

CARLSBERGFONDET

Testing the Cosmological principle

M. Rameez (with R. Mohayaee, S. Sarkar and J. Colin)



The Niels Bohr
International Academy

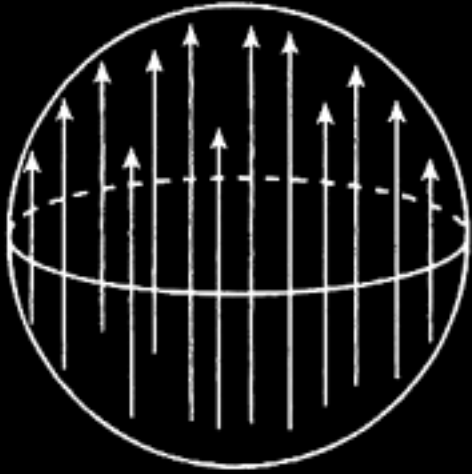
UNIVERSITY OF
COPENHAGEN



Cosmology 2018
Dubrovnik

The cosmological principle

The Universe is (statistically) **isotropic** and **homogeneous** (on large scales).

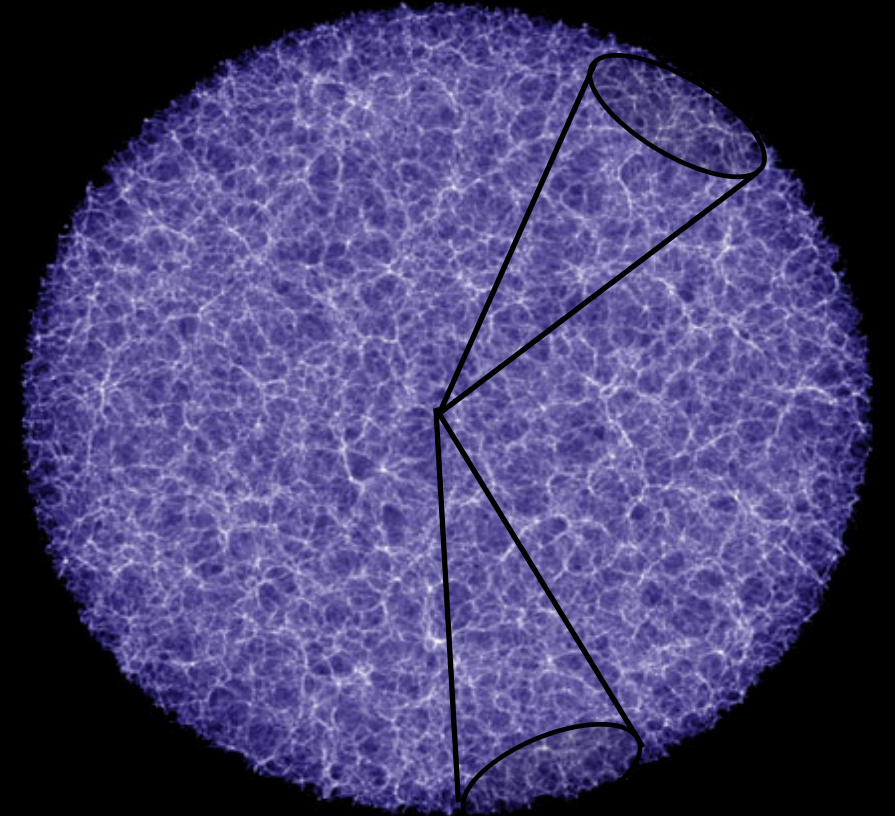


Homogeneous
Not isotropic



Isotropic
Not homogeneous

No special positions or directions in the Universe.

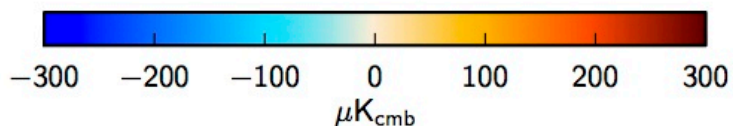
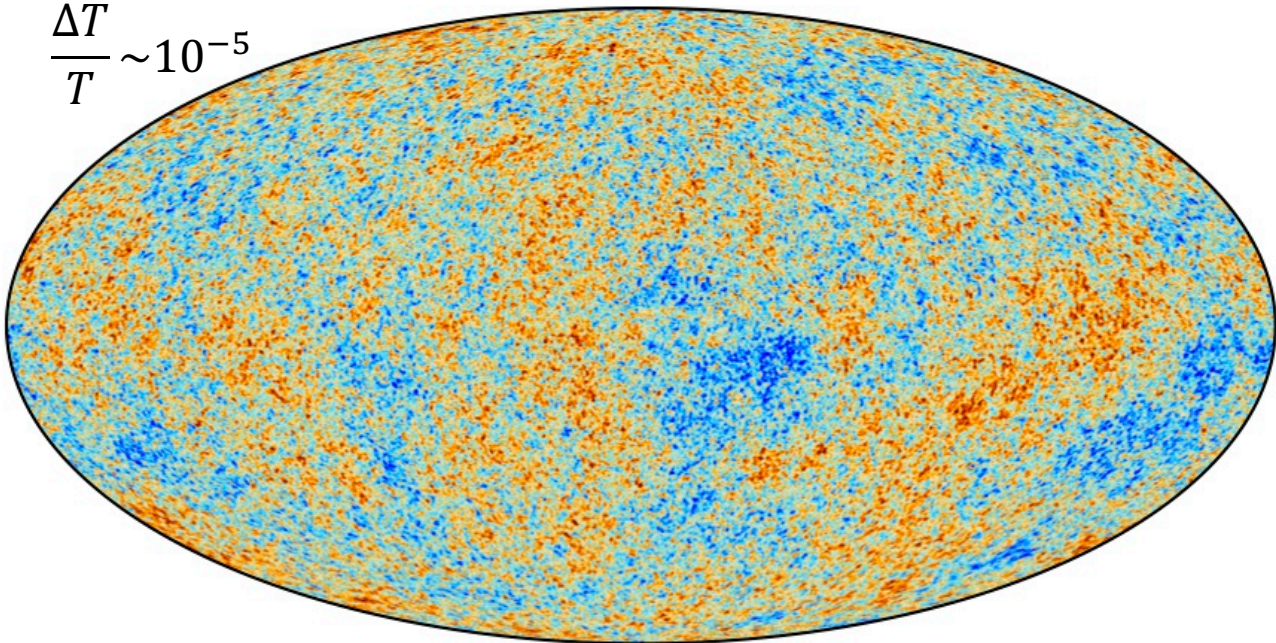


Stationary observer:

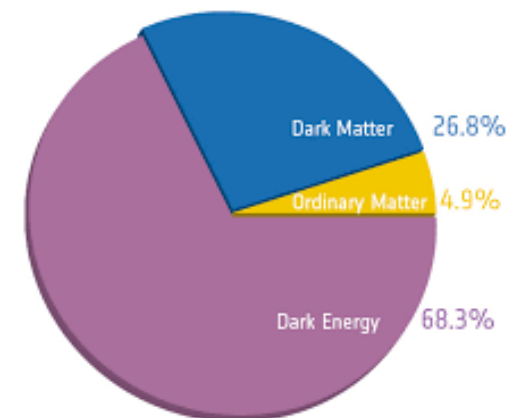
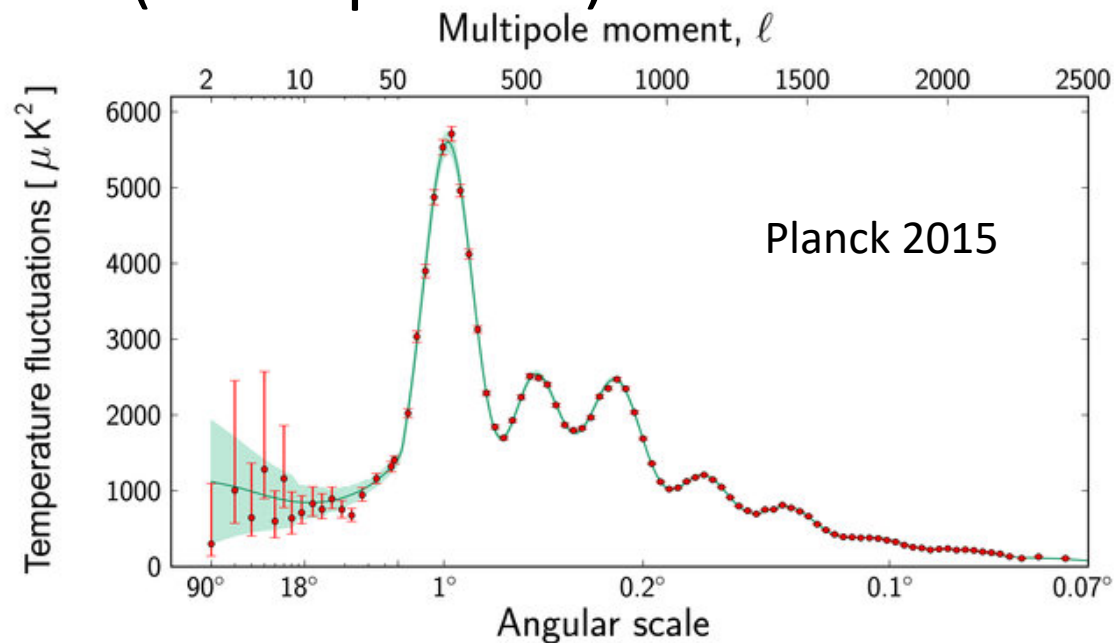
- Sees same number of sources per solid angle in all directions
- Large angles, deep enough survey

“Data from the Planck satellite show the universe to be highly isotropic” (Wikipedia)

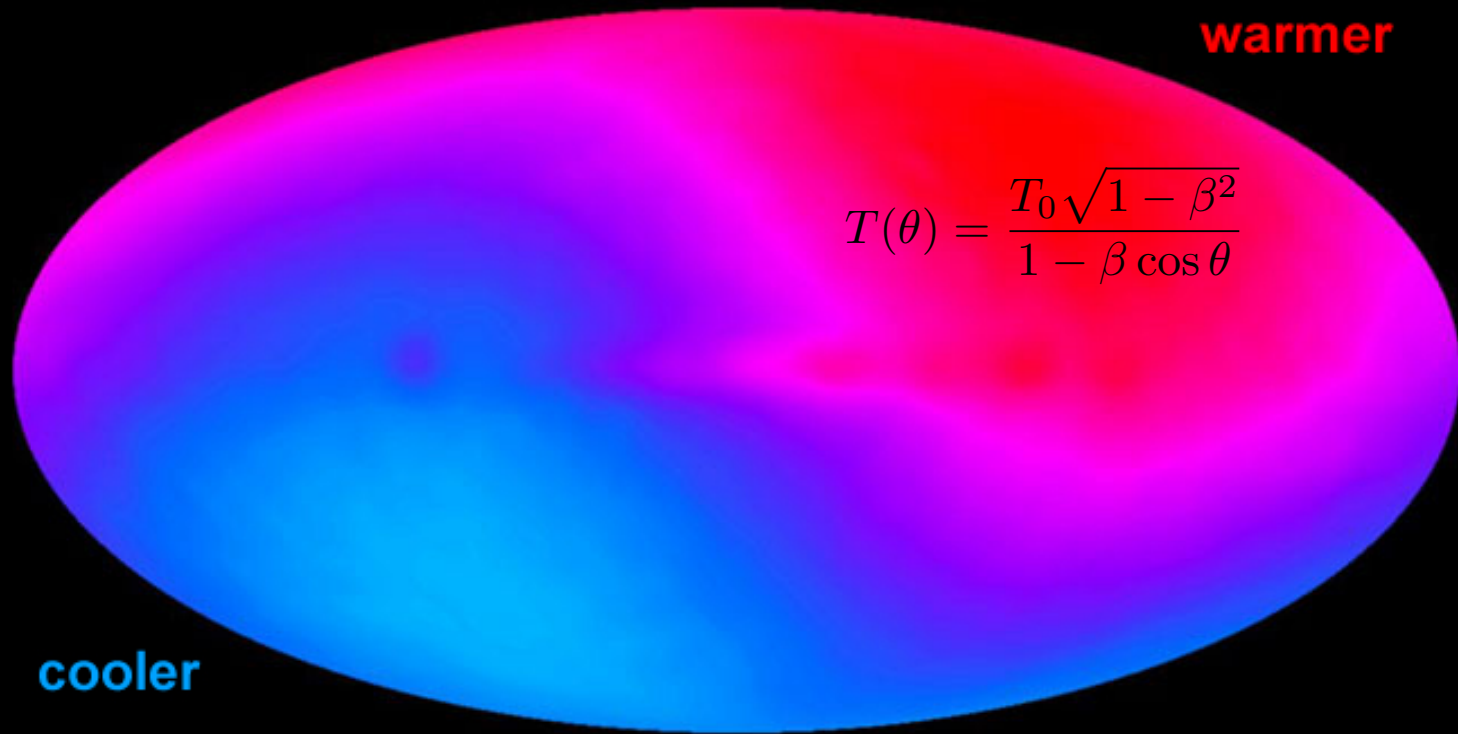
$$T = 2.725 \text{ K}$$
$$\frac{\Delta T}{T} \sim 10^{-5}$$



We observe a statistically isotropic Gaussian random field of small temperature fluctuations (fully quantified by the 2-point correlations \rightarrow angular power spectrum)



The CMB Dipole: Our motion through the cosmos?



Net motion of the Solar System barycentre:
369 +/- 2 km/s w.r.t CMB rest frame
towards

R.A = 168.0, DEC = -7.0

- Motion of the Sun around the Galaxy
~225 +/- 18 km/s
- The motion of the Local Group 627 +/- 22
km/s [ApJ, 709, 483](#)

COBE Experiment, 1996
Planck 2015

$$\frac{\Delta T}{T} \sim 10^{-3}$$

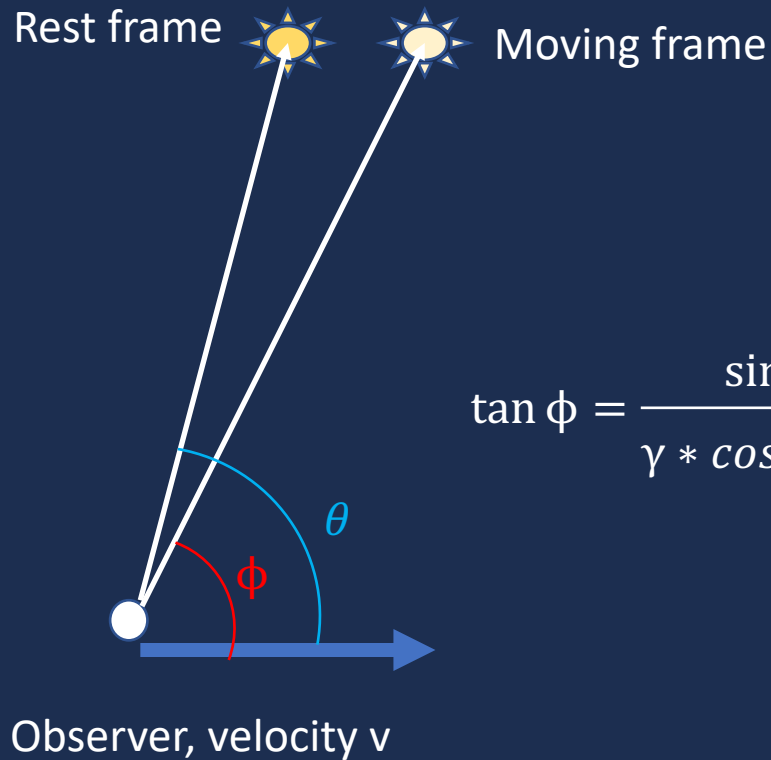
What is the origin of this motion?

A moving observer - Kinematic Dipole

$$\sigma(\theta)_{obs} = \sigma_{rest} \left[1 + \left[2 + x(1 + \alpha) \right] \frac{v}{c} \cos(\theta) \right]$$

Aberration

Rest frame Moving frame



$$\tan \phi = \frac{\sin \theta}{\gamma * \cos \theta - \frac{v}{c}}$$

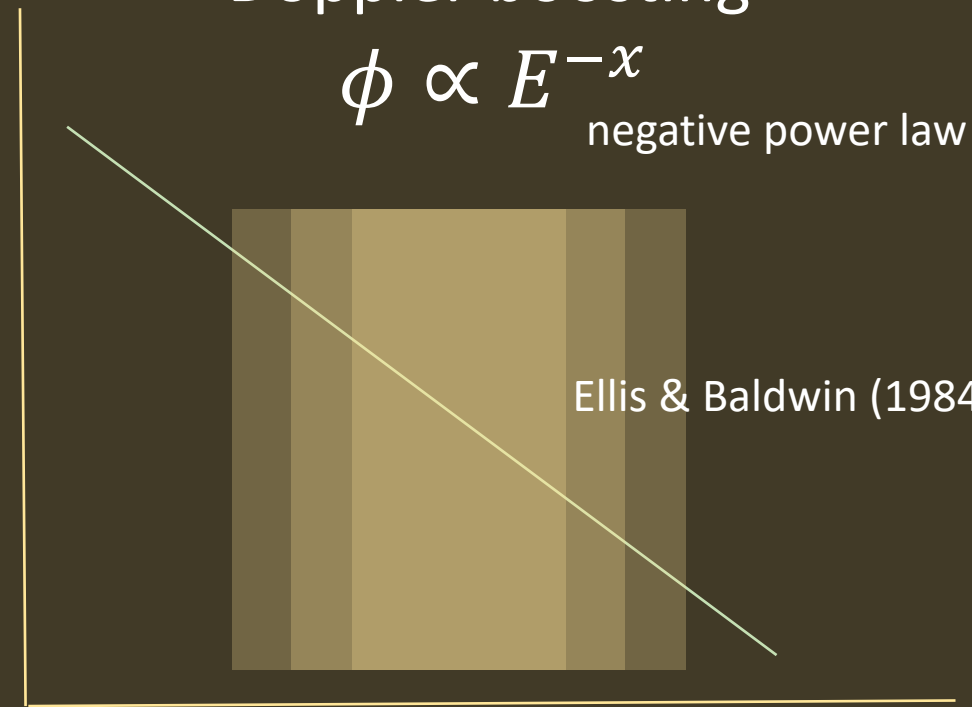
+

Doppler boosting

$$\phi \propto E^{-x}$$

negative power law

Differential flux



Flux limited catalog -> more sources in direction of motion

Dipoles in a catalogue of galaxies

In an all-sky catalogue with sources of redshift distribution $D(z)$ from directionally unbiased survey with N sources

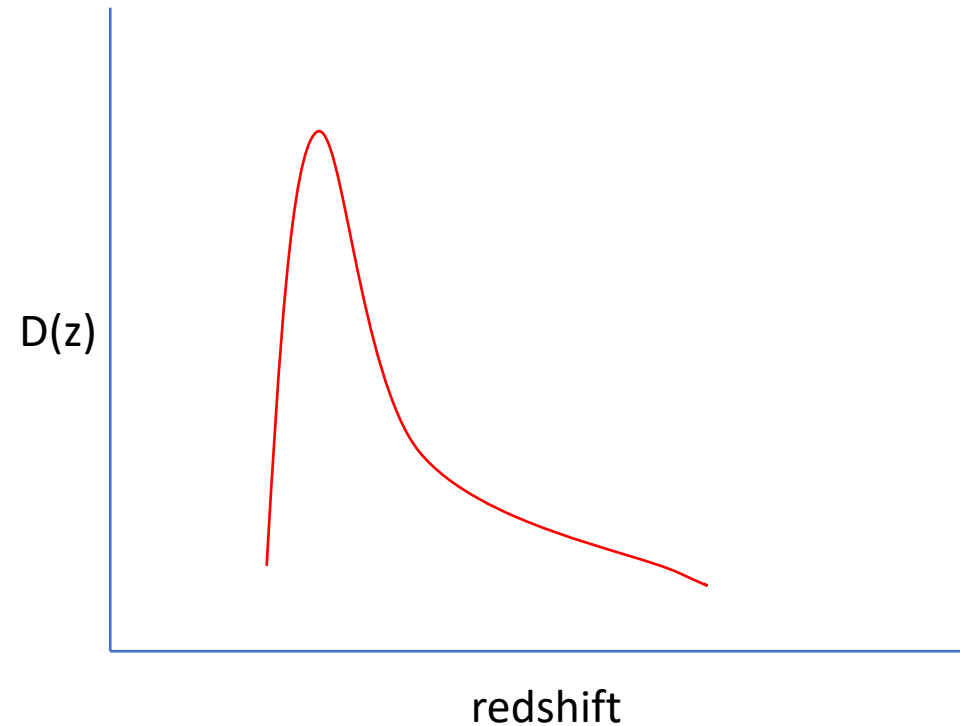
$$\vec{\delta} = \vec{\mathcal{K}}(\vec{v}_{obs}, x, \alpha) + \vec{\mathcal{R}}(N) + \vec{\mathcal{S}}(D(z)) + \vec{\mathcal{F}}$$

$\vec{\mathcal{K}}$ → **The Kinematic dipole**, depends on source spectrum, source flux function, observer velocity

$\vec{\mathcal{R}}$ → **The random dipole**, $\propto 1/\sqrt{N}$, isotropically distributed in direction

$\vec{\mathcal{S}}$ → **The structure dipole**, local anisotropy due to growing structure

$\vec{\mathcal{F}}$ → **Foregrounds**, mainly stars and other Galactic contamination



This talk:

Dipole in radio catalogue of galaxies, NVSS and SUMSS

~600000 galaxies

$z \sim 1$, deep survey . $\vec{\mathcal{D}}(D(z)) \rightarrow 0$

High redshift radio galaxies and divergence from the CMB dipole

J. Colin, R. Mohayaee, M. R. and S.Sarkar

MNRAS 471 (2017) no.1, 1045-1055 arXiv:1703.09376

Dipole in catalogue of galaxies from infrared survey, Wide Field Infrared Survey Explorer (WISE)

~2.4 million

$z \sim 0.14$, shallow survey

The dipole anisotropy of AllWISE galaxies

M.R. , R. Mohayaee, S.Sarkar and J. Colin

MNRAS 477 (2018) no.2, 1772-1781 arXiv:1712.03444

A dipole in the deceleration parameter?

