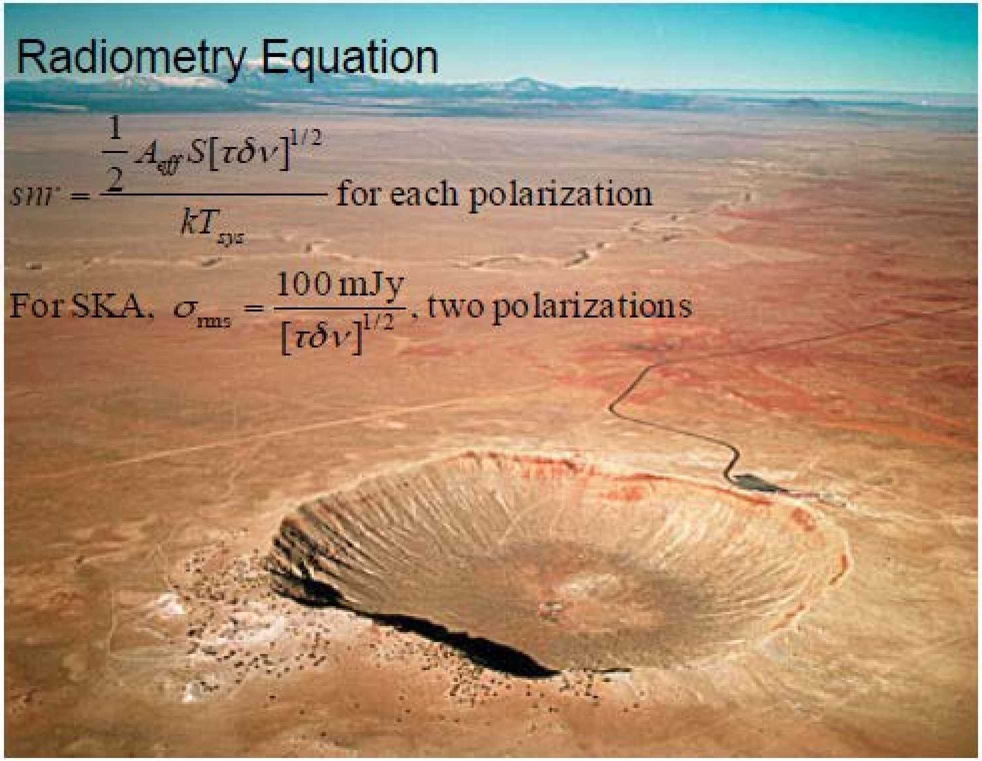
Cosmology opportunities at 1Ghz and below with wide FOV with the SKA.



Filipe B. Abdalla

THE ROYAL SOCIETY
CELEBRATING 350 YEARS

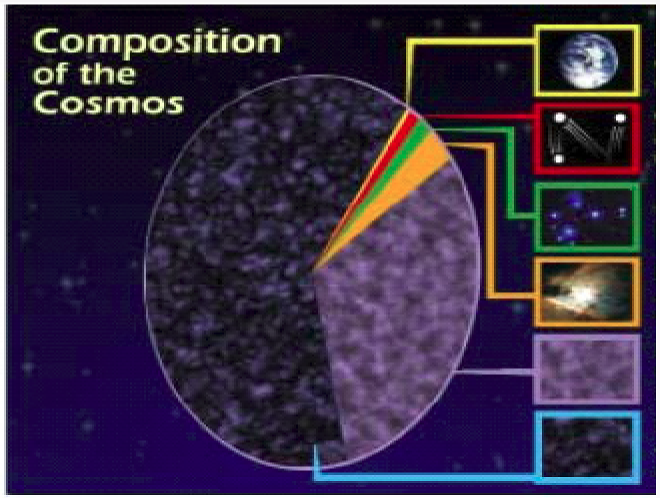
Outline of the talk

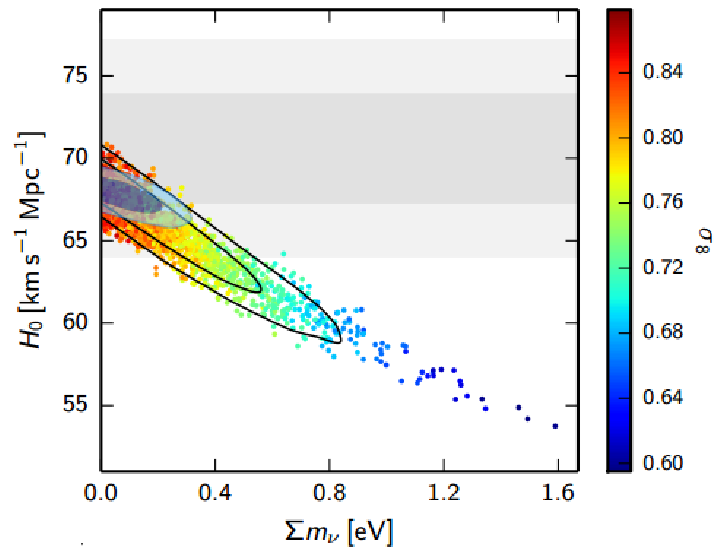
- Science opportunities below 1GHz we can achieve
- Links to the design and engineering.

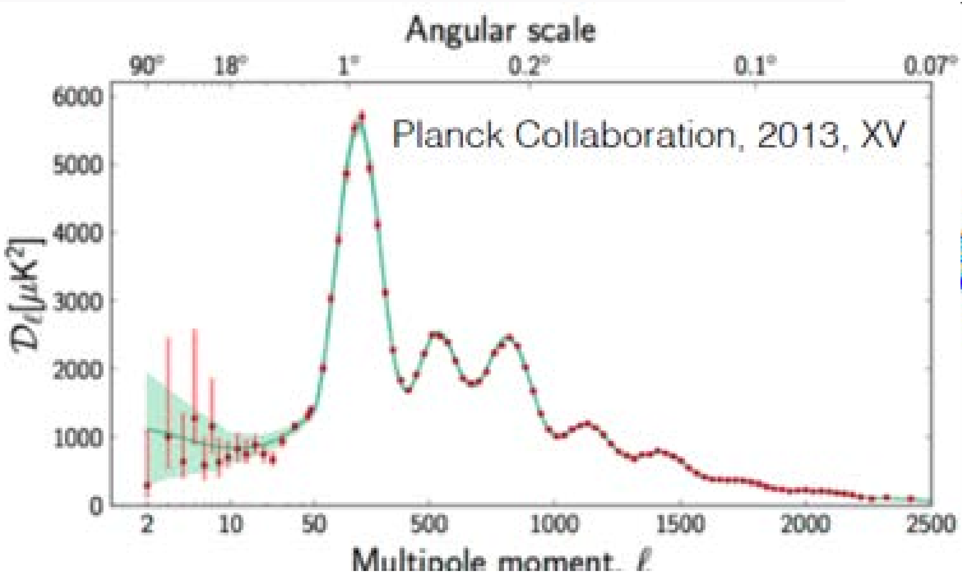
THE ROYAL SOCIETY

UCL

Cosmology: Concordance Model







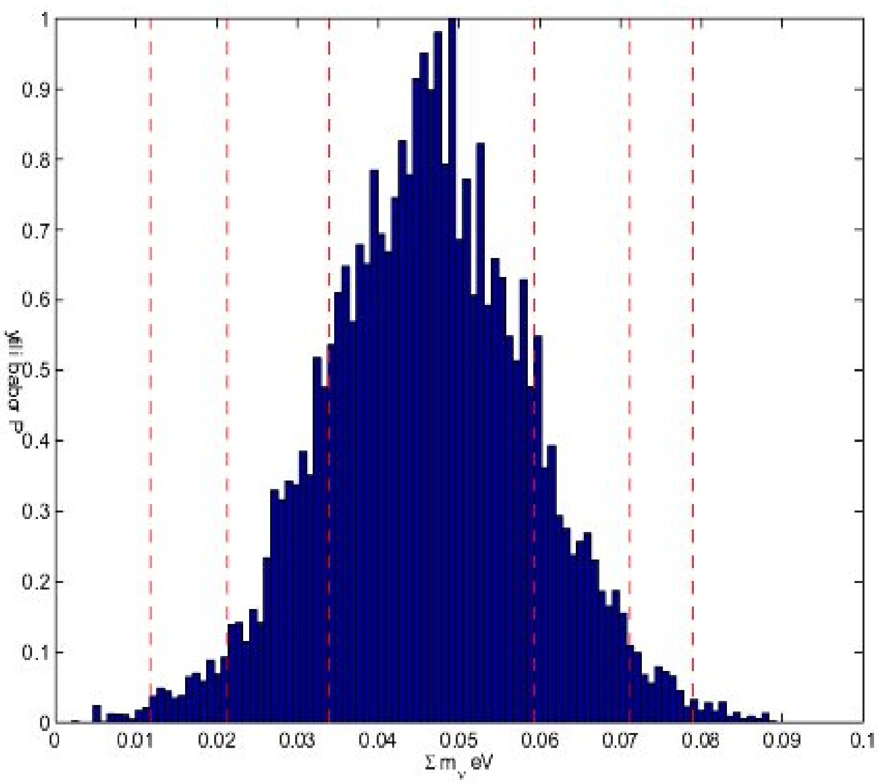
Outstanding questions:
- initial conditions (inflation?, f_{nl})
- nature of the dark matter
- nature of the dark energy
- value of the neutrino mass

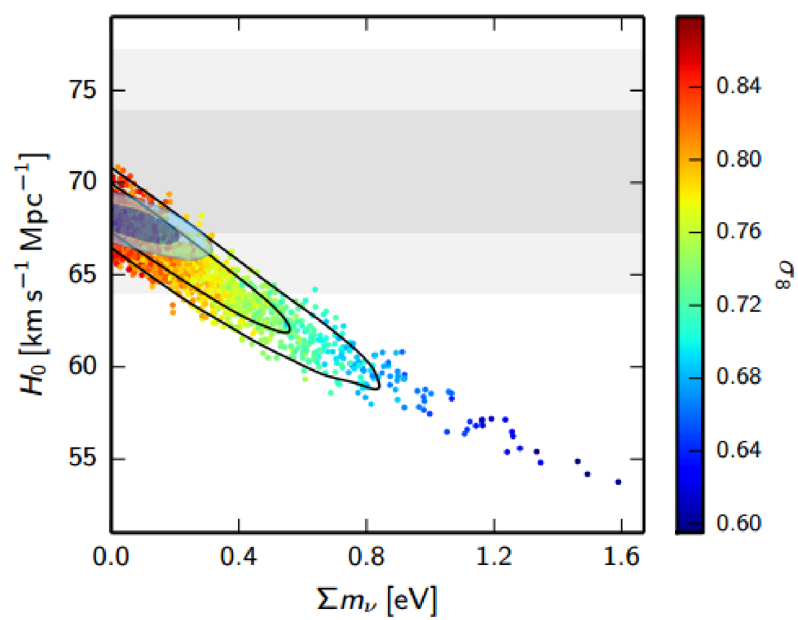
There are fluctuations at all scales but there is a preferred scale of around 1 deg.

Predictions of measuring neutrino masses with SKA + CMB: from 2007.

