Galaxy Formation in the Universe through Near-Infrared Spectroscopy

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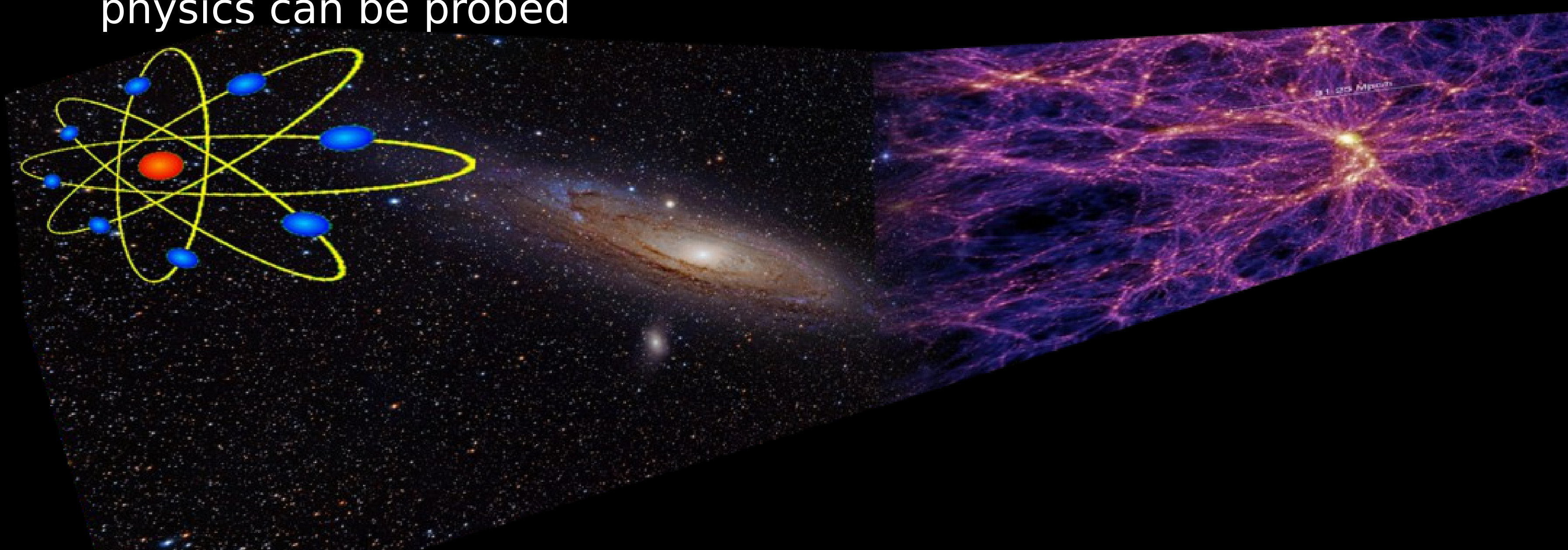
Bridging the gap between large and small scales

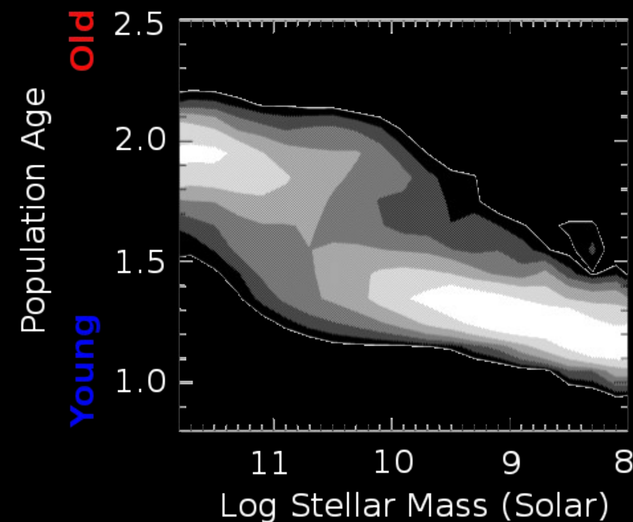
- Galaxies provide a fundamental link between particle physics and cosmology (large scale structure of the Universe)
- Cosmology missions treat galaxies as test particles (e.g. Euclid), but lack the required capabilities to understand their formation and evolution
- The process of galaxy formation involving 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



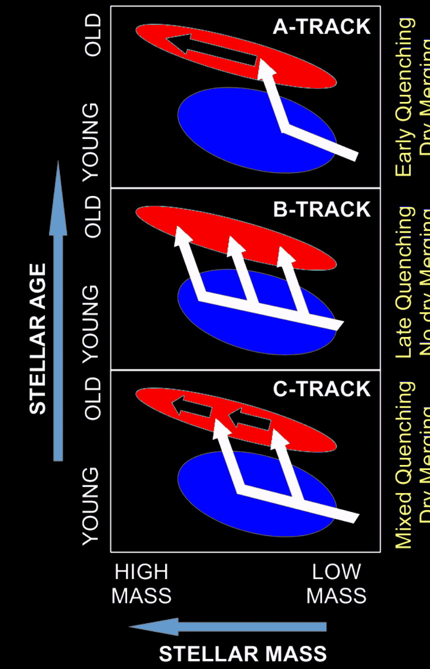
How do we bridge this gap?

- 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

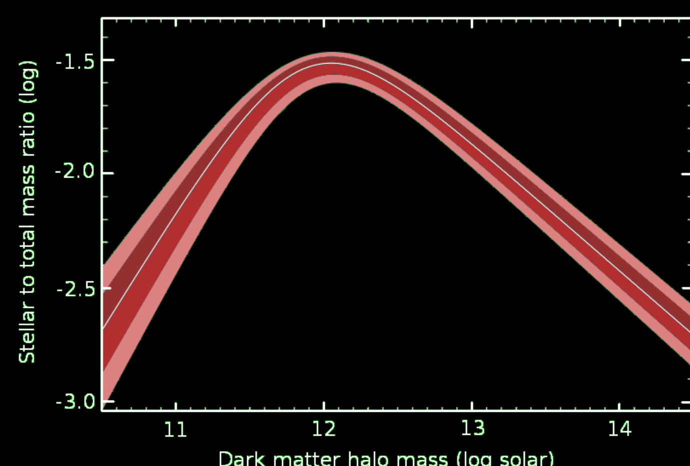


Kauffmann et al. (2003)

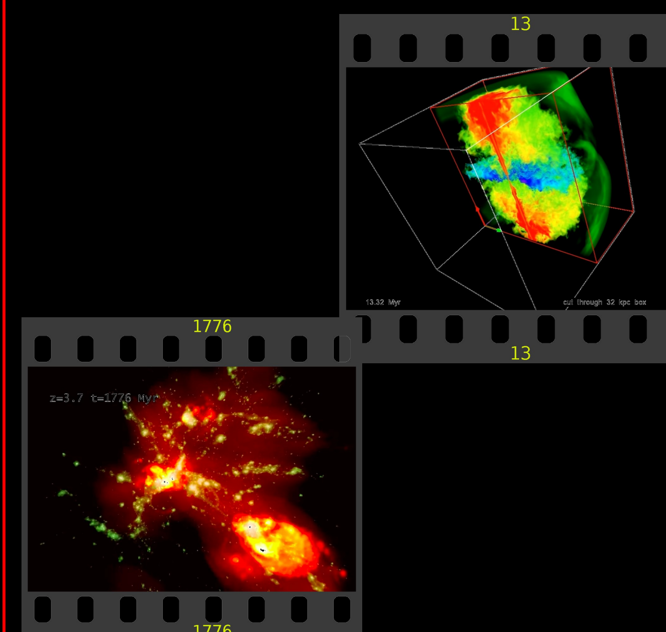


Faber et al. (2007)

Star formation / black hole growth interplay

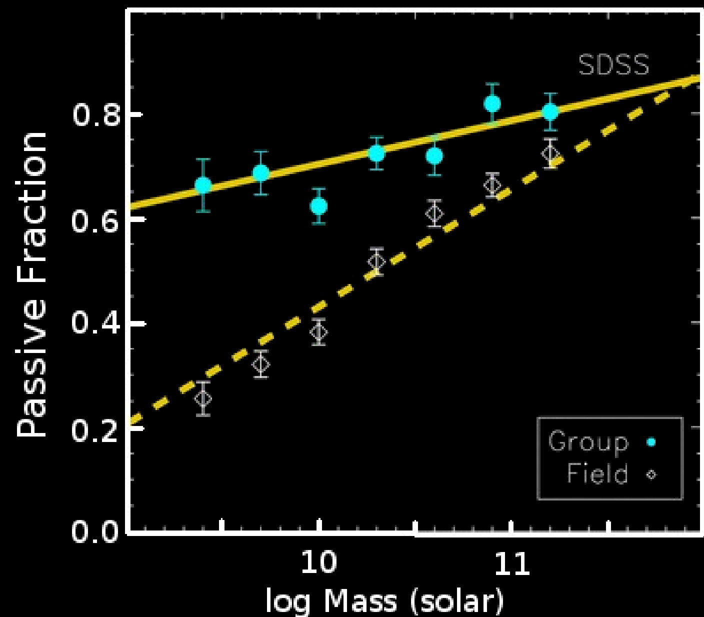


Moster et al. (2010)

