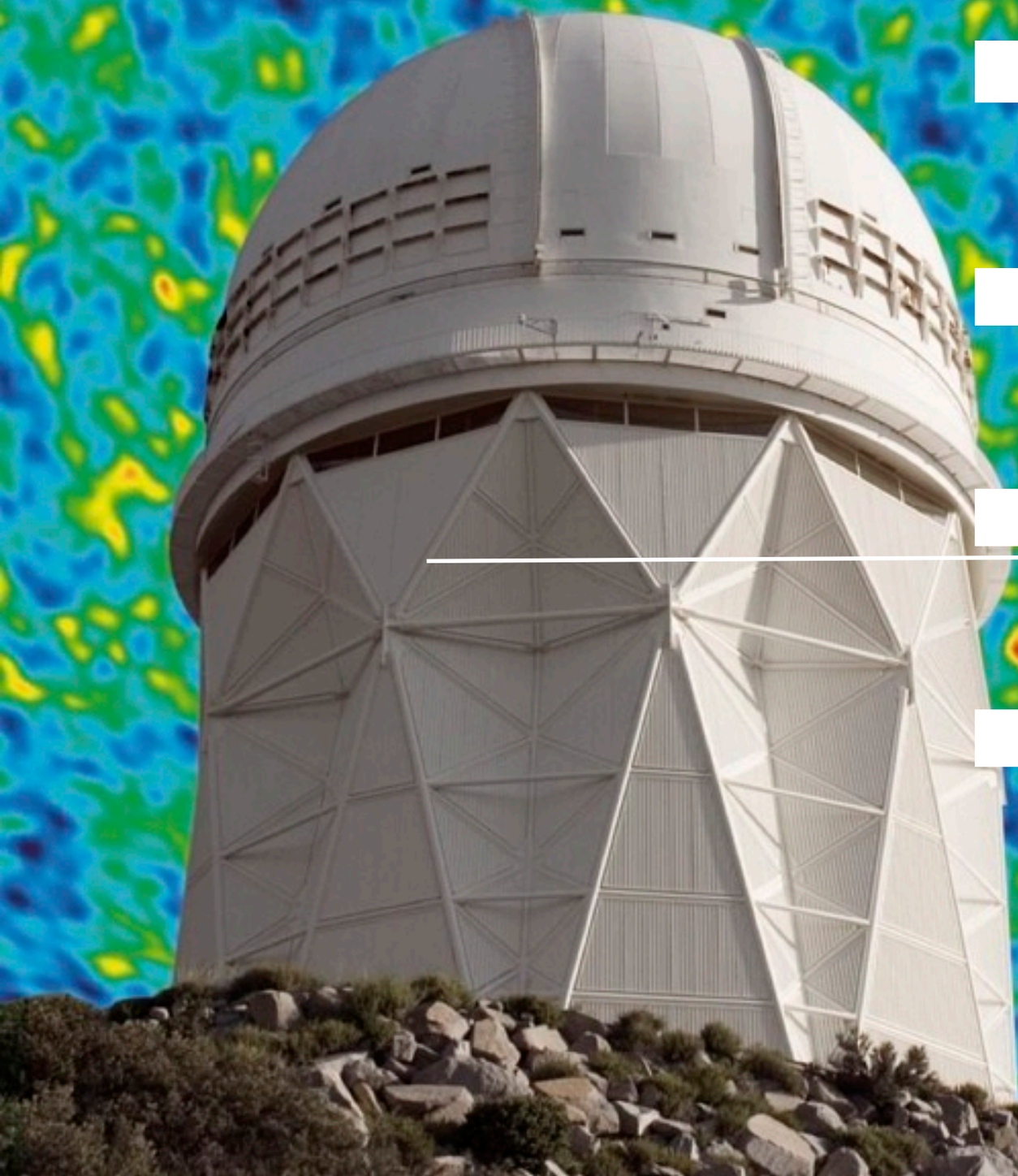
Measuring and Mapping the Universe

BAO and MS-DESI

Outline

- What is BAO?
- What is MS-DESI?
- Fibers?
- Why do I care?



Schlegel/BigBOSS/WMAP

HISTORY

CMB
380,000 yr

Deceleration by gravity

Acceleration by dark energy!

Inflation

BIG BANG

1st Stars
about 400 million yrs.

Big Bang Expansion

13.7 billion years

NASA

DECOUPLING

- The story of the universe starts at the Big Bang and a lot happens up to the time of cosmic microwave background (CMB).

- What we see in the CMB radio maps is the time when the universe became **transparent**, (so we can see the CMB), called

  the time of matter-radiation decoupling

  (or surface of last scatter)

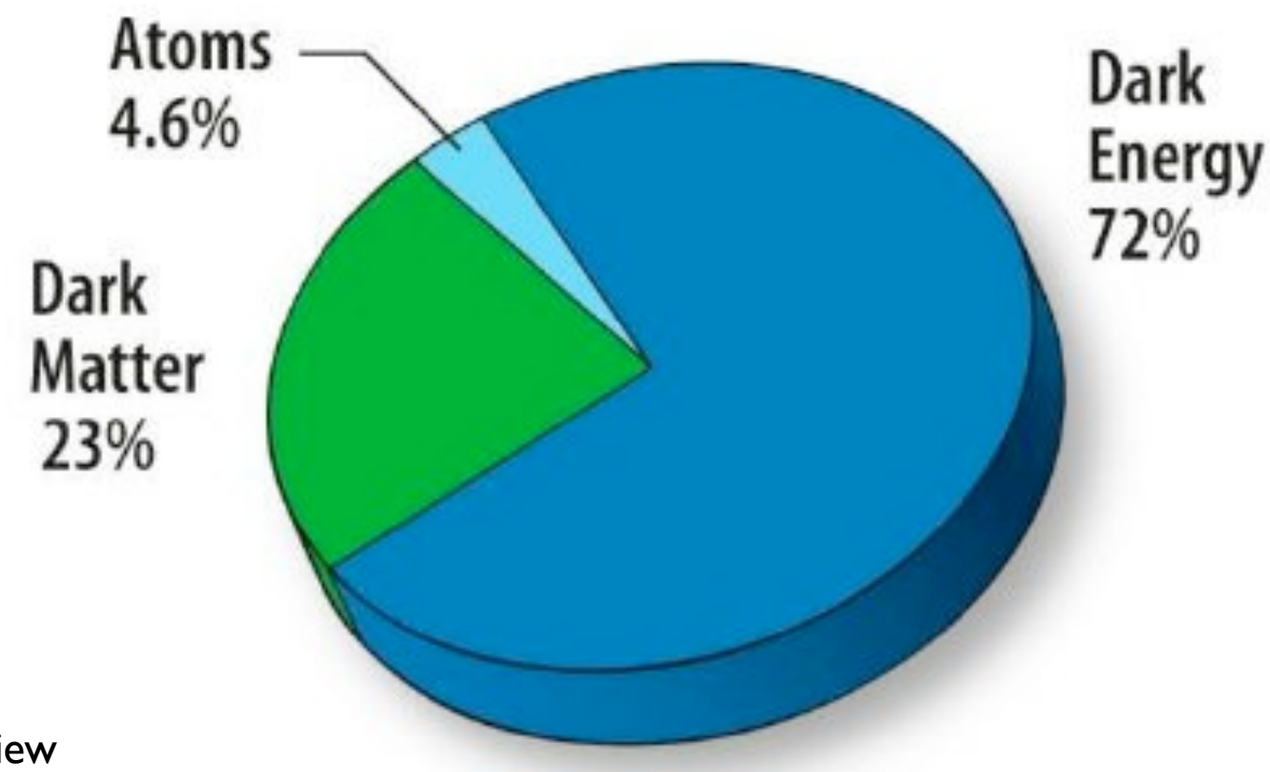
Dark Energy Science

Dark energy constitutes 72% of the energy-density of the Universe
Discovered in 1998, 1999 from supernova cosmology.

Measurements of Omega and Lambda from 42 High-Redshift Supernovae, Perlmutter et al 1999
Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant, Riess et al 1998

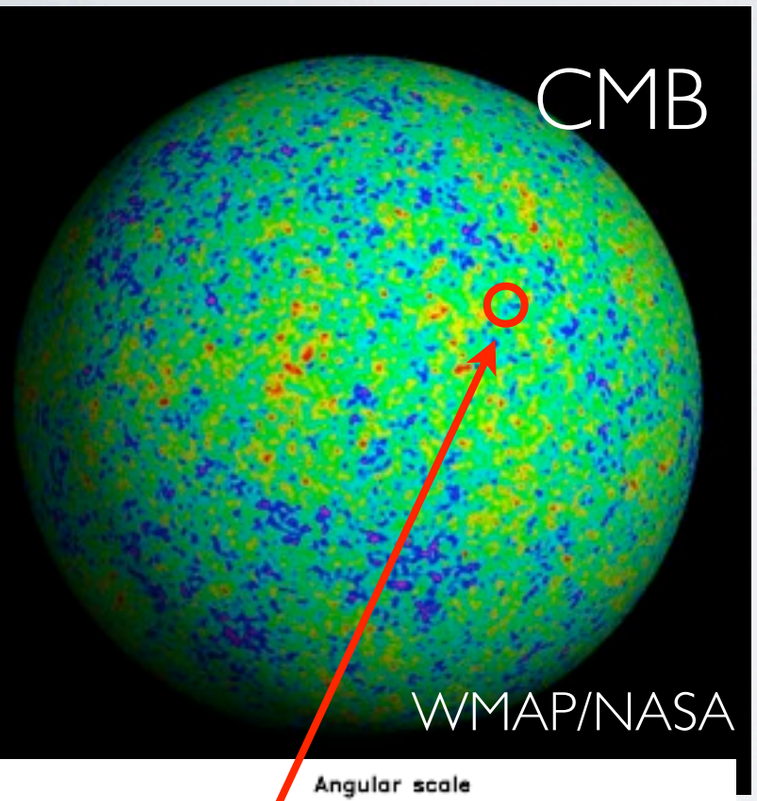
Confirmed in 2003 from microwave background.

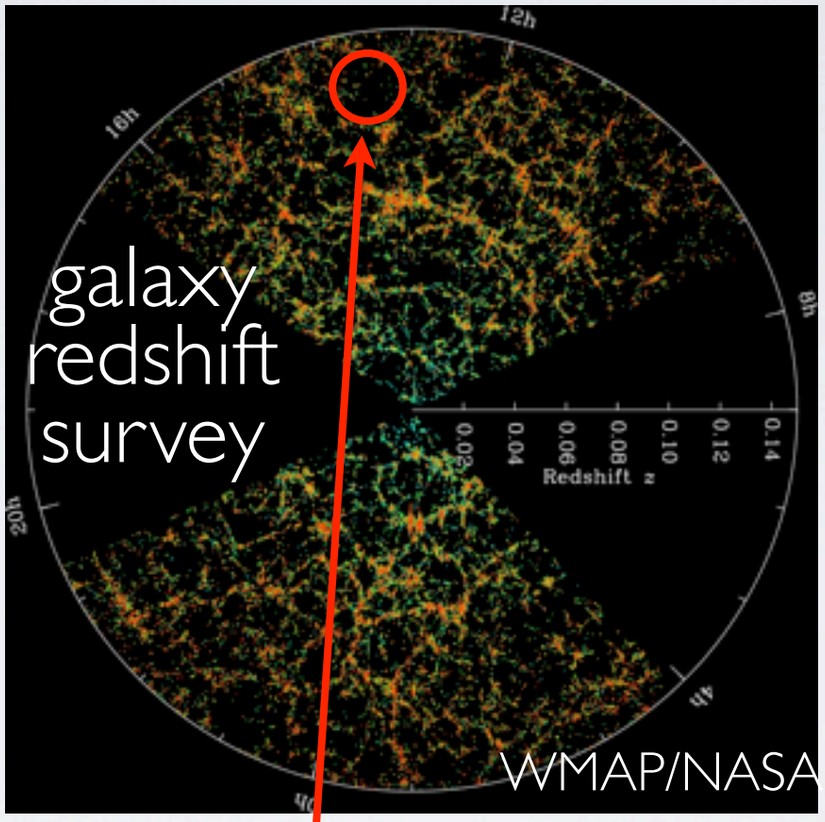
First-Year Wilkinson Microwave Anisotropy Probe (WMAP)[1] Observations: Determination of Cosmological Parameters, Spergel et al 2003

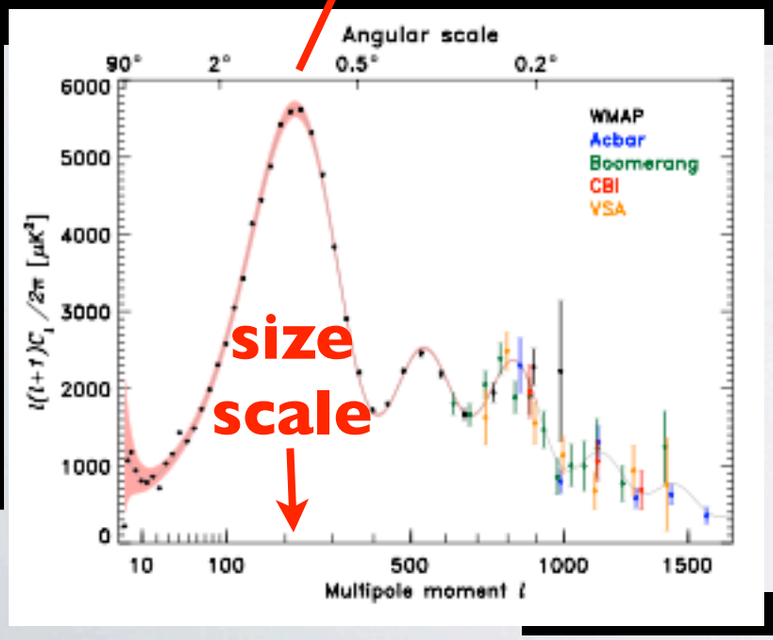


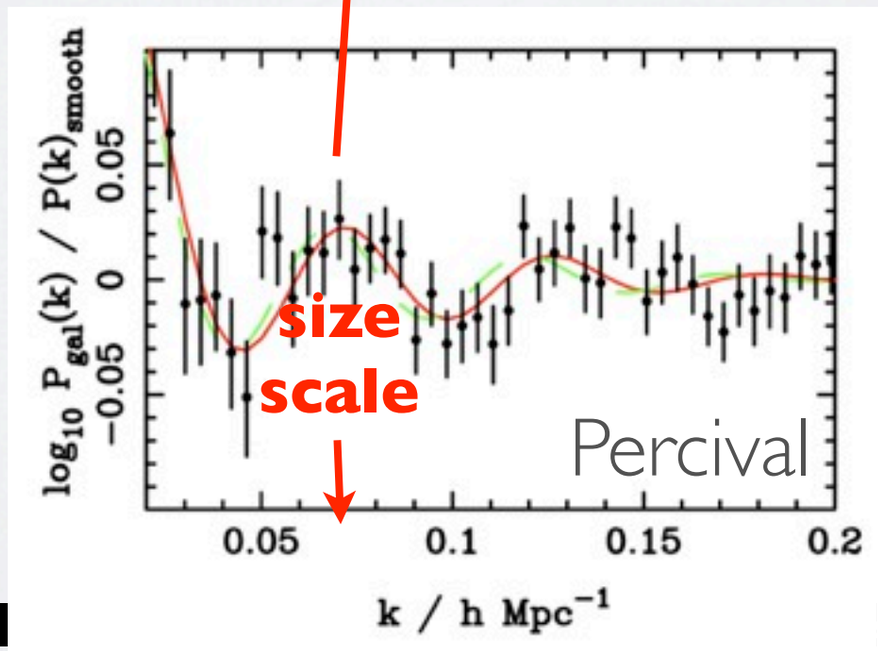
WHAT IS BAO?

- Baryons = "stuff" like atoms, not **γ** and not **ν**.









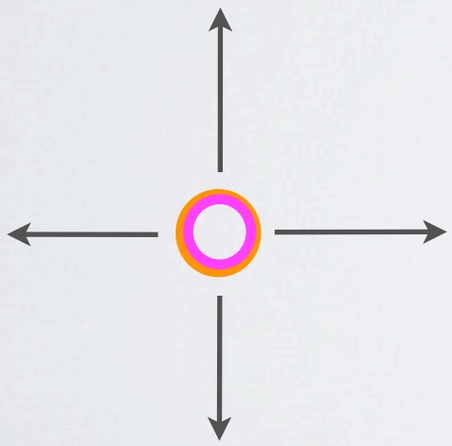
- BAO = Baryon Acoustic Oscillations
  - Characteristic size hot spots (=density peaks) in cosmic microwave-mm background (CMB) ...
  - become "frozen in" to expansion, and...
  - same oscillations observed today as concentrations in galaxies (baryonic matter).

BAO~ RIPPLE IN POND, FLASH-FROZEN

- Size "frozen-in" to expansion at de-coupling (in co-moving coords)

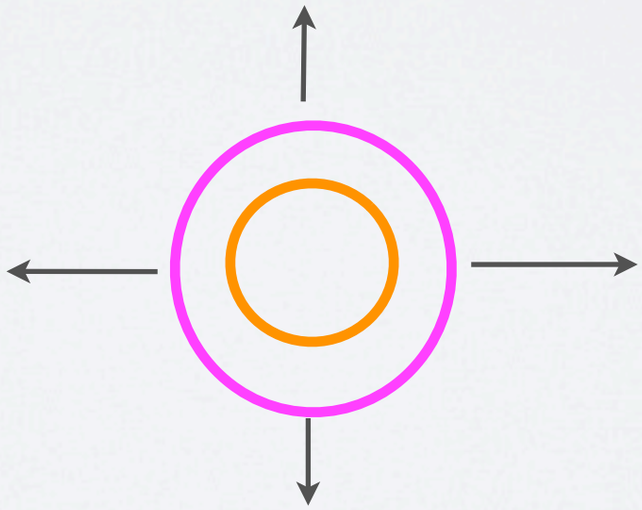
First: Hot plasma: density perturbation: spreads like ripple in pond.

