# Integral Field Spectroscopy in the Near IR

## Instrumentation, techniques and data reduction

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*GH School 2014*

75 AÑOS CSIC Consejo Superior de Investigaciones Científicas
CENTRO DE ASTROBIOLOGÍA
ASOCIADO AL NASA ASTROBIOLOGY INSTITUTE
CSIC INTA

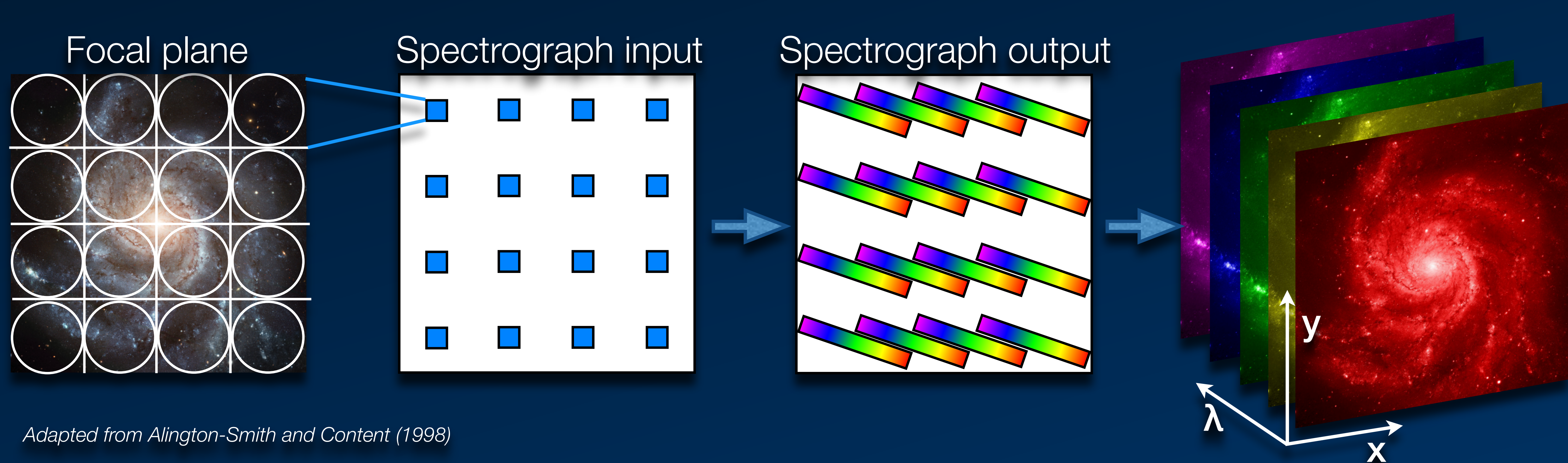
# Overview of the talk

- Integral field spectroscopy in the NIR
  - Basic concepts
  - Sky emission
  - Atmospheric transmission
- Observing techniques
  - Nodding and jittering
  - Adaptive optics
- Science with near-IR IFS data
- Present and future of near-IR IFS

# IFS in the near-IR: basic concepts

# IFS in the NIR: basic concepts

- Integral field spectrograph = Spectrograph + Integral field unit
- IFU: divides the 2D FoV into a continuous array
  - Lenslet array: input image split up by a microlens array
  - Fibres: input image formed on a bundle of optical fibers
  - Fibres + lenslets: array of lenslets in front of the fibre bundle
  - Image slicer: input image formed on a mirror that re-arrange the image into a pseudoslit




*Adapted from Alington-Smith and Content (1998)*

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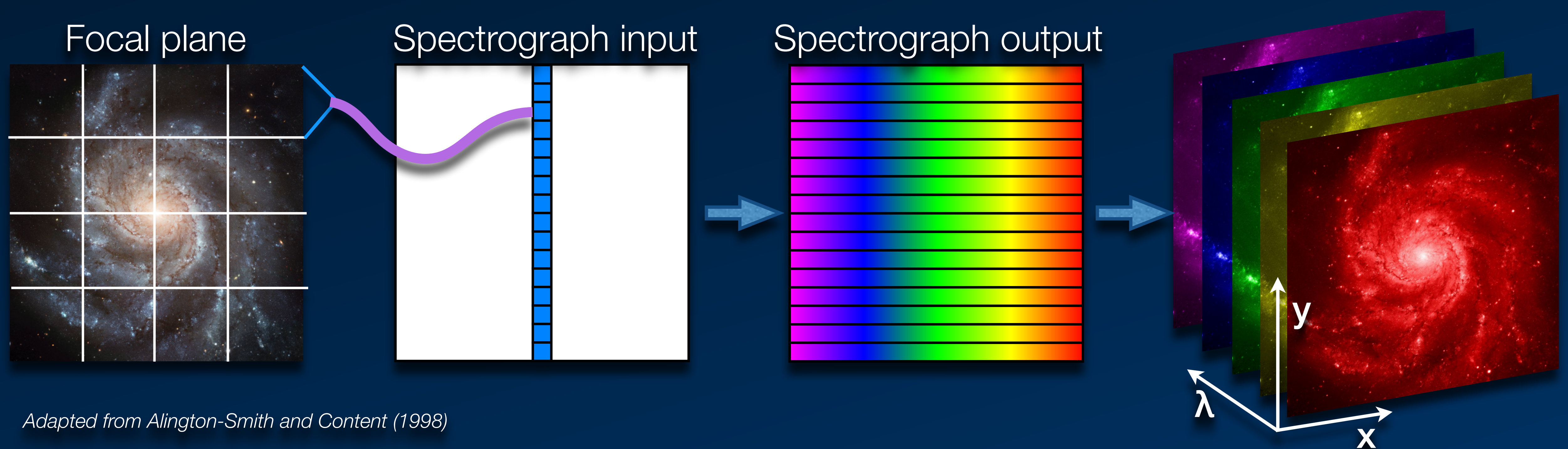


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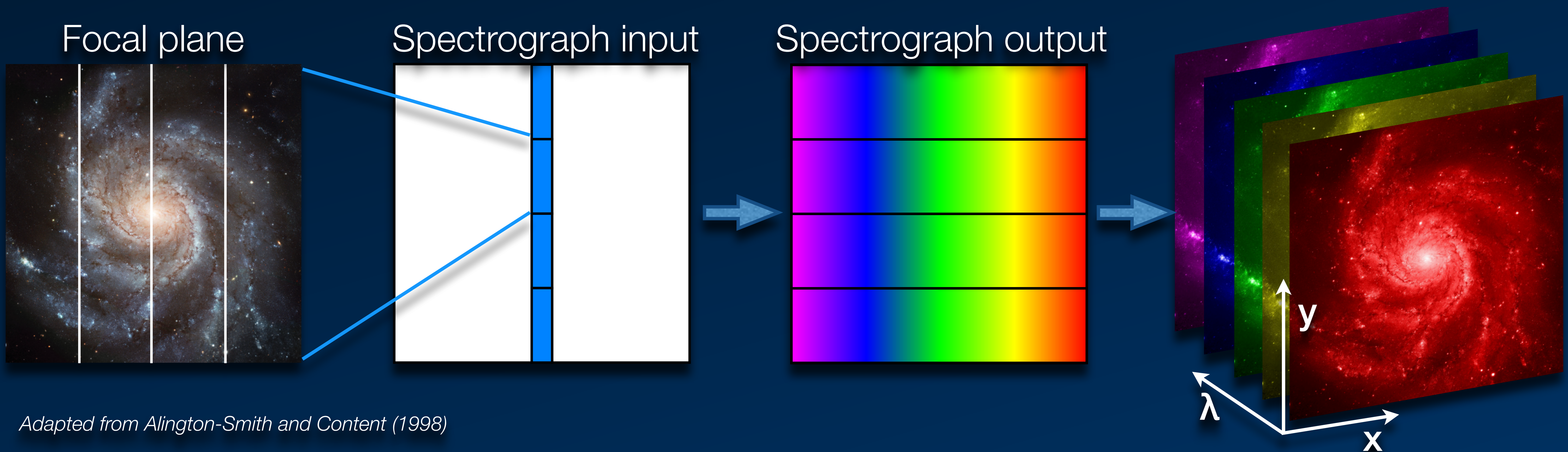


