Large-Scale Structure: Next Frontier for Tests of NG

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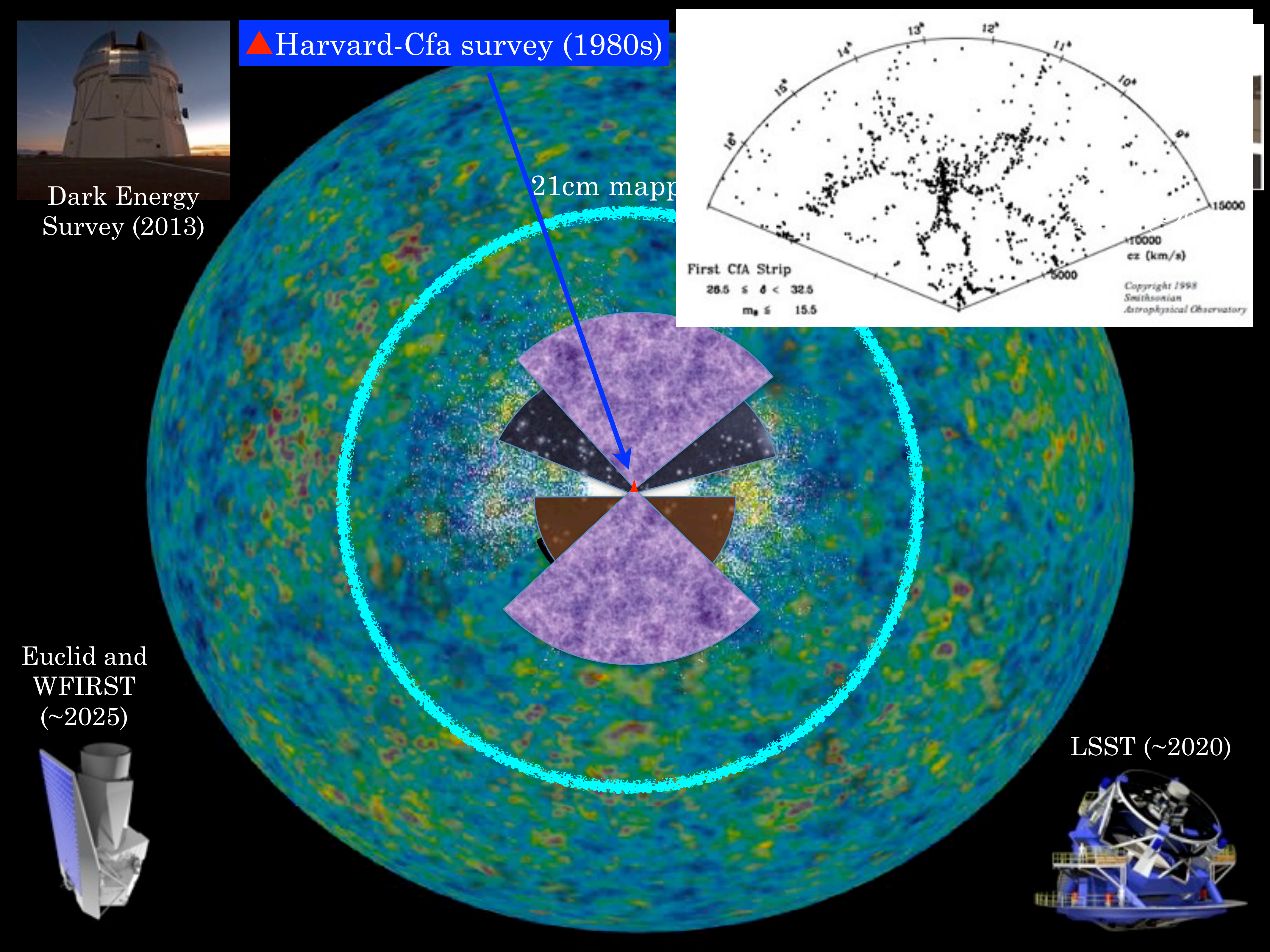
Harvard-Cfa survey (1980s)
Dark Energy Survey (2013)
21cm mapp
Euclid and WFIRST (~2025)
LSST (~2020)
First CfA Strip
26.5 ≤ δ < 32.5
m_B ≤ 15.5
15000
10000
cz (km/s)
5000
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Next Frontier: Large-Scale Structure

	CMB	LSS
dimension	2D	3D
# modes	$\propto l_{max}^2$	$\propto k_{max}^3$
systematics & selection func.	relatively clean	relatively messy
temporal evol.	no	yes
can slice in	λ only	λ, M, bias...

LSS tracers and their statistical probes

- Clusters of galaxies
  - 1-point function - cluster counts (dn/dlnM), sens to DE
  - 2-pt function - sensitive to f_{NL}
- Galaxies: LRG, ELG, also quasars
  - 2-point function: pretty well understood, easily measured
  - 3-pt function: powerful, but issues in predicting b_G(k, a, env)
  - also galaxy-CMB cross-correlation
- Shear from WL:
  - 2-point function: measurements systematics dominated
  - 3-pt function: future; systematics a huge challenge
  - also gal-gal (γ-g), shear peaks, ...

Forecasts for $f_{NL}(k)$

$$f_{\rm NL}(k) = f^*_{\rm NL}\left(\frac{k}{k_*}\right)^{n_{f_{\rm NL}}}$$

Projected errors $\sigma(f^*_{\rm NL})$ and $\sigma(n_{f_{\rm NL}})$, and the corresponding pivots

Variable	DESI ~~BigBOSS~~	BigBOSS+Planck C_ℓs	Planck bispec	**BigBOSS+all Planck**
$\sigma(f^*_{\rm NL})$	3.0	2.6	4.4	2.2
$\sigma(n_{f_{\rm NL}})$	0.12	0.11	0.29	0.078
$\mathrm{FoM}^{(\rm NG)}$	2.7	3.4	0.78	5.8
k_{piv}	0.33	0.35	0.080	0.24

area in f_{NL}^*-n_{fNL} plane

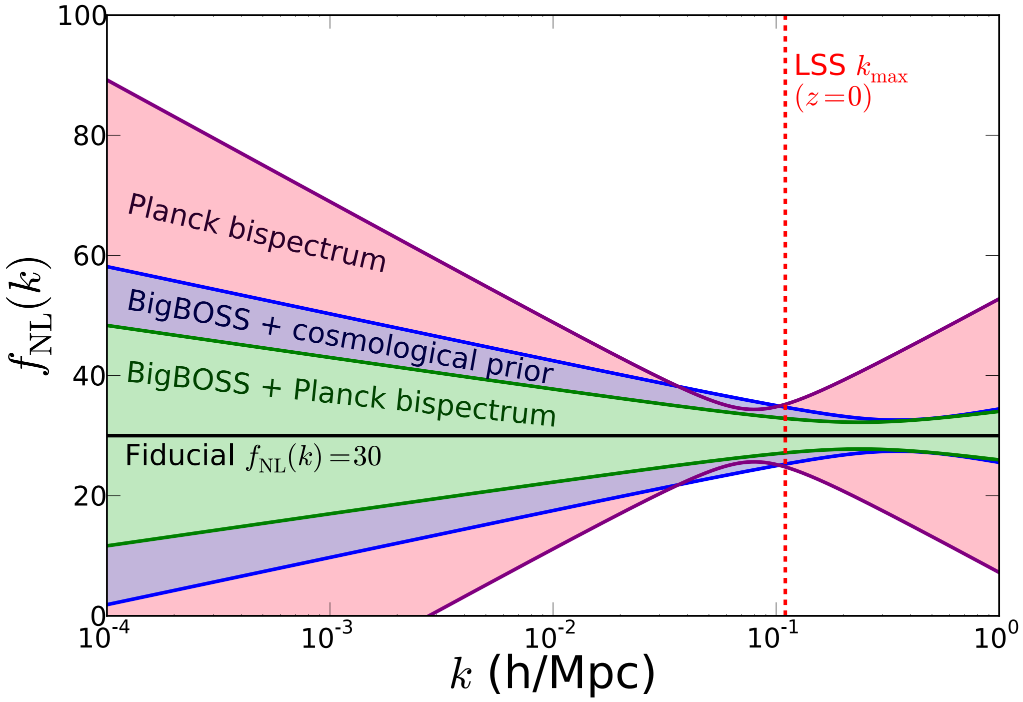
NB: The LSS forecasts are very uncertain, much more so than the CMB

