Title: Primordial Non-Gaussianity and Large-Scale Structure

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URL: http://pirsa.org/10040042

Abstract: The primordial density fluctuations that seeded large-scale structure are known to be nearly Gaussian, as predicted by most early universe models like slow-roll inflation. Many of these models predict a small (but nonzero!) amount of primordial non-gaussianity, which can subtly affect the statistics of CMB anisotropies. Surprisingly, even a small primordial non-gaussianity can produce enormous changes in the large-scale clustering of galaxies and quasars at late times. I will describe the origin of this effect, and review recent constraints on non-gaussianity using measurements of the clustering of galaxies and quasars in SDSS.

Nongaussianity & Large-scale Structure

Neal Dalal
CITA

with
O. Doré, D. Huterer, A. Shirokov & more

Nongaussianity

1. why I'm interested
2. why everyone else is interested
3. what NG does to large-scale structure
4. constraints!
5. the future

but first, a brief prologue...

Lensing survey

- with J. Hennawi, M. Gladders, H. Dahle, M. Oguri, et al.
- imaging at WIYN, NOT, Subaru, HST, spectroscopy at Gemini
- increased the number of known lenses by about 5x
- Goals include:
  - ✦ measure masses — calibrate mass-observables relations
  - ✦ find background high-z galaxies that are magnified
  - ✦ measure profiles — test theoretical predictions, constrain cluster physics (e.g. gastrophysics)

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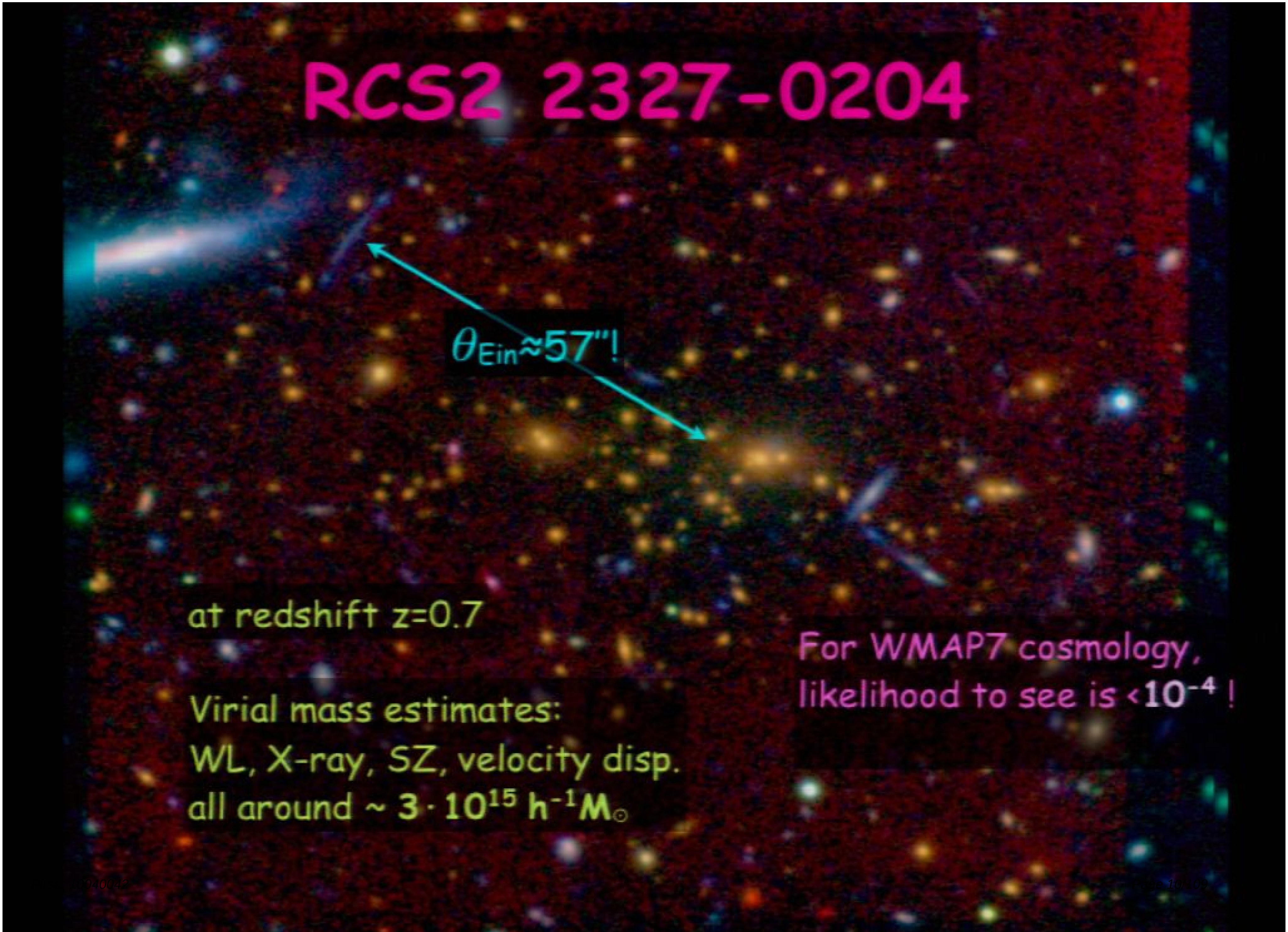

RCS2 2327-0204
θEin≈57''!
at redshift z=0.7
Virial mass estimates:
WL, X-ray, SZ, velocity disp.
all around ~ 3·10^15 h^-1 M⊙
For WMAP7 cosmology,
likelihood to see is <10^-4 !

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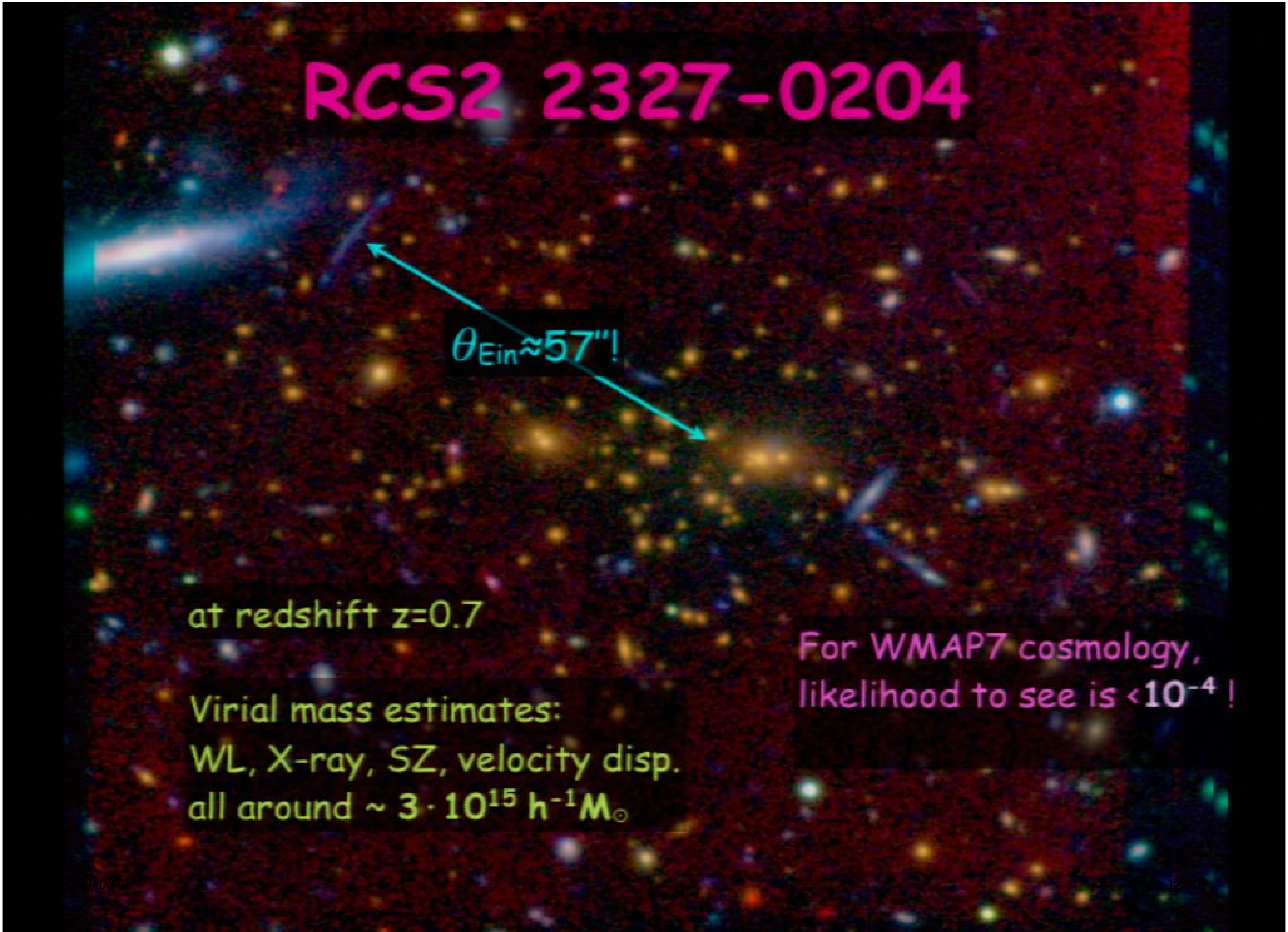

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any way to save our universe?

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one possibility:

primordial nongaussianity!

Primordial nongaussianity

- sensitive probe of early-universe physics
- hot topic -- over 100 papers last year alone!
- has surprising effects on large-scale structure

References

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* Afshordi & Tolley (2008), PRD 78 123507 (0806.1046)
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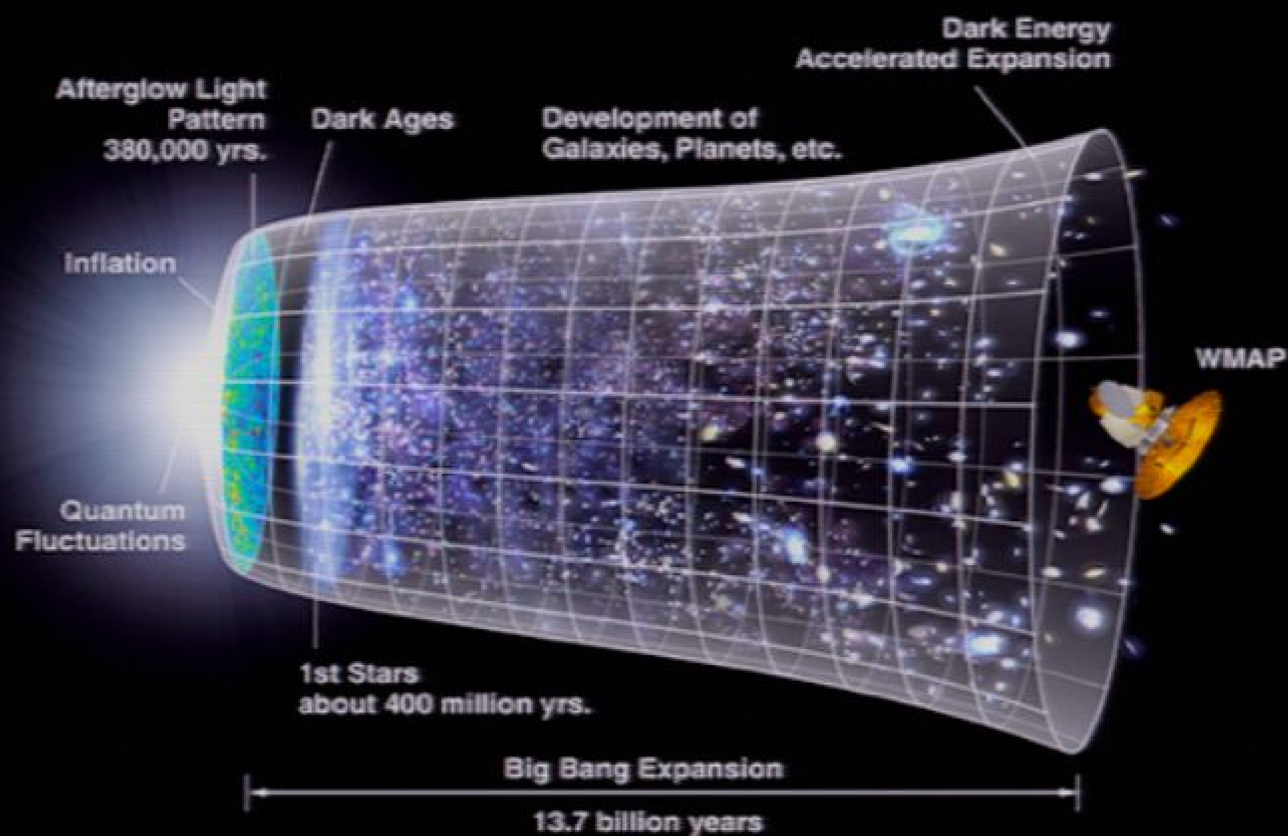
History of the universe



NASA/WMAP Science Team

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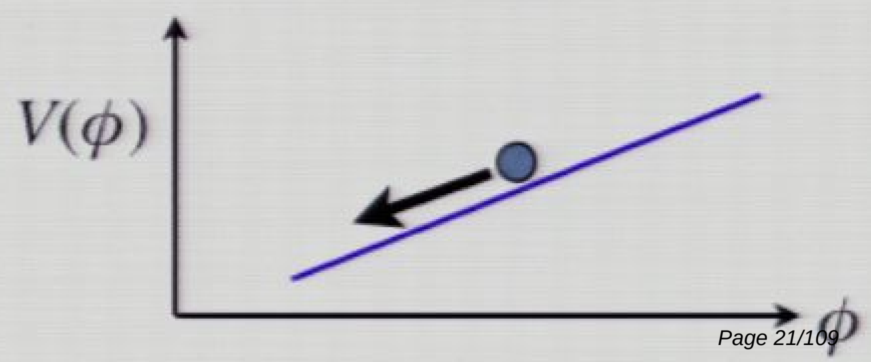

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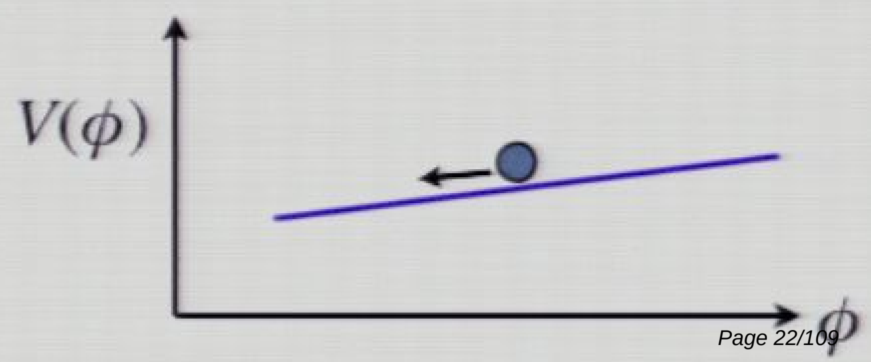
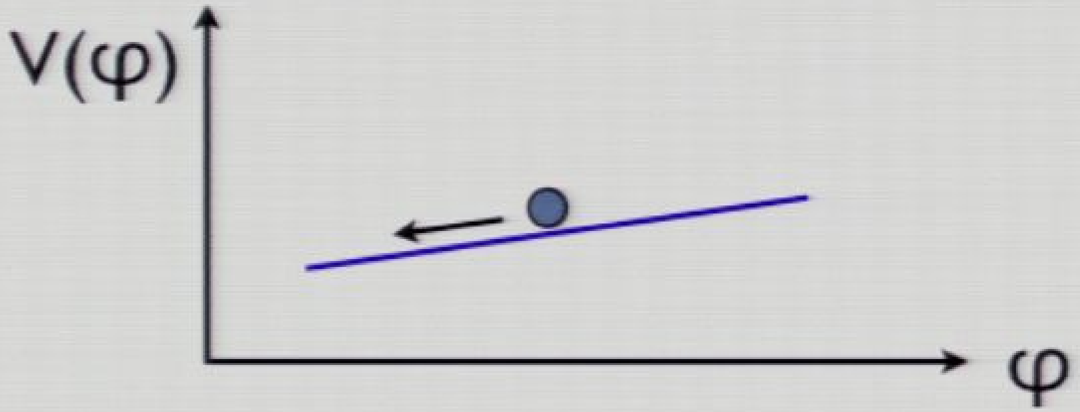
  → like a free field in de Sitter



Perturbations



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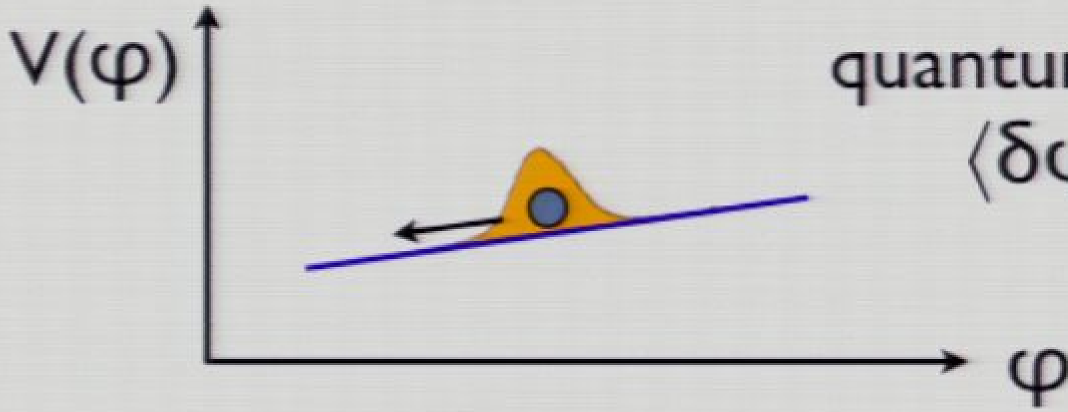

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$\langle \delta\varphi^2 \rangle \sim H^2 \propto \rho$

height of potential

- as universe inflates,
  microscopic → macroscopic
  quantum → classical

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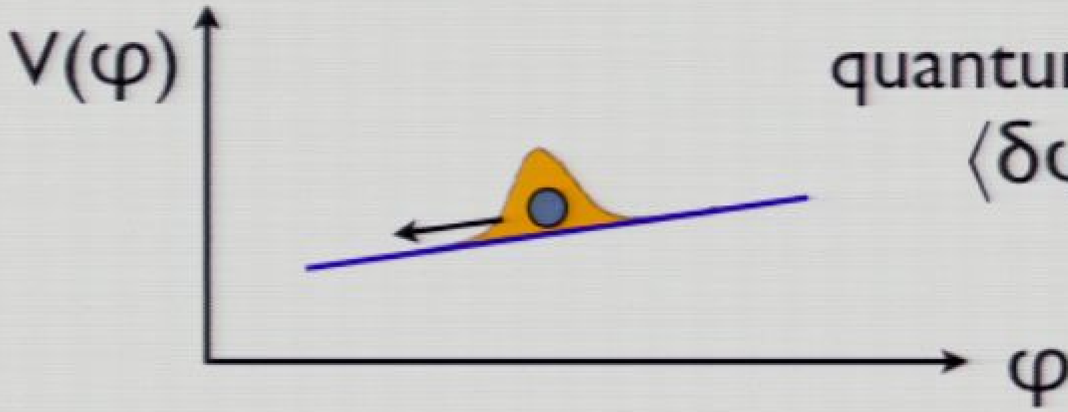

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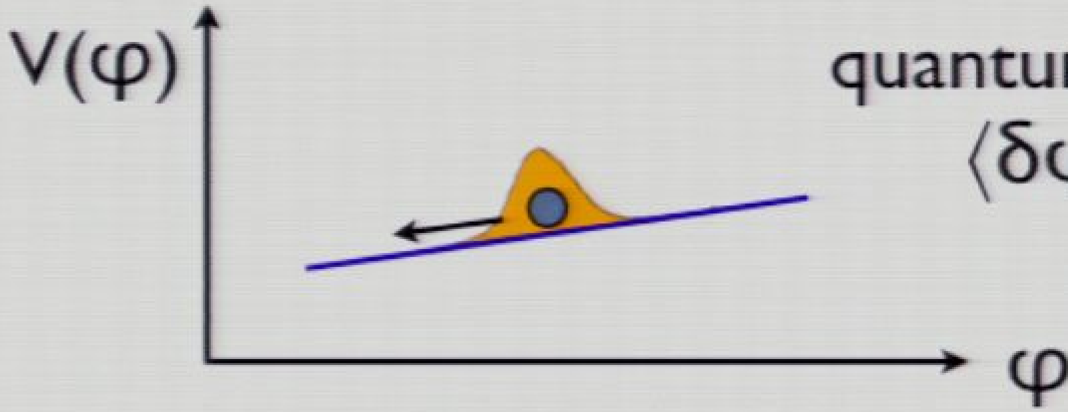

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- (nearly) flat potential V ⇒ (nearly) scale-invariant spectrum $\langle \delta\varphi^2 \rangle$
- spectral index $(1-n_s) \propto V'/V$ slow-roll parameter ε