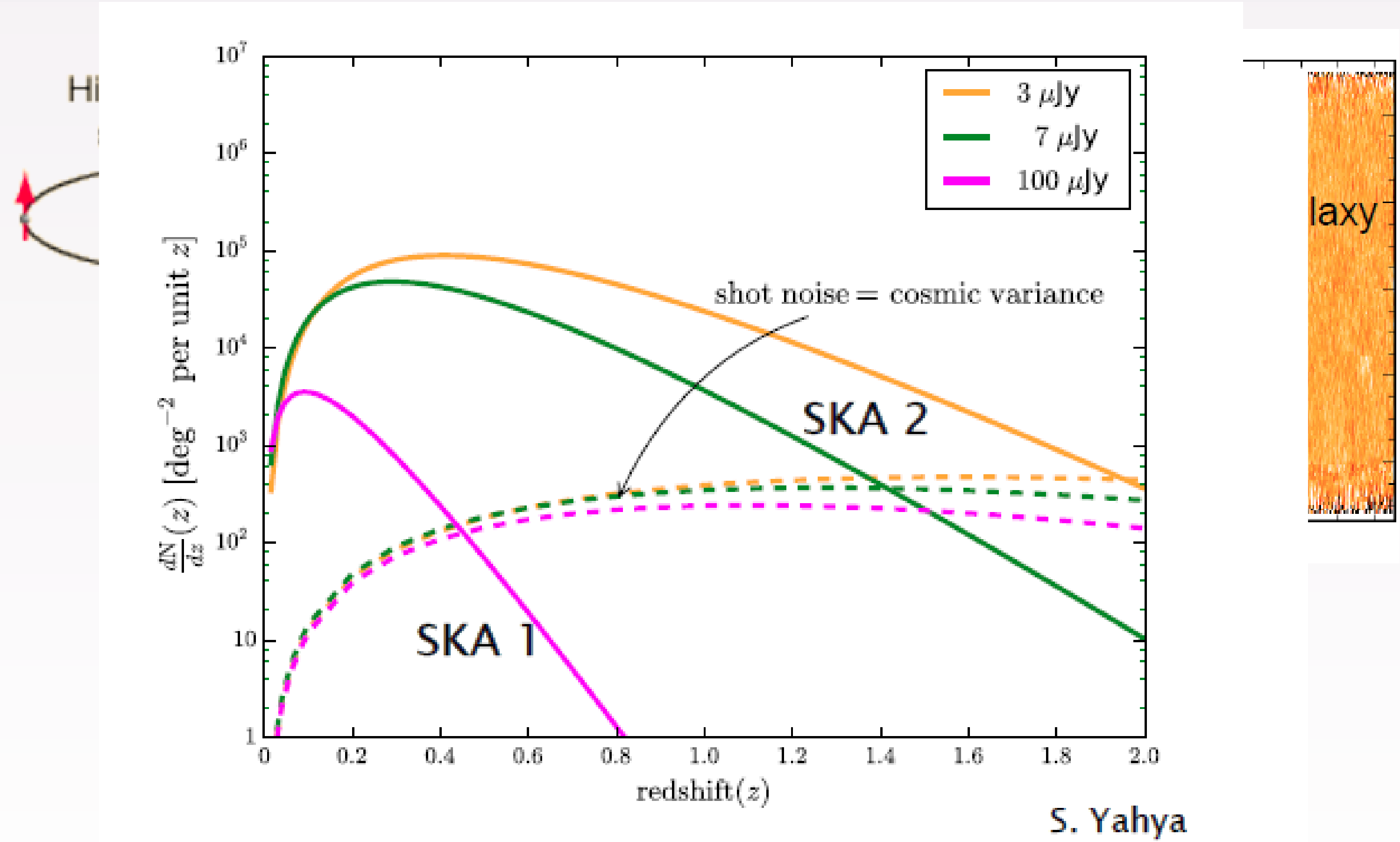
Message to understand, the statistics for datasets in cosmology moves slowly if there is not a technology step Or novel idea!

Photometric redshifts or Space missions can attempt this, but there are potential problems…





SKA is a Hydrogen detector



SKA1 ~ 10^7 galaxies over 5,000 deg^2
SKA2 ~ 10^9 galaxies over 30,000 deg^2

Growth and Power Spectrum of density fluctuations

$$ds^2 = -(1+2\psi)dt^2 + a^2(1+2\phi)dx^2$$

$$\delta G_{\nu\mu} = \frac{8\pi G}{c^4}\delta T_{\nu\mu}$$

$$\frac{\partial^2\delta}{\partial t^2} + 2H\frac{\partial^2\delta}{\partial t^2} = \left(\frac{c_s}{a}\right)^2 \nabla^2\delta + 4\pi G\rho\delta$$

Field of density fluctuations

$$\delta(x) = \frac{\delta\rho(x)}{\bar{\rho}}$$

Fourier transform

$$\delta(k) = \int d^3x\, e^{-ik\cdot x}\,\delta(x)$$

Power spectrum essentially square of Fourier transform

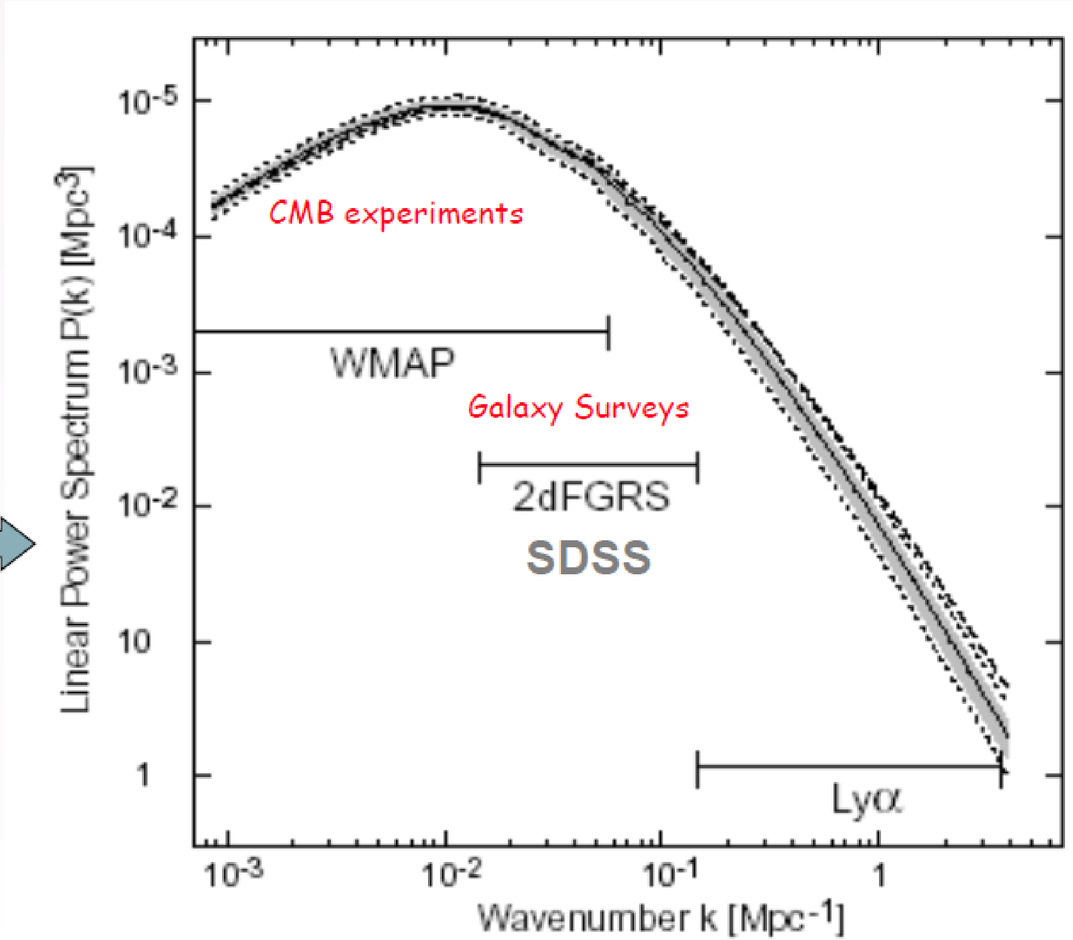
$$\langle\delta(k)\delta(k')\rangle = (2\pi)^3\hat{\delta}(k-k')\,P(k)$$

with $\hat{\delta}$ **the delta function**

Power spectrum is Fourier transform of two-point correlation function

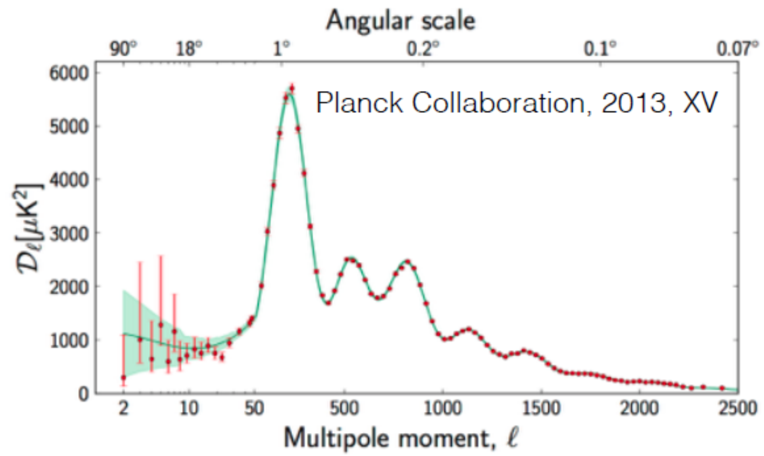
$$\xi(x) = \langle\delta(x_2)\delta(x_1)\rangle = \int\frac{d^3k}{(2\pi)^3}\,e^{ik\cdot x}\,P(k)$$

where $x = x_2 - x_1$



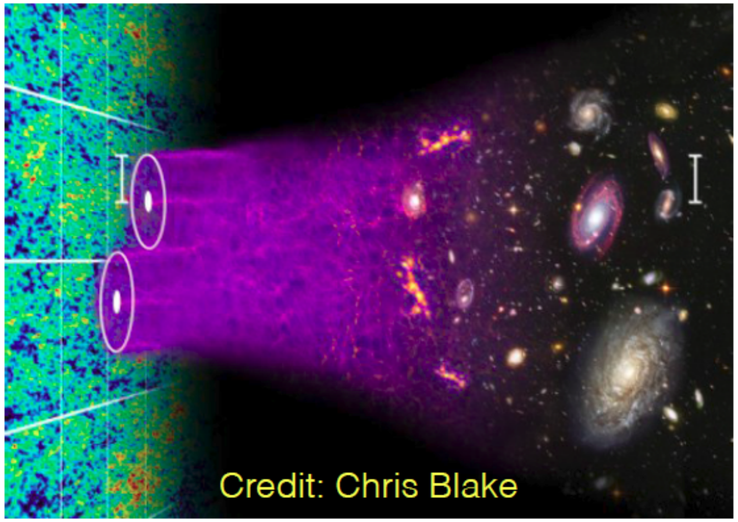
Baryon Acoustic Oscillations (BAOs)

- Acoustic waves imprinted on CMB 380,000 years after Big Bang
  - Acoustic scale set by distance light travelled at that time
  - Scale known to 0.2% precision from CMB power spectrum (147.4±0.3 Mpc)

