Cross-correlations of CMB lensing as tools for cosmology and astrophysics

Alberto Vallinotto
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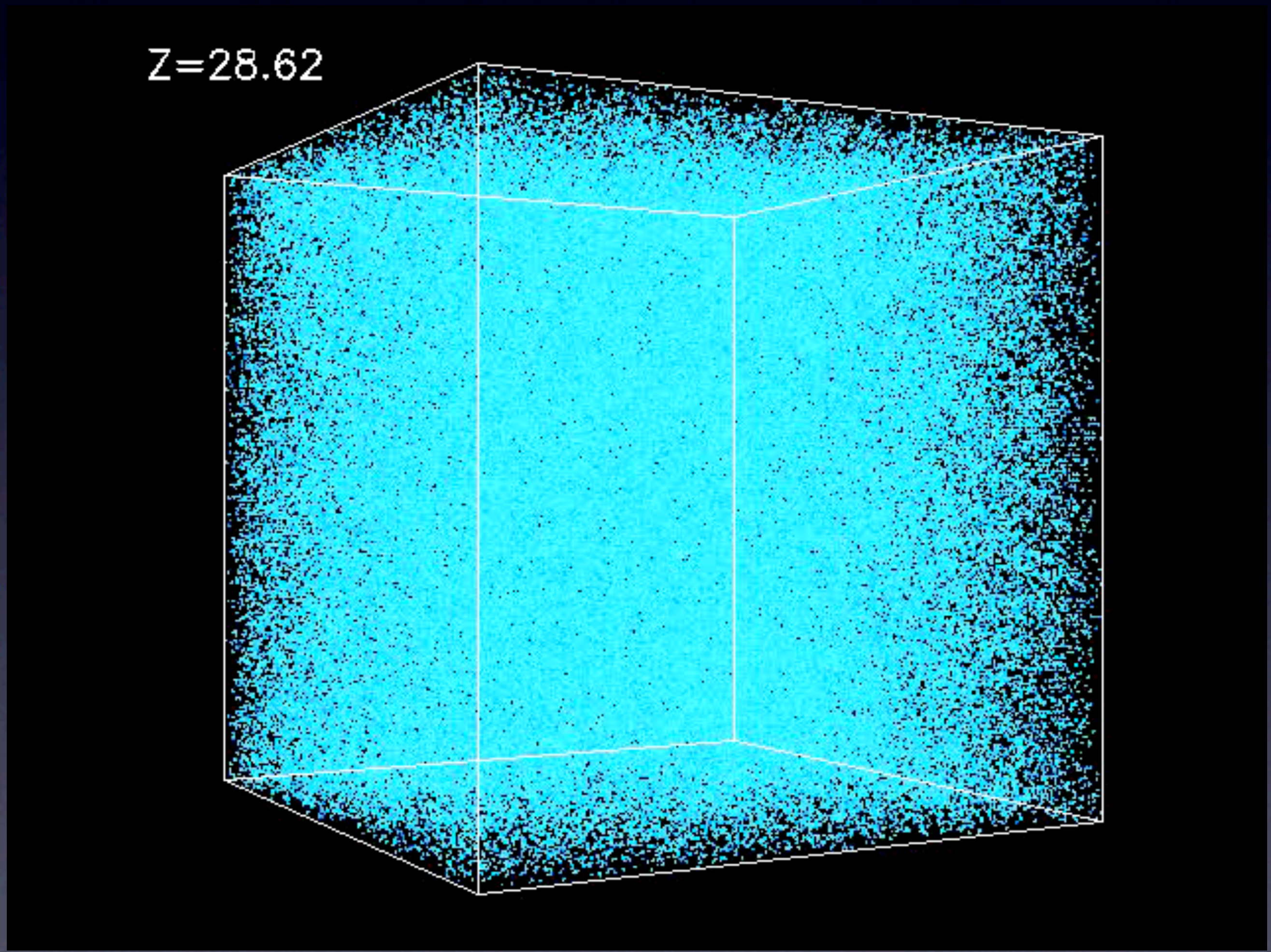
Dark matter, large scales

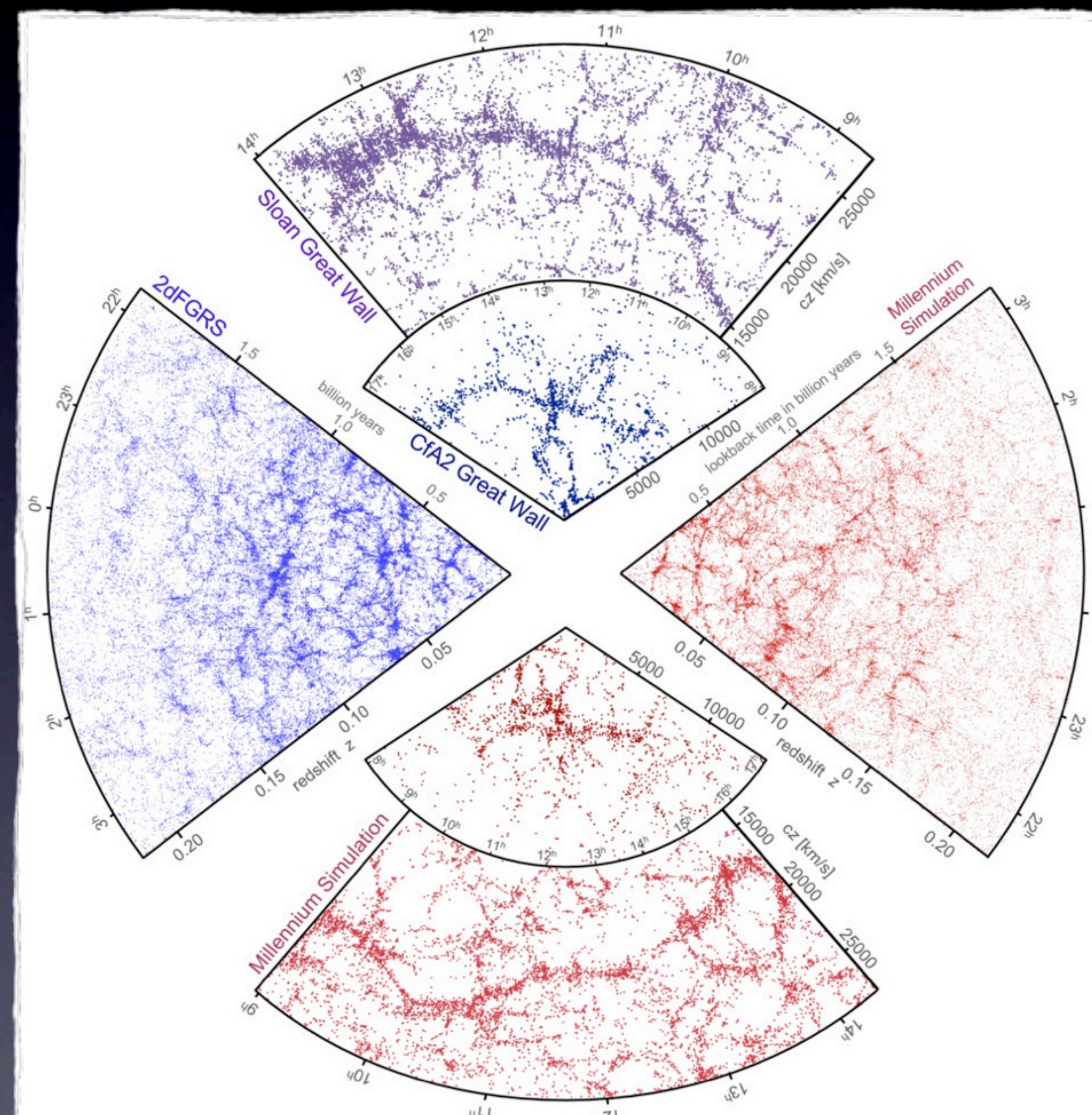
- Structure forms through gravitational collapse...
- ... starting from initial conditions consistent with CMB.



[Kravtsov, 2005]

Dark matter, large scales

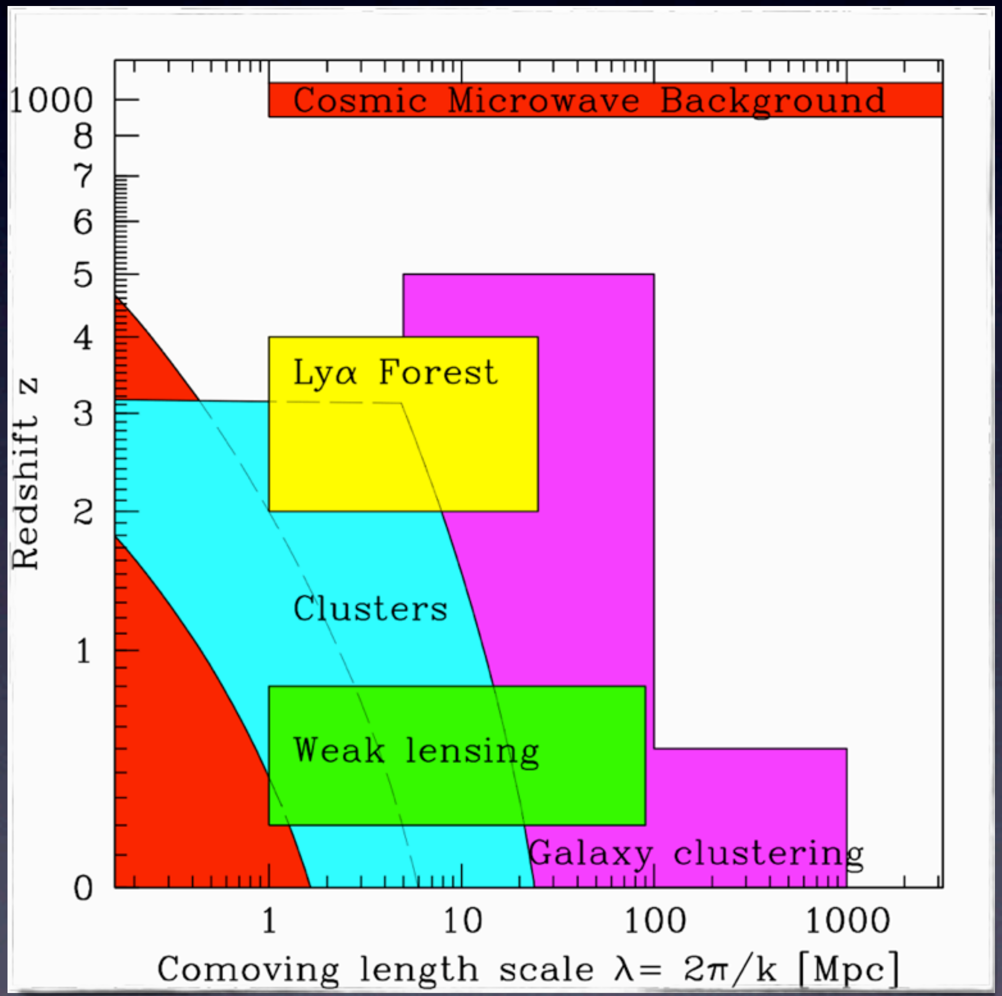
- Structure forms through gravitational collapse...
- ... starting from initial conditions consistent with CMB.
- Simulations results are consistent with observational evidence from LSS surveys on large scales.
- We look at the universe through an inhomogeneous medium.



