Testing concordance cosmology on large and small cosmic scales

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Outline:

- Testing large angular correlations in the CMB sky

  G. Efstathiou, Y.Z. Ma and D. Hanson. MNRAS 407 (2010) 2530

- Testing early Universe models from B-mode polarization

  Y.Z. Ma, W. Zhao and M.L. Brown, JCAP 10 (2010) 007

- Testing tilted Universe from peculiar velocity field

  Y.Z. Ma, C. Gordon and H. Feldman, arXiv: 1010.4276

- Conclusion

Does the Universe lack large angular correlations?

Two Points Correlation Function

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

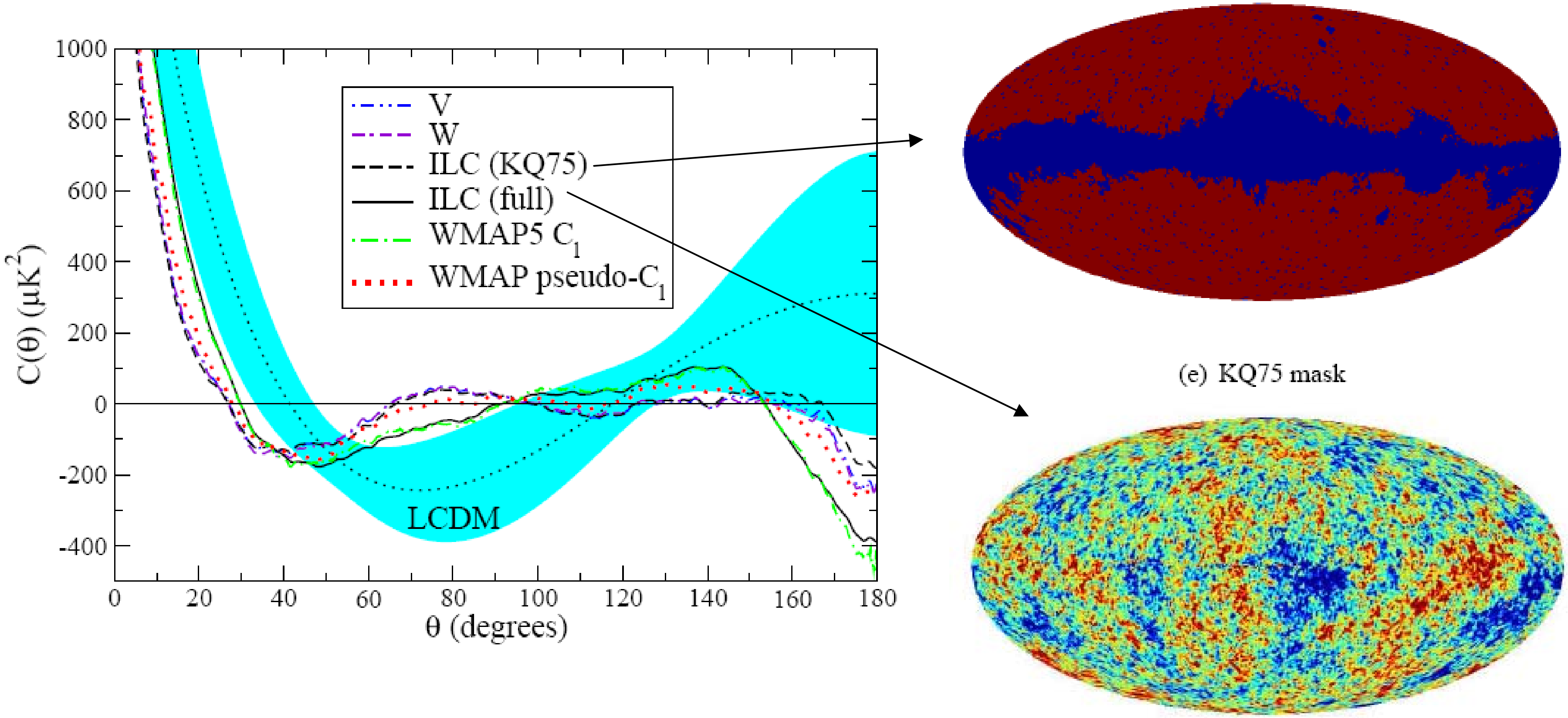
$Y_{lm}(n)$ are the spherical harmonics

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

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

$$S_{1/2} = \int_{-1}^{1/2} [C(\theta)]^2 d\cos\theta$$

Arguments of lack of large angular correlations



(e) KQ75 mask

(a) WMAP 5-year ILC map

Copi et al. 2009

CHHS08

Data Source	$S_{1/2}$ $(\mu\mathrm{K})^4$	$P(S_{1/2})$ (per cent)	$6\mathcal{C}_2/2\pi$ $(\mu\mathrm{K})^2$	$12\mathcal{C}_3/2\pi$ $(\mu\mathrm{K})^2$	$20\mathcal{C}_4/2\pi$ $(\mu\mathrm{K})^2$	$30\mathcal{C}_5/2\pi$ $(\mu\mathrm{K})^2$
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

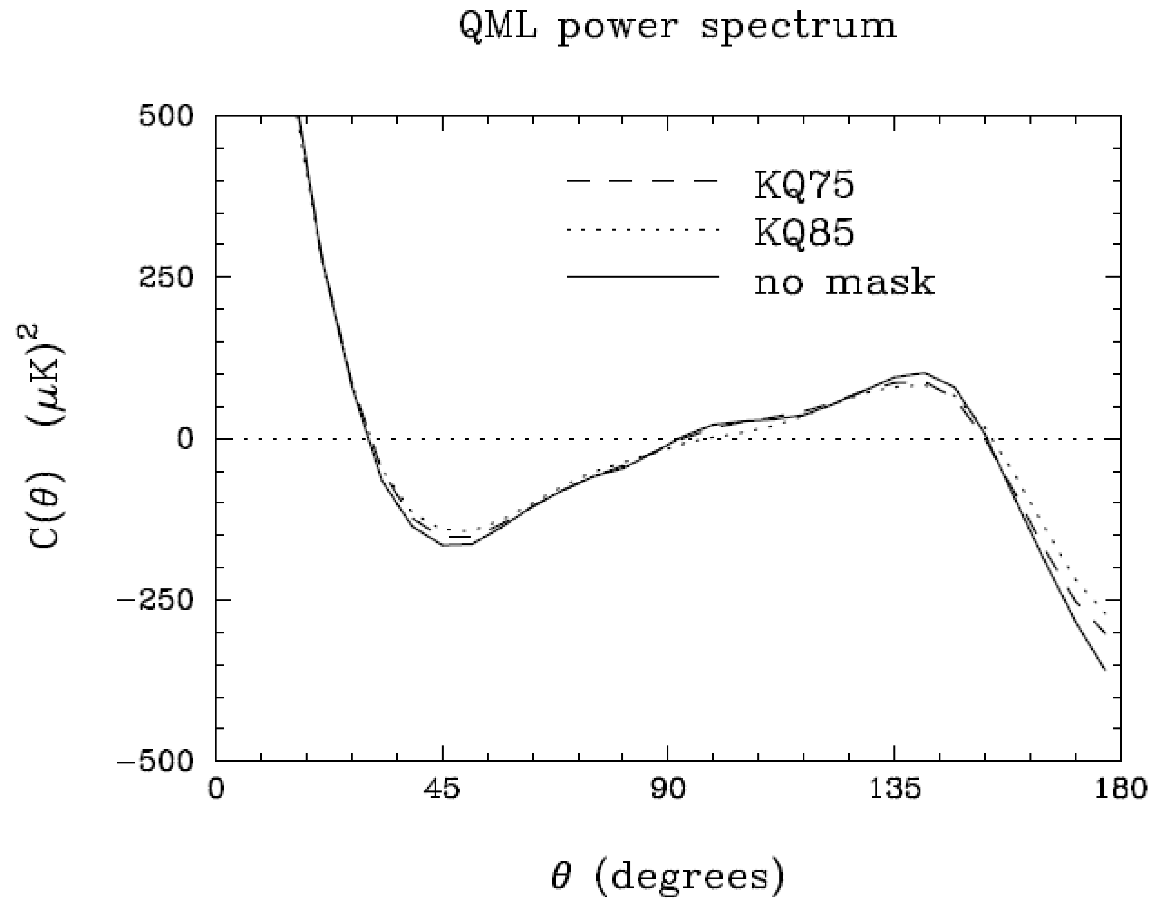
Thus the full-sky results seem inconsistent with cut-sky results and they appear inconsistent in a manner that implies that *most of the large-angle correlations in reconstructed sky maps are inside the part of the sky that is contaminated by the Galaxy.*

- The reason of the low p value:

  cut-sky estimator of ACF on a cut sky

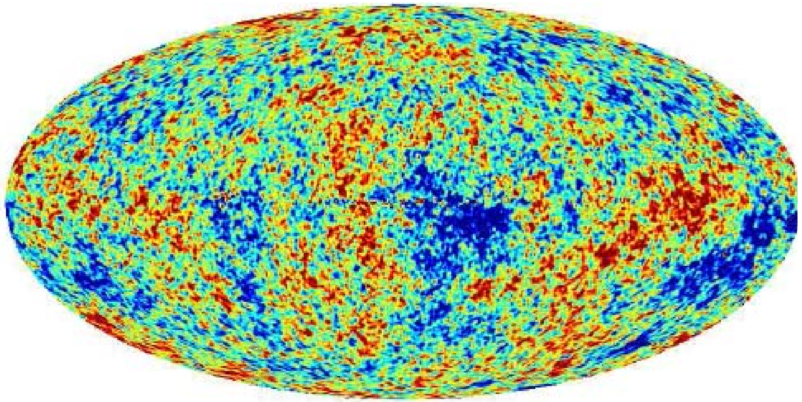
  + a posteriori choices of the form of the $S_{1/2}$ statistic.

