Title: Cosmology with 21cm sky

Date: Oct 23, 2008 01:40 PM

URL: http://pirsa.org/08100061

Abstract:

21cm Cosmology

T. Chang

P. McDonald

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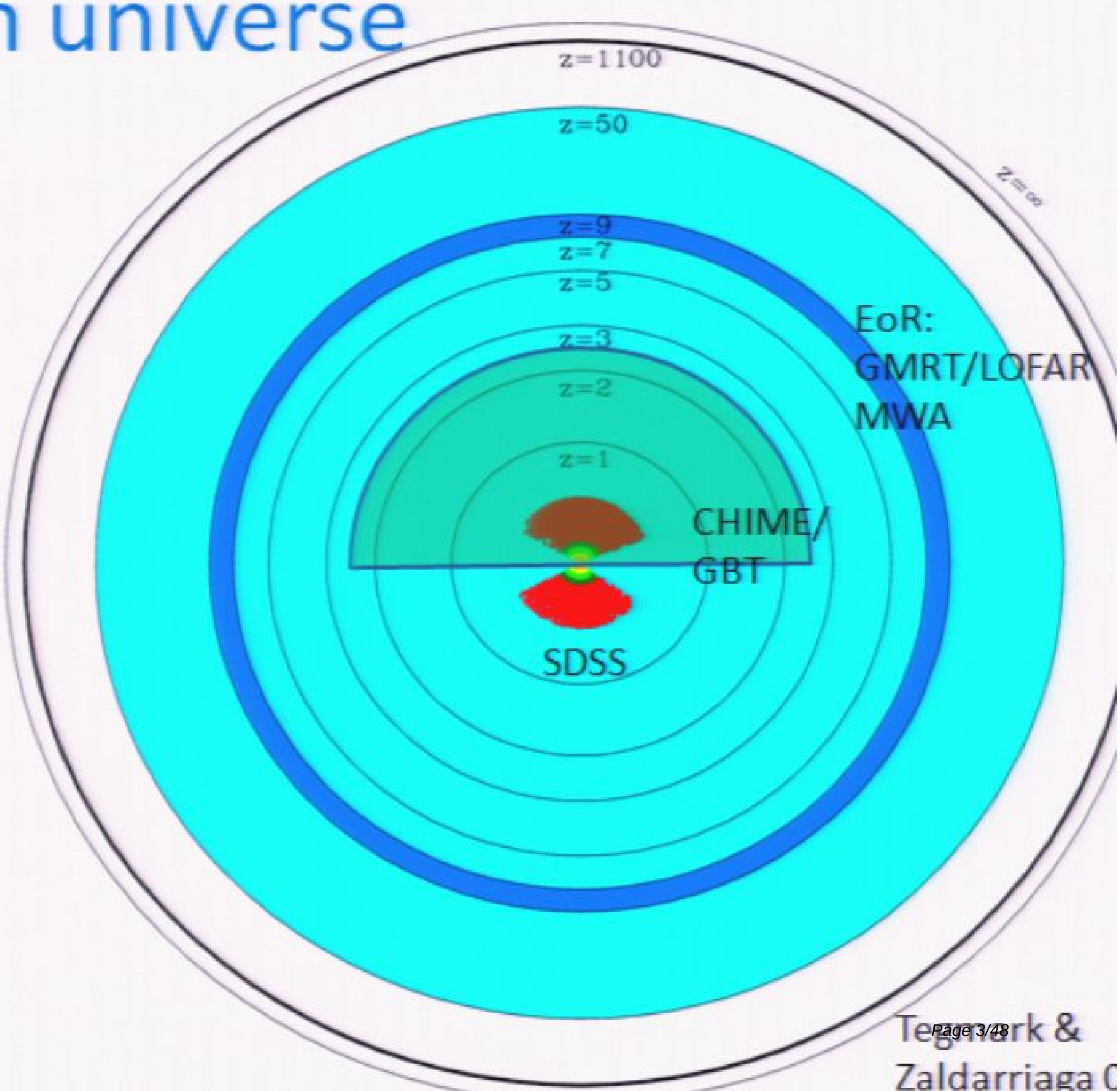
The 21 cm universe

- Cosmological LSS treasure grove (UP04, Loeb&Zaldarriaga 04, Lewis&Challinor 07, etc)
- Up to 10^{18} modes: z=50 (Jeans/Hubble)^3
- Physics: Lensing, gravity waves, primordial NG, BAO, AP
- GW to r ~ 10^{-8}
- f_{NL}~ 10^{-4}
- Astrophysics: EoR, galaxy evolution
- Experiments NOW



Tegmark & Zaldarriaga

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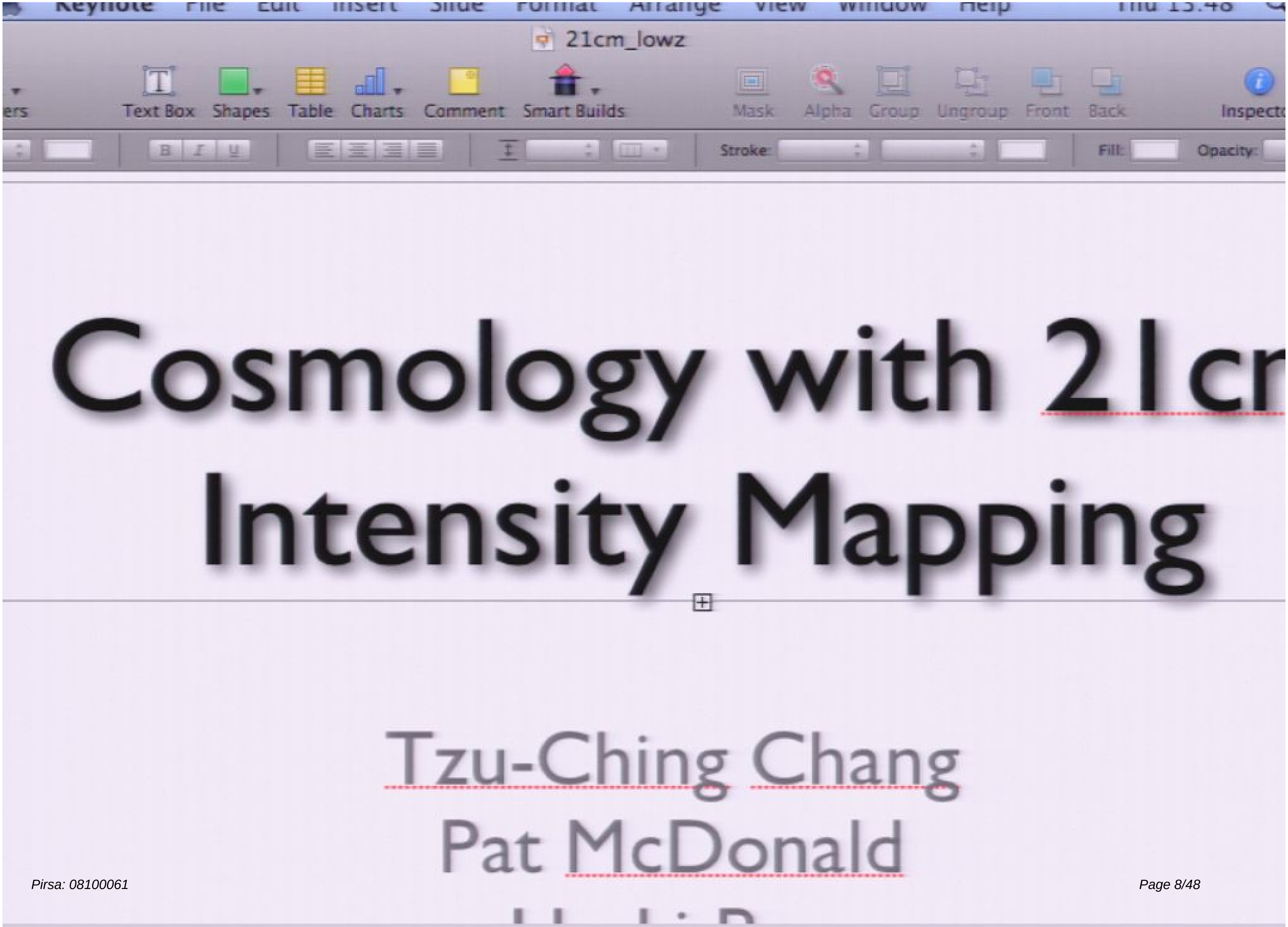

Cosmology with 21c
Intensity Mapping

Tzu-Ching Chang
Pat McDonald

Cosmology with 21cm Intensity Mapping

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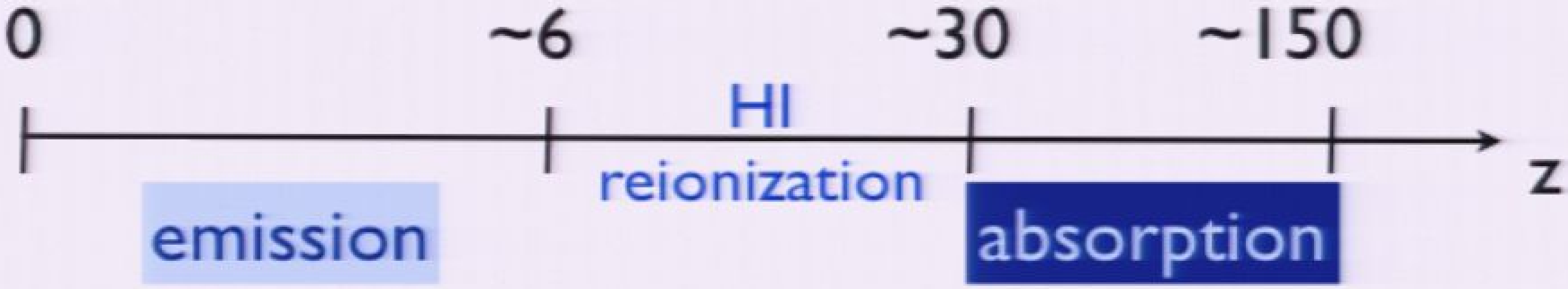
21cm Overview



