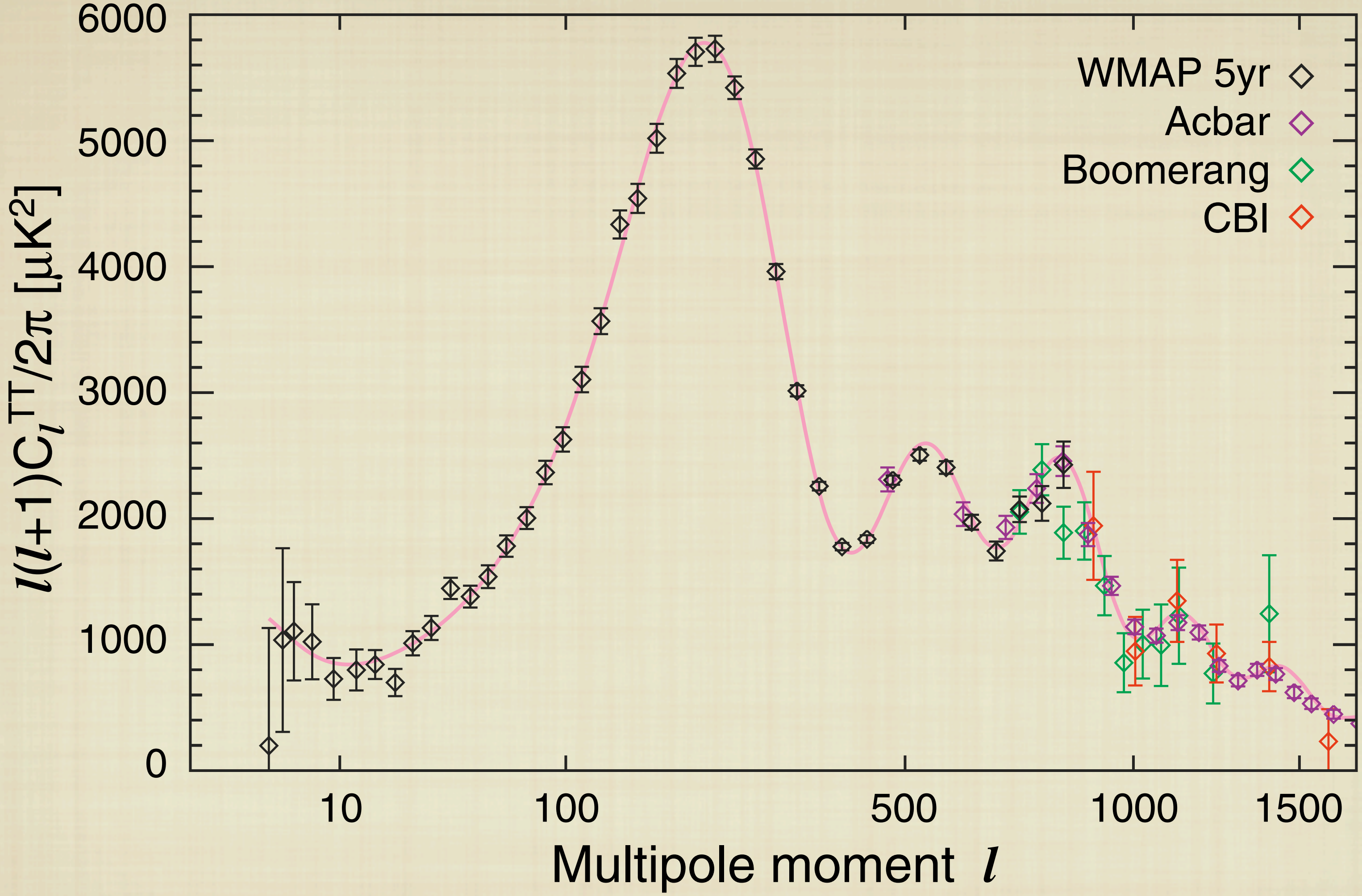
Probing primordial non-gaussianity and testing gravity with large scale structure surveys

Olivier Doré (CITA)

Neal Dalal (CITA)
Dragan Huterer (U. Michigan)
Tingting Lu (CITA)
Ue-Li Pen (CITA)
Alex Shirokov (CITA)
Yong-Seon Song (ICG, Porstmouth)

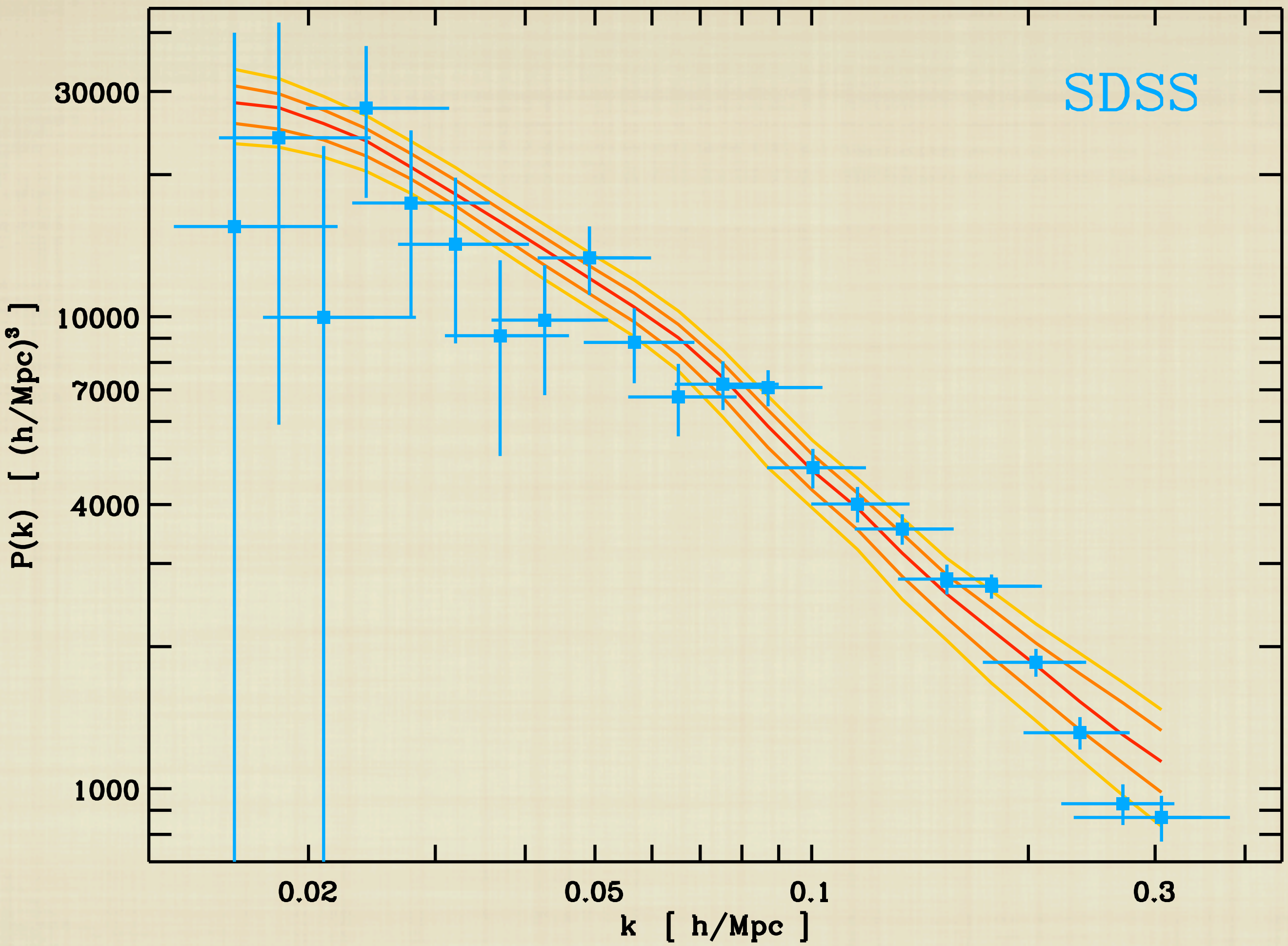
Harmony in the CMB



- Simple flat ΛCDM model with 6 parameters (Ω_{CDM}, Ω_B, N_S, A_S, H, τ) is an excellent fit
- For T, $l>30$, we have $\chi^2_{eff}=1.06$ (PTE 9.6%)

Nolta et al. 08

Cosmological contrasts... and yet concordance



WMAP agrees with low z mass distribution (modulo the bias)
(same for 2dF)

Spergel et al. 06

One standard model

- Cosmology now has a standard model and is going through an era of observational concordance. The flat ΛCDM fits all current data (CMB, LSS, SN, WL) with only six parameters

- The current strong "phenomenological" success means:

  - The primordial inhomogeneities are mostly adiabatic with a nearly scale invariant power spectrum

  - We have a successful GR based theory of linear perturbations to evolve them

  - We have a good description of the main components even if we do not know what they are

We can now ask various sets of questions:

- Ask question within the model

  - What else can we learn about the components of the model, e.g. neutrino?
  - Did the Universe really undergo an Inflationary phase?
  - What is Dark Energy?
  - What is Dark Matter?

  - How did the Universe get reionized?

- Explore further the data and look for "anomalies", i.e. deviations from this model

Outline

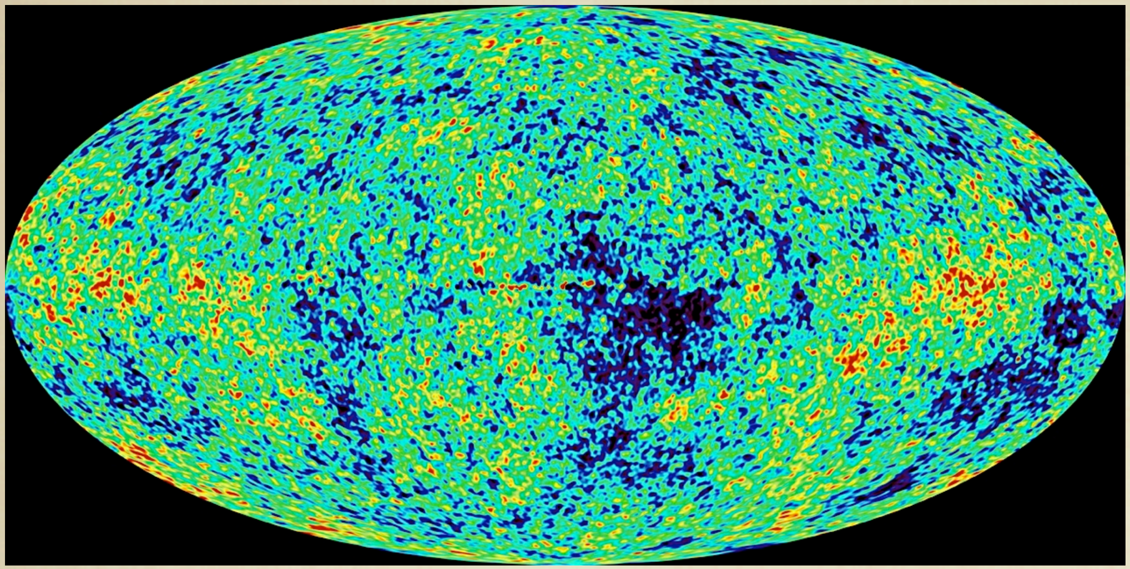
- Do we live in an Inflationary Universe? How can we address this question with coming large scale surveys?
- What is the nature of Dark Energy? Is there really Dark Energy? How to test gravity on cosmological scales?

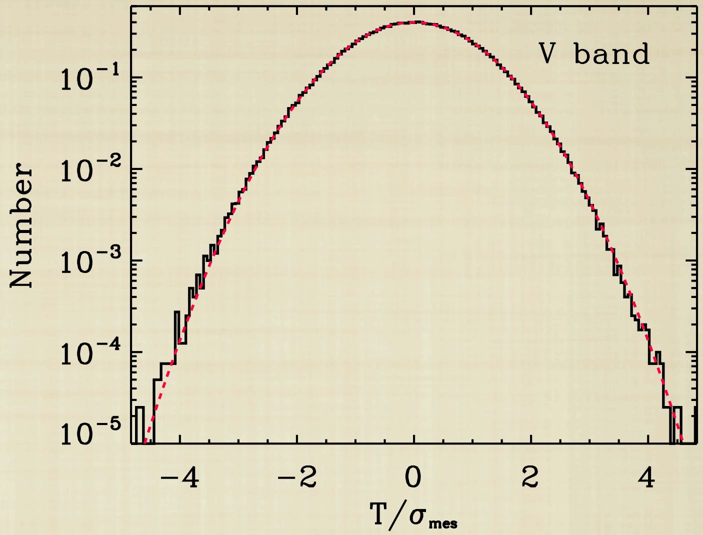
What is Inflation?

