Cosmological surveys

Lecture 1

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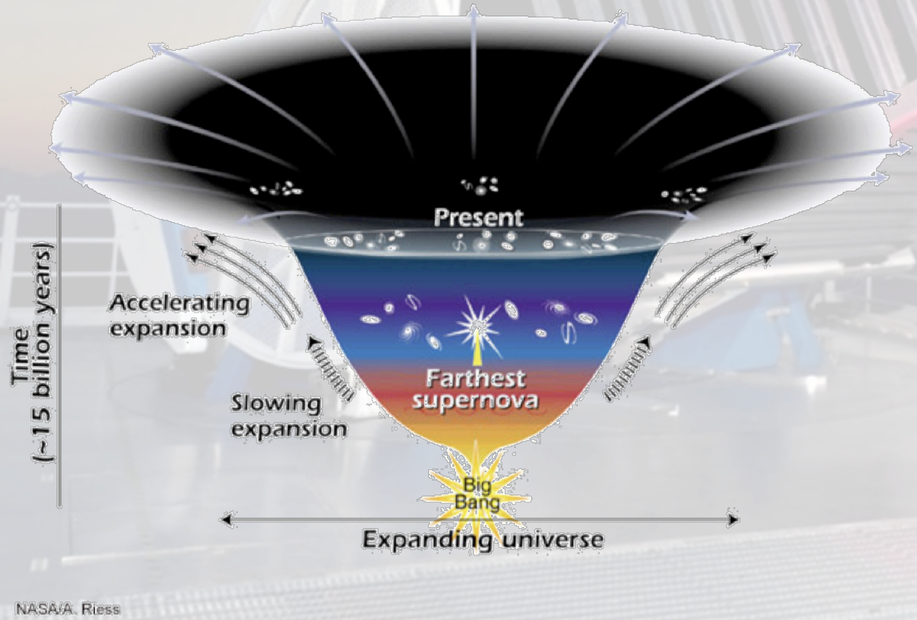
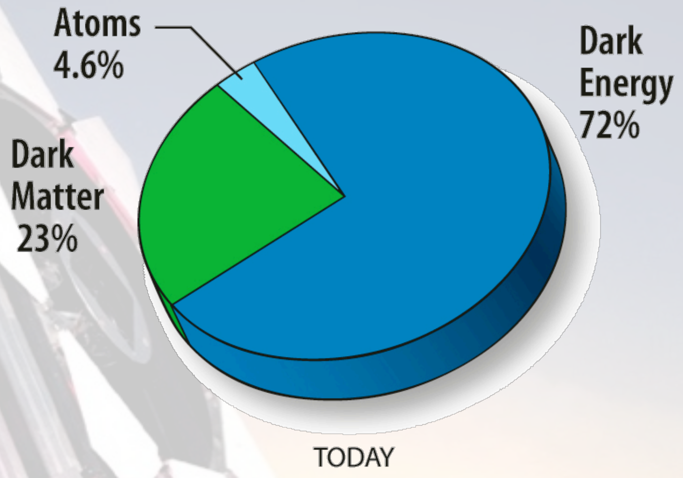
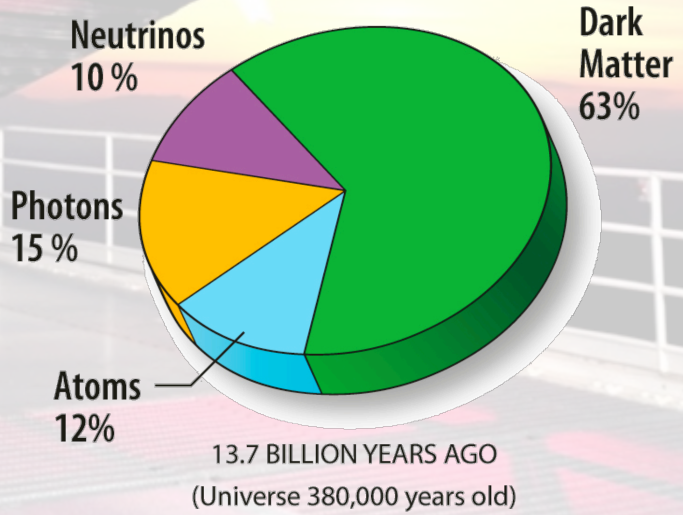
The standard “model” for cosmology

$$\frac{H^2}{H_0^2} = \Omega_R a^{-4} + \Omega_M a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda$$

$$\frac{H^2}{H_0^2} = \Omega_M a^{-3} + (1 - \Omega_M)$$







The problem of Λ

ΛCDM fits all (believable?) current data well
It's the simplest (mathematical) model available
But … we cannot explain Λ with physics

- why so small?

$$\rho_\Lambda|_{\rm obs} = \frac{\Lambda}{8\pi G} \sim (10^{-3}\,{\rm eV})^4$$

$$\rho_\Lambda|_{\rm theory} \sim (M_{\rm new\ physics})^4 \sim (1\,{\rm TeV})^4 >> \rho_\Lambda|_{\rm obs}$$

- why so fine tuned?

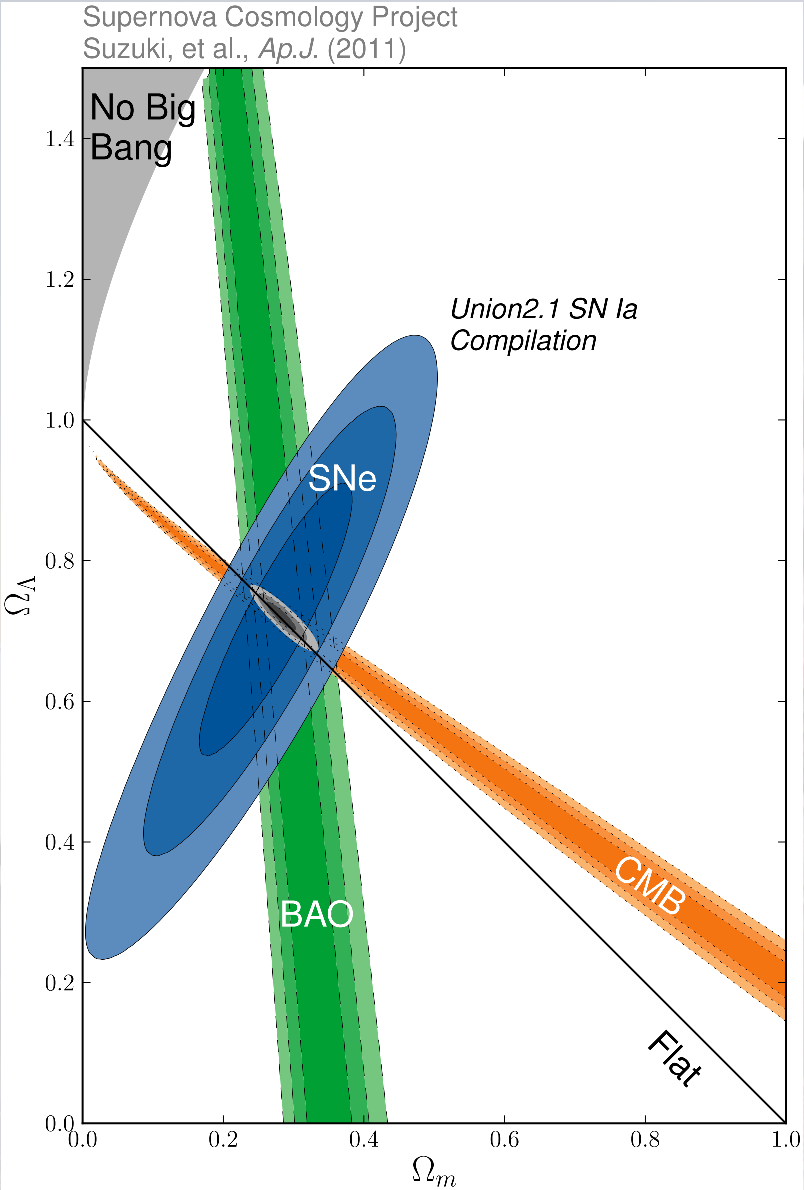
$$\rho_\Lambda \lesssim \rho_m \;\; : \;\; \text{crucial for structure formation}$$

$$\text{but } \rho_\Lambda \propto a^0 \text{ while } \rho_m \propto a^{-3}$$

Many alternative explanations

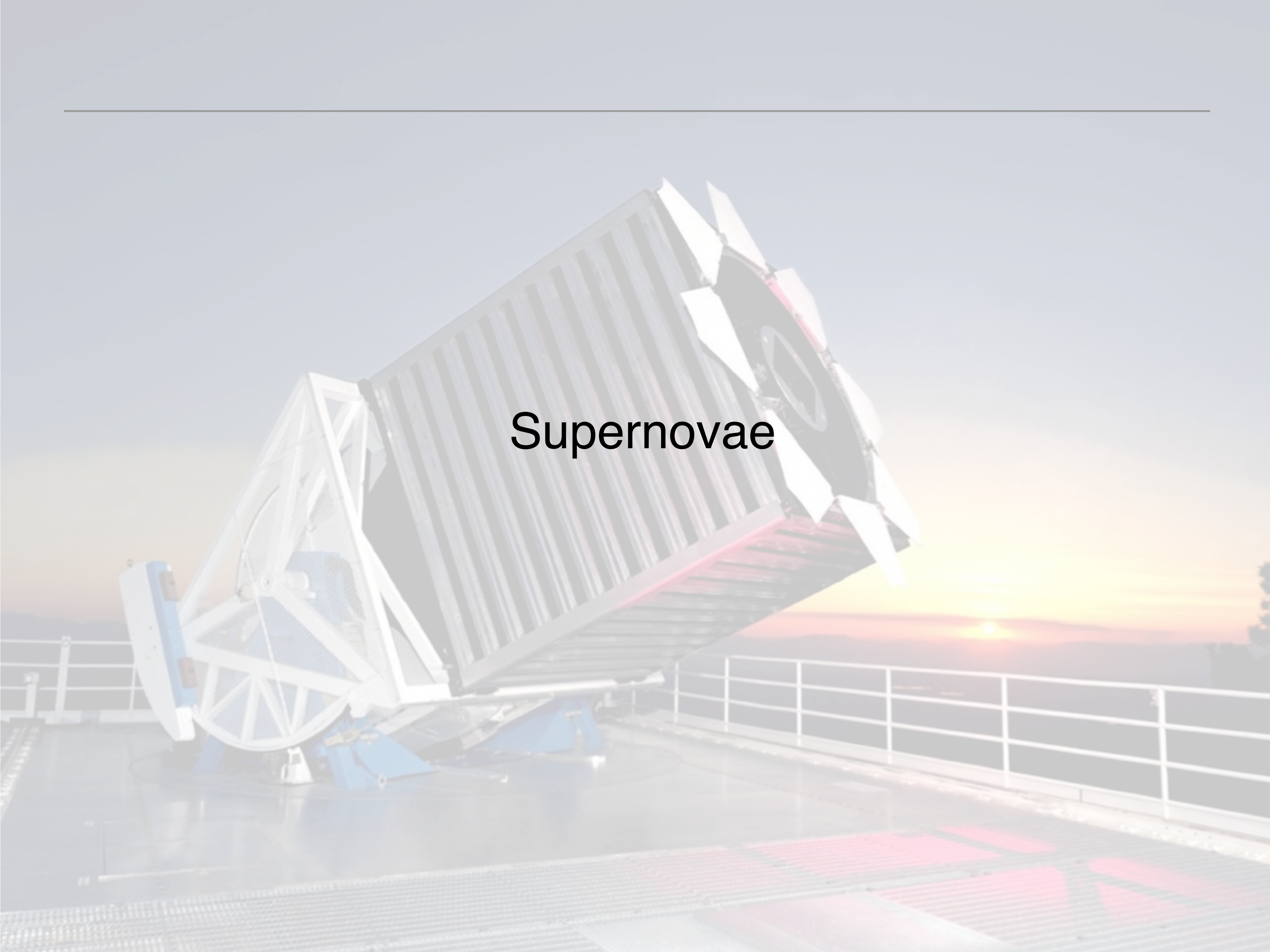
- modify gravity on large-scales or at low densities?
- more general scalar field model?
- link with Dark Matter?
- back-reaction from structure growth?

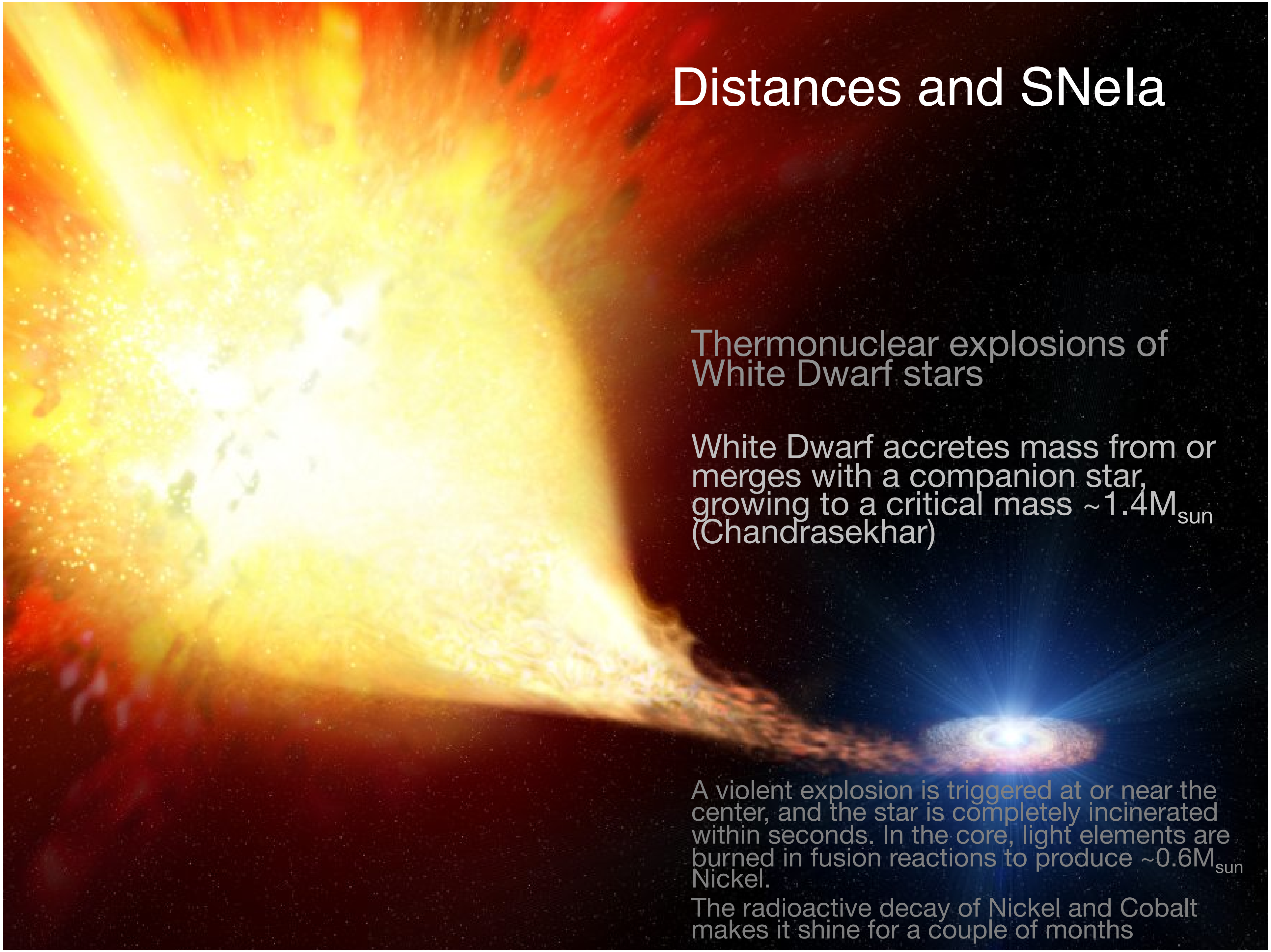
Goal of this lecture



How did we get here?

Supernovae





Distances and SNeIa

Thermonuclear explosions of White Dwarf stars

White Dwarf accretes mass from or merges with a companion star, growing to a critical mass ~$1.4M_{sun}$ (Chandrasekhar)

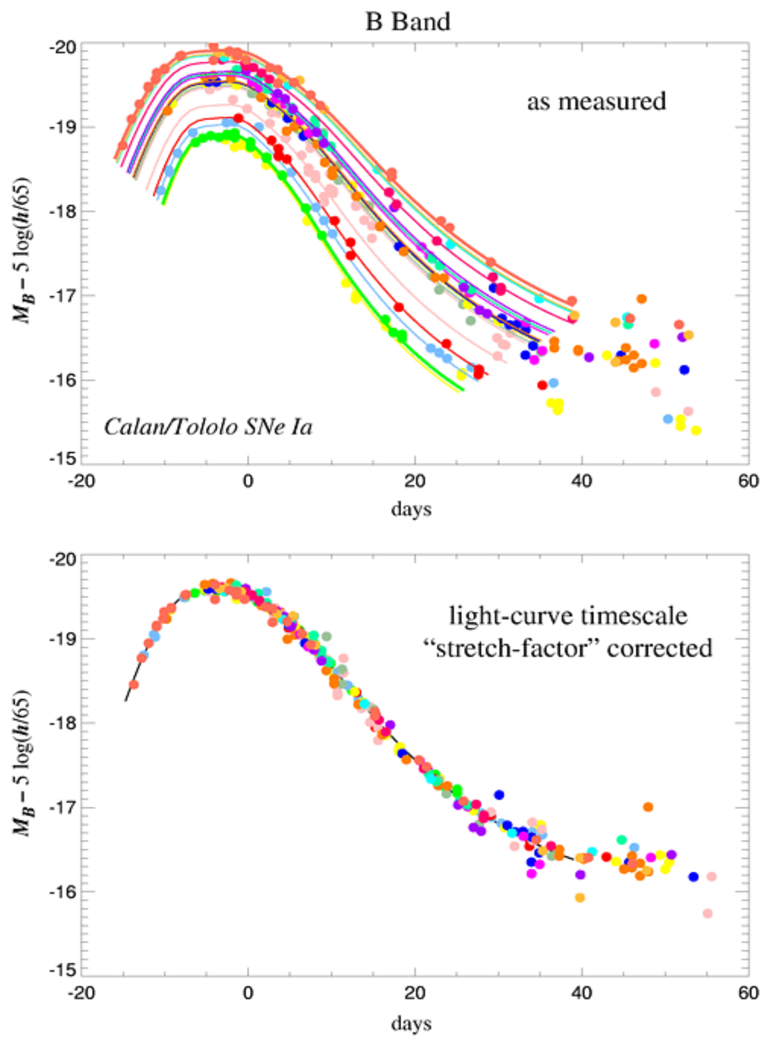
A violent explosion is triggered at or near the center, and the star is completely incinerated within seconds. In the core, light elements are burned in fusion reactions to produce ~$0.6M_{sun}$ Nickel.

The radioactive decay of Nickel and Cobalt makes it shine for a couple of months

Standardizable Candles

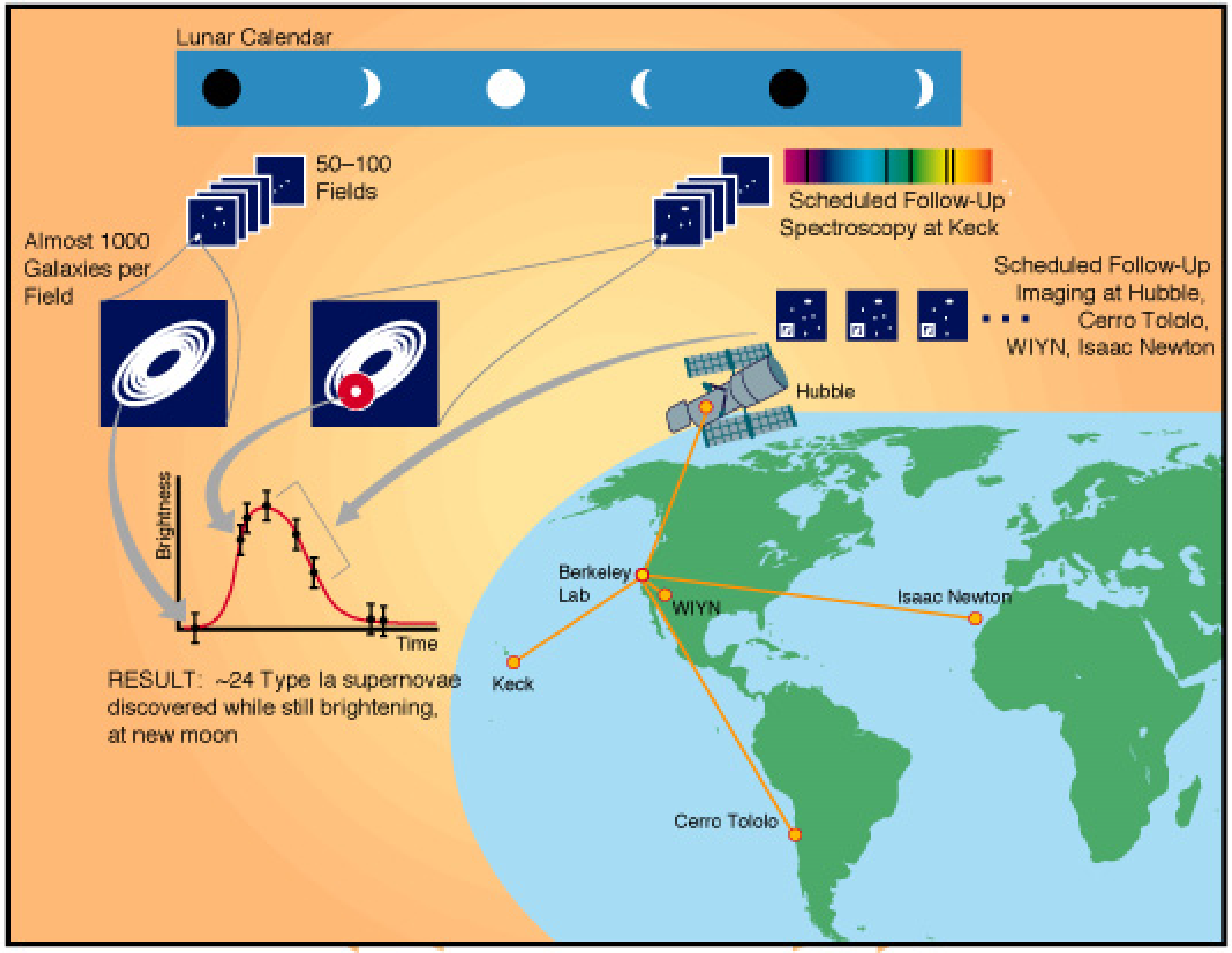
After correction, σ ~0.16 mag (~8% distance error)

Overall, now ~3% in distance

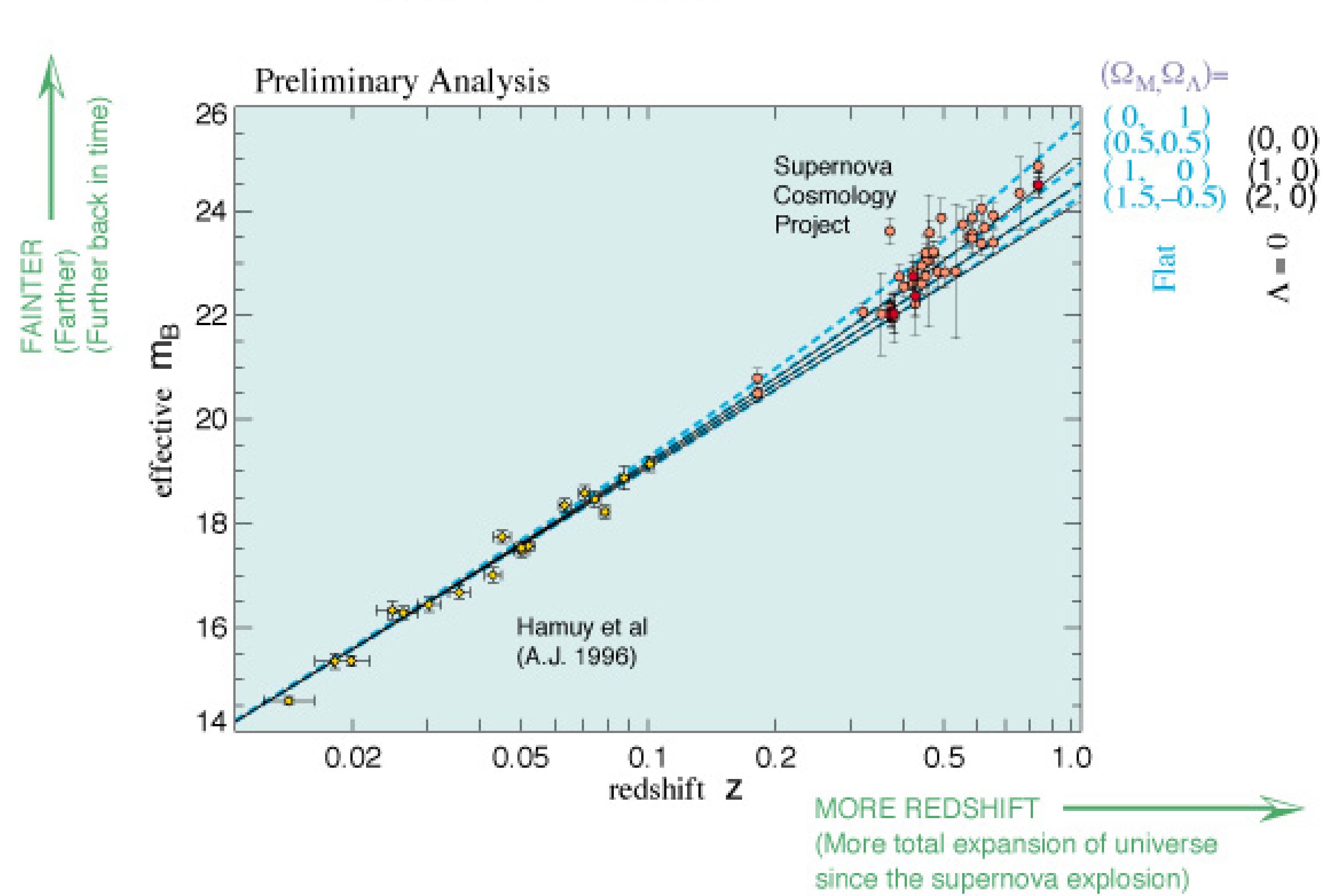


Kim et al. 1997

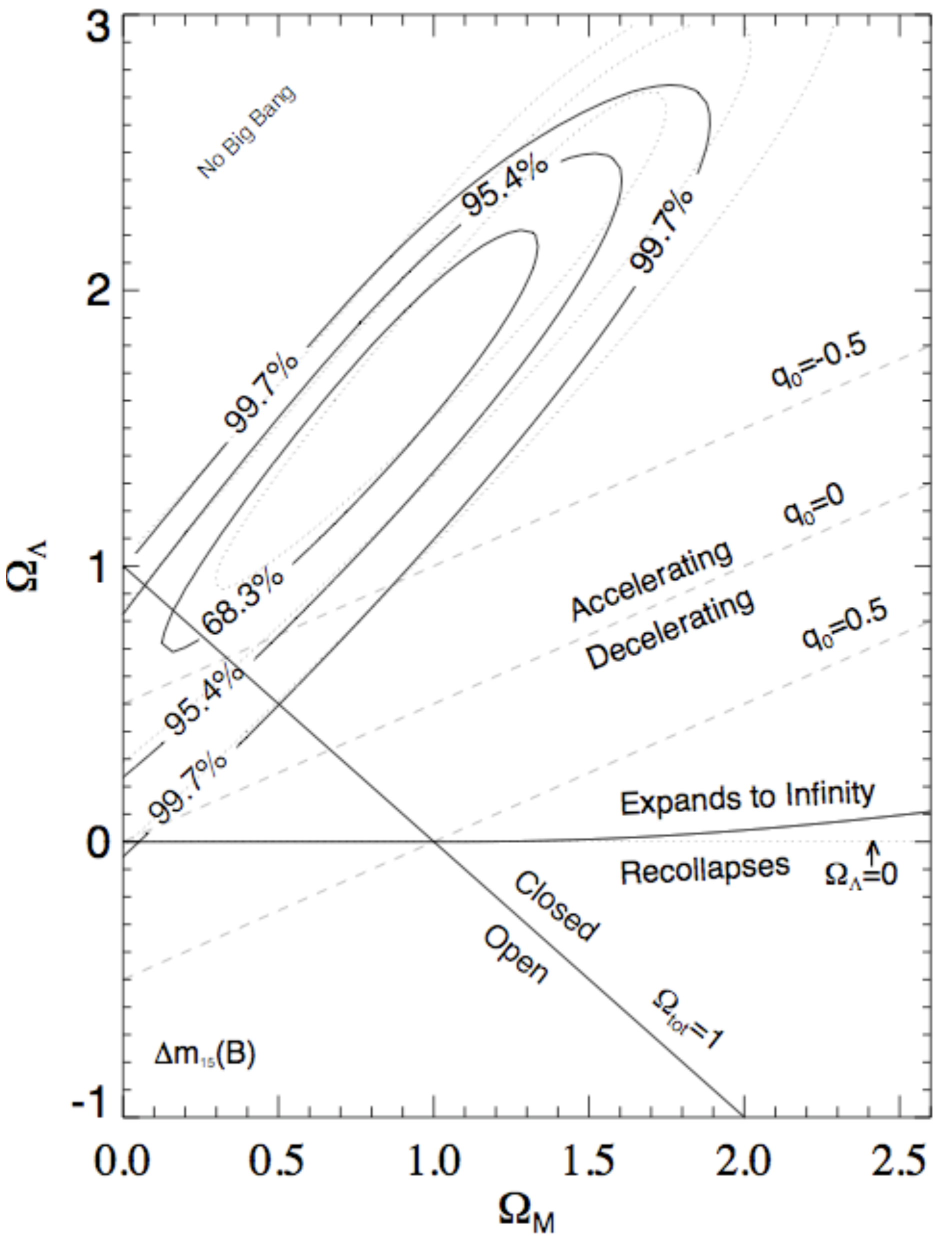
Industrial Astronomy



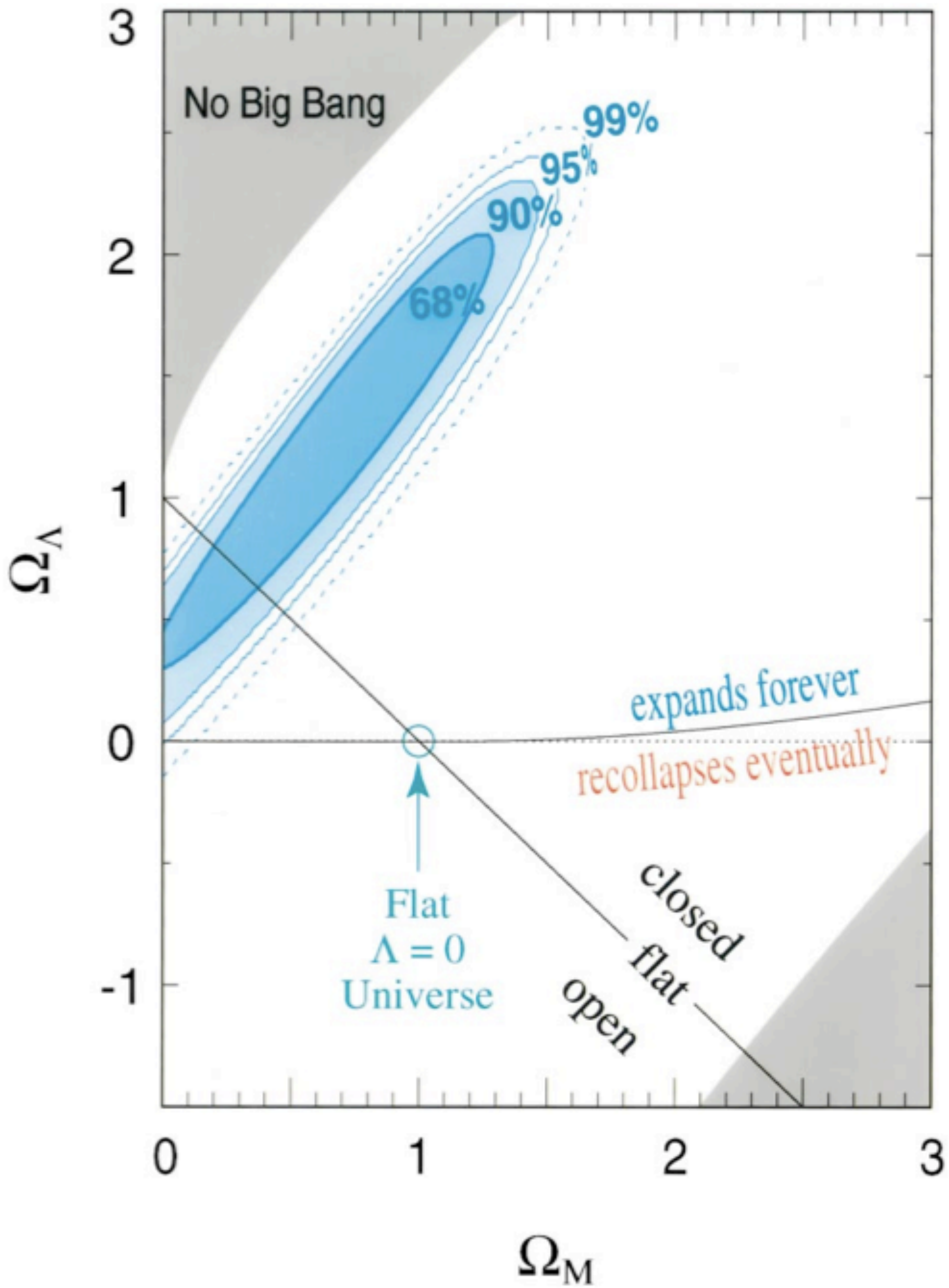
SN Hubble Diagram (circa 1999)



