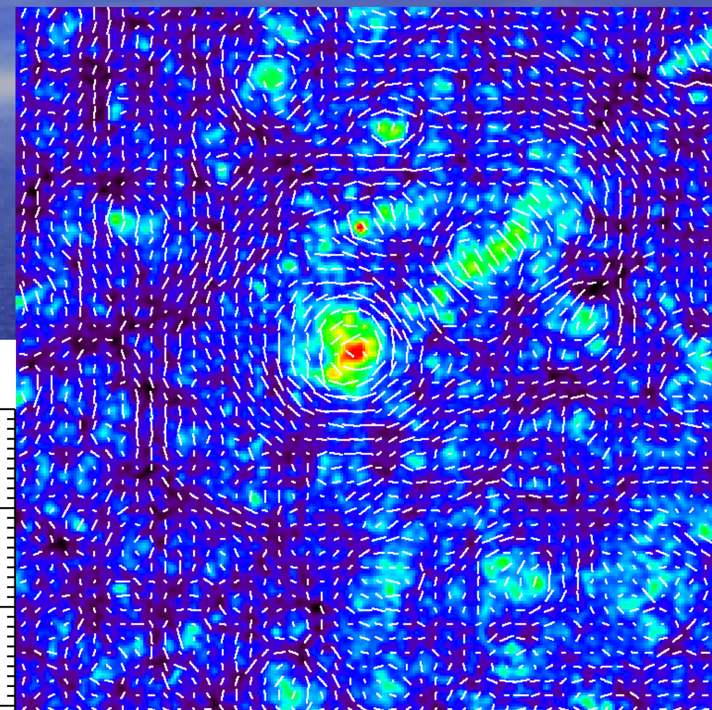
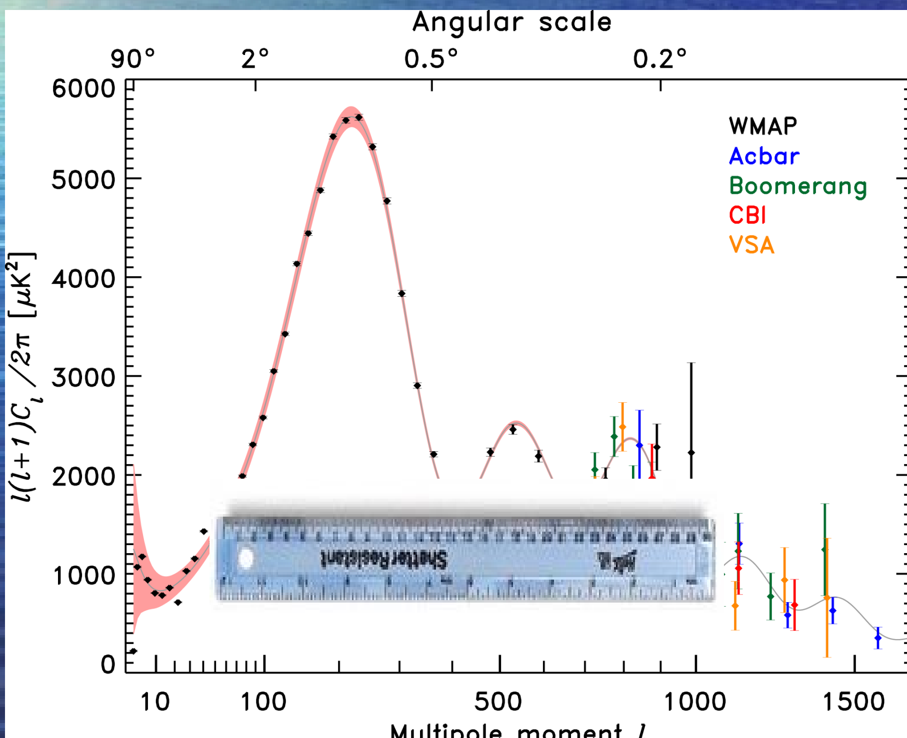
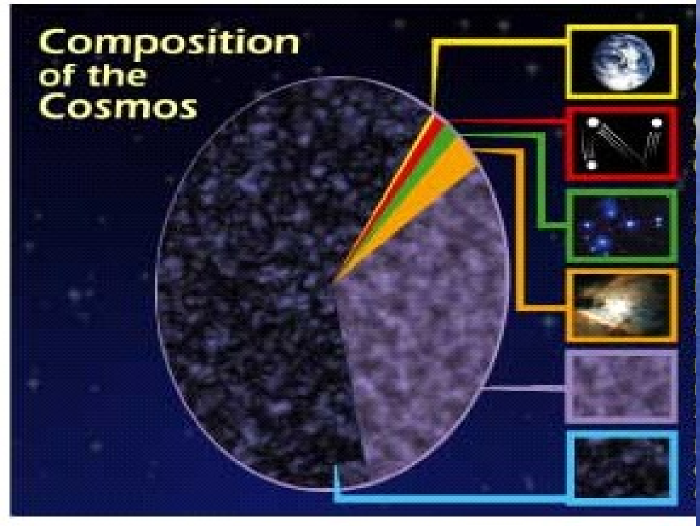
Cosmology & dark energy with the SKA:





F. B. Abdalla

Cosmology: Concordance Model



Heavy elements 0.03%

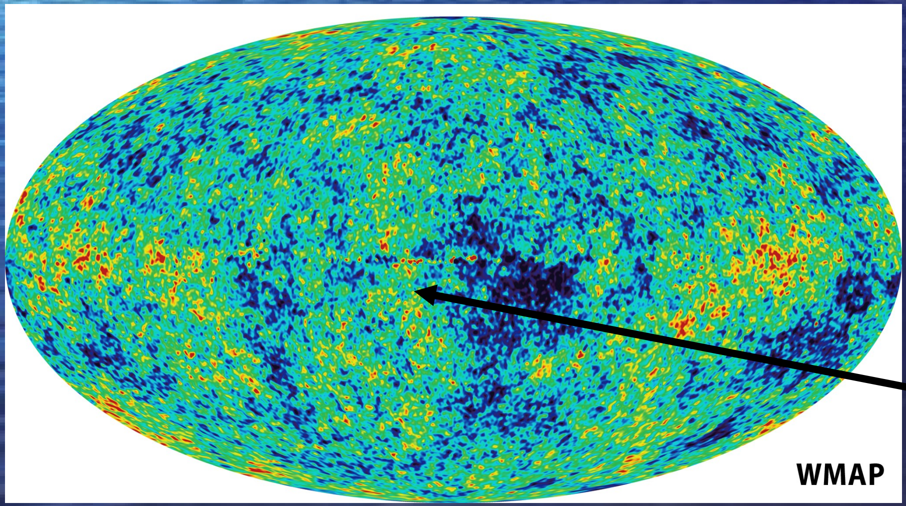
Neutrinos 0.3%

Stars 0.5%

H + He gas 4%

Dark matter 20%

Dark Energy 75%

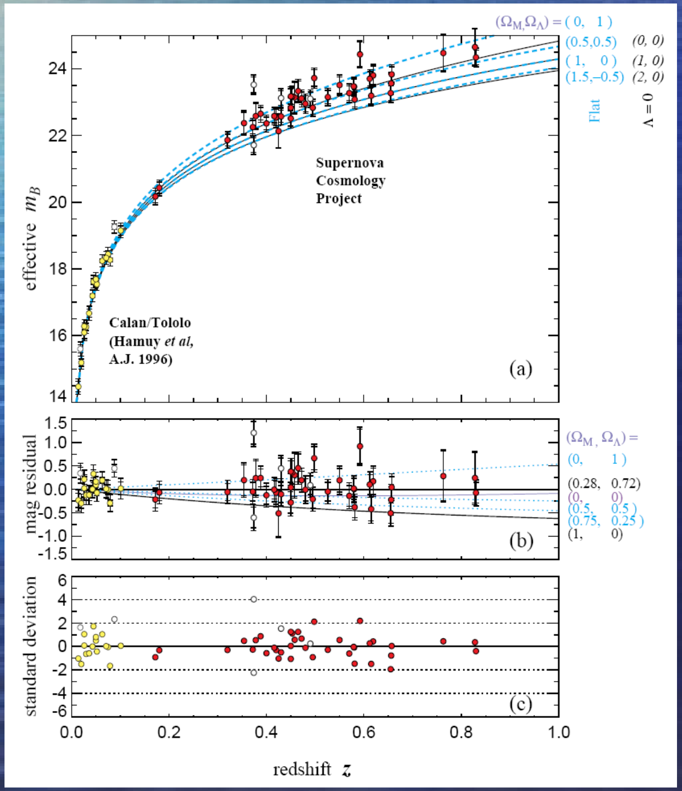


Outstanding questions:
- initial conditions (inflation?)
- nature of the dark matter
- nature of the dark energy
- value of the neutrino mass

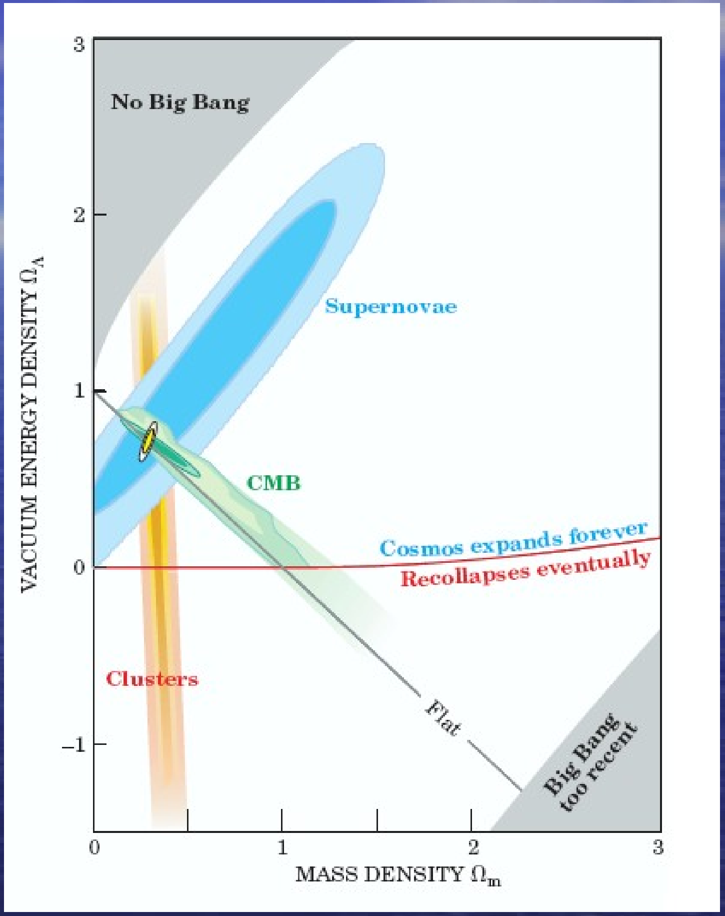
There are fluctuations at all scales but there is a preferred scale of around 1 deg.

Background

- The discovery of the **accelerated expansion** of the Universe

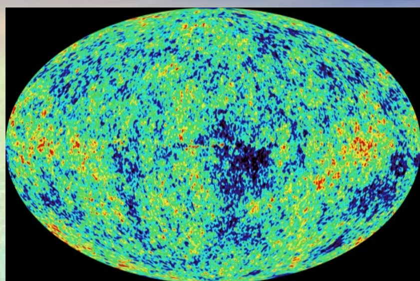


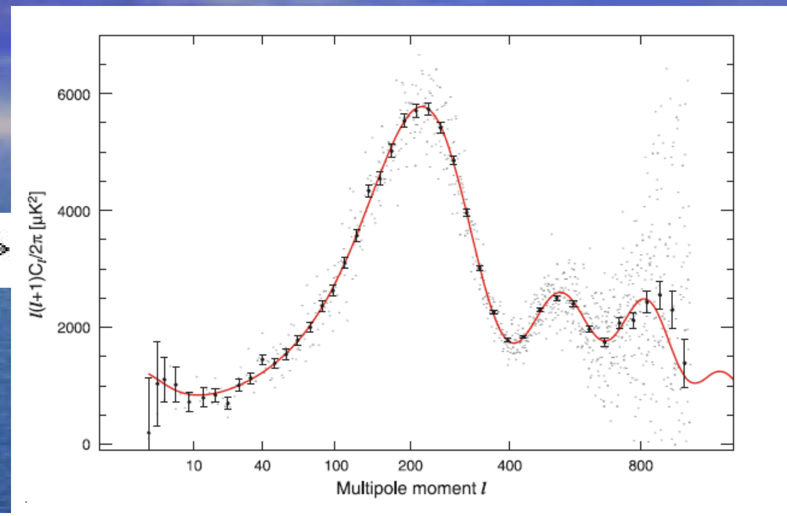
Perlmutter et al 1997



The cosmic concordance model is confirmed by observations of CMB SNe Ia and large scale structures

Universe is flat(ish), dark energy exists

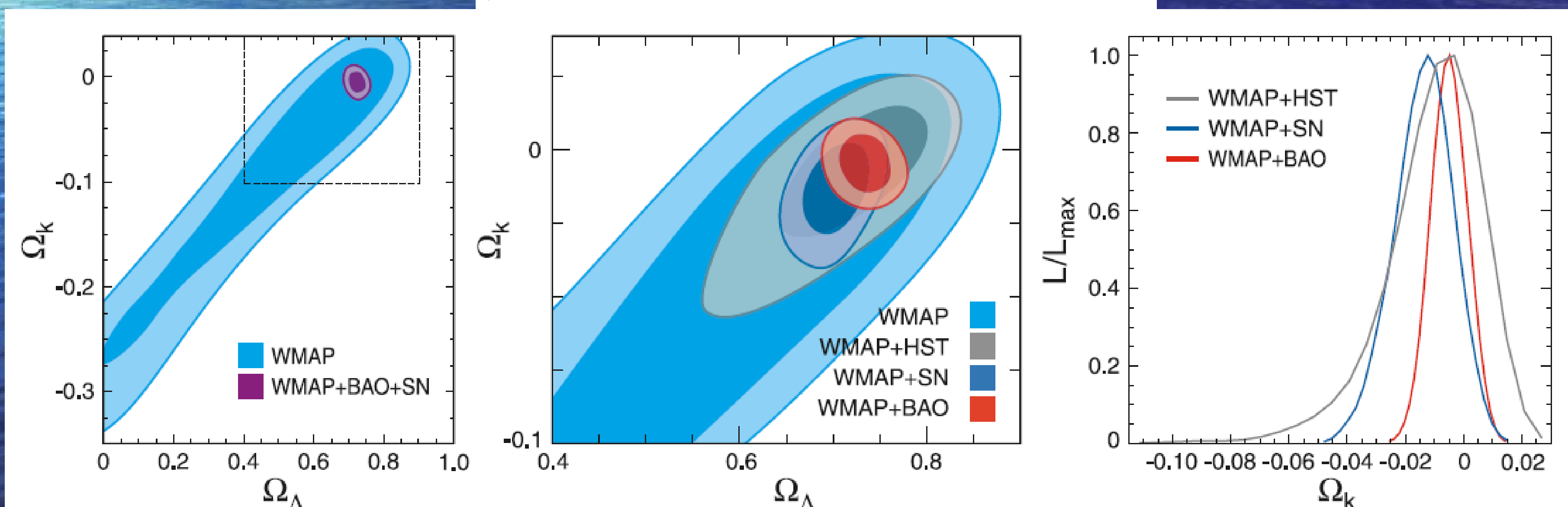




Empty D_A~10 kpc/arcsec

Flat D_A~0.05 kpc/arcsec

Angle $\theta = s / D_A$



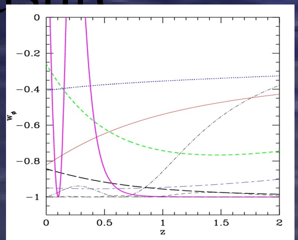
Dark Energy:
Stress Energy vs. Modified Gravity

Stress-Energy: $G_{\mu\nu} = 8\pi G\,[T_{\mu\nu}(\text{matter}) + T_{\mu\nu}(\text{dark energy})]$

Gravity: $G_{\mu\nu} + f(g_{\mu\nu}) = 8\pi G\, T_{\mu\nu}(\text{matter})$

Key Experimental Questions:

- Is DE observationally distinguishable from a cosmological constant, for which $T_{\mu\nu}(\text{vacuum}) = \Lambda g_{\mu\nu}/8\pi G$?
  To decide, measure *w*: what precision is needed?
- Can we distinguish between gravity and stress-energy?
- If $w \neq -1$, it likely evolves: how well can/must we measure d*w*/da to make progress in fundamental physics?



Very Brief Overview on explaining the accelerated expansion

Dark Energy

- Cosmological constant → W=-1
- Quintessence
- ⋮

→ w=w(time)

modification of Einstein's gravity

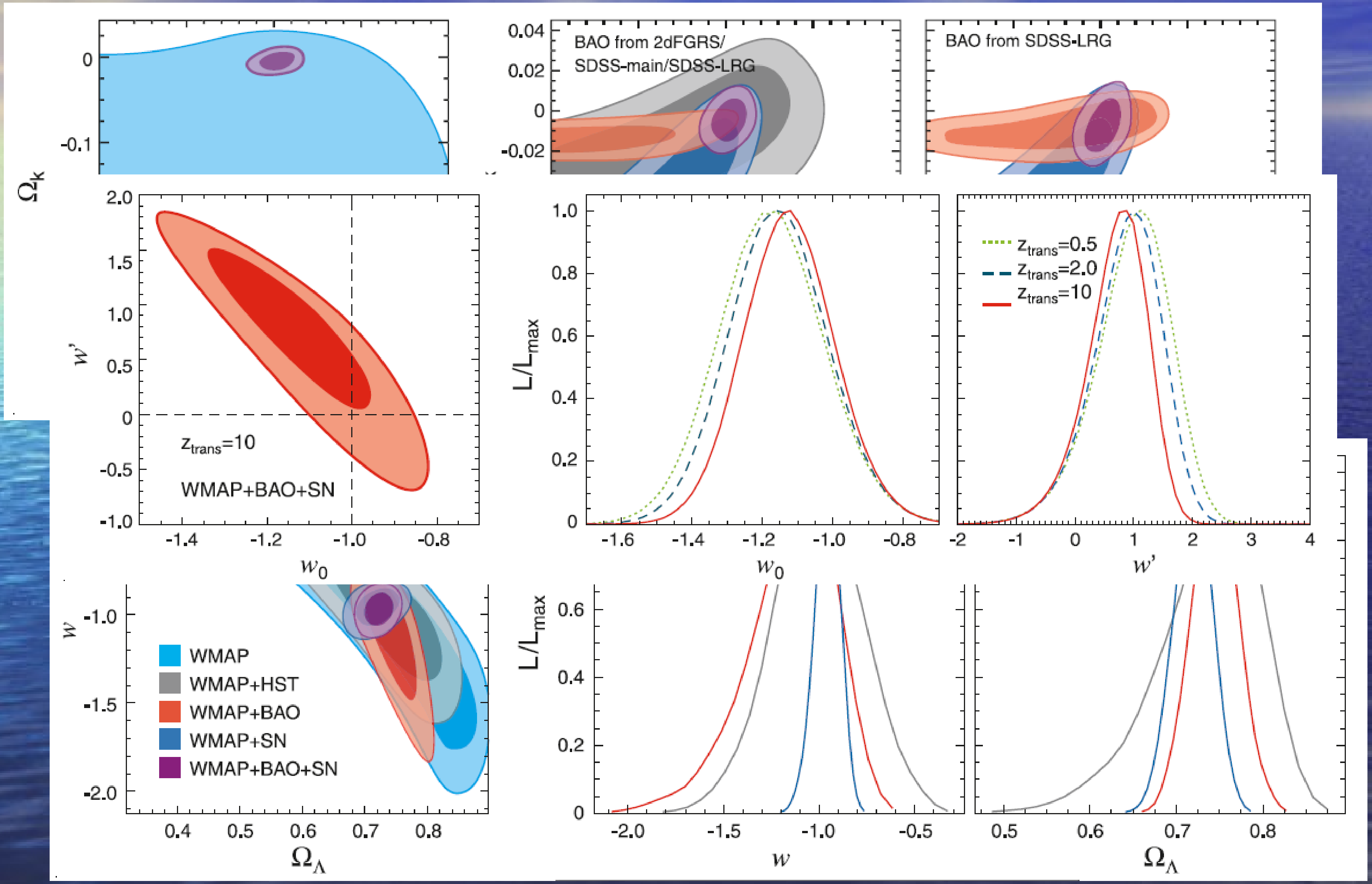
String theory

⋮

$$w = p_{DE}/\rho_{DE}.$$

Dark Energy equation-of-state parameter *w*

Current knowledge on w: (WMAP-5)



Probing Dark Energy with the Expansion History of the Universe

$$H^2(z) = \left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left(\Omega_m(1+z)^3 + \Omega_{de}(1+z)^{3(1+w)}\right)$$

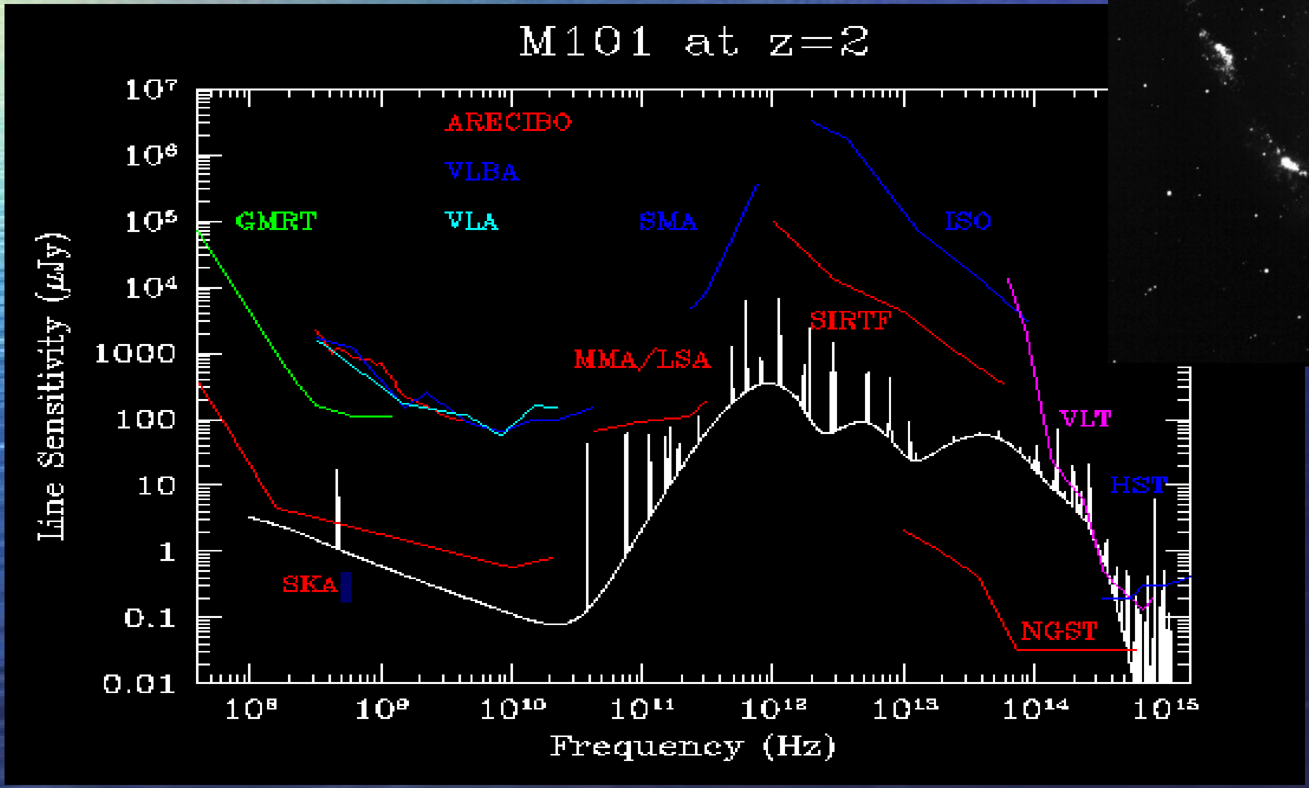
- comoving distance $$r(z) = \int \frac{dz}{H(z)}$$
- standard candles $$d_L(z) = (1+z)r(z)$$
- standard rulers $$d_A(z) = (1+z)^{-1}r(z)$$
- volume factor $$\frac{dV}{dzd\Omega} = r^2(z)H(z)$$
- growth of structure depends on H(z) probed with power spectrum $$\delta_m'' + \frac{3}{2}a^{-1}\left[1 - w(a)(1-\Omega_m(a))\right]\delta_m' - \frac{3}{2}a^{-2}\Omega_m(a)\delta_m = 0$$

The SKA and dark energy

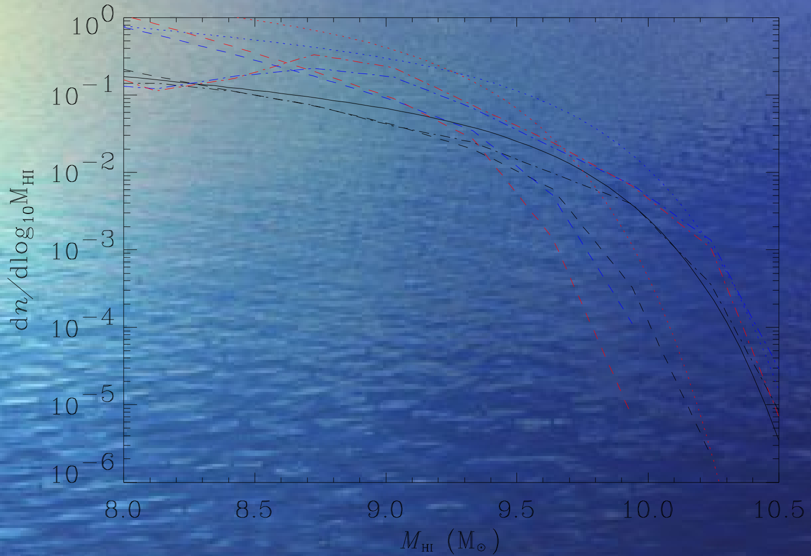
The SKA:

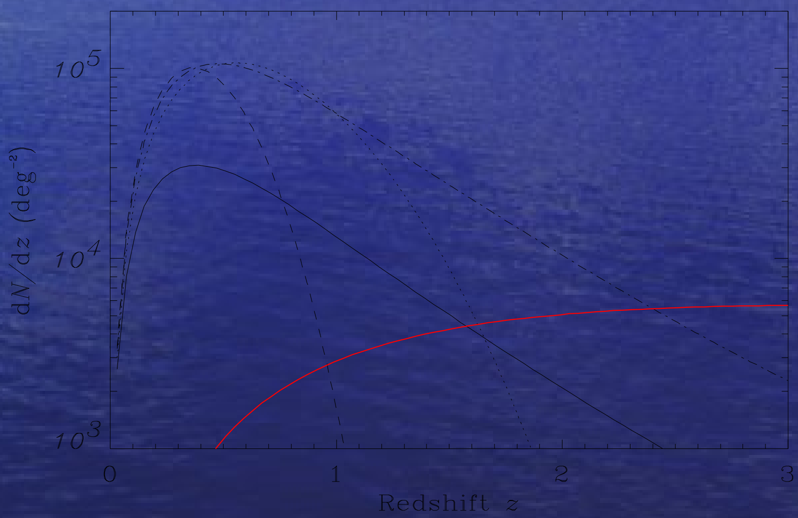
- An extremely powerful survey telescope at with the capability to follow up individual objects with high angular and time resolution
- ~ 1 km2 collecting area
  - limited gains achievable by reducing receiver noise – need more microwave photons
- Frequency range 0.1 – 25 GHz
- Angular resolution: 0.1 arcsec @ 1.4 GHz
- FOV: ~ 1-100 deg^2 ?

