Statistical Studies of Galaxy Properties

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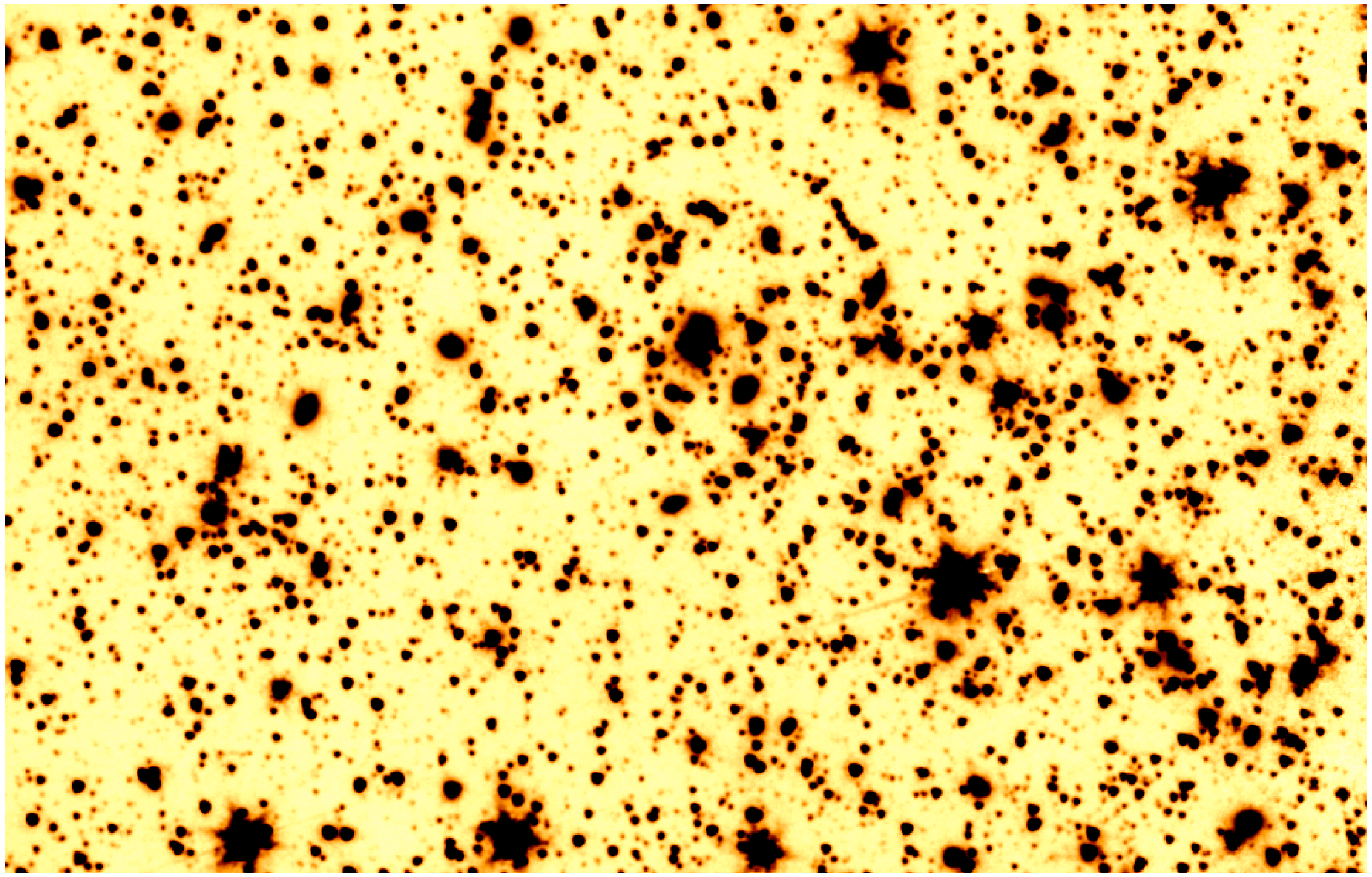
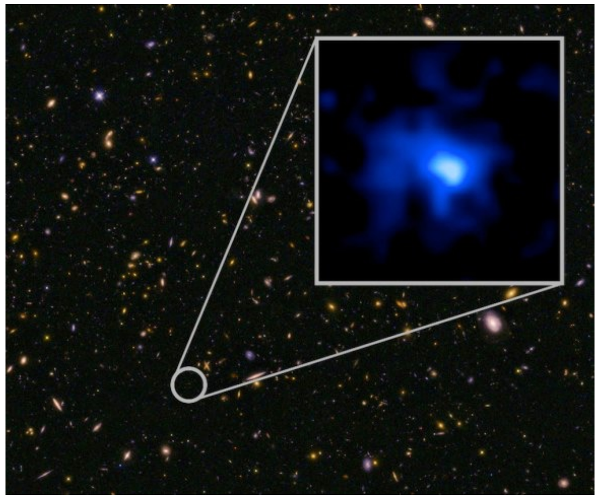
Formation and Evolution of Galaxies 2023-2024 Q1
Rijksuniversiteit Groningen

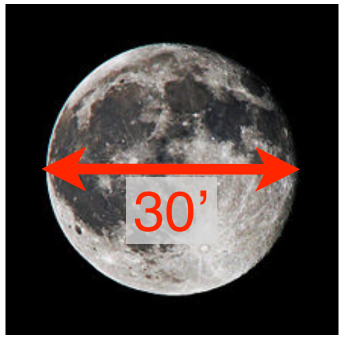
Studying galaxy populations at different redshifts

Statistical studies

Collective galaxy properties





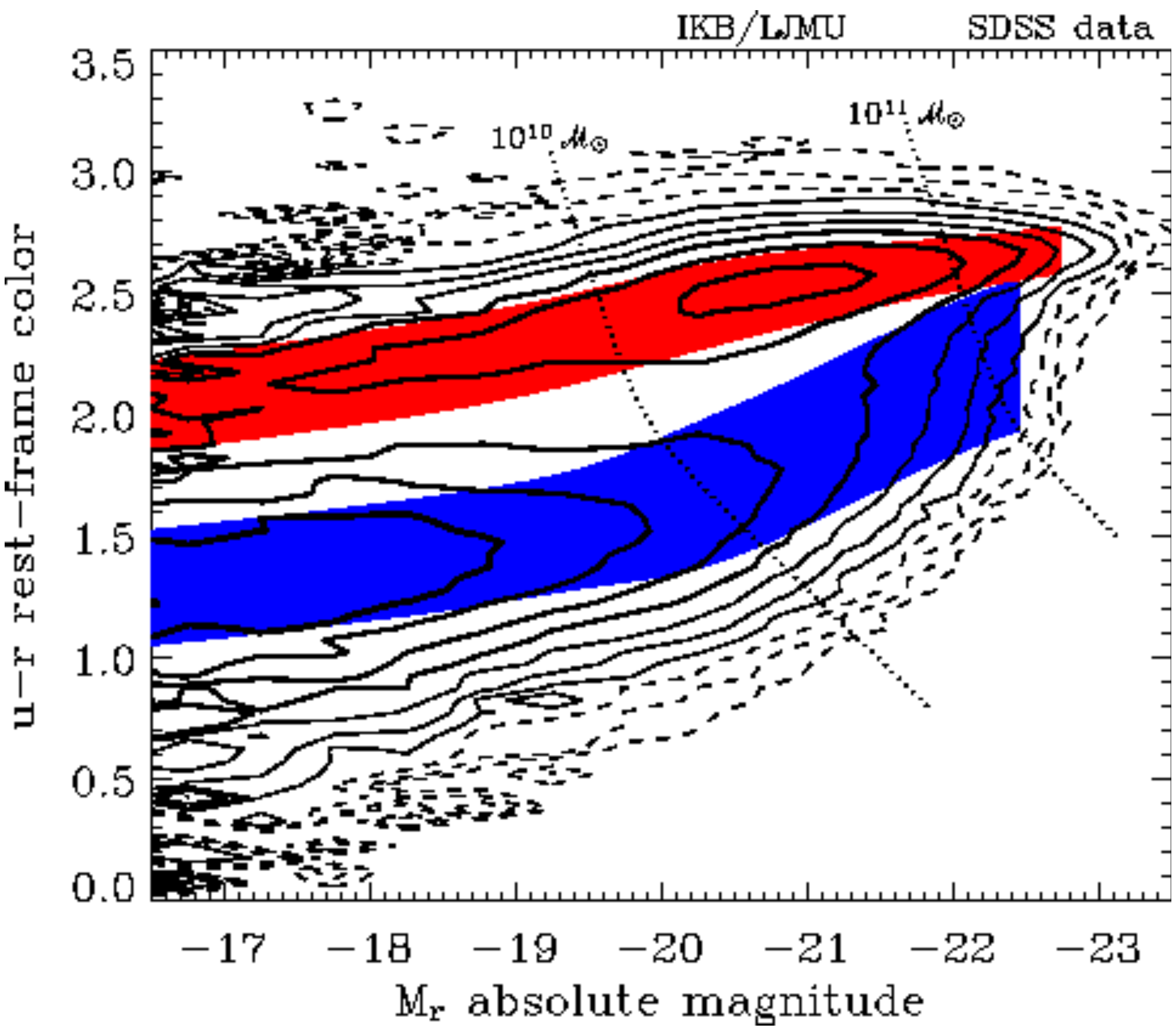


9 arcmin

Blank patches of the sky contain thousands/millions of galaxies

Colour-colour diagrams

Even the most basic parameters of large galaxy samples contains very valuable information!



Baldry et al. (2004)

Counting Galaxies - the Galaxy Luminosity Function (GLF)

Just as distribution of stellar luminosities reflects physics of star formation and stellar structure, we might hope to learn about galactic evolutionary processes by studying the distribution of galaxy luminosities.

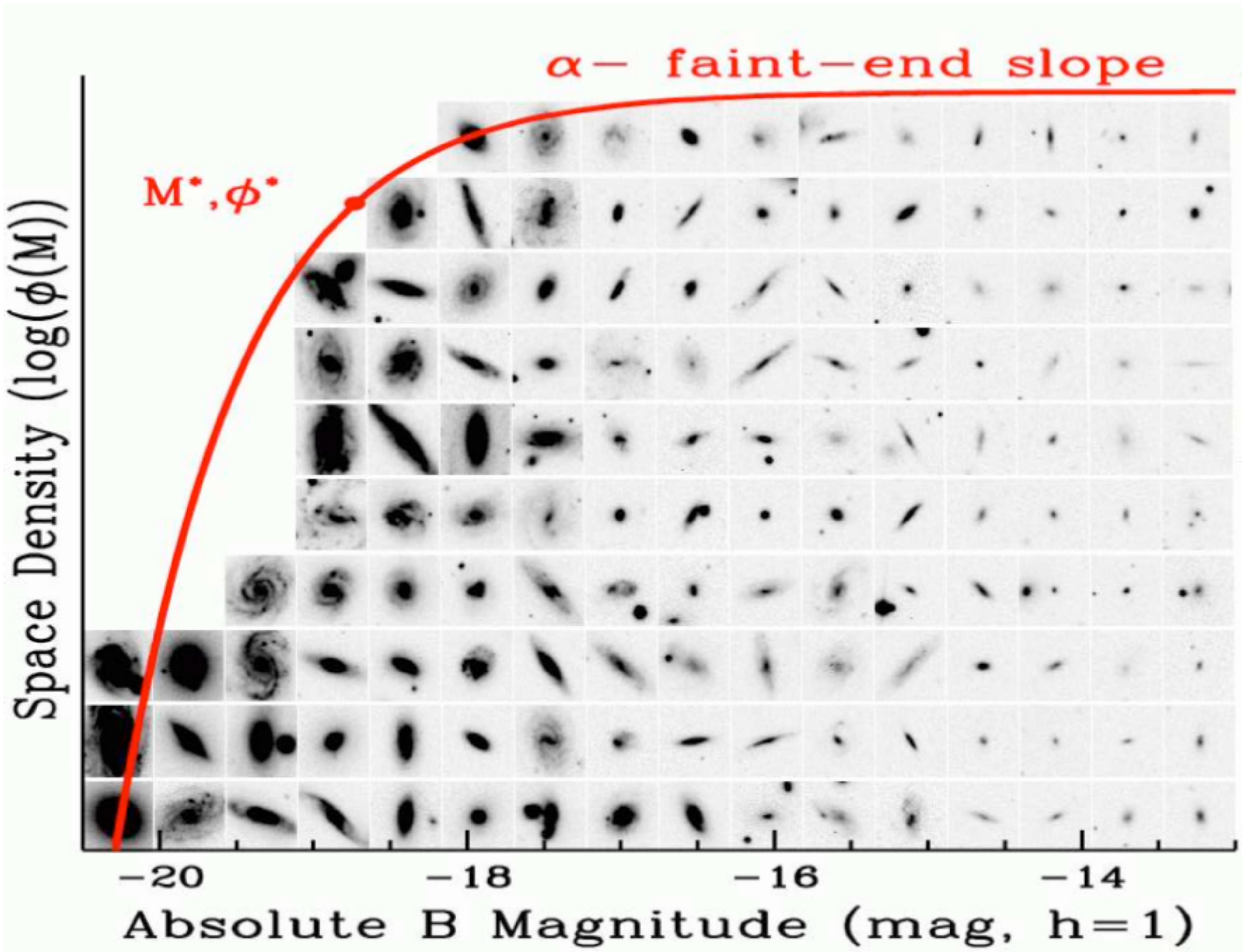
The *galaxy luminosity function* $\Phi(M)$, $\Phi(M)dM$ is the *number of galaxies that have absolute magnitudes in the range* (M, $M+dM$):

$$\int_{-\infty}^{\infty} \Phi(M) dM = \nu$$

where ν is the total number of galaxies per unit volume

The field galaxy luminosity function involves measuring apparent magnitudes of all the galaxies in some representative sample. Individual brightnesses are converted to absolute magnitudes by estimating distances usually by applying Hubble's law to their observed redshifts.

