



Mapping the Cosmic Web with the largest all-sky surveys

Maciej Bilicki

SARChI Postdoctoral Fellow

Astrophysics, Cosmology and Gravity Centre

Department of Astronomy, University of Cape Town

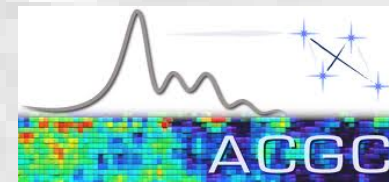
maciek@ast.uct.ac.za

Main collaborators:

Tom Jarrett (UCT), John Peacock (IfA Edinburgh),

Michelle Cluver (UCT), Louise Steward (UCT) et al.

*IAU Symposium 308: The Zeldovich Universe
Genesis and Growth of the Cosmic Web
24 June 2014*



The need for all-sky surveys 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 verified *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

State of the art in all-sky (3D) galaxy surveys

(until very recently)

- The **largest all-sky catalogue of extended sources** (i.e., galaxies): the Two Micron All Sky Survey (**2MASS XSC**, Jarrett et al. 2000) *1 million galaxies*, complete up to $K_s = 13.9$ mag ($z \sim 0.1$)



- 2MASS Redshift Survey of *44,000 galaxies* (**2MRS**, Huchra et al. 2012): **complete all-sky redshift coverage**, but only up to $\langle z \rangle = 0.03$

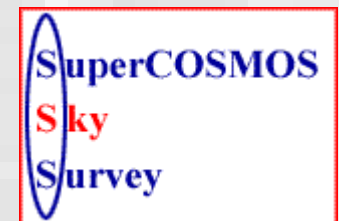
- Going deeper with 2MASS spectroscopic redshifts: the **2M++ compilation** by Lavaux & Hudson, 70,000 2MASS galaxies

- New data from the Wide-field Infrared Survey Explorer (**WISE**) probe much deeper than 2MASS – but only *photometrically...*



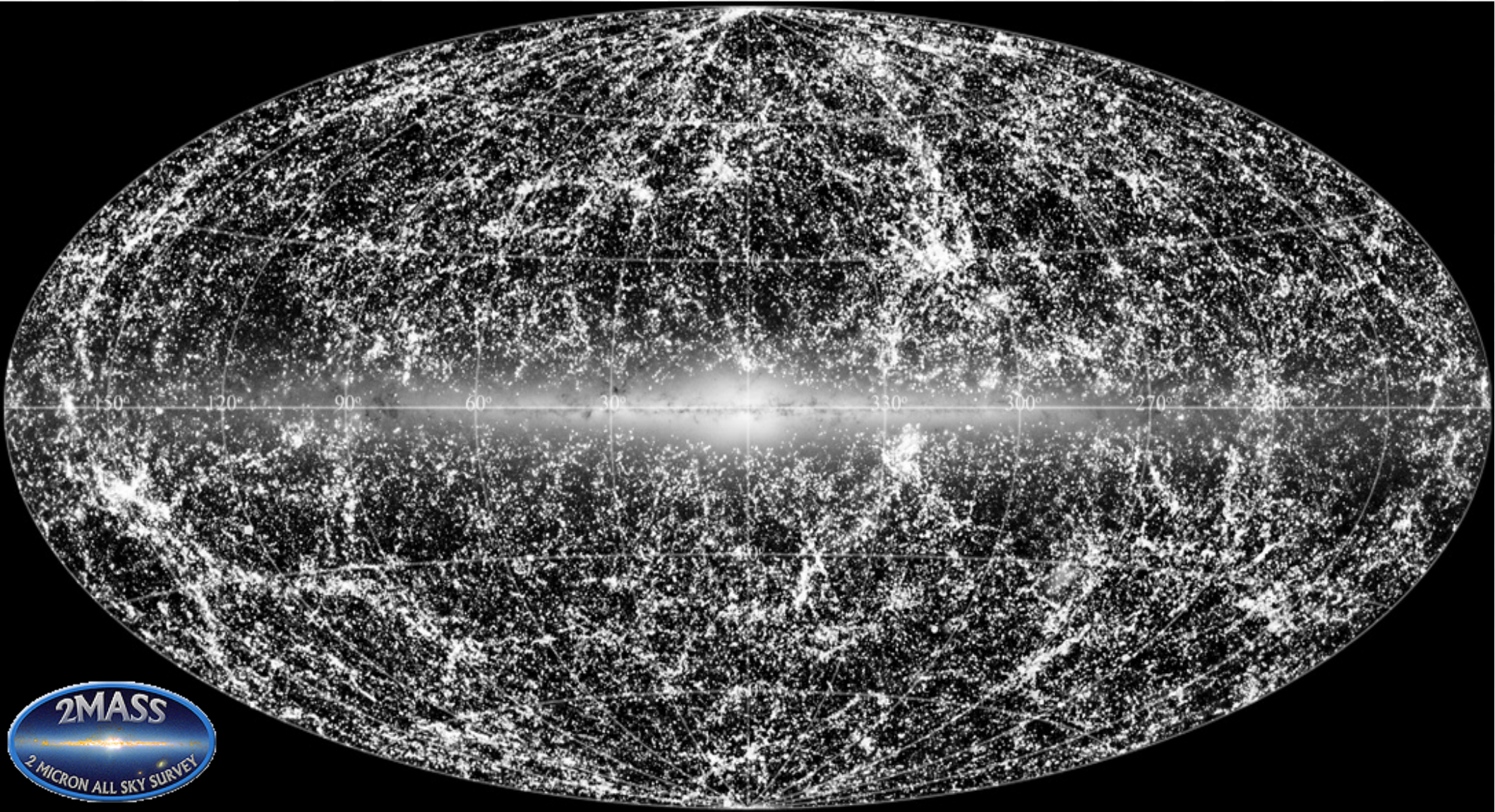
- In addition, a '**WISE XSC**' is still to be made (Jarrett, Magoulas, Cluver et al.)

