Galaxy surveys

We will discuss:

- ★ Why galaxy surveys are important
- ★ The first generation of large sky surveys
- ★ Contribution from *HST*
- ★ Future

Sterrewacht Leiden

THEMIYA NANAYAKKARA

@themiyan

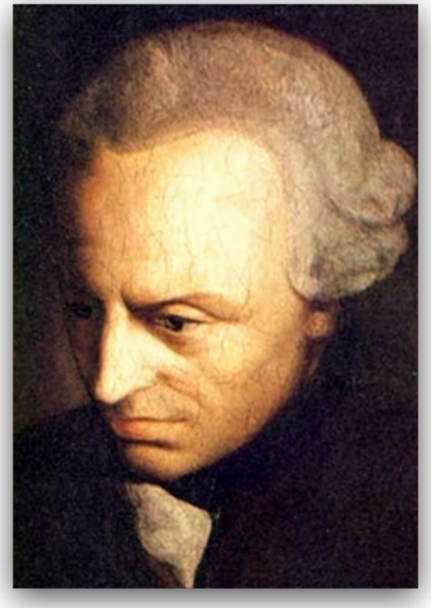
With contributions from Prof. Rychard Bouwens and Dr. Jacqueline Hodge Leiden Observatory

What is a galaxy?
A historical perspective

Depiction of an epicyclic planetary model. Qutb al-Din al-Shirazi (1236 – 1311)

Horoscope of Prince Iskandar, grandson of Tamerlane, the Turkman Mongol conqueror, by Imad al-Din Mahmud al-Kashi, from The Book of the Birth of Iskandar (ca. 1384) – Source: Wellcome Library, London.

What is a galaxy?
A historical perspective



Immanuel Kant
1724 – 1804

"Perhaps the diffuse nebulae are distant island universes?"

Charles Messier
1730 – 1817

Compiled an astronomical catalogue consisting of 110 nebulae and star clusters in the late 18th century. These objects are to this day referred to at "Messier objects". Today we know that he saw galaxies (39), nebulae (7), planetary nebulae (5), and star clusters (55).

William Herschel
1738 – 1822

A similar catalogue of nebulous objects was compiled by the German-born British William Herschel, also by the end of the 18th century.

Before the 1920s, we had no evidence for the existence of other galaxies

The first long exposure photo of the Andromeda galaxy: "some kind of spiral nebula inside our galaxy"

1887, Isaac Roberts

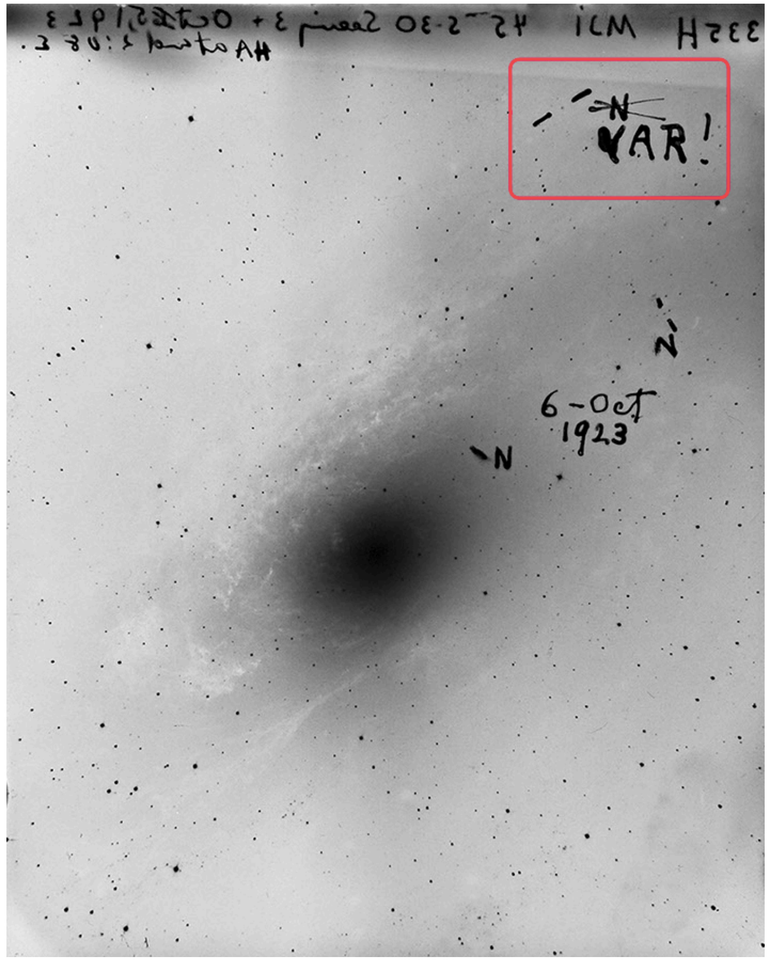
The Andromeda galaxy

Our nearest spiral galaxy,
2.5 million light years away

Edwin Hubble

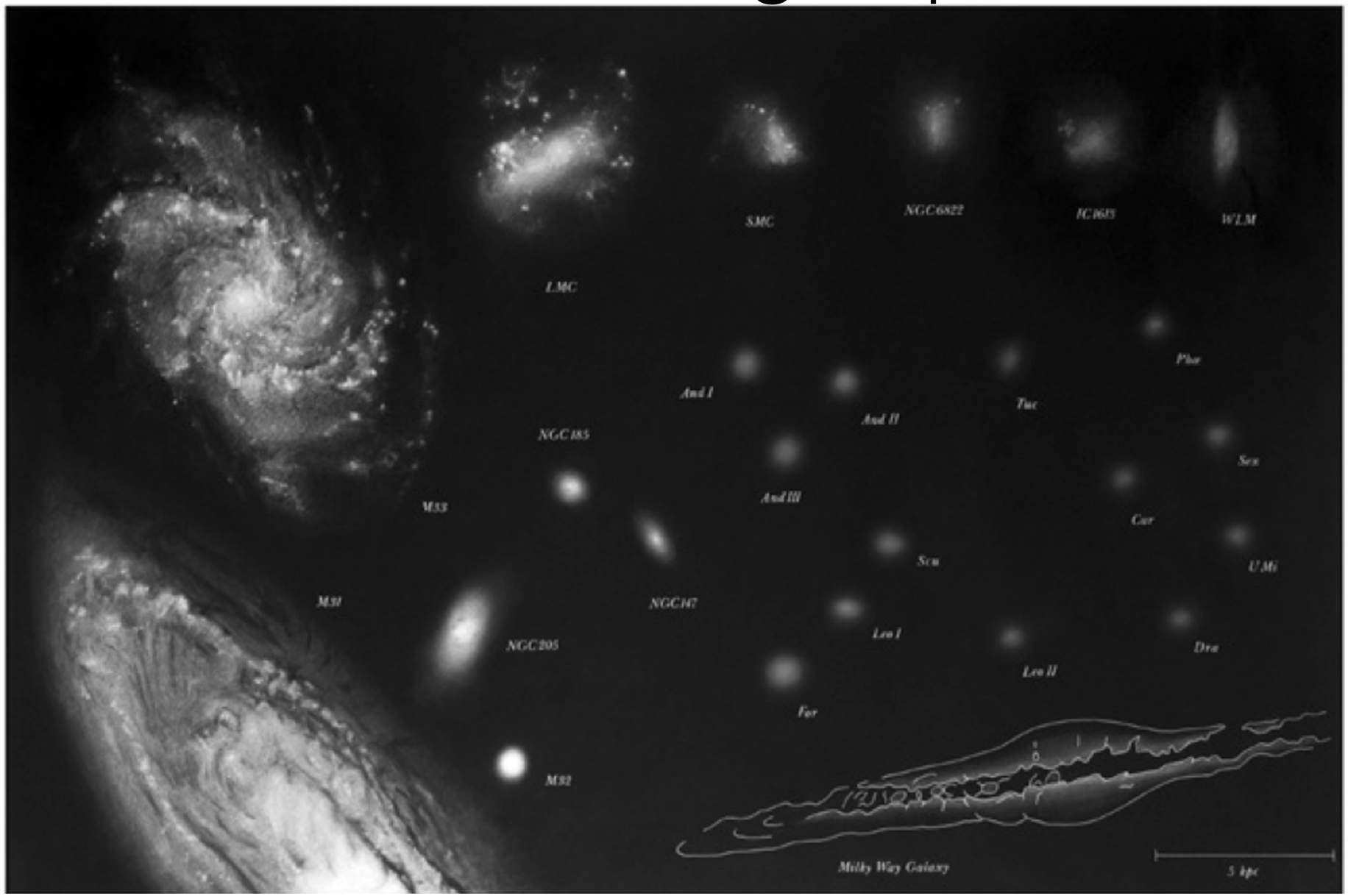
- In the 1920's, Hubble observed variable stars in the Andromeda 'nebula' M31. Assuming these stars had the same luminosities as Cepheid variables within our Galaxy, he concluded that M31 must be at least 300 kpc away.

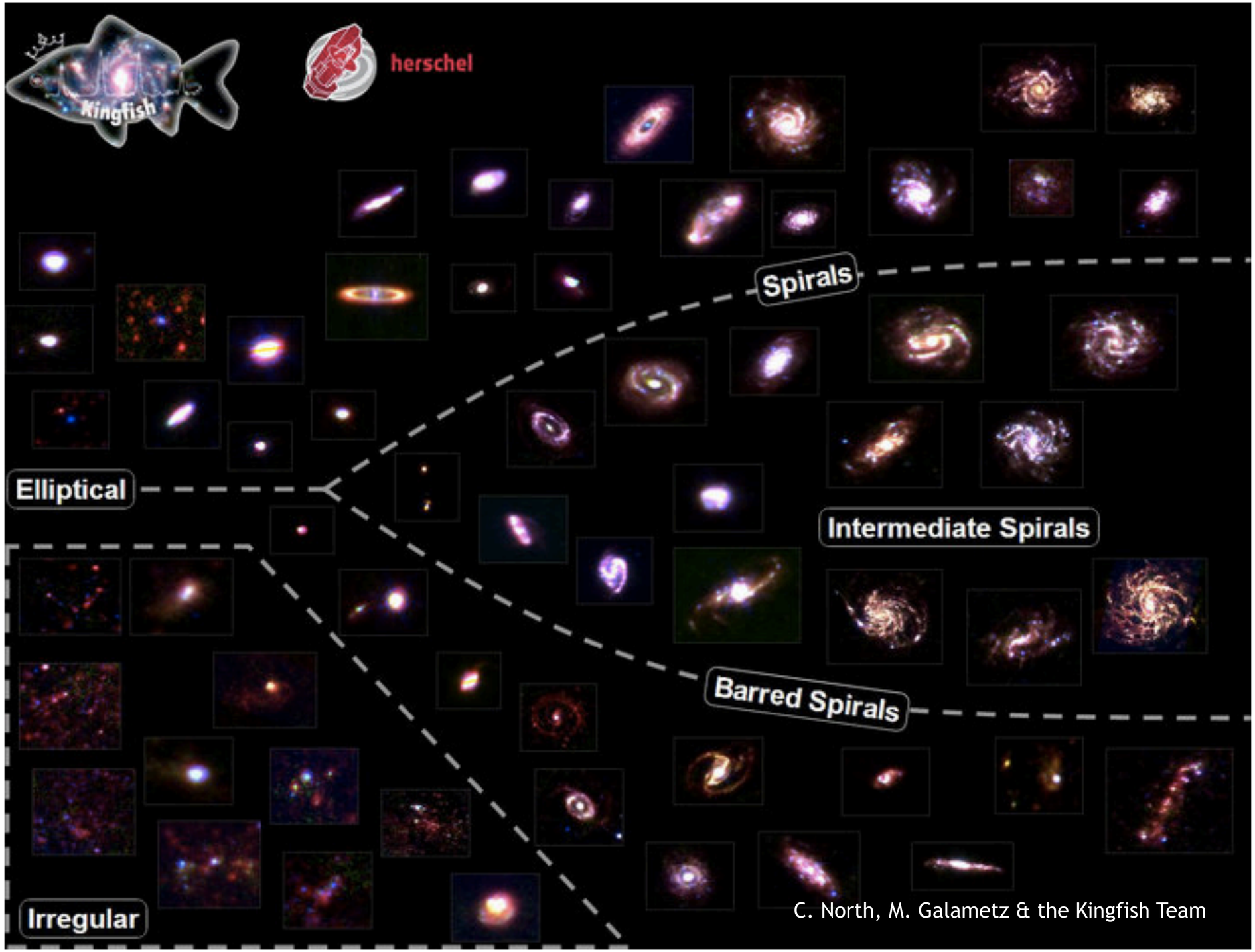
Photo courtesy Observatories of the Carnegie Institution of