GLF - schematic view



Driver 2004 PASA, 21, 344

GLF - the Schechter function

In an attempt to find a general analytic fit to galactic luminosity functions, Schechter (1976) proposed the functional form:

$$\boxed{\phi(L)\ dL \sim L^{\alpha}\ e^{-L/L^*} dL}$$

which can also be written (in terms of absolute magnitudes):

$$\boxed{\phi(M)\ dM \sim 10^{-0.4(\alpha+1)M}\ e^{-10^{0.4(M^*-M)}} dM}$$

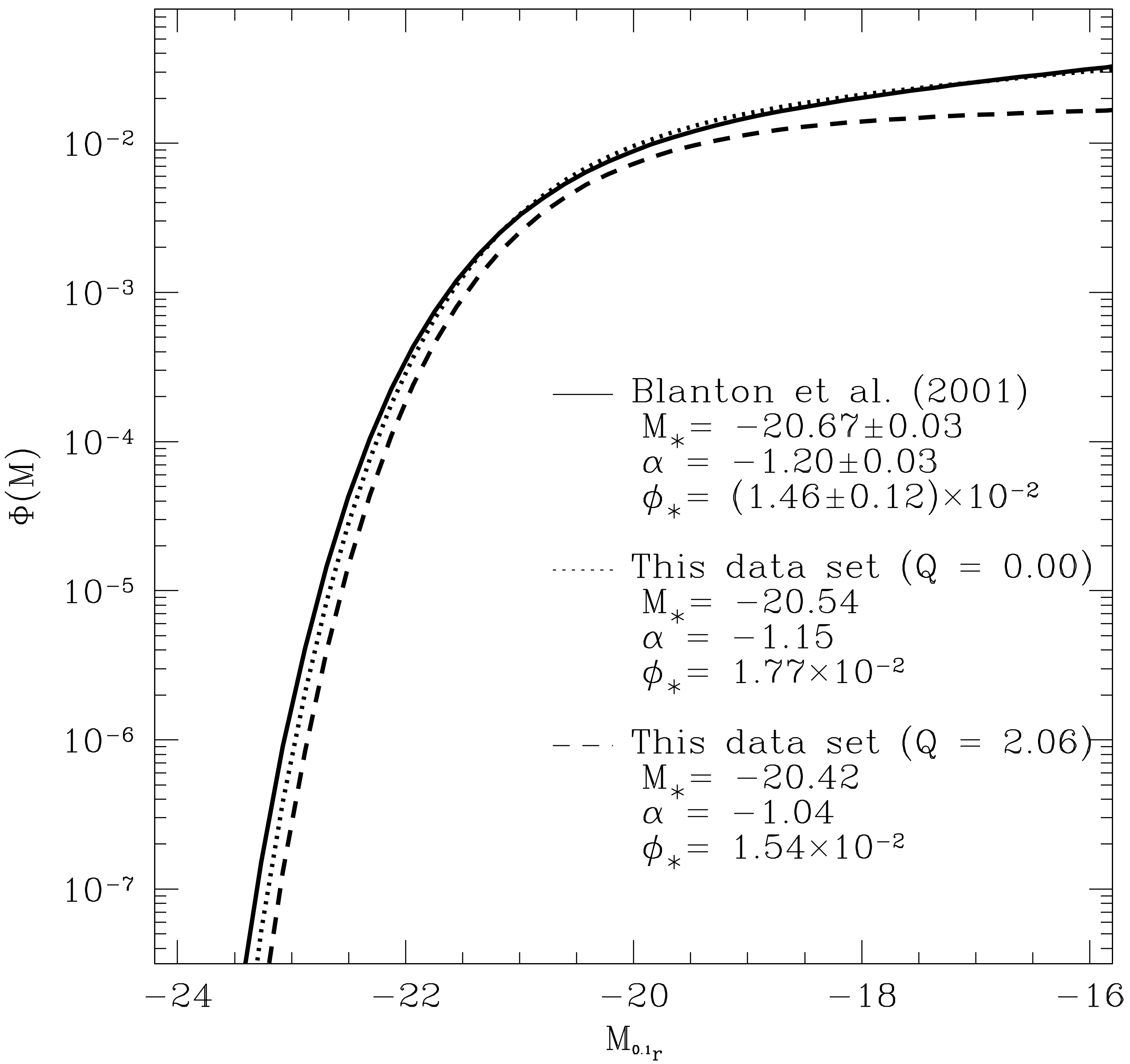
A power law with a high luminosity exponential cut-off

In both forms α (the slope of the power-law at low luminosities) and L^* (the break luminosity) are free parameters that are used to obtain best fit to available data.

Local: α= -1.0 and M^*_B = -21
Virgo: α= -1.24 and M^*_B = -21 ± 0.7

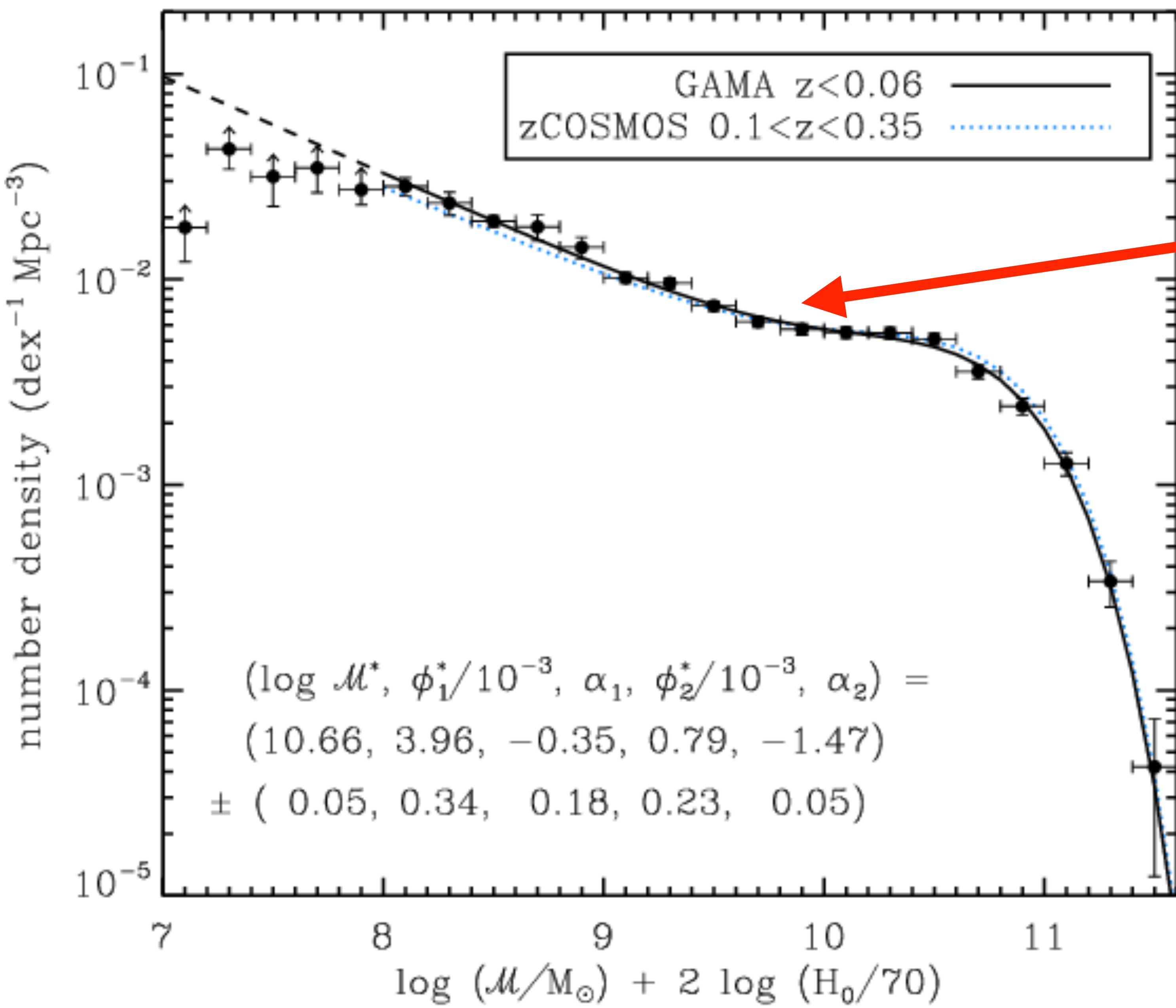
i.e., this is NOT a universal (luminosity) function. It seems to depend upon environment (and redshift).

The local GLF at optical wavelengths - early determinations



Blanton et al. (2001)

The GLF: a double Schechter function



More recent computations of the GLF indicate that it follows a double Schechter function up to at least z=1 (dip cannot be reproduced with single Schechter)

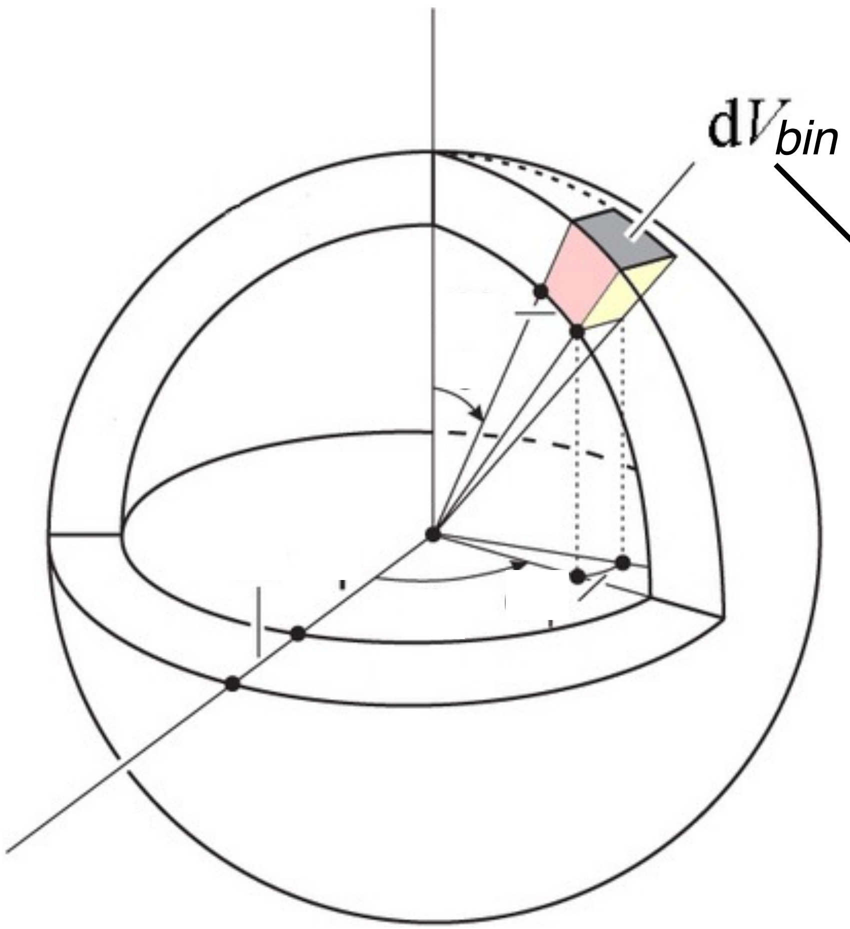
Baldry et al. (2011)

GLF computation: the Vmax method

bin all the galaxies in the survey in luminosity and redshift

(log10 L; log10L+Δ(log10L)) “dex” units

(z; z+Δz) ⟶ ***Vbin*** (comoving)



for faint galaxies the effective volume may be smaller

Vmax < Vbin

GLF computation: the Vmax method

bin all the galaxies in the survey in luminosity and redshift

- Find the largest distance at which a galaxy with observed abs magnitude M_i can be found in order to have apparent magnitude equal to the limit of the sample m_{lim}

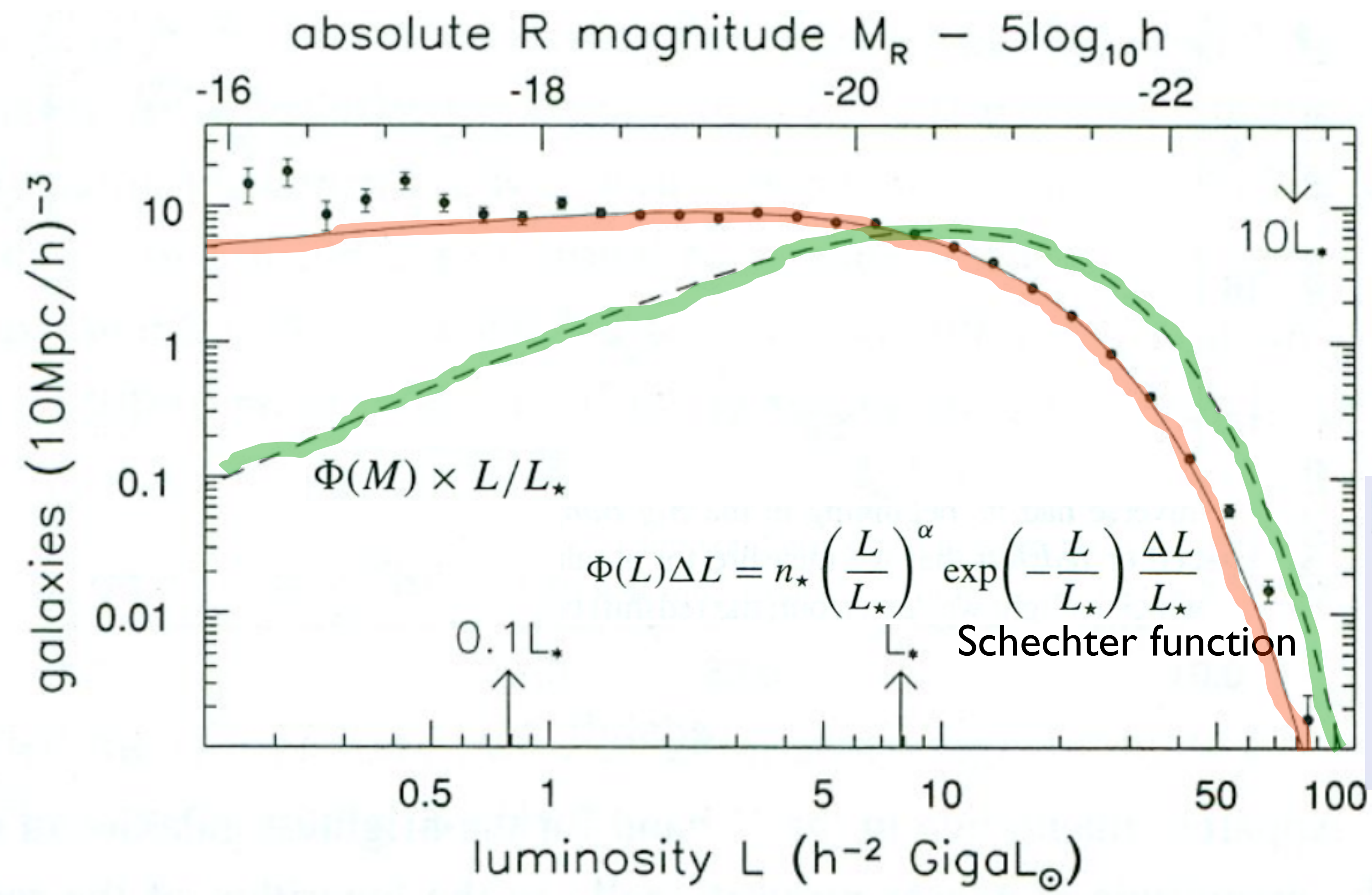
- Volume of the sample corresponding the distance is V_{max}. This is the volume available for the galaxy. The galaxy could have been anywhere inside the volume.

