The cross-correlation of the Lyman-a forest and weak lensing of the CMB: a new cosmological tool

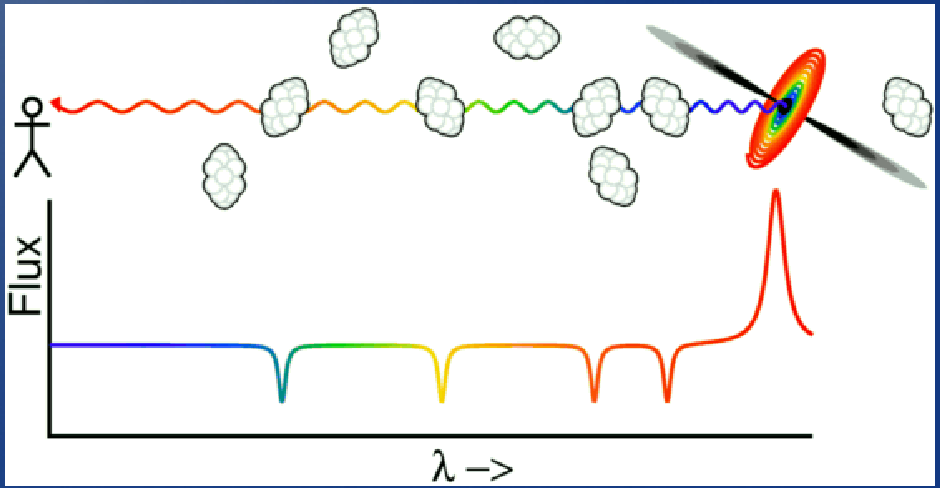
Alberto Vallinotto
Fermi National Accelerator Laboratory

Outline

- Introduction: Lyman-α forest and CMB convergence field
- Physical meaning of the observables
- Results
- Present and future applications
- Reference papers:
  - AV, S. Das, D. Spergel, M. Viel, arXiv:0903.4171, submitted to PRL.
  - AV, M. Viel, S. Das, D. Spergel, *in prep.*

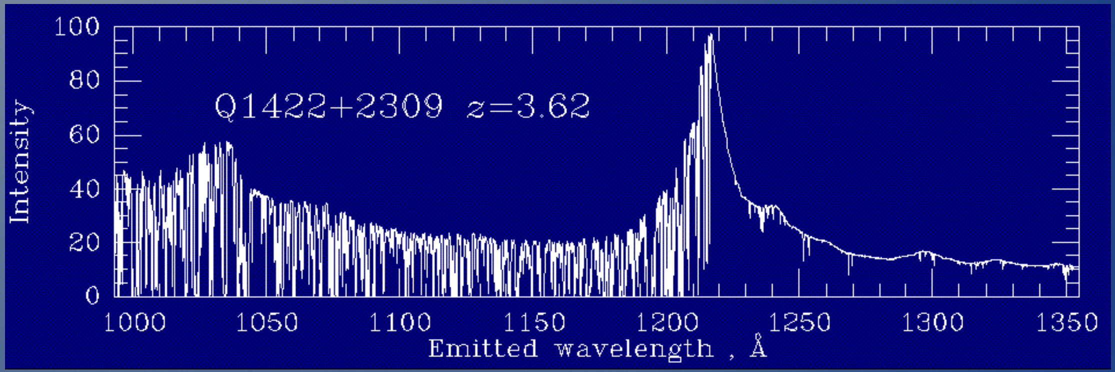
Lyman-α Forest

- 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.



Lyman-α Forest

- Understanding the forest requires understanding and modeling the physics of the IGM.
- Great help comes from simulations.



- Fluctuations in the flux are related to overdensities

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

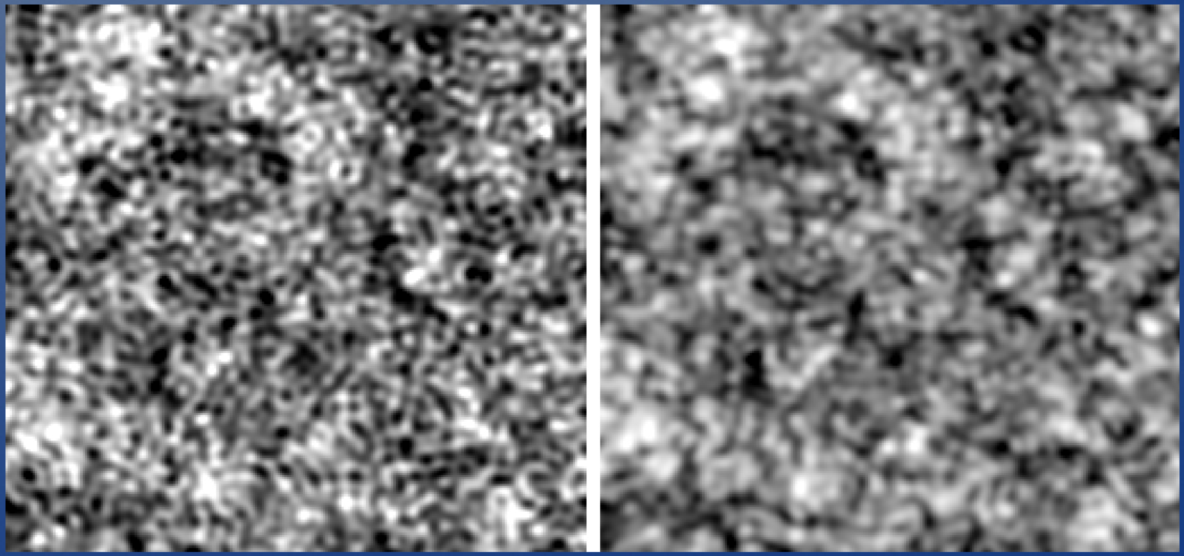
- To first approximation [Viel et al. 2001] $\delta_H \approx \delta$
- The flux-matter relation has many sources of uncertainty.

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

Weak lensing of the CMB

- 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)].

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



Original vs reconstructed deflection field. (Hirata and Seljak, 2003)

Physical Motivation

- Does it make sense to x-correlate Lyman-α forest and CMB convergence?
  - K depends on the dark matter overdensity integrated along the los (no bias)
  - The flux “should” be proportional to the matter fluctuations along the los.
- What we may learn from it?
  - Get a handle on the Lyman-α flux-dark matter bias.
  - Use this xcorrelation as a cosmological tool to measure cosmological parameters and build tests.

Physical meaning of the observables

- $\langle \delta \mathcal{F} \kappa \rangle$ correlates the integrated fluctuation in the flux along the los with the CMB convergence.
  - Sensitive to intermediate to large scales
  - Measures the matter fluctuations in the forest responsible for the lensing of CMB along the los.
  - More affected by uncertainties of the flux-matter relation

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

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

Physical meaning of the observables

- $\langle \delta \mathcal{F}^2 \kappa \rangle$ correlates the total flux variance along the los with the CMB convergence.
  - Measures the enhanced growth of structure in overdense regions.
  - Sensitive to intermediate to small scales.
  - Expected to be larger than $\langle \delta \mathcal{F} \kappa \rangle$

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

$$\delta \mathcal{F}^2(\hat{n}) \approx \int_{\chi_i}^{\chi_Q} d\chi A^2 \beta^2 \delta^2(\chi, \hat{n})$$

Calculation (1)

- Ideally, it is "just" a matter of evaluating these couple of integrals...

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

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

Calculation (2)

- However, things become more complicated when we introduce gaussian window functions that account for the finite resolution of the spectrograph and of the CMB experiment.

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

Calculation (2)

- However, things become more complicated when we introduce gaussian window functions that account for the finite resolution of the spectrograph and of the CMB experiment.

