Title: Dipoles in the Sky

Date: Feb 28, 2012 11:00 AM

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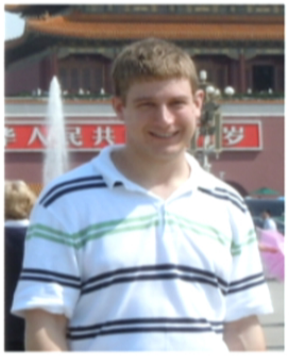
Abstract: The standard cosmological model posits that the universe is homogeneous and statistically isotropic on its largest scales. However, there is no fundamental reason why these properties have to hold, and in fact they can be broken due to interesting new physics. Moreover, there is some evidence from recent WMAP observations for 'anomalies' - including departures from statistical isotropy - on the largest observable scales. Large-scale structure (LSS) - including the distribution of galaxies in the universe - presents a new frontier in testing statistical isotropy and homogeneity, and we are entering an epoch with orders-of-magnitude improvement in the statistics of LSS. In this talk I first review general tests of statistical isotropy using LSS. I then describe results from research done in collaboration with my student Cameron Gibelyou on testing aspects of the statistical isotropy - in particular, dipolar modulations of the galaxy counts - using existing LSS surveys.

Dipoles in the sky

Dragan Huterer

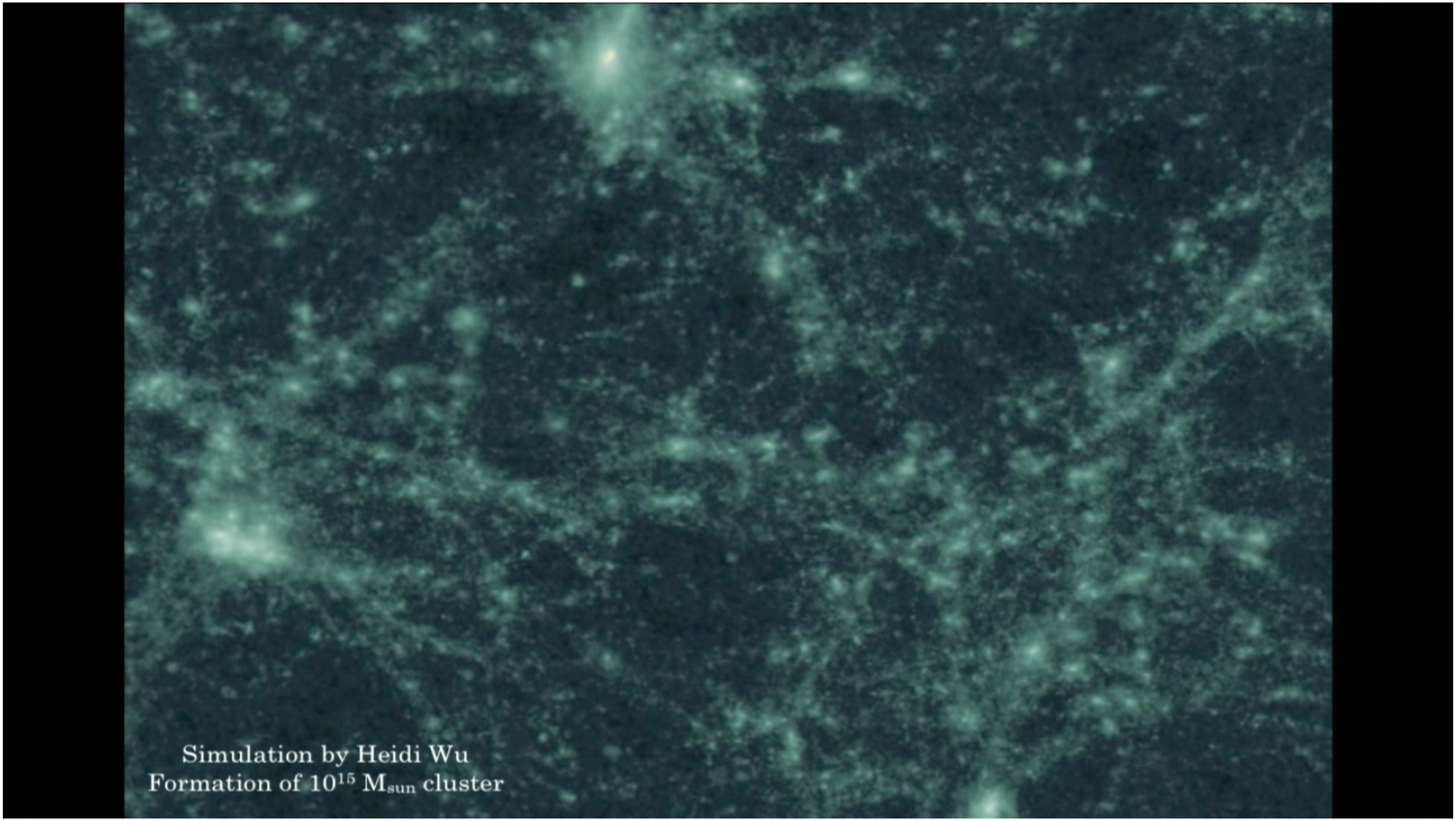
Physics Department
University of Michigan

Work with Cameron Gibelyou
(Michigan PhD April 2012)



Fundamental Physics from LSS

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


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

Large-scale structure

$O(10^9)$ galaxies
$O(10^7)$ with spectra
$O(10^6)$ quasars
$O(10^5)$ clusters

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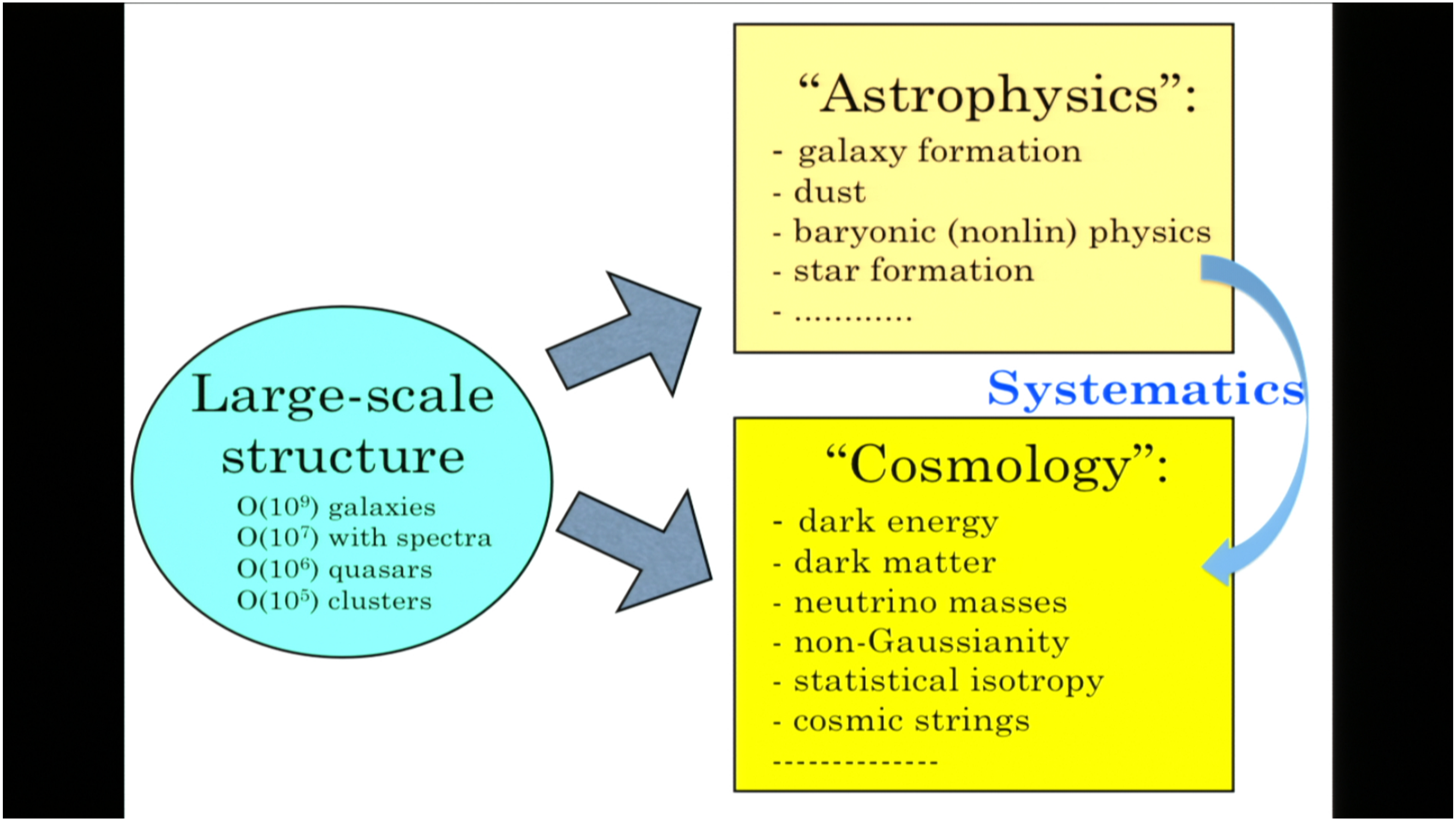
"Astrophysics":

- galaxy formation
- dust
- baryonic (nonlin) physics
- star formation
- …………

"Cosmology":

- dark energy
- dark matter
- neutrino masses
- non-Gaussianity
- statistical isotropy
- cosmic strings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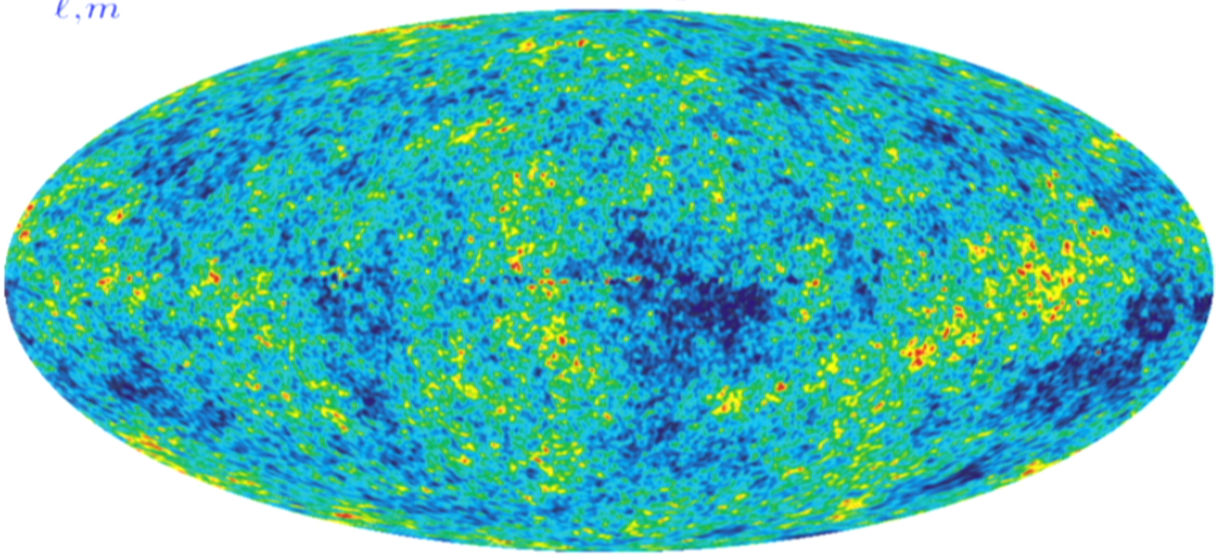
Initial conditions in the universe

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



Statistical Isotropy:

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

Gaussianity:

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

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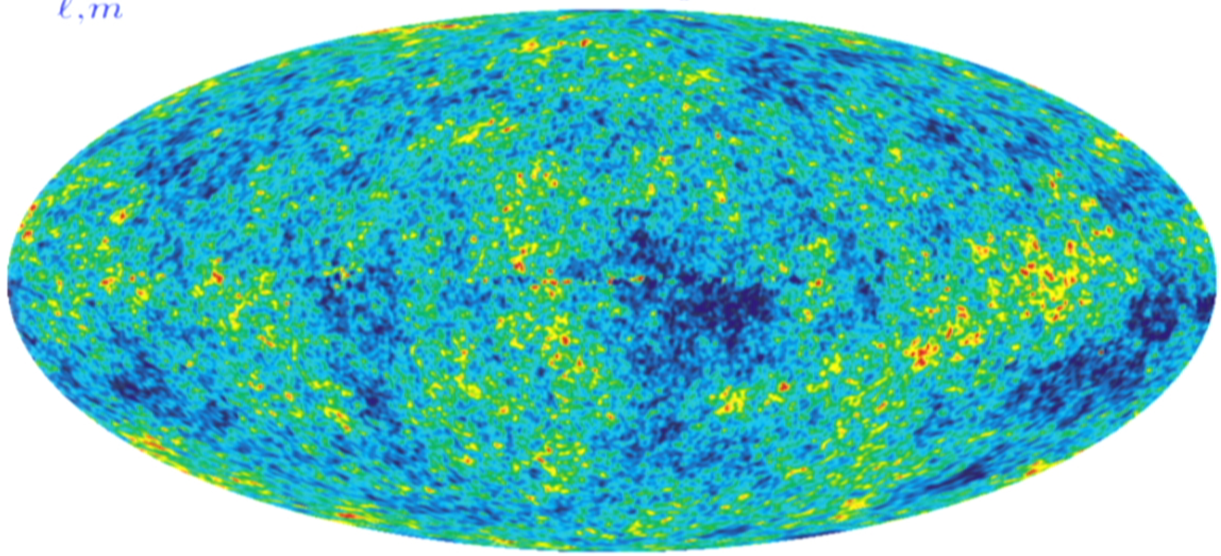

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Statistical Isotropy simplified:

T = fluctuating field on the sky

Statistically Isotropic: $\langle T(\hat{\mathbf{n}})T(\hat{\mathbf{n}}')\rangle = C(\hat{\mathbf{n}}\cdot\hat{\mathbf{n}}')$

NOT Stat. Isotropic: $\langle T(\hat{\mathbf{n}})T(\hat{\mathbf{n}}')\rangle = C(\hat{\mathbf{n}},\hat{\mathbf{n}}')$

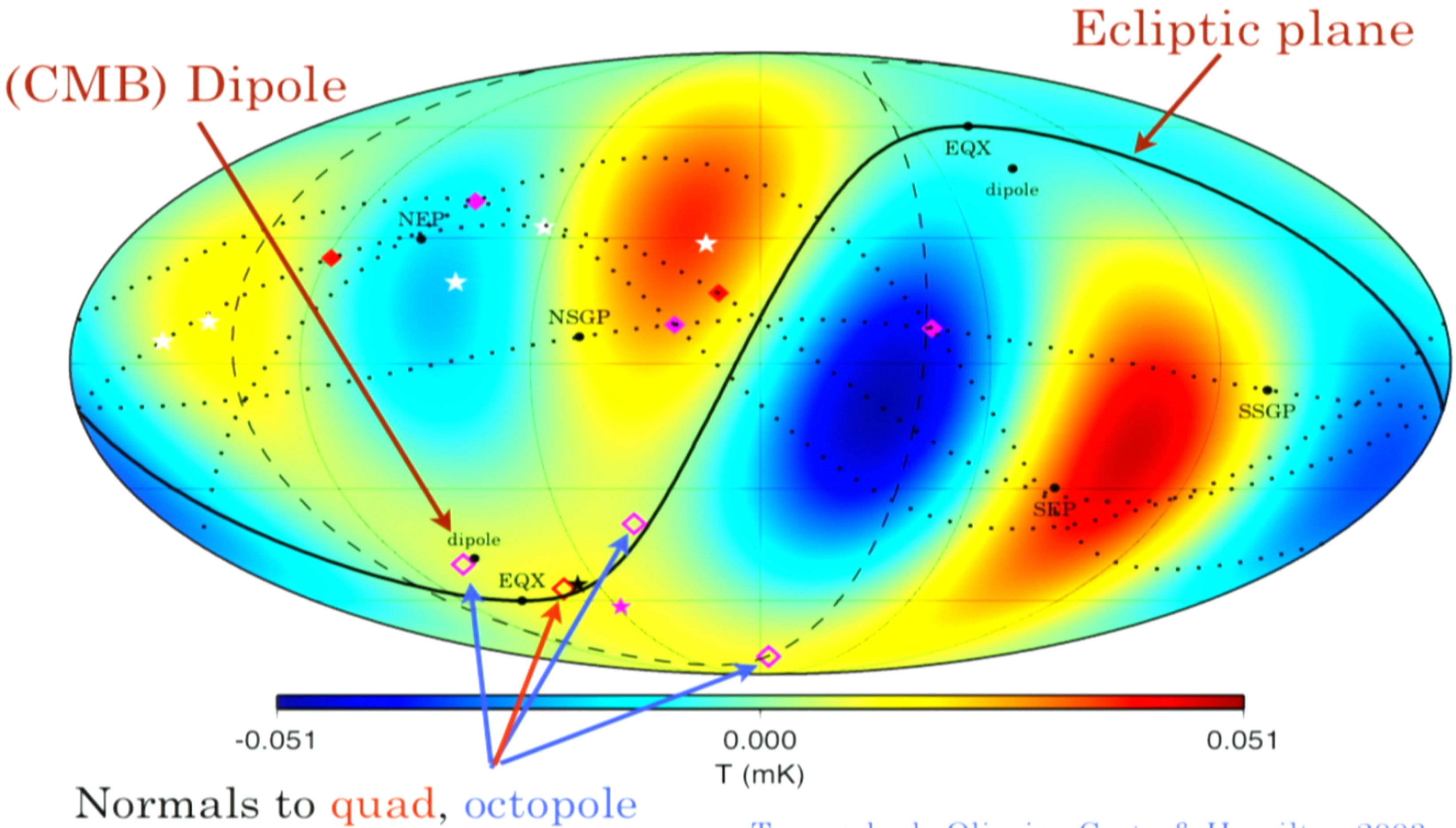
same as

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

Assuming SI, we get most results in cosmology
(e.g. average 2ℓ+1) modes for each ℓ across the sky