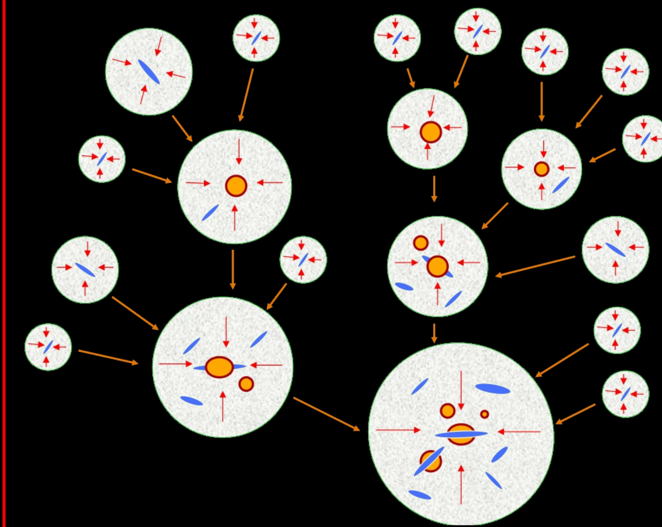


Simulation data from Pontzen & Khochfar

Environment

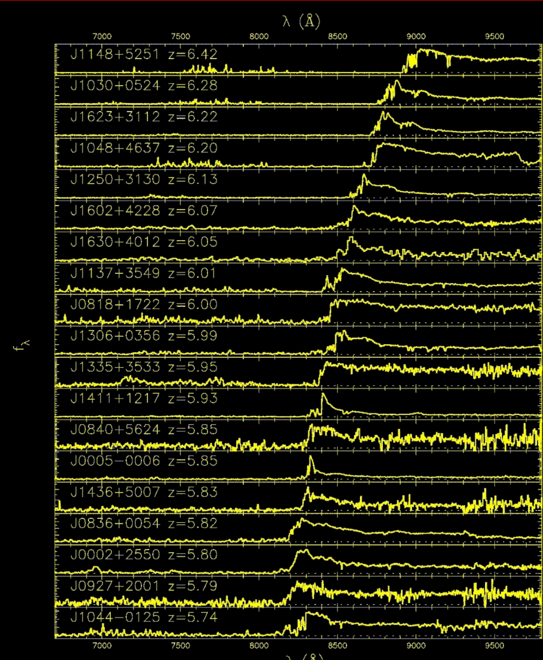


McGee et al. (2011)

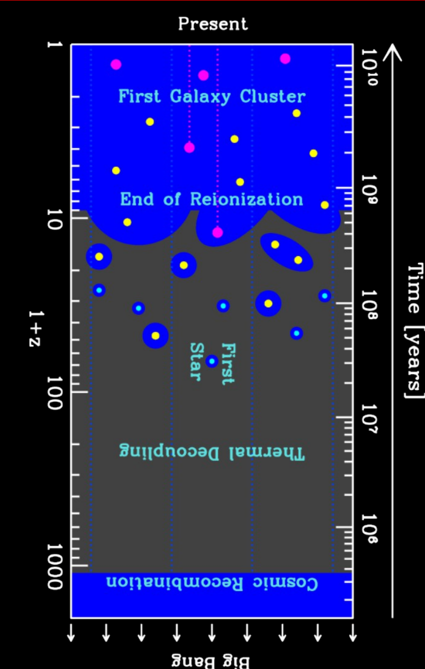


Ponman (2013)

Reionization



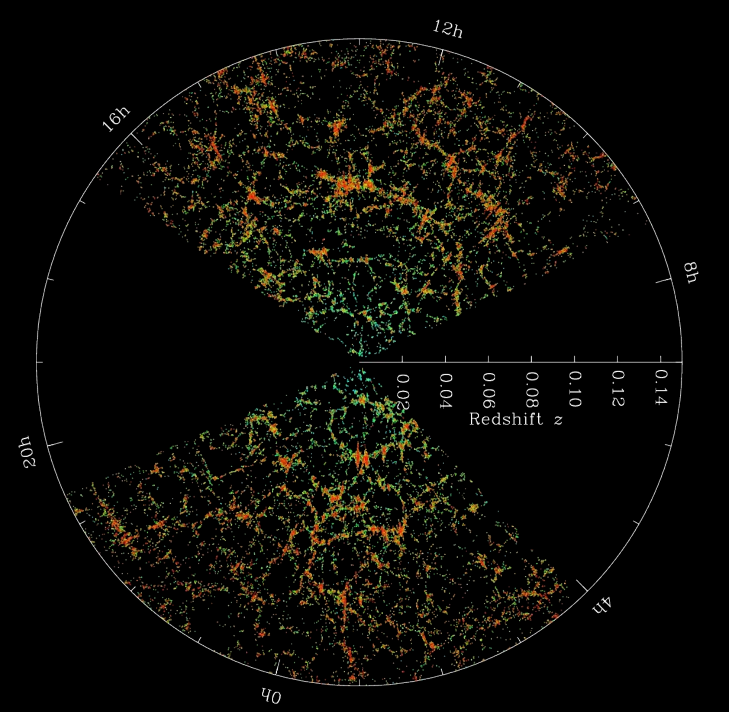
Fan et al. (2006)



Barkana & Loeb (2007)

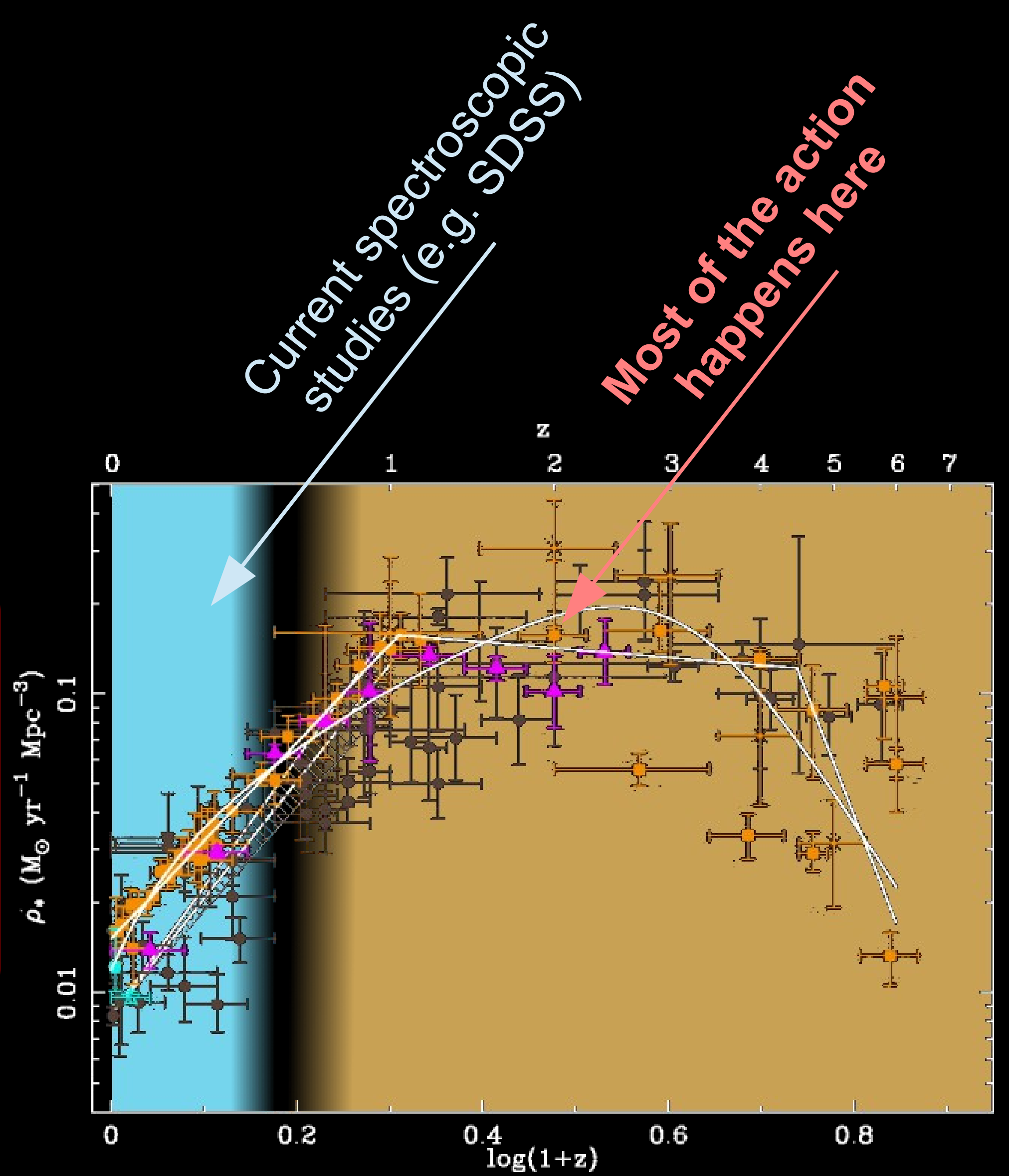
Best previous example

- 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 succesful
  - High quality spectroscopy
  - Probing large volumes ($\gtrsim 1 Gpc^3$)
  - ~1 million galaxies