What will the SKA see? Normal/Starburst galaxies



What will the SKA see?





- 10^9 galaxies in 3D over 20000 deg^2 in a few years.
- 10^10 galaxies in 2D over 20000 deg^2 in a few years.

Results agree well with other results including semi-analytic calculations.

DS2-T1 Simulations: T0=July2006

- *Continuum Surveys – Oxford, Leiden, (Herts, UCL):*

  Richard Wilman (Oxford); simulation deliverable T0+18

  Ilse van Bemmel (Leiden); deliverable to be finalised (MeqTree Ionosphere module?)

- *Line HI Surveys – Oxford, Groningen, Swinburne*

  Danail Obreschkow *(Oxford); simulation deliverable T0+12*

  Rense Boomsa (Groningen); deliverable to be finalised (High-res HI module?)

- *Magnetism – Cambridge, Bonn*

  Martin Krause+replacement (Cambridge); simulation deliverable T0+18

  Tigran Arshakian (Bonn); deliverable to be finalised (Galactic Foreground module?)

- *Pulsar Surveys – Manchester*

  Roy Smits (Manchester), simulation deliverable T0+15

- *EOR – Paris, Lisbon;*

  Paola Di Matteo (Paris), simulation deliverable T0+21

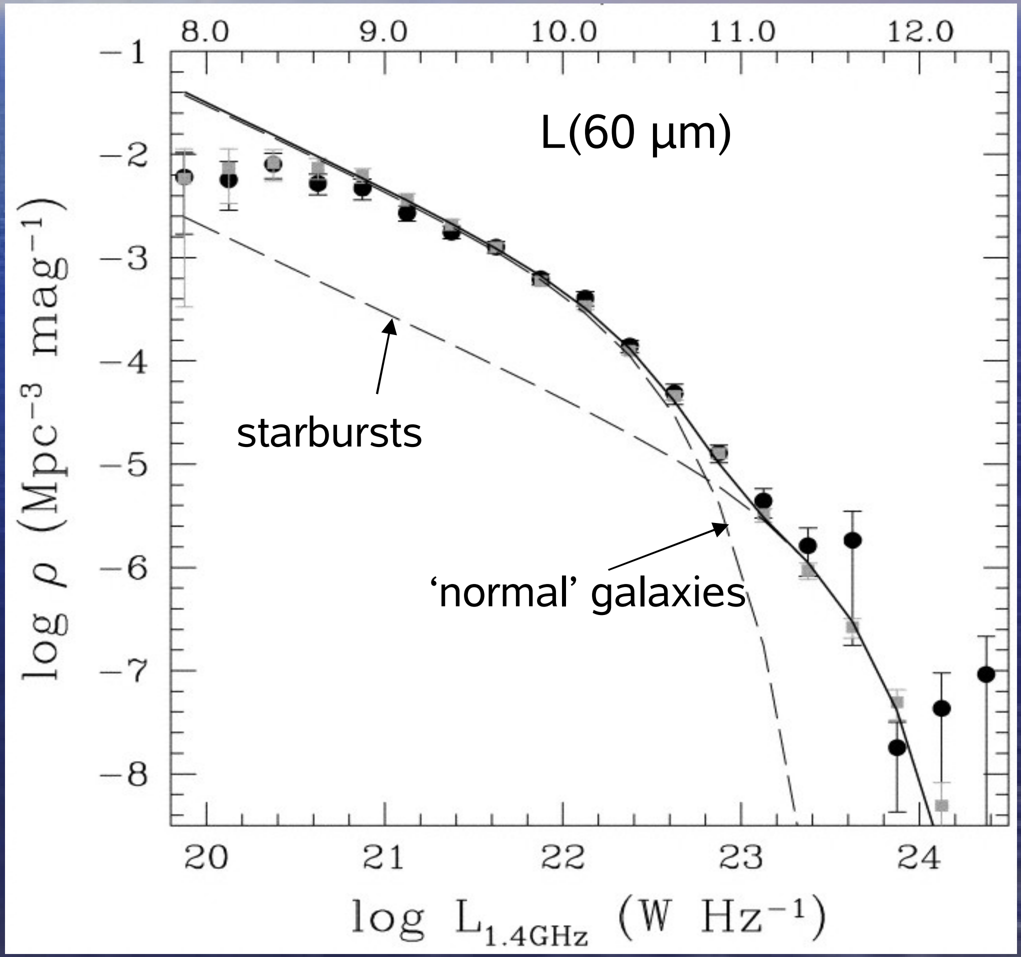
Better simulations: Two populations of star-forming galaxies

- Double Schechter-fn fit representing normal galaxies and starbursts

- We assume LF flattens below $L_{1.4\ GHz} = 10^{20.5}$ W/Hz and integrate down to 10^{19} W/Hz (SFR ~ 0.01 M /yr)

- No need for an extra population of normal galaxies via an optical LF (à la Hopkins/Windhorst)

Wilman et al, 2008



Basic methodology

In each cell, for each source type:

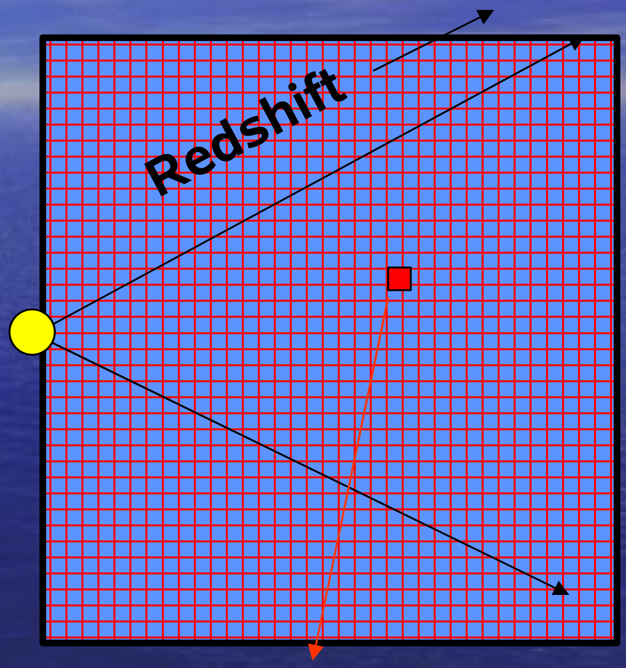
- Define DM halo mass for each source type and compute bias b(M,z)

- Compute mean number of sources above flux limit, n_0, in absence of clustering

- Amplify fluctuations in underlying DM density field:

$$n/n_0 \sim \exp[\, b(M,z)\, (\Delta\rho/\rho)_{DM} \,]$$

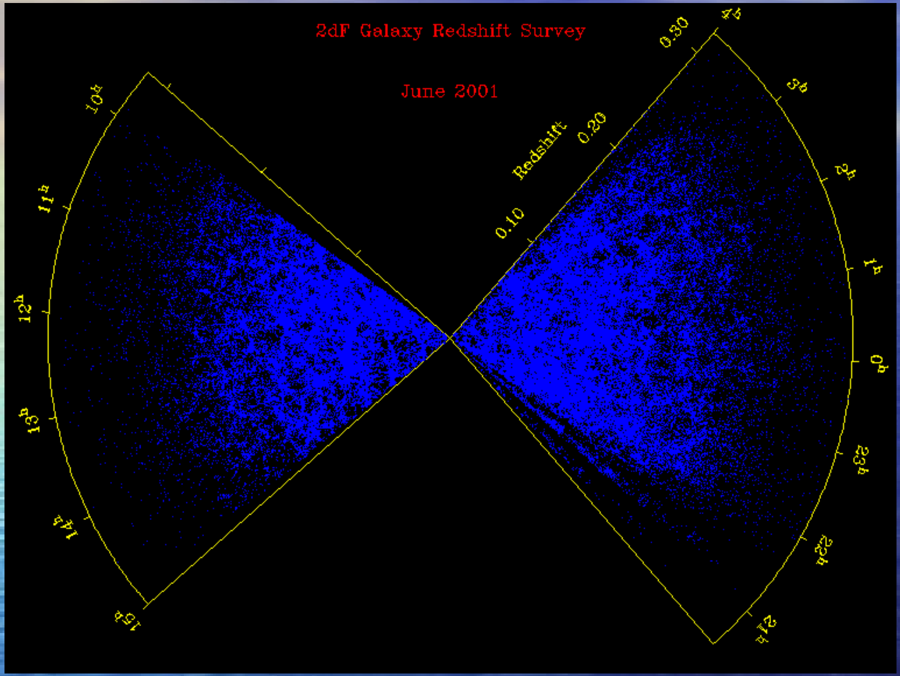
- Poisson sample the LF



$(\Delta\rho/\rho)_{DM}$ evolved under linear theory in each 20 Mpc/h cell

Wilman et al, 2008

From a survey to a P(k)



Galaxies are found in RA, DEC, and z.

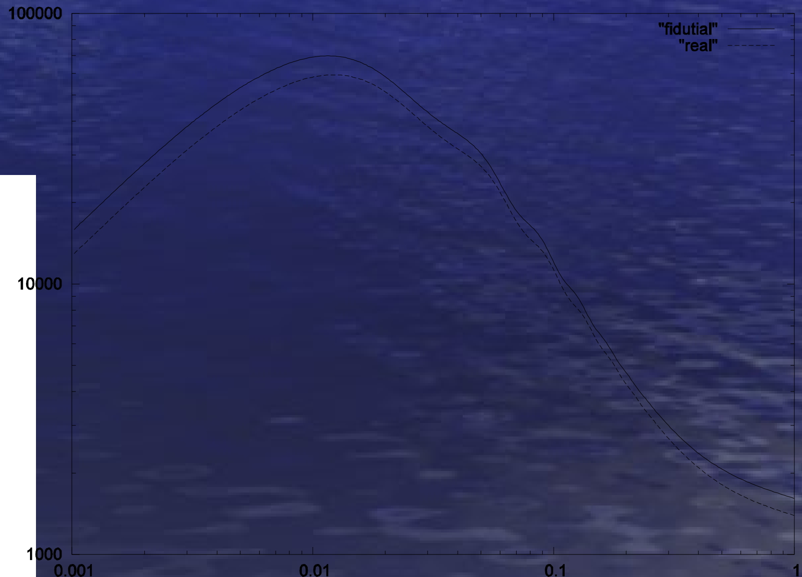
In order to measure P(k).
We have assume a cosmology
To change from (RA,DEC)
to (k_par,k_per)

$$H(z) = h\sqrt{\Omega_m(1+z)^3 + \Omega_X \exp\left[3\int_0^z \frac{1+w(z)}{1+z}dz\right]}$$

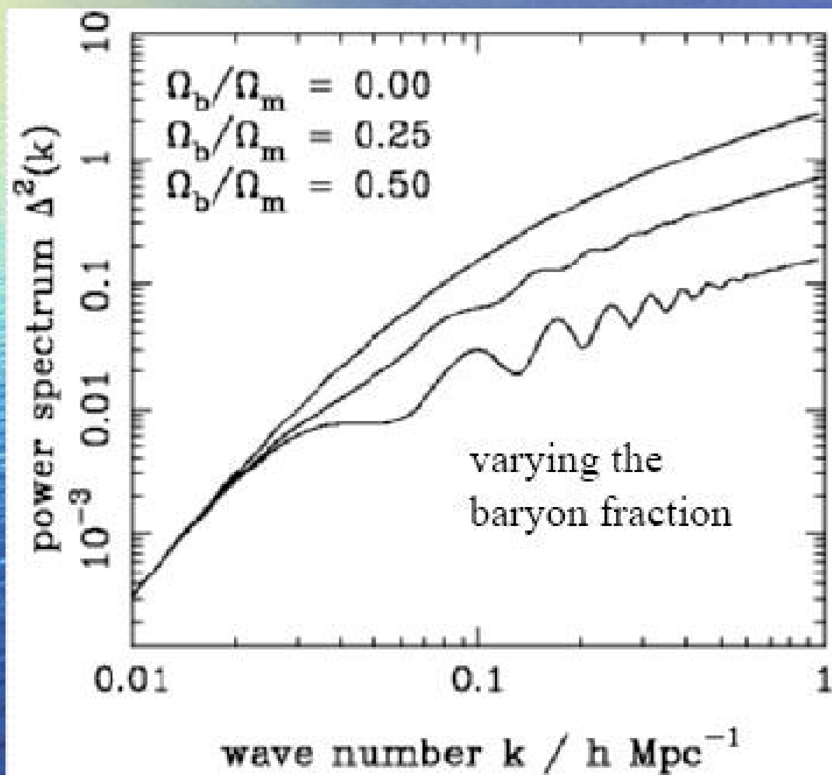
$$D_A(z) = \frac{c}{1+z}\int_0^z \frac{dz}{H(z)} \qquad r_\parallel = \frac{c\Delta z}{H(z)}$$

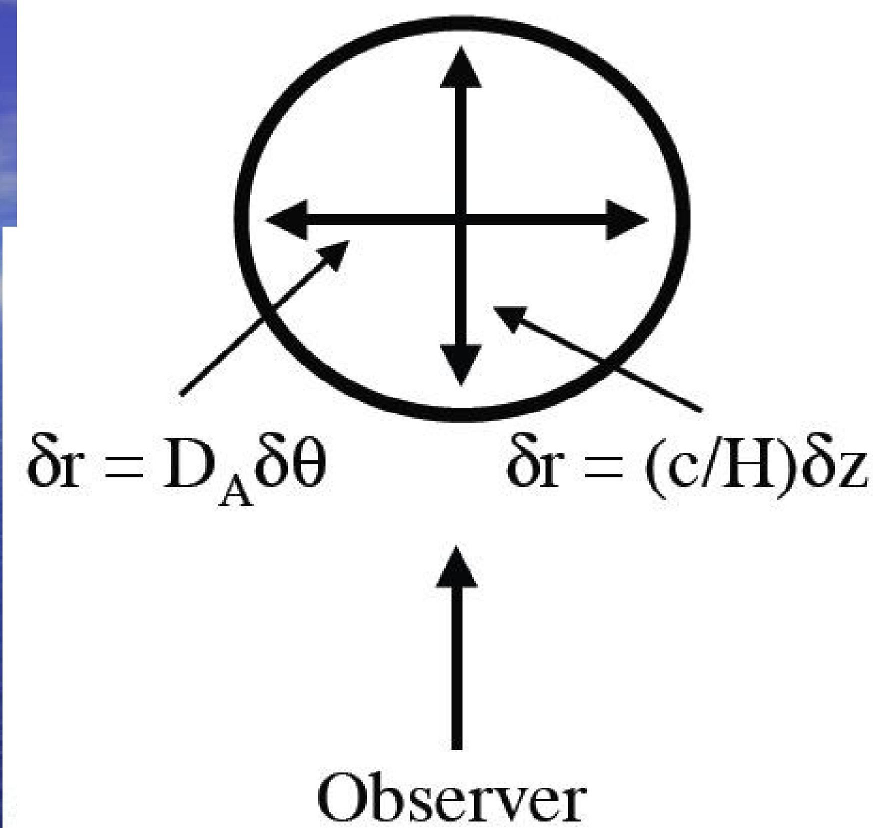
$$r_\perp = (1+z)D_A(z)\Delta\theta$$

$$P_{\rm obs}(k_{{\rm ref}\perp}, k_{{\rm ref}\parallel}) = \frac{D_A(z)^2_{\rm ref} \times H(z)}{D_A(z)^2 \times H(z)_{\rm ref}} P_{\rm true}(k_\perp, k_\parallel)$$



BAO in LSS





$$H(z) = h\sqrt{\Omega_m(1+z)^3 + \Omega_X \exp\left[3\int_0^z \frac{1+w(z)}{1+z}dz\right]}$$

$$D_A(z) = \frac{c}{1+z}\int_0^z \frac{dz}{H(z)} \qquad r_\parallel = \frac{c\Delta z}{H(z)}$$

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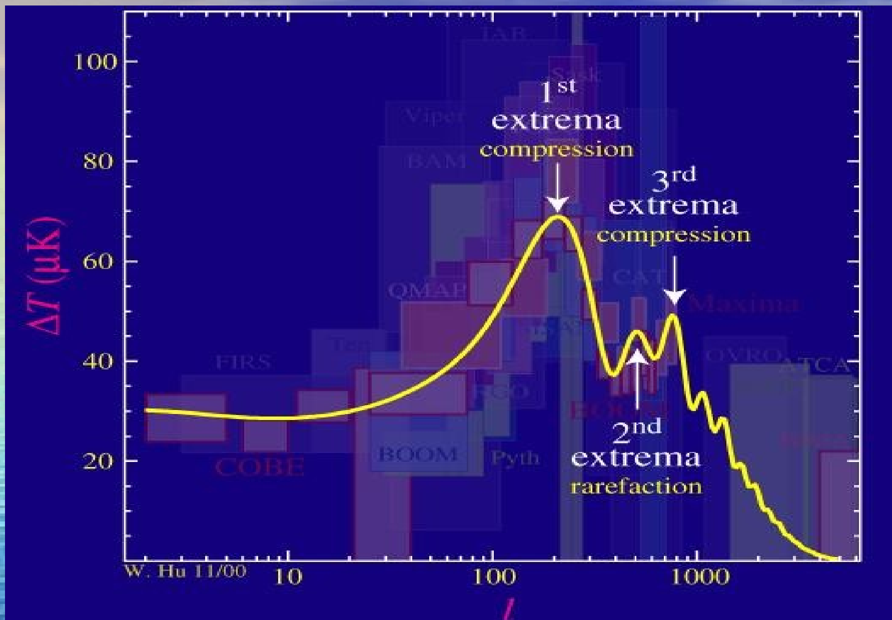
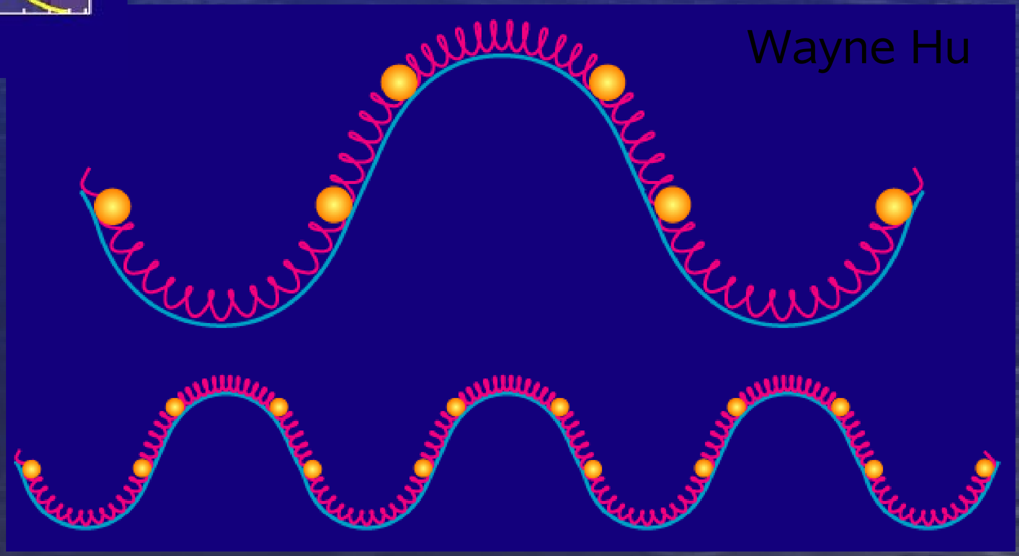
Sound waves:



After recombination:

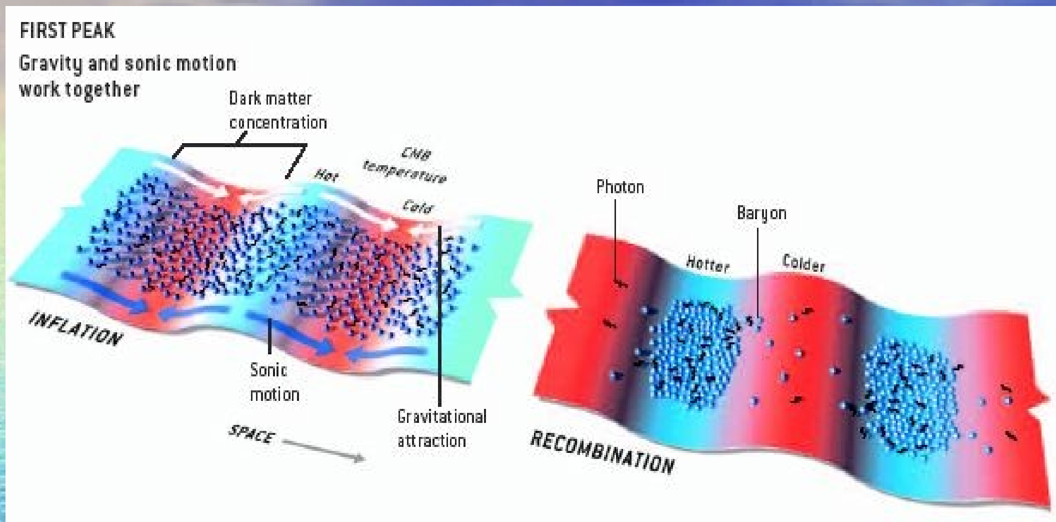
- Universe is neutral.
- Photons can travel freely past the baryons.
- Phase of oscillation at t_{rec} affects late-time amplitude.
- Waves are frozen

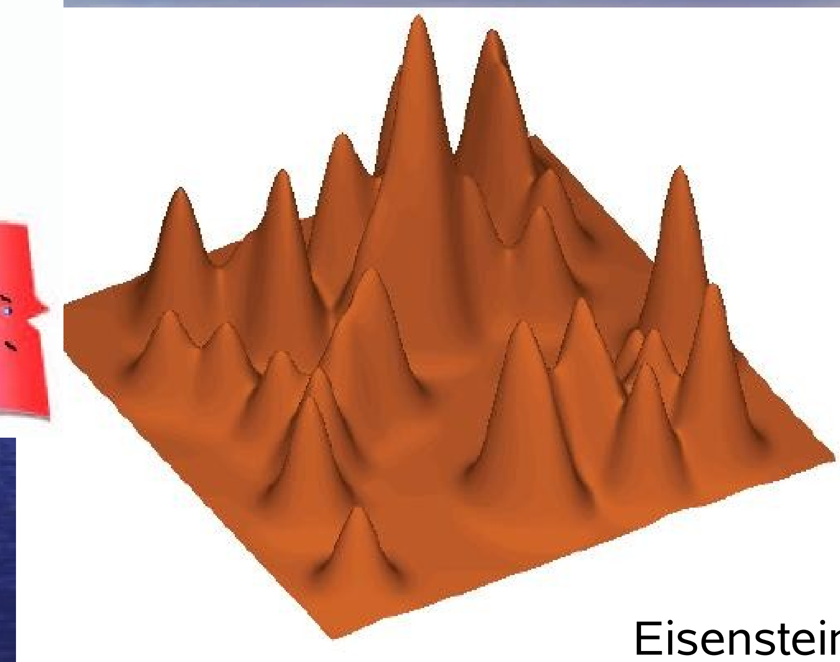


Before recombination:

- Universe is ionized.
- Photons provide enormous pressure and restoring force.
- Perturbations oscillate as acoustic waves.

