Fundamental Physics from Large-scale Structure

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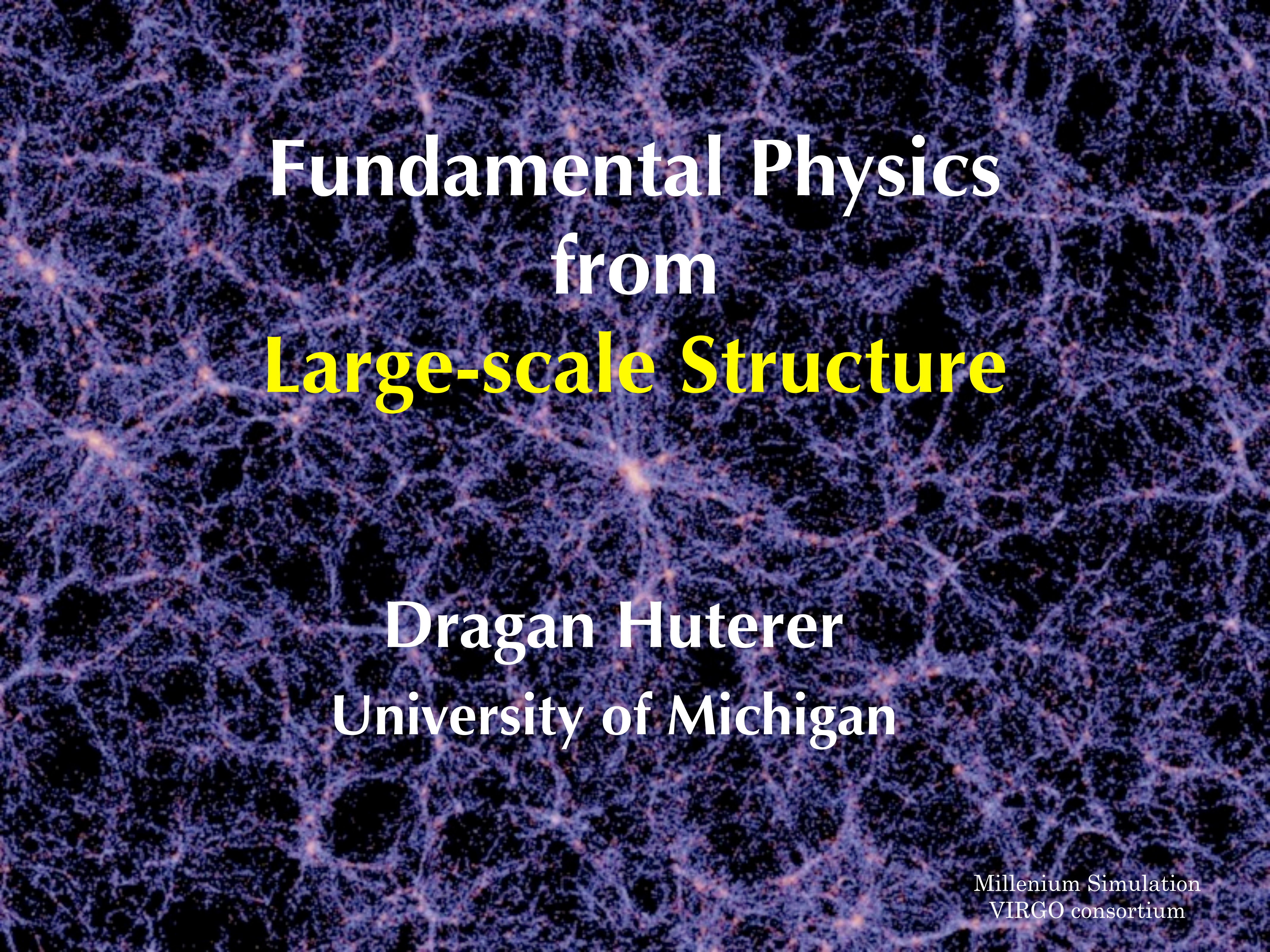
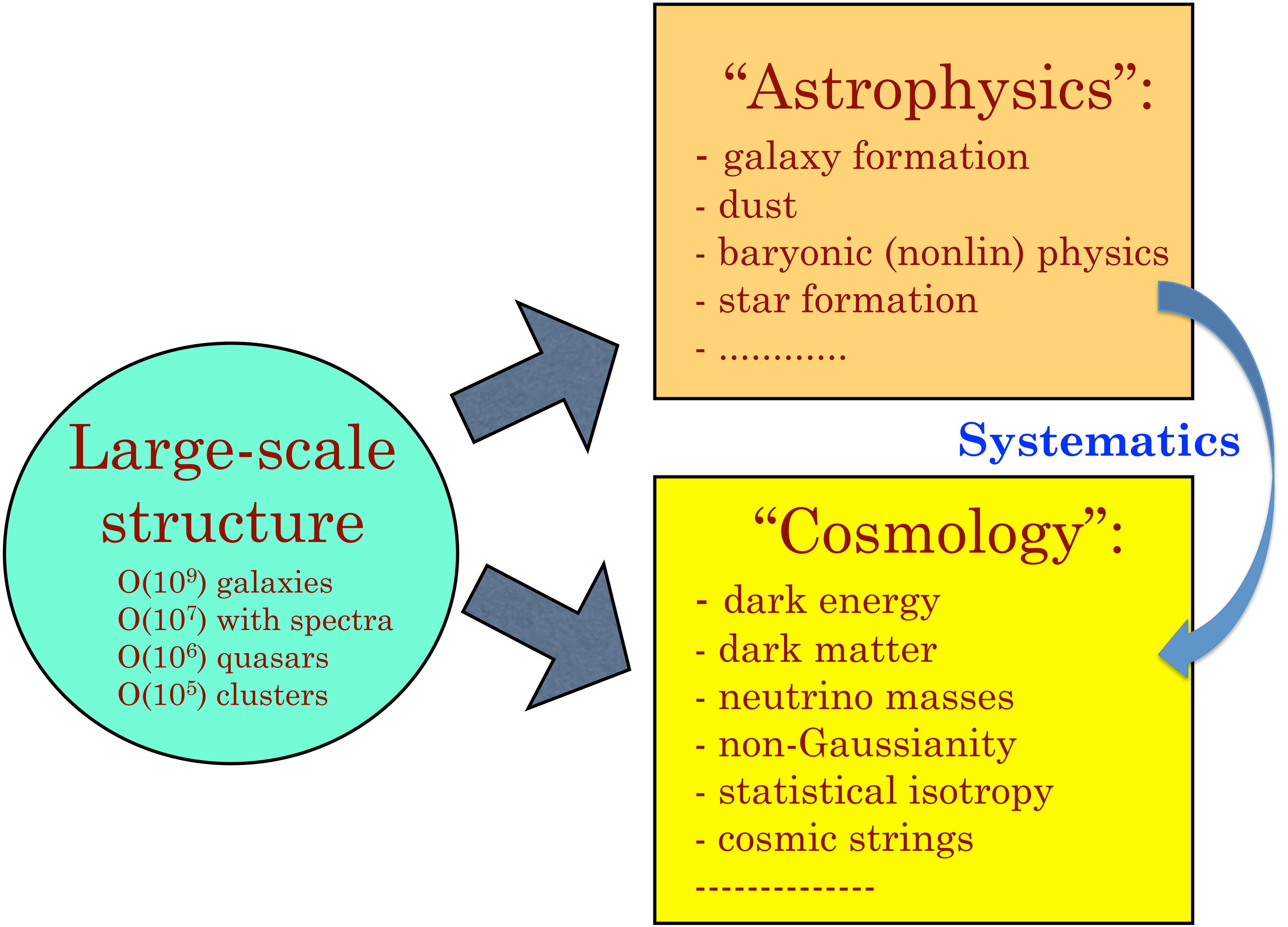


Millenium Simulation
VIRGO consortium

Outline of talk

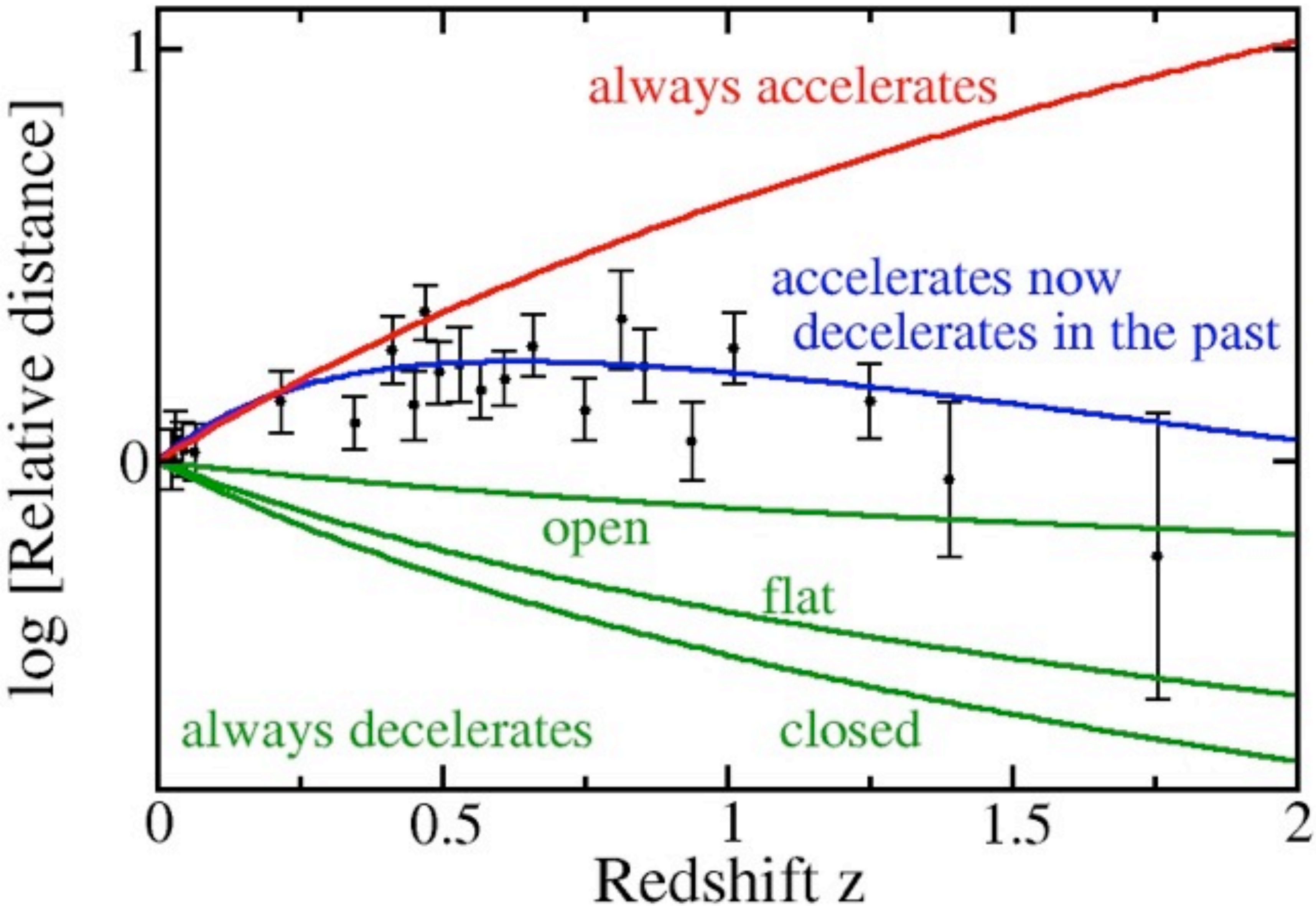
1. Constraining dark energy and the challenges - and opportunities - it presents

2. Large-scale structure and the coming opportunities in measuring fundamental physics, including primordial non-Gaussianity