- Select all galaxies with abs magnitudes in the range (M,M+dM). An estimate of the luminosity function is

- $\Phi(M)dM = \sum[1/V_{max}(i)]$ ← weight factor for each galaxy

Integrating the GLF

Galaxy Counts



$L_* \approx 8 \times 10^9 h^{-2} L_\odot$

$h = 0.75$

$L_* \approx 2 \times 10^{10} L_\odot$

$n_* = 0.019 h^3\,\mathrm{Mpc}^{-3}$

$\alpha = -0.7$

Number of galaxies $\Phi(M)$ per $(10\text{Mpc}/h)^3$ in bins of absolute magnitude M_R

(most galaxies are faint)

Fraction of light (or luminosity) by galaxies/L-bin (luminosity contribution from faint galaxies is small)

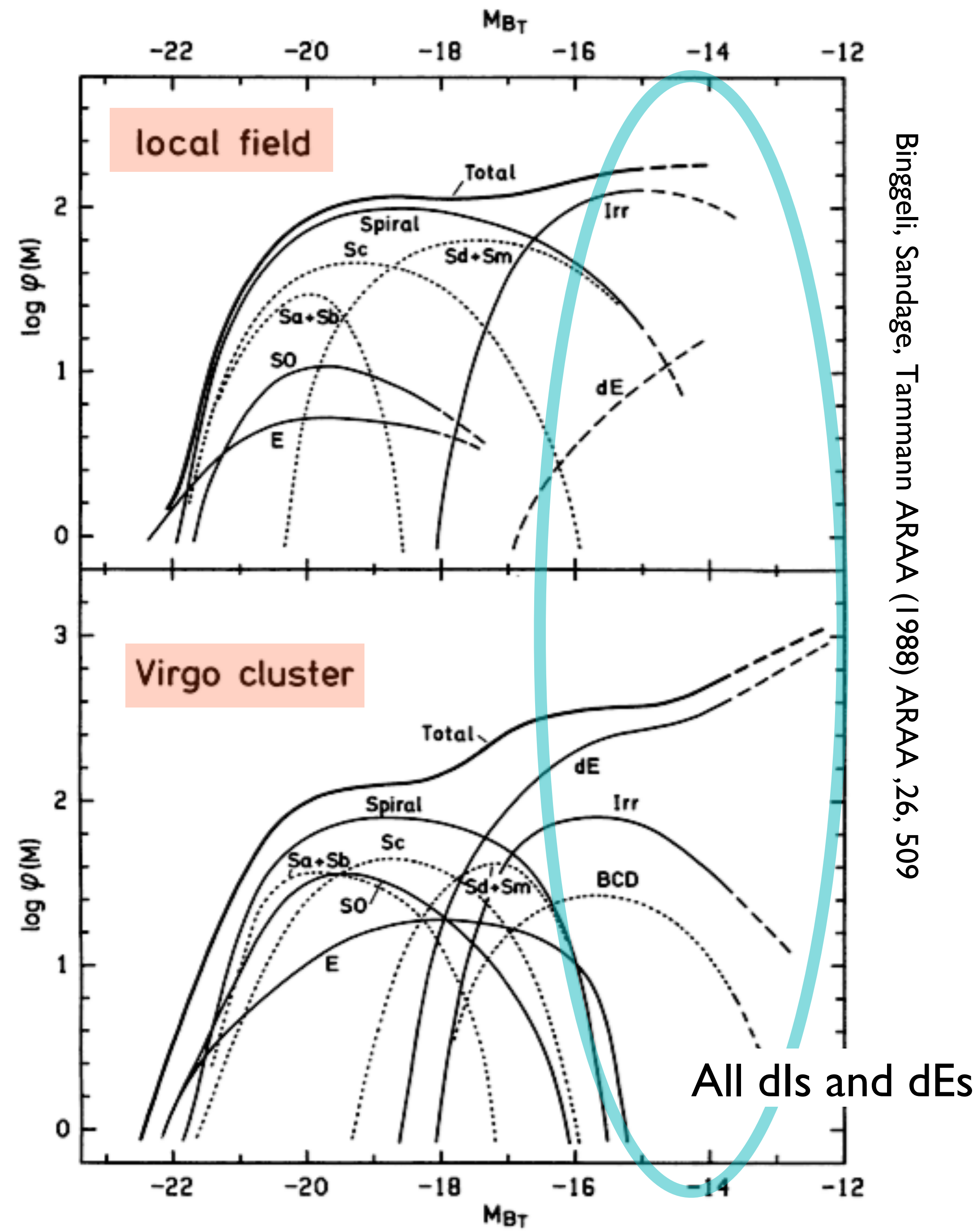
Contribution of different galaxy types

LF of cluster & local field broken down into different types

Largest fraction in either environment of all galaxies are dwarfs (dE and Irr). Even though S and E the most prominent in terms of mass and luminosity.

More E in Virgo…

The total luminosity function in either environment is the sum of the individual luminosity functions of each Hubble type.

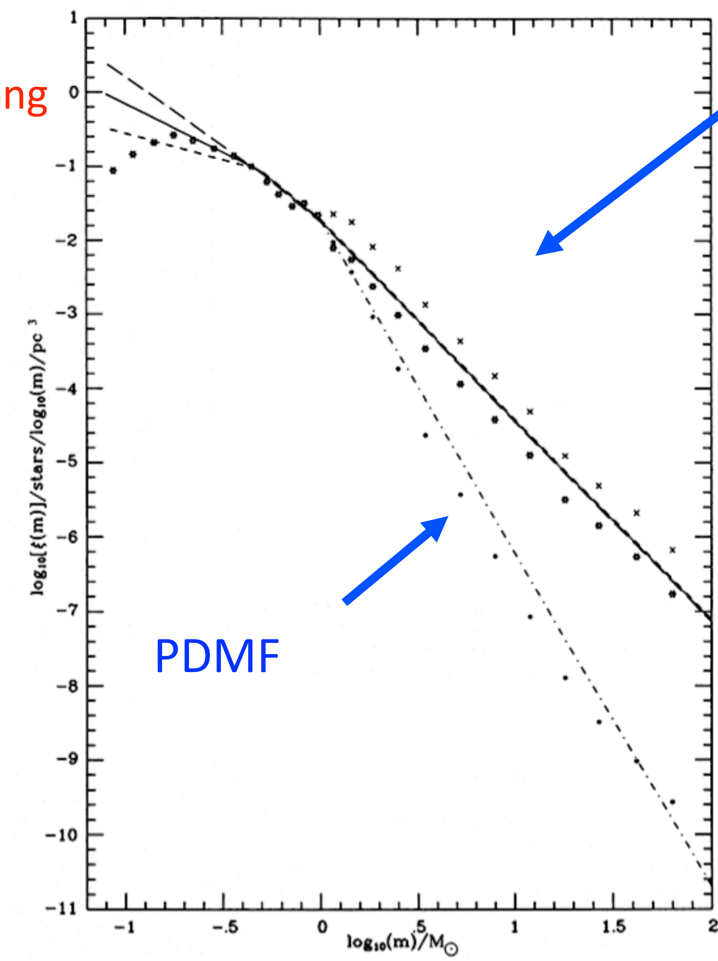


Binggeli, Sandage, Tammann ARAA (1988) ARAA ,26, 509

From luminosities to stellar masses

- •IMF (initial mass function) $\Psi(m, t)$, number of stars formed per unit volume (at t=0); often approximated as a power law: $\Psi(m)\,dm = \Psi_0\, m^{-\alpha}$
- •LF (luminosity function) currently observed number of stars observed per unit luminosity per unit volume
- •PDMF (present day mass function) number of stars observed today per unit mass per unit volume. This needs to be corrected for the time evolution of the IMF up to the present day,