Becker, Huterer & Kadota, 2012; see also Giannantonio et al, 2012

$f_{NL}(k)$ forecasts

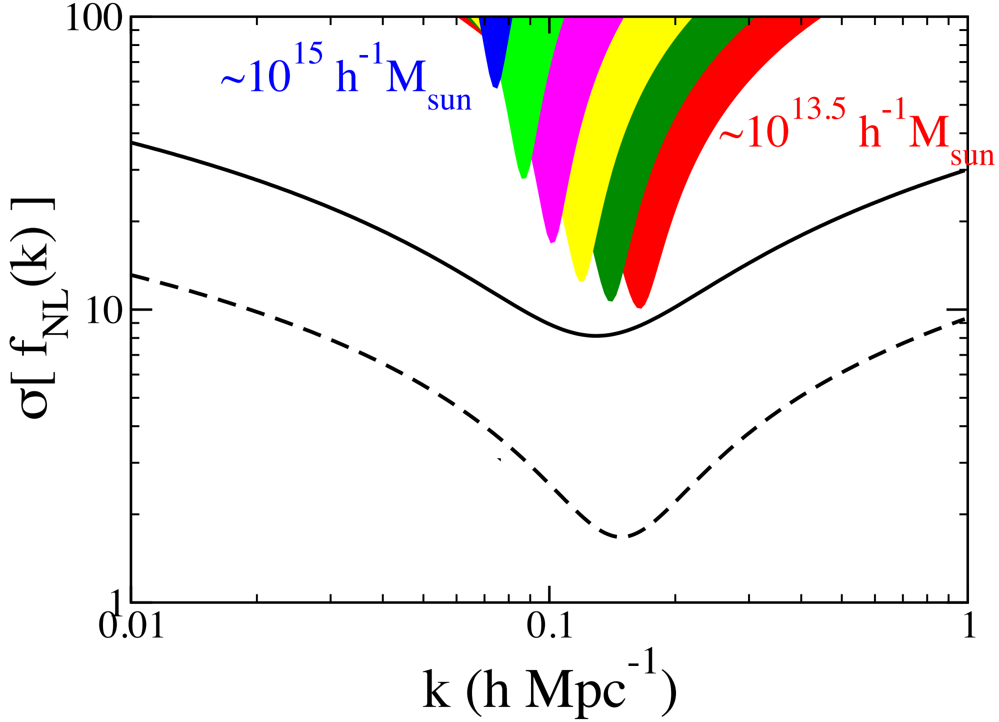
$$f_{\rm NL}(k) = f_{\rm NL}^{*} \left(\frac{k}{k_*}\right)^{n_{f_{\rm NL}}}$$

CMB and LSS are very complementary



Becker, Huterer & Kadota 2012

Halos of mass M probe NG on scale $k \sim M^{-1/3}$



Shandera, Dalal & Huterer 2012

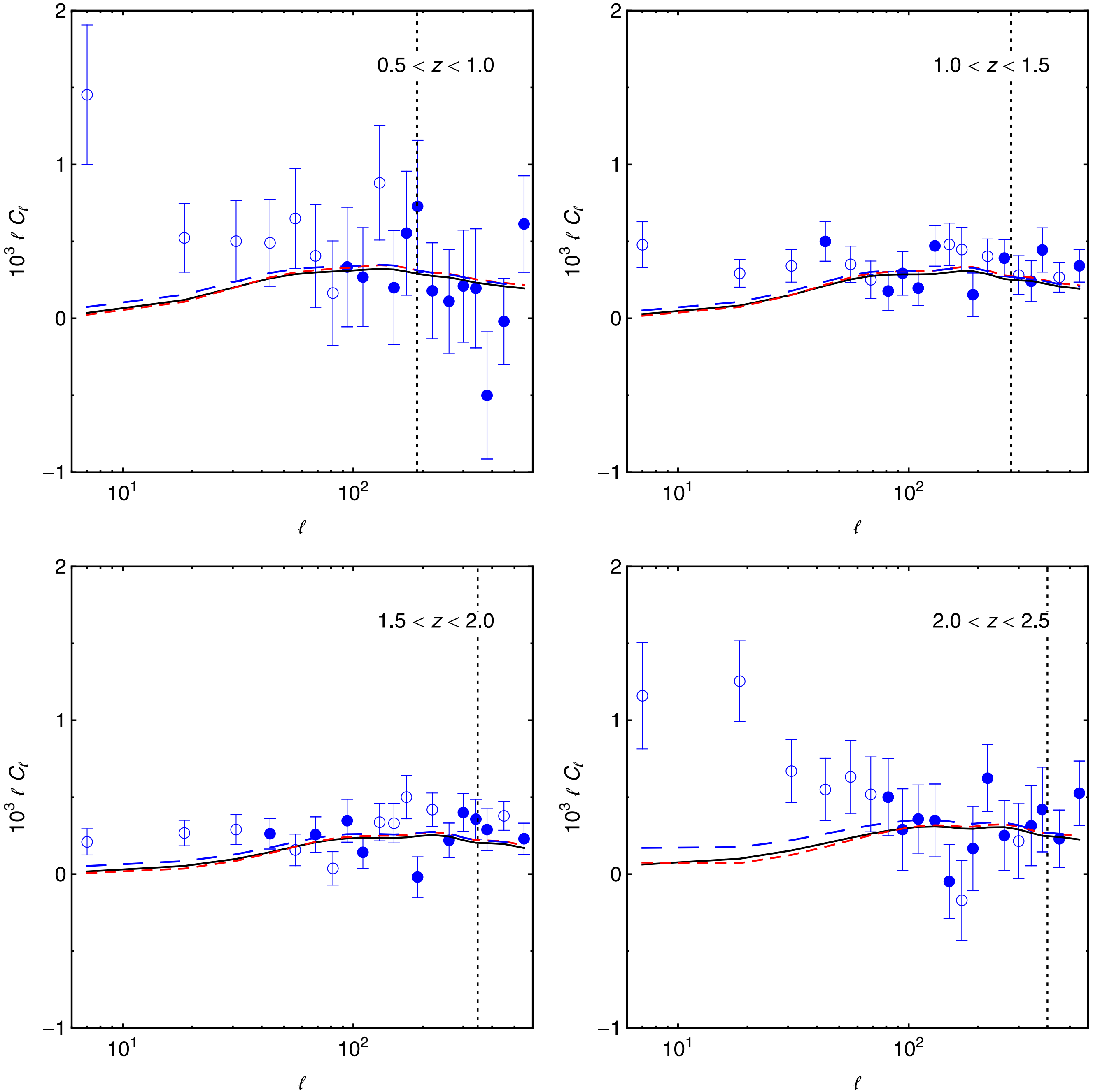
In general, LSS can probe:

$$\Delta b_{NG} \propto \begin{cases} k^{-2} \text{ (local)} \\ k^{-1} \text{ (folded)} \\ k^{0} \text{ (equilateral)} \\ k^{-\alpha} \text{ (generic); } 0 \le \alpha \le 3 \end{cases}$$

Dark Energy Survey Instrument (DESI)

- Huge spectroscopic survey on Mayall telescope (Arizona)
- ~5000 fibres, ~15,000 sqdeg, ~20 million spectra
- LRG in $0 < z < 1$, ELG in $0 < z < 1.5$, QSO $2.2 < z < 3.5$
- Great for DE (RSD, BAO)
- **Great for NG** - 3D P(k, z), bispectrum...
- start 2018, funding DOE + institutions

But... systematics!



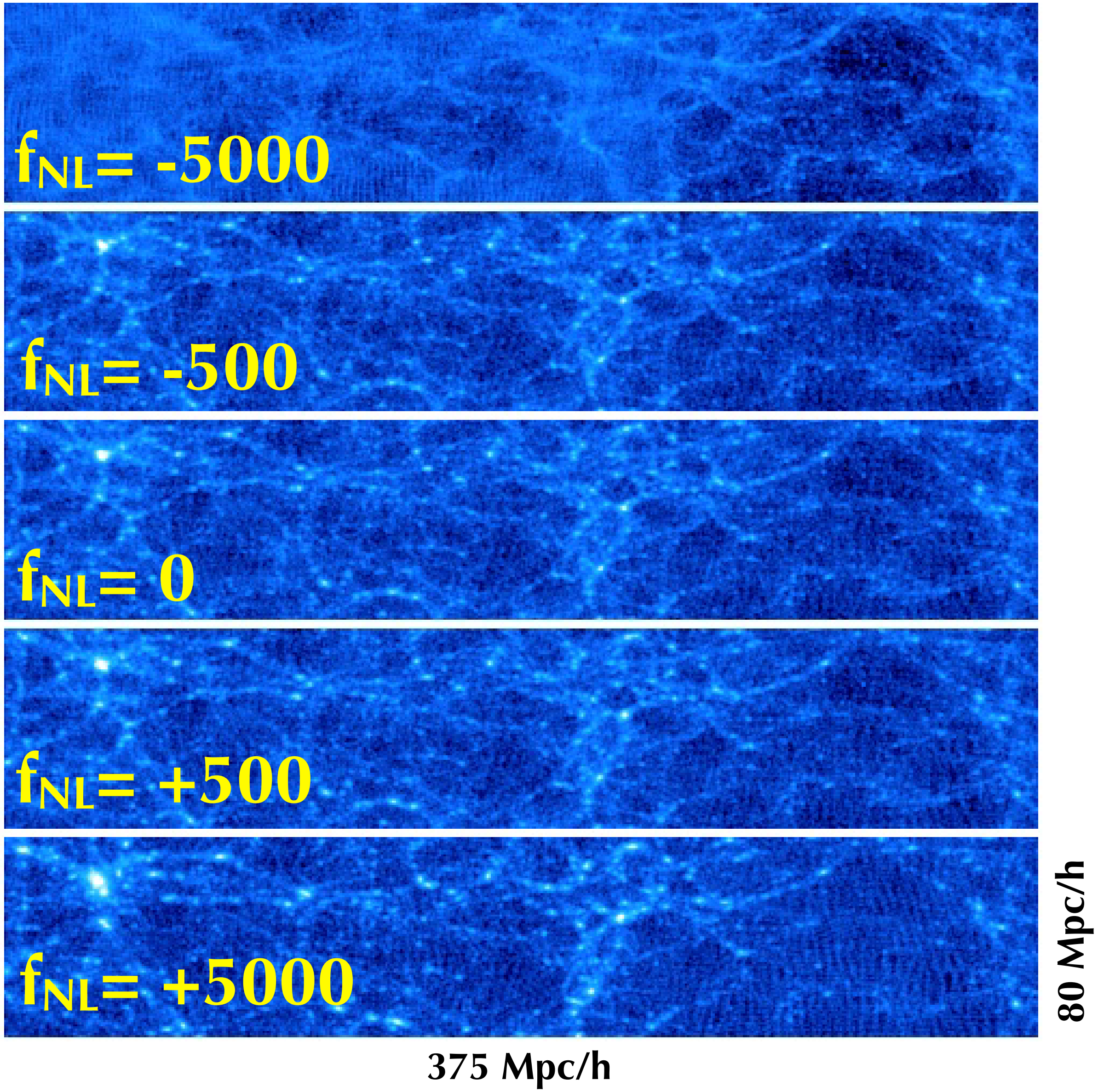
QSO power spectra from SDSS;
open circle points not used since they may be systematics-contaminated!

