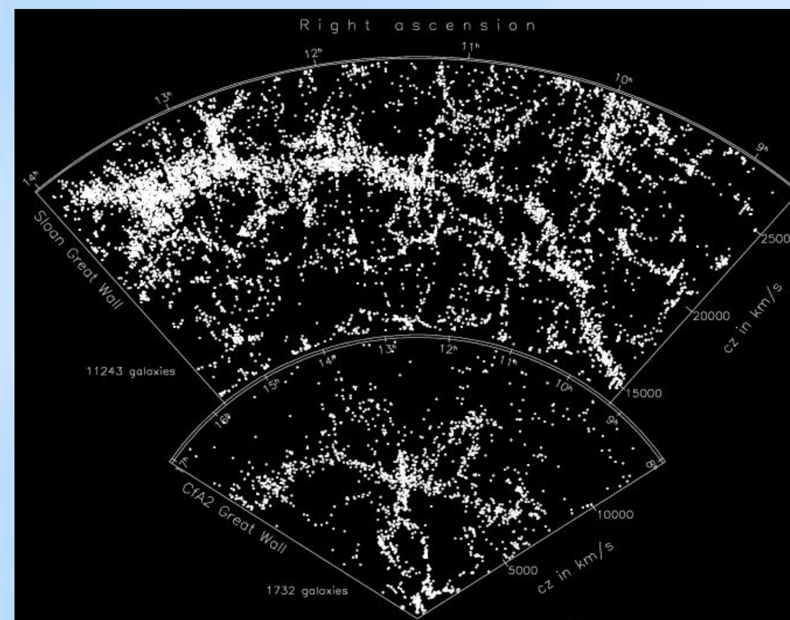
# Cosmological surveys

## Observing the large-scale structure of the Universe

*A subjective review*


**Maciej Bilicki**
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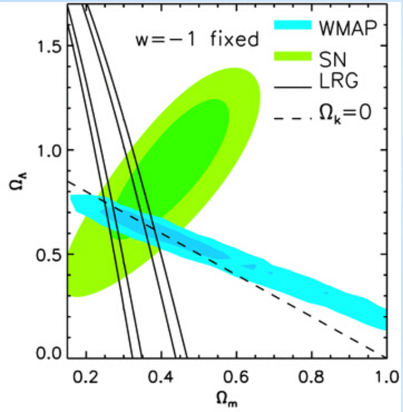
& University of Zielona Góra (Poland)

# Surveys of galaxies: why do we need them?

* **The distribution of galaxies** results from physical processes since the Big Bang until now (gravitational collapse, galaxy formation, ...)

* By studying the **statistical properties of the large-scale structure** we measure **cosmological parameters** (determining the past and future fate of the Universe):
  – mean **matter density** (“baryonic” and dark matter)
  – **cosmological constant** (dark energy)
  – current and past **expansion rate** (Hubble constant)




Reid et al. 2010

* **Key words**: density power spectrum; galaxy correlation function; baryon acoustic oscillations; growth rate of structure; …

*See also the lectures by Rien van de Weijgaert!*

# Observational cosmology: what we already know

**More precisely: what is most consistent with observations**

* Most of the **matter** in the Universe is in a “**dark**” form – interacting only gravitationally and (probably) weakly

* Universal **expansion** has been **accelerating** for a couple billion years – **dark energy** is now dominating the mass-energy balance

* The Universe has **null curvature** – space is globally flat

* The Universe is **homogeneous** and **isotropic** on the largest scales

* The **growth of structure** is consistent with general relativity

# Questions...

## What we don't fully (or at all) know yet

* What is **dark matter**? (Particles? What kind? Something else??)

* What is **dark energy**? (Cosmological constant? Negative pressure? Artefact of the overly simplistic model? More exotic models?)

* Is **general relativity** correct on the largest scales? (Modified gravity?)

* How large are the scales of global **isotropy and homogeneity**?

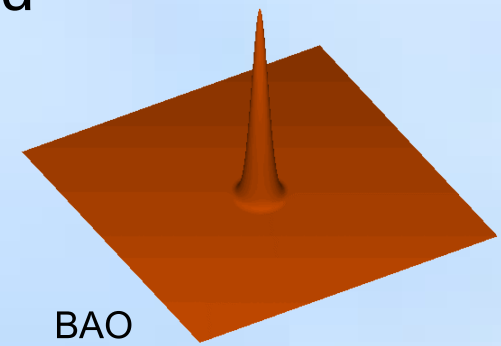
* Are we a **typical observer**? (Basis of the **Copernican principle**...)

* More detailed **(g)astrophysical aspects**:
– history of galaxy formation, build-up of galaxies from primordial gas;
– collisions and mergers of galaxies;
– build-up of galaxy clusters and large-scale voids...

# Cosmology with the large-scale structure

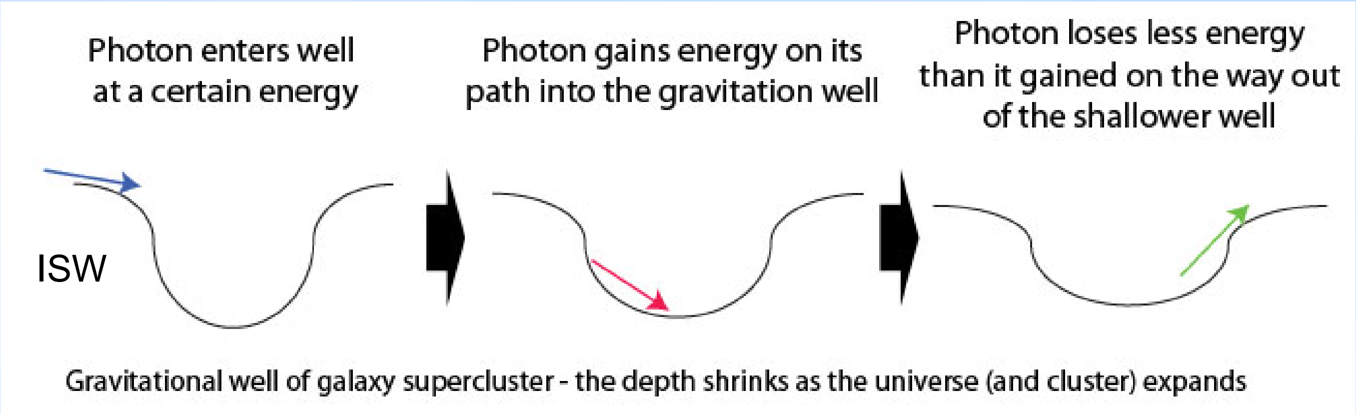
## Two examples of important cosmological tests with the LSS:

- ***Baryon acoustic oscillations***: frozen relics of sound waves propagating through the early Universe, imprinted today in galaxy correlations
  → **standard ruler** testing the rate of expansion, hence the cosmic acceleration and dark energy




Daniel Eisenstein

- ***Integrated Sachs-Wolfe effect***: cosmic background photons change their energy passing through matter over- and underdensities
  → this effect would be null if there was no dark energy (in a flat Universe)

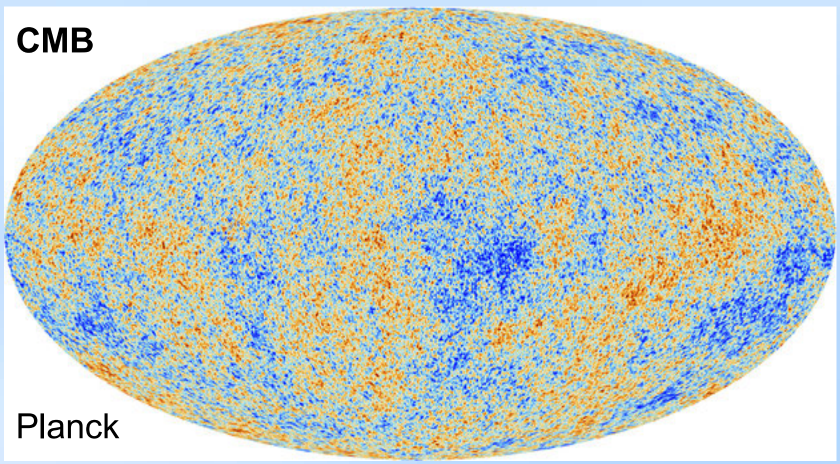


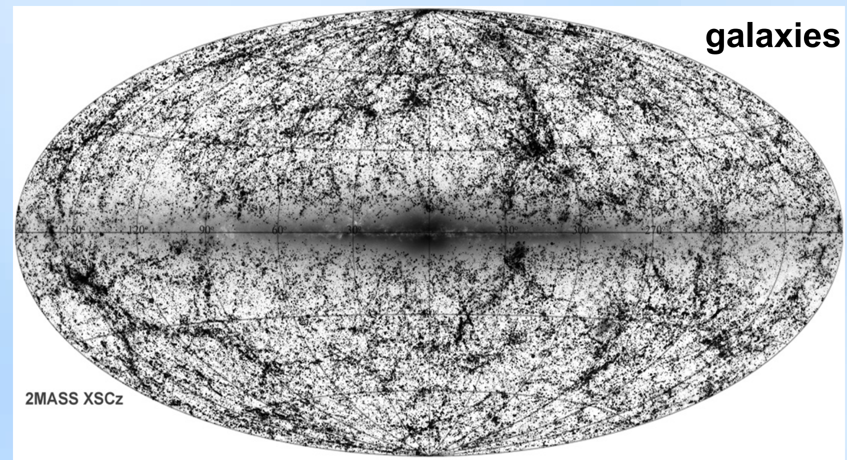

NASA

# Build-up of the large-scale structure

Formed out of *primordial density fluctuations*

imprinted today in the *cosmic microwave background*




**Universe 13.8 billion years ago**

(380,000 years after the Big Bang)

**Universe today**

(13.8 billion years after the Big Bang)

Fluctuations of 1 part in 100,000

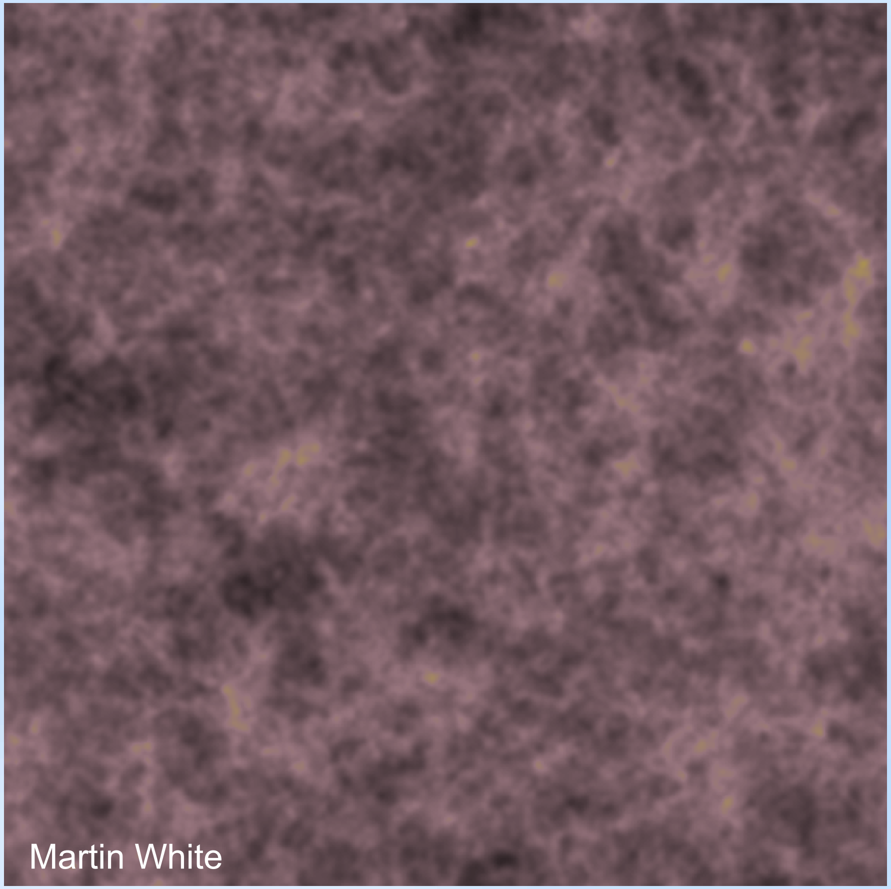
Clusters and superclusters of galaxies

Voids and filaments

Large density contrasts

# Build-up of the large-scale structure

Formed via the ***gravitational instability*** mechanism:



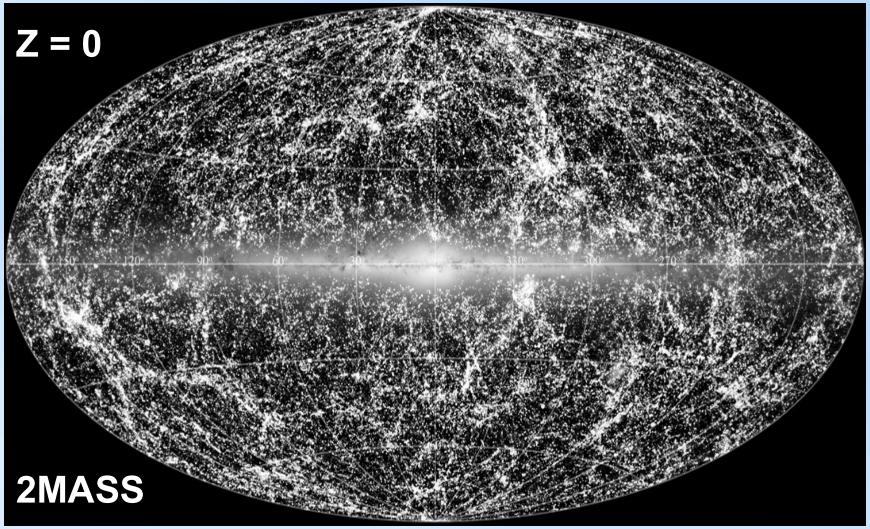

• **Overdense regions collapse** under their own gravity to become galaxies, clusters and superclusters of galaxies

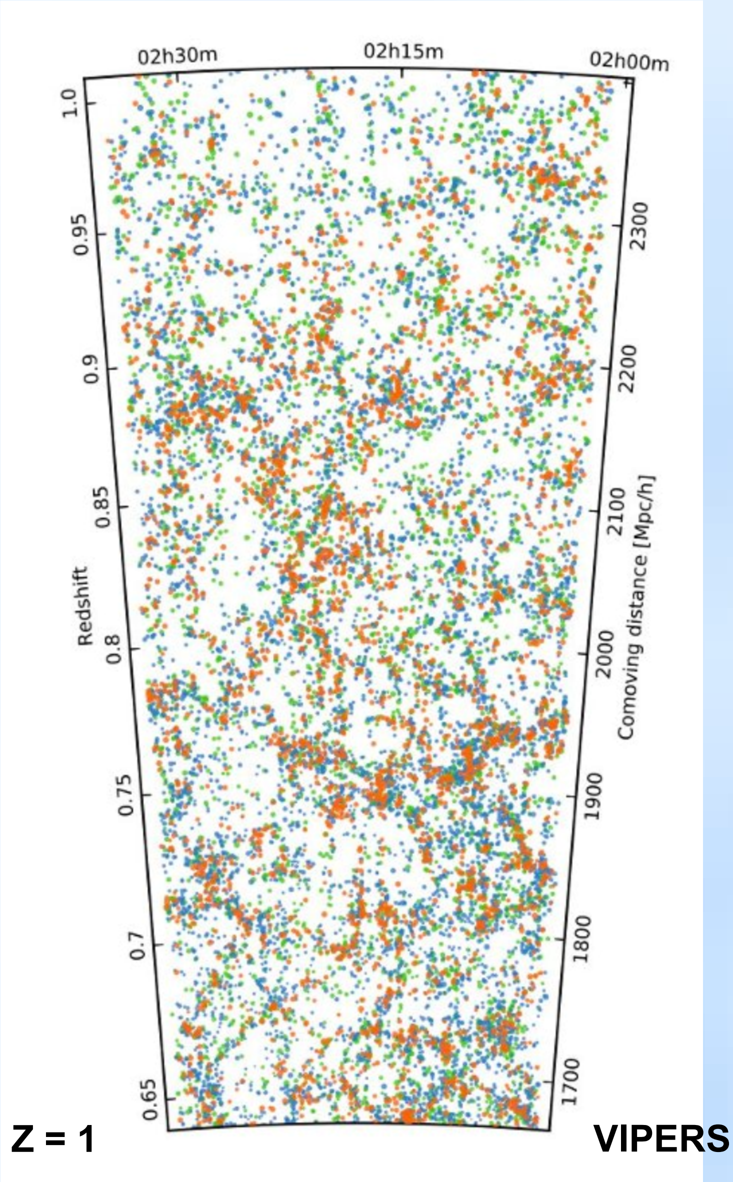
• **Underdense regions expand** faster than the background to become voids of densities much lower than the average

More **complete picture** thanks to **numerical simulations** *(Wojtek Hellwing's lectures!)*

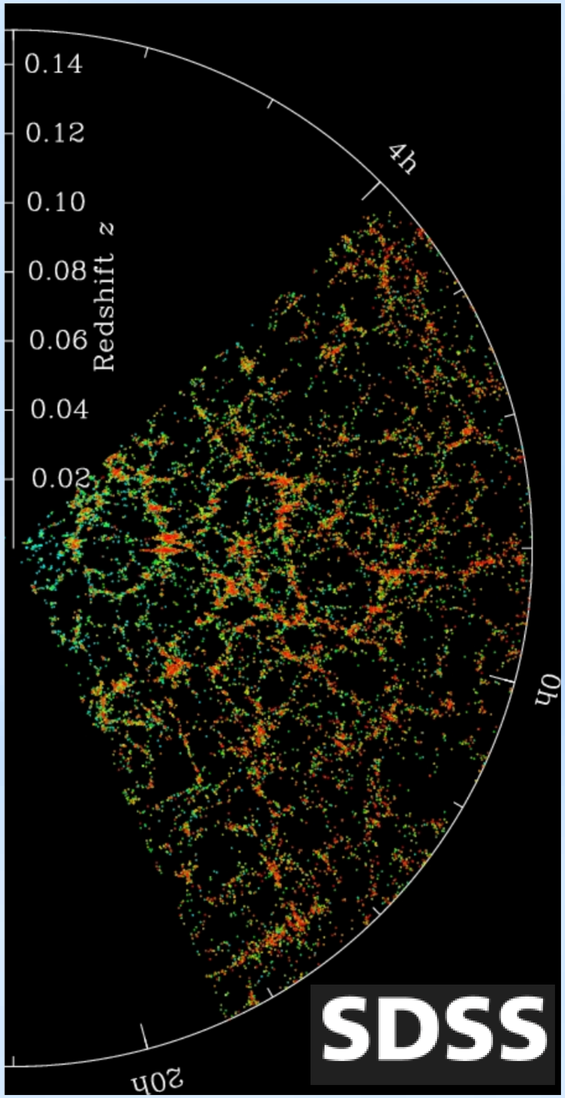
# Large-scale structure of the Universe

Galaxies organized into
a network of interconnected
*filaments* and *walls*,
surrounding giant *voids*:
the ***cosmic web***



# Observing the large-scale structure




• We need **representative samples** of the Universe: covering *large areas* of the sky and reaching as *far from us* as possible

• The most successful to date: the **Sloan Digital Sky Survey** (SDSS), 3 mln spectra on 25% of sky

• A **trade-off** 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*

# But let's rewind a bit

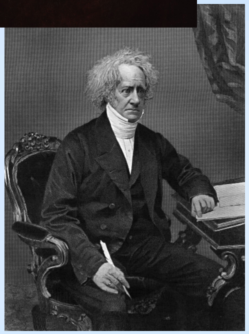
# Surveys of galaxies: a bit of history

## Discovery of the „*nebulae*” *

**In addition to those seen with the naked eye*

**Nicolas Louis de Lacaille** (1768)
Southern sky

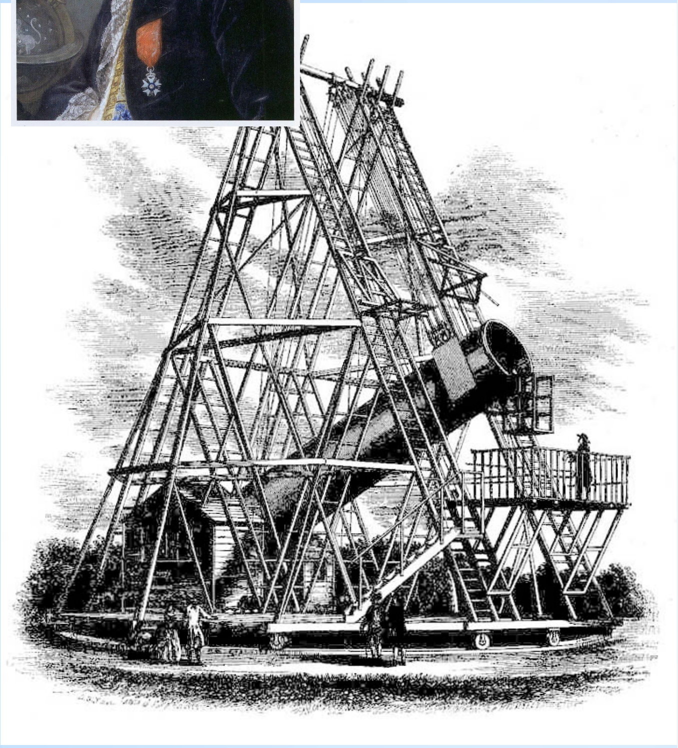
**Charles Messier** (1771) – Northern sky
103 objects “interfering” with comet search



**William** and **John Herschel**
(18th and 19th century):

thousands of nebulae
thanks to large telescopes

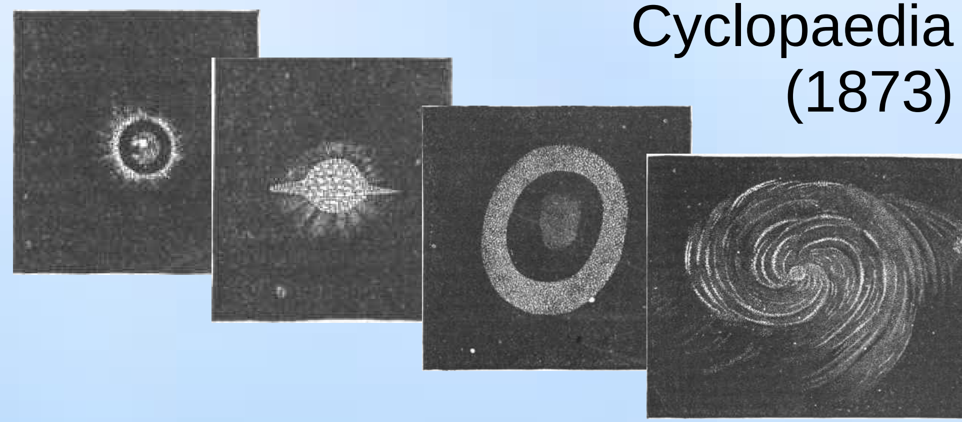
New General Catalogue (NGC)



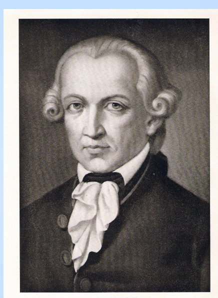
# What are the *nebulae*?

19th century:

The American Cyclopaedia (1873)



different types of nebulae
- clusters of stars,
- planetary nebulae,
- other (spirals)...

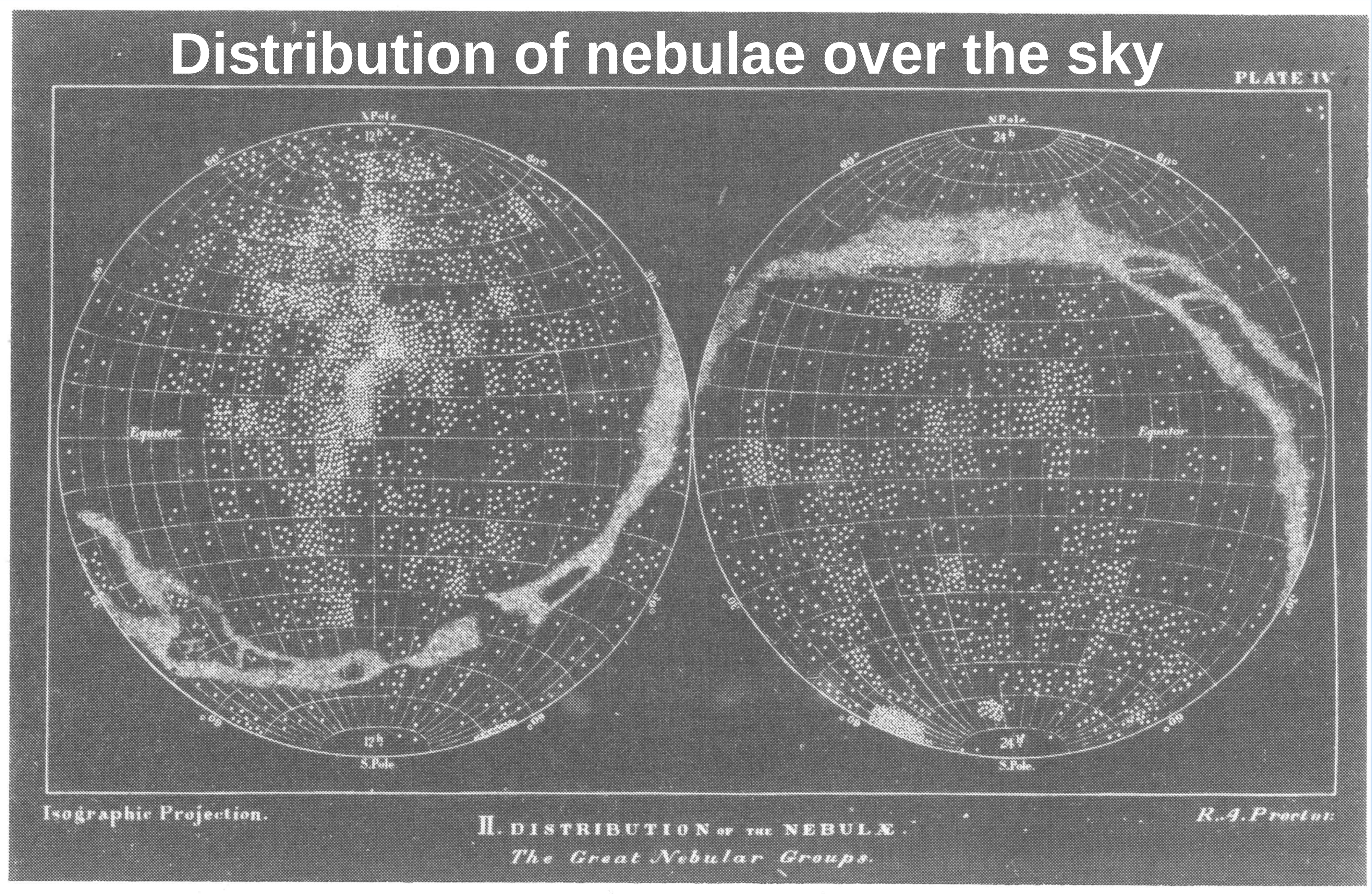


**“Island universes”?**
(Immanuel Kant speculated already in 1755)

**John Herschel** (ca. 1850)**:**
nebulae are clustered independently of stars
(e.g. in the Virgo constellation)

*Unwittingly discovered the large-scale structure of the Universe!*

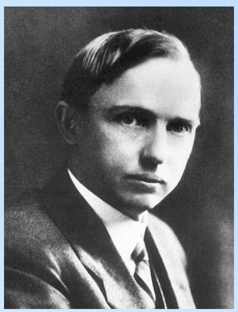
# General Catalogue (1878)

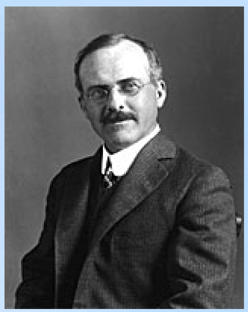


# The Great Debate

## What are the spiral nebulae?

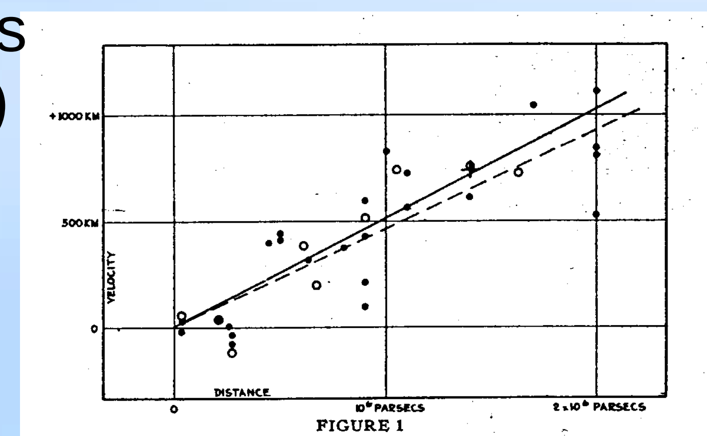
**Vesto Slipher** (since 1913): huge radial velocities of spiral nebulae (hundreds of km/s) – and most of them are *receding* from us





The “Great Debate” 26/04/1920
**Harlow Shapley**: spirals inside the Milky Way
**Heber Curtis**: nebulae are other “galaxies”

Settled soon – **Edwin Hubble** (1923):
Andromeda Nebula is hundreds of thousands light years from us *(today's value: 2.5 mln ly)*

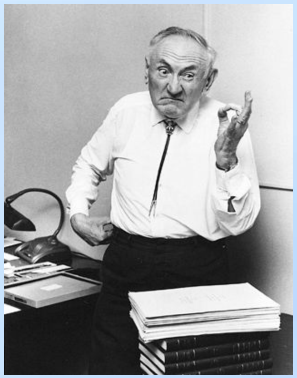



Island Universe – and not static
“Recession of the nebulae”:
**The Universe is expanding***

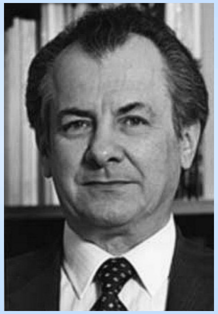
**Note: Hubble never admitted that clearly*

# Large-scale structures

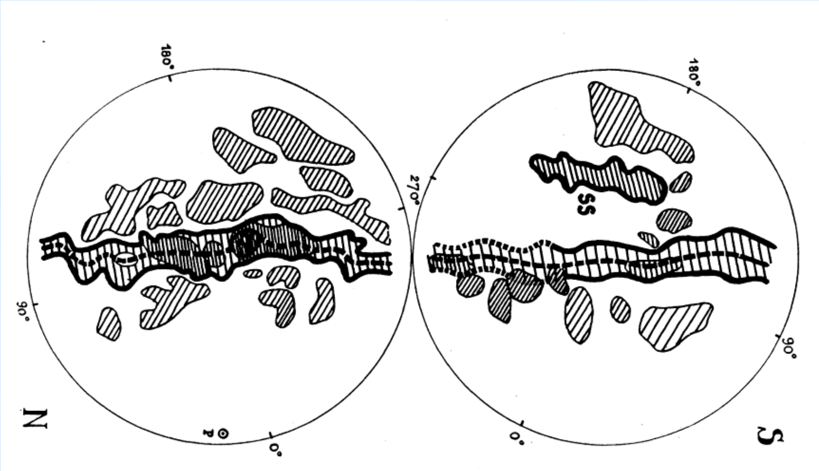
## How are galaxies distributed?

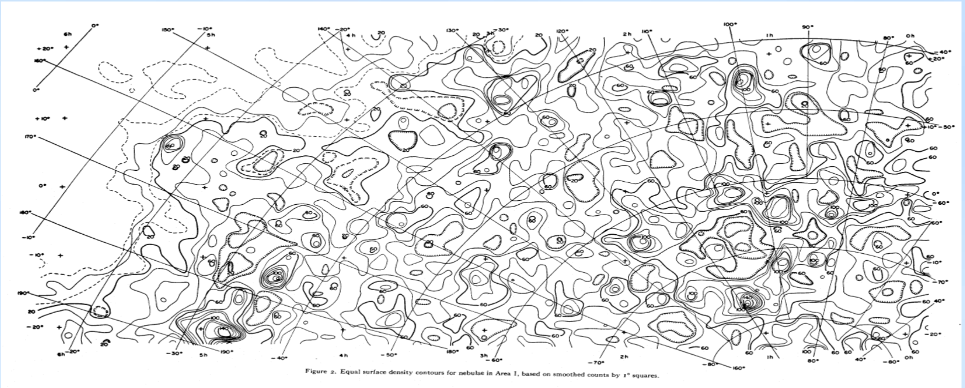


Since 1920s: galaxies are often in **clusters**
(H. Shapley, Fritz Zwicky, George Abell...)



