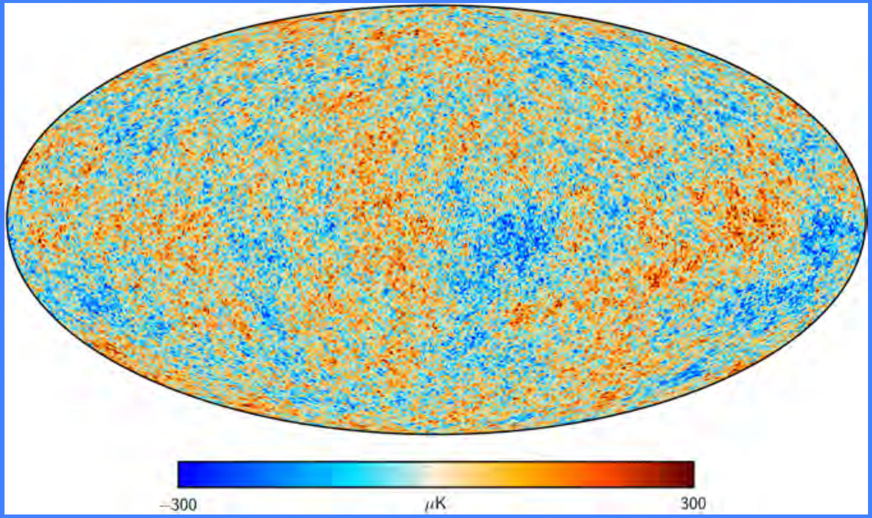
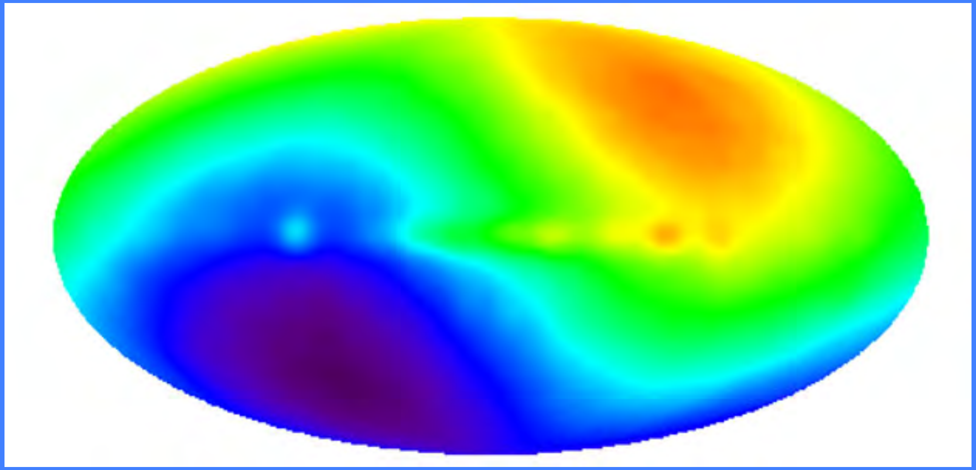
Constraints on the birth of the universe and the origin of cosmic dark flow

Grant J. Mathews -*University of Notre Dame*

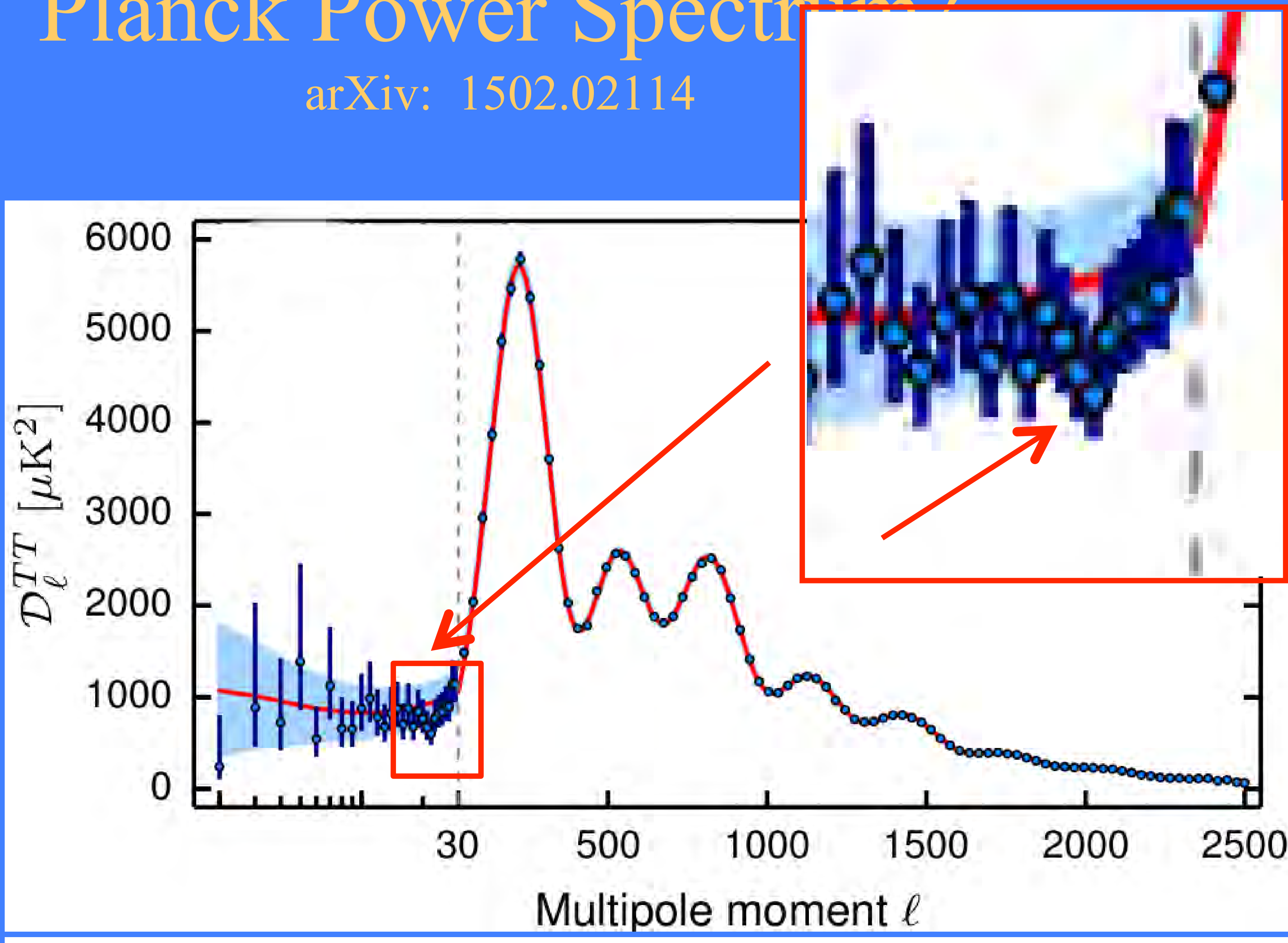
2015: The Spacetime Odyssey Continues
Peperska Muren, Stockholm
June 2-5, 2015