Riess et al. (1998, AJ)

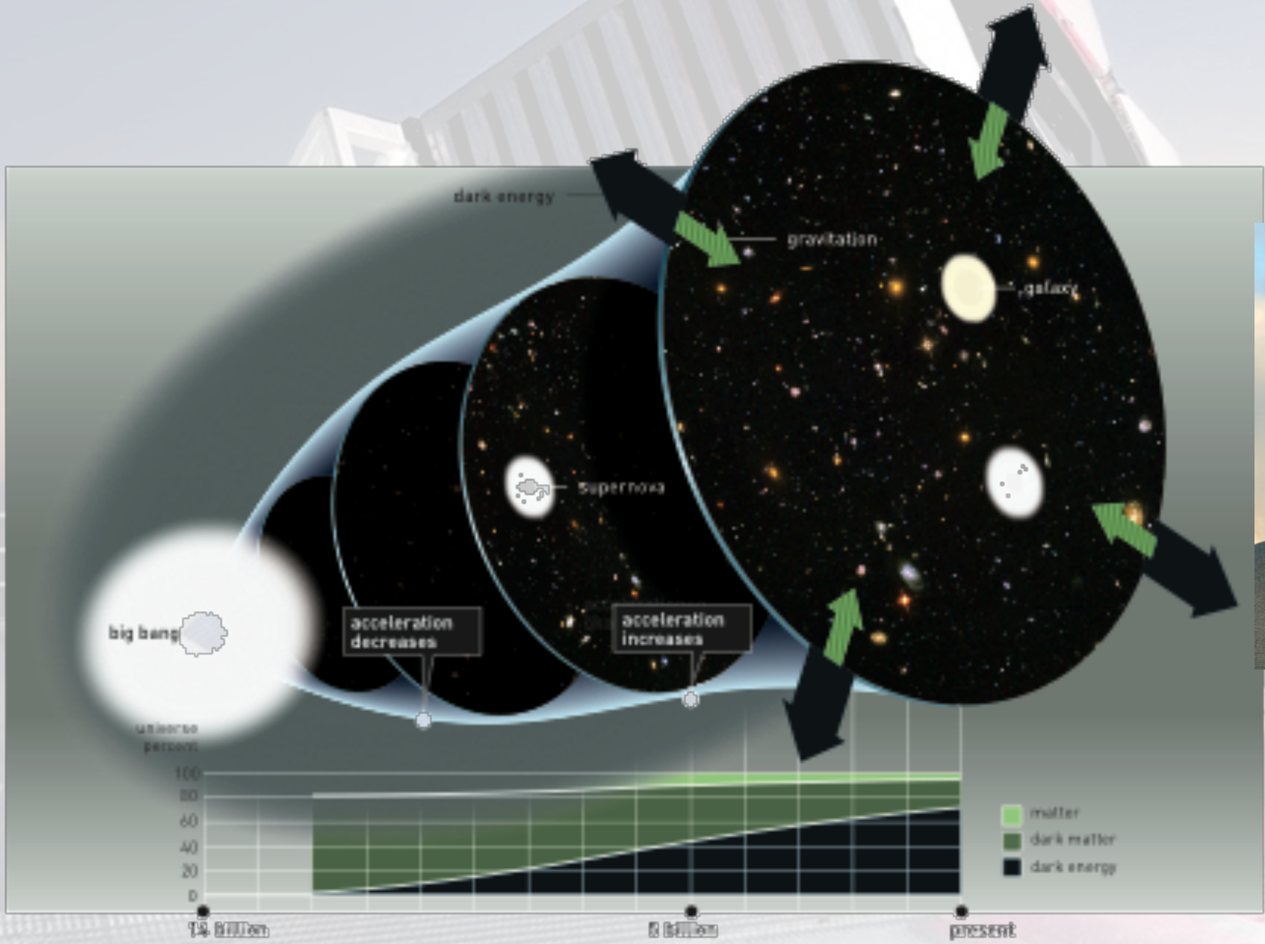


Perlmutter et al. (1999, ApJ)

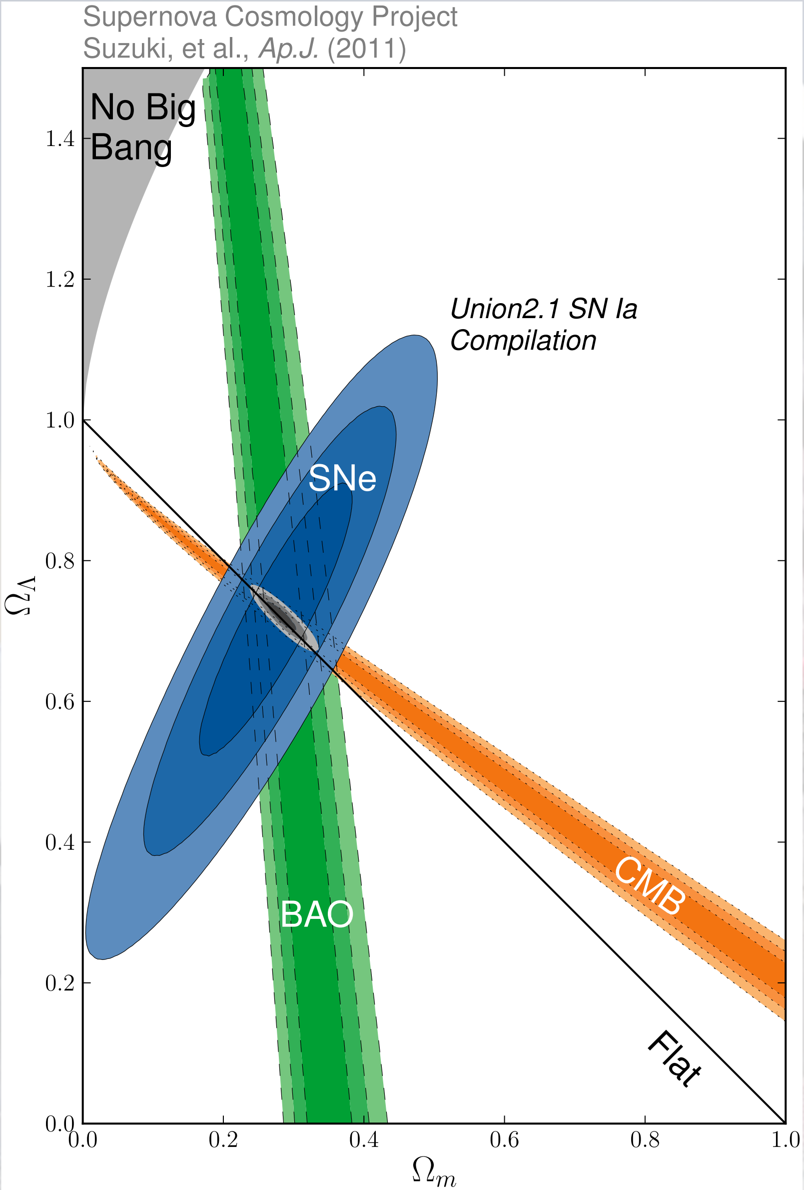


Nobel Prize 2011

"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"



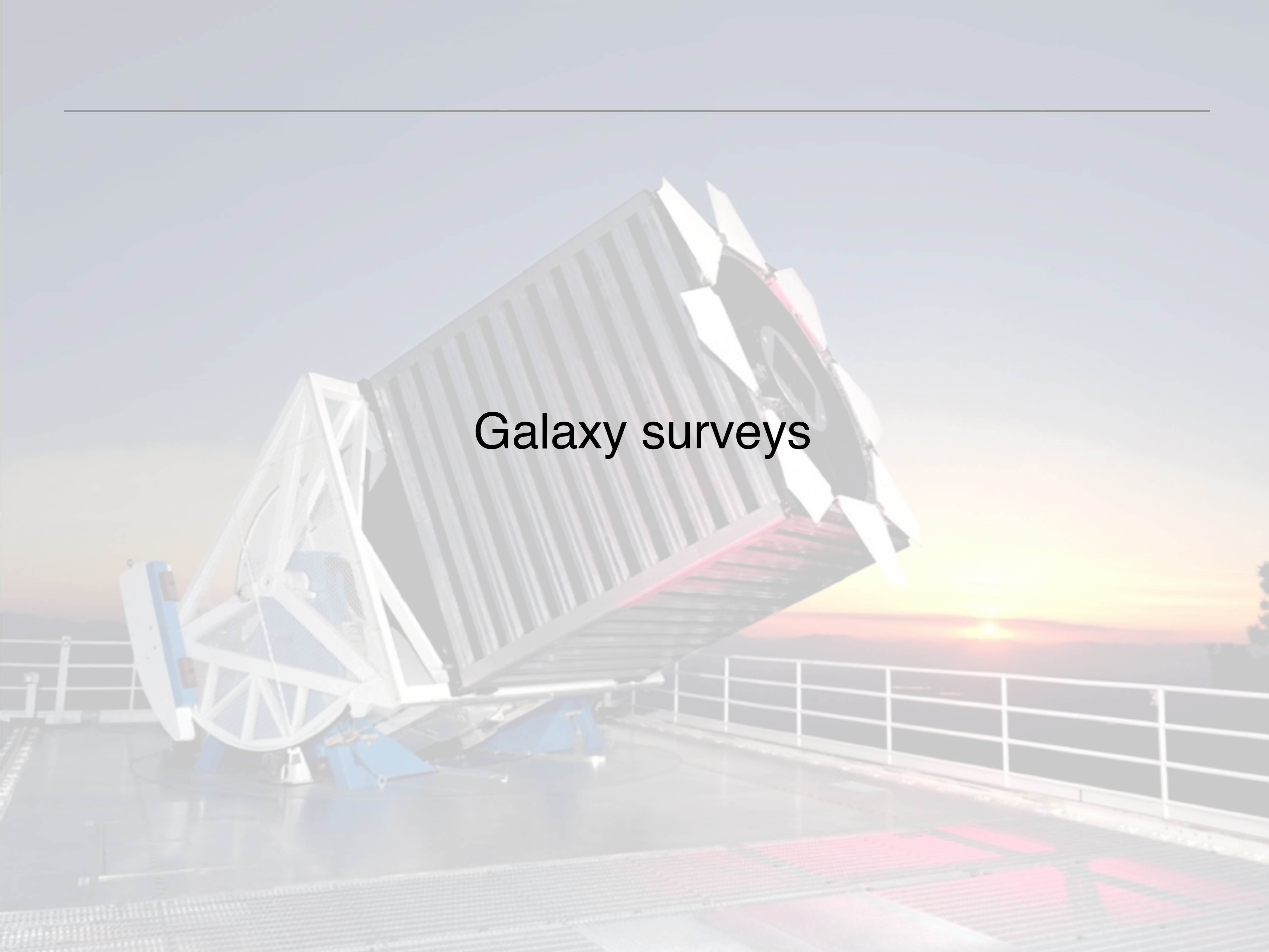
Goal of this lecture



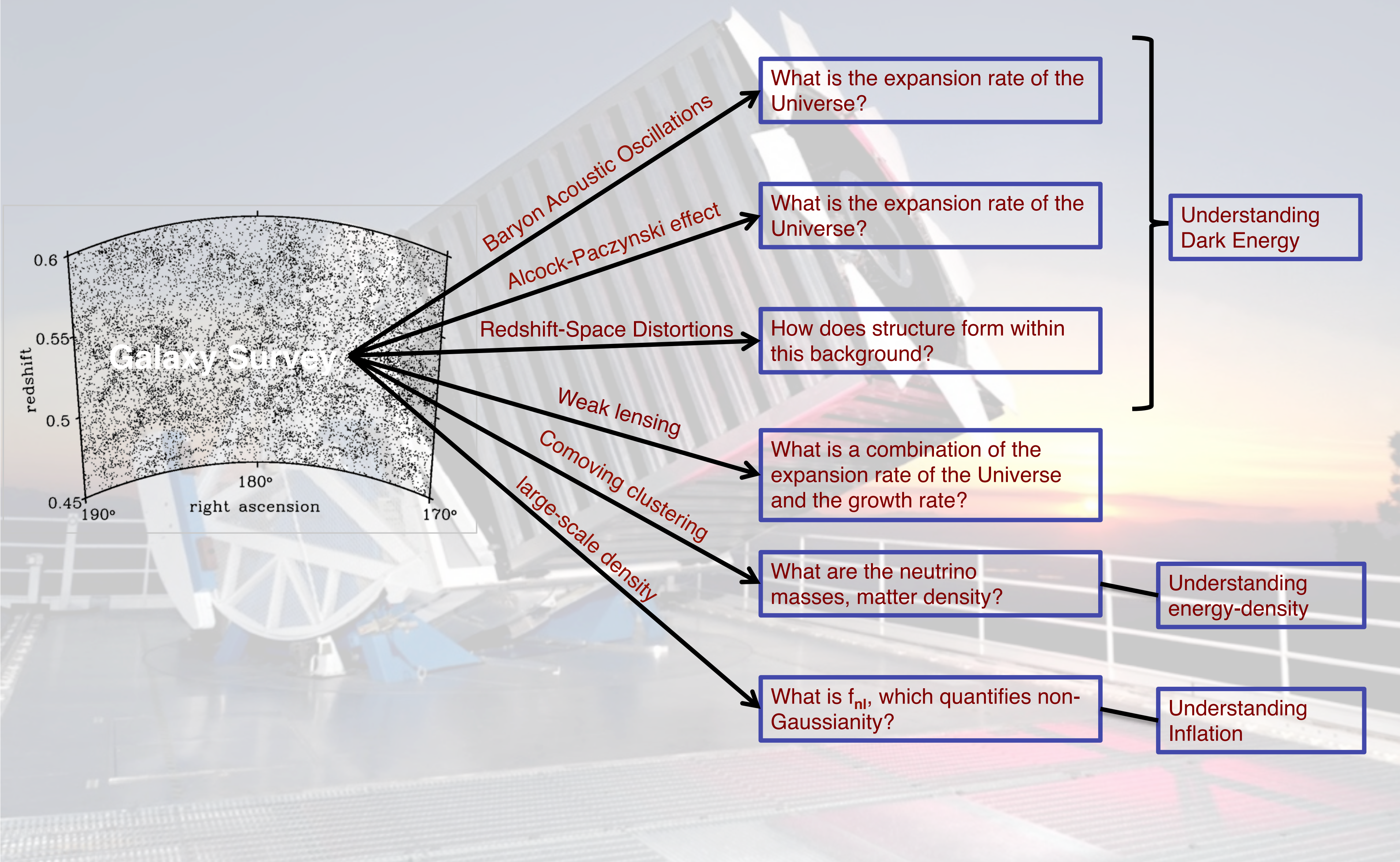
How did we get here?

Supernovae tell us we live in a lambda dominated Universe

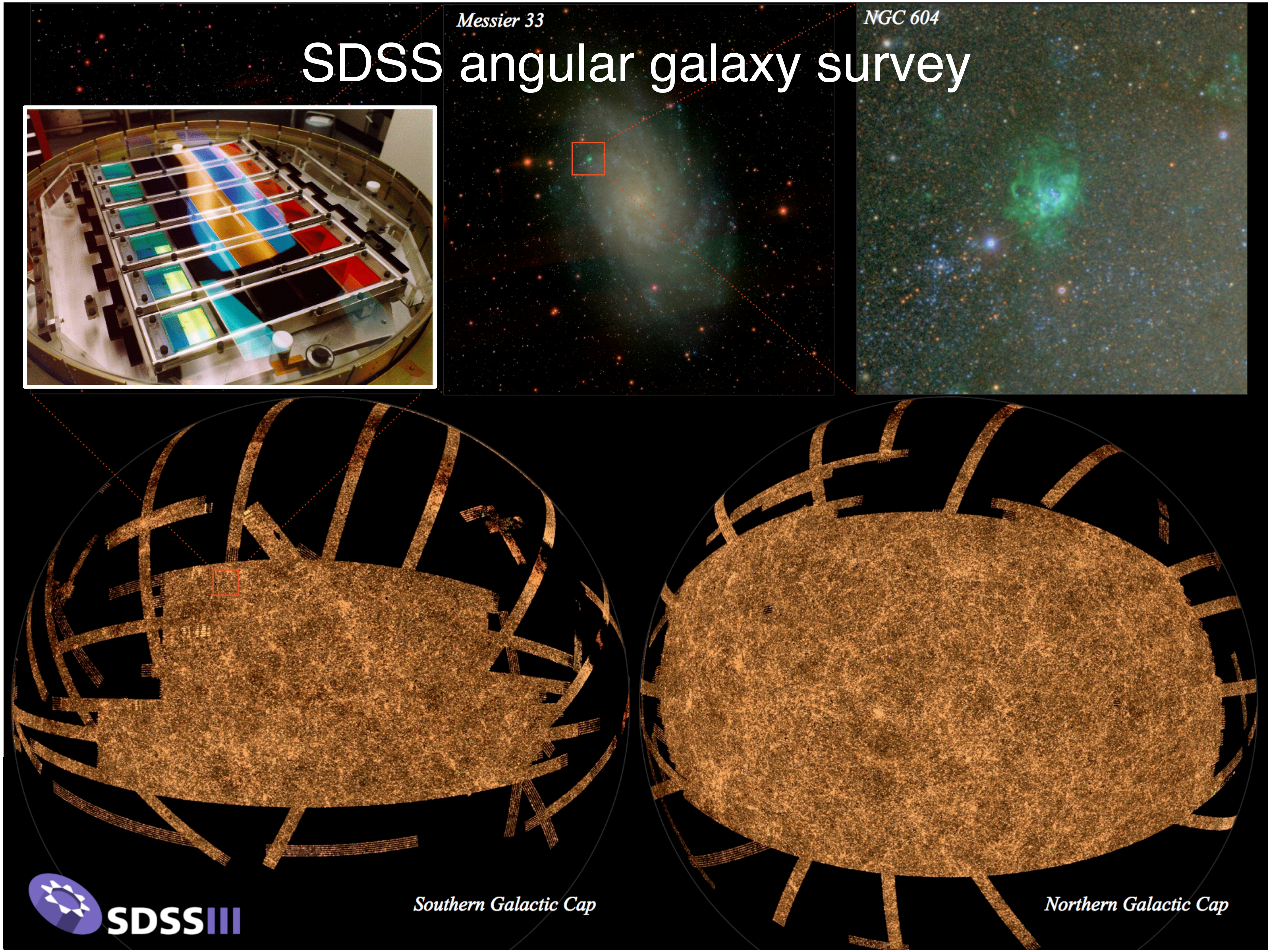
Galaxy surveys



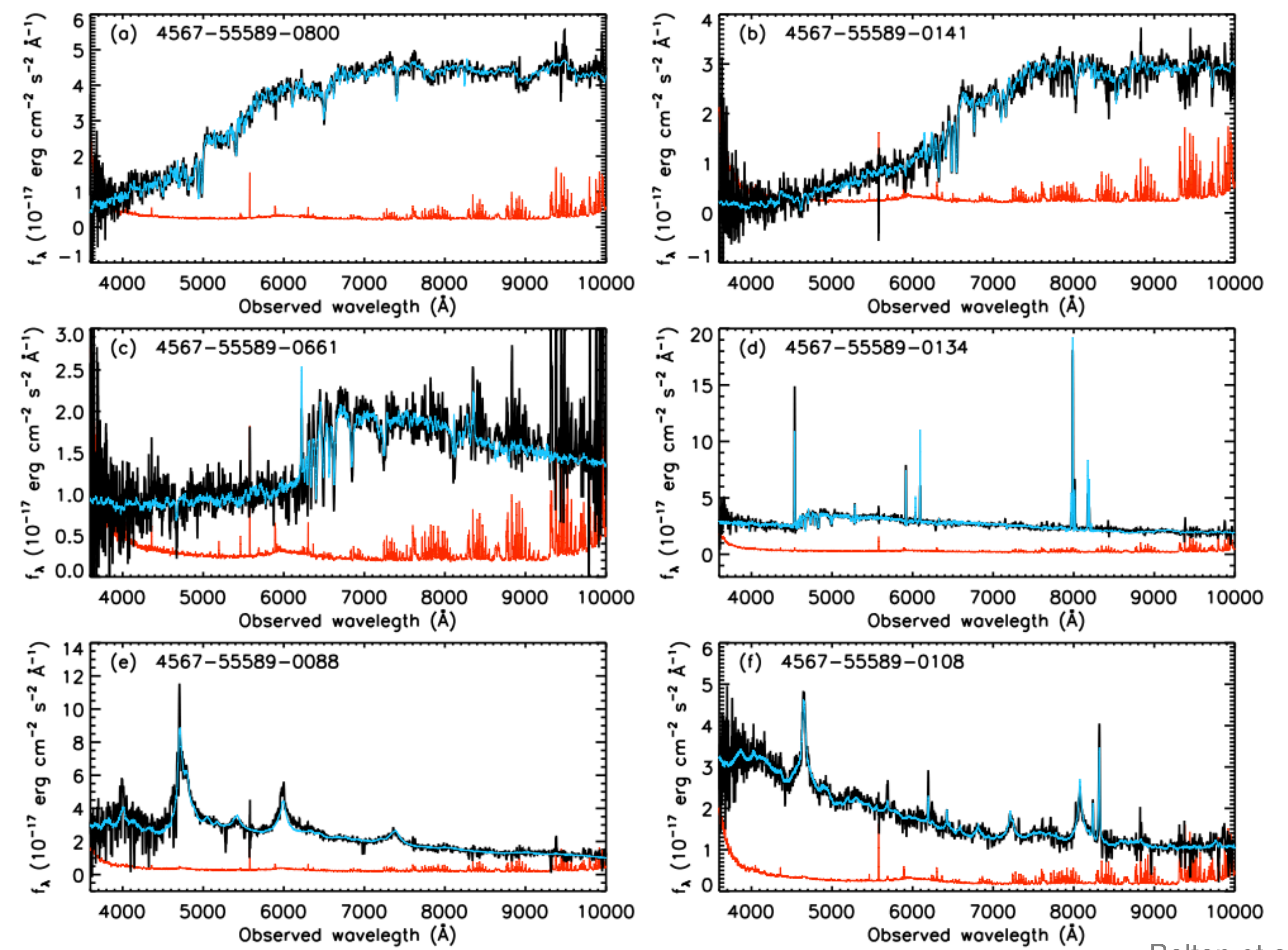
Cosmology from surveys



SDSS angular galaxy survey



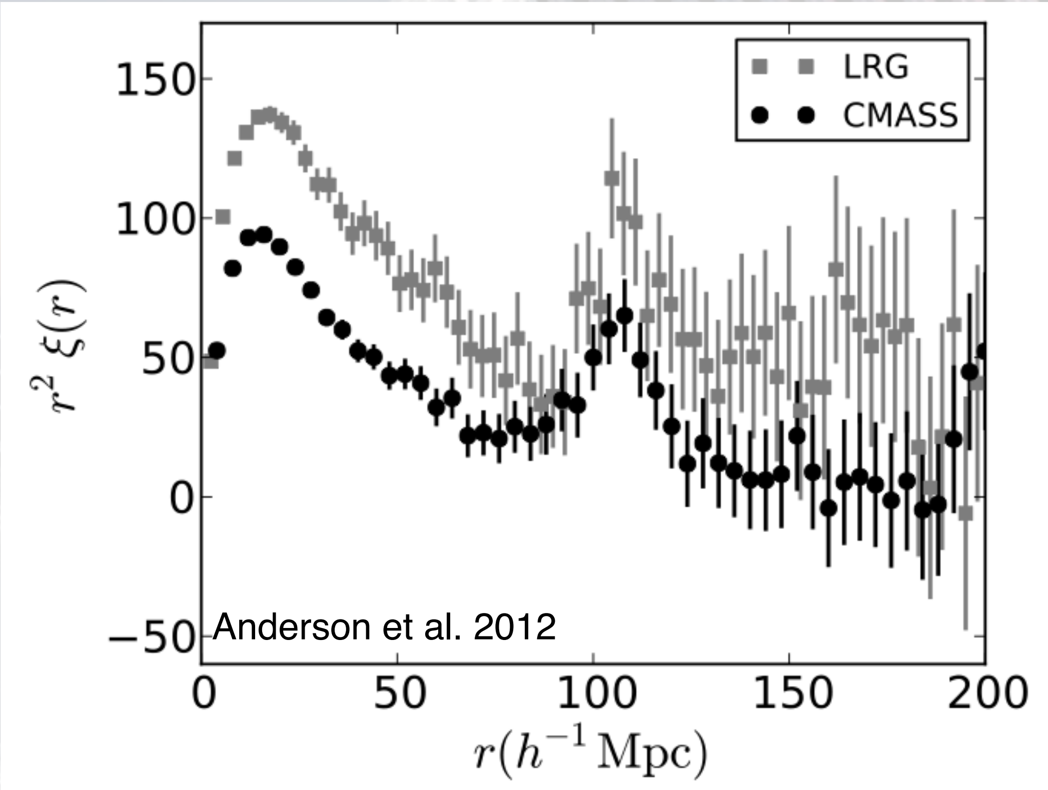
Spectra gives recession velocities and redshifts



Bolton et al. 2012

Galaxy survey "history"

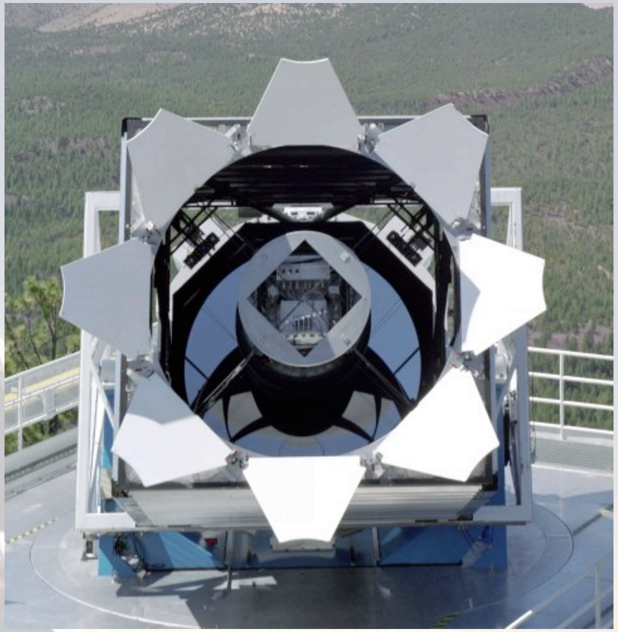
- 1986 CfA 3500
- 1996 LCRS 23000
- 2003 2dFGRS 250000
- 2005 SDSS-I/II 800000
- 2012 SDSS-III 1500000



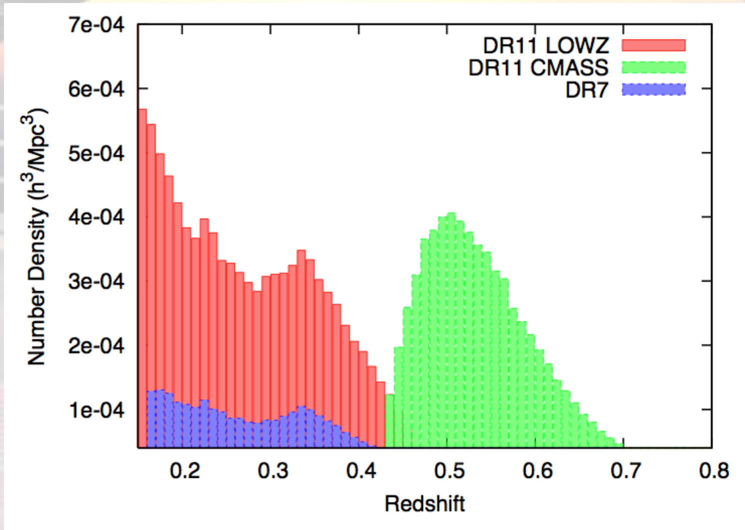
Fractional error in the amplitude of the fluctuation spectrum

1970	x100
1990	x2
1995	±0.4
1998	±0.2
1999	±0.1
2002	±0.05
2003	±0.03
2009	±0.01
2012	±0.002

Baryon Oscillation Spectroscopic Survey



- Duration: Fall 2009 - Summer 2014
- Telescope: 2.5m Sloan
- Upgrade to SDSS-II spectrograph
  - 1000 smaller fibers
  - higher throughput
- Spectra:
  - 3600 Å < λ < 10, 000 Å New spectrograph
  - $R = \lambda/\Delta\lambda = 1300 - 3000$
  - (S/N) at mag. limit
    - 22 per pix. (averaged over 7000-8500Å)
    - 10 per pix. (averaged over 4000-5500Å)
- Area: 10,000 deg2
- Targets:
  - **1.5×10^6 massive galaxies, $z < 0.7$, $i < 19.9$**
  - 1.5×10^5 quasars, $z>2.2$, $g<22.0$
  - 75,000 ancillary science targets, many categories



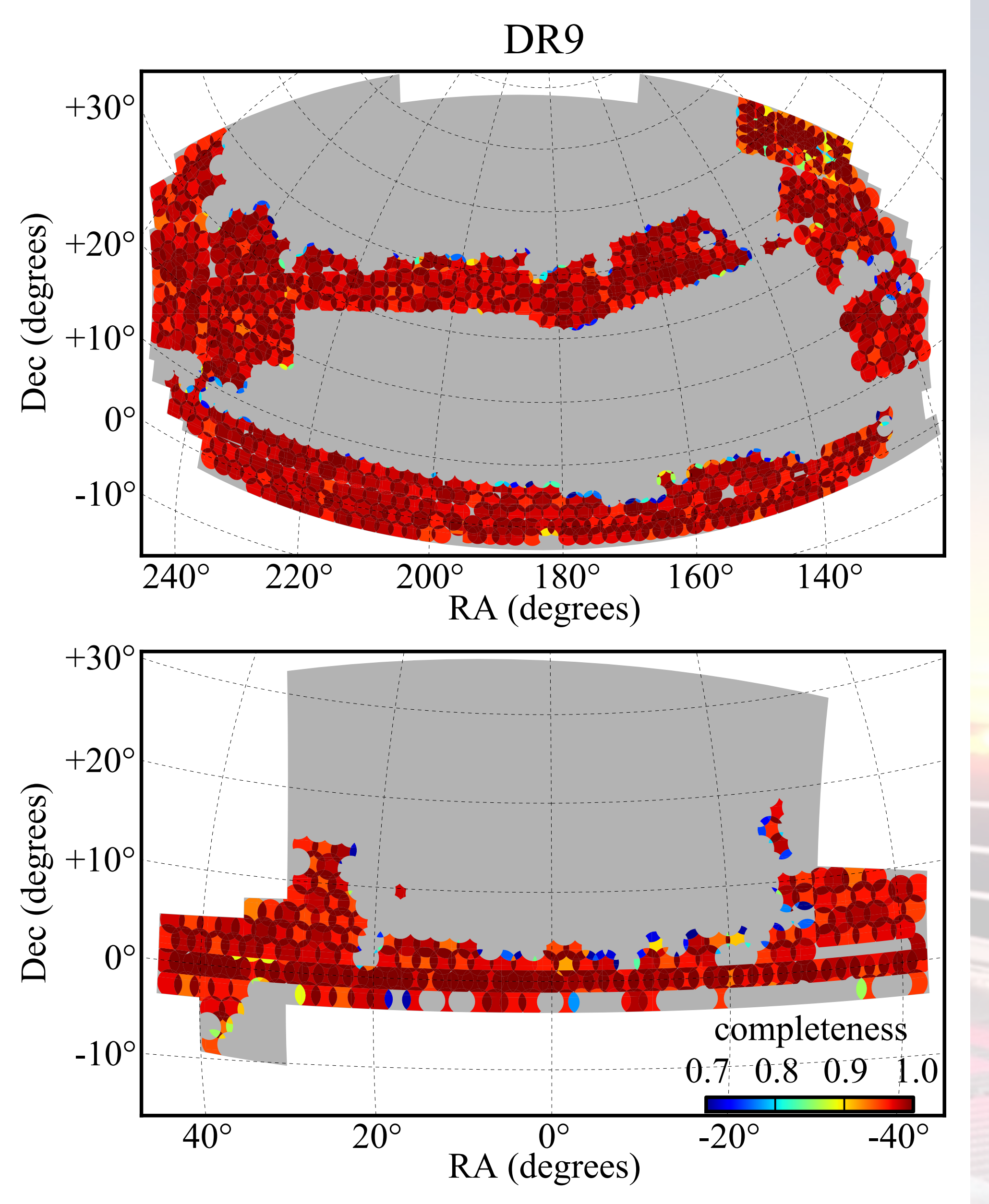
The Sloan Digital Sky Survey telescope

A collaborative effort … BOSS

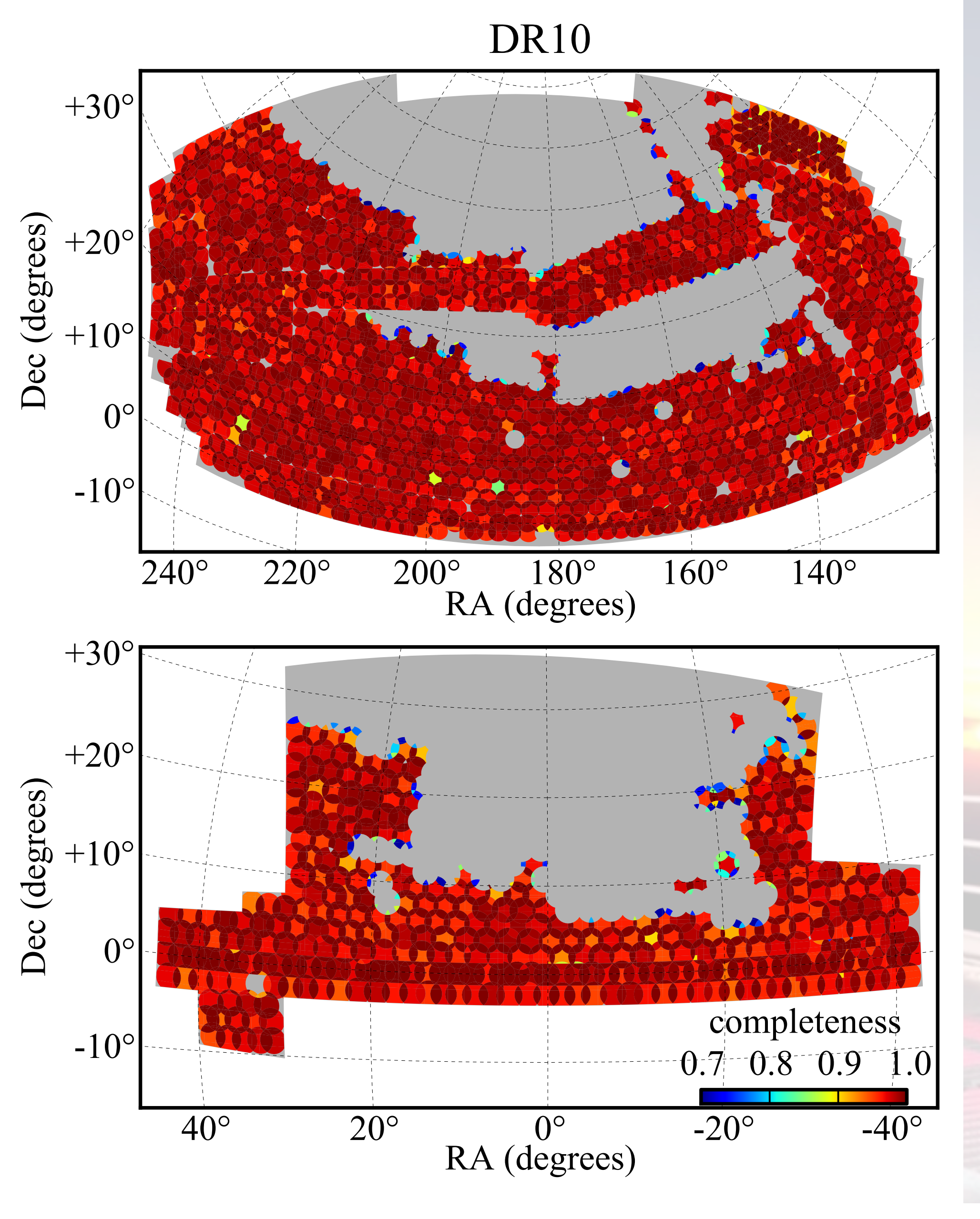
Lauren Anderson[1], Eric Aubourg[2], Stephen Bailey[3], Dmitry Bizyaev[4], Michael Blanton[5], Adam S. Bolton[6], J. Brinkmann[4], Joel R. Brownstein[6], Angela Burden[7], Antonio J. Cuesta[8], Luiz N. A. da Costa[9,10], Kyle S. Dawson[6], Roland de Putter[11,12], Daniel J. Eisenstein[13], James E. Gunn[14], Hong Guo[15], Jean-Christophe Hamilton[2], Paul Harding[15], Shirley Ho[3,14], Klaus Honscheid[16], Eyal Kazin[17], D. Kirkby[18], Jean-Paul Kneib[19], Antione Labatie[20], Craig Loomis[21], Robert H. Lupton[14], Elena Malanushenko[4], Viktor Malanushenko[4], Rachel Mandelbaum[14,21], Marc Manera[7], Claudia Maraston[7], Cameron K. McBride[13], Kushal T. Mehta[22], Olga Mena[11], Francesco Montesano[23], Demetri Muna[5], Robert C. Nichol[7], Sebastián E. Nuza[24], Matthew D. Olmstead[6], Daniel Oravetz[4], Nikhil Padmanabhan[8], Nathalie Palanque-Delabrouille[25], Kaike Pan[4], John Parejko[8], Isabelle Pâris[26], Will J. Percival[7], Patrick Petitjean[26], Francisco Prada[27,28,29], Beth Reid[3,30], Natalie A. Roe[3], Ashley J. Ross[7], Nicholas P. Ross[3], Lado Samushia[7,31], Ariel G. Sánchez[23], David J. Schlegel[⋆3], Donald P. Schneider[32,33], Claudia G. Scóccola[34,35], Hee-Jong Seo[36], Erin S. Sheldon[37], Audrey Simmons[4], Ramin A. Skibba[22], Michael A. Strauss[21], Molly E. C. Swanson[13], Daniel Thomas[7], Jeremy L. Tinker[5], Rita Tojeiro[7], Mariana Vargas Magaña[2], Licia Verde[38], Christian Wagner[12], David A. Wake[39], Benjamin A. Weaver[5], David H. Weinberg[40], Martin White[3,41,42], Xiaoying Xu[22], Christophe Yèche[25], Idit Zehavi[15], Gong-Bo Zhao[7,43]