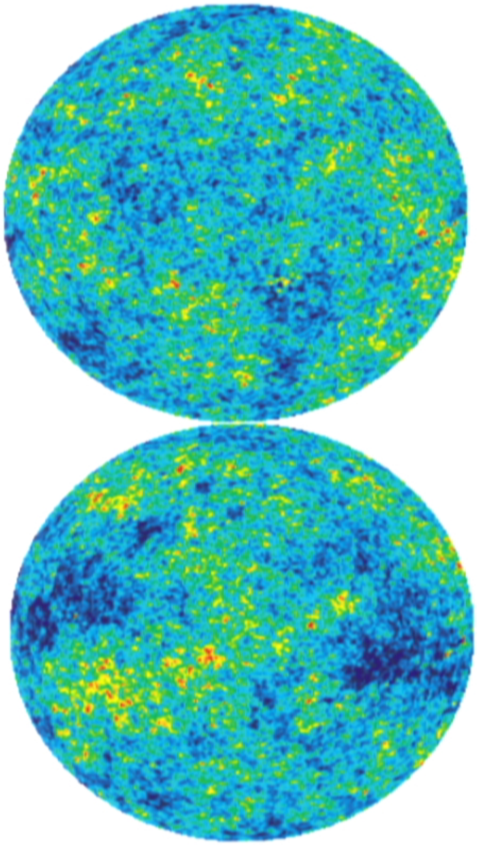
CMB large-angle “anomalies”

L=2+3 alignments

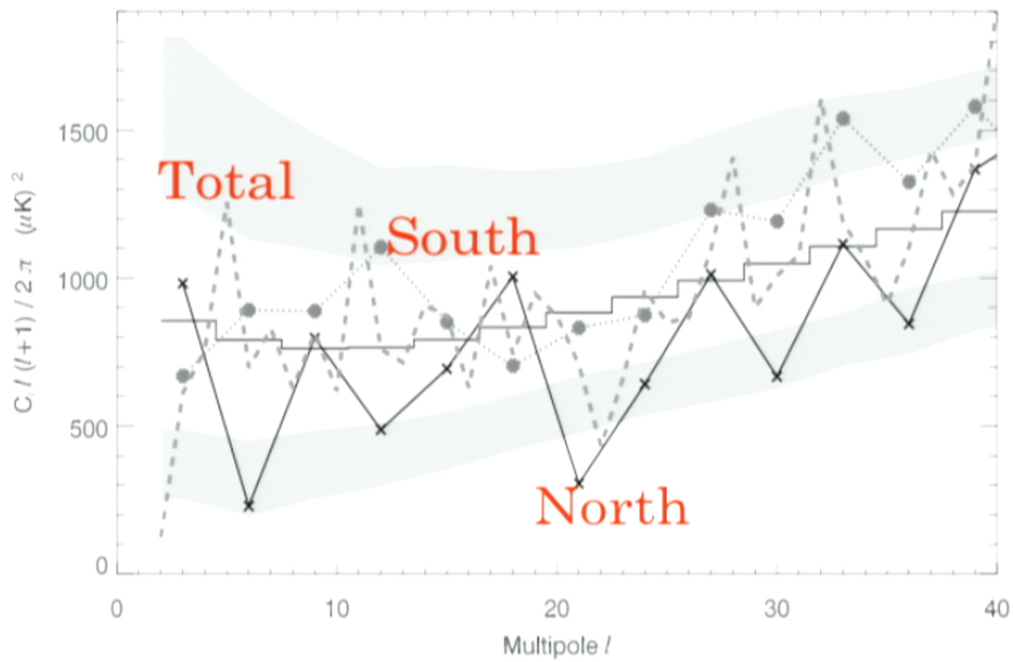


Tegmark, de Oliveira-Costa & Hamilton 2003
Schwarz, Starkman, Huterer & Copi 2004, 06, 10

N/S power asymmetry ("hemispherical anomaly")

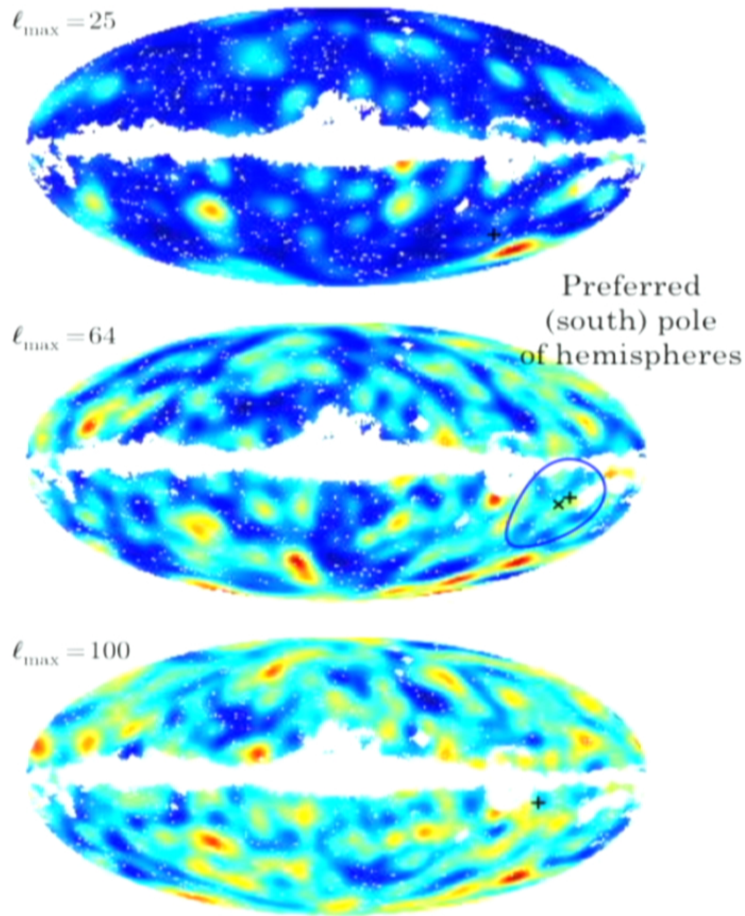


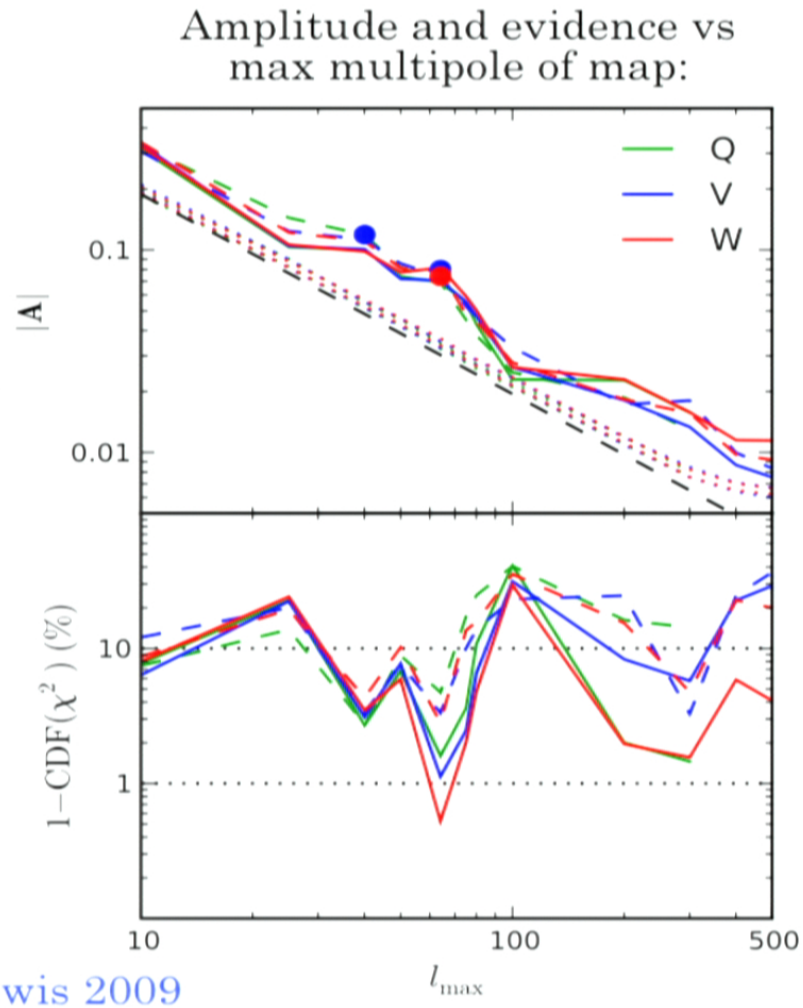
South (ecliptic) has more power than north



Eriksen et al 2004;
Hansen, Banday and Gorski 2004

Hemispherical anomaly: latest (from WMAP)





Hanson & Lewis 2009

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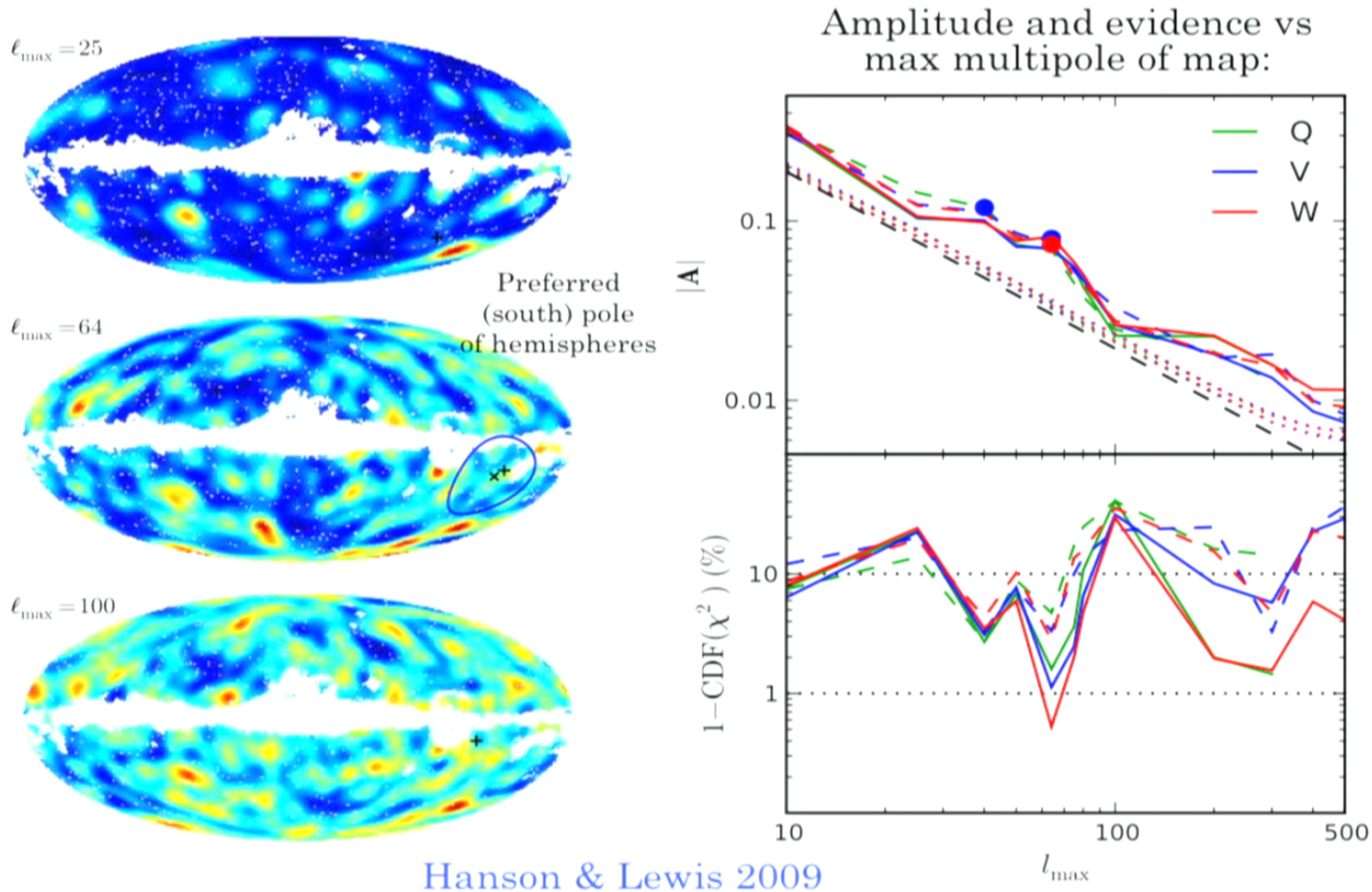
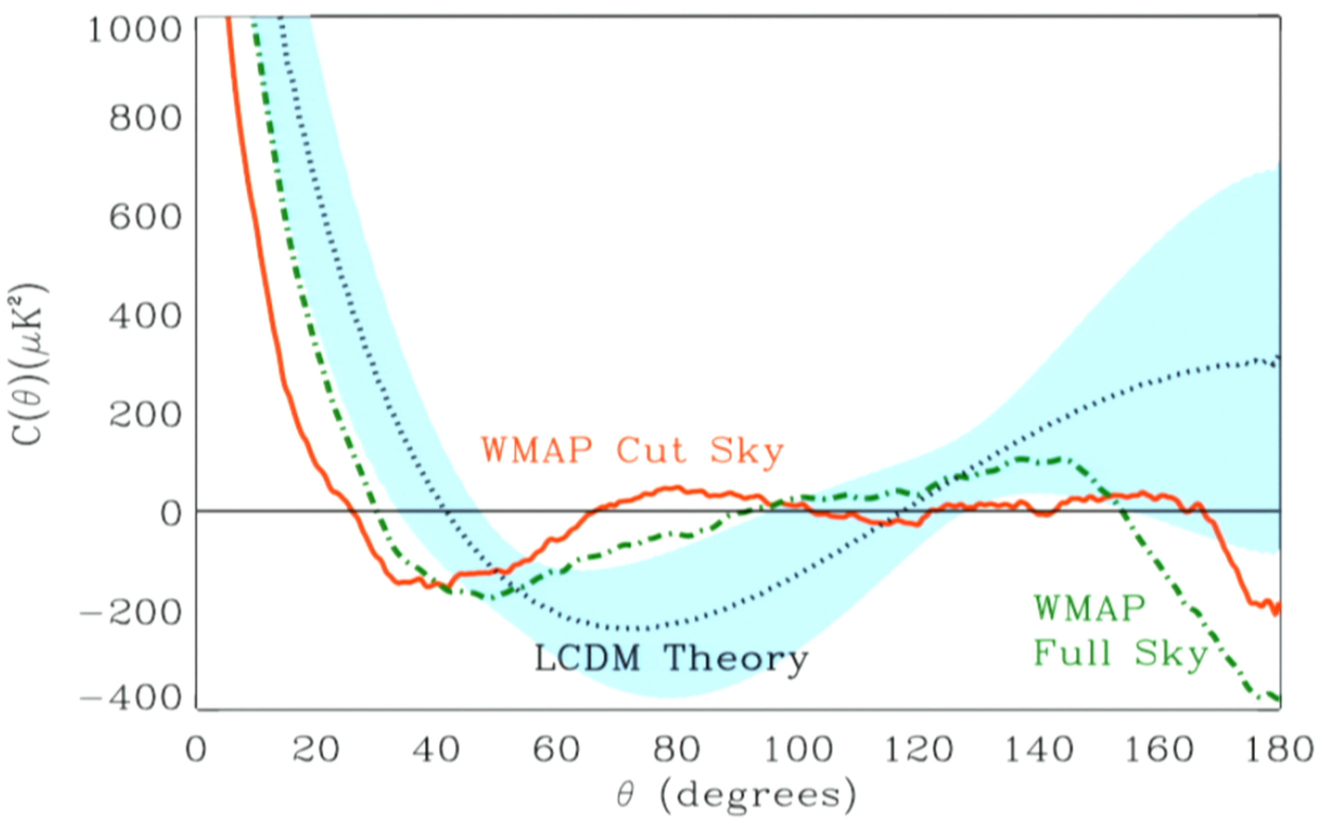