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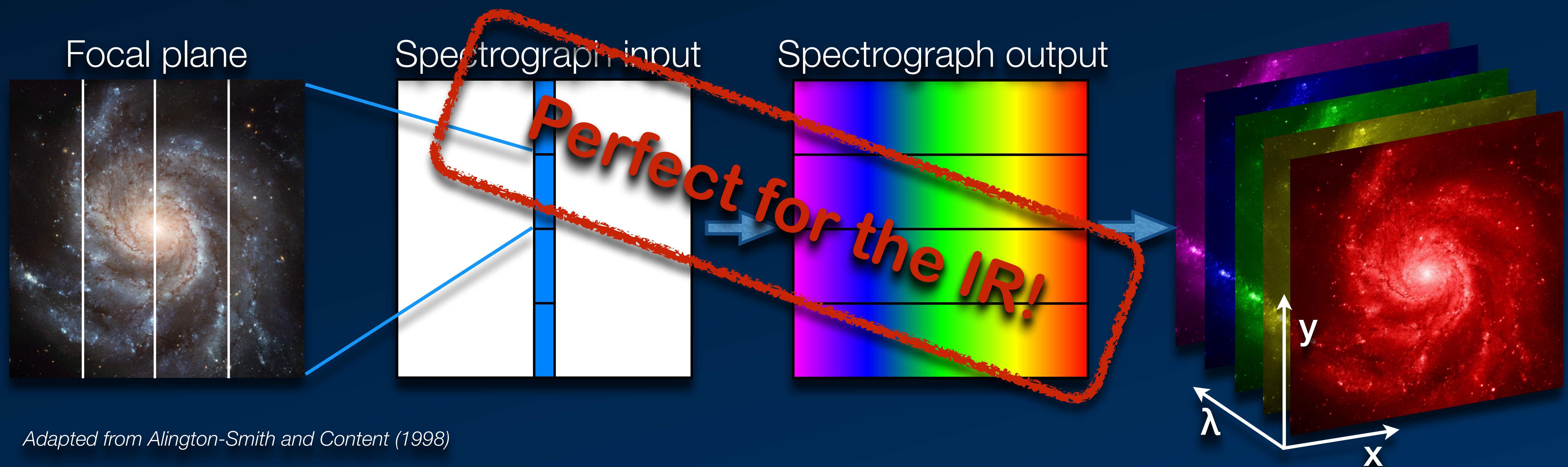


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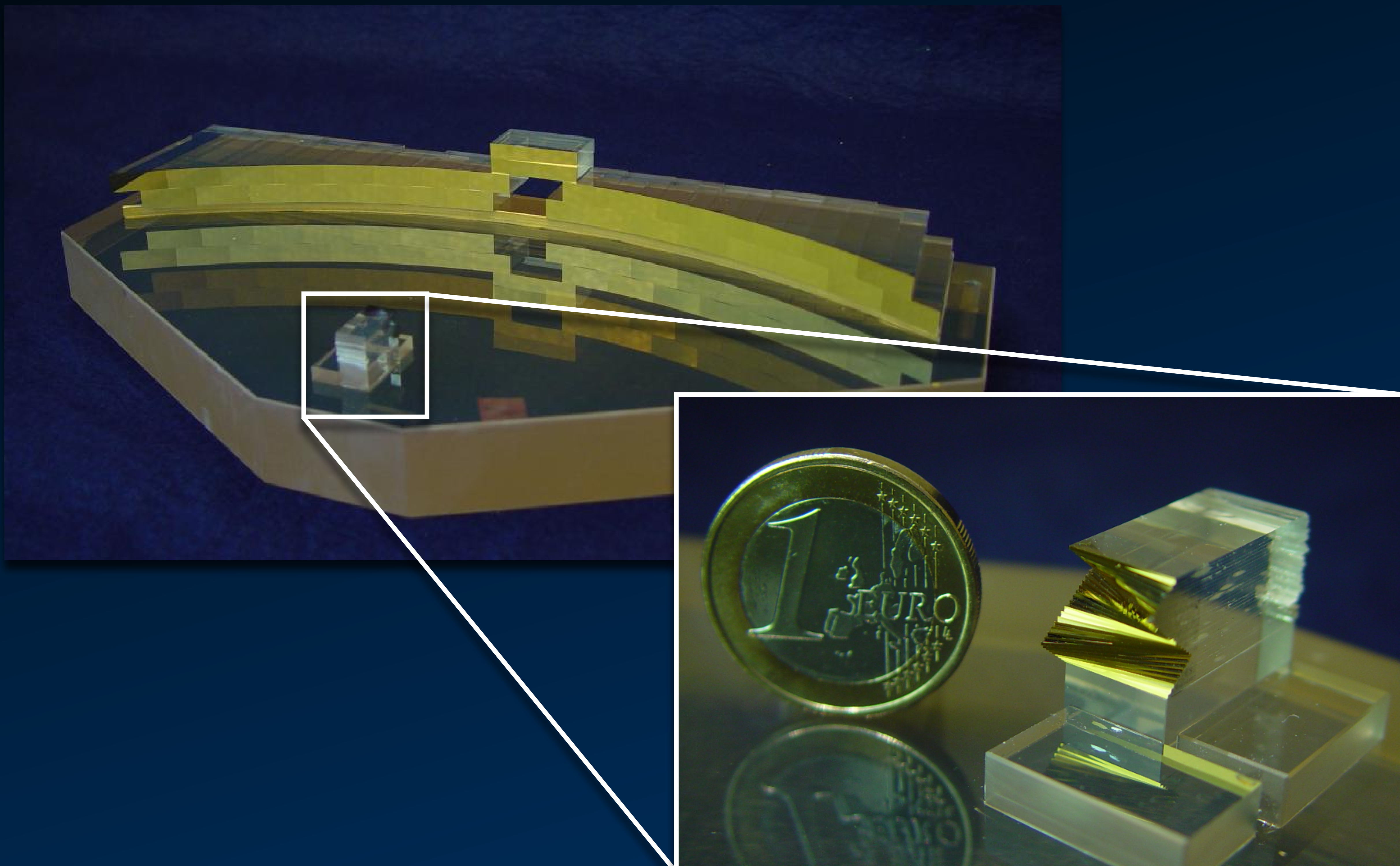

