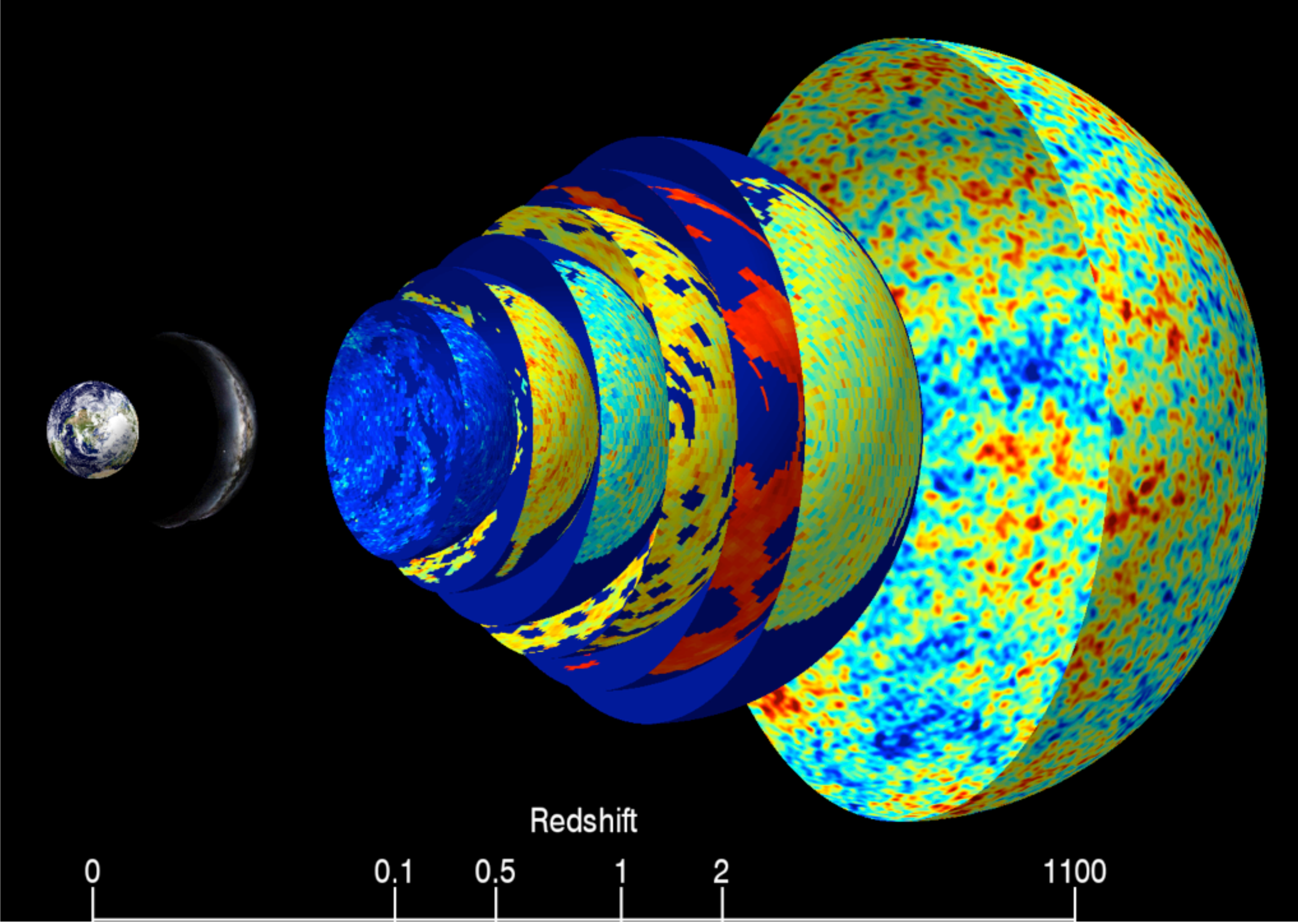


Tommaso Giannantonio
LMU Munich & Excellence Cluster

Improved PNG constraints with Galaxy Clustering and ISW

Santander, 25.6.2013

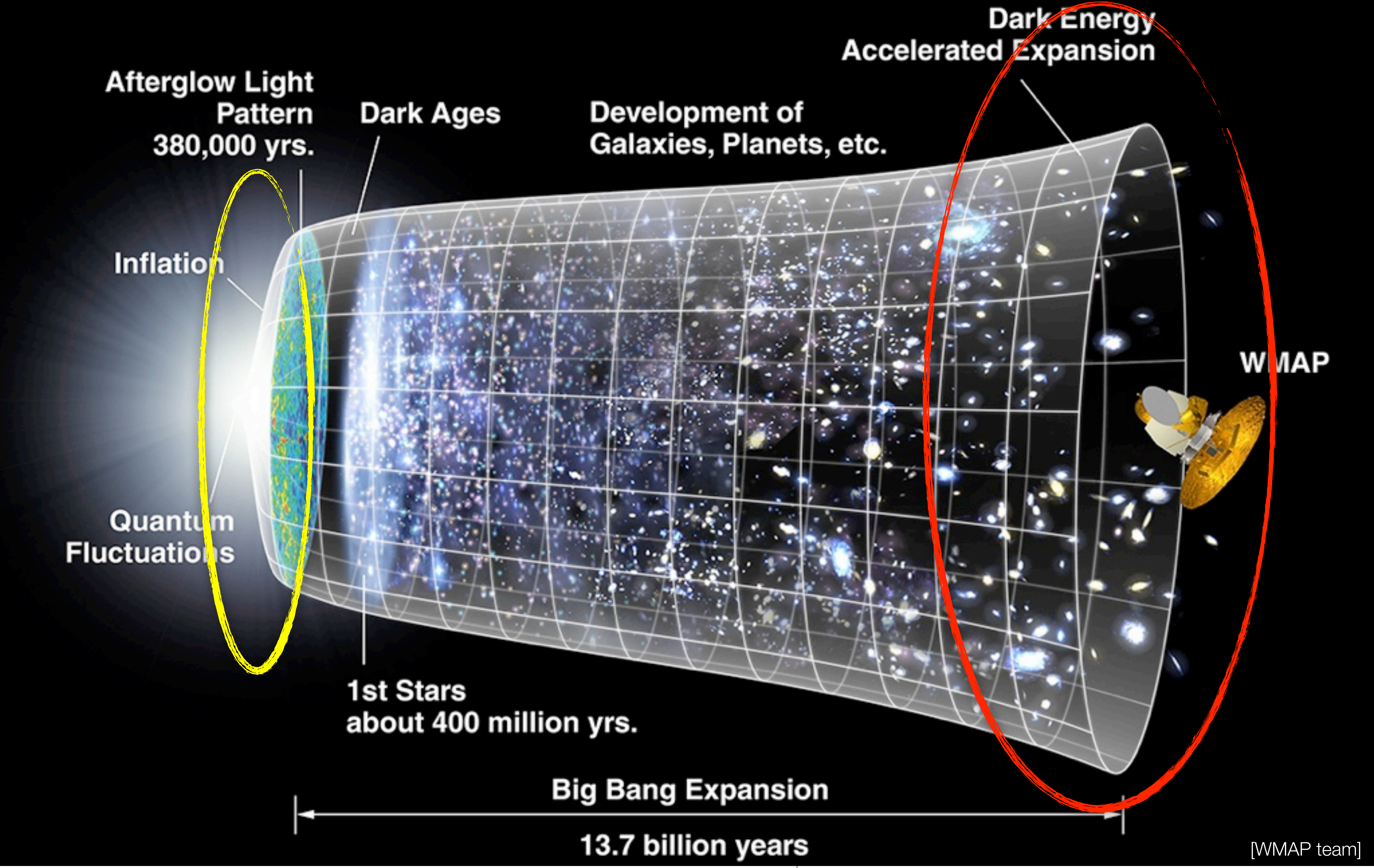
Outline

- Primordial non-Gaussianity (PNG) & the large-scale structure (LSS)
- Data: Galaxy clustering and correlation with CMB (ISW effect)
- Systematics analysis
- Results on PNG
- Extension to galaxy clusters
- Outlook & conclusions

TG et al., arXiv:1303.1349, PRD submitted

Mana, TG et al., arXiv:1303.0287, MNRAS accepted

Collaborators: A. Ross, W. Percival, R. Crittenden, J. Weller, M. Kilbinger, A. Mana, G. Hütsi, B. Nichol



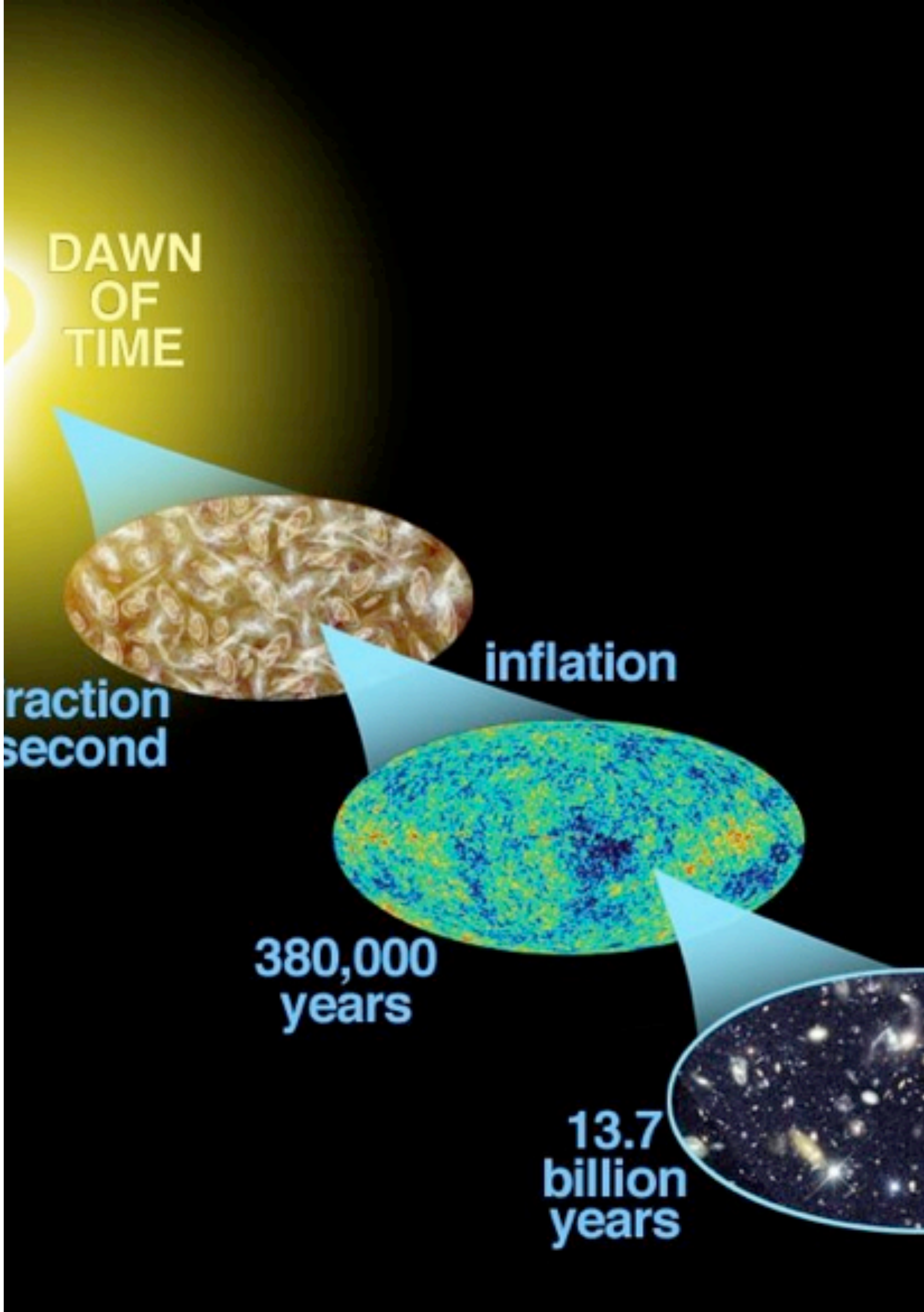
Inflation and dark energy

Open questions
at early and late times

The origin of cosmic perturbations

- Primordial quantum fluctuations
- Stretched by inflation
- Horizon exit at t*(k)
- Super-horizon evolution
- Seeds for radiation (CMB) and matter (LSS) structure

Observing the present Universe, we can learn of its beginning!



[Credit: WMAP]

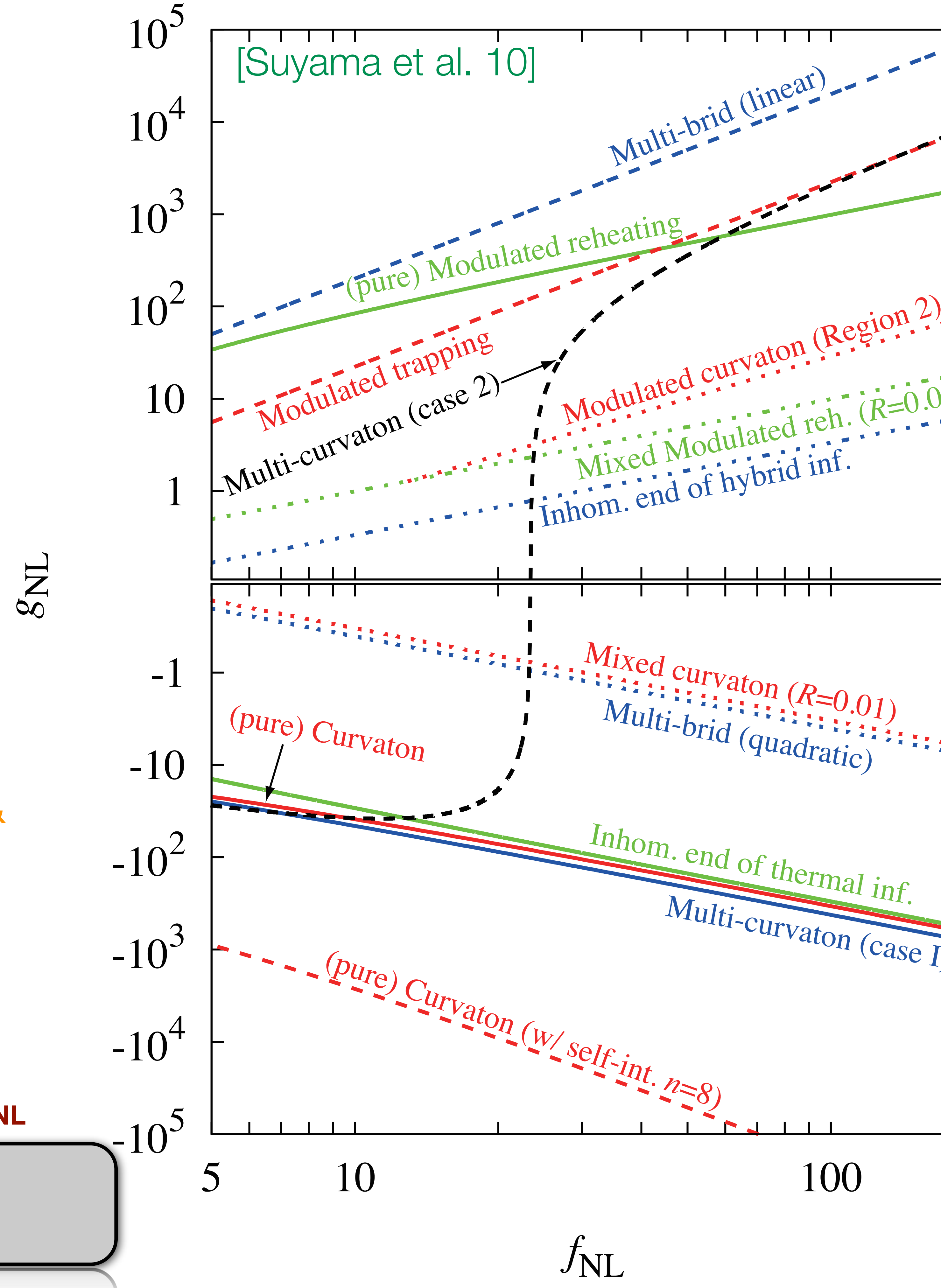
Constraining the early universe

- **(Too) many inflation models** available:
  - single / many field
  - slow or fast decay, what kinetic terms?
  - cyclic/ekpyrotic models...
- Simplest single-field models predict:
  1. near-flatness ✓
  2. nearly scale-invariant power spectrum ✓
  3. curvature perturbations only ~ [Valiviita & TG 09] Now confirmed by Planck 13
  4. nearly Gaussian distribution ? Now confirmed by Planck 13
- Other models: parametrisation:

  Φ: primordial potential; ϕ Gaussian.

