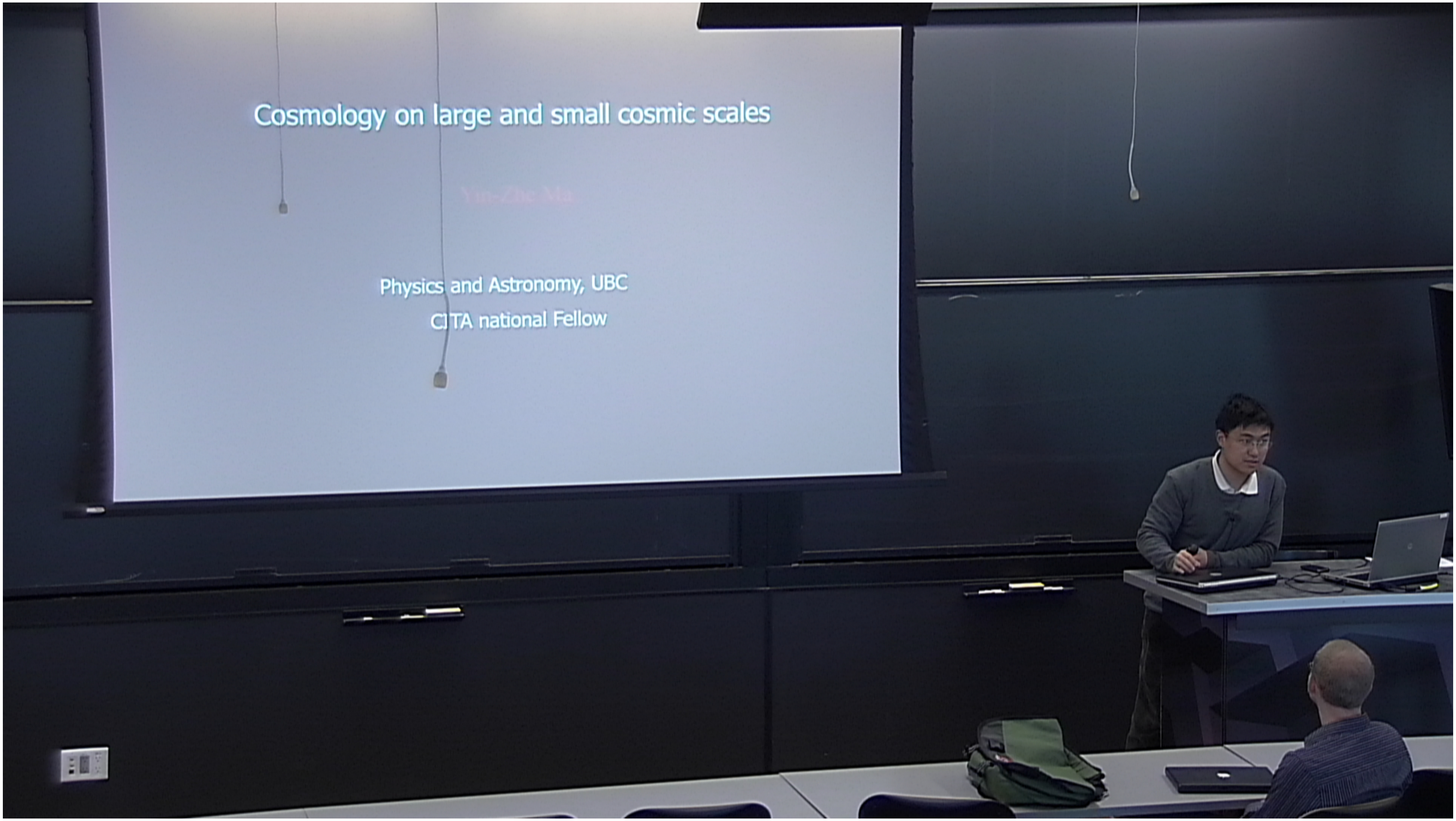
Title: Cosmology on Large and Small Cosmic Scales

Date: Jan 31, 2012 11:00 AM

URL: http://pirsa.org/12010134

Abstract: In this talk, I am going to test the concordance cosmology in three different cosmic scales. (1) On the super-horizon scale, â€œCopi etal. (2009)â€• have been arguing that the lack of large angular correlations of the CMB temperature field provides strong evidence against the standard, statistically isotropic, LCDM cosmology. I am going to argue that the â€œad-hocâ€• discrepancy is due to the sub-optimal estimator of the low-l multipoles, and a posteriori statistics, which exaggerates the statistical significance. (2) LCDM model also predict the existence of primordial gravitational wave, for which B-mode polarization will be a powerful tool to distinguish different models of the early Universe; (3) On Galactic scales, â€œWatkins et al. (2008)â€• shows that the very large bulk flow prefers a very large density fluctuation, which seems to contradict to the LCDM model. We provide a physical explanation for this big bulk flow, based on the assumption that CMB frame does not coincide with matter rest frame, resulting in the tilted Universe. We show that the â€˜tilted Universeâ€™ could well explain the bulk flow phenomena and more importantly, the constraints for this tilted Universe can lead to the constraint on the number of e-folds of inflation; (4) In addition, cosmic Mach Number from peculiar velocity catalog may provide a powerful test of the growth of the structure.


Cosmology on large and small cosmic scales
Physics and Astronomy, UBC
CITA national Fellow

Cosmology on large and small cosmic scales

Yin-Zhe Ma

Physics and Astronomy, UBC

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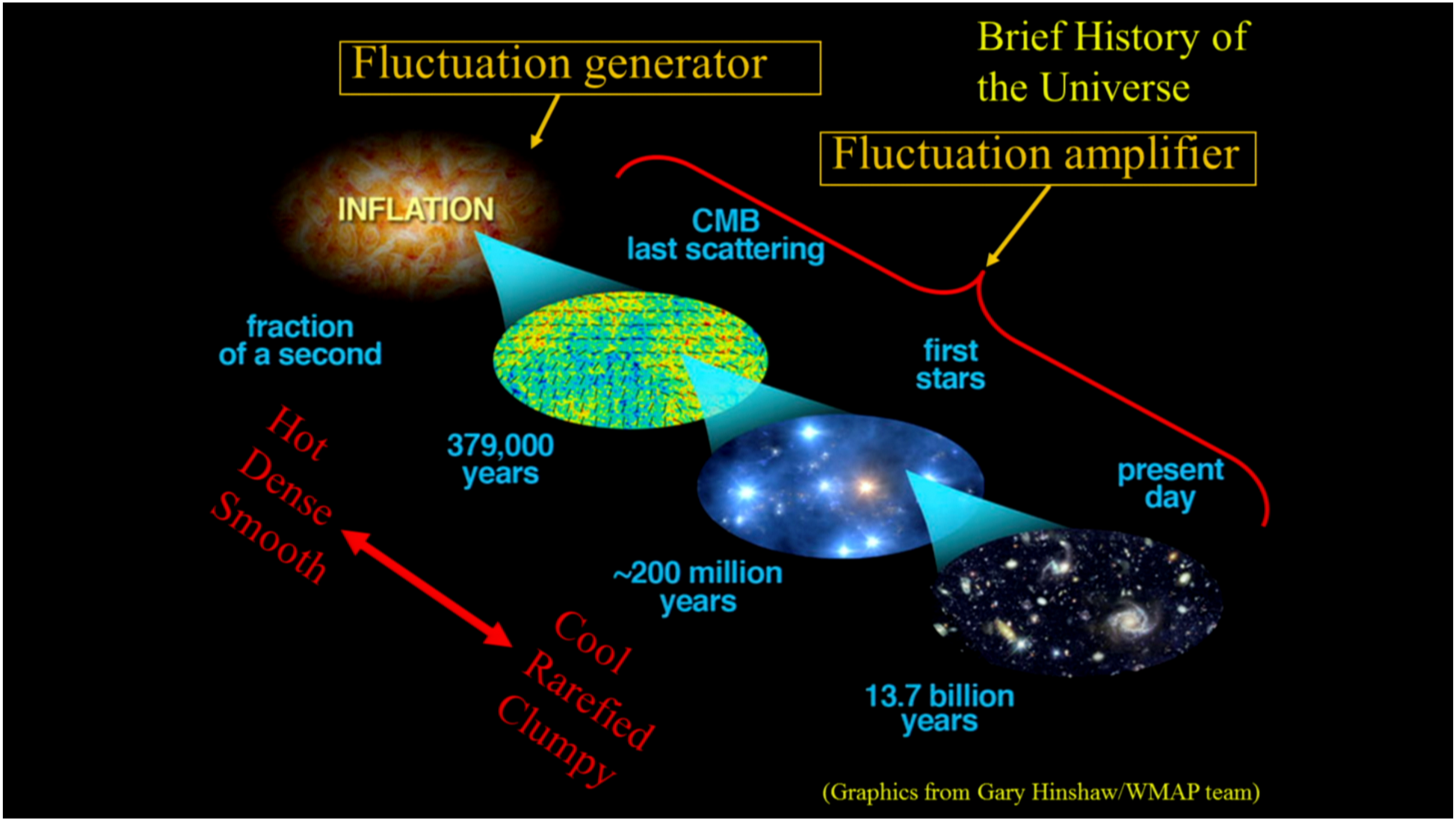
Fluctuation generator
Brief History of the Universe
Fluctuation amplifier
INFLATION
CMB
last scattering
fraction
of a second
first
stars
379,000
years
present
day
~200 million
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13.7 billion
years
Hot
Dense
Smooth
Cool
Rarefied
Clumpy
(Graphics from Gary Hinshaw/WMAP team)

Is the Universe statistical isotropy?

↓

Does the Universe lack large angular correlations?

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↓

Does the Universe lack large angular correlations?

Two Points Correlation Function

$$\Delta T(\theta,\phi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\phi)$$

$Y_{lm}(n)$ are the spherical harmonics

$$\begin{aligned} C(\theta) &= \langle \Delta T(\mathbf{n}) \Delta T(\mathbf{n}+\theta) \rangle_\theta \\ &= \frac{1}{4\pi} \sum_{lm} \sum_{l'm'} \langle a_{lm} a^*_{l'm'} \rangle \, Y_{lm}(\mathbf{n}) Y_{l'm'}(\mathbf{n}+\theta) \\ &= \frac{1}{4\pi} \sum_{l=2}^{l_{\max}} (2l+1) C_l P_l(\cos\theta) \end{aligned}$$

$$C_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$$

Sum to lmax=15 is enough

$$\begin{aligned} S_{1/2} &= \int_{-1}^{1/2} C^2(\theta) d\cos\theta \\ &= \int_{60^0}^{180^0} C^2(\theta) \sin\theta d\theta \end{aligned}$$

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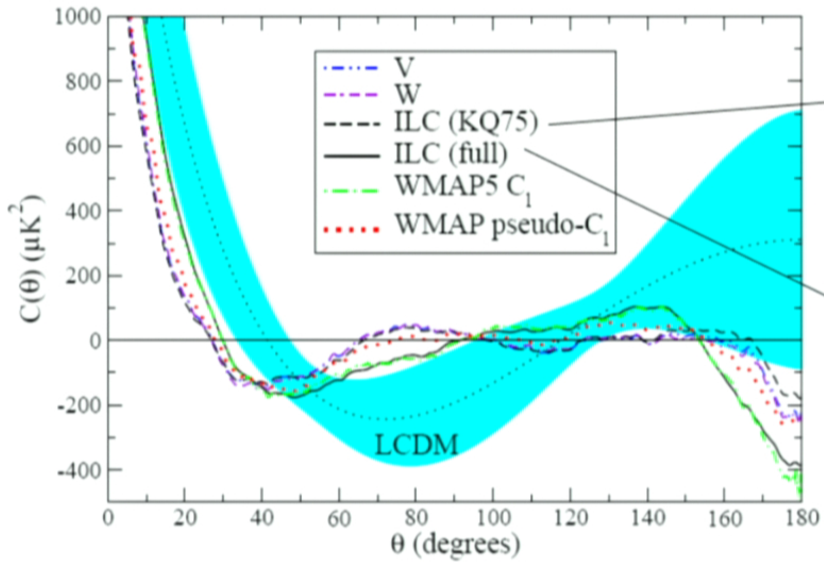
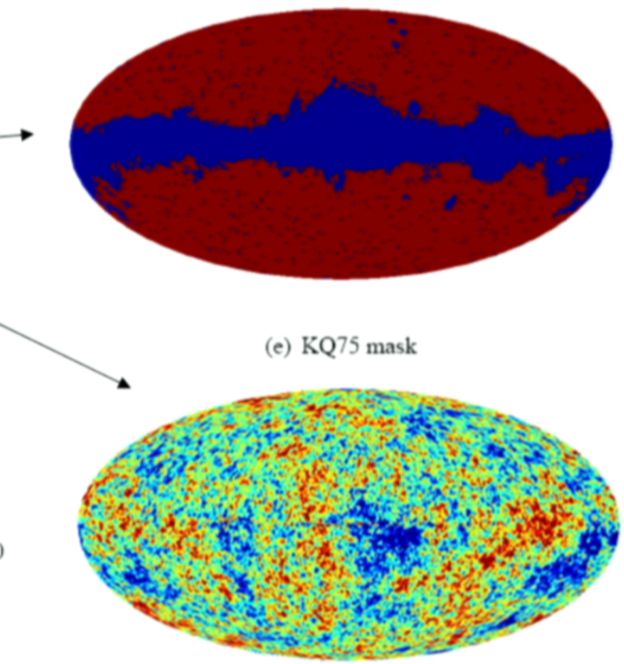
Arguments of lack of large angular correlations



Copi et al. 2009



(e) KQ75 mask

(a) WMAP 5-year ILC map

CHHS08

Data Source	$S_{1/2}$ $(\mu K)^4$	$P(S_{1/2})$ (per cent)	$6\mathcal{C}_2/2\pi$ $(\mu K)^2$	$12\mathcal{C}_3/2\pi$ $(\mu K)^2$	$20\mathcal{C}_4/2\pi$ $(\mu K)^2$	$30\mathcal{C}_5/2\pi$ $(\mu K)^2$
V3 (kp0, DQ)	1288	0.04	77	410	762	1254
W3 (kp0, DQ)	1322	0.04	68	450	771	1302
ILC3 (kp0, DQ)	1026	0.017	128	442	762	1180
ILC3 (kp0), $\mathcal{C}(>60^\circ)=0$	0	—	84	394	875	1135
ILC3 (full, DQ)	8413	4.9	239	1051	756	1588
V5 (KQ75)	1346	0.042	60	339	745	1248
W5 (KQ75)	1330	0.038	47	379	752	1287
V5 (KQ75, DQ)	1304	0.037	77	340	746	1249
W5 (KQ75, DQ)	1284	0.034	59	379	753	1289
ILC5 (KQ75)	1146	0.025	81	320	769	1156
ILC5 (KQ75, DQ)	1152	0.025	95	320	768	1158
ILC5 (full, DQ)	8583	5.1	253	1052	730	1590
WMAP3 pseudo-C_ℓ	2093	0.18	120	602	701	1346
WMAP3 MLE C_ℓ	8334	4.2	211	1041	731	1521
Theory3 C_ℓ	52857	43	1250	1143	1051	981
WMAP5 C_ℓ	8833	4.6	213	1039	674	1527
Theory5 C_ℓ	49096	41	1207	1114	1031	968