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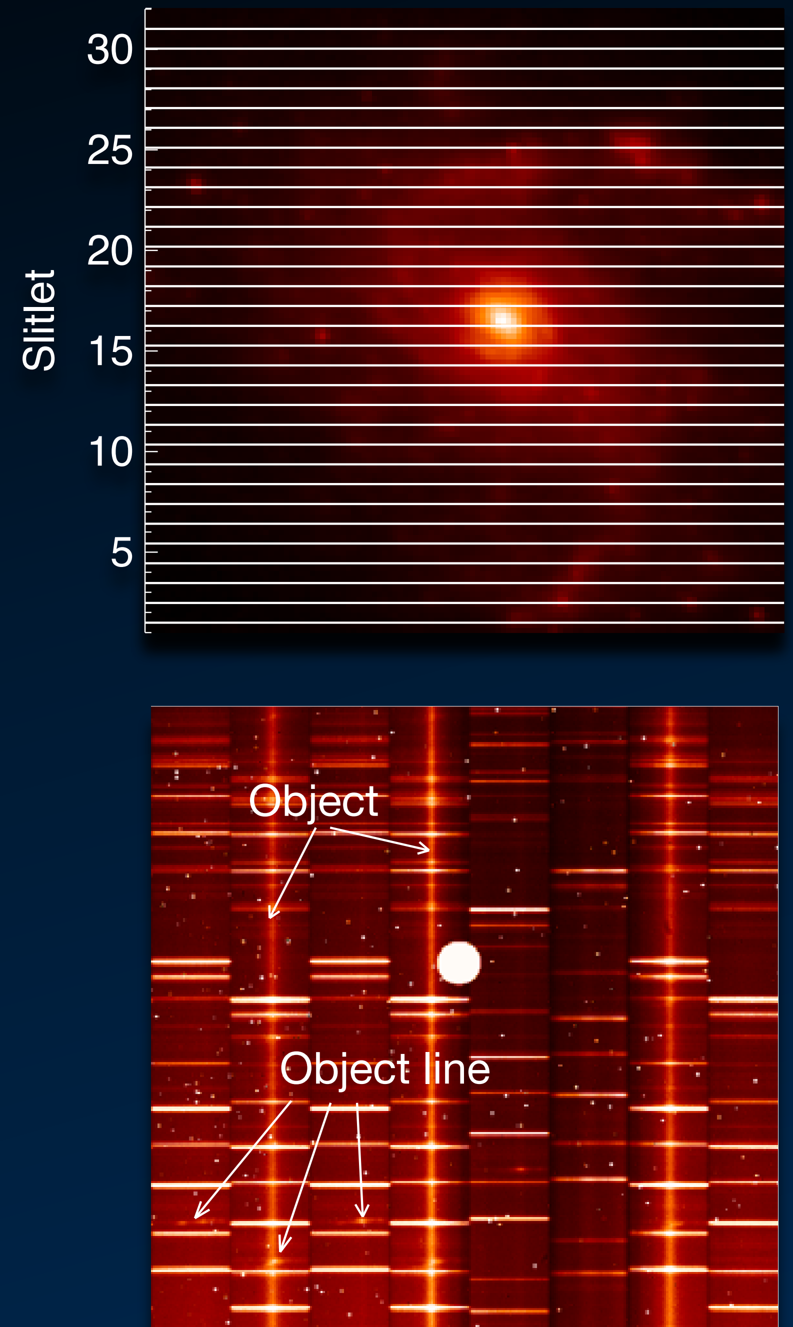
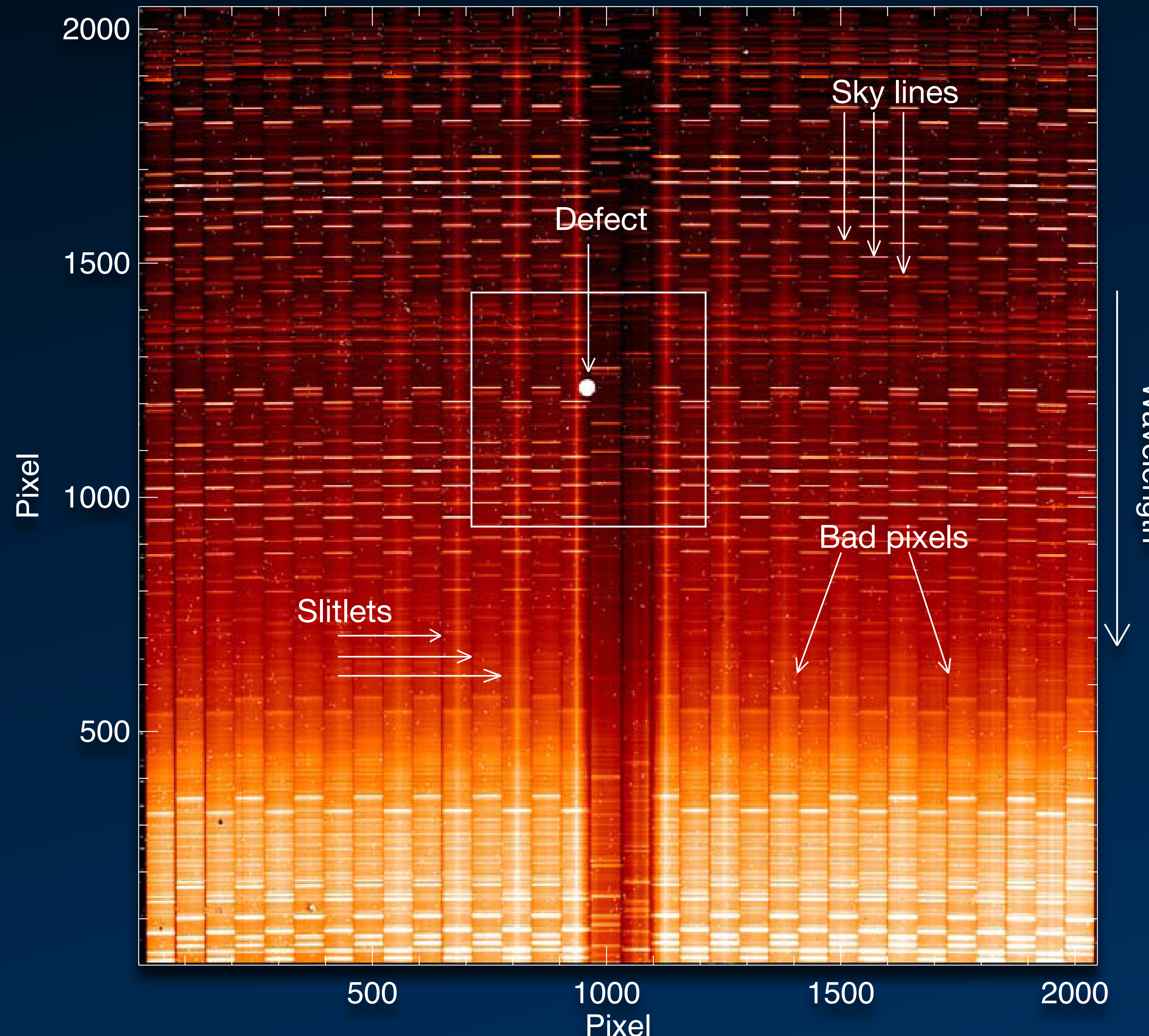
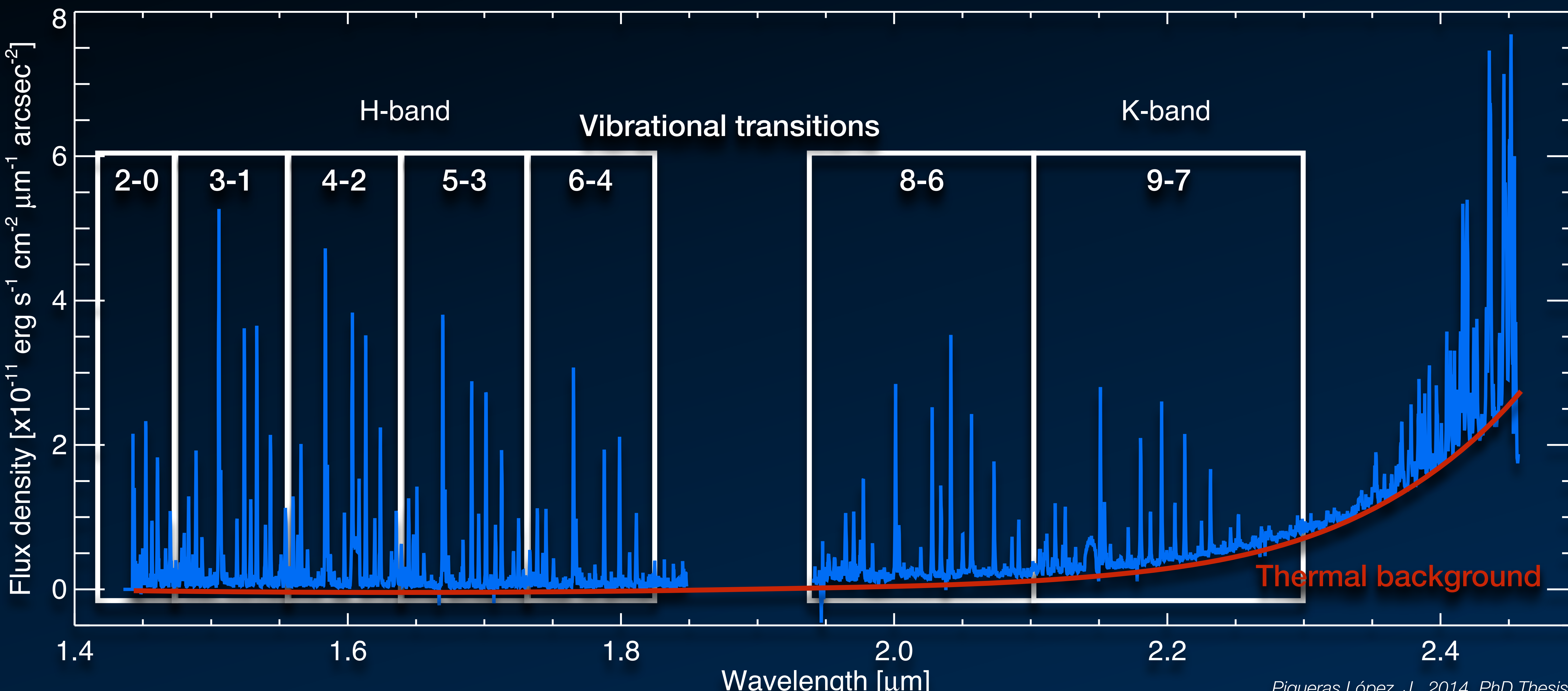