Probing the bulk of galaxy formation

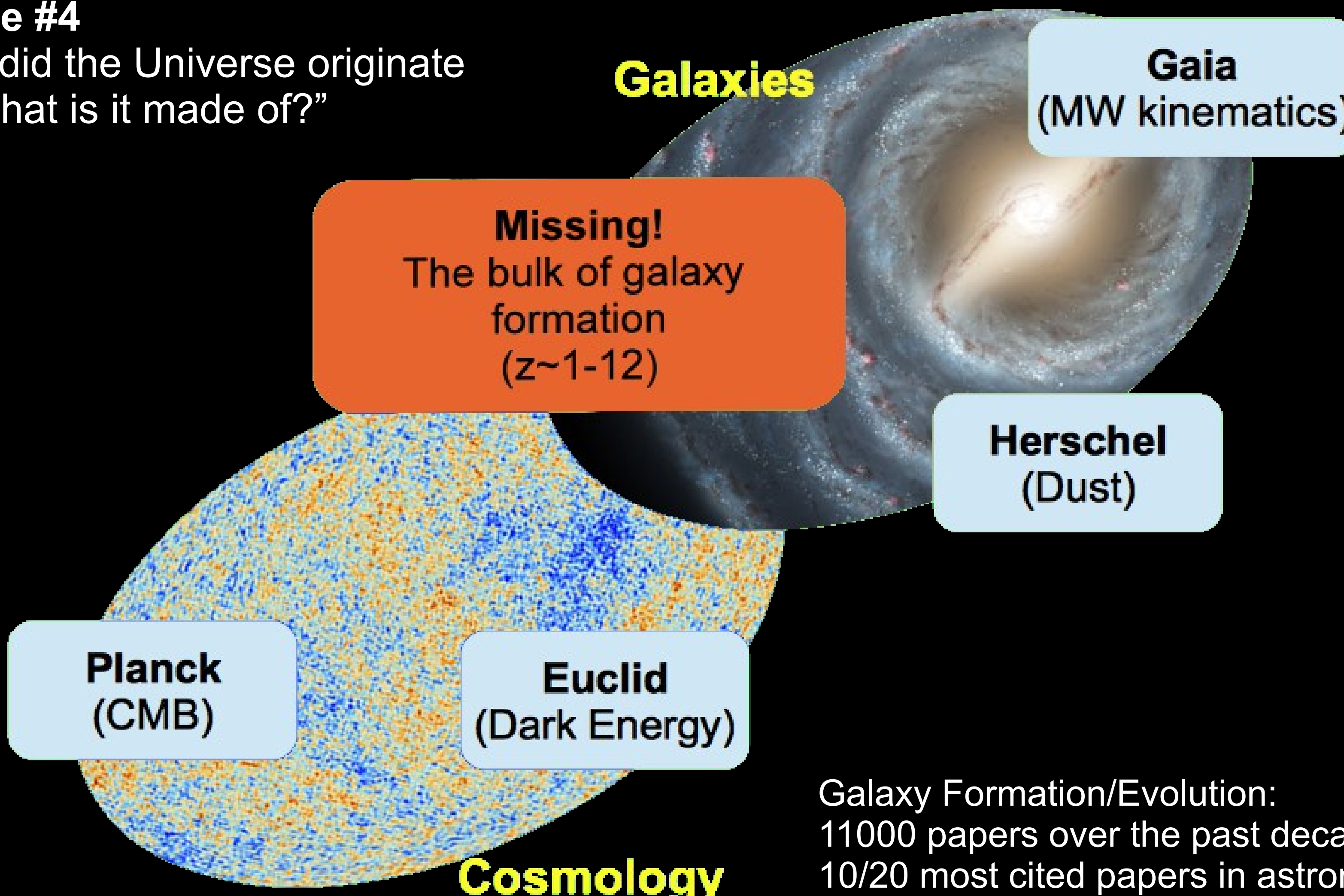
- However, SDSS only probes galaxy formation in the narrow z<0.1-0.2 window
- ... which represents the most recent 10-20% of the age of the Universe, missing the bulk of the complex processes leading to our current Universe
- Two key cosmic epochs need to be probed in a similar amount of detail
  - The peak of galaxy formation and black hole growth (z~1-3)
  - 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

Two main themes, same instrument

The peak of galaxy Formation
z=1-3

Information-rich optical spectrum shifts into the Near-infrared

Stellar Populations

Chemical Enrichment

Galaxy Dynamics

Environment: Halos vs Galaxies

The first galaxies
z=6-12

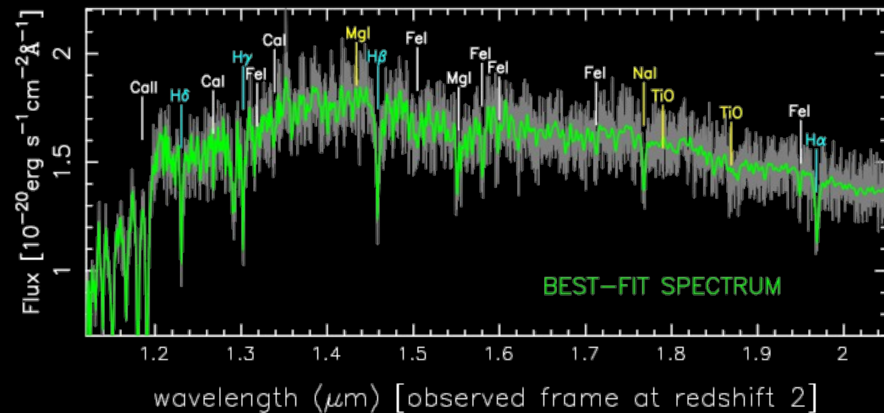
Lyman-α region shifts into the Near-infrared

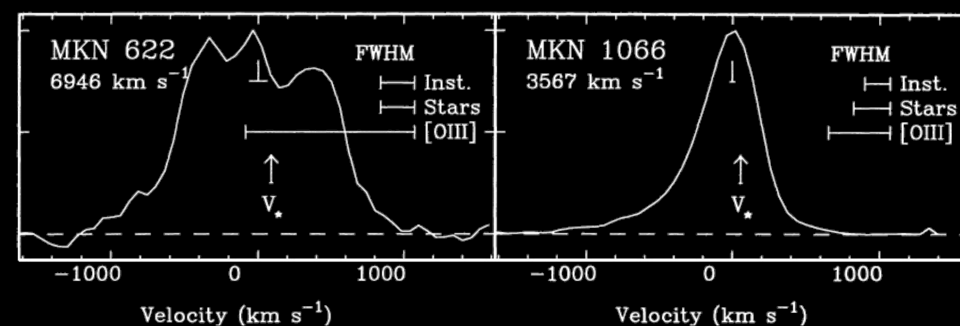
Lyman-break galaxies
(+ Ly-α emitters)

Clustering of the first galaxies

Re-ionization sources

Black Hole activity

<table>
<tr>
<td>Stellar populations
Star formation histories</td>
<td>Line strengths
Spectral fitting</td>
<td>

Chronos white paper (Ferreras et al. 2013)</td>
</tr>
<tr>
<td>Galaxy dynamics (gas and stars)</td>
<td>Velocity dispersion
Outflows
Rotation curves</td>
<td>

Nelson & Whittle (1995)</td>
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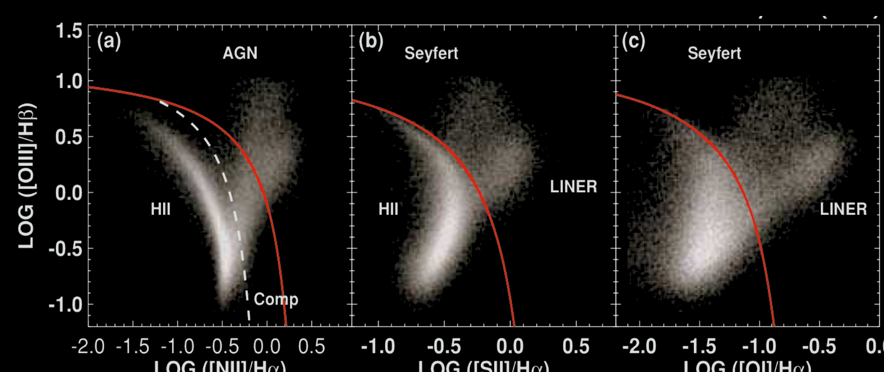
<tr>
<td>Star formation / black hole growth interplay</td>
<td>Emission line diagnostics</td>
<td>