Agarwal, Ho & Shandera, on arXiv very shortly...

Large-Scale Structure in Three Easy Steps:

Step 1:
Produce theory predictions
(including from simulations)

Simulations with non-Gaussianity (f_{NL})

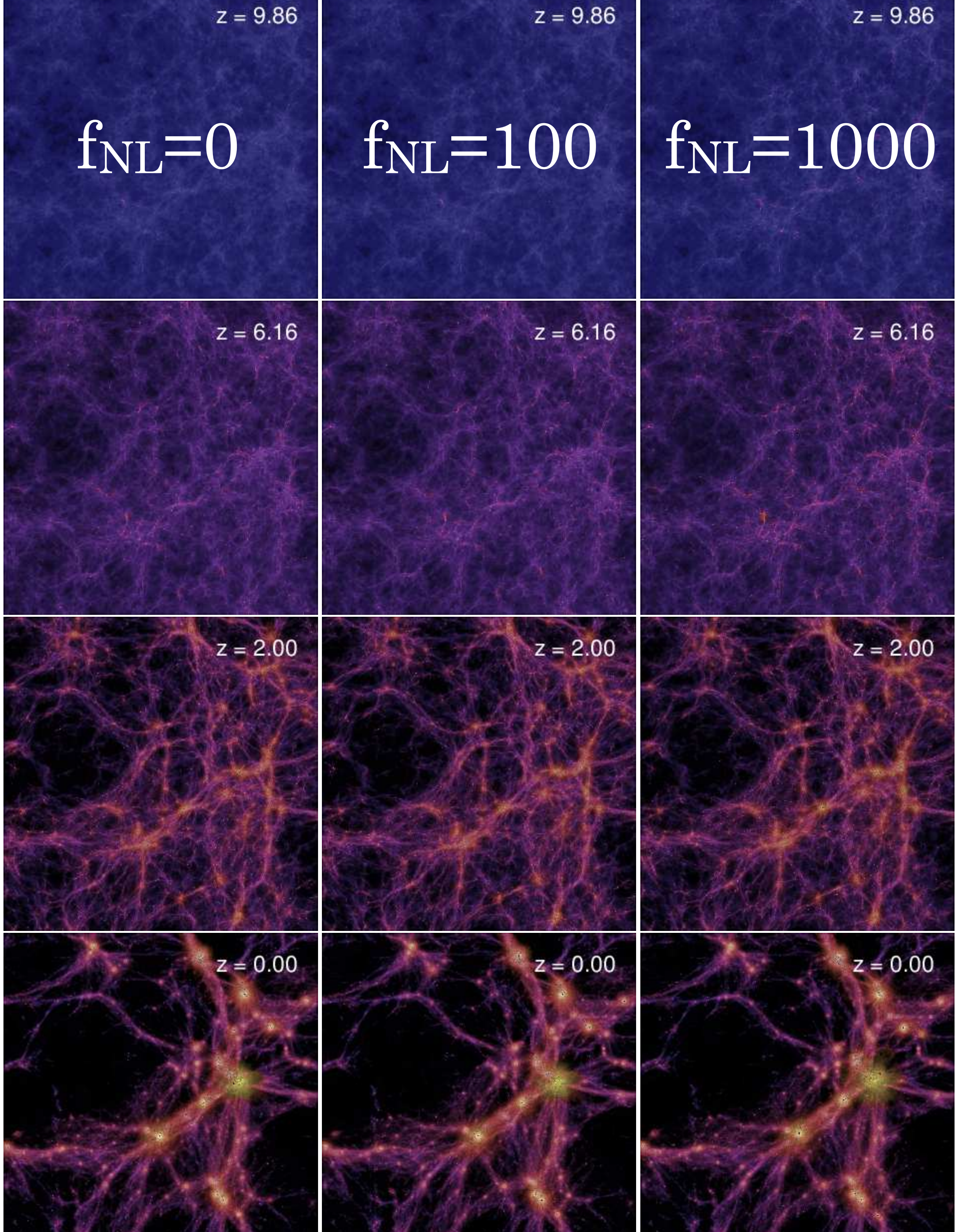


- Under-dense region evolution decrease with f_{NL}
- Over-dense region evolution increase with f_{NL}

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

Dalal et al. 2008

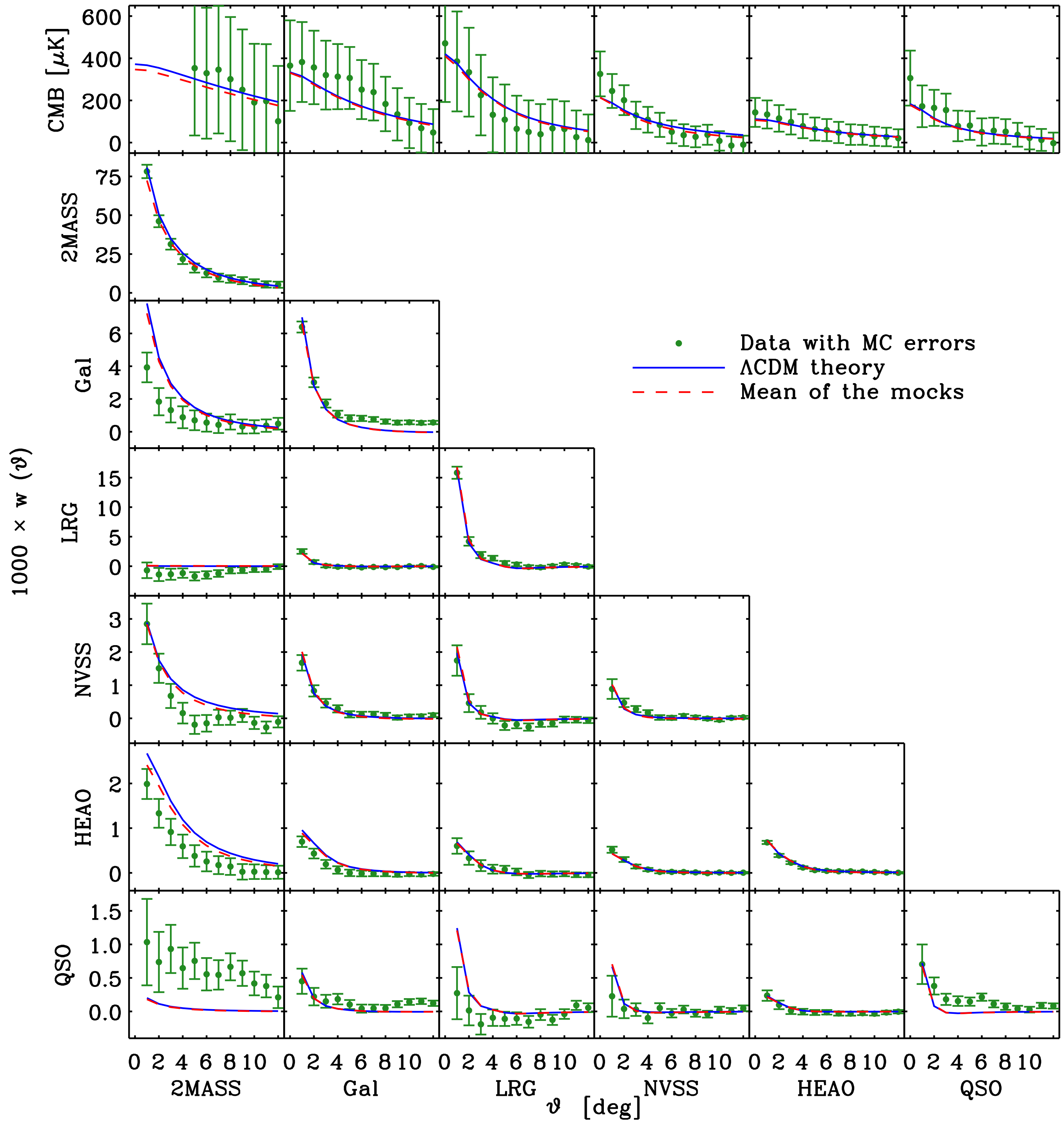
...and now with baryons!