EMH09

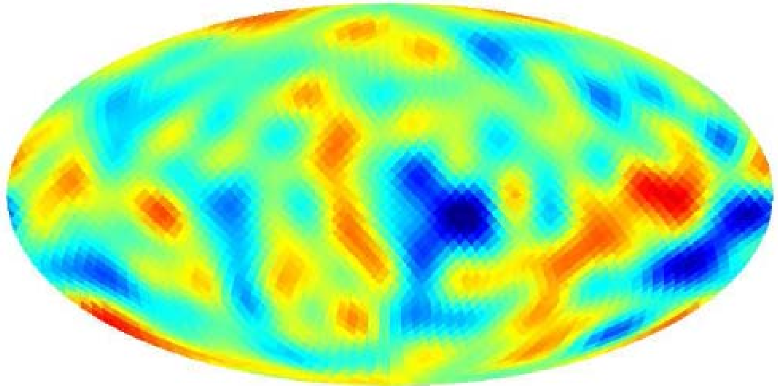


$l_{max} = 32$

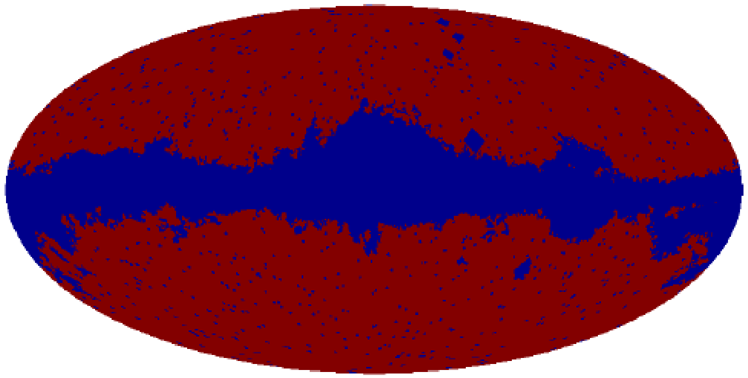
The QML estimator effectively performs the reconstruction for a_{lm},
but uses the assumption of statistical isotropy to downweight
'ambiguous' modes that are poorly constrained by the sky cut.



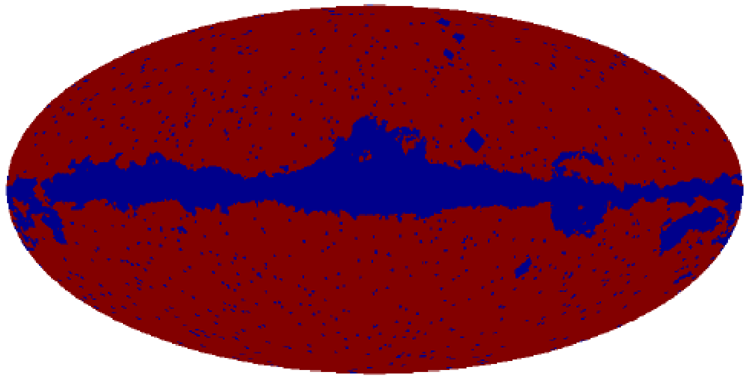
(a) WMAP 5-year ILC map



(c) whole-sky map smoothed to $l_{max} = 15$

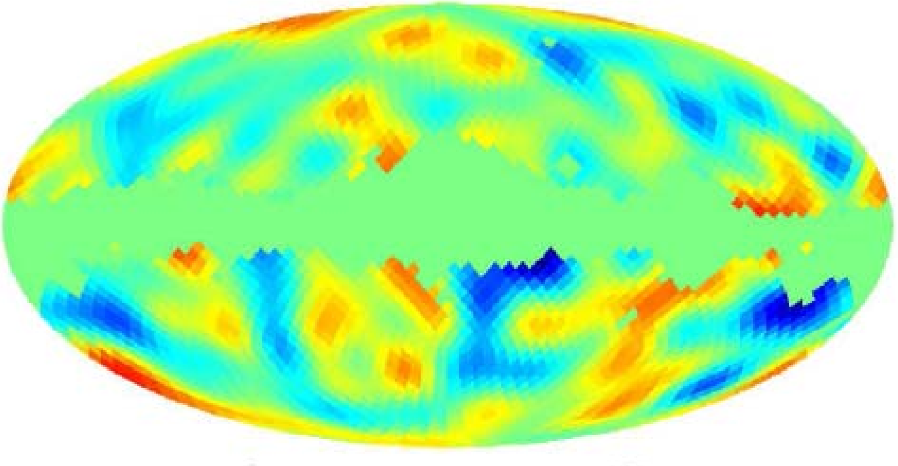


(e) KQ75 mask

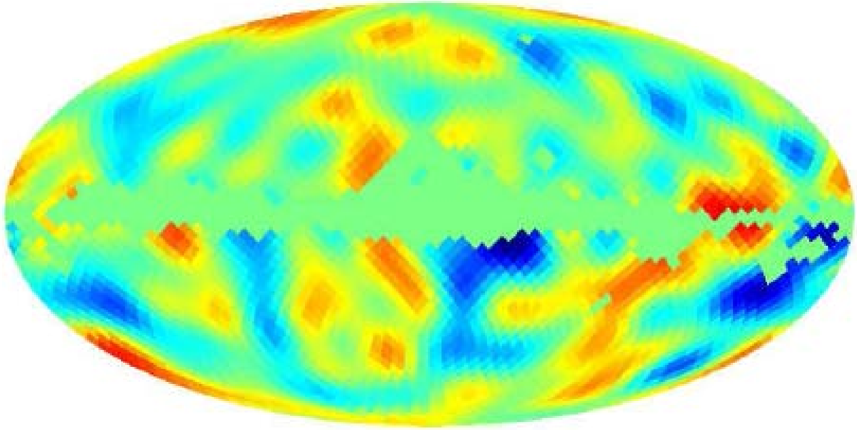


(f) KQ85 mask

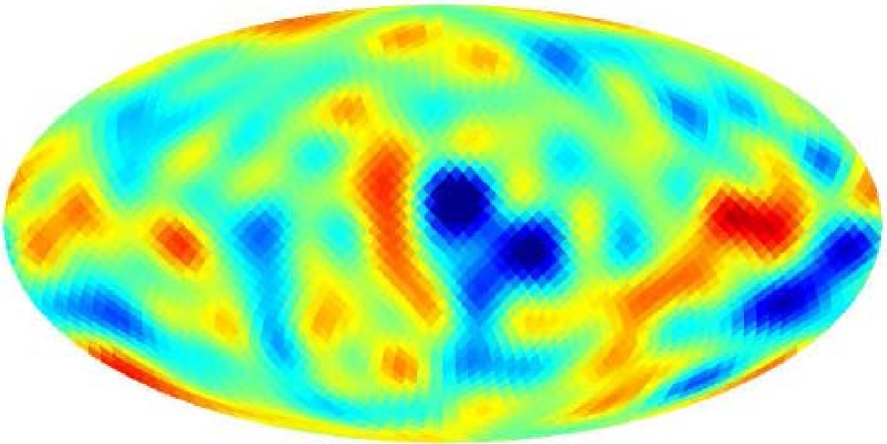
(g) Scales (Unit: mK)



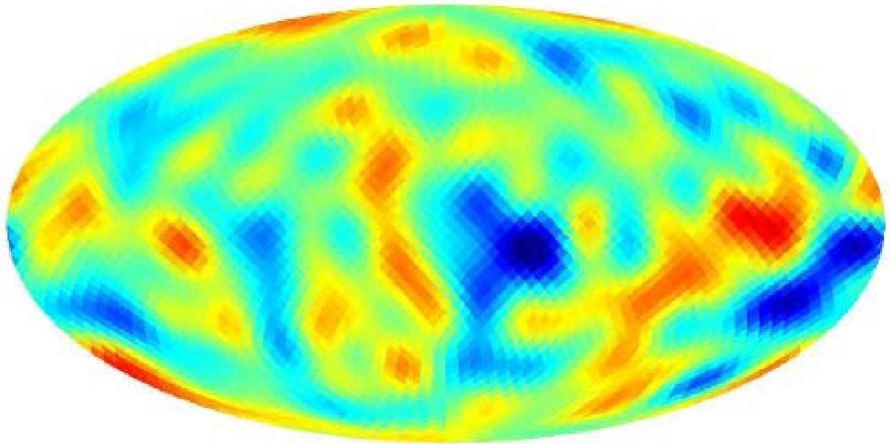
(c) Smoothed map $l_{max} = 15$ masked by KQ75



