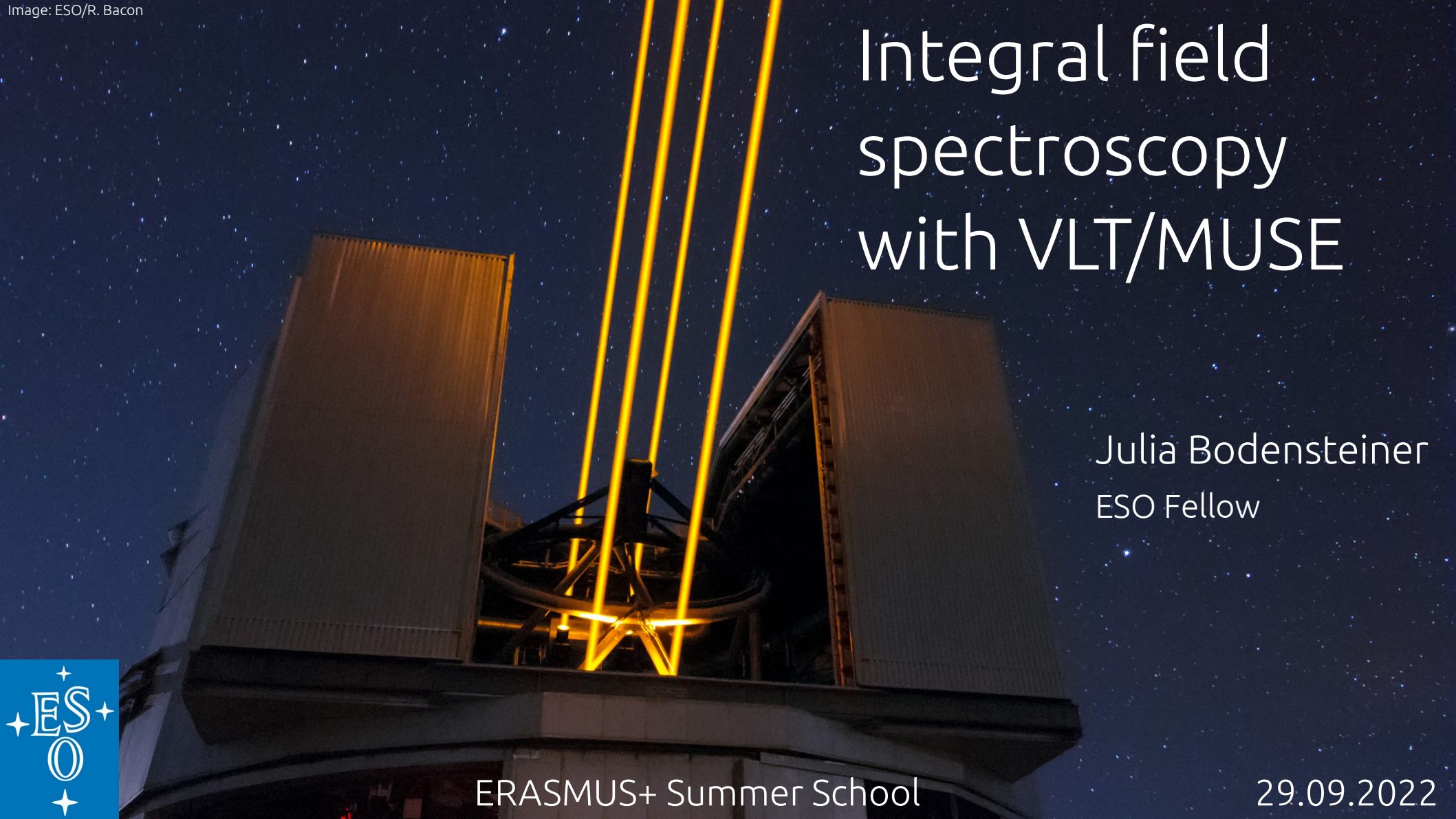


Image: ESO/R. Bacon

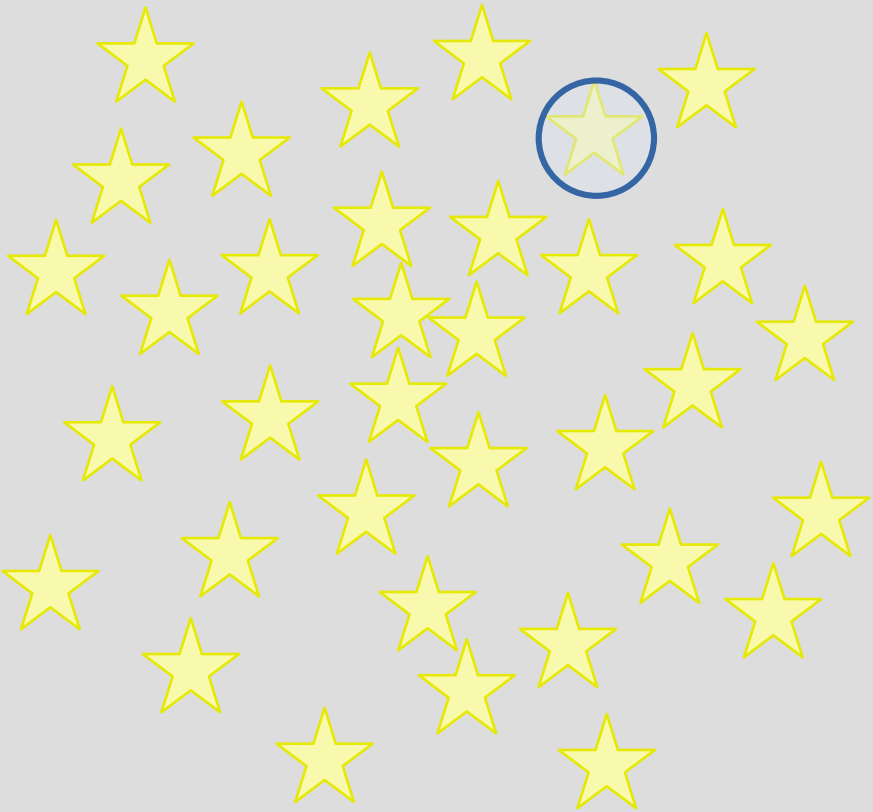
Integral field spectroscopy with VLT/MUSE

Julia Bodensteiner
ESO Fellow

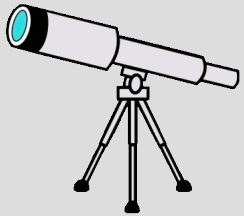
ERASMUS+ Summer School

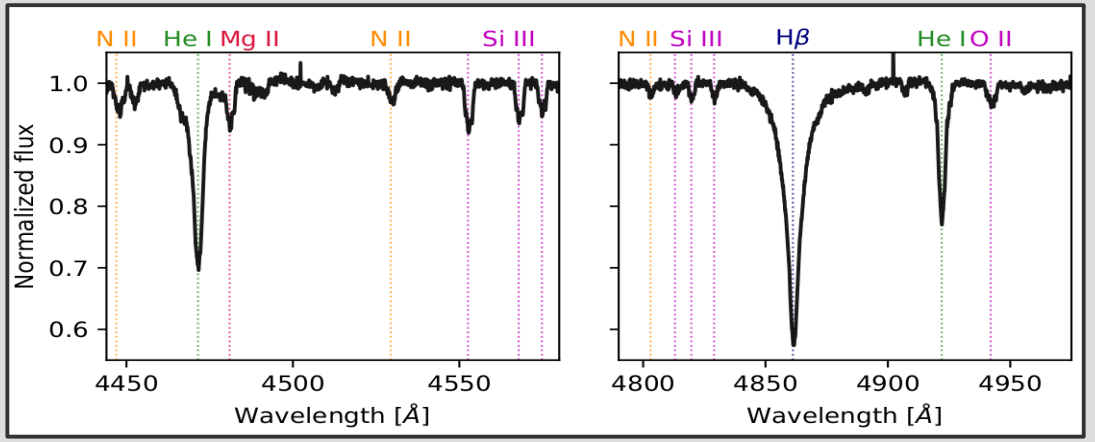
29.09.2022

Why integral field spectroscopy

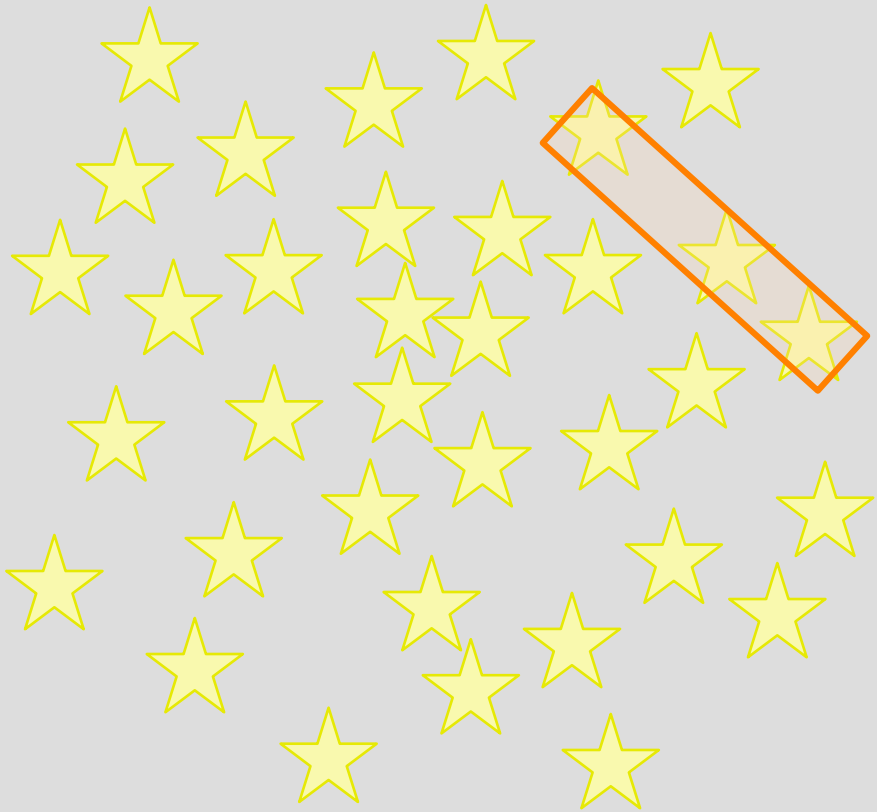


1D spectroscopy
(for example fiber-fed)

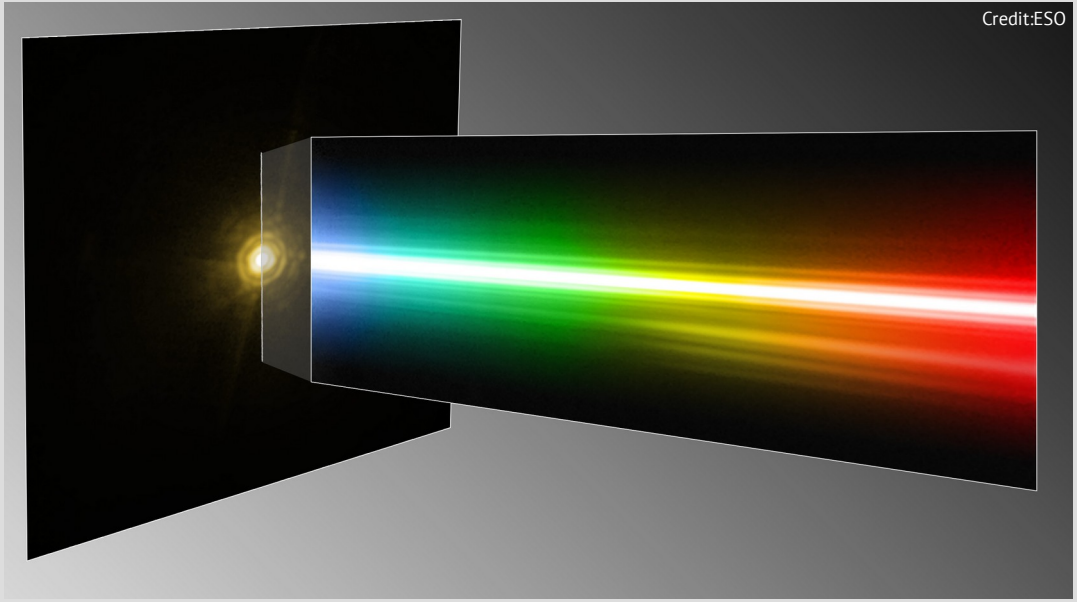




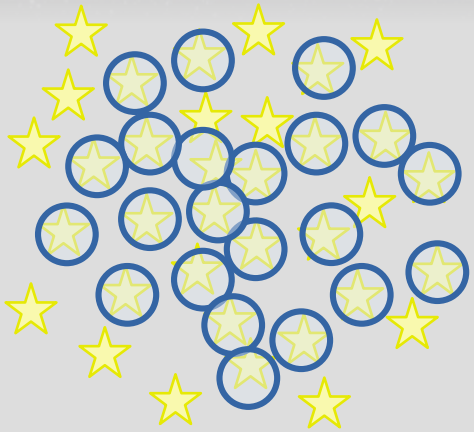
Why integral field spectroscopy



(2D) spectroscopy
for example with a long slit

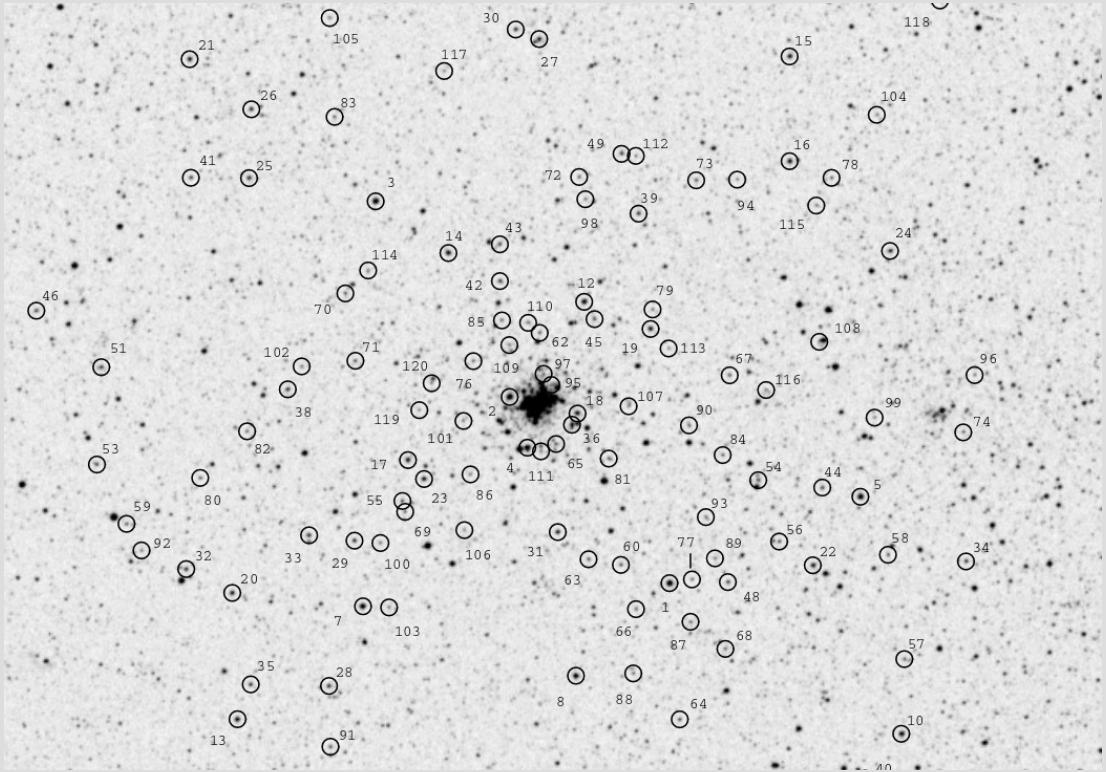


Why integral field spectroscopy

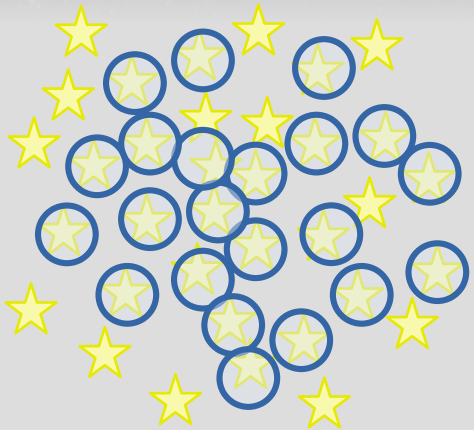


Multi-object 1D spectroscopy

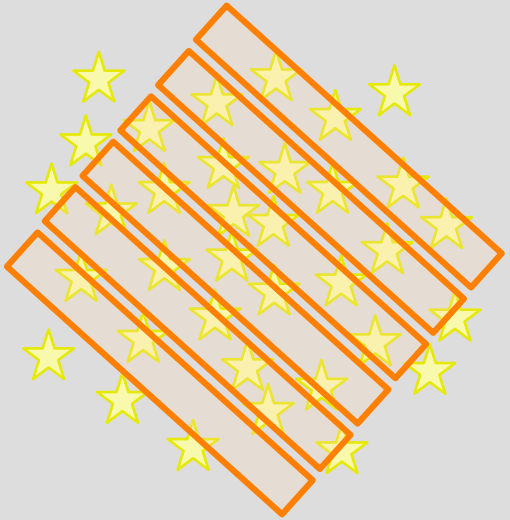
NGC 330 in the SMC
Evans et al. 2006



Why integral field spectroscopy



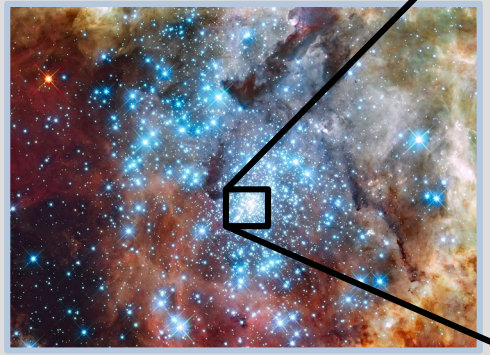
Multi-object 1D spectroscopy

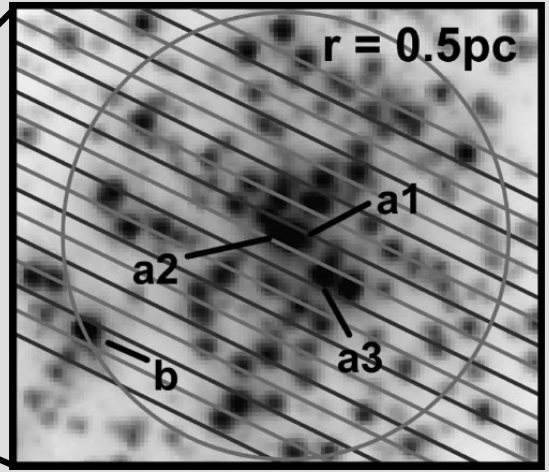


Multi-slit 2D spectroscopy

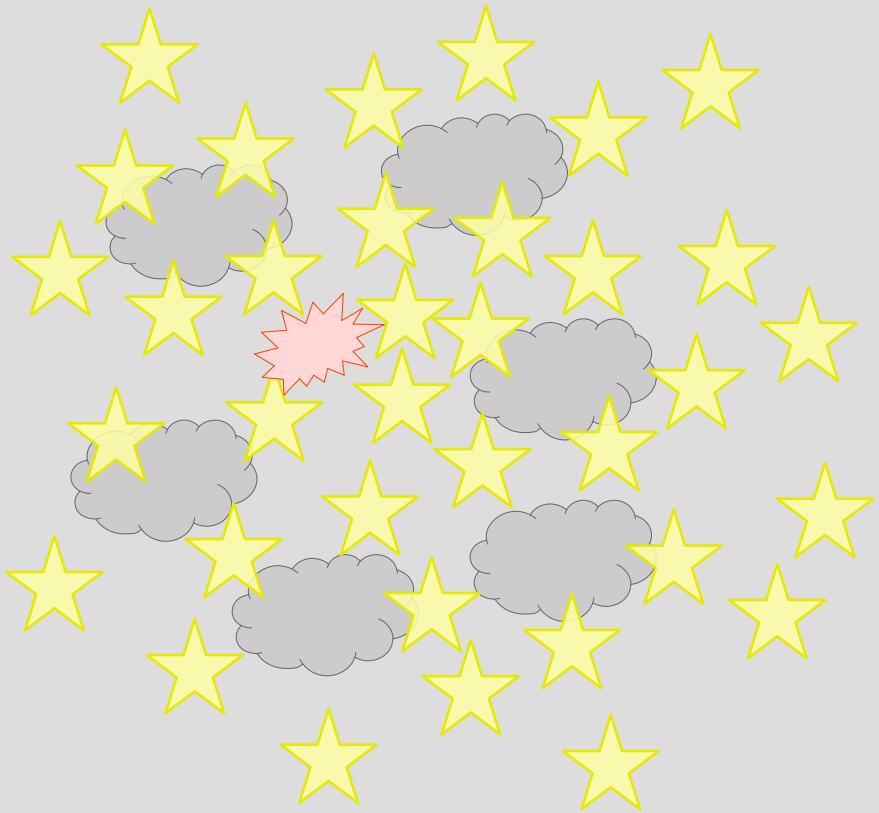
R136 (LMC)

