1. Why do we want to do deep surveys?
2. Different types of surveys, survey design
3. What instruments are needed?
4. Recent and on-going surveys
5. Next generation surveys and facilities
Introduction

- Astrophysics progress is linked to progress in observational techniques
- Theories make predictions which can be verified or falsified by observations
- Observations open a discovery space which may challenge theories
- Observational Cosmology is the most challenging as extreme measurement precision at extreme depth over most of the Universe is ultimately needed!
Why do we want to do deep galaxy surveys?

- To measure galaxy evolution
- To measure cosmological parameters
- To answer fundamental questions:
  - When did first galaxies appear?
  - How did they assemble?
  - What is responsible for the accelerated expansion of the Universe?
  - Some form of energy / particle or modified Gravity?
The key role of surveys in Cosmology

- “Continents mapping”: Map the distribution of galaxies in space
- “Population surveys”: understand the properties of galaxies, in relation with their environment
- “Discovery surveys”: pushing the observational frontier
- Provide reference samples

Establish a robust scenario for galaxy formation and evolution

Constrain the Cosmological model
Different galaxy survey types

- Imaging – photometric surveys
- Spectroscopic surveys
Images are nice but how far are they? Imaging + spectroscopy!
Photometric surveys

- Positions
- Luminosity (magnitudes)
- Colors
- Shapes
- Spectral energy distribution
  - Photometric redshifts
  - Mass, age...

MegaCam: 256 millions pixels

CFHT in Hawaii
Comptages de galaxies: \( N(m) \)
Spectral energy distribution & derivatives

Photometry: over a broad wavelength range:
- Tracer of stellar populations
- Measurement of *mass (red SED)
- Measurement of star formation (blue SED)
- Extinction
- Age (of last burst of SF)

Photometric measurements

SED fit with stellar population template
Spectroscopic surveys

- Access to the 3\textsuperscript{rd} dimension by measuring velocity - redshift
  - Accuracy 10-300 km/s
- Counting galaxies \( N(z,m) \)
- Stars and gas content
- Dynamics from internal velocity field
Velocity accuracy: mapping capability

Spectro-z

Photo-z

ESA-EUCLID spectroscopic survey
Spectra

$z = 0, \, I_{AB} = 0$

Rest-frame

$\lambda$ (Angstroms)
The Redshift

\[ 1 + z = \frac{\lambda_{\text{obs}}}{\lambda_{\text{em}}} \]

- The shift in observed vs. emitted wavelength is a consequence of motion
  - Blueshift when moving towards the observer
  - Redshift when moving away from the observer

- In an expanding Universe objects are moving away from each other: Redshift
  - Redshift is distance: \( v = Hd \)

- Looking to a galaxy in rotation: velocity field with blue/red shift
Measuring photometric redshifts

- Photo-z is a redshift derived from photometric data
- Use the SED
- Correlate against a set of templates
- Same process as for *-mass, SFR, age, etc.
- Accuracy $\delta z \sim 3\text{-}5\%$
  - Probability distribution function
- Pb of catastrophic redshifts
Measuring spectroscopic redshifts

- Based on cross-correlation with templates
- Identify emission / absorption features
- Take continuum into account

EZ engine: Garilli et al., 2010, PASP, 122, 827
How are galaxy surveys designed?

- Wide vs. Deep
- Wavelength
- Spatial and spectral resolution
- Total survey time

- Wedding cake approach
Planning a survey: examples

- VLT 8m + VIMOS
- 500 objects per observation
- How much time to survey 10,000 objects?