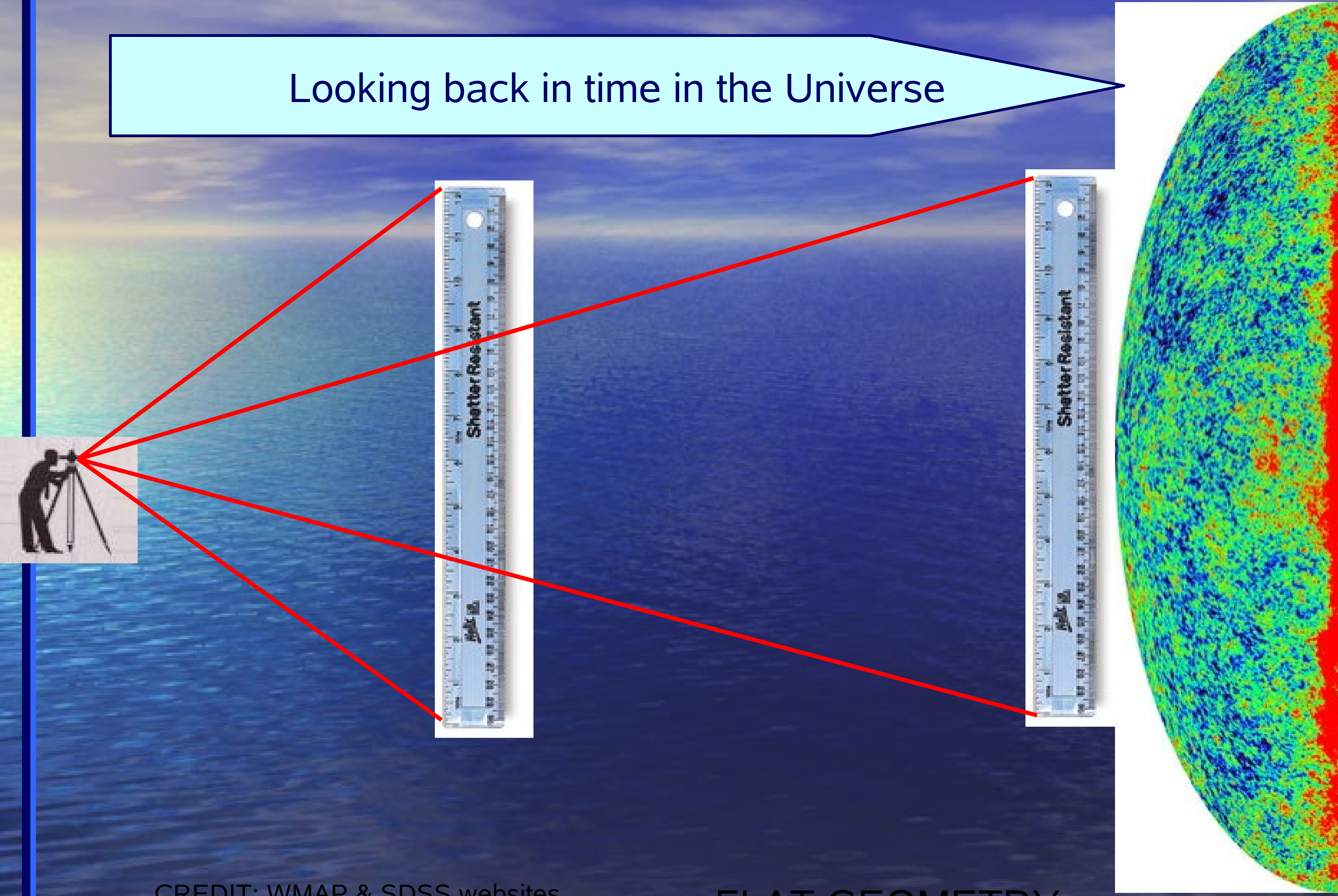
Sound Waves





- At recombination the fundamental wave is frozen in a phase where gravity enhances the gravitational pull, but only ordinary matter undergoes sonic compressions.
- The dark matter pull in baryons and photons by gravitational attraction.
- At recombination gravity and sonic motion work together to raise the radiation temperature in the troughs (blue) and lower the temperature at the peaks (red).

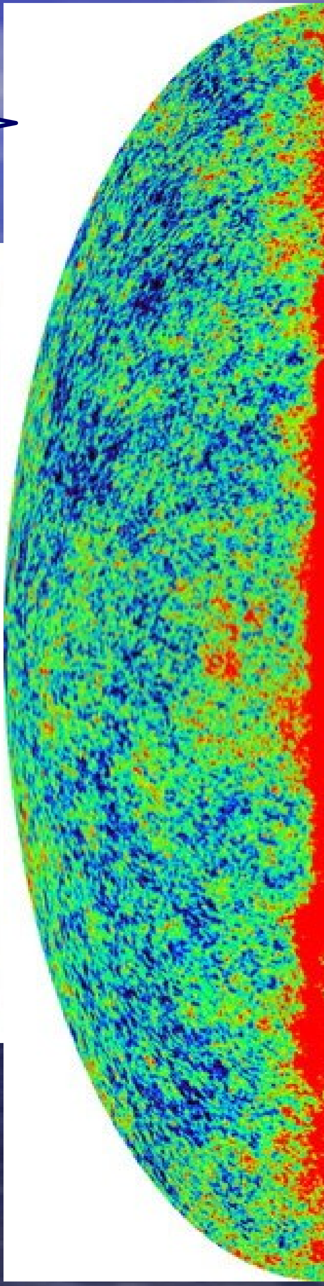
Looking back in time in the Universe

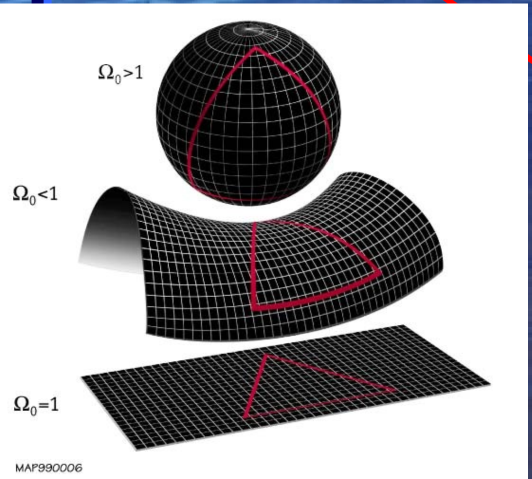


CREDIT: WMAP & SDSS websites

FLAT GEOMETRY

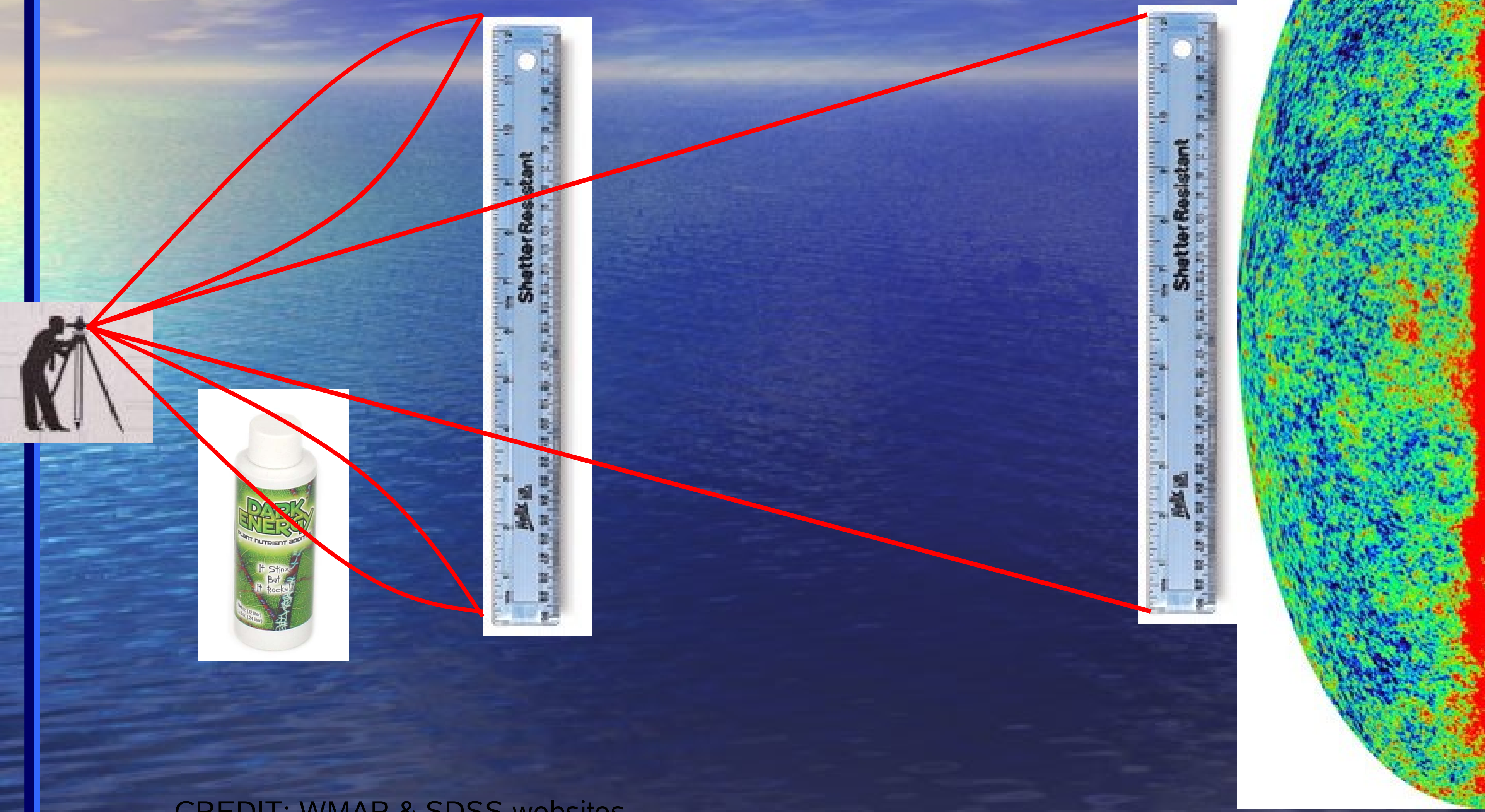
Looking back in time in the Universe





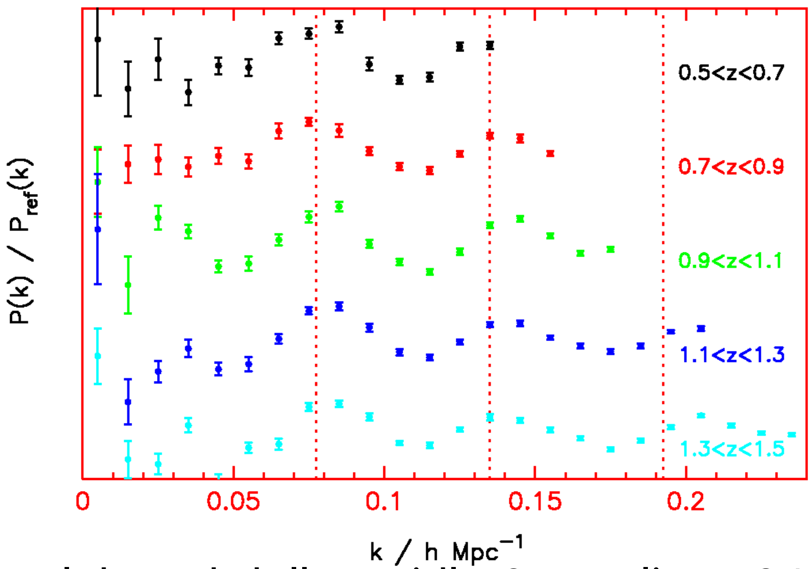
CLOSED GEOMETRY

Looking back in time in the Universe



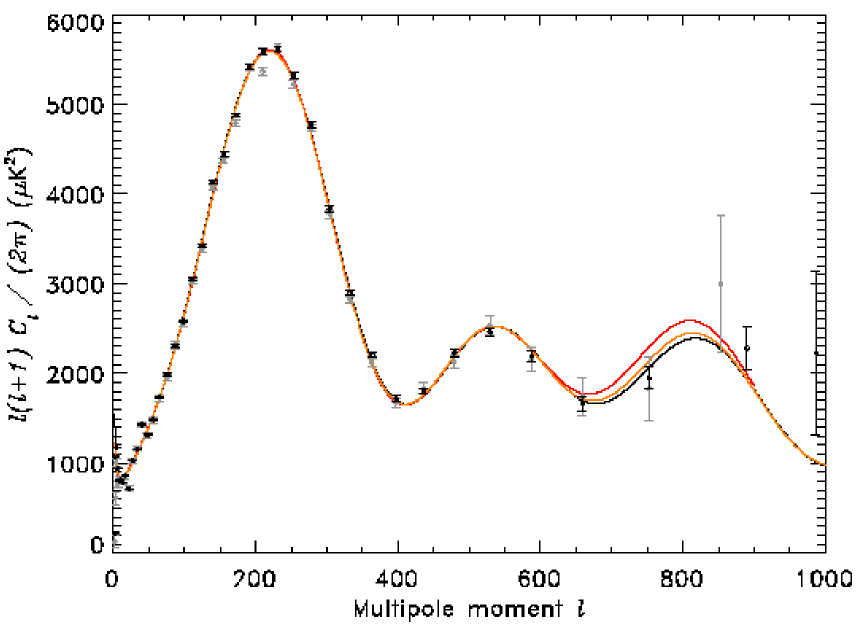
CREDIT: WMAP & SDSS websites

Experiment: ‘wiggles’



Blake, Abdalla, Bridle & Rawlings 04

Care: what “k_max” are you allowed to use on a P(k) measurement at high z?



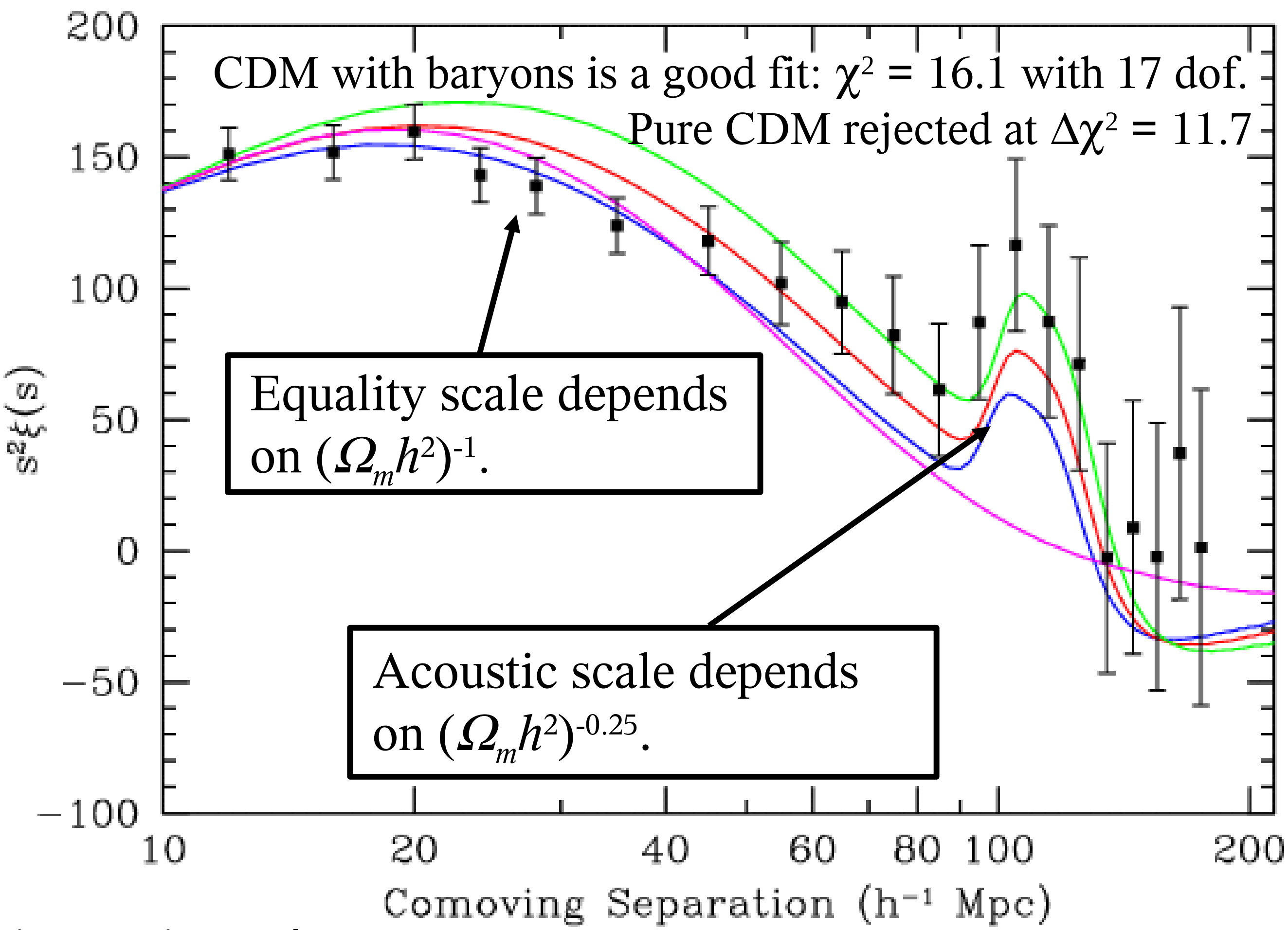
Tangential rods: can cancel , so that

$D_A(z=z_{eff}) / D_A(z=1000) = \theta_{CMB} / \theta_{wiggles}$

Radial rods: extra information from isotropy (c.f. AP test), and z<2 key regime.

As s now measured (independent of baryons etc), we have a standard rod.

SDSS BAO: Model Comparison



Eisenstein et al. 05

$\Omega_m h^2$ = 0.12

$\Omega_m h^2$ = 0.13

$\Omega_m h^2$ = 0.14

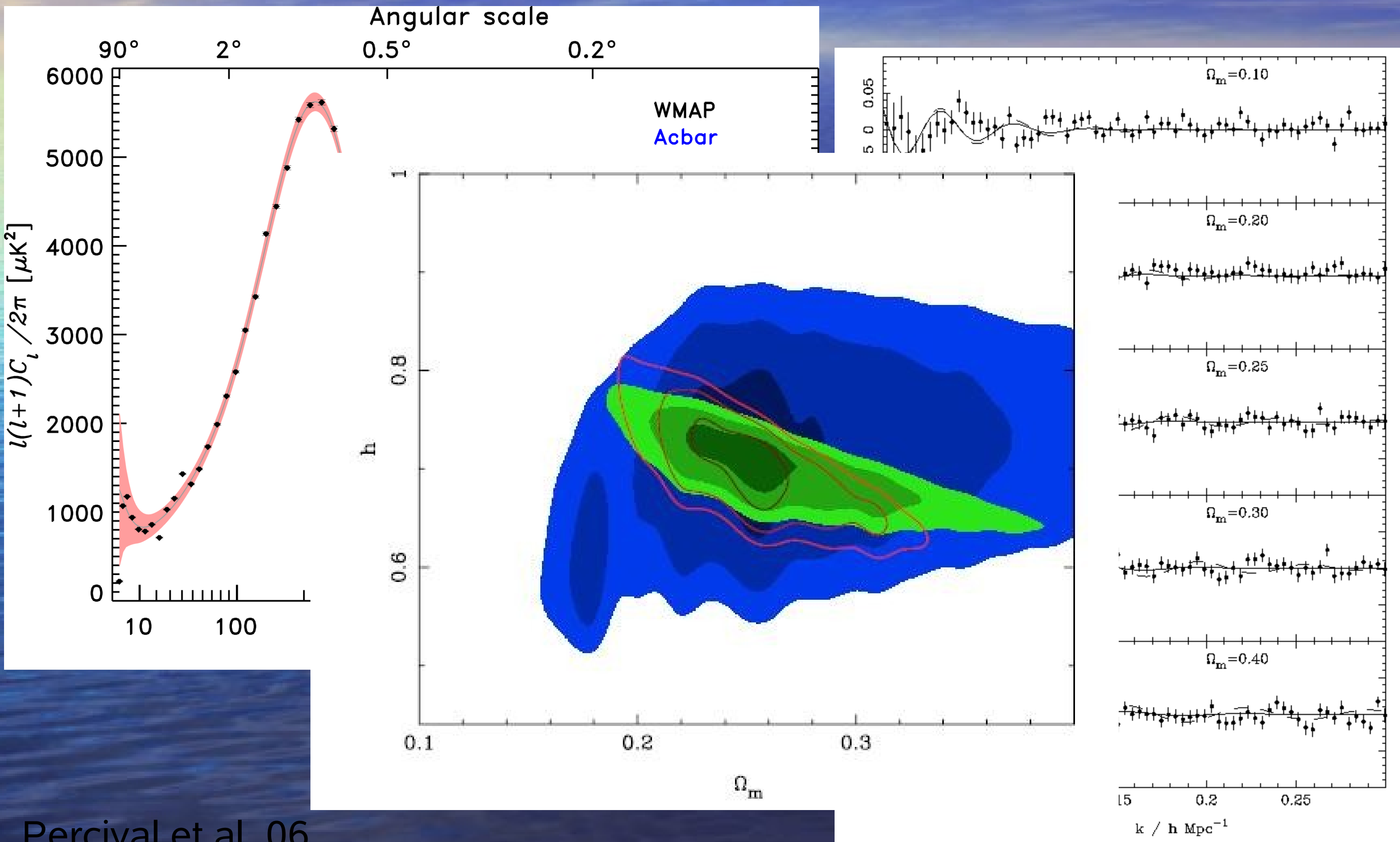
$\Omega_b h^2$ = 0.00

Fixed

$\Omega_b h^2$=0.024

n_s=0.98, flat

WMAP & SDSS fourrier space



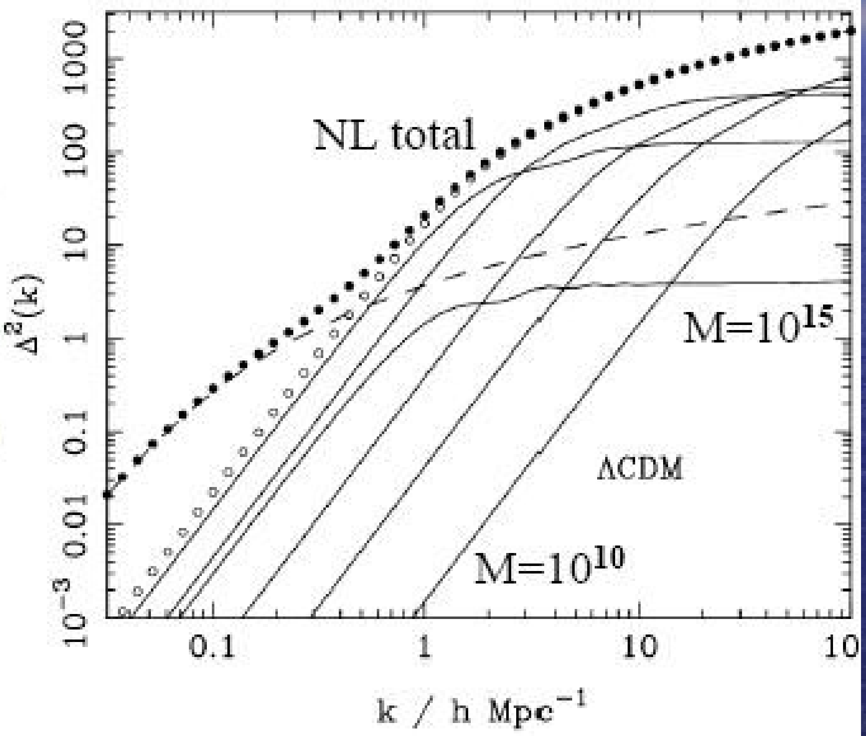
Percival et al. 06

BAO systematic effects:

Suppose that we measure an observed power that is related to the linear power by

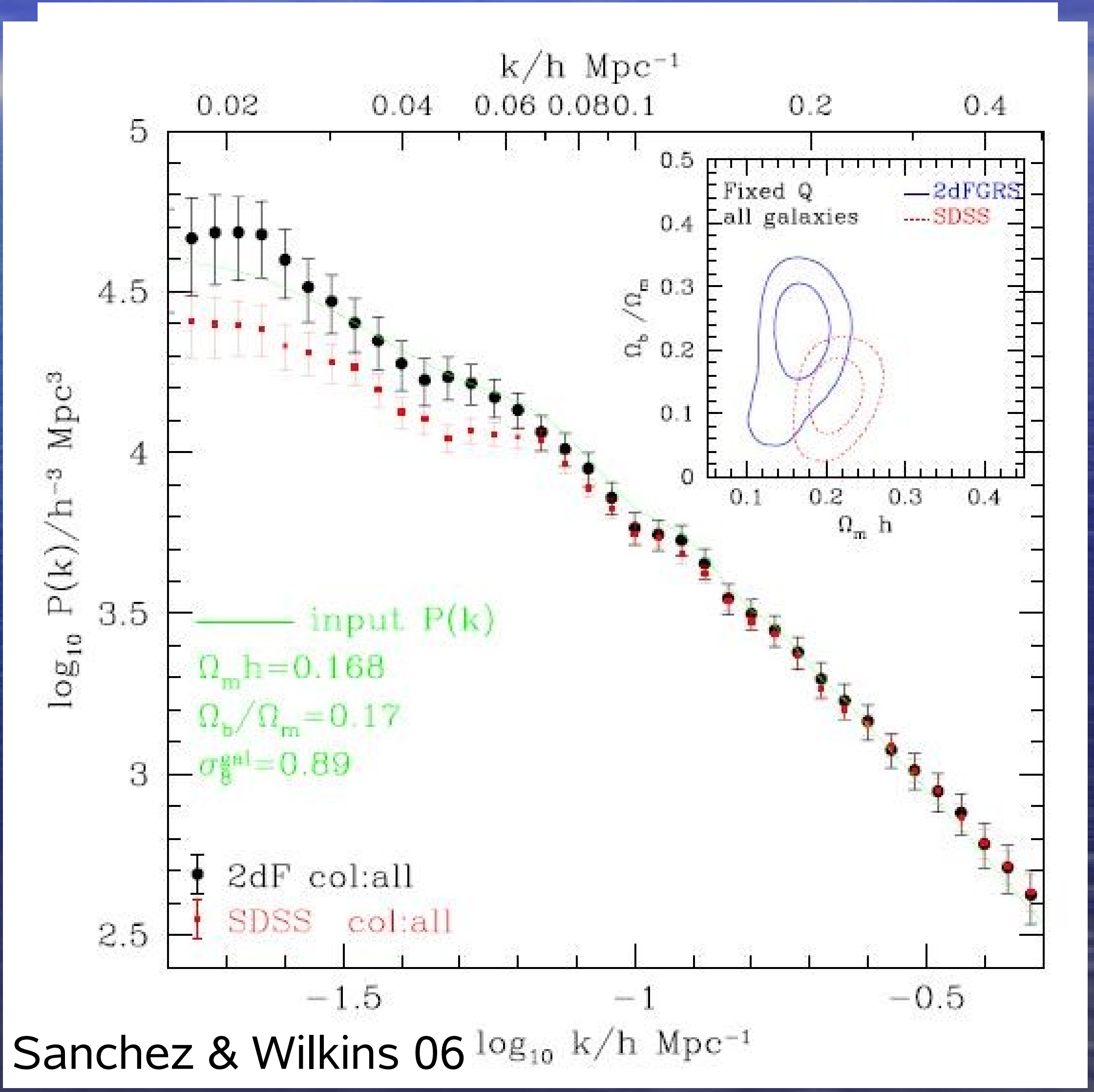
$$P(k)_{\rm obs} = b^2(k)P(k)_{\rm lin} + P(k)_{\rm extra}$$

If $b^2(k)$ and $P(k)_{\rm extra}$ are smooth, then can separate out oscillations



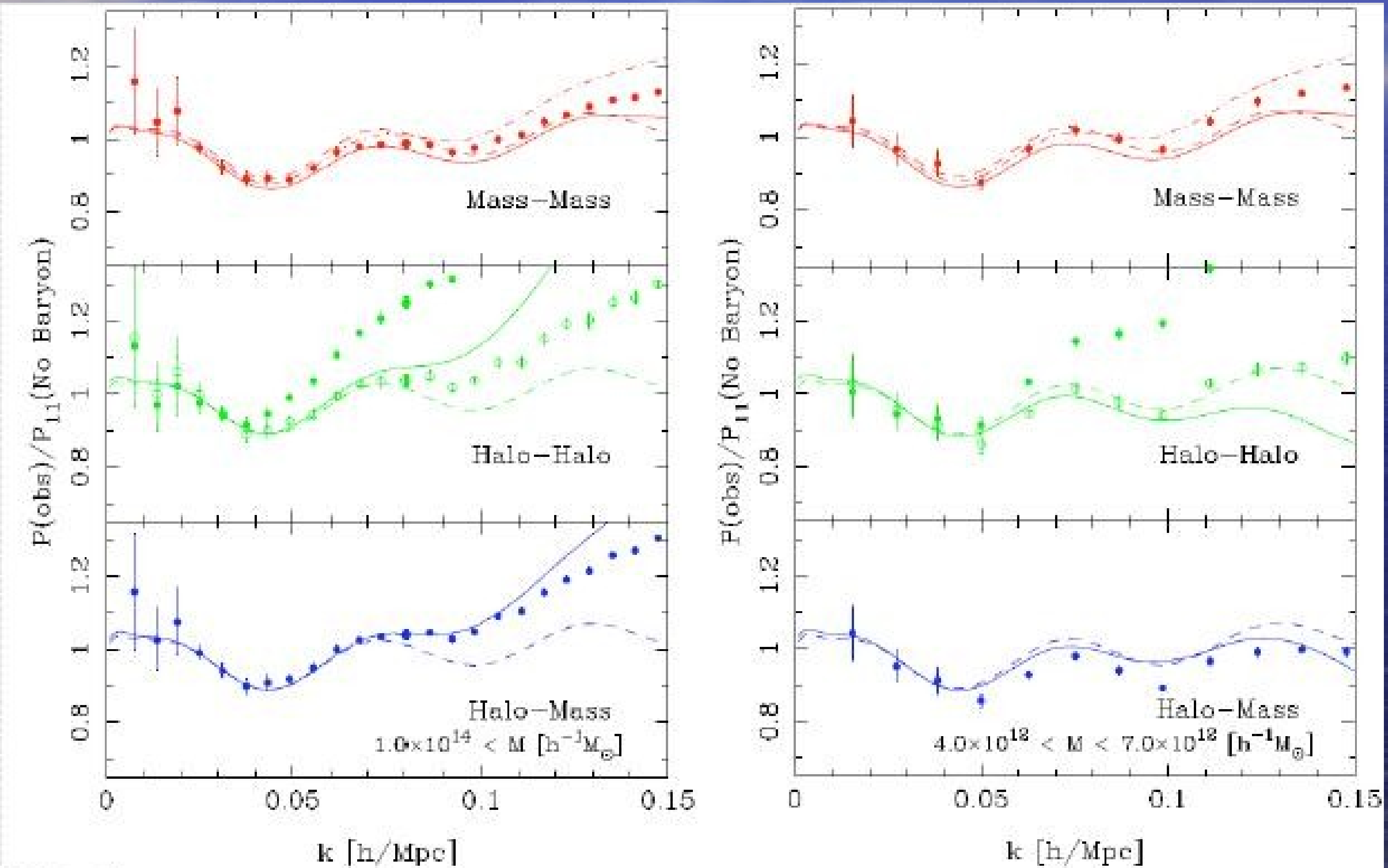
$$B_{\rm obs} = \frac{P(k)_{\rm obs}}{\bar{P}(k)_{\rm obs}} = g(k)B_{\rm lin} + [1 - g(k)]$$

Systematic effects: galaxy bias



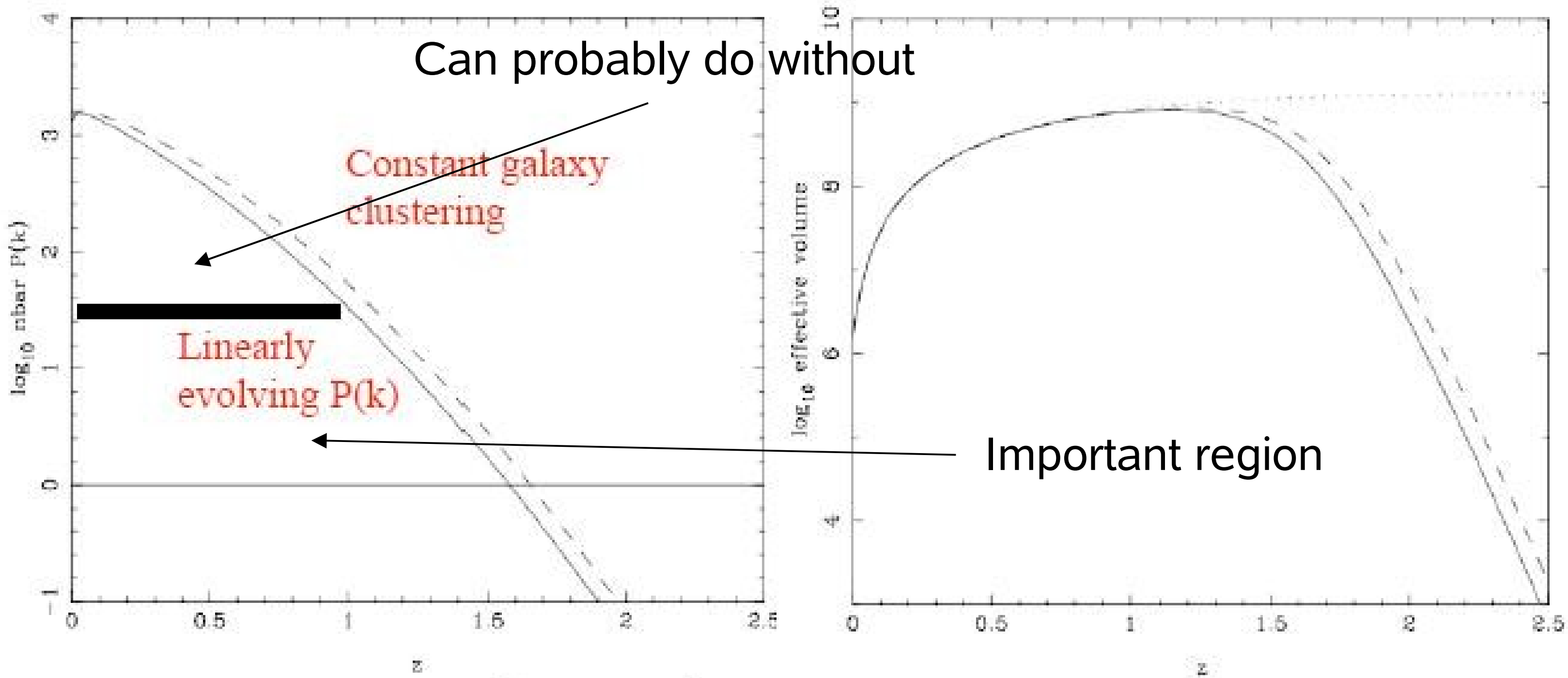
Cole, Sanchez & Wilkins 06

BAO systematic effects:



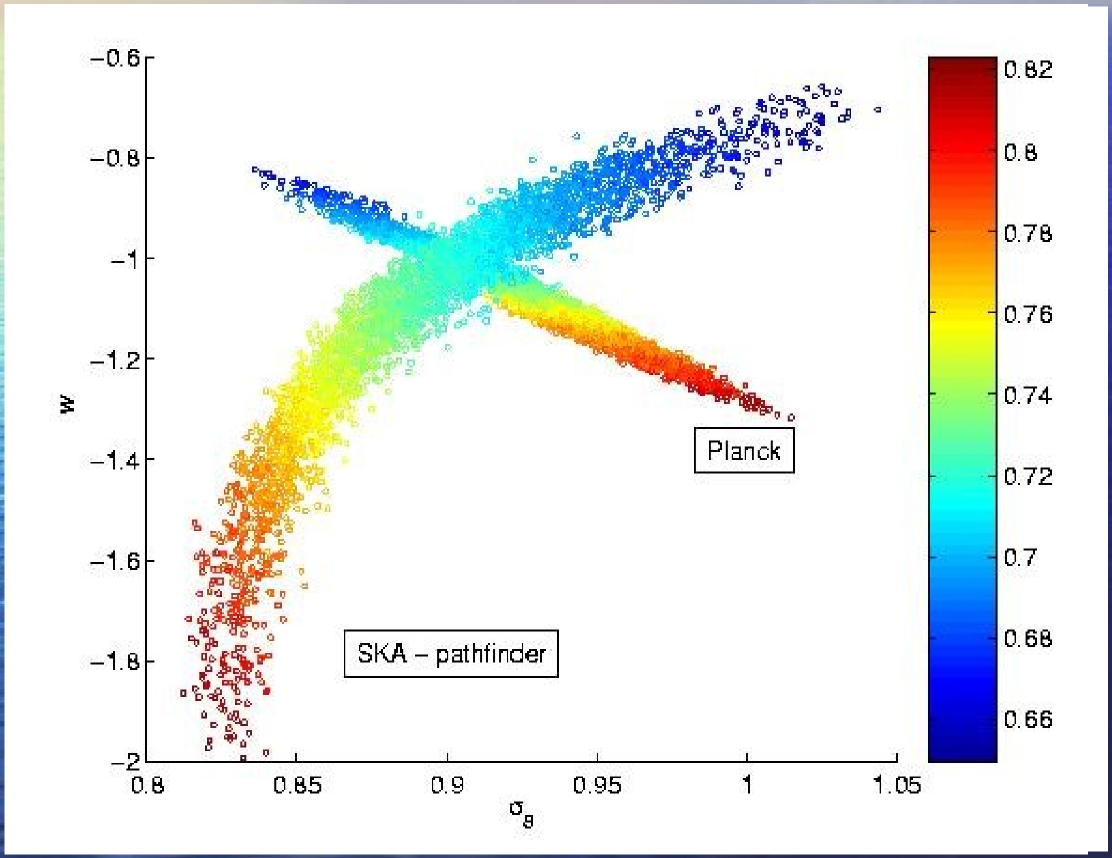
Plots from
Smith, Scoccimarro & Sheth 2006, astro-ph/0609547

Many power spectra:



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

SKA results on w:

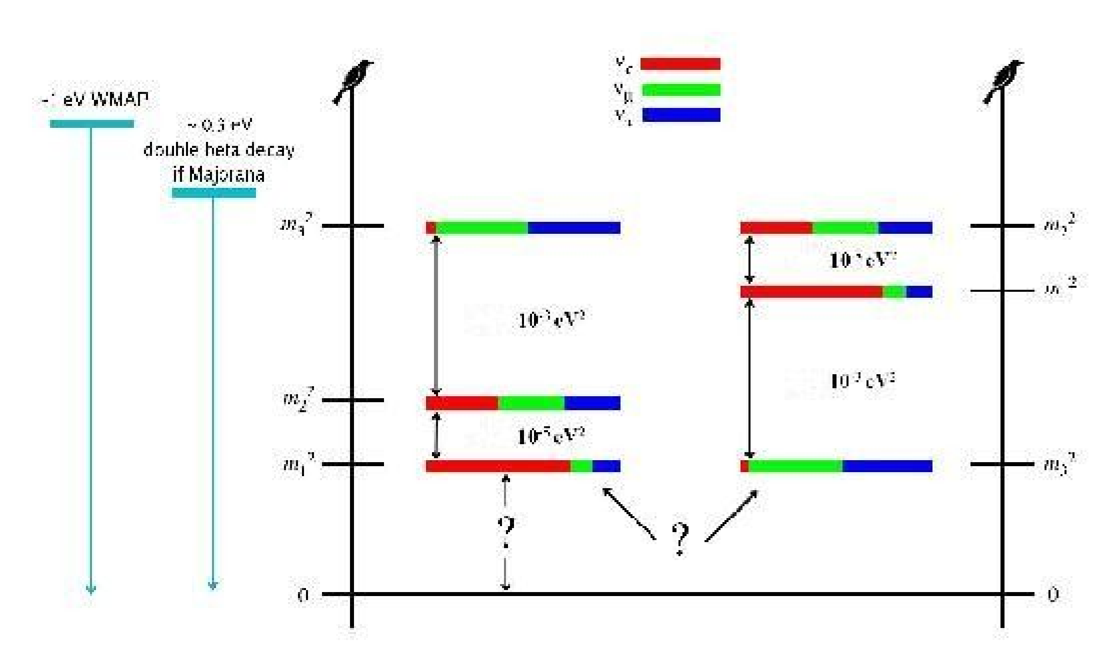


- Pathfinder equivalent to WFMOS ~ below 5%
- Need ~15% SKA or a ~10% compact SKA for this to be cosmologically interesting.
- Full SKA gets error to ~.7% with wiggles +CMB
- Number of galaxies probed: ~10^9 from z=0 to z=2 (Abdalla & Rawlings 05)
- Probe which is independent of Planck priors.

Abdalla, Blake & Rawlings 08 in prep.

The SKA and neutrino physics

Neutrino Physics – Mass hierarchies



Neutrinos Oscillate

2 possible hierarchies given neutrino data: normal and inverted

2 possible scenarios:

Quasi-degenerate or non-degenerate spectrum

parameter	best fit	3σ range
Δm^2_{21} $[10^{-5}eV]$	8.1	7.2–9.1
Δm^2_{31} $[10^{-3}eV]$	2.2	1.4–3.3
$\sin^2\theta_{12}$	0.30	0.23–0.38
$\sin^2\theta_{23}$	0.50	0.34–0.68
$\sin^2\theta_{13}$	0.000	$\leq$ 0.047

Unknowns:

(ii) Which hierarchy
- mass effects, 3rd mixing angle

(iv) Absolute mass scale
- beta decay / 0xnu 2xbeta

Neutrino Physics - Mass

Cosmological mass:

$$\Omega_\nu = \frac{3}{11}\frac{m_\nu N_\nu n_\gamma}{\rho_c} = \frac{m_\nu N_\nu}{94h^2 eV}$$

Electron neutrino mass:

$$m^2_{\nu_e} = c^2_{12}c^2_{13}m^2_1 + s^2 12 c^2_{13}m^2_2 + s^2_{13}m^2_3.$$

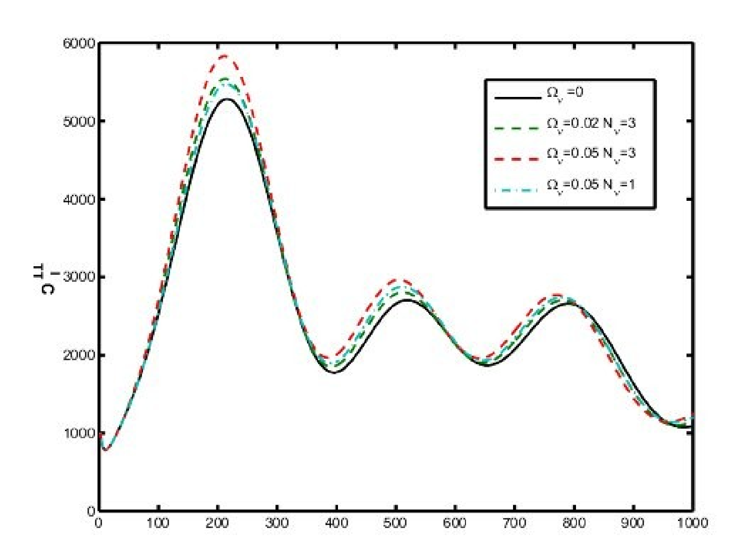
0? 0? 0?

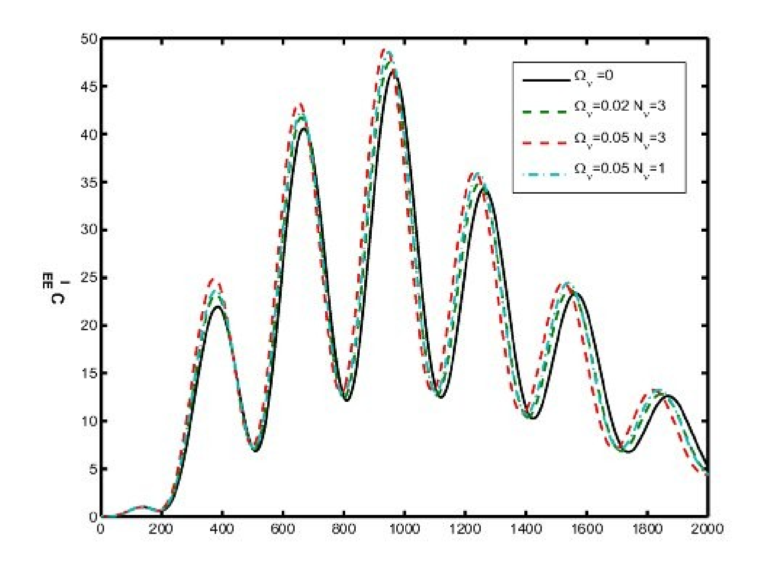
Majorana mass:

$$m_{\nu\nu} = \sum_i |U_{ei}|^2 m_i\,.$$

May be hard to measure these masses if they add up to zero

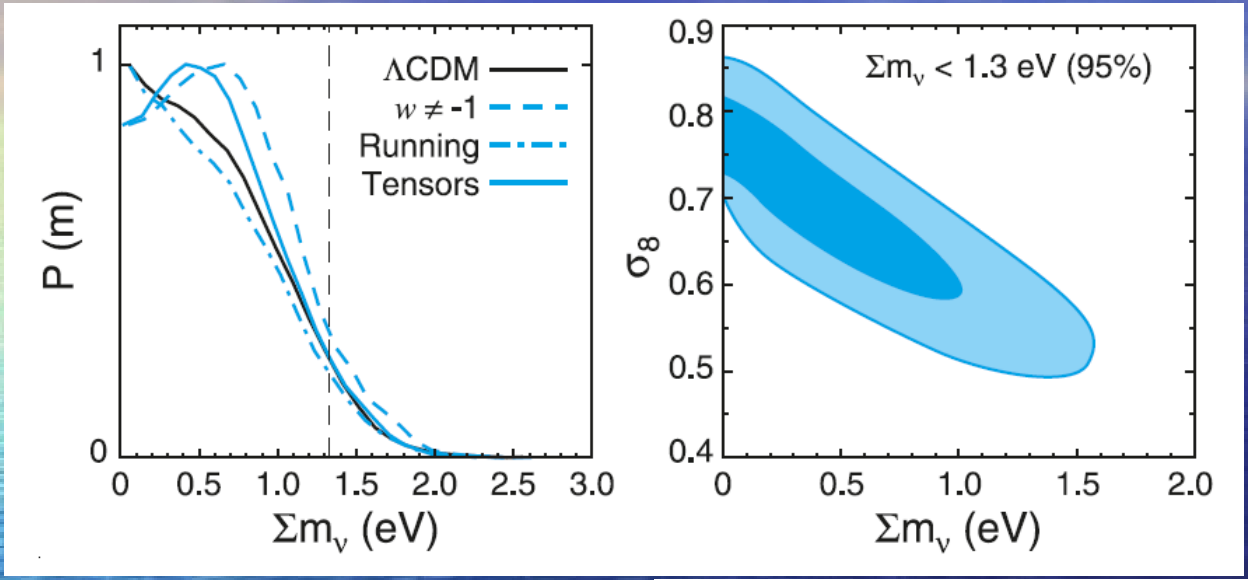
Neutrino Physics - CMB



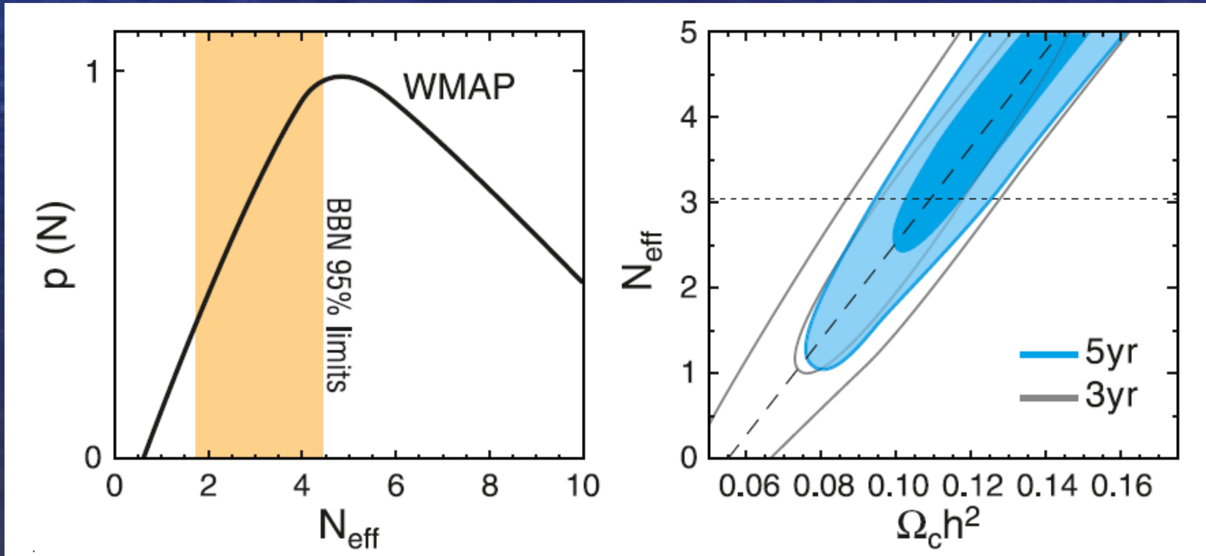


- CMB is affected by neutrino physics
- However degeneracies are so large that it is makes CMB experiments alone useless to probe neutrino masses
- Future Planck results will help constrain other parameters / remove degeneracies