Gerard de Vaucouleurs (1953):
nearby clusters gathered in
a flattened “**Supergalaxy**”
of 100 million light years in size



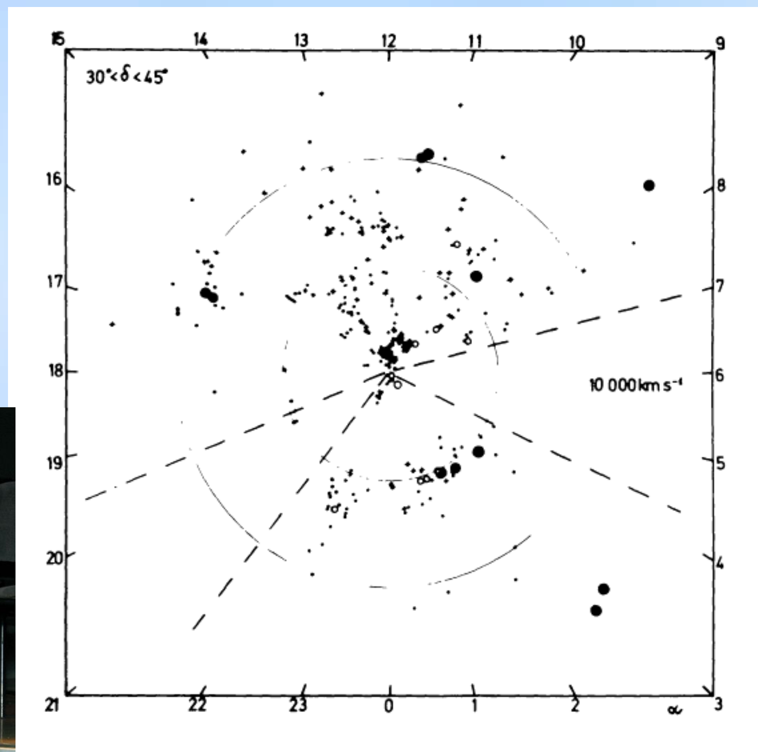



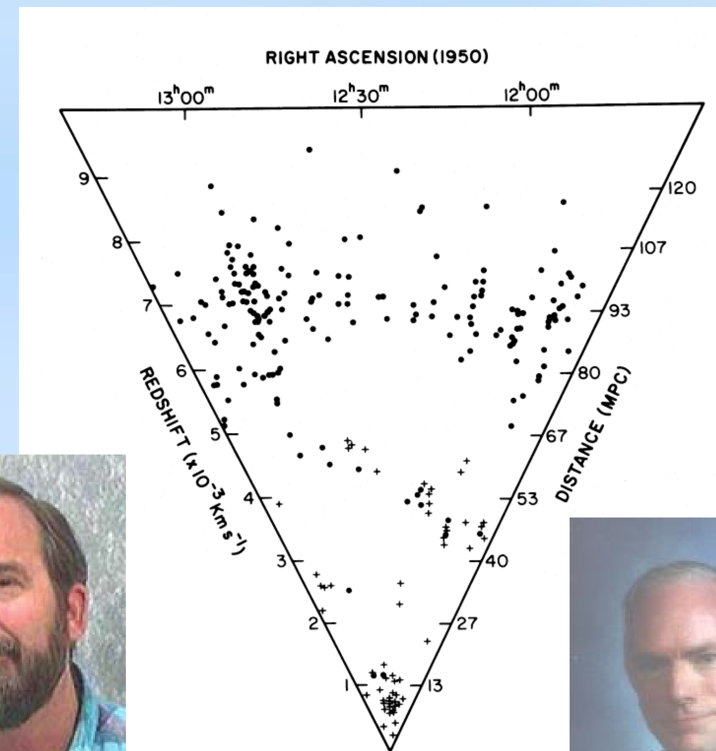
Shane and Wirtanen (1967):
Lick Observatory catalogue
over one million galaxies
**two-dimensional maps**

# Sponge-like structure of the Universe

**Jaan Einasto** and collaborators (1977),
**Stephen Gregory & Laird Thompson** (1978):

Clusters and superclusters of galaxies make up “filaments” with huge “voids” (dozens of megaparsecs*) in between

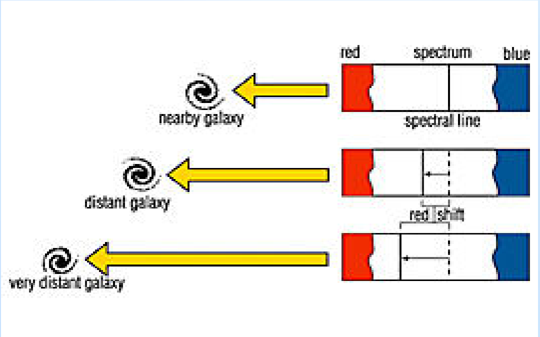



*1 parsec = 3.26 light years

# Era of 3D galaxy surveys

$z = \Delta\lambda / \lambda$

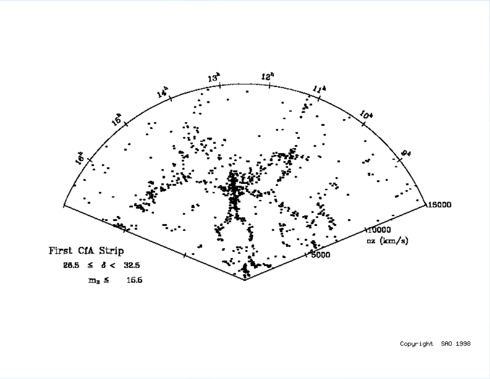



- Three coordinates of galaxies:
  two angular ones and the **redshift**
- Redshift as a useful proxy for distance:

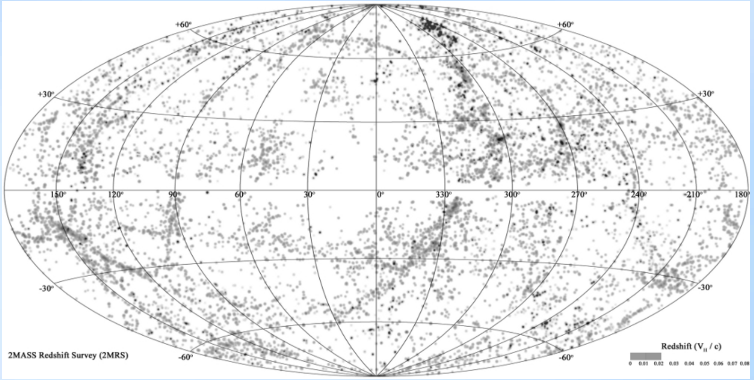
  $\mathbf{z} \approx H_0 \times \mathbf{d} / c \quad \Rightarrow \quad \mathbf{d \approx 4000\, z}$ [Mpc]

  (z – redshift, d – distance, $H_0$ – Hubble constant, c – speed of light)

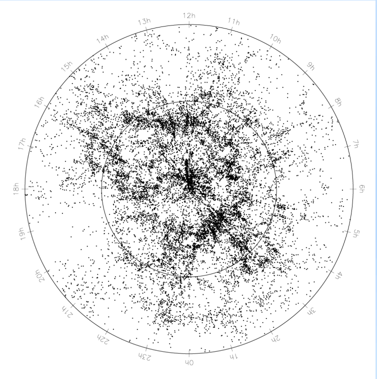
- Large ***redshift surveys*** since late 1970s, possible thanks to CCD and (later) multi-fibre spectroscopy
- Three-dimensional “maps”, projected on 2D – since 1980s



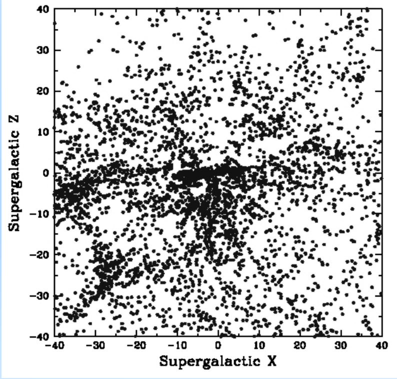

*Cone plot*




*All-sky projection*



*“Hockey puck”*

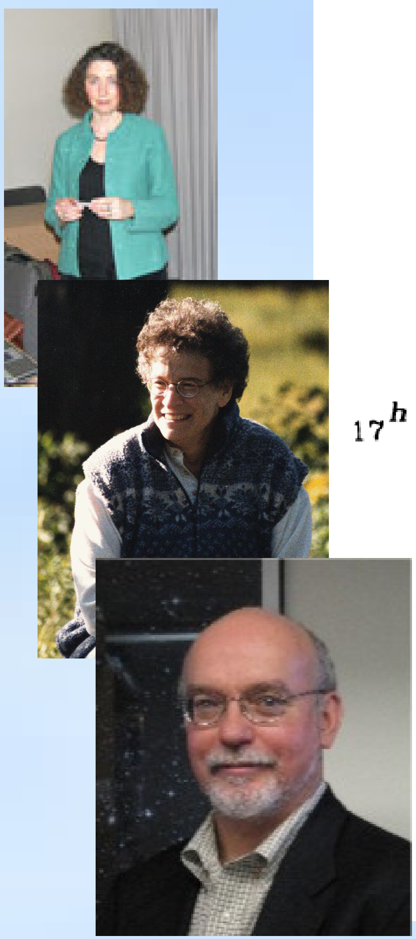


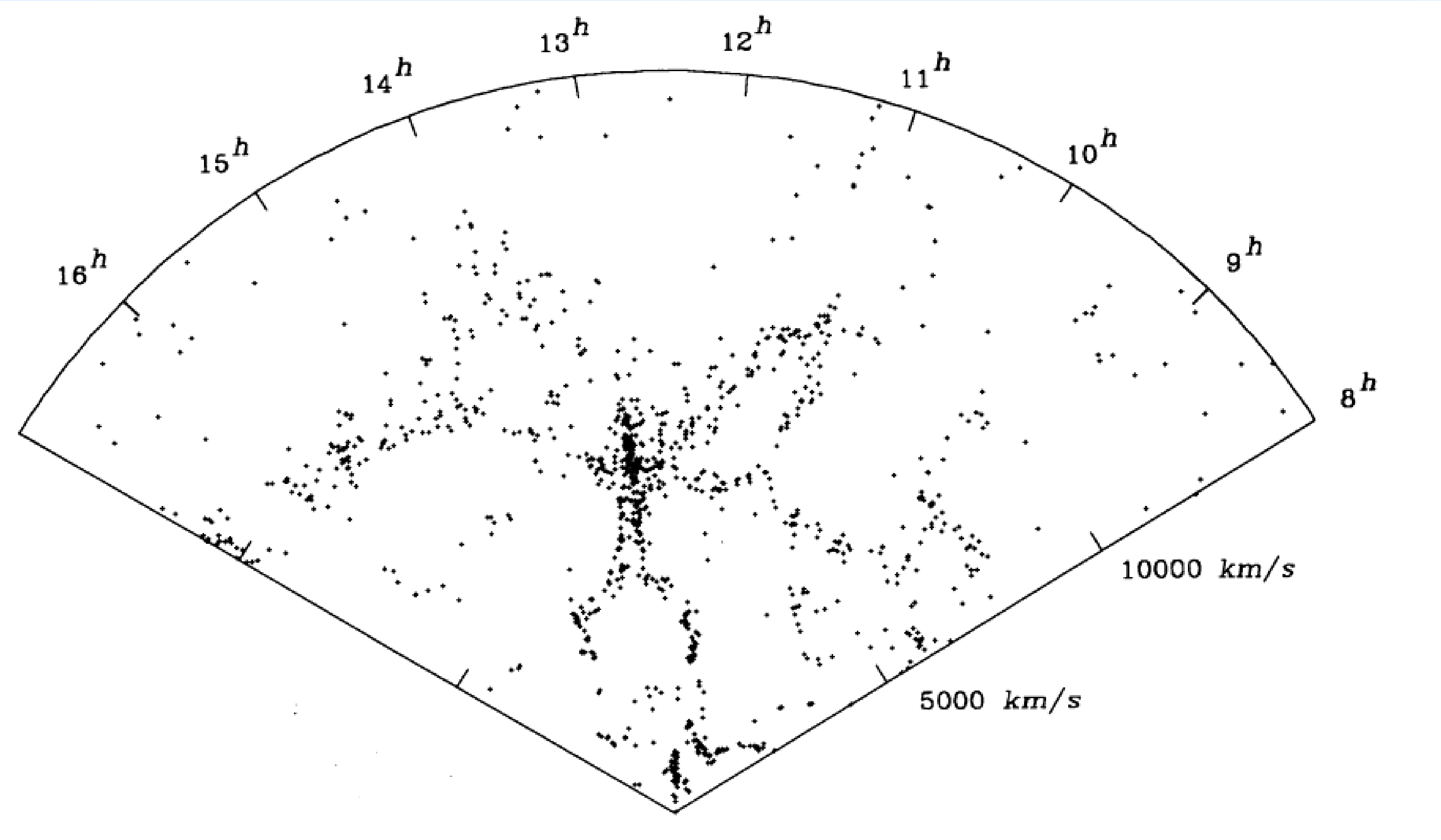

*Slice*

# Large sky surveys in 3D

Since 1980s, larger and larger surveys

An early example: the “slice of the Universe” from the **CfA2** survey (de Lapparent, Geller & Huchra 1986)



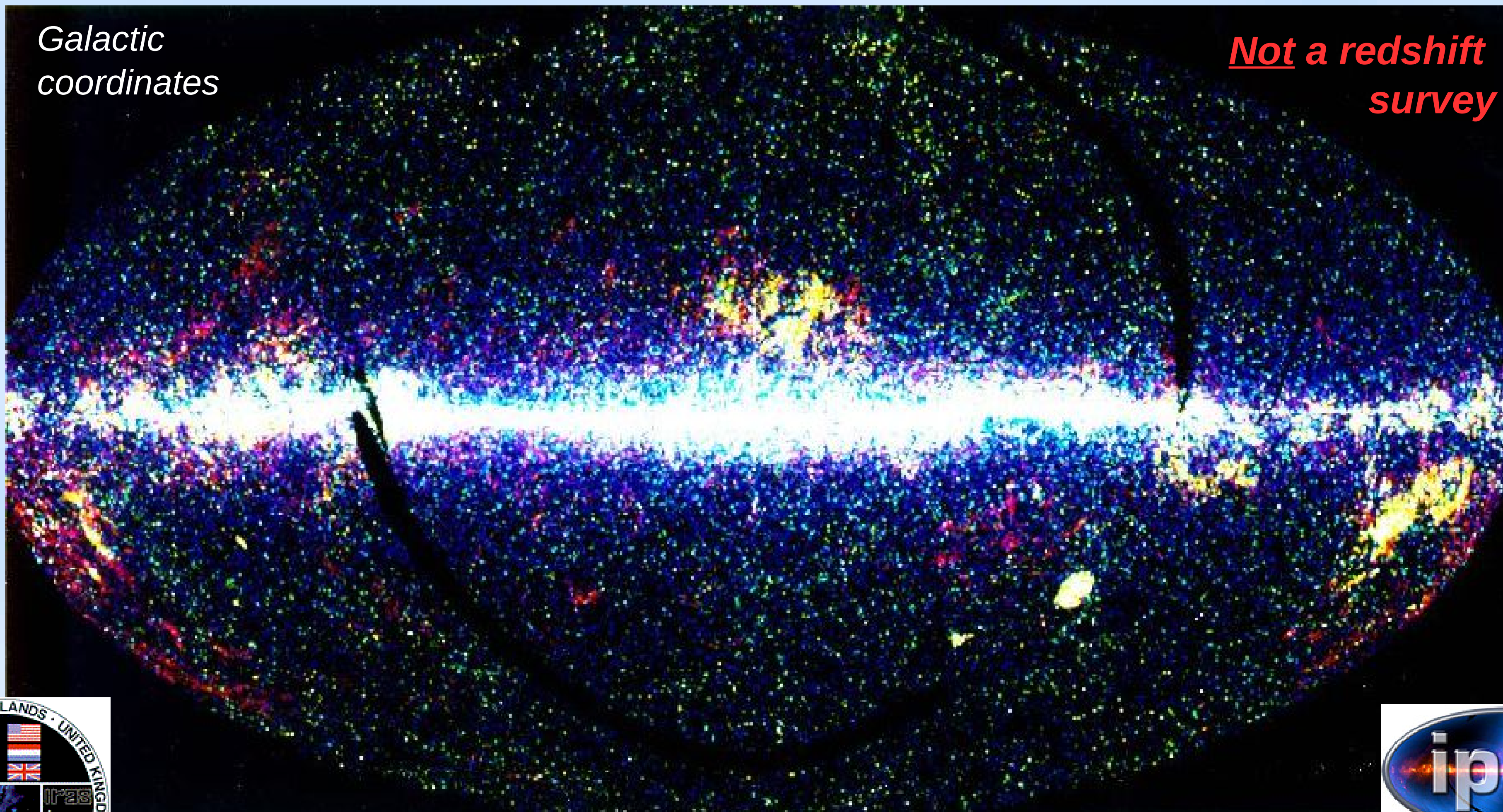


# Space-borne surveys...

**IRAS satellite** (1983) – a 60-cm telescope

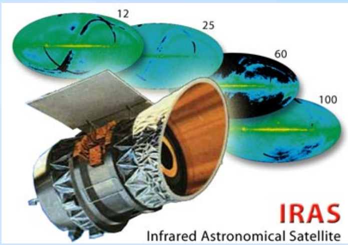
mid- and far-infrared (12 – 100 μm)

detected about 350,000 infrared sources




*IPAC / NASA*

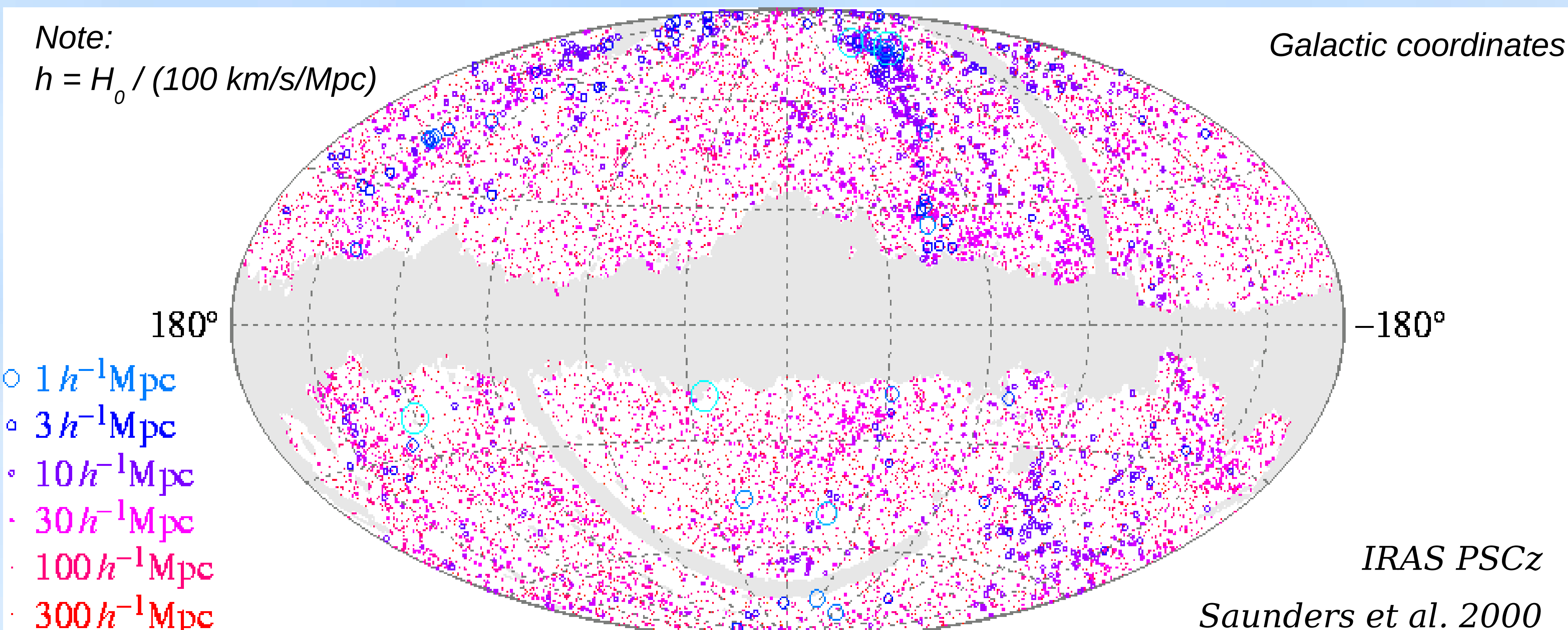
# First all-sky *redshift* survey...




Galaxies preselected from **IRAS** observations: positions and fluxes

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



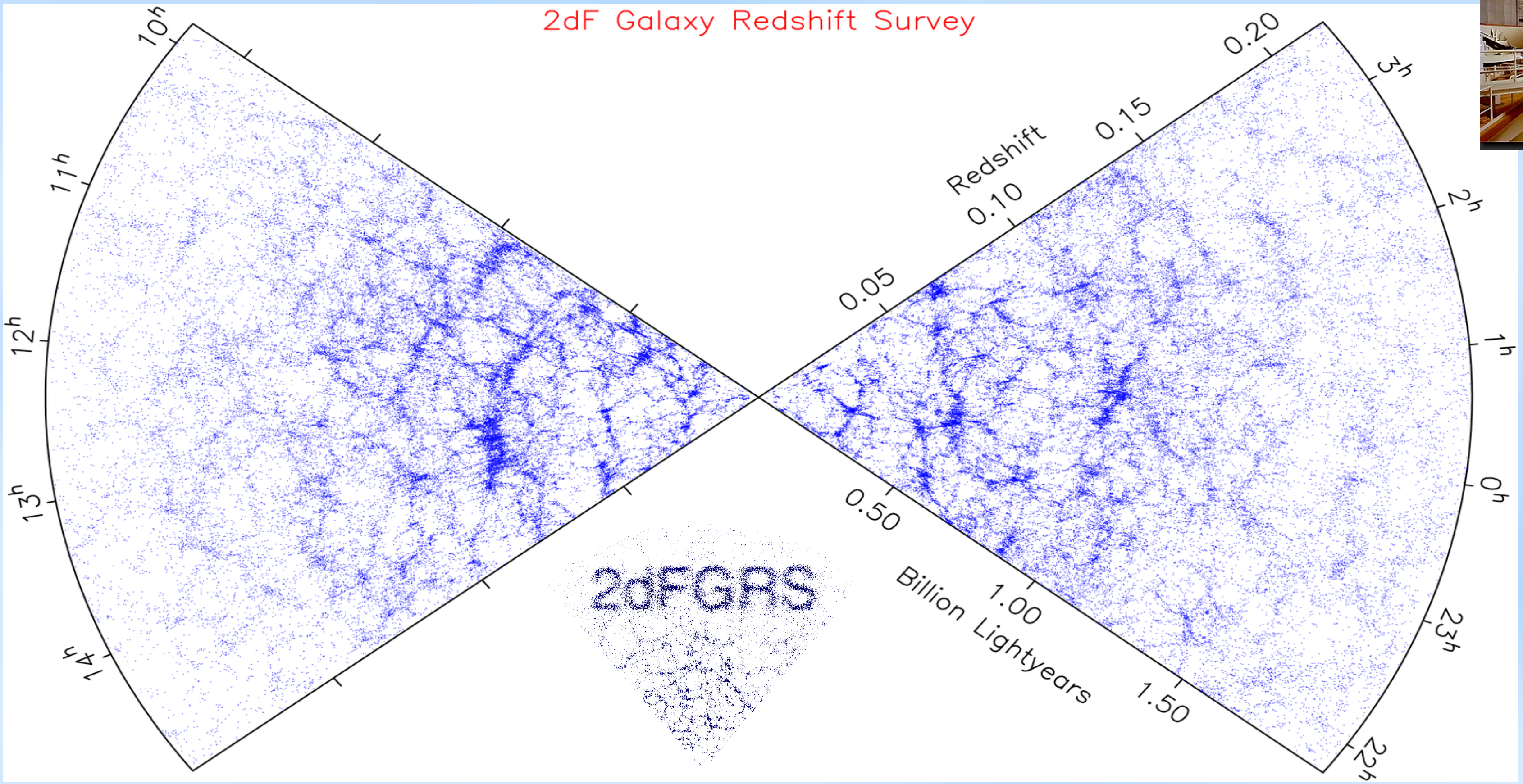
# Deep ground-based surveys...

**Two-degree-Field Galaxy Redshift Survey** (1997-2002)

3.9-m Anglo-Australian Telescope with a field of view 2°

Over 200,000 galaxies with redshifts on approx. 4% of sky

Reached to ~2 billion light years from us (z ~ 0.2)

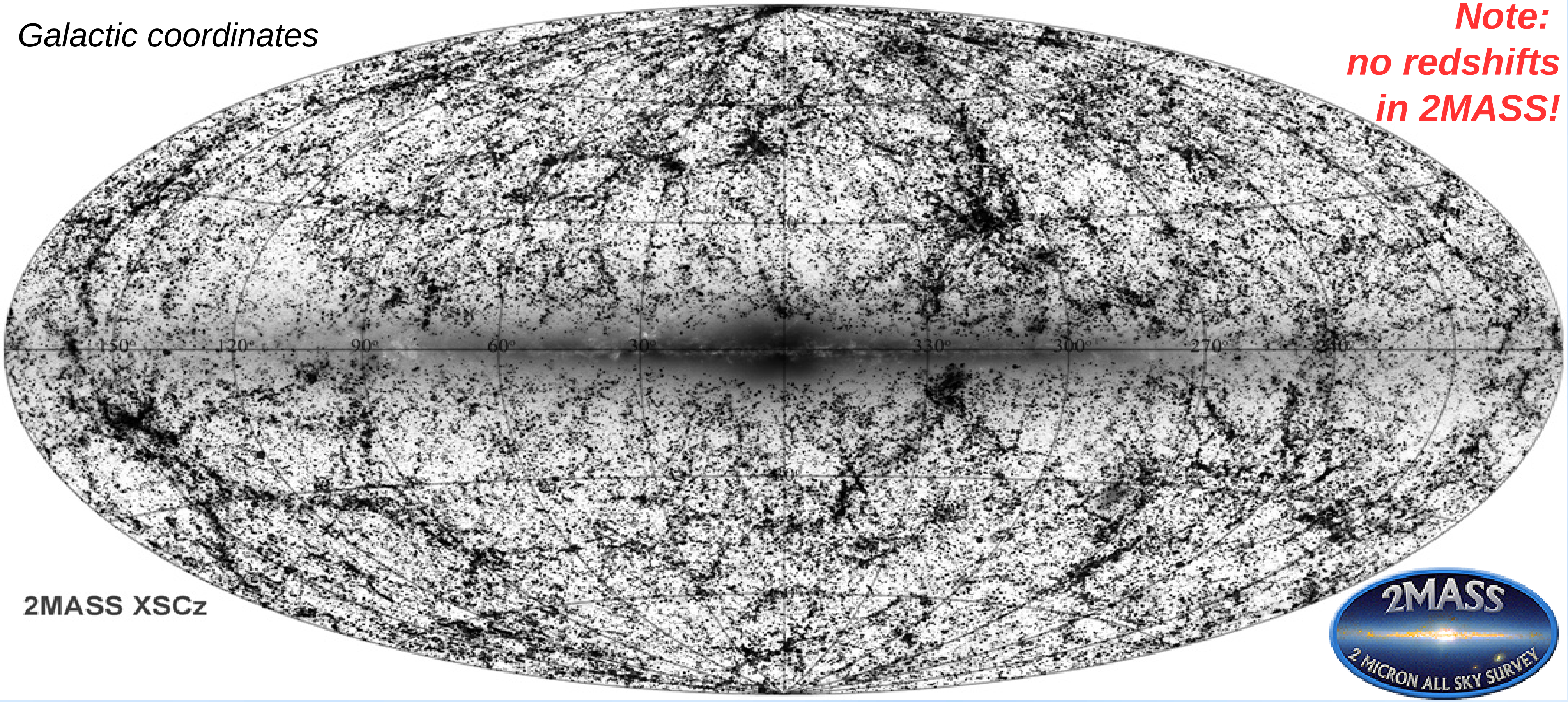
# Near infrared...

First survey of the entire sky at wavelengths 1 – 2.5 μm:

**Two Micron All Sky Survey, 2MASS** (1997-2001)

Two ground-based telescopes 1.3-m, photometry in 3 bands ($JHK_s$)

Over 1 million galaxies up to ~1 Gpc, almost 500 mln stars

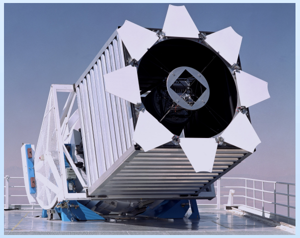


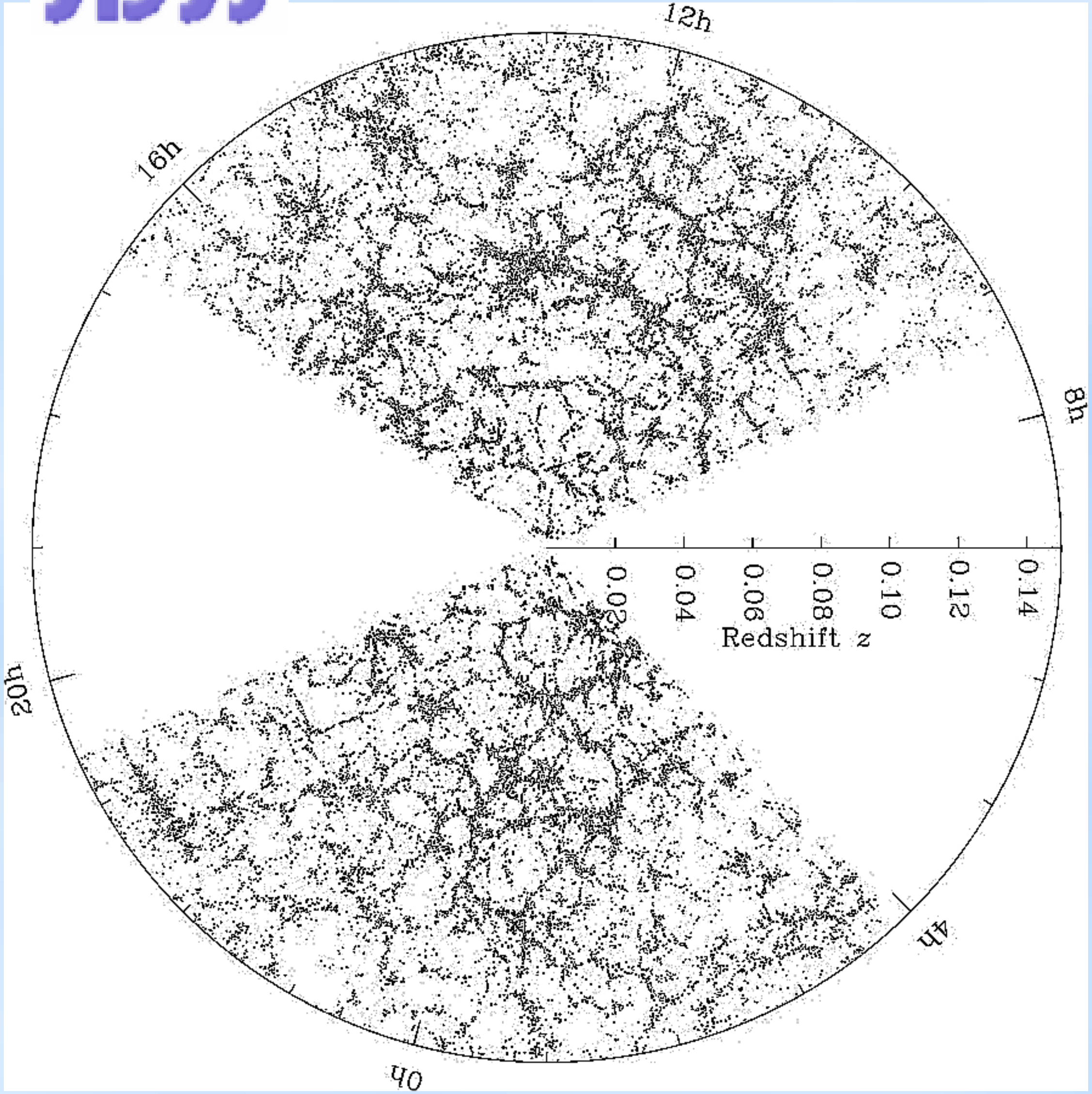

***Note: no redshifts in 2MASS!***

# The largest...

<u>The largest so far spectroscopic galaxy survey:</u>

**Sloan Digital Sky Survey, SDSS** (since 2000)
Three stages so far, 12 data releases






Observing 35% of the sky from a site in New Mexico (~25% in spectroscopy)

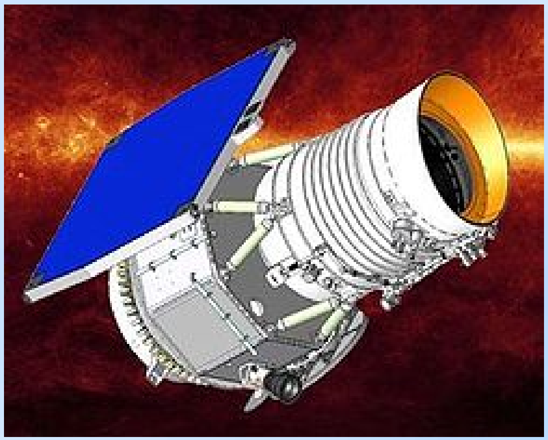
Currently over 2.4 mln galaxies and 0.5 mln quasars with measured redshifts

Additionally some 200 million of extragalactic sources with optical photometry in 5 bands

# The deepest...

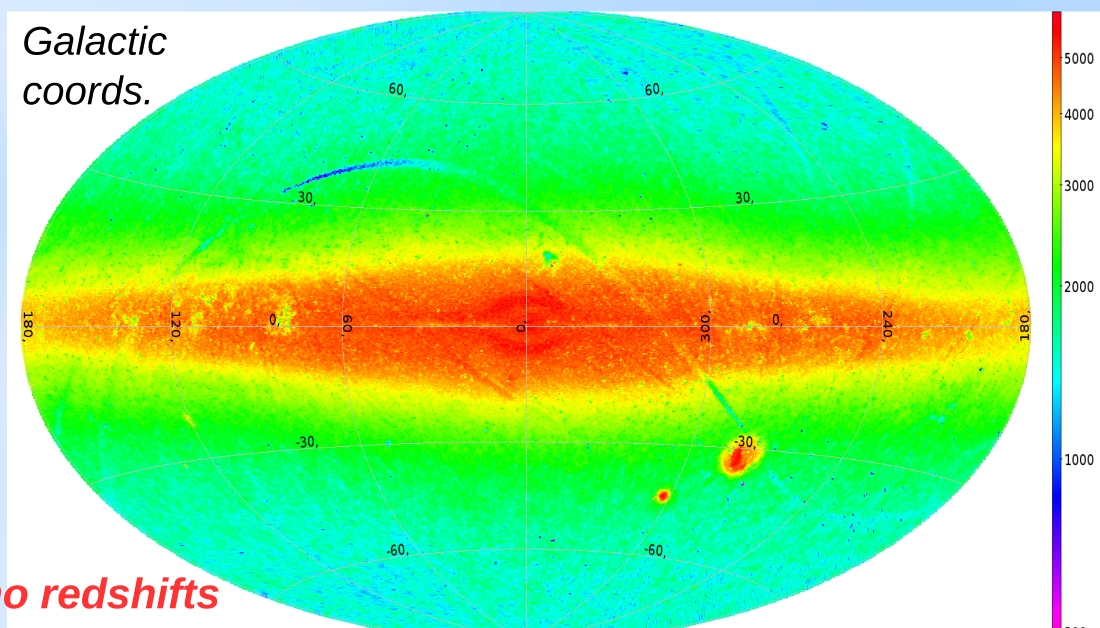
The deepest so far survey of the entire sky:

**Wide-field Infrared Survey Explorer, WISE** (since 2010)



Space-bourne photometric survey
in mid-infrared (3.5 – 23 μm)
40-cm telescope orbiting the Earth

A catalogue of 750 mln sources,
of which about 100 mln galaxies
and ~3 million quasars




***no redshifts here either!***

Low angular resolution (>5”)
hinders source type
identification (stars/galaxies/…)
*[but see automatised approach: Kurcz, MB, et al. (2016)]*

# The largest...

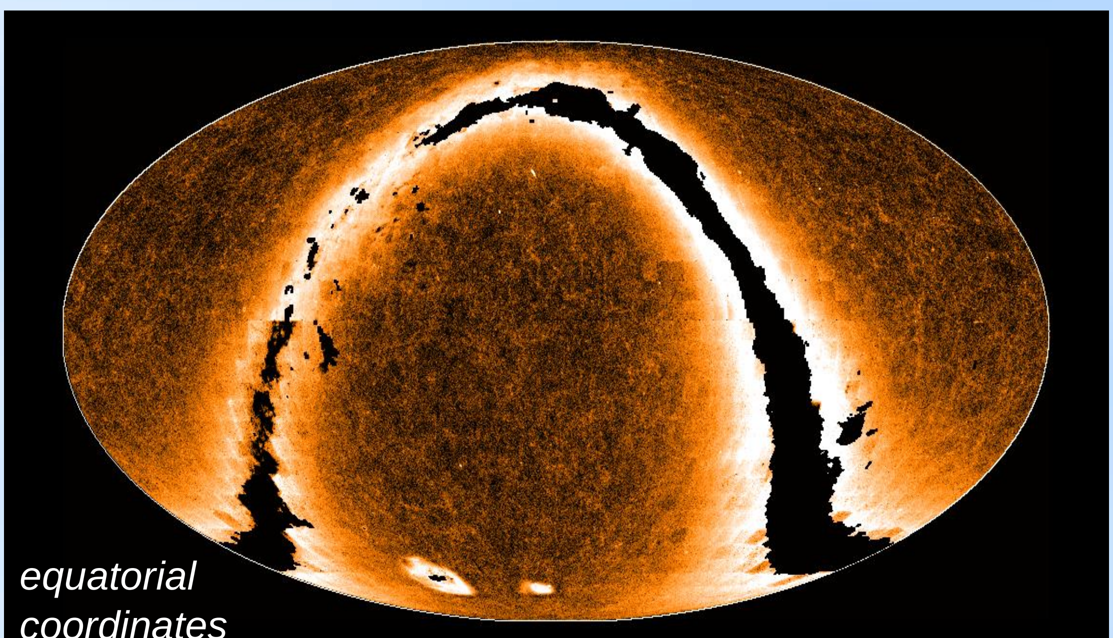
<u>The largest catalogue of all-sky optical data:</u>

**SuperCOSMOS Sky Survey**

SuperCOSMOS
Sky
Survey

Scanned and digitised photographic plates, original data obtained late 20-th century

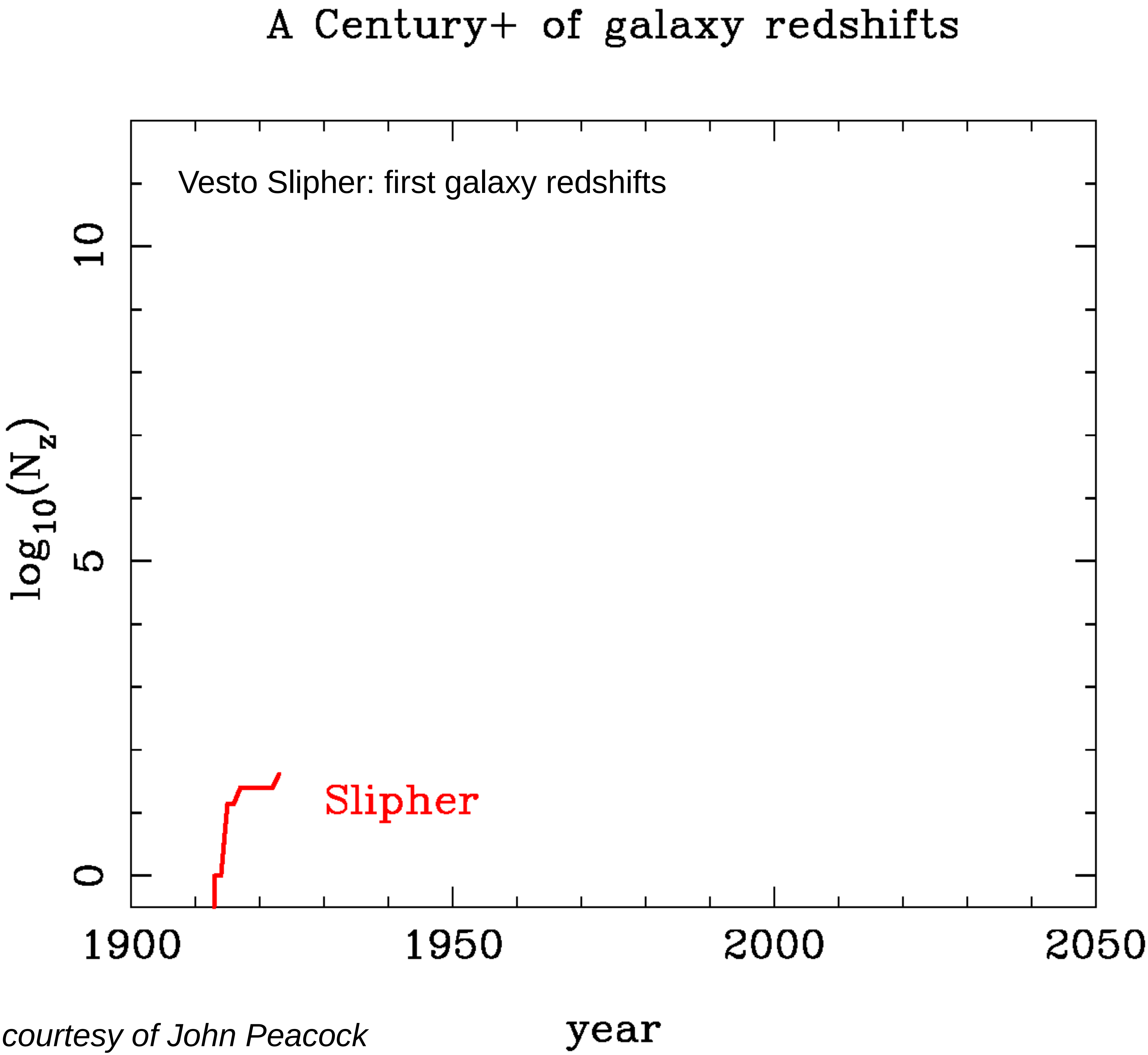
*Again, not a redshift survey!*




Still the largest dataset of optical data covering the entire celestial sphere! (will be superseded by **Gaia** – but only for stars)

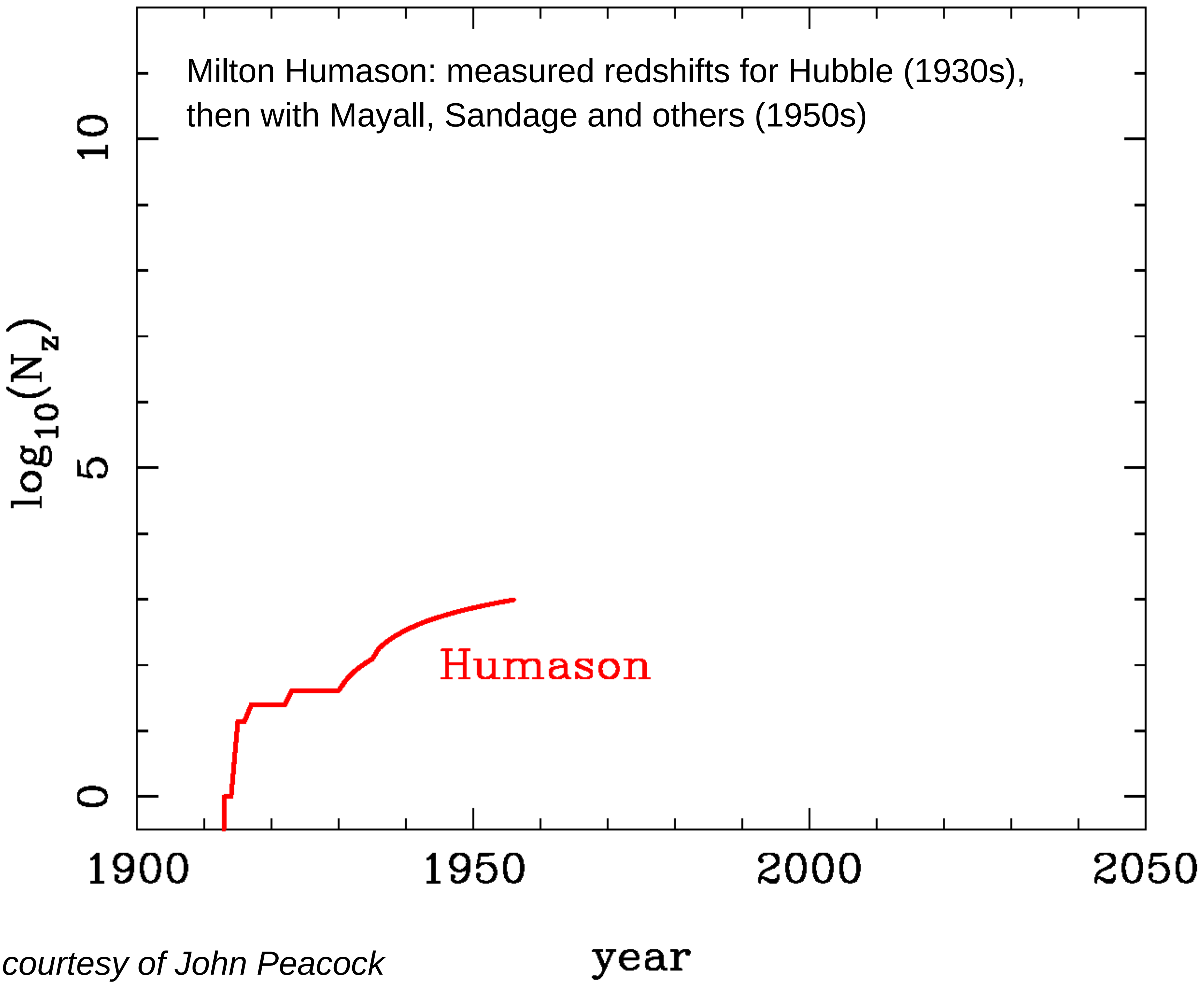
Almost 2 billion catalogued sources, of which ~10% scientifically useful

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

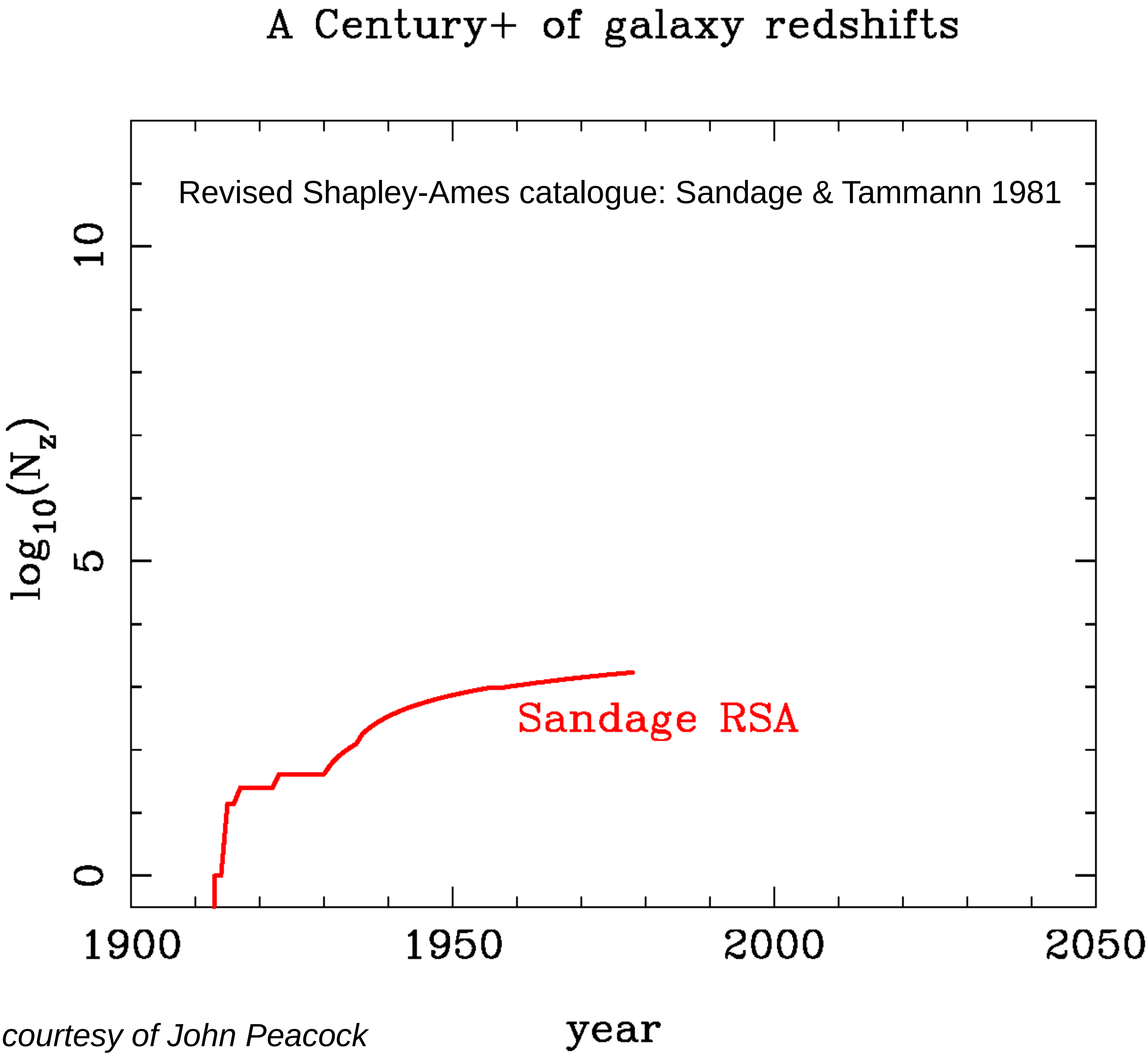



*Plots courtesy of John Peacock*

# A Century+ of galaxy redshifts




*Plots courtesy of John Peacock*

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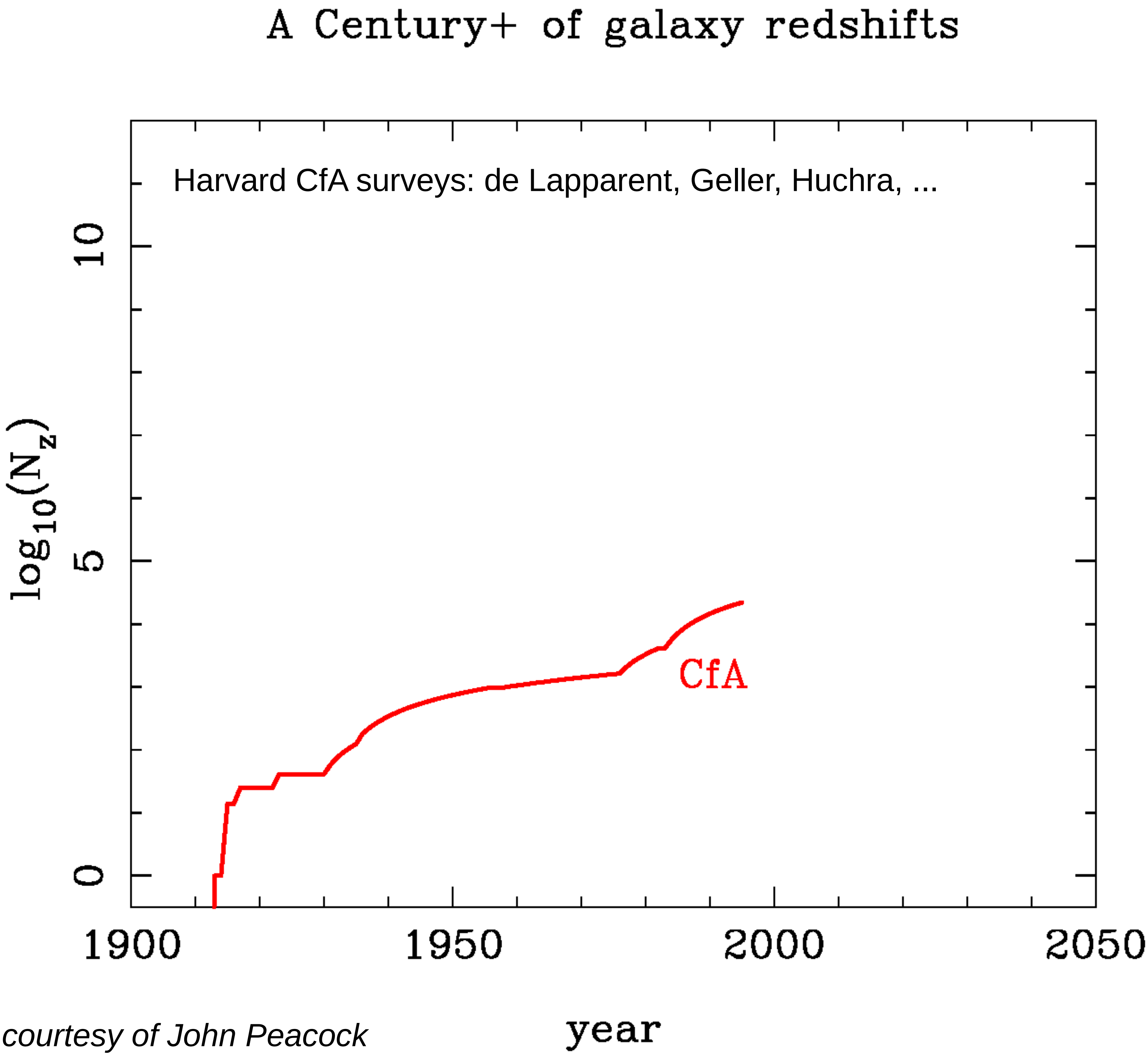


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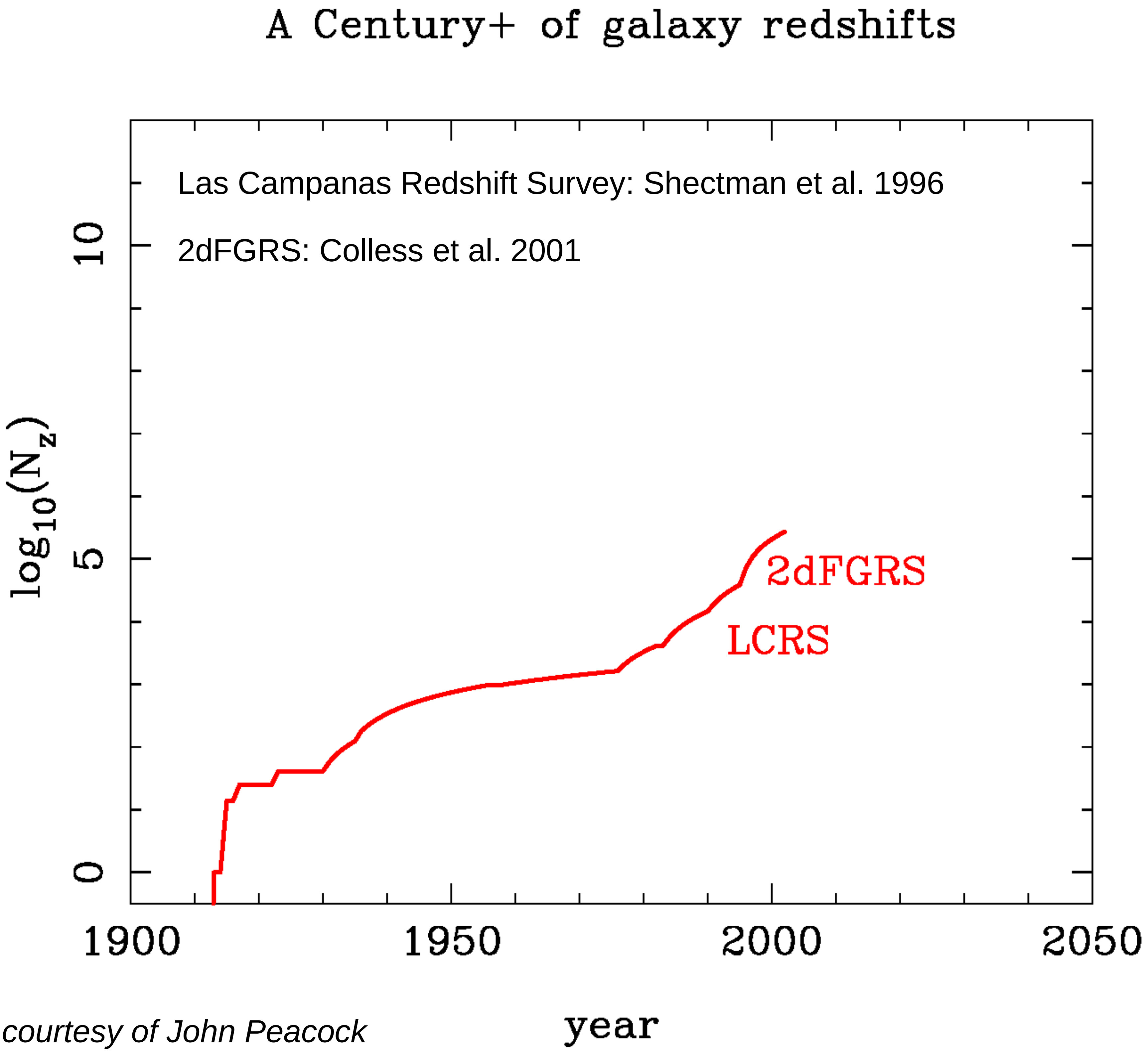


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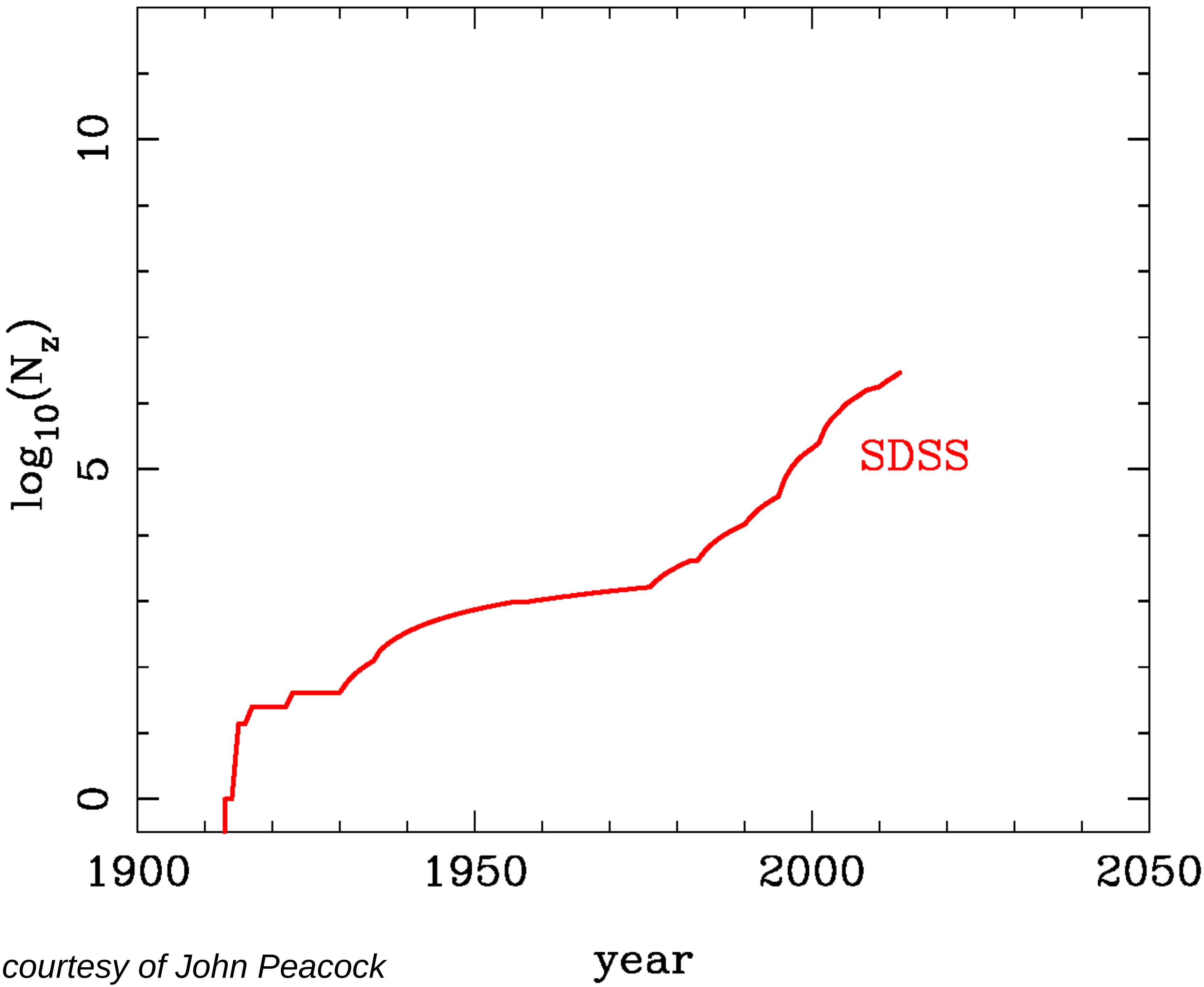
# A Century+ of galaxy redshifts

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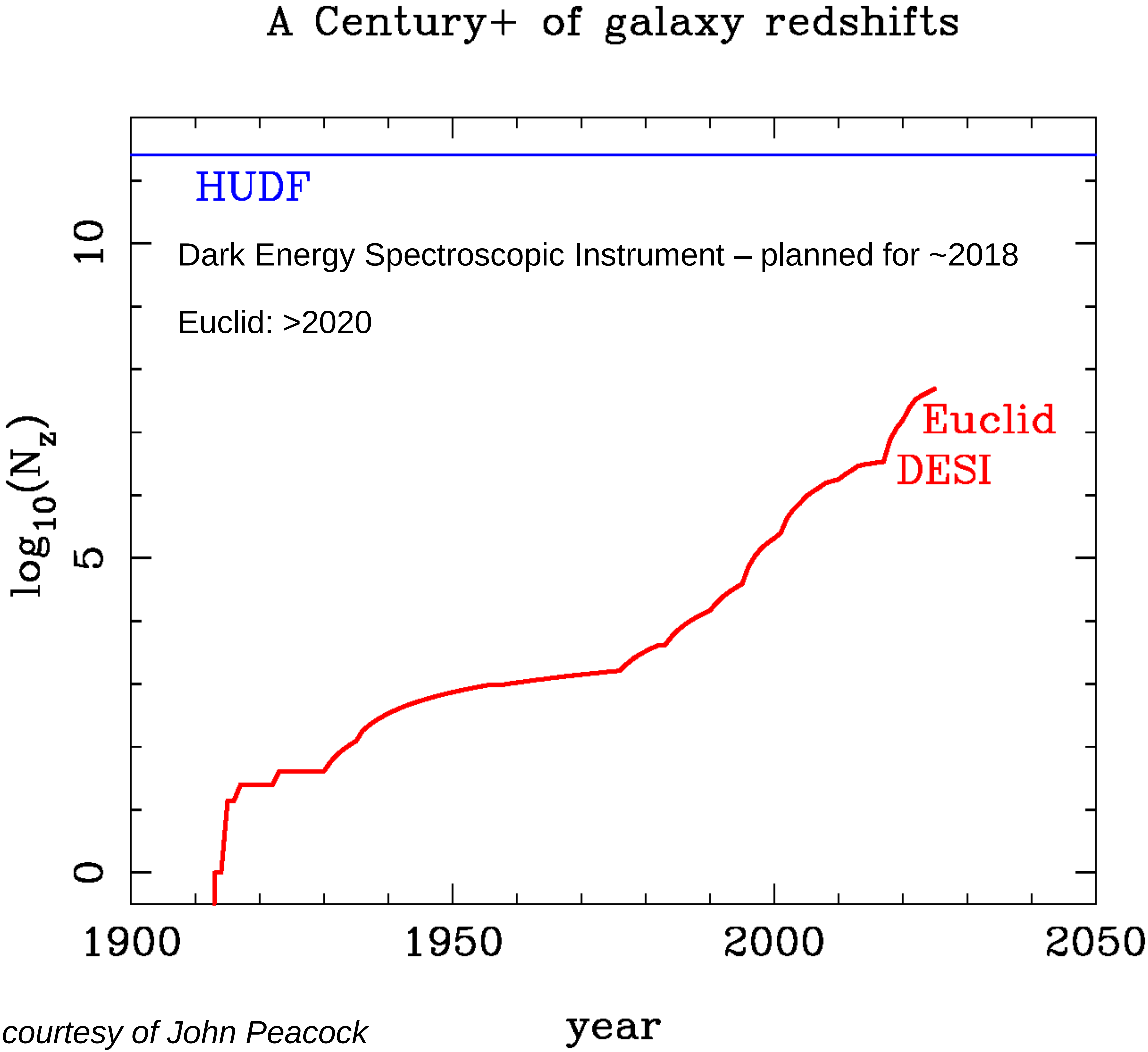



*Plots courtesy of John Peacock*

# The present and near future of galaxy surveys

**Some surveys happening now:**

* **SDSS** (currently stage IV): galaxies, quasars (spectroscopy)

* Dark Energy Survey (**DES**): optical photometry on 5000 $deg^2$

* Kilo-Degree Survey (**KiDS**): precise optical and near-IR (**VIKING**) photometry on 1500 $deg^2$ (ESO)

* Vista Hemisphere Survey (**VHS**): near-infrared photometry over half of the sky (ESO)

* and many, many others

**Terabytes of data**

# Near and more remote future of galaxy surveys

**Planned surveys (examples):**

- **TAIPAN** – spectroscopy of 500,000 galaxies at z~0.1 (from 2016)
- Dark Energy Spectroscopic Experiment (**DESI**) – spectroscopy of ~30 million galaxies (from 2018?)
- Square Kilometer Array (**SKA**) – array of radiotelescopes in South Africa and Australia; millions of galaxies at (emitted) 21 cm wavelength (from ~2020?; precursors already operating/built)
- **Euclid** – European space-bourne near-IR telescope; slitless spectroscopy and deep photometry on ~1/3 of the sky; 2020s(?)
- Large Synoptic Survey Telescope (**LSST**) – photometric survey on an 8.4-m telescope in Chile; ~40 billion(?) sources (~2023?)