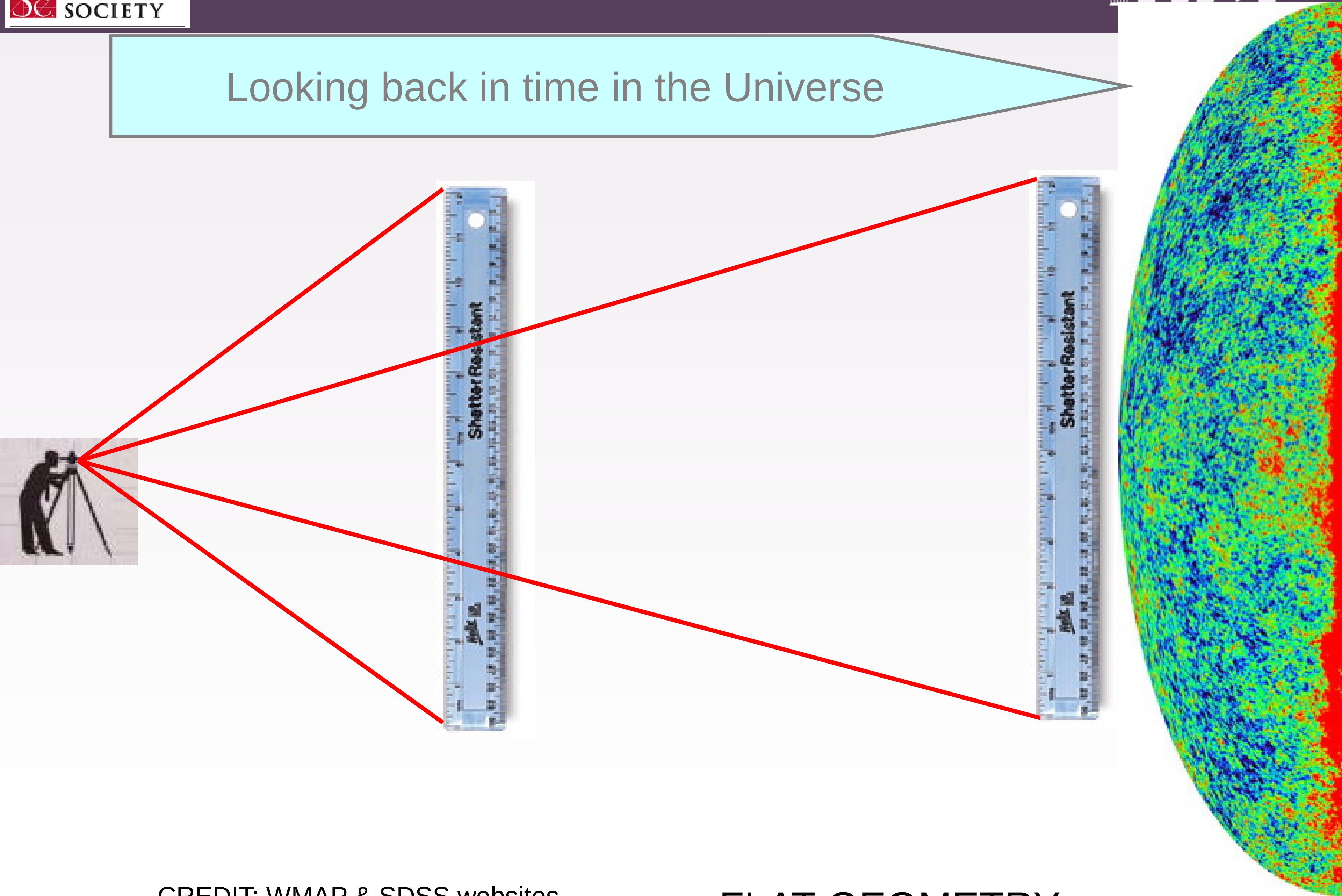


- Simulations clearly show that this preferred scale is imprinted on all matter in the Universe at the level of ~5%

- **BAOs are a "standard ruler" to measure expansion history of the Universe**
  - **Constrain cosmological models and dark energy**