- Inflation was introduced to solve the problems of the "standard Big Bang" model like flatness and the horizon problem
- Key feature: during an extended period of time, the universe is expanding exponentially. Fluctuations are generated during this phase
- This is achieved by introducing in the matter sector (a) new scalar field(s) Φ with a well chosen potential $V(\Phi)$
- For a given $V(\Phi)$ there are relations between derivatives of V and observables like n_s , r and $dn_s/d\ln k$
- Testing Inflation is mostly testing these consistency relations
- Current data support the simplest predictions of Inflation
  - Flat Universe
  - Nearly scale invariant power spectra
  - ICs are mostly Gaussian

Guth 81, Sato 81, Linde 82, Albrecht & Steinhardt 82
Guth & Pi 82, Starobinsky 82, Mukhanov & Chibisov 81, Hawking 82, Bardeen et al. 83
Linde 05, Lyth & Riotto 99 for reviews

Inflation, non-gaussianity and density peaks





- The CMB as we observe it is Gaussian but simplest inflationary models predict small but nonzero non-gaussianity (non-linear evolution of the potential)

- The statistical analysis of this map supports the simplest Inflation predictions:
  - Geometry of the universe Flat at ~3% (WMAP 5 + HST)
  - Power spectrum index nearly scale invariant n_s=0.963±0.015 (WMAP5 only)
  - Limits on Non-Gaussian component to ~0.1% in power

- Gaussianity observationally supports Inflation as much as Flatness... so the level of non-Gaussianity predicted by Inflation has to be looked after too
- for $\Phi \rightarrow \Phi + f_{NL} (\Phi^2 - \langle\Phi^2\rangle)$, simplest models predict $f_{NL} \sim O(0.1)$ (e.g. Salopek & Bond 90, Maldacena 2003) but other models also predict higher f_{NL} (~100) so that seeing or not-seeing primordial NG is important

- Current WMAP constraints (from T bispectrum): $f_{NL} \lesssim O(100)$ (CL 95%) and we can expect $f_{NL} \lesssim O(10)$ from Planck

Non-Gaussianity and Peak density

- Looking again at the CMB as setting the ICs
- The abundance of rare peaks at low and high z is strongly affected by skewness in the ICs:
  - Can we constrain f_{NL} using halo statistics like dN/dM or bias?
- So far, qualitative estimates of dN/dM have been made using (extended) Press-Schechter (Verde et al. 01, Scoccimarro 04, Sefusatti et al. 06)
- Simulations are obviously required to properly address the effect of f_{NL} on dN/dM (Kang et al. 07, Grossi et al. 07)

Large Scale structures depends on F_{NL}

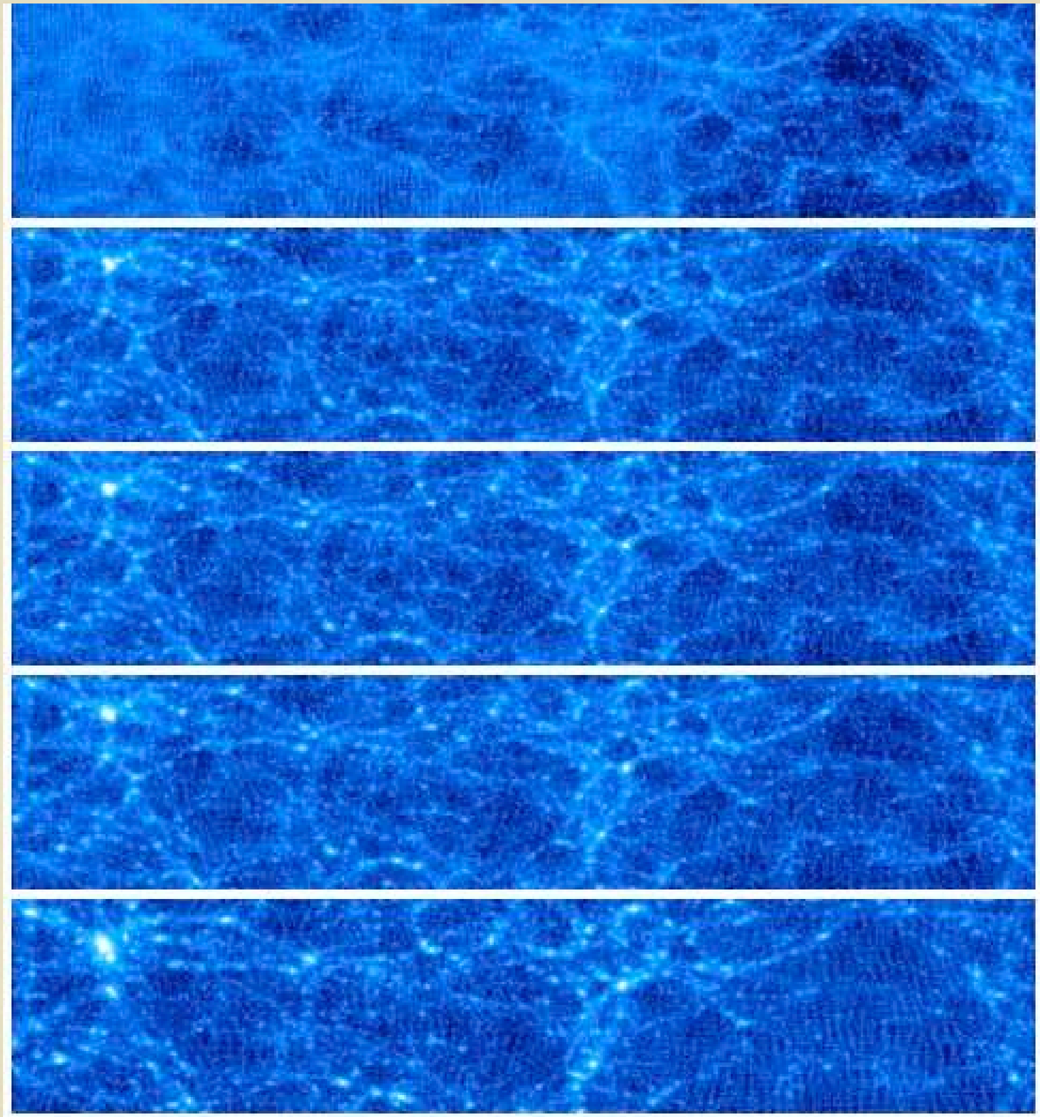
f_{NL}=-5000

f_{NL}=-500

f_{NL} = 0

f_{NL}=500

f_{NL}=5000



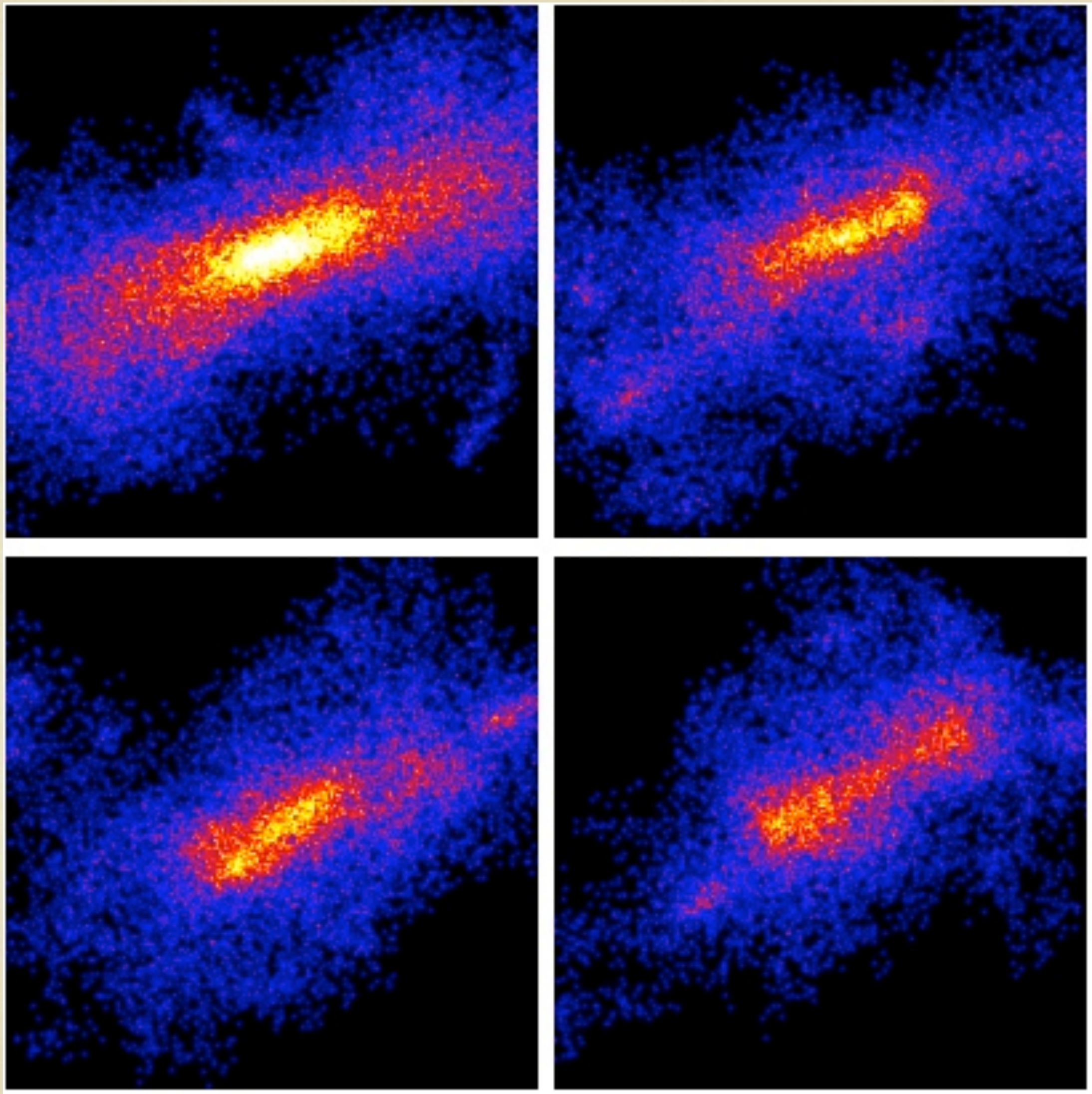
- Under-dense regions evolution decrease with F_{NL}
- Over-Dense regions evolution increase with F_{NL}

- Same initial Conditions, different F_{NL}
- Slice through a box in a simulation $N_{part}=512^3$, L=800 Mpc/h

One cluster at a time...