*Piqueras López, J., 2014, PhD Thesis*

# Sky emission

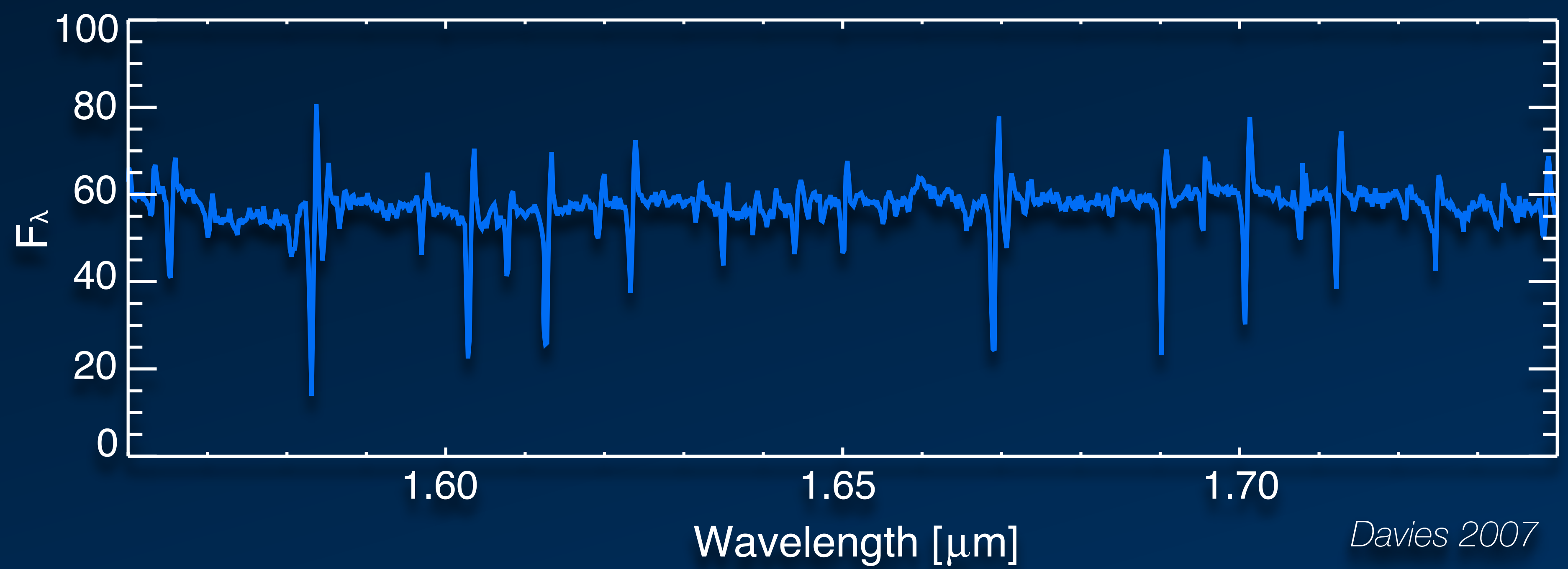



*Piqueras López, J., 2014, PhD Thesis*

- Two sources:
  - Thermal background: atmospheric (+ telescope) emission dominates beyond ~2.3 µm
  - Airglow emission: OH vibrational lines that dominates below ~2.3 µm

# Sky emission

- Dominant source of noise in fully processed data
- Line emission is usually several orders of magnitude above from other sources
- In most cases, to obtain separate sky frames is mandatory to subtract the sky lines (IFS limited FoV)
- Sky line subtraction:
  - 'Classical' first-order approach: object spectrum - sky spectrum
  - Due to rapid variability of the emission, not enough for IFS data: P-Cygni residuals




*Davies 2007*

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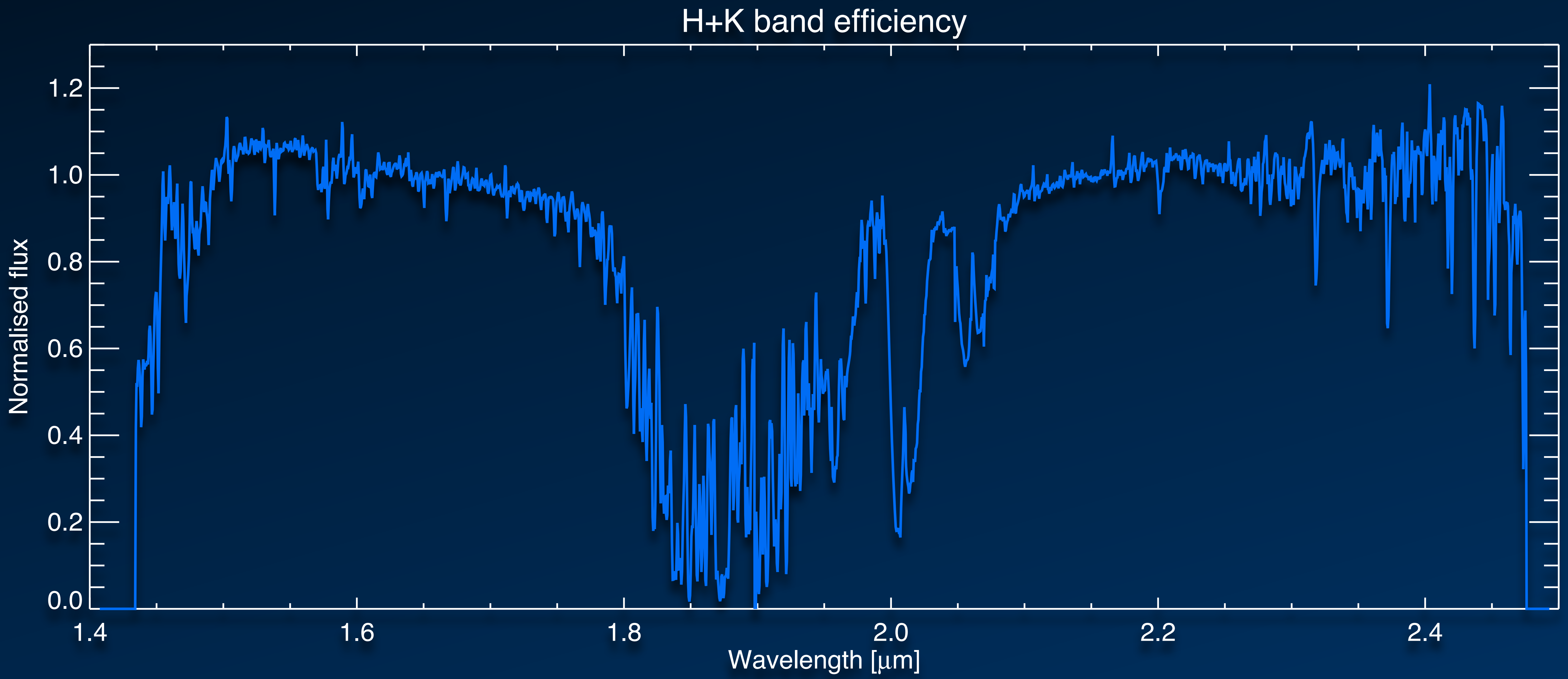
- Sky line subtraction:
  - ‘Classical’ first-order approach: object spectrum - sky spectrum
  - Due to rapid variability of the emission, not enough for IFS data: P-Cygni residuals
  - More sophisticated methods are already implemented (e.g. Davies 2007), to account for variability and compensate for instrumental flexures.
- However, although they might be a nuisance, sky lines could be also useful:
  - As reference for wavelength calibration: object and sky frames are observed using the same configuration
  - As a valuable option to characterise the spectral resolution of our data