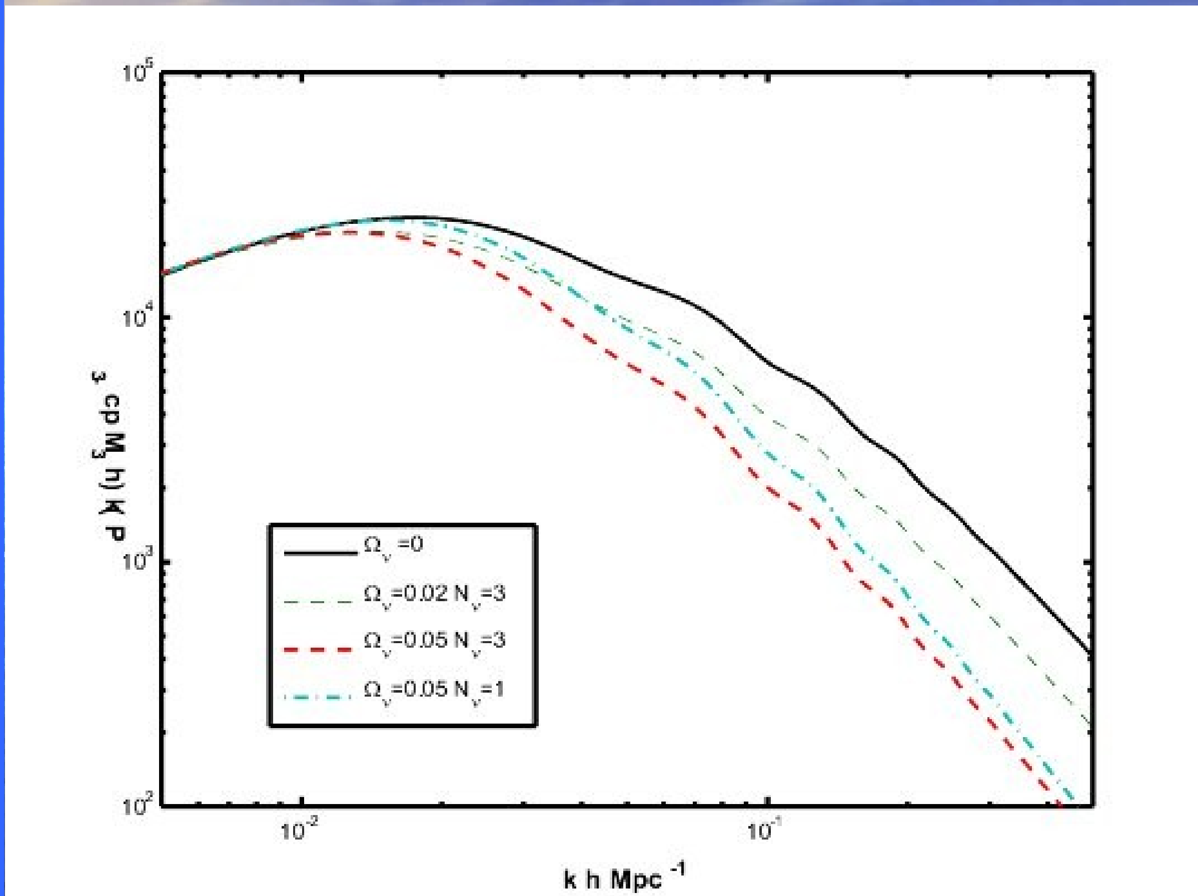
Current CMB bounds



Fukugita et al. 06
Dunkley et al. 08



Neutrino Physics - LSS



Three observable:

(ii) overall damping of the power spectrum at small scales

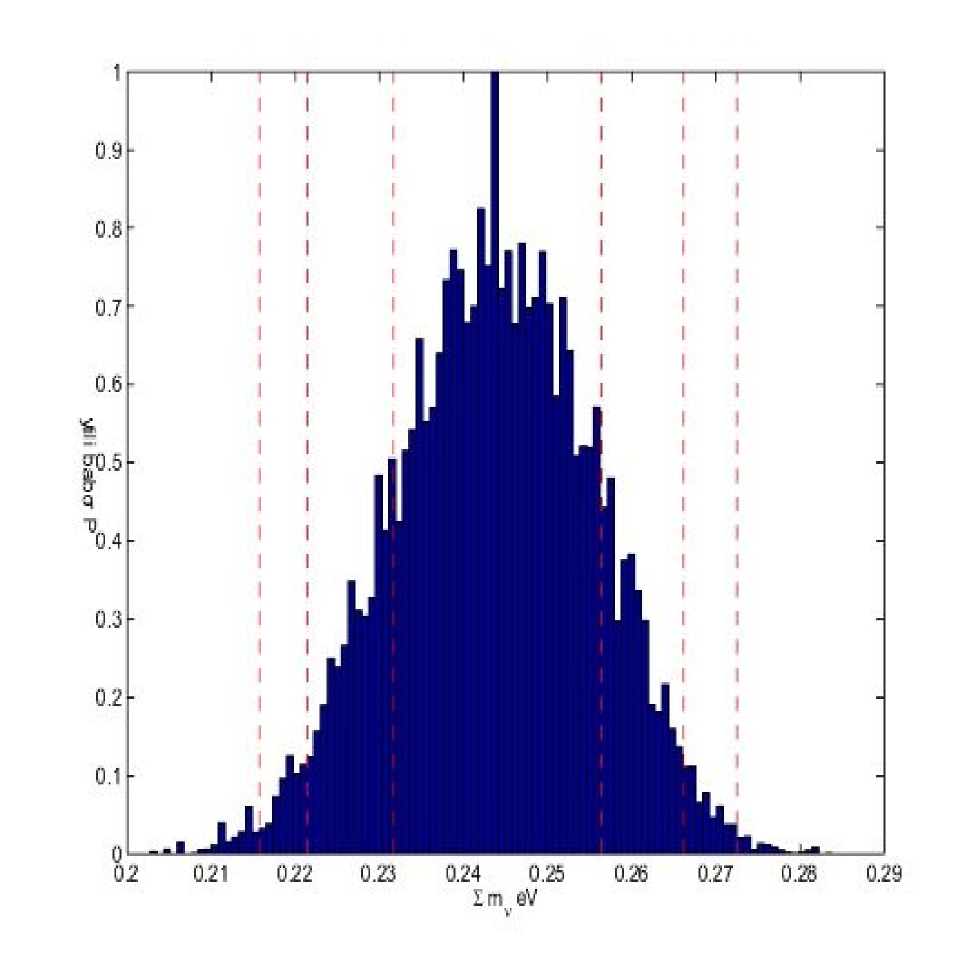
(iii) Scale where this damping occur

(iv) Growth of structure

$$\frac{\Delta P_m(k)}{P(k)} \simeq -8 f_\nu .$$

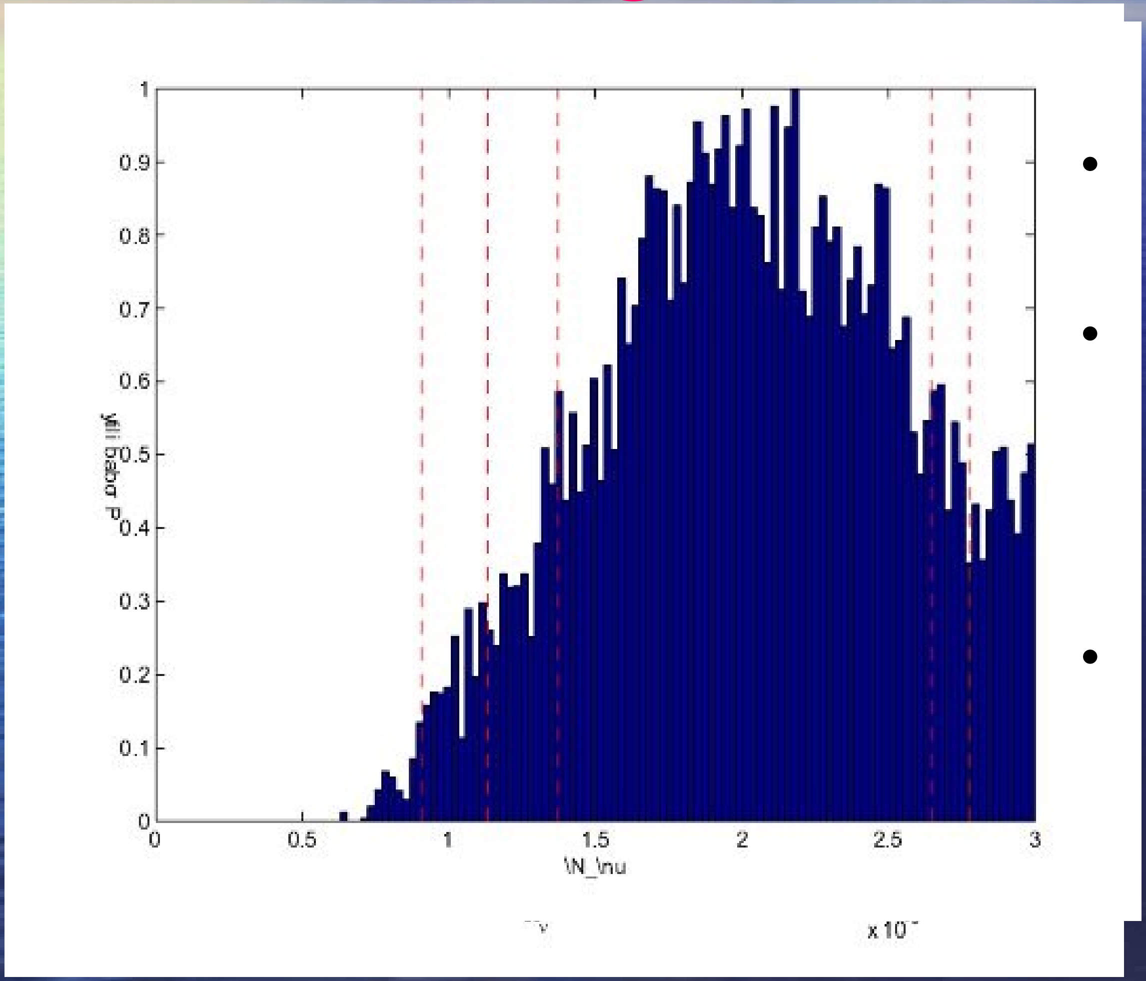
Can we distinguish between cases with N neutrinos with mass M and N/2 neutrinos with mass 2M?

CMB complementarities – Measuring masses



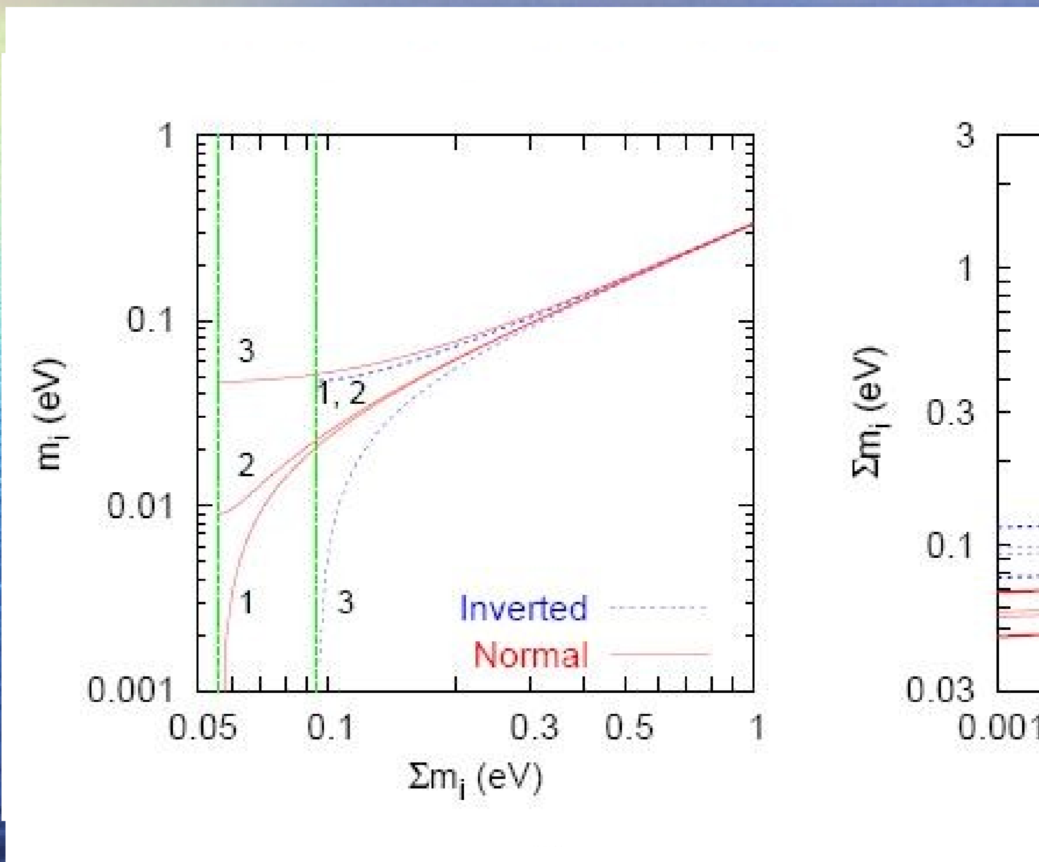
- CMB helps with degeneracy problem
- Degeneracy between n_s, sigma_8 and Omega_nu
- Result in mass measurement of order ~10 per cent if the range is in the quasi-degenerate regime.

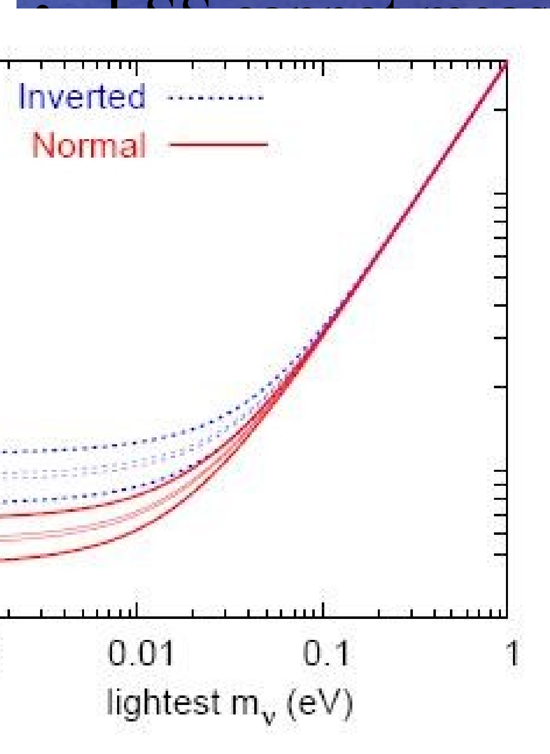
CMB complementarities – Measuring hierarchies



- CMB helps with degeneracy problem
- Independently neither LSS or CMB experiments can measure N_nu
- A combination of both can constrain N_nu to a certain extent.

Lowest mass allowed: ~0.05eV





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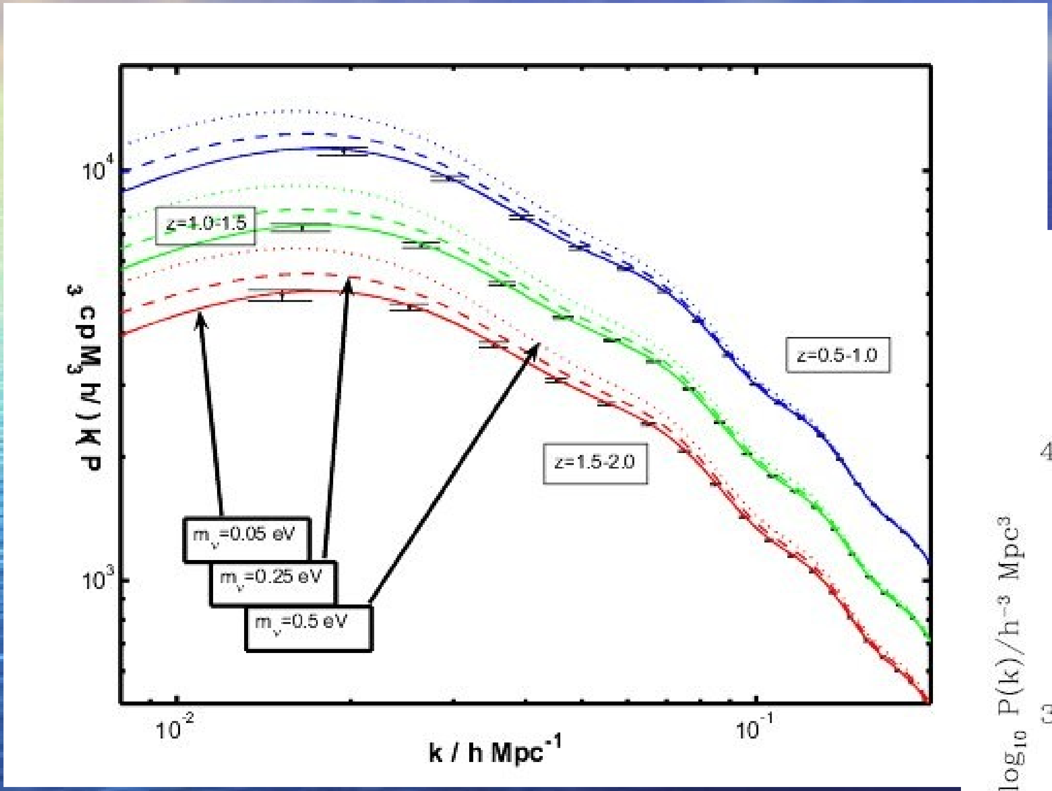
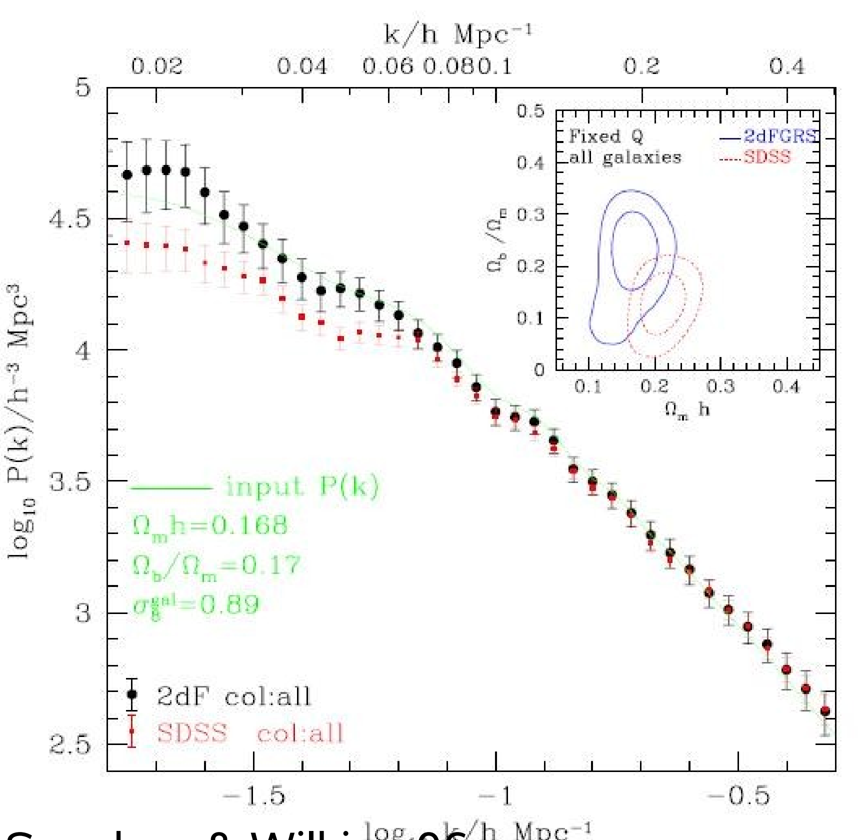
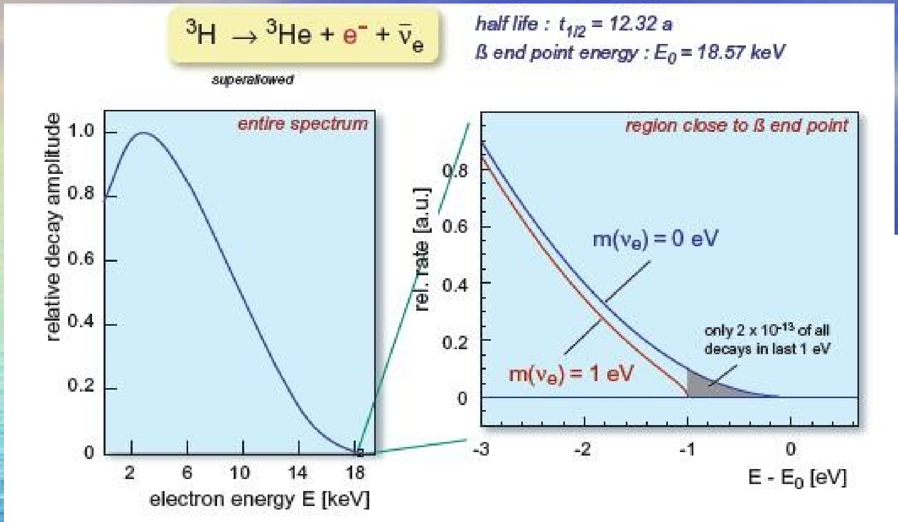
Again beware of systematic effects!!!!



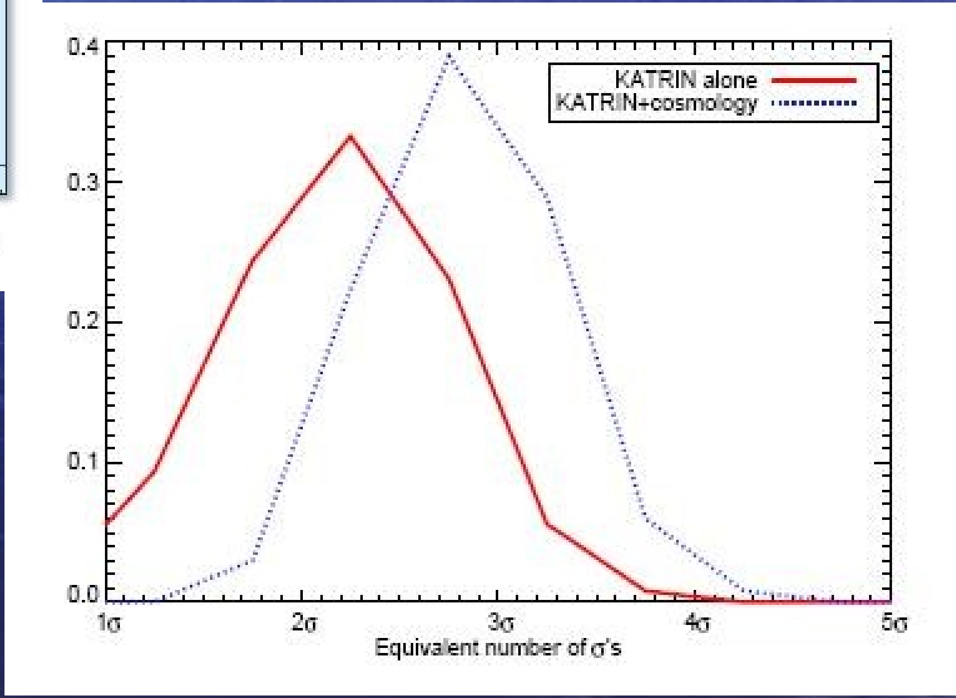


Cole, Sanchez & Wilkins 06

Other possibilities:



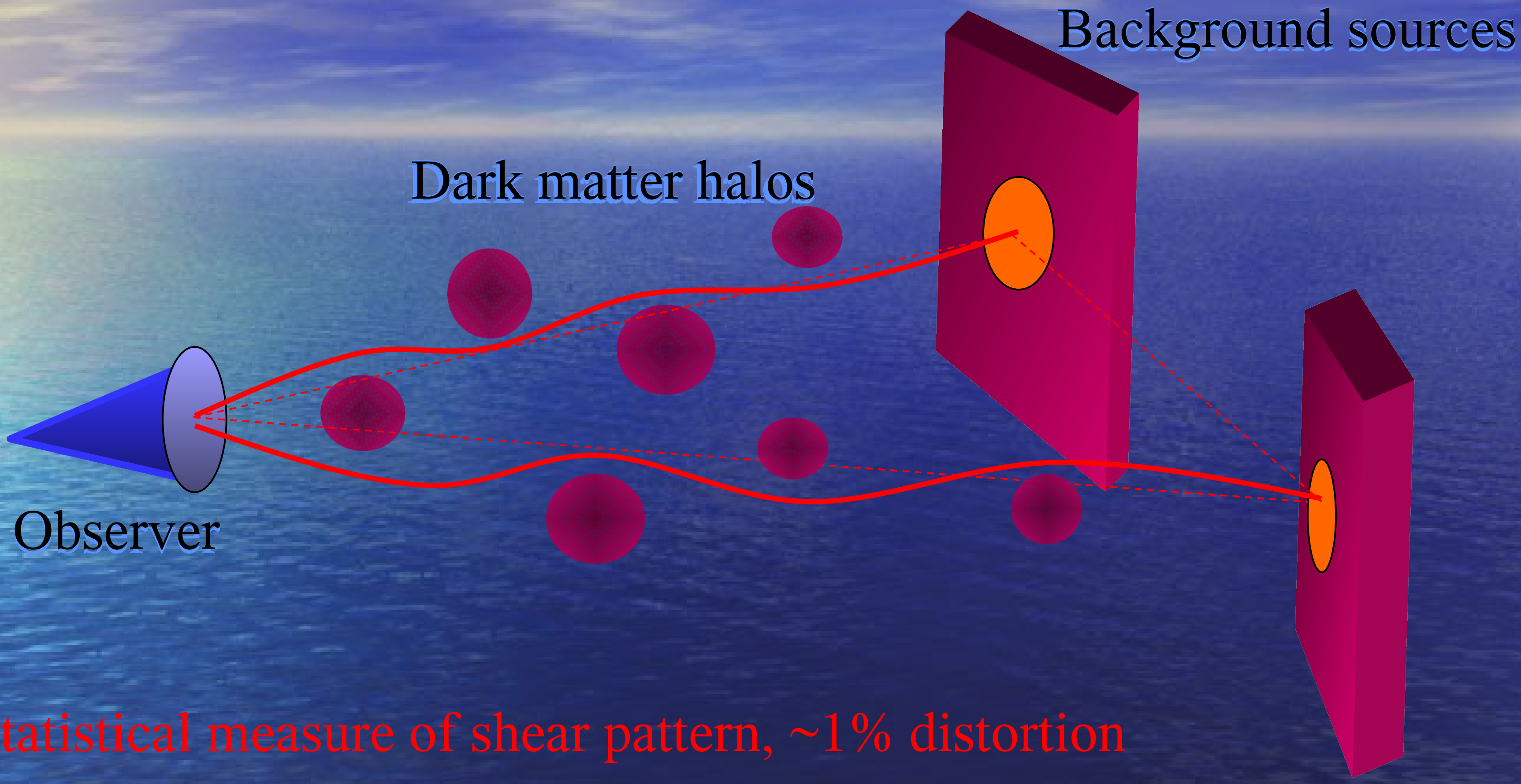
- Mass spectrometer measuring the end point in beta decay
- Sensitive to 0.2eV for the electron neutrino mass. This corresponds to a sum of the mass eigenstates equal to 0.6eV
- Can be combined with cosmology.
- Other possibility is a weak lensing all sky survey: can reach an error of 0.04eV