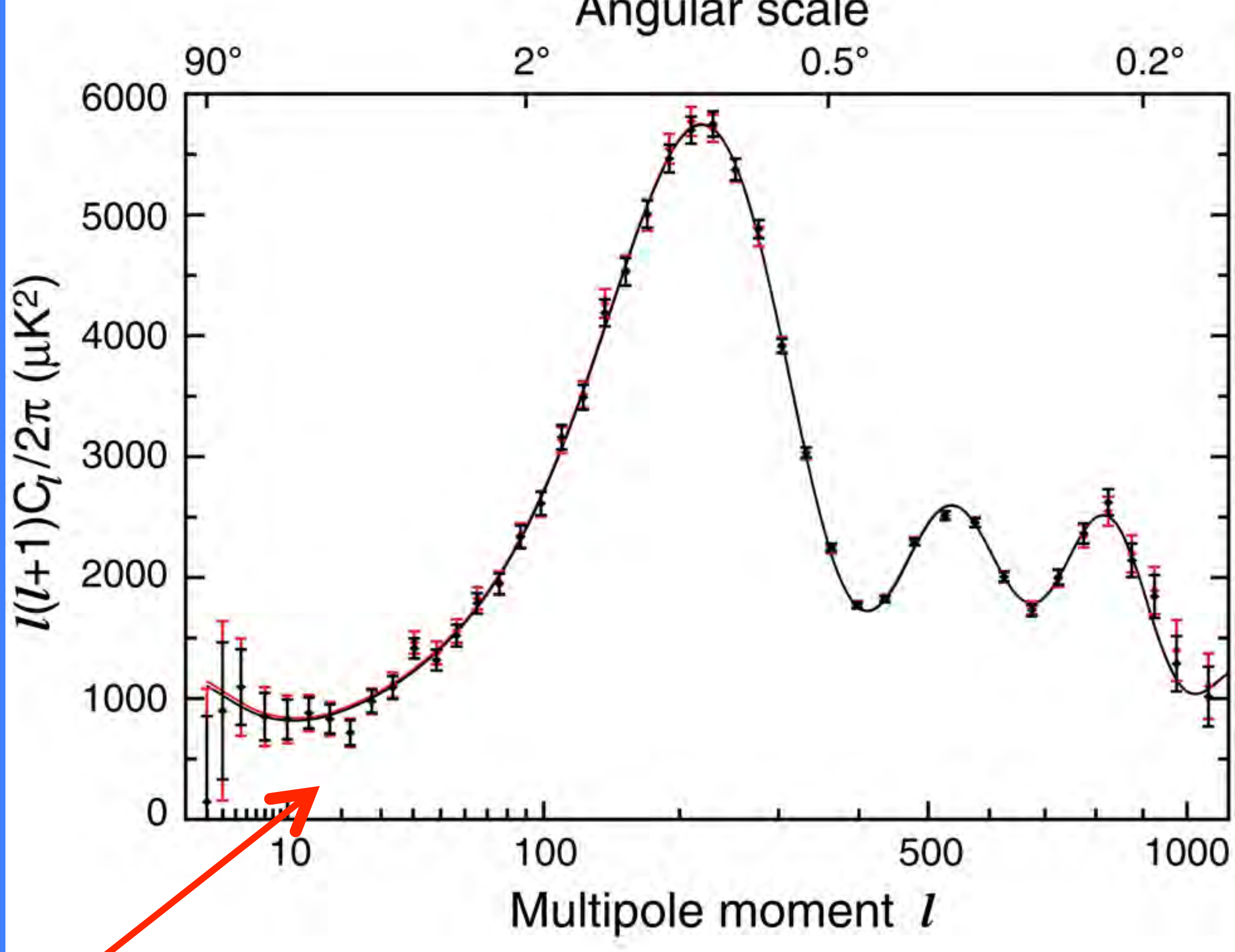


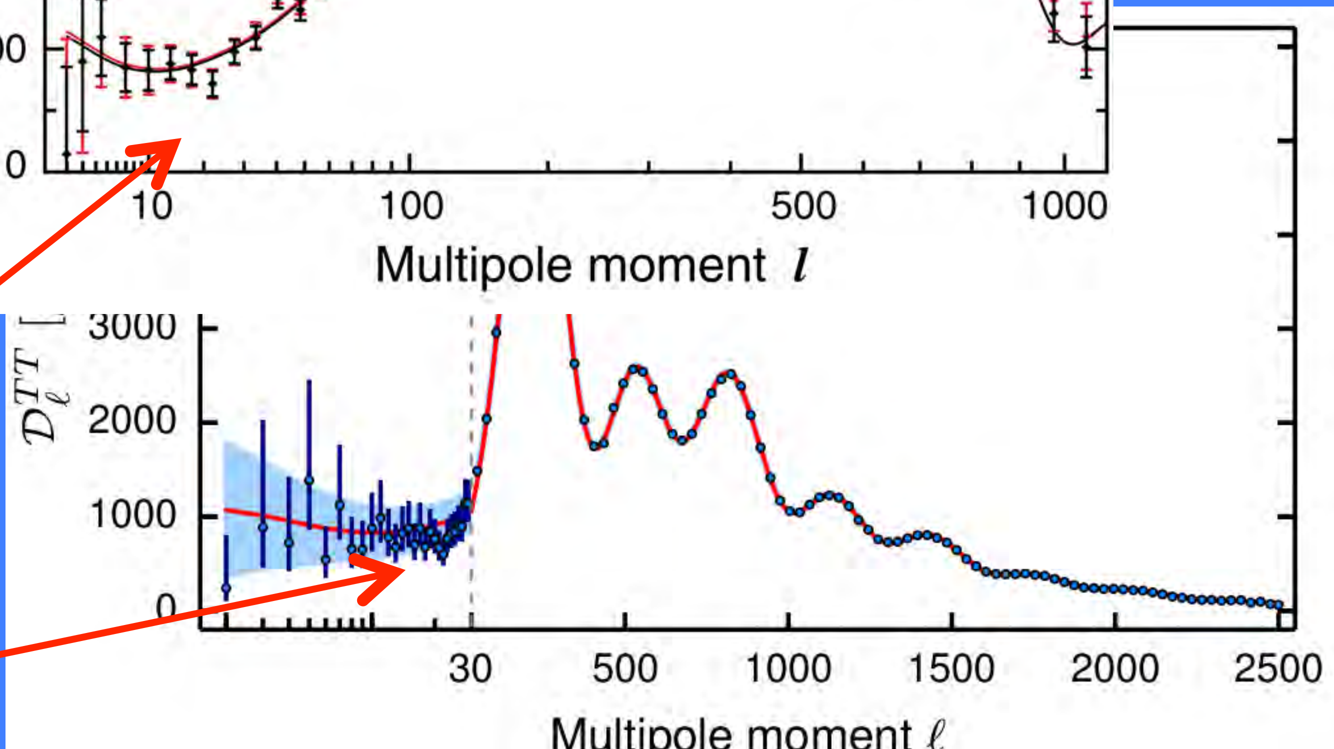
Is there something new in the Planck Power Spectrum?

arXiv: 1502.02114

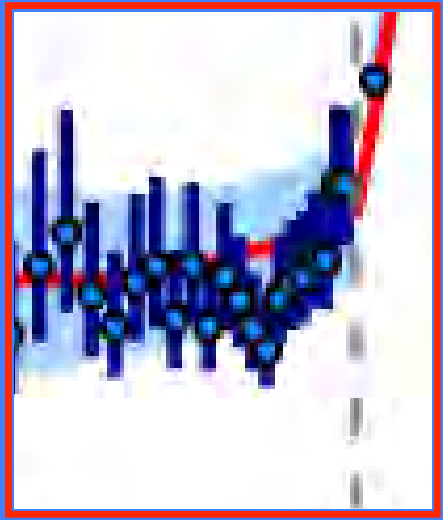


WMAP 9yr


Angular scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ (μK²)
10
100
500
1000
Multipole moment l


$\mathcal{D}_\ell^{TT}$
3000
2000
1000
0
30
500
1000
1500
2000
2500
Multipole moment ℓ

Some possible explanations for dip at ℓ = 10-40



- Cosmic Variance
- Modified inflation effective potential
  - Harza, et al. arXiv:1405.2012
- Planck-mass particles coupled to inflation
  - GJM, Gangopadhya, Ichiki, Kajino arXiv: 1504.06913
- ….
- ….

Possible evidence for Planck-scale resonant particle production during inflation

G JM., Gangopadhyay,. Ichiki, Kajino, arXiv:1504.06913;
D. Chung, E. W. Kolb, A. Riotto, and I. I. Tkachev,D62, 043508 (2000);
GJM, D. Chung, K. Ichiki, T. Kajino, and M.Orito, PRD70, 083505 (2004).

- Planck-mass particles generically exist in compactification schemes of string theory from the:
  - Kaluza-Klein states
  - Winding modes
  - Massive excited (string) modes
- Coupling such particles with the inflaton field is also generic
- Premise of this idea:
  - Suppose this coupling happens during the ~10 e-folds of inflation accessible to observation

- The total Lagrangian density is given as :

$$\mathcal{L}_{\rm tot} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) + i\bar{\psi}\gamma^\mu\psi - m\bar{\psi}\psi + N\lambda\phi\bar{\psi}\psi$$

- Then the fermion has the effective mass :

$$M(\phi) = m - N\lambda\phi$$

- This vanishes for a critical value of the inflaton field, $\phi_* = m/N\lambda$

Fermions will be quickly generated at some time t_* when the effective mass vanishes at φ_*

- The fermion vacuum expectation value is :

$$\langle\bar{\psi}\psi\rangle = n_*\Theta(t-t_*)\exp\left[-3H_*(t-t_*)\right]$$

where Θ is a step function.

- The modified E.O.M. for the scalar field is:

$$\ddot{\phi} + 3H\dot{\phi} = -V'(\phi) + N\lambda\langle\bar{\psi}\psi\rangle$$

Slow-roll

$$\dot{\phi} = \frac{-V'(\phi) + N\lambda\langle\bar{\psi}\psi\rangle}{3H}$$

Fluctuation at horizon crossing:

$$\delta_H(a) = \frac{H^2}{5\pi\dot{\phi}}$$

$$\delta_H = \frac{[\delta_H(a)]_{N\lambda=0}}{1 + \Theta(a - a_*)(N\lambda n_*/|\dot{\phi}_*|H_*)(a_*/a)^3 \ln(a/a_*)} \quad (6)$$

Causes Dip

Can relate to a given wave number k

$$\ln \frac{k}{a_0 H_0} = 62 + \ln\left[\frac{a}{a_*}\right] + \ln\left[\frac{a_*}{a_{\rm end}}\right] - \ln \frac{10^{16}\,{\rm GeV}}{V_k^{1/4}} + \ln \frac{V_k^{1/4}}{V_{\rm end}^{1/4}} - \frac{1}{3}\ln \frac{V_{\rm end}^{1/4}}{\rho_{\rm reh}^{1/4}}$$

=> Revised primordial power spectrum

$$\delta_H(k) = \frac{[\delta_H(a)]_{N\lambda=0}}{1 + \Theta(k - k_*) A (k_*/k)^3 \ln(k/k_*)}$$