<table>
<thead>
<tr>
<th>Survey type</th>
<th>Limiting magnitude</th>
<th>Useful exposure time</th>
<th>Total exposure time</th>
<th>Total time with overheads</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide</td>
<td>22.5</td>
<td>0.75h</td>
<td>15h</td>
<td>19h</td>
</tr>
<tr>
<td>Deep</td>
<td>24</td>
<td>4h</td>
<td>80h</td>
<td>100h</td>
</tr>
<tr>
<td>Ultra-Deep</td>
<td>25</td>
<td>15h</td>
<td>300h</td>
<td>330h</td>
</tr>
</tbody>
</table>
Measuring galaxy evolution with galaxy surveys

- Distribution in LSS
- Luminosity / SFR / Mass evolution
- High redshift populations
  - Pre-selected: LBG, BzK, LAE, SMGs, EROs, DRGs
  - The most distant LBGs, LAE
  - Faint QSOs

- N(z)
- Galaxy density field
- Correlation function
- Luminosity Function
- Luminosity Density
- Mass function
- SFH
- $\rho_{\text{STARS}}$

Track evolution versus Environment, Luminosity, galaxy type, …
Some Principles

- Surveys need to be unbiased
  - Volume, luminosity/mass, type, environment...
  - Proper photometric catalogs
- Statistically robust
- Complete census

- Selection function control
  - Apriori hypotheses
  - Large deep imaging surveys
- Large samples
- Multi-wavelength

2 types of surveys: photometric and spectroscopic
What instruments are needed?

- Wide field imaging cameras
  - Visible
  - Infrared
  - Space: UV, mid/far-IR
  - All wavelengths!!
- Wide field multi-object spectrographs
  - Multi-slit
  - Multi-fiber
Historical perspective

- Early times: galaxies one by one (Hubble...)
- The invention of multi-object spectroscopy
  - First efficient MOS in the ’90s
- ’90s: the golden age
  - 2dFGRS, SDSS in the local U.
  - CFRS, LDSS: z~1
  - LBG: z~3
- Today: the precision age
Spectra, one by one

E. Hubble
Multi-object spectroscopy

- Deep multi-color imaging
- Target selection
- Multi-object spectroscopy

Today MOS have $N_{\text{obj}} \gg 100$

Multiplies the efficiency of your telescope by $N_{\text{obj}}$!
Instrument design and development

- Instrument making is fundamental to astrophysics
- Relies on new & improved technology
  - Optics, detectors, mechanics, control (active)
  - Space technology
  - Software: data processing, databases
- Professional project development
  - Skilled instrument scientists and specialty engineers
  - Project management
- Expensive telescopes (~1B€) and instruments (~15M€ ground-based / ~150M€ space-based)
Instrument development cycle

- Define science goals: science requirements
  - Survey volume, number of objects, redshift
- Derive technical requirements
  - Field of view, wavelength, resolution, throughput
  - Global performances
- Produce strawman opto-mechanical design
- Identify new technology developments: grating, detectors,
  - Produce prototypes
- Manufacture all parts
- Assembly, integration and tests
  - Measure performances, calibrate
- First light

SPACE: 50-100% longer!
Multi-Object Spectrograph have become the work-horse of many observatories

- Dans tous les observatoires majeurs: CFHT-MOS/SIS, Keck-LRIS, VLT-FORS, GMOS, Keck-DEIMOS, VLT-VIMOS, IMACS ...
Past and present deep spectroscopic surveys

<table>
<thead>
<tr>
<th>Survey</th>
<th>Instrument</th>
<th>redshift</th>
<th># galaxies</th>
</tr>
</thead>
<tbody>
<tr>
<td>2dFGRS</td>
<td>2dF/AAT</td>
<td>0&lt;z&lt;0.5</td>
<td>220000</td>
</tr>
<tr>
<td>SDSS</td>
<td>SDSS/Apache Point</td>
<td>0&lt;z&lt;0.5</td>
<td>930000</td>
</tr>
<tr>
<td>CFRS - 1995</td>
<td>CFHT-MOS</td>
<td>0&lt;z&lt;1.2</td>
<td>600</td>
</tr>
<tr>
<td>LBG - 1999</td>
<td>KECK-LRIS</td>
<td>2.5&lt;z&lt;4.5</td>
<td>1000</td>
</tr>
<tr>
<td>DEEP2, 2005+</td>
<td>KECK-DEIMOS</td>
<td>0.7&lt;z&lt;1.4</td>
<td>50000</td>
</tr>
<tr>
<td>VVDS, 2005+</td>
<td>VLT-VI MOS</td>
<td>0&lt;z&lt;5</td>
<td>50000</td>
</tr>
<tr>
<td>zCOSMOS, 2007+</td>
<td>VLT-VI MOS</td>
<td>0&lt;z&lt;1.2</td>
<td>20000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.4&lt;z&lt;3</td>
<td>10000</td>
</tr>
<tr>
<td>VIPERS, 2009+</td>
<td>VLT-VI MOS</td>
<td>0.5&lt;z&lt;1.2</td>
<td>100000</td>
</tr>
<tr>
<td>VUDS, 2010+</td>
<td>VLT-VI MOS</td>
<td>2.5&lt;z&lt;6.7</td>
<td>10000</td>
</tr>
<tr>
<td>GOODS</td>
<td>VLT FORS2</td>
<td>0&lt;z&lt;7.1</td>
<td>1000</td>
</tr>
</tbody>
</table>