Host, Lahav, Abdalla & Eitel 07

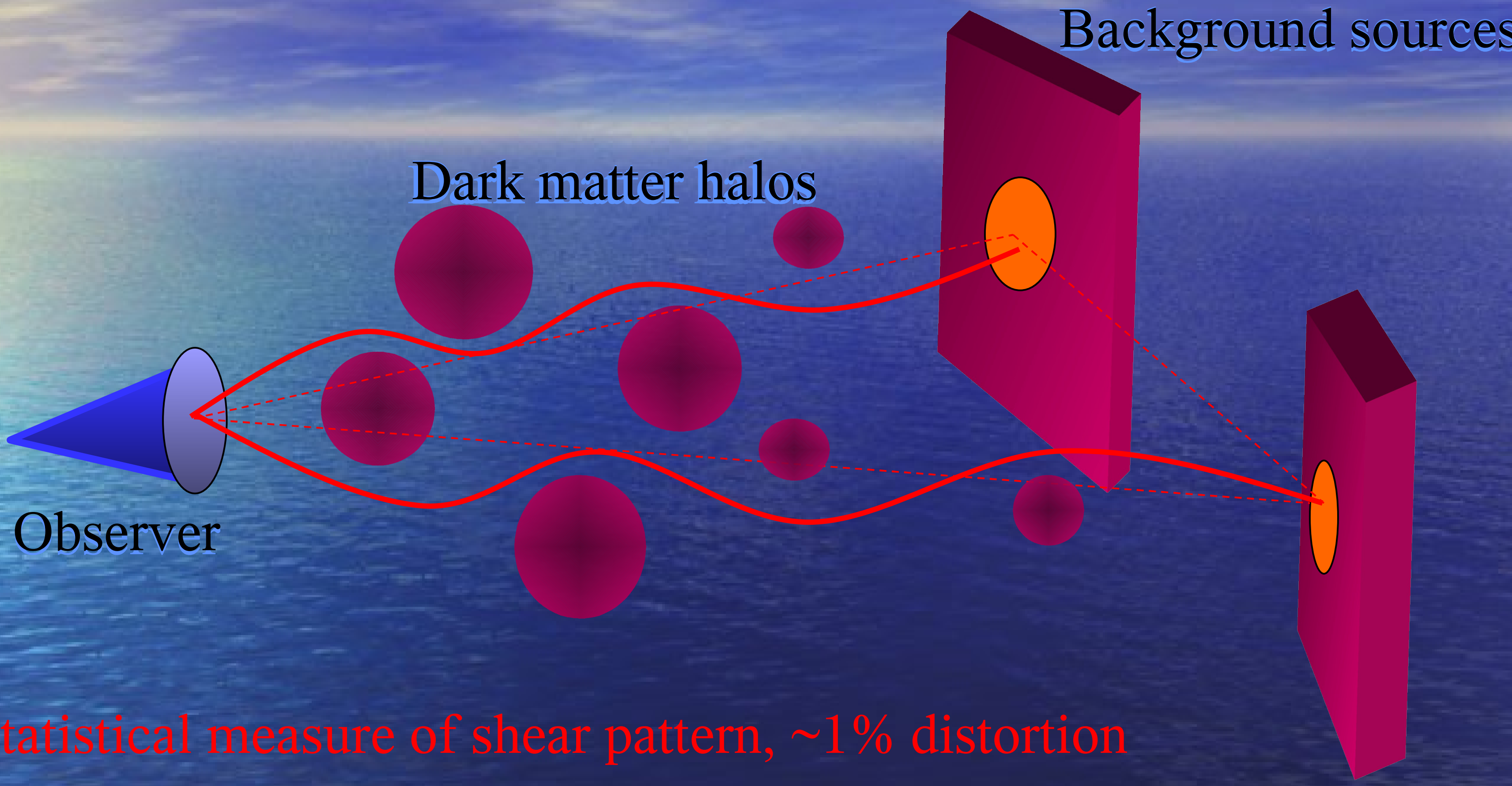
The SKA and weak lensing

Weak Lensing: Cosmic Shear



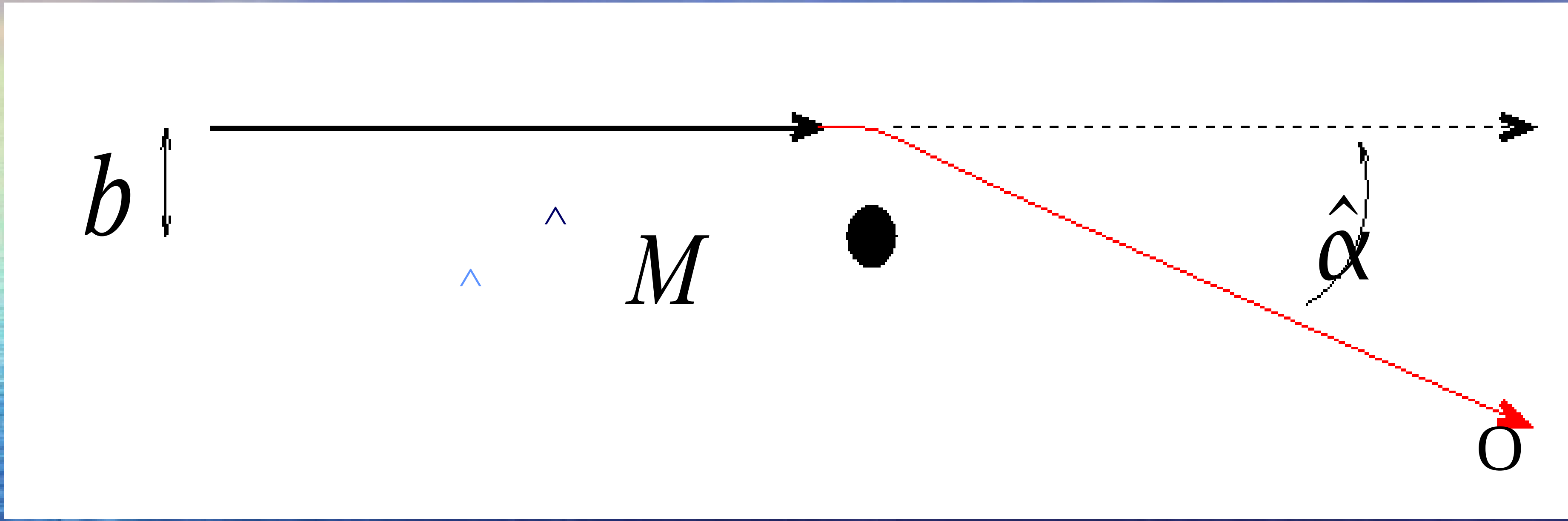
- Statistical measure of shear pattern, ~1% distortion
- Radial distances depend on *geometry* of Universe
- Foreground mass distribution depends on *growth* of structure

Weak Lensing: Cosmic Shear



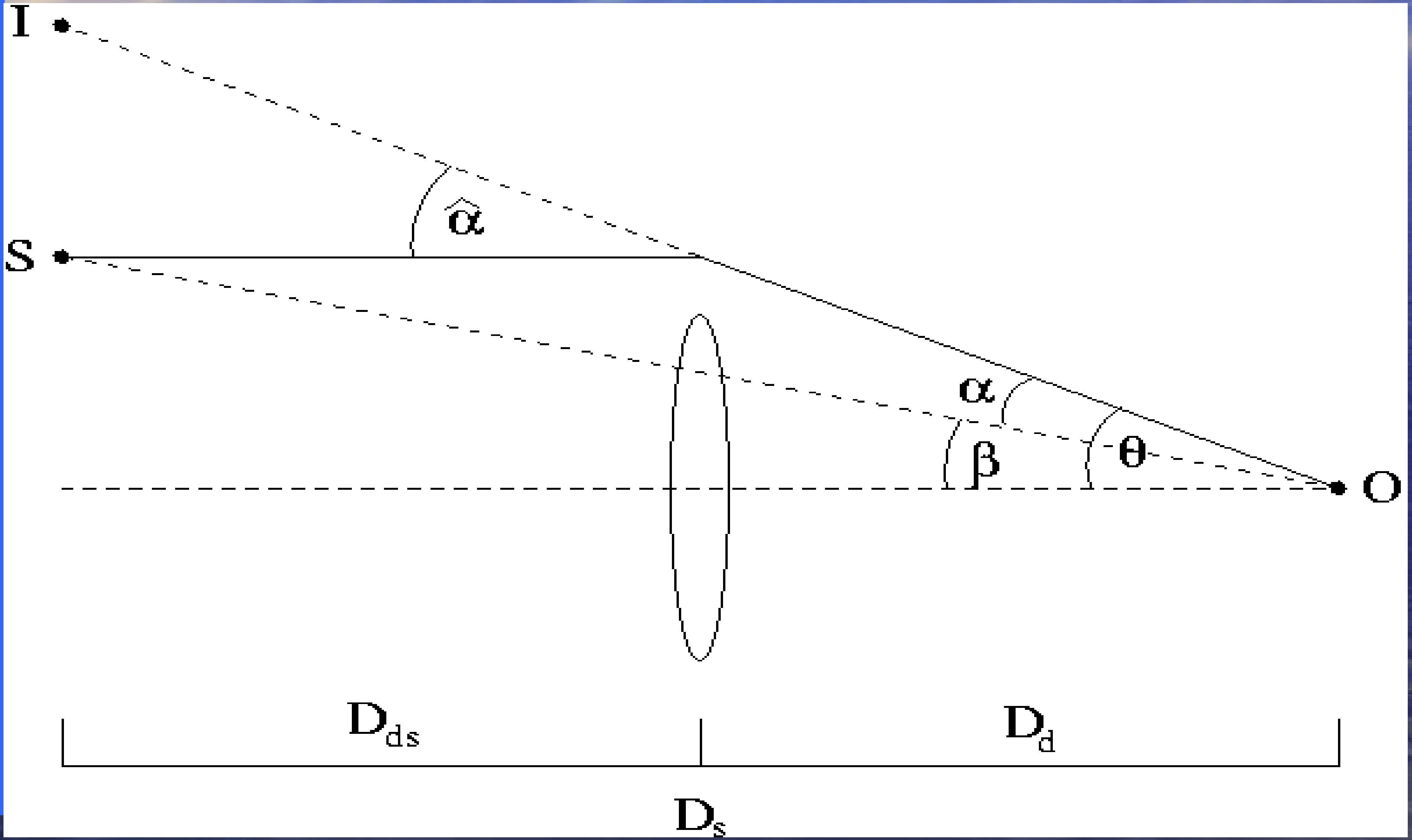
- Statistical measure of shear pattern, ~1% distortion
- Radial distances depend on *geometry* of Universe
- Foreground mass distribution depends on *growth* of structure

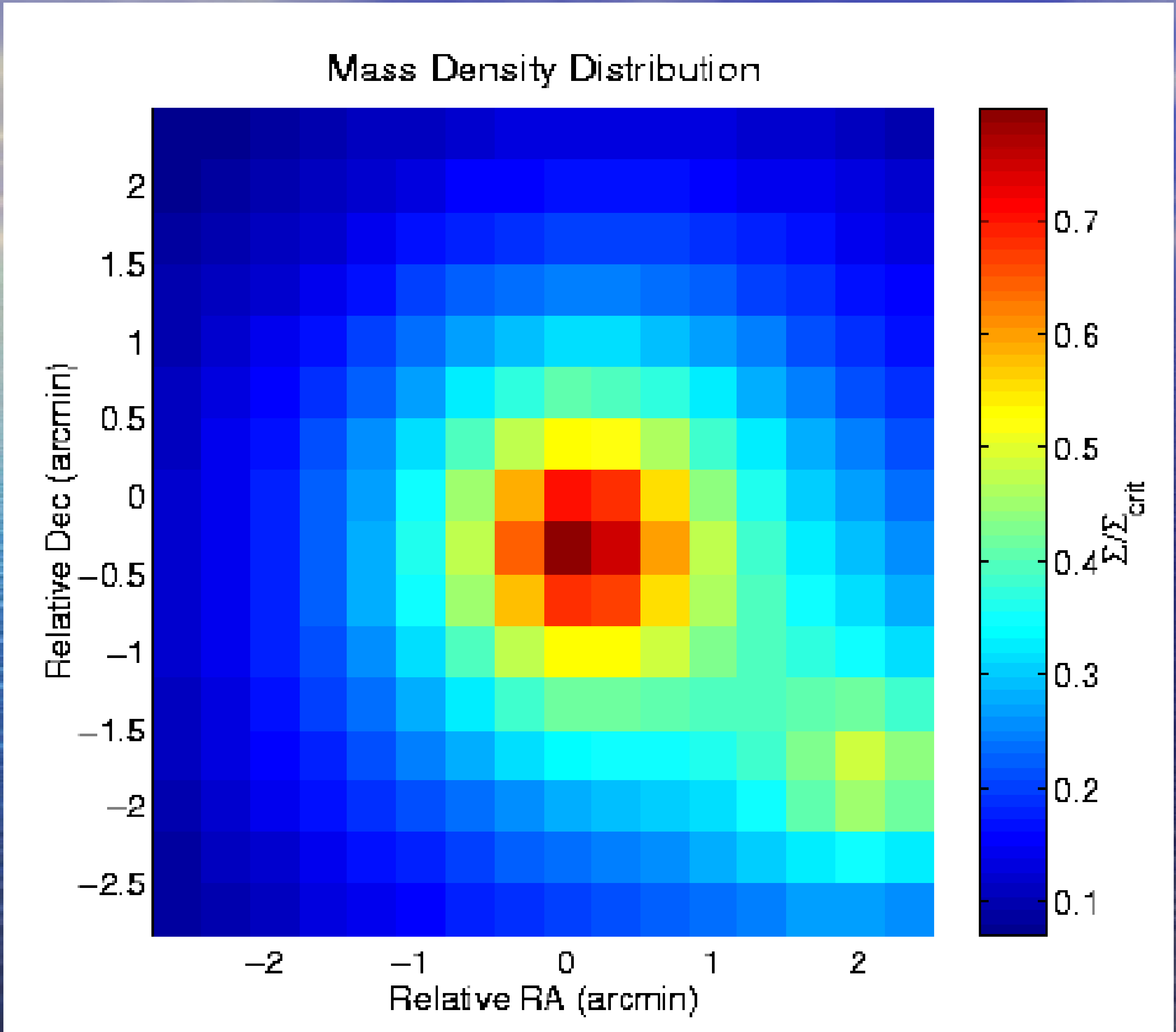
Just one equation from GR

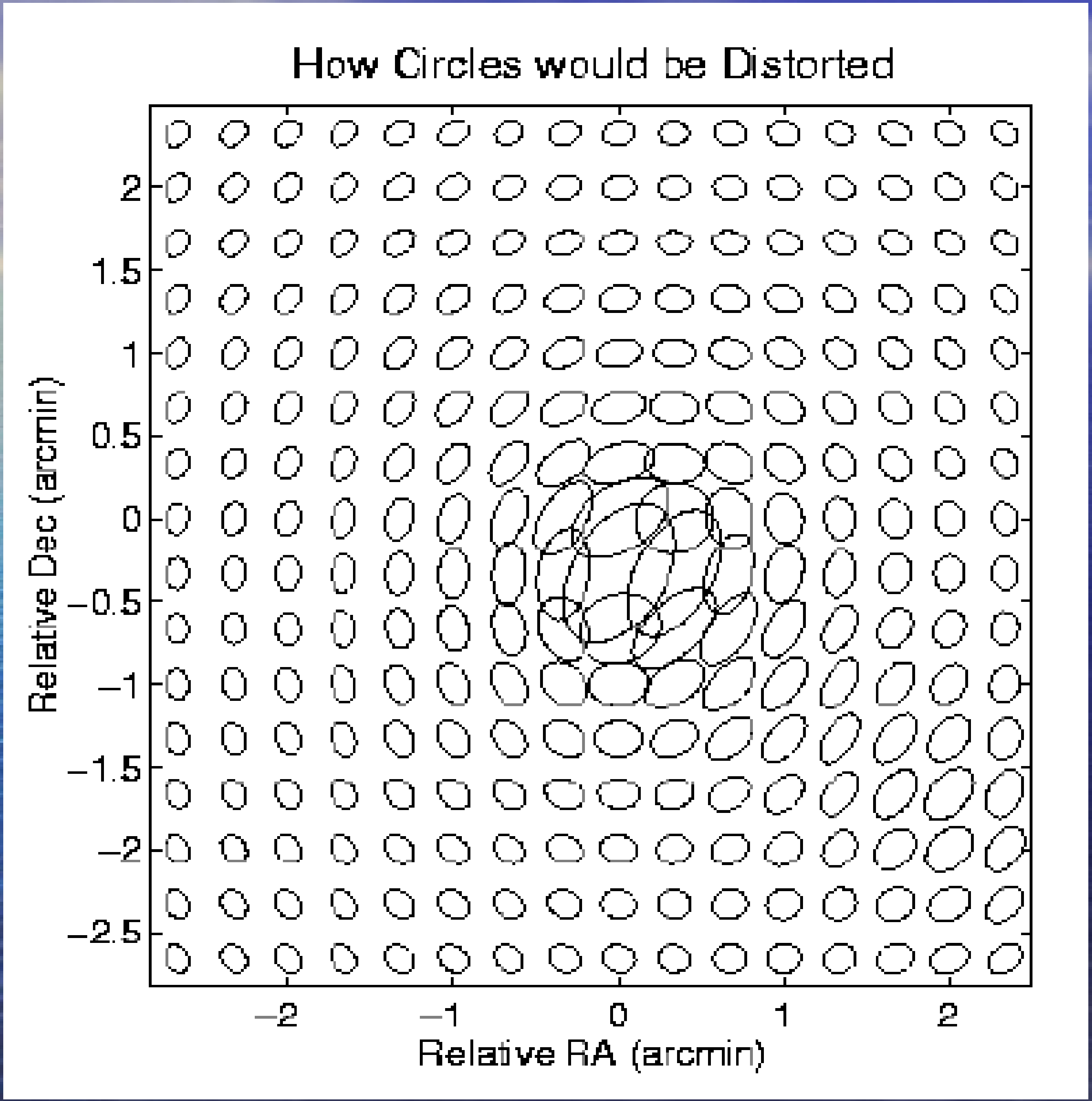


- $\hat{\alpha} = 4 G M / (c^2 b)$
- NB. Independent of light wavelength

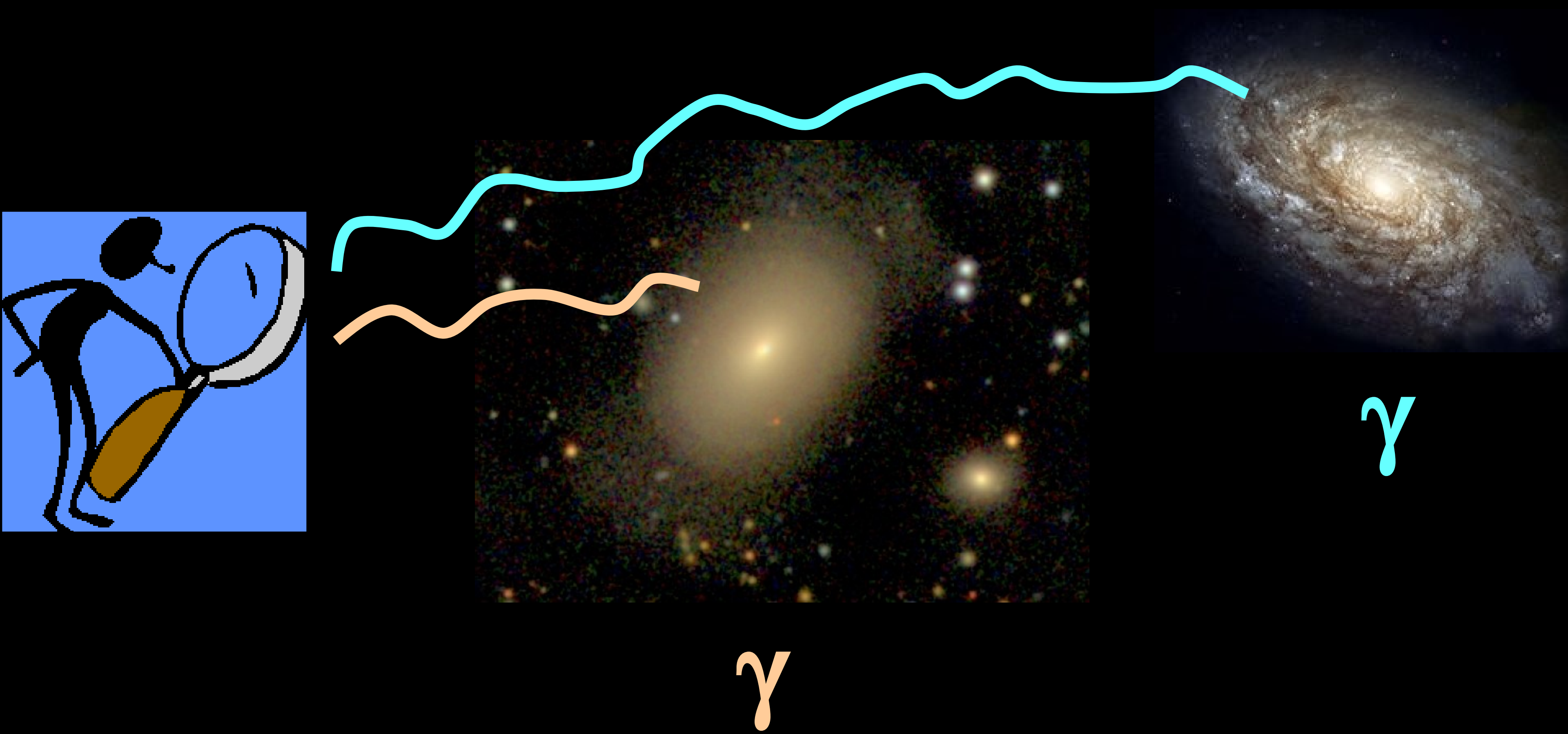
Apparent deflection angle α



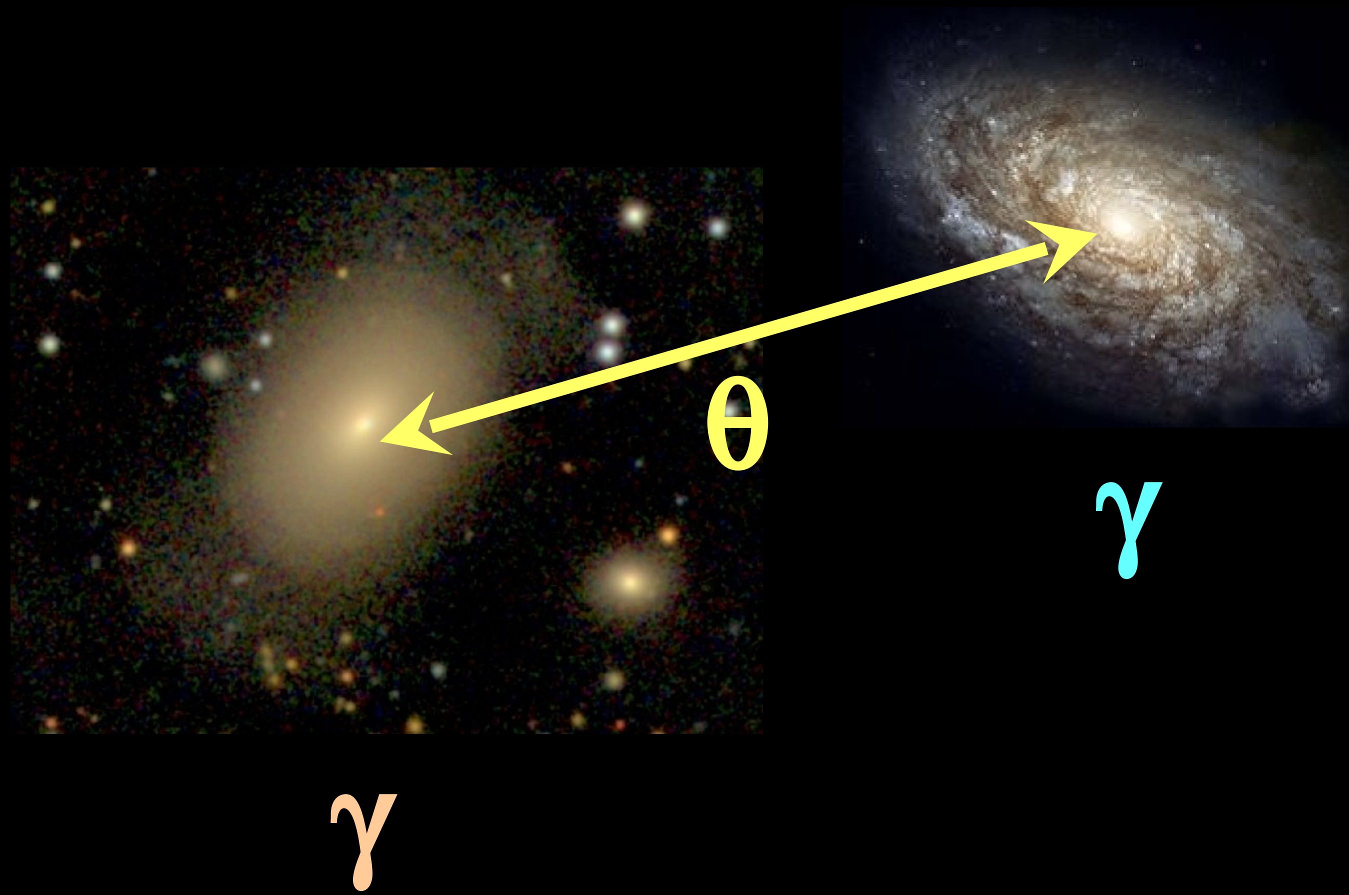

Mass Density Distribution
Relative Dec (arcmin)
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2.5
−2
−1
0
1
2
Relative RA (arcmin)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Σ/Σ_{crit}


