Probing the large-scale structure with the largest photometric catalogs: today and tomorrow

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Main collaborators on these projects:
John Peacock (Edinburgh), **Tom Jarrett** (Cape Town), **Enzo Branchini** (Rome)
Plus those who led the applications: D. Alonso, A. Balaguera-Antolinez, A. Cuoco, B. Stölzner...

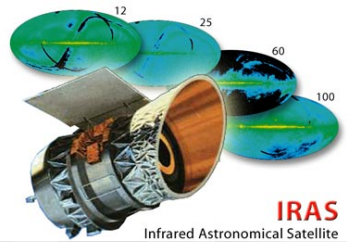
Statistical challenges for large-scale structure in the era of LSST, Oxford, 20 April 2018

The need for very wide-angle large-scale structure datasets at $z \gtrsim 0$

- There is cosmological information at **low redshifts**
  (effects of Λ, non-linear evolution, departures from general relativity, …)
- There is cosmological information at the **largest angular scales**
  (relativistic effects, primordial non-Gaussianity, …)
- Low redshift is **small volume**:
  need to **maximise sky coverage and number density of tracers**
- Tracing the largest scales requires **very wide-angle galaxy datasets**
- **Ideal situation**: all-sky* complete galaxy catalogue(s) **from z=0 up to "a lot"**
- **Redshifts essential** to trace evolution, do tomography, identify cosmic web, …
- Very **challenging for spectroscopy:**
  trade-offs between sky coverage, depth, and completeness – **sparse sampling**

**meaning all available extragalactic sky; realistically: ~3π sterad*

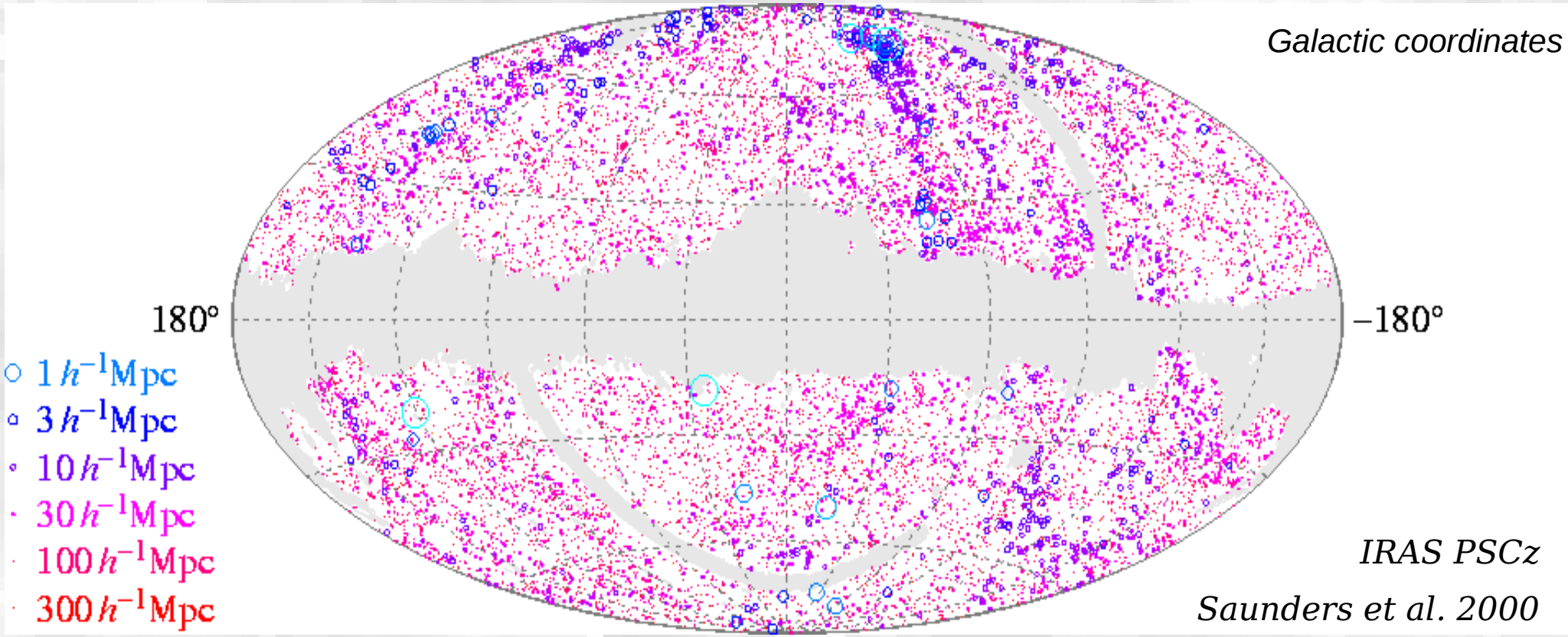
The first all-sky spectroscopic redshift survey: IRAS PSCz



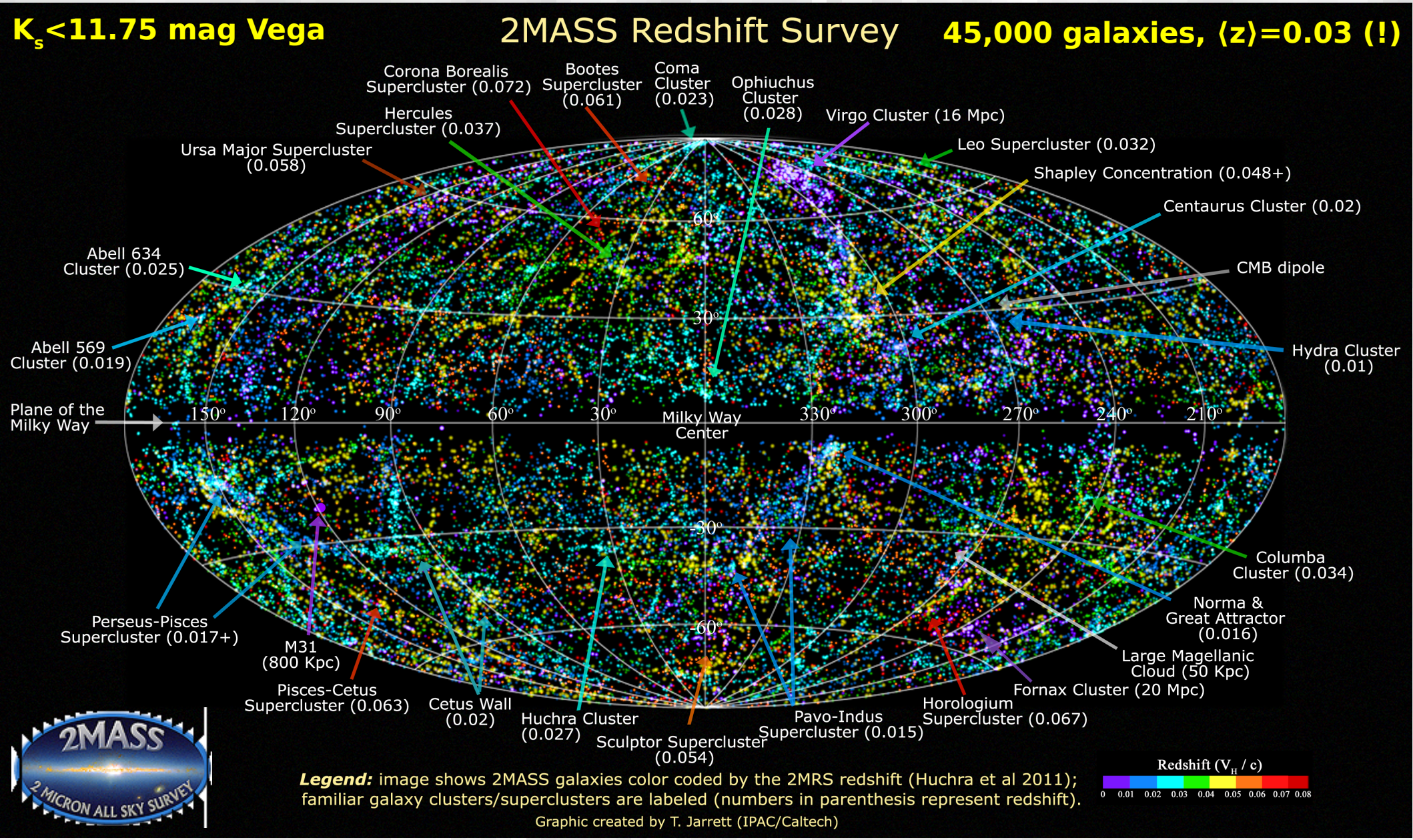
Galaxies preselected from **IRAS** far-IR observations

About 15,000 redshifts measured or extracted from external surveys (all ground-based): **PSCz survey**

First 3-dimensional map of (almost) the entire extragalactic sky



Today's largest uniform all-sky spectroscopic redshift sample: 2MRS



Huchra et al. 2012 (plot by Tom Jarrett)

All-sky redshifts: present and future

- **No ongoing all-sky spectroscopic campaign** to go deeper than PSCz and 2MRS
- **2M++** by Lavaux & Hudson (2011) partly fills the gap, but is non-uniform
- **Hope for a z~0.1 all-sky spec-z dataset** from **Taipan** in the South (da Cunha et al. 2017) joined with **SDSS + LoRCA** in the North (Comparat et al. 2016)
- **Taipan to start this year; LoRCA – ?**
- Nothing starting for complete all-sky higher-redshift spectroscopic samples (although **(e)BOSS+DESI+4MOST** give hope for sparsely-sampled ~3π coverage)
- Promise for all-sky low-resolution redshift sample from **SPHEREx** (Dore et al. 2014)
- **Currently all-sky 3D information possible only by joining existing photometric samples and estimating photometric redshifts**

