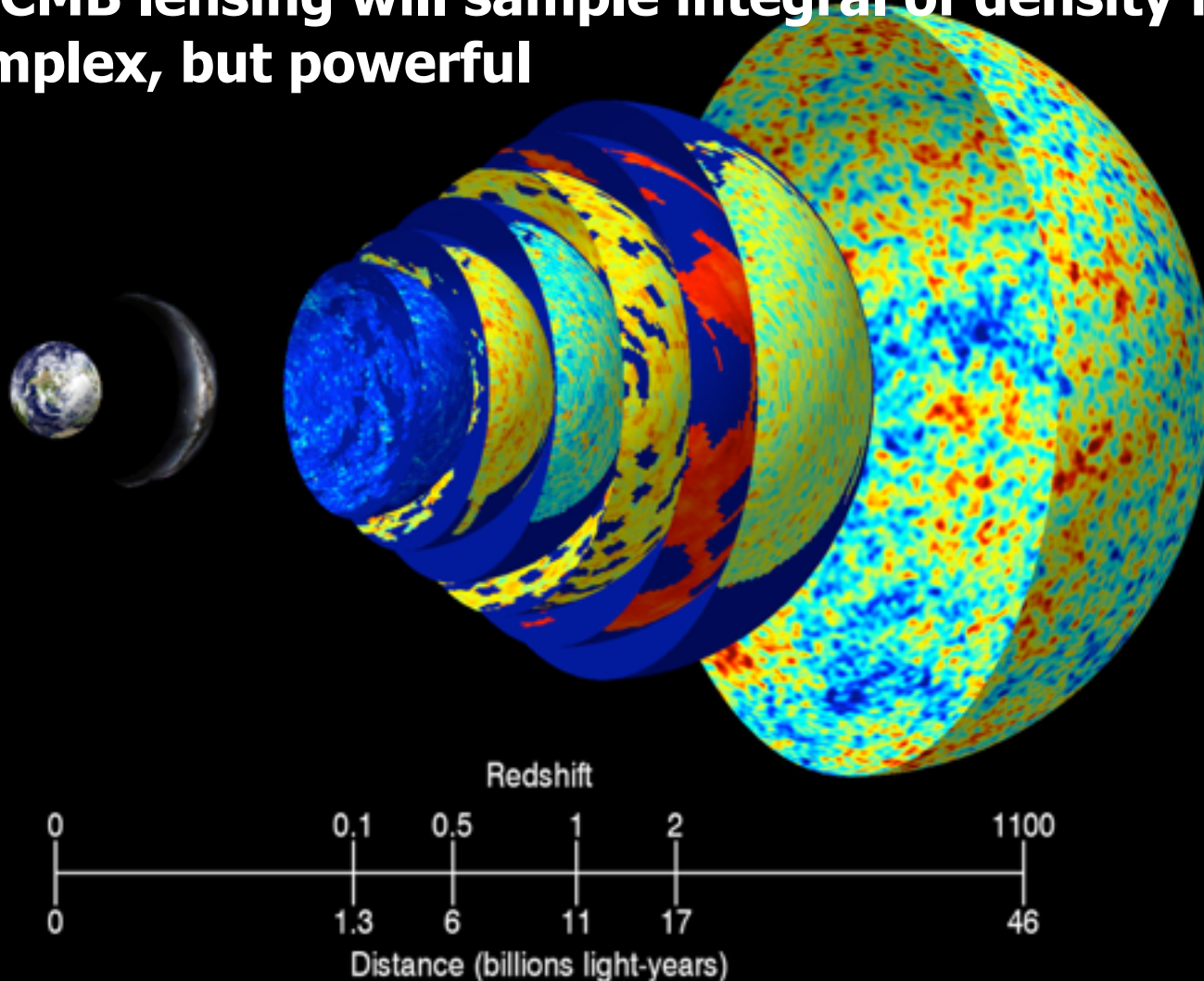
Statistical power increases with # of modes