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

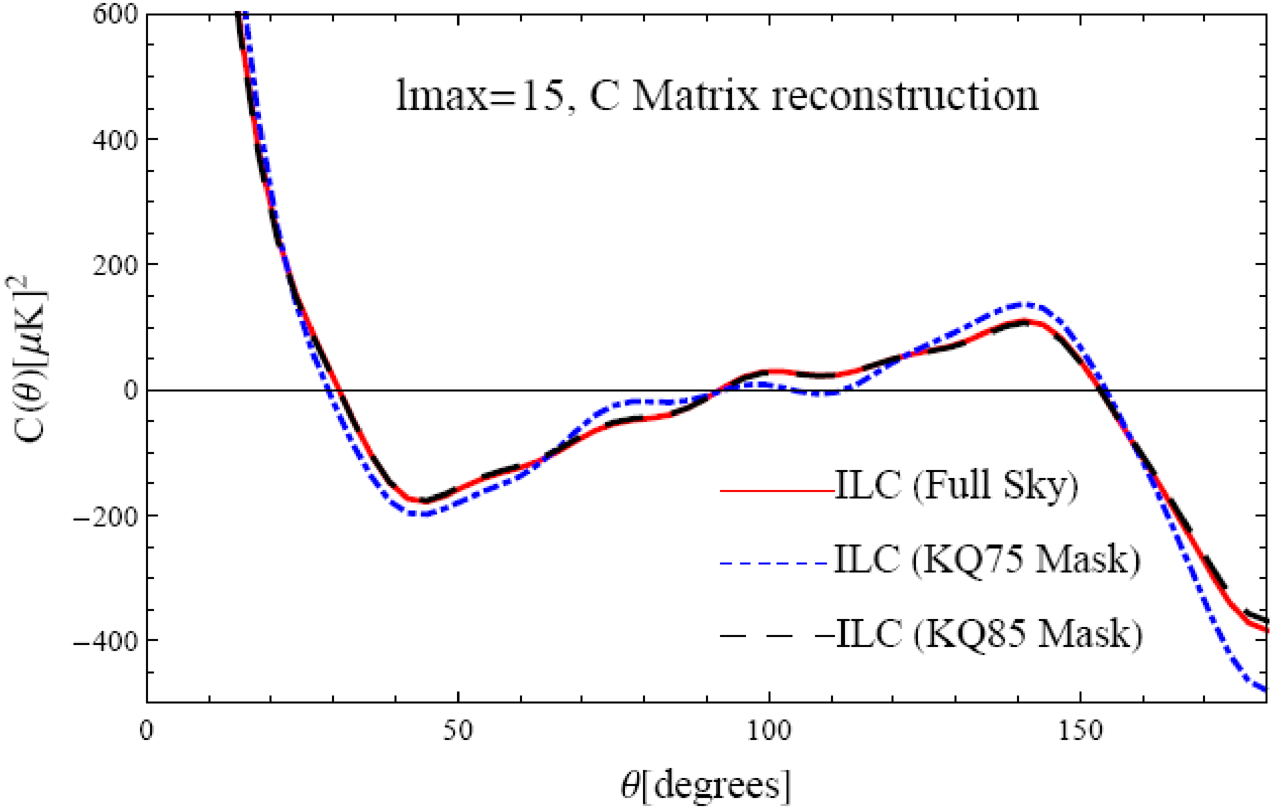


(c) Reconstruction map to $l_{max} = 15$ (KQ75 mask)



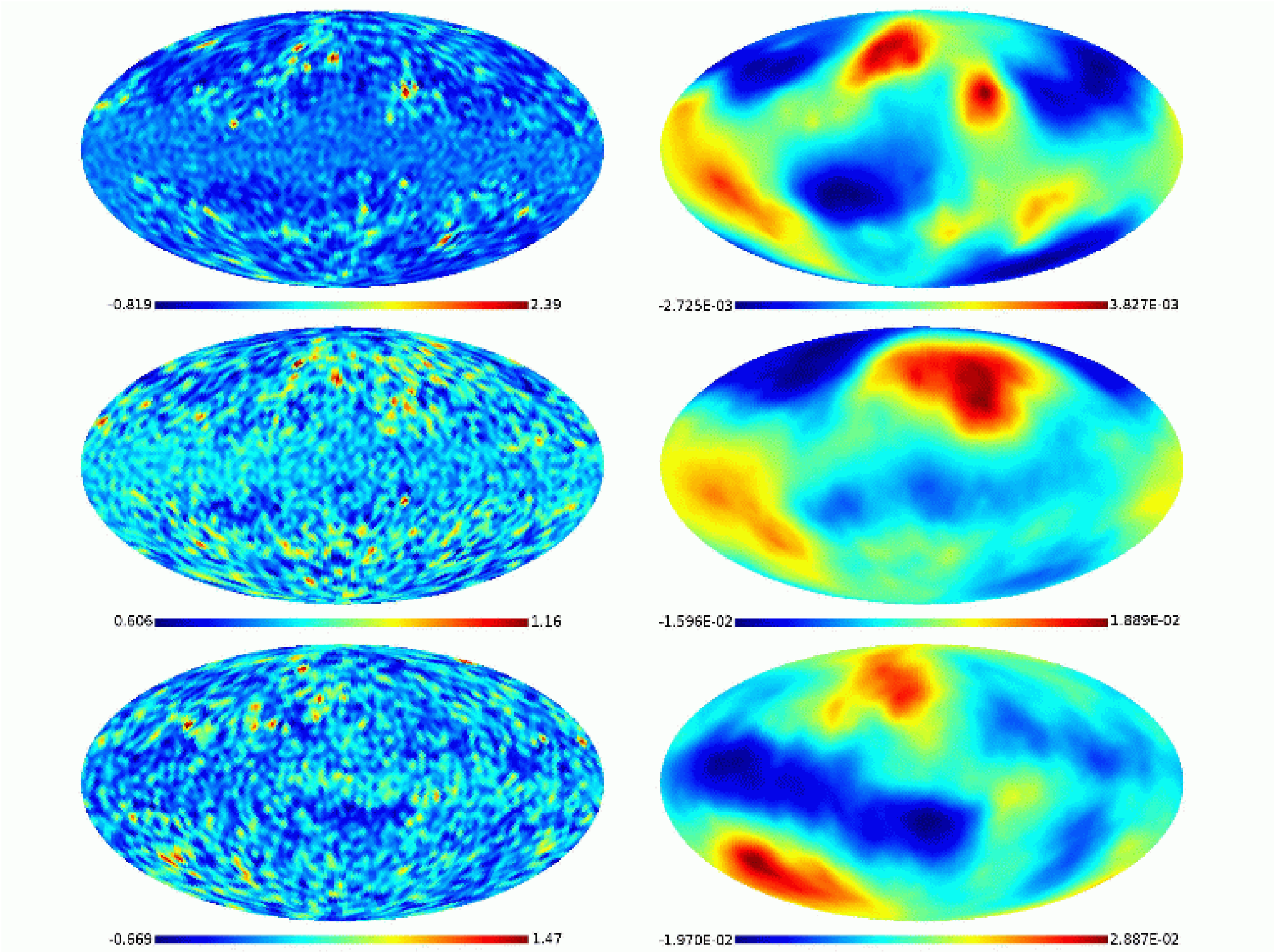
(d) Reconstruction map to $l_{max} = 15$ (KQ85 mask)

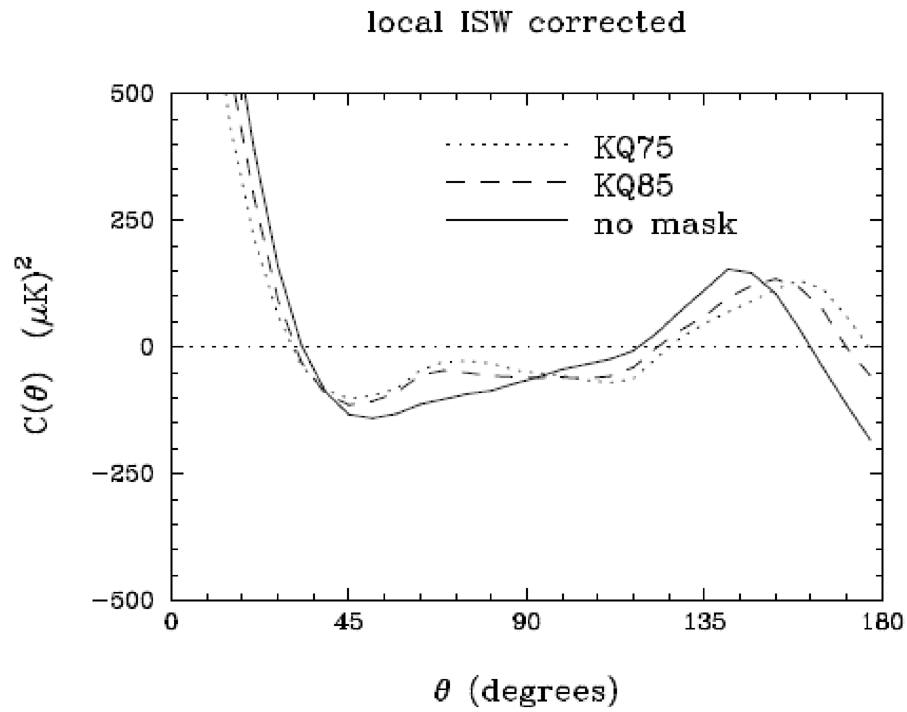
Results for $C(\theta)$



What is a posteriori statistic?