**Petabytes of data**

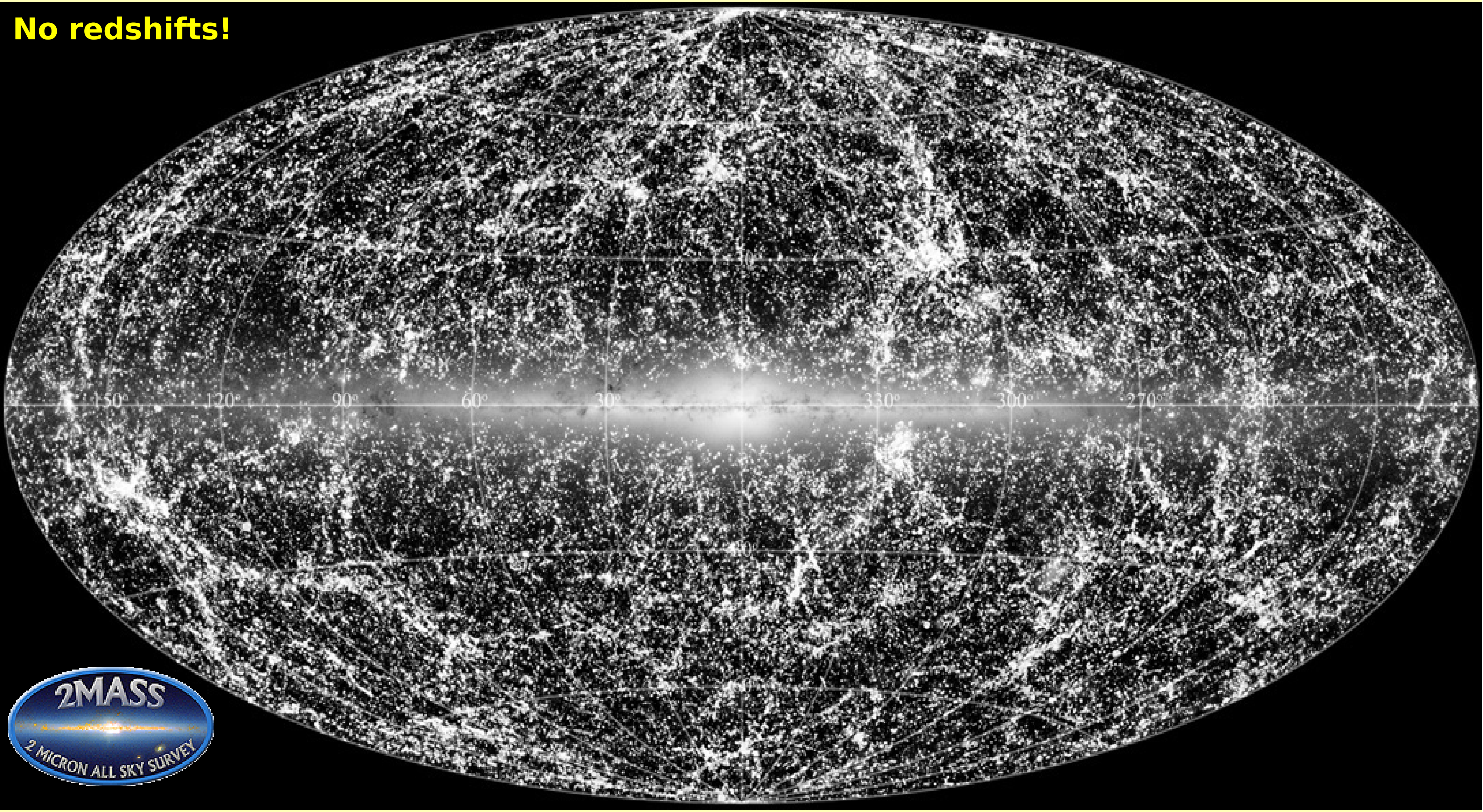
# Cosmology marches on

# The largest all-sky dataset of confirmed galaxies

## 2MASS eXtended Source Catalog: 1.6 million galaxies

of which 1 million within completeness limit of $K_s$<13.9

**No redshifts!**

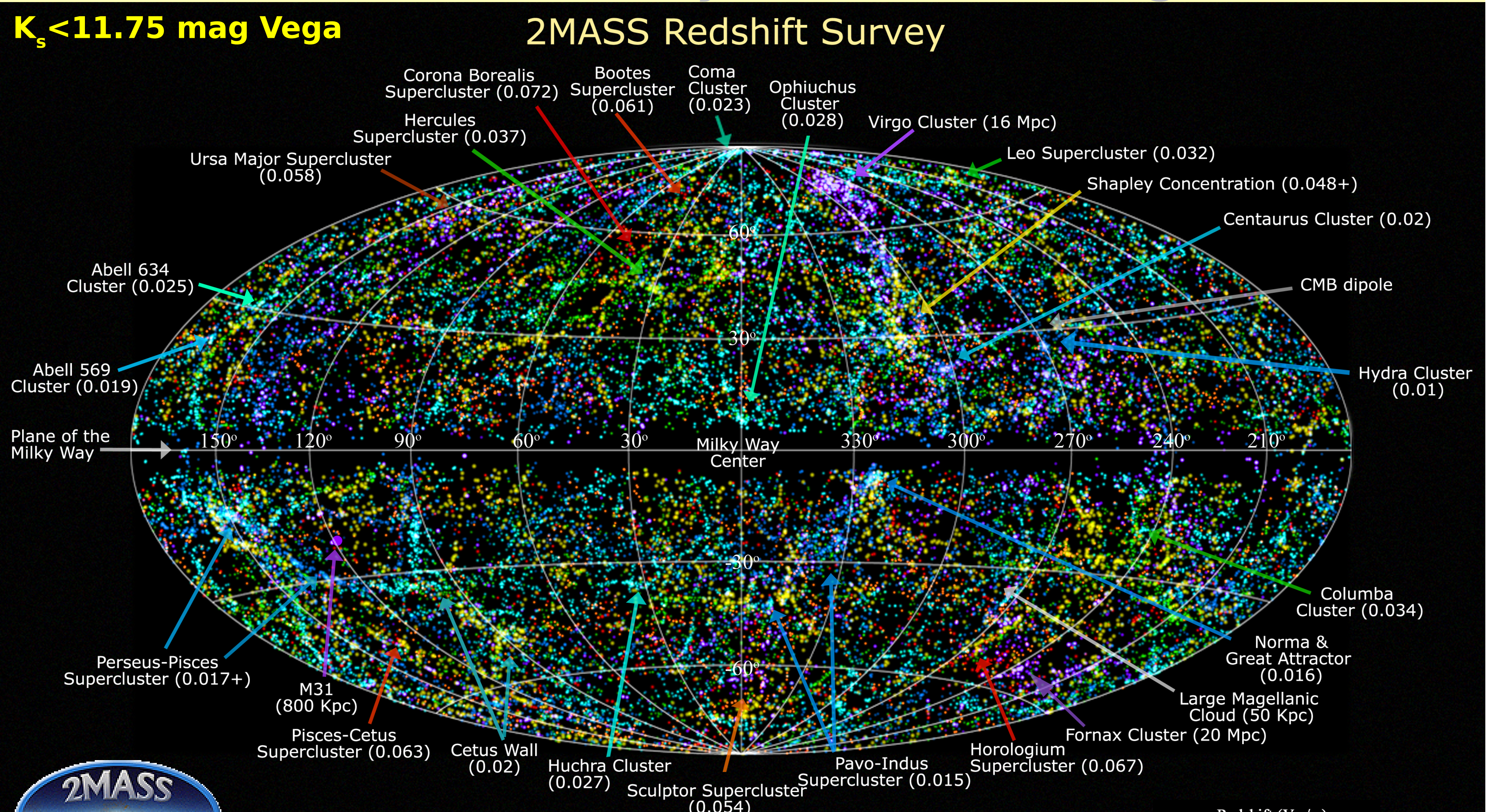



***Jarrett 2004; Skrutskie et al. 2006***

# The largest uniform all-sky redshift sample

## 2MASS Redshift Survey (2MRS): 45,000 galaxies

**$K_s$<11.75 mag Vega**




***Legend:*** image shows 2MASS galaxies color coded by the 2MRS redshift (Huchra et al 2011); familiar galaxy clusters/superclusters are labeled (numbers in parenthesis represent redshift).

Graphic created by T. Jarrett (IPAC/Caltech)

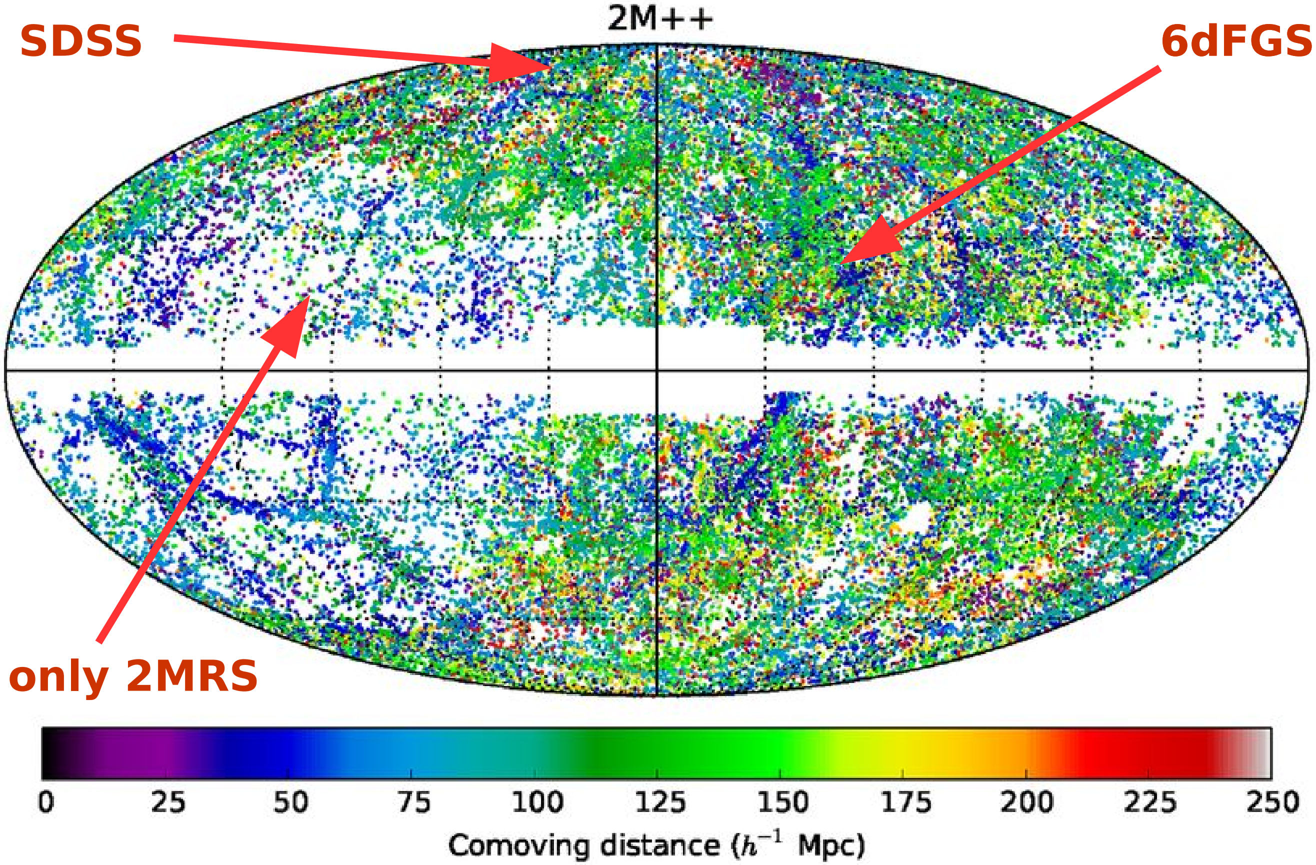
***Huchra et al. 2012 (plot by Tom Jarrett)***

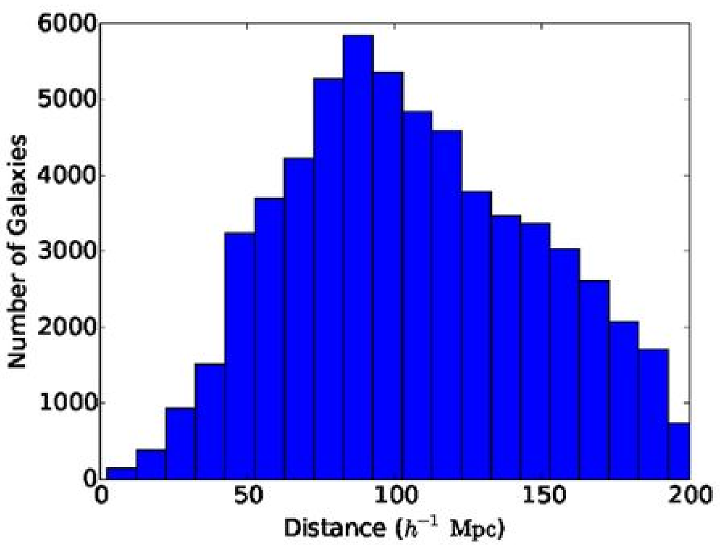
# 2M++ galaxy redshift catalogue:

**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



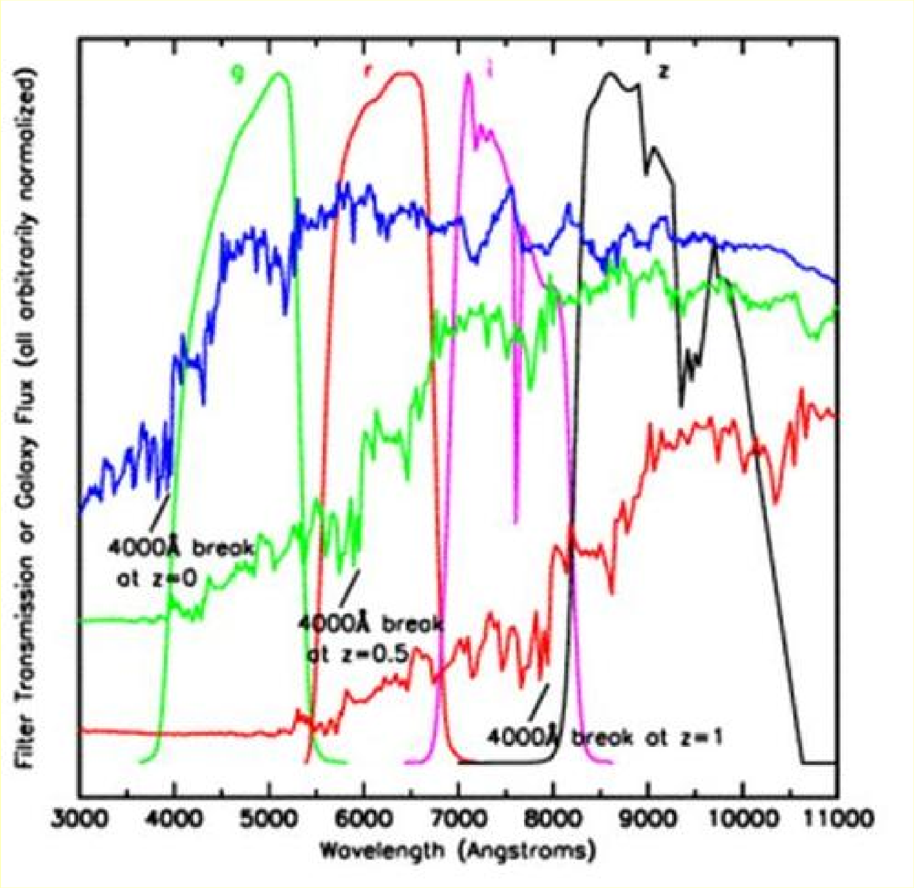




*Lavaux & Hudson 2011; Carrick et al. 2015*

# New data = new possibilities

Multiwavelength astronomy

**Joining photometric catalogs** from various wavelengths allows us to extract additional information



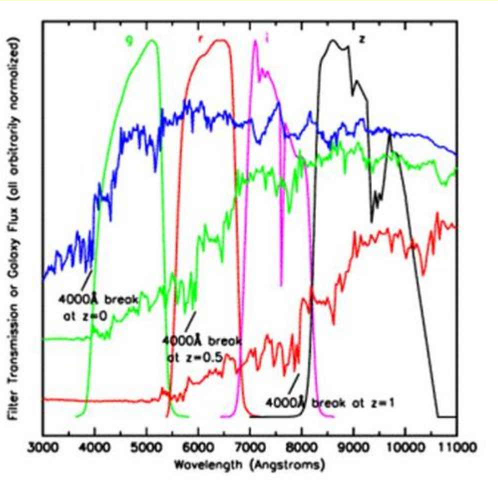

Example: ***photometric redshifts***
Redshift is *estimated* from flux variations in particular passbands (rather than *measured* from line shifts)

**Pros**: a much faster and cheaper way to trace the 3D distribution of millions of galaxies – only way for the future

**Cons**: much worse* precision than available from spectroscopy
*usually by two orders of magnitude

*More generally: **SED fitting** for various galaxy properties – workshop on Friday*

# Photometric redshifts



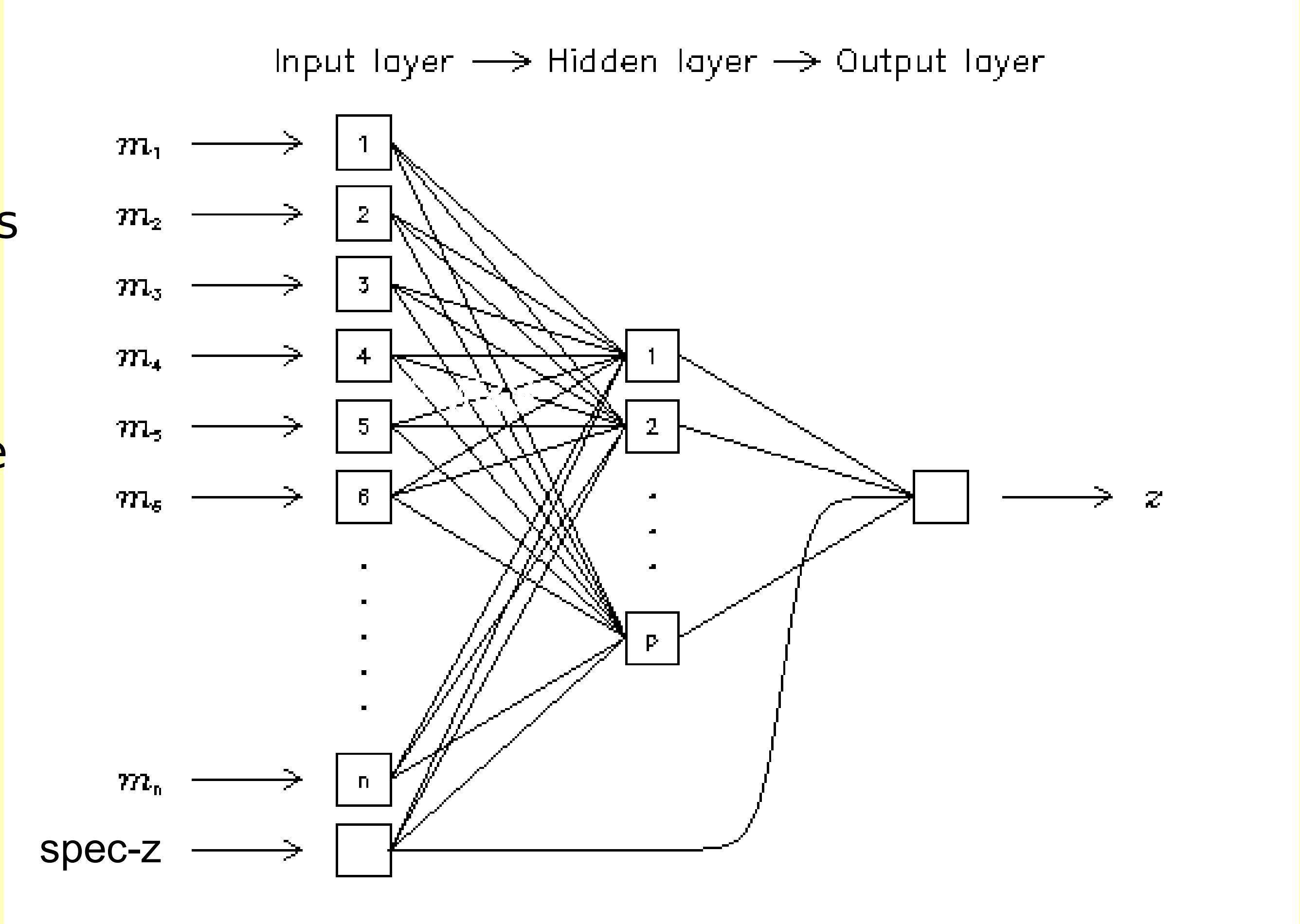

Cosmological **shift** of **lines** and of the **continuum**

+ **decrease** in bolometric **flux** + evolution

= wavelength-dependent **magnitude changes**

- **Machine learning** algorithms (such as **neural networks**) can be **trained** on **spectroscopic** data to derive best-fit **photo-zs** for a given set of passbands

- Photo-zs can be also derived **without training sets** through **SED fitting**

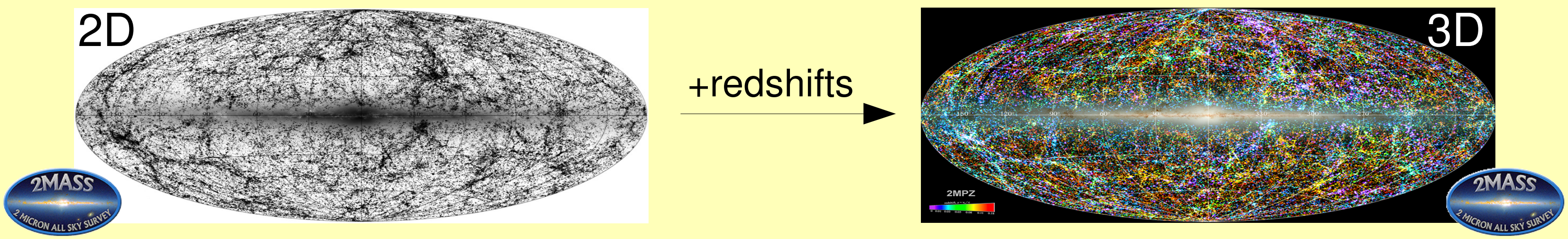



*ANNz, Collister & Lahav 2004*
*ANNz2, Sadeh et al. 2015*

# Photometric redshifts in practice:

## 2MASS Photometric Redshift catalog (2MPZ)

We added the 3rd dimension to the 2MASS catalog thanks to the additional photometry from WISE and SuperCOSMOS surveys
(built on earlier attempts by Jarrett 2004; Francis & Peacock 2009)

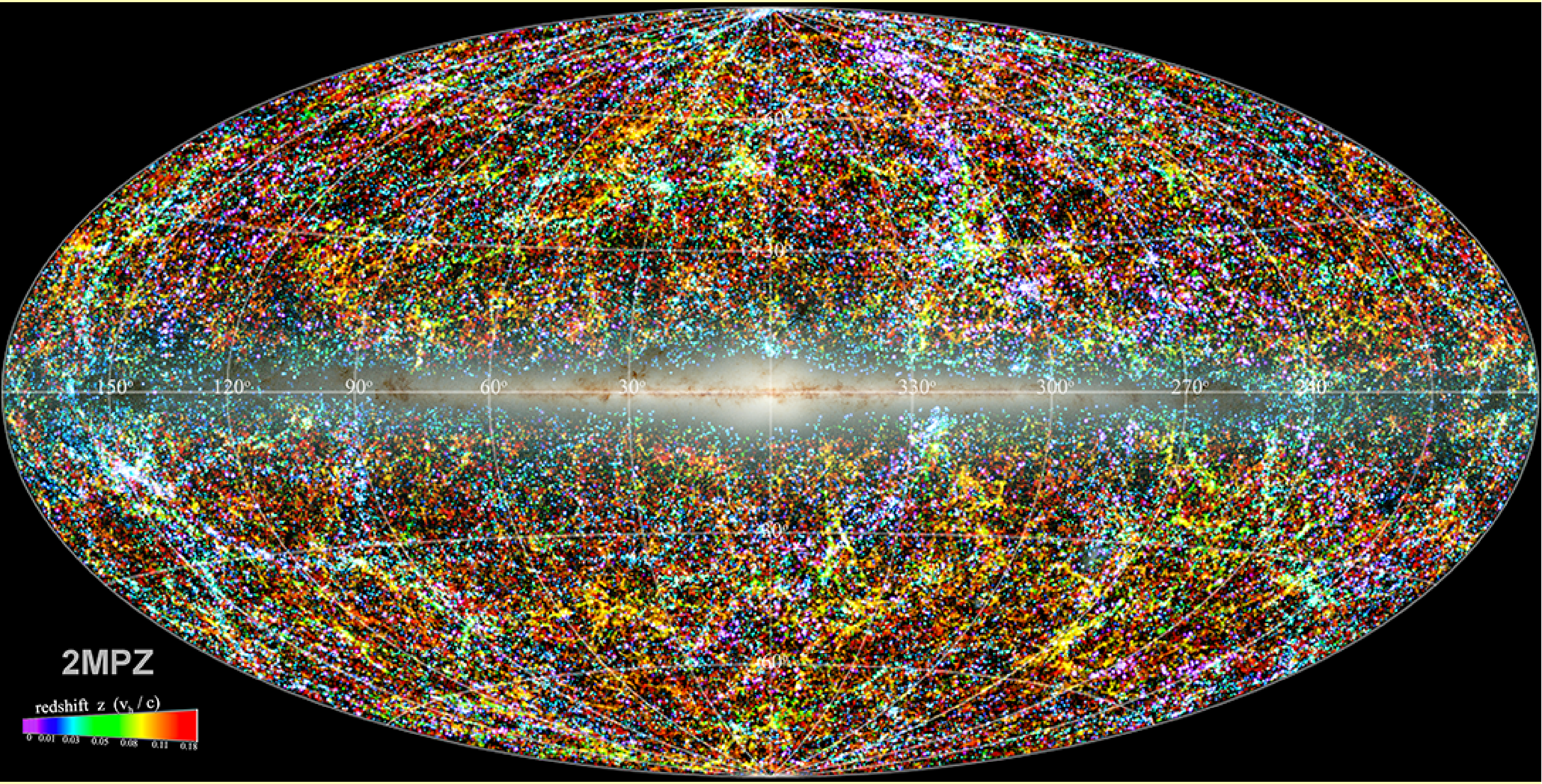



- Photometric redshifts in 2MPZ have **precision of ~12%** – sufficient for various cosmological applications
- Publicly available catalog of almost **one million galaxies**
- Now followed by a 3x deeper WISE x SuperCOSMOS dataset

MB, Jarrett, Peacock et al. (2014); MB, Peacock, Jarrett et al. (2016)

# Photometric redshifts in practice:

## 2MASS Photometric Redshift catalog (2MPZ)

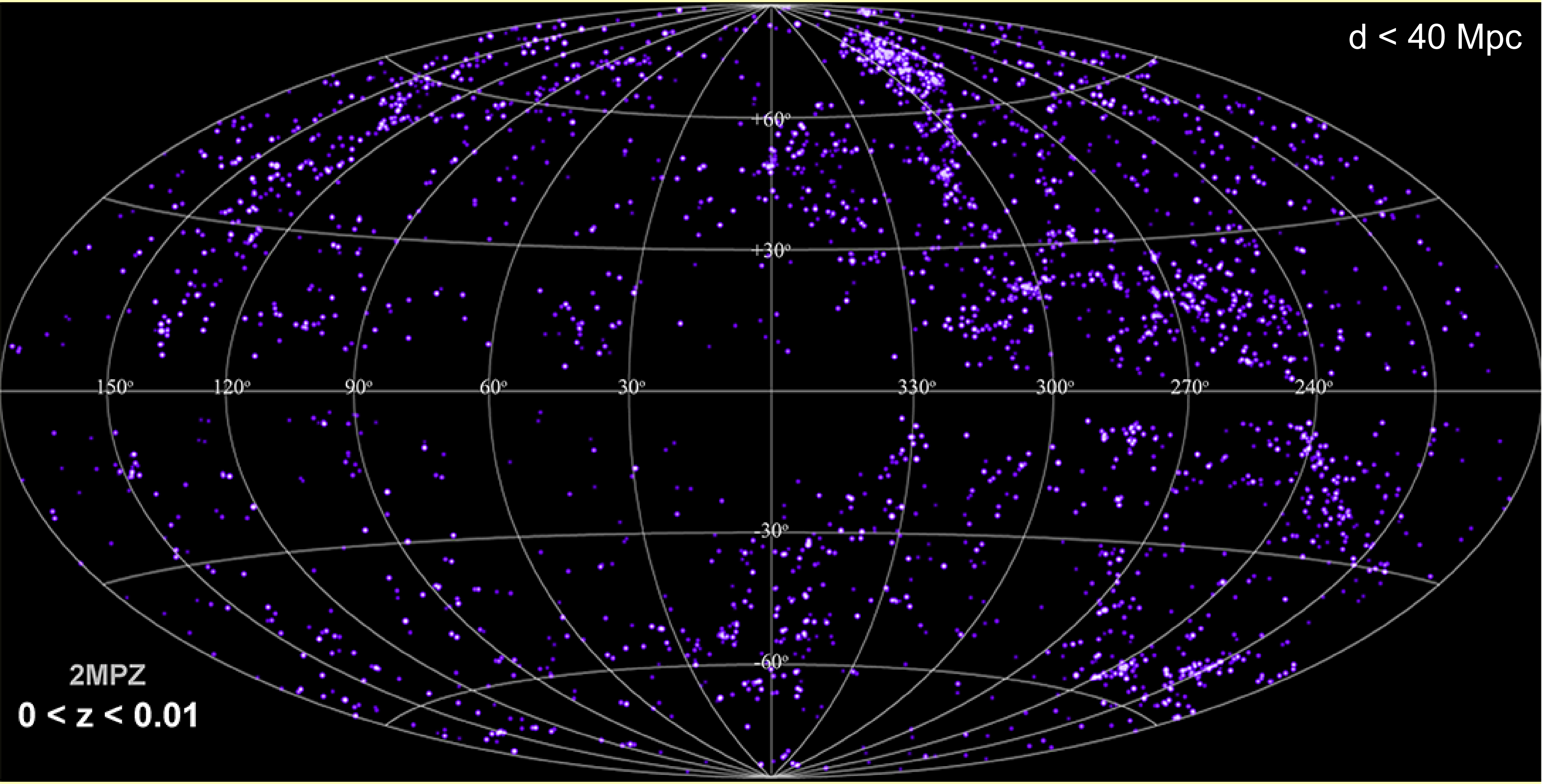



Color-coding according to photometric redshifts (0<z<0.2) [plot by Tom Jarrett]

# 2MASS Photometric Redshift catalogue

## 1 million galaxies in 3D

Slices through the Universe




Plot by Tom Jarrett

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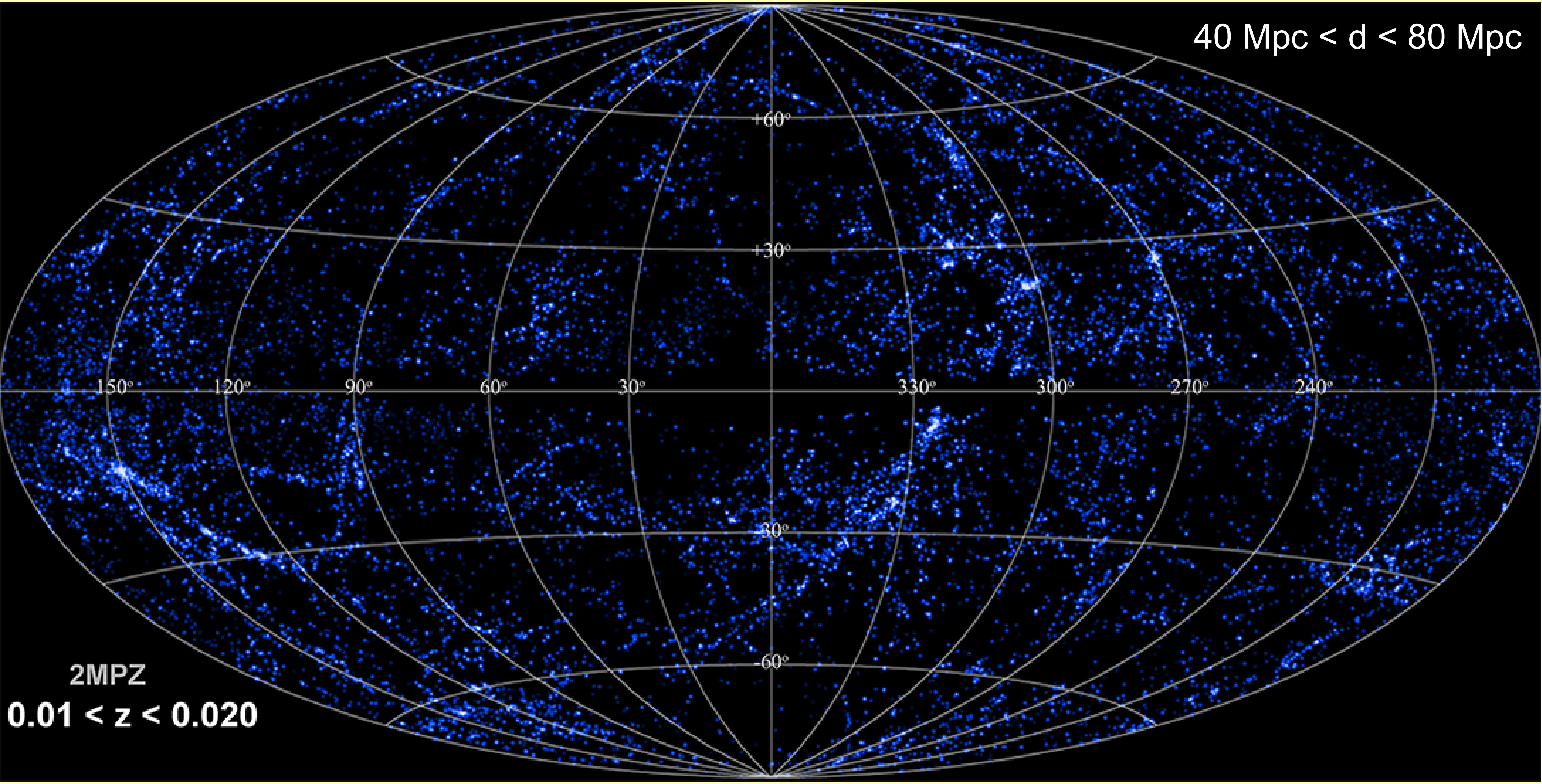


Plot by Tom Jarrett

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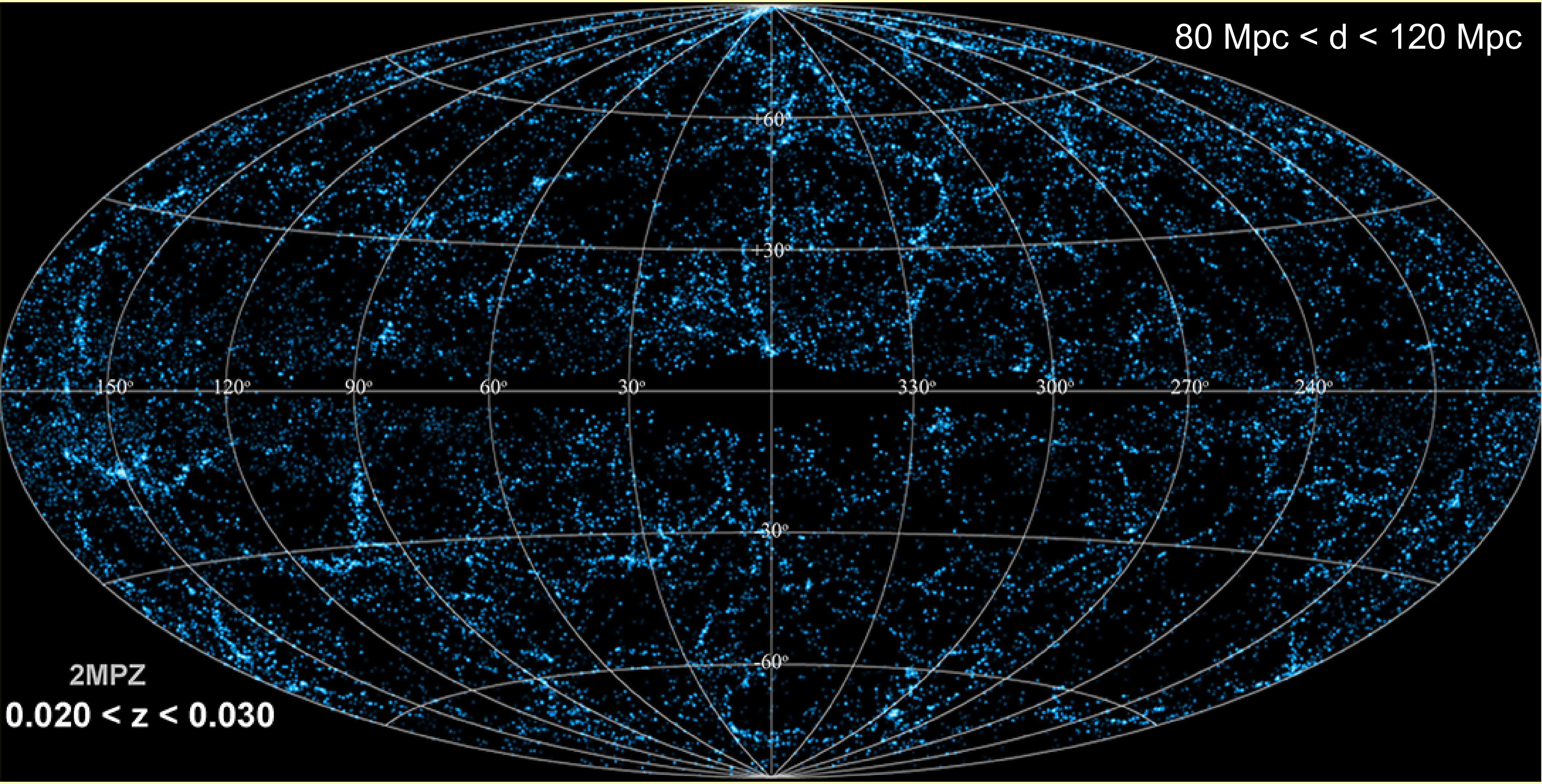