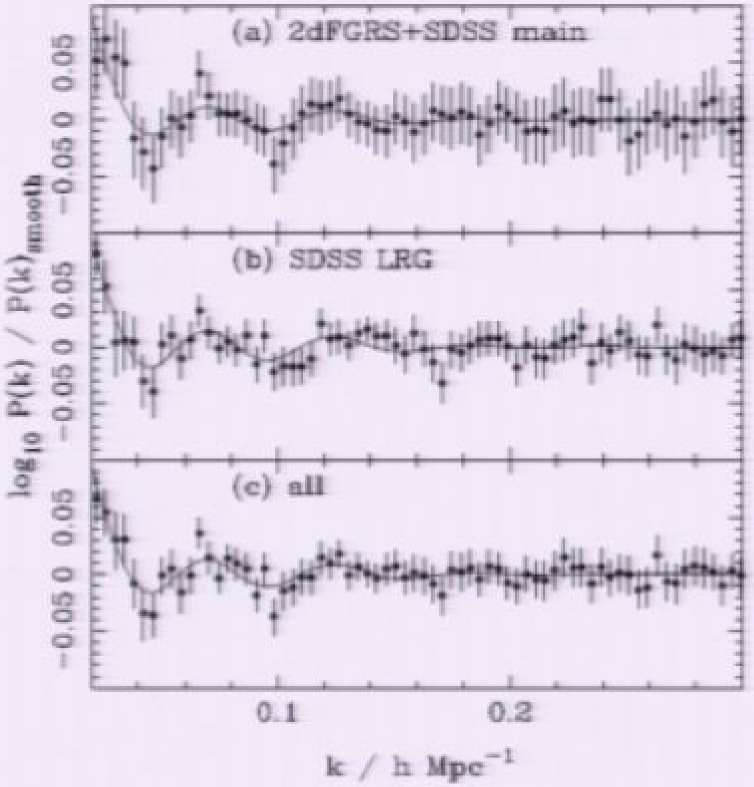
HI Brightness Temperature:

$$\Delta T = \frac{3 n_{\mathrm{HI}} \lambda^3 T_*}{32 \pi H \tau_{1\to 0}(1+z)} \left(1 - \frac{T_{cmb}}{T_s}\right)$$

$$= 300\ (1+\delta) \left(\frac{\Omega_{HI}}{10^{-3}}\right) \left(\frac{h}{0.73}\right) \left(\frac{\Omega_m + (1+z)^{-3}\Omega_\Lambda}{0.35}\right)^{-0.5} \left(\frac{1+z}{1.9}\right)^{0.5} \mu\mathrm{K}$$

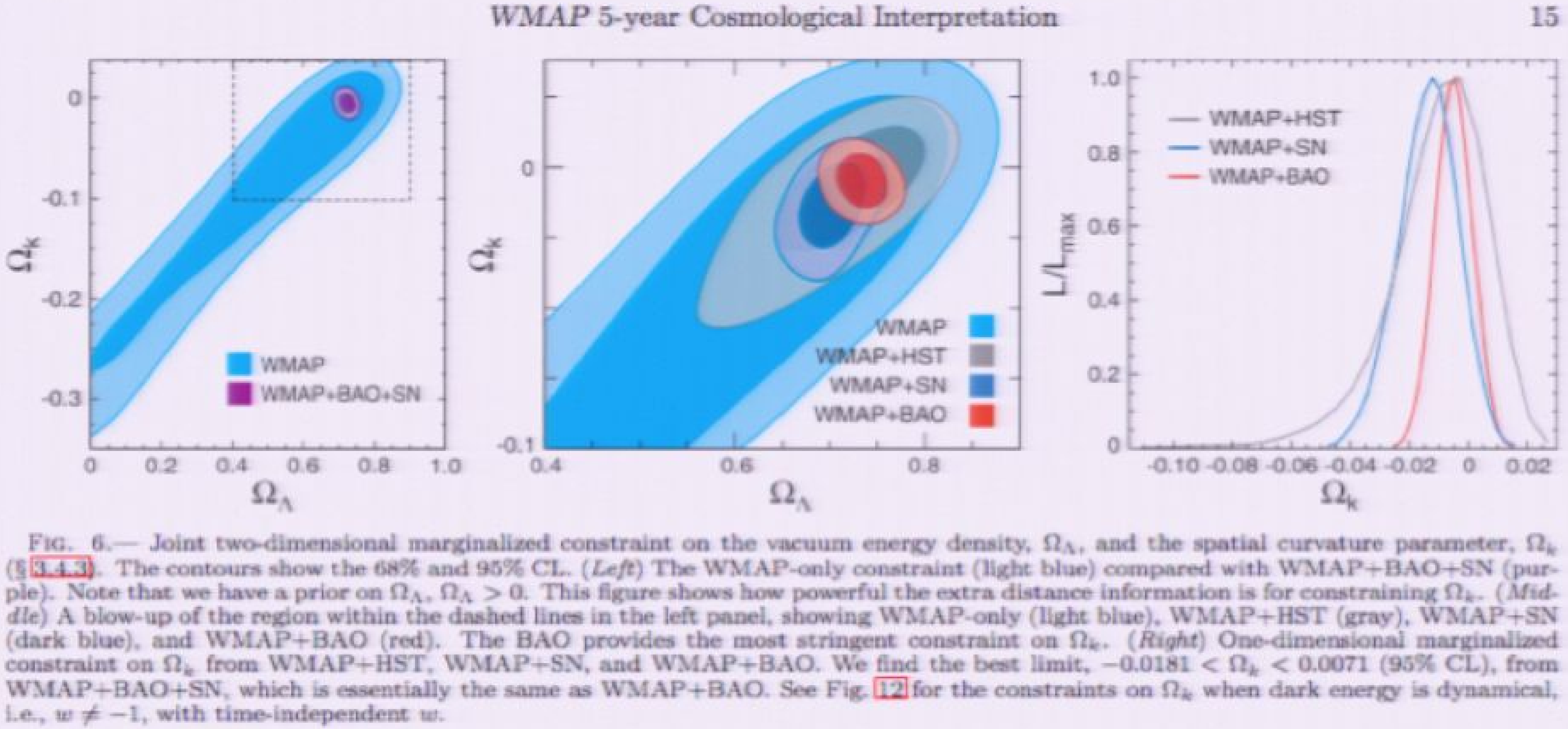
Baryon Acoustic Oscillations (BAO) – Dark Energy Probe

- CMB acoustic oscillations: imprinted standard ruler, 100 Mpc.
- Present in current matter distribution
- Blake and Glazebrook, Seo & Eisenstein et al: standard ruler measures H(z) and D(z).
- Measures dark energy equation of state w, w'



Percival et al. 2008

BAO - Great Tool for Precision Cosmology



WMAP 5-year Cosmological Interpretation 15

FIG. 6.— Joint two-dimensional marginalized constraint on the vacuum energy density, Ω_Λ, and the spatial curvature parameter, Ω_k (§ 3.4.3). The contours show the 68% and 95% CL. (*Left*) The WMAP-only constraint (light blue) compared with WMAP+BAO+SN (purple). Note that we have a prior on Ω_Λ, $\Omega_\Lambda > 0$. This figure shows how powerful the extra distance information is for constraining Ω_k. (*Middle*) A blow-up of the region within the dashed lines in the left panel, showing WMAP-only (light blue), WMAP+HST (gray), WMAP+SN (dark blue), and WMAP+BAO (red). The BAO provides the most stringent constraint on Ω_k. (*Right*) One-dimensional marginalized constraint on Ω_k from WMAP+HST, WMAP+SN, and WMAP+BAO. We find the best limit, $-0.0181 < \Omega_k < 0.0071$ (95% CL), from WMAP+BAO+SN, which is essentially the same as WMAP+BAO. See Fig. 12 for the constraints on Ω_k when dark energy is dynamical, i.e., $w \neq -1$, with time-independent w.

Komatsu et al. 2008

BAO- Mapping Large-scale Structure

- Current and proposed projects: measure individual galaxy redshifts - BOSS, AAO, HETDEX, WFMOS (optical spectra), KAOS, DES, LSST (photo-z), SKA (21cm), ADEPT (space), etc.

- This talk: measure collective large-scale structure traced by HI, without resolving individual objects - Hundreds of galaxies in each BAO pixel : Intensity Mapping (Chang et al. 2008; Wyithe & Loeb 2008).

HI Intensity Mapping (IM)

- Similar to CMB; large survey area, low surface brightness, but in 3D
- Current highest individual 21cm emission measured: z~0.3
- IM allows access to much larger distance with existing technology
- Indication of feasibility: this talk

BAO - Hydrogen Intensity Mapping Experiments

- Measure BAO wiggles at $0 < z < 3$ with HI (300MHz - 1.4 GHz)
- Signal ~100 micro Kelvin at mean density
- Foreground large: $T_{fg} \sim 1$ K, $dT_{fg} \sim 10$ mK, but spectrally smooth.
- Radio Cylinder Telescope + HI Intensity Mapping: economical way to measure dark energy properties
- CHIME: Canadian Hydrogen Imaging Experiment 10,000 m^2, 0.8<z<2.5

HI BAO Experiment Prospects

- CHIME (Canadian Hydrogen Intensity Mapping Experiment); Cosmic Variance limited Hubble Survey

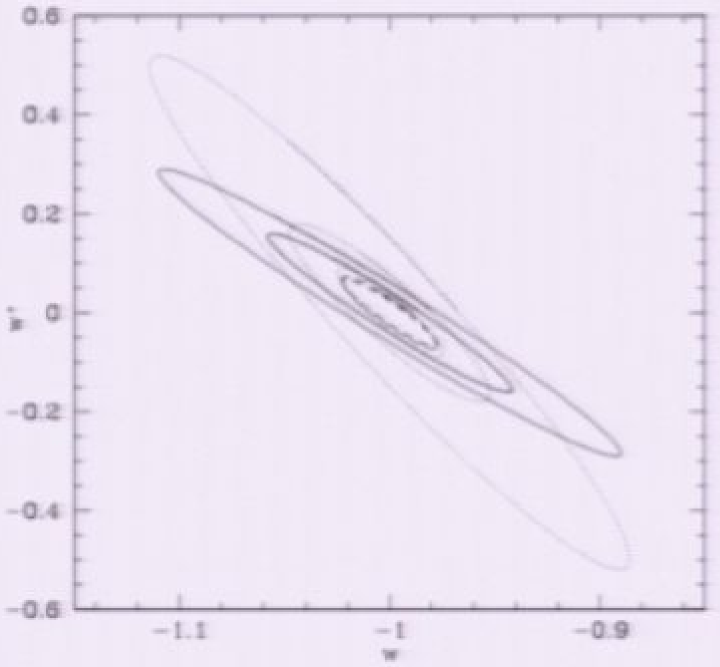


FIG. 4. The $1-\sigma$ contour for IM combined with Planck (inner thick solid for baseline model, outer thin solid for worst case), the Dark Energy Task Force stage I projects with Planck (outer dotted), the stage I and III projects with Planck (intermediate dotted), the stage I, III, and IV projects with Planck (inner dotted), and all above experiments combined (dashed, again thick for baseline, thin for worst case; the two contours are nearly indistinguishable).

