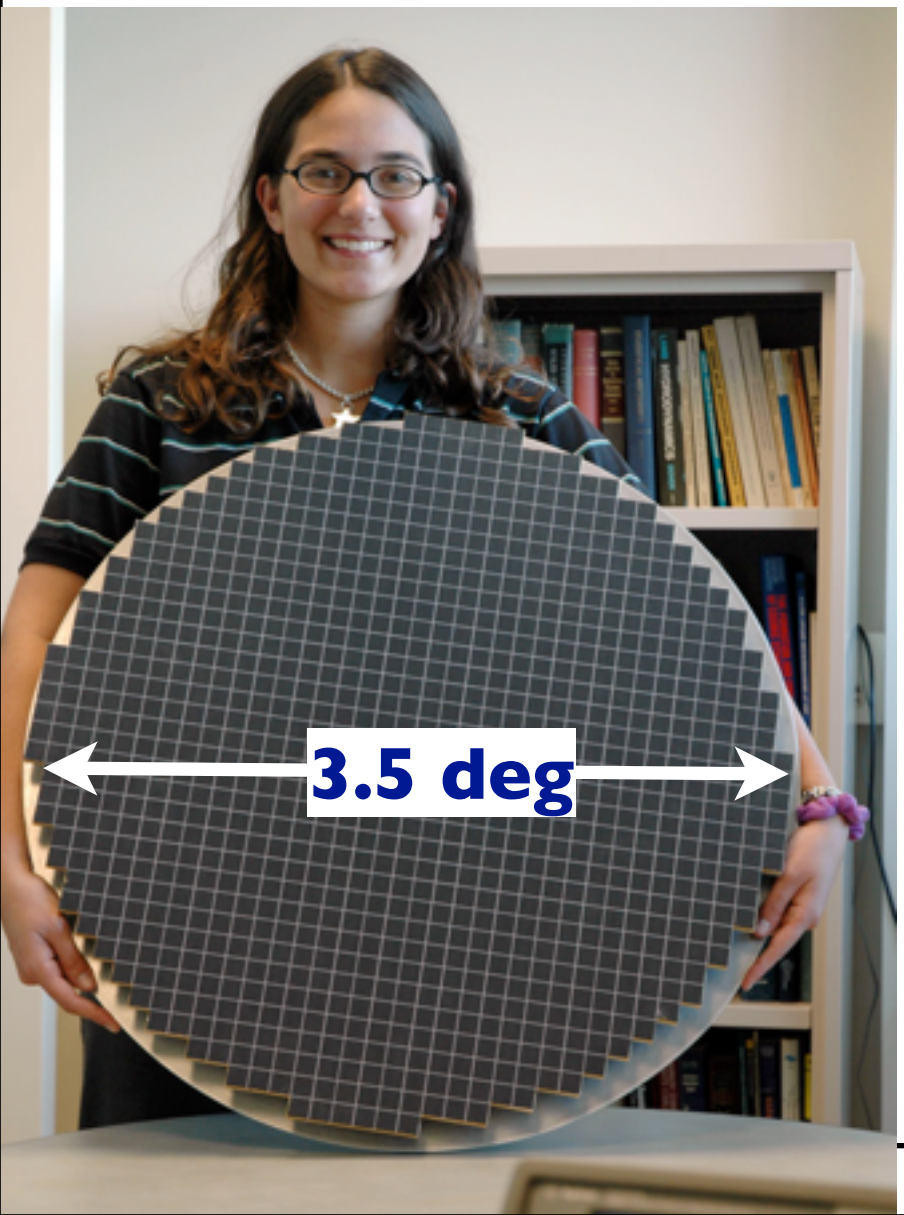
# Future optical surveys will not be "big"



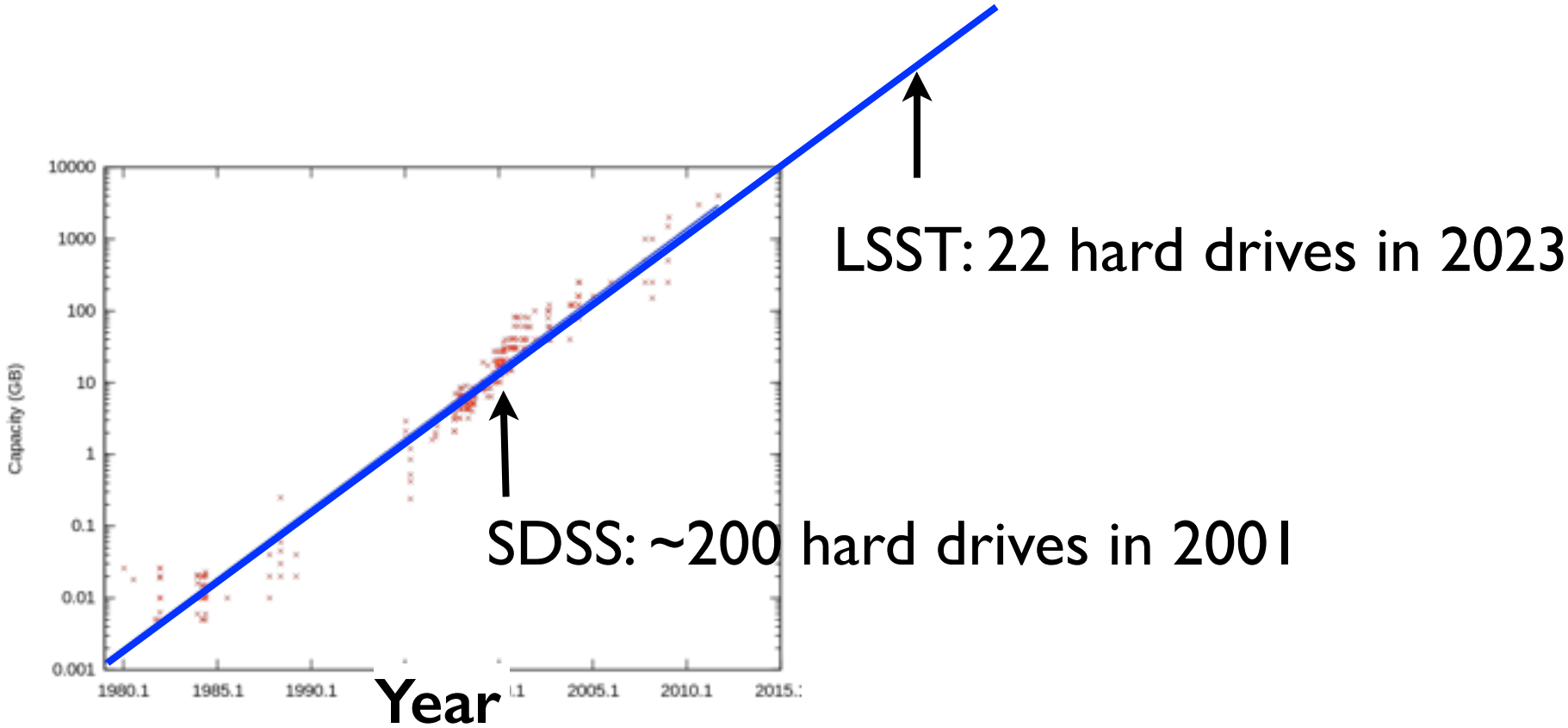

**SDSS (1998+)**:
120 Mpix, 55 sec readout

**LSST (2021+)**:
3.2 Gpix, 2 sec readout

700X peak data rate
10X faster per amplifier
**20 years later**

# Future optical surveys will not be "big"

Peak storage occurs 2.3 years into any survey
(for any project collecting data linearly with time)




Storage on hard drives has increased faster than Moore's Law, doubling every 1.6 years since 1980 (http://en.wikipedia.org/wiki/Hard_drive).

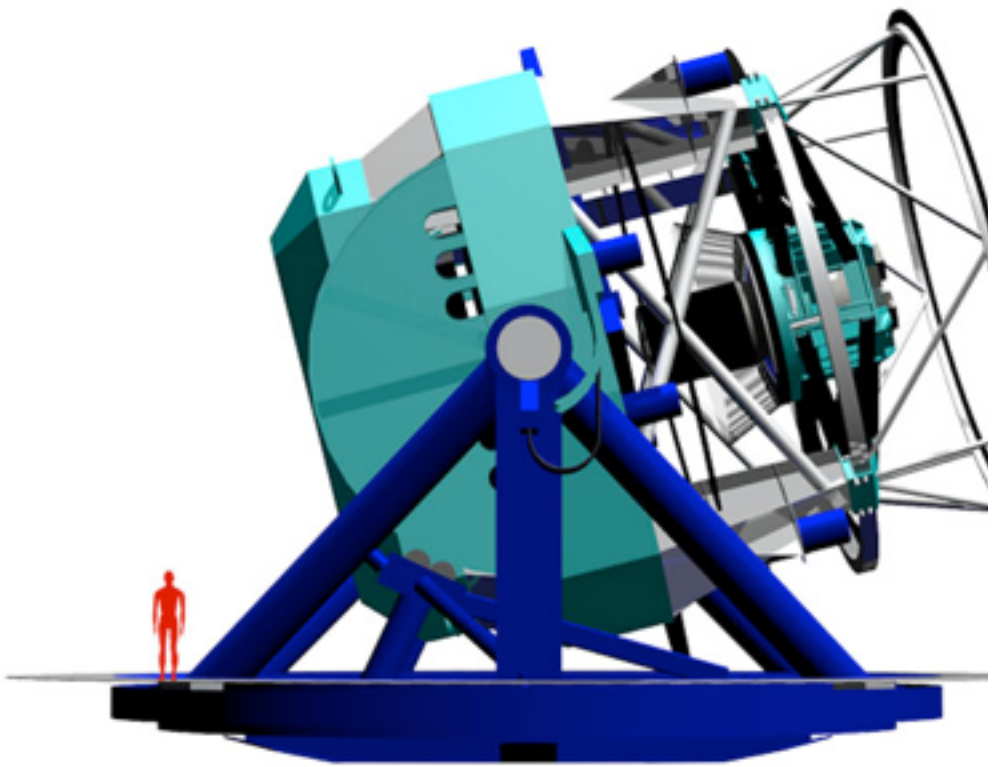
# Future optical surveys will not be "big"

The "perfect instrument" on the LSST telescope

*Time-tag, energy-tag every photon*
*over 9.6 deg$^2$ focal plane, 100 % efficiency*

6.9 x $10^{16}$ photons/night -> 550 PB/night

*Data more severe than SDSS only if delivered before 2033*



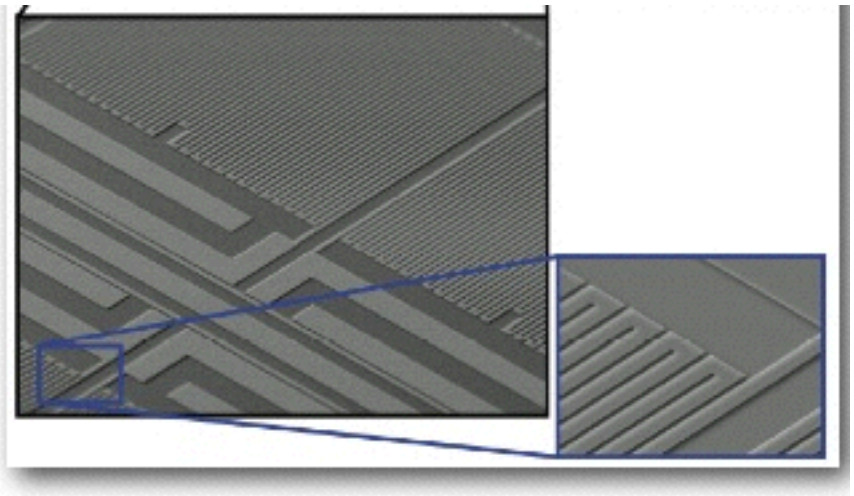


Figure 2. An optical lumped element (OLE) MKID array made of a 40 nm thick TiN film.

# Future optical surveys will not be “big”

## … but forward modeling those data could be “big”

Forward modeling using MCMC on terabytes of data not feasible
Modern techniques:

- stochastic variational inference
- distributed MCMC

# Cosmology on the Beach: Experiment to Cosmology

**Monday: Fitting the universe, detectors + imaging maps**

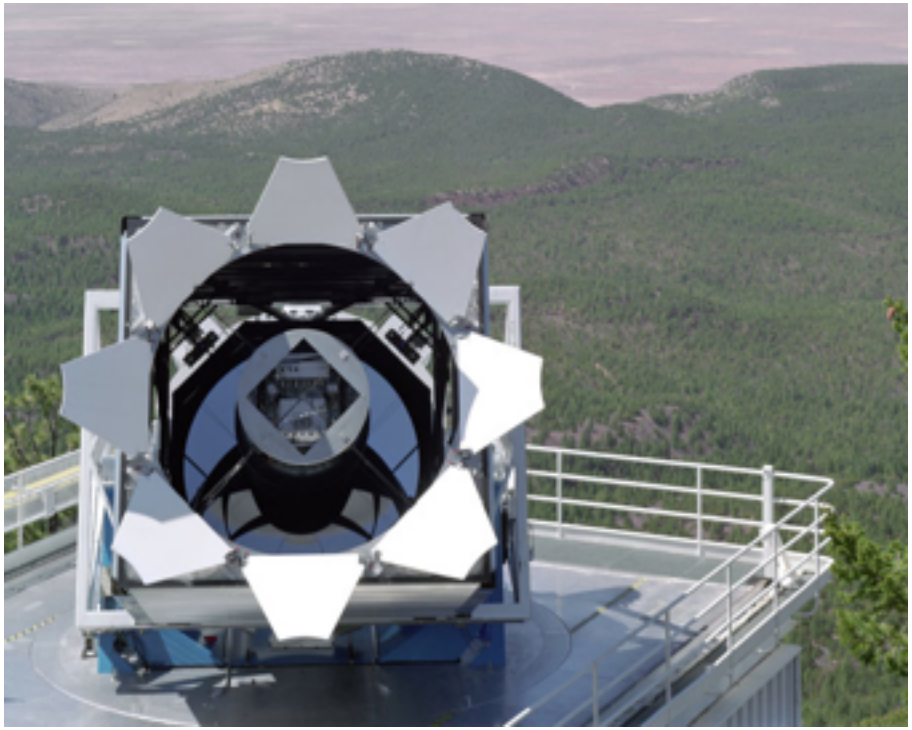
**Tuesday: Sloan Digital Sky Survey (SDSS)**

**Thursday: spectroscopic data,**
**or DESI, Euclid**

# Yup, we can map the full sky

| | |
|---|---|
| **SDSS-I** | 1998 |
| **SDSS-II** | 2005 |
| **SDSS-III/BOSS** | 2008 |
| **SDSS-IV/eBOSS** | 2014 |
| | 2020 |