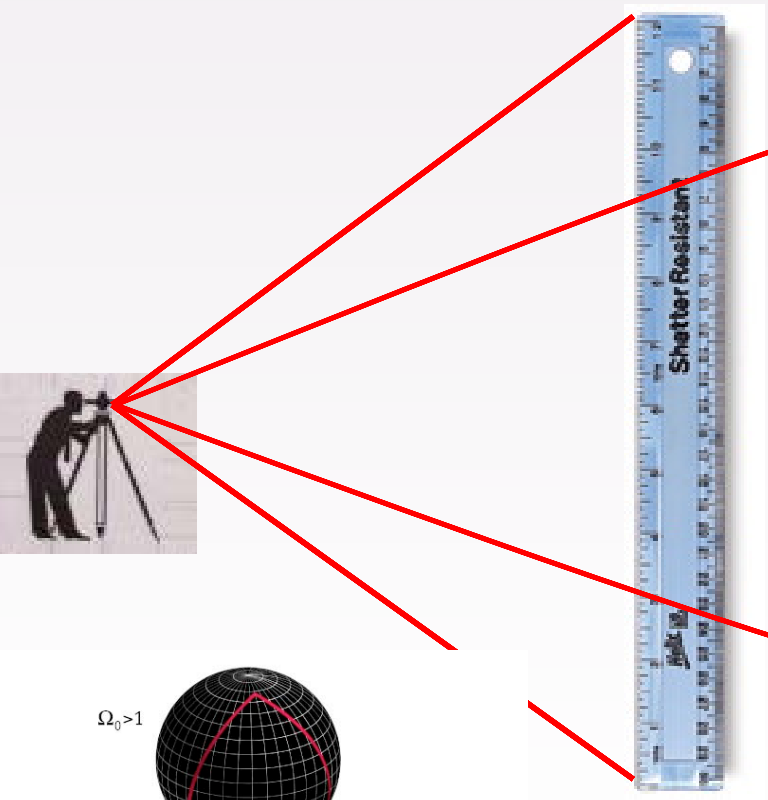
Looking back in time in the Universe

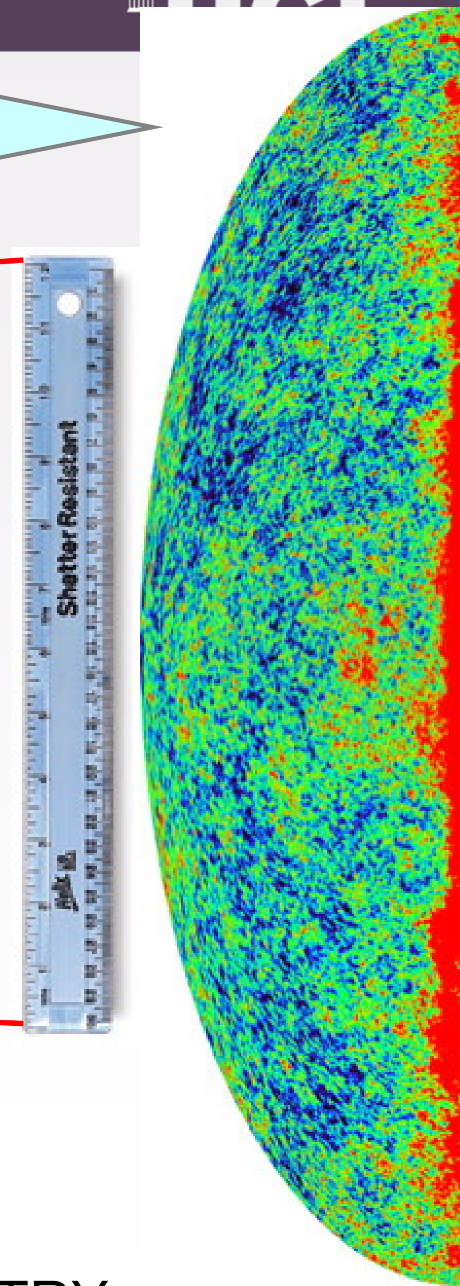


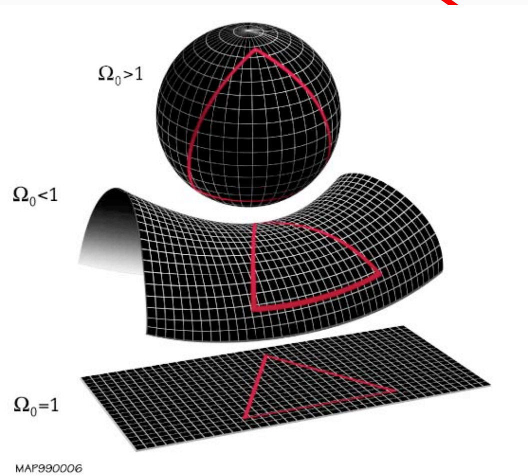
CREDIT: WMAP & SDSS websites

FLAT GEOMETRY

Looking back in time in the Universe

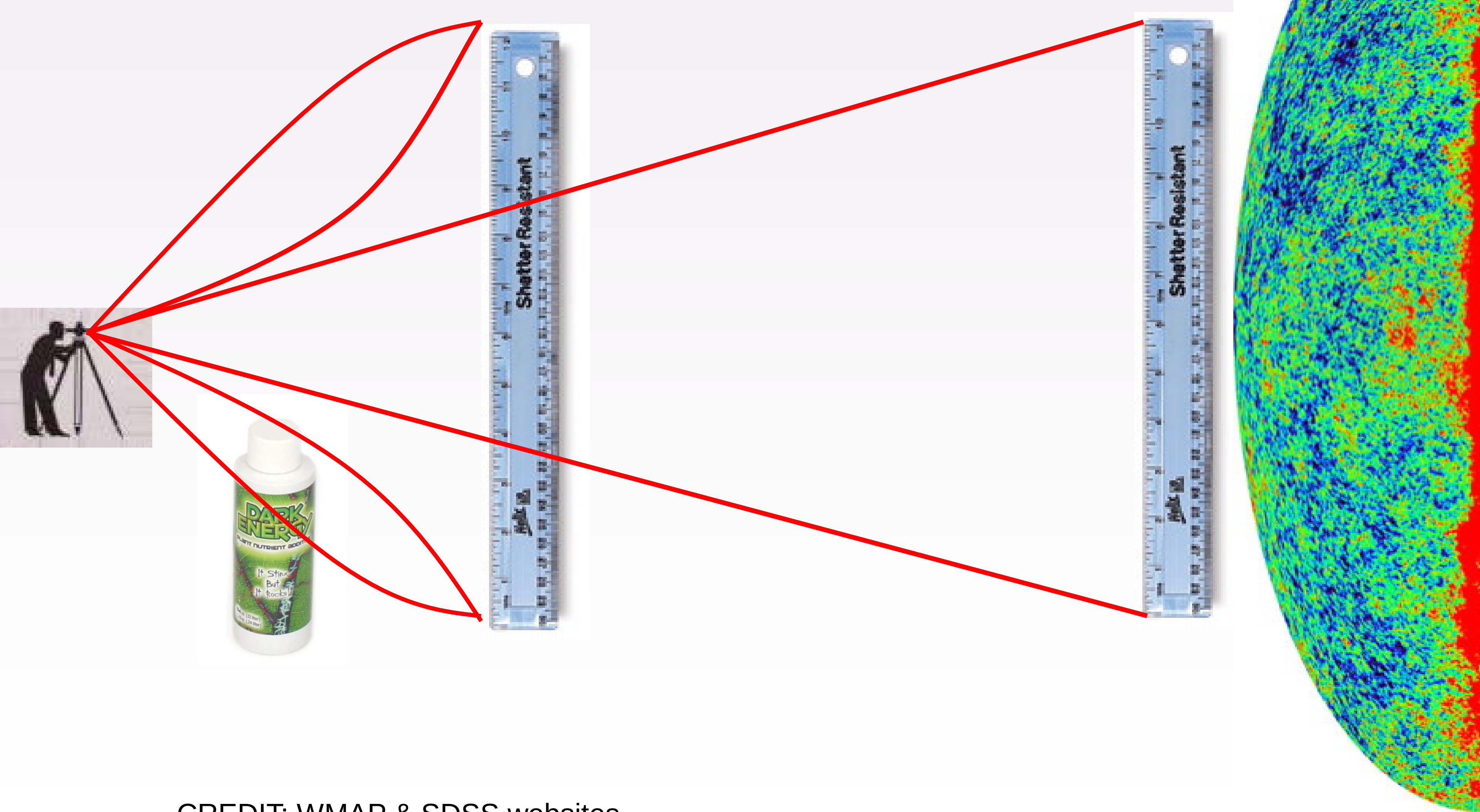






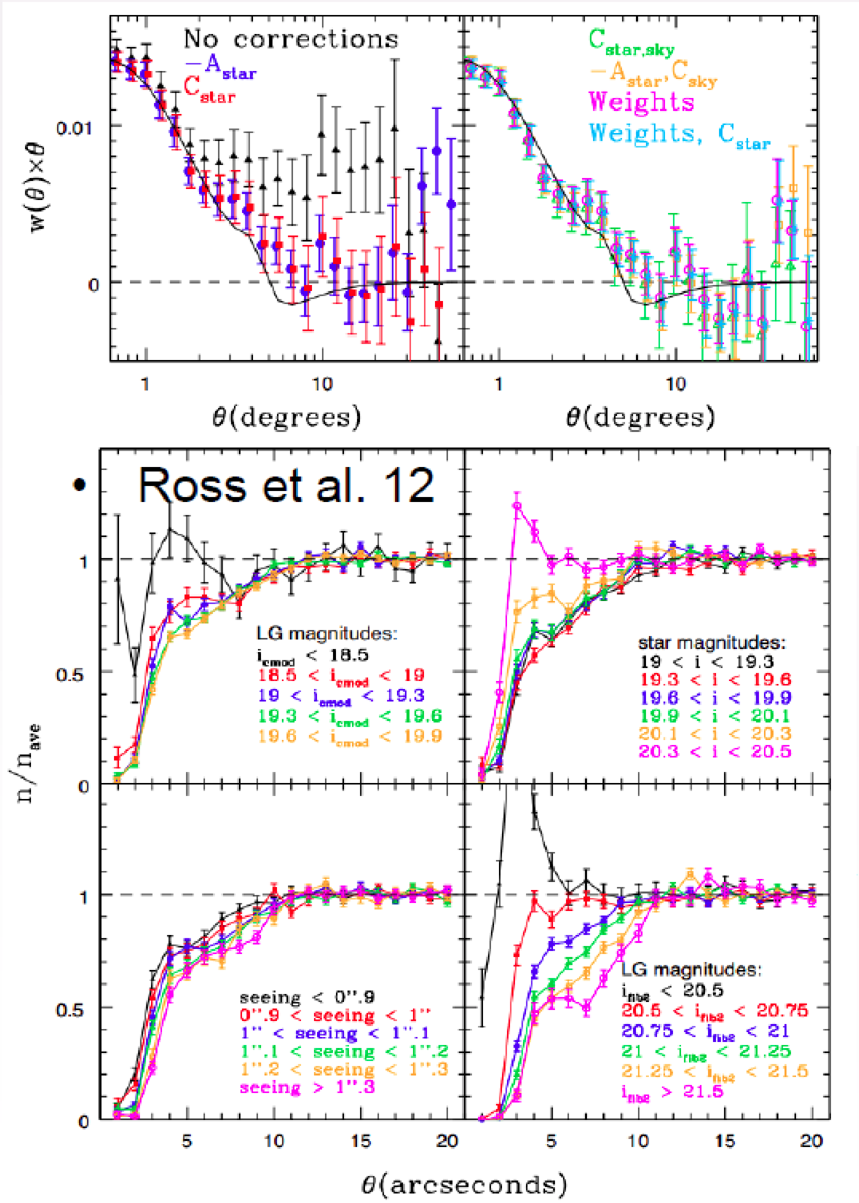
CLOSED GEOMETRY

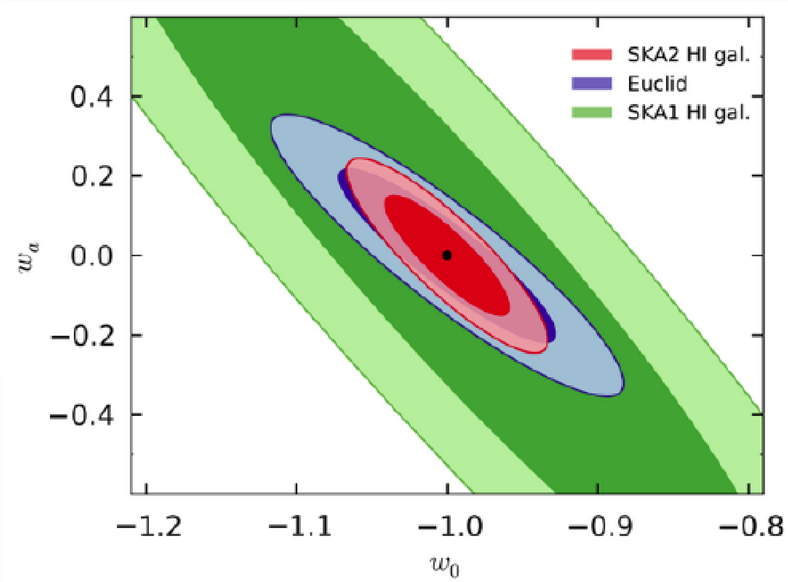
Looking back in time in the Universe



CREDIT: WMAP & SDSS websites

Optical: stars are always a problem





In the optical stars require corrections for theta larger than A couple of degrees!!!!

BAO features are ~ few degrees
Large scales for f_NL features are ~ 100s degrees

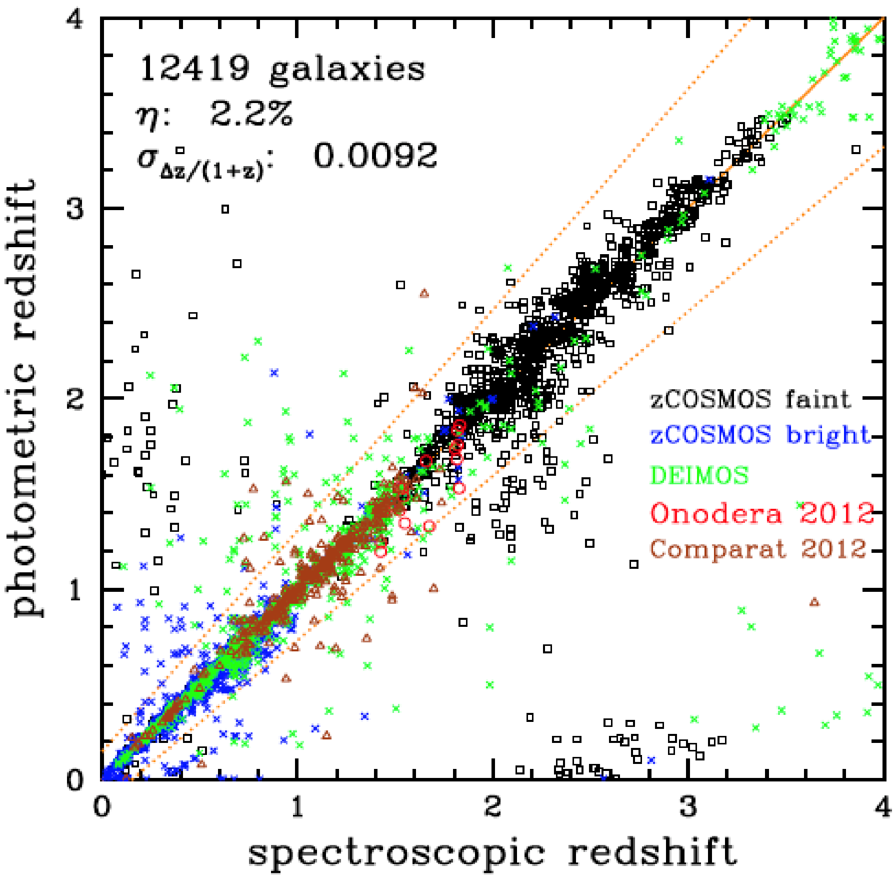
Results from Bull (BAO chapter)

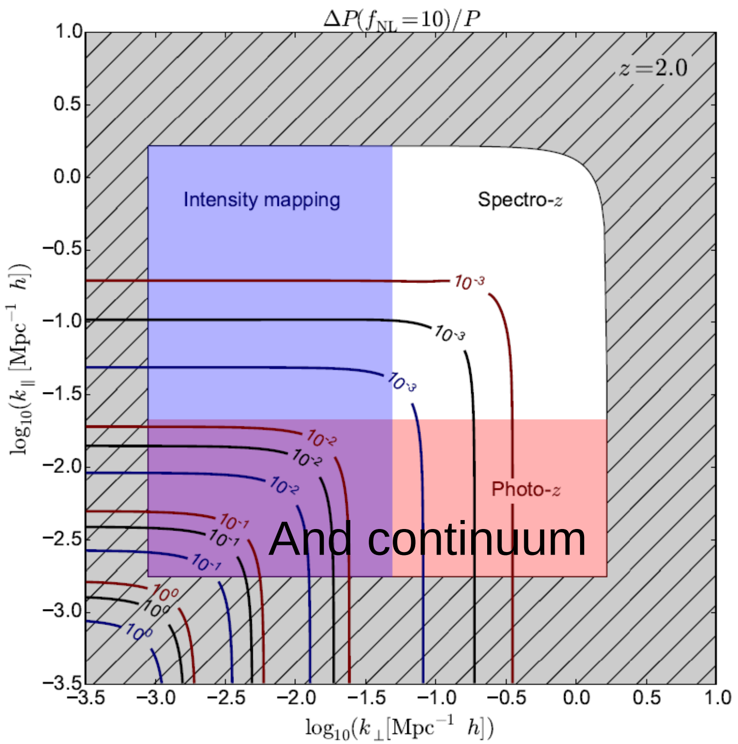
k [Mpc^{-1}]

There is a lot more than can be done… with other techniques before a fully capable SKA2!

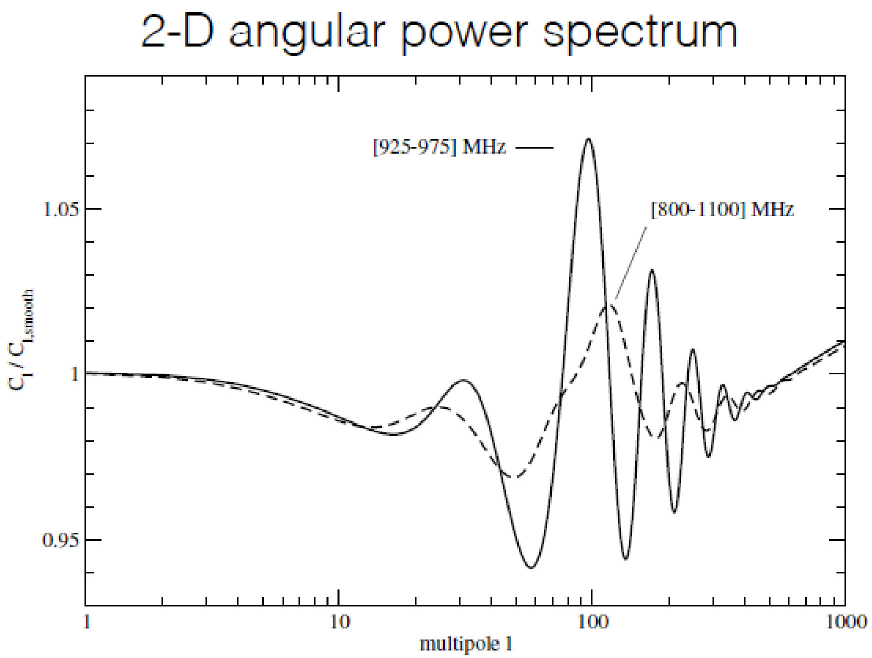
- Aperture arrays, PATHs and SKA1 will be able to perform intensity mapping experiments.
- Most of the statistical power from the above can be done much if intensity mapping is successful
- Combining radio and optical photo-z data will allow for the best calibrated cosmology dataset.
- SKA will also be able to measure the weak lensing signal form galaxies.