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

cutoff scales

Calculation (2)

- However, things become more complicated when we introduce gaussian window functions that account for the finite resolution of the spectrograph and of the CMB experiment.

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

cutoff scales

- These window function reflect the cylindrical symmetry of the physical observables.

Calculation (3)

- The calculation of $\langle \delta \mathcal{F}^2 \kappa \rangle$ requires the evaluation of a 6D integral.

Calculation (3)

- The calculation of $\langle \delta \mathcal{F}^2 \kappa \rangle$ requires the evaluation of a 6D integral.
- Workaround: it is possible to obtain a clever series solution that requires only evaluation and tabulation of 1D integrals (thus numerically extremely more efficient).

Calculation (3)

- The calculation of $\langle \delta \mathcal{F}^2 \kappa \rangle$ requires the evaluation of a 6D integral.
- Workaround: it is possible to obtain a clever series solution that requires only evaluation and tabulation of 1D integrals (thus numerically extremely more efficient).
- The analytical results take into account non-linear effects (HyperExtended Perturbation Theory, Couchman and Scoccimarro, 2001)
- As a first step, the numerical results are calculated at tree-level in cosmological perturbation theory.

Calculation (4)

- To evaluate the S/N, we need to estimate

$$\langle \delta_q \delta_{q'} \delta_c \delta_{c'} \rangle \text{ and } \langle \delta_q^2 \delta_{q'}^2 \delta_c \delta_{c'} \rangle$$

Calculation (4)

- To evaluate the S/N, we need to estimate
  $$\langle \delta_q \delta_{q'} \delta_c \delta_{c'} \rangle \text{ and } \langle \delta_q^2 \delta_{q'}^2 \delta_c \delta_{c'} \rangle$$
- Cosmic variance is dominated by the terms containing $\langle \delta_c \delta_{c'} \rangle$

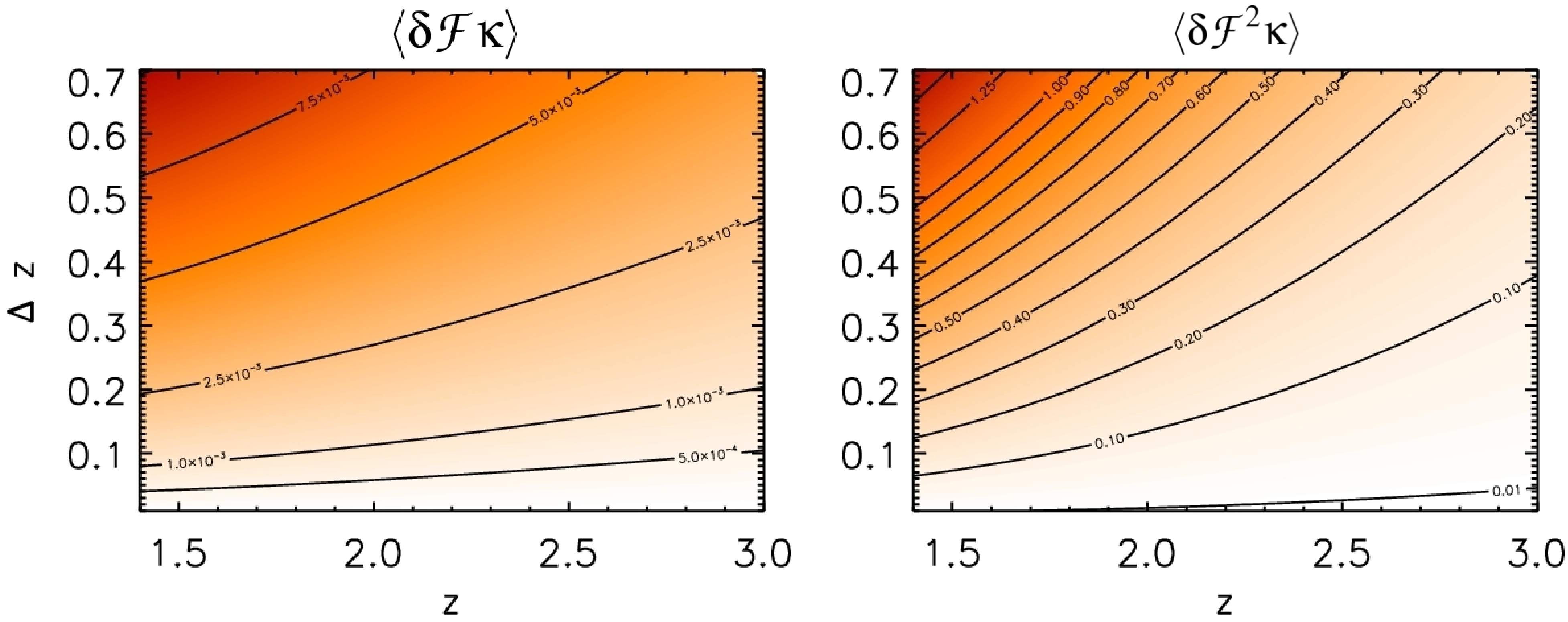
Calculation (4)

- To evaluate the S/N, we need to estimate

$$\langle \delta_q \delta_{q'} \delta_c \delta_{c'} \rangle \text{ and } \langle \delta_q^2 \delta_{q'}^2 \delta_c \delta_{c'} \rangle$$

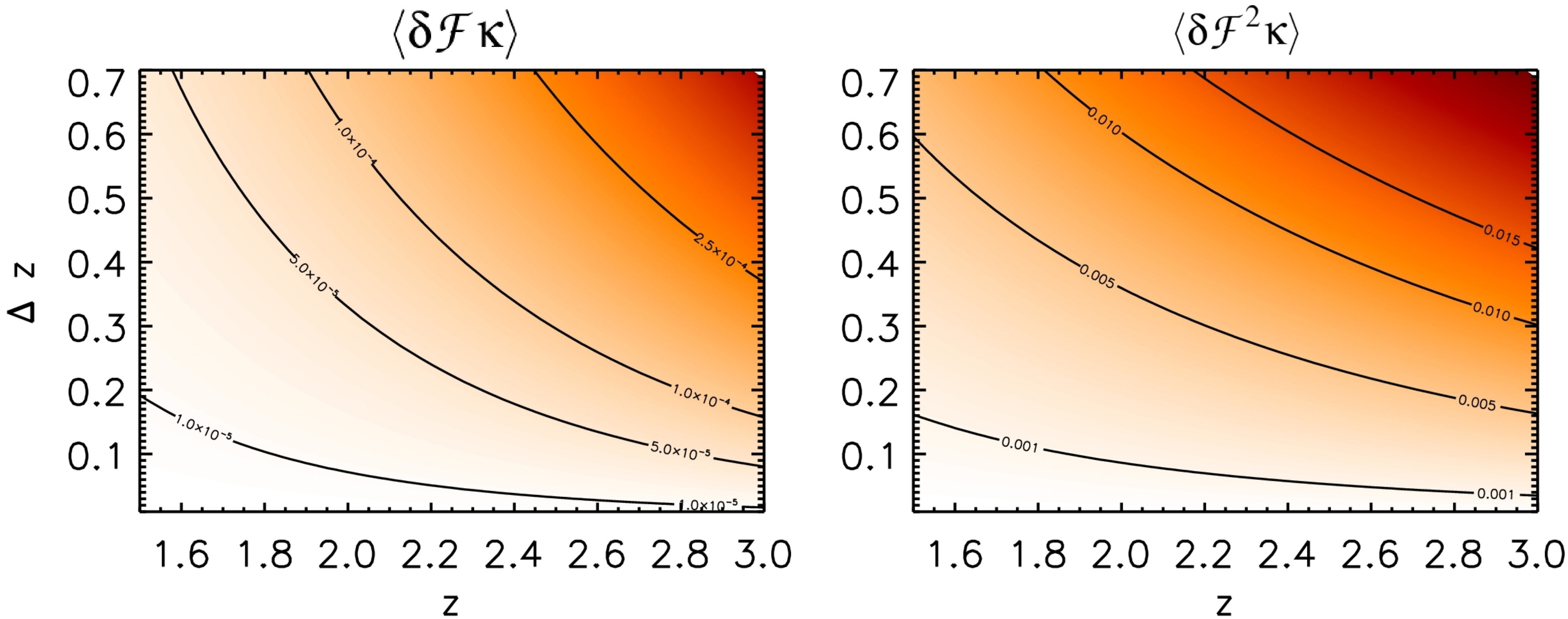
- Cosmic variance is dominated by the terms containing $\langle \delta_c \delta_{c'} \rangle$.
- An *estimate* of the cosmic variance can be obtained using Wick's theorem.