  Amount of departure from Gauss: f_{NL} , g_{NL}

$$\Phi = \phi + f_{NL}\,\phi^2 + g_{NL}\,\phi^3$$

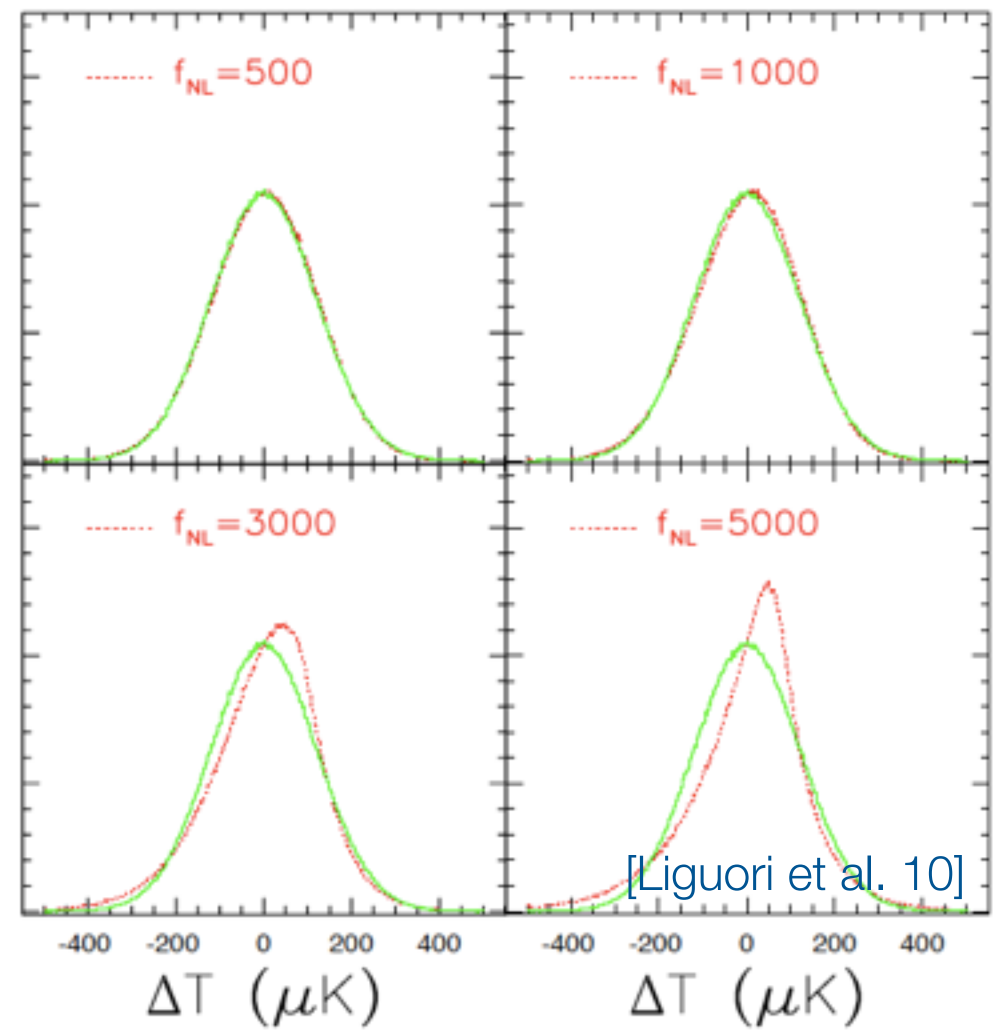


Measuring non-Gaussianity

- Many possible types! Different configurations: kernel W. Φ: primordial potential; φ Gaussian.

$$\Phi(\mathbf{x}, z_*) = \varphi(\mathbf{x}, z_*) + (f_{\rm NL} * W * \varphi * \varphi)\,(\mathbf{x}, z_*)$$

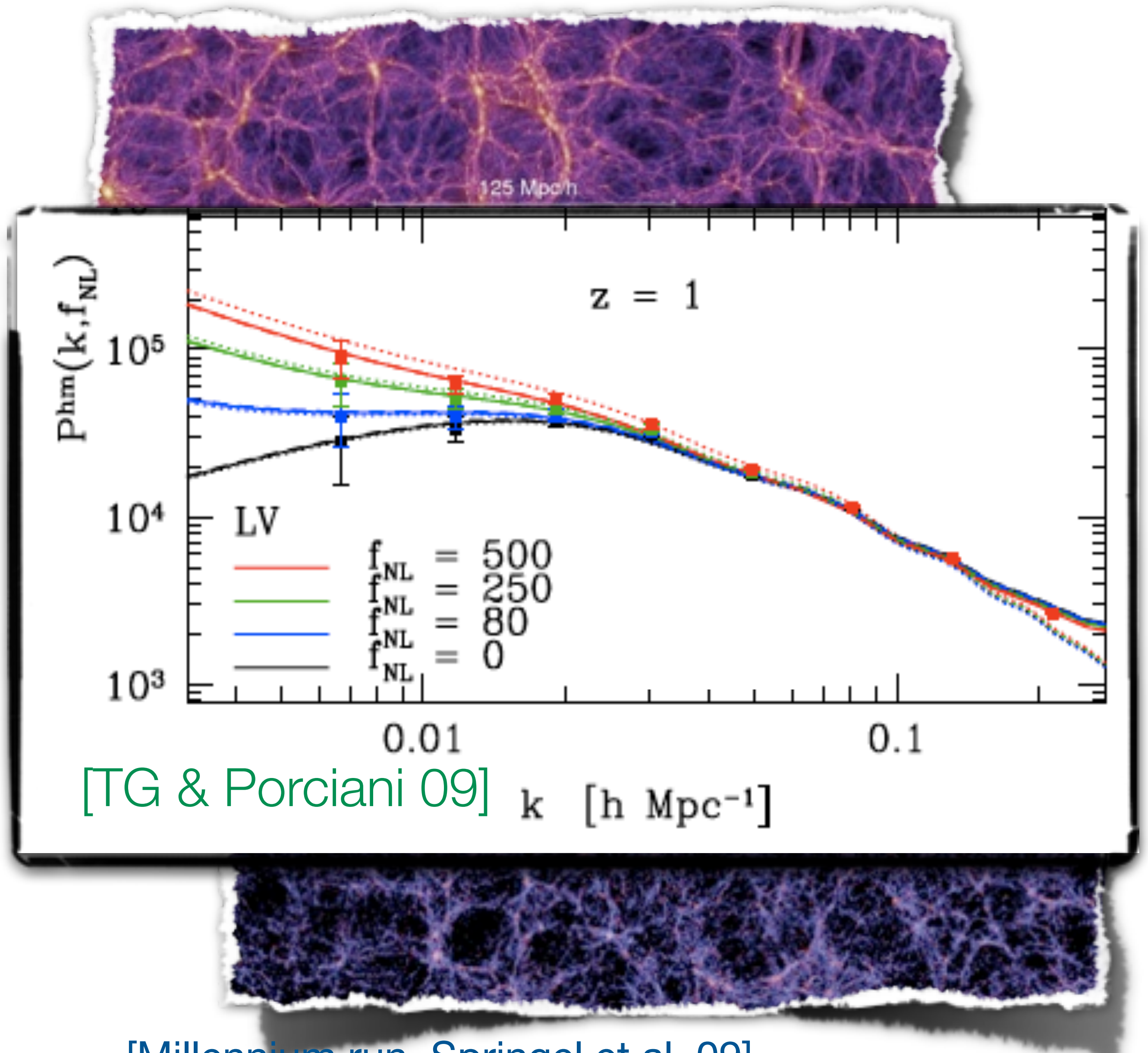
- Amount of NG: f_{NL} measurable from CMB Bispectrum = ‹ΘΘΘ›
  - local case (W=1): WMAP9: $-3 < f_{NL} < 77$ (95%) [Hinshaw et al. 12]
  - **Planck: f_{NL} = 2.7 ± 5.8 (1σ) !**
- Also from LSS Bispectrum = ‹δδδ›
  - hard to distinguish from late-time NG



[Liguori et al. 10]

Additional LSS technique:
scale-dependent bias
[Dalal et al. 07, Afshordi et al. 08, Slosar et al. 08, TG & Porciani 09]

Primordial Non-Gaussianity and the LSS



[Millennium run, Springel et al. 09]

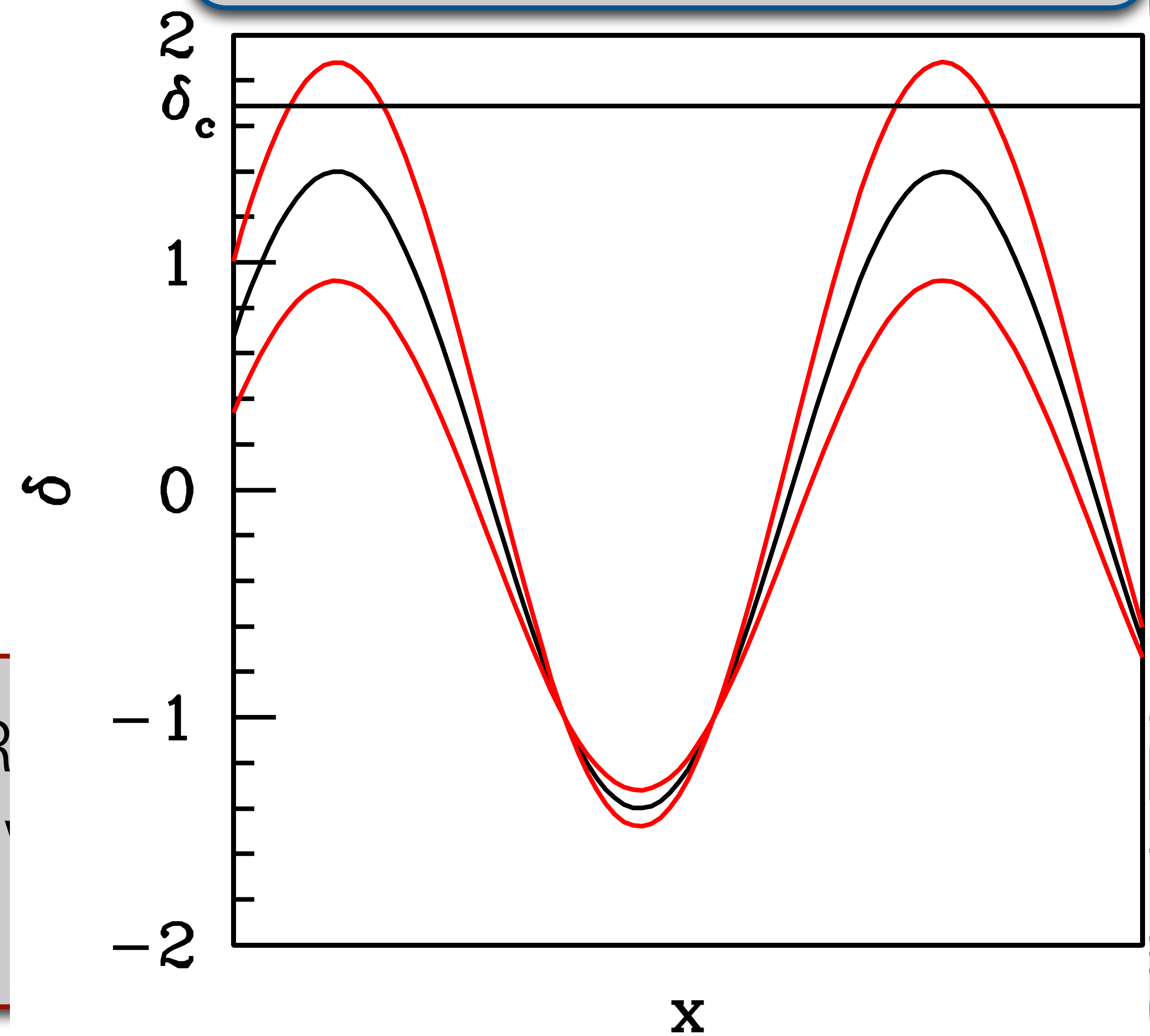
- Dark matter perturbations δ_m > dark matter haloes δ_h > galaxies δ_g
  - halo bias, $\delta_h = b_h\, \delta_m$
  - galaxy bias, $\delta_g = b_g\, \delta_m$
- With Primordial Non-Gaussianity: scale-dependent, **non-local** b [Dalal et al 07, +]
- **Measure:** Spectra ‹gal-gal› ~ b^2 and ‹gal-CMB› ~ b → measure bias → constraints on PNG! [Slosar et al 08, Xia et al 10, 11, Ross et al. 12, TG et al. 13]

$$b(k, f_{NL}, g_{NL}) \simeq b_{Gauss} + \beta_f\, \mathbf{f_{NL} / k^2} + \beta_g\, \mathbf{g_{NL} / k^2}$$

Physical sense of scale-dependent bias

- Halo collapse above critical overdensity
- Add short modes: One realisation: one halo forms
- Multiple realisations with rms: halos more likely to form near large-scale overdensities: **bias**
- With non-Gaussianity: more small-scale fluctuations where large-scale overdensity

$$\delta_s + \delta_m \approx \delta_s\,(1 + 2f_{NL}\,\phi_l)$$

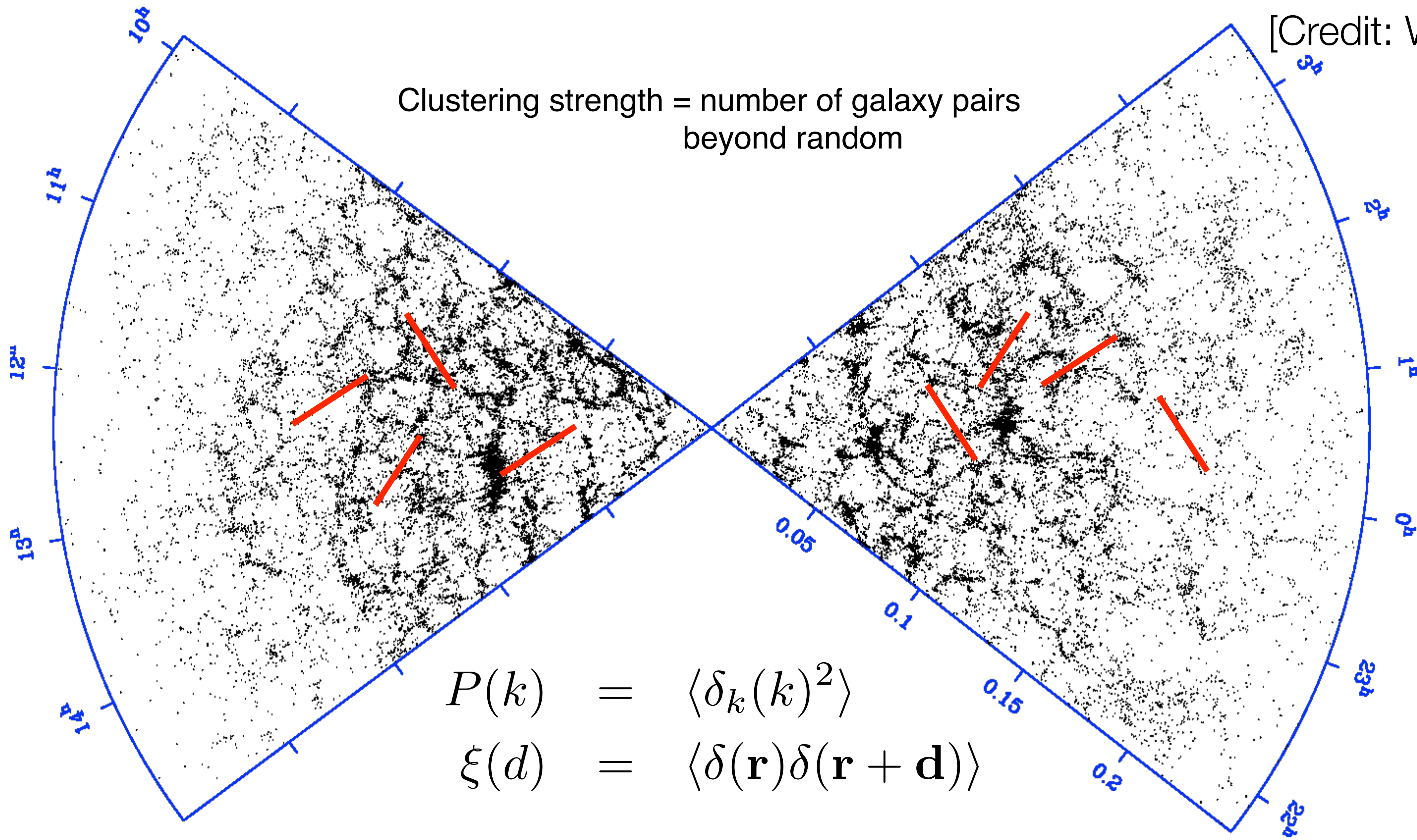


More bias on large scales!