$$A = |\dot{\phi}_*|^{-1} N \lambda n_* H_*^{-1}$$

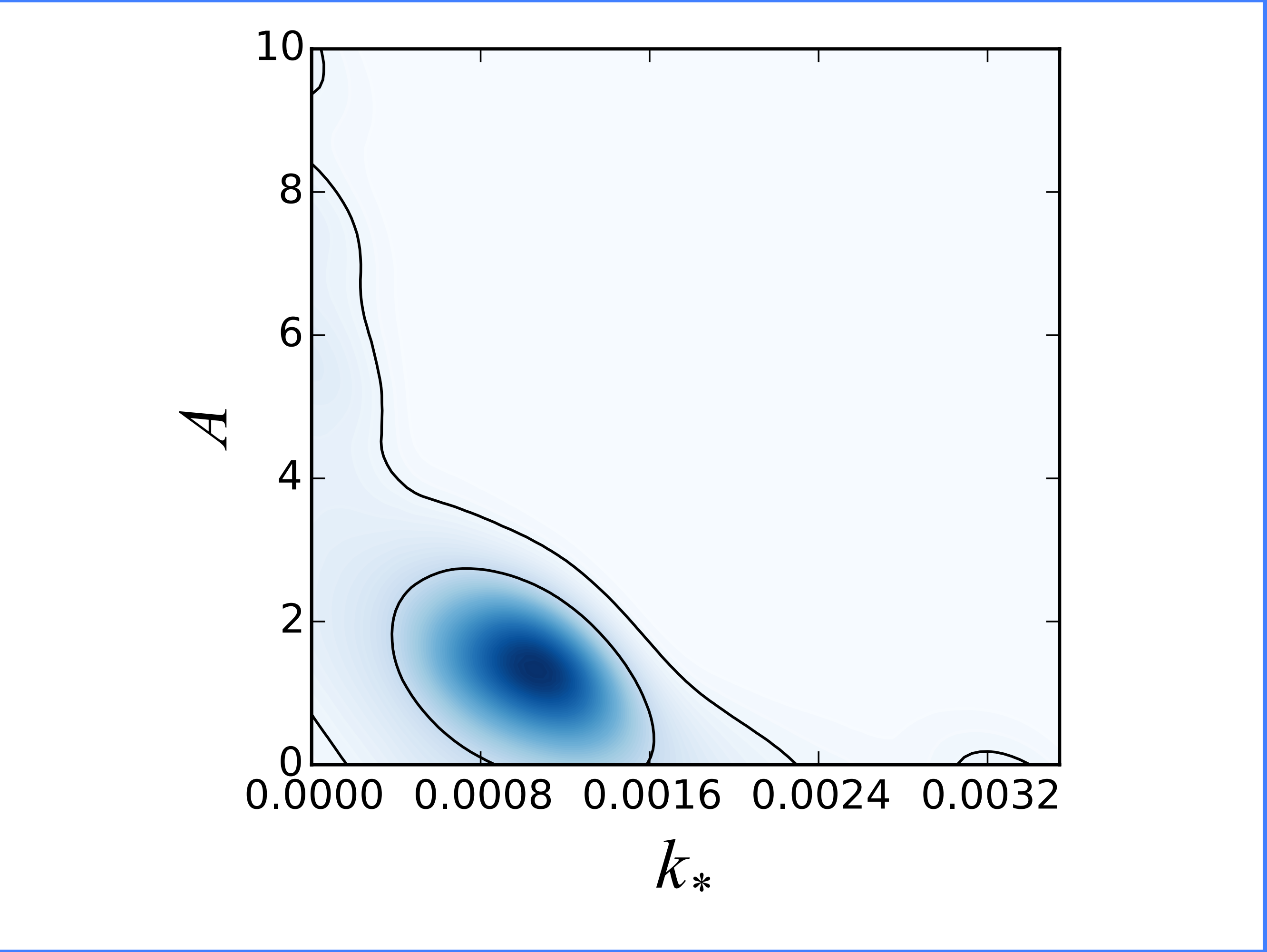
A = amplitude

k_* wave number associated with particle creation

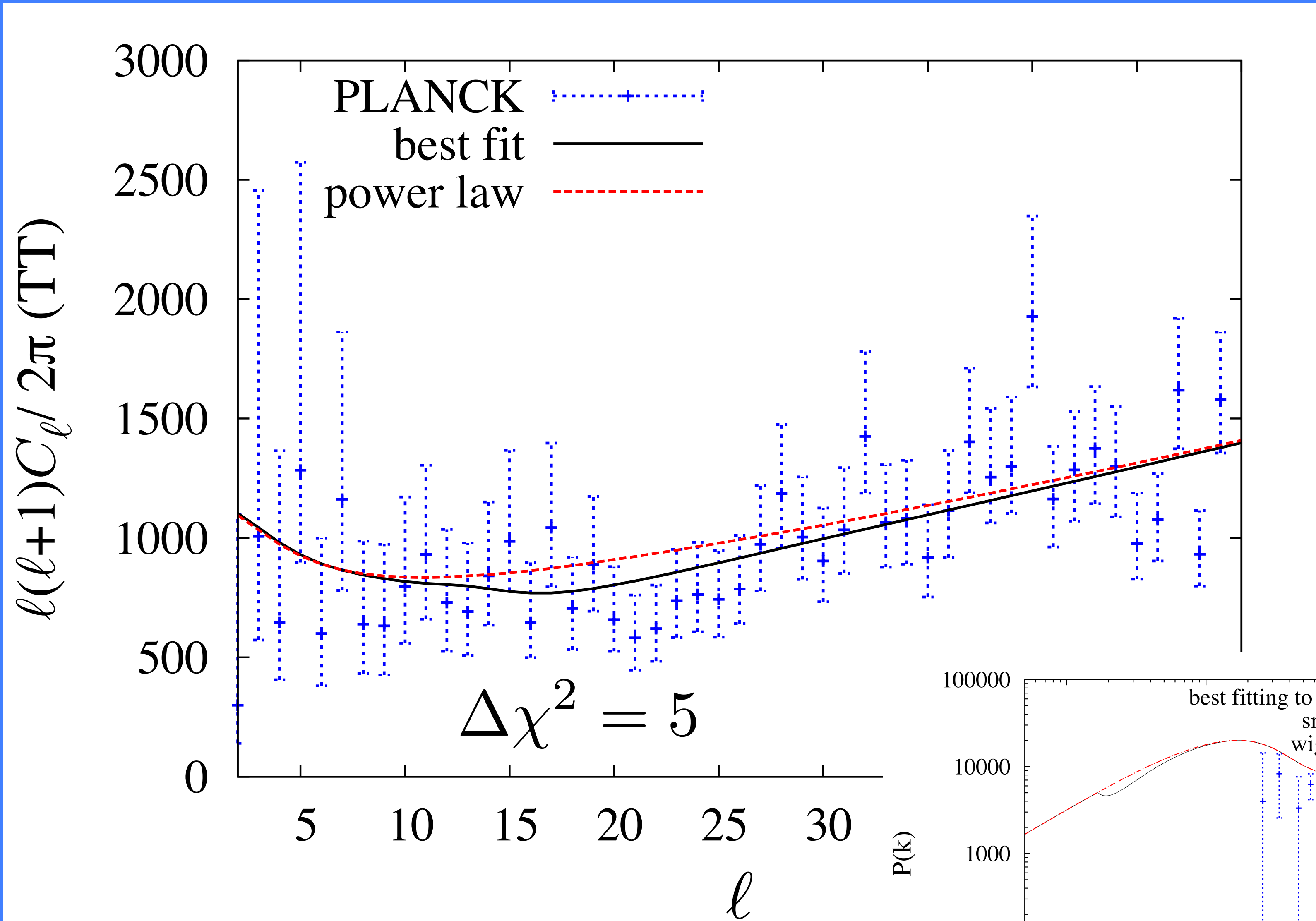
Analysis

- Markov Chain Monte-Carlo analysis using Planck Data and the CosmoMC code
- Marginalized over A and k_*, along with the six parameters, $\Omega_b h^2, \Omega_c h^2, \theta, \tau, n_s, A_s$

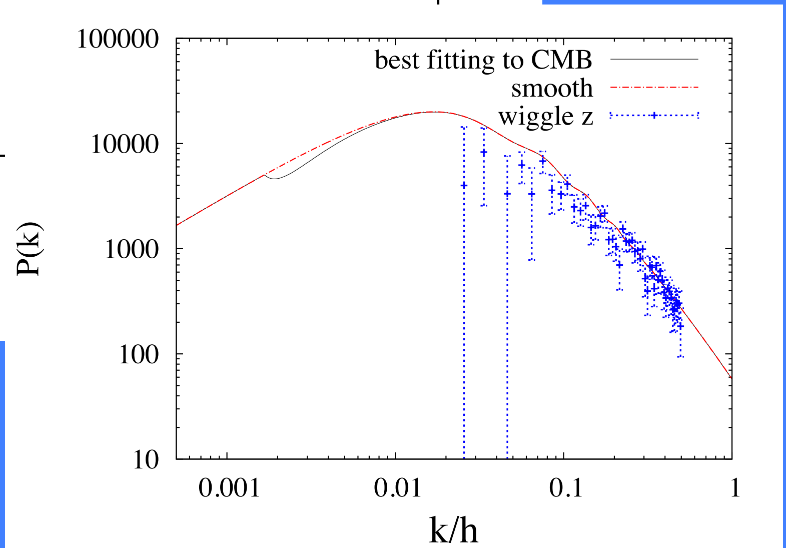
Results



$A = 1.7 \pm 1.5$ $\quad$ $k_* = 0.0011 \pm 0.0004\ h\ \mathrm{Mpc}^{-1}$



PLANCK
best fit
power law
$\ell(\ell+1)C_\ell/2\pi$ (TT)
$\Delta\chi^2 = 5$
ℓ



best fitting to CMB
smooth
wiggle z
P(k)
k/h

A and k_* relate to the inflaton coupling λ and the fermion mass m for a given inflation model:

$$A = |\dot{\phi}_*|^{-1} N \lambda n_* H_*^{-1}$$

$$n_* = \frac{2}{\pi^2} \int_0^\infty dk_p \, k_p^2 \, |\beta_k|^2 = \frac{N\lambda^{3/2}}{2\pi^3} |\dot{\phi}_*|^{3/2}$$

$$A \sim 1.3 N \lambda^{5/2}$$

A=1.5 => $N\lambda^{5/2} \sim 1$

$$m = N\lambda\phi_*$$

$$\phi_* = \sqrt{2\alpha N} m_{pl}$$

$2/3 < \alpha < 2$

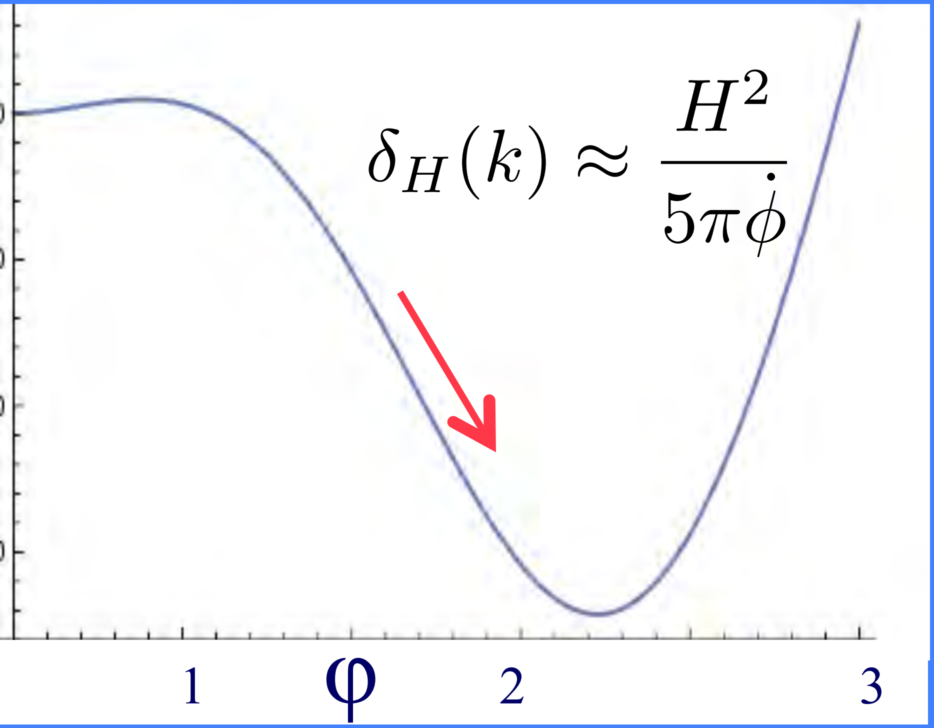
$m \sim$ 6-10 $M_{pl}/\lambda^{3/2}$

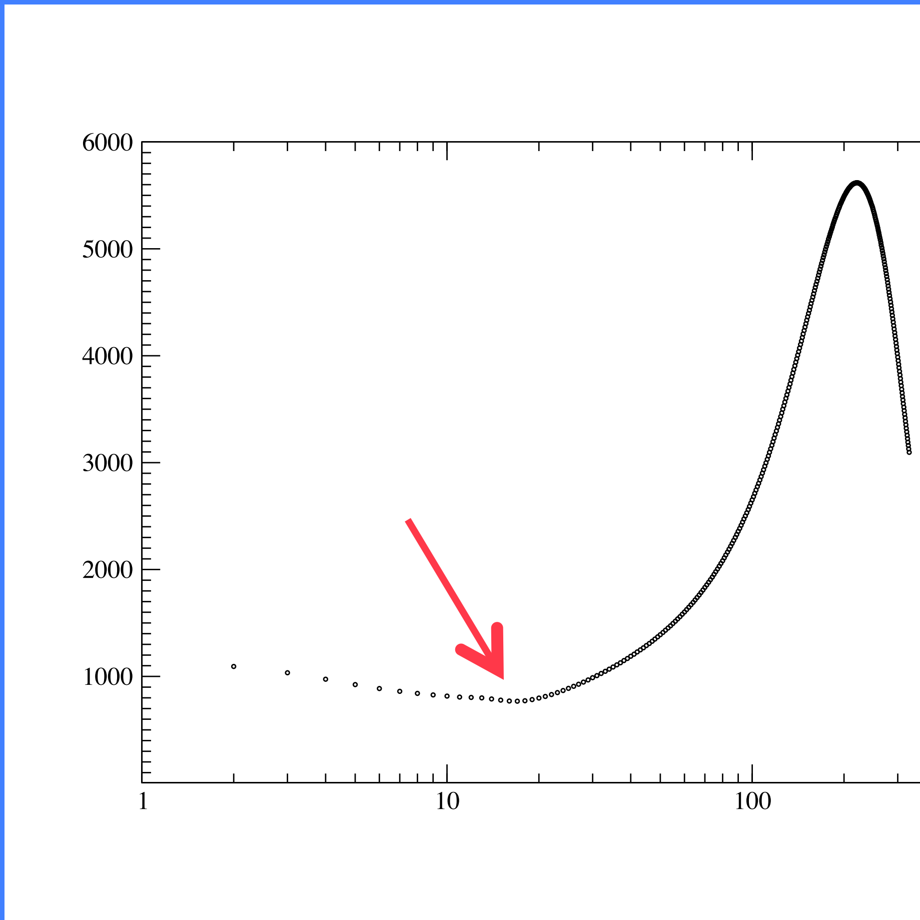
Is there another possibility?

- Modify the inflaton effective potential during inflation

Modified Inflaton effective potential

$$V(\varphi) = \frac{1}{2}m\varphi^2 + \lambda M_{Pl}^4 \exp\left[(-\varphi/\varphi_1)^\alpha\right]$$





Could this potential have another consequence?

- Cosmic Dark Flow

Landscape after inflation:

"Tilt" due to quantum entanglement

Mersini-Houghton & Holman PRD (2008)

$$\Phi = \Phi^0 + \delta\Phi \simeq \Phi^0 \left[1 + \frac{V(\phi)F(b,V)}{3M_{pl}^2}\left(\frac{r}{L_1}\right) \right]$$