Copi et al. 2009

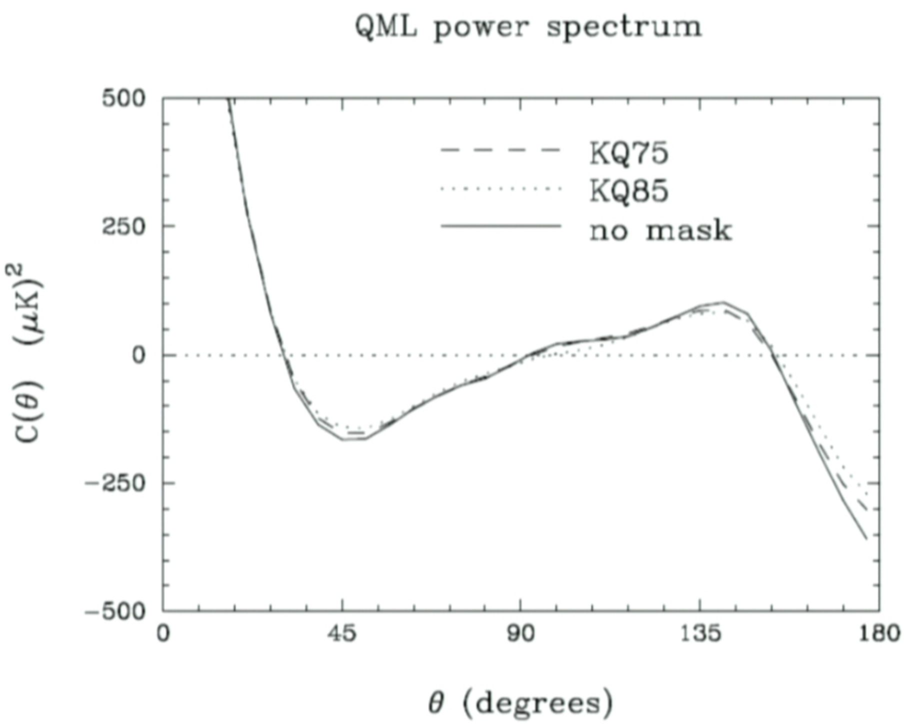
Thus the full-sky results seem inconsistent with cut-sky results and they appear inconsistent in a manner that implies that *most of the large-angle correlations in reconstructed sky maps are inside the part of the sky that is contaminated by the Galaxy.*

- The reason of the low probability value:

  Direct Pixel Estimator of Angular Correlation Function on a cut sky

  + a posteriori choice of the $S_{1/2}$ statistic.

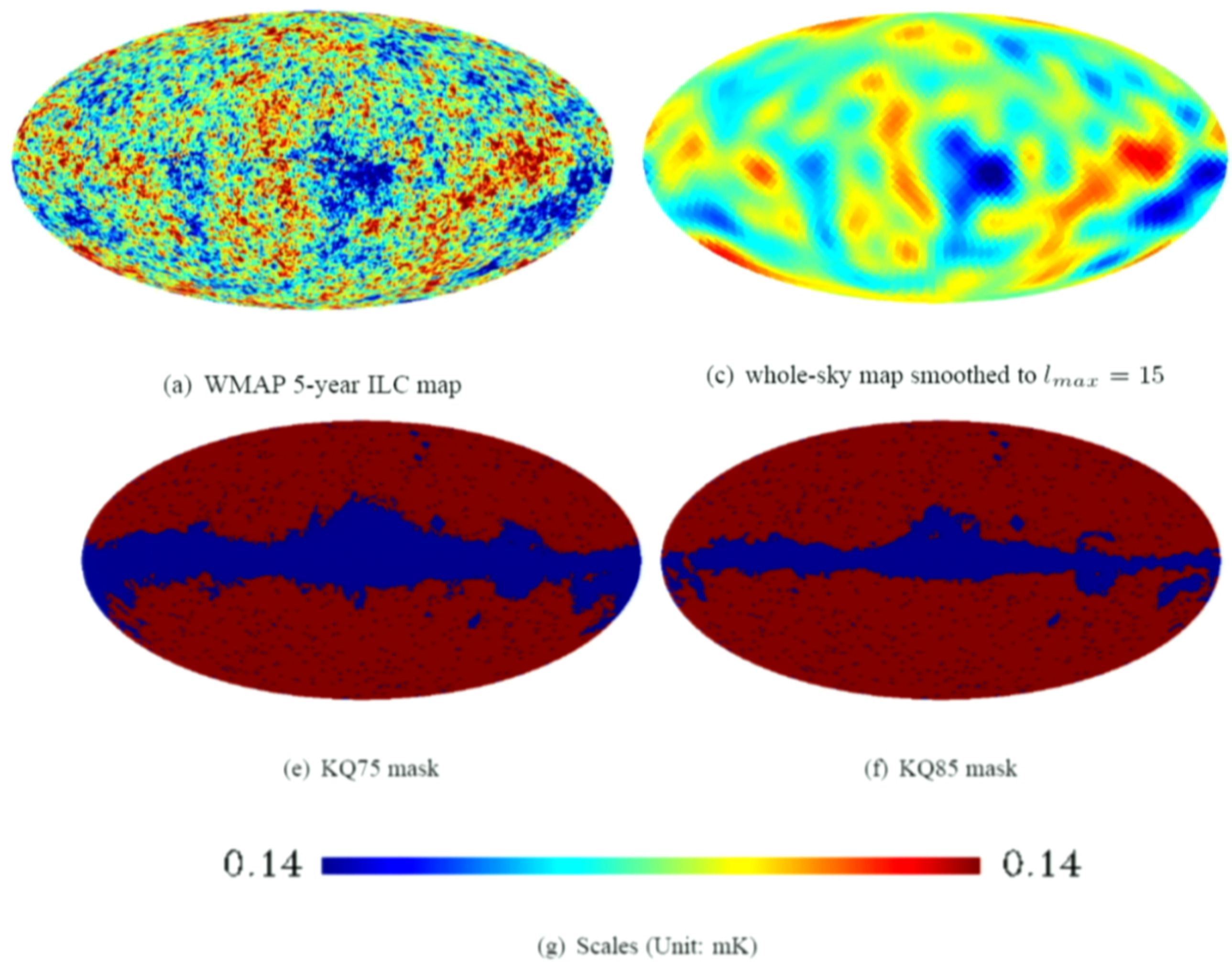
G. Efstathiou, YZM and D. Hanson, MNRAS 407(2010)2530



$l_{max}=32$

EMH09

The Quadratic Maximum Likelihood estimator effectively performs the reconstruction for a_{lm}, but uses the assumption of statistical isotropy to downweight 'ambiguous' modes that are poorly constrained by the sky cut.


(a) WMAP 5-year ILC map
(c) whole-sky map smoothed to $l_{max} = 15$
(e) KQ75 mask
(f) KQ85 mask
0.14
0.14
(g) Scales (Unit: mK)

Isocurvature perturbation (not adiabatic) can provide intrinsic dipole modulation on the sky:

M. Turner 1991:

$$\frac{u}{c} \simeq \frac{H_0^{-1}}{L}\frac{\delta\varphi}{\varphi_0}$$

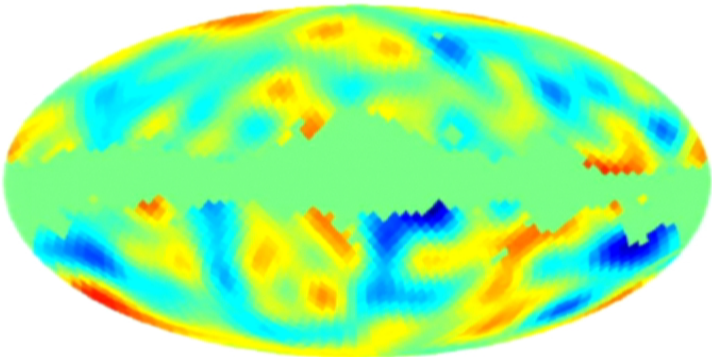
$$u/c \simeq H_0^{-1}/L \simeq e^{-\Delta N}$$

↓

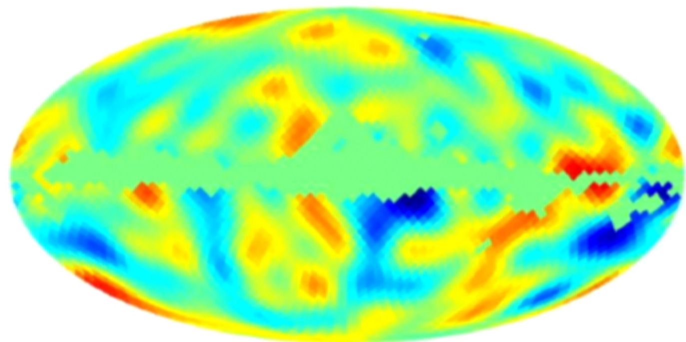
Primordial isocurvature fluctuation

$$l = H_i^{-1} \xrightarrow{\text{inflation}} L = e^{\Delta N} H_0^{-1}$$

$$\Delta N = N - N_{\text{min}}$$

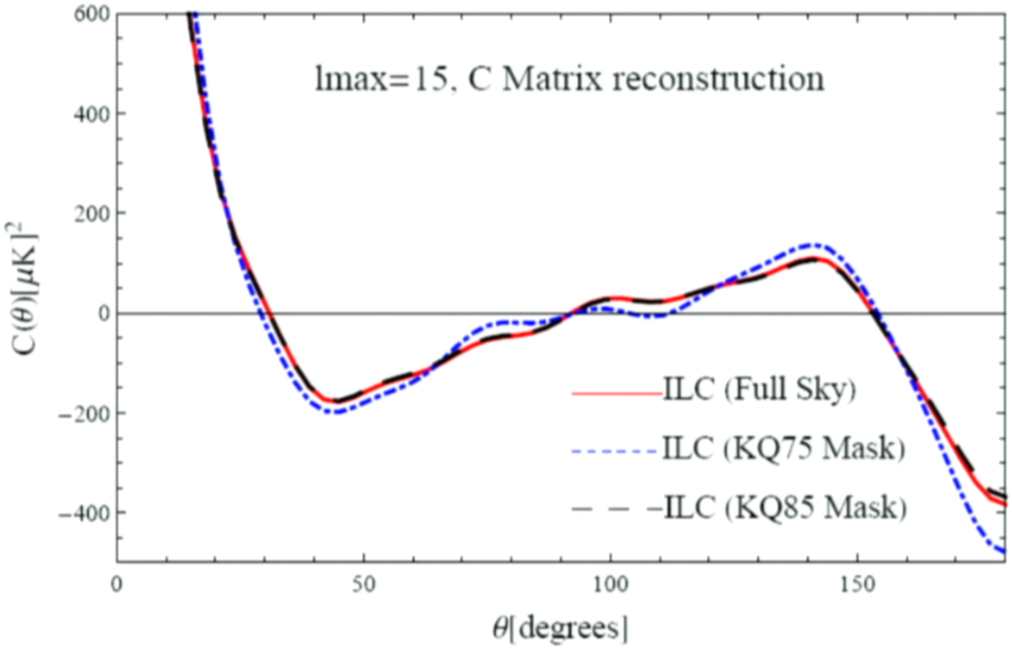


(c) Smoothed map $l_{max} = 15$ masked by KQ75

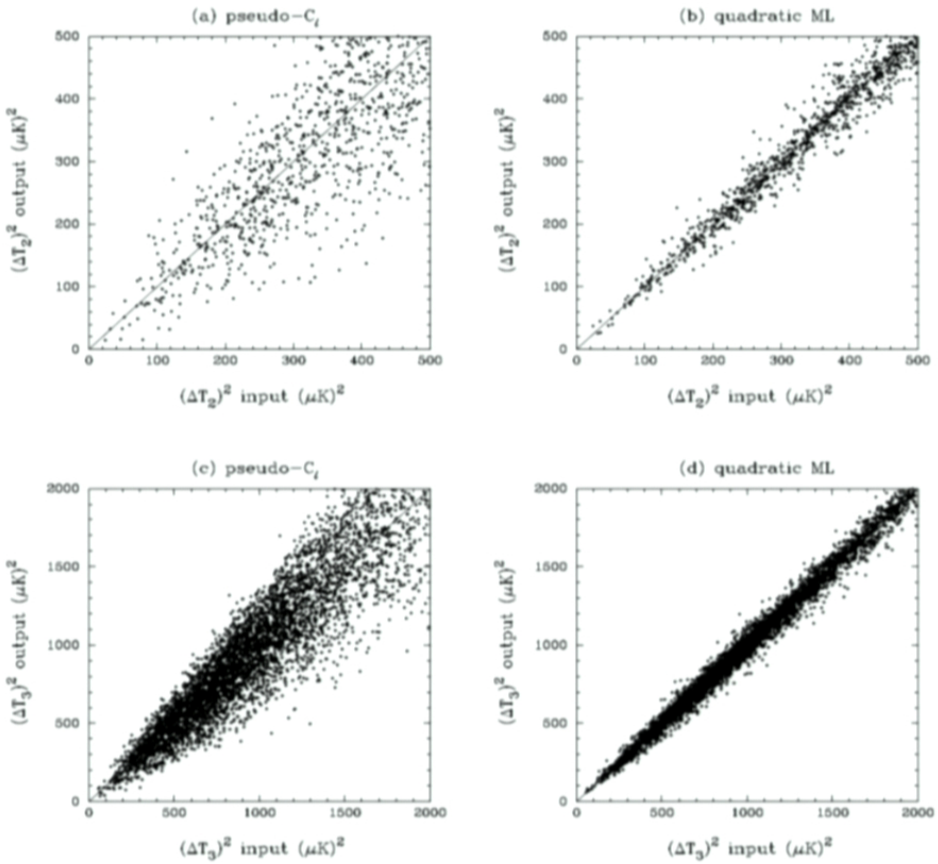


(d) Smoothed map $l_{max} = 15$ masked by KQ85

Results for $C(\theta)$

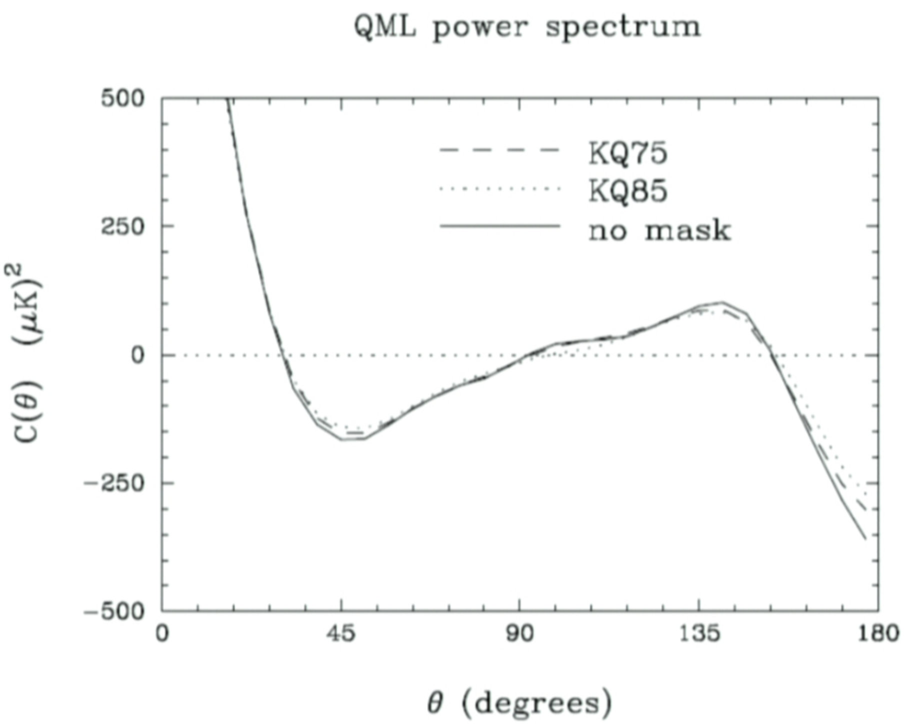


Compare different estimators



Efstathiou 2003.