**DESI-North**
**DESI-South?**
**Euclid**



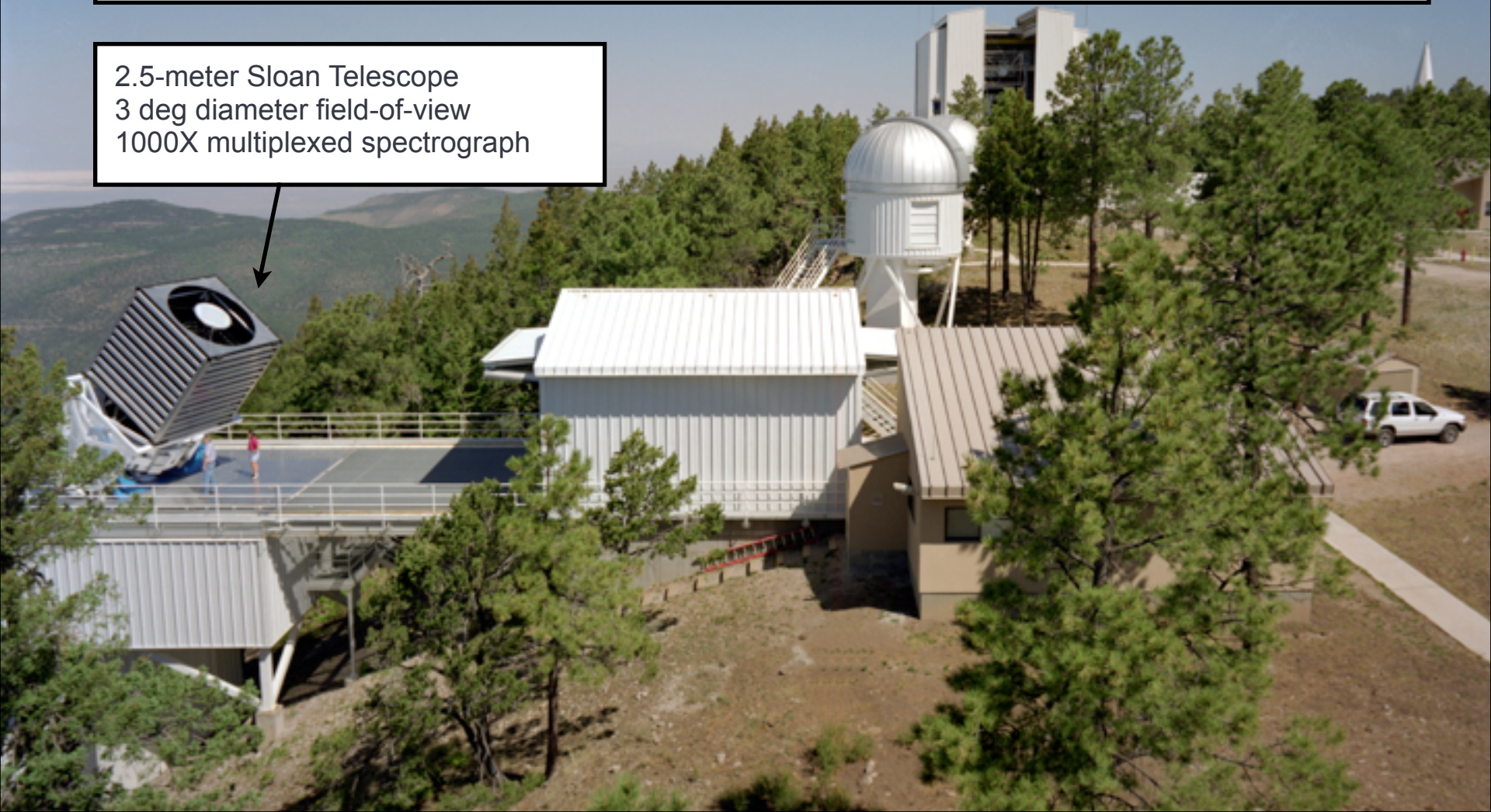
2.5-m Sloan Telescope, Apache Point, NM

DESI @ Mayall Telescope, Kitt Peak, AZ

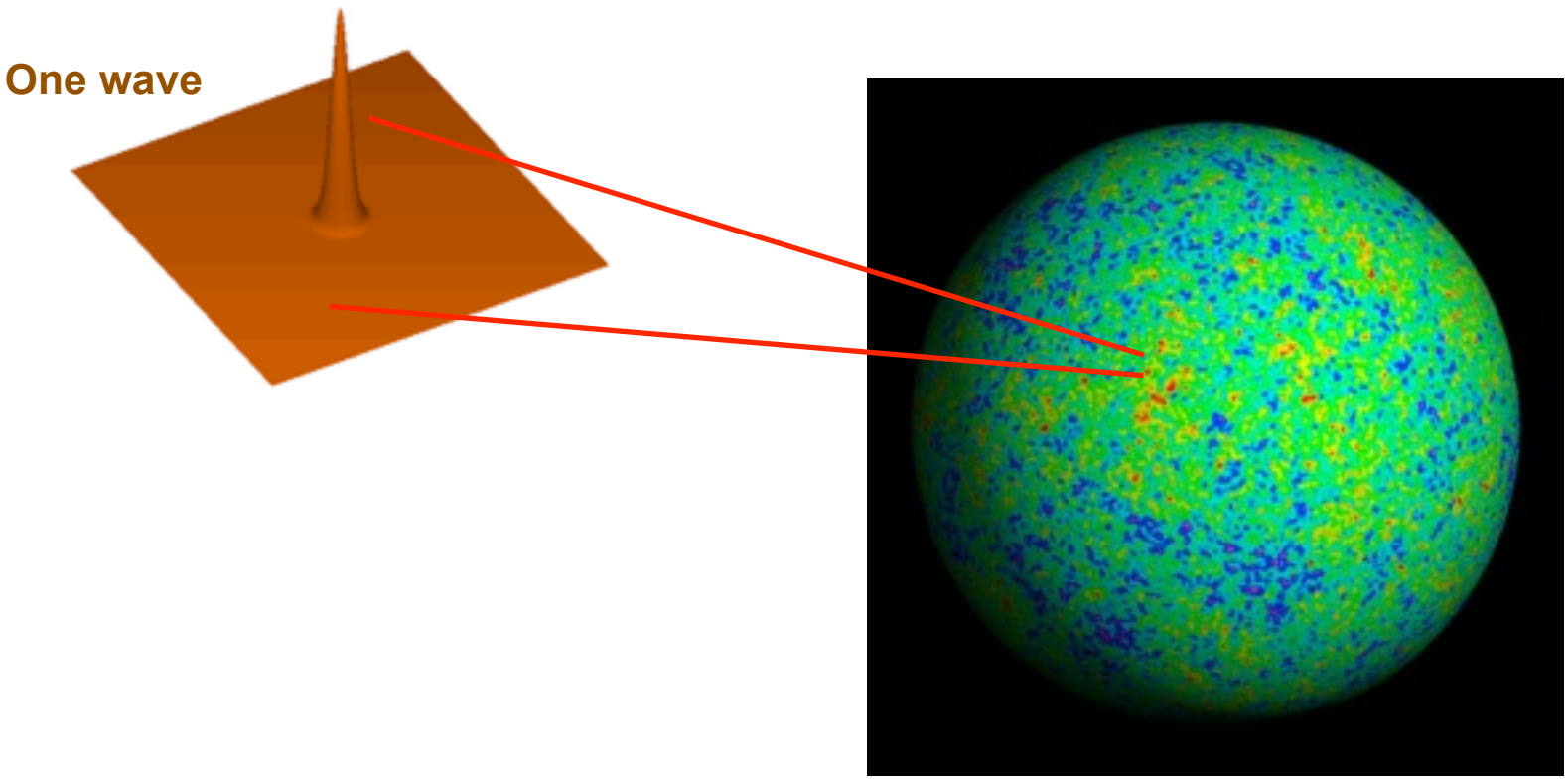
# BOSS
# Baryon Oscillation Spectroscopic Survey

**Key Project uses most capable BAO instrument in the world**

2.5-meter Sloan Telescope
3 deg diameter field-of-view
1000X multiplexed spectrograph

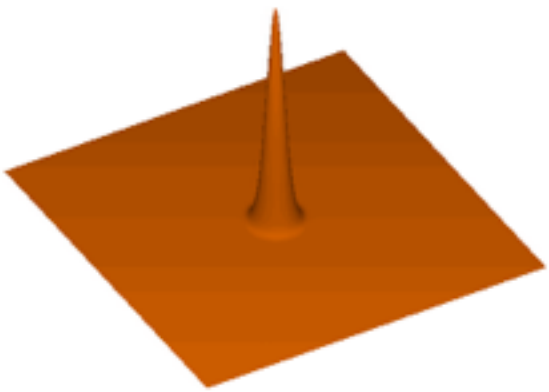


# SDSS-III (BOSS) designed as a BAO experiment

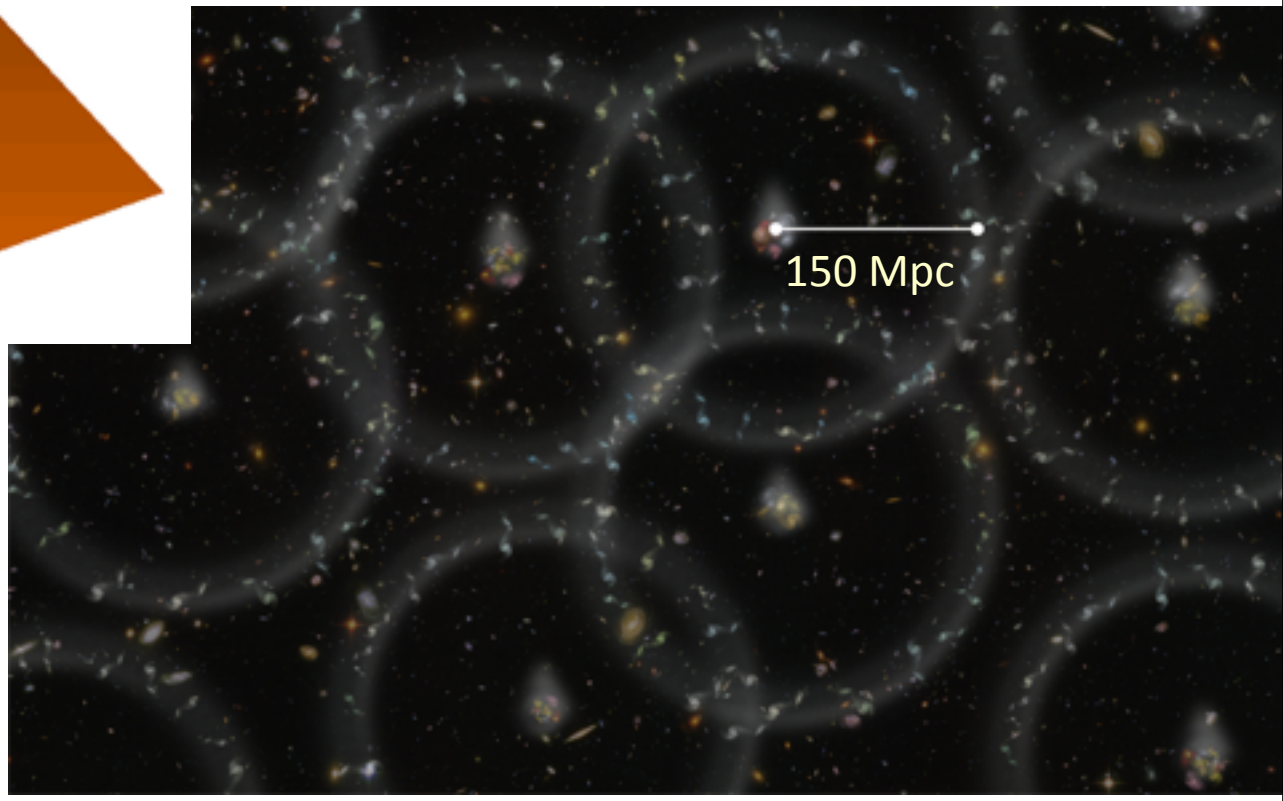



Map of Universe at 380,000 years (CMB)

# SDSS-III (BOSS) designed as a BAO experiment

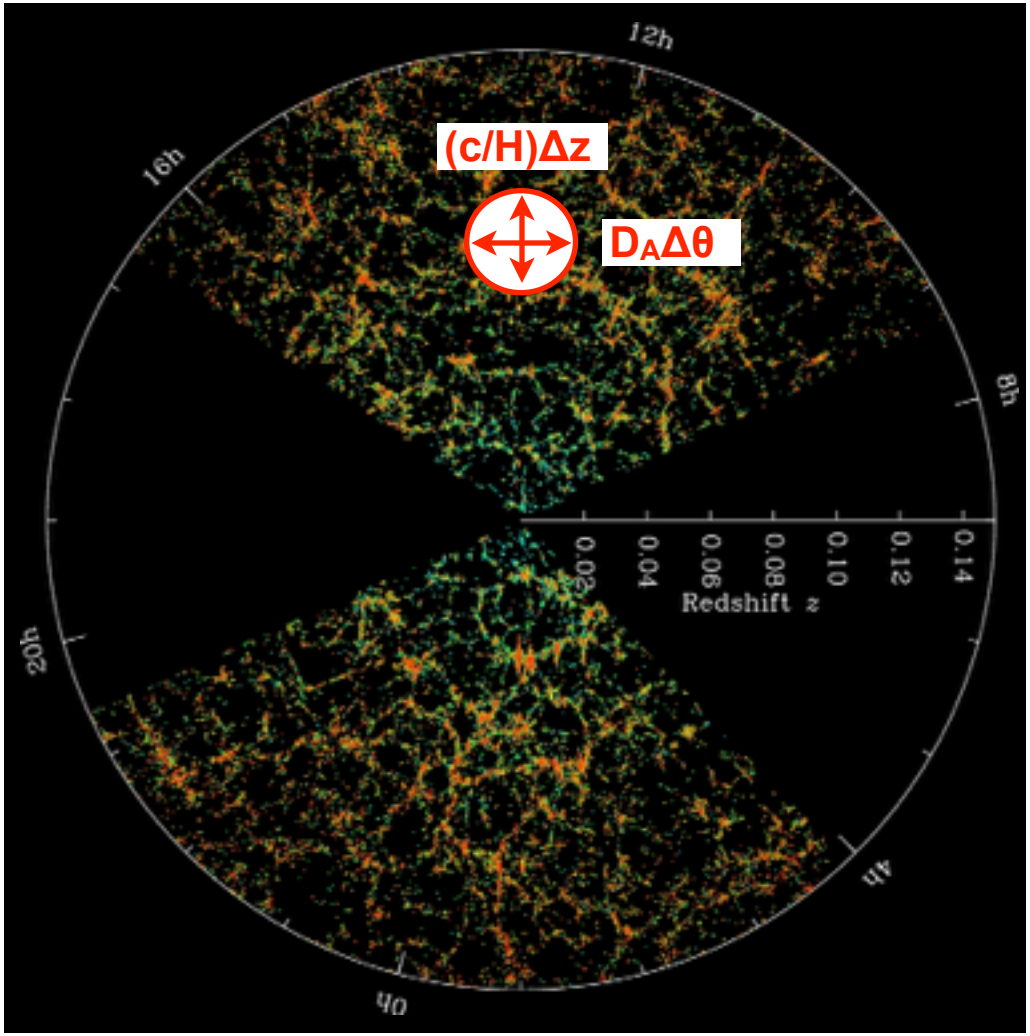


**Galaxy map (somewhat exaggerated)**
**This really is a peak in configuration space**



# Spectroscopic redshifts → much more info

## BOSS measures BAO in 3-D maps




BAO measures two standard rulers:
- o Angular diameter distance, $\mathbf{D_A}$
- o Line-of-sight Hubble parameter, **H**

Gravity measured from redshift-space distortions (RSD)

**$D_A$ is the integral of H**

$$H(z) = \sqrt{\Omega_M(1+z)^3 + (1-\Omega_M-\Omega_\Lambda)(1+z)^2 + \Omega_\Lambda}\,, \tag{2.4}$$

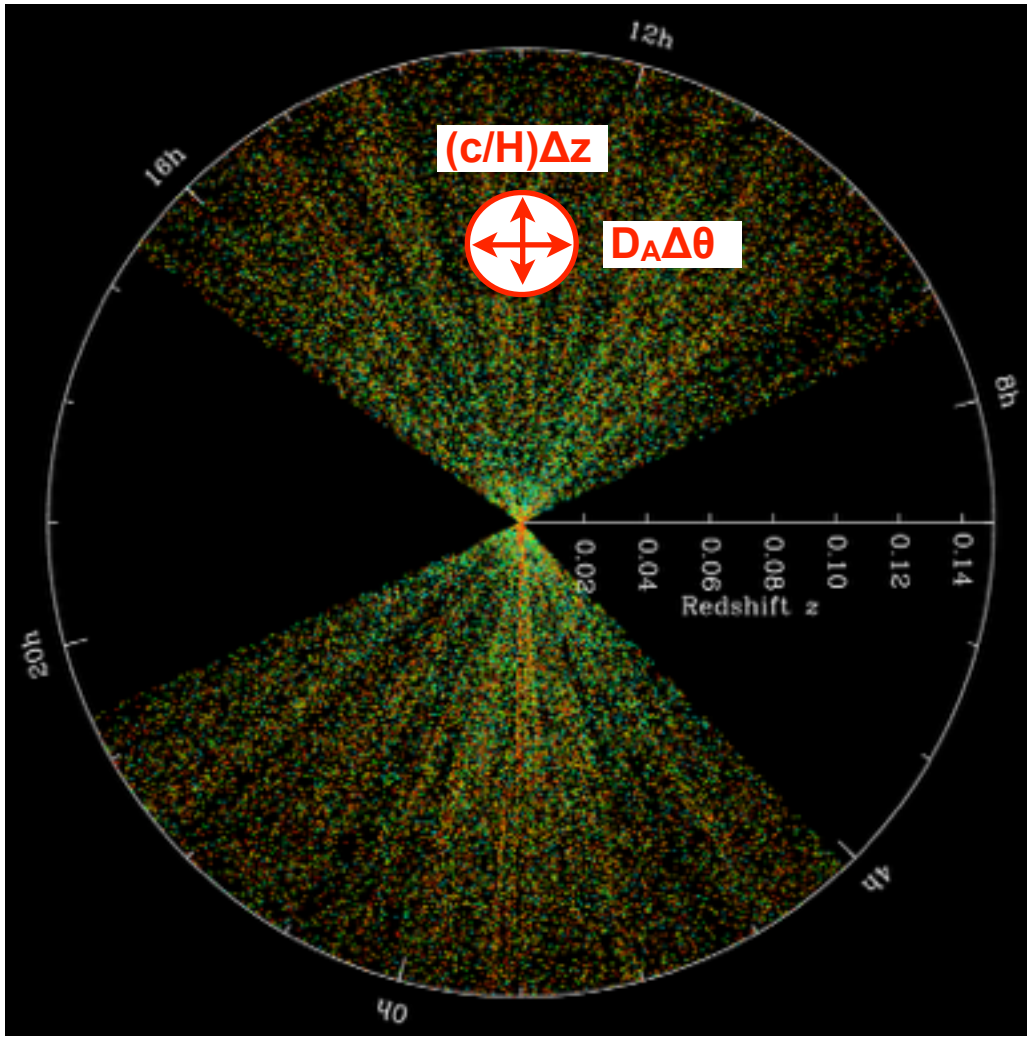
$$d_A(z) = \begin{cases} (-K)^{-1/2}\sinh\left[(-K)^{1/2}\chi(z)\right] & K<0\,, \\ \chi(z) & K=0\,, \\ K^{-1/2}\sin\left[K^{1/2}\chi(z)\right] & K>0\,, \end{cases} \tag{2.5}$$

where

$$K = 1-\Omega_M-\Omega_\Lambda, \qquad \chi(z) = \int_0^z \frac{dz'}{H(z')} \tag{2.6}$$

# Spectroscopic redshifts → much more info

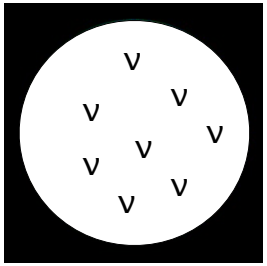
## BAO+RSD not competitive w/out spectroscopy

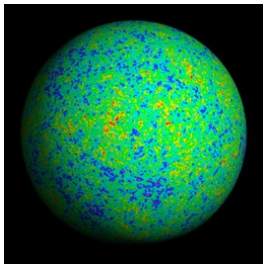


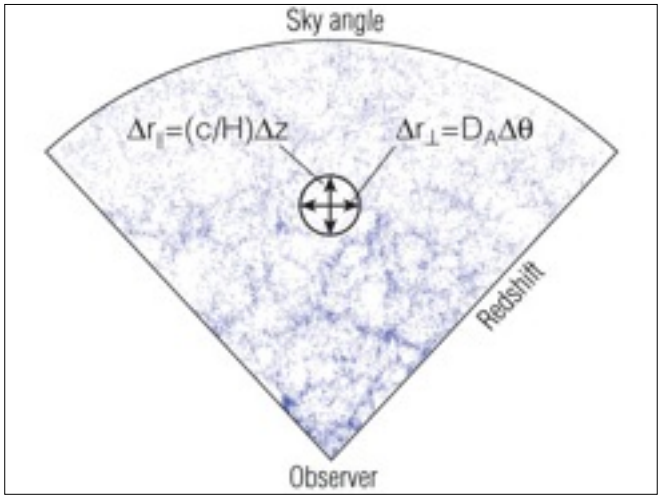

Imaging-only surveys can produce photo-z redshifts with errors Δz~0.03

- o BAO from $D_A$ degraded by factor ~5
- o BAO from H(z) not measured
- o Gravity (RSD) not measured