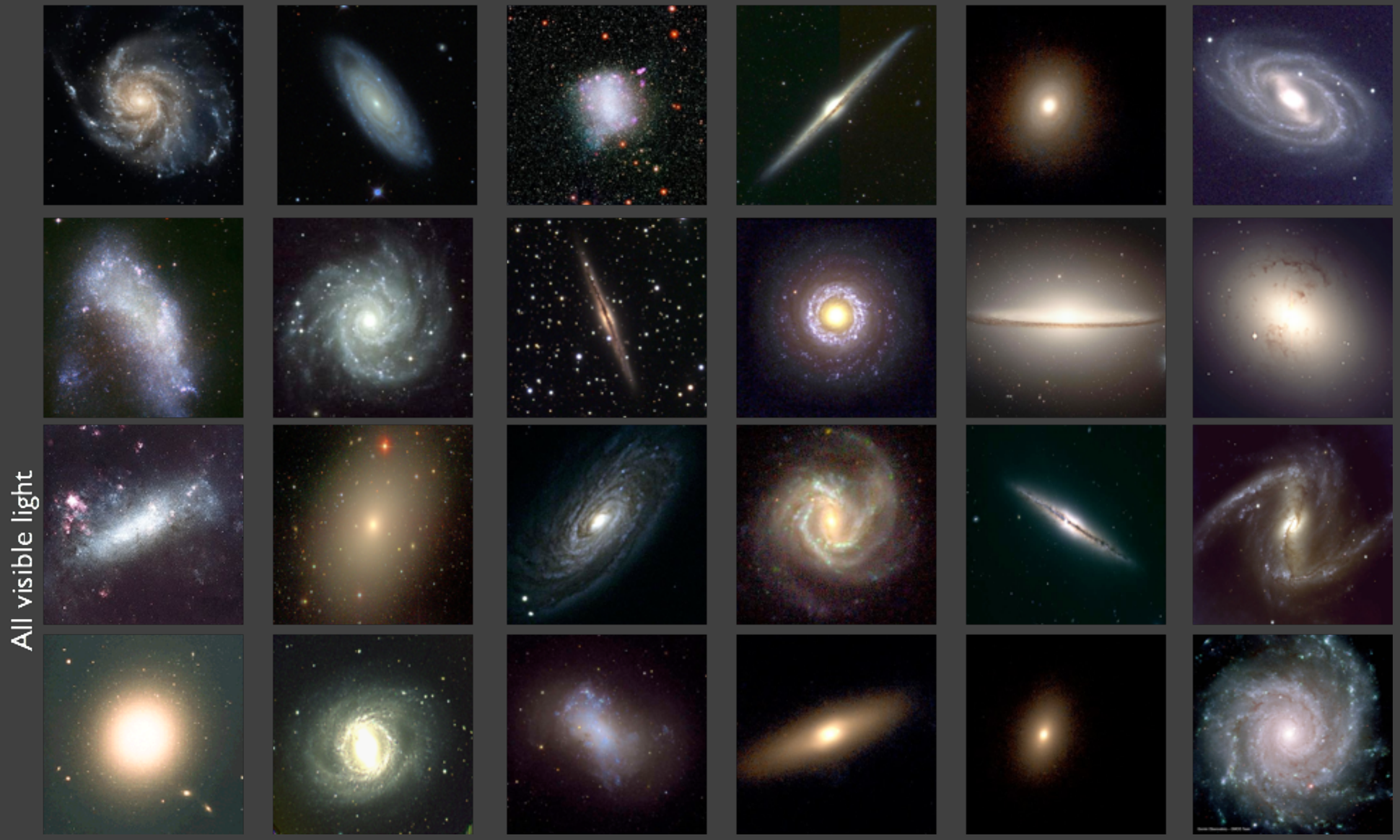
Courtesy Carnegie Observatories

The local group



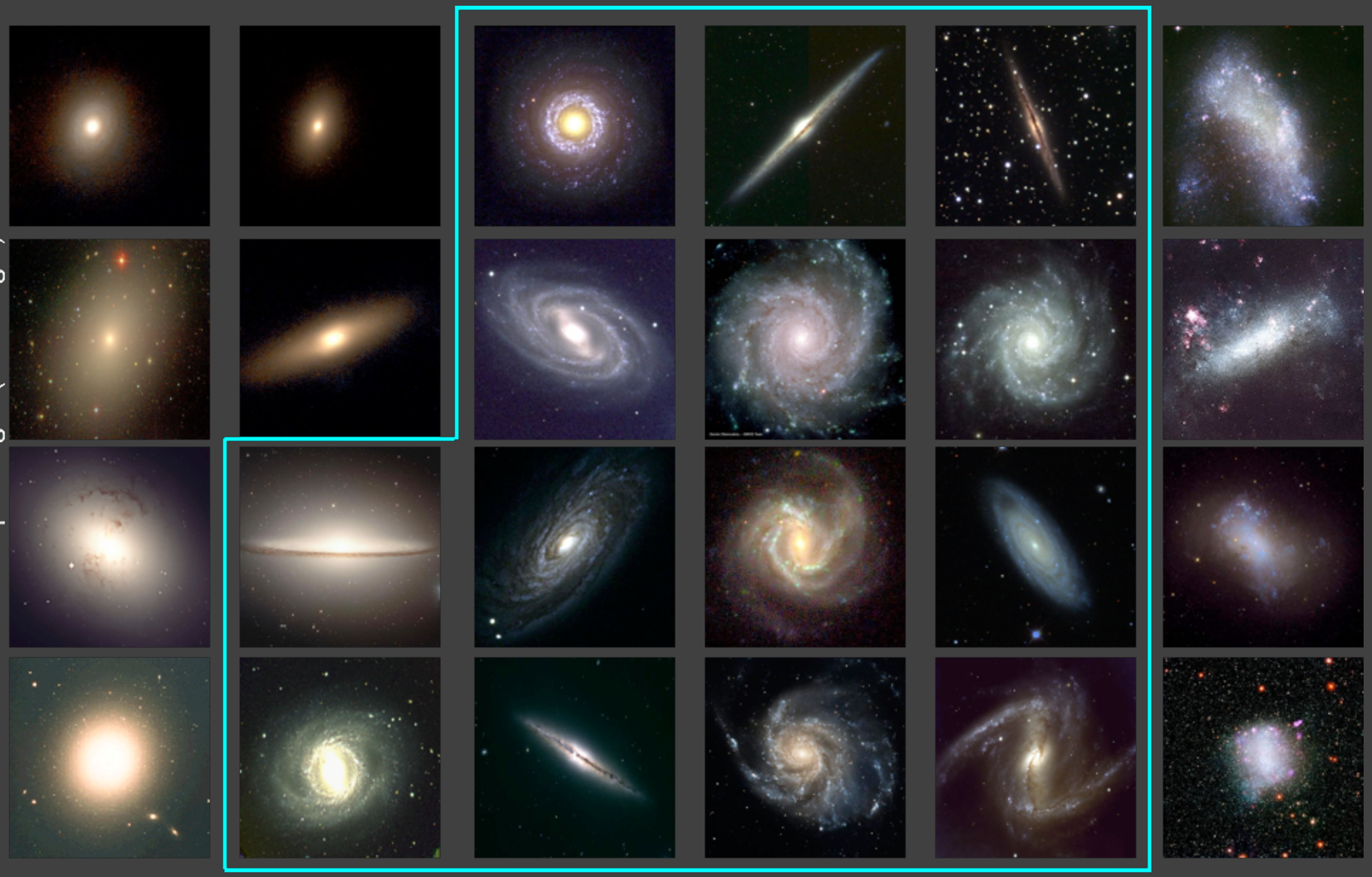

Kingfish
herschel
Spirals
Elliptical
Intermediate Spirals
Barred Spirals
Irregular
C. North, M. Galametz & the Kingfish Team

Beyond the local group



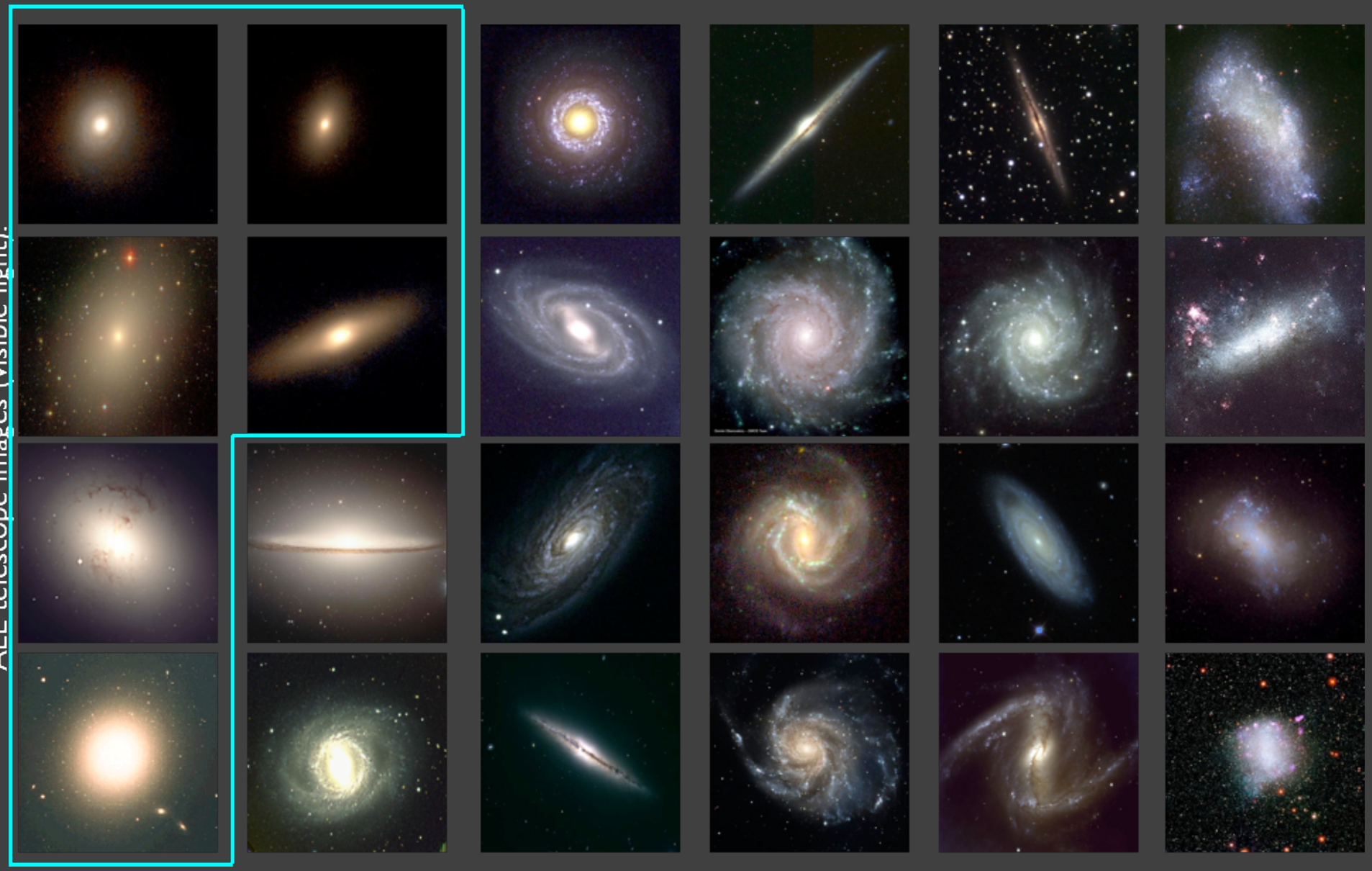
3 Basic Galaxy Types: Spirals

ALL telescope images (visible light).



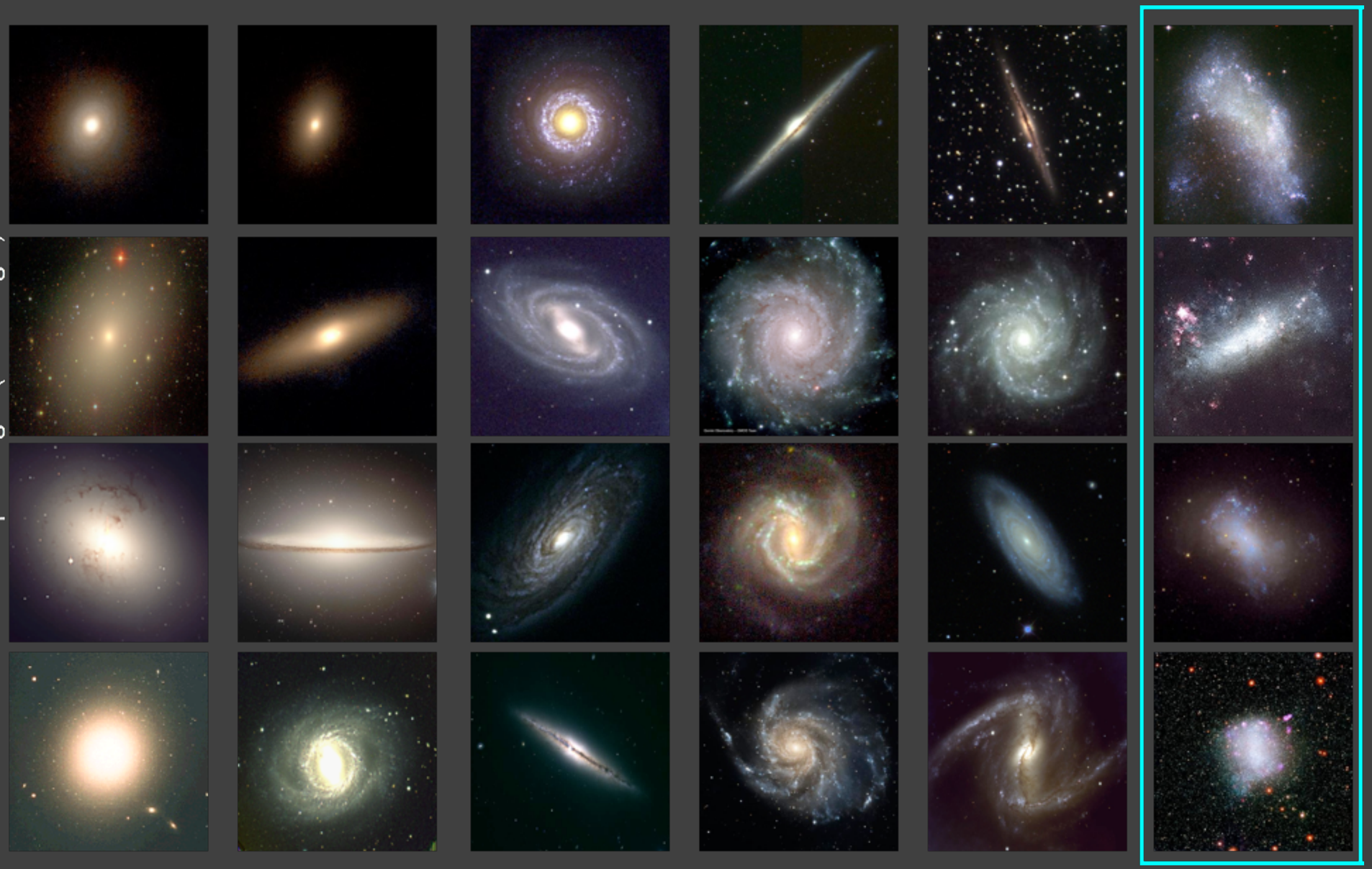
3 Basic Galaxy Types: Ellipticals

ALL telescope images (visible light).



3 Basic Galaxy Types: Irregulars

ALL telescope images (visible light).