# Atmospheric transmission: Efficiency curves

- Atmospheric absorption in the near-IR: vibrational transitions of water vapor



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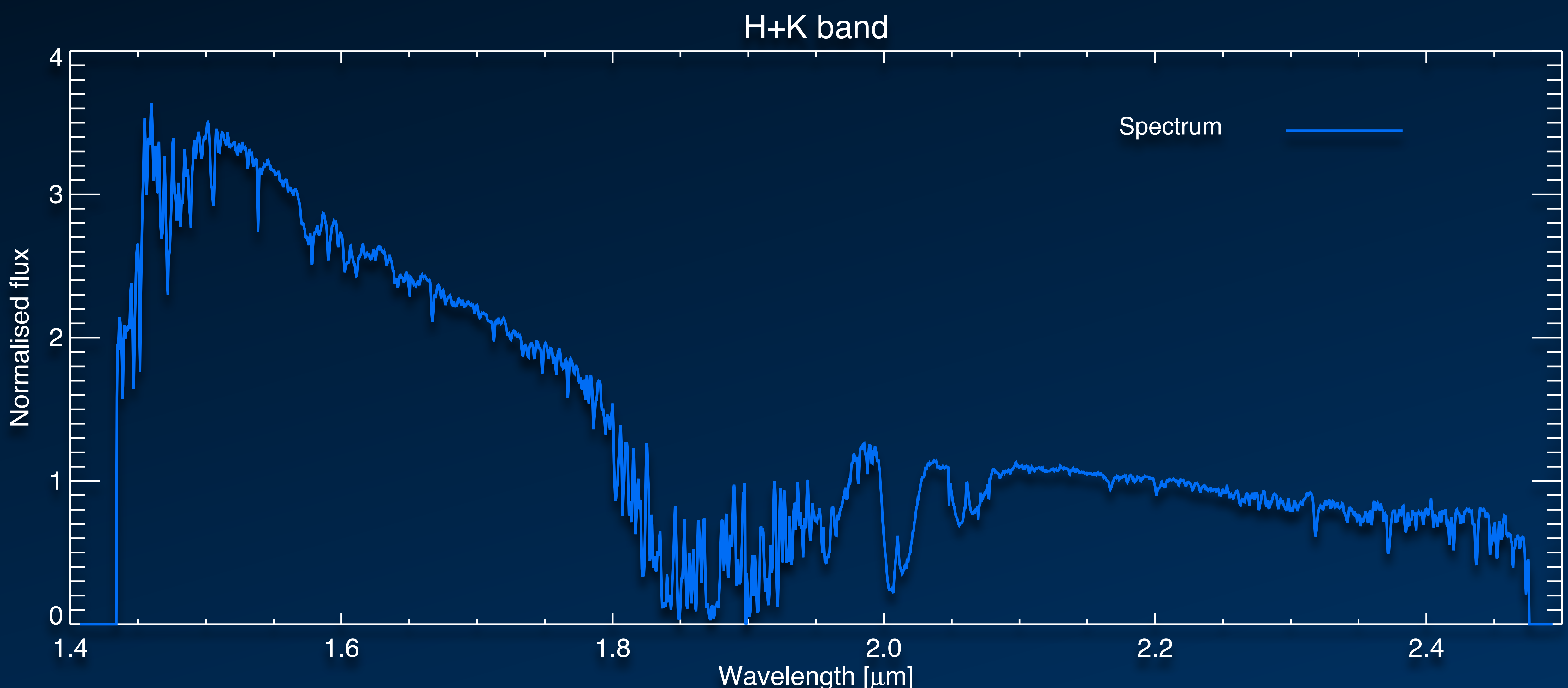
- Depends on the airmass, varies with time…
- Although it can be modeled, it is usually corrected using standard stars: efficiency curves



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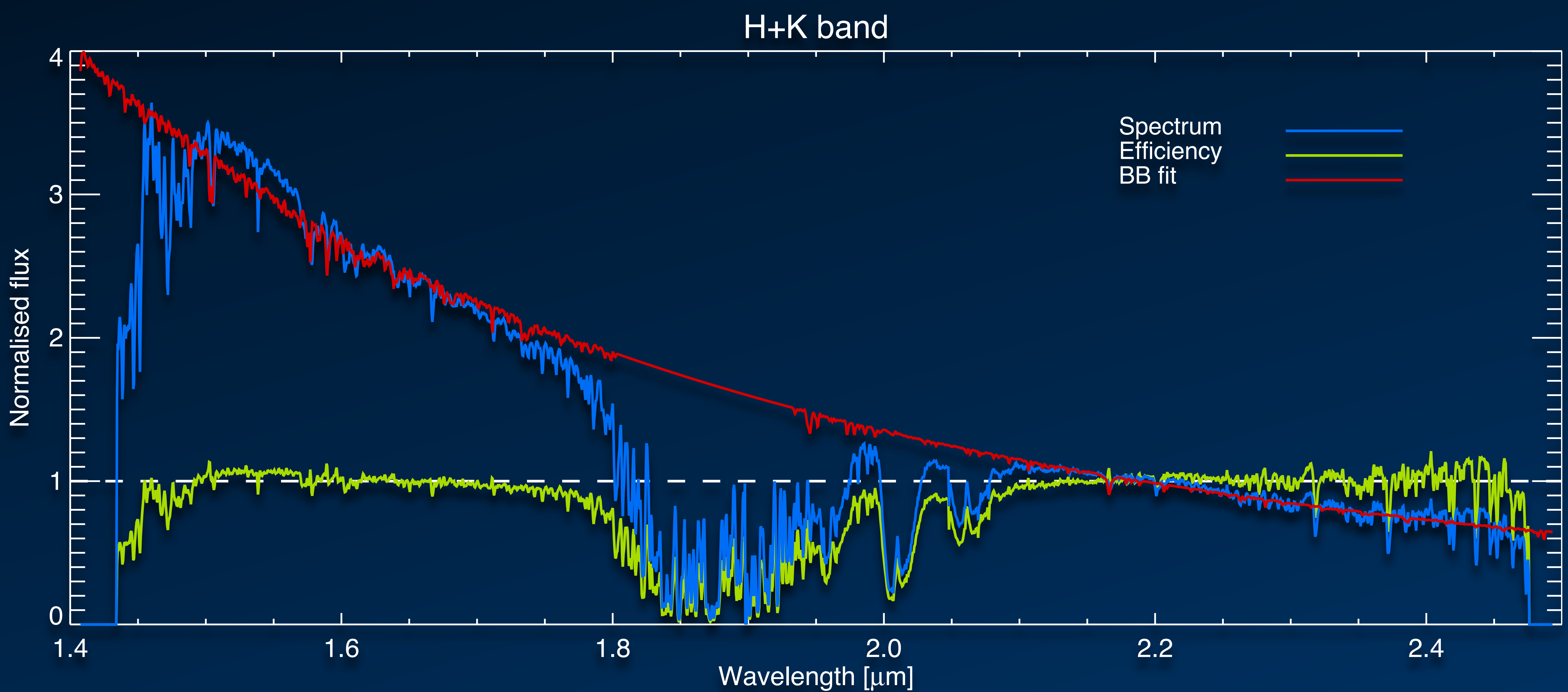