Early time - photons and baryon equilibrium



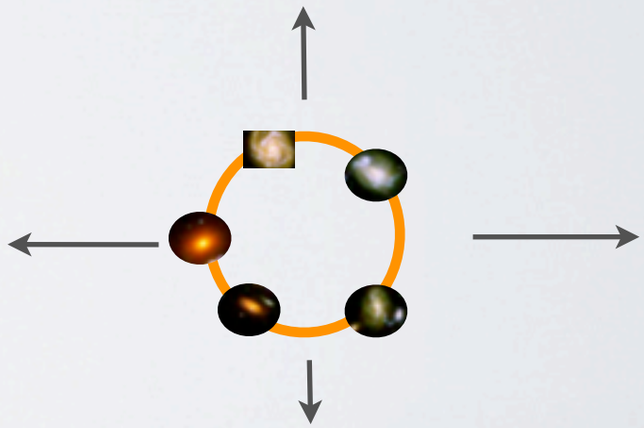
photons and baryons move each other

After Recombination - photons de-couple, *free-stream*



heavy baryons slow, motion of wave stalls

Late -expansion, baryons → galaxies at density peaks



baryons retain characteristic size

BAO~ RIPPLE IN POND, FLASH-FROZEN

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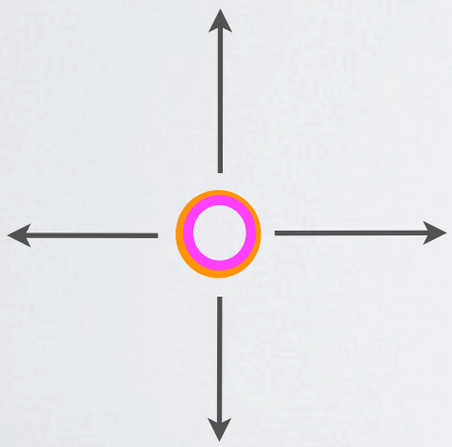

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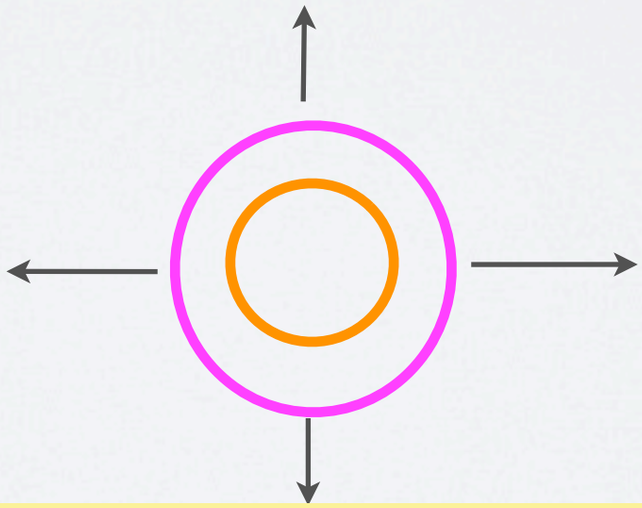

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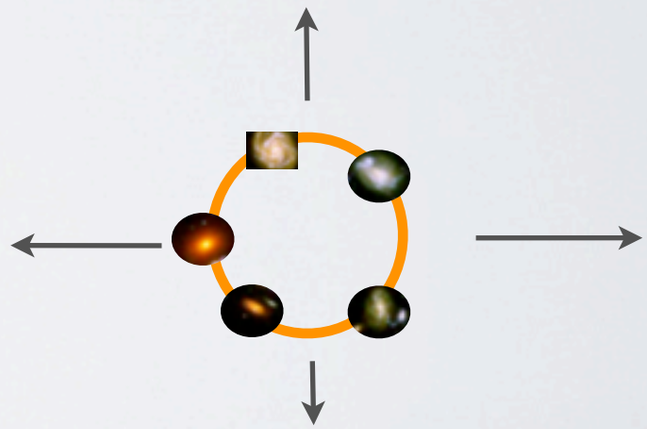


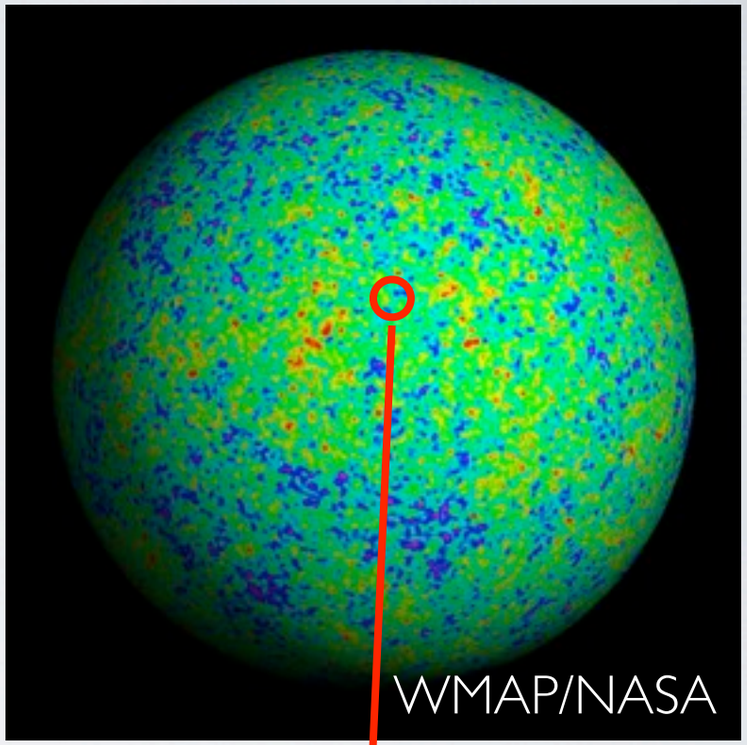
size scale ~ sound wave travel distance by $t_{decoupling}$

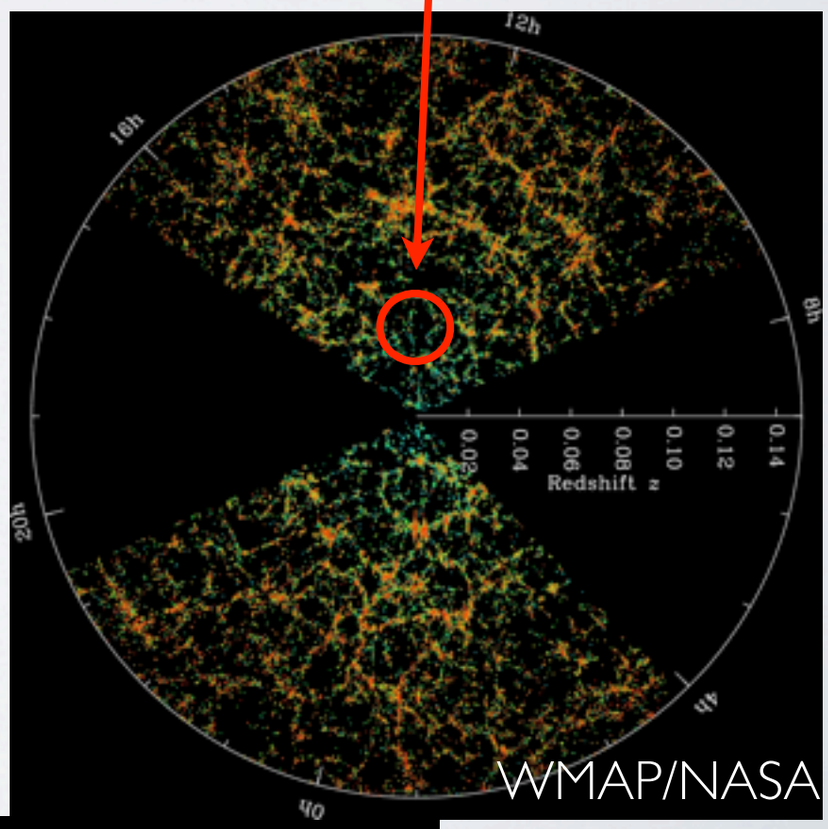
WHY DO WE CARE ABOUT BAO?

- The BAO size grows with expansion, due to....
- cosmology...
- including dark energy (DE),

- BUT we know the *physics, i.e. the instrinsic properties* of the BAO very well... and measured at CMB time

- Can use BAO as a **probe** of expansion ⇒cosmology parameters

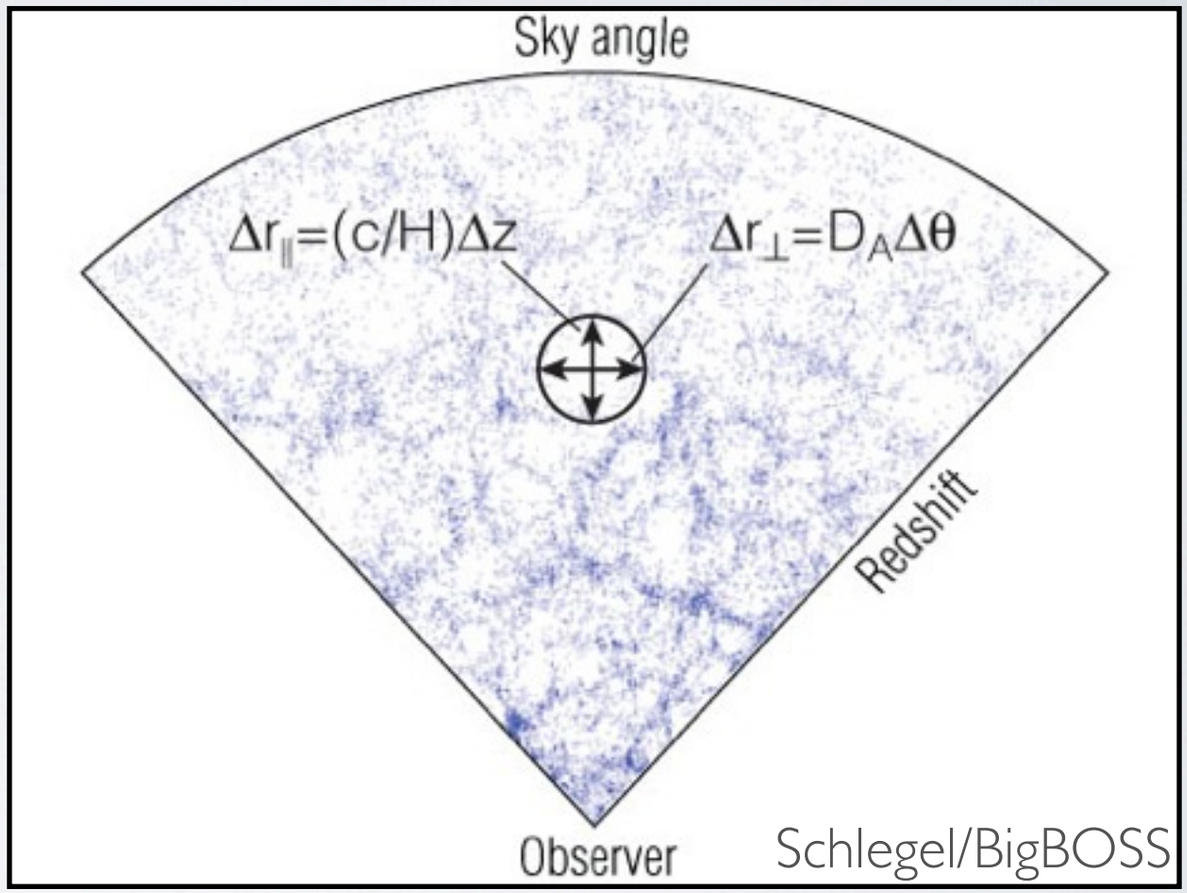




STANDARD RULER

- Supernovae = Standard Candle
  - known power lets you predict brightness

- BAO=standard ruler in comoving coords
  - known **initial size →** predict **apparent size (z)**
  - Note: two ways of measuring, *parallel* (*z*) and *perpendicular* (*angles*) to line of sight.