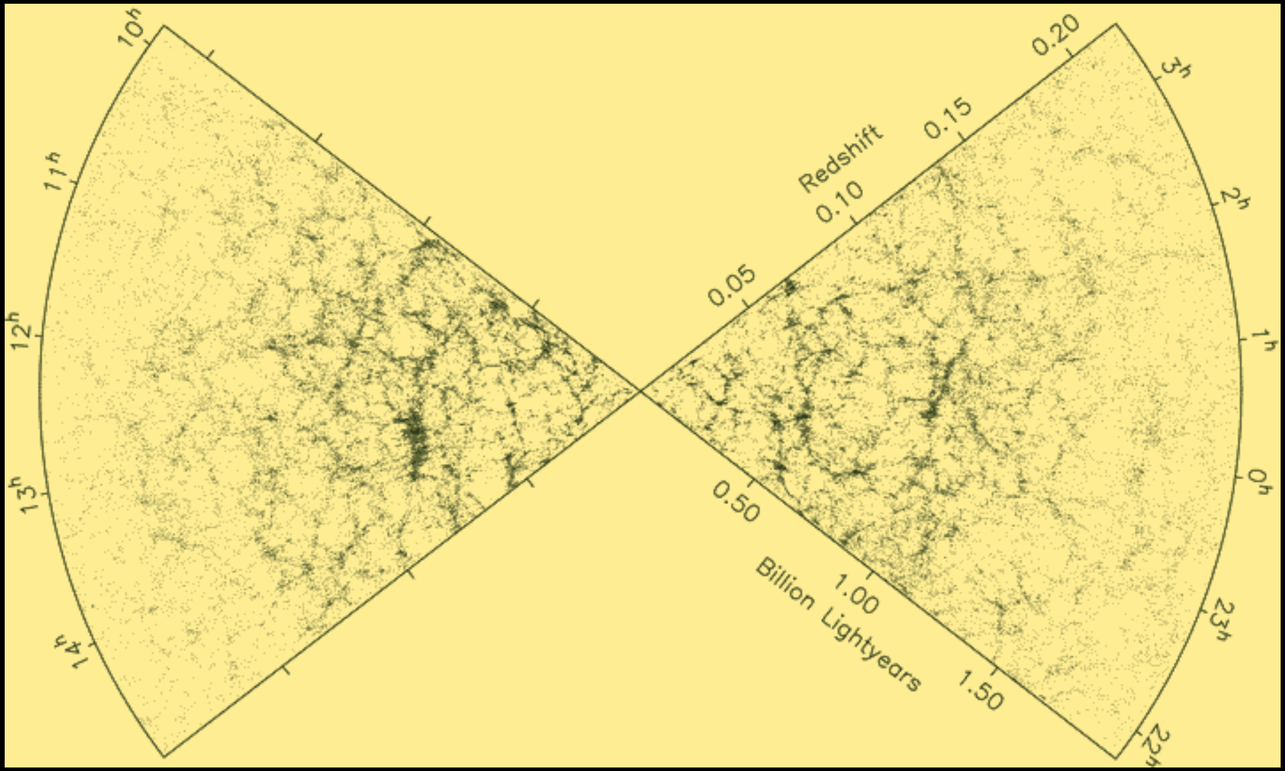


Why galaxy surveys

- To perform statistically significant analysis of galaxy evolution it is important to:
  - Observe complete samples of galaxies (e.g. mass, magnitude etc.)
  - Obtain multi-wavelength photometric data
  - Supplement with spectroscopy
- Galaxy surveys can be
  - all sky surveys focusing on a wide are but shallow
  - deep surveys with limited sky coverage but probing fainter and high redshift targets

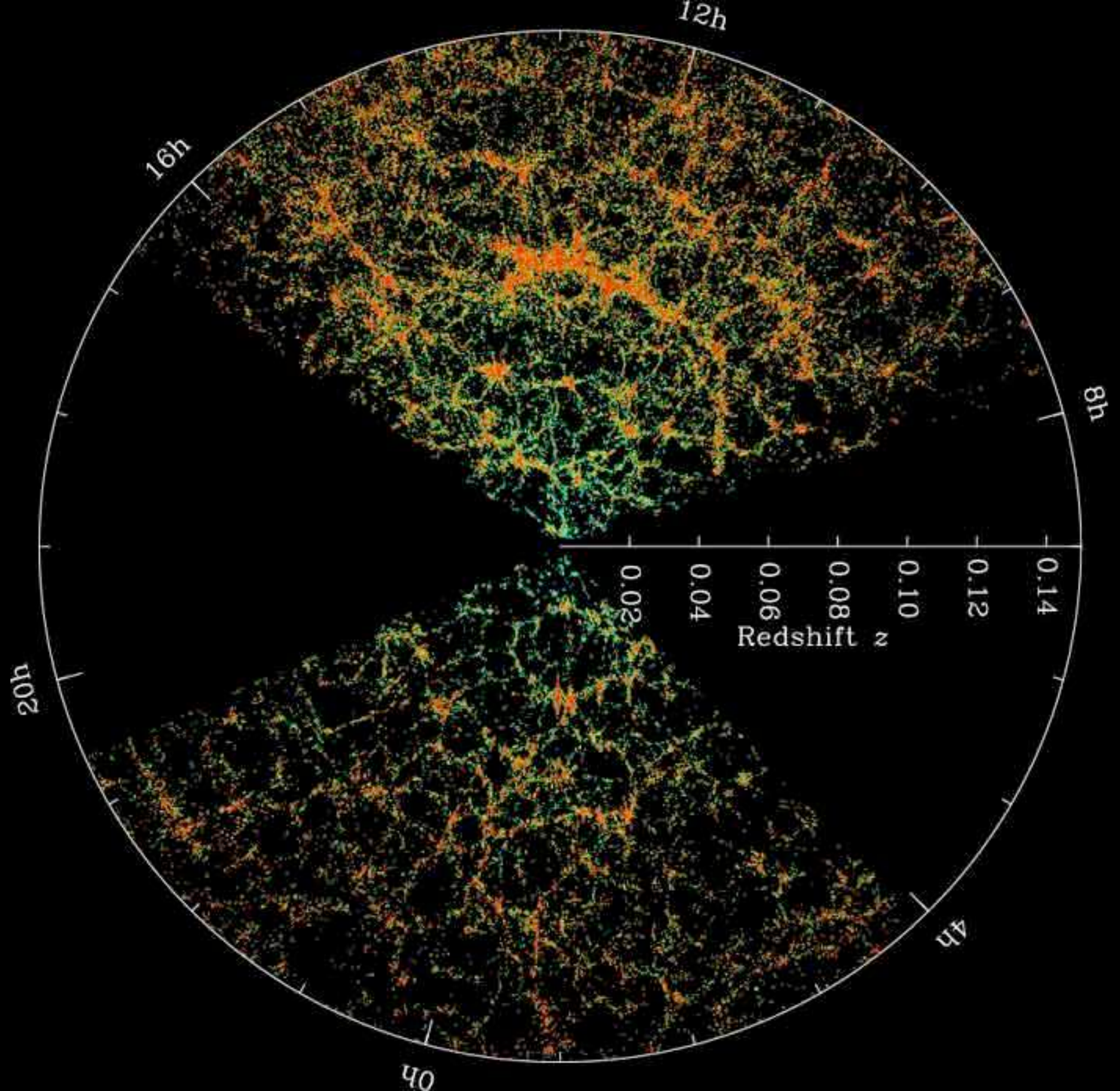
2dFGRS

- ~250,000 spectra covering ~1500 sq deg
- Contributed significant advancements to cosmology



SDSS

- SDSS revolutionised our understanding of galaxy evolution
- 100 million + galaxies observed along with 1 million + galaxy spectra so far



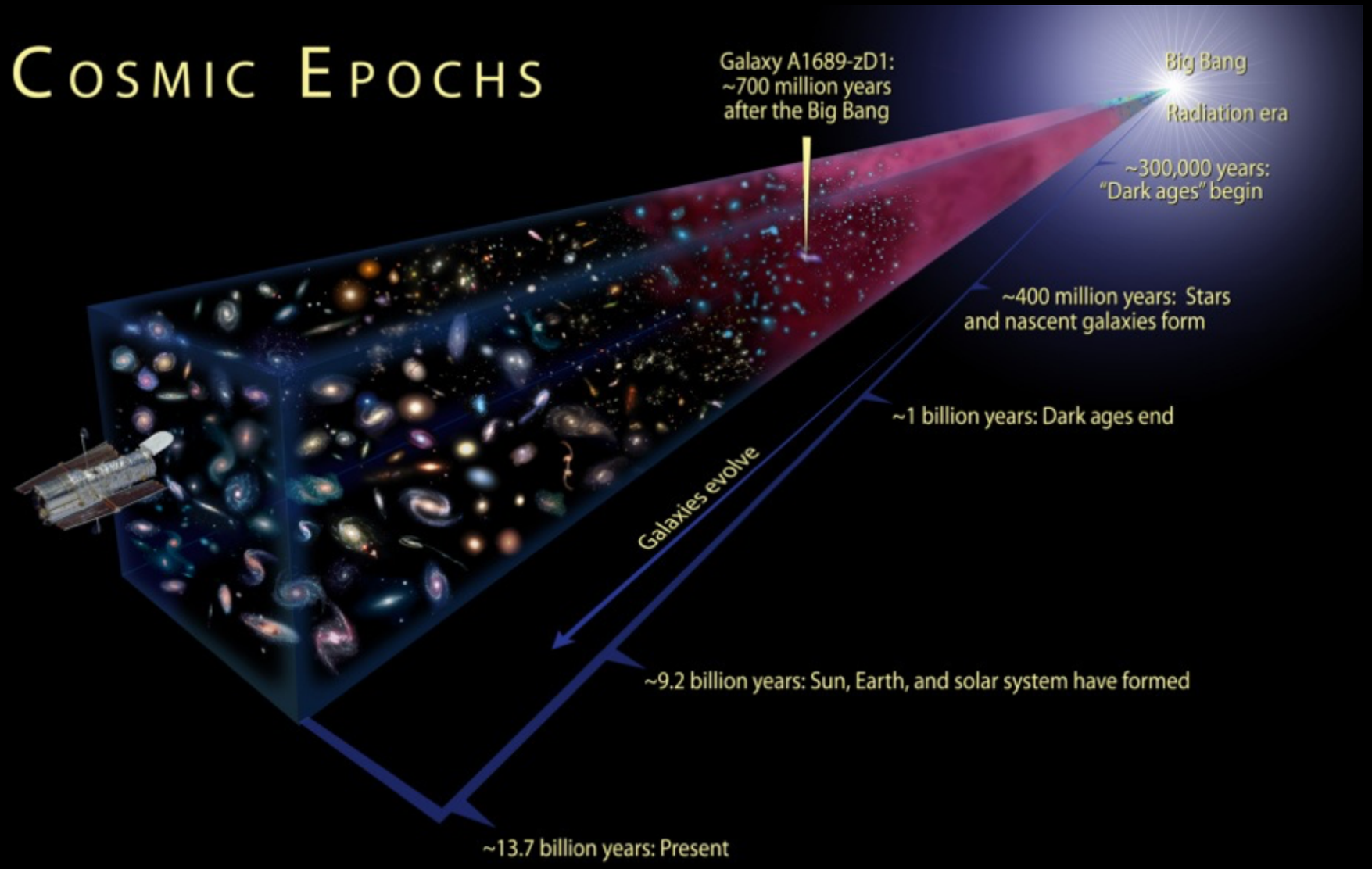
GAMA survey

- GAMA: Galaxy And Mass Assembly
- Includes around ~300,000 galaxy spectra
- Complemented by IFU observations by SAMI survey of ~3000 galaxies

These surveys have contributed immensely to our understanding of the Universe

- Some key results include:
  - ⋆ Bimodal distribution of galaxies in the local universe and its implications to galaxy evolution (e.g. Baldry et al., 2004; Menci et al., 2005; Martinez et al., 2006)
  - ⋆ Constraints on star-formation quenching mechanisms (e.g. Baldry et al., 2006; Cortese & Hughes, 2009; Davies et al., 2016)
  - ⋆ IMF and its universality (Baldry & Glazebrook, 2003; Hoversten & Glazebrook, 2008; Gunawardhana et al., 2011)
  - ⋆ The discovery of low surface brightness and faint dwarf galaxies in the local universe and their population properties (e.g. Zucker et al., 2004; Barazza et al., 2006; Williams et al., 2016)
  - ⋆ The discovery of methane dwarfs (Strauss et al., 1999; Tsvetanov et al., 2000)
  - ⋆ The discovery of populations of high redshift quasars (Fan et al., 2001, 2003, 2004, 2006), merger histories of galaxies (e.g. Bell et al., 2006; Ferreras et al., 2017)
  - ⋆ Constraints on the cosmological parameters from the local universe (e.g. Budav´ari et al., 2003; Tegmark et al., 2004; Eisenstein et al., 2005; Gheller et al., 2016)

To study high-z galaxies we need to go deeper in the expense of FoV



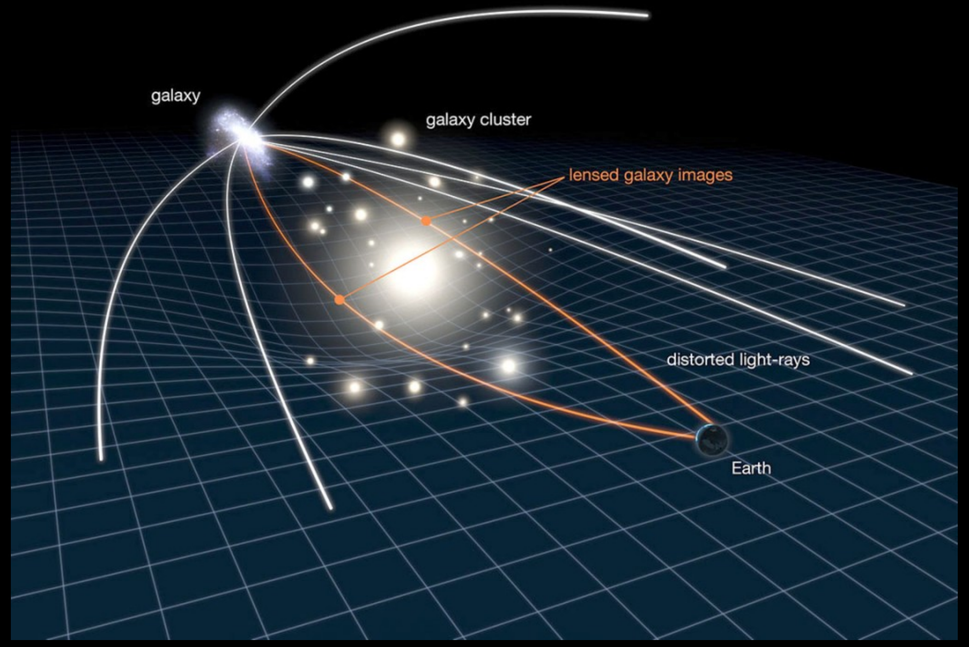
Hubble deep fields

- Hubble space telescope advanced our understanding of the early Universe
- Deep multi-wavelength exposures in multiple pointings in the sky e.g. COSMOS, GOODS-N/S, HDFS, EGS, UDS
- Opened up a new window to study cosmic galaxy evolution
- These fields are supplemented by many other ground and space based observations
- Some large legacy programs include CANDLES, RELICS, BUFFALO