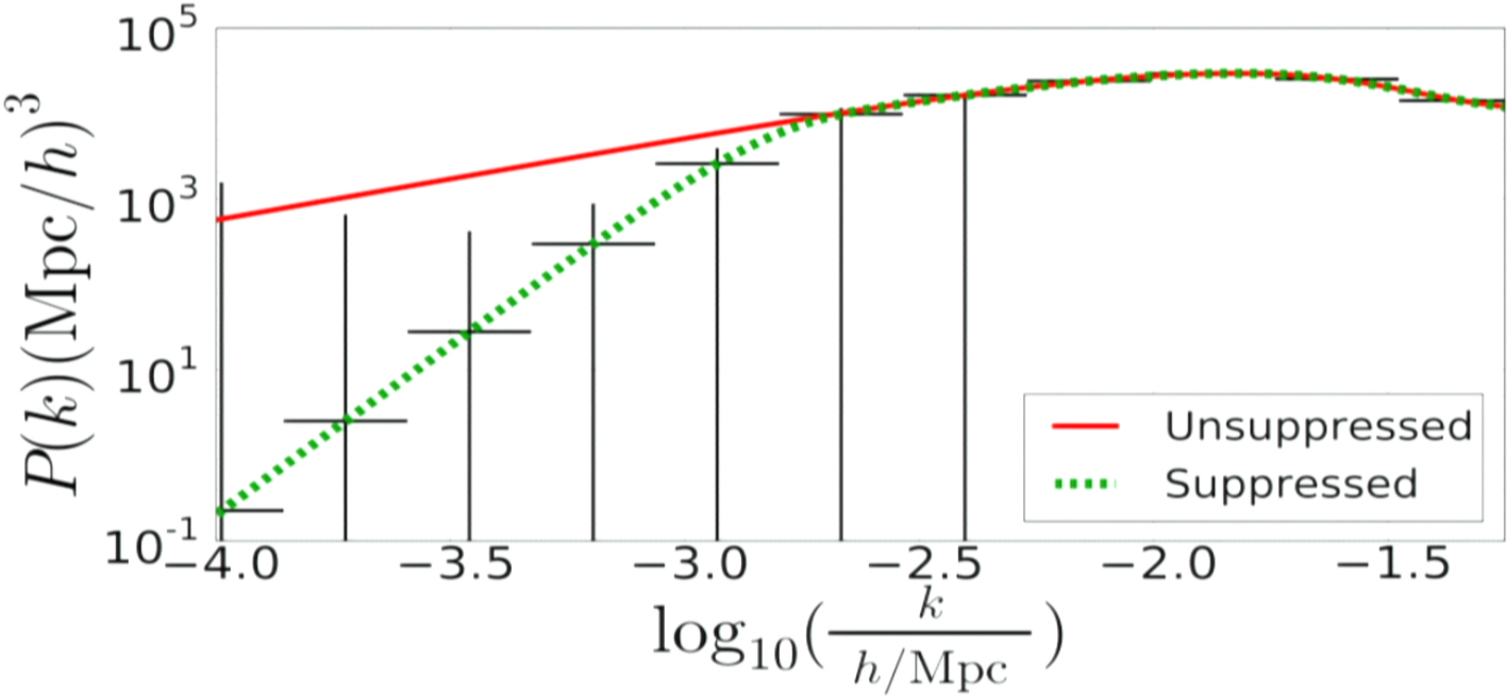
Hanson & Lewis 2009

Missing power above 60°



Hinshaw et al 1996 (COBE);
Spergel et al 2003 (WMAP)
Copi et al 2007, 2009; Sarkar et al 2010

Using LSS to test whether low P(k) is the cause of low C(θ)



Can do this with LSS if you have a HUGE number of galaxy redshifts, as assumed in plot above

(LSST with gazillion redshifts)

Gibelyou, Huterer & Fang 2010

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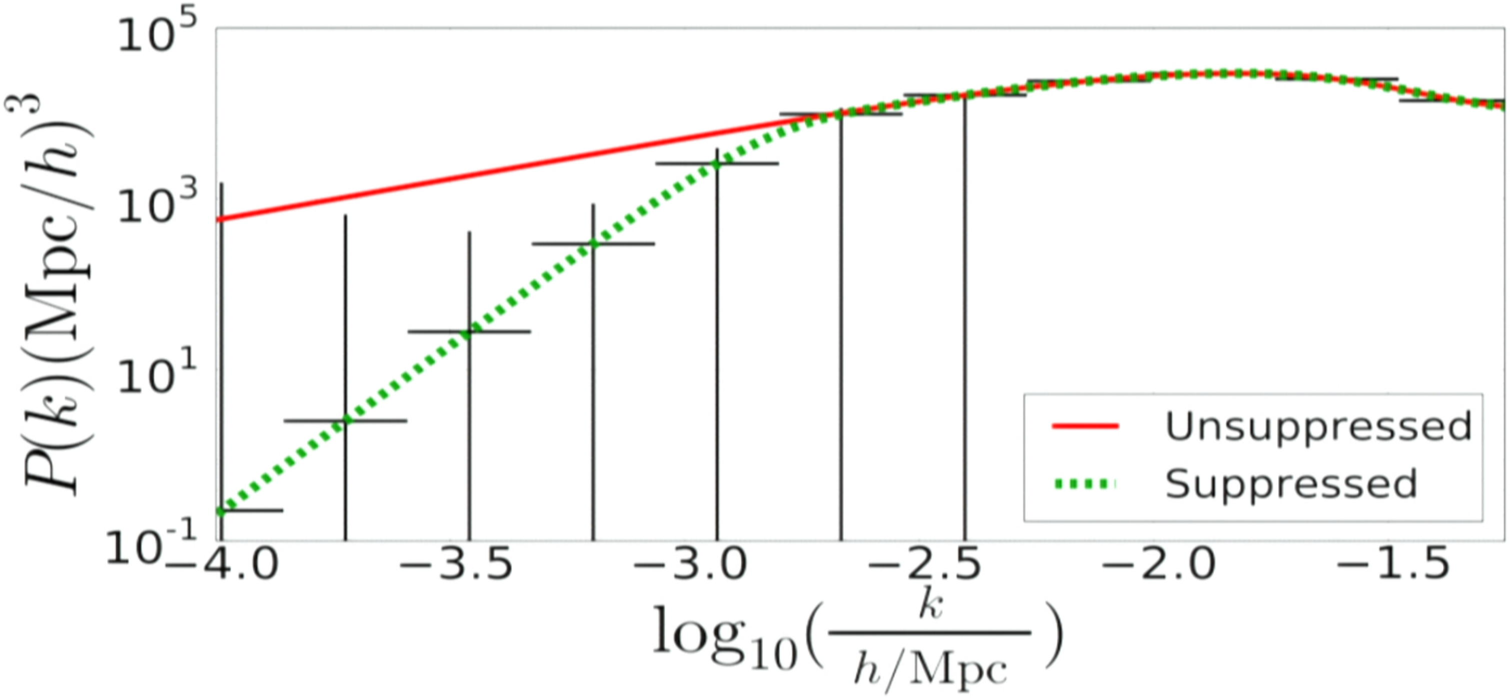

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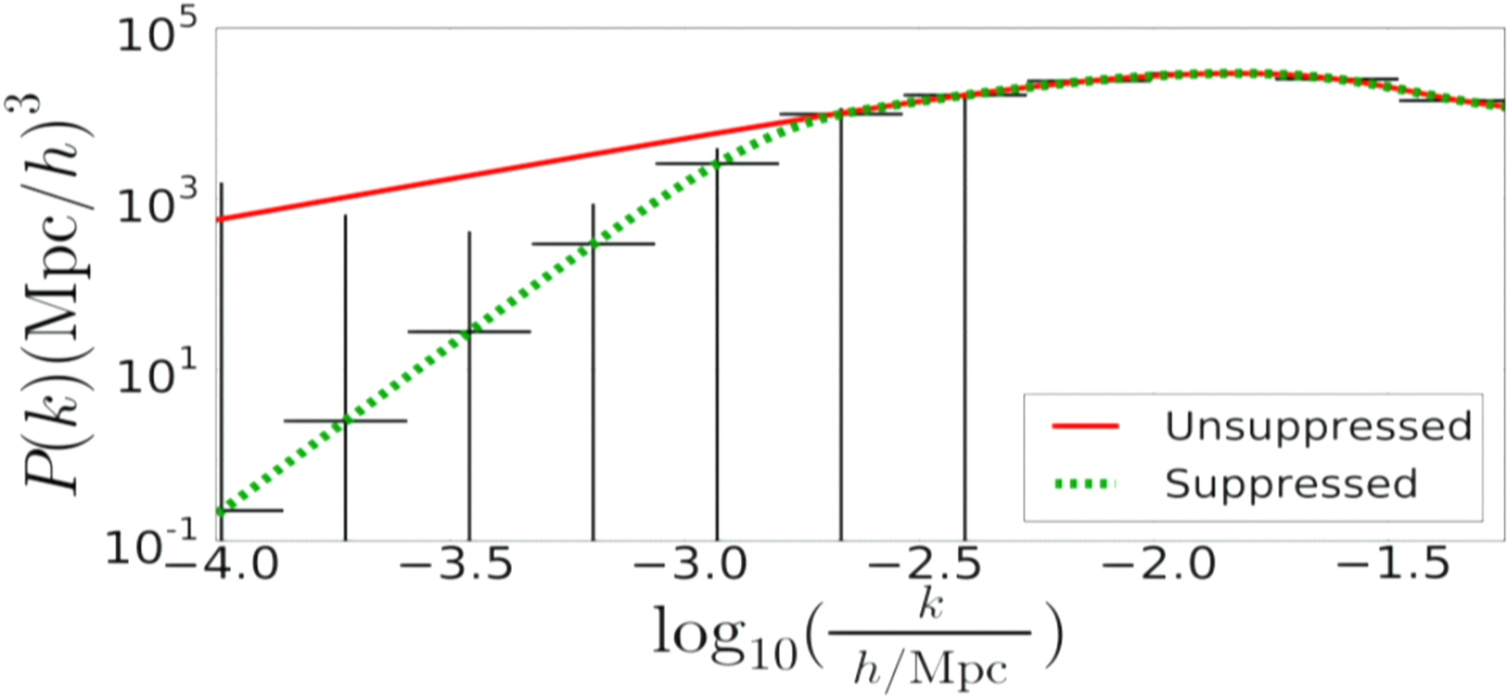

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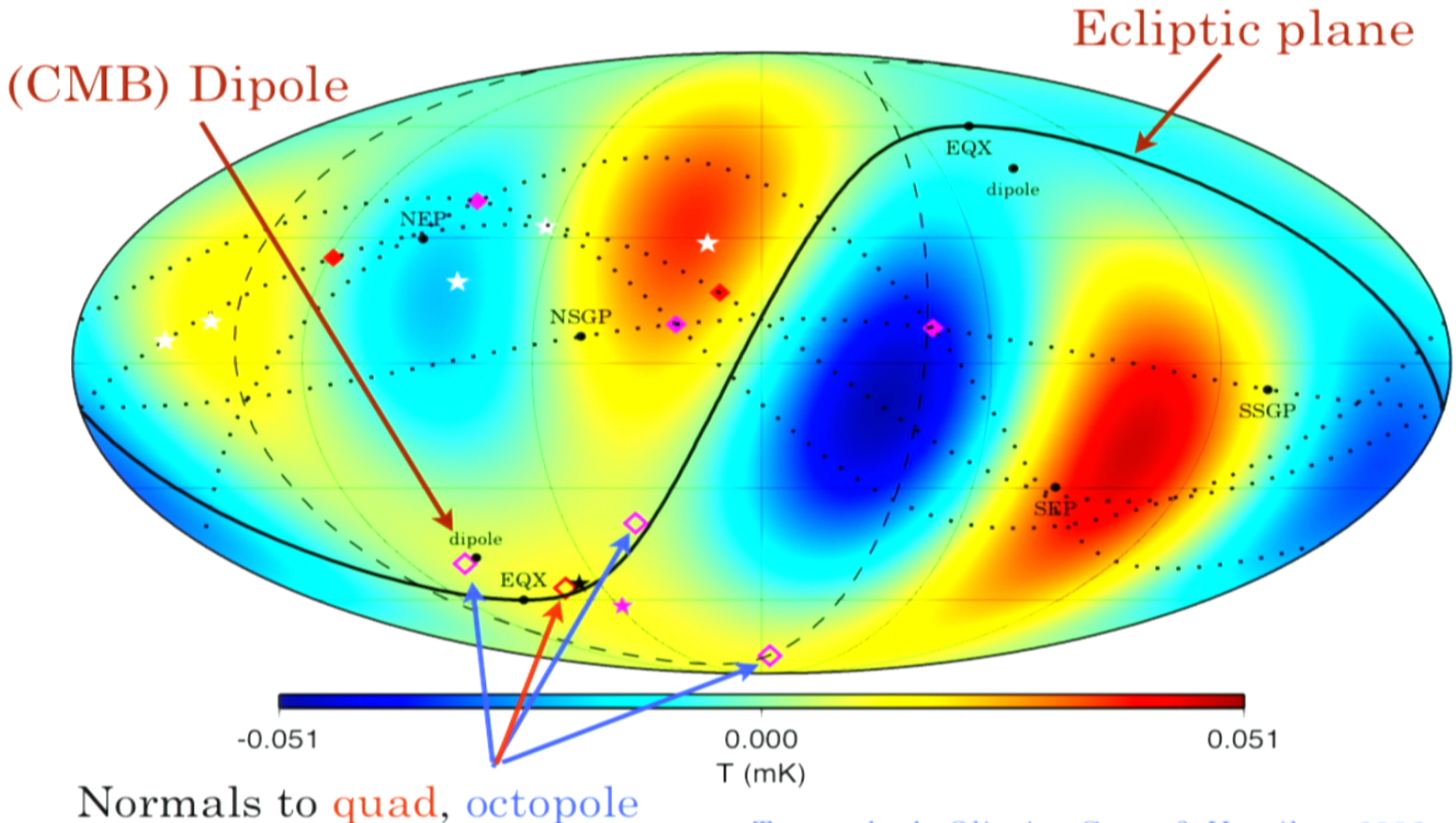

Tegmark, de Oliveira-Costa & Hamilton 2003
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Kinematic and Intrinsic Dipoles in CMB and LSS

Nomenclature:

- Local structure dipole: due to finite volume, we are looking 'along a filament' of LSS
- Kinematic dipole: due to our motion wrt the CMB or LSS
- Intrinsic dipole: primordial origin

Type of Dipole	Expected Value in CMB	Expected Value in LSS
kinematic	$\sim v/c \sim 10^{-3}$	$\sim v/c \sim 10^{-3}$
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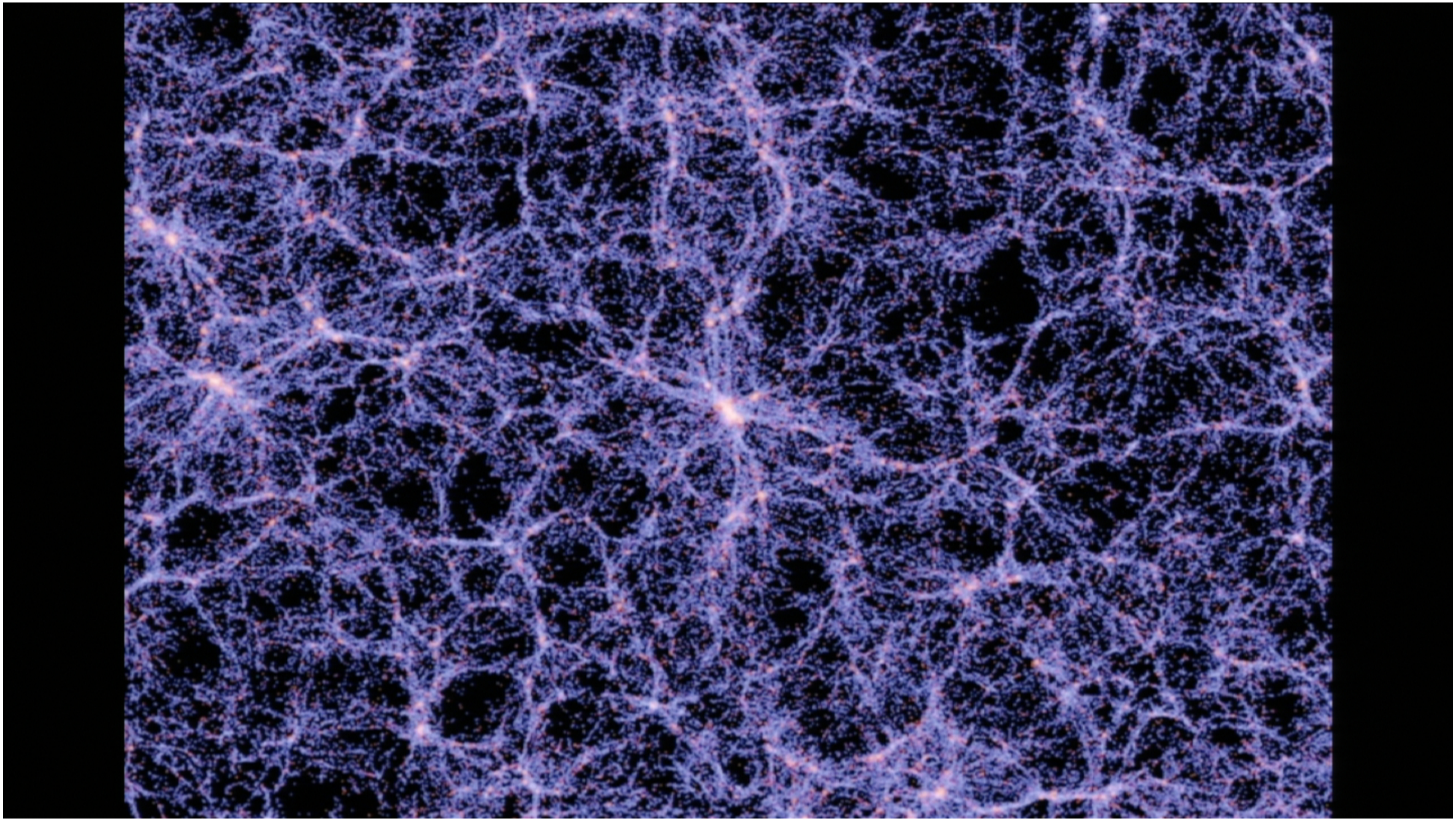
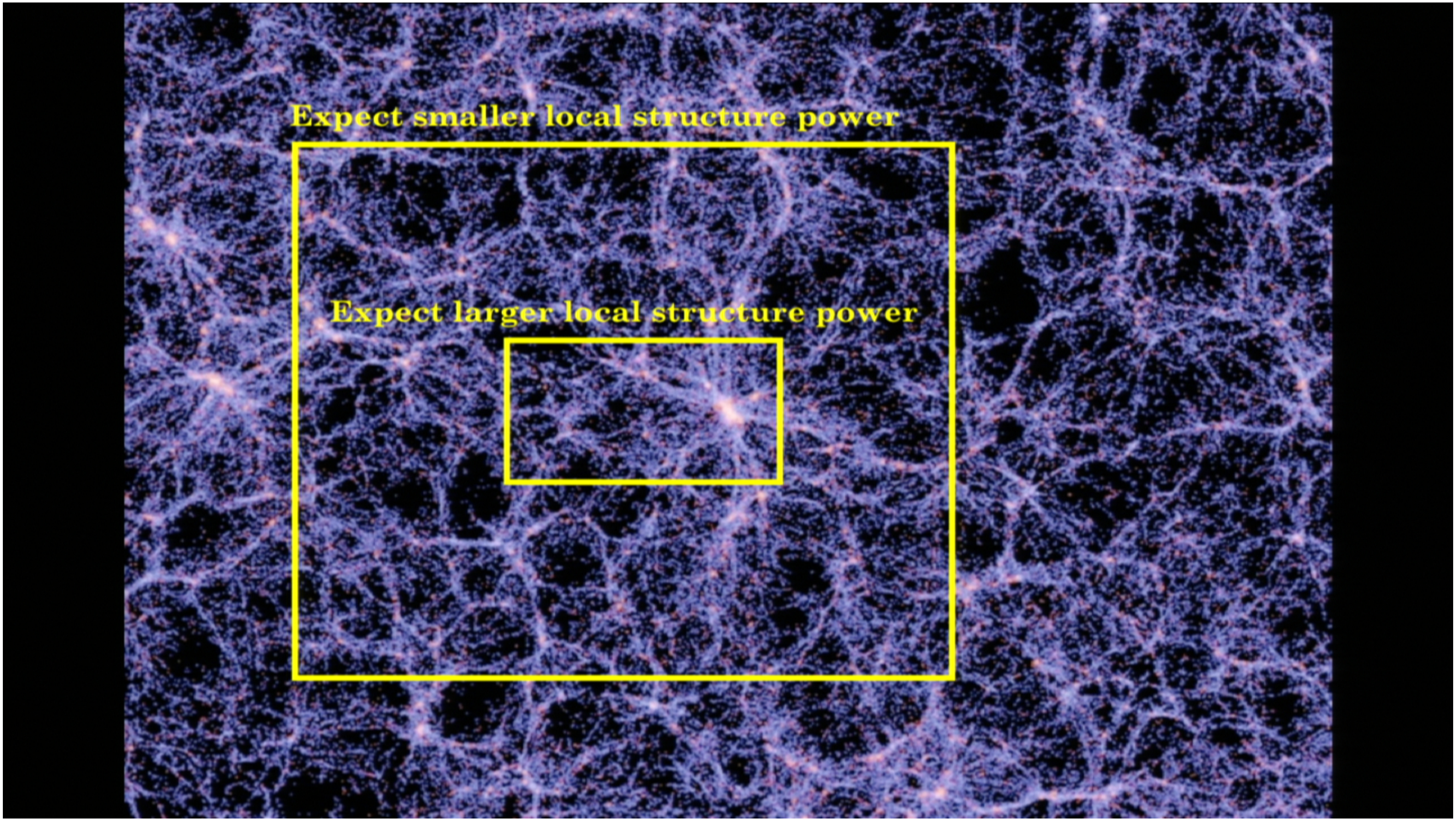
Kinematic Dipole: vital statistics