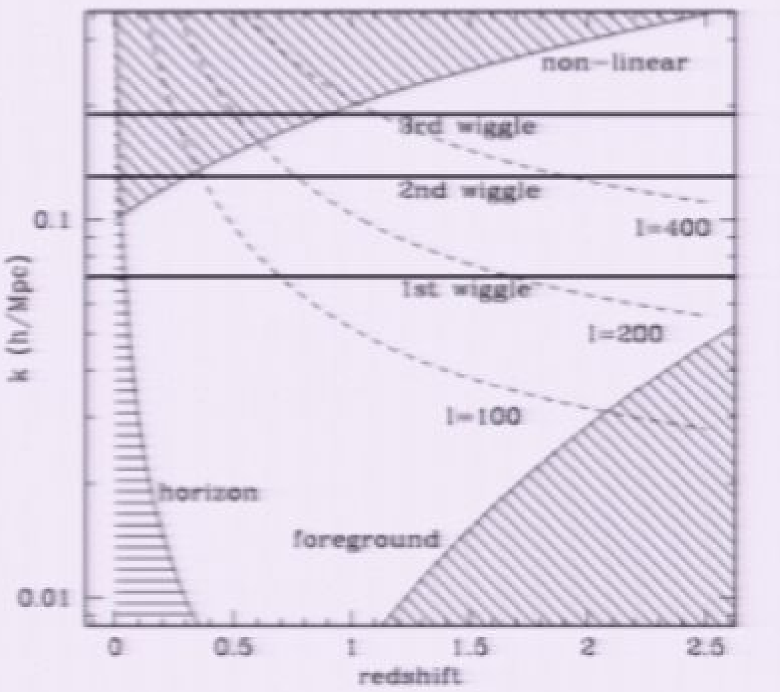


FIG. 3: The observable parameter space in redshift and in scale (k) for BAO. The shaded regions are observationally inaccessible (see text). The horizontal lines indicate the scale of the first three BAO wiggles, and the dashed lines show contours of constant spherical harmonic order ℓ.

Chang, Pen, Peterson, McDonald 2008

21cm universe at low-z

- emitted by neutral hydrogen, ~ 2% of baryons
- dominated by DLA (damped Lyman alpha systems)
- nature, mass, space density not known, but not important for IM
- Questions:
  - Is HI a good tracer of Large-scale Structure?
  - How much HI there is at z ~1?

How well does HI trace Large-scale Structure?

HIPASS HI Survey

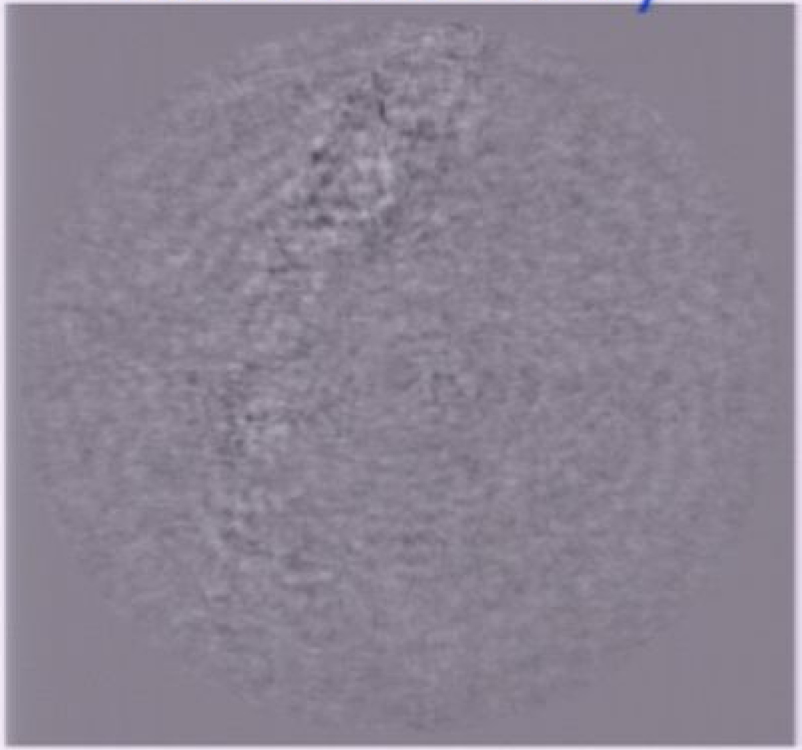


Figure 1. The HIPASS data cube $R < 127h^{-1}$ Mpc, projected in a cartesian coordinate system towards the south pole.

6dF Optical Galaxy Survey

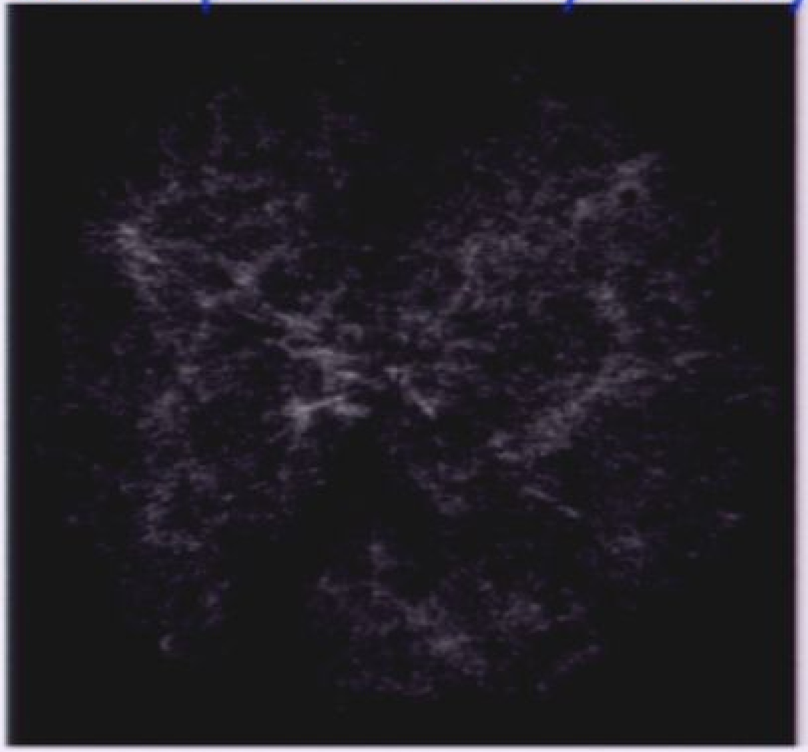


Figure 2. The 6dFGS catalog for $R < 127h^{-1}$ Mpc, also projected towards the south pole. The missing wedges are the galactic plane.

HIPASS & 6dFGS Large-scale Structure cross-correlation at z ~ 0.04

Pen et al. 2008

HI & Optical cross-correlation

Pen et al. 2008

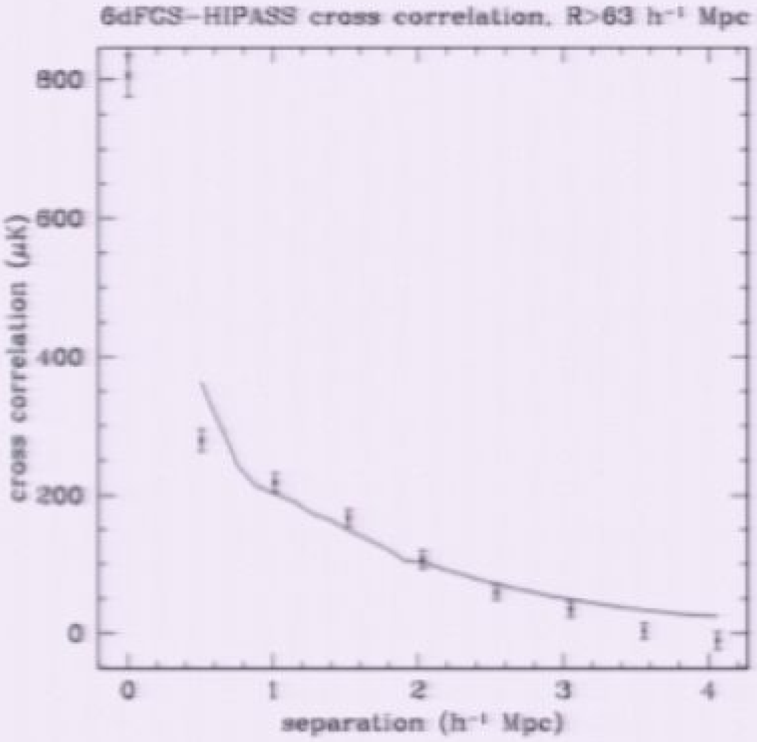


Figure 4. The correlation function of hydrogen 21 cm emission when stacked around optically selected galaxies from the 6dFGS. The solid line is a standard clustering model. The point at zero separation is the mean flux from 6dF galaxies, while points at larger separations measure the associated surrounding large scale structure. HI emission from the 6dF galaxies could spill up to 1 h^{-1} Mpc into neighboring bins at the $\sim 20\mu$K level.

- Show good correlation between Hydrogen and Optical galaxy surveys
- Neutral hydrogen traces Large-scale Structure

What is Ω_{HI} at z=1?

Cross-correlating GBT HI & DEEP2 optical galaxies at z ~ 0.7-1.1

- Measure HI & optical cross-correlation on 10 Mpc (spatial) x 2 Mpc (radial) scales
  - Test of Intensity Mapping idea
- HI fluctuations on these scales at z=0.9:

$$T = 280 \pm 80\ \mu\mathrm{K}$$

- Assuming b=r=1,at z=0.9:

$$\Omega_{\mathrm{HI}} \sim (9.3 \pm 2.7) \times 10^{-3}$$

- Highest-redshift detected HI in emission! (c.f., z=0.3)

Chang, Pen, Bandura, Peterson 2008 in prep.