low mass, long lived stars

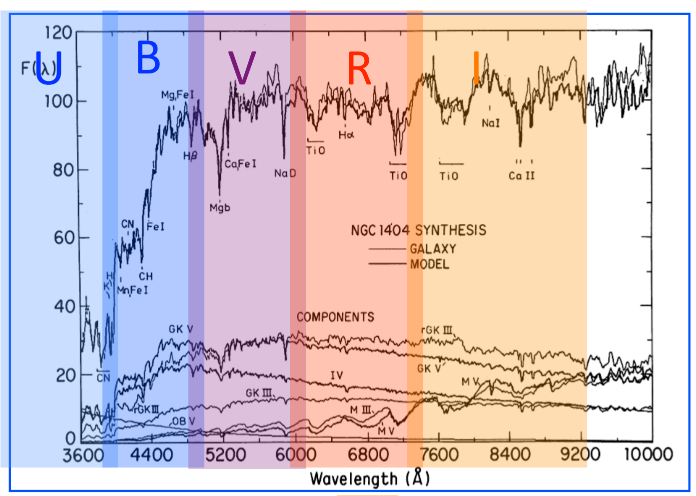


IMF

PDMF

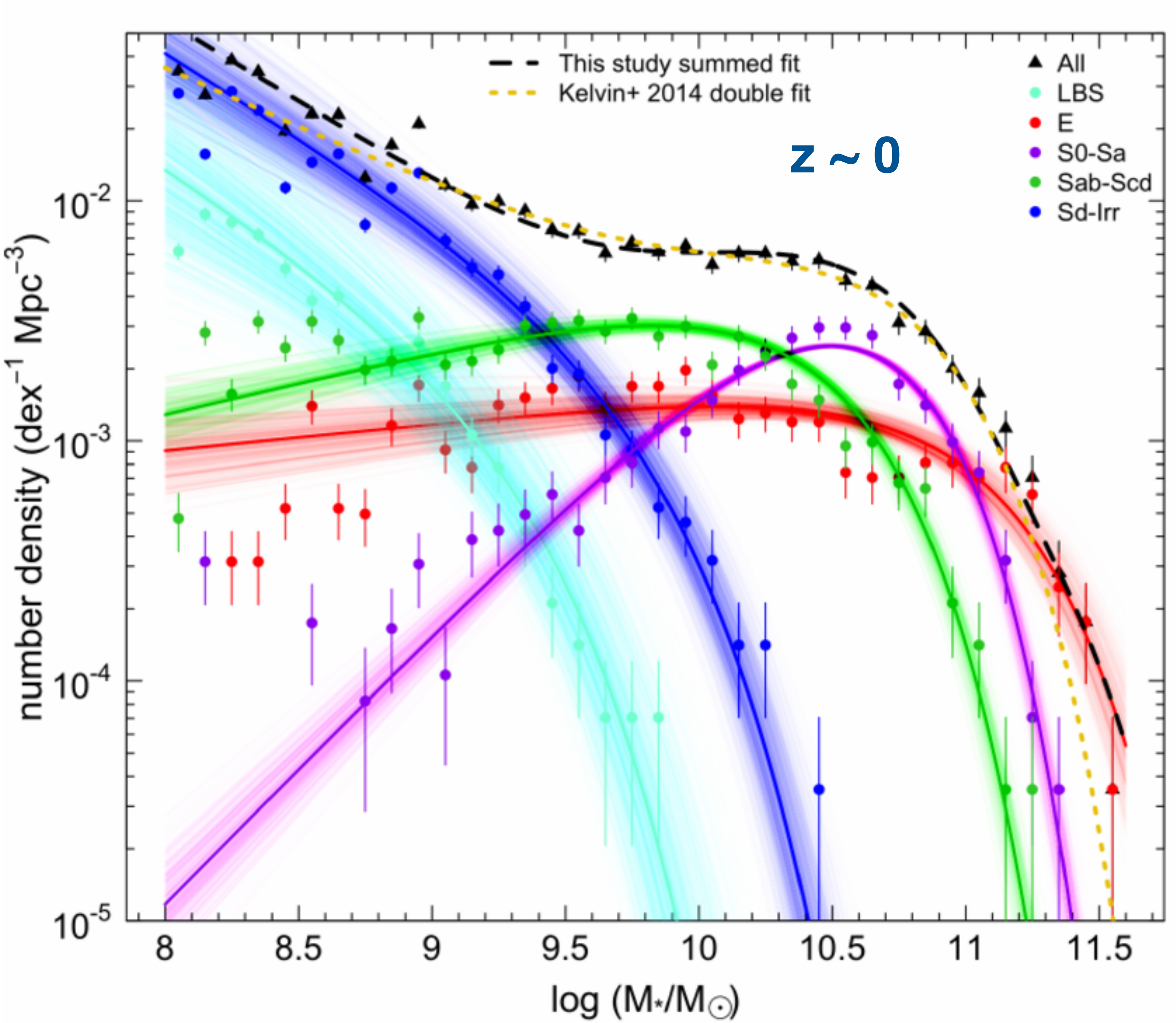
high mass, short lived stars

Kroupa, Tout & Gilmore 1993 MNRAS, 262, 545



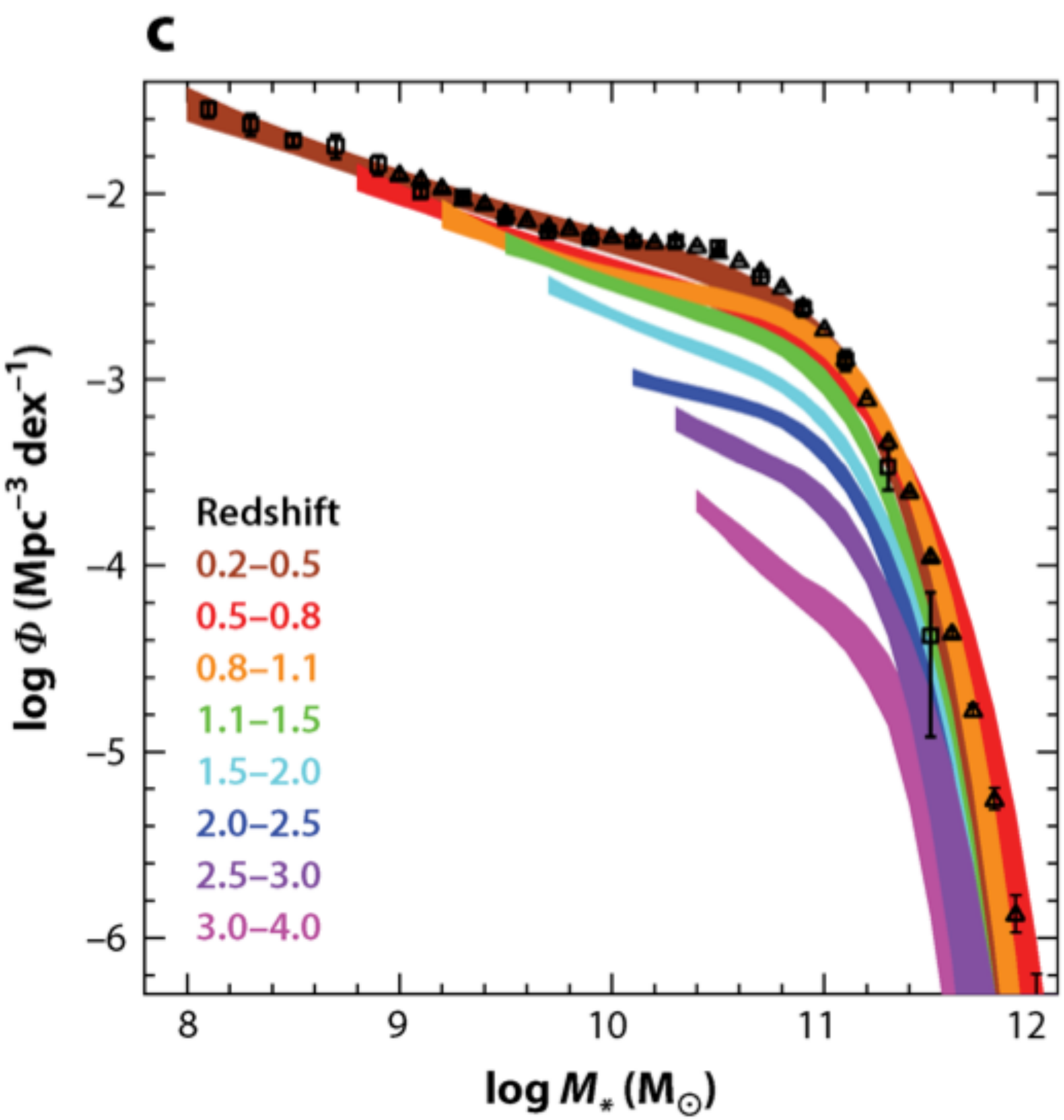
Star Formation History

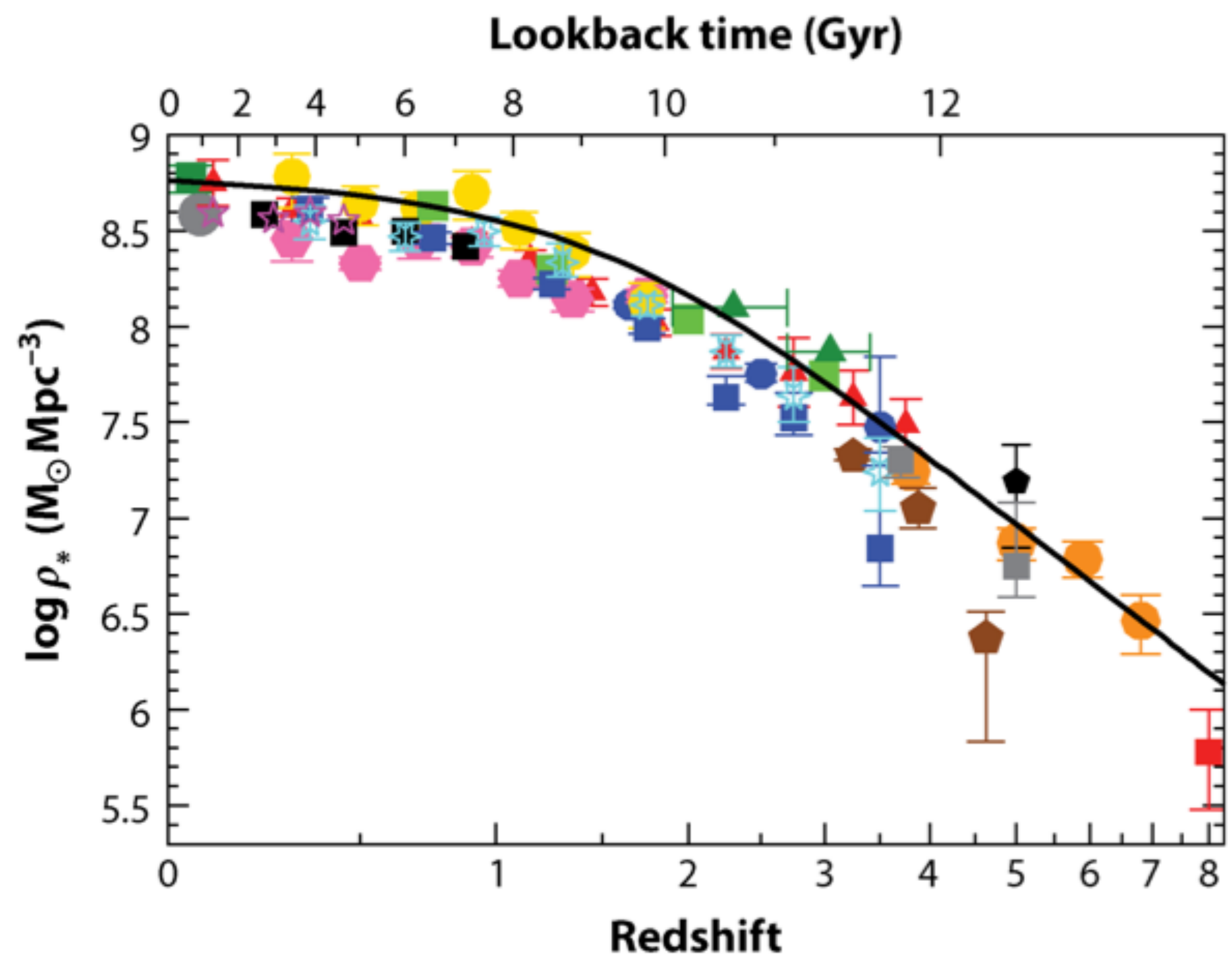
The Galaxy Stellar Mass Function (GSMF)



Moffett et al. (2016)

The GSMF and cosmic stellar mass density - redshift evolution

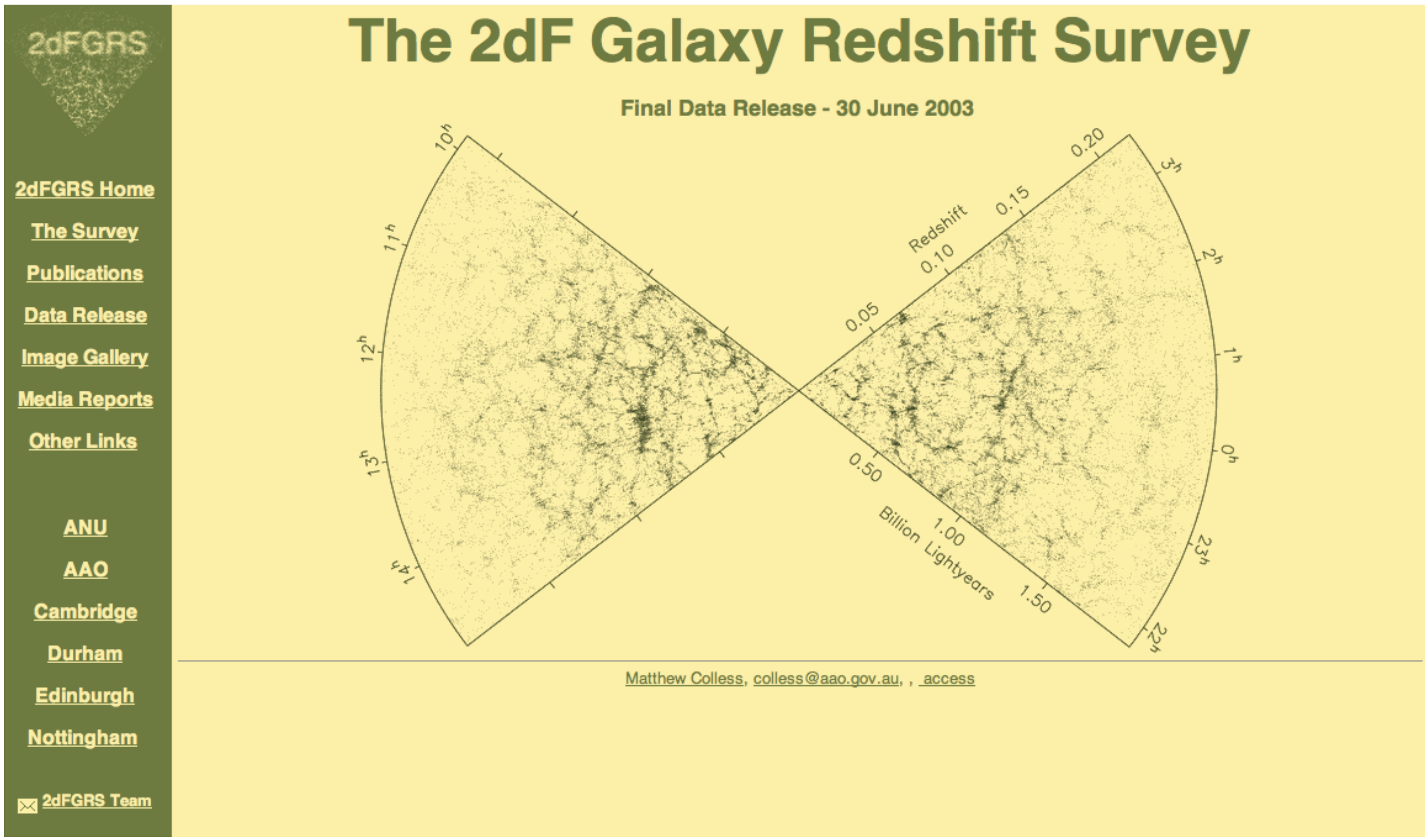




Madau & Dickinson (2014)
and references therein

Large-area surveys:
study of local Universe

2DF Galaxy Redshift Survey



http://www2.aao.gov.au/~TDFgg/

Millennium Galaxy Catalogue

MGC
Millennium Galaxy Catalogue

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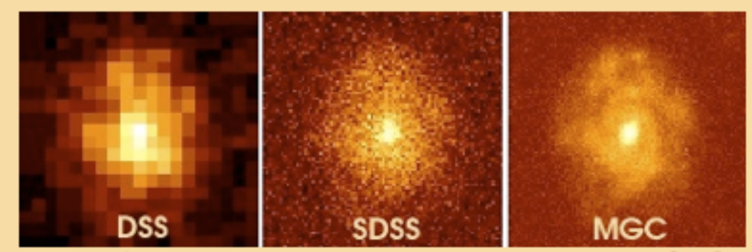
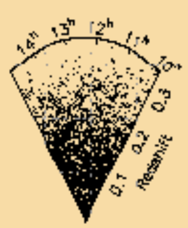
Millennium Galaxy Catalogue

The Millennium Galaxy Catalogue (MGC) is a 37.5 deg^2, medium-deep, B-band imaging survey obtained with the Wide Field Camera on the INT. The survey region is a long, 35 arcmin wide strip along the equator, covering from 10h 00m to 14h 45m and is fully contained within the regions of both the Two Degree Field Galaxy Redshift Survey (2dFGRS) and the Sloan Digital Sky Survey (SDSS).

There are 144 WFC pointings and each was observed for a single 750 s exposure (example field), resulting in a limiting central surface brightness of 26 mag/arcsec^2. Object catalogues have been generated from the imaging data using SExtractor (E. Bertin). These provide a robust, well-defined, catalogue of galaxies in the range $13 < B < 24$ mag. Thus the MGC represents a new wide-angle galaxy resource which firmly connects the local and distant universe within a single dataset.

To give an impression of the quality and depth of the MGC, this figure shows galaxy images from the Digitized Sky Survey and SDSS alongside the MGC image of the same galaxy. For local ($B < 20$ mag) galaxies, the data allow the decomposition of galaxies into disks and bulges and hence provide the level of detail necessary to perform meaningful comparisons with both high-redshift observations and theories of galaxy evolution and formation.





MGCz is an AAT/2dF redshift survey of those $B < 20$ galaxies (10,095 in total) not already observed by either the 2dFGRS or SDSS, in order to provide redshifts for the full $B < 20$ sample. Additional (mop-up) observations, particularly for low-surface brightness galaxies, were obtained with Gemini/GMOS, NTT/EMMI, TNG/DOLORES and ANU 2.3m/DBS, resulting in an overall redshift completeness of 96%. The median redshift of this sample is 0.12.

Here are some figures and further explanations describing the survey and a selection of scientific results.

Sep 2006, Joe Liske

http://www.eso.org/~jliske/mgc/

The SDSS

The most ambitious survey of the sky ever undertaken.

Imaging survey of 8600 square degrees.

Redshifts of more than 1,000,000 galaxies & QSOs.

Robotic 2.5m telescope - imaging & Spectrscopy



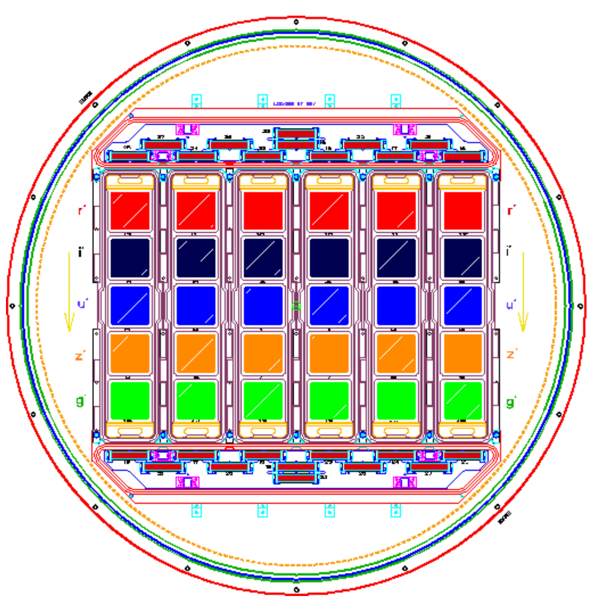


SLOAN - hardware

The SDSS used a dedicated 2.5-m f/5 modified Ritchey-Chretien altitude-azimuth telescope located at Apache Point Observatory (2788m), New Mexico, USA. It is equipped with two powerful special-purpose instruments. The 120-megapixel camera which can image 1.5 square degrees of sky at a time. A pair of spectrographs fed by optical fibres measured spectra of (and hence distances to) more than 600 galaxies and quasars in a single observation. A custom-designed set of software pipelines kept pace with the enormous data flow from the telescope.