Intensity mapping, continuum surveys and Photometric redsfhits.





Intensity mapping

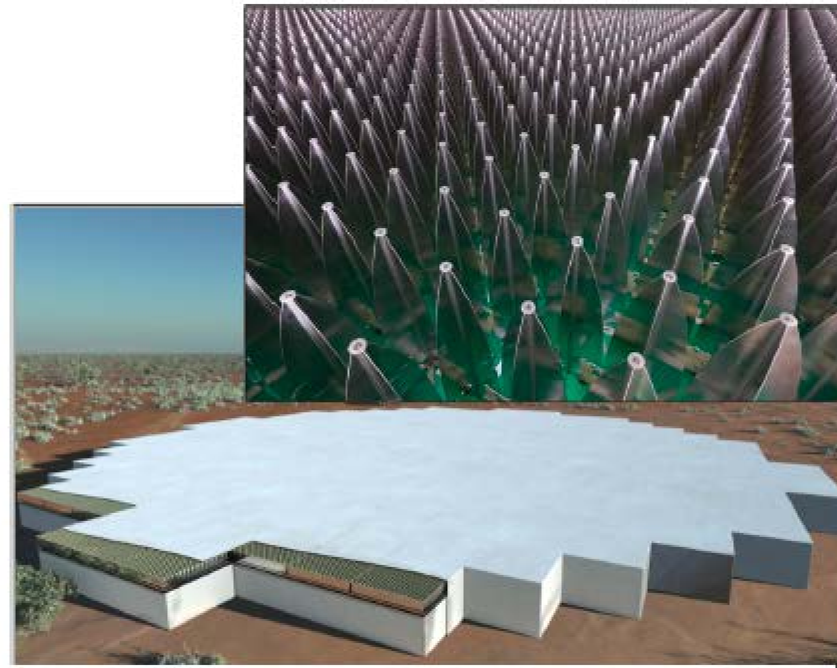


- BAOs on scales few deg to ~30 arcmin at z=0.3
- Average in frequency to reduce noise (larger bandwidth)
- Averaging over ~50 MHz (equivalent to delta z ~ 0.05) is optimal
- Average more than this smoothes out the BAO wiggles

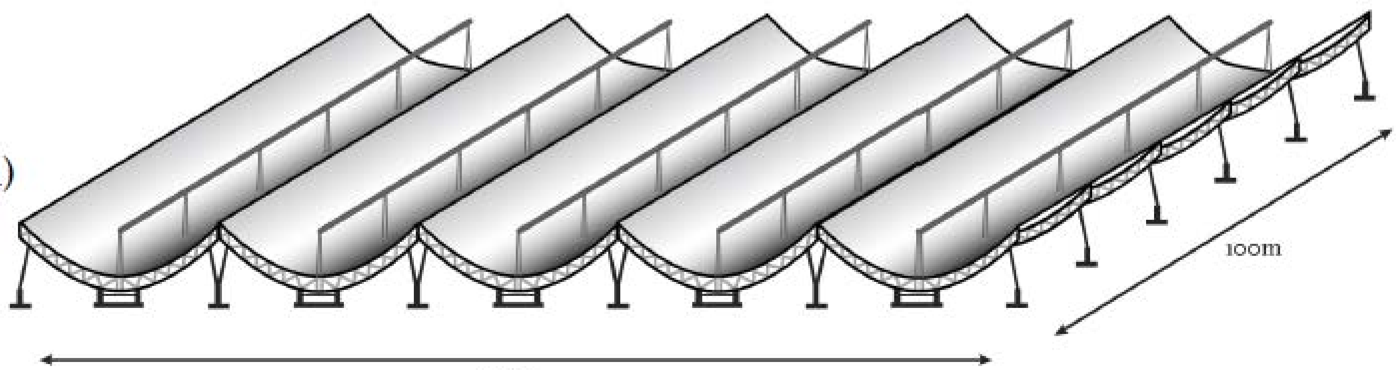
Experiments…

- Interferometers
  - Provide higher resolution
  - Ideally minimum baseline ~ 10 m for large scales…

Dense aperture array systems



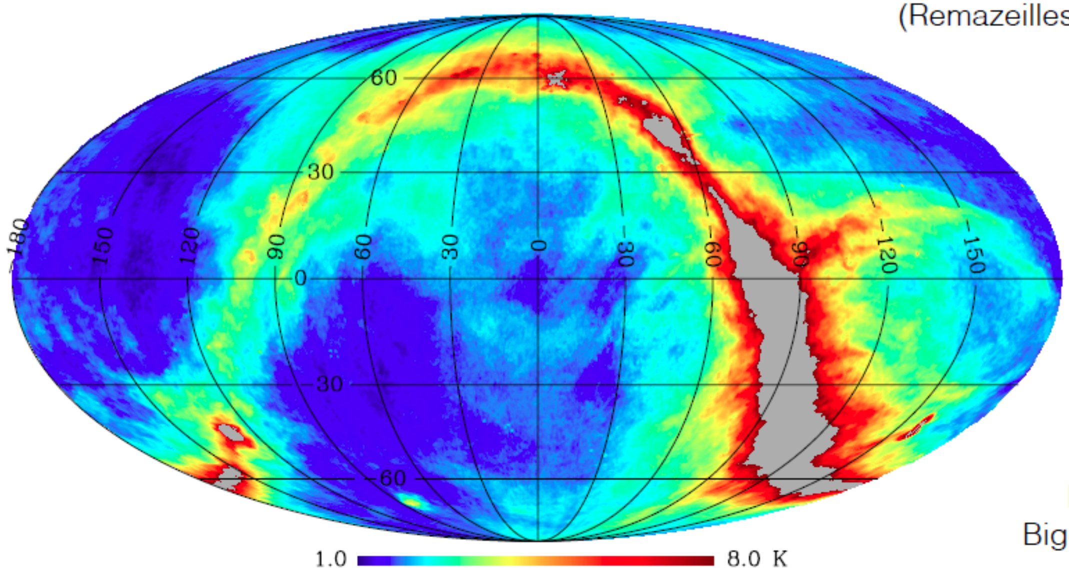
- CHIME (Canada)
- Tianlai (China)
- HIREX(SA)



Foreground contamination

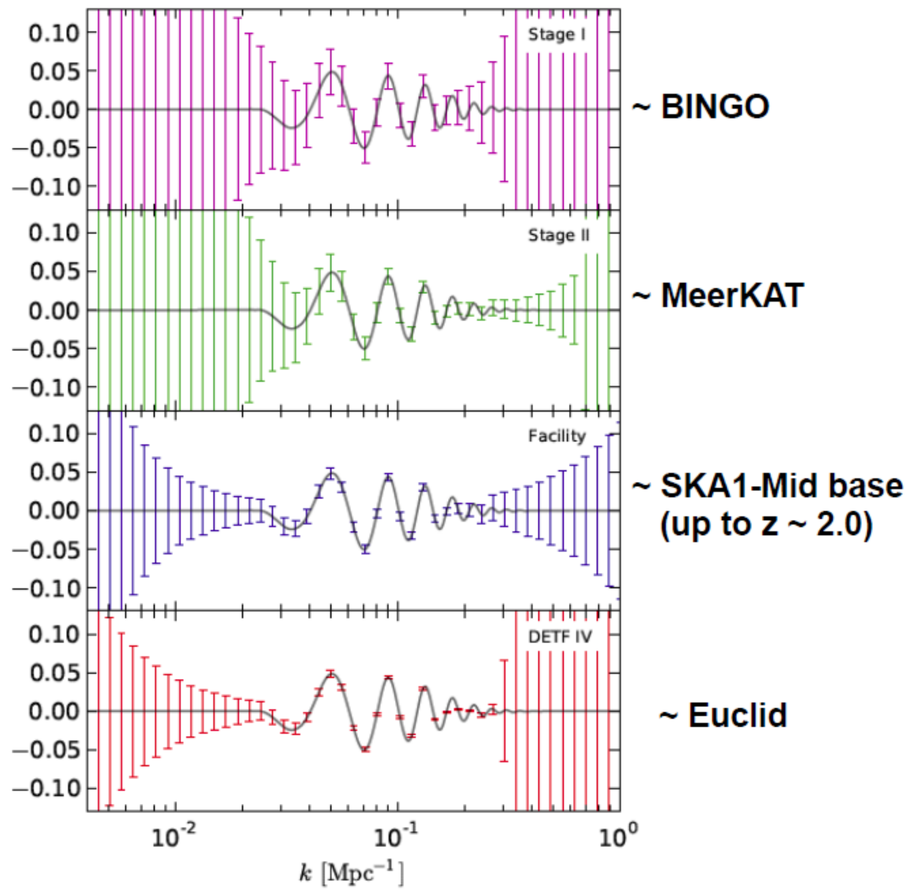
- Diffuse Galactic continuum radiation - synchrotron and free-free radiation
- Spectrum expected to be smooth (should allow for it to be subtracted)
- Mean ~5K at 1 GHz
- Fluctuations on degree scales **~70mK**
- Note: HI signal ~ 0.1 mK !

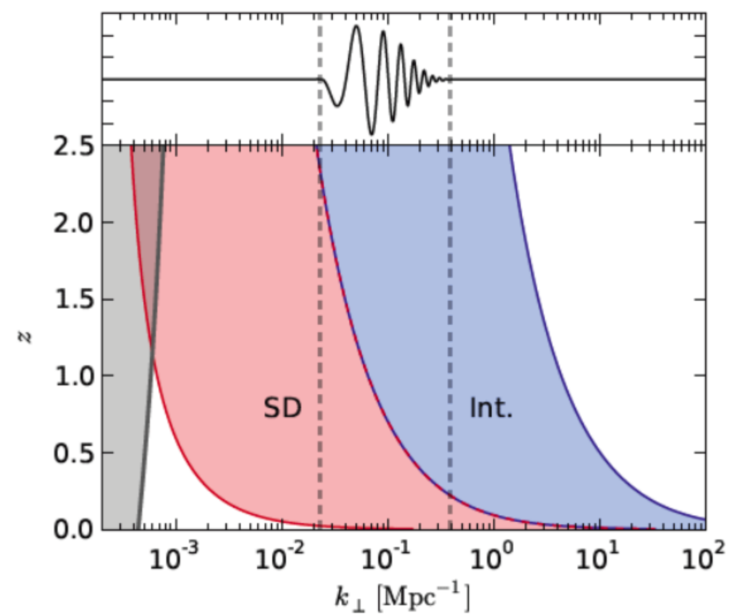
Improved 408 MHz Haslam map now available
(Remazeilles et al. 2015)



Battye et al. (2013);
Bigot-Sazy et al. (in prep.)