- Plus: all-sky photographic data, digitized and calibrated (**SuperCOSMOS catalogues**)



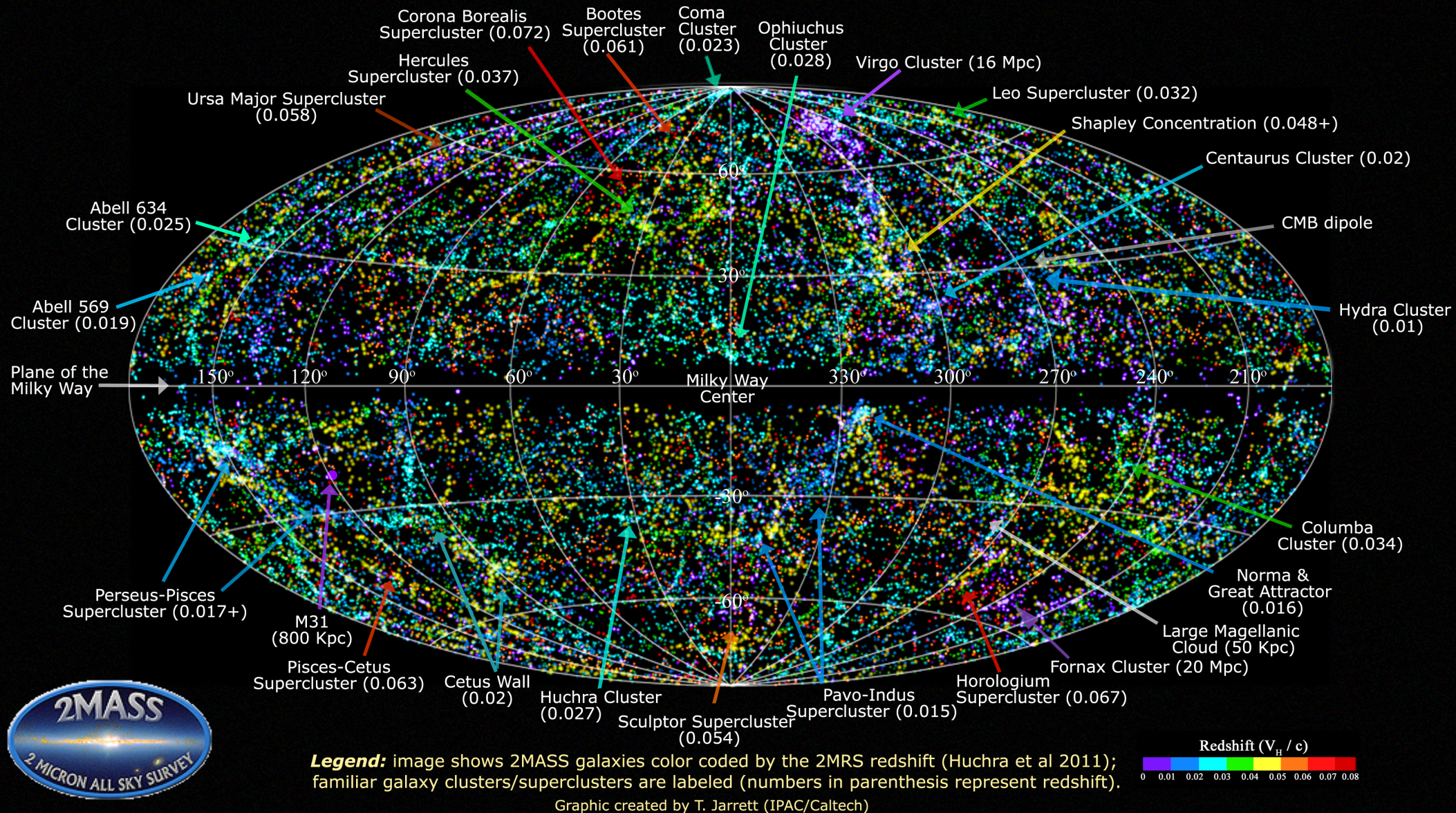
The largest all-sky catalogues of extended sources