[Springel et al., 2005]

Dark matter, large scales

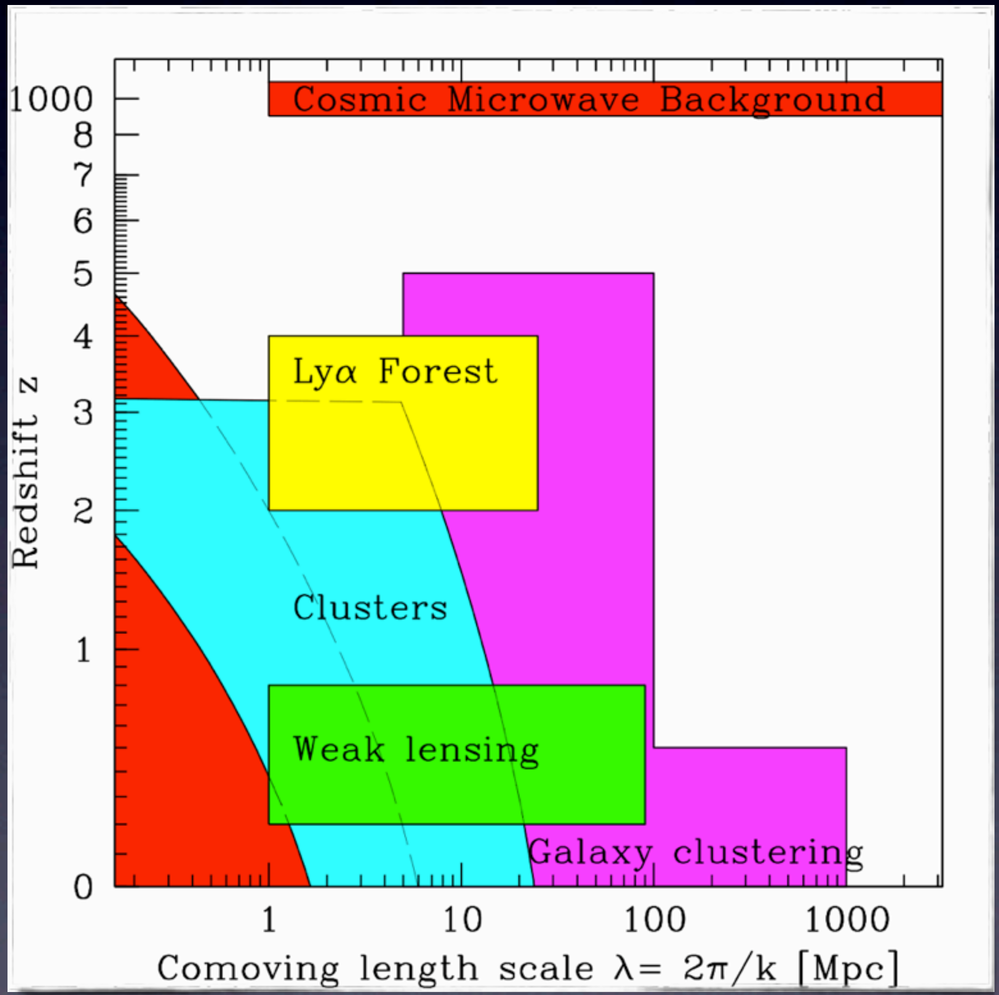
- Being dark, we cannot "see" DM.
- Two ways to probe its distribution in the universe:
  - Using "tracers": intuitively, overdensities in the DM field should be matched by overdensities in other "visible" stuff
    - Galaxies, quasars and clusters
    - Neutral Hydrogen (Lyman-α, 21cm)
    - CMB temperature
  - Measuring the distorsion of images by the DM grav. field.
- Different tracers allow to probe the DM field on different scales.
- Different tracers are "biased" in different ways.



[Tegmark, 2002]

CMB lensing correlations in brief

- The CMB convergence field depends only on the distribution of dark matter integrated along the los, all the way to the last scattering surface.
- The good: CMB convergence field is the cleanest probe of the dark matter density field.



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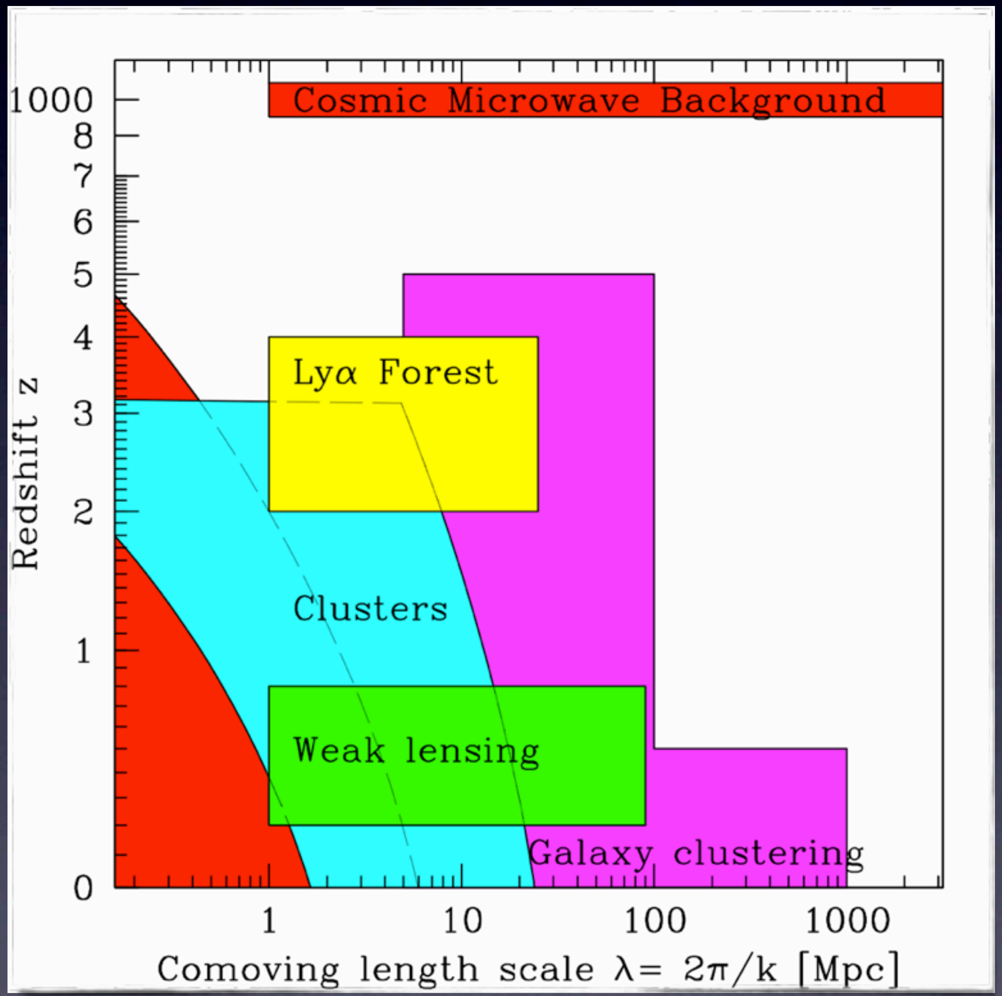

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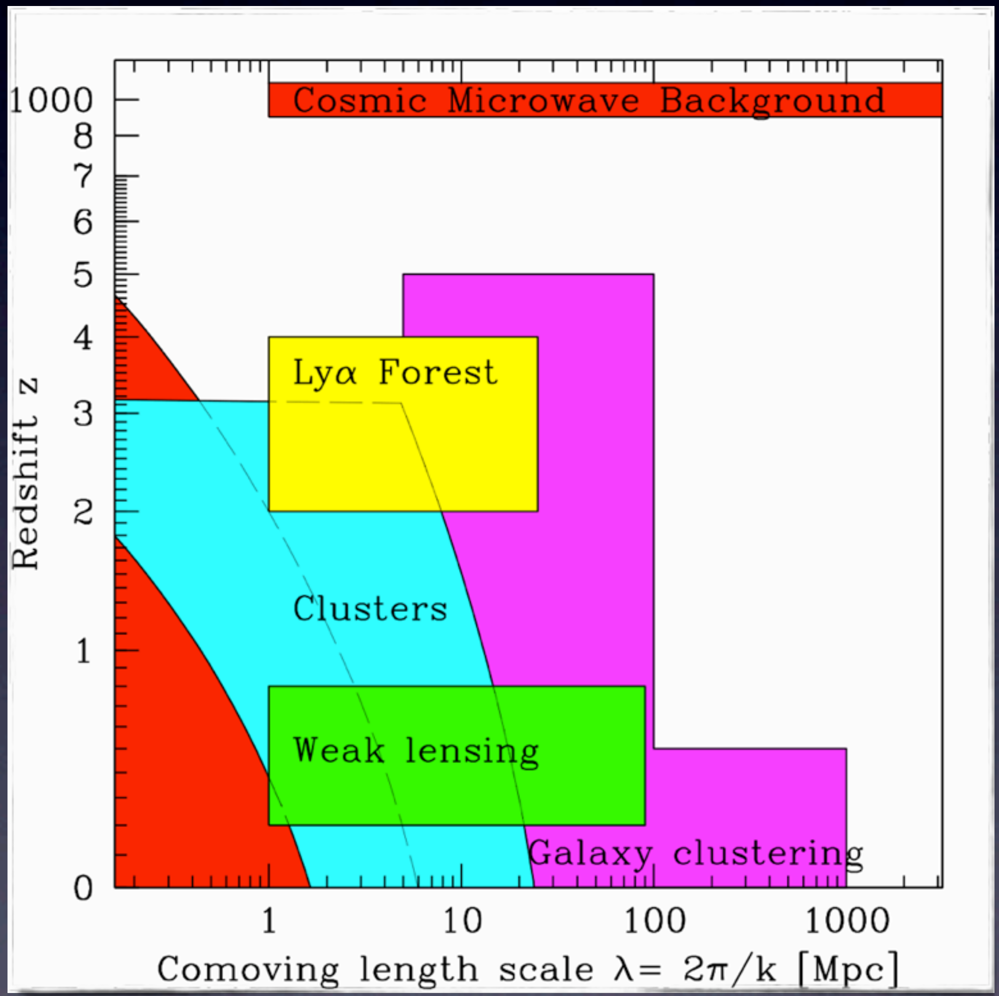
- The bad: CMB convergence field is an integrated measure of the density field along the los.
- The ugly: high resolution CMB experiments are required to measure it.