And more!
From Baldry et al., 2010
VVDS: the final sample

Magnitude selected samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Selection</th>
<th>redshift</th>
<th>galaxies</th>
<th>galaxies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Spectro-z</td>
<td>z&gt;1.4</td>
</tr>
<tr>
<td>Wide</td>
<td>$I_{AB} \leq 22.5$</td>
<td>0&lt;z&lt;1.5</td>
<td>35000</td>
<td>-</td>
</tr>
<tr>
<td>Deep</td>
<td>$I_{AB} \leq 24$</td>
<td>0&lt;z&lt;5</td>
<td>15000</td>
<td>970</td>
</tr>
<tr>
<td>UltraDeep</td>
<td>$I_{AB} \leq 24.75$</td>
<td>0&lt;z&lt;5</td>
<td>863</td>
<td>220</td>
</tr>
<tr>
<td>Ly$\alpha$</td>
<td>Flux</td>
<td>2&lt;z&lt;6.5</td>
<td>204</td>
<td>204</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td>~51000</td>
<td>~1400</td>
</tr>
</tbody>
</table>

- >51000 galaxies with redshifts
- A total of ~1400 galaxies with 1.4<z<6.5 and spectroscopic redshifts
**zCOSMOS**

On HST-COSMOS 2 deg$^2$ field

- **With VLT-VIMOS**
  - **Wide**: 2 deg$^2$, 20000 spectra, $I_{AB} \leq 22.5$, $0 < z < 1.2$ (Public)
  - **Deep**: 1 deg$^2$, 5000 spectra, BzK+UGR selected $1.5 < z < 3$

1.5$ < z < 3$

Combined spectra with Lya in emission vs; in absorption
Serendipitous power of MOS

- **main target**
- **Slits**
- **Serendipitous Lya @ 1216Å**
- **Target spectrum**
- **Photometrically invisible Lya emitter**
Follow-up surveys

- Select clean samples from deep spectroscopic surveys
- Example of 3D integral field spectroscopy surveys
  - MASSIV: a complete sample, 80 galaxies from VVDS at $1<z<1.8$ with IFU-3D (At the peak of star formation), kinematics/dynamical studies
  - SINS: ~100 galaxies $z\sim2$
Next generation surveys and facilities

- Need to go fainter/deeper
  - Faint end of the luminosity function
  - Early objects – reionisation
- Need to observe in the near infrared
  - SED redshifted out of the visible/CCD domain for $z>7$
- Need to observe large volumes
  - Get rid of cosmic variance effects
  - Access to very large scales for cosmology
- Continue to build-up the wedding cake!
Future surveys and facilities

- Very wide field, all-sky to $z\sim 2$
  - Cosmology and galaxy evolution
  - VIMOS-VIPERS, on-going: $10^5$ redshifts, $z\sim 1$
  - Big-Boss, SUMIRE-PFS...: $3 \times 10^7$ redshifts, $z\sim 1-1.5$
  - ESA-EUCLID: $5 \times 10^7$ redshifts, $z\sim 2$

- Large surveys, $z\sim 2-5$
  - UltraVista: on-going
  - VUDS at VLT: $10^4$ redshifts, on-going

- Reionisation, SFH, $z>5$
  - JWST: NIRSPEC, MIRI
  - EELT: DIORAMAS, EAGLE
VUDS: VIMOS Ultra-Deep Survey

- Large program on VLT (640h)
- Magnitude selected $23 \leq i_{AB} \leq 25$
- VIMOS: 14h blue + 14h red integrations
- On-going: 10,000 galaxies

$N$ galaxies with measured spectroscopic redshift

$1/16$th of survey
VIPERS: 100000z at $z \sim 1$

- VLT-VIMOS
- Measure growth rate

VIPERS

- What is real?
- What is simulated?