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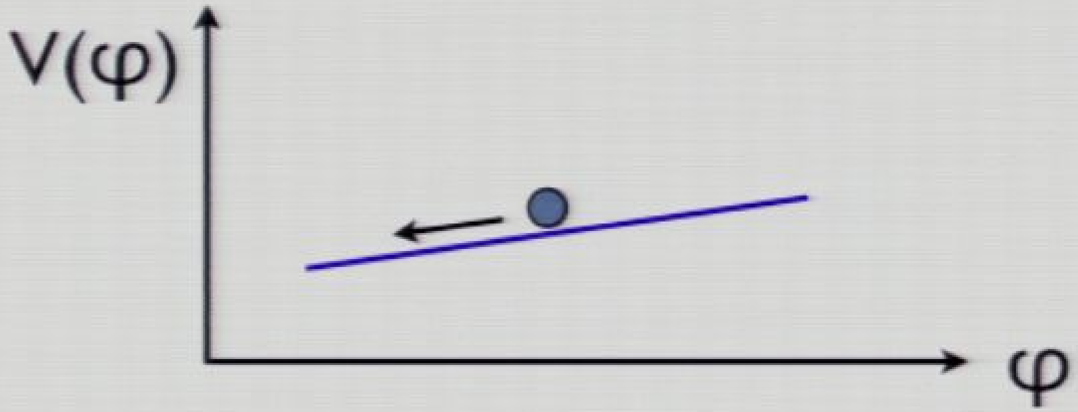

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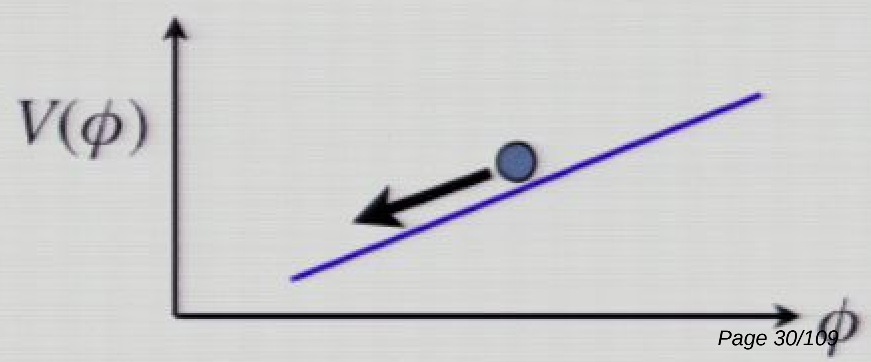

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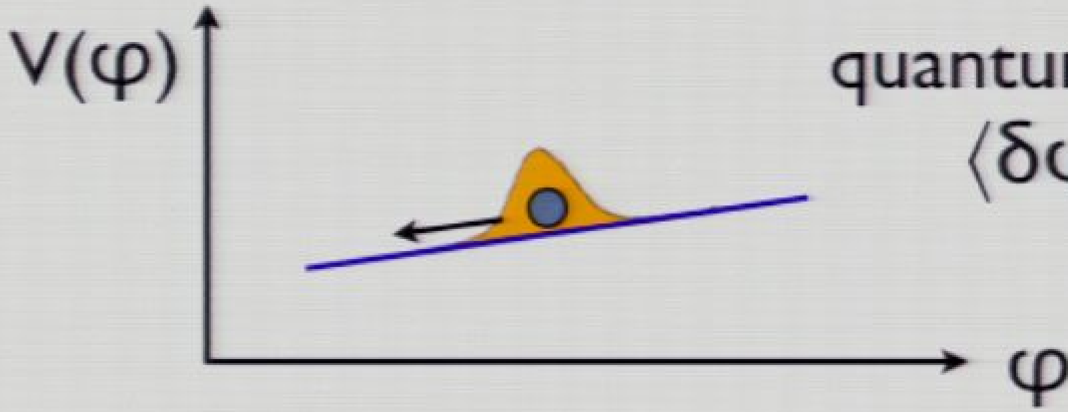

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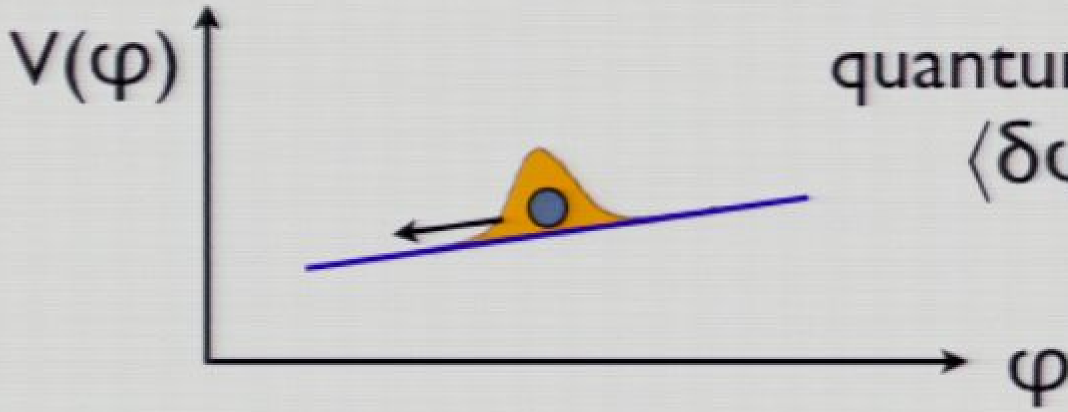

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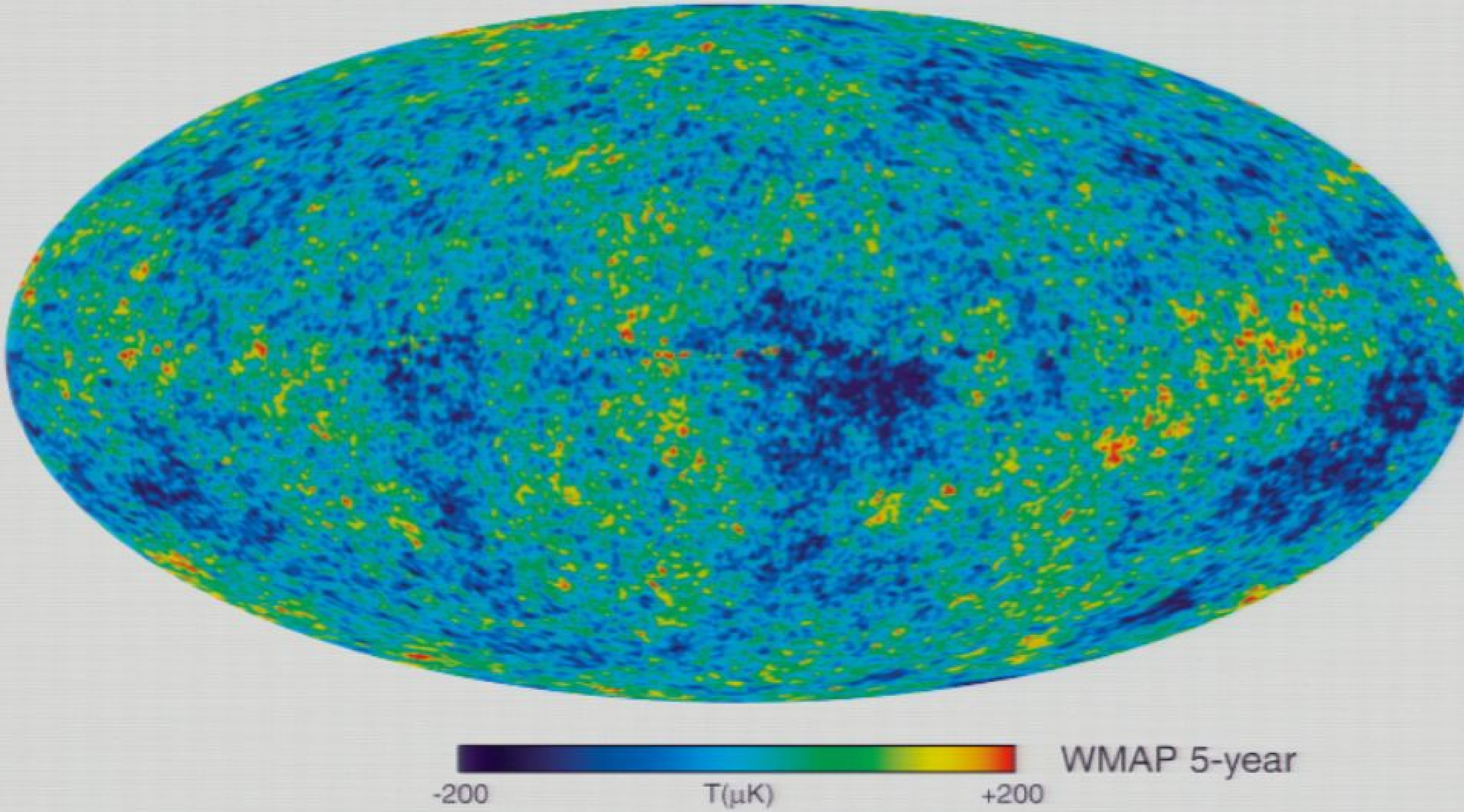
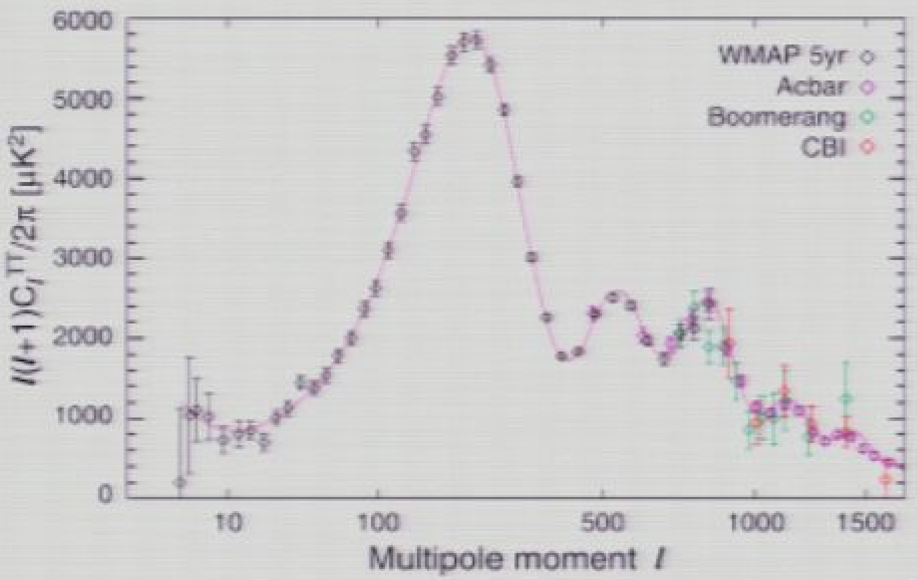
about 380,000 years later

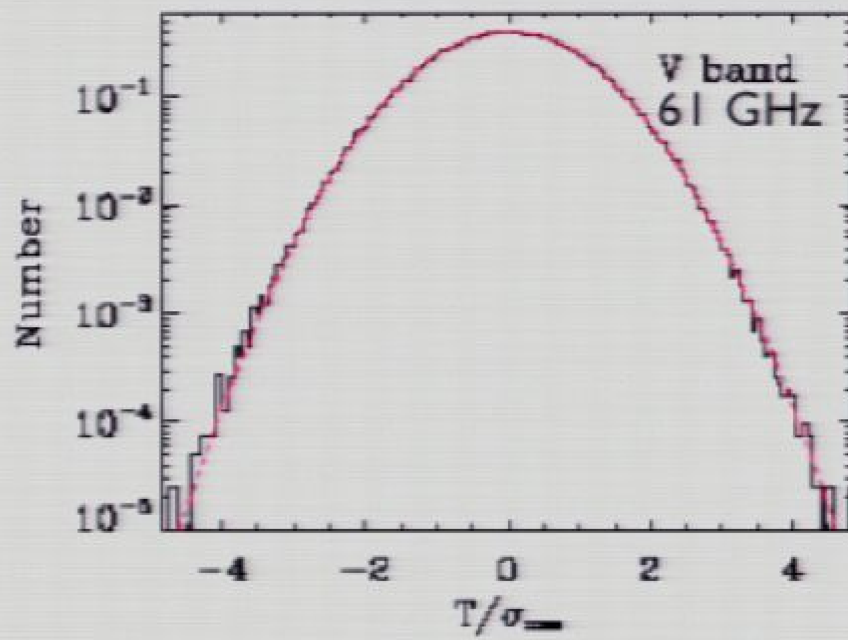


CMB data support inflation



- CMB fluctuations are almost scale-invariant $n_s \approx 0.96$ (looks different due to evolution: gravity+hydro)

- CMB fluctuations are (close to) Gaussian!



Inflation report card

Universe is:

- (nearly) homogeneous & isotropic ✓
- (nearly) flat ✓

Perturbations are:

- (nearly) scale-invariant ✓
- adiabatic ✓
- (nearly) Gaussian ✓

- but inflation generically predicts SOME nongaussianity

simplest nongaussianity

see, e.g.,
Maldacena (2003

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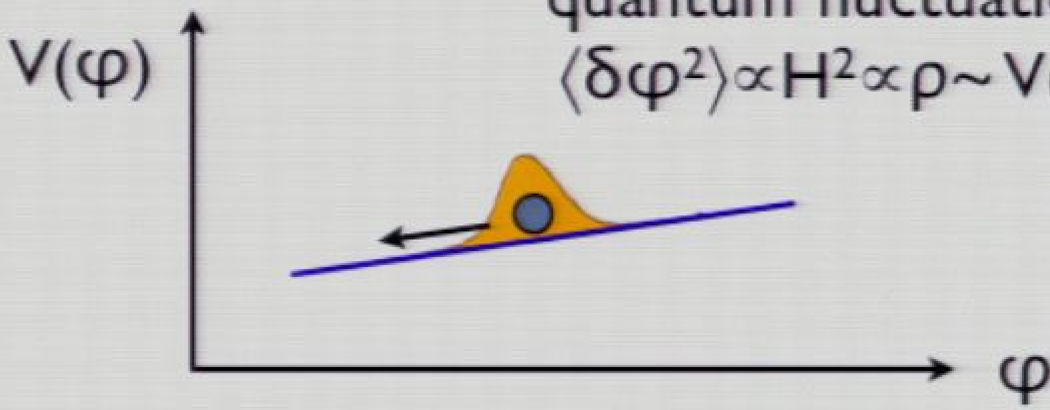

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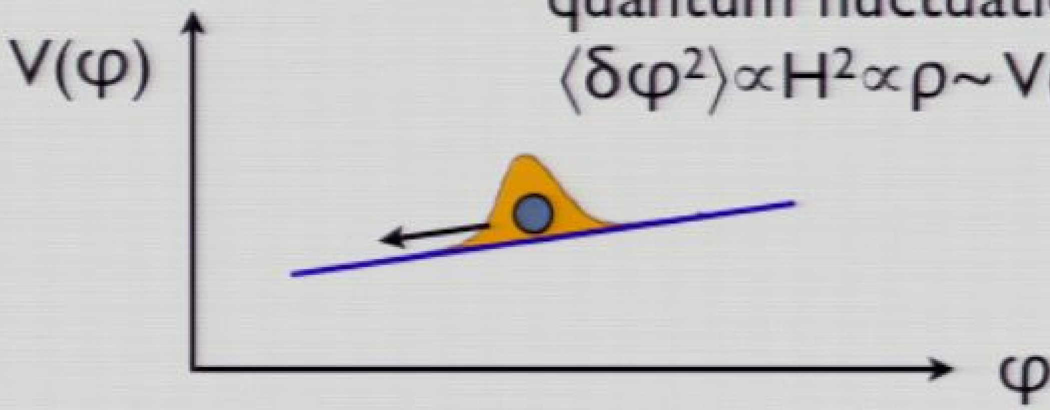

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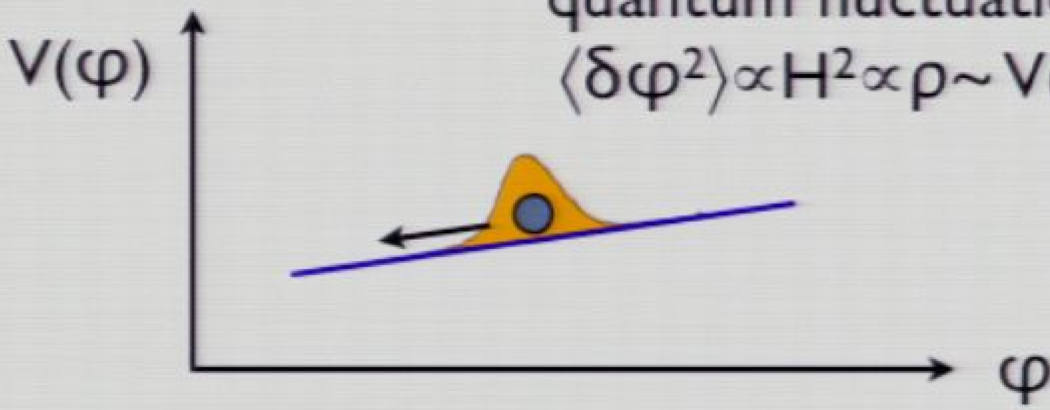

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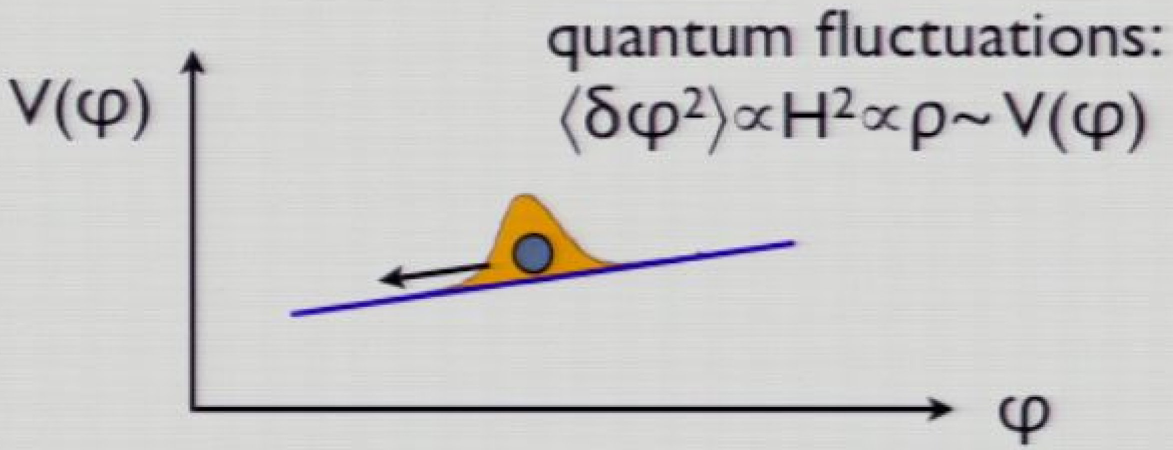

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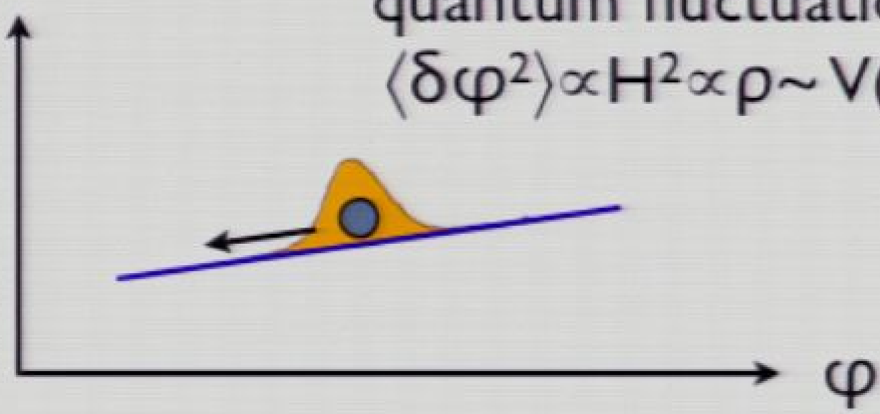

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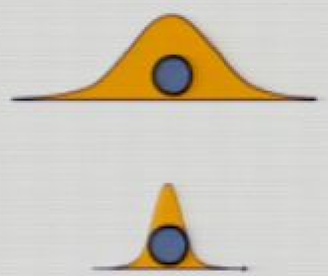

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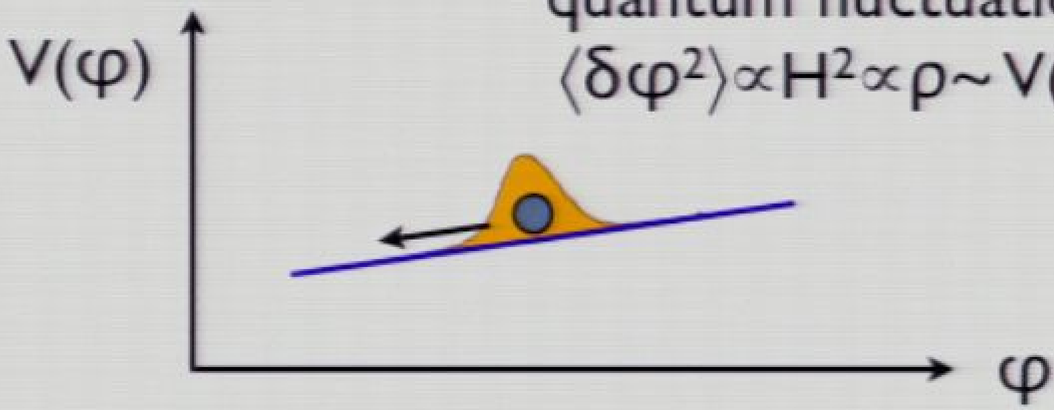

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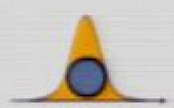

- nonzero correlation $f_{NL} \langle \delta\varphi_{long} \, \delta\varphi_{short}{}^2 \rangle$ ⇒nongaussianity!