The SDSS-II/SNLS3 Joing Lightcurve Analysis sample of SN1a

740 SN1a, $z=0.01$ to $z=1.4$

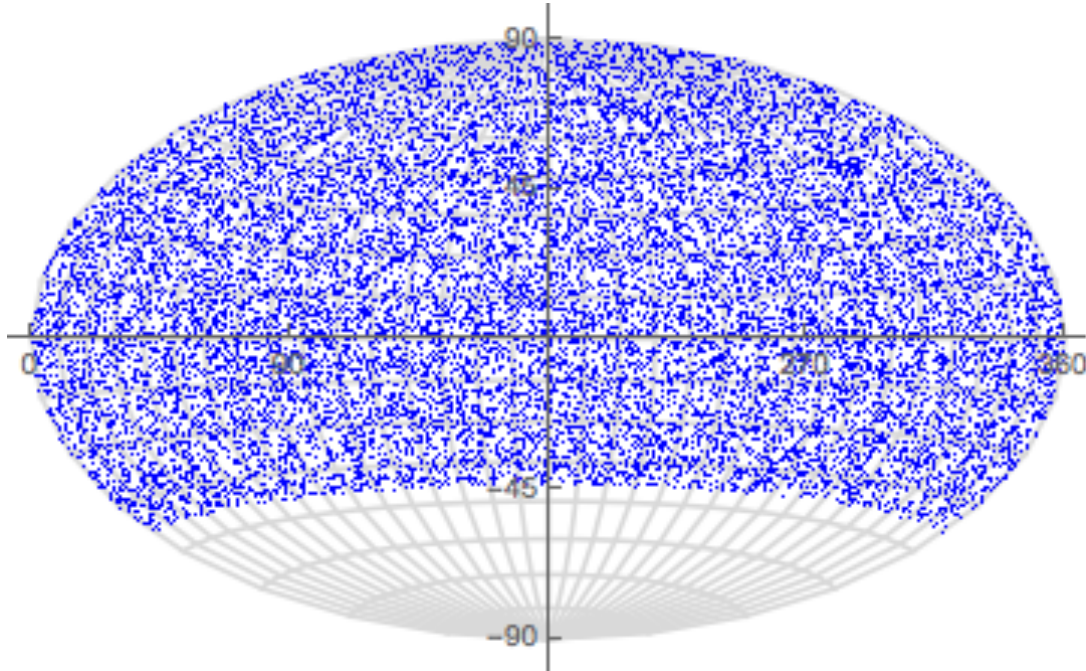
Apparent cosmic acceleration due to local bulk flow

J. Colin, R. Mohayaee, M. R. and S.Sarkar

Submitted to Nature Sci Rep , arXiv:1808.04597

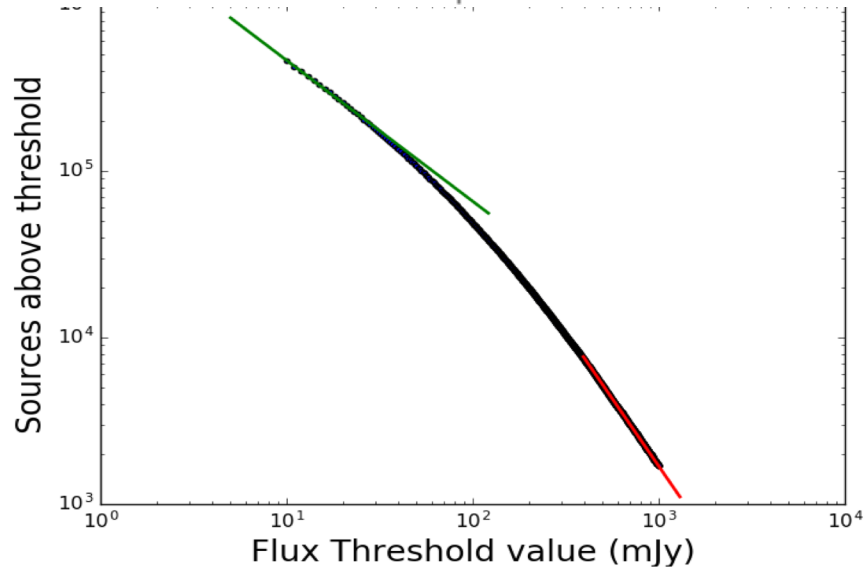
<https://github.com/rameez3333/> Dipole_JLA and catana repositories.

The NRAO VLA Sky Survey (NVSS)



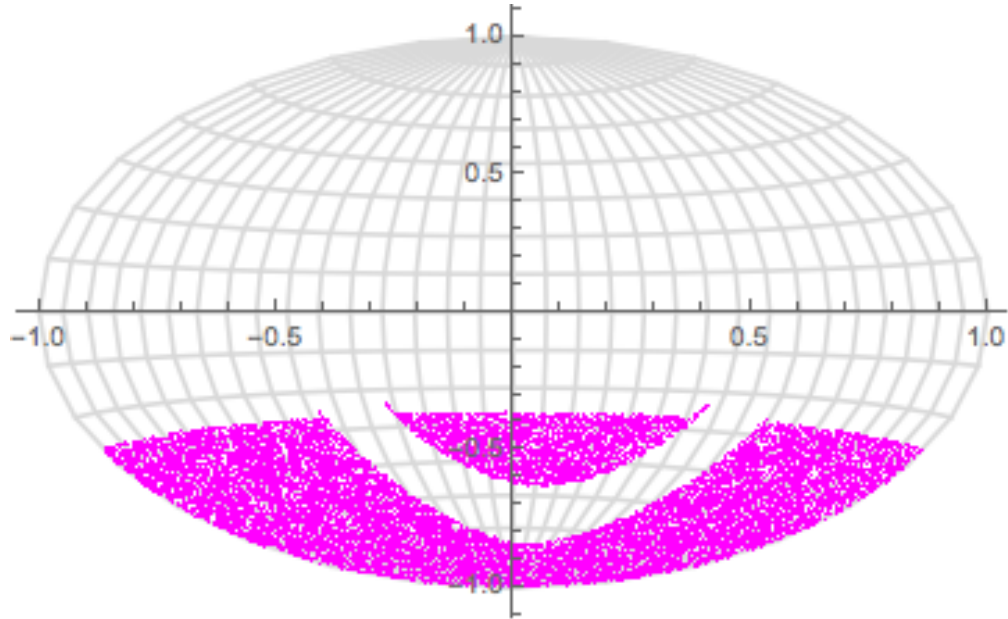
1.4 GHz survey of the Northern sky, by the National Radio Astronomy Observatory. Down to dec = -40.4°

1,773,488 sources above 2.5 mJy. But 'complete' with uniform sky exposure only above 10 mJy



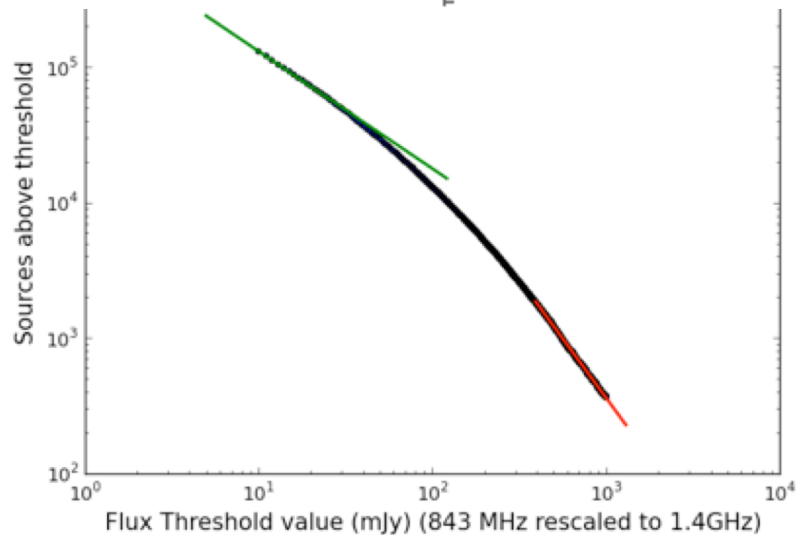
Phys. Rev. D, 78, 043519

Sydney University Molonglo Sky Survey (SUMSS)

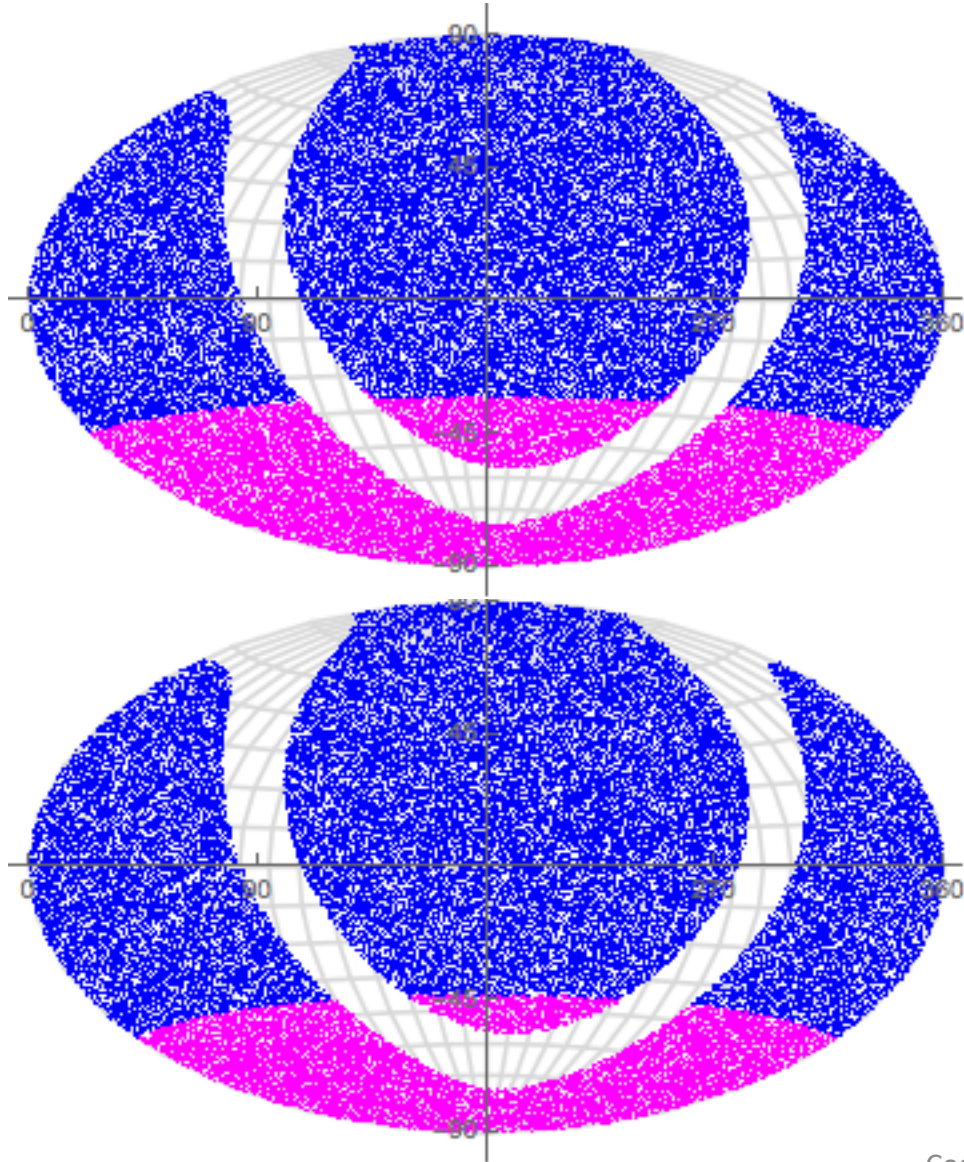


843 MHz survey of the Southern sky, by the Molonglo Observatory Synthesis telescope. Dec $< -30.0^\circ$

211050 radio sources. Similar sensitivity and resolution to NVSS



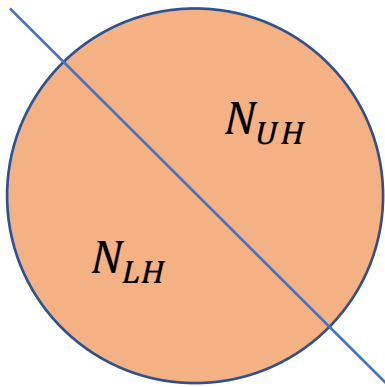
The NVSUMSS-Combined All Sky catalog



- Rescale SUMSS fluxes by $(843/1400)^{-0.75}$
- Remove Galactic Plane at ± 10 degree in NVSS
- Remove NVSS sources below and SUMSS sources above dec -30 (or -40)
- Apply common threshold flux cut on both samples
- $z \sim 1$, < 120 sources at $z < 0.3$ at 90% C.L.

Estimators for the Dipole

$$\vec{D}_H = \hat{z} * \frac{N_{UH} - N_{LH}}{N_{UH} + N_{LH}}$$



Vary the direction of the hemispheres until maximum asymmetry is observed

Easy visualization

High Bias and statistical error $2.6/\sqrt{N}$

$$\vec{D}_H = \frac{\hat{z}}{N} \int_{\phi=0}^{\phi=2\pi} \int_{\theta=0}^{\theta=\pi} \sigma(\theta) \frac{|\cos\theta|}{\cos\theta} \sin\theta d\theta d\phi$$

$$\vec{D}_{3D} = \frac{1}{N} \sum_{i=1}^N \hat{r}_i$$

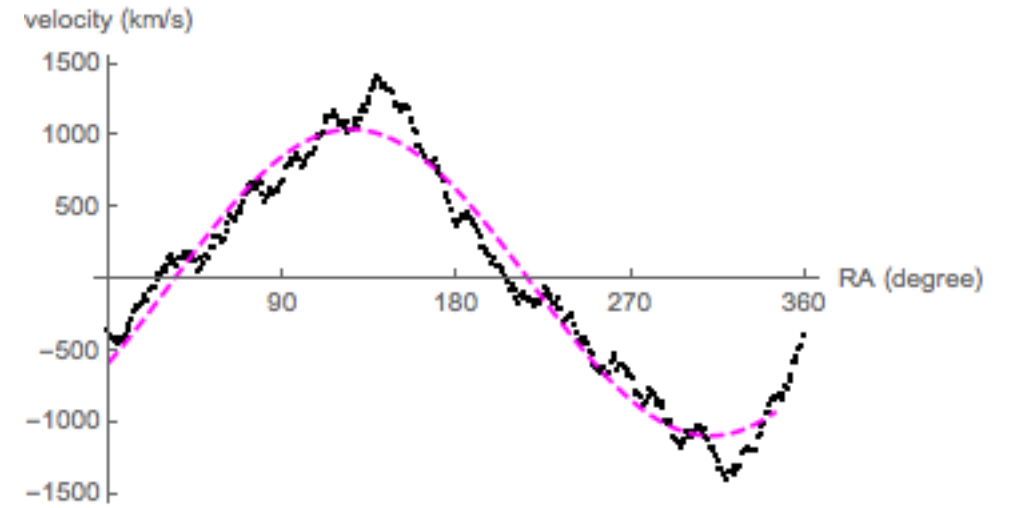
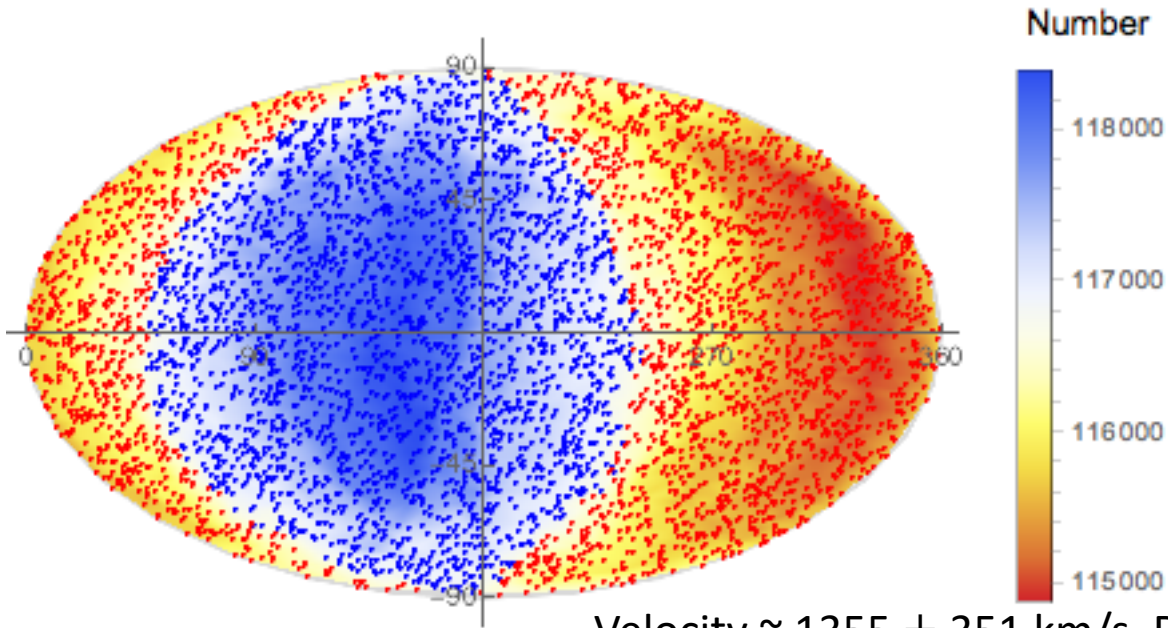
Add up unit vectors corresponding to directions in the sky for every source

Relatively lower bias and statistical error $1/\sqrt{N}$

Rubart and Schwarz 2013

$$\vec{D}_C = \frac{\hat{z}}{N} \int_{\phi=0}^{\phi=2\pi} \int_{\theta=0}^{\theta=\pi} \sigma(\theta) \cos\theta \sin\theta d\theta d\phi$$

Results



Velocity $\sim 1355 \pm 351$ km/s, Dir within 10° of CMB dipole direction.

Statistical significance, ~ 2.81 Sigma, with the 3D linear estimator, constrained mainly by the catalogue size

**Bengaly et al 2018 JCAP 1804 (2018) no.04, 031 find a 5.1 sigma dipole in TGNSS !
(Possibly due to low z source contamination)**

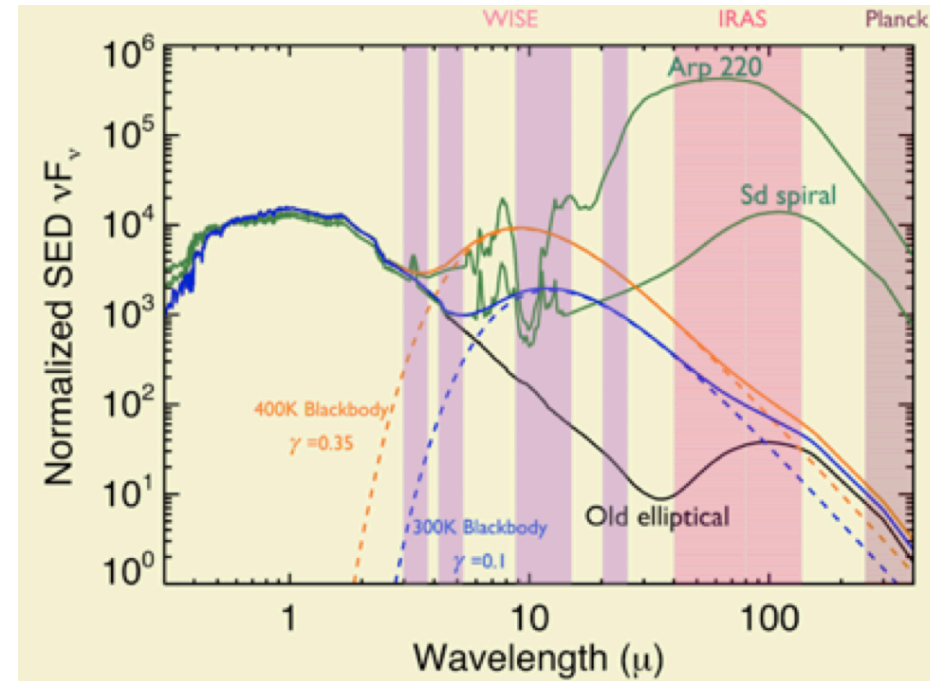
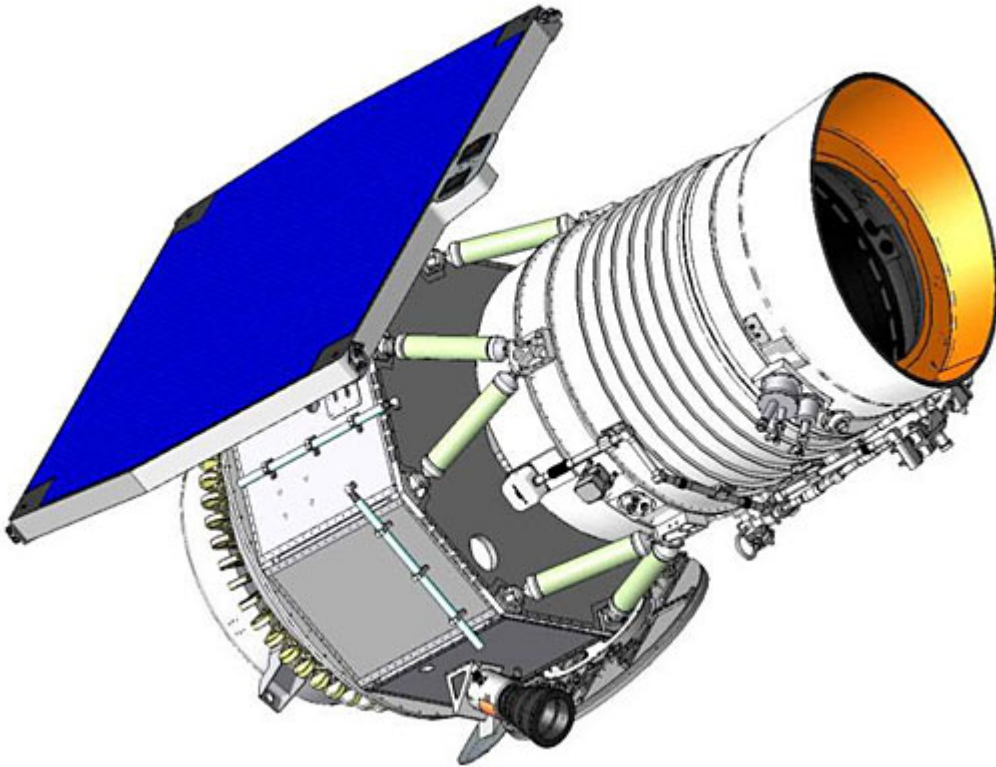
**SKA phase 1 measurement $\sim 10\%$
Bengaly (et al) 2018 : 1810.04960v1**

The Widefield Infrared Survey Explorer

All sky infrared survey over 10 months, in the bands 3.4, 4.6, 12 and 22 μm using a 40 cm diameter telescope

Generated a catalog of 746 million+ objects, most of which are stars.