- 40000 redshifts so far
Breaking the z-frontier: need for efficient NIR multi-object spectrographs

- **NOW**
  - MOSFIRE on Keck: 2011
    - YJHK, 6x6 arcmin$^2$
    - 45 slits
  - KMOS on VLT, 2012?
    - YJHK, 7 arcmin diameter
    - 24 IFUs, 2.8x2.8 arcsec$^2$
  - LUCIFER on LBT
  - EMIR on GTC

- **NEXT**
  - PFS: 2016
  - NIRSPEC-JWST: 2018
  - EUCLID: 2019
Some new facilities for surveys

- SUMIRE – PFS
- JWST
- EELT
- EUCLID
SuMIRe

- Major study of dark energy
- Subaru Measurement of Images and Redshifts
  1. imaging with 0.9B-pixels 3t CCD camera from 2011
  2. spectroscopy with \( \approx 2000 \) objects >2015
- best measurements of dark energy params in this decade
- 3D map of dark matter to observe structure formation
- same telescope for both imaging and spectroscopy like SDSS but 8.2m!
technical specs

- BAO
  - correlate distance from BAO to redshift $\rightarrow$ dark energy
  - targets selected with HSC
  - go beyond BOSS: $z \approx 0.6 - 1.6$
  - most efficient (least exposure): OII emission 372.7, 373.0 nm
  - need 600-1000nm, $R \approx 3000$
  - measure w down to 3%
- Space telescope
- Diameter: 6.5m
- 0.6-25 microns
- Observe first light
- Launch 2018

JWST
JWST instruments

- **NIRCAM**: 0.6-5 microns
  - 2.2′x4.4′
- **NIRSPEC**: 1-5 microns
  - 3′x3′
  - Multi-slit
- **MIRI**: 5 to 27 microns
  - Imaging and spectroscopy
  - 1.3′x1.7′
EELT: Europea, « Extremely Large Telescope »

Construction to be decided in 2012
DIORAMAS (OPTIMOS)
A wide field imaging & multi-slit spectrograph for the EELT

- One single instrument for the deepest images and the deepest spectra possible with an ELT
- Multi-slit for the most accurate sky subtraction for faint objects
- Capability to work with GLAO-corrected images
- Optional capability: Integral field unit

DIORAMAS @ EELT = FORS+VIMOS+HAWKI+KMOS @ VLT

A powerful imaging-MOS which can do surveys!
DIORAMAS
Innovative and robust concept

- Wide field up to 44 arcmin², use seeing limited or GLAO-corrected images, 0.05 arcsec/pix
  - 2 Visible and 2 NIR quadrants, with 0.6-1μm overlap
- Imaging and MOS (slits) from 0.37 to 1.6 μm
  - IFU possible
- Superb optical design and compact mechanical layout
- Opto-mechanical systems using industry standards, no R&D required
- Low risk
Wide field, multi-mode

>30,000 sources in 7’x7’ to r_{AB}=29.8

JWST-NIRCAM

JWST-NIRSPEC

Multi-slit R~300, 480 slits
Multi-slit R~3000, 1600 slits
DIORAMAS
High level of performances

- Excellent image quality and high throughput (~70%)
- Extremely deep imaging from $u'$ to H
- High multiplex: 160 slits in HR, 480 slit in LR, 0.37 to 1.6µm
- Limiting magnitude (4h): AB~29 in imaging, AB~26.5 in MOS
- GLAO: from 0.7 to 0.4 arcsec over FOV

Gain @1µm compared to JWST-NIRSPEC: x5 multiplex, x2.5-5 the FOV, at equivalent depth/unit time
DIORAMAS: ‘first light’ science