2MASS

First survey of the entire sky at near-IR wavelengths

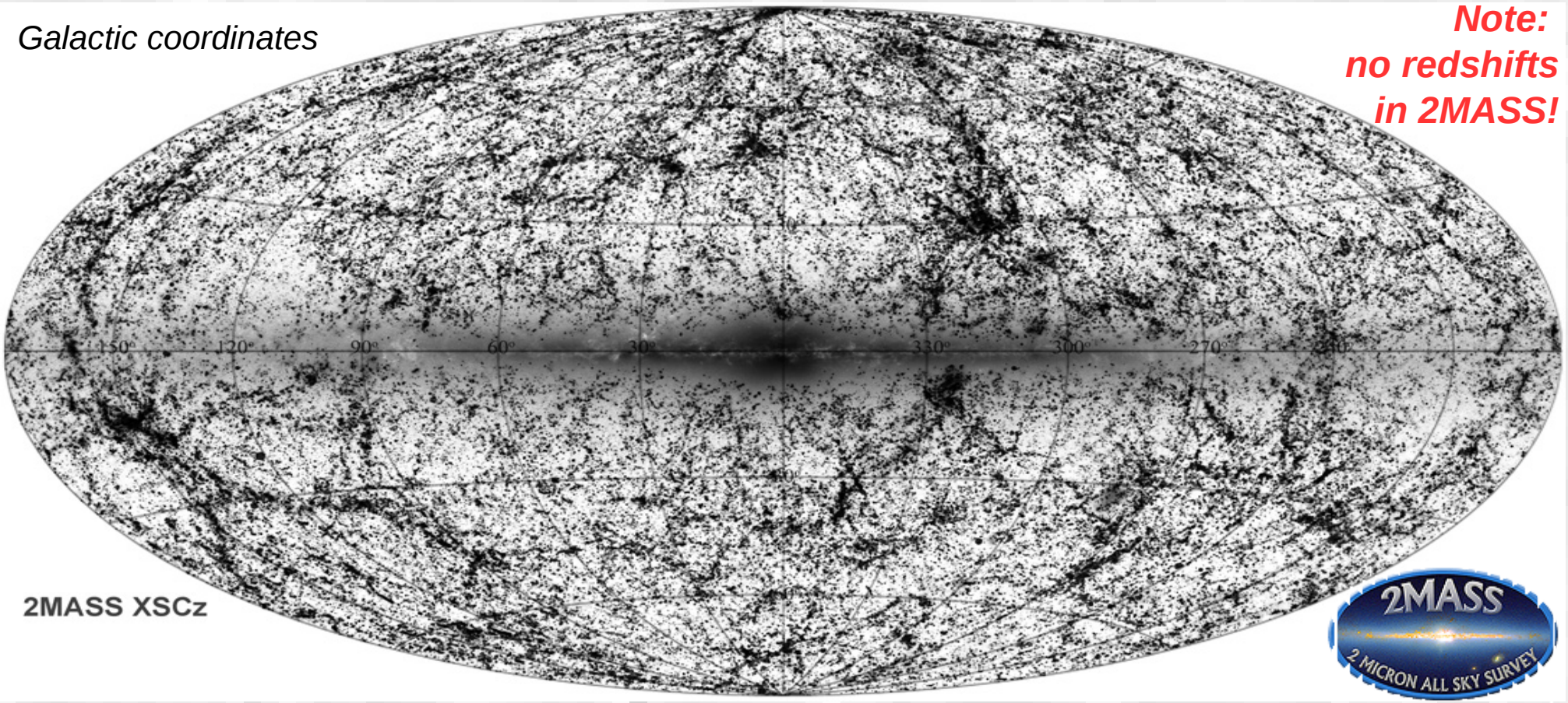
Two Micron All Sky Survey (1997-2001)

Two ground-based telescopes 1.3-m, photometry in 3 bands (J H K_s)

Over 1 million galaxies up to z~0.2, almost 500 million stars

Galactic coordinates

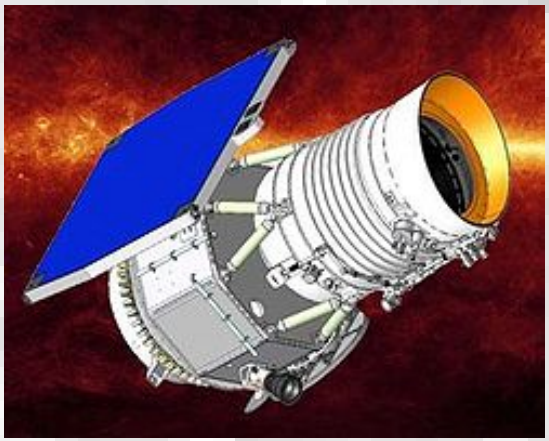
Note: no redshifts in 2MASS!



WISE

The deepest so far survey of the entire sky:

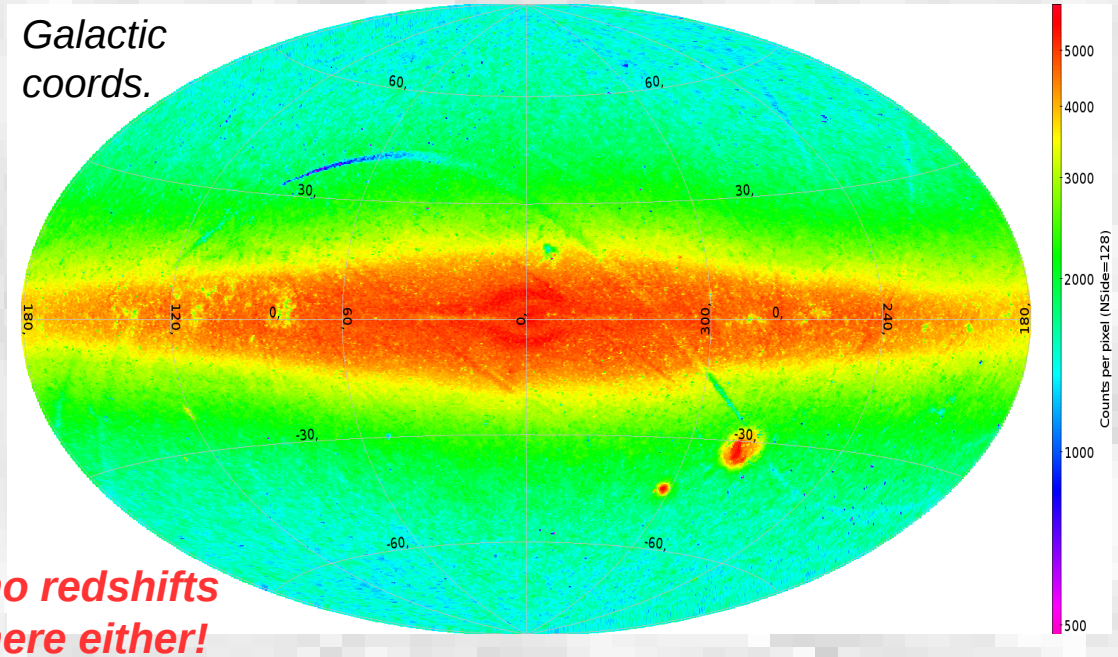
Wide-field Infrared Survey Explorer (since 2010)



Space-borne photometric survey

in the mid-infrared (3.5 – 23 μm)

40-cm telescope (still) orbiting the Earth



no redshifts here either!

Currently a catalog of 750 mln sources, of which about 100 mln galaxies and ~3 million quasars

Low angular resolution (>5”) hinders **source type identification** (stars / galaxies / quasars…)

[but see automatised approach: Kurcz, MB, et al. (2016); Solarz, MB, et al. (2017)]

SuperCOSMOS

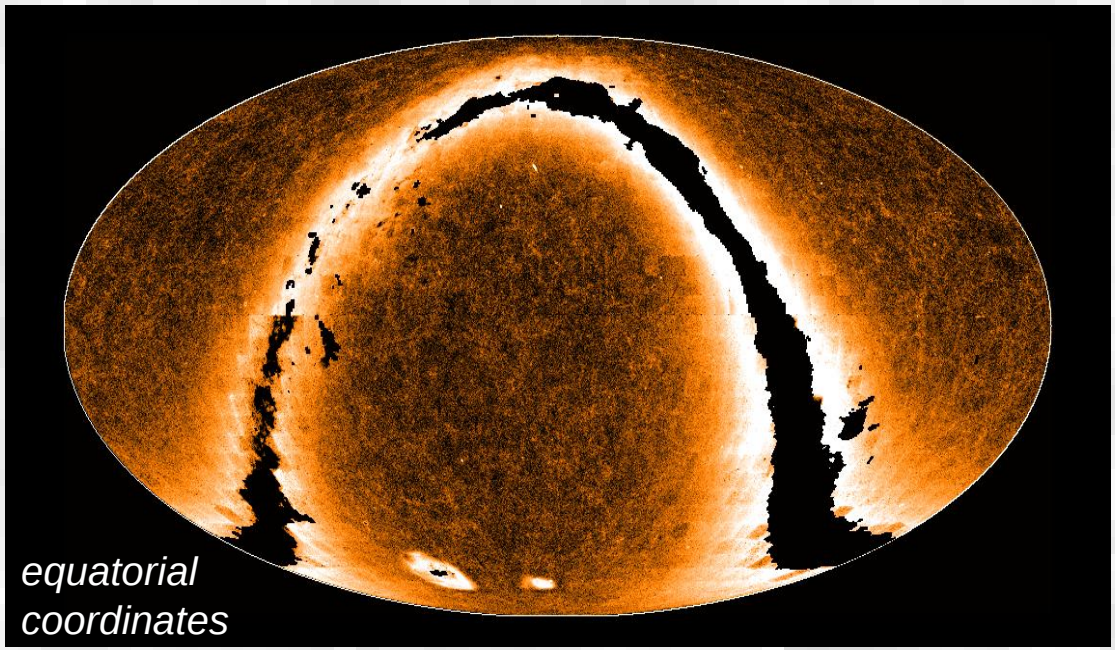
The largest existing catalog of all-sky optical data:

SuperCOSMOS Sky Survey

SuperCOSMOS Sky Survey

Scanned and digitised photographic plates (bands B R I), original data obtained in late 20-th century (!!!) (UK-Schmidt + POSS-II)

Again, not a redshift survey!



