



Cosmology with the largest all-sky galaxy surveys

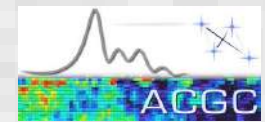
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Main collaborators on this project:

John Peacock, Tom Jarrett, Michelle Cluver
+ GAMA team + Polish WISE team

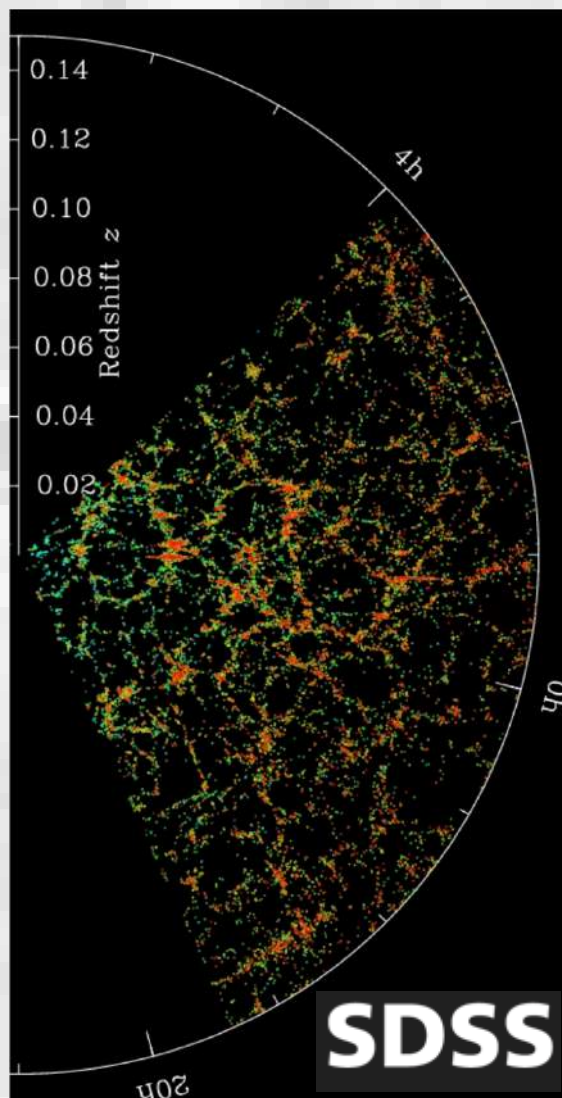


NARODOWE CENTRUM NAUKI



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Observing the Universe at large



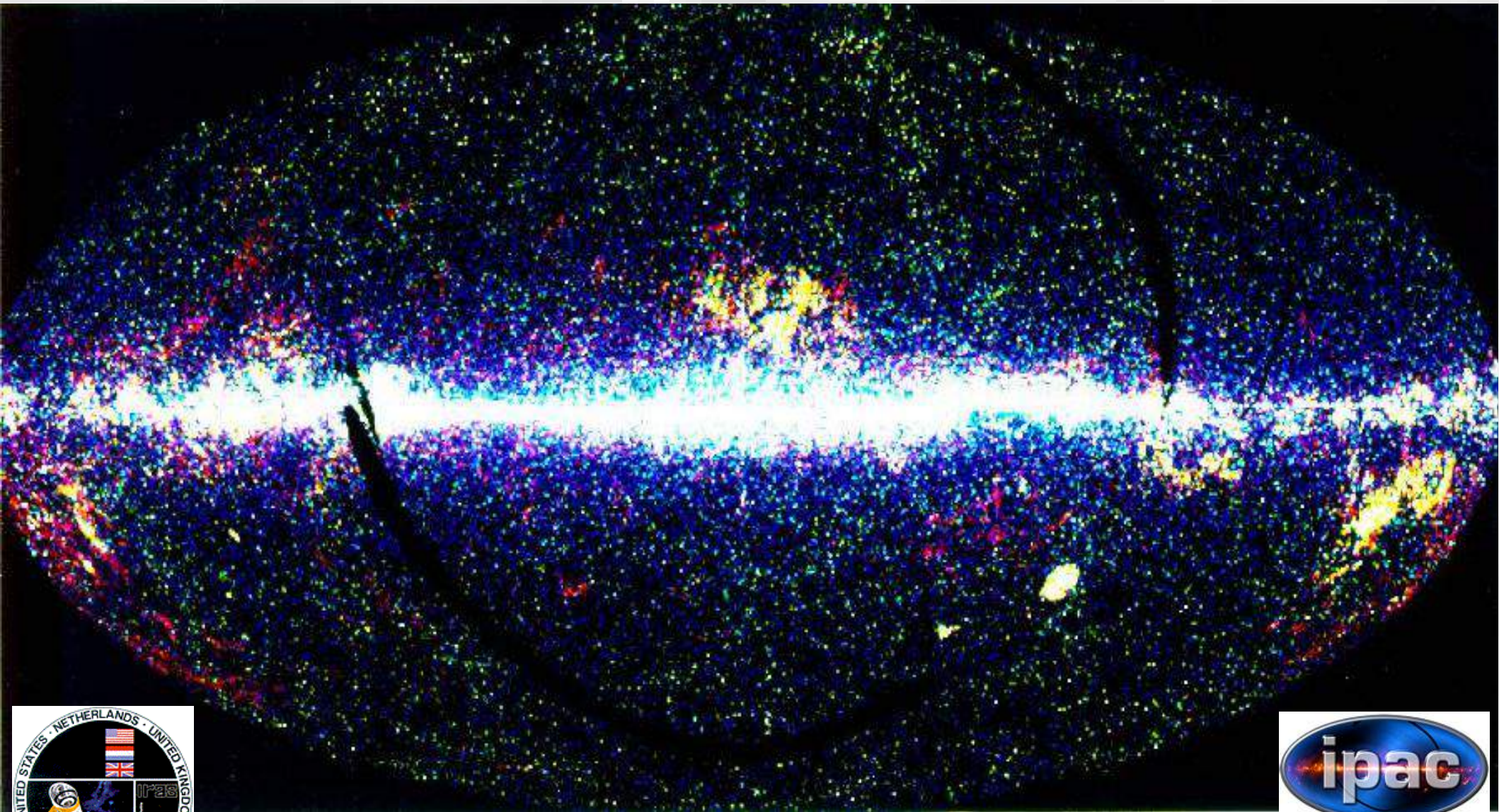
- We need **representative samples** of our Universe: covering *large areas* of the sky and reaching as *far* in redshift as possible
- The most successful to date has been the **Sloan Digital Sky Survey**, spectra on 25% of the sky
- A **trade-off** is made between *how much of the sky* is covered and *how deep* a survey can reach → observing the wide-angle 3D galaxy distribution is *expensive* and *time-consuming*

The need for all-sky surveys (preferably) in three dimensions

- To obtain a **complete picture of the Universe** we need to observe the **entire sky** ($=4\pi$ steradians), in 3 dimensions and deep
- **Early Universe** very **homogeneous and isotropic**; but what about today? (the **Copernican Principle** needs to be studied *observationally*)
- Related **cosmological tests** require observing the whole celestial sphere in 3D:
 - Are the **CMB anomalies** confirmed as today's anisotropy and/or inhomogeneity?
 - How large are the **bulk flows** of galaxies? Are they in conflict with the CP?
 - What structures **pull the Local Group** of galaxies?
- Other probes – e.g. the **integrated Sachs-Wolfe** effect, **CMB lensing on LSS** or **baryon acoustic oscillations** – also need surveys of large coverage and volume