Anderson et al. 2012; arXiv:1203.6565

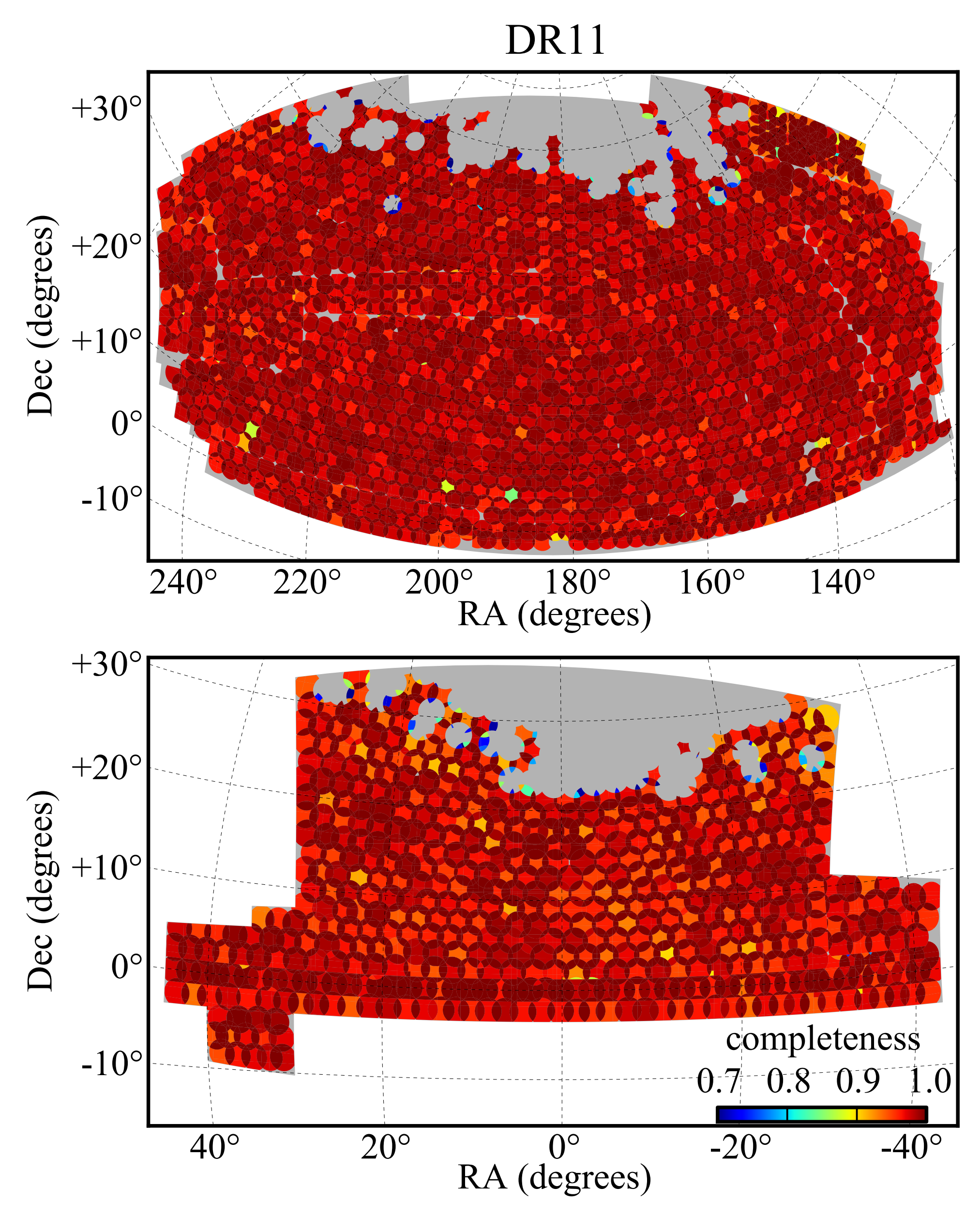
BOSS DR9 galaxies



BOSS DR10 galaxies



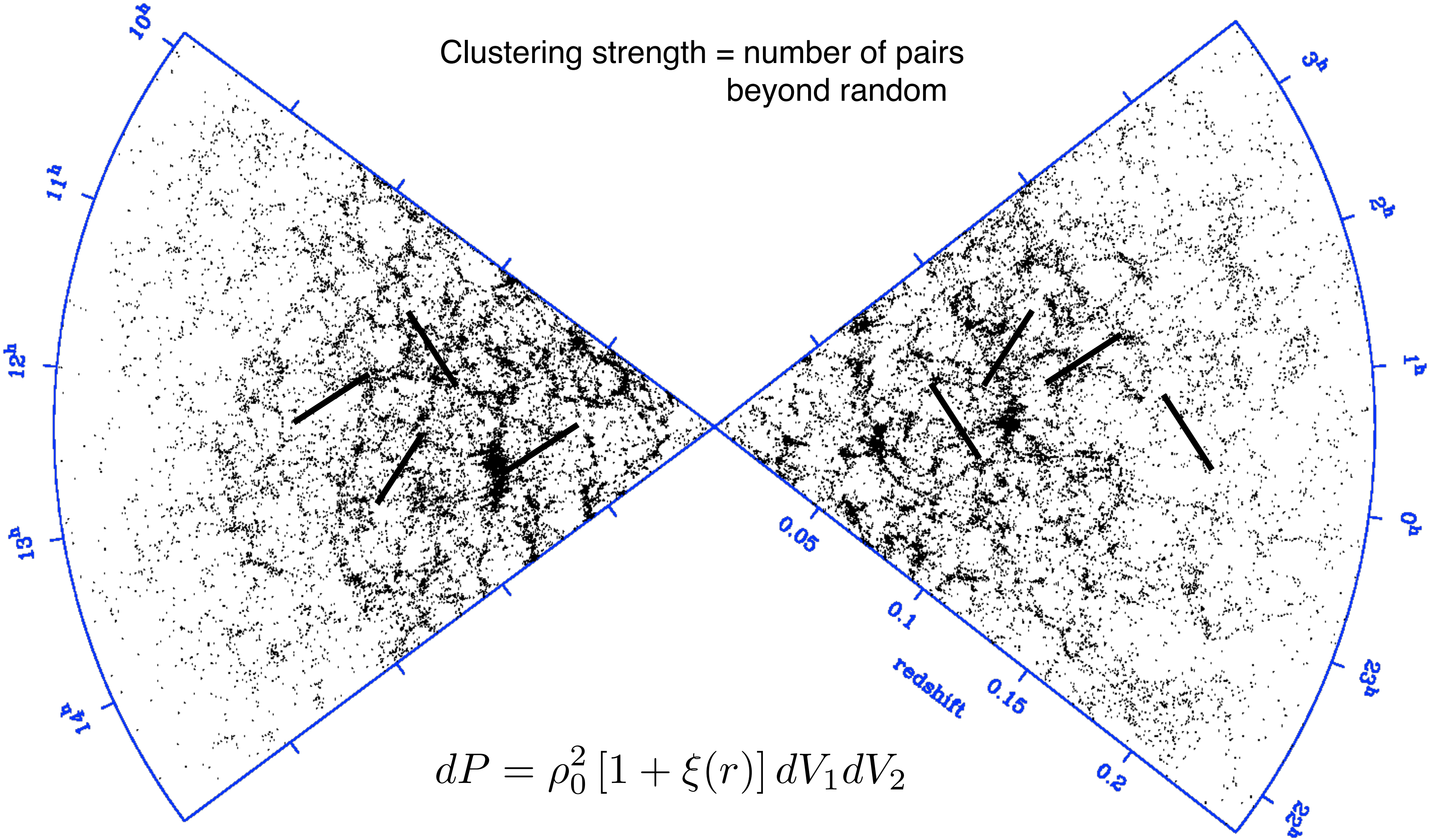
BOSS DR11 galaxies



Clustering

What does “clustering” mean?

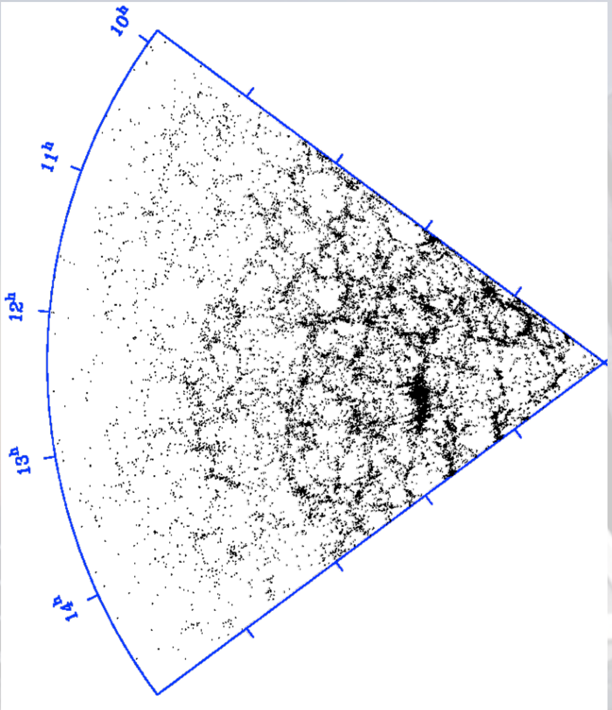
Clustering strength = number of pairs beyond random



$$dP = \rho_0^2 \left[1 + \xi(r)\right] dV_1 dV_2$$

2dFGRS

Over-density fields



“probability of seeing structure”, can be recast in terms of the overdensity

$$\delta = \frac{\rho - \rho_0}{\rho_0}$$

The correlation function is simply the real-space 2-pt statistic of the field

$$\xi(r) = \langle \delta(\mathbf{x})\delta(\mathbf{x}+\mathbf{r}) \rangle$$

Its Fourier analogue, the power spectrum is defined by

$$P(k) = \langle \delta(\mathbf{k})\delta(\mathbf{k}) \rangle$$

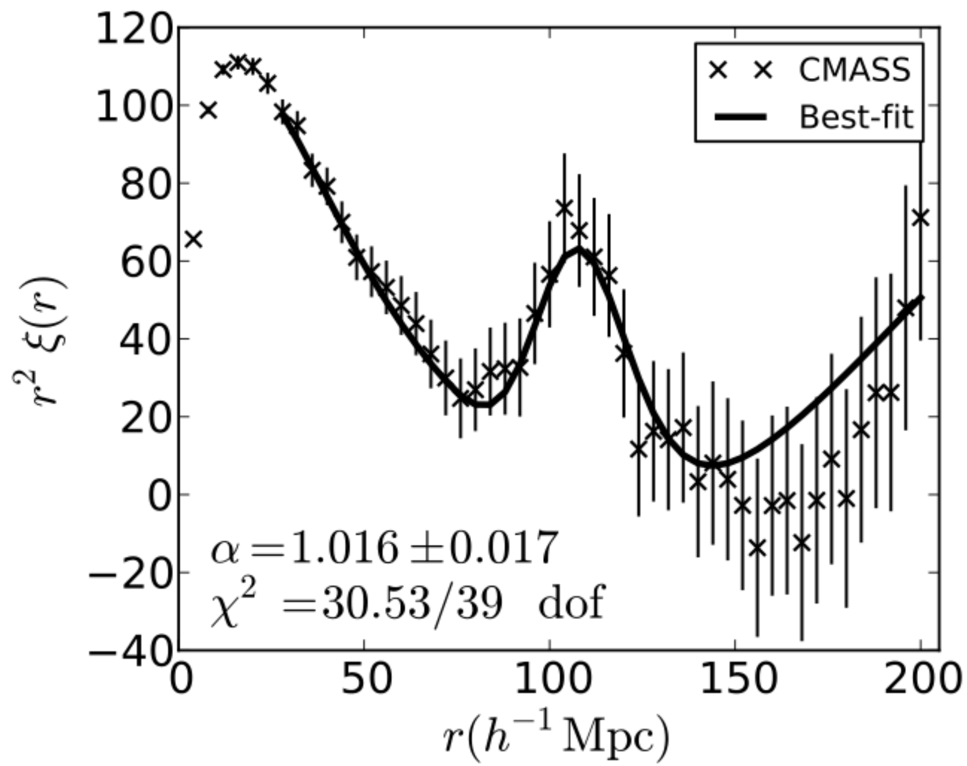
By analogy, one should think of “throwing down” Fourier modes rather than “sticks”

Real-space correlation function

$$\begin{aligned}\xi(\mathbf{x_1},\mathbf{x_2}) &= \langle\delta(\mathbf{x_1})\delta(\mathbf{x_2})\rangle\\ &= \xi(\mathbf{x_1}-\mathbf{x_2})\\ &= \xi(|\mathbf{x_1}-\mathbf{x_2}|)\end{aligned}$$

from statistical homogeneity

from statistical isotropy

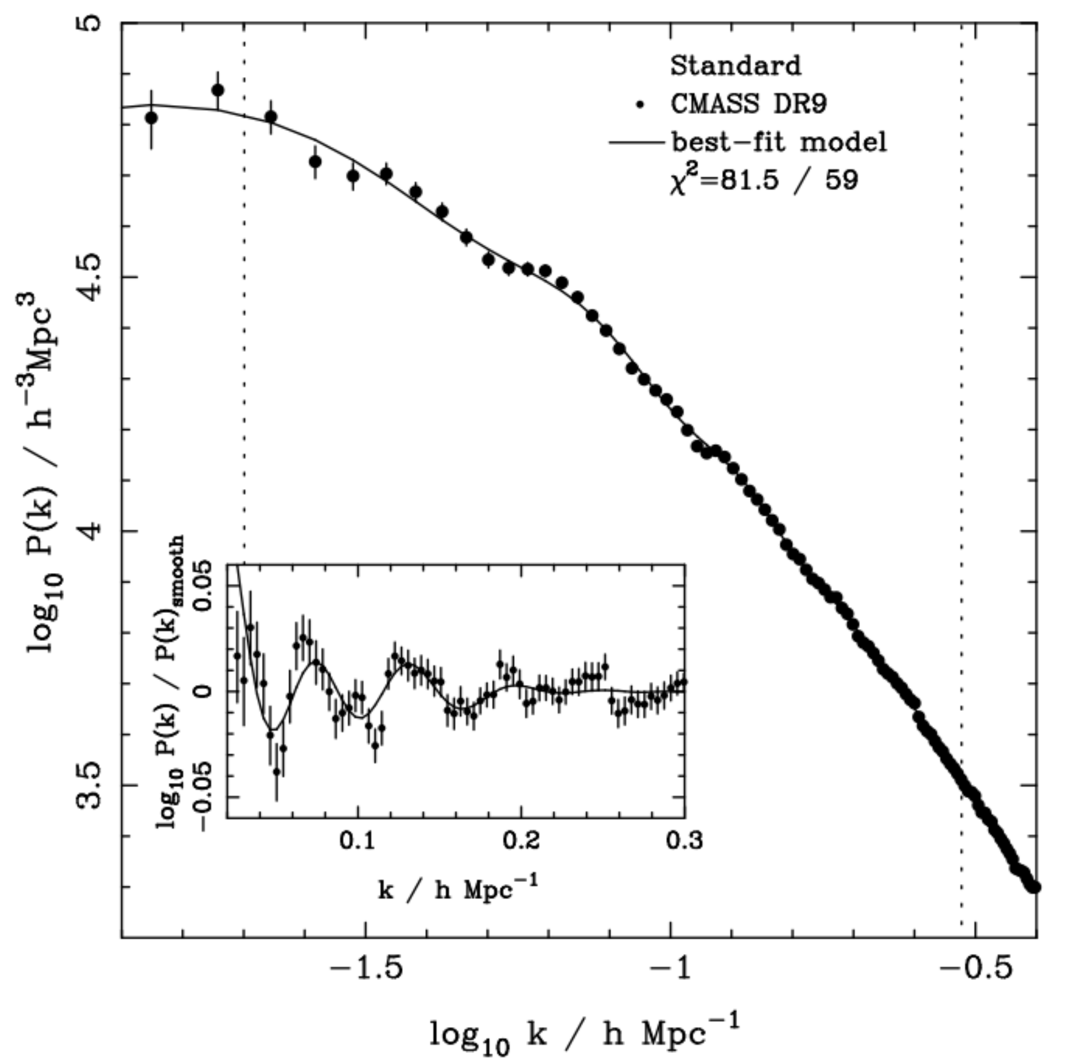


Power spectrum

$$\langle\delta(\mathbf{k_1})\delta(\mathbf{k_2})\rangle = (2\pi)^3\delta_D(\mathbf{k_1}-\mathbf{k_2})P(k_1)$$

from statistical homogeneity

from statistical isotropy

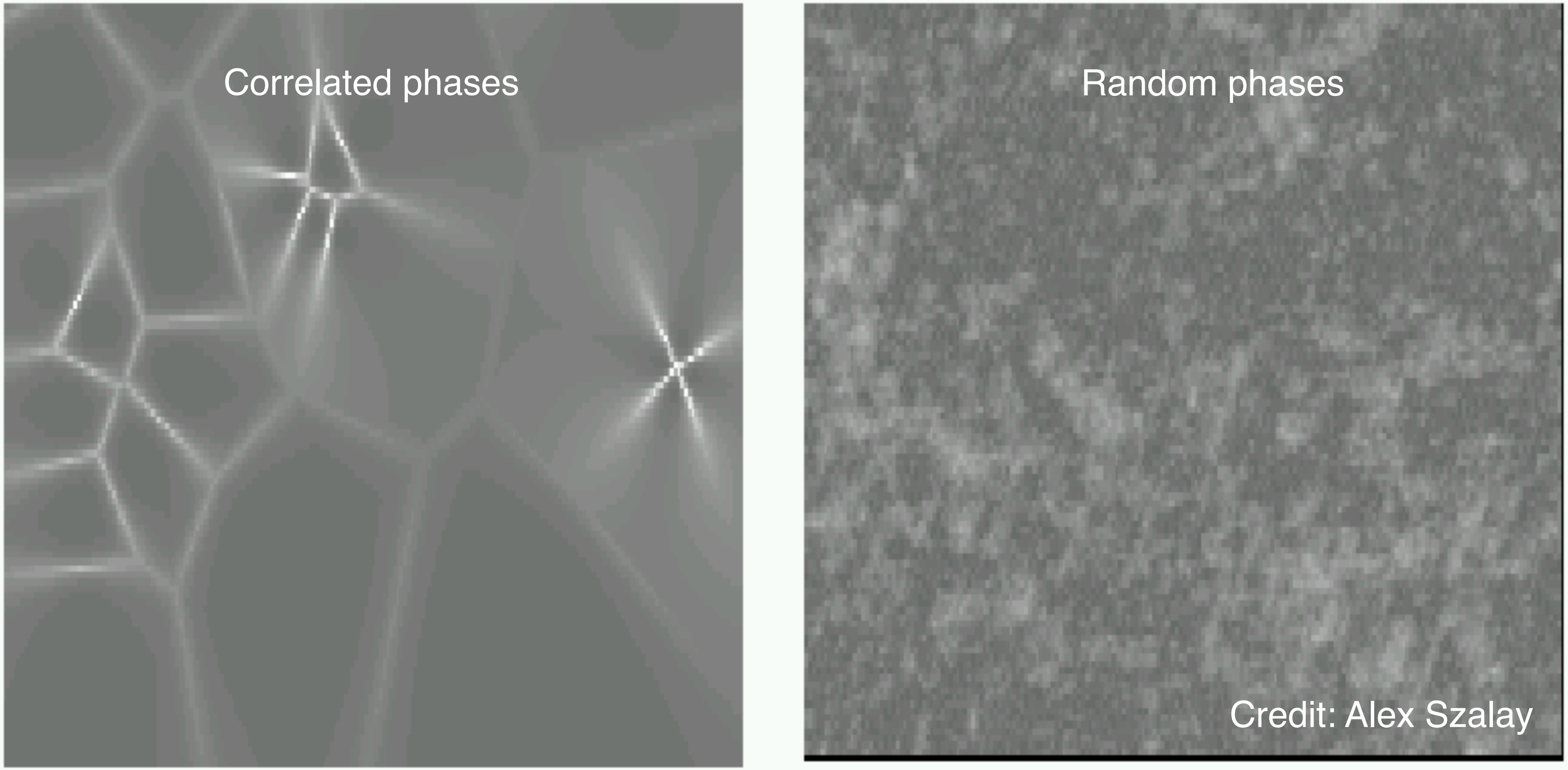


$$\Delta^2(k) = \frac{k^3P(k)}{2\pi^2}$$

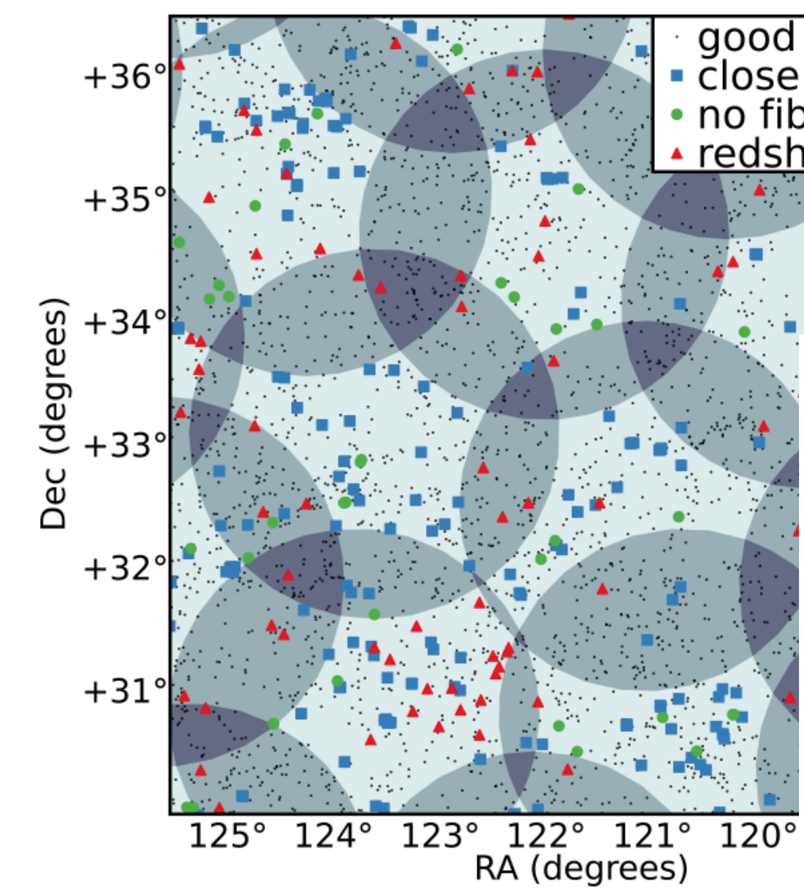
Power spectrum often written in dimensionless form

Statistically complete knowledge?

Gaussian random field: knowledge of either the correlation function or power spectrum is sufficient – they are statistically complete … but …

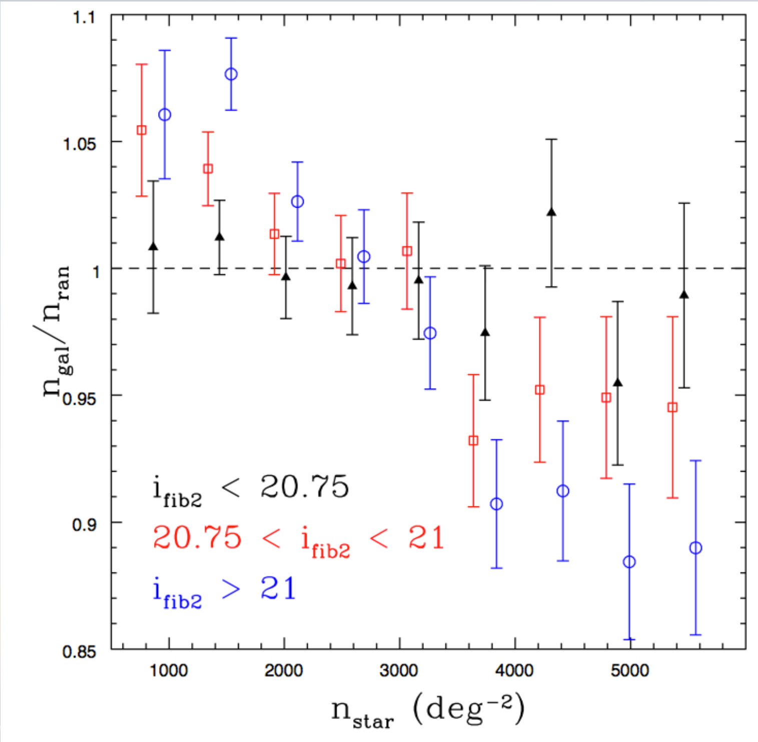


Modeling the angular galaxy mask

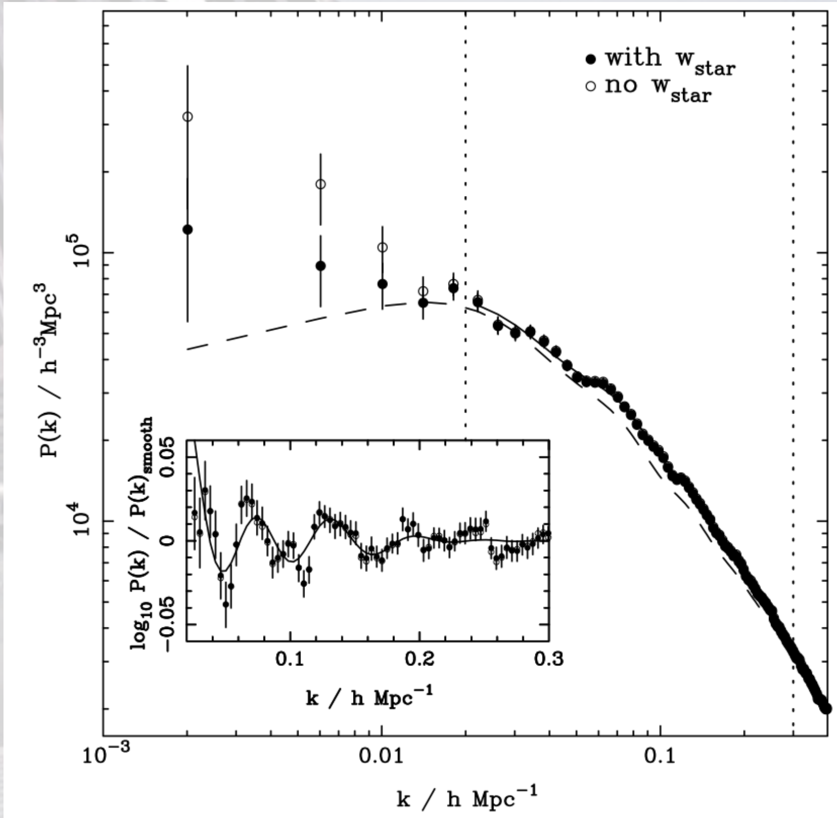


Property	NGC	SGC	total
$\bar{N}_{\rm gal}$	222 538	60 792	283 330
$\bar{N}_{\rm known}$	3766	1810	5576
$\bar{N}_{\rm star}$	7201	1771	8972
$\bar{N}_{\rm fail}$	3751	1122	4873
$\bar{N}_{\rm cp}$	14 116	3640	17 756
$\bar{N}_{\rm missed}$	4931	1911	6842
$\bar{N}_{\rm used}$	207 246	57 037	264 283
$\bar{N}_{\rm obs}$	233 490	63 685	297 175
$\bar{N}_{\rm targ}$	256 303	71 046	327 349
Total area / deg^2	2635	709	3344
Effective area / deg^2	2584	690	3275

Target density fluctuations

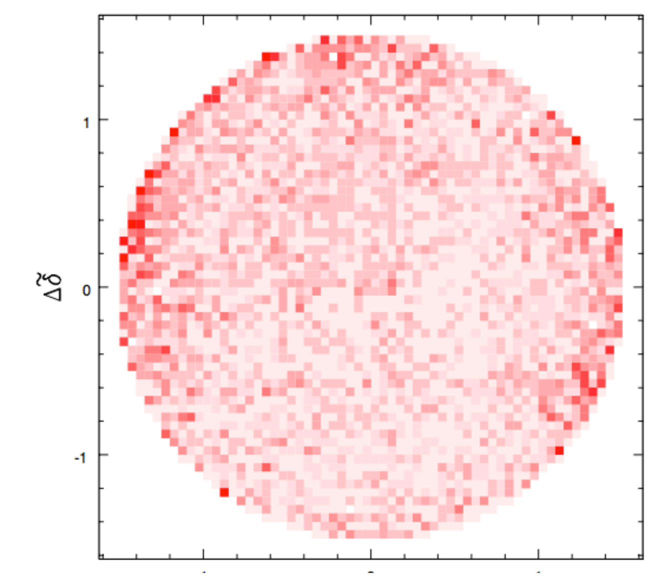


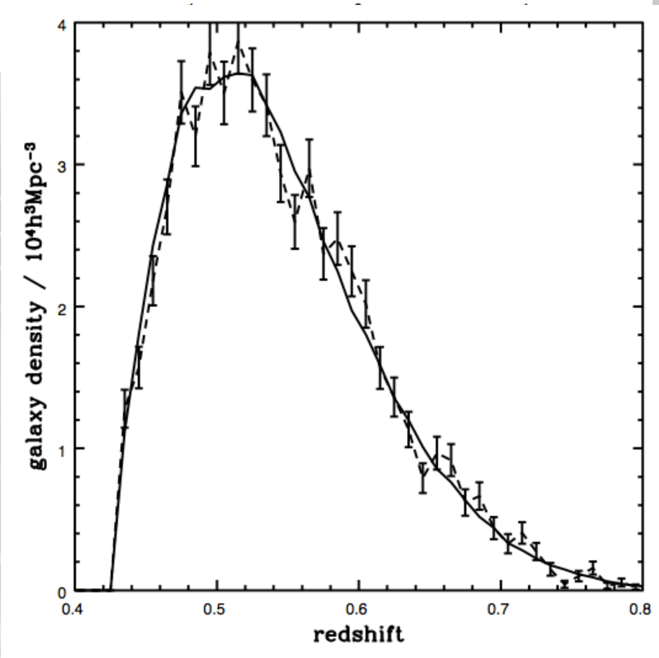
Target density correlates with stellar density and brightness
Corrected by weighting
See Ross et al. for more details