Directionally unbiased survey strategy, arc second angular resolution, multi band photometry.



Getting rid of the stars

following from MNRAS448,1305–1313 (2015)

- Magnitude cuts in different bands, Galactic plane cut at ± 15 degrees
 - Sample of 2.46 million Galaxies, 76% complete, with 1.8% star contamination

Cross correlate with deep surveys over a very narrow sky (SDSS, GAMA) to determine how many are stars and how many are Galaxies

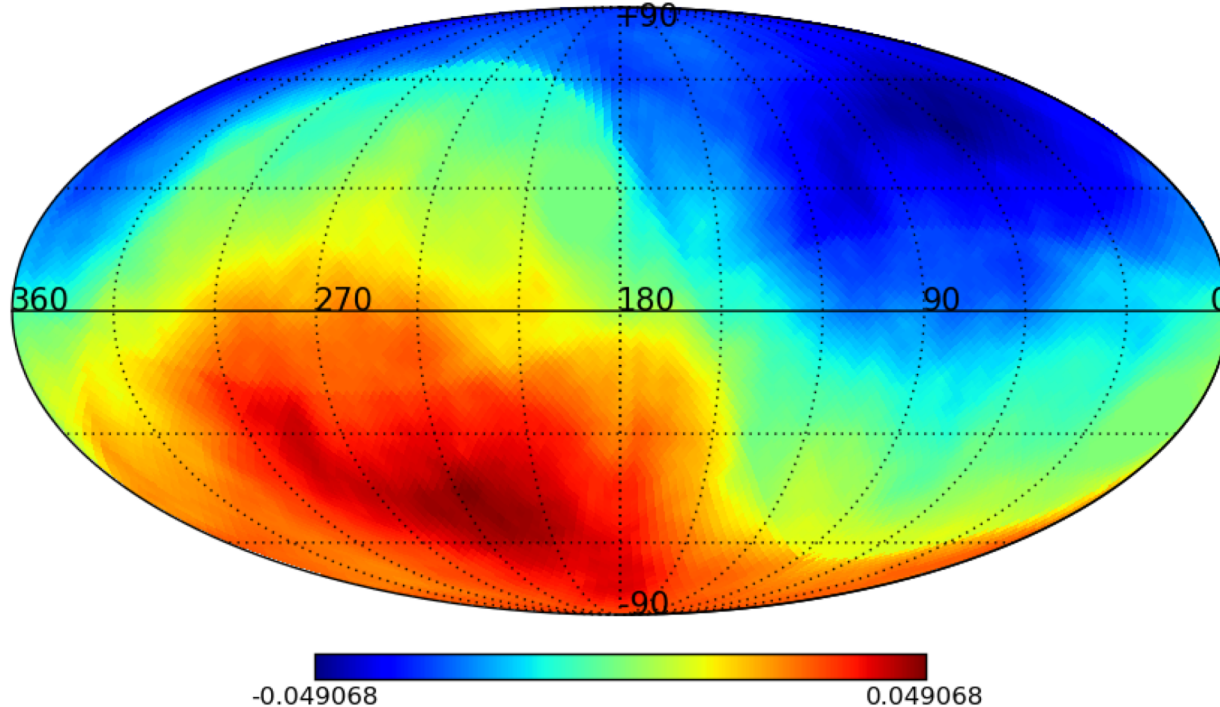
The maximum is in the direction (AllWISE)
 237.4° RA, -46.6° Dec
 331.9° | 6.02° b

110 degrees from the CMB direction

Dipole magnitude ~ 0.049

Fully kinematic interpretation ~ 6000 km/s

in agreement with MNRAS 445 (2014) L60-L64



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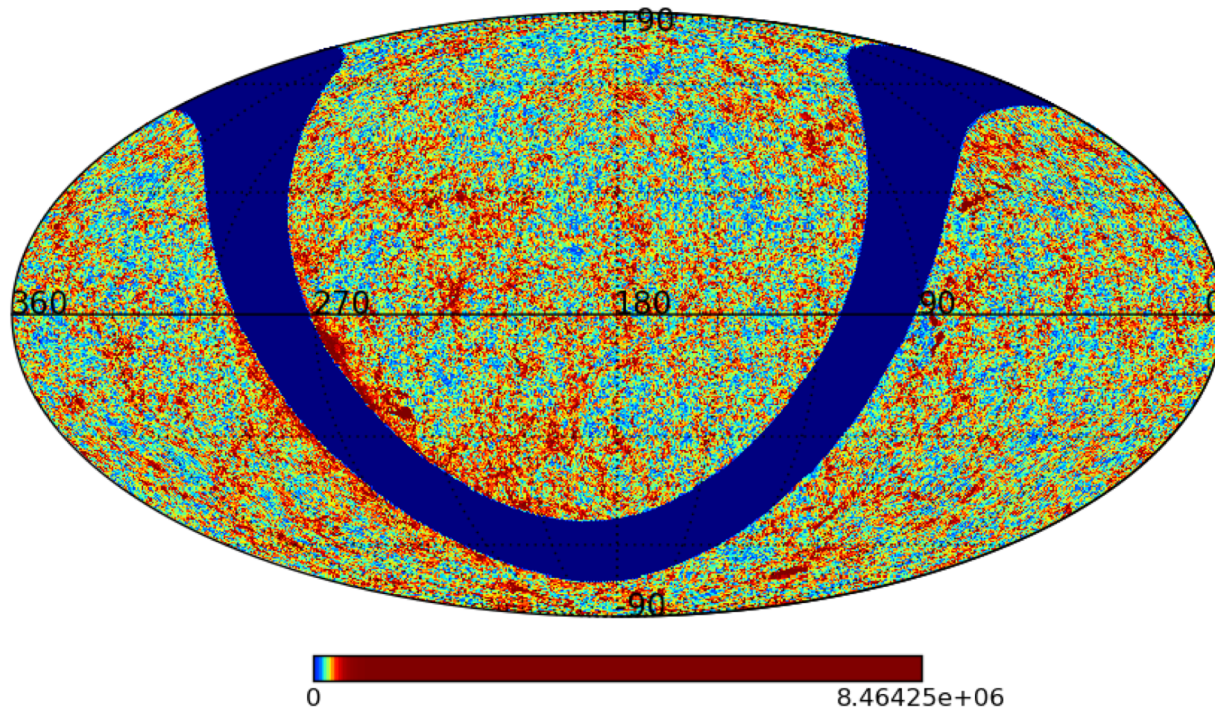
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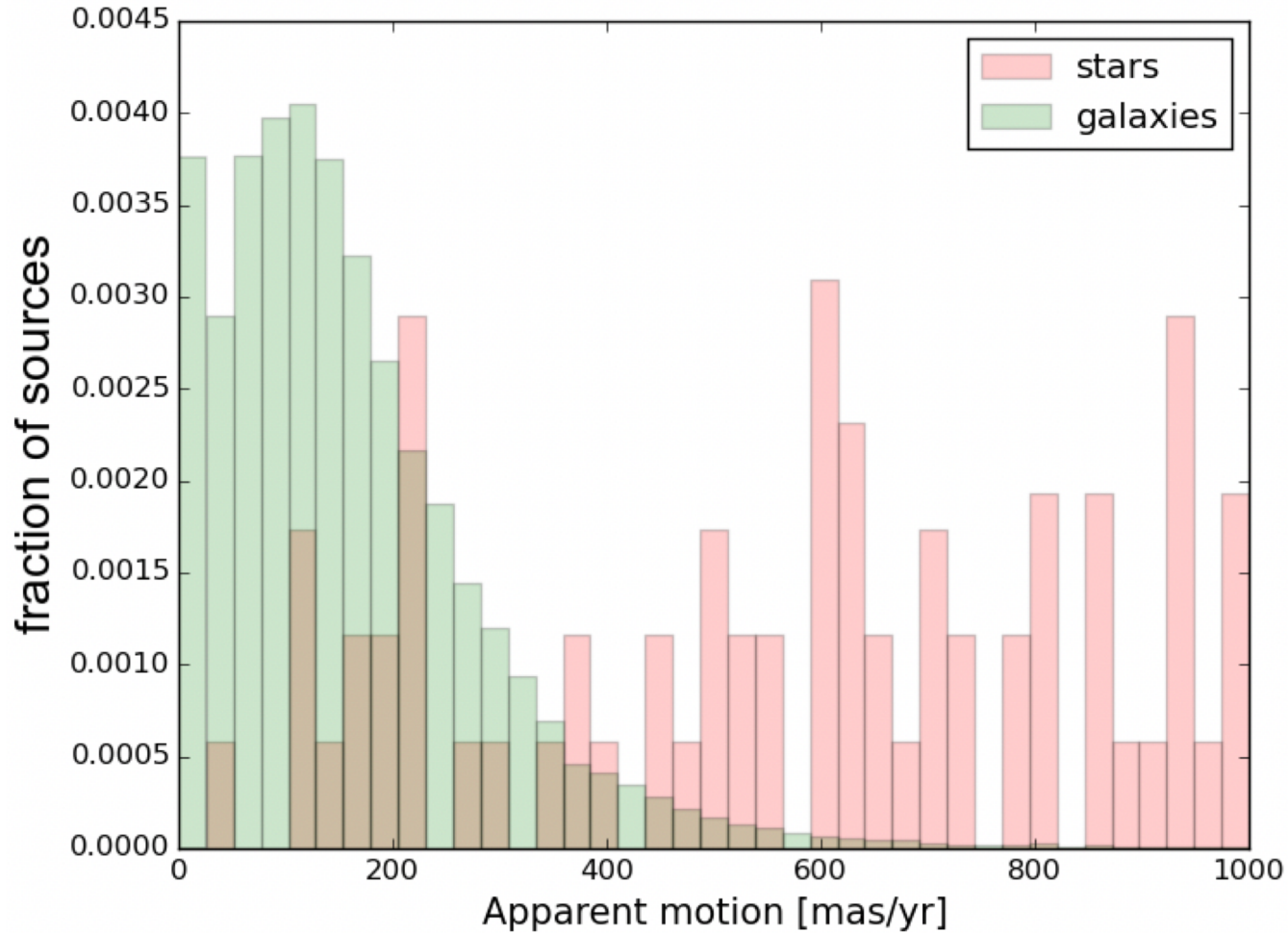
Dipole magnitude ~ 0.049

Fully kinematic interpretation ~ 6000 km/s

in agreement with MNRAS 445 (2014) L60-L64



Getting rid of even more stars



Apparent motion = parallax + proper motion

Stars in the Galaxy have higher apparent motions 400 mas/yr up to many arc seconds/year

Cuts on apparent motion can bring star contamination down to 0.1%, while still keeping ~1.8 million galaxies.

182.9° RA, -55.6° DEC, 50.1° from the CMB

Dipole magnitude reduces to 0.014

Star galaxy identification by cross correlating with SDSS

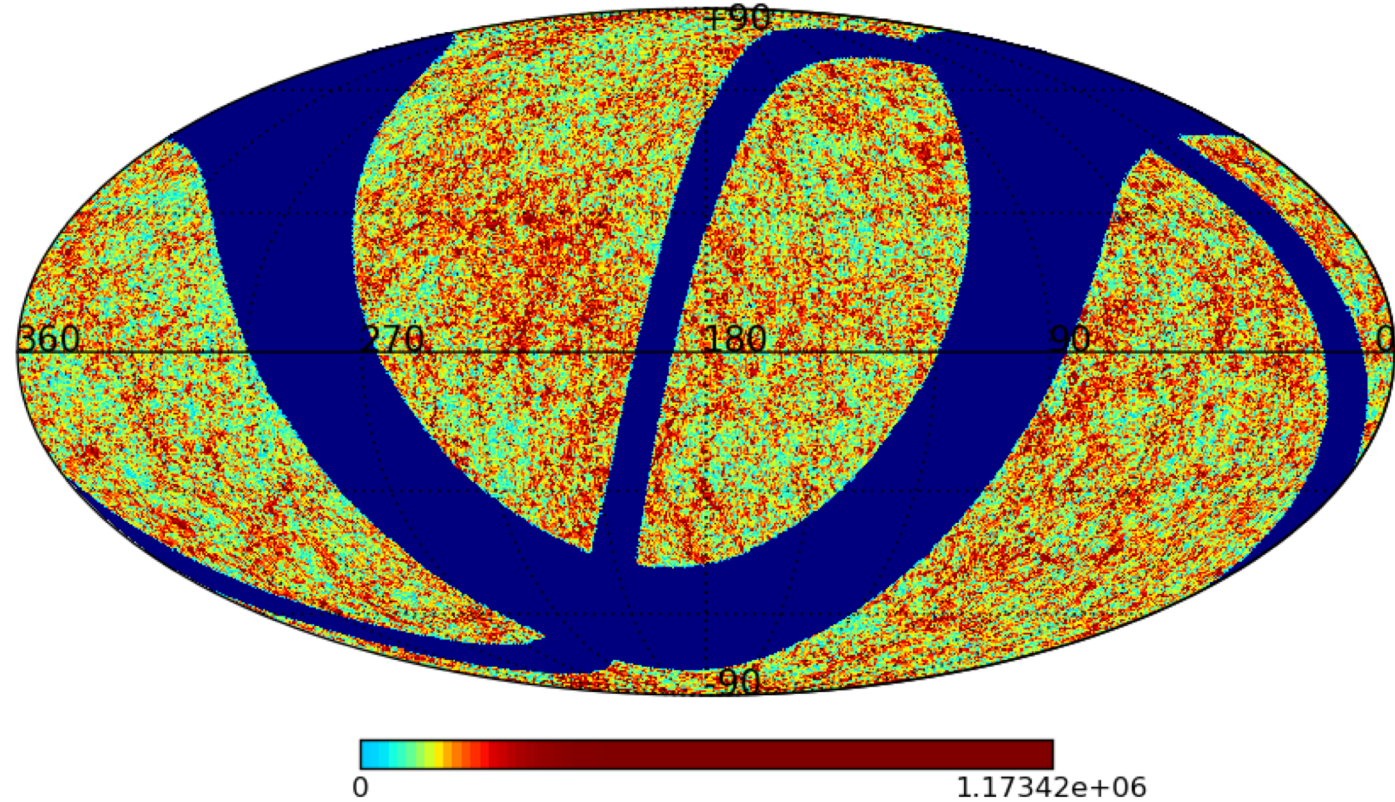
Suppressing local anisotropies

~200 Mpc

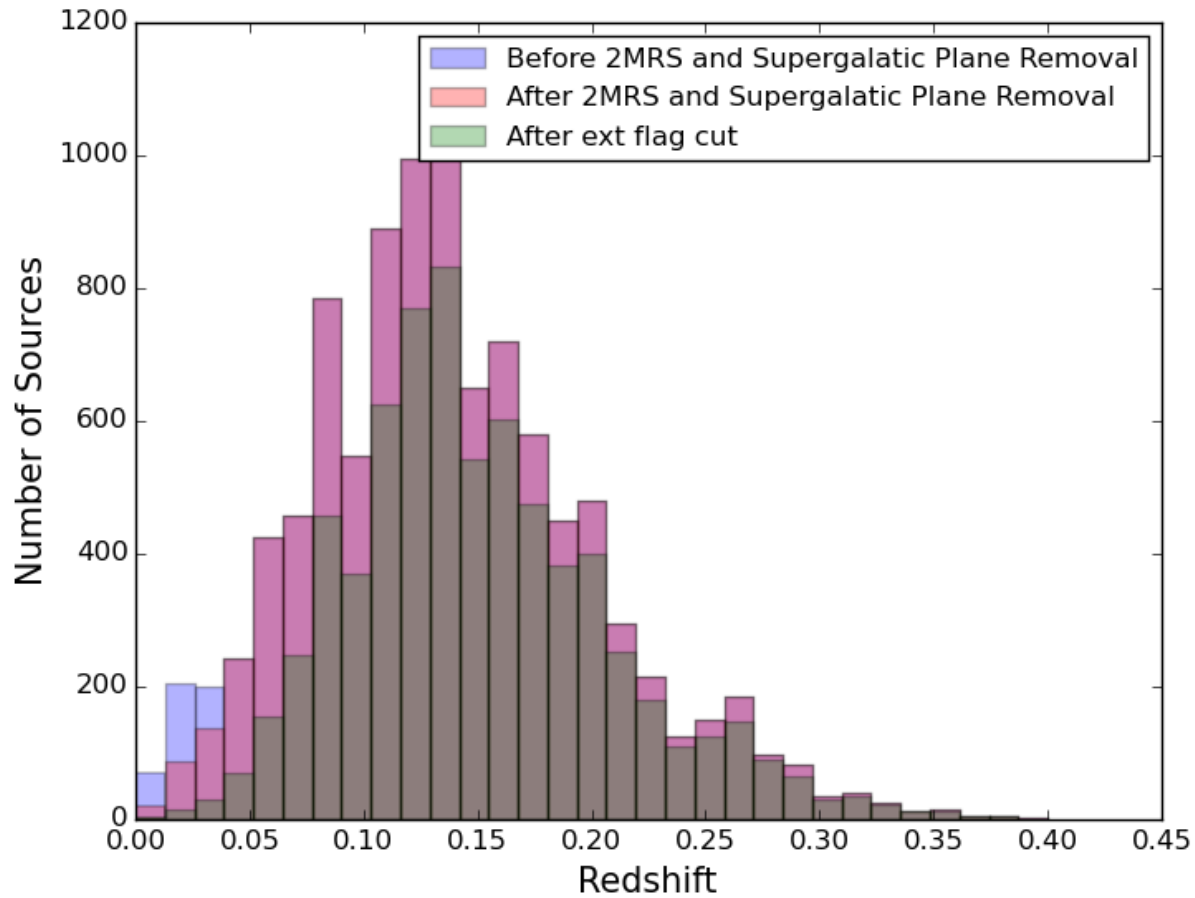
Remove extended sources and the supergalactic plane.

Further reduce $z < 0.03$ sources by cross correlating with 2MRS and removing the correlated sources.

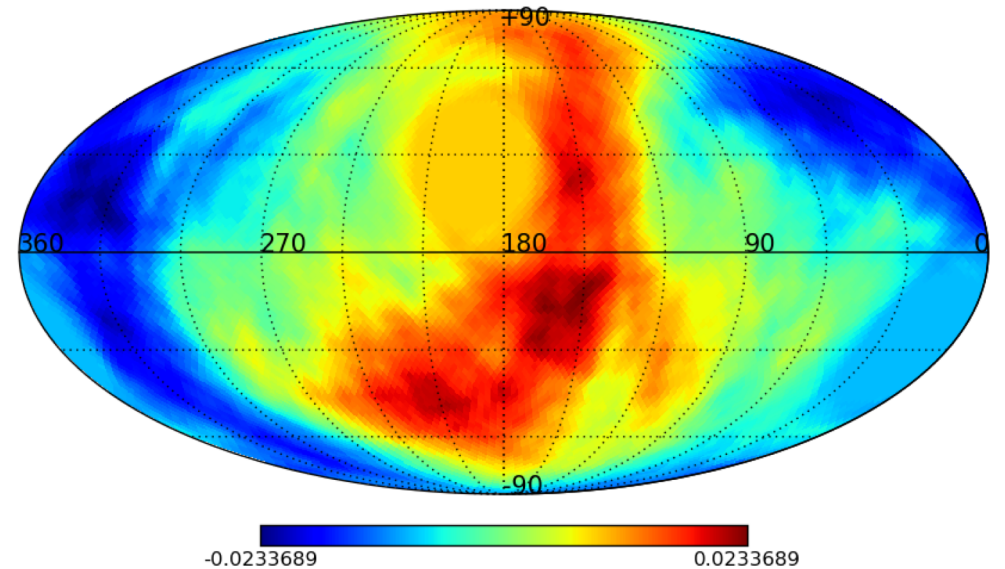
6.1'' PSF



Redshift distribution of the sample



$d = 0.0124 > 3600$ km/s if fully kinematic
 172.6° RA, -6.6° Dec ($\sim 4.5^\circ$ from CMB)
Total dipole is at least 4.6σ statistically significant.