- Earth around Sun: speed ~ **30 km/s**, direction annually varying (Blake & Wall, 2002); values of CMB dipole are cited with this subtracted out, so that dipole is due only to Sun's velocity wrt CMB
- Sun around Galaxy: speed ~ **220 km/s** (or more precisely, Sun with respect to Local Standard of Rest, and LSR with respect to Milky Way (Itoh, Yahata, Takada, 2010), direction (l,b) = (90,0) (Courteau and van den Bergh, 1999)
- Sun with respect to the Local Group: speed ~ **306 km/s**, direction (l,b) = (99, -4) +/- (5, 4) (Courteau and van den Bergh, 1999; see their Table 2 for historical details)
- Local Group with respect to CMB (peculiar velocity): speed ~ **622 km/s**, direction (l,b) = (272, 28) (Maller et al., 2003, computed using Courteau and van den Bergh's value for Sun wrt LG) (peculiar velocity predicted from linear-theory LCDM ~ 470 km/s)
- Overall CMB kinematic dipole: speed ~ **370 km/s**, direction (l,b) = (264.4, 48.4) (Kogut et al., 1993) (note that the speed would be higher if not for the fact that the above two vectors point in near-opposite directions)




Expect smaller local structure power
Expect larger local structure power

Theoretical prediction for angular power spectrum

$$C_\ell = 4\pi \int_0^\infty d\ln k\, \Delta^2(k, z=0)\, I^2(k)$$

where

$$I(k) \equiv \int_0^\infty dz\, W(z) \frac{D(z)}{D(0)}\, j_\ell(k\chi(z))$$

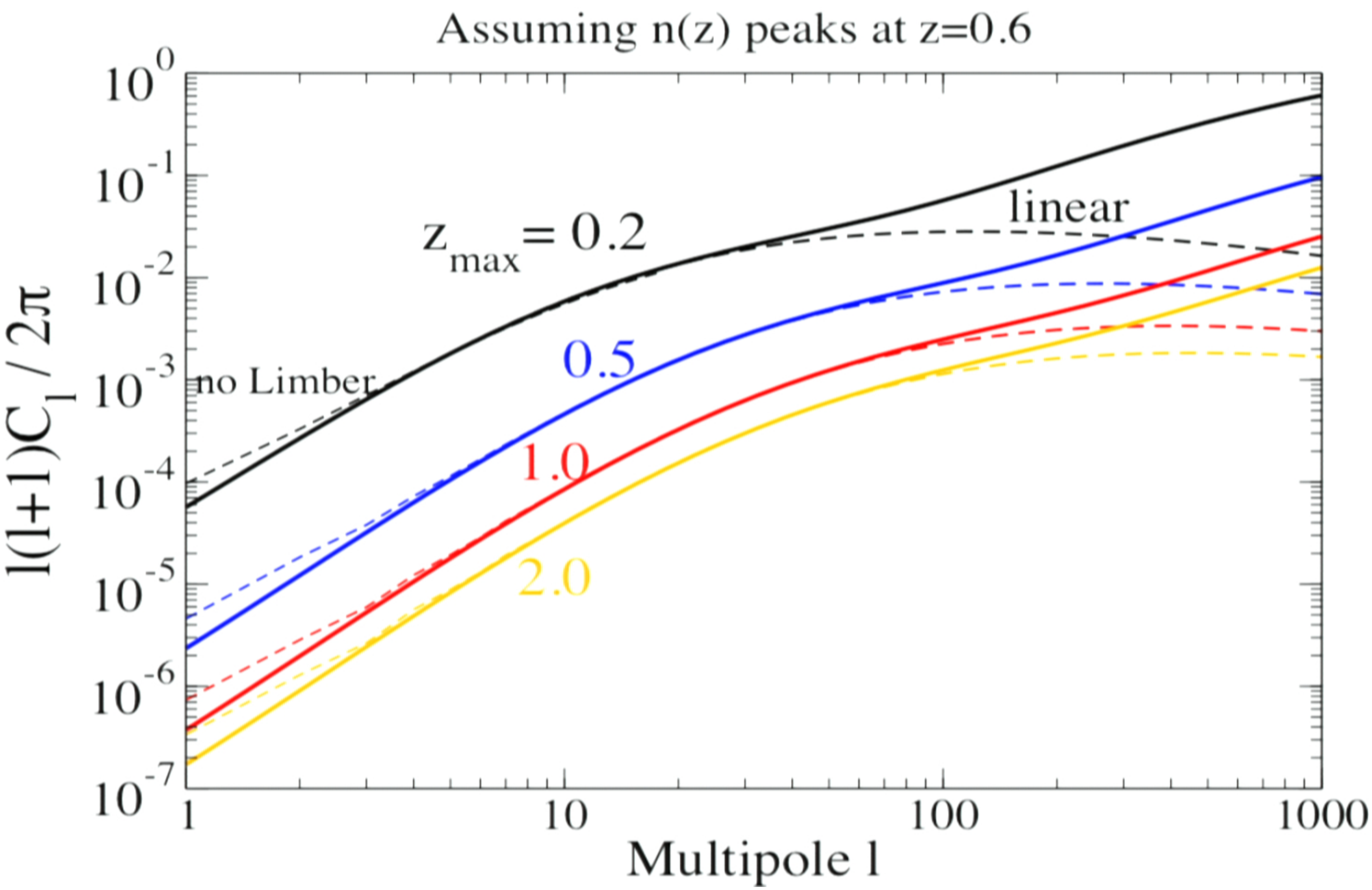
$$W(z) = \frac{b(z)N(z)}{\int_{z_{\rm min}}^{z_{\rm max}} N(z)dz}$$

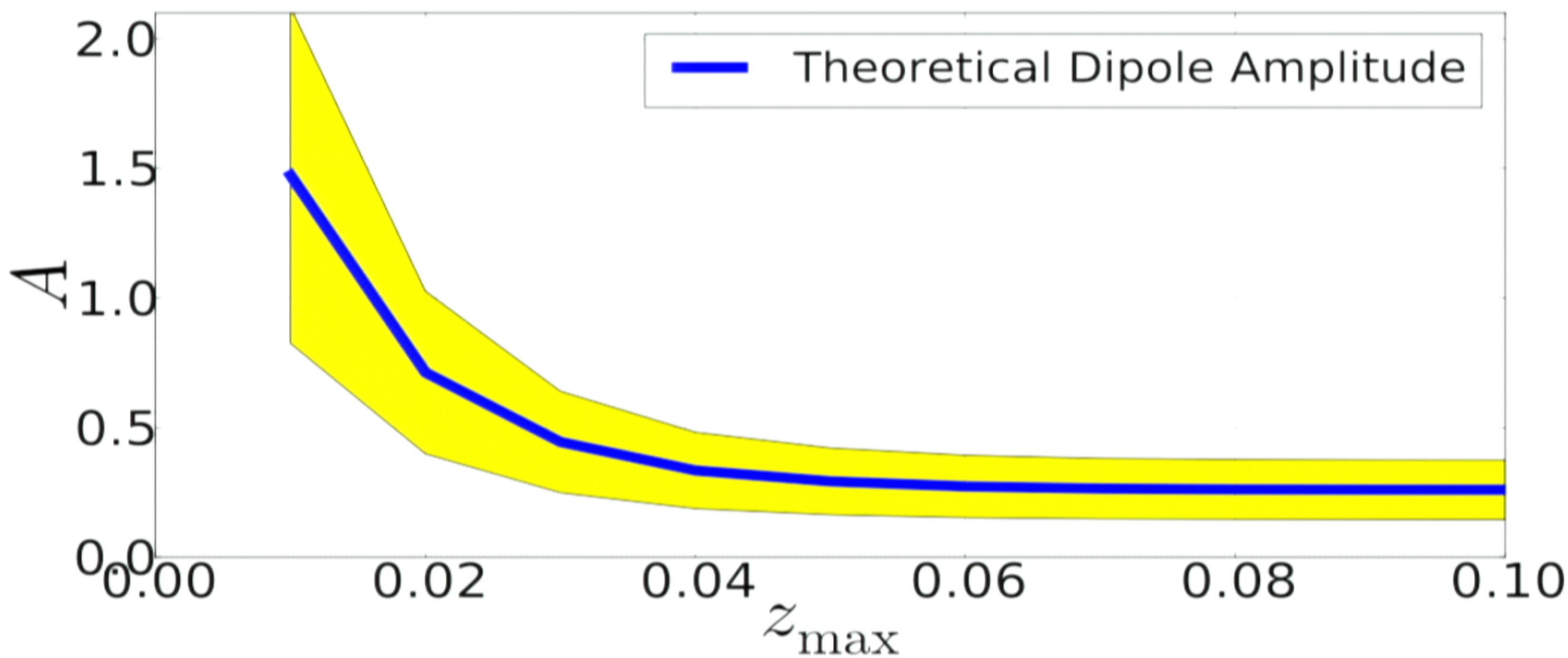
Note in particular: $N(\hat{\mathbf{n}}) = \bar{N}(\hat{\mathbf{n}})\left[1 + A\,(\hat{\mathbf{d}}\cdot\hat{\mathbf{n}})\right]$

$$C_1 \equiv \frac{4\pi}{9}A^2 = \text{dipole power}$$

$$\sigma(C_\ell) = \sqrt{\frac{2}{(2\ell+1)\,f_{\rm sky}}}\,C_\ell = \text{cosmic variance error}$$

Expected power spectrum of LSS





(not actually converging in this plot
since there we run out of fewer galaxies at higher z
in this sample)

In literature, usually:
flux-weighted dipole

$$\mathbf{v} = \frac{2f(\Omega_M)}{3H_0\Omega_M}\,\mathbf{g}$$

$$\mathbf{g}(\mathbf{r}) = \frac{G}{b}\int \rho_g(\mathbf{r}')\,\frac{\mathbf{r}'-\mathbf{r}}{|\mathbf{r}'-\mathbf{r}|^3}\,d^3\mathbf{r}' = \frac{G}{b}\sum_i M_i\frac{\hat{\mathbf{r}}_i}{r_i^2}$$

$$= \frac{4\pi G}{b}\sum_i \frac{M_i}{L_i}\frac{L_i}{4\pi r_i^2}\hat{\mathbf{r}}_i = \frac{4\pi G}{b}\sum_i \frac{M_i}{L_i} S_i \hat{\mathbf{r}}_i\ ,$$

Assume M/L is constant, weigh galaxies with measured flux S_i to get **g**

Why you might not get convergence to the kinematic dipole...

- Long-wavelength perturbations

  Grischuk & Zeldovich 1978
  Turner 1991
  Gordon, Hu, Huterer, & Crawford 2005
  Erickcek, Carroll & Kamionkowski 2008

- Isocurvature perturbations

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- Bubble collisions (but tiny effect?)

  Johnson et al., Kleban et al...

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This work: looking at the number density of galaxies in different directions

Relativistic aberration:
galaxies "bunch up" in direction of motion

$$n(\theta,\phi) \rightarrow n(\theta,\phi)\,[1+2\beta\cos\alpha]$$

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Methodology

Hirata 2009

$$\frac{\delta N}{\bar{N}}(\hat{n}) = A\hat{\mathbf{d}} \cdot \hat{\mathbf{n}} + \sum_i k_i t_i(\hat{n})$$

Dipole modulation of number counts

Systematics templates (k_i is amplitude)

Motivated by similar models suggested in context of the CMB, e.g.

$$T_{\rm obs}(\hat{\mathbf{n}}) = T(\hat{\mathbf{n}})\left[1 + w(\hat{\mathbf{n}})\right]$$

Gordon, Hu, Huterer, Crawford 2005

$$P_{\rm obs}(\mathbf{k}) = P(k)\left[1 + w(\hat{\mathbf{k}})\right]$$

Ackerman, Carroll & Wise 2007
Pullen & Kamionkiwski 2009

Solution and an estimator:

Hirata 2009

$$\hat{\mathbf{x}} = F^{-1} g$$

$$g_i = \sum_D T_i(\hat{n}_D) - \frac{N_D}{N_R} \sum_R T_i(\hat{n}_R)$$

$$F_{ij} = \frac{N_D}{N_R} \sum_R T_i(\hat{n}_R) T_j(\hat{n}_R)$$

$$[\text{where } \mathbf{x} = (d_x, d_y, d_z, k_1, \ldots k_N, C)]$$

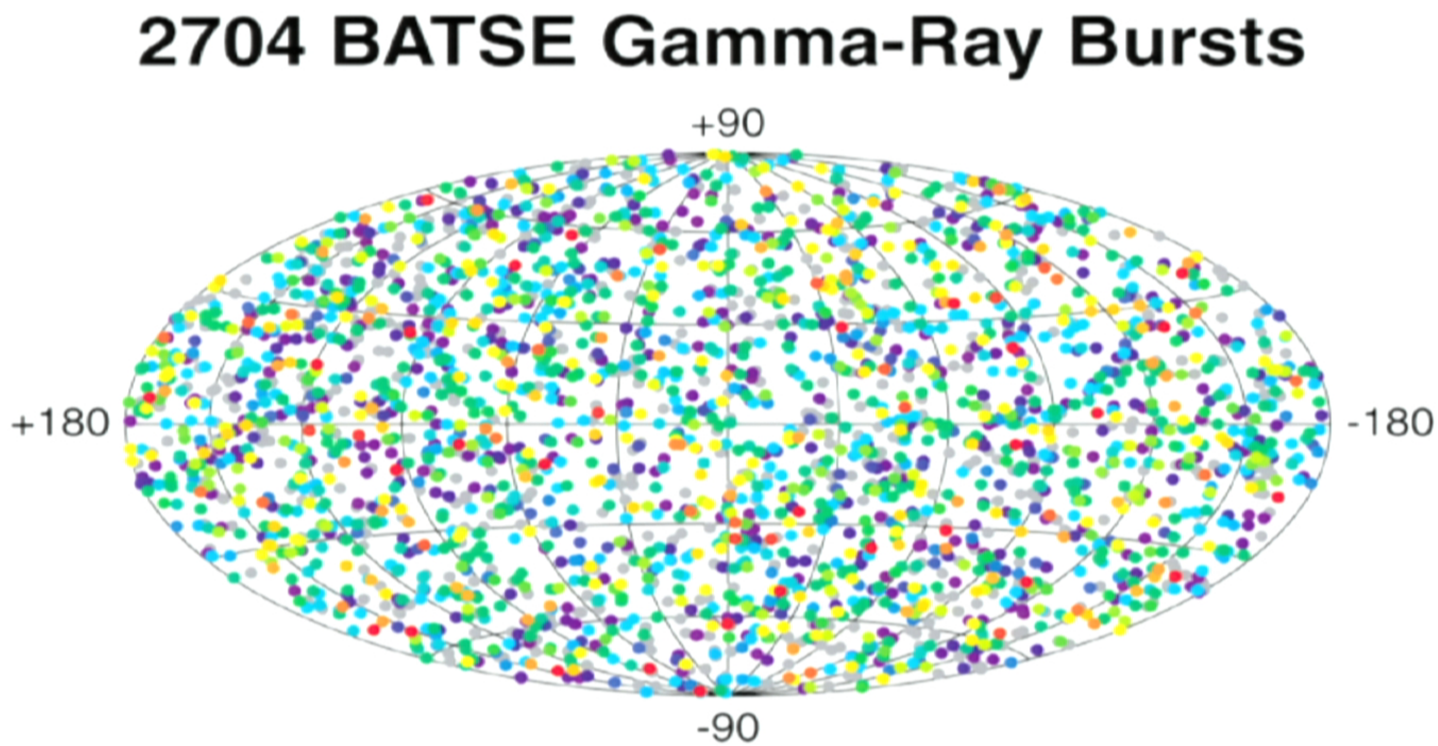
If you want just amplitude marginalized over direction, that's easy too:

$$\mathcal{L}(A) \propto \int \exp\left[-\frac{1}{2}(A\hat{d} - d_{\rm best})\mathrm{Cov}^{-1}(A\hat{d} - d_{\rm best})\right] d^2\hat{d}$$

Surveys and Results

Gibelyou & Huterer 2012
in preparation **and preliminary**

BATSE on Compton Gamma-Ray observatory



Transparent to structure in our Galaxy!