galaxy redshift survey data

(Little) BOSS - State of the Art

FIVE YEAR project, 2009-2015

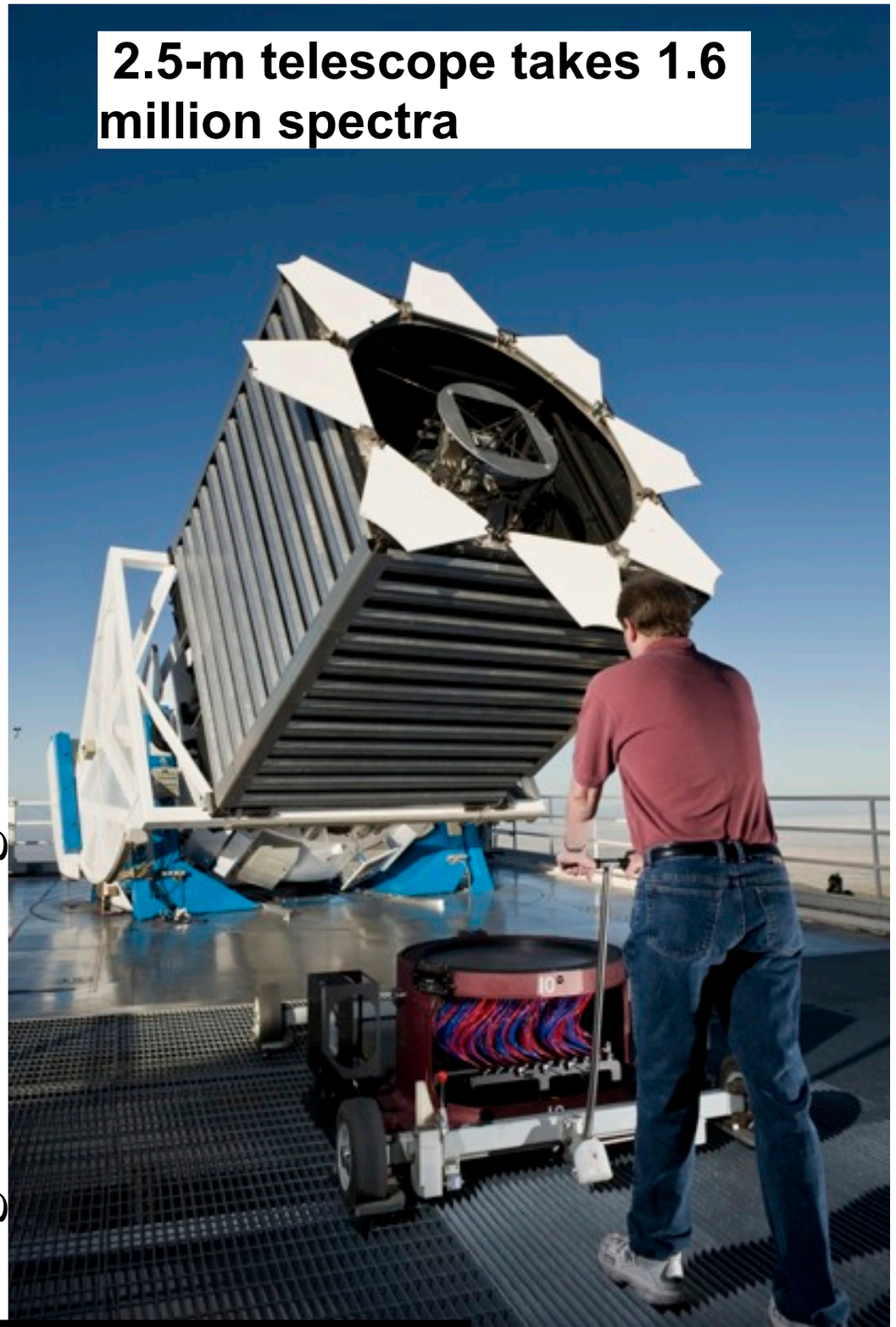


Figure D. Schlegel

(Little) BOSS - State of the Art

FIVE YEAR project, 2009-2015

1.5 million galaxies at $0.15 < z < 0.7$
160,000 QSOs at $2.1 < z < 3.5$

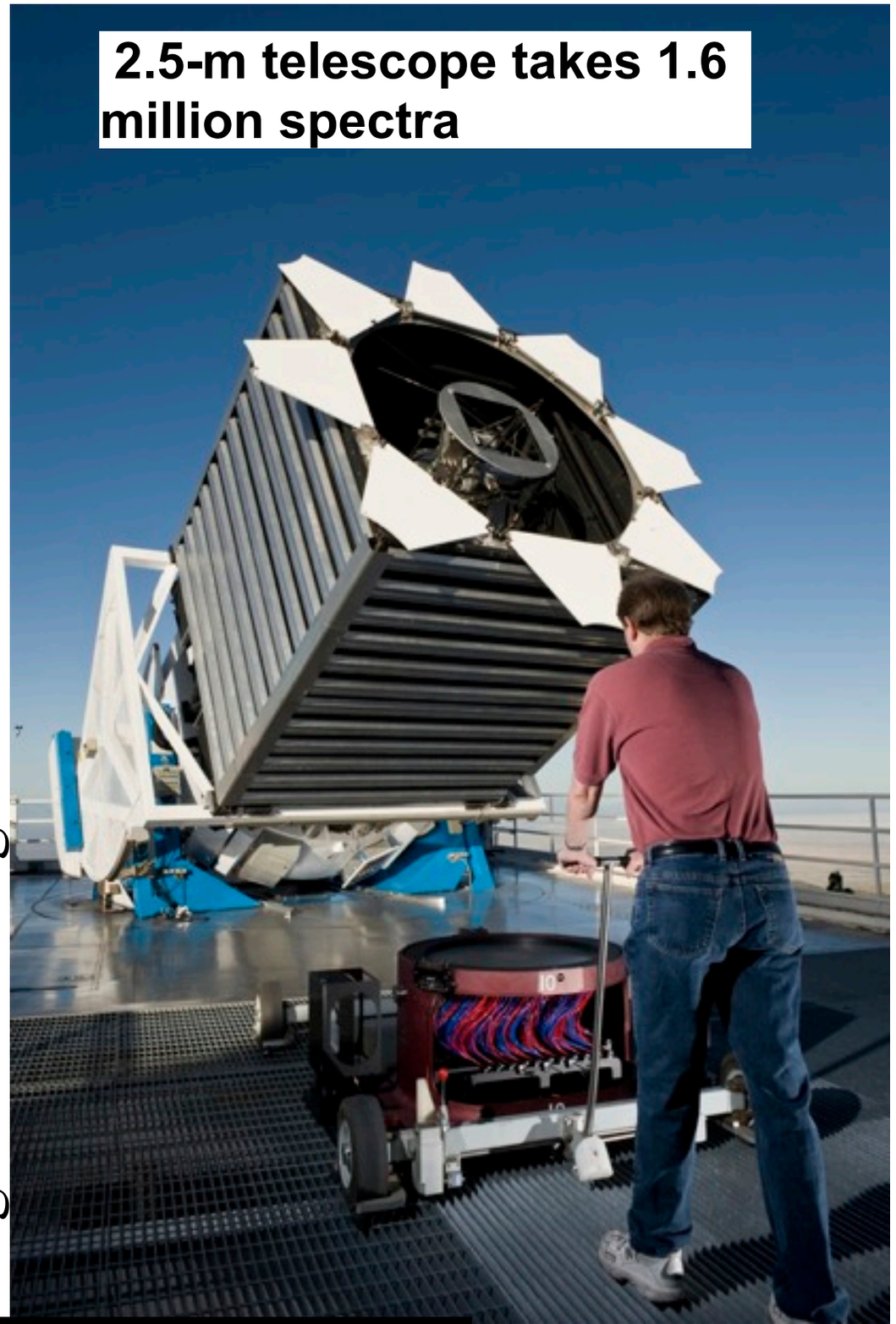


Figure D. Schlegel

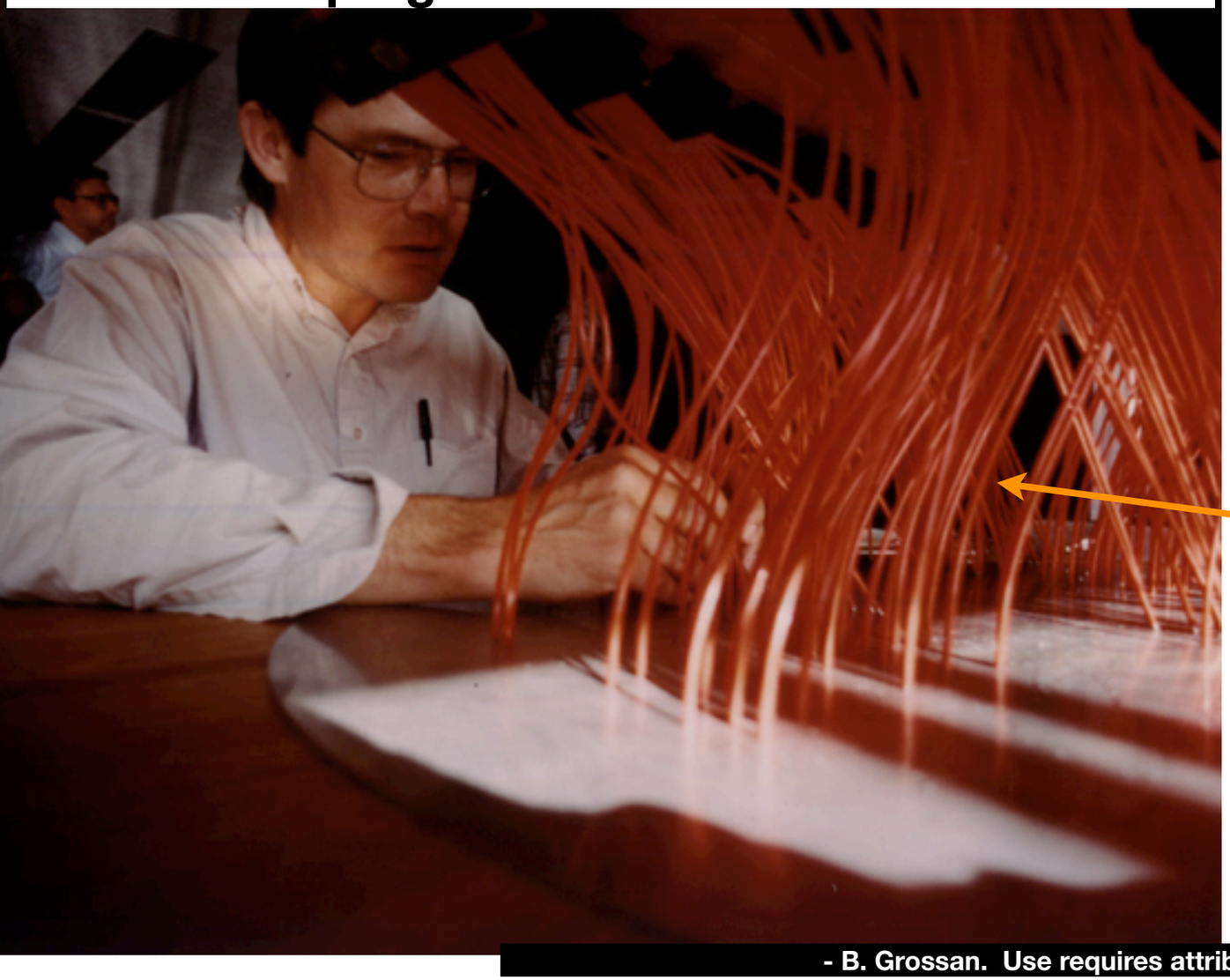
But BOSS has Limits!

1.6 million spectra

Multi-fiber spectrograph
1000 fibers
→ 1000 spectra
→ 1000 redshifts per observation

Photos D. Schlegel

Technicians plug fibers



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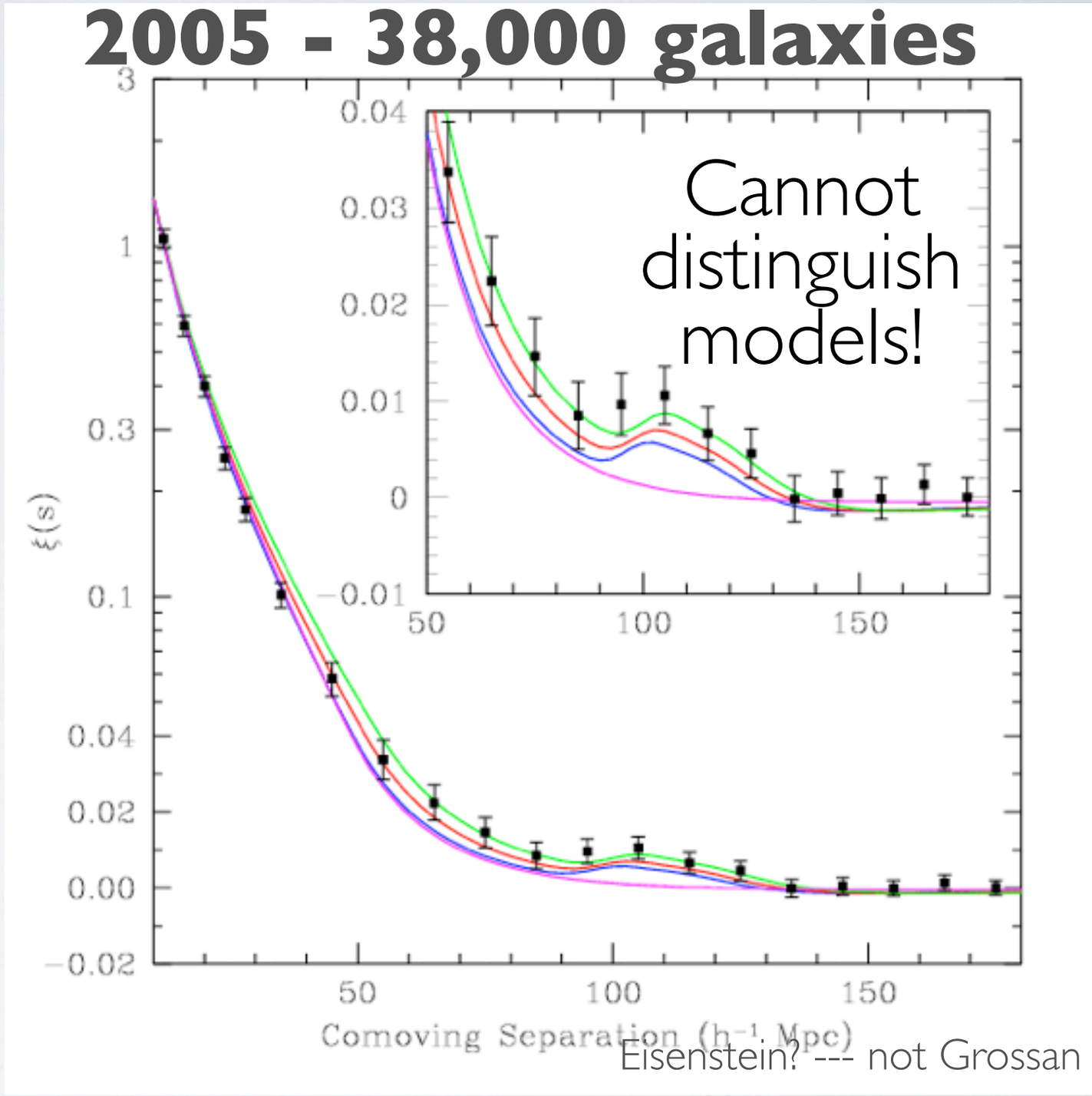
Technicians plug fibers

Photos D. Schlegel

Doubling to 3 million barely possible, takes full decade!

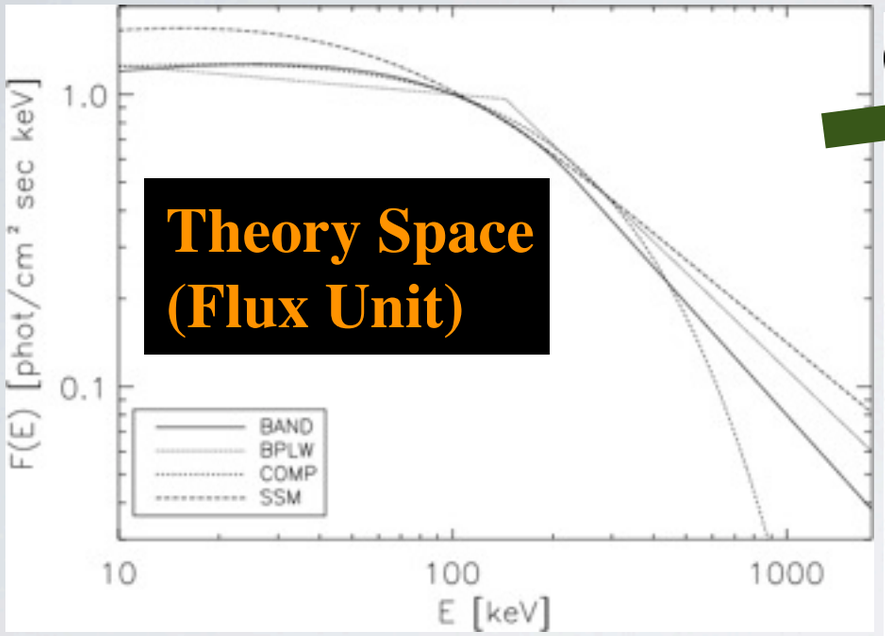
WHY MORE?

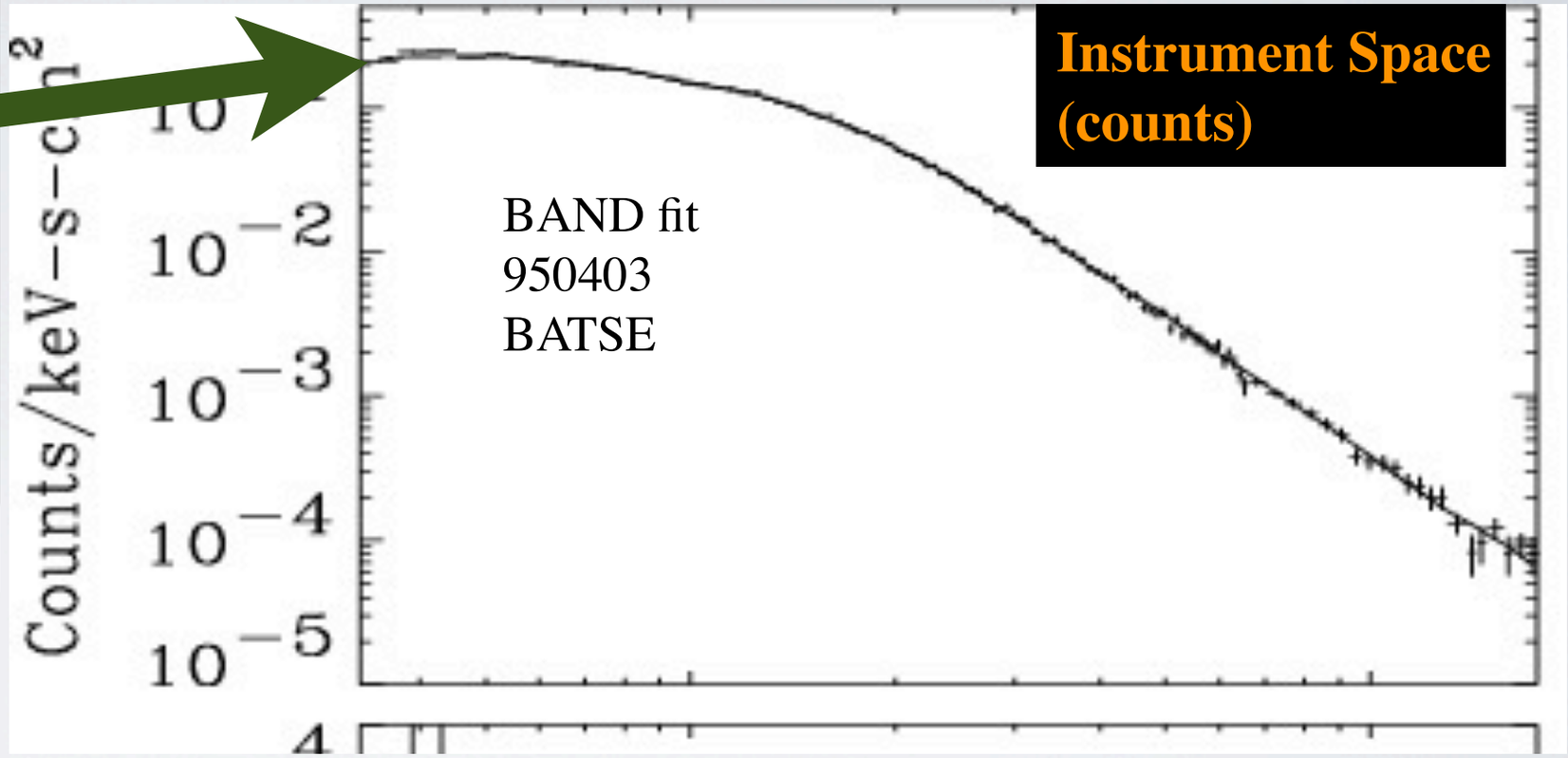
- This is the era of Precision Cosmology
  - Want to measure very subtle effect to < 1 %
  - The more space you sample, the smaller the error
  - **NEED MORE PRECISION!**



Eisenstein? --- not Grossan

FLASHBACK: DO YOU REMEMBER "FROM EMISSION TO DETECTORS LECTURE?





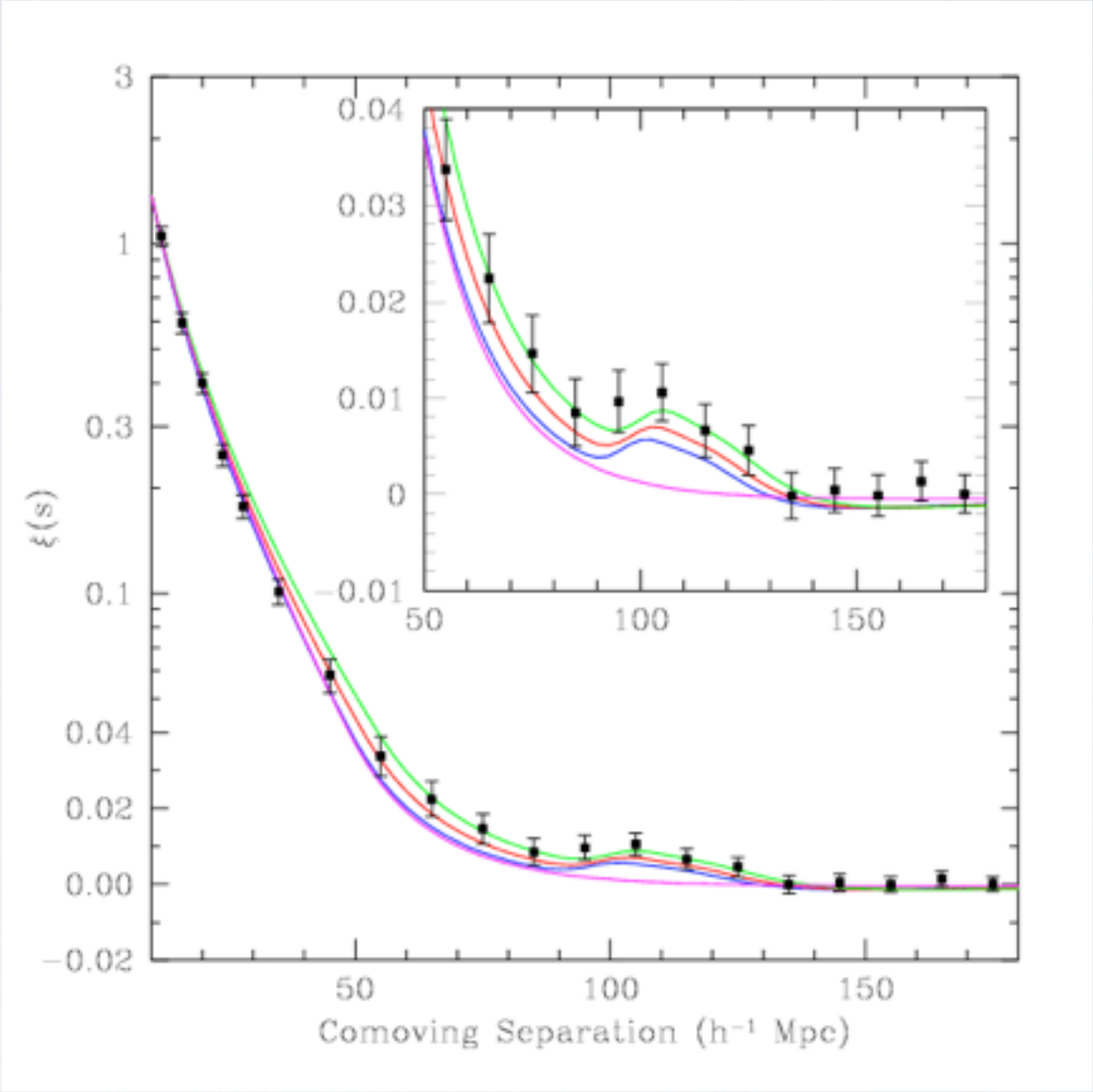
- On the Theory spectrum at left, the various theories are drawn
- On top of the X-ray spectrum at right, in instrumental units (counts observed) we see the ONE theory line that fits --->
- Observations allowed us to measure the spectral parameters

FLASHBACK: APPLIED

- The plot we saw 2 slides back is a great example of this, If theory shows differences in observations, it will allow us to measure the right parameters:

  >Theoretical lines with different parameter values (color) are drawn over observations, here the correlation function (the typical separation observed in the galaxies in the galaxy survey).

>The actual figure shows that, for our error bars, we CANNOT measure what we want (as often happens).



WISH LIST FOR COSMOLOGY

- Dark Energy:
  - BAO z=0 → 3.5
  - Redshift Space Distortions z=0 → 3.5
    - *(Guzzo et al 2008, Blake et al 2011)*

- Particle Physics from Astronomy: Neutrino Masses

- Inflation: Detect Non-Gaussianity

All can be studied with galaxy z-surveys

SURVEYS

- Remember, red shift surveys are 3-D !!!

movie removed, but try
http://www.youtube.com/watch?v=_pDZW-RAXcc

BUT HERE'S WHAT WE NEED...

- Luminous Red Galaxies (20X more than BOSS)

- BAO in Quasar Absorption Lines (15 X BOSS, to z=3)

- Emission Line Galaxies to z=1.6

BUT HERE'S WHAT WE NEED...

- Luminous Red Galaxies (20X more than BOSS)
- BAO in Quasar Absorption Lines (15 X BOSS, to z=3)
- Emission Line Galaxies to z=1.6

Impossible, you would need 10^7 spectra!
...Right?

