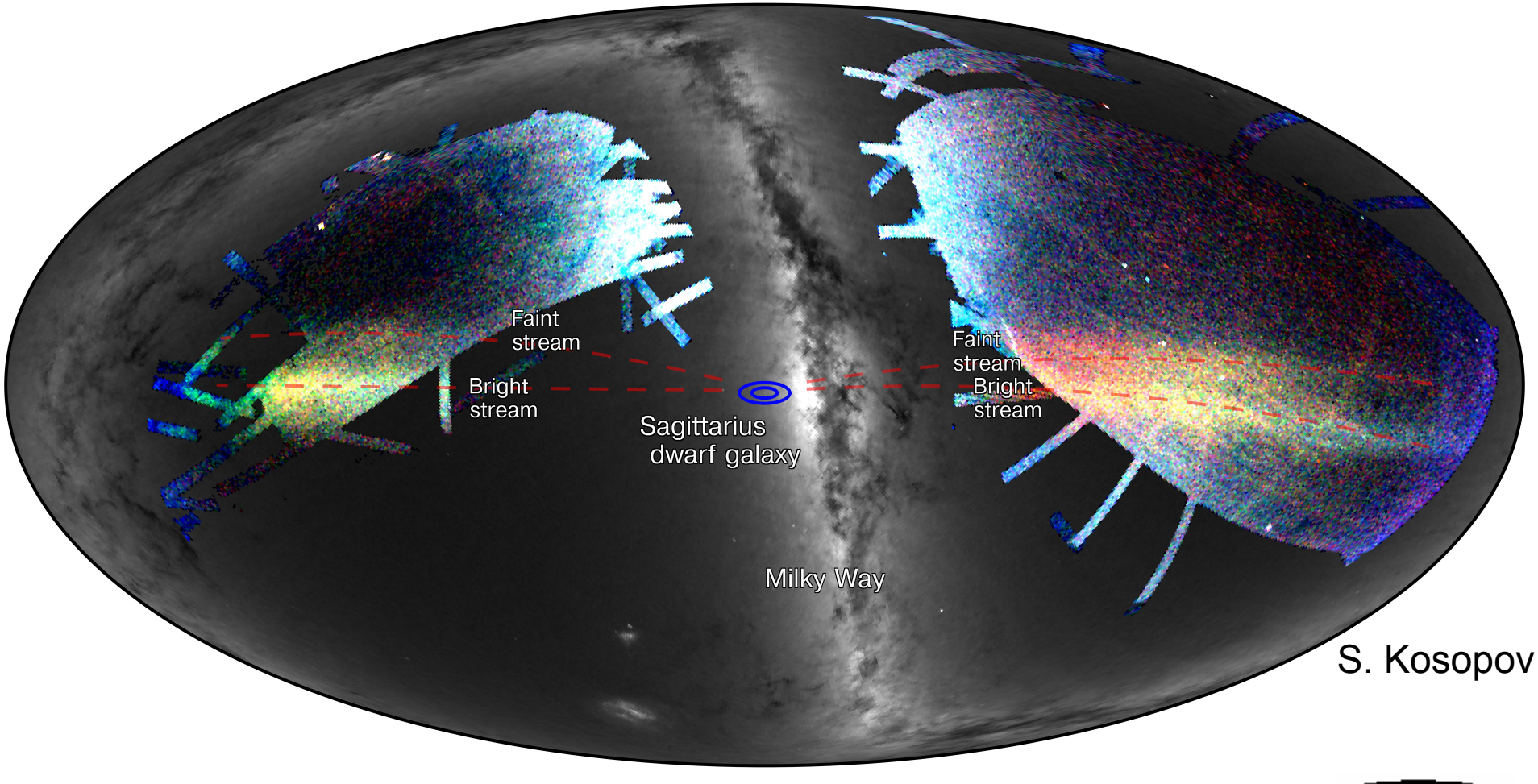
The far-reaching impact of surveys carried out with ≤ 4m – class telescopes



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- **The Aim of Surveys:** to chart and to monitor the constituents of the Universe in a systematic way, and to discover new types of objects or phenomena (Djorgovski et al. 2012)

- **The Power of Surveys:** they provide data to a wide range of scientific topics (see for example SDSS), and make available large statistical samples of objects that can be studied in a systematic way, as populations or as tracers of larger structures to which they belong (Djorgovski et al. 2012)

The Limitations of Surveys:

in imaging:

seeing & spatial resolution;
spatial coverage;
depth & S/N

in spectroscopy:

spectral resolution;
fibre vs. IFU;
depth & S/N;
sparse-sampling

Loss of scientific information;
need for follow-up observations

Can we talk of Survey Types?

Digital sky surveys are the dominant sources of data since the 1990's, and have triggered the development of electronic, web-accessible tools such as archives and Virtual Observatories, as well as of new computational techniques, i.e. data mining.

Which type of survey?

-- Galactic Archaeology Surveys: resolved stars in Local Group galaxies;

-- Cosmological Surveys: redshift and large scale distribution of external galaxies;

-- Archaeo-Cosmo Surveys: imaging with or without spectroscopy of resolved stars in Local Group galaxies, and integrated stellar populations in external galaxies.

Galactic Archaeology Surveys

Imaging:

-- *The Pan-Andromeda Archaelogical Survey*, PandAS: imaging of M31 and M33 at the 3.6m CFHT;

-- *The Optical Gravitational Lensing Experiment,* OGLE: imaging and variability survey of the Milky Way bulge and the Magellanic Clouds at the 1.3m Polish in Las Campanas;

-- *The Massive Compact Halo Object Survey,* MACHOS: microlensing survey and photometric monitoring of stars in the Milky Way bulge and the Magellanic Clouds at the Mt Stromlo 50 inch;

-- *Experience pour la Recherche d'Objets Sombres,* EROS: microlensing survey and imaging survey of the Milky Way halo and the LMC at the ESO 40cm, ESO Schmidt 1m, OHP 1.5m;

-- *The INT/WFC Photometric Hα Survey*, IPHAS: Hα imaging of the northern Galactic plane at the INT;

-- *The SuperCOSMOS Hα survey*, SHS: photometric Hα survey of the southern Galactic plane at the AAO/UKST;

-- *The VST photometric Hα survey of the southern Galactic plane*, VPHAS, at the 2.6m VST;

-- *The Southern Hα Sky Survey Atlas of the southern hemisphere sky*, SHASSA, at the Swarthmore robotic instrument in CTIO;

-- *The VISTA Magellanic Survey*, VMC: near-IR imaging of the Magellanic Clouds, at the 4.1m VISTA;

-- *The VISTA Variables in the Via Lactea*, VVV: near-IR imaging of the central regions of the Milky Way, at the 4.1m VISTA

Spectroscopy:

-- *The Sloan Extension for Galactic Understanding and Exploration*, SEGUE: optical, mid resolution, fiber spectroscopy of stars in the Milky Way, deeper than SDSS, at the Apache Point 2.5m;

-- *The Radial Velocity Experiment*, RAVE: optical high-resolution spectroscopy of Milky Way stars at the AAO Schmidt 1.2m;

-- *Galactic Archaeology with HERMES*, GALAH: optical, high resolution, fiber spectroscopy of stars in the disk and halo of the Milky Way, at the AAT 3.9m;

-- *The Multi-Object APO Radial Velocity Exoplanet Large-area Survey*, MARVEL: spectroscopic monitoring of Milky Way stars to detect gas giant planets in the optical, at the Apache Point 2.5m;

-- *The Wisconsin Hα Mapper*, WHAM: spectroscopy of the diffuse interstellar HII gas in the Milky Way, at the WHAM 15cm in Kitt Peak;

-- *The APO Galactic Evolution Experiment*, (SDSS III) APOGEE: near-IR, high resolution, fiber spectroscopy of stars in the Milky Way disk and bulge, at the Apache Point 2.5m;

PandAS: from 2008 to 2011

220 hours over 3 years
400 deg^2 observed: 150 kpc around M31
50 kpc around M33

S/N = 10 at g = 25.5 mag and i = 24.5 mag, reaching 3 mag below the tip of the RGB

10^7 stars measured in M31!