Kewley et al. (2006)</td>
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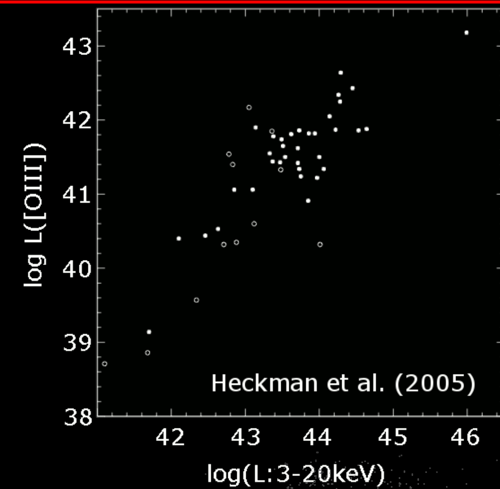
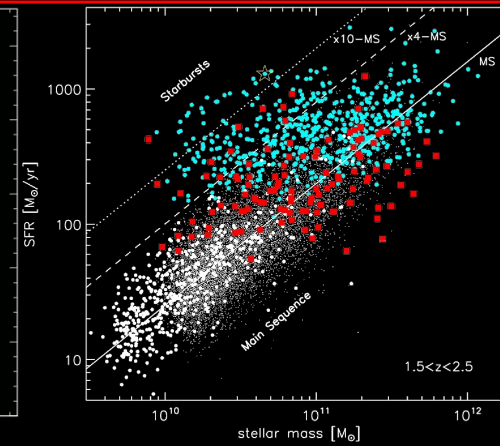
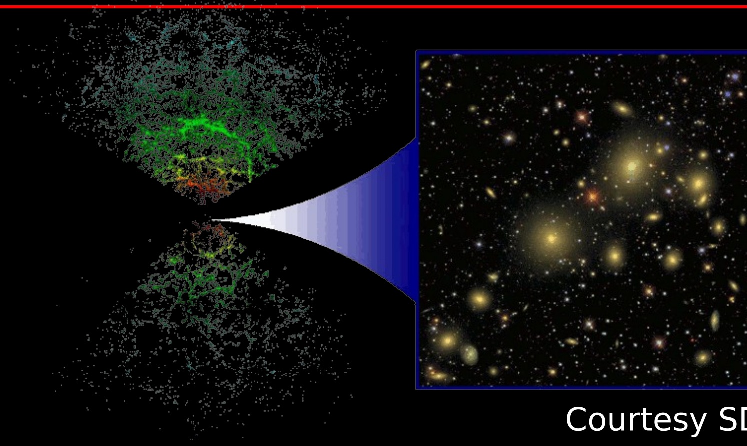
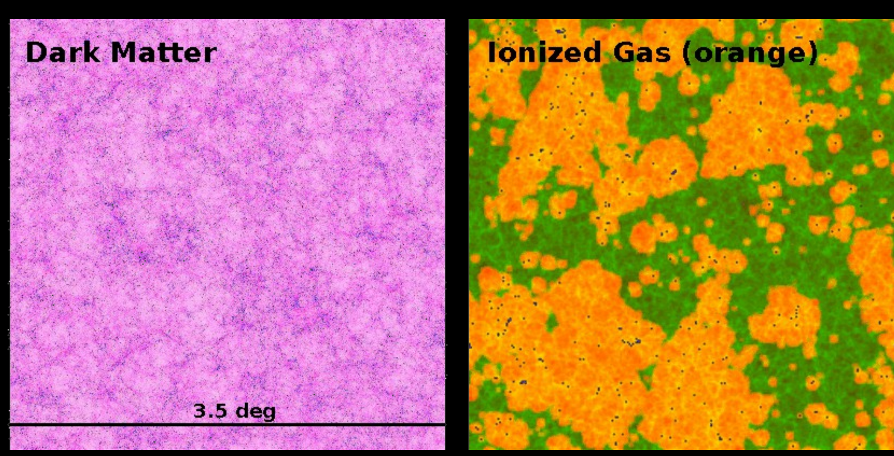
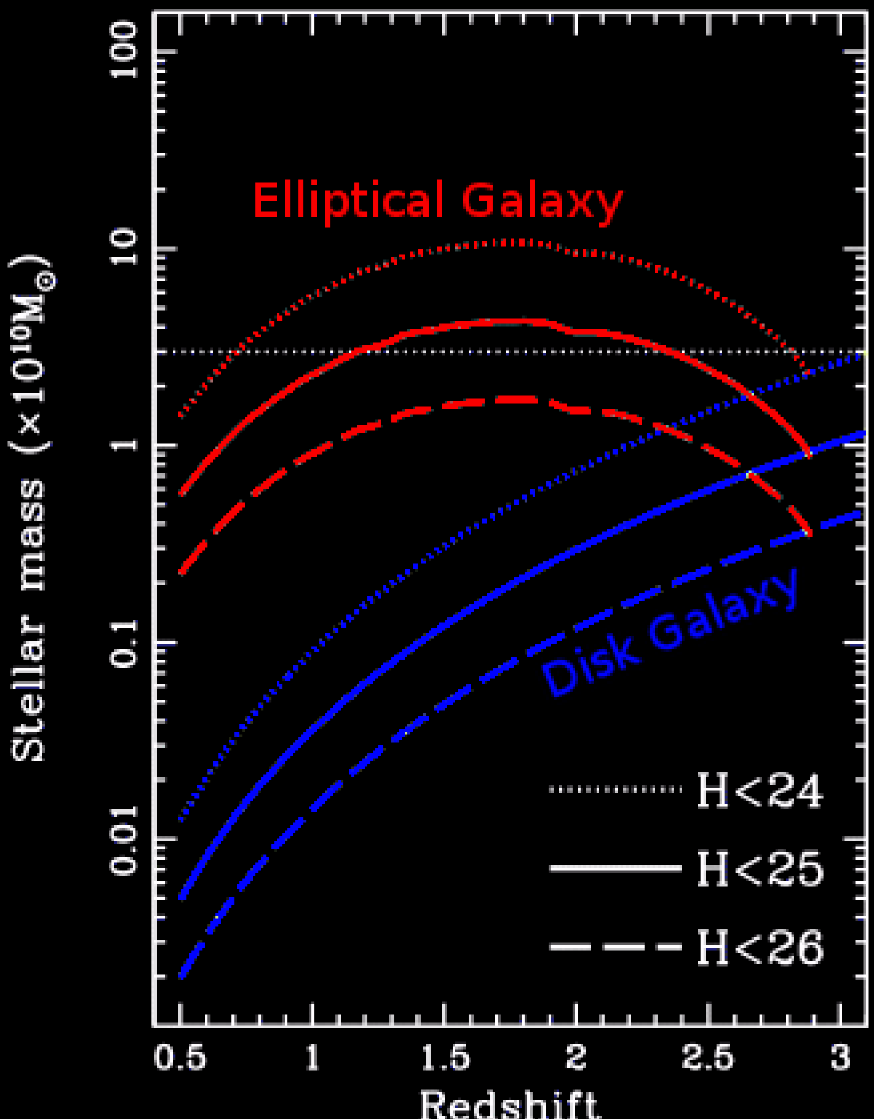
Black hole growth Star formation	[OIII] luminosities [OII],Hα	 Heckman et al. (2005)  Rodighiero et al. (2011)
Environment and mergers	Redshift determination with Δv~100-200km/s	 Courtesy SDSS
Clustering and reionization	Redshift determination with Δv~100-200km/s	 Iliev et al. (2012)

What type of survey is needed?