The Ground-Based Stage IV BAO Experiment

BigBOSS

BigBOSS collaboration

- Brookhaven National Laboratory
- Ewha Womans University, Korea
- Fermi National Accelerator Laboratory
- French Participation Group
  - APC, IAP- Paris; CPP, CPT, LAP Marseille; CEA, IRFU – Saclay
- Johns Hopkins University
- Lawrence Berkeley National Laboratory
- National Optical Astronomy Observatory
- New York University
- The Ohio State University
- Shanghai Astronomical Observatory
- SLAC National Accelerator Laboratory
- Spanish Participation Group
  - IAA, Granada; IAC, Tenerife; ICC, Barcelona; IFT, Madrid; U. Valencia
- UK Participation Group
  - Durham, Edinburgh, UC London, Portsmouth
- University of California, Berkeley
- University of Kansas
- University of Michigan
- University of Pittsburgh
- University of Science and Technology of China
- University of California, Santa Cruz/Lick Observatory
- University of Utah
- Yale University

- Brookhaven National Laboratory
- Ewha Womans University, Korea
- UK Participation Group
  - Durham, Edinburgh, UC London

Update:

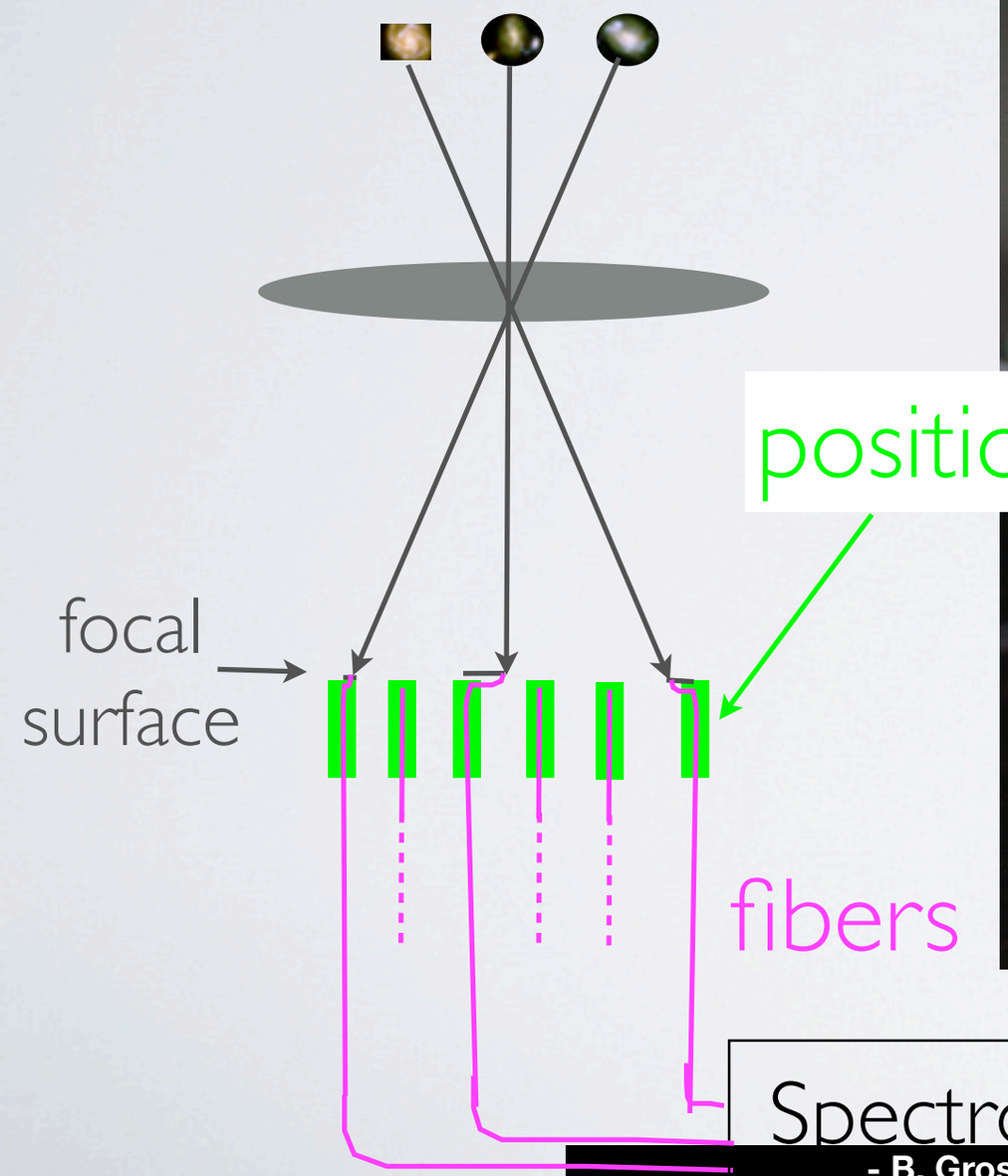
Since all these slides were made, BigBOSS has changed it's name to MS-DESI

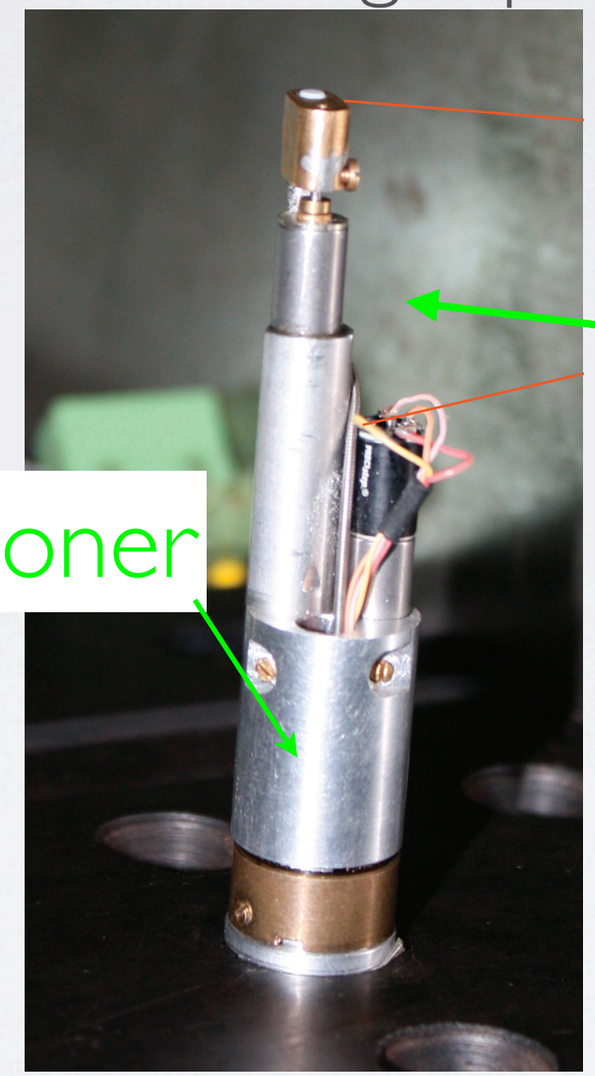
... Medium Scale Dark Energy Spectroscopic Experiment

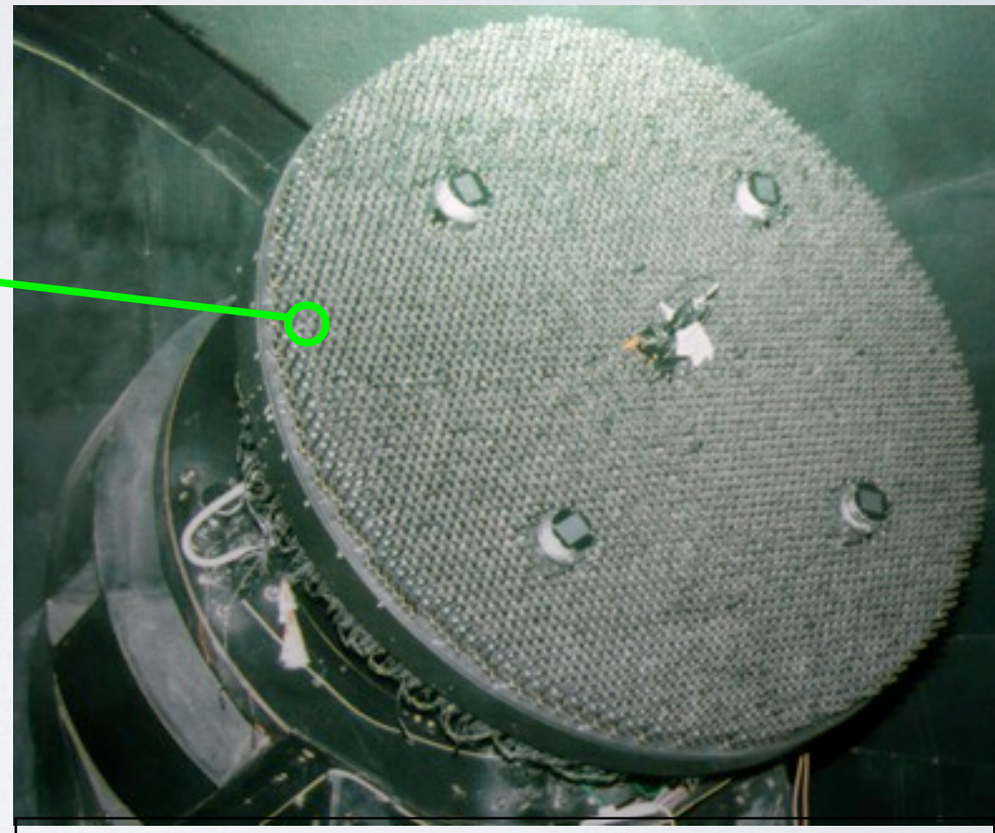
desi.lbl.gov

KEY OF BB INSTRUMENT: 5000 SPECTRA PER POINTING VIA ROBOT POSITIONERS

- 5000 positioners put fiber at target position



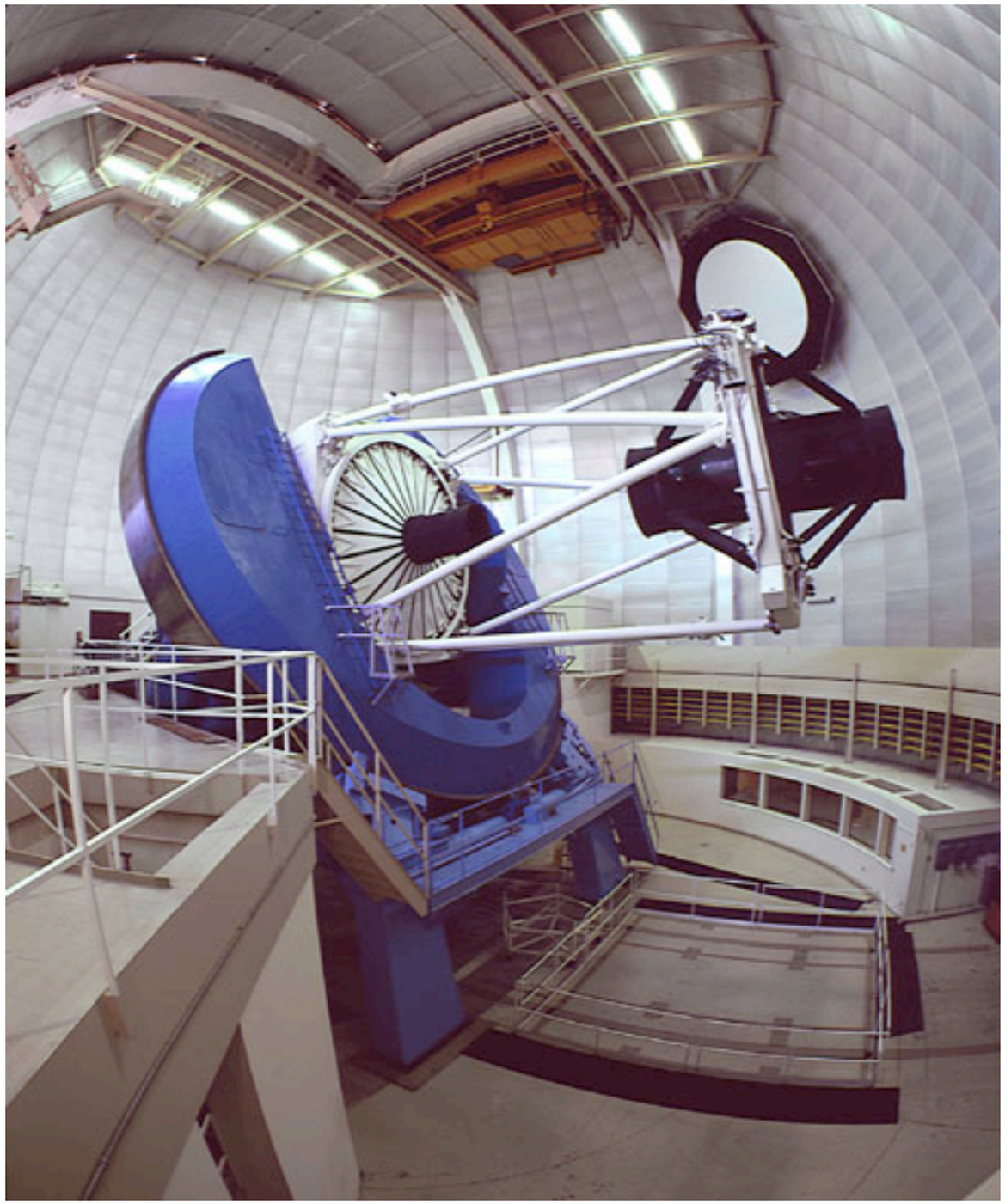




Focal Plane filled with positioners

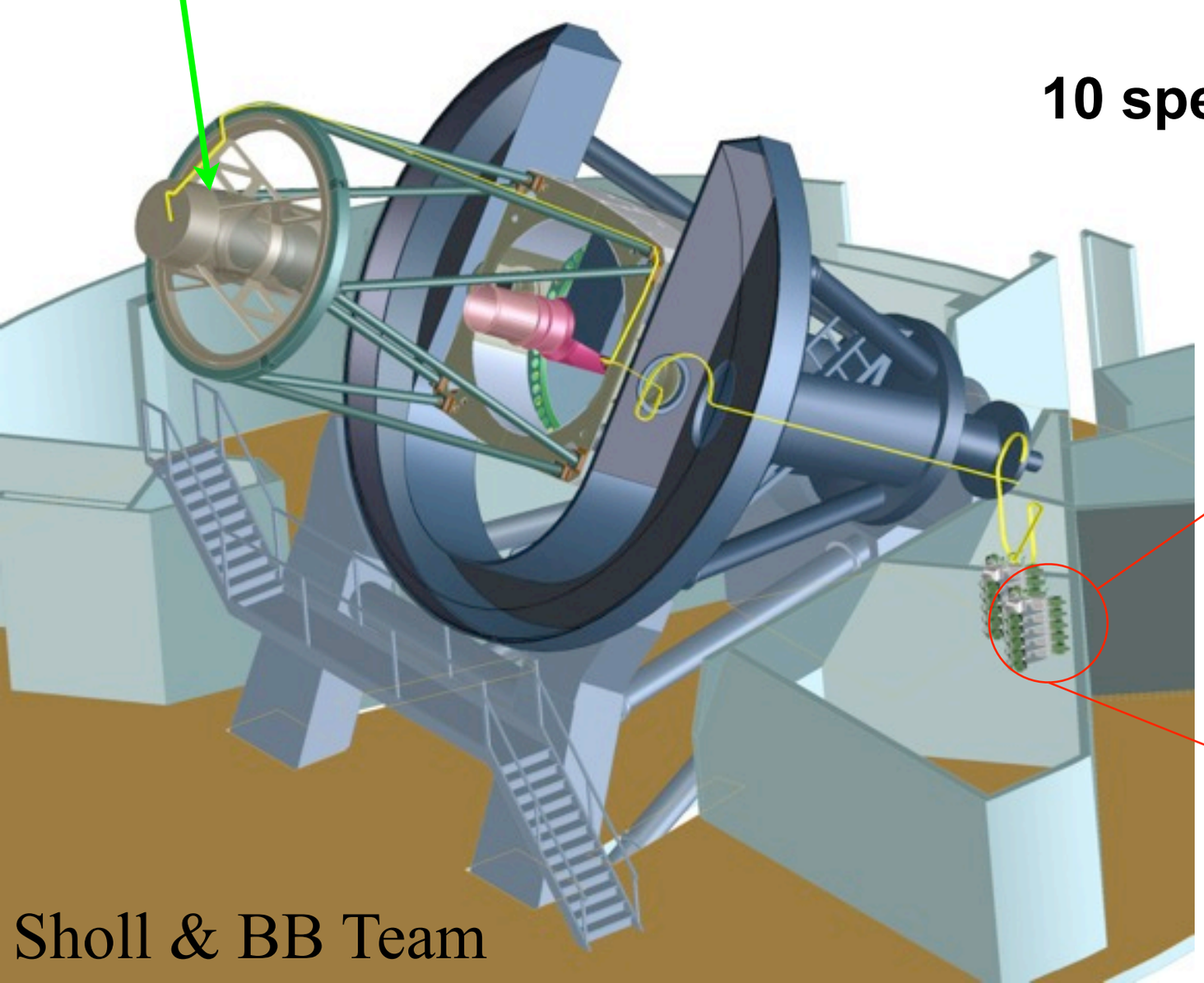
Kitt Peak 4-m (Mayall) at Kitt Peak, Arizona USA today...

Capable of
- holding heavy corrector
- 3 deg. field

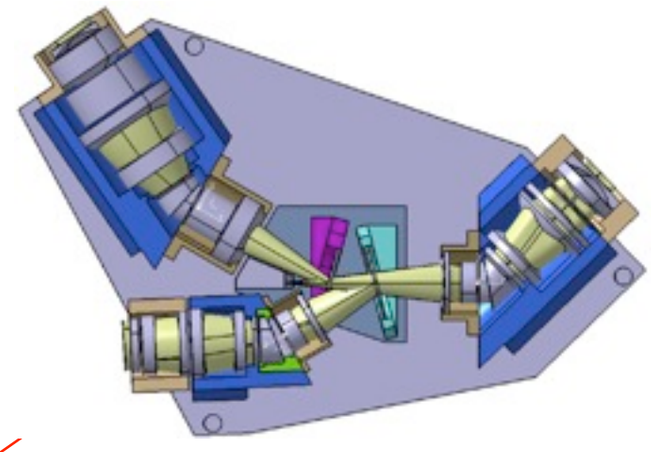


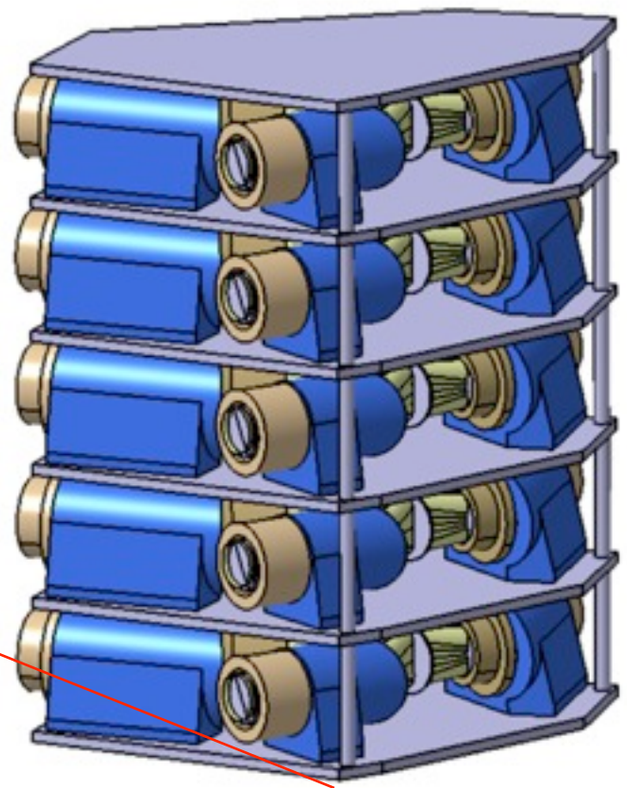
Mayall with BigBOSS

Huge Volume of universe with 3-degree field
5000 robotic fiber positioners
10 spectrographs
15 million spectra!