Some results:
-- Detection of an extended halo around M31 and tidal streams of different metallicity;

-- Detection of an extended and tidally distorted halo around M33;

-- Discovery of 28 dwarf spheroidal galaxies with M_V fainter than -10 mag

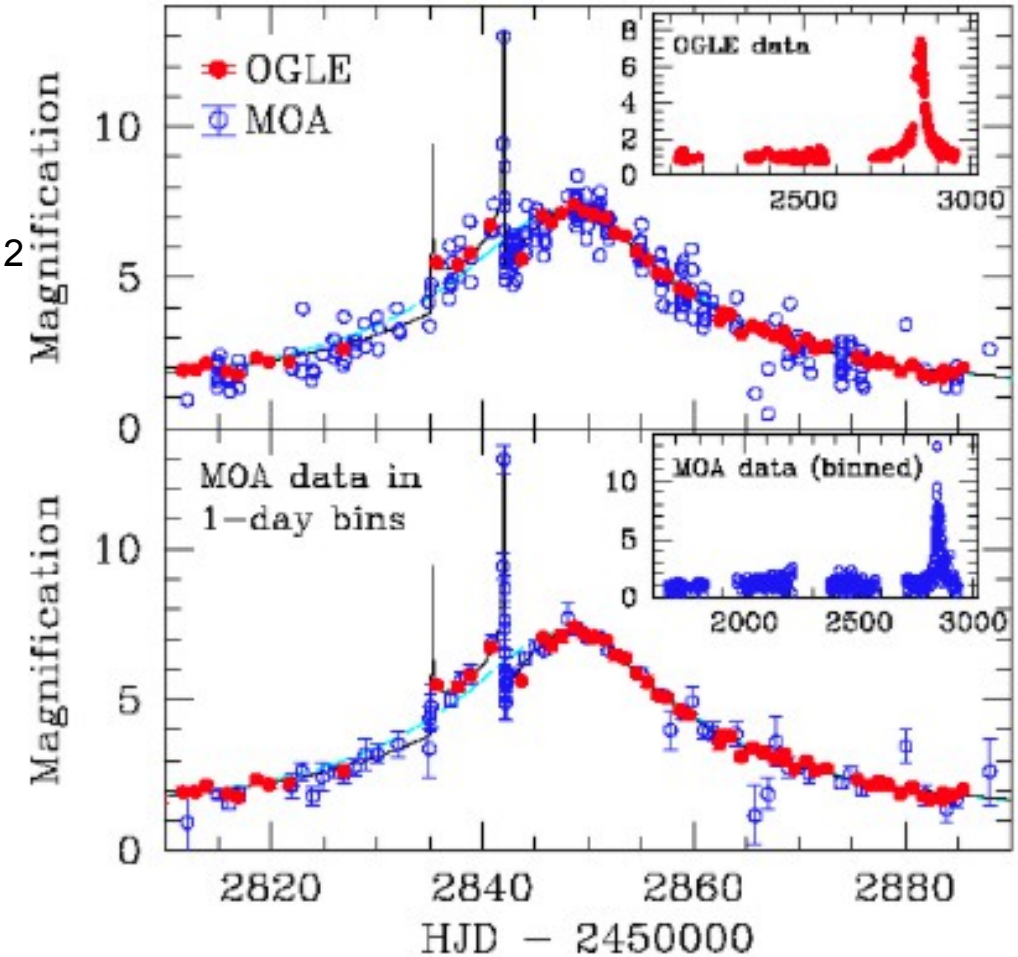
-- Discovery of a thin plane of co-rotating dwarf galaxies orbiting M31

-- Discovery of new globular clusters, especially around M31

See www.astro.uvic.ca/~alan/PANDAS

OGLE: a survey 25 years long

Imaging in the V- and I-bands with a pixel scale of 0.4 – 0.26 arcsec/pix, over 130 deg^2 of the Galactic bulge, 2200 deg^2 of the Galactic disk, and 650 deg^2 of the Magellanic Clouds and bridge



Some results:

-- Observation of the first microlensing events in 1993;

-- Discovery of the first extrasolar planets with transits and gravitational microlensing;

-- Discovery of a number of Kuiper belt objects;

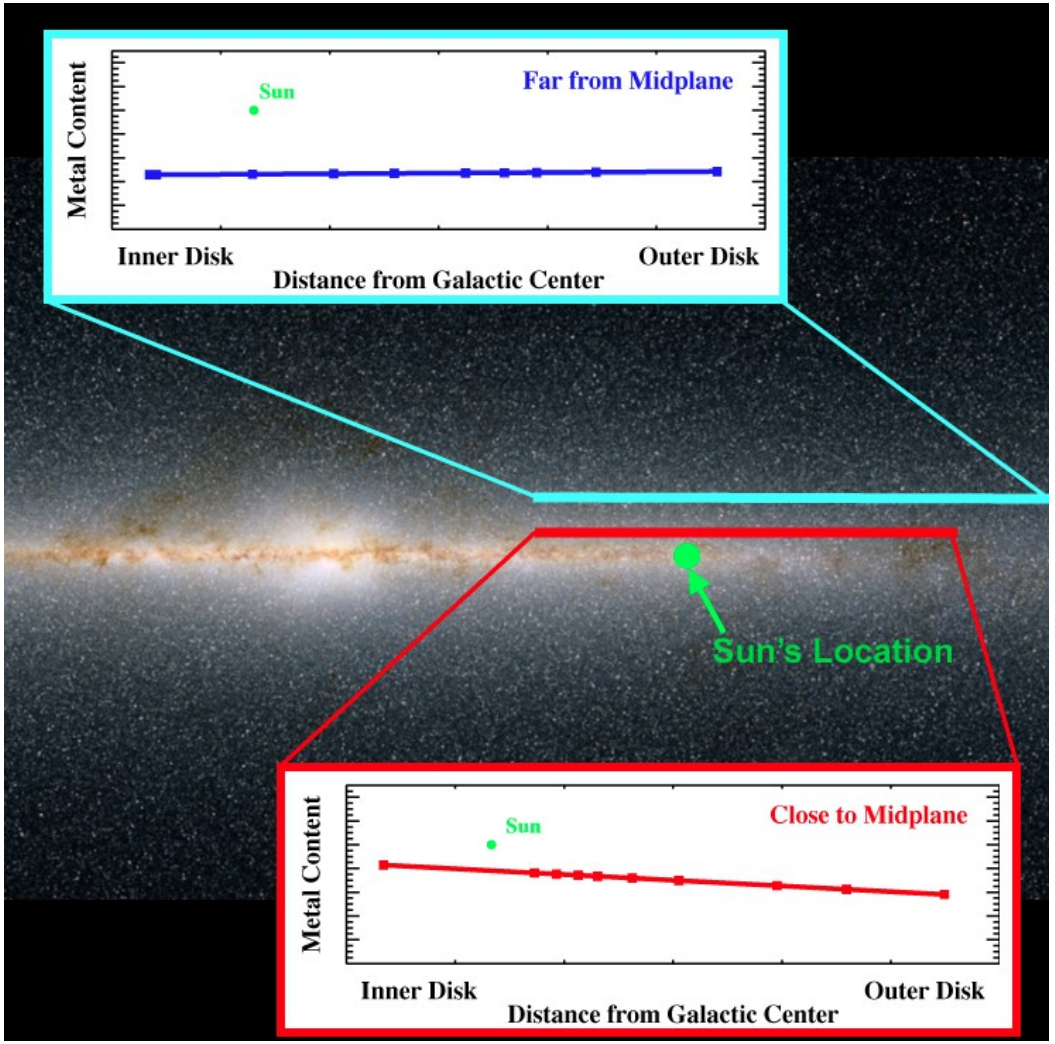
-- Observation of thousands of variable stars;

-- Building of extinction maps of the Galactic bulge and centre;

-- Determination of the 3D structure of the bulge, the Magellanic Clouds and bridge.
See ogle.astrouw.edu.pl

SEGUE: from 2004 to 2009

Optical spectroscopy at R = 2000 over an area of 1317 (-1) and 1438 deg^2 (-2). Max 800 fibers per plate.
118151 (-1) and 240000 (-2) stars observed at g < 19 mag.