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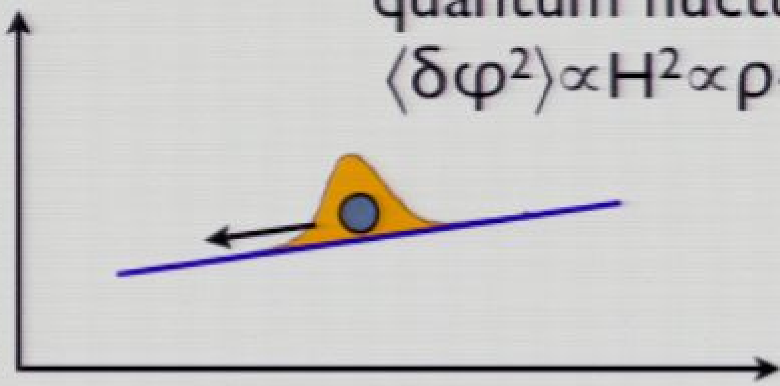
see, e.g., Maldacena (2003



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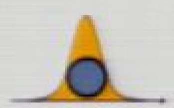

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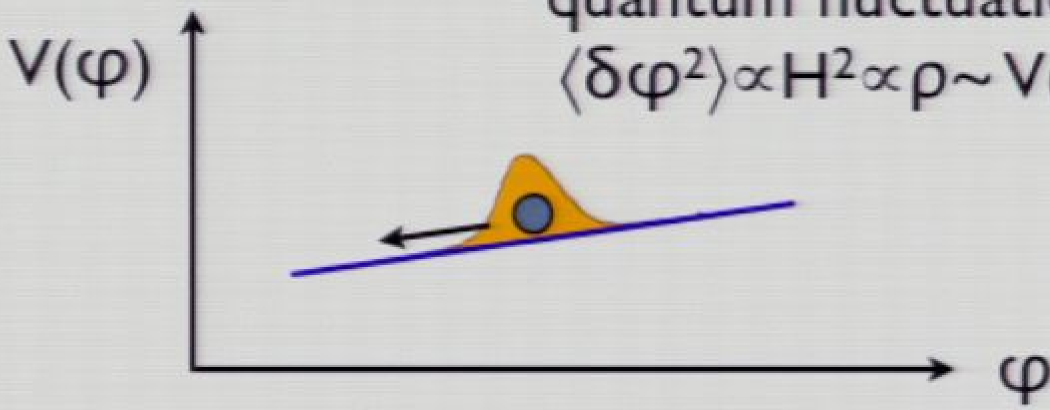

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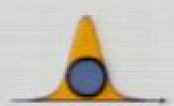

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depends on V'

- for a single field, we a have consistency relation between f_{NL} and $1-n_s$.
- ANY significant detection of local f_{NL} immediately kills ALL single-field models (!)
- But you **can** easily get big f_{NL} in more complicated models

Curvaton scenario

- density fluctuations produced by some **other** field σ that is unimportant during inflation, but dominates afterwards
- this field σ decays, and fraction r of its fluctuations become the observed curvature perturbations ζ
- e.g. $V=m^2\sigma^2$, so $\delta V=m^2(2\sigma\,\delta\sigma + \delta\sigma^2)$
- $\delta\rho/\rho=2\,\delta\sigma/\sigma + (\delta\sigma/\sigma)^2$
- if $\zeta=r\,\delta\rho/\rho$, then comparing to $\zeta + f_{NL}\,\zeta^2$, we see

➡ $f_{NL}\sim r^{-1}$, can be large (e.g. $f_{NL}\sim 100$)

f_{NL} expectations

model	expect
slow-roll scalar	$f_{NL} \sim 1$ ⟵ from nonlinear gravity
multiple fields (e.g. curvaton)	anything, e.g. $\lvert f_{NL}\rvert \sim 1\text{-}100$
not inflation (e.g. ekpyrotic)	$f_{NL} \sim 30$

reviews: see Langlois (2010)
Lehners & Steinhardt (2009

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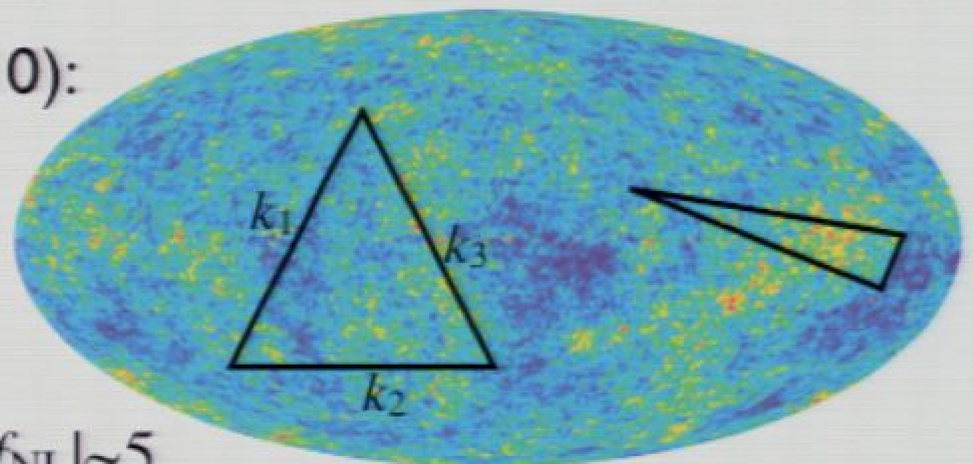
CMB constraints

Measurements of CMB bispectrum:

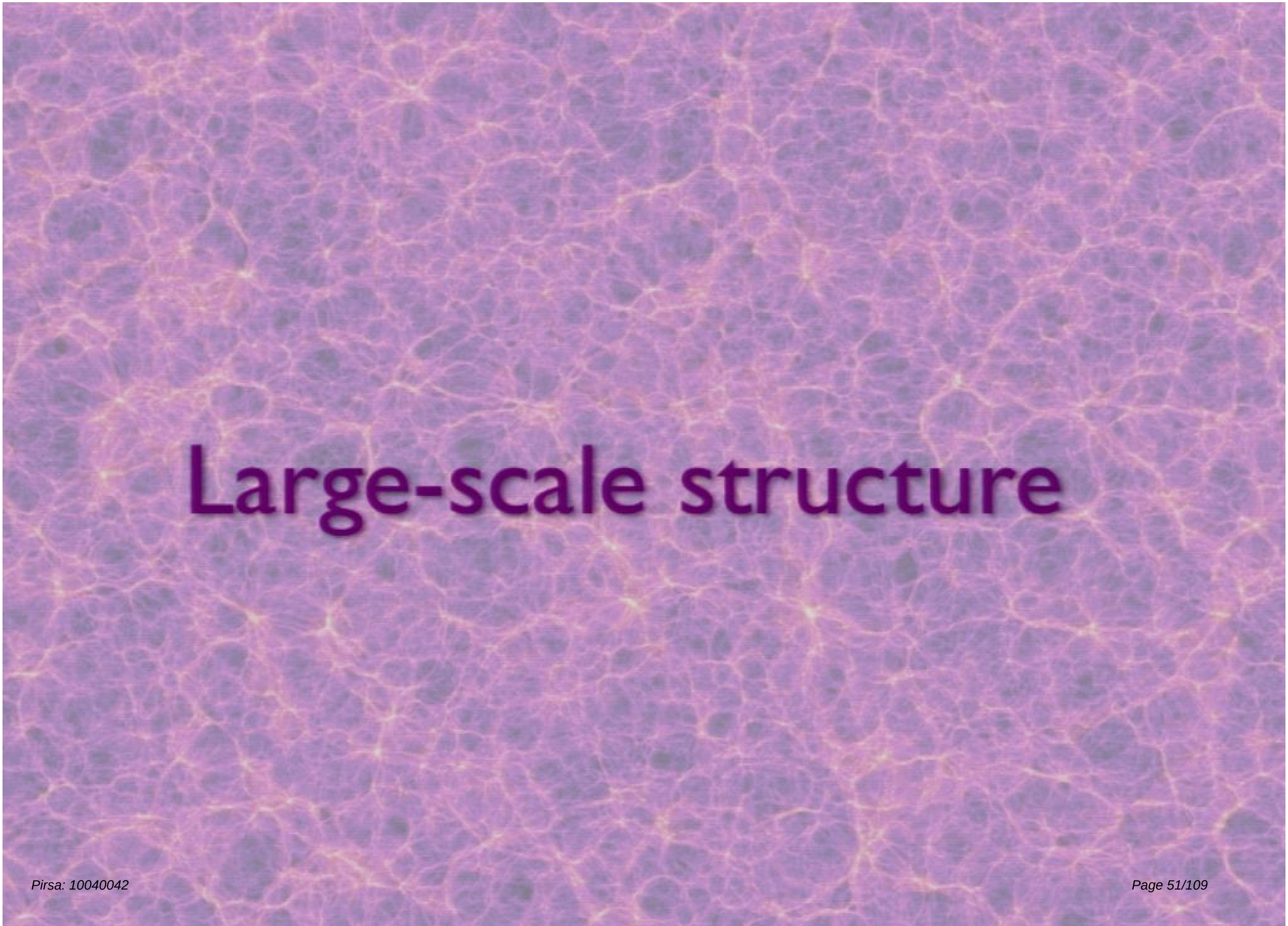
- WMAP7 (Komatsu et al. 2010):

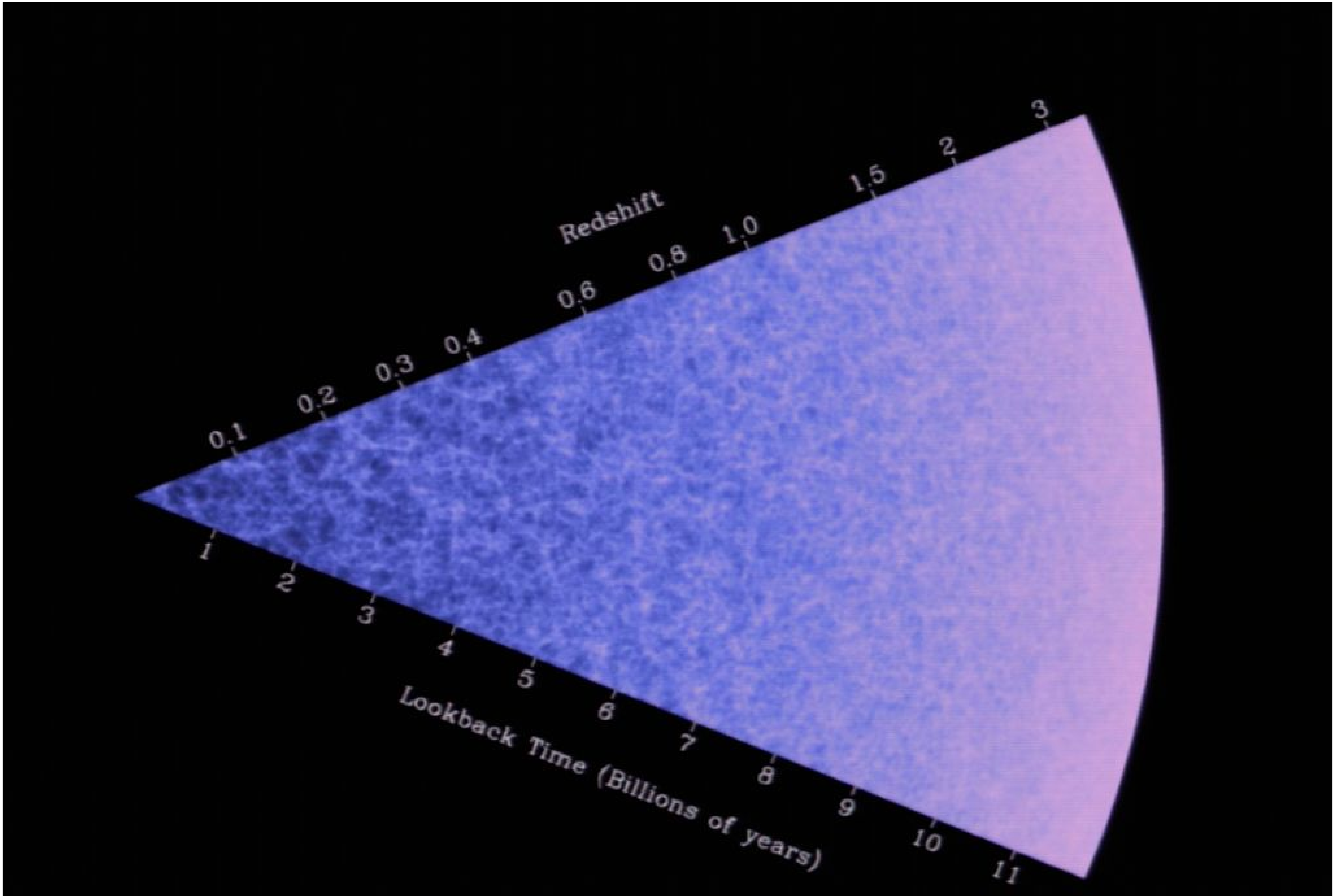
  $-10 < f_{NL} < 74$ (95% conf)



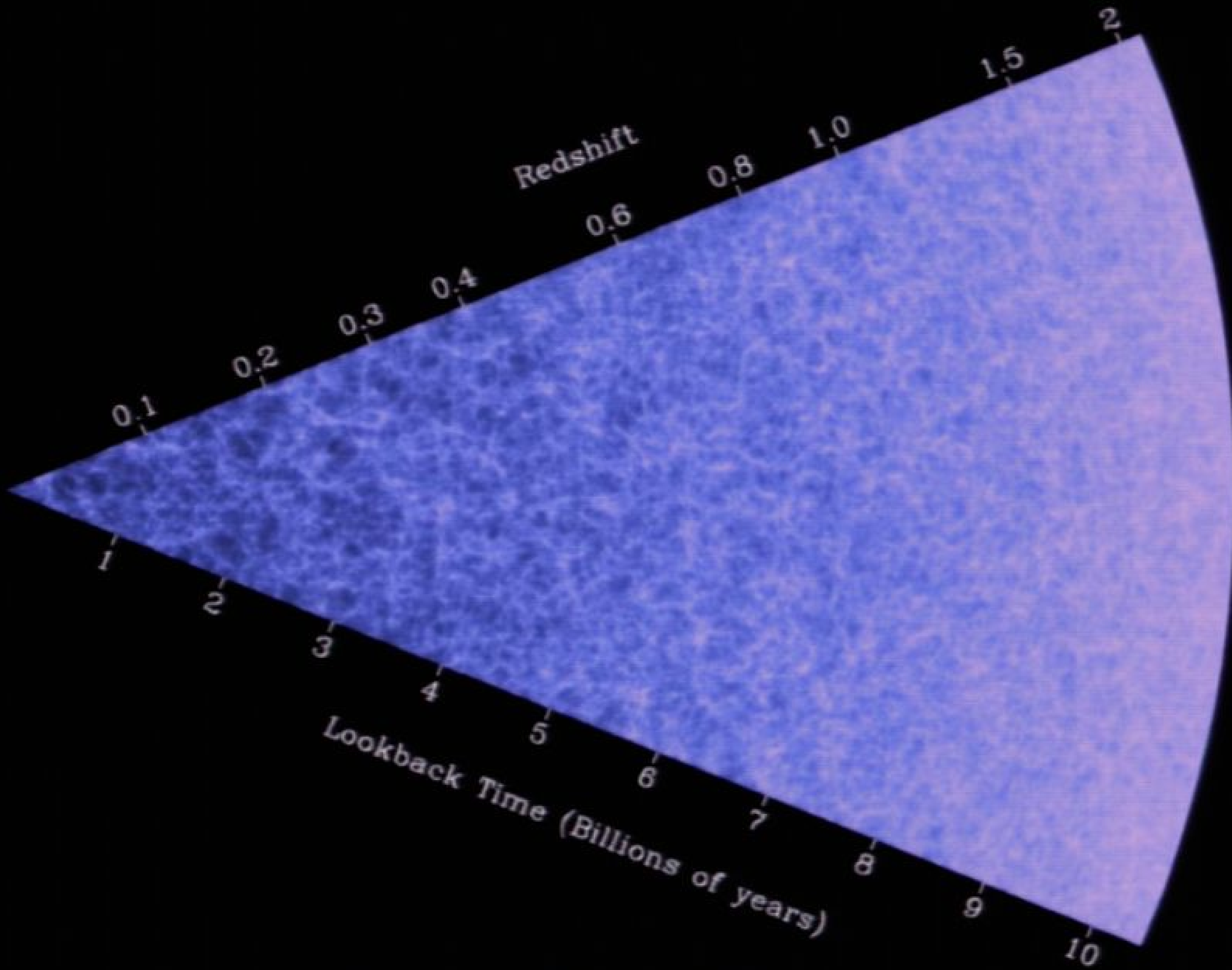
- Planck: forecasted to reach $|f_{NL}| \sim 5$
  - limited eventually by secondaries (e.g. lensing)

can we do better?


Large-scale structure



Horizon Run (Kim et al. 2009)



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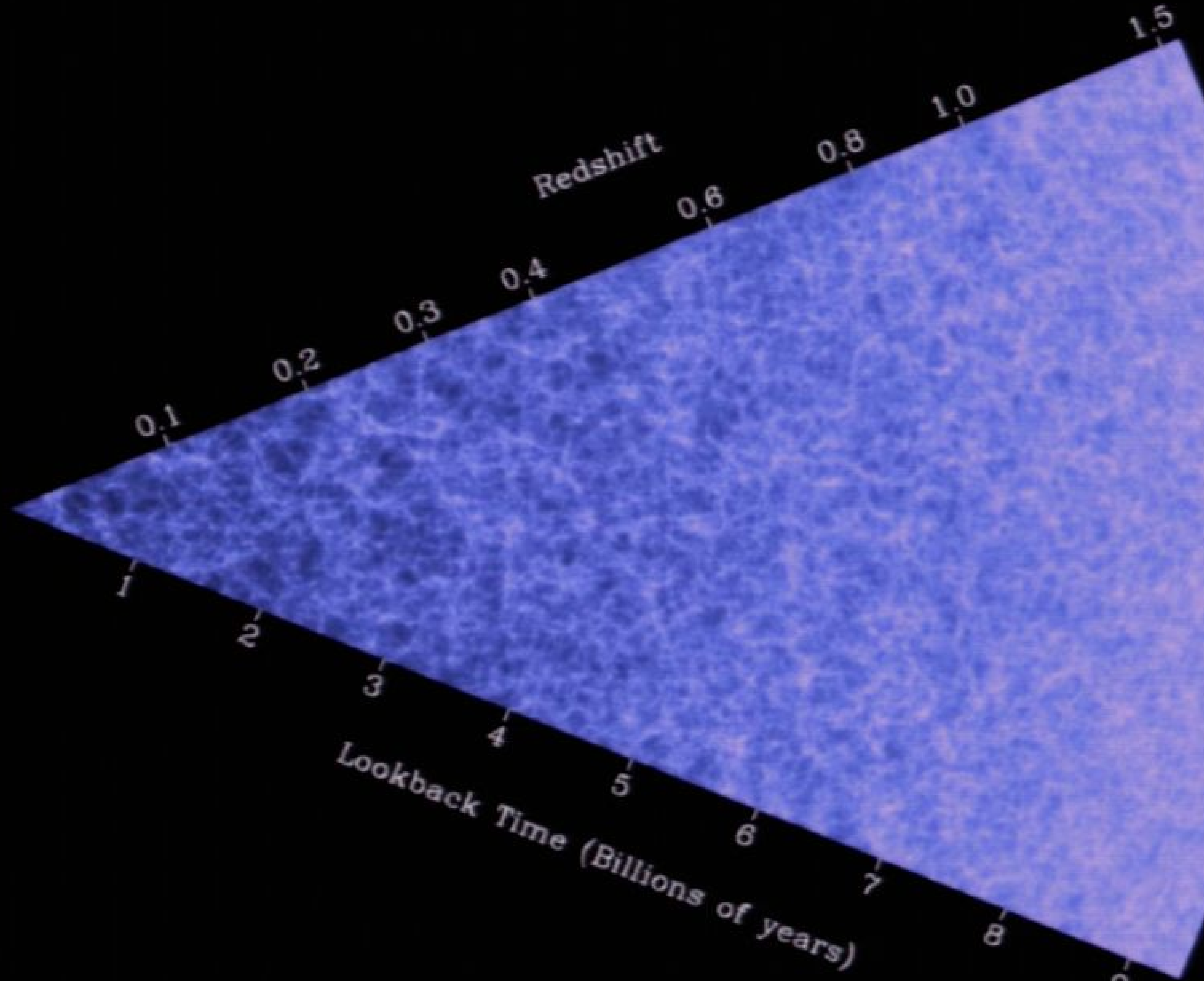