First all-sky galaxy survey: IRAS satellite (1980s)

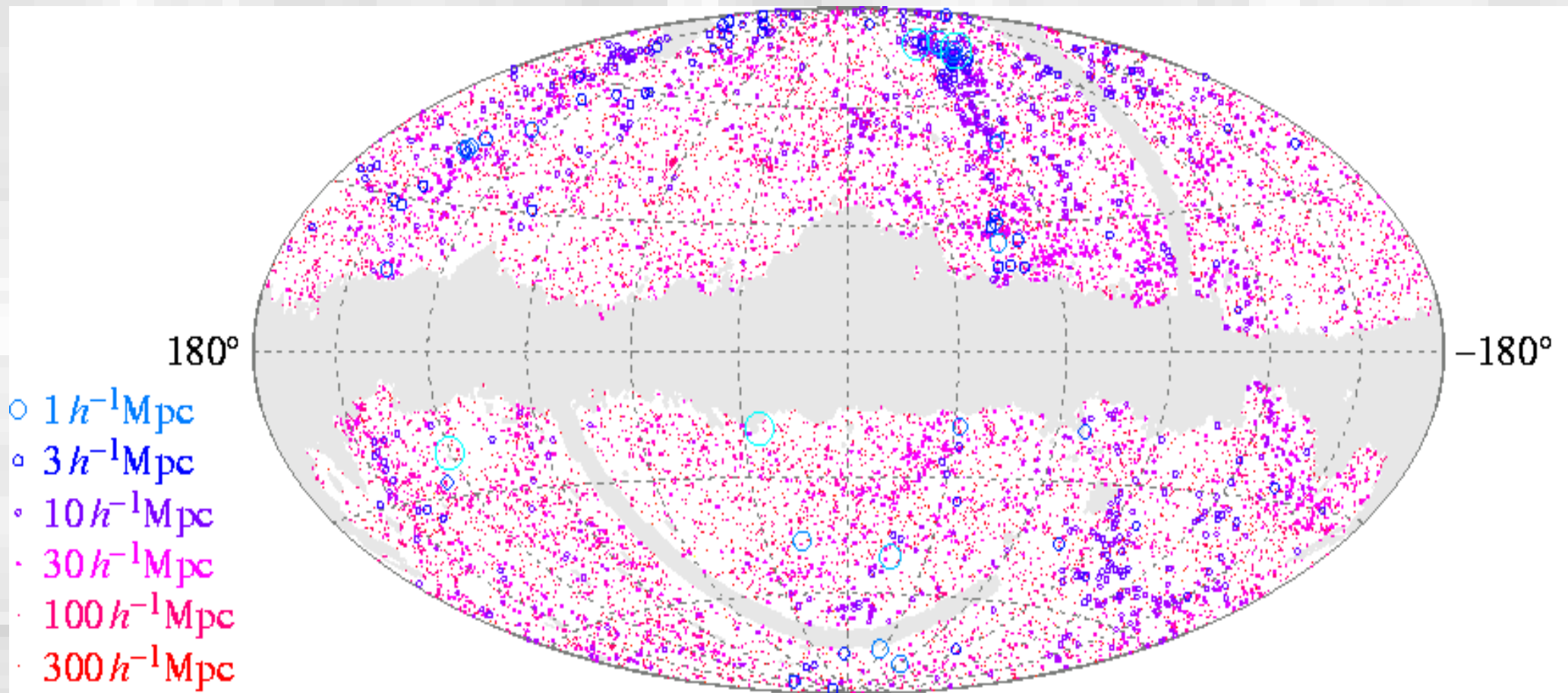
Detected about 350,000 infrared sources



IPAC / NASA

IRAS redshift survey (PSCz)

15,000 sources over 84% of sky



Saunders et al. 2000



Roman, IRAS and all-sky surveys all in one (important) paper

THE ASTROPHYSICAL JOURNAL, 349:408–414, 1990 February 1
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LOCAL GRAVITY AND LARGE-SCALE STRUCTURE

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ABSTRACT

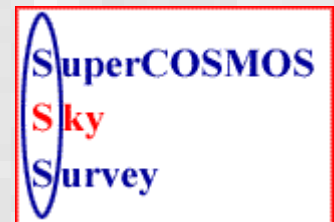
The magnitude and direction of the observed dipole anisotropy of the galaxy distribution can in principle constrain the amount of large-scale power present in the spectrum of primordial density fluctuations. We here confront the data, provided by a recent redshift survey of galaxies detected by the *IRAS* satellite, with the predictions of two cosmological models with very different levels of large-scale power: the biased Cold Dark Matter dominated model (CDM) and a baryon-dominated model (BDM) with isocurvature initial conditions. We investigate model predictions for the Local Group peculiar velocity, v_R , induced by mass inhomogeneities distributed out to a given radius, R , for $R \lesssim 10,000 \text{ km s}^{-1}$. We develop several convergence measures for v_R , which can become powerful cosmological tests when deep enough samples become available. For the present data sets, the CDM and BDM predictions are indistinguishable at the 2σ level and both are consistent with observations. A promising discriminant between cosmological models is the misalignment angle between v_R and the apex of the dipole anisotropy of the microwave background.

Subject headings: cosmic background radiation — cosmology — dark matter — infrared: sources

All-sky (3D) galaxy surveys

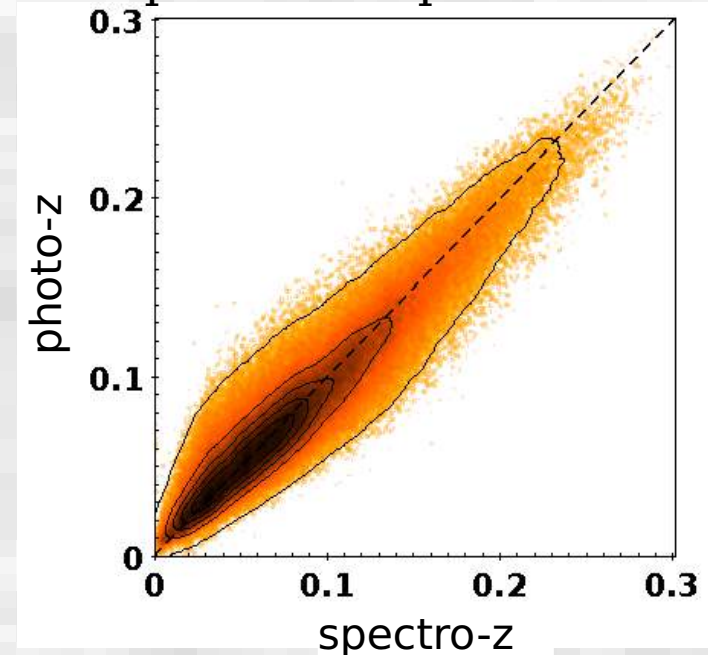
Current status

- The Two Micron All Sky Survey Extended Source Catalog (**2MASS XSC**, Jarrett et al. 2000): *1.6 million galaxies*, complete up to $z \sim 0.1$, photometric
- 2MASS Redshift Survey of *44,000 galaxies* (**2MRS**, Huchra et al. 2012): **complete all-sky redshift coverage**, but only up to $\langle z \rangle = 0.03$
- Going deeper with 2MASS spectroscopic redshifts: the **2M++ compilation** by Lavaux & Hudson, 70,000 2MASS galaxies
- Wide-field Infrared Survey Explorer (**WISE**) **much deeper than 2MASS** – but only photometric, and no source type identification
- In particular, a '**WISE XSC**' is still to be made (Jarrett, Magoulas, Cluver et al.)
- All-sky photographic data, digitized and calibrated: **SuperCOSMOS** optical catalogues – released in 2000s; extended sources identified (Hambly et al. 2001; Peacock et al. 2015 in prep.)