# BAO: What tracer objects to use?





$z=10^{11}$ Neutrino background
(not for BAO ruler, but horizon at ν decoupling)

$z=1087$ CMB: Planck will measure $d_A$ to 0.1%

$z=20$ H gas in 21-cm emission

$z=5$ Ly-α emitter galaxies
QSO absorption lines

$z=2$ Galaxies,
galaxy clusters,
SNe

$z=0$

All existing BAO measurements

Definitely the hard way,
but it's been suggested!
(Angulo et al 2006)
(Zhan et al 2008)

# BAO: What tracer objects to use?

**We need only sparsely sample these tracers for BAO**

Requirement: Sample linear modes at 100 $h^{-1}$Mpc

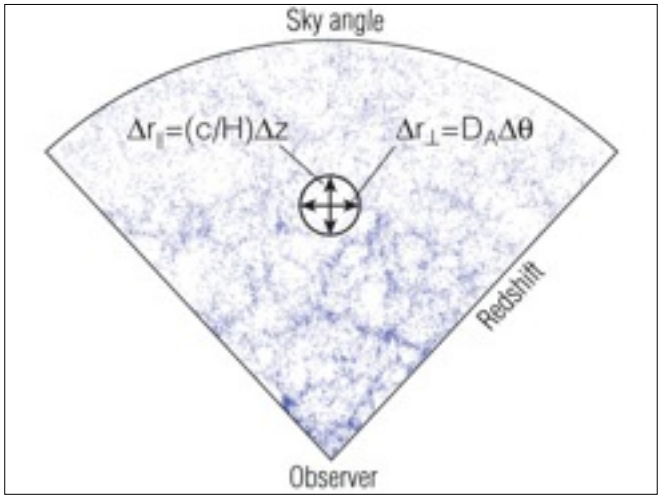
Shot noise ~ (1 + 1/nP)

P = power at 100 Mpc

n = sampling density

Shot noise small if nP>3 ⇒ n > 1 per (10 $h^{-1}$Mpc)$^3$n

If tracers are ***biased*** relative to dark matter, we need even fewer (because P>1)




z=20

H gas in 21-cm emission

z=5

Ly-α emitter galaxies
QSO absorption lines

z=2

Galaxies,
galaxy clusters,
SNe

z=0

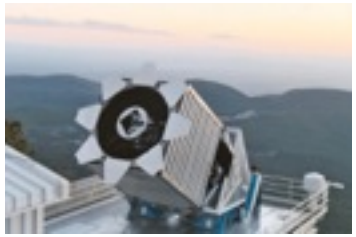
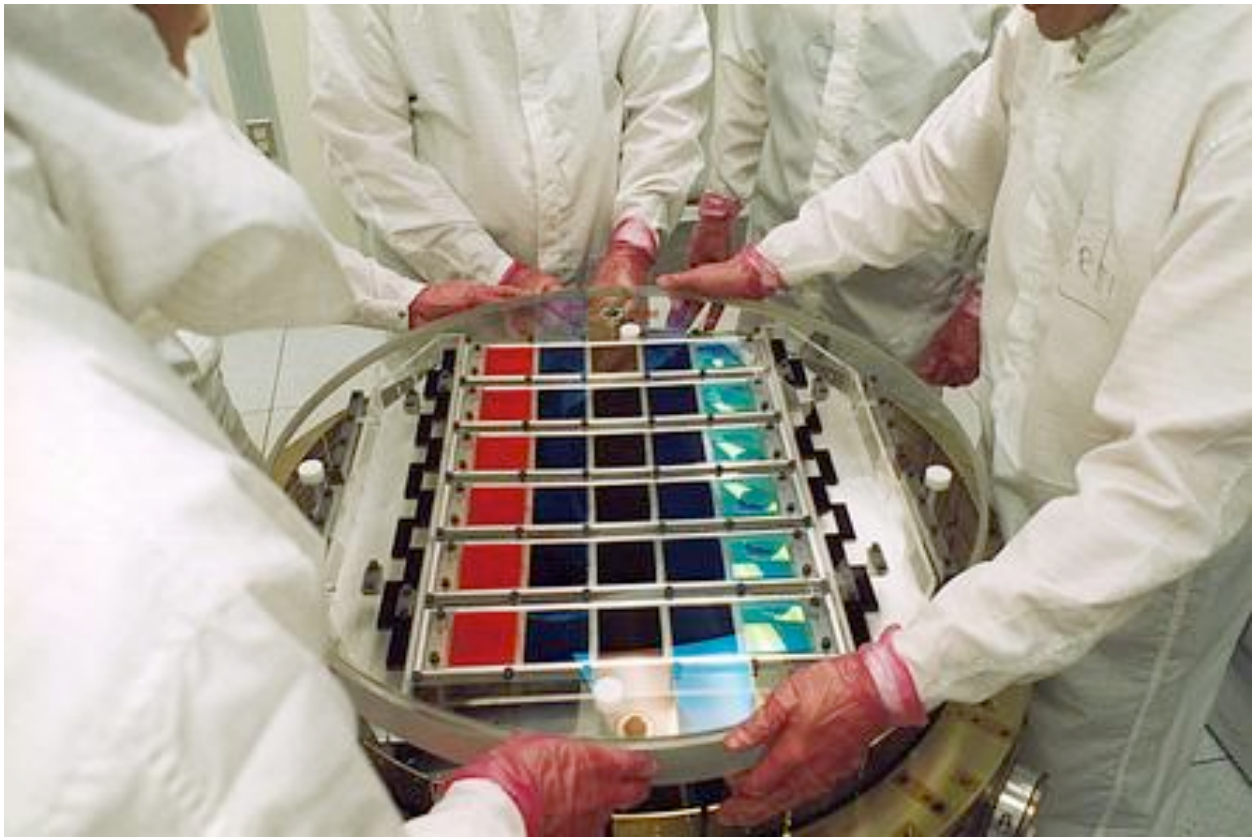


Image sky
↓
Select targets
↓
Design plug-plates
↓
Plug fibers
↓
Observe!
↓
Extract spectra
↓
Subtract sky spec.
↓
Fit redshift
↓
Make 3-D map
↓
Test physics!

# Image the sky first, 1998-2004, 2008-2009

120 Mpix camera (now in Smithsonian)



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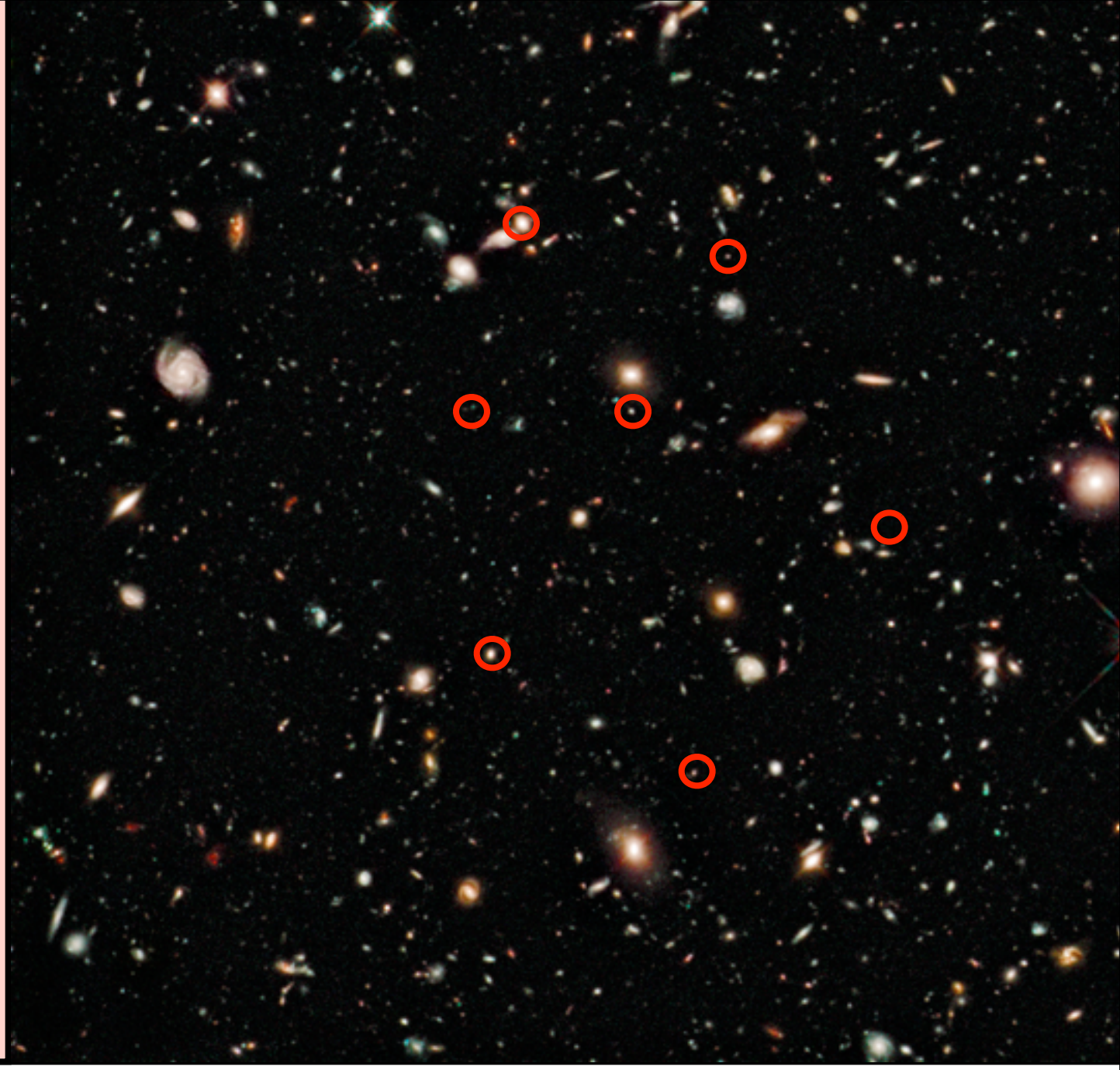

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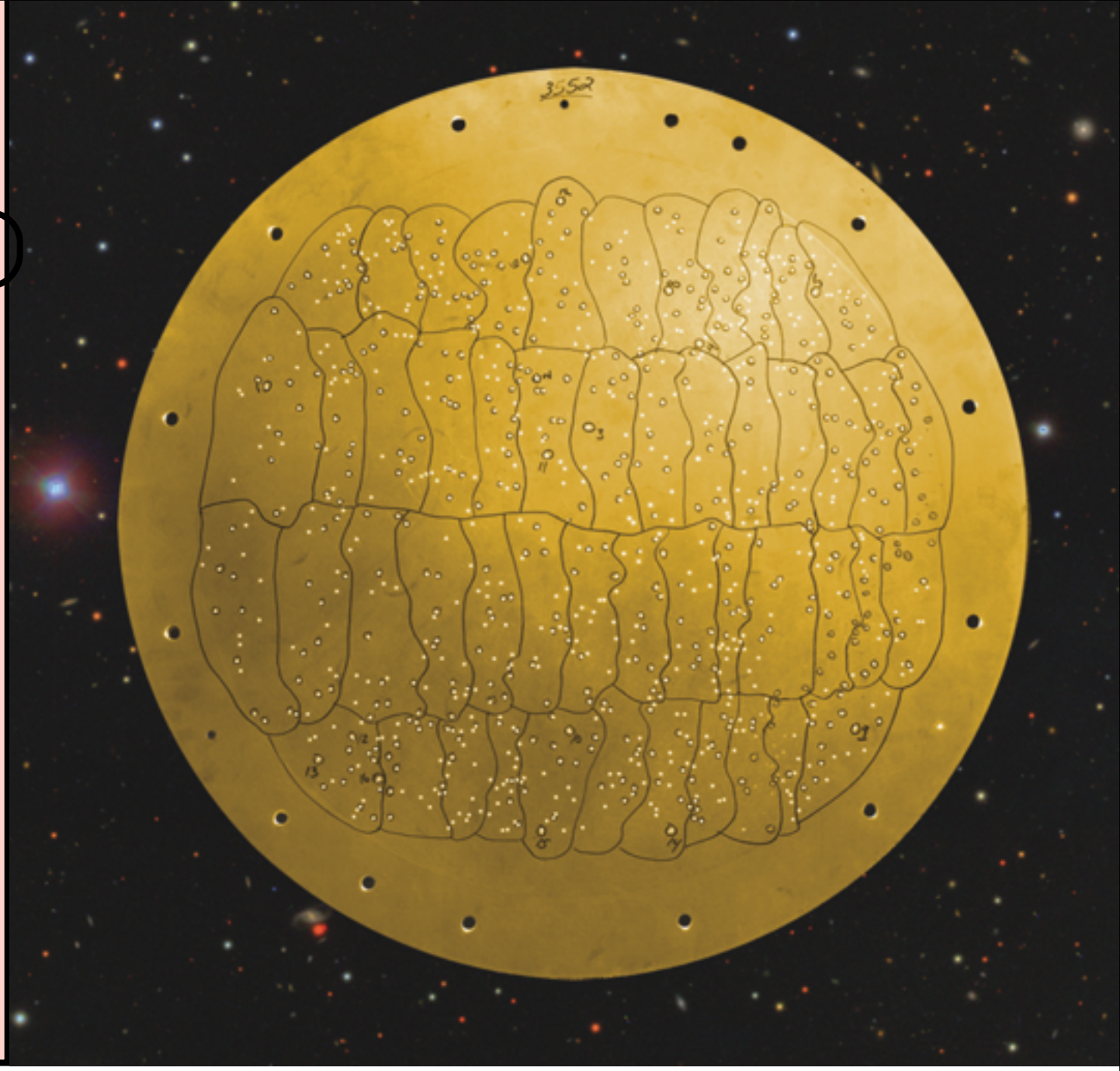

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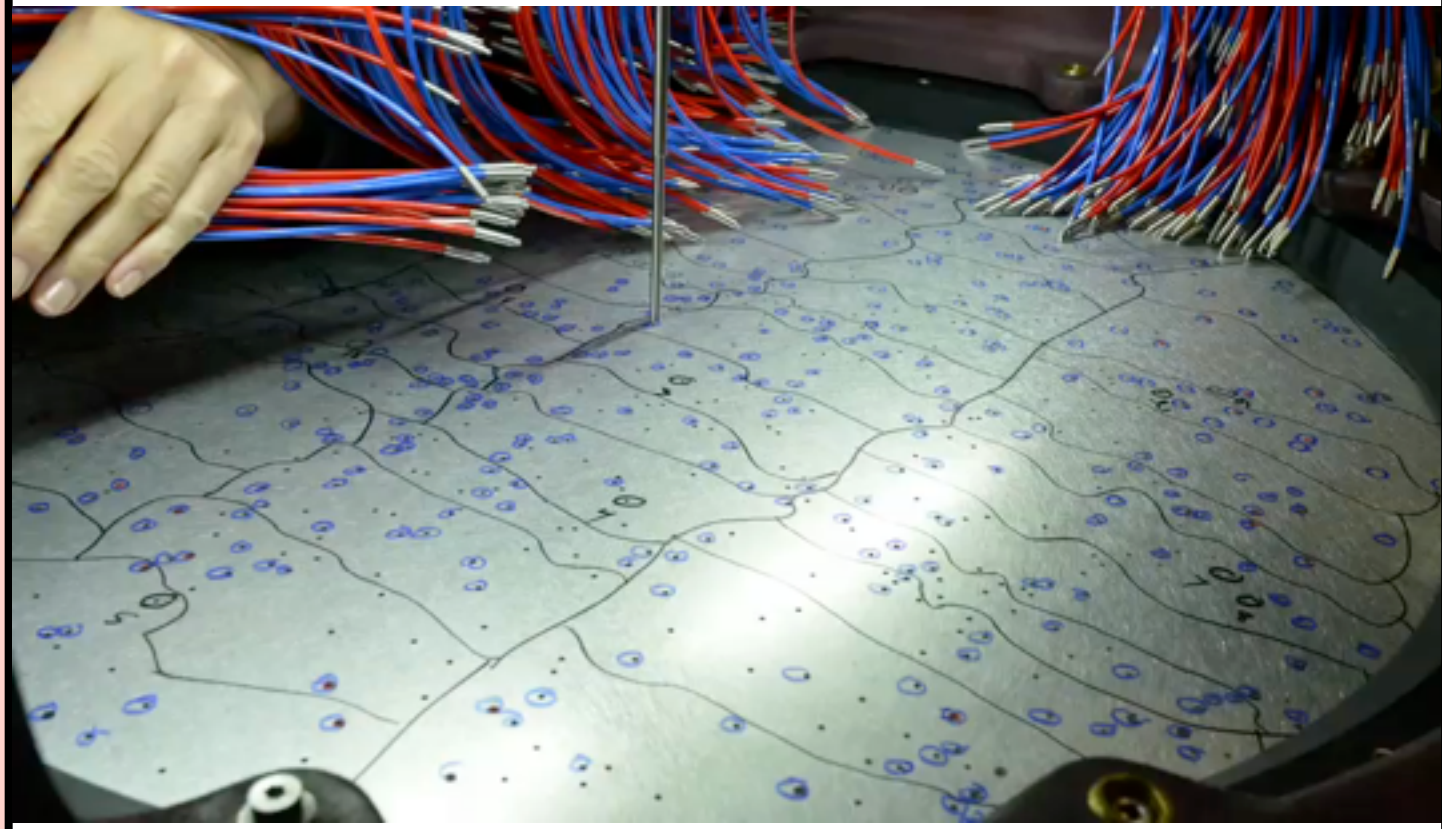
Test physics!