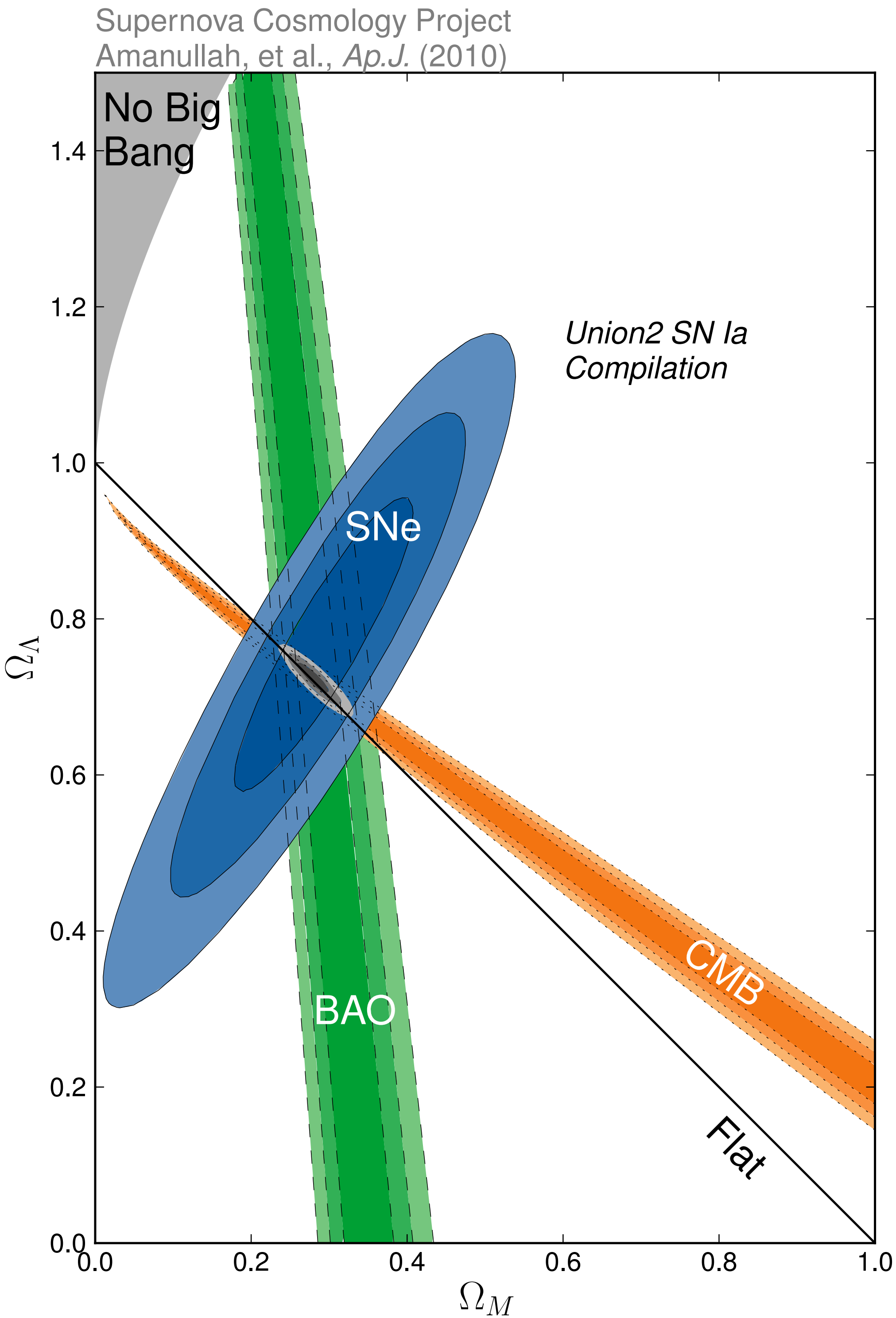

Large-scale structure
O(10^9) galaxies
O(10^7) with spectra
O(10^6) quasars
O(10^5) clusters
"Astrophysics":
- galaxy formation
- dust
- baryonic (nonlin) physics
- star formation
- ....
Systematics
"Cosmology":
- dark energy
- dark matter
- neutrino masses
- non-Gaussianity
- statistical isotropy
- cosmic strings

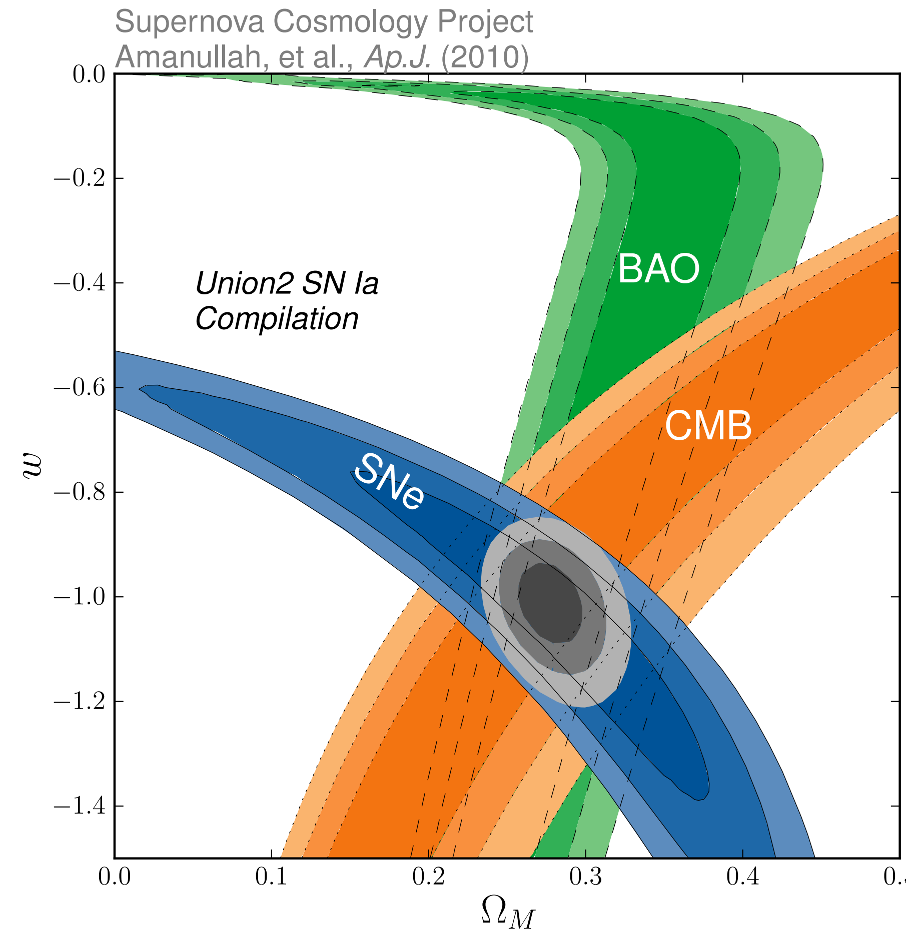
Dark Energy
and
the Challenges it Presents

Evidence for Dark energy from type Ia Supernovae



Union2 SN compilation binned in redshift





$$\Omega_{\mathrm{DE}} \equiv \frac{\rho_{\mathrm{DE}}}{\rho_{\mathrm{crit}}}$$

$$w \equiv \frac{p_{\mathrm{DE}}}{\rho_{\mathrm{DE}}}$$

To shed light on dark energy, search for 'departures from normal' in the data

- Variation of eq. of state w → (none yet)
- Clustering of DE → (super hard)
- DM-DE interactions → (none yet)
- Early dark energy → (none yet)
- Modified gravity (MG) → (none yet)

$$H^2 - F(H) = \frac{8\pi G}{3}\rho, \quad \text{or} \quad H^2 = \frac{8\pi G}{3}\left(\rho + \frac{3F(H)}{8\pi G}\right)$$

(MG) (DE)

Growth of density fluctuations can decide: $\ddot{\delta} + 2H\dot{\delta} - 4\pi\rho_M\delta = 0$

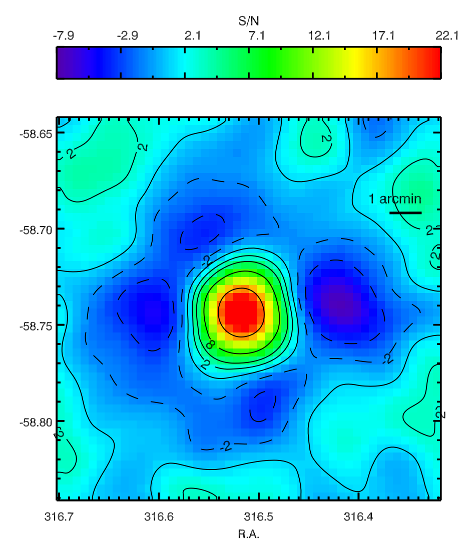
- Unusually massive, distant galaxy clusters (next)

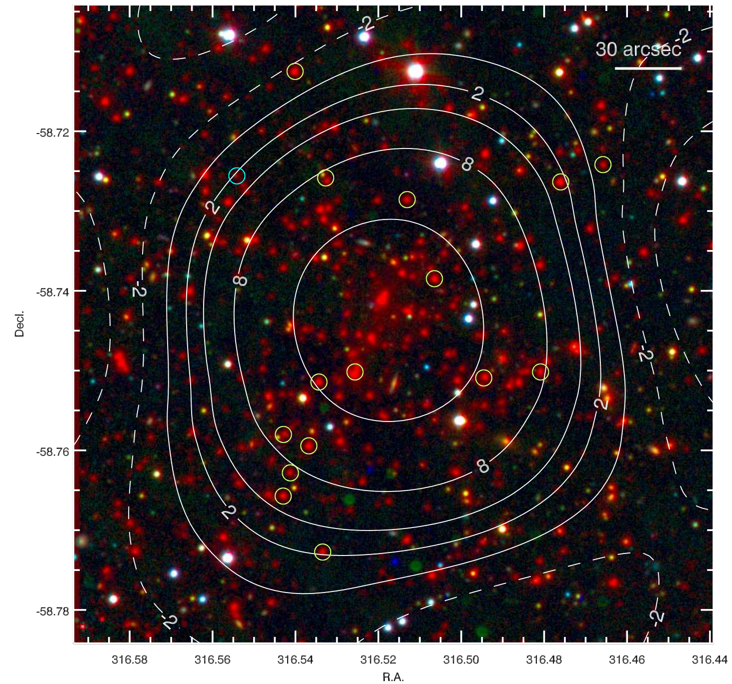
Simulation by Heidi Wu
Formation of 10^{15} M_{sun} cluster

High-z, high-M - "pink elephant" - clusters of galaxies

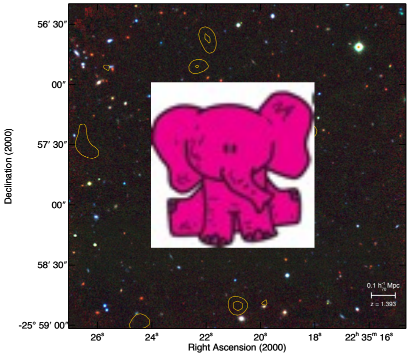
- SPT-CL J0546-5045: $z=1.067$, $M \approx (8.0 \pm 1.0) \cdot 10^{14}\, M_{sun}$
- XMMU J2235.3-2557: $z=1.39$, $M \approx (8.5 \pm 1.7) \cdot 10^{14}\, M_{sun}$
- SPT-CL J2106-8544: $z=1.132$, $M \approx (1.3 \pm 0.2) \cdot 10^{15}\, M_{sun}$

Some authors have claimed the existence of these clusters is in conflict with the standard cosmological model





Hoyle, Jimenez & Verde (2010);
Cayon, Gordon & Silk (2010);
Holz & Perlmutter 2010



Are the pink elephants in conflict with LCDM?!