2MASS Photometric Redshift catalogue (2MPZ)

- We cross-matched **2MASS XSC** (near-IR, J H K_s) with all-sky **WISE** (mid-IR, 3.4μm and 4.6μm) and **SuperCOSMOS** (optical, B R I)
- We calculated **photometric redshifts** with the ANNz algorithm (Collister & Lahav 2004), trained on a representative spectroscopic subsample
- **2MPZ catalogue** with **1 million galaxies**, **$\langle z \rangle = 0.08$** , covering **most of the sky**
- Some statistics of the photo-z estimates:
 - 1-sigma scatter $\sigma_{\Delta z} = 0.015$
 - median error $|\Delta z|/z = 13\%$
 - only **3% of outliers** $> 3\sigma_{\delta z}$
- 2MPZ is **available for download** from the Wide Field Astronomy Unit at the Institute for Astronomy, Edinburgh:
<http://surveys.roe.ac.uk/ssa/TWOMPZ>

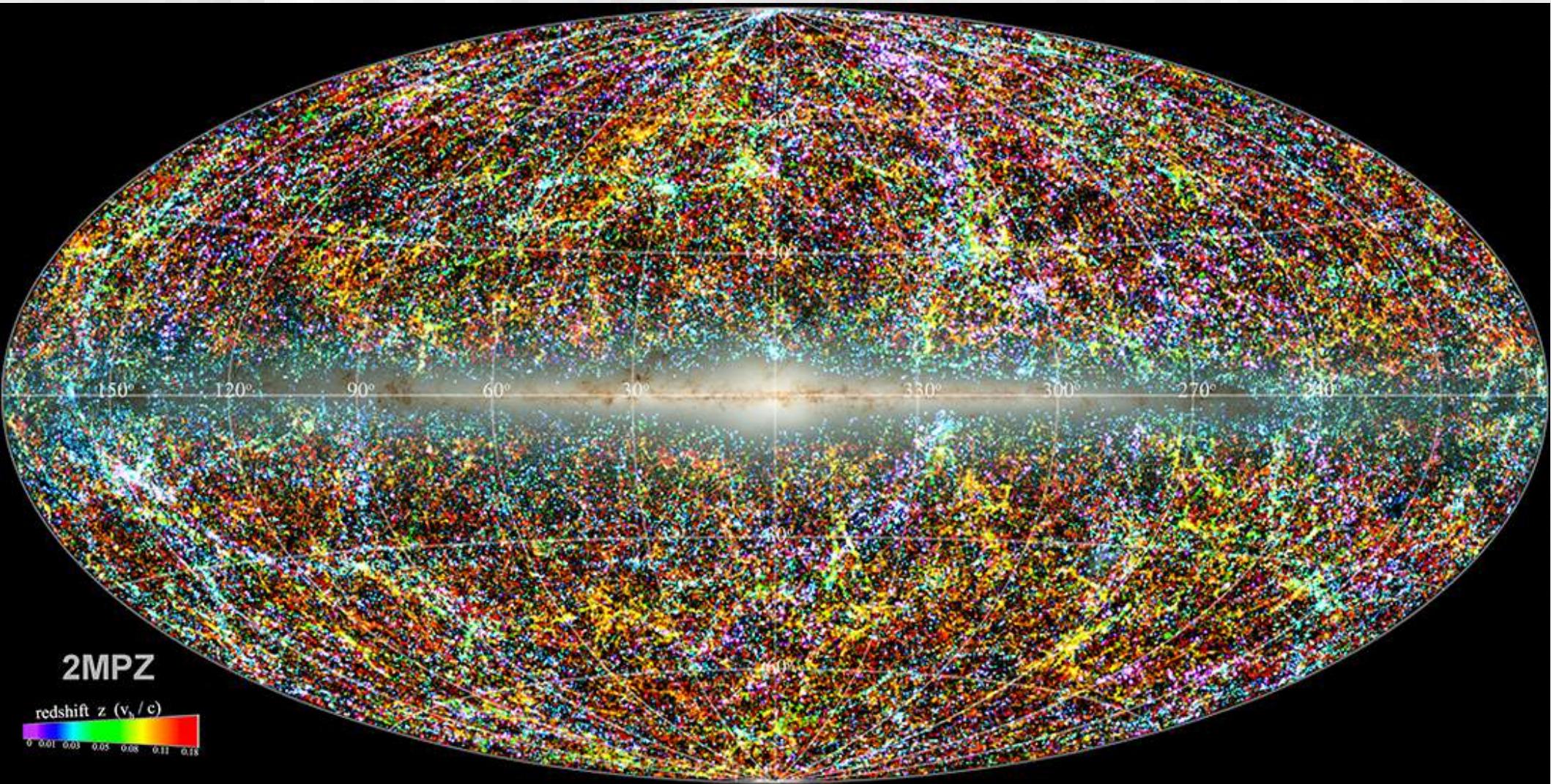


MB, Jarrett, Peacock, Cluver & Steward, 2014, ApJS, arXiv:1311.5246

2MASS Photometric Redshift catalogue

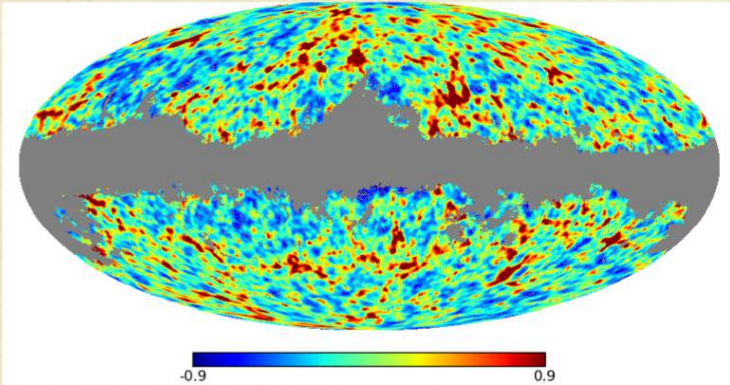
1 million galaxies in 3D

Colour-coded by photometric redshifts

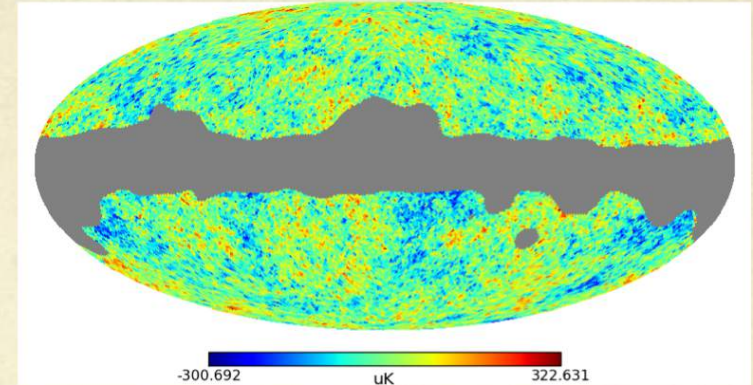
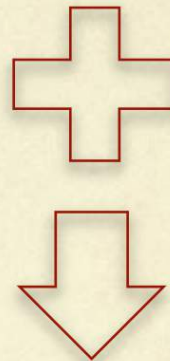