Intensity mapping: for SKA1 we require autocorrelations.

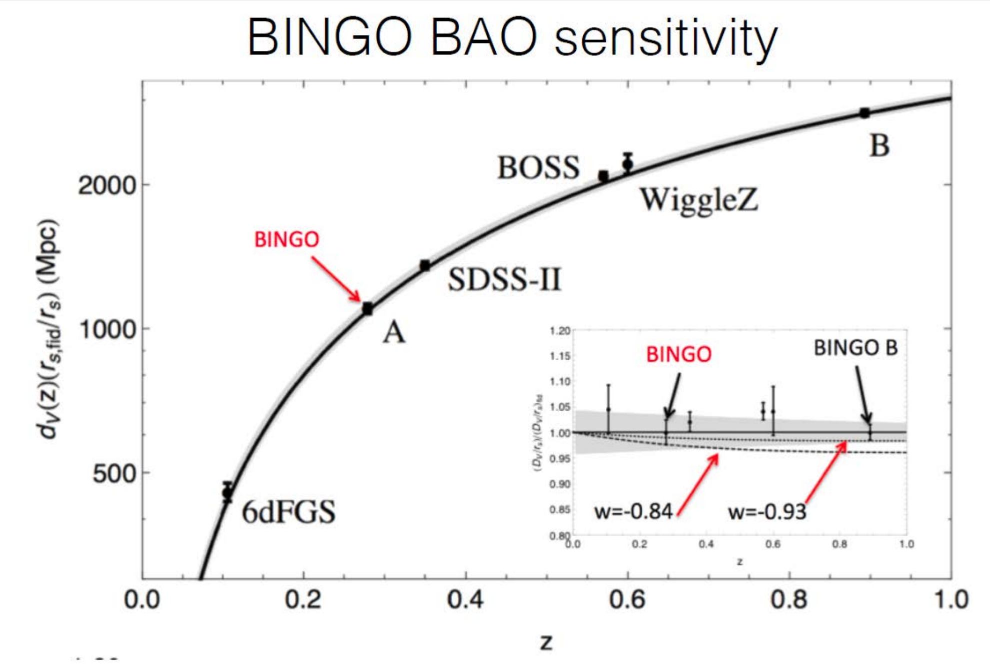


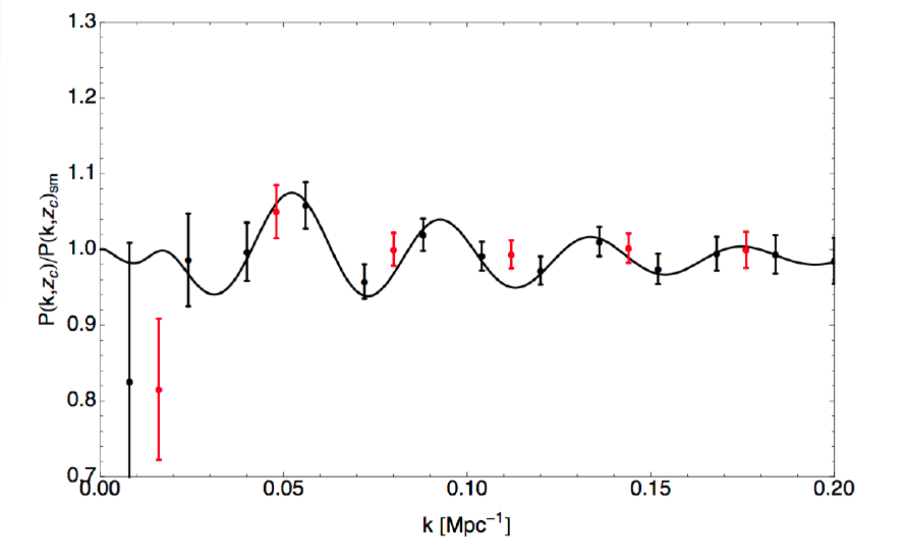


One can achieve the same statistical power with intensity mapping however we require to be able to calibrate autocorrelations if we have dishes…. If we have aperture arrays, we can cross correlate elements of a station in some redshift ranges.

Bingo is a ~40m dish, compared to one MFAA station…

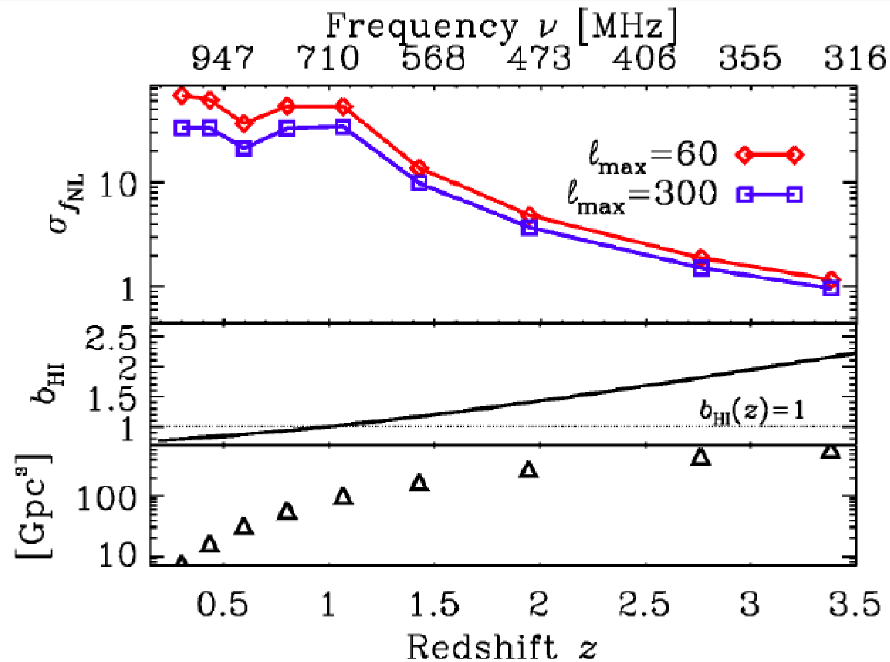
- One message to come is that an SKA MFAA demonstrator would be able to do science in a competitive way (just not the highlighted science that justifies the entire SKA2 design.
- For comparison a station for MFAA would be comparable to Bingo…
- The aim is to learn how to perform the experiment in advance…
- Learn how to deal with tricky parts of the analysis (foregrounds)
- BINGO is mostly funded (Brazil approved already 3M dollars), site in Uruguay, receiver and horn design from Manchester.





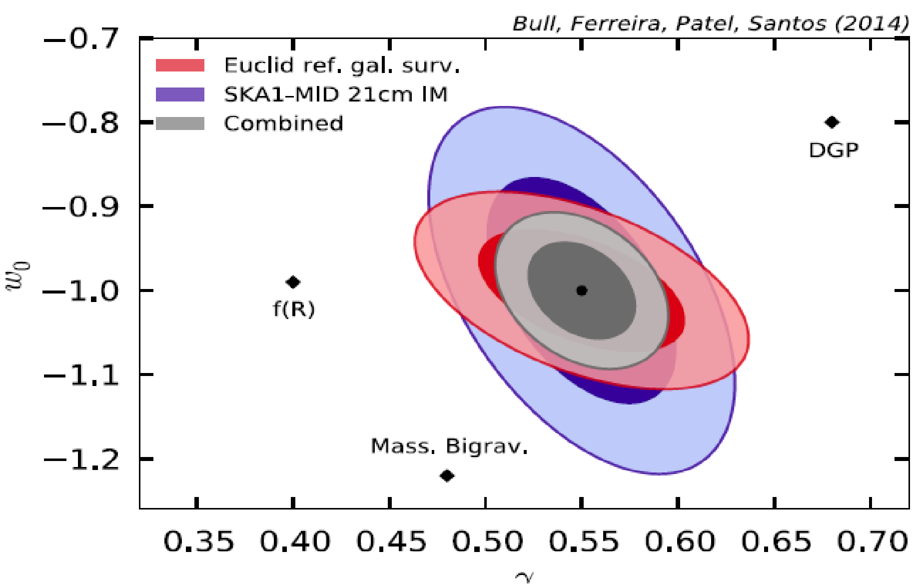
Cosmology on the Largest Scales

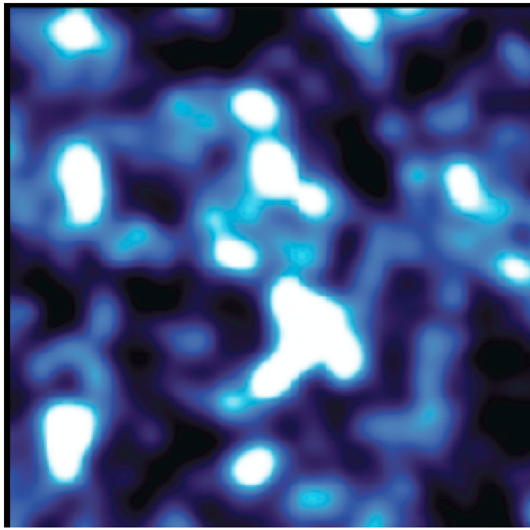
Primordial non-Gaussianity (IM)



Need to consider correlations between elements between stations, i.e. maybe break stations in bits…

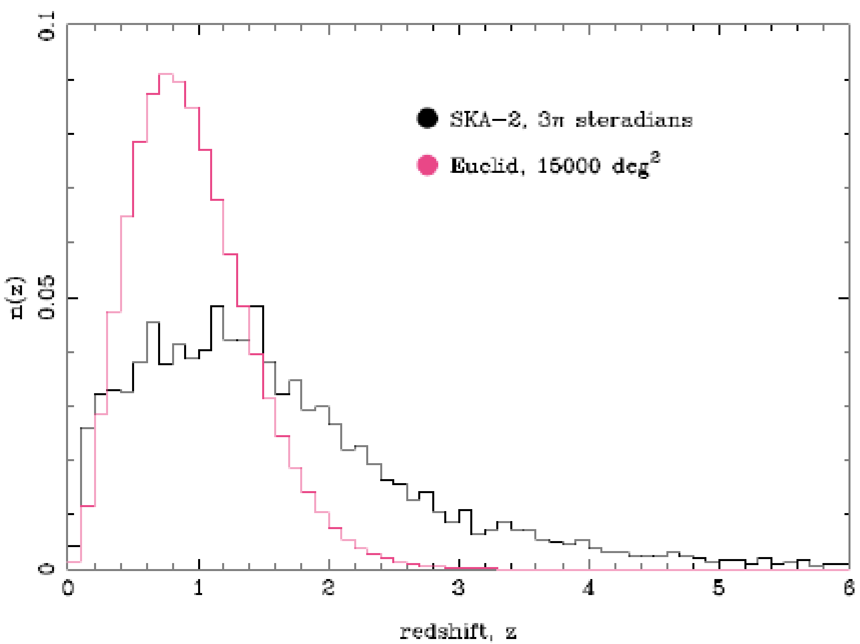
Modified gravity (IM)

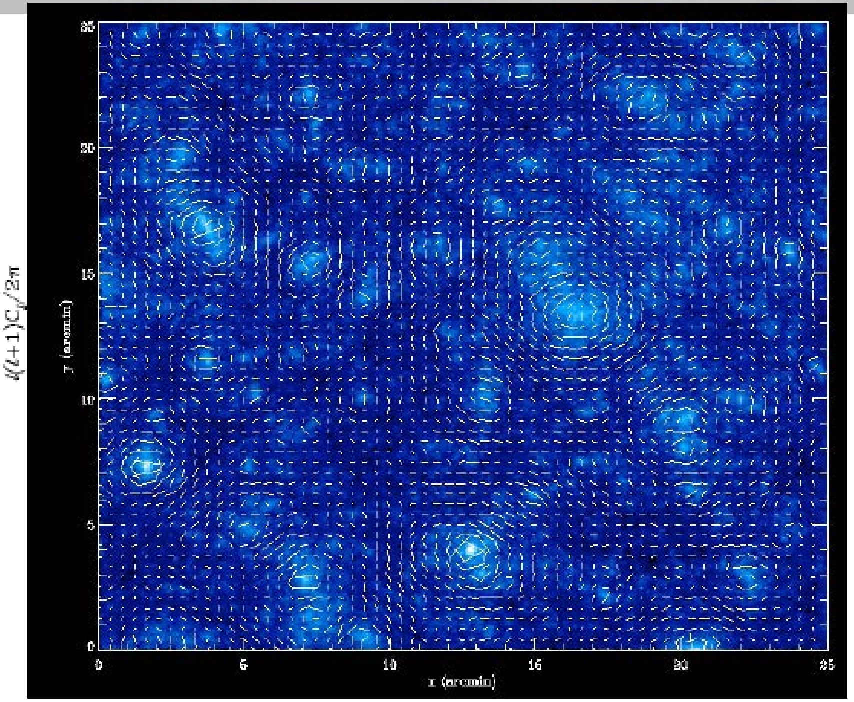




Large scale SKA surveys offer exciting and unique opportunities for weak lensing analyses

- A 2-year SKA-2 survey will complement Euclid:





How will we know the redshift distribution for these galaxies?