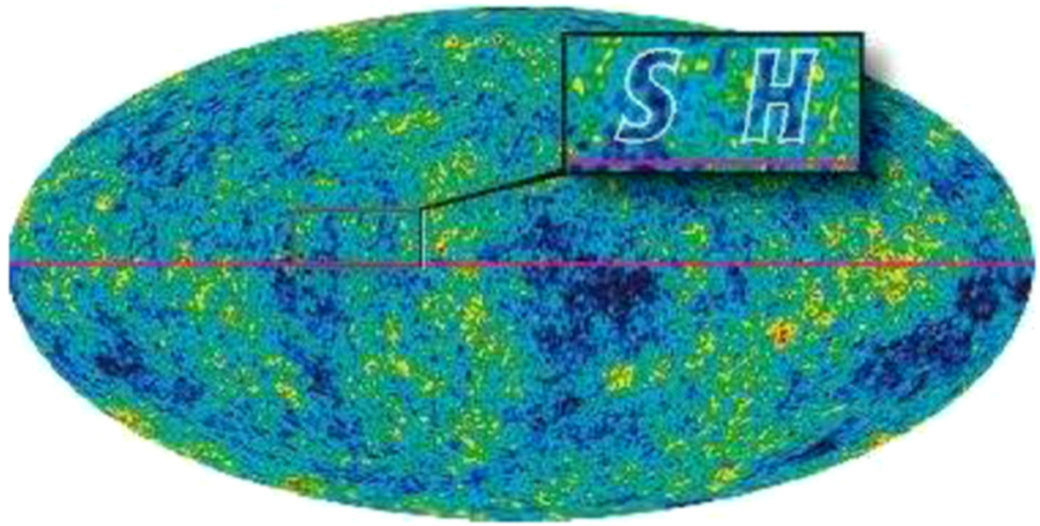
EMH09



$l_{max}=32$

The Quadratic Maximum Likelihood estimator effectively performs the reconstruction for a_{lm} , but uses the assumption of statistical isotropy to downweight 'ambiguous' modes that are poorly constrained by the sky cut.

What is the probability of this "SH" initial occurrence?

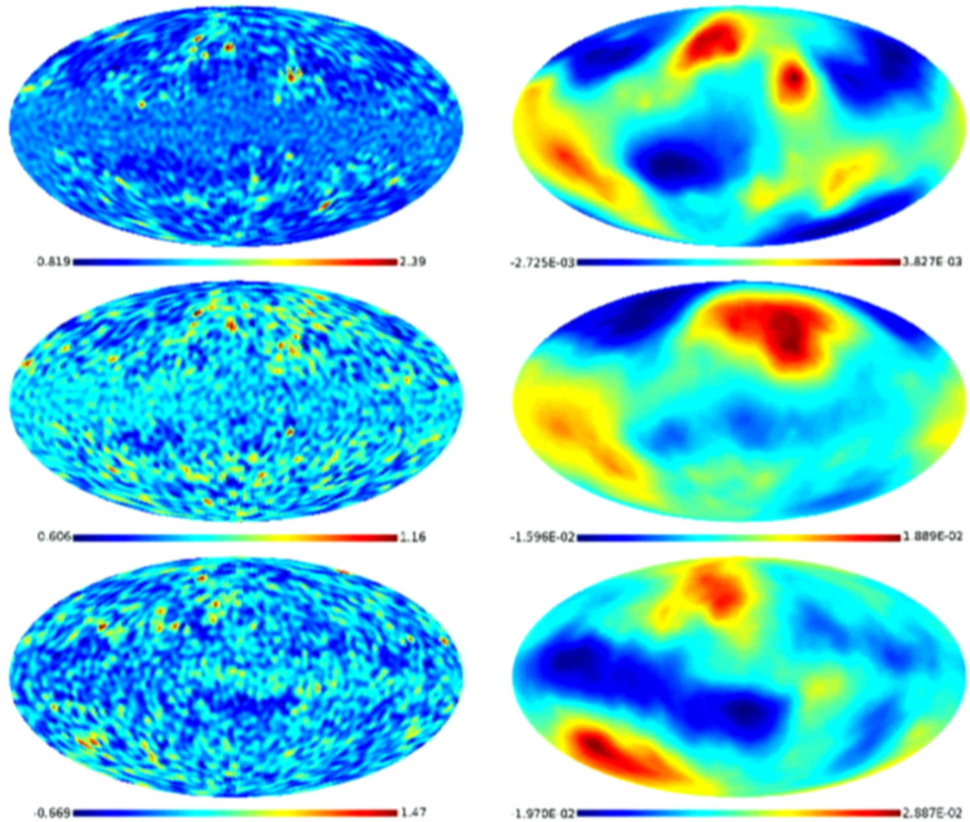


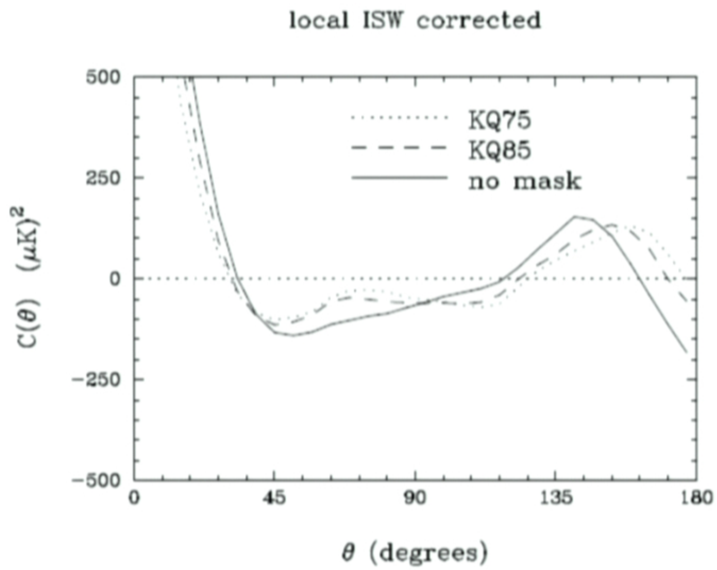
Bennett, WAMP7

Many CMB analysts ask: what is the oddities can I find in the data given the LCDM model.

However, most sensible question is: given this data, what is the probability of the LCDM model?

$$\frac{\Delta T^{\mathrm{ISW}}}{T_{\mathrm{CMB}}} = 2\int_{t_{\mathrm{LS}}}^{t_0} \frac{\dot{\Phi}(\vec{x}(t),t)}{c^2}\,\mathrm{d}t,$$





Francis and Peacock

0909.2495

$S_{1/2}$ statistic :

$$10360\ (\mu K)^4\ \text{(all-sky)}.$$
$$6463\ (\mu K)^4\ \text{(KQ85 mask)}$$
$$5257\ (\mu K)^4\ \text{(KQ75 mask)}.$$

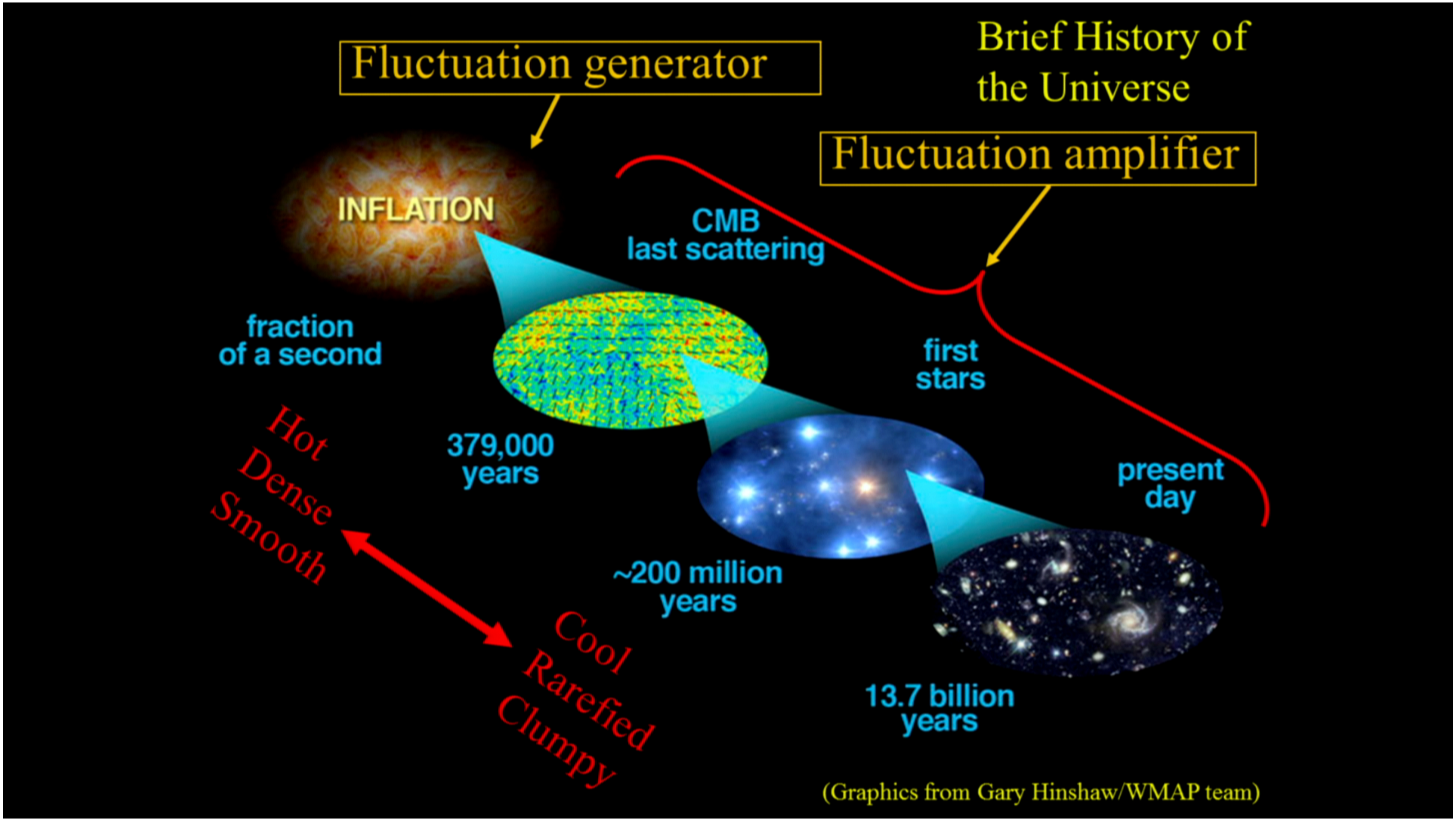
All consistent with the concordance LCDM model at the few percent level.

1. Argue that there is a physical alignment of local structure with potential fluctuation at LSS that conspires to remove large scale correlations outside the Galactic mask. (implausible)
2. A posteriori statistics

G. Efstathiou, YZM and D. Hanson, MNRAS 407(2010)2530

Efstathiou et al. (2009) corrected the full-sky *WMAP* ILC map for the estimated Integrated Sachs-Wolfe (ISW) signal from redshift $z < 0.3$ as estimated by Francis & Peacock (2009). The result was a substantial increase in the $S_{1/2}$. Yet there is no large-scale cosmological significance to the orientation of the sky cut or the orientation of the local distribution of matter with respect to us, thus the result from Spergel et al. and Copi et al. must be a coincidence.

C Bennett et al. 2010 (WMAP7)


Brief History of the Universe
Fluctuation generator
Fluctuation amplifier
INFLATION
CMB last scattering
fraction of a second
first stars
379,000 years
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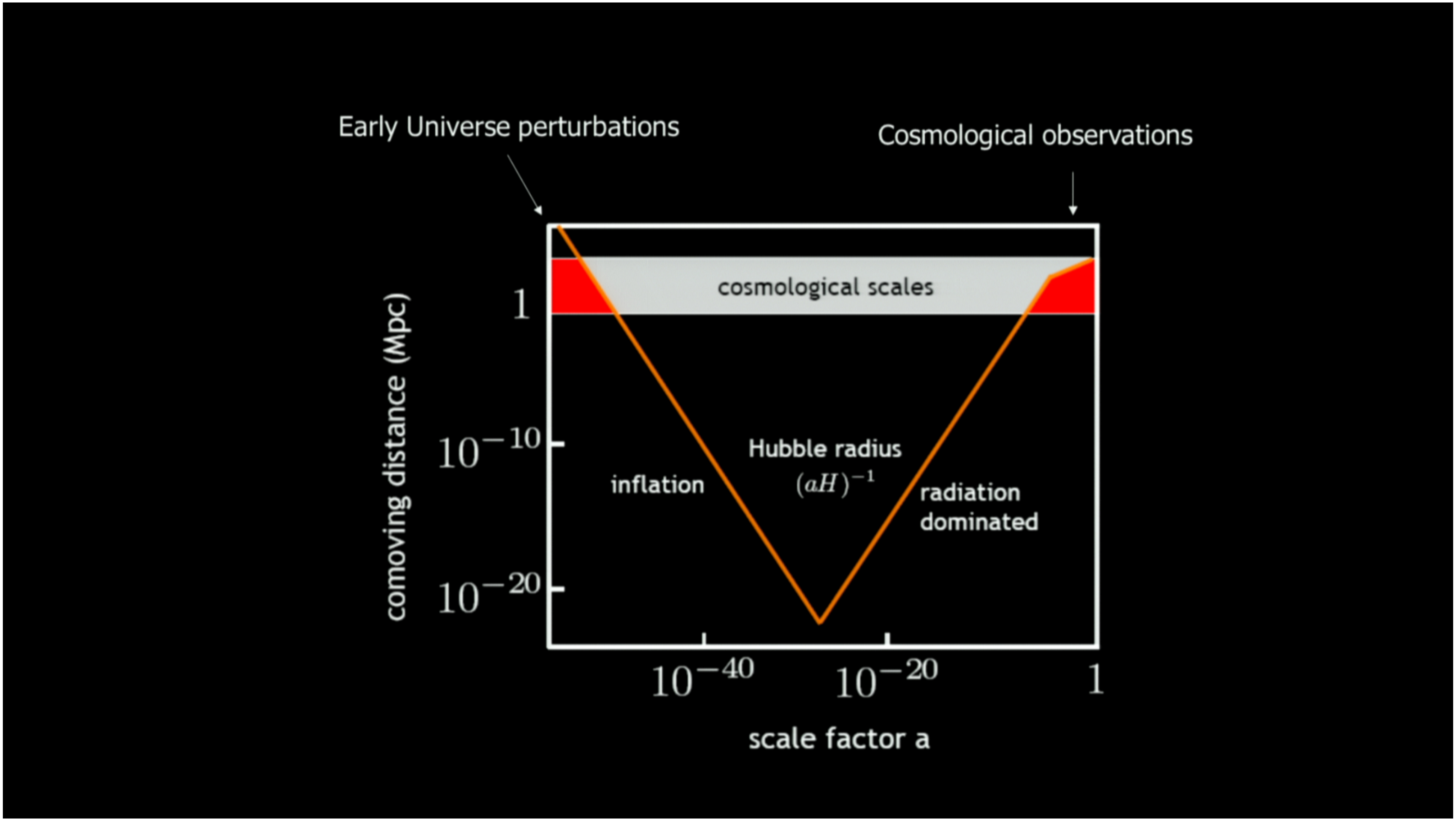
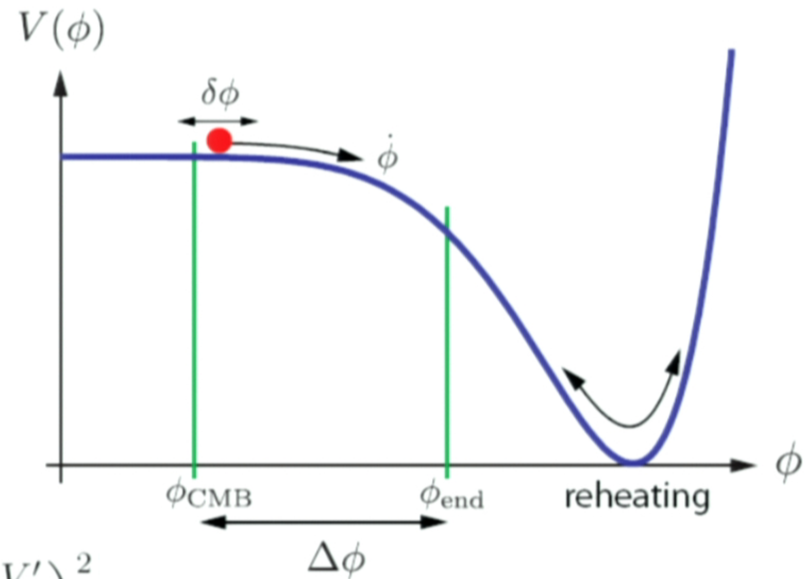