[Credit: S. Dodelson]

Galaxy & CMB Clustering: Correlation functions

[Credit: W. Percival]



Clustering strength = number of galaxy pairs beyond random

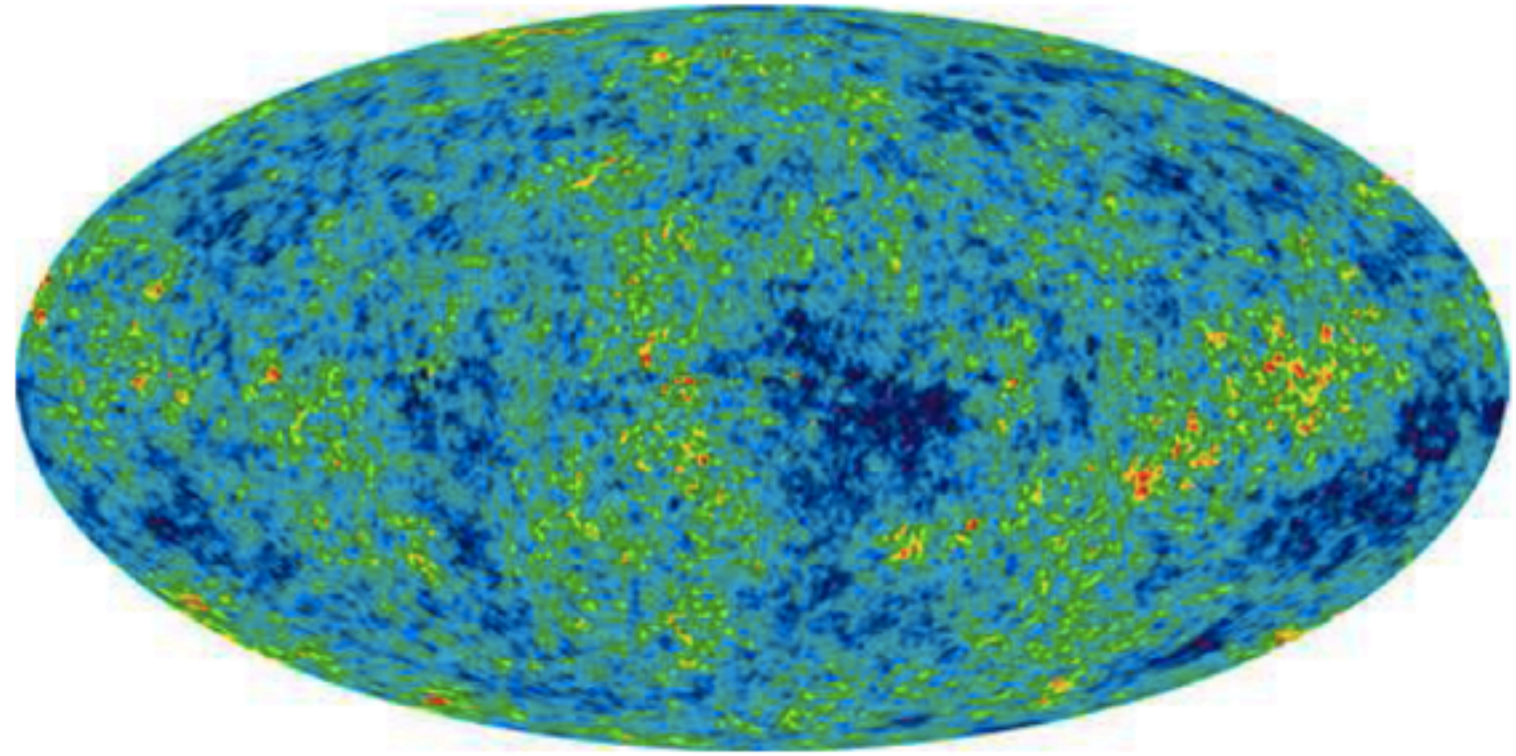
$$P(k) = \langle \delta_k(k)^2 \rangle$$
$$\xi(d) = \langle \delta(\mathbf{r})\delta(\mathbf{r}+\mathbf{d}) \rangle$$

2dFGRS

- Fluctuations in **CMB temperature, galaxy density**: $\Theta \equiv \delta T/T \quad \delta \equiv \delta\rho/\rho$

$$w^{ISWg}(\vartheta) \equiv \langle \Theta^{ISW}(\hat{\mathbf{n}}_1)\delta^g(\hat{\mathbf{n}}_2) \rangle$$
$$w^{gg}(\vartheta) \equiv \langle \delta^g(\hat{\mathbf{n}}_1)\delta^g(\hat{\mathbf{n}}_2) \rangle$$

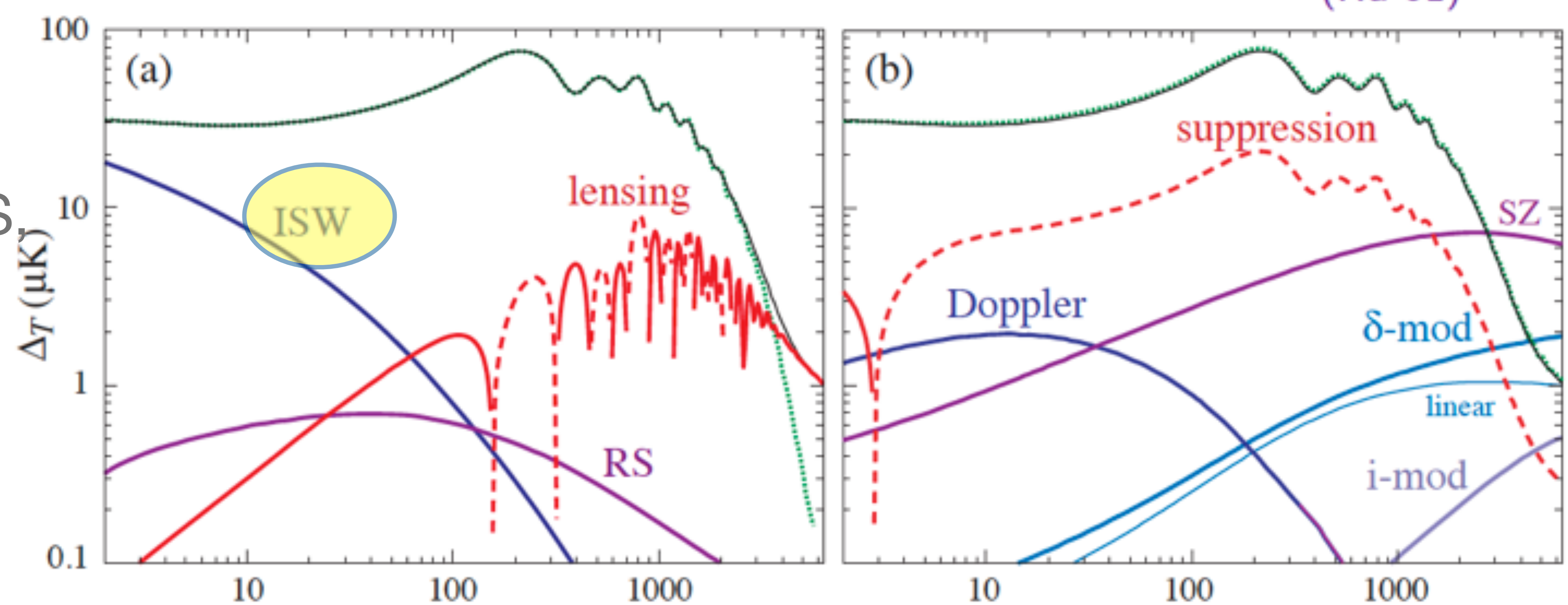
CMB anisotropies



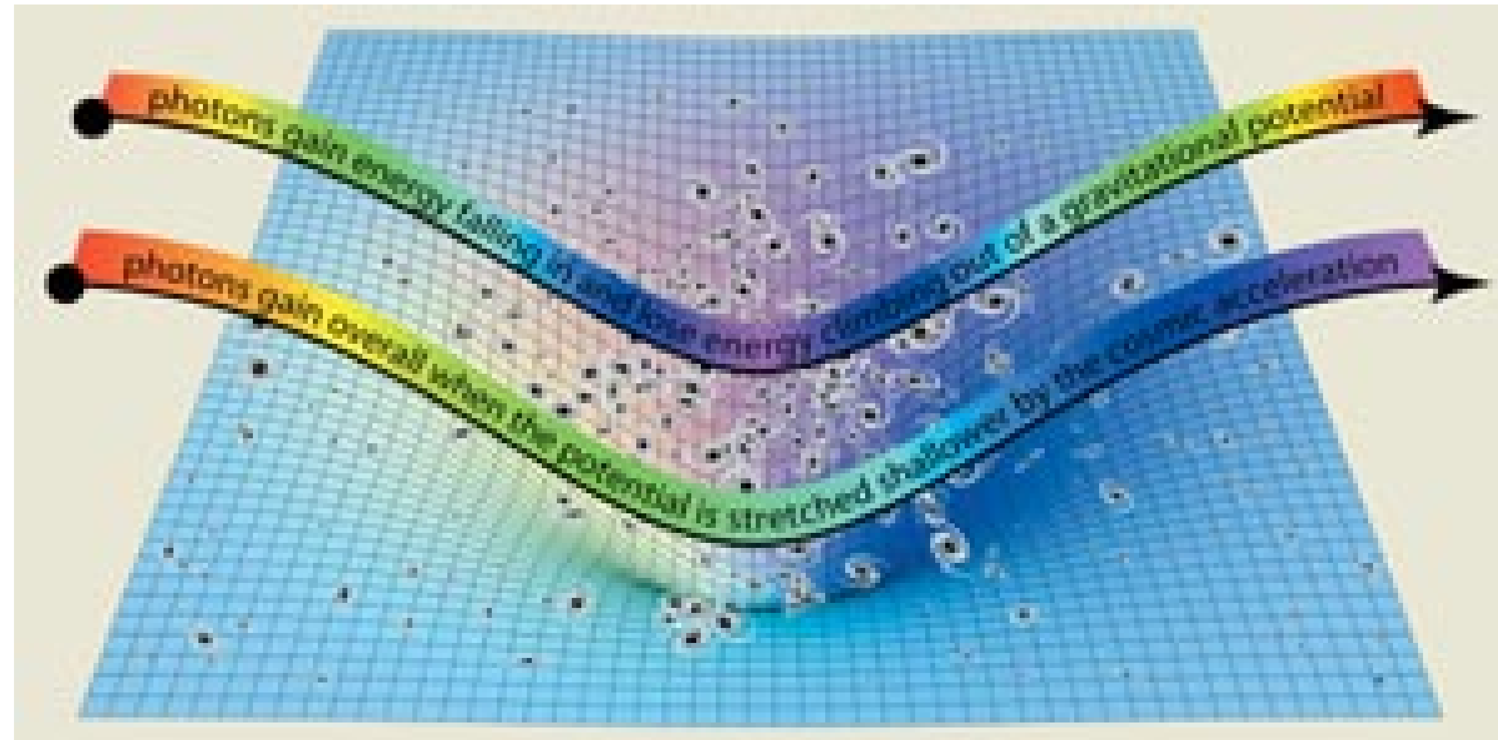
- **Primary**: at last scattering
  - from T, δ, **v** fluctuations

- **Secondary**:
  - global & local **reionisation** (suppression, new Doppler, OV, SZ effects)
  - **gravity** (lensing, RS, **ISW effect**)

(Hu 01)



The integrated Sachs-Wolfe effect [Sachs & Wolfe 67]



- Secondary effect on the CMB:

$$\frac{\delta T}{T} = 2 \int_{\gamma} \dot{\Phi}[r(t), t] dt$$

- No effect in matter domination as

$$\dot{\Phi} = 0$$

- Early ISW in radiation era

- **Late** ISW if dark energy (or curvature) dominates

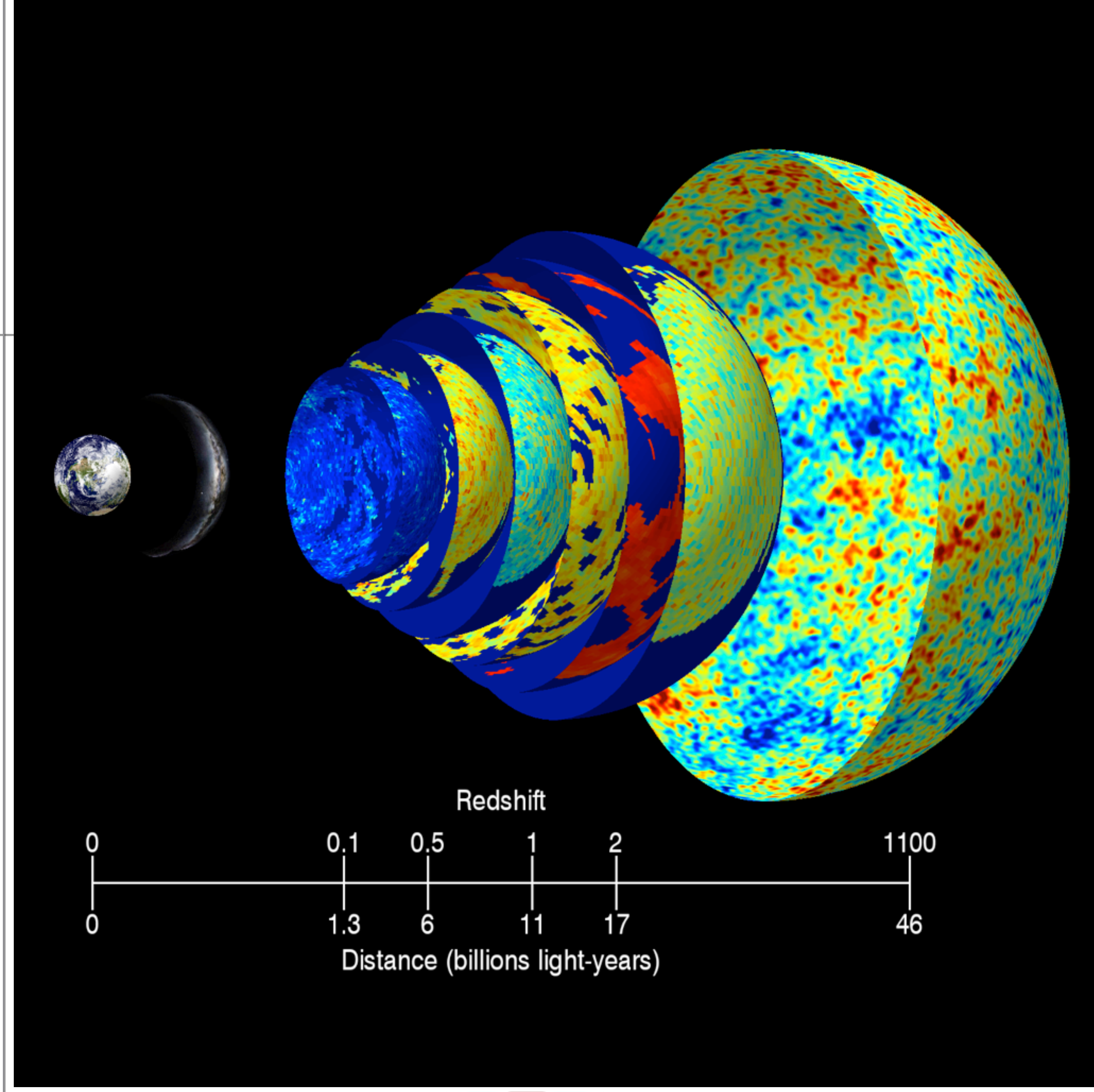
- **Probe of Dark Energy, but small in TT**