Photometric: 2MASS XSC of 1 million galaxies

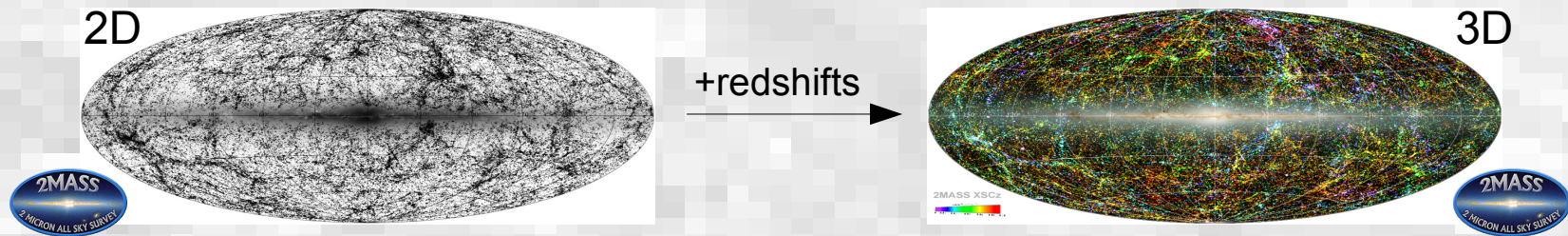


The largest all-sky catalogues of extended sources

Spectroscopic: 2MASS Redshift Survey of 44,000 galaxies



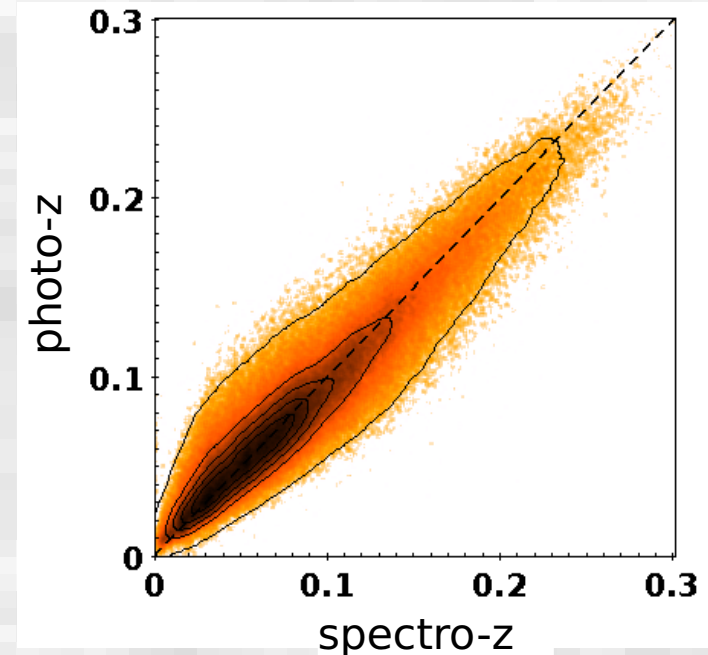
Towards larger all-sky 3D catalogues



- We added the *third dimension* to the 2MASS XSC sample
- **One third** of all 2MASS galaxies have **redshifts** from large spec-z surveys: **2dFGRS, 6dFGS** or **SDSS**
- **Not much hope** for supplementing the remaining 2/3 with **spec-z soon**
- More economic approach: **estimate redshifts** based on other information –
– such as fluxes, i.e. photometry
- Widely used technique of **photometric redshifts**

2MASS Photometric Redshift catalogue (2MPZ)