Early Universe perturbations
Cosmological observations
cosmological scales
1
10^{-10}
10^{-20}
comoving distance (Mpc)
inflation
Hubble radius
$(aH)^{-1}$
radiation
dominated
10^{-40}
10^{-20}
1
scale factor a



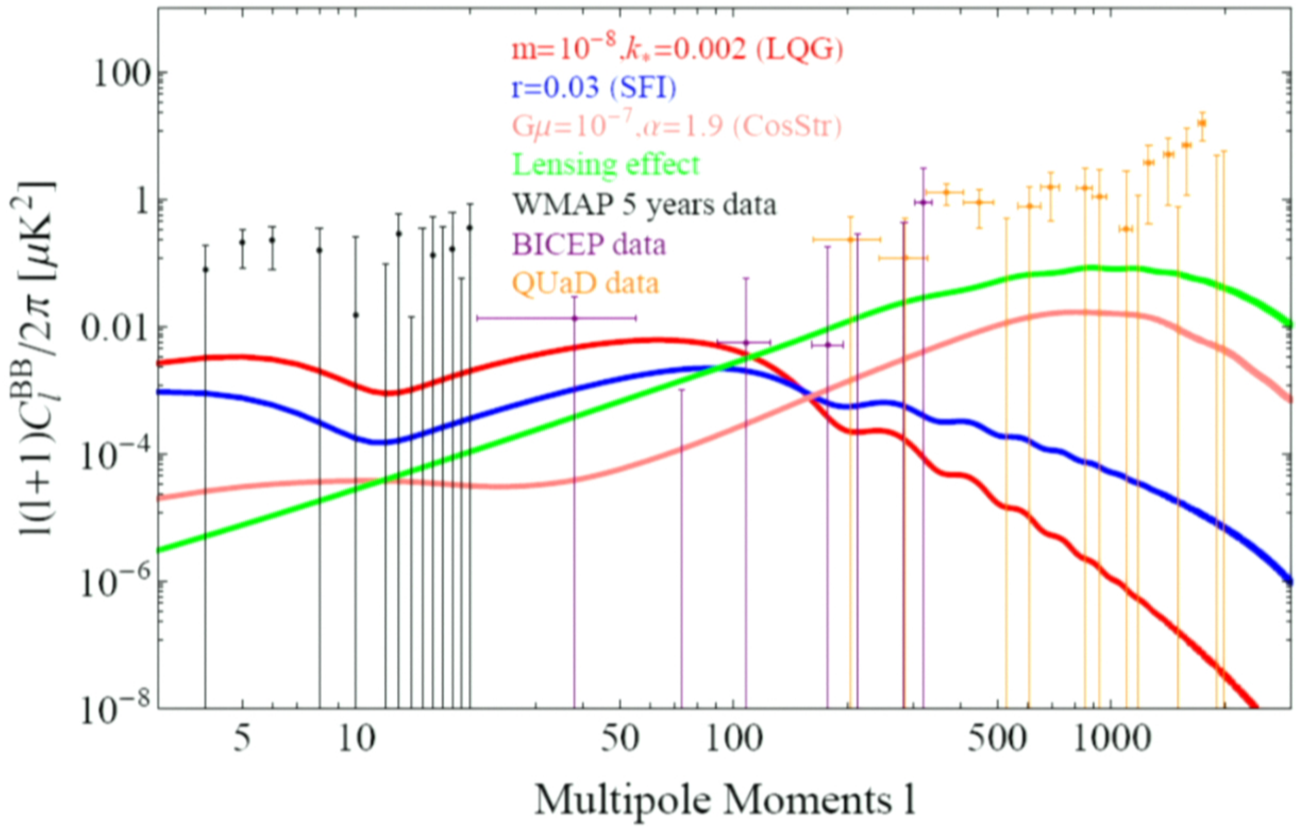
$$r \equiv \frac{P_t}{P_s} = 8 M_{\rm pl}^2 \left(\frac{V'}{V}\right)^2$$

Lyth bound: $$\frac{\Delta\phi}{M_{\rm pl}} \gtrsim \left(\frac{r}{0.01}\right)^{\frac{1}{2}} \qquad V^{\frac{1}{4}} = 1.06 \times 10^{16} \mathrm{GeV} \left(\frac{r}{0.01}\right)^{\frac{1}{4}}$$

Braneworlds…

$$C_l^{BB} = C_l^{BB,0}\left(\frac{G\mu}{G\mu_0}\right)^2$$

Models and current data:



YZM, W. Zhao and M. L. Brown, JCAP 10(2010)007

Summary of constraints:

SFI model:
- BICEP+QUaD, BB Only: $r = 0.02^{+0.31}_{-0.26}$ (1σ CL)
- WMAP7+BAO+H0: $r \leq 0.24$ (2σ)

Cosmic String:
- BICEP+QUaD, BB Only: $G\mu < 8.01 \times 10^{-7}$ (2σ CL)
- WMAP5+ACBAR+BOOMERGANG +CBI+QUaD+BIMA+SDSS+BBN: $G\mu < 2.2 \times 10^{-7}$ (2σ)

↑

Battye and Moss, 1005.0479

Future data will improve the constraints.

YZM, W. Zhao and M. L. Brown, JCAP 10(2010)007

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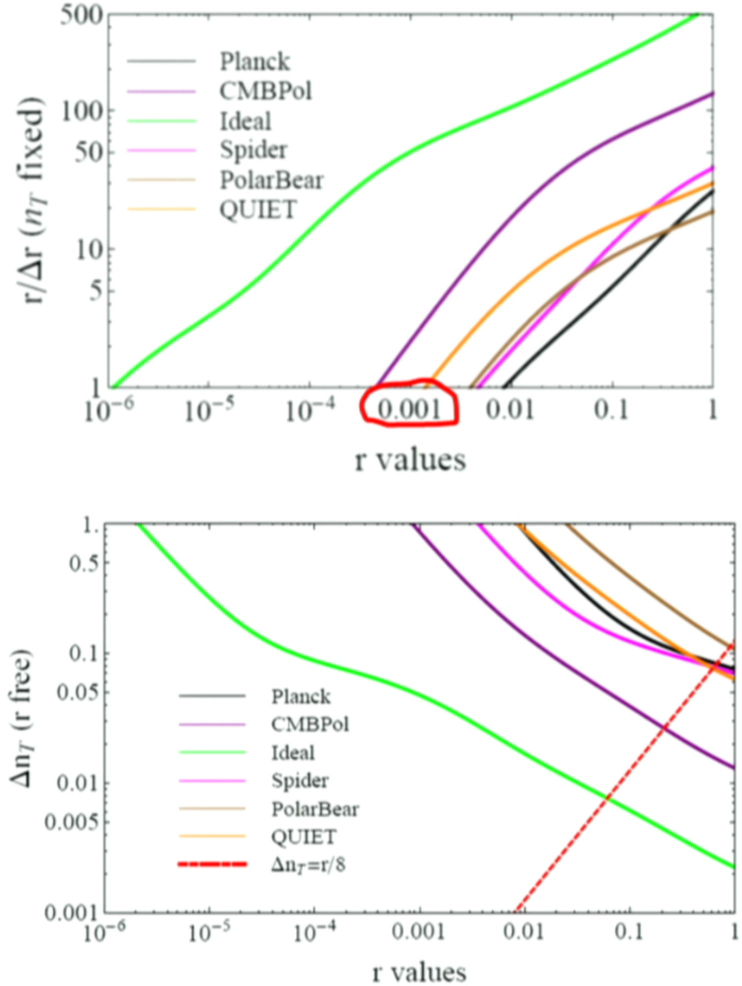
Results: Forecast for future experiments



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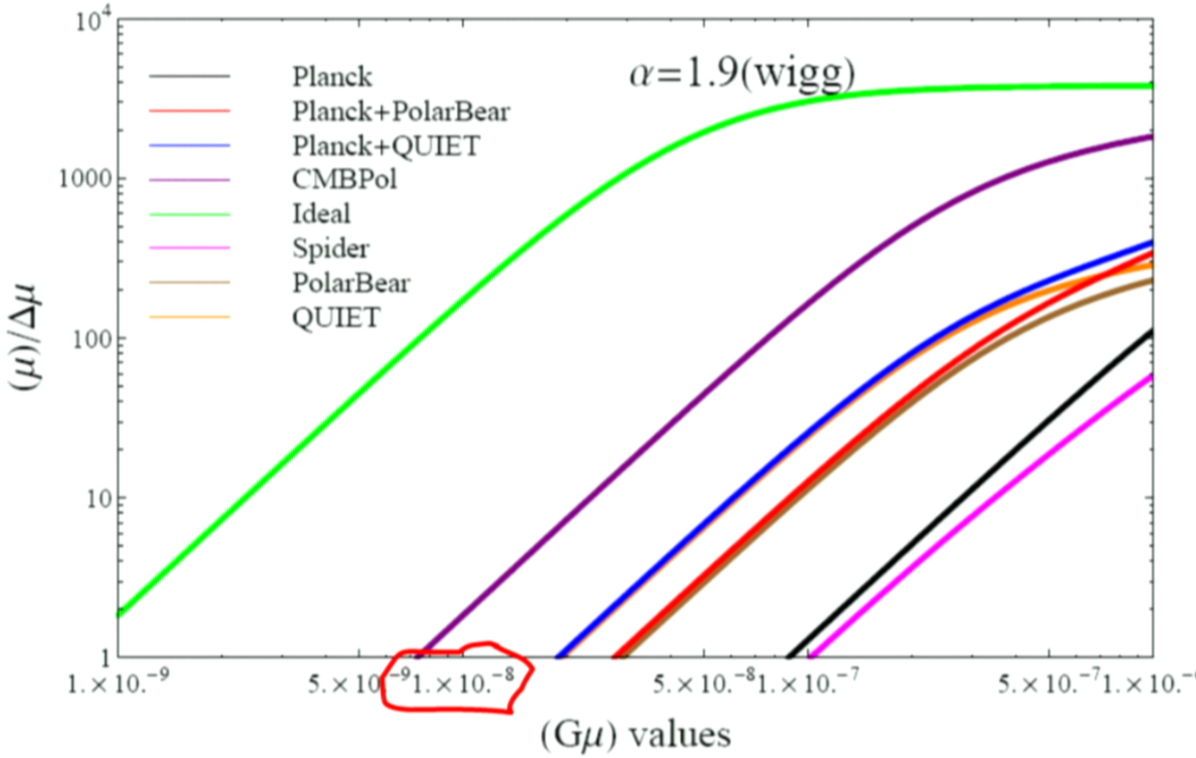
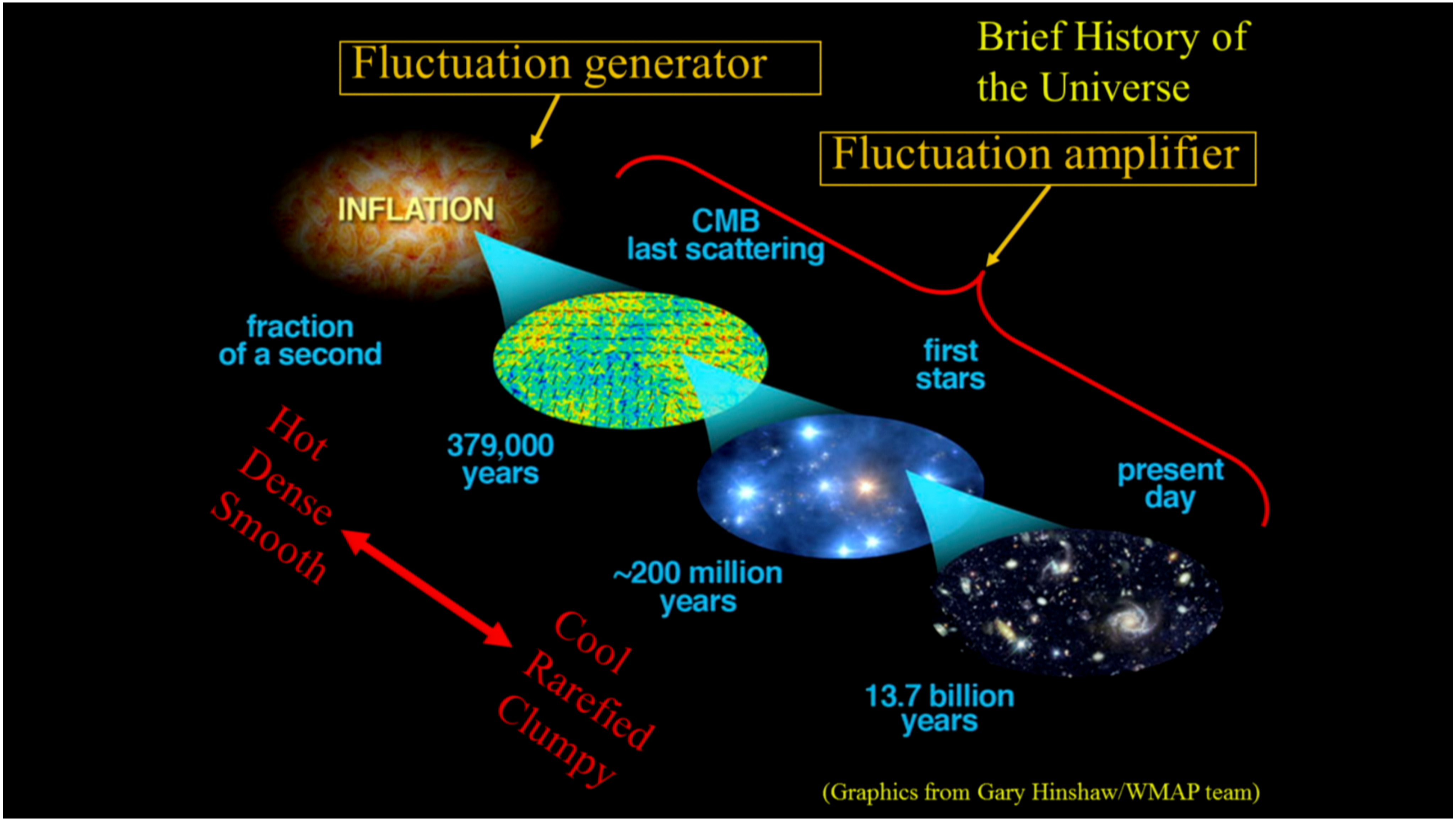