Crowther et al. 2016





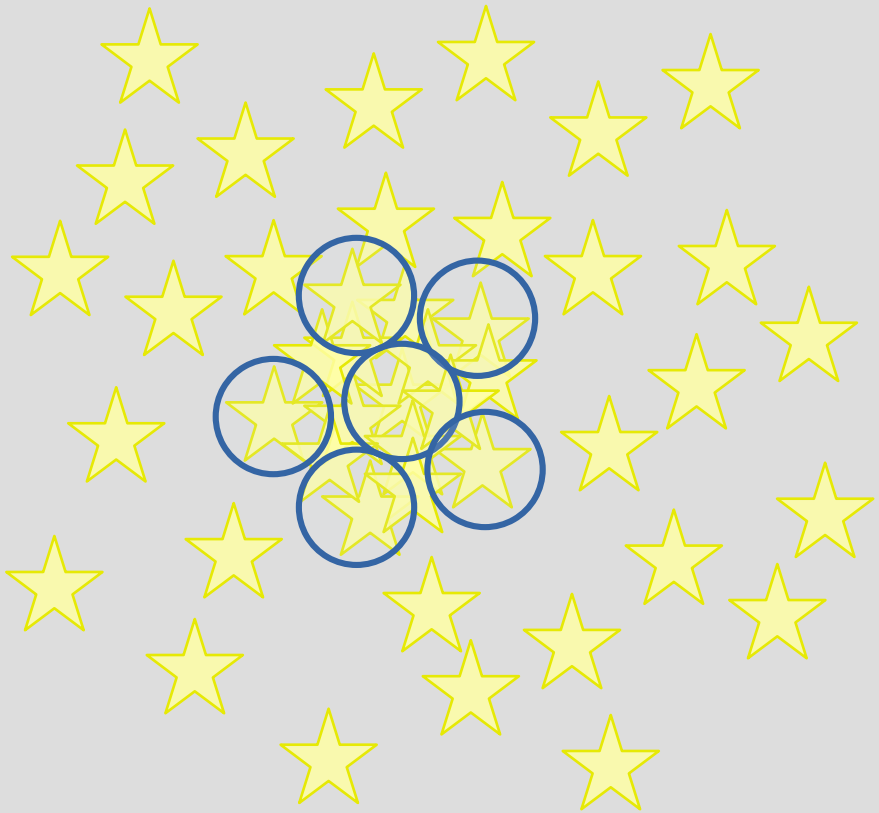
Why integral field spectroscopy



Integral field spectroscopy

- background emission

Why integral field spectroscopy



Integral field spectroscopy

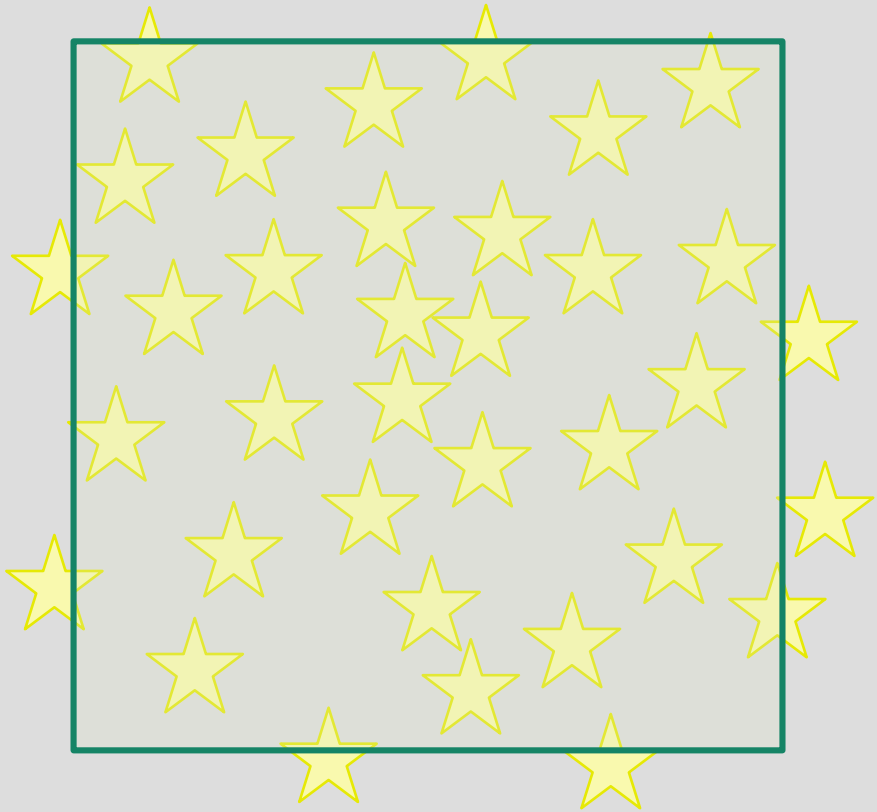
- background emission
- very crowded fields

Why integral field spectroscopy

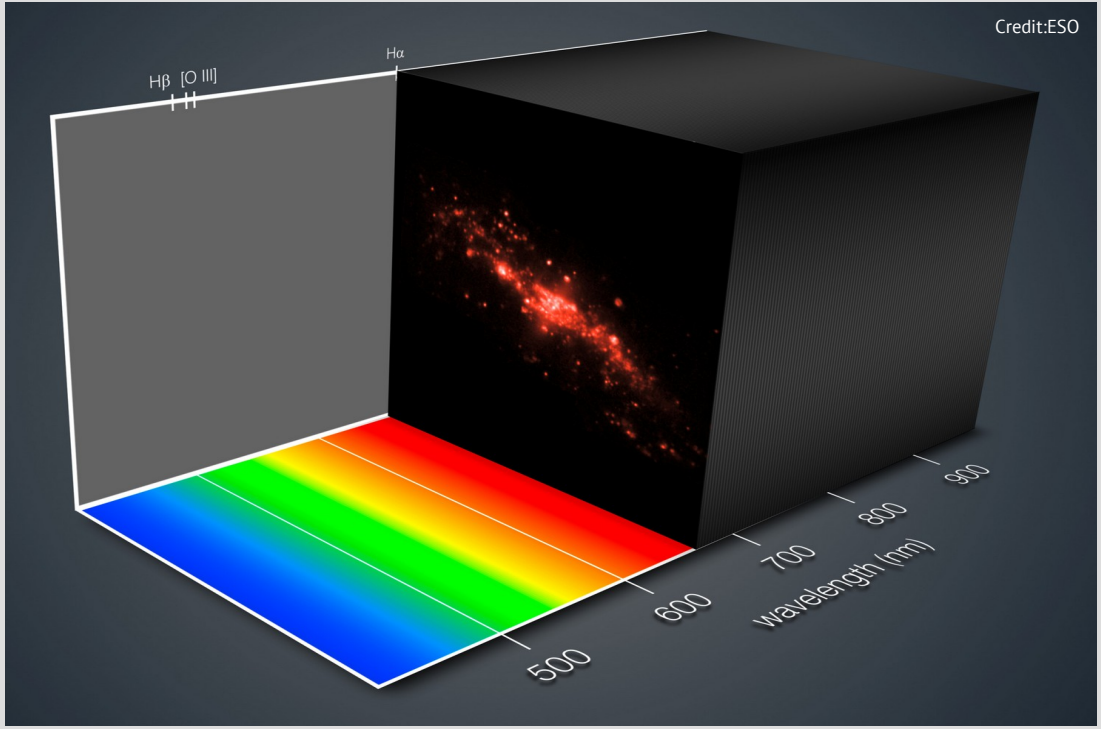
Integral field spectroscopy

- background emission
- very crowded fields
- extended objects

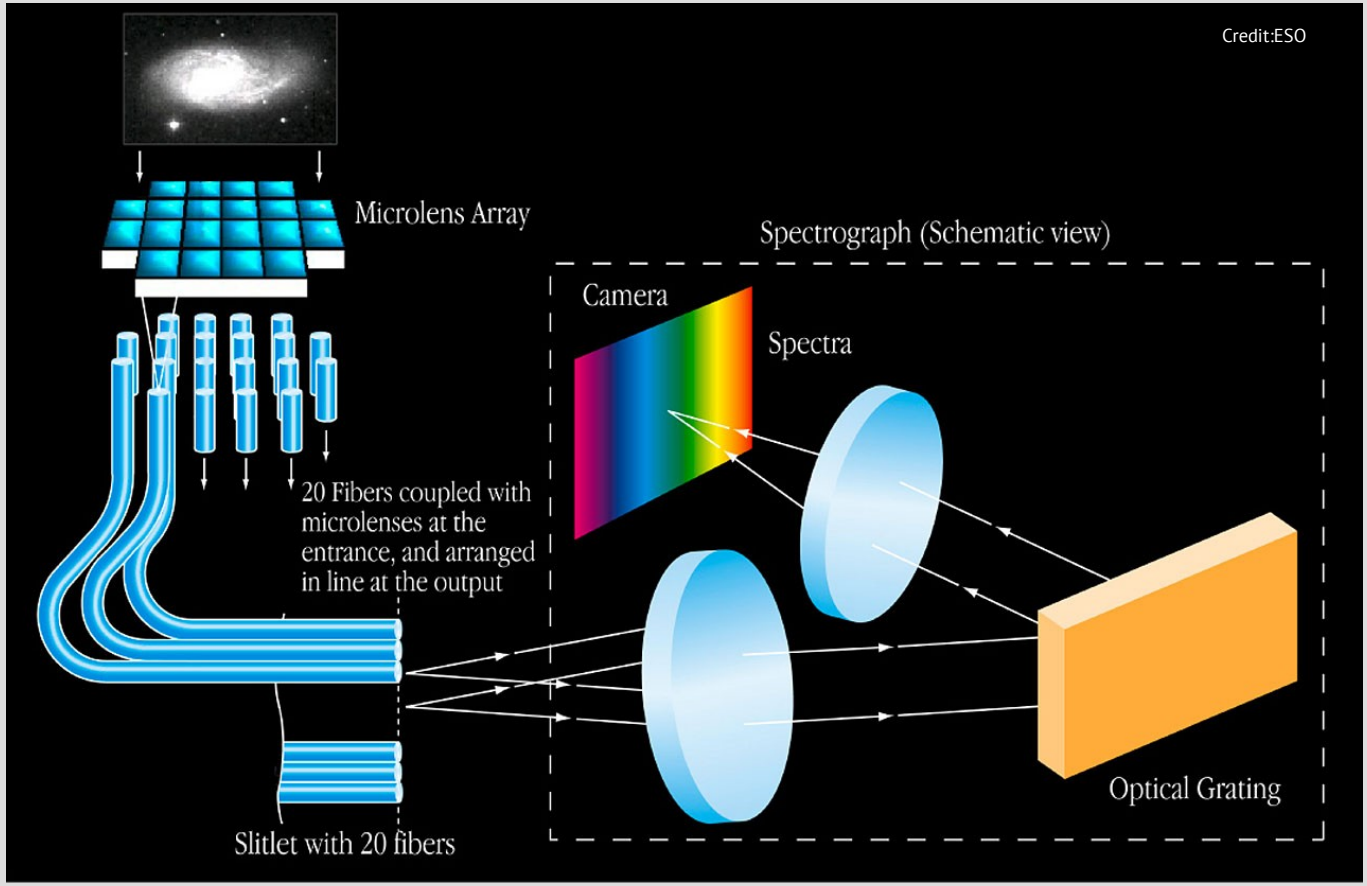
Why integral field spectroscopy



(3D) Integral field spectroscopy
= photometry + spectroscopy



Different methods of IFS



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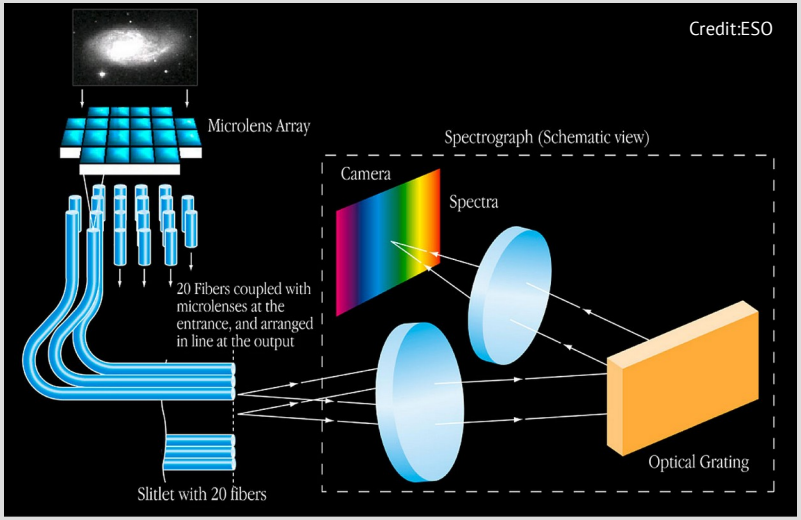
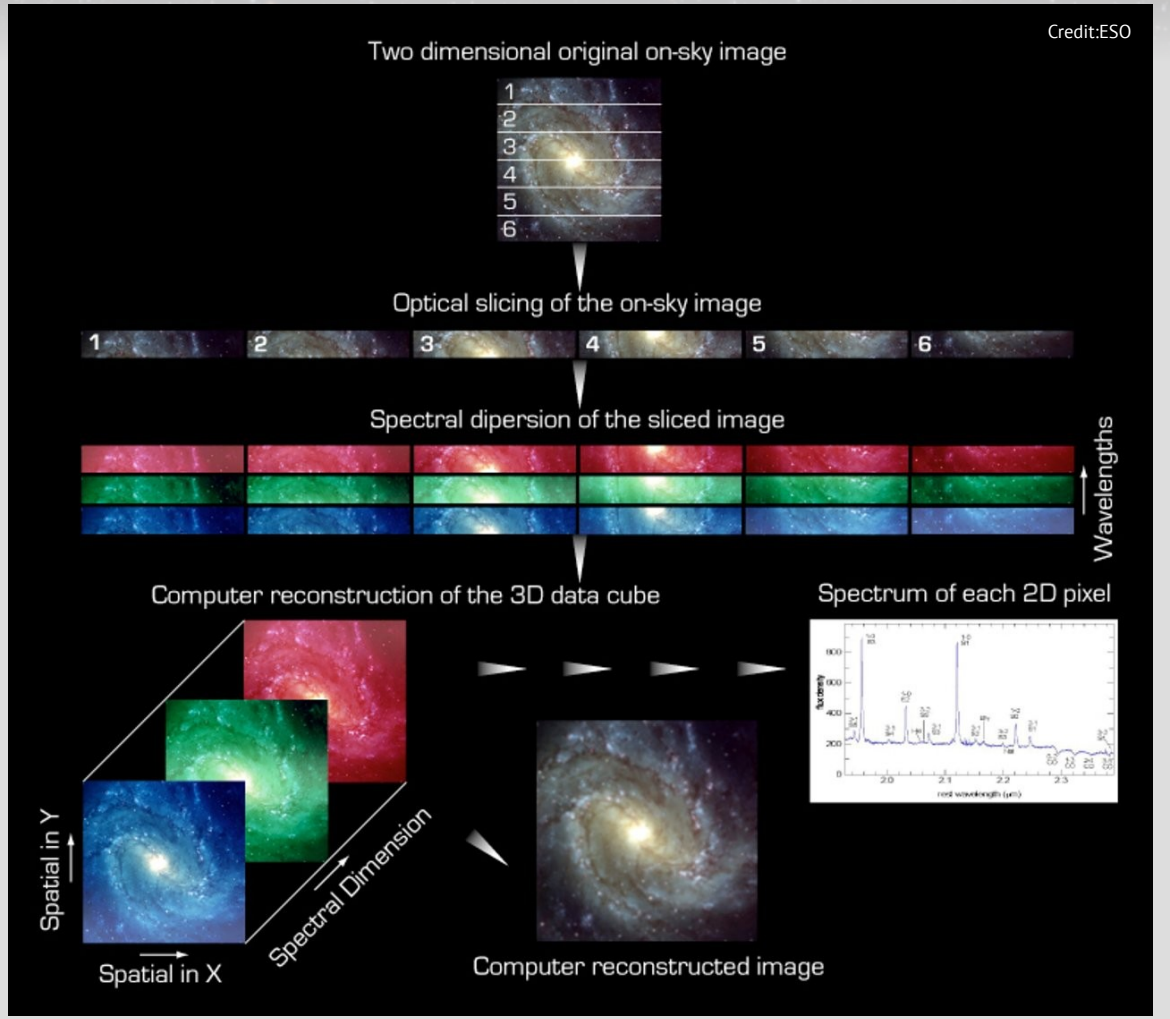
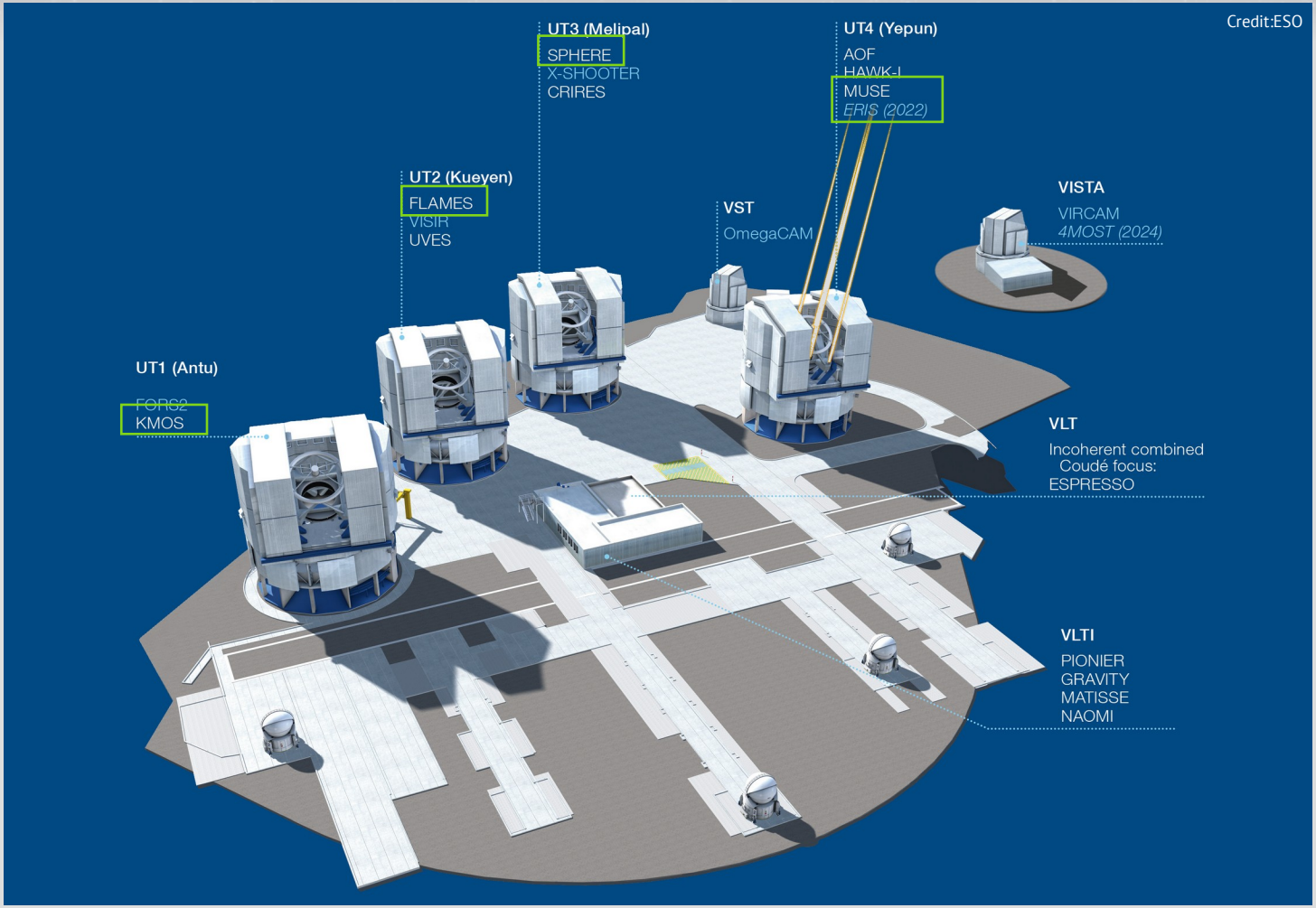
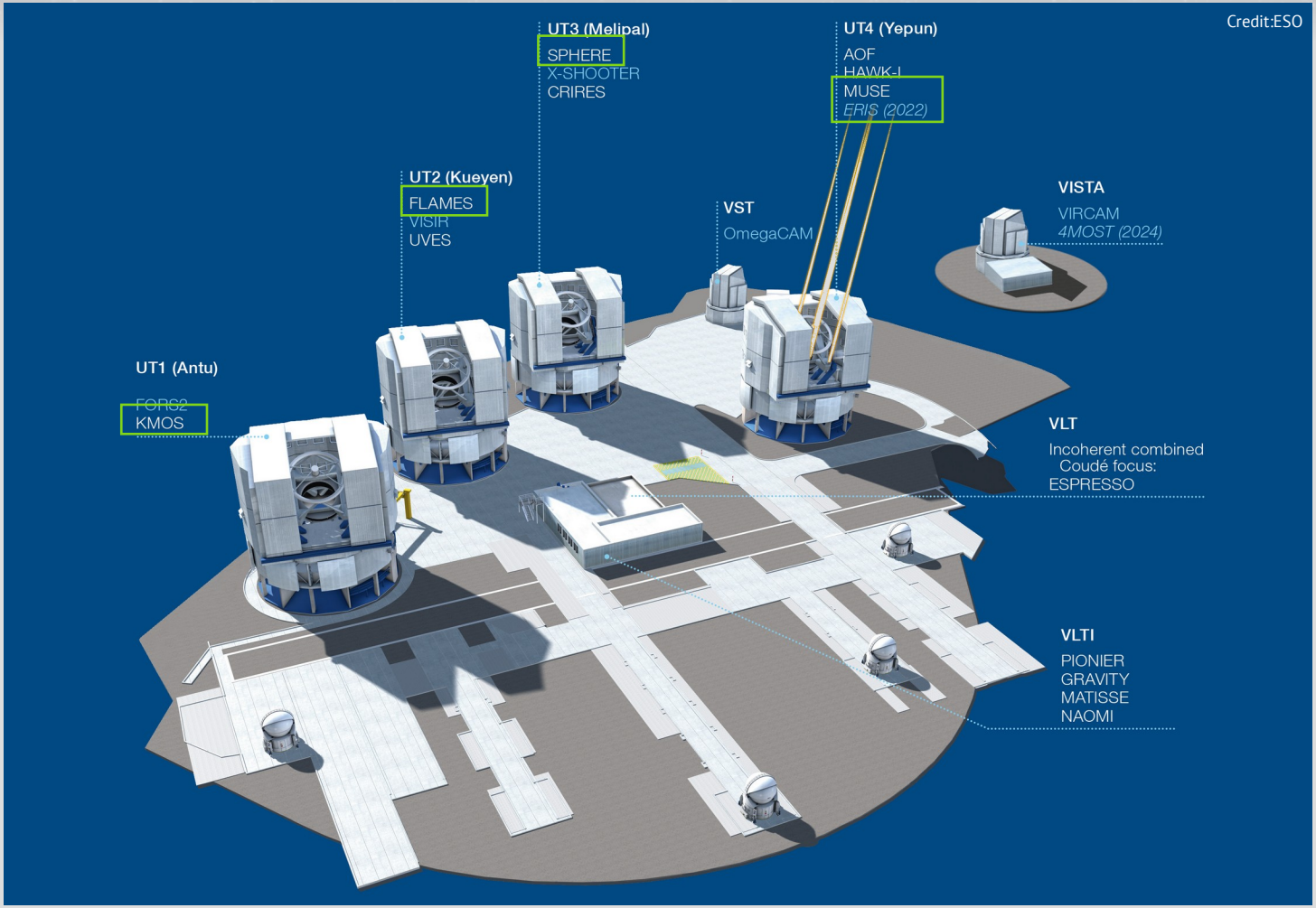