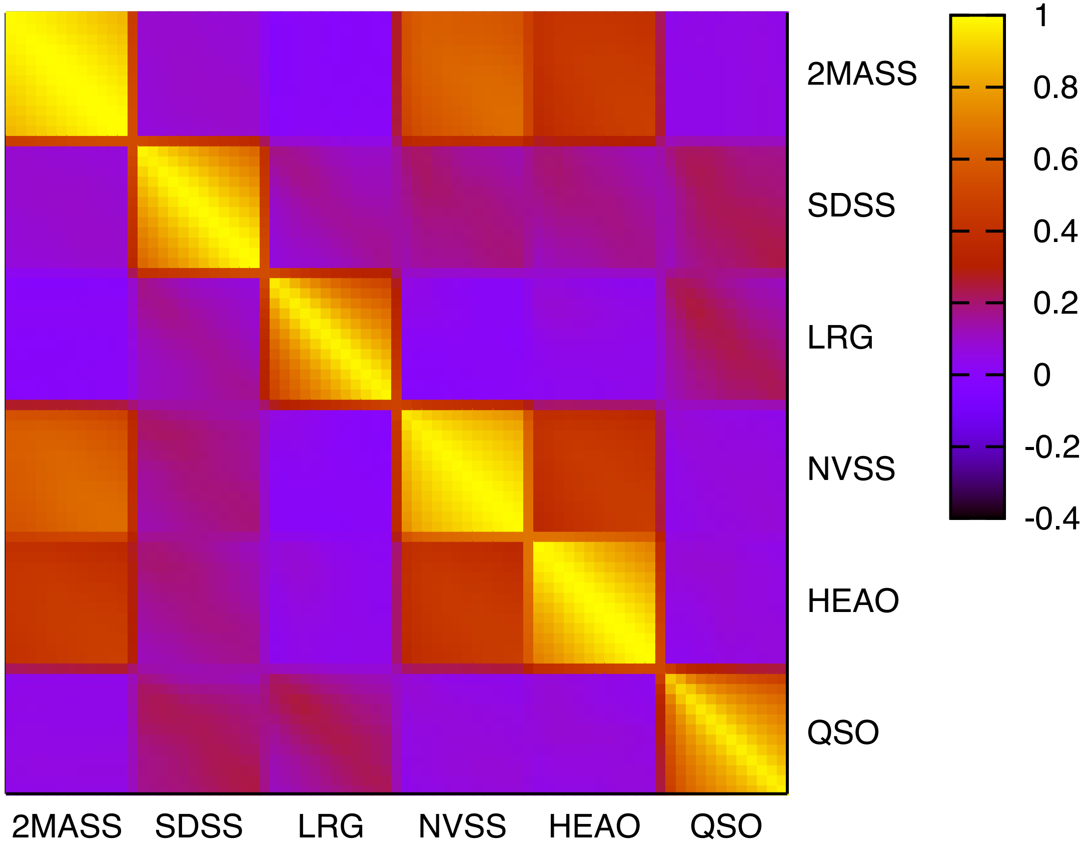
Zhao, Li,
Shandera & Jeong,
arXiv:1307.5051

Step 2:
Use multiple LSS probes in dataset,
and figure out statistics of their signal