Ross et al. 2012; arXiv:1208.1491

Redshift failures & close pairs



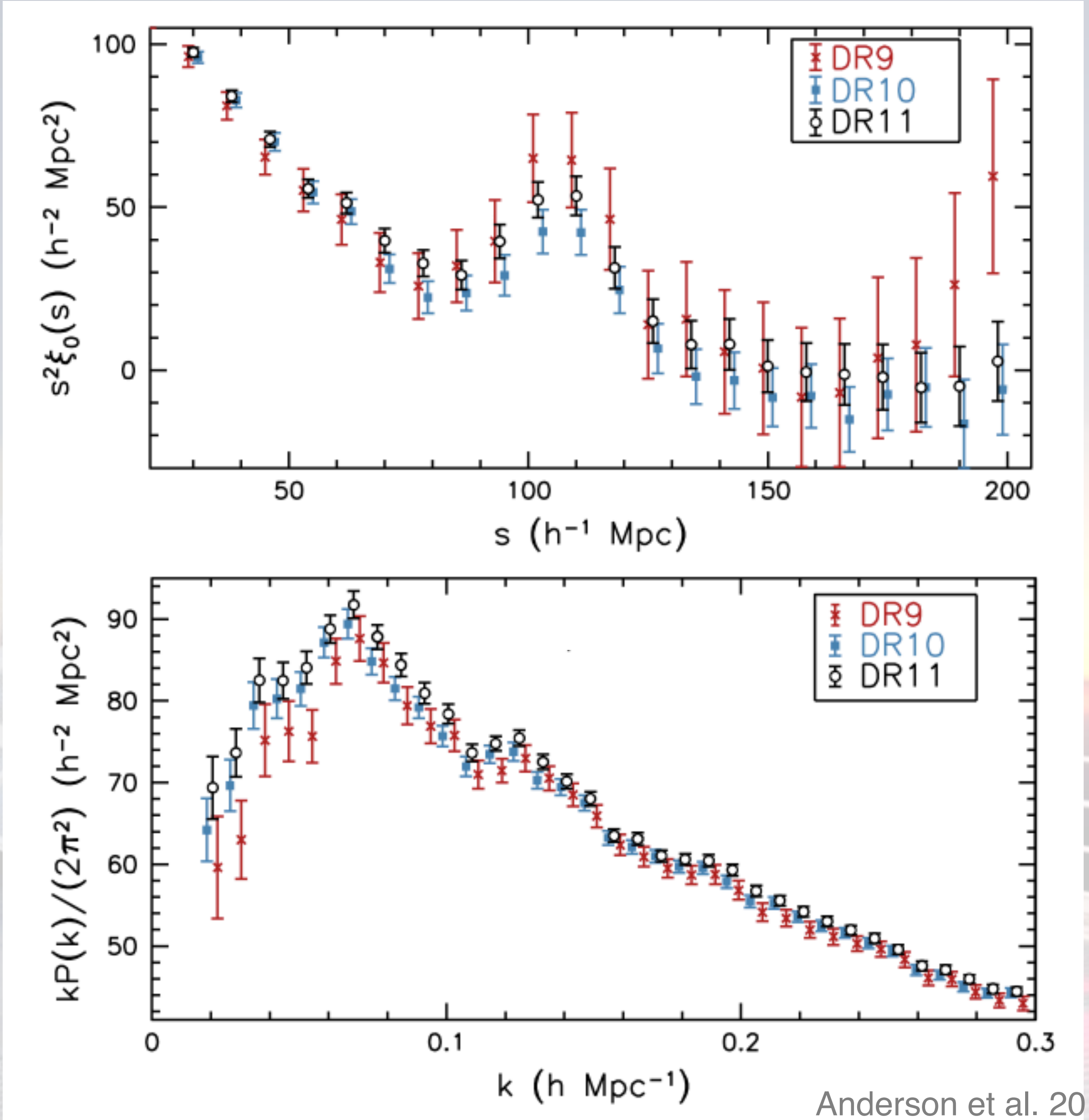


Spectra where we failed to get an accurate redshift are spatially correlated
Close pairs obviously correlated with density

Correct both by upweighting the nearest target with good classification

Ross et al. 2012; arXiv:1208.1491

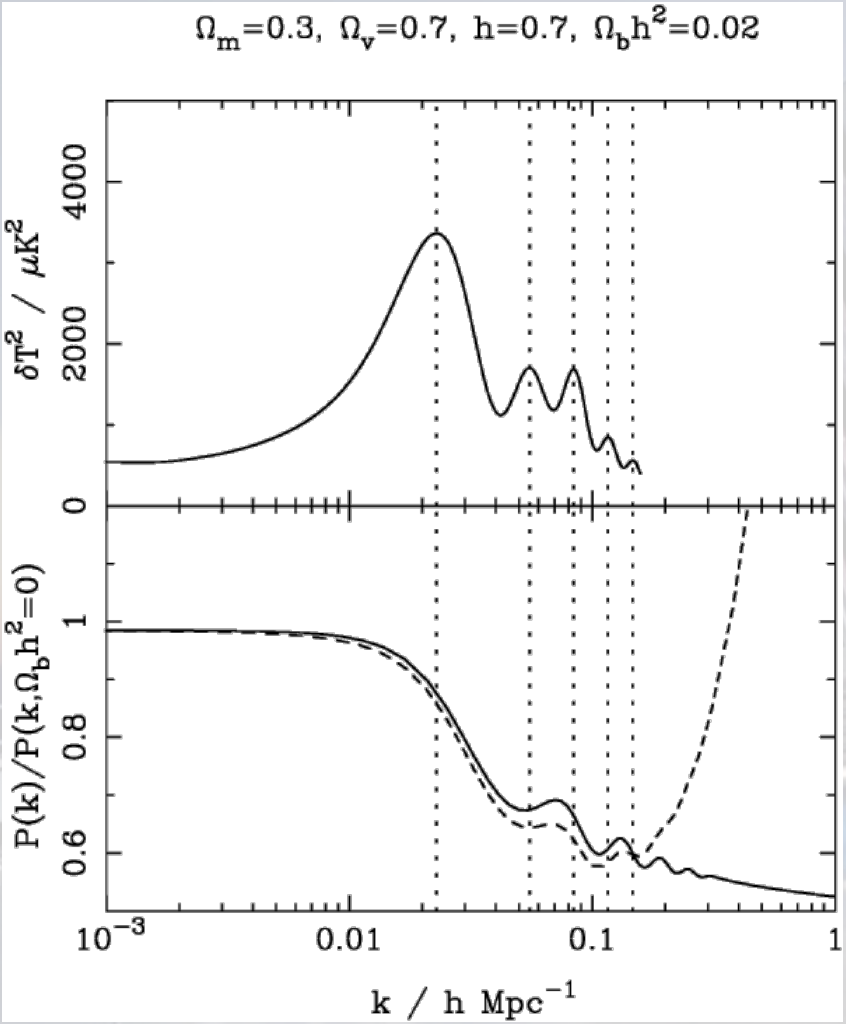
Measured 2-point functions

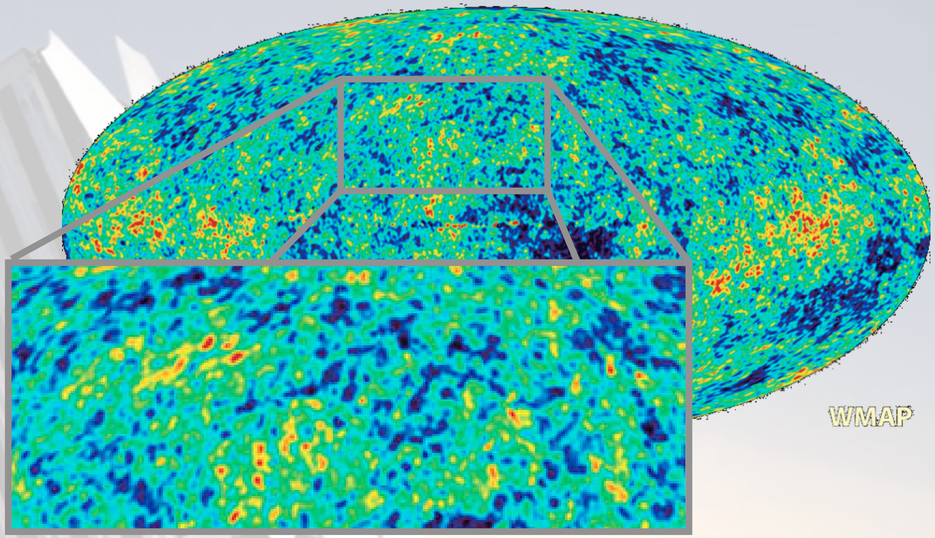


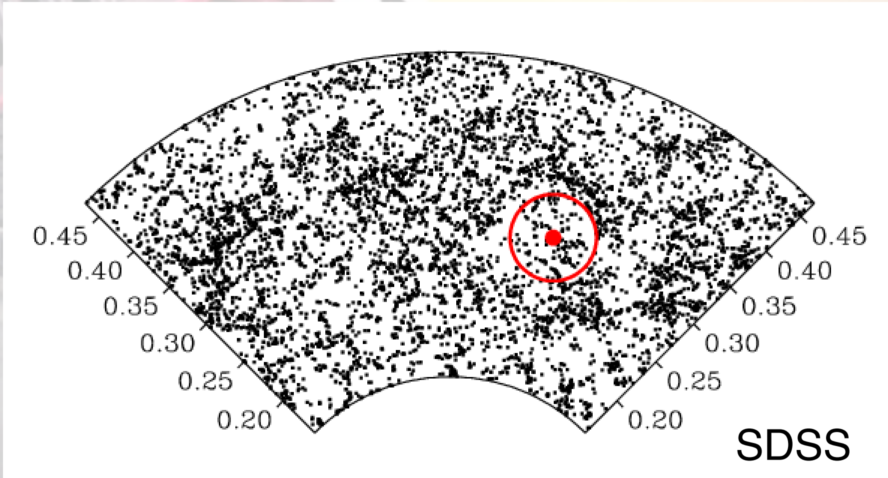
Anderson et al. 2013; arXiv:1312.4877

The matter power spectrum

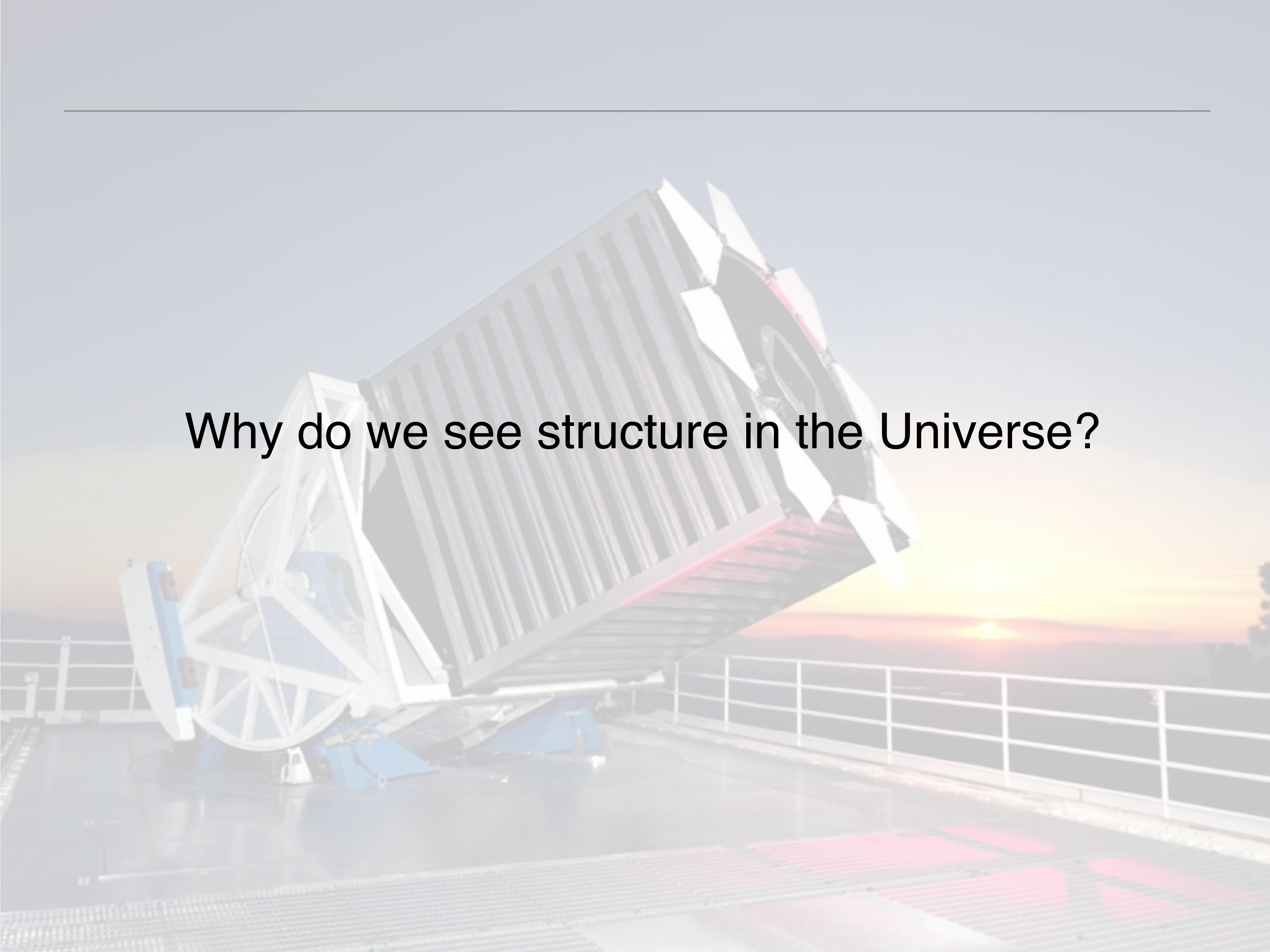
Comparison of CMB and LSS power spectra







Why do we see structure in the Universe?



Why is there structure?

Inflation (a period of rapid growth of the early Universe driven by a scalar field) was postulated to solve some serious problems with "standard" cosmology:

• why do causally disconnected regions appear to have the same properties? – they were connected in the past

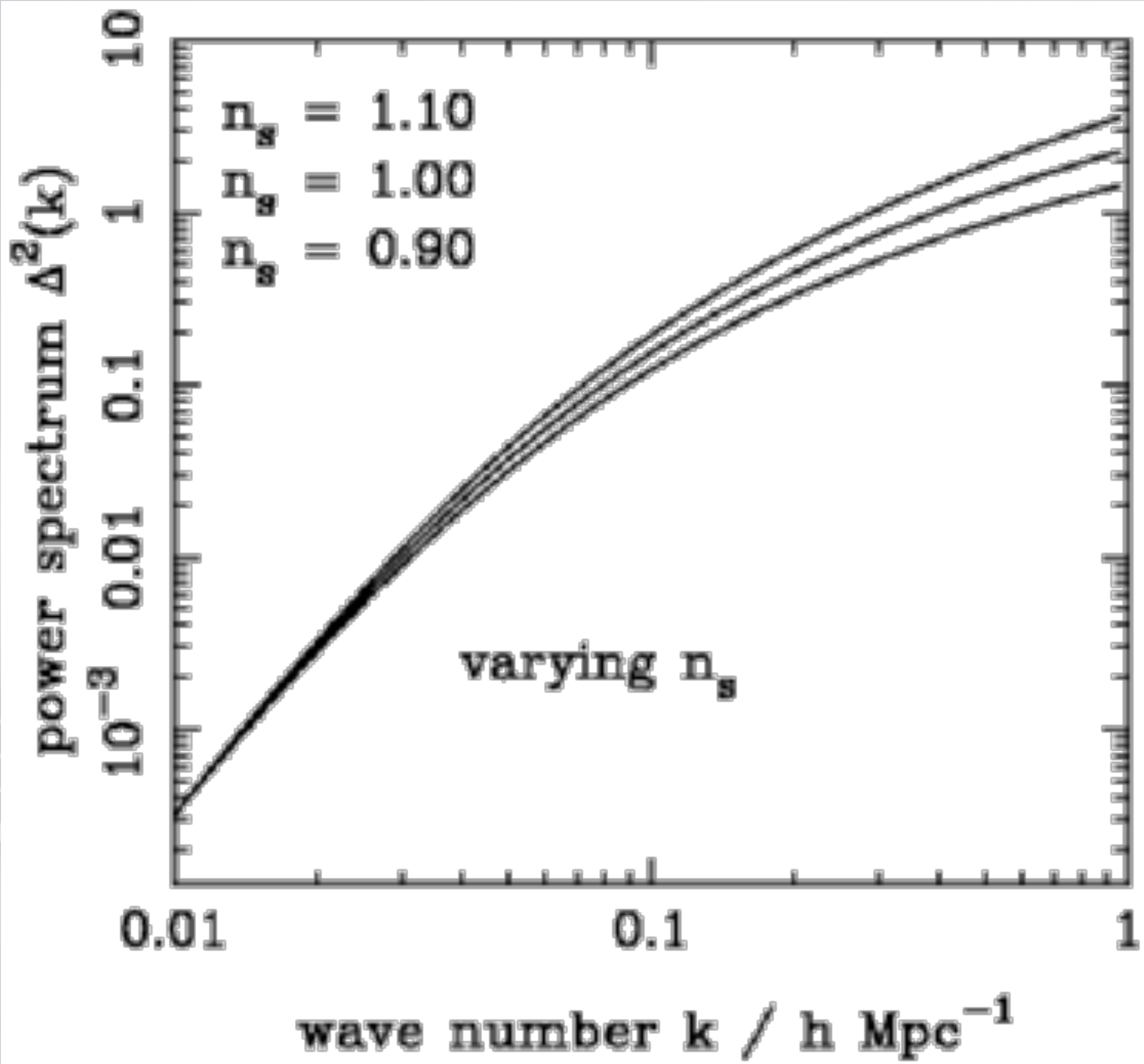
• why is the energy density of the Universe close to critical density? – driven there by inflation

$$P(k) = k^n$$

$$(n \approx 1)$$

•what are the seeds of present-day structure? - Quantum fluctuations in the matter density are increased to significant levels

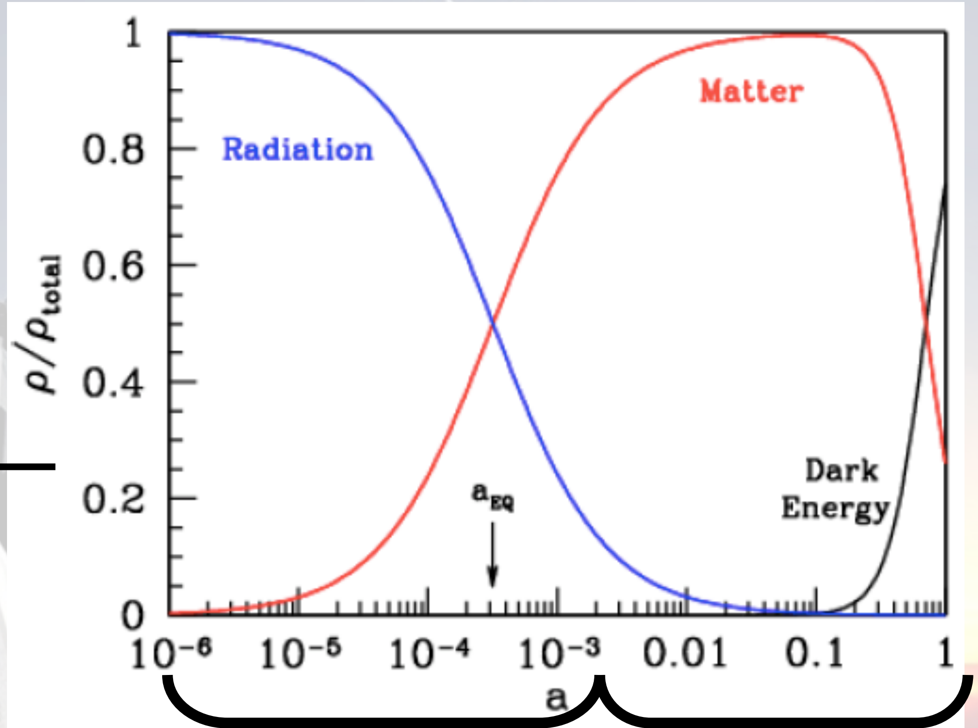
Matter P(k) depends on inflation



$$P(k) = k^n$$

$$(n \approx 1)$$

Evolution of the power spectrum after inflation



Inflation

Transfer function

Matter/DE domination

Non-linear

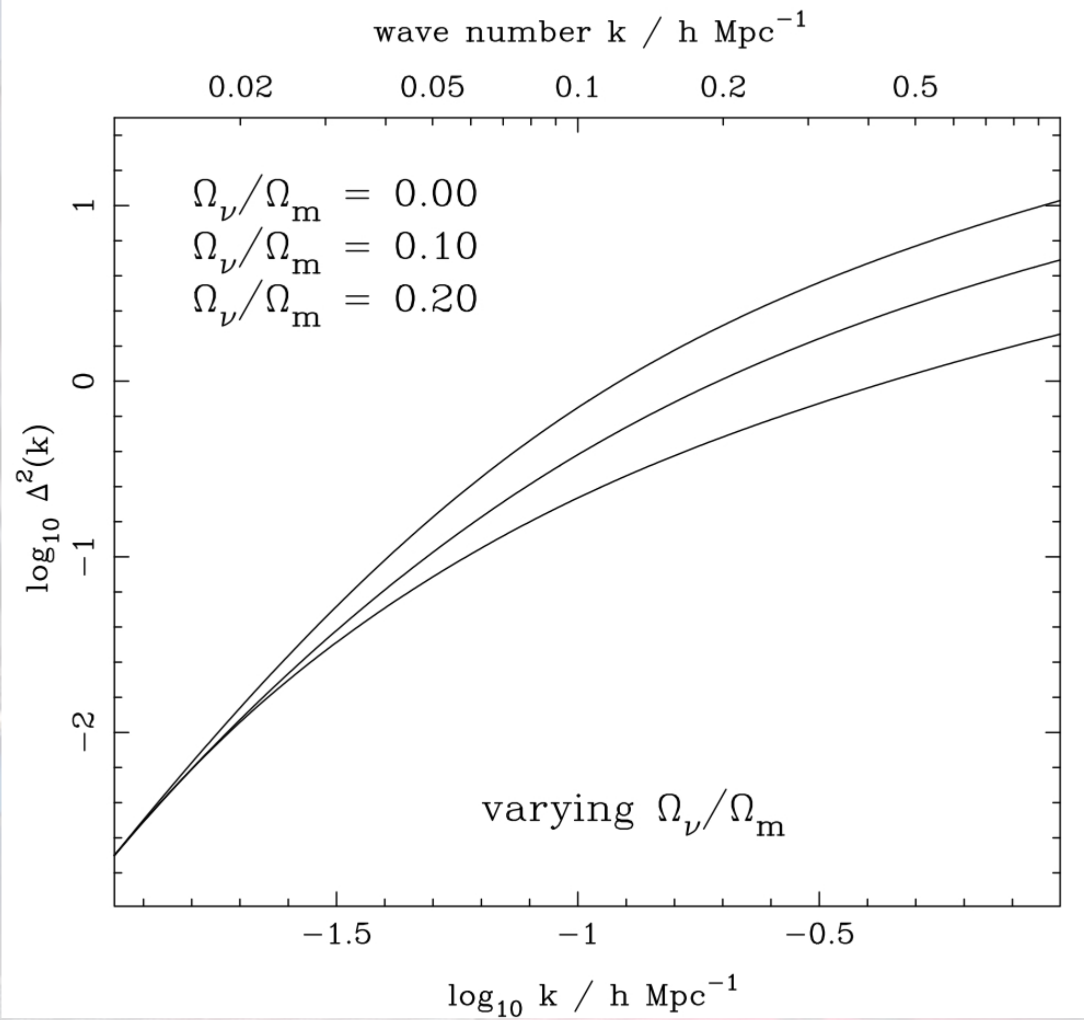
linear growth independent of scale

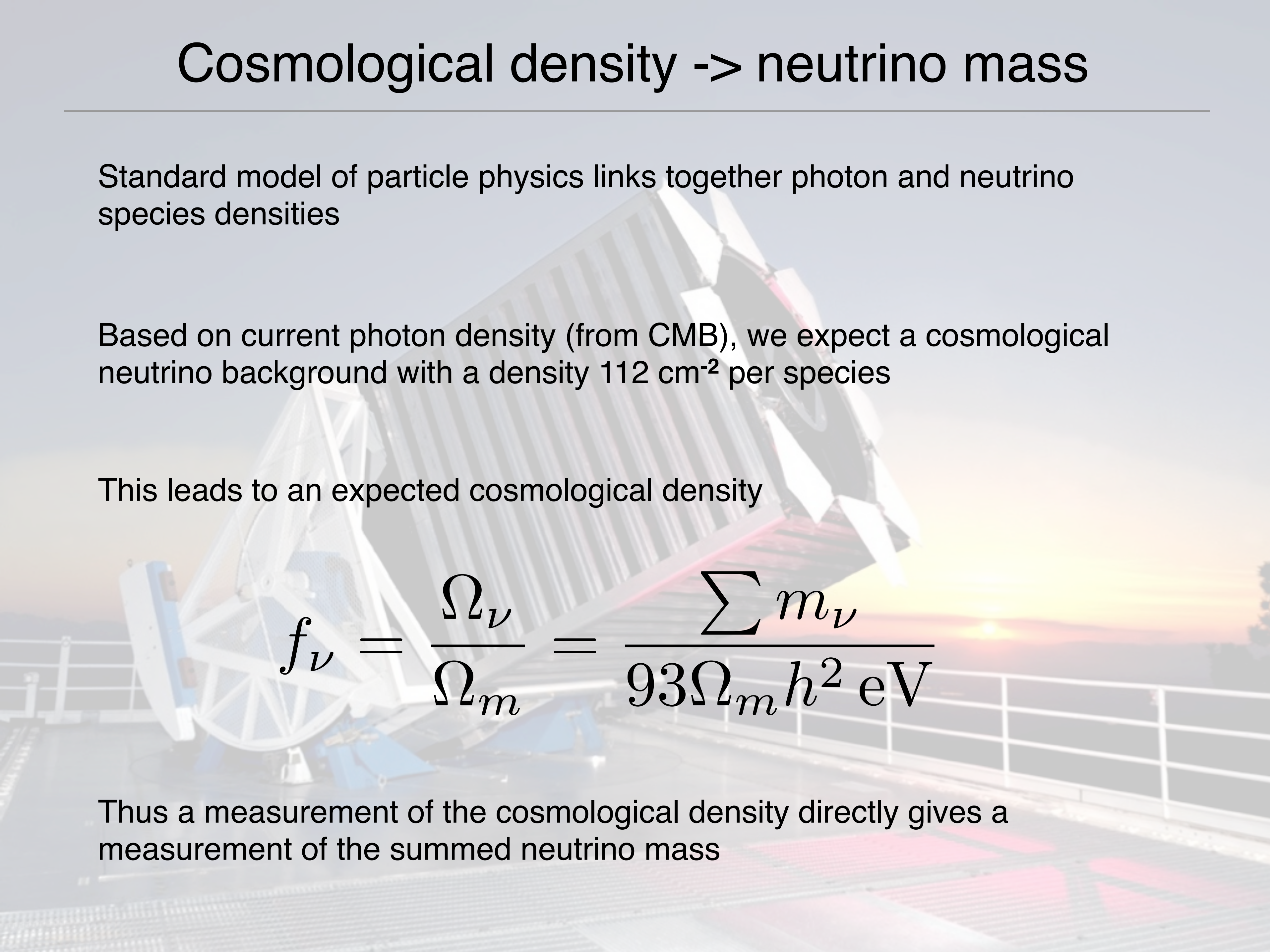
$$P_{\text{lin}}(k) = k^n T^2(k) D^2(a)$$

(comoving coordinates)

The effect of massive neutrinos

The existence of massive neutrinos can also introduce a suppression of T(k) on small scales relative to their Jeans length. Partly degenerate with the suppression caused by radiation epoch. Position depends on neutrino-mass equality scale.





Cosmological density -> neutrino mass

Standard model of particle physics links together photon and neutrino species densities

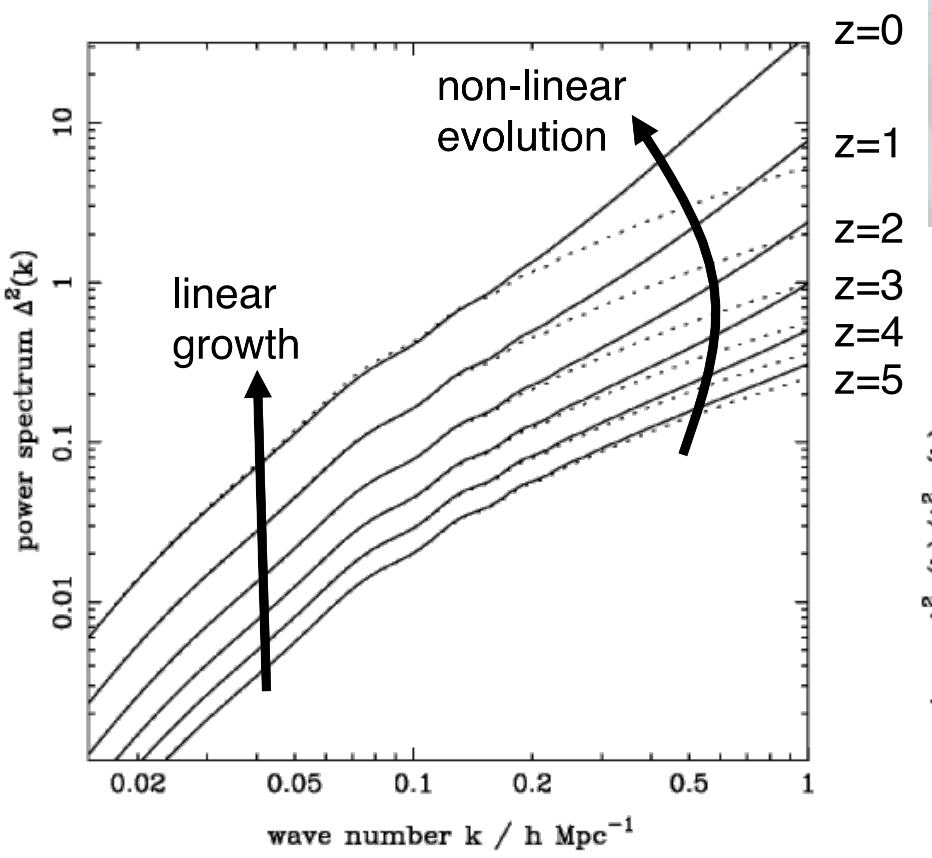
Based on current photon density (from CMB), we expect a cosmological neutrino background with a density 112 cm^{-2} per species

This leads to an expected cosmological density

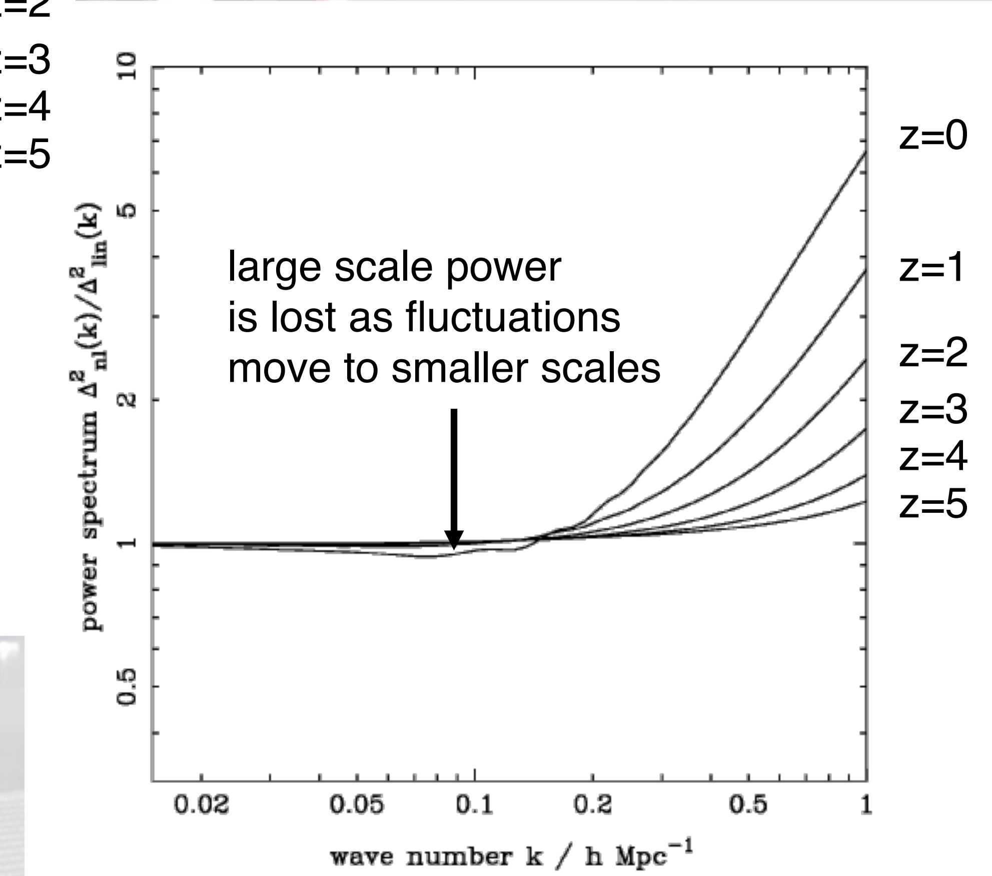
$$f_\nu = \frac{\Omega_\nu}{\Omega_m} = \frac{\sum m_\nu}{93\Omega_m h^2\,\mathrm{eV}}$$