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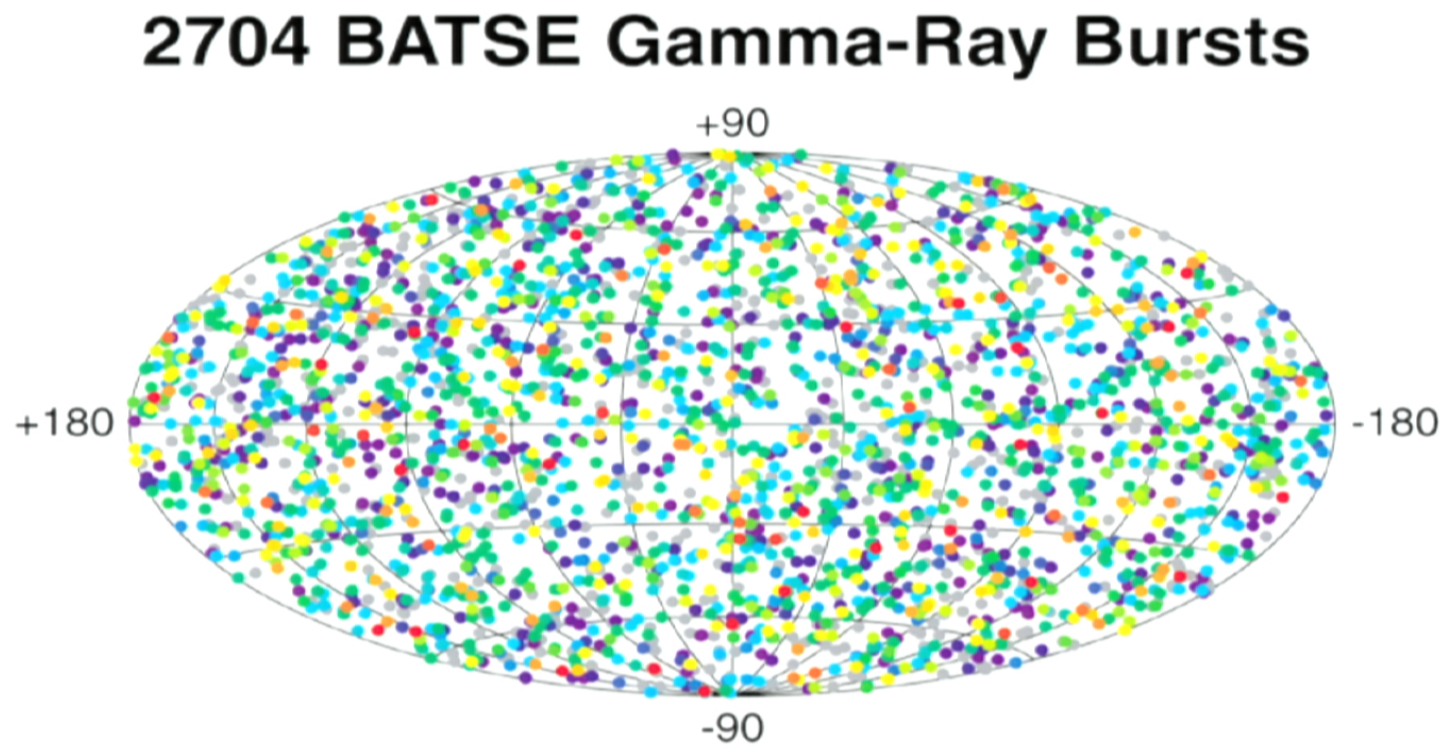

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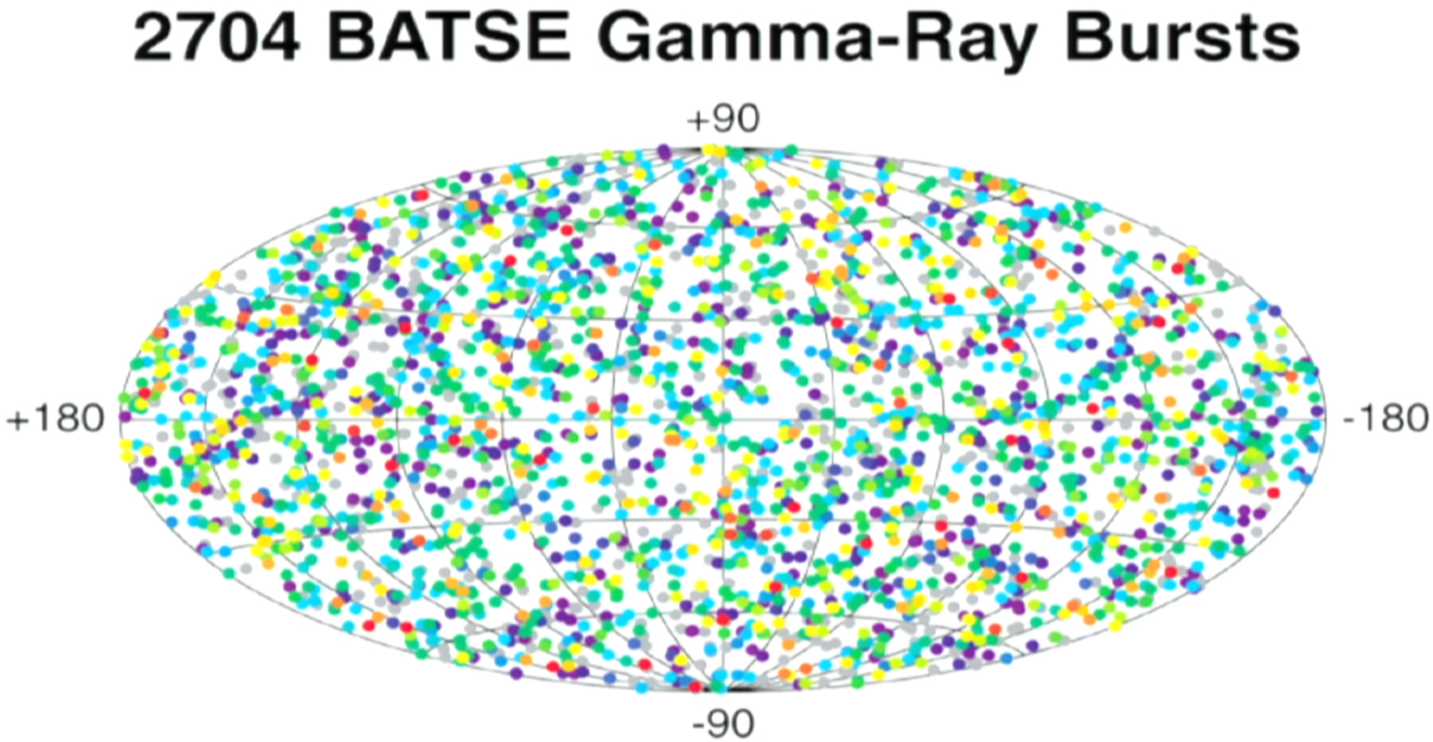
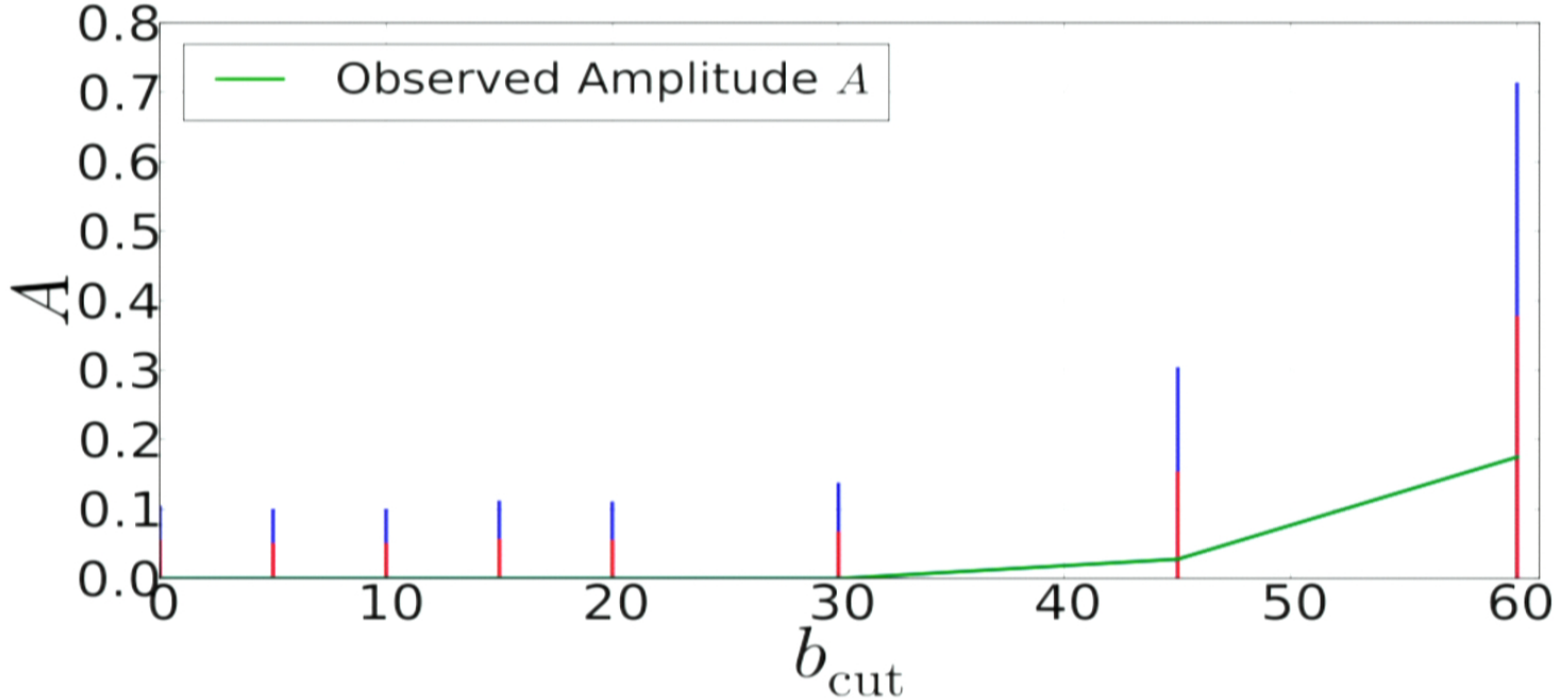


Transparent to structure in our Galaxy!

Theory vs. Observation, BATSE GRBs



Constraints are a factor of ~10 too weak to detect expected dipole A=O(0.01) due to small density of GRBs, but this still presents a useful check

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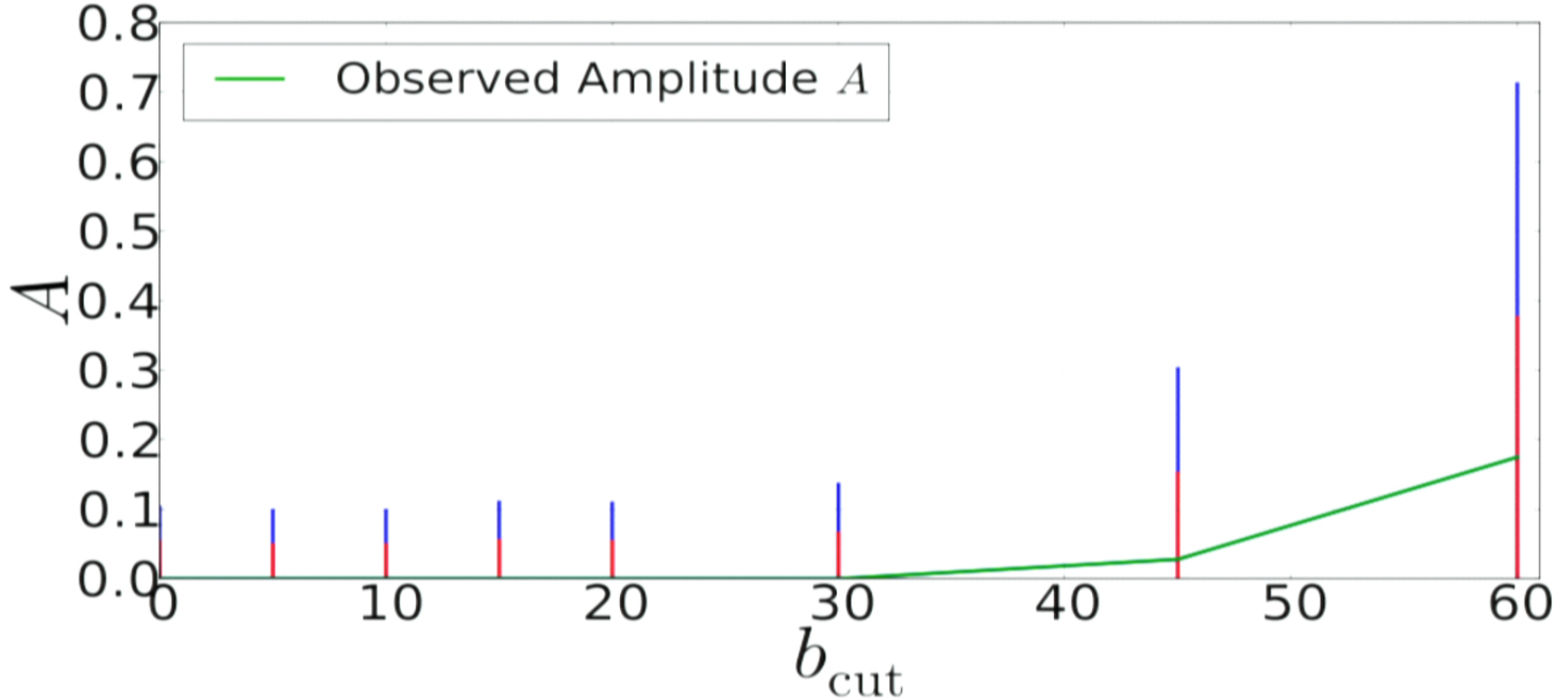

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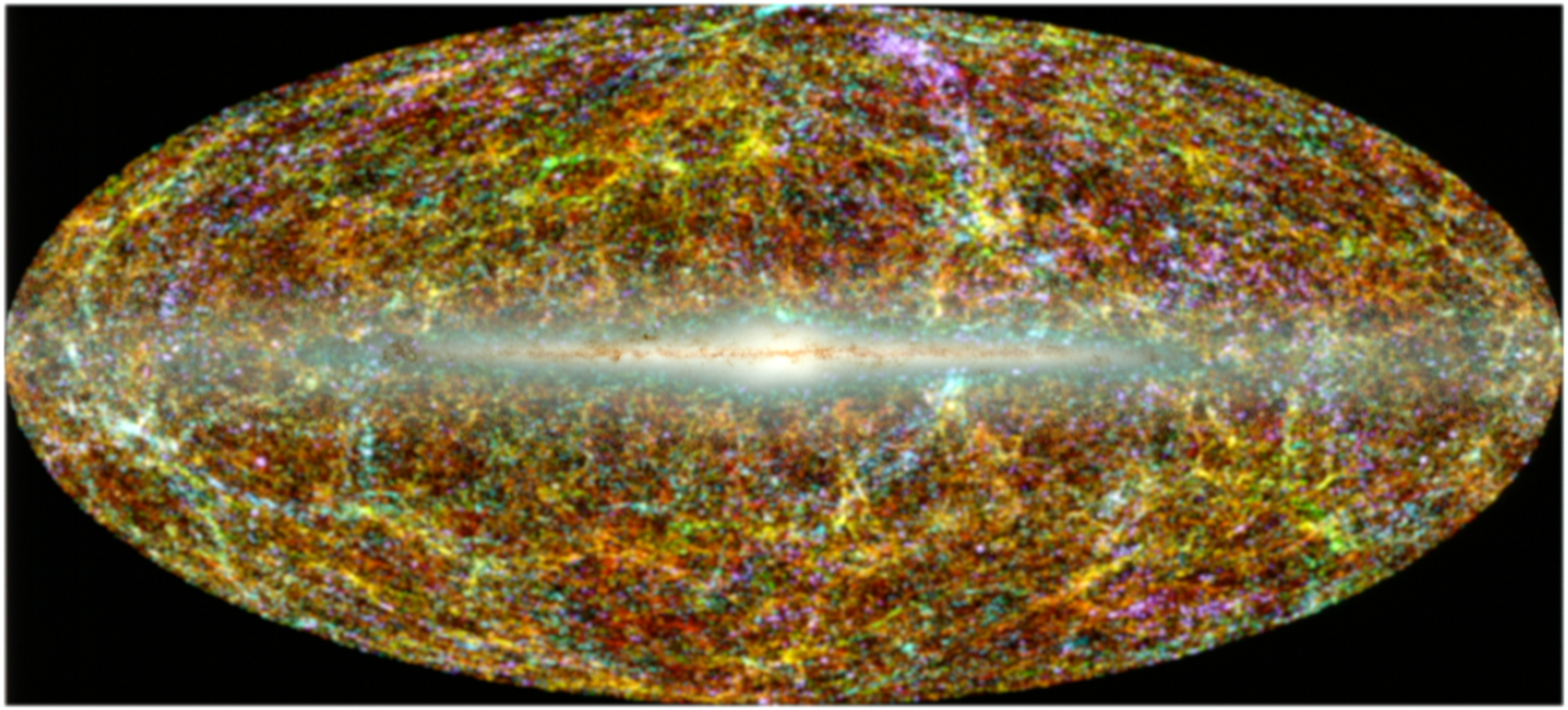
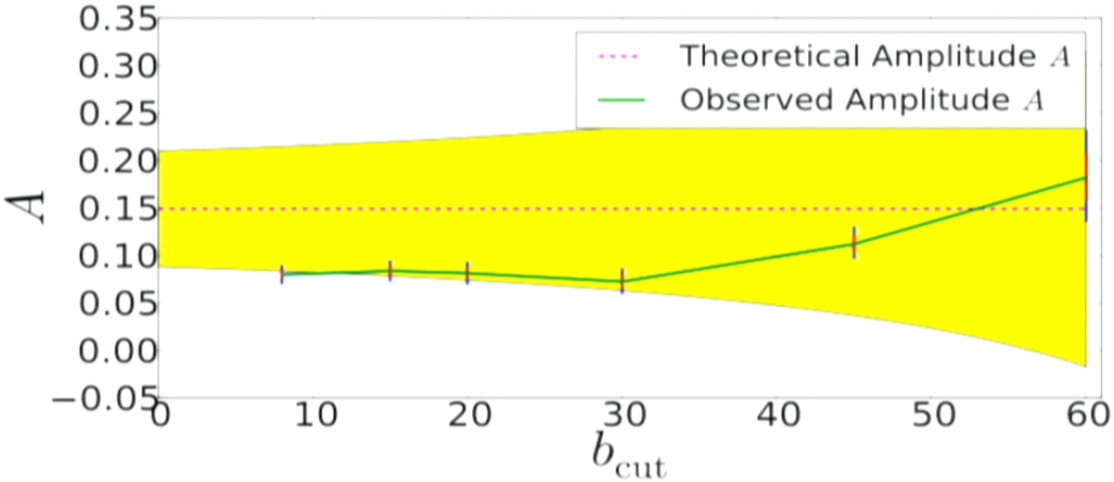
Two Micron All Sky Survey (2MASS)