L_1 = scale of quantum interference ~ 1000 r_H

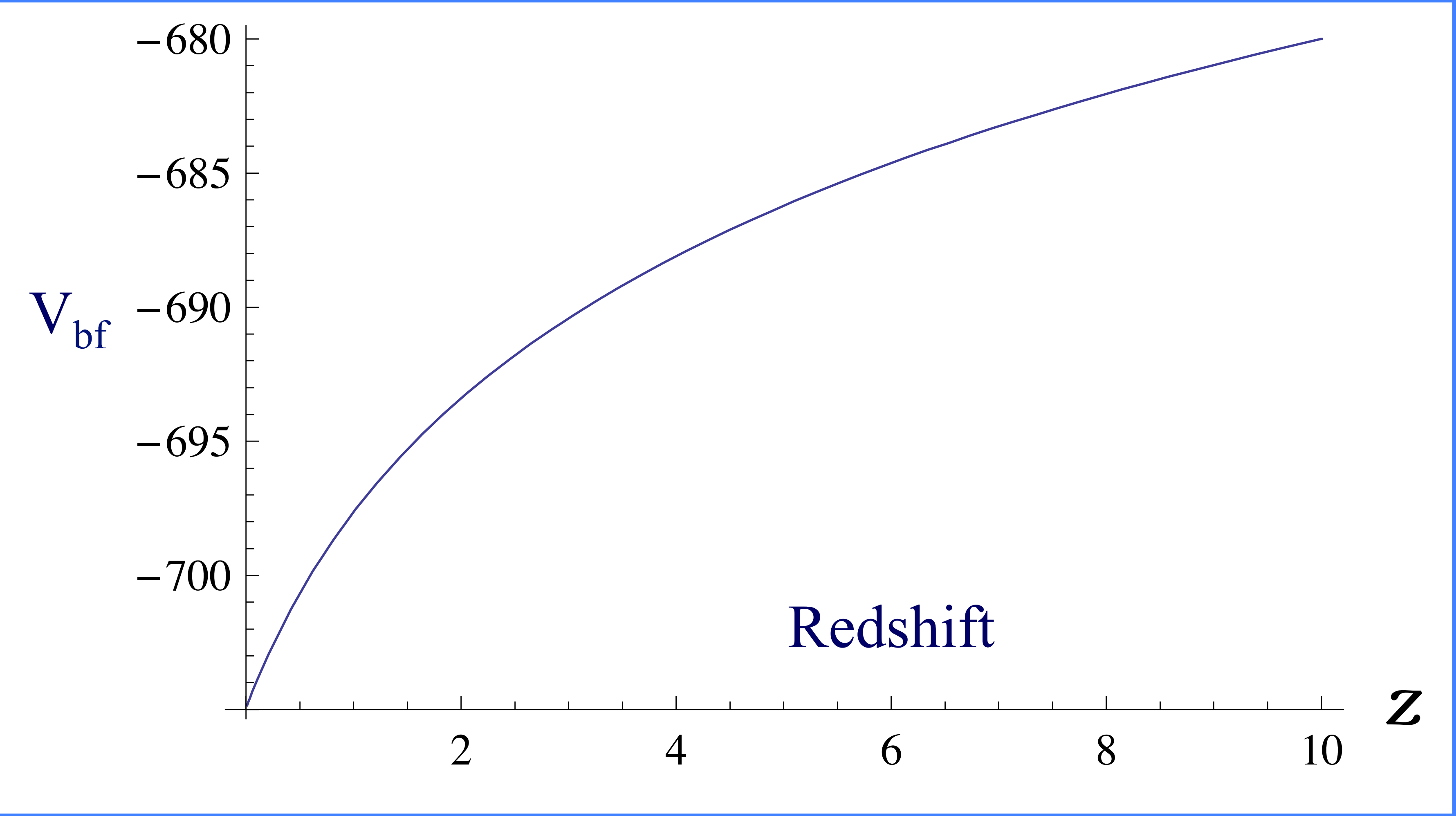
Dark flow velocity =

$$\beta = \frac{v}{c} \simeq \alpha\left(\frac{\Delta T}{T}\right)\Big|_{\text{dip}} \simeq \frac{4\pi}{15}\left(\frac{r_H}{L_1}\right)\left(\frac{V(\phi)F(b,V(\phi))}{18M_{\text{Pl}}^4}\right)$$

Predicted dark flow velocity ~700 km s^{-1}

$$V(\phi) = V_0 \exp\left(-\lambda \frac{\phi}{M_P}\right)$$

Mersini-Houghton & Holman PRD (2008)



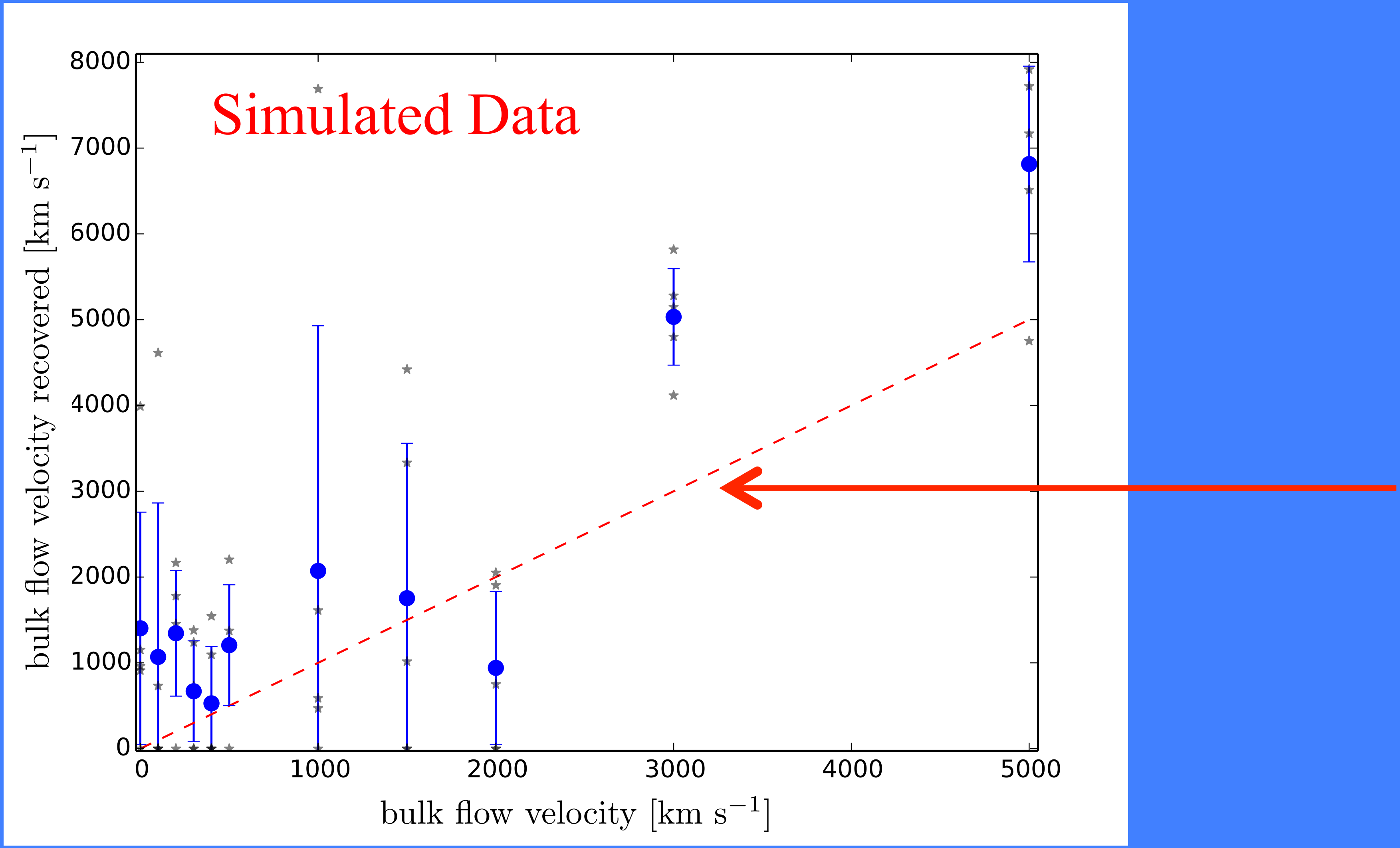
Searches for Dark Flow

GJM, Rose Garnavich, Yamazaki, Kajino, arXiv1412.1529

TABLE I. Summary of dark flow searches. Distance and redshifts are either the maximum or a characteristic value if available.

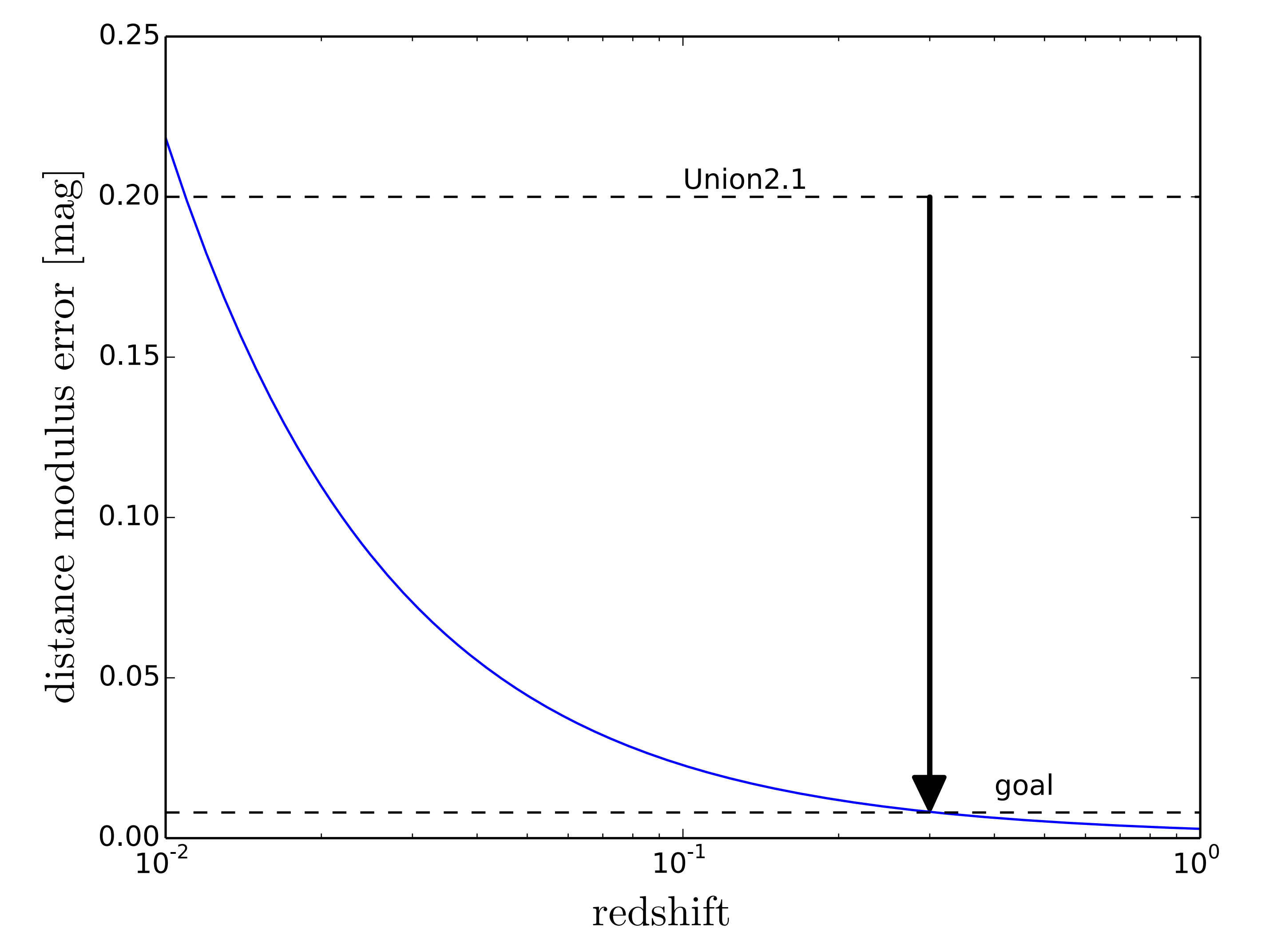
Reference	Obj. Type	No. Obj.	Redshift Range	Distance (h^{-1} Mpc)[a]	$v_{\rm bf}$ (km s^{-1})	$(l, b)^\circ$
Kashlinsky et al. (2010), [2]	kSZ	516	$z < 0.12$	< 345	934 ± 352	$(282 \pm 34, 22 \pm 20)$
		547	$z < 0.16$	< 430	1230 ± 331	$(292 \pm 21, 27 \pm 15)$
		694	$z < 0.20$	< 540	1042 ± 295	$(284 \pm 24, 30 \pm 16)$
		838	$z < 0.25$	< 640	1005 ± 267	$(296 \pm 29, 39 \pm 15)$
Dai et al. (2011), [23]	SN Ia	132	$z < 0.05$	< 145	188 ± 120	$(290 \pm 39, 20 \pm 32)$
		425	$z > 0.05$	> 145	——	——-
Weyant et al. (2011), [26]	SN Ia	112	$z < 0.028$	< 85	538 ± 86	$(250 \pm 100, 36 \pm 11)$
Ma et al. (2011), [22]	galaxies & SN Ia	4536	$z < 0.011$	< 33	340 ± 130	$(285 \pm 23, 9 \pm 19)$
Colin et al. (2011), [27]	SN Ia	142	$z < 0.06$	< 175	260 ± 130	$(298 \pm 40, 8 \pm 40)$
Turnbull et al. (2012), [28]	SN Ia	245	$z < 0.05$	< 145	245 ± 76	$(319 \pm 18, 7 \pm 14)$
Feindt et al. (2013), [29]	SN Ia	128	$0.015 < z < 0.035$	$45 - 108$	243 ± 88	$(298 \pm 25, 15 \pm 20)$
		36	$0.035 < z < 0.045$	$108 - 140$	452 ± 314	$(302 \pm 48, -12 \pm 26)$
		38	$0.045 < z < 0.060$	$140 - 188$	650 ± 398	$(359 \pm 32, 14 \pm 27)$
		77	$0.060 < z < 0.100$	$188 - 322$	105 ± 401	$(285 \pm 234, -23 \pm 112)$
Ma & Scott (2013), [25]	galaxies	2404	$z < 0.026$	< 80	280 ± 8	$(280 \pm 8, 5.1 \pm 6)$
Rathaus et al. (2013), [30]	SN Ia	200	$z < 0.2$	< 550	260	$(295, 5)$
Planck XIII (2014), [6]	kSZ	95	$0.01 < z < 0.03$	30 - 90	< 700	——-
		1743	$z < 0.5$	< 2000	< 254	——-
Appleby et al. (2014), [31]	SN Ia	187	$0.015 < z < 0.045$	45 - 130	——	$(276 \pm 29, 20 \pm 12)$
Cartesian fit - present work	SN Ia	198	$z < 0.05$	< 145	270 ± 50	$(295 \pm 30, 10 \pm 15)$
		432	$z > 0.05$	> 145	1000 ± 600	$(120 \pm 80, -5 \pm 30)$
Cosine fit - present work	SN Ia	191[b]	$z < 0.05$	< 145	325 ± 54	$(276 \pm 15, 37 \pm 13)$
		387	$z > 0.05$	> 145	460 ± 260	$(180 \pm 34, 65 \pm 340)$