Results: signal (SDSS-III + Planck)



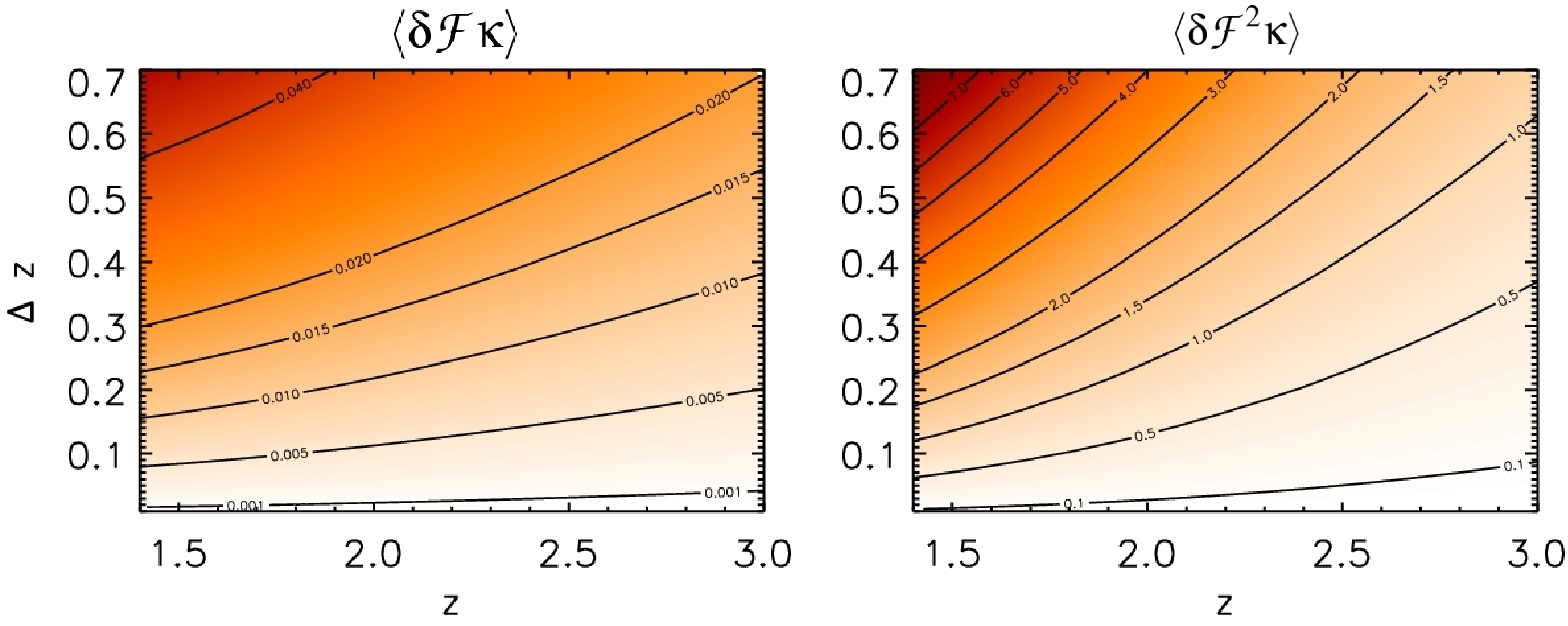
- A=β=1: turn off IGM physics
- $k_L = 4.8h\,\mathrm{Mpc}^{-1}$ (SDSS-III) $k_C = 0.021h\,\mathrm{Mpc}^{-1}$ (Planck)
- Signal decreases with z: probing less collaped regions
- The signal for $\langle\delta\mathcal{F}^2\kappa\rangle$ is much larger than the $\langle\delta\mathcal{F}\kappa\rangle$'s one.

Results: signal (SDSS-III + Planck)



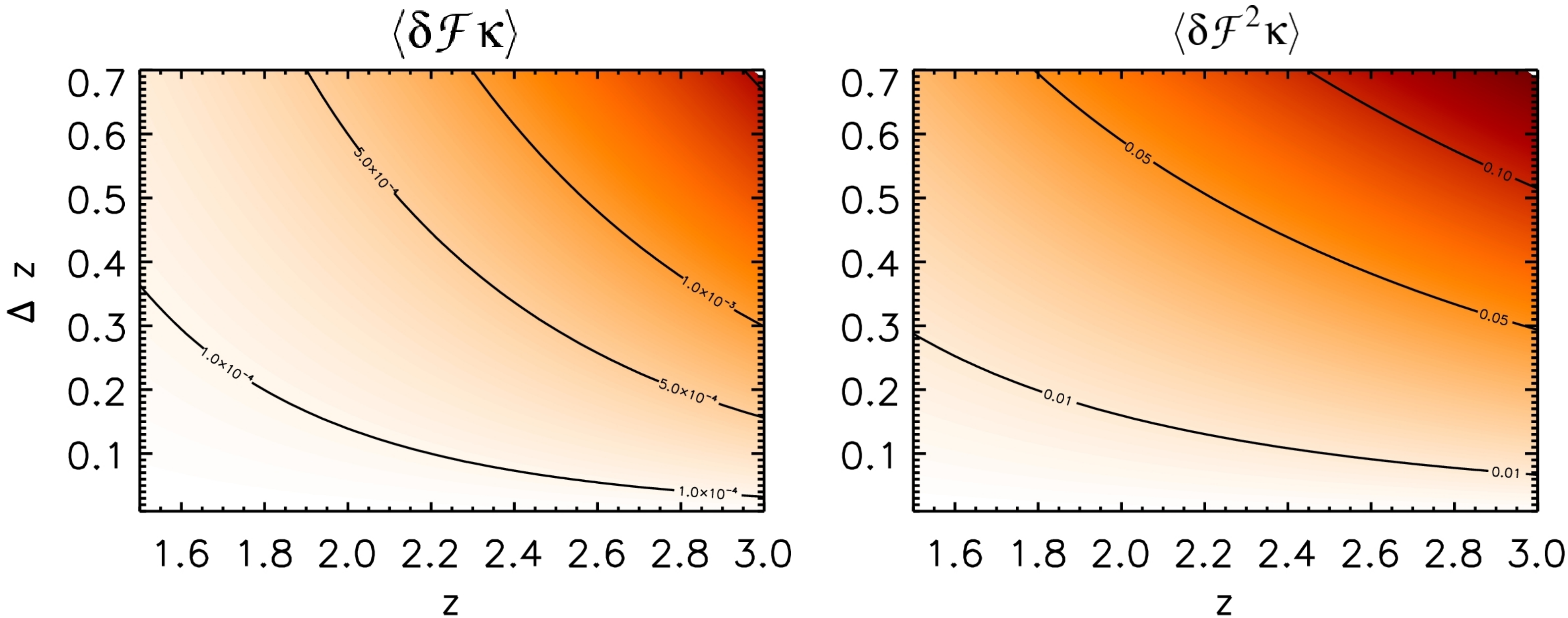
- A(z) turned on
- $k_L = 4.8h\,\mathrm{Mpc}^{-1}$ (SDSS-III) $k_C = 0.021h\,\mathrm{Mpc}^{-1}$ (Planck)
- The signal for $\langle \delta\mathcal{F}^2\kappa \rangle$ is much larger than the $\langle \delta\mathcal{F}\kappa \rangle$'s one.