Different integral field units at ESO



Different integral field units at ESO and elsewhere

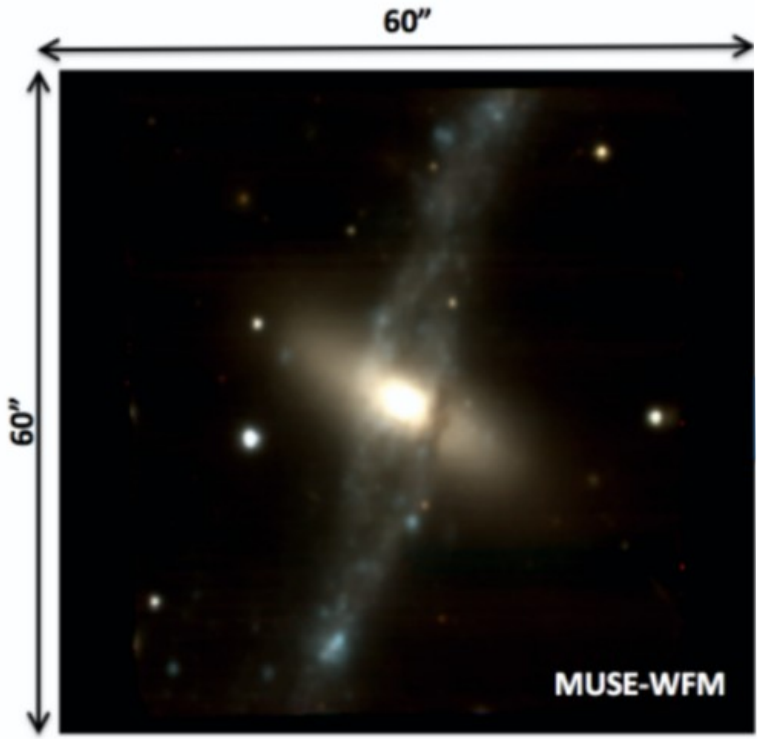


GTC
- MEGARA

JWST
- MIRI
- NIRSpec

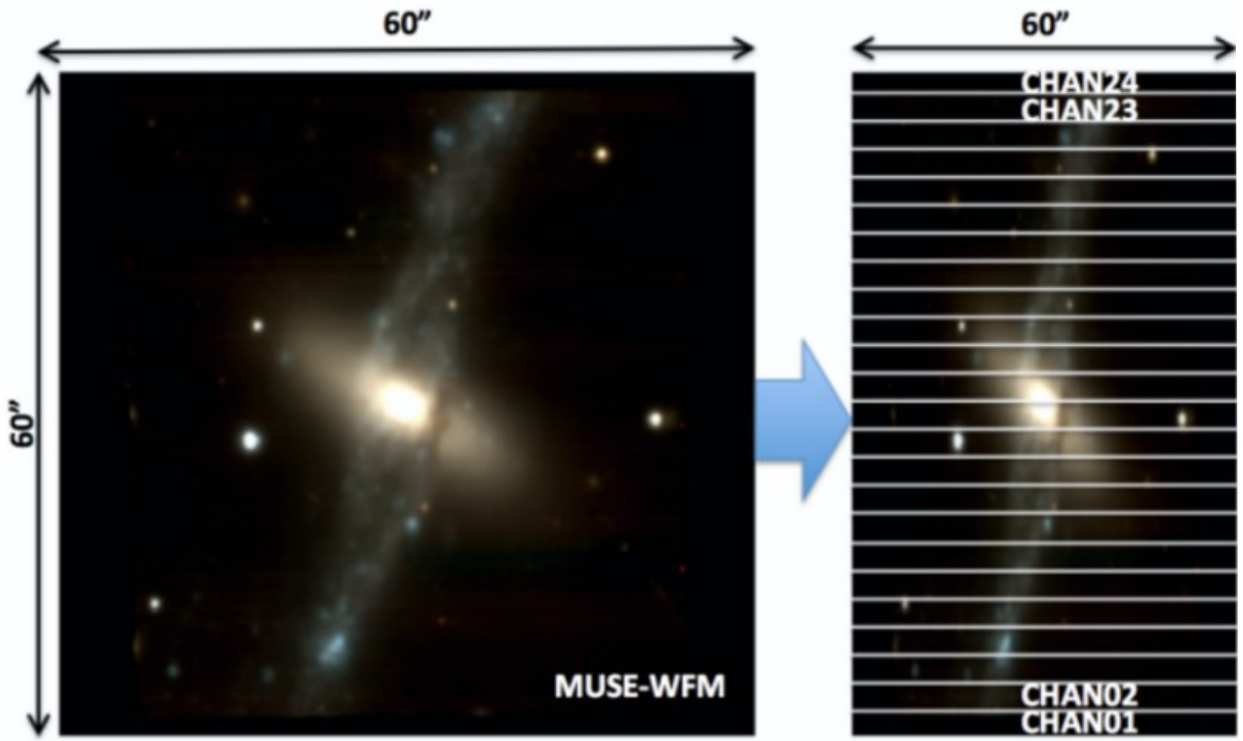
ELT
- HARMONI
- METIS

MUSE image slicing method



Video of the light path in MUSE

MUSE image slicing method



Video of the light path in MUSE

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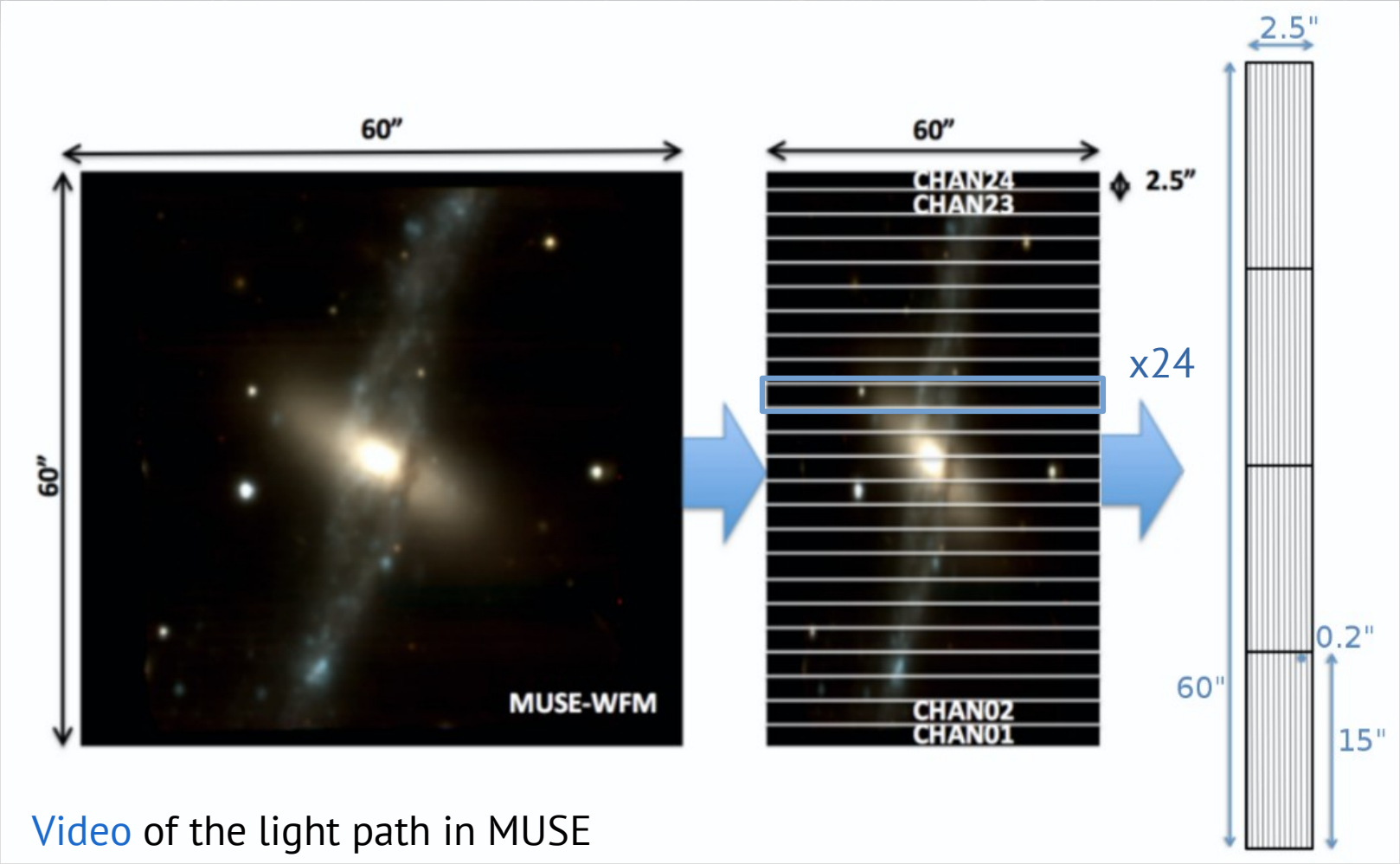
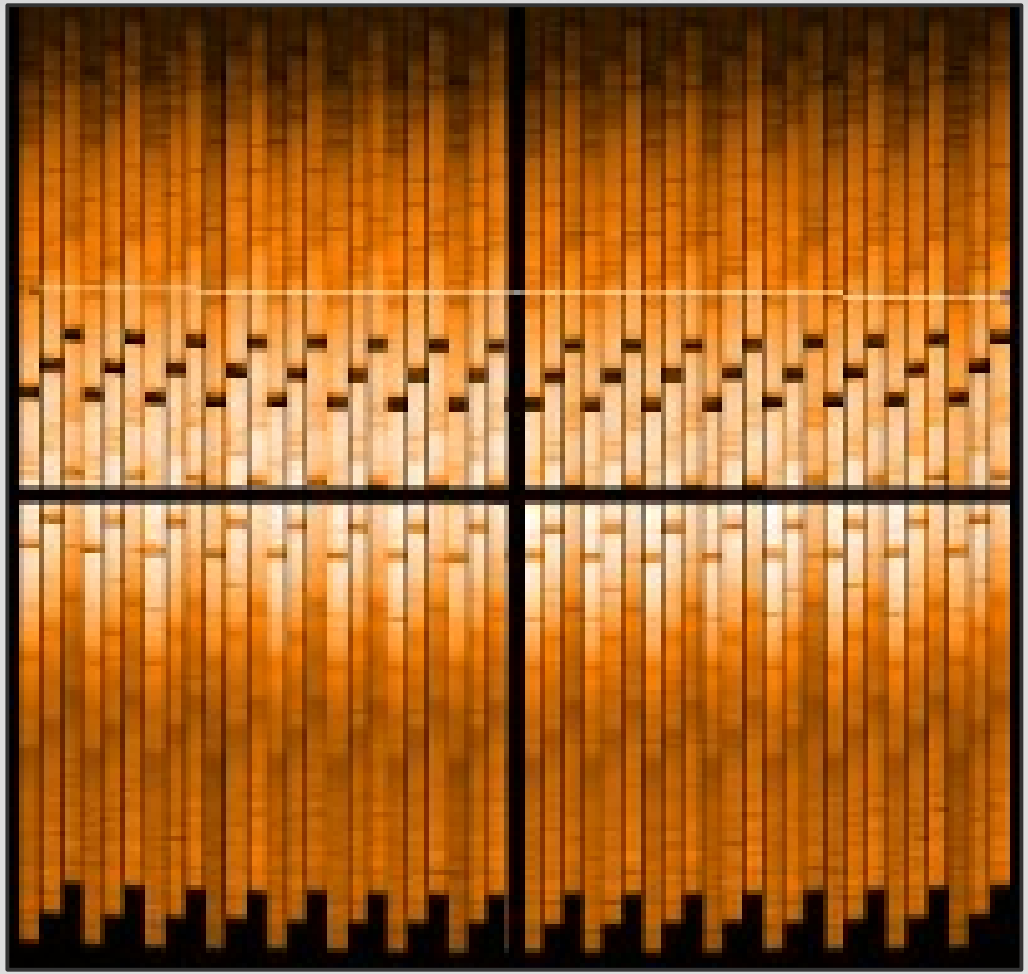