YZM, W. Zhao and M. L. Brown, JCAP 10(2010)007



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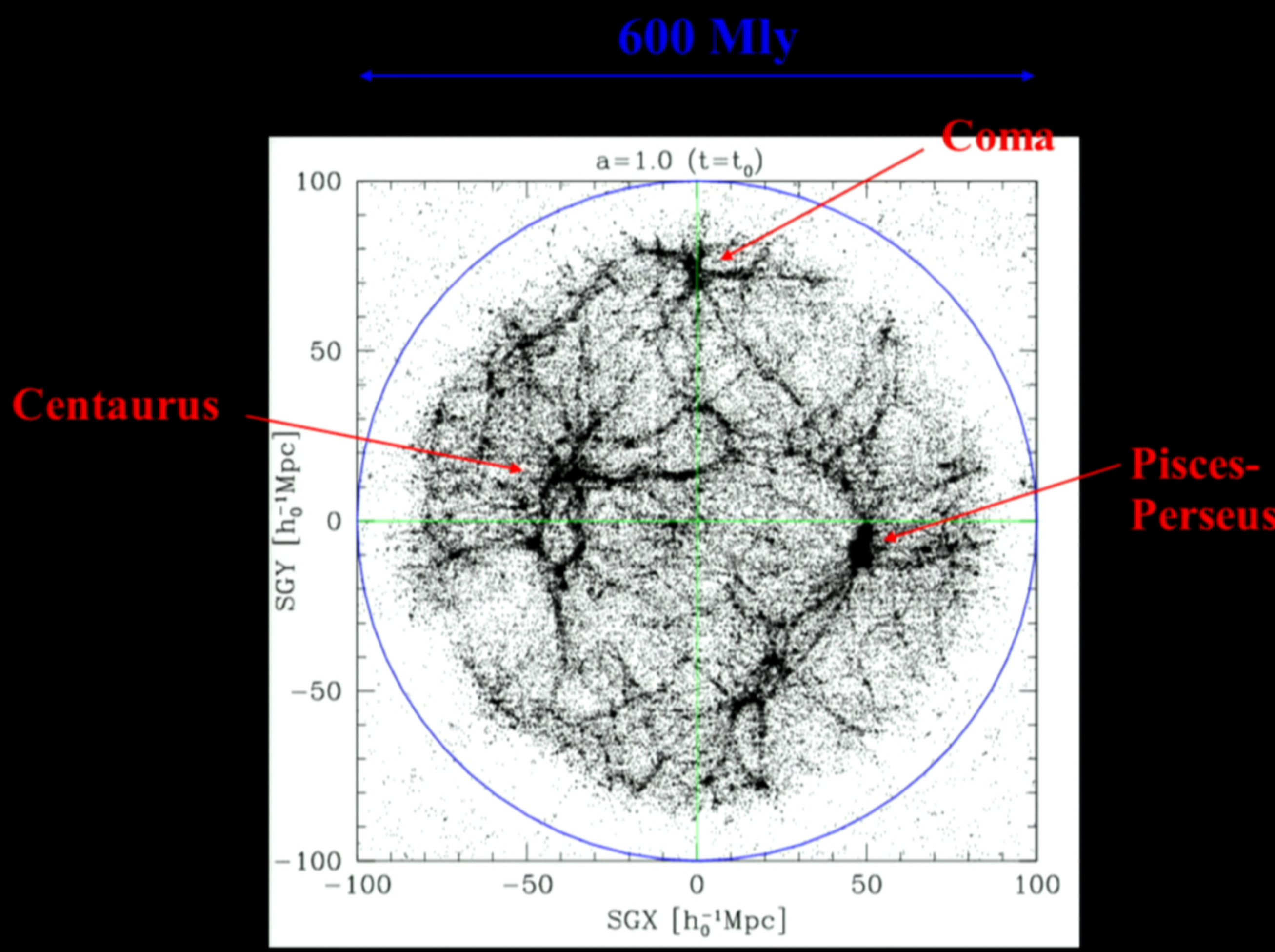
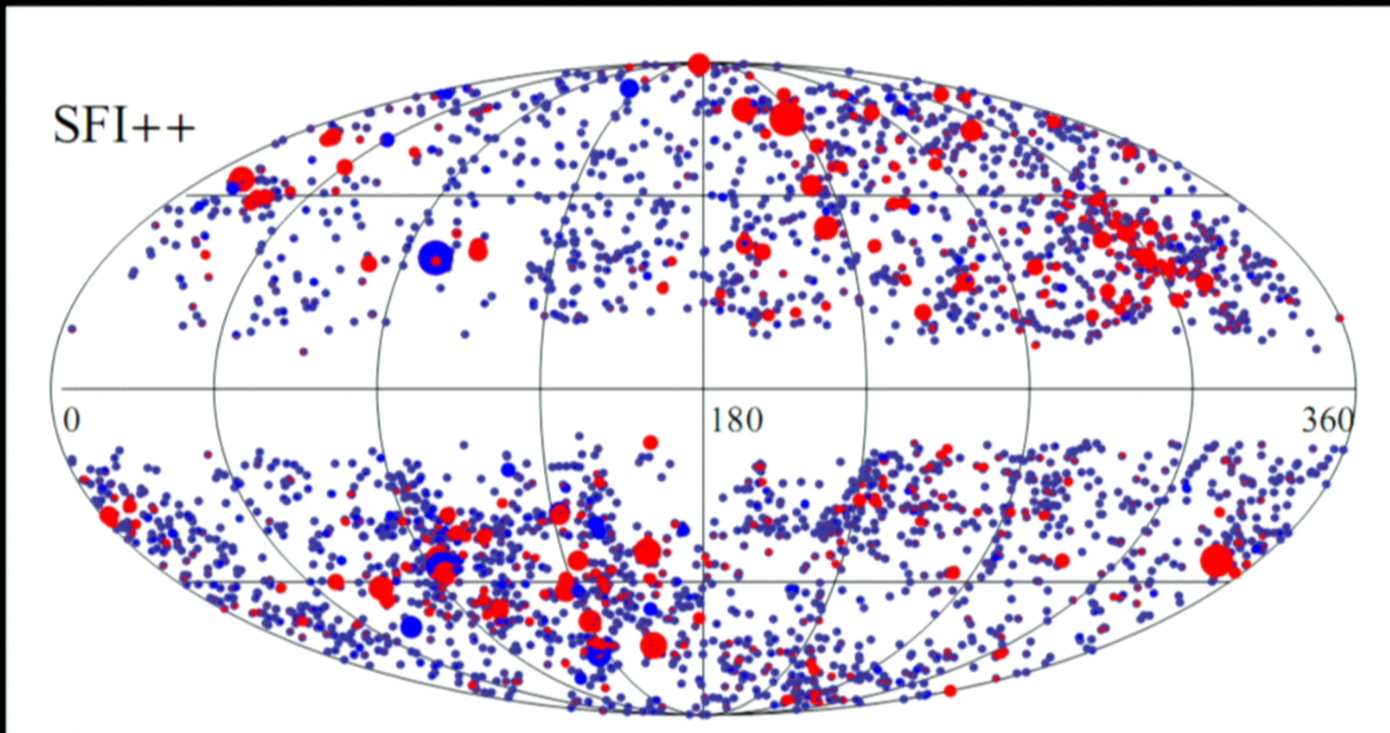


600 Mly
Coma
Centaurus
Pisces-
Perseus
a=1.0 (t=t0)
SGY [h0-1Mpc]
SGX [h0-1Mpc]
100
50
0
−50
−100


SFI++
0
180
360

Linear perturbation theory in LCDM

$$\dot{\delta} + ikv = 0.$$ (Quasi-static limit)

$$v(k,\eta) = \frac{i}{k}\frac{d}{d\eta}\left[\frac{\delta}{D_1}D_1\right] = \frac{i\delta(k,\eta)}{kD_1}\frac{dD_1}{d\eta}$$

$$f \equiv \frac{a}{D_1}\frac{dD_1}{da}$$

$$v(k,a) = \frac{ifaH\delta(k,a)}{k}$$

$$P_v(k) = \frac{H^2}{k^2} f^2(\Omega_{m,0}, \Omega_\Lambda)\, P(k)$$

Do cosmology:

$$P(k) = \sigma_8^2 C k \left(1 + [6.4(k/\Gamma) + 3(k/\Gamma)^{1.5} + (1.7k/\Gamma)^2]^{1.13}\right)^{-2/1.13}$$

EBW fitting formulae

$$\Gamma = \Omega_{m0} h \exp\left[-\Omega_{b0}\left(1 + \frac{\sqrt{2h}}{\Omega_{m0}}\right)\right]$$

Uncertainty.

Alternatively

Cosmic Mach Number:

$$M(R,z) = \left(\frac{\langle V^2(R,z) \rangle}{\langle \sigma^2(R,z) \rangle} \right)^{\frac{1}{2}}$$

$$\langle V^2(R,z)\rangle \;=\; \frac{H^2(z)}{2\pi^2}\int_0^\infty P_{\theta\theta}(k,z)W^2(kR)dk \;\simeq\; \frac{H_0^2}{2\pi^2}\int_0^{1/R} dk P_{\theta\theta}(k)$$

$$\langle \sigma^2(R,z)\rangle \;=\; \frac{H^2(z)}{2\pi^2}\int_0^\infty P_{\theta\theta}(k,z)\left[1 - W^2(kR)\right]dk$$

$$\simeq \frac{H_0^2}{2\pi^2}\int_{1/R}^\infty dk P_{\theta\theta}(k)$$

$$P_{\theta\theta}(k,z) \;=\; f^2(k,z)P(k,z)$$

W(x): top-hat window function

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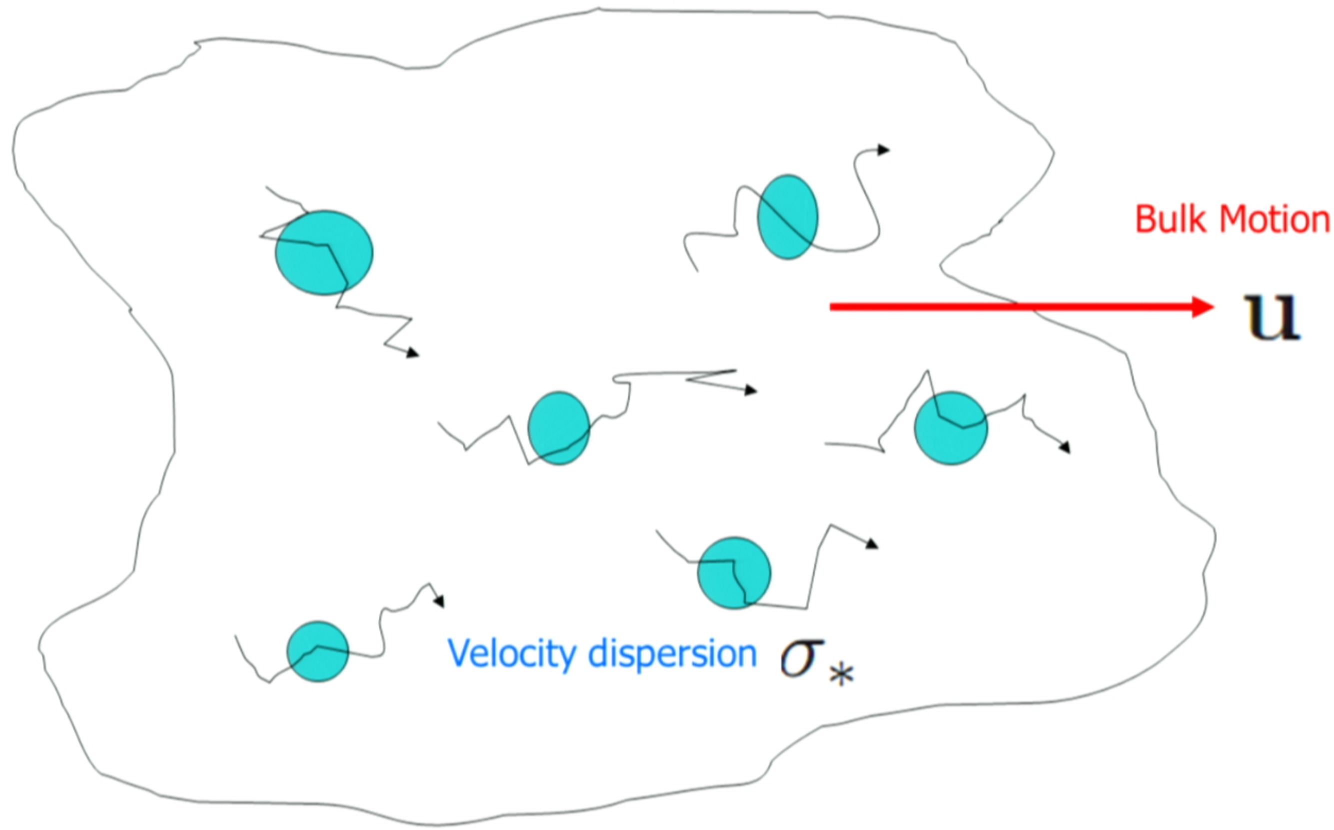
$$\simeq \frac{H_0^2}{2\pi^2} \int_{1/R}^\infty dk P_{\theta\theta}(k)$$

$$P_{\theta\theta}(k,z) = f^2(k,z) P(k,z)$$

W(x): top-hat window function


Bulk Motion
u
Velocity dispersion σ_*

Calculate CMN from peculiar velocity catalog:

$$M = |\mathbf{u}|/\sigma_*$$

line-of-sight velocity S_n

measurement error σ_n

redshift z

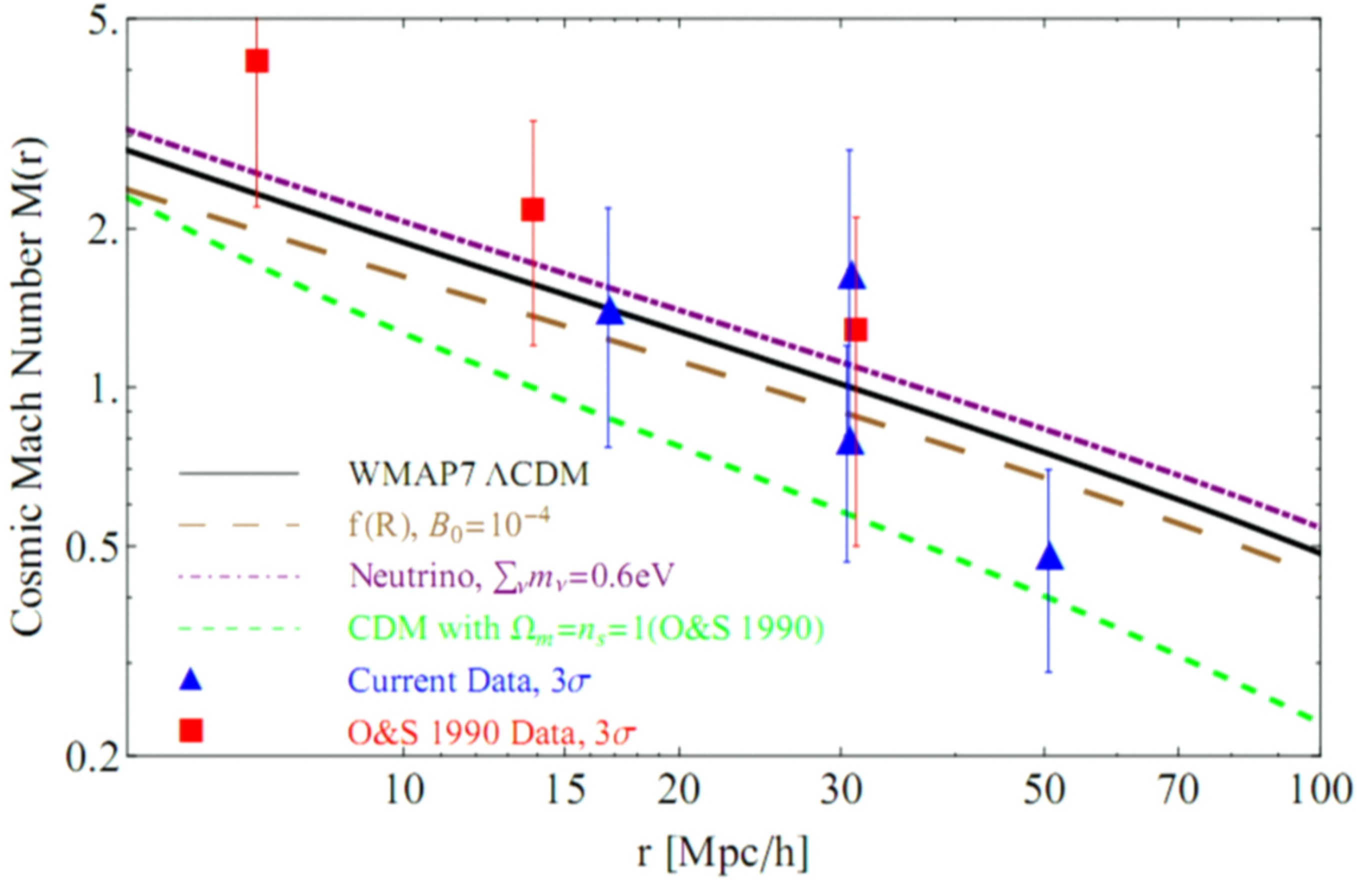
Galactic longitude latitude (l, b)

The uncertainty in $(S_n - \hat{r}_{n,i} u_i)$: $(\sigma_n^2 + \sigma_*^2)^{\frac{1}{2}}$

$$L(\mathbf{u}, M) = \prod_{n=1}^{N} \frac{1}{\sqrt{\sigma_n^2 + \sigma_*^2}} \exp\left(-\frac{1}{2} \frac{(S_n - r_{n,i} u_i)^2}{\sigma_n^2 + \sigma_*^2} \right)$$

$$= \prod_{n=1}^{N} \frac{1}{\sqrt{\sigma_n^2 + (|u|/M)^2}} \exp\left(-\frac{1}{2} \frac{(S_n - r_{n,i} u_i)^2}{\sigma_n^2 + (|u|/M)^2} \right)$$

$$L(M) \sim \int L(\mathbf{u}, M) d^3 u$$



YZM, J. P. Ostriker and G. Zhao, 1106.3327

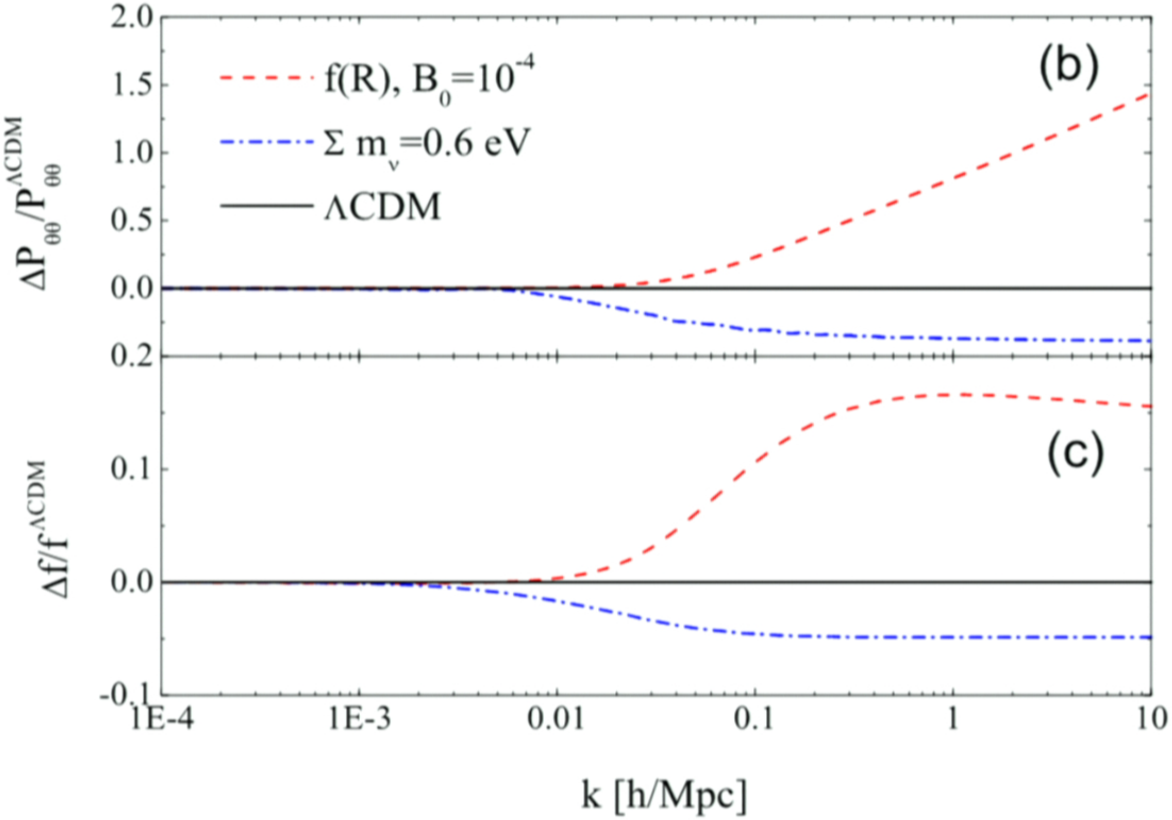
Alternative theory of Gravity, e.g. f(R) model

$$G_{\mathrm{eff}} = \mu(a, k)G$$

$$\mu(a, k) = \frac{1 + \beta_1 \lambda_1^2 k^2 a^s}{1 + \lambda_1^2 k^2 a^s}$$

Zhao et al., PRD 2009 $\beta_1 = 4/3$ $\quad s \sim 4$ $\quad B_0 = \frac{2H_0^2 \lambda_1^2}{c^2}$

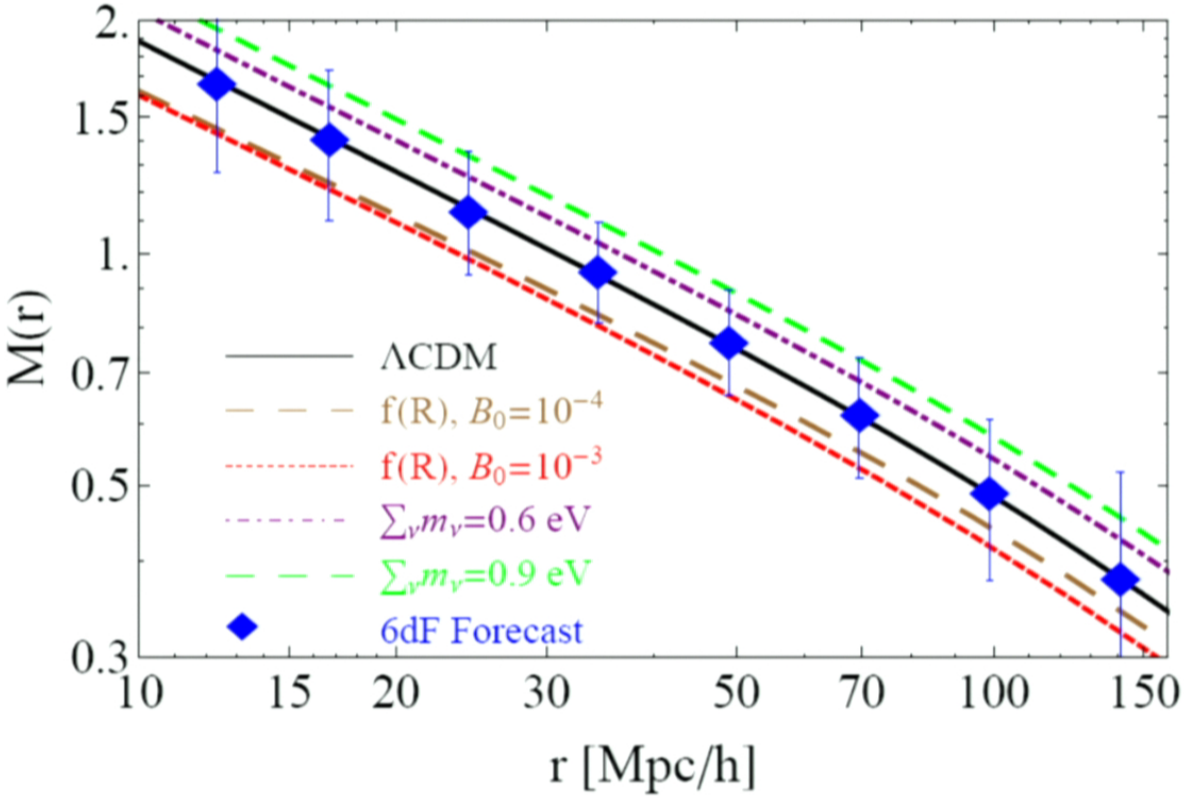
Massive neutrino can also produce scale-dependent growth



$$f \equiv \frac{a}{D_1}\frac{dD_1}{da}$$

LCDM: $f(\Omega_{m,0}, \Omega_\Lambda) \approx \Omega_{m,0}^{0.6}$ Lahav et al. 1991

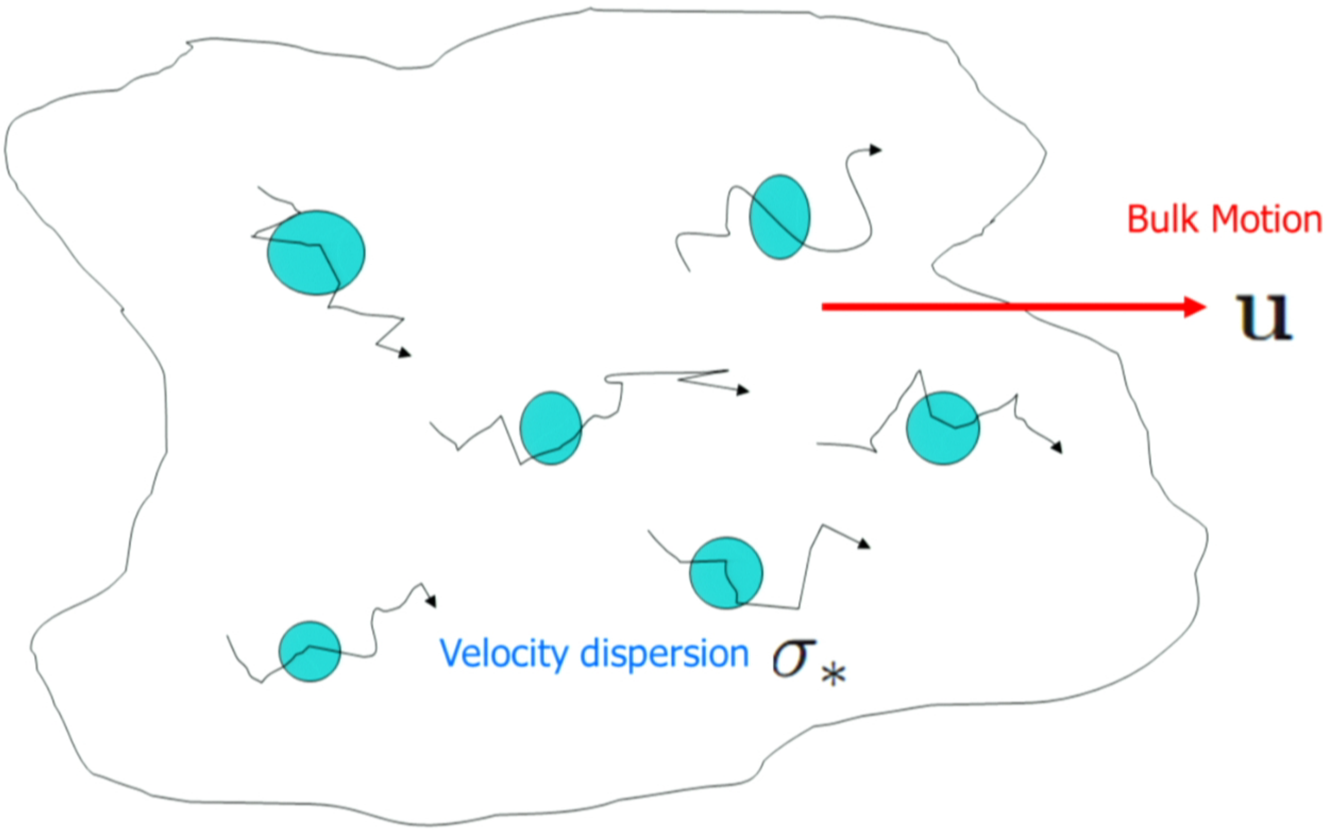
6dF: Jones et al., 2009 MNRAS. 399, 683J



