Near-future large-scale surveys in the optical and infrared

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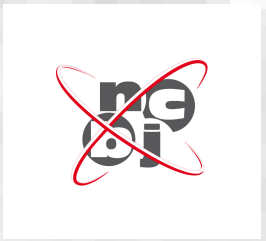
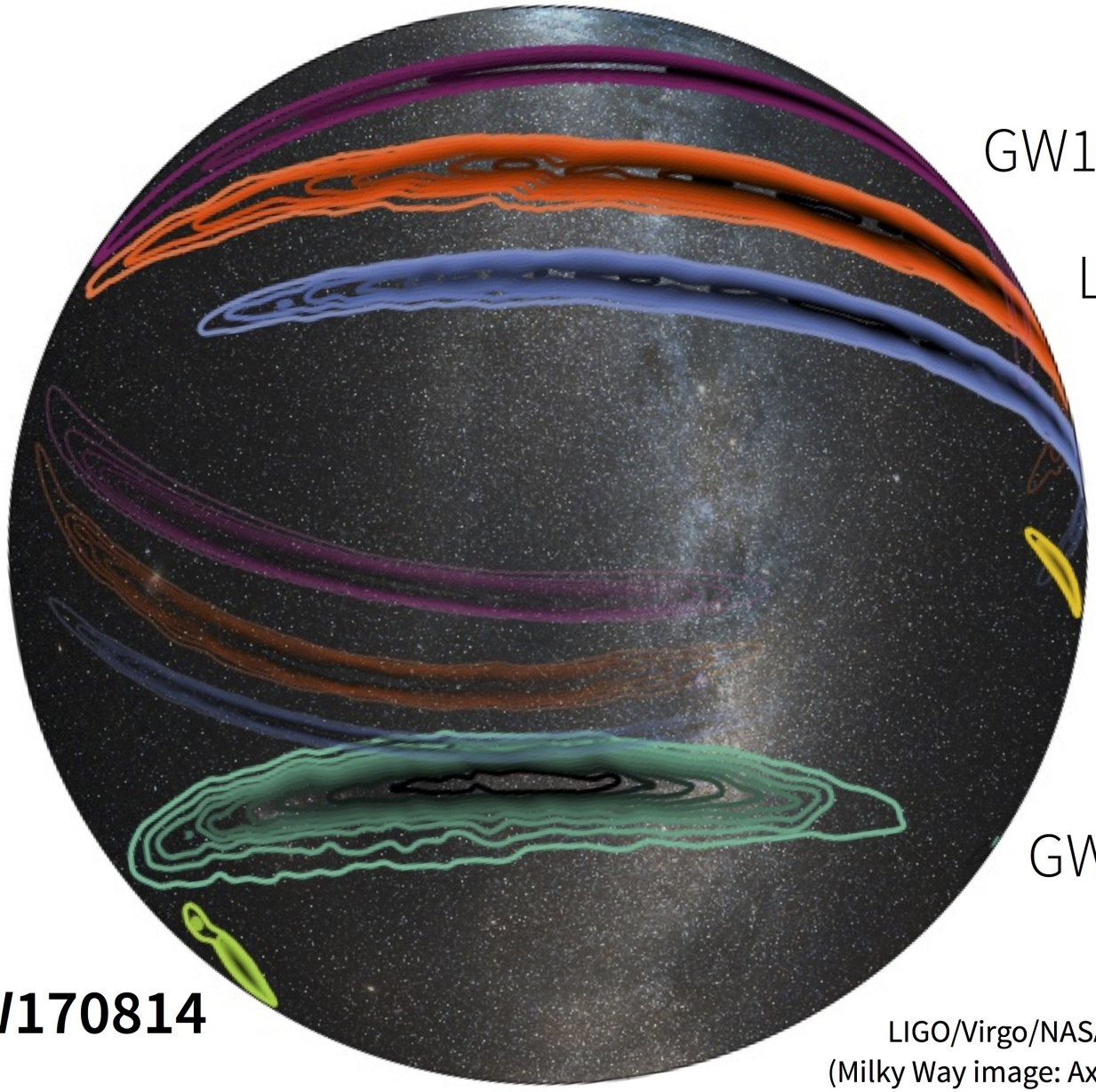


Multi-messenger signals

Gravitational waves...



GW170104

LVT151012

GW151226

GW170817

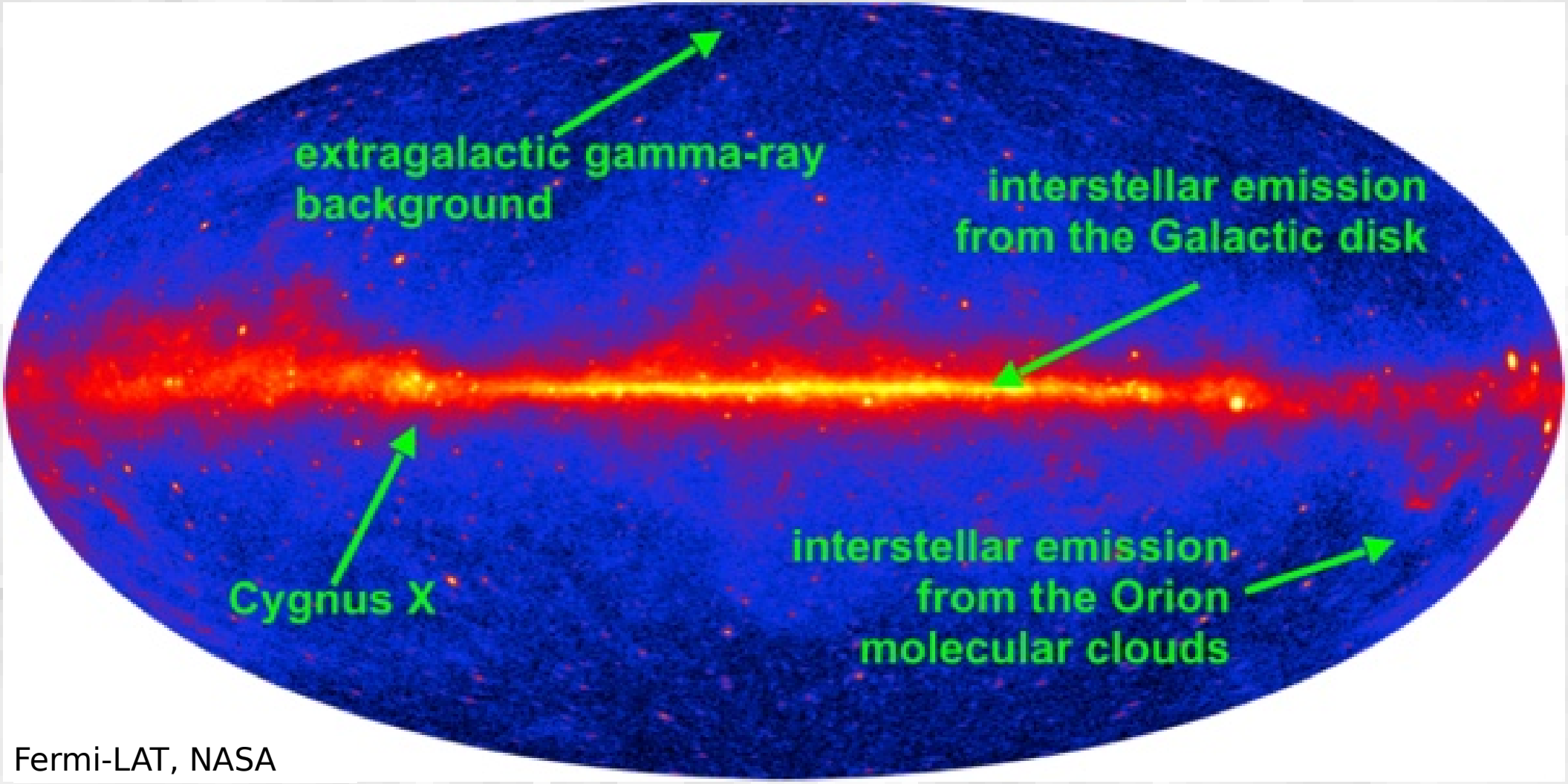
GW150914

GW170814

LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

Multi-messenger signals

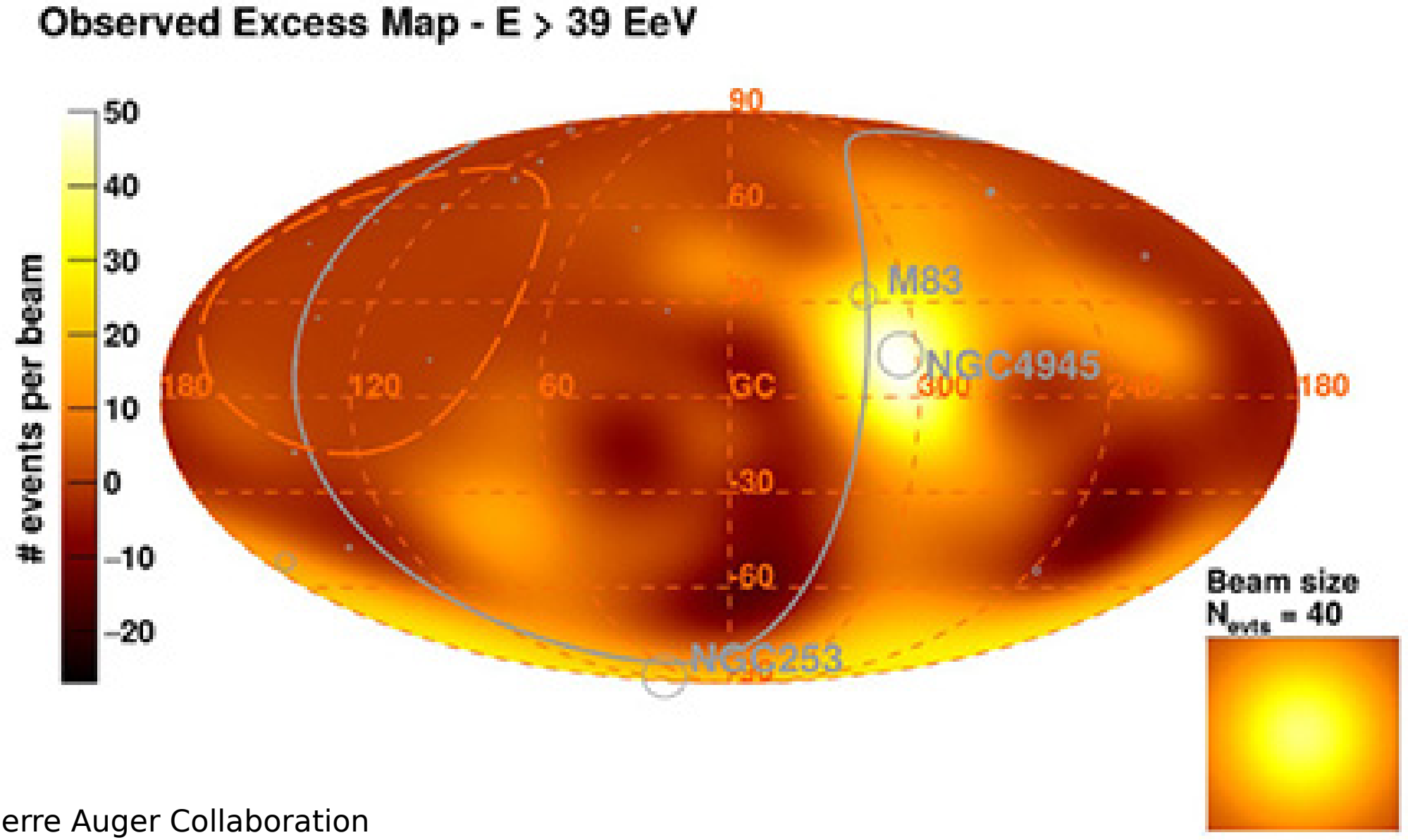
Gamma-ray background...