Results: signal (SDSS-III + *Pol*)



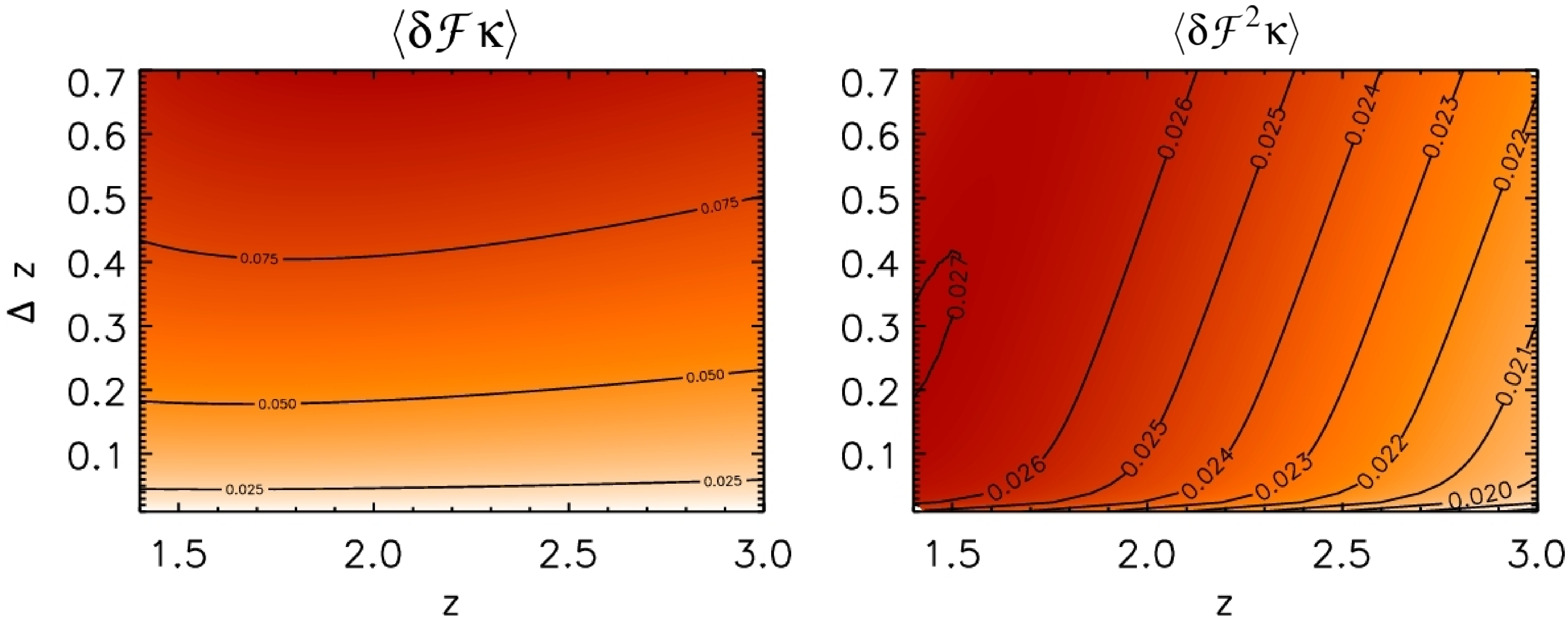
- Hypothetical CMB polarization experiment ("*Pol*")
- $k_L = 4.8h\,\mathrm{Mpc}^{-1}$ (SDSS-III) $k_C = 0.064h\,\mathrm{Mpc}^{-1}$ (*Pol*)
- Signals clearly increase with better resolution for κ
- The signal for $\langle \delta\mathcal{F}^2\kappa \rangle$ is much larger than the $\langle \delta\mathcal{F}\kappa \rangle$'s one.

Results: signal (SDSS-III + *Pol*)



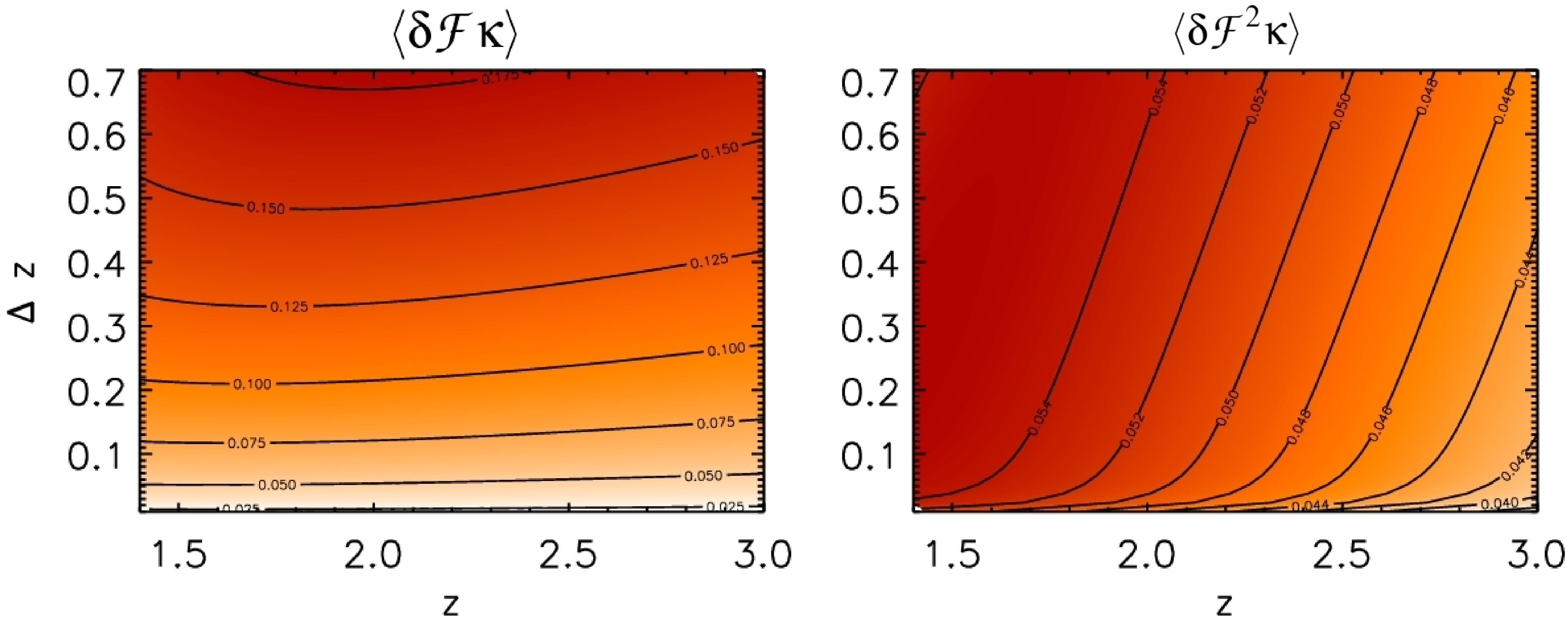
- A(z) turned on.
- $k_L = 4.8h\,\mathrm{Mpc}^{-1}$ (SDSS-III) $k_C = 0.064h\,\mathrm{Mpc}^{-1}$ (*Pol*)
- Signals clearly increase with better resolution for κ
- The signal for $\langle \delta\mathcal{F}^2\kappa \rangle$ is much larger than the $\langle \delta\mathcal{F}\kappa \rangle$'s one.