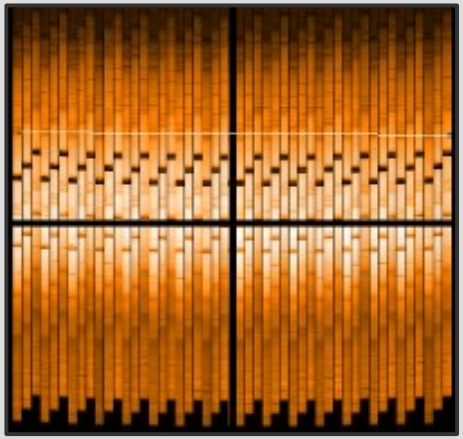
Video of the light path in MUSE

MUSE ‘raw’ data

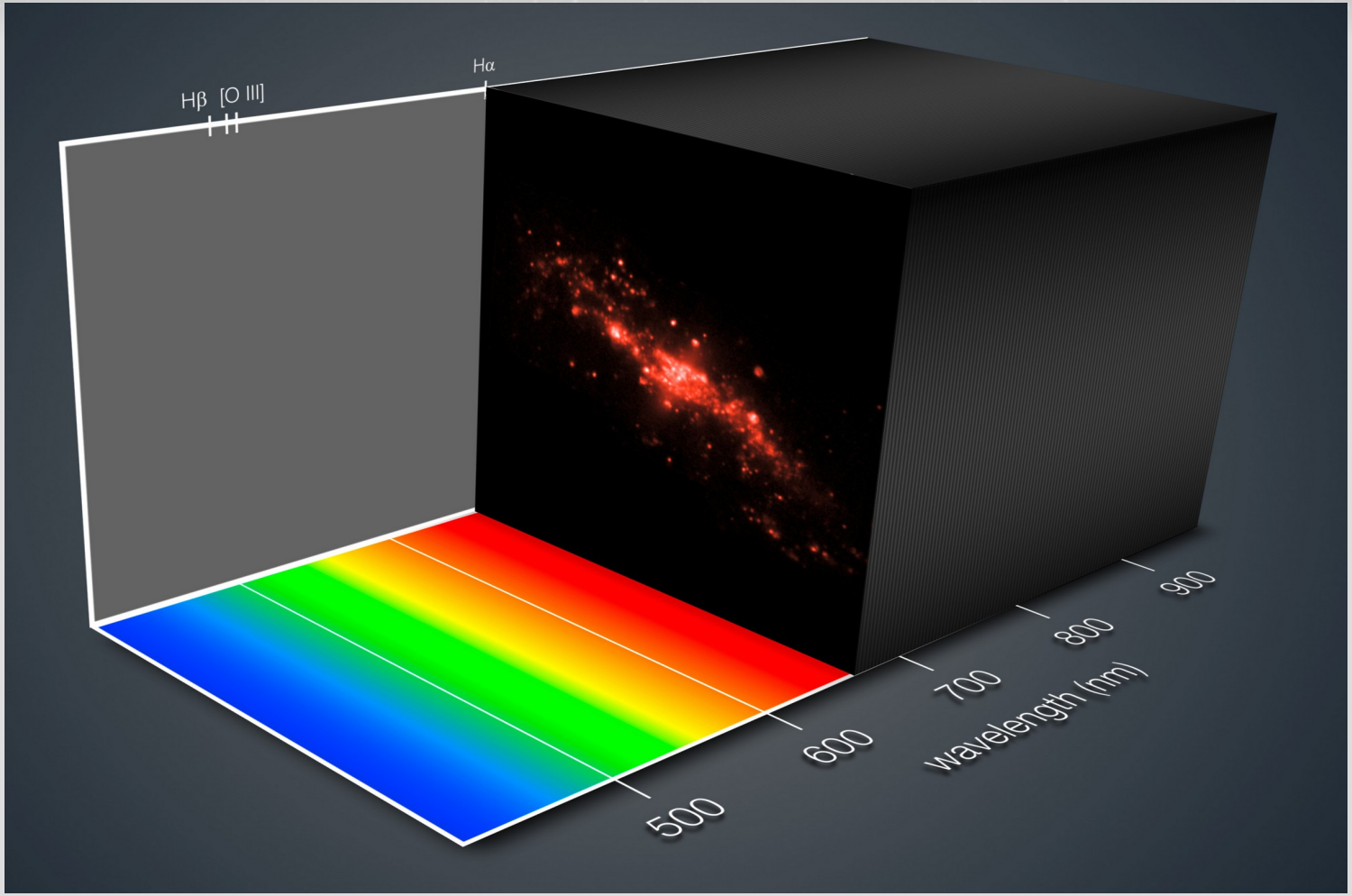


x24

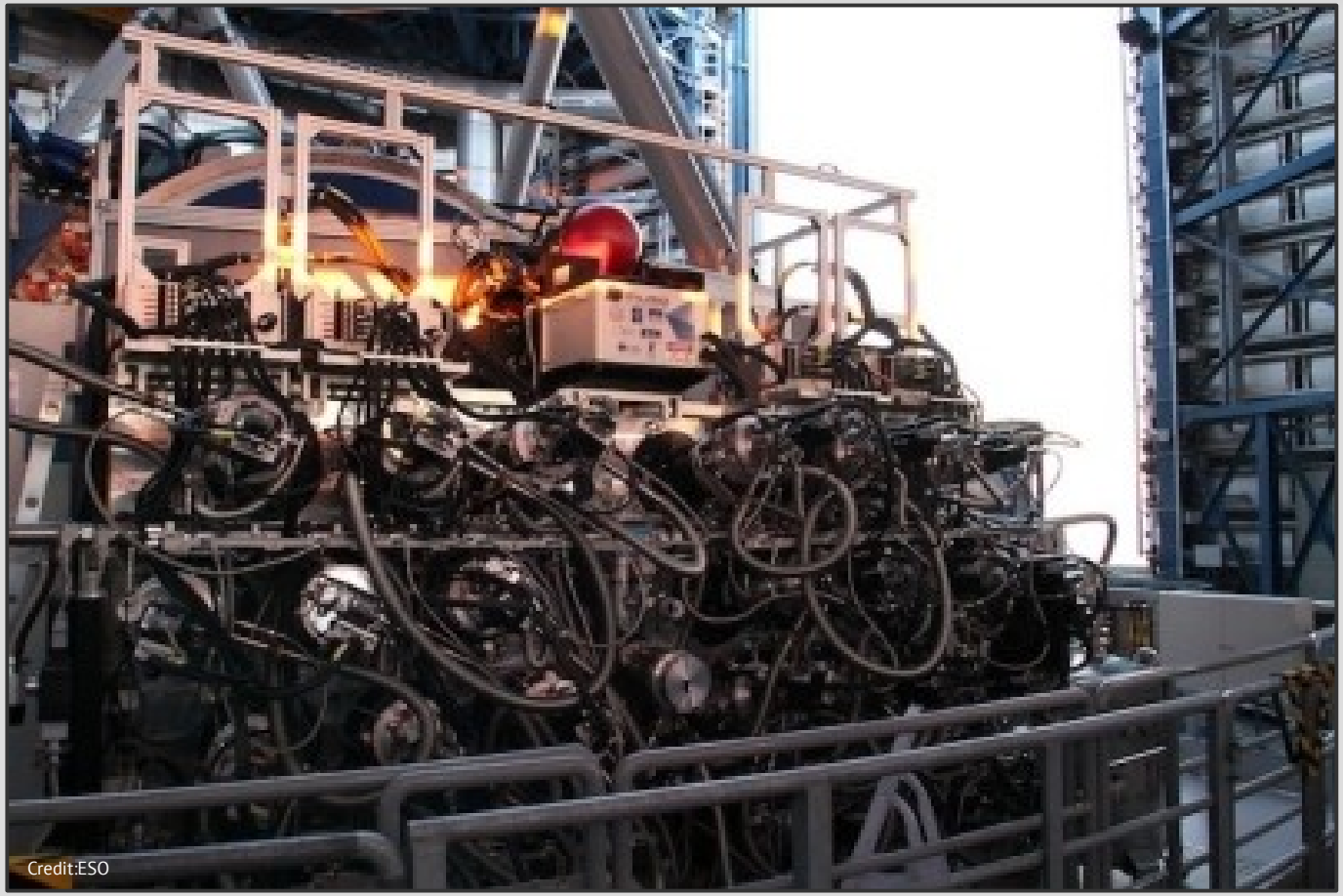
MUSE reduced data



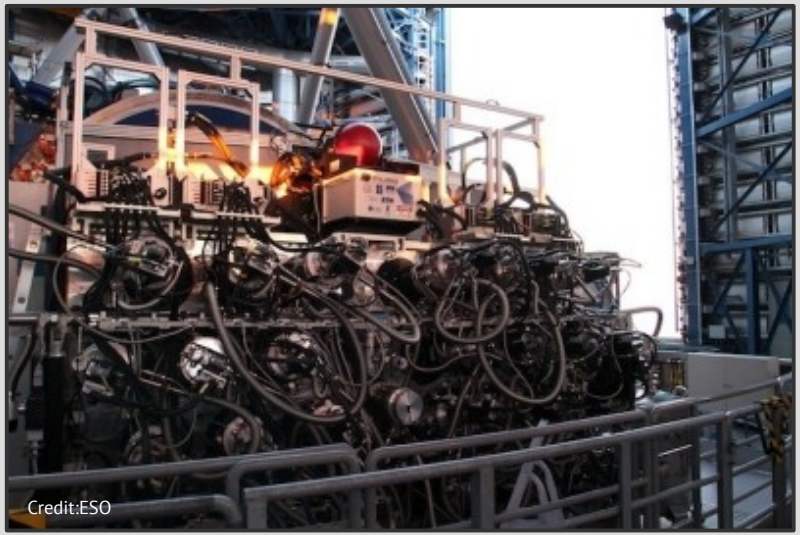
320 x
321 x



MUSE at the VLT



MUSE at the VLT



MUSE specs

- resolution: ~1700 – 3700 (blue – red)

- two FoVs:
  WFM: 1’ x 1’ (0.2” x 0.2” sampling)
  NFM: 7.5” x 7.5” (0.025” x 0.025” sampling)

- two wavelength modes: nominal vs. extended

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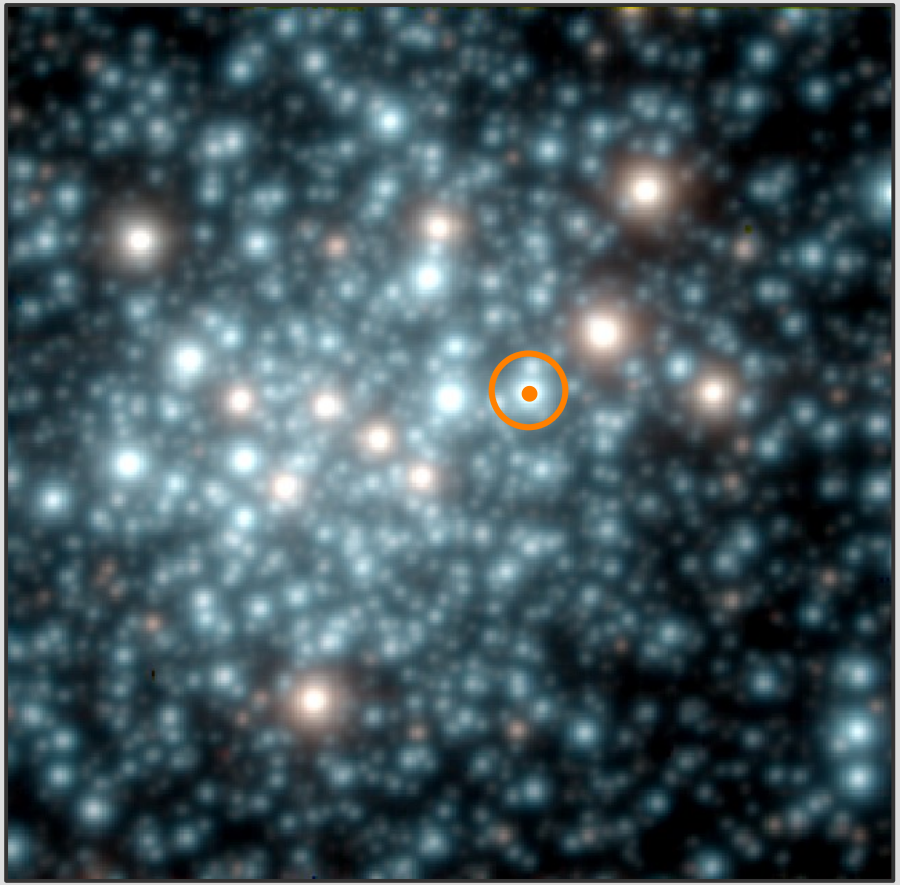
- AO or no-AO support

Extraction of spectra

= measure flux at each wavelength

Extraction of spectra

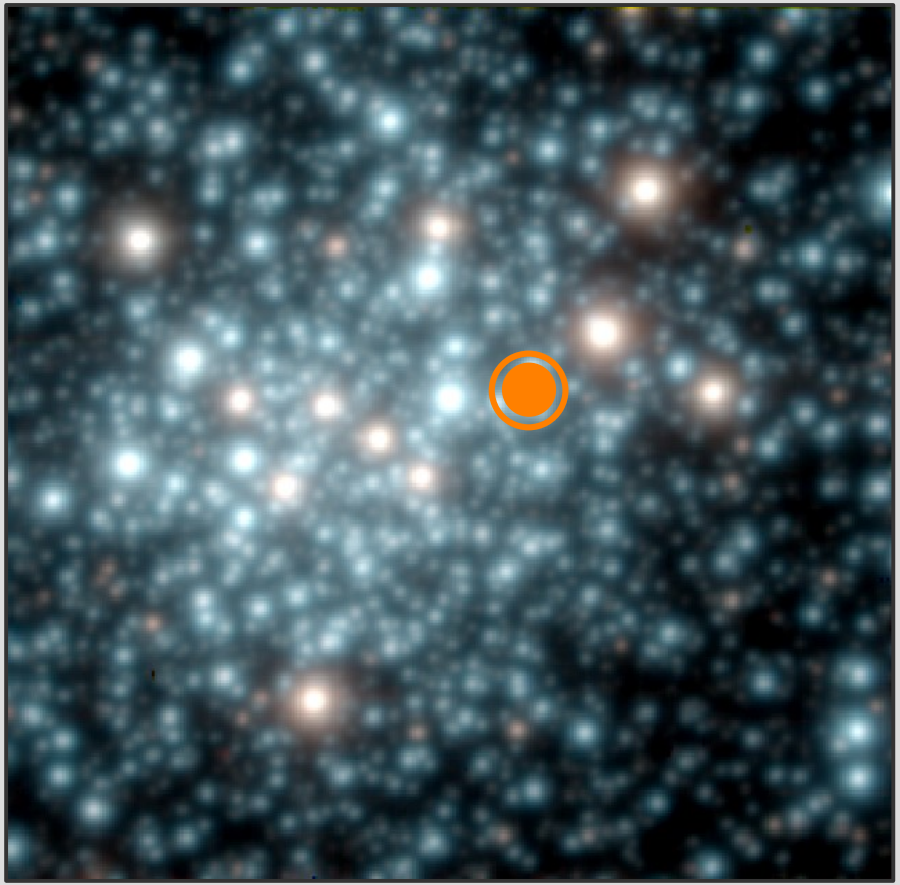


= measure flux at each wavelength

- extraction of the brightest pixel

level of sophistication

Extraction of spectra



= measure flux at each wavelength

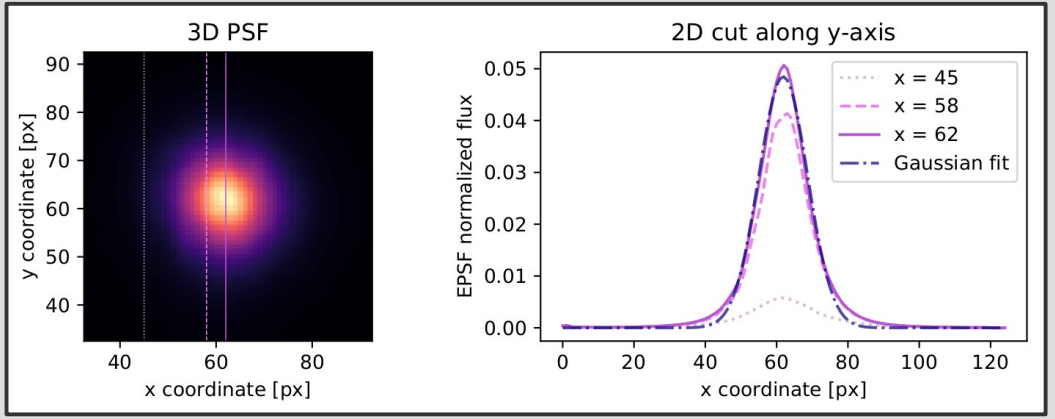
- extraction of the brightest pixel
- aperture photometry

level of sophistication

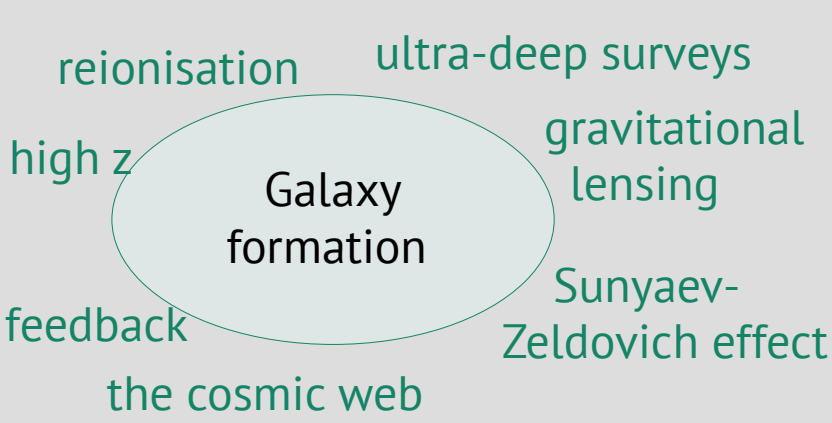
Extraction of spectra

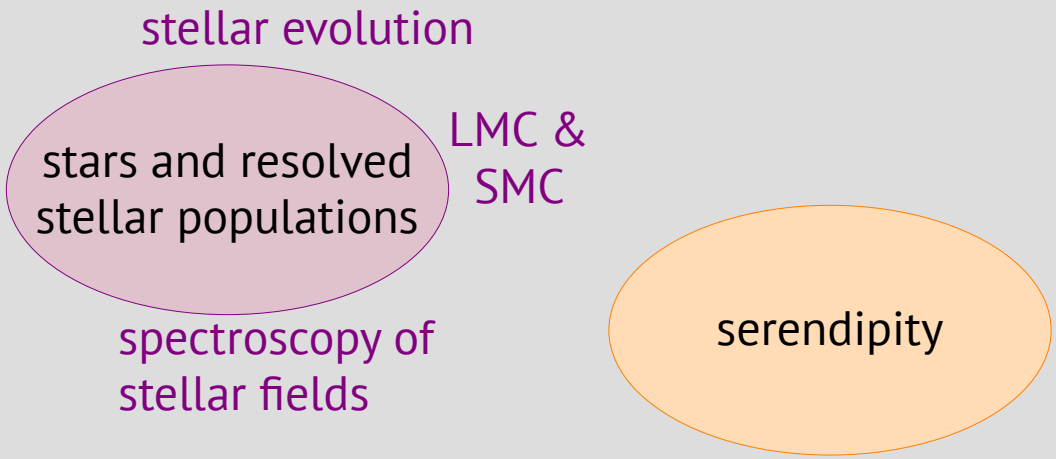
= measure flux at each wavelength

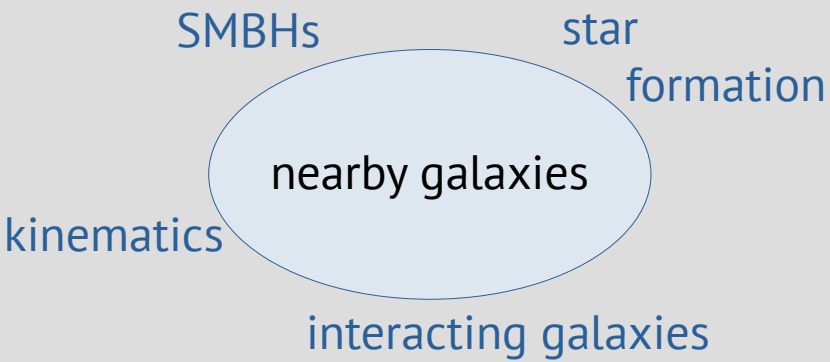
- extraction of the brightest pixel
- aperture photometry
- PSF-fitting
  → e.g. PampelMUSE (*Kamann+ 2018*)