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CMB lensing correlations in brief

- Cross-correlations of CMB lensing with other tracers of the density field allows to extract two kinds of informations:
  - Astrophysical information: since we're directly correlating a biased tracer with what it is supposed to trace, we can put constraints on the biasing relation.
  - Cosmological information: since both observables are sensitive to cosmological parameters.
- Applications: Lyman-α forest and 21-cm emission from neutral hydrogen...

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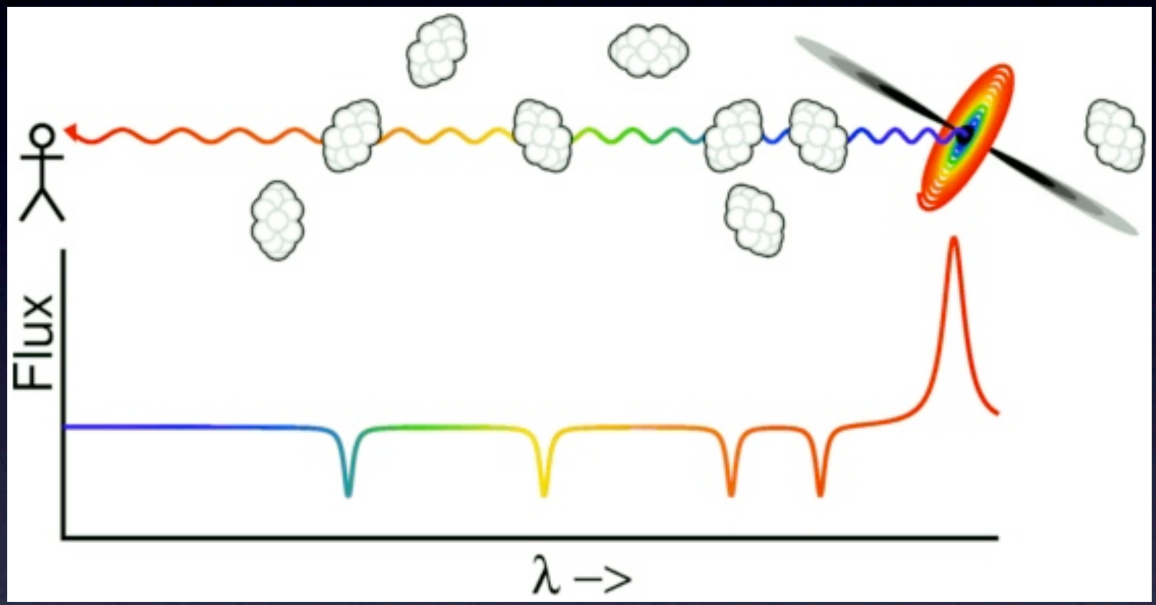
- Applications: Lyman-α forest and 21-cm emission from neutral hydrogen... from a theorist point of view!

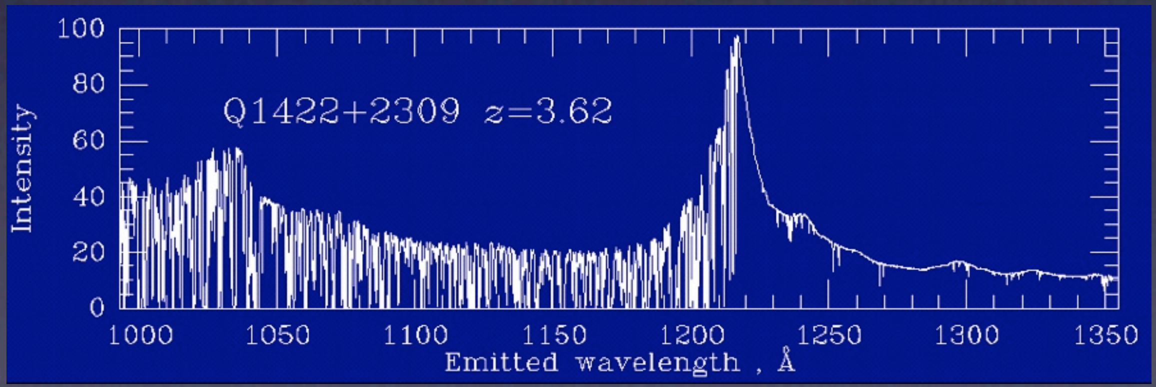
Cross-correlation of CMB lensing and the Lyman-α forest

Lyman-α forest and CMB lensing cross-correlation

- Quasar emits light which, as it travels through the universe, is redshifted.
- Whenever light travels through a gas cloud, a fraction of it (that at the cloud's redshift has the appropriate frequency) is scattered through Lyman-α transition in neutral hydrogen.



- The quasar spectra is then characterized by a "forest" of "absorption" lines.
- The forest is a map of neutral H along the los.
- Understanding the forest requires understanding and modeling the physics of the IGM.



- Fluctuations in the flux are related to overdensities

$$\mathcal{F} = \exp\left[-A(1+\delta)^{\beta}\right]$$

- On large scales (> 1 Mpc) the Lyman-α forest can be used as a dark matter tracer [Viel et al. 2001]

$$\delta_{\mathrm{IGM}} \approx \delta$$

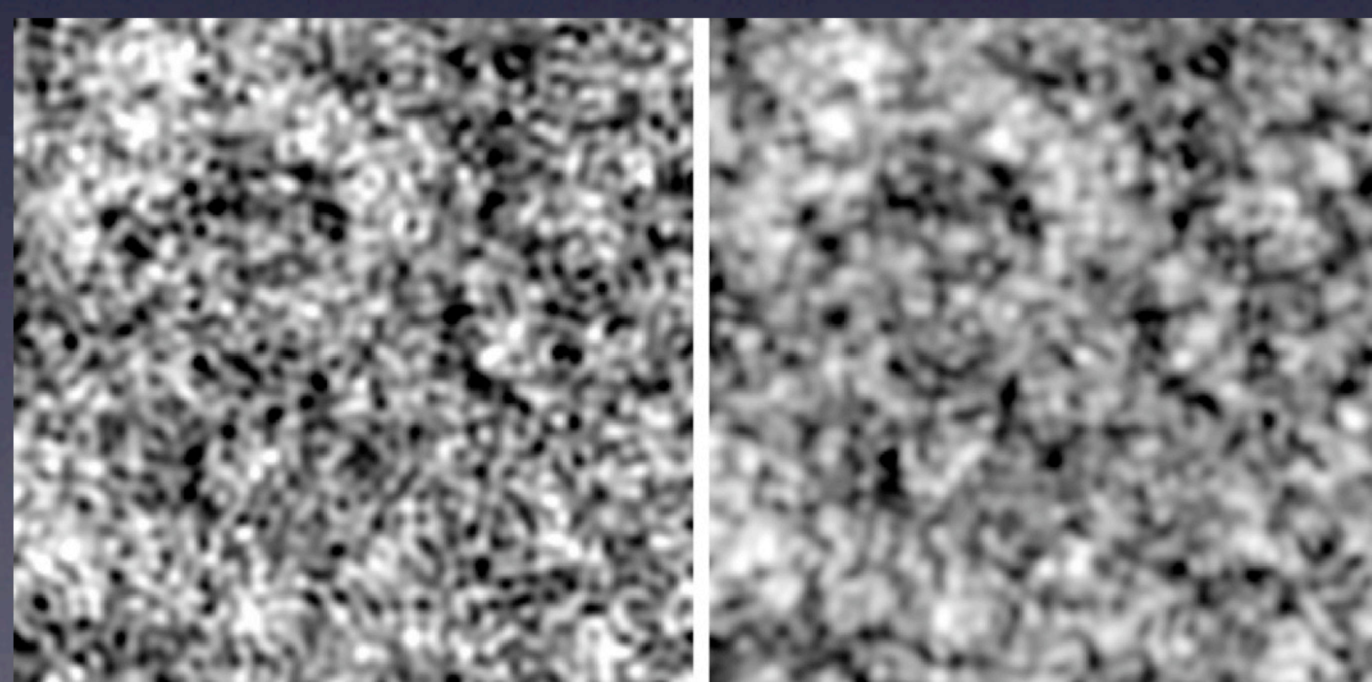
$$\delta\mathcal{F}^r(\vec{n}) = \int_{\chi_i}^{\chi_Q} d\chi\, \delta\mathcal{F}^r(\vec{n},\chi) \approx \int_{\chi_i}^{\chi_Q} d\chi\, (-A\beta)^r\, \delta^r(\vec{n},\chi)$$

- The flux-matter relation has many sources of uncertainty.

Lyman-α forest and CMB lensing cross-correlation

- Weak lensing depends to the distribution of matter between the observer and the source.
- Quadratic optimal estimators allow the reconstruction of the CMB lensing convergence field [Hu and Okamoto (2000), Hirata and Seljak (2003)].

$$\kappa(\hat{n}, \chi_F) = \frac{3H_0^2\Omega_m}{2c^2} \int_0^{\chi_F} d\chi \, W_L(\chi, \chi_F) \frac{\delta(\hat{n}, \chi)}{a(\chi)}$$



Original vs reconstructed deflection field [Hirata and Seljak, 2003]

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It is "just" a matter of evaluating a couple of integrals...

$$\langle \delta\mathcal{F}^r(\hat{n})\kappa(\hat{n}) \rangle \quad = \frac{3H_0^2\Omega_m}{2c^2}\int_0^{\chi_F} d\chi_c \frac{W_L(\chi_c,\chi_F)}{a(\chi_c)} \int_{\chi_i}^{\chi_Q} d\chi_q \, (-A\beta)^r \, \langle \delta^r(\hat{n},\chi_q)\, \delta(\hat{n},\chi_c) \rangle$$

“Just” a couple of integrals...

- Things become complicated when we take into account the finite resolution of the observational programs.
- The nature of the observables naturally breaks the spherical symmetry of the problem.

$$W_\alpha = \exp\left[-\frac{k_\parallel^2}{k_L^2}\right]$$

$$W_\kappa = \exp\left[-\frac{\vec{k}_\perp^2}{k_C^2}\right]$$

Cutoff scales

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- Things become complicated when we take into account the finite resolution of the observational programs.