Results: detectability (SDSS-III +Planck)



- S/N for a single line-of-sight. $1.6 \cdot 10^5$ los for SDSS-III, 10^6 for BigBoss.
- *Estimates* for total S/N is ~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 correlated with Boss (BigBoss)
- The growth of structure enters “twice” in the case of $\langle\delta\mathcal{F}^2\kappa\rangle$: once for long-wv and once for short-wv, but the noise is dominated by long-wv only.

Results: detectability (SDSS-III +Pol)



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

Caveats

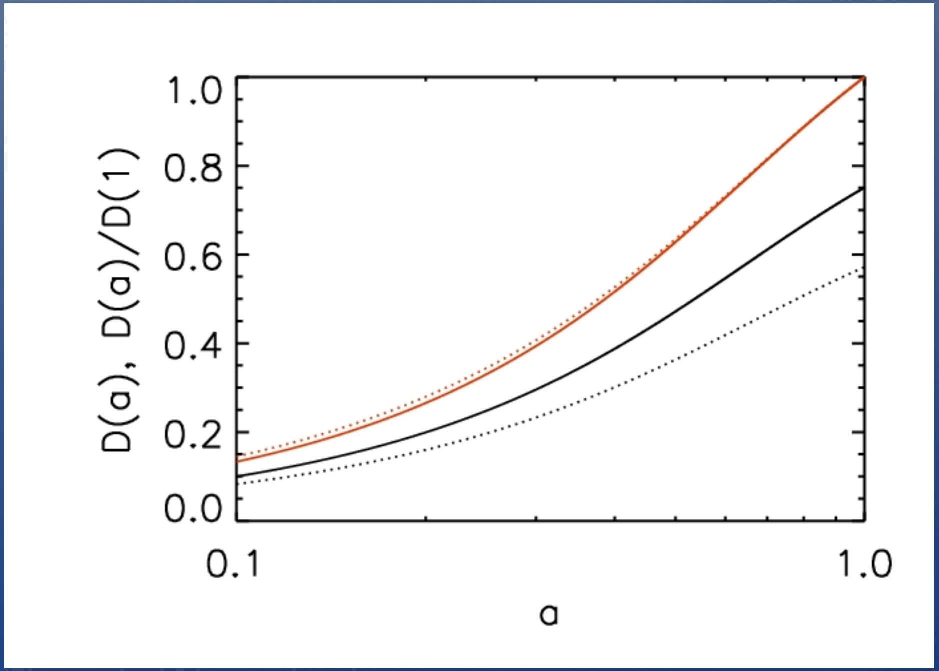
1. Numerical results currently do not take into account non-linear effects due to gravitational collapse.
   - Extension is straightforward
   - Signal and S/N are expected to increase
2. All results do not take into account the physics of IGM on small scales ($\leq 1h^{-1}$ Mpc) and use "gaussian approximation" to evaluate cosmic variance
   - Final answer will come from numerical sims.

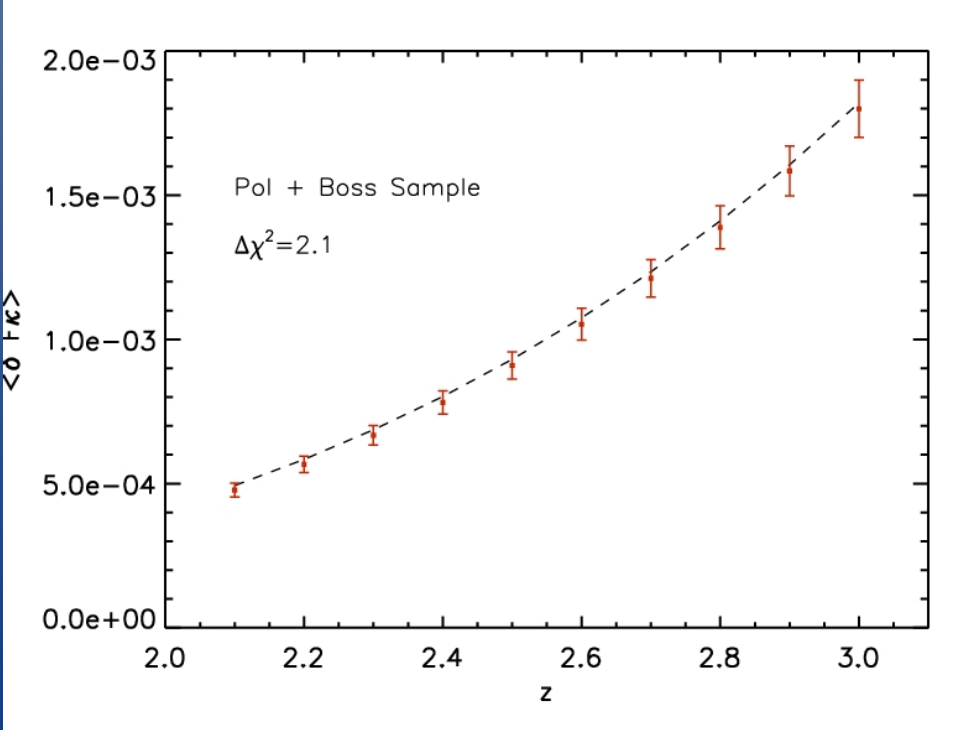
Applications and Prospects

- Use to obtain independent constraints on the IGM physics and flux-matter relation
  - Currently under way
- Signal is sensitive to growth of structure
  - test early dark energy models.
- $\langle \delta \mathcal{F}^2 \kappa \rangle$ is sensitive to modes $k \geq 0.1 h\,\mathrm{Mpc}^{-1}$
  - constrain neutrino masses.
  - test scale dependent modifications of gravity.

Preliminary Cosmological Applications: Early Dark Energy with $\langle \delta \mathcal{F} \kappa \rangle$

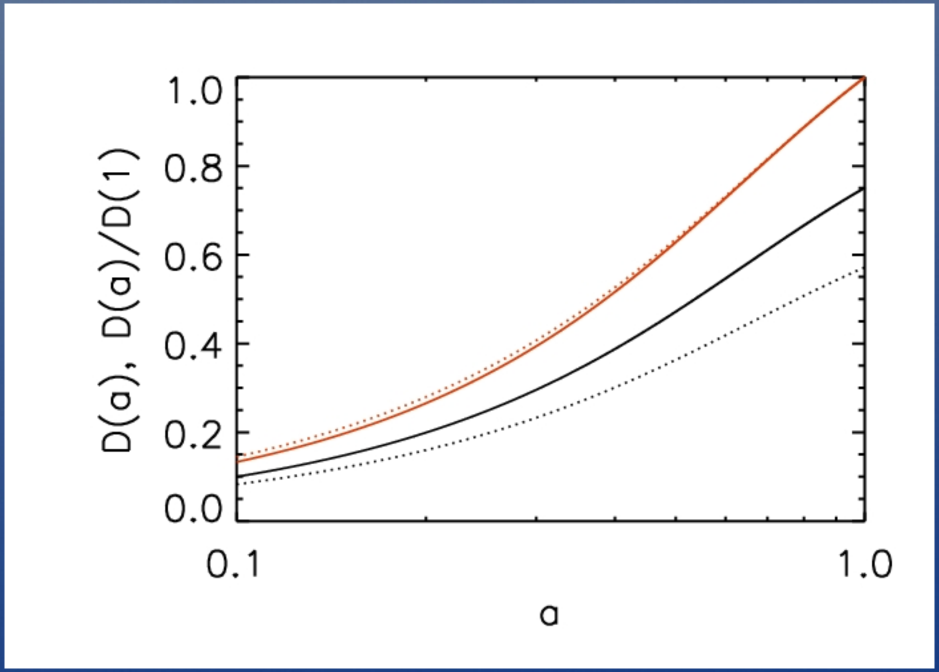
- $\langle \delta \mathcal{F} \kappa \rangle$ yields a large S/N
- Caveat: a precise understanding of the IGM physics is required
- Caveat: gravity-induced non-linearities need to be taken into account
- More success considering modified gravity theory b/c of their scale dependence.