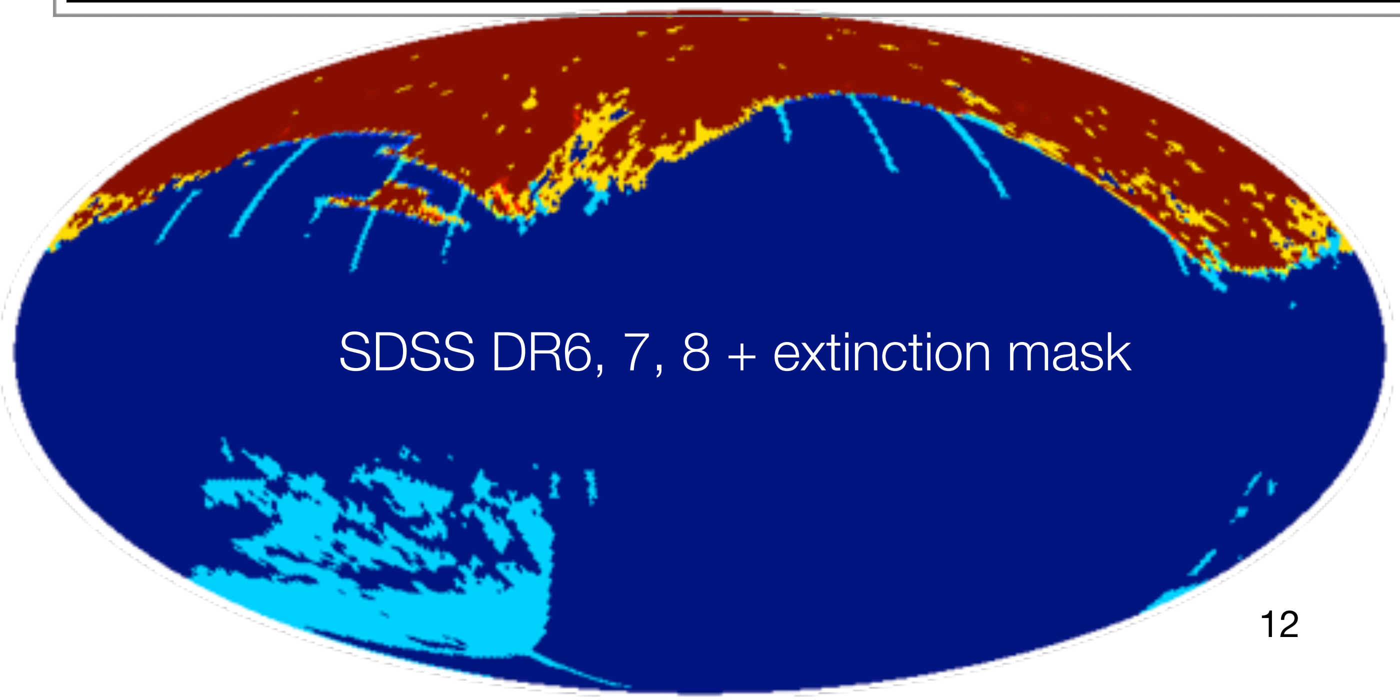
- **ISW**: **highly correlated with LSS** through the gravitational potential Φ

ISW signal: Detectable cross-correlating <CMB x LSS>
[Crittenden & Turok 95]

Combined LSS+ISW data, updated [TG et al. 08, 12, 13]

- **Data maps**, pixellated
  - density: 6 galaxy catalogues:
    - infra-red **2MASS**
    - optical **SDSS DR8: (main galaxies**, luminous red **LRG**, DR6 **quasars**)
    - radio **NVSS**
    - X-ray **HEAO**
  - CMB temperature: WMAP7
- **Masks**
  - survey geometry
  - (galactic) foregrounds - extinction

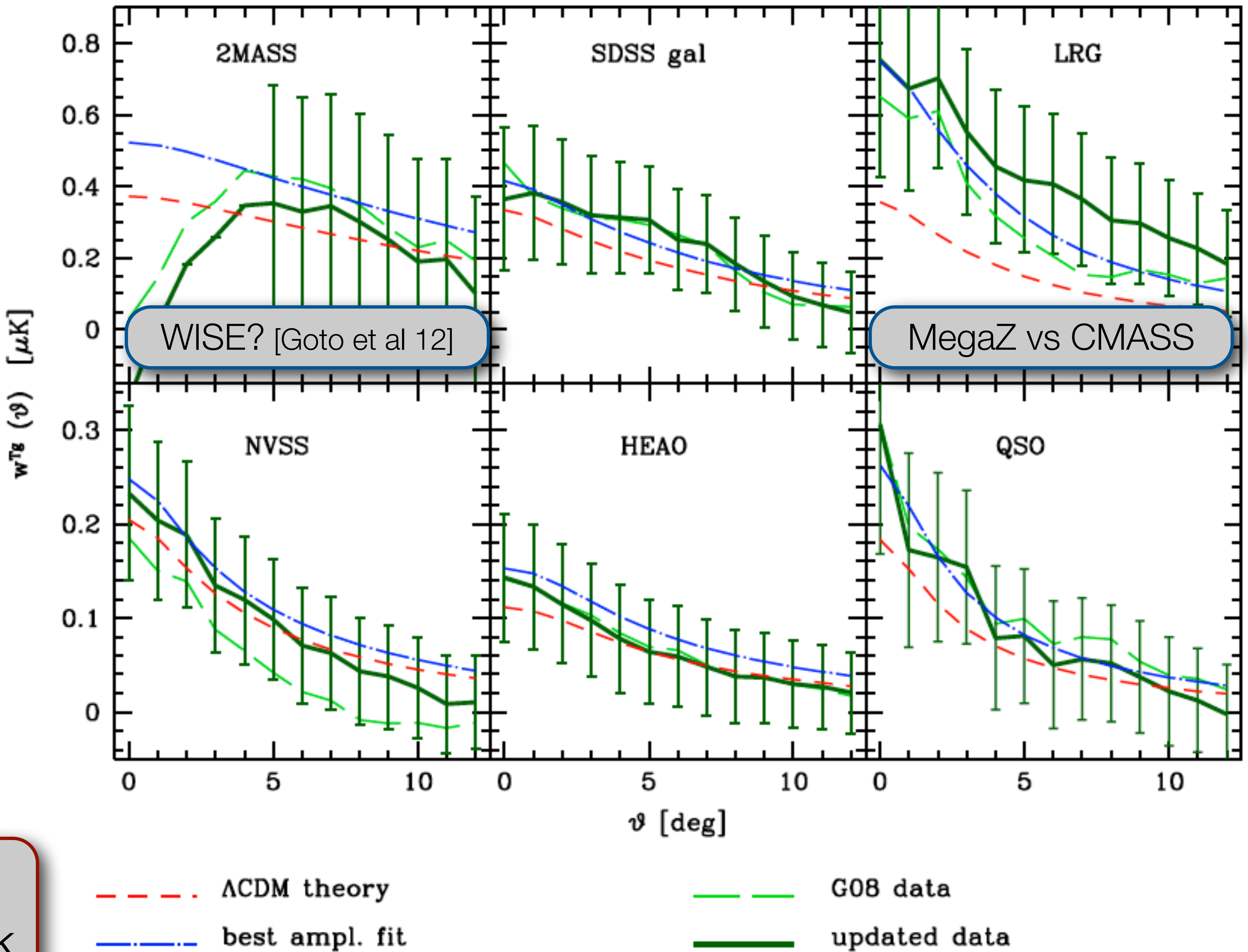




Measured ⟨Tg⟩ correlations

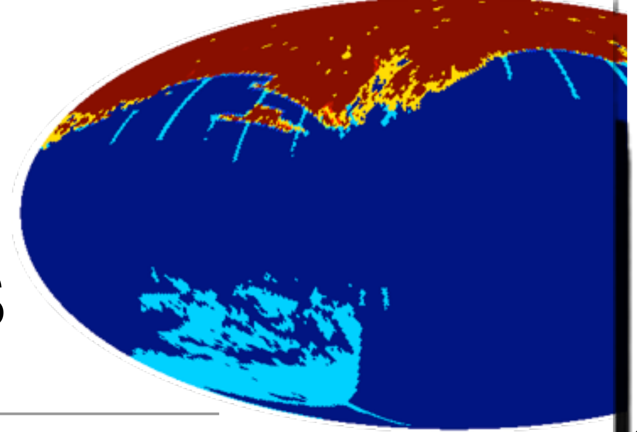
[TG et al. 12, MNRAS]

- Non-zero only with dark energy
- Covariance: Monte Carlos
- ~ agrees with LCDM & older data
- **Total S/N = 4.4 σ (± 0.4)** (single amplitude fitting)

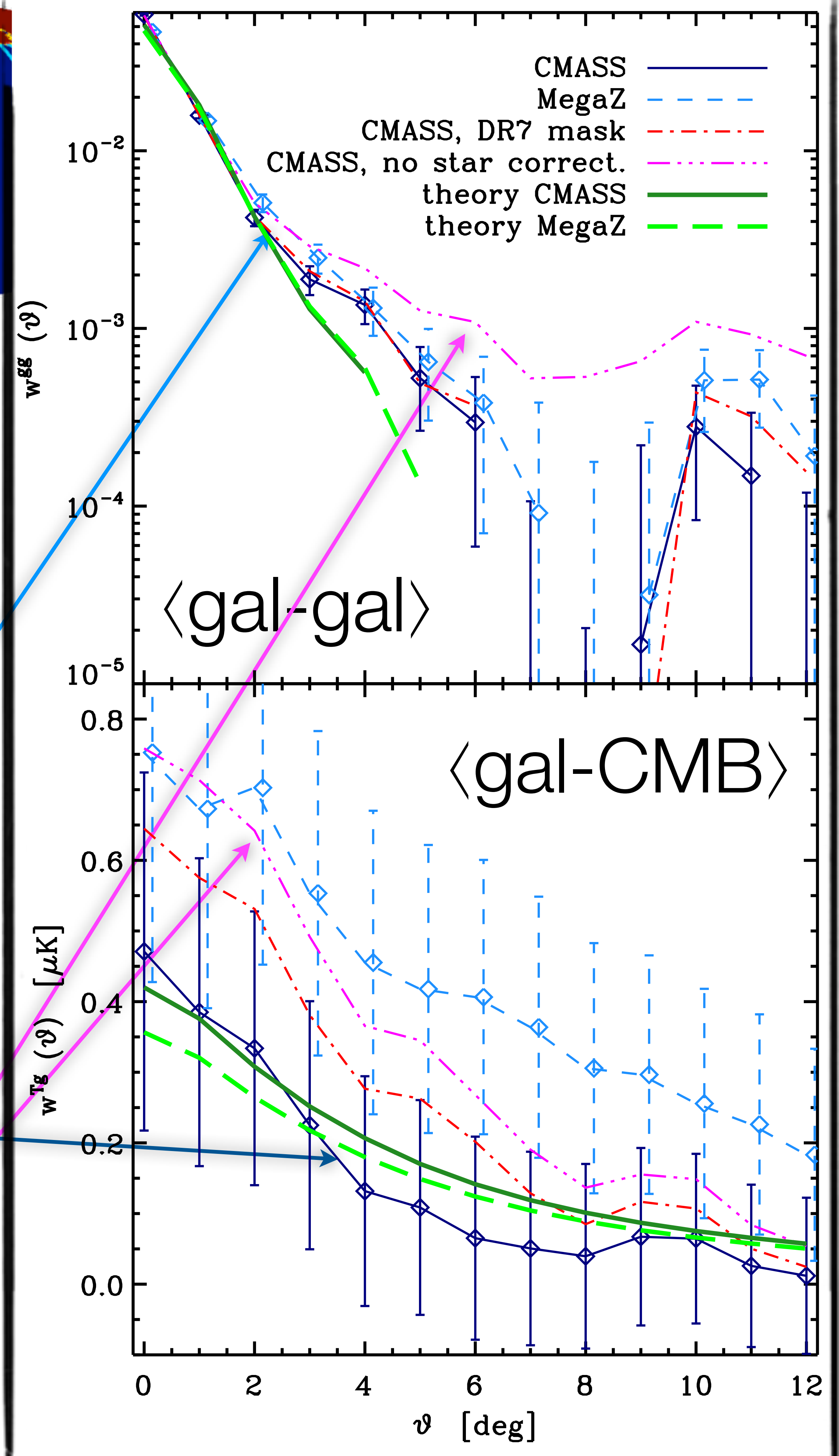


Independent evidence for Dark Energy at >4σ

LRG systematics



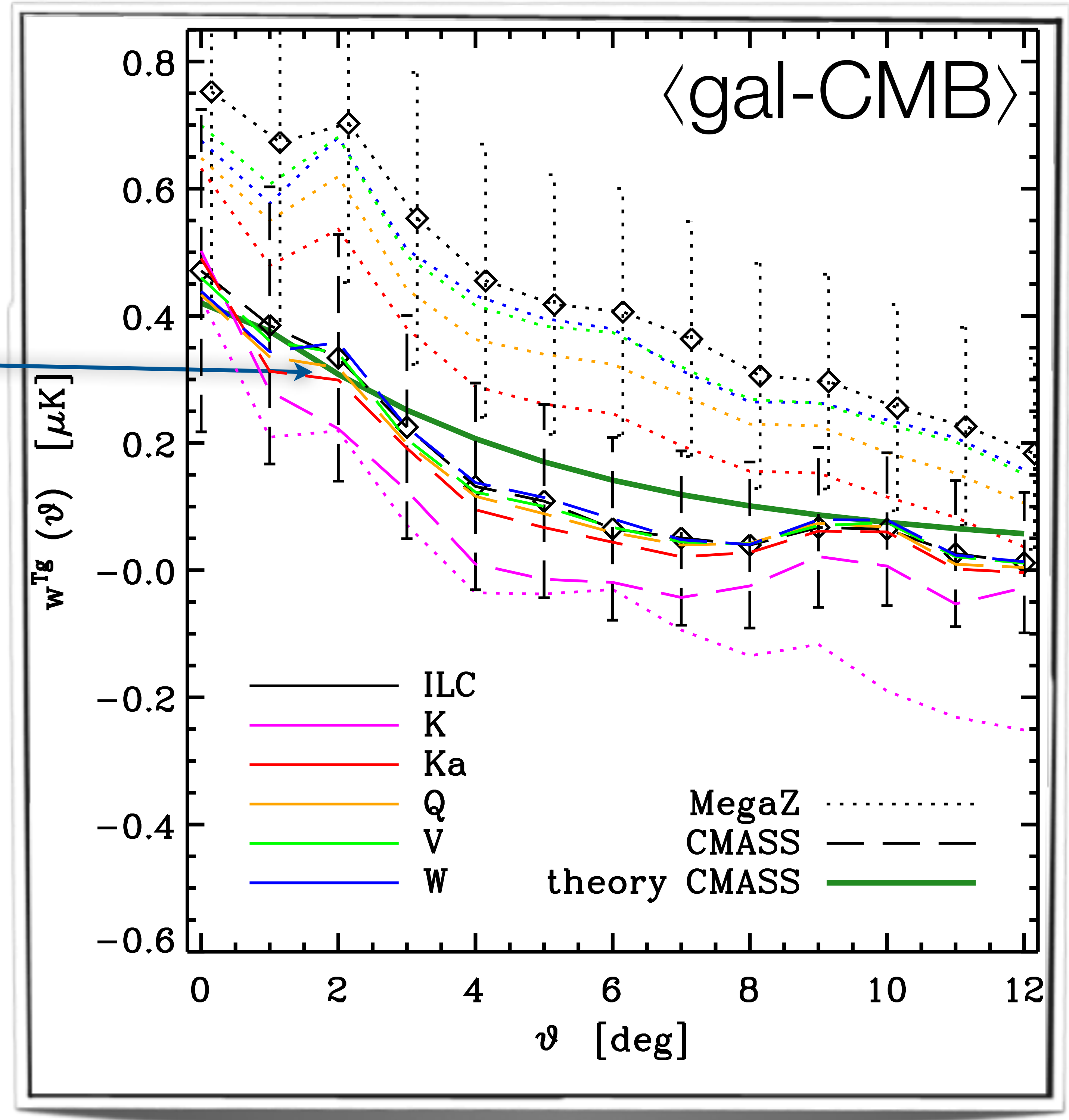
- Thomas et al. 10 **MegaZ** vs Ross et al. 11 SDSS DR8 photometric **CMASS**
- Similar redshift range, CMASS South coverage
- CMASS: correction for stellar systematics
  - Fewer galaxies observed where lots of stars!
  - Many (15%) with BOSS spectra
- **ACF**: MegaZ show more excess power on large scales --> stars or primordial?
- **CCF**: CMASS lower, in agreement with LCDM
- If no star correction, same area: higher A/CCF