Pushing further with *HST*

Find a Massive Object that magnifies a significant volume of the universe

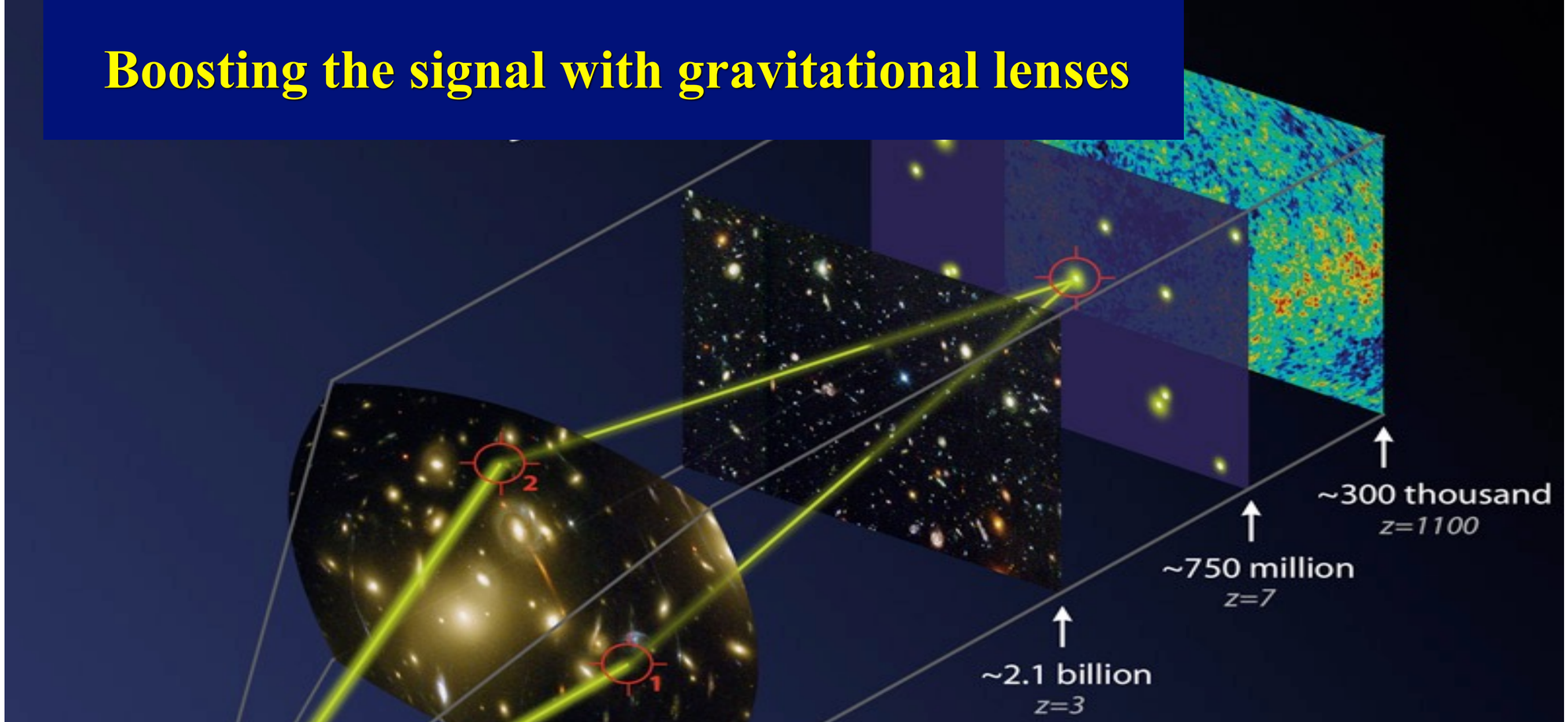
Massive Galaxy Cluster



Increase Sensitivity

Decrease Volume

Boosting the signal with gravitational lenses



- massive clusters of galaxies act like telescopes
- magnify galaxies behind (far behind - far back in time)
- magnified “lensed” galaxies are distorted into long curved shapes
- allows us to see galaxies at high redshift in otherwise-impossible detail.

What is the trick to try to push fainter?

Target that region of the sky with very deep observations with Hubble and other powerful telescopes

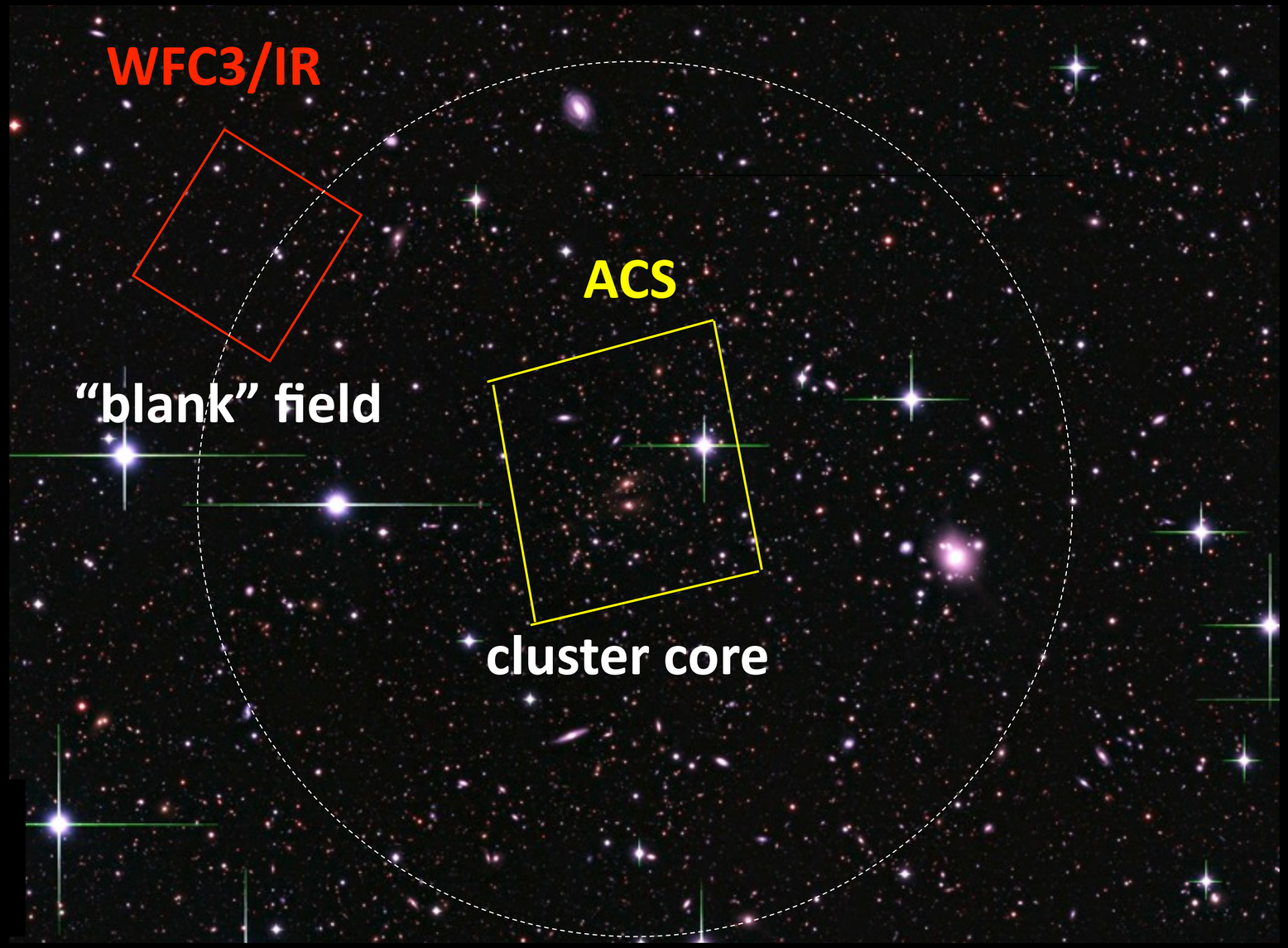
Massive Galaxy Cluster

Integrate for 140 orbits with Hubble

70 orbits in the optical

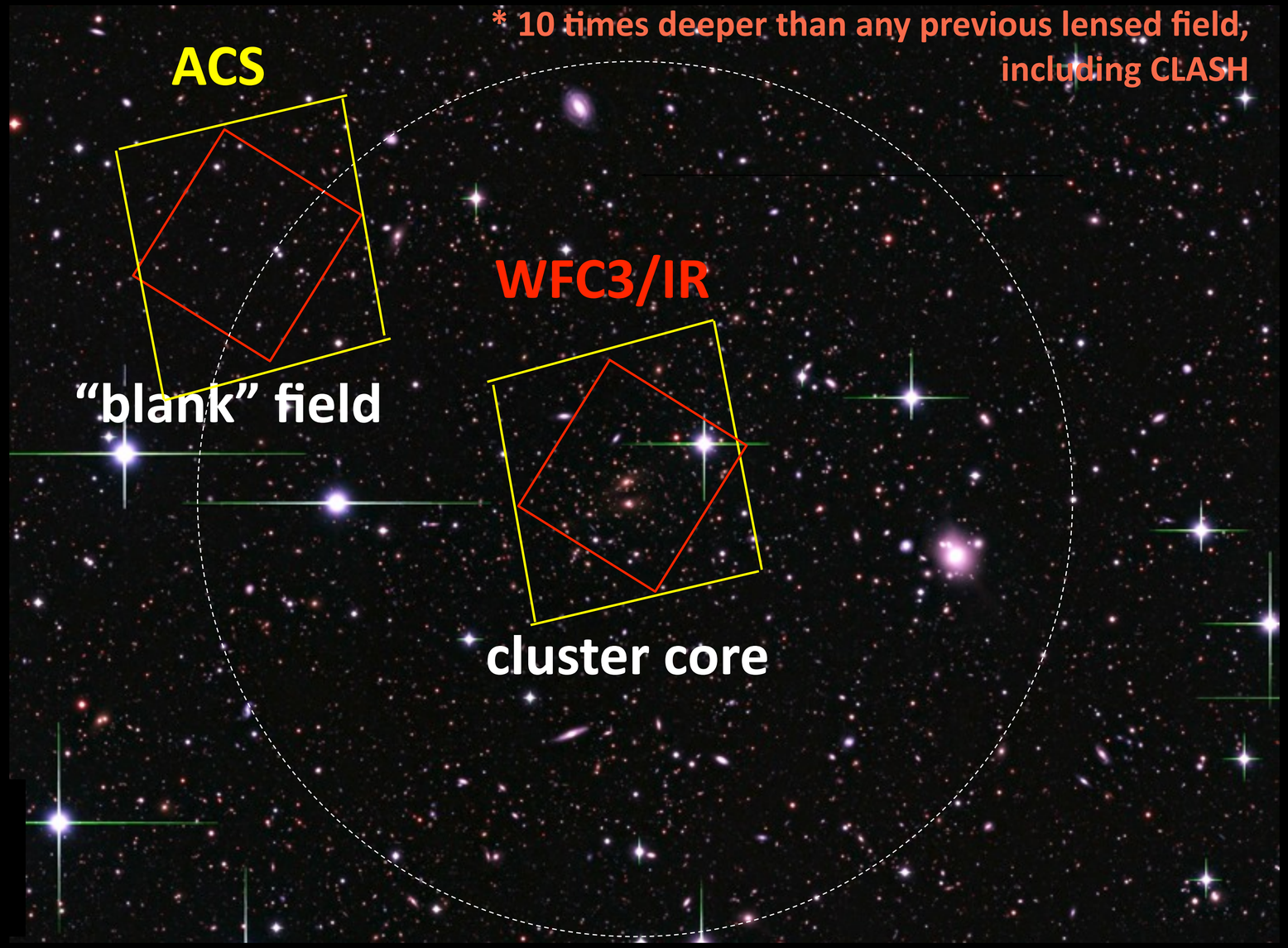
70 orbits in the near-IR

Hubble has observed both lensed and “blank” fields simultaneously in parallel

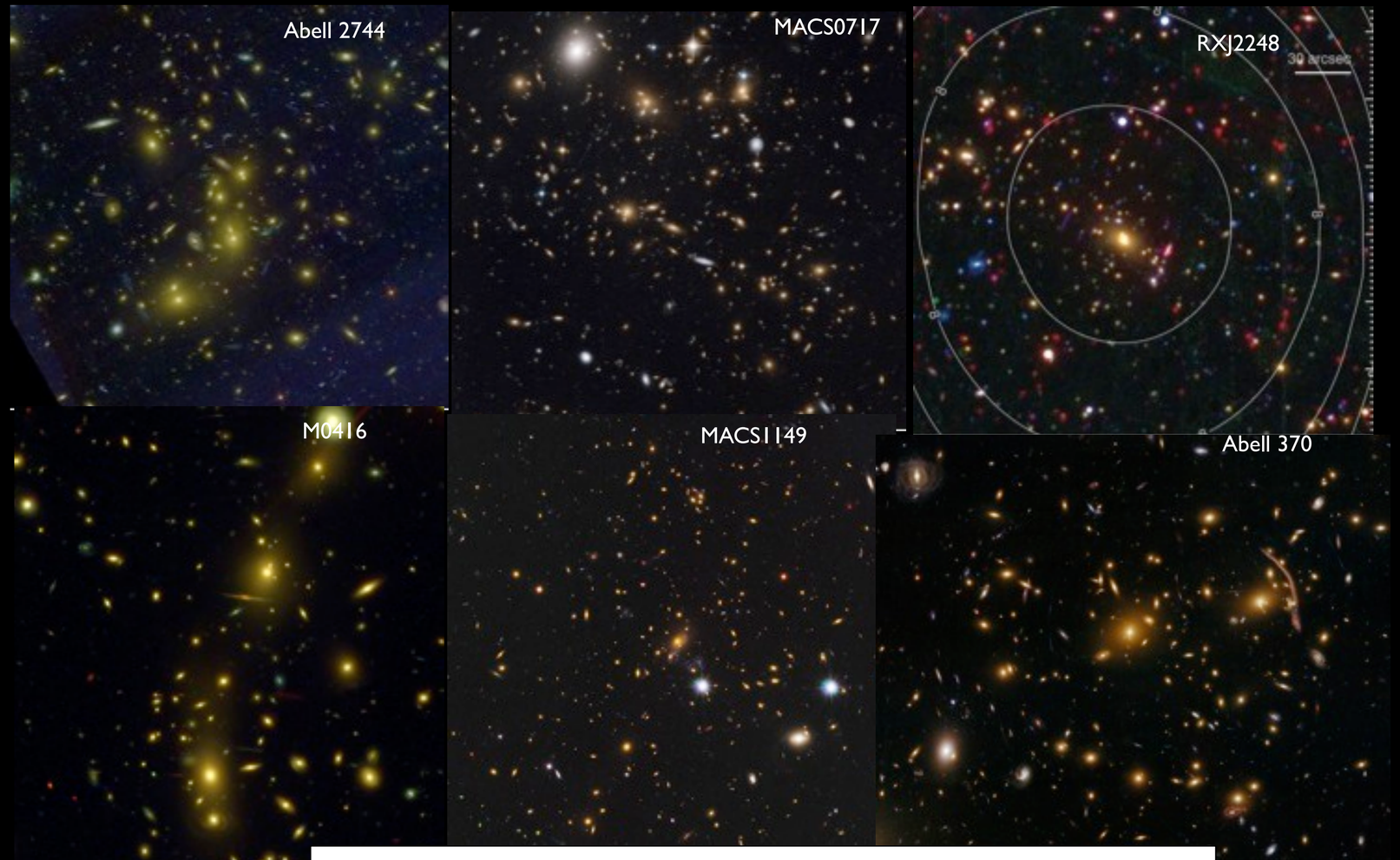


Swap cameras 6 months later / earlier

70 orbits ACS + 70 orbits WFC3/IR* on every field



Repeat this over six massive clusters to improve the statistics and control for cosmic variance