Thus a measurement of the cosmological density directly gives a measurement of the summed neutrino mass

Linear vs Non-linear behaviour

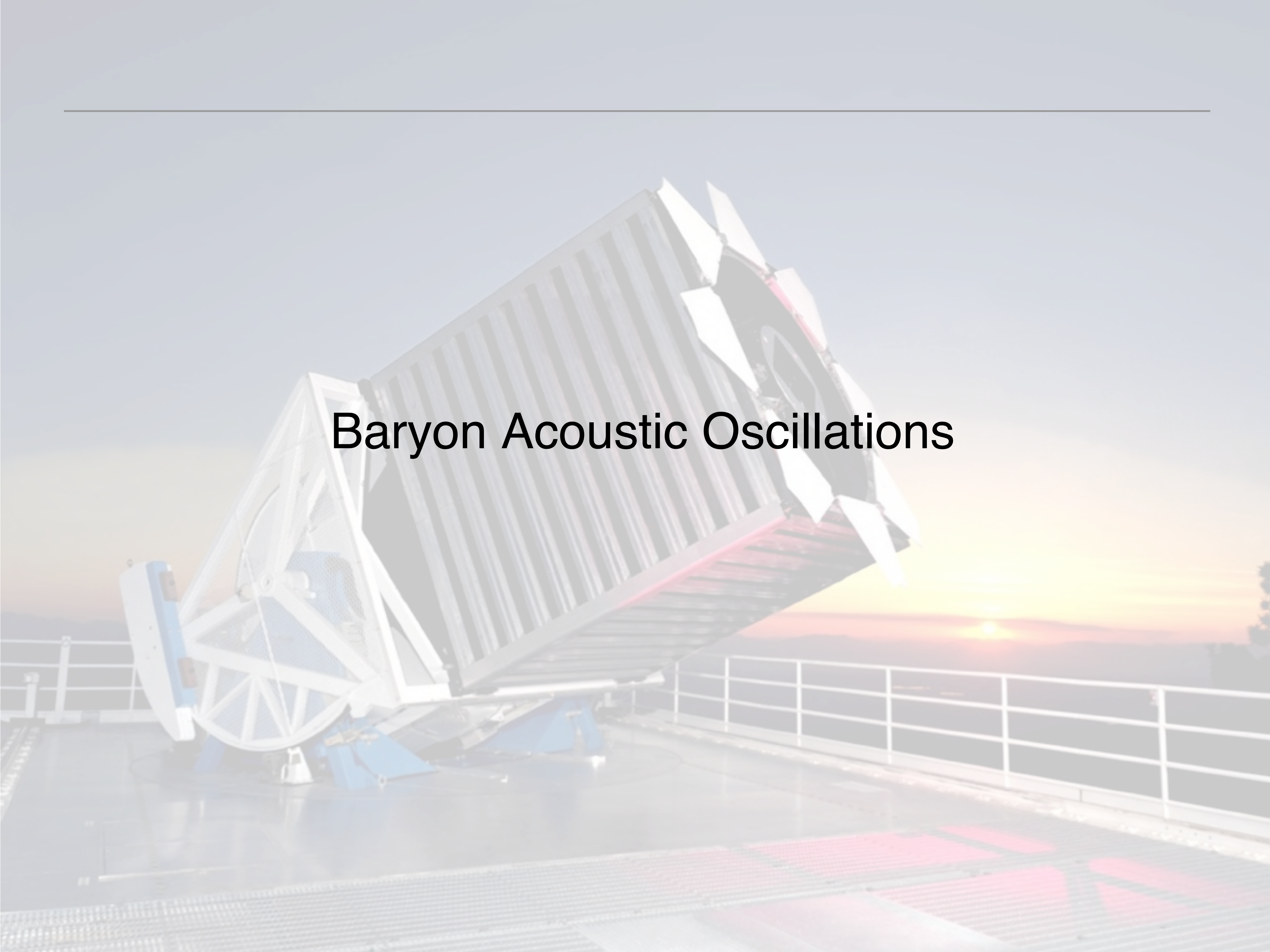


Cannot easily measure growth directly from galaxy surveys as degenerate with galaxy bias

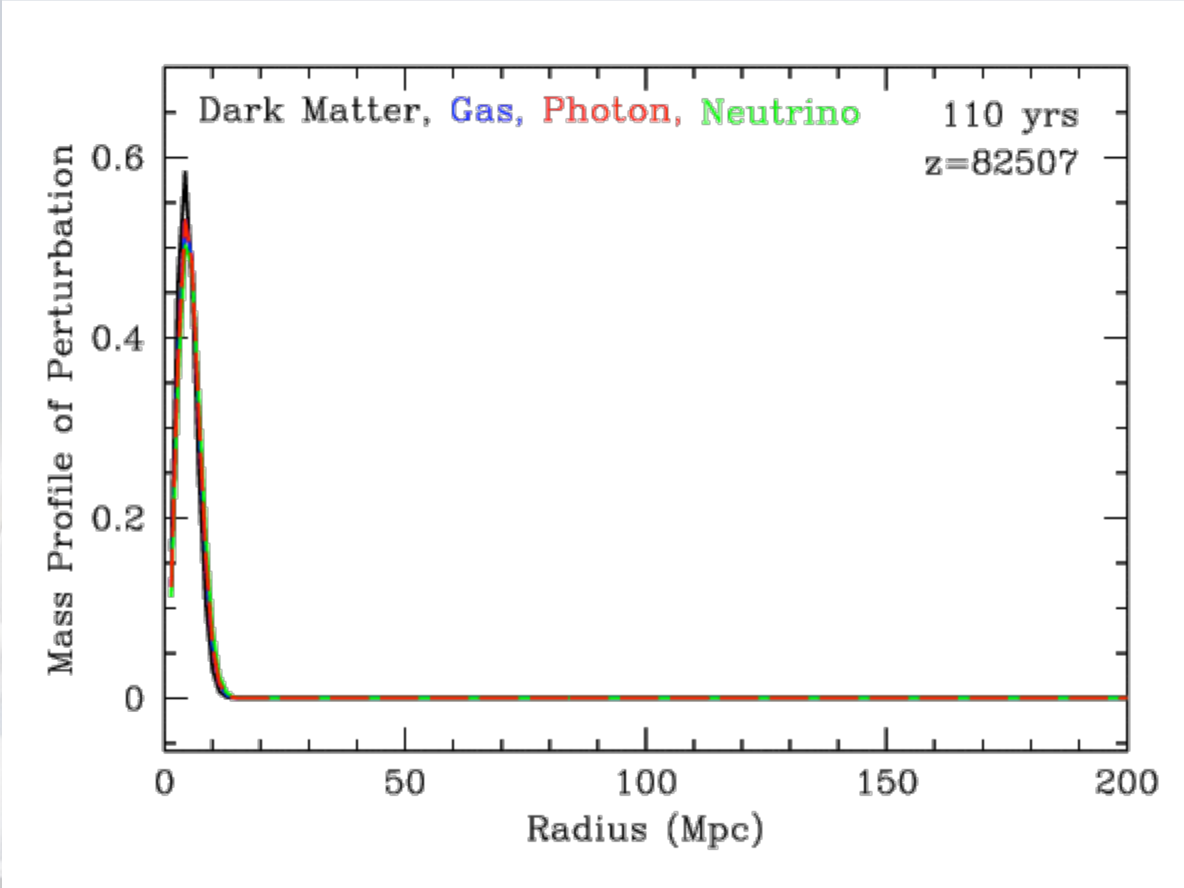


P(k) calculated from Smith et al. 2003, MNRAS, 341,1311 fitting formulae

Baryon Acoustic Oscillations



Configuration space description

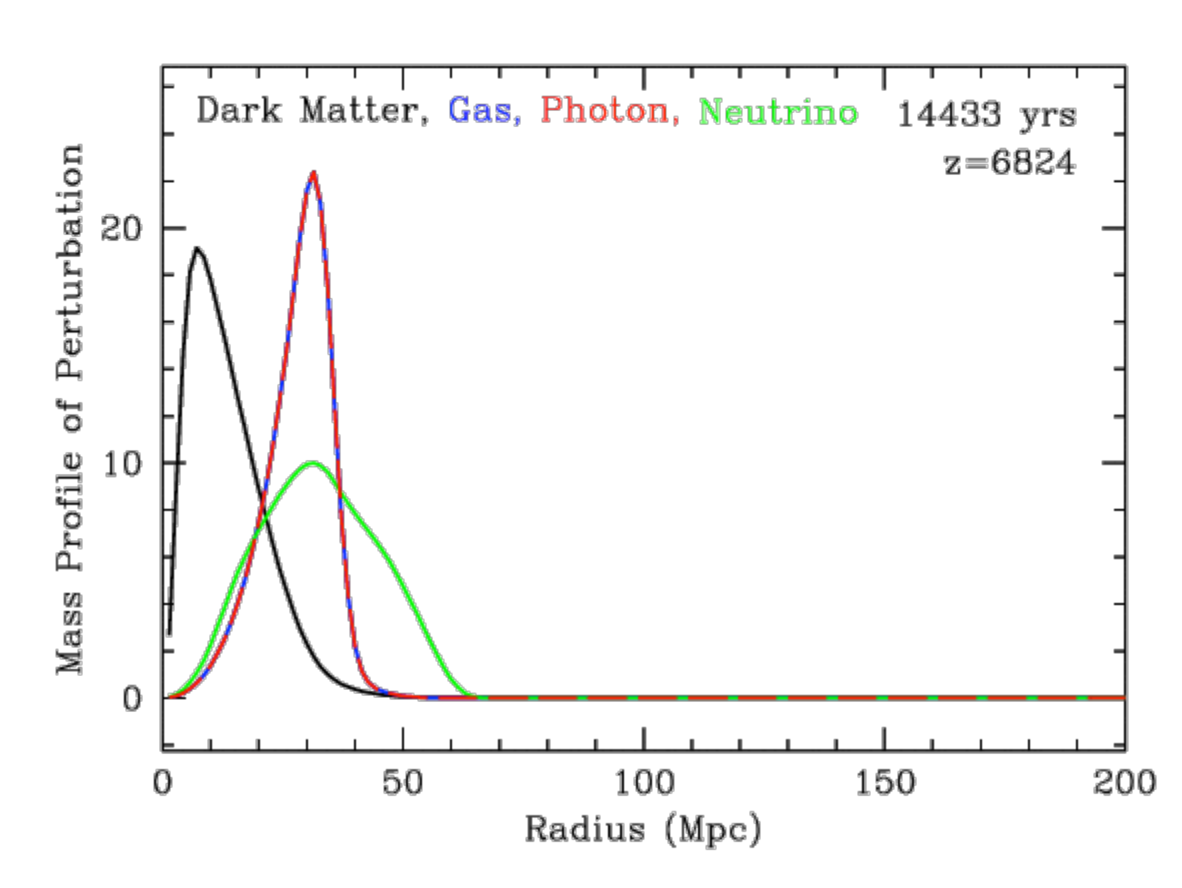


$\Omega_m h^2=0.147$, $\Omega_b h^2=0.024$

position-space description: Bashinsky & Bertschinger
astro-ph/0012153 & astro-ph/02022153

plots by Dan Eisenstein

Configuration space description



$\Omega_m h^2=0.147,\ \Omega_b h^2=0.024$

position-space description: Bashinsky & Bertschinger
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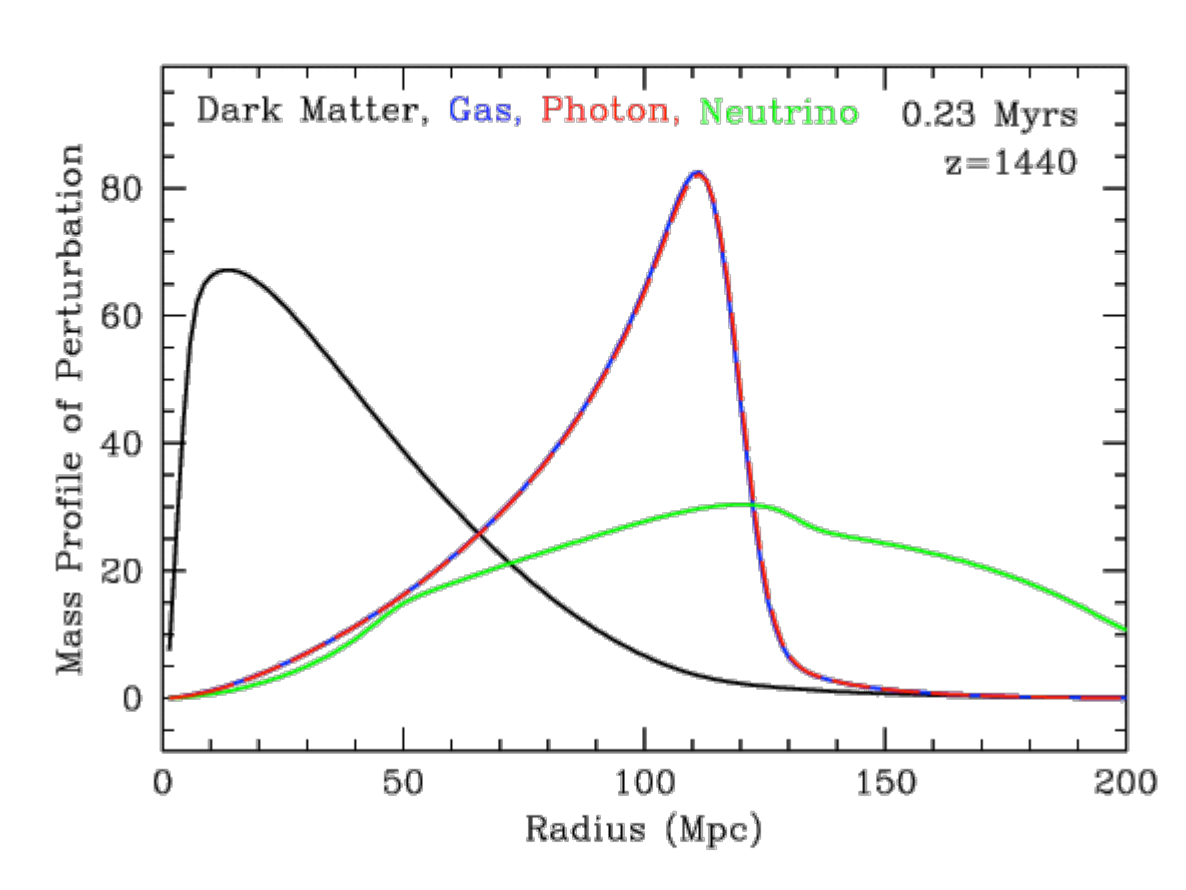
Configuration space description

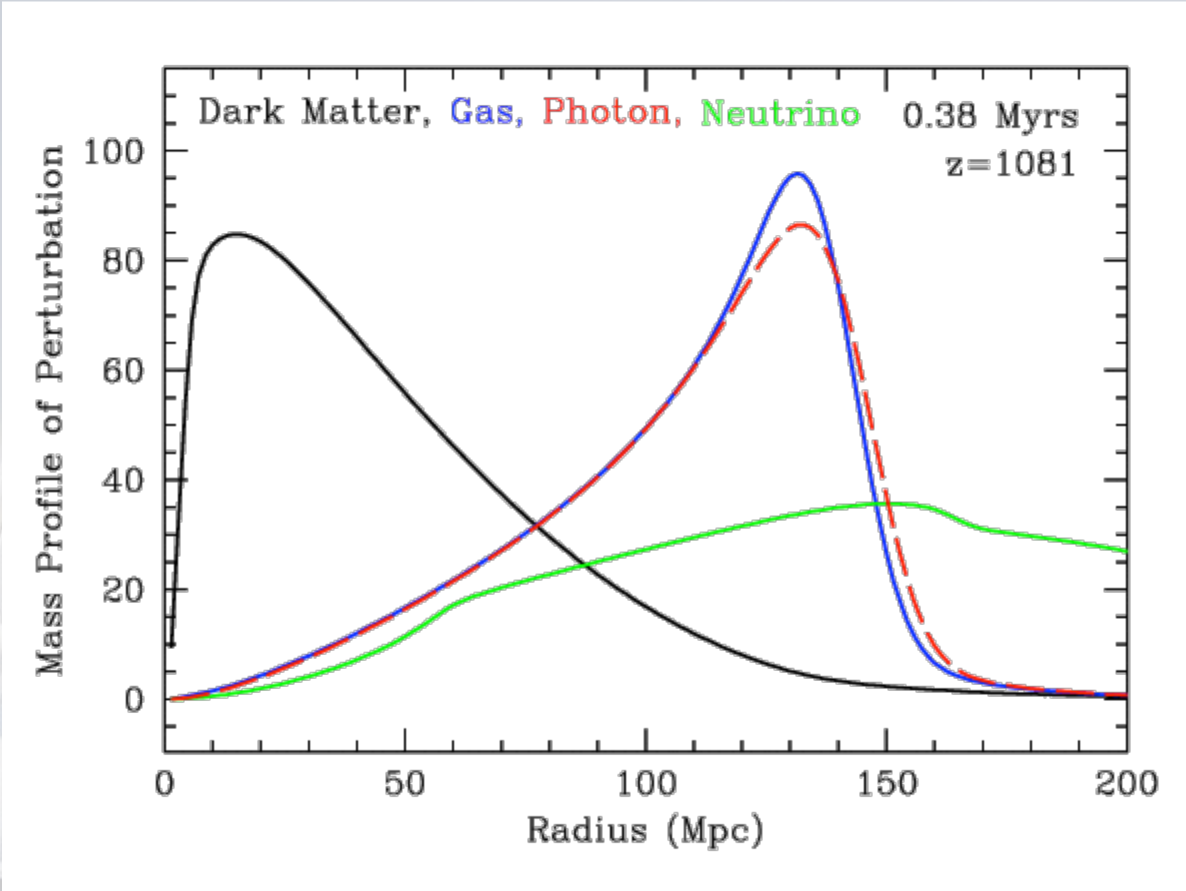


$\Omega_m h^2=0.147,\ \Omega_b h^2=0.024$

position-space description: Bashinsky & Bertschinger
astro-ph/0012153 & astro-ph/02022153

plots by Dan Eisenstein

Configuration space description



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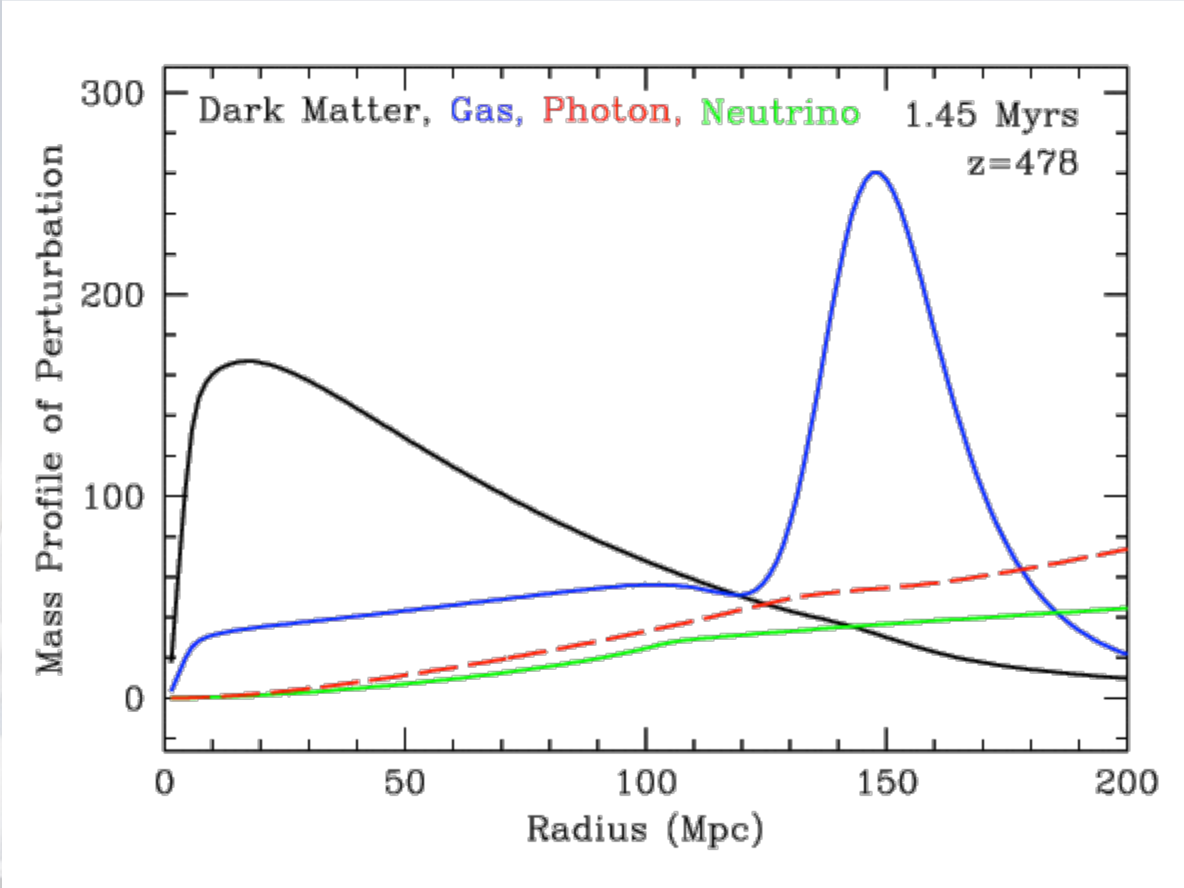

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plots by Dan Eisenstein

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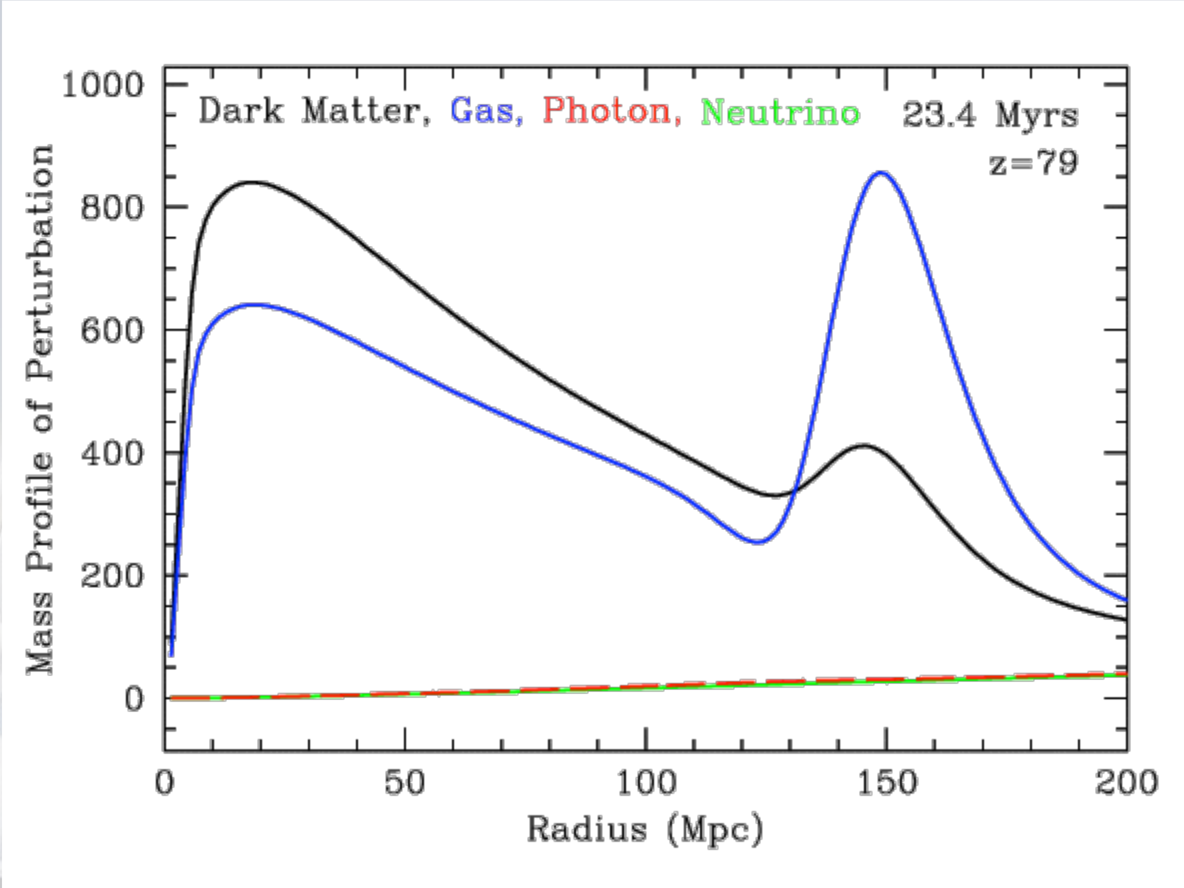

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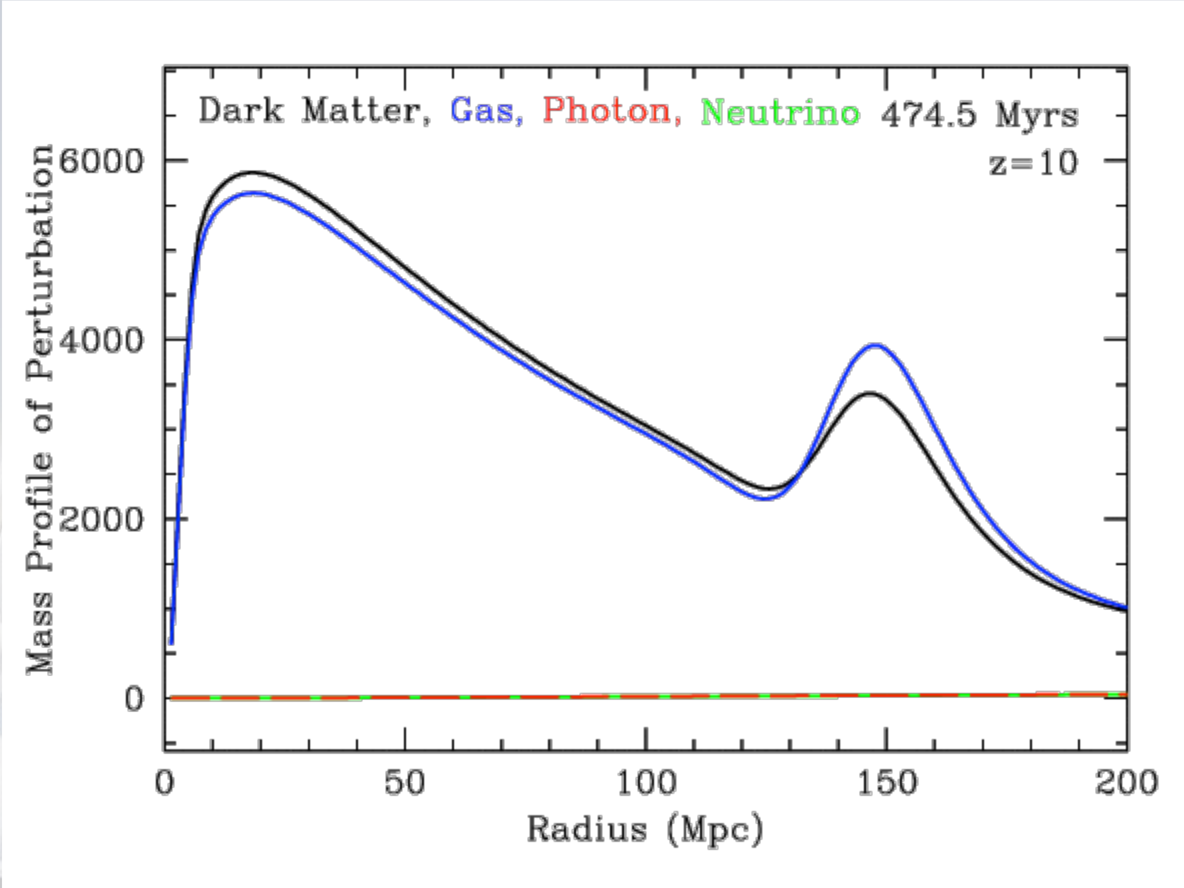
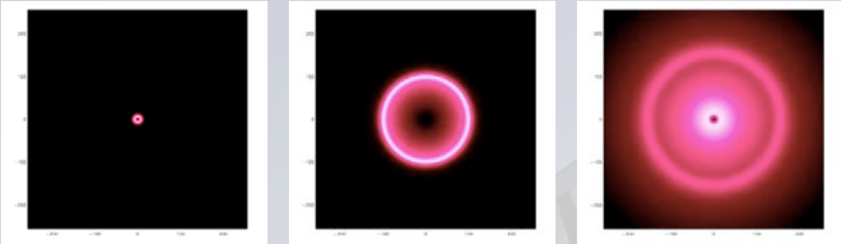


$\Omega_m h^2=0.147$, $\Omega_b h^2=0.024$

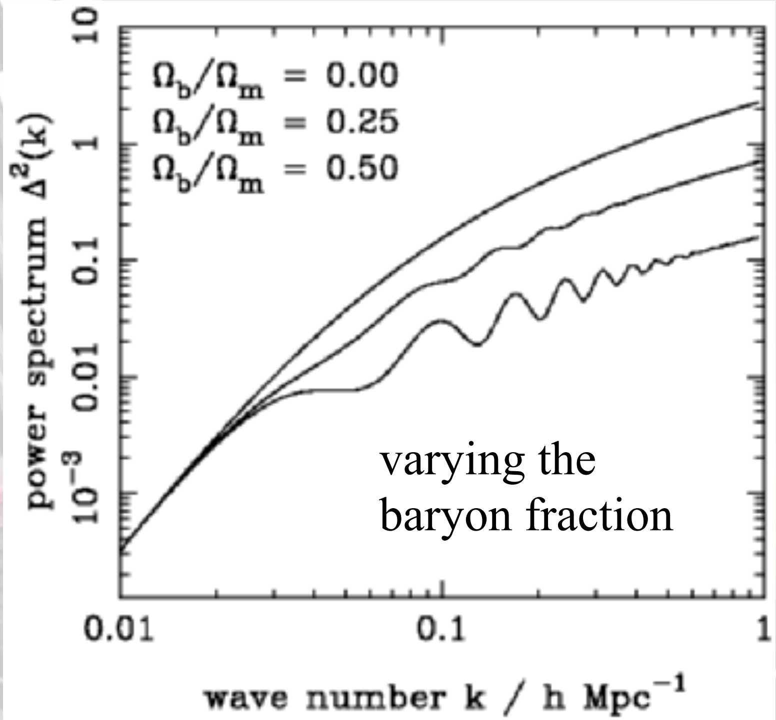
position-space description: Bashinsky & Bertschinger
astro-ph/0012153 & astro-ph/02022153

plots by Dan Eisenstein

Baryon Acoustic Oscillations (BAO)



(images from Martin White)



To first approximation, BAO wavelength is determined by the comoving sound horizon at recombination