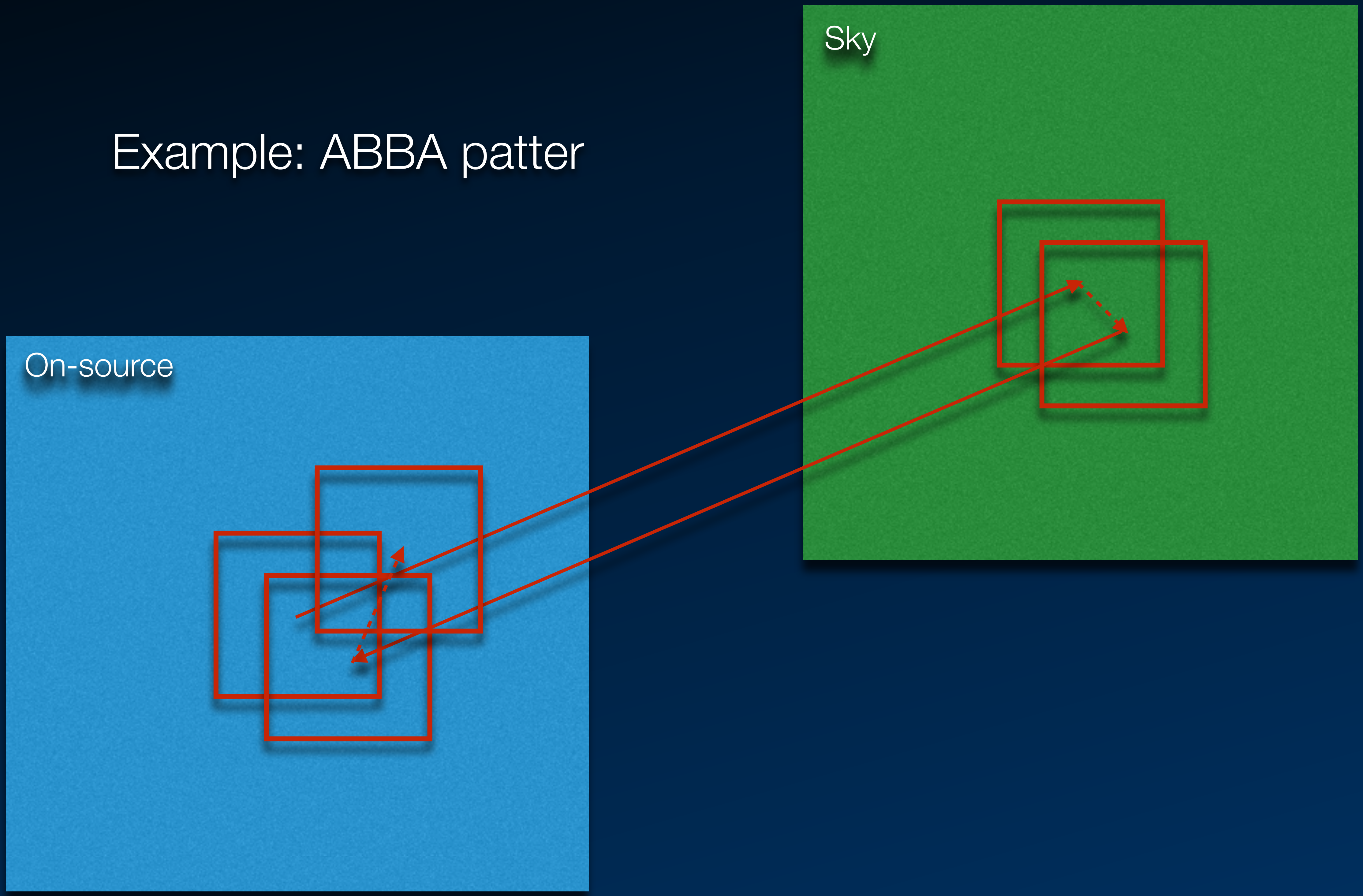
# Observing techniques

# Observing techniques

- Observing in the near-IR
  - Near-IR detectors are not as efficient as optical ones: relatively large number of ‘bad’ pixels and defects.
  - Strong background emission of the sky
    - Detectors could be rapidly saturated.
    - Additional sky exposures are mandatory in most of the cases.
  - Atmospheric transmission.
- How do we deal with that?
  - Split the exposures into shorter ones (50s, 100s, 150s, 300s…)
  - Use jittering patterns to avoid detector defects / bad pixels.
  - Nodding the telescope between on-source and sky positions to characterise the sky emission.
  - Observing standard stars for flux calibration.

# Observing techniques

Example: ABBA patter



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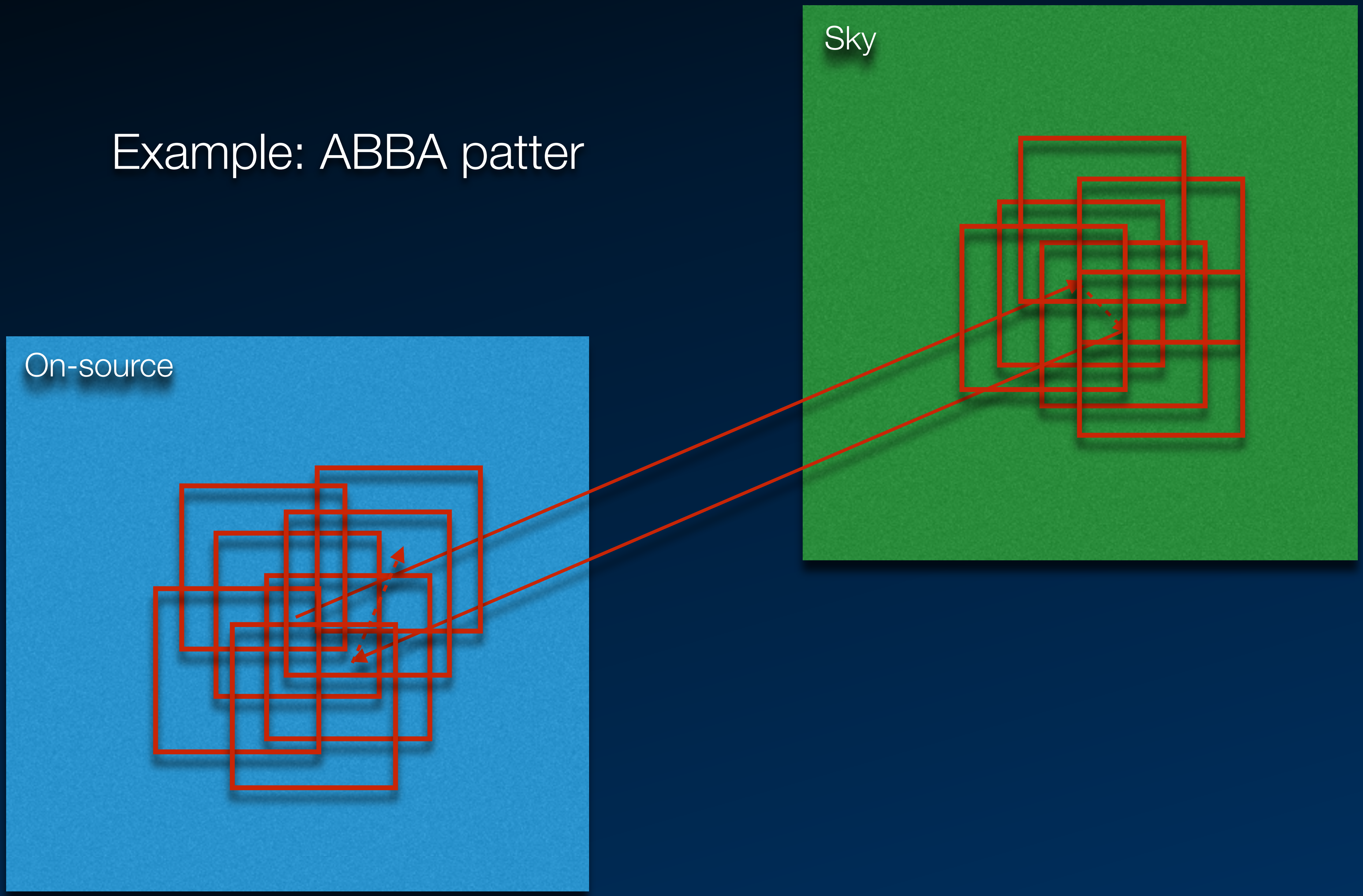

# Adaptive Optics

- Basics of adaptive optics:
  - Problem: images blurred due to the refractive turbulent atmosphere.
  - Prevents large telescopes to achieve their diffraction limit.
- The principle of AO: correct in real time the spatial and temporal variations of the optical path length along the line of sight.
- Well suited for near-IR observations: easy to obtain better corrections at longer wavelengths