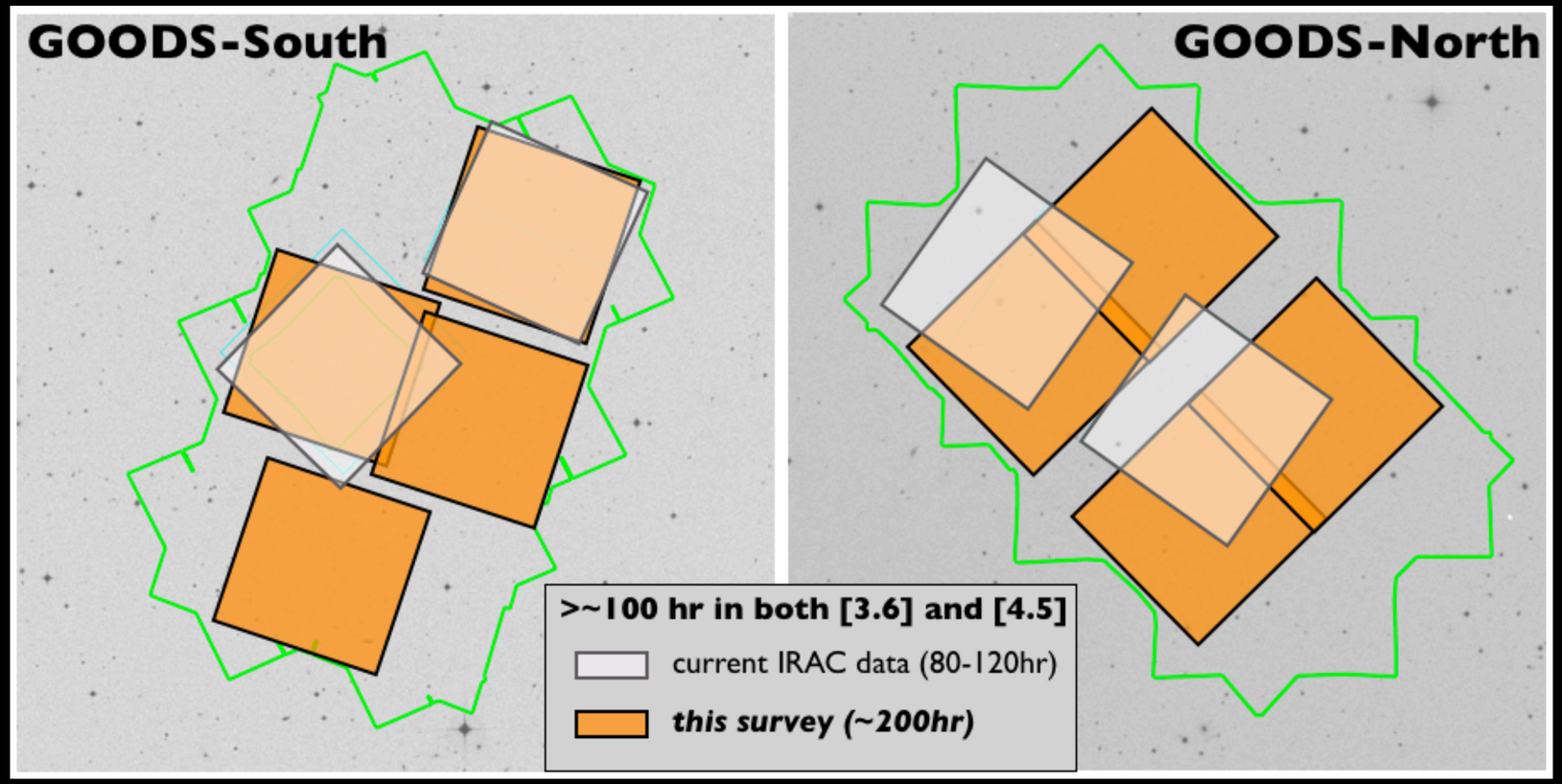


spending 840 orbits

Even Deeper Spitzer/IRAC Observations

e.g. 732-hour GREATS program (PI Labbe)

200 hour depth IRAC data over 200 arcmin^2
26.7 mag at 5σ
Enable Individual detections [OIII], Hα for 0.5 L* galaxies

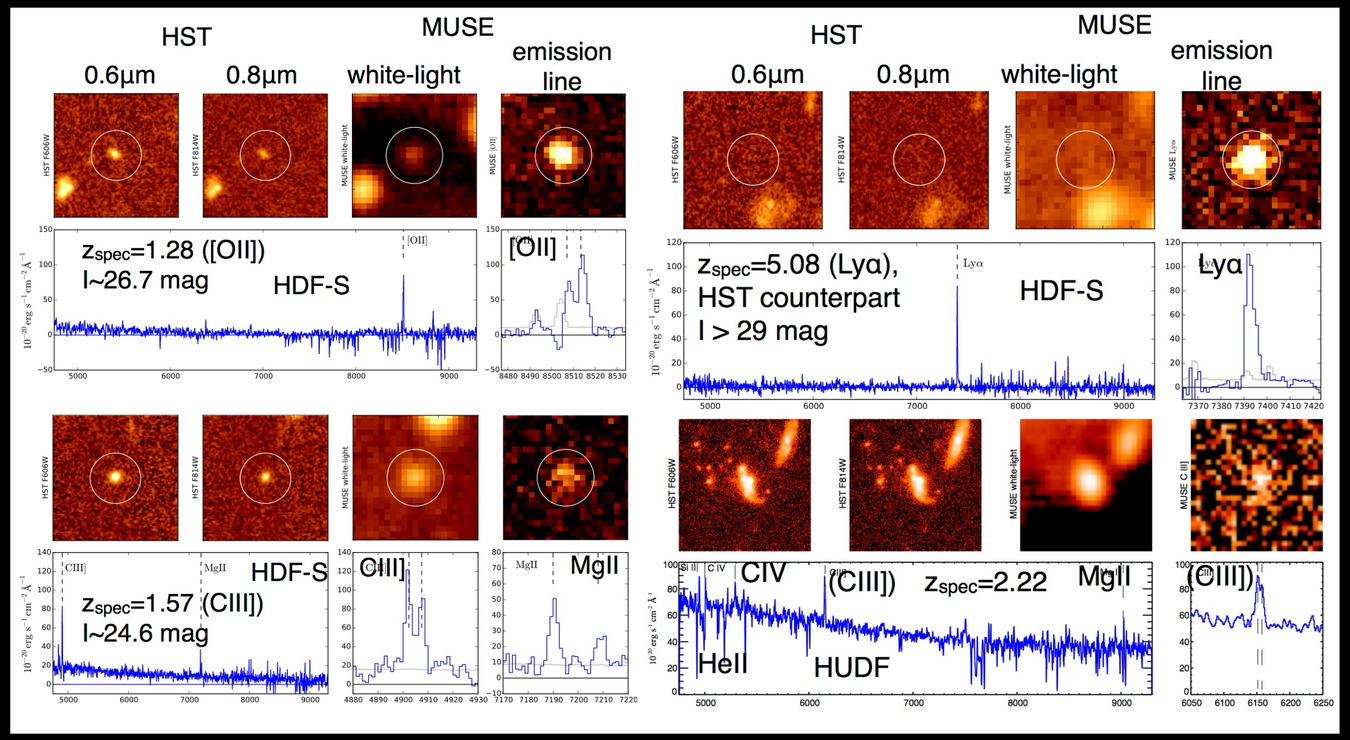


Role of spectroscopic surveys

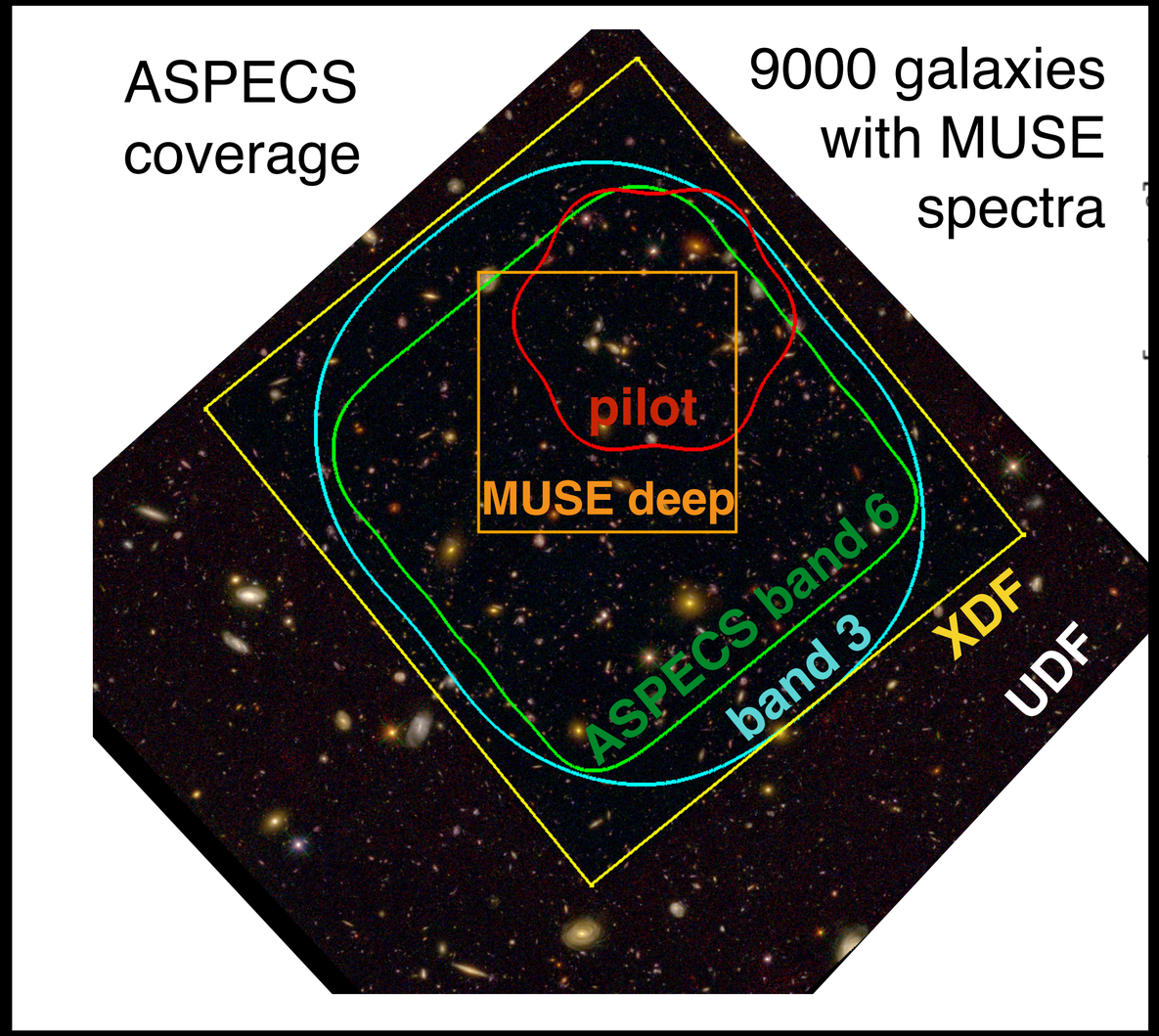
- Redshift information crucial to constrain evolutionary properties
- Surveys from instruments such as MUSE have contributed significantly to enhance the product value of *Hubble* observations

MUSE

- Current observations have gone deeper than HST in UDF alone with 1000+ galaxy redshifts at high-z
- Currently undertaking a single 160h exposure: The DEEPEST pointing in the Universe