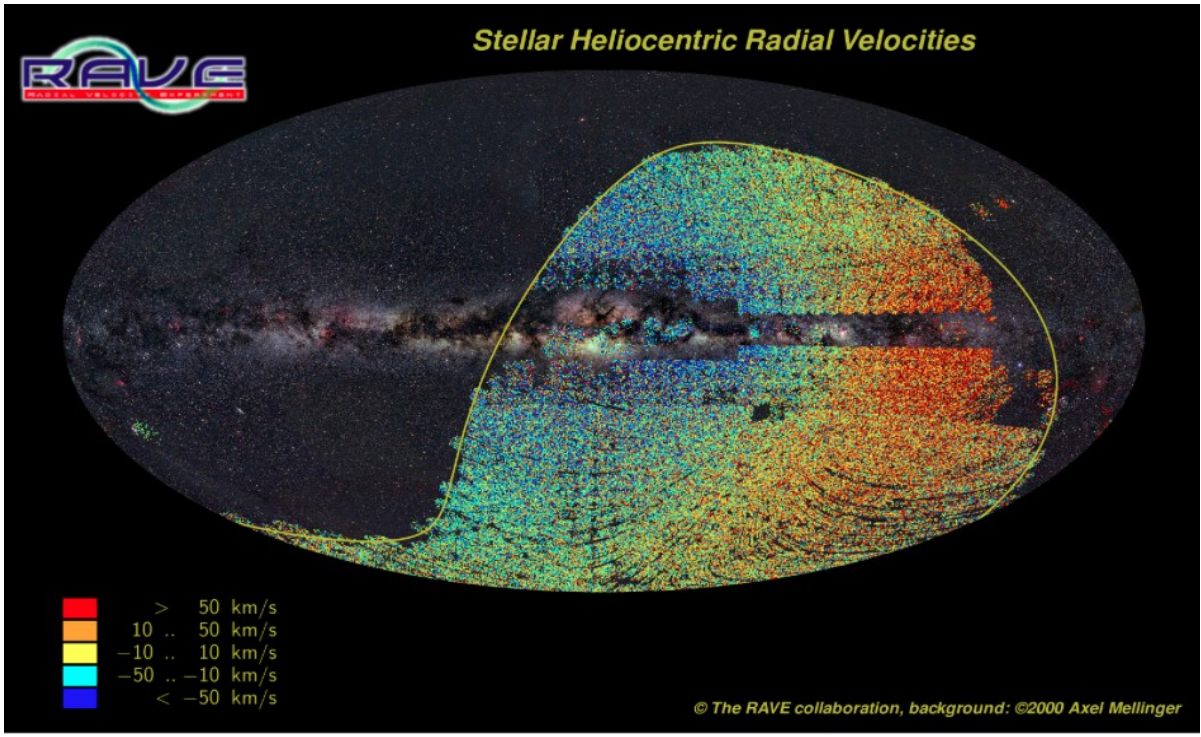
Some results:
-- Metallicity gradients from old thin and thick disk stars. Flattening of radial gradient at higher heights, consistent with a turbulent disk at high z;

-- Existence of continuous and mono-tonic decreasing distribution of scale height from mono-abundance sub-populations: no clear distinction between thin and thick disk;

-- Discovery of the ultra-faint dwarf galaxy SEGUE 1 with M_V = -2 and the largest M/L of 3400; discovery of the spheroidal dwarf SEGUE 2 with M_V = -2.5 and M/L = 650; confirmation of Sagittarius and Orphan streams;

-- Bimodal distribution of CN and CH strengths in globular clusters stars;
See www.sdss3.org/surveys/segue2.php

RAVE: from 2003 to 2013



Spectral range: 8410 – 8795 Ang
at R = 7000, 150 fibers per pointing,
limiting magnitude I = 13 mag.
457555 stars observed

Some results:
-- median Milky Way escape velocity is 533 km/s, larger than the circular velocity of ~220 km/s. Confirmed existence of a dark matter halo outside the solar circle;

-- G and K stars towards the Poles give a discontinuity (in kinematics and magnitude counts) separating the thin and thick disks with scale heights of 10 pc and 36 pc;

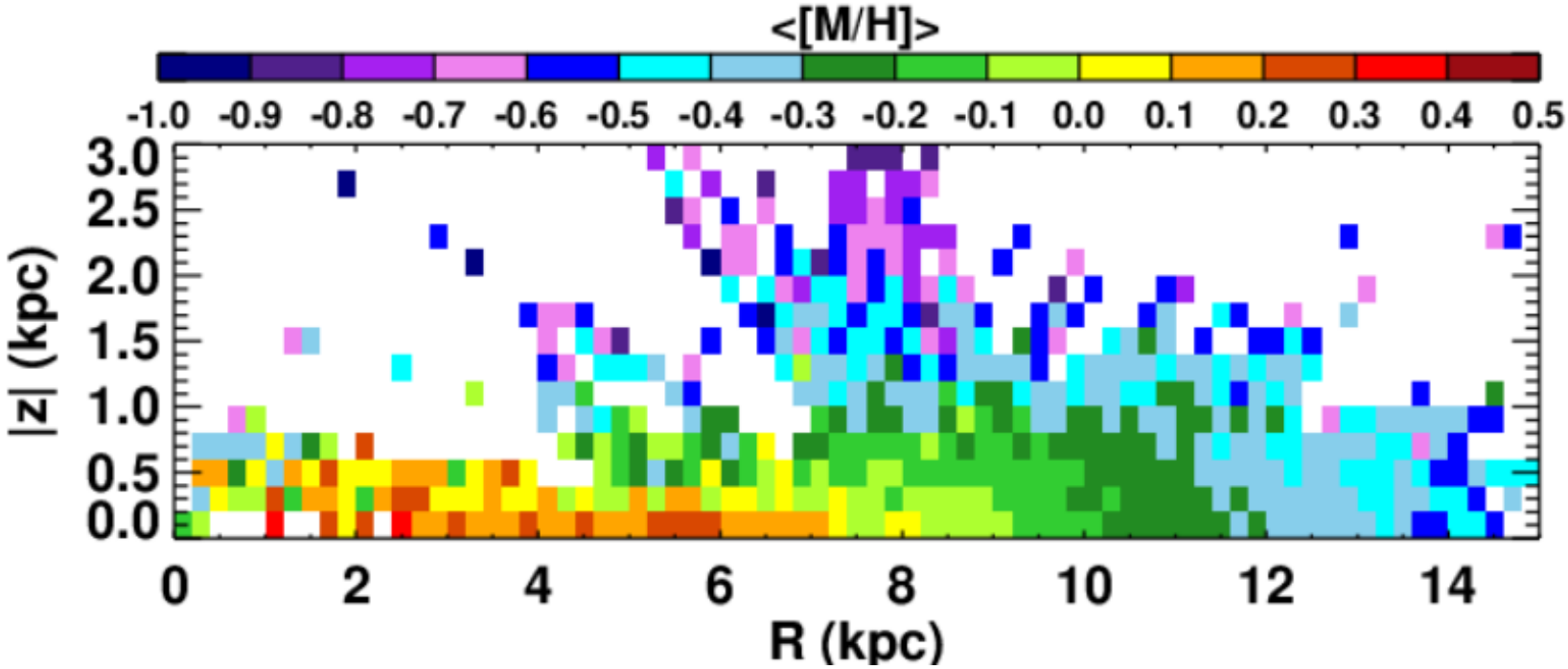
-- No vertical stream with hundreds of stars detected in the solar neighborhood; confirmation of the Aquarius stream in the halo;

-- [α/Fe] values of thick disk, metal-poor stars are enhanced (core-collapse SN), with little scatter (well mixed ISM), and similar to halo values (similar IMF);