- The nature of the observables naturally breaks the spherical symmetry of the problem.

- A clever series solution yielding an efficient numerical computation scheme can actually be found for both the correlators and their variance.

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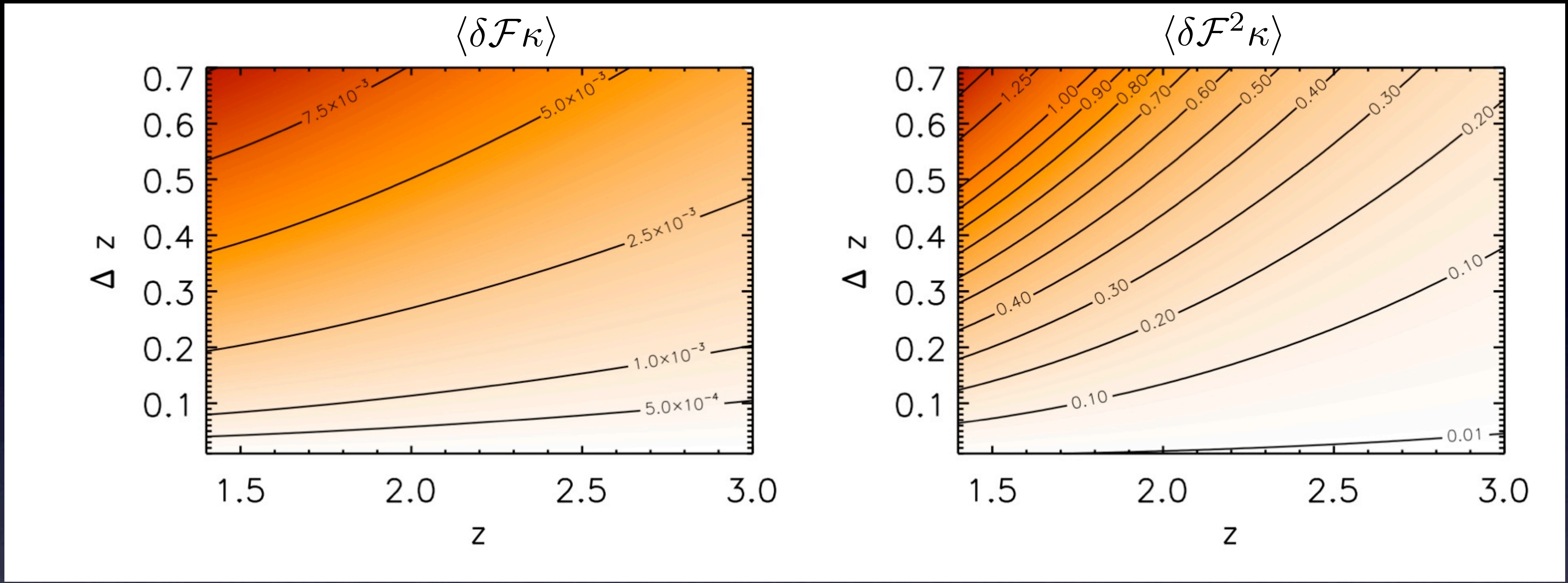
Cutoff scales

Results: correlators (BOSS+Planck)



[AV, Das, Spergel, Viel, 2009]

- Turn off IGM physics (A=β=1)
- $k_L = 4.8\, h\,\mathrm{Mpc}^{-1}$ (SDSS-III), $k_C = 0.021\, h\,\mathrm{Mpc}^{-1}$ (Planck)
- Signal decreases with increasing z: probing less collapsed regions
- Signal for $\langle \delta\mathcal{F}\kappa \rangle$ is smaller than the one for $\langle \delta\mathcal{F}^2\kappa \rangle$.

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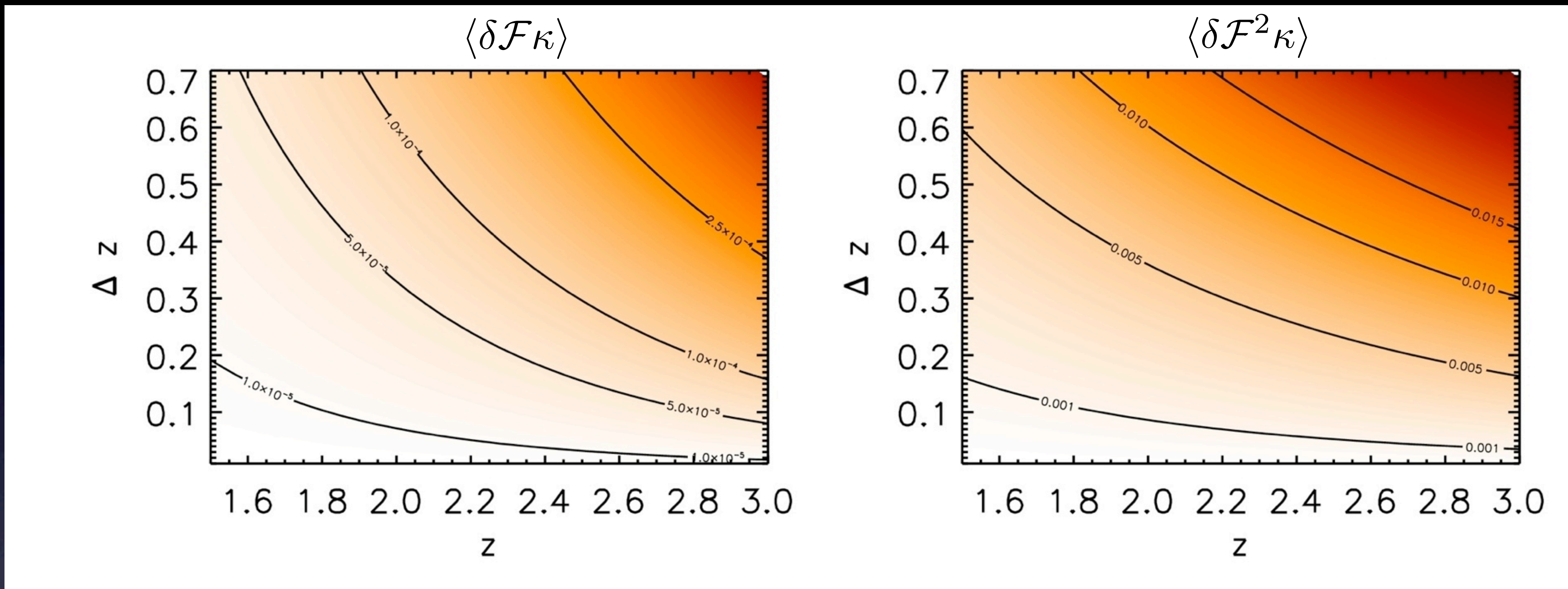

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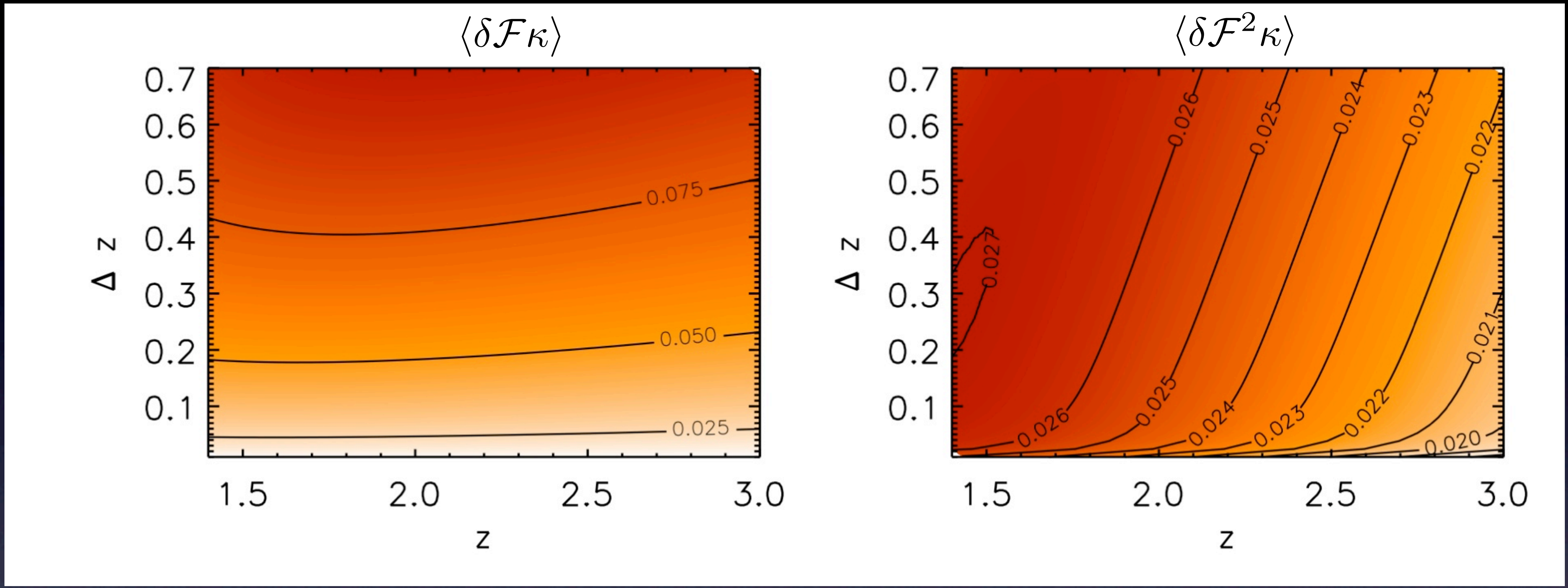
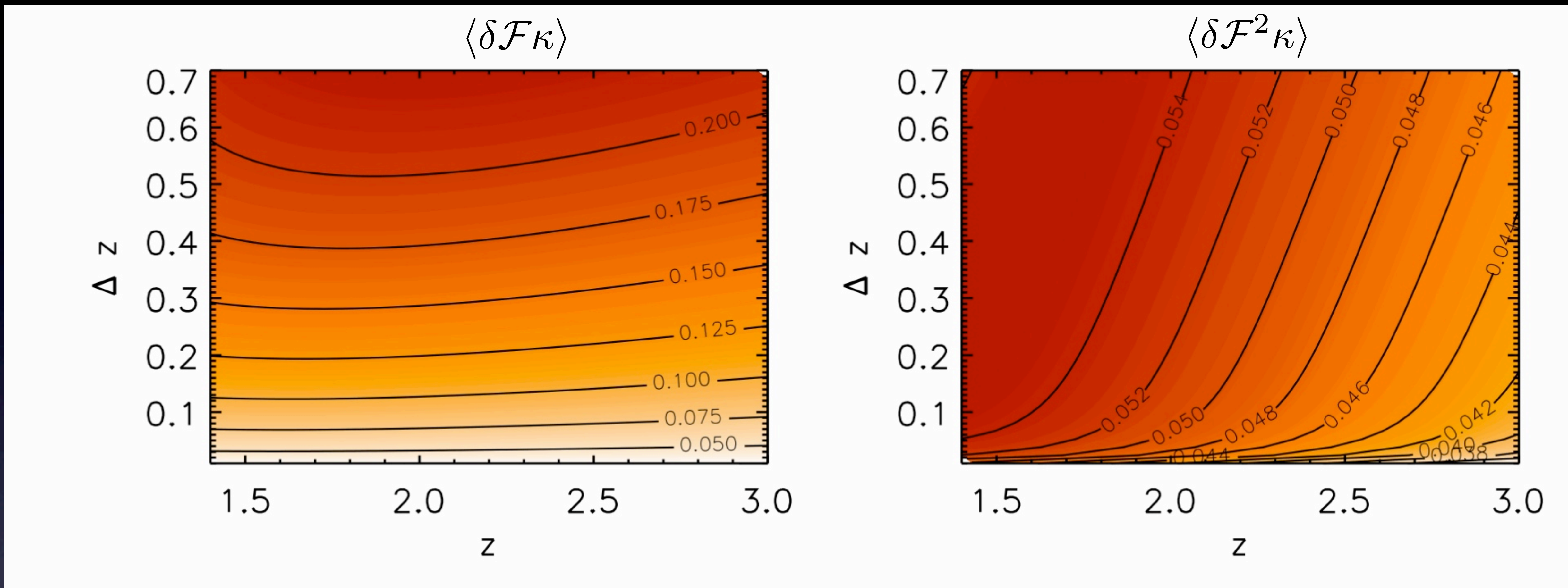
Results: detectability (BOSS+Planck)