4 things to account for:

1. **Sample variance** - the Poisson noise in counting rare objects in a finite volume

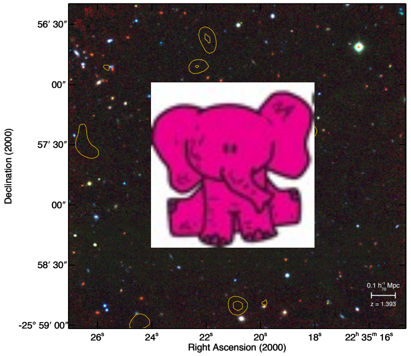
2. **Parameter variance** - uncertainty due to fact that current data allow cosmological parameters to take a range of values

3. **Eddington bias** - since dn/dM is exponentially falling with M, mass measurement error will preferentially 'scatter' the cluster into higher mass

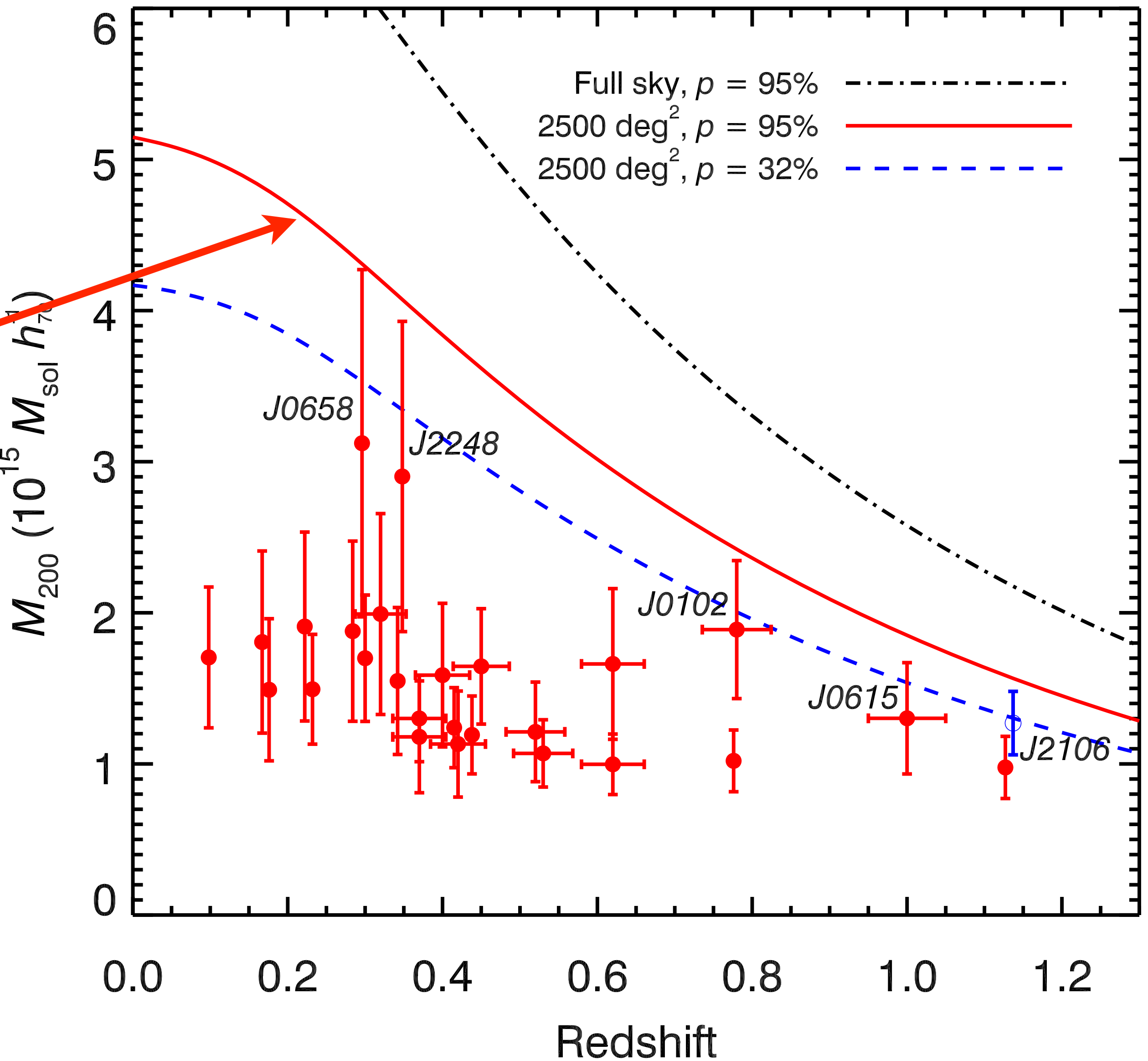
4. **Survey sky coverage** - needs to be fairly assessed

Mortonson, Hu & Huterer 2010

No conflict - for now.



95% limit



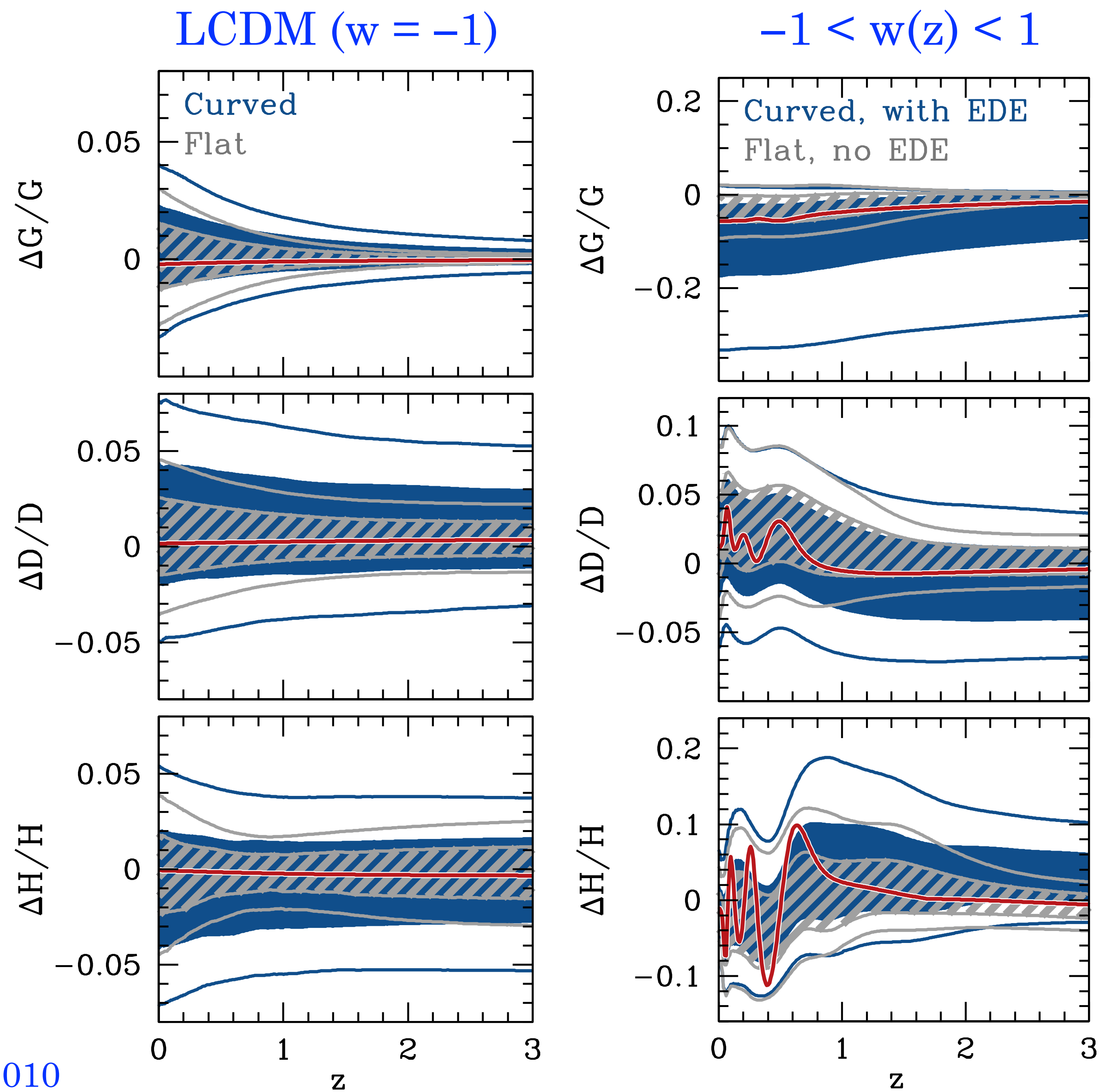
Foley et al 2011 arXiv:1101.1286 (SPT team);
Mortonson, Hu & Huterer 2010

Falsifying **general classes** of DE models

Predictions on D/G/H
(68% and 95%)
from **current data**
(SN+CMB+BAO+H_0)

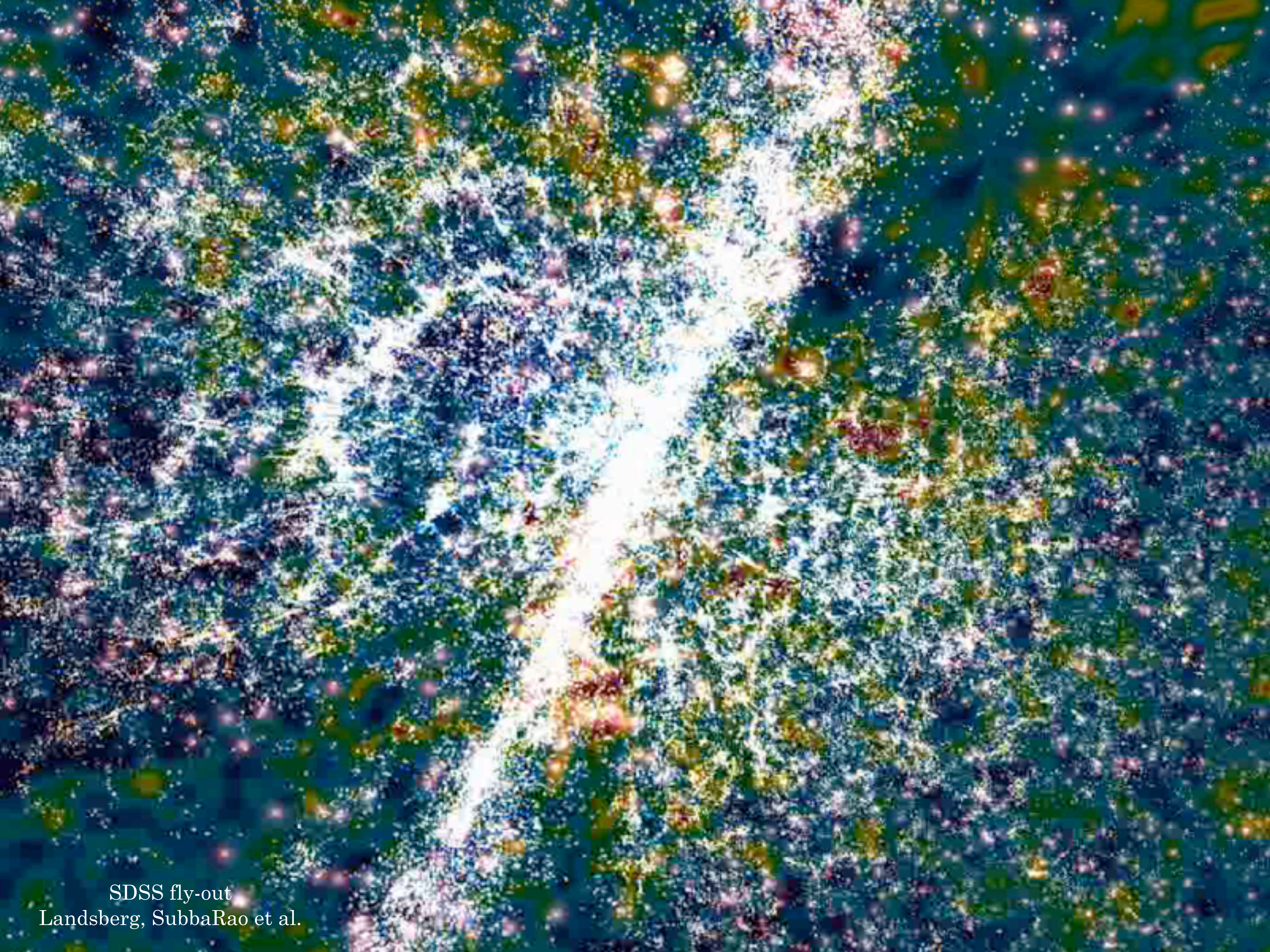
Allowed deviations
around best-fit
LCDM value shown