-- Studies of variable stars, and of DIBs to constrain reddening;

-- Detection of stellar streams around globular clusters; see www.rave-survey.org

APOGEE: from 2011 to 2014



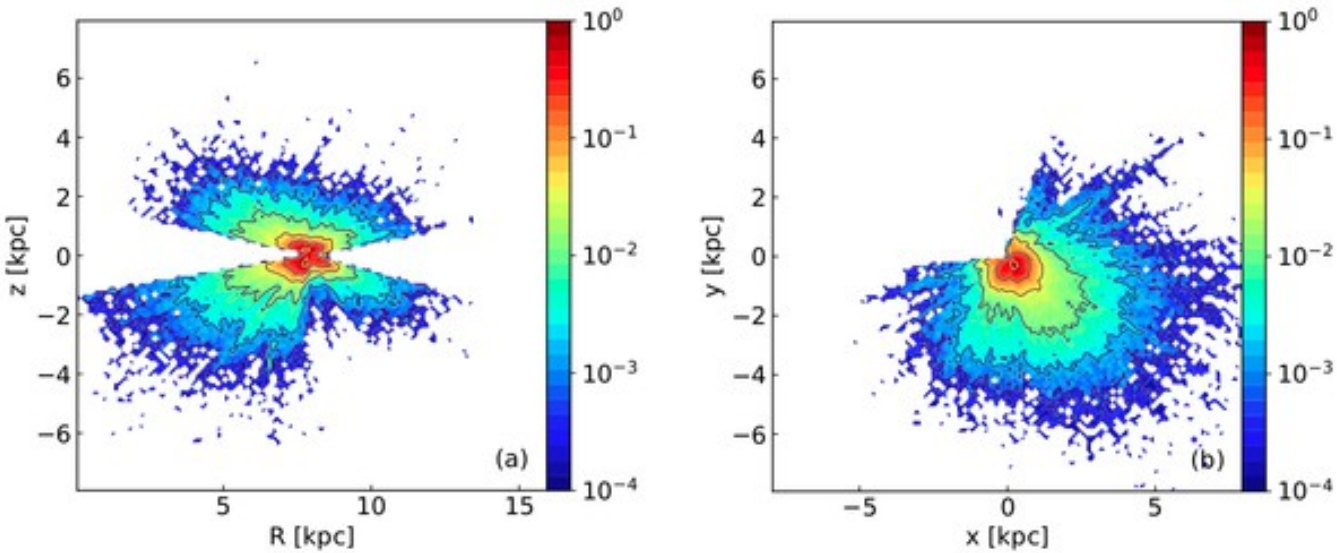
Near-IR (1.5 – 1.7 μm) spectroscopy at R = 22500 and S/N > 100; 300 fibers (2" in diameter) in FOV, 100000 giant stars observed at H < 12.2 mag

Some results:
-- Large scale metallicity maps of the Galactic disk with individual stars;

-- Radial metallicity gradients from open clusters: steeper slope at R < 10 kpc and nearly flat trend at R > 10 kpc;

-- Discovery of 7 [Fe/H] ~ -2 stars in Galactic bulge with α abundances similar to metal-poor stars in the thick disk;
See www.sdss3.org/apogee_publications.php

GALAH: started in 2014



Optical spectroscopy at R = 28000; 400 fibers in FOV; DR2 (2014 – 2018) provides data for 342682 stars at V < 14 mg

Some results:

-- Galactic thin disk (low α) has a negative vertical gradient in [M/H] and a nearly flat vertical gradient of α elements; possibly consistent with radial migration. Galactic thick disk (high α) has a weaker vertical [M/H] gradient that can be caused by radial migration and/or minor episodes of heating;

-- Detection of the Hercules stream with stars of [Fe/H] > 0.2 and moving groups in stars closer than 250 pc using the (u,v) plane;
See www.galah-survey.org/papers

Cosmological Surveys

-- *Las Campanas Redshift Survey*, LCRS: mid resolution spectroscopy of ~26000 galaxies up to z = 0.2, at the Las Campanas 2.5m DuPont;

-- *Two degrees Field and Six degrees Field Galaxy Redshift surveys*, 2dFGRS and 6dFGRS: mid resolution spectroscopy of galaxies in regions in the northern and southern Galactic poles, at the AAO 3.9m;

-- *The Baryon Oscillation Spectroscopic Survey*, (SDSS III) BOSS: mid resolution spectroscopy of luminous red galaxies and quasars at the Apache Point 2.5m;

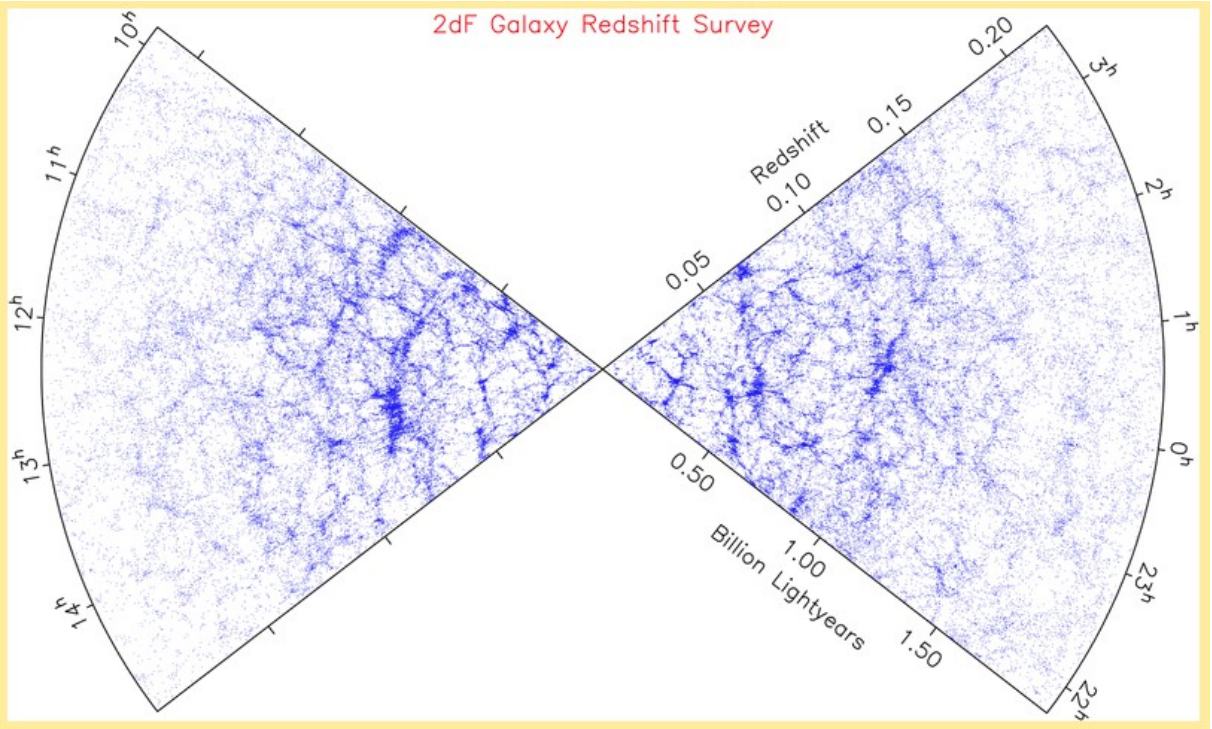
Disadvantages: low S/N spectra which are not really optimal to study stellar populations unless they are stacked. In this case we loose information about cosmic variance!

-- *The Sloan Digital Sky Survey*, SDSS: mid resolution spectroscopy of more than a million galaxies, AGN and quasars at the Apache Point 2.5m.