By cross correlating with Galaxy and Mass Assembly

Residual clustering dipole

- For a Copernican observer:

$$\langle D_{cls} \rangle = \sqrt{\frac{9}{4\pi} C_1}$$

$$C_l = b^2 \frac{2}{\pi} \int_0^\infty f_l(k)^2 P(k) k^2 dk$$

$$f_l(k) = \int_0^\infty j_l(kr) f(r) dr$$

$$f(r) = \frac{H(z)}{H_0 r_0} \frac{dN}{dz}$$

Using Planck 2015 cosmological parameters and astropy, using the the redshift distribution as dN/dz

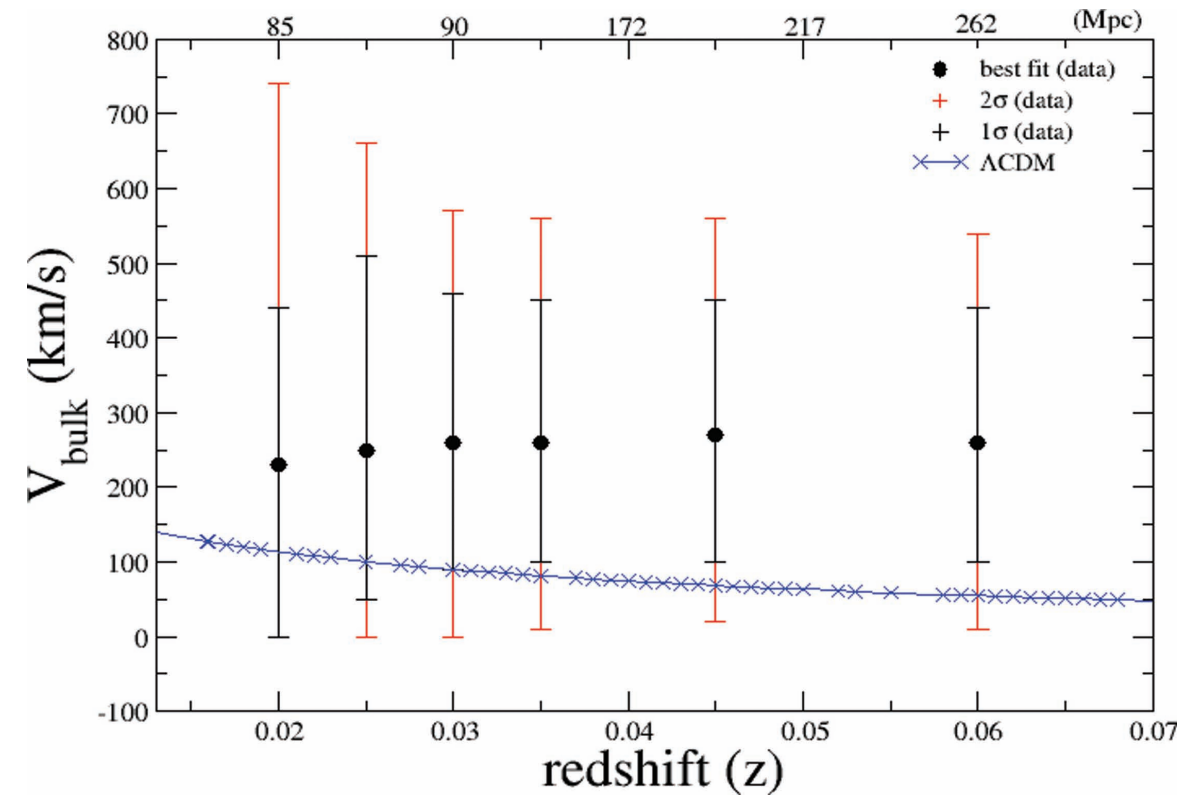
$$\langle D_{cls} \rangle < 0.0018$$

In the final sample

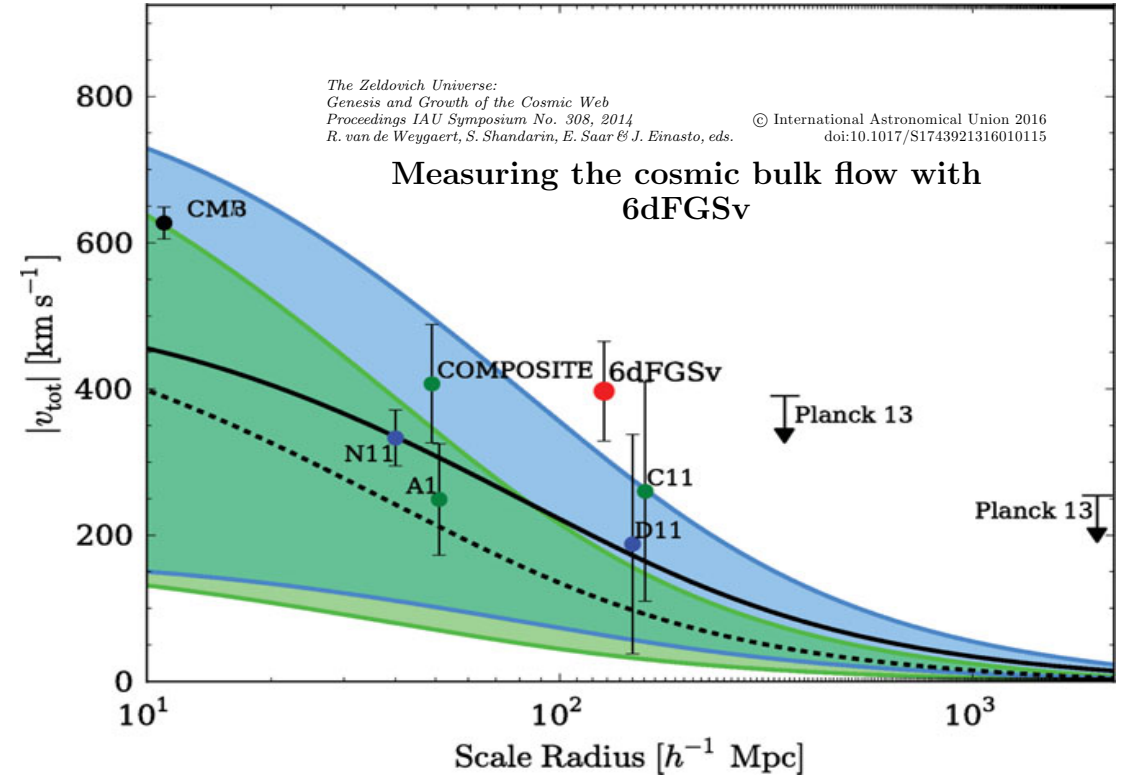
$$D_{kin} = 0.0106$$

Velocity of ~ 3000 km/s

Hints that we are not a Copernican Observer



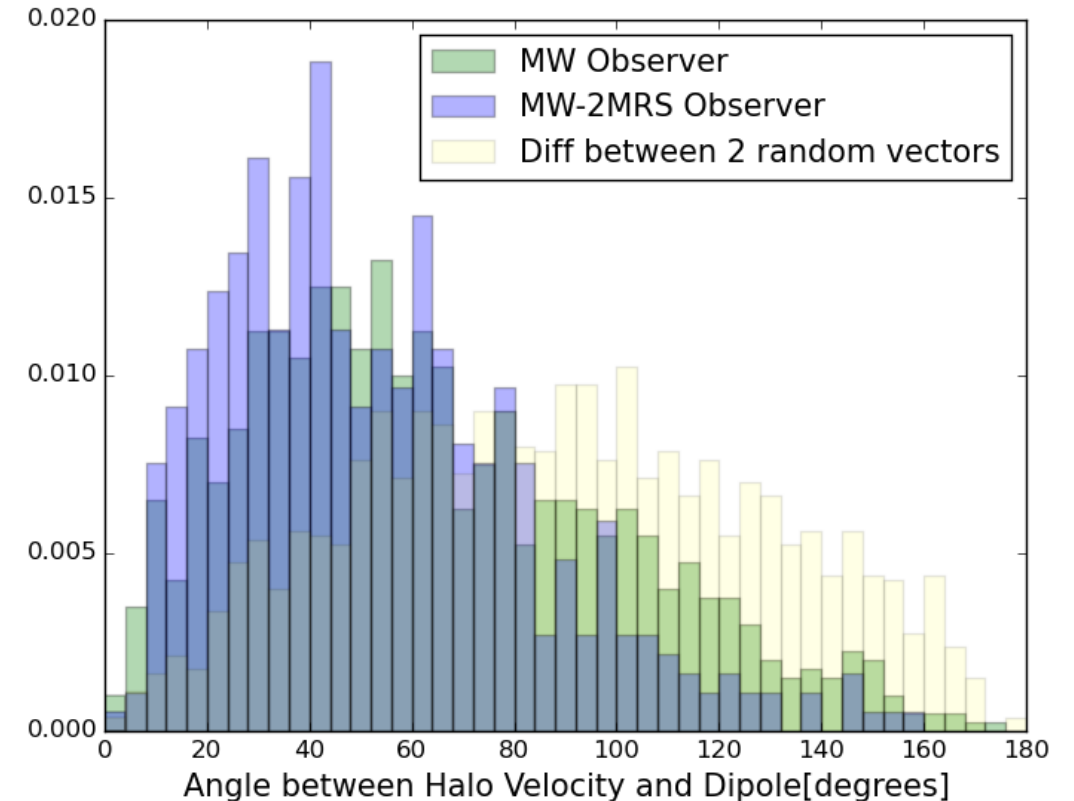
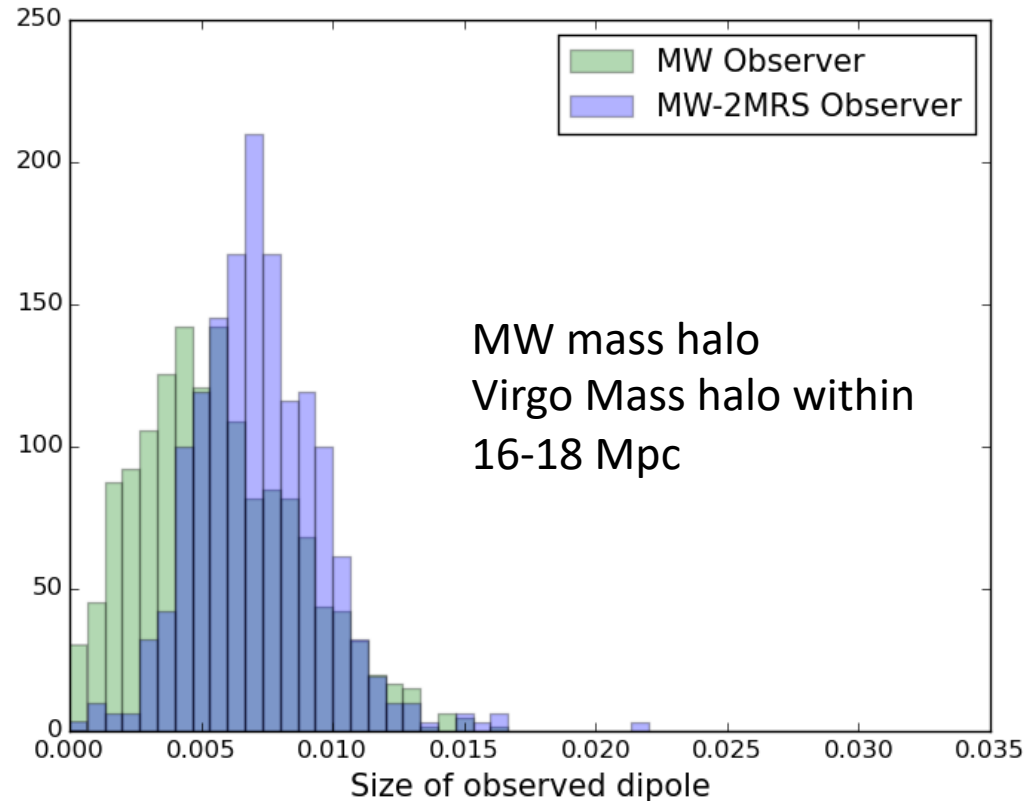
Measuring the cosmic bulk flow with 6dFGSv



Colin J., Mohayaee R., Sarkar S. & Shafieloo A., 2011, MNRAS, 414, 264

Dark Sky N Body Simulations

First trillion particle simulation of the Λ CDM universe.



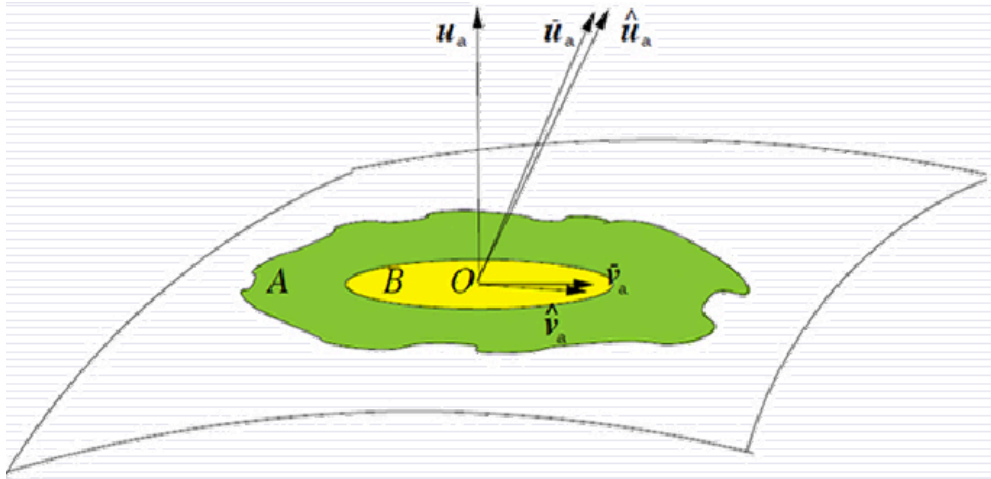
Only $\sim <1\%$ of halos with MW-like mass and velocity are inside bulk flows > 240 km/s on scales exceeding 260 Mpc

$$\langle D_{cls} \rangle = 0.0076 \pm 0.0022$$

$$\langle D_{kin} \rangle = 0.0048 \pm 0.0024$$

$$V = 1260 \pm 629 \text{ km/s}$$

The tilted Friedmann Universe



If we are inside a large local ‘bulk flow’.

(Tsagas 2010, 2011, 2012; Tsagas & Kadiltzoglou 2015)

... if so there should be a dipole asymmetry in the inferred deceleration parameter in the same direction – i.e. towards the CMB dipole

The patch A has mean peculiar velocity \tilde{v}_a with $\vartheta = \tilde{D}^a v_a \gtrless 0$ and $\dot{\vartheta} \gtrless 0$ (the sign depending on whether the bulk flow is accelerating or decelerating)

Inside region B, the r.h.s. of the expression

$$1 + \tilde{q} = (1 + q) \left(1 + \frac{\vartheta}{\Theta}\right)^{-2} - \frac{3\dot{\vartheta}}{\Theta^2} \left(1 + \frac{\vartheta}{\Theta}\right)^{-2}, \quad \tilde{\Theta} = \Theta + \vartheta,$$

drops below 1 and the comoving observer ‘measures’ *negative* deceleration parameter in one direction of the sky

The FLRW Universe in Kinematics

“Cosmology is the search for two numbers. The Hubble parameter H_0 and the deceleration parameter q_0 ” – Alan Sandage

- $H = \frac{\dot{a}}{a}$

- $q \stackrel{\text{def}}{=} - \frac{\ddot{a}a}{\dot{a}^2}$ (defined with a minus to be positive for a decelerating universe)

$$q = \frac{\Omega_M}{2} - \Omega_\Lambda \text{ (in } \Lambda\text{CDM)}$$

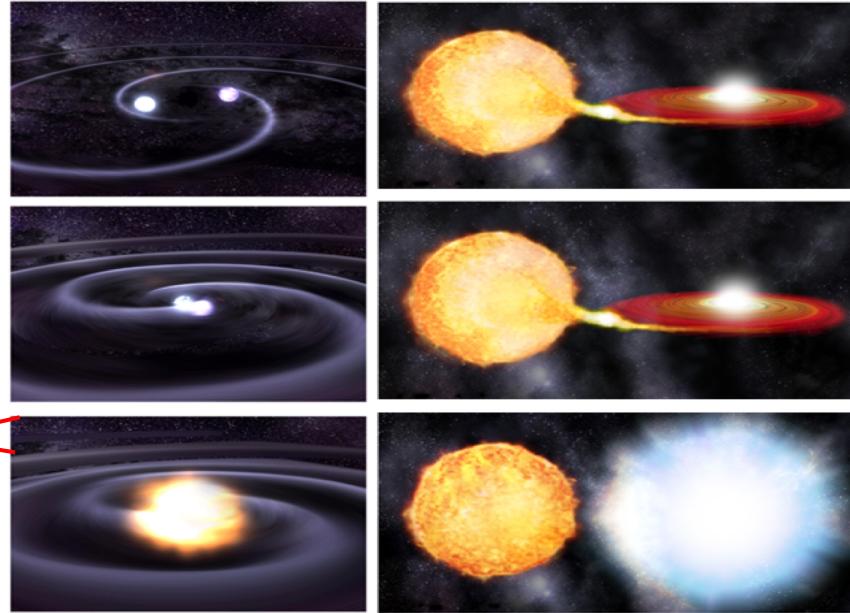
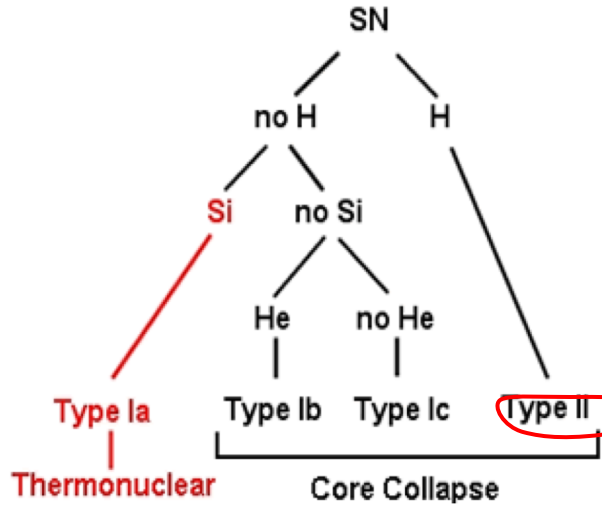
- $j = \frac{\ddot{a}}{aH^3}$

$$d_L(z) = \frac{cz}{H_0} \left\{ 1 + \frac{1}{2} [1 - q_0]z - \frac{1}{6} \left[1 - q_0 - 3q_0^2 + j_0 + \frac{kc^2}{H_0^2 a_0^2} \right] z^2 + O(z^3) \right\}$$

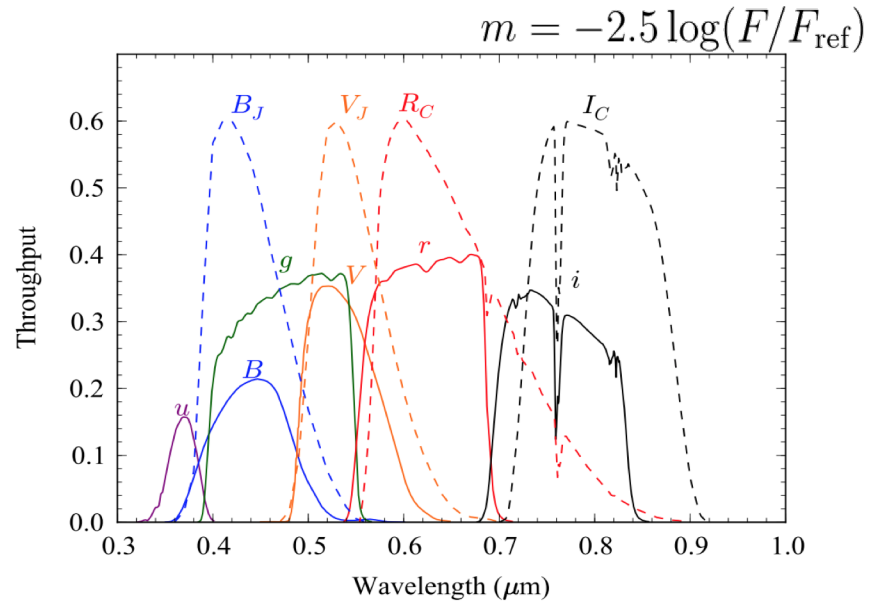
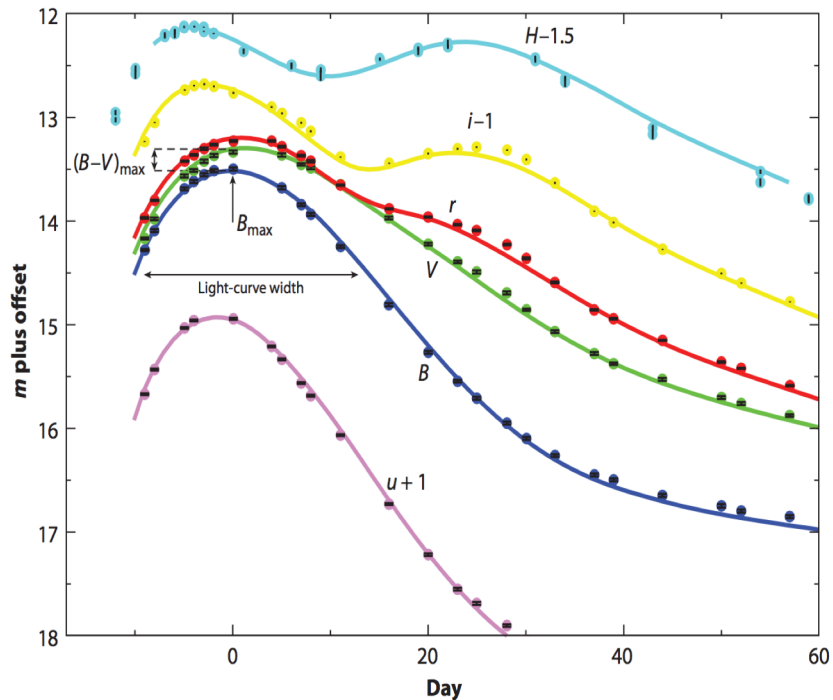
Matt Visser 2004

Tilt : $q_0 \rightarrow q_m + q_d \cos(\theta_{|cmb-SN|}) F(S)$

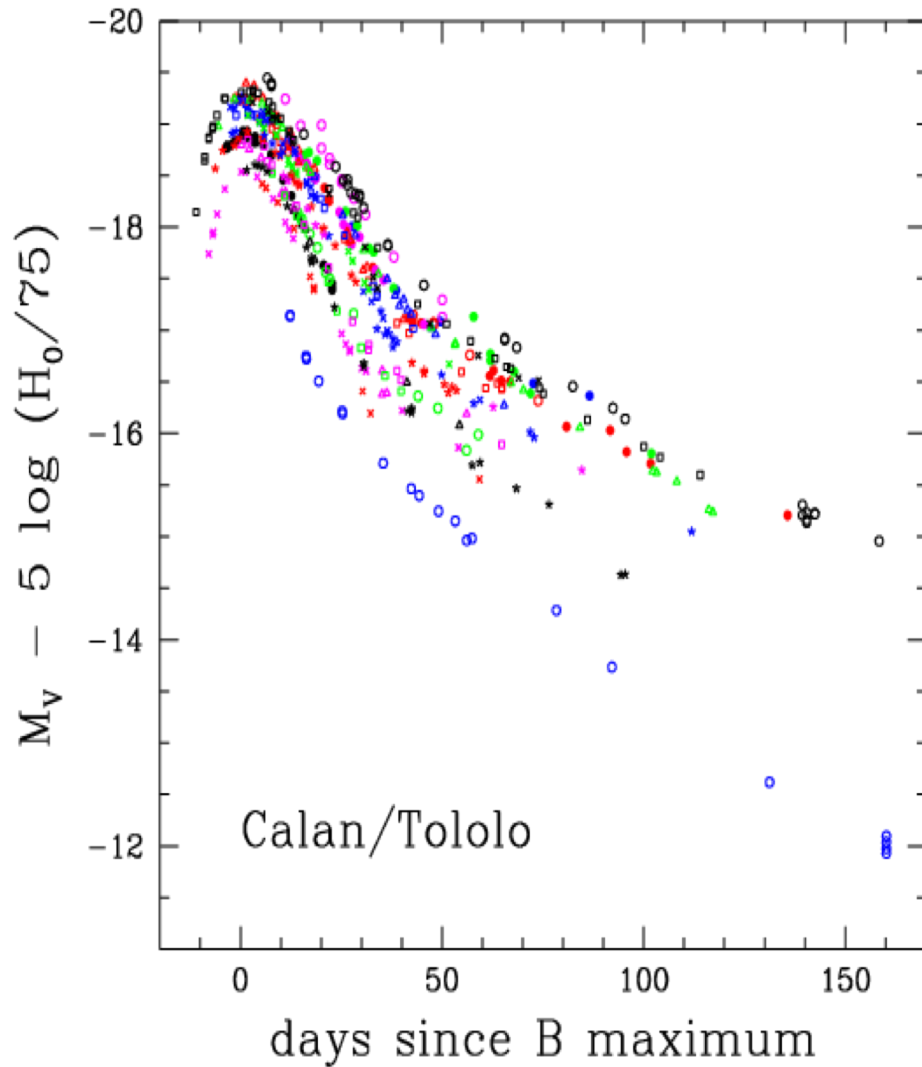
WHAT ARE TYPE IA SUPERNOVAE?