Humans have plugged these fibers > 2 million times…



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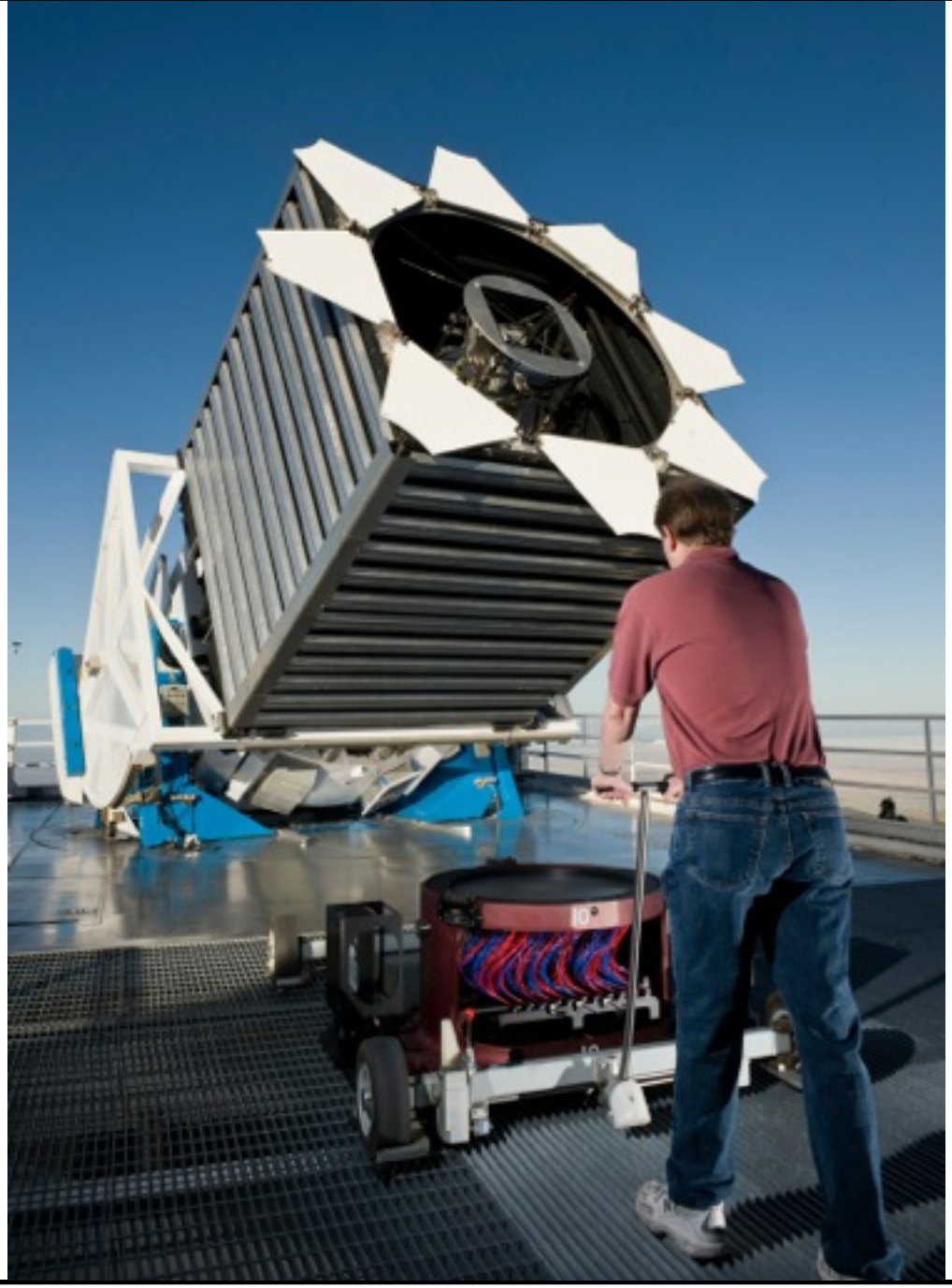

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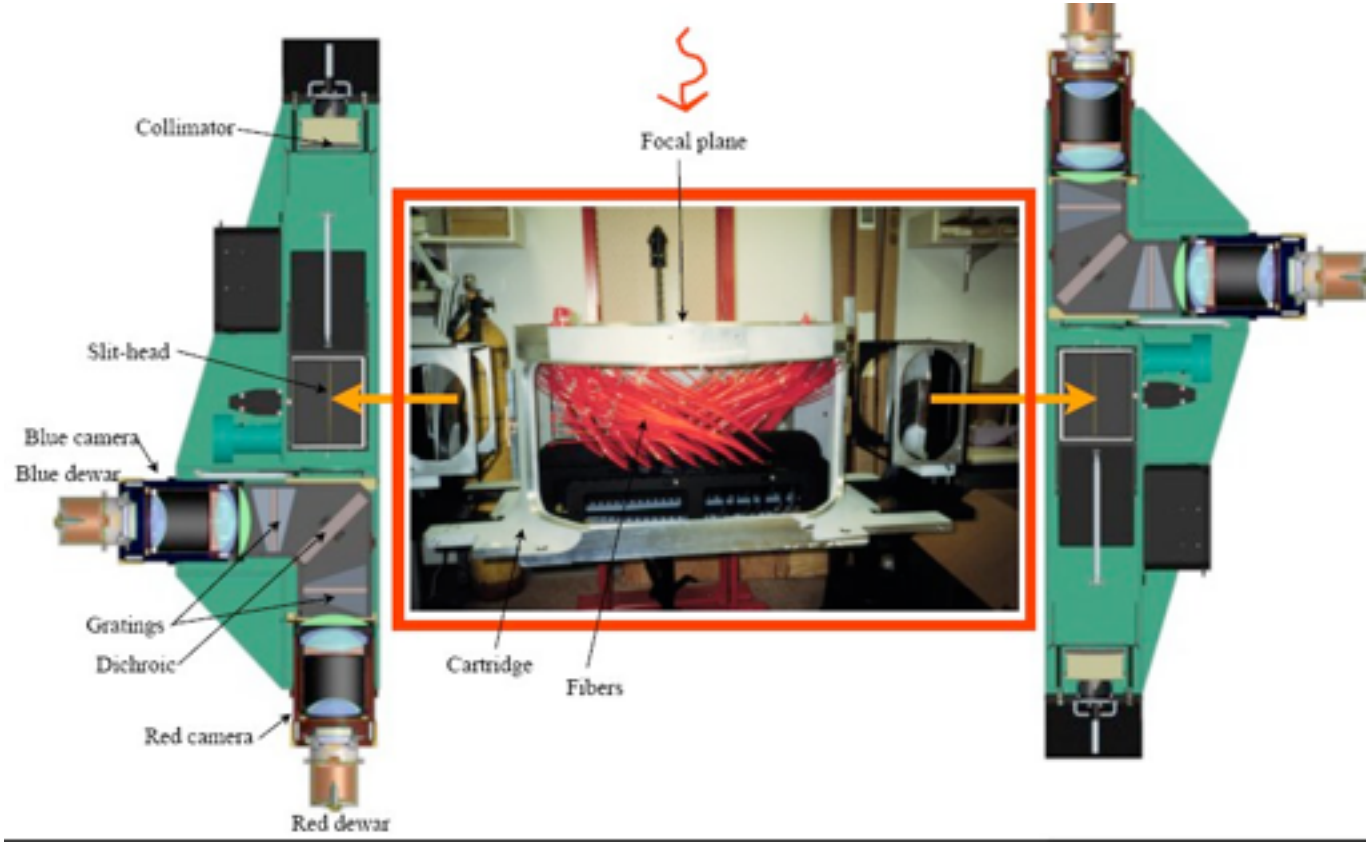
↓
Test physics!

## BOSS best-in-world spectrograph for large surveys

"Targeted upgrade" (completely rebuilt) in 2008-2009
Multiplexed with 1000 fibers feeding 2 spectrographs

New plate every hour



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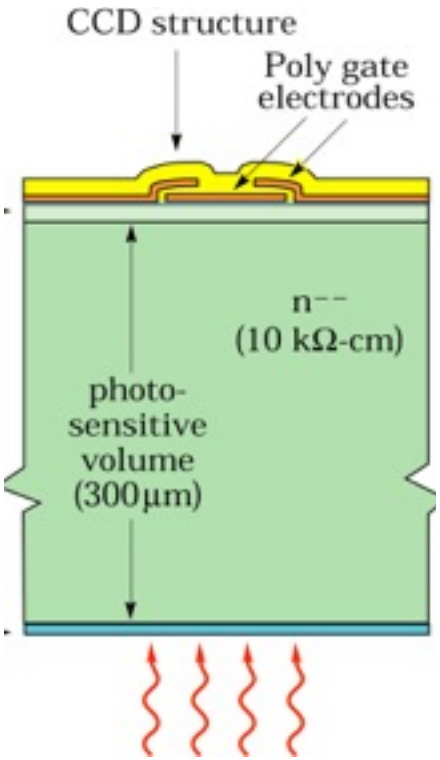
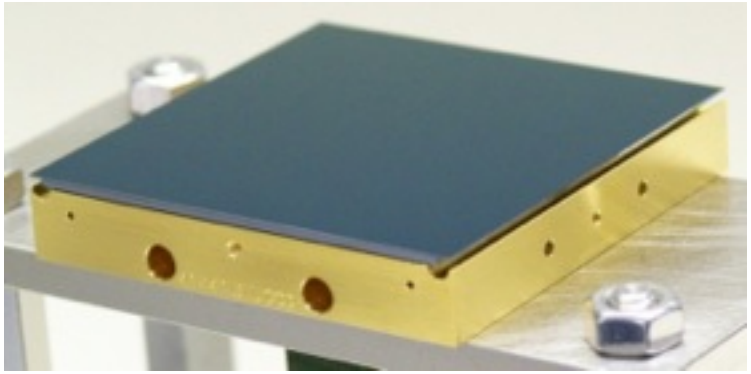
# BOSS best-in-world detectors




LBNL CCD



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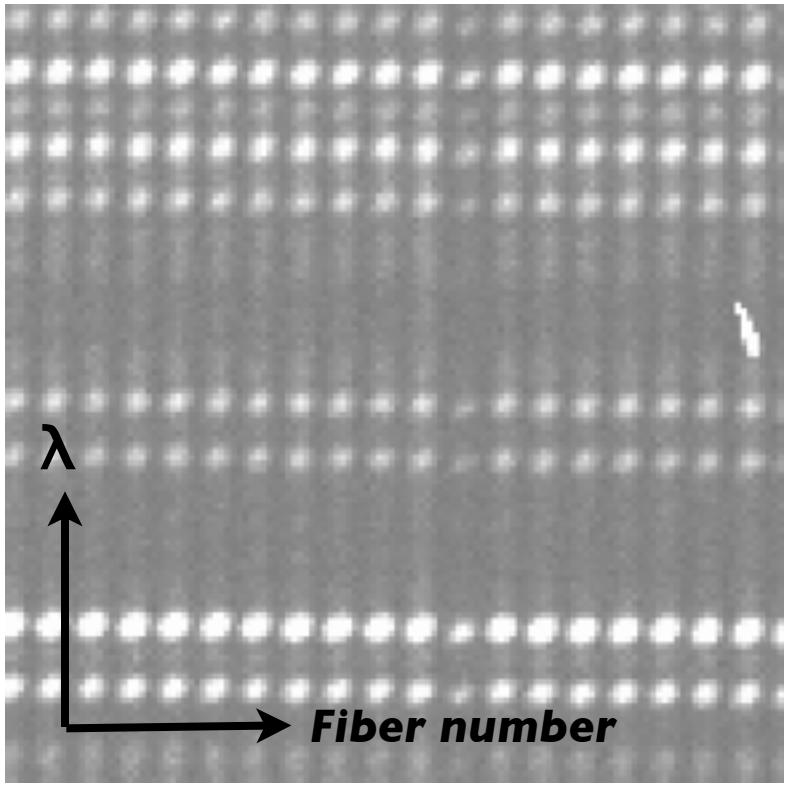
## One science image




**Parameters to fit:**
~5000 trace positions
~5000 wavelength solutions
~10,000 PSF model
~20,000 sky spectra
~2,000,000 object spectra values

Image sky
↓
Select targets
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Design plug-plates
↓
Plug fibers
↓
Observe!
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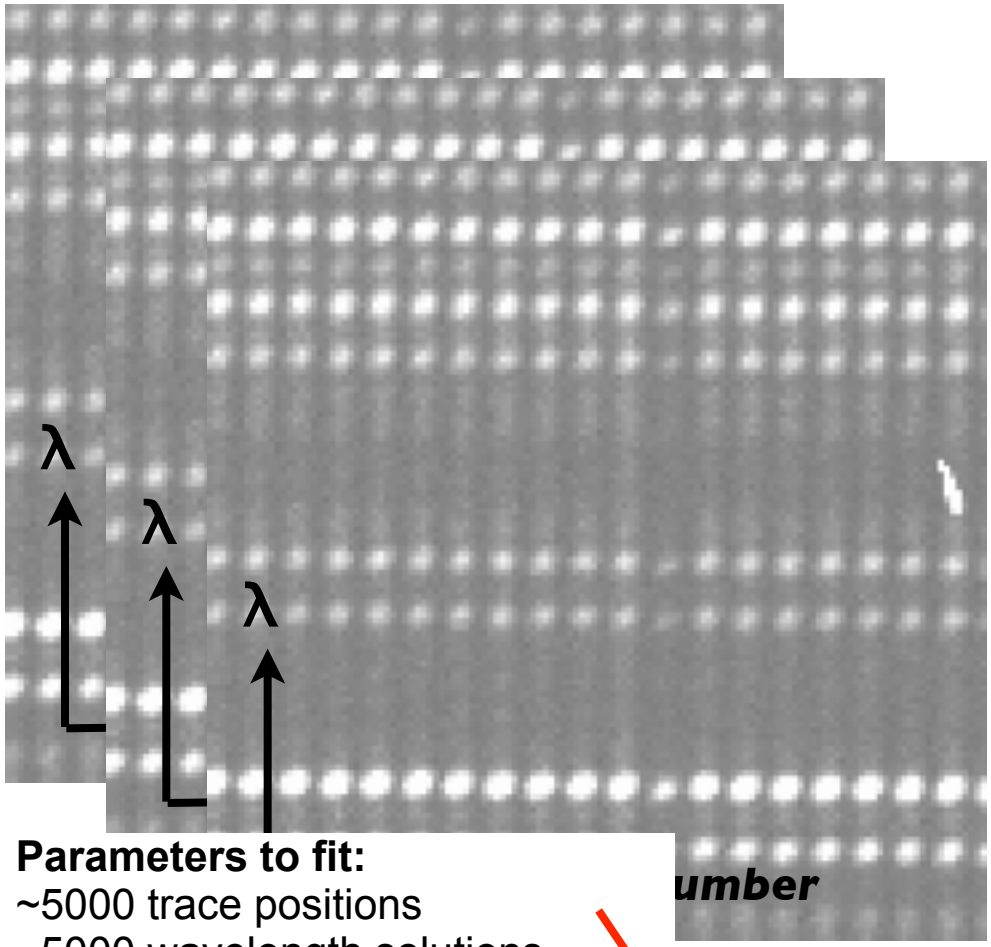
**Extract spectra**
↓
Subtract sky spec.
↓
Fit redshift
↓
Make 3-D map
↓
Test physics!

## One science image x N exposures




**Parameters to fit:**
~5000 trace positions
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~10,000 PSF model
~20,000 sky spectra
~2,000,000 object spectra values

x N

Image sky
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Plug fibers
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Observe!
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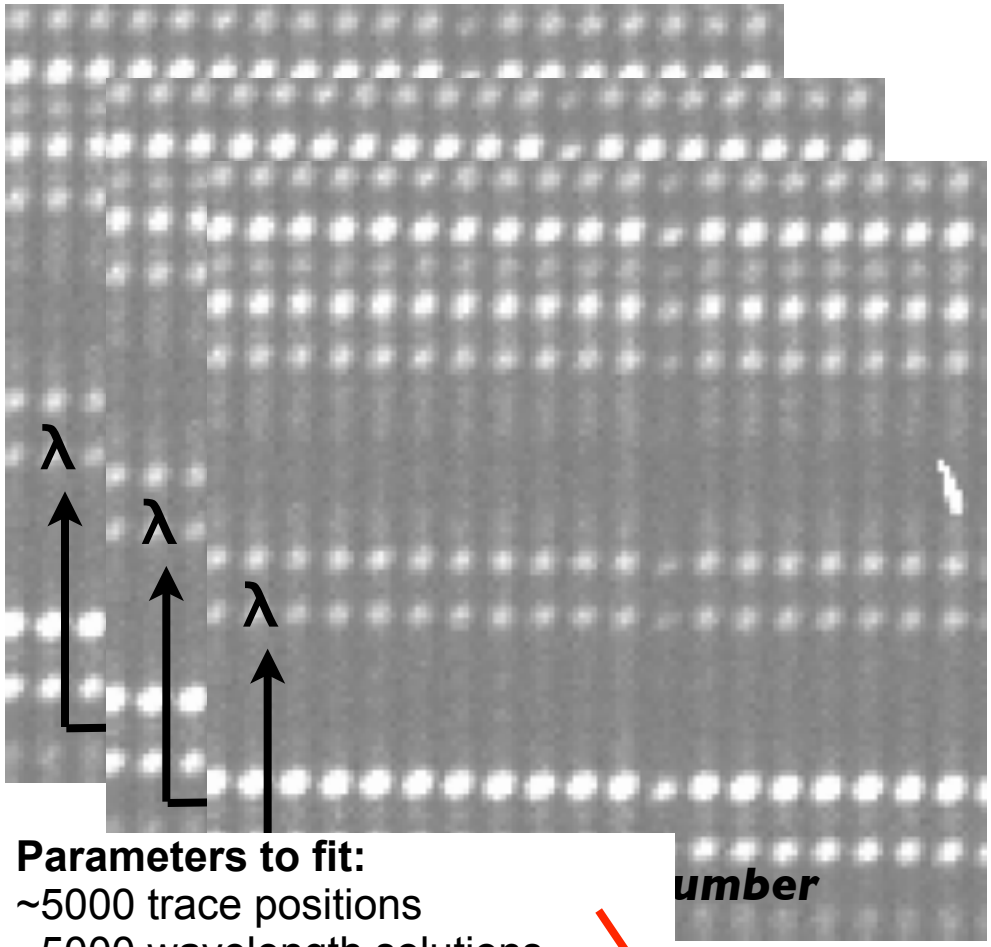
Test physics!