ACF at large scales: difficult

LRG systematics

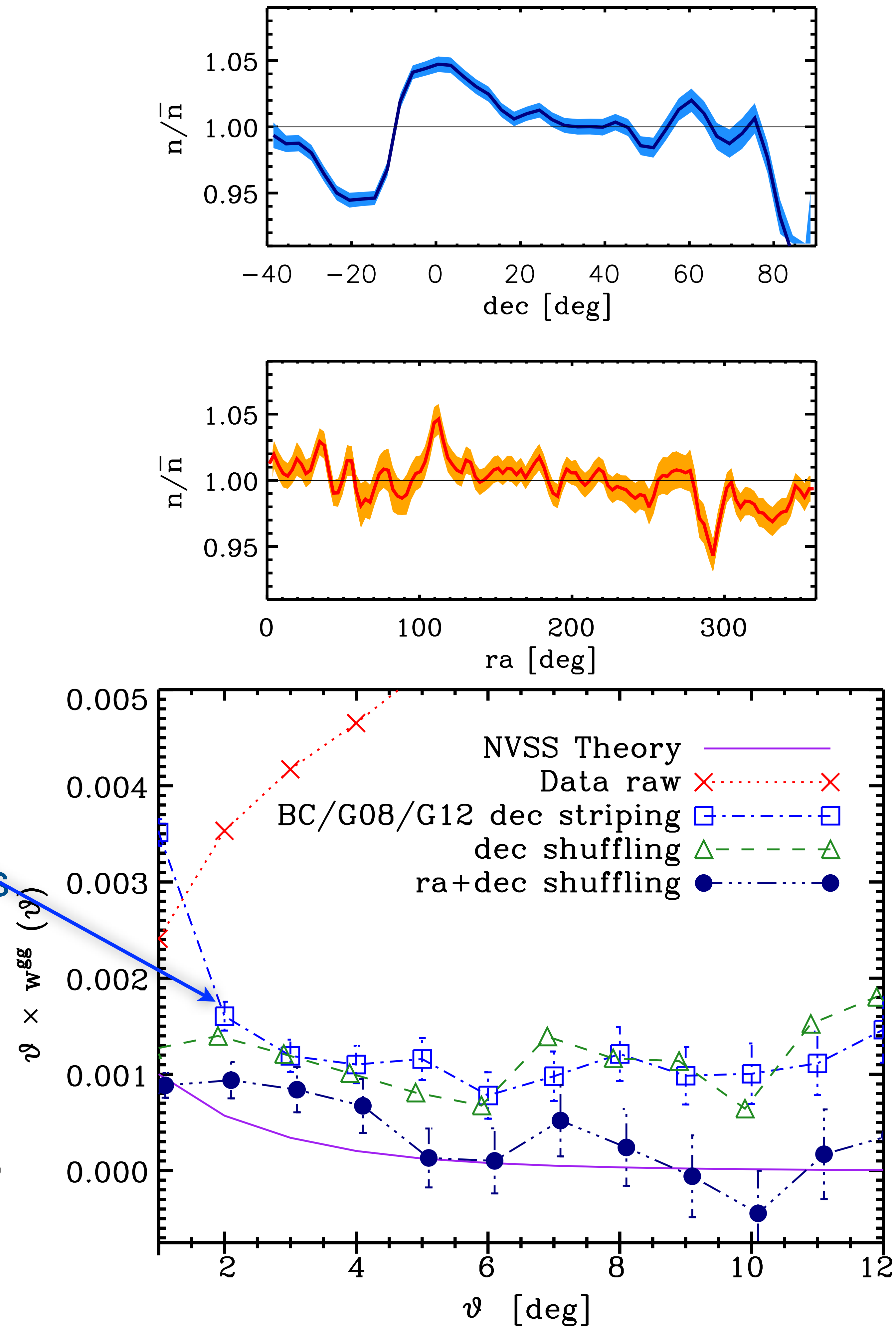
- Frequency independence:
  - Very stable CCF, with all WMAP bands!
  - Evidence for superior quality of CMASS data
  - Stellar contamination negligible



Use these LRGs!
Now suitable for f_{NL} analysis.

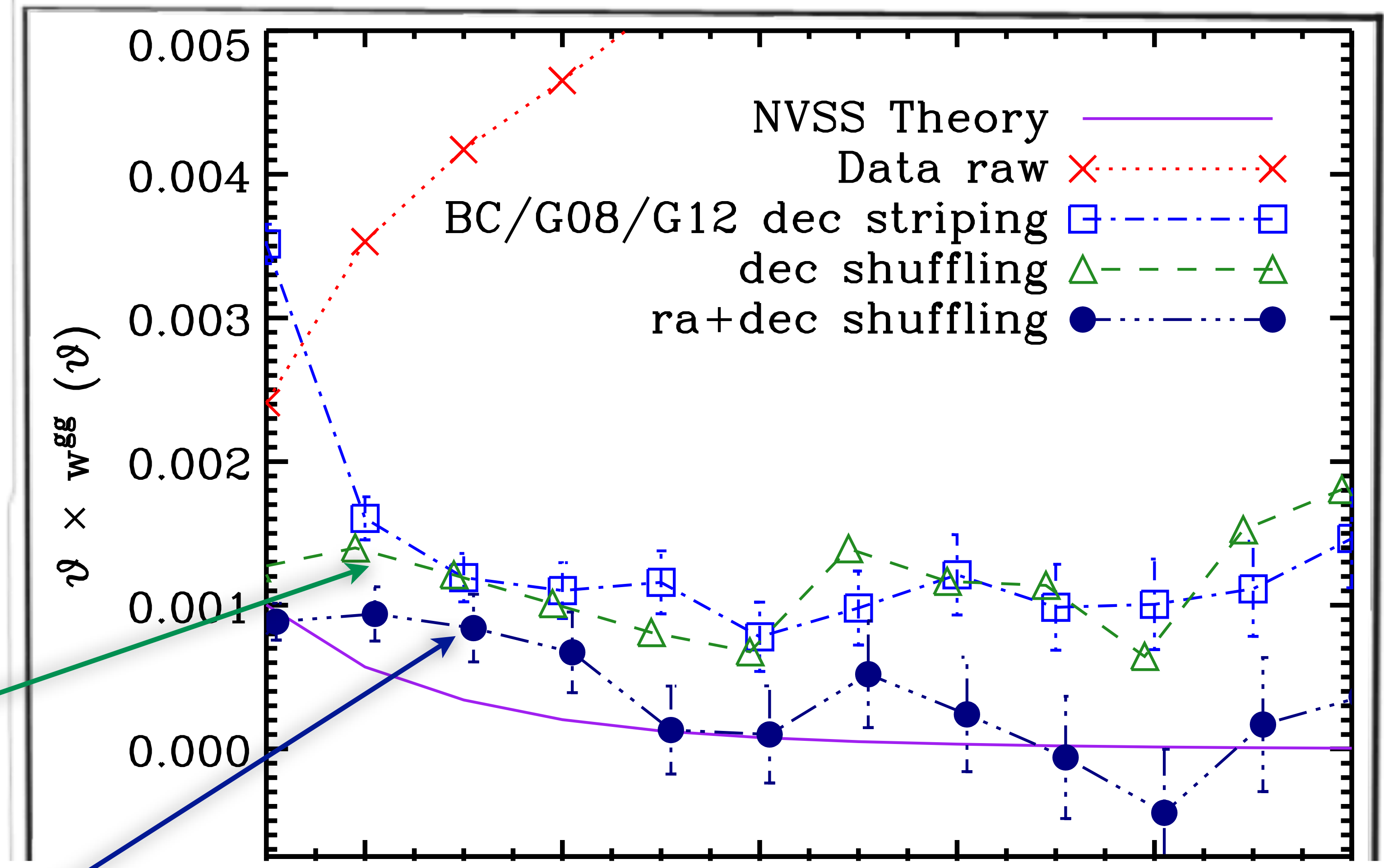
NVSS systematics

- Known problem: number density changes in dec & smaller r.a. effect
- Large effects on ACF. Corrections:
  - 'Striping' in dec bands and rescaling n density [Boughn &Crittenden01, Smith et al 08, TG et al. 08, 12]
  - Cutting Flux < 10 mJy [Blake et al. 04, Xia et al. 10, 11]
  - Give infinite variance to m = 0 modes [Smith et al. 07] - best but difficult in real space
- Arbitrary, results vary!
- **Discard this auto-correlation as well?**



NVSS ‘shuffling’

- **A possible fix:**
- Get r.a., dec mask as BOSS gets redshift mask: modulated randoms
- (1) If assuming only dec effect:
  - random map R_1 assigning random r.a. to observed dec.
- (2) Both r.a. dec corrections:
  - also randoms R_2 assigning random dec to observed r.a.
- **Weigh data D by (R_1 R_2) in ACF**
- Validated with mocks



Quasar systematics

- **Excess power at large separations**
- **Stellar contamination** fraction κ (SDSS samples)

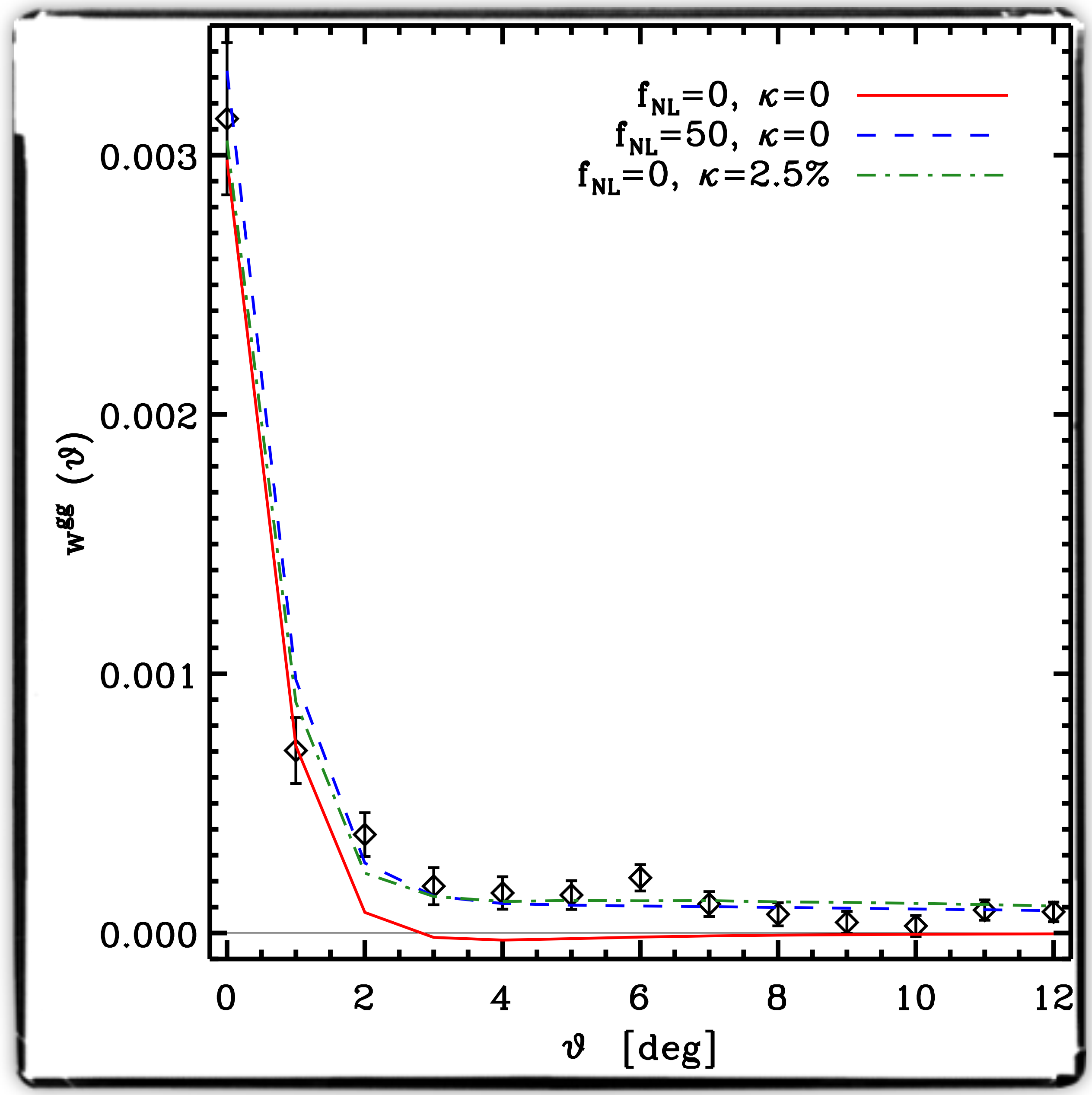
$$w^{\rm obs}(\vartheta) = (1-\kappa)^2\, w^{\rm qso}(\vartheta) + \kappa^2\, w^{\rm star}(\vartheta)$$

- Degeneracy in plateau

$f_{NL} = 50 \sim \kappa = 2.5\ \%$

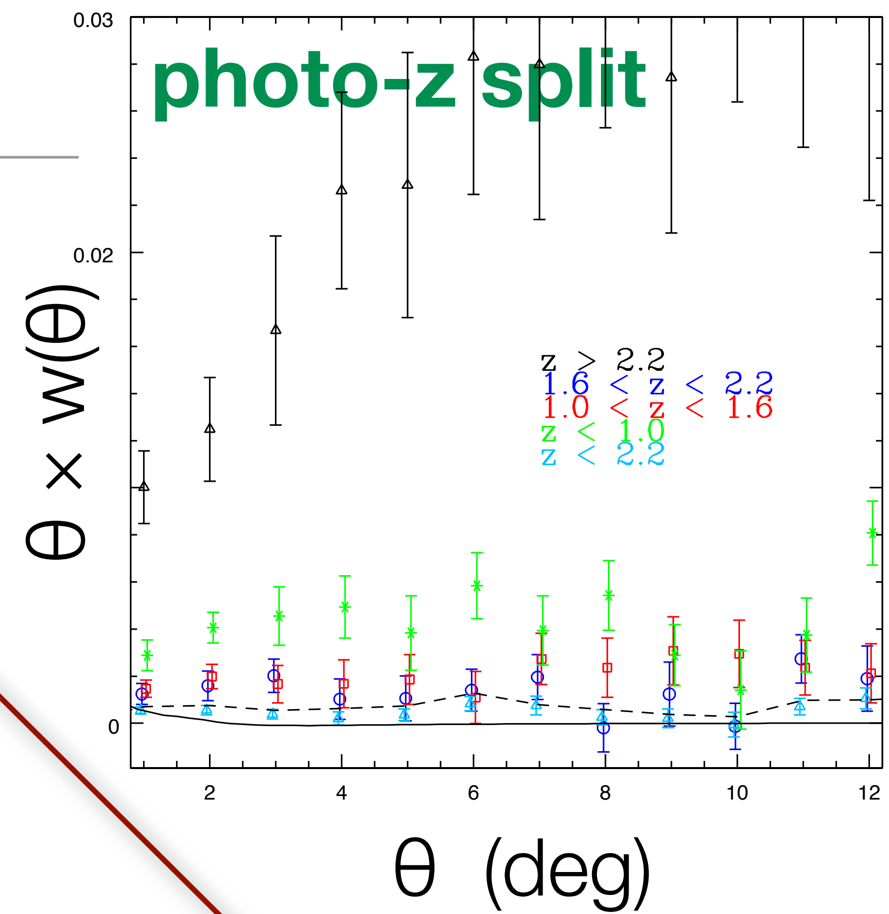
- Prior from ⟨qso-stars⟩ correlation: does not solve (only ~1%)

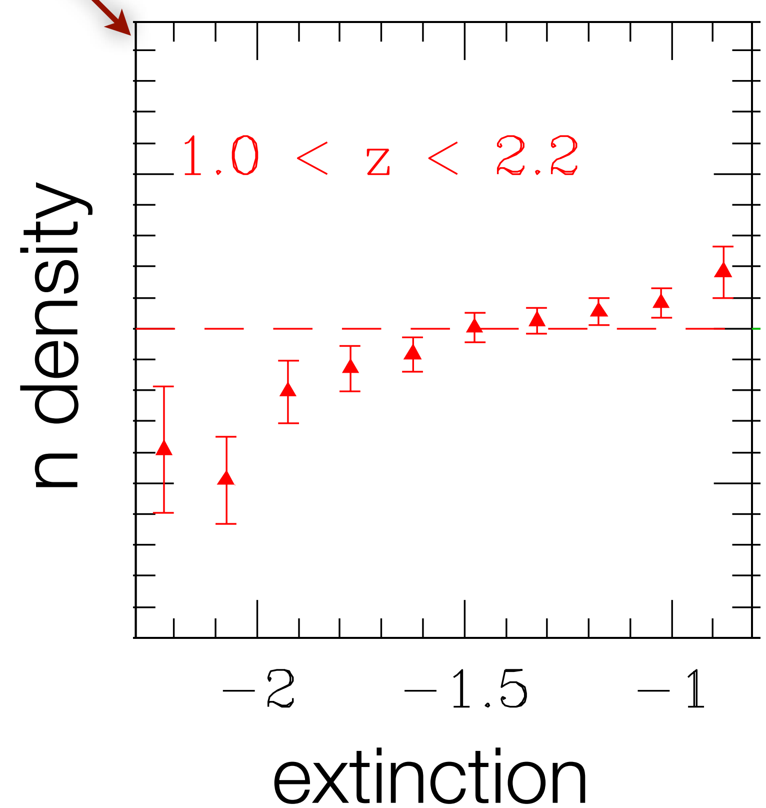
- Further systematics - or f_{NL} - needed to explain plateau...