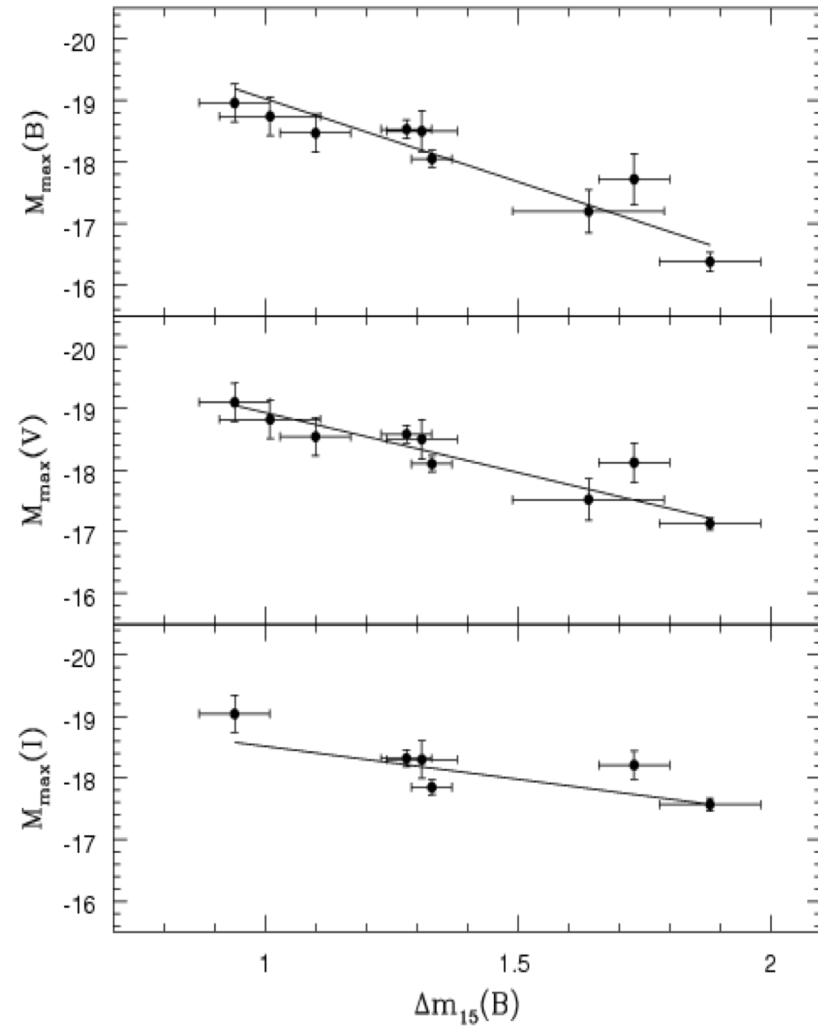
A white dwarf accreting matter from a binary companion, reignites when crossing ~ 1.44 Solar Masses



THEY ARE CERTAINLY *NOT* ‘STANDARD CANDLES’



Hamuy, arXiv:311.5099

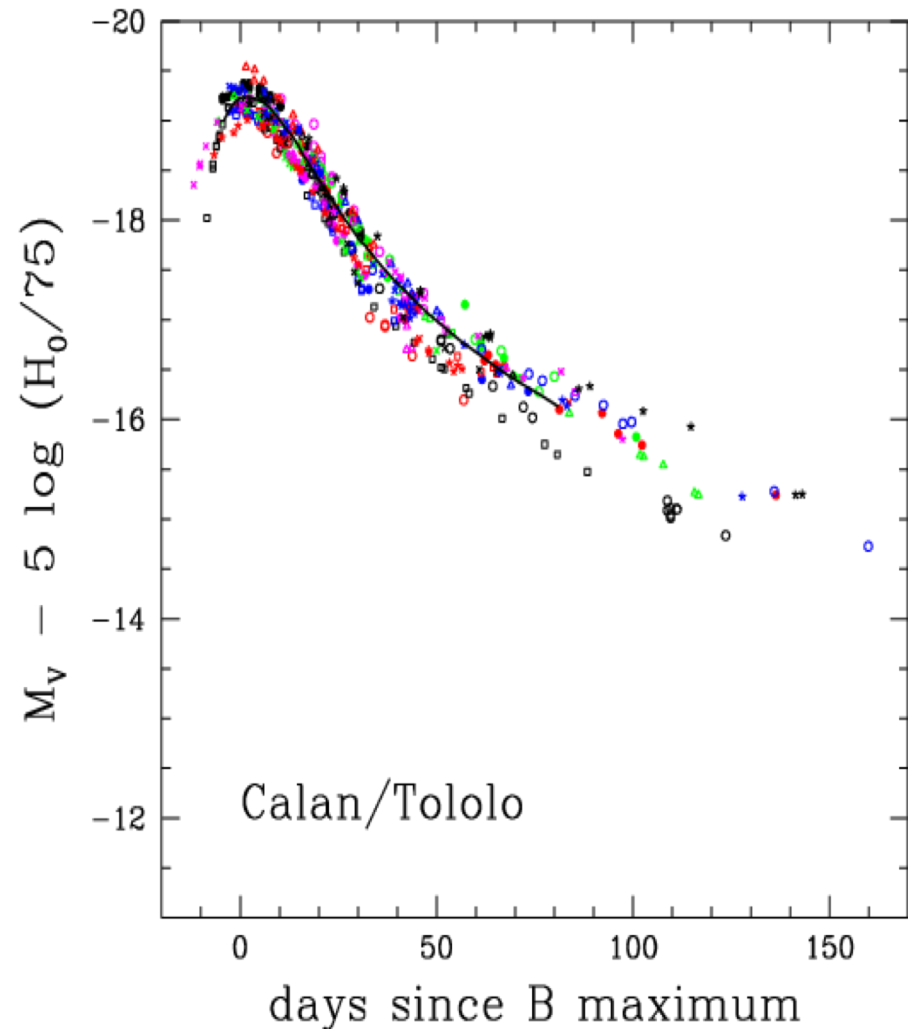
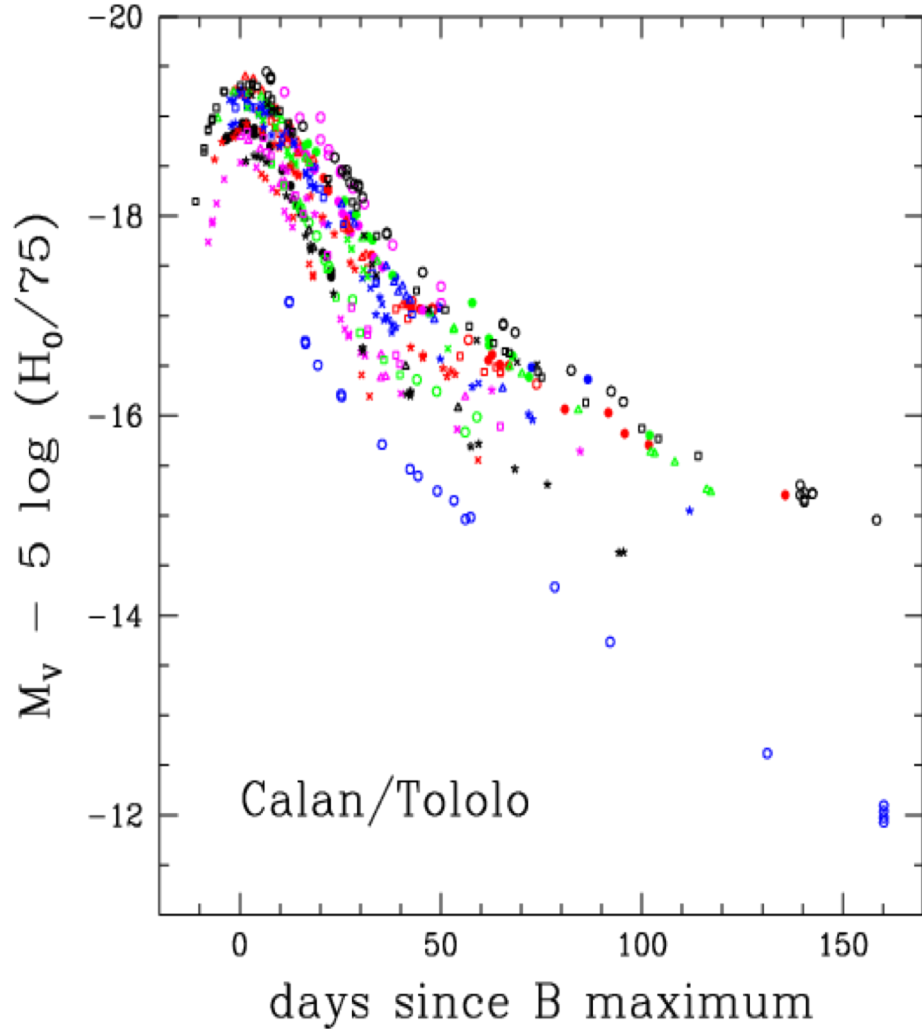


Phillips, ApJ 413:L105, 1993

But they can be ‘standardised’ using the observed correlation between their peak magnitude and light-curve width (NB: this is *not* understood theoretically)

TYPE IA SUPERNOVAE AS 'STANDARDISABLE CANDLES'

Corrected
data



Distance modulus

$$\mu_B = m_B^* - M + \alpha X_1 - \beta C$$

$$= 25 + 5 \log_{10} \frac{d_L}{\text{Mpc}}$$

Use a standard template (e.g. SALT 2) to make 'stretch' and 'colour' corrections ...

SPECTRAL ADAPTIVE LIGHTCURVE TEMPLATE

(For making 'stretch' and 'colour' corrections to the observed lightcurves)

$$\mu_B = m_B^* - M + \alpha X_1 - \beta C$$

B-band

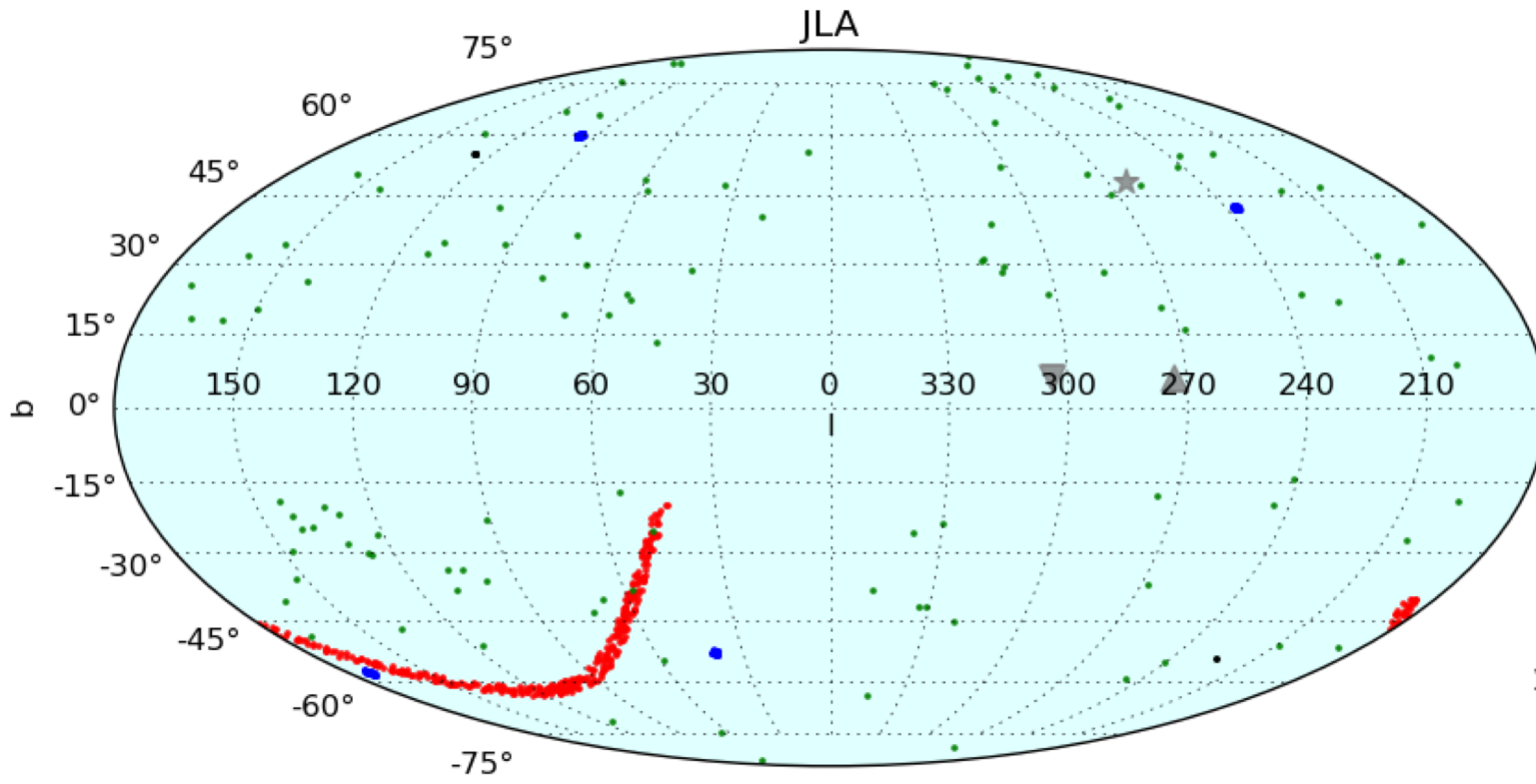
SALT 2 parameters

Betoule *et al.*, A&A 568:A22,2014

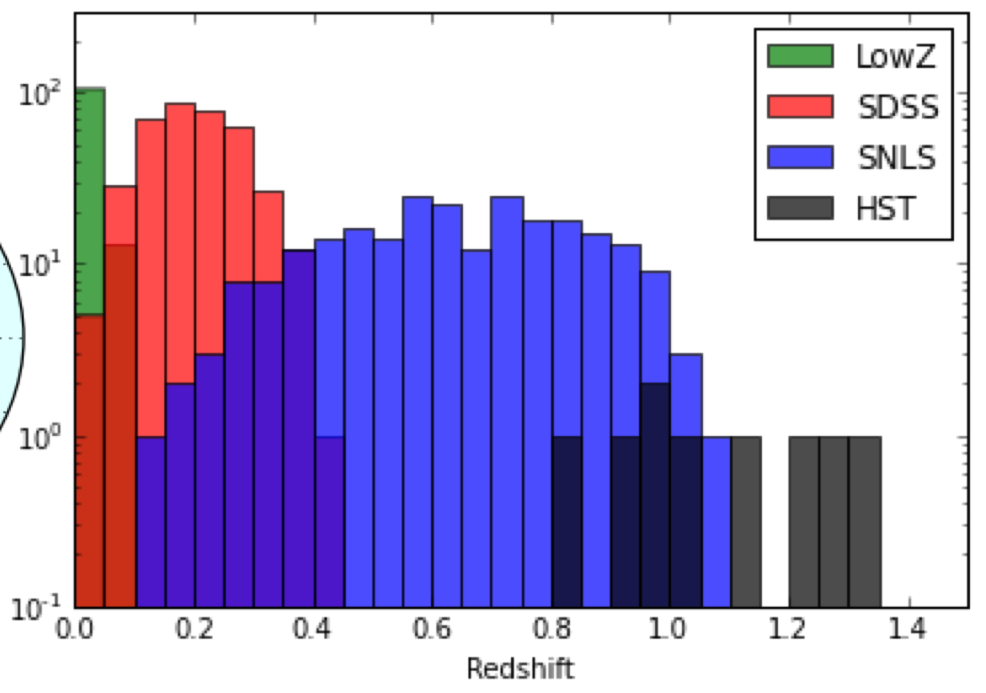
Name	z_{cmb}	m_B^*	X_1	C	M_{stellar}	?
03D1ar	0.002	23.941 ± 0.033	-0.945 ± 0.209	0.266 ± 0.035	10.1 ± 0.5	?
03D1au	0.503	23.002 ± 0.088	1.273 ± 0.150	-0.012 ± 0.030	9.5 ± 0.1	?
03D1aw	0.581	23.574 ± 0.090	0.974 ± 0.274	-0.025 ± 0.037	9.2 ± 0.1	?
03D1ax	0.495	22.960 ± 0.088	-0.729 ± 0.102	-0.100 ± 0.030	11.6 ± 0.1	?
03D1bp	0.346	22.398 ± 0.087	-1.155 ± 0.113	-0.041 ± 0.027	10.8 ± 0.1	?
03D1co	0.678	24.078 ± 0.098	0.619 ± 0.404	-0.039 ± 0.067	8.6 ± 0.3	?
03D1dt	0.611	23.285 ± 0.093	-1.162 ± 1.641	-0.095 ± 0.050	9.7 ± 0.1	
03D1ew	0.866	24.354 ± 0.106	0.376 ± 0.348	-0.063 ± 0.068	8.5 ± 0.8	
03D1fc	0.331	21.861 ± 0.086	0.650 ± 0.119	-0.018 ± 0.024	10.4 ± 0.0	
03D1fq	0.799	24.510 ± 0.102	-1.057 ± 0.407	-0.056 ± 0.065	10.7 ± 0.1	
03D3aw	0.450	22.667 ± 0.092	0.810 ± 0.232	-0.086 ± 0.038	10.7 ± 0.0	
03D3ay	0.371	22.273 ± 0.091	0.570 ± 0.198	-0.054 ± 0.033	10.2 ± 0.1	
03D3ba	0.292	21.961 ± 0.093	0.761 ± 0.173	0.116 ± 0.035	10.2 ± 0.1	
03D3bl	0.356	22.927 ± 0.087	0.056 ± 0.193	0.205 ± 0.030	10.8 ± 0.1	

There may well be other variables that the magnitude correlates with ...

The Joint Lightcurve Analysis (JLA) Sample



Betoule et. al. *Astron.Astrophys.* 568 (2014) A22



The SDSSII/SNLSIII Joint Lightcurve Analysis (JLA) catalogue of SN1a
740 SN1a , 551 of which are in the hemisphere opp to the CMB motion
Redshifts corrected using SMAC, which has a bulk flow (gray triangle)
631 are in the opp hemisphere to SMAC BF

Peculiar velocity impact on SN1a magnitude

$$1 + z = (1 + \bar{z})(1 + z_{pec}^{hel})(1 + z_{pec}^{SN})$$

$$d_L(z) = \bar{d}_L(\bar{z}) (1 + z_{pec}^{hel})(1 + z_{pec}^{SN})^2$$

Davis et. al. *Astrophys.J.* 741 (2011) 67

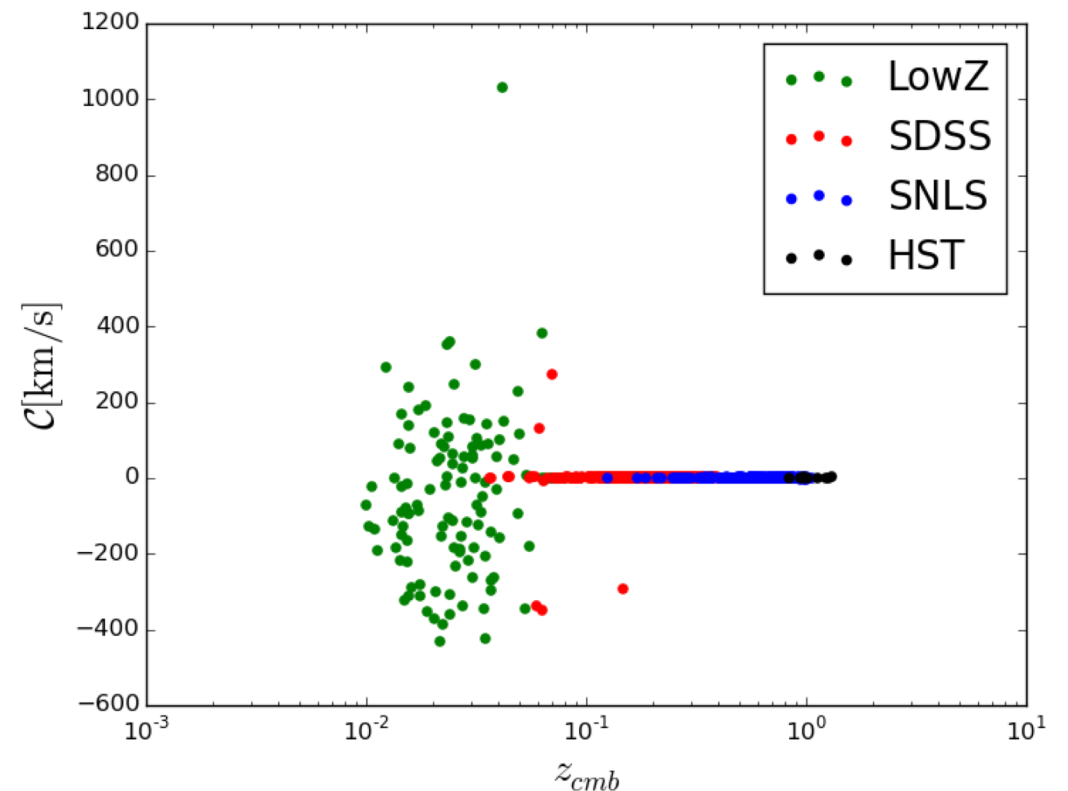
JLA (and Pantheon) redshifts and magnitudes have been corrected to account for the local bulk flow.

#name	zcmb	zhel	dz	mb	dmb	x1	dx1	color	dcolor
03D1au	0.503084	0.504300	0	23.001698	0.088031				
03D1aw	0.580724	0.582000	0	23.573937	0.090132				
03D1ax	0.494795	0.496000	0	22.960139	0.088110				
03D1bp	0.345928	0.347000	0	22.398137	0.087263				
03D1co	0.677662	0.679000	0	24.078115	0.098356				
03D1dt	0.610712	0.612000	0	23.285241	0.092877				
03D1ew	0.866494	0.868000	0	24.353678	0.106037				
03D1fc	0.330932	0.332000	0	21.861412	0.086437				
03D1fa	0.798566	0.800000	0	24.510389	0.101777				

z_{hel} → measured

z_{cmb} → inferred using a flow model

$$C = [(1 + z_{hel}) - (1 + z_{cmb})(1 + z_d)] \times c$$



SN1a at $z > 0.06$ are assumed (arbitrarily) to be in the CMB rest frame. (only uncorrelated 150 km/s in error budget)
 Wrong 'correction' to SDSS2308 in JLA. Many such mistakes in Pantheon (eg : SN2246).