## One science image x N exposures + M calibrations




**Parameters to fit:**
~5000 trace positions
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~10,000 PSF model
~20,000 sky spectra
~2,000,000 object spectra values

x N x M

Image sky
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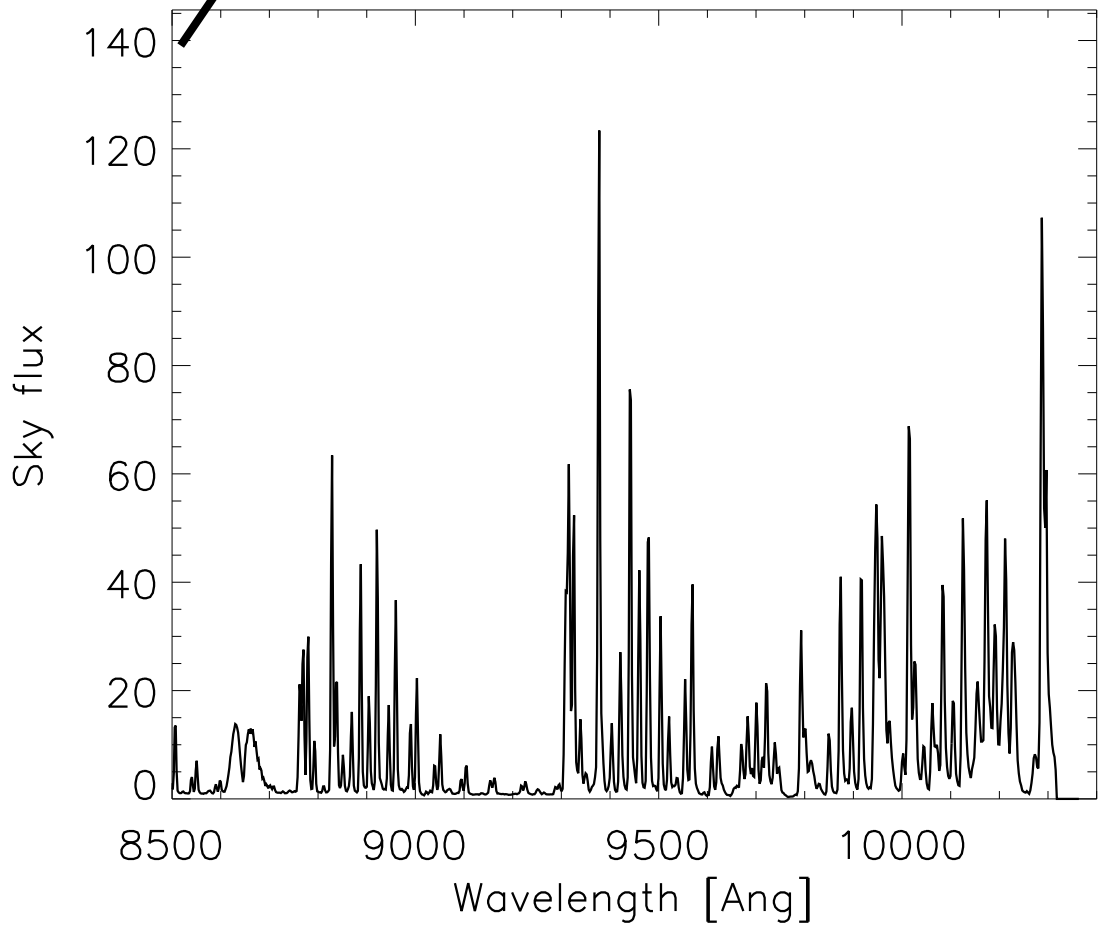
**Sky background is ~100 in these units**



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**Subtract sky spec.**
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Fit redshift
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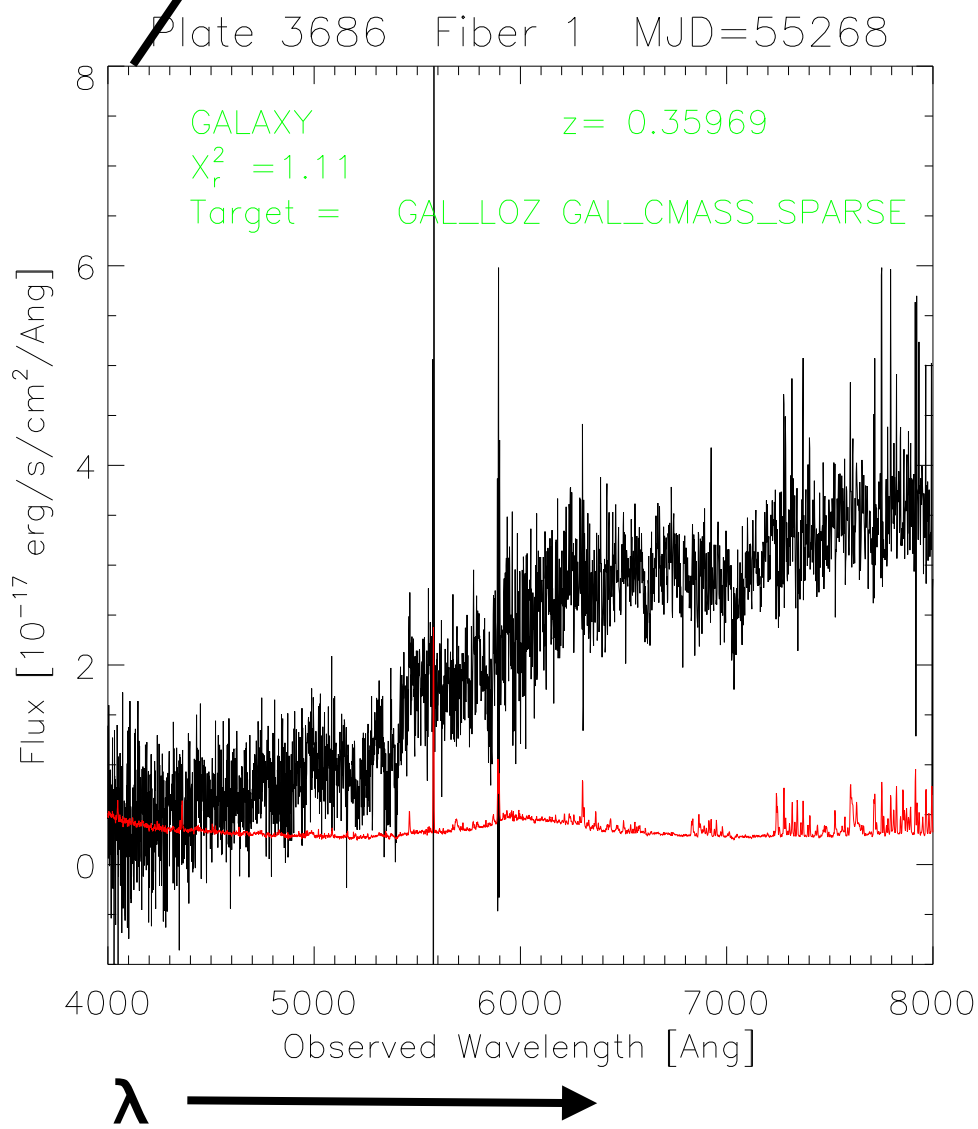
**Galaxy spectrum is ~1 in these units**



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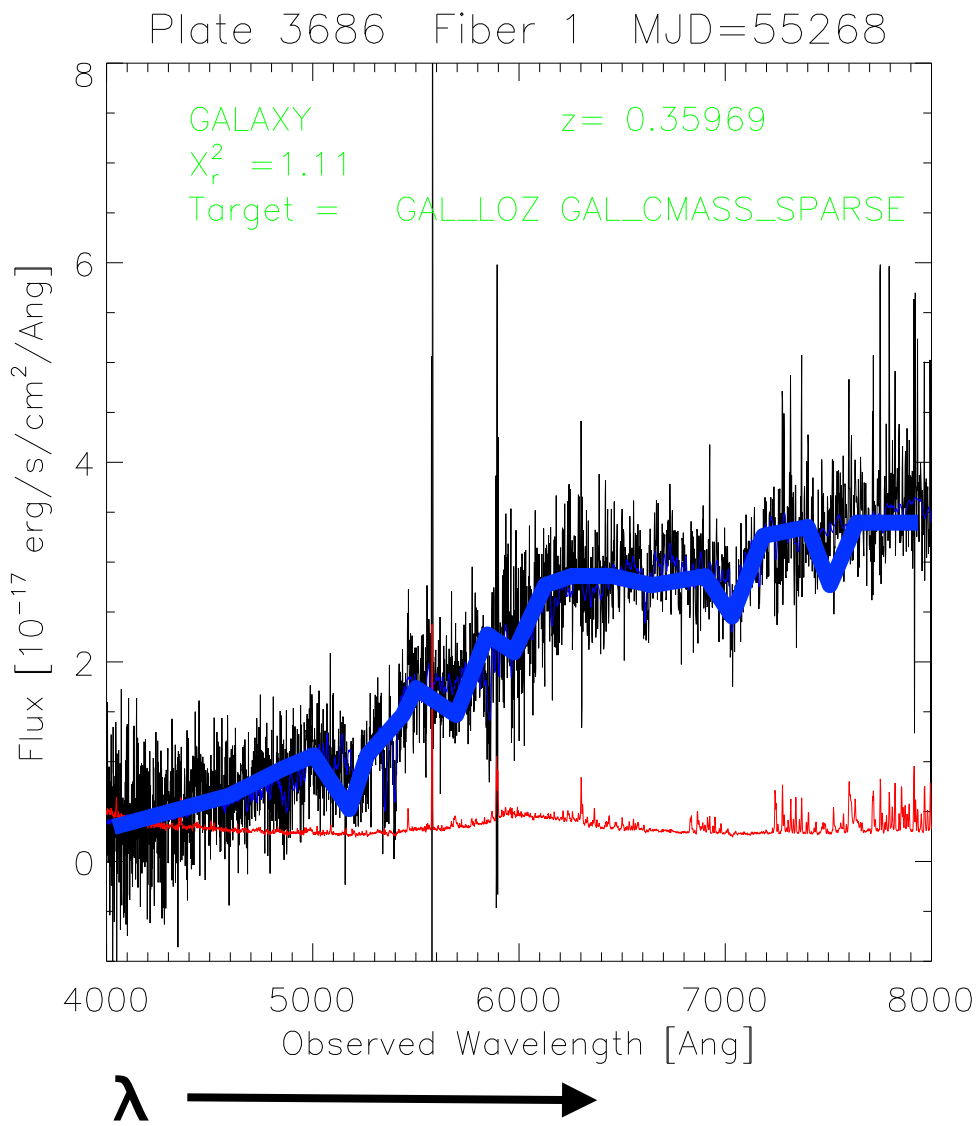
Test physics!

## Classify as galaxy @ z=0.3597



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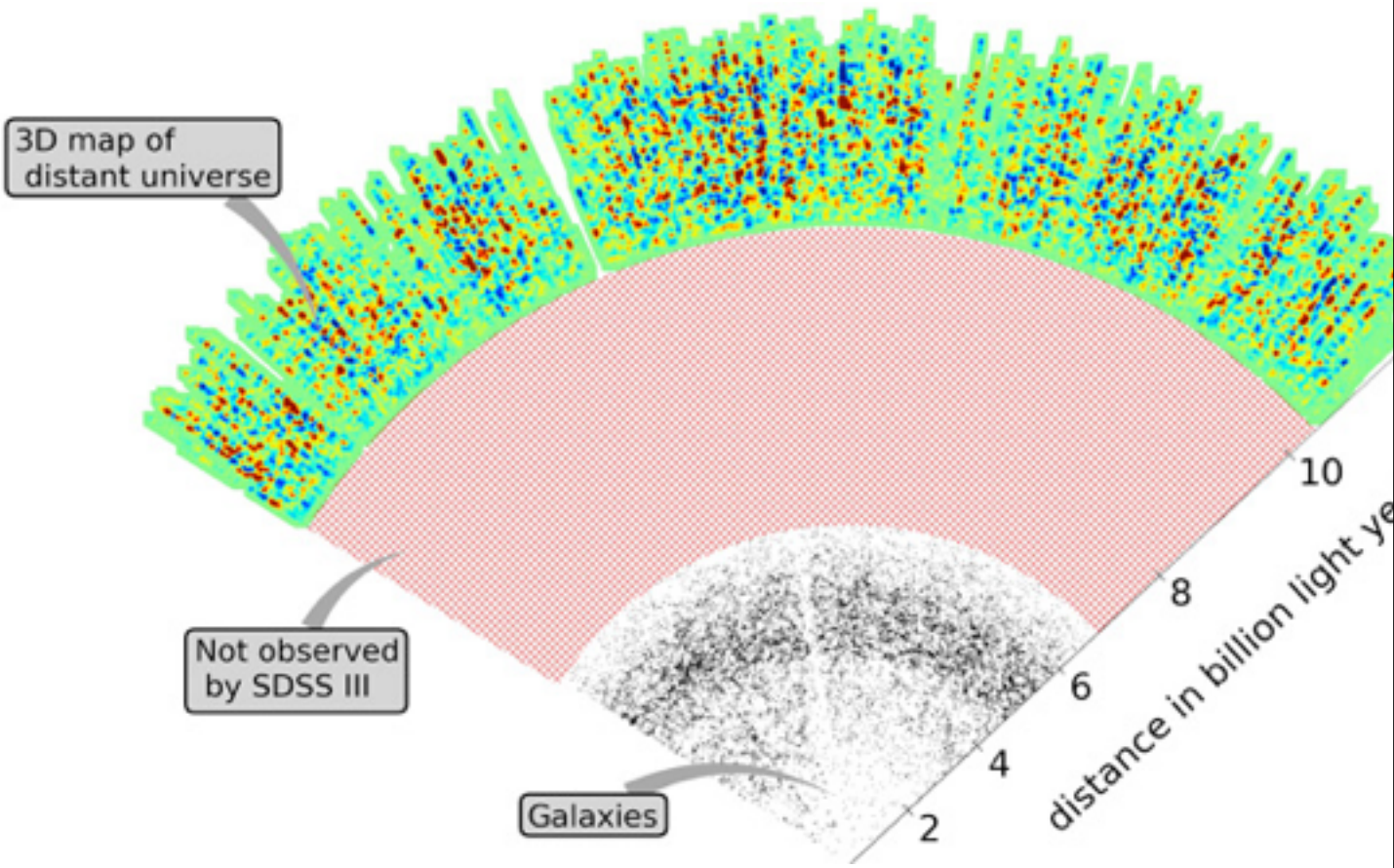
**Make 3-D map**
↓
Test physics!

**BOSS is 98% complete**
**1.4 million galaxies + 160,000 Lyman-alpha quasars**



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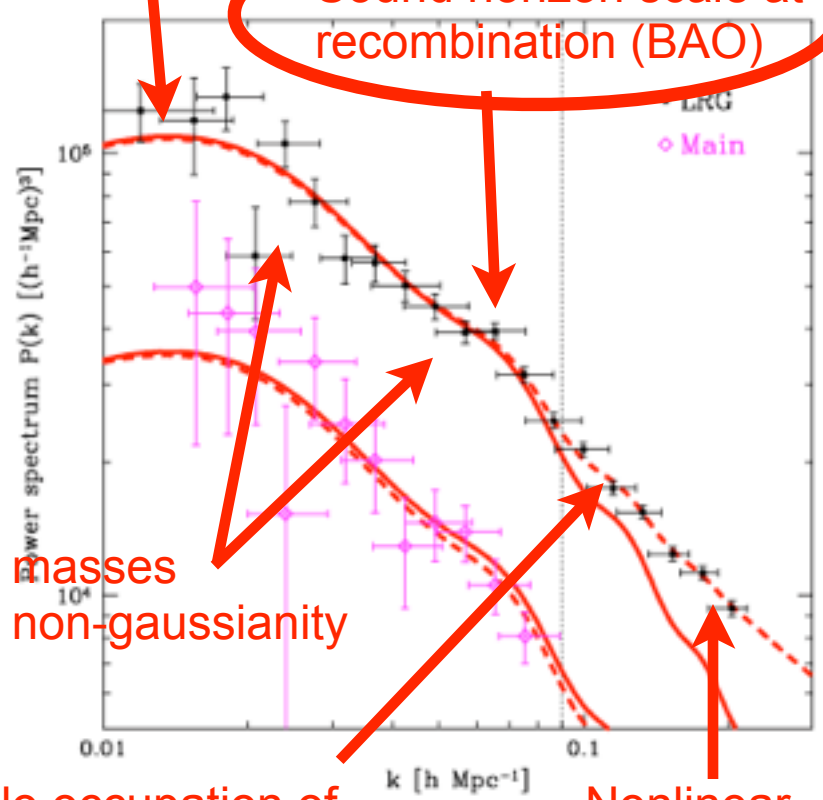
**Today's physics tests:**
**Collapse all that info into a few statistics**

Turn-over depends upon horizon size at matter-radiation equality

Sound horizon scale at recombination (BAO)