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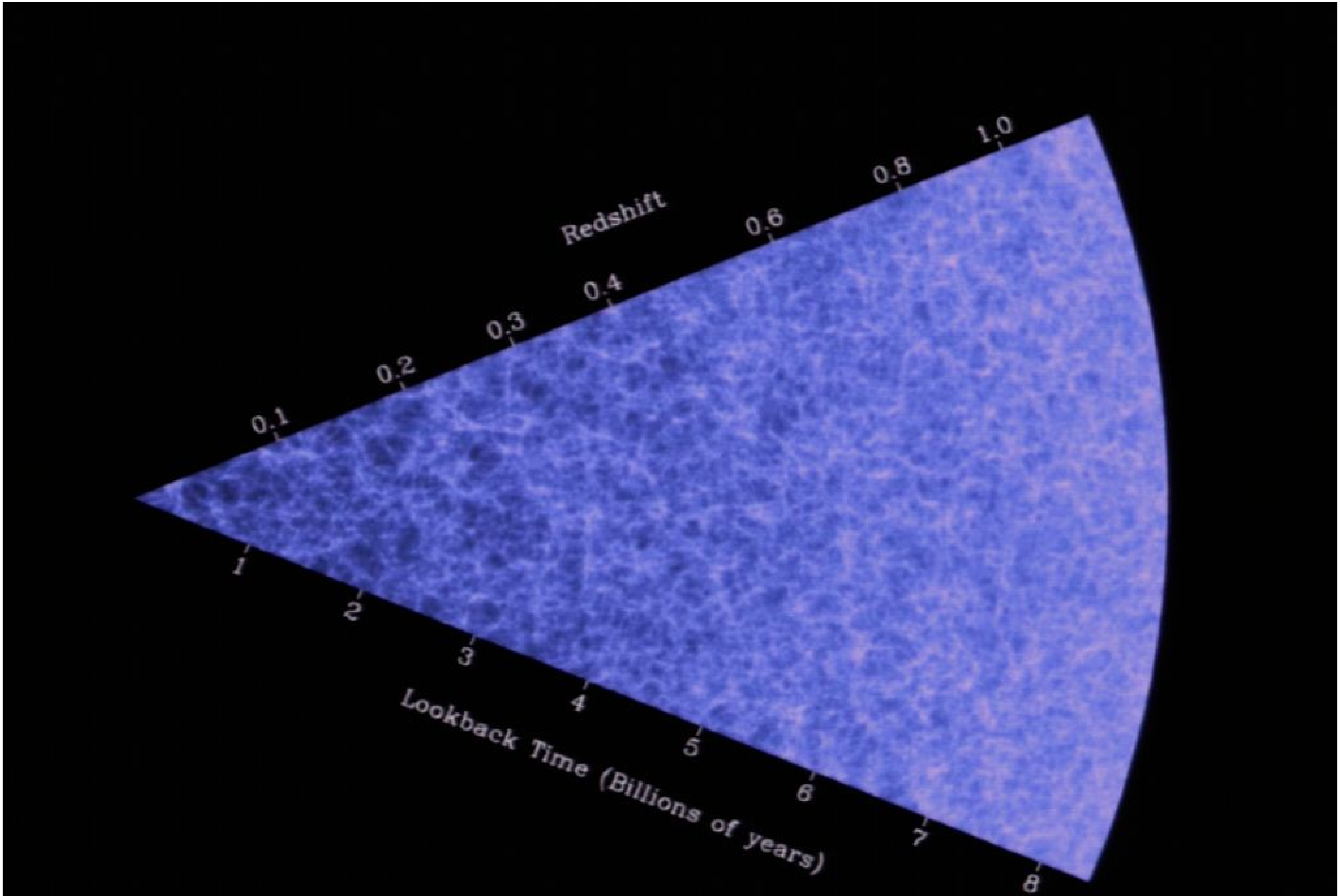

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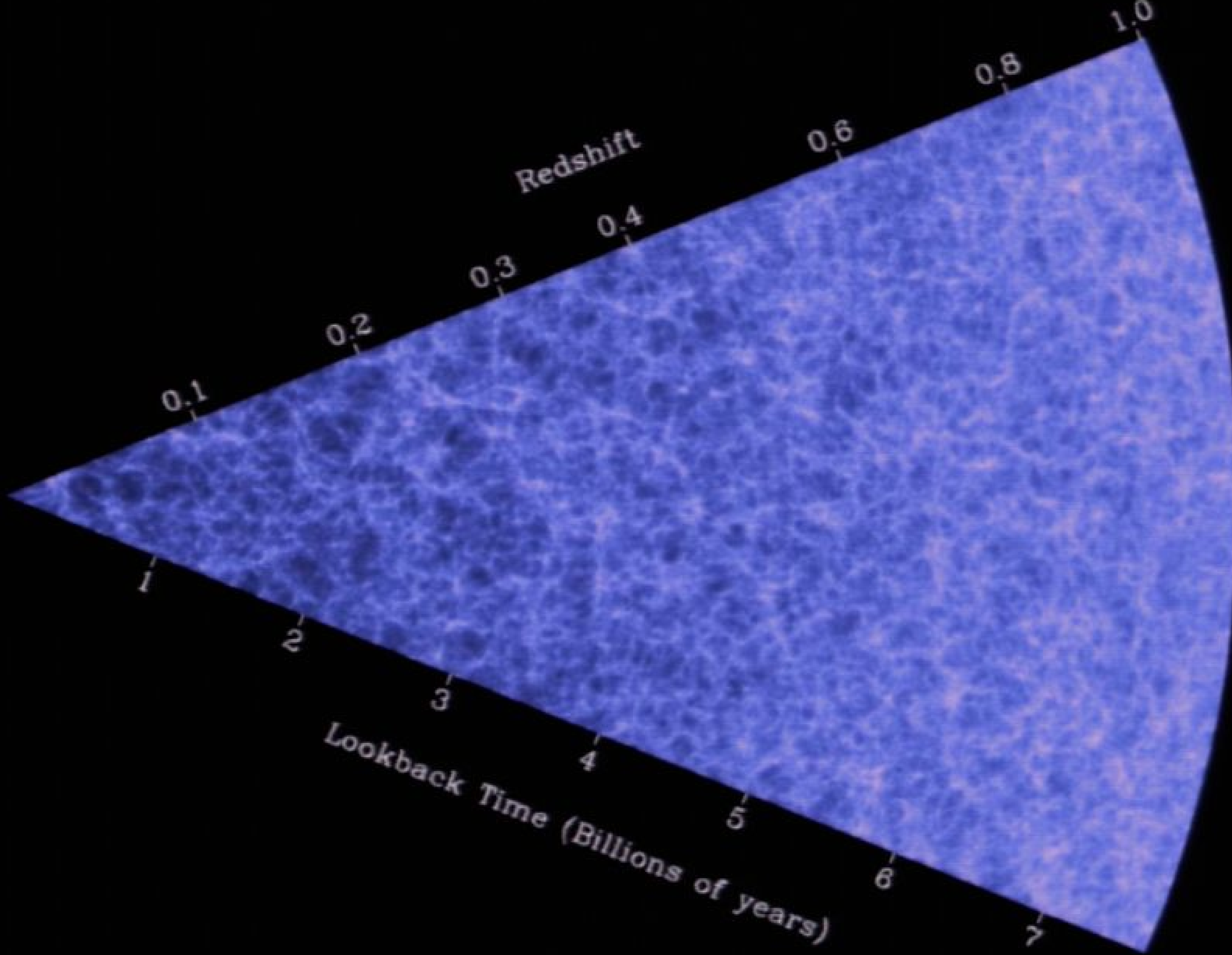

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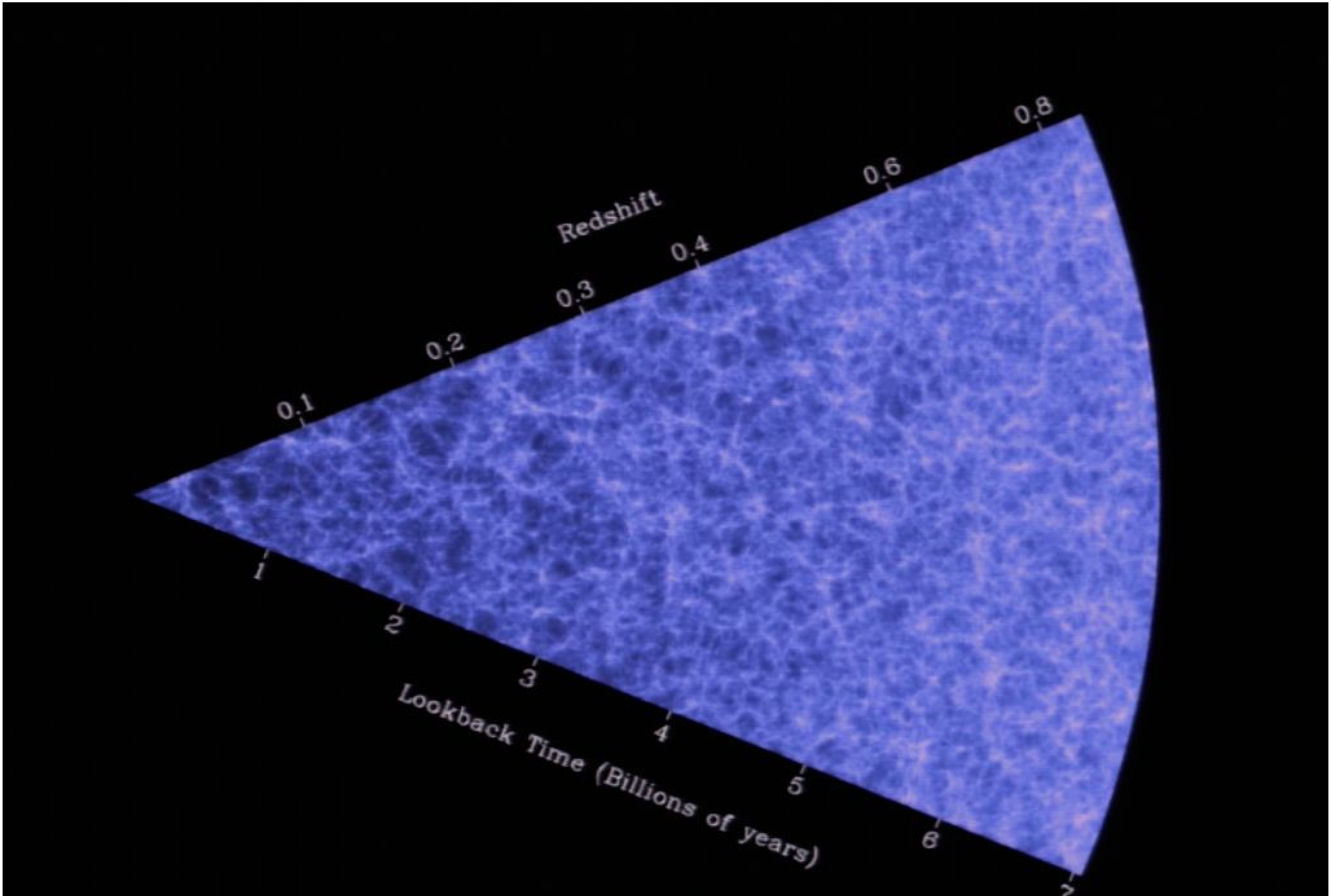

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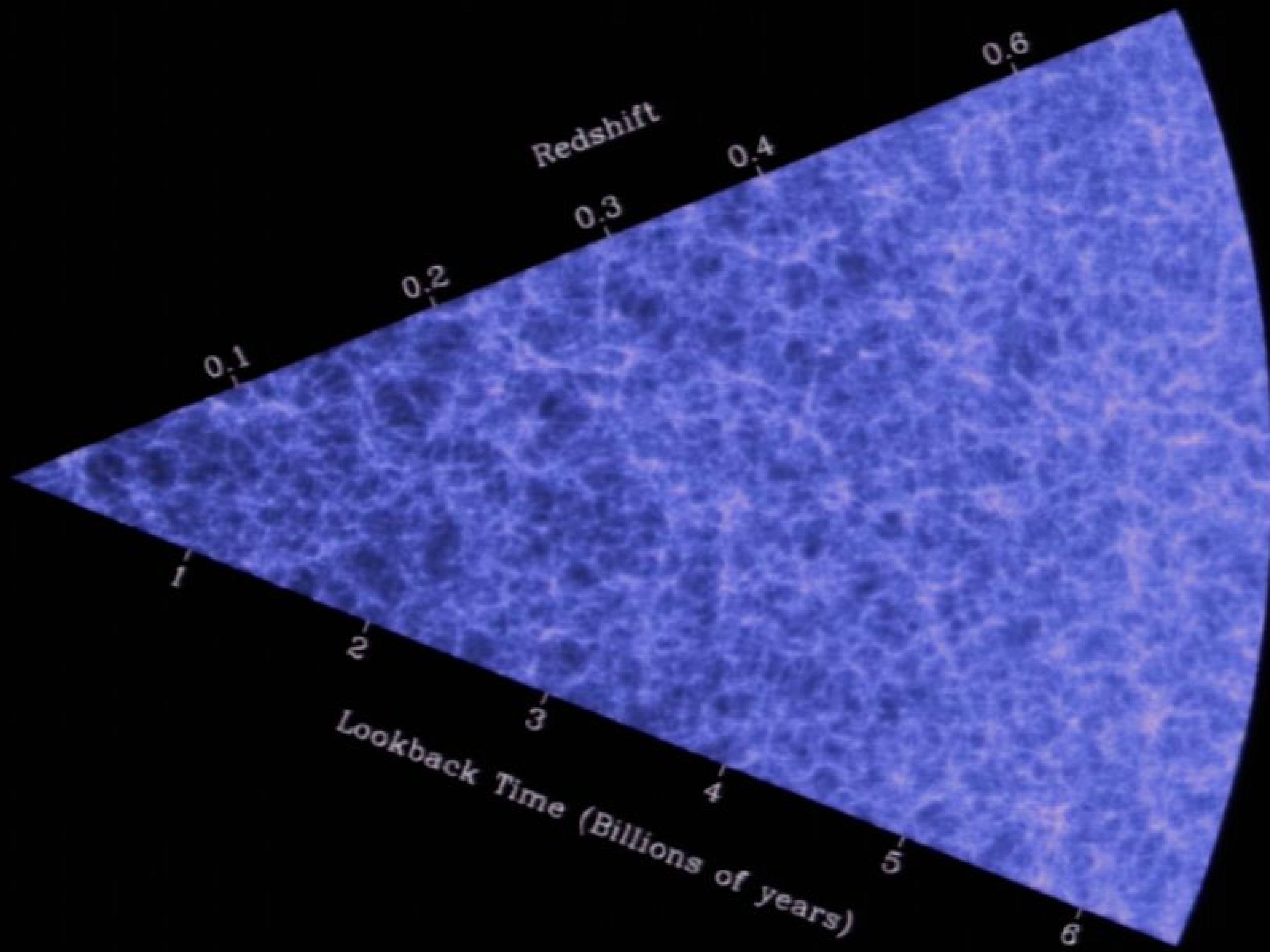
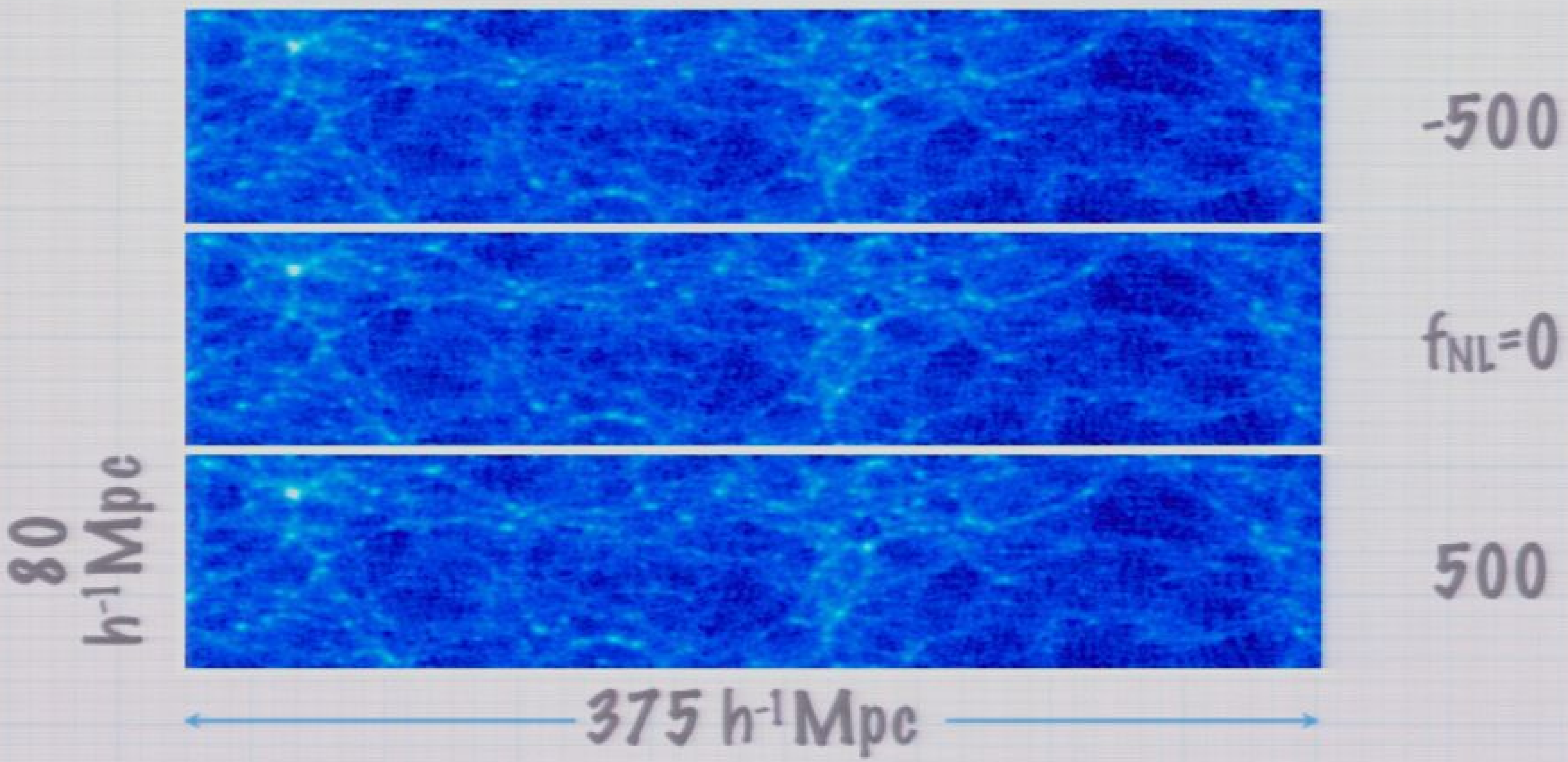


Horizon Run (Kim et al. 2009)

NG & large-scale structure



it doesn't seem like much changes!

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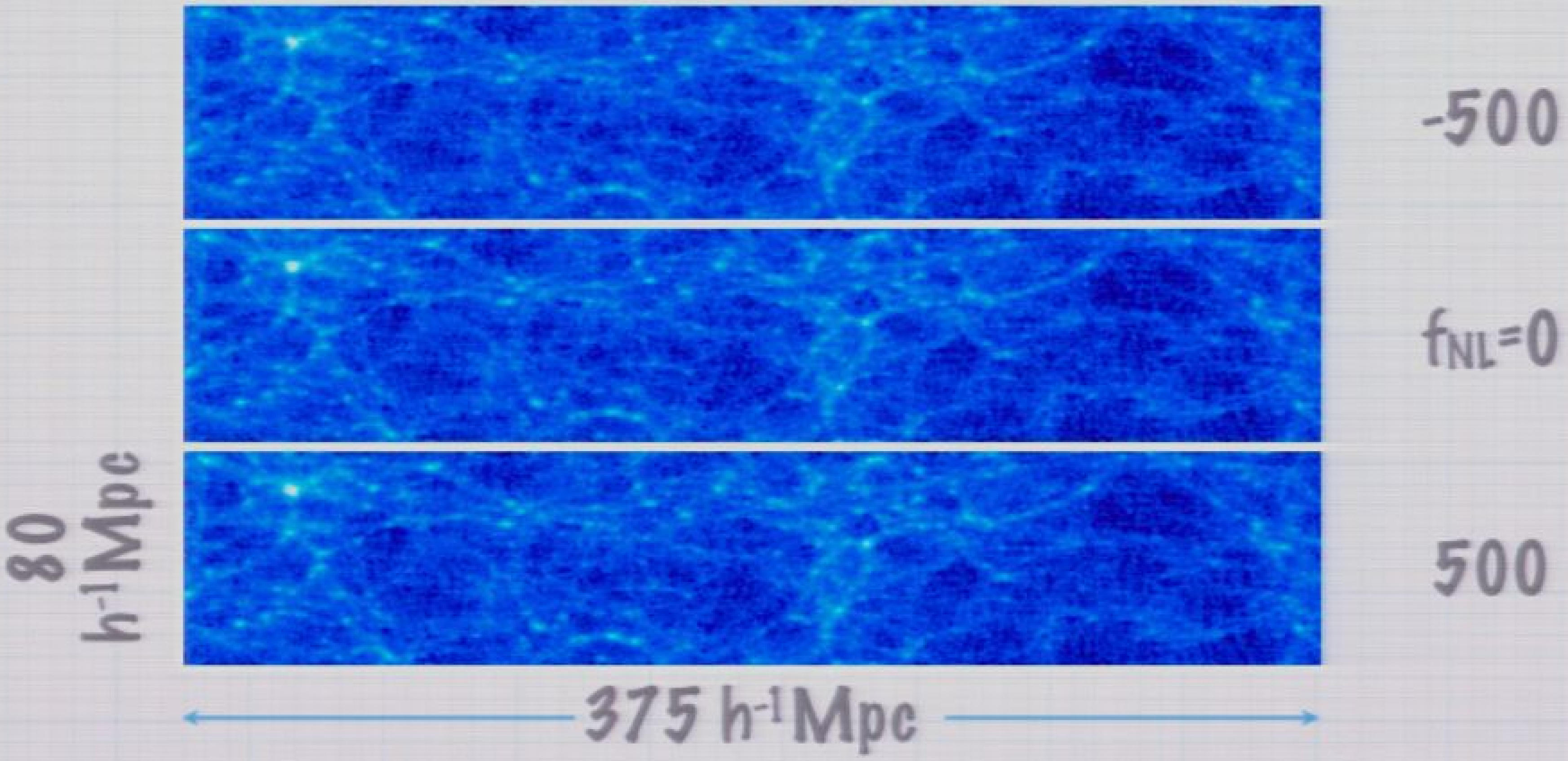