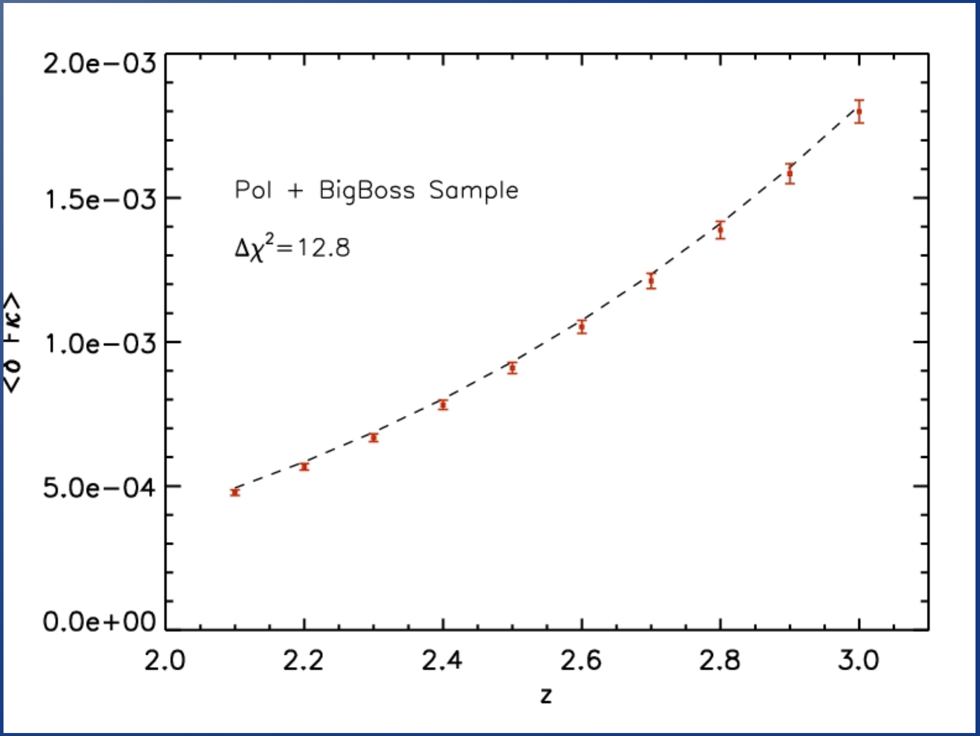




Preliminary Cosmological Applications: Early Dark Energy with $\langle \delta \mathcal{F} \kappa \rangle$

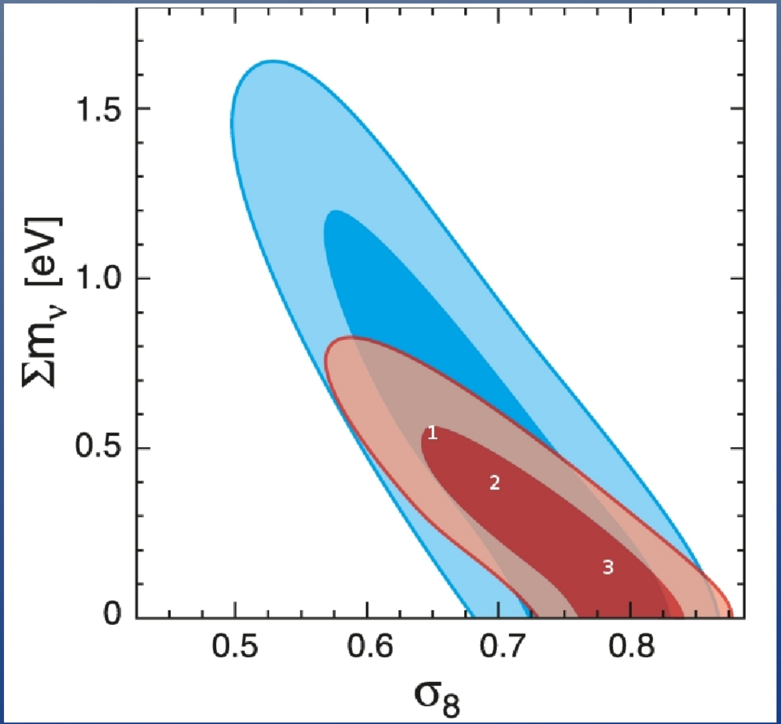
- $\langle \delta \mathcal{F} \kappa \rangle$ yields a large S/N
- Caveat: a precise understanding of the IGM physics is required
- Caveat: gravity-induced non-linearities need to be taken into account
- More success considering modified gravity theory b/c of their scale dependence.

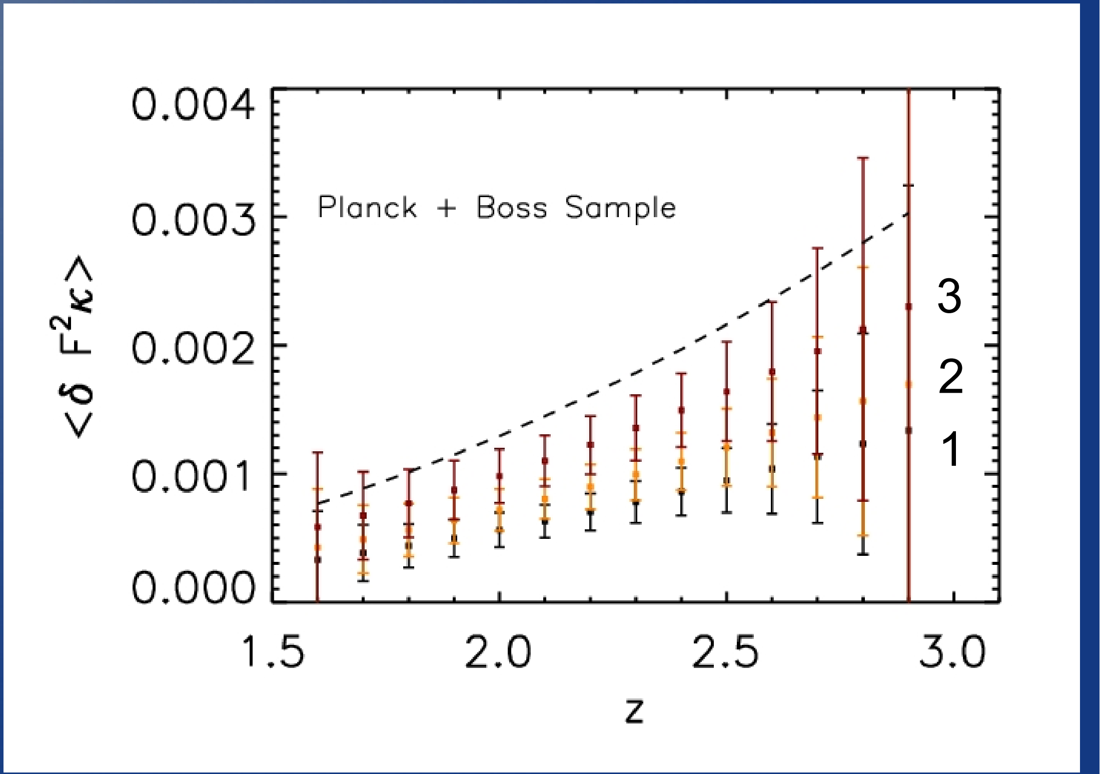




Preliminary Cosmological Applications: neutrino masses with $\langle \delta \mathcal{F}^2 \kappa \rangle$