f_{NL}=+5000
$M = 1.2\ 10^{16}\ M_\odot$

f_{NL}=+500
$M = 5.9\ 10^{15}\ M_\odot$

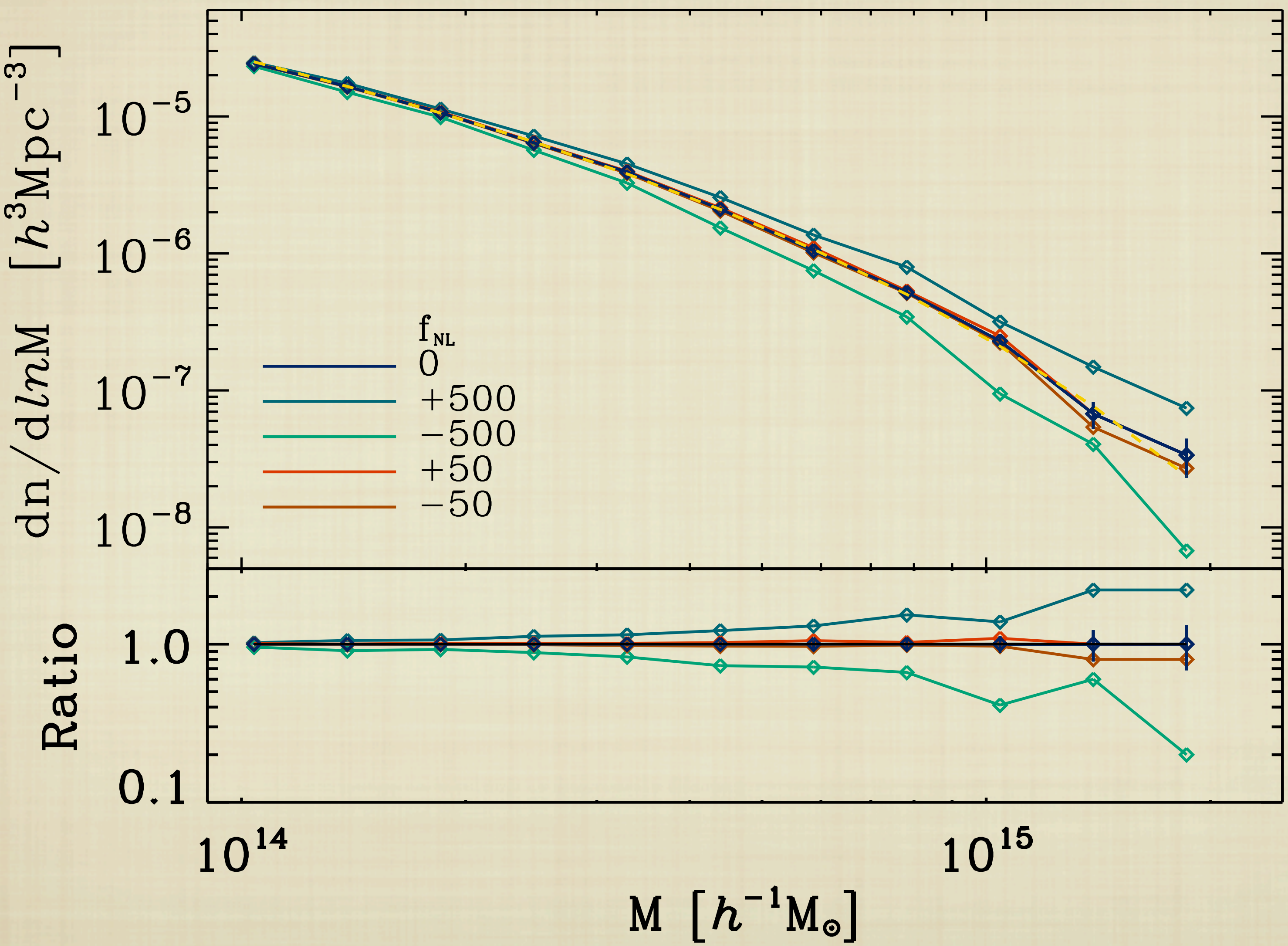


f_{NL}=0
$M = 5.1\ 10^{15}\ M_\odot$

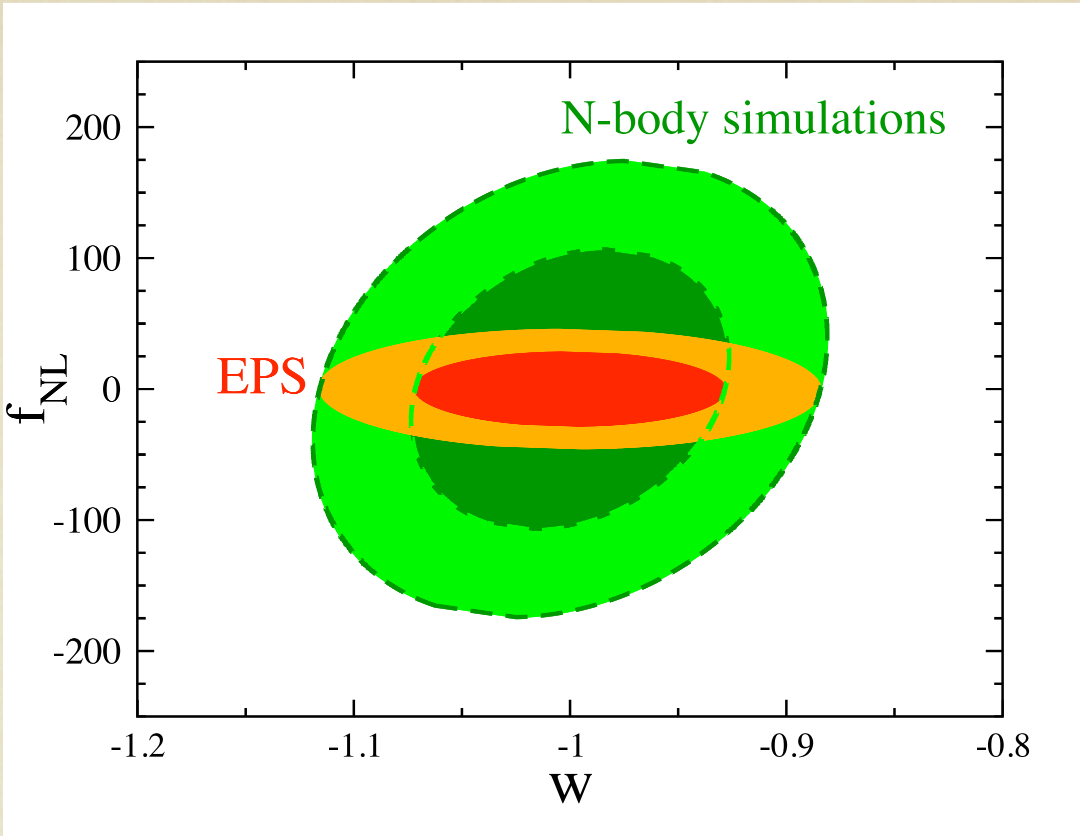
f_{NL}=-500
$M = 4.3\ 10^{15}\ M_\odot$

- Most massive cluster in a 512^3 simulation
- For small enough f_{NL}, same peaks arise, but with different heights (implying different masses)
- Can we extend to any cluster?

Measured Halo Mass functions



Measuring f_{NL} with dN/dM?



- We developed a simple but accurate enough prescription to compute the mass function as a function of cosmological parameters and f_{NL} (More later if you are interested)

- SPT like survey, ie 4000 sq. deg up to z=1.5
- ~7000 clusters with M>2 10^4 $M_\odot$
- $|f_{NL}| \sim< 100$
- Not really a nuisance for w

Halo clustering: Analytical estimates I

- NG parametrized as

$$\Phi = \phi + f_{NL}(\phi^2 - \langle\phi^2\rangle)$$

where Φ is a gaussian field

- It follows that

$$\nabla^2\Phi_{NG} = \nabla^2\phi + 2f_{NL}\left[\phi\nabla^2\phi + |\nabla\phi|^2\right]$$

- Since Φ is a Gaussian field, we know the joint statistics of Φ, $\nabla\Phi$ and $\nabla^2\Phi$ and using Poisson equation ($\nabla^2\Phi \propto \delta$) we can write down the PDF of δ_{NG} as a function of δ. That leads to e.g.

$$S_3 = \frac{\langle\delta^2_{NG}\rangle}{\sigma^4} = 12 f_{NL}\frac{\langle\phi\delta\rangle}{\sigma^2}$$

- Near peaks, $|\nabla\Phi|^2$ is negligible and we get

$$\delta_{NG} \simeq \delta(1 + 2f_{NL}\phi)$$

Halo clustering: Analytical estimates II

- With this formula,

$$\boxed{\delta_{NG} \simeq \delta(1+2f_{NL}\phi)}$$

- it is easy to compute the peak-peak correlation function ($\delta>\delta_{crit}$) (or the peak density) (à la BBKS)

$$\boxed{\xi_{pk} = b_L^2\left[\xi_{\delta\delta} + 4f_{NL}\delta_{crit}\xi_{\phi\delta}\right]}$$

- Or more interestingly the bias of the peak-peak correlation (a la BBKS)

$$\boxed{P_{pk}(k) = b_L^2 P(k)\left[1+4f_{NL}\delta_{crit}\frac{3\Omega_m}{2ar_H^2k^2}\right]}$$

- We obtain the following scale dependent bias

$$\boxed{\Delta b(k) = 2b_L f_{NL}\delta_{crit}\frac{3\Omega_m}{2ar_H^2k^2}}$$

- This result differs from the usual constant linear bias... but derivation of this result generally assumes locality of the "galaxy" formation process... whereas here our NG type is non local for δ . If we were to consider a NG of the type $\delta_{NG} = \delta + f_{NL}\delta^2$, then we would not find any scale dependent bias

Scale-dependent bias

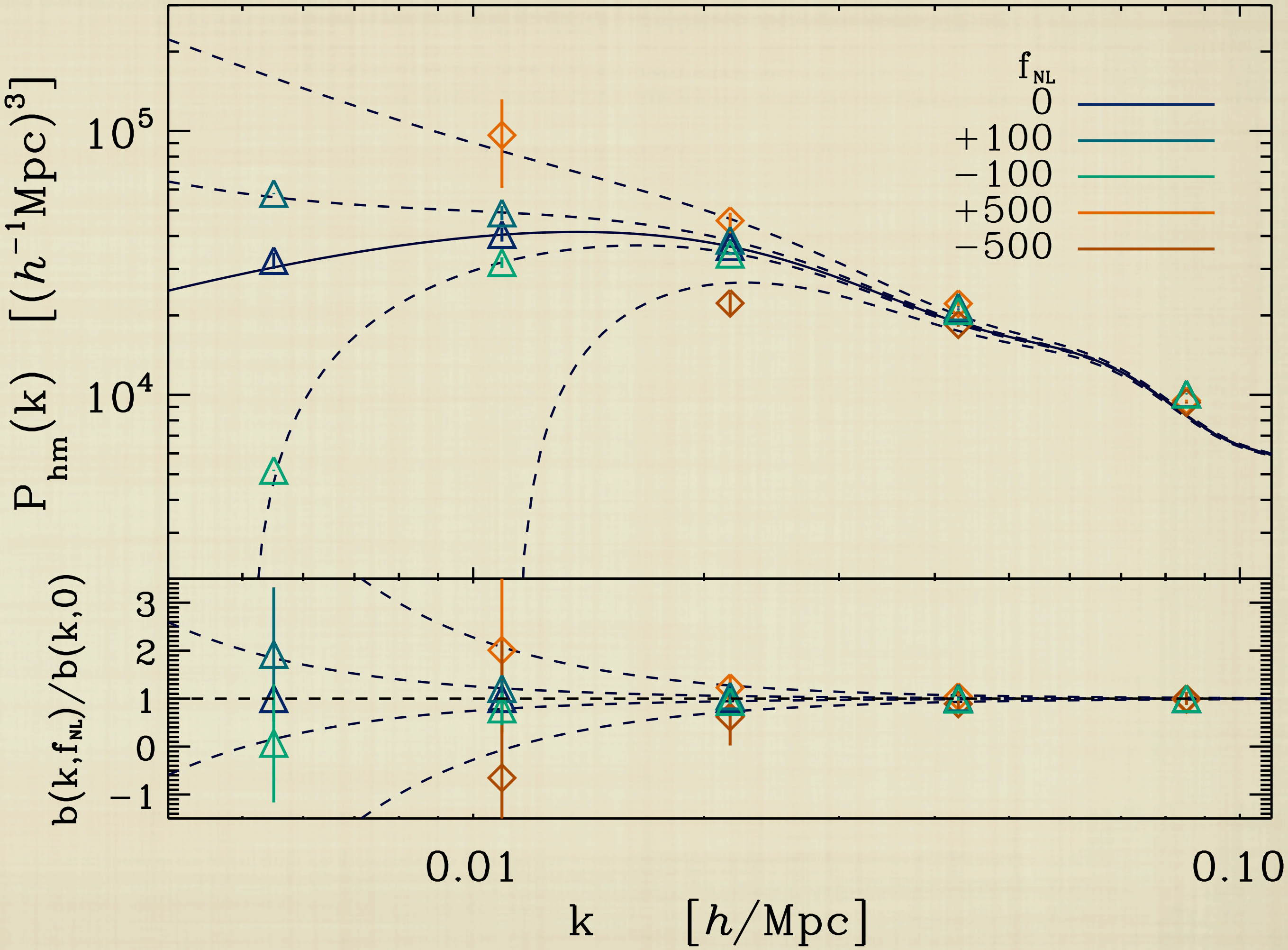
$$\Delta b(k) = 2 b_L f_{NL} \delta_{crit} \frac{3\Omega_m}{2 a r_H^2 k^2}$$