Pittsburgh Radio Cylinder Prototype

CMU Cylinder Prototype

- Testbed for CHIME
- Technical challenges:
  - Foreground subtraction
  - Radio Frequency Interference

Summary

- 21cm line provides a good probe of cosmology
- **HI Intensity Mapping**: an efficient/economical way of measuring BAO/dark energy
  - Neutral hydrogen traces large-scale structure at low-z
    - HIPASS/6dF cross-correlation shows good correlation
  - Good amount of neutral hydrogen at z ~ 1
    - GBT/DEEP2 cross-correlation: $\Omega_{\mathrm{HI}} \sim 10^{-3}$
  - Issues of foregrounds, RFI removal, calibration, etc.
    - Pittsburgh radio cylinder prototype underway
- Prospects of measuring BAO with HI: CHIME!

Why we need the precision LSS measurements that 21 cm can make possible - beyond BAO.

Patrick McDonald

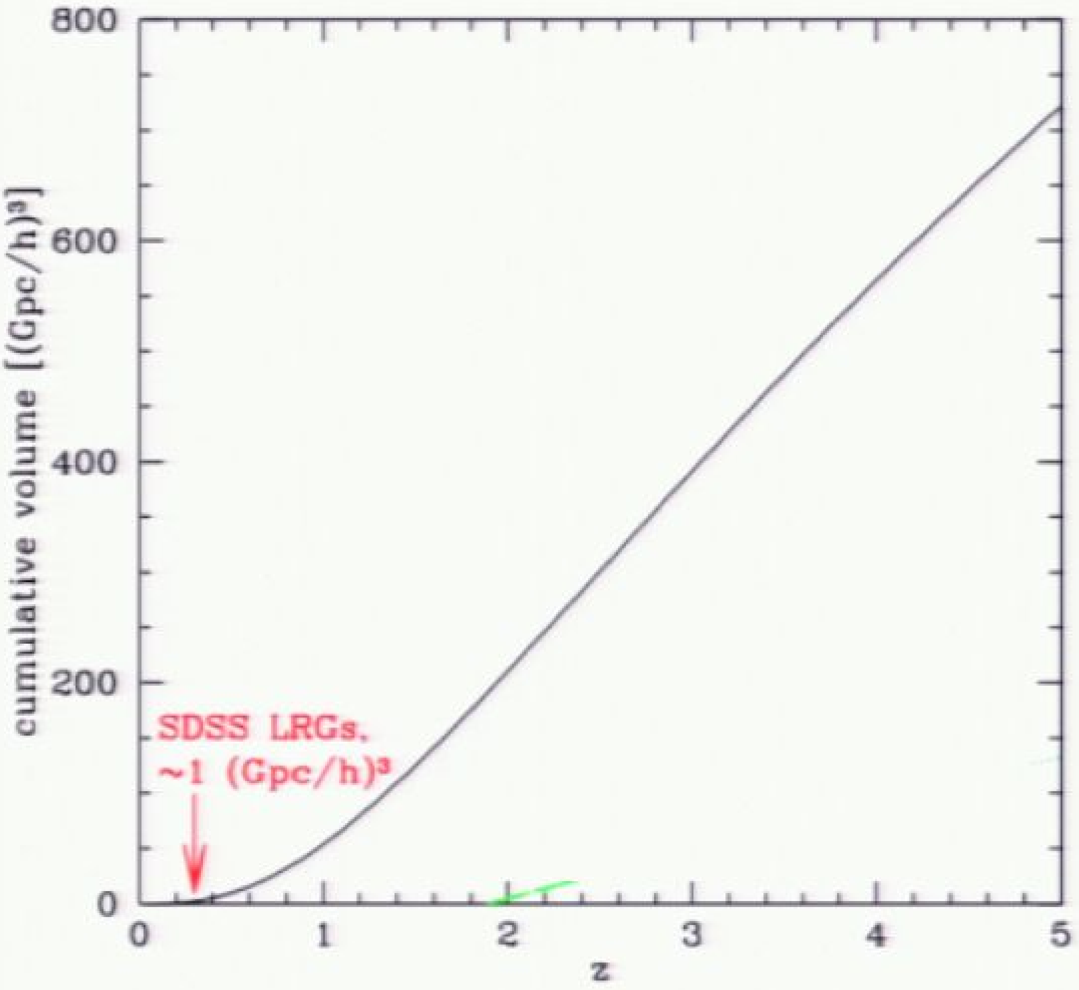
(CITA)

Why we need the precision LSS measurements that 21 cm can make possible - beyond BAO.

Patrick McDonald

(CITA)

LSS: how much there is to do!

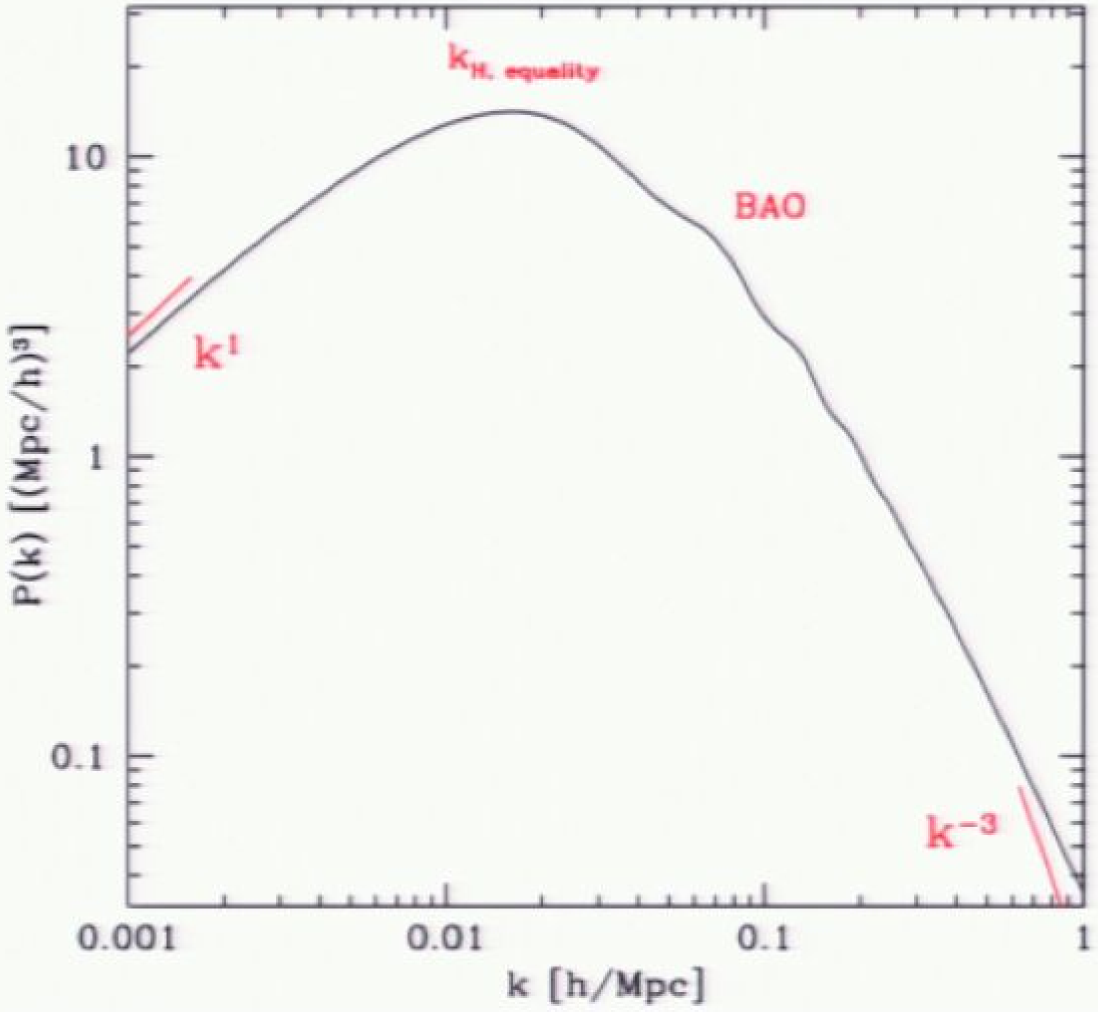


- Very little of the volume has been mapped.
- The linear scale is smaller at high z, so the number of useable modes actually goes up even faster than volume.
- New ideas suggest that there is much to be gained from much higher S/N (galaxy density) than we thought before.

Why we need the precision LSS measurements that 21 cm can make possible - beyond BAO.

Patrick McDonald
(CITA)

Linear power



The BAO-only approach assumes everything here except the small wiggles is effectively noise.

There is *no compelling reason for this*, since we understand the ~BAO scale and larger scales theoretically at least as well as we understand other DE probes like SN or clusters.

How to use multiple tracers of density with different bias (e.g., galaxy types) to beat the cosmic variance limit.

- Originally, Seljak (0807.1770) applied the multi-tracer idea to measuring non-Gaussianity of the initial conditions.
- McDonald & Seljak (0810.0323) applied it to redshift-space distortions (peculiar velocities), and from there constraining dark energy (or other things).
- Bottom line: order of magnitude improvements in measurements of the rate of growth of structure $dD/da(z)$ with similar improvement in DE constraints… and more.

Bias: the relation between ~galaxy and mass density - linear on large scales.

$$\boxed{\delta_{gi} = b_i\ \delta_m + \epsilon_i + \ldots}$$

galaxy density perturbation

bias factor

mass density perturbation

noise

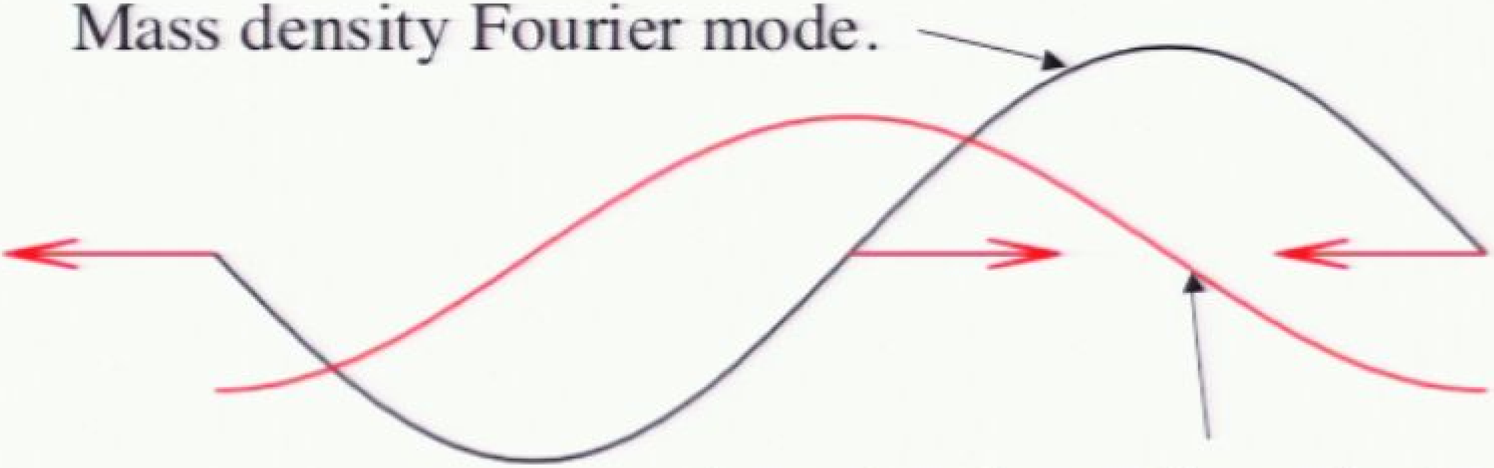
Quite generally justifiable as a Taylor series in δ_m (McDonald 2006, McDonald & Roy in prep.)