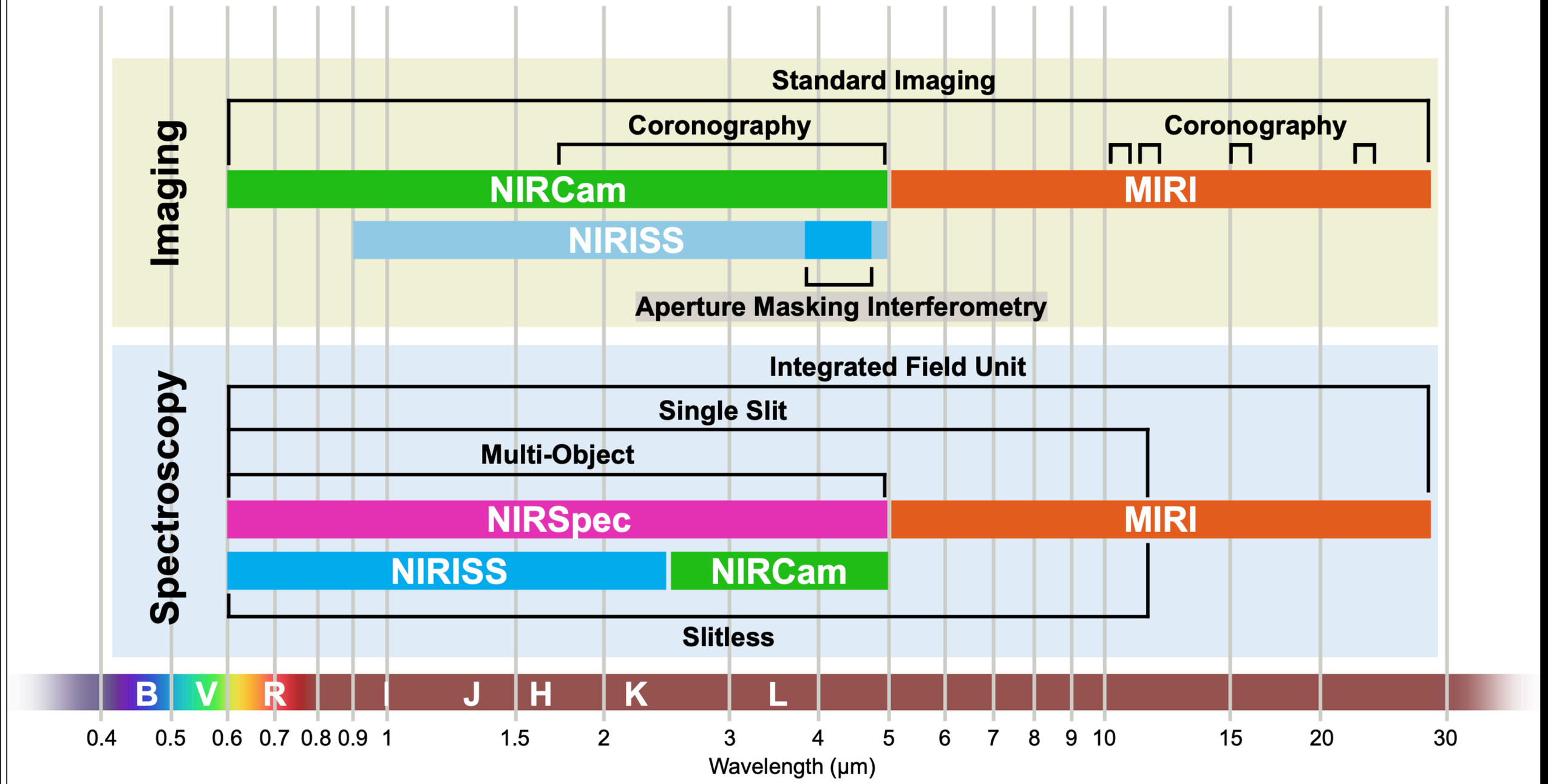


Sub-mm observations from ALMA



JWST

- Scheduled to be launched in 2021
- Will observe in Near and mid-Infra red up to 28μm


Imaging
Standard Imaging
Coronography
Coronography
NIRCam
MIRI
NIRISS
Aperture Masking Interferometry
Spectroscopy
Integrated Field Unit
Single Slit
Multi-Object
NIRSpec
MIRI
NIRISS
NIRCam
Slitless
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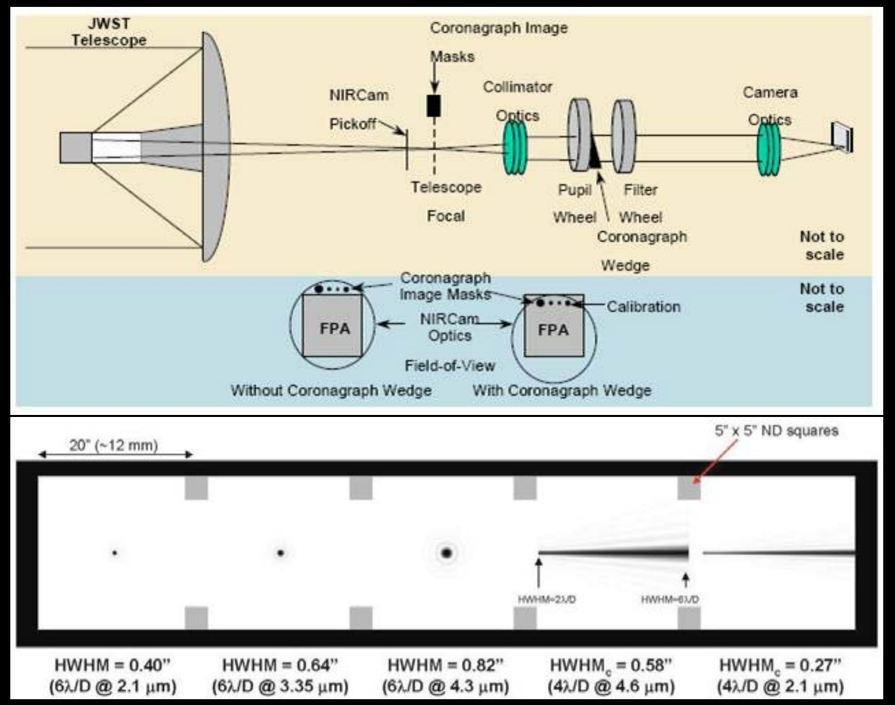
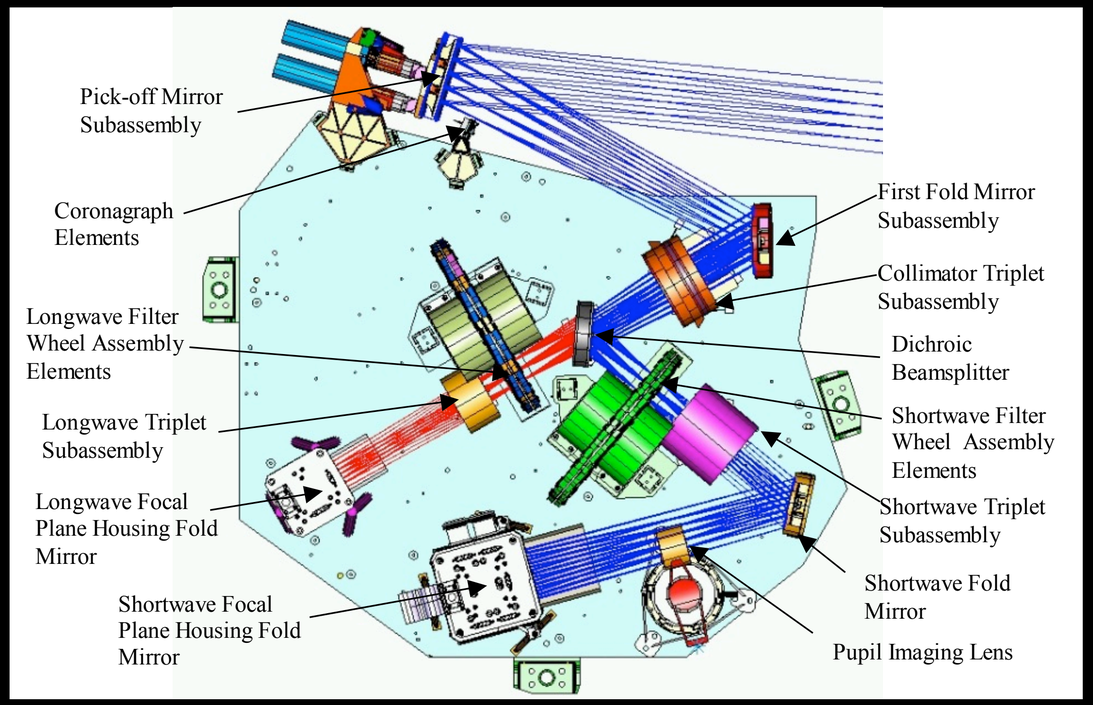
30
Wavelength (μm)

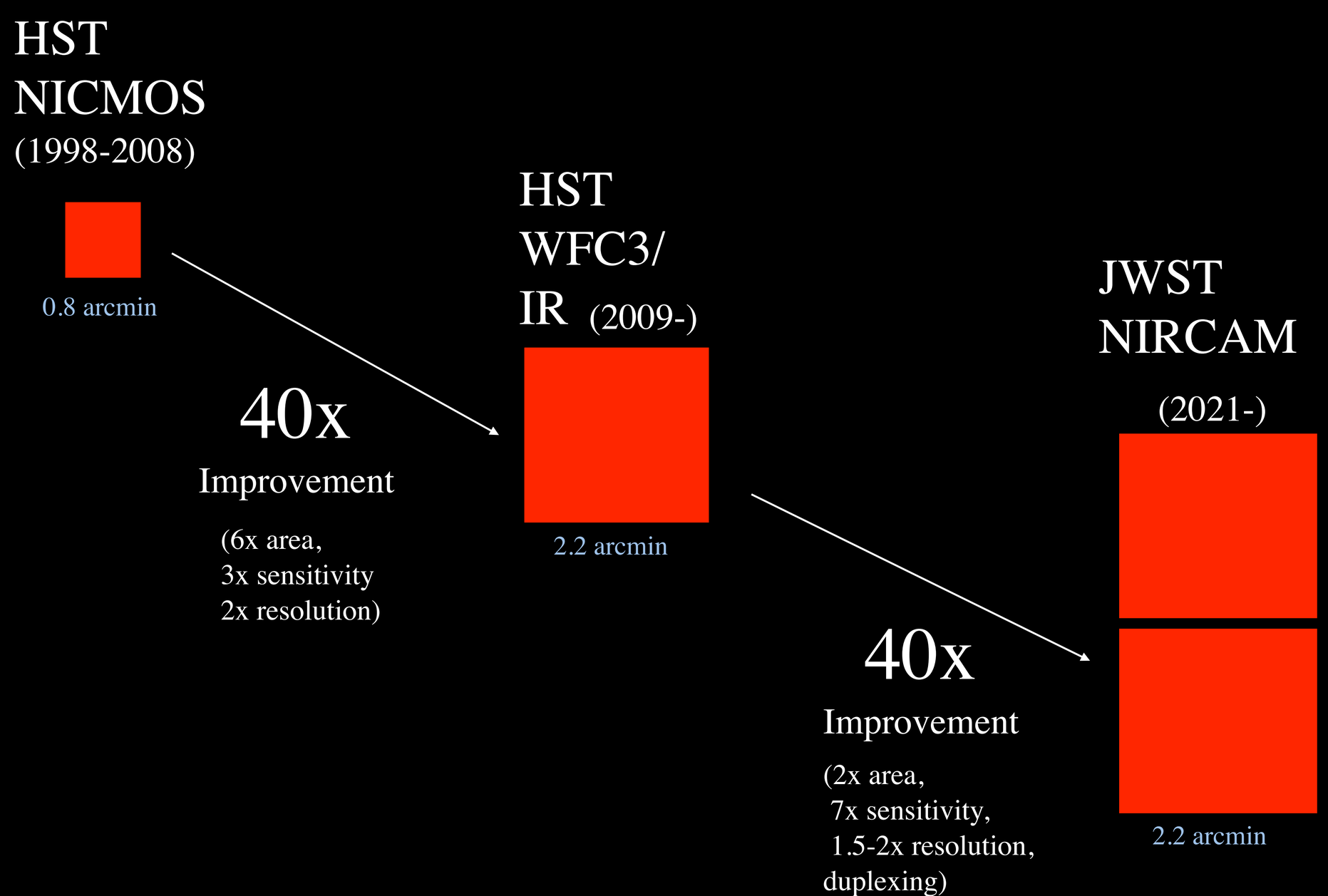
NIRCam will provide the deepest near-infrared images ever and will identify primeval galaxy targets for the NIRSpec

- Developed by the University of Arizona with Lockheed Martin STAR Labs
  - Operating wavelength: 0.6 – 5.0 microns
  - Field of view: 2.2 x 4.4 arc minutes
  - Angular resolution (1 pixel): 32 mas < 2.3 microns, 65 mas > 2.4 microns
  - Imagery: R= 4, 10, 100 filters
  - Spectroscopy: grisim (slit-less) R~2000 2.4 – 5 microns
  - Coronagraph



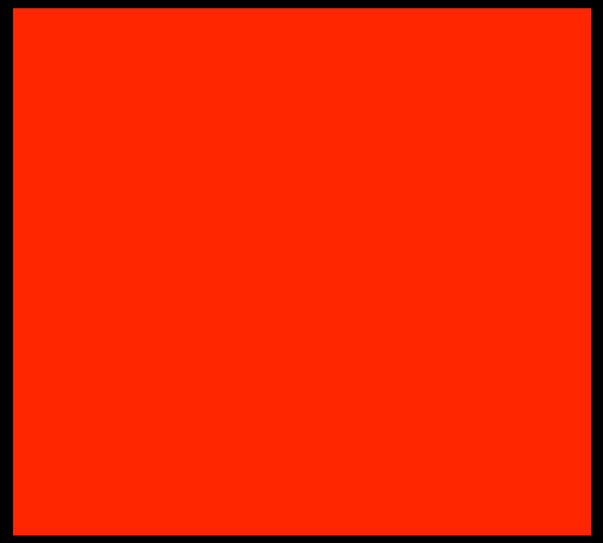


WFC3/IR serves as an essential pathfinder (at <2μ)



Spitzer IRAC Pathfinder at 2-5μ

Spitzer
IRAC
(2004-)



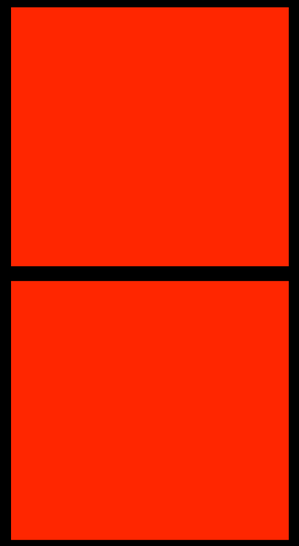
5.2 arcmin

>1000x

Improvement and
few confusion issues

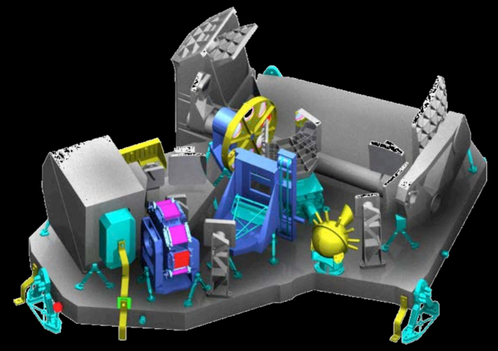
(70x sensitivity,
10x resolution,
0.35x area)