Halo-Matter cross power spectrum for

1.6 10^{13}<M<3.2 10^{13} $M_\odot$

b~2.3

bias ratio



- Strong scale dependance in the linear regime
- Good agreement with sims and analytics
- 512^3 (1024^3) simulations with box size 800 (1600) Mpc/h

Constraints from P(k): Galaxy surveys, BAO, and ISW

- To measure the large scale bias offers a new opportunity to measure f_{NL}
- This effect should be easy to measure since there is a very specific k and z dependance on large scales
- A LRG survey (b_L=2, n=4. 10^{-5} (h^{-1}Mpc$)^{-3}$) out to z=0.7 could give $f_{NL} \leq 5\ f_{sky}^{-1/2}$
- This effect will also shift the first BAO peak at k=0.07h/Mpc by 0.4% at z=1 for f_{NL}=100, which would lead to a 1~2% bias in w if unaccounted for
- It also opens the (unexplored yet) possibility to use void statistics to measure f_{NL}. Can we do that with current (Lyα?) SDSS data?
- Results studied and confirmed by various groups (Matarrese & Verde 07, Afshordi & Tolley 07, Slosar et al. 07, Desjacques, Seljak & Iliev 08)

First constraints

- Most powerful currently are SDSS photometric quasars and LRGs
  - Slosar et al. 07 Finds -29<f_{NL}<69 (95% CL)
  - WMAP5 Temperature bispectrum : -9<f_{NL}<111 (95% CL)
  - Together : -1<f_{NL}<70 (95% CL)

- Exciting and simple follow-up idea by seljak 08
  - By using different populations with different bias, you can measure the relative bias and not the absolute bias. This avoids cosmic variance.
  - Prospects for next generation LSS are f_{NL} ~1 (Euclid, Adept) or ~8 for BOSS

Slosar et al. 07
seljak 08, 09
McDonald & Seljak 08

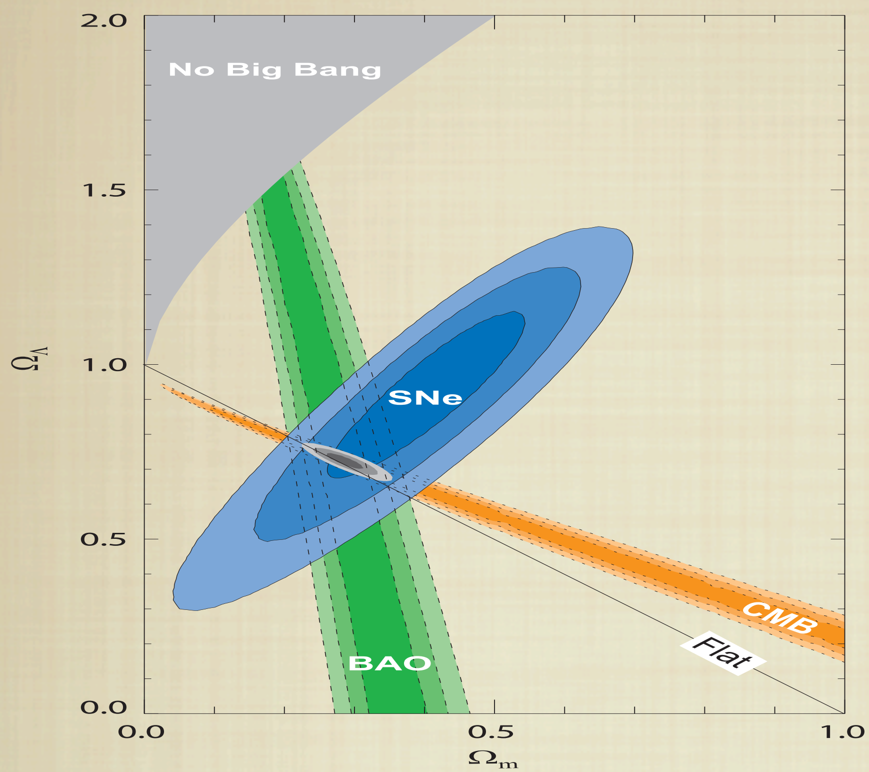
Summary

- We proposed a new and measurable observational signature of primordial non-gaussianity (constant f_{NL} type)
- We proposed a simple and accurate fitting formula for the halo mass function as a function of f_{NL}
- We showed how to calculate peak statistics for f_{NL} cosmologies and in particular the bias shape
- We tested our predictions against N-body simulations and fund a remarkable agreement
- As a consequence, the measure of the large scale halo biases should lead to f_{NL} constraints superior to Planck, i.e. $f_{NL} < O(1)$
- All those conclusions rely on one type of "local NG", what happens if we take into account $f_{NL}(k)$ for example remains to be studied

Outline

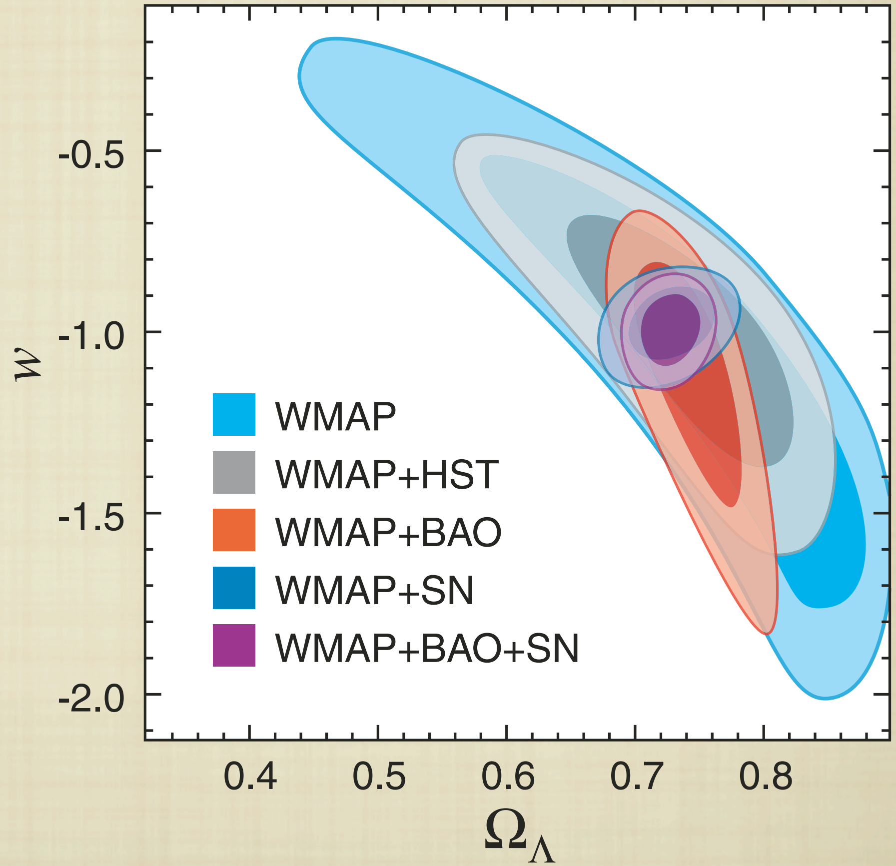
- Do we live in an Inflationary Universe?
  - How can we address this question with coming large scale surveys?
- What is the nature of Dark Energy? Is there really Dark Energy?
  - How to test gravity on cosmological scales?