- Stellar-mass limited survey: $H_{AB} \lesssim 24\text{-}26$
- ~1-2 million, high-quality spectra (continuum)
- Resolution R~1500
- Similar comoving volume as SDSS:
  - $V(z<0.2)=0.5\ \mathrm{Gpc}^3$
  - z~1-3: 23 deg^2
  - z~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



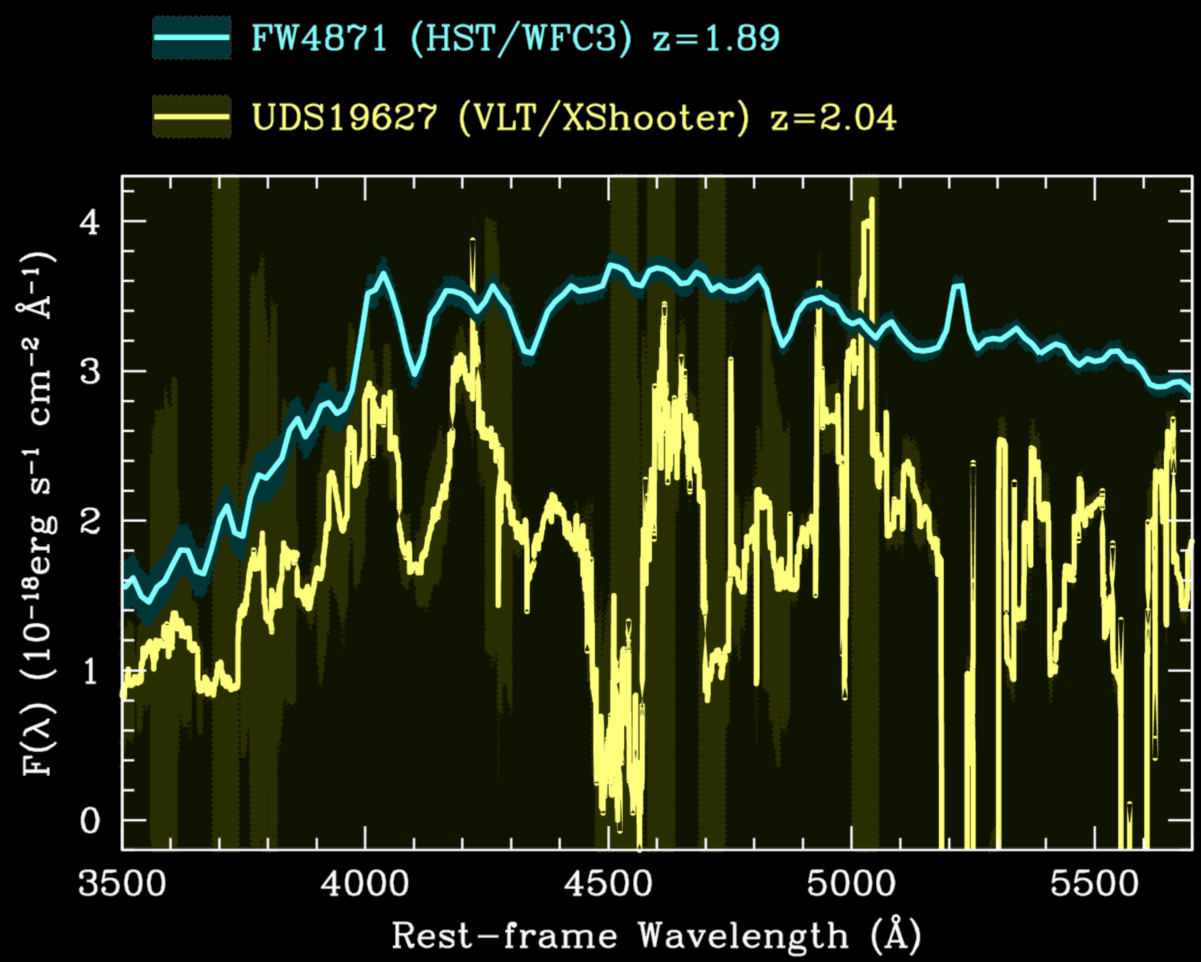
Why NIR from space?

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~2)

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

Ground-based plagued by atmospheric effects:

- Airglow
- Absorption
- Time variability



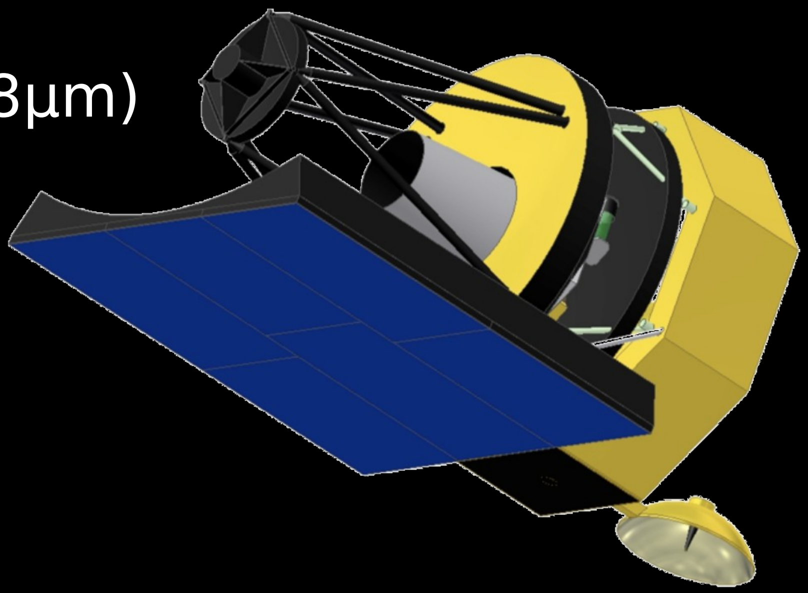
Chronos

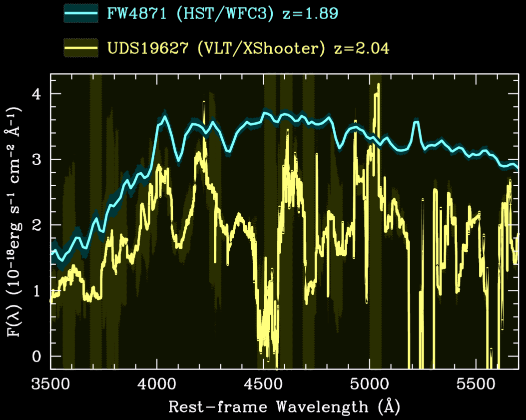
WHAT?

- Large spectroscopic survey
- Probe optical region at z~1-3 and Lyman-α at z>6
- High quality data (continuum)

HOW?

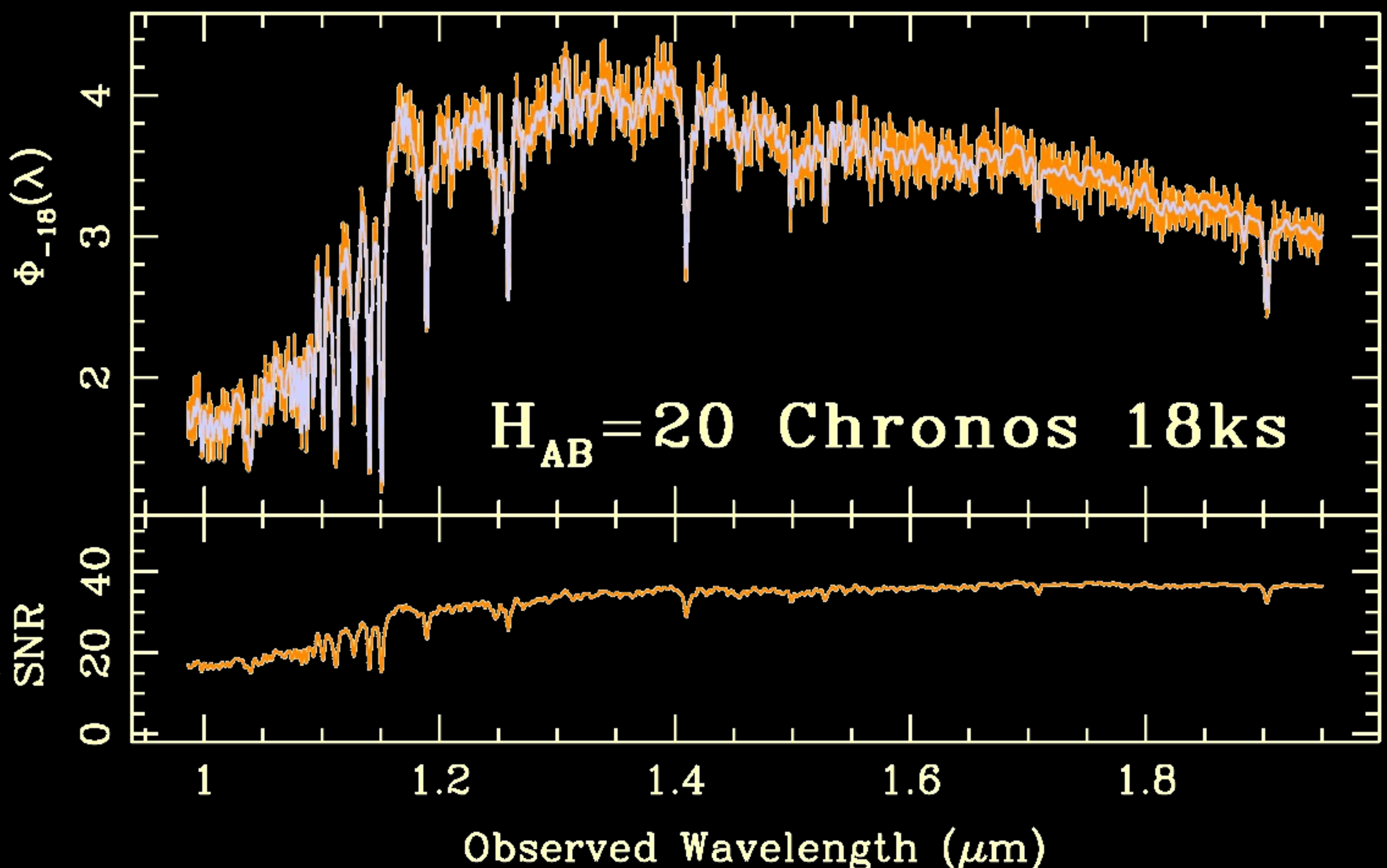
- 2.5m space telescope
- Near-infrared spectrograph (0.9-1.8μm)
- High multiplex (~5000)
- R=1,500 spectral resolution