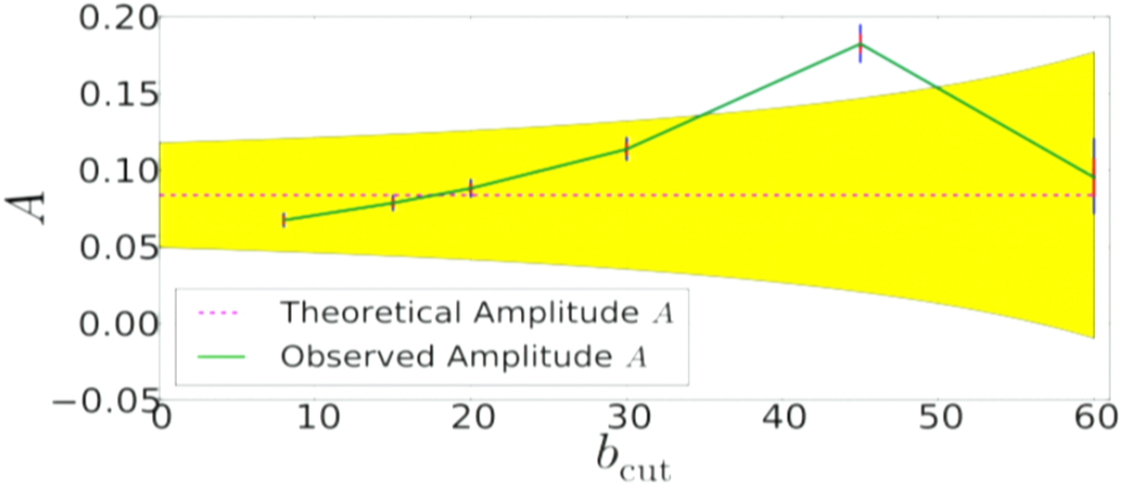


- Imaged 99.998% of sky at 1.25, 1.65 and 2.16 microns
- Extended Source Catalog: about 1.6 million extragalactic sources
- Mean redshift 0.05-0.07, depending on the cut (fainter $\Rightarrow$ deeper)



2MASS,
Ks<12.5

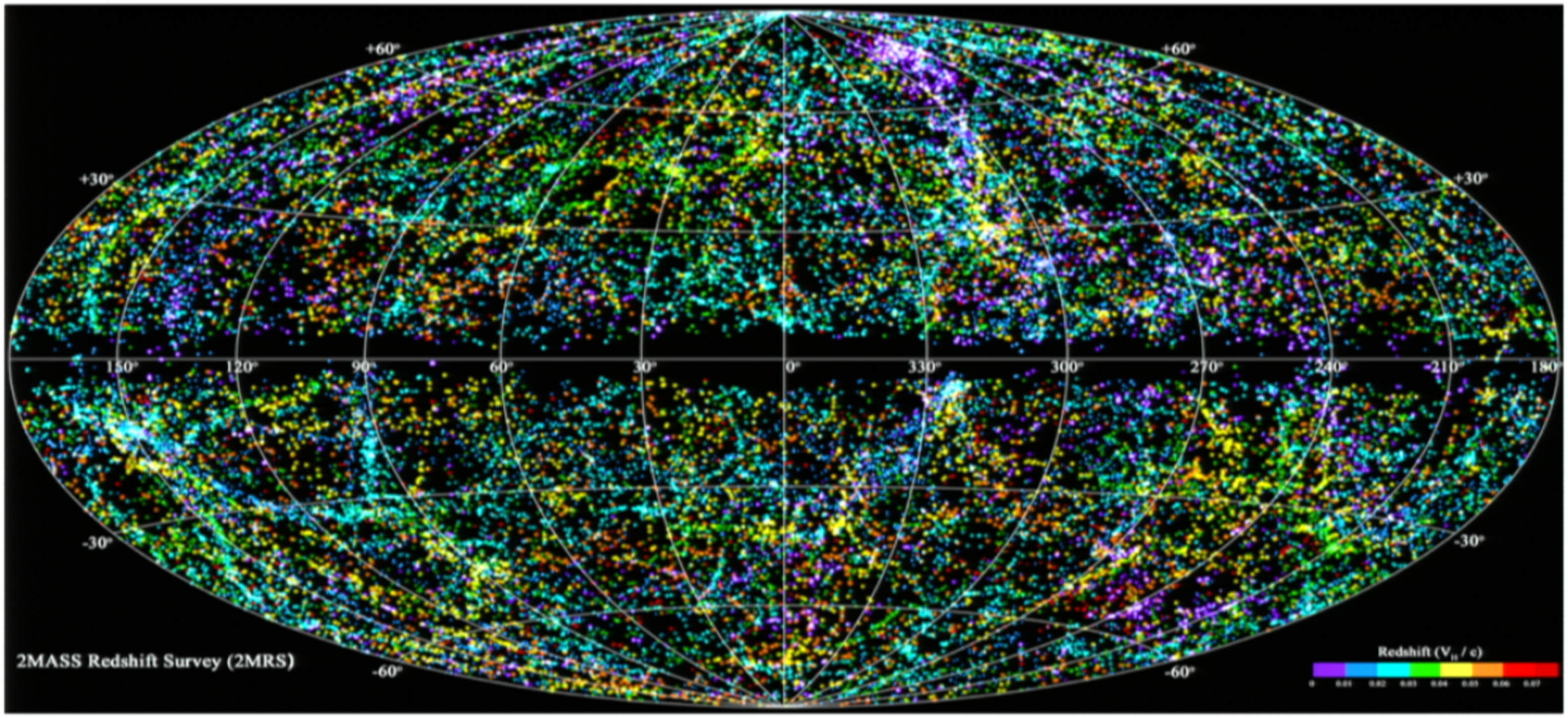
2MASS,
Ks<13.5



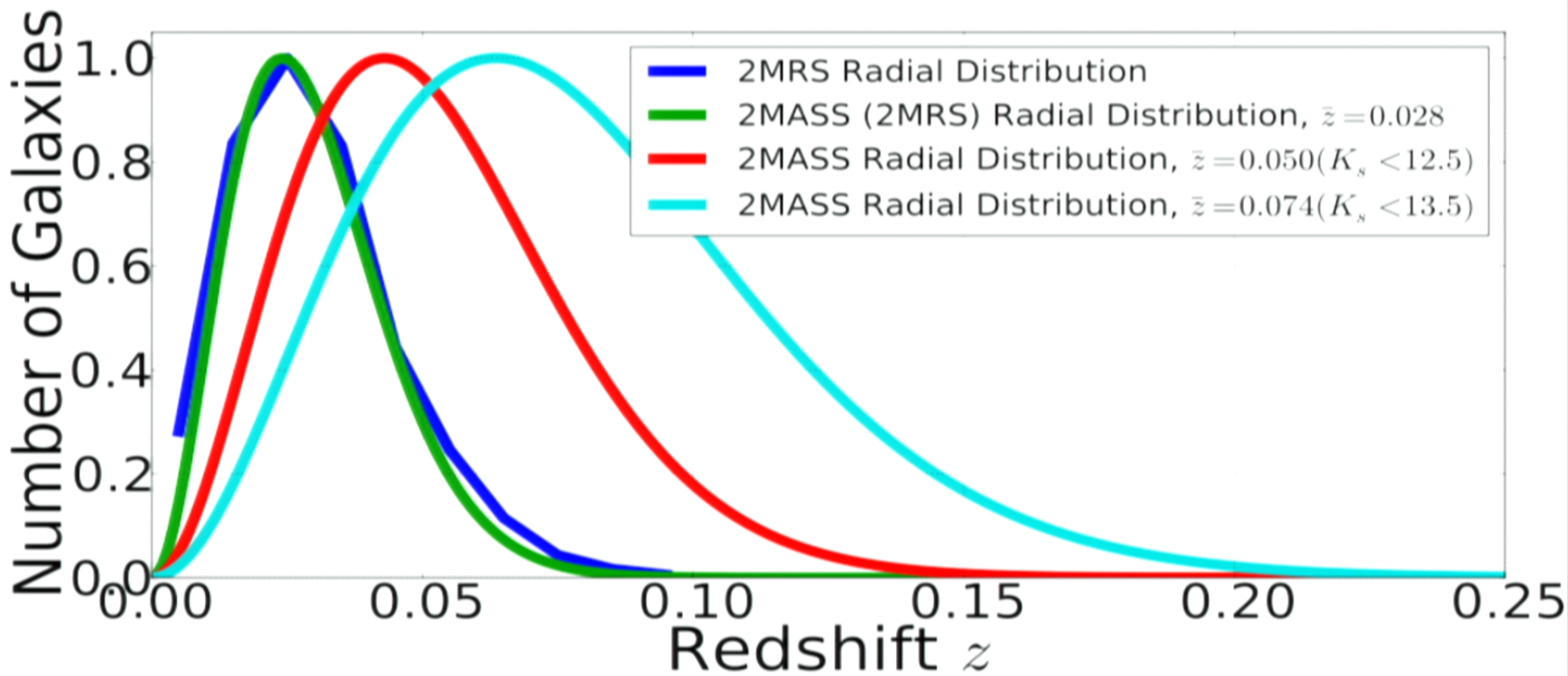
2MASS Redshift Survey (2MRS)

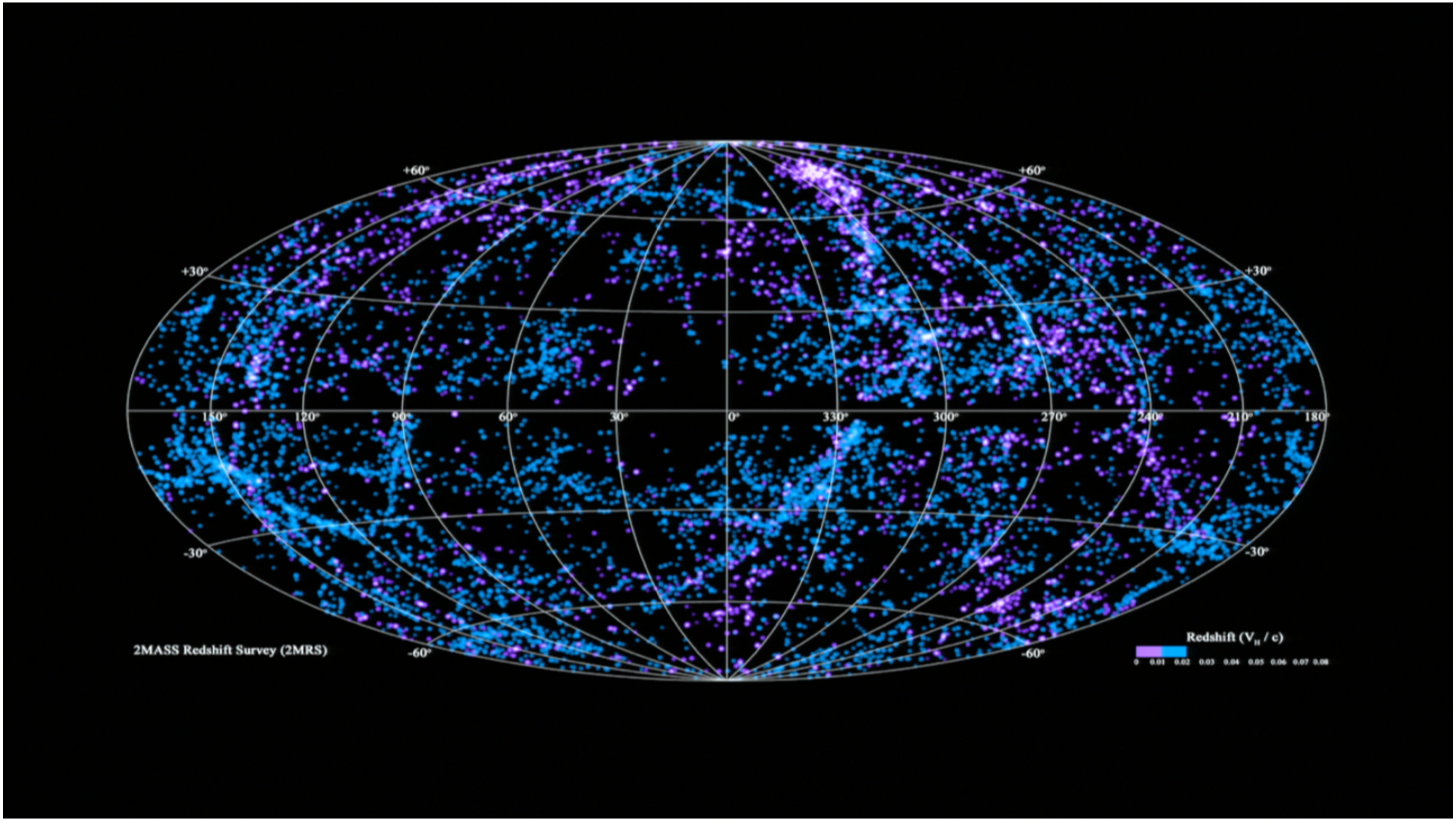
>40,000 redshifts

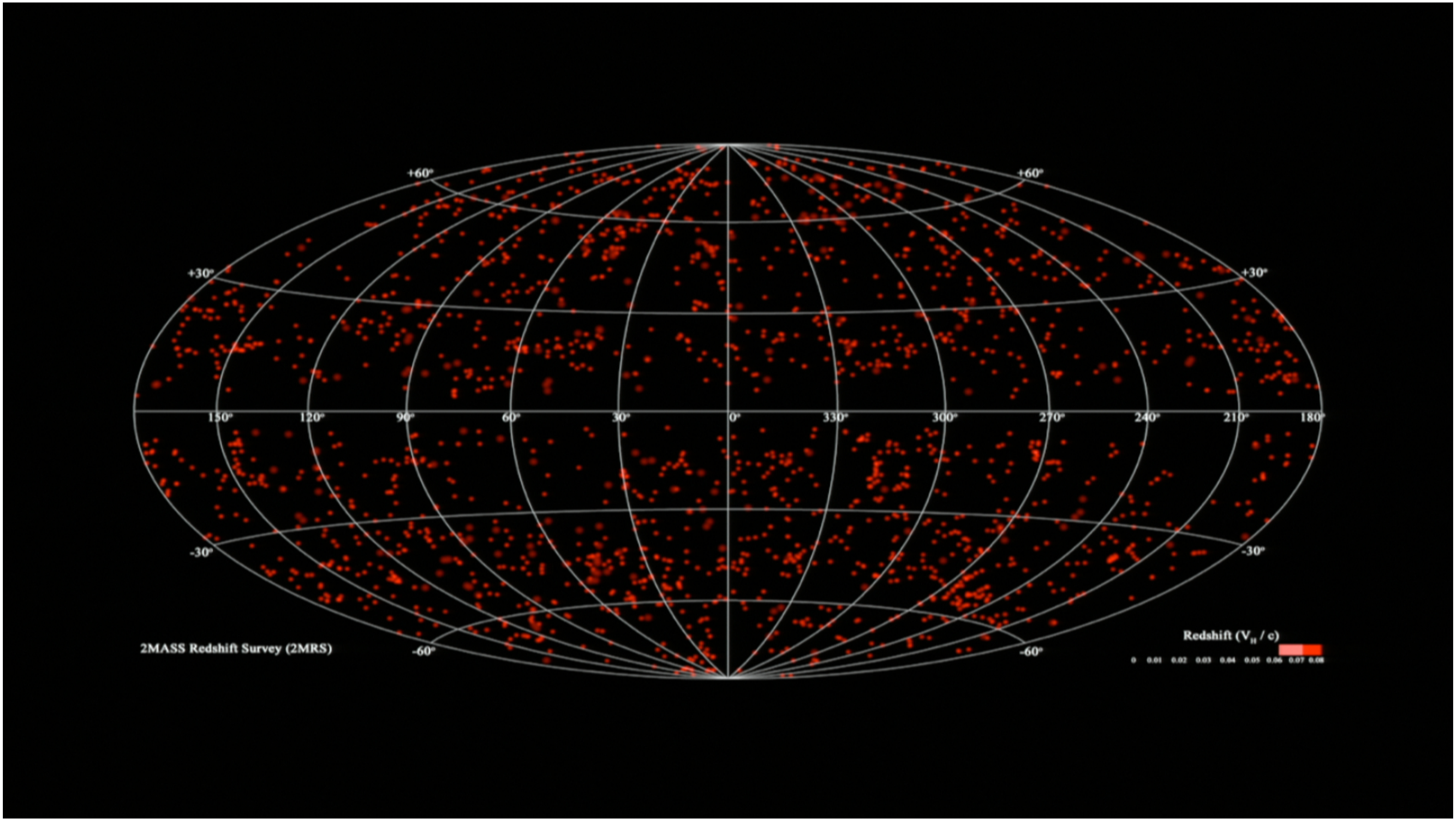
Ks < 11.75 mag



Huchra et al, arXiv:1108.0669


Number of Galaxies
1.0
0.8
0.6
0.4
0.2
0.0
0.00
0.05
0.10
0.15
0.20
0.25
Redshift z
2MRS Radial Distribution
2MASS (2MRS) Radial Distribution, $\bar{z}=0.028$
2MASS Radial Distribution, $\bar{z}=0.050 (K_s < 12.5)$
2MASS Radial Distribution, $\bar{z}=0.074 (K_s < 13.5)$