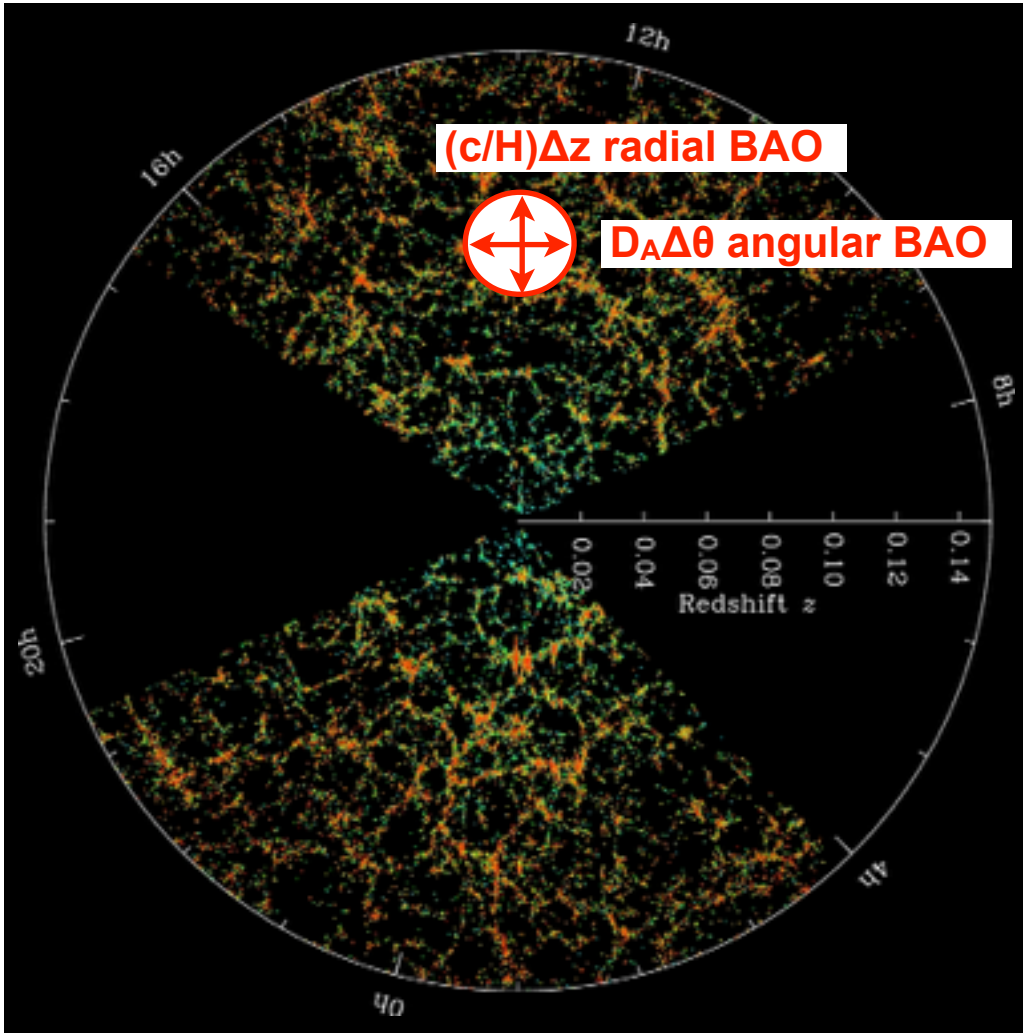


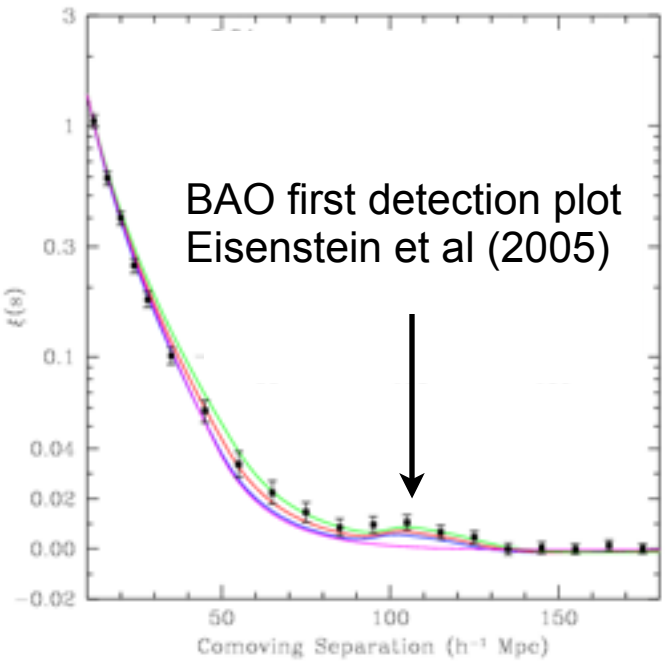

Neutrino masses
Inflation: non-gaussianity

Galaxy halo occupation of dark matter halos (HOD)

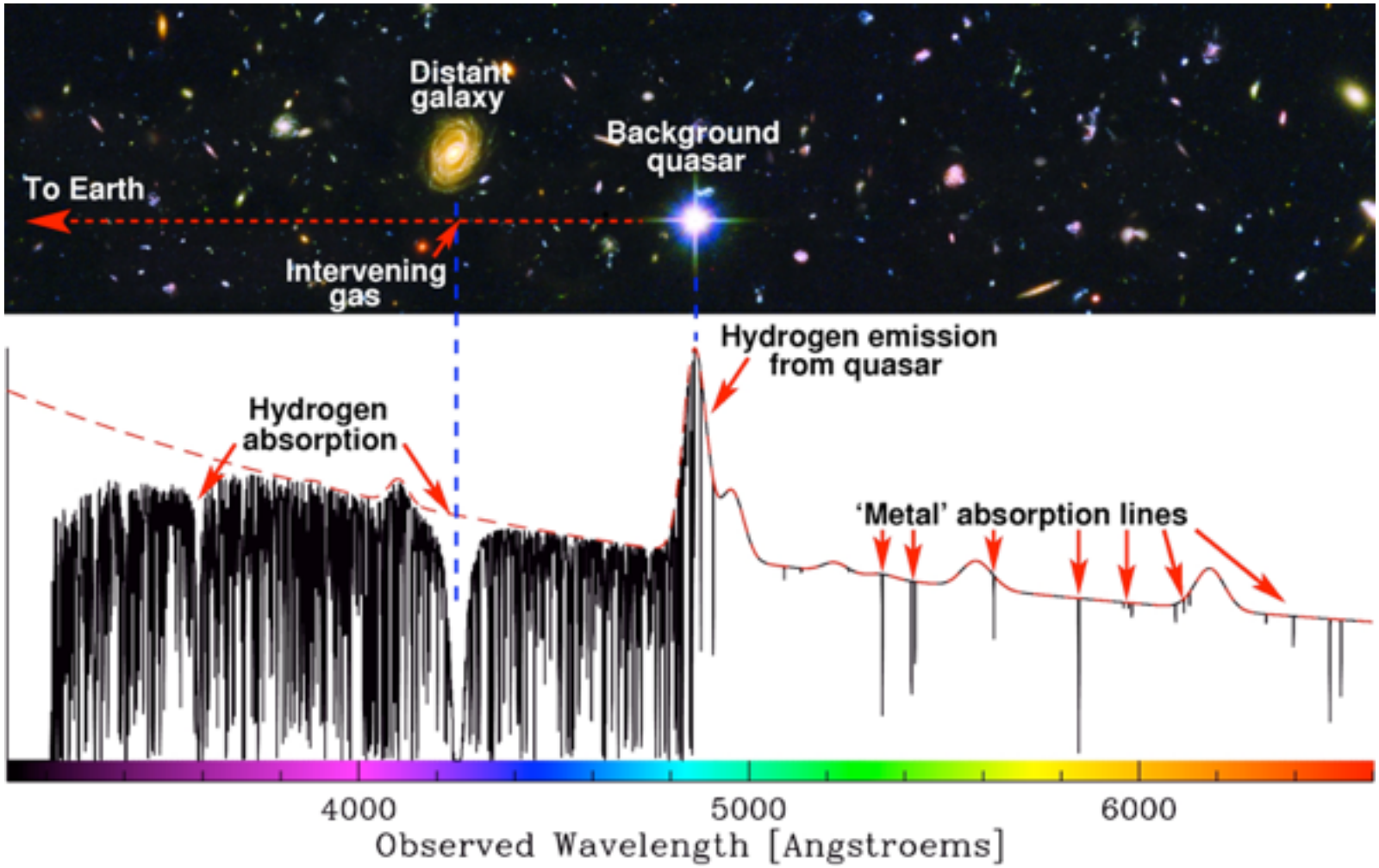
Nonlinear growth

# BOSS Key Project: BAO scale from galaxies at z=0 → 0.6 and Lyman-alpha forest at z=2 →3

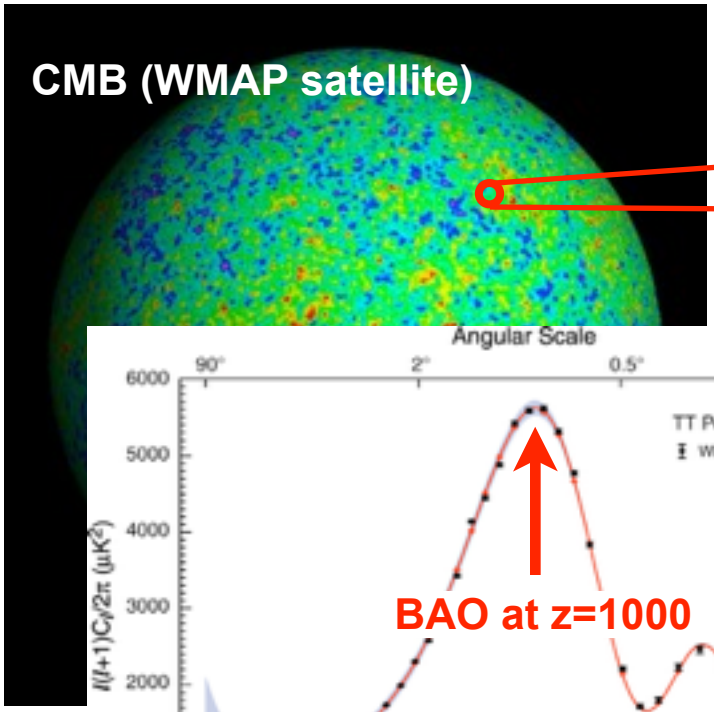


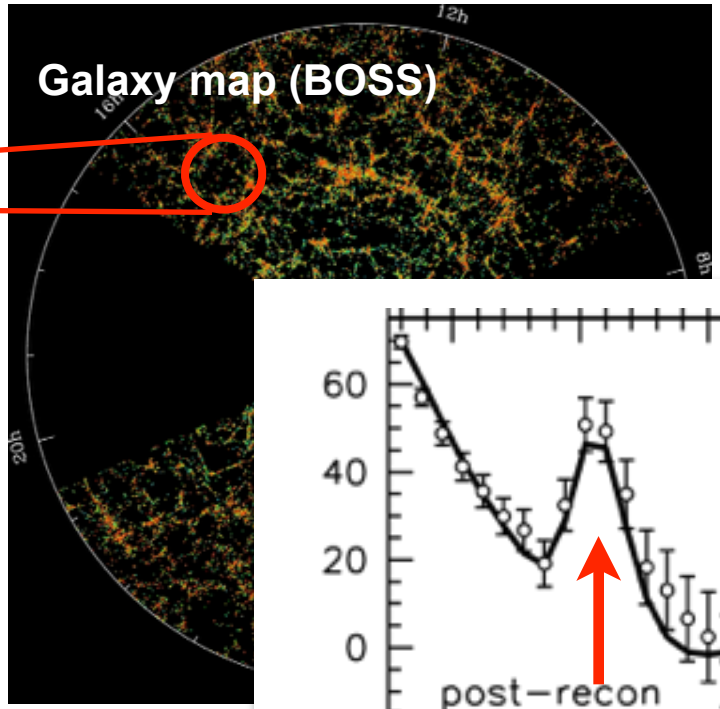
# BOSS Key Project: BAO scale from galaxies at z=0 → 0.6 and Lyman-alpha forest at z=2 →3

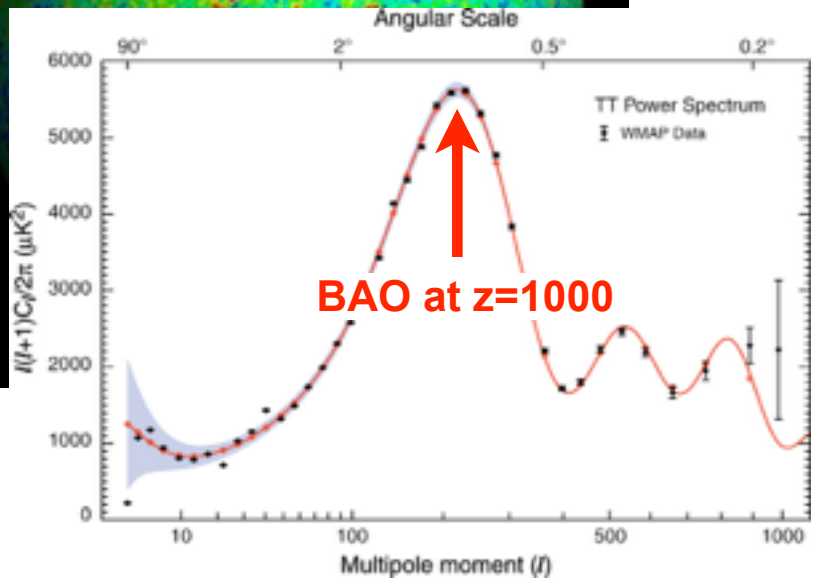


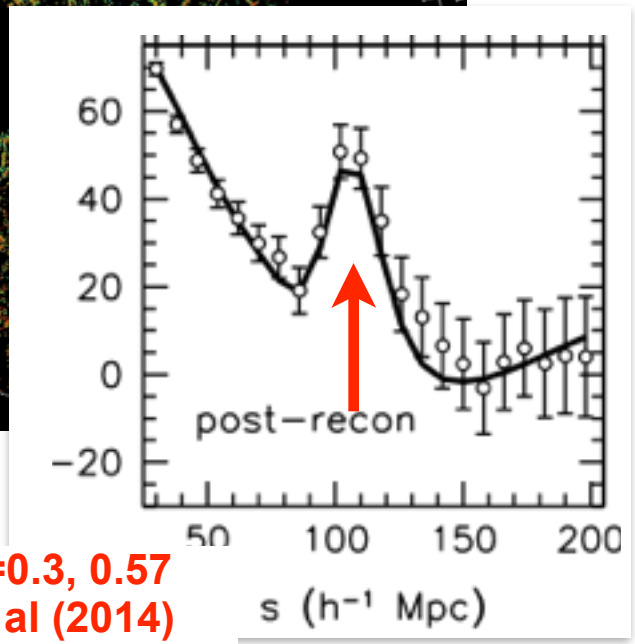
# BOSS BAO results from galaxies at z=0.3, z=0.6




BAO ruler

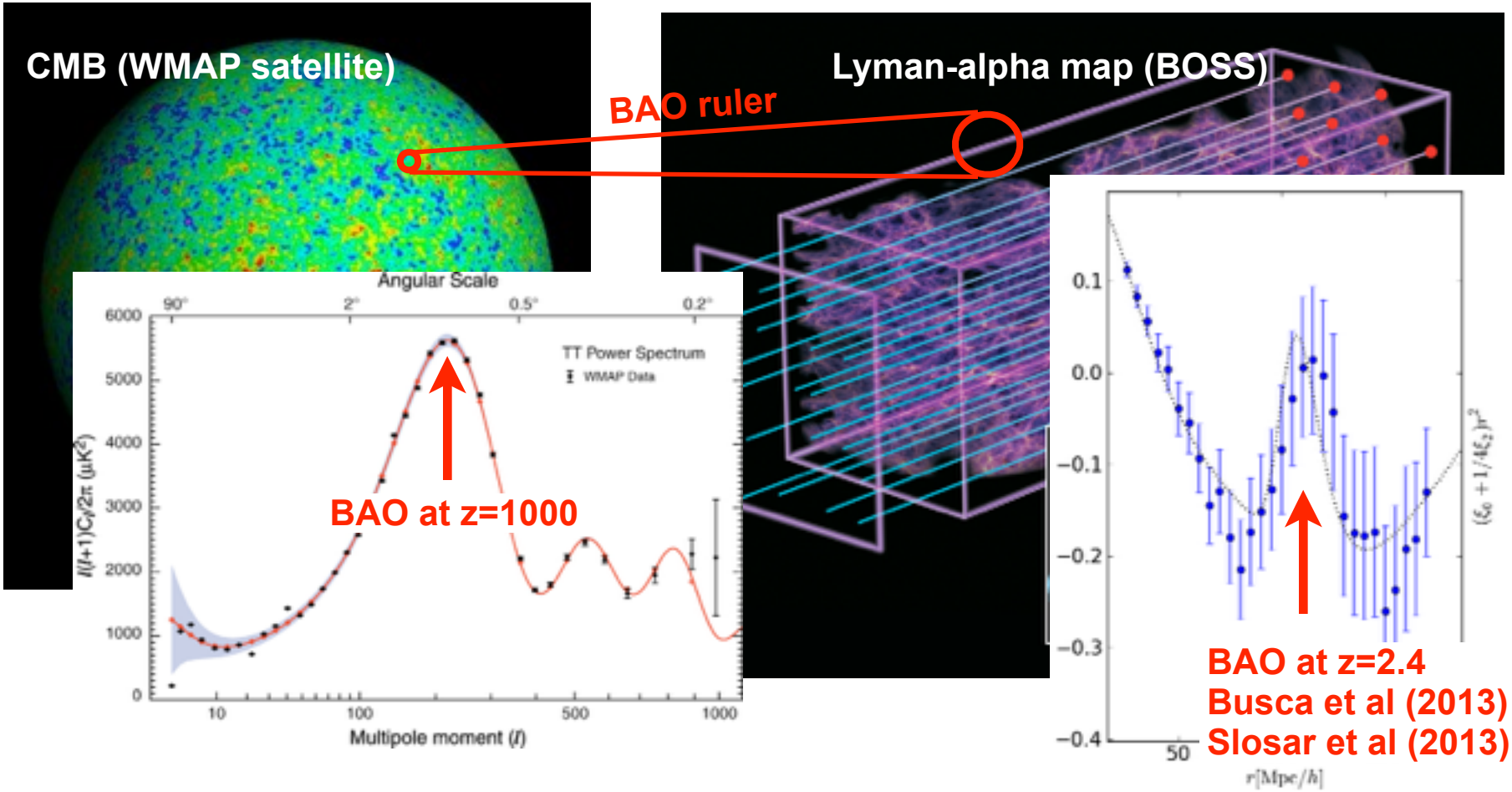


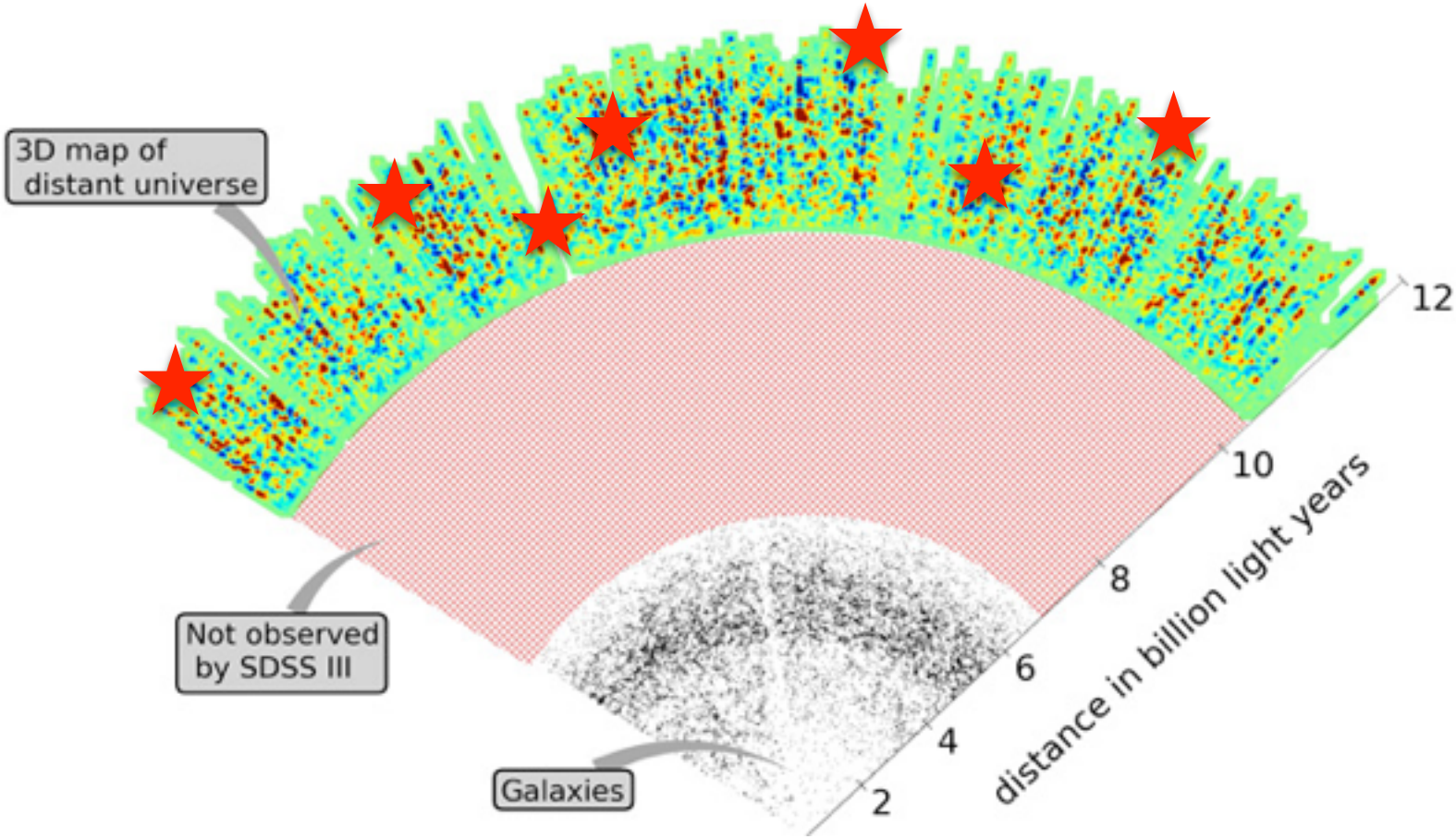

BAO at z=0.3, 0.57
Tojeiro et al (2014)
Anderson et al (2014)