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





Francis and Peacock

0909.2495

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

$S_{1/2}$ statistic :

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

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

Testing the early Universe models from CMB B-mode polarization

It is possible to distinguish the schemes of fundamental microscopic physics from CMB B-mode polarization

1. Single field inflation model from effect field theory

$$ds^2 = -c^2 dt^2 + a^2(t)(\delta_{ij} + h_{ij}) dx^i dx^j$$

$$\langle h_{\mathbf{k}} h_{\mathbf{k}'} \rangle = (2\pi)^3 \delta^3(\mathbf{k} - \mathbf{k}') \frac{2\pi^2}{k^3} P_t(k)$$

$$P_t(k) = A_t(k_0) \left(\frac{k}{k_0} \right)^{n_t}$$

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

Lyth bound:

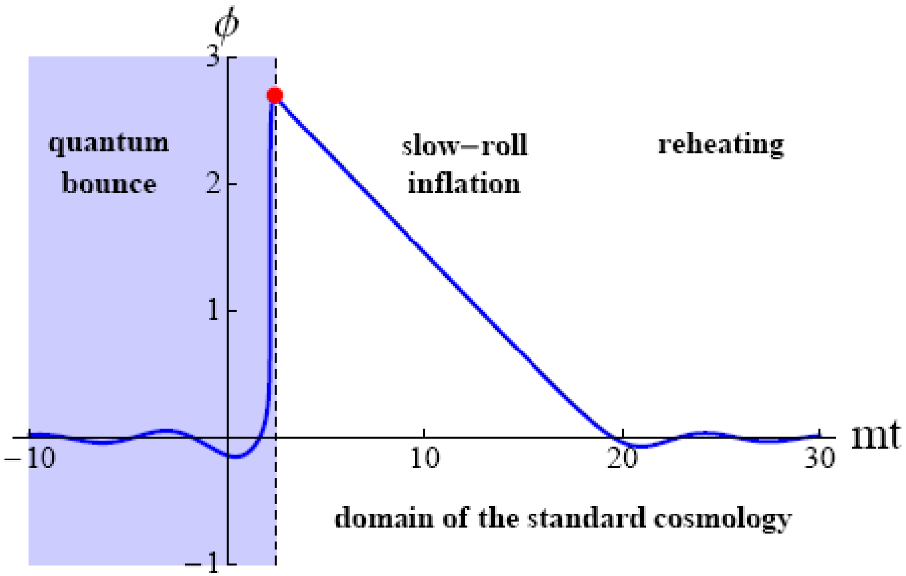
$$\frac{\Delta\phi}{\mathrm{M_{pl}}} \gtrsim \left(\frac{r}{0.01}\right)^{\frac{1}{2}} \qquad V^{\frac{1}{4}} = 1.06 \times 10^{16}\mathrm{GeV}\left(\frac{r}{0.01}\right)^{\frac{1}{4}}$$

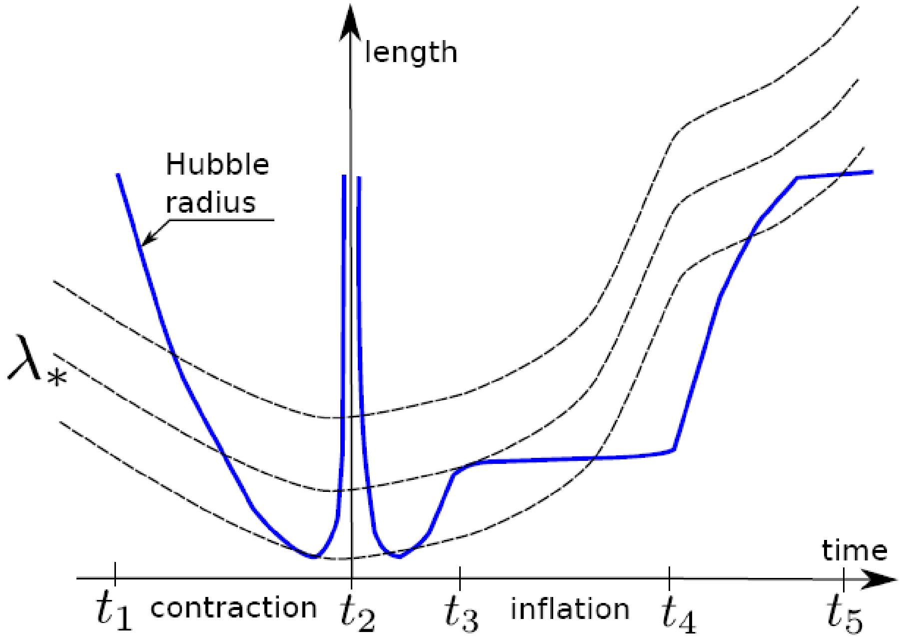
Consistency relation:

$$n_t = -\frac{r}{8}$$

2. A possible model of Loop Quantum cosmology from LQG

$$H^2 = \frac{\kappa}{3}\rho\left(1 - \frac{\rho}{\rho_c}\right)$$





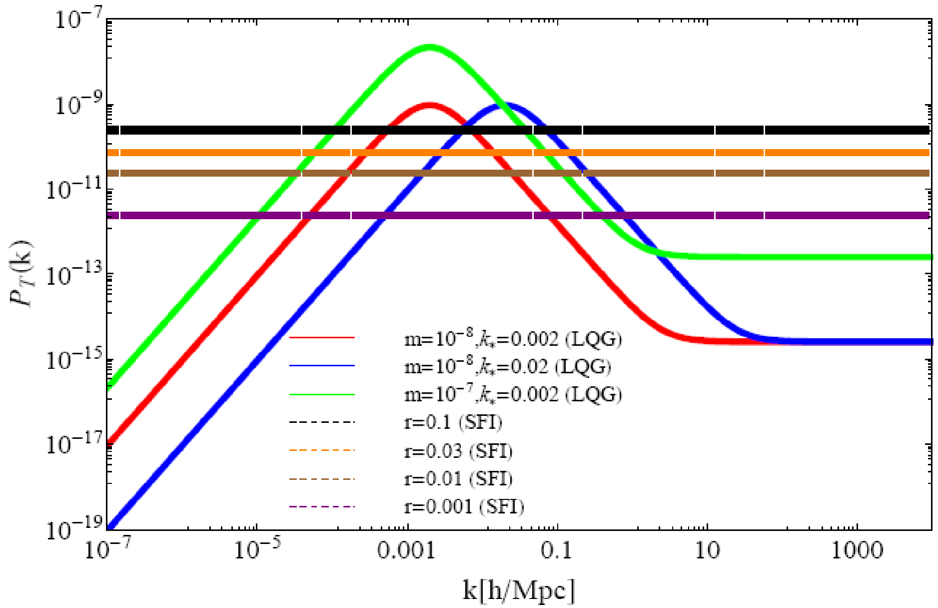
Mielczarek et. al, PRD 81:104049,2010

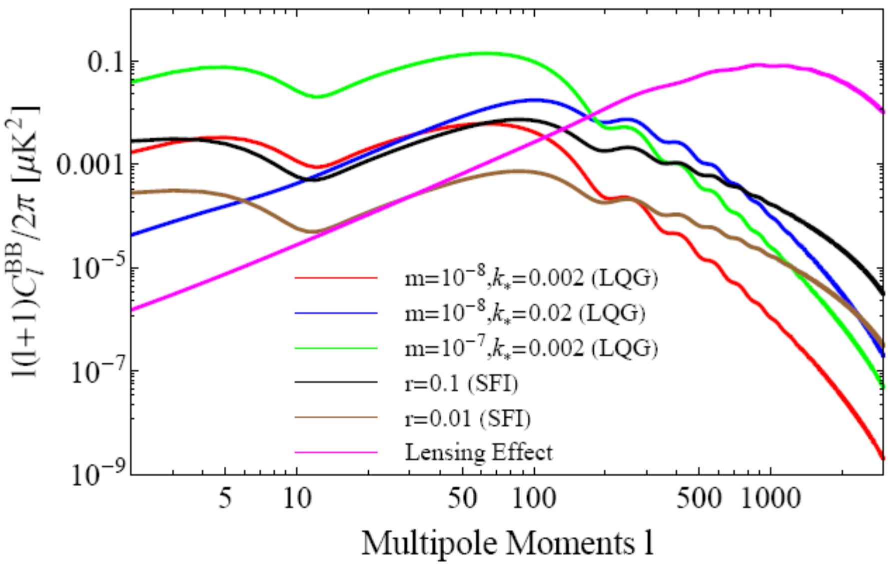
Grain and Barrau, PRL 102:081301,2009

Mielczarek et. al, PRD 81:104049,2010

Grain and Barrau, PRL 102:081301,2009

$$P_t = \frac{4N_e}{3\pi}\left(\frac{m}{\mathrm{M_{pl}}}\right)^2 \frac{1}{1+(k_*/k)^2}\left[1+\frac{4\times(8\pi)^{0.32}\times(m/\mathrm{M_{pl}})^{-0.64}-2}{1+(k/k_*)^2}\right]$$