+60°
+60°
+30°
+30°
150°
120°
90°
60°
30°
0°
330°
300°
270°
240°
210°
180°
-30°
-30°
-60°
-60°
2MASS Redshift Survey (2MRS)
Redshift (V_H / c)
0 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08


+60°
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120°
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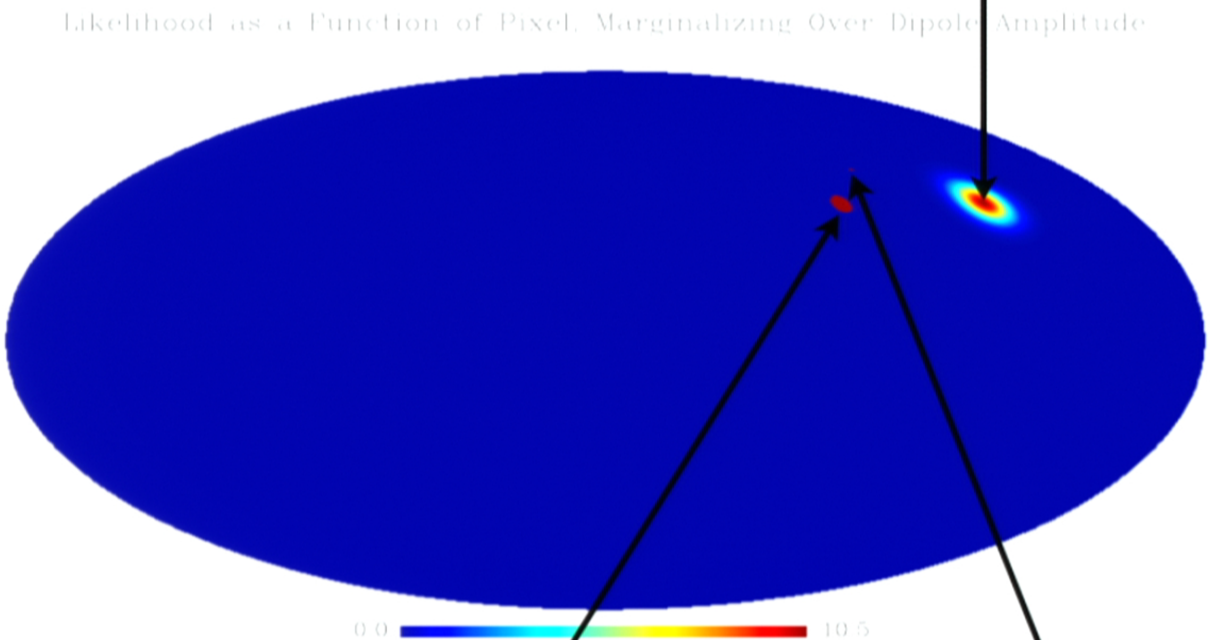
240°
210°
180°
-30°
-30°
-60°
-60°
2MASS Redshift Survey (2MRS)
Redshift (V_H / c)
0 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08

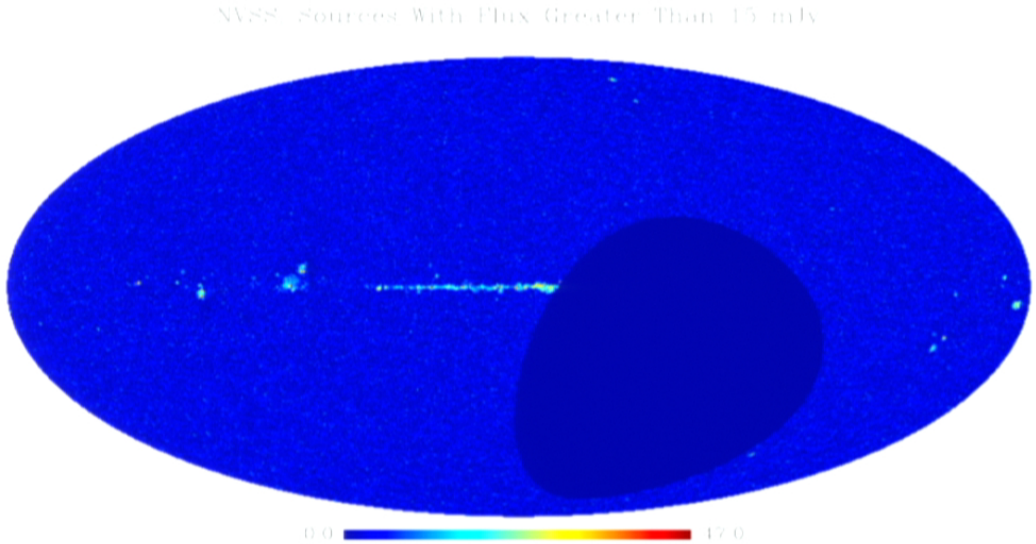
2D-projected local-structure dipole
(this work) for 2MRS sample
(in limit of large z, may converge to
kinematic dipole)



Flux-weighted local-structure
dipole (Maller et al., 2003)
(a measure of *acceleration*
due to gravity for the *Local Group*)

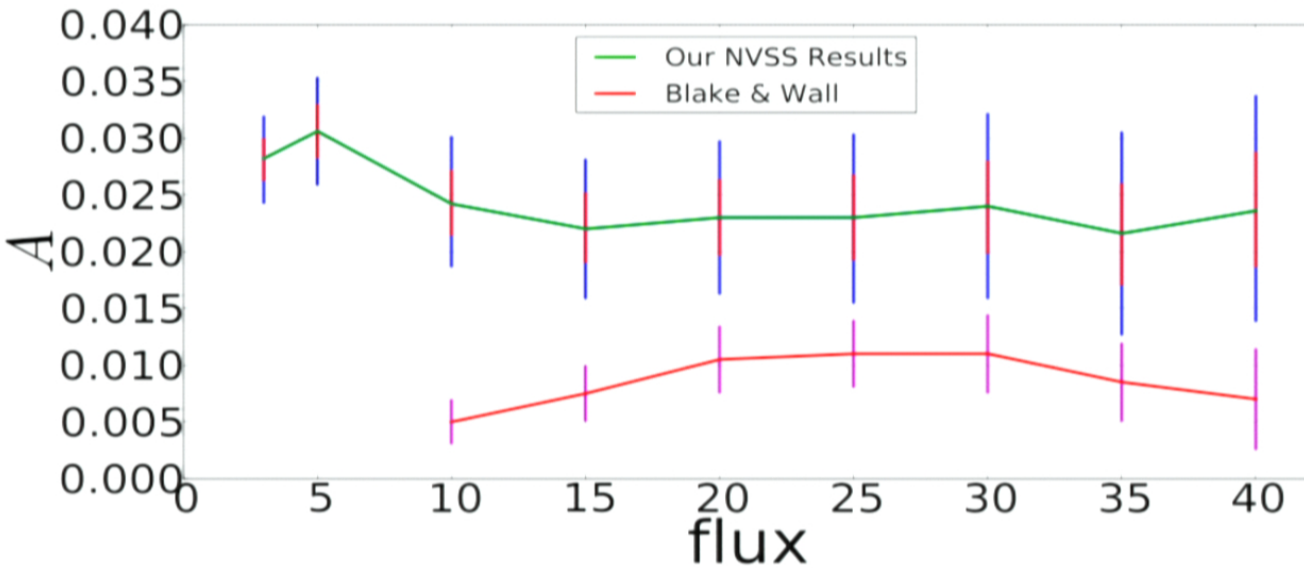
CMB kinematic dipole (Kogut et al.)
(a measure of the *velocity* of the
Sun)

NRAO VLA Sky Survey (NVSS)



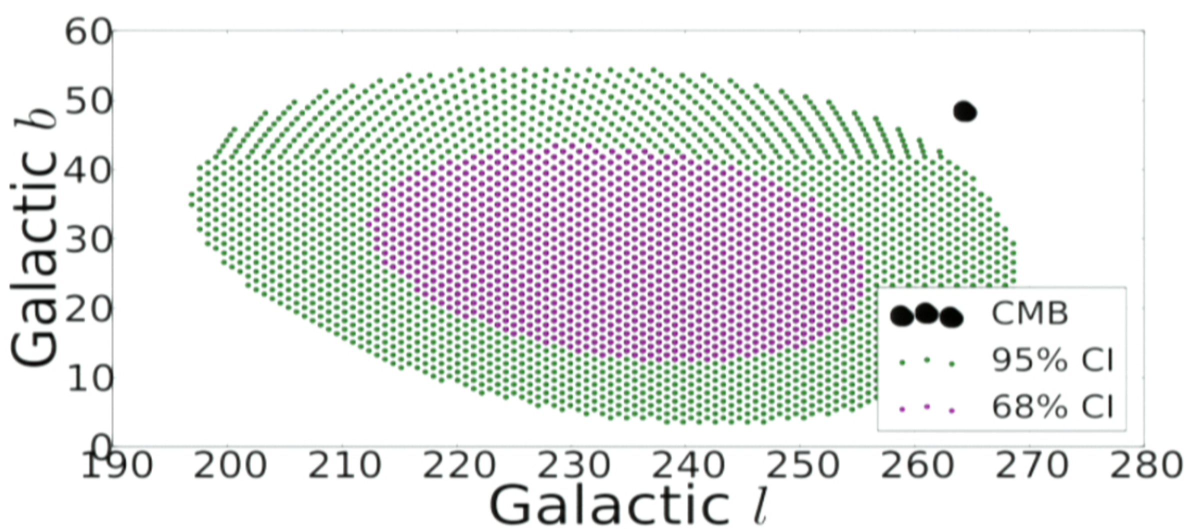
surveyed 82% of the sky at 1.4 GHz

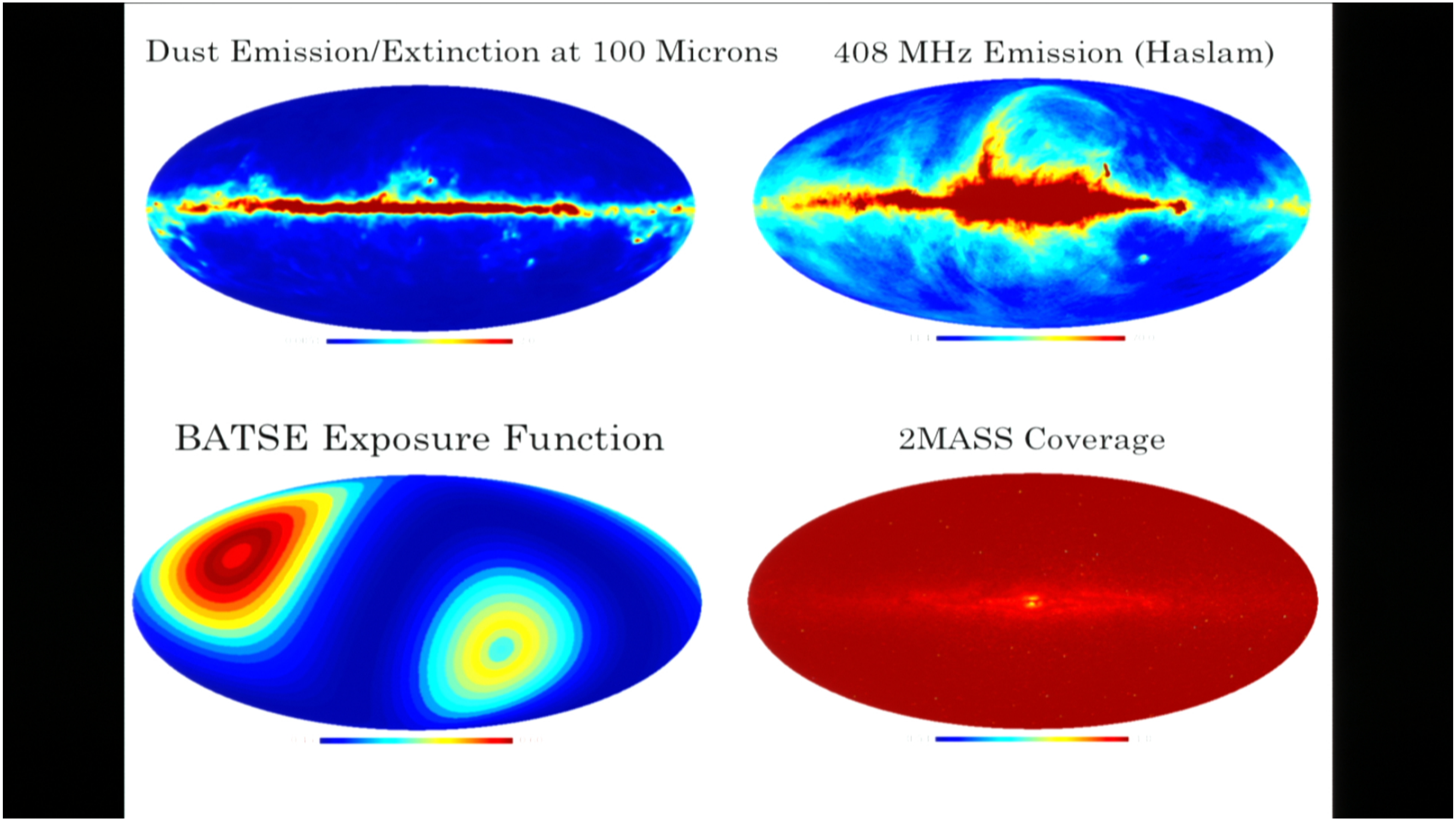
1.8 million sources down to ~2.5 mJy;
declination-dep. striping goes away for sources > 15 mJy



VERY
PRELIMINARY

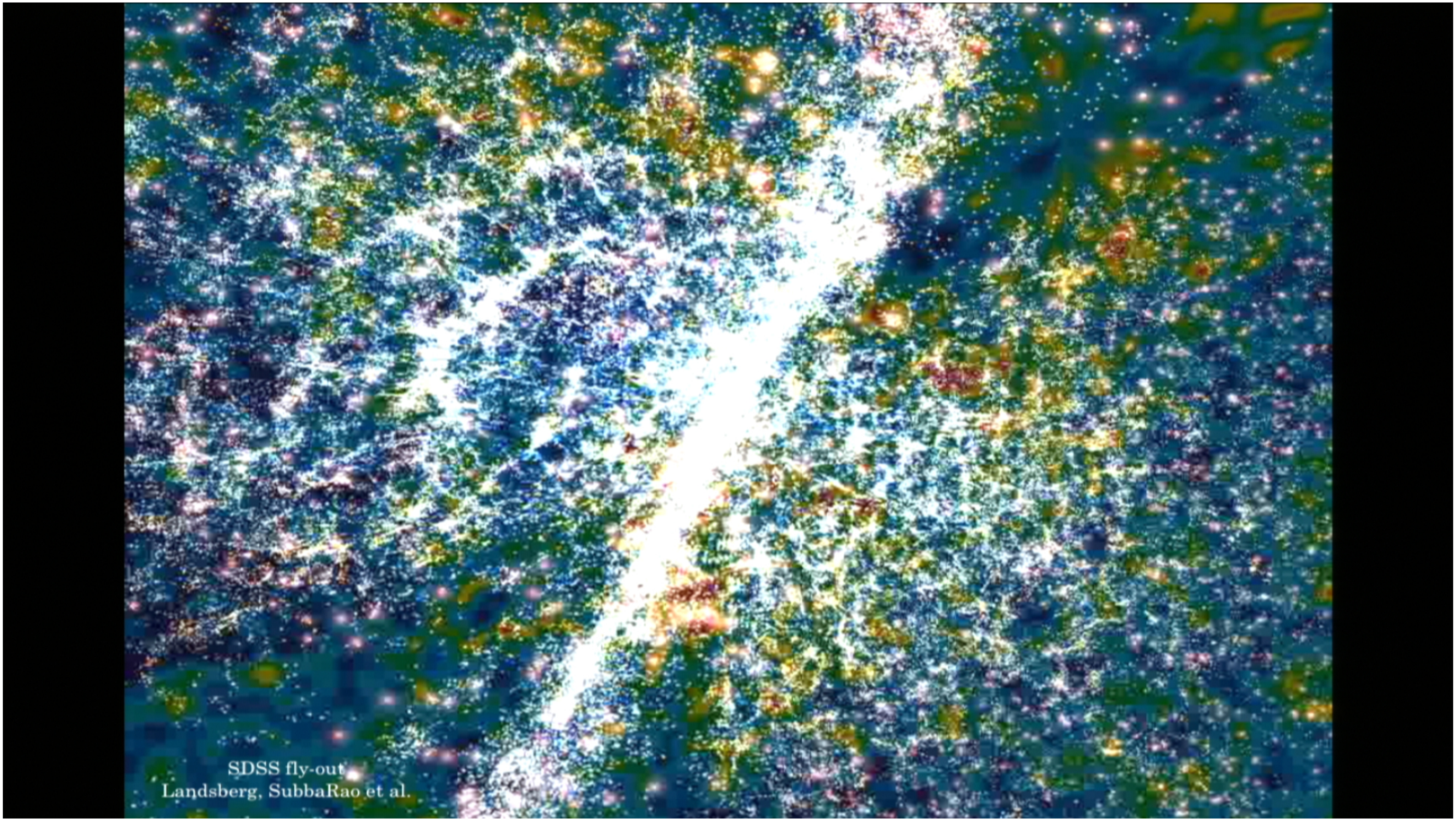
expect ~3/4 of
the dipole signal
to be kinematic
in origin (so
should match up
with the CMB)