# BOSS BAO results from Lyman-alpha forest at z=2.4

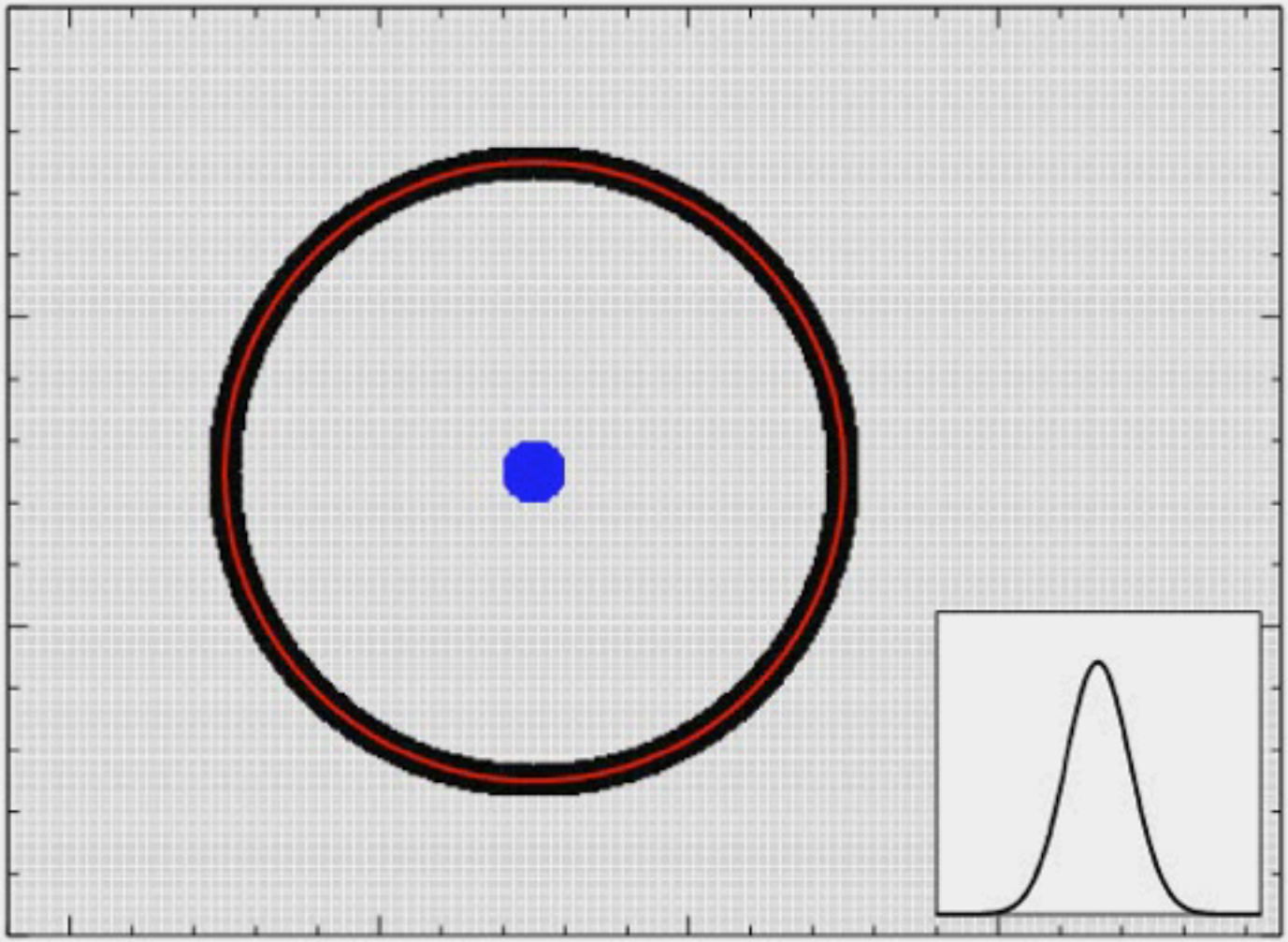


# BOSS BAO results from cross-power of Lyman-alpha forest, QSOs

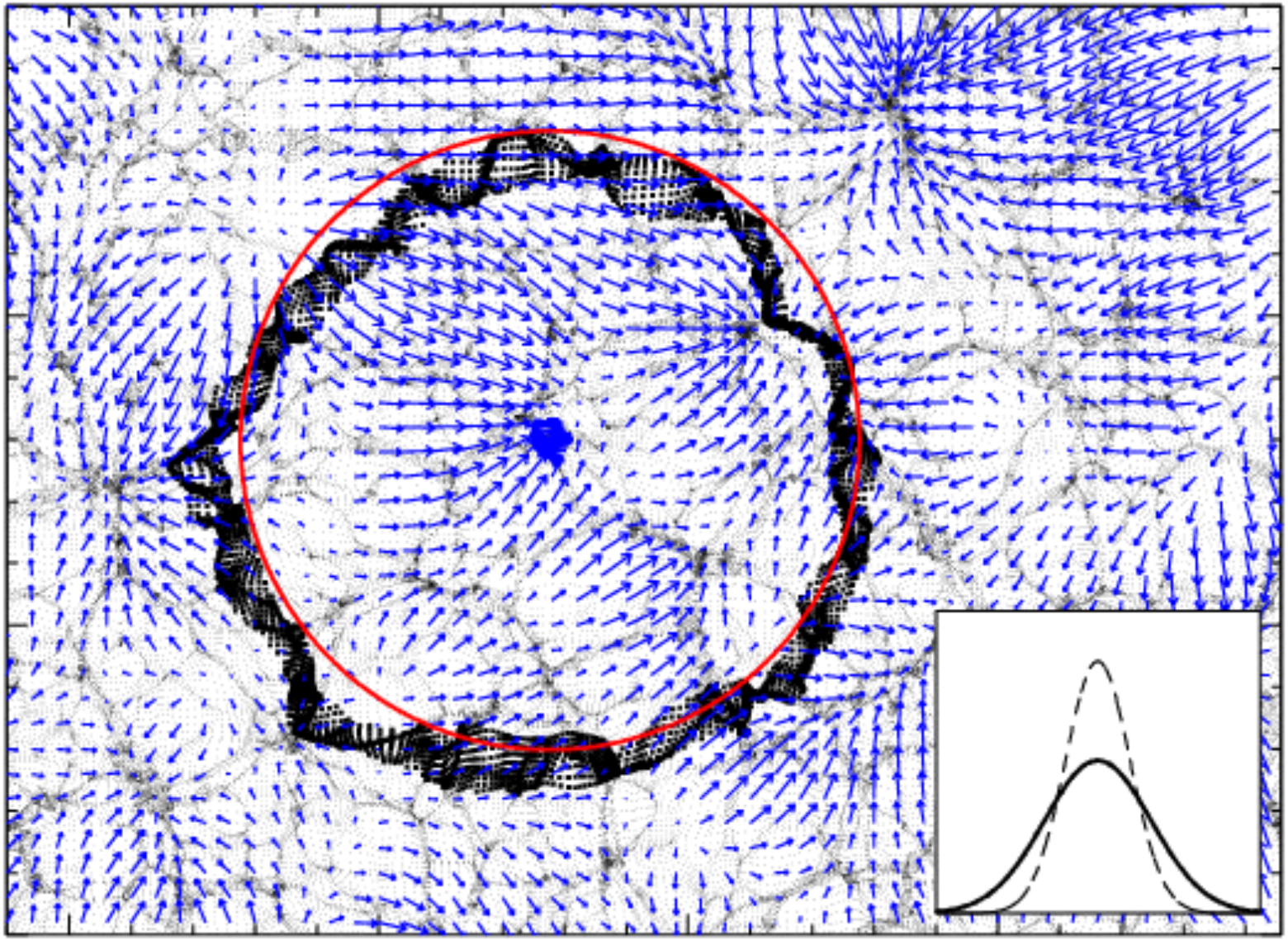
**Completely new, c.f. Font-Ribera et al 2014, O'Connell et al 2014**
**Similar advantages to a CMB cross-power measure**



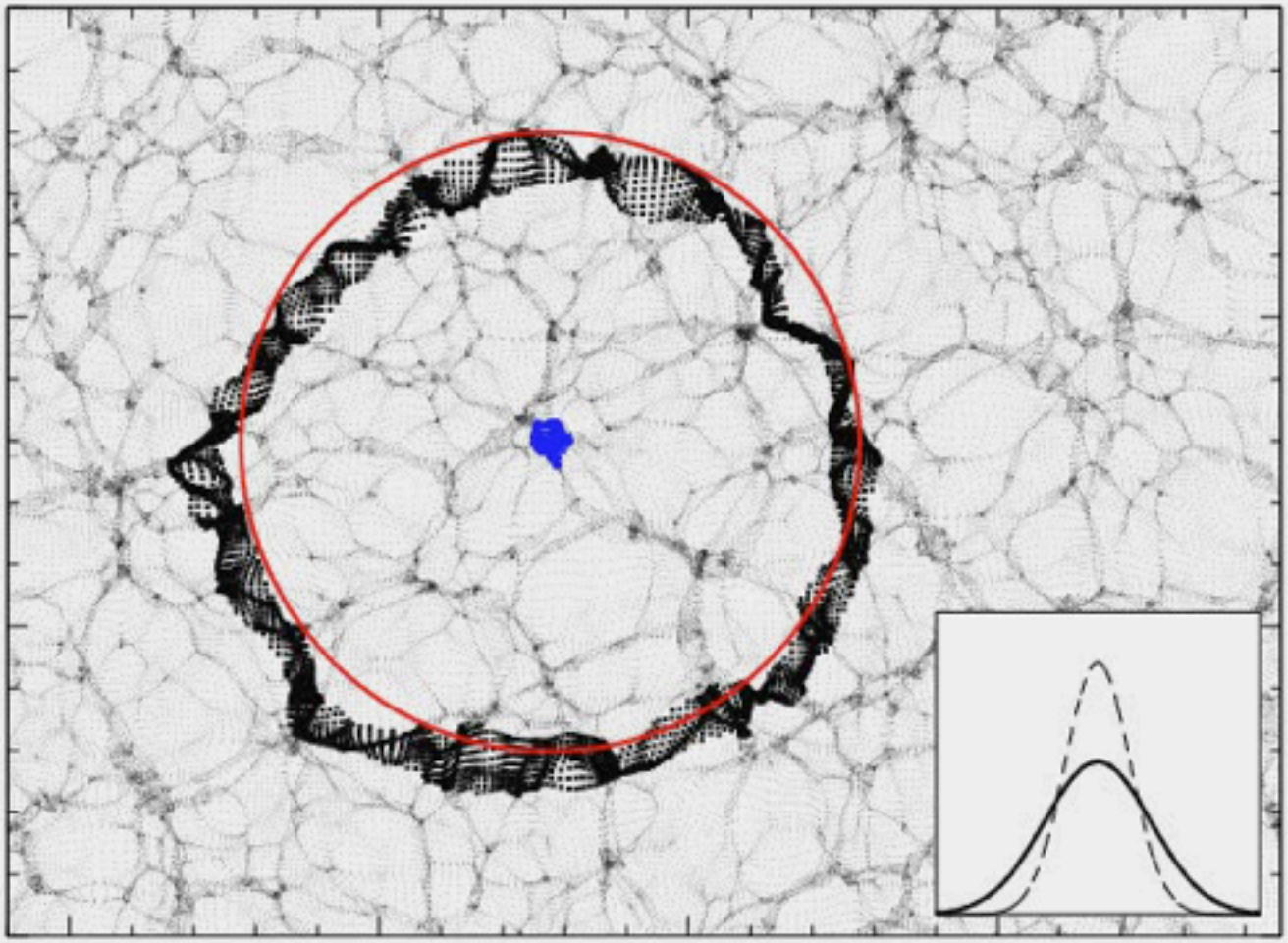
# Nonlinear Evolution



# Reconstruction : II

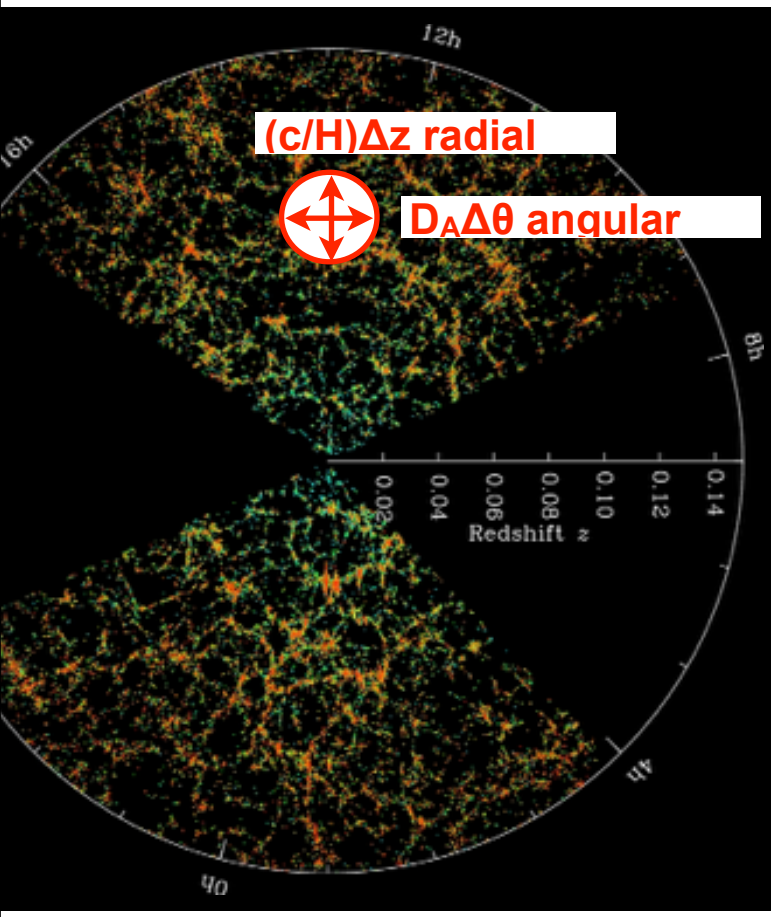


# Reconstruction : III



# BOSS results
# redshift space distortions (RSD)

**BOSS galaxy map** → **2-d correlation fn.**



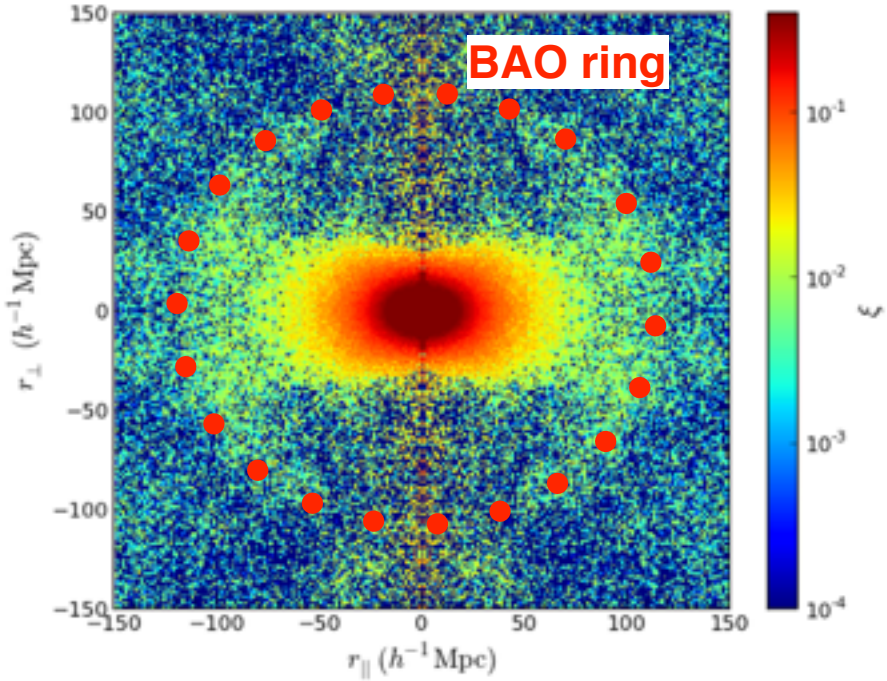




**Figure 2.** The two-dimensional correlation function of DR11 sample measured in bins of $1h^{-1} \times 1h^{-1}$ Mpc$^2$. We use first two Legendre multipoles of the correlation function in our study rather than the two-dimensional correlation function displayed here.