10 spectrographs

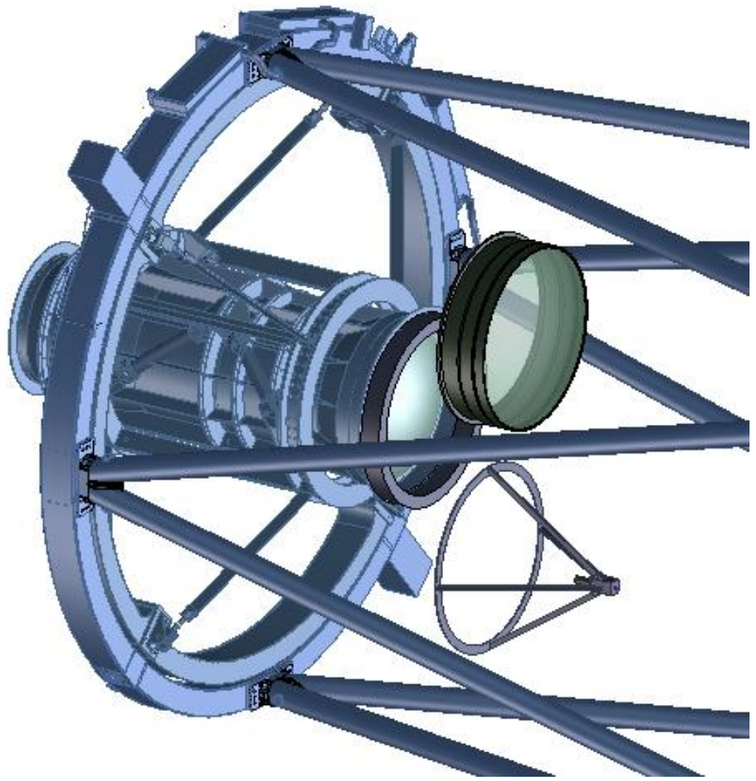


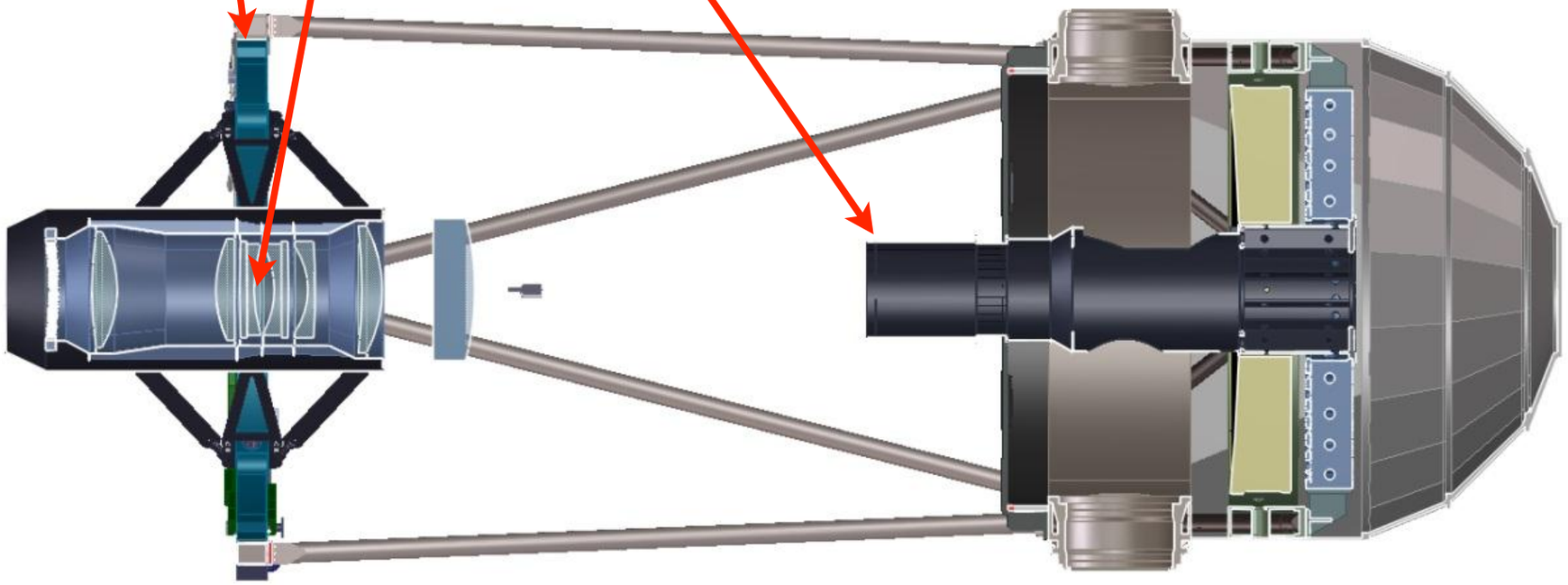


Corrector

The Ground-Based Stage IV BAO Experiment
BigBOSS

- 3 degree field at the focal plate to 5000 fibers on 12 mm pitch.
- Tip-tilt-focus compensation mechanism.
- Atmospheric chromatic dispersion compensator.
- Mount for fiber view camera.
- Mount for f/8 secondary mirror – Cass instruments.





Thanks to FNAL DEC group for Blnaco 4-m mechanical model

The Ground-Based Stage IV BAO Experiment

BigBOSS

BigBOSS project

Construct BigBOSS instrument:

3 deg diameter FOV prime focus corrector
5000 fiber positioner
10x3 spectrographs, 3400-10,600 Ang

Conduct BigBOSS Key Project

495 nights at Mayall 4-m
14,000 deg^2 survey
50,000,000 spectra

- 20,000,000+ galaxy redshifts
- 3,000,000+ QSOs

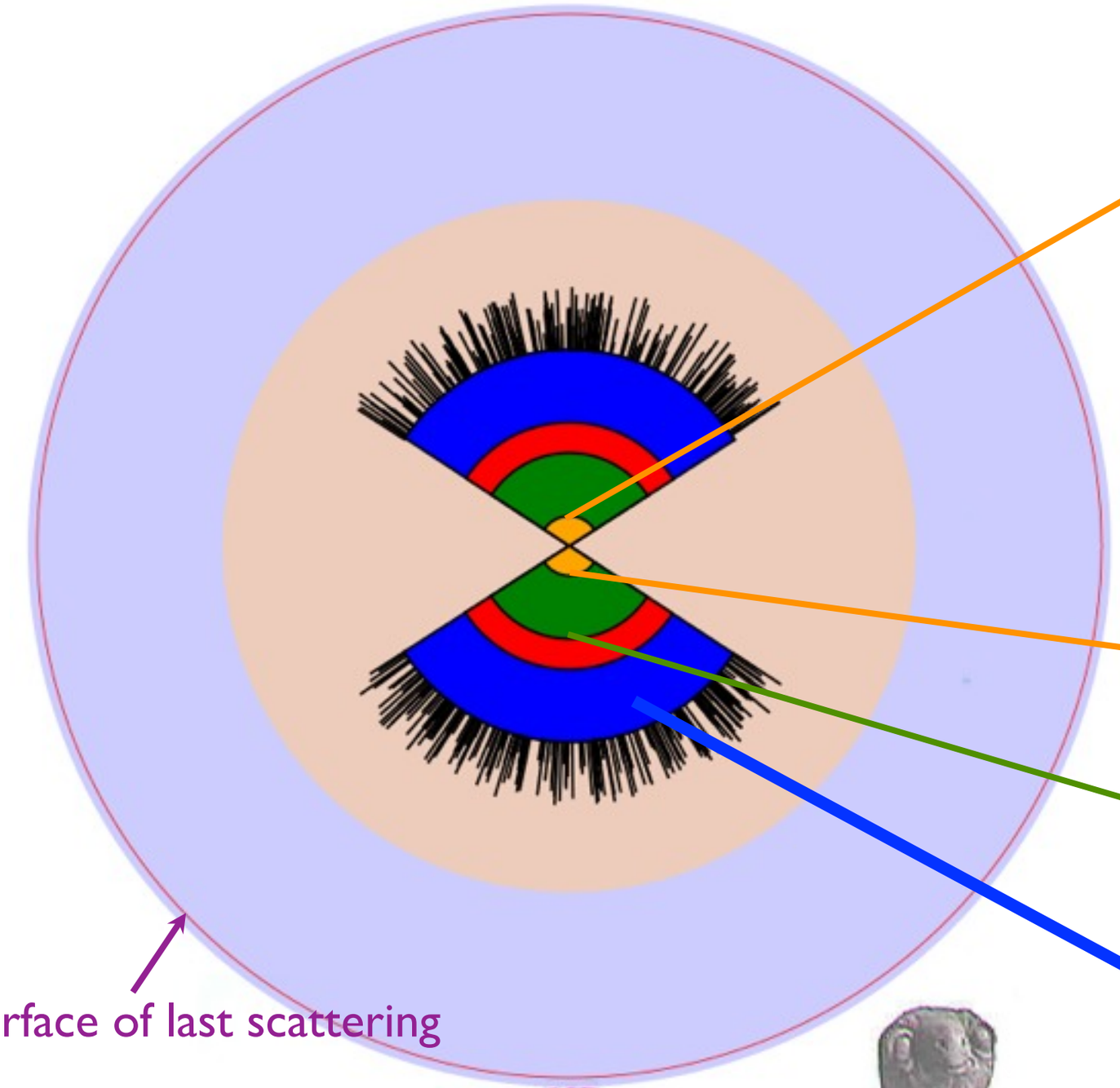
The Ground-Based Stage IV BAO Experiment

BigBOSS

Science Goals: BAO from 20+ million redshifts

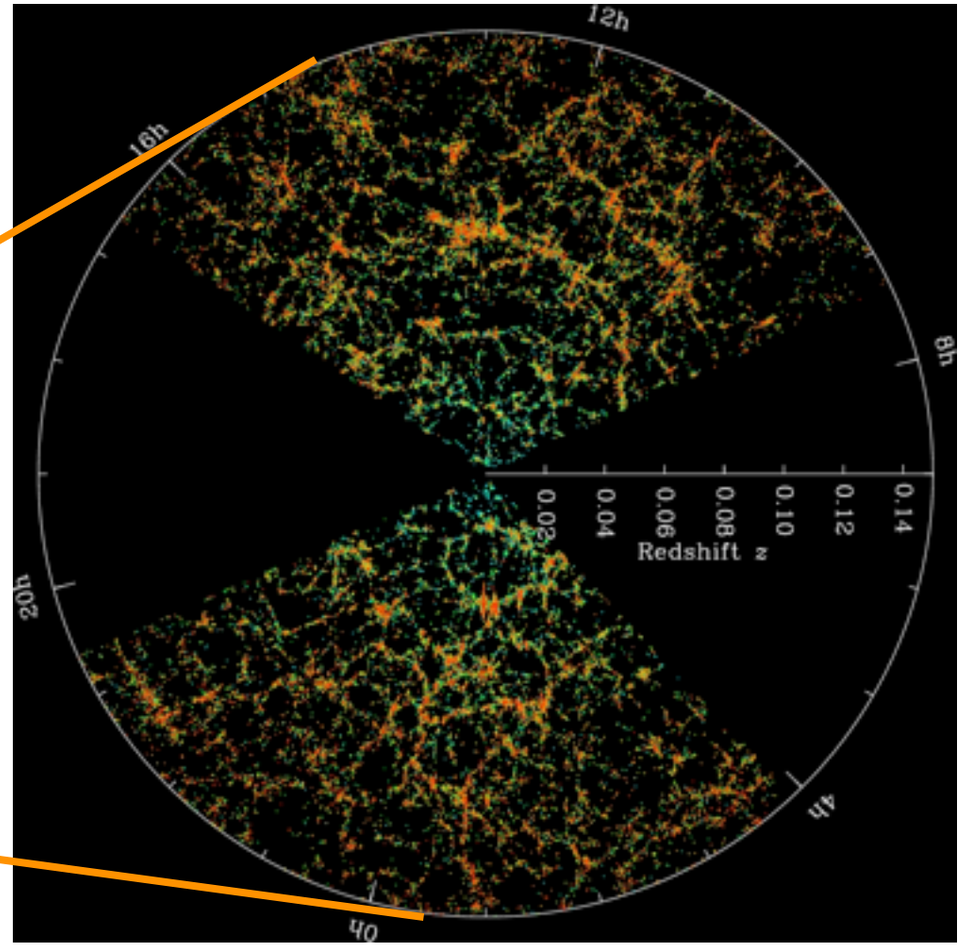
Sensitivity to new physics scales as volume surveys -- # of modes

Our observable Universe



Surface of last scattering

Volume mapped by SDSS + SDSS-II



Volume to be mapped by SDSS-III/BOSS (ca. 2014)

BigBOSS @NOAO

BigBOSS science reach

BigBOSS will enlarge redshift-space maps to 24 million objects

10X larger than SDSS + SDSS-II + BOSS

2.5 million QSOs

18 million ELGs

4 million LRGs

1. Luminous Red Galaxies (LRGs)

LRGs have been the workhorse of BAO surveys (SDSS, BOSS)
All LRG spectra look nearly identical to z~1

Entire spectrum used for redshift,
dominant features are "4000 Angstrom break" and "Ca H+K lines" to z=1.2

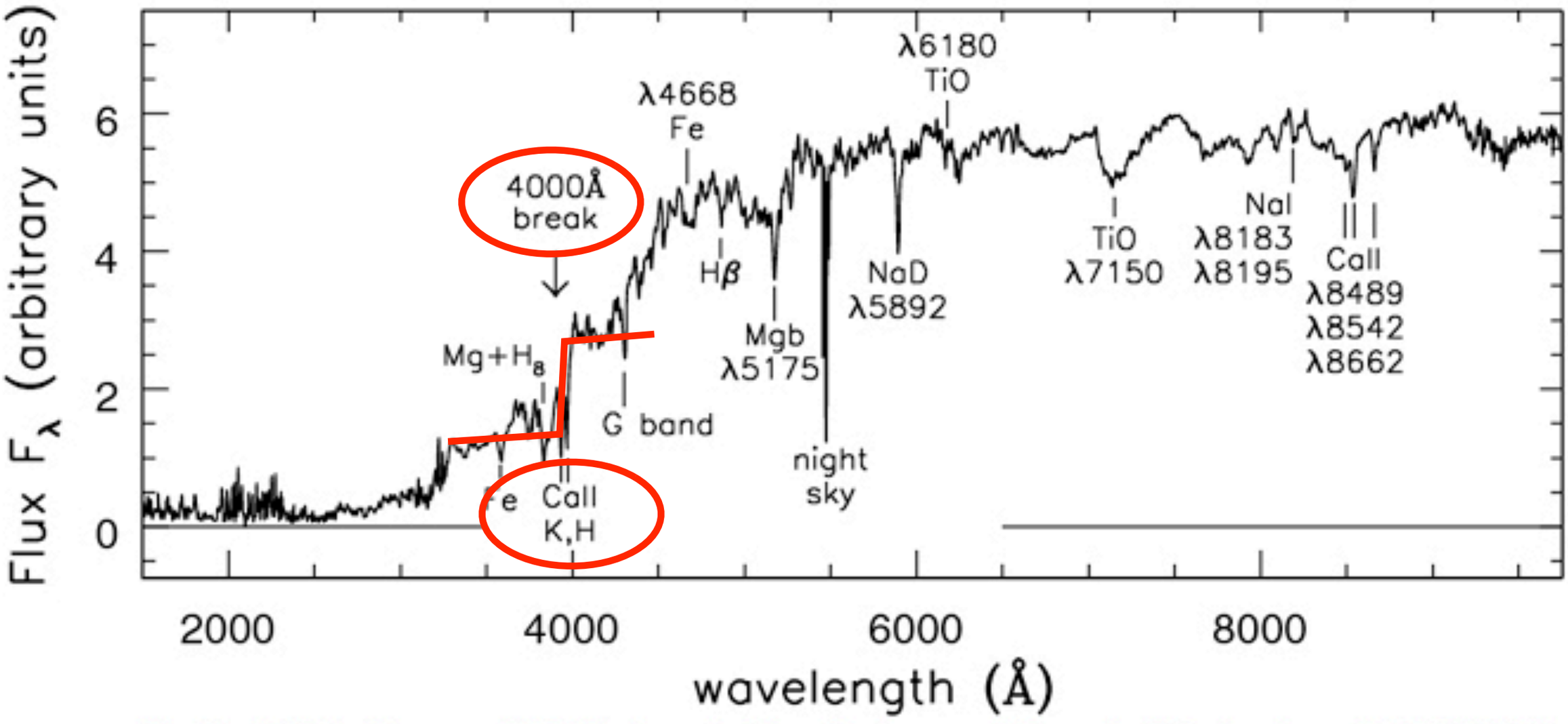


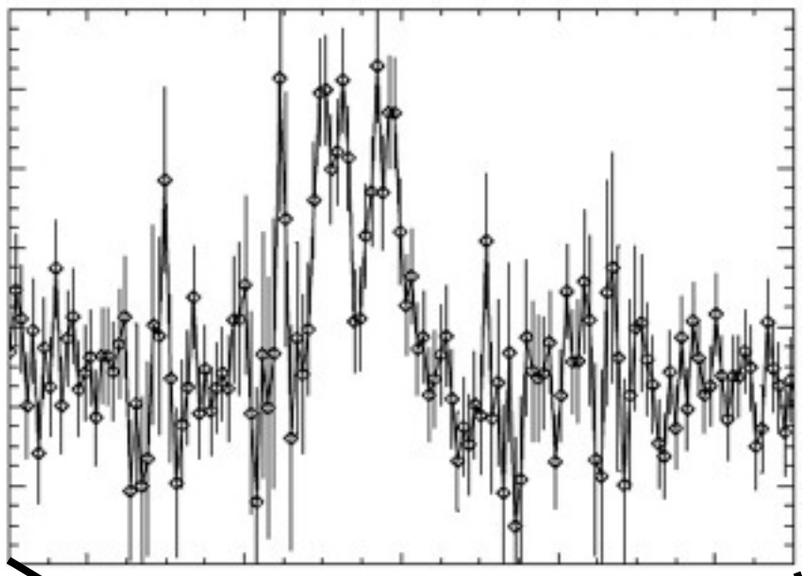
Fig 6.17 (A. Kinney) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