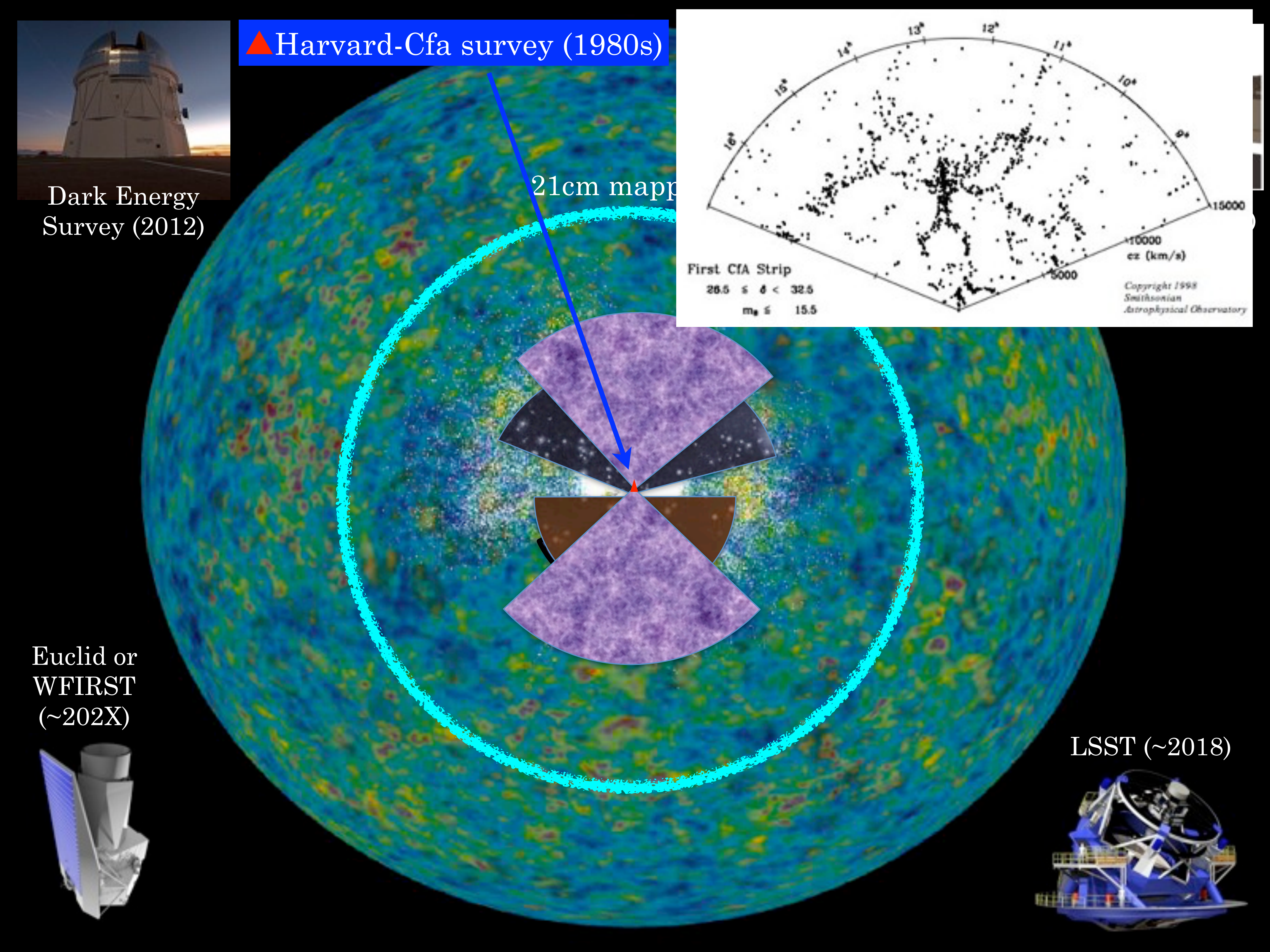
Red curve:
sample model
consistent with data



Mortonson, Hu & Huterer 2010

Cosmology with Large-Scale Structure (LSS)


SDSS fly-out
Landsberg, SubbaRao et al.



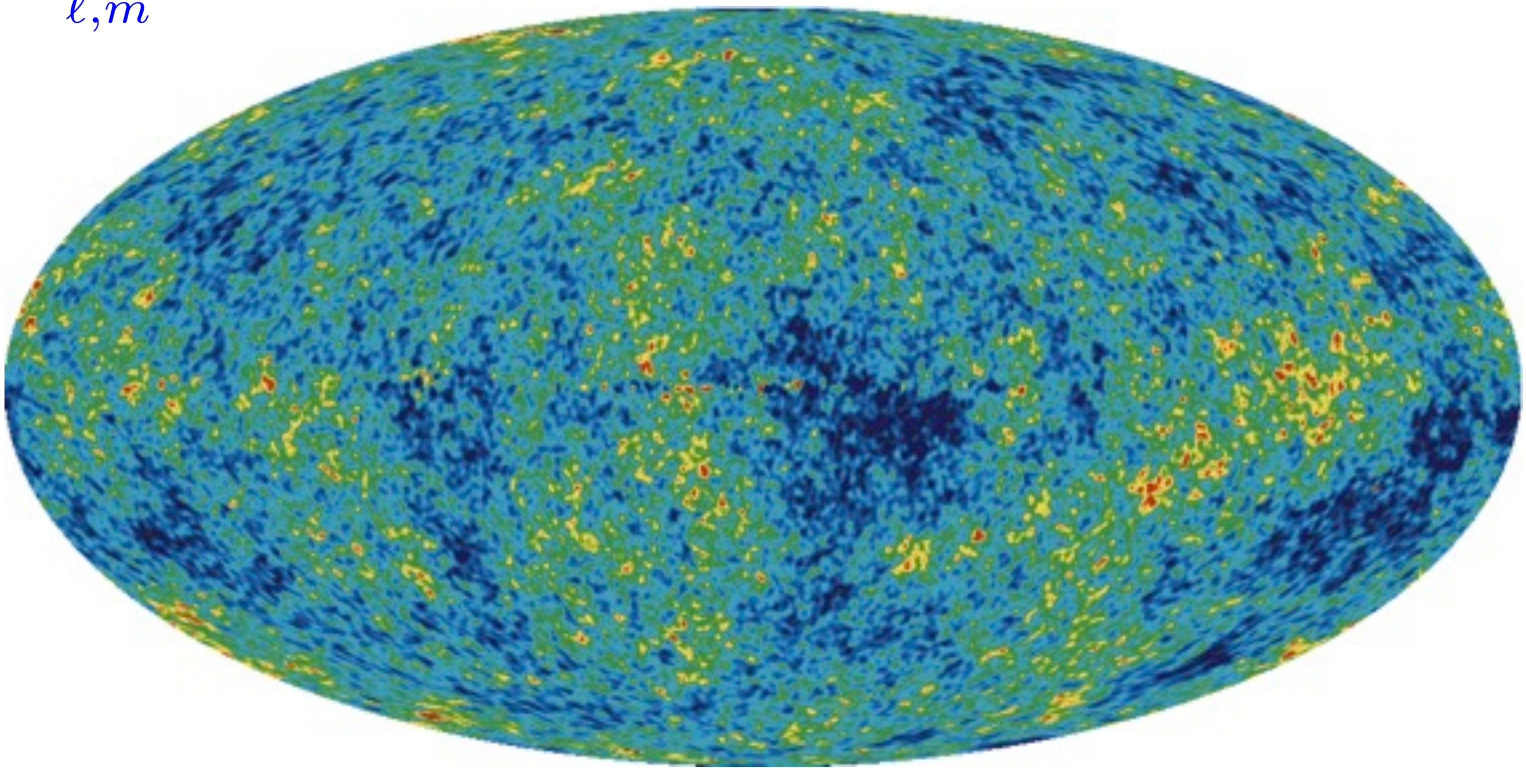
Harvard-Cfa survey (1980s)
Dark Energy Survey (2012)
21cm mapp
First CfA Strip
26.5 ≤ δ < 32.5
m_B ≤ 15.5
cz (km/s)
15000
10000
5000
Copyright 1998 Smithsonian Astrophysical Observatory
Euclid or WFIRST (~202X)
LSST (~2018)

Fundamental Physics from LSS

- Amount, clustering of Cold Dark Matter
- Expansion history (⇔dark energy)
- Modified Gravity (⇔dark energy)
- Self-interactions of dark matter
- Neutrino masses ($\sum m_\nu \leq 0.3$ eV)
- Features in inflationary potential
- Statistical isotropy of the universe
- Primordial non-Gaussianity of density perturbations

Initial conditions in the universe

$$\frac{\delta T}{T}(\theta,\phi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\theta,\phi) \qquad \ell \simeq \frac{180^\circ}{\theta}$$



Generic inflationary predictions:

Statistical Isotropy:

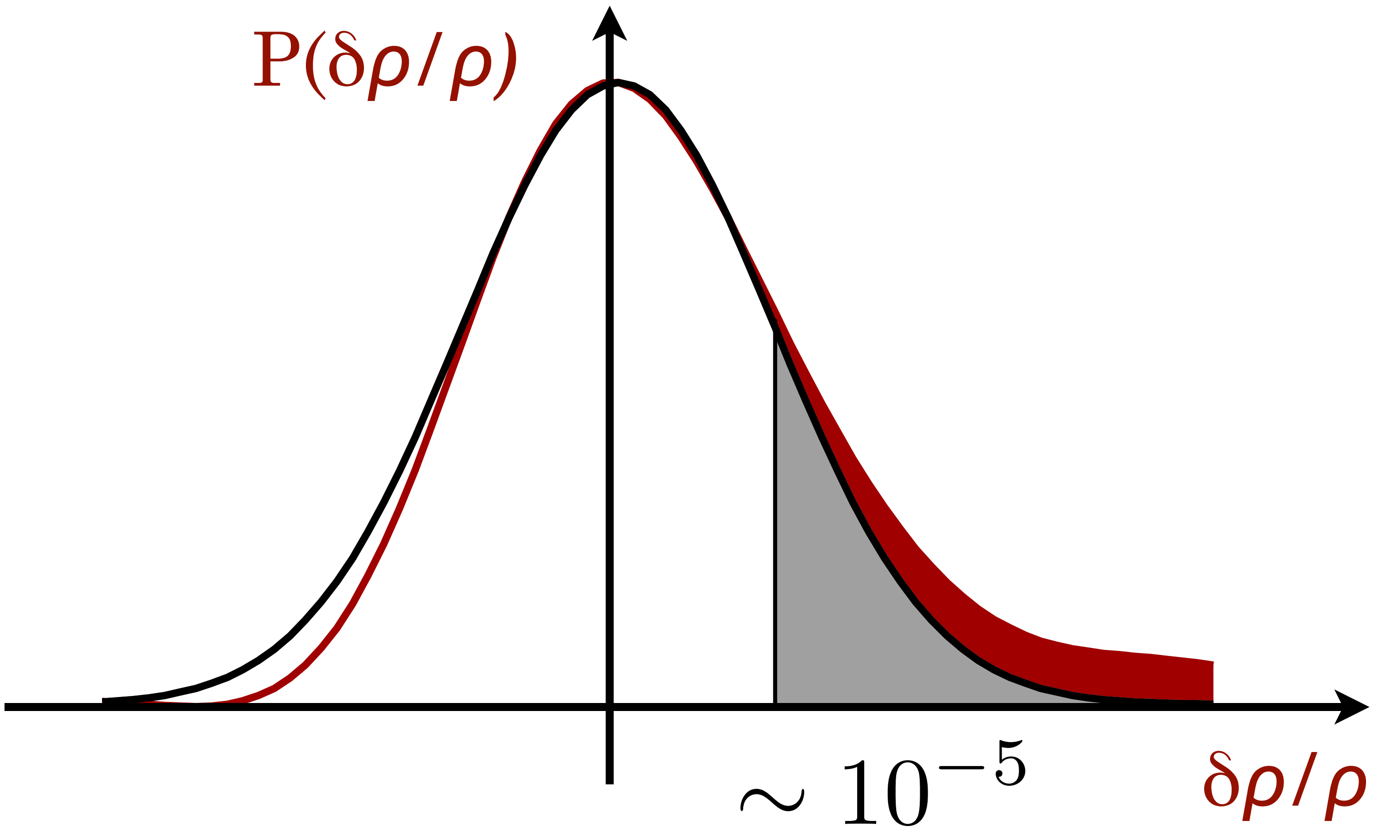
$$\langle a_{\ell m}\, a_{\ell' m'} \rangle \equiv C_{\ell\ell' mm'} = C_\ell \delta_{\ell\ell'} \delta_{mm'}$$

- Nearly scale-invariant, statistically isotropic spectrum of density perturbations
- Background of gravity waves
- (Very nearly) gaussian initial conditions:

Gaussianity:

$$\langle a_{\ell m}\, a_{\ell' m'}\, a_{\ell'' m''} \rangle = 0$$

Primordial non-Gaussianity



Standard Inflation, with...