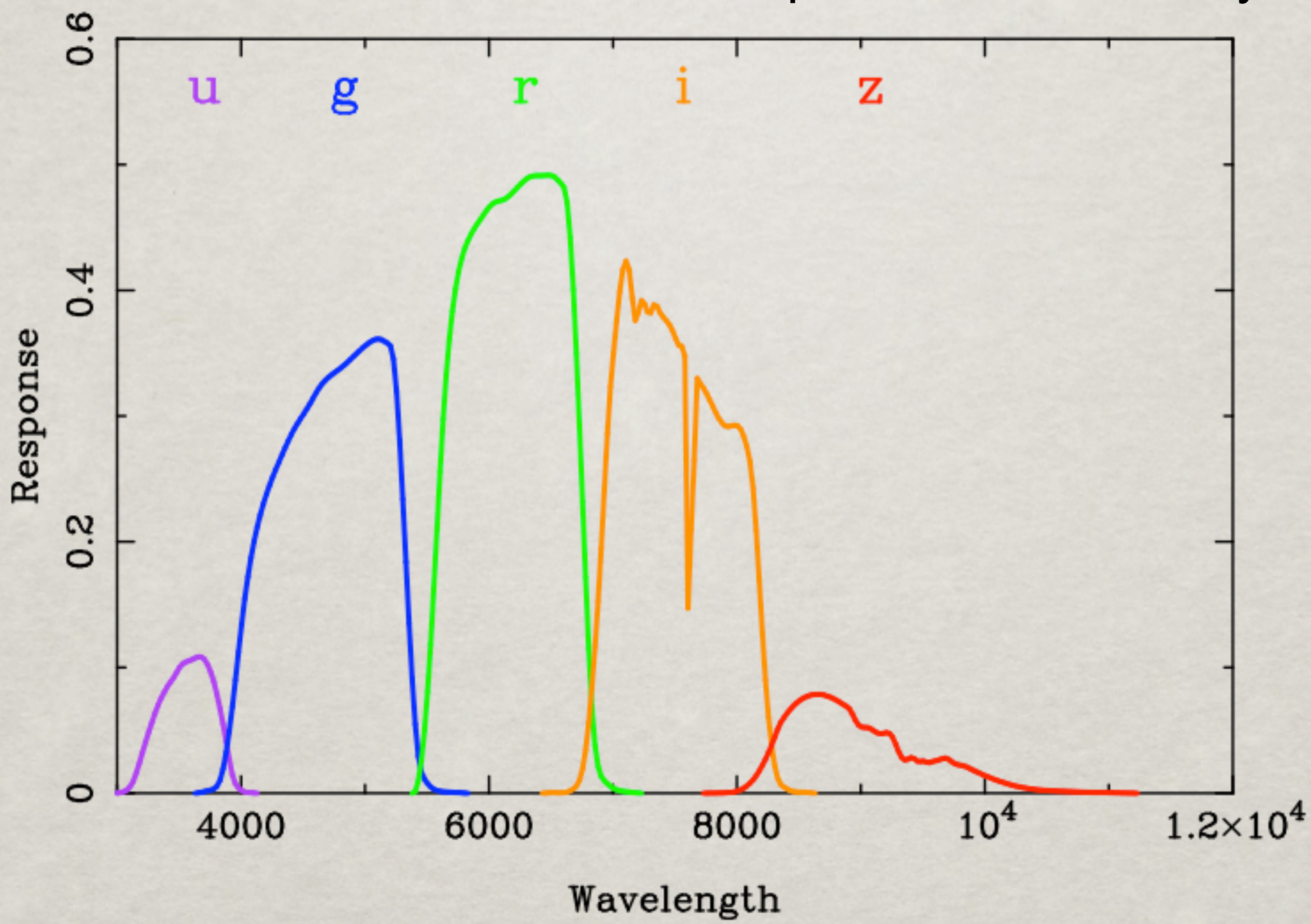
Imager: 30 SITe/Tektronix 2048 by 2048 pixel CCDs: r, i, u, z, g filters. Drift scan mode: camera slowly reads CCD as data collected.

spectrographs: in a single exposure ~600 spectra of galaxies to the spectroscopic limit of r' ~ 18.2 over the field of the telescope. R~2000, λ3900-9100Å.

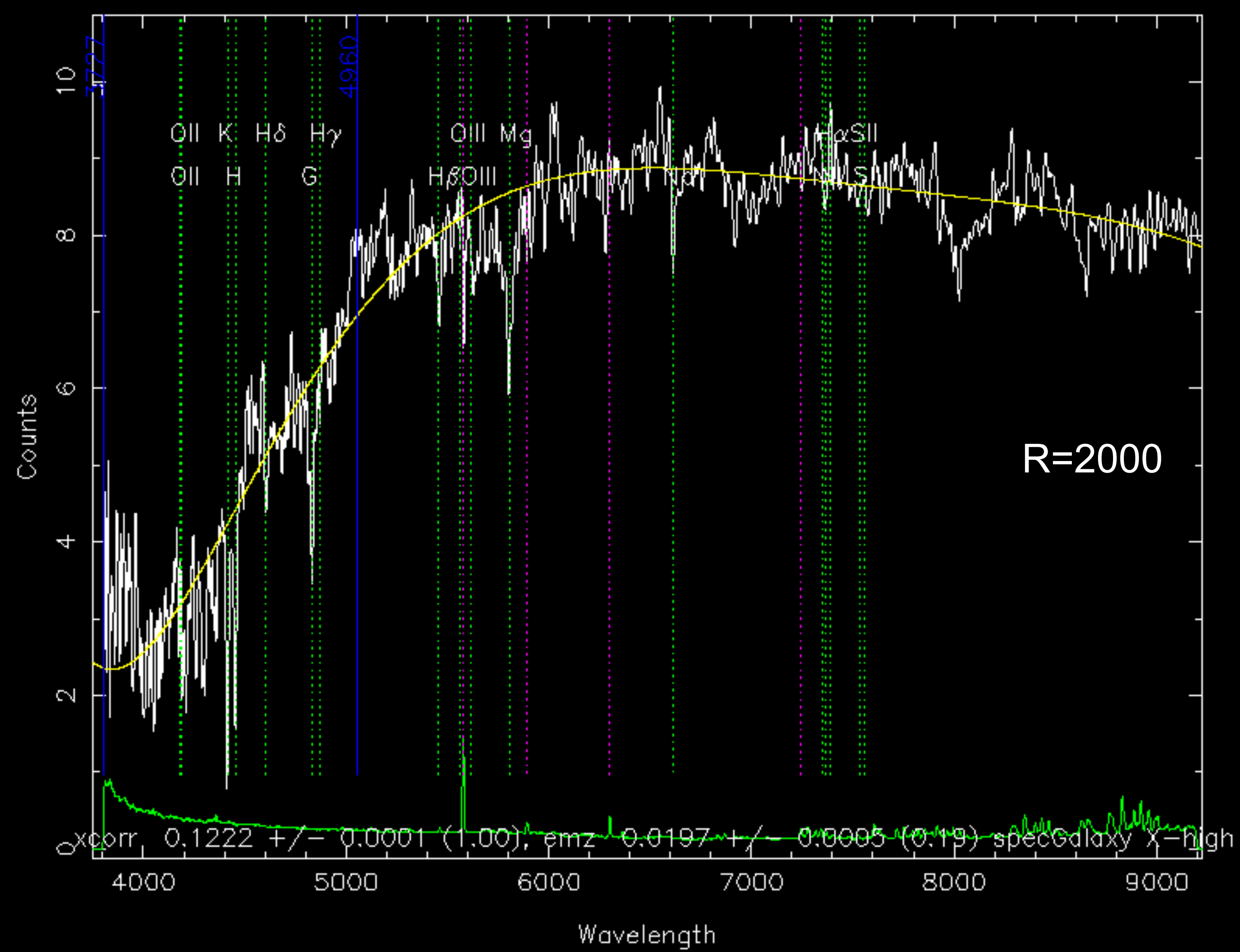


Magnitude System(s)

special Sloan filter system



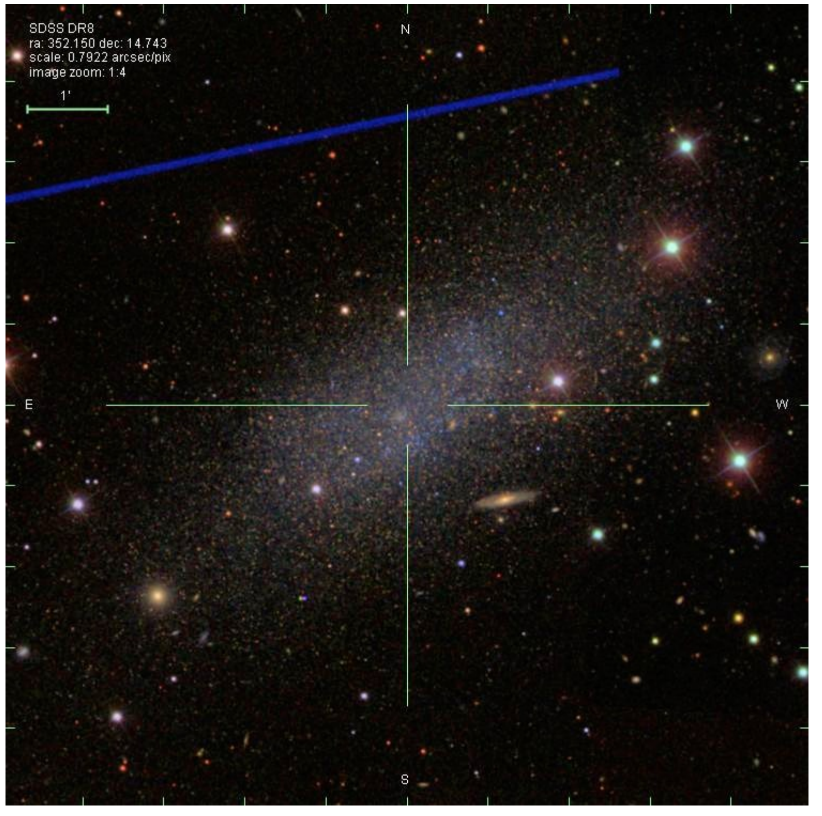
Typical Sloan Galaxy Spectrum



The Sloan Digital Sky Survey

SDSS has been and continues to be an ambitious and influential survey. Over many years of operations (SDSS-I, 2000-2005; SDSS-II, 2005-2008, SDSS-III, 2008-2014), it obtained deep, multi-colour images covering more than a quarter of the sky and created 3-dimensional maps containing more than 930,000 galaxies and more than 120,000 quasars. SDSS data have been released to the scientific community and can be easily accessed via http://www.sdss.org/

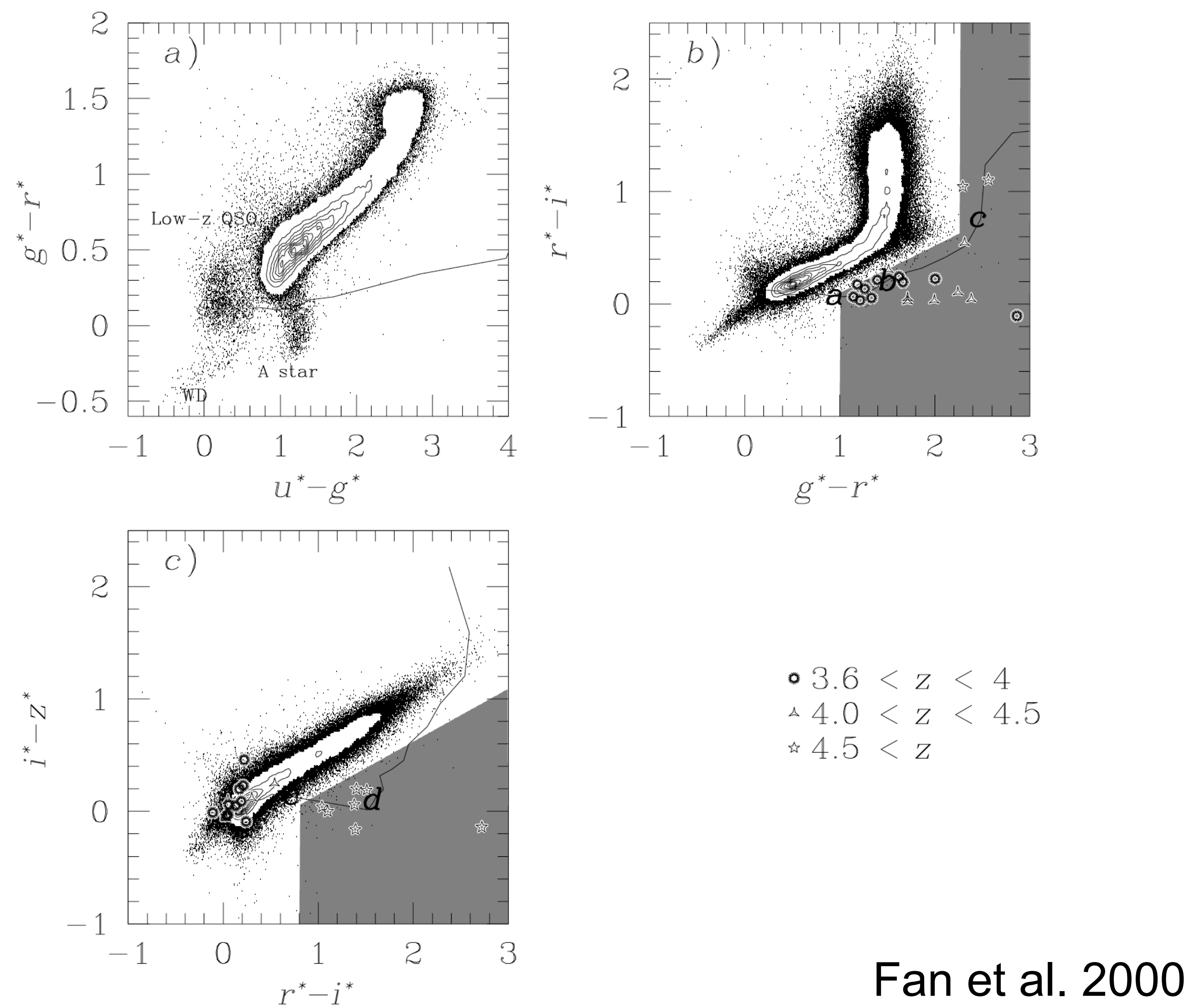
The latest generation of the SDSS (SDSS-IV, 2014-2020) focus is
- •extending precision cosmological measurements to earlier phase of cosmic history (eBOSS),
- •expanding its infrared spectroscopic survey of the Galaxy in the northern and southern hemispheres (APOGEE-2)
- •using the Sloan spectrographs to make spatially resolved maps of individual galaxies (MaNGA).



Quasars in SDSS

- QSO's are relatively easy to identify
- Point sources
- Colours off the main regions occupied by stars

- Characteristic sequence in colour space as redshift increases
  - need for redder bands (i,z) for high-redshift objects

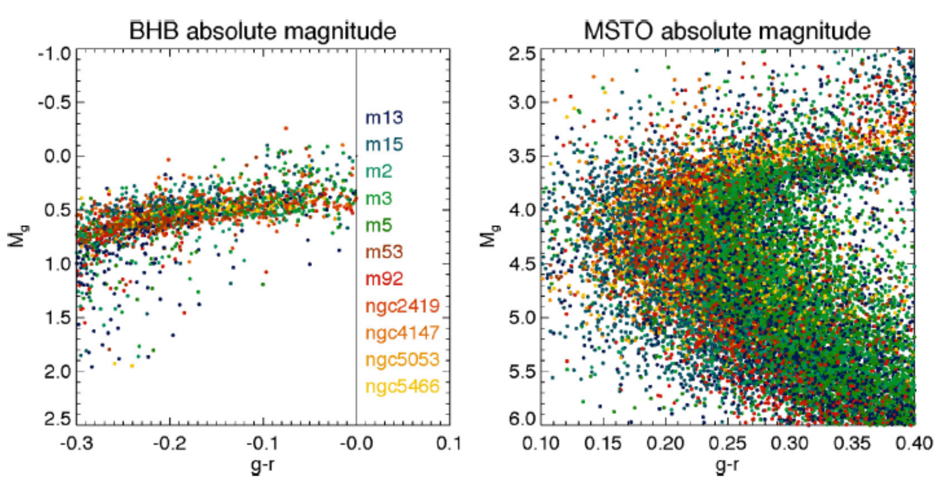


Fan et al. 2000

ılor-color diagrams for all stellar objects in 75 deg^2 of SDSS imaging data from run 752, with $i^* < 20.2$. The inner parts of the diagrams are ›urs, linearly spaced in the density of stars in color-color space. The shaded areas on the g^*-r^* vs. r^*-i^* and the r^*-i^* vs. i^*-z^* diagrams ːlection criteria used to select quasar candidates. The solid line is the median track of simulated quasar colors as a function of redshift (adapted). The letters "a," "b," "c," and "d" indicate the positions on the locus of median color quasars at $z = 3.6, 4.1, 4.6$, and 5.0, respectively. Colors med SDSS quasars at $z > 3.6$ are also plotted on the diagrams.