Plot by Tom Jarrett

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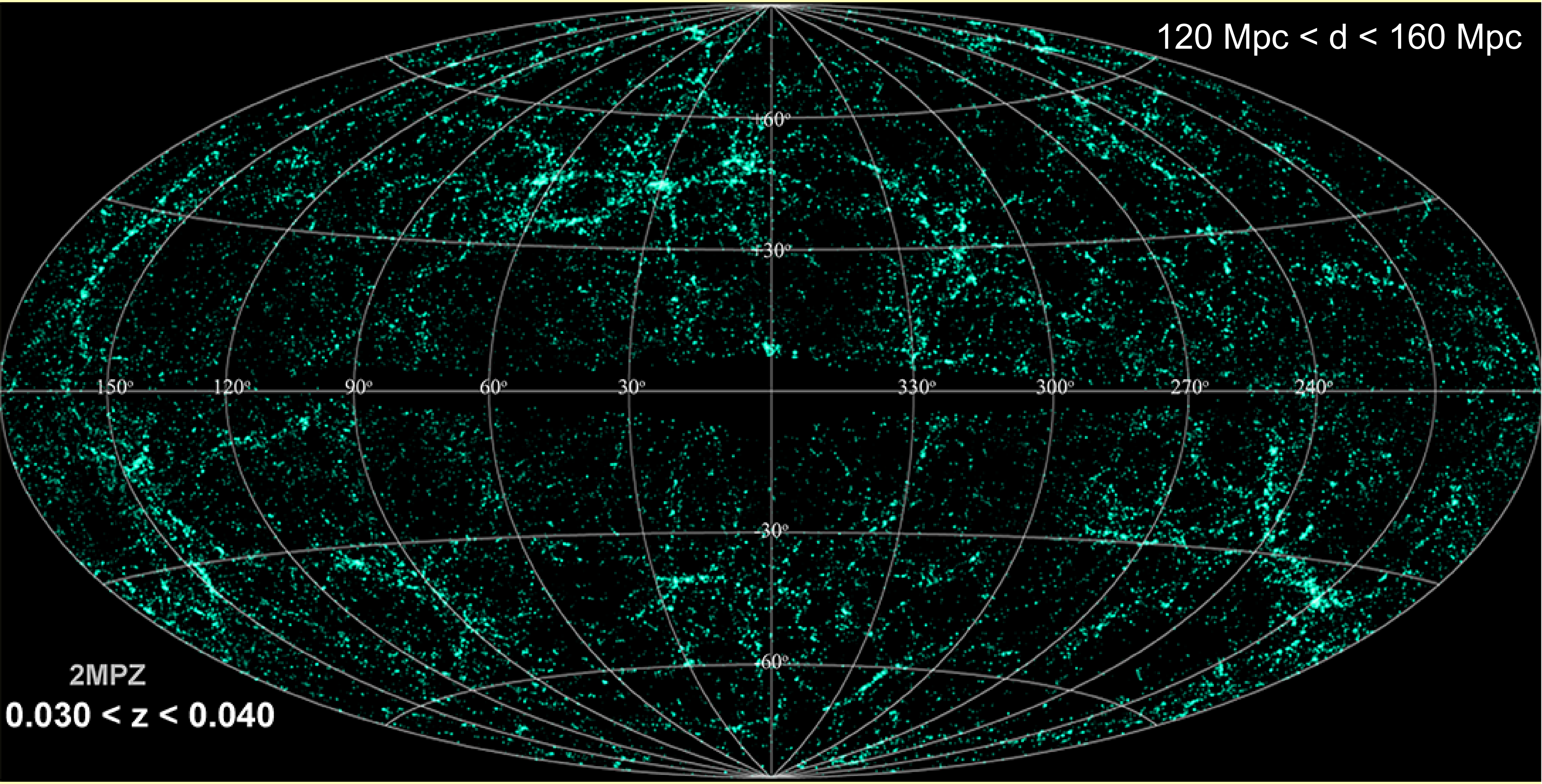


Plot by Tom Jarrett

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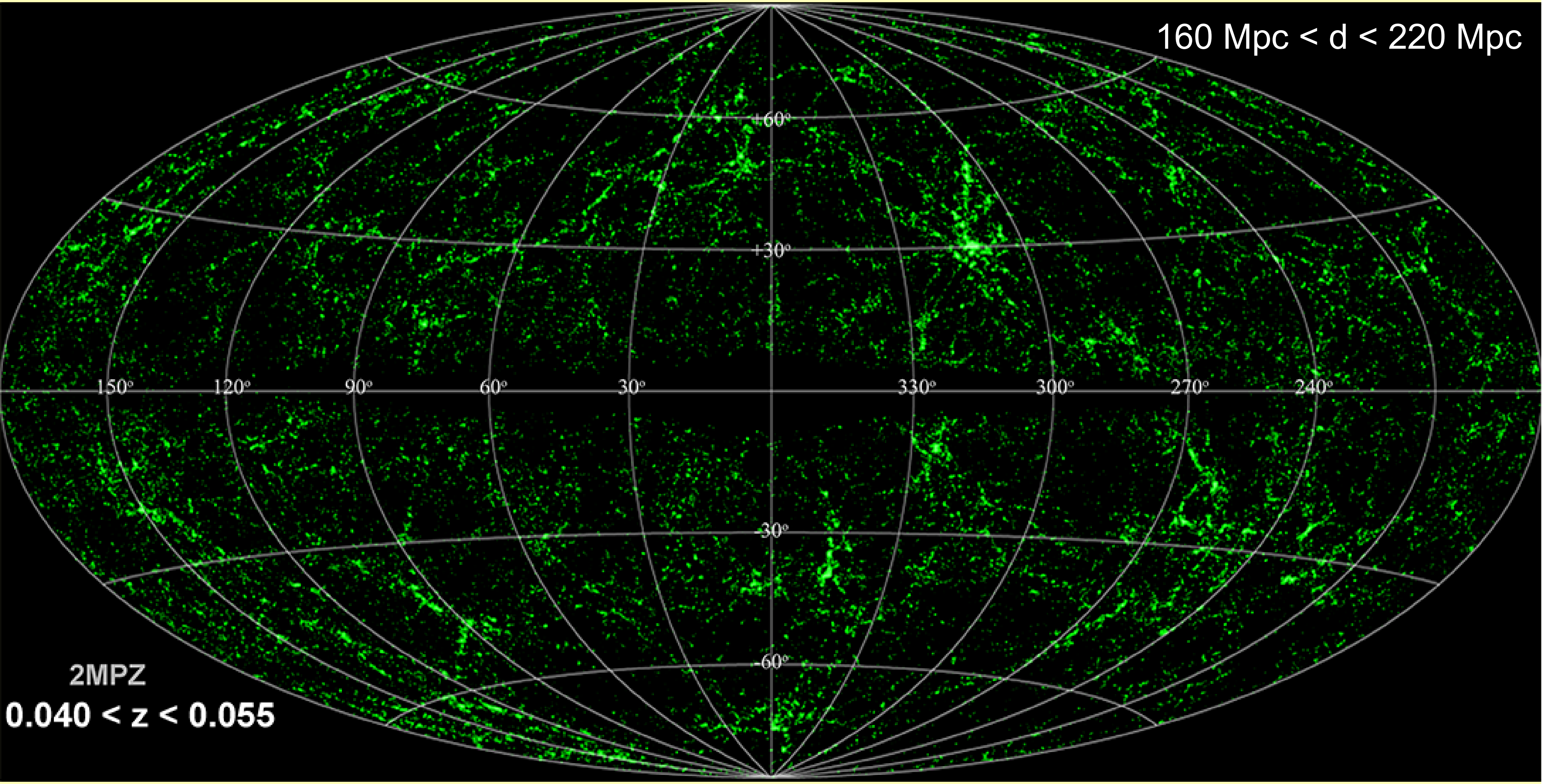


Plot by Tom Jarrett

# 2MASS Photometric Redshift catalogue

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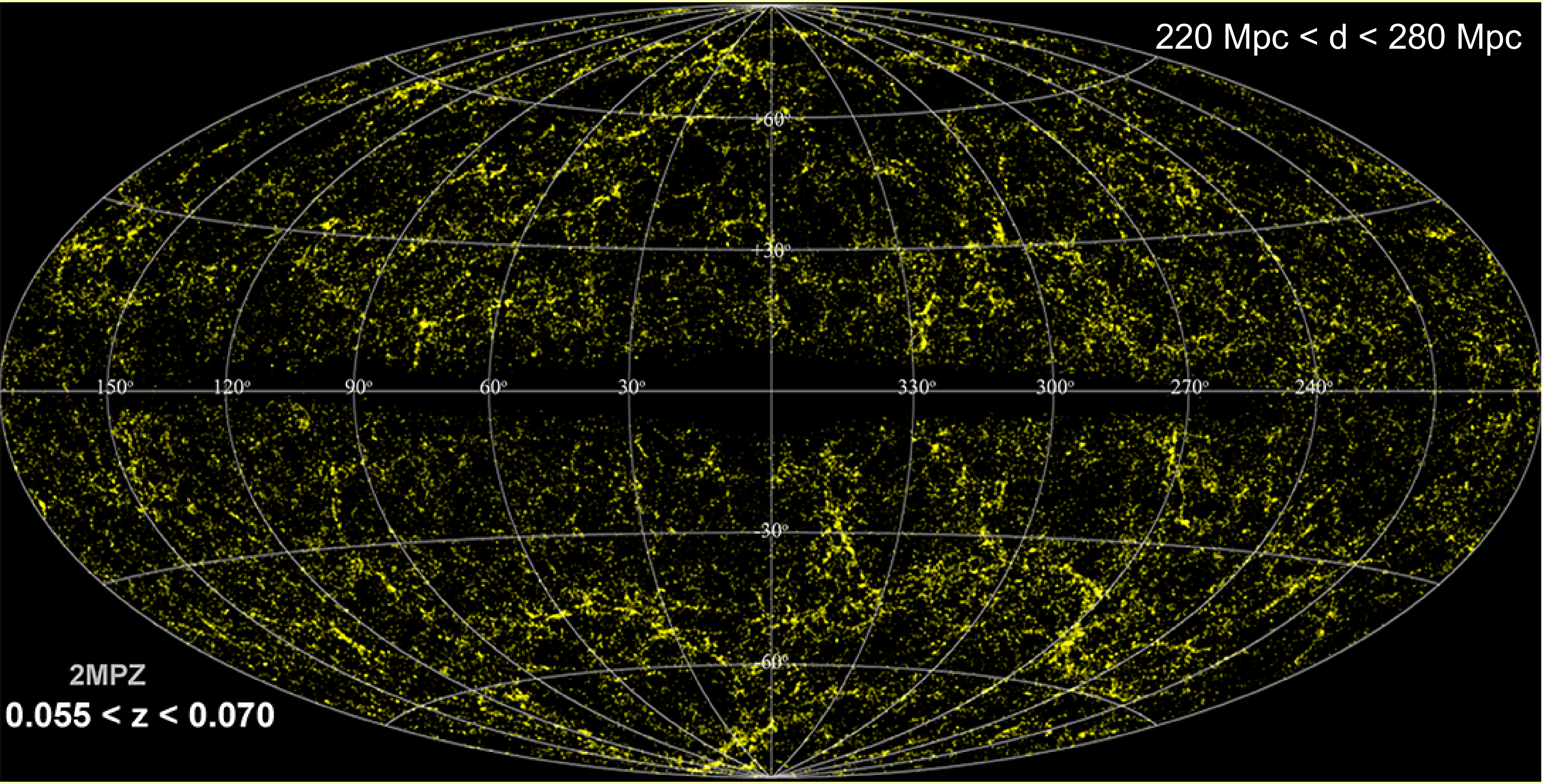


Plot by Tom Jarrett

# 2MASS Photometric Redshift catalogue

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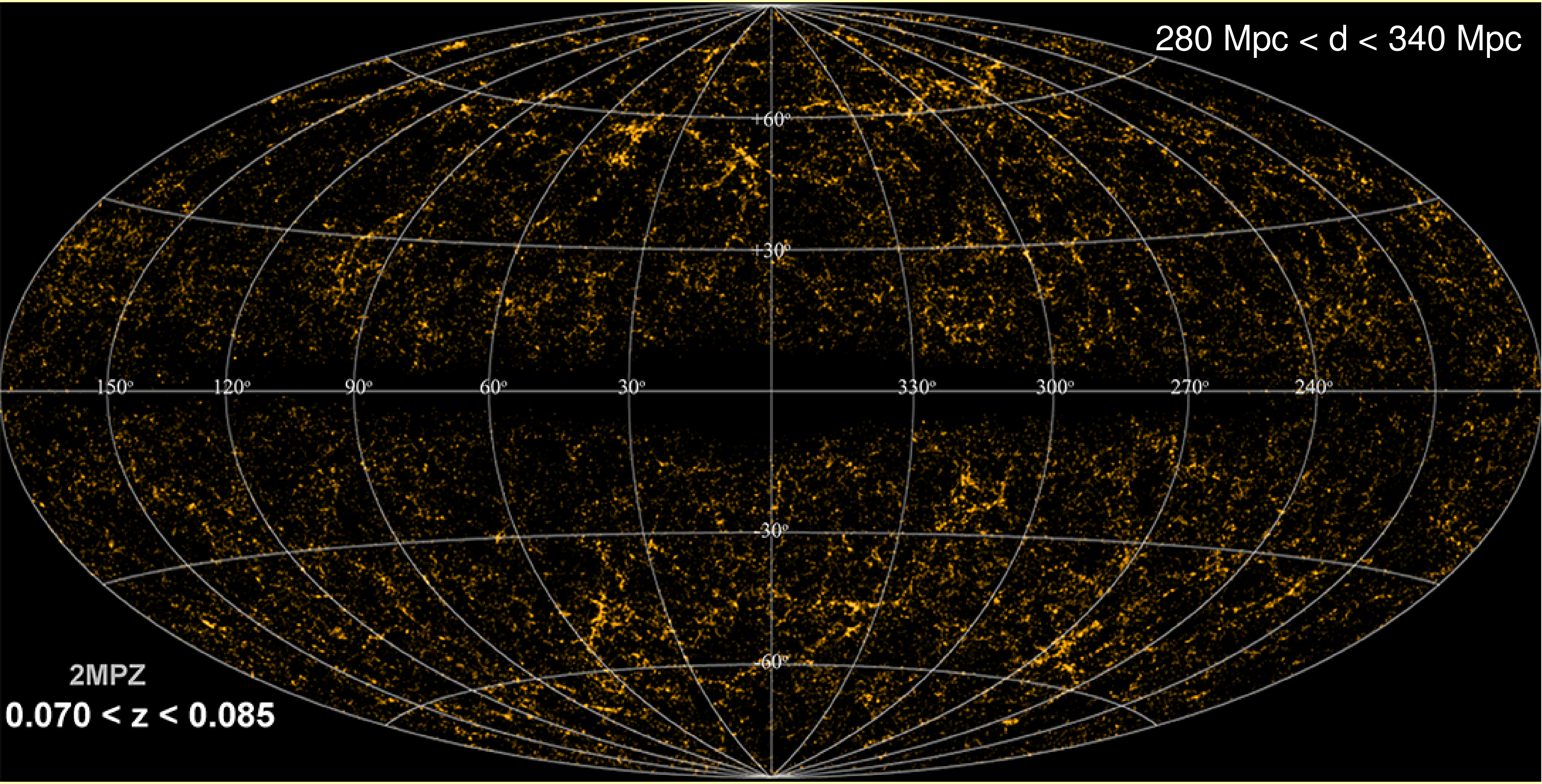
Slices through the Universe

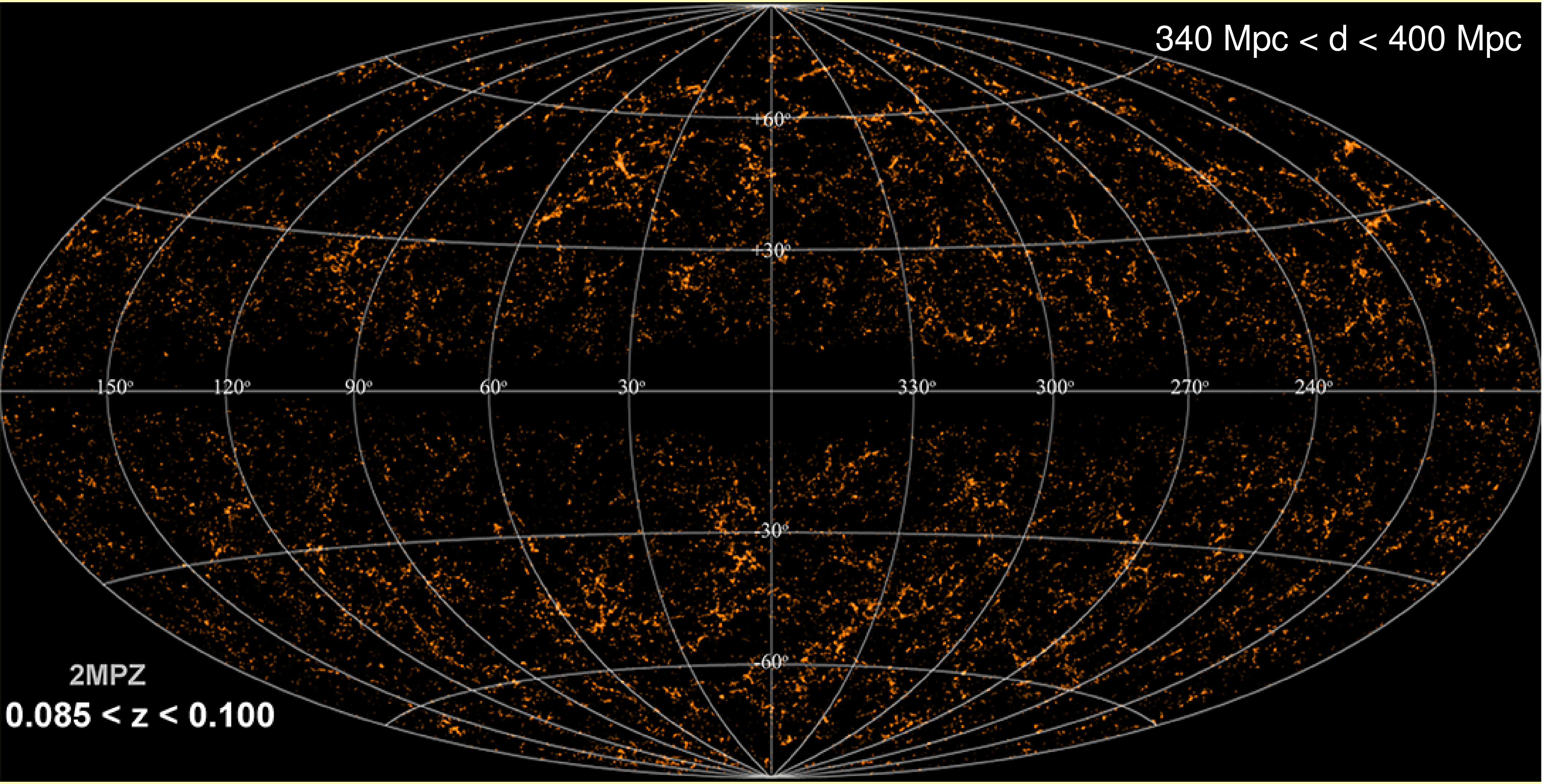



Plot by Tom Jarrett

# 2MASS Photometric Redshift catalogue

## 1 million galaxies in 3D

Slices through the Universe




Plot by Tom Jarrett

# 2MASS Photometric Redshift catalogue

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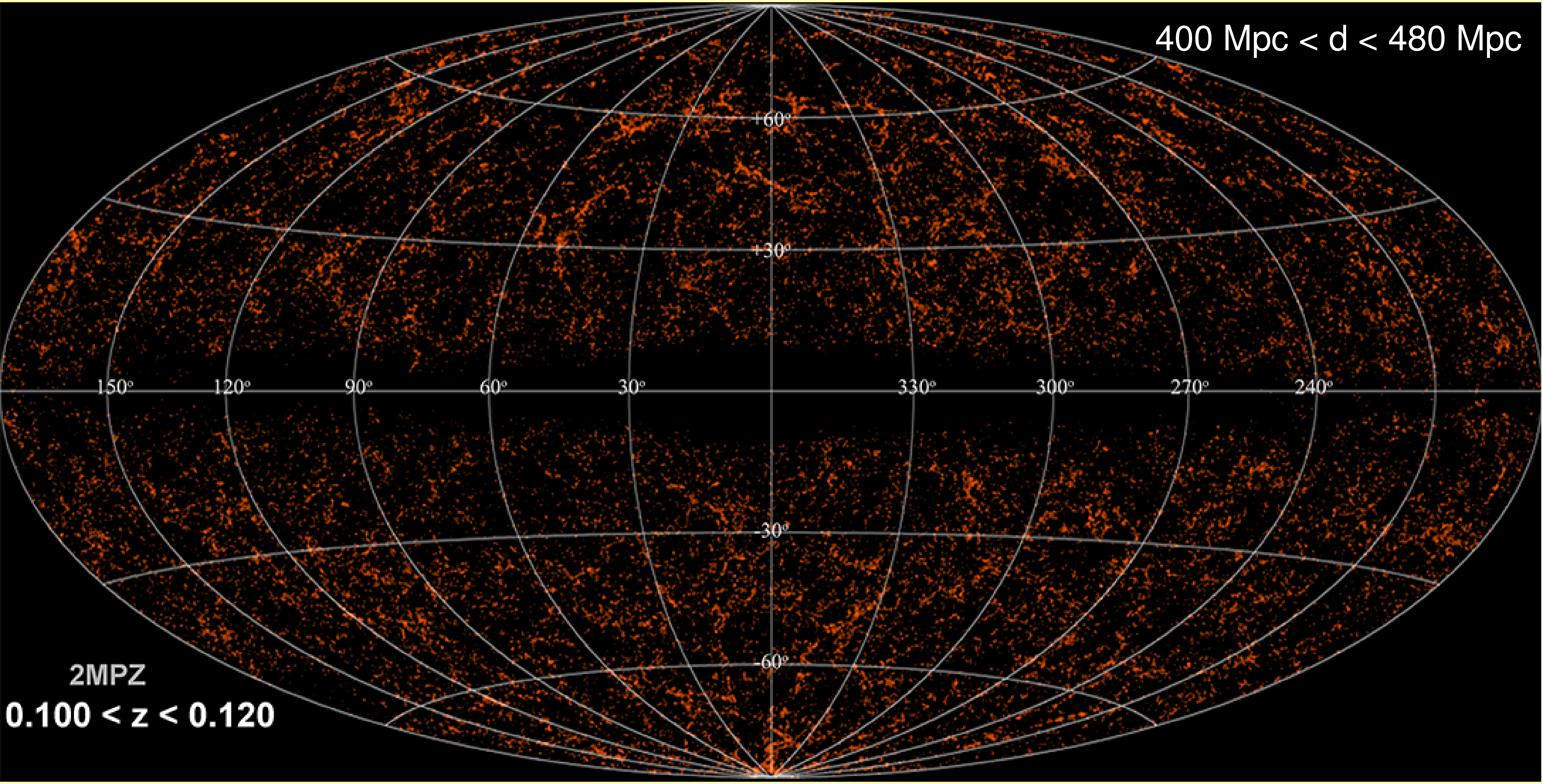
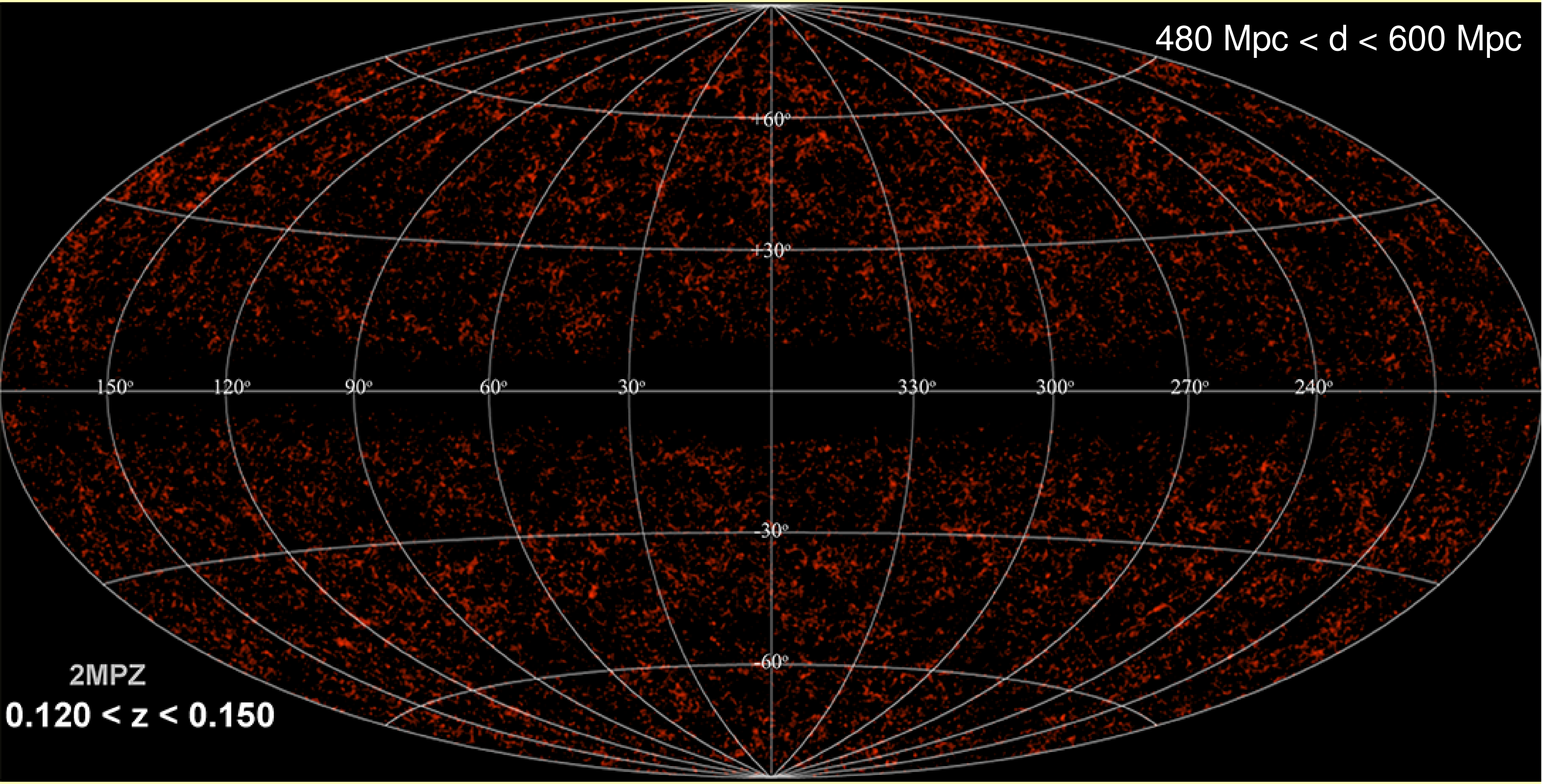