[AV, Das, Spergel, Viel, 2009]

- S/N for single line-of-sight. $1.6 \cdot 10^5$ los for Boss, ~10^6 los for BigBoss.
- Estimates for total S/N are ~30 (75) for $\langle \delta \mathcal{F} \kappa \rangle$ and ~9.6 (24) for $\langle \delta \mathcal{F}^2 \kappa \rangle$ when Planck dataset is xcorrelated with Boss (BigBoss).
- The growth of structure enters twice for $\langle \delta \mathcal{F}^2 \kappa \rangle$: once for the long-wavelengths and once for the short wavelengths. The variance is dominated by long wavelengths only.

Results: detectability (BOSS+*ActPol*)



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- S/N for single line-of-sight. $1.6 \cdot 10^5$ los for Boss, ~10^6 los for BigBoss.
- Estimates for total S/N are ~50 (130) for $\langle \delta \mathcal{F} \kappa \rangle$ and ~20 (50) for $\langle \delta \mathcal{F}^2 \kappa \rangle$ when ActPol dataset is xcorrelated with Boss (BigBoss).
- S/N does not depend on the redshift evolution of A and β.

Caveats

- Numerical results currently do not take into account non-linear effects due to gravitational collapse
  - Extension is straightforward
  - Signal is expected to increase, S/N is hard to say.
- All results do not take into account small scales (<1 Mpc) IGM physics and use "gaussian approximation" to evaluate the correlators' variance

Cosmological application: neutrino masses

$\langle \delta \mathcal{F}^2 \kappa \rangle$ is sensitive to intermediate to small scales and to the power spectrum normalization σ_8.

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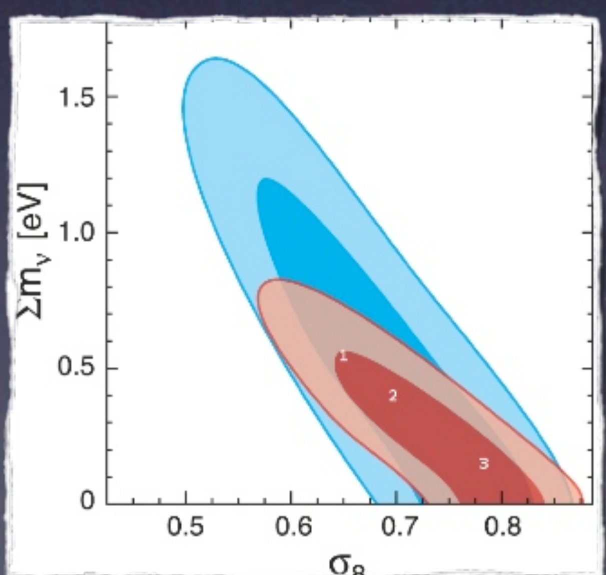

[Komatsu et al., 2008]

$\sum m_\nu$ and σ_8 are not independent if they are to be consistent with CMB measurements.

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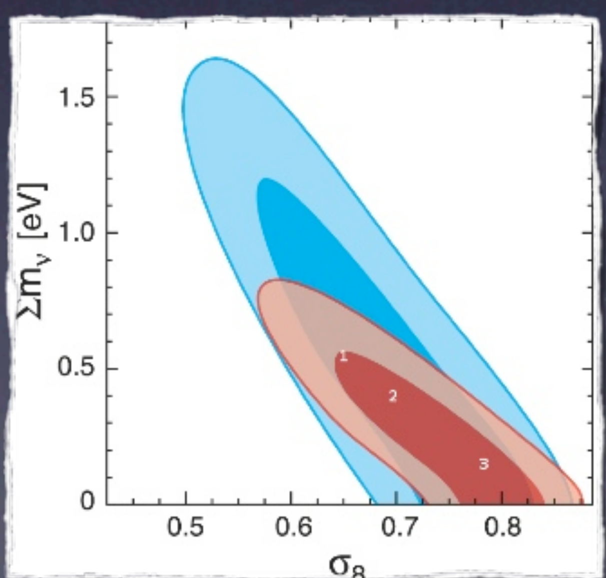
We can use $\langle \delta \mathcal{F}^2 \kappa \rangle$ to put limits on the neutrino mass



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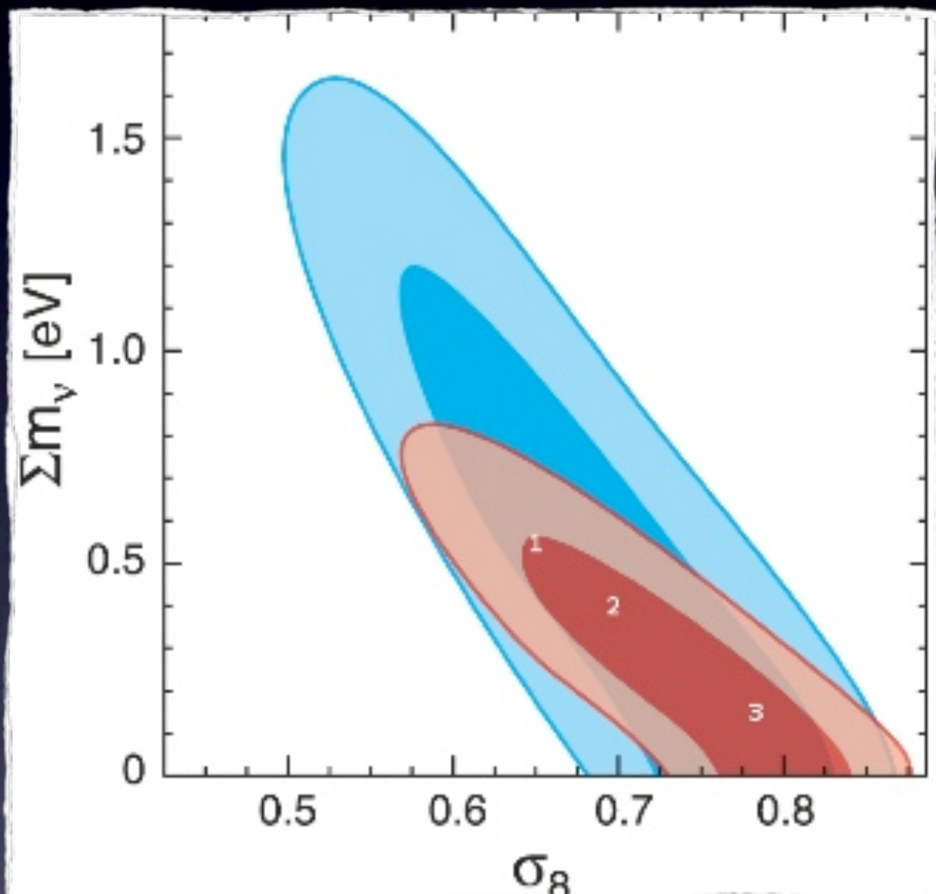