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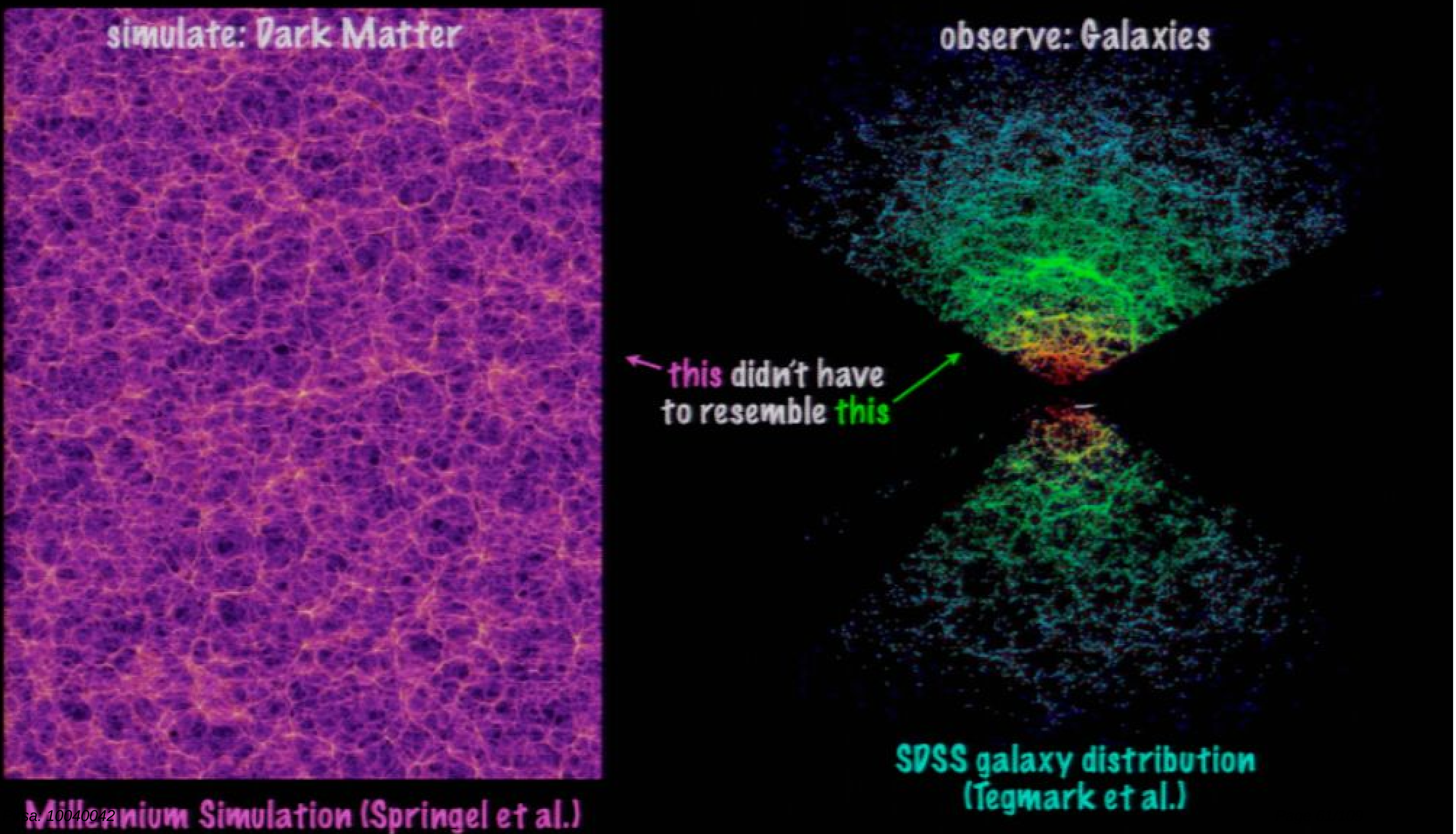
Observing the Cosmic Web



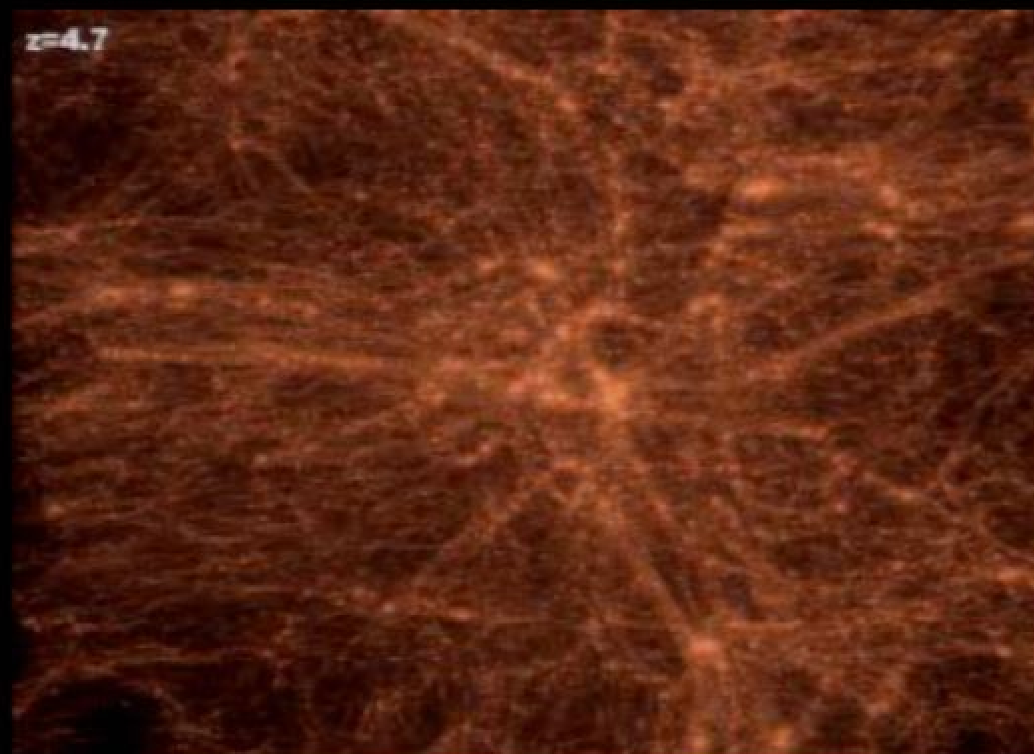
* Fortunately, essentially all tracers (like galaxies or quasars) live inside of Dark Matter Halos

* massive halos form from collapse of peaks of the initial (linear) density field, so peak statistics $\rightarrow$ halo statistics

dark matter halos

Halos are cosmological objects that are:

- collapsed in all 3 dimensions
- gravitationally self-bound,
- virialized



"Via Lactea"
Diemand et al. 2006

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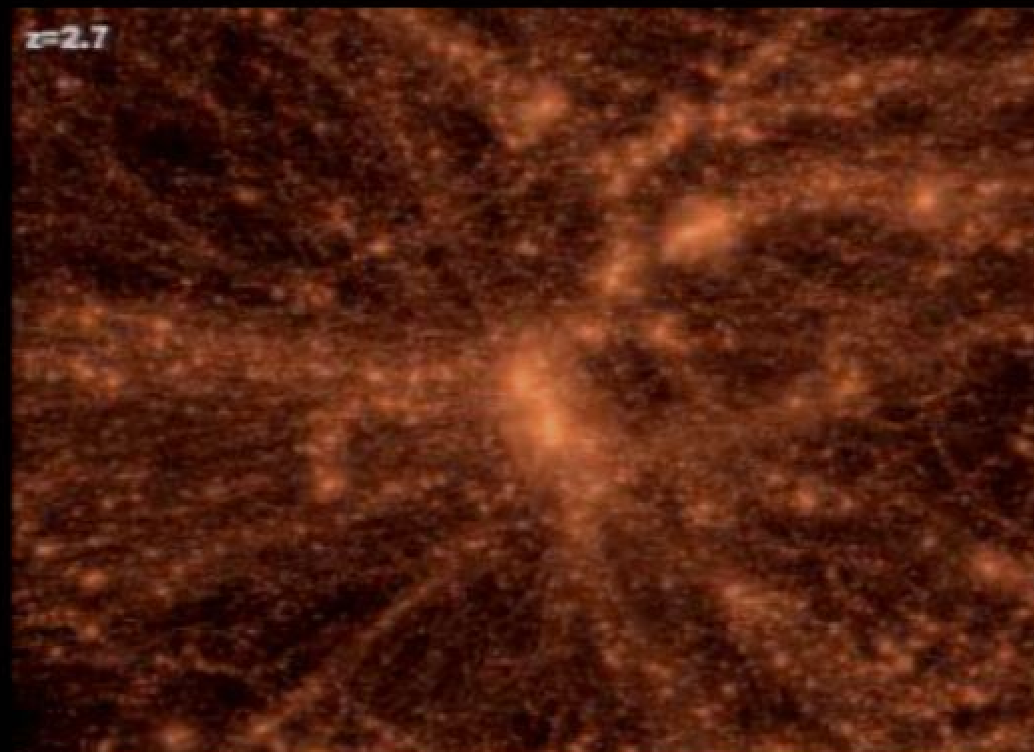

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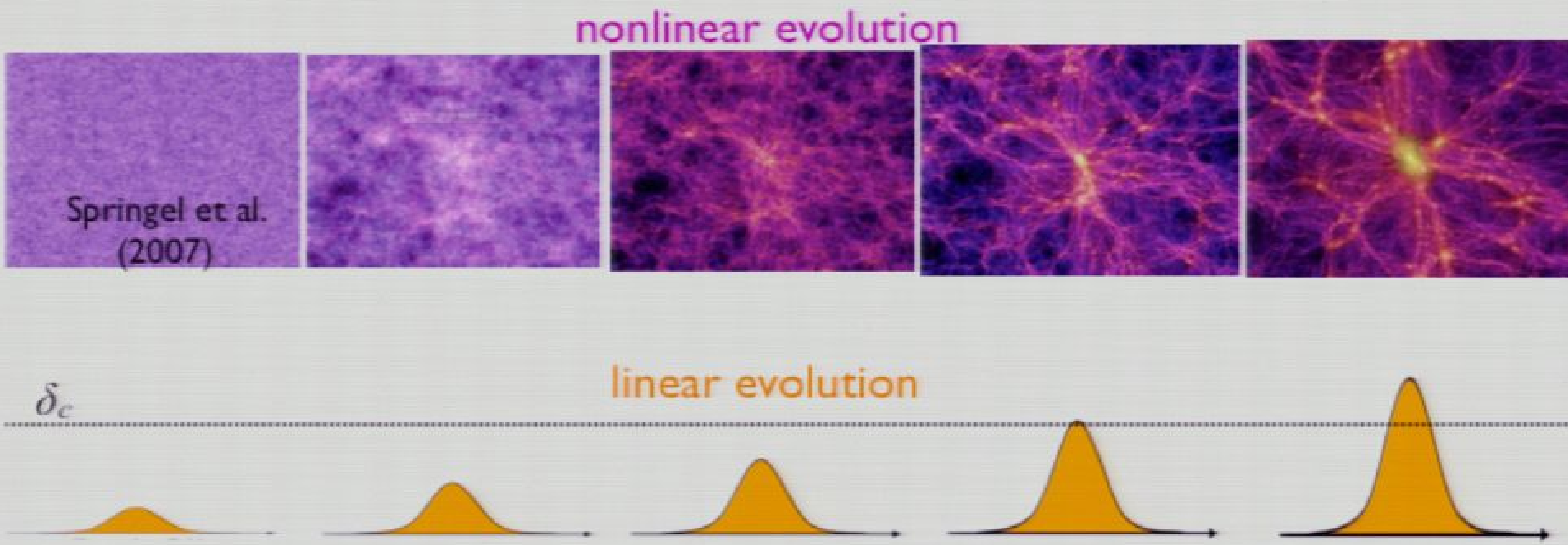
halo formation (over)simplified

- this seems complicated! but we can model halo formation simply, using a (reasonable) correspondence with linear perturbation theory



- halos collapse when **linearly evolved** peak height reaches a threshold δ_c (Gunn & Gott 1972)

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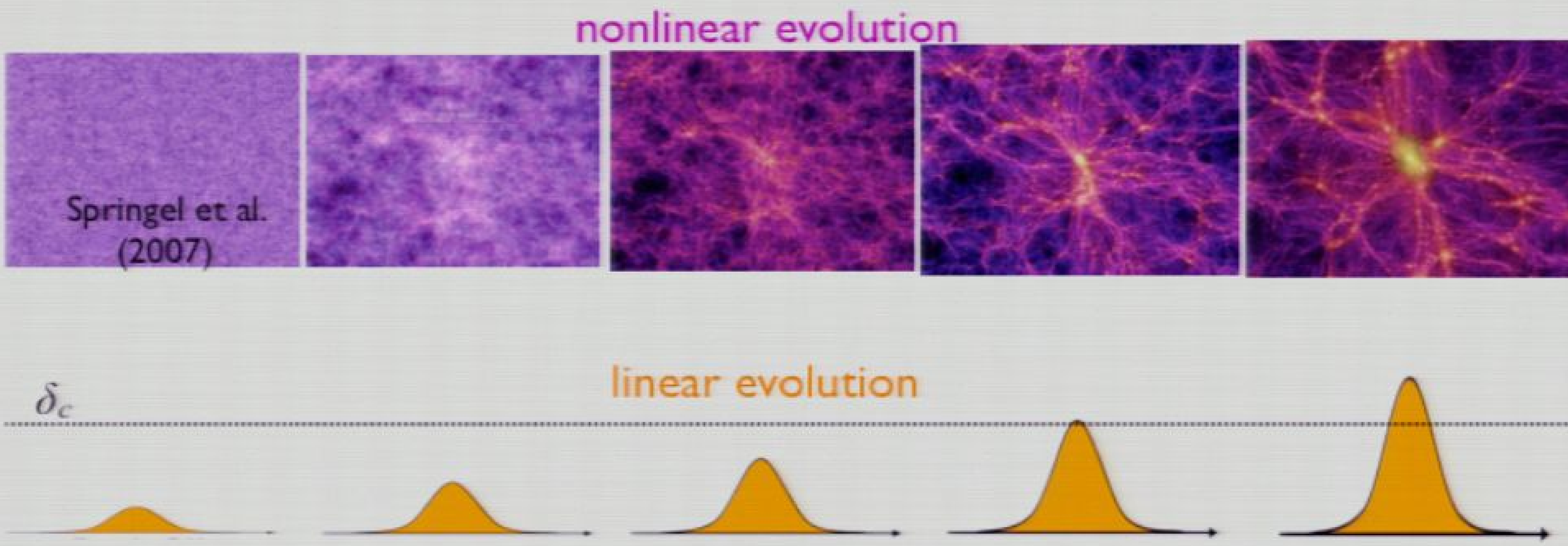

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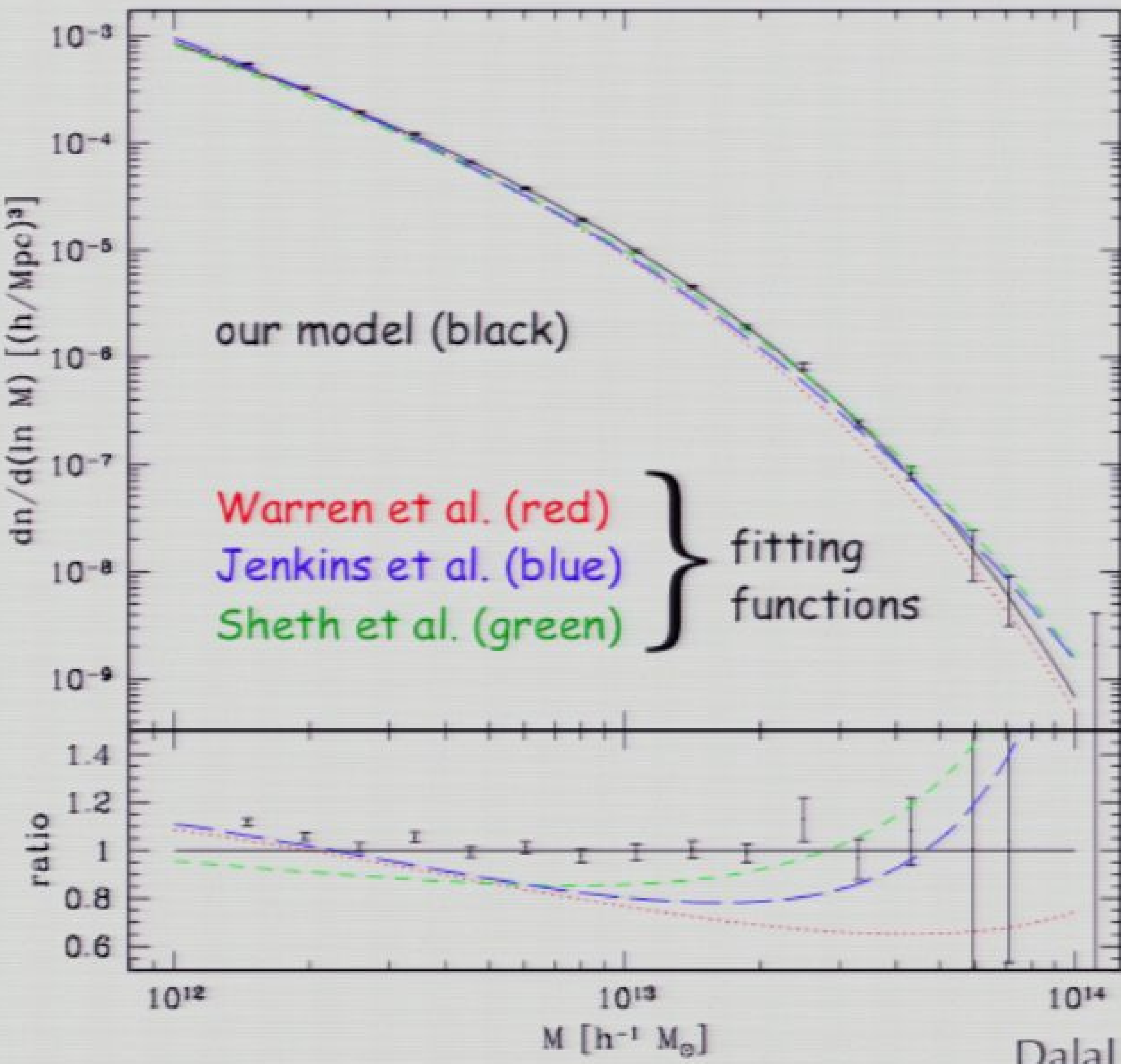
(Gaussian) halo mass function



Dalal et al. 2010c

peaks in local NG

usual parameterization is $\Phi_{NG} = \varphi + f_{NL}\,\varphi^2$

Salopek & Bond 1990;
Komatsu & Spergel 2001;
Maldacena 2003

see Dalal et al. 2008

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$$\nabla^2\Phi_{NG} = \nabla^2\varphi + 2\,f_{NL}[\varphi\nabla^2\varphi + |\nabla\varphi|^2]$$

see Dalal et al. 2008

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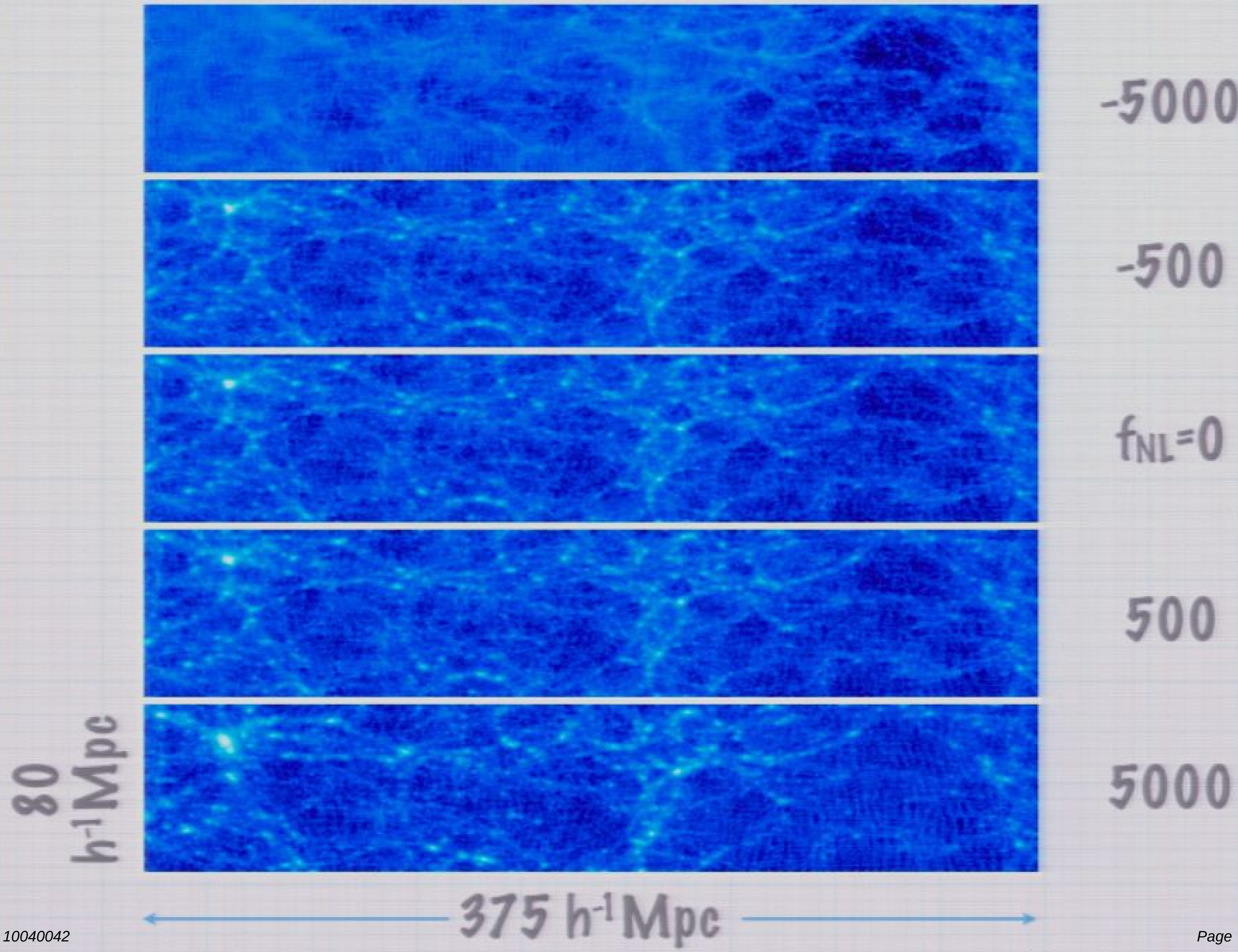
near high peaks, this is bigger than this