SLOAN: also stars

- High-latitude fields: easier to probe into halo
- Density of halo stars is very low ➔ need good criteria to isolate objects
  - main sequence turn-off stars
  - RR Lyrae on variability
  - BHB on colour



Belokurov 2013

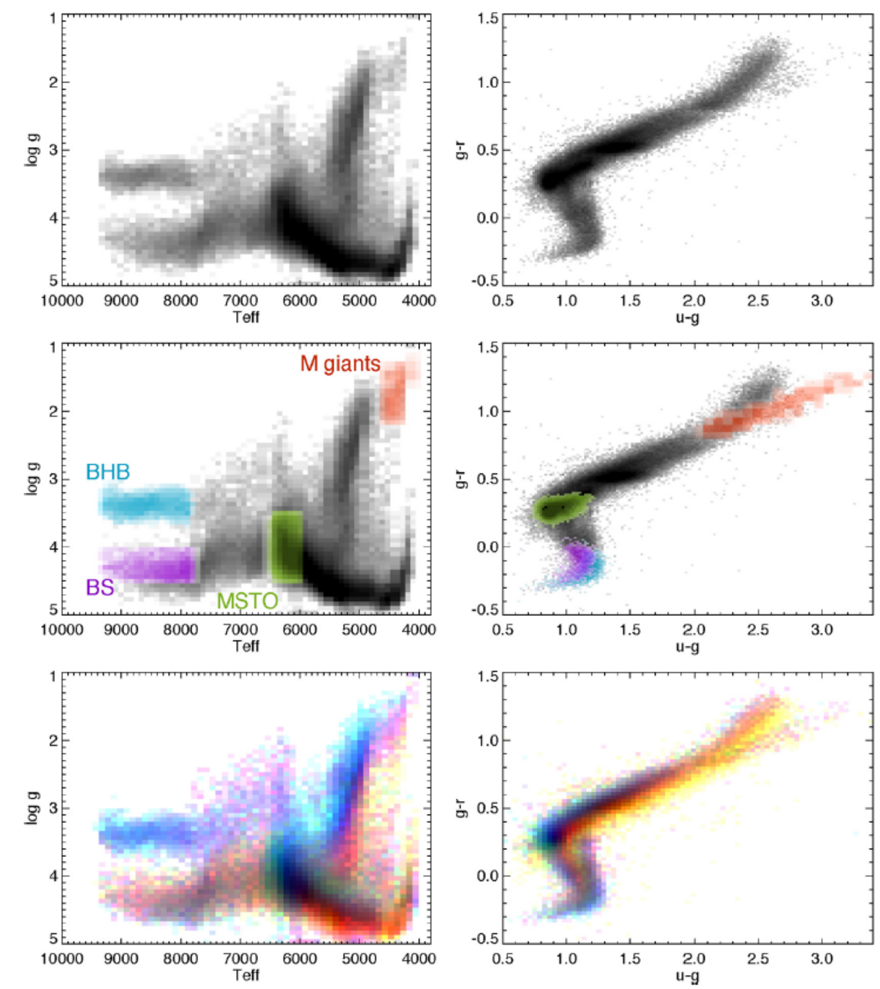
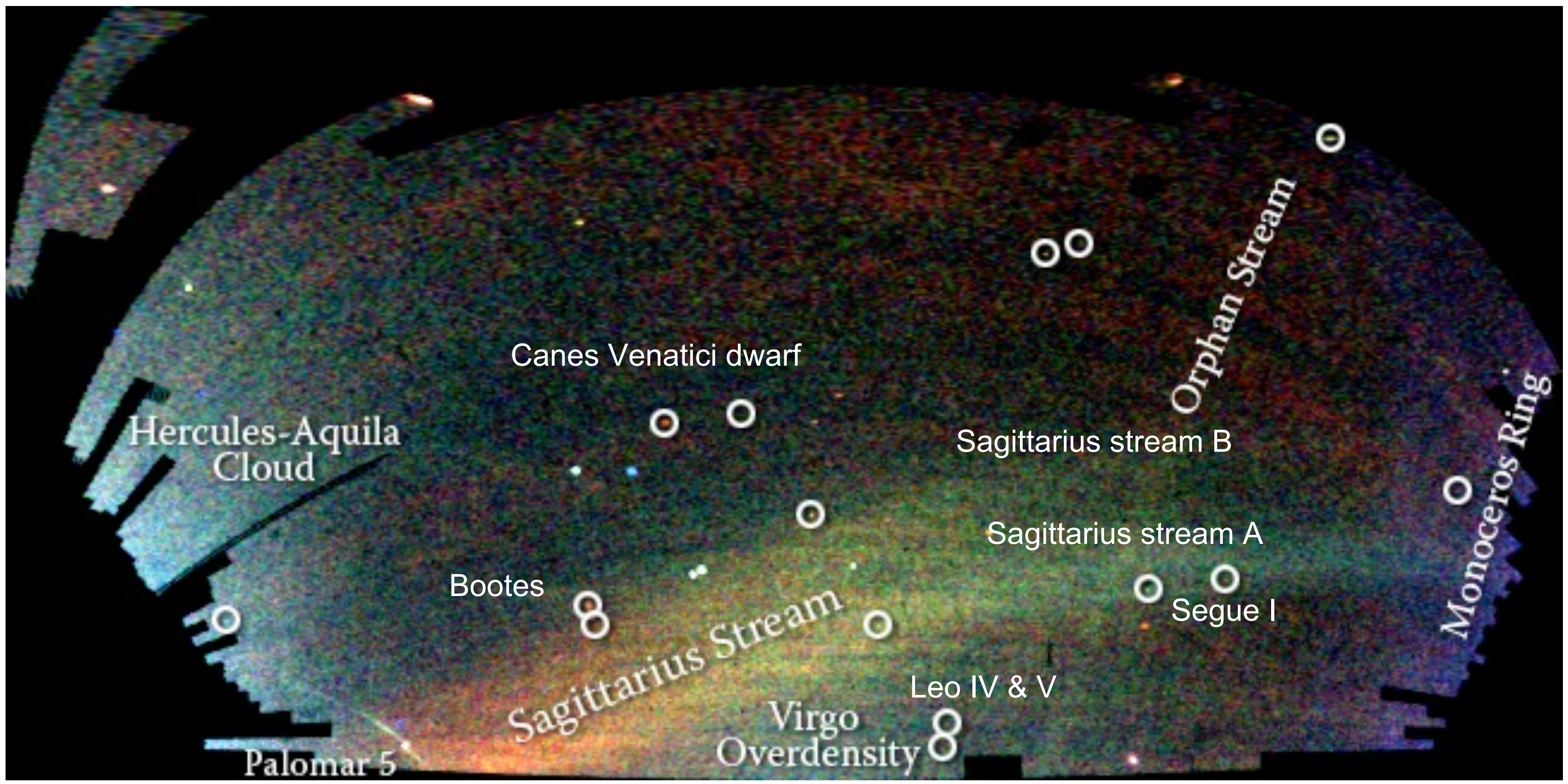


Fig. 2. Stellar tracer selection in the SDSS database. *Left:* Density of stars in the plane of surface gravity $\log g$ and effective temperature $T_{\rm eff}$ for ~180,000 DR8 spectra with $15 < g < 17.5$. *Right:* Stars with spectroscopy from the left column are plotted on the plane of $u-g$ and $g-r$ color. **Top:** overview of the sample, darker shades of grey indicate higher density. **Middle:** Selecting the tracers. BHB (blue), Blue Straggler (violet), MSTO (green) and M-giant (red) stars are chosen in the left column based on their temperature and surface gravity. Density of selected stars is then over-plotted in $u-g$, $g-r$ space using the same color scheme. **Bottom:** Metallicity distribution in the sample. This shows false RGB images (left and right) constructed with 3 grey-scale density distributions of stars picked based on their [Fe/H]. Red component is for metal-rich stars with $-0.75 < [Fe/H] < 0$, green (intermediate) $-1.5 < [Fe/H] < -0.75$ and blue (metal-poor) $-3 < [Fe/H] < -1.5$.

SLOAN - also stars!

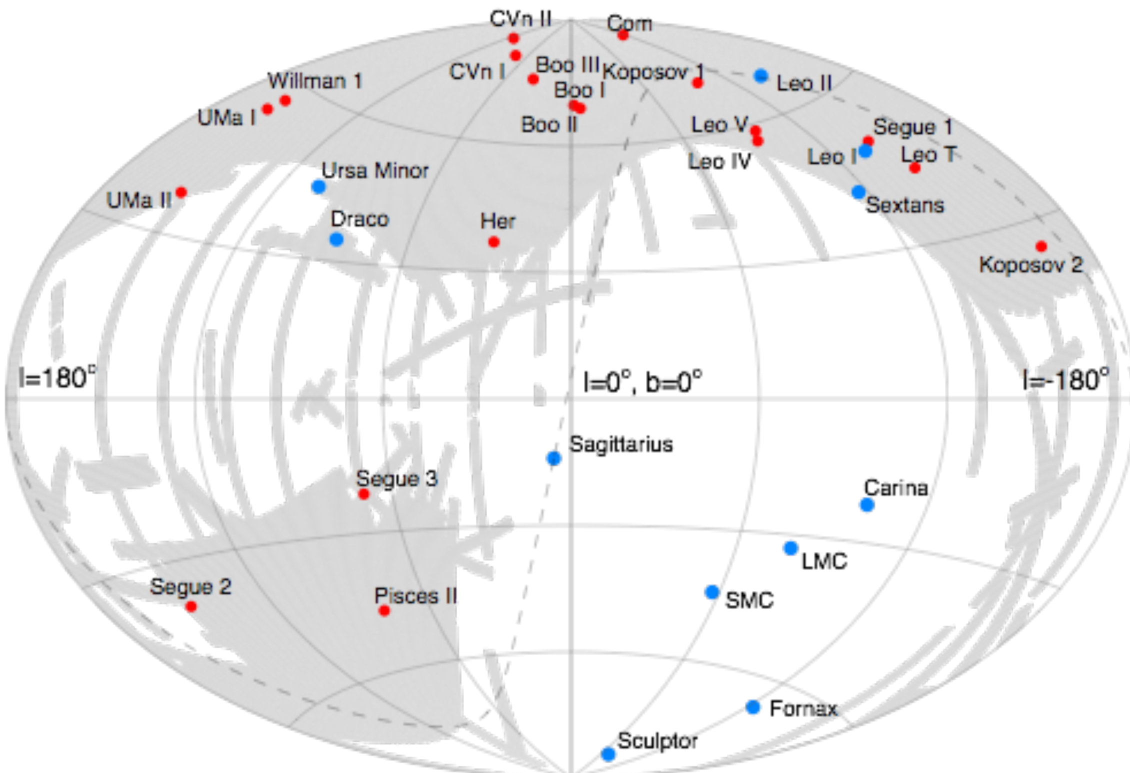
the field of streams



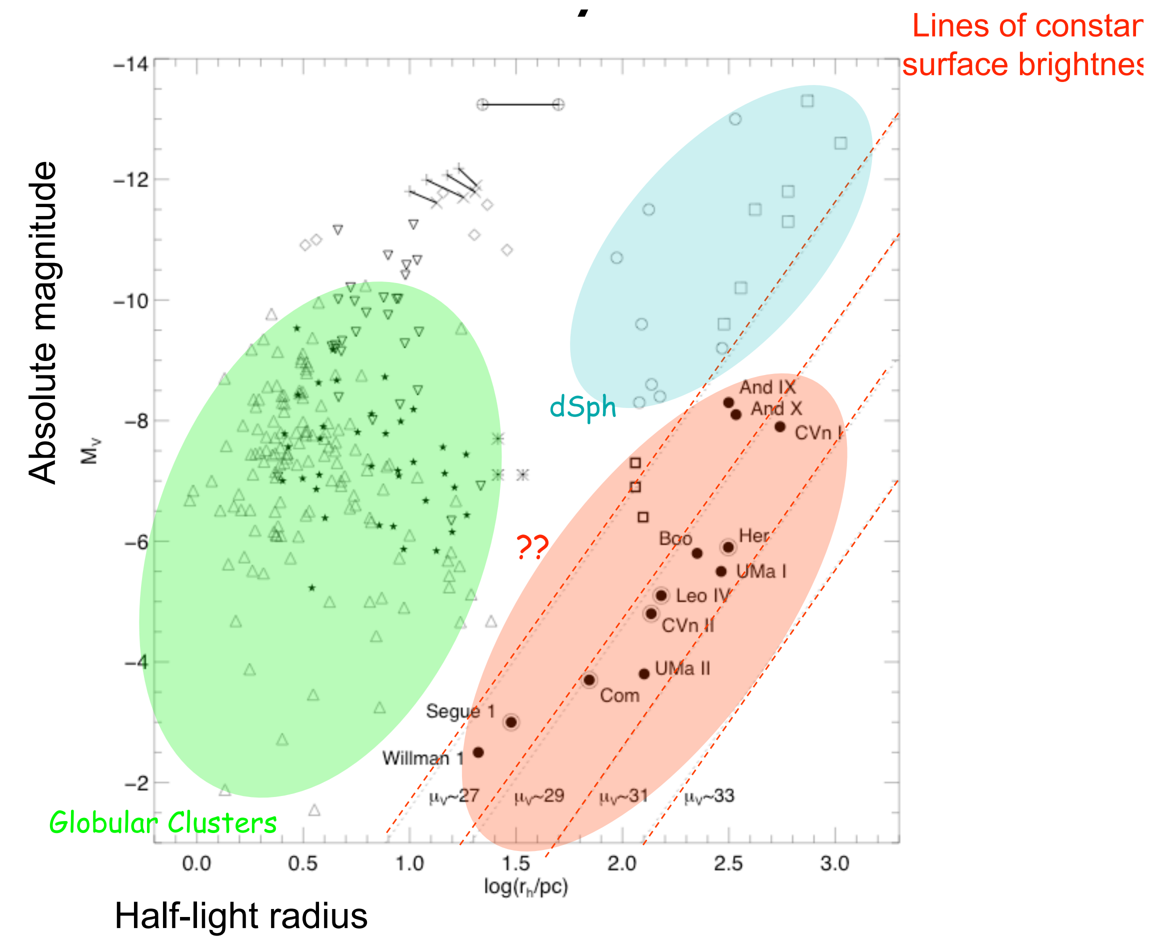
here is a map of individual stars seen in SDSS field of view - colour coded by distance. Sagittarius stream is very prominent. Also many new very faint galaxies found - called “ultra-faint” galaxies.