Would need a very high bulk flow to be detectable at $z > 0.05$



GJM, Rose Garnavich, Yamazaki, Kajino, arXiv1412.1529

Need reduced Error in Distance Modulus



Need 30,000 Redshifts out to z~0.3

LSST?

Status

There appears to be a dark flow <300 km s^{-1} out to > 150 Mpc h^{-1}

Dark flow is not ruled out at higher redshifts

Is it possible to lower the landscape prediction?

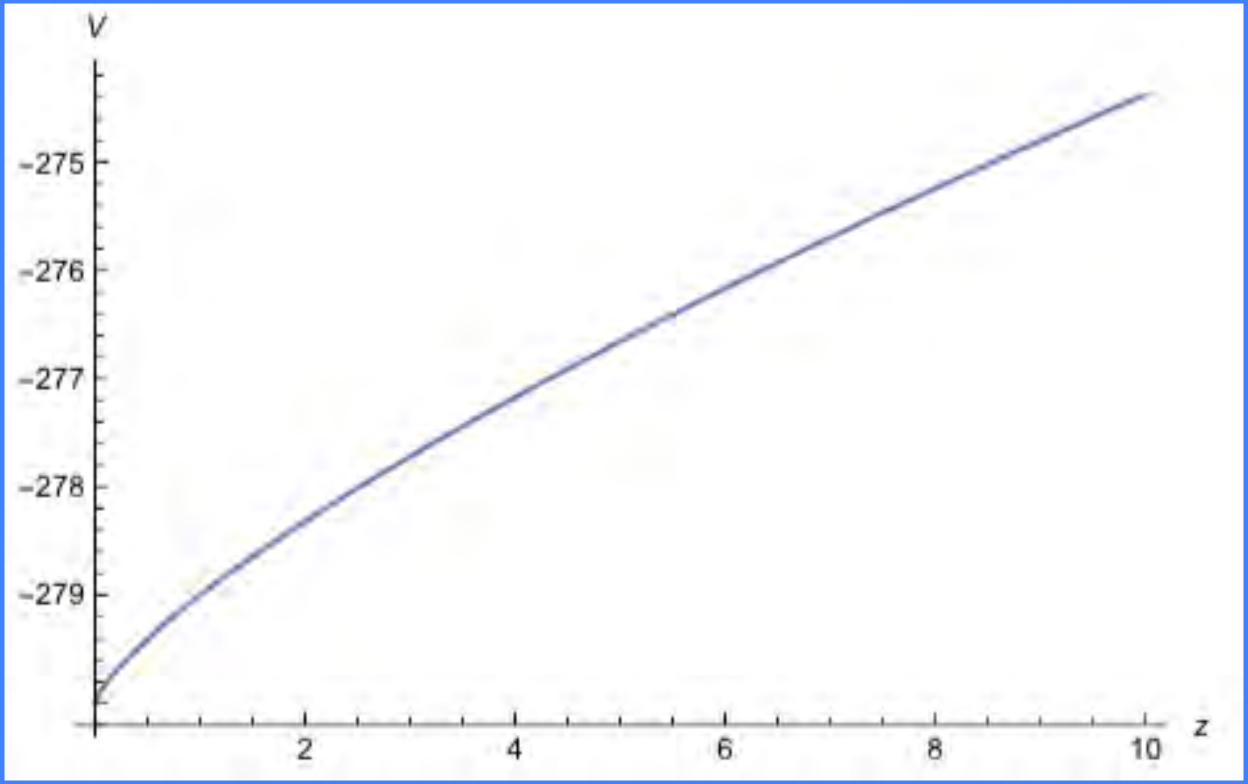
$$\beta = \frac{v}{c} \simeq \alpha\left(\frac{\Delta T}{T}\right)\Big|_{\rm dip} \simeq \frac{4\pi}{15}\left(\frac{r_H}{L_1}\right)\left(\frac{V(\phi)F(b,V(\phi))}{18 M_{\rm Pl}^4}\right)$$

Yes, for an effective potential with a steep drop

Apparent Bulk flow velocities (km s^{-1})

$$V(\varphi) = \frac{1}{2}m\varphi^2 + \lambda M_{Pl}^4 \exp\left[(-\varphi/\varphi_1)^\alpha\right]$$

V_{bf}



Redshift

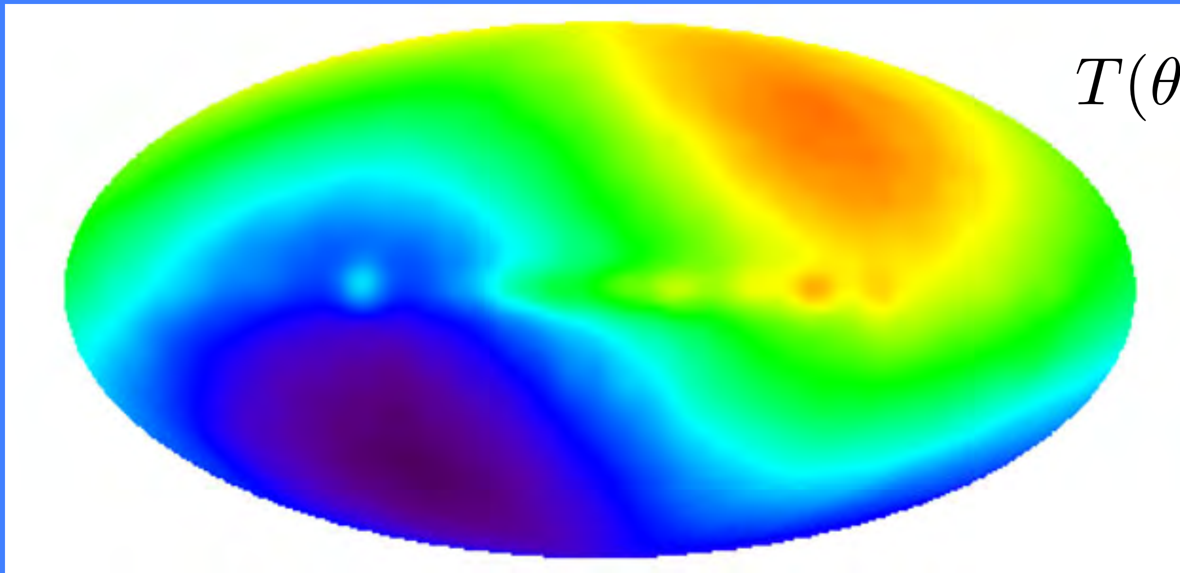
Conclusions

- Possible evidence of new Planck-scale physics in the CMB power spectrum for $\ell = 20\text{-}40$.
- Or an abrupt change in the inflation effective potential
- There is a possible existence of dark flow of ~ 250 km s^{-1} out to a scale of nearly 200 Mpc h^{-1}
- However, detection of dark flow at high redshift remains ambiguous.
- Need a more complete sky coverage and larger sample of SNIa (*LSST*)

Theoretical Motivation for Dark/Bulk Flow

- Open inflation => pre-inflation isocurvature fluctuations visible (Kurki-Suonio, GJM (1991), Sasaki et al (1993), …
  - CMB dipole ≠ CMB rest frame
- Existence of other fields in addition to inflation – Turner (1981), Linde (1995) …
- Double Inflation (Langlois 1996)
- Pre-inflation landscape – Quantum entanglement of the wave-function for the universe with those of super-horizon modes
  - Mersini-Houghton (2005), Holman & Mersini-Houghton (2006) and Holman, Mersini- Houghton & Takahashi (2008a)

CMB Dipole



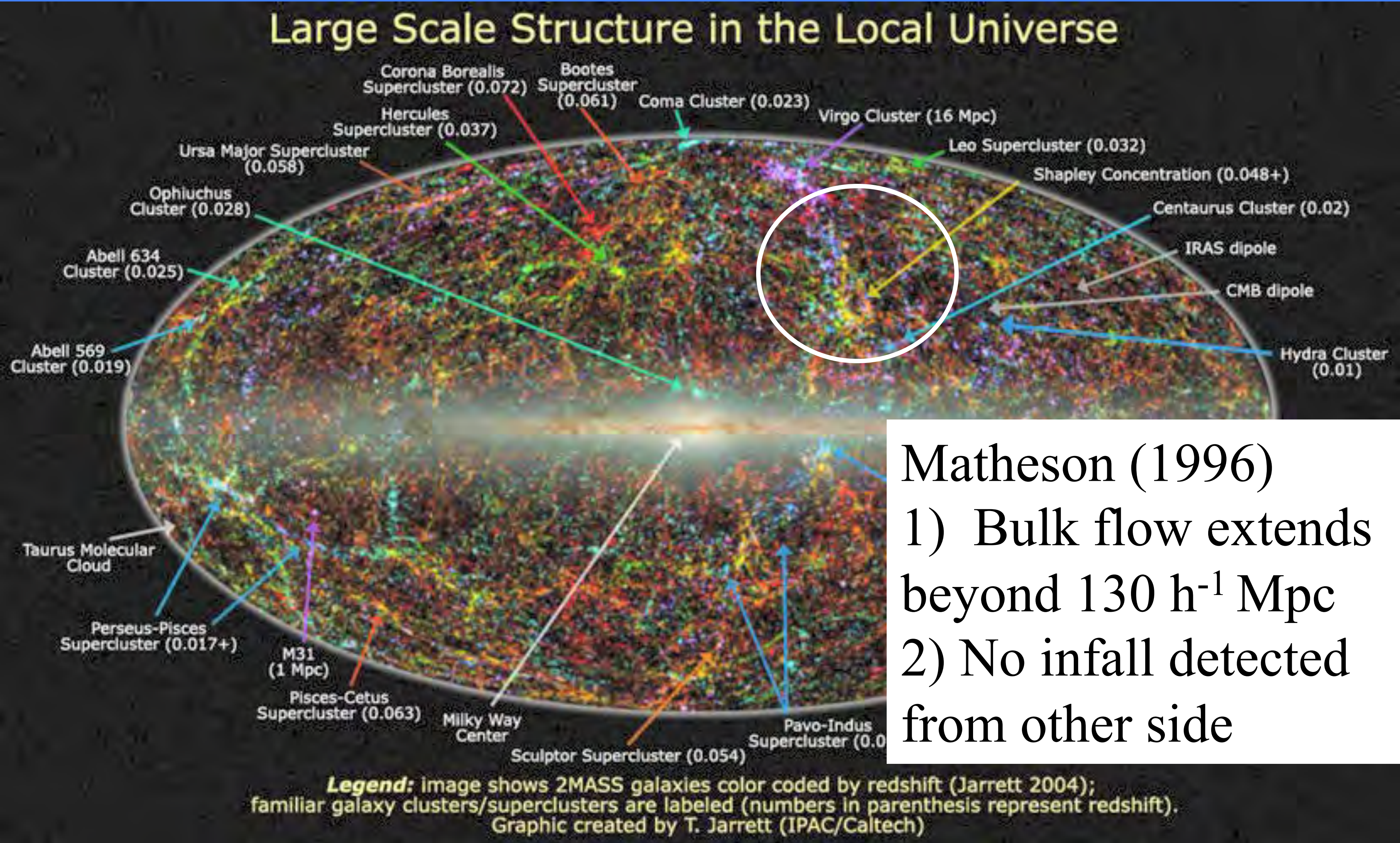
$$T(\theta) = T_{CMB}(1 - \beta \cos\theta)$$