Plot by Tom Jarrett

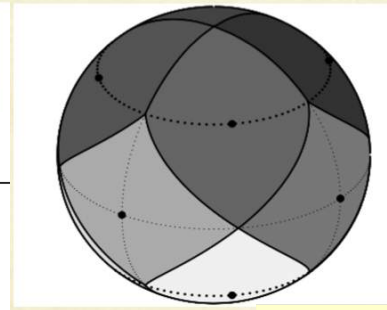
Cosmological tests with 2MPZ: integrated Sachs-Wolfe effect from 2MPZ x Planck effort led by Louise Steward (UCT)



2MPZ galaxy distribution
in redshift shells

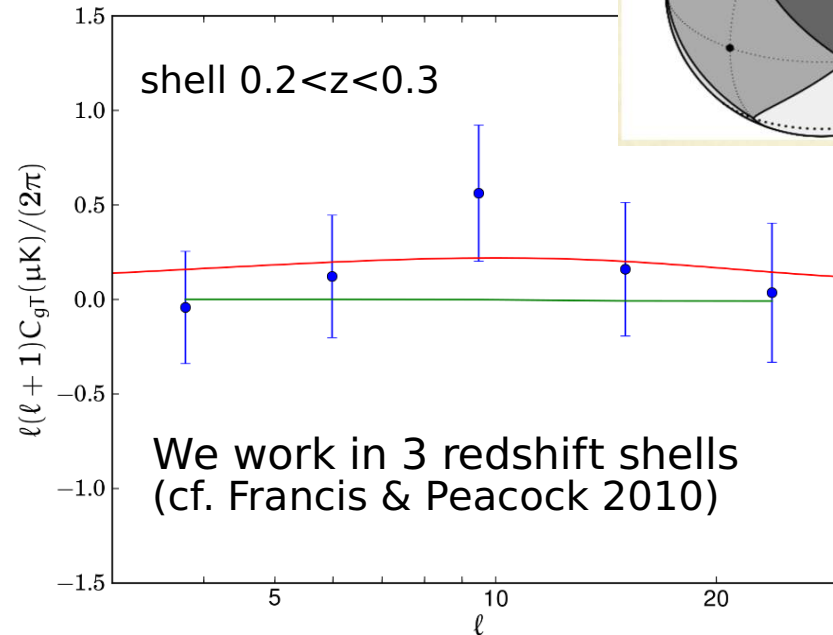


Planck temperature map



**ISW signal and
its significance**

Cross-correlation



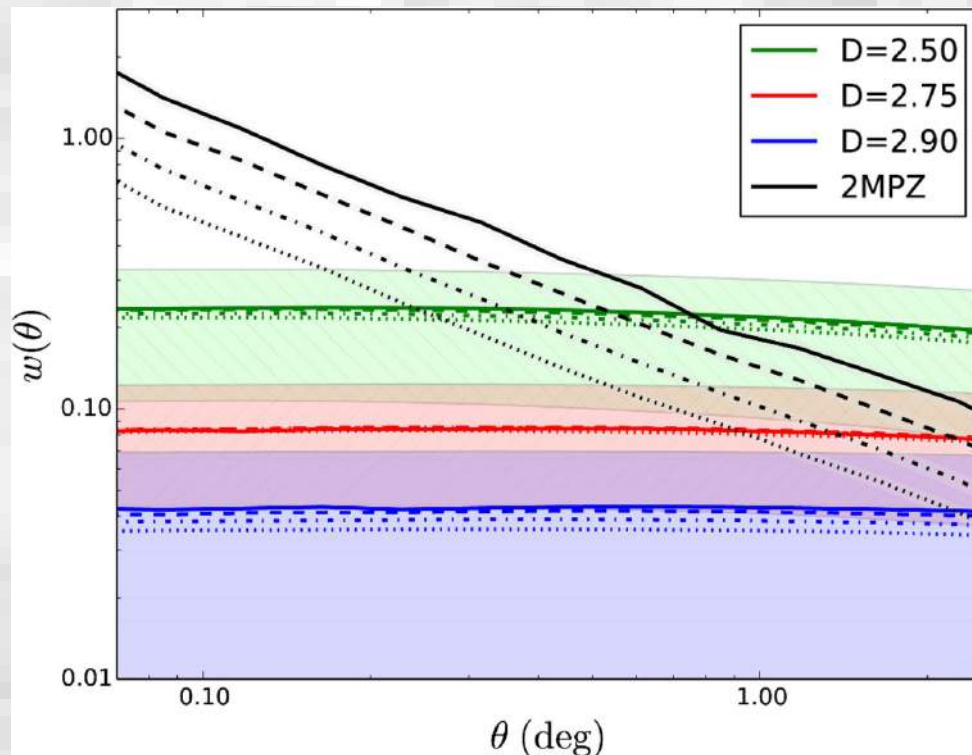
- **Not much of any ISW detection:**
less than 1σ , odds $< 1.5 : 1$ over no ISW
(cf. odds $1.5 : 1$ in Francis & Peacock '10)
- **2MASS is too shallow** for ISW,
need to probe deeper (WISE...)

Steward, MB, Jarrett et al. in prep.

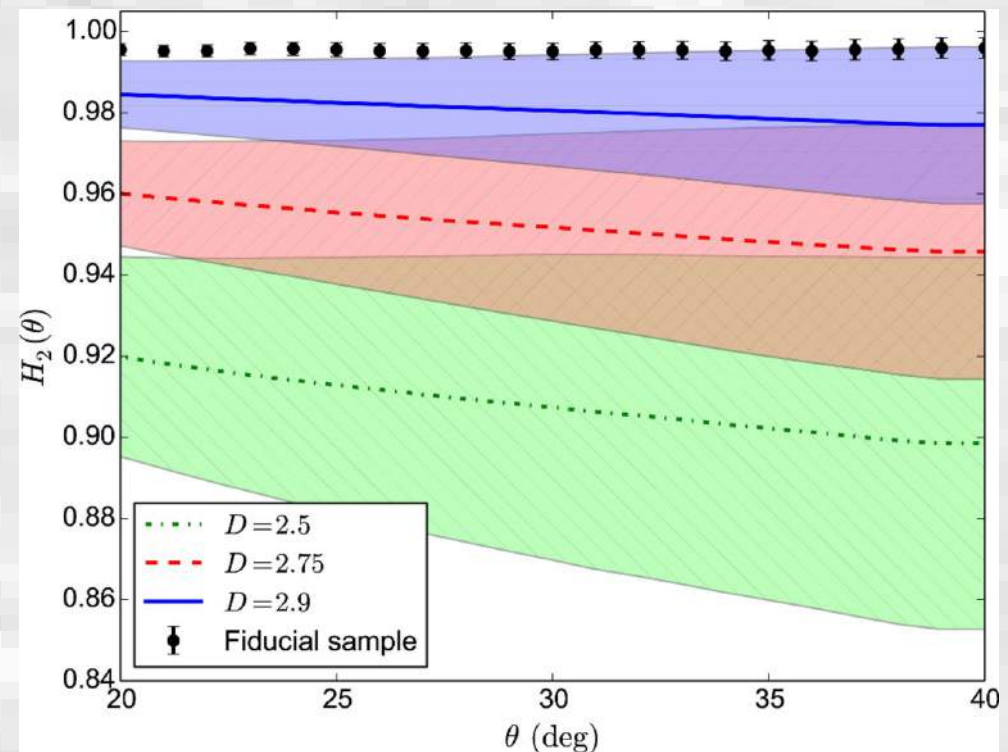
$$C_{gT} =$$

Cosmological tests with 2MPZ: looking for fractal signatures in galaxy distribution