Cosmic variance limit for BAO only reached at $z < 0.7$ & $z = 1100$

More modes at smaller scales

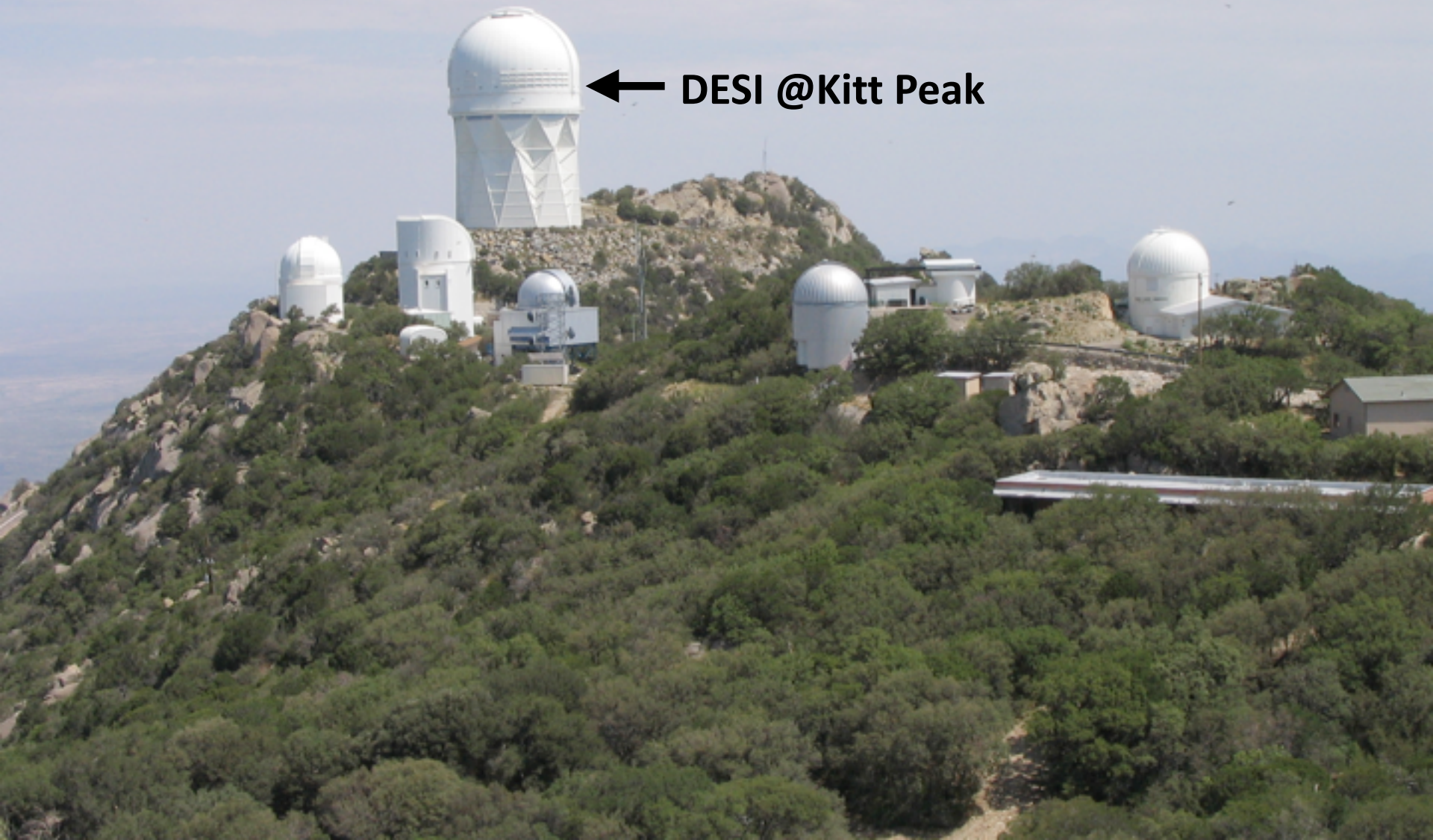
Galaxy + CMB lensing will sample integral of density fields