Consequently, we use only z_{hel} and subtract out the corrections to m_B

Peculiar velocity impact on SN1a magnitude

$$1 + z = (1 + \bar{z})(1 + z_{pec}^{hel})(1 + z_{pec}^{SN})$$

$$d_L(z) = \bar{d}_L(\bar{z}) (1 + z_{pec}^{hel})(1 + z_{pec}^{SN})^2$$

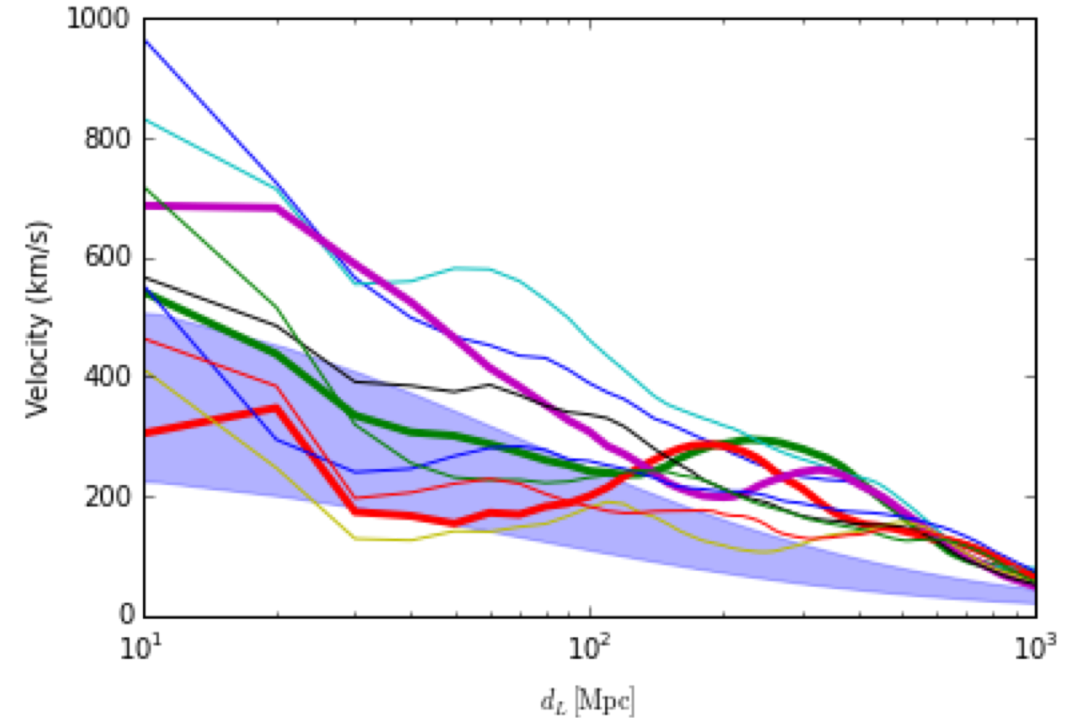
Davis et. al. *Astrophys.J.* 741 (2011) 67

JLA (and Pantheon) redshifts and magnitudes have been corrected to account for the local bulk flow.

#name	zcmb	zhel	dz	mb	dmb	x1	dx1	color	dcolor
03D1au	0.503084	0.504300	0	23.001698	0.088031				
03D1aw	0.580724	0.582000	0	23.573937	0.090132				
03D1ax	0.494795	0.496000	0	22.960139	0.088110				
03D1bp	0.345928	0.347000	0	22.398137	0.087263				
03D1co	0.677662	0.679000	0	24.078115	0.098356				
03D1dt	0.610712	0.612000	0	23.285241	0.092877				
03D1ew	0.866494	0.868000	0	24.353678	0.106037				
03D1fc	0.330932	0.332000	0	21.861412	0.086437				
03D1fa	0.798566	0.800000	0	24.510389	0.101777				

z_{hel} → measured

z_{cmb} → inferred using a flow model



SN1a at $z > 0.06$ are assumed (arbitrarily) to be in the CMB rest frame. (only uncorrelated 150 km/s in error budget)
 Wrong 'correction' to SDSS2308 in JLA. Many such mistakes in Pantheon (eg : SN2246).

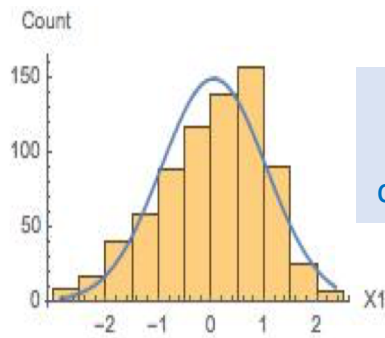
Consequently, we use only z_{hel} and subtract out the corrections to m_B

CONSTRUCT A MAXIMUM LIKELIHOOD ESTIMATOR

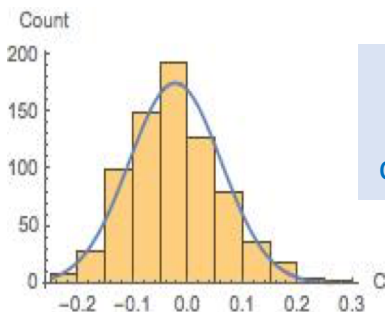
\mathcal{L} = probability density(data|model)

$$\begin{aligned} \mathcal{L} &= p[(\hat{m}_B^*, \hat{x}_1, \hat{c}) | \theta] \\ &= \int p[(\hat{m}_B^*, \hat{x}_1, \hat{c}) | (M, x_1, c), \theta_{\text{cosmo}}] \\ &\quad \times p[(M, x_1, c) | \theta_{\text{SN}}] dM dx_1 dc \end{aligned}$$

Well-approximated as Gaussian



JLA data
'Stretch'
corrections



JLA data
'Colour'
corrections

$$p[(M, x_1, c) | \theta] = p(M | \theta) p(x_1 | \theta) p(c | \theta),$$

$$p(M | \theta) = \frac{1}{\sqrt{2\pi\sigma_M^2}} \exp\left(-\left[\frac{M - M_0}{\sigma_{M0}}\right]^2 / 2\right)$$

$$p(x_1 | \theta) = \frac{1}{\sqrt{2\pi\sigma_{x0}^2}} \exp\left(-\left[\frac{x_1 - x_{10}}{\sigma_{x0}}\right]^2 / 2\right)$$

$$p(c | \theta) = \frac{1}{\sqrt{2\pi\sigma_{c0}^2}} \exp\left(-\left[\frac{c - c_0}{\sigma_{c0}}\right]^2 / 2\right)$$

Likelihood

$$p(Y|\theta) = \frac{1}{\sqrt{|2\pi\Sigma_l|}} \exp \left[-\frac{1}{2}(Y - Y_0)\Sigma_l^{-1}(Y - Y_0)^T \right]$$

$$p(\hat{X}|X, \theta) = \frac{1}{\sqrt{|2\pi\Sigma_d|}} \exp \left[-\frac{1}{2}(\hat{X} - X)\Sigma_d^{-1}(\hat{X} - X)^T \right]$$

$$\mathcal{L} = \frac{1}{\sqrt{|2\pi(\Sigma_d + A^T\Sigma_l A)|}} \times \exp \left(-\frac{1}{2}(\hat{Z} - Y_0 A)(\Sigma_d + A^T\Sigma_l A)^{-1}(\hat{Z} - Y_0 A)^T \right)$$

cosmology

intrinsic distributions

SALT2

Simultaneously fit for

- q_m
- $j_0 - \Omega_k$
- q_d
- S
- α
- $x_{1,0}$
- $\sigma_{x_{1,0}}$
- β
- c_0
- σ_{c_0}
- M_0
- σ_{M_0}

Confidence regions

$$p_{\text{cov}} = \int_0^{-2 \log \mathcal{L} / \mathcal{L}_{\text{max}}} \chi^2(x; \nu) dx$$

$$\mathcal{L}_p(\theta) = \max_{\phi} \mathcal{L}(\theta, \phi)$$

1,2,3-sigma

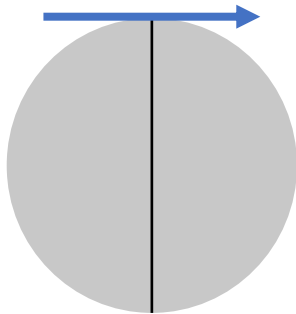
solve for Likelihood value

Results

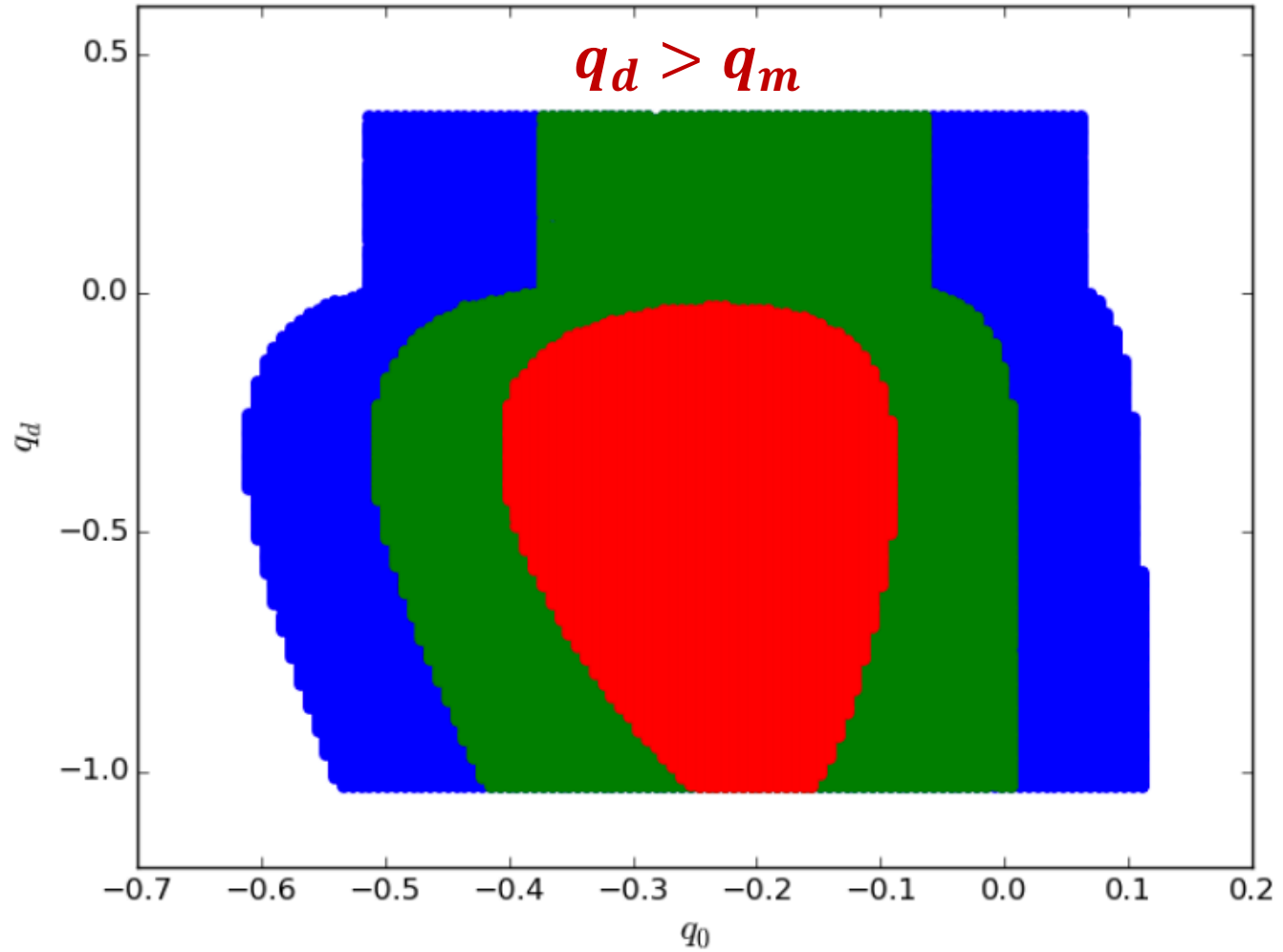
	$-2 \log \mathcal{L}_{\max}$	q_m	q_d	S	$j_0 - \Omega_k$
No Dipole: JLA z_{CMB}	-213.84	-0.3140	-	-	0.03729
As above with no acceleration ($q_m = 0$)	-204.30	0	-	-	-0.8240
Dipole with no scale dep.: $\mathcal{F}(z, S) = 1$	-218.02	-0.2275	-0.03087	-	-0.3232
As above with no acceleration ($q_m = 0$)	-212.95	0	-0.03403	-	-0.8857
Top hat dipole $\mathcal{F}(z, S) = 1$ for $z < S$	-219.83	-0.1673	-0.8317	0.06282	-0.4651
As above with no acceleration ($q_m = 0$)	-217.28	0	-0.9914	0.0656	-0.8468
Exponential dipole: $\mathcal{F}(z, S) = e^{-z/S}$	-220.49	-0.2461	-0.3328	0.2290	-0.2047
As above with no acceleration ($q_m = 0$)	-214.84	0	-0.4521	0.1698	-0.8232
Linear dipole: $\mathcal{F}(z, S) = 1 - z/S$	-217.72	-0.1861	-0.4574	0.3892	-0.4169
As above with no acceleration ($q_m = 0$)	-216.35	0	-1.448	0.0904	-0.8537

The dipolar component of q is larger than the monopole, and extends out to $z \sim 0.22$

Accelerating
Universe



Decelerating
Universe out to $z \sim 0.2$



The significance of q_0 being negative is only 2σ !

Cosmic acceleration may simply be an artefact of our being located inside a 'bulk flow'!
(and looking mostly only in one direction)

Conclusions

The dipolar modulation of high redshift radio galaxies is at 2.81σ tension with the kinematic interpretation of the CMB dipole, suggesting a velocity of ~ 1355 km/s instead of 369 km/s

Infrared galaxies show a 4.6σ kinematic + clustering dipole in the CMB direction, favouring a velocity of ~ 1260 km/s, and can be reconciled with the kinematic interpretation of the CMB dipole only for a non Copernican observer rare in a Λ CDM universe at the level of $<1\%$.

SN1a data allow for a dipole in q_0 out to $z \sim 0.2$, and a nonzero value for the monopole in q_0 is disfavoured only at 2σ . The dipole is a natural, expected, GR consequence of bulk flows, which are expected even in universes with $\Lambda = 0$.

An a posteriori cautionary tale

Then:

Riess et al 1998

60 SNe from $z \sim 0.02$ to 0.62

Perlmutter et al 1999

60 SNe from $z=0.01$ to 0.83

Acceleration at 99% C.L.

All in the hemisphere opposite to the CMB dipole

No peculiar velocity corrections of any kind.
(Introduced only in ~ 2014 in JLA, not used in Union II)

Today:

740 SNe in total

632 in hemisphere opposite CMB dipole

108 in same hemisphere as CMB dipole

Exercise:

Select ~ 60 from the 108 with similar redshifts

Best fit will be a decelerating Universe

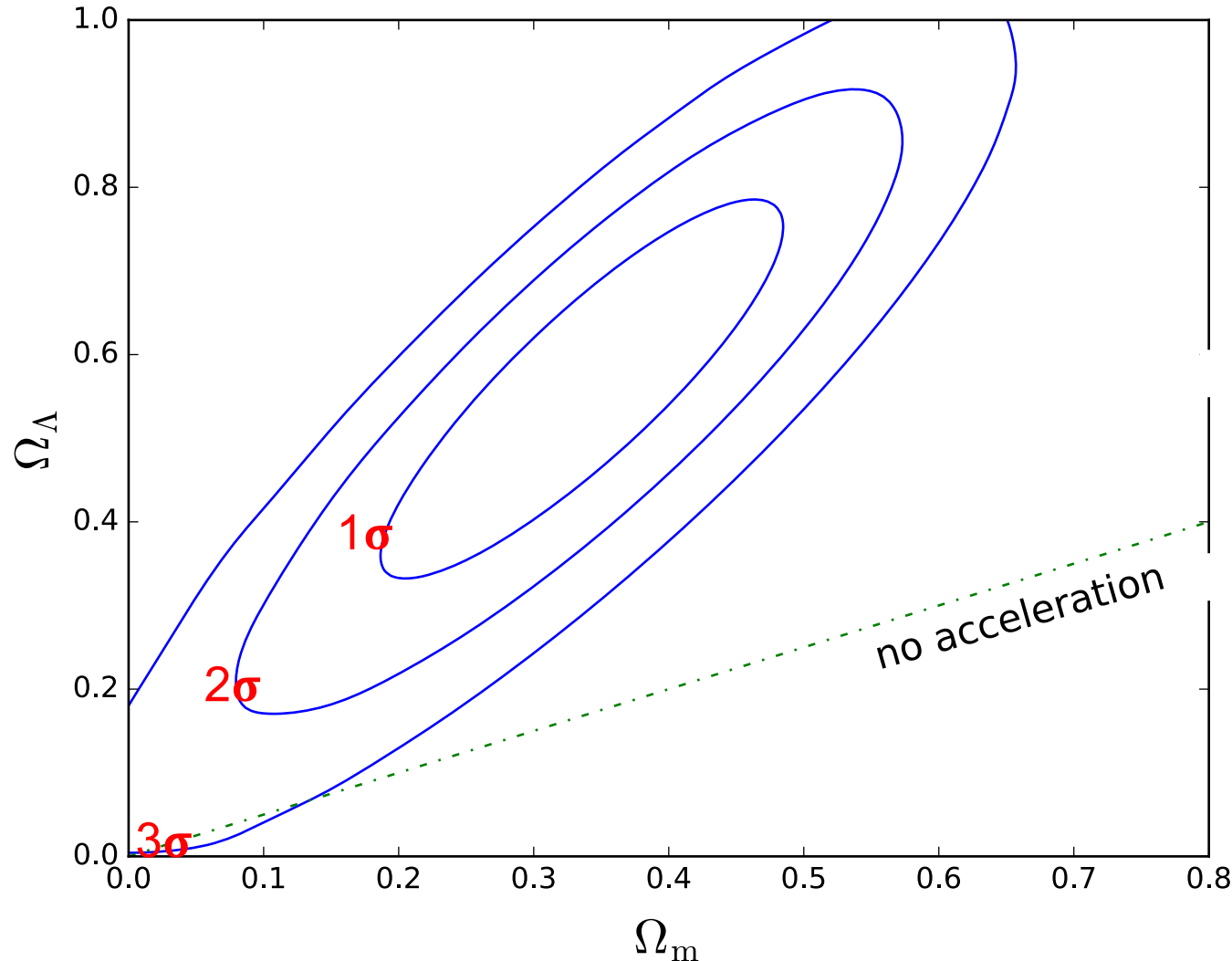
Bernal et al. Phys. Lett. B

765, 163170 (2017)

Anisotropy in the reconstructed deceleration parameter

Data consistent with uniform expansion @ $<3\sigma$!

Opens up interesting possibilities e.g. could the cosmic fluid be *viscous* – perhaps associated with structure formation (e.g. Floerchinger *et al*, PRL **114**:091301,2015)



profile likelihood

MLE, best fit

Ω_M 0.341

Ω_Λ 0.569

α 0.134

x_0 0.038

$\sigma_{x_0}^2$ 0.931

β 3.058

c_0 -0.016

$\sigma_{c_0}^2$ 0.071

M_0 -19.05

$\sigma_{M_0}^2$ 0.108

Nielsen, Guffanti & Sarkar., Sci.Rep.6:35596,2016

Rubin & Hayden (ApJ 833:L30,2016) verify the results of Nielsen et al
 but then argue that the light-curve fit parameters may be redshift-dependent

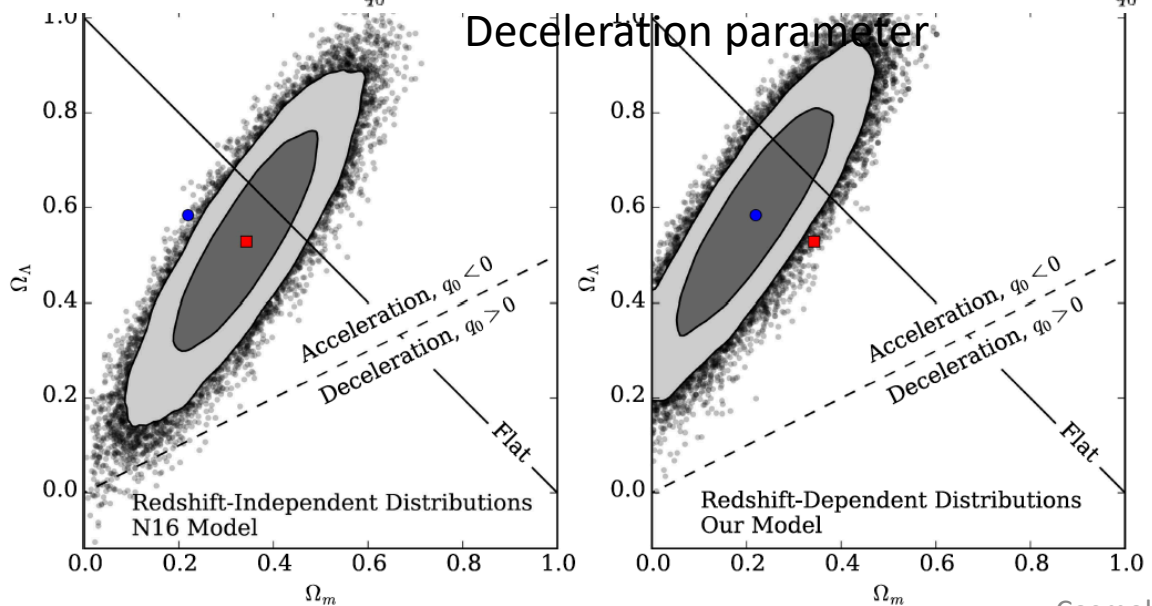
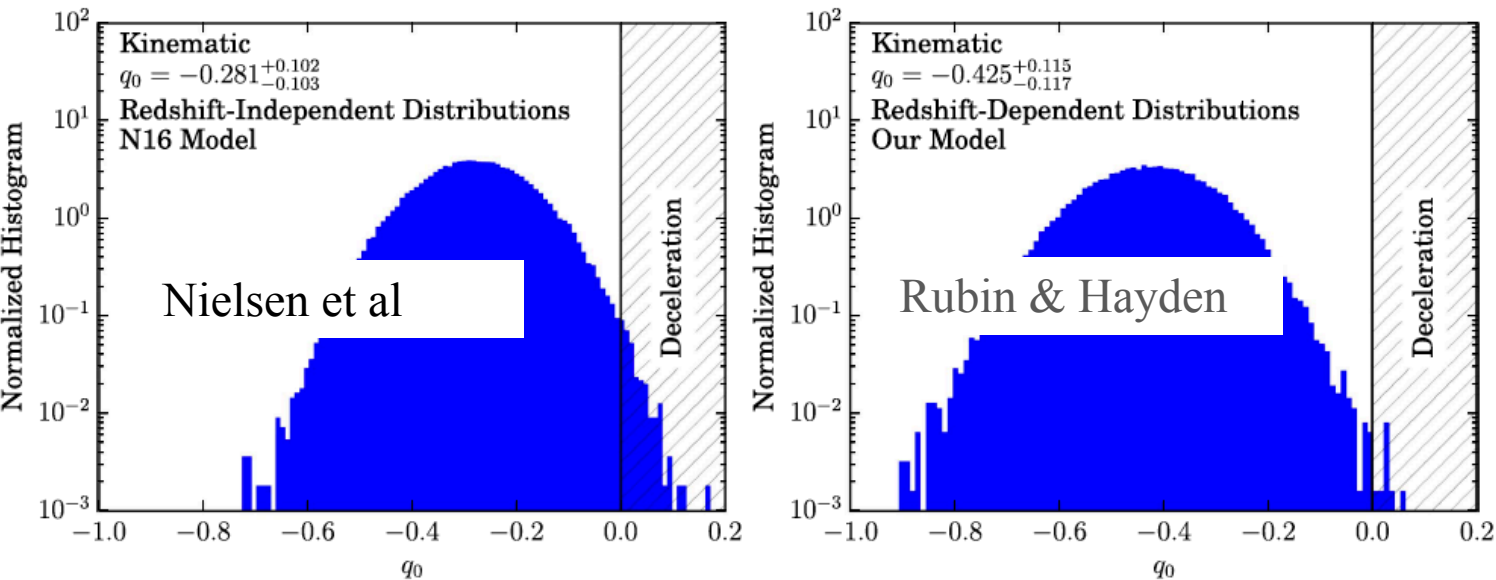


Figure 2. Ω_m - Ω_Λ constraints enclosing 68.3% and 95.4% of the samples from the posterior. Underneath, we plot all samples. The left panel shows the constraints obtained with x_1 and c distributions that are constant in redshift, as in the N16 analysis; the right panel shows the constraints from our model. The red square and blue circle show the location of the median of the respective posteriors.

