Galaxy Formation in the Universe through Near-Infrared Spectroscopy

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Bridging the gap between large and small scales

- Galaxies provide a fundamental link between particle physics and cosmology (large scale structure of the Universe).
- Cosmology missions treat galaxies as test particles (e.g. Euclid), but lack the required capabilities to understand their formation and evolution.
- The process of galaxy formation involving gas hydrodynamics, star formation, feedback, and black hole astrophysics are still largely known at a “first order” level.
- Galaxies are unique laboratories where the complexity of the baryon physics can be probed.
How do we bridge this gap?

- Galaxy formation can only be tackled with large, high quality spectroscopic datasets.
- Spectroscopic surveys provide the data needed to probe in detail mechanisms such as:
  - Galaxy bimodality
  - AGN/SF activity
  - Environment
  - Reionization in the Universe
Galaxy bimodality

Star formation / black hole growth interplay
The Sloan Digital Sky Survey (SDSS) collected high quality spectra from ~1 million galaxies, mainly probing a large volume of the “nearby” (z<0.1-0.2) Universe.

Although the key science driver of SDSS was cosmology, its contribution to galaxy formation has made a huge impact (over 80% of “official” SDSS papers)

50% of top cited papers over the past decade involve galaxy surveys

Essential ingredients that made it successful
- High quality spectroscopy
- Probing large volumes (\(\geq 1 \text{Gpc}^3\))
- \(~1\text{ million galaxies}\)
Probing the bulk of galaxy formation

- However, SDSS only probes galaxy formation in the narrow $z<0.1-0.2$ window
- ... which represents the most recent 10-20% of the age of the Universe, missing the bulk of the complex processes leading to our current Universe
- Two key cosmic epochs need to be probed in a similar amount of detail
  - The peak of galaxy formation and black hole growth ($z\sim1-3$)
  - The formation of the first galaxies and reionization of the Universe ($z>6$)

Hopkins & Beacom(2006)
A logical step in ESAs Cosmic Vision

Theme #4
“How did the Universe originate and what is it made of?”

Galaxy Formation/Evolution:
11000 papers over the past decade.
10/20 most cited papers in astronomy in 2006

Planck (CMB)
Euclid (Dark Energy)
Gaia (MW kinematics)
Herschel (Dust)

Missing!
The bulk of galaxy formation (z~1-12)

Cosmology

Galaxy Formation/Evolution:
11000 papers over the past decade.
10/20 most cited papers in astronomy in 2006
Two main themes, same instrument

The peak of galaxy Formation
\[ z=1-3 \]
- Information-rich optical spectrum
- Lyman-\( \alpha \) region shifts into the Near-infrared
- Stellar Populations
- Chemical Enrichment
- Galaxy Dynamics
- Environment: Halos vs Galaxies

The first galaxies
\[ z=6-12 \]
- Lyman-\( \alpha \) region shifts into the Near-infrared
- Lyman-break galaxies (+ Ly-\( \alpha \) emitters)
- Clustering of the first galaxies
- Re-ionization sources
- Black Hole activity
<table>
<thead>
<tr>
<th>Stellar populations</th>
<th>Line strengths</th>
<th>Galaxy dynamics (gas and stars)</th>
<th>Star formation / black hole growth interplay</th>
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<tr>
<td>Star formation</td>
<td>Spectral fitting</td>
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<td>histories</td>
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</tbody>
</table>

- Stellar populations: Star formation histories
- Line strengths: Spectral fitting
- Galaxy dynamics (gas and stars): Velocity dispersion, Outflows, Rotation curves
- Star formation / black hole growth interplay: Emission line diagnostics

![Image: Stellar populations](image1.png)

![Image: Galaxy dynamics](image2.png)

![Image: Star formation](image3.png)

![Image: Galaxy dynamics](image4.png)

Kewley et al. (2006)
Chronos white paper (Ferreras et al. 2013)

<table>
<thead>
<tr>
<th>Topic</th>
<th>Description</th>
<th>Image</th>
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</thead>
<tbody>
<tr>
<td>Black hole growth</td>
<td>[OIII] luminosities [OII],Hα</td>
<td><img src="image1.png" alt="Image" /></td>
</tr>
<tr>
<td>Star formation</td>
<td></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>Environment and mergers</td>
<td>Redshift determination with $\Delta v \sim 100-200$ km/s</td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>Clustering and reionization</td>
<td>Redshift determination with $\Delta v \sim 100-200$ km/s</td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
</tbody>
</table>

*Courtesy SDSS*

Iliev et al. (2012)

Rodighiero et al. (2011)
What type of survey is needed?

- **Stellar-mass limited survey**: $H_{AB} \lesssim 24-26$
- ~1-2 million, high-quality spectra (continuum)
- Resolution $R \sim 1500$
- Similar comoving volume as SDSS:
  - $V(z<0.2) = 0.5$ Gpc$^3$
  - $z \sim 1-3$: 23 deg$^2$
  - $z \sim 6-12$: 13 deg$^2$
  - DM halo evolution: Factor 2x
- 2-tiered survey
  - Deep ($H_{AB} < 24$): 40-50 deg$^2$
  - Ultra-Deep ($H_{AB} < 26$): 5-10 deg$^2$
Why NIR from space?