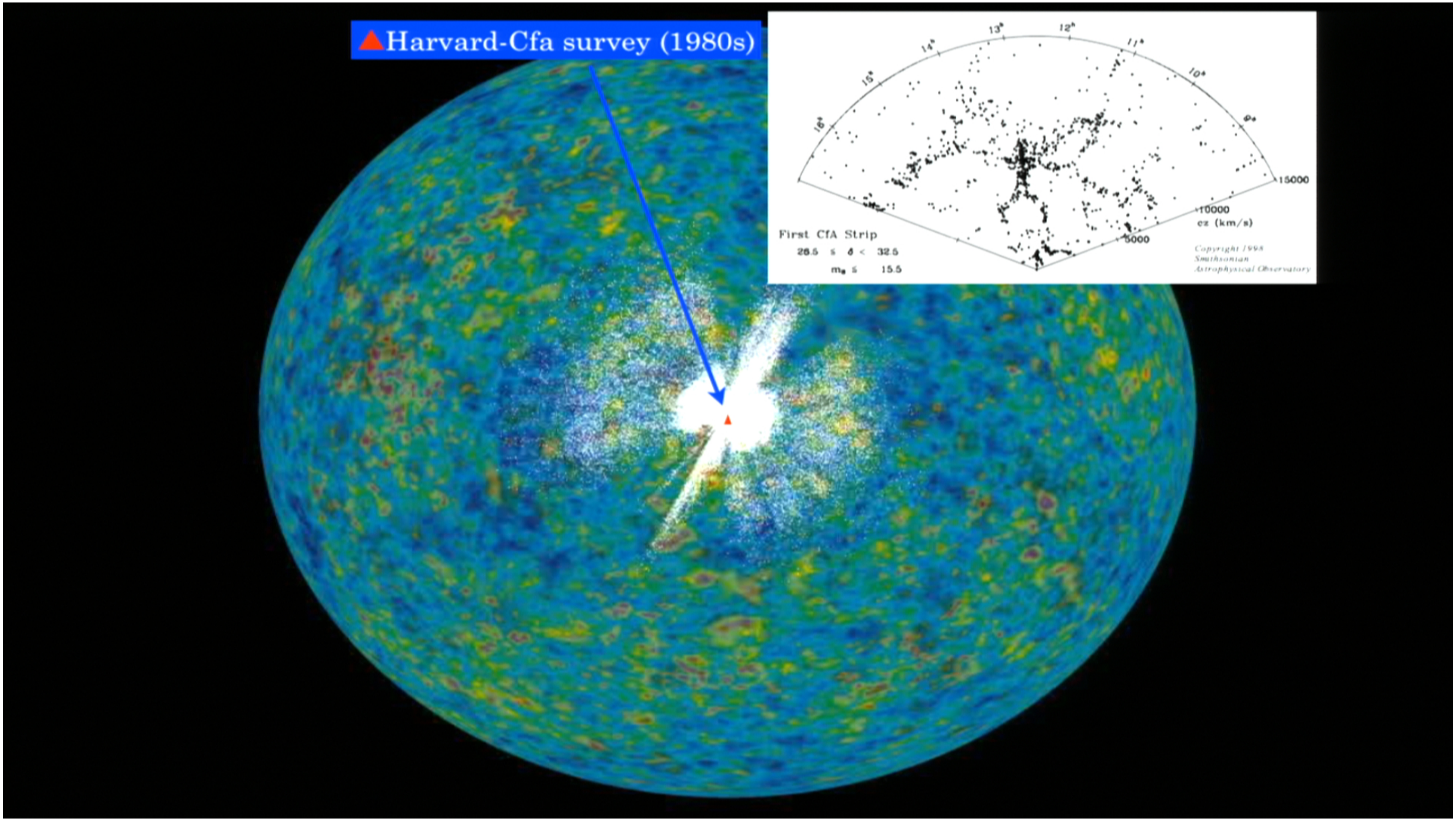


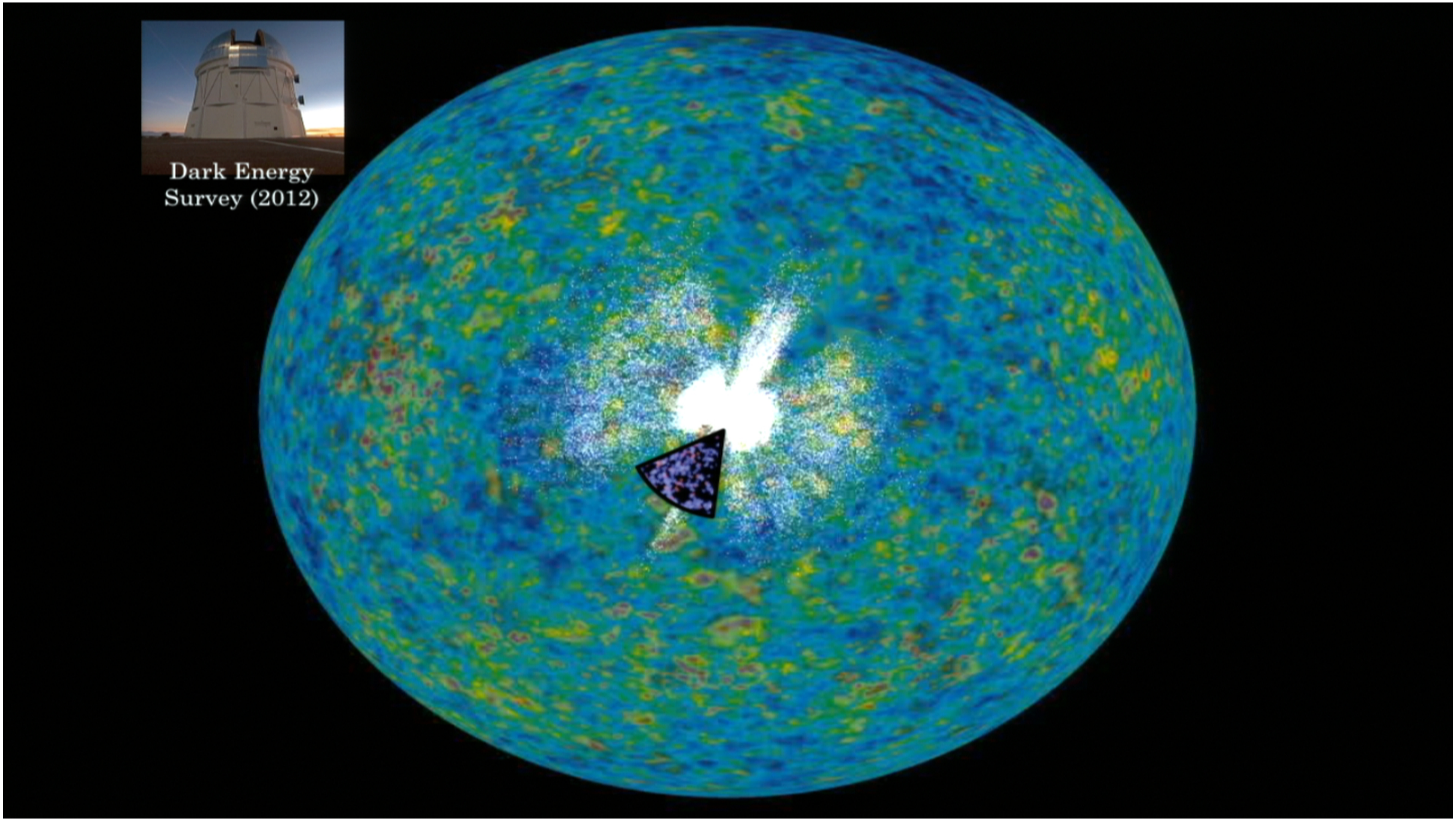

Dust Emission/Extinction at 100 Microns
408 MHz Emission (Haslam)
BATSE Exposure Function
2MASS Coverage

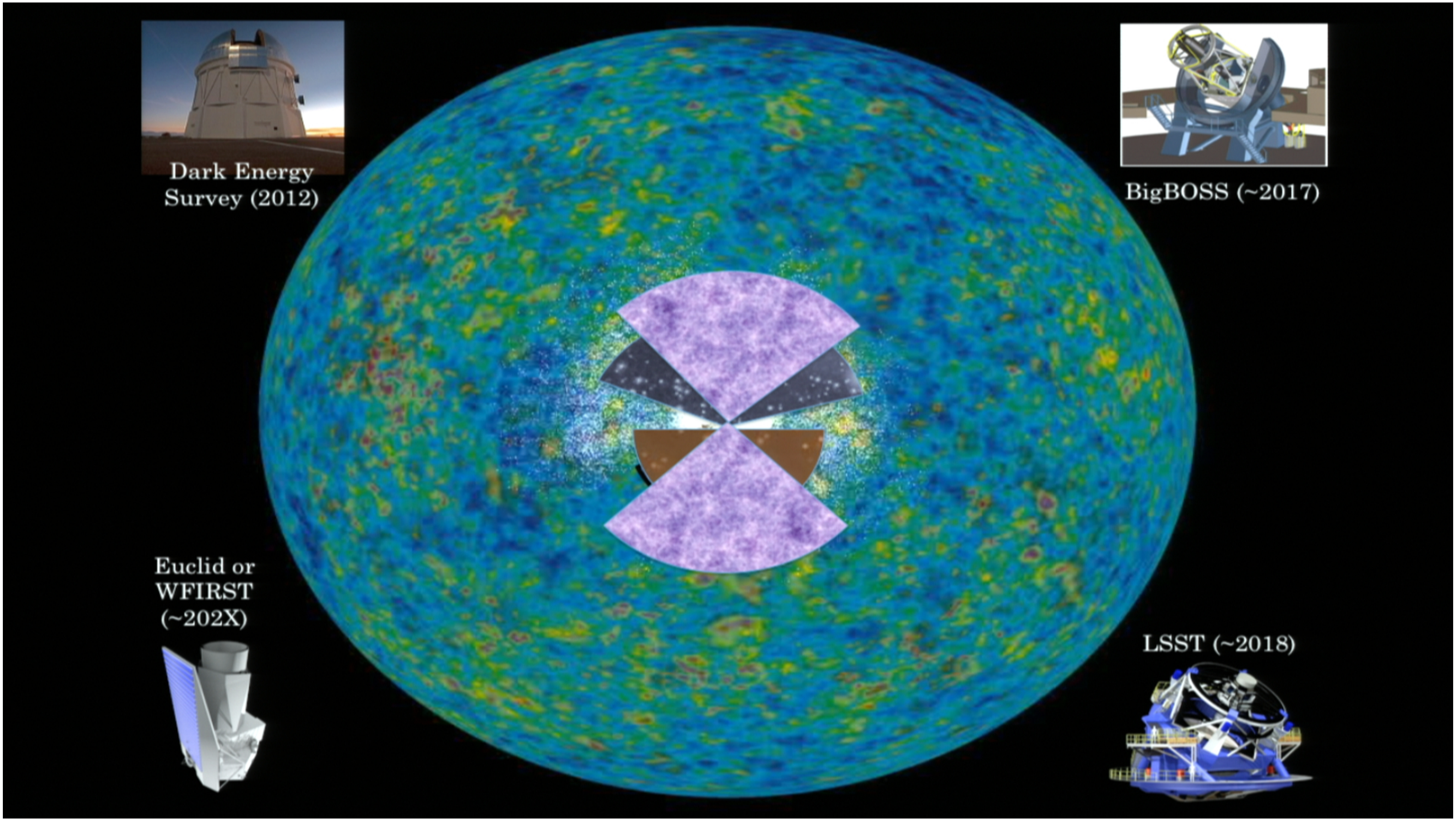
Fundamental Physics from LSS

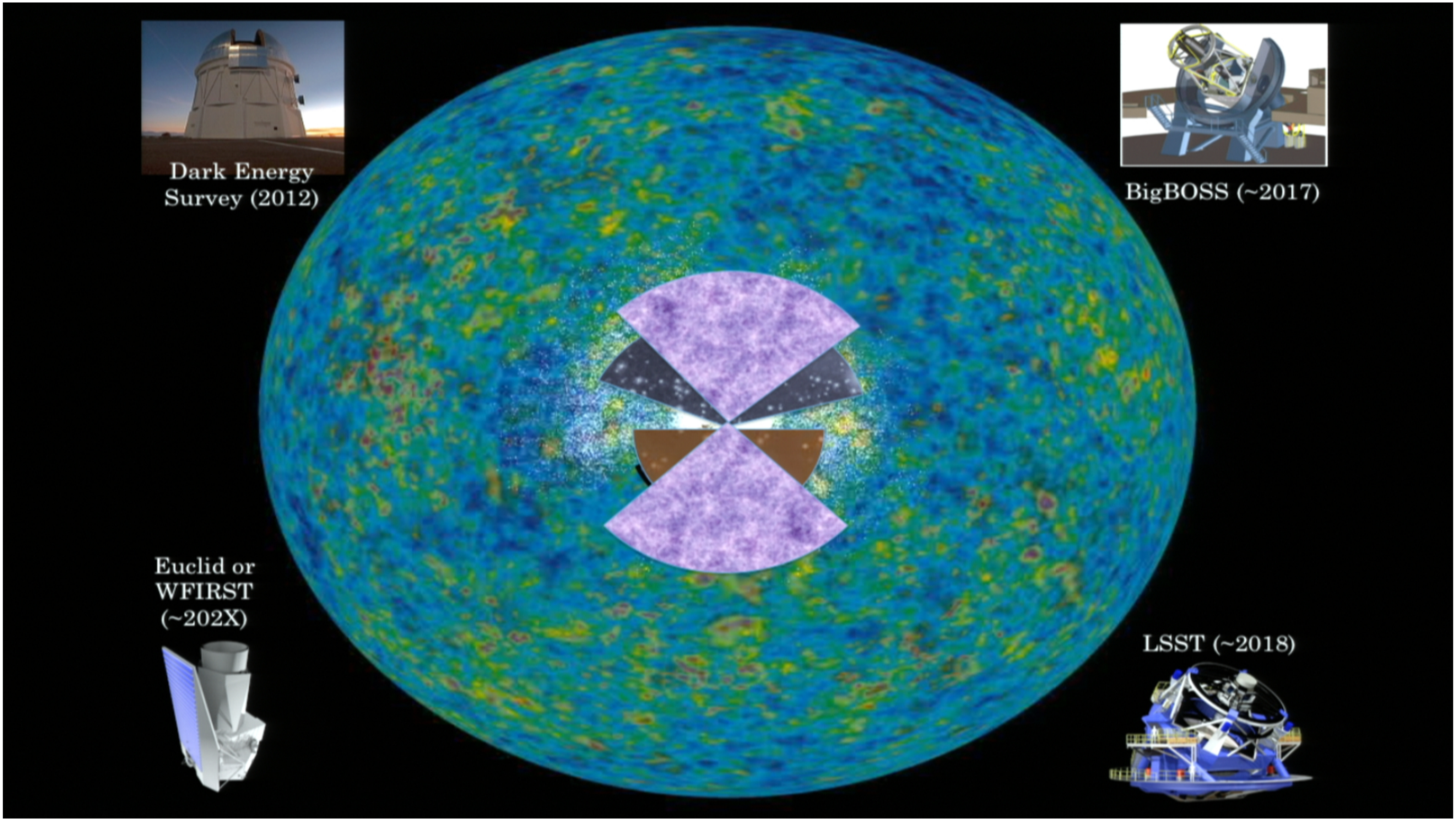
- Amount, clustering of Cold Dark Matter
- Expansion history (⇔dark energy)
- Modified Gravity (⇔dark energy)
- Self-interactions of dark matter
- Neutrino masses ($\sum m_\nu \leq 0.3$ eV)
- Features in inflationary potential
- Primordial non-Gaussianity of density perturbations
- Statistical isotropy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


SDSS fly-out
Landsberg, SubbaRao et al.


Harvard-Cfa survey (1980s)
First CfA Strip
26.5 ≤ δ < 32.5
m_B ≤ 15.5
15000
10000
cz (km/s)
5000
Copyright 1998
Smithsonian
Astrophysical Observatory


Dark Energy
Survey (2012)


Dark Energy
Survey (2012)
BigBOSS (~2017)
Euclid or
WFIRST
(~202X)
LSST (~2018)


Dark Energy Survey (2012)
BigBOSS (~2017)
Euclid or WFIRST (~202X)
LSST (~2018)

Conclusions

- LSS is a great tool to test fundamental physics beyond the cosmological parameters, for example statistical isotropy of the universe
- Comparison with CMB is particularly interesting. It tests long-wavelength perturbations and other exotic physics (and models of inflation)
- So far, our (relatively modest) tests with LSS given results consistent with standard, statistically isotropic expectation
- With BOSS, DES, LSST, BigBOSS, Euclid, WFIRST, etc the LSS is entering a new era of precision tests => expect much better constraints of fundamental physics