Galaxy power spectrum:

$$P_g(k) = b^2\ P_m(k) + N + \ldots$$

Noise power $N \simeq \bar{n}_g^{-1}$ approximately set by the number density of galaxies (works well in simulations)

Peculiar velocities in LSS



Mass density Fourier mode.

Associated peculiar velocity mode. Flow into density maxima, out of voids.

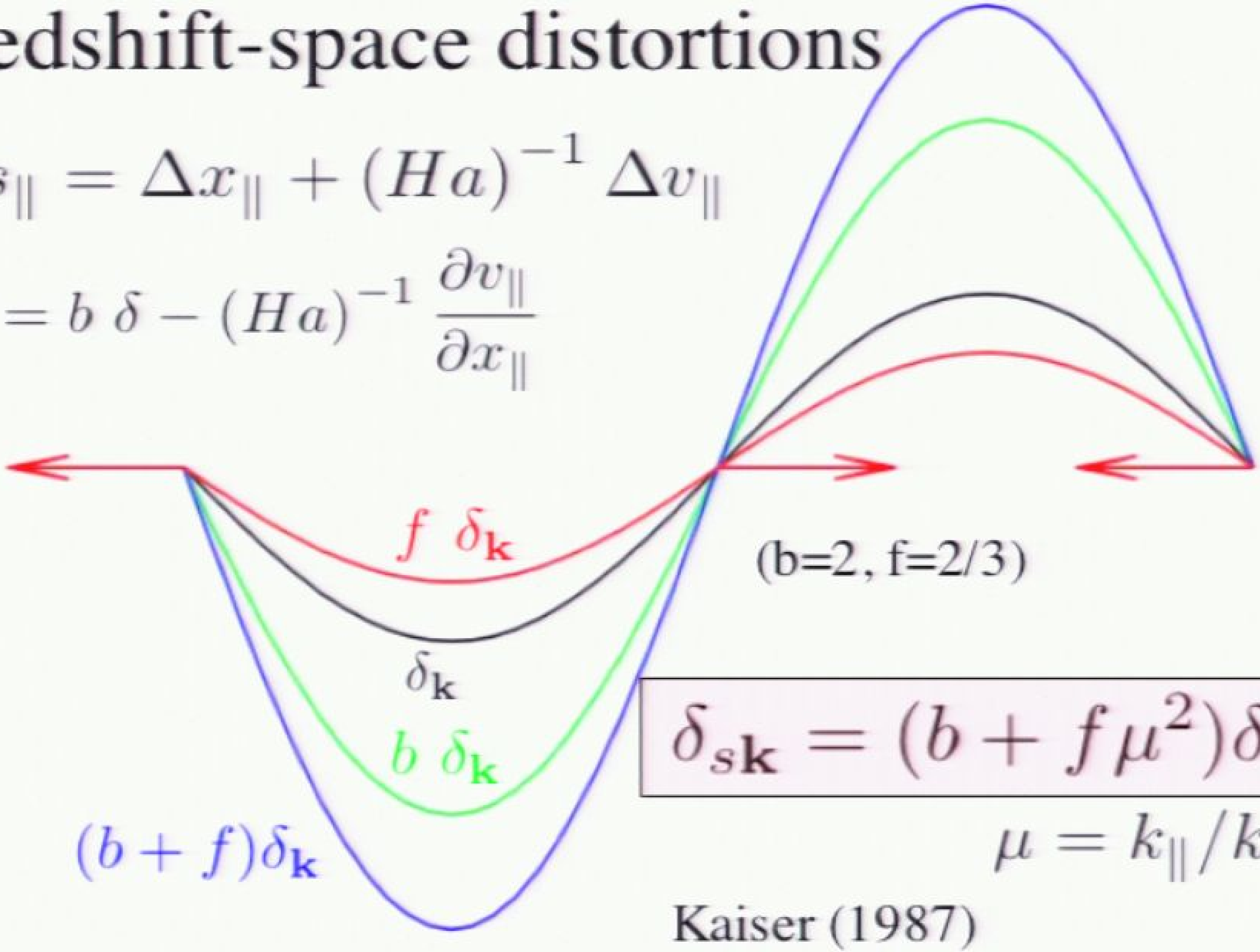
$$\mathbf{v}_{\mathbf{k}} = -iHaf\frac{\mathbf{k}}{k^2}\delta_{\mathbf{k}}$$

$$f = \frac{d\ln D}{d\ln a} \simeq \Omega_m^{0.6}$$

Redshift-space distortions

$$\Delta s_{\parallel} = \Delta x_{\parallel} + (Ha)^{-1}\,\Delta v_{\parallel}$$

$$\delta_s = b\,\delta - (Ha)^{-1}\,\frac{\partial v_{\parallel}}{\partial x_{\parallel}}$$



(b=2, f=2/3)

$$\boxed{\delta_{s\mathbf{k}} = (b + f\mu^2)\delta_{\mathbf{k}}}$$

$$\mu = k_{\parallel}/k$$

Kaiser (1987)

How to beat cosmic variance with multiple tracers

For illustration, assume no noise.
The random density field cancels from the ratio of densities of two types of galaxy.

$$\frac{\delta_{g2}}{\delta_{g1}} = \frac{(b_2 + f\mu^2)\cancel{\delta}}{(b_1 + f\mu^2)\cancel{\delta}} = \frac{\alpha + \beta\mu^2}{1 + \beta\mu^2}$$

$$\alpha = \frac{b_2}{b_1} \qquad \beta \equiv \frac{f}{b_1} = \frac{1}{b_1}\frac{d\ln D}{d\ln a}$$

With only two modes (e.g., radial and transverse), we can measure bias ratio and distortion factor perfectly!
With small noise the error scales like N/P.

But wait… what good is knowing $\beta = \frac{f}{b_1}$ when we don't know b_1?

Go back to the equation for the galaxy density:

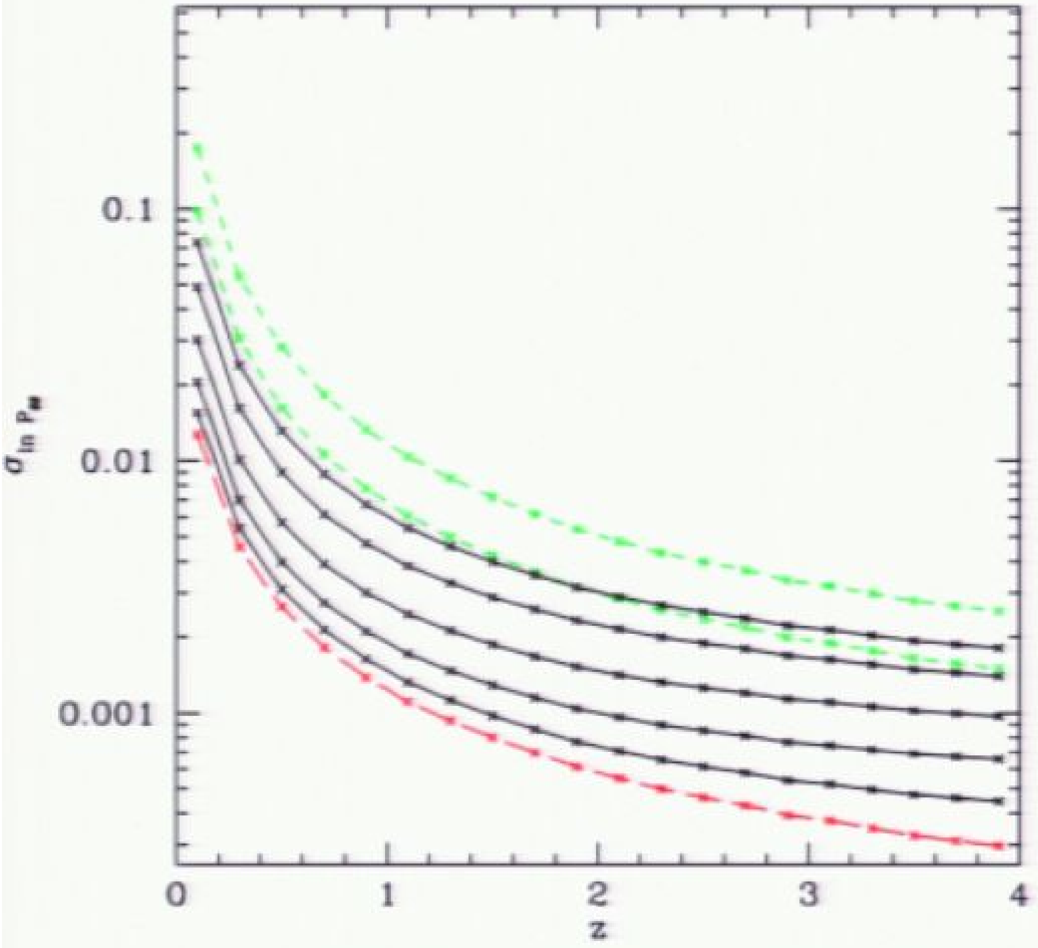
$$\delta_{g1} = (b_1 + f\mu^2)\delta = \left(\beta^{-1} + \mu^2\right) f\delta$$

We have a perfect measurement of $f\delta \propto \theta$, the velocity divergence - use this to measure

$$P_{\theta\theta} \equiv \left(\frac{d\ln D}{d\ln a}\right)^2 P_m$$

So we haven't entirely eliminated cosmic variance, but have eliminated confusion with bias.