Fermi-LAT, NASA

Multi-messenger signals

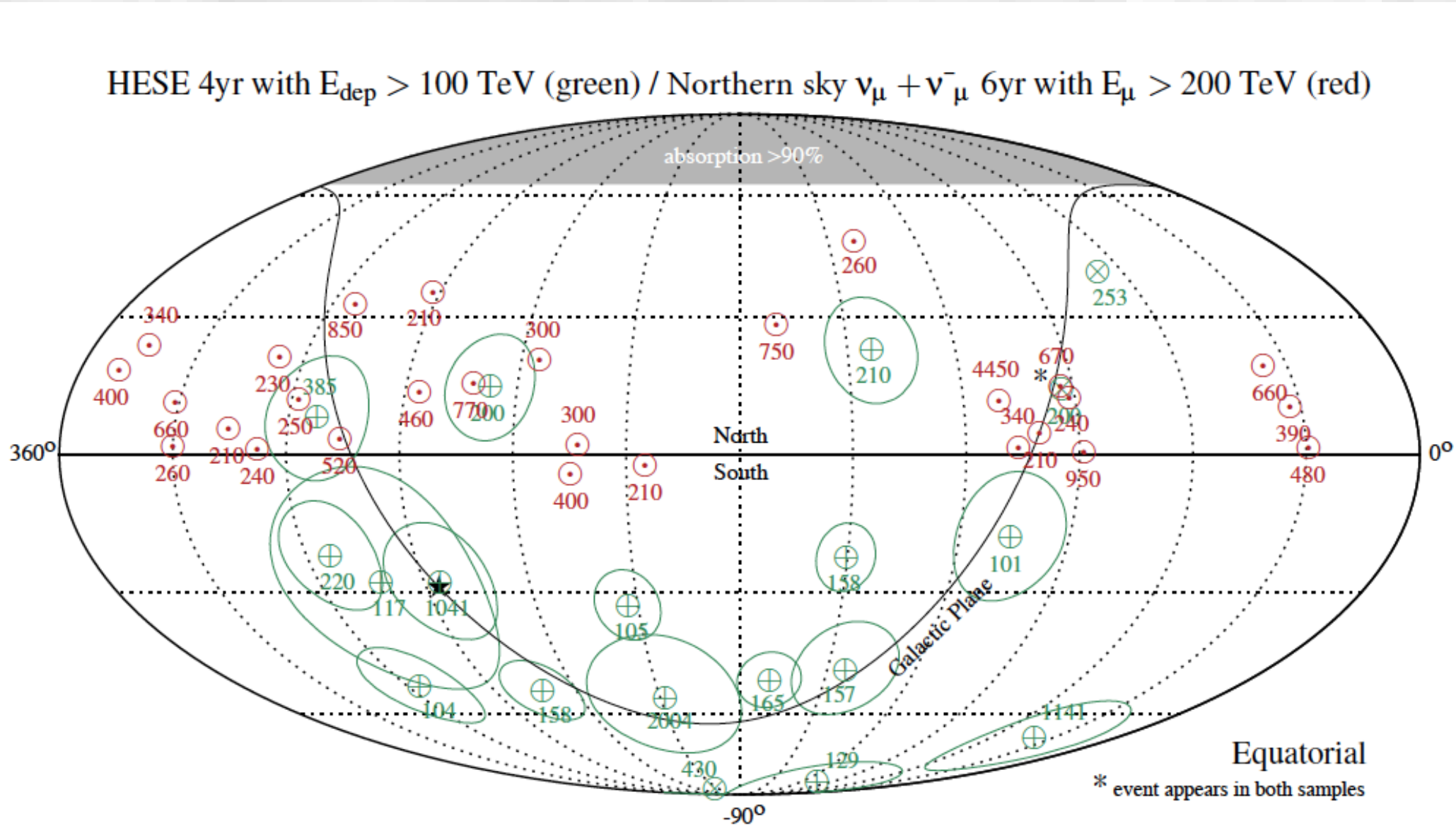
Ultra-High Energy Cosmic Rays...



Pierre Auger Collaboration

Multi-messenger signals

High-energy neutrinos...



IceCube

Multi-messenger signals

- **...often arrive from the entire sky (4π steradians)**

  → especially if they are of extragalactic origin

  → even if they show (significant) anisotropies

- We want to **compare them with the large-scale galaxy distribution**

  → to search for their optical / infrared / electromagnetic counterparts

  → to search for correlations in angular and radial distributions

  → to understand the nature of their sources...

- We therefore need **all-sky, deep, complete, 3-dimensional galaxy catalogs**

  → also with value-added information such as:

  * galaxy (stellar) masses,

  * star formation rates, ...

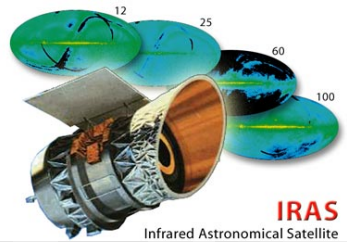
- **Meeting all these requirements simultaneously is a challenge**

  (close to “impossible”)

Charting the sky

- **Spectroscopic**
  - → provides exact redshifts, i.e. ~**distances**
  - → allows to unambiguously tell the **nature of the sources** (star/galaxy/quasar...)
  - → gives direct access to **three-dimensional large-scale structure**
  - → requires **input datasets** for spectroscopic follow-up
  - → infeasible to measure spectra for the majority of detected sources
  - → **sparse sampling** needed due to time and cost constraints
- **Photometric**
  - → provides **complete, deep, wide-angle datasets**
  - → allows to **map previously uncharted** sky areas
  - → does not directly provide redshifts
  - → requires **multi-wavelength coverage** for distance estimates (**photo-zs**)
  - → makes **source classification challenging** (overlaps in color space etc.)

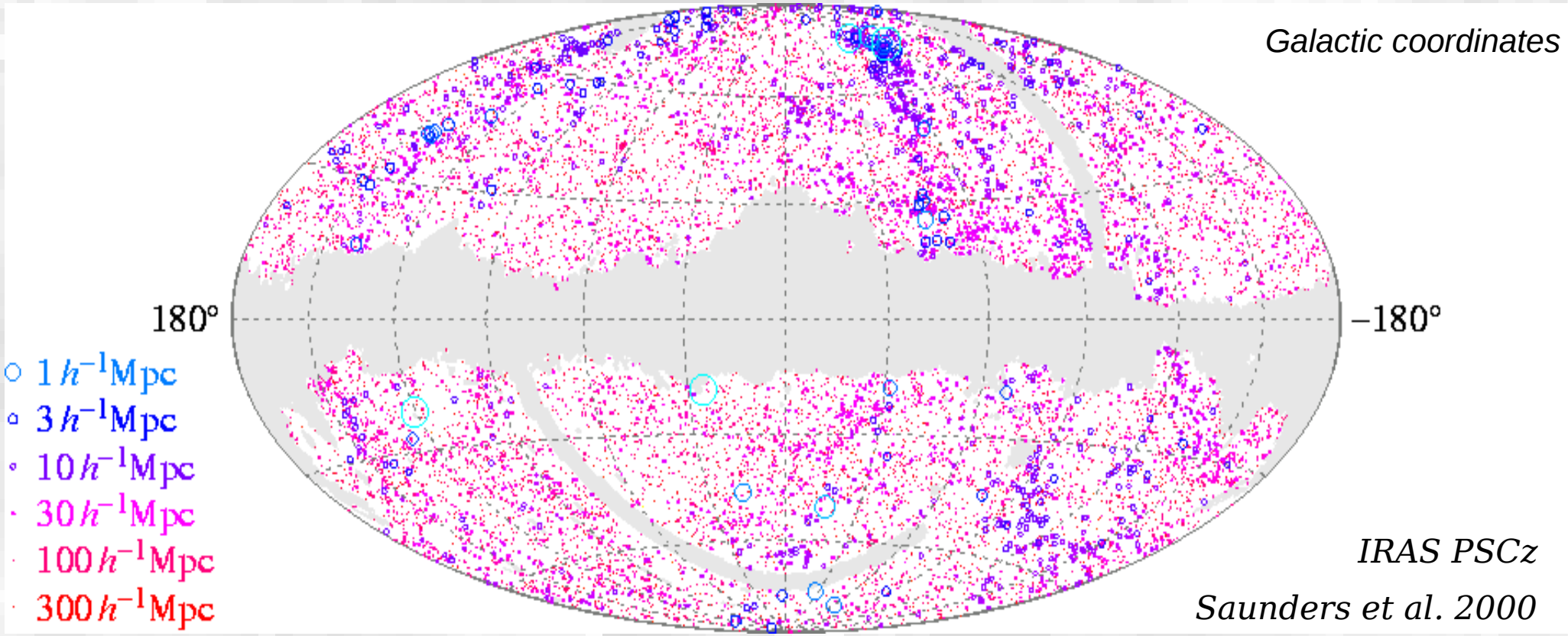
The first all-sky spectroscopic redshift survey: IRAS PSCz