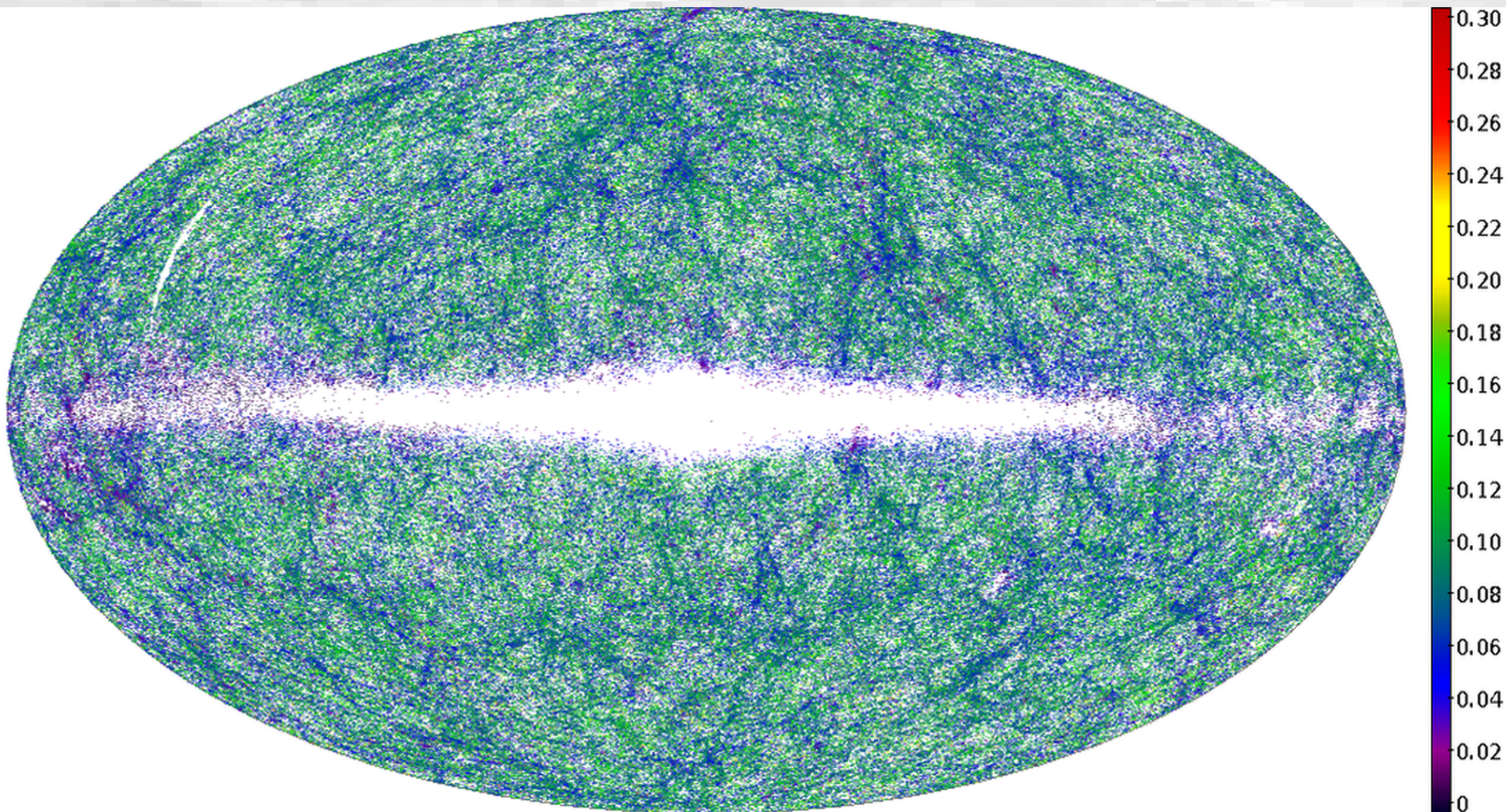
- We cross-matched **2MASS XSC** (near-IR, J H K_s) with all-sky **WISE** (mid-IR, 3.4μm and 4.6μm) and **SuperCOSMOS** (optical, B R I)
- We applied the **ANNz** (*Artificial Neural Networks*, Collister & Lahav 2004), trained on a representative spectroscopic subsample of 350,000 galaxies
- **2MPZ catalogue** 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>



2MASS Photometric Redshift catalogue

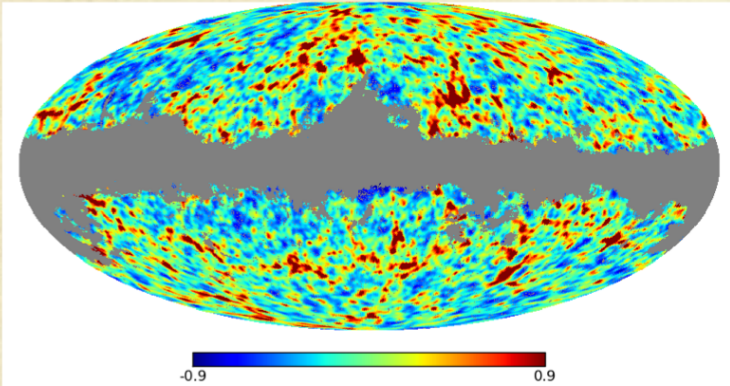
1 million galaxies in 3D

Colour-coded by photometric redshifts

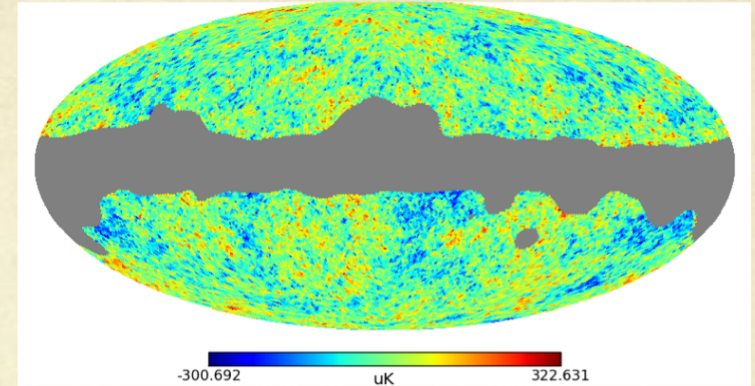


Galactic coordinates

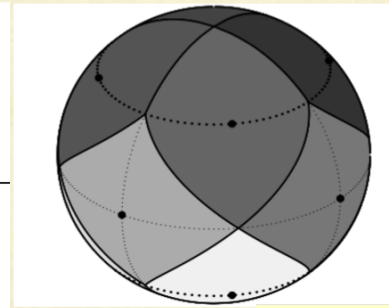
First cosmological results from 2MPZ: integrated Sachs-Wolfe effect from 2MPZ x Planck effort led by Louise Steward (UCT)