Using LSS (and CMB) tracers - correlation functions

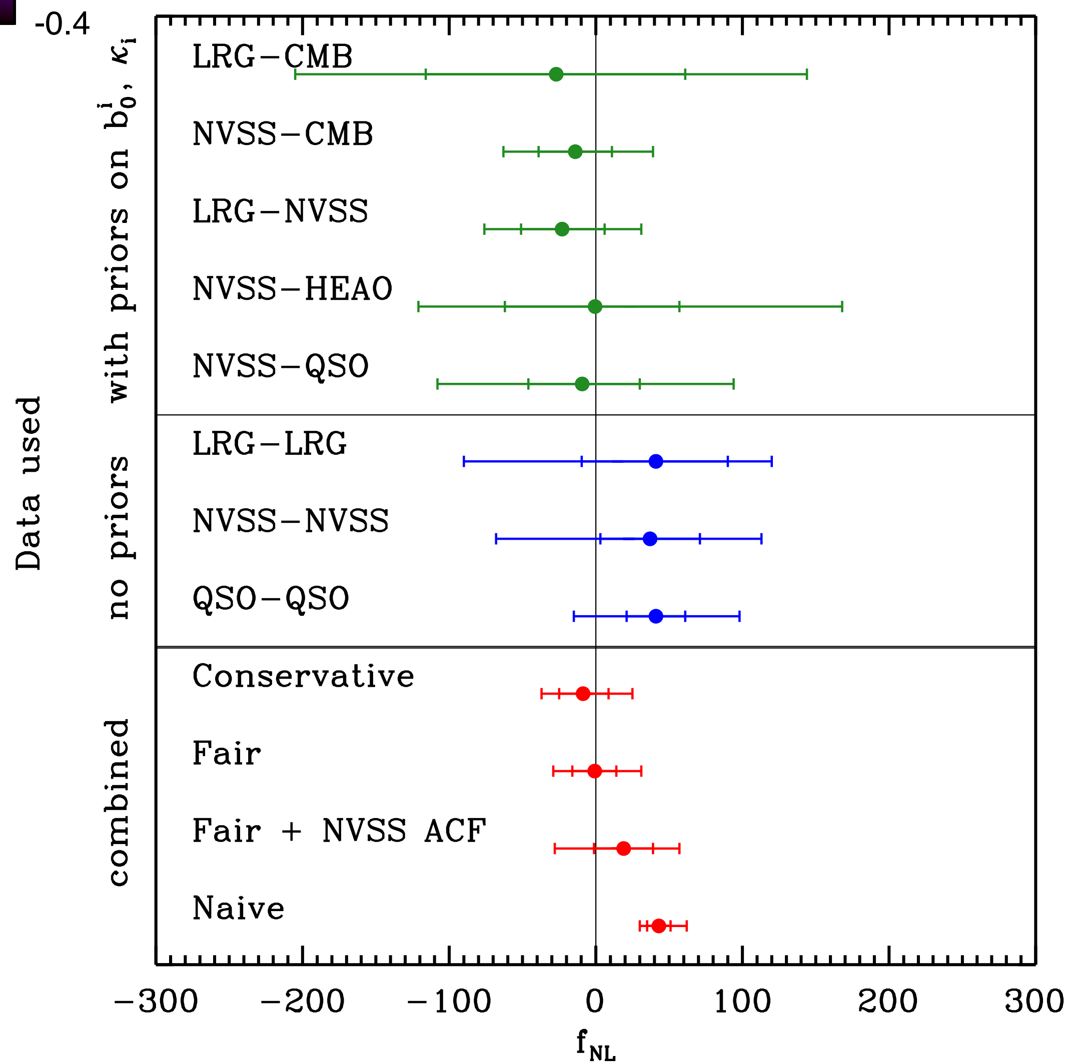


Giannantonio et al. 2013



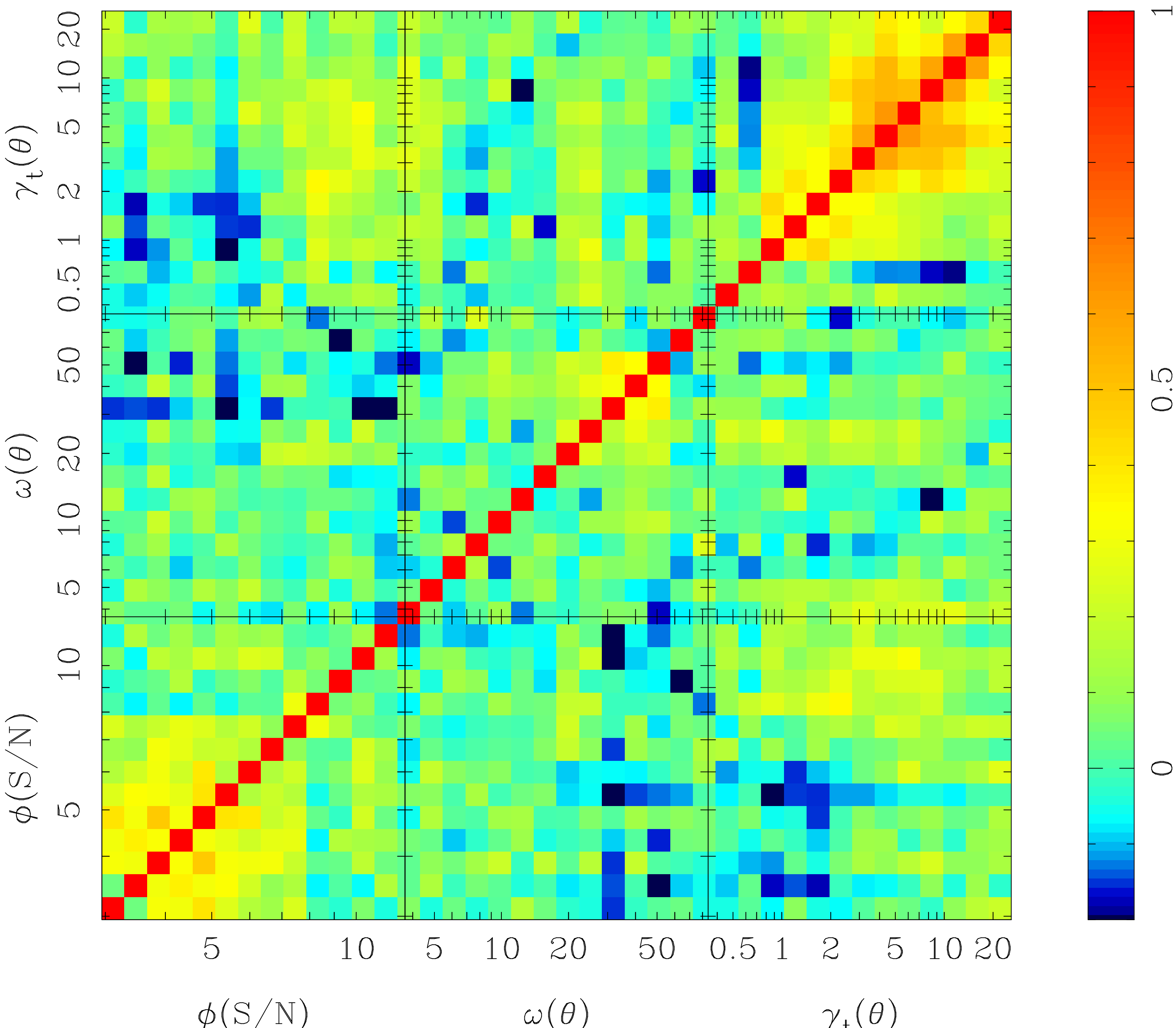
Covariance matrix

Final constraints:



Giannantonio et al. 2013

Covariance of weak lensing probes



Shear peaks

Shear 2-pt

Tangential shear profile

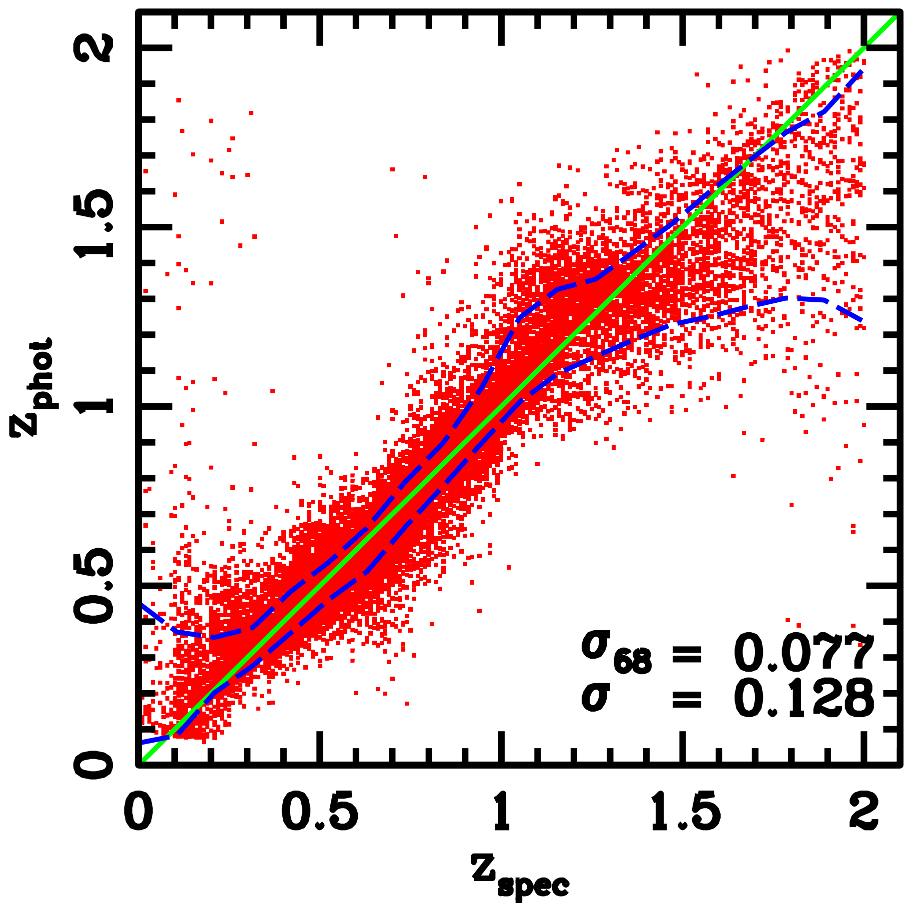
results from numerical simulations

Marian, Smith et al. 2013

Step 3:
Control the Systematic Errors

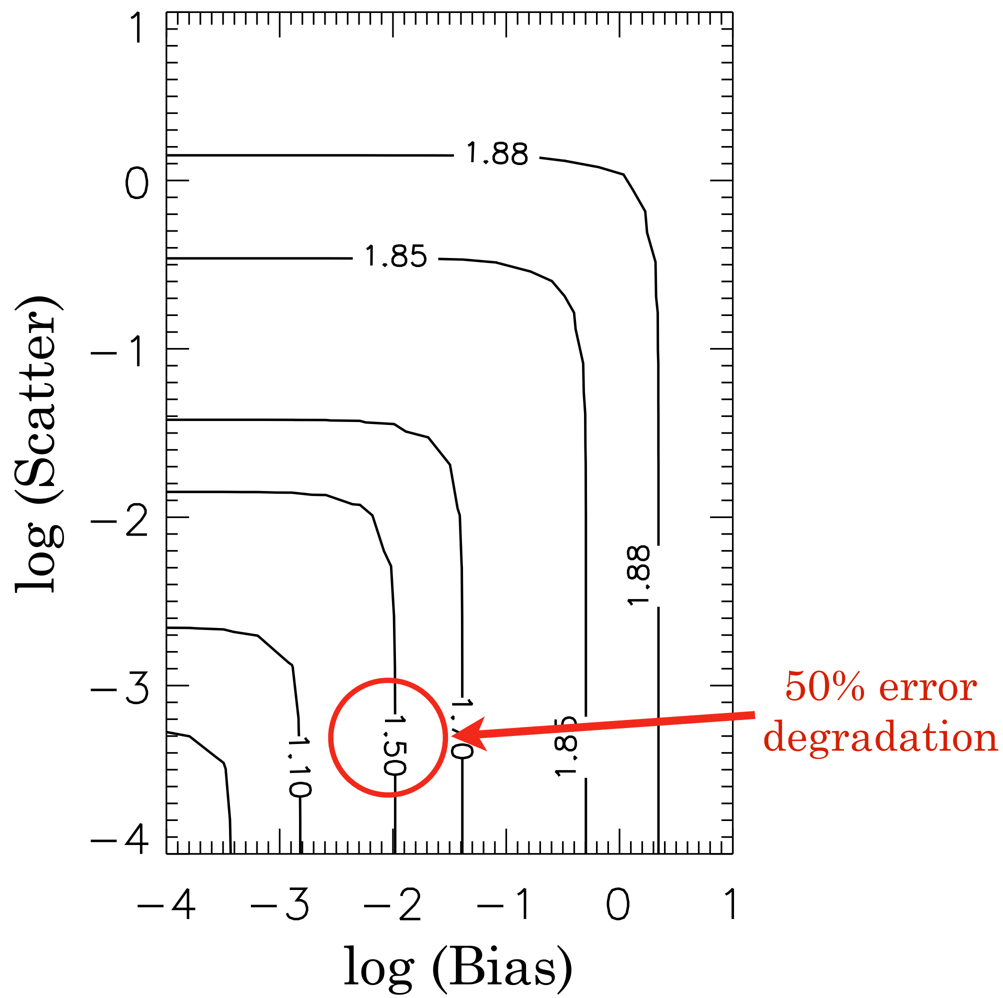
Poster child for the systematics: photometric redshift errors

z_{phot}-z_{spec}
from "training set"