- Statistical tests based on angular auto-correlations to look for fractal signatures
- 2MASS galaxy distribution within $z < 0.3$ **inconsistent with fractal models**



Angular correlation function



Homogeneity index
(=1 for ideally homogeneous distribution)

Alonso, ..., MB, et al., 2015, MNRAS, arXiv:1412.5151

More cosmological applications of the 2MASS Photo-Z catalogue

Published:

- **Testing Isotropy in the Local Universe** with luminosity function variations; no significant anisotropy detected (Appleby & Shafieloo 2014)
- **Identifying galaxy clusters** by combining spectroscopic and photometric redshifts (Xu, Wen & Han 2014)
- **Reconstruction of the gravitational potential** in the context of Planck ISW analysis (Planck 2015 results XXI)

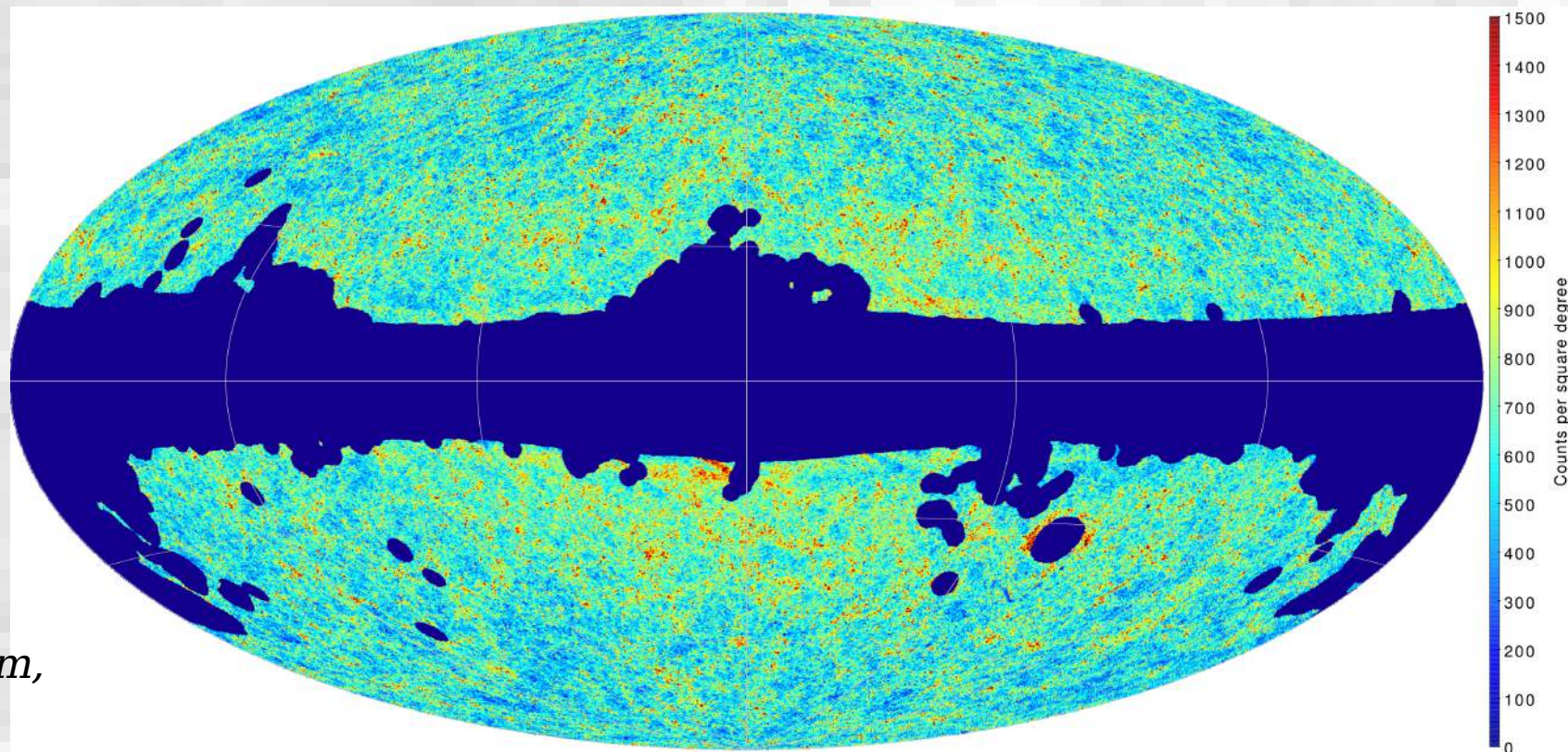
In preparation or planned:

- **Cosmology with galaxy angular correlations in redshift shells** as a test-bed for future samples like Euclid (A Balaguera-Antolinez, MB, E Branchini, et al.)
- **Acceleration of the Local Group:** sources of the pull, **convergence?** (revisiting Erdogan et al. 2006 & MB et al. 2011 – M Krupa, MB, A Pollo) cf. Juszkiewicz et al. 1990...
- **Bulk flow** from luminosity function fluctuations (M Feix, MB, A Nusser)



Going deeper over 75% of sky: 20 million galaxies from WISE x SuperCOSMOS

- **All-sky galaxy sample much deeper than 2MASS:**
Mid-IR **WISE** paired up with optical **SuperCOSMOS** data, $\langle z \rangle \sim 0.2$
- Cross-match at $|b| > 10^\circ$ gives **170 million sources**, but mostly stars (blends)
- A colour-based **clean-up** of star blends leaves almost **20 million galaxies**
- Work in progress on automatic selection of galaxies (Krakowski, Małek, MB)