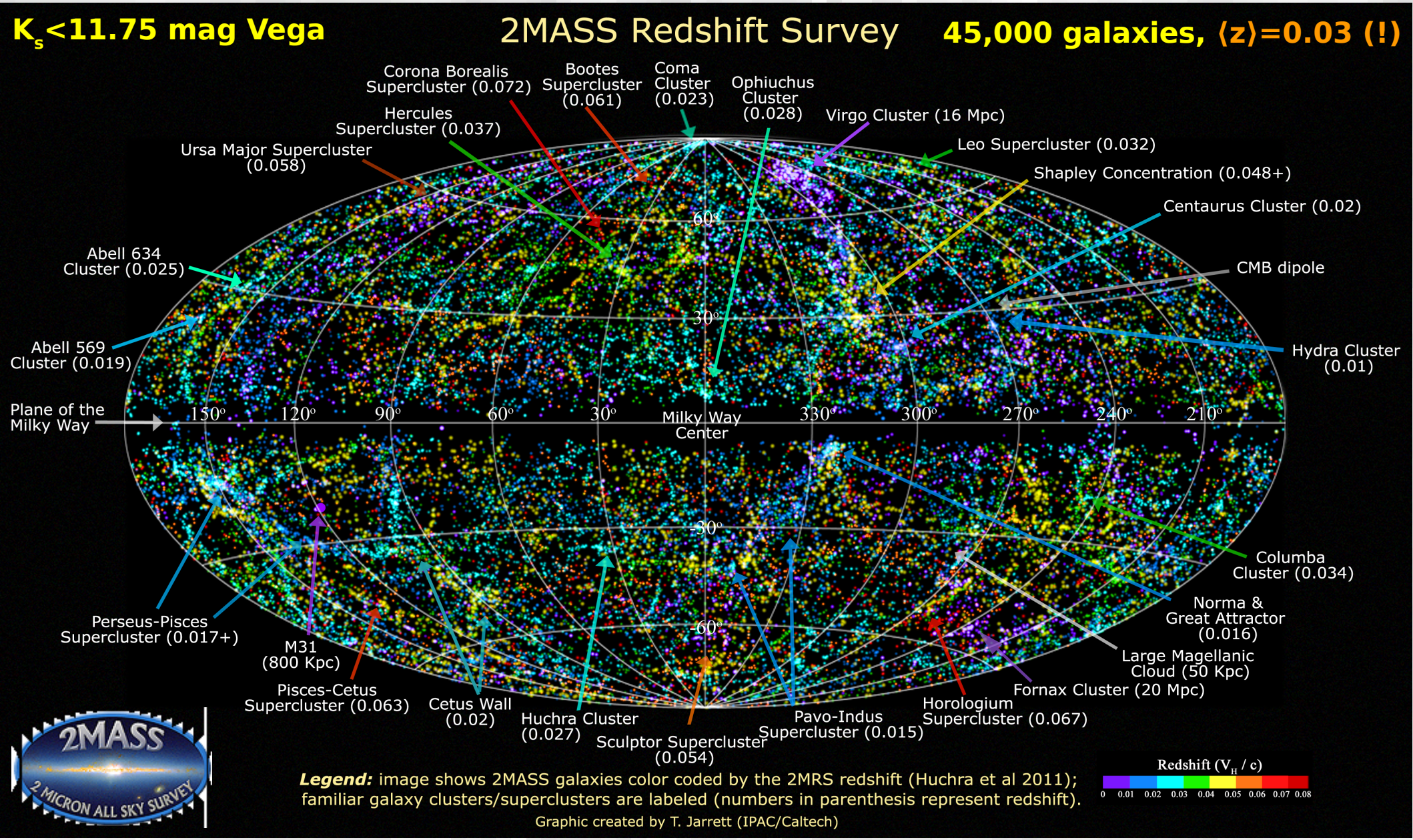
Galaxies preselected from **IRAS** mid-infrared observations

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

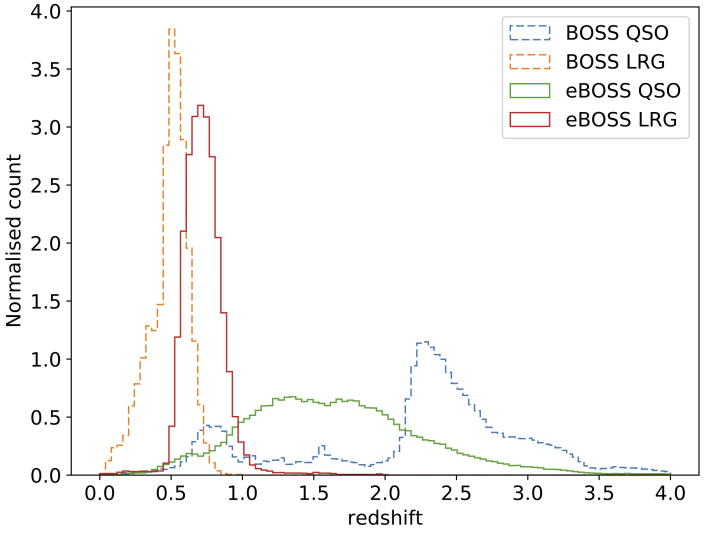


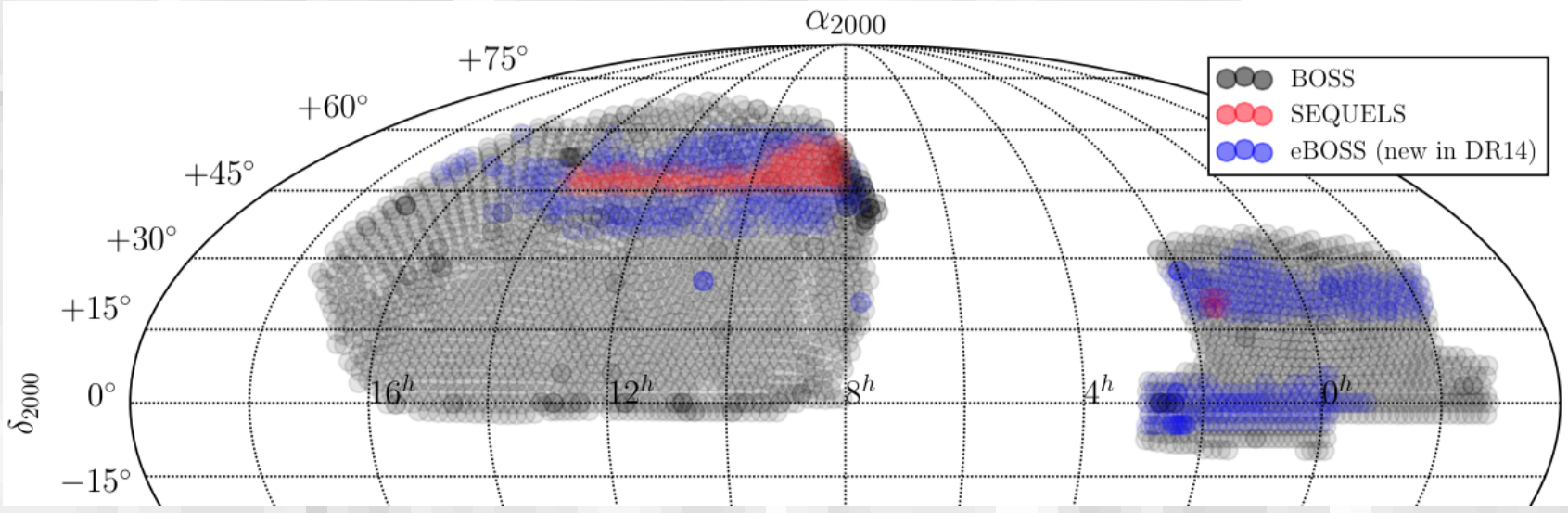
Huchra et al. 2012 (plot by Tom Jarrett)

The largest existing spectroscopic survey:

Sloan Digital Sky Survey

- **Stars, galaxies and quasars** preselected from SDSS photometry (now +WISE)
- Sparse sampling strategies to target **luminous red galaxies**, **emission line galaxies**, **quasars** at specific redshift ranges, …
- Spectroscopic data cover **~1/4th of the sky**, currently some **3 million extragalactic spectra**
- **Current stage** SDSS-IV: eBOSS
- **Fourteen data releases** so far, #15 forthcoming December 2018



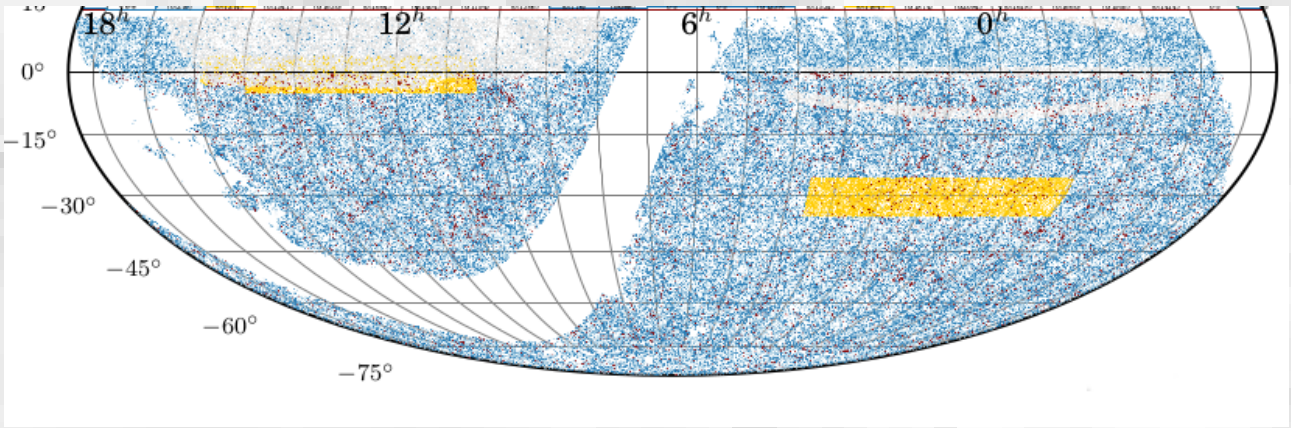


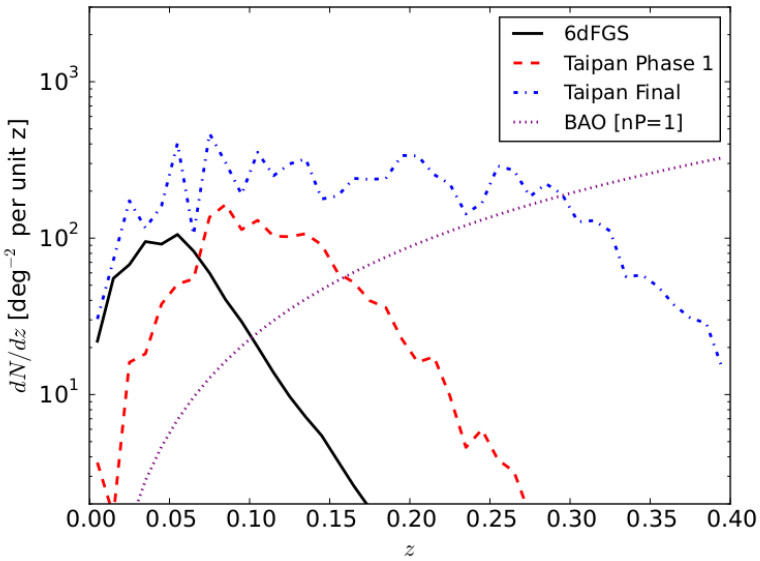
SDSS DR14
Abolfathi et al. 2018

Near-future spectroscopic surveys:

TAIPAN

- Spectroscopic survey to comprehensively map the **entire southern sky at low-z**
- A southern **extension of SDSS-Main** + **higher-z red galaxies** for flat dN/dz
- **Target selection**: currently from 2MASS XSC+PSC, also KiDS, later SkyMapper
- In total **~2 million galaxies**: complete sampling to z<0.2 + sparse at 0.2<z<0.4
- Also: **peculiar velocities** via the fundamental plane at z<0.1
- Expected to start **next year**...





da Cuhna et al. 2017

nP: ratio of true clustering power to that from shot noise

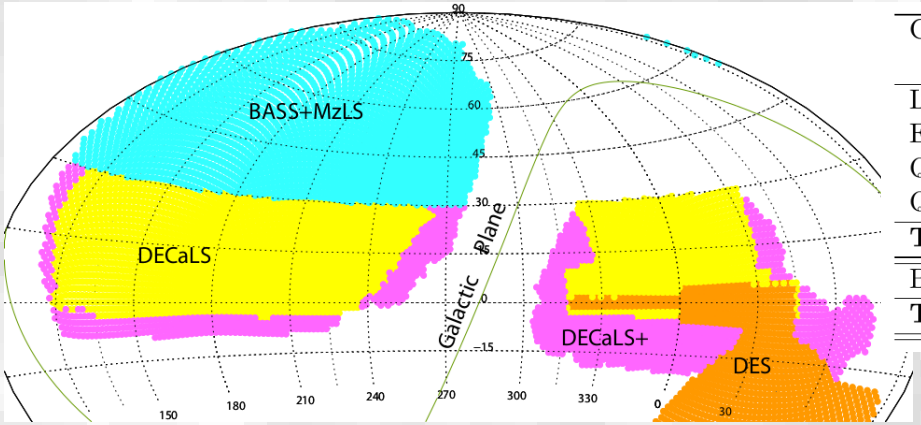
Near-future spectroscopic surveys:

Dark Energy Spectroscopic Instrument (DESI)

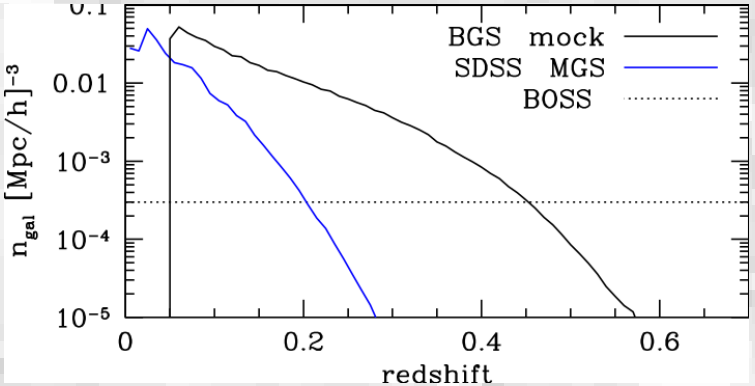
- Essentially a **major extension of SDSS** to larger area, higher number density and wider redshift coverage
- **Targets** selected from several optical surveys (DECaLS, BASS, MzLS) + WISE
- ~14,000 deg^2: **1/3rd of the sky**
- **Bright Galaxy Sample**: flux-limited r<19.5, z~0.2, **10 million** galaxies
- **Luminous Red Galaxies**: color-selected with Zmag<20.5, up to redshift z<1.0, **~4 million** sources
- **Emission Line Galaxies**: color selection at r<23.5, redshift range 0.6<z<1.6, **over 17 million** objects
- **Quasars**: optical+WISE color selection at r<23 giving some **~2.5 million** QSOs at 0<z<4
- **Starting in 2019!**

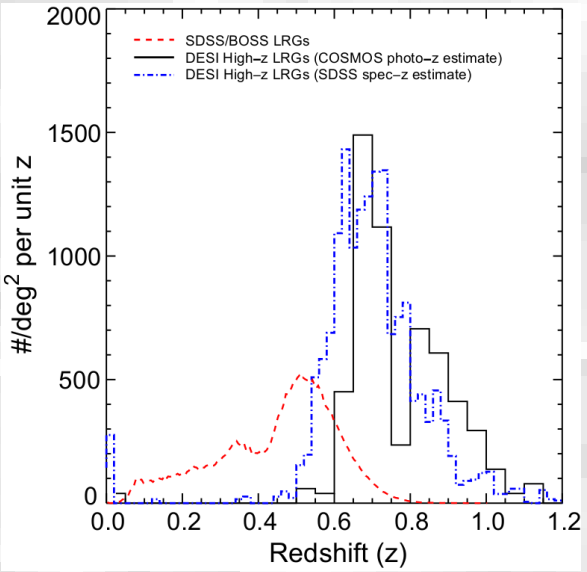
Near-future spectroscopic surveys:

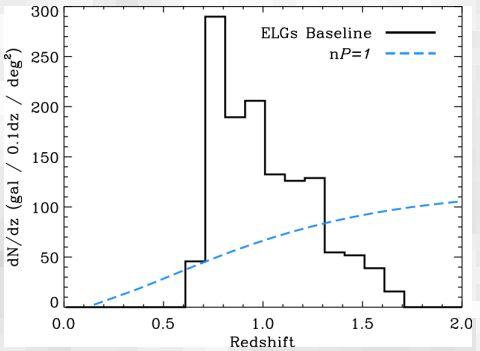
Dark Energy Spectroscopic Instrument (DESI)

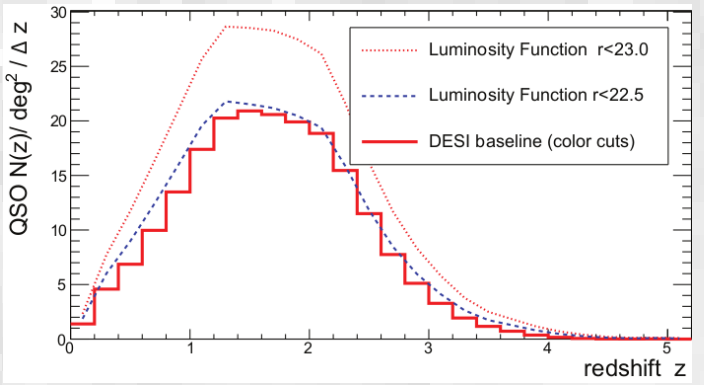


Galaxy type	Redshift range	Bands used	Targets per deg^2	Exposures per deg^2	Good z's per deg^2	Baseline sample
LRG	0.4–1.0	$r,z,W1$	350	580	285	4.0 M
ELG	0.6–1.6	g,r,z	2400	1870	1220	17.1 M
QSO (tracers)	< 2.1	$g,r,z,W1,W2$	170	170	120	1.7 M
QSO (Ly-α)	> 2.1	$g,r,z,W1,W2$	90	250	50	0.7 M
Total in dark time			**3010**	**2870**	**1675**	**23.6 M**
BGS	0.05–0.4	r	700	700	700	9.8 M
Total in bright time			**700**	**700**	**700**	**9.8 M**









DESI collaboration 2016

Near-future spectroscopic surveys:

SDSS stage V

- SDSS will **extend to the south**: second telescope at Las Campanas (Chile)
- The "**Black Hole Mapper**": multi-epoch optical spectra for more than 400,000 X-ray sources, mostly **quasars/AGNs**
- Planned **timeline**: 2020-2025

SDSS-V Black Hole Mapper Targeting				
Science Goals	**Primary Selection**	**Density [deg^{-2}]**	**N$_{targets}$**	**N$_{epochs}$**
Reverberation mapping, BH masses	Optical QSOs, $i < 20$	30–50	1,500	174
BH accretion and outflow astrophysics, changing look quasars	Optical QSOs, $i < 19$	10	25,000	3–13
eROSITA follow-up, AGN, X-ray binaries, galaxy clusters	$f_{X-ray} \geq 2.5 \times 10^{-14}$ erg s^{-1} cm^{-2}, $i < 21.5$	20–50	400,000	1–3

Kollmeier et al. 2017

Near-future spectroscopic surveys:

4MOST

- A number of Galactic and extragalactic spectroscopic surveys using the **4-metre Multi-Object Spectroscopic Telescope** (refurbished VISTA on Paranal, Chile)
- To cover (large) swaths of the **southern sky**
- Extragalactic:

  → **cosmology redshift survey** (bright sample, LRGs, ELGs, QSOs)

  selection from (probably) VISTA Hemisphere Survey (VHS) + WISE + DES

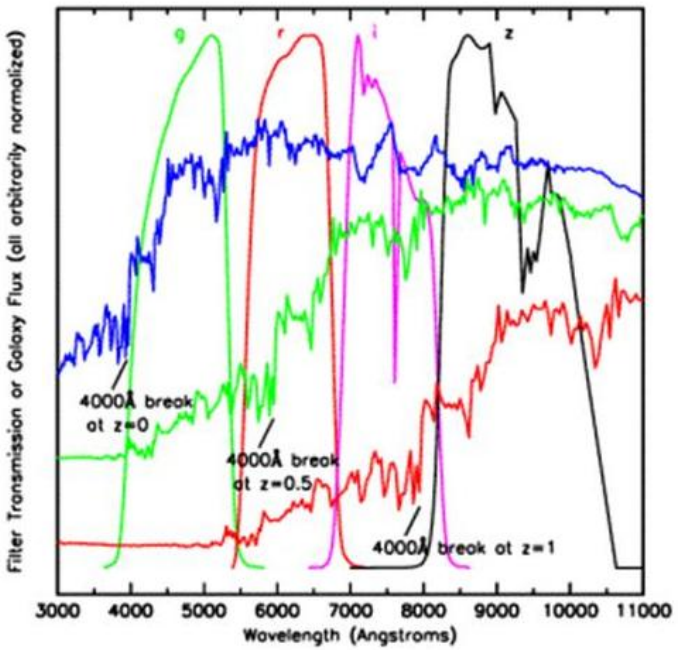
  → **eROSITA follow-up**: galaxy clusters, AGNs