2dFGR: from 2001 to 2003

Optical spectroscopy at
R ~ 600, 400 fibers in FOV

245591 objects observed,
mostly galaxies at B < 19.5 mag,
over an area of 1500 deg^2



Some results:

-- Measurement of the power spectrum of galaxy clustering on scales up to 300 h^{-1}Mpc;

-- Measurement of the Hubble constant and the baryon density in combination with observations of the CMB;

-- Characterization of the luminosity function of galaxies of different types, in the field and in clusters;

-- Constrain on the environmental dependence of the star formation rate of galaxies;

See www.2dfgrs.net

Archaeo-Cosmo Surveys

Imaging:

-- *Sloan Digital Sky Survey,* SDSS: u-to-z imaging of a large portion of the northern hemisphere, to be extended to the southern one, at the Apache Point 2.5m;

-- *The Advanced Large, Homogeneous Area Medium Band Redshift Astronomical Survey,* ALHAMBRA: multi-wavelength imaging of galaxies at the CAHA 3.5m;

-- *The VST Kilo-Degree Survey,* KIDS: optical imaging for weak lensing, high-z quasars and galaxy clusters, at the 2.6m VST;

-- *The Javalambre Physics of the Accelerating Universe Astronomical Survey,* JPAS: imaging through 56 filters between U and J bands of 8000 deg^2 in the northern sky, at the OAJ 2.5m and 80cm telescopes;

-- *The Panoramic Survey Telescope and Rapid Response System,* Pan-STARRS: optical monitoring of the northern sky, at the 1.8m PS1 and PS2;

-- *VST ATLAS:* optical imaging of the southern sky targeting luminous red galaxies, high-z galaxies and quasars, at the 2.6m VST;

-- *The Dark Energy Survey,* DES: optical to J-band imaging of supernovae, galaxy clusters and gravitational lensing, at the CTIO 4m Blanco

-- *The VST survey of Early-type Galaxies,* VEGAS: optical imaging (ugri) of ETGs in groups and clusters, at the 2.6m VST;

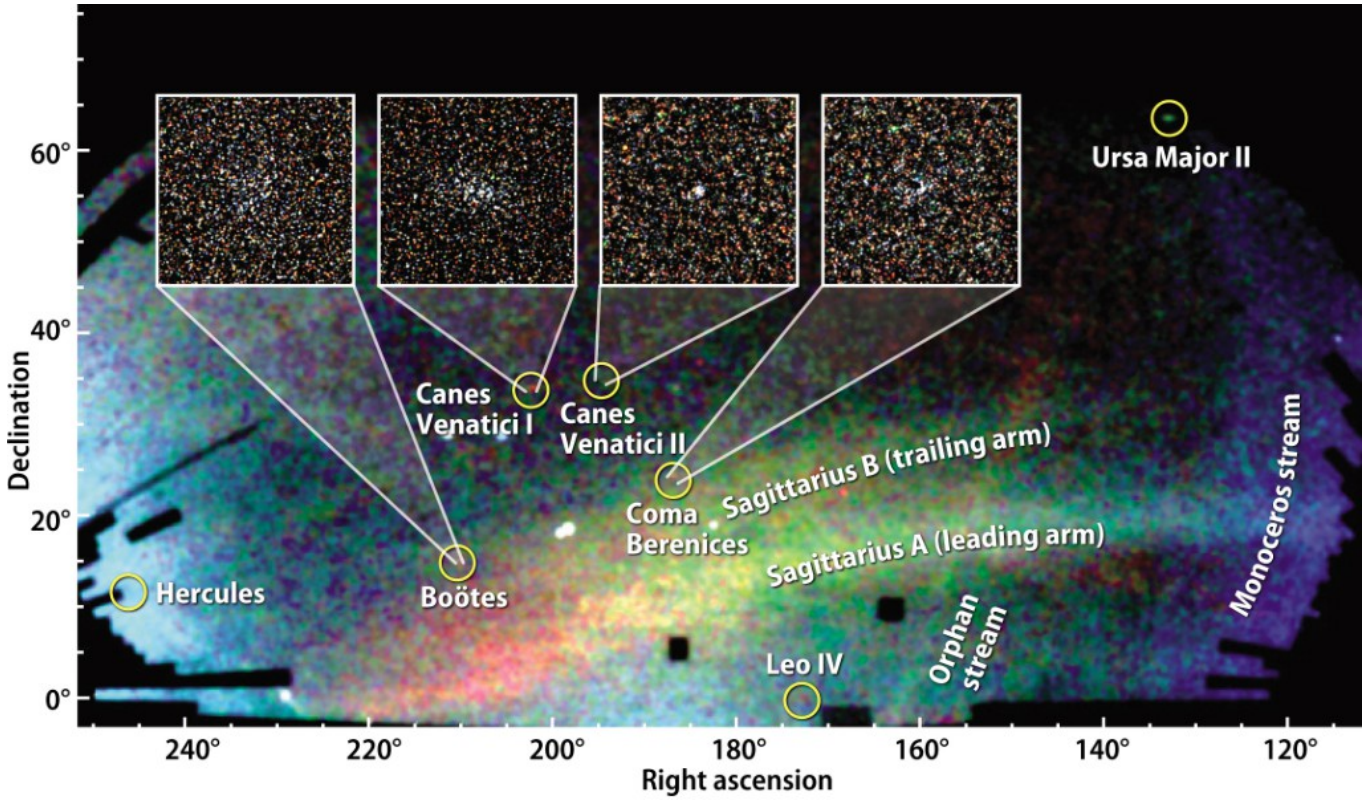
-- *The VISTA Kilo-Degree Survey,* VIKING: near-IR imaging targeting high-z quasars and galaxy clusters at the 4.1m VISTA;

-- *The VISTA Hemisphere Survey,* VHS: near-IR imaging of the souther hemisphere targeting stars, merging history of Milky Way, large-scale structure and high-z quasars, at 4.1m VISTA;

-- *The VISTA Deep Extragalactic Observations Survey,* VIDEO: near-IR imaging of AGN, massive galaxies and galaxy clusters, at 4.1m VISTA;

-- *The UKIRT Infrared Deep Sky Survey,* UKIDSS: deeper 2MASS survey including the Galactic plane, targeting brown dwarfs, high-z starburst galaxies, early-type galaxies, galaxy clusters at $1 < z < 2$ and $z = 7$ quasars, at UKIRT;

SDSS imaging: 14055 deg^2 of sky in ugriz, at 0.4"/pix and down to ~26.5 mag/arcsec^2



V. Belokurov

-- Discovery and characterization of Galactic streams: Sagittarius, Virgo, Monoceros, Orphan, GD-1, NGC5466 and Pal 5 Tidal streams;