Generically, Loop model has a characteristic tilt

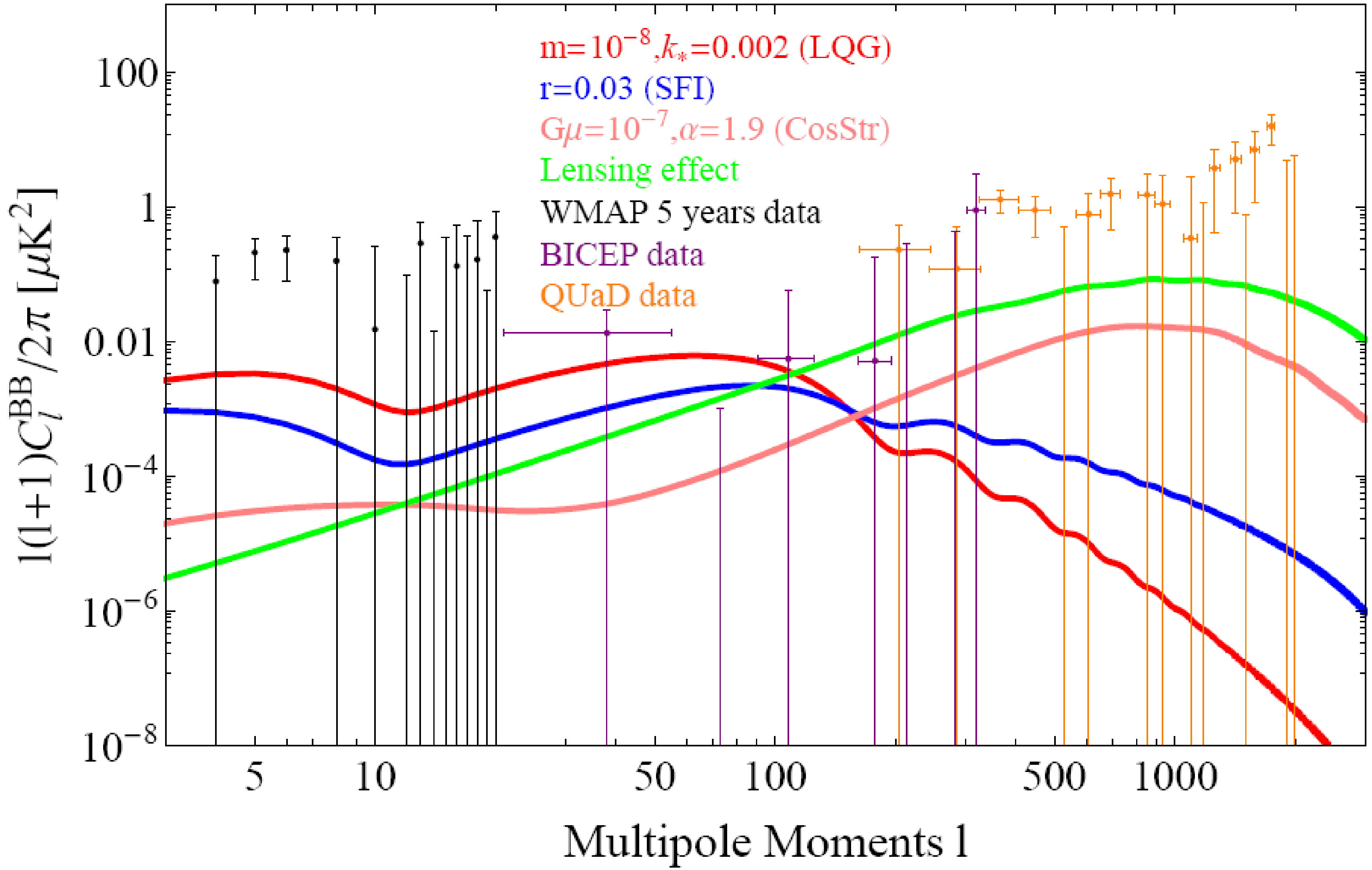
3. Cosmic string from Brane-Inflation

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

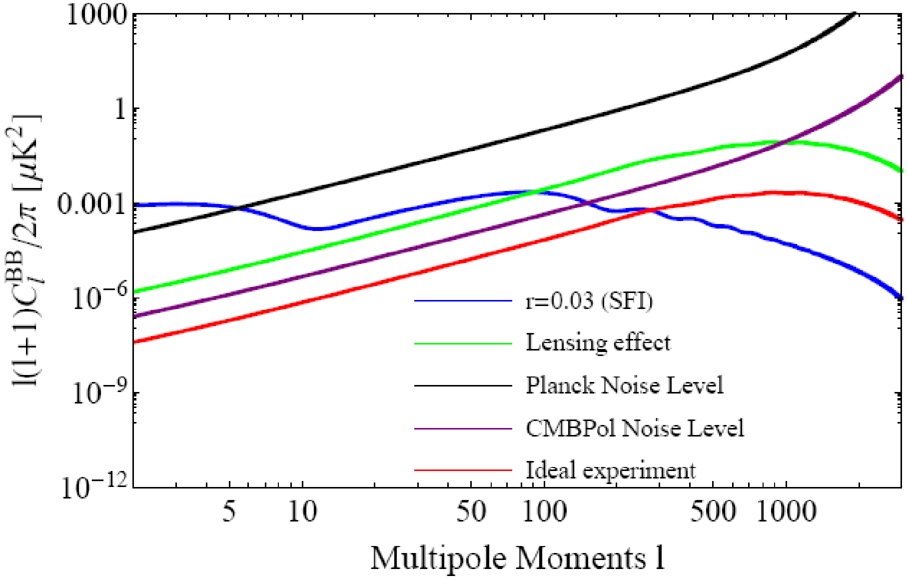
CMBACT:

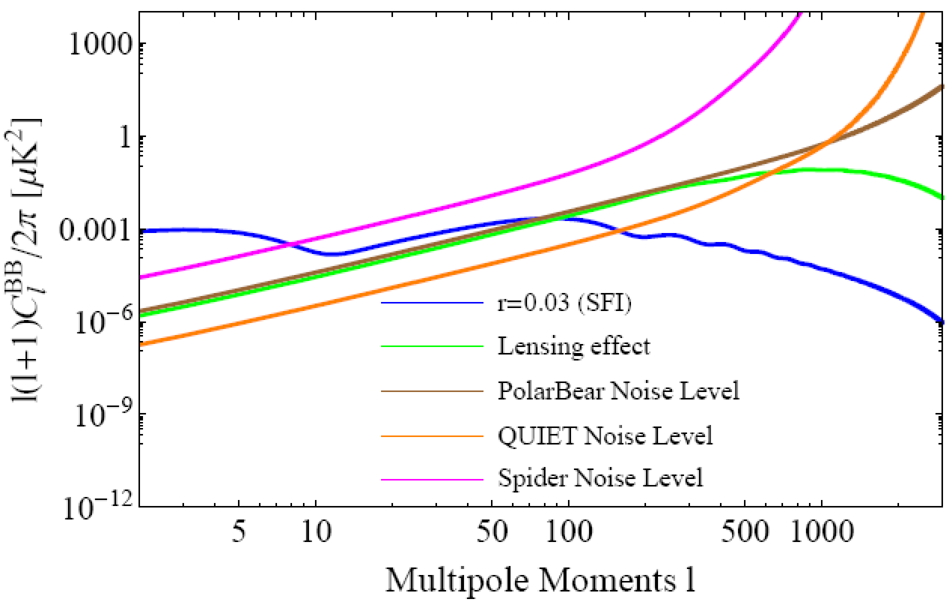
http://www.sfu.ca/levon/cmbact.html.