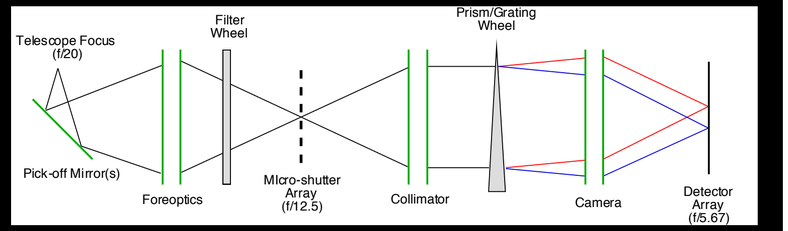
JWST
NIRCAM
(2021-)

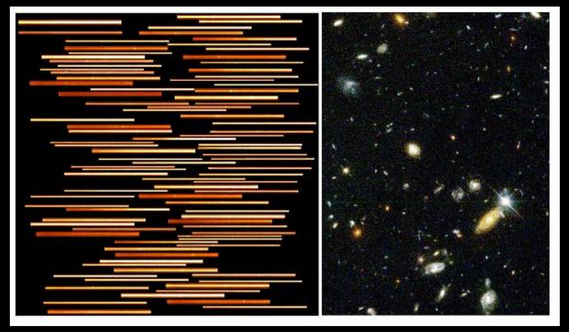


2.2 arcmin

The NIRSpec will acquire near-infrared spectra of up to 100 objects in a single exposure



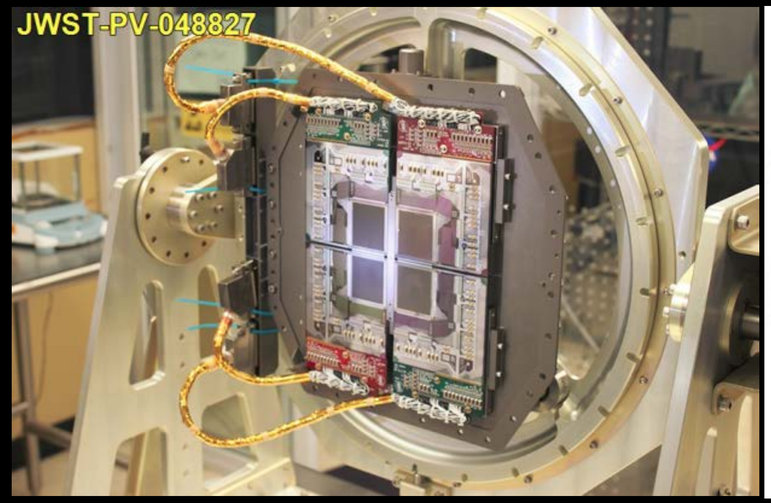


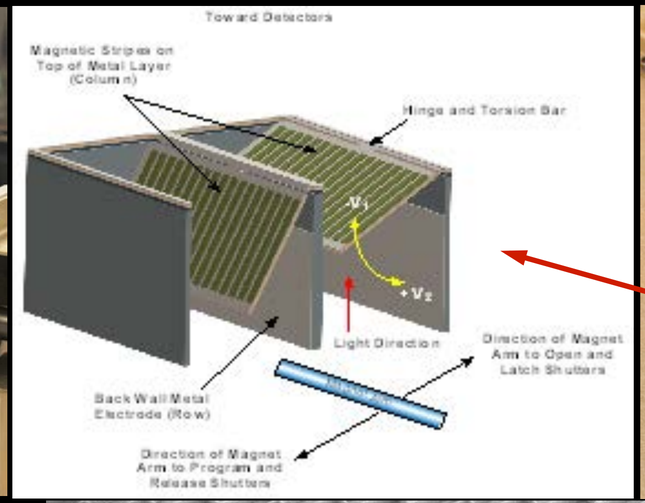


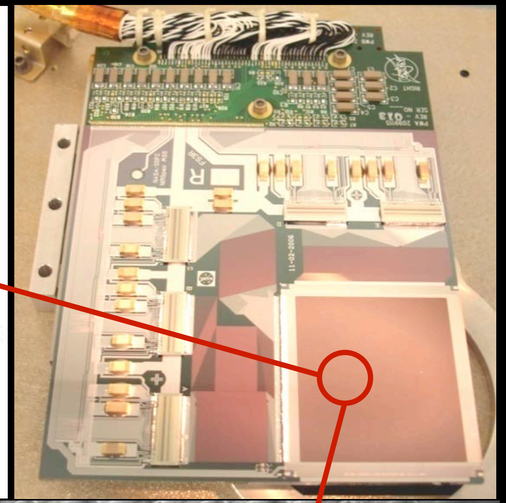
- Developed by the European Space Technology Center (ESTEC) with Astrium and Goddard Space Flight Center
  - Operating wavelength: 0.6 – 5.0 microns
  - Spectral resolution: 100, 1000, 3000
  - Field of view: 3.4 x 3.4 arc minutes
    - Aperture control:
      - Programmable micro-shutters, 250,000 pixels
        - 203 x 463 mas clear aperture (267 x 528 mas pitch)
      - Fixed long slits & transit spectroscopy aperture
        - 200, 400, 1600 mas slit width
      - Image slicer (IFU) 3x3 arc sec FOV (100 mas slice width)
  - All aperture control modes available with any spectral resolution mode

NIRSpec can obtain spectra of 100 compact galaxies simultaneously

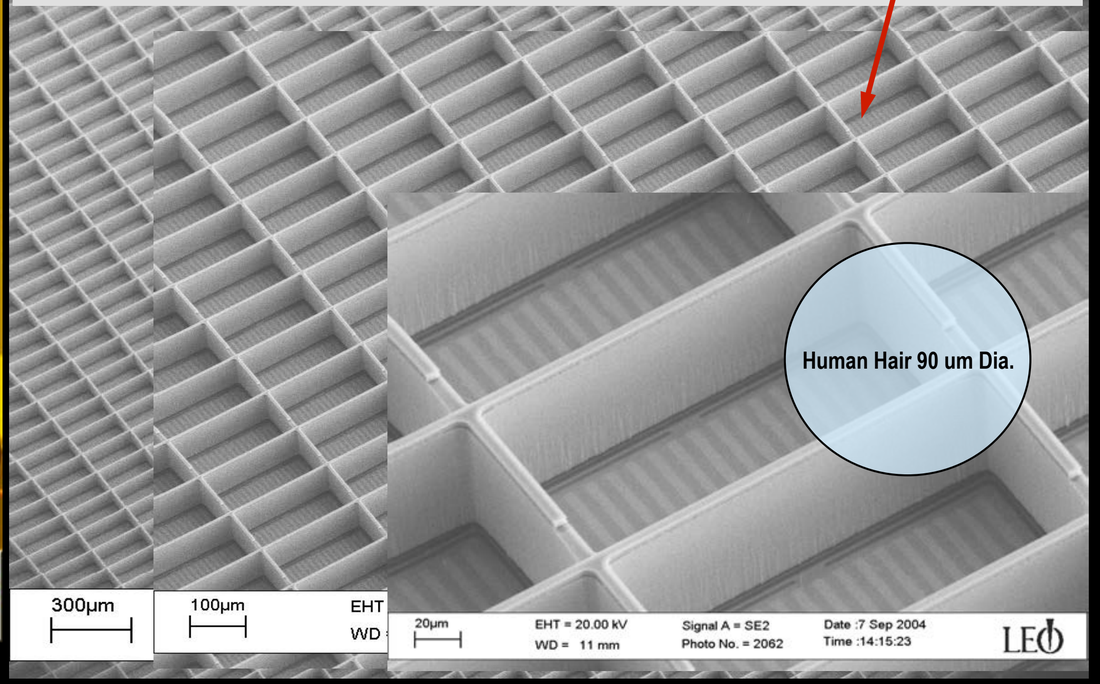
Aperture control: 250,000 programmable micro-shutters

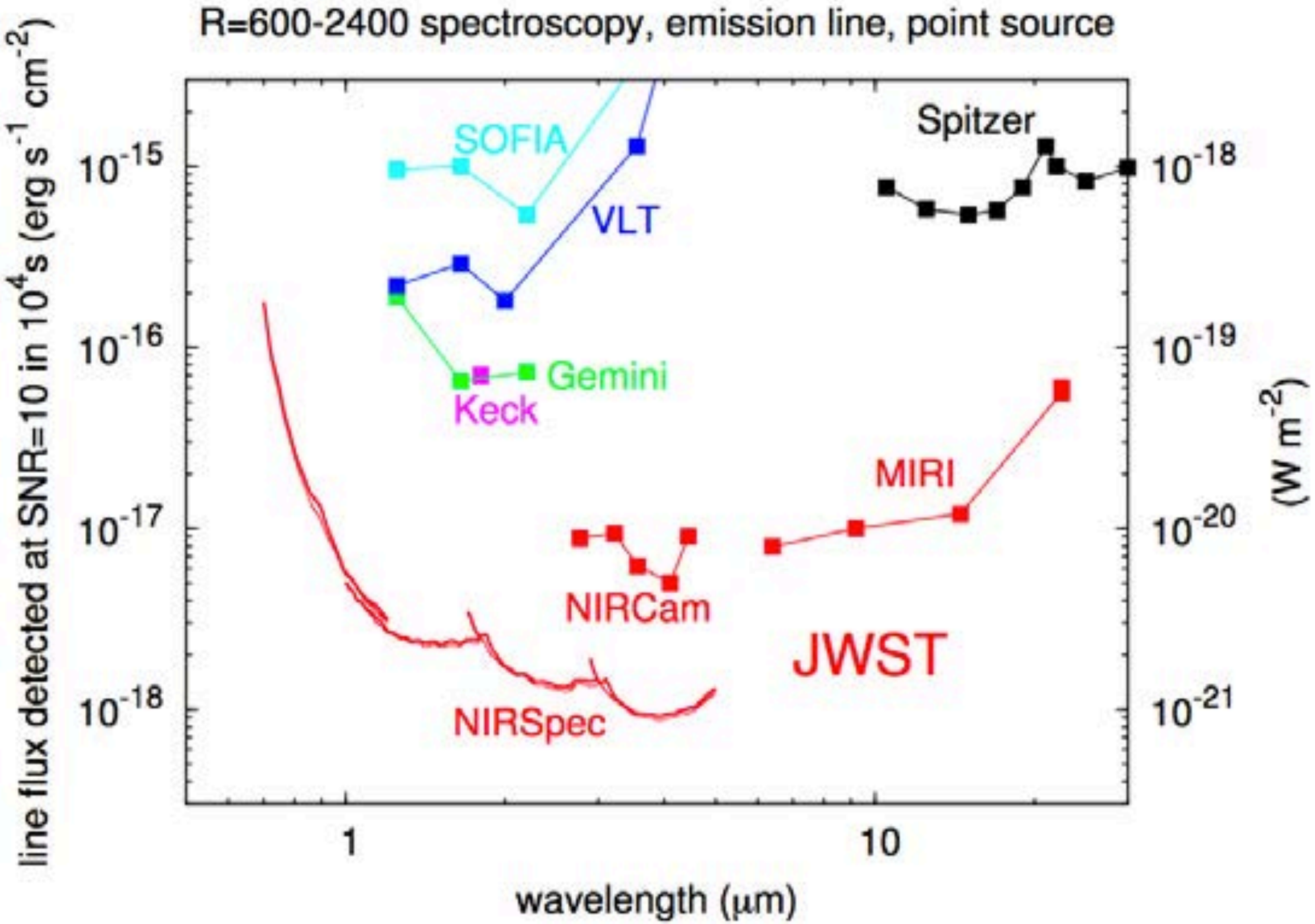




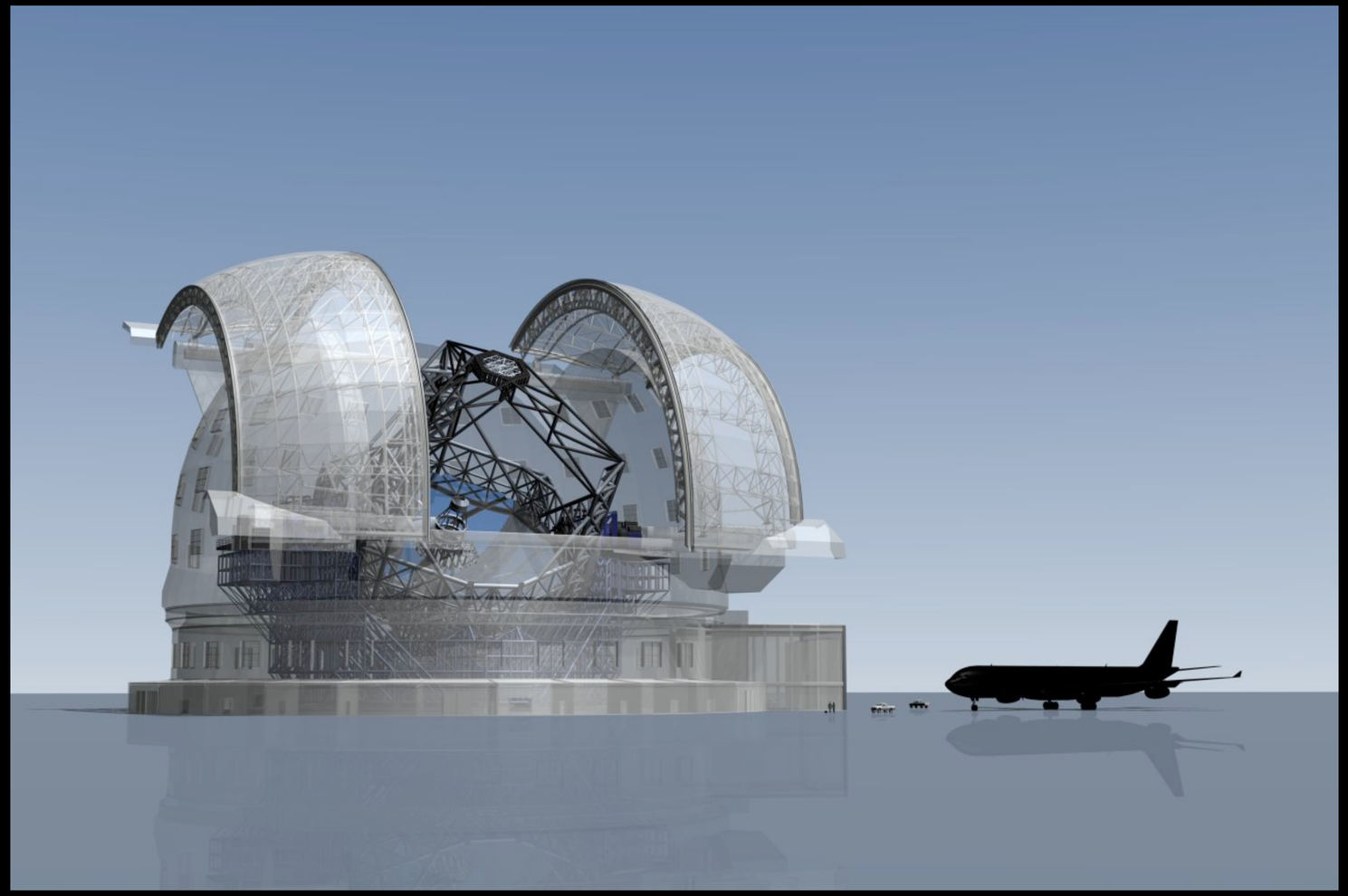


203 x 463 mas shutter pixel clear aperture, 267 x 528 mas pitch, 4 x 171 x 365 array