**Samushia et al 2014**

# BOSS Key Project Goals

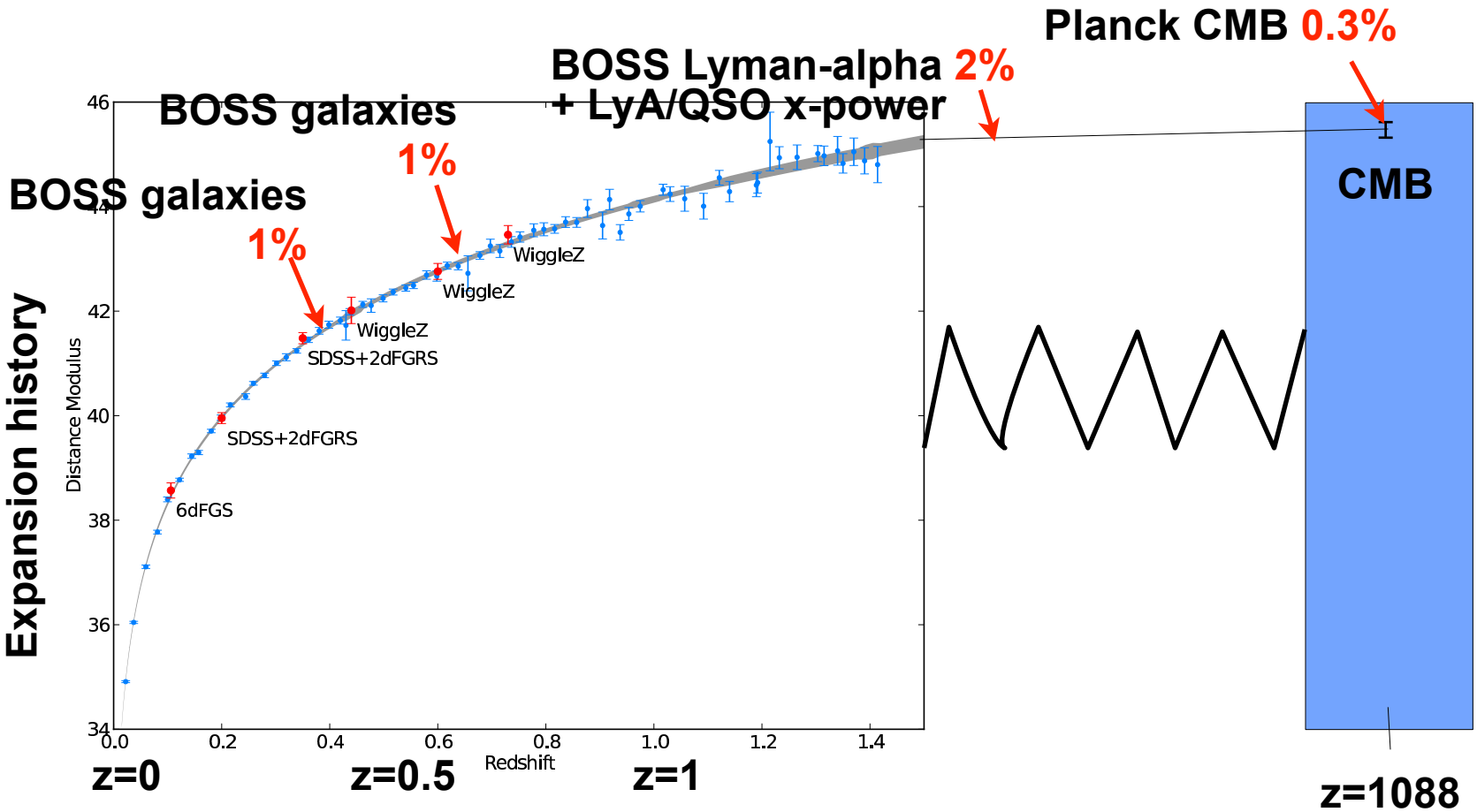
**BOSS-BAO from galaxy redshifts at z < 0.7**

$d_A$, H(z) measured to 1.0, 1.8% at z=0.35

$d_A$, H(z) measured to 1.0, 1.7% at z=0.60

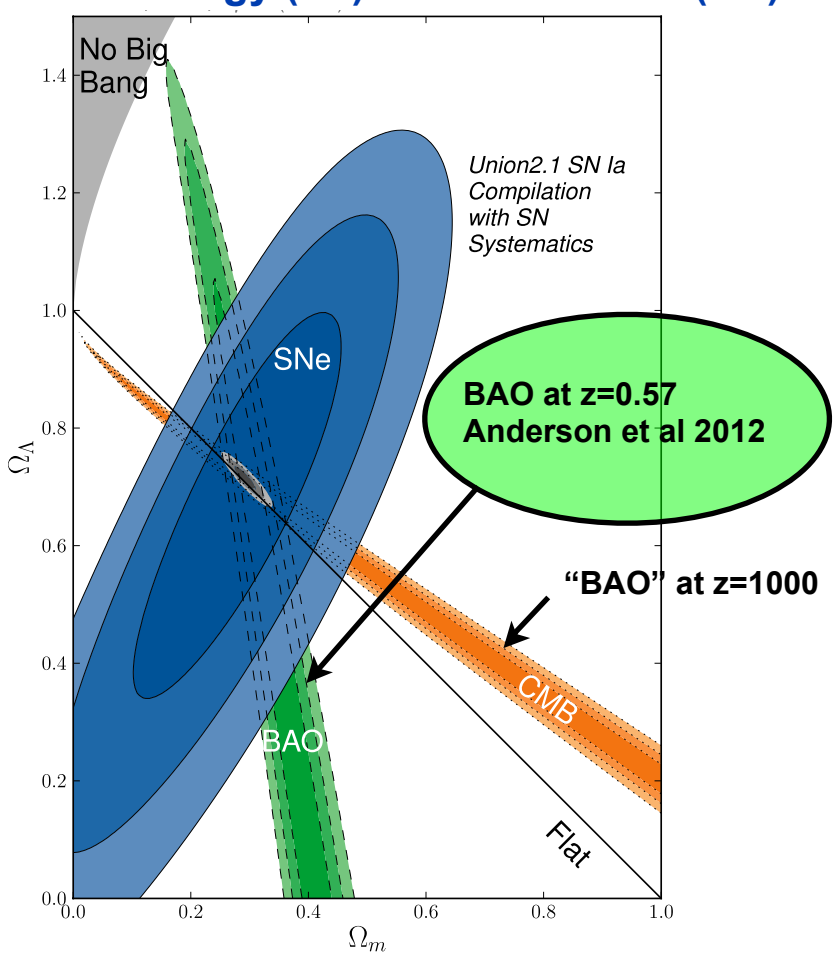
**BOSS-BAO from Lyman-alpha forest at z > 2**

$d_A$, H(z) combined measured to 1.9% at z=2.4



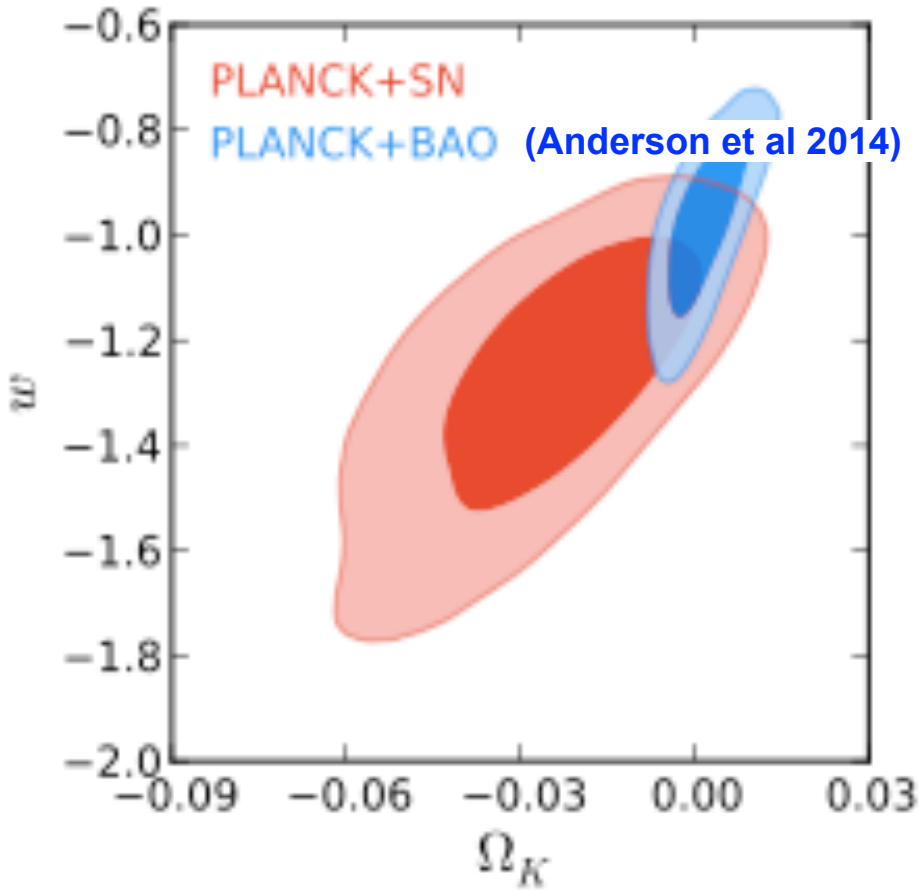
# BOSS Key Project results

## Dark energy ($\Omega_\Lambda$) vs. dark matter ($\Omega_m$)




*from Anderson et al (2012)*

## Dark energy eqn. of state($w_o$) vs. curvature ($\Omega_K$)



# BOSS BAO + Planck

**Combination of BOSS + Planck probes early universe inflation models**
**A number that is neither 0 nor -1**

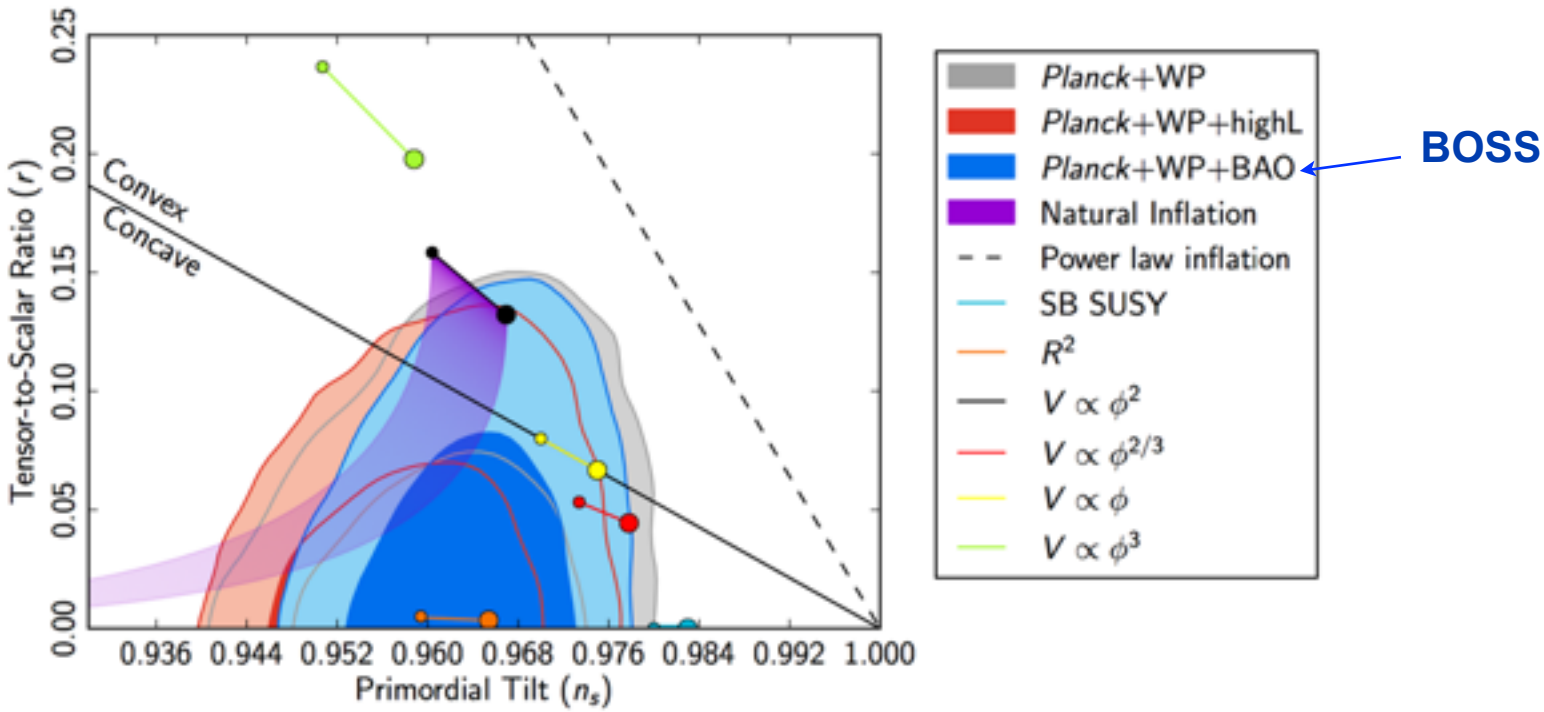
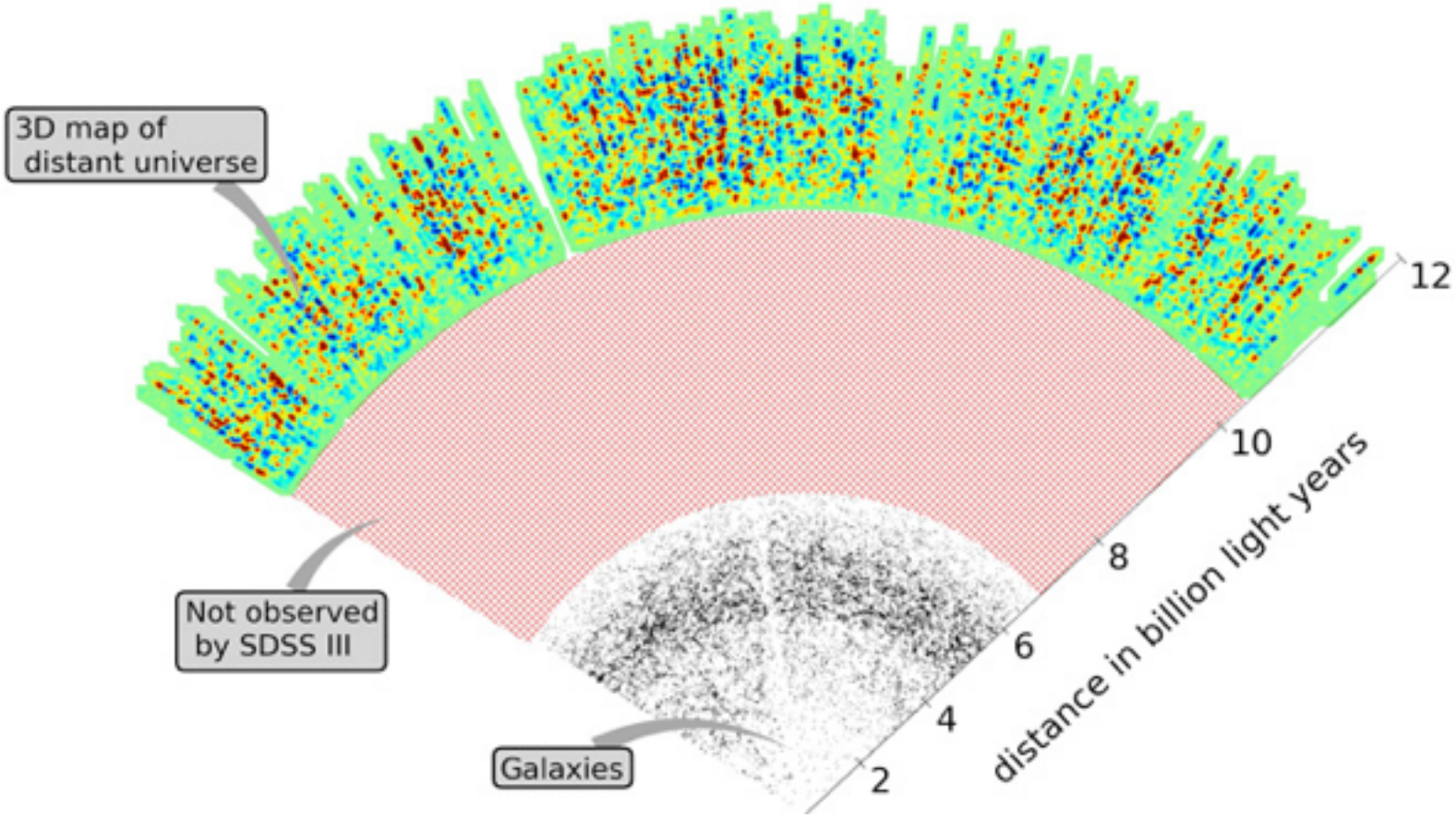



**Fig. 26.** Marginalized 68 % and 95 % confidence levels for $n_s$ and $r$ from Planck+WP and BAO data, compared to the theoretical predictions of selected inflationary models.

*from Planck overview paper (2013)*

# BOSS: Where are we in 2014?

**Jan 2012: Galaxy BAO from 33% of data**
**Nov 2012: Lyman-alpha BAO from 33% of data**
**Jan 2014: Galaxy BAO from 90% of data**
**Apr 2014: Lyman-alpha BAO from 90% of data**
**Dec 2014: All data released**