Quasar systematics

- Splitting by **photo-z**: **worse**
  - Higher excess power at high
  - Cut? But then correlation density-extinction, and other systematics
- Splitting by **i-mag** also unstable
  - Large-angle ACF fluctuates
- Remaining systematics - calibration? [Pullen & Hirata 12] [Leistedt et al. 13]
- QSO ACF **unreliable** on large scales - too **faint**. BOSS cut at i < 19.9, these at i ~ 21+





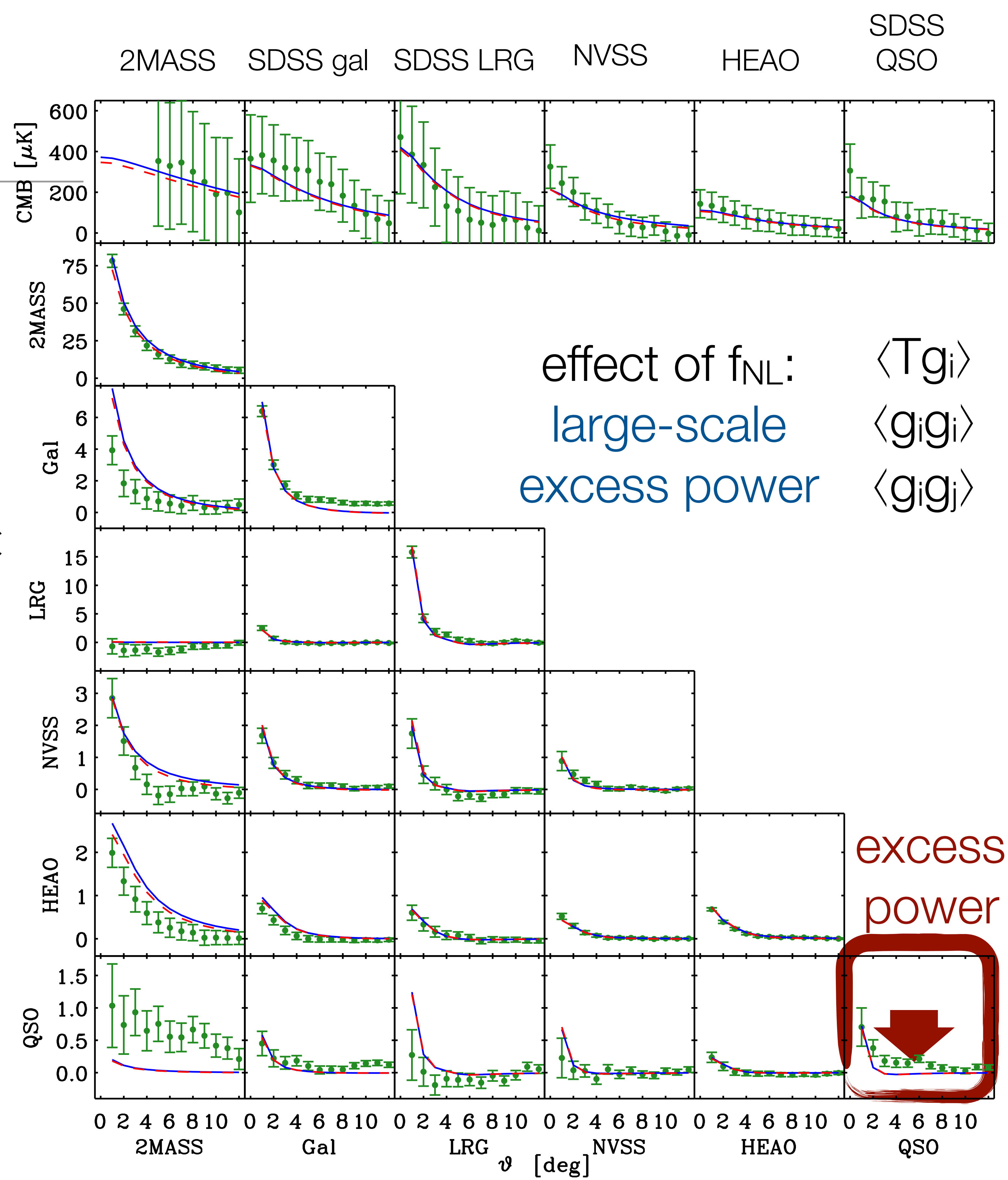
Discard quasar ACF

Full bias analysis of LSS + ISW data & f_{NL}

- Measure (local) $\mathbf{f_{NL}}$ via b
- **⟨Tg⟩** ∝ b, **⟨gg⟩** ∝ b^2
- **Data**: all 27 2-pt functions!
- **Gaussian bias:**
  - Most cases: $b_1^i(z) = 1 + \dfrac{b_0^i - 1}{D^{\gamma_i}(z)}$
  - Quasars: $b_1^{\rm QSO}(z) = \dfrac{b_0^{\rm QSO}}{D^{\gamma_{\rm QSO}}(z)}$
  - $\gamma_i = 2$, $\gamma_{\rm QSO} = 1.6$
- **dn/dz uncertainty:**

$$w_{\rm obs}^{g_i g_j}(\vartheta) = \beta_{ij}\, w^{g_i g_j}(\vartheta)$$

- **Nuisance parameters:**
  - $6\ b_0^i\ +\ 3\ \kappa_i\ +\ 15\ \beta_{ij}$

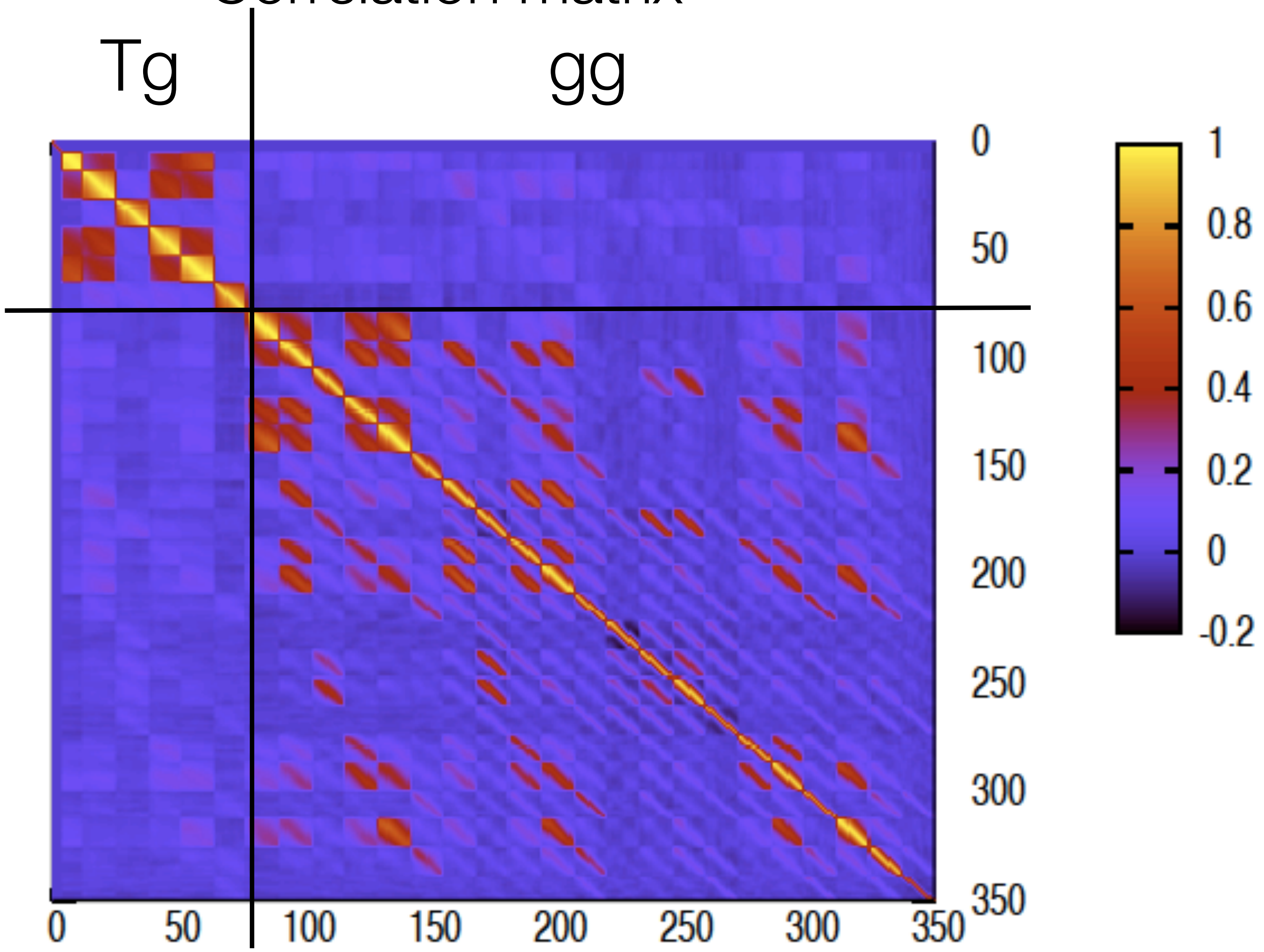


Monte Carlo likelihood analysis

- Full Covariance Matrix (351x351) from 10,000 Monte Carlo mocks
- Theory models: with modified Camb code
- Nested sampling: Multinest [Feroz et al. 09]
- **Results with all data + WMAP CMB TT prior:**

naive: **$30 < f_{NL} < 62$!!!** @ 95% c.l.

Correlation matrix =



Further study to understand this...

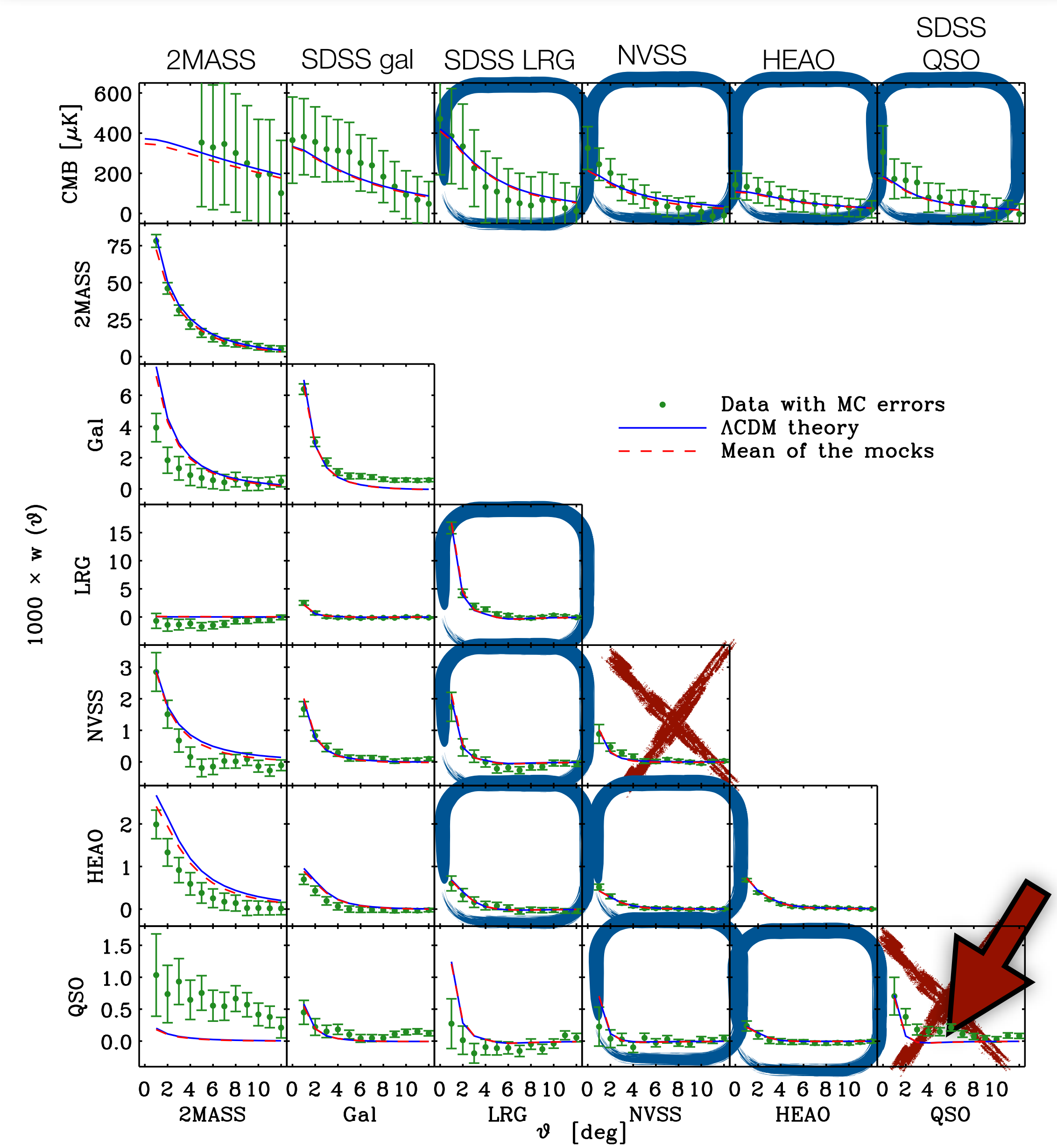
What can we trust?

- Non-zero f_{NL} driven by **quasar** auto-correlations (+ residual NVSS excess)
- Not all data equally reliable: 3 results
  - Full data
  - Ultra-conservative: drop 2MASS, main gal, and all ACF except BOSS LRGs
  - Fair: drop only NVSS, QSO auto-correlation
- **Cross-correlations safer** than auto-correlations, keep them

full, unreliable: **30 < f_{NL} < 62** @95%

ultra-conservative: **-37 < f_{NL} < 25** @95%

'fair': **-29 < f_{NL} < 31** @95%



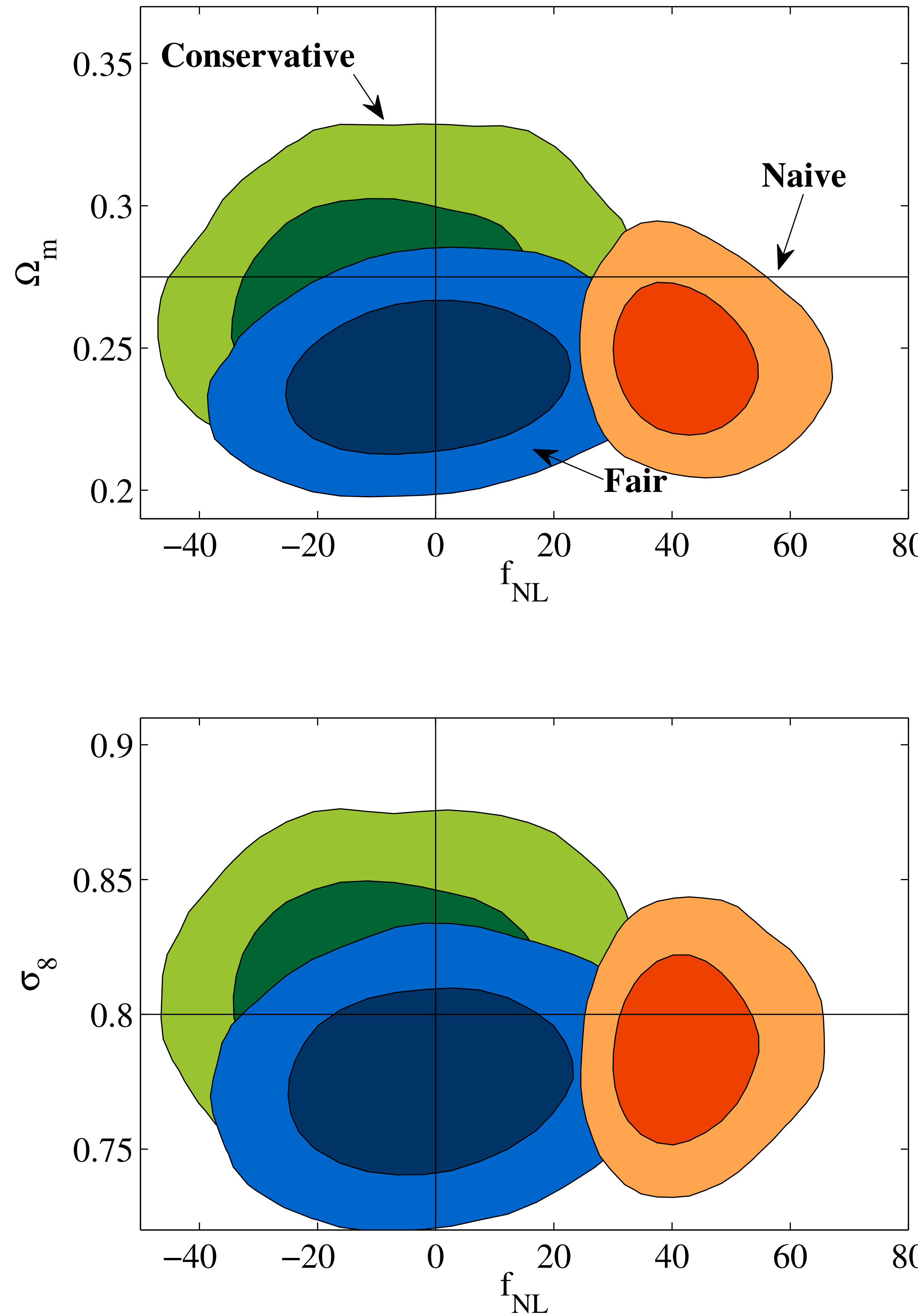
NO evidence for non-Gaussianity!