How Circles would be Distorted
Relative Dec (arcmin)
Relative RA (arcmin)
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2.5
−2
−1
0
1
2

Cosmic shear two point tomography

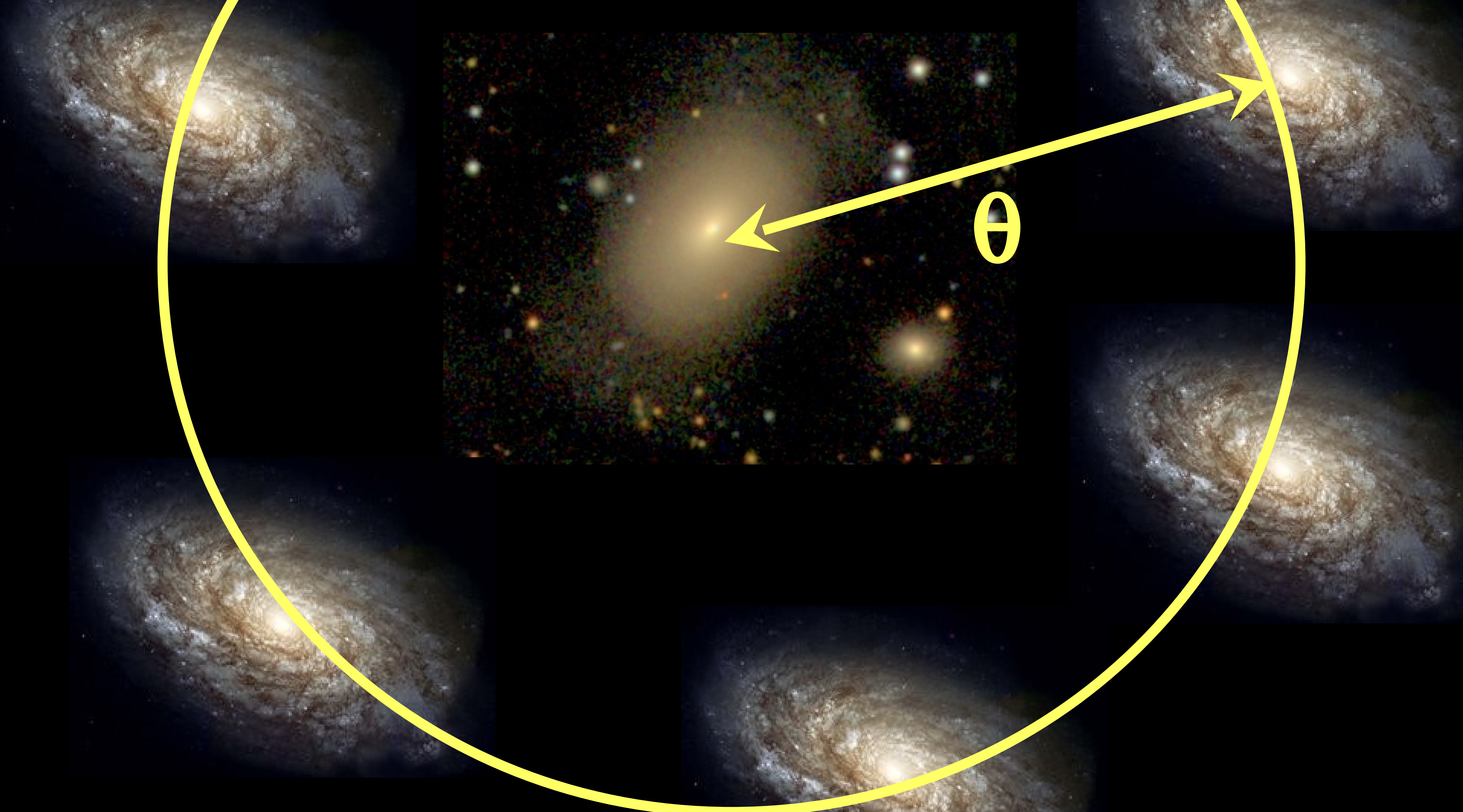


Cosmic shear two point tomography



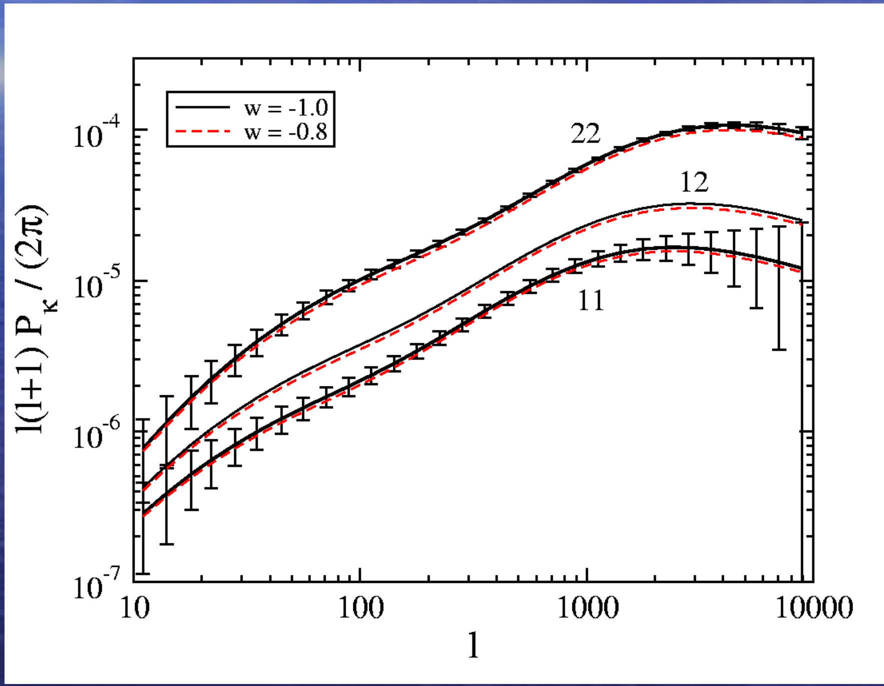
Cosmic shear two point tomography

$$\xi_\gamma = \langle \gamma(\mathbf{x})\gamma^*(\mathbf{x}+\theta)\rangle$$



Cosmic Shear & Weak Lensing Tomography

- Measure shapes for millions of source galaxies
- Shear-shear & galaxy-shear correlations probe distances & growth rate of perturbations
- Requirements: Sky area, depth, redshifts (usually photo-z's), image quality & stability



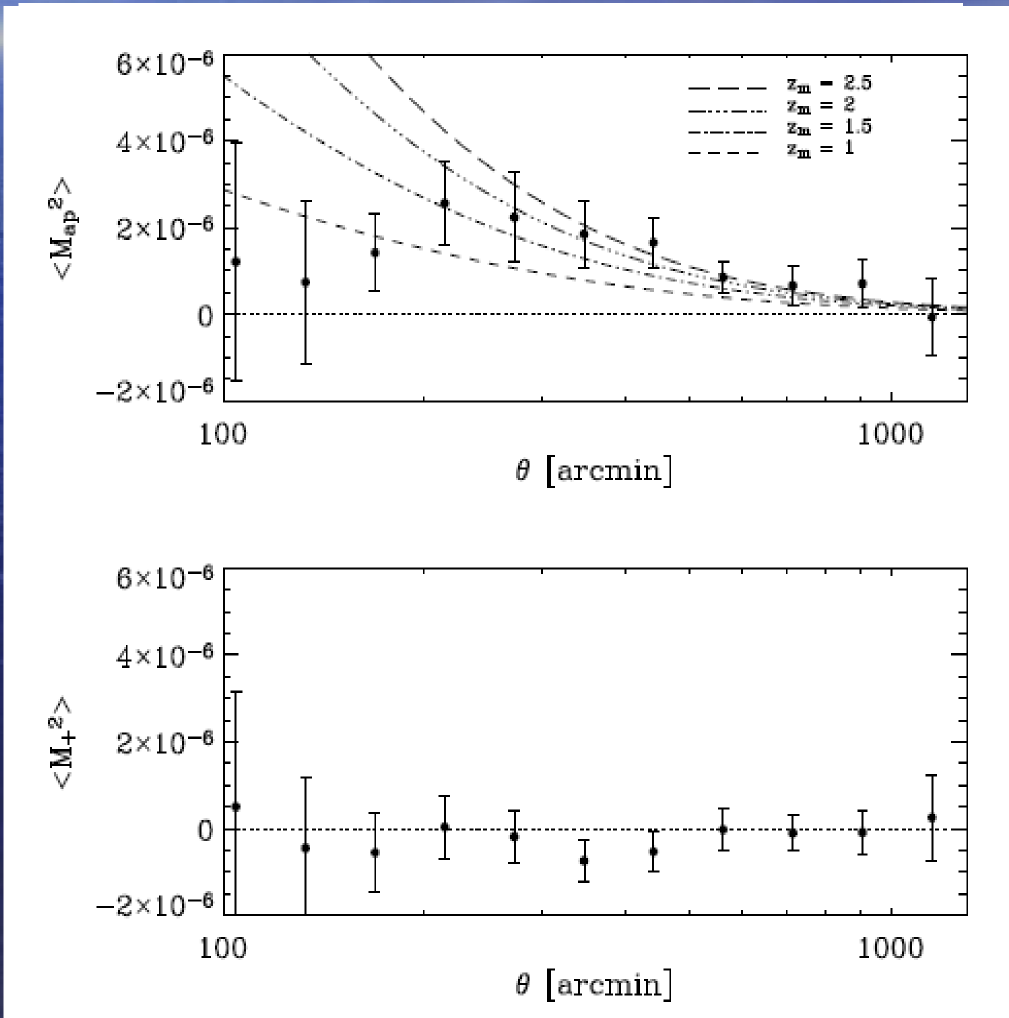
Huterer

$$C_\ell^{x_a x_b} = \int dz \frac{H(z)}{D_A^2(z)} W_a(z) W_b(z) P^{s_a s_b}(k = \ell / D_A; z)$$

$$\Delta C_\ell = \sqrt{\frac{2}{(2\ell + 1) f_{sky}}} \left(C_\ell + \frac{\sigma^2(\gamma_i)}{n_{eff}} \right)$$

Results with data available

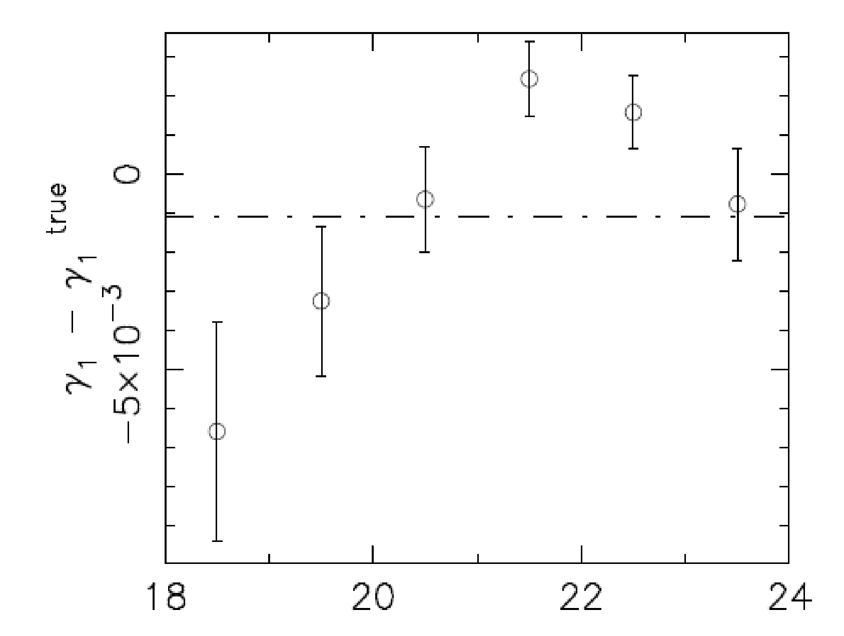
- Results from FIRST data indicate the presence of lensing but data is poor.
- Many systematic effects have to be taken into account
- Bandwidth smearing, lack of knowledge of
  - the redshift of sources
  - w effect
  - Hour-DEC smearing
  - source fragmentation
  - time averaging, etc…



Chang et al. 05

Optical vs radio calibration:

Deconvolution vs modelling of image effects, many steps have been taken in optical astronomy to understand the measurements of ellipticities, what is the effect of this in a radio counterpart? i.e. Cleaning vs a MeqTrees approach???



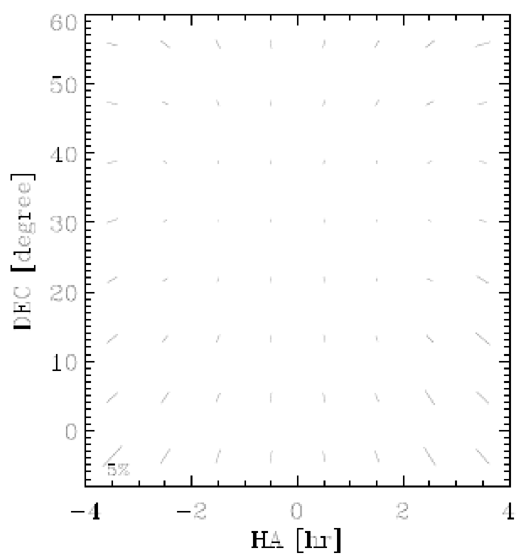


FIG. 3.— The artificial shear pattern induced by the HA-DEC effect. The length and direction of the plotted lines indicate the amplitude and orientation of the distortion, respectively. The line at the bottom-left indicates a distortion of 5%.

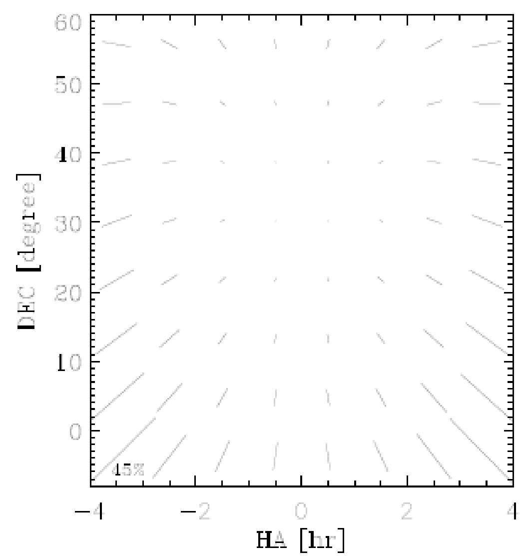
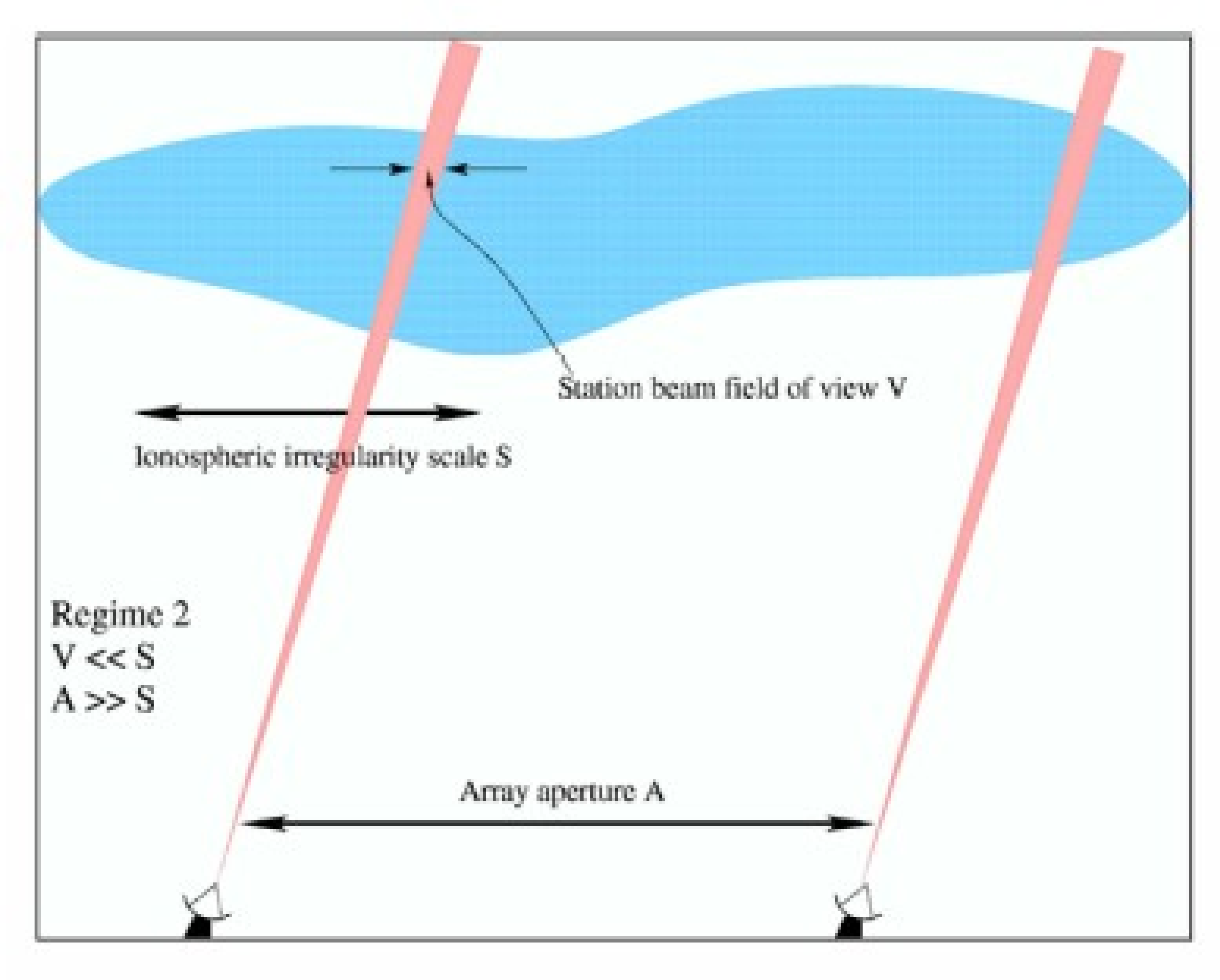


FIG. 4.— The artificial shear pattern induced by the non-coplanar effect, for the case of $(l, m) = (7', 7')$ away from the phase-tracking center. The line at the bottom-left indicates a distortion of 45%.

Further problems for radio telescopes



- Ionosphere can introduce defocusing and has to be calibrated. Worst for low frequencies

Other non-radio problems… Intrinsic alignements.

$$e^{o} = e^{i} + \gamma$$

$$\xi_e = \langle e^{o}(\mathbf{x}) e^{o*}(\mathbf{x} + \theta) \rangle$$

$$\langle e^{a}_{\rm obs} e^{b}_{\rm obs} \rangle = \langle e^{a}_{\rm s} e^{b}_{\rm s} \rangle + \langle \gamma^{a} e^{b}_{\rm s} \rangle + \langle \gamma^{b} e^{a}_{\rm s} \rangle + \langle \gamma^{a} \gamma^{b} \rangle$$

What we measure

Cosmic shear

Additional contributions

Effect on cosmic shear of changing w by 1%

Cosmic Shear

$$e^o = e^i + \gamma$$

$$\xi_e = \langle e^o(\mathbf{x}) e^{o*}(\mathbf{x}+\theta) \rangle$$

$$\langle e^a_{\rm obs} e^b_{\rm obs} \rangle = \langle e^a_{\rm s} e^b_{\rm s} \rangle + \langle \gamma^a e^b_{\rm s} \rangle + \langle \gamma^b e^a_{\rm s} \rangle + \langle \gamma^a \gamma^b \rangle$$

What we measure

Cosmic shear

Additional contributions

To remove these we need good photometric redshfits

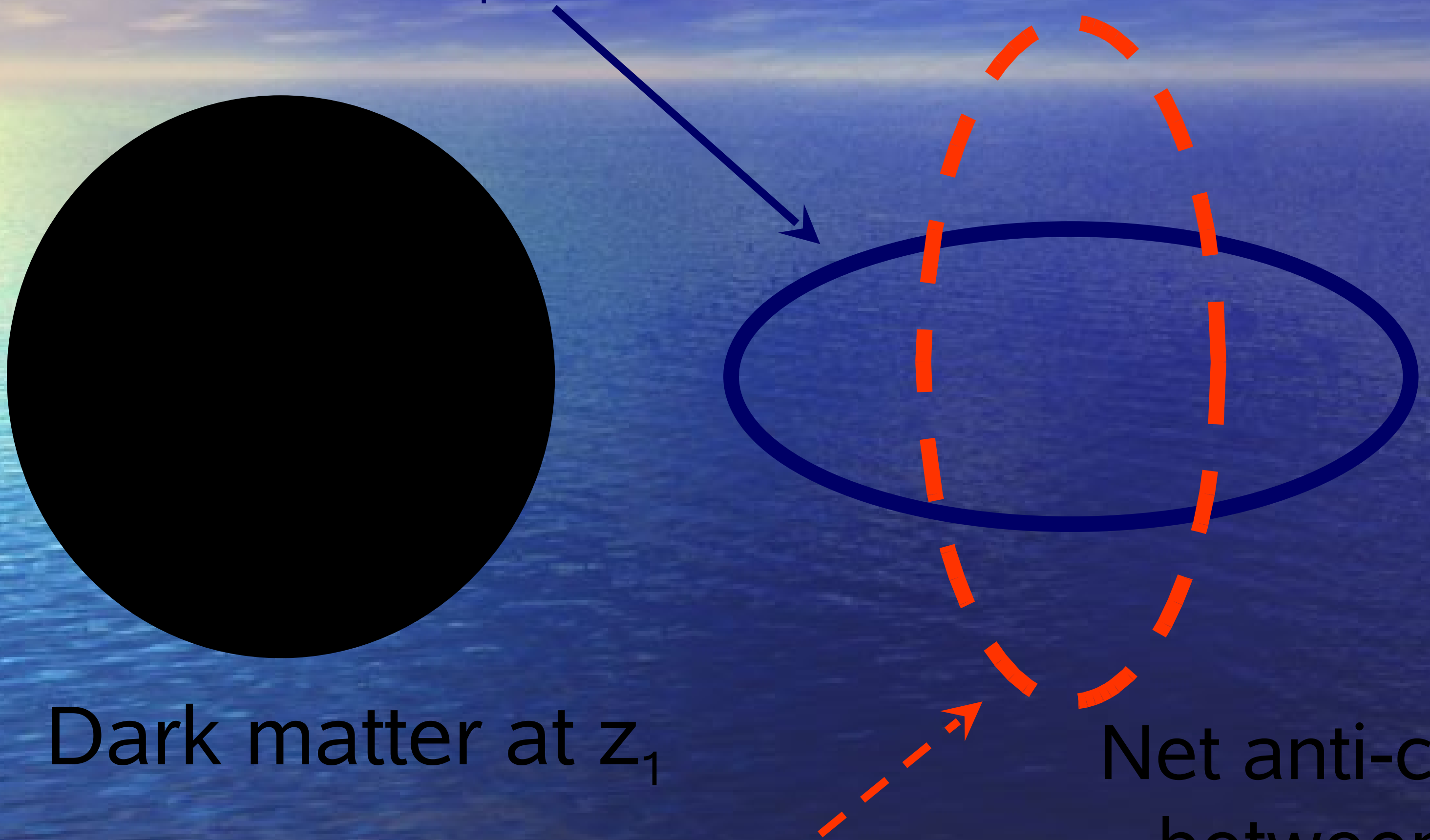
Intrinsic Alignments (IA)