Models and current data:

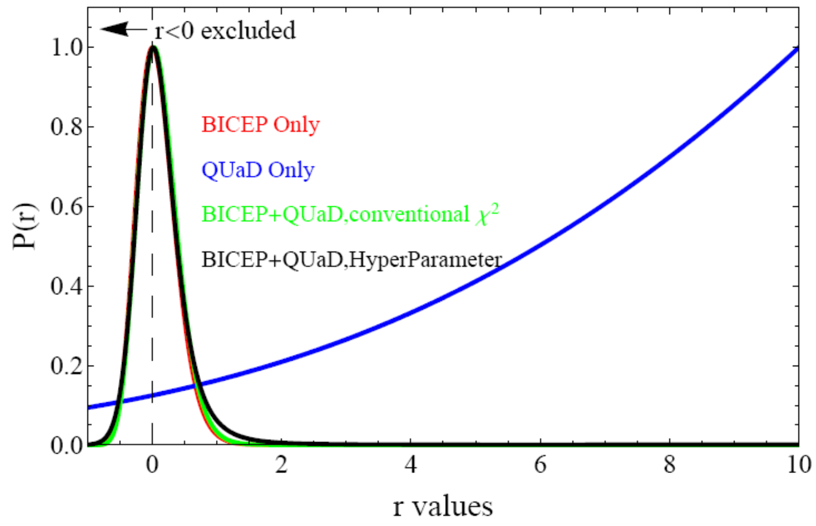


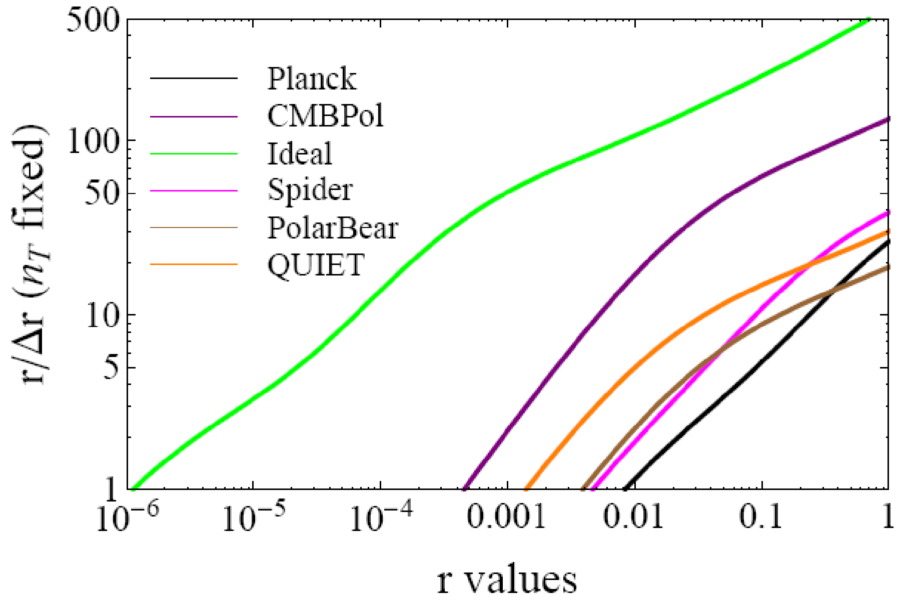
Future experiments: Instrumental noises

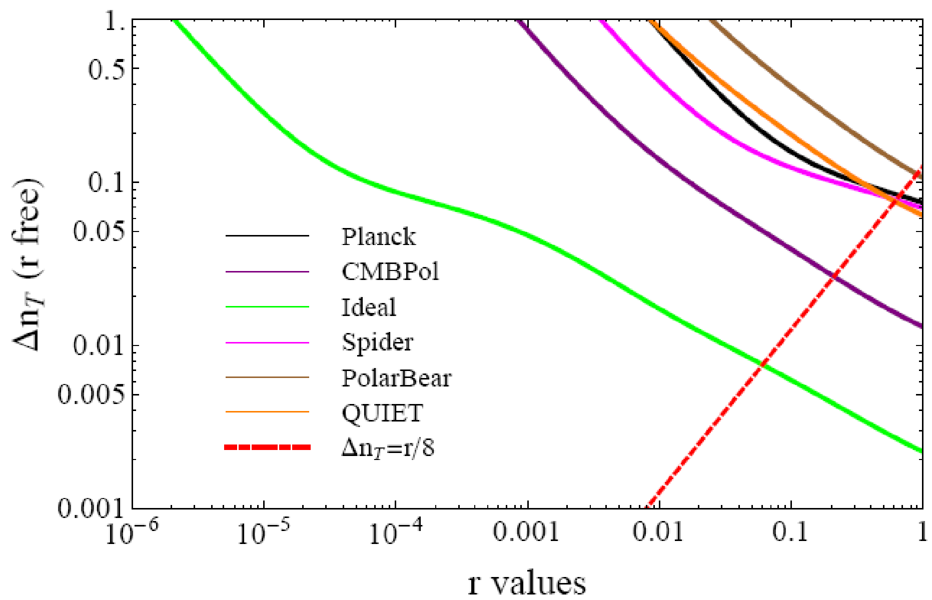




Constraining Single field slow-roll inflation model

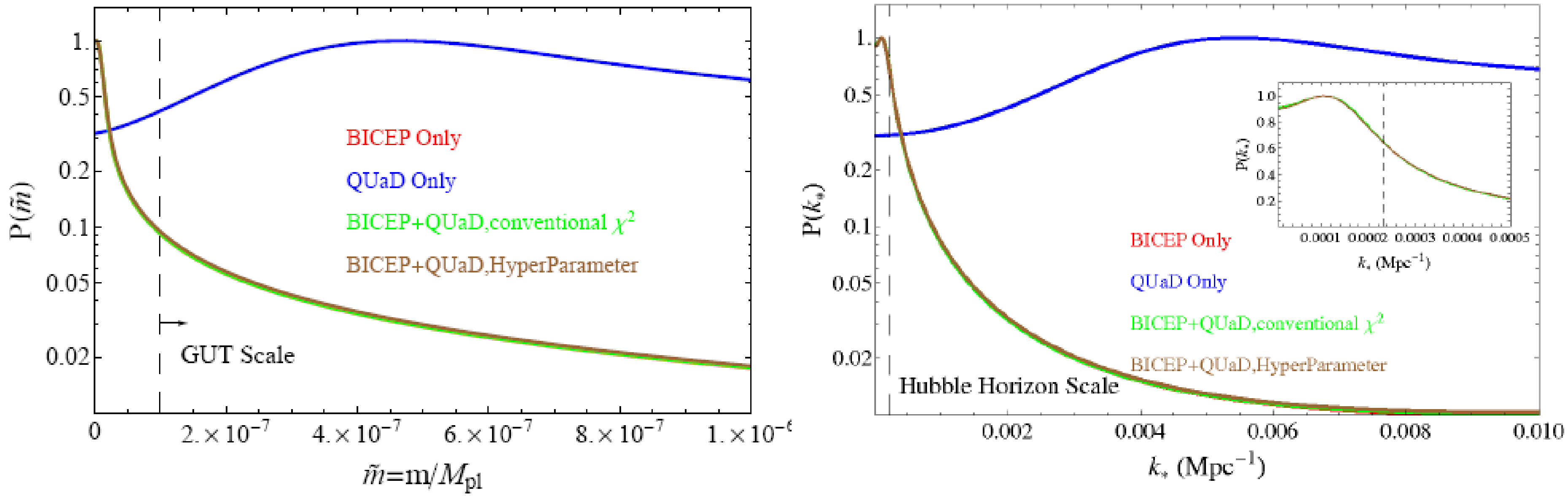


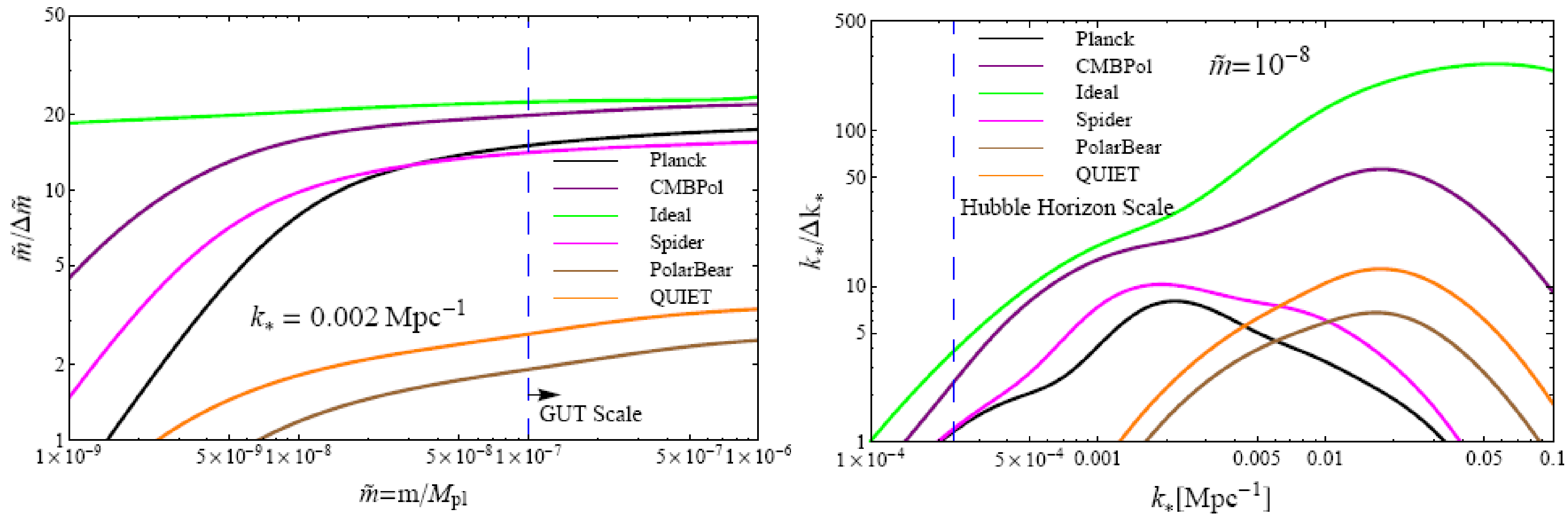




Loop Quantum Gravity:

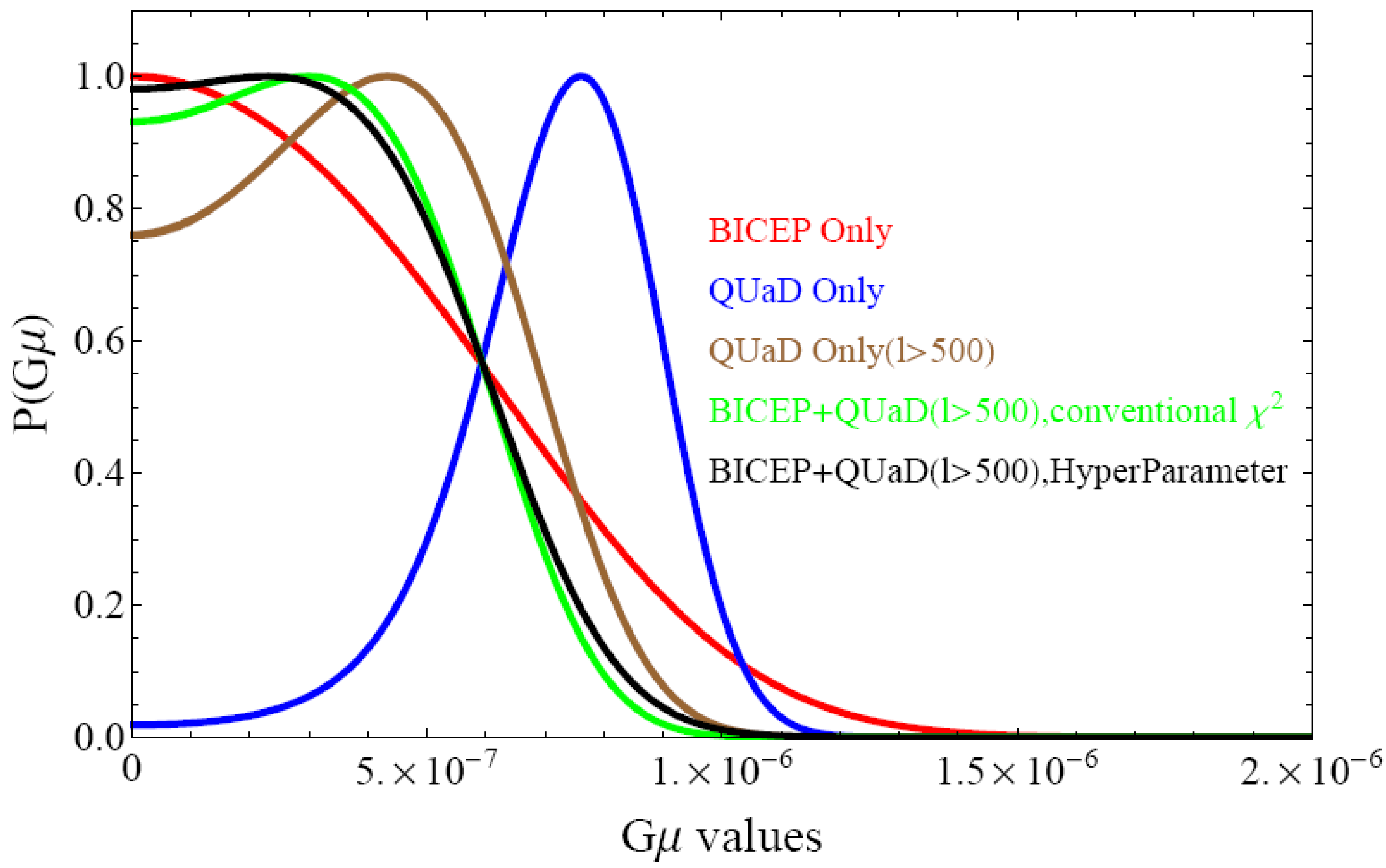