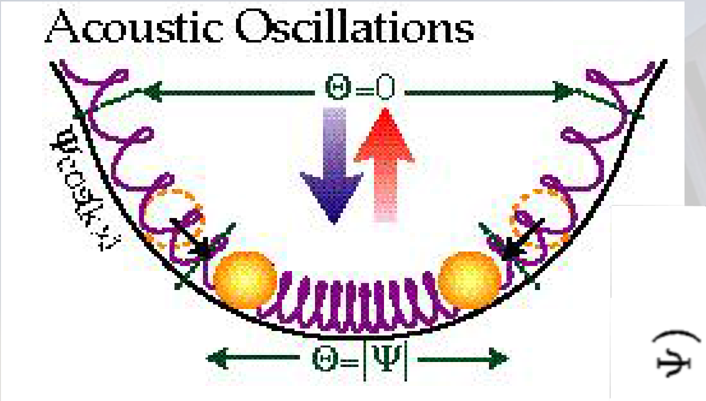
$$k_{\rm bao} = 2\pi/s$$

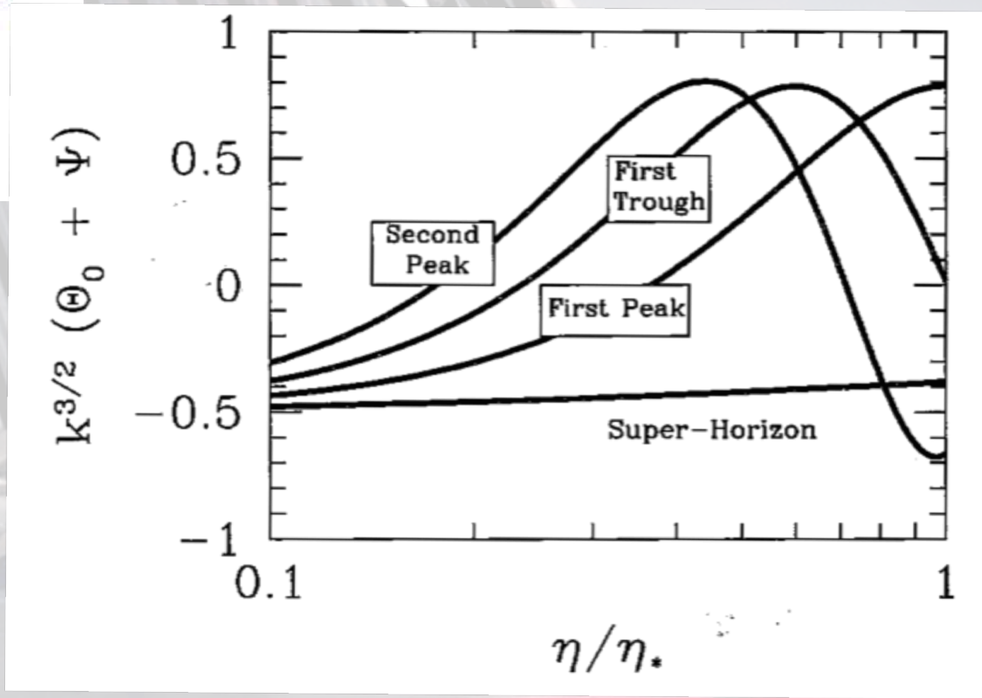
$$s = \frac{1}{H_0 \Omega_m^{1/2}} \int_0^{a_*} da \frac{c_s}{(a + a_{\rm eq})^{1/2}}$$

comoving sound horizon ~110h^{-1}Mpc, BAO wavelength 0.06hMpc^{-1}

Acoustic Oscillations in the matter distribution

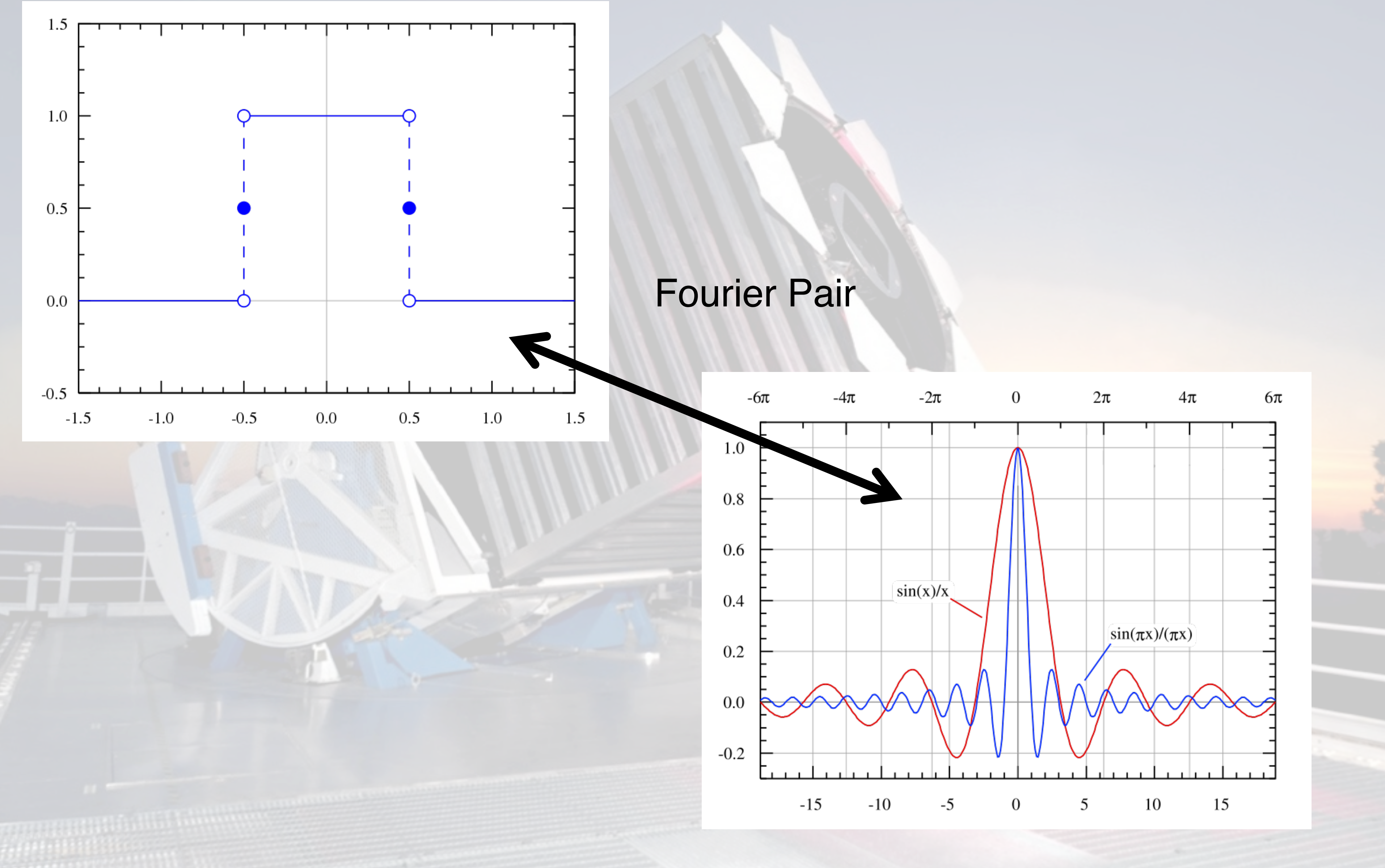
$$\ddot{\Theta}_0 + k^2 c_s^2 \Theta_0 = F$$





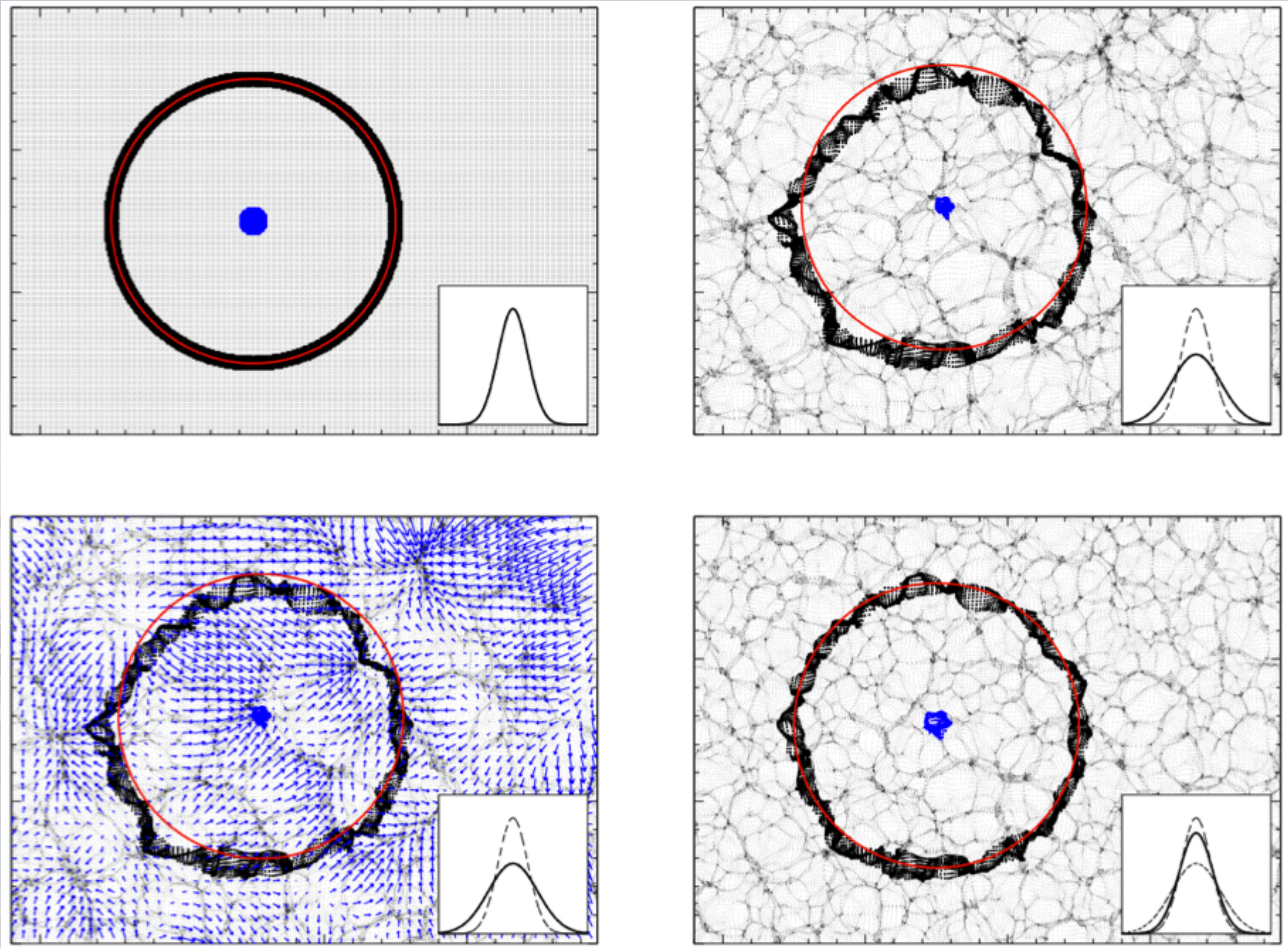
Dodelson "modern cosmology"

descriptions describe the same physics



Reconstruction

Non-linear movement on BAO scales



Padmanabhan et al. 2012; arXiv:1202.0090

A simple reconstruction algorithm

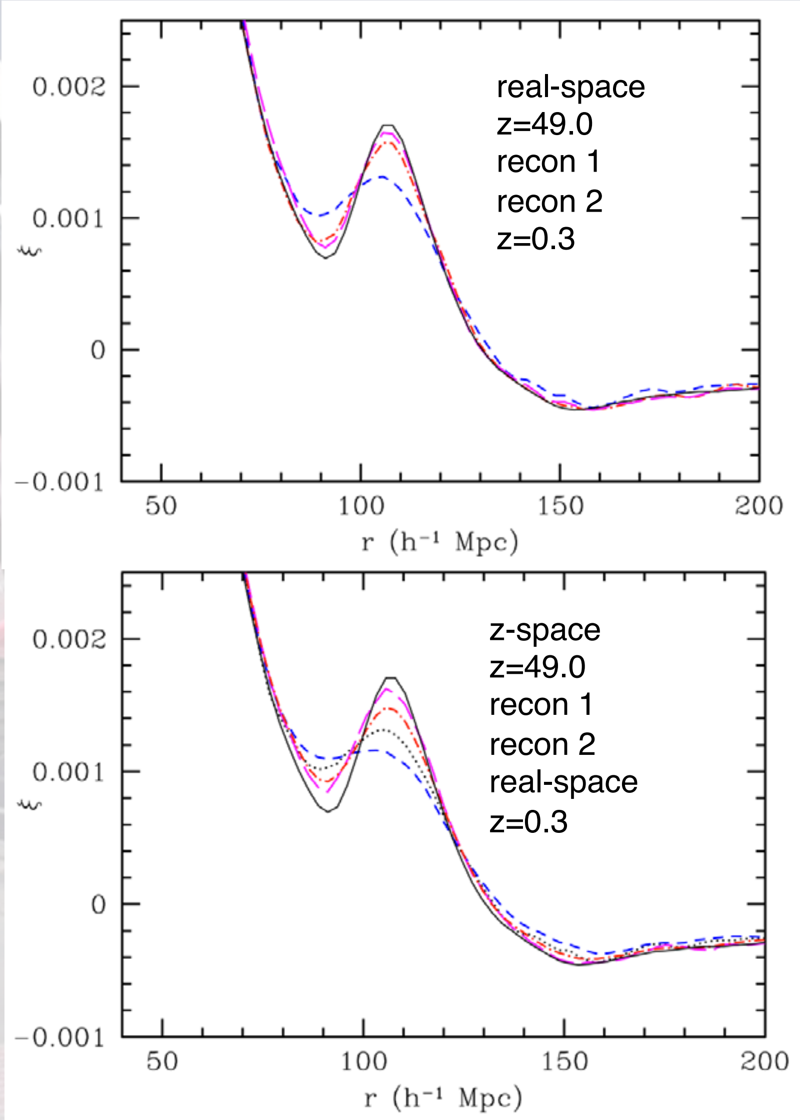
"Smoothing" dominated by large-scale flows

Smooth field and move galaxies by predicted (linear) motion

Breaks coherence between large-scale and small-scale motion

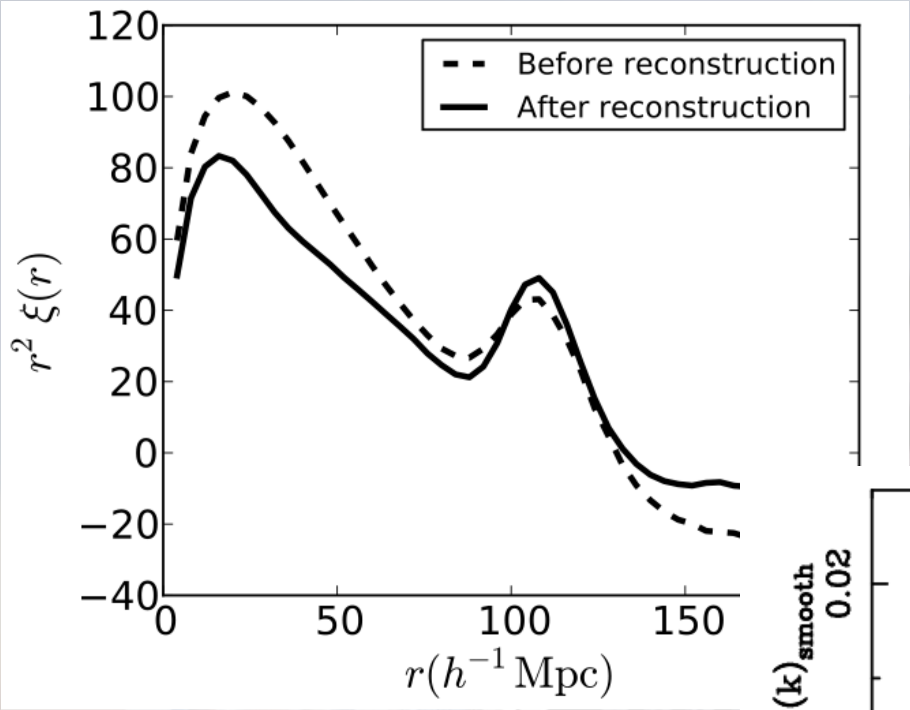
Does not recover the linear field, but does reduce the non-linear smoothing

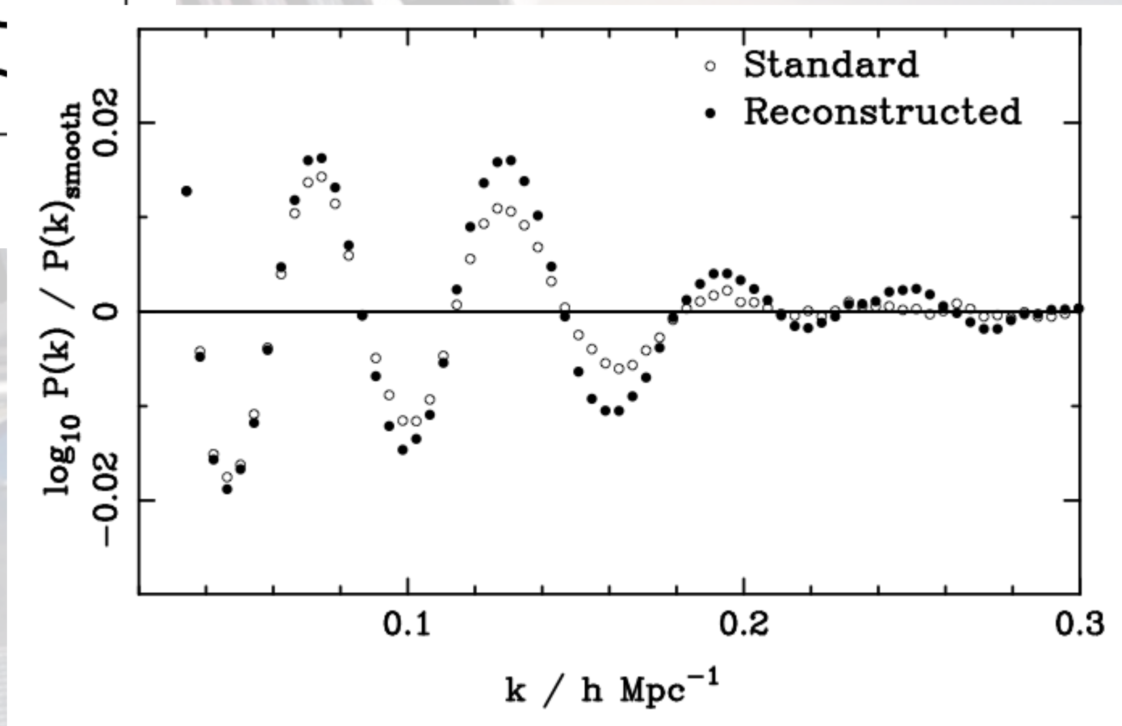
See Padmanabhan et al. (2008; arXiv: 0812.2905) for a perturbation theory derivation of this



Eisenstein et al. 2006: arXiv:0604362

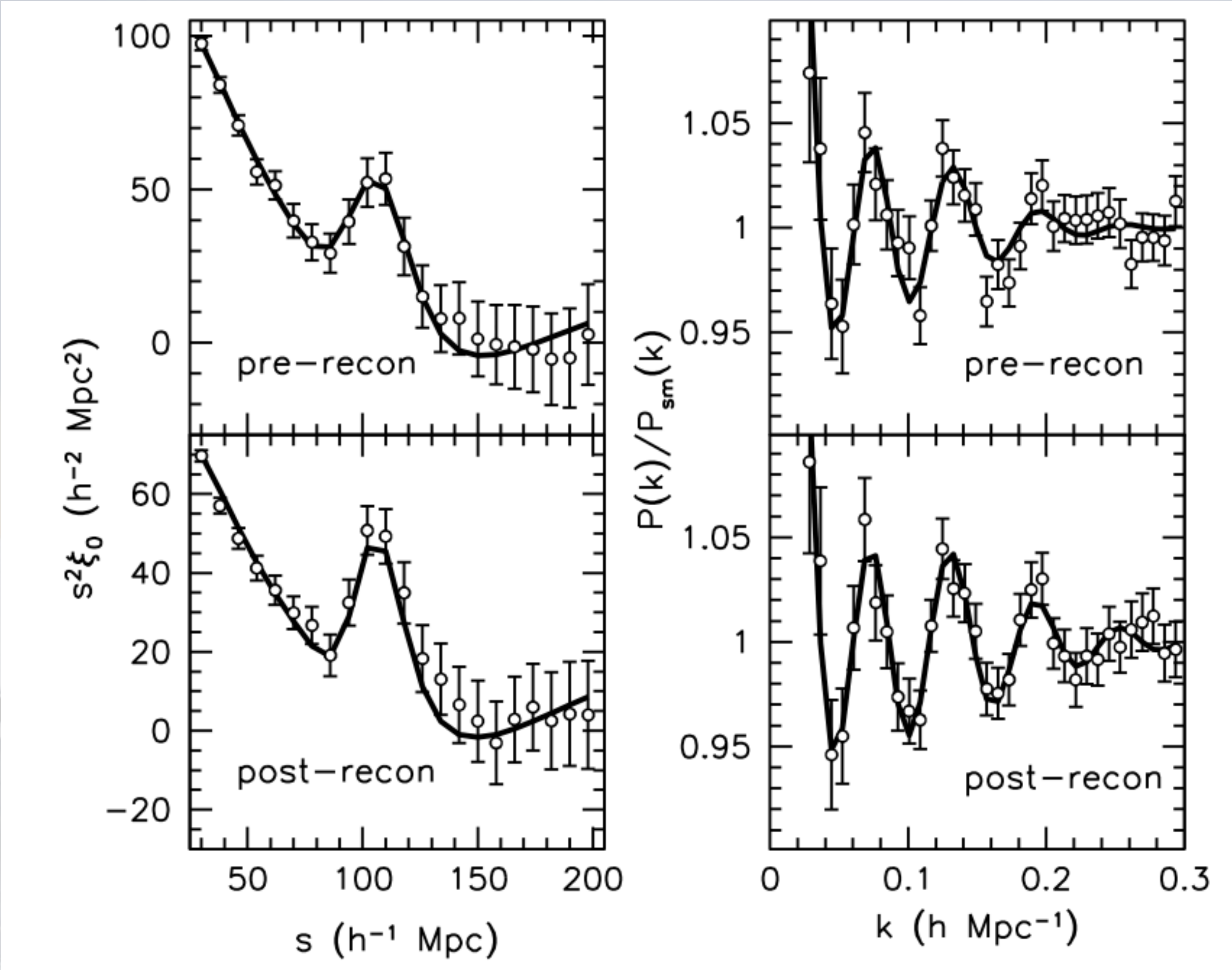
Reconstruction on SDSS-III mocks





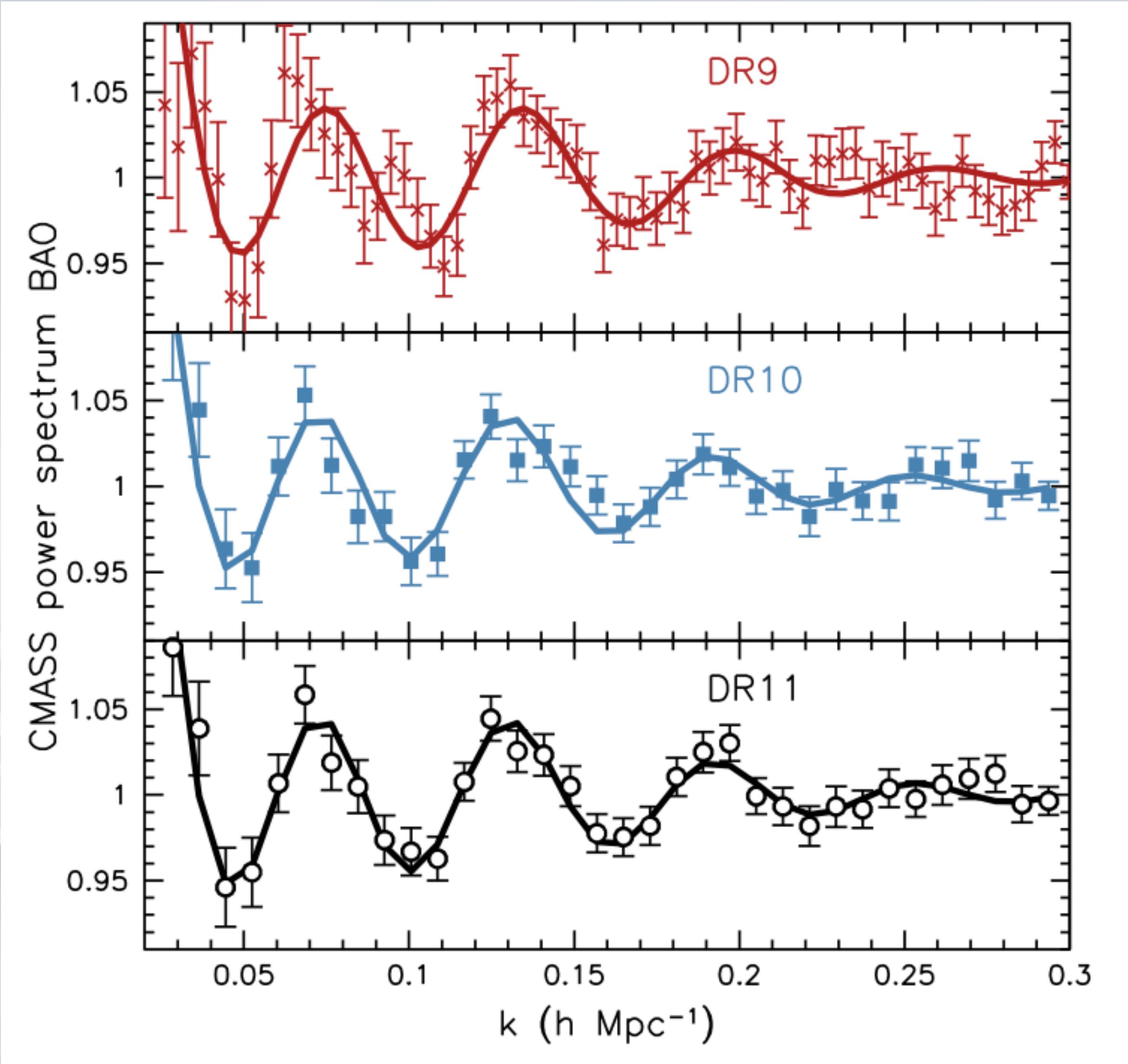
Anderson et al. 2012; arXiv:1203.6565

The improvement from reconstruction



Anderson et al. 2013; arXiv:1312.4877

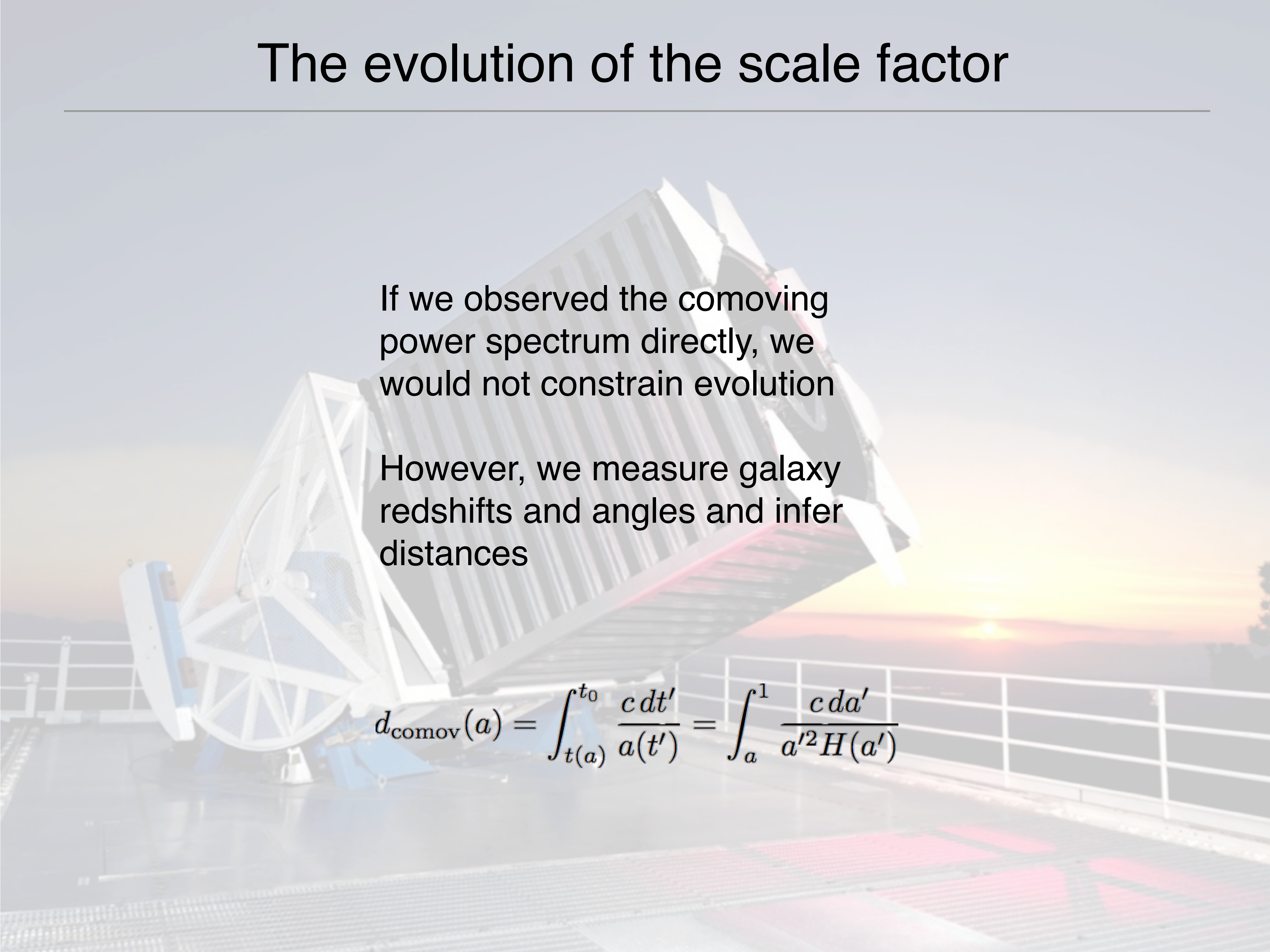
The improvement DR9 - DR11



Anderson et al. 2013; arXiv:1312.4877

Galaxy clustering as a standard ruler

The evolution of the scale factor

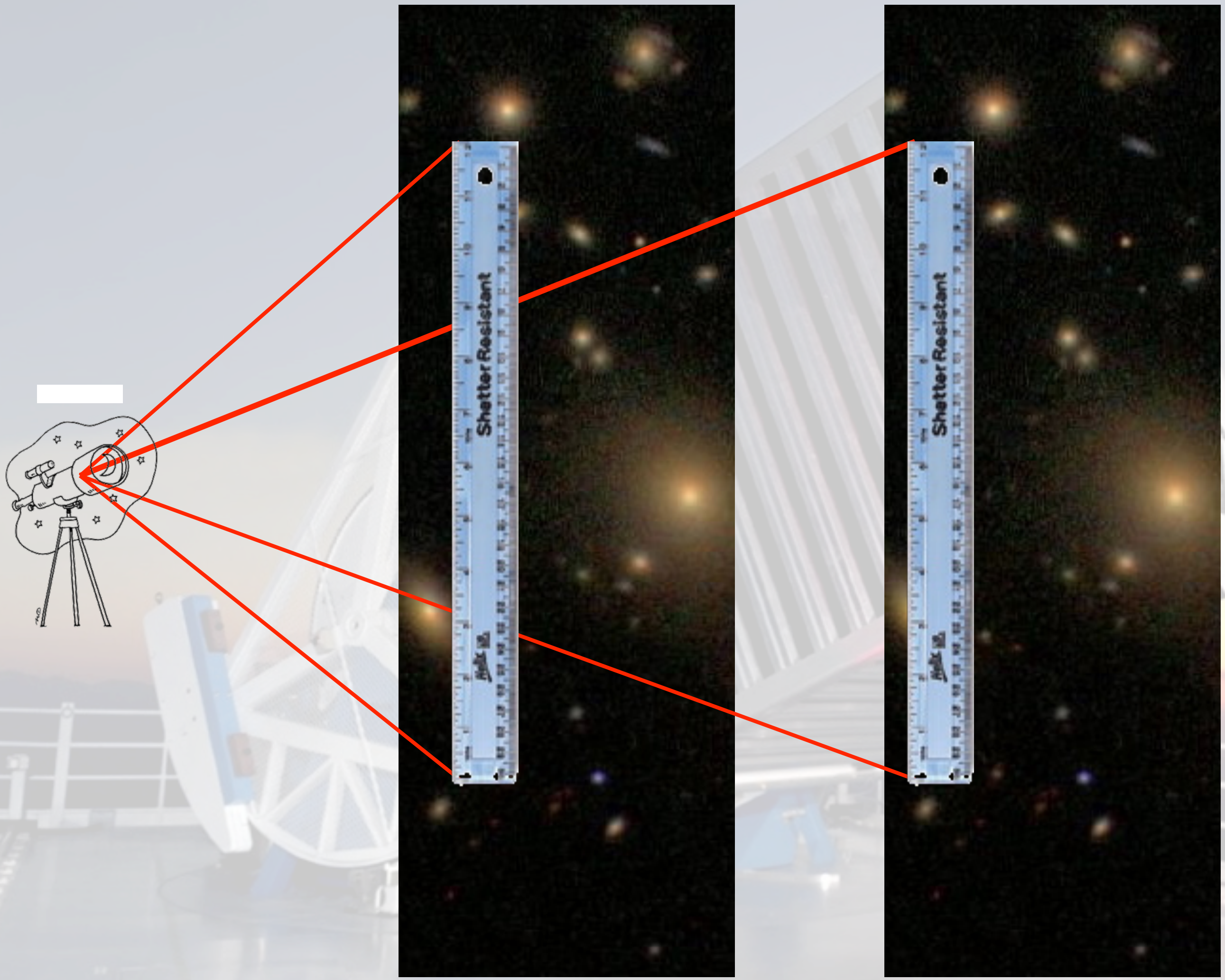


If we observed the comoving power spectrum directly, we would not constrain evolution

However, we measure galaxy redshifts and angles and infer distances

$$d_{\mathrm{comov}}(a) = \int_{t(a)}^{t_0} \frac{c\,dt'}{a(t')} = \int_{a}^{1} \frac{c\,da'}{a'^2 H(a')}$$