Brown et al. (2014)

Cross-Correlations

Project mass distribution once again

$$C_\ell \equiv < \delta^{2D}\delta^{*2D} >= 4\pi \int \Delta^2(k) W_i(k) W_j \frac{\mathrm{d}k}{k}$$

Window Function

$$W_\ell(k) = \int f(z) j_\ell(kz) \mathrm{d}z$$

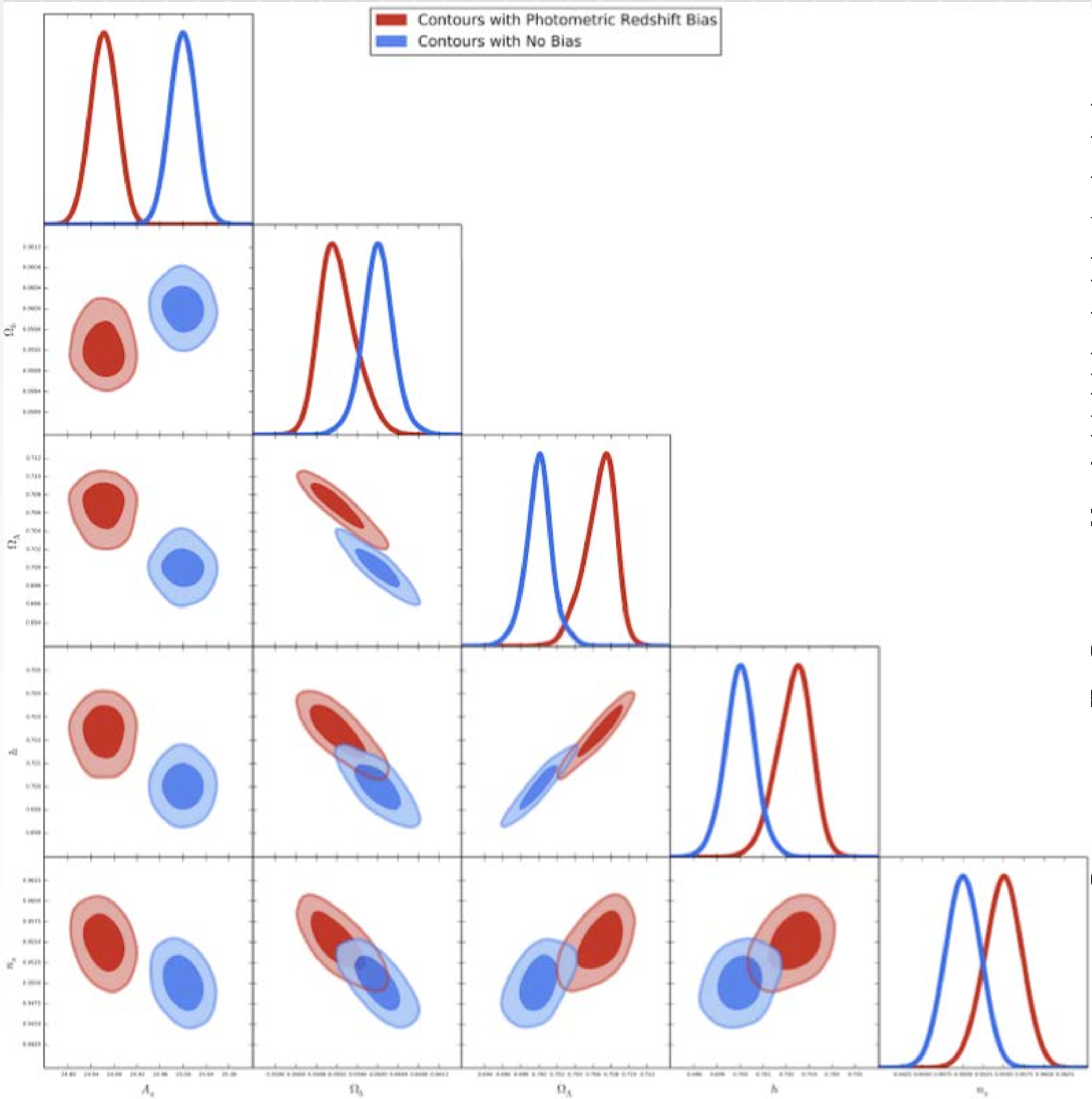
Weight

$$f(z) = n(z) D(z) \frac{\mathrm{d}z}{\mathrm{d}x}$$

$$\left[M_{X,l}\right]_{i,j} = C_{(X)}^{ij}(l) + \delta^{ij} N^i(l)$$

$$P(\mathbf{a}_{lm}|X) = \frac{1}{\left((2\pi)^k |\mathbf{M}_{X,l}|\right)^{\frac{1}{2}}} \exp\left[-\frac{1}{2}\mathbf{a}_{lm}^T \mathbf{M}_{X,l}^{-1} \mathbf{a}_{lm}\right]$$

Schulz 2010



w_0	h	τ_r	n_s
-0.9	0.7	0.09	0.95
-0.94 – -0.84	0.68 – 0.72	0.06 – 0.12	0.946 – 0.953
-0.92 – -0.88	0.69 – 0.71	0.08 – 0. 10	0.945 – 0.955

	σ_1	σ_2	σ_3
	0.1	0.1	0.1
– 1.245	0.096 – 0.106	0.096 – 0.106	0.096 – 0.106
– 1.204	0.099 – 0.102	0.099 – 0.101	0.099 – 0.101

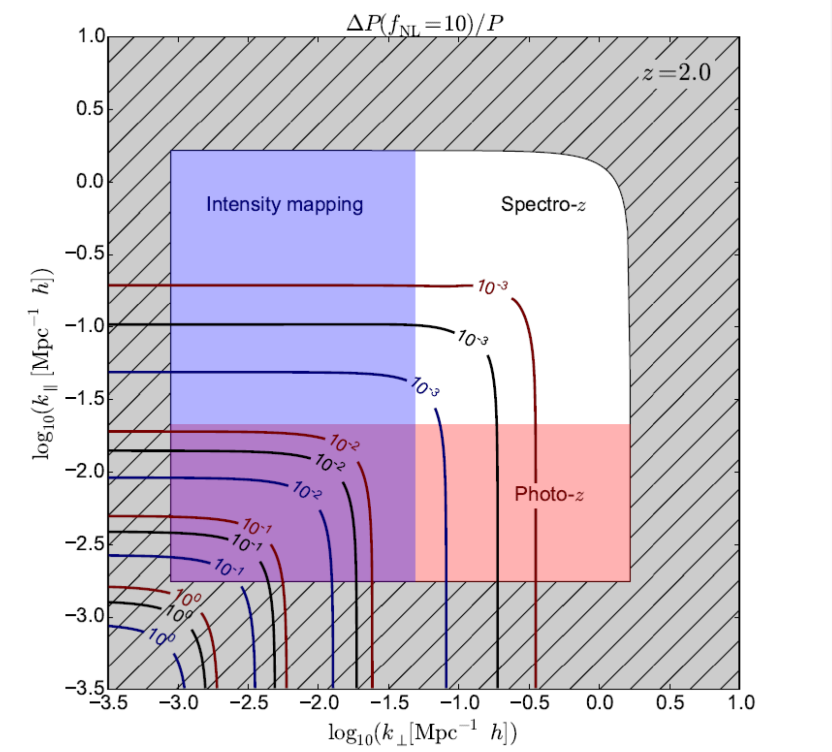
ısity mapping and galaxy surveys
:alibrate statistically calibrate the
of continuum and weak lensing
o one part in 1000 IF there is a
verlap…. Hence the lower
es are important!

a complex problem… takes ~1
a supercomputer with ~1000
only 3 redshift bins…

McLeod, Balan & Abdalla 16

What to use: Galaxies or IM?

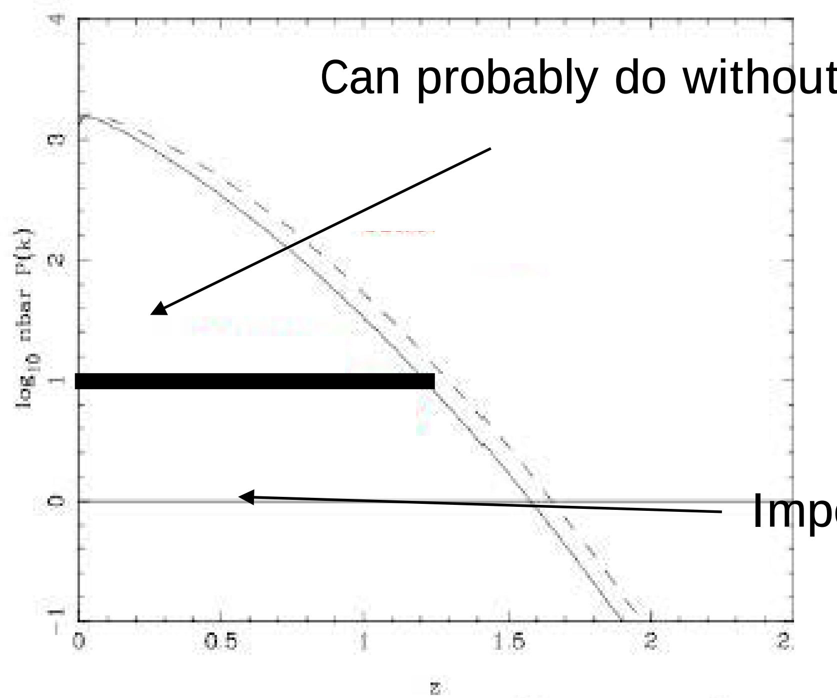
- Ultimatelly both, galaxies are harder to obtain but are much more reliable tracers with less systematic effects.
- IM is much more powerful statistically.
- There is more information at smaller scales with galaxies.
- We use different parts of the data to deal with each sample.



How to relate this to engineering for MFAA/SKA2?