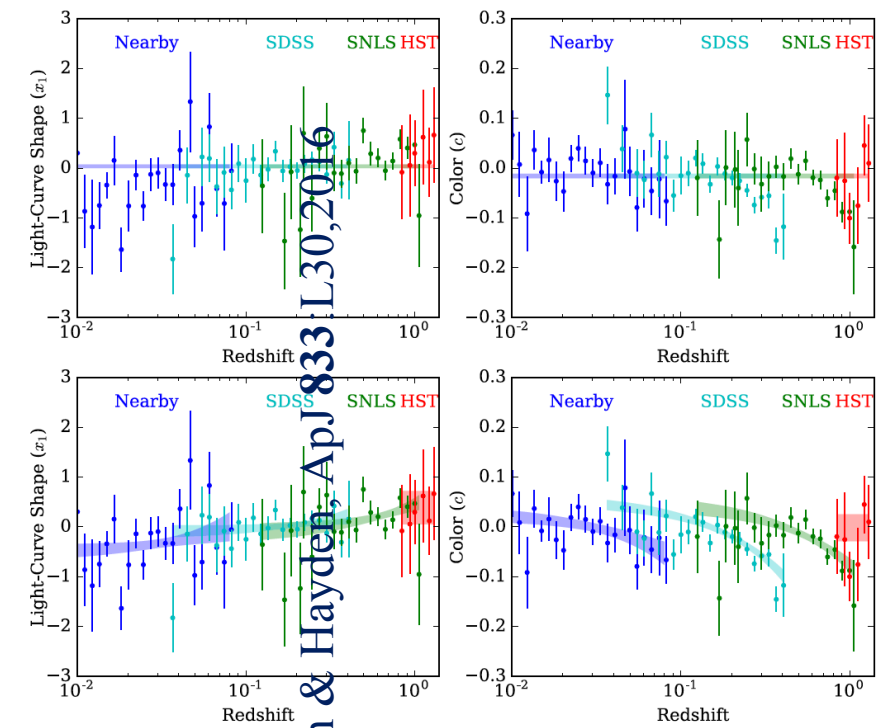
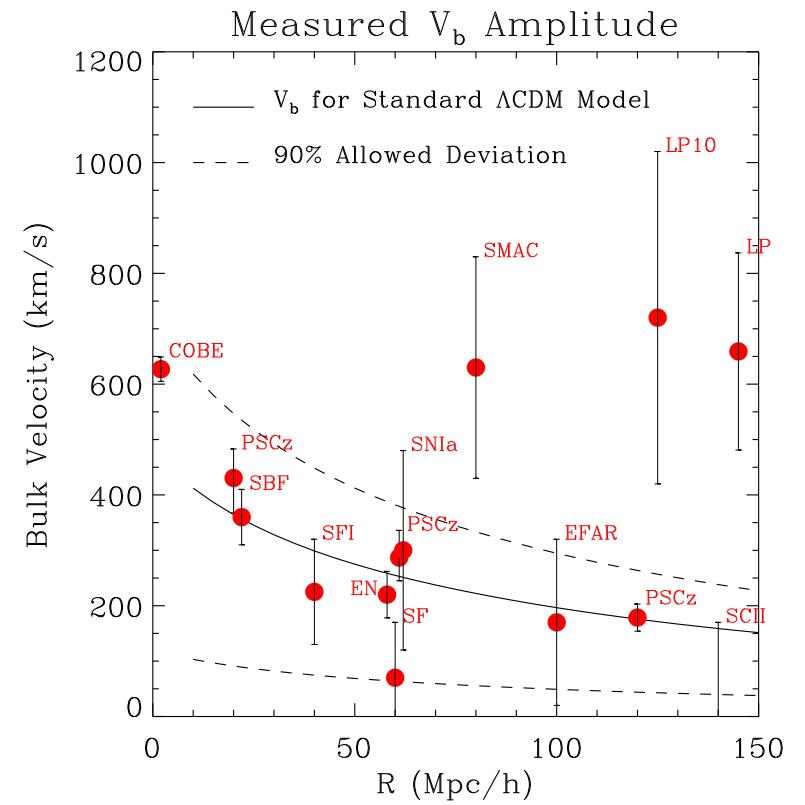
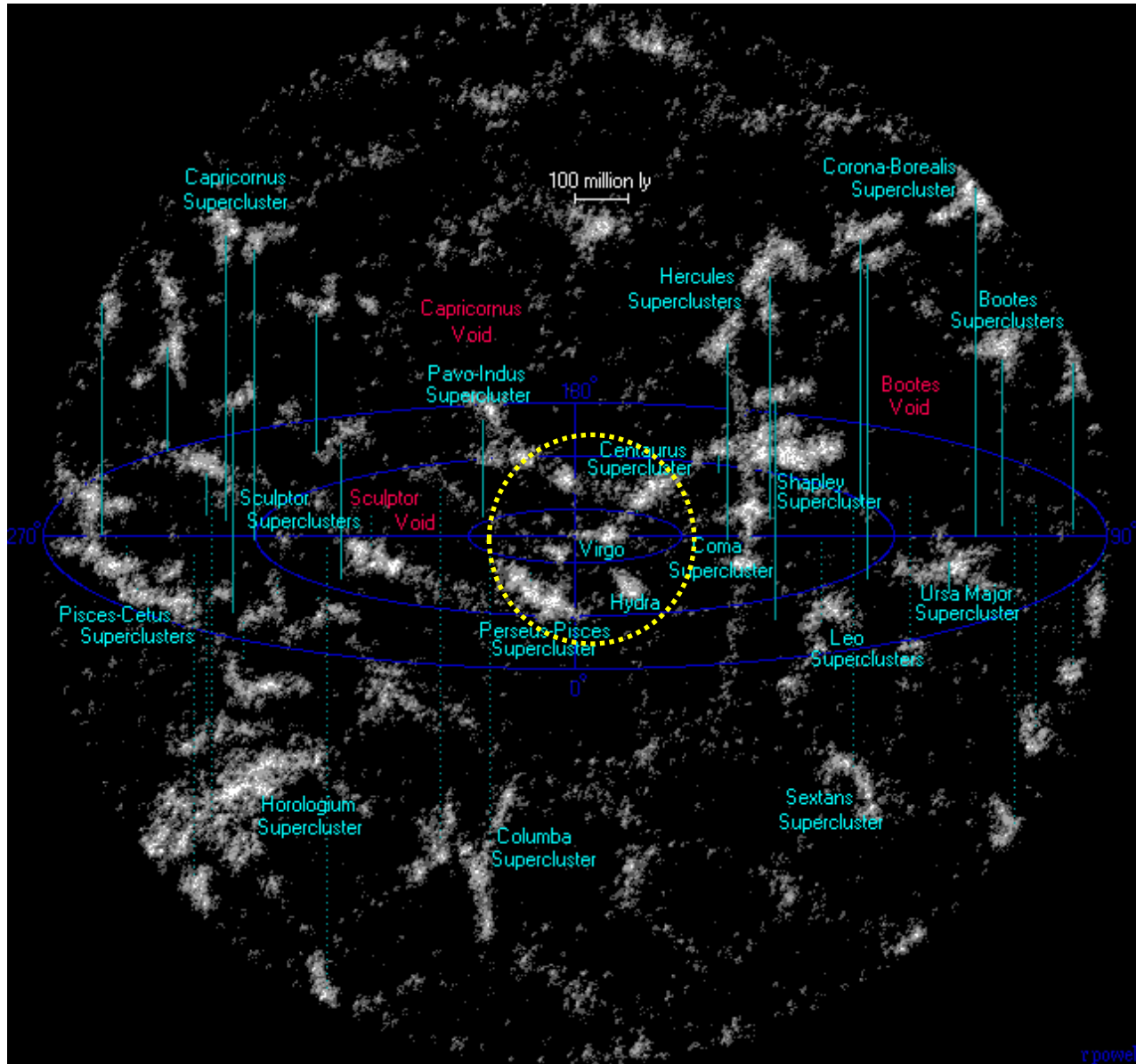


Figure 1. Binned x_1 (left panels) and c (right panels) light-curve parameters as a function of redshift for the JLA sample. The trend of color with redshift within each ground-based sample is expected due to the combination of the color-luminosity relation combined with redshift-dependent luminosity detection limits. The top panels show the 68% credible constraints on a constant-in-redshift model, as was used in N16. The bottom panels show our proposed revision. Failing to model the drift in the mean observed distributions demonstrated by the bottom panels will tend to cause high-redshift SNe to appear brighter on average, therefore reducing the significance of accelerating expansion.

Two out of 3 parameters that go into the distance modulus have been examined by eye and made sample and redshift dependent.
 Against the principles of blinded data analysis.
 20 hyperparameters to standardize 740 SN1e

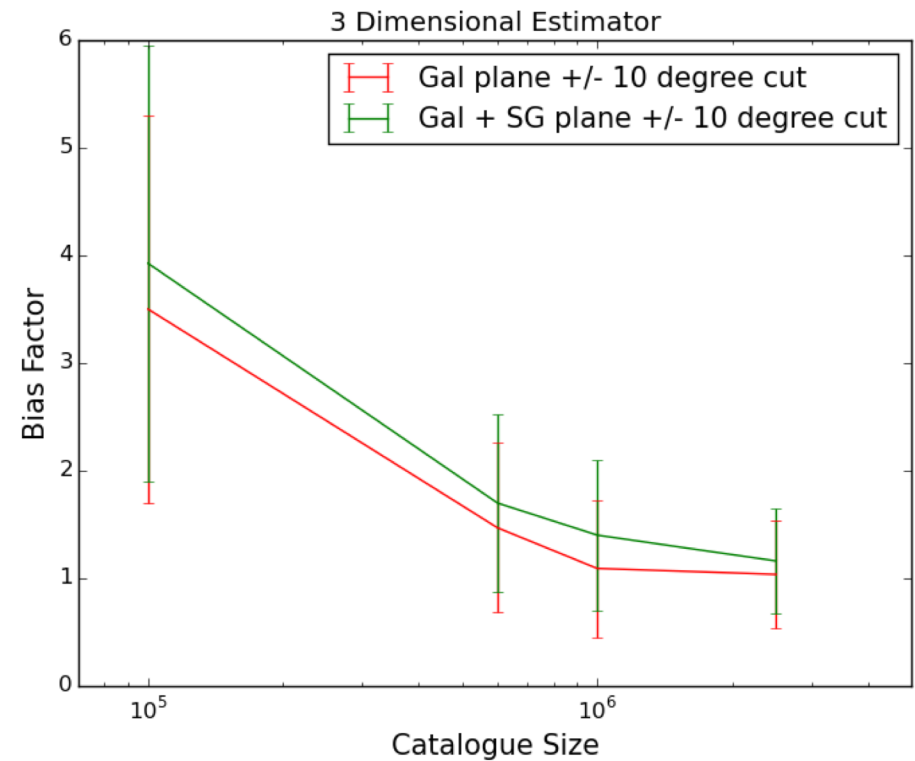
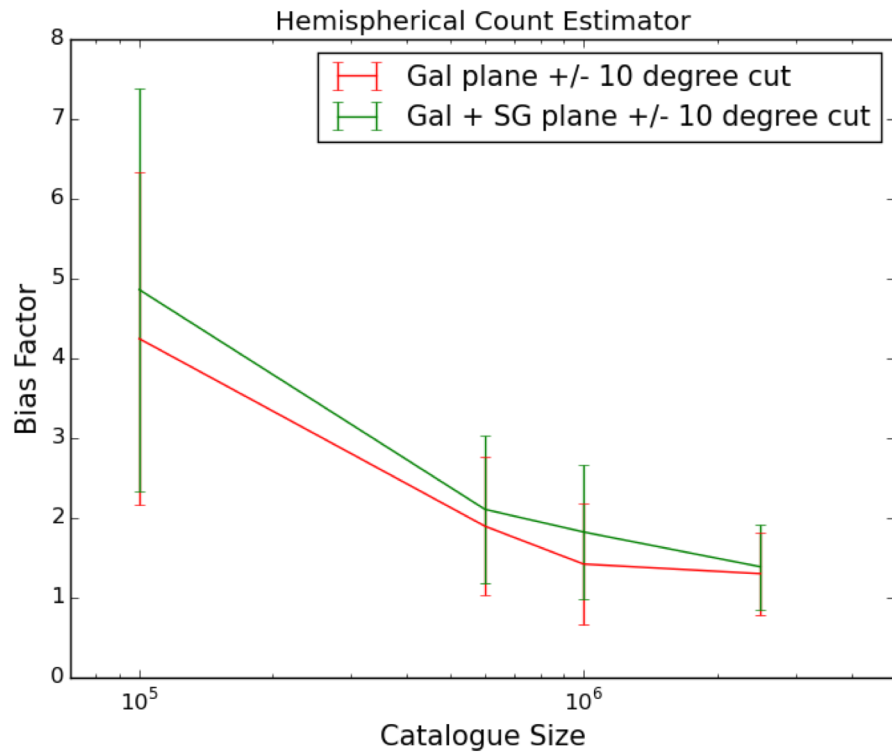
Even if this is justified, the significance with which a non-accelerating universe is rejected rises only to $\lesssim 4\sigma$... still inadequate to claim a 'discovery' (even though the dataset has increased from ~ 50 to 740 SNe Ia in 20 yrs)!



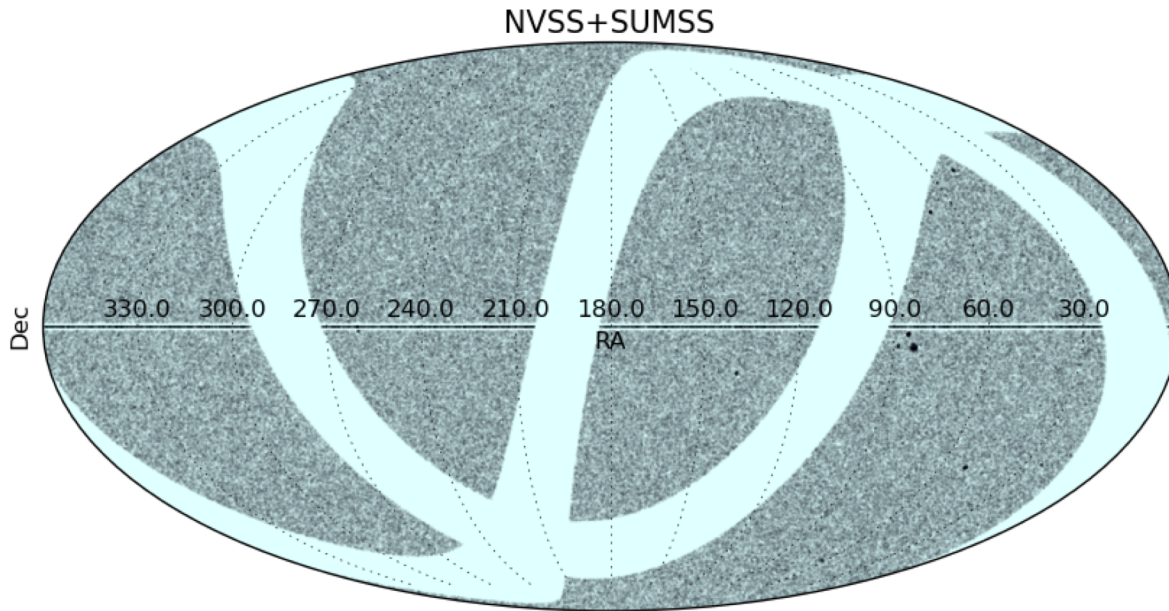
Estimators for the Dipole

$$\vec{D}_H = \hat{z} * \frac{N_{UH} - N_{LH}}{N_{UH} + N_{LH}}$$

$$\vec{D}_{3D} = \frac{1}{N} \sum_{i=1}^N \hat{r}_i$$



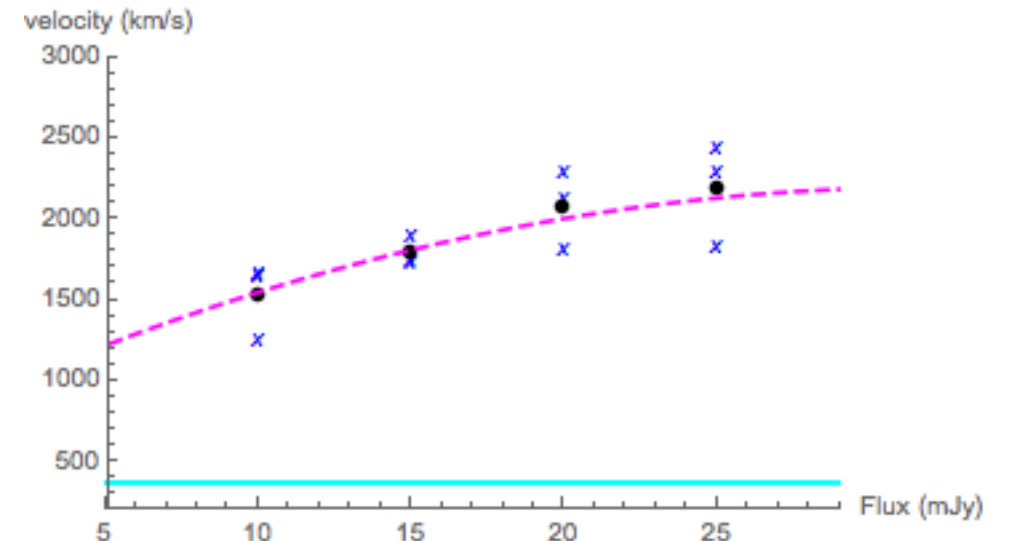
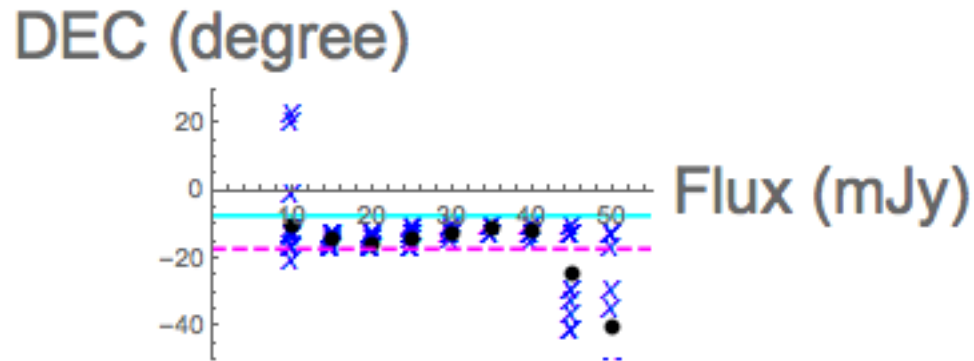
Local Sources contamination?



Remove the Supergalactic plane. Disk like structure containing the majority of clusters at $z < 0.03$

Remove sources within 1 arcsecond of 2MRS $z < 0.03$ sources

No significant impact on the velocity/direction of the dipole



	$-2 \log \mathcal{L}_{\max}$	q_m	q_d	S	$j_0 - \Omega_k$	α	β	M_0	σ_{M_0}
Rubin & Hayden (22 param.) with no dipole	-331.6	-0.4574	–	–	0.1458	0.1345	3.067	-19.07	0.1074
As above with no acceleration ($q_m = 0$)	-315.6	0	–	–	-1.351	0.1323	3.048	-19.01	0.1088
Rubin & Hayden (22 param.) with dipole $\propto e^{-z/S}$	-335.9	-0.3867	-0.2325	0.1825	-0.1779	0.1337	3.028	-19.06	0.1076
As above with no acceleration ($q_m = 0$)	-326.9	0	-2.186	0.05034	-1.333	0.1325	3.02	-19.01	0.1087
Rubin & Hayden (16 param.) with no dipole	-242.4	-0.3873	–	–	0.2937	0.1345	3.063	-19.05	0.1080
As above with no acceleration ($q_m = 0$)	-229.9	0	–	–	-0.8444	0.1325	3.051	-19.00	0.1094
Rubin & Hayden (16 param.) with dipole $\propto e^{-z/S}$	-250.2	-0.3329	-0.2091	0.2726	0.04258	0.1336	3.021	-19.04	0.1081
As above with no acceleration ($q_m = 0$)	-241.2	0	-0.3585	0.1794	-0.8645	0.132	3.009	-19.00	0.1093
Rubin & Hayden (16 + 3 param.) with no dipole	-253.4	-0.09894	–	–	-0.102	0.1346	3.023	-19.07, -19.00, -18.94, -18.78	0.1082
As above with no acceleration ($q_m = 0$)	-253	0	–	–	-0.2661	0.1344	3.016	-19.06, -18.99, -18.92, -18.77	0.1084

Even with the sample and redshift dependent treatment for $x_{1,0}$ and c_0 proposed by R&H, $q_m=0$ is disfavoured only at 2.4 sigma and allows for a large q_d extending to $z \sim 0.18$

If $x_{1,0}$ and c_0 can be sample or redshift dependent, why not M_0 ? Undermines the use of SN1a as standard candles but justified by AIC.