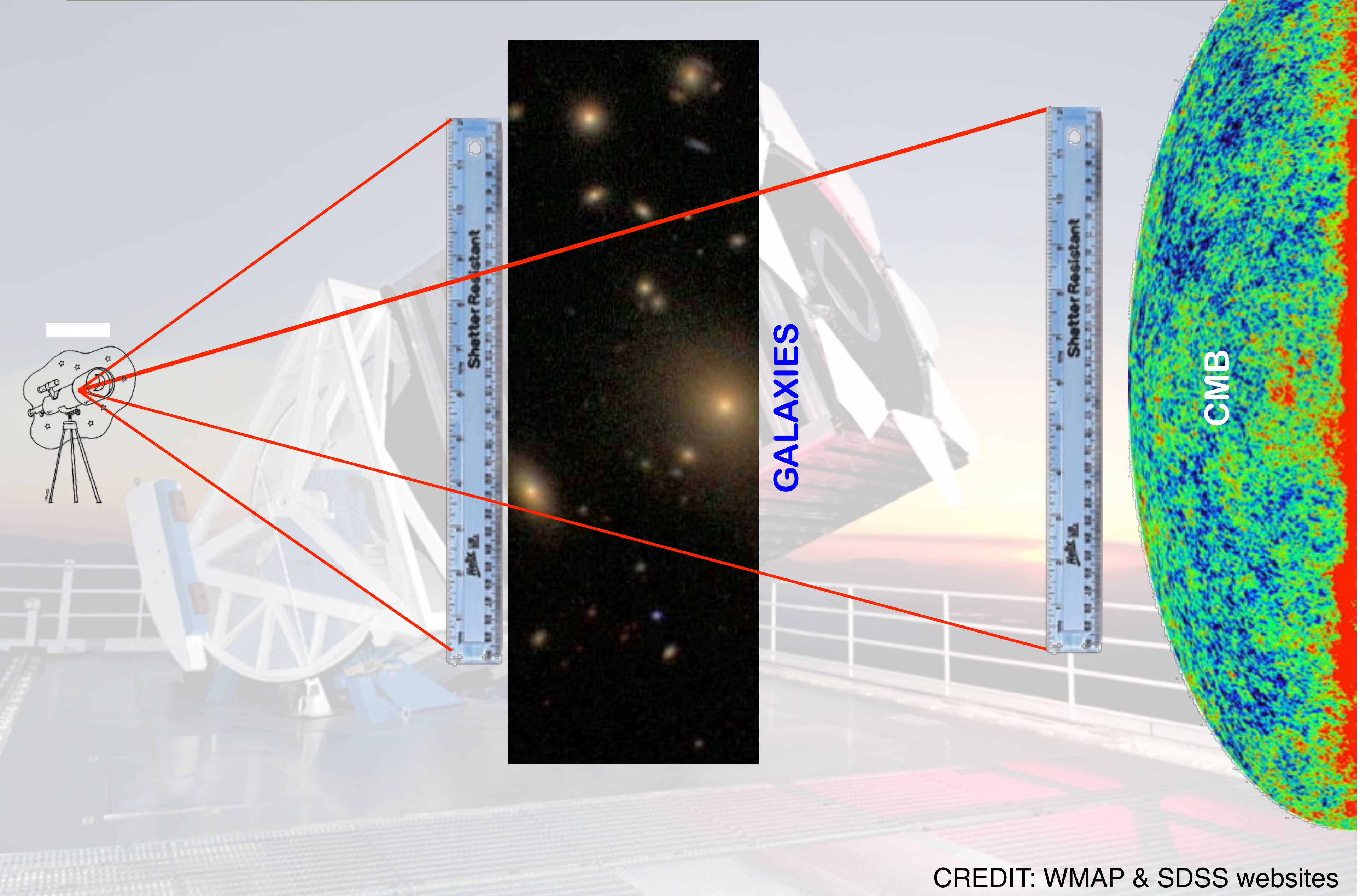
The power spectrum as a standard ruler



z=0.2 z=0.35

CREDIT: WMAP & SDSS websites

The power spectrum as a standard ruler



CREDIT: WMAP & SDSS websites

BAO as a standard ruler

Changes in cosmological model alter measured BAO scale ($\Delta d_{\mathbf{comov}}$) by:

Radial direction $\frac{c}{H(z)}\Delta z$

(evolution of Universe)

Angular direction

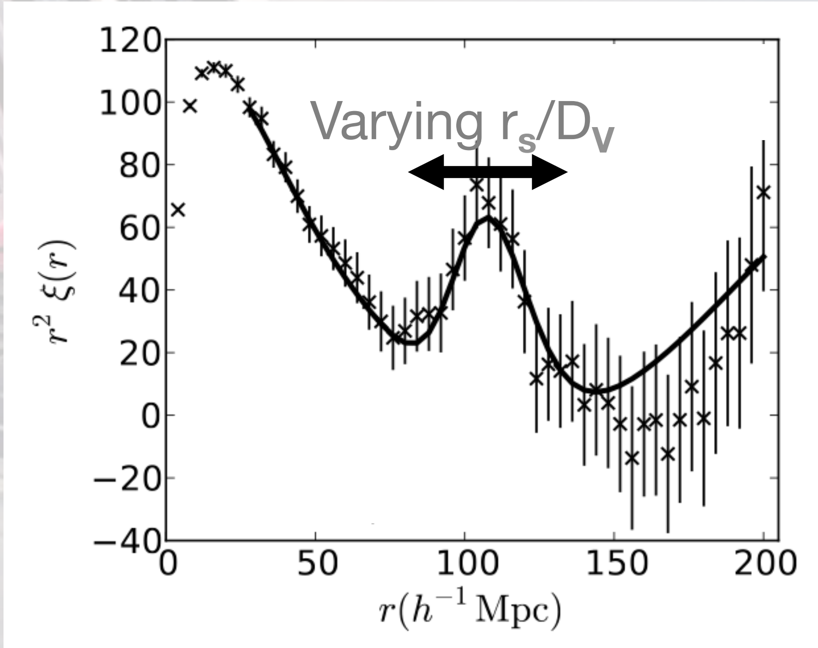
$$(1+z)D_A\Delta\theta$$

(line of sight)

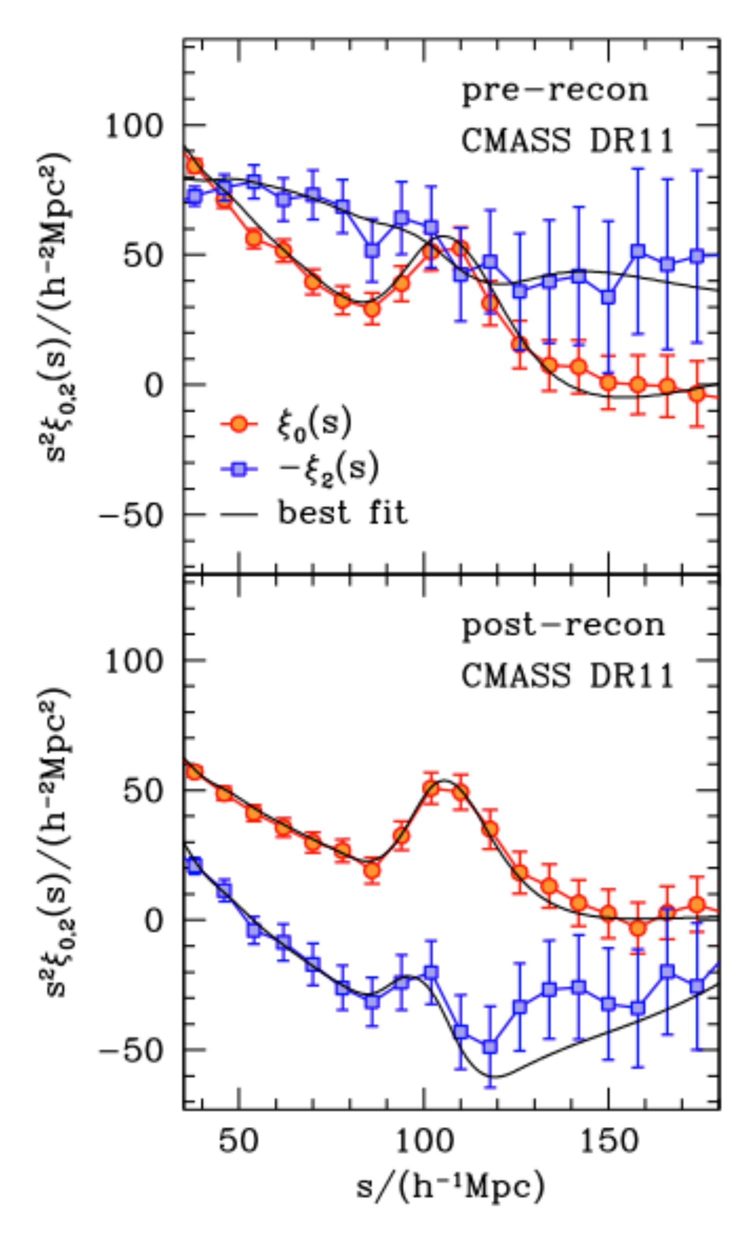
If we are considering radial and angular directions using randomly orientated galaxy pairs, we constrain (to 1st order)

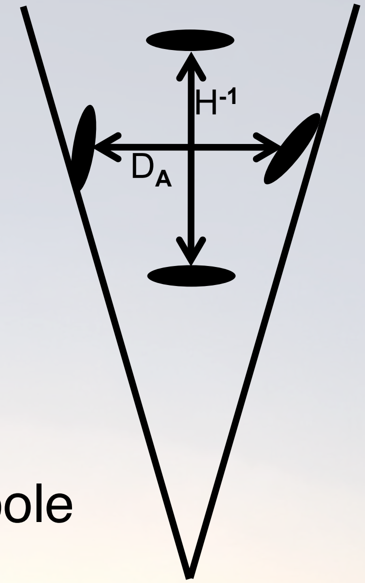
$$D_V = \left[(1+z)^2 D_A^2(z)\frac{cz}{H(z)}\right]^{1/3}$$

BAO position (in a redshift slice) therefore constrains some multiple of $\frac{r_s}{D_V}$



Fitting BAO along and across line-of-sight





monopole

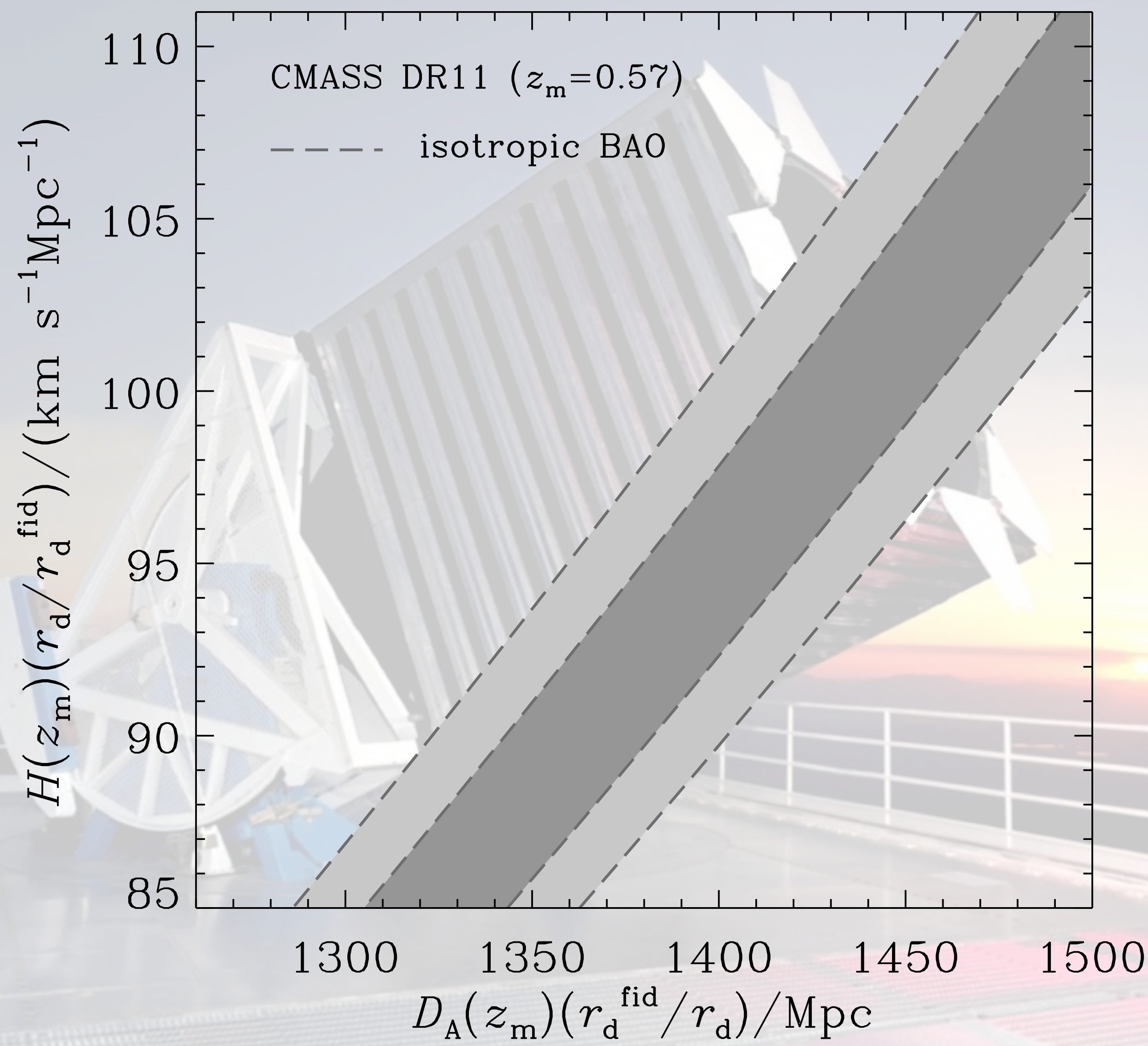
$$\xi_2^s(r) = \frac{3}{2}\int_{-1}^{+1} d\mu\ \xi^s(r,\mu)$$

quadrupole

$$\xi_2^s(r) = \frac{5}{2}\int_{-1}^{+1} d\mu\ \xi^s(r,\mu)\frac{3\mu^2-1}{2}$$

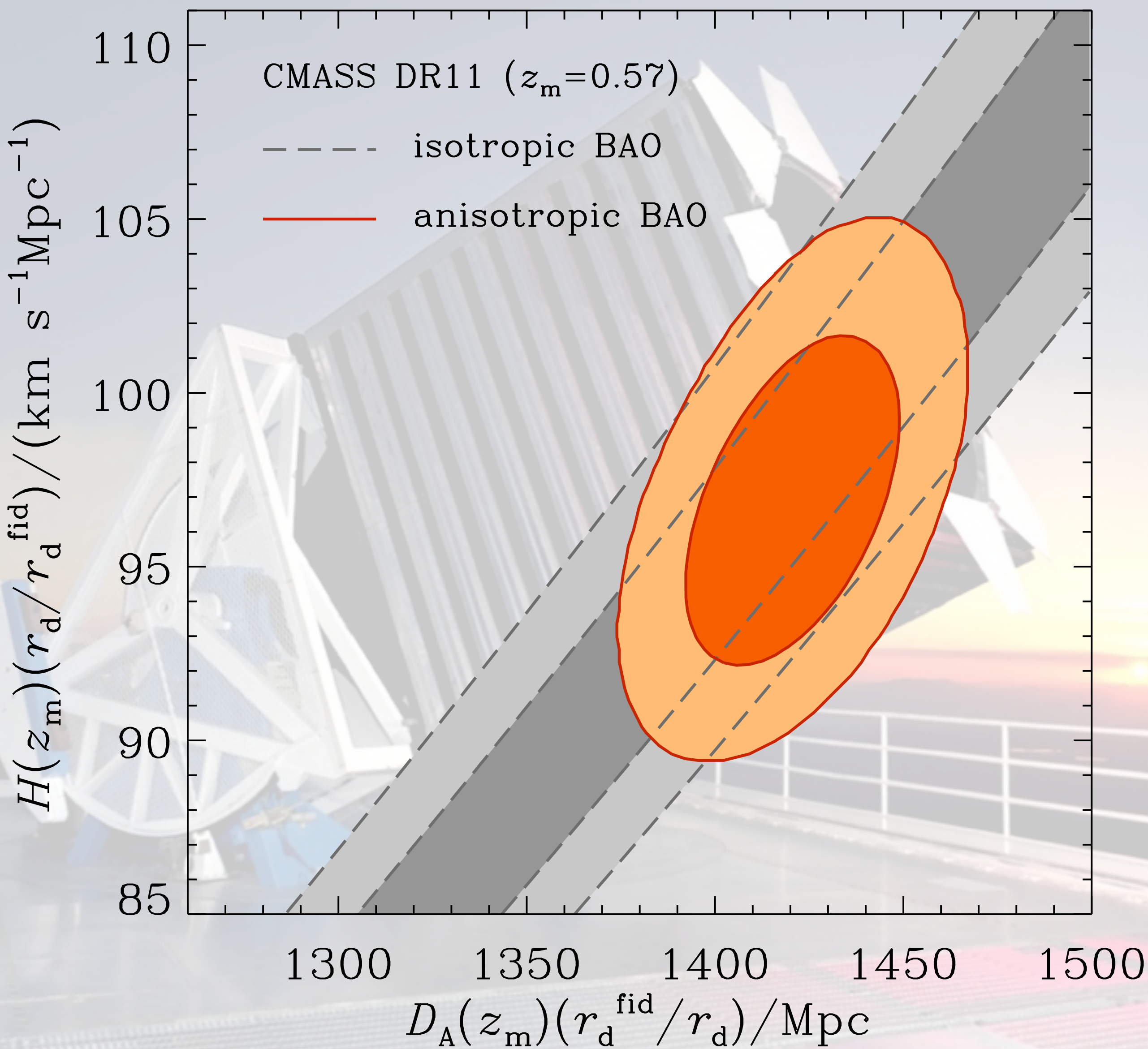
Anderson et al. 2013; arXiv:1312.4877

DR11 Measurements vs CMB



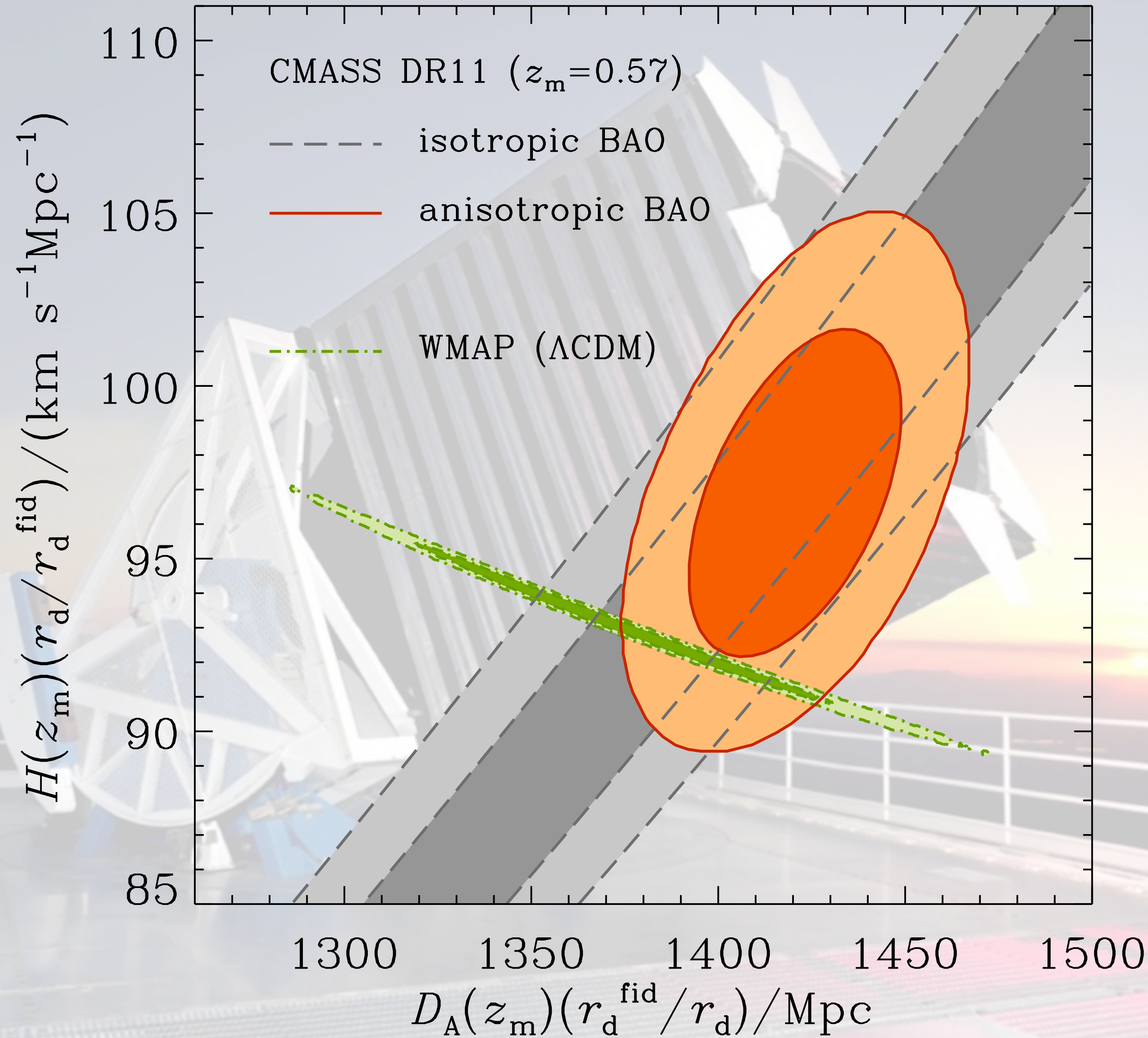
Anderson et al. 2013; arXiv:1312.4877

DR11 Measurements vs CMB



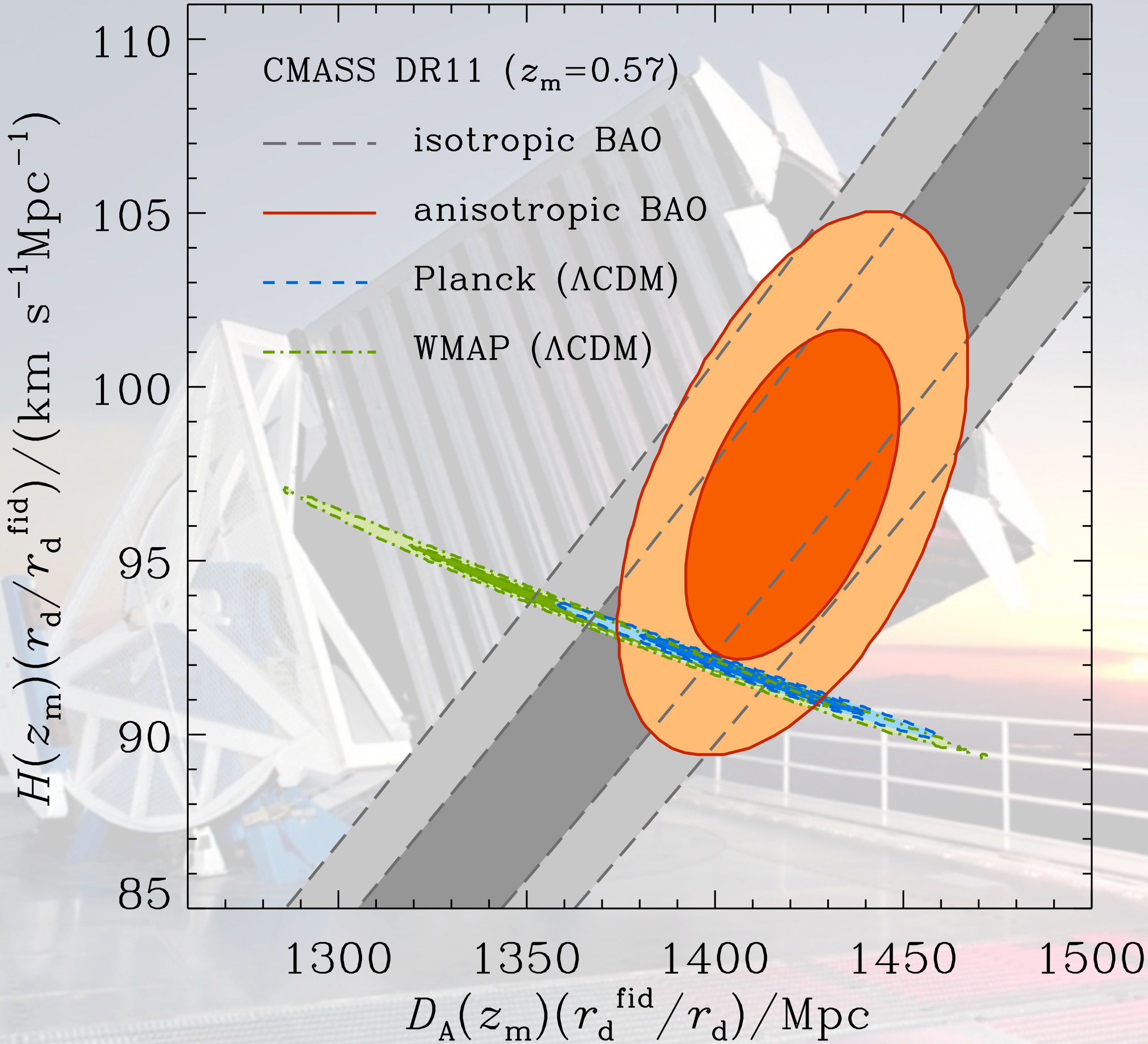
Anderson et al. 2013; arXiv:1312.4877

DR11 Measurements vs CMB



Anderson et al. 2013; arXiv:1312.4877

DR11 Measurements vs CMB



Anderson et al. 2013; arXiv:1312.4877

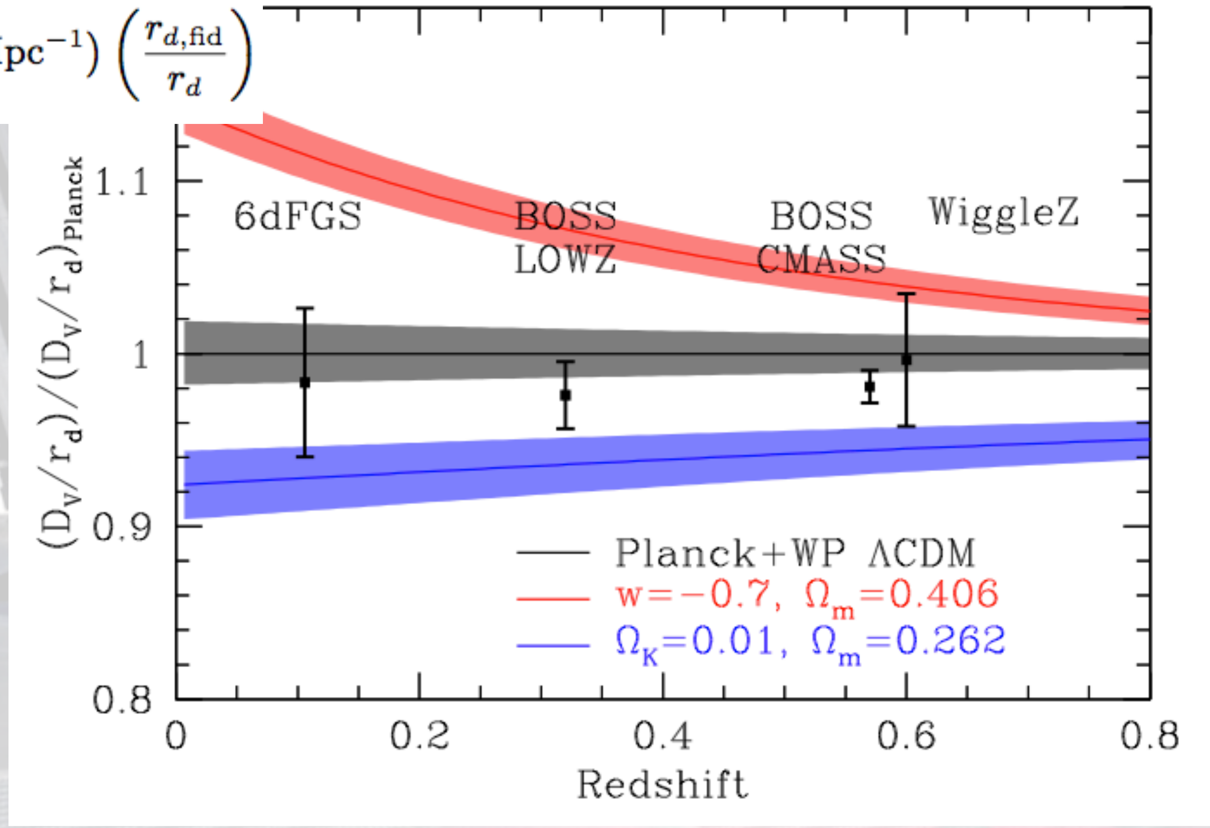
Results

$$D_V(0.57) = (2055 \pm 28\ \mathrm{Mpc}) \left(\frac{r_d}{r_{d,\mathrm{fid}}}\right)$$

$$D_V(0.32) = (1275 \pm 36\ \mathrm{Mpc}) \left(\frac{r_d}{r_{d,\mathrm{fid}}}\right),$$

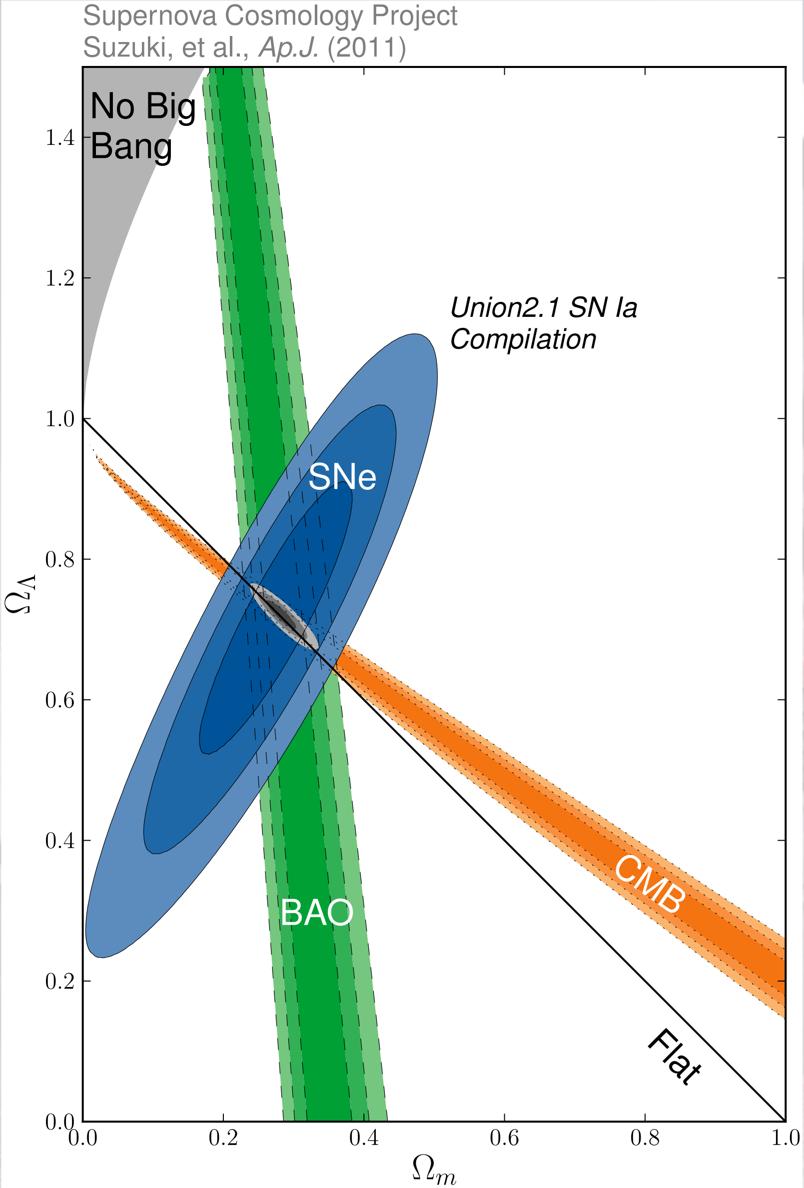
$$D_A(0.57) = (1386 \pm 26\ \mathrm{Mpc}) \left(\frac{r_d}{r_{d,\mathrm{fid}}}\right),$$

$$H(0.57) = (94.1 \pm 4.7\ \mathrm{km\ s^{-1}\ Mpc^{-1}}) \left(\frac{r_{d,\mathrm{fid}}}{r_d}\right)$$



Anderson et al. 2013; arXiv:1312.4877

Goal of this lecture



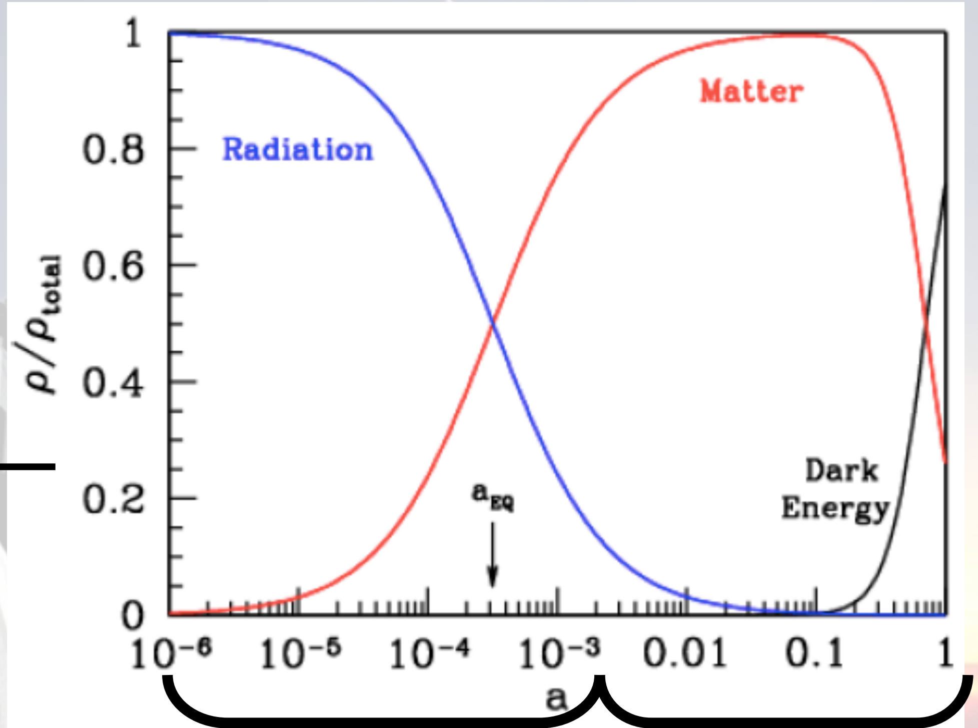
How did we get here?

Supernovae tell us we live in a lambda dominated Universe

BAO tell us we live in a low matter density Universe

A more direct way of measuring the matter density?

Evolution of the power spectrum after inflation



Inflation

Transfer function

Matter/DE domination

Non-linear

$$P_{\rm lin}(k) = k^n T^2(k) D^2(a)$$

(comoving coordinates)

linear growth independent of scale

Jeans length

The transfer function depends on the composition of the matter (CDM, baryons, neutrinos, etc.)

An important scale is the Jeans Length which is the scale of fluctuation where pressure support equals gravitational collapse,

$$\lambda_J = \frac{c_s}{\sqrt{G\rho}}$$

where c_s is the sound speed of the material, and ρ is its density.