$$\beta = V/c$$

	V (km/sec)	$(l_{\rm Gal}, b_{\rm Gal})^\circ$	Refs
Sun-CMB (COBE/DMR-based)	369.5 ± 3.0	$(264.44 \pm 0.3, 48.4 \pm 0.5)$	Kogut et al (1993)
Sun-LSR	20.0 ± 1.4	$(57 \pm 4, 23 \pm 4)$	Kerr & Lynden-Bell (1986)
LSR-GC	222 ± 5	$(91.1 \pm 0.4, 0)$	Fich et al (1989)
GC - CMB	552.2 ± 5.5	$(266.5 \pm 0.3, 29.1 \pm 0.4)$	Kogut et al (1993)
Sun - LG	308 ± 23	$(105 \pm 5, -7 \pm 4)$	Yahil et al (1977)
LG-CMB	627 ± 22	$(276 \pm 3, 30 \pm 3)$	Kogut et al (1993)

Great Attractor: 35h^{-1} Mpc

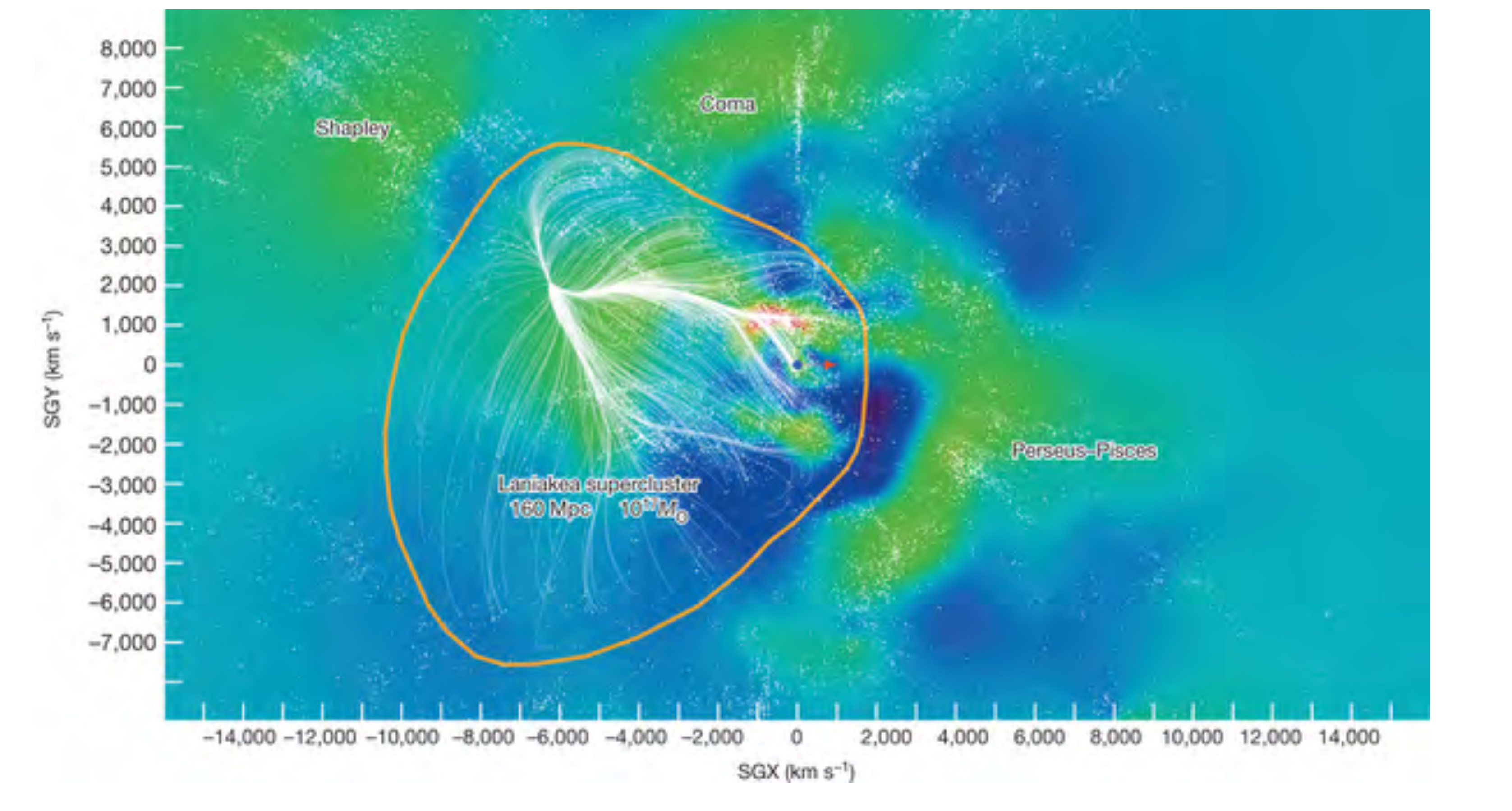
Lynden-Bell (1983)



Matheson (1996)

1) Bulk flow extends beyond 130 h^{-1} Mpc
2) No infall detected from other side

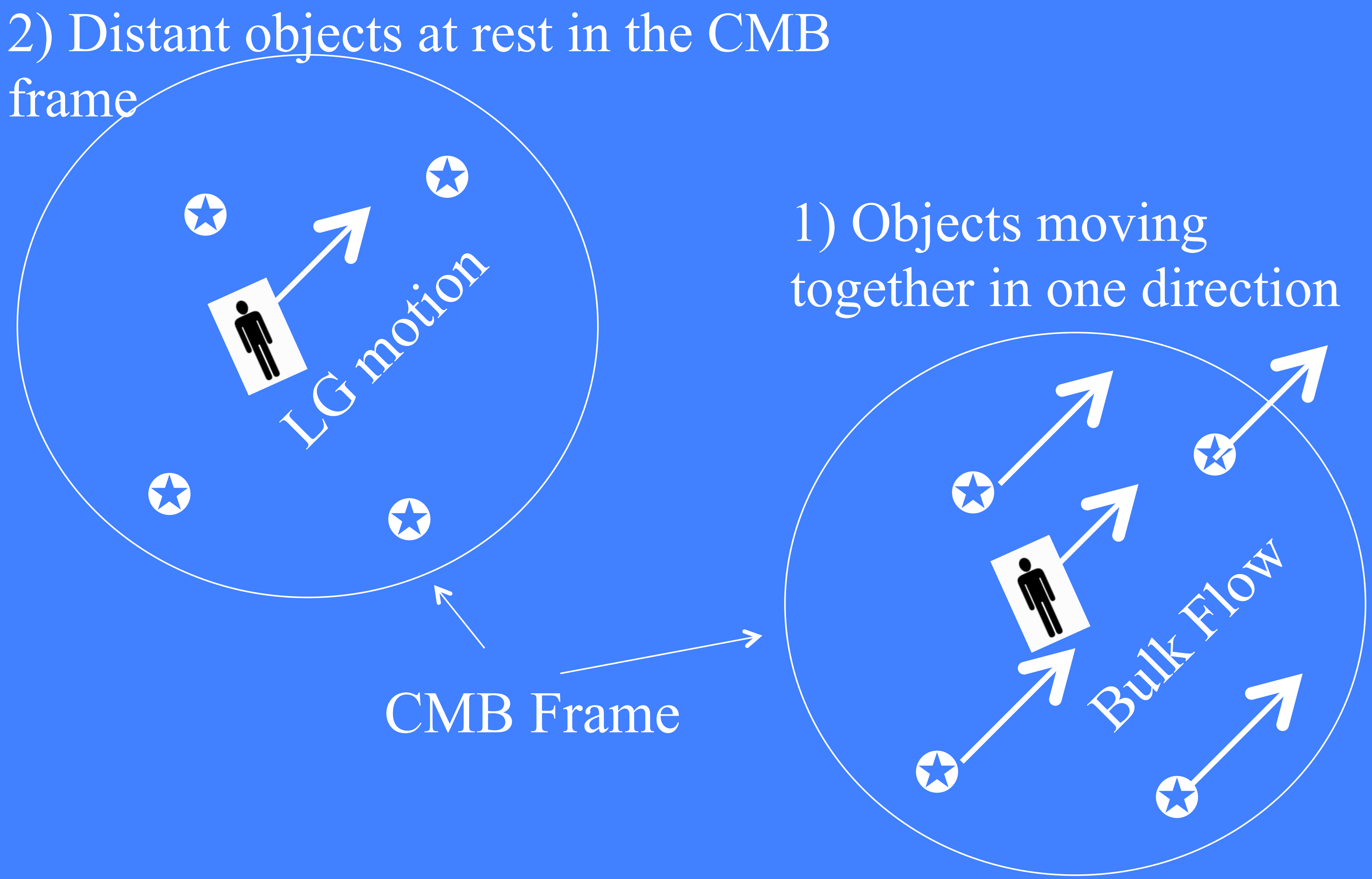
Laniakea Supercluster ~160 Mpc h^{-1}



R. B. Tully, et al. Nature 513, 71 (2014)

Is it possible to detect bulk flow out to larger distances?

GJM, Rose, Garnavich, Yamazaki, Kajino arXiv1412.1529



Kinetic Sunyev-Zeldovich Effect

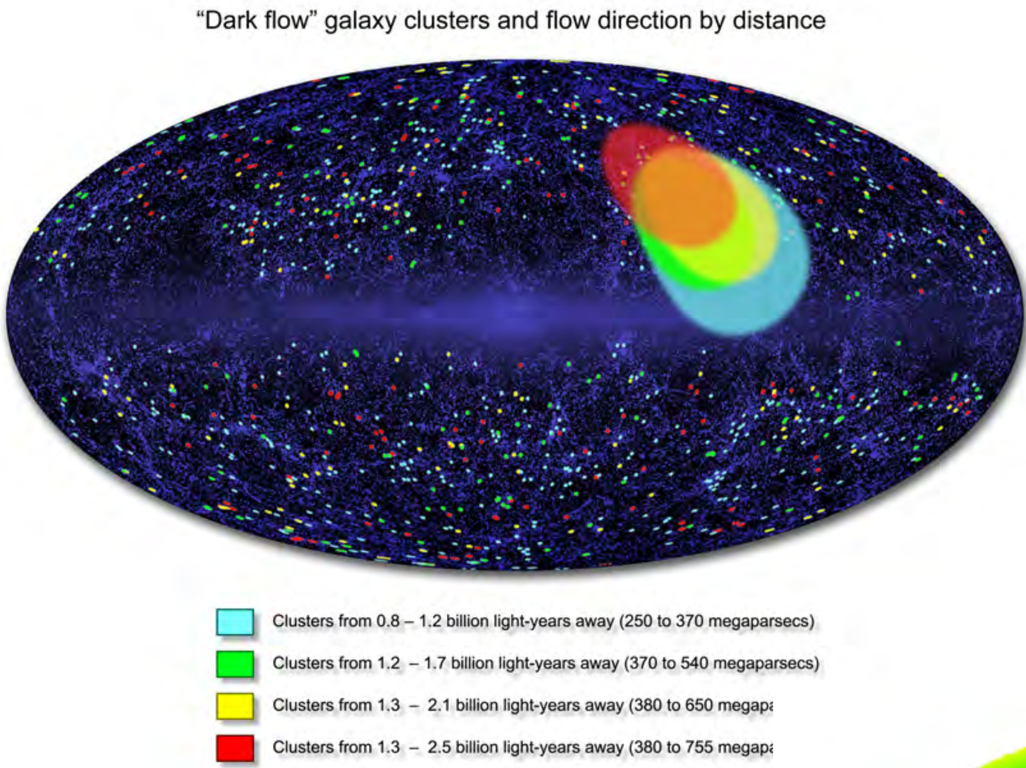
Kashlinsky (2012)