Combine first light study of ~100 galaxies $z>7$ with galaxy assembly $1<z<6$ on 10000 galaxies

- 88 arcmin², 2 DIORAMAS pointings
- ugrizYJH GLAO imaging, AB~30, 20h per pointing: 40h
- NB imaging $z\sim8.8$: 2x5h
- R~300 GLAO MOS, AB~27.5, 10x2h masks per pointing: 40h
- IFU (optional), 4 gal per pointing, 25 pointings, 100h
The ESA-Euclid space mission

- The major space cosmology mission for the next decade
- Selected by ESA in Oct. 2011
- Launch 2019
- Goals: understand the nature of dark matter and dark energy
Euclid
Mapping the Geometry of the Dark Universe

http://www.euclid-ec.org
Science drivers of the Euclid Mission

Understand the origin of the Universe’s accelerating expansion

→ probe the properties and nature of dark energy, dark matter, gravity and distinguish their effects decisively

→ by tracking their observational signatures on the
  • geometry of the universe: Weak Lensing + Galaxy Clustering
  • cosmic history of structure formation: WL, z-space distortion, clusters of galaxies

→ controlling systematic residuals to an unprecedented level of accuracy, that cannot be reached by any other competing missions/telescopes
The Euclid high-precision machine

Space VIS and NIR observer of stars and galaxies

VIS Imaging
NIR Photometry

Tomographic Shear machine

NIR Spectroscopy
NIR Imaging

Galaxy Redshift machine

Dark Matter and Galaxy PowerSpectra-meters

Cosmological explorer of gravity and fundamental physics

Legacy science

Euclid
Meeting Euclid France Paris
Dec. 02, 2011
Euclid mission element

- Launch Soyuz, end 2019 L2 Orbit
- 6 years mission
- Telescope: 1.2 m
- Instruments:
  - **VIS**: Visible imaging channel:
    - 0.54 deg², 0.10” pixels, 0.16” PSF FWHM,
    - 1 broad band R+I+Z (0.55-0.92μm),
    - 36 CCD detectors, galaxy shapes
  - **NISP**: NIR photometry channel:
    - 0.54 deg², 0.3” pixels,
    - 3 bands Y,J,H (1.0-1.7μm),
    - 16 HgCdTe detectors, photo-z’s
  - **NISP**: NIR Spectroscopic channel:
    - 0.54 deg²,
    - R(mean)=250,
    - 0.9-1.7μm, slitless, spectro redshifts
I. Wide Survey: 15,000 deg$^2$: Extragalactic sky - 5.2 years

- **Visible:**
  - Diffraction limited images (0.16 ” FWHM PSF)
  - Galaxy shapes for $1.5 \times 10^9$ galaxies to $RIZ_{AB} \leq 24.5$ (AB, 10σ Extended source)
  - 30-40 gal/amin$^2$, $<z> \sim 0.9$

- **NIR photometry:**
  - $Y, J, H \leq 24$ (AB, 5σ Point source), 0.33”/pixel
  - photo-z’s errors $<0.05(1+z)$ with ground based PS, DES, LSST, HSC, etc...

- **NIR slitless Spectro:**
  - R=250 at 1.2 micron:
  - Redshifts for $50 \times 10^6$ gal with em. line fluxes $>4 \times 10^{-16}$ ergs/cm$^2$/s at $0<z<2$ and
  - spectro-z errors $< 0.001$

II. Deep Survey: 40 deg$^2$ (at ecliptic poles?) 1 visit/month - 6 months

- Science: +2 magnitudes in depth for both visible and NIR imaging data.
- Spectroscopy of $\sim 10,000$ galaxies
- Calibrations: monitoring of PSF (>40 visits over 6 years), calib. of NIR data
Summary

- Deep galaxy surveys have become a central tool for cosmology
- Existing instrumentation produces a lot of great surveys, lot of data, mostly public
- Next generation surveys require complex hence expensive facilities
  - Whole sky survey to z~2 now planned (Euclid)
  - First light survey planned (JWST)
  - ELTs to start soon
- Bright future for galaxy surveys!