-> Complex, but powerful



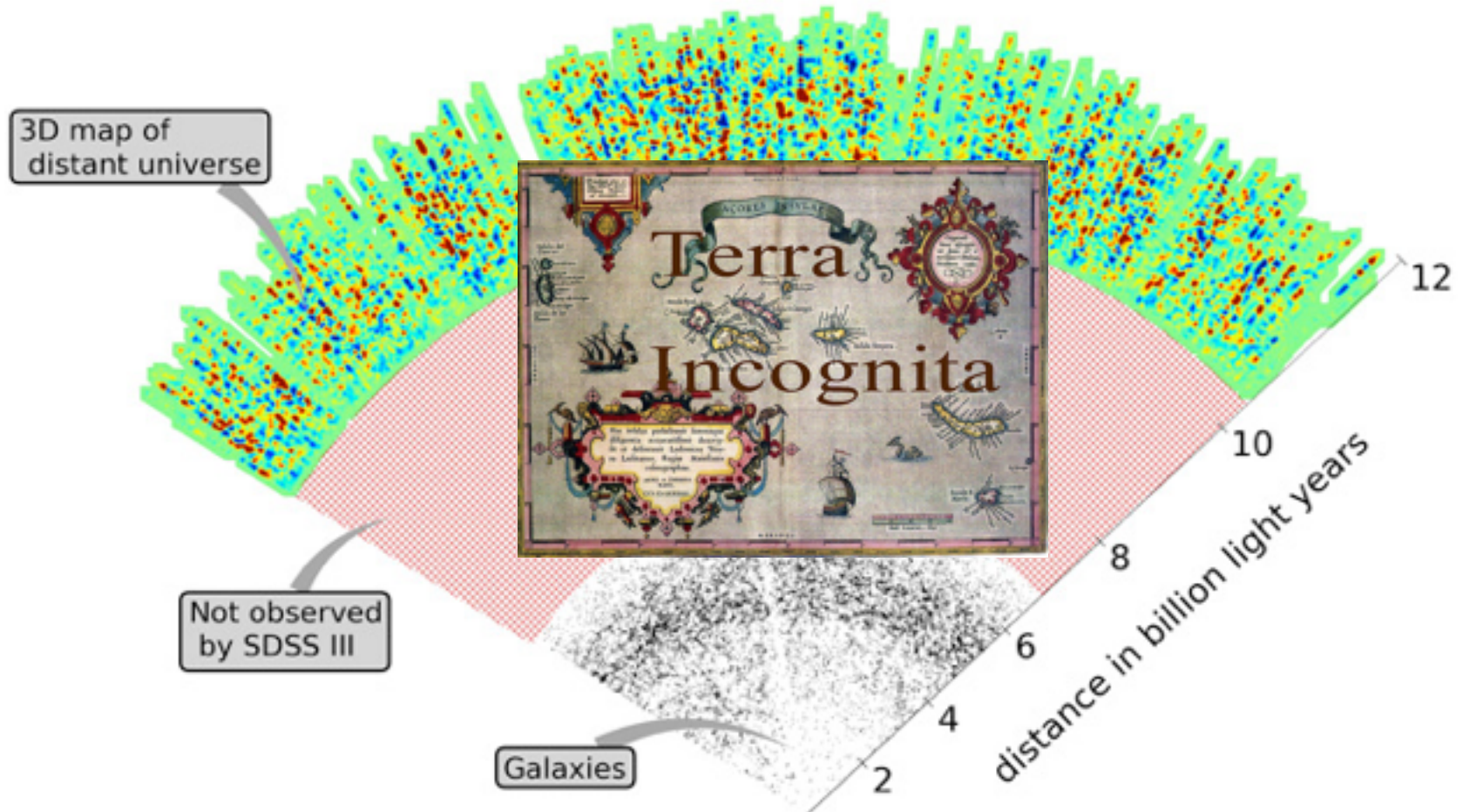
Future BAO experiments will sample $z > 0.7$