$$P_t = \frac{4N_e}{3\pi}\left(\frac{m}{\mathrm{M_{pl}}}\right)^2 \frac{1}{1+(k_*/k)^2}\left[1+\frac{4\times(8\pi)^{0.32}\times(m/\mathrm{M_{pl}})^{-0.64}-2}{1+(k/k_*)^2}\right]$$

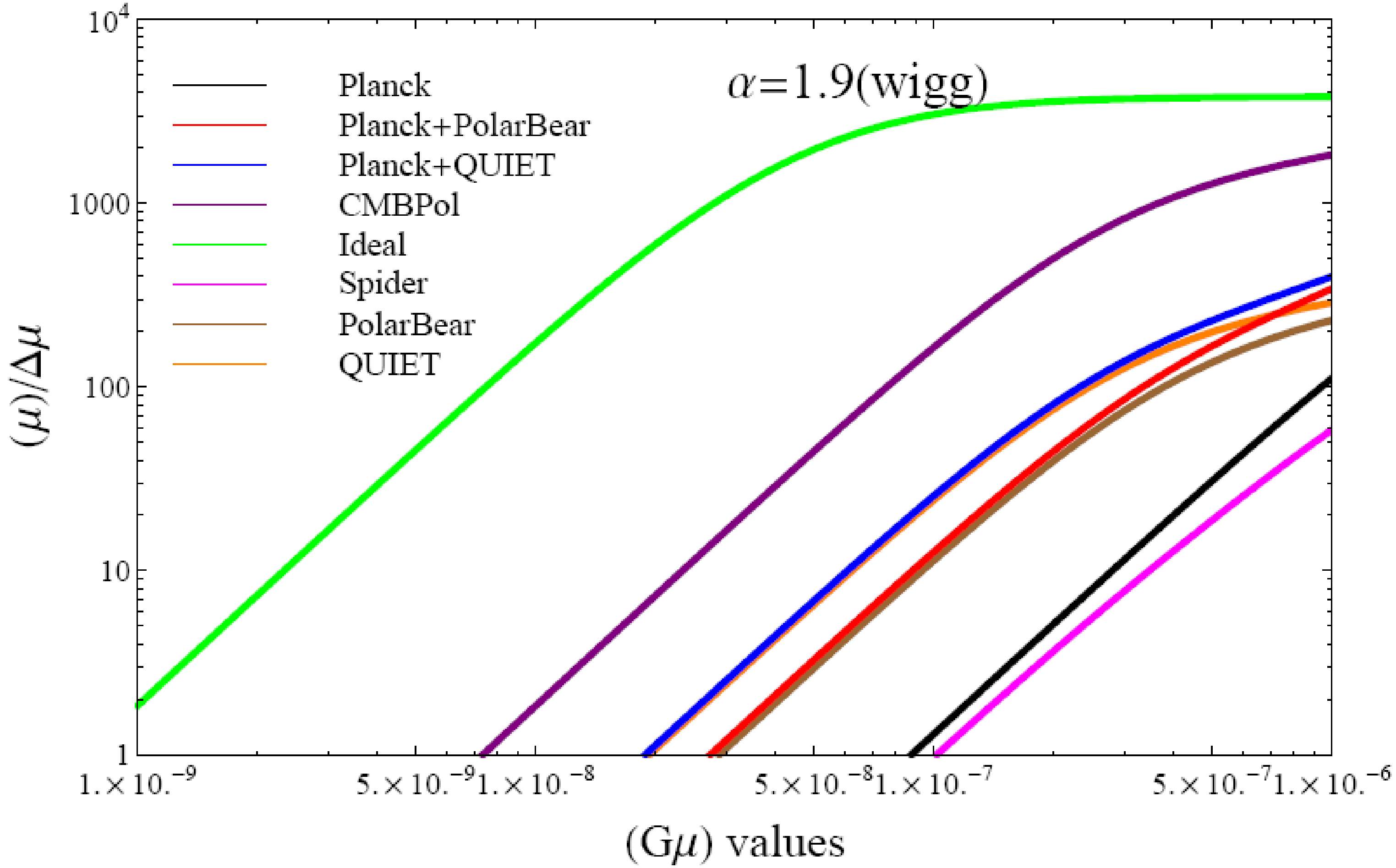




Planck
CMBPol
Ideal
Spider
PolarBear
QUIET
$k_* = 0.002\,\mathrm{Mpc}^{-1}$
GUT Scale
$\tilde{m}/\Delta\tilde{m}$
$\tilde{m}$=m/$M_{\rm pl}$
$\tilde{m}$=10^{-8}
Hubble Horizon Scale
$k_*/\Delta k_*$
$k_*[\mathrm{Mpc}^{-1}]$