Plot by Tom Jarrett

# 2MASS Photometric Redshift catalogue

## 1 million galaxies in 3D

Slices through the Universe

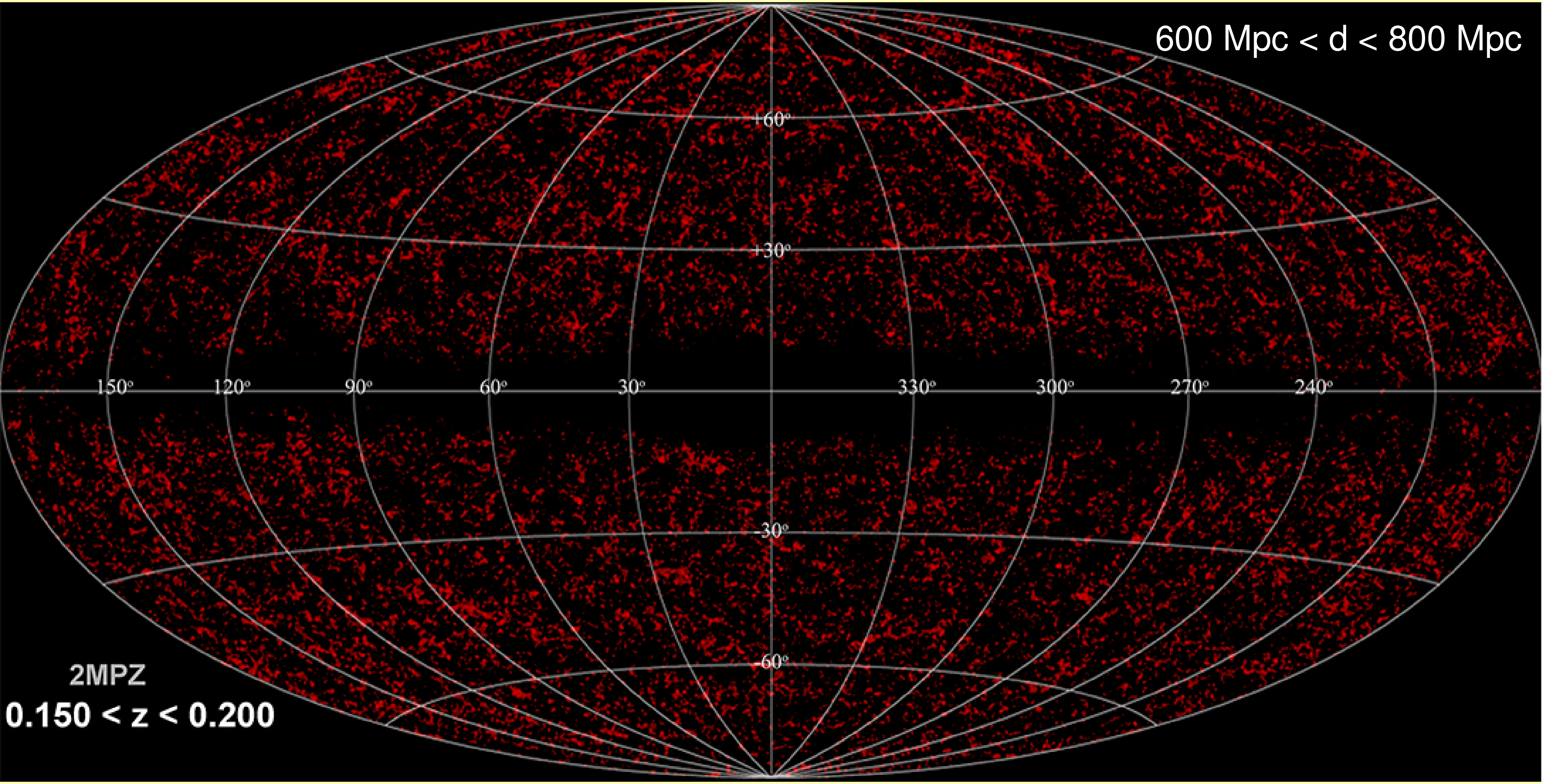



Plot by Tom Jarrett

# 2MASS Photometric Redshift catalogue

## 1 million galaxies in 3D

Slices through the Universe

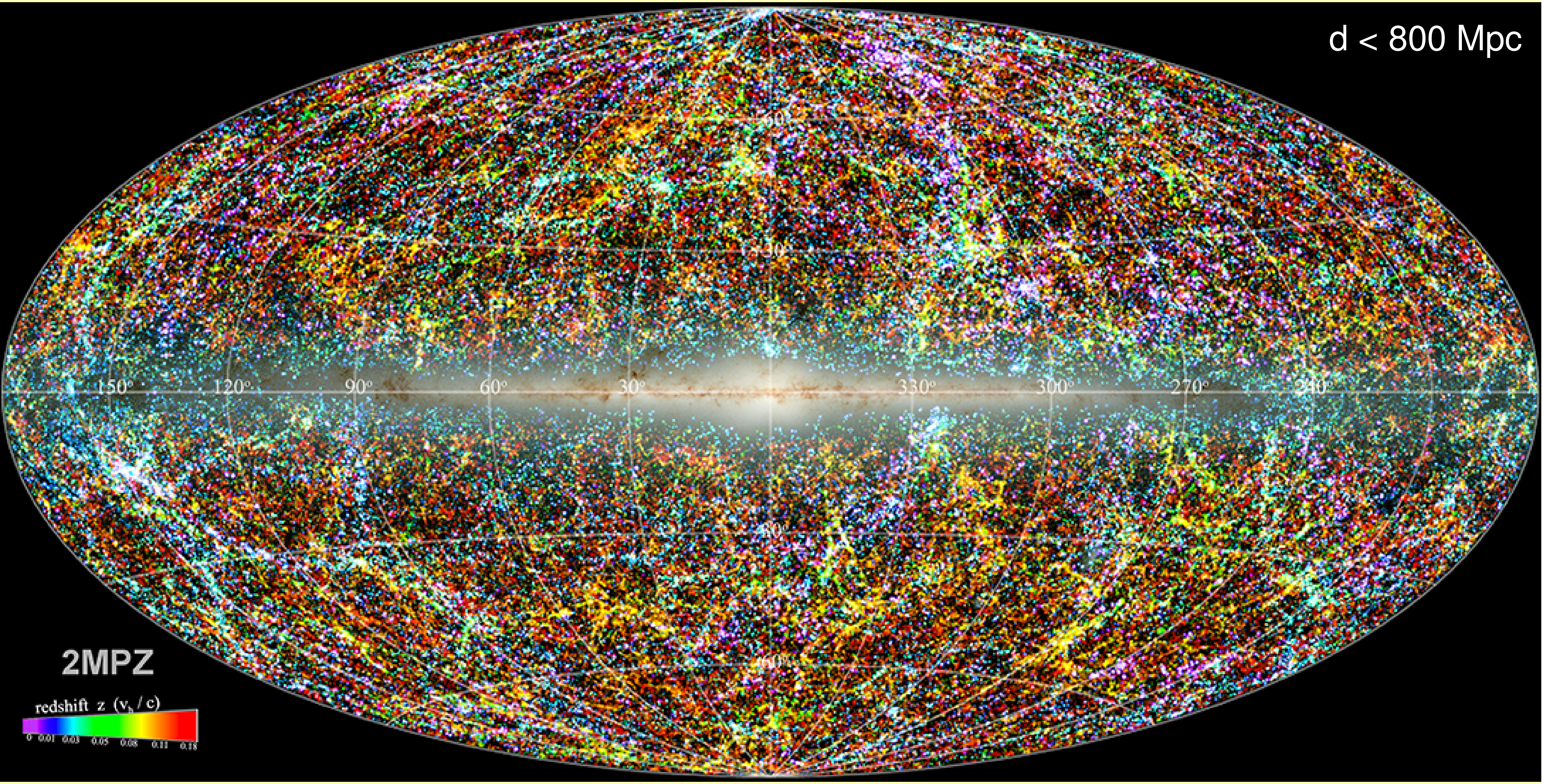



Plot by Tom Jarrett

# 2MASS Photometric Redshift catalogue

## 1 million galaxies in 3D

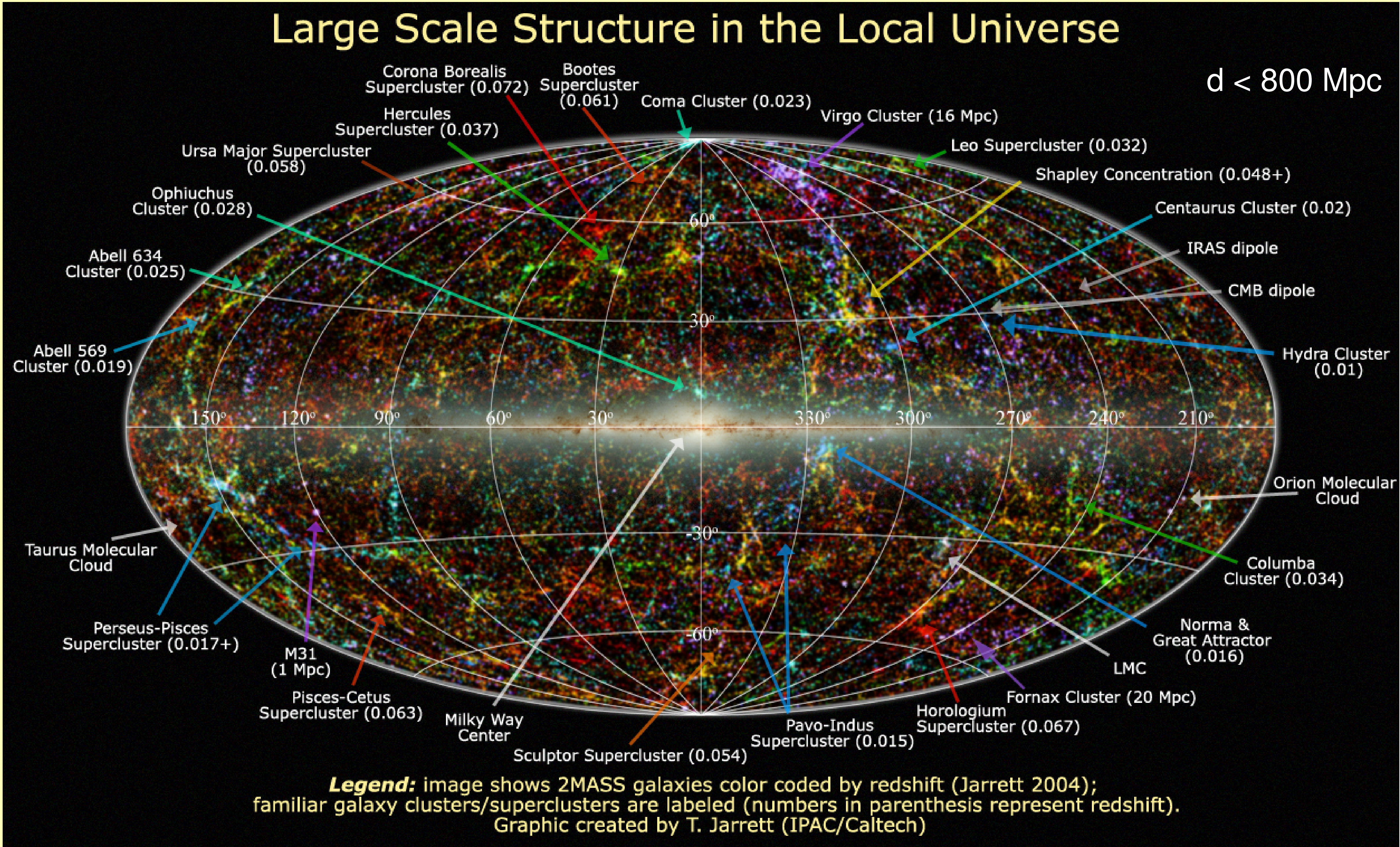
Colour-coded by redshift




Plot by Tom Jarrett

# 2MASS Photometric Redshift catalogue

## Finder chart



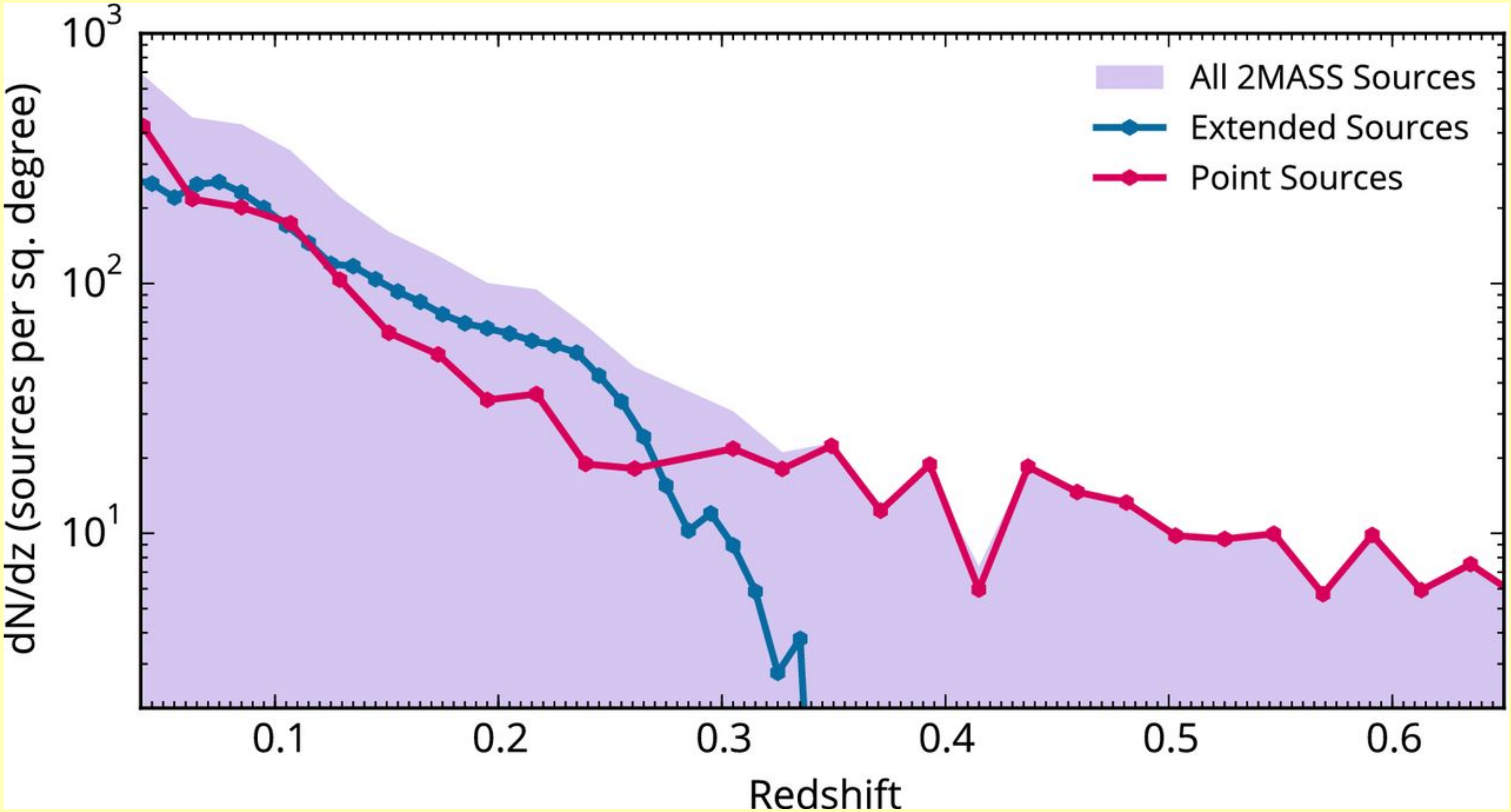
# Some cosmological applications of the 2MASS Photo-Z catalog

- **Reconstruction of the “local” gravitational potential** in the context of Planck integrated Sachs-Wolfe effect analysis (Planck 2015 results XXI)
- **Testing Isotropy in the Local Universe** with luminosity function variations; no significant anisotropy detected (Appleby & Shafieloo 2014)
- **Testing universal homogeneity** with angular auto-correlations: no evidence for departure from homogeneity within z<0.3 (Alonso+ 2015)
- 2MPZ proposed as one of the input catalogs for **gravitational wave** electromagnetic counterpart search (Antolini & Heyl 2016; Evans et al. 2016)
- Several other applications already published or in preparation

# (Many) galaxies in the 2MASS *Point* Source Catalog:

## a (potentially) all-sky sample deeper than 2MASS *XSC*

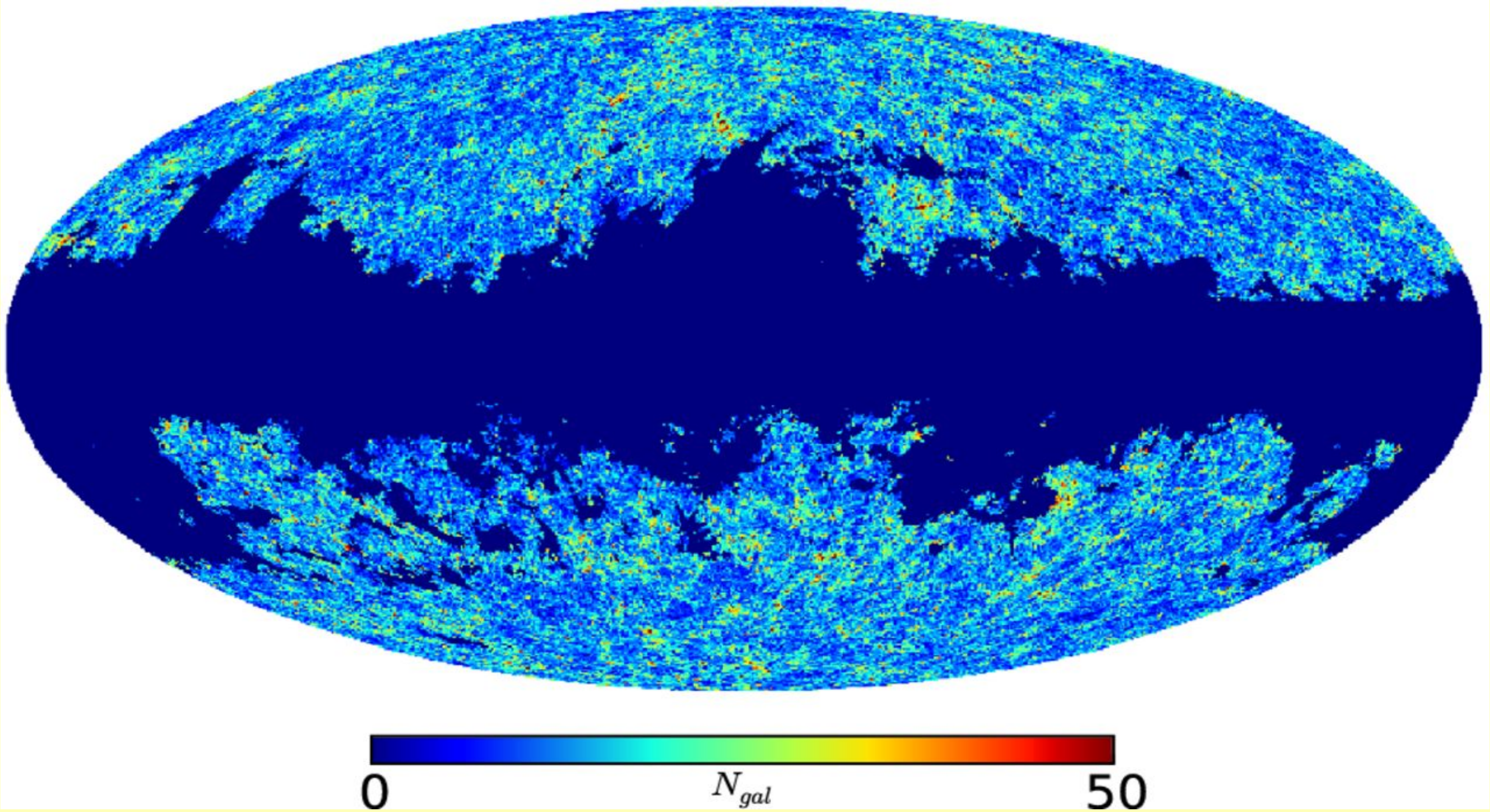
- **Rahman, Menard & Scranton (2016)**
  about **1.6 million galaxies in 2MASS PSC** from a “clustering redshifts” analysis
- **No obvious way to extract them**, though



# Extracting galaxies from 2MASS PSC

## an "all-sky" sample deeper than 2MASS *XSC*

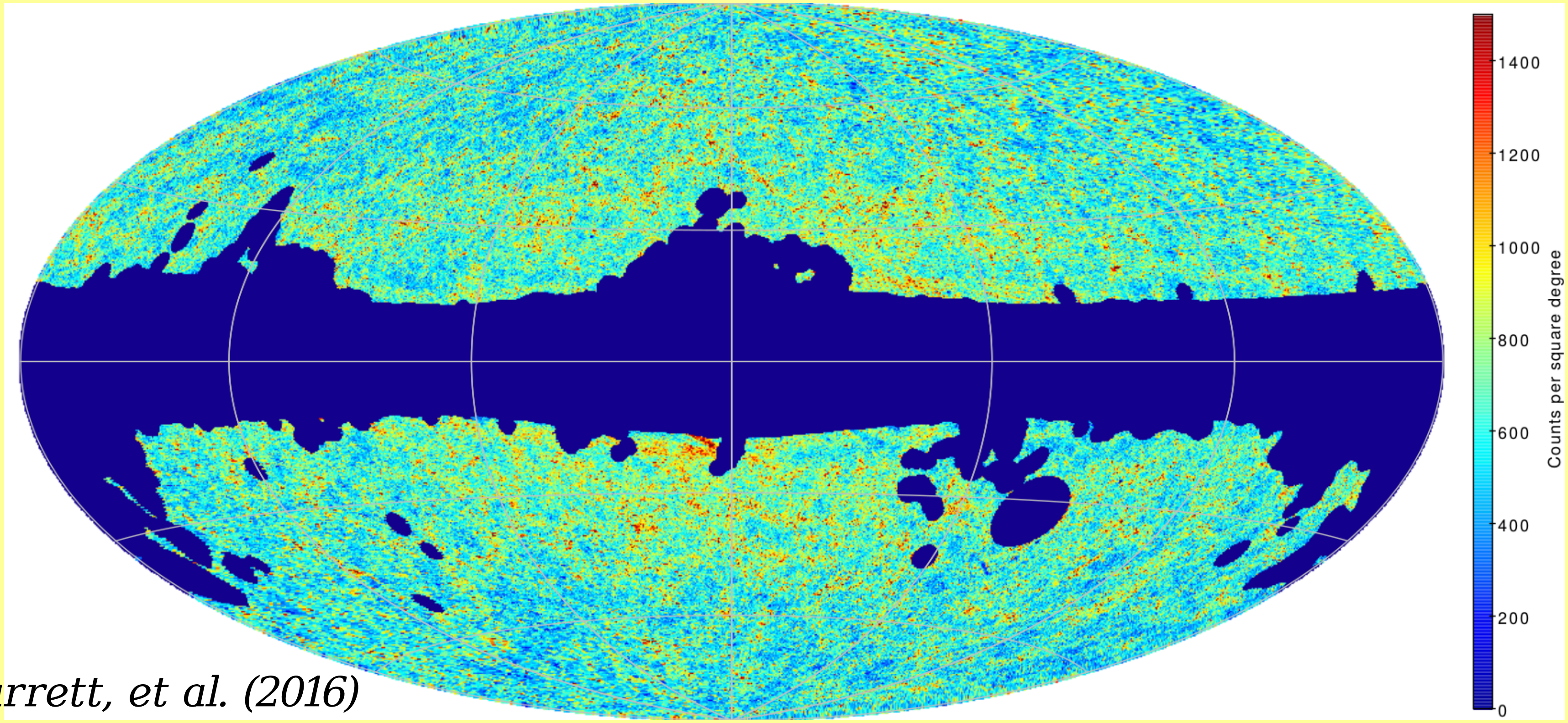
- Kovacs & Szapudi 2015: **star/galaxy separation in 2MASS PSC** by adding **WISE** photometry
- A simple **cut of J – W1 ≥ 1.7** found to be a very efficient separator
- Resulting sample of **~2.4 million XSC+PSC galaxies** on half of the sky (after masking)
- Adding SuperCOSMOS allows to calculate **photo-zs** (as in 2MPZ) – Kovacs & MB in prep.



# Beyond 2MASS:

## 20 million galaxies from WISE x SuperCOSMOS

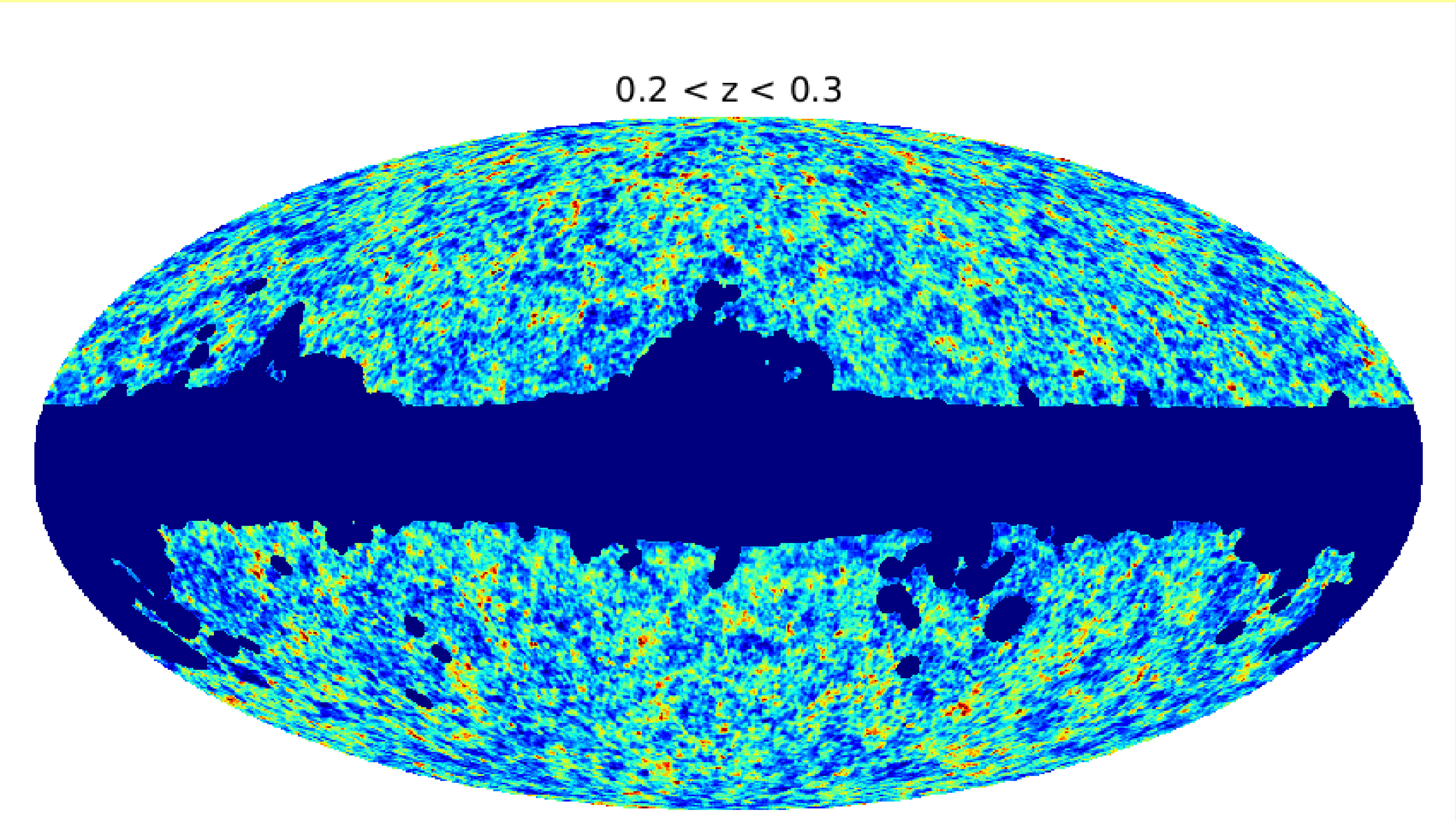
- **All-sky galaxy sample much deeper than 2MASS:**
  Mid-IR **WISE** paired up with optical **SuperCOSMOS**, mean z=0.2
- Appropriate **clean-up** of star contamination gives almost **20 million galaxies**
  *(for machine-learning approach: see Krakowski, Małek, MB, et al., 2016)*
- **Photometric redshifts** computed for all the galaxies, with **precision of ~14%**




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

# The cosmic web ~3 Gyr ago

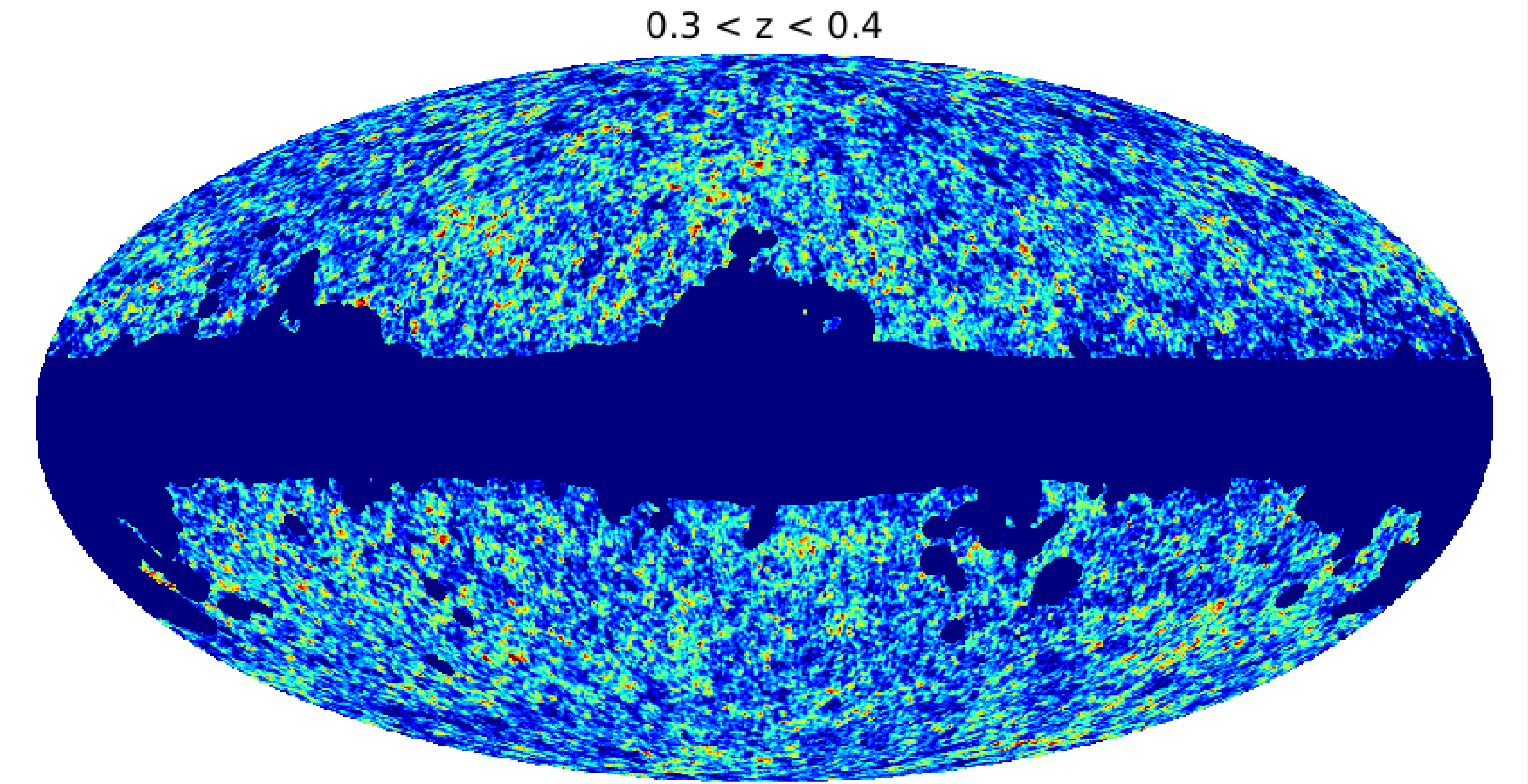
## as seen by WISE x SuperCOSMOS




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

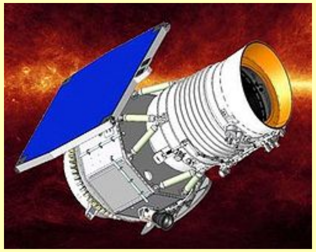
# The cosmic web ~4 Gyr ago

## as seen by WISE x SuperCOSMOS




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

# All-sky probes: the power of



- **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) and than SuperCOSMOS: another “layer” for all-sky cosmology (**galaxies even at z>1**; Jarrett et al. 2016)

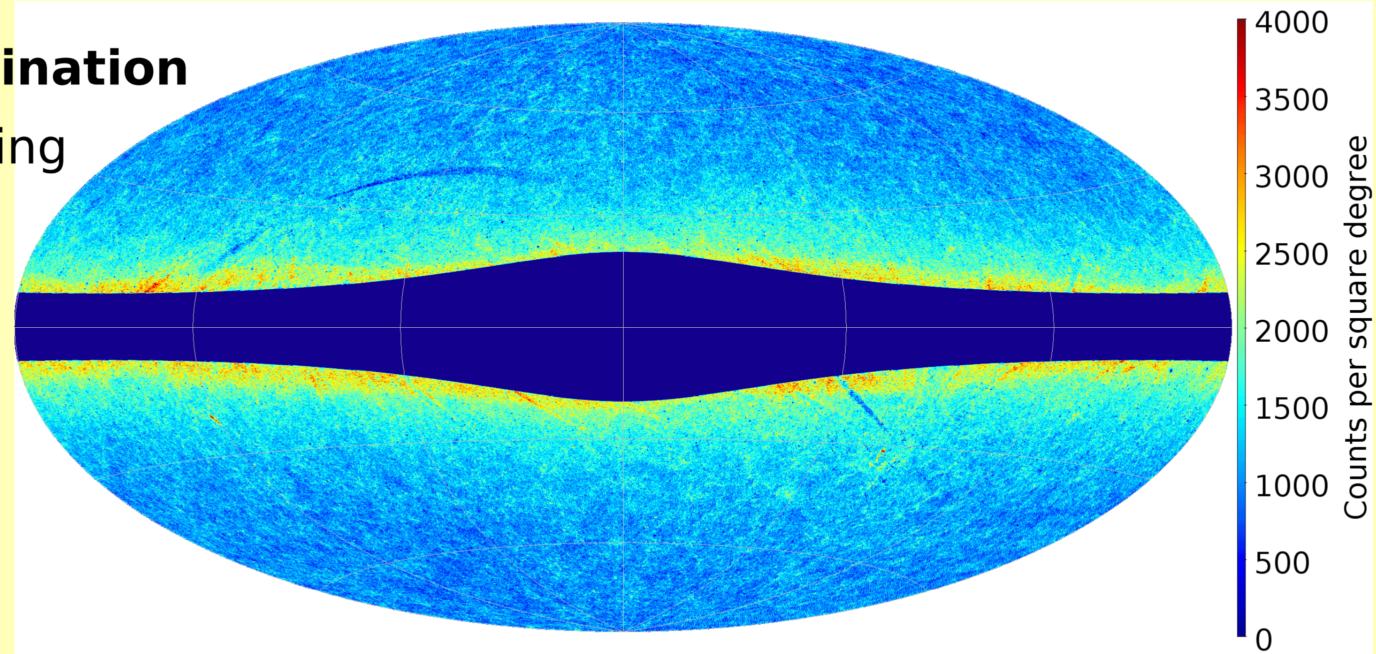
- Full **cosmological potential of WISE** still to be explored: galaxies very difficult to extract; stars dominate even at high latitudes

- **Ongoing**: automatic **star-galaxy-QSO separation** (first results: Kurcz, MB, Solarz, et al. 2016)

# 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




*Kurcz, MB, Solarz, et al. (2016)*

# Going deeper with ...and beyond

- WISE on its own can't provide **photo-zs** (only 2 bands at full depth)

- Full potential only by cross-matching with other wide-angle data:

  **V**ista **H**emisphere **S**urvey (near-IR, 2π), **D**ark **E**nergy **S**urvey (optical, 5000 $deg^2$), **Ki**lo **D**egree **S**urvey (optical, 1500 $deg^2$), ...

  → photo-zs, tomographic analyses, QSOs...

- Will be of use for **LOFAR**, **ASKAP**, ... (counterparts, redshift distributions)

- Getting prepared for future very big data:

  → **Euclid** & **LSST** will be mostly *photometric redshift* probes

  → **SKA** will need source identification and optical/IR counterparts

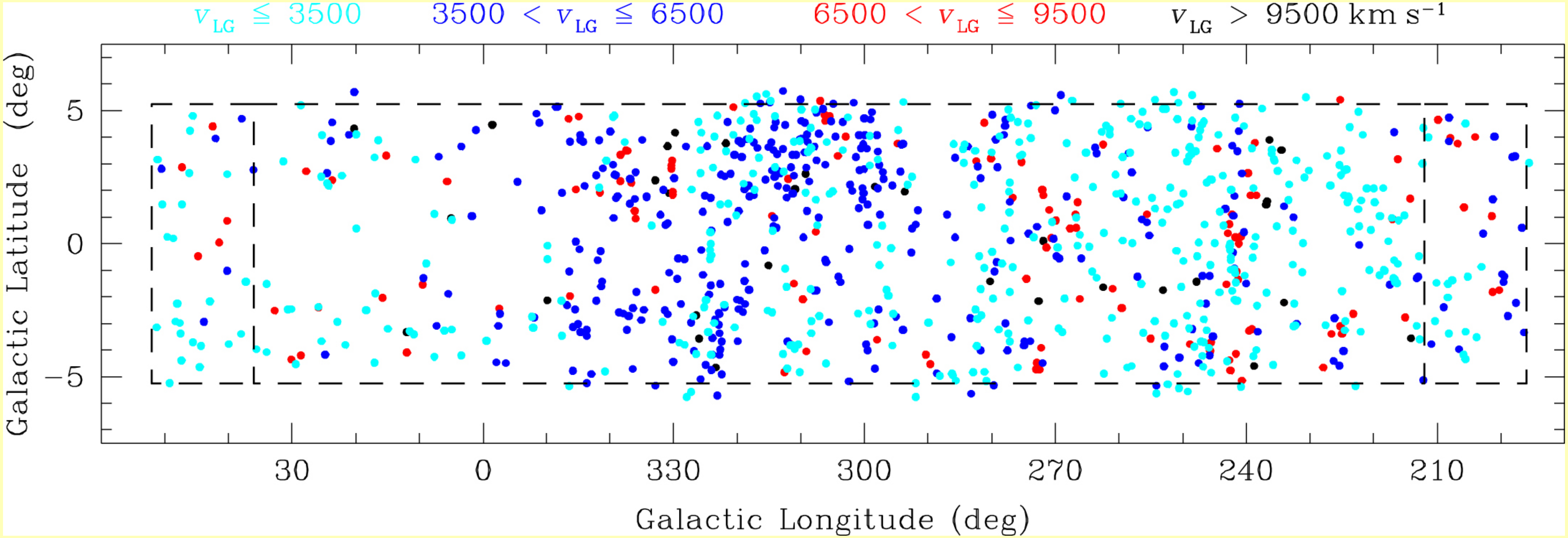
# Near future prospects at z~0.1

- There is now a chance that the entire **2MASS XSC** will become **spectroscopic**

- South: **TAIPAN** – eventually an r-band selected survey (r<17.5), but in the first phase (2016-17) will target Southern 2MASS XSC galaxies
- North: **LORCA** proposal to get spec-zs of the Northern 2MASS XSC sources not measured by 2MRS nor SDSS (Comparat et al. 2016)
- This will give a >**1-million spec-z** sample on **most of sky**, 3x deeper than the current 2MRS, and with much better precision than 2MPZ
- Great sample for **cosmic web** and **flow** studies at low redshifts (reconstructions, dipoles, bulk flows...)