Dark Energy: the evidences



Free Ω_K

Kowalski et al. 08



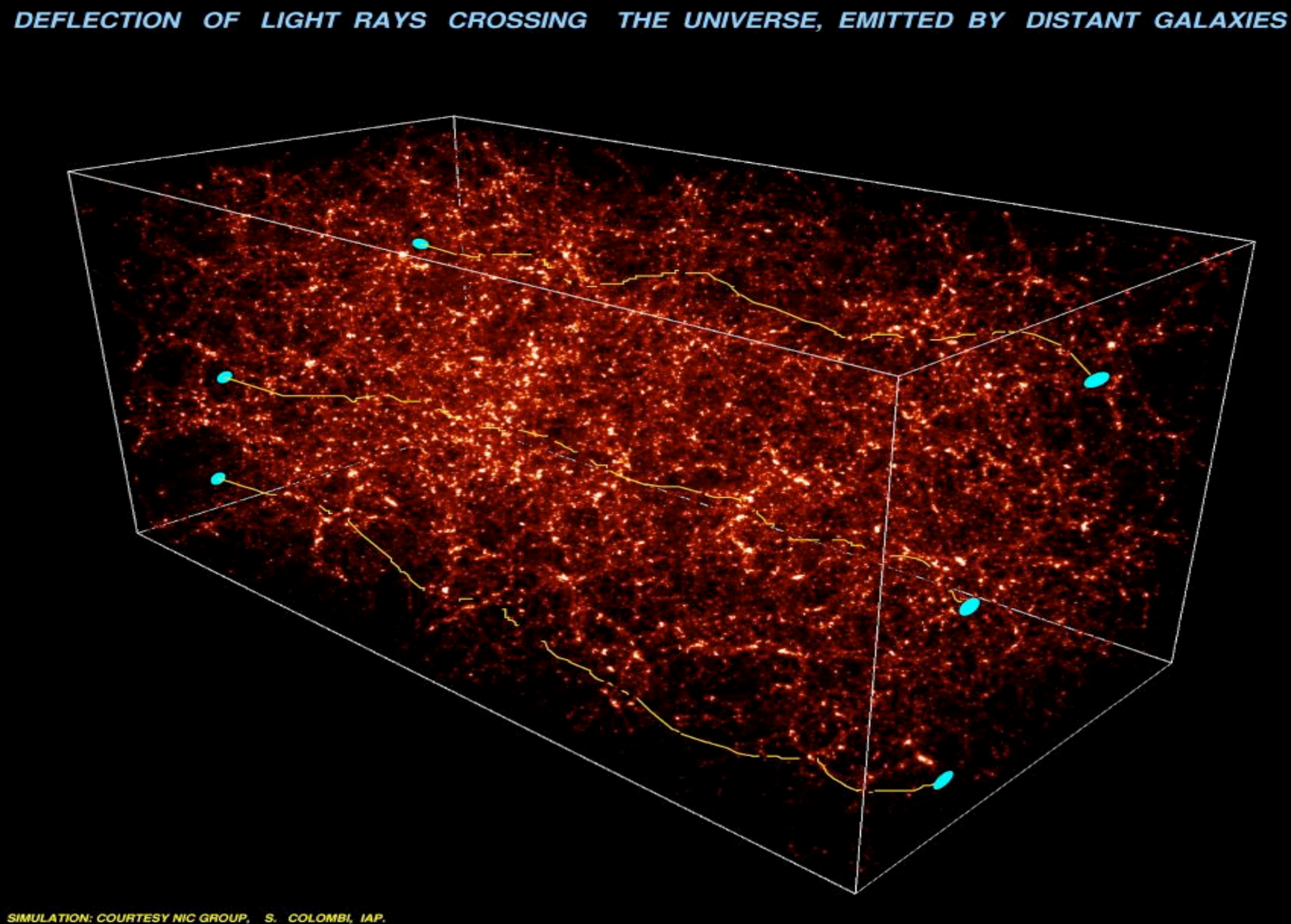
Ω_K =0

Komatsu et al. 08

Learning about Dark Energy

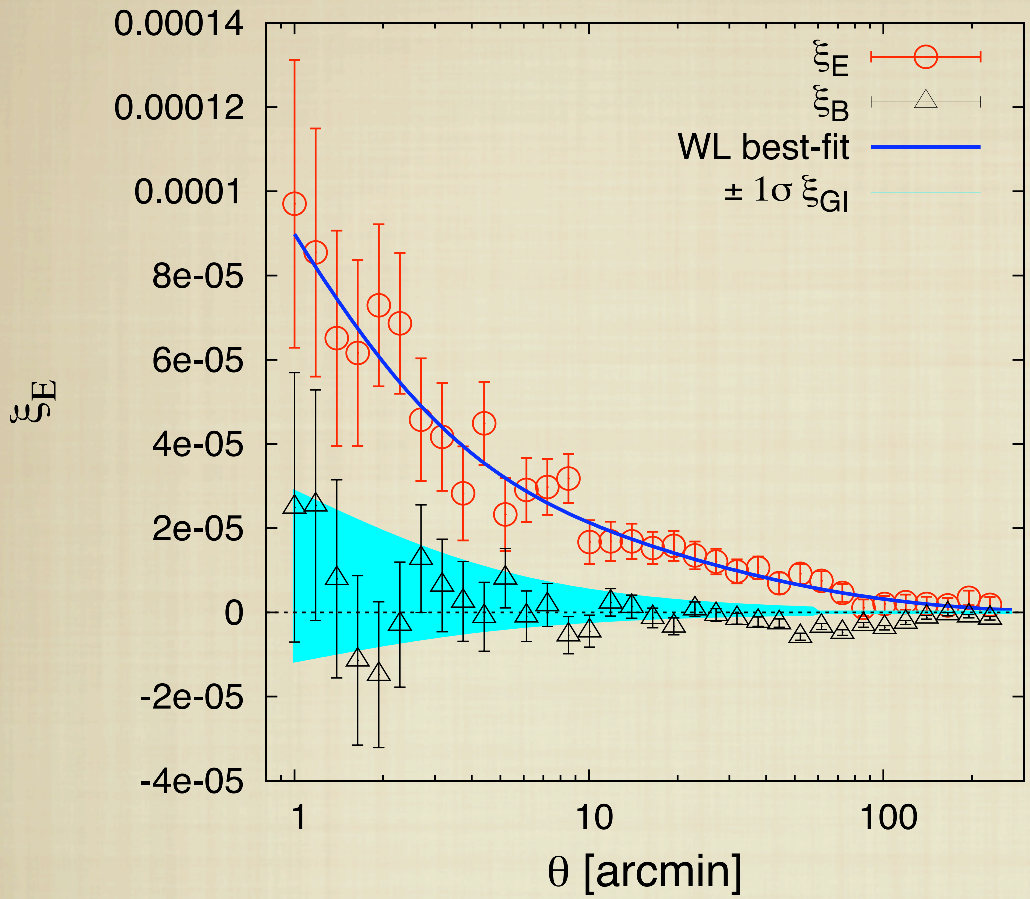
- Evidences for Dark Energy are solid and diverse
  - Geometry (SN, BAO, peaks of the CMB)
  - Growth of perturbations (Galaxy surveys, Cluster counts, WL)
- But theoretical interpretation is more difficult, i.e. new physics
  - is DE a new "substance", e.g. a cosmological constant, or a quintessence field, ...?
  - Is it a breakdown of gravity on cosmological scales? Is it a manifestation of extra-dimensions (DGP) or more complex metric theory like f(R) theories?
  - Can we distinguish both?
    - It will require both geometry and growth... but it is not theoretically granted at linear order (e.g. Bertschinger & Zukin 08)

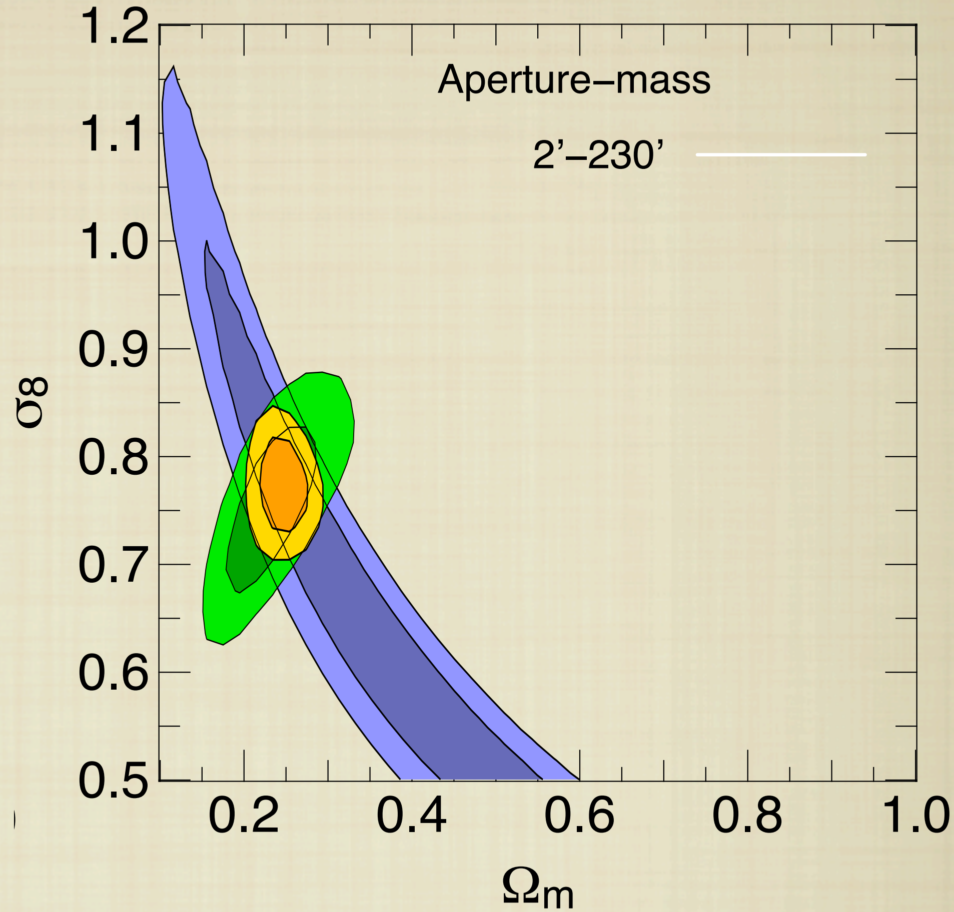
Weak-gravitational lensing



courtesy of S. Colombi, IAP

Cosmic shear holds its promises





- CFHTLS current analysis: 57 square degree (3 times more already observed and now being analyzed), down to a magnitude i'=24.5
- We are now able to measure weak-lensing in the linear regime, i.e. from 1' up to 4 Deg here

L. Fu et al. 07

A first (simplistic) approach

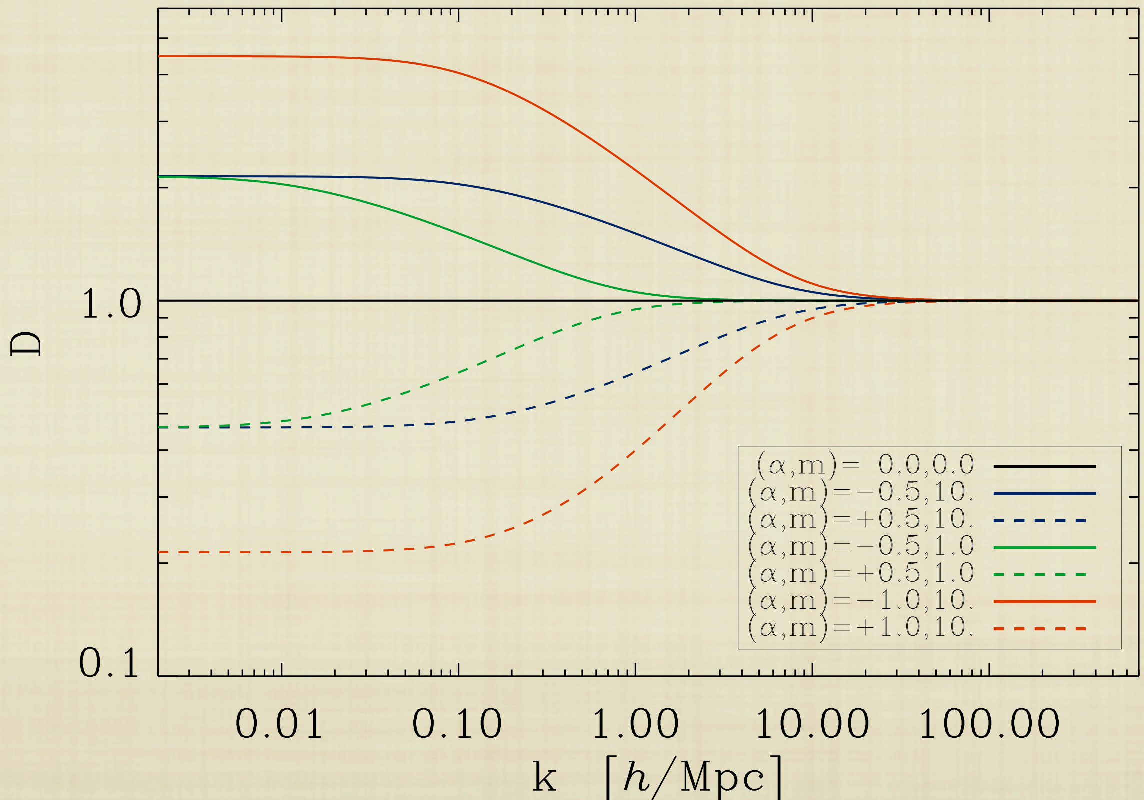
- Adding a Yukawa term to the usual Newtonian potential
- "Generic" extension to a linearized metric theory of gravity

$$\Phi(\mathbf{r}) = (1-\alpha)\Phi(\mathbf{r},0) + \alpha\Phi(\mathbf{r},m)$$

$$\Phi(\mathbf{r},m) = G\int \frac{\rho(\mathbf{r}')d^3\mathbf{r}'}{|\mathbf{r}-\mathbf{r}'|}e^{-m|\mathbf{r}-\mathbf{r}'|}.$$

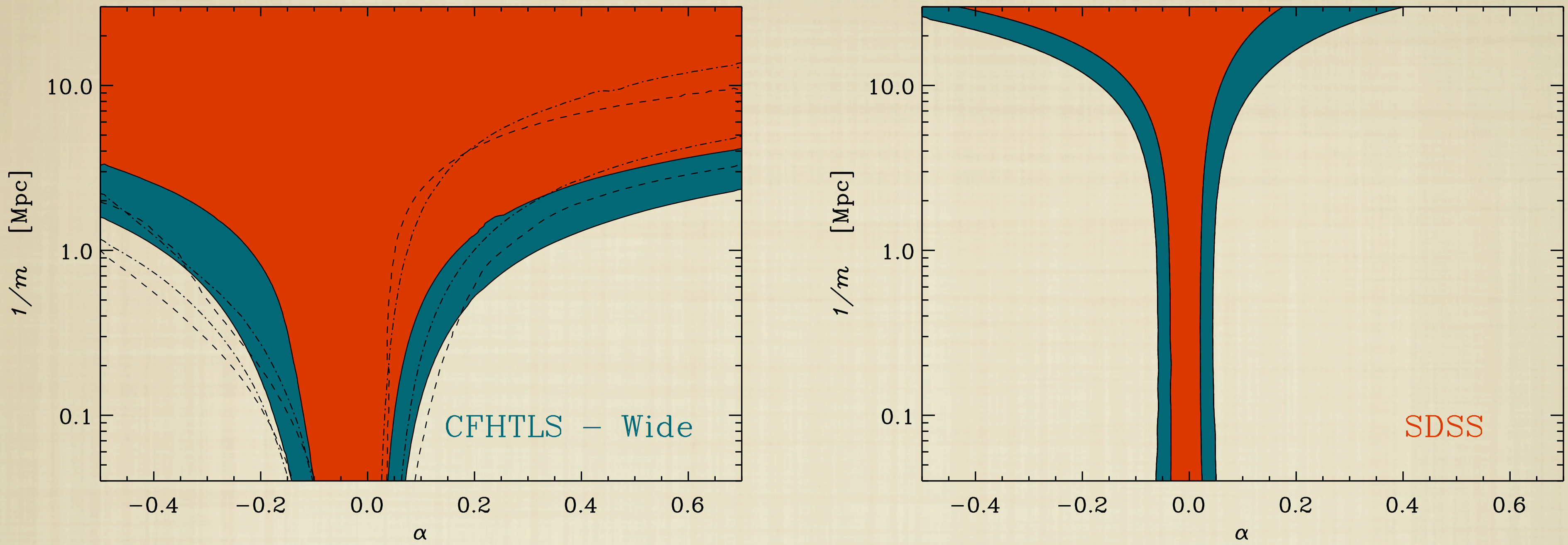
$$\tilde{\Phi}(\mathbf{k},a) = -\frac{3}{2}\frac{H_0^2\Omega_{m0}}{a}\frac{\tilde{\delta}(\mathbf{k},t)}{k^2}f(\mathbf{k},a)$$

$$f^{Yuk}(\mathbf{k}) \equiv f(\mathbf{k}) = 1 - \alpha\frac{1}{1+\left(\frac{k}{a\ m}\right)^2}.$$



O.D., M. Martig, Y. Mellier et al. 07
Sealfon et al. 05
White & Kochanek 91
Zhytnikov & Nester 94
...