Cosmic string from Brane Inflation:





Planck
Planck+PolarBear
Planck+QUIET
CMBPol
Ideal
Spider
PolarBear
QUIET
α=1.9(wigg)
$(\mu)/\Delta\mu$
$(G\mu)$ values

Summary of constraints:

SFI model:

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

LQG model, BICEP+QUaD BB Only:

$$m \leq 1.36 \times 10^{-8}\mathrm{M_{pl}} \quad k_* < 2.43 \times 10^{-4}\mathrm{Mpc}^{-1}\ (1\sigma\ \mathrm{CL})$$

Cosmic String:

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

↑ Battye and Moss, 1005.0479

Future data will be powerful to constrain these three models and may even distinguish them.

Constraining the tilted Universe from peculiar velocity field

There are several assumptions in the analysis of very large bulk flow:

- CMB frame is the same as cosmic rest frame
- Small scale velocity dispersion $\sigma_* = 150.0 \text{ km/s}$.
- Window function is on scale: 50 Mpc/h.

  but each catalogue has its characteristic scale
- Directly combine catalogues, which may induce systematics

- Testing the first and second assumptions: tilted Universe
- Testing the other assumptions: future work

If there is a relative motion between CMB frame and cosmic rest frame:

Observed line of sight velocity in cosmic rest frame:

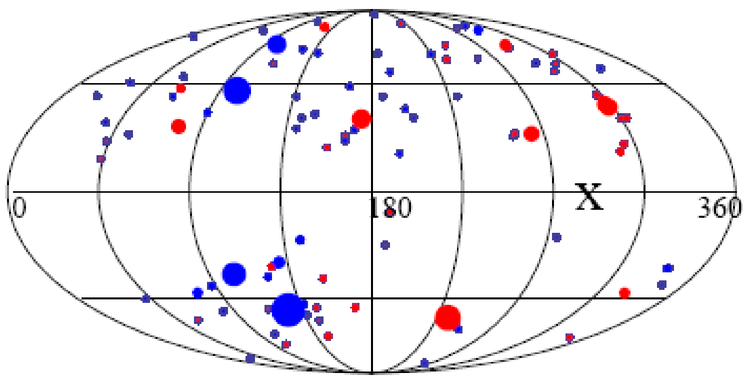
$$p_n(\mathbf{u}) = \breve{S}_n - \breve{\hat{r}}_{n,i} u_i,$$

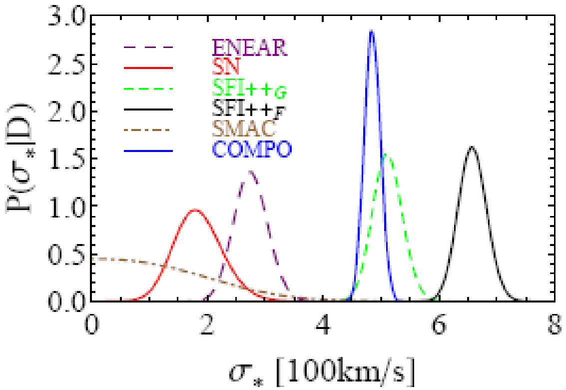
Covariance matrix:

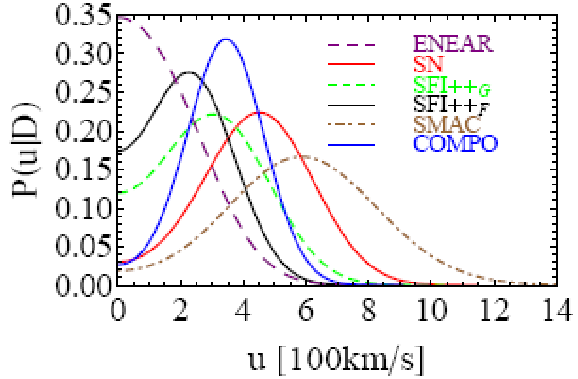
$$G_{nm} \;=\; \langle v_n v_m \rangle + \delta_{nm}(\sigma_n^2 + \sigma_*^2)$$

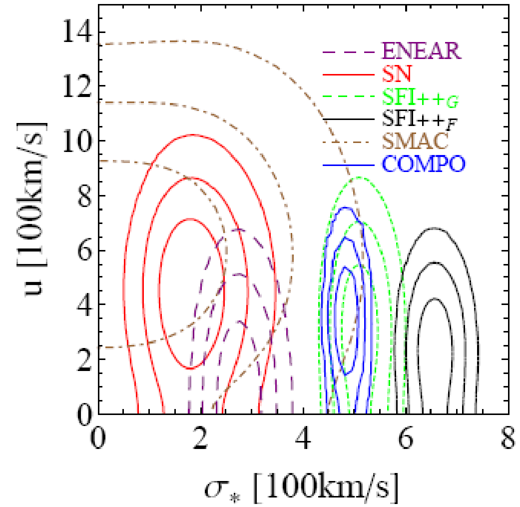
Likelihood of tilted velocity and small scale velocity dispersion:

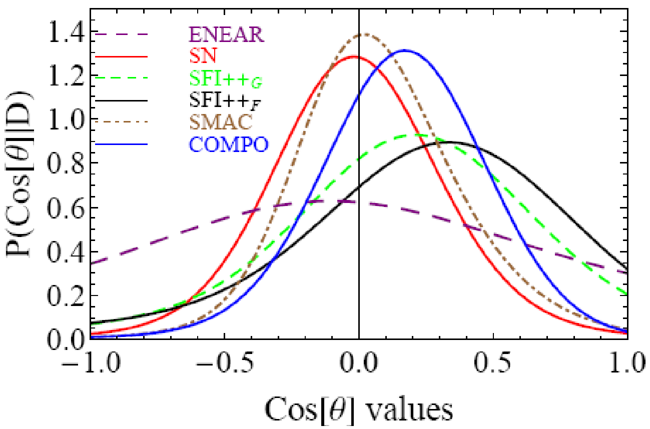
$$L(\mathbf{u}, \sigma_*) = \frac{1}{(\det G_{nm})^{\frac{1}{2}}} \exp\left(-\frac{1}{2} p_n(\mathbf{u}) G^{-1}_{nm} p_m(\mathbf{u})\right)$$

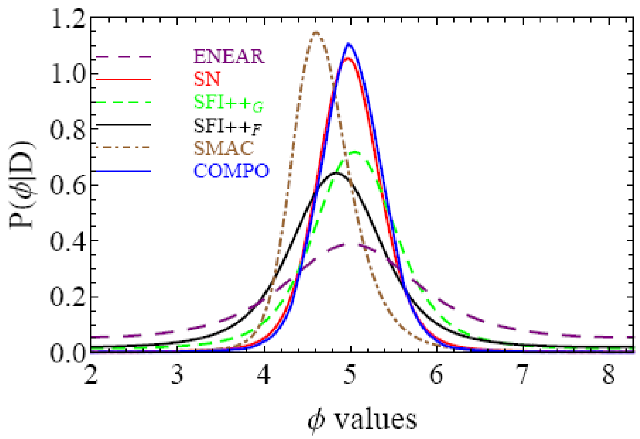












The angles are consistent with Watkins et al.2009

The physical implication of tilted velocity:

Super-horizon dipole modulation can only be generated by isocurvature perturbation:

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

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

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

It therefore provides constraints on the number of e-folds of inflation

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	$4.83^{+0.16}_{-0.12}$	$3.44^{+1.25}_{-1.27}$	$285.12^{+23.89}_{-19.50}$	$9.08^{+18.52}_{-17.84}$	$6 \leq \Delta N \leq 8$

Therefore, inflation has to last modest number of e-folds.

Summary:

- Apparent lack of large angular correlation:

cut-sky pixel-estimator+ a posteriori statistic

- Current B-mode polarization data has already reached the constraining level of all the other data; future data will be more powerful in constraining early Universe.
- Tilted Universe is a potentially interesting scheme to explain bulk flow phenomena.