$P_{\theta\theta}$ from full Fisher matrix for finite noise



- Hypothetically map 30000 sq. deg.
- Green: single b=1 (bottom) or 2 (top) tracers (note smaller bias is better).
- Black: both, S/N=1, 3, 10, 30, 100 (at k=0.4 h/Mpc)
- Red: cosmic variance

$$k_{\max} = 0.1\ [D(0)/D(z)]\ \mathrm{h/Mpc}$$

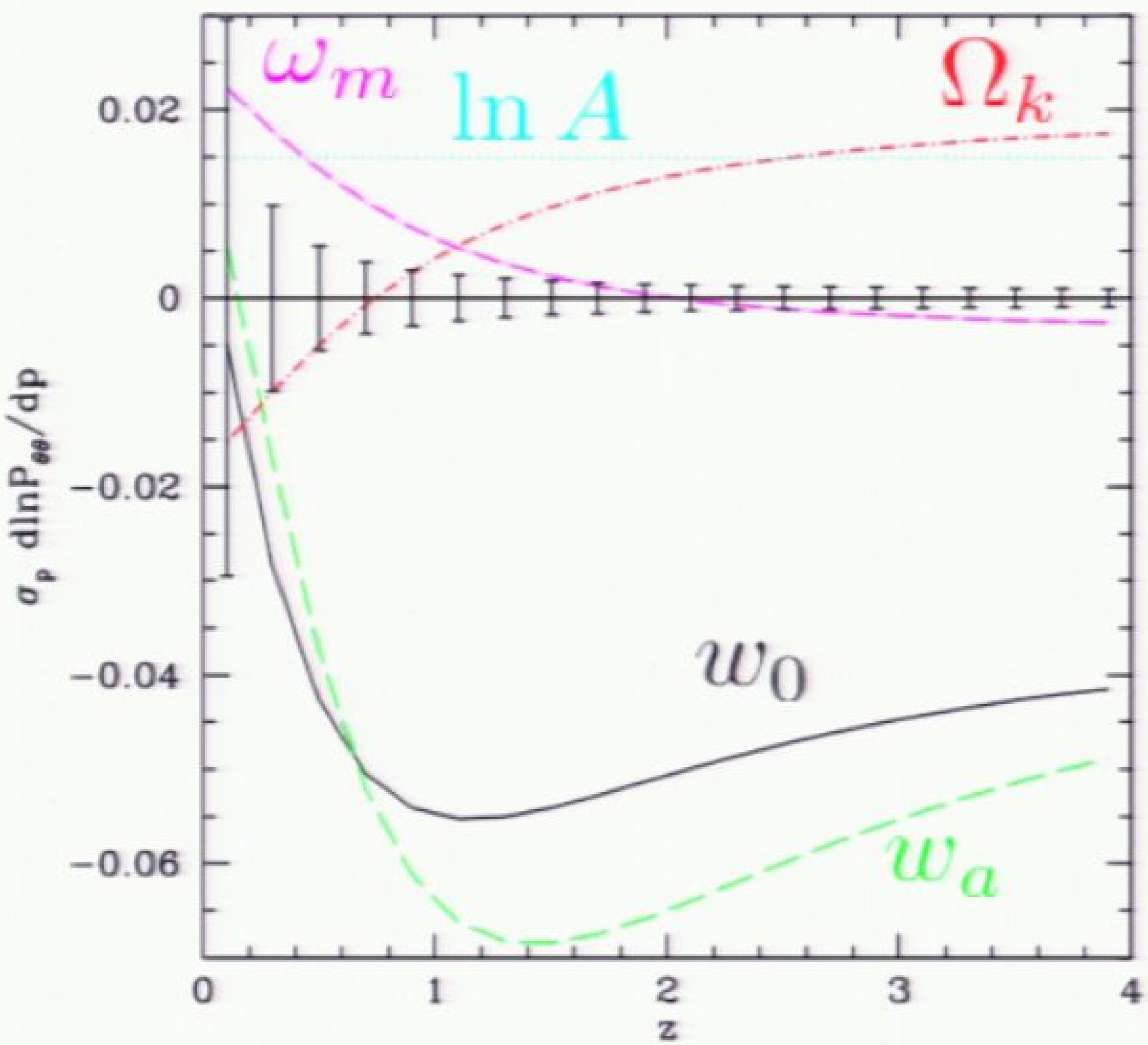
Constraints on parameterized Dark Energy

$$w(a) = \frac{p_{\rm DE}}{\rho_{\rm DE}} = w_0 + w_a(1 - a)$$

The “Dark Energy Task Force” suggested using the inverse of the area within the 95% confidence contours on a measurement of w_0 and w_a as a “Figure of Merit” for surveys.

This FoM gives a somewhat arbitrary but usefully standardized way to quantify the general constraining power of a survey.

Parameter dependence of $P_{\theta\theta}(k = 0.1\ \mathrm{h/Mpc})$



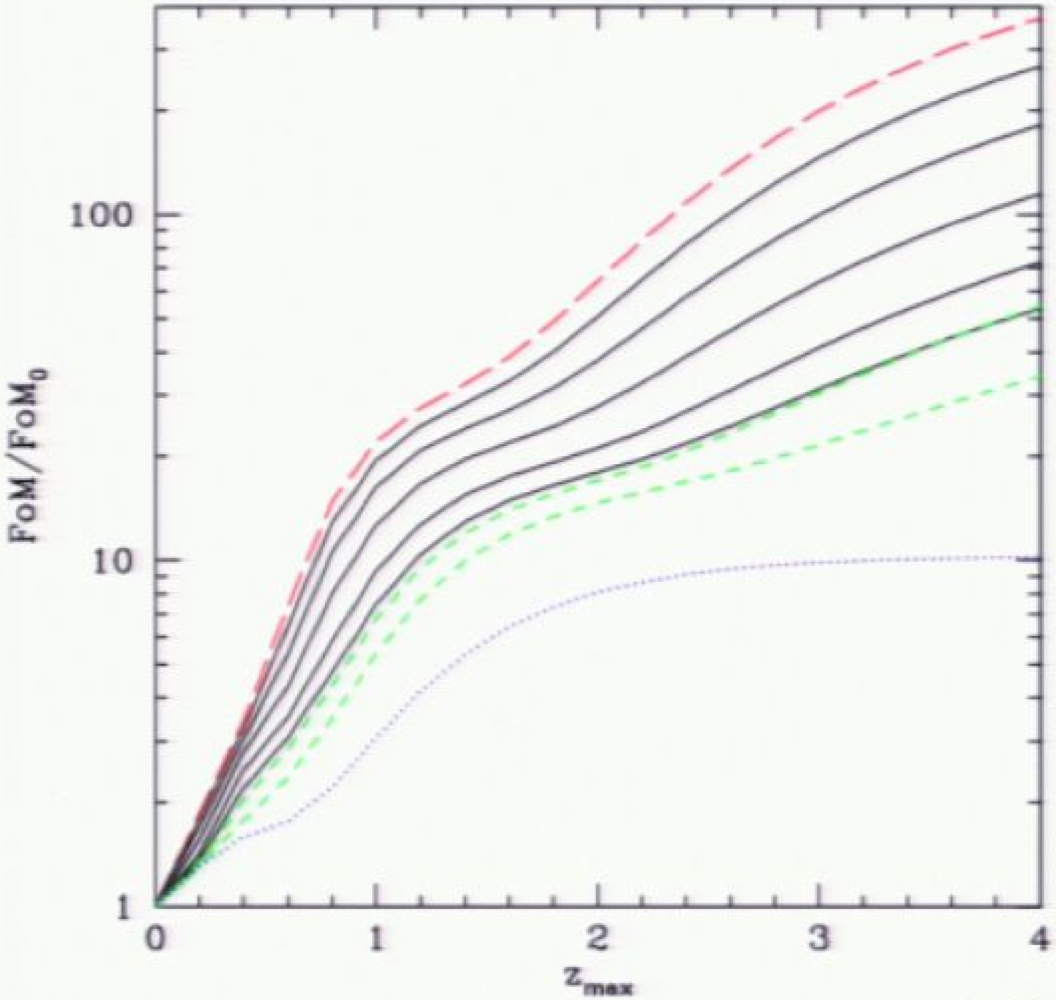
Error bars show the projected errors for S/N=10 (on the BAO scale), and 3/4 sky.

Fixed $\omega_b,\ \theta_s,\ n_s$ along with other parameters.

Parameters scaled by typical error levels (inc. Planck).

$$P_{\theta\theta} \equiv \left(\frac{d\ln D}{d\ln a}\right)^2 P_m$$

FoM with $P_{\theta\theta}$ constraints



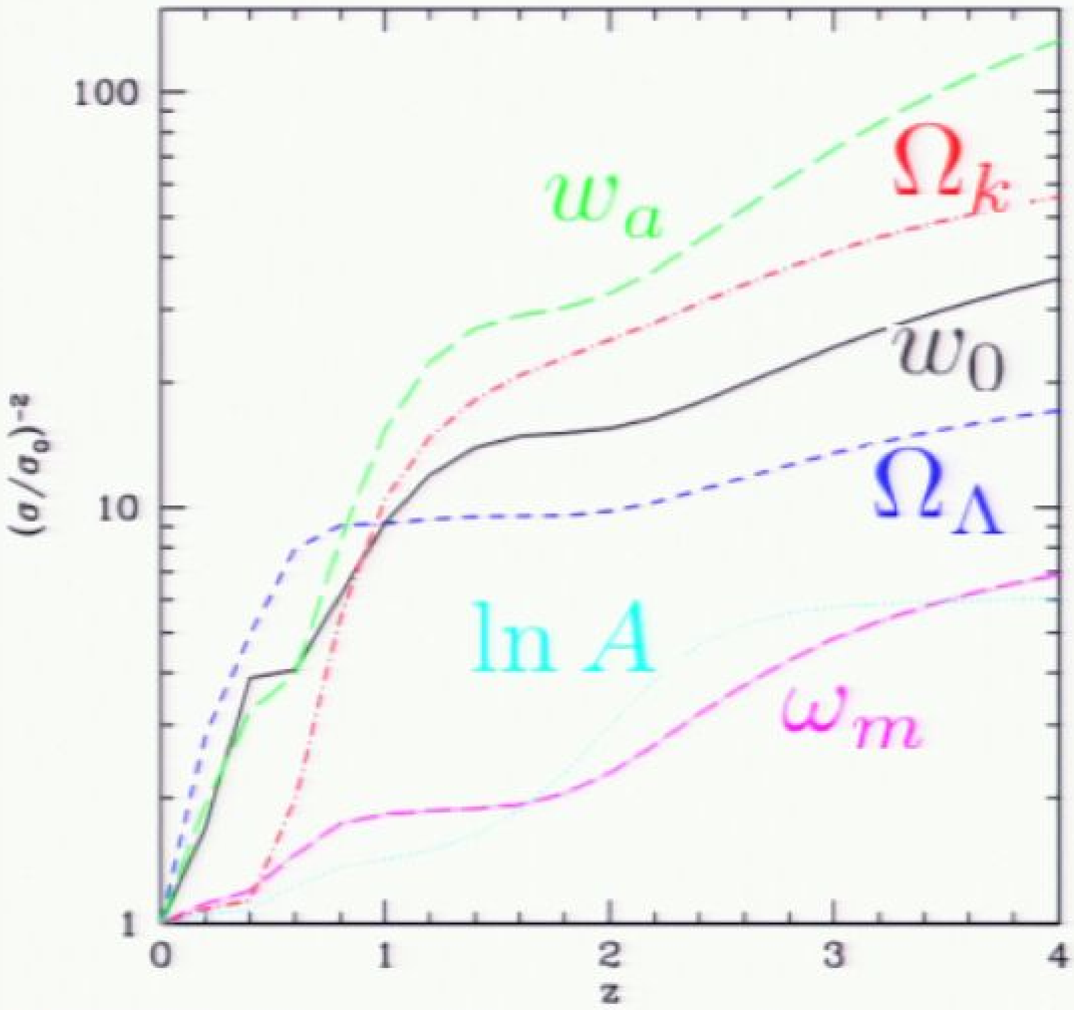
- Baseline is Planck+DETF "Stage-II" (~presently happening lensing, SN, clusters)
- Includes BAO from the same survey (blue is BAO only)
- 3/4 sky up to z_max.
- Green: single b=1 (top) or 2 (bottom) tracers.
- Black: both tracers, S/N=1, 3, 10, 30, 100 (at k=0.4 h/Mpc)
- Red: cosmic variance limit