Credit: ESO/Y. Beletsky

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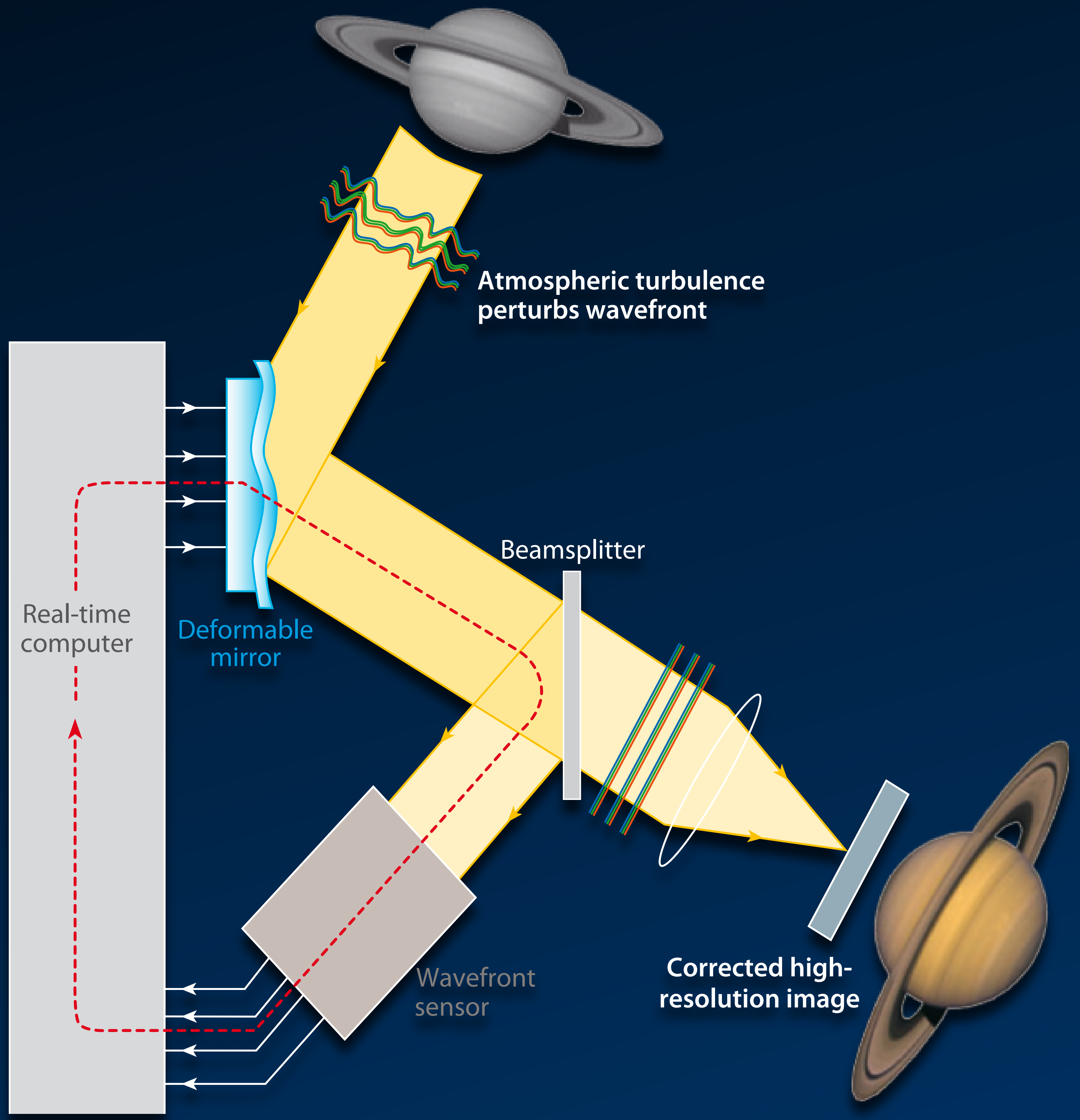