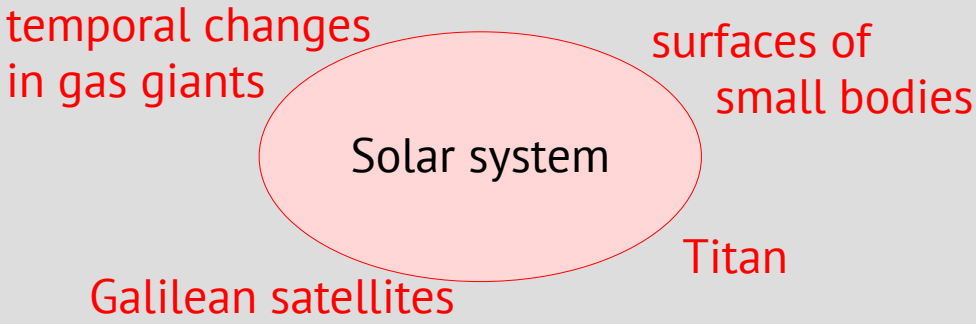


MUSE science highlights

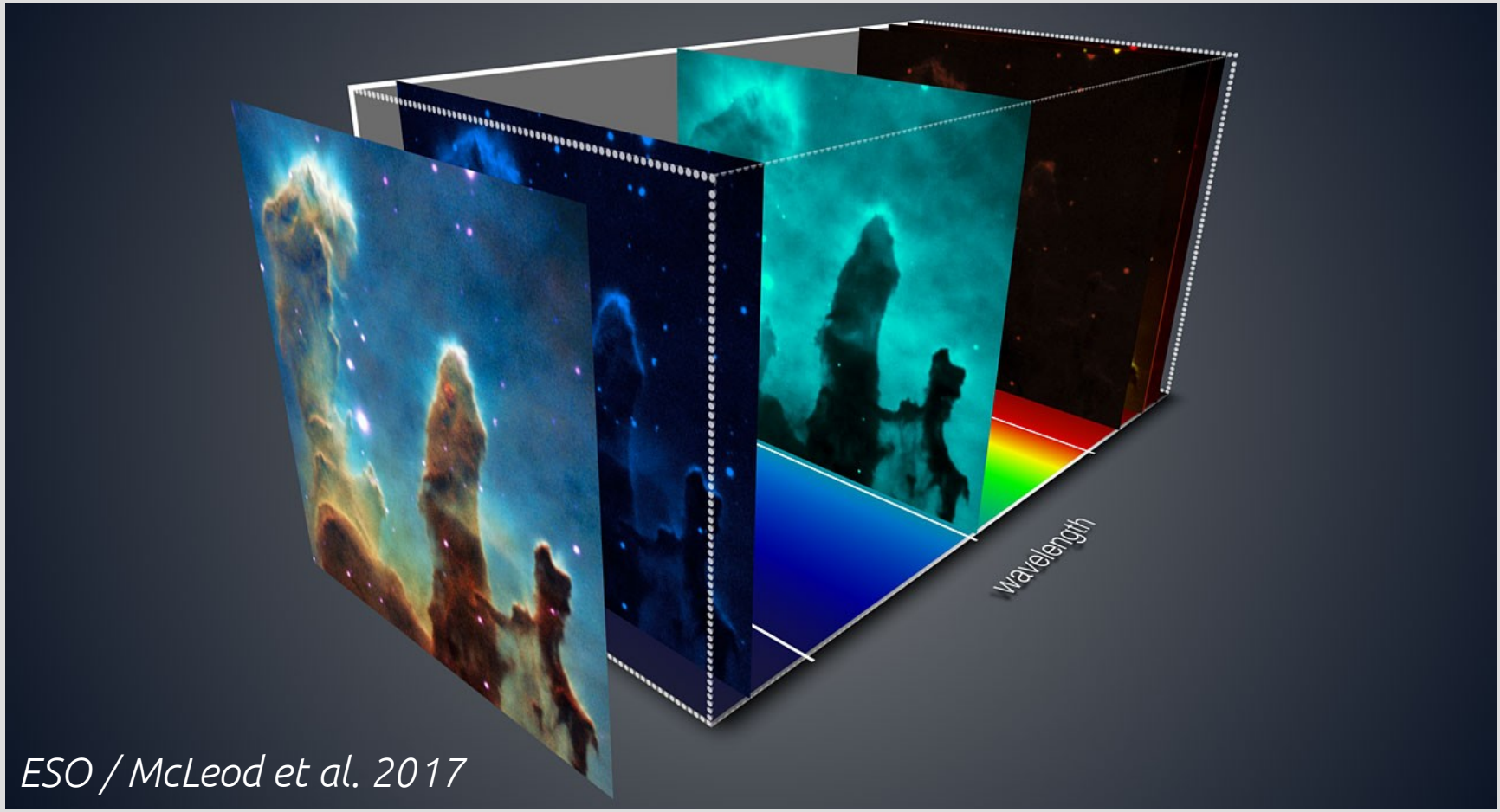






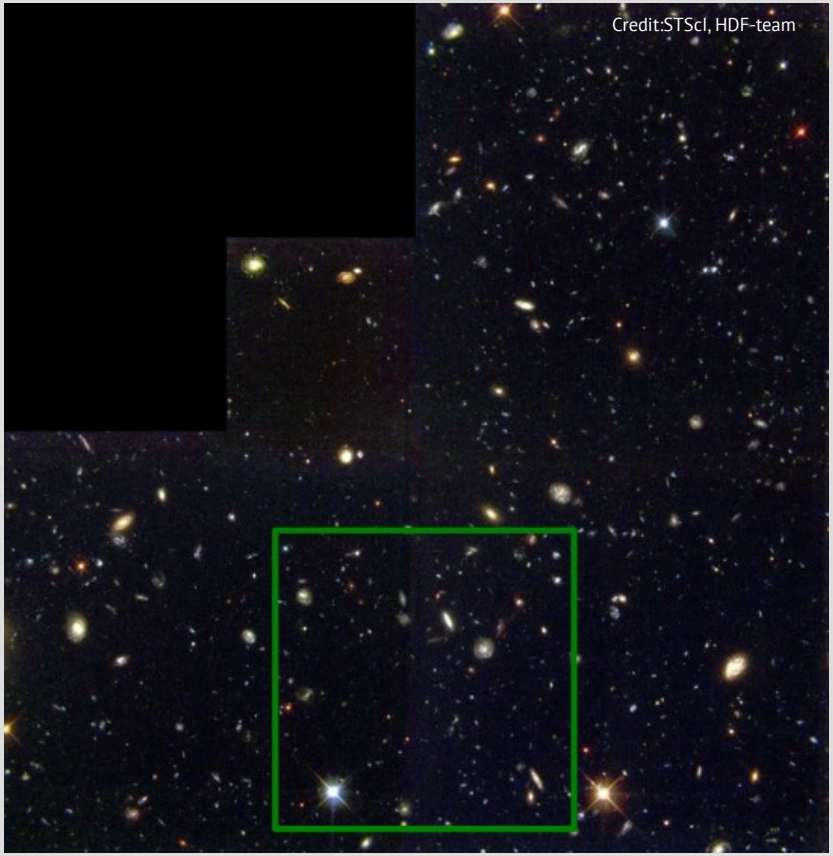


MUSE science highlight I: the pillars of creation



MUSE science highlight II: Hubble Deep field

Bacon et al. 2015



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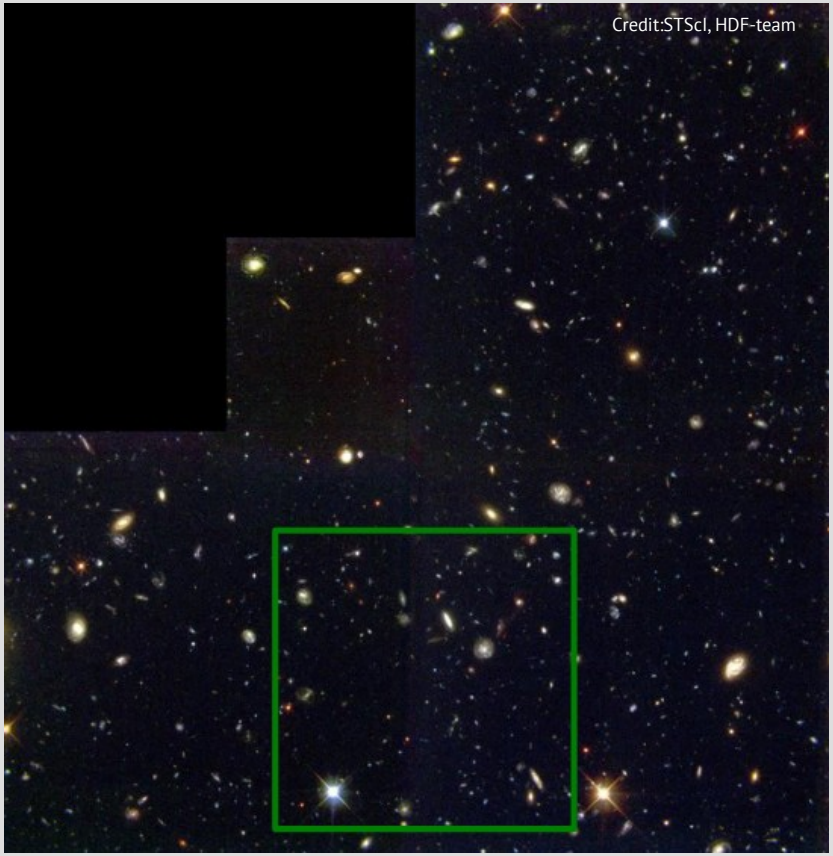

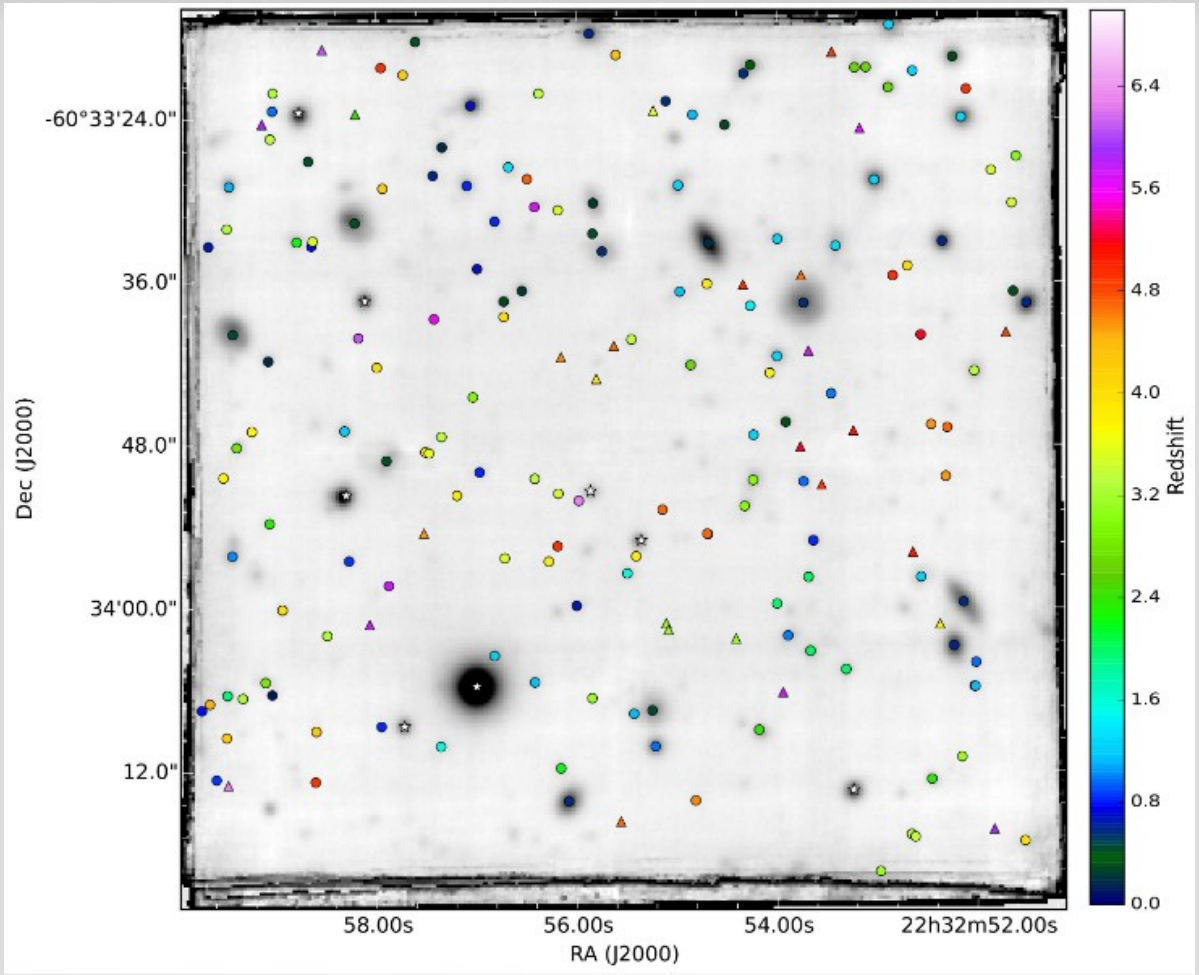

access the MUSE data

MUSE science highlight III: mosaic of NGC 4650 A

ESO/MUSE consortium/R. Bacon

MUSE observations of resolved stellar populations

eso1802 — Science Release

Odd Behaviour of Star Reveals Lonely Black Hole Hiding in Giant Star Cluster

17 January 2018

Astronomers using ESO's MUSE instrument on the Very Large Telescope in Chile have discovered a star in the cluster NGC 3201 that is behaving very strangely. It appears to be orbiting an invisible black hole with about four times the mass of the Sun — the first such inactive stellar-mass black hole found in a globular cluster and the first found by directly detecting its gravitational pull. This important discovery impacts on our understanding of the formation of these star clusters, black holes, and the origins of gravitational wave events.

MUSE observations of resolved stellar populations

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Youtube video

eso2116 — Science Release

Black hole found hiding in star cluster outside our galaxy

11 November 2021

Using the European Southern Observatory's Very Large Telescope (ESO's VLT), astronomers have discovered a small black hole outside the Milky Way by looking at how it influences the motion of a star in its close vicinity. This is the first time this detection method has been used to reveal the presence of a black hole outside of our galaxy. The method could be key to unveiling hidden black holes in the Milky Way and nearby galaxies, and to help shed light on how these mysterious objects form and evolve.

MUSE observations of resolved stellar populations

Youtube video

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But see *El-Badry & Burdge 2022*

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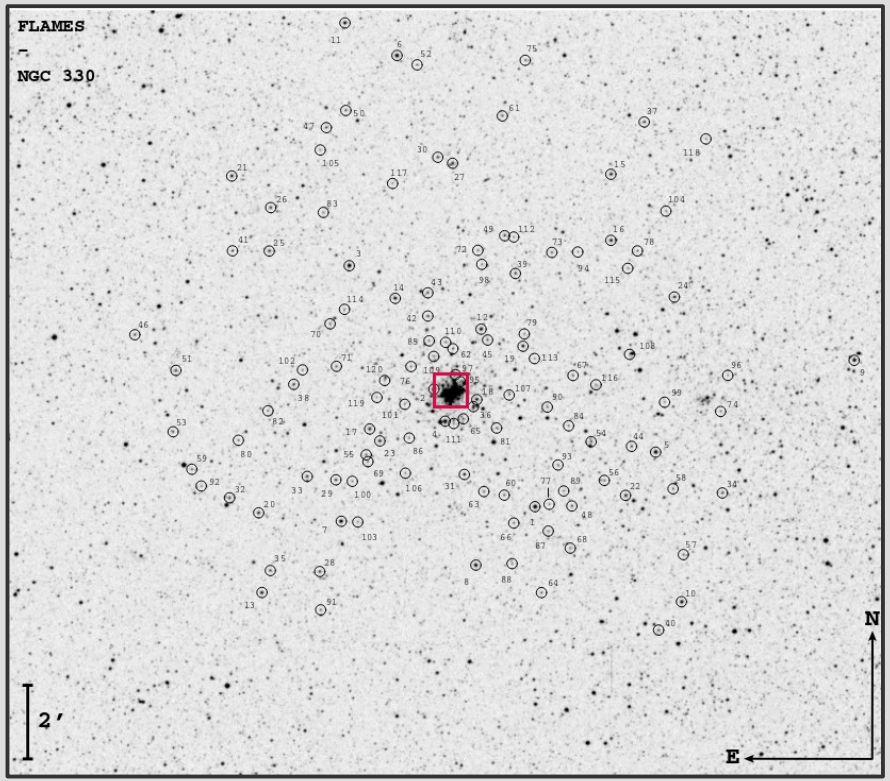
MUSE observations of NGC 330

Evans et al. 2006



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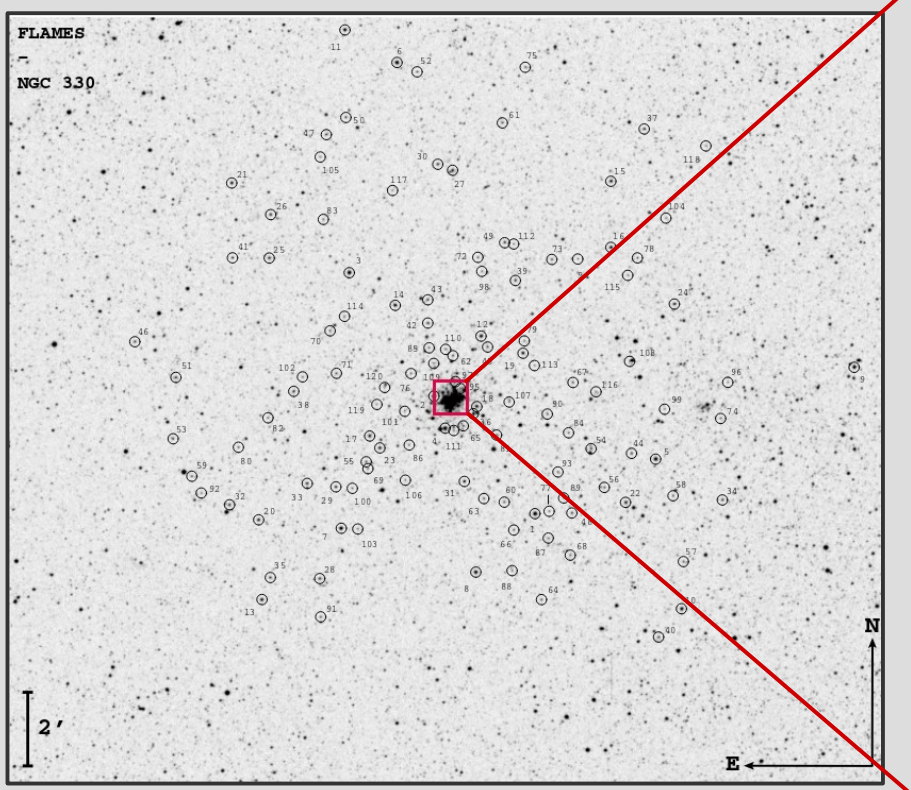
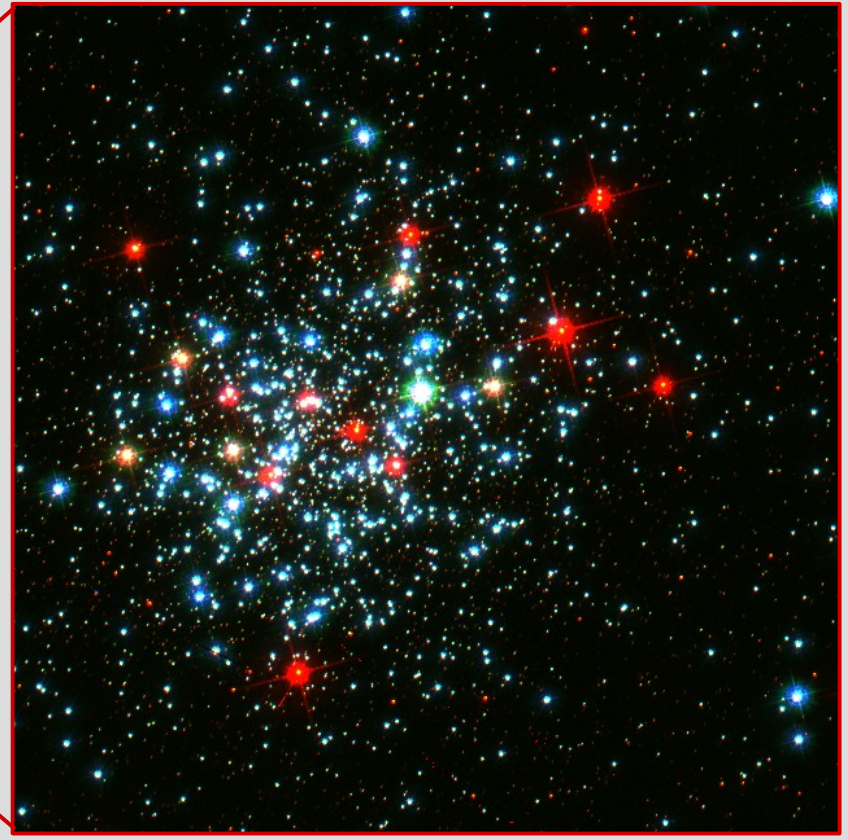