Could bias w results by 100%

Normalised to Super-COSMOS
Heymans et al 2004

Intrinsic-shear correlation (GI)

Galaxy at z_1 is tidally sheared



Hirata & Seljak

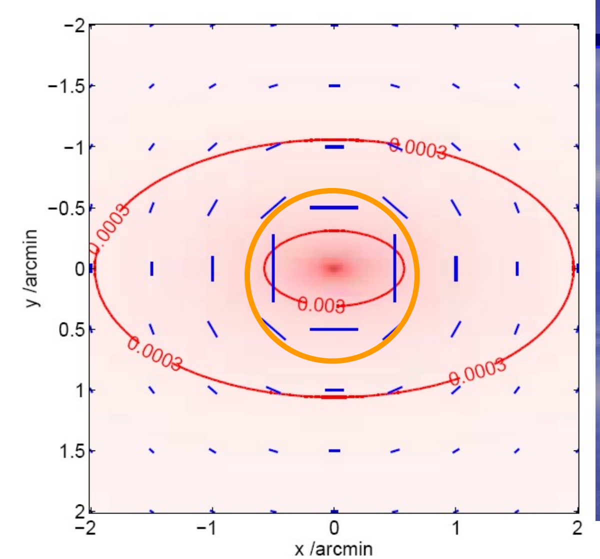
Dark matter at z_1

High z galaxy gravitationally sheared tangentially

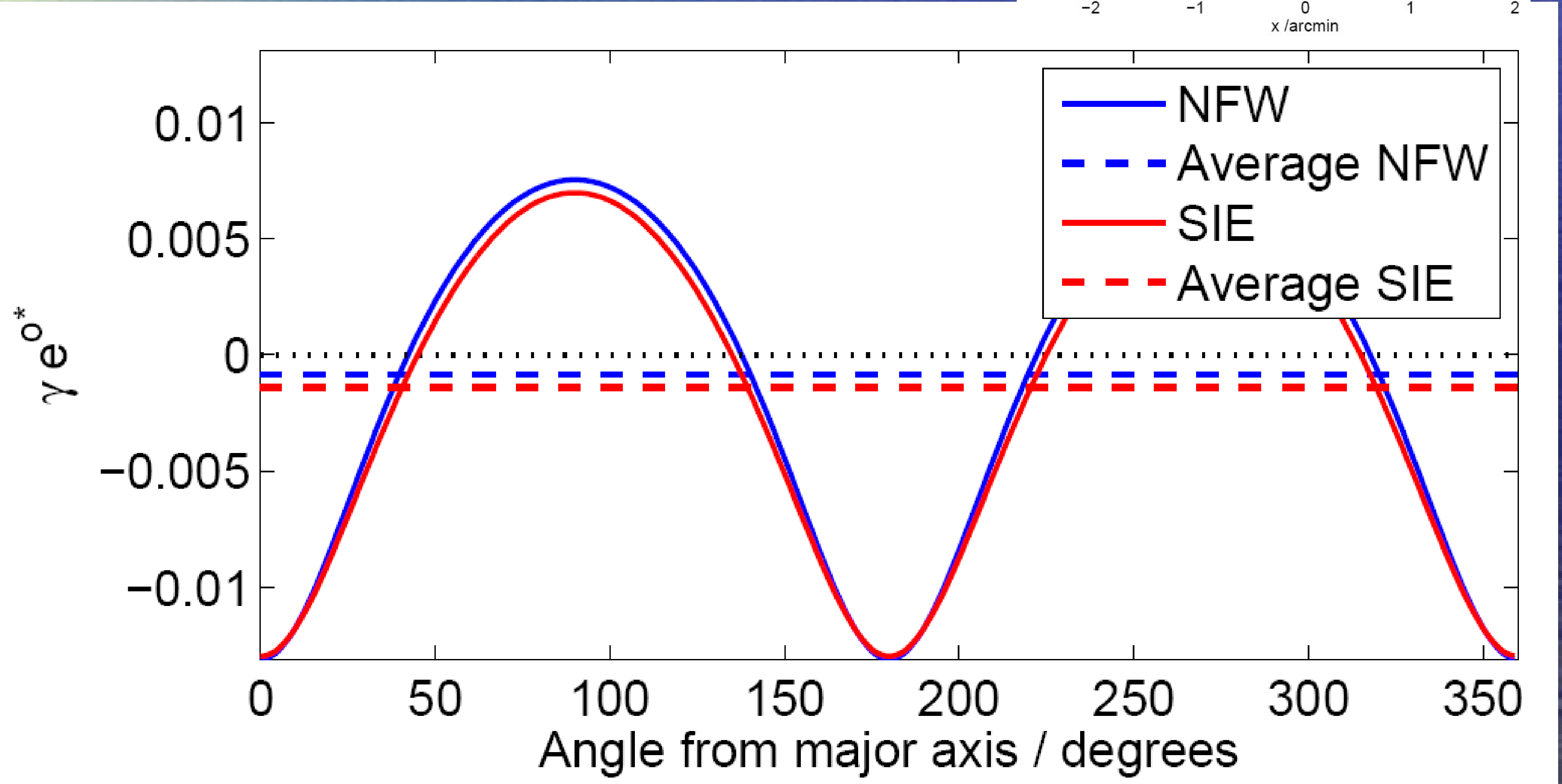
Net anti-correlation between galaxy ellipticities with no prefered scale

GI alignements:

$$\langle e^a_{\rm obs} e^b_{\rm obs}\rangle = \langle e^a_{\rm s} e^b_{\rm s}\rangle + \langle \gamma^a e^b_{\rm s}\rangle + \langle \gamma^b e^a_{\rm s}\rangle + \langle \gamma^a \gamma^b\rangle$$



Bridle & Abdalla



Removing intrinsic alignments:

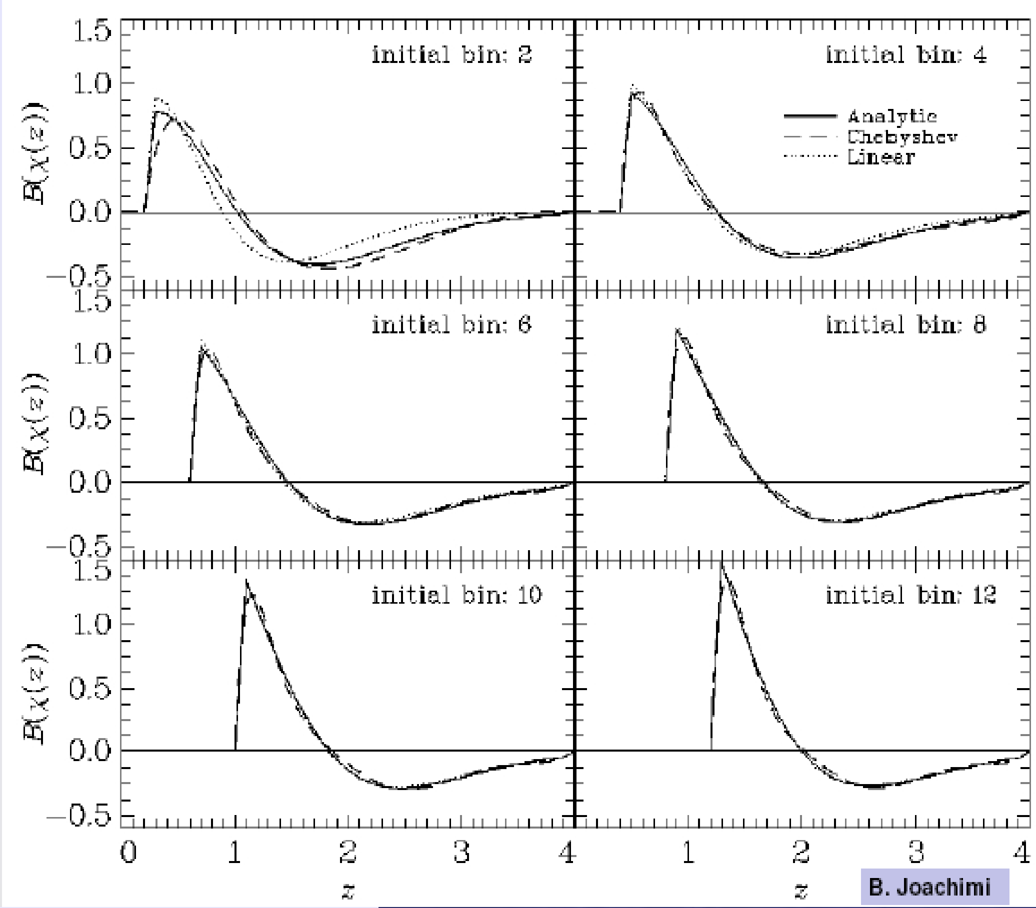
- Finding a weighting function insensitive of shape-shear correlations. (Schneider / Joachimi)

  - Is all the information still there?
- Modelling of the intrinsic effects (Bridle & King.)

  - FOM definitely will decreased as need to constrain other parameters in GI correlations.
- Using galaxy-shear correlation function.
- In any case there will be the need of a given photometric redshift accuracy for optical surveys, this is not a problem for radio surveys.

Nulling method

- Use maths of weak lensing to downweight all contributions where there are close dark matter clumps near the



projected surface mass density:

$$\kappa^{(i)}(\boldsymbol{\theta}) = \int_0^{\chi_{\rm hor}} \mathrm{d}\chi\, p^{(i)}(\chi)\, \kappa(\boldsymbol{\theta},\chi) = \frac{3H_0^2\Omega_{\rm m}}{2c^2} \int_0^{\chi_{\rm hor}} \mathrm{d}\chi\, \frac{g^{(i)}(\chi)\,\chi}{a(\chi)}\, \delta\left(\chi\,\boldsymbol{\theta},\chi\right)$$

$$\text{with}\quad g^{(i)}(\chi) = \int_\chi^{\chi_{\rm hor}} \mathrm{d}\chi' p^{(i)}(\chi') \left(1 - \frac{\chi}{\chi'}\right)$$ flat universe

replace distance distribution $p^{(i)}(\chi)$ by new weight function $B^{(i)}(\chi)$

No contributions from matter at $\hat{\chi}_i$ if the constraint $g^{(i)}(\hat{\chi}_i) = \int_{\hat{\chi}_i}^{\chi_{\rm hor}} \mathrm{d}\chi\, B^{(i)}(\chi) \left(1 - \frac{\hat{\chi}_i}{\chi}\right) = 0$ is fulfilled

Intrinsic-shear correlation (GI) and the galaxy-shear correlation

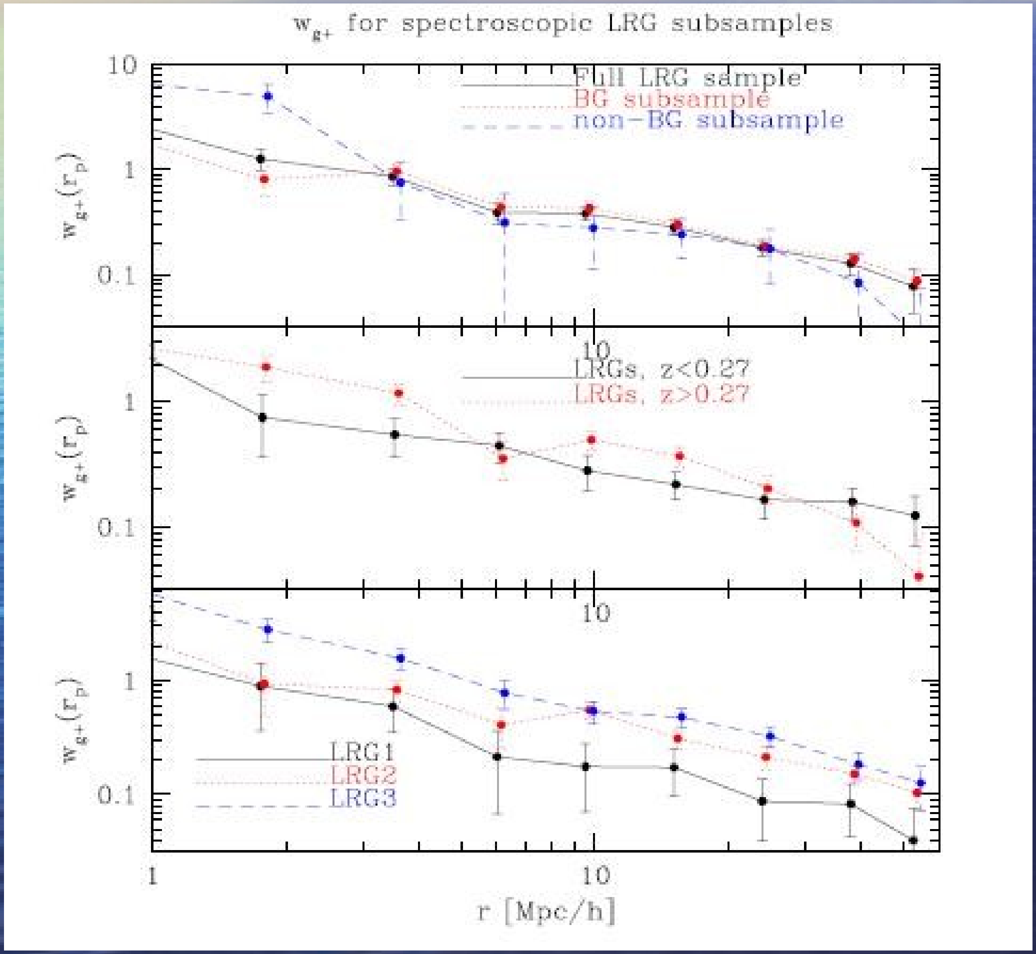
Galaxy at z_1 is tidally sheared

Dark matter at z_1

High z galaxy gravitationally sheared tangentially

With position shear correlation one can know how much alignement there is

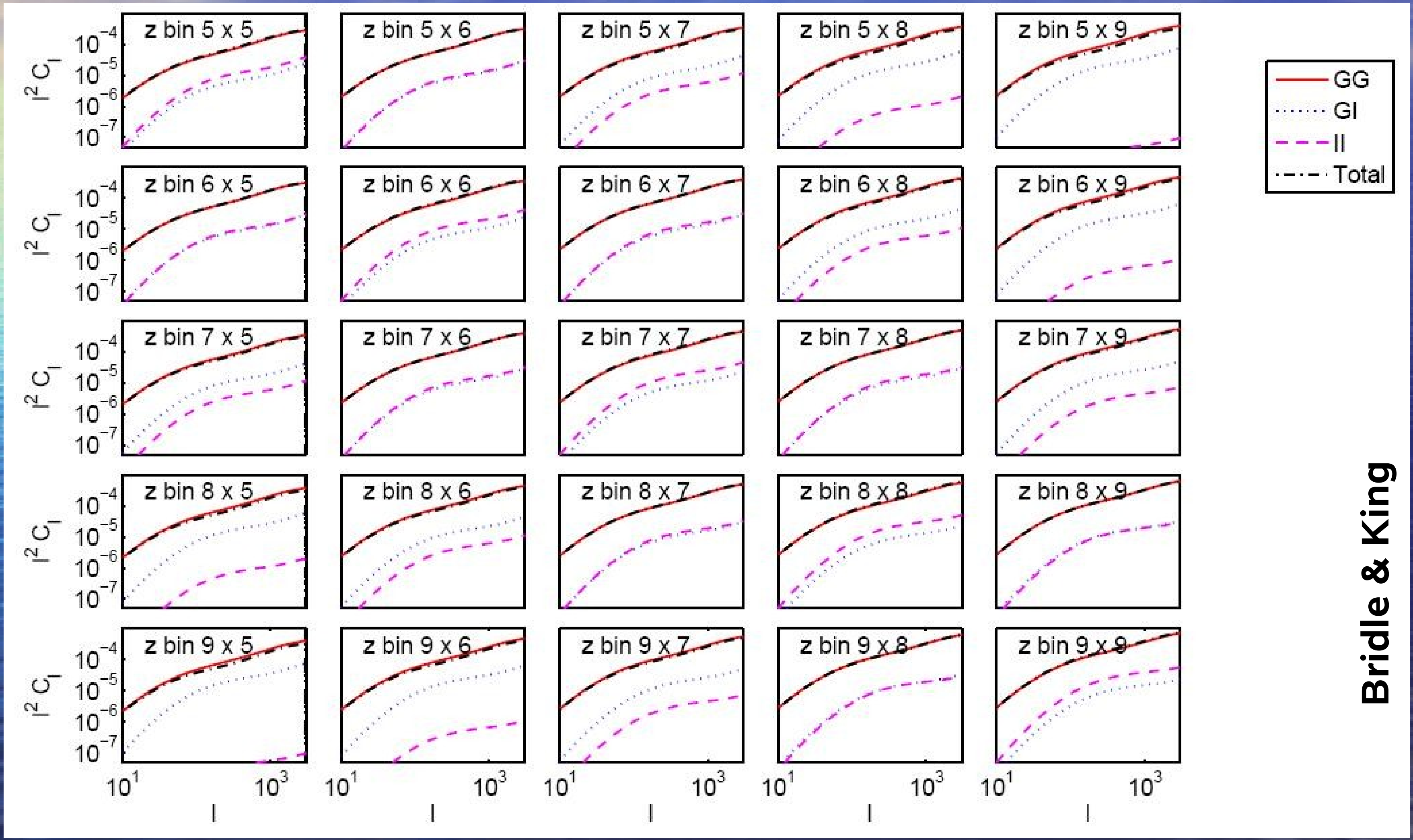
Measurements of intrinsic alignments using spectroscopic redsfhits:



Mandelbaum et al. 05

- Can measure intrinsic alignments with shear-position correlation function.
- Currently: 13000 2SLAQ gals
- Probe z evolution

Modelling method:

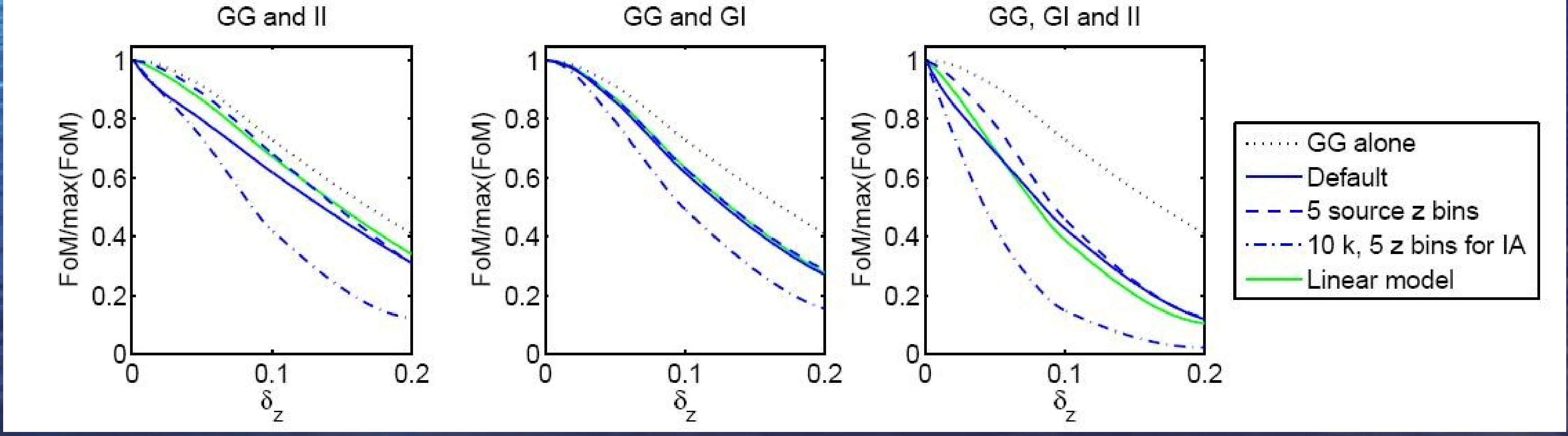


Modelling method -> Usual optical astronomer question: Are photo-zs good enough?

Survey – σ_{68}	$0 < z < 1.5$	$1.5 < z < 3$	$0 < z < 3$
Des	0.346	0.559	0.412
$Des + IR$	0.147	0.175	0.155
Pan	0.327	0.548	0.391
$Pan + IR$	0.128	0.166	0.139
$LSST$	0.167	0.276	0.196
$LSST + IR$	0.085	0.119	0.094
$Ideal$	0.122	0.173	0.136
$Ideal + IR$	0.047	0.075	0.054
$Ideal + u$	0.052	0.122	0.067
$Ideal + u + IR$	0.036	0.063	0.043

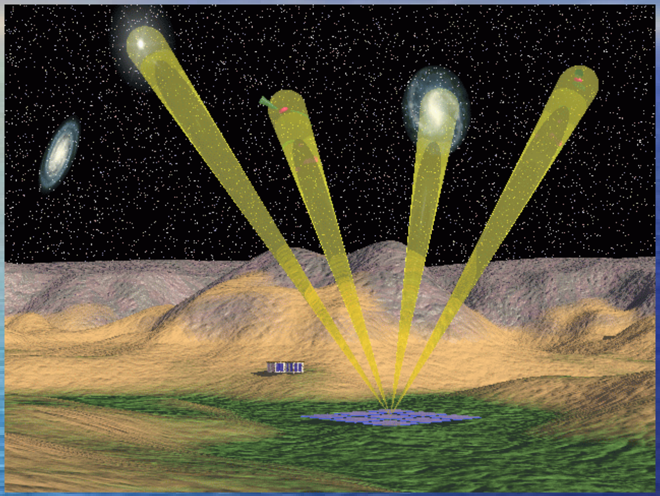
- The FOM is a slow function of the photo-z quality if we consider only the shear-shear term.
- If we consider modelling the shape-shear correlations this is not the case anymore.
- This does not include the galaxy-shear correlation function so “reality” is most likely in between this “pessimistic” result and the optimistic result of neglecting GI

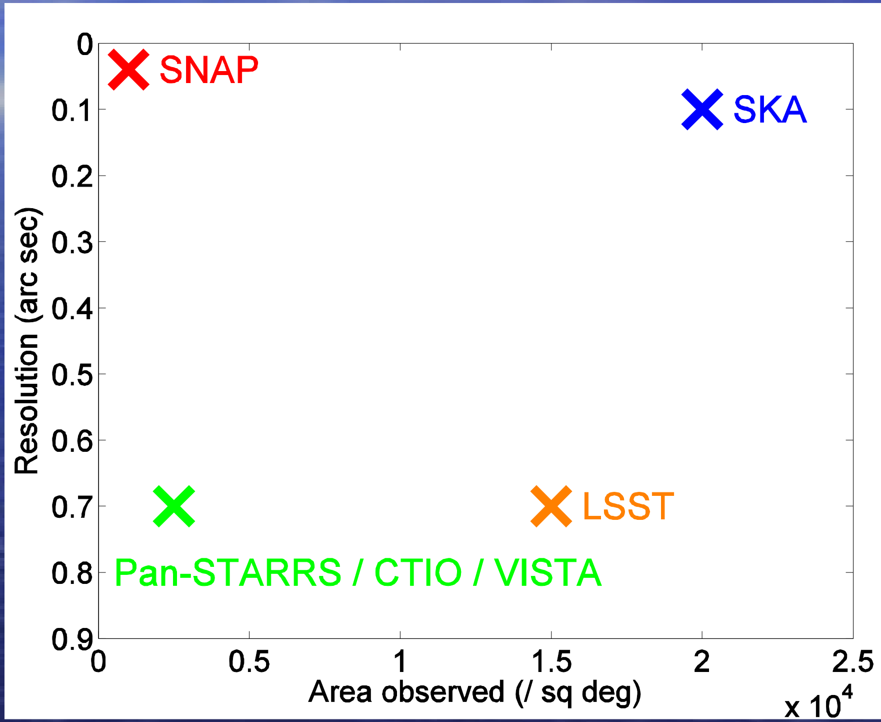
Abdalla, Amara, Capak
Cypriano, Lahav & Rhodes



Bridle & King

Radio route to weak lensing:





Blake, Abdalla, Bridle, Rawlings 04

- PSF known. Just question of modelling it!!!
- Redshifts are spectroscopic
- Given spectroscopy: Intrinsic alignments easier to remove, smaller systematic effect.
- But: is it feasible in practice.

Requires: (i) good image quality and low systematics for measuring shear; (ii) source density (iii) wide-field to beat down cosmic variance (particularly away from strongly non-linear scales); (iv) lensing tomography.

Conclusions:

- The SKA can bring us a whealth of new science in cosmology

  - Measurement of dark energy parameters

  - Measurement of neutrino parameters up to the limits currently allowed

  - Mapping of the dark matter distribution via weak lensing with reduced systematic effects compared to optical astronomy
- However, lots of challenges:

  - To what extent is the science doable by different designs?

  - To what extent are current extrapolations of number counts correct?

  - How small will be the systematics on BAO and wl once real issues are folded?
- Look forward to pathfinders in the next years