eBOSS, HETDEX, DESI, PFS, Euclid

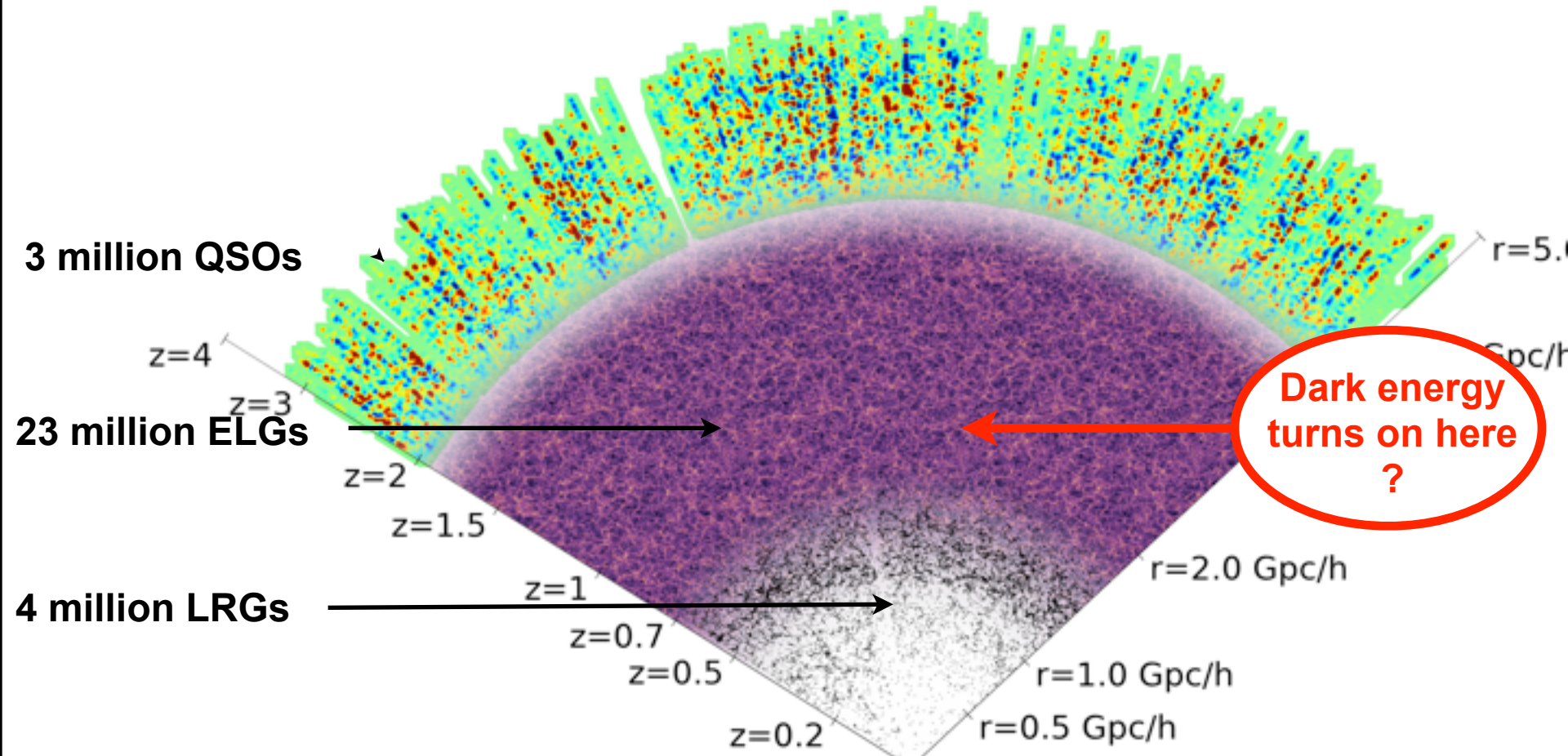


← DESI @Kitt Peak

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

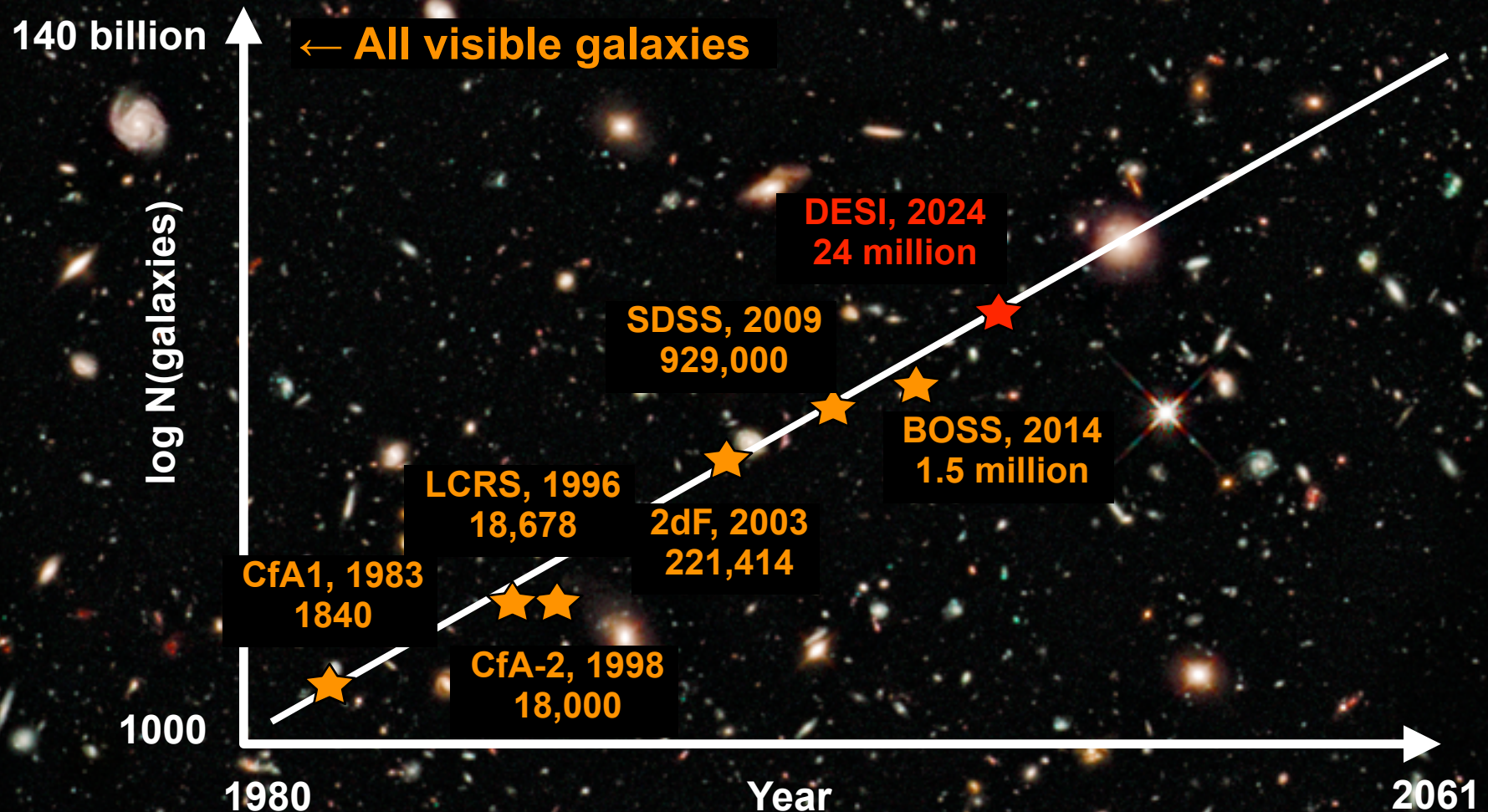


DESI will sample a volume $>50 h^{-3}\text{Gpc}^3$