Results

- Conservative & Fair: consistent with standard model, no PNG
- Fair data + WMAP7: prefer slightly lower matter content
- No significant degeneracies f_{NL} - other parameters
- NVSS ACF still problematic (alone has double peak), we do not use it, but **consistent with 0**

'conservative': **f_{NL} = -6 ± 15.5 (1σ)**
'fair': **f_{NL} = +1 ± 15 (1σ)**

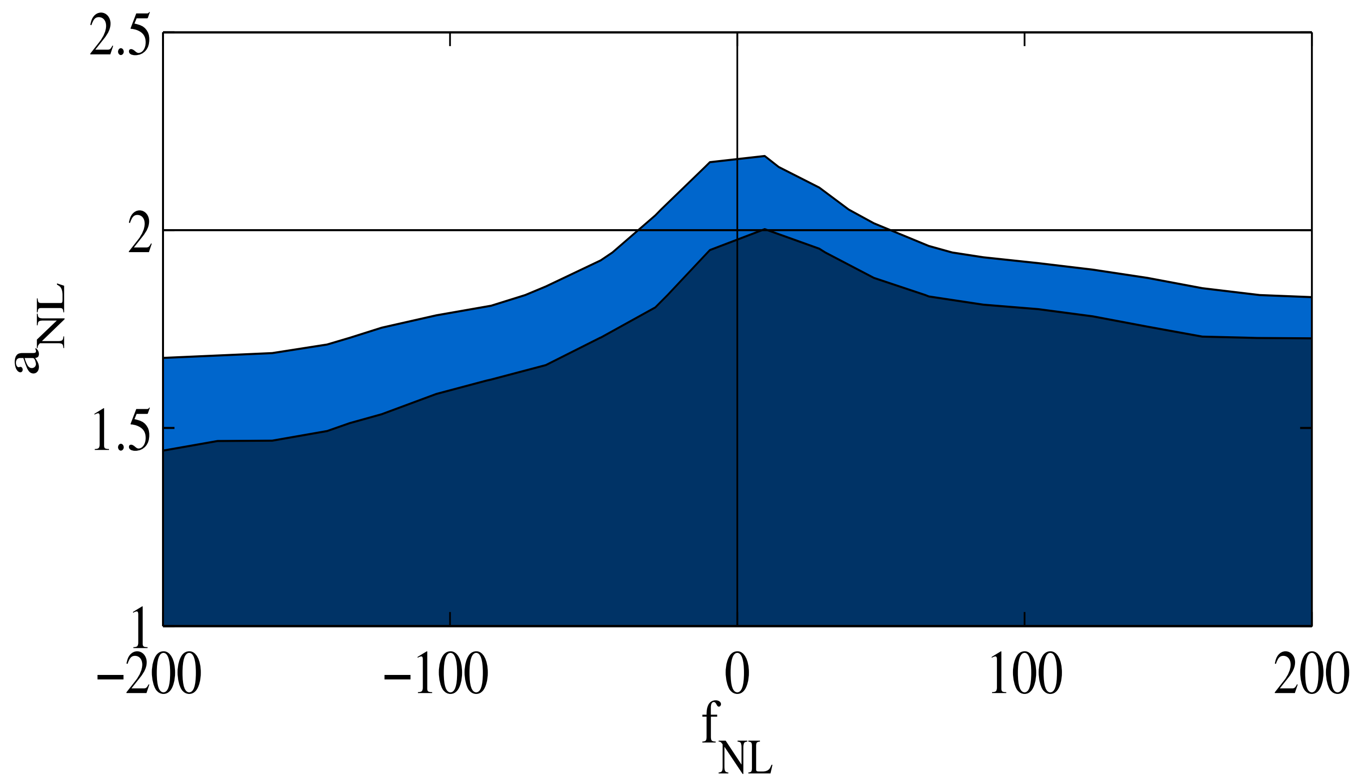
- Later confirmed by Planck: **f_{NL} = +2.7 ± 5.8 (1σ)**



Extended PNG

- **Variable slope** of scale-dependent bias: $\mathbf{a_{NL}}$
  - accounts for both non-local model or for local $f_{NL}(k)$
  - $a_{NL} = 2$ for local, scale-independent case
- **Kurtosis g_{NL} model**
  - we assume bias fitting formula by Smith, Ferraro, LoVerde 12, optimistic assumption!
  - Marginalizing over f_{NL}: (degeneracy partially broken)

$-5.8 \cdot 10^5 < g_{NL} < 1.7 \cdot 10^5$ @95%



Bayesian evidence

- Model selection A vs B:

$$\mathcal{P}(\Theta) = \frac{\mathcal{L}(\Theta)\,\Pi(\Theta)}{\mathcal{Z}(M)}$$

- Bayes' factor B = Z(A) / Z(B)
- Occam's razor
- Drawback: some prior dependence

Jeffrey's scale

$\lvert \ln B_{01} \rvert$	Odds	Probability	Strength of evidence
< 1.0	$\lesssim 3:1$	< 0.750	Inconclusive
1.0	$\sim 3:1$	0.750	Weak evidence
2.5	$\sim 12:1$	0.923	Moderate evidence
5.0	$\sim 150:1$	0.993	Strong evidence

All PNG models are disfavoured

Parameters	Data	$\ln(\mathcal{Z})$	$\ln B = \Delta \ln(\mathcal{Z})$	Odds	Interpretation
ΛCDM	CMB + our	-3983.41 ± 0.13	0	—	—
$+ f_{\rm NL}$	('fair')	-3985.03 ± 0.13	-1.62 ± 0.18	1 : 5	Weak evidence against $f_{\rm NL}$
$+ g_{\rm NL}$		-3985.31 ± 0.13	-1.90 ± 0.18	1 : 7	Weak evidence against $g_{\rm NL}$
$+ f_{\rm NL} + g_{\rm NL}$		-3986.59 ± 0.13	-3.18 ± 0.19	1 : 24	Moderate evidence against $f_{\rm NL} + g_{\rm NL}$
wCDM		-3984.31 ± 0.13	-0.90 ± 0.18	2 : 5	Inconclusive

Extension to galaxy clusters

[A. Mana, TG, et al. 13, MNRAS accepted]

- Largest bound structures
- Probe high-mass tail of mass function dn/dM (we use Tinker et al. 10 + **LoVerde** et al. 08)
- High bias: great for PNG
- Observables:
  - Counts N_i in richness bin i (N_{200}: # of red galaxies at $R < R_{200}$)
    - nuisance params: L_1, L_2, $\sigma_{N|M}$
  - Masses from weak lensing data
    - nuisance params: β
  - **Power spectrum**
    - nuisance params: σ_z, B, q_{NL}

$$N_i = \int dz \int dN_{200} \frac{dn}{dM} \frac{dM}{dN_{200}} w(N_{200})$$

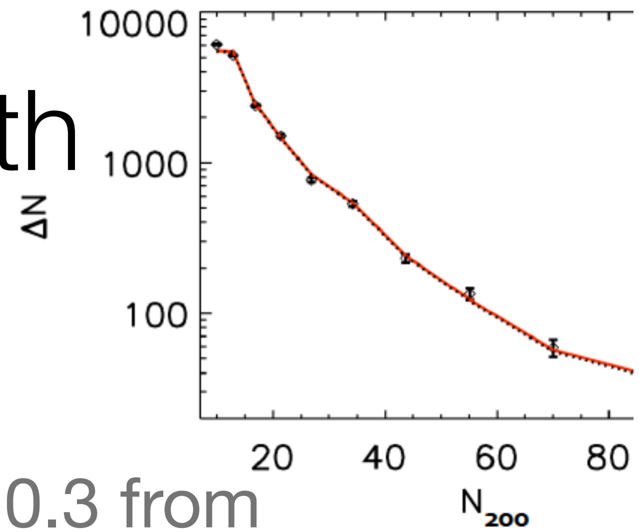
mass function — Jacobian of scaling relationship — richness bin selection

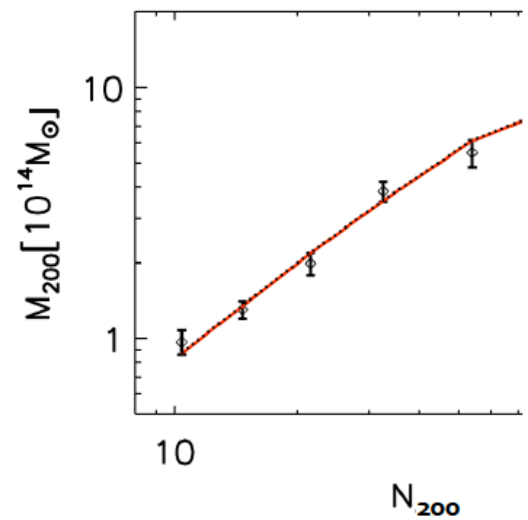
$$P(k) = b_{\rm eff}^2 (1 + q_{\rm NL} k^{3/2}) f(k) P_{\rm lin}(k)$$

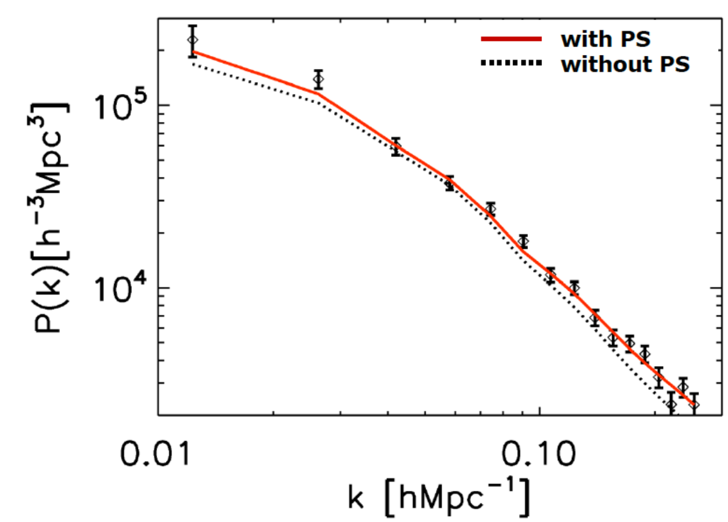
simple non-lin model — photo-z smoothing

Cosmology with MaxBCG

[A. Mana, TG, et al. 13]



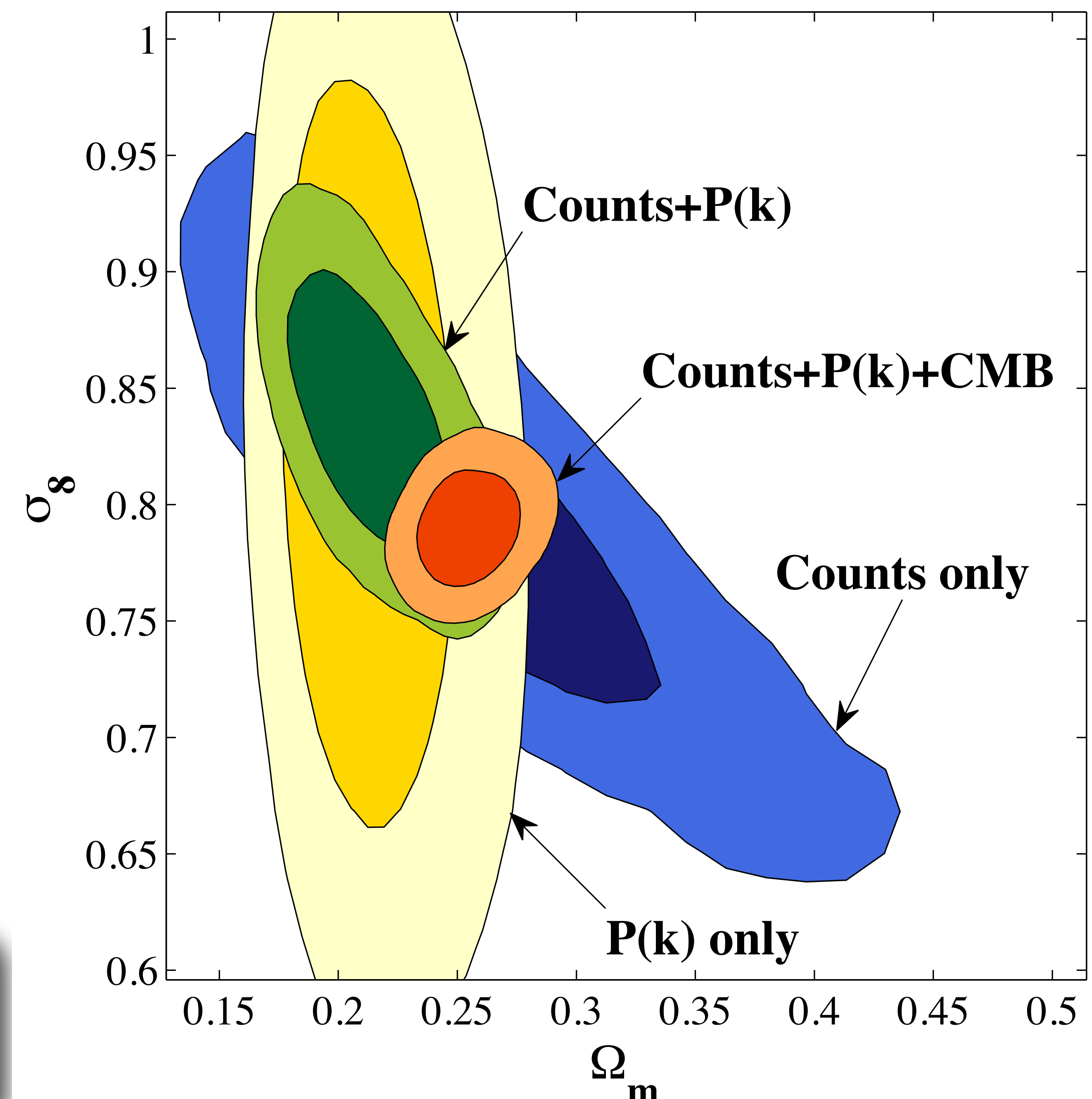




- 14,000 clusters to $z < 0.3$ from SDSS-DR7 [Koester et al. 07]

- Data and covariances:
  - Counts by Rozo et al. 09
  - Masses by Johnston et al. 07
  - **P(k)** by Huetsi 09

- MCMC analysis over:
  - Cosmology (σ_8, Ω_m, $\mathbf{f_{NL}}$)
  - Nuisance parameters (L_1, L_2, $\sigma_{N|M}$, β, σ_z, B, q_{NL})



Counts+Masses: agree with Rozo et al. 09
adding PS: significant improvement!