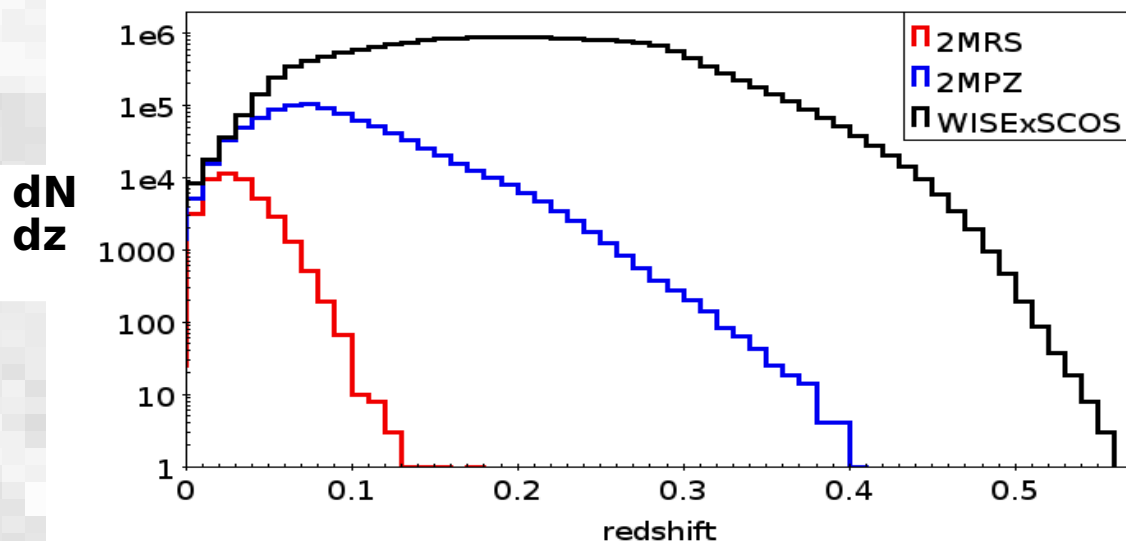
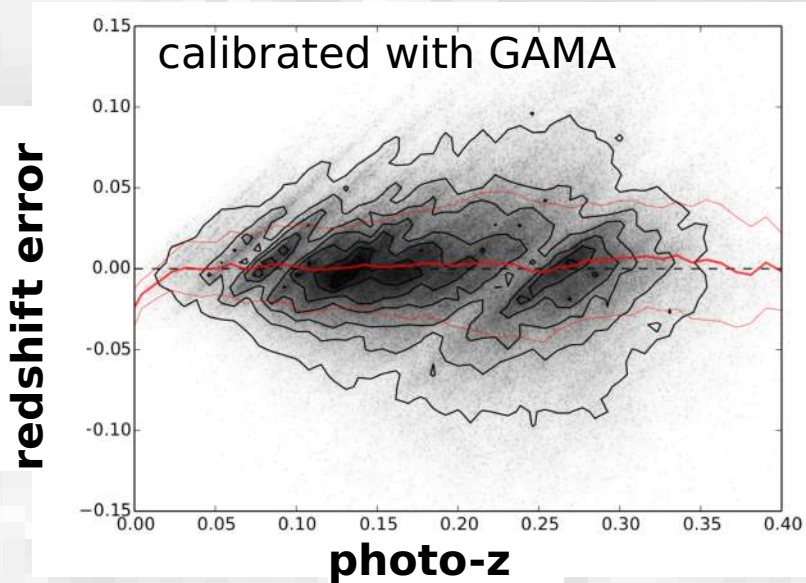
*MB, Peacock,
Jarrett, Cluver
& the GAMA team,
in prep.*



The largest all-sky 3D sample

20 million galaxies from WISE x SuperCOSMOS

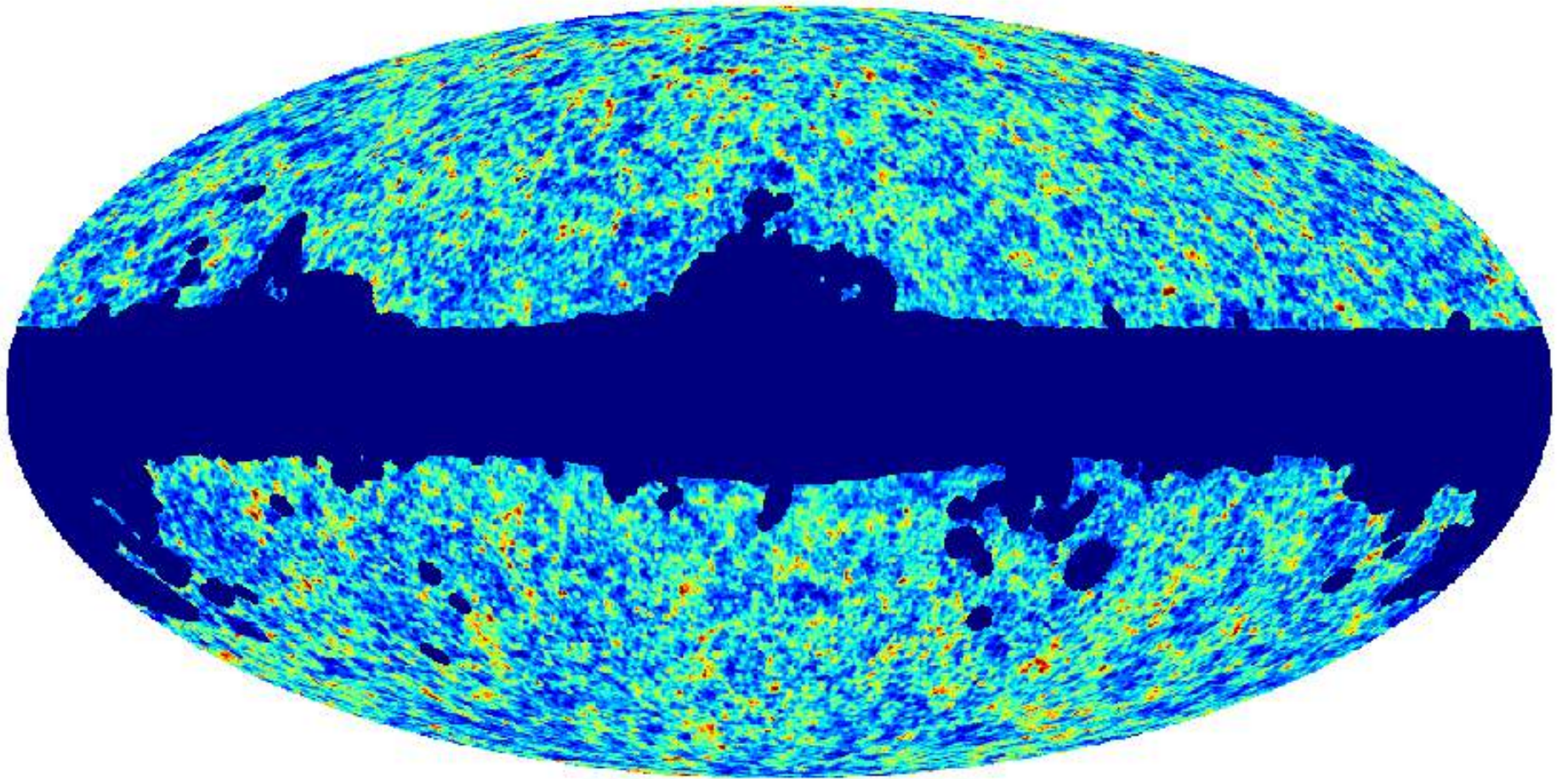
- **WISE x SuperCOSMOS photo-z catalogue:** much deeper than 2MPZ
- **Four photometric bands** for photo-z's: optical **B,R**, infrared **W1,W2**
- Training set: **GAMA-II** most recent data ($r < 19.8$ in 3 equatorial patches)
- Median redshift **$z \sim 0.2$** , but probes the LSS to **$z \sim 0.4$**
- Photo-z performance: $\sigma_{\Delta z} = 0.03$, median **error 14%** and **3% outliers**