  → **WAVES**: faint low-redshift galaxies from KiDS+VIKING

  → **TiDES**: extragalactic transients + supernova redshifts
- Final footprints, selections, number densities etc. still to be decided
- **Expected start**: ~2021

Photometric surveys: deeper, wider, more complete

- **… but no exact redshifts**
- Multi-wavelength optical+IR coverage allows to estimate ***photometric redshifts***: Cosmological **shift** of **lines** and of the **continuum** + **decrease** in observed **flux** + evolution = **wavelength-dependent flux changes**
- Much **less precise** than spectroscopic: scatter of 0.01(1+z) is an achievement
- Good photo-zs are however **accurate**: mean bias of dz~0
- **At least 4 bands needed** for robust photo-zs; optical for z<1 + near-infrared for z>1

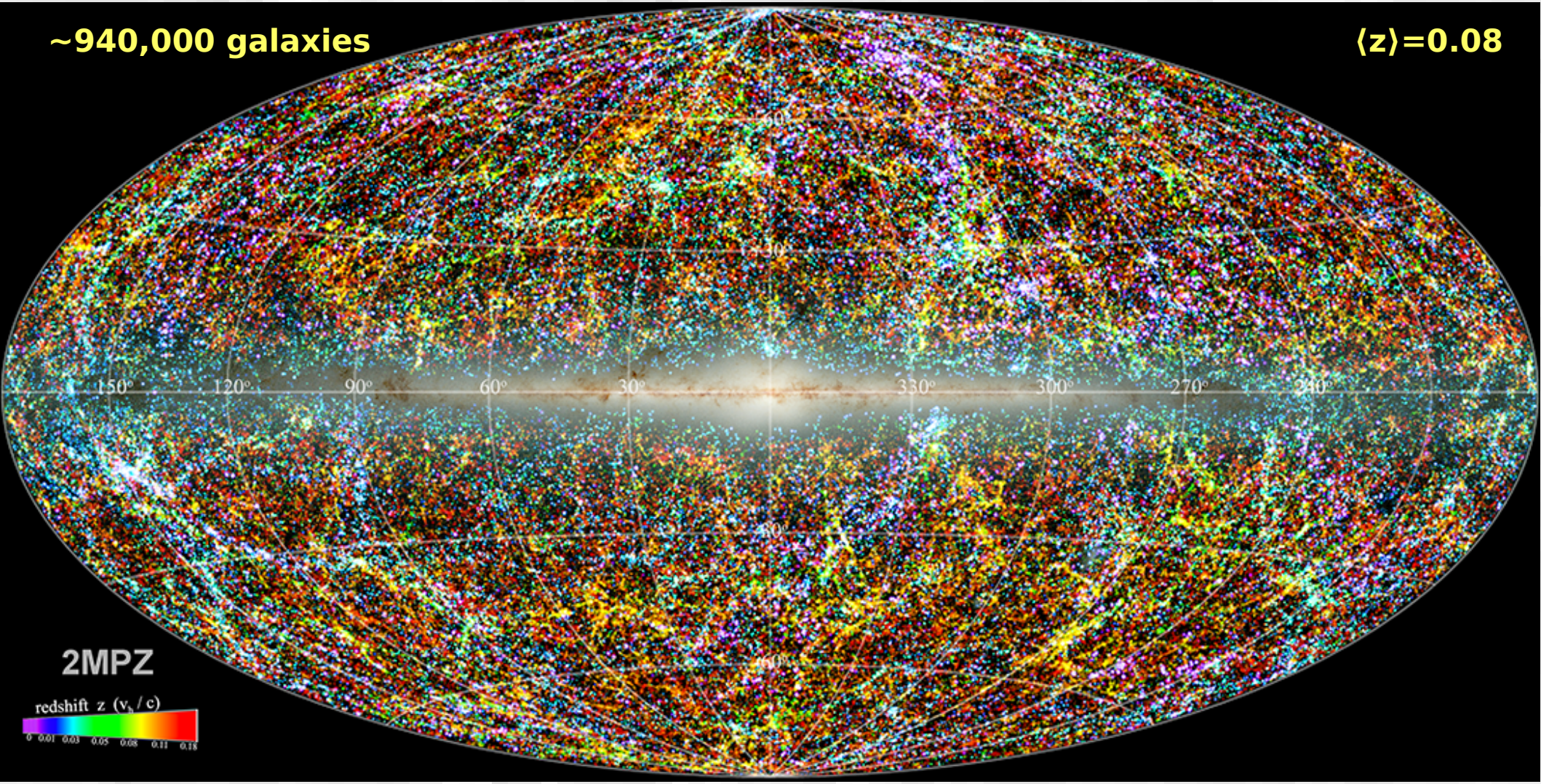


- **Two main methods** for photo-zs: template fitting; machine learning
- **Machine learning** requires complete spectroscopic samples for calibration (training)
- **Template fitting** depends on robust spectral templates (knowledge of SEDs)
- Alternative approach: **clustering redshifts** based on cross-correlations

An example: 2MASS Photometric Redshift catalog

2MPZ, Bilicki et al. 2014

Color-coded by photometric redshifts



Plot by Tom Jarrett

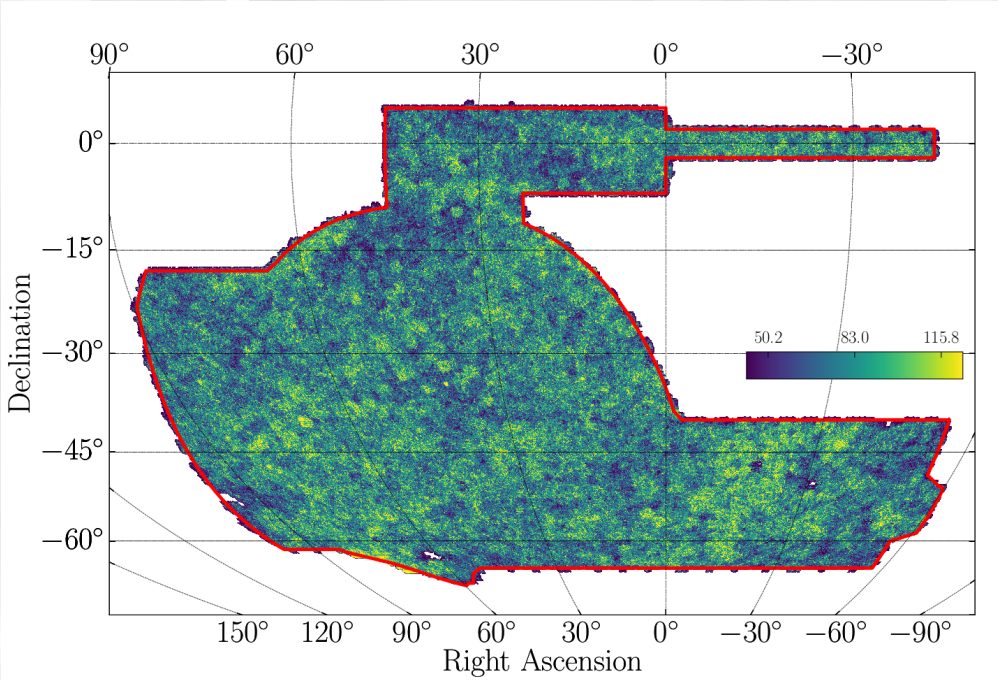
New era in photometric surveys

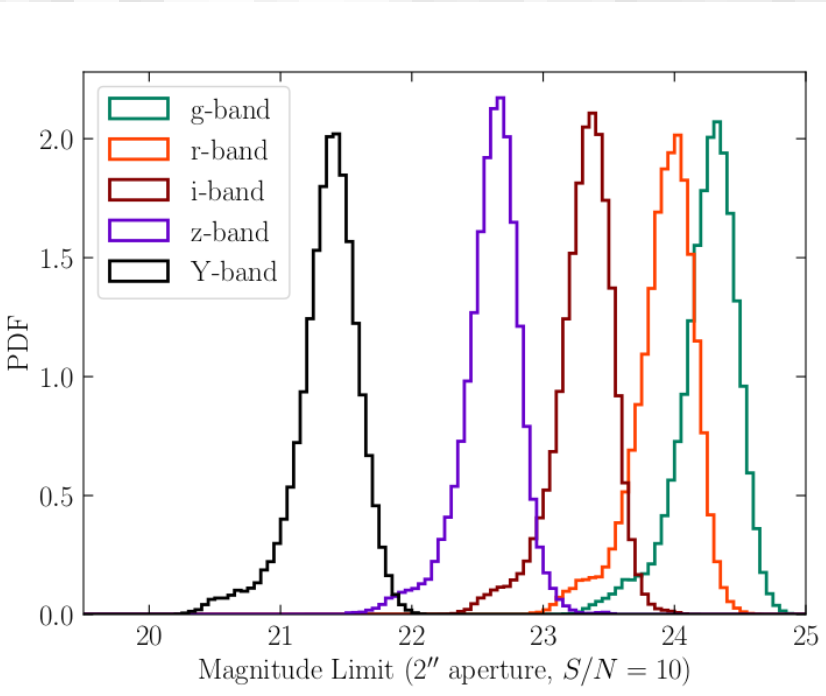
- Three major ongoing photometric surveys aimed at weak lensing:
  → **Dark Energy Survey (DES)**
  → **Kilo-Degree Survey (KiDS)** [supplemented with VIKING]
  → **Hyper-Suprime Cam Subaru Strategic Program (HSC SSC)**
- **DES** covers the largest area
- **HSC** is the deepest and with best seeing (angular resolution)
- **KiDS+VIKING** is unique in 9-band coverage on area and seeing similar to HSC and depth larger than DES
- **Science enabled** by these surveys:
  → **cosmic shear** analyses on unprecedented angular scales
  → **cross-correlations** using cosmic shear and galaxy distribution
  → complete samples of **galaxy clusters and quasars** at broad redshift ranges
  → etc.