Cosmic Mach Number can be a sensitive test of structure growth

Another puzzle: very large bulk flow

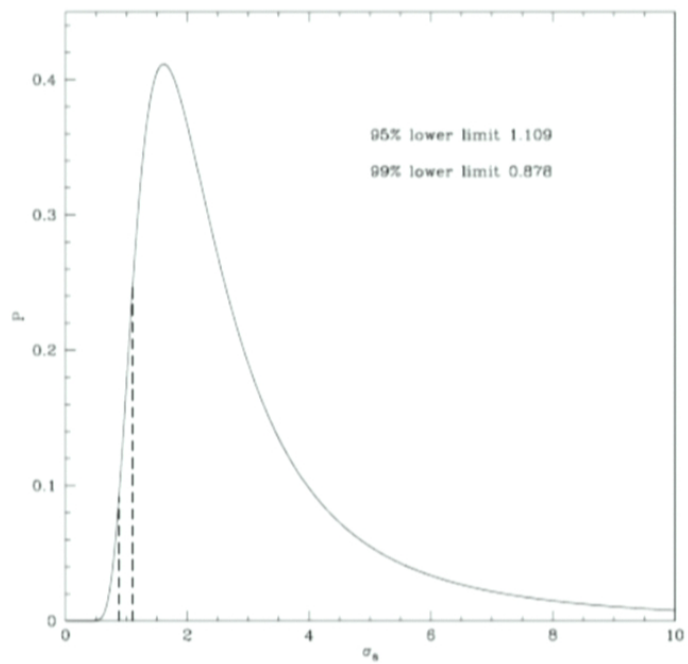
Another puzzle: very large bulk flow


Bulk Motion
u
Velocity dispersion σ_*

Very Large bulk flow:

$$P_v(k) = \frac{H^2}{k^2}\, f^2(\Omega_{m,0}, \Omega_\Lambda)\, P(k)$$

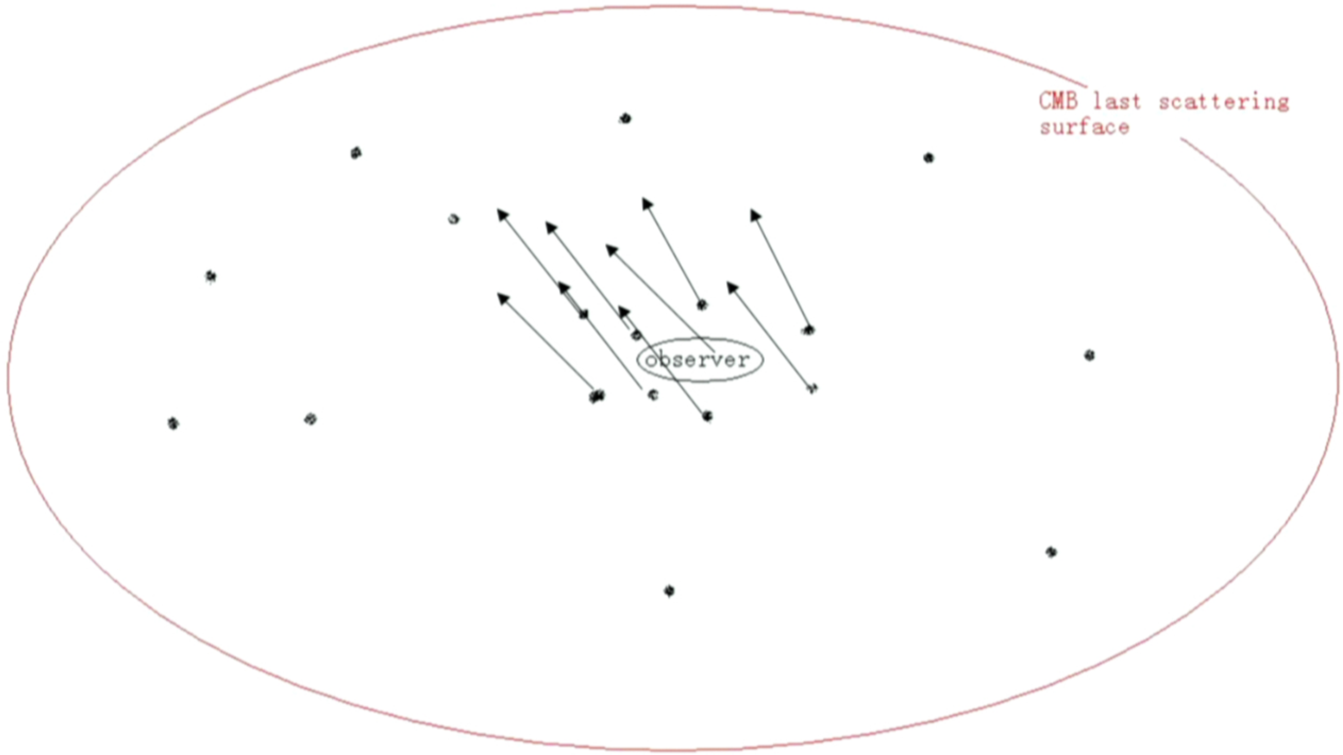
Watkins et al.2009:



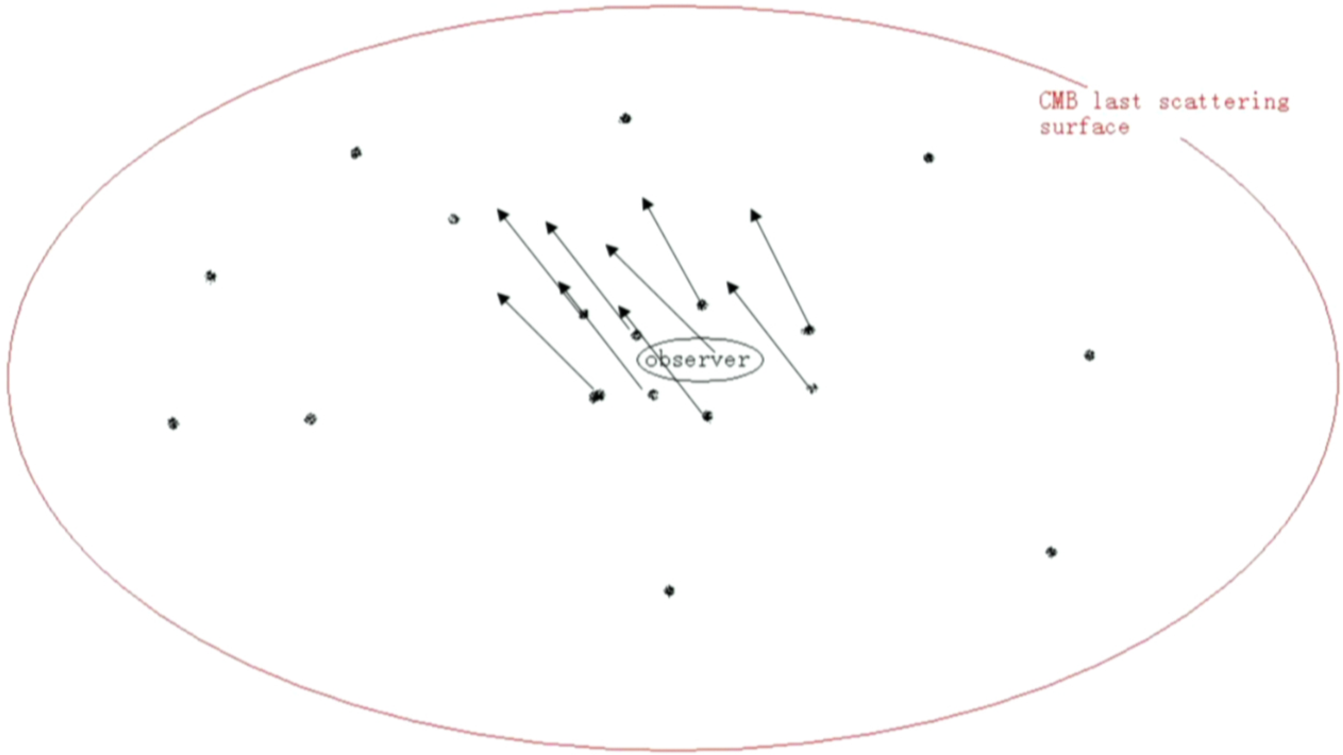
WMAP 7-year best-fit:

$$0.801 \pm 0.030$$

V= $407 \pm 81\ \mathrm{km\ s^{-1}}$



CMB defined rest frame= matter rest fame



CMB defined rest frame= matter rest fame

$$\left\langle {v_R}^2 \right\rangle_{R \to \infty} = 0$$

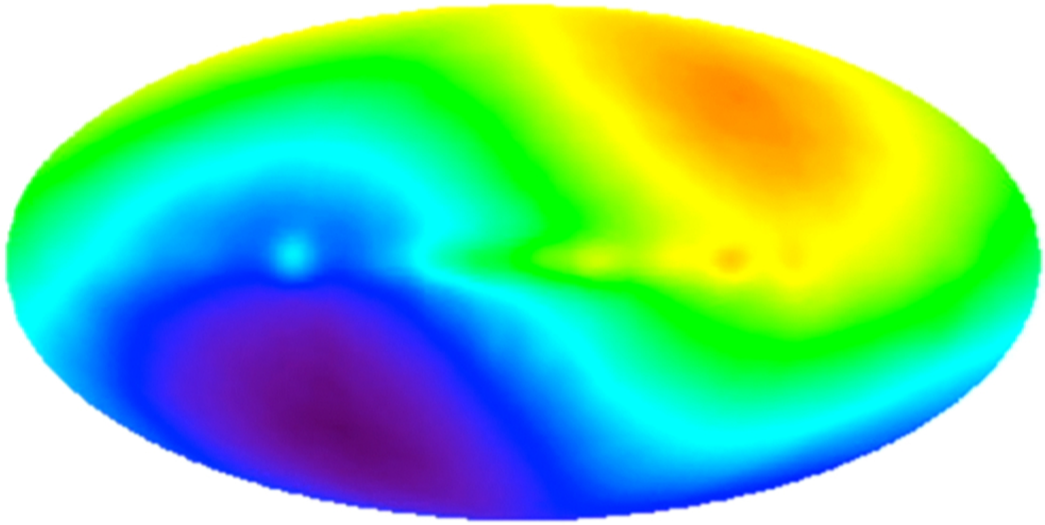
This scenario depends on the assumption: CMB dipole is due to our local motion w.r.s. to the CMB rest frame:

$$cz = H_0 r + \hat{\mathbf{r}} \cdot [\mathbf{v}(\mathbf{r}) - \mathbf{v}(0)]$$

→ CMB dipole

However, it is possible that there is a large scale inhomogeneity across the sky, i.e an intrinsic dipole:

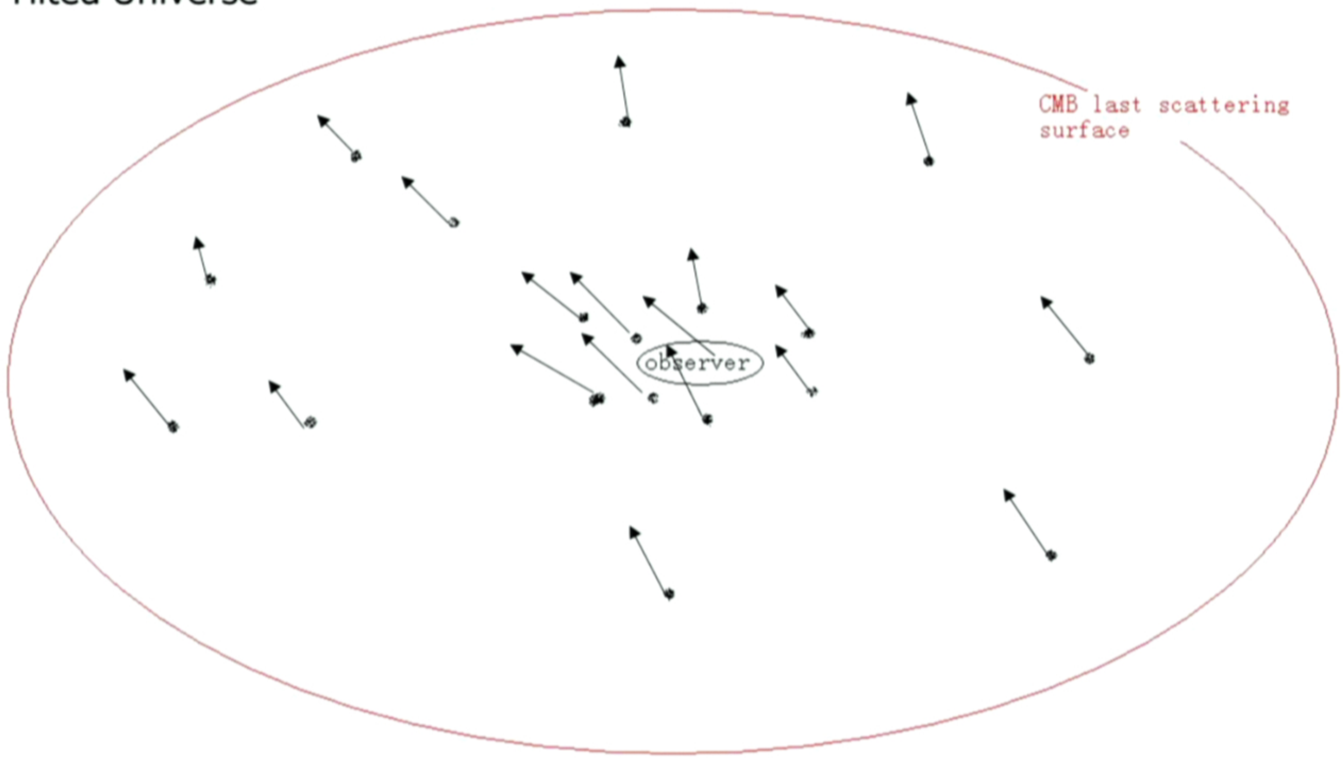
CMB dipole= intrinsic fluctuation+ kinetic dipole



If part of the CMB dipole is due to intrinsic fluctuations on the LSS surface, when you subtract our local motion, you actually subtract out the intrinsic dipole as well, in this case:

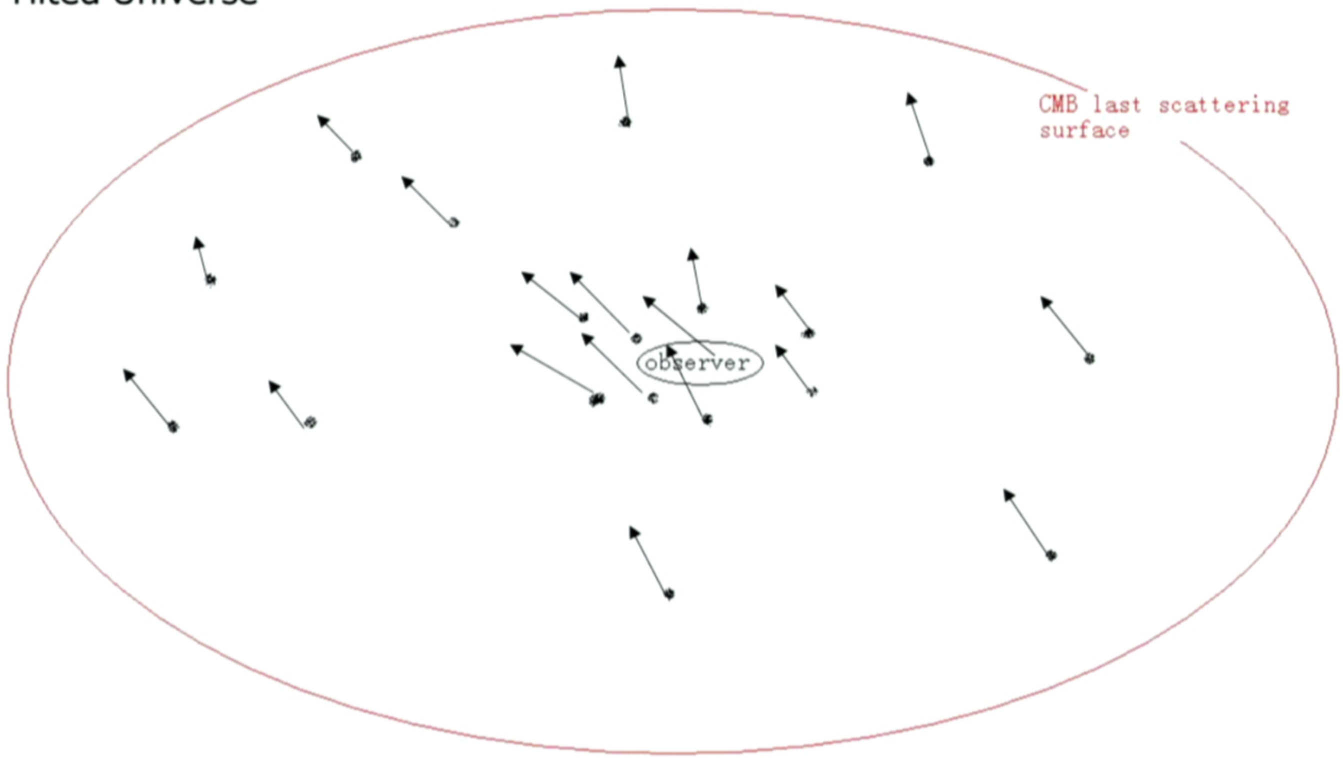
CMB defined rest frame ≠matter rest frame