Milone et al. 2018



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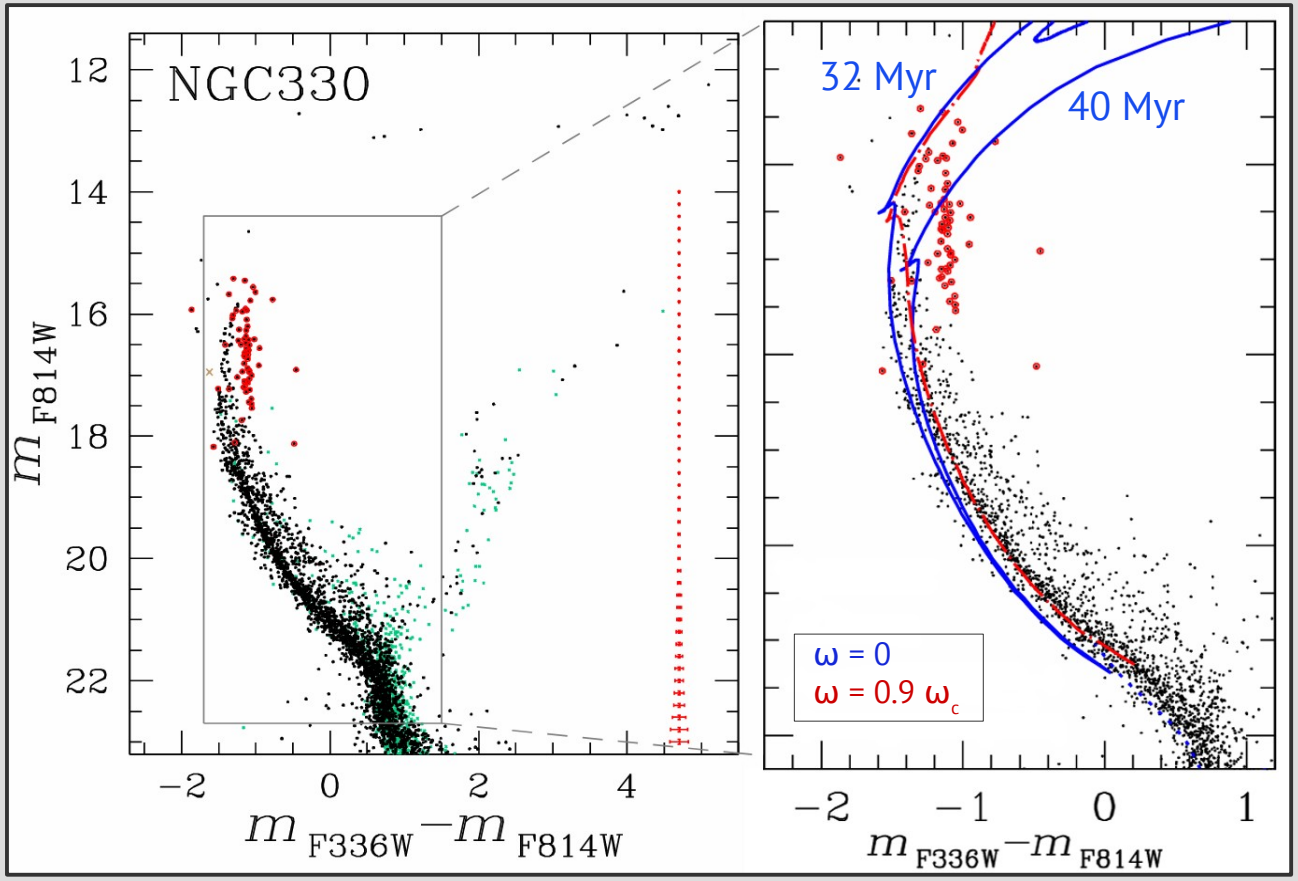
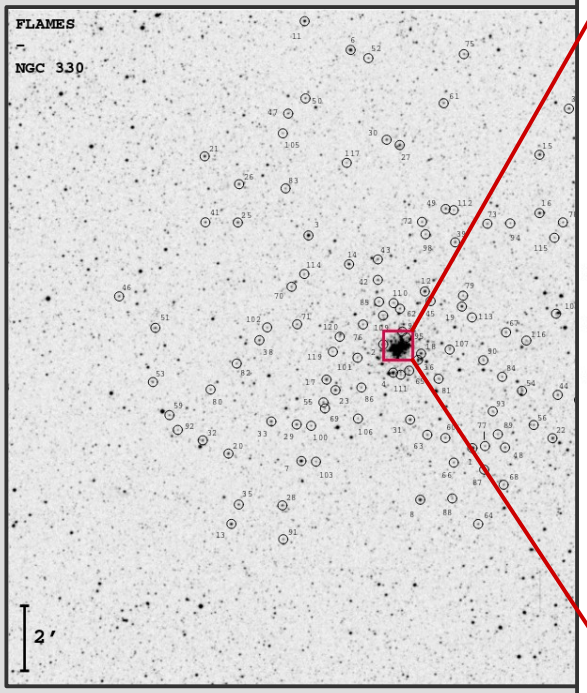


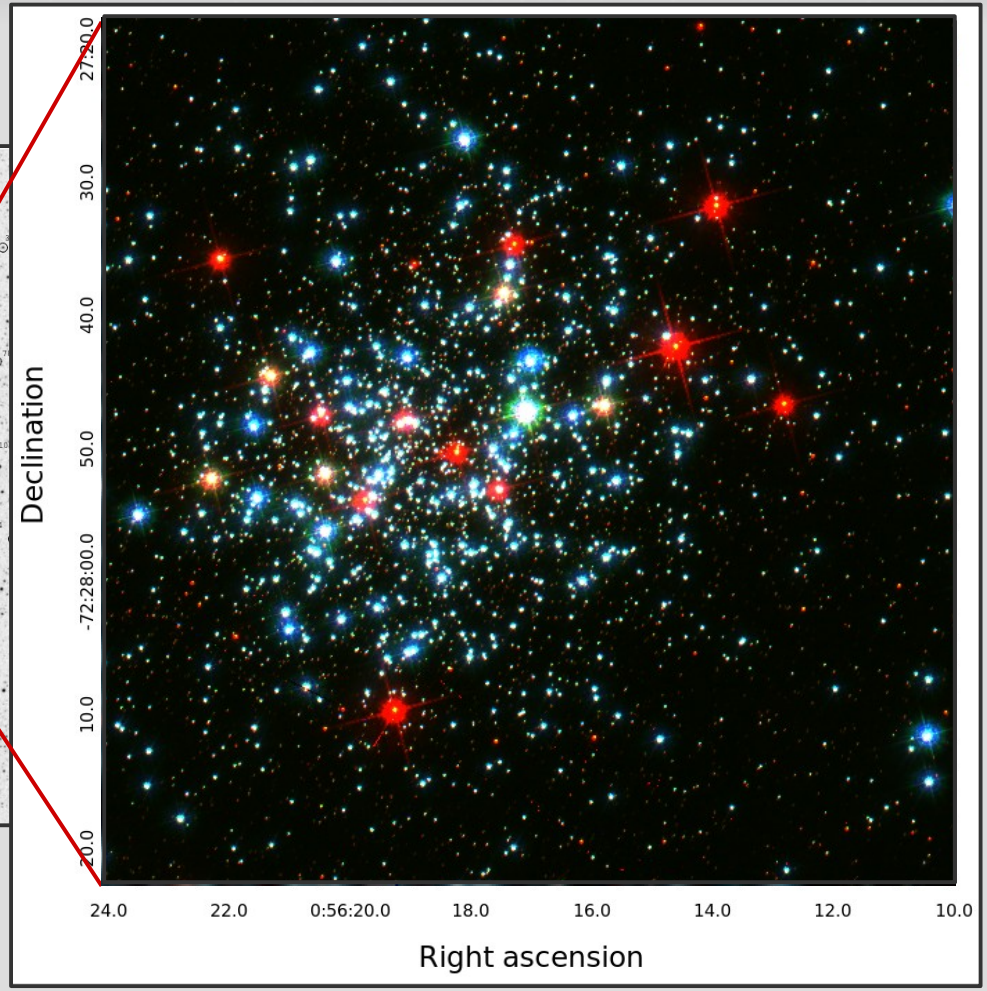
- intermediate-age cluster (~35 Myr)
- Small Magellanic Cloud ($Z = 0.2\ Z_\odot$)
- split main sequence
- $M_{tot} \sim 10^5\ M_\odot$

HST observations of NGC 330

Milone et al. 2018

Evans et al. 2006





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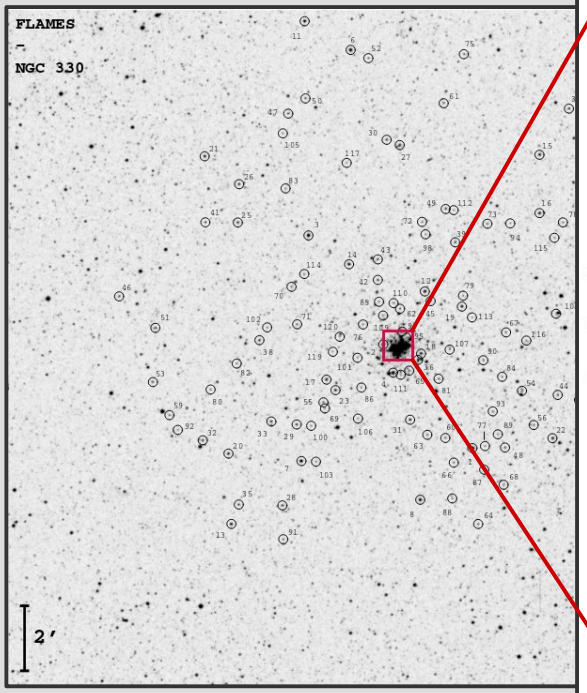
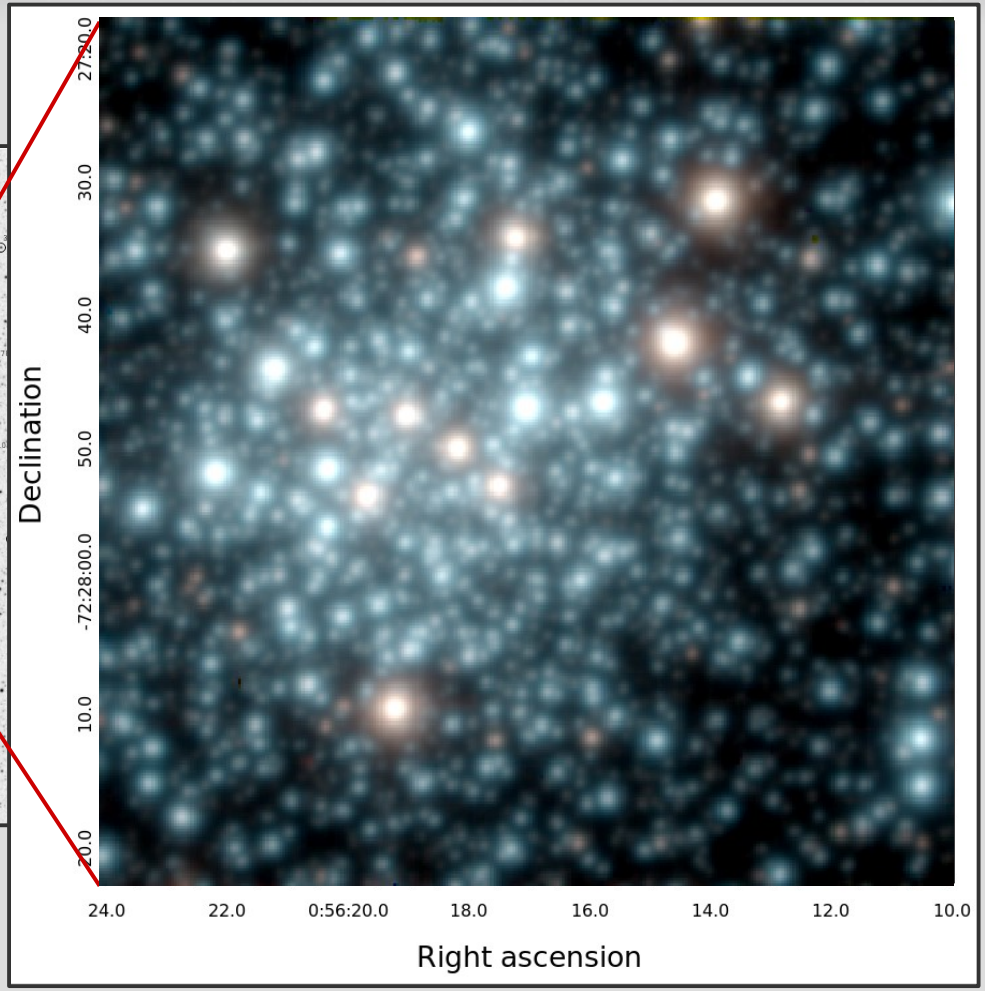
Bodensteiner et al. 2020

Evans et al. 2006





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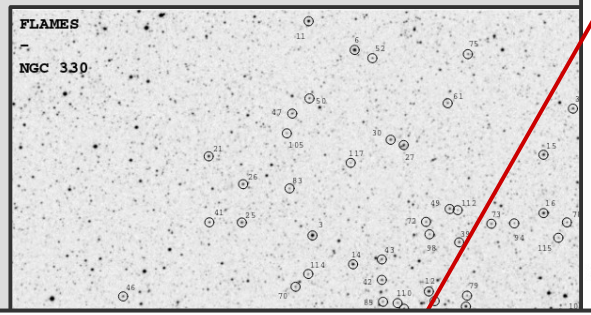
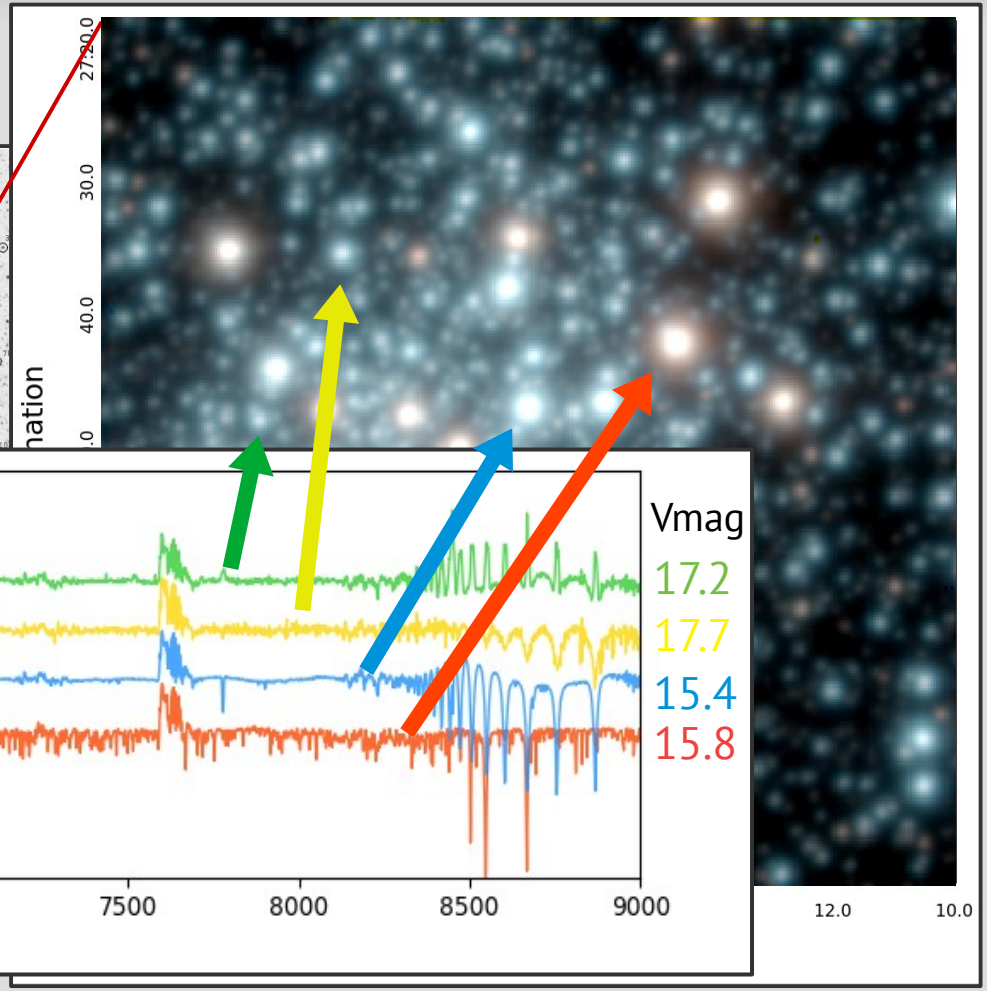
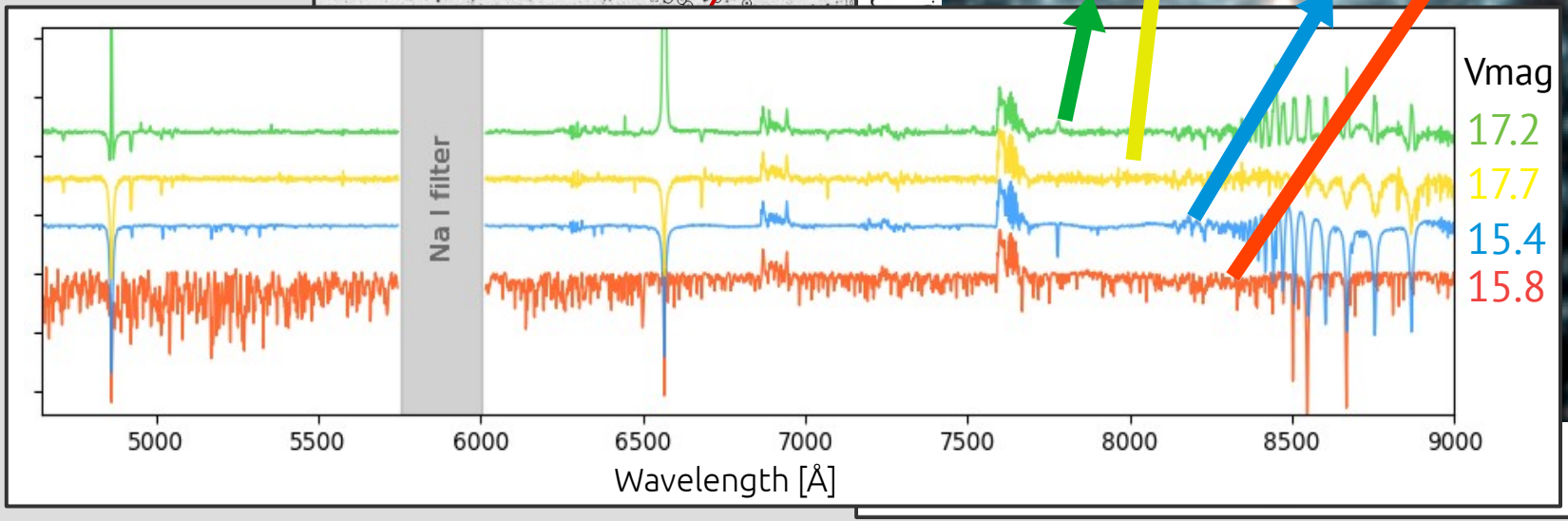
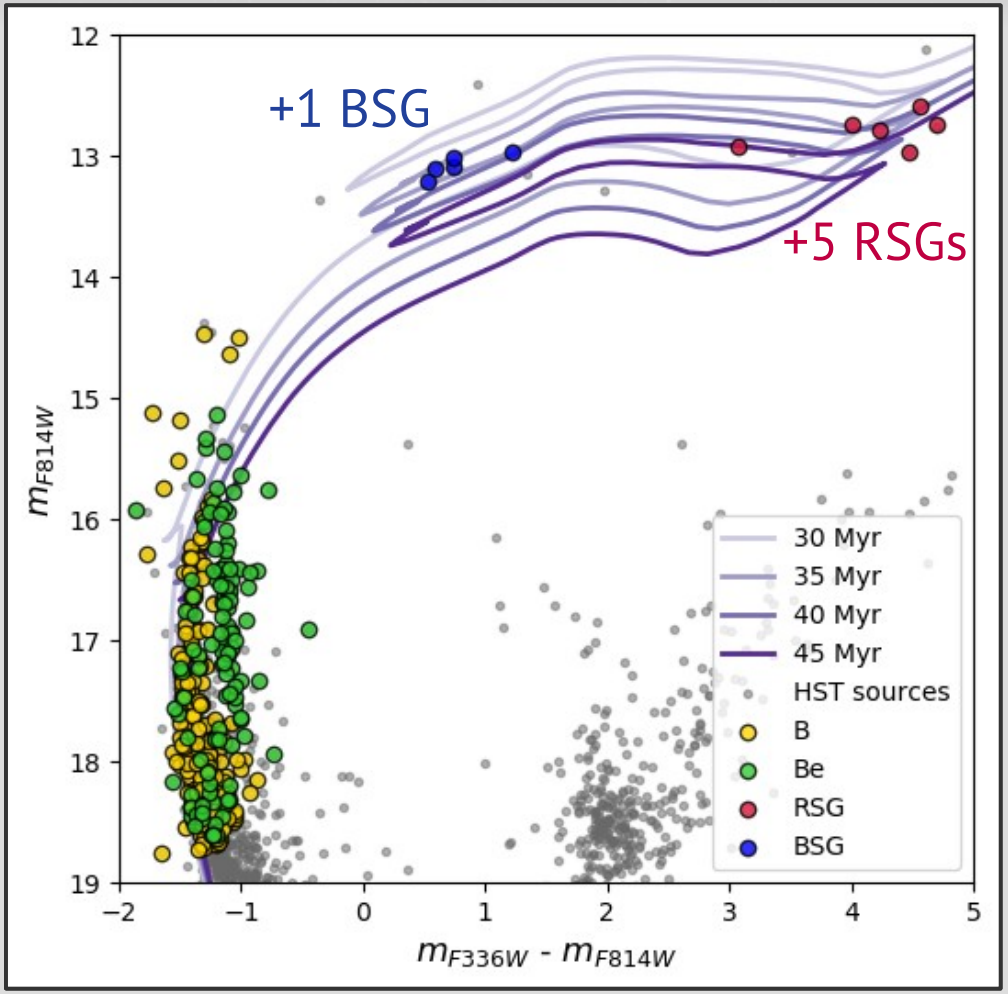