C. Cunha

Requirements



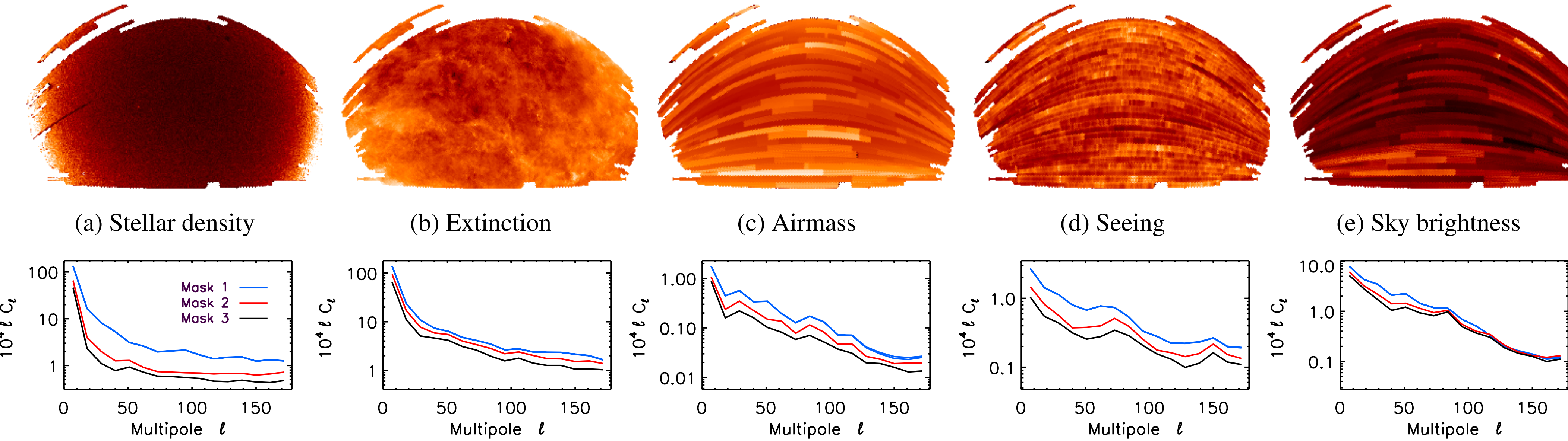
Ma, Hu & Huterer 2006

For the NG measurements, photo-z but also: (photometric) calibration errors

- **Detector sensitivity**: sensitivity of the pixels on the camera vary along the focal plane. Sensitivity of a given pixel can change with time.
- **Observing conditions**: spatial and temporal variations.
- **Bright objects**: The light from foreground bright stars and galaxies affects the sky subtraction procedure, which impairs the surveys' completeness near bright objects.
- **Dust extinction**: Dust in the Milky Way absorbs light from the distant galaxies.
- **Star-galaxy separation**: In photometric surveys, faint stars can be erroneously included in the galaxy sample. Conversely, galaxies are sometimes misclassified as stars and culled from the sample. Remember, stars are *not* randomly distributed across the sky.
- **Deblending**: Galaxy images can overlap, and it can be difficult to cleanly separate photometric and spectroscopic measurements for the blended objects.

Huterer et al 2013

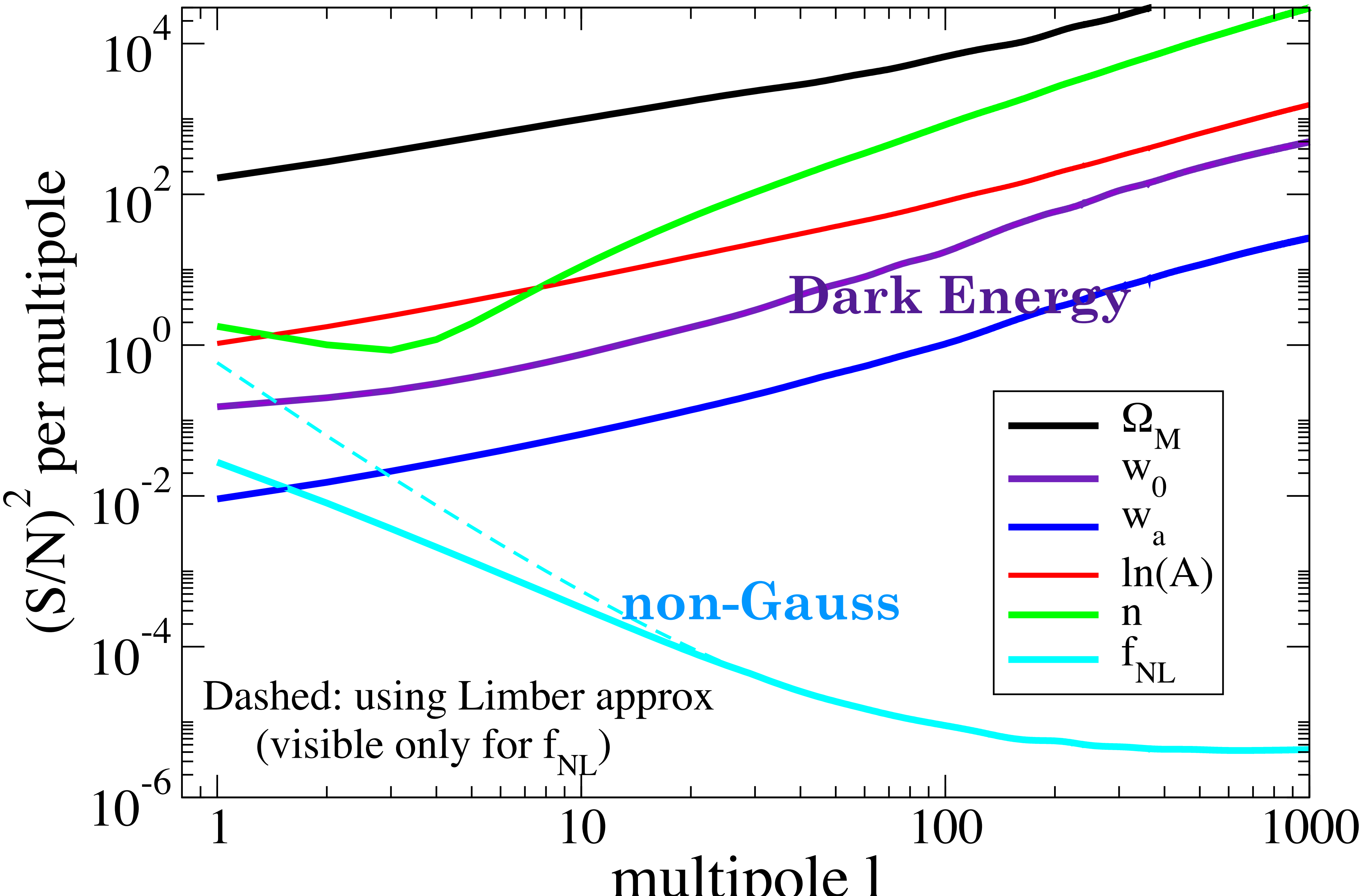
Example II: LSS calibration errors



- dominate on large angular scales
- can be measured, removed using same or other data

Leistedt et al 2013

Non-Gaussianity constraints are special: they come from large angular/spatial scales



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Calibration errors unleashed: effects on cosmological parameters and requirements for large-scale structure surveys

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How do the **most generic calibration errors** look (in the power spectrum)?
How do they affect NG (and DE) parameters?

Related works: Pullen & Hirata 2012, Leistedt et al 2013, Agarwal et al, in prep.

(True) Galaxy density field:

$$\frac{N(\hat{\mathbf{n}}) - \bar{N}(\hat{\mathbf{n}})}{\bar{N}(\hat{\mathbf{n}})} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\hat{\mathbf{n}})$$

Calibration defined:

$$N_{\rm obs}(\hat{\mathbf{n}}) = c(\hat{\mathbf{n}}) N(\hat{\mathbf{n}})$$

Calibration expanded in spherical harmonics:

$$c(\hat{\mathbf{n}}) = 1 + \sum_{\ell m} c_{\ell m} Y_{\ell m}(\hat{\mathbf{n}})$$

Statistical properties of two fields:

$$\langle a_{\ell m} \rangle = 0; \quad \langle a_{\ell m} a^*_{\ell m} \rangle = \delta_{mm'} \delta_{\ell\ell'} C_\ell$$

$$\langle c_{\ell m} \rangle = c_{\ell m}; \quad \langle c_{\ell m} c^*_{\ell m} \rangle = |c_{\ell m}|^2$$

Defining the observed overdensity: t_{lm} coefficients

$$\delta^{\rm obs}(\hat{\mathbf{n}}) \equiv t(\hat{\mathbf{n}}) = \sum_{\ell m} t_{\ell m} Y_{\ell m}(\hat{\mathbf{n}})$$

Final result for the **observed** power spectrum is:

$$\langle t_{\ell m} t^*_{\ell' m'}\rangle = \frac{1}{(1+\epsilon)^2}\left\{ \underbrace{\delta_{mm'}\delta_{\ell\ell'}C_\ell}_{\text{isotropic}} + \underbrace{\left[U^{\ell\ell'}_{mm'}\, C_{\ell'} + (U^{\ell\ell'}_{mm'})^*\, C_\ell\right] + \sum_{\ell_2 m_2} U^{\ell_2\ell}_{m_2 m}(U^{\ell_2\ell'}_{m_2 m'})^*\, C_{\ell_2} + c_{\ell m}c^*_{\ell' m'}}_{\text{breaks statistical isotropy}} \right\}$$