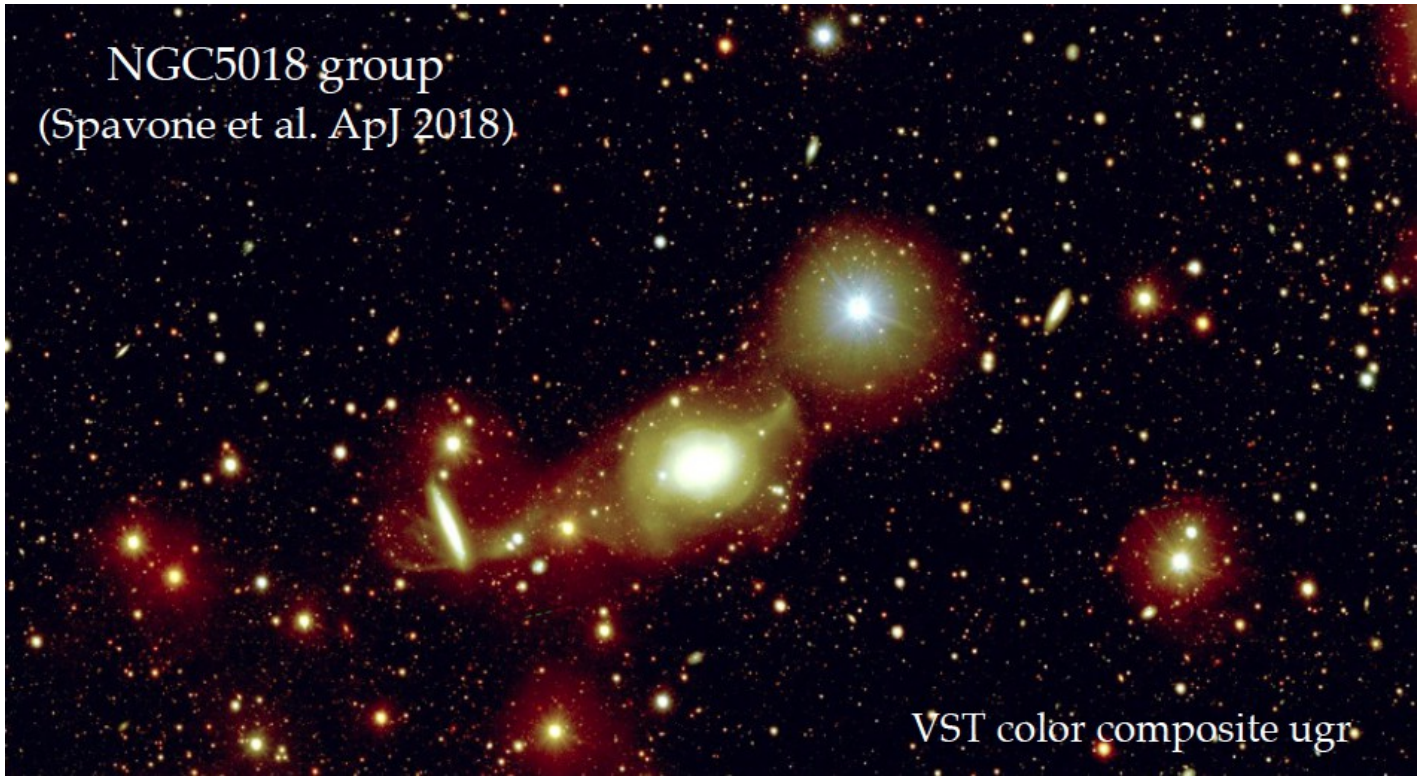
-- Discovery of new, faint dwarf galaxies around the Milky Way and in the Local Group;

-- Discovery of tidal features in external galaxies;

-- Large statistical sample of galaxy and merger morphologies, and large scale structure, and for luminosity functions of different types of galaxies

VEGAS: The Fornax Deep Survey with VST

26 deg^2 in the Fornax cluster, imaged in ugri bands with 0.21"/pix to a depth of:
31 mag/arcsec^2 in g
28 mag/arcsec^2 in r
27 mag/arcsec^2 in i



Goals:

-- detailed morphology and structure of galaxies (brighter than 15 mag in B) inside the cluster virial radius;

-- characterization of stellar halos in ETGs;

-- detection and characterization of tidal tails, stellar streams and shells around galaxies;

-- census and study of globular clusters

See www.na.astro.it/vegas/VEGAS/Welcome.html

Spectroscopy:

-- *The Sloan Digital Sky Survey*, SDSS: optical (near-IR) imaging and mid resolution, fiber spectroscopy of stars in the Milky Way, external galaxies and quasars, at the Apache Point 2.5m;

-- *The Galaxy Mass And Assembly Survey*, GAMA: optical, mid resolution, fiber spectroscopy of external galaxies, at the 3.9m AAT. Imaging in optical and near-IR is provided by VIKING and KIDS;

-- *The ATLAS^{3D} survey:* optical, mid resolution, IFU spectroscopy of 260 early-type galaxies at d < 42 Mpc, at the 4.2m WHT;

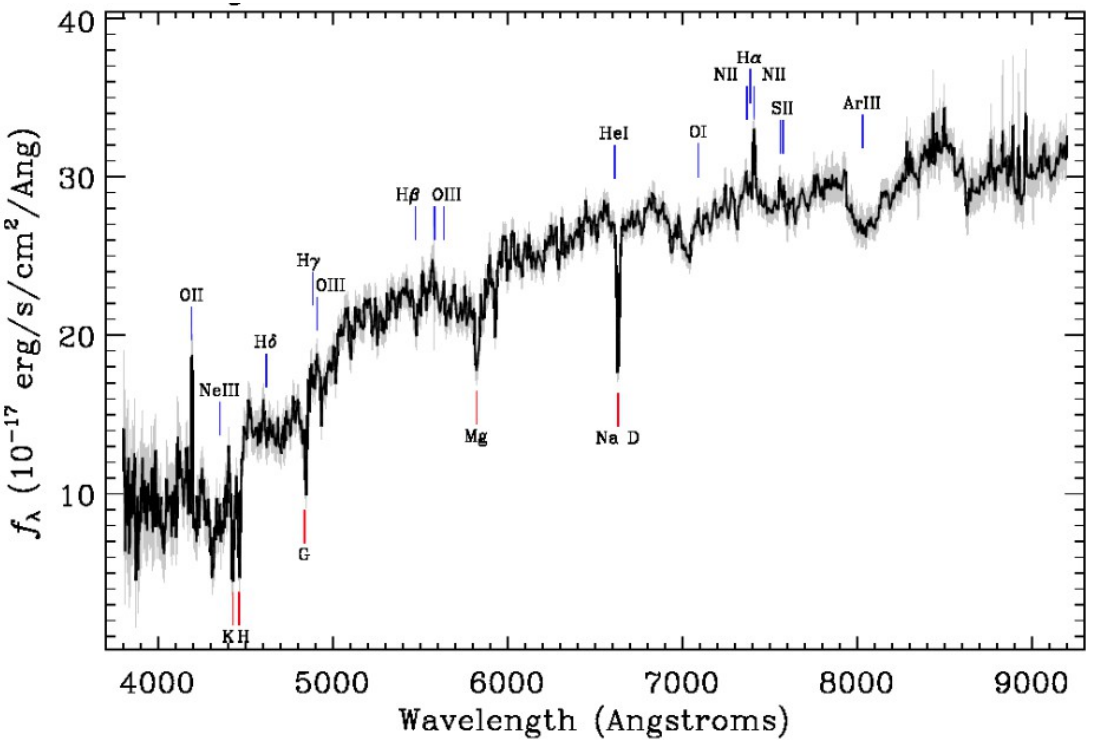
-- *The Calar Alto Legacy Integral Field Area Survey*, CALIFA: optical, mid resolution, IFU spectroscopy of external galaxies, at the CAHA 3.5m;

-- *The SAMI Galaxy Survey:* optical, mid resolution, IFU spectroscopy of external galaxies, at the 3.9m AAT;

-- *Mapping Nearby Galaxies at APO*, MaNGA: optical, mid resolution, IFU spectroscopy of nearby galaxies, at the Apache Point 2.5m

SDSS *spectroscopy:*

Optical spectral range at R ~ 2000, 640 fibers per plate (1000 for BOSS), fiber diameter 3 arcsec (2 arcsec for BOSS). Limiting mag: r = 17.77



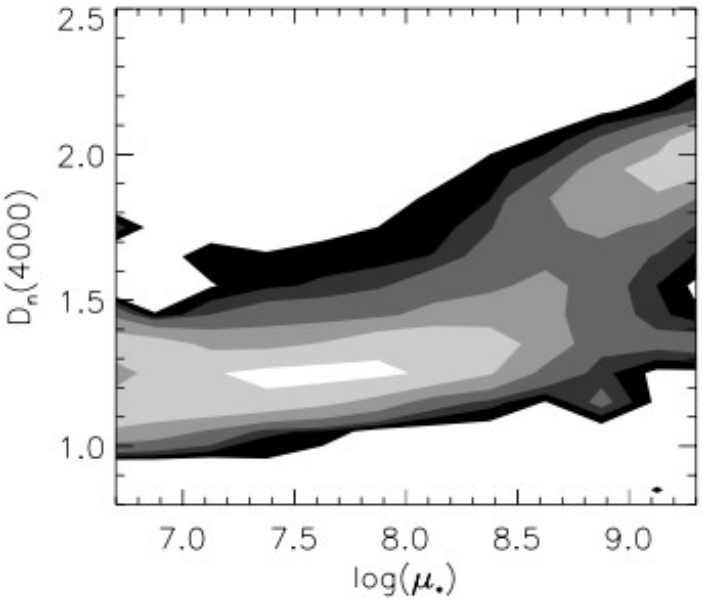
What can we measure?