New era in photometric surveys

- **Dark Energy Survey (DES)**, mapping **5000 deg²** of southern sky in optical-NIR ***grizy***
- Will be 5 years of observations in total, finishing this year
- Target **depths of *r* >24 mag** built up over the years, typical **seeing of ~0.9”**
- **Data Release 1** covering three years, over 300 million galaxies

DES DR1 galaxy density



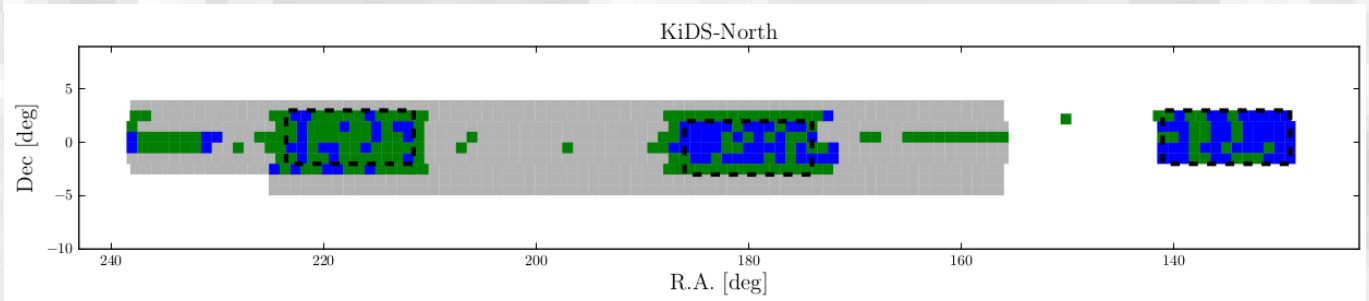


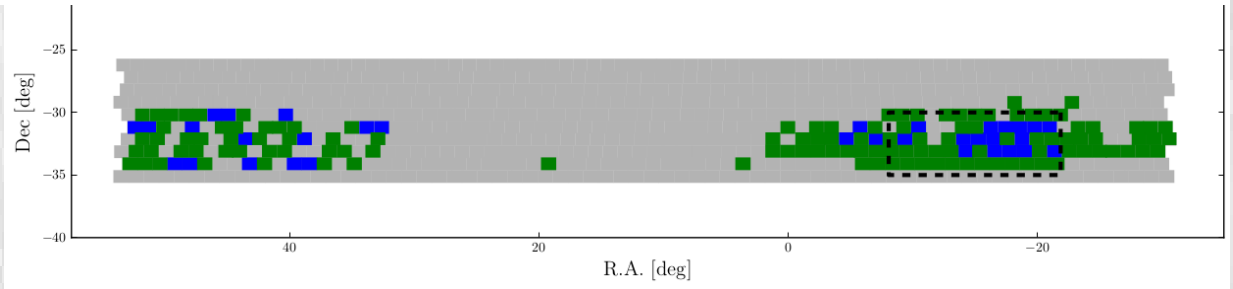
Abbott et al. 2018

New era in photometric surveys

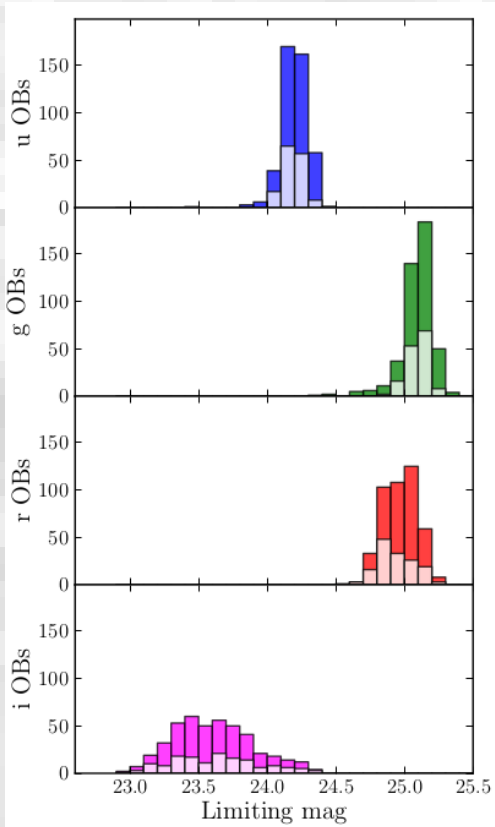
- **Kilo-Degree Survey (KiDS)**, target ~**1500 deg²** in ***ugri***
- Observations to finish in 2019
- Pointed observations, build-up of area at target depth (**r~25 mag**), **seeing ~0.7”**
- Supplemented with near-IR **VIKING** *zyJHK* at similar depth: 9-band coverage
- **KiDS DR3** including 40 million sources on ~450 deg2
- Forthcoming DR4 on 1000 deg² joint with VIKING

de Jong et al. 2017



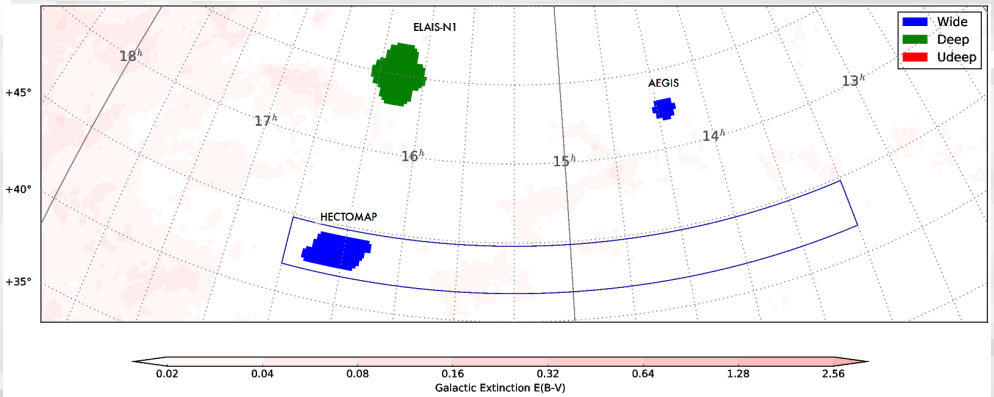


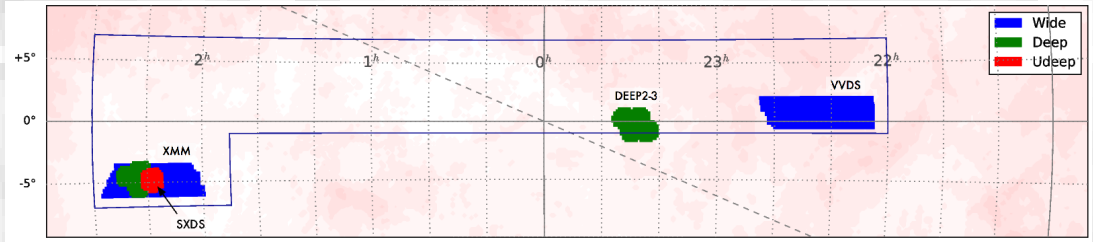
Grey: target
Green: DR3
Blue: DR1+2



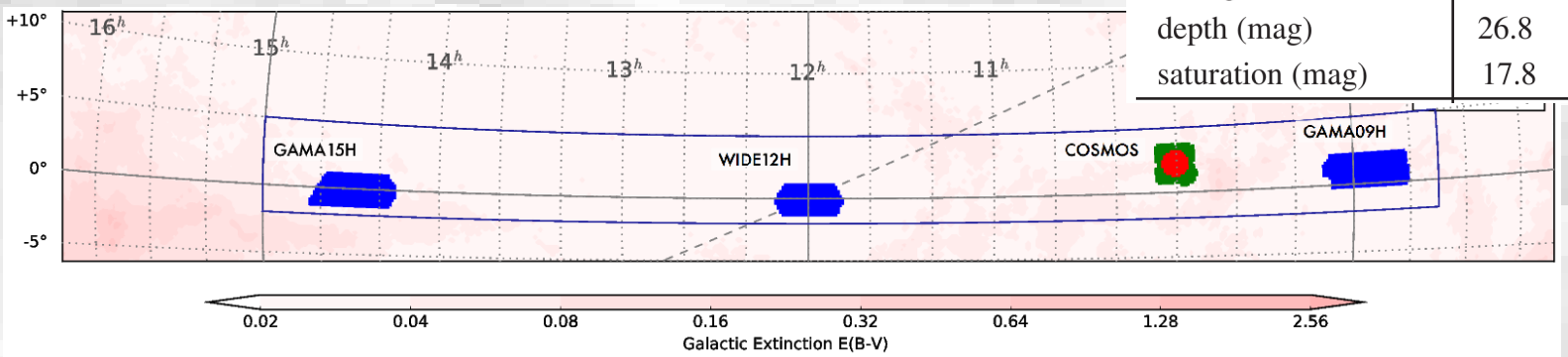
New era in photometric surveys

- **Hyper-Suprime Cam Subaru Strategic Program (HSC SSC)** on **1400 deg²**
- Started in 2014, to finish in 2020
- Optical-NIR ***grizy***, target ***r*~26** mag with **excellent seeing of ~0.6”** in *i*-band
- **First data release** from 1.7yrs of observations: 108 deg², 70 million sources





Wide	g	r	i	z	y
exposure (min)	10	10	20	20	20
seeing (arcsec)	0.72	0.67	0.56	0.63	0.64
depth (mag)	26.8	26.4	26.4	25.5	24.7
saturation (mag)	17.8	17.8	18.4	17.4	17.1



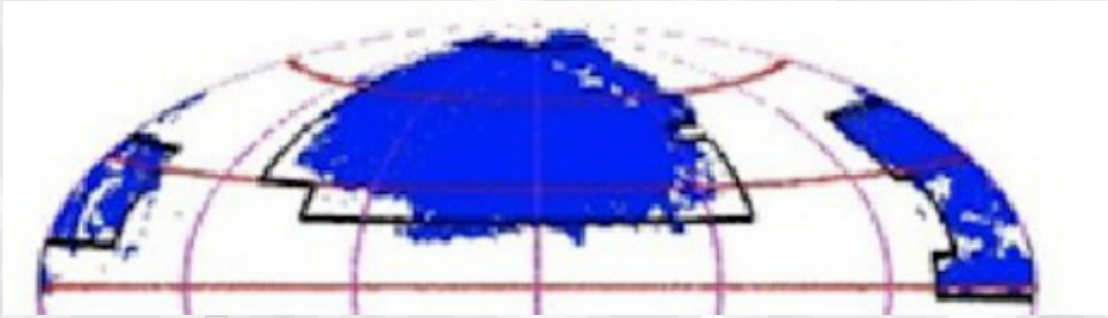
Depth of SDSS Main!