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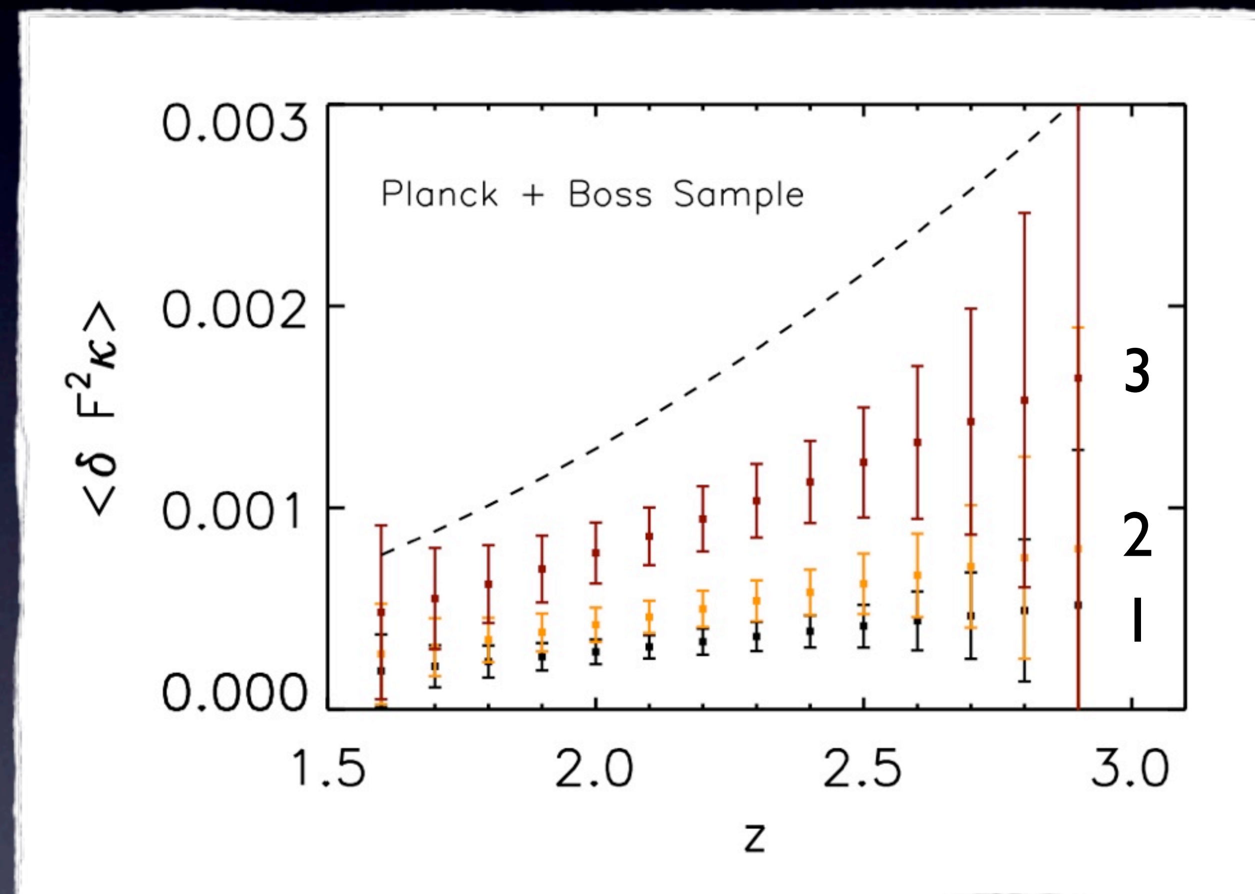

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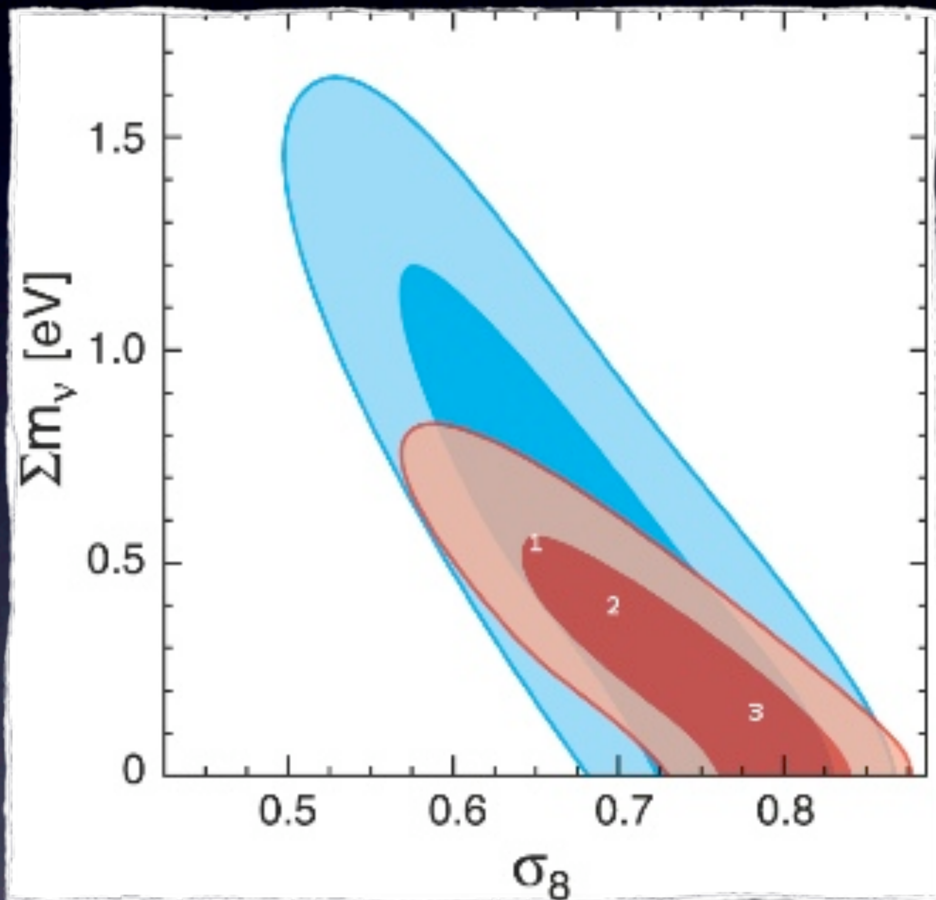

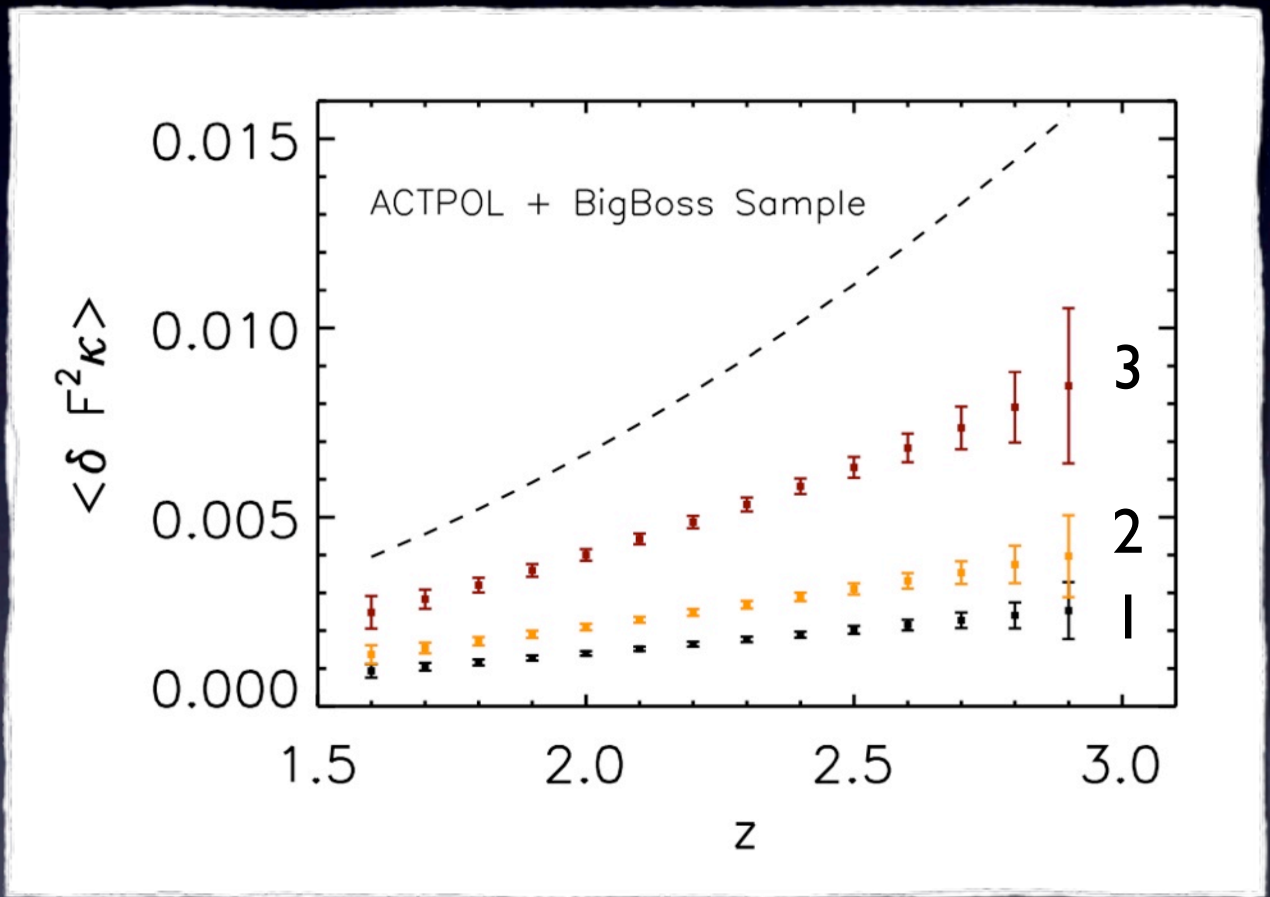

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Bottom line

- The xcorrelation between the Lyman-α forest and the CMB lensing convergence will be detectable with very near future data sets (Planck + BOSS)
- It allows to probe
    - How well Lyman-α flux traces dark matter
    - Growth of structure at the Lyman-α redshifts
    - Matter power spectrum on intermediate-to-small scales
    - Scale dependent modifications of gravity
- Numerical simulations will be crucial for a better understanding (in progress at LANL).

Cross-correlation of CMB lensing and 21-cm radiation field from HI

Fun facts about 21-cm

- 21-cm radiation is emitted from the hyperfine transition of neutral hydrogen ground state.

- Up until reionization (z~10), hydrogen remains neutral (HI). UV background from star forming galaxies ionizes most of the HI between z~10 and z~6.

- Reionization is complicated astrophysical process. Most 21-cm experiments (GMRT, PAPER, LoFAr, MWA) target epoch of reionization.

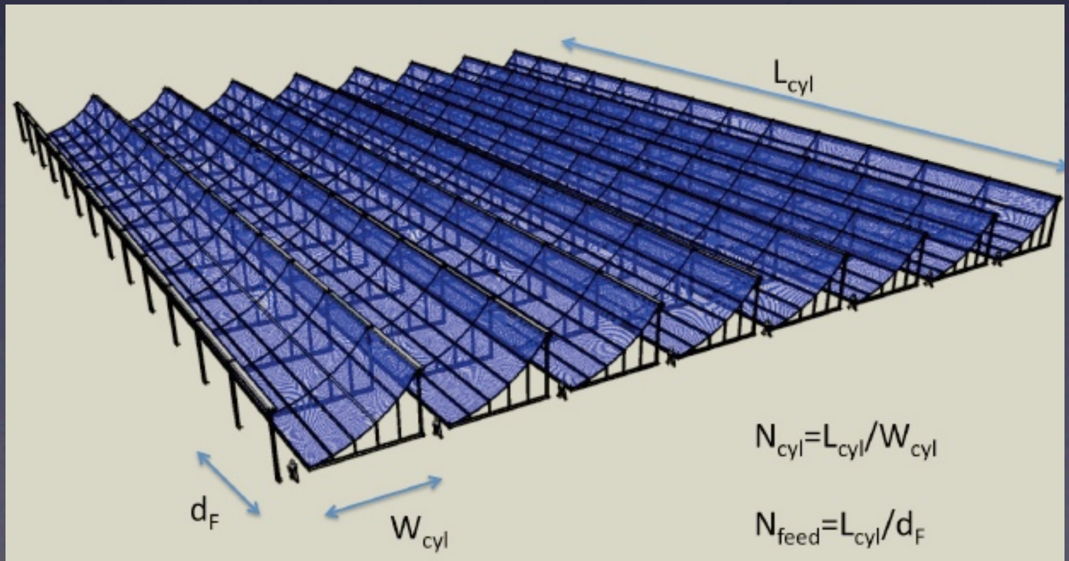
- At low redshift ($z \lesssim 6$) HI survives only in low density lyman-α absorbers and self shielded damped lyman-α systems.