-- First detection of metal poor stars, e.g. Caffau's star at log(Z) < -6.16 (Caffau et al. 2011).
It requires follow-up with high-resolution spectroscopy;

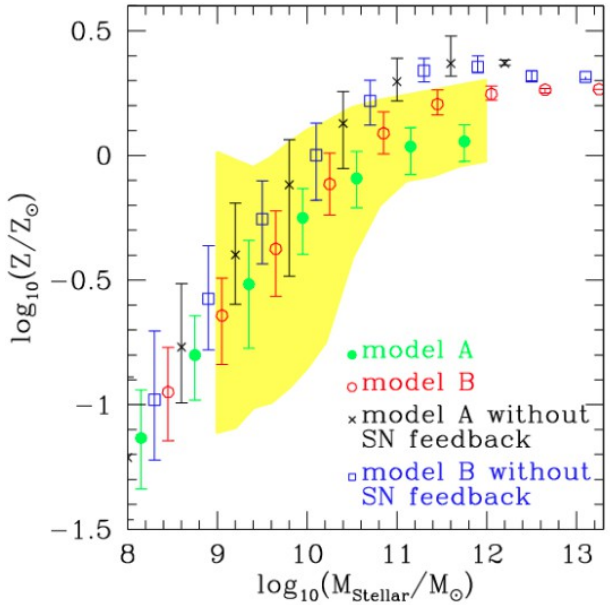
-- Accurate determination of spectroscopic redshifts, necessary to identify galaxy groups and clusters;

-- Determination of ionization conditions of galaxy ISM and measurement of galaxy activity: star formation, AGN, LINER, QSO;

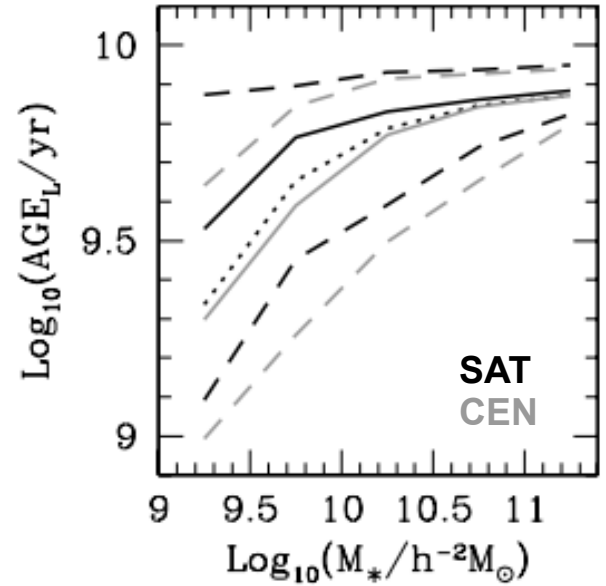
-- Derivation of galaxy SFR, spectral indices, average age, metallicity and element abundances of integrated stellar populations, galaxy star formation history



Kauffmann et al. (2003)



Lagos et al. (2009)



Pasquali et al. (2010)

Some results:

-- Galaxy properties primarily depend on stellar mass and surface mass density, both are a proxy for the secular evolution and the star-formation/assembly history of galaxies;

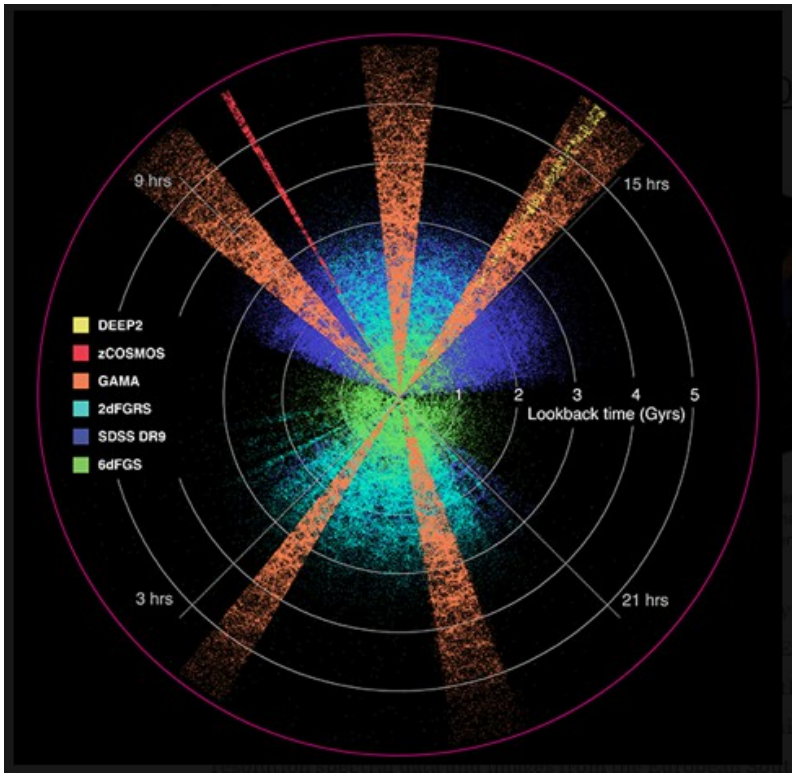
-- Stellar mass – metallicity (both stellar and gas-phase) relation extends over 3 dex in M_*, and is used to constrain galaxy evolution;

-- Galaxy properties also depend on environment (galaxy hierarchy and halo mass), whose main effect is to quench galaxy star formation;

-- Identification of QSOs and study of their variability and clustering

GAMA: from 2008 to 2014

Optical spectroscopy at R = 1000 - 1600 down to r = 19.8, over 286 deg^2 and for ~300000 galaxies.
392 fibers per plate



lcrar.org

Some results:

-- Measurement of the dark matter halo function of galaxy groups/clusters;

-- Determination of galaxy stellar mass function down to MCs to constrain feedback processes;

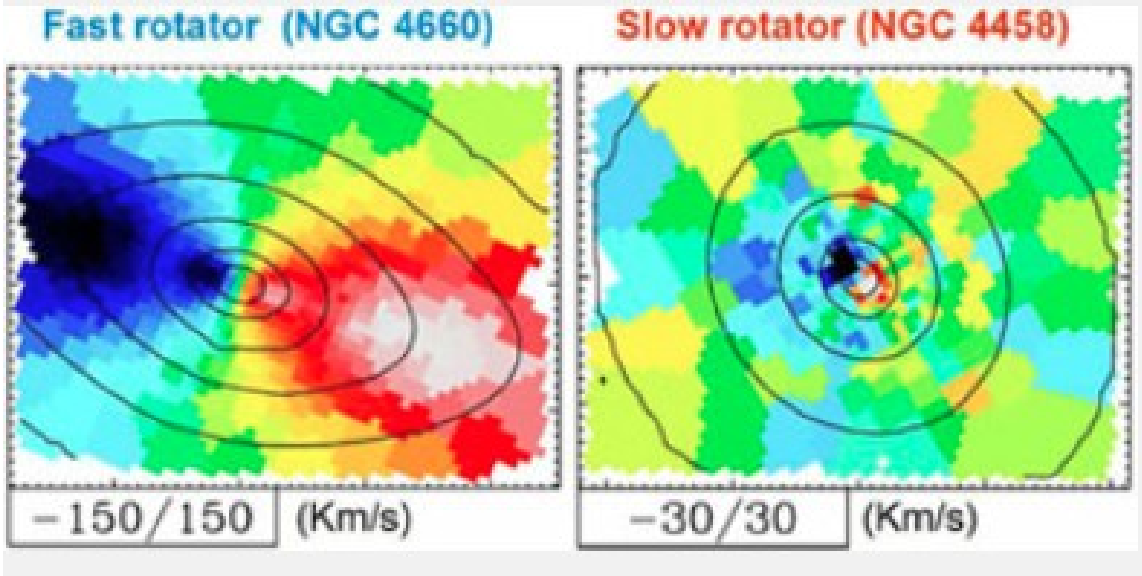
-- Measurement of the galaxy merging rate as a function of galaxy type, mass and environment;

-- Determination of the dependence of galaxy star formation rate on galaxy type, mass and environment;

-- Determination of the dust mass function as a function of galaxy mass and type;

See www.gama-survey.org

ATLAS^{3D}: from 2007 to 2008



Spectroscopy in the range 4800 to 5380 Ang. at R ~ 1300.