2. Emission Line Galaxies (ELGs)

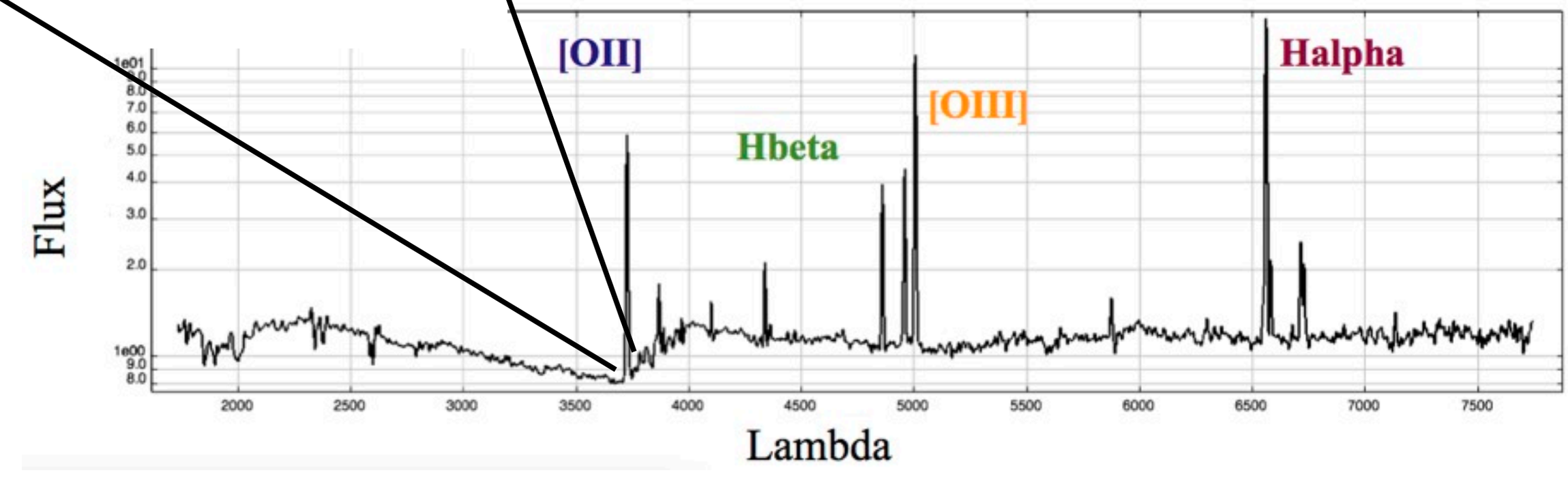
ELGs unique signature of [O II] doublet, detectable from z=0 to z=1.7

Well-studied as the ~5% brightest galaxies in the DEEP2 survey

ELGs drive BigBOSS wavelength coverage, throughput, & resolution

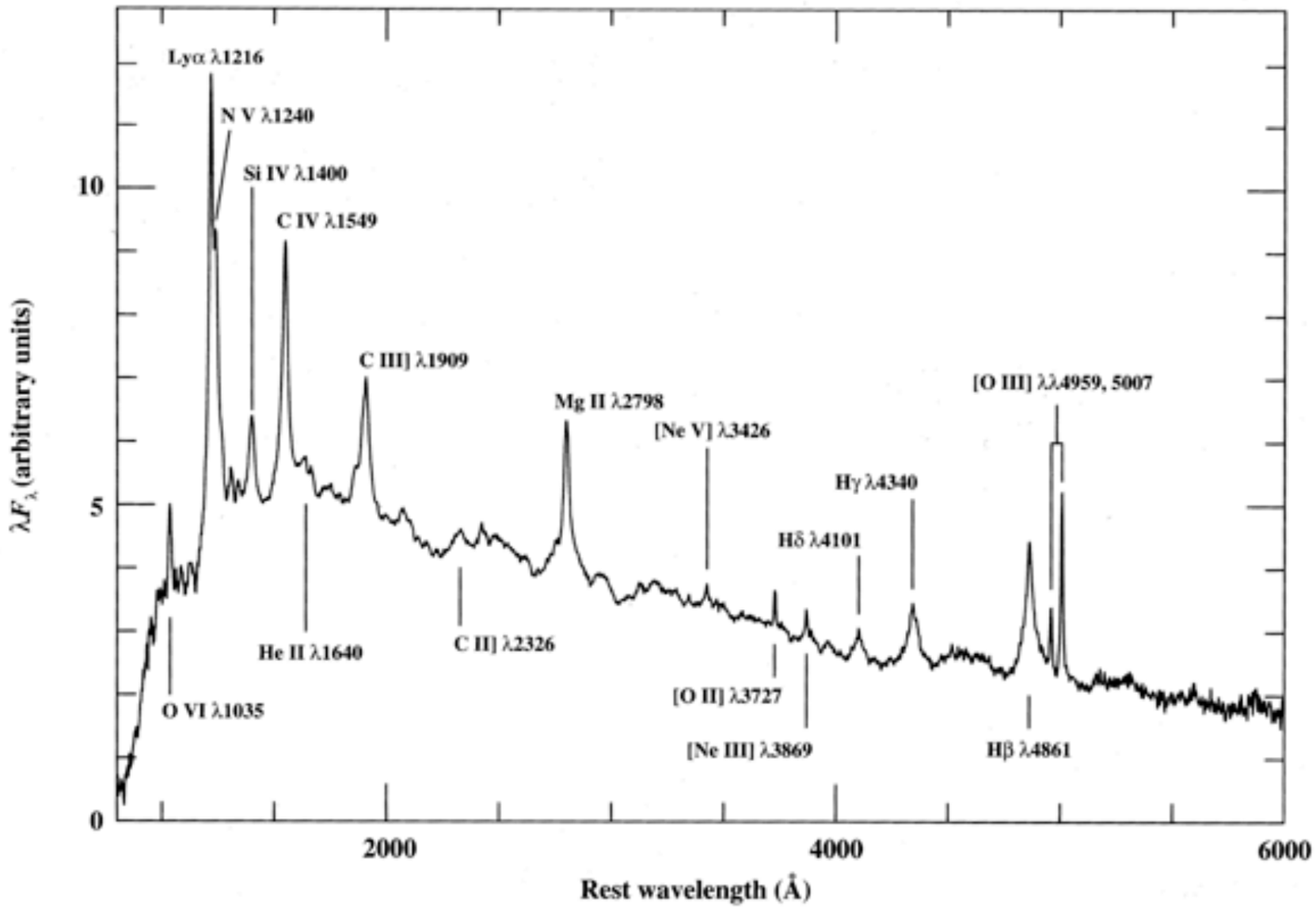


[O II] doublet at 3726.032 + 3728.815 Ang
BigBOSS detects to z=1.6 at 9700 Ang



3. QSOs as tracers

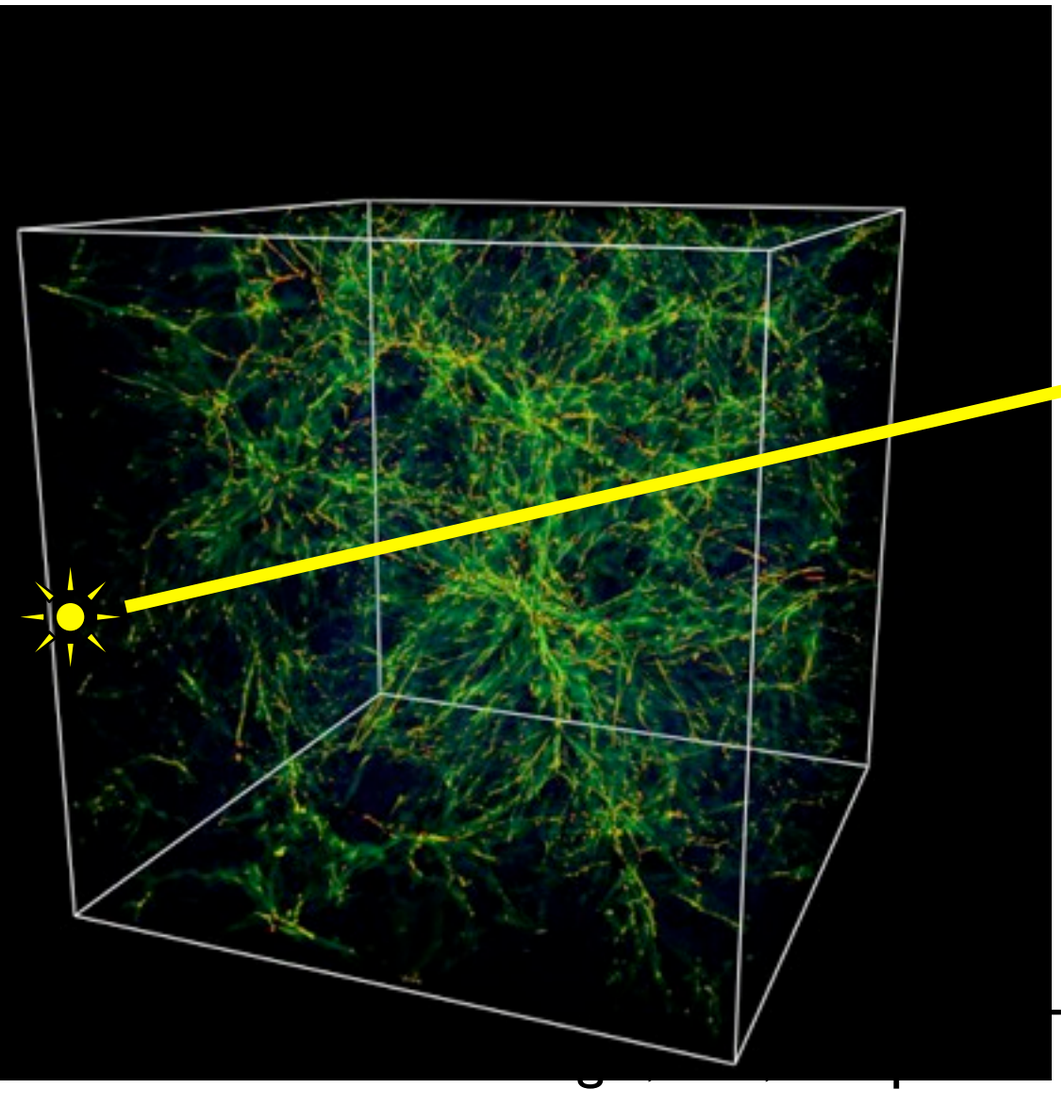
QSO spectra very obvious even at very faint S/N
BOSS survey easily identifies to g=22, BigBOSS will extend to g=23.5

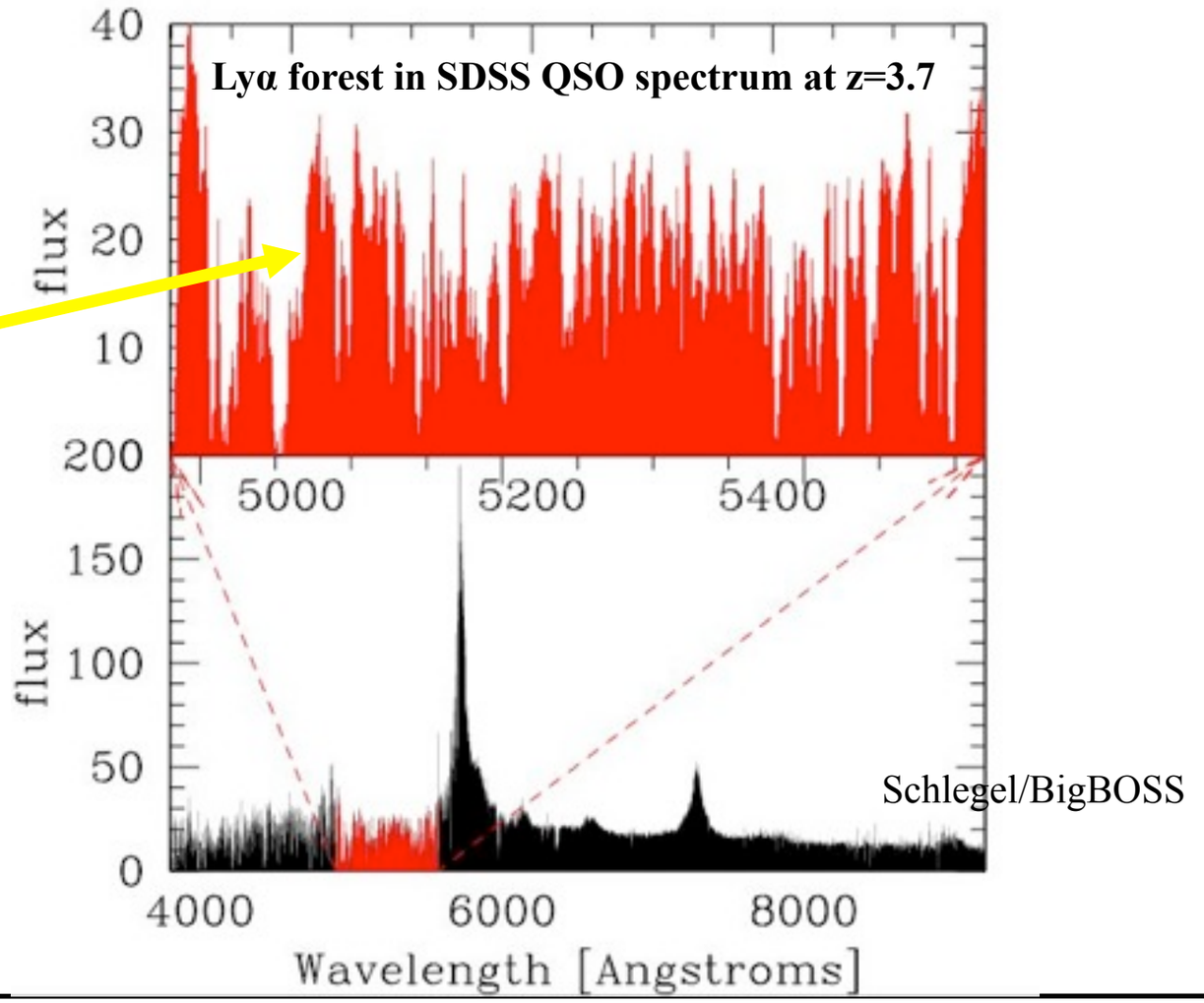


Lya Forest BAO

Two simultaneous spectroscopic surveys from 2009-2014
→ BAO from 1.5 million galaxies at z=0.3, 0.6
→ **BAO from QSOs at 2.2<z<3**

Simulation of the IGM (R. Cen)
Neutral H in 25 h^{-1}Mpc box

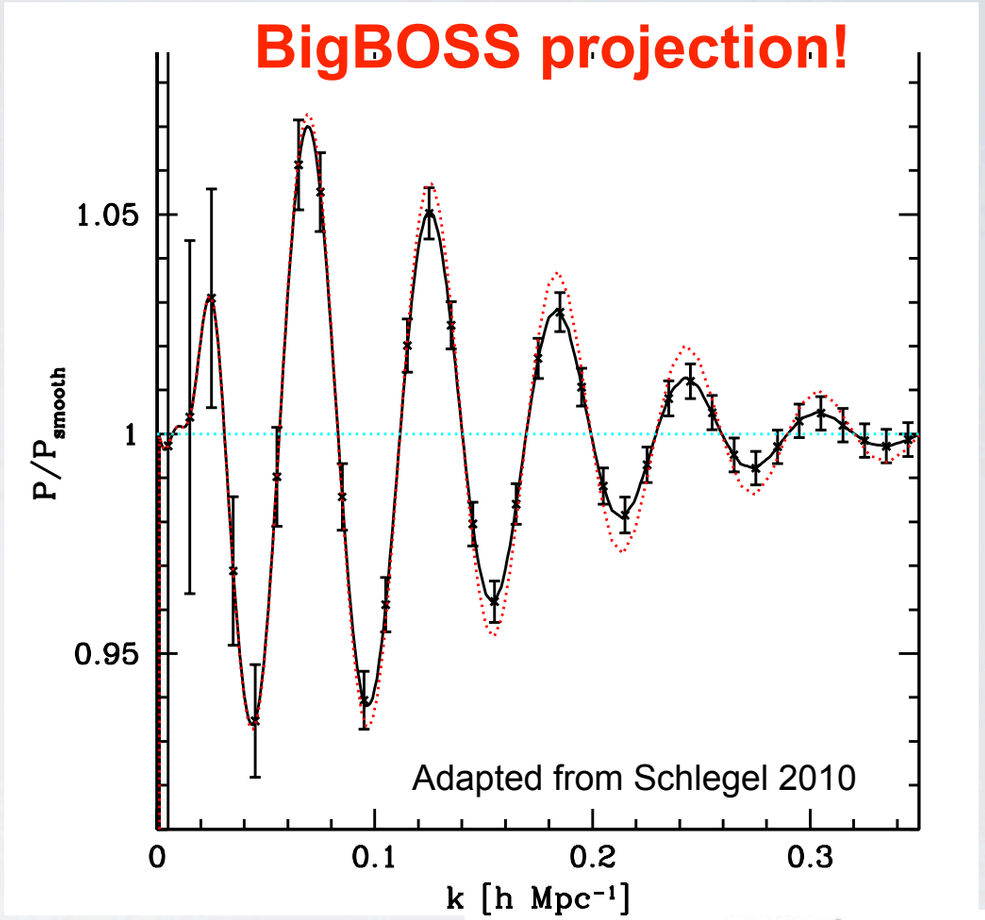


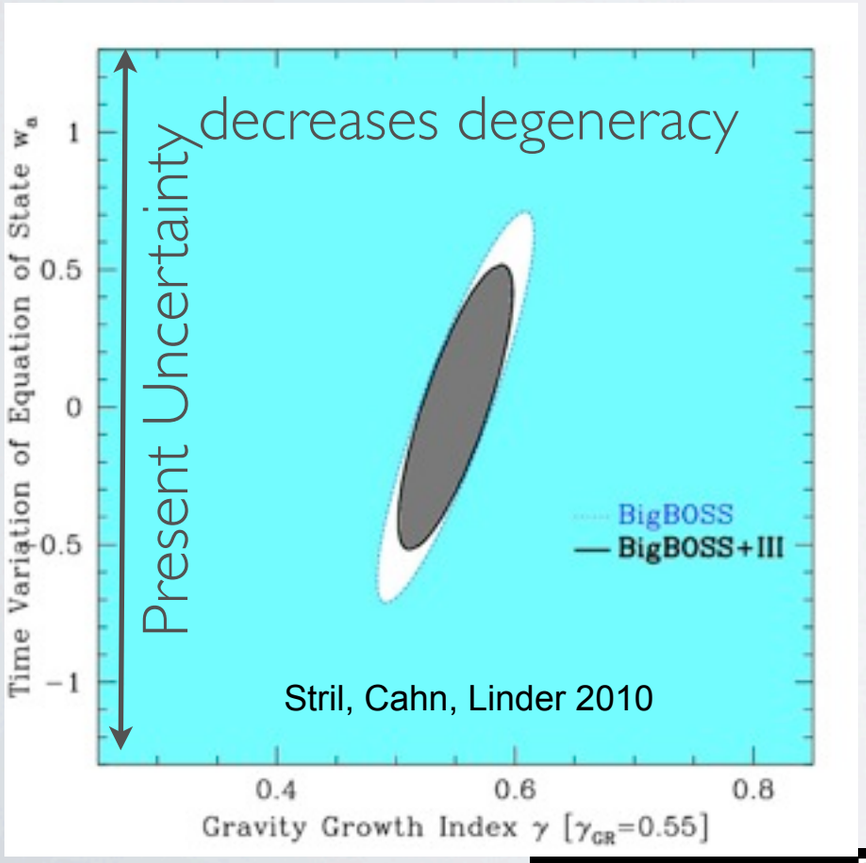


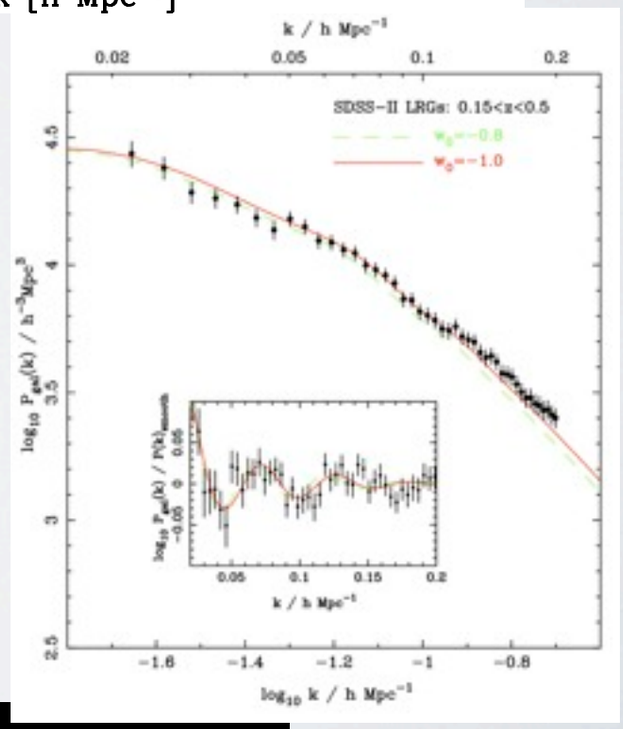
Schlegel/BigBOSS

MEASUREMENTS:DARK ENERGY

- From precise measurements of the power spectrum...
  - W_0 (DE Equation of State Parameter)
  - W_a (derivative; $W_a = 0$ is cosmological constant.)