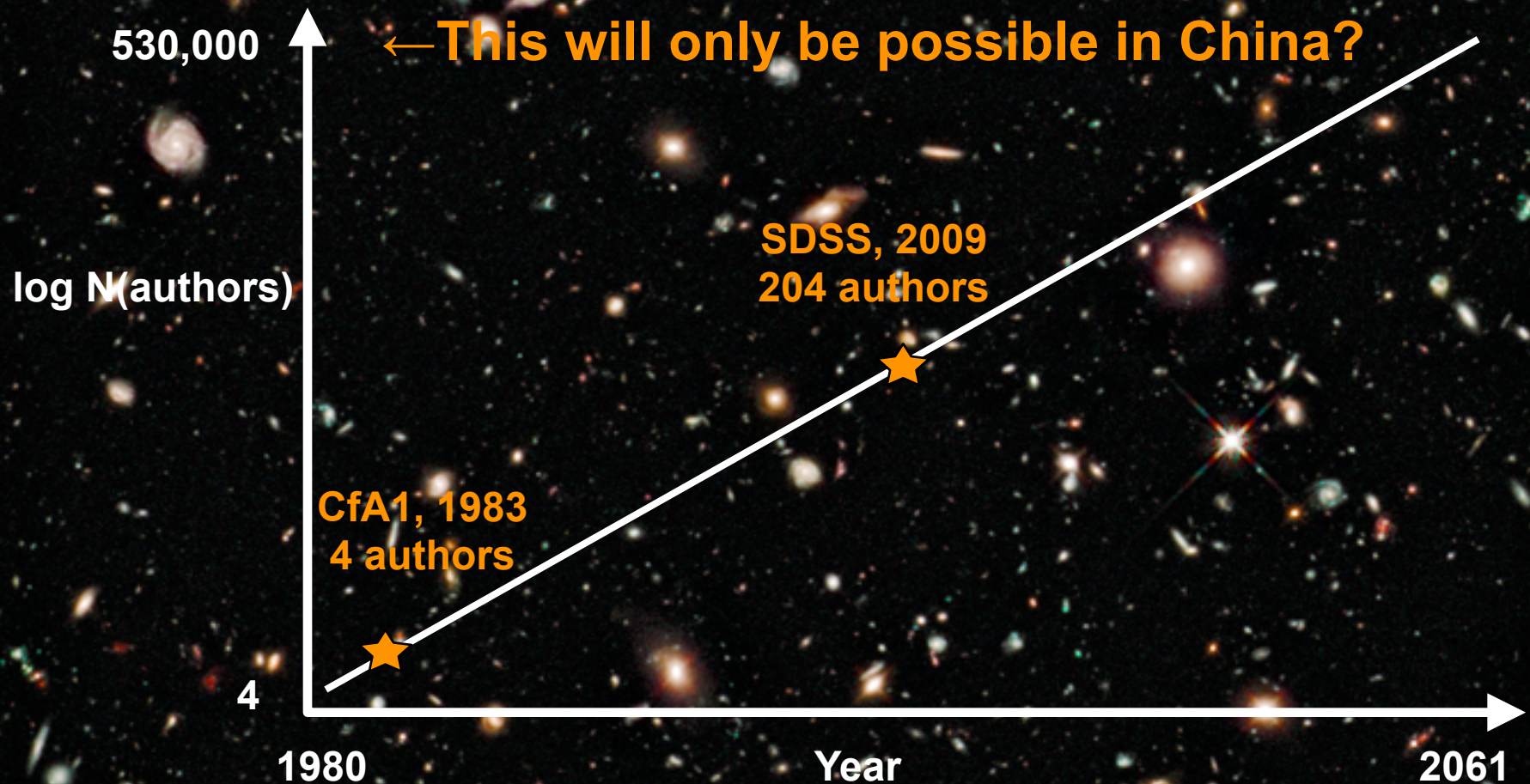
Redshift surveys increasing exponentially in size

Large enough for BAO starting in 2005



Redshift surveys increasing exponentially in size

Large enough for BAO starting in 2005



Future CMB experiments racing to detect B-modes

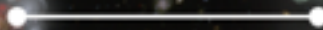
BICEP2/Keck/BICEP3, ACTPol, SPTPol, Polarbear/Simons Array
SPIDER, EBEX



Summary

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

450 million light years



- 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