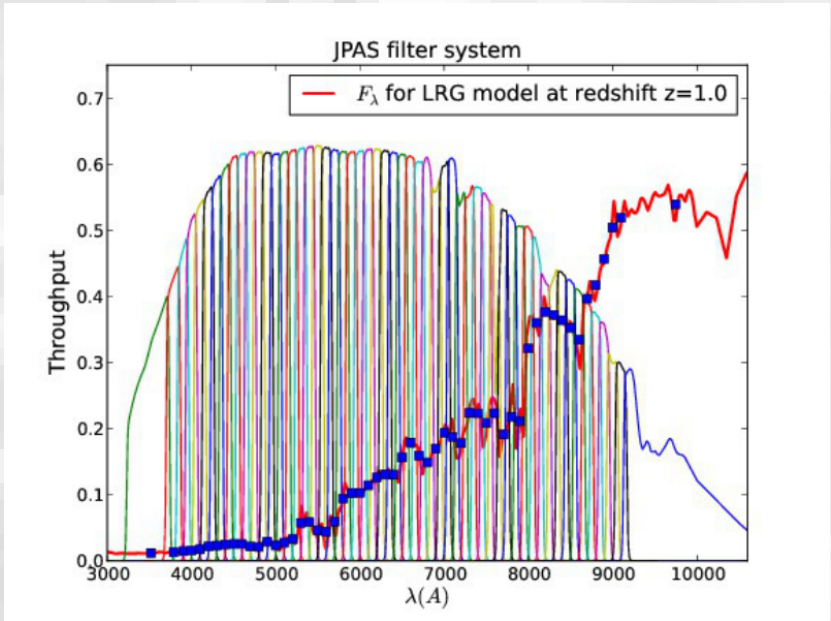
Aihara et al. 2018

Between photometry and spectroscopy: J-PAS narrow-band survey

- Idea: use **couple dozen very narrow photometric filters** to probe the spectrum without a spectrograph
- Javalambre-Physics of the Accelerated Universe Astrophysical Survey (**J-PAS**): 56 filters of 154Å-width covering the full optical range
- This allows for **very precise photo-zs** of dz=0.003(1+z) [i.e. 10x better than with broad bands]
- Will observe ~**8500 deg² of the northern sky** to ~22.5 mag depth
- Expected 90 million **LRGs+ELGs** and several million **QSOs**
- **Start 2019**

Benitez et al. 2014





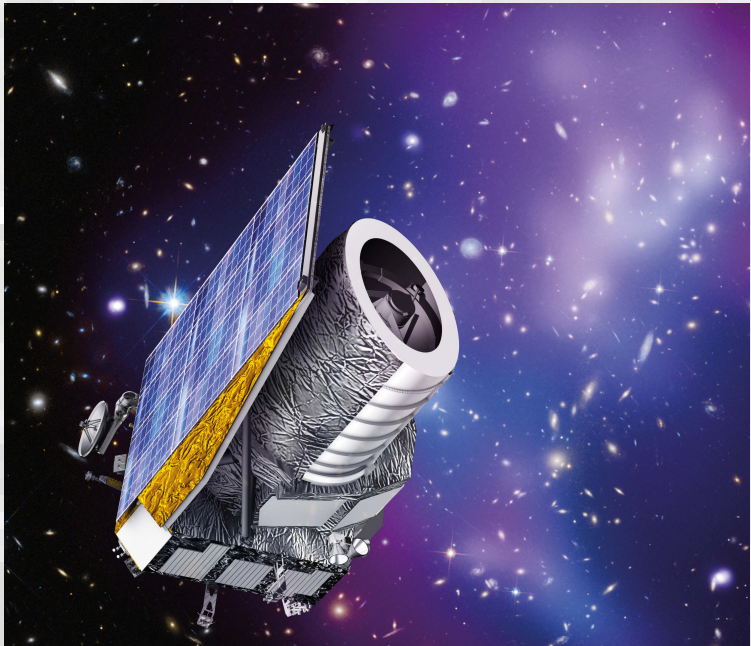
What's next

LSST

- **Large Synoptic Survey Telescope (LSST)**
- **8.4 meter telescope** on Cerro Pachon (Chile)
- **10-year survey** in ***ugrizy*** bands, fast and wide-angle, ~20,000 deg^2
- Will map the **entire southern sky repeatedly**: multi-color and time-domain
- Expected **depth of r=27.5** for stacked images – some 1 mag deeper than HSC-wide
- Some **10 billion (10^{10}) galaxies** expected at this depth
- All this together with **cosmic shear information**
- **AGNs** from color–astrometry–variability selection: some **~17 million**
- **Timeline**: science verification 2021-22; main survey start 2023

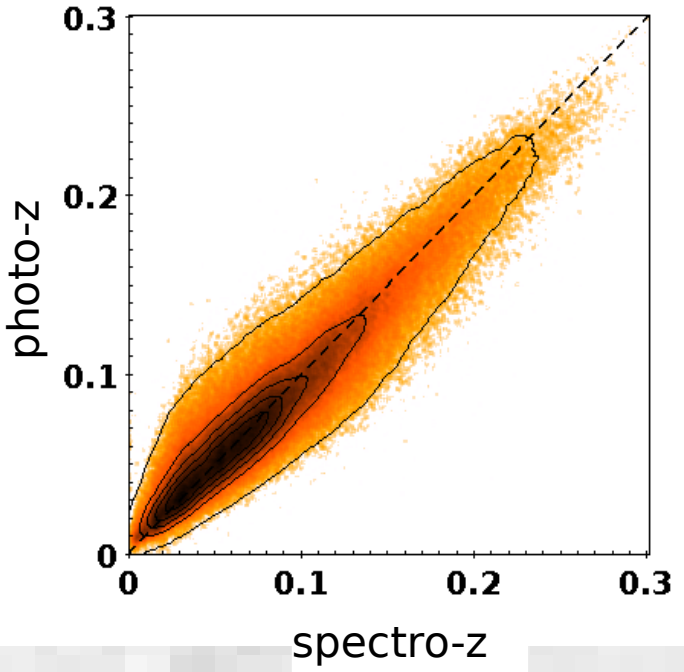
What's next
Euclid

- **Space-borne** spectroscopic and photometric mission to study very wide-angle large-scale structure at high redshift (**spectroscopy: 0.7<z<1.2; photometry: z<2**)
- Grism slitless spectroscopy: **~50 million galaxies** with redshift precision 0.001(1+z)
- Photometry in very broad optical `VIS' (R+I+Z) and narrower NIR Y,J,H
  1.5 billion galaxies
- Angular **resolution of 0.1"-0.3"** – precise measurements of galaxy shapes
- To map **15,000 deg² of extragalactic sky**
- Limiting magnitudes: VIS =24.5, Y,J,H=24.0
- Plus a **deep survey on 40 deg²**, fainter by 2 mag
- Main science: weak lensing; galaxy clustering
- Expected launch: **2021**



2MASS Photometric Redshift catalog (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 catalog** with **1 million galaxies**, **⟨z⟩=0.08 (d~350 Mpc)**, covers **most of the sky**
- Some statistics of the photo-z estimates:
  → **bias~0** and 1-sigma scatter $\boldsymbol{\sigma_{\Delta z}}$**= 0.015**
  → median error **|Δz|/z = 13%**
  → only **3% of outliers** $>3\sigma_{\delta z}$
- 2MPZ is **available for download** from **http://surveys.roe.ac.uk/ssa/TWOMPZ**

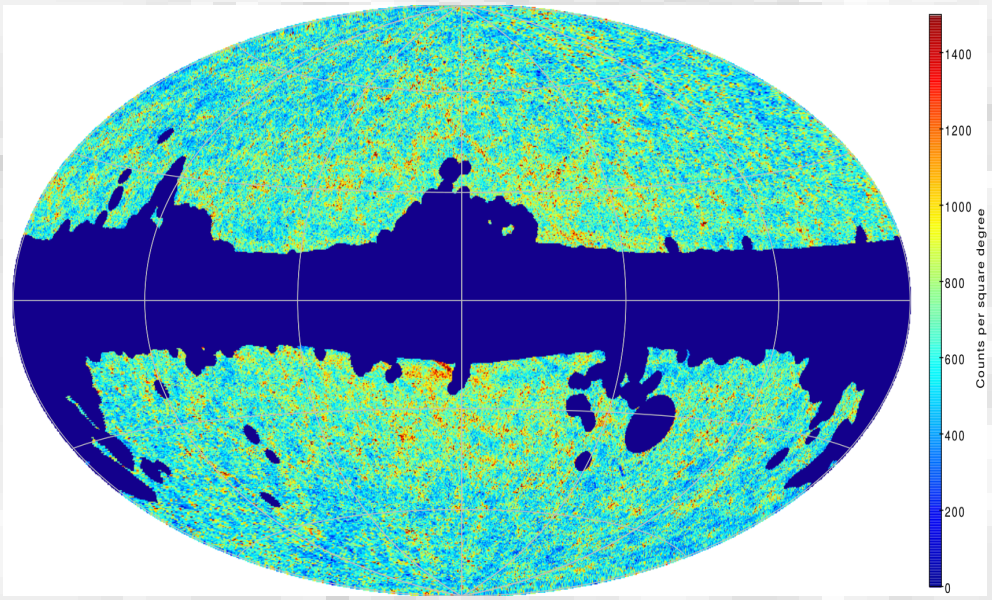


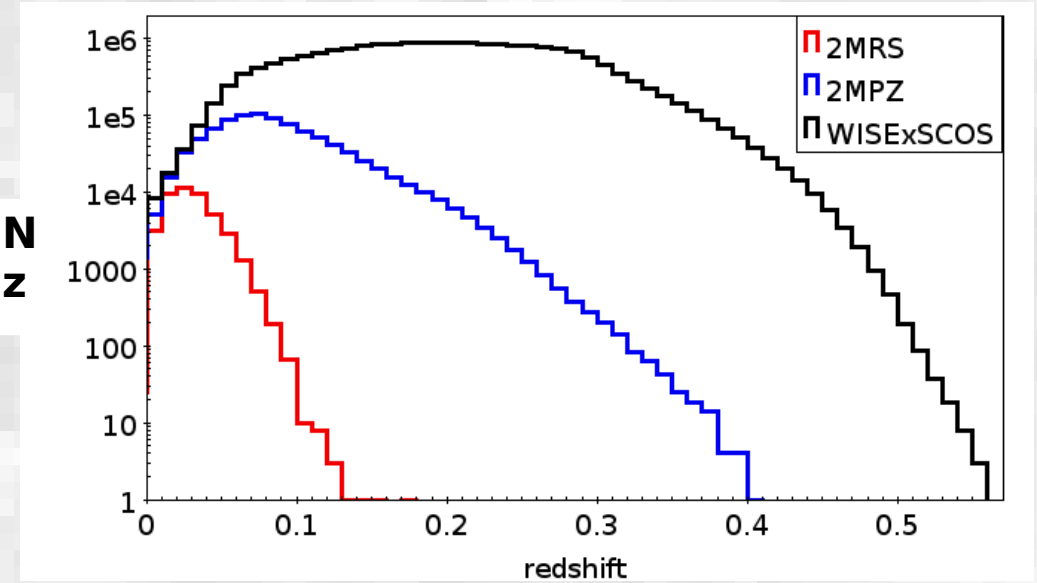
MB, Jarrett, Peacock, Cluver & Steward, 2014, ApJS, arXiv:1311.5246