This is an example of two similar galaxies, roughly with the same stellar mass (a few $10^{10}$ solar masses) and at the same redshift ($z \sim 2$)

Compare the $\sim 1$ hour exposure from space (HST) with 5 hours from the ground (VLT). Spectra shown at the same resolution ($R \sim 100$ in H-band)

Ground-based plagued by atmospheric effects:

- Airglow
- Absorption
- Time variability
**WHAT?**

- Large spectroscopic survey
- Probe optical region at $z \sim 1-3$ and Lyman-$\alpha$ at $z > 6$
- High quality data (continuum)

**HOW?**

- 2.5m space telescope
- Near-infrared spectrograph (0.9-1.8$\mu$m)
- High multiplex ($\sim 5000$)
- $R=1,500$ spectral resolution
Simulated case for a 2.5m (i.e. HST-like) space telescope, optimized for NIR moderate-resolution spectroscopy (i.e. Chronos)

Typical massive galaxy at $z \sim 2$
Let us consider two cases of very deep integration times. (Low Zodiacal background assumed)

As reference, the HUDF/ACS images have a total integration time of $\sim 1$Ms.

These limits are extremely challenging/unfeasible even for the future generation of ground-based telescopes (e.g. E-ELT).
A simulation for an “E-ELT”-like aperture (D~40m) from the ground. We use the same characteristics as the previous simulations (for Chronos) but including sky absorption and airglow.

Rather optimistic as we assume perfect sky subtraction.
<table>
<thead>
<tr>
<th></th>
<th>Chronos</th>
<th>JWST NIRSpec</th>
<th>E-ELT Optimos-EVE</th>
<th>VLT MOONS</th>
<th>VLT KMOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area (m²)</td>
<td>4.5</td>
<td>25</td>
<td>978</td>
<td>52</td>
<td>52</td>
</tr>
<tr>
<td>FOV (deg²)</td>
<td>0.2</td>
<td>2.50x10⁻³</td>
<td>0.0107 (7'Ø)</td>
<td>0.15</td>
<td>0.0113 (7.2'Ø)</td>
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<tr>
<td>Multiplex</td>
<td>5000</td>
<td>100</td>
<td>30</td>
<td>500</td>
<td>24</td>
</tr>
<tr>
<td>Etendue</td>
<td>0.9</td>
<td>0.06</td>
<td>10.46</td>
<td>7.8</td>
<td>0.59</td>
</tr>
<tr>
<td>$t_{SN=20}(H=24)$ ks</td>
<td>150</td>
<td>60</td>
<td>25</td>
<td>5200</td>
<td>5200</td>
</tr>
<tr>
<td>Integration time, 1 million spectra (yr)</td>
<td>1</td>
<td>19</td>
<td>26</td>
<td>330</td>
<td>6866</td>
</tr>
</tbody>
</table>

*Chronos* is unrivalled as a NIR spectroscopic survey telescope.

Future facilities such as JWST and E-ELT will be complementary, rather than competing.

Actual survey time ~ 5 x Integration time (... of exclusive use!)

Survey Time (years)
Telescope

- Heritage from Euclid, Herschel and Gaia
- 2.5m diameter telescope, 1deg FoV
- Korsch/Ritchey-Chrétien design
- Zerodur or SiC mirror optics
- Image quality FWHM<0.3” (i.e. not diffraction limited)
- Size and weight compatible with Ariane V launch
Spectrograph

- Single instrument (cost effective)
- 8 identical multi-object spectrographs
- Fixed format spectrograph giving $R \sim 1500$ over 0.9-1.8$\mu$m
- NIR detector technology
  - Space-qualified technology will be available (e.g. Teledyne H4RG)
- Eight 4kx4k arrays
- Other options will be considered (e.g. Selex, Teledyne-H2RG)
Target Selection: DMDs

- Baseline for target selection is Texas Instruments (TI) digital micro-mirror (DMD) device, 2048x1024 (13.8μm pixel)

- Bi-stable angle provides on/off 'shutter' at position of each source

- Preliminary space qualification during Euclid Phase A (Zamkotsian+ SPIE 7932)

- Long heritage in digital projectors near you!

- Needs development programme for drive electronics and AR coatings
Target Selection: Alternatives

- Space-qualified MEMS devices also under development in Europe
- Institute of Microtechnology at Neuchâtel, Switzerland have demonstrated smaller format (32x64) electrostatically actuated Si micromirror array with good fill factor and operation to <100K
- Alternative technologies such as liquid crystal spatial light modulators and beam steering optics will also be studied during the pre-Phase A design


Manufactured 2048-element micromirror array
**Target Selection: Catalogue**

- *Chronos* is a fully spectroscopic mission. Requires *imaging* for the pre-selection of targets.
- Targets will be provided by the Euclid wide and deep surveys:
  - Wide (15-20,000deg$^2$) $H_{AB} \sim 24$
  - Deep (40deg$^2$) $H_{AB} \sim 26$
- Future extension of ESO/VISTA-based NIR surveys
- Subaru/HyperSuprimeCam, LSST
- WFIRST (?) would also aid in faint target selection
- Cost-effective on board imaging: “DMD-off” channel
**Chronos in a nutshell**

- *Chronos* is the only feasible facility to link cosmology and local studies of the Universe. Very large community of extragalactic astrophysicists.

- *Chronos* will provide the highest quality NIR spectroscopic data from ~1-2 million galaxies over the z~1-12 range. Main science drivers:
  - Understand the peak of galaxy formation and black hole growth
  - Characterize the epoch and sources of reionization
  - Immense legacy value (cosmology, transients, brown dwarves)

- Within the coming *decades* it will not be possible to obtain the required quality from ground-based observatories

- Synergies with Herschel, Euclid, LSST, ALMA, SKA
  - *Chronos* will not compete with, but complement and empower large facilities such as JWST, E-ELT