IFU FOV = 33 x 41 arcsec^2, sampled with 0.94 arcsec^2 lenslets (1431).

260 early-type galaxies observed

Some results:

-- Accurate measurement of galaxy kinematics, i.e. rotation velocity vs velocity dispersion or fast vs slow rotators;

-- Accurate determination of bulge-to-total stellar mass ratios, mass-to-light ratios;

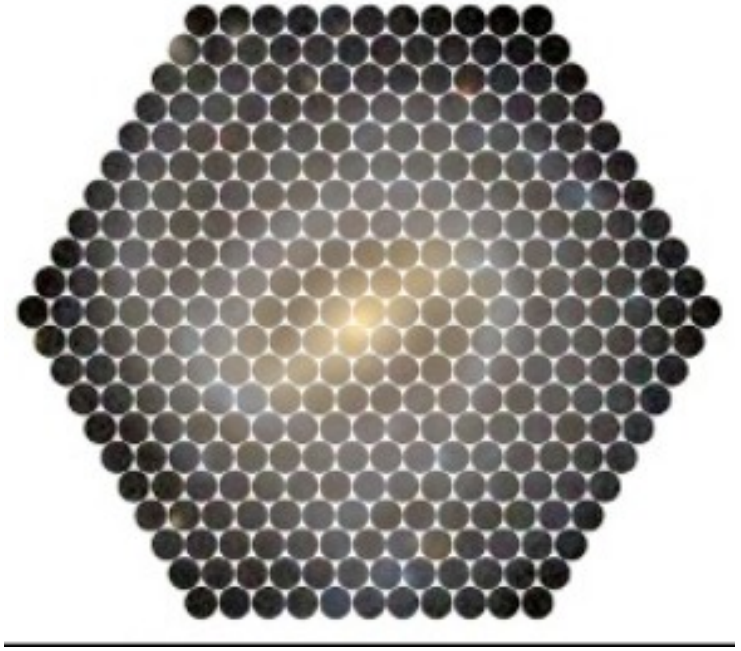
-- Determination of star formation histories from spectral indices;

-- Study of AGN outflows;

-- Study of galaxy Initial Mass Function: bottom vs Galactic IMF

See www-astro.physics.ox.ac.uk

CALIFA: from 2010 to 2017



Optical spectroscopy at R = 850 and 1650 of 600 galaxies in the range 0.005 < z < 0.03.

IFU FOV = 74 x 64 arcsec^2 with 331 object fibers. Fiber diameter = 2.7 arcsec.

Some results:

-- Detailed study of HII regions as a function of galaxy type, mass, and galacto-centric distance;

-- Determination of radial gradients of the ISM oxygen abundance, star formation rate and star formation history, stellar mass and metallicity;

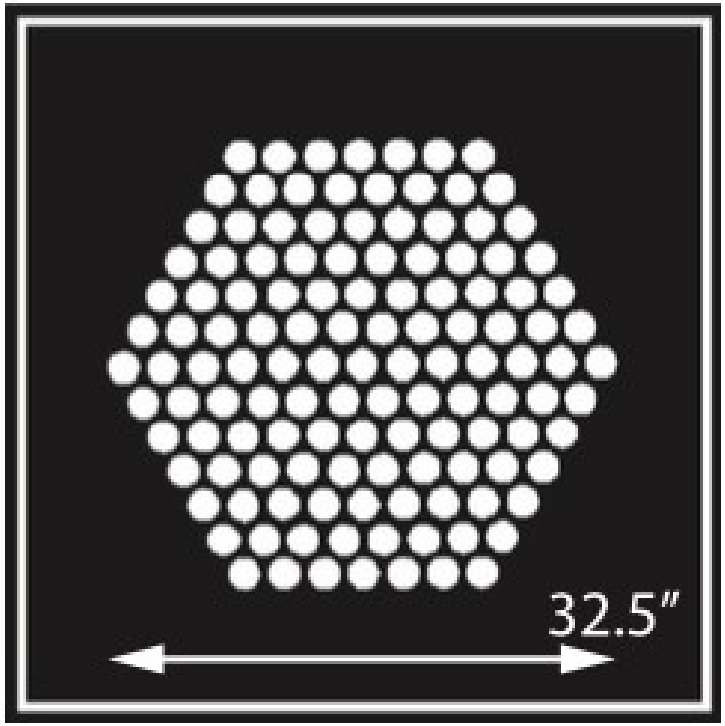
-- Spatially resolved study of mergers, LINERS and diffuse ISM;

-- Kinematical study of galaxy bulges and bars;

-- Determination of stellar orbits (circular vs radial) and their spatial distribution within spiral galaxies;

-- Study of the galaxy IMF: bottom vs Galatic. See califa.caha.es

MaNGA: on-going since 2014



Optical spectroscopy at R = 2000 of 10000 galaxies.

17 IFUs with FOV between 12 and 32 arcsec^2 filled with 19 to 127 fibers, each 2 arcsec in diameter.

Some results:

-- Spatially resolved properties of the ISM, ionization and chemistry;

-- Radial gradients of galaxy star formation history as indicated by spectral indices, stellar mass;

-- Spatially resolved mass surface – gas metallicity relations for disk galaxies;

-- Kinematically decoupled galaxy cores, gas and stellar kinematics;

-- IMF in spiral and early-type galaxies;

-- Environmental dependence of stellar age and metallicity gradients

The next planned Surveys

-- *The Galaxy Assembly as a function of Mass and Environment Survey*, GAME: multi-wavelength imaging of galaxies in clusters, at the 2.6m VST; on-going

-- WEAVE Survey: optical, mid to high resolution, fiber and IFU spectroscopy of Milky Way stars, external galaxies and QSOs, at the 4.2m WHT; starting in 2019

-- *The Dark Energy Spectroscopic Instrument*, DESI: optical, mid resolution, fiber spectroscopy of galaxies and quasars (imaging is provided by complementary surveys), at the 4m Mayall; starting in 2019

-- SDSS V Pioneering Panoptic Spectroscopy: optical to near-IR, mid resolution, fiber and IFU, multi-epoch spectroscopy of 6 million objects, stars and galaxies, from the Apache Point Observatory and Las Campanas Observatory; starting in 2020

-- *4-metre Multi-Object Spectroscopic Telescope*, 4MOST: optical fiber spectroscopy at R = 5000 and 20000, of stars in the MW halo, bulge and disk, and in the MCs. It serves as cosmological survey and for the study of galaxy evolution in the field and clusters, and of AGNs; at 4.1m VISTA, starting in 2022

Summary

- A large number of imaging surveys have mapped the sky (more in the northern than in the southern hemisphere) at optical and infrared wavelengths.
  The trend now is to go deeper and possibly with a better seeing: this is relevant to studies of reddened Galactic regions, high-redshift galaxies and galaxy evolution.
  Compare for example SDSS with HSC (Subaru Hyper Suprime-Cam) survey.
  Competition with space-based telescopes: e.g. EUCLID, WFIRST, JWST.

- Several spectroscopic surveys have been carried out in the optical (except for APOGEE), using wide field fiber spectrographs, most in the North but now extending also to the South.
  The trend is to use IFUs which are particularly important for studies of galaxy evolution, and for fibers to go deeper.
  No significant competition with space: WFIRST works at the resolution of SDSS as JWST (but the latter is not a survey telescope). EUCLID has much lower resolution.
  Competition comes from ground-based surveys such as SDSS V, 4MOST and the future spectroscopic follow-up of HSC.