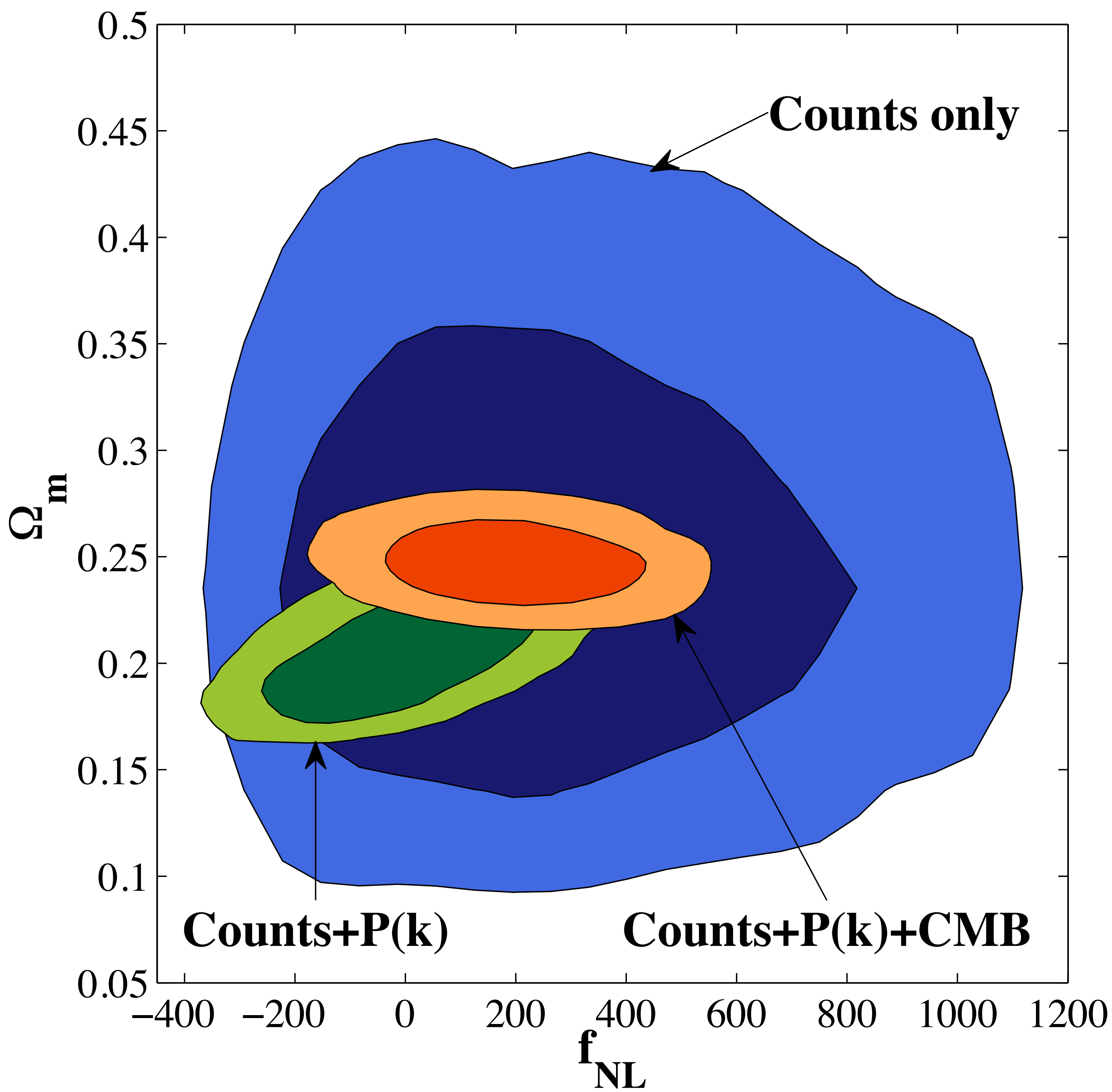
Application to non-Gaussianity

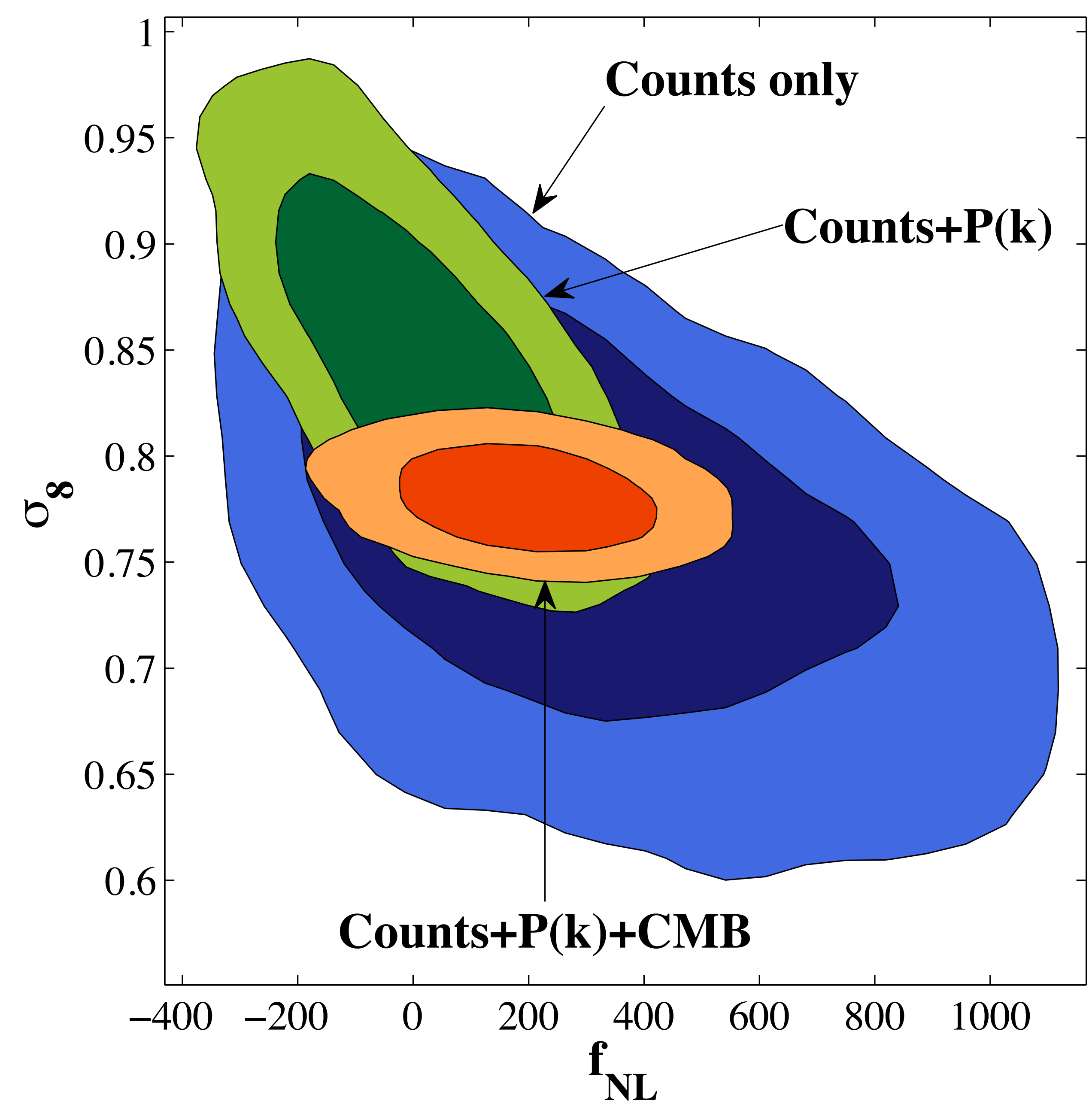
- From cluster data alone:

f_{NL} = 12 ± 157 (1σ)

- Mass function sensitive to ALL types of PNG

[See also Shandera et al. 13]

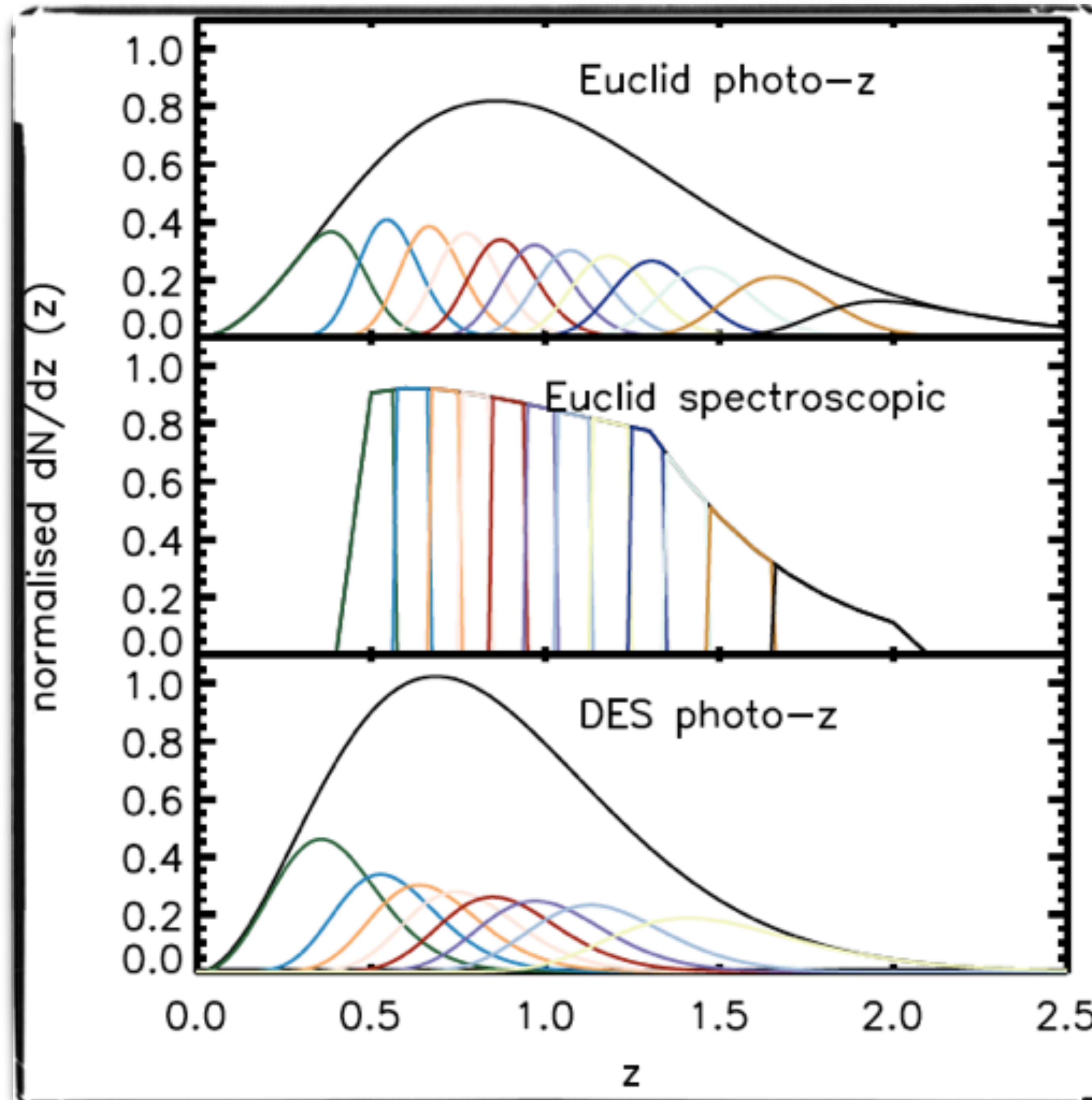




Primordial NG with DES and Euclid

[TG et al. 11 MNRAS]

- Combining: lensing + galaxy clustering
- Following Hu & Jain 04
- Including primordial non-Gaussianity
    - **DES**: Fermilab-led mission
        - Taking data now in Chile
        - Photo-z, deep to z~1.5
        - 300 M galaxies
        - 5,000 sq. deg
- **Euclid**: approved ESA mission
    - In L2 orbit, launch ~2019
    - **Imaging** (vis+IR): 2 bn galaxies
    - Slitless **spectra**: 80 M galaxies
    - 15,000-20,000 sq. deg



Results
[TG et al. 11 MNRAS]

Critical assumpion for f_{NL}: $b_{fiducial}(z) \sim (1+z)^{1/2}$, similar to Orsi et al. 09.

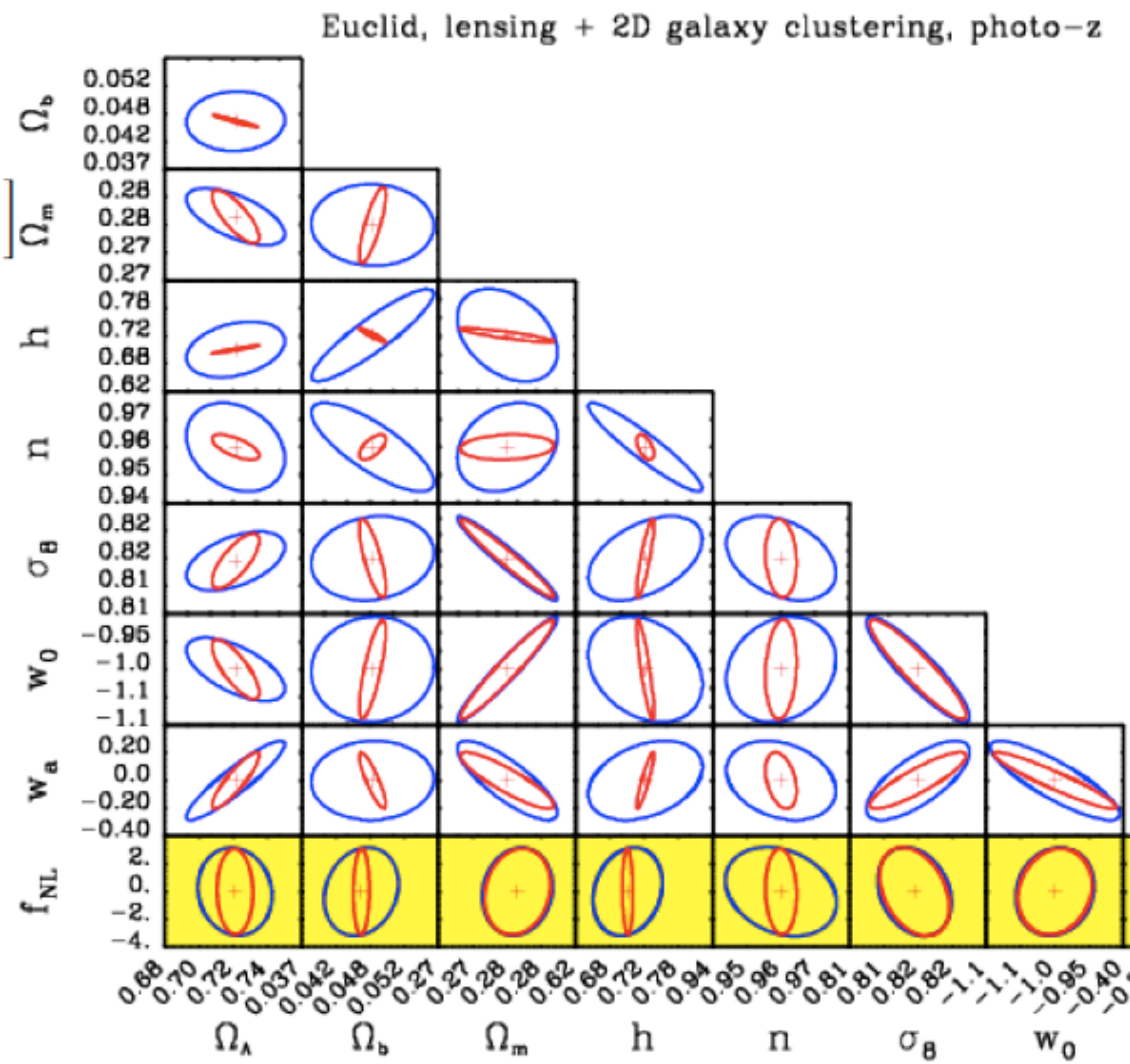
- **Combined** lensing + 2D gal spectrum Fisher forecast:

$$C_l^{\epsilon_i \epsilon_j} \qquad C_l^{g_i g_j} \qquad D_{l\alpha}^{\epsilon_i \epsilon_j} = \frac{\partial C_l^{\epsilon_i \epsilon_j}}{\partial \vartheta_\alpha}$$

$$F^x_{\alpha\beta} = f_{\rm sky} \sum_{l=l_{\rm min}}^{l_{\rm max}} \frac{(2l+1)}{2} \,{\rm Tr}\left[\mathbf{D}^x_{l\alpha} \left(\tilde{\mathbf{C}}^x_l\right)^{-1} \mathbf{D}^x_{l\beta} \left(\tilde{\mathbf{C}}^x_l\right)^{-1} \right]$$

[Hu & Jain 04]

- includes ⟨lens-gal⟩ spectrum
- Red: with Planck TT priors
- Euclid accuracy on local f_{NL}: ±3
- **DES: accuracy on f_{NL} ~ ±8**
- Running: n_{fNL} ~ ±0.12 if f_{NL} = 30
- Main issue will be **systematics**!



Conclusions & Future Work

- Extended analysis of PNG with latest combined LSS+ISW data
- NO non-Gaussianity: **-6 ± 15 (1σ)**: simplest inflation is OK
- **Systematics** a **big issue in ACFs**: any evidence of PNG should be confirmed by cross-correlations between independent data
- Planck bispectrum: f_{NL} = 2.7 ± 5.8 (1σ)
- **DES**: f_{NL} ± 8 [TG et al. 11]
  for DE: gal-gal, CMB-gal, CMB-shear
- **HETDEX**: High z, Lyman-α survey: 3-point
- **Euclid**: f_{NL} ± 3 ... if systematics under control