MB, Peacock, Jarrett & GAMA, to be submitted

The cosmic web ~3 Gyr ago as seen by WISE & SuperCOSMOS

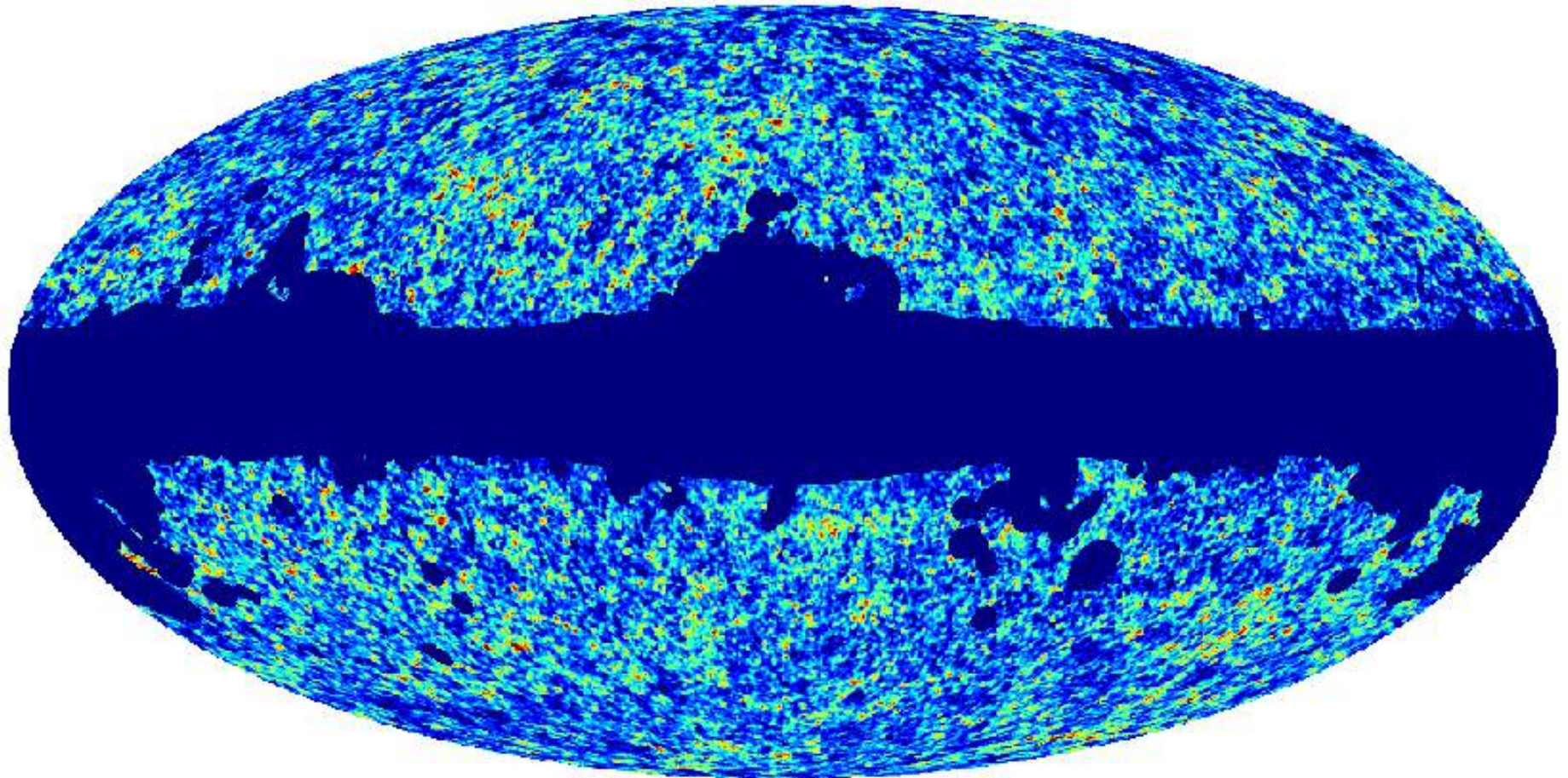
$0.2 < z < 0.3$



*MB, Peacock, Jarrett
& GAMA, in prep.*

The cosmic web ~4 Gyr ago as seen by WISE & SuperCOSMOS

$0.3 < z < 0.4$



*MB, Peacock, Jarrett
& GAMA, in prep.*

Cosmological applications of the WISE x SuperCOSMOS photo-z catalogue

Ongoing:

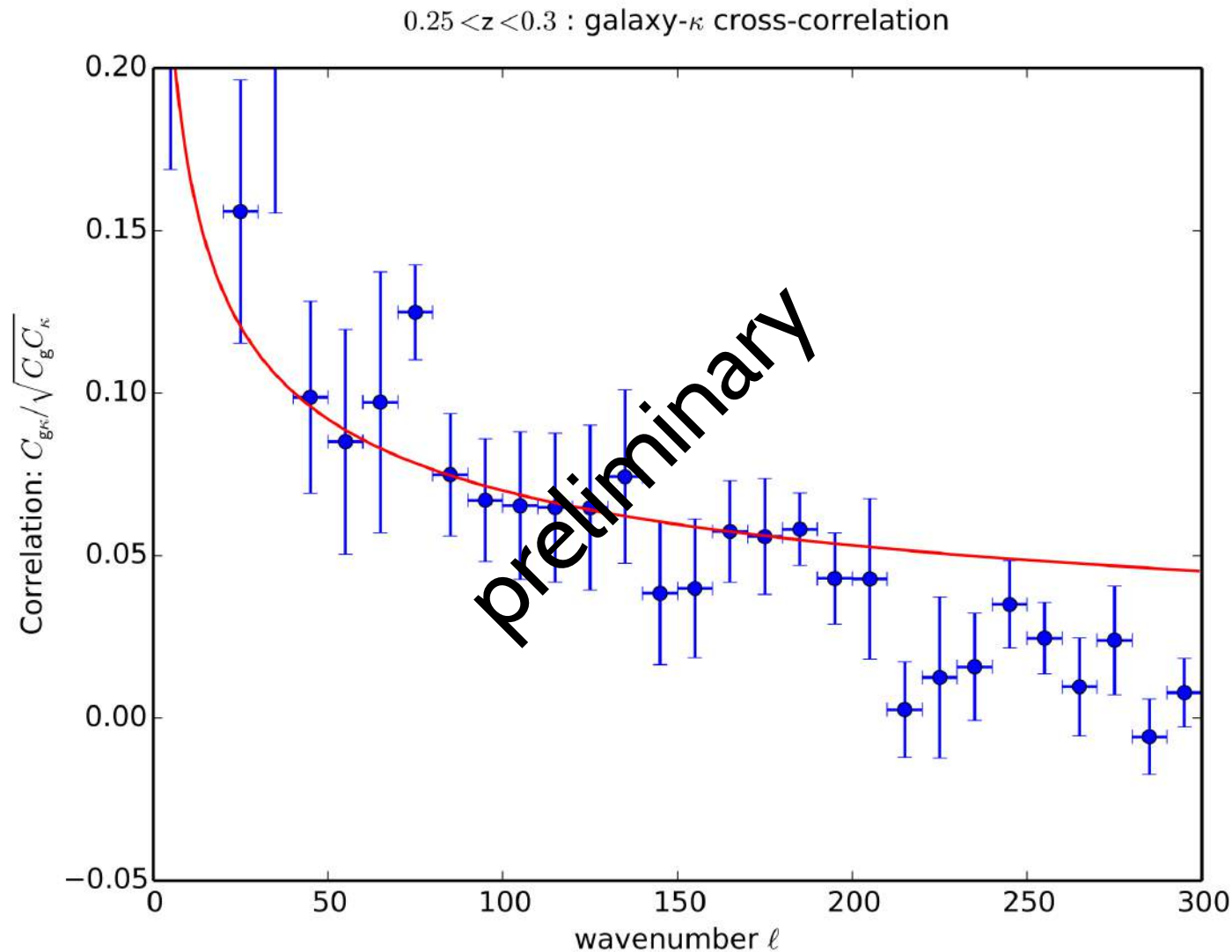
- Bright end of the sample is one of the **input catalogues** for a forthcoming hemispherical spectroscopic survey **TAIPAN** (Aussies + Jarrett, Magoulas, MB)
- **Cross-correlation with CMB lensing** for constraints on the growth of structure (Peacock & Bilicki in prep.)
- **Cross-correlation with Fermi** data for constraints on dark matter (A Cuoco, MB, E Branchini, al.)
- **Testing global isotropy** through dipolar modulations in number counts (M Yoon)
 - cf. Gibelyou & Huterer 2012; Yoon et al. 2015

Planned / ideas...