Any deviation from GR?



- We do not find any evidence from deviation from GR on scales > 0.4h/Mpc and <10 h/Mpc
- Because of projection effects and sheer volume difference, SDSS performs much better
- A combined limit on m is : m>67.6Mpc (95%CL), that is m<9.4 10^{-32} eV
- Simple parametric approach, only a foretaste of what is to come
- Conclusions are limited to the parametrization we choose
- A more promising approach might consist in testing GR directly through a set of consistency relations

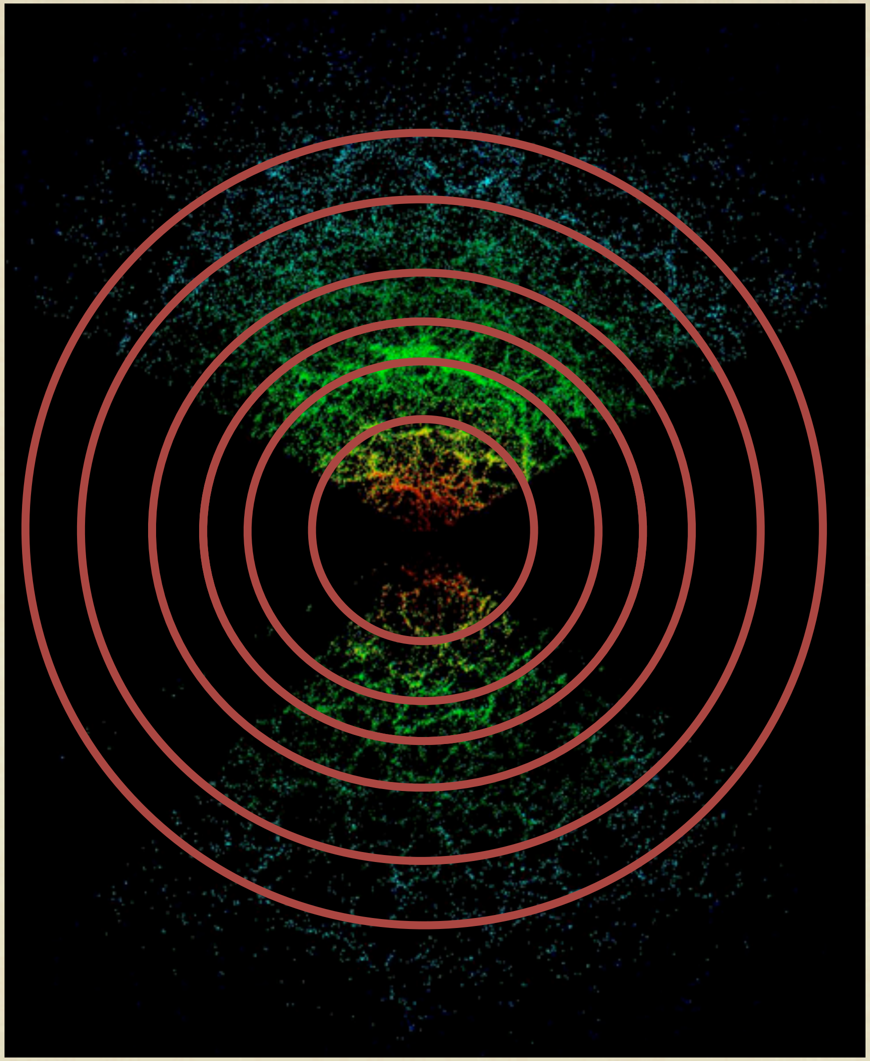
O.D., M. Martig, Y. Mellier et al. 07

A natural extension

- Given the theoretical uncertainties, i.e. the large freedom in the choice of theories to test, it seems more sensible to develop a model independent approaches
- A promising program consists in developing a set of self-consistency cosmological tests for GR
- As a first step in developing this program, we study how to use jointly galaxy and weak gravitational surveys
- This starts from the simple fact that any weak-lensing survey is also a galaxy count survey
- In particular, we show how to predict the weak gravitational lensing signal from a galaxy survey
- We will combine probes of δ_M and of $\nabla(\Psi-\Phi)$ to test both the Poisson equation and the anisotropic stress constraints

Y.-S. Song & O.D. 08

A simple test



SDSS

- We compare the continuous integral of the lensing kernel to a discretized version build with galaxy templates

Predicting the weak gravitational lensing from galaxy density

- Quasi-static evolution of perturbations, i.e. perturbations constant within a redshift shell
- From the galaxy projected density, we can build a template for the lensing signal

$$C_l^{i\,gg} = \frac{2\pi^3}{(l+1/2)^3}\Delta D_i D_i W^g(D_i) W^g(D_i)\Delta_{\Phi\Phi}(a_i,k)\ .$$

$$C_\ell^{s\,dd} = \frac{2\pi^2}{l+1/2}\sum_{i=1}^{n}\Delta D_i D_i \frac{4(D_s-D_i)^2}{D_s^2 D_i^2}\Delta_{\Phi\Phi}(a_i,k)$$

- Discretized form of Poisson equation $k^2\phi = 4\pi G a^2 \rho_m \delta_m$

$$\Delta^i_{\Phi\Phi} = \frac{9}{8\pi^2(l+1/2)}\frac{D_i^3}{\Delta D_i}\left(\frac{dz}{dD}n_i b_i\right)^{-2}\frac{\Omega_m^2 H_0^4}{a_i^2}C_\ell^{i\,gg}.$$

$$\tilde{C}_\ell^{s\,dd} = \sum_{i=1}^{n}\frac{1}{b_t^{i\,2}}F_\ell^i$$

$$F_l^i = \frac{9}{(\ell+1/2)^2}\frac{D_i^2(D_s-D_i)^2}{D_s^2}\left(\frac{dz}{dD}n_i\right)^{-2}\frac{\Omega_m^2 H_0^4}{a_i^2}C_\ell^{i\,gg}$$

Measuring the bias

- Using galaxy-lensing correlation

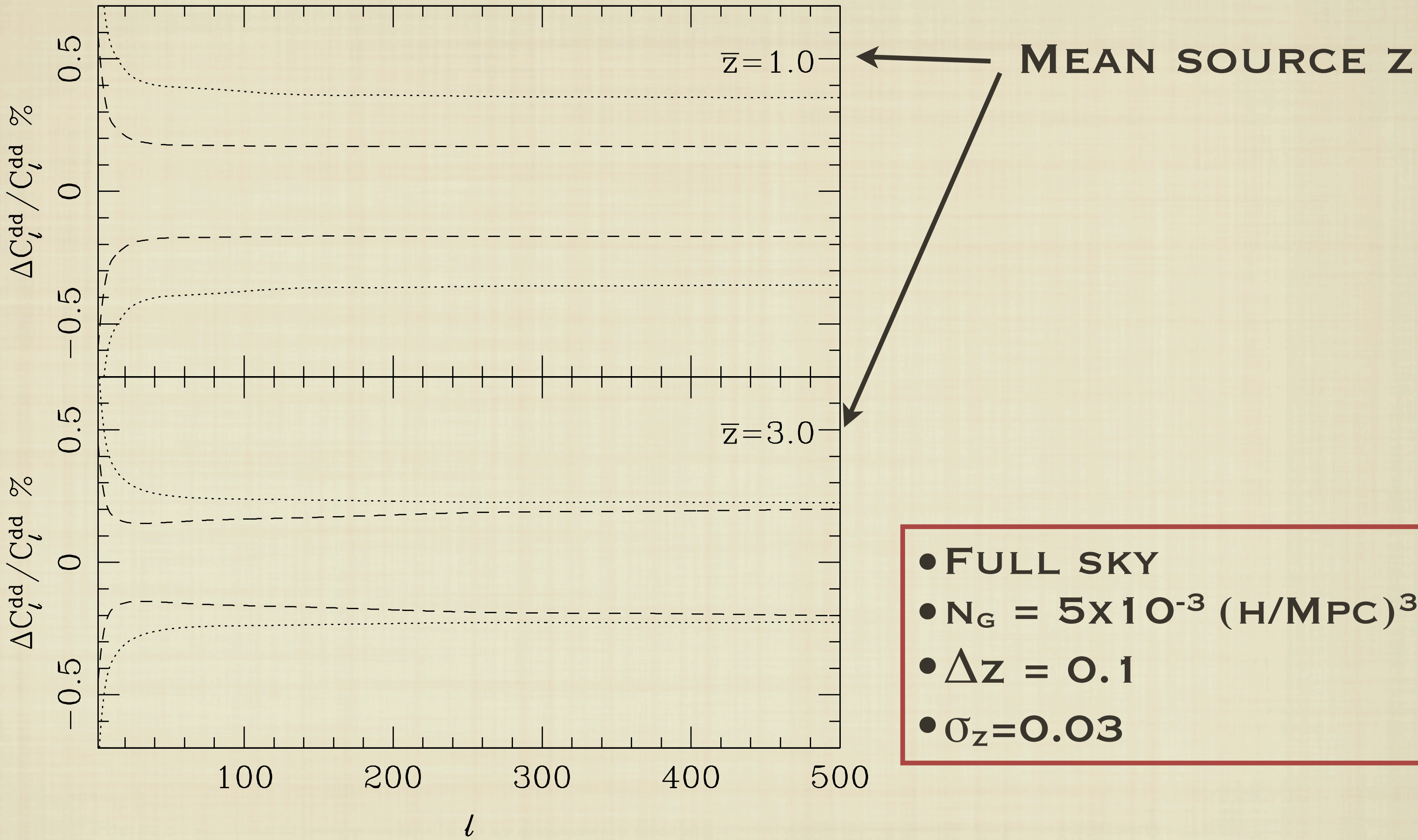
$$\left(\frac{S}{N}\right)^2_j = \sum_{s=0}^{3.2}\sum_{l=l_{\min}}^{l_{\max}} \frac{f_{\rm sky}(2l+1)(C_\ell^{\delta_g^j d_s})^2}{(C_\ell^{\delta_g^j\delta_g^j}+N_\ell^{\delta_g^j\delta_g^j})(C_\ell^{d_s d_s}+N_\ell^{d_s d_s})}$$

z_j	0.05	0.55	1.05	1.55	2.05	2.55	3.05
$(S/N)_j$	160	430	300	170	88	35	6.6
$\Delta b_j/b_j(\%)$	0.63	0.23	0.33	0.58	1.1	2.8	15

- Using Velocity or Galaxy velocity measurements
  - Bias not degenerate with other cosmological parameters like w_0 and w_a

z_j	0.05	0.55	1.05	1.55	2.05	2.55	3.05
$\frac{\Delta b_j}{b_j}(\%)$	0.75	0.37	0.33	0.38	0.45	0.53	0.57