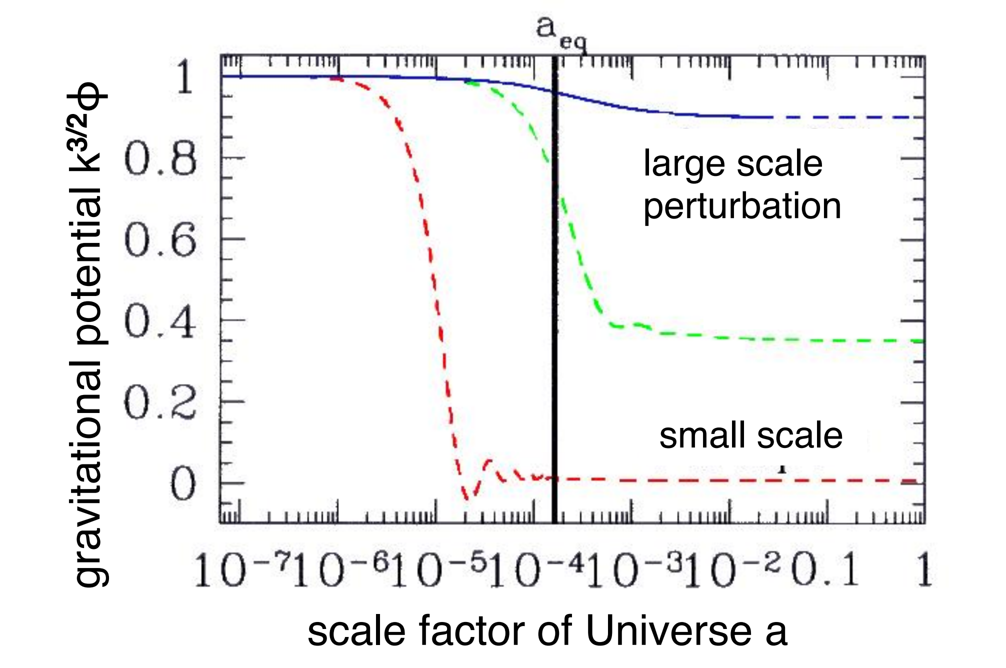
"F=ma" for perturbation growth

$$\ddot{\delta} = (\text{gravity} - \text{pressure})\delta$$

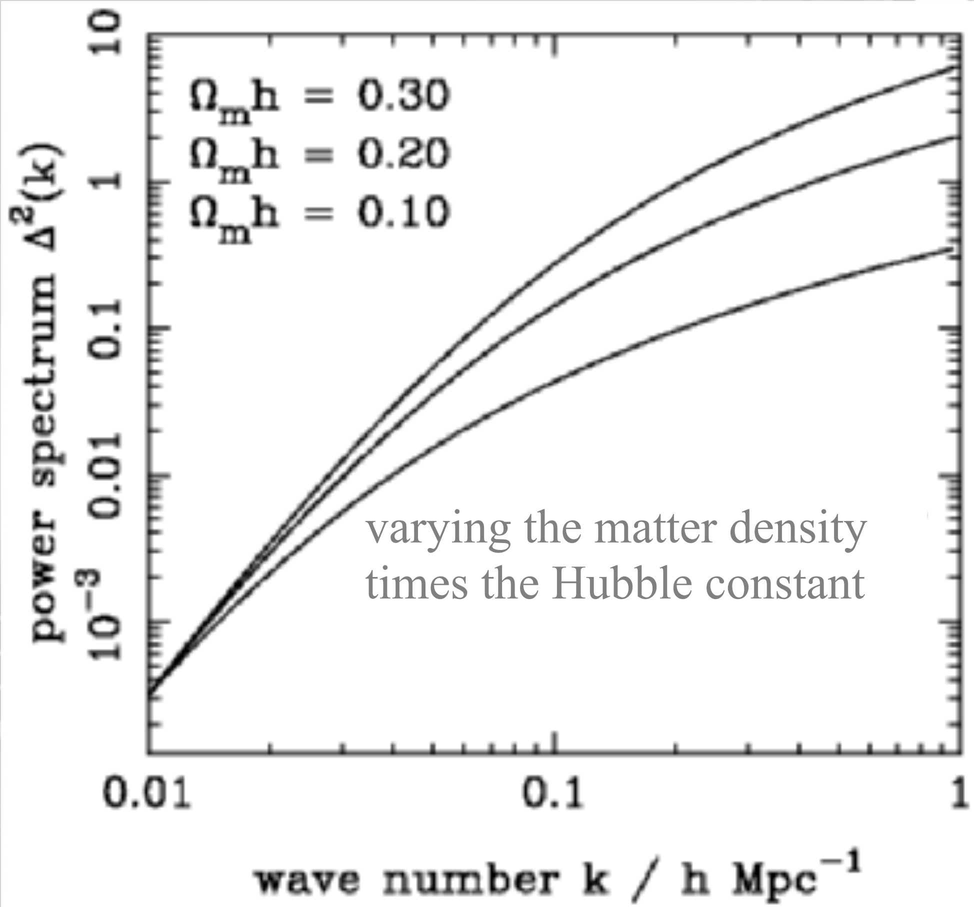
depends on Jeans scale

Transfer function evolution

In radiation dominated Universe, pressure support means that small perturbations cannot collapse. Jeans scale changes with time, leading to smooth turn-over of matter power spectrum. Projected cut-off dependent on matter density times the Hubble parameter $\Omega_m h$.

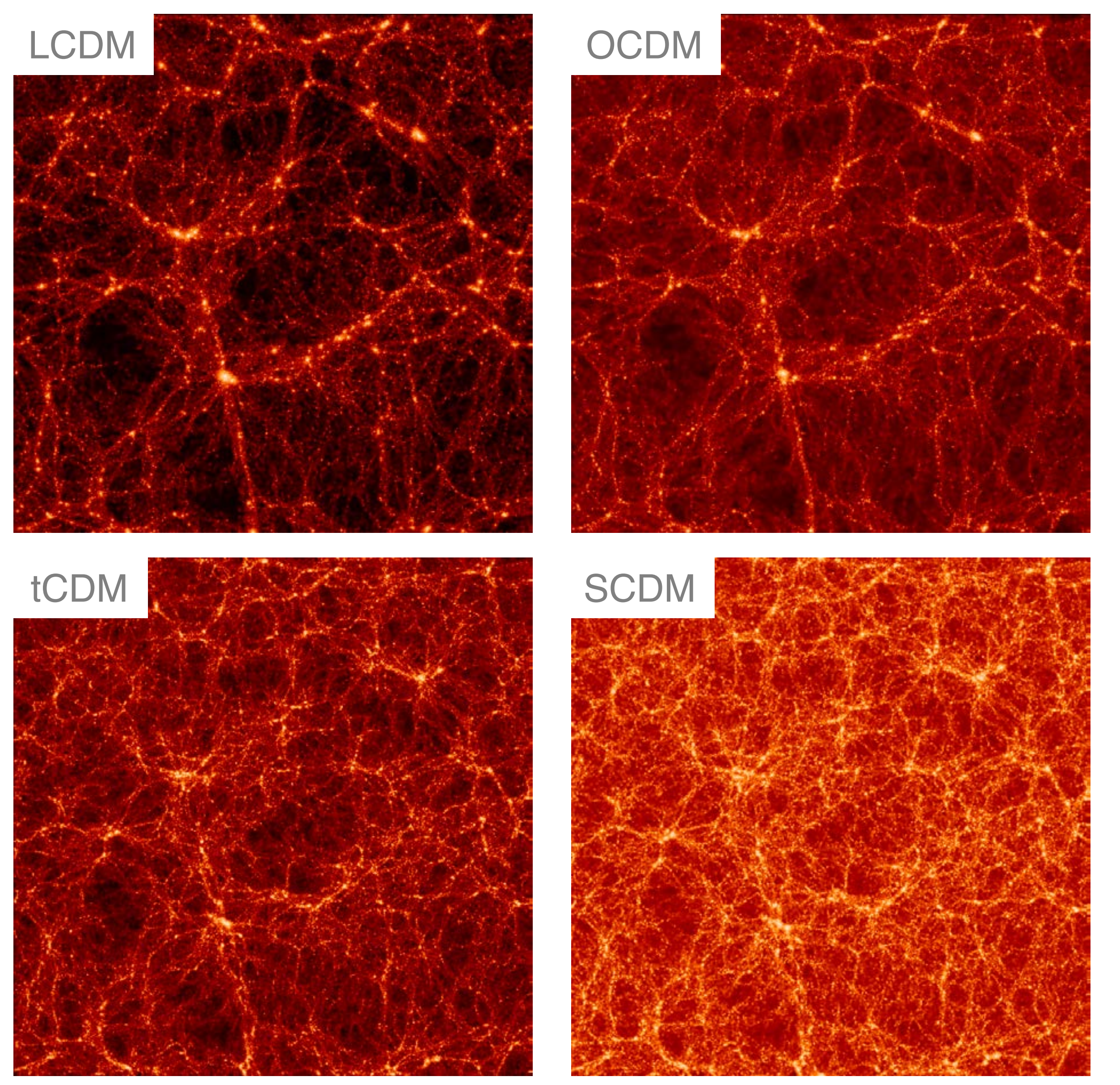


The power spectrum turn-over



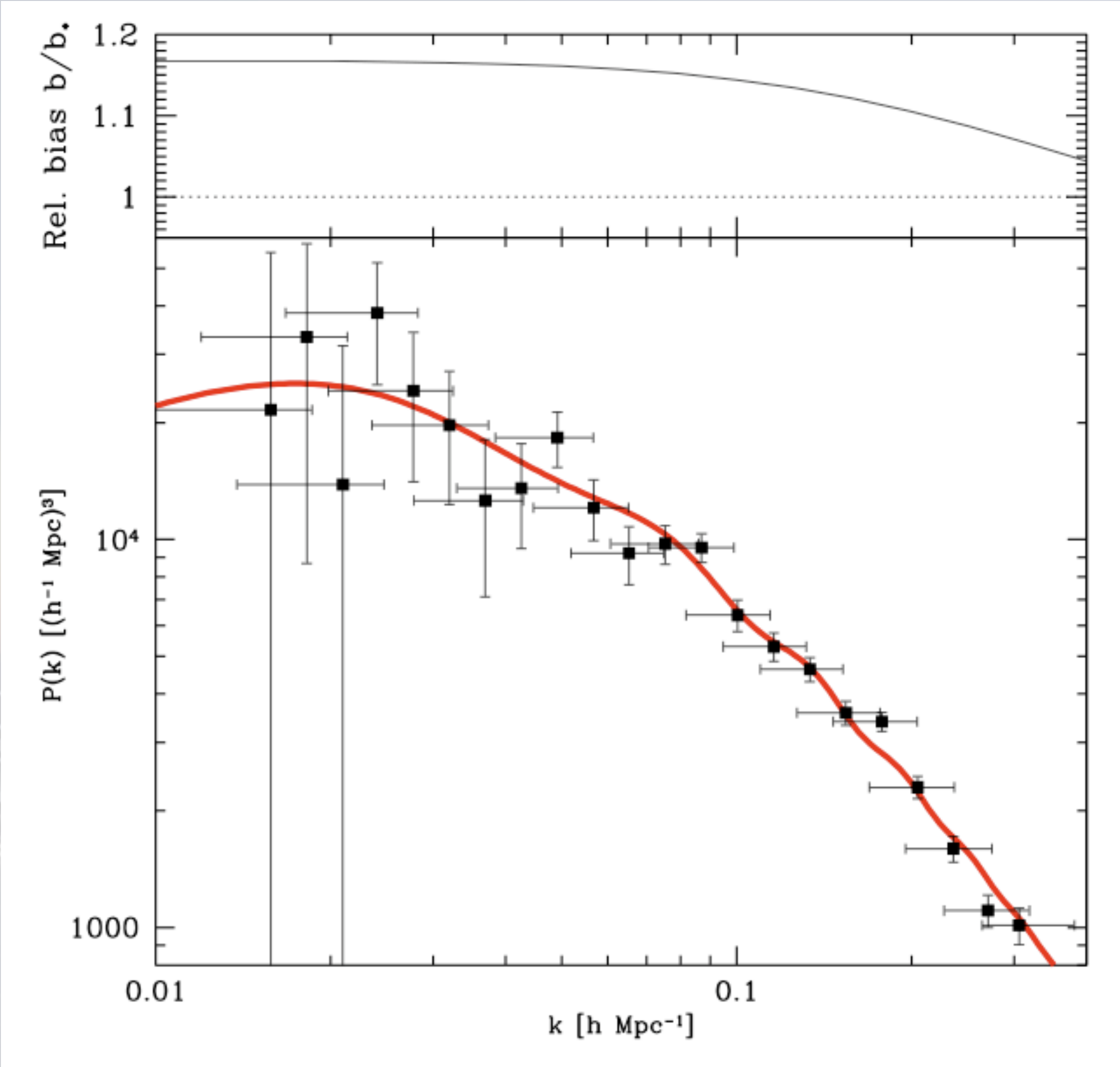
Amplitude of effect depends on matter density – how long before matter-radiation equality

The shape of the power spectrum



credit: VIRGO consortium

Analysis of the SDSS DR2 main galaxies

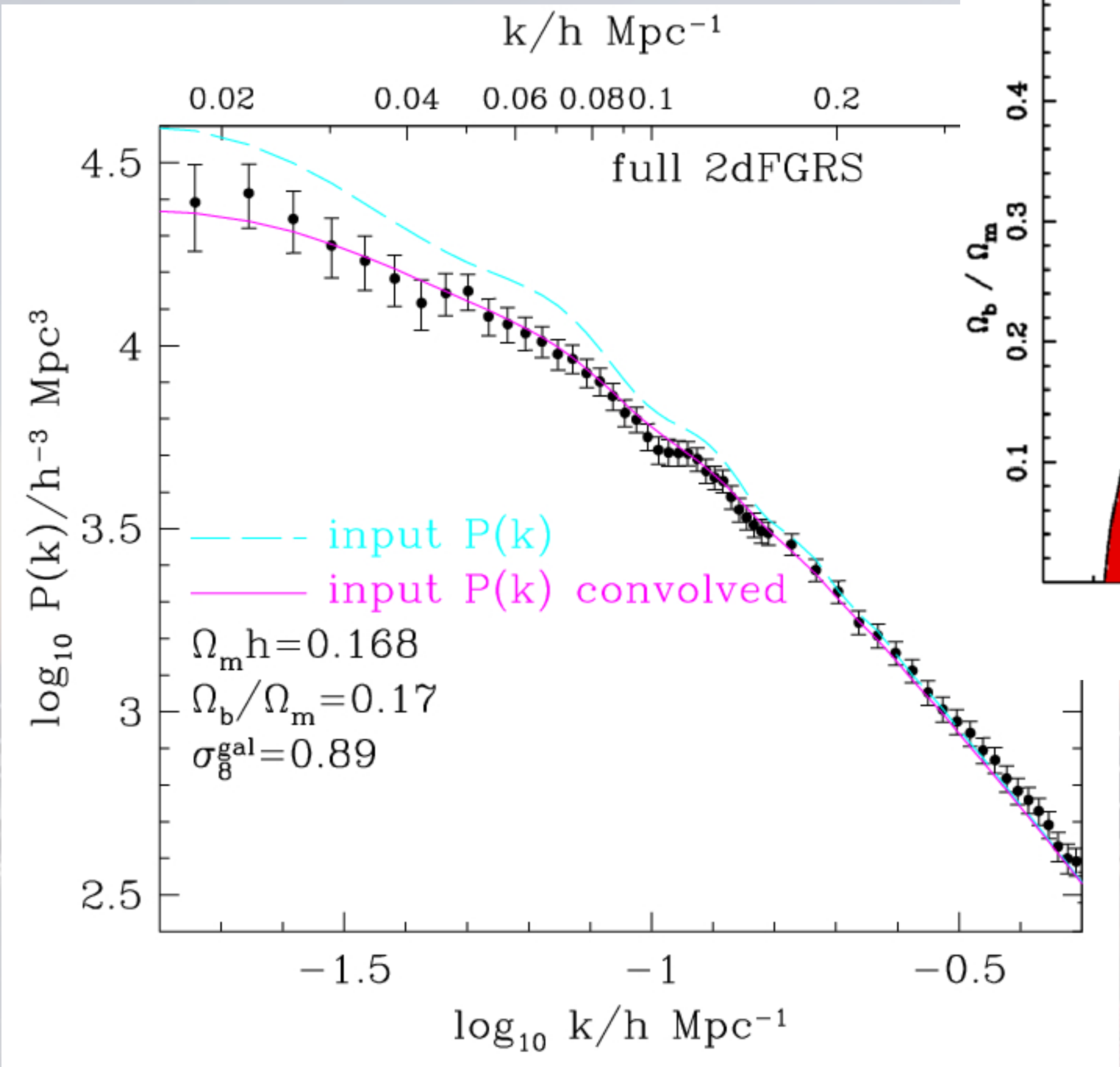


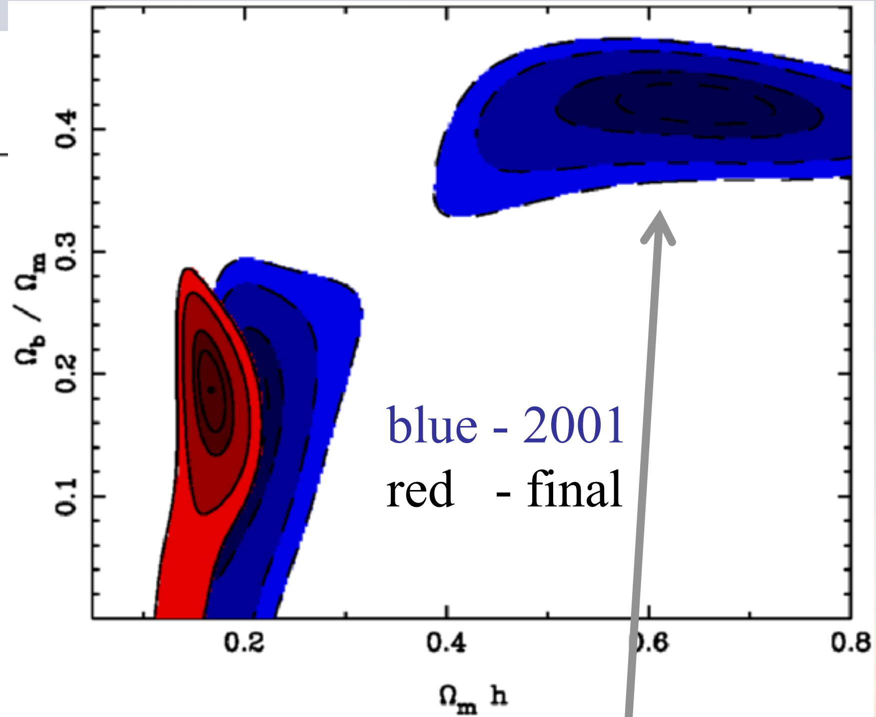
Recovered power spectrum from early sample drawn from the Sloan Digital Sky Survey.

Correction applied for the large-scale bias evolution through the survey

Tegmark et al. 2004, arXiv:0310725

Analysis of the final 2dFGRS sample

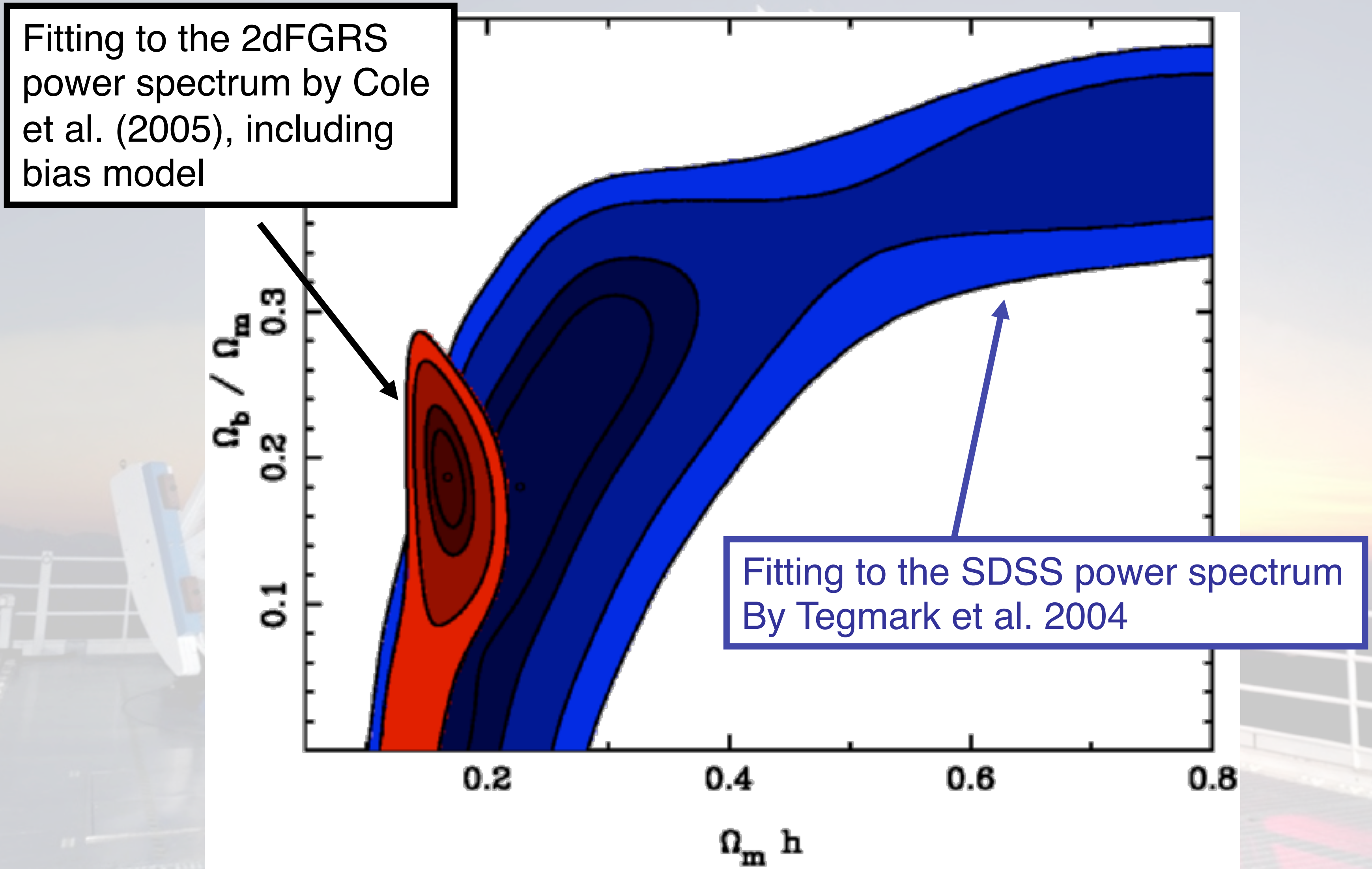




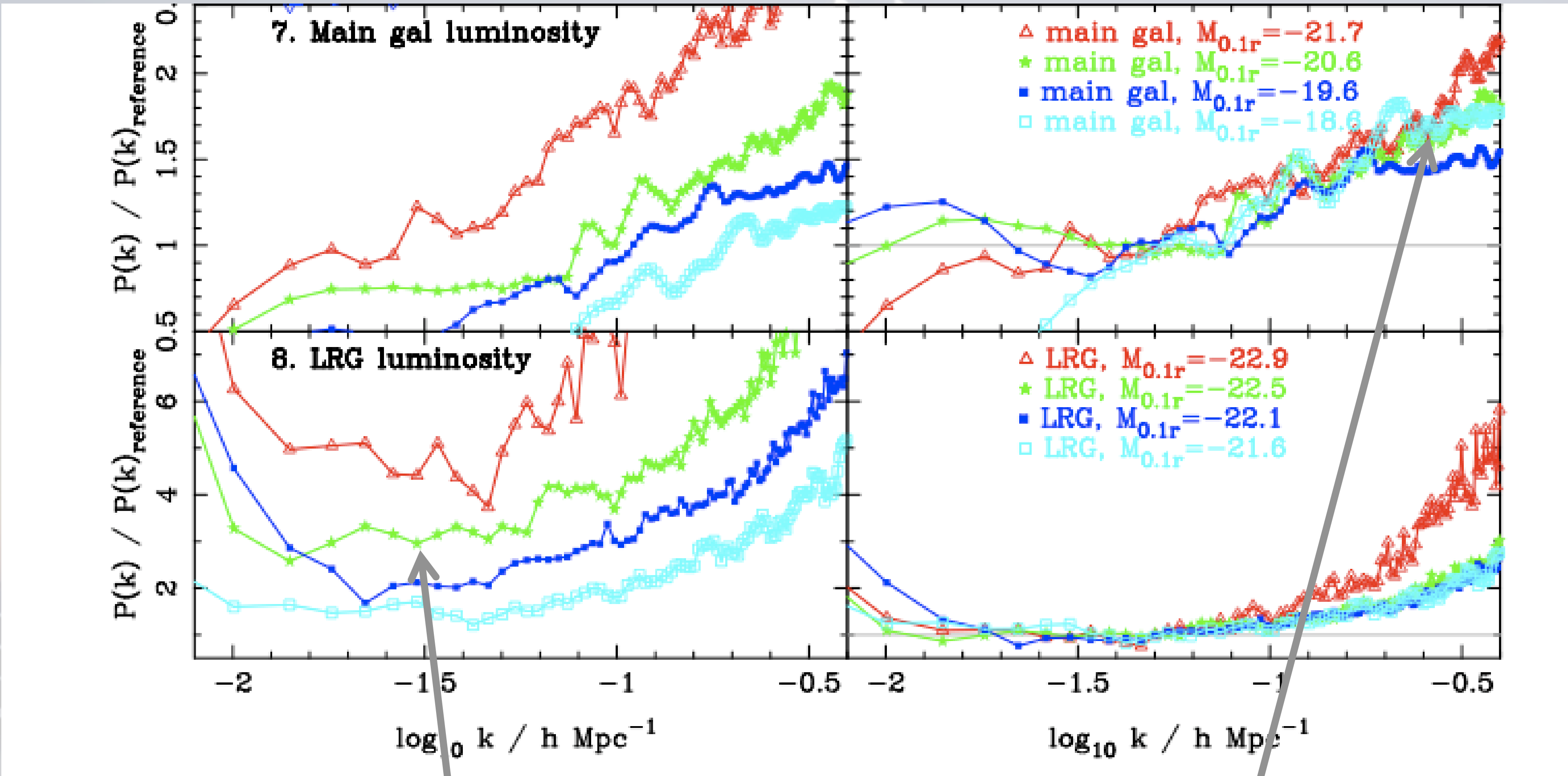
with complete survey, only one solution
– high baryon solution has disappeared

Cole et al. 2005, MNRAS, 362, 505

power spectrum shape constraints



the problem is scale-dependent bias

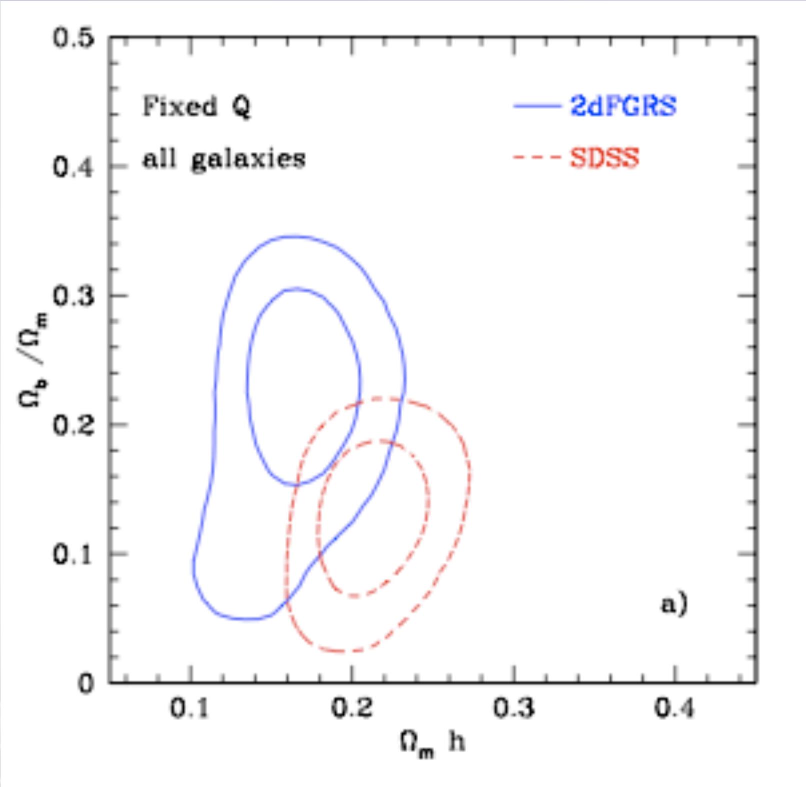


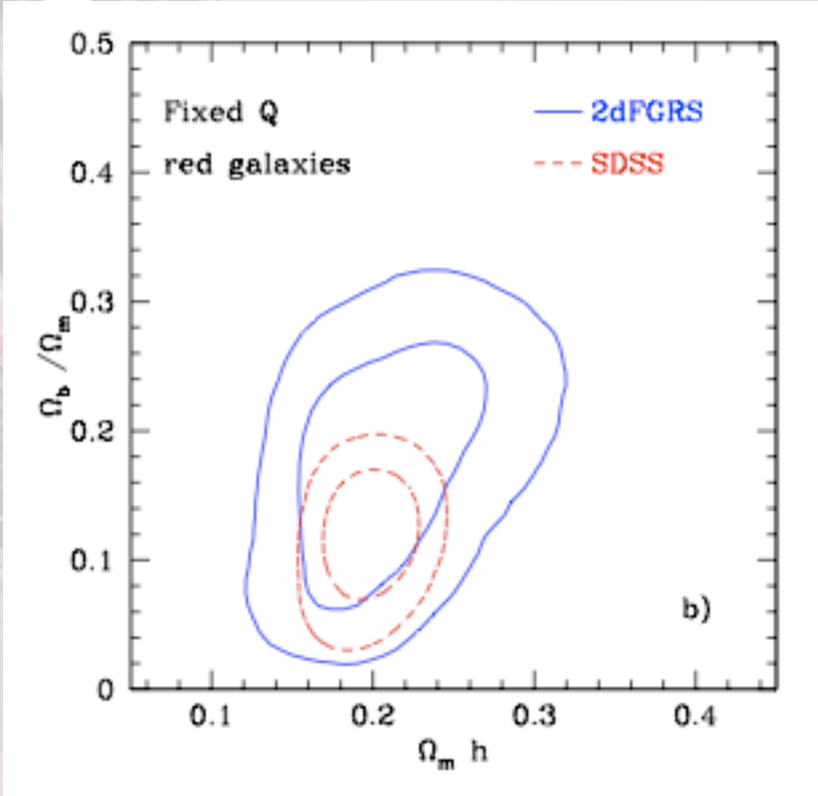
linear behaviour strongly depends on luminosity

non-linear behaviour depends on luminosity

Percival et al. 2007, astro-ph/0608636

the problem is scale-dependent bias

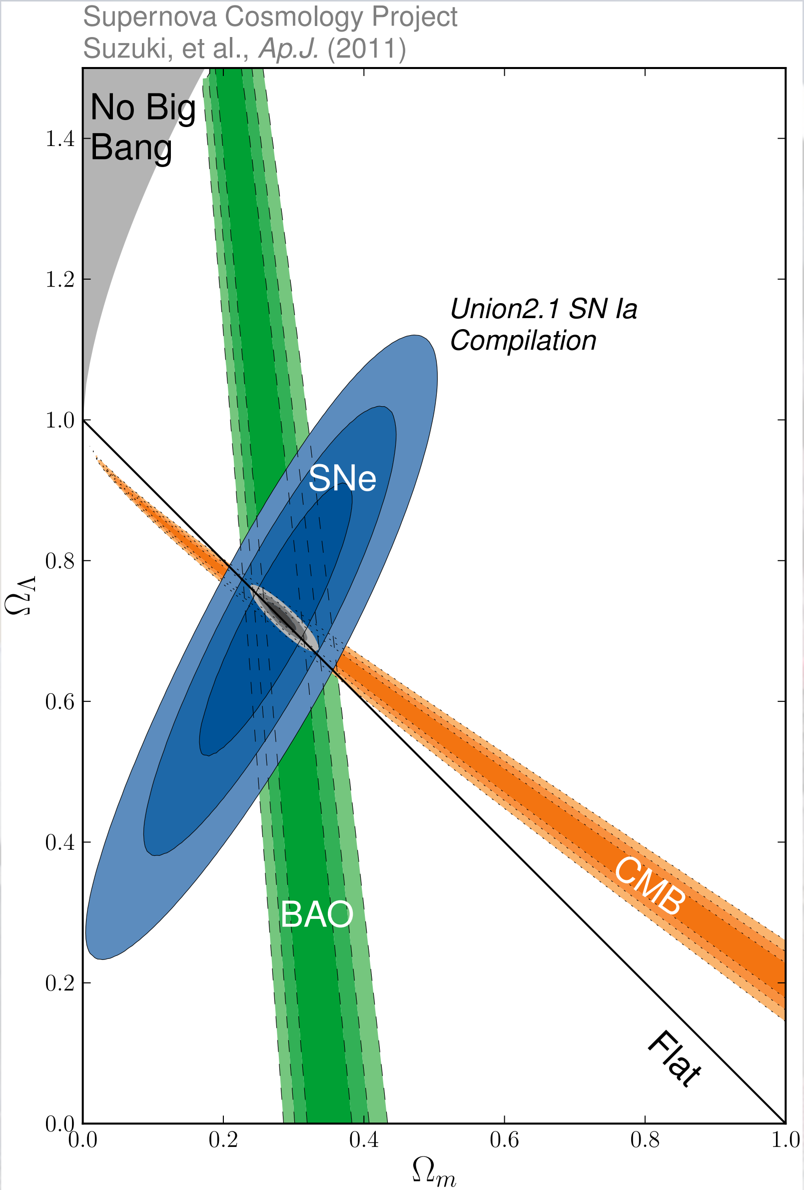




By subdividing 2dFGRS into red and blue galaxies, Sanchez & Cole also concluded that differences with SDSS were caused by scale-dependent galaxy bias

Sanchez & Cole 2007, arXiv:0708.1517

Goal of this lecture



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