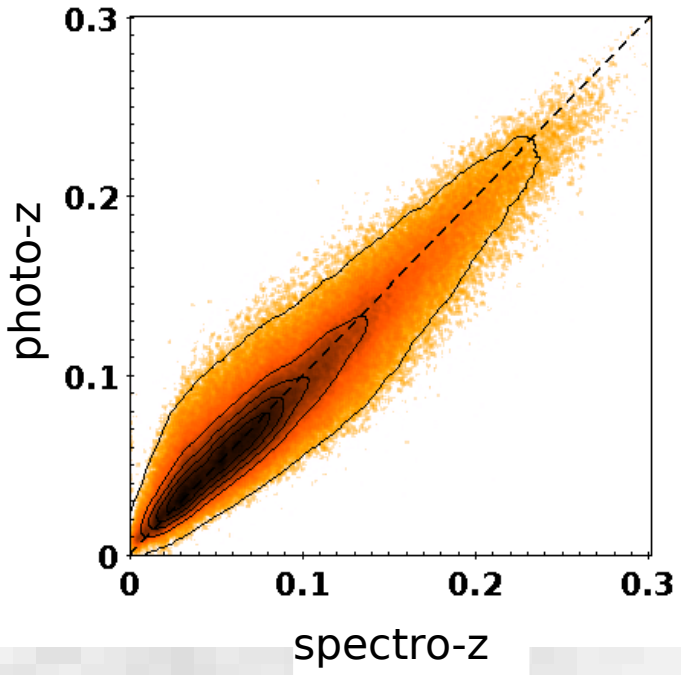
Still the largest optical dataset covering the entire sky!
(is being replaced by **Gaia** –
– but only for point sources)

Almost 2 billion catalogued sources, of which ~10% scientifically useful (blending, artefacts)

Hambly et al. 2001abc; Peacock et al. 2016

2MASS Photometric Redshift catalog (2MPZ)

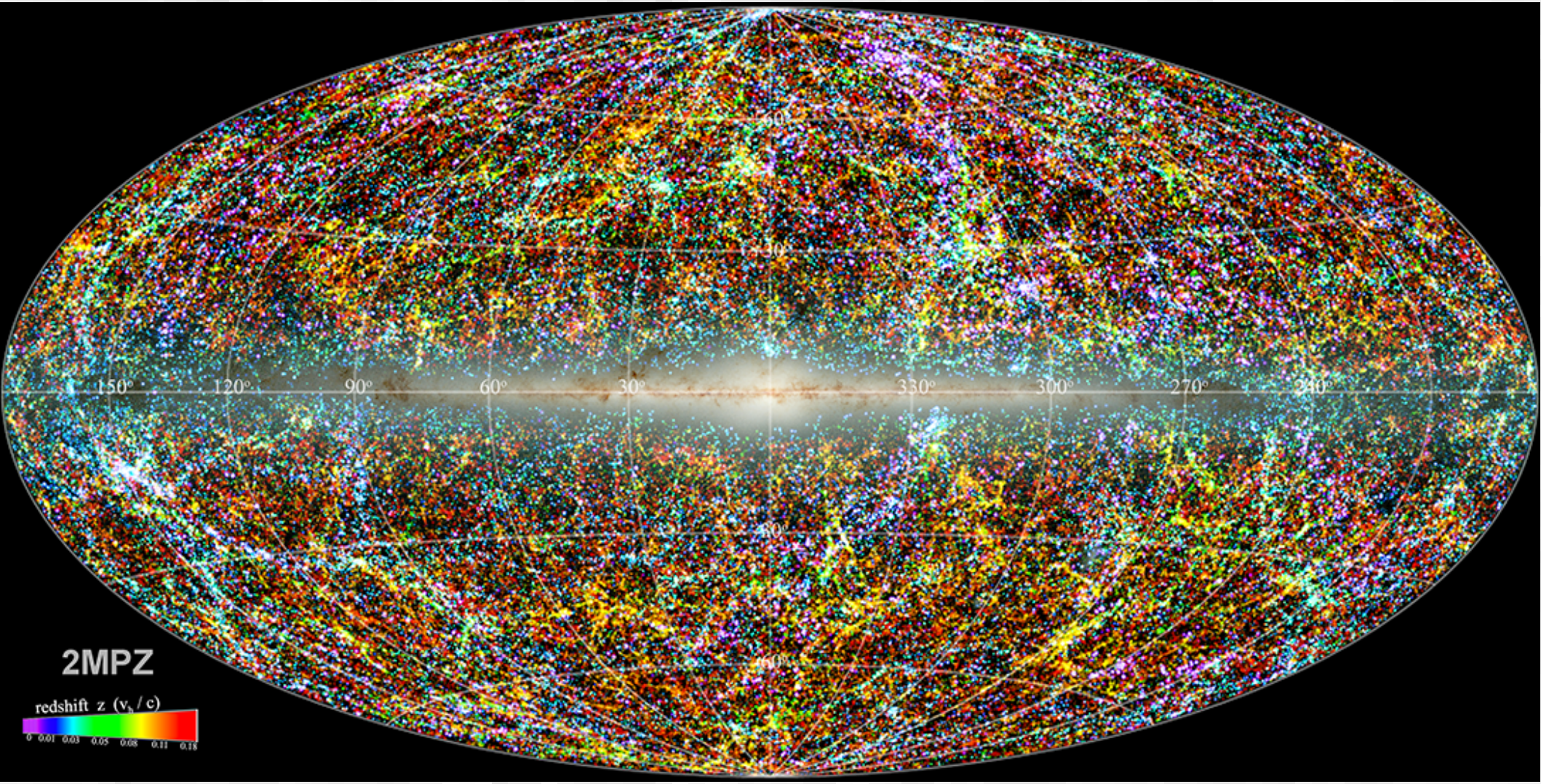
- **Cross-match of 2MASS XSC, WISE and SCOS**
  WISE and SCOS much deeper than 2MASS, resulting 2MPZ incompleteness ~5%
- **Eight-band photometry**: B, R, I, J, H, Ks, 3.5μ, 4.6μ
- **Photometric redshifts** using the ANNz software by Collister & Lahav (2004)
- **Spectroscopic training** from SDSS Main, 2dFGRS, 6dFGS, 2MRS ("2M++"++): representative and deep enough for **unbiased photo-z calibration**
- **2MPZ catalogue** with **1 million galaxies**, **⟨z⟩=0.08**, covering **most of the sky (>90%)**
- (Reasonably) **precise and accurate photo-zs:**
  → **unbiased** and with scatter $\boldsymbol{\sigma_{\Delta z}}$**= 0.015**
  → median error **|Δz|/z = 13%**
  → only **3% of outliers** $>3\sigma_{\delta z}$
- **Available for download** from
  http://surveys.roe.ac.uk/ssa/TWOMPZ



MB, Jarrett, Peacock, Cluver & Steward, ApJS, 2014

2MASS Photometric Redshift catalog

Color-coded by photometric redshifts

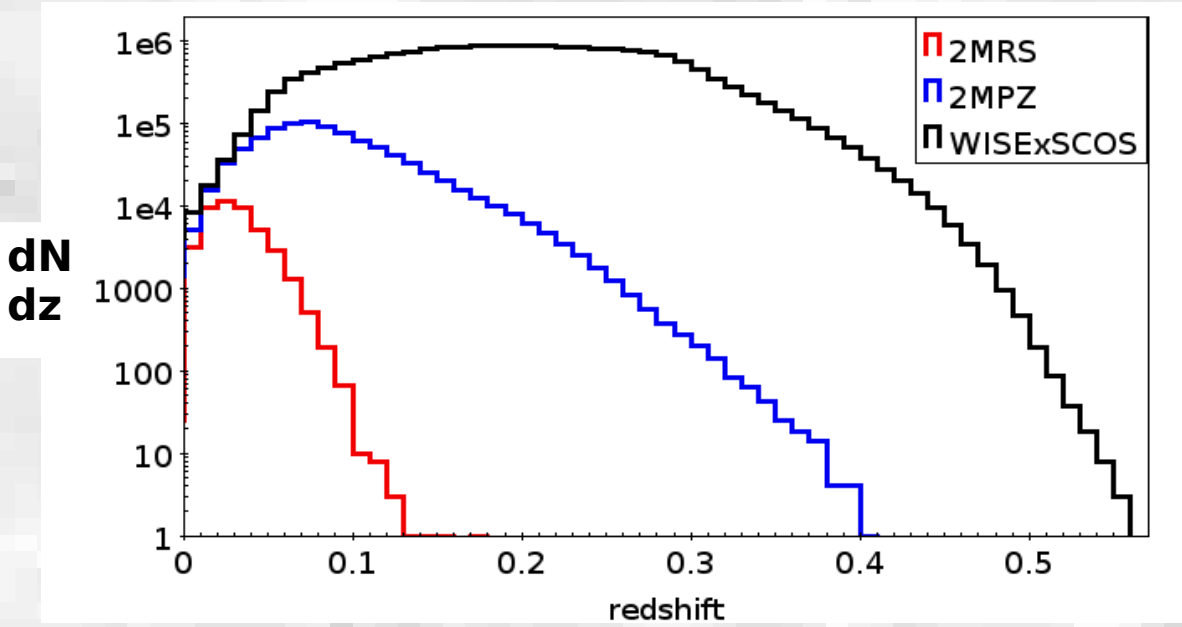


Plot by Tom Jarrett

Beyond 2MASS on 3π steradians:

20 million galaxies from WISE x SuperCOSMOS

- **"All-sky" galaxy sample much deeper than 2MASS:**
  WISE paired up with **SuperCOSMOS**, R_{AB}<19.5, $[3.4\mu]_{Vega}$<17 mag
- Cross-match at |b|>10° gives **170 million sources**, but mostly stars (blends)
- A colour-based **clean-up of star blends** leaves almost **20 million galaxies**
- **Four-band photometry**: B, R, 3.4μ & 4.5μ
- **Calibration set** for photo-zs: spectroscopic **GAMA** (Driver et al. 2011)
- Median redshift of WIxSC: **z~0.2**, but probes the LSS **to z~0.4** on ~75% of the sky



- Photo-z performance:
  mean **|Δz|<0.01**,
  $\sigma_{\Delta z}$= 0.033,
  median **error 14%**
  and **3% outliers**

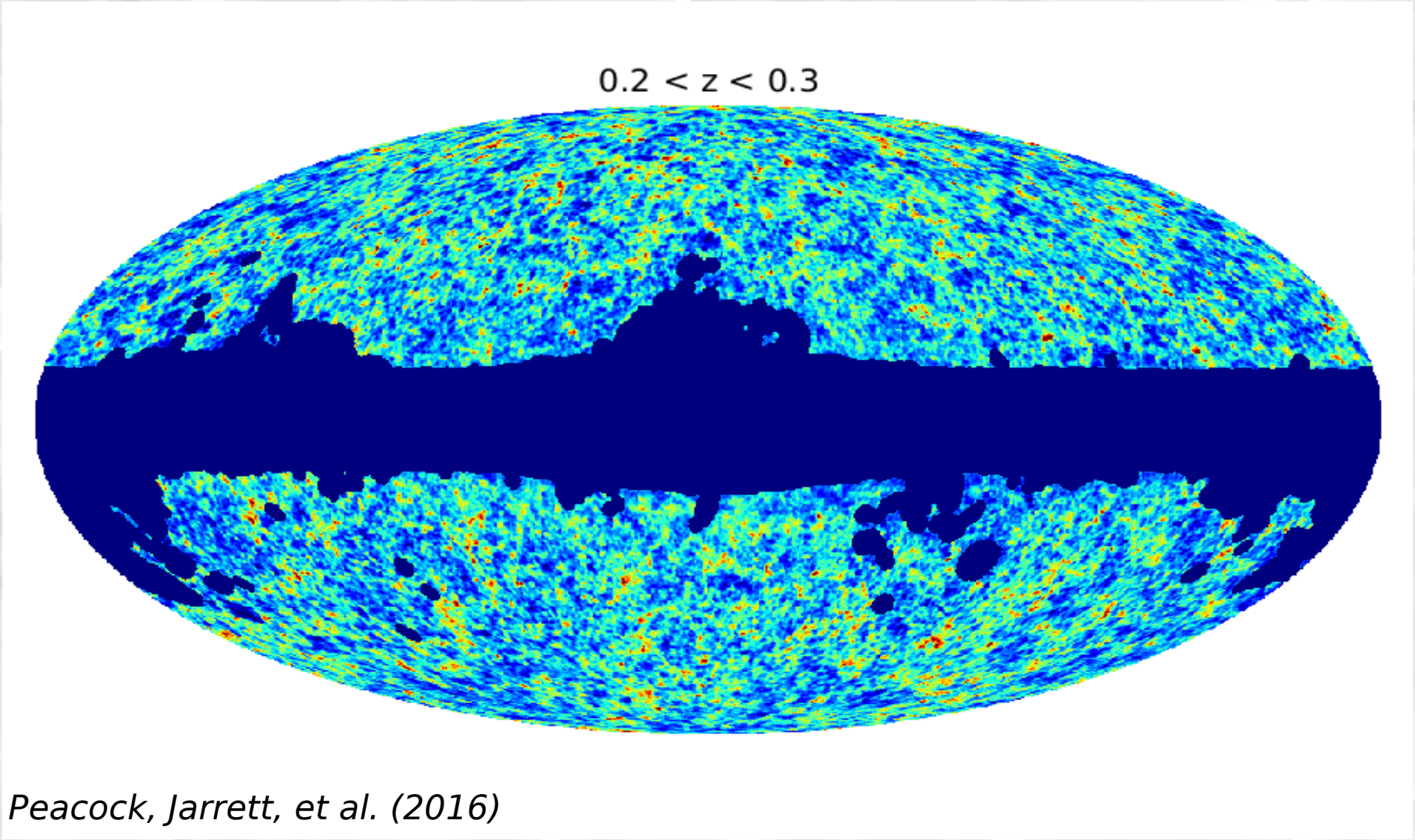
MB, Peacock, Jarrett & GAMA (2016)

Data at http://ssa.roe.ac.uk/WISExSCOS

The cosmic web ~3 Gyr ago

as seen by WISE x SuperCOSMOS

The only such picture currently available at >π sterad from any (photometric) redshift survey

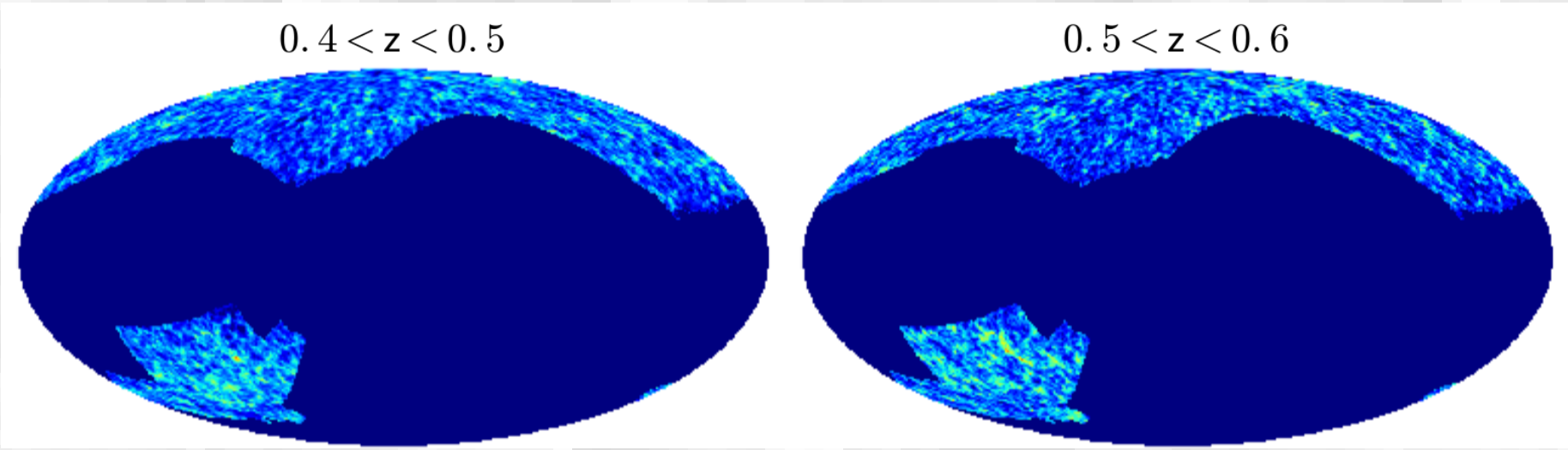


MB, Peacock, Jarrett, et al. (2016)

Larger depth, smaller coverage:

SDSS DR12 photometric redshift catalog

- Public **SDSS DR12 catalog** from Beck et al. (2016) based on ***ugriz* imaging**
- About **185 million extended sources** with photo-z estimates, ⟨z⟩~0.45
- Of these 55 million have **photo-zs of scientific quality** for z<0.6
- Typical redshift scatter of $\boldsymbol{\sigma_z \sim 0.03(1+z)}$ but with variations depending on colours and photometric quality; quantified in “photo-z classes”
- Covering about **10,000 deg² of Northern sky**