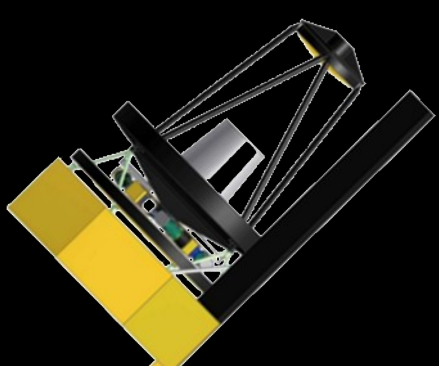


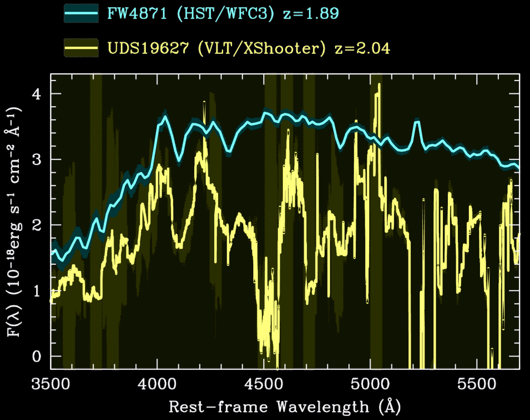


Simulated case for a 2.5m (i.e. HST-like) space telescope, optimized for NIR moderate-resolution spectroscopy (i.e. Chronos)

Typical massive galaxy at z~2



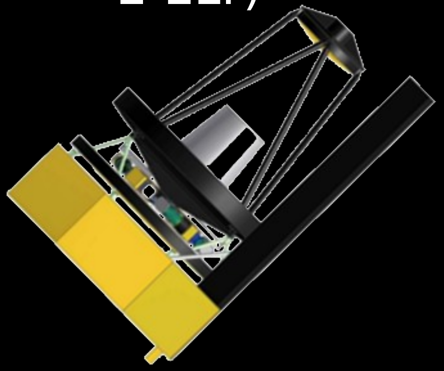


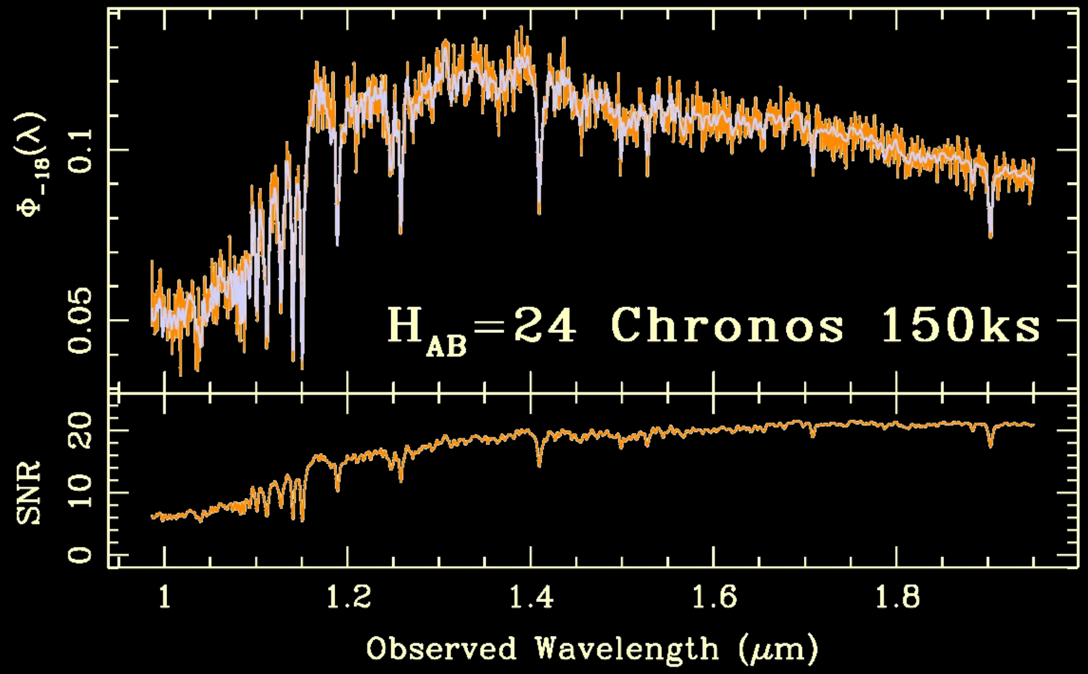


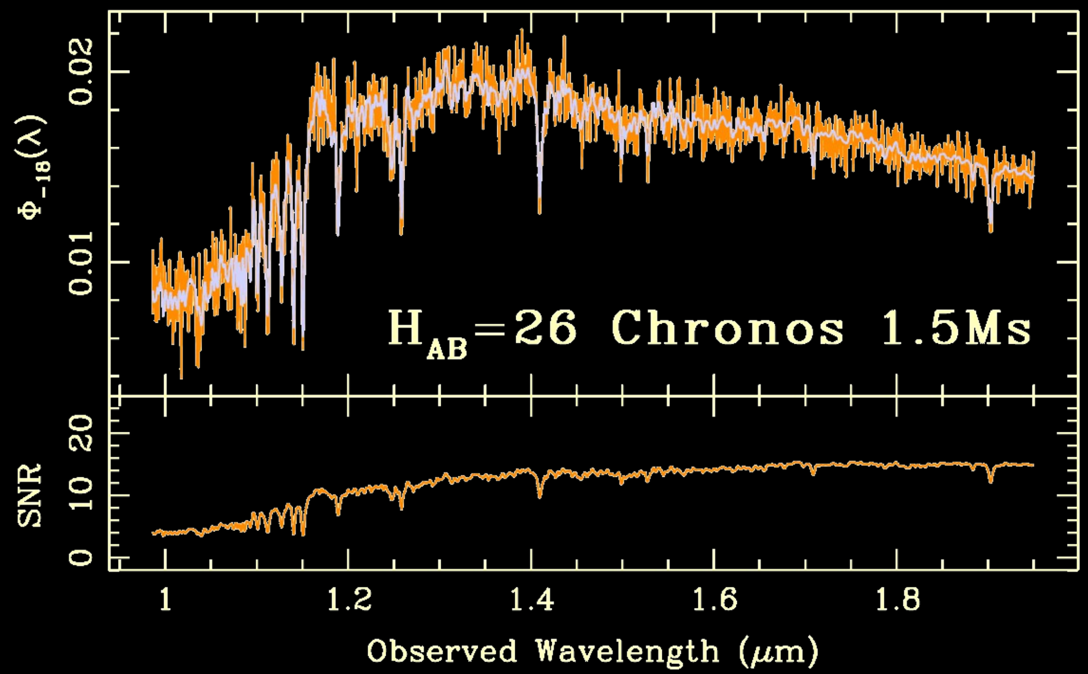
Let us consider two cases of very deep integration times. (Low Zodiacal background assumed)

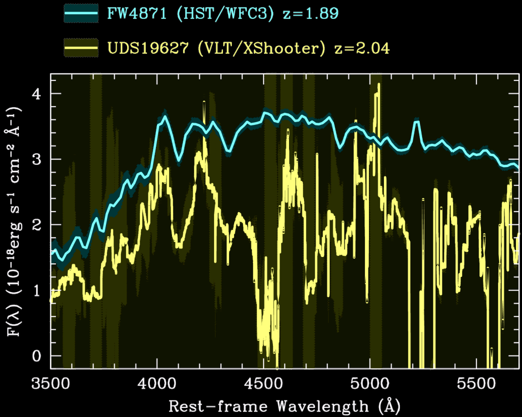
As reference, the HUDF/ACS images have a total integration time of ~1Ms

These limits are extremely challenging/unfeasible even for the future generation of ground-based telescopes (e.g. E-ELT)