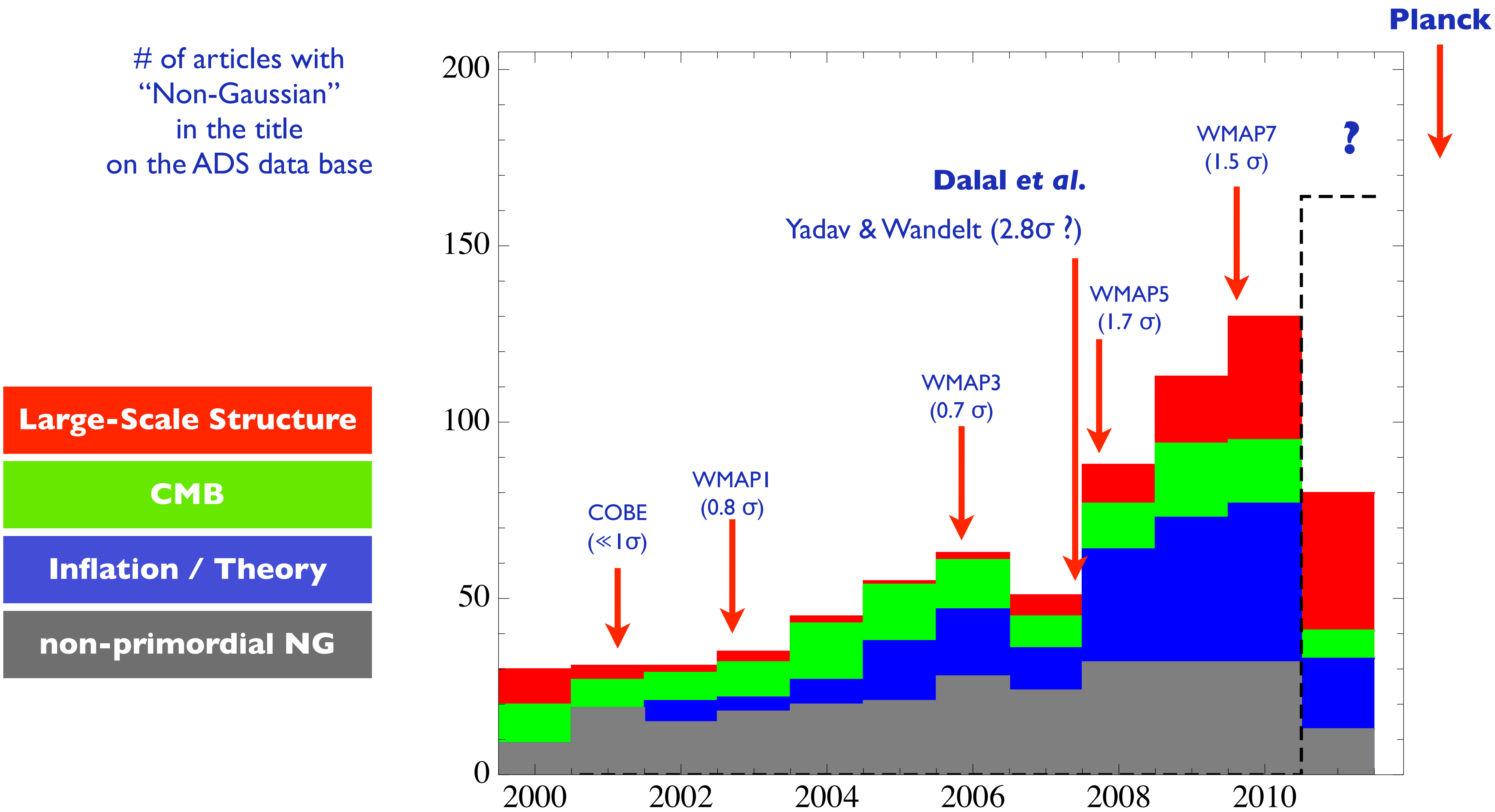
1. a single scalar field
2. the canonical kinetic term
3. always slow rolls
4. in Bunch-Davies vacuum
5. in Einstein gravity

produces **unobservable** NG

Therefore, measurement of nonzero NG would point to a **violation** of one of the assumptions above

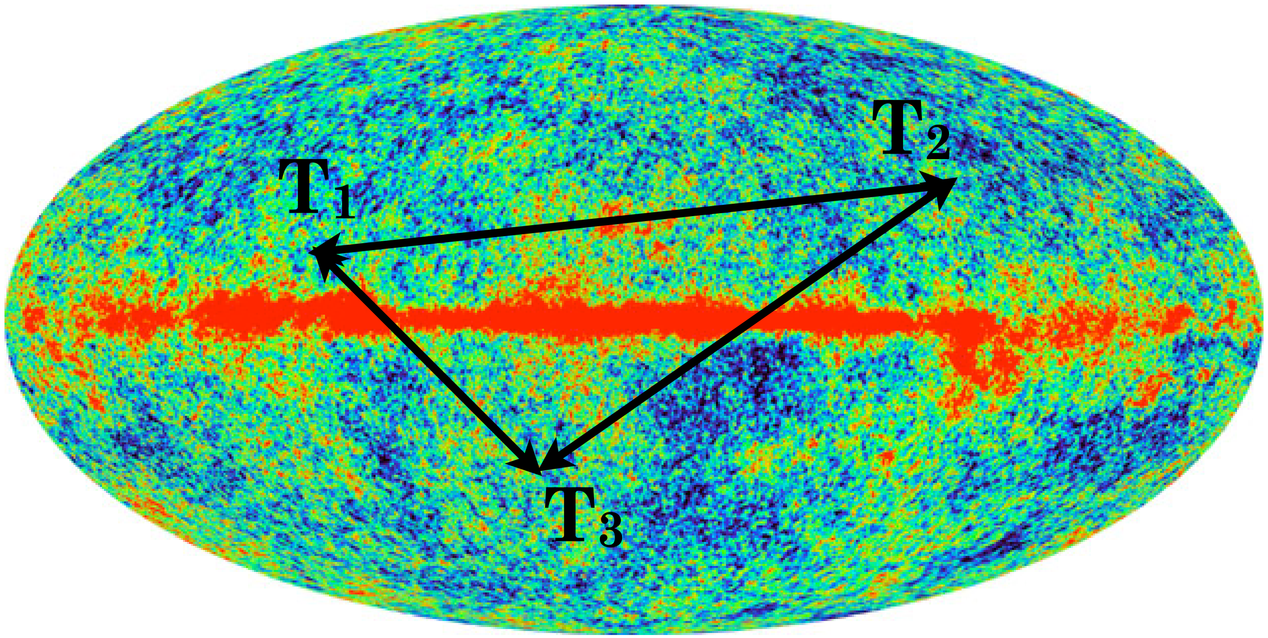
e.g. X. Chen, Adv. Astronomy, 2010; Komatsu et al, arXiv:0902.4759

Non-Gaussianity papers in the past 10 years



Produced by Emiliano Sefusatti

NG from 3-point correlation function



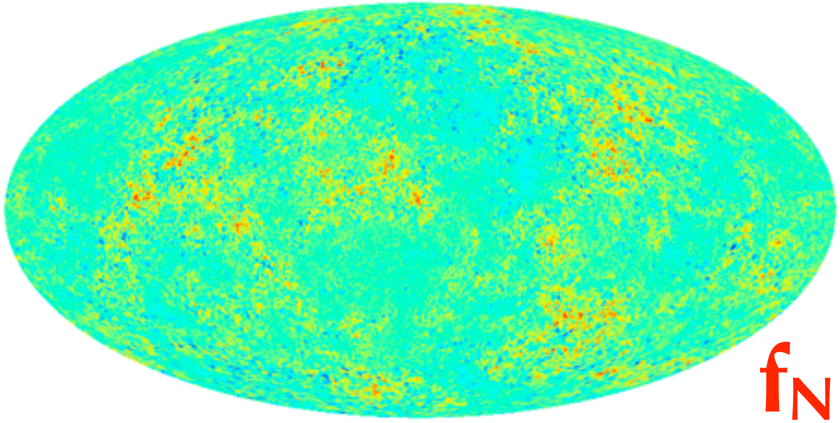
Commonly used "local" model of NG

$$\Phi = \Phi_G + f_{\rm NL}\left(\Phi_G^2 - \langle\Phi_G^2\rangle\right)$$

Then the 3-point function is related to f_{NL} via (in k-space)

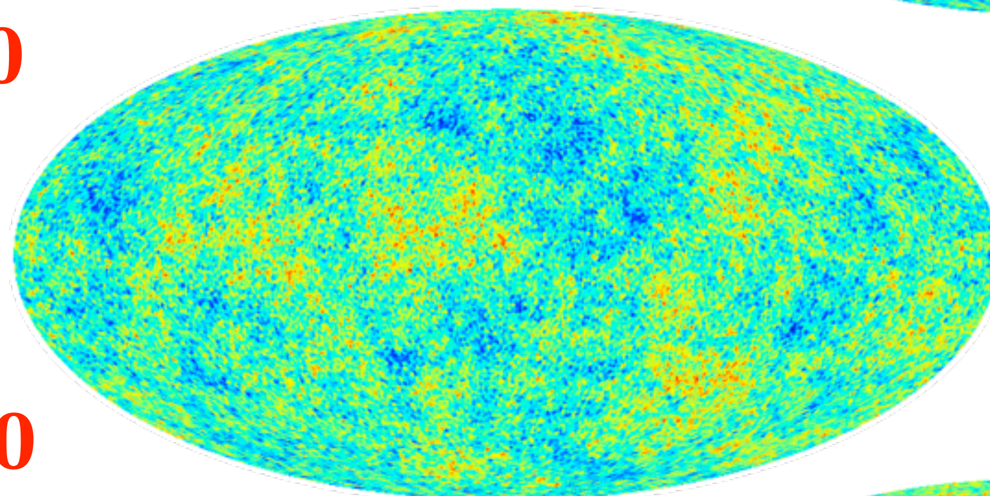
$$B(k_1, k_2, k_3) \sim f_{\rm NL}\left[P(k_1)P(k_2) + \text{perm.}\right]$$