- On large enough scales (~10 Mpc) it is still reasonable to assume that HI traces the DM overdensity field.

- Frequency dependence of the foregrounds should allow their subtraction like in the CMB case.

Large scales 21cm surveys

- 21-cm intensity mapping survey at low redshift (z=0-4) using a packed rectangular CRT array allows to image the large scale structure of the universe at low cost (and low resolution).



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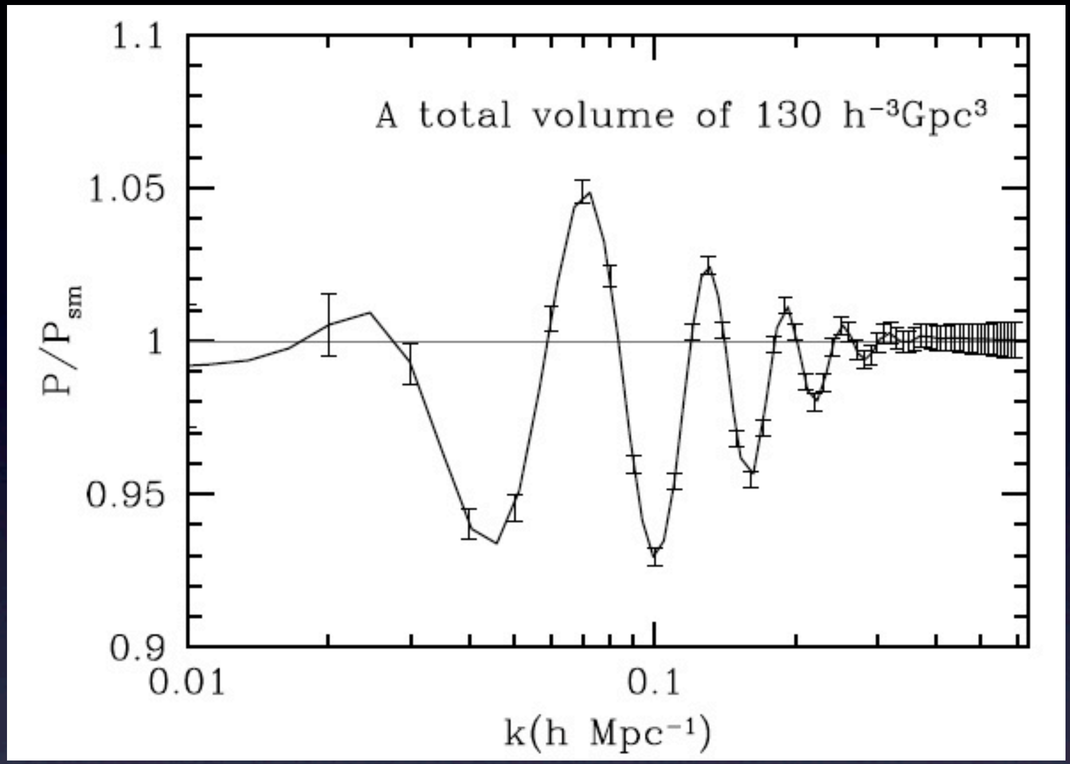

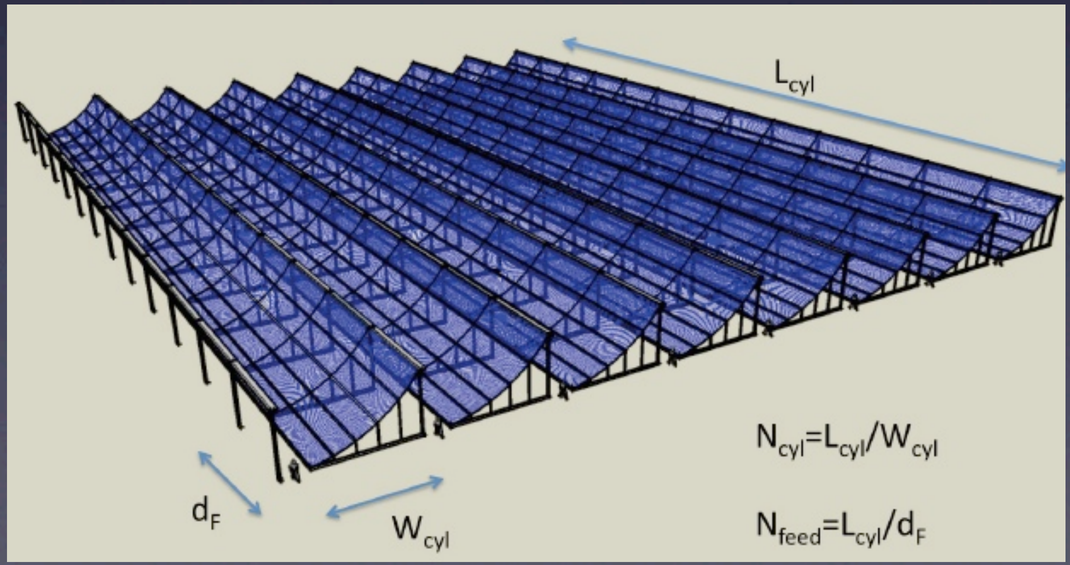

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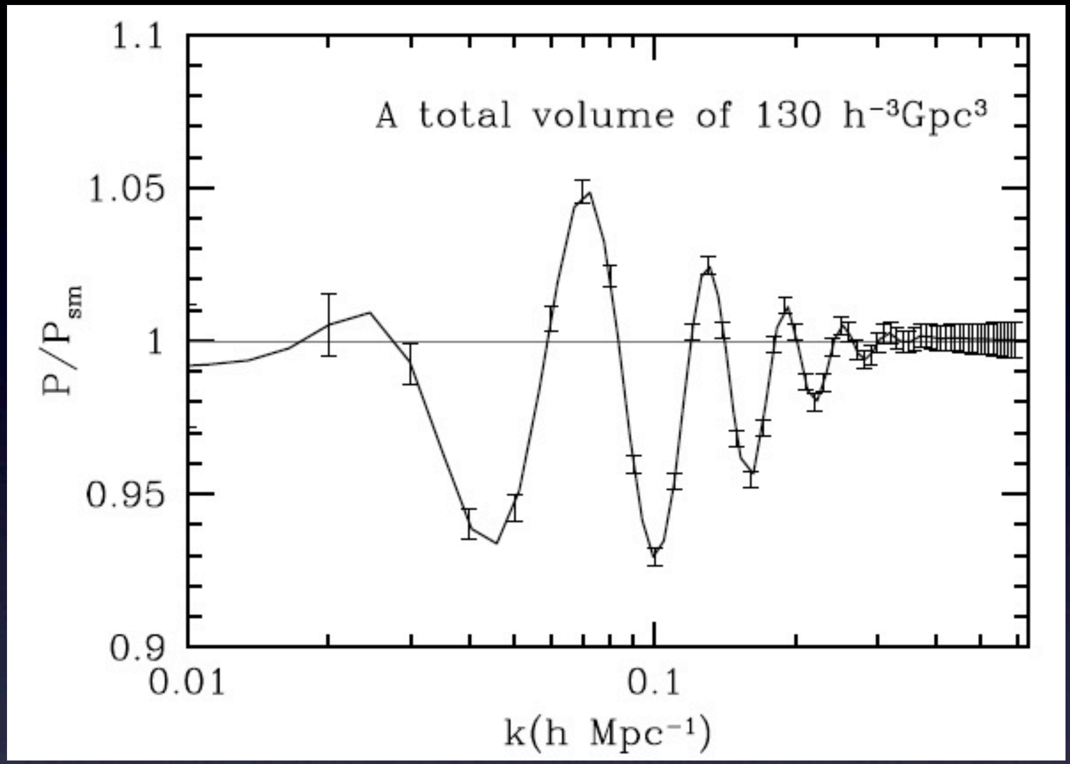