Massive star content

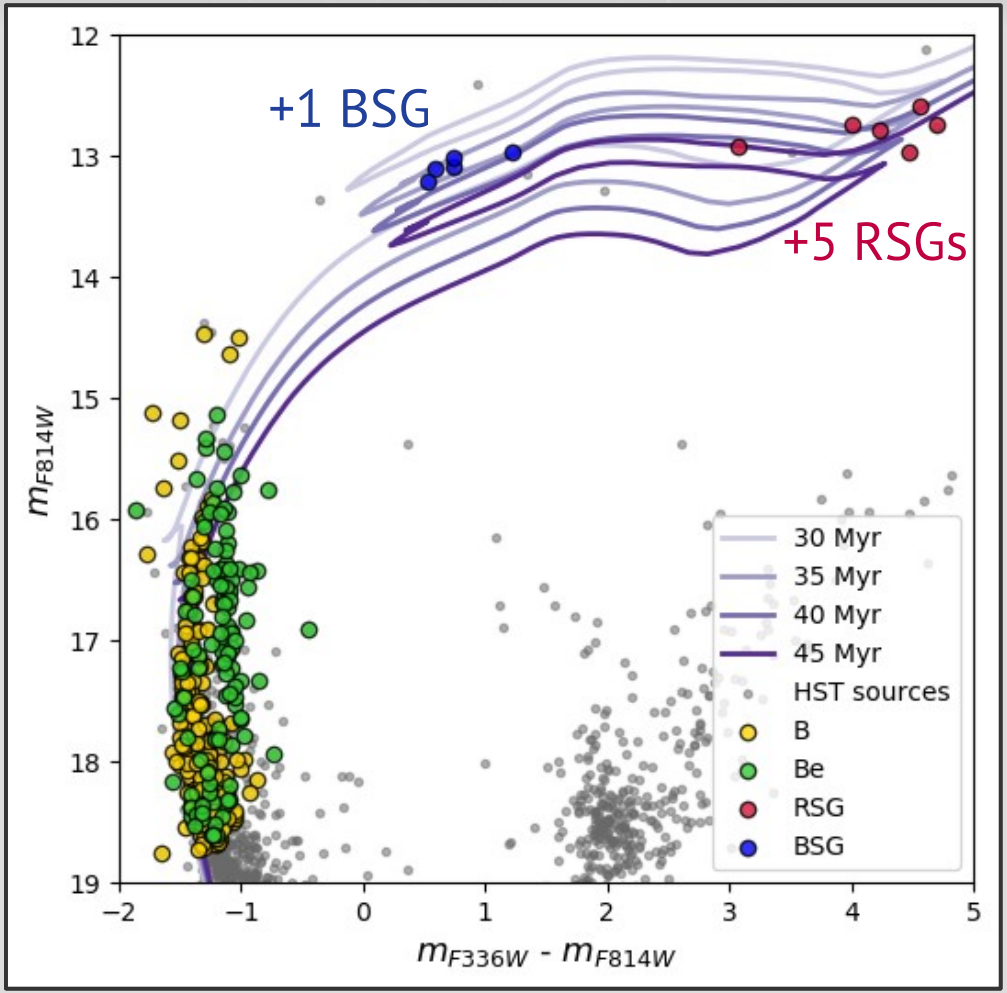


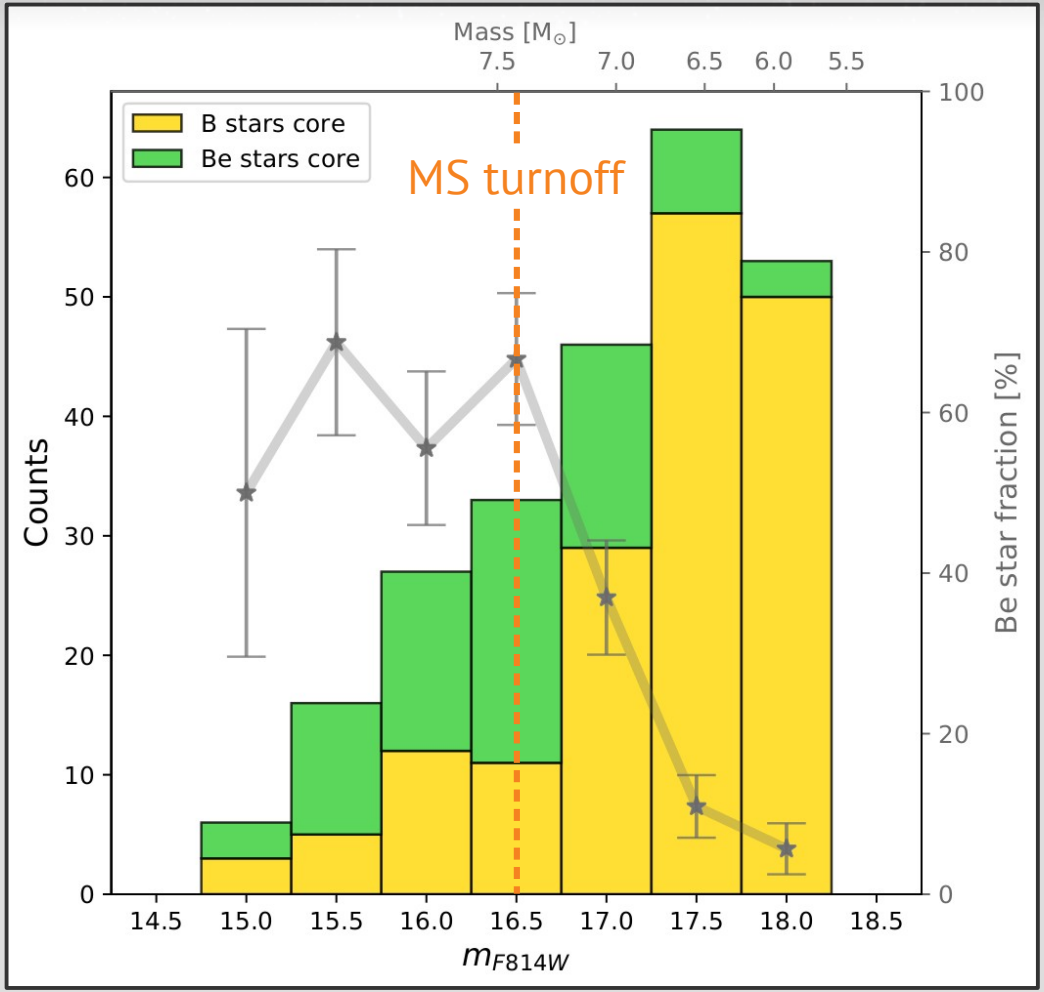
spectra of > 400 stars
(in 1h of observation)

x 6 (epochs)