$$k_{\max} = 0.1\ [D(0)/D(z)]\ \mathrm{h/Mpc}$$

$$\text{Best case has } \sigma_{w_0} = 0.0023$$

$$z < 2,\ S/N = 10 \text{ has } \sigma_{w_0} = 0.0074$$

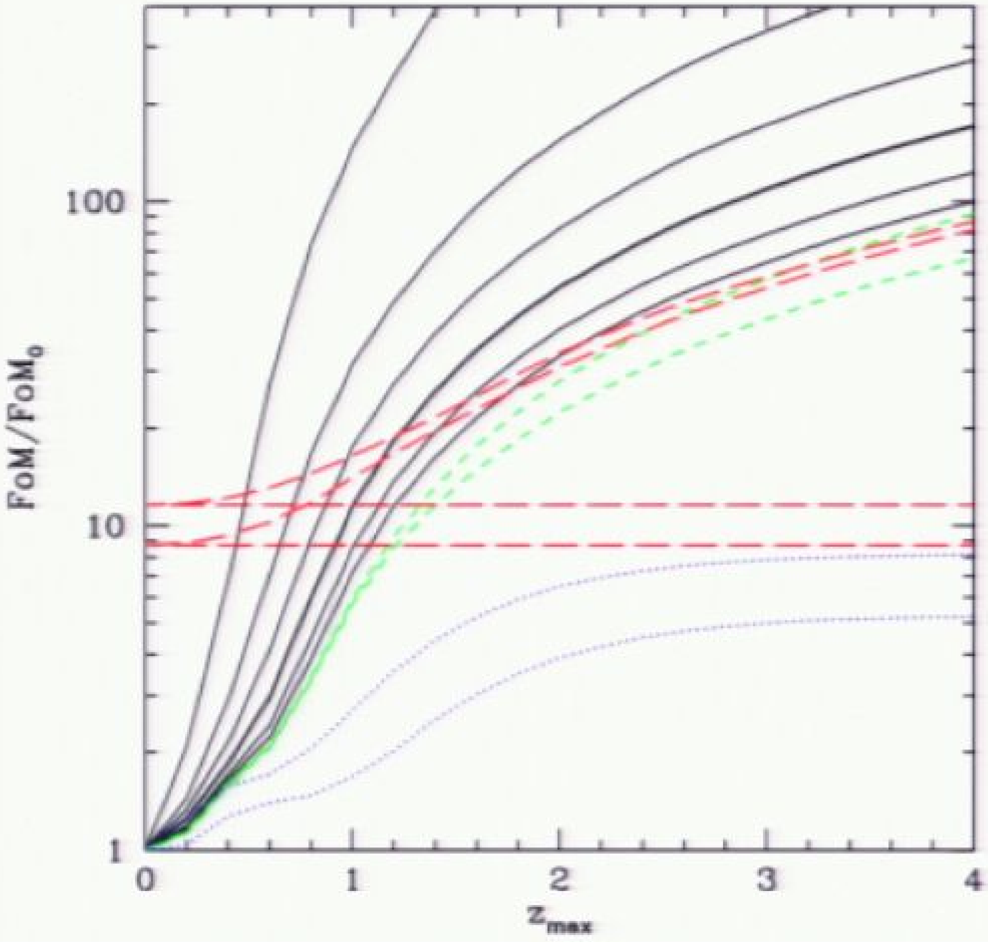
General parameter improvements.



- Baseline is Planck+DETF "Stage-II" (~presently happening lensing, SN, clusters)
- Includes BAO from same survey
- S/N=10 (not the best one could do)
- 3/4 sky
- b=1,2 tracers

FoM with the most complete constraints

(BAO, redshift-space, geometric (inc. AP), transfer function).



- Including all information adds a factor of ~3-5 over redshift-space distortions alone.
- Red shows SNAP or LSST lensing (from DETF), alone, or with weakest redshift survey (green)
- 3/4 sky up to z_max.
- Green: single b=1 (top) or 2 (bottom) tracers.
- Black: both tracers, S/N=1, 3, 10, 30, 100, 1000 (at k=0.4 h/Mpc)

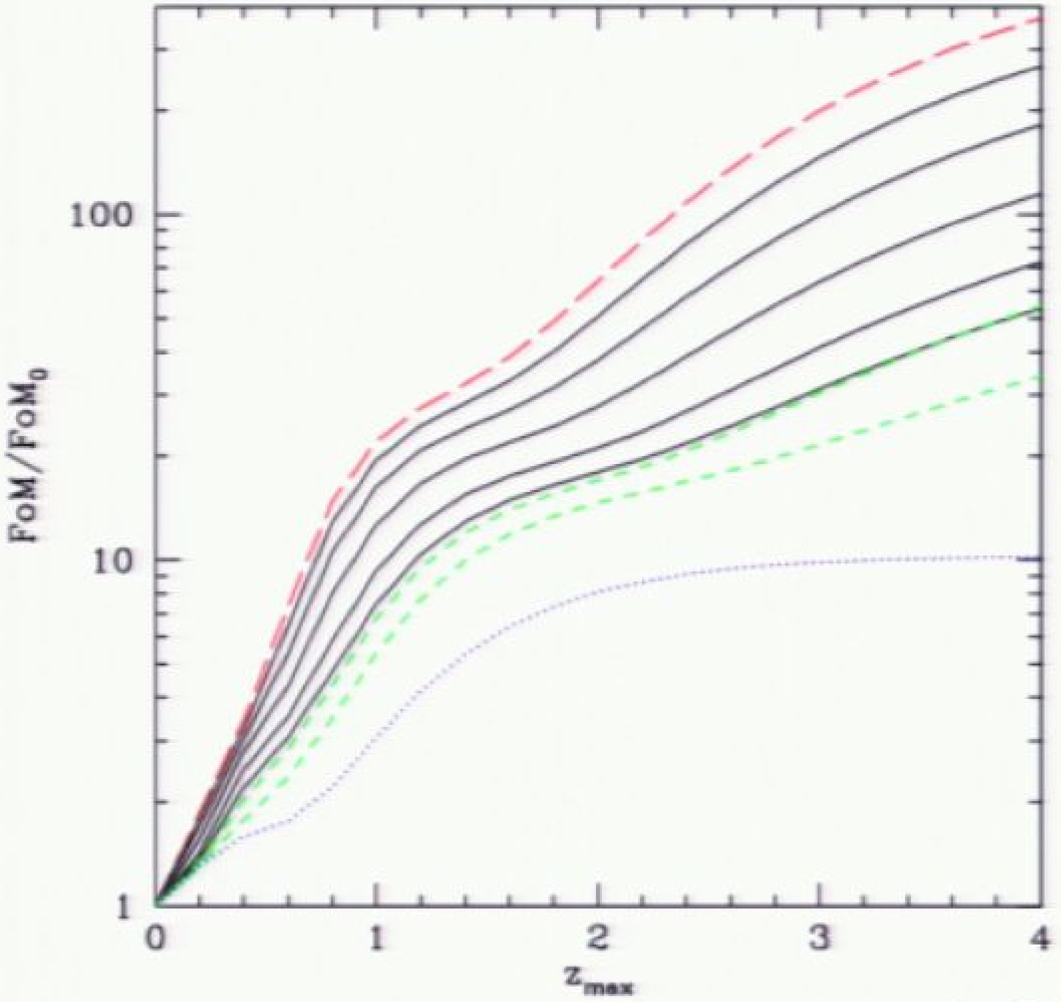
We can't actually calculate μ when we only observe redshift (velocity) and angle.

$$\mu = \frac{\hat{k}_{||}}{\sqrt{\hat{k}_{||}^2 + f_{\mathrm{AP}}^{-2}\ \hat{k}_{\perp}^2}} \qquad f_{\mathrm{AP}} = H(z)\ D_A(z)$$

Can use this to measure f_{AP} perfectly.

$$\frac{\delta_{g2}}{\delta_{g1}} = \frac{\alpha + \beta\ \mu^2(f_{\mathrm{AP}})}{1 + \beta\ \mu^2(f_{\mathrm{AP}})}$$