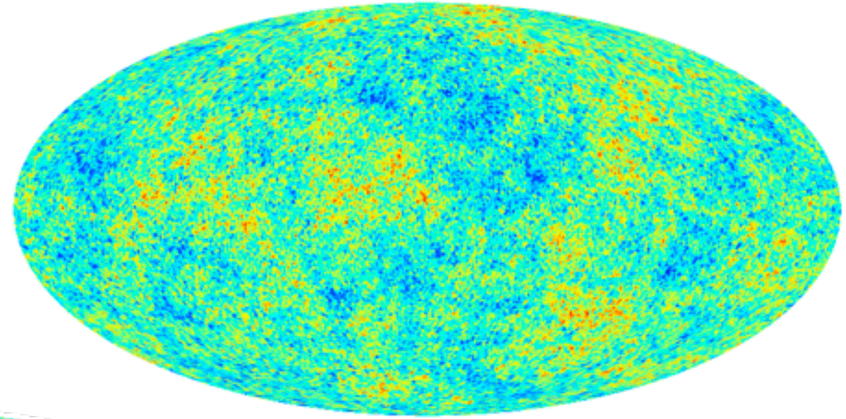
Using publicly available NG maps by Elsner & Wandelt



f_{NL}= -5000

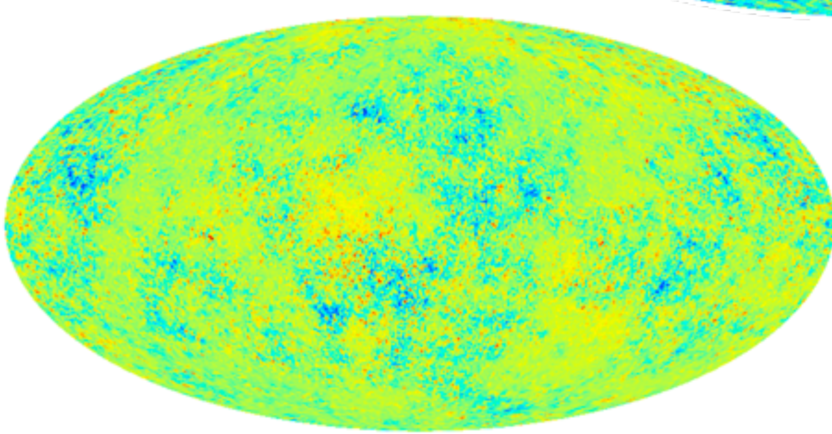
f_{NL}= 0



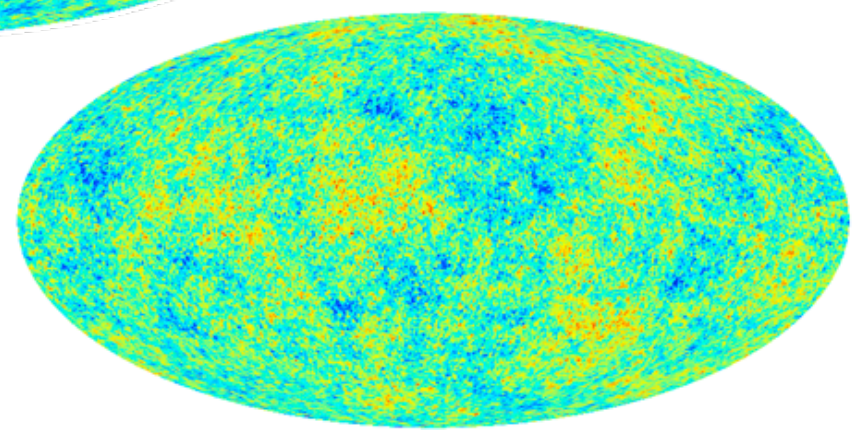


f_{NL}= -500

f_{NL}= +5000



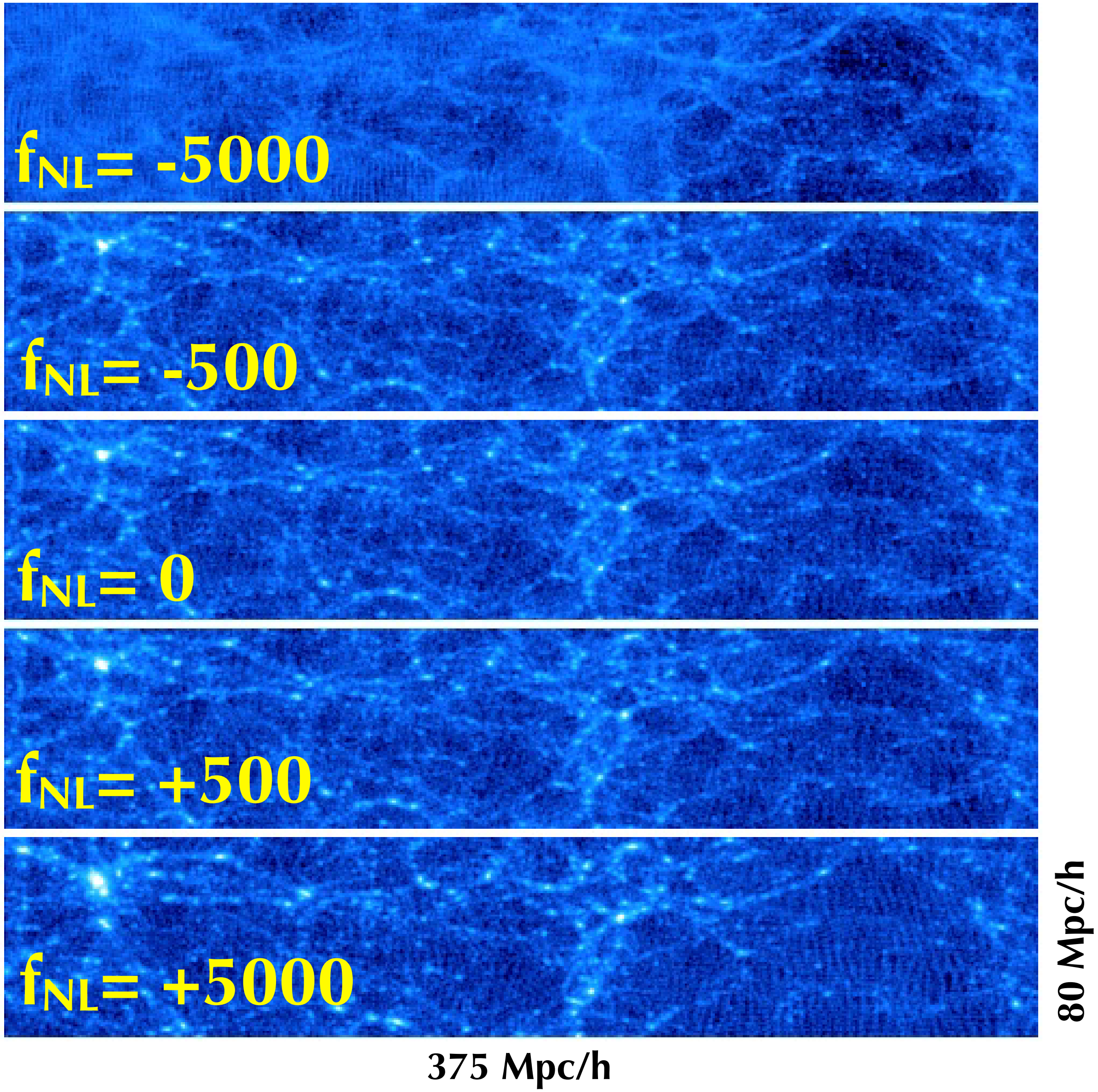
f_{NL}= +500



Current constraint from WMAP: f_{NL}=32±21

Effects of primordial NG on the bias of galaxies/halos

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, Doré, Huterer & Shirokov, PRD 2008

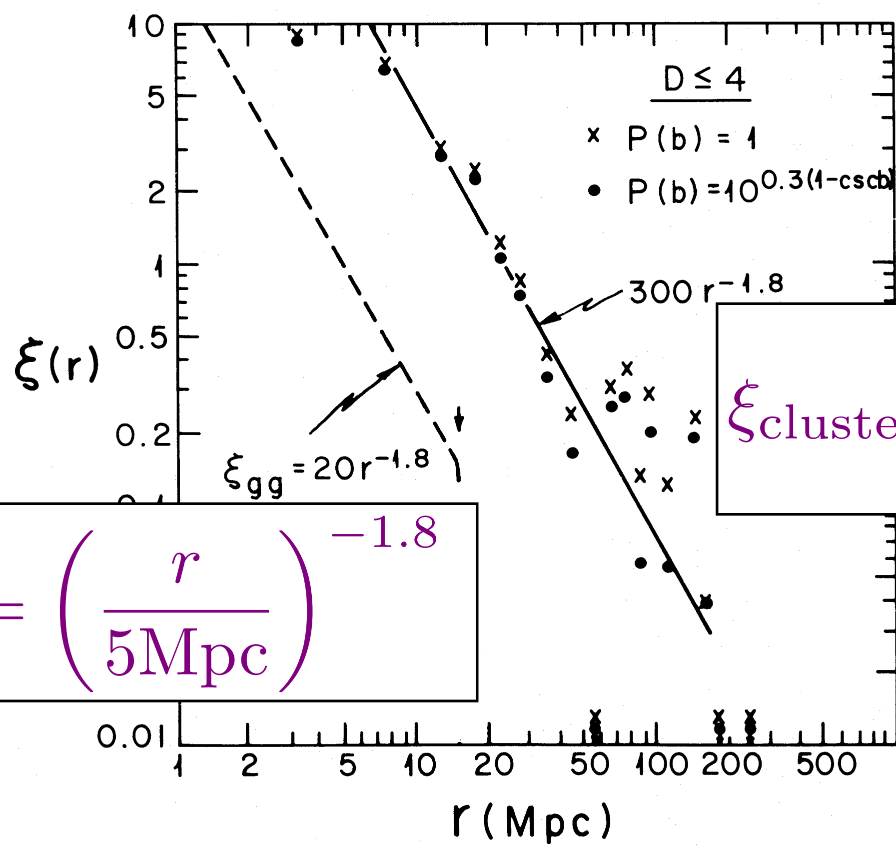
Does galaxy/halo bias depend on NG?

$$\text{bias} \equiv \frac{\text{clustering of galaxies}}{\text{clustering of dark matter}} = \frac{\left(\frac{\delta\rho}{\rho}\right)_{\text{halos}}}{\left(\frac{\delta\rho}{\rho}\right)_{\text{DM}}}$$

cosmologists measure

theory predicts

usually nuisance parameter(s)