Bodensteiner et al. 2020

Massive star content



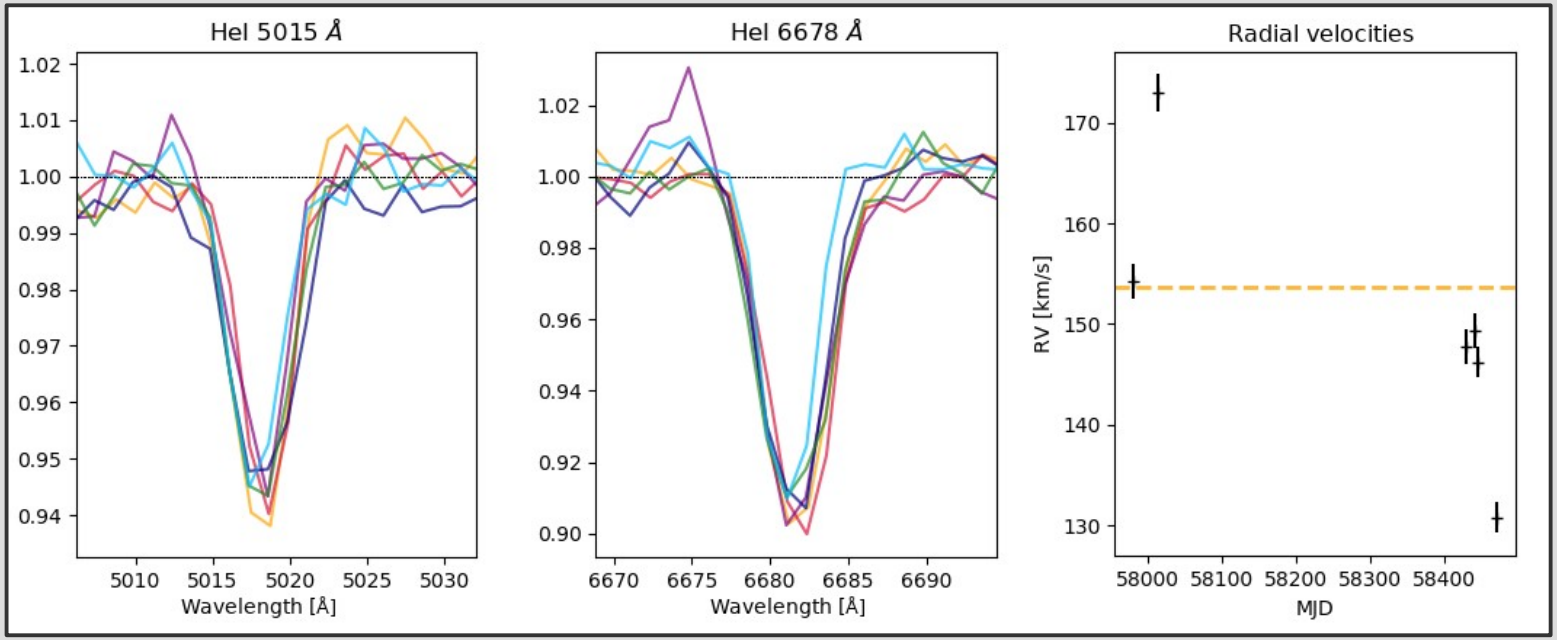


Binary properties and stellar parameters

Bodensteiner et al. 2021

* measure RVs

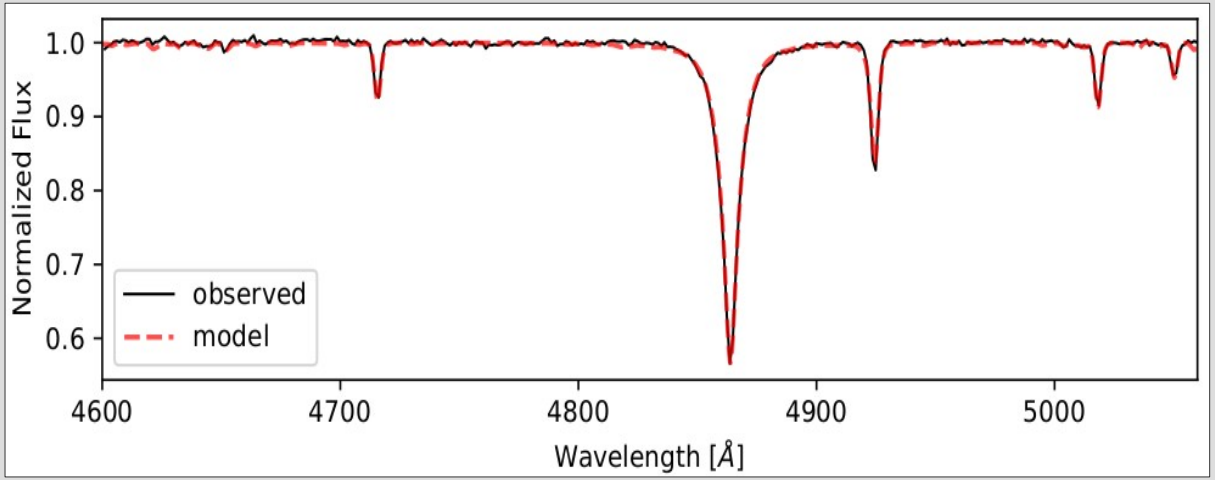
* detect binary candidates

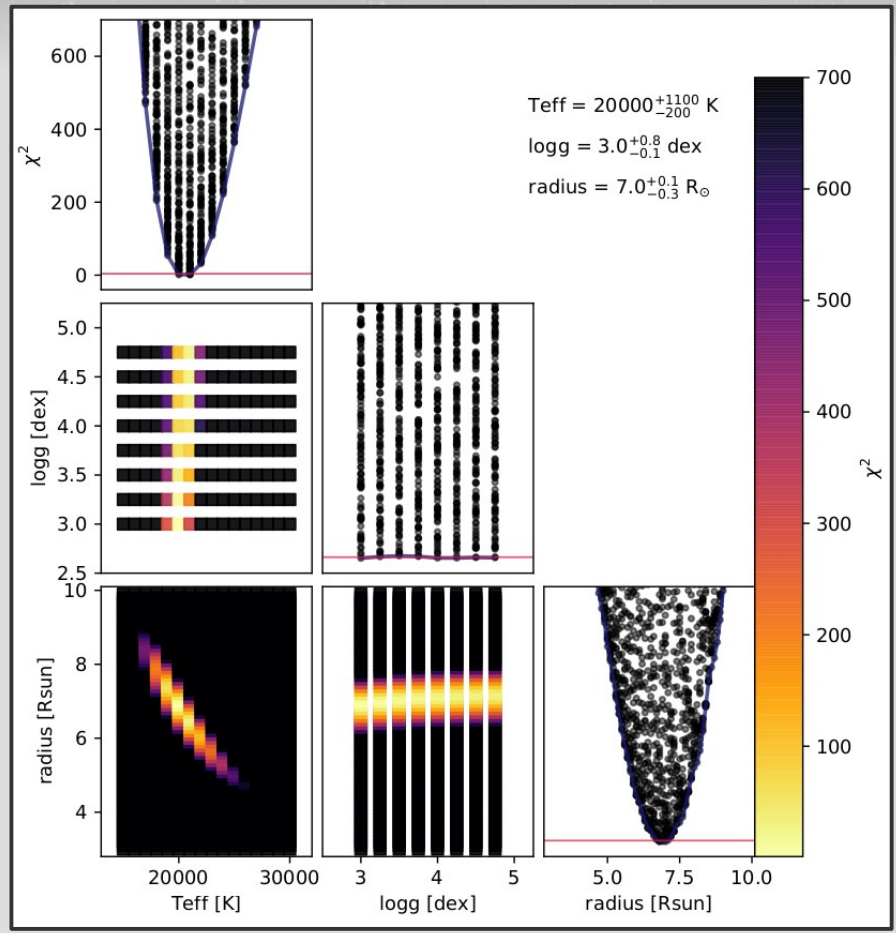


Binary properties and stellar parameters

* combine spectra

* atmosphere analysis
  → T_{eff}, log g, vsini





Bodensteiner et al. 2022

Binary properties and stellar parameters

* measure RVs
* detect binary candidates
* combine spectra
* atmosphere analysis
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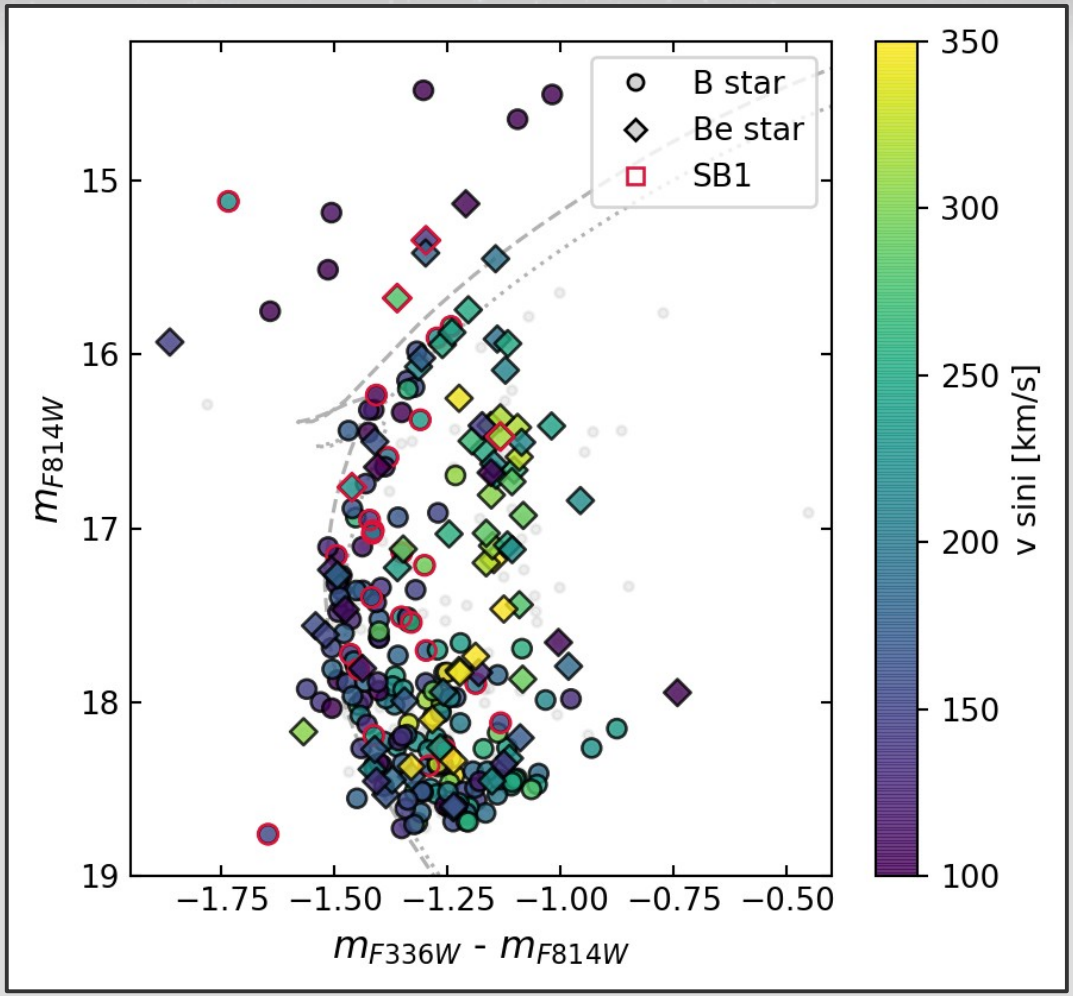
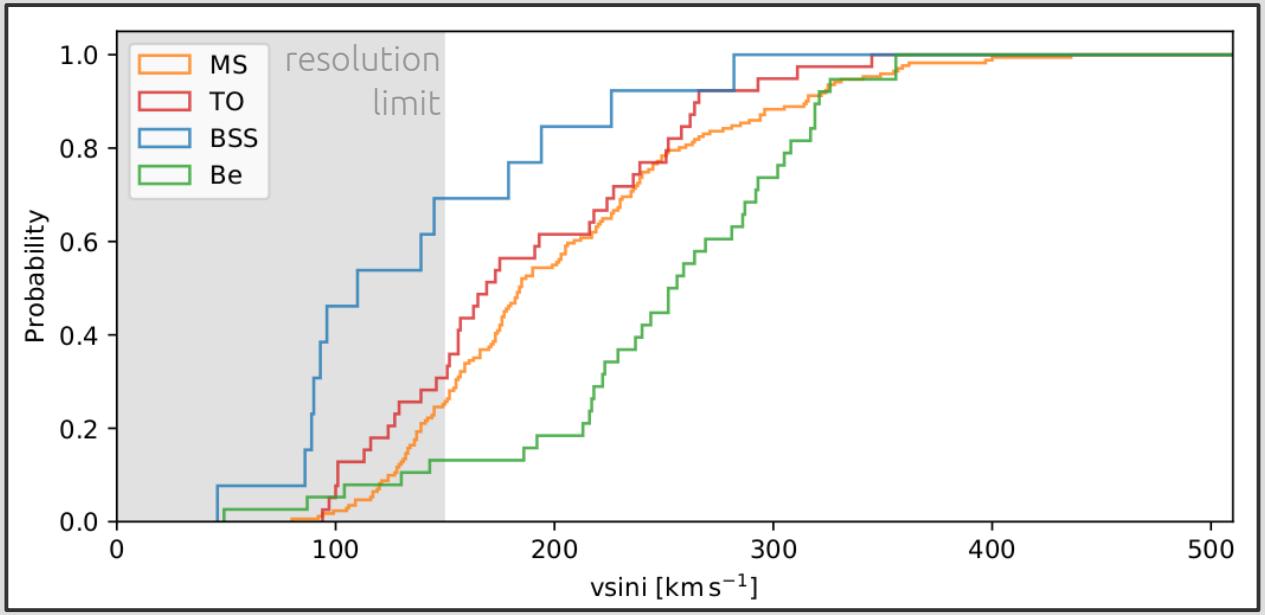
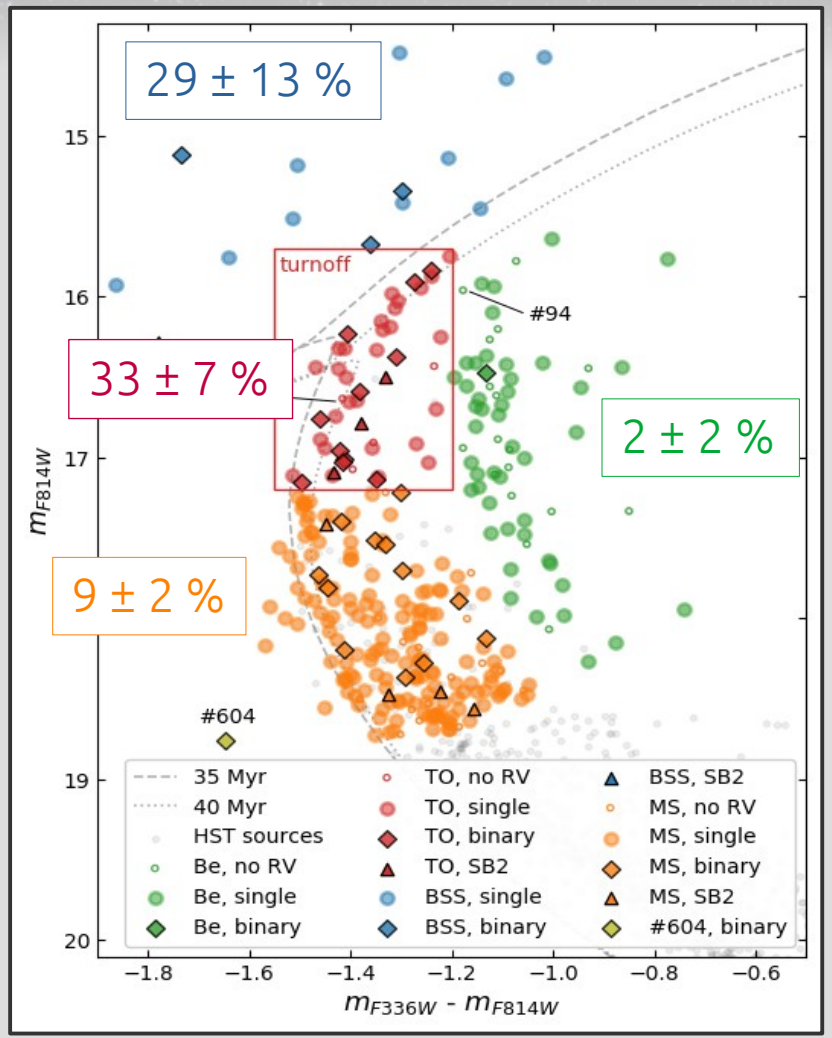
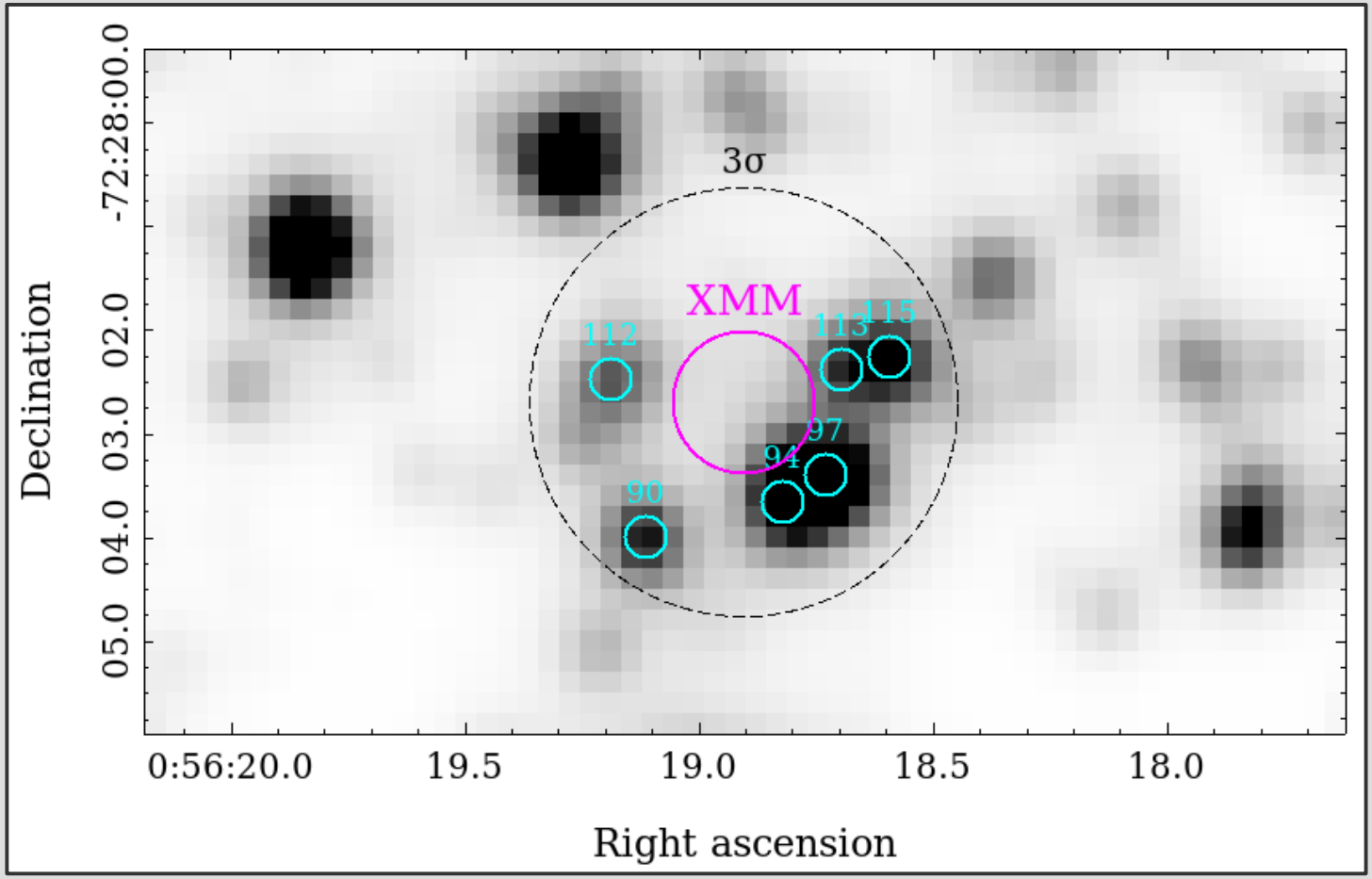


Stellar parameters in an evolutionary context





A Be-Xray binary candidate



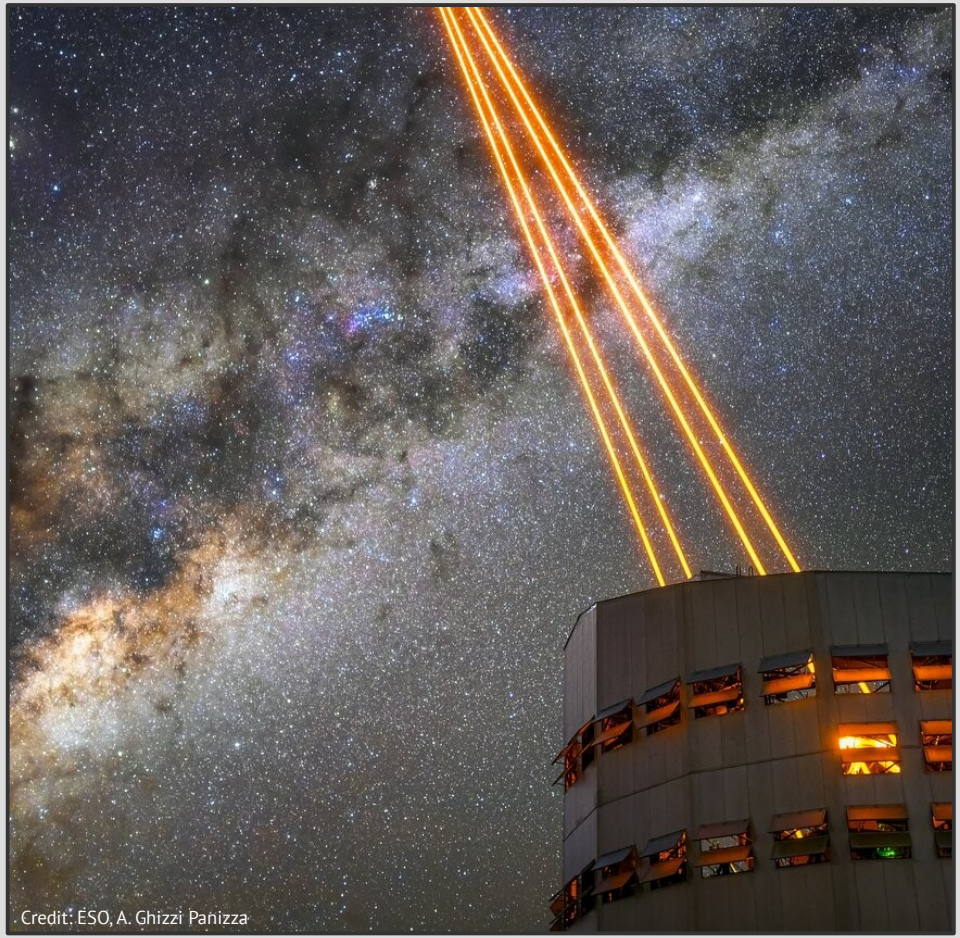
Take-away points

* IFS is great! :-)
  IFS = photometry + spectroscopy

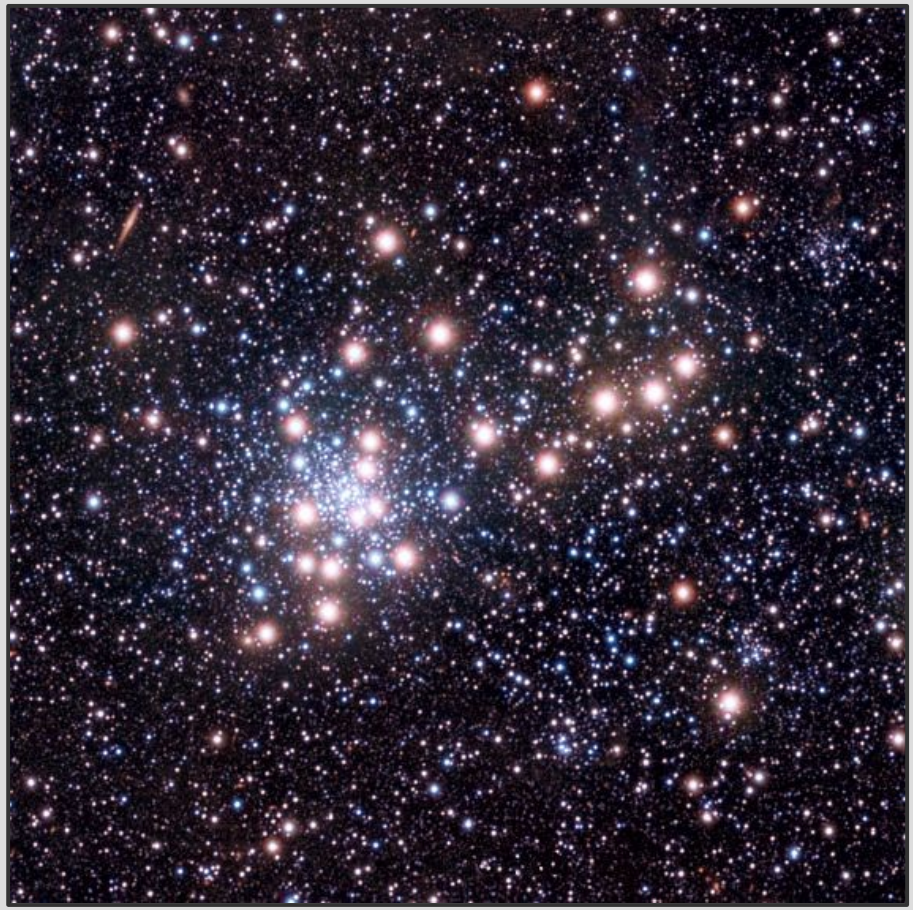
* … particularly great for extended objects and resolved stellar populations

* lots of new IFUs on new telescopes (JWST, ELT)

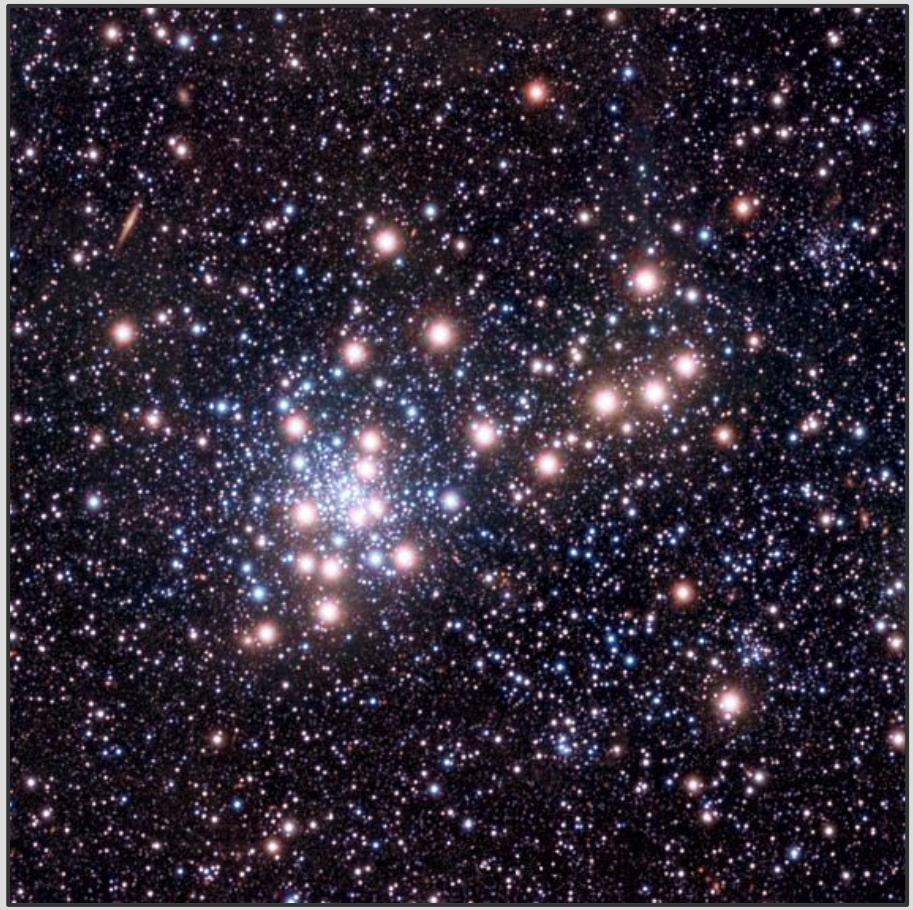
* (current) downsides:
  - size of the FoV
  - spectral resolution



Hands-on session: NGC 2100



Hands-on session: NGC 2100



* play with the cube
* investigate the interstellar medium
* find red and blue supergiants
* find all Hα emitters
* count the O-type stars
* extract spectra
  - from one pixel
  - with aperture photometry
  - with PSF fitting

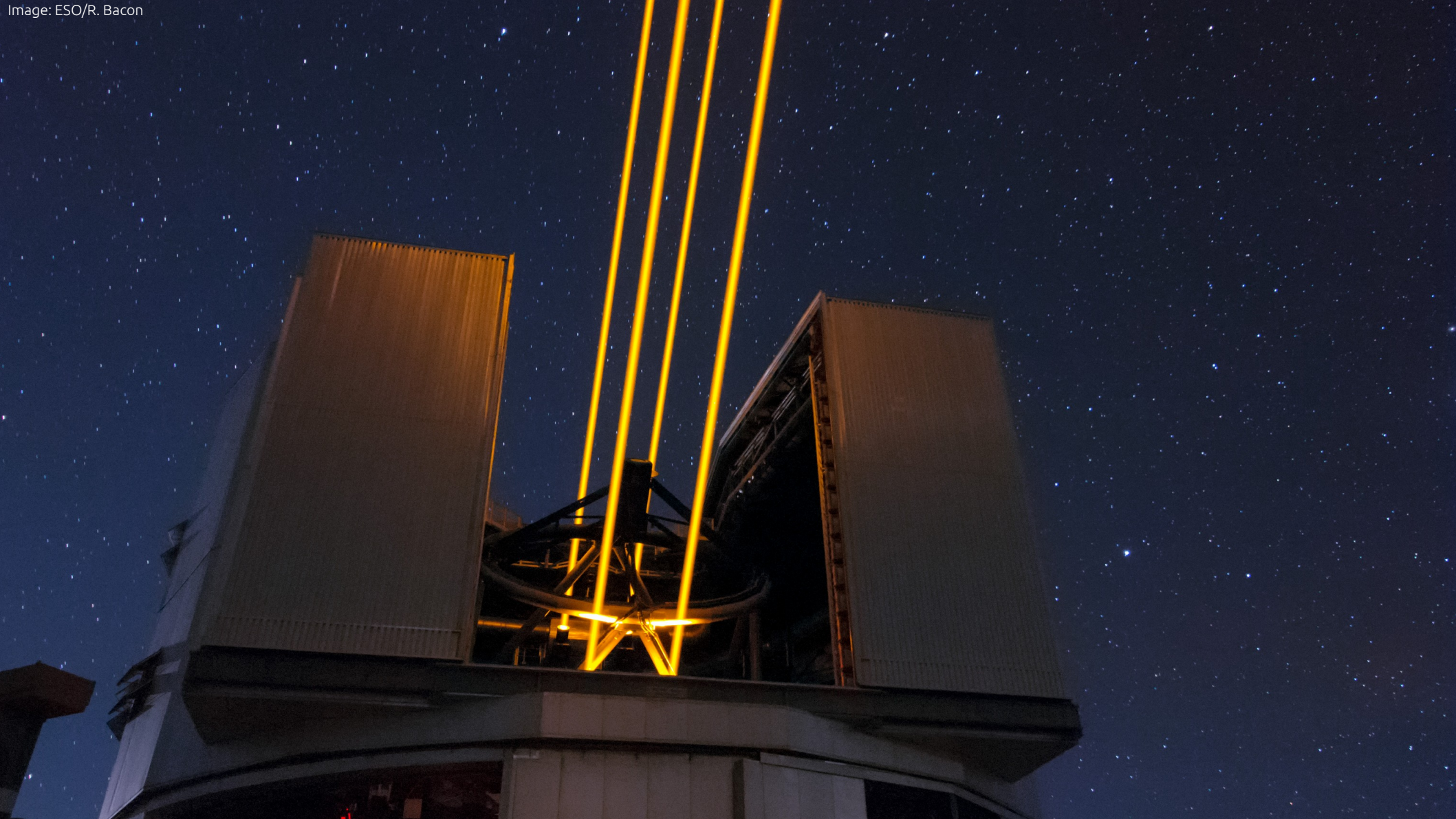


Image: ESO/R. Bacon