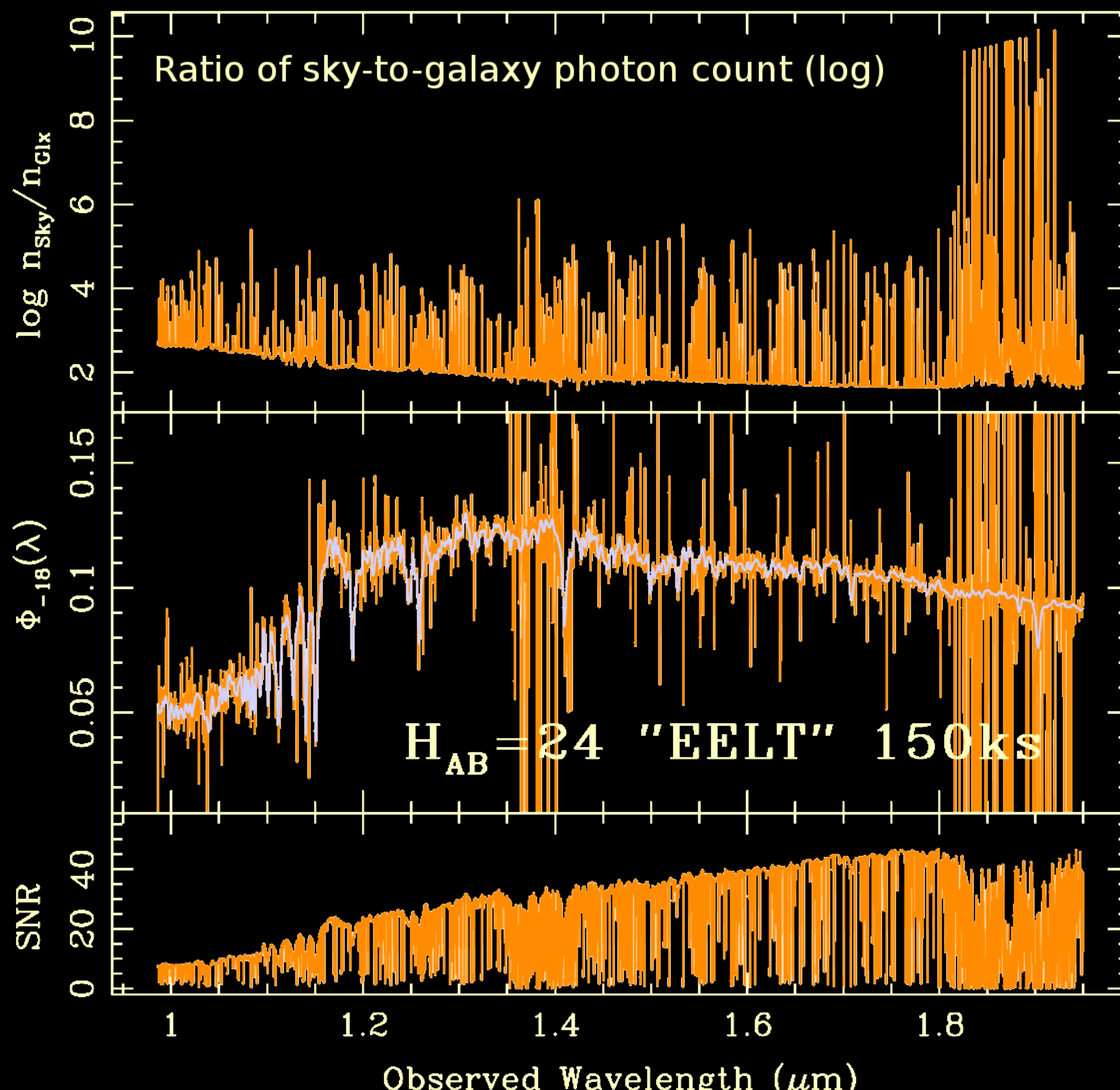




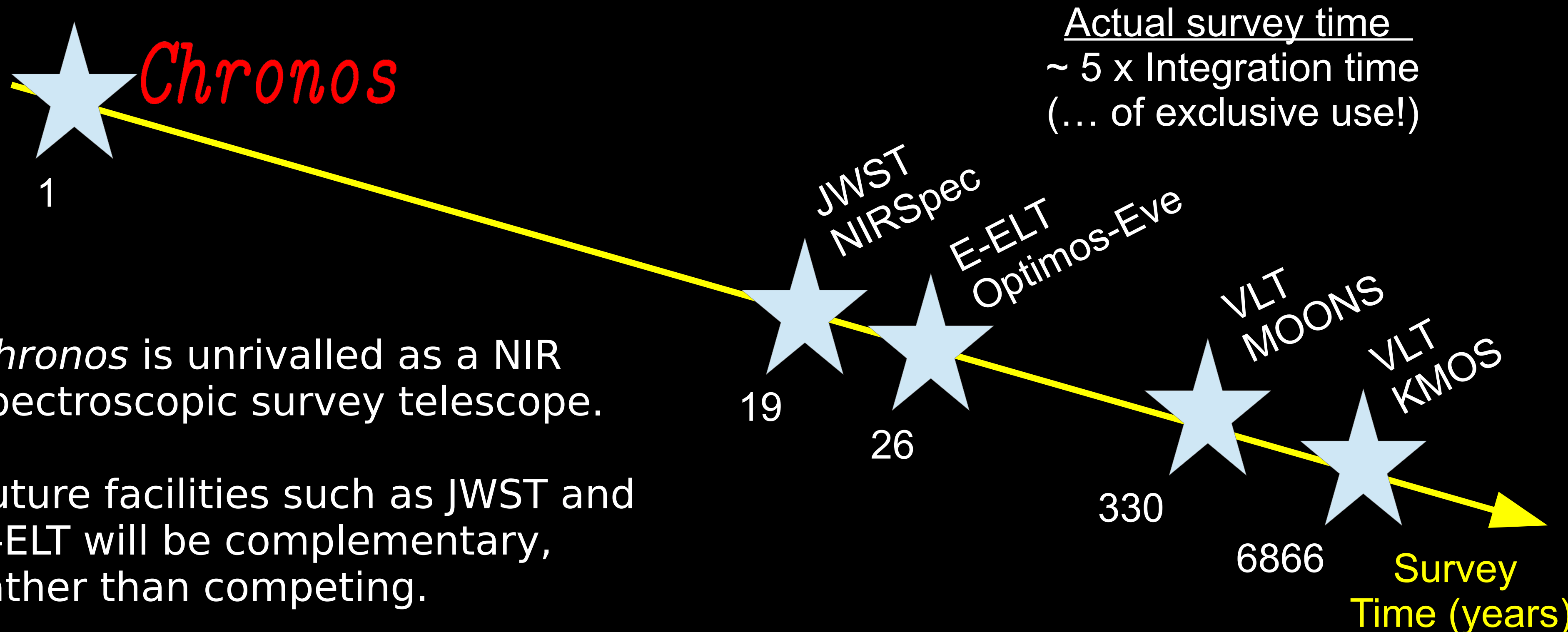


A simulation for an "E-ELT"-like aperture (D~40m) from the ground. We use the same characteristics as the previous simulations (for Chronos) but including sky absorption and airglow.

Rather optimistic as we assume perfect sky subtraction.



	Chronos	*JWST NIRSpec*	*E-ELT Optimos-EVE*	*VLT MOONS*	*VLT KMOS*
Area(m^2)	4.5	25	978	52	52
FOV(deg^2)	0.2	2.50×10^{-3}	0.0107 (7'Ø)	0.15	0.0113 (7.2'Ø)
Multiplex	5000	100	30	500	24
Etendue	0.9	0.06	10.46	7.8	0.59
$t_{SN=20}$(H=24) ks	150	60	25	5200	5200
Integration time, 1 million spectra (yr)	1	19	26	330	6866