FoM with $P_{\theta\theta}$ constraints



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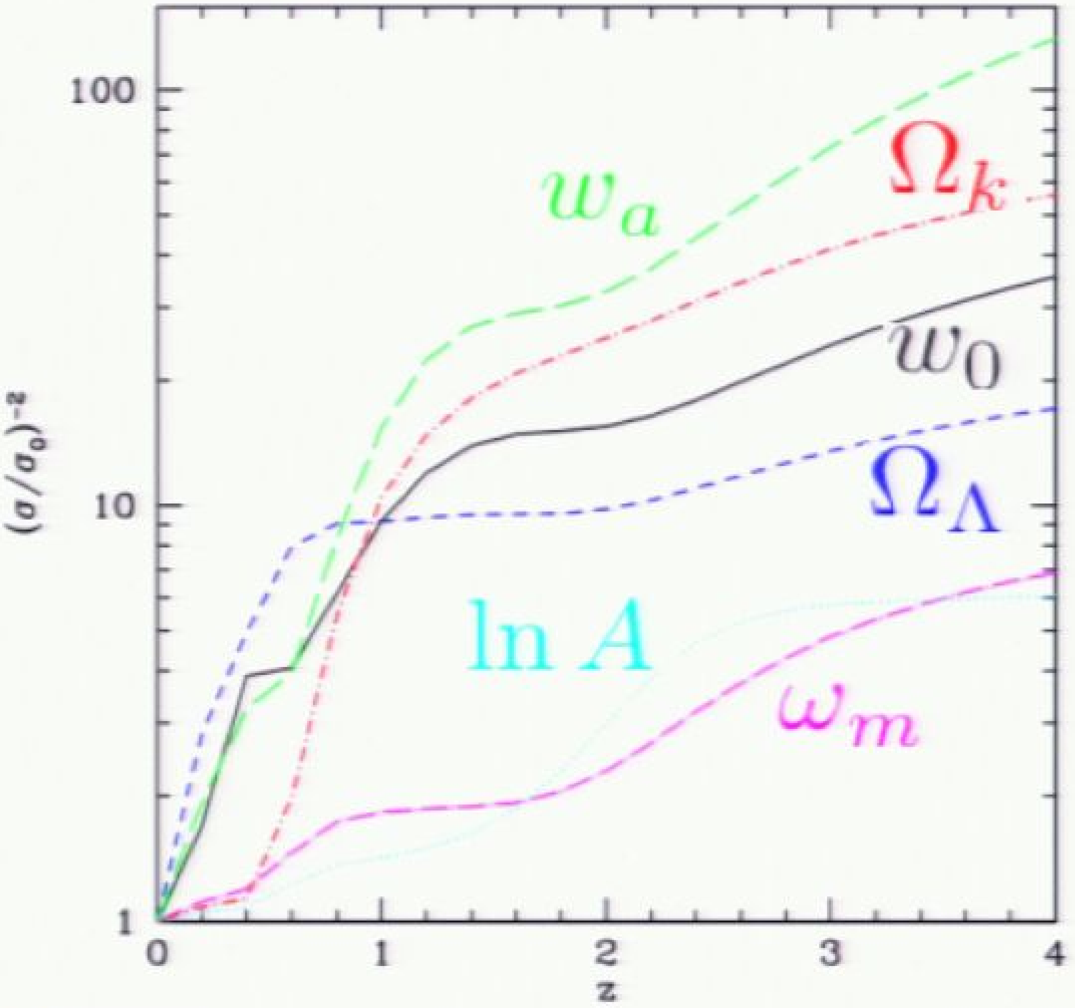

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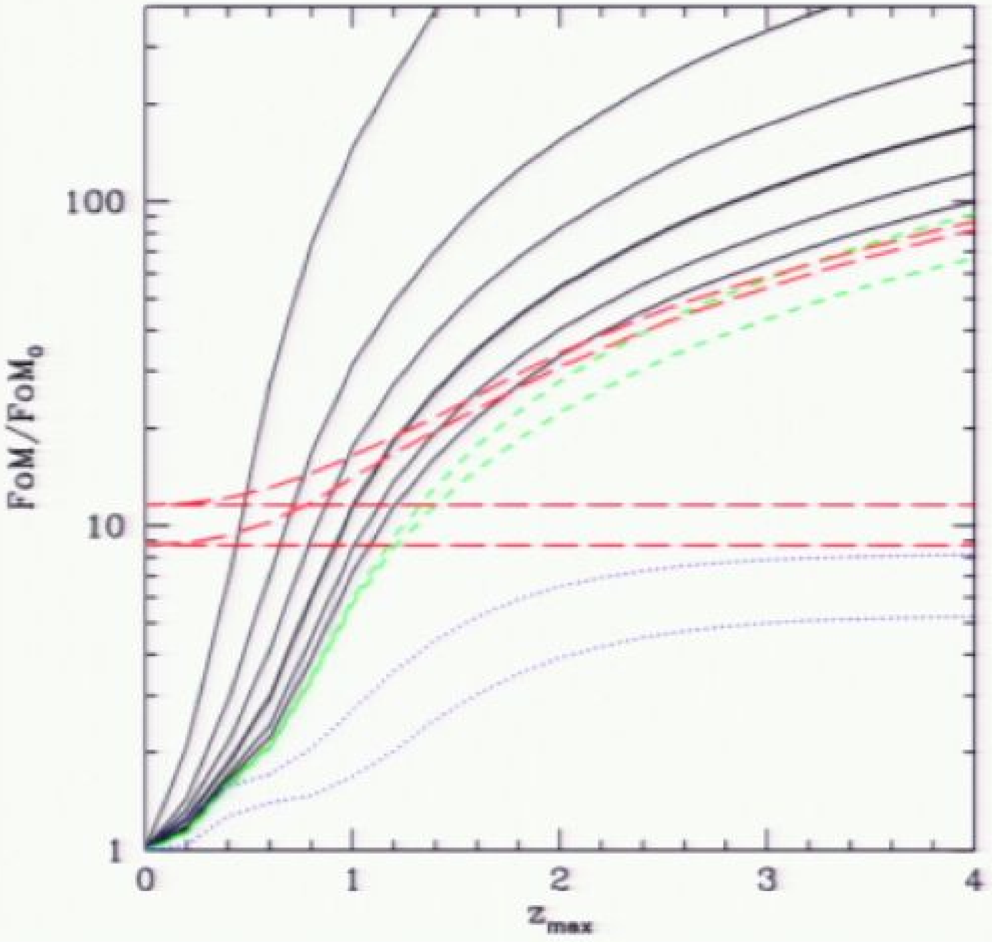

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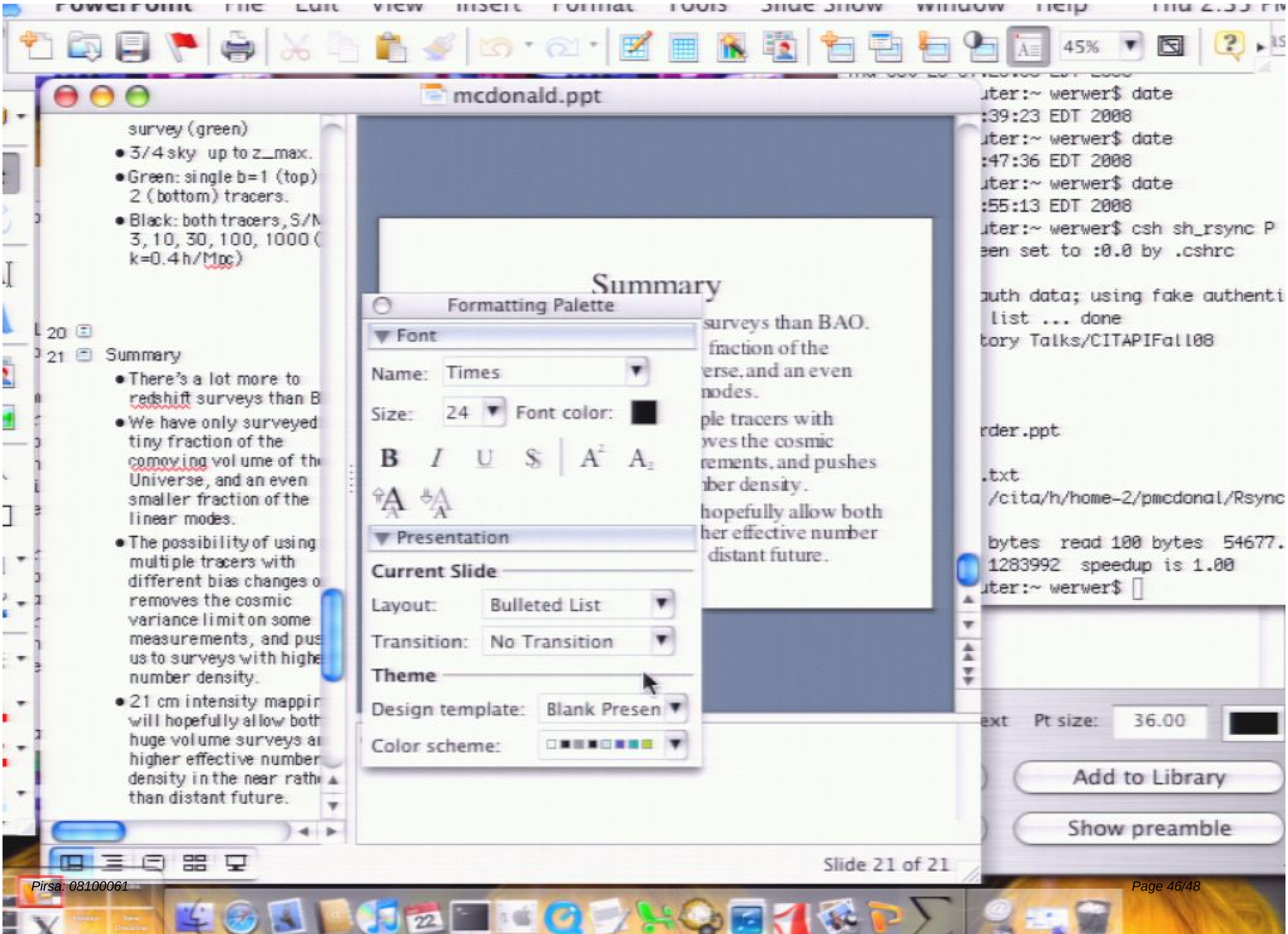
Summary

- There's a lot more to redshift surveys than BAO.
- We have only surveyed a tiny fraction of the comoving volume of the Universe, and an even smaller fraction of the linear modes.
- The possibility of using multiple tracers with different bias changes or removes the cosmic variance limit on some measurements, and pushes us to surveys with higher number density.
- 21 cm intensity mapping will hopefully allow both huge volume surveys and higher effective number density in the near rather than distant future.



survey (green)
- 3/4 sky up to z_max.
- Green: single b=1 (top) 2 (bottom) tracers.
- Black: both tracers, S/N 3, 10, 30, 100, 1000 (k=0.4 h/Mpc)

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