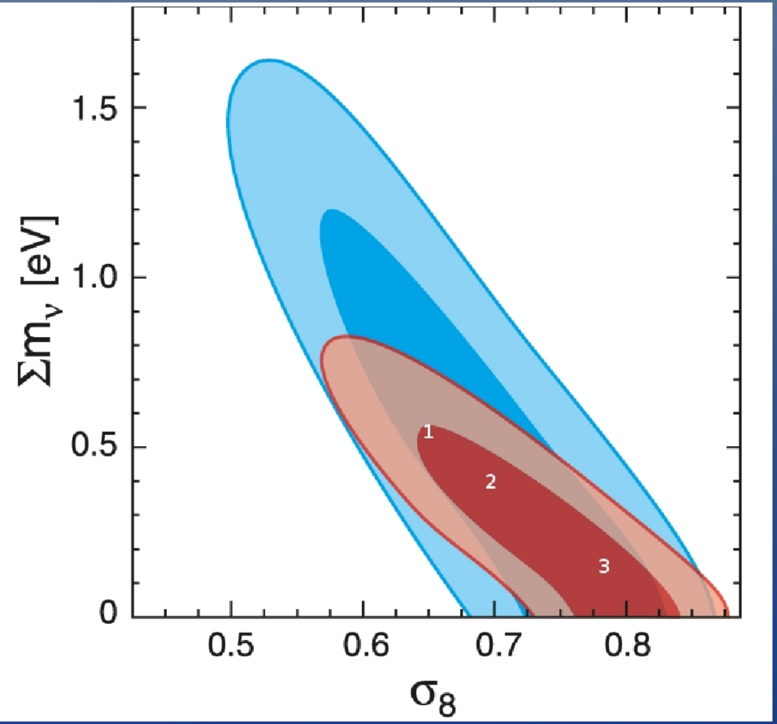
- $\langle \delta \mathcal{F}^2 \kappa \rangle$ is sensitive to intermediate to small scales
- Caveat: non-linear effects due to gravitational collapse need to be taken into account.

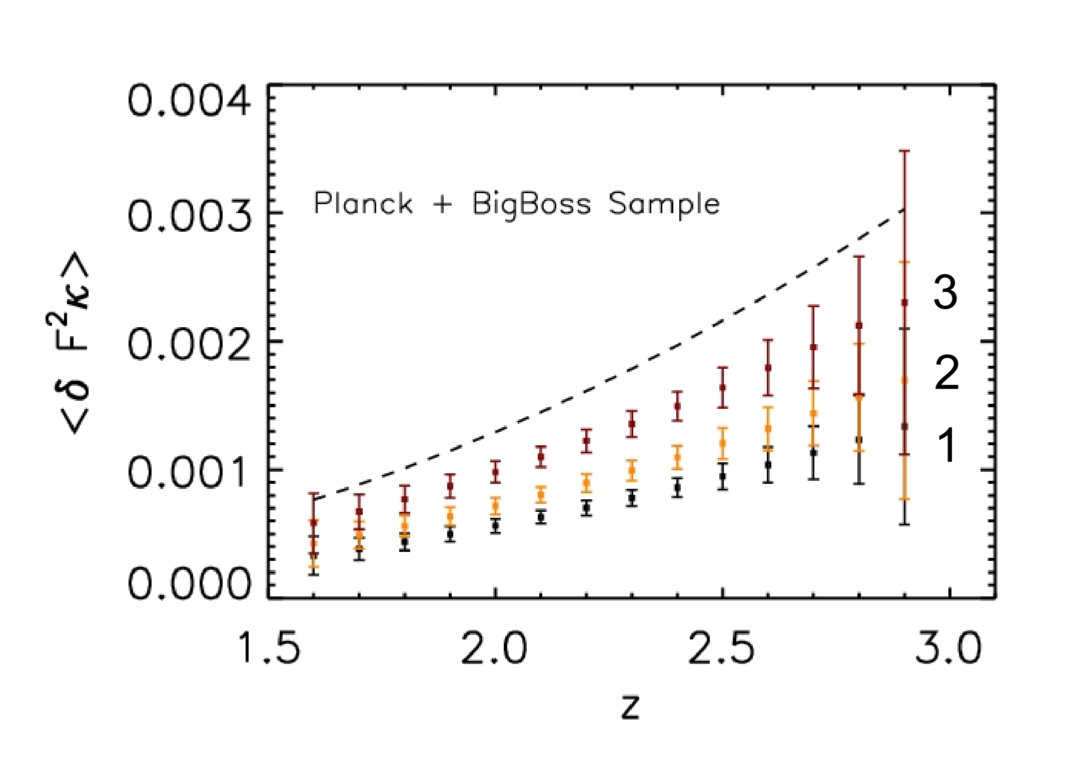




Preliminary Cosmological Applications: neutrino masses with $\langle \delta \mathcal{F}^2 \kappa \rangle$

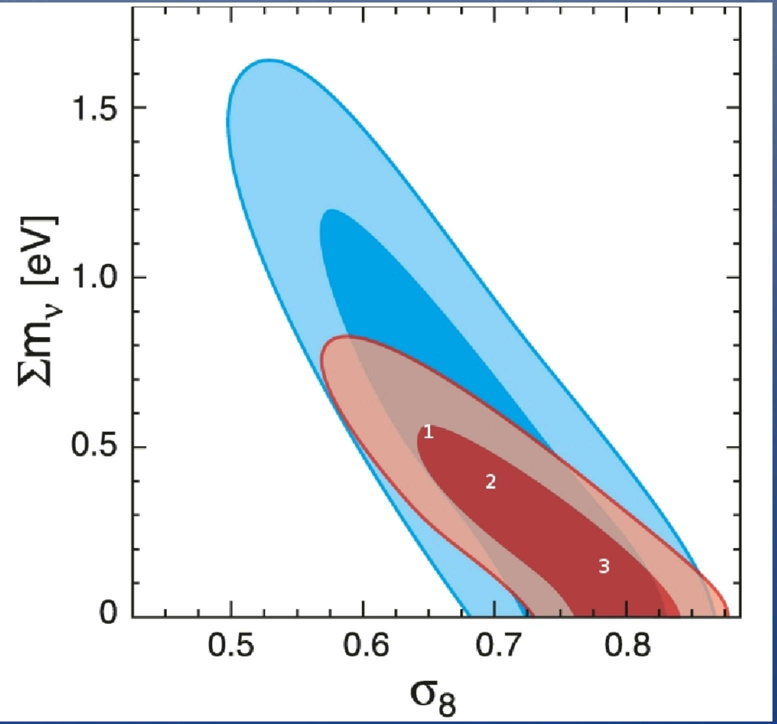
- $\langle \delta \mathcal{F}^2 \kappa \rangle$ is sensitive to intermediate to small scales
- Caveat: non-linear effects due to gravitational collapse need to be taken into account.