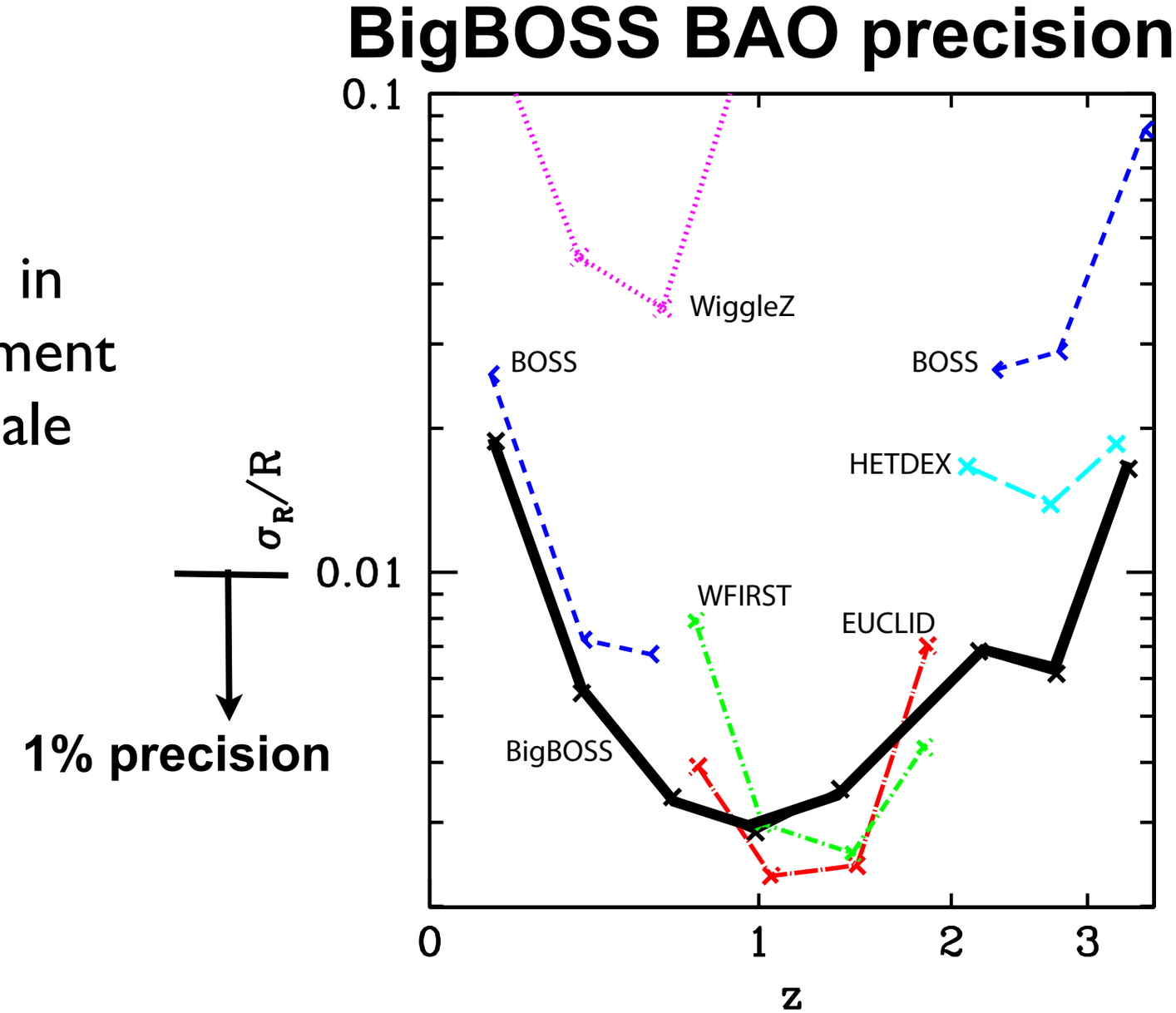


BigBOSS science reach: BAO

Dark energy from Stage IV BAO

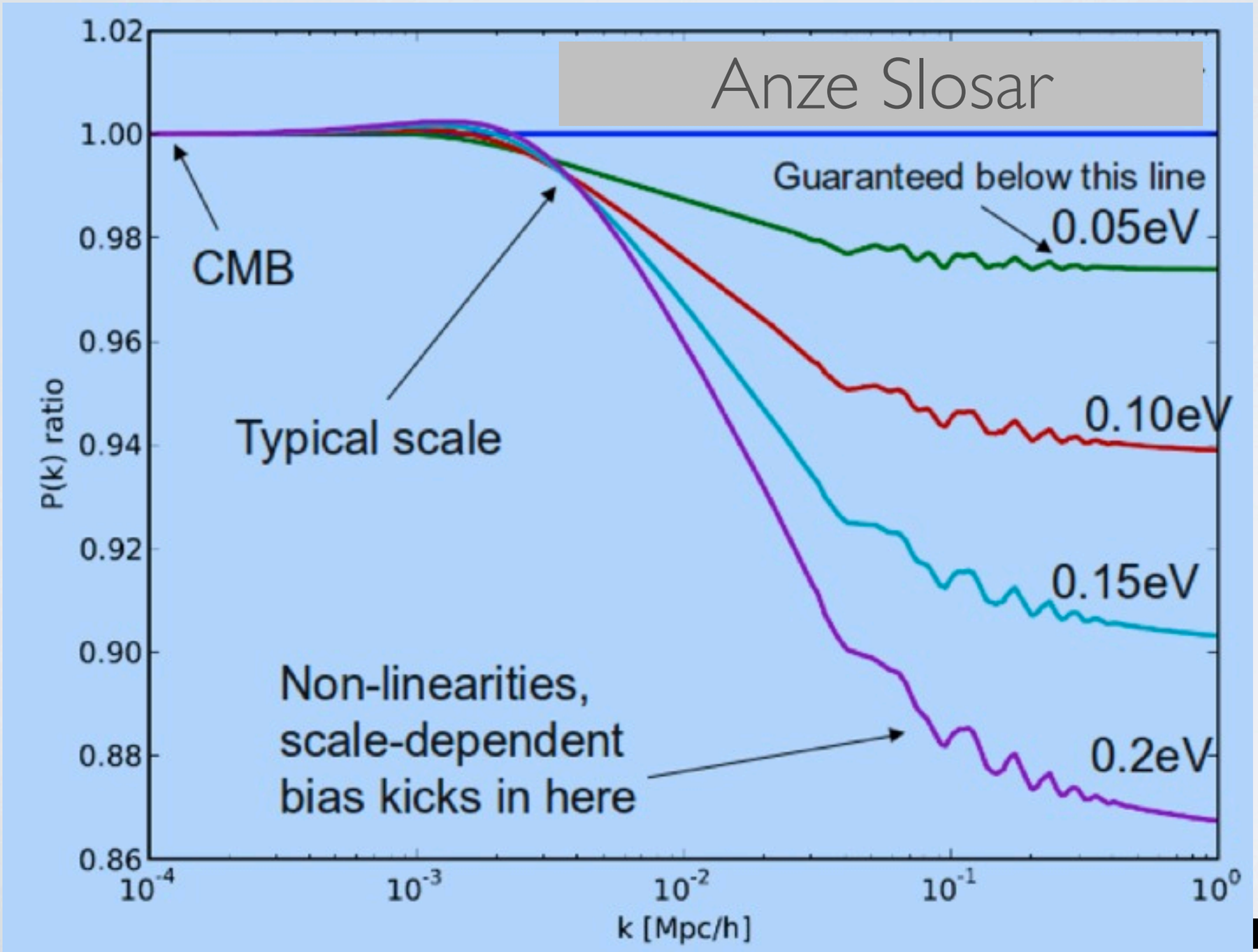
— *Geometric probe with 0.3-1% precision from z=0.5 -> 3*

Precision in measurement of size scale



MEASURE νs VIA POWER SPECTRUM

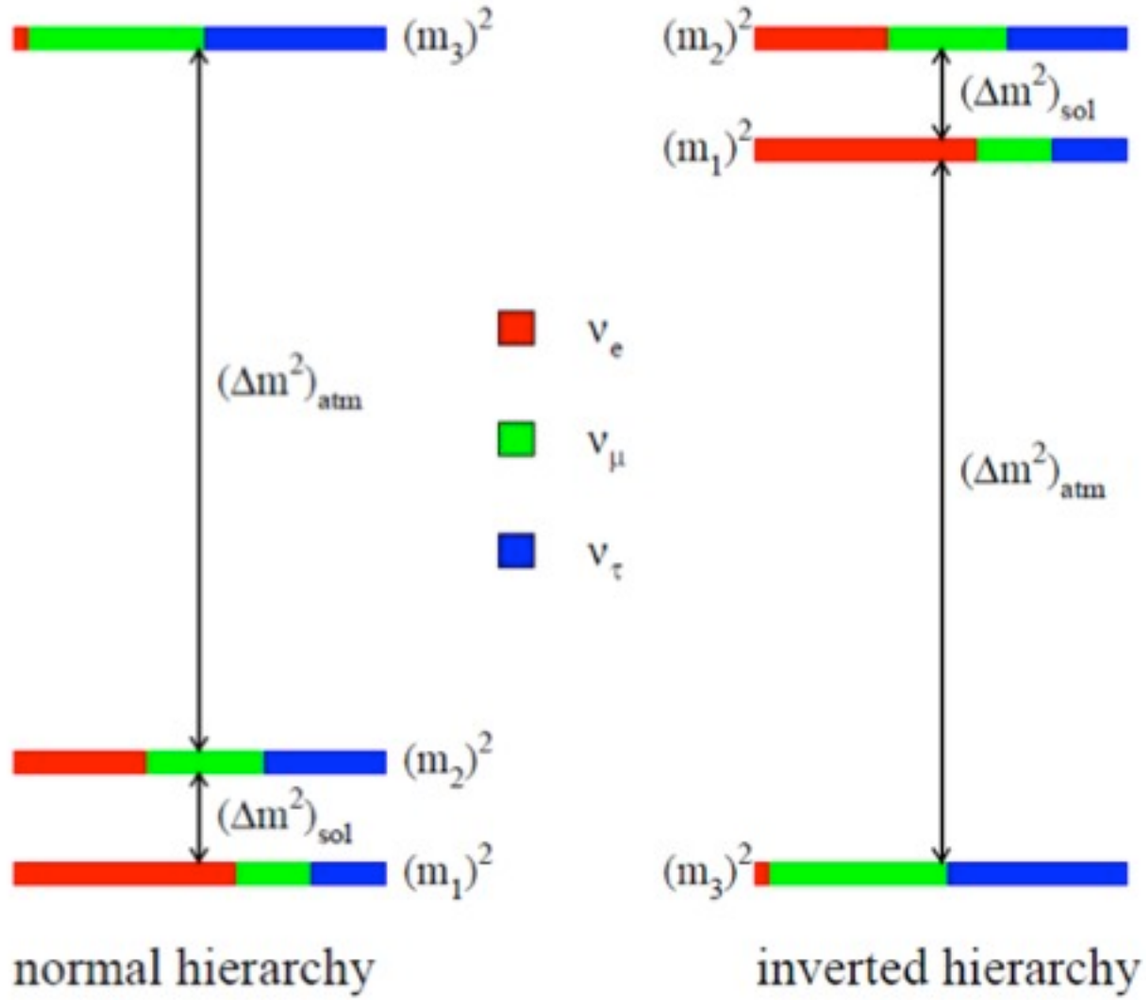
- Ratio of Power Spectra - $P_{with\ \nu}(k)/P_{without}(k)$



Beyond BAO: Neutrino Masses

Terrestrial experiments measure Δm^2 of neutrino masses
BOSS and BigBOSS measure the summed mass

Sensitivity is 0.024 eV
Measured from power spectrum of galaxy map



c.f. Anze Slosar's "Measuring the Neutrino Mass..."

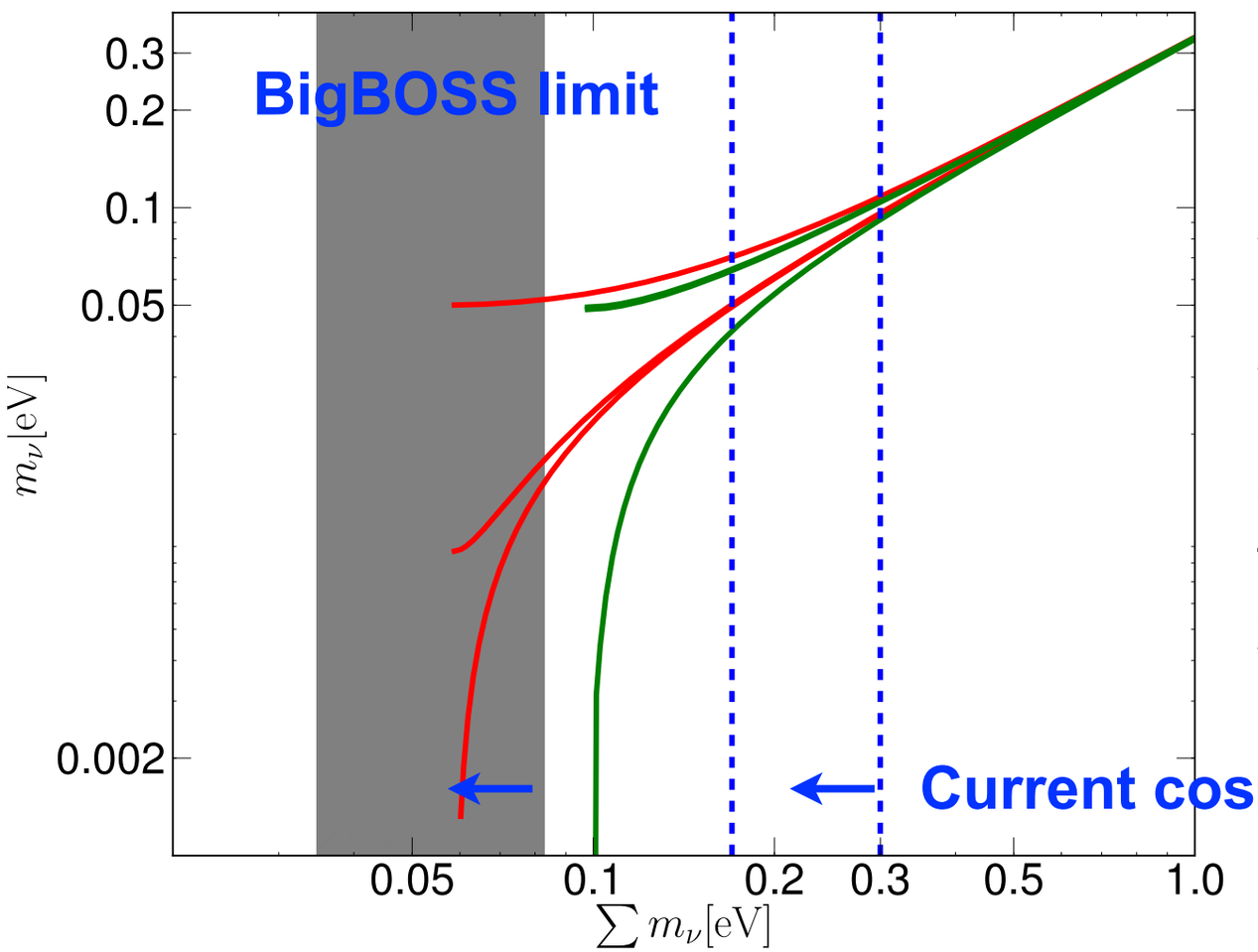
BOSS + BigBOSS: Mapping the linear modes in the un

Here, m_nu is the mass of the lightest nu, because you know the two spacings and total.

Sum of neutrino masses measurable from BAO surveys

Small-scale suppression of galaxy P(k) and QSO LyA

Expect to distinguish normal/inverted hierarchy



Red=Normal hierarchies

Green=Inverted

$\Delta m_{21}^2 = 7.58\times10^{-5}\text{eV}^2$ (KAMLAND)

$\Delta m_{32}^2 = 2.43\times10^{-3}\text{eV}^2$ (MINOS)

Sum of neutrino mass > 0.05 eV for normal hierarchy;
x2 for inverted

Beyond BAO: Inflation

BigBOSS will substantially improve slope of primordial spectrum

Combines with Planck

Significance will depend upon number of modes in BigBOSS (k_{max})

$$P(k) \propto (k/k_0)^{n_s + \frac{1}{2}\alpha_s \ln(k/k_0)}$$

BigBOSS will have high sensitivity to non-Gaussianities in the early Universe

Planck sensitivity f_{NL}=5, BigBOSS f_{NL}=3.9

Bispectrum of BigBOSS may improve this further

$$\Phi = \phi + f_{\rm NL}\left(\phi^2 - \left\langle\phi^2\right\rangle\right) + \ldots$$

Experimentally:
term in P(k) ~ $(1+k^{-2})$

c.f. Pat McDonald: "Projections..."