Cancels effects of calibration monopole

True power

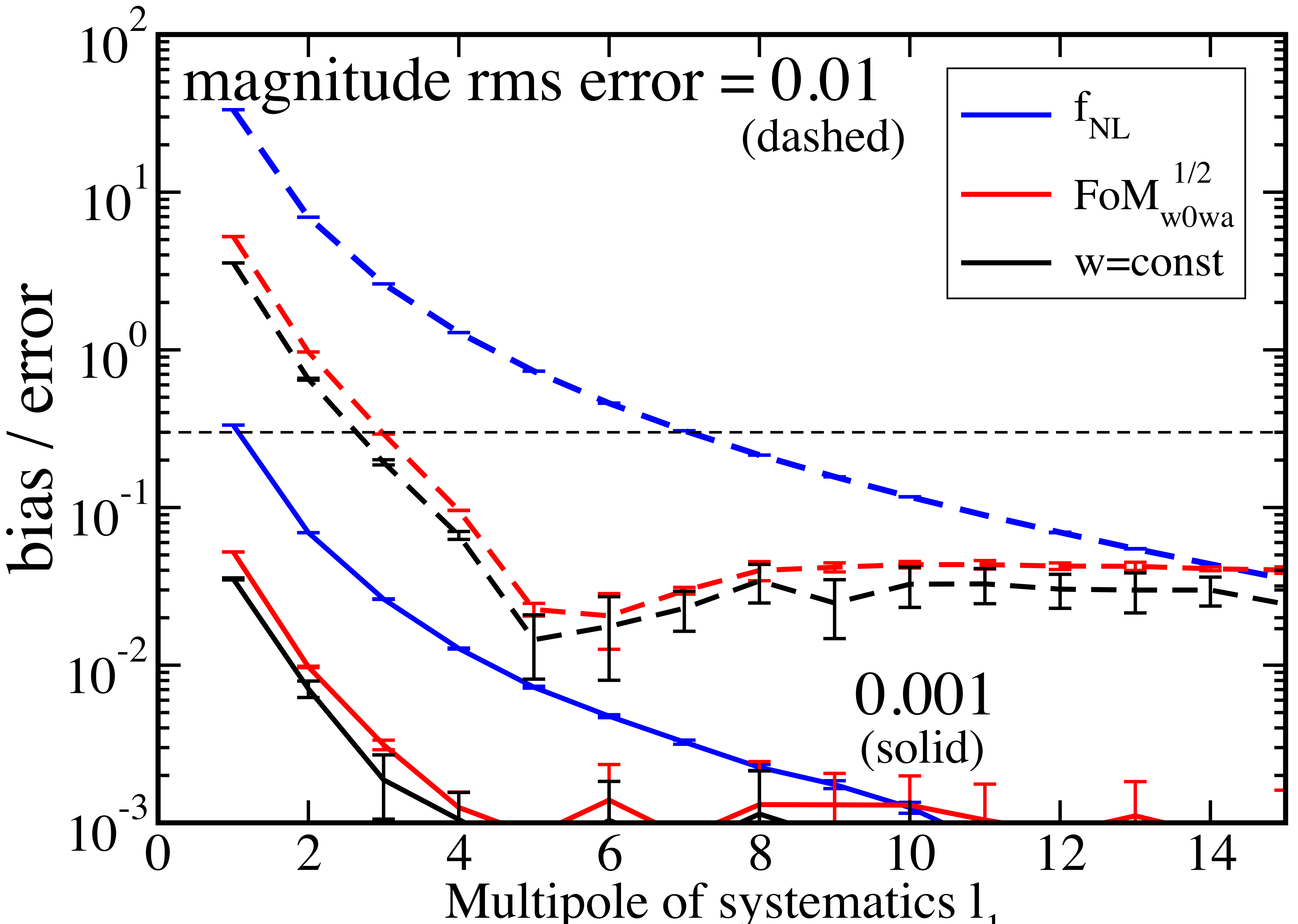
Calibration (biases)

where $\quad U^{\ell_2\ell}_{m_2 m} \equiv \sum_{\ell_1 m_1} c_{\ell_1 m_1} R^{\ell_1\ell_2\ell}_{m_1 m_2 m}$

$$R^{\ell_1\ell_2\ell}_{m_1 m_2 m} \equiv (-1)^m \sqrt{\frac{(2\ell_1+1)(2\ell_2+1)(2\ell+1)}{4\pi}} \begin{pmatrix} \ell_1 & \ell_2 & \ell \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \ell_1 & \ell_2 & \ell \\ m_1 & m_2 & -m \end{pmatrix}$$

Huterer et al 2013

Bias/error ratios per calib error in *single* multipole



Moreover, this implies stringent requirement on the uniformity of faint-end magnitude (i.e. - uniformity of depth of survey)

$$\frac{\delta N}{N}(\hat{\mathbf{n}}) \;\equiv\; c(\hat{\mathbf{n}}) \;=\; \ln(10)\, s(z)\, \delta m_{\rm max}(\hat{\mathbf{n}})$$

what I called 'calibration error'

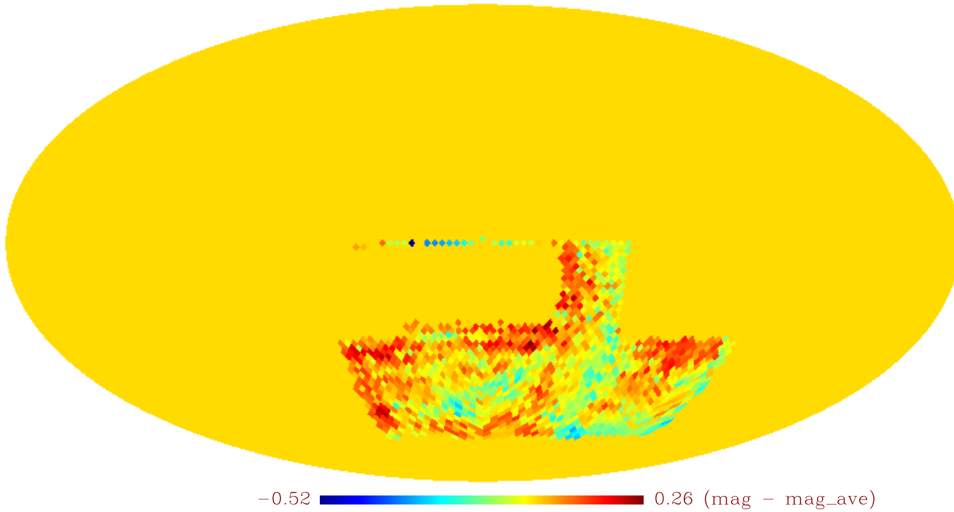
where

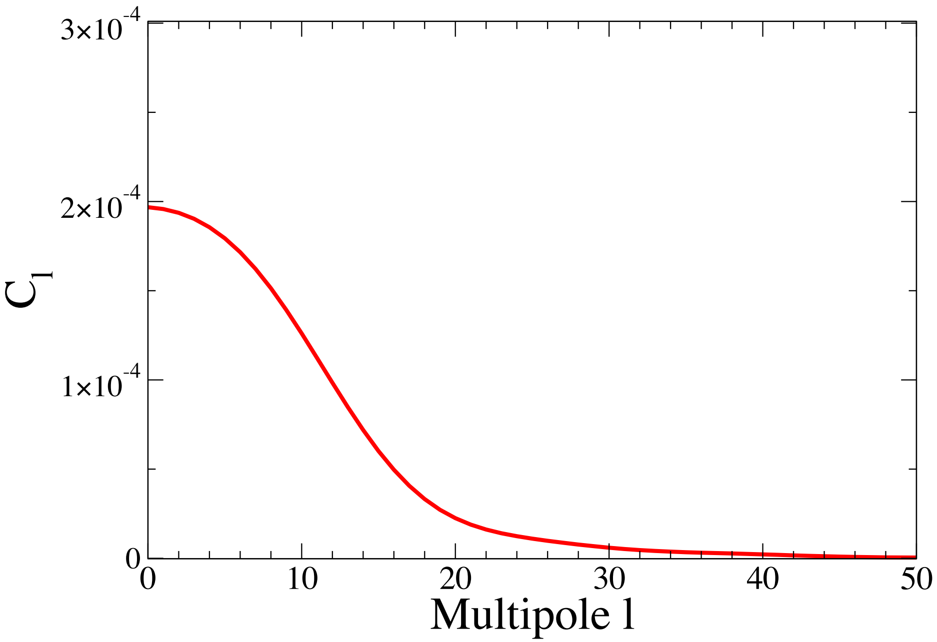
$$s(z) \equiv \left. \frac{d \log_{10} N(z, > m)}{dm} \right|_{m_{\rm max}}$$

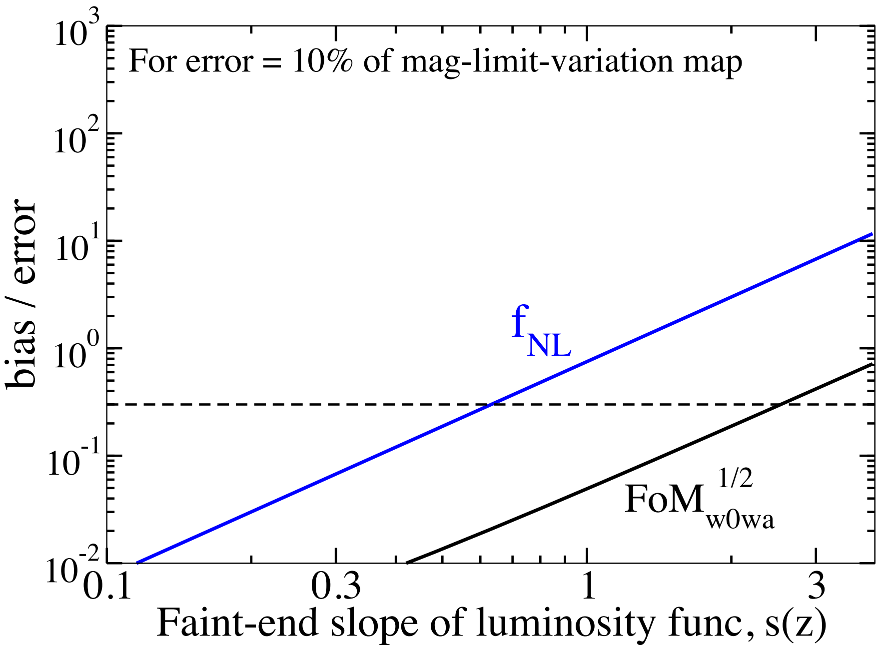
is the faint-end slope of the LF

Calibration bias: Worked Example 1

DES magnitude limit (J. Annis)