$$\xi_{\text{clusters}}(r) = \left(\frac{r}{25\text{Mpc}}\right)^{-1.8}$$

$$\xi_{\text{galaxies}}(r) = \left(\frac{r}{5\text{Mpc}}\right)^{-1.8}$$

Bahcall & Soneira 1983

Bias of dark matter halos

$$P_h(k,z) = \boxed{b^2(k,z)}\, P_{\rm DM}(k,z)$$

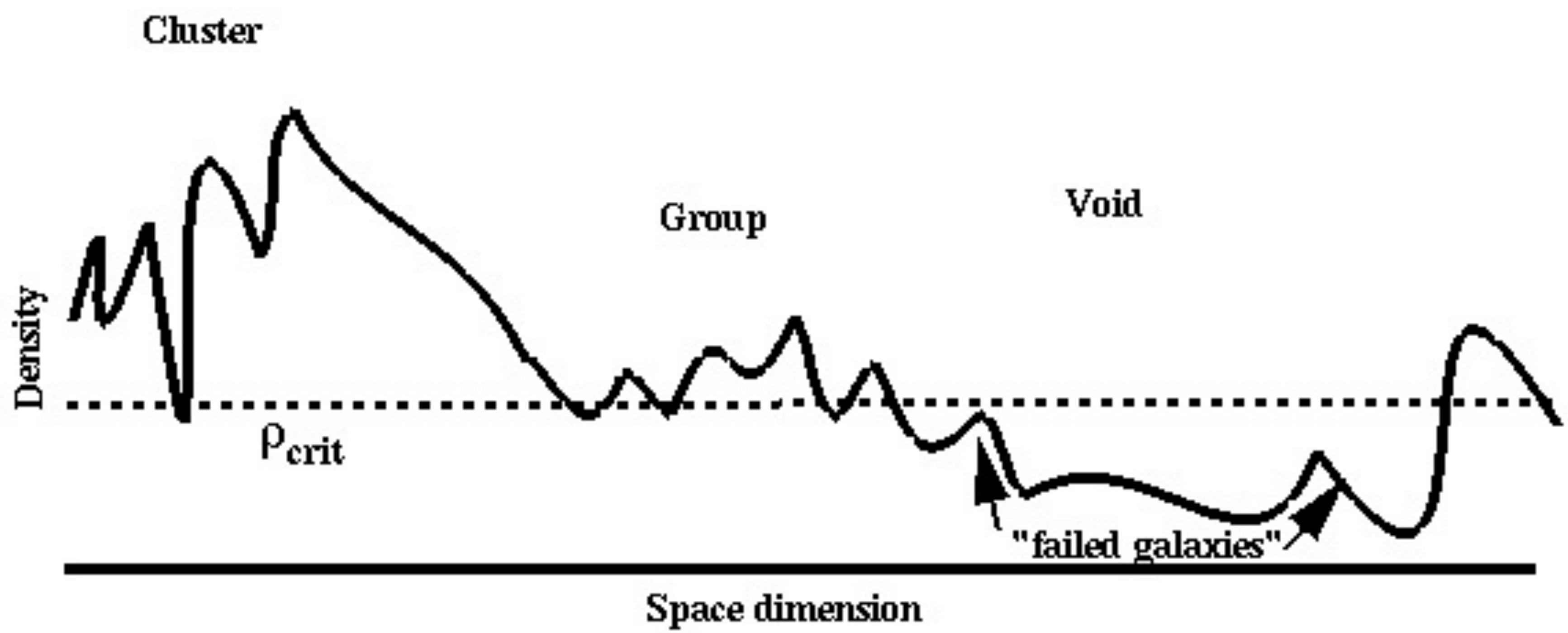
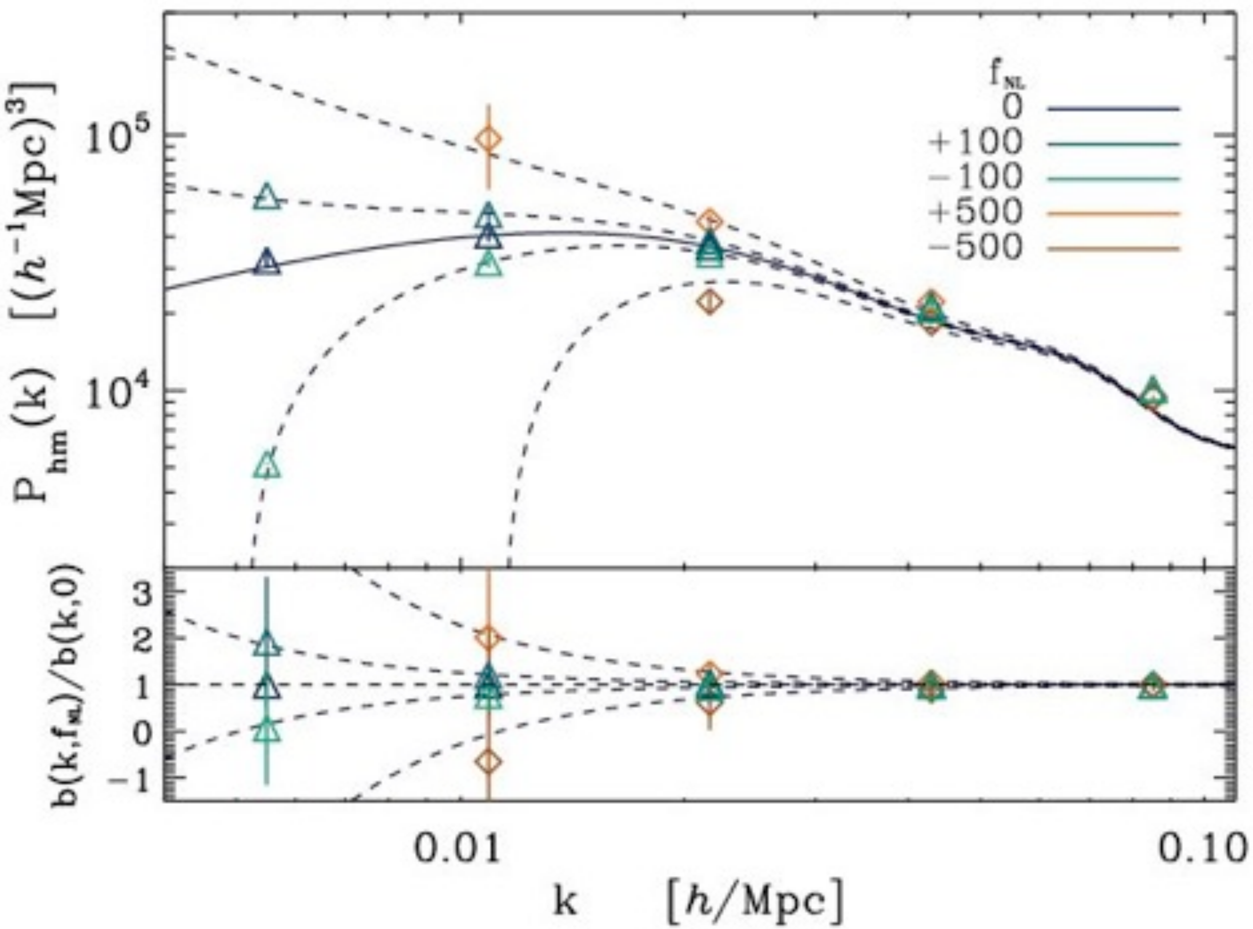


figure credit: Bill Keel

Simulations and theory both say: large-scale bias is scale-independent
(theorem if halo abundance is function of local density)

Scale dependence of NG halo bias

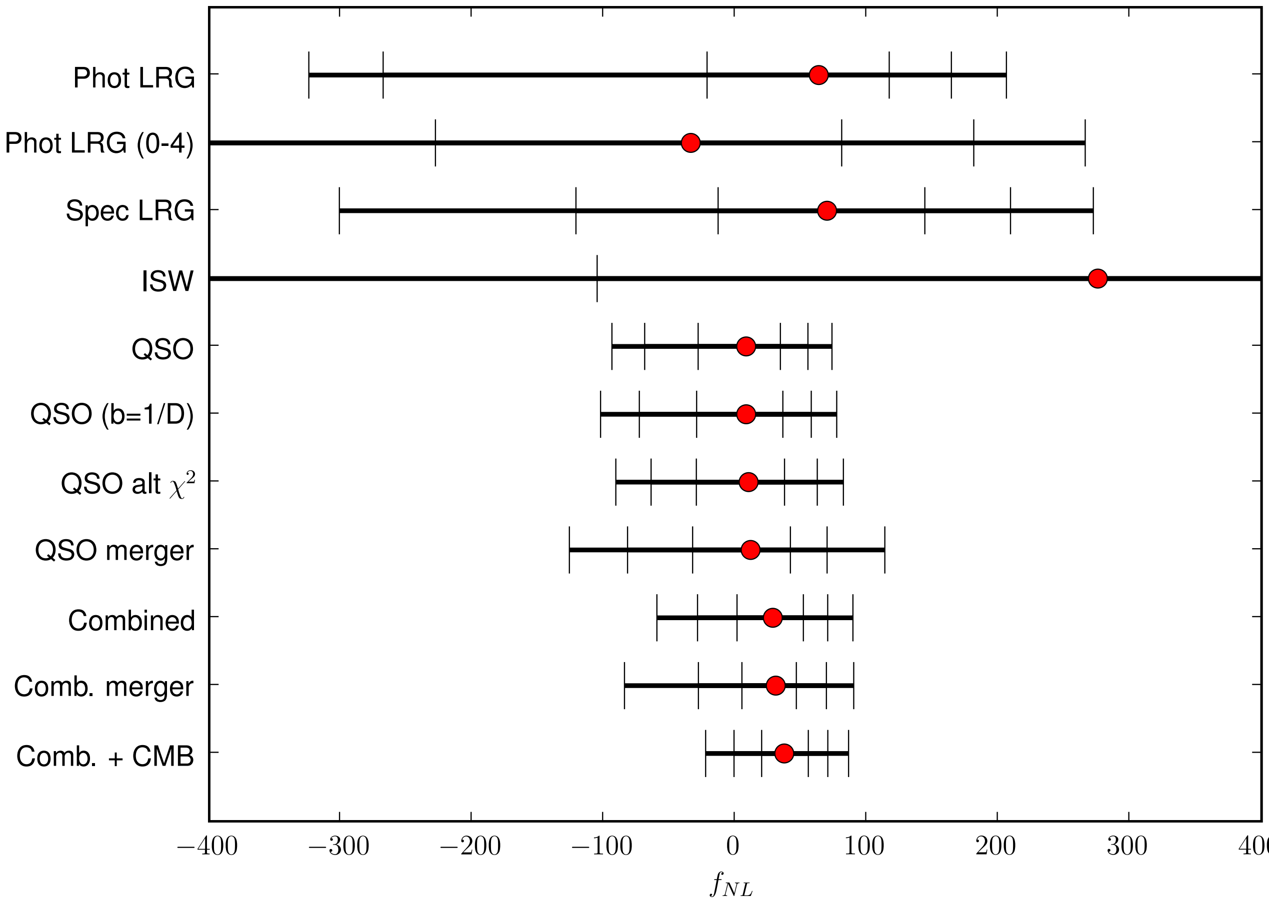


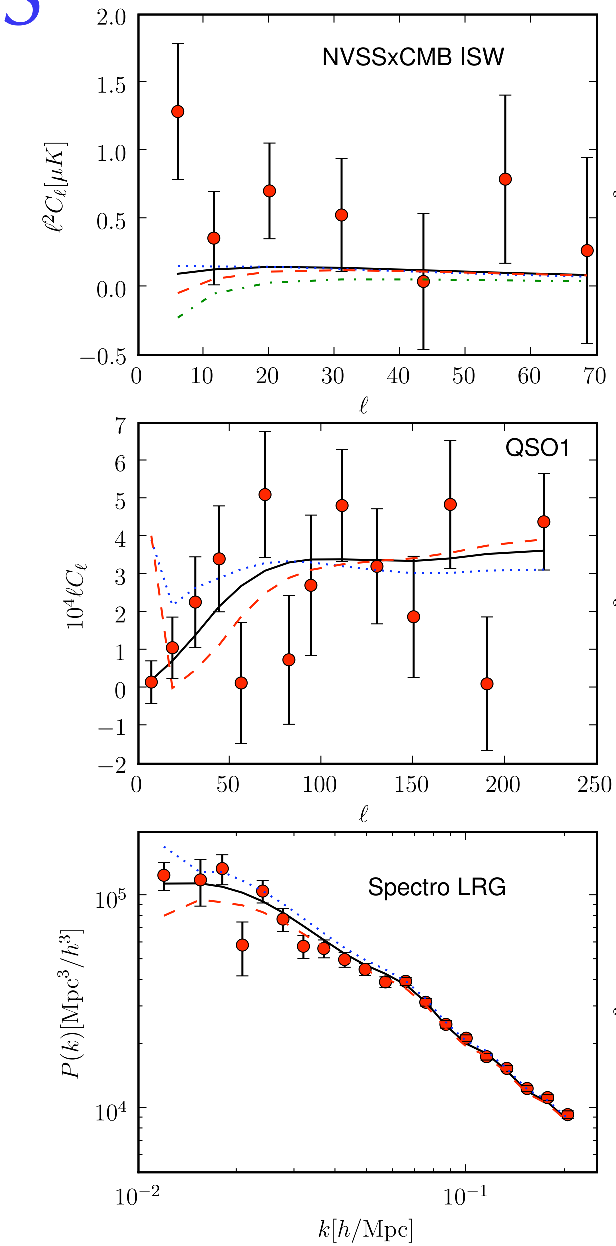
$$b(k) = b_G + f_{NL}\,(b_G - 1)\frac{3\,\Omega_M H_0^2}{T(k)D(a)\,k^2}$$

Verified using a variety of theoretical derivations and numerical simulations.