Planck 2015

Parameter	<i>Planck</i> TT+lowP+lensing
$\Omega_b h^2$	0.02226 ± 0.00023
$\Omega_c h^2$	0.1186 ± 0.0020
$100\theta_{MC}$	1.04103 ± 0.00046
τ	0.066 ± 0.016
$\ln(10^{10} A_s)$	3.062 ± 0.029
n_s	0.9677 ± 0.0060
H_0	67.8 ± 0.9
Ω_m	0.308 ± 0.012
$\Omega_m h^2$	0.1415 ± 0.0019
$\Omega_m h^3$	0.09591 ± 0.00045
σ_8	0.815 ± 0.009
$\sigma_8 \Omega_m^{0.5}$	0.4521 ± 0.0088
Age/Gyr	13.799 ± 0.038
r_{drag}	147.60 ± 0.43
k_{eq}	0.01027 ± 0.00014

<https://arxiv.org/pdf/1706.09309.pdf>

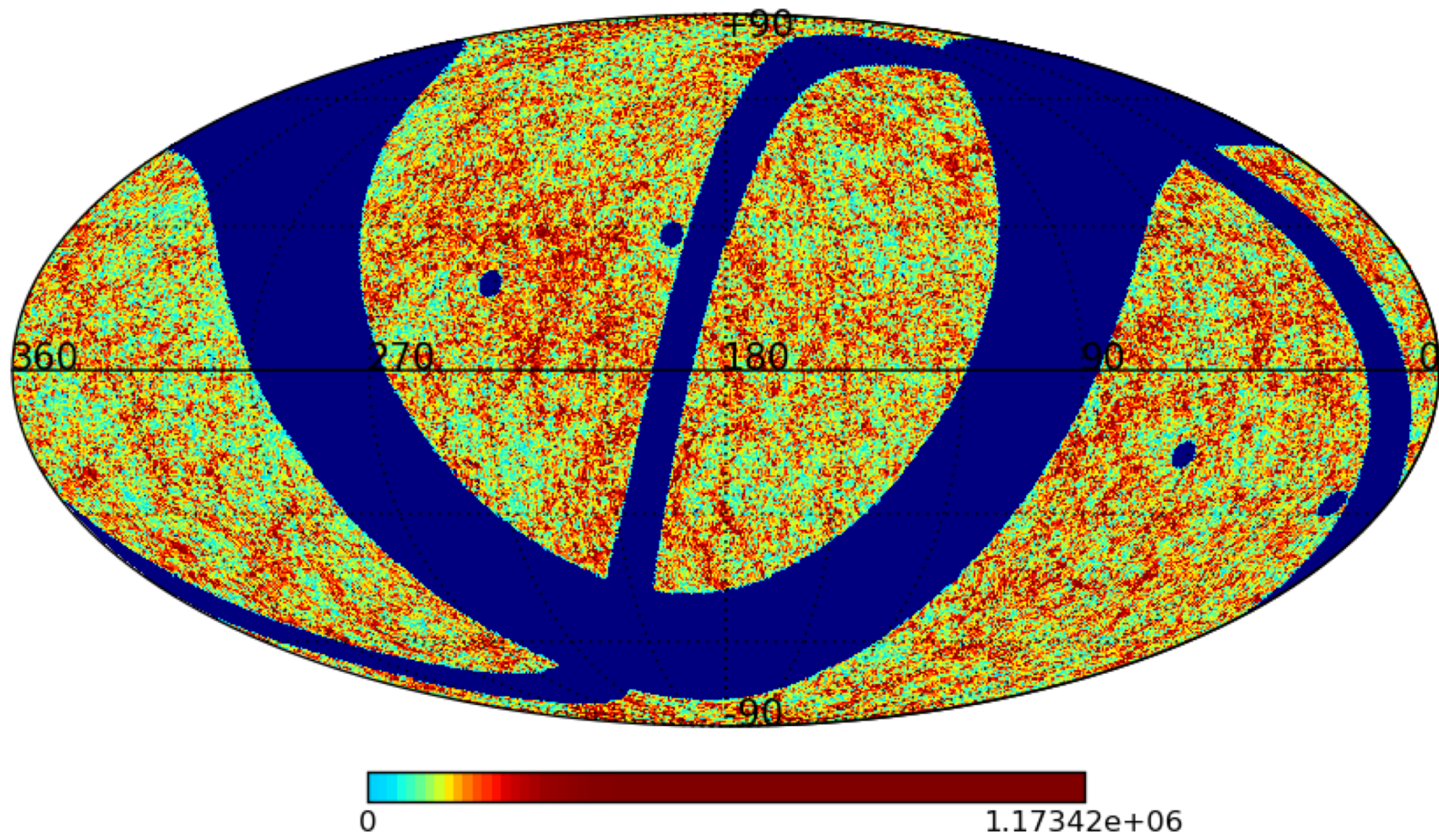
<https://arxiv.org/pdf/1505.07800.pdf>

On the measurement of cosmological parameters

Rupert A. C. Croft, Matthew Dailey (CMU)

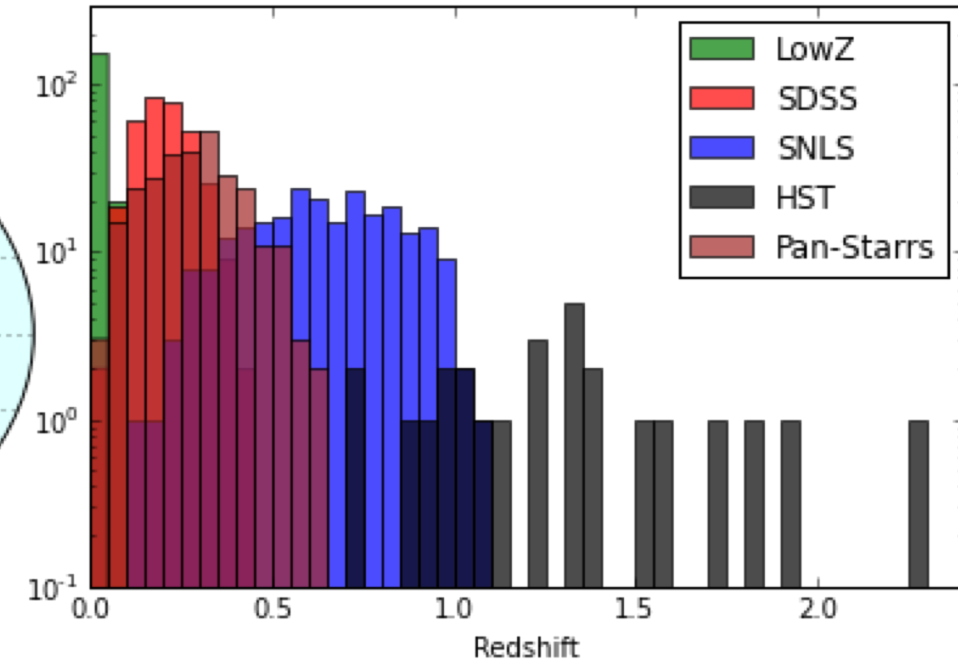
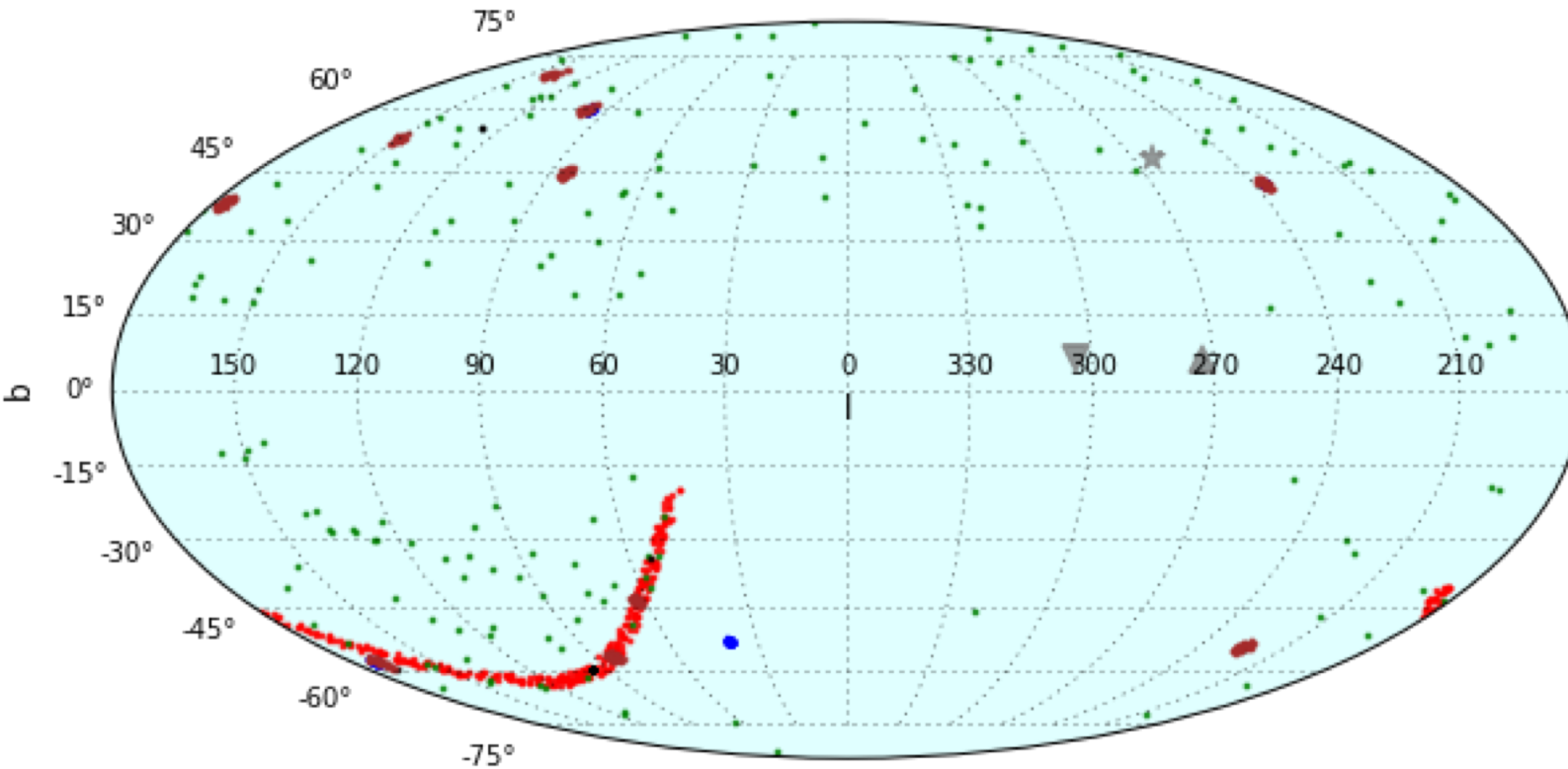
(Submitted on 14 Dec 2011 (v1), last revised 21 Jul 2015 (this version, v2))

We have catalogued and analysed cosmological parameter determinations and their error bars published between the years 1990 and 2010. Our study focuses on the number of measurements, their precision and their accuracy. The accuracy of past measurements is gauged by comparison with the WMAP7 results. The 637 measurements in our study are of 12 different parameters and we place the techniques used to carry them out into 12 different categories. We find that the number of published measurements per year in all 12 cases except for the dark energy equation of state parameter w_0 peaked between 1995 and 2004. Of the individual techniques, only BAO measurements were still rising in popularity at the end of the studied time period. The fractional error associated with most measurements has been declining relatively slowly, with several parameters, such as the amplitude of mass fluctuations σ_8 and the Hubble constant H_0 remaining close to the 10% precision level for a 10–15 year period. The accuracy of recent parameter measurements is generally what would be expected given the quoted error bars, although before the year 2000, the accuracy was significantly worse, consistent with an average underestimate of the error bars by a factor of ~ 2 . When used as complement to traditional forecasting techniques, our results suggest that future measurements of parameters such as fNL , and w_a will have been informed by the gradual improvement in understanding and treatment of systematic errors and are likely to be accurate. However, care must be taken to avoid the effects of confirmation bias, which may be affecting recent measurements of dark energy parameters. For example, of the 28 measurements of Ω_{Λ} in our sample published since 2003, only 2 are more than 1 σ from the WMAP results. Wider use of blind analyses in cosmology could help to avoid this.



The Pantheon compilation

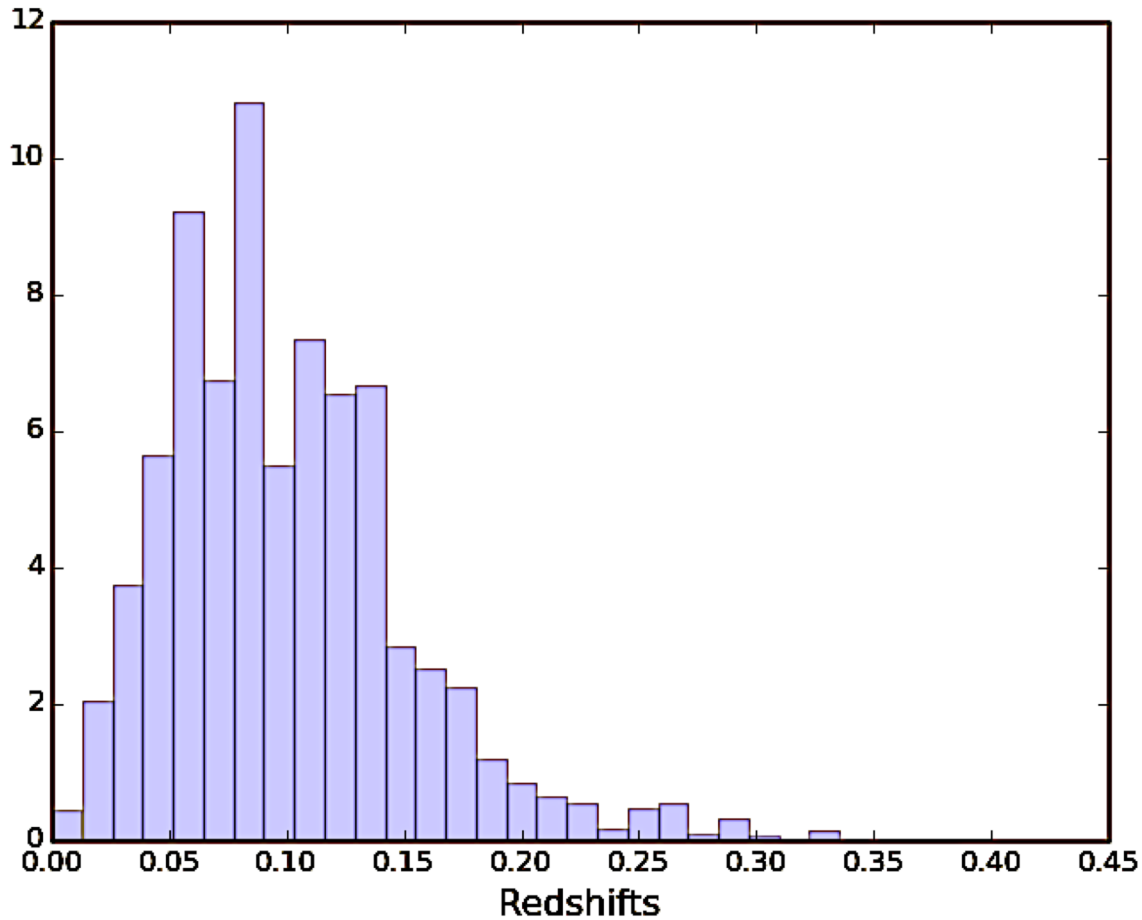
Scolnic et al. *Astrophys.J.* 859 (2018) no.2, 101



JLA + additional SN1a from Pan Starrs and HST
1048 SN1a, redshifts corrected for peculiar velocities using the 2M++
flow field
890 are in the hemisphere opposite the 2M++ bulk flow

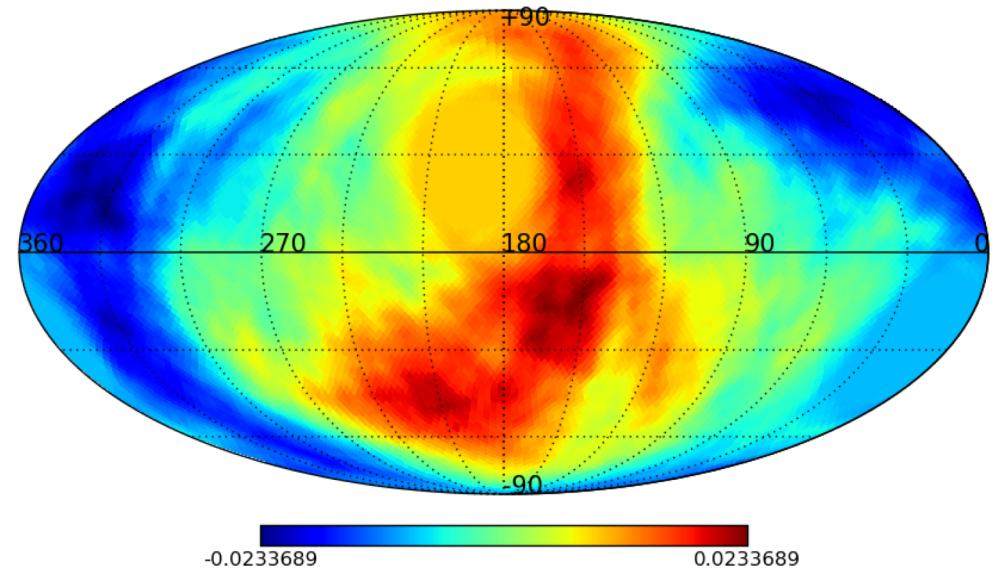
However, we use only JLA!

Redshift distribution of the removed sources

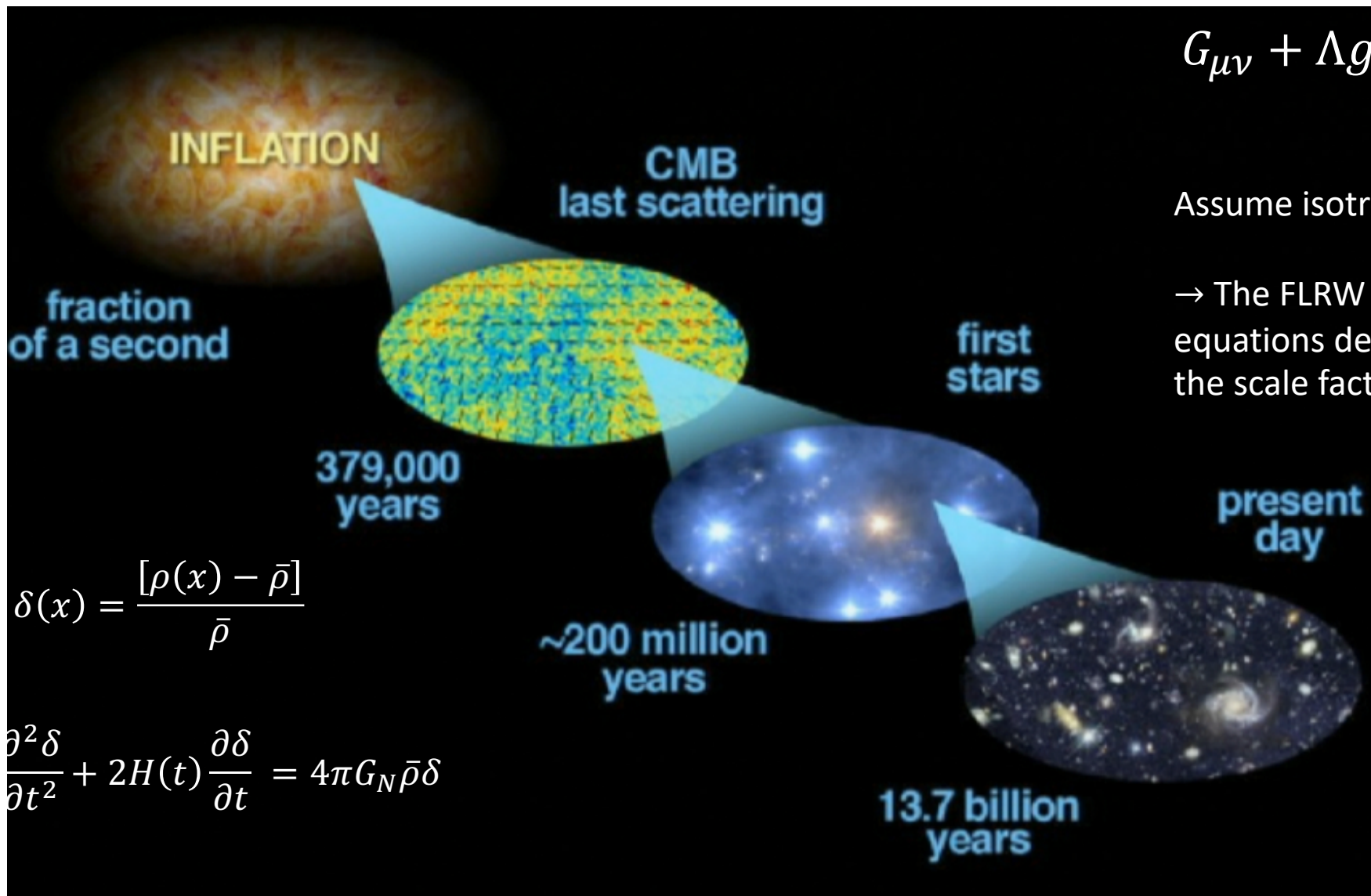


$d = 0.0124 > 1200$ km/s if fully kinematic
 172.6° RA, -6.6° Dec ($\sim 4.5^\circ$ from CMB)

Total dipole is at least 4.2σ statistically significant.



By cross correlating with Galaxy and Mass Assembly



$$G_{\mu\nu} + \Lambda g_{\mu\nu}$$

Assume isotropic

→ The FLRW equations describe the scale factor

$$\delta(x) = \frac{[\rho(x) - \bar{\rho}]}{\bar{\rho}}$$

$$\frac{\partial^2 \delta}{\partial t^2} + 2H(t) \frac{\partial \delta}{\partial t} = 4\pi G_N \bar{\rho} \delta$$