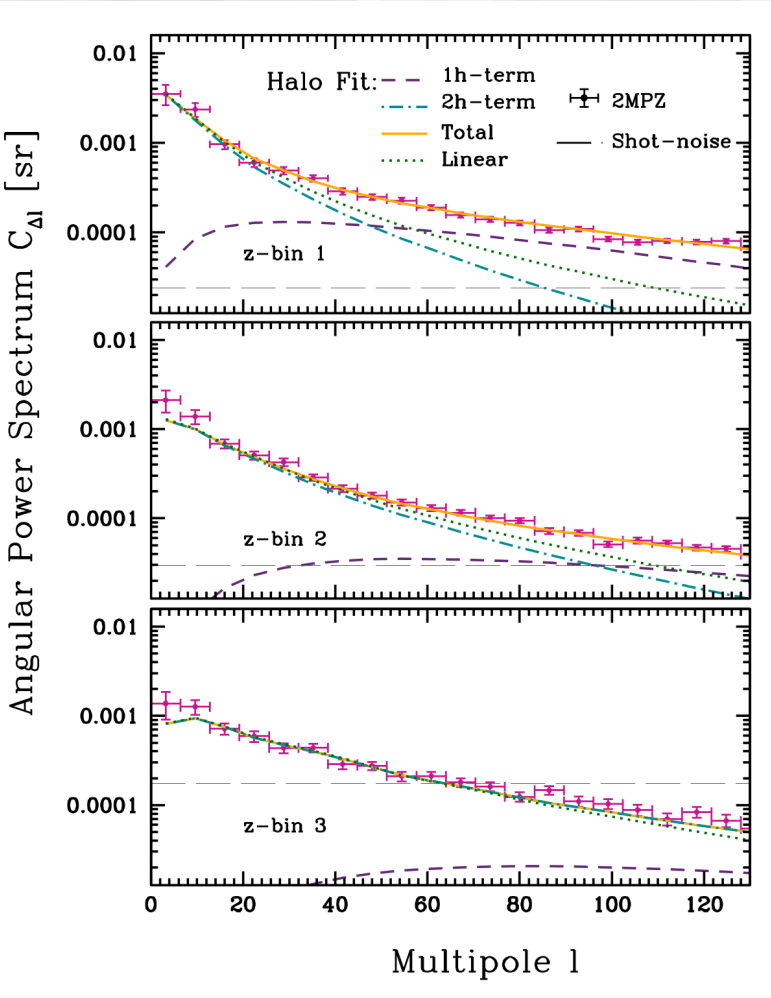


Angular power spectrum of 2MPZ

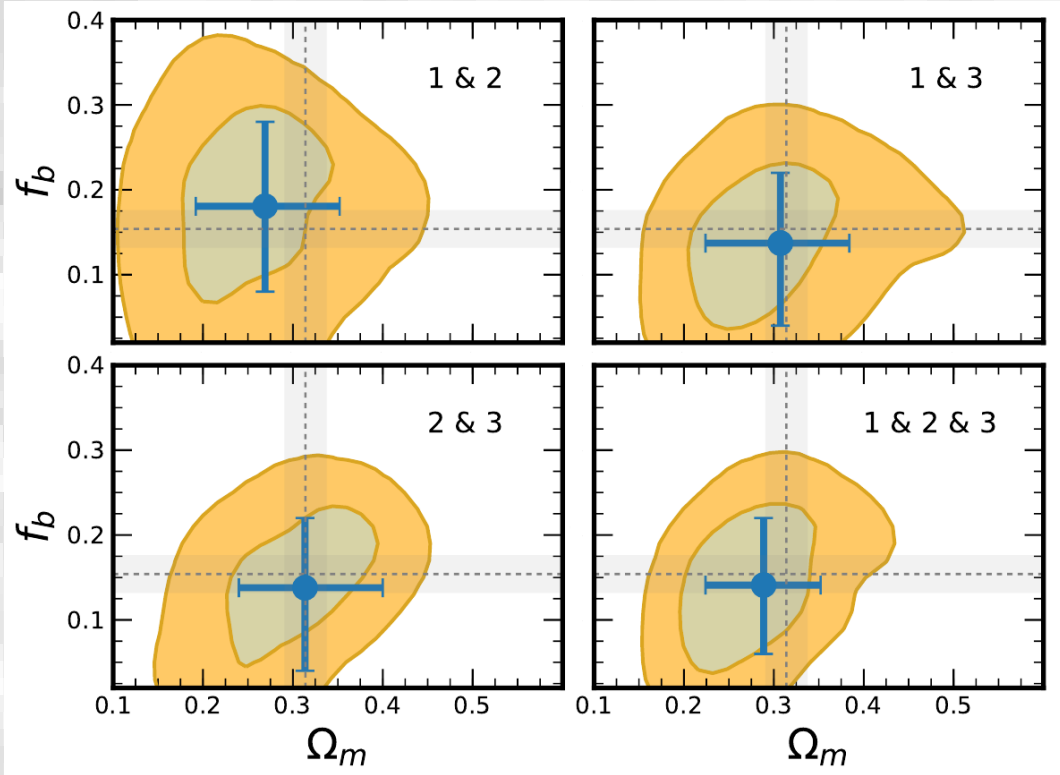
- **Projection of 3D power spectrum**, sensitive to cosmological parameters

$$C_\ell^{gg} = \int dz \frac{d\chi}{dz} \frac{1}{\chi^2(z)} b^2(z) N^2(\chi) P(k, z)$$

- Computed in three separate **redshift bins** (“tomography” + combinations)
- **Validation** of the dataset, constraints on **matter density** and **baryon fraction**



- Similar analysis still to be attempted for **WISExSCOS** and **SDSS DR12 photo-z** datasets (systematics...)



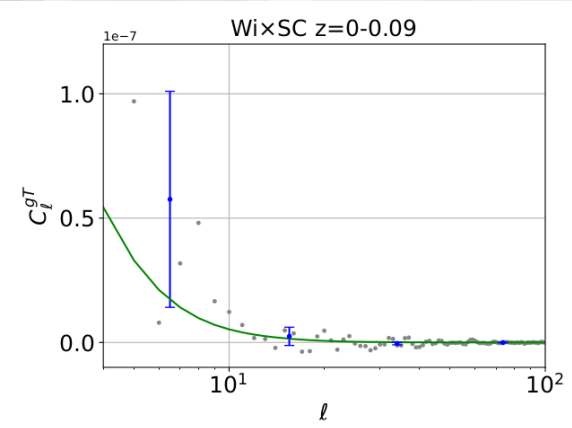
Balaguera-Antolinez, MB, Branchini & Postiglione, 2018

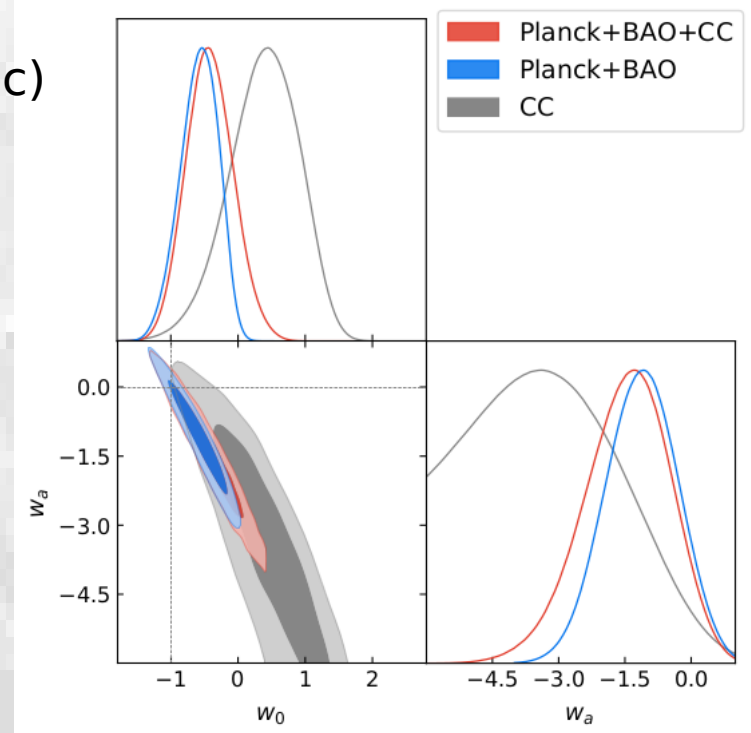
Integrated Sachs-Wolfe effect through cross-correlation of CMB x source catalogs

- **Secondary anisotropy of the CMB** induced by changing gravitational potentials
- Detectable in **angular cross-correlation** between CMB and galaxy catalogs:

$$C_\ell^{cT} = \frac{3\Omega_m \mathrm{H}_0^2}{c^3\left(l+\frac{1}{2}\right)^2}\int dz\, b_c(z)\frac{dN}{dz}H(z)D(z)\frac{d}{dz}\left(\frac{D(z)}{a(z)}\right)P\left(k=\frac{l+\frac{1}{2}}{\chi(z)}\right)$$

- We used **Planck** vs. **2MPZ**, **WISExSCOS**, **SDSS** galaxies & quasars, **NVSS** radio data
- Measured **in redshift shells** (except NVSS), results from all the catalogs **combined**
- Overall **detection significance 5σ** (first time from c-c)
- Constraints on **dark energy** e.o.s. $w(z)=w_0+w_a z/(1+z)$
- **Deeper all-sky redshift datasets needed** for these to improve