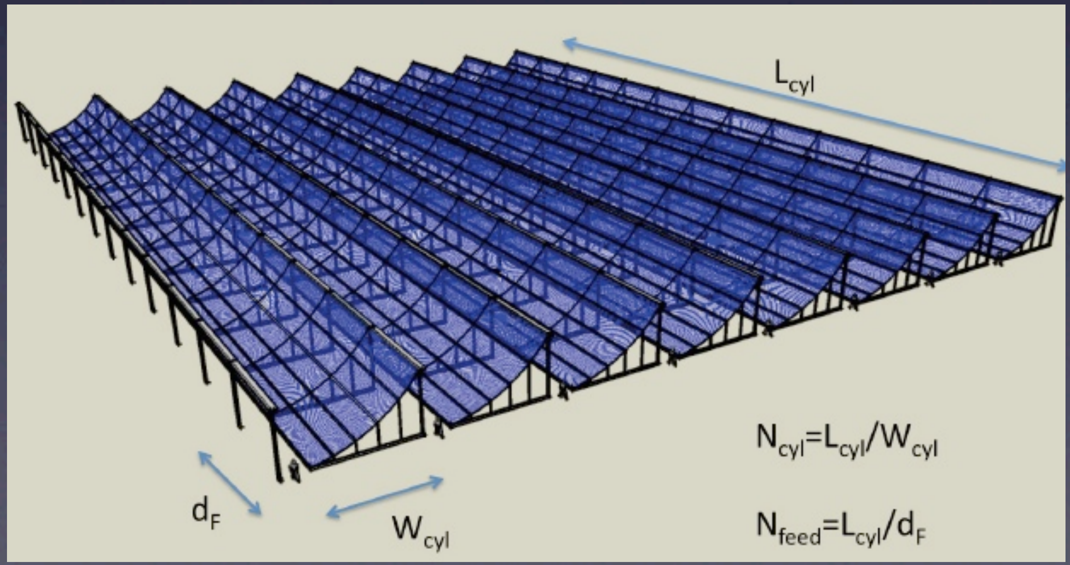

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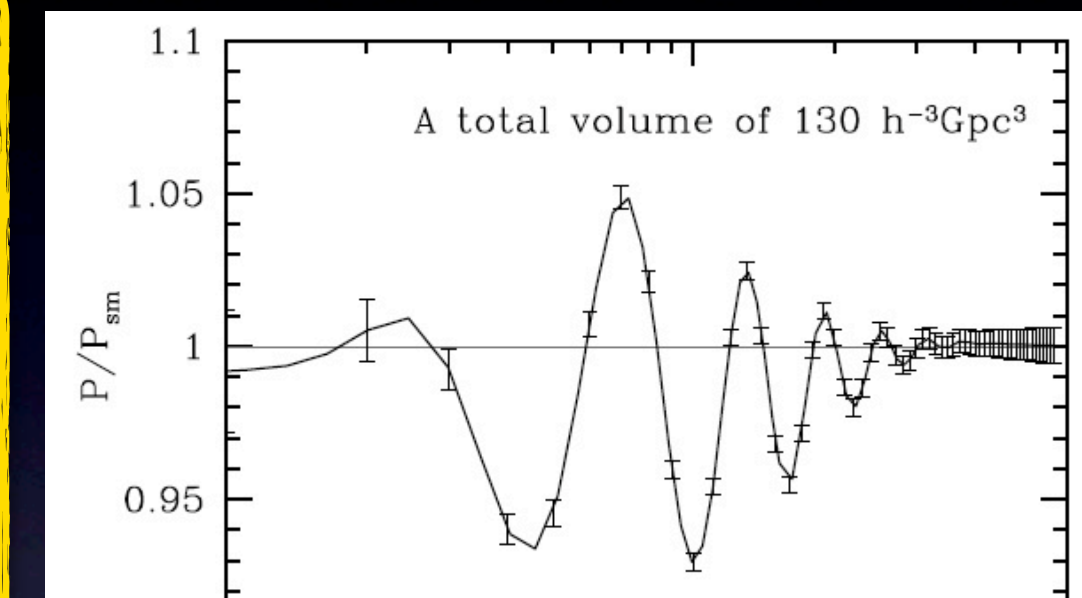
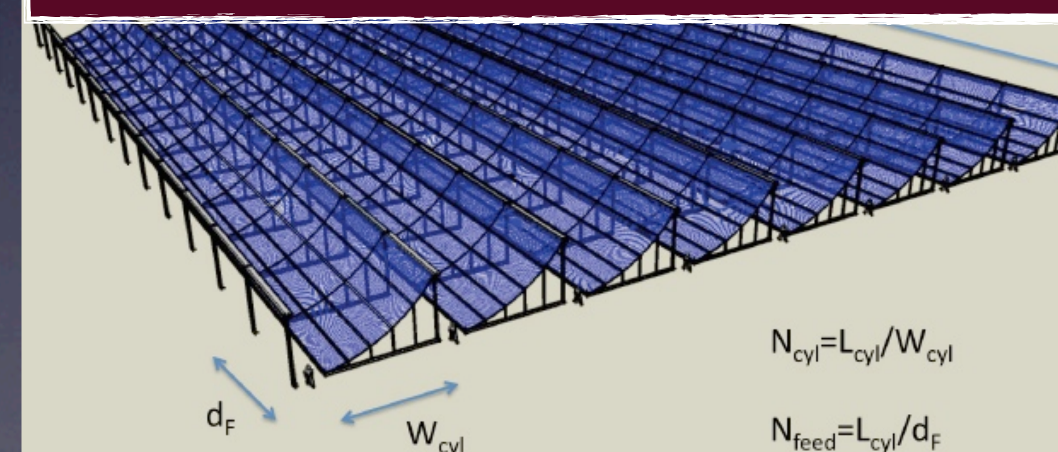


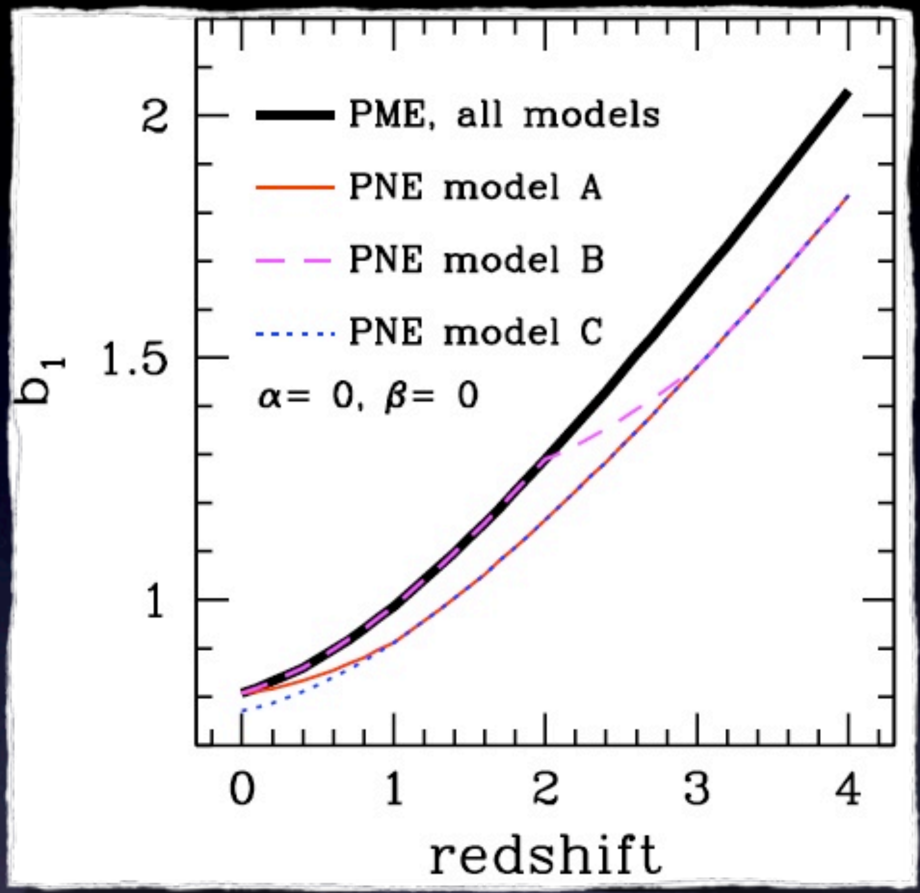
Very high future potential!

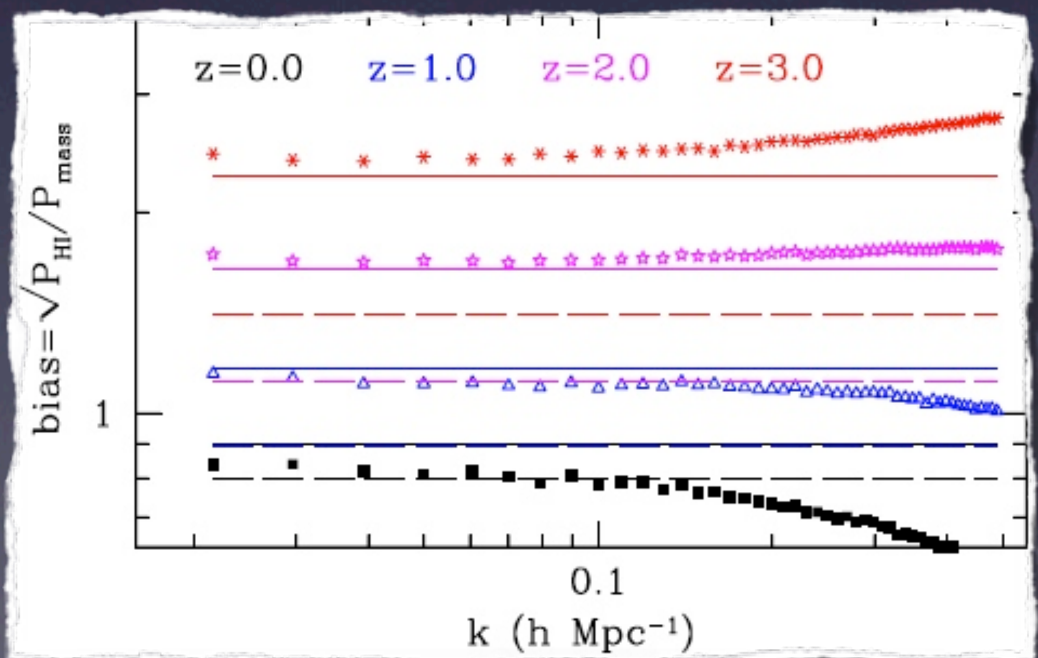


[Seo et al., 2009]

Large scales HI bias evolution

- With a prescription to evolve the HI mass function, we have been able to bracket the HI bias evolution.
  - The (poorly measured) evolution of $\Omega_{HI}(z)$. We consider three limiting cases (A, B, C).
  - Two limiting ways of assigning the total HI to halos:
    - Fix the number density (PME)
    - Fix the halo mass (PNE).
- Agrees reasonably well with measurements carried out on simulations.
- How to measure it? Cross-correlate with CMB lensing!





[Marin, Gnedin, Seo, AV, 2009]

CMB lensing and 21-cm

- Theoretical prediction of the correlation and its variance are similar to the Lyman-α forest case. However, the resolution of the 21-cm experiment varies with redshift.

- Just need to evaluate this correlator and its variance...

$$\langle \kappa(\vec{n})\delta_T(\vec{n})\rangle = \frac{3H_0^2\Omega_m}{2c^2} g_{10} \int_0^{\chi_{\rm LSS}} \frac{d\chi_c}{a(\chi_c)} W_L(\chi, \chi_{\rm LSS}) \int_{\chi_i}^{\chi_f} d\chi_H \, \langle \delta(\vec{n}, \chi_c)\delta(\vec{n}, \chi_H)\rangle$$

CMB lensing and 21-cm

- Theoretical prediction of the correlation and its variance are similar to the Lyman-α forest case. However, the resolution of the 21-cm experiment varies with redshift.
- Assume fiducial CRT design as in Seo et al., 2009 for the radio telescope.
- Aim: measuring the redshift evolution of large scale HI bias. For this I calculate the S/N for redshift slices of thickness Δz.
- Total S/N benefits from the large number of pixels.

Preliminary

Preliminary

[Vallinotto, 2011, in prep.]

Conclusions

- CMB lensing is the cleanest (albeit integrated) probe of the DM density field.
- X-correlations with density field tracers are expected to yield observable results.
- As probes of the DM density field, these x-correlations yield cosmological results.
- As probes of the biasing relation of the DM tracers, these x-correlations produce relevant astrophysical information.