R=600-2400 spectroscopy, emission line, point source
line flux detected at SNR=10 in 10^4s (erg s^{-1} cm^{-2})
(W m^{-2})
wavelength (μm)
SOFIA
VLT
Spitzer
Gemini
Keck
MIRI
NIRCam
JWST
NIRSpec
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
1
10

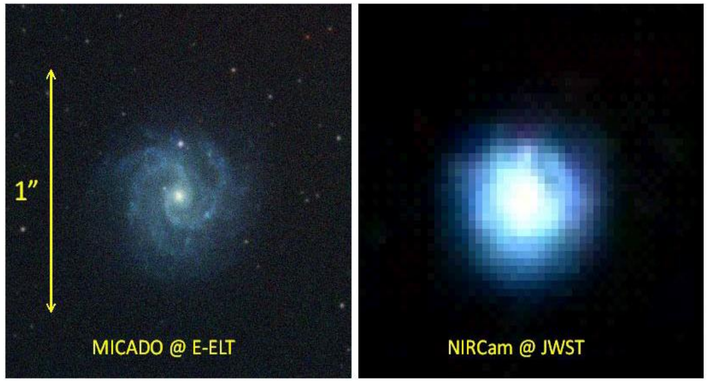
European Extremely Large Telescope
39-meter diameter
(2024+)



www.eso.org

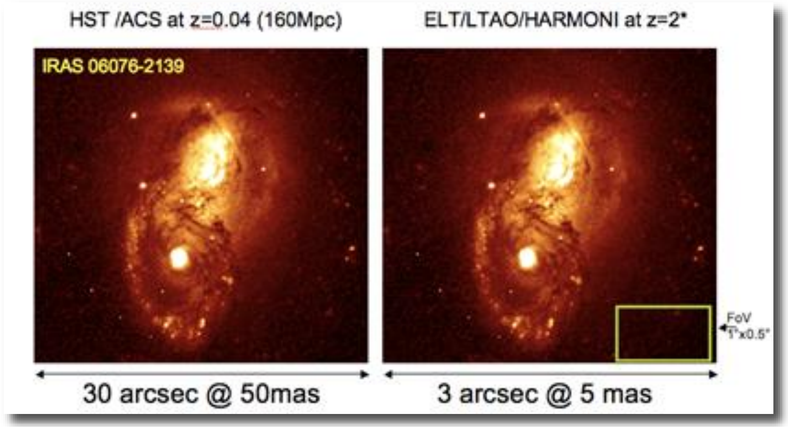
Attributes of Optical/NIR E-ELT Instruments

ELT-CAM
(MICADO)



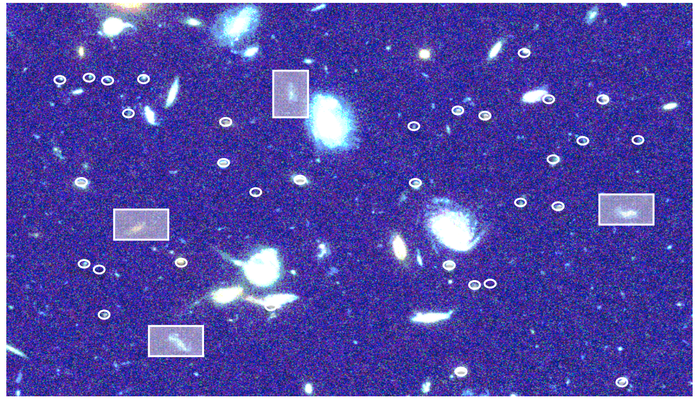
Deep imaging in selected areas to probe the rest-frame UV LF

ELT-IFU
(HARMONI)



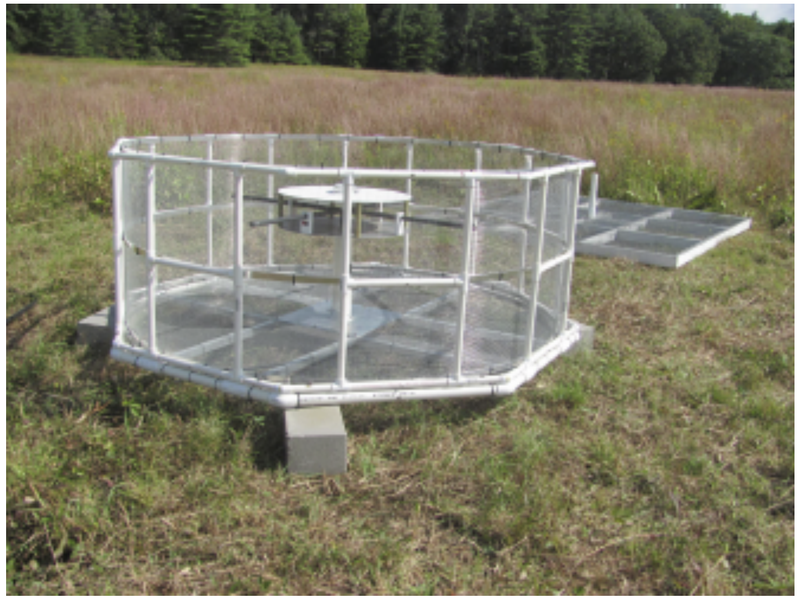
Diagnostic spectroscopy of ionizing radiation using rest-frame UV metal lines

ELT-MOS
(MOSAIC)



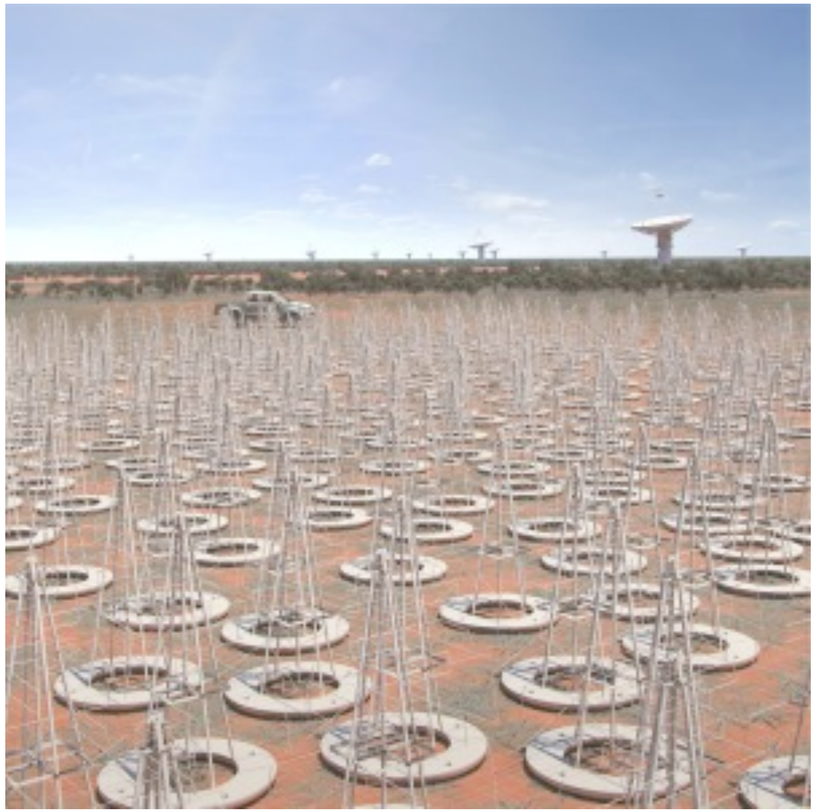
High spectral resolution studies of stacked z~5-7 sources to probe covering fraction of low ionizing and neutral gas

21cm observations: HERA and SKA



HERA prototype (Neben+16)

Square Kilometer Array



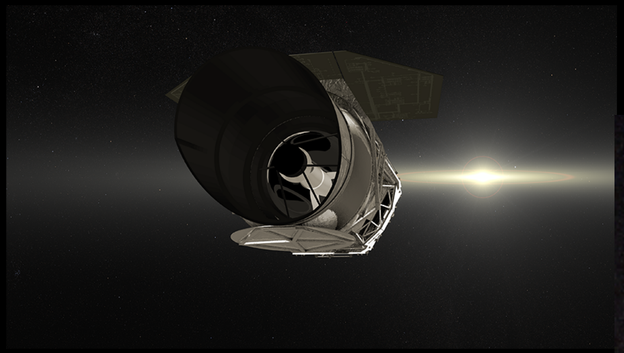
The Hydrogen Epoch o
Reionization Array (HE
(Pober et al. 2014; DeB
2016) is drawing on
lessons learned by the M
PAPER to reach the
calibration and foregrou
isolation accuracy requi
make a signicant detecti
characterization of the
cosmological signal.

should detect the EOR
spectrum at z 9 with a
noise ratio of 19.3

- Hydrogen Epoch of Reionization Array (HERA;Pober+14)
  - Improving Calibration and foreground isolation accuracy w experiences of PAPER and MWA (redundant baseline-> redundant calib.)
  - Aiming a 21cm power spectrum detection w S/N~20 at z~9

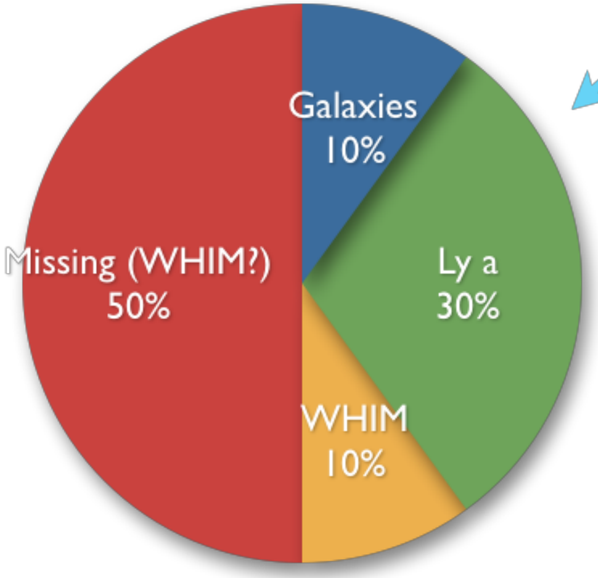
- Square Killometer Array (SKA; ~2030)

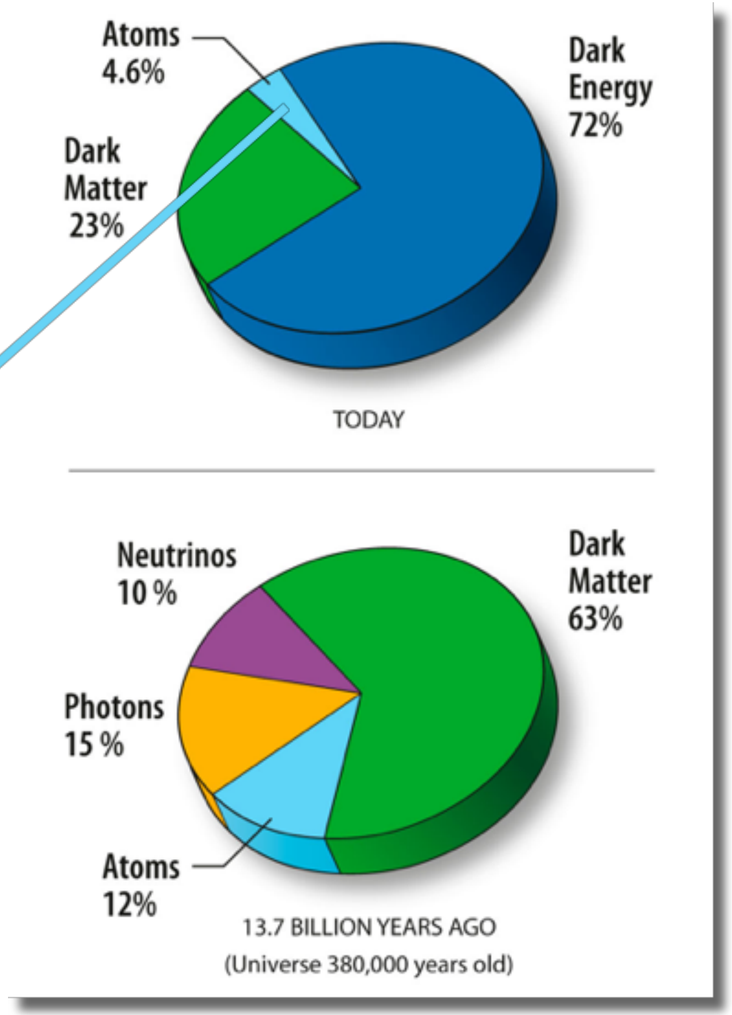
Post JWST



The cosmic inventory

- Only ~10% of the baryons are detectable as stars and cold gas!
- Almost 90% of the baryons is thought to exist as a warm/hot (10^5-10^7 K) intergalactic medium.





The most interesting things are yet to come…..