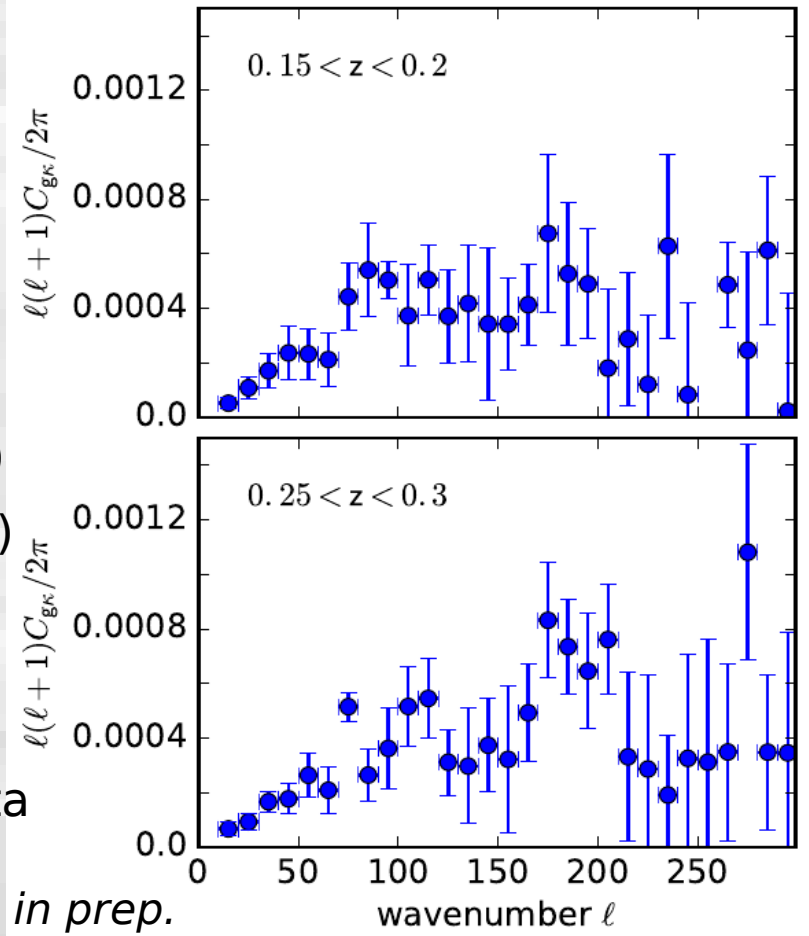
Stölzner, Cuoco, Lesgourgues & MB, 2018

CMB lensing at low redshifts

- **CMB photons lensed** by the large-scale structure from last scattering surface to z=0
- **Broad kernel** peaking at high *z*, **but sensitive to low redshifts** as well

$$C_\ell^{XY} = \int_0^\infty \frac{dz}{c} \frac{H(z)}{\chi^2(z)} W^X(z) W^Y(z) P\left(k = \frac{\ell + \frac{1}{2}}{\chi(z)}, z\right) \qquad W^\kappa(z) = \frac{3\Omega_m}{2c} \frac{H_0^2}{H(z)} (1+z)\chi(z) \frac{\chi_* - \chi(z)}{\chi_*}$$

- Peacock & MB in prep:
  - * **tomographic cross-correlation** of 2MPZ, WIxSC and SDSS-DR12 with Planck lensing, **0<z<0.6**
  - * **significant detection** in all the Δz=0.05 bins
  - * constraints on **z=0 growth rate** and **σ_8(z)**
- See also Raghunathan+2017 (WISExSCOS, stacking) and Bianchini & Reichardt 2018 (2MPZ, x-correlation)
- **Improvement expected** from:
  1) better **wide-angle CMB lensing** maps;
  2) deeper **wide-angle (photometric) redshift** data

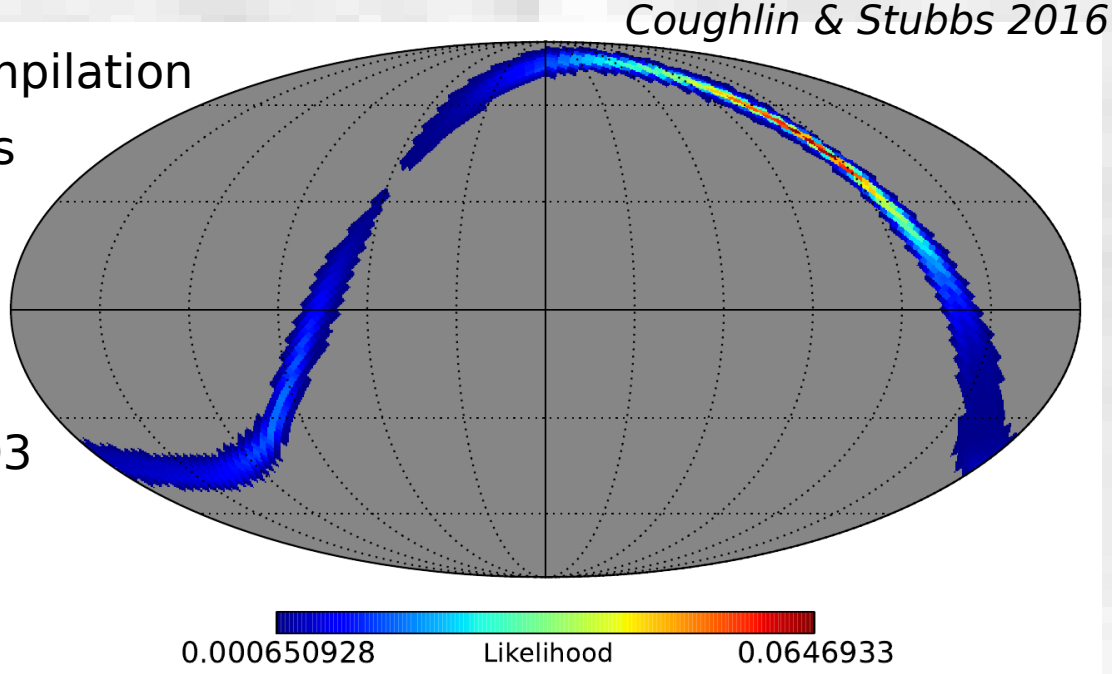


Peacock & MB, in prep.

2MPZ as an input catalog for gravitational wave follow-up

- **Gravitational wave events** are followed up electromagnetically for **counterparts**
- **First success for binary neutron star merger GW170817**
- E-M observers need **input galaxy catalogs** to maximize probability of detection
- **2MPZ is ideal at z<0.15** being all-sky, very complete, and multi-wavelength (e.g. *Evans, …, MB et al.* 2016; *Antolini & Heyl* 2016)
- 2MPZ is **essential part of GLADE** compilation popular among LIGO/Virgo and partners
- All of the GW detections so far were at distances **well mapped by 2MPZ**
- This may change with LIGO/Virgo run O3 so **deeper catalogs needed**
  → WISE x SuperCOSMOS…?

Coughlin & Stubbs 2016

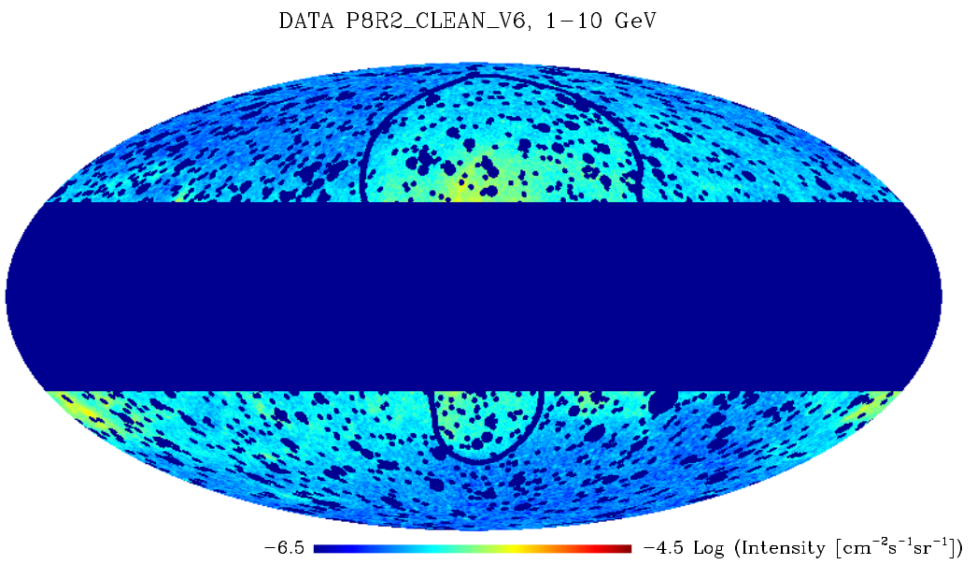


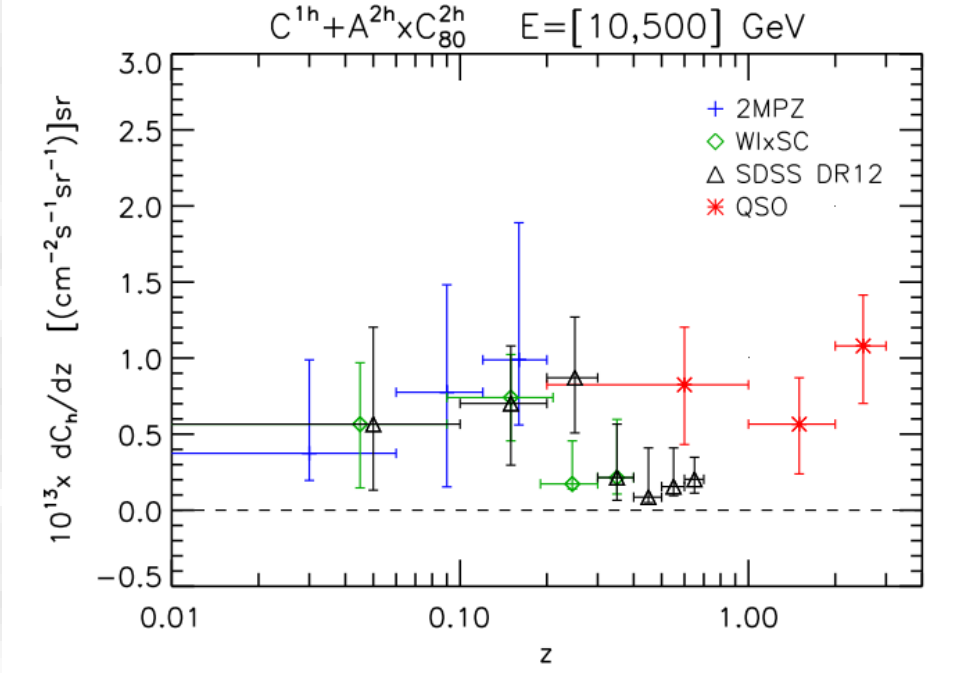
(Near) future prospects in tracing wide-angle large-scale structure