Tilted Universe



CMB defined rest frame ≠ matter rest fame

Tilted Universe



CMB defined rest frame ≠ matter rest fame

$$\left\langle {v_R}^2 \right\rangle_{R\to\infty} \neq 0$$

"Compensate" the intrinsic dipole as a "tilted velocity" **u**

Observed line of sight velocity in matter rest frame:

$$p_n(\mathbf{u}) = S_n - \hat{r}_{n,i} u_i$$

Covariance matrix:

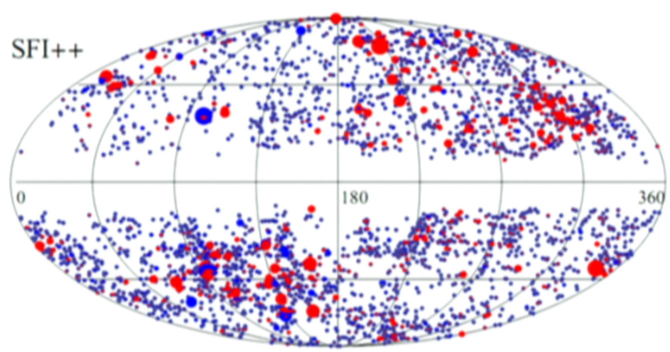
$$G_{nm} = \langle v_n v_m \rangle + \delta_{nm}(\sigma_n^2 + \sigma_*^2)$$

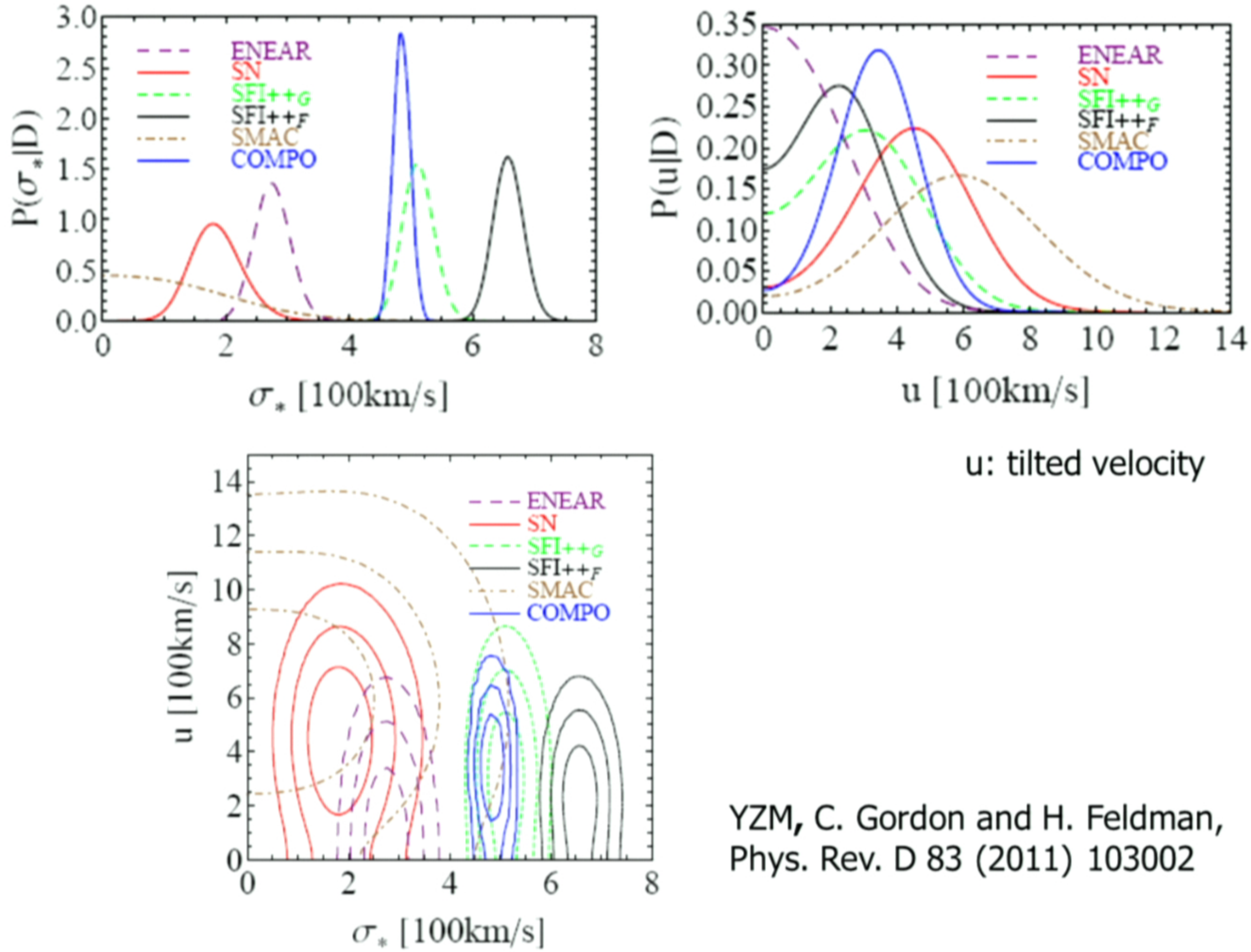
$$\downarrow$$

$$\xi(\mathbf{r}, \mathbf{r}') = \sin\theta \sin\theta' \xi_\perp(\Delta r, z, z') + \cos\theta \cos\theta' \xi_\parallel(\Delta r, z, z')$$

Likelihood:

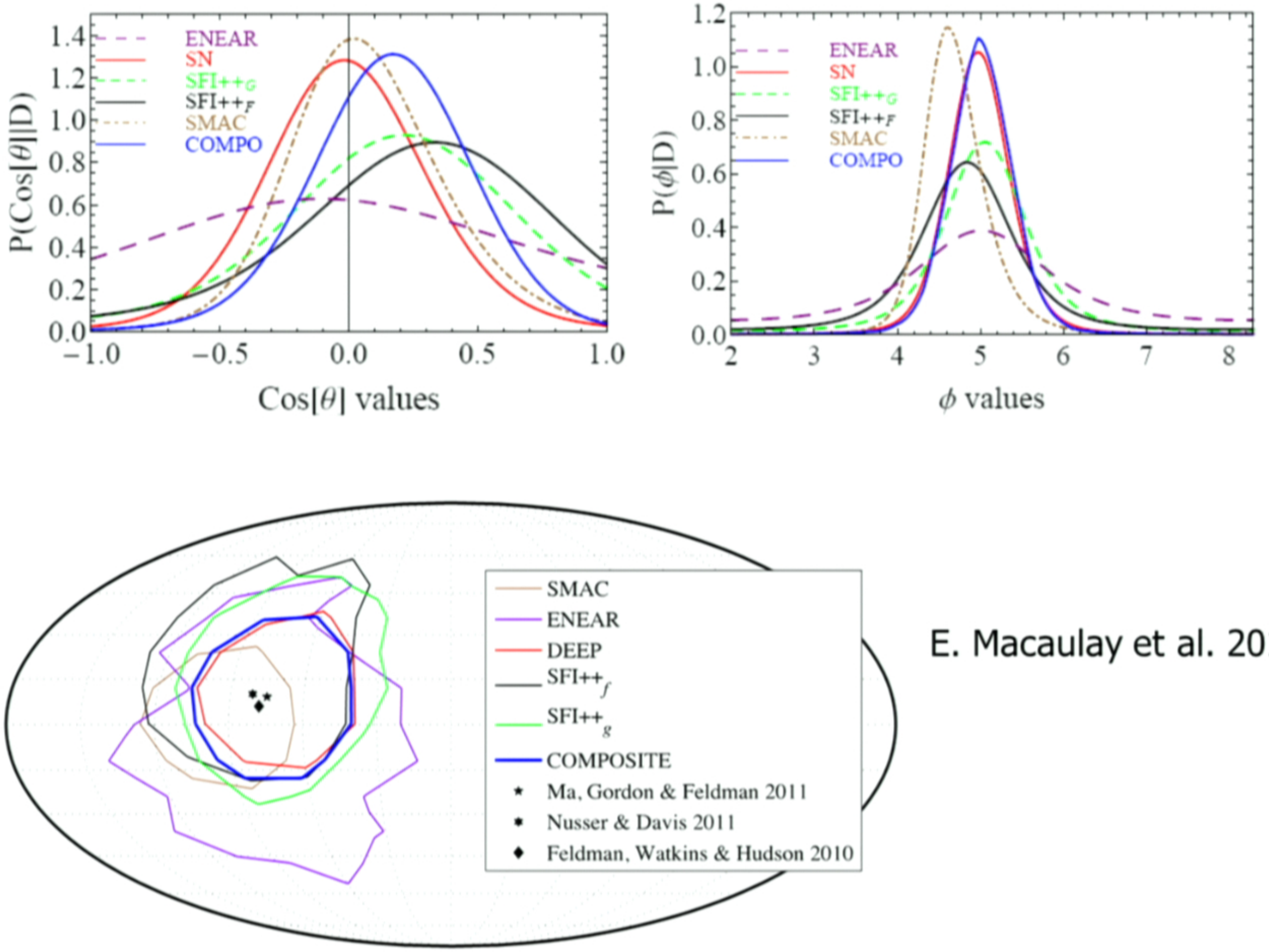
$$L(\mathbf{u}, \sigma_*) = \frac{1}{(\det G_{nm})^{\frac{1}{2}}} \exp\left(-\frac{1}{2} p_n(\mathbf{u}) G_{nm}^{-1} p_m(\mathbf{u})\right)$$





u: tilted velocity

YZM, C. Gordon and H. Feldman, Phys. Rev. D 83 (2011) 103002



E. Macaulay et al. 2011

Physical meaning:

Isocurvature perturbation (not adiabatic) can provide intrinsic dipole modulation on the sky:

M. Turner 1991:

$$\frac{u}{c} \simeq \frac{H_0^{-1}}{L} \frac{\delta\varphi}{\varphi_0}$$

$$u/c \simeq H_0^{-1}/L \simeq e^{-\Delta N}$$

Primordial isocurvature fluctuation

$$l = H_i^{-1} \xrightarrow{\text{inflation}} L = e^{\Delta N} H_0^{-1}$$

$$\Delta N = N - N_{\min}$$

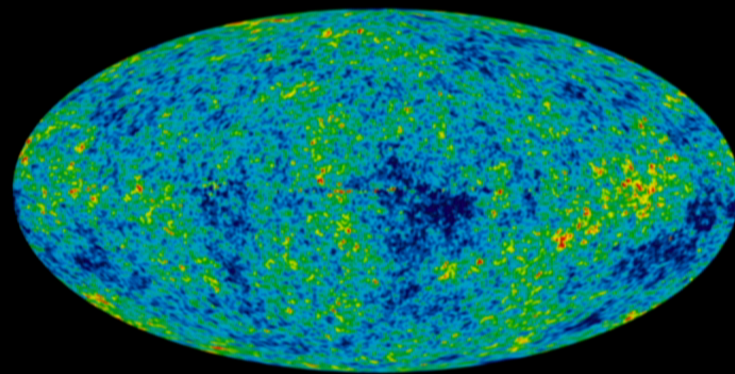
$$u/c \simeq H_0^{-1}/L \simeq e^{-\Delta N}$$

Catalogues	depth (Mpc/h)	σ_* [100km/s]	u [100km/s]	l (degrees)	b (degrees)	ΔN (2σ)
ENEAR	29	$2.75^{+0.29}_{-0.30}$	$0^{+2.23}_{\times}$	$287.15^{+68.93}_{-68.31}$	$-3.80^{+37.51}_{-35.98}$	$\Delta N \geq 7$
SN	32	$1.79^{+0.44}_{-0.40}$	$4.52^{+1.76}_{-1.85}$	$284.90^{+22.91}_{-22.07}$	$-0.98^{+18.77}_{-18.29}$	$6 \leq \Delta N \leq 9$
SFI++$_G$	34	$5.10^{+0.26}_{-0.25}$	$3.05^{+1.60}_{-1.93}$	$289.69^{+34.94}_{-34.85}$	$10.25^{+26.83}_{-25.46}$	$\Delta N \geq 6$
SFI++$_F$	34	$6.57^{+0.25}_{-0.24}$	$2.26^{+1.22}_{-1.57}$	$276.81^{+40.09}_{-38.97}$	$15.75^{+28.42}_{-27.05}$	$\Delta N \geq 6$
SMAC	65	$0.0^{+1.70}_{\times}$	$5.86^{+2.43}_{-2.39}$	$263.81^{+23.58}_{-18.46}$	$1.09^{+18.62}_{-16.03}$	$6 \leq \Delta N \leq 8$
COMPOSITE	33	$4.83^{+0.16}_{-0.12}$	$3.44^{+1.25}_{-1.27}$	$285.12^{+23.89}_{-19.50}$	$9.08^{+18.52}_{-17.84}$	$6 \leq \Delta N \leq 8$

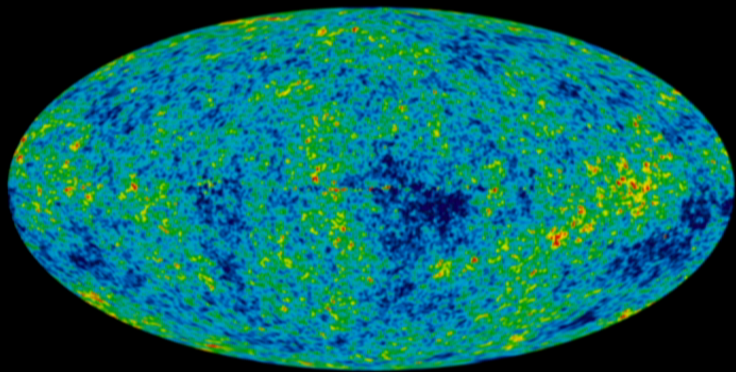
Our data implies that inflation lasts not very longer than 60 e-folds

YZM, C. Gordon and H. Feldman, Phys. Rev. D 83 (2011) 103002

Summary:



Summary:



- Apparent lack of large angular correlation:

cut-sky pixel-estimator+ a posteriori statistic

- Current B-mode polarization has been and will be an important test of early Universe.

- Peculiar velocity of galaxies can provide much information on structure growth, therefore a powerful tool to distinguish modify gravity and non-zero neutrinos.
- Tilted Universe is potentially an interesting scheme to explain the anomaly of very large bulk low.