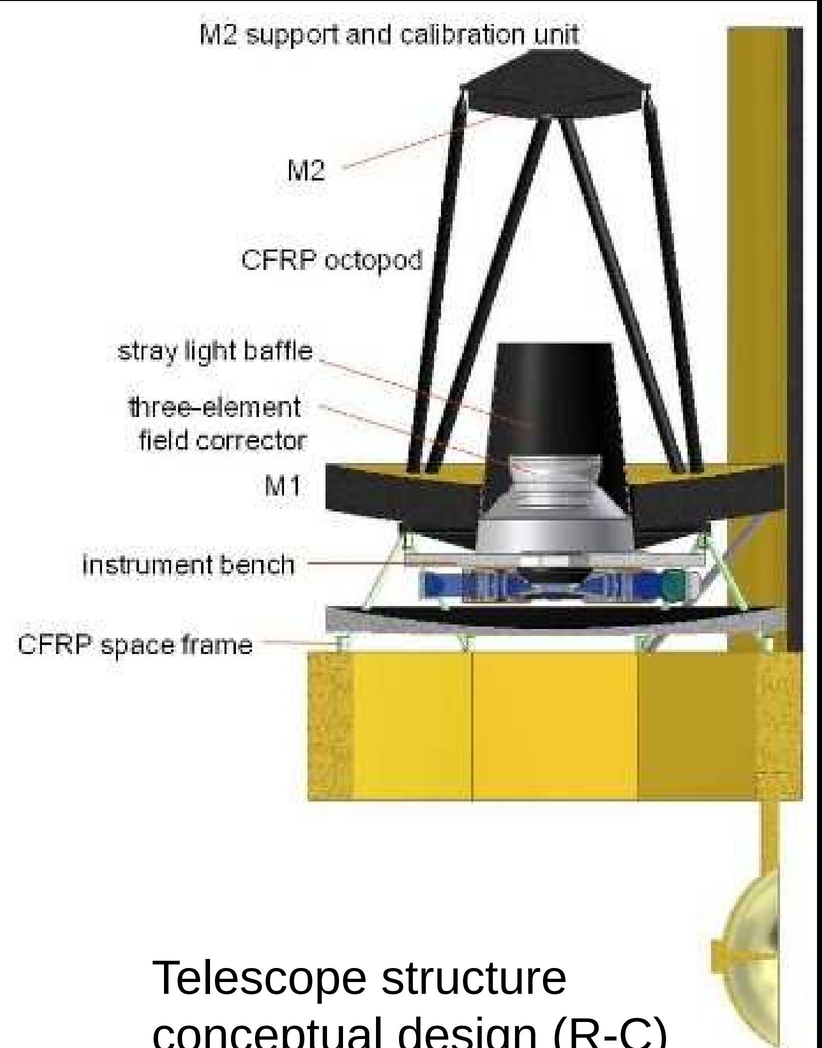


Chronos is unrivalled as a NIR spectroscopic survey telescope.

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

Telescope

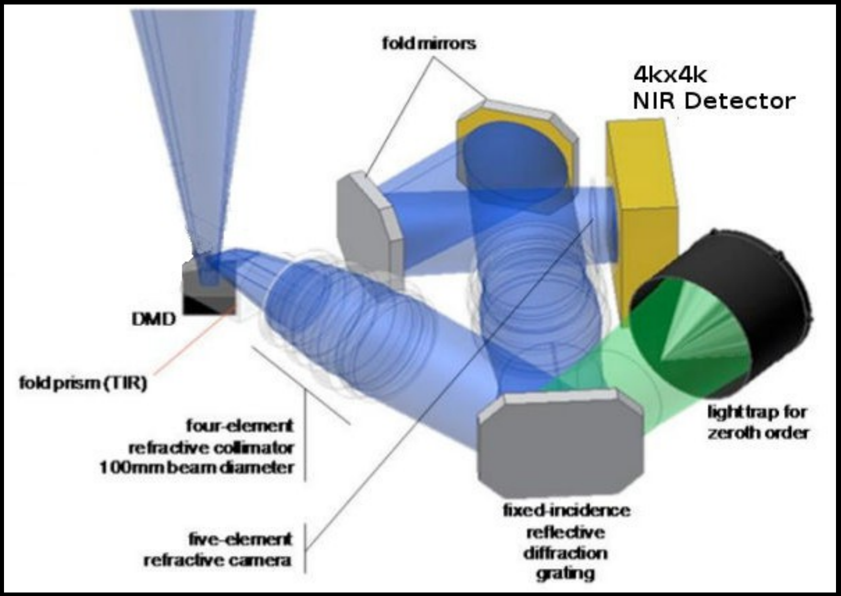
- Heritage from Euclid, Herschel and Gaia
- 2.5m diameter telescope, 1deg FoV
- Korsch/Ritchey-Chrétien design
- Zerodur or SiC mirror optics
- Image quality FWHM<0.3” (i.e. not diffraction limited)
- Size and weight compatible with Ariane V launch



Telescope structure conceptual design (R-C)

Spectrograph

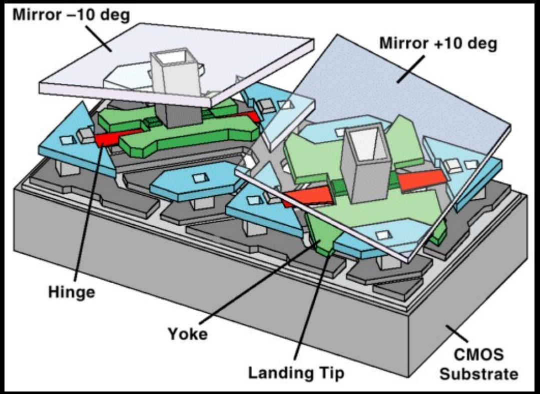
- Single instrument (cost effective)
- 8 identical multi-object spectrographs
- Fixed format spectrograph giving R~1500 over 0.9-1.8μm
- NIR detector technology
  - Space-qualified technology will be available (e.g. Teledyne H4RG)
  - Eight 4kx4k arrays
  - Other options will be considered (e.g. Selex,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



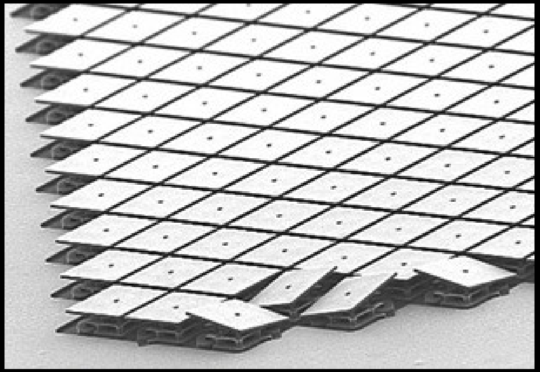
Baseline single channel spectrograph

Target Selection: DMDs

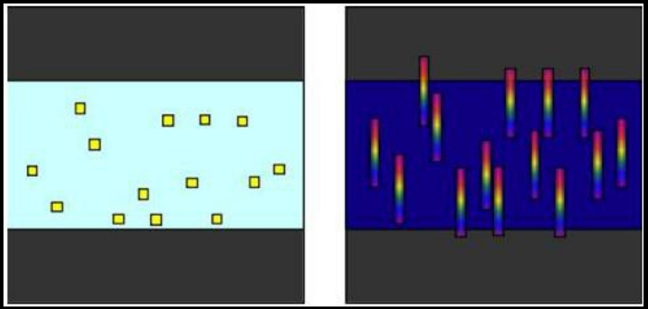
- Baseline for target selection is Texas Instruments (TI) digital micro-mirror (DMD) device, 2048x1024 (13.8μm pixel)
- Bi-stable angle provides on/off 'shutter' at position of each source
- Preliminary space qualification during Euclid Phase A (Zamkotsian+ SPIE 7932)
- Long heritage in digital projectors near you!
- Needs development programme for drive electronics and AR coatings



DMD MEMS construction



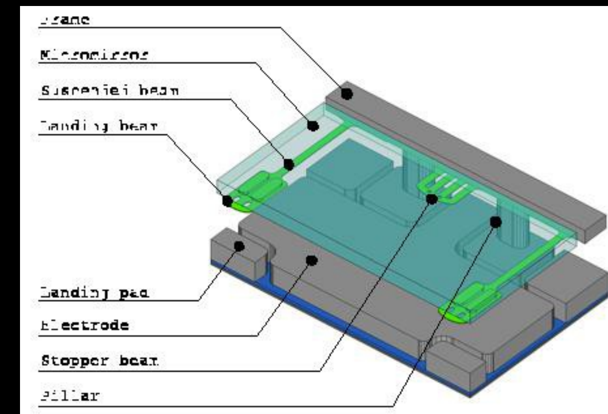
DMD mirror array



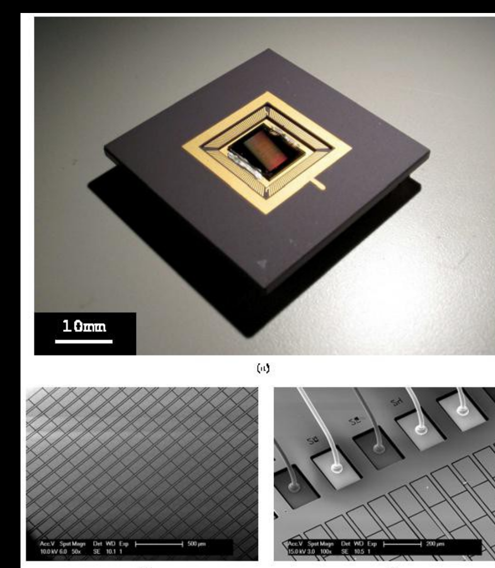
DMD target selection

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



Principle of operation (source: Canonica et al, J. Micromech. Microeng. 23, 055009, 2013)



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}~24
  - Deep (40deg^2) H_{AB}~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

http://www.chronos-mission.eu
arXiv:1306.6333