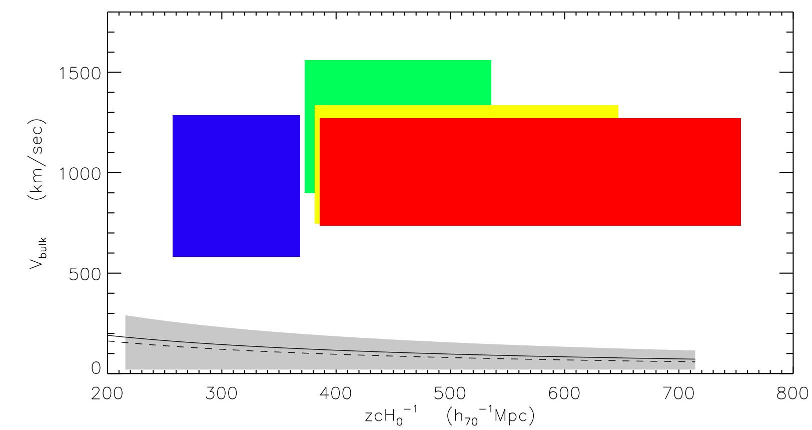
$$\langle \tau \frac{\Delta \nu}{\nu} \rangle = -\langle \tau \frac{\vec{v}}{c} \rangle \hat{x}_{obs}$$

$$\langle \vec{v} \rangle = \bar{\tau} \vec{v}_{cl}$$

Net effect: Redshift of CMB photons along line of sight to the cluster.

Dark Flow

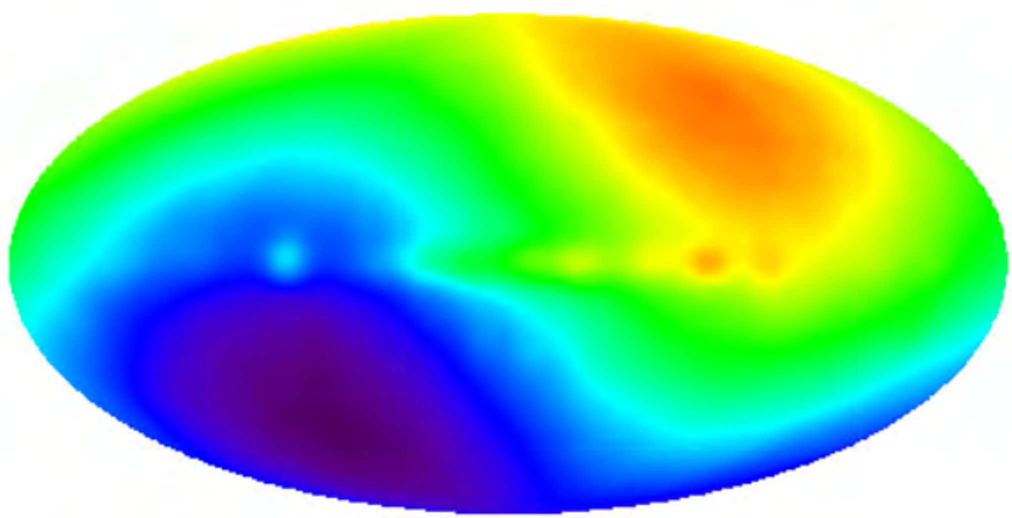




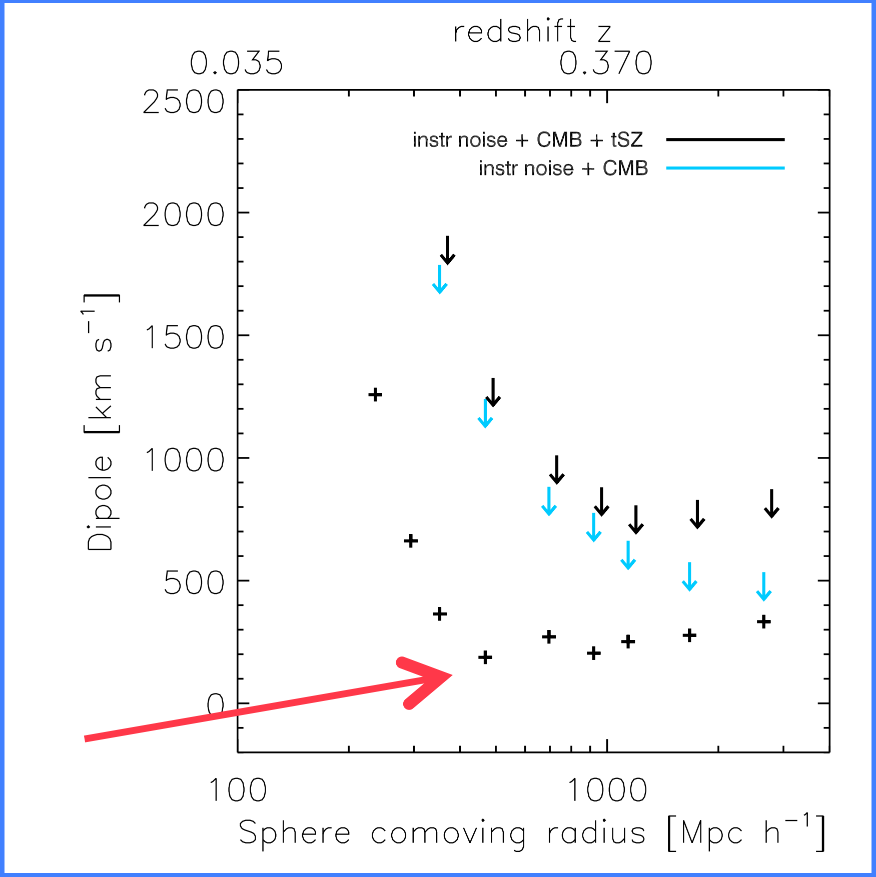
Kashlinsky (2012)

V_{BF} = 800±200 km s^{-1}

(l,b) = (283±14, 12±14)



But!! Planck Data seem to contradict this: arXive:1303.5090



$V_{bf} < 254$ km s^{-1}

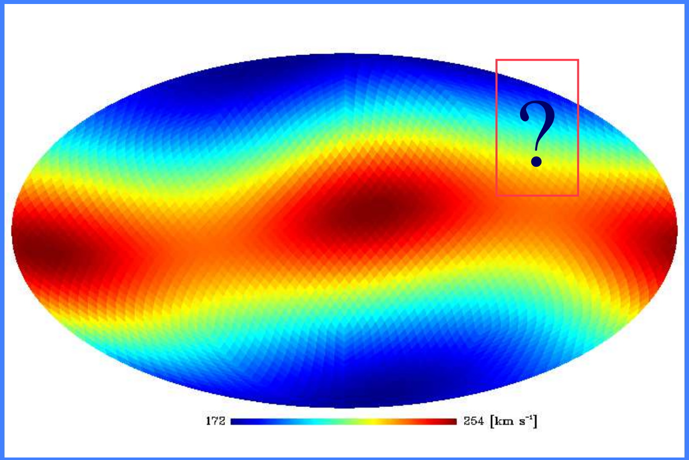
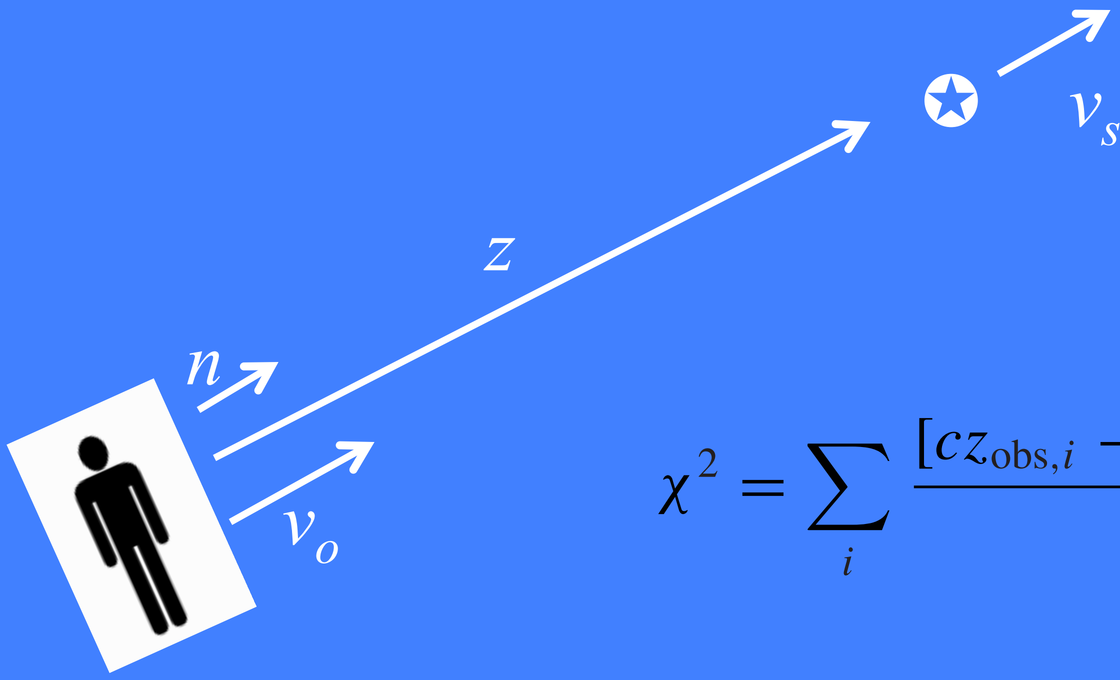


Fig. 8. Mollweide projection in Galactic coordinates of the upper limit (at 95 % C.L.) of the kSZ dipole amplitude from applying the uMMF approach to HFI frequency maps using the whole MCXC cluster sample. In no direction is the dipole detected at more than 2 σ.