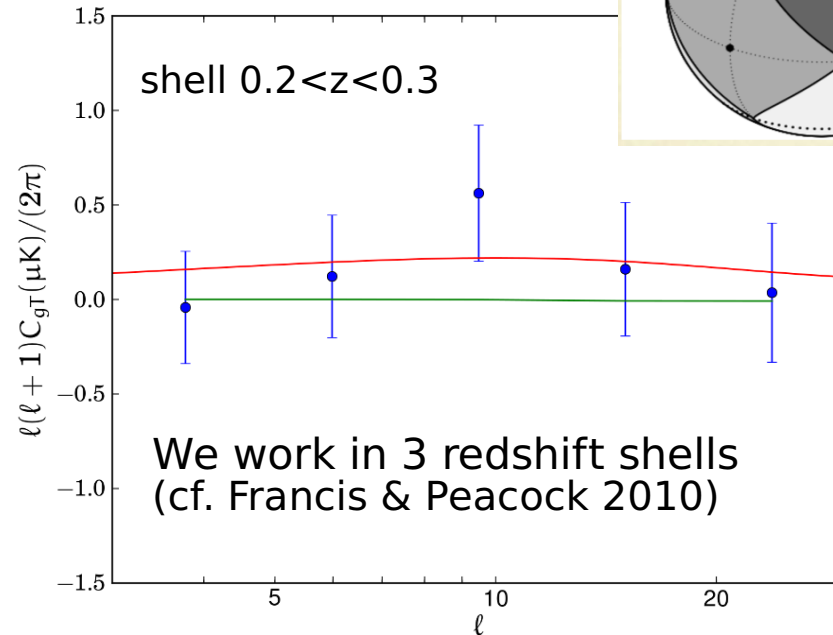
2MPZ galaxy distribution



Planck temperature map



Cross-correlation



ISW signal and its significance

- We see **mild preference for ISW**: less than 2σ , odds $3.4 : 1$ over no ISW (cf. odds $1.5 : 1$ in Francis & Peacock '10)
- Good **photo-z's help**, but **2MASS** is **too shallow** even if it was fully spectroscopic

Steward, MB, Peacock, Jarrett, in prep.

$$C_{gT} =$$

More cosmological applications of the 2MASS Photo-Z catalogue

Found on arXiv:

- **Testing Isotropy in the Local Universe** (Appleby & Shafieloo, arXiv:1405.4595)
- **Identifying galaxy clusters** (Xu, Wen & Han, arXiv:1406.0943)

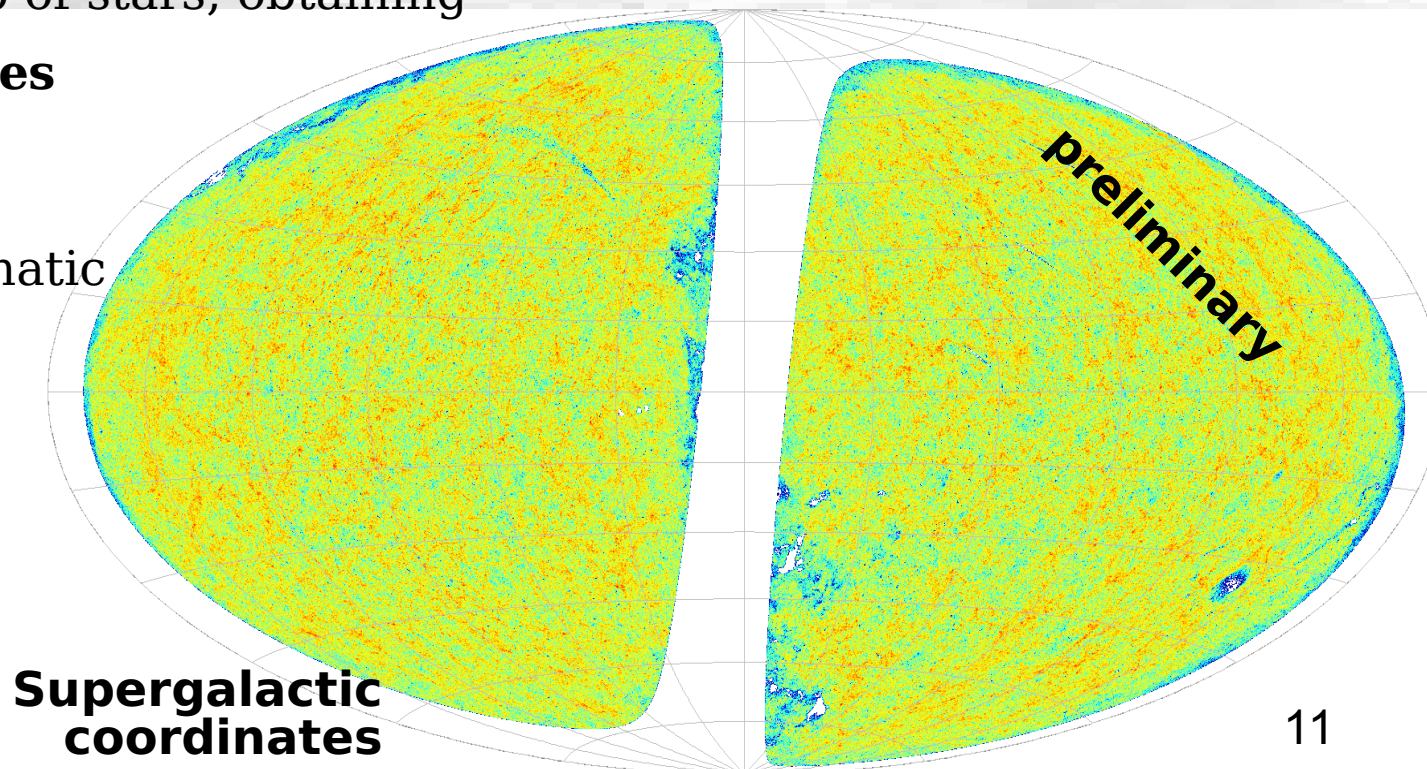
In preparation:

- **Near-infrared luminosity function** at $z \sim 0$ (cf. Branchini et al. 2012) from the largest sample to date and **bulk flow** in a sphere of $r \sim 300$ Mpc/h from LF variations (cf. Nusser et al. 2011) – led by **Martin Feix** (see also Feix et al. 2014)
- **Looking for the transition to homogeneity** (cf. Alonso et al. 2014) – led by **David Alonso**
- **Acceleration of the Local Group:** sources of the pull, **convergence?** (revisiting Bilicki et al. 2011; see Nusser et al. 2014)
- **Hopefully many more...**

The largest all-sky galaxy sample

20 million galaxies from WISE x SuperCOSMOS

- **All-sky galaxy sample much deeper than 2MASS:**
IR **WISE** paired up with optical **SuperCOSMOS** data,
flux-limited to **$R < 19.5$** (AB)
- Cross-match at $|b| > 10^\circ$ gives **170 million sources**, but mostly stars
- We made a first clean-up of stars, obtaining
some **20 million galaxies**
and **~2 million QSOs**
- To be refined with automatic
classification (via SVM:
Małek et al. in prep.)

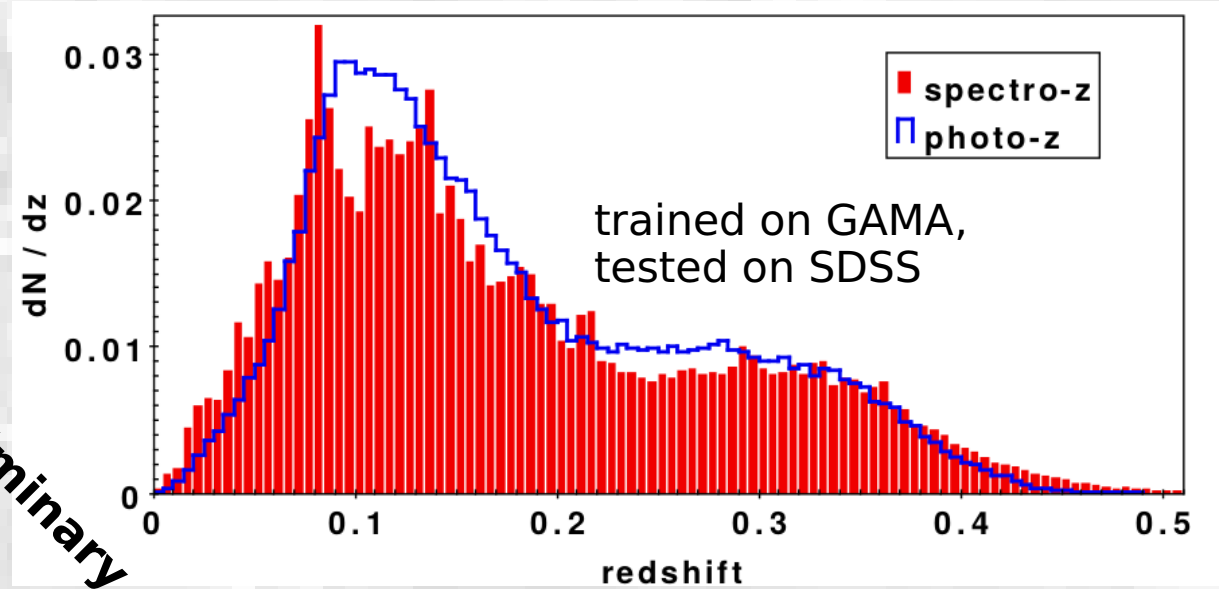
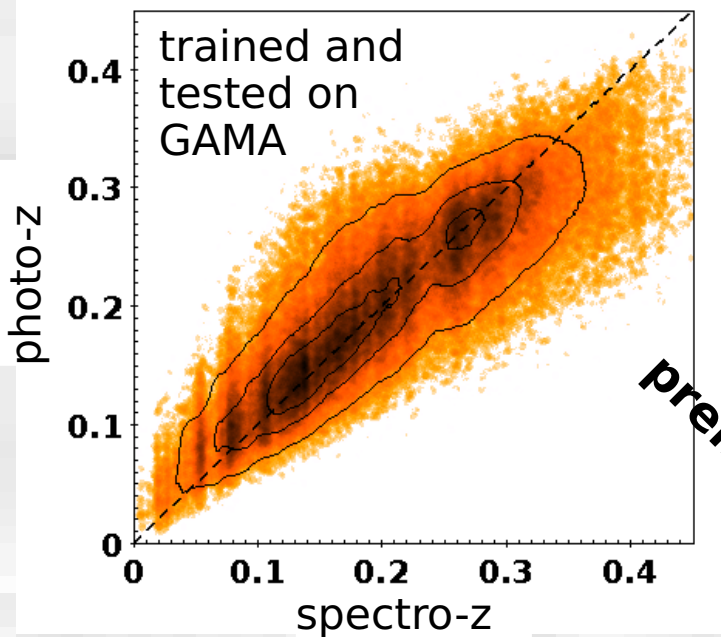