Dalal, Doré, Huterer & Shirokov 2008

Constraints from **current** data: SDSS





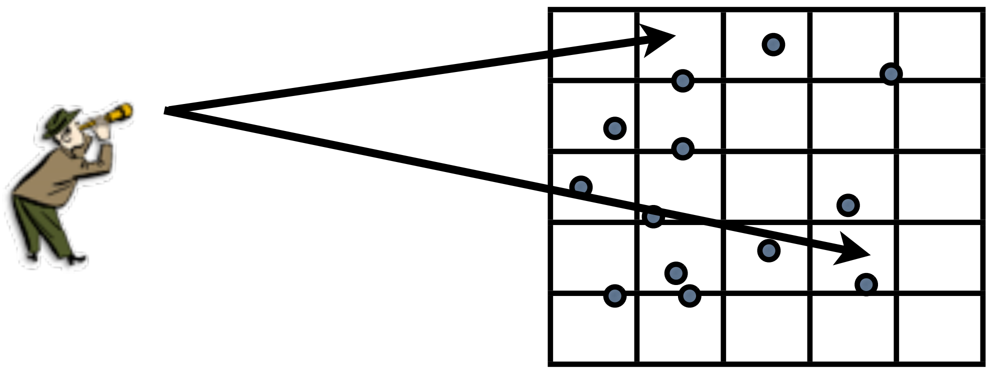
f_{NL} = 8 +/- 30 (68%, QSO)

f_{NL} = 23 +/- 23 (68%, all)

Slosar et al. 2008

[**Future** data forecasts for LSS: $\sigma(f_{NL}) \approx O(\text{few})$
at least as good as, and highly complementary to, Planck CMB]

Forecast: f_{NL} from the clustering of **galaxy clusters**



Encouraging sign:
NG can survive marginalization over numerous nuisance parameters

DES cluster survey forecasts

Nuisance parameters		Marginalized errors—Full Covariance								
		Counts			Covariance			Counts + Covariance		
Halo bias	M_{obs}	$\sigma(\Omega_{DE})$	$\sigma(w)$	$\sigma(f_{NL})$	$\sigma(\Omega_{DE})$	$\sigma(w)$	$\sigma(f_{NL})$	$\sigma(\Omega_{DE})$	$\sigma(w)$	$\sigma(f_{NL})$
Marginalized	Marginalized	∞	∞	∞	∞	∞	∞	0.069	0.23	**6.0**
Known	Marginalized	0.097	0.33	**2.1×10^3**	0.13	0.43	**12**	0.065	0.22	**5.4**
Marginalized	Known	∞	∞	∞	0.099	0.34	**7.0**	0.0036	0.014	**3.8**
Known	Known	0.0051	0.023	**94**	0.042	0.13	**5.1**	0.0036	0.014	**1.8**

Cluster **counts** mainly probe **DE** parameters
Cluster **covariance** (clustering) mainly probes **f_{NL}**

Cunha, Huterer & Doré 2010

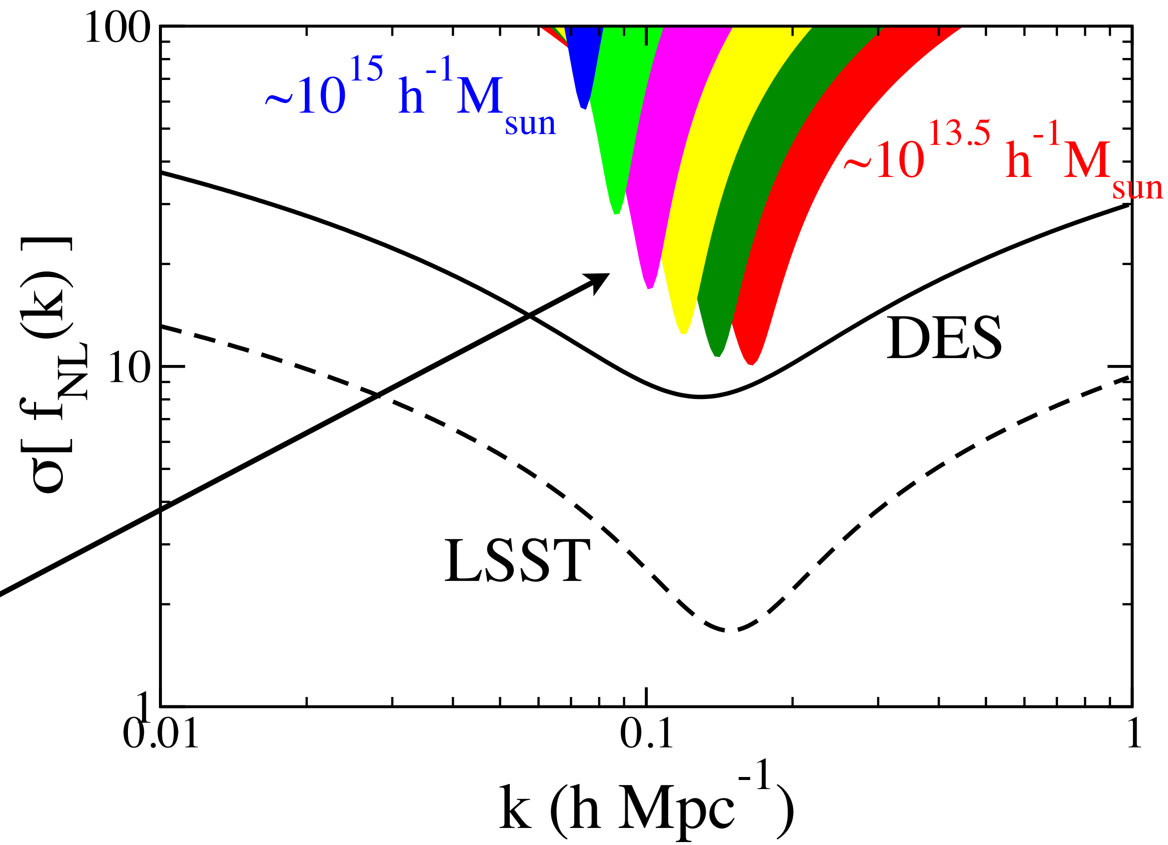
Future: using LSS to probe scale-dependent NG

- Scale-dep NG models are motivated by particle theory (single-field inflation with self-interaction; mixed curvaton-inflaton models)
- Effects on LSS are significant, but theory predictions are uncertain ⇒ ongoing theoretical and simulation work
- Understanding of astrophysics (of DM halos, etc) required in order to probe fundamental physics

Scale-dependent NG ansatz:

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

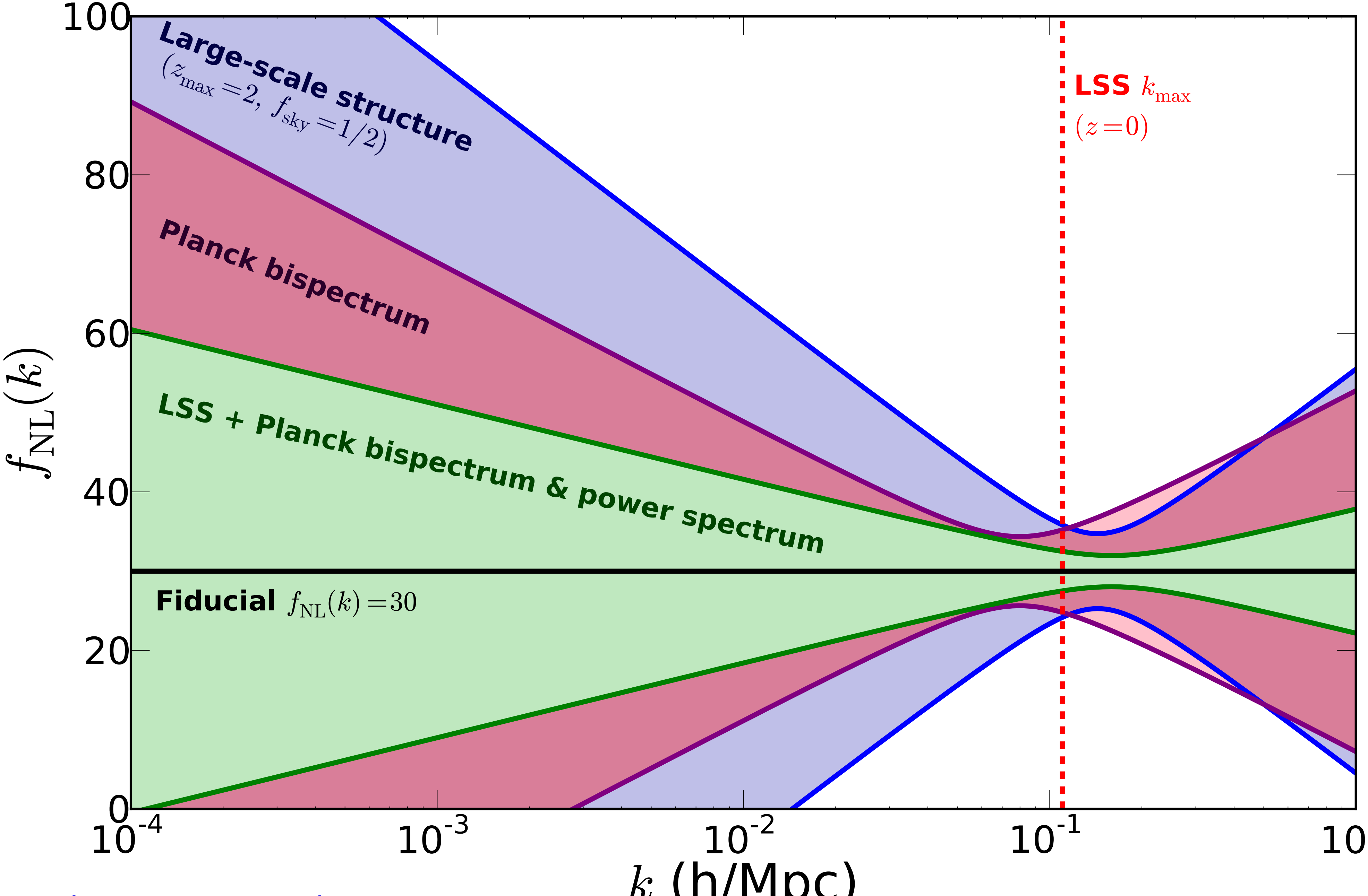
Halos of mass M probe NG on scale $k \sim M^{-1/3}$



Shandera, Dalal & Huterer, 2011

CMB, LSS, and CMB+LSS **forecasts**

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



Becker, Huterer & Kadota 2011 + in prep

How non-Gaussianity helps test inflation

- Negligible $f_{NL} \Rightarrow$ consistent with single-field, canonical kinetic term, slow-roll
- Measured f_{NL} ($\geq O(1)$) $\Rightarrow$ multi-field or higher-order derivatives, e.g.
- Scale dependence, $f_{NL}(k) \Rightarrow$ multi-field (e.g. curvaton) or self-interactions

Further (technical) reading

Advances in Astronomy special issue on

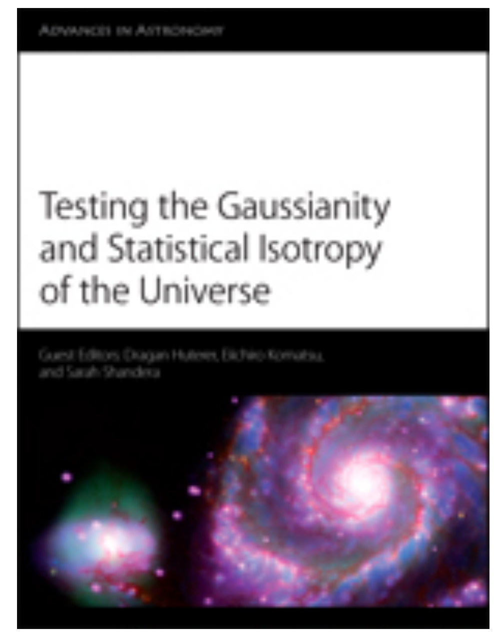
"Testing the Gaussianity and Statistical Isotropy of the Universe"

http://www.hindawi.com/journals/aa/2010/si.gsiu/

15 review articles (all also on arXiv)

Testing the Gaussianity and Statistical Isotropy of the Universe

Guest Editors: Dragan Huterer, Eiichiro Komatsu, and Sarah Shandera



Non-Gaussianity from Large-Scale Structure Surveys, Licia Verde
Volume 2010 (2010), Article ID 768675, 15 pages

Non-Gaussianity and Statistical Anisotropy from Vector Field Populated Inflationary Models, Emanuela Dimastrogiovanni, Nicola Bartolo, Sabino Matarrese, and Antonio Riotto
Volume 2010 (2010), Article ID 752670, 21 pages

Cosmic Strings and Their Induced Non-Gaussianities in the Cosmic Microwave Background,

Aspen workshop on NG
May 20 - June 10, 2012

Current Workshop Details

WORKSHOPS - SUMMER 2012

Deadline for Applications is January 31, 2012

*** denotes the organizer responsible for participant diversity in the workshop**

May 20 – June 10
Non-Gaussianity as a Window to the Primordial Universe
Organizers:
Neal Dalal, University of Toronto
Olivier Dore, JPL, NASA
Dragan Huterer, University of Michigan
DongHui Jeong, Caltech
Marc Kamionkowski, Caltech
Fabian Schmidt*, Caltech
Sarah Shandera, Perimeter Institute