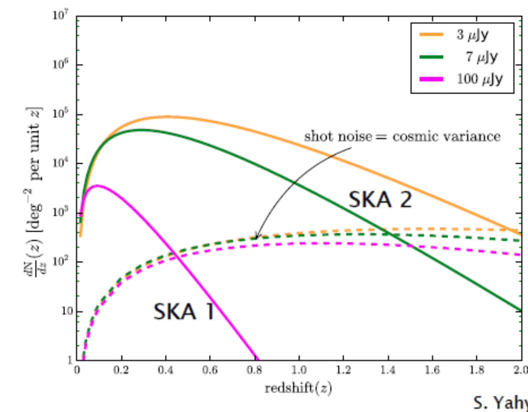
Cosmic variance of the power spectra:

Can probably do without



Important region

$$\sigma_{\ln P} = \frac{2\pi}{(Vk^2\Delta k)^{1/2}}\left(\frac{1+nP}{nP}\right)$$



S. Yahya

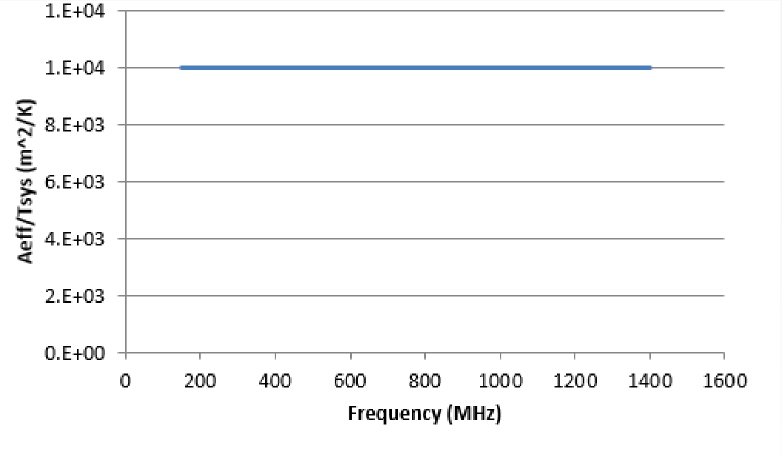
Measurement error is dominated by

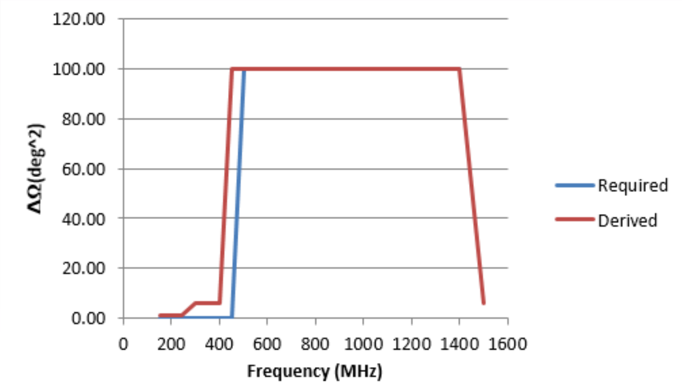
blue -> statistical nature of fluctuations,

black -> number of galaxies measured.

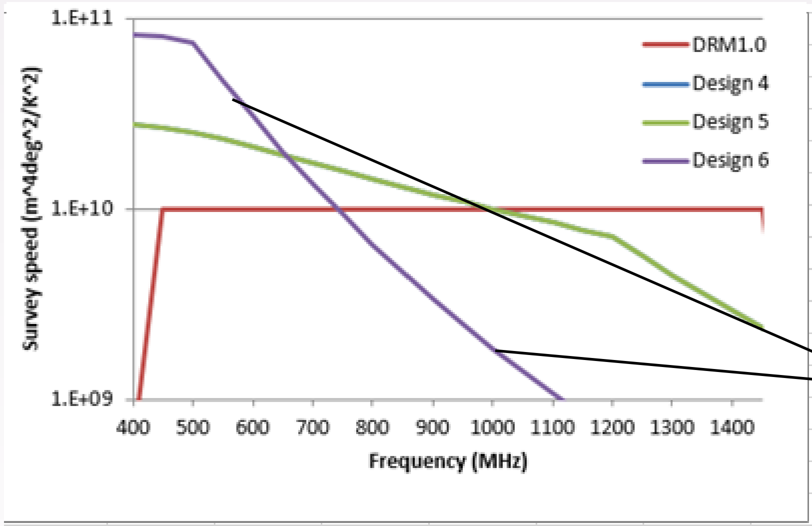
Remind ourselves Why the requirements are there… and THINK are we doing the right thing!!!:

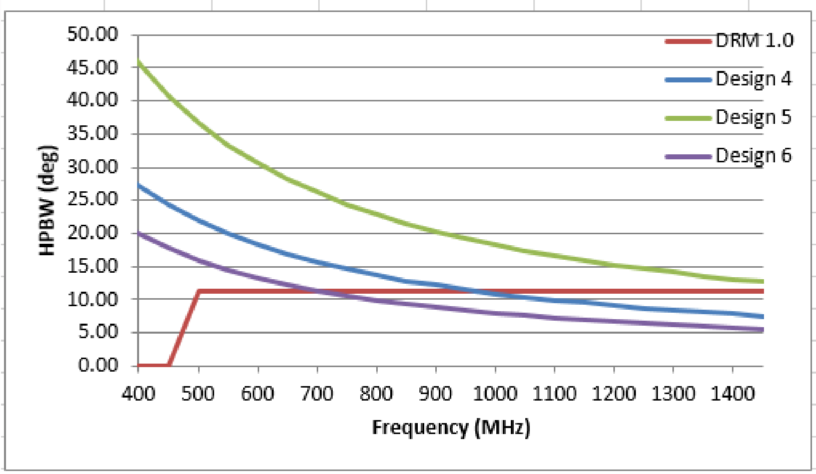
- First estimates of requirements for cosmology from Abdalla and Rawlings 05.
  - Assume constant A/T_sys…!!
  - Trade off this with FOV
  - Idea was to consider technologies….
  - No guess of shaping the A/T_sys…
- So requirements aside!!!
- Should these remain constants?!
  - This is a physics requirement problem, not an engineering one

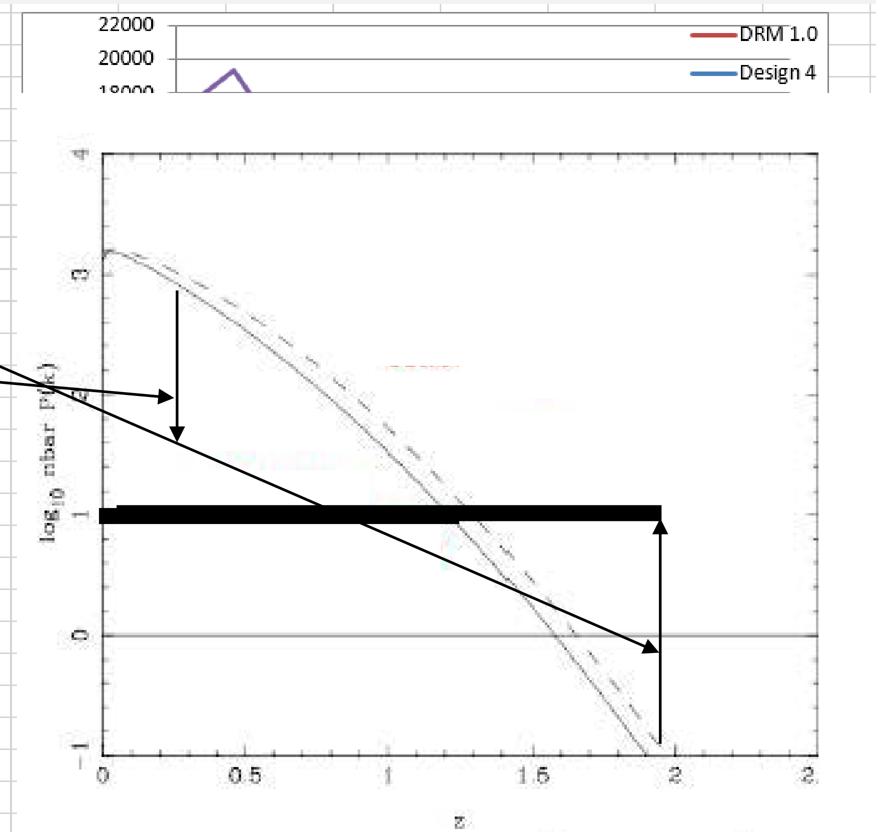




Lessons for design:



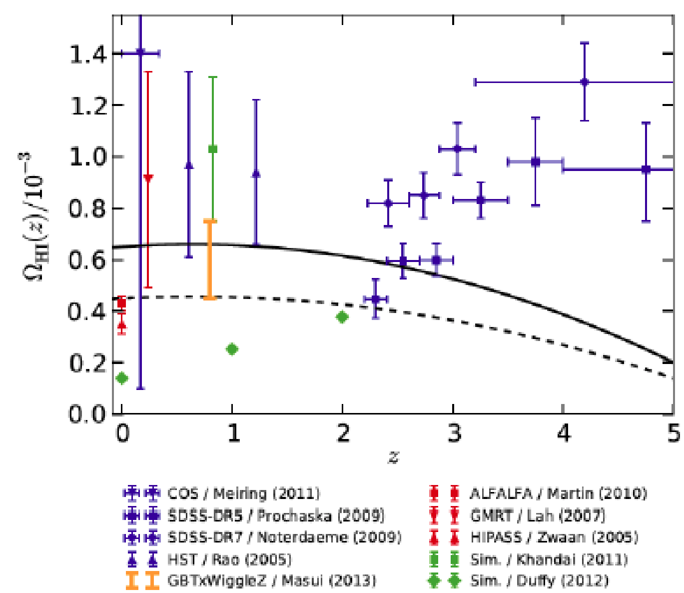




$$\sigma_{\ln P} = \frac{2\pi}{(Vk^2\Delta k)^{1/2}} \left(\frac{1 + nP}{nP} \right)$$

What is the optimal solution for the survey speed?

- To first order you want to detect, in the same same objects whether they are placed at any redsfhits..
  - Below equation for the relation between the mass d a give redsfhit for a given circular velocity a given si noise and a given exposure time.
- So the short answer zeroth order answer is th want a scaling with the luminosity distance sc
- To higher orders, this will depend on the size galaxies, the array distribution, for intensity m it will depend on the rms fluctuations, bias, or
- However caveats: what does the beam look l What



$$\Omega_{\rm HI} \equiv \frac{\rho_{\rm HI}(z)[\text{comoving}]}{\rho_c(z=0)}$$

$$M_{\rm HI}(z) = \frac{16\pi}{3}\frac{m_{\rm H}}{A_{12}hc}\frac{D_L^2(z)}{1+z}f^{-1}\frac{V(z)}{\sqrt{V(z)/\Delta V}}S_{\rm N}\sigma_{\rm 4h}\sqrt{\frac{4}{t}}$$

$$S_{lim} = \frac{2kT_{sys}}{A_{eff}\sqrt{2\Delta\nu t}}$$

Conclusions

- The current status of the cosmological background.
- Oportunities for cosmology below GHz.
  - Measuring neutrino masses
  - Measuring dark energy
  - Measuring the larger scales in our Universe
  - Calibrating optical and continuum surveys
- Some pathfinders have similar collecting areas as a science demonstrator.
- Best designs what can be done with pathfinders
  - Remind ourselves where do designs and requirements come from!
  - Designs that prioritise low frequency good data
  - Potential for sparse designs to improve on where data will be sparse.