neglecting 2nd term gives: $\delta_{NG} \approx \delta\,(1 + 2\,f_{NL}\varphi)$

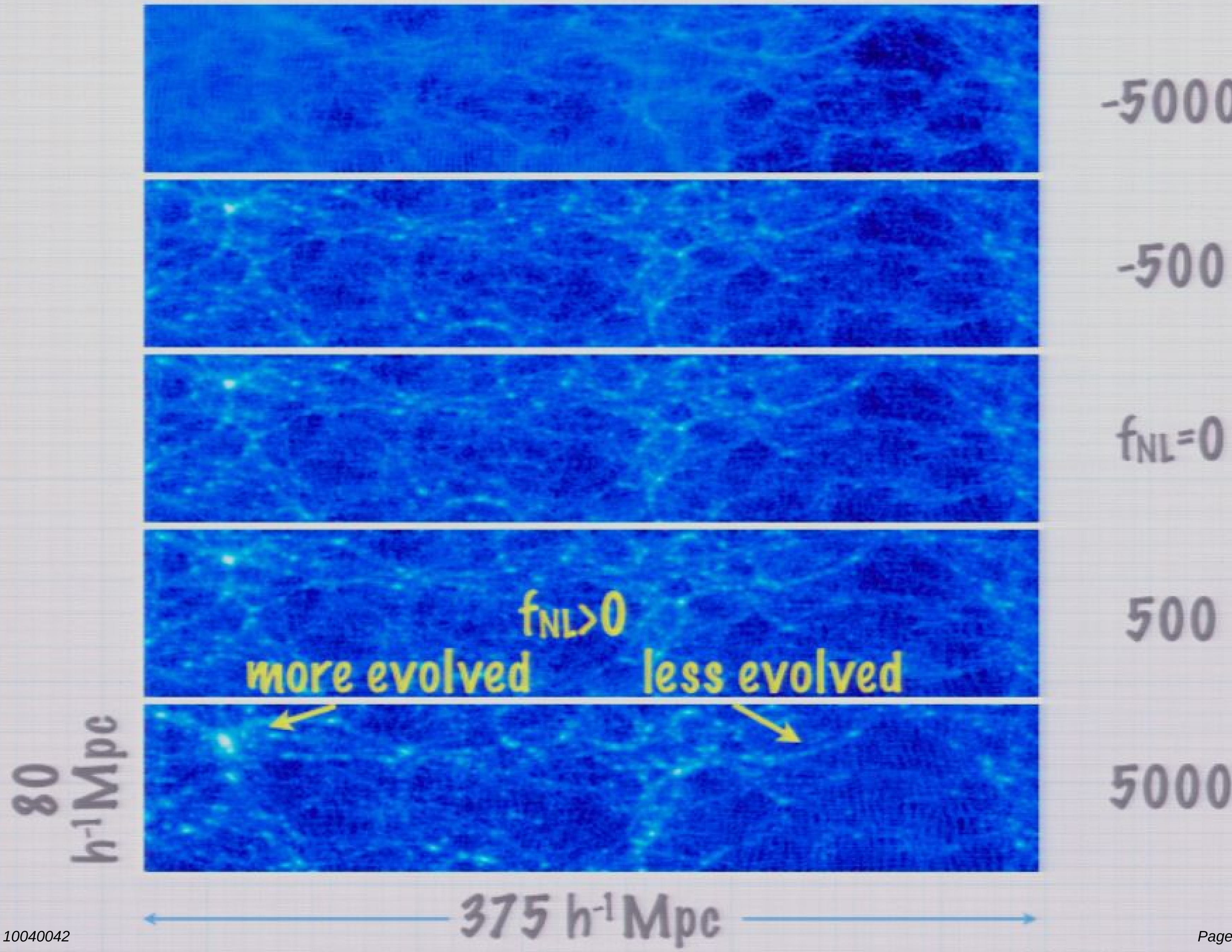
see Dalal et al. 2008

* this f_{NL}-dependent change in peak heights changes the number of halos that form

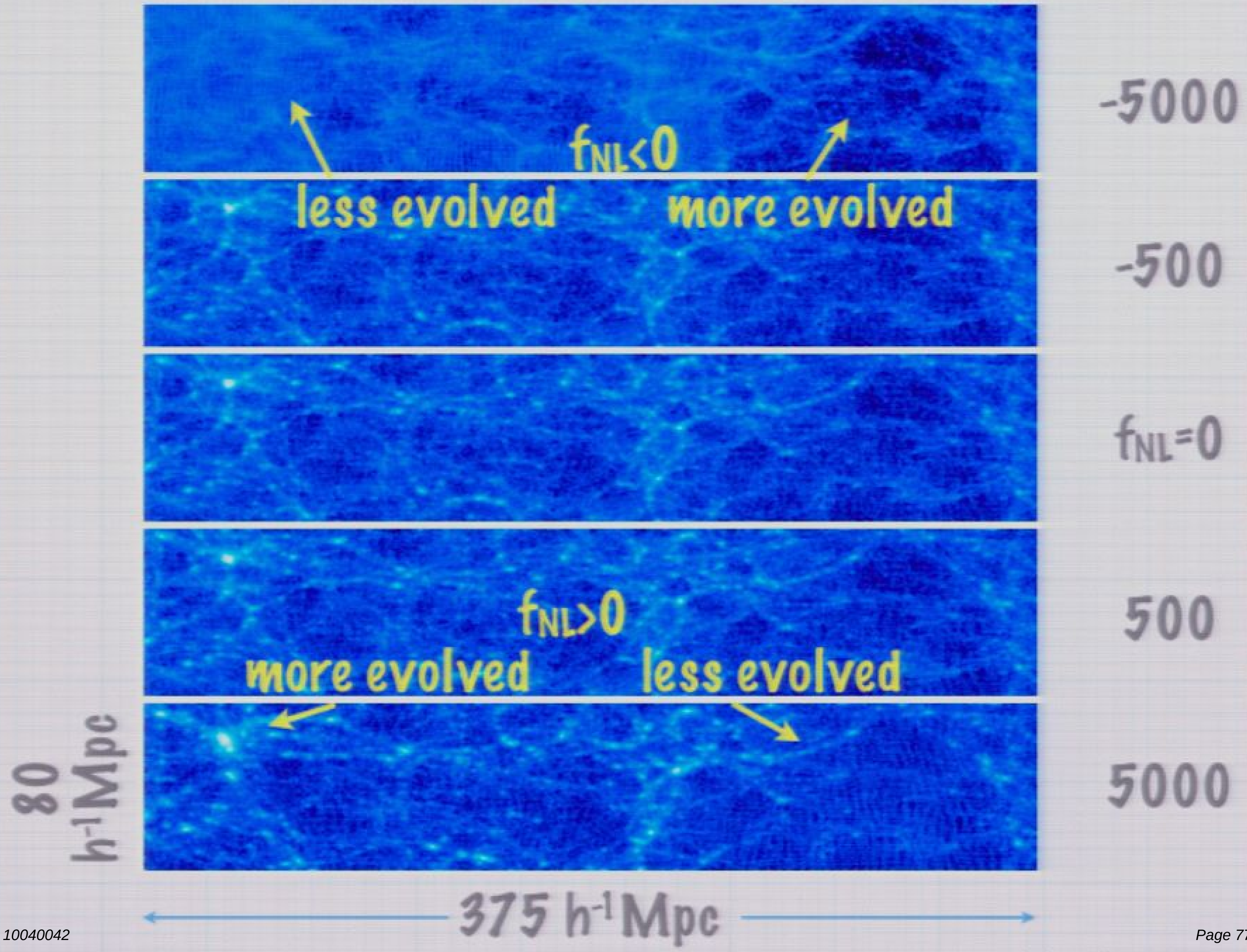
* so counting objects can be used to probe NG, though this signature is often degenerate with other cosmological parameters (see e.g. Matarrese et al. 2000, LoVerde et al. 2008)



see Dalal et al. 2008



see Dalal et al. 2008



see Dalal et al. 2008

halo clustering

* predict halo clustering from the clustering of peaks
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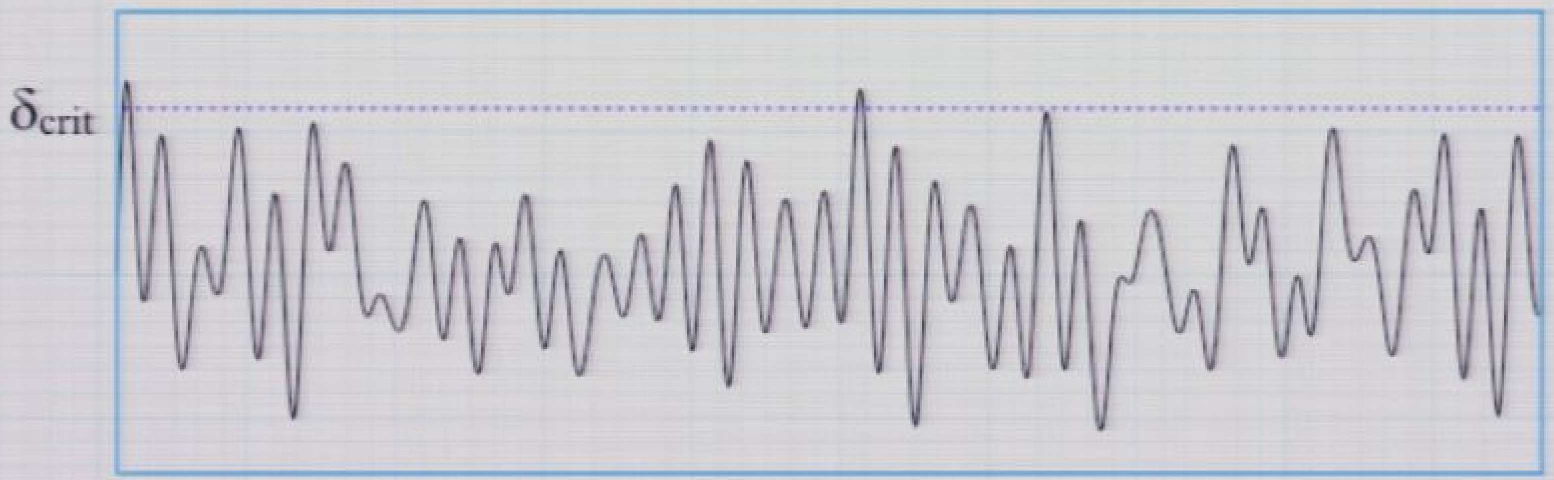

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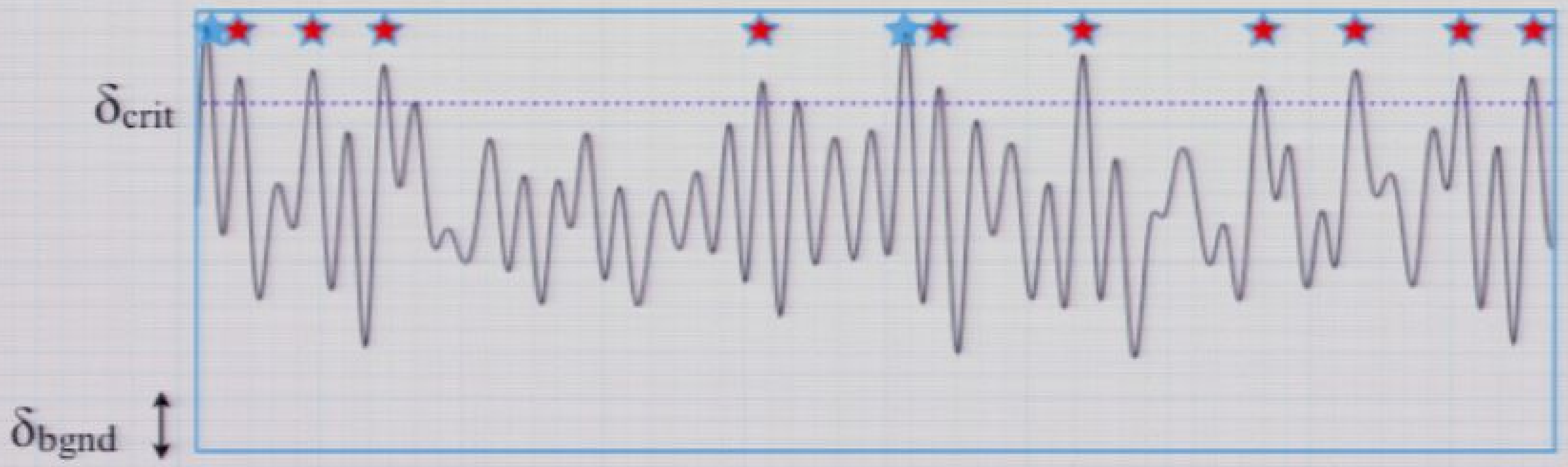
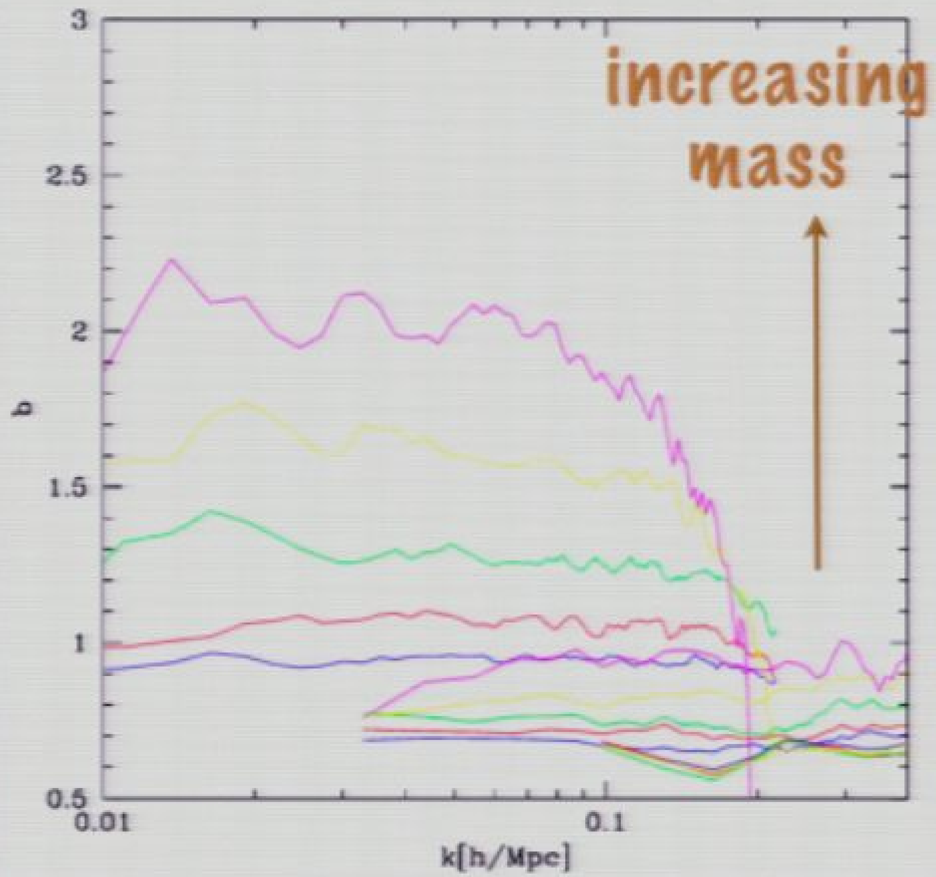


* for large scales where $\delta \ll 1$, this gives $\delta_h \simeq b\,\delta$, $\xi_h = b^2\,\xi$, etc.

(Gaussian) halo bias

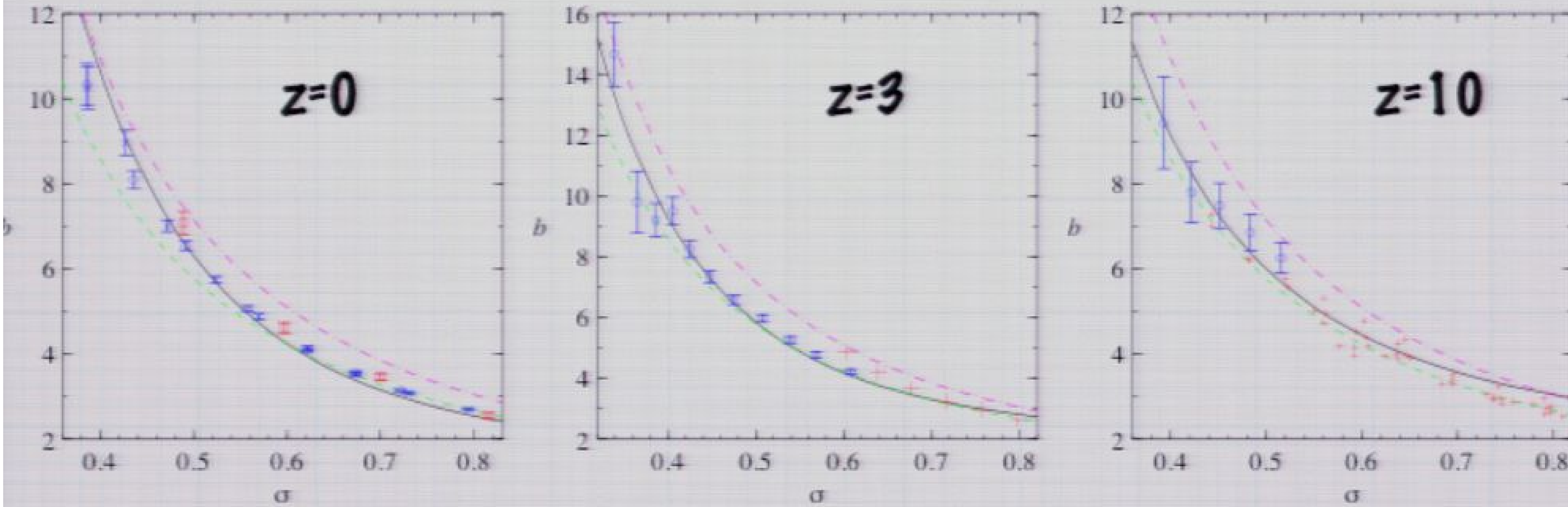
- If halo formation depends only on local matter distribution, then we expect b→const as k→0 (Scherrer & Weinberg 1998)
- and that's what we see in simulations!
- with NG, peaks depend on potential φ, which is non-local!