- **Spectroscopic samples are catching up** for >π sterad extragalactic coverage: Taipan+SDSS-Main+LORCA (low-z, complete); eBOSS+DESI+4MOST (high-z, sparse)
- More remotely: **low-resolution redshifts** from Euclid (& SPHEREx?); **radio HI redshift data** from SKA and its precursors (ASKAP, MeerKAT?)
- On the photometric side, nothing better than SuperCOSMOS exists for **all-sky optical**
- Need to wait for **LSST joined with e.g. DECALS** to fill this gap
- LSST on its own will be a **breakthrough** thanks to flux-limited 0<z<[deep] coverage with no colour preselection – and (hopefully) excellent photometric redshifts
- **Wide-angle radio** datasets (NVSS, TGSS, LOFAR, eVLA) [to] give ~3π but no redshifts
- **Challenges** in forthcoming data very different from the current ones: **systematics will dominate over statistics** (photo-zs, non-uniformities, modeling...)

Cross-correlation with Fermi-LAT extragalactic gamma-ray background

- **Extragalactic γ-ray background** from **blazars, AGNs, star-forming galaxies**, but could also be from self-annihilating or decaying **dark matter** particles
- Similar detection technique as ISW: **cross-correlation** of the γRB with the same catalogs
- **Significant detection** in multiple redshift- and γ-ray energy-bins (**up to 16σ**)
- Visible **evolution in spectral and clustering properties** of γRB sources
- Future analysis will give limits on various **postulated dark matter particle** properties





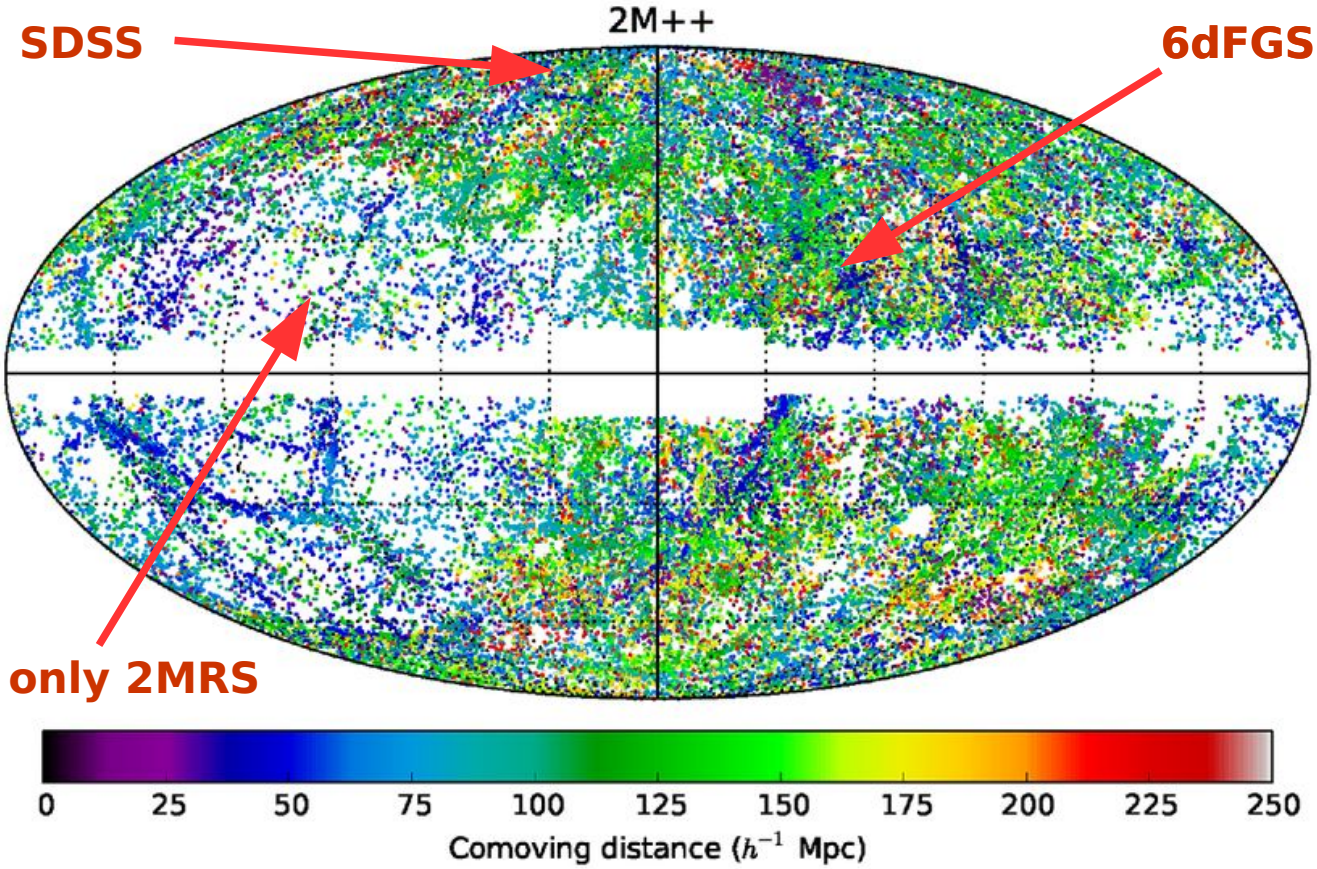
Cuoco, MB, Branchini & Xia, ApJS, 2017

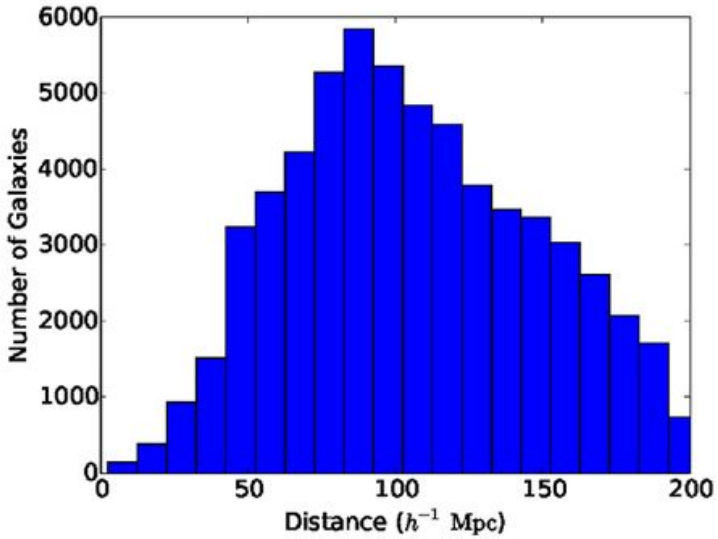
2M++ galaxy redshift catalog:

70,000 2MASS galaxies with spectroscopic redshifts

combined from 2MRS, 6-degree Field Galaxy Survey and SDSS

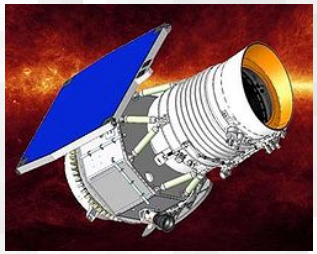
Non-uniform due to lack of redshifts in part of the volume