A powerful method

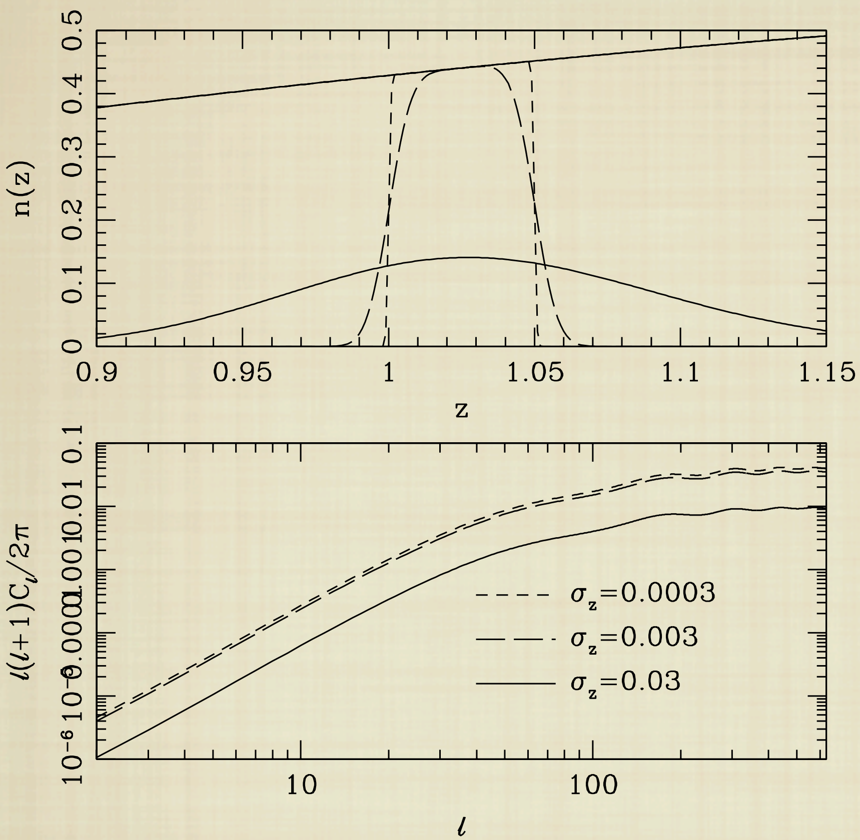


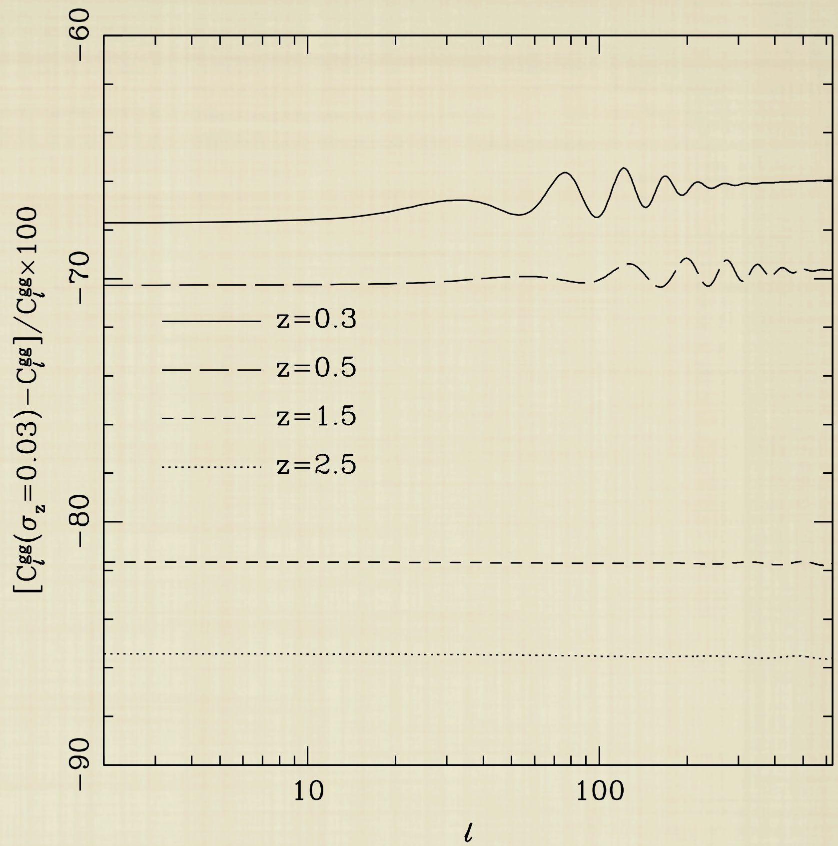
- Full sky
- N_G = 5x10^{-3} (h/Mpc)^3
- Δz = 0.1
- σ_z=0.03

- Statistical errors only
- Promising results but there are complications
- Promising... if accurate

Photo-z effects

$$\sigma_{photo}(z) = \sigma_z(1+z)$$

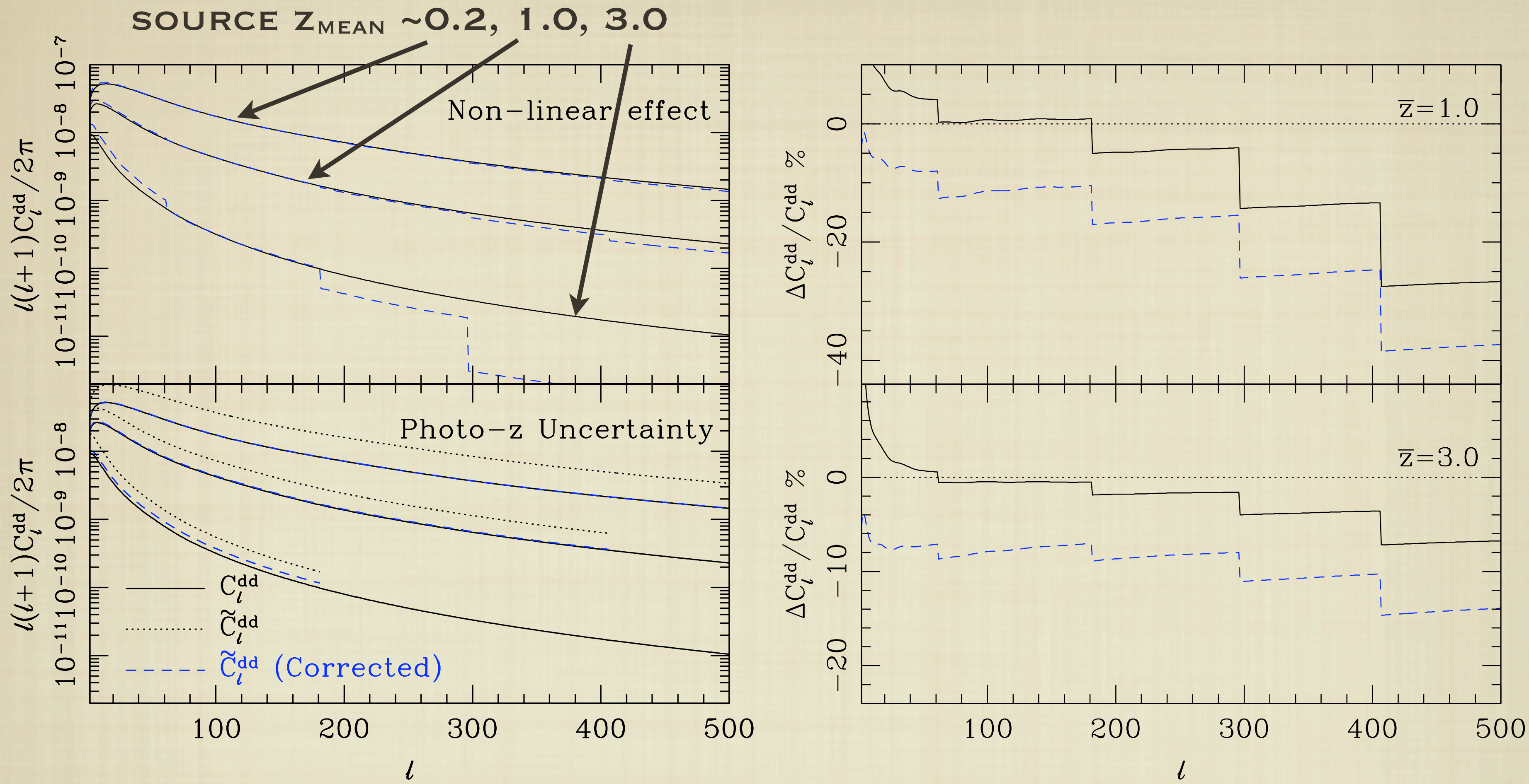




$$\boxed{C_\ell^{gg}(z_i) \propto \int k^2 dk P_{mm}(k) \left[\int_{z_{i,min}}^{z_{i,max}} dz A\, n_g(z)^2 j_\ell(k\eta)\right]^2}$$

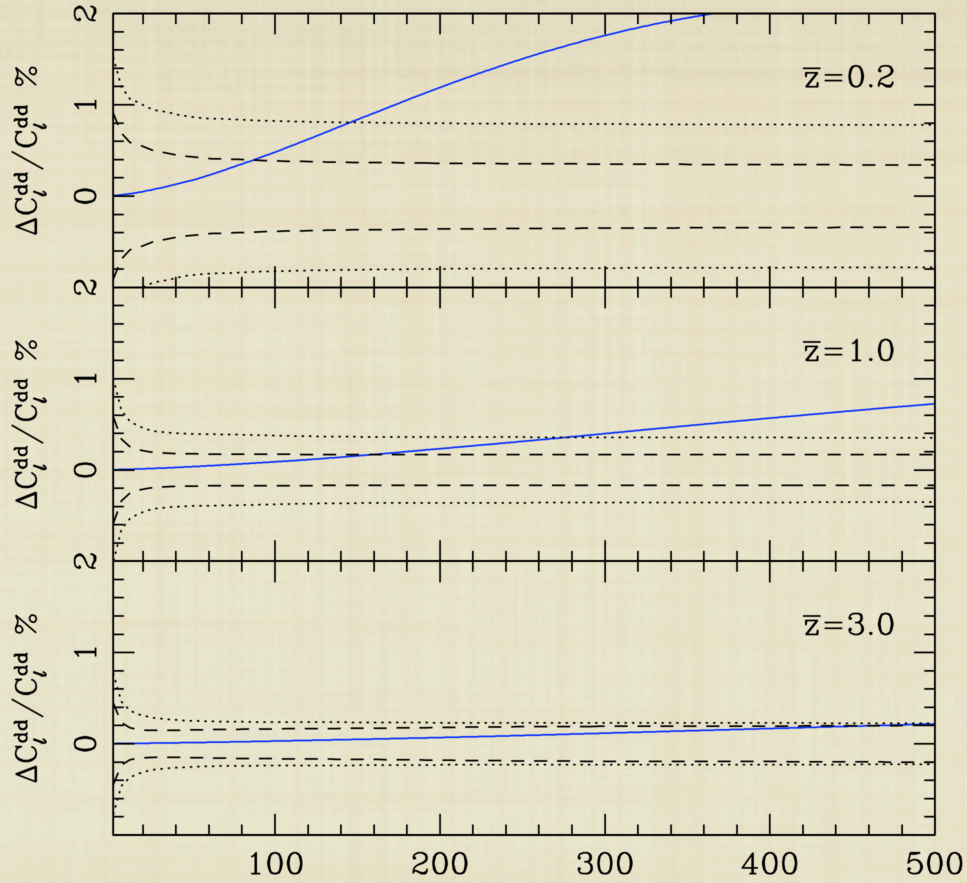
- When projecting the galaxy over-density, inaccuracy in photo-z introduces an extra bias, almost linear

Predicting the weak gravitational signal



- Slices with Δz=0.1, full sky, σ_z = 0.03, n_g = 5×10^{-3} $(h/\mathrm{Mpc})^3$
- Source distribution at 0.2, 1.0, 3.0
- A few percent accuracy seems possible when corrected for various observational artifacts

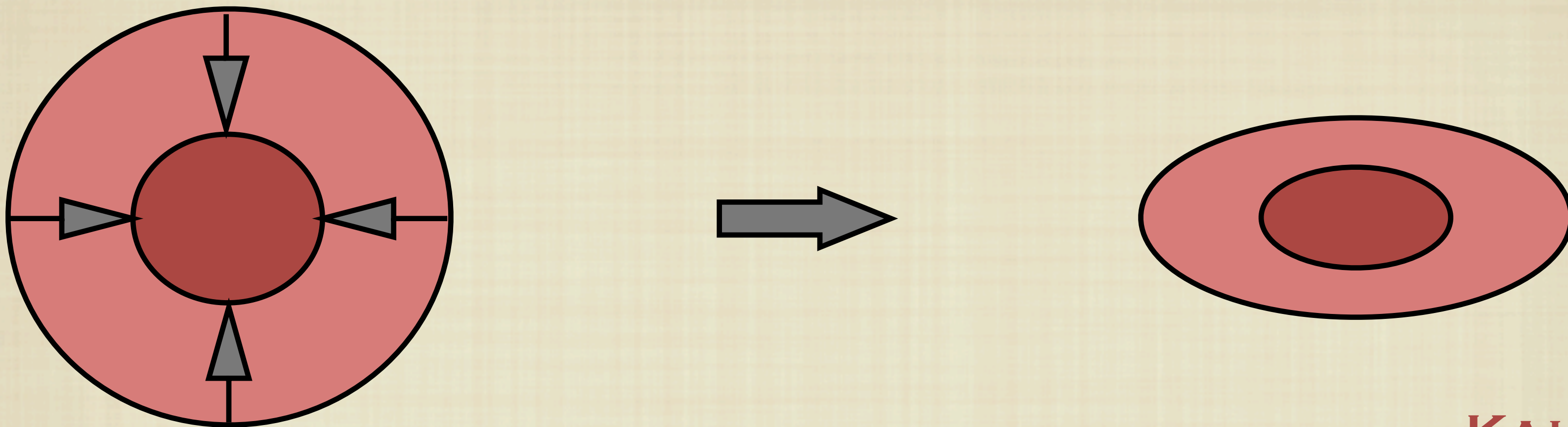
What do we learn?