Belokurov et al. 2007 ApJ, 658, 337

New dwarf galaxies from SDSS

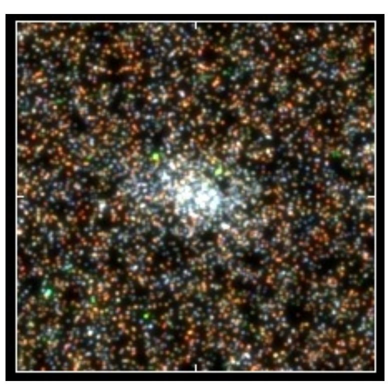


from Vasily Belokurov, SDSS data release 8



Belokurov et al. 2007, ApJ, 654, 897

Canes Venatici I



D = 220kpc

R_h = 550pc

M_V = -7.9

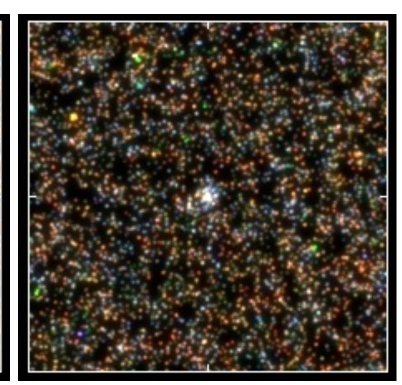
Bootes

D = 60kpc

R_h = 220pc

M_V = -5.8

Canes Venatici II



D = 150kpc

R_h = 140pc

M_V = -4.8

Coma Bernices

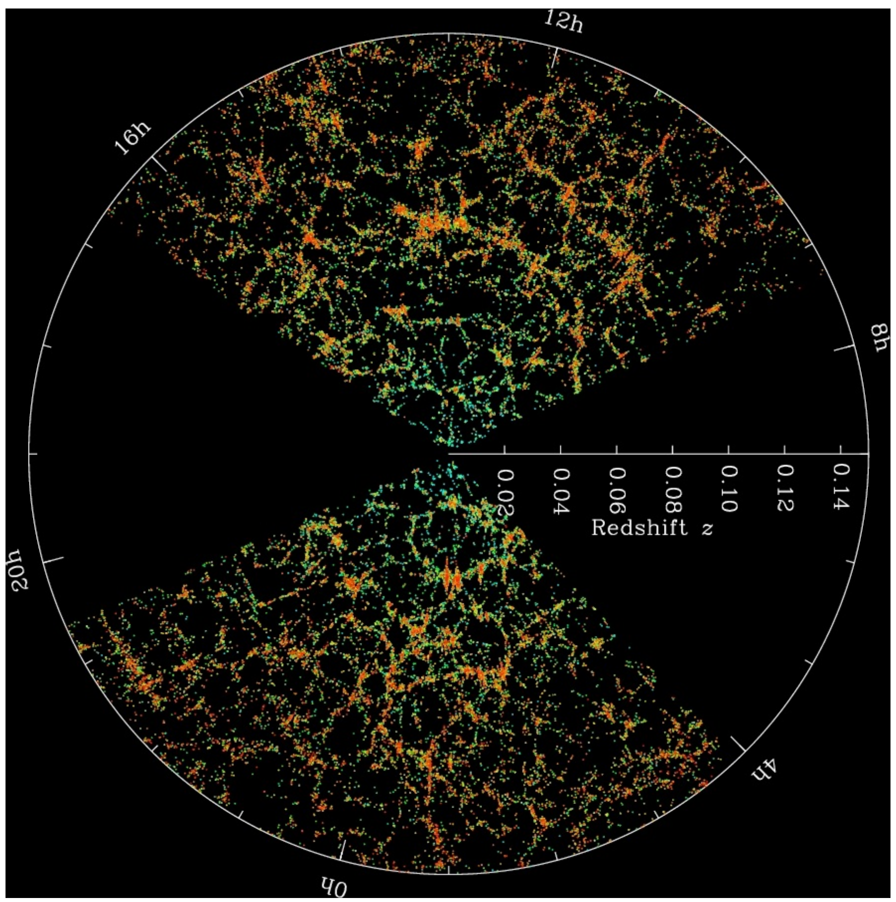
D = 44kpc

R_h = 70pc

M_V = -3.7

http://www.ast.cam.ac.uk/~vasily/

SLOAN - Systematic characterisation of galaxies



huge survey

With the large samples from SDSS and 2dF Galaxy Survey a more quantitative approach to galaxy classification had to be developed, driven by the need to analyse huge samples automatically. What is lost in the detail is more than made up by the HUGE statistics of galaxies of different properties.

The early Sloan releases created samples of ~200 000 galaxies. There are more than 1 million galaxies in the sample, and the results from photometry have changed substantially the picture with the smaller sample.

The latest releases focus more on spectroscopy

Did the SDSS find anything new?

The low-z universe has been well studied up through the years - was there anything new to be found?

Tully-Fisher
Faber-Jackson
Luminosity functions
Mg_2-σ
Colour-Magnitude
etc.

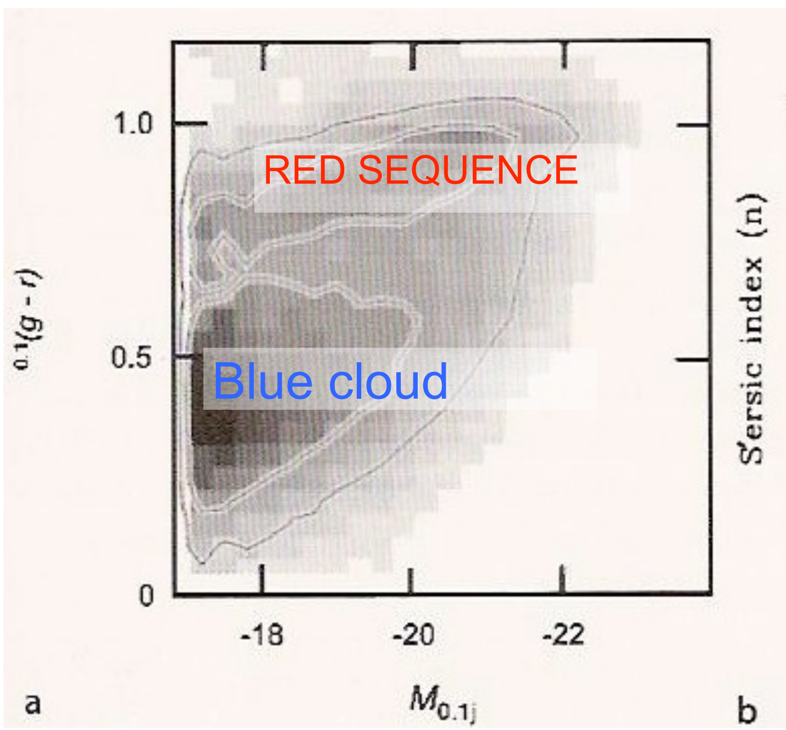
Main progress areas:

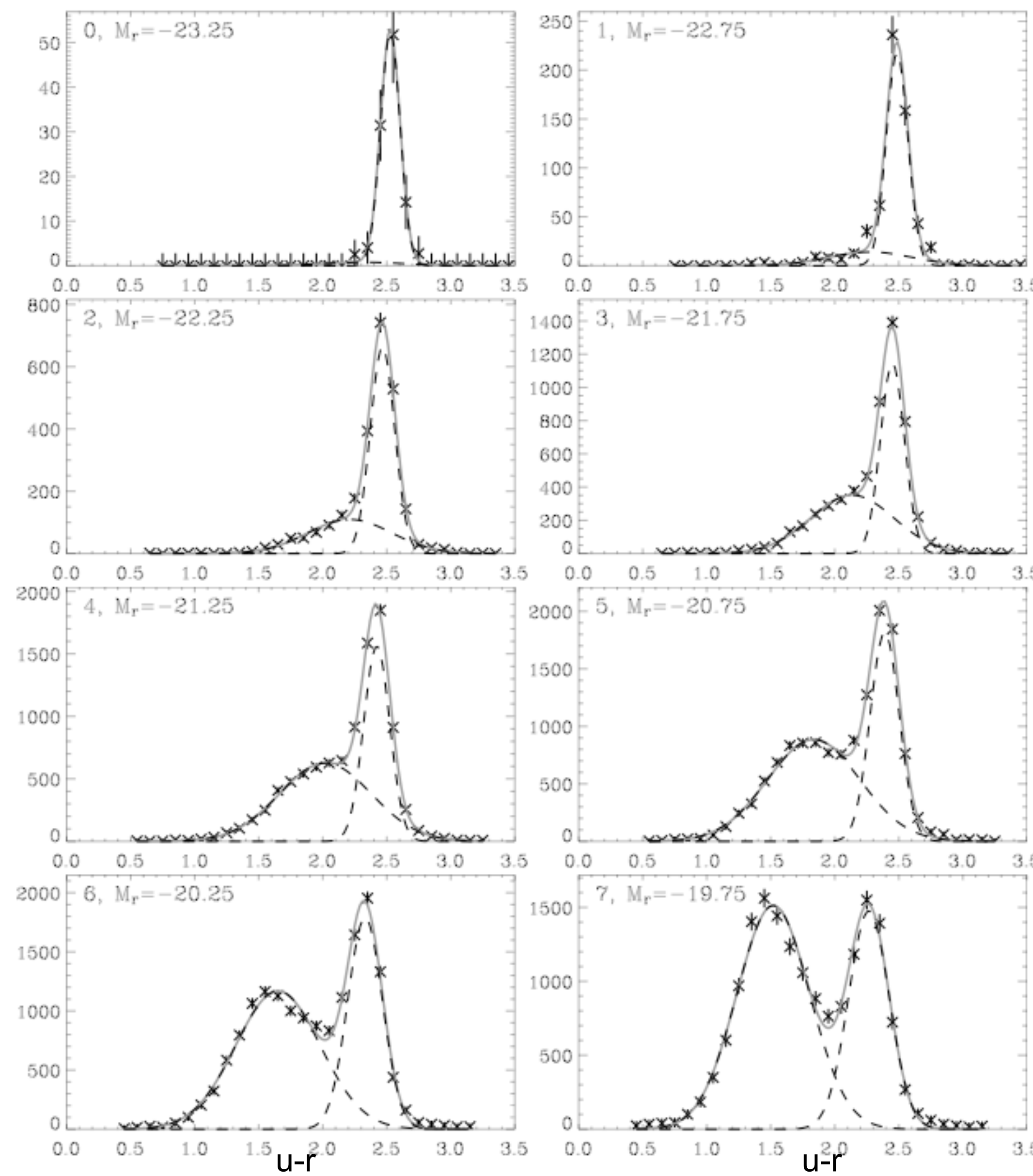
Yes!

✔ Well-understood selection function allows the construction of **distribution functions**.
✔ The vastness of the sample provides large samples of **extreme objects**.
✔ Well-known trends can be studied with very **high precision**.

Bi-model Colour Distribution

red most luminous



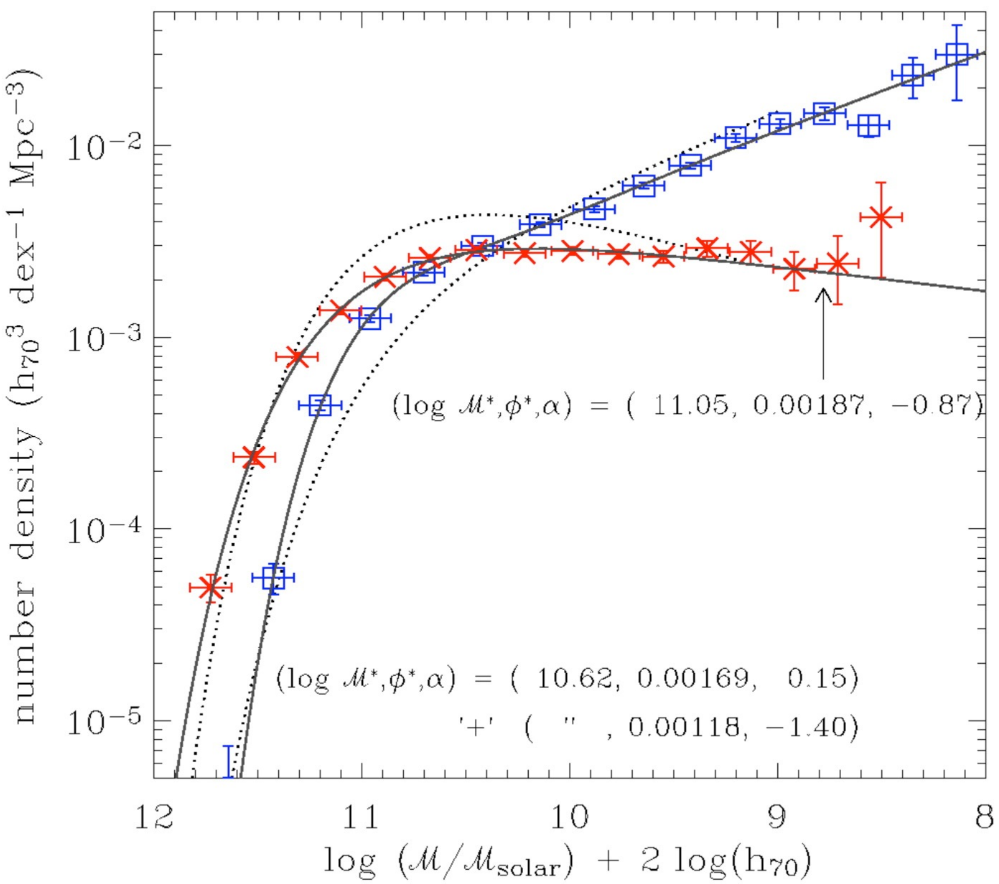


Baldry et al. 2004 ApJ, 600, 681

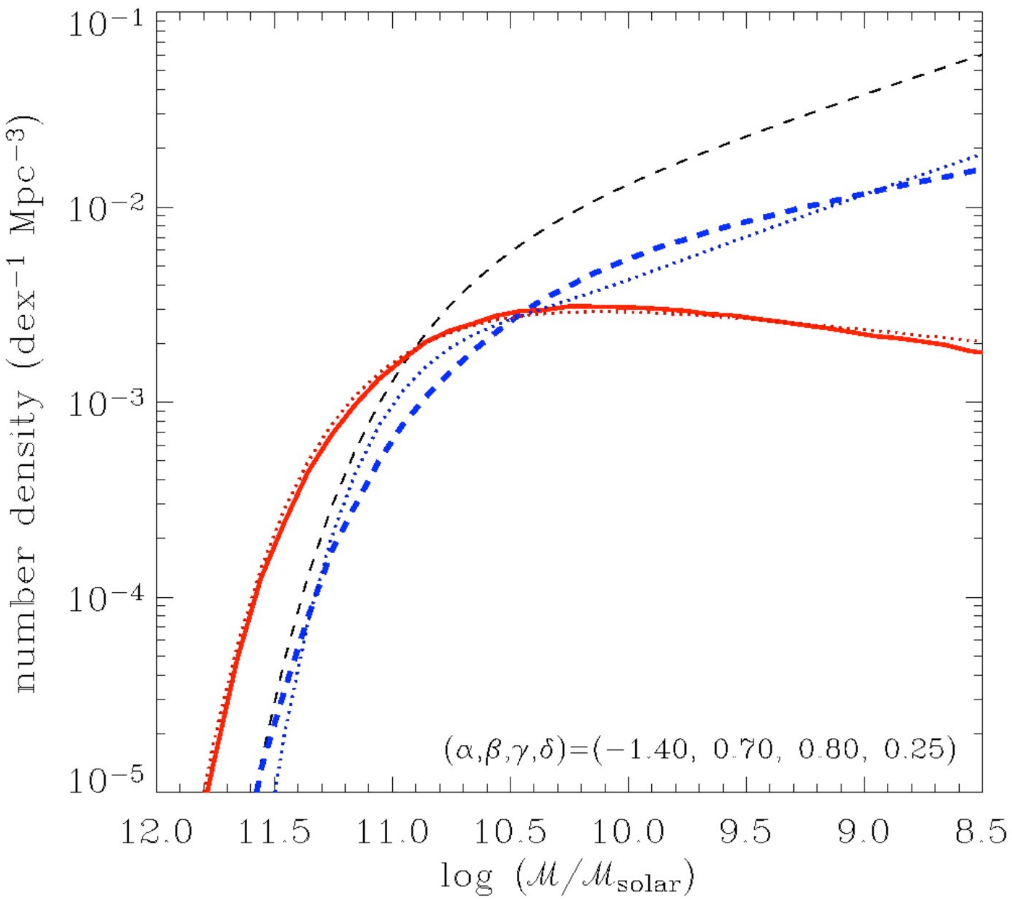
blue dominate faint magnitudes

Mass functions

data



models (merging)