# What about the "Zone of Avoidance"?

- Low Galactic latitudes (|b|<5°) **impenetrable in the optical** (extinction!) and **very problematic also in the infrared** (stellar crowding!)
- However, ZoA is almost **transparent for extragalactic (redshifted) HI**
- **HIZOA** (**Staveley-Smith et al. 2016**): **900 galaxies in the Southern ZOA** with z<0.04
- Limited only by the instrument (flux...), and **penetrates even through the Bulge**!
- **Tip of the iceberg**; many structures hidden behind the Milky Way (Norma/Great Attractor; Perseus-Pisces; Vela...) – **great prospects for MeerKAT, ASKAP, APERTIF, SKA ...**

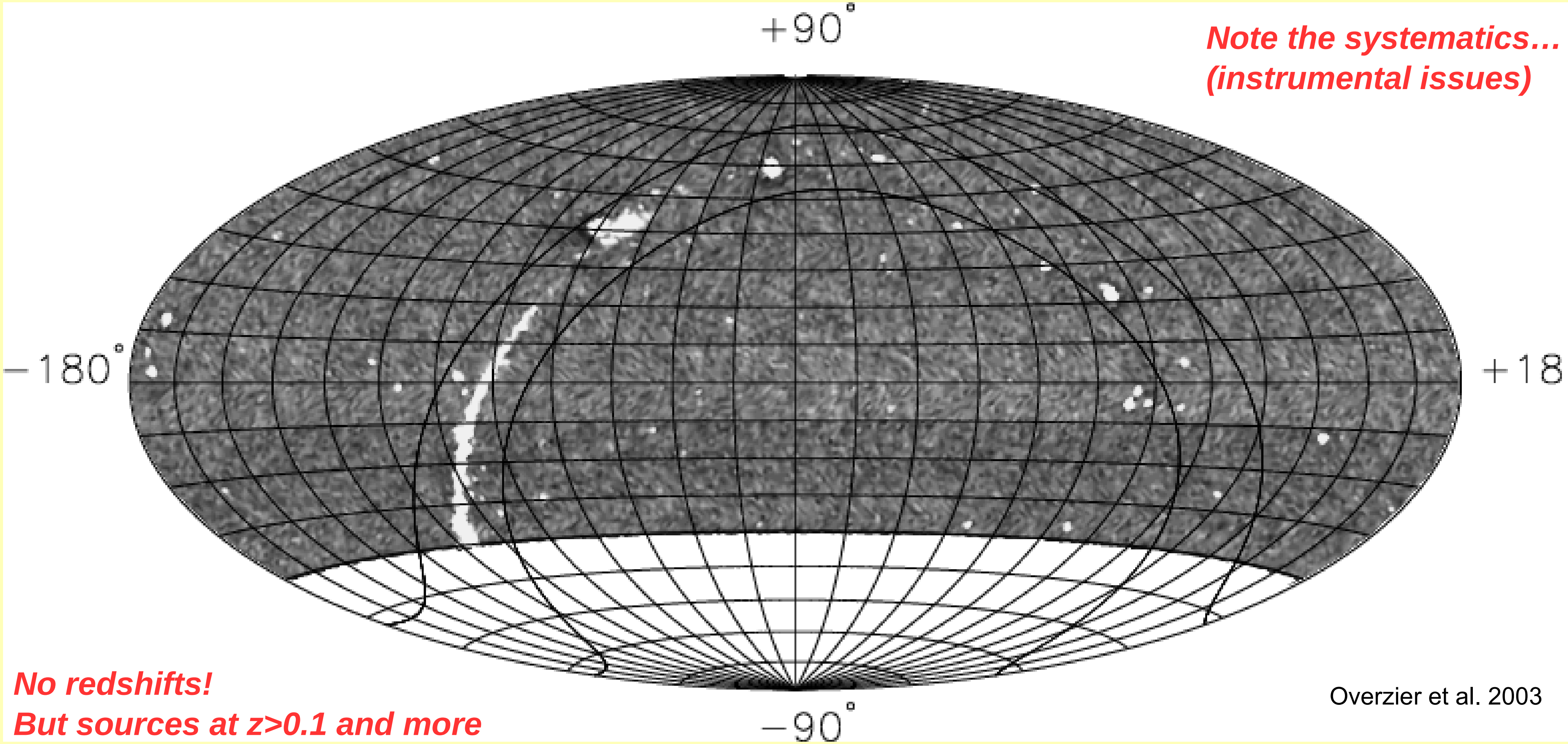


# Radio mapping of the large scale structure

- **Is the future!** (SKA…)

- Current datasets: The NRAO VLA Sky Survey (**NVSS**, Condon et al. 1998)
  Conducted with the Very Large Array (VLA)
  1.8 million sources detected at 1.4 GHz, δ>-40°

*Note the systematics…*
*(instrumental issues)*




*No redshifts!*
*But sources at z>0.1 and more*

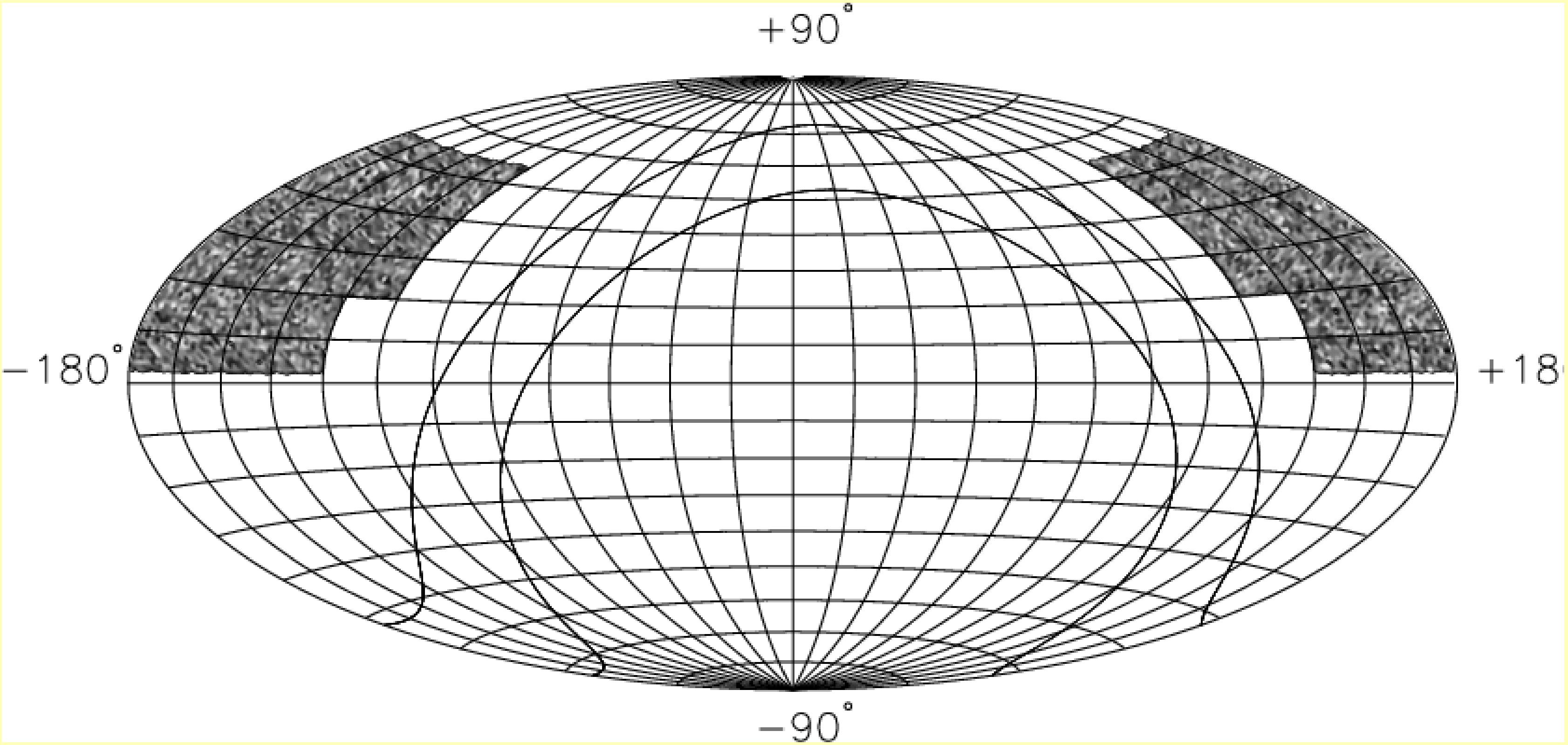
Overzier et al. 2003

# Radio mapping of the large scale structure

- **Is the future!** (SKA…)

- Current datasets: Faint Images of the Radio Sky at Twenty centimeters (**FIRST**, Becker et al. 1995)

  1 million sources within the SDSS footprint, at 1.4 GHz but better sensitivity and resolution than NVSS

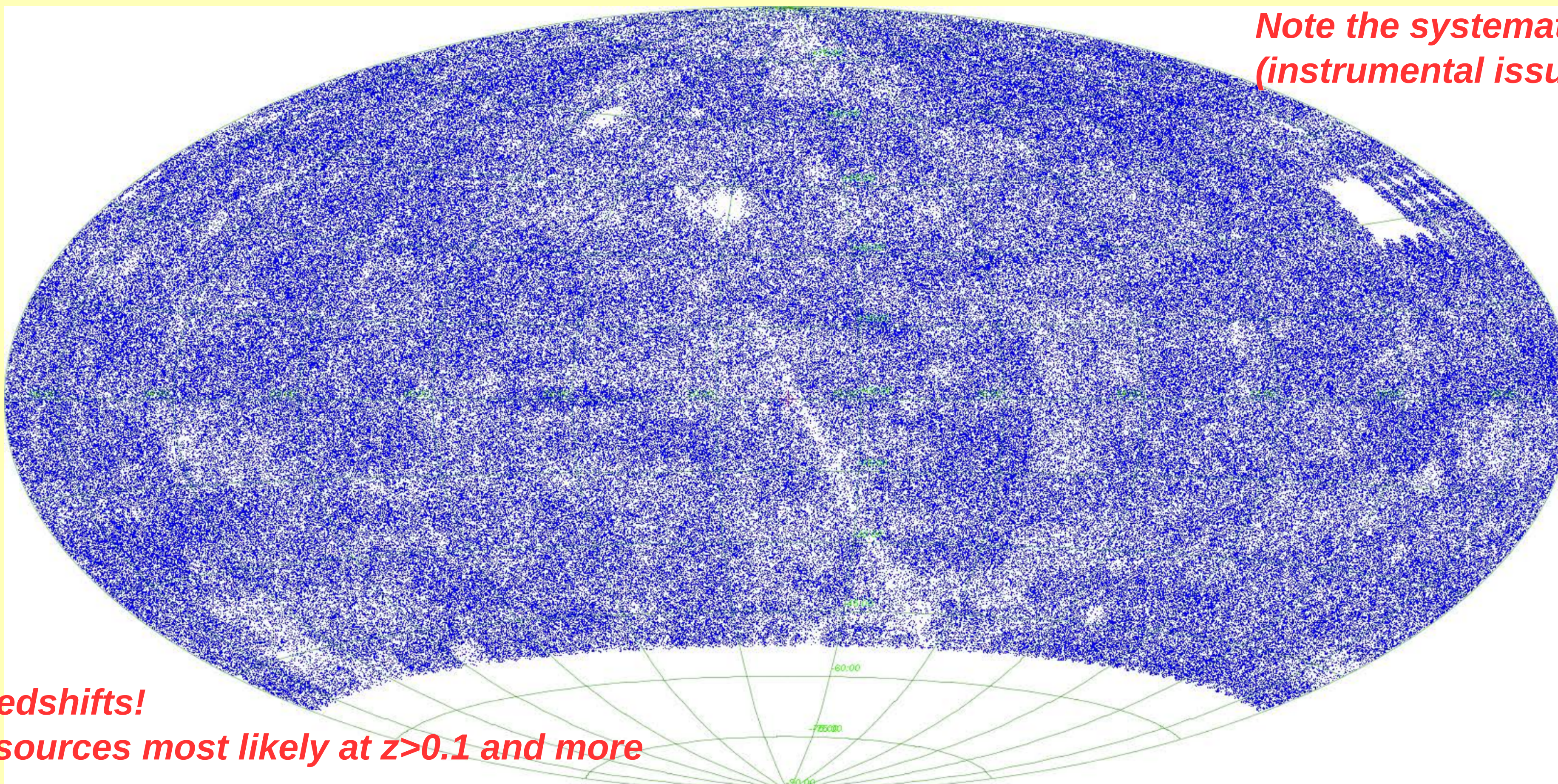



***No redshifts!***
***But sources at z>0.1 and more***

Overzier et al. 2003

# Radio mapping of the large scale structure

- **Is the future!** (SKA…)
- Current datasets: NVSS, FIRST, SUMSS (Southern counterpart to NVSS)
- ...and now also at low frequencies (150 MHz: **LOFAR**, **MWA**, ...)
- The **GMRT 150 MHz** All-sky Radio Survey: First Alternative Data Release TGSS ADR1 (Intema et al. 2016): 640,000 sources, δ>-53° (90% of the sky)

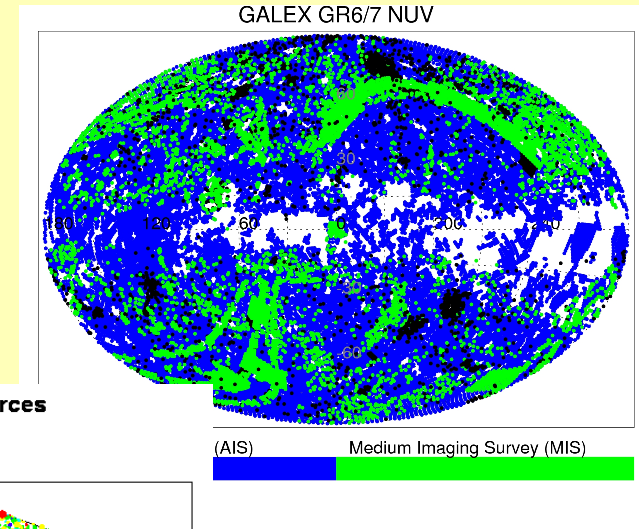


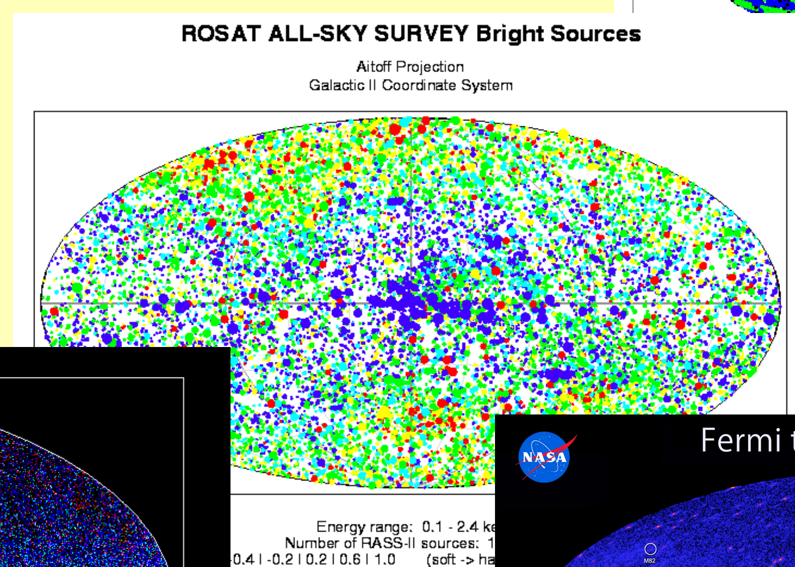
***Note the systematics…***
***(instrumental issues)***

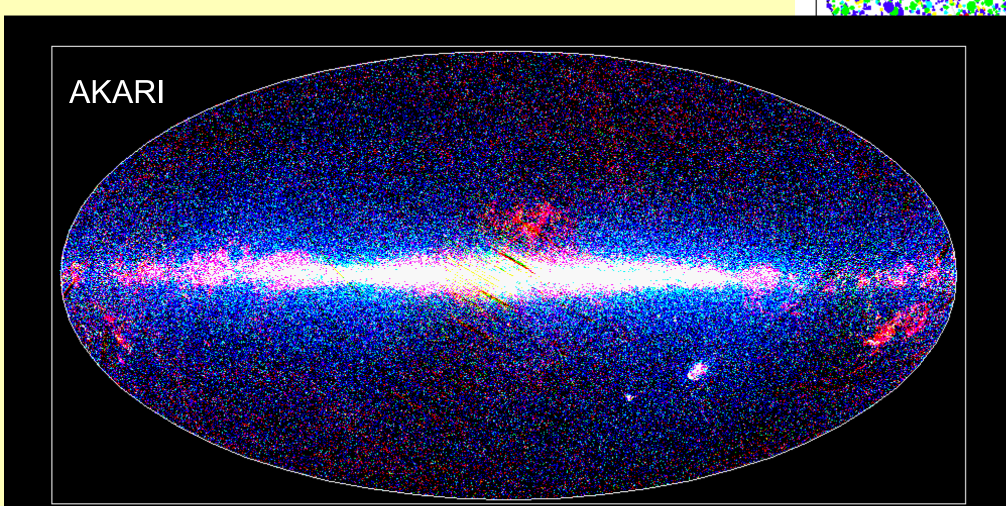
***No redshifts!***
***But sources most likely at z>0.1 and more***

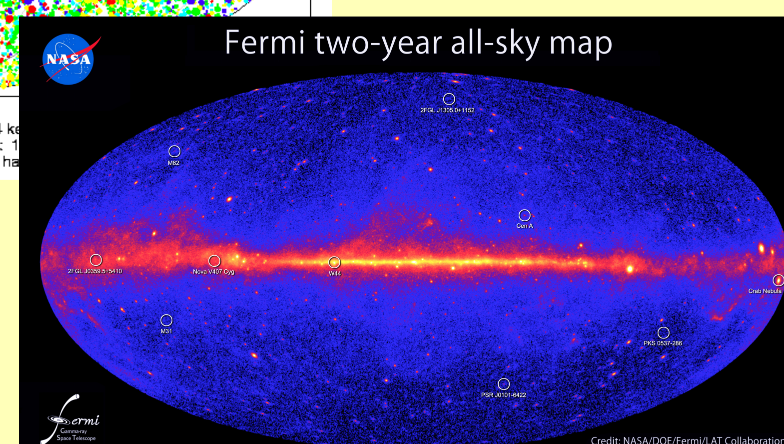
# Other frequencies

- The large scale structure is (being) mapped also at other frequencies – usually from space
- Examples:
  - **UV** (GALEX satellite)
  - **X-ray** (ROSAT, eROSITA [planned])
  - various **infrared** bands (AKARI satellite)
  - **gamma-ray** (Fermi-LAT)



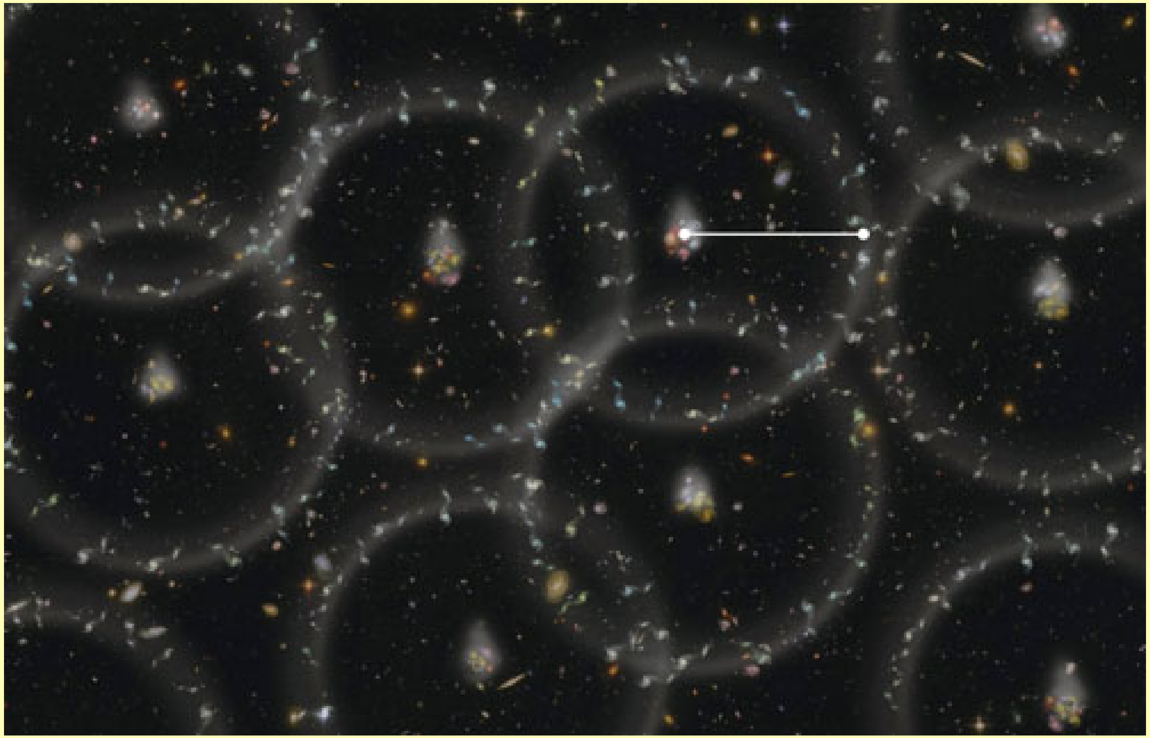



# Cosmological inference from large-scale structure

## Baryon acoustic oscillations

- Frozen relics of sound waves propagating through the early Universe, imprinted today in galaxy correlations

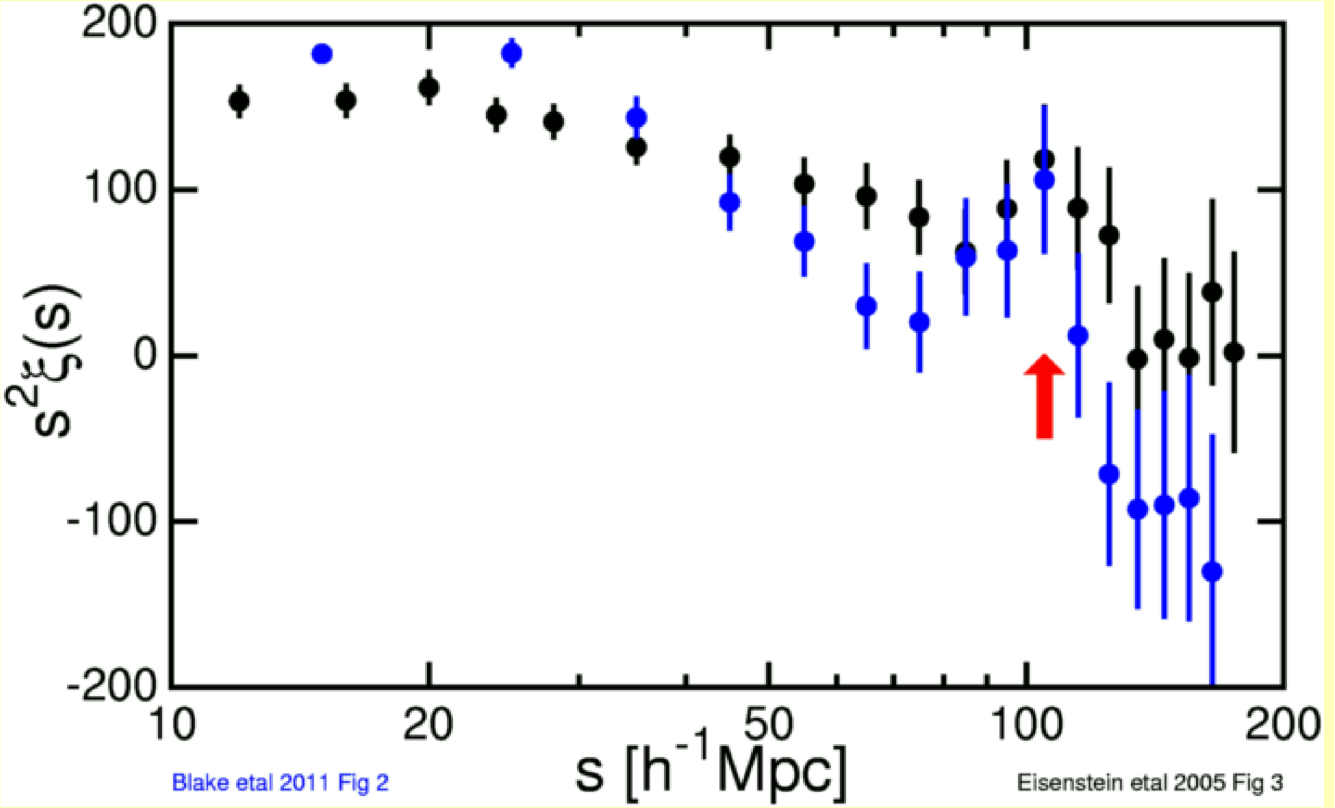
- **Standard ruler** testing the rate of expansion, hence the cosmic acceleration and dark energy



Cartoon by BOSS

# Cosmological inference from large-scale structure
## Baryon acoustic oscillations

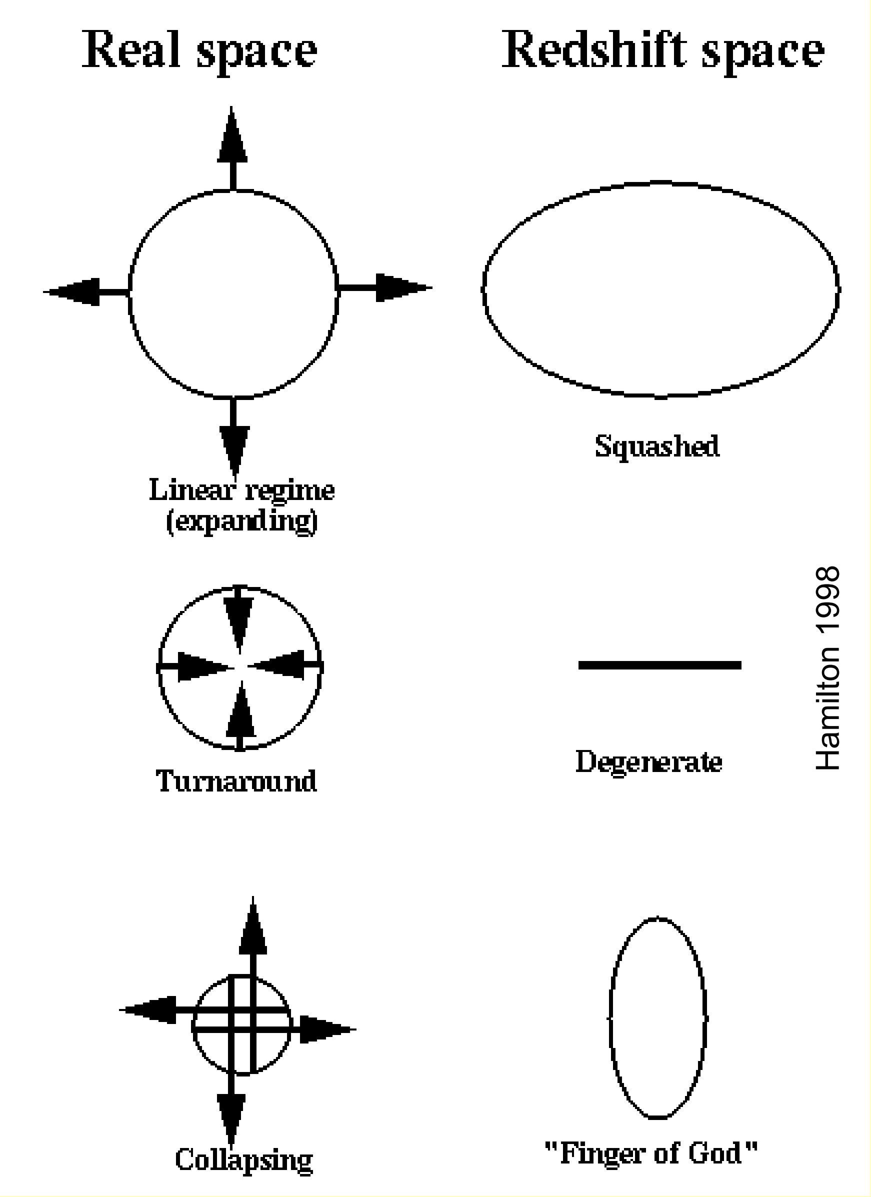
- Measured from the **two-point galaxy correlation function**, BAOs seen as a characteristic peak at a redshift-dependent scale
- This **acoustic scale** can be compared to the one well-known from the CMB
- This allows to measure "**distance to a given redshift**" and the Hubble parameter at this redshift (rate of expansion)



# Cosmological inference from large-scale structure

## Redshift-space distortions

- The **two-point correlation function** looks differently in the line of sight direction and the one orthogonal to it (plane of the sky)
- These differences come from **processes of gravitational collapse** projected on the "redshift space" (in which observations are made)



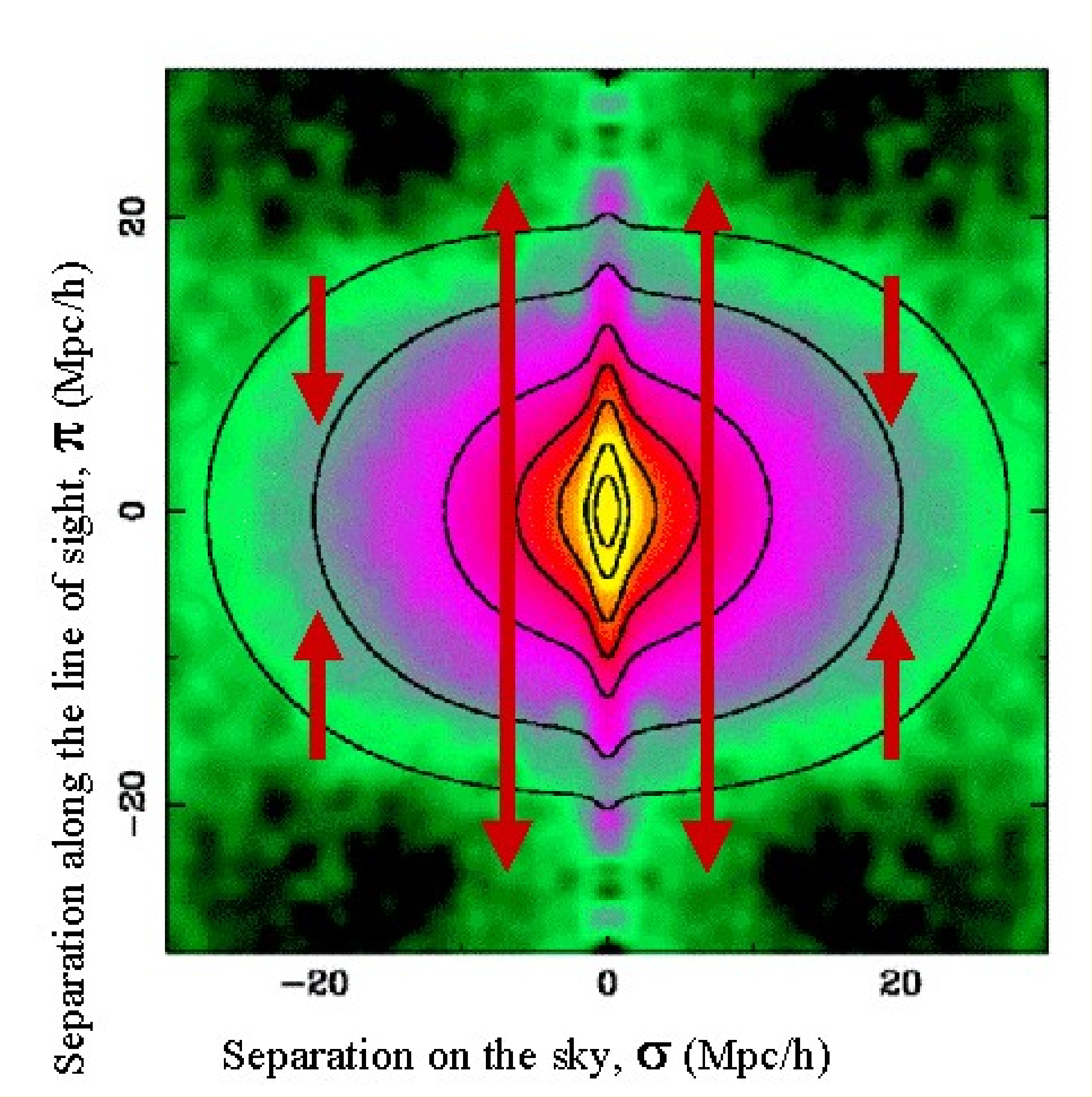
# Cosmological inference from large-scale structure

## Redshift-space distortions

- The amount of “squash” and elongation in the correlation function depends on cosmological parameters, in particular the **growth rate** of structure
- Measuring the correlation functions and comparing to various models we can infer the **growth rate at various redshifts** and check if this growth is consistent with theory predictions (e.g. general relativity / modified gravity...)
- Together with BAOs, these are the two major probes benefiting from **clustering properties of matter**, imprinted in the correlation functions measured from **spectroscopic redshift surveys**
  (Note: Fourier space counterpart of correlation functions –
  the **power spectrum** – is also employed)