See However: Atrio-Barandela arXive:1303.6614 => detection with Planck
1411.4180- detection in WMAP9 + Planck

Redshift distance relations provide another test

$$z = \tilde{z} + (1 + \tilde{z})\hat{n} \cdot (\vec{v}_s - \vec{v}_o),$$
$$D_L(z) = (1 + 2\hat{n} \cdot \vec{v}_s - \hat{n} \cdot \vec{v}_o)\tilde{D}_L(\tilde{z})$$



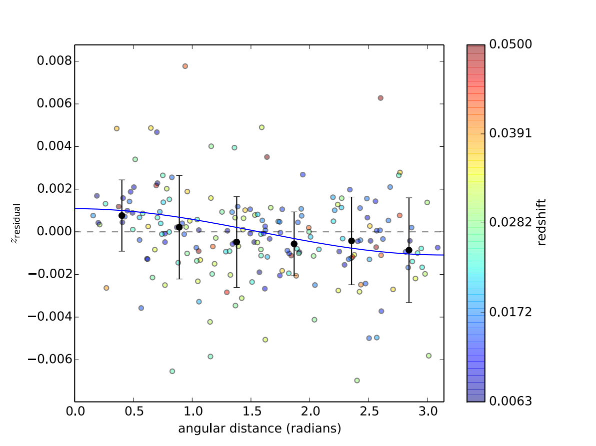
$$\chi^2 = \sum_i \frac{[cz_{\mathrm{obs},i} - (r_i + v_{\mathrm{pred},i})]^2}{\sigma_i^2}$$

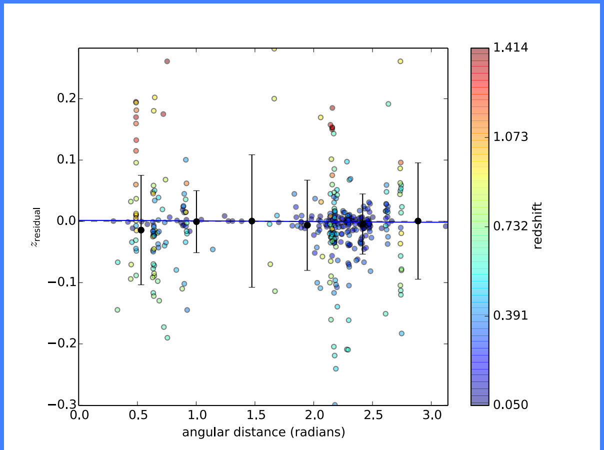
MCMC Analysis of Cartesian velocity components

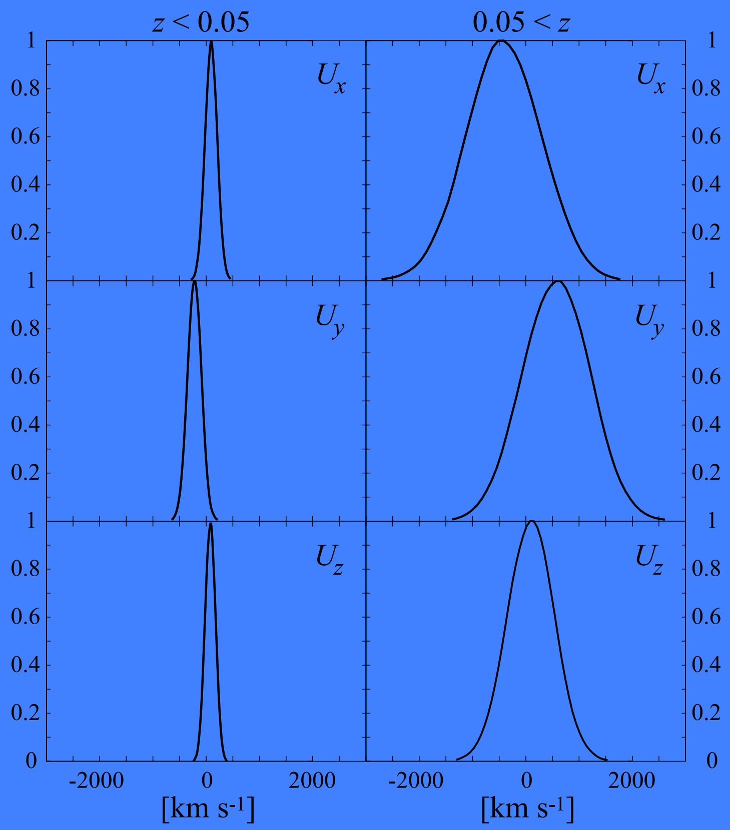
640 SNIa distances
Union 2.1 Data Set

GJM, Rose, Garnavich, Yamazaki, Kajino arXiv1412.1529

Cos(θ)





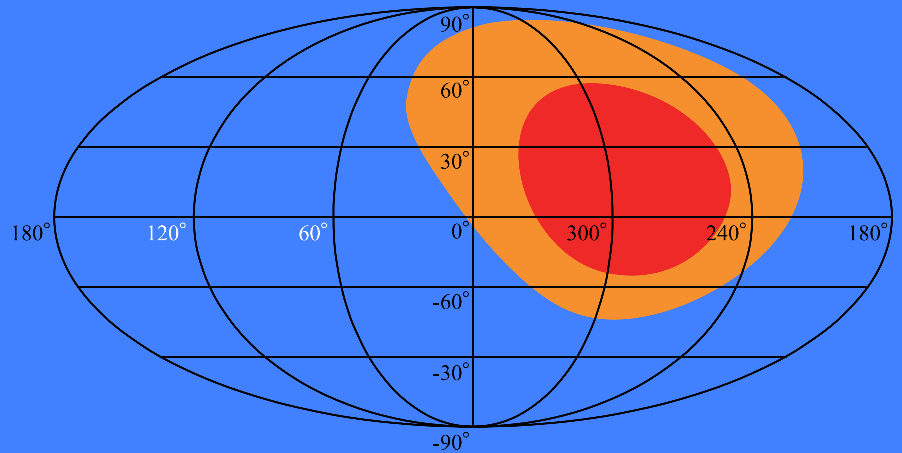


SNIa Bulk Flow

$(l, b) = (295 \pm 30, 10 \pm 15)^\circ$

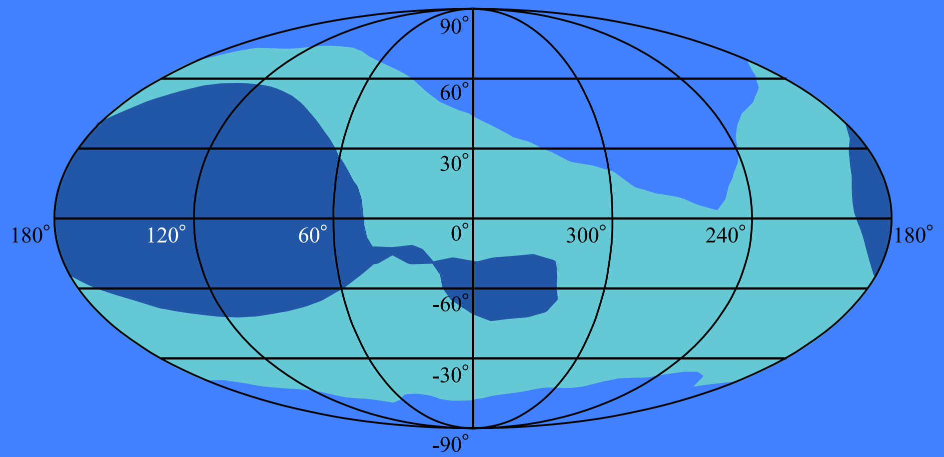
Z < 0.05

$v_{bf} = 270 \pm 50 \text{ km s}^{-1}$



Z > 0.05

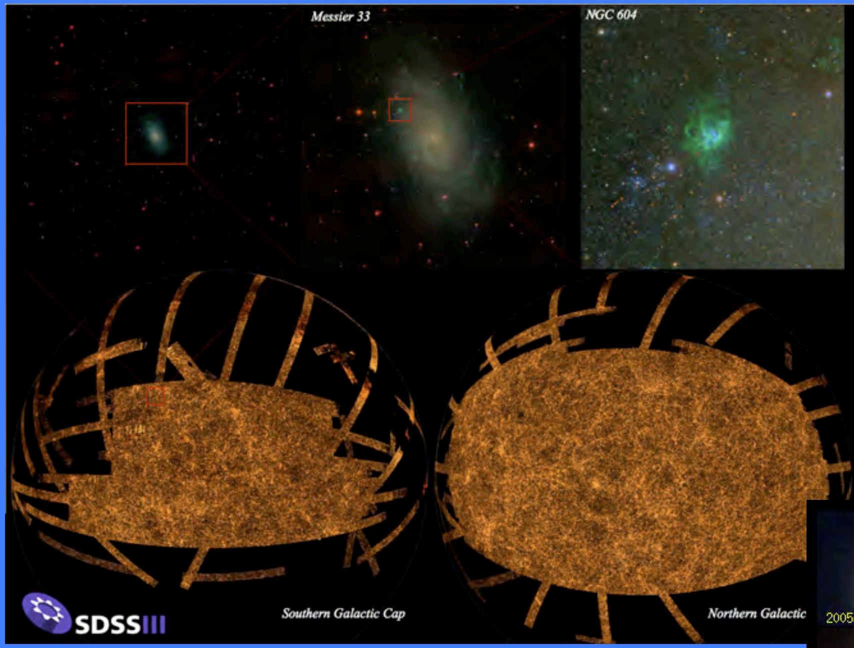
$v_{bf} = 1000 \pm 600 \text{ km s}^{-1}$



Need more statistics at high redshift

What about SDSS II?

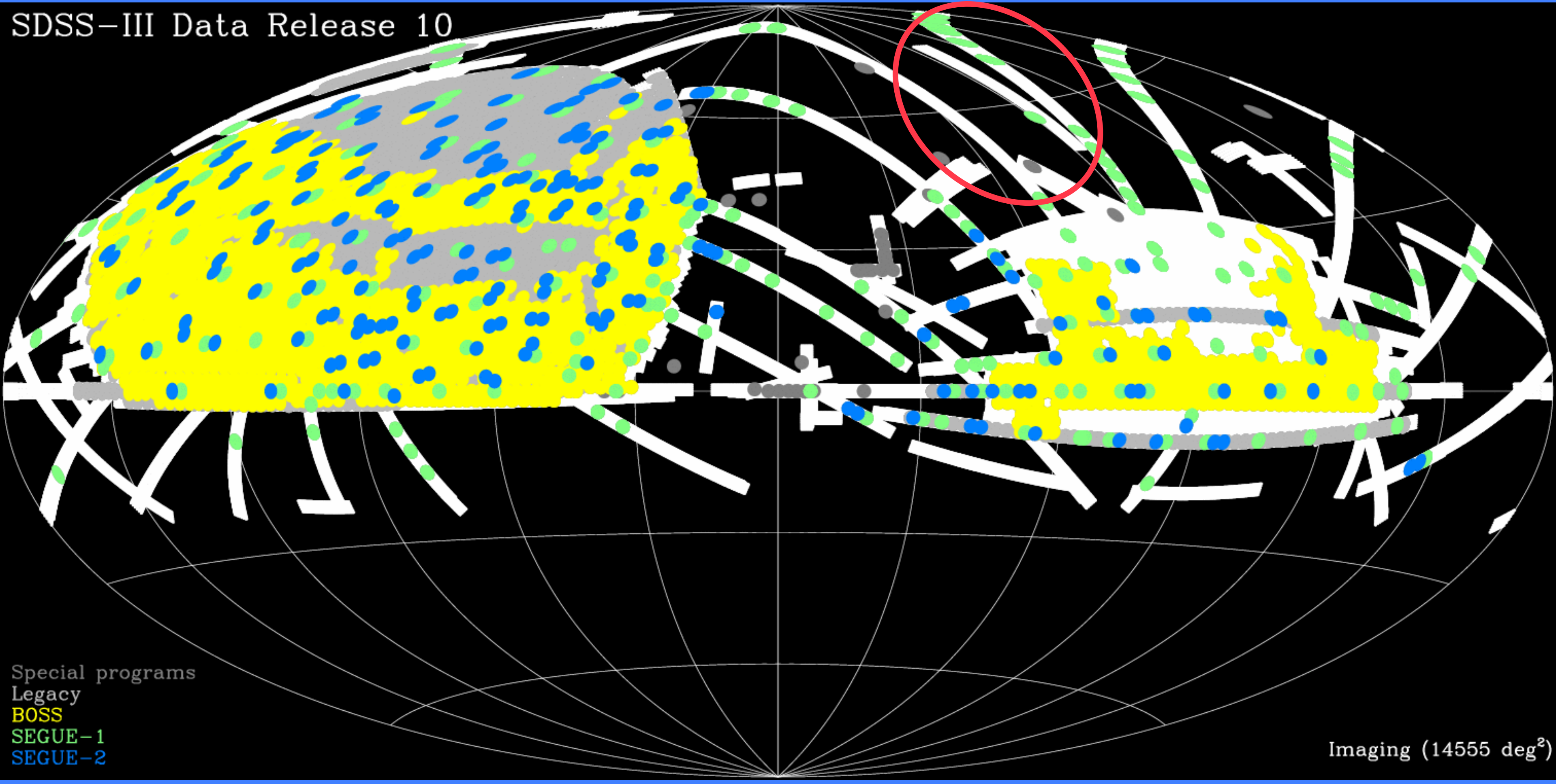
Mathews, Rose, Garnavich, Yamazaki Kajino (2014)



1.8 billion galaxies

> 1000 SNe

SDSS



Not enough sky coverage along the direction of flow