- Several order improvement in constraints of f(R) theories
- Current constraints on $B_0<1$ (Song et al. 06), blue curve here corresponds to $B_0\sim10^{-5}$
- More generally a test of Poisson equation and of the lack of shear stress
- Only one step in a more general program to be developed

Redshift distortions

- On linear scales

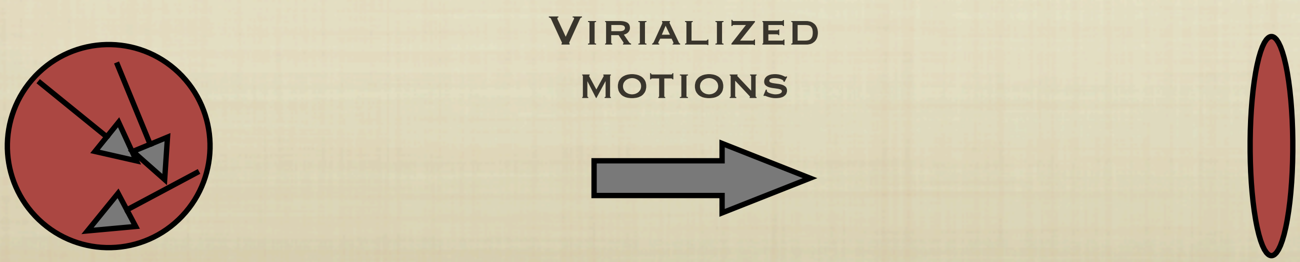


Kaiser 87

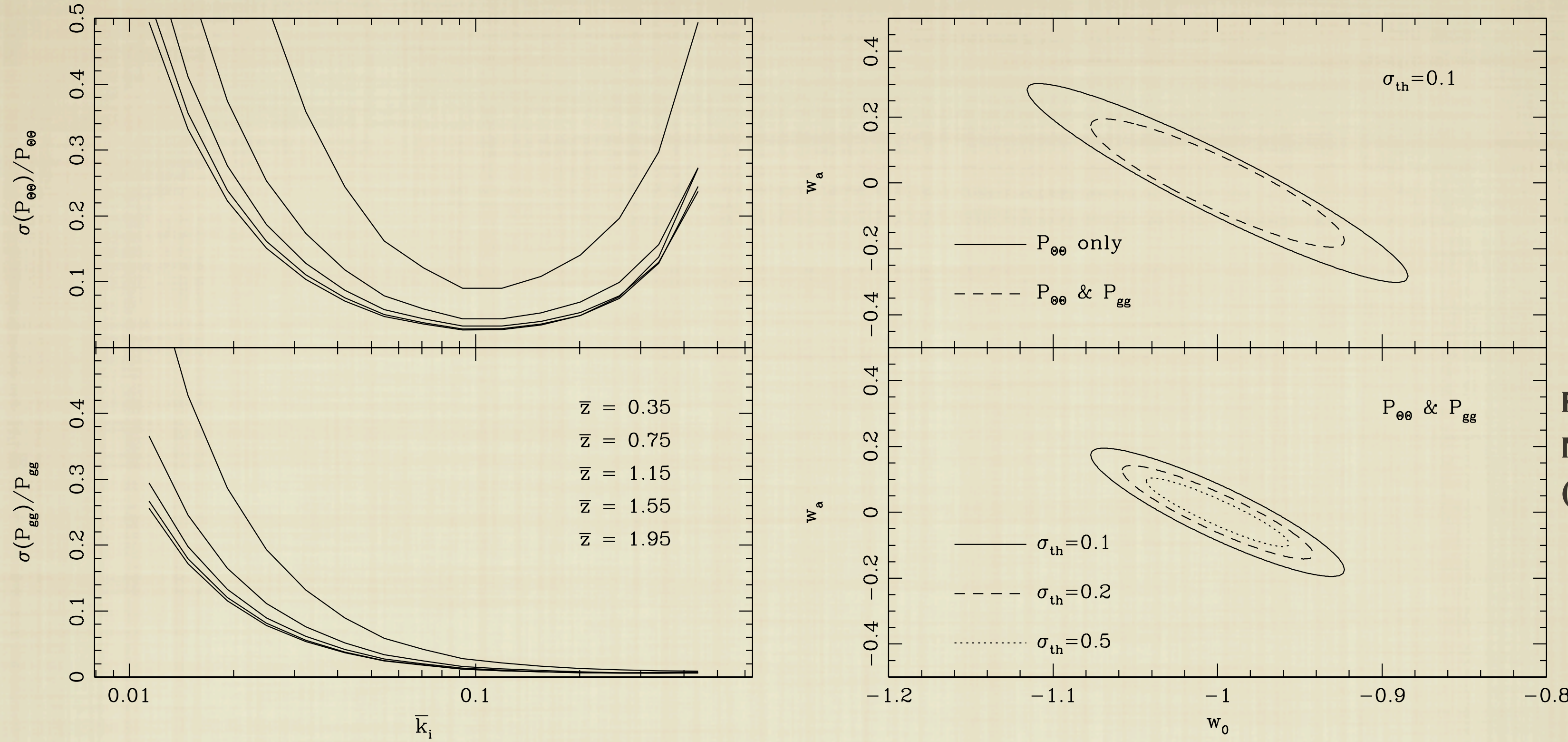
$$\delta_k \longrightarrow b\delta_k(1 + f\mu^2/b)$$

$$\boxed{\mathrm{P}_g^{obs}(\vec{k}) = \left[P_{gg}(\vec{k}) + 2\frac{\mu^2}{aH}P_{g\theta_g}(\vec{k}) + \frac{\mu^4}{(aH)^2}P_{\theta_g\theta_g}(\vec{k})\right] F(k^2\sigma_v(z)^2\mu^2)}$$

- On non-linear scales, “Finger of god effect”



Measuring velocities with spectroscopic surveys



Fsky=1
$N_G = 5\times10^{-3}$
$(h/Mpc)^3$

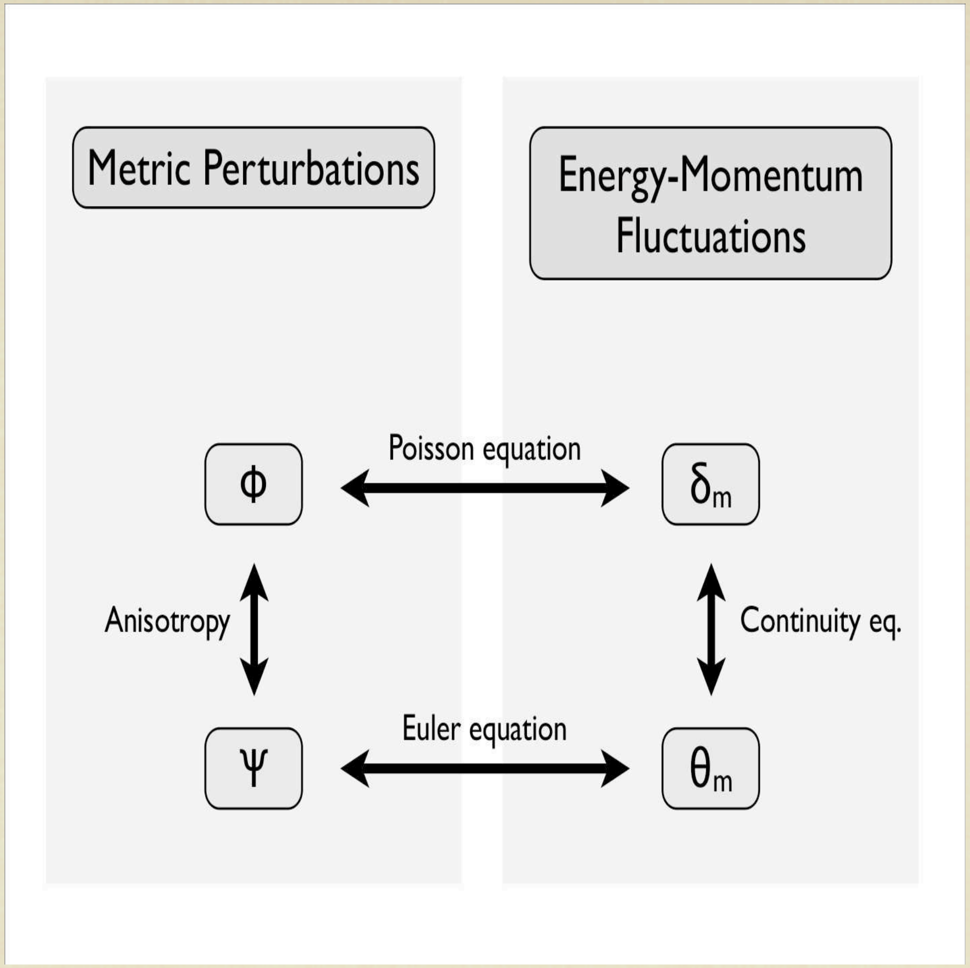
$$\boxed{F_{\alpha\beta}(k_i, z_j) = \int \frac{k^2 dk}{2(2\pi)^2} \int_{-1}^{+1} d\mu V_{eff}(k,\mu,z_j) \frac{\partial P_g(k,\mu,z_j)}{\partial p_\alpha} \frac{\partial P_g(k,\mu,z_j)}{\partial p_\beta}}$$

$$V_{eff}(k,\mu,z) = \left[\frac{nP_g(k,\mu,z)}{nP_g(k,\mu,z)+1}\right]^2 V_{survey}(z)$$

- Unbiased probe of δ_M
- Limited by non-linear effects for k>0.2 h/Mpc
- Required large volume spectroscopic survey

Song and Percival 08, McDonald & Seljak 08, White et al. 08

A closed web of relations



- If we could probe independently each side of each equations, then we are de facto testing GR
- Breaking any one would hint at different type of new physics
- Can we do it in practice?

What are the probes available?

- Probing Ψ:
  - Velocities through large scale redshift distortions
- Probing δ_M
  - Velocities through redshift distortions
  - Galaxy surveys, but beware of bias, redshift distortions (non-linear) and photometric redshift uncertainties
- Probing $\nabla(\Psi-\Phi)$
  - Weak gravitational lensing

- DE clustering, Dark sector interactions, DGP, f(R) will alter significantly these relations

Summary

- Future generation surveys (LSST, BOSS, etc.) hold exciting promises
  - We will learn about DE and its various parametrization
  - We will also be able to construct various self-consistency tests of GR. This is probably under-emphasized so far and should be as important
- We presented one example, based on testing the Poisson equation and the lack of anisotropic stress on large scales using galaxies to predict the lensing signal
- After having studied various possible contamination of this test, it seems practical and we plan to apply it to current data, e.g. CFHTLS
- Only a first step and large program of self-consistency test of GR needs to be developed

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