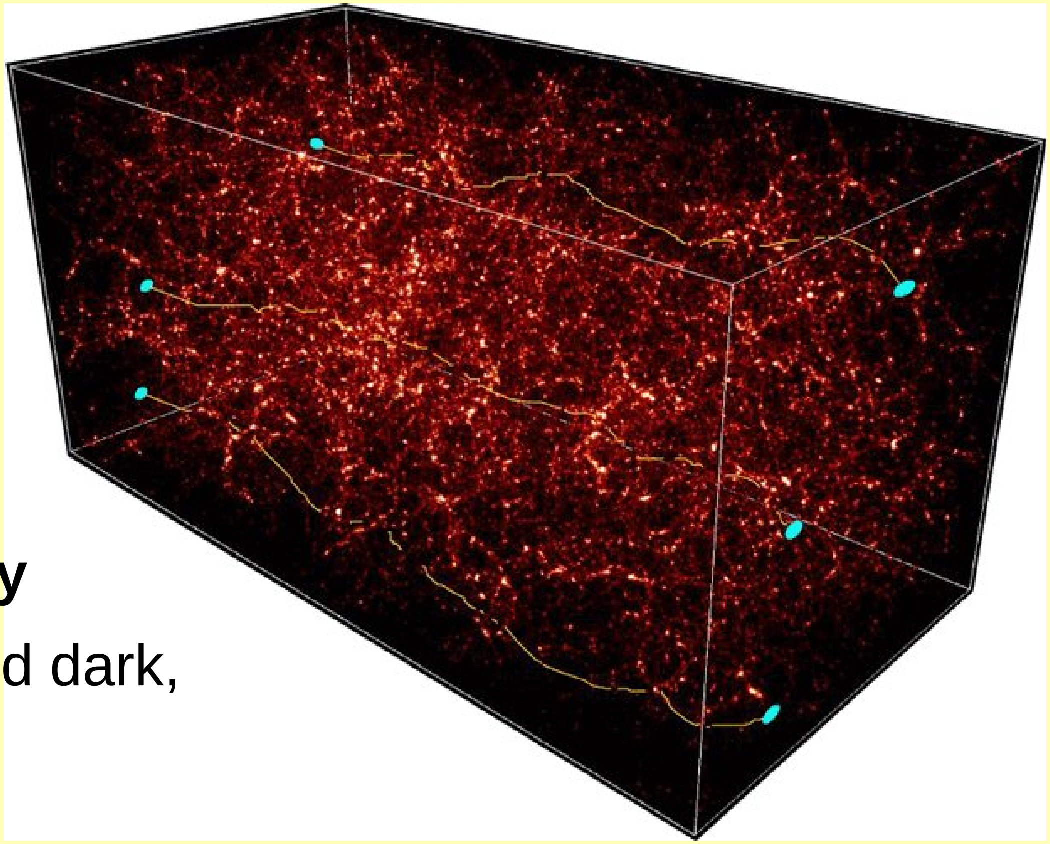
# Cosmological inference from large-scale structure

## Redshift-space distortions




The 2dF Galaxy Redshift Survey Team (2001)

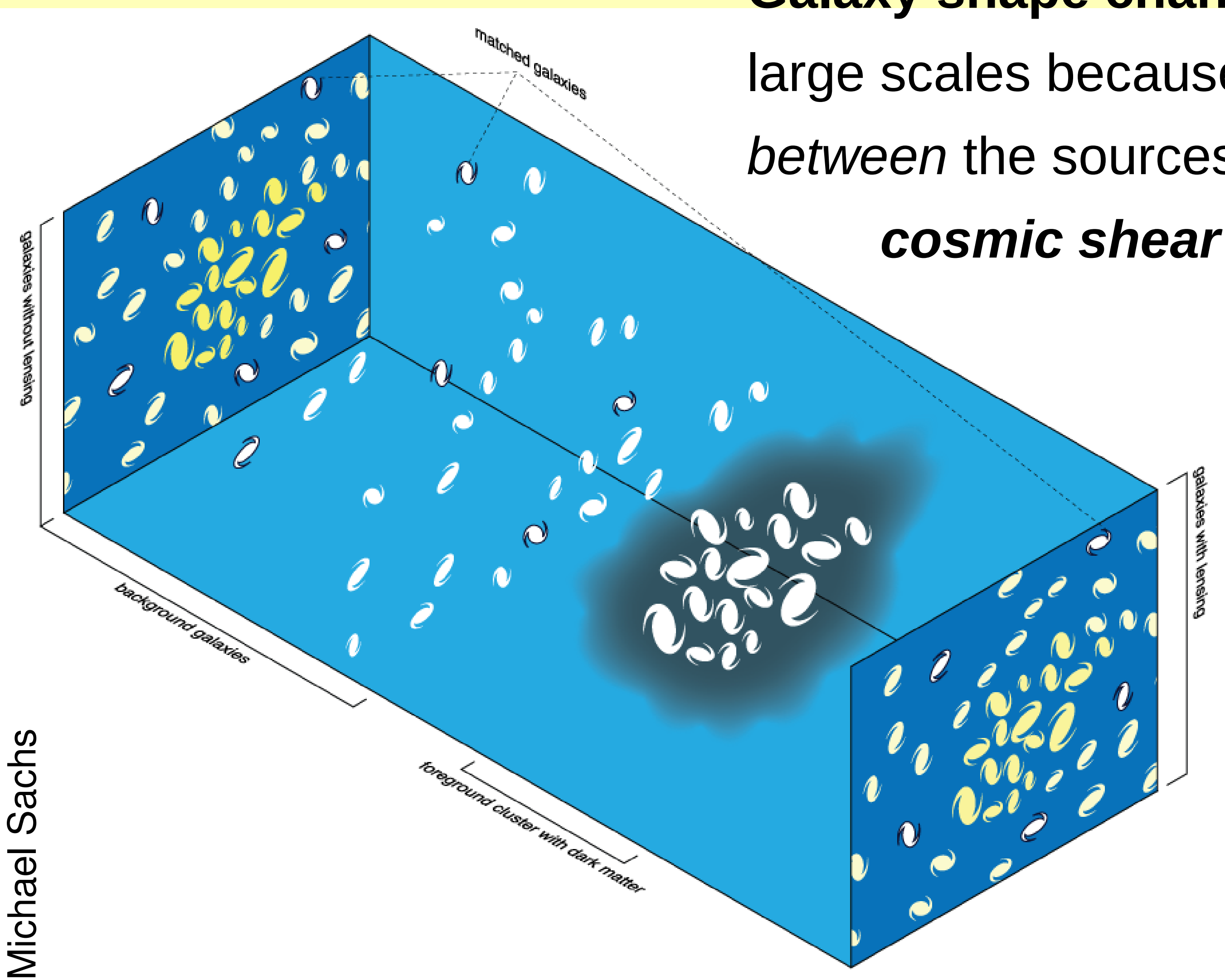
# Cosmological inference from large-scale structure
## Weak gravitational lensing



- On their way from the sources to the observer, paths of photons are **distorted** by the intervening matter: **gravitational lensing**
- Gravitational lensing **probes directly** all types of matter: both luminous and dark, baryonic and non-baryonic...
- Of most interest for cosmology is the ***weak lensing*** regime, in which observed **galaxy shapes** undergo tiny changes

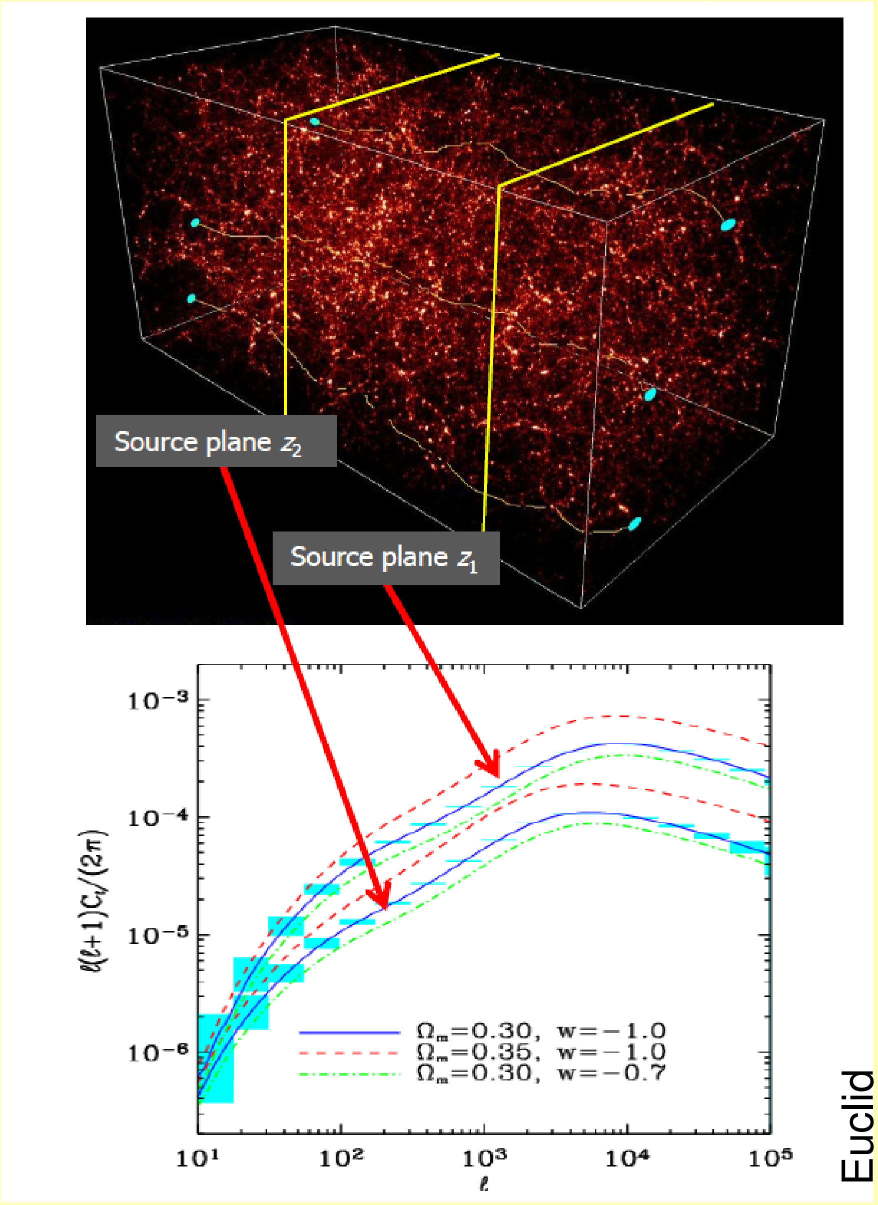
# Cosmological inference from large-scale structure
## Weak gravitational lensing

- **Galaxy shape changes** are correlated on large scales because of the masses lying *between* the sources and the observer – ***cosmic shear***



# Cosmological inference from large-scale structure

## Weak gravitational lensing




- The amount of cosmic shear depends mostly on the **amount and clustering properties of matter** between the source and observer
- The **cosmic shear signal** is looked for in correlation functions / power spectra of galaxy shapes (rather than of clustering like in BAO or RSD)
- Weak lensing measurements require **extremely good quality imaging** – from the ground possible only in places like Chile (very good seeing)

# Cosmological inference from large-scale structure
## Cross-correlations

- In addition to joining (*cross-matching*) various catalogs covering the same sky areas, one can also **cross-correlate** them to extract information
- General idea: if two surveys probe the same large-scale structure (or its effect on the measurements), then x-correlation will give non-zero signal
- Cosmological parameters are inferred from **cross power spectra** or **cross-correlation functions** of the two surveys / catalogs
- Cross-correlations benefit from **as large sky coverage as possible** [signal to noise ~ sqrt(coverage)]
- Usually done using maps (most often made with **HEALPix**)

*Górski et al. 2005*

# Cosmological inference from large-scale structure

## Cross-correlations

- Cross-correlations are a **powerful technique** especially if the signal we look for is much lower than other signals in the data (e.g. ISW in CMB)
- They also allow to **mitigate systematics** if they are different between the two cross-correlated surveys (e.g.: instrumental effects)
- Note: if one of the maps comes from a galaxy survey, usually spectroscopic redshifts are **not** needed – a **2D map** is sufficient + some information on galaxy **redshift distribution** for instance via photometric redshifts

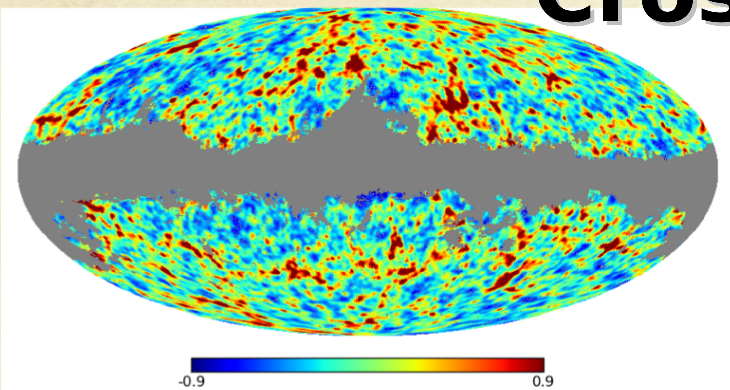
# Cosmological inference from large-scale structure

## Cross-correlations

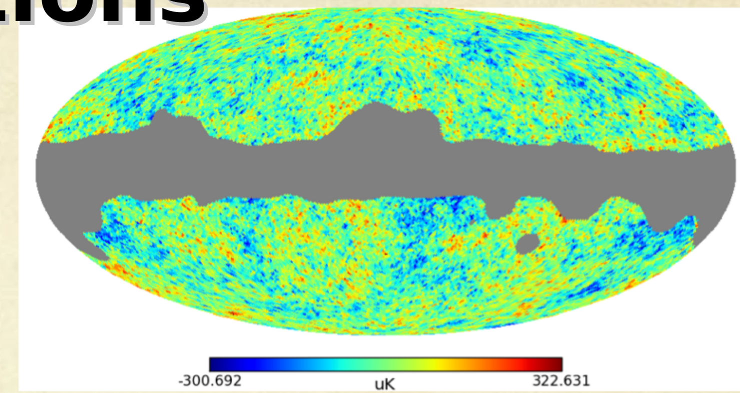
- First proposed by Crittenden & Turok (1996) to look for the **ISW effect** by x-correlating CMB (COBE) and LSS (ROSAT X-ray) maps
- **First detection of ISW** was made later, only after WMAP data came online – from x-correlation with NVSS data and the HEAO1 A1 X-ray data (Boughn & Crittenden 2004)
- Now a **standard technique** to measure ISW with WMAP or Planck x-correlated with various surveys such as those discussed in these slides

# Cosmological inference from large-scale structure

## Cross-correlations

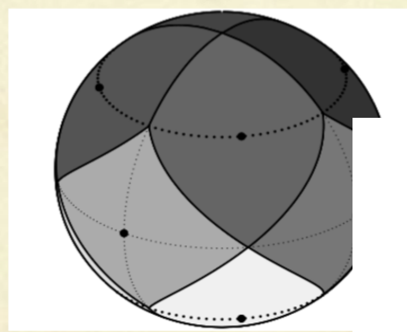



**2MPZ galaxy distribution**
in redshift shells



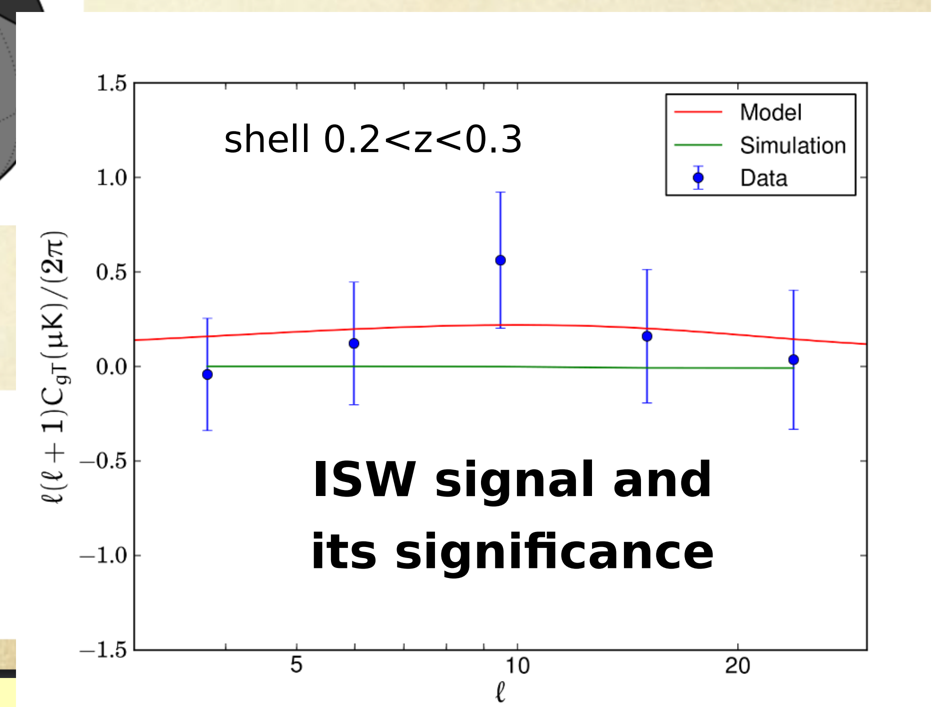

**Planck temperature map**

**Cross-correlation**



Cross power spectrum (approx.)

$$C_{\mathrm{gT}} = \frac{1}{(2\ell+1)} \sum_{m=-\ell}^{\ell} \frac{a^{\mathrm{g}}_{\ell m}}{\sqrt{f^{\mathrm{g}}_{\mathrm{sky}}}} \frac{a^{\mathrm{T}*}_{\ell m}}{\sqrt{f^{\mathrm{T}}_{\mathrm{sky}}}},$$

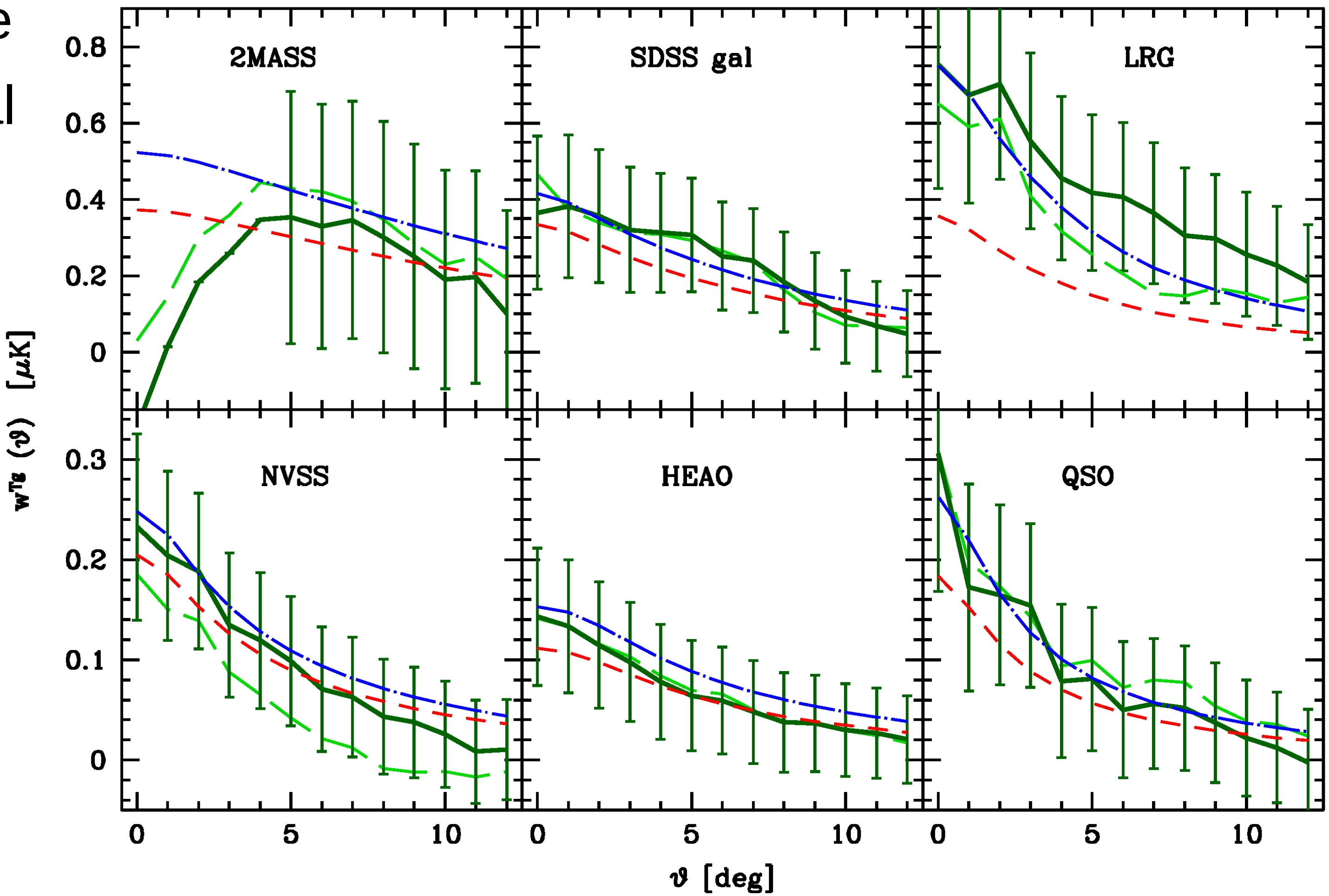



*MSc thesis by Louise Steward, UCT (2014)*

# Cosmological inference from large-scale structure

## Cross-correlations

- **Detection of ISW**: evidence for dark energy as the Universe is flat
- In principle could be also used to constrain **dark energy properties** – challenging, as the x-correlation signal is low (~4 sigma)

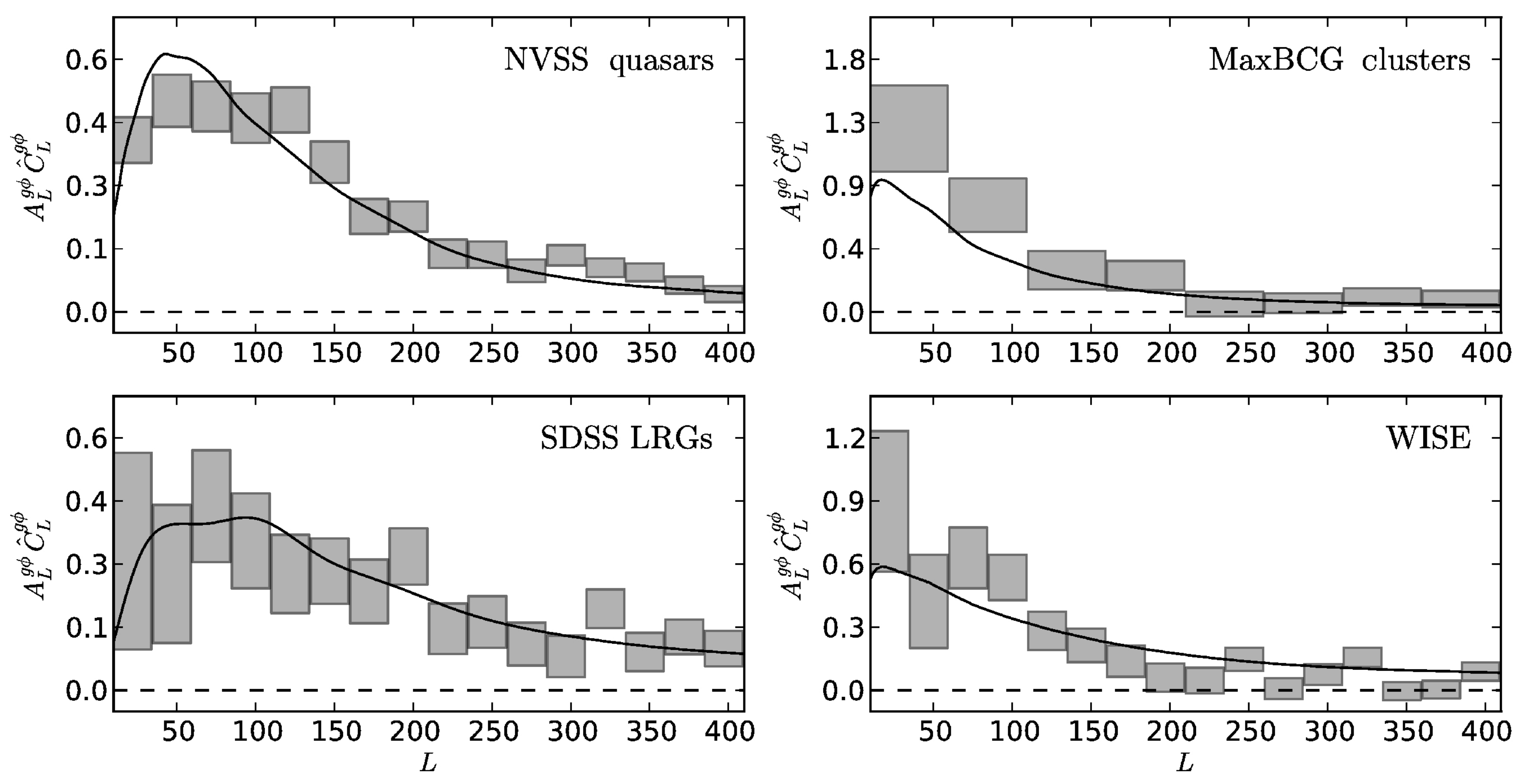



Giannantonio et al. 2010

# Cosmological inference from large-scale structure

## Cross-correlations

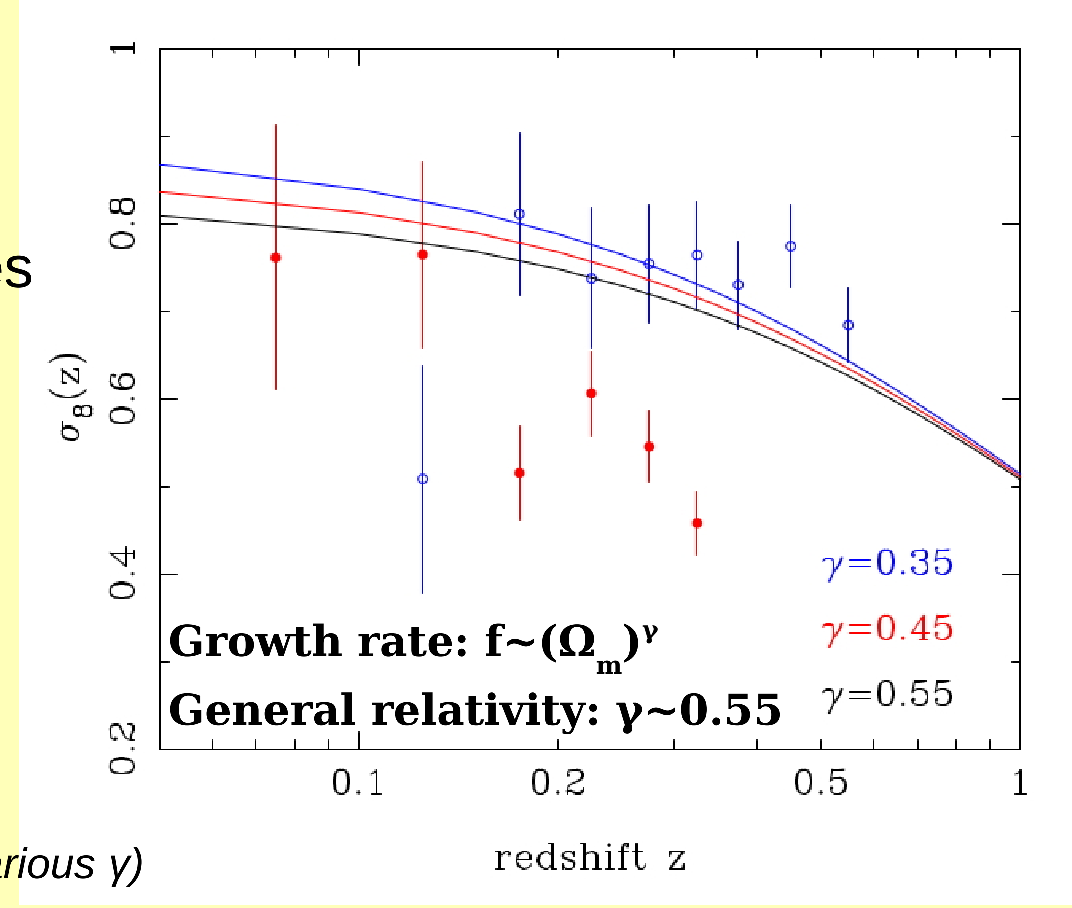
- Another example: **gravitational lensing of the CMB** x-correlated with the large-scale structure maps




Planck Collaboration 2013 XVII

# Cosmological inference from large-scale structure
## Cross-correlations

- Gravitational lensing of the CMB x-correlated with the LSS maps
- The amplitude of this cross-correlation depends on the **growth rate** of structure – provides a test independent from redshift-space distortions in galaxy auto-correlations
- The signal is currently **limited by CMB maps** rather than the LSS ones (e.g.: Planck CMB lensing map is noise-dominated)




*Plot from Peacock & MB in prep.*
*(note: datapoint colors aren't related to the lines for various γ)*

# Cosmological inference from large-scale structure
## Cross-correlations

- Gravitational lensing of the CMB x-correlated with the LSS maps: now extended to x-correlations of **CMB lensing with cosmic shear**
- Cosmic shear probes (all) matter distribution while LSS maps are sensitive to **galaxy bias** ($\delta_g = b\ \delta_m$)
- An **emerging approach** as both the CMB lensing maps and wide-angle cosmic shear catalogs started being available only in the last ~5 years
- Several detections made so far, but **no cosmological constraints yet**
- **Great promise** for ongoing and future surveys (cosmic shear: KiDS, DES, Euclid...; CMB lensing: ACT, SPT, ...)

# Cosmological inference from large-scale structure
## Cross-correlations

- Many other maps and surveys have been x-correlated; for instance:
  - Planck **thermal Sunyaev-Zeldovich** maps vs. galaxy data for constraints on baryonic physics (warm-hot intergalactic medium, filaments, …)
  - CMB lensing vs. **submillimeter** galaxy maps
  - **Cosmic *Infrared* Background** vs. galaxy maps for constraints on the sources of the CIB
  - **Gamma-ray background** as measured by Fermi-LAT vs. galaxy maps for constraints on the sources on the gamma-ray signal
  - The latter can also be used to constrain some **dark matter models**, also by x-matching with cosmic shear

# Cosmological inference from large-scale structure

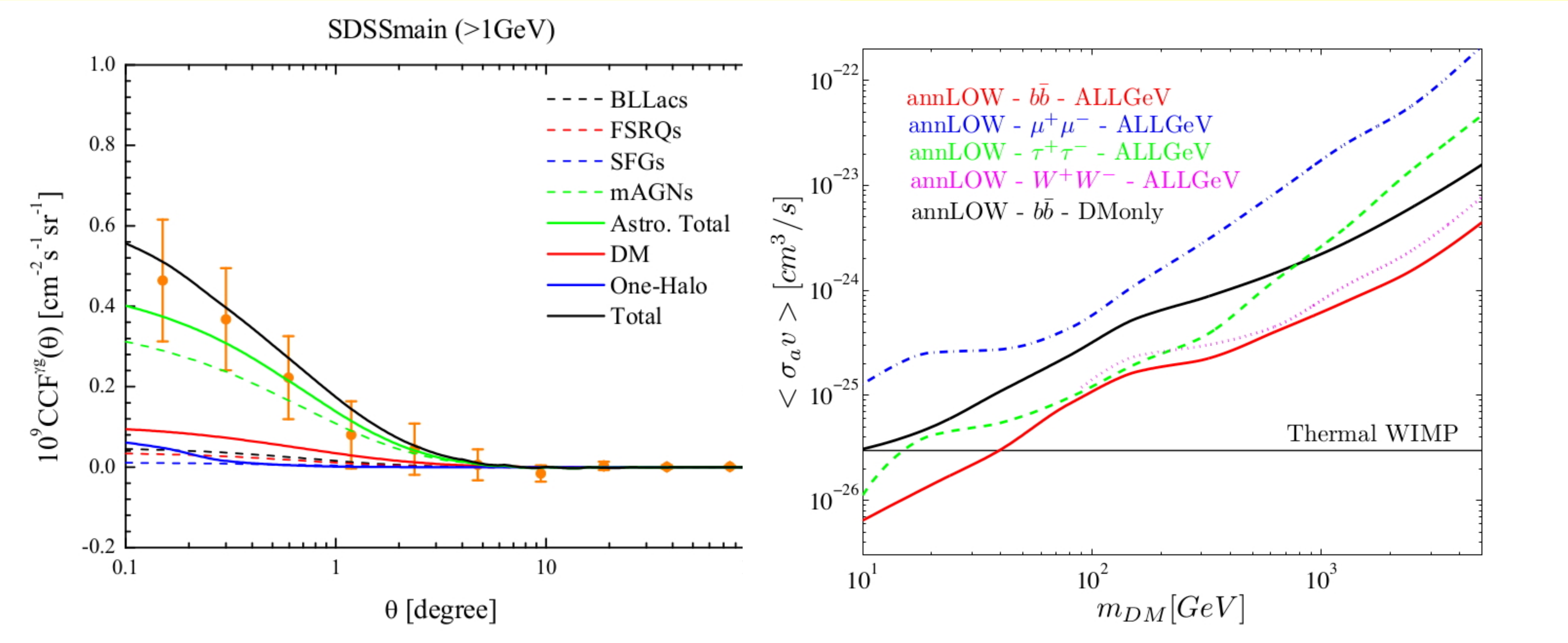
## Cross-correlations

- Gamma-ray background as measured by Fermi-LAT vs. galaxy maps or cosmic shear to constrain some dark matter models
- If dark matter **self-annihilates or decays**, gamma-ray signal would be produced, and localized to where structures (galaxies, clusters) are
- There is **signal in gamma-ray vs. LSS measurements**, but within the current errors can be **fully explained by "standard" astrophysics** (blazars, AGNs, star formation)
- No signal yet in gamma-ray vs. cosmic shear – limited by systematics
- Still, one can put **upper limits on dark matter annihilation or decay** cross-sections etc. – an emerging probe of particle physics

# Cosmological inference from large-scale structure

## Cross-correlations

- Gamma-ray background as measured by Fermi-LAT vs. galaxy maps to constrain some dark matter models




*Cuoco et al. 2015*

# Cosmological inference from large-scale structure

## Gravitational waves?

- A **new window** on the Universe is open thanks to first two GW detections
- Future GW observatories (Einstein Telescope...) may provide thousands of detections and effectively new large-scale structure maps in GW
- GW events provide the **luminosity distance** to the sources, but **not** the redshift (*standard sirens*)
- Possibility to constrain cosmological parameters from GW event maps and their cross-correlations with the LSS (e.g. Oguri 2016)

**Measuring the distance-redshift relation with the cross-correlation of gravitational wave standard sirens and galaxies**

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