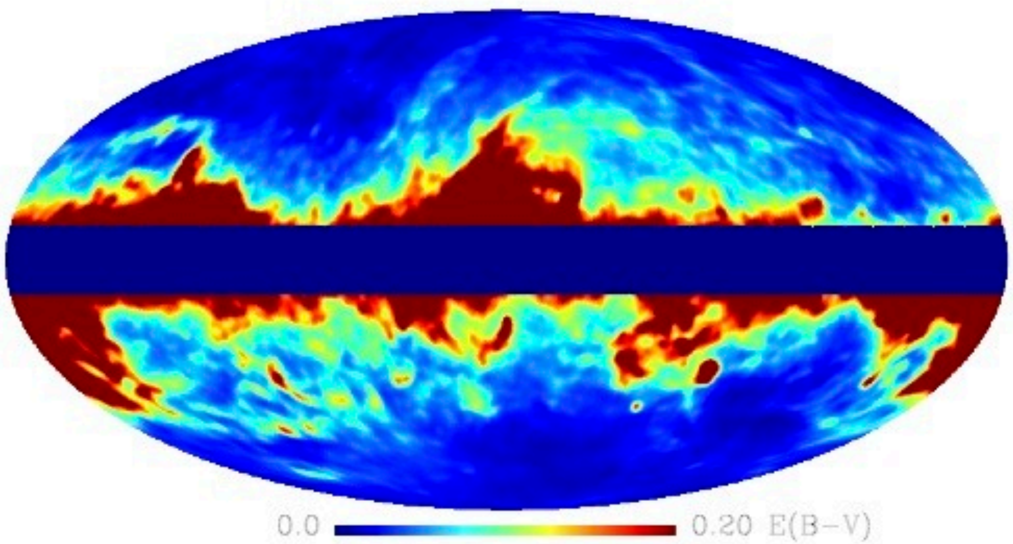




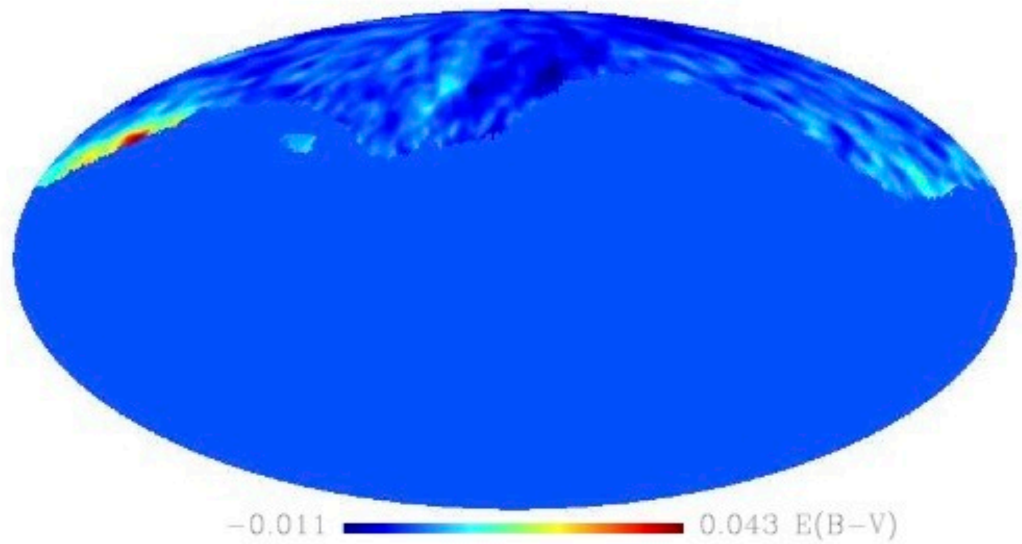


Calibration bias: Worked Example 2

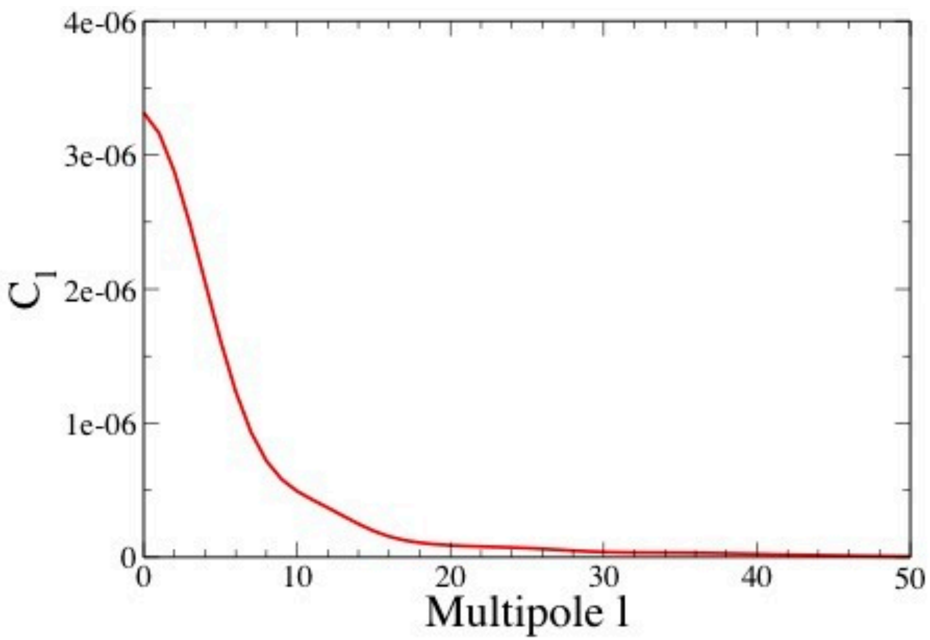
SFD dust map



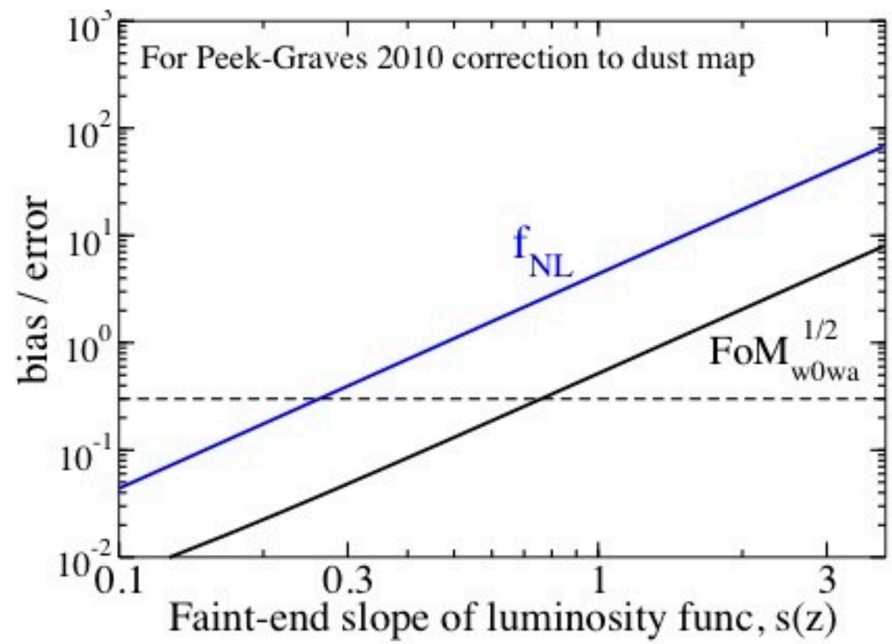
PG10 corrections to map



angular power of corrections



bias/error in cosmology



Challenges for NG/LSS program

... and approximate current status

- Motivate NG models ✓ (single-field, multiple fields, self-int)
- Utilize a variety of observables in LSS and CMB to get at NG ✓
- Develop fast, near-optimal estimators to extract NG from the CMB ✓ and LSS ✓✗
- Develop theory to relate NG models to LSS observables ✓✗ (messy; still need to check with sims)
- Develop theory to use LSS info from 1, 2 pt function of halos ✓ and galaxies/QSO ✓✗ (both with concerns)
- Control the systematic errors, esp large-scale LSS ✓✗
- Use galaxy bispectrum ✗ and weak lensing bispectrum ✗✗ to get at primordial NG [eg f_{NL}^{equil}]

EXTRA SLIDES

Bias/error for calib error in *a range of* multipoles