Baldry et al. 2004 ApJ, 600, 681

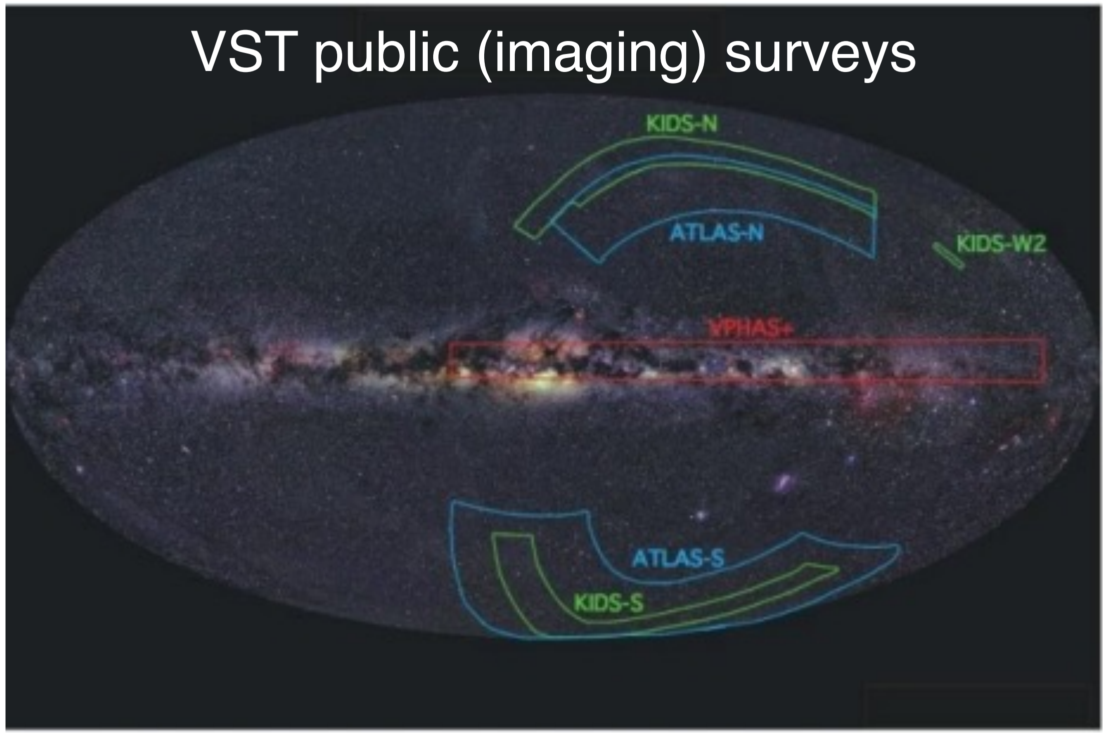
New Perspectives

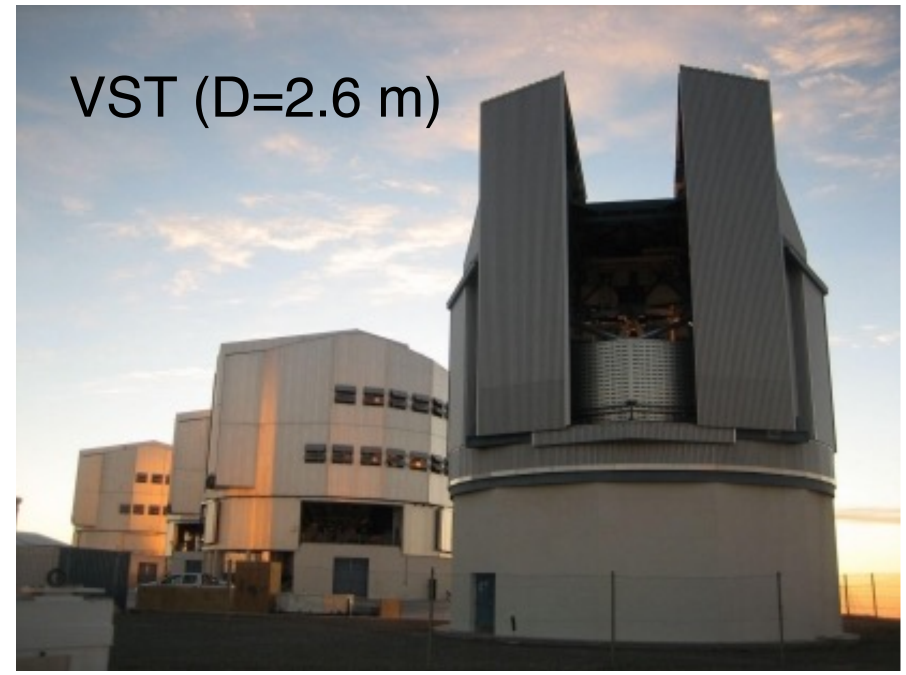
The advent of huge surveys like sloan, and 2DF have provided the opportunity to automatically quantify the properties of galaxies which in the past relied more upon the eye of the experienced observer

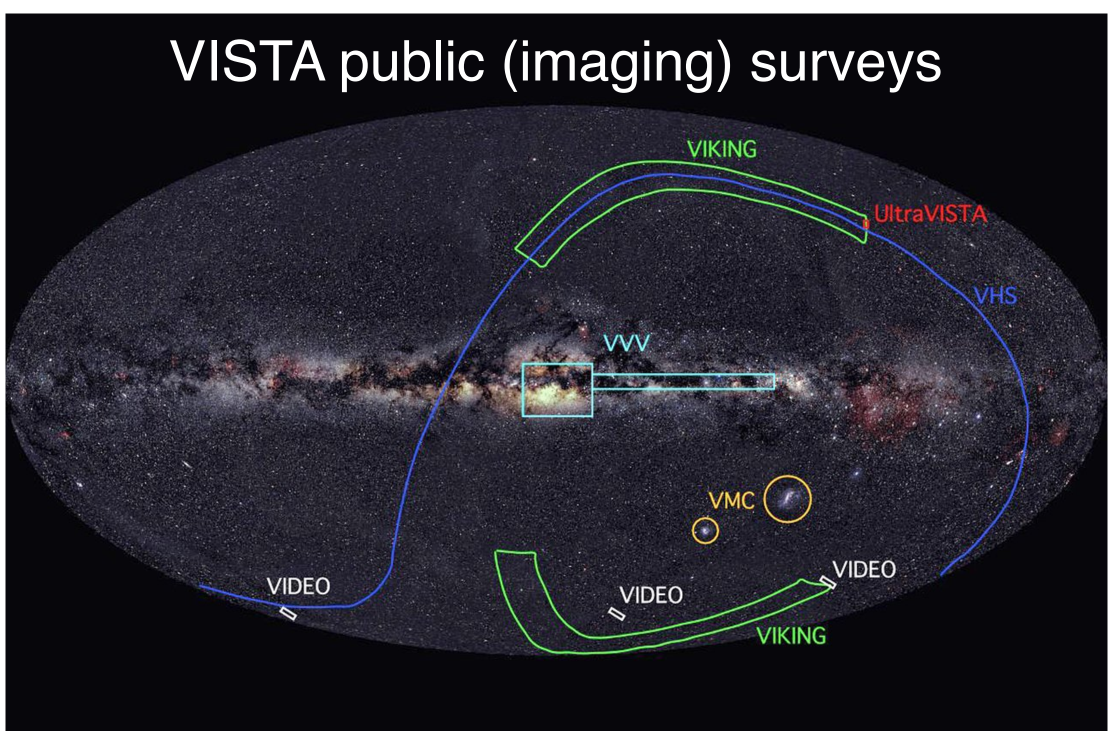
In many ways the blue and red sequences parallels the division into late and early type galaxies.

Statistics allow more detailed statements:
Red sequence contains 20% of galaxies by number, but they contribute 40% of the stellar luminosity density and 60% of the average stellar mass density at the present epoch.

More recent wide-area galaxy surveys

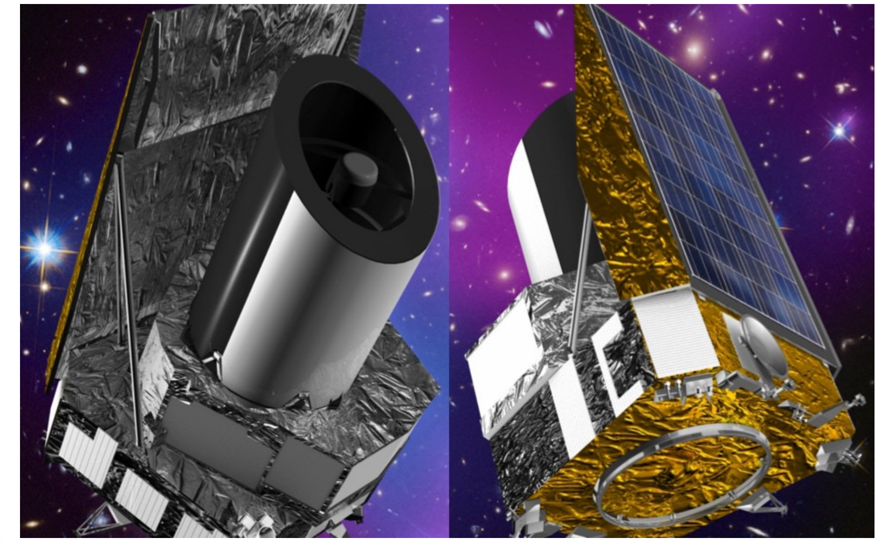


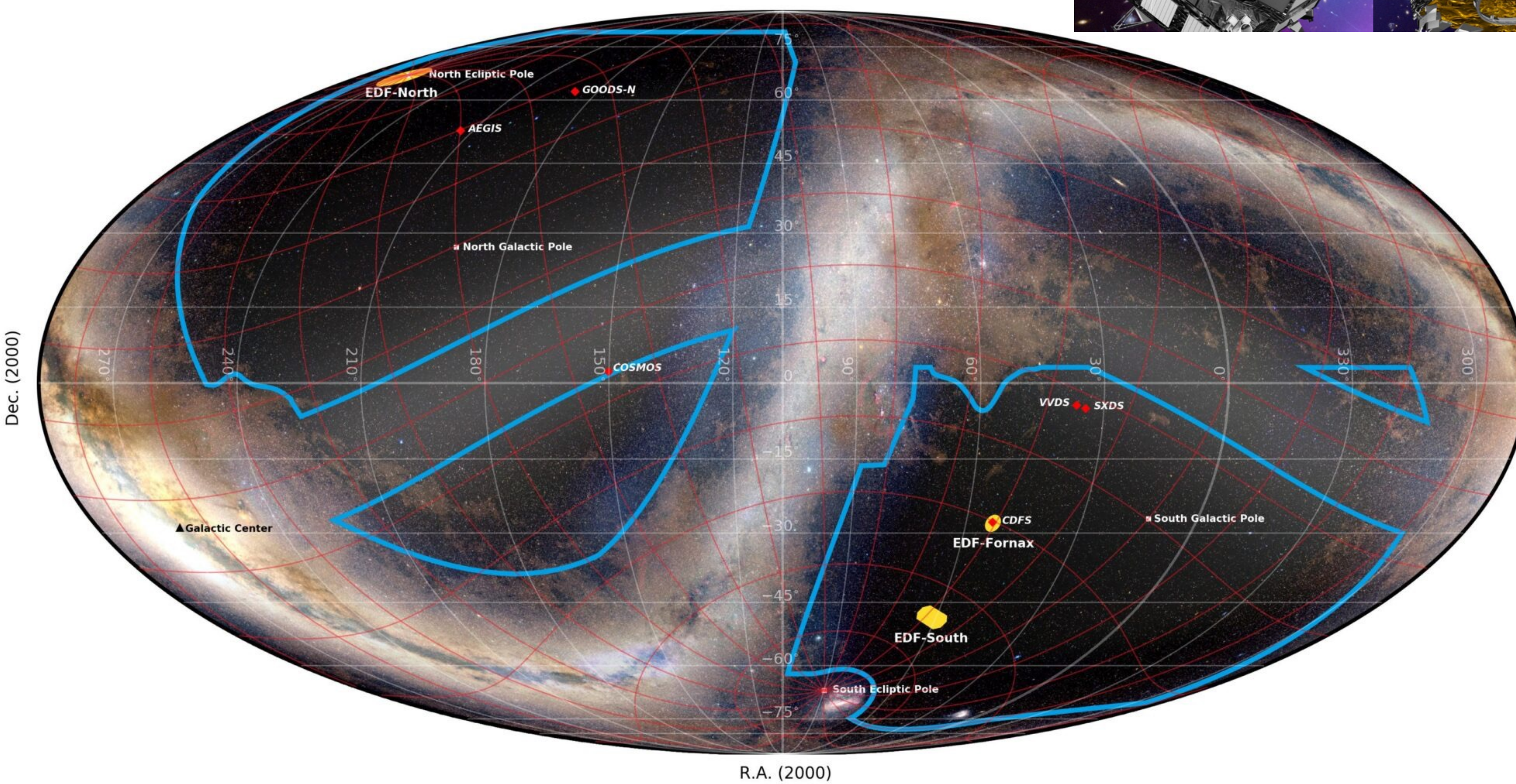




Now carries
4MOST
(spectrograph)

Euclid





The 15,000 deg.^{2} Euclid Wide Survey, the 53 deg.^{2} Euclid Deep Survey, and the 6 deep auxiliary fields (6.5 deg.^{2}) [Mollweide Celestial]

Euclid Wide Survey region of interest : 16 Kdeg.^{2} compliant with a 15 Kdeg.^{2} survey

Euclid Deep Fields : North=20 deg.^{2}, Fornax=10 deg.^{2}, South=23 deg.^{2}

Euclid deep auxiliary fields (GOODSN=0.5, AEGIS=1, COSMOS=2, VVDS=0.5, SXDX=2, CDFS=0.5 deg.^{2})

Background image: Euclid Consortium / Planck Collaboration / A. Mellinger

Science with galaxy surveys over different areas of the sky

Area: ~ a few sq. arcmin to a few sq. deg

individual galaxy properties; galaxy LF; galaxy SMF

Area: >> a few sq. deg

Observational cosmology; study of rare objects (e.g. QSOs)