Seljak & Warren (2004)

(Gaussian) halo bias

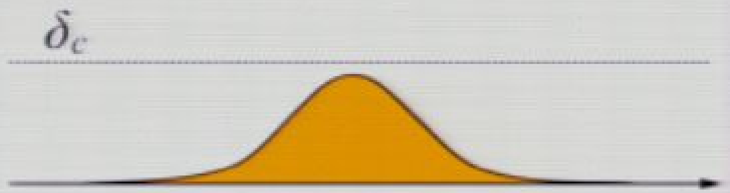
Dalal et al. 2010c



curves: our model (black)
Mo & White (magenta) ← Press-Schechter
Sheth et al. (green)

Nongaussian halo bias

consider the effect of a background mode with density δ and potential φ on peaks



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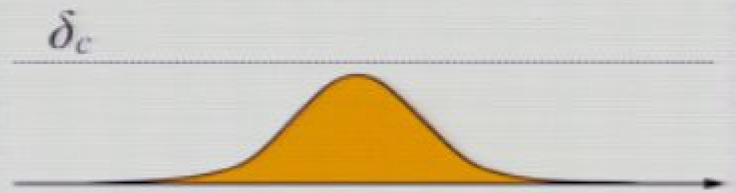

* density δ raises peak heights

see Dalal et al. 2008

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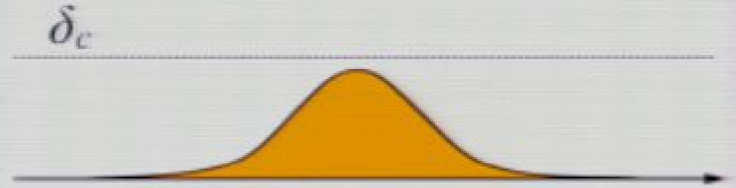

- density δ raises peak heights
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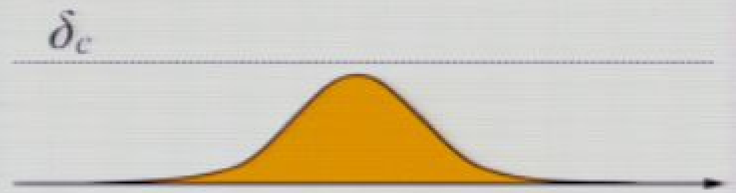

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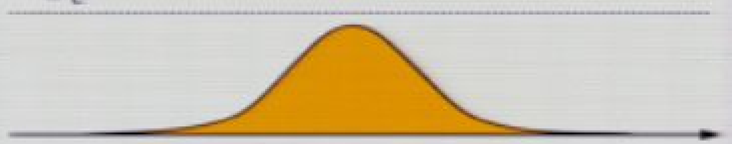

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$$\delta_h(k) = b\left[1 + 2 f_{NL}\delta_c \frac{3\Omega_m}{2aTr_H^2 k^2}\right]\delta(k)$$

$$= b_{NG}(k)\delta(k)$$

see Dalal et al. 2008

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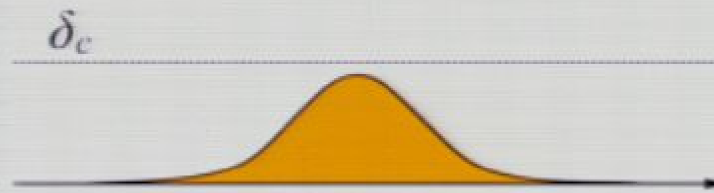

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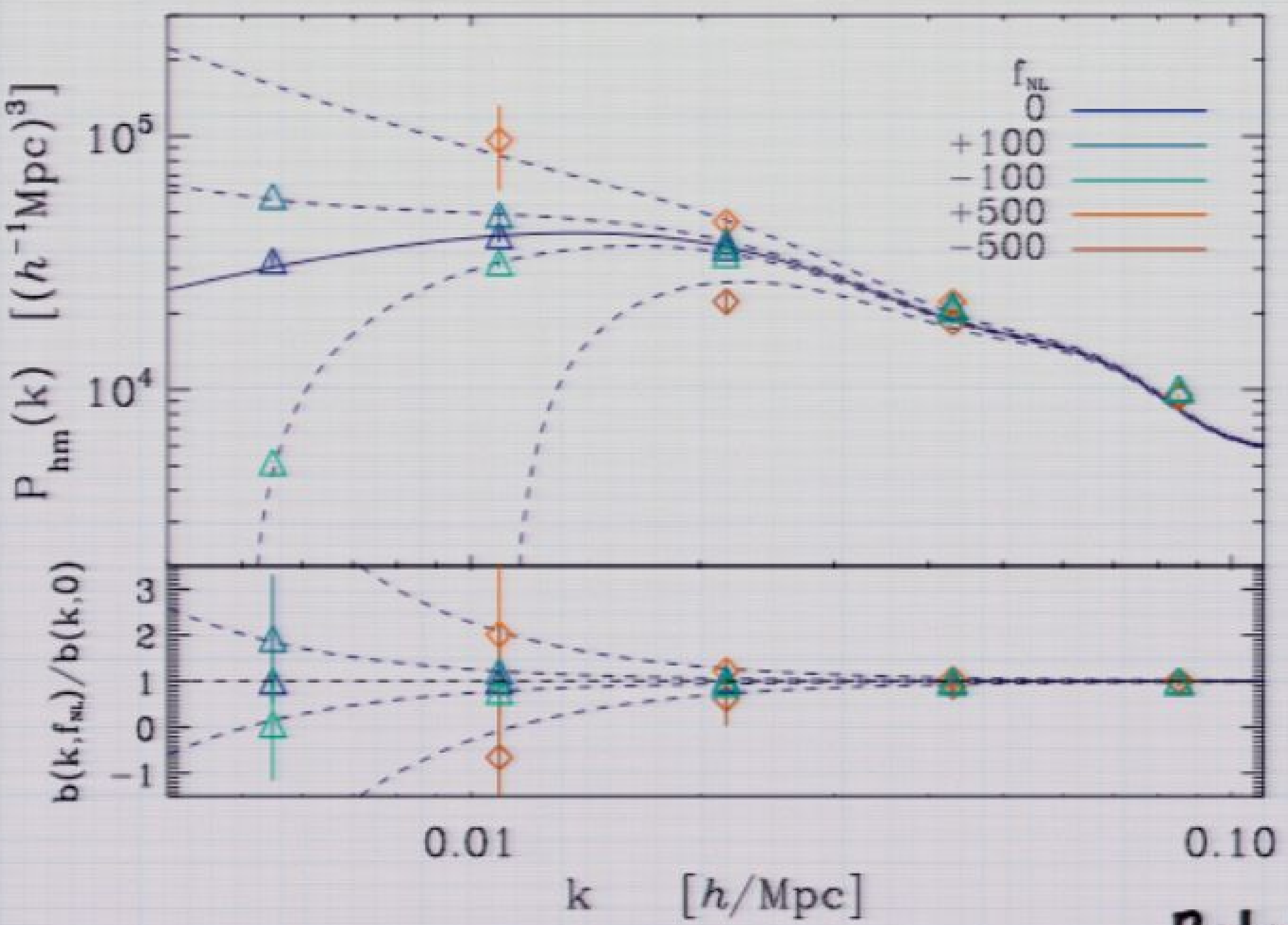
$$\begin{aligned} \delta_h(k) &= b\left[1 + 2 f_{\rm NL}\delta_c \frac{3\Omega_m}{2aTr_H^2 k^2}\right]\delta(k) \\ &= b_{\rm NG}(k)\delta(k) \end{aligned}$$

this is the important piece!!

see Dalal et al. 2008

Large-scale clustering

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



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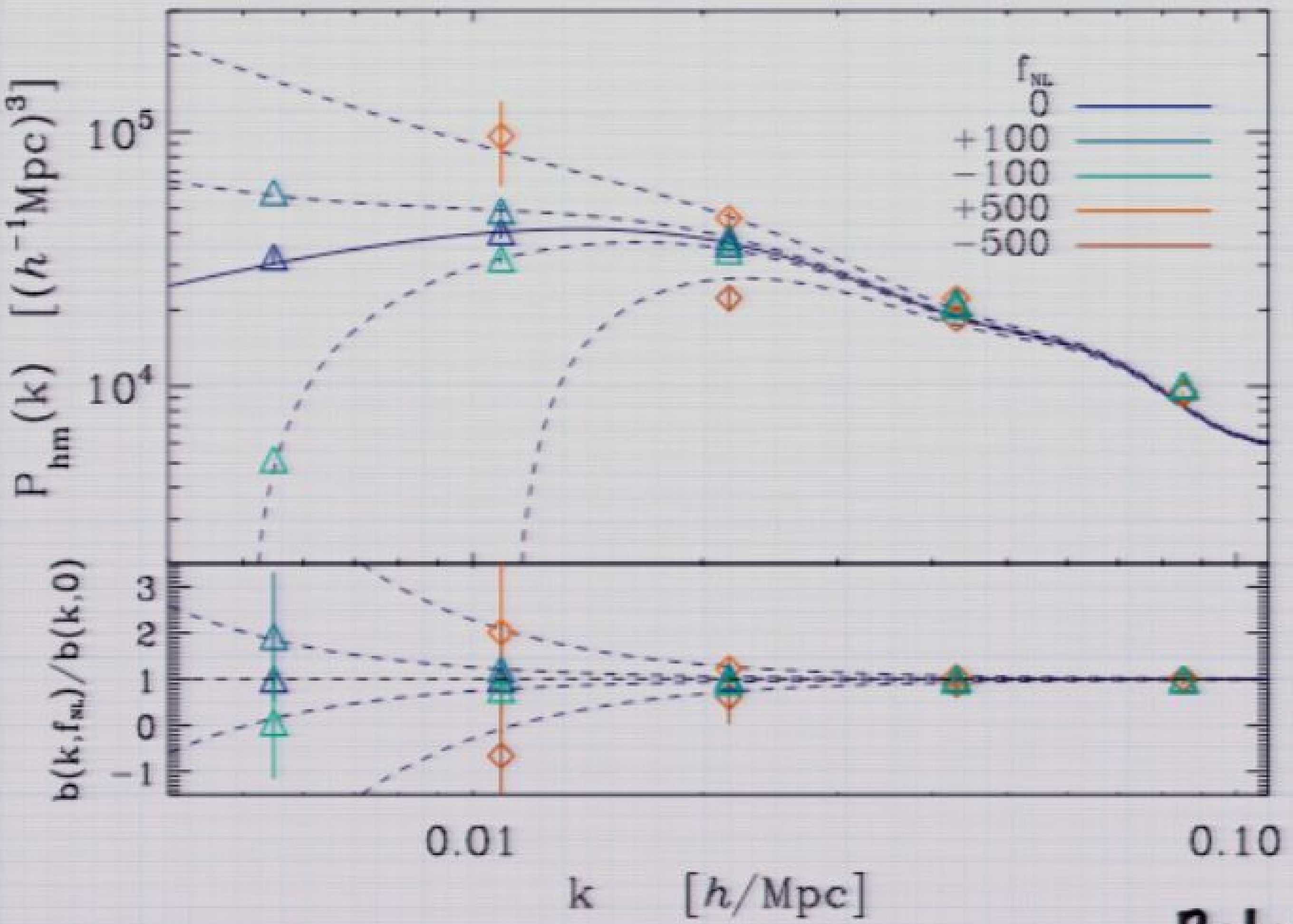

Dalal et al (2008a)

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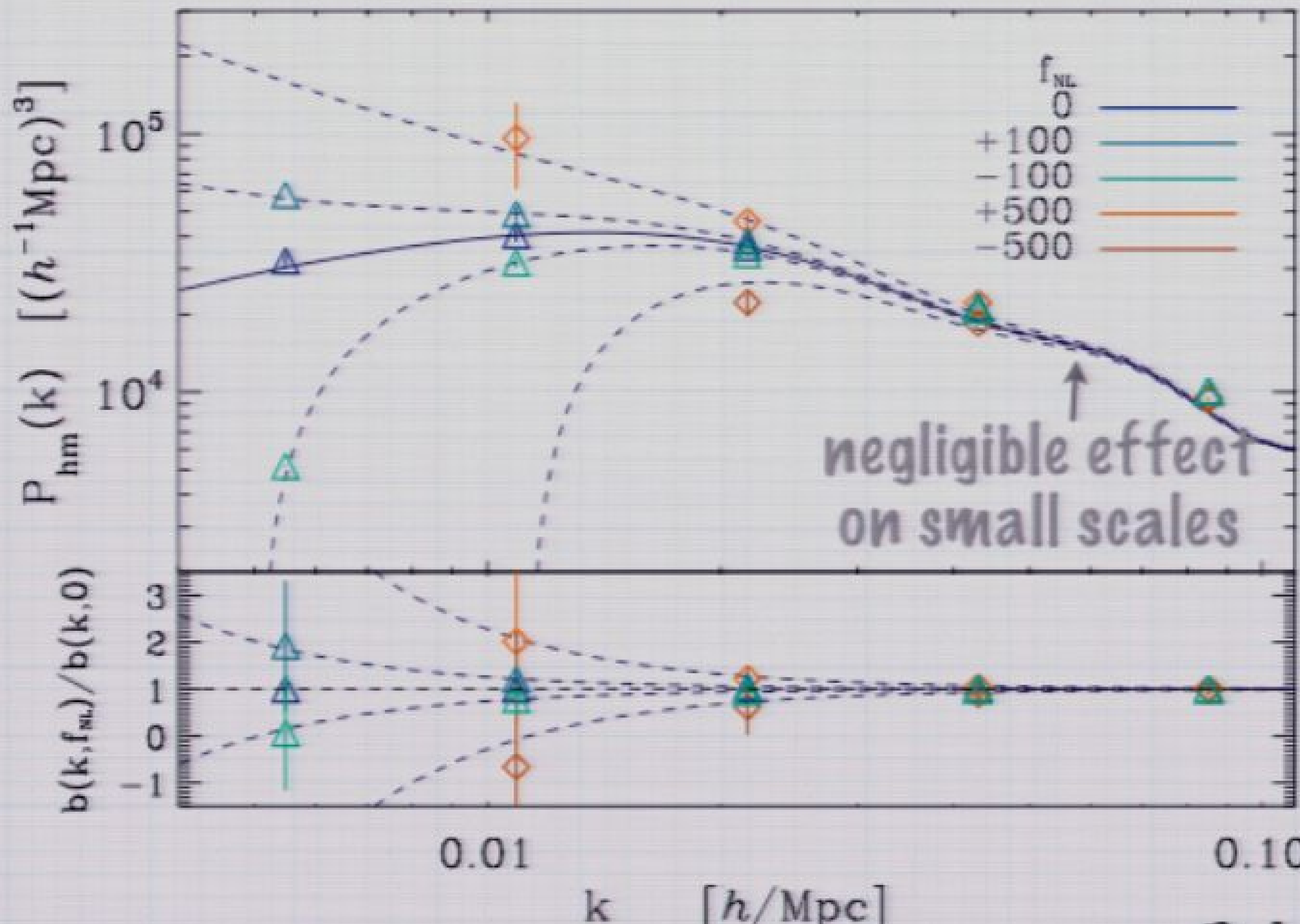

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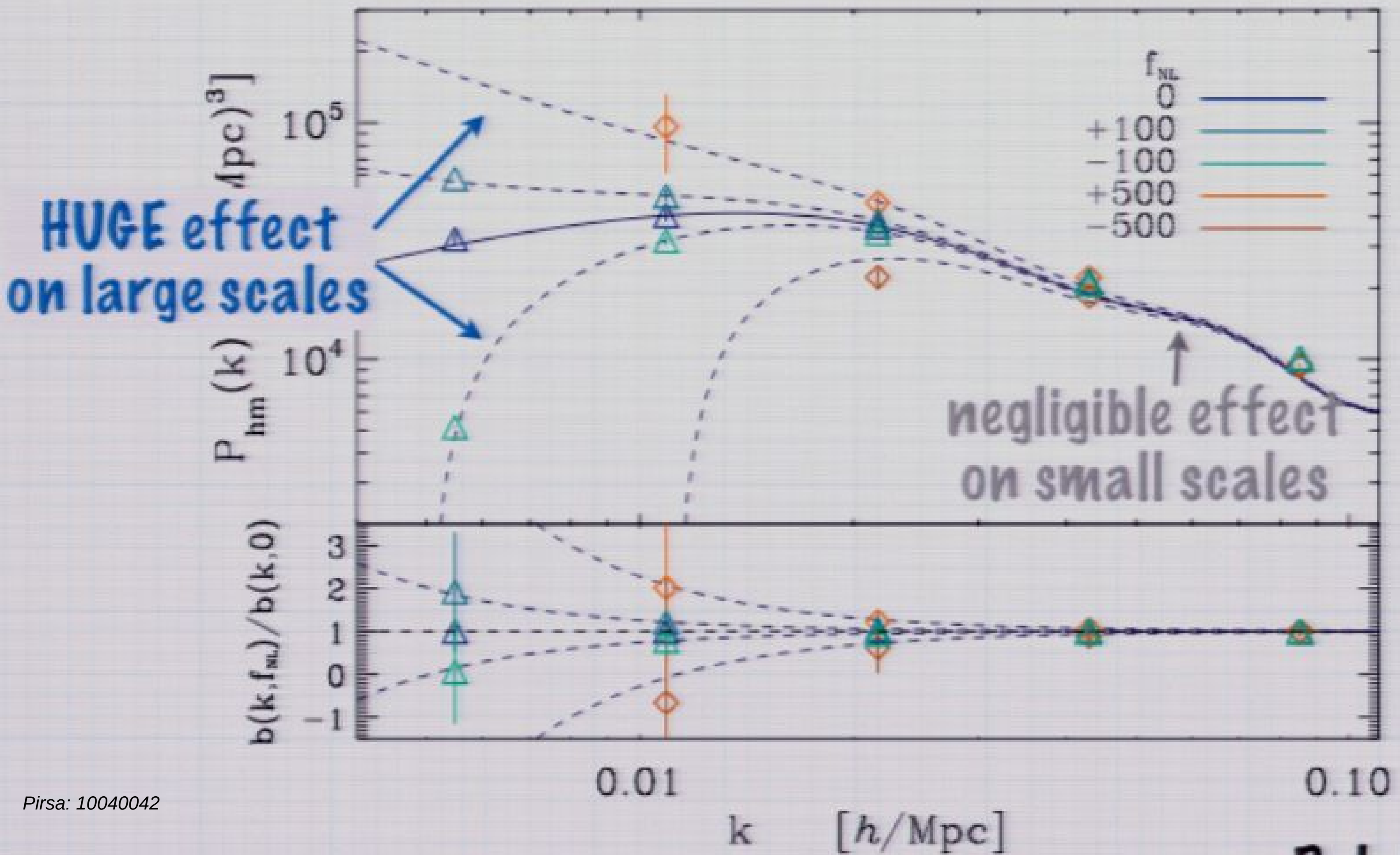


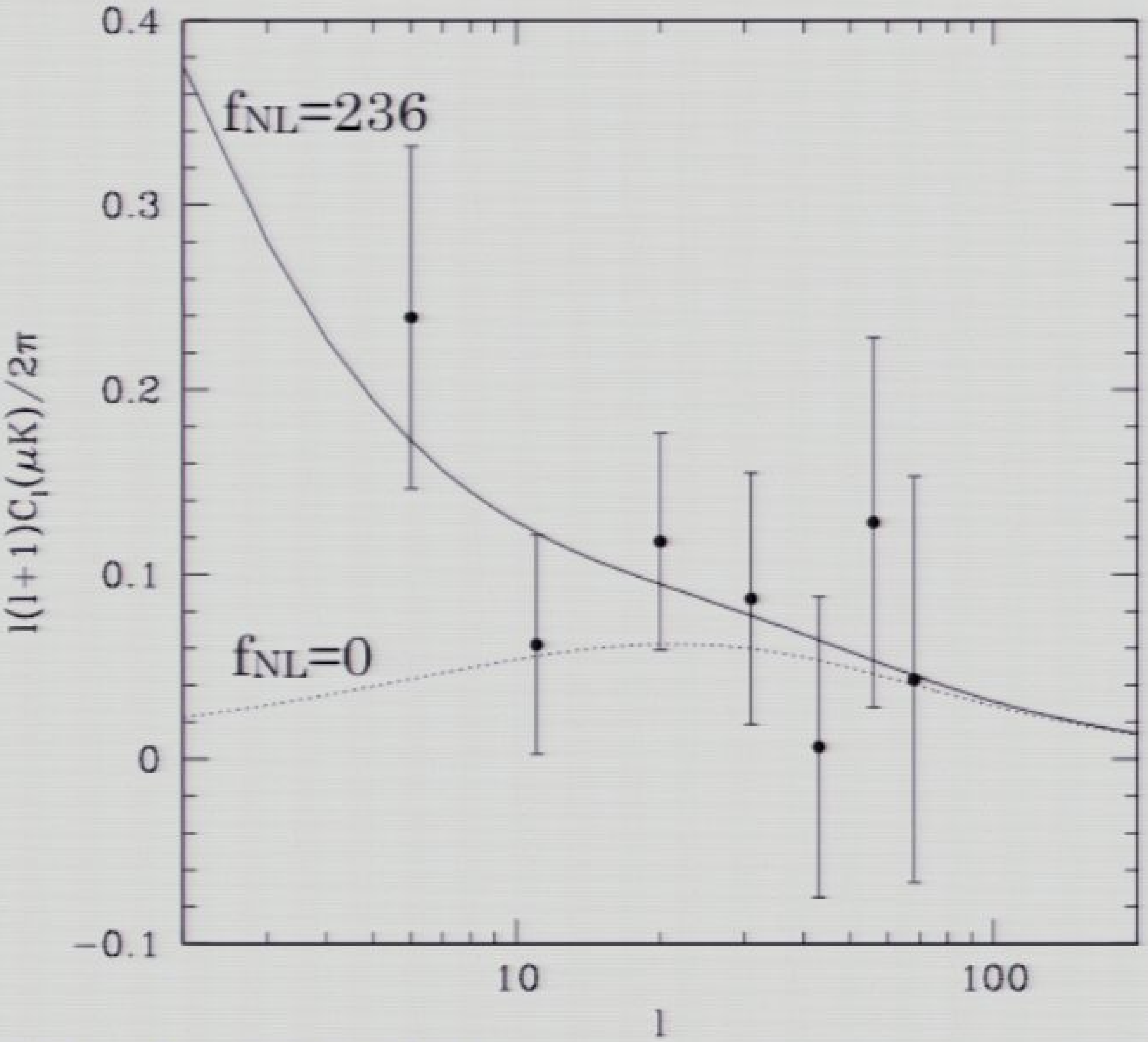
observational constraints on f_{NL}

how to measure this?

* Want large scales (k<0.01) :
  - ➡ large f_{sky}
  - ➡ high z
* possible issues:
  * require photometric calibration across the sky to be very homogeneous.
  * Foregrounds (e.g. Galactic dust extinction) can mimic the signal!