Going deeper over 70% of sky:

20 million galaxies from WISE x SuperCOSMOS

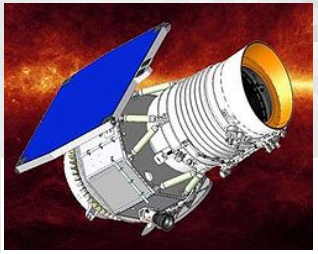
- **Almost all-sky galaxy sample much deeper than 2MASS:**
  Mid-IR **WISE** paired up with optical **SuperCOSMOS ("WISE x SCOS")**
- About **20 million galaxies on ~70% of sky** useful for extragalactic science
- Median redshift: **z~0.2** (d~900 Mpc), but probes the LSS **to z~0.4**
- Photo-z performance: $\sigma_{\Delta z}$ **= 0.033,** median **error 14%** and **3% outliers**



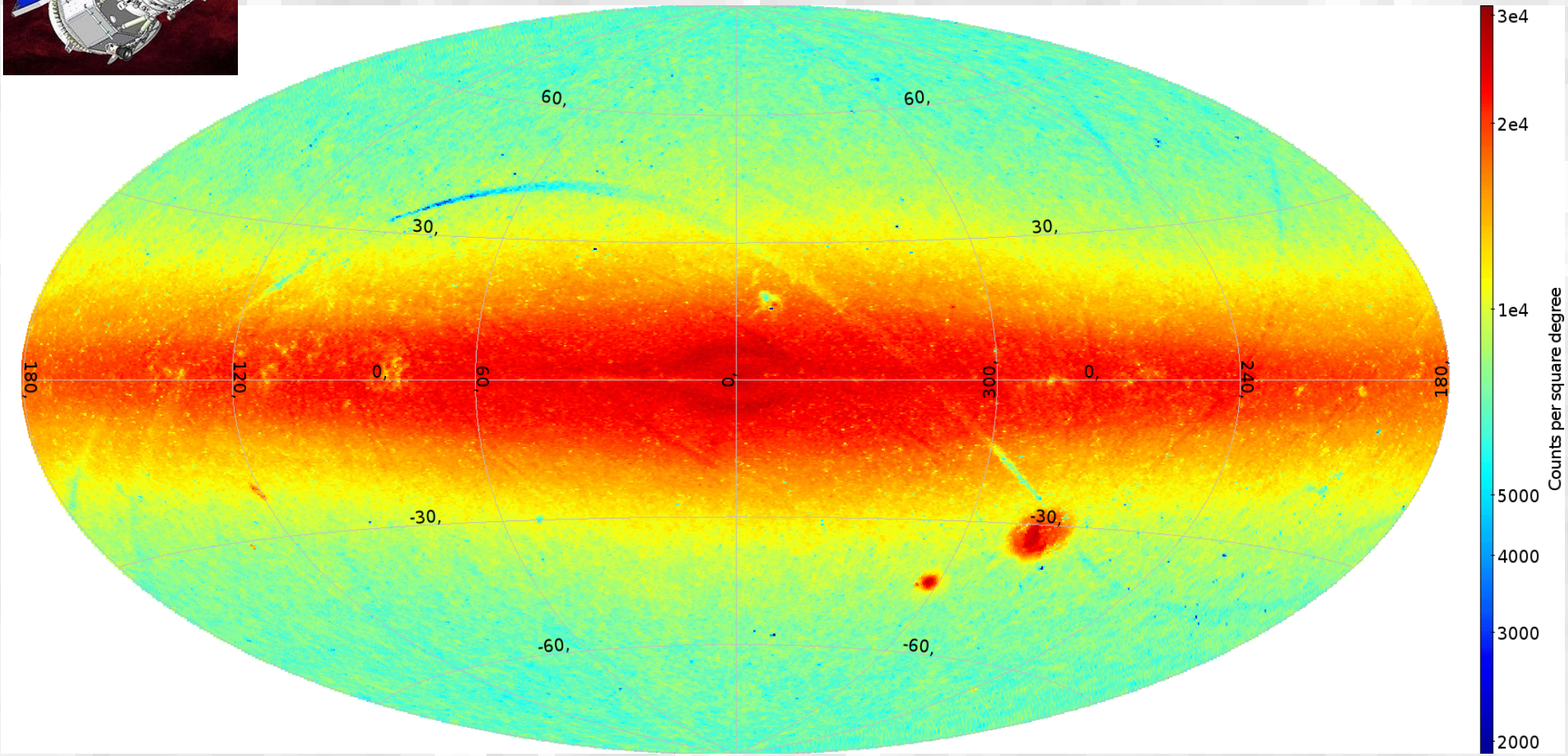


MB et al. ApJS, 2016, arXiv:1607.01182

All-sky probes: the power of WISE



600 million sources within uniformity flux limits

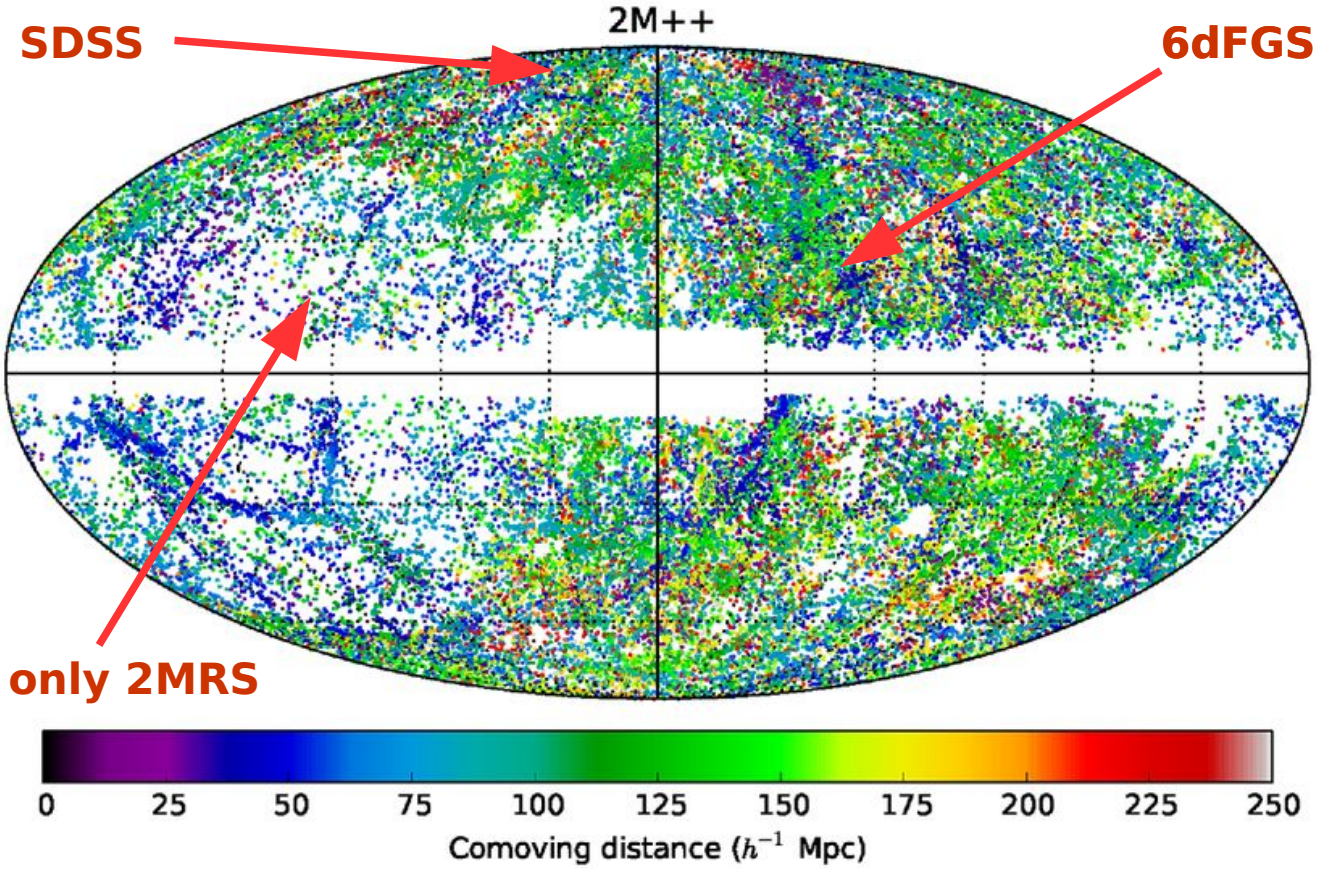


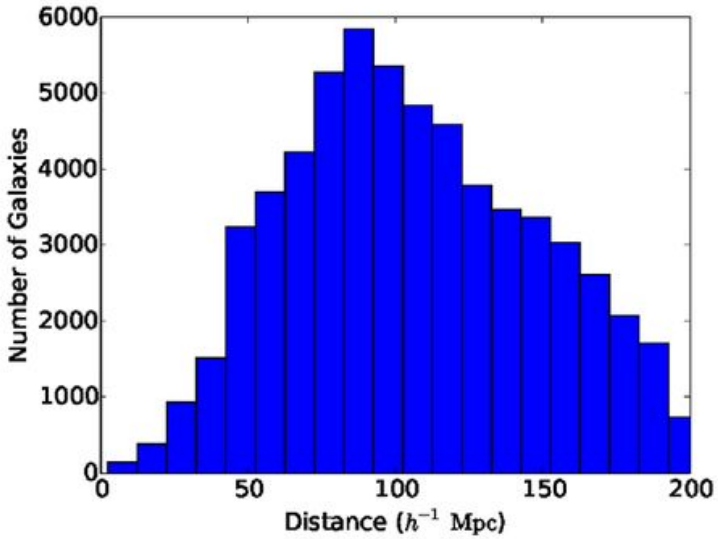
2M++ galaxy redshift catalog:

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