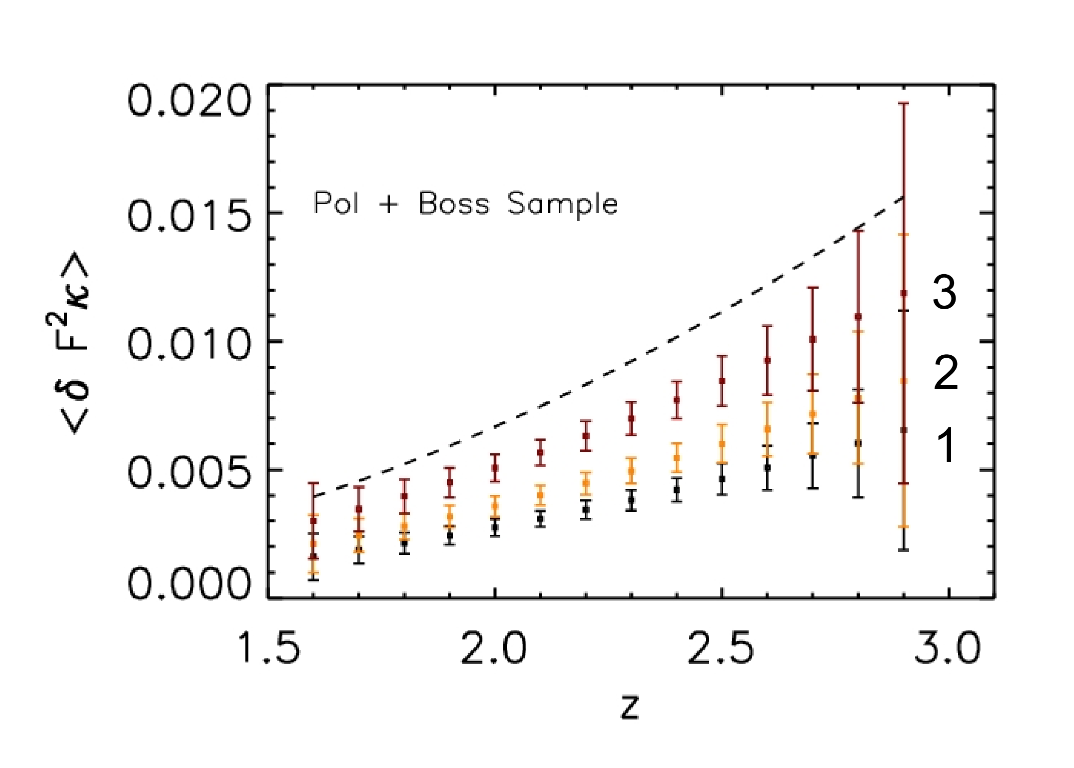




Preliminary Cosmological Applications: neutrino masses with $\langle \delta \mathcal{F}^2 \kappa \rangle$

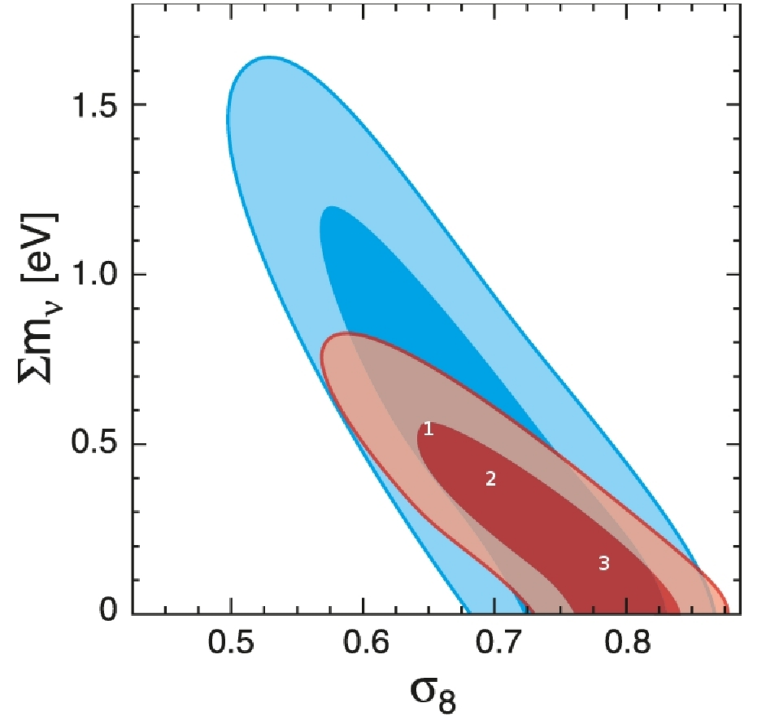
- $\langle \delta \mathcal{F}^2 \kappa \rangle$ is sensitive to intermediate to small scales
- Caveat: non-linear effects due to gravitational collapse need to be taken into account.

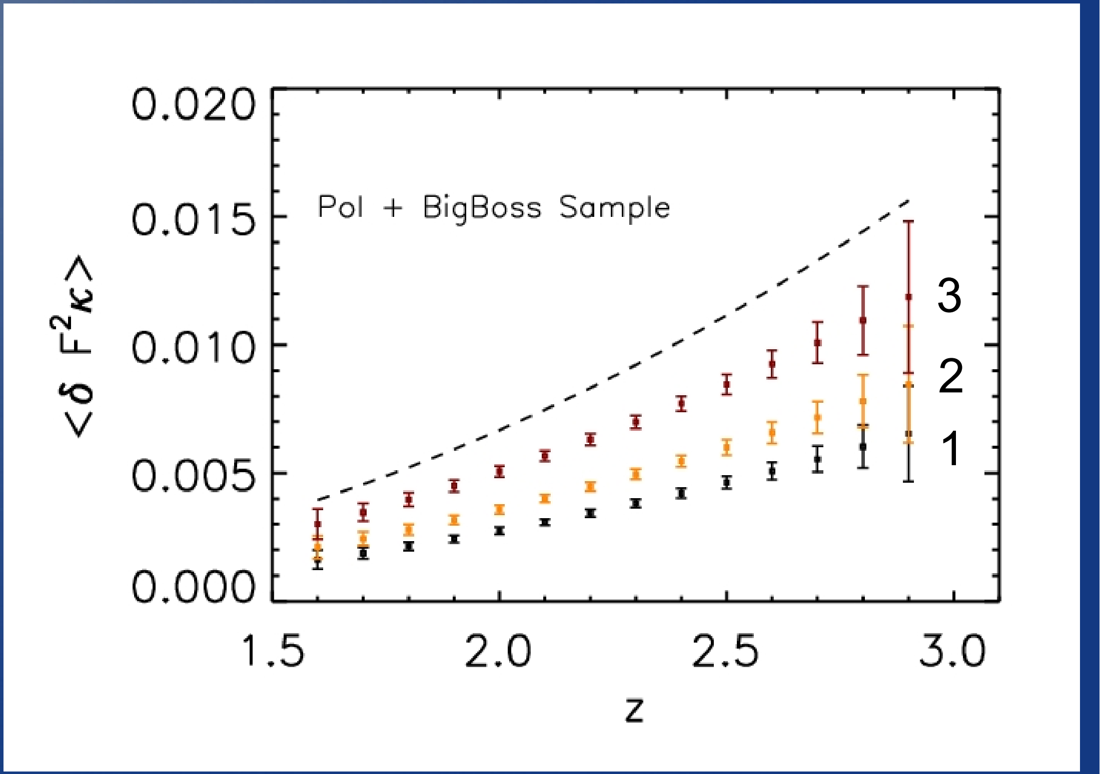




Preliminary Cosmological Applications: neutrino masses with $\langle \delta \mathcal{F}^2 \kappa \rangle$

- $\langle \delta \mathcal{F}^2 \kappa \rangle$ is sensitive to intermediate to small scales
- Caveat: non-linear effects due to gravitational collapse need to be taken into account.





Conclusions

- The x-correlation of Lyman-α flux and CMB convergence maps will be detectable with near future data sets (Planck + Boss).
- It will allow to probe
  - How well the flux traces dark matter
  - Growth of structure at the Lyman-α redshifts
  - Power spectrum on intermediate to small scales
  - Scale dependent modifications of gravity
- Numerical simulations will be crucial for a better understanding.