➡ **datasets used for BAO measurements are ideal.**

Constraints from: NVSS radio sources, $z\sim1$



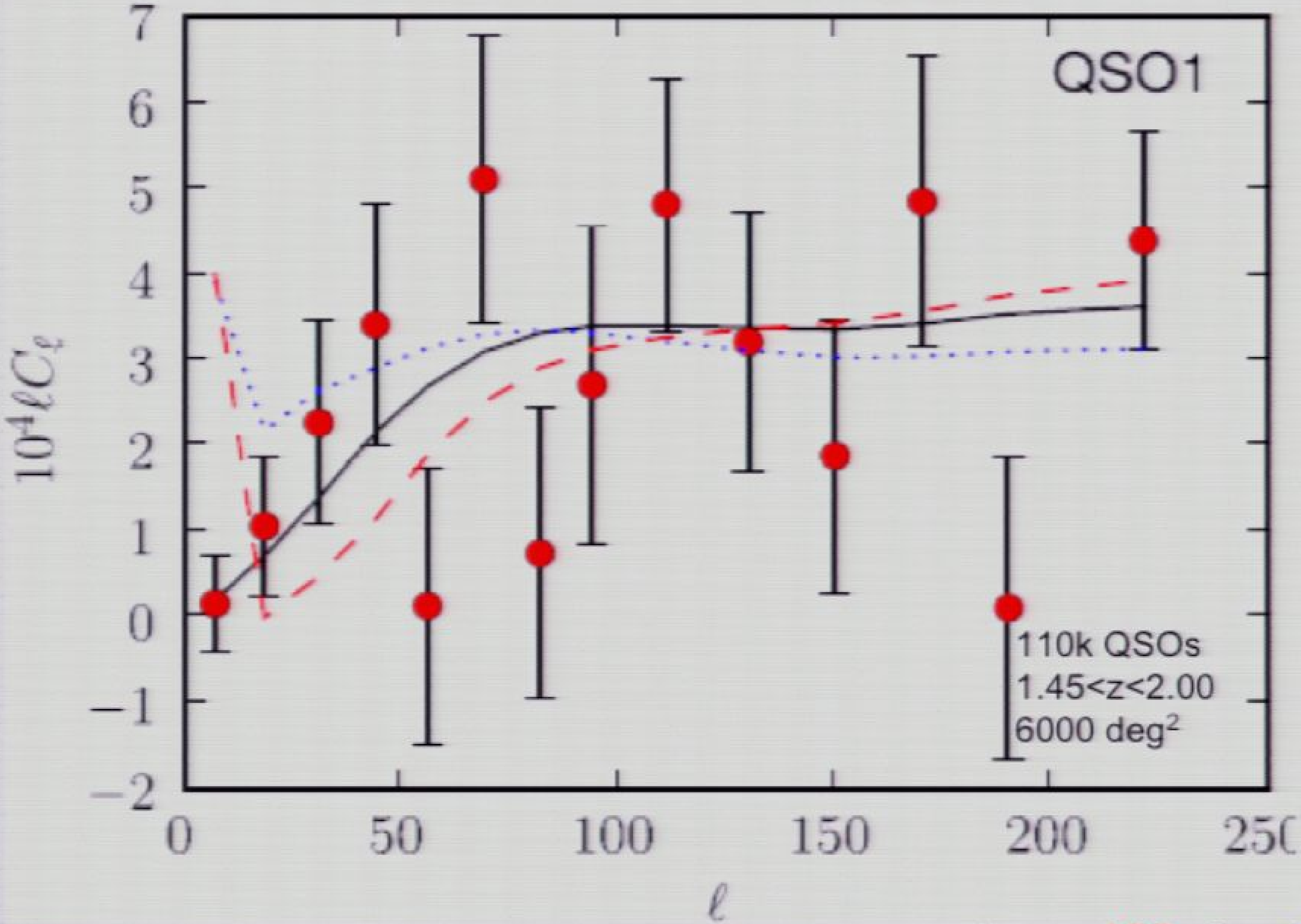
$f_{NL} = 236$ +/- 127 (68%)

Afshordi & Tolley 2008

Application to SDSS

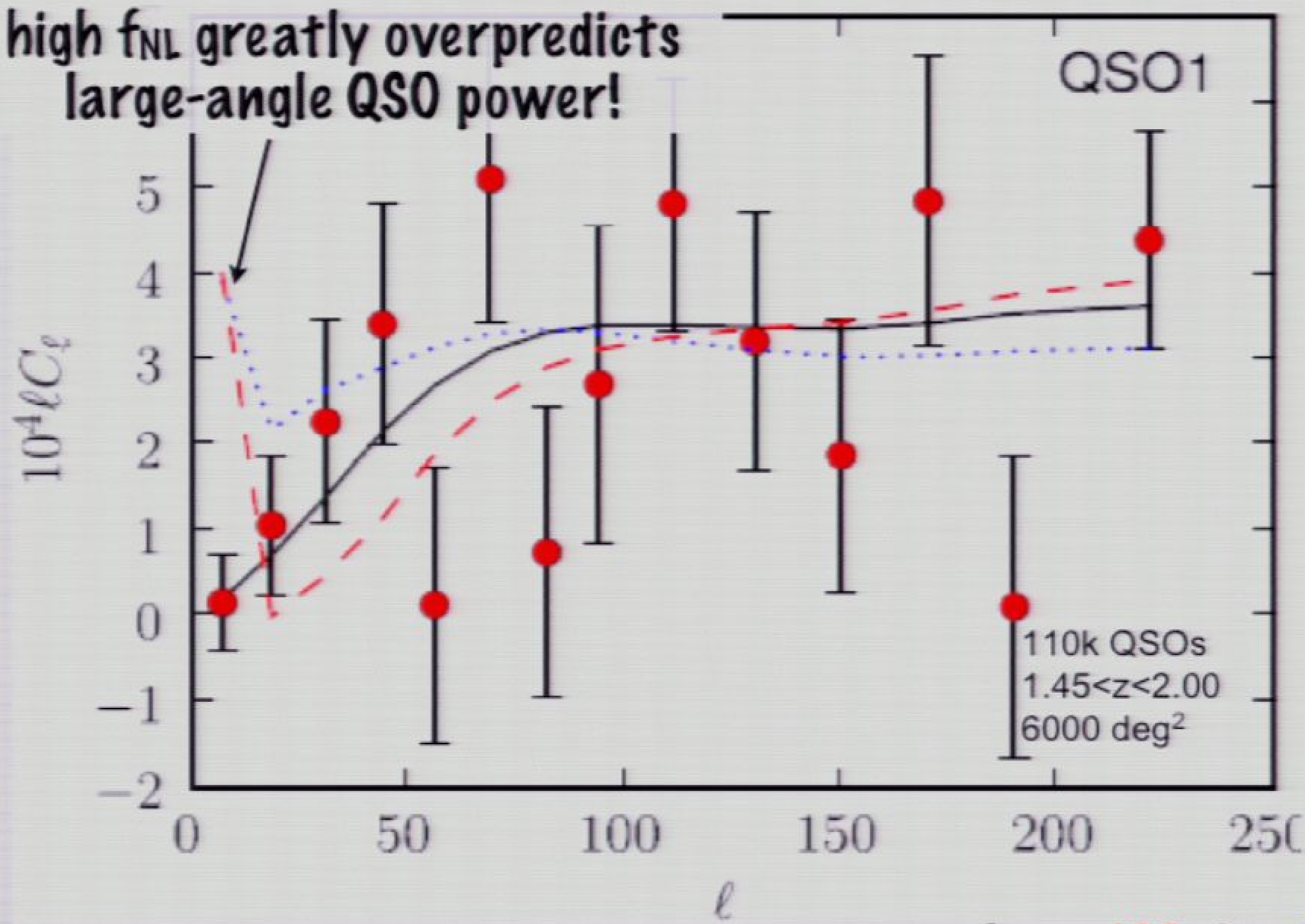
- Samples:
  - Spectro-z LRGs (Tegmark et al 06)
  - Photo-z LRGs (Padmanabhan et al 07)
  - Photo-z quasars (Ho et al 08 ISW sample) – $1.45<z<2.00$ slice (0.65—1.45 excluded due to red star correlation)
  - ISW effect (from Ho et al 08, no constraining power)
- \+ CMB (WMAP5+CBI+ACBAR+VSA), SNLS
  - Fixes underlying matter power spectrum shape
- Search for evidence of excess power on the largest scales in the survey.

courtesy of Chris Hirata



f_{NL} = -100, 0, +100

Slosar et al. (2008)



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Slosar et al. (2008)

current constraints: SDSS

at 95% confidence:

- CMB: $f_{NL} = 51 \pm 60$ (Komatsu et al. 2008)
- LSS: $f_{NL} = 31{+}39{-}60$ (Slosar et al. 2008)
- combined: $f_{NL} = 37{+}33{-}38$
- Overall $\sim 2\sigma$ evidence for $f_{NL}>0$
- what's in the near future... ?

Future NG from measurements of b(k)

- Numerous cosmological probes, such as the baryon acoustic oscillations (BAO) or probes of Integrated Sachs-Wolfe effect (galaxy-CMB cross-corr) can be used to measure b(k)

- The effect (going as k^{-2}) provides a fairly unique signature and a clear target; almost no degeneracy with other cosmological parameters

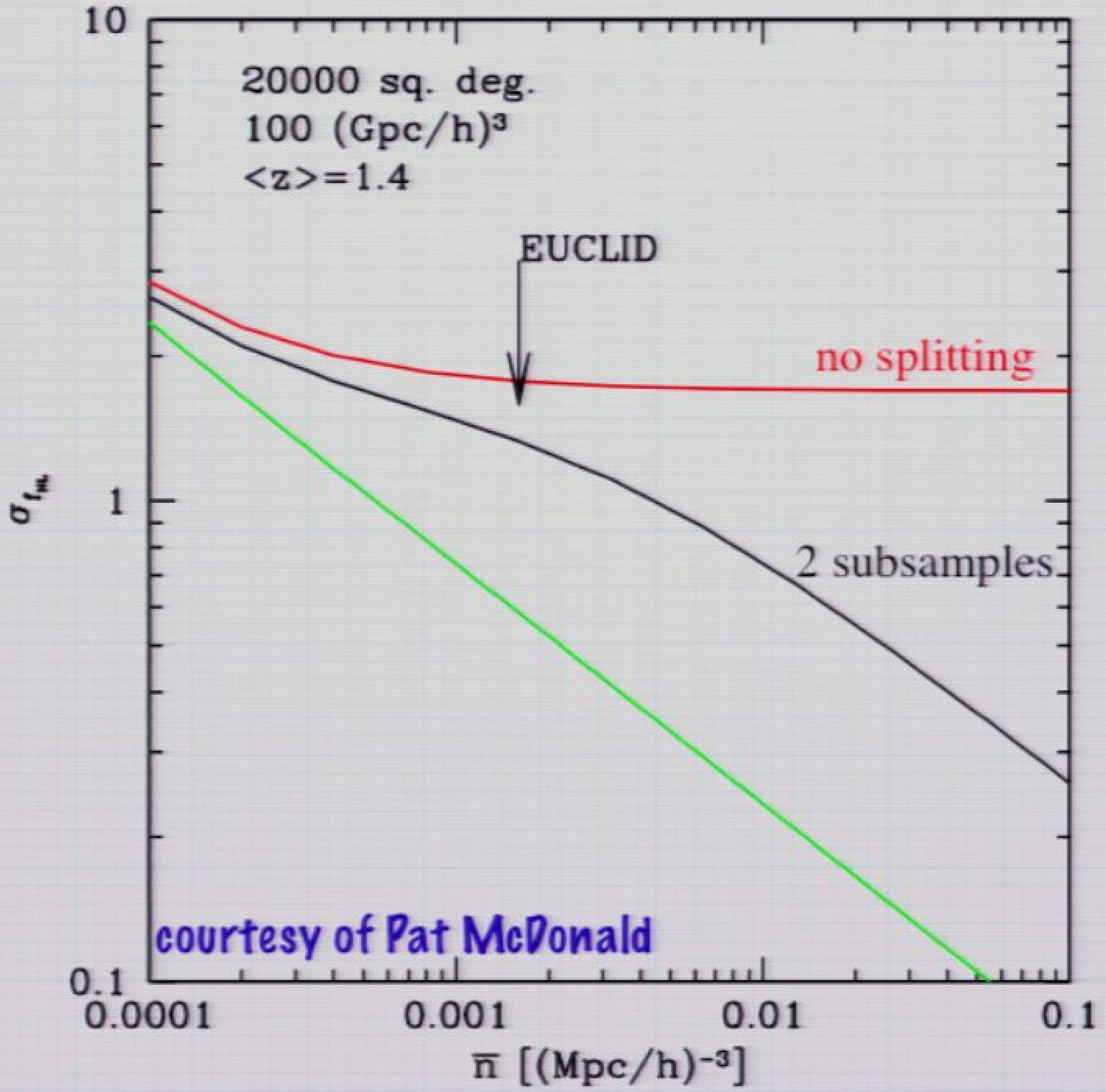
- Expect accuracy of order sigma(f_{NL})<10 or even ~1 in the future

TABLE 1
GALAXY SURVEYS CONSIDERED

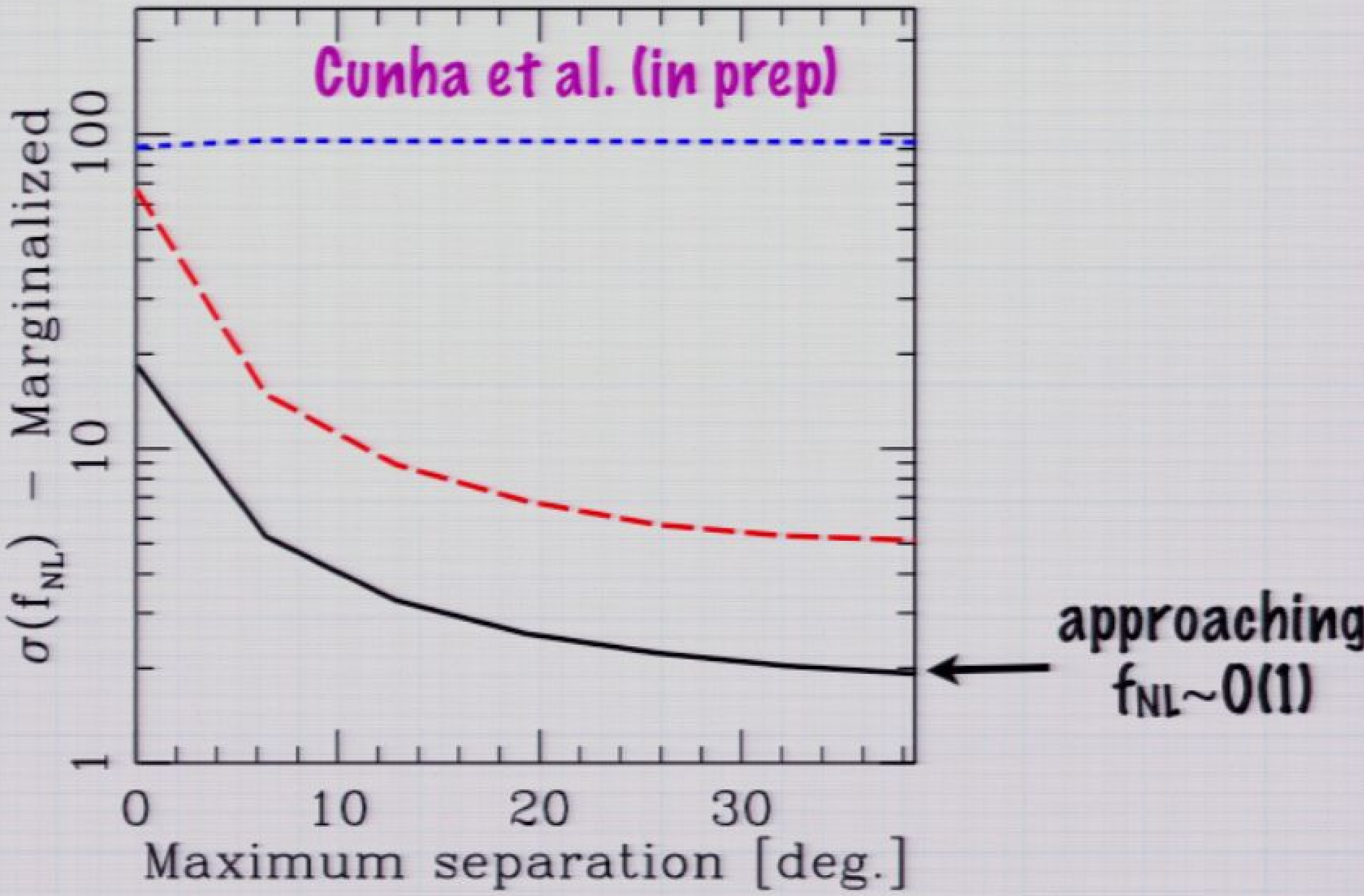
survey	z range	sq deg	mean galaxy density $(h/Mpc)^3$	$\Delta f_{NL}/q'$ LSS
SDSS LRG's	$0.16 < z < 0.47$	7.6×10^3	1.36×10^{-4}	40
BOSS	$0 < z < 0.7$	10^4	2.66×10^{-4}	18
WFMOS low z	$0.5 < z < 1.3$	2×10^3	4.88×10^{-4}	15
WFMOS high z	$2.3 < z < 3.3$	3×10^2	4.55×10^{-4}	17
ADEPT	$1 < z < 2$	2.8×10^4	9.37×10^{-4}	1.5
EUCLID	$0 < z < 2$	2×10^4	1.56×10^{-3}	1.7
DES	$0.2 < z < 1.3$	5×10^3	1.85×10^{-3}	8
PanSTARRS	$0 < z < 1.2$	3×10^4	1.72×10^{-3}	3.5
LSST	$0.3 < z < 3.6$	3×10^4	2.77×10^{-3}	0.7

!

Carbone, Verde & Matarrese 2008; Afshordi & Tolley 2008


20000 sq. deg.
100 (Gpc/h)³
<z>=1.4
EUCLID
no splitting
2 subsamples
courtesy of Pat McDonald
10
1
0.1
0.0001
0.001
0.01
0.1
n̄ [(Mpc/h)⁻³]

Galaxy clusters



the future

* clusters have mass ~1000× larger than galaxies
  ⇒ probe 10× larger scales

* so we can constrain scale-dependence of $f_{NL}(k)$!
  (in progress with S. Shandera)

* Lyman-α Forest (e.g. from BOSS / BigBOSS) also looks promising for this

* forecasts look good enough to rule out / detect many alternatives to inflation (e.g. ekpyrotic)

Summary

- Non-Gaussianity is a **really** sensitive & informative probe of early universe physics
  - complementary to tensors
- we can predict how LSS is modified for nonzero f_{NL} .
  - mass function: bigger f_{NL} means more clusters
  - clustering: f_{NL} causes scale-dependent bias on ultra-large scales
  - and of course halo bispectrum is modified...
- current LSS constraints (Slosar et al.): $f_{NL} = 37+33-38$
- upcoming surveys can get to $|f_{NL}| < 1$!
  improvement in LSS bounds by **2 orders of magnitude!**

stop

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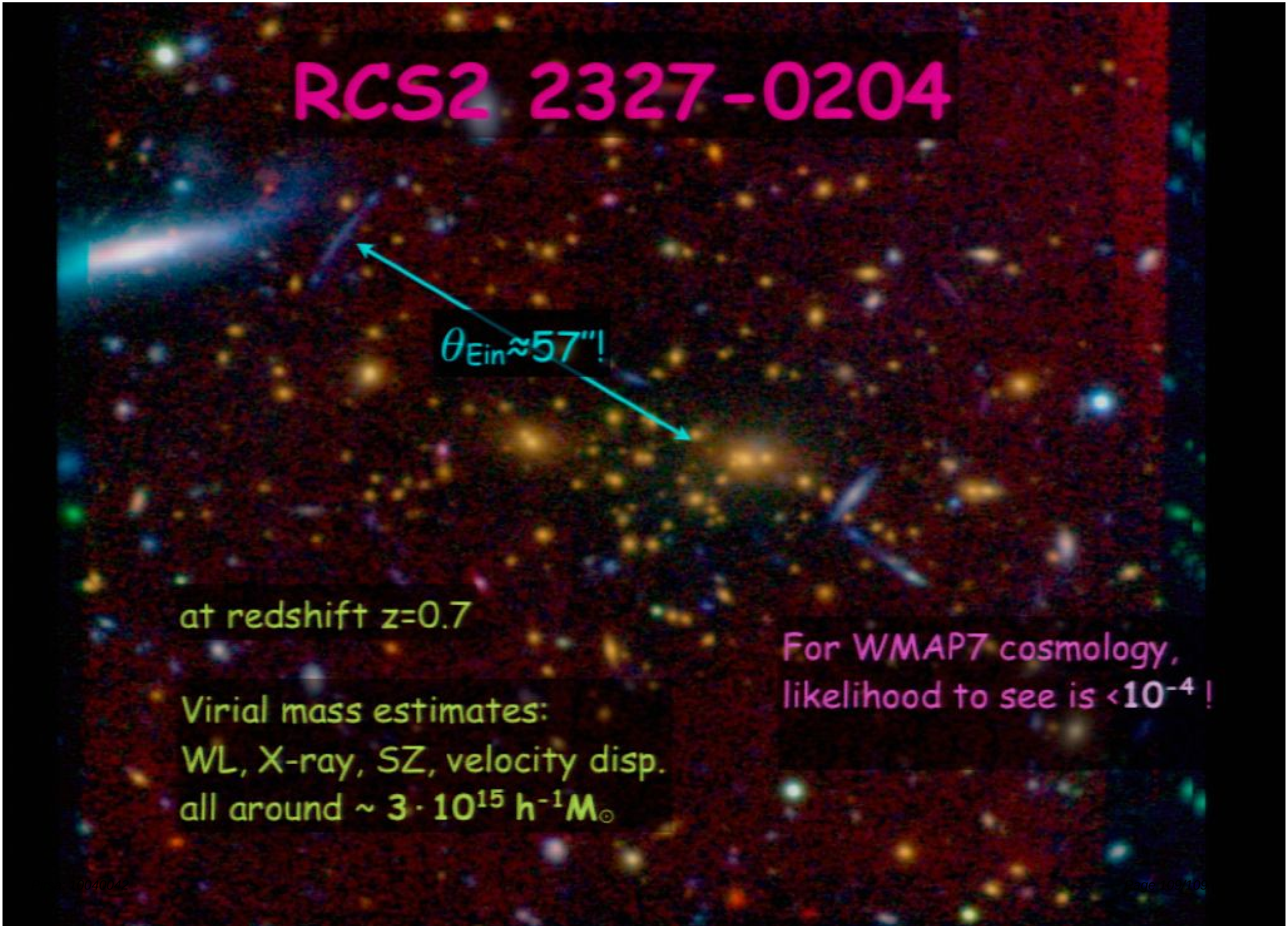
RCS2 2327-0204
$\theta_{Ein} \approx 57''$!
at redshift z=0.7
Virial mass estimates:
WL, X-ray, SZ, velocity disp.
all around ~ $3 \cdot 10^{15}\ h^{-1} M_\odot$
For WMAP7 cosmology,
likelihood to see is $< 10^{-4}$!