The largest all-sky 3D sample

20 million galaxies from WISE x SuperCOSMOS

- **WISE x SuperCOSMOS photo-z catalogue:** much deeper than 2MASS
- **Five photometric bands** for photo-z's: optical **B,R**, infrared **W1,W2,W3**
- Training sets: **GAMA** most recent data and **SDSS DR10**
- Median redshift **z~0.2**, but probes the LSS reliably **to z~0.35**
- Photo-z performance: $\sigma_{\Delta z} = 0.032$, median **error 12%** and **3% outliers**

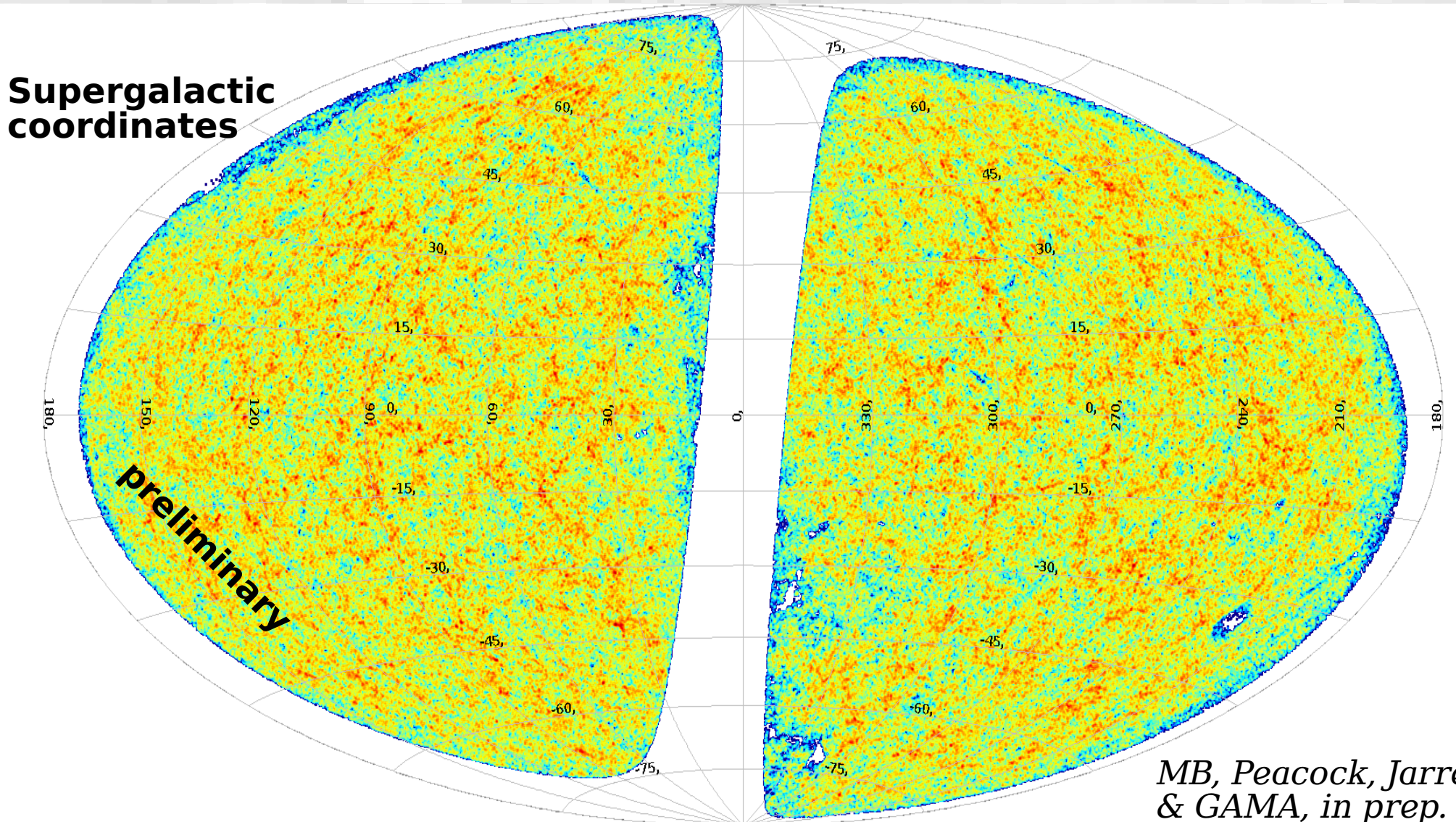


The cosmic web 2.5 Gyr ago

large-scale structure at redshift $z \sim 0.2$

shell of $0.19 < z_{\text{phot}} < 0.21$

1.7 million galaxies

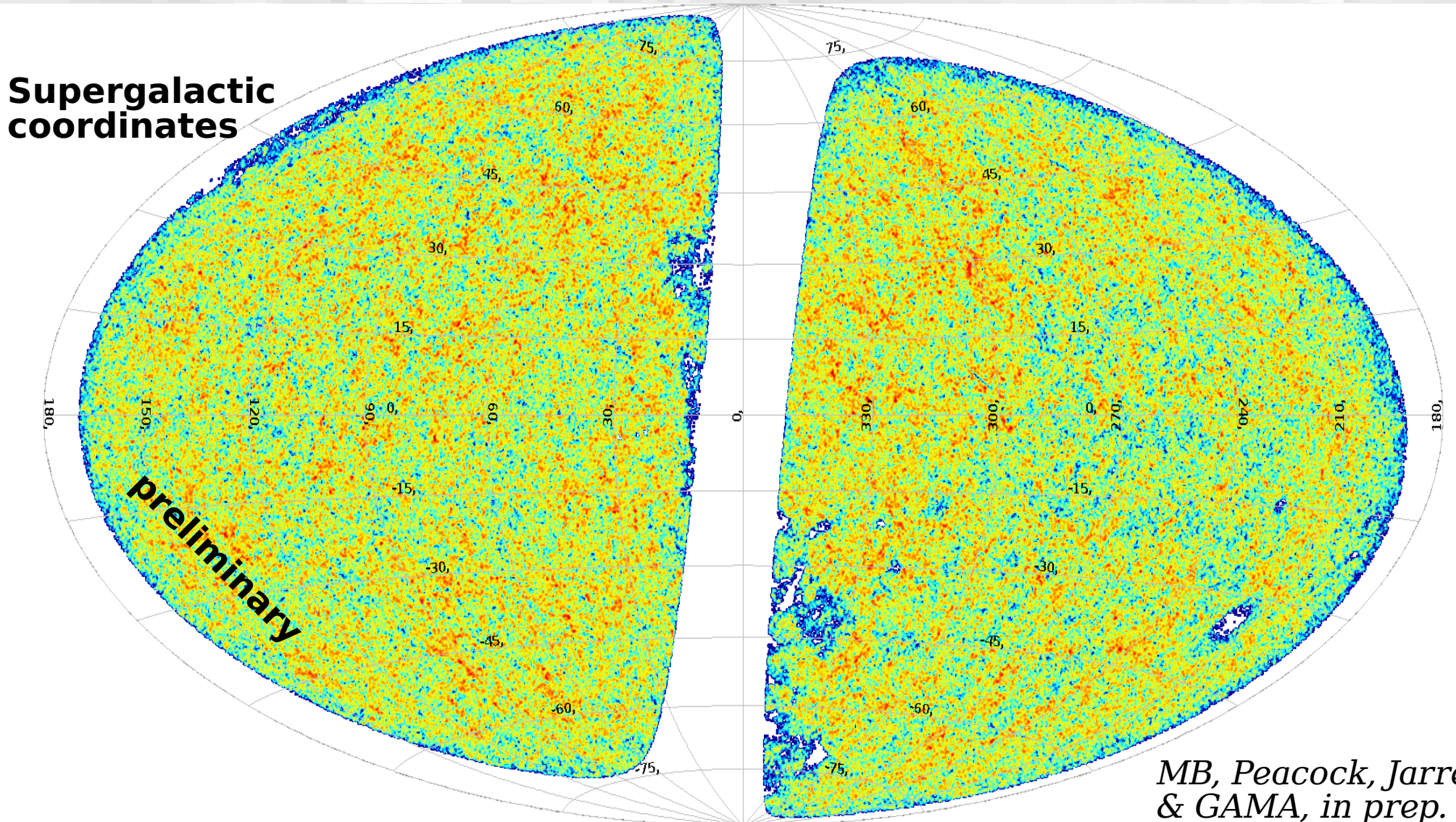


The cosmic web 3.5 Gyr ago

large-scale structure at redshift $z \sim 0.3$

shell of $0.29 < z_{\text{phot}} < 0.31$

1.2 million galaxies



Possible cosmological applications of the WISE x SuperCOSMOS photo-z catalogue

Similar as for the 2MPZ but on scales ~ 3 times larger:

- **Testing isotropy and homogeneity** of the Universe up to $z \sim 0.4$
- **Integrated Sachs-Wolfe** effect with a hope for a decent S/N
- **Largest-scale bulk flow** from the luminosity function
- **Pull on the Local Group** from scales > 1 Gpc?
- **Identifying galaxy clusters** for Sunyaev-Zeldovich
- ...

Not practicable so far with all-sky data (e.g. 2MPZ):

- **Cross-correlation with CMB lensing** to constrain e.g. non-Gaussianity
- **Angular BAO** – cf. DES science case (see Blake & Bridle 2005)
- **Certainly many more!**



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 catalogues (2MPZ, WISE x SuperCOSMOS) now probe up to $z=0.4$**
- **2MPZ publicly available, feel free to use for your applications!**

<http://surveys.roe.ac.uk/ssa/TWOMPZ>