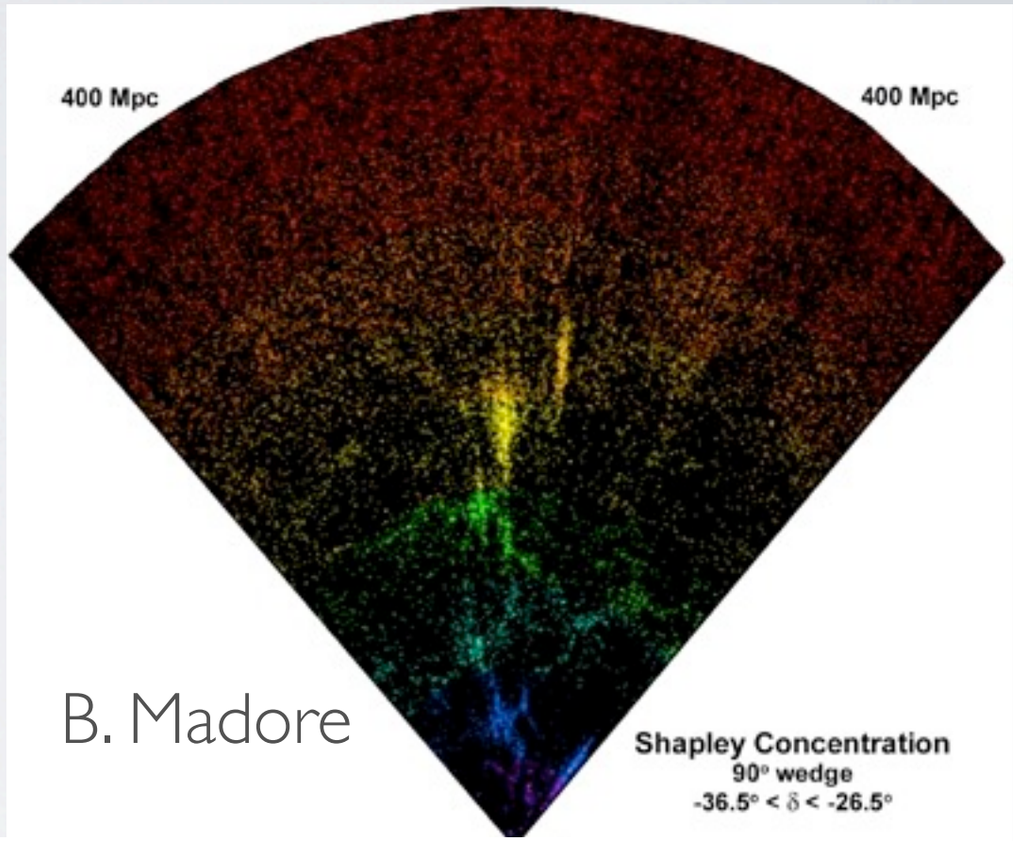
REDSHIFT SPACE DISTORTIONS

> *(Guzzo et al 2008, Blake et al 2011)*

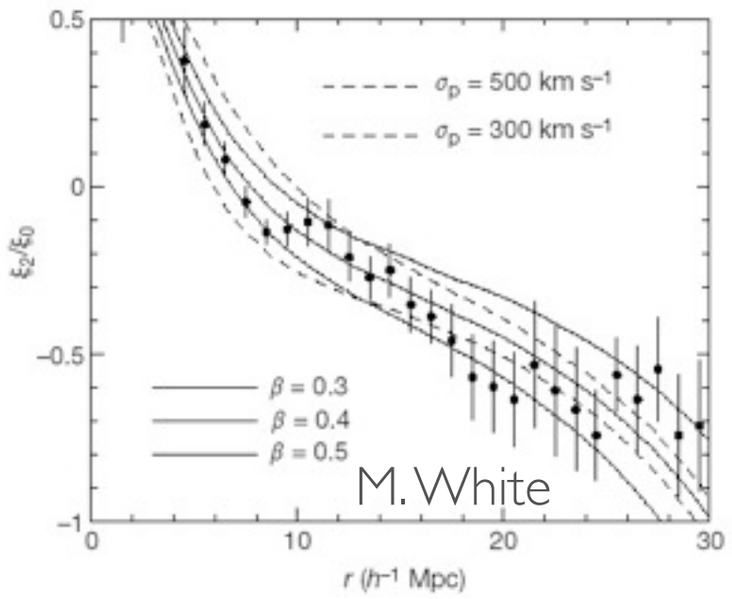
- Small Scale: clusters elongated in z direction
  - "finger of god" effect
  - random peculiar velocities on top of expansion

- Kaiser Effect - larger scales
  - non-random, coherent infall velocities

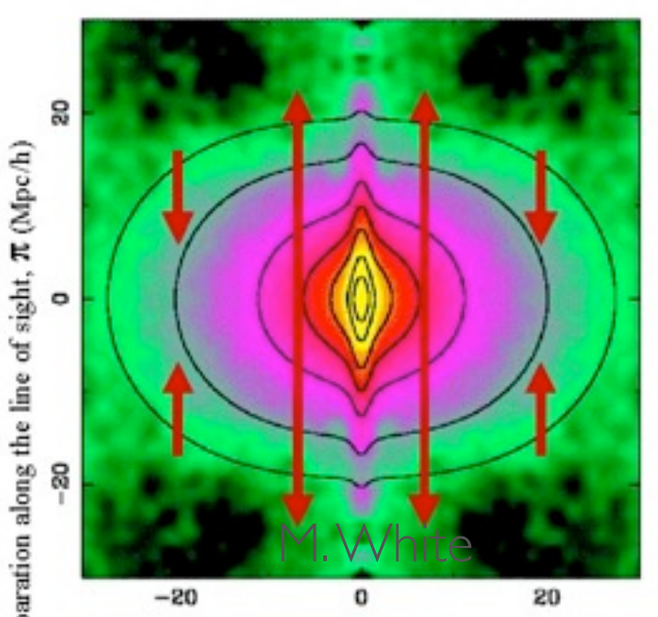
- Difference in correlation function ∥ vs. ⊥ to line of sight ⇒ ratio *very* sensitive to cosmological parameters.



B. Madore



M. White



M. White

Linder et al.: 1105.1194, 1109.1846
Reid & White: 1105.4165
Seljak, McDonald et al: 1109.1609, 1109.1888
Saito et al.: 1006.0699, 1101.4723

BigBOSS Stage IV science reach

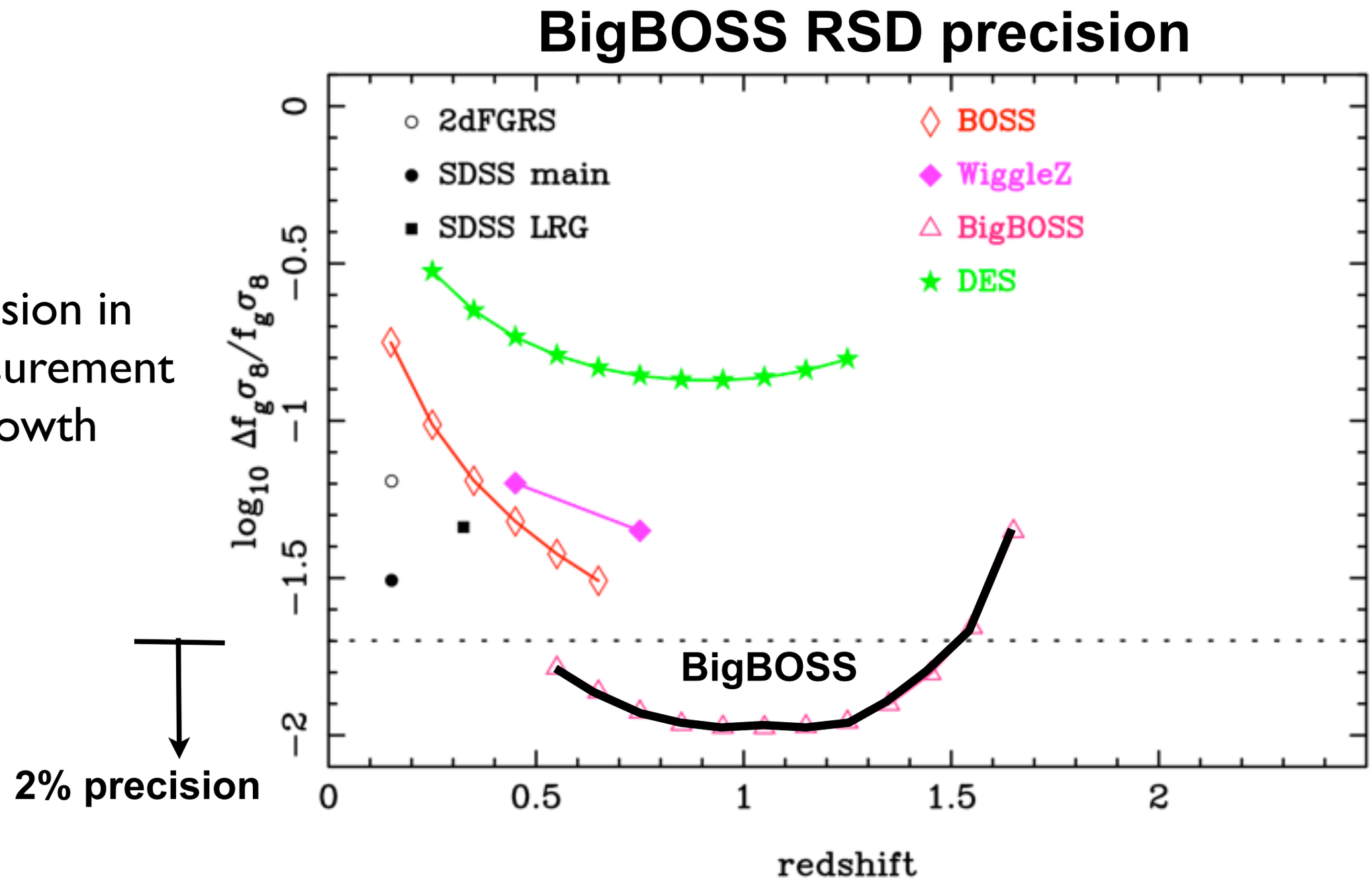
Um... what are those vertical axis units/??

Growth Rate=how quickly d delta rho/ dlog a

Dark energy from Stage IV RSD

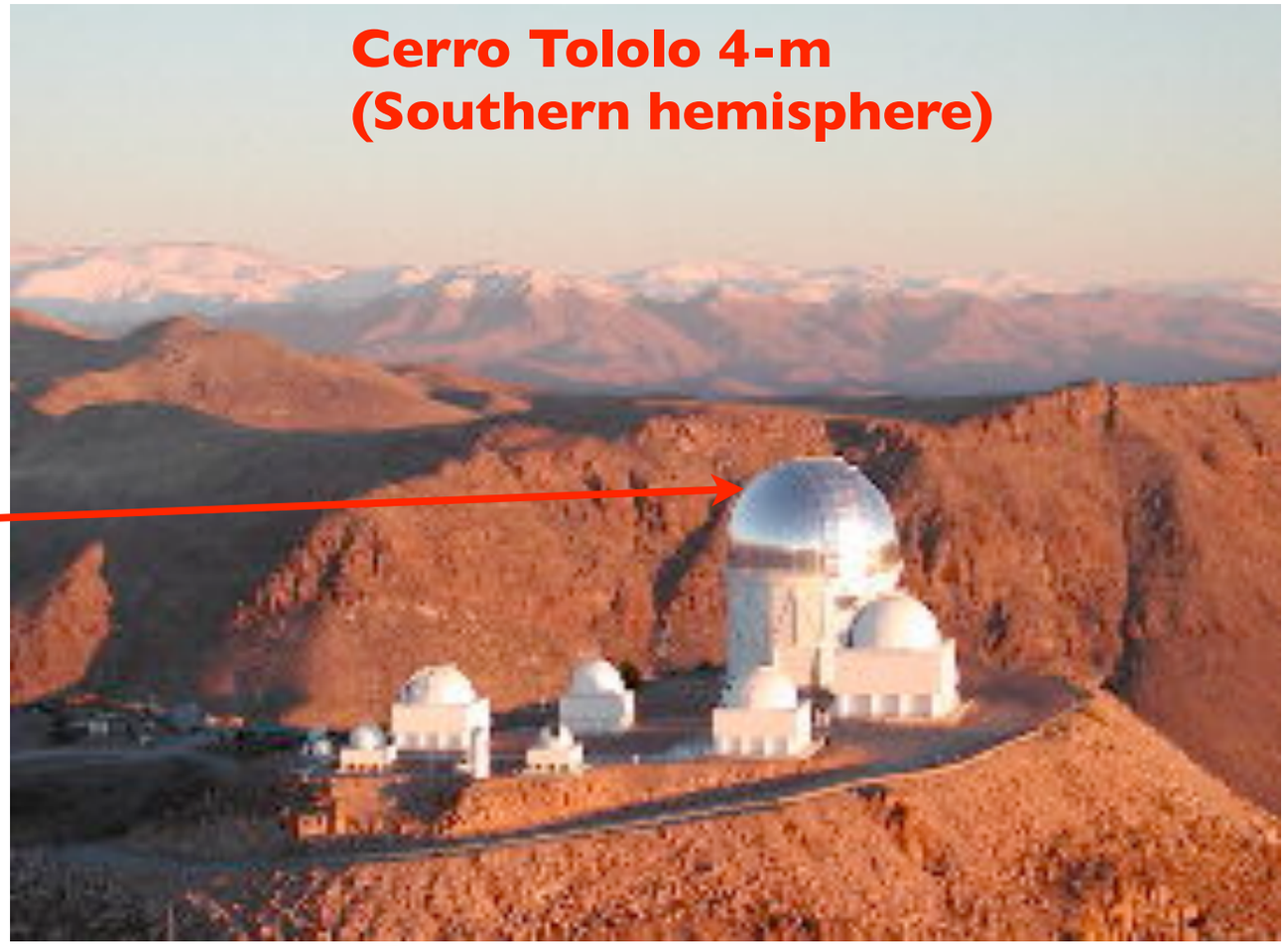
— *Gravitational growth with 2% precision from z=0.5 -> 1*

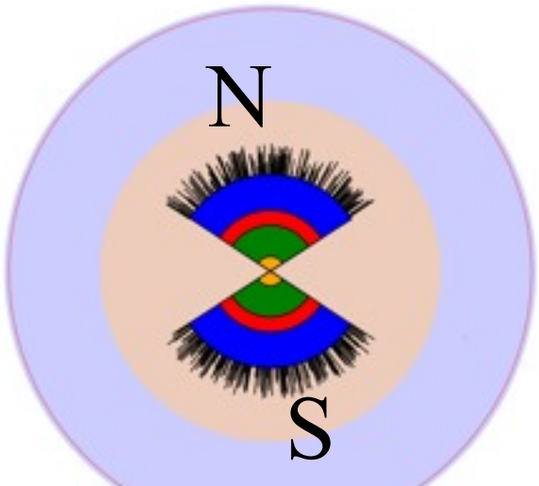
Precision in measurement of growth rate



BigBOSS "full-sky" possible

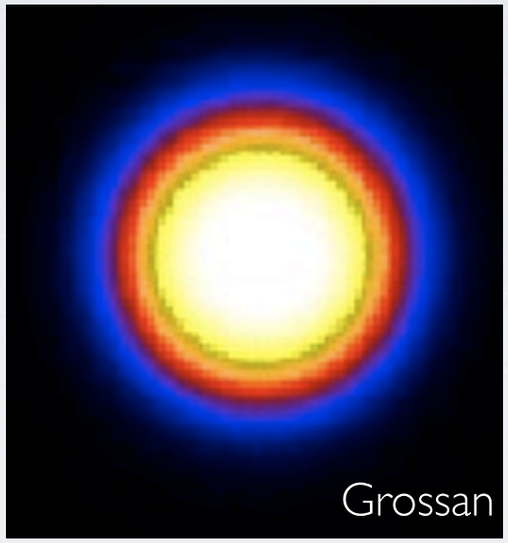
- "Full-sky" survey possible by moving instrument south after 2020

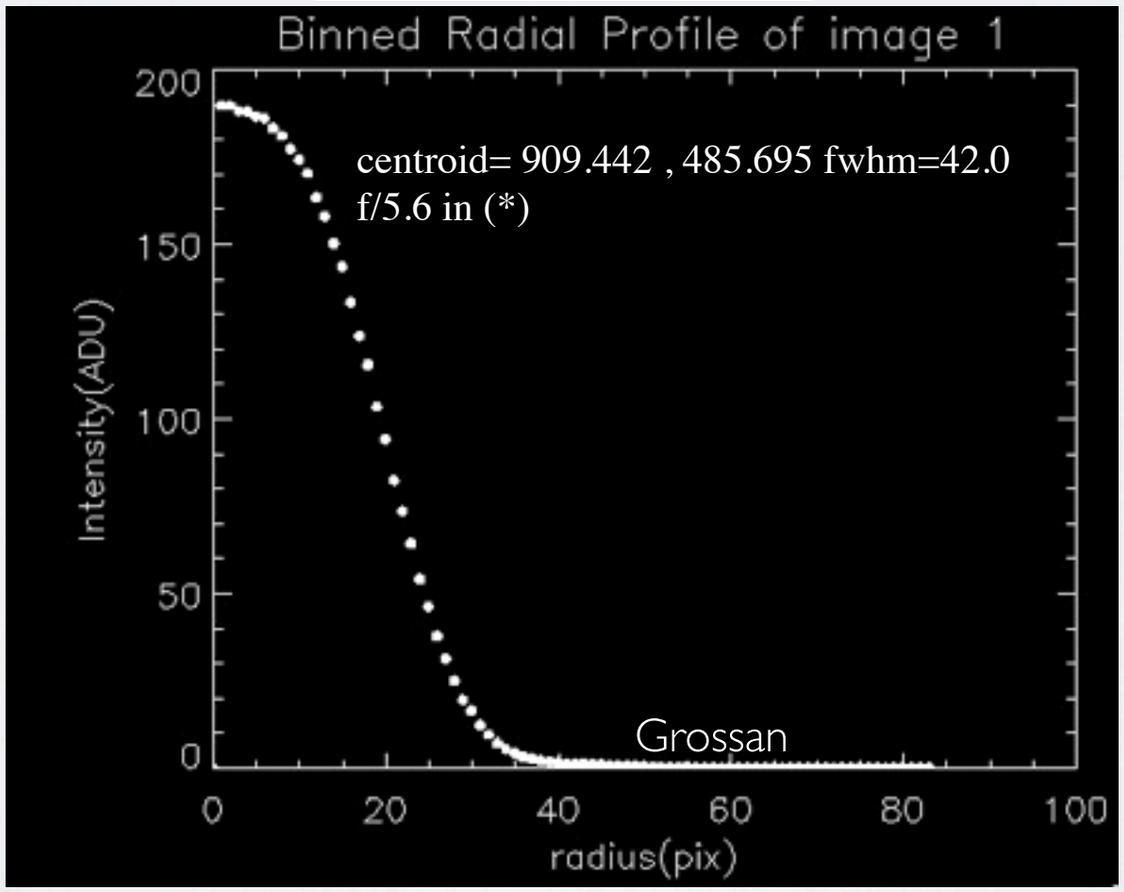




OPTICAL FIBERS CRITICAL

- See Lecture on Measuring Optical Fiber Performance!





Summary

BigBOSS designed as BAO+RSD stage IV

— 20 million galaxies + 2.5 million QSOs

— BAO: Geometry, 1% precision from z=0.5 →1.6 and z=2→3

— RSD: Gravitational growth, 2% precision @ 5 redshifts

— Neutrino masses at 0.024 eV

— Inflation probe using more modes than Planck

BigBOSS is a stage IV experiment to deliver by 2020

—Won't get started for a few years; you could think about working on it!

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END

- THANKS!