- **Similar as for 2MPZ but on 3x larger scales** (modulo smaller sky coverage and more severe systematics), e.g.:
 - **Integrated Sachs-Wolfe** effect with a hope for a decent S/N
 - **Large-scale flows** (bulk flow, pull on the Local Group)

Cosmological applications of the WISE x SuperCOSMOS photo-z catalogue

- **Cross-correlation with CMB lensing** for constraints on the growth of structure

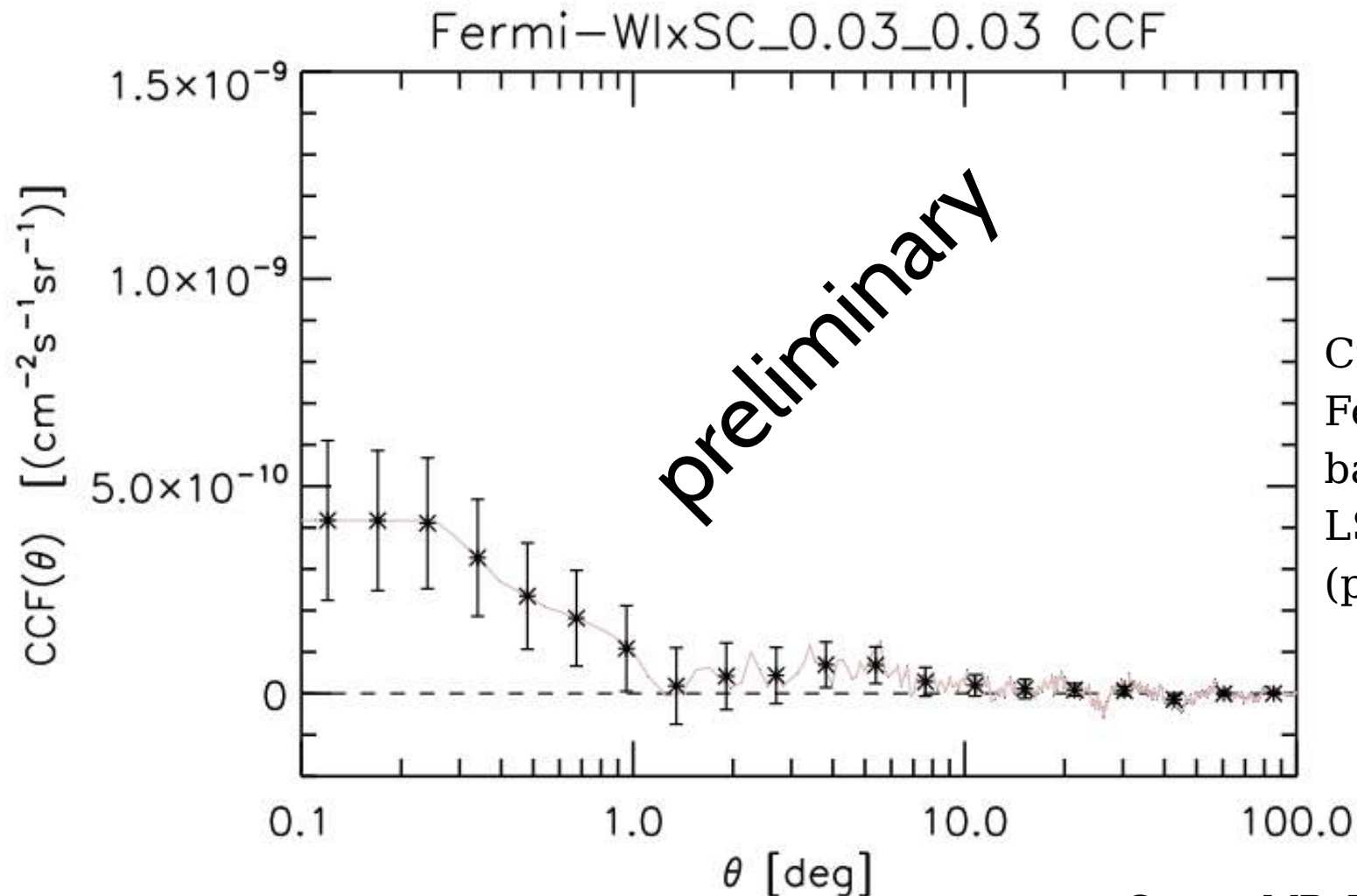


Cross-correlation of
Planck CMB
lensing convergence
with LSS in $0.25 < z < 0.30$
(plot from J Peacock)

Peacock & MB in prep.

Cosmological applications of the WISE x SuperCOSMOS photo-z catalogue

- **Cross-correlation with Fermi** data for constraints on dark matter (A Cuoco et al.)



Cross-correlation of
Fermi gamma-ray
background with
LSS in $0.20 < z < 0.30$
(plot from A Cuoco)

Cuoco, MB, Branchini et al. in prep.

All-sky probes:



- **Wide-field Infrared Survey Explorer (WISE)** satellite data:
all-sky photometric catalogue in 3.4, 4.6, 12 and 23 μm
- **One of the largest all-sky samples:** over **700 million** sources
- **WISE** itself is **much deeper** than 2MASS (by ~ 3 mag) as well as than SuperCOSMOS: another “layer” for cosmology (L^* galaxies at $z \sim 0.5$)
- Full **cosmological potential** still to be explored:
WISE data dominated by stars even at high latitudes
- **Ongoing work:** automatic **star-galaxy-QSO separation** in WISE
(MB & Polish WISE team: Kurcz et al. in prep.) – **poster by M Krupa**

All-sky probes:



...especially once combined with other datasets

- Forthcoming wide-angle catalogues, e.g.:
Pan-STARRS (optical, 3π)
Vista Hemisphere Survey (near-IR, 2π)
Dark Energy Survey (optical, 5000 deg^2)
Kilo Degree Survey (optical, 1500 deg^2) [Leiden]
→ photo-z's, tomographic analyses, ...
- Getting prepared for future very big data: **SKA**, **Euclid**, **LSST**, ...
- Euclid & LSST will be mostly *photometric* redshift probes
- SKA will need source identification and optical/IR counterparts



Summary

- All-sky galaxy surveys essential to comprehensively map the cosmic web
- Many key cosmological applications require very wide angle coverage in 3D
- We now have access to the largest volumes on $>3\pi$ steradians of the sky
- Third dimension at these scales possible (only) with photometric redshifts
- New galaxy catalogues (2MPZ, WISE x SuperCOSMOS) now probe up to $z \sim 0.4$