Lavaux & Hudson 2011; Carrick et al. 2015

All-sky probes: the power of WISE

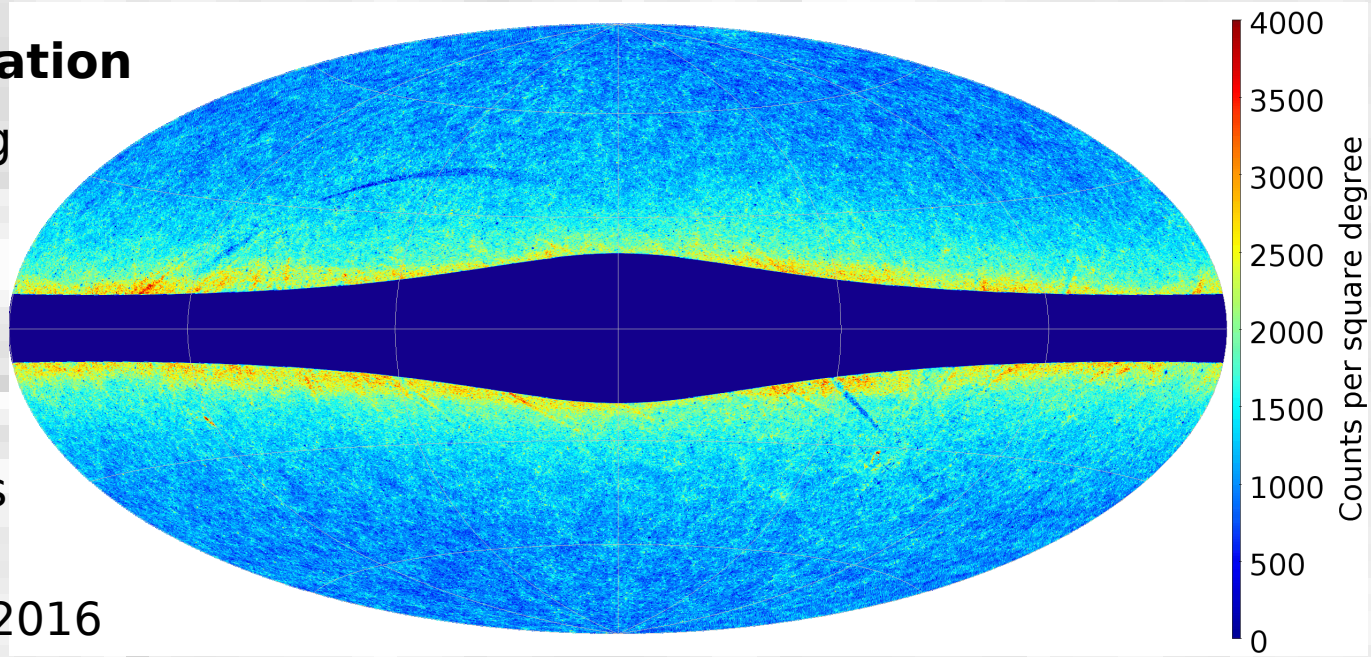


- **Wide-field Infrared Survey Explorer** (WISE) satellite data: **all-sky photometric catalogue** in 3.4, 4.6, 12 and 23 μm
- **One of the largest all-sky samples**: 750 million sources …of which **~100 million** are **galaxies and QSOs**
- **WISE** itself is **much deeper** than 2MASS (by ~3 mag): another “layer” for all-sky cosmology (**galaxies even at z>1**; *Jarrett, …, MB, et al.* 2017)
- Full **cosmological potential of WISE** still to be explored: galaxies very difficult to extract; stars dominate even at high latitudes
- Automatic **star-galaxy-QSO separation in WISE:** first efforts partially successful (*Kurcz, MB, Solarz, et al.* 2016); rare object detection (obscured quasars? *Solarz, MB, et al.* 2017)

All-sky probes: the power of WISE

Star/galaxy/QSO separation with machine learning

- We used the **support vector machines** algorithm trained on SDSS spectroscopic
- Current **results for W1<16** Vega (1 mag brighter than WISE flux limit) due to limitations of the training set (practically no SDSS galaxies at W1>16)
- **45 million galaxy candidates on ~80% of sky**
- Inevitable stellar **contamination at low latitudes** – blending due to 6” WISE beam
- Work in progress on improving with better methods and input samples

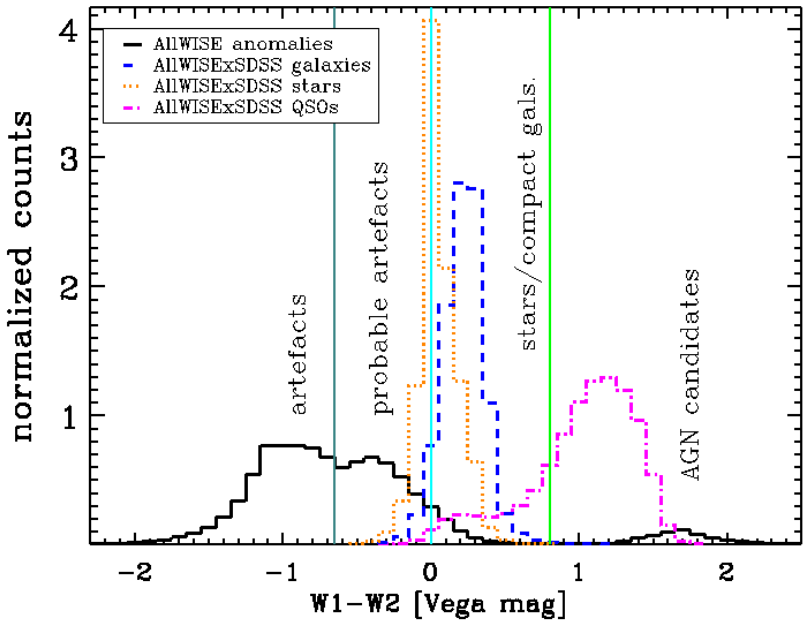


Kurcz, MB, Solarz, et al. A&A, 2016

All-sky probes: the power of WISE

Rare object detection with machine learning

- **Support vector machines** were used in “one-class” mode: training set as “known” sources, the rest as “unknown” (***anomalies***)
- Training data derived from optical SDSS → detected *anomalies* have **specific WISE mid-IR colors**

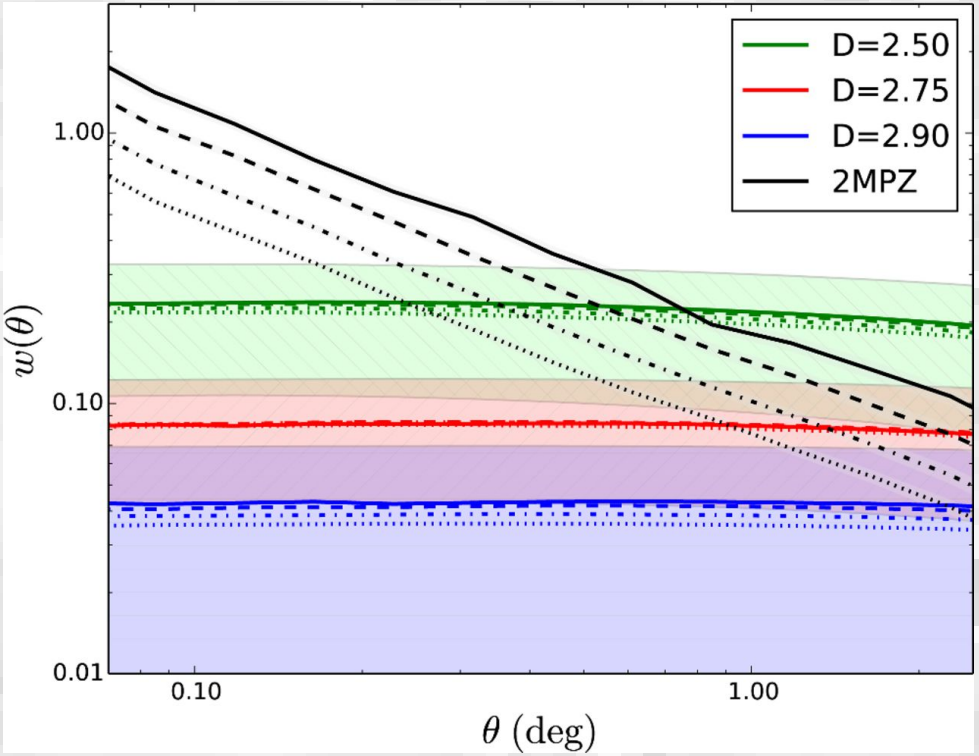


- An all-sky population of **very “red” objects** [3.4μ]-[4.6μ] > 0.8 mag Vega
- Properties consistent with highly obscured dusty **quasars** at (maybe) large redshifts
- **Spectroscopic follow-up** needed to confirm their nature

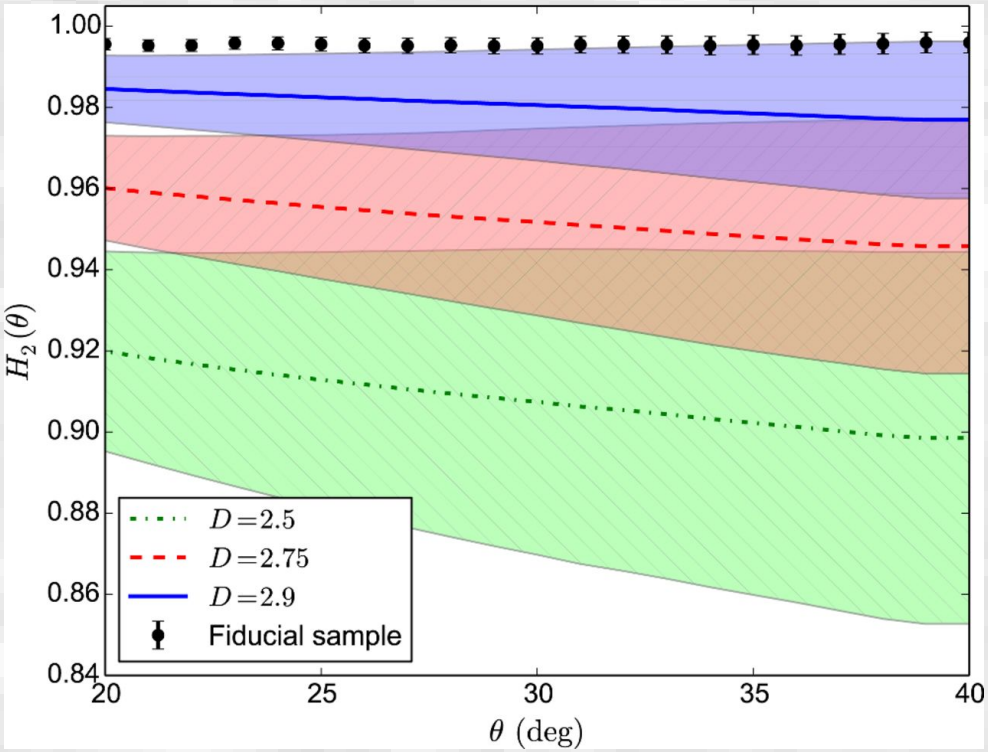
Solarz, MB, et al., A&A, 2017

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

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



Angular correlation function



Homogeneity index
(=1 for ideally homogeneous distribution)

Alonso, ..., MB+ 2015, MNRAS, arXiv:1412.5151