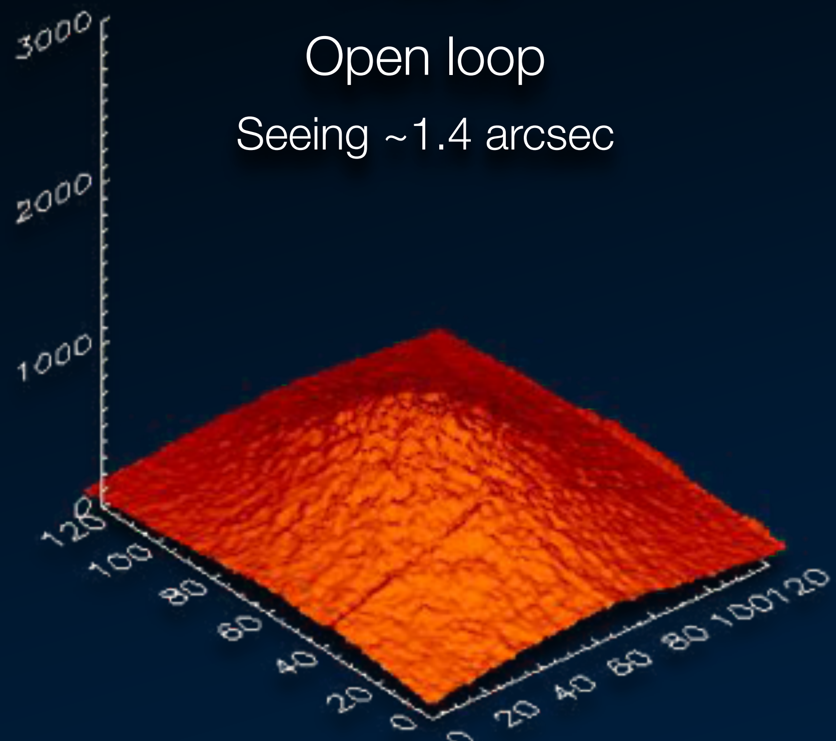

*Adapted from Davies and Markus 2012*

# Adaptive Optics

H-band

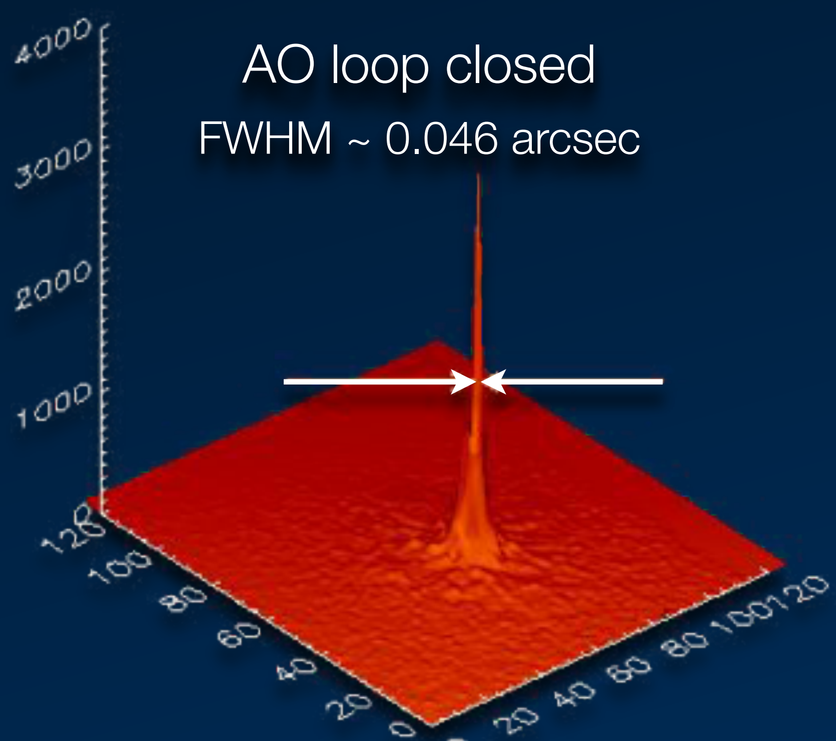
Open loop

Seeing ~1.4 arcsec




AO loop closed

FWHM ~ 0.046 arcsec

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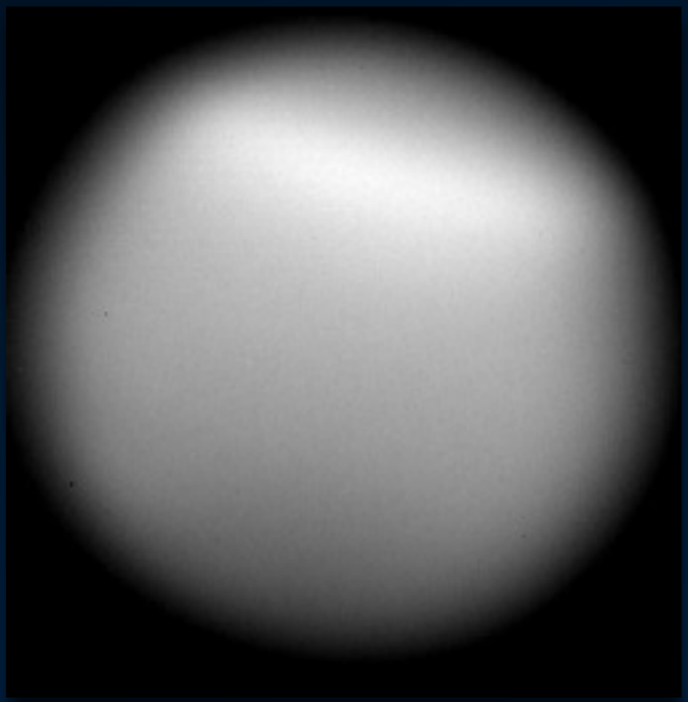
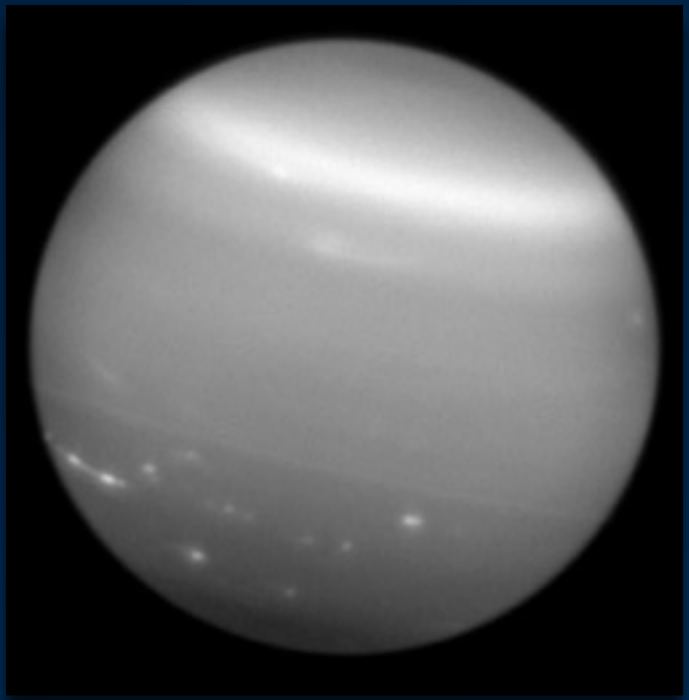
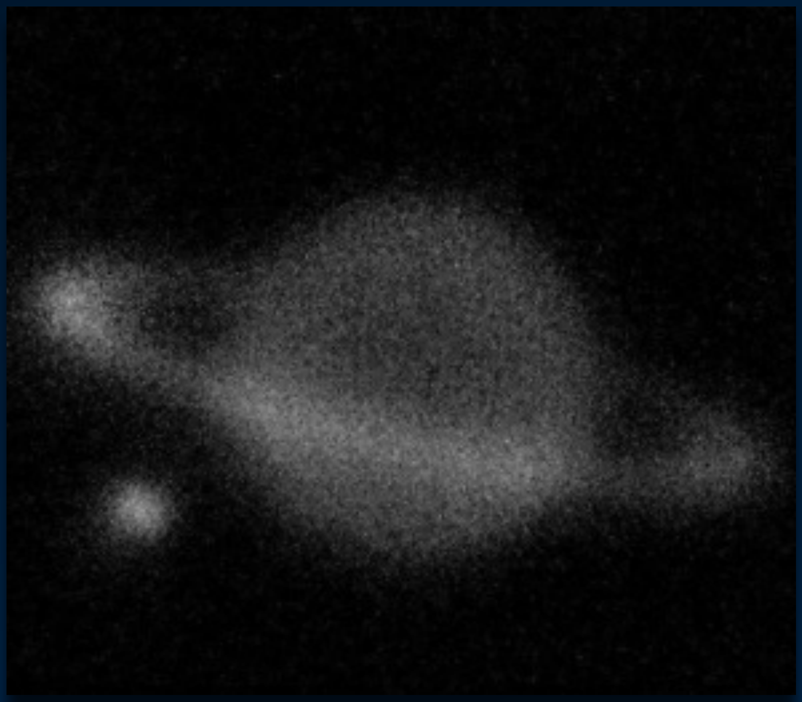
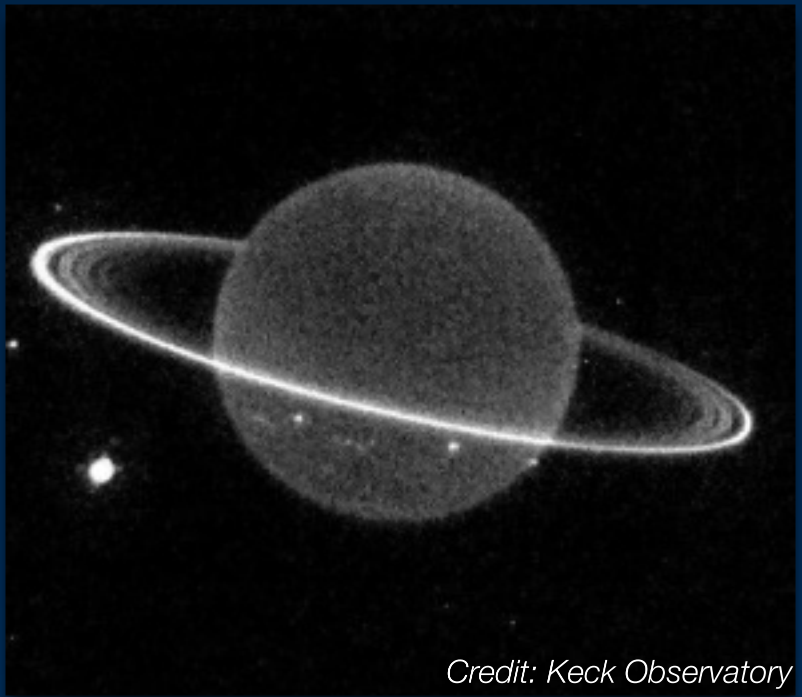




K-band





# Adaptive Optics

- Adaptive optics observations:
  - Natural guide star (NGS)
    - A close (d < 10"), bright star (R < 15 mag) is needed.
    - Under these conditions, the diffraction limit of the telescope could be approached or achieved.
    - Sky coverage ~10%
  - Laser guide star (LGS)
    - A laser beam is used to create an artificial star by resonant fluorescence of Na atoms.
    - However, a tip-tilt star (d < 1', R < 18 mag) is also required for first-order corrections of the wavefront.
    - For larger apertures, it does not cover the full aperture at the heigh of the turbulent layers (cone effect, focal anisoplanatism)

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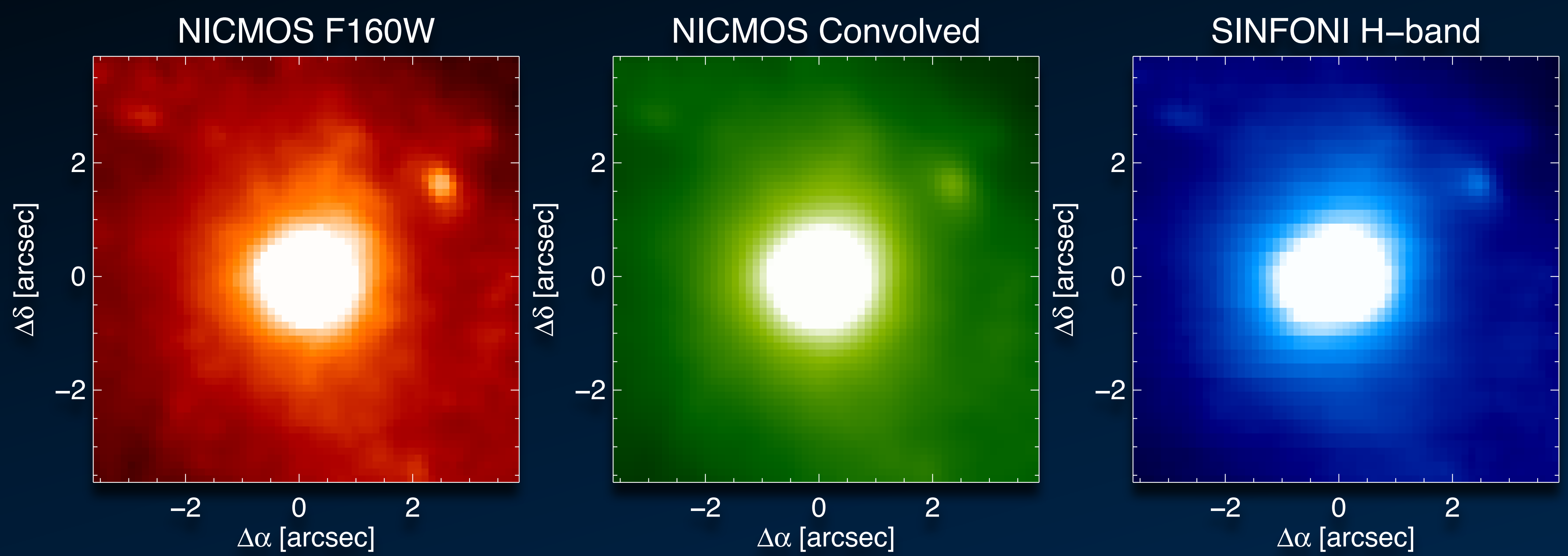
# PSF: AO vs seeing-limited observations




*Piqueras López, J., 2014, PhD Thesis*

$$I_{SINFONI} = I_{NICMOS} \otimes B$$

$$PSF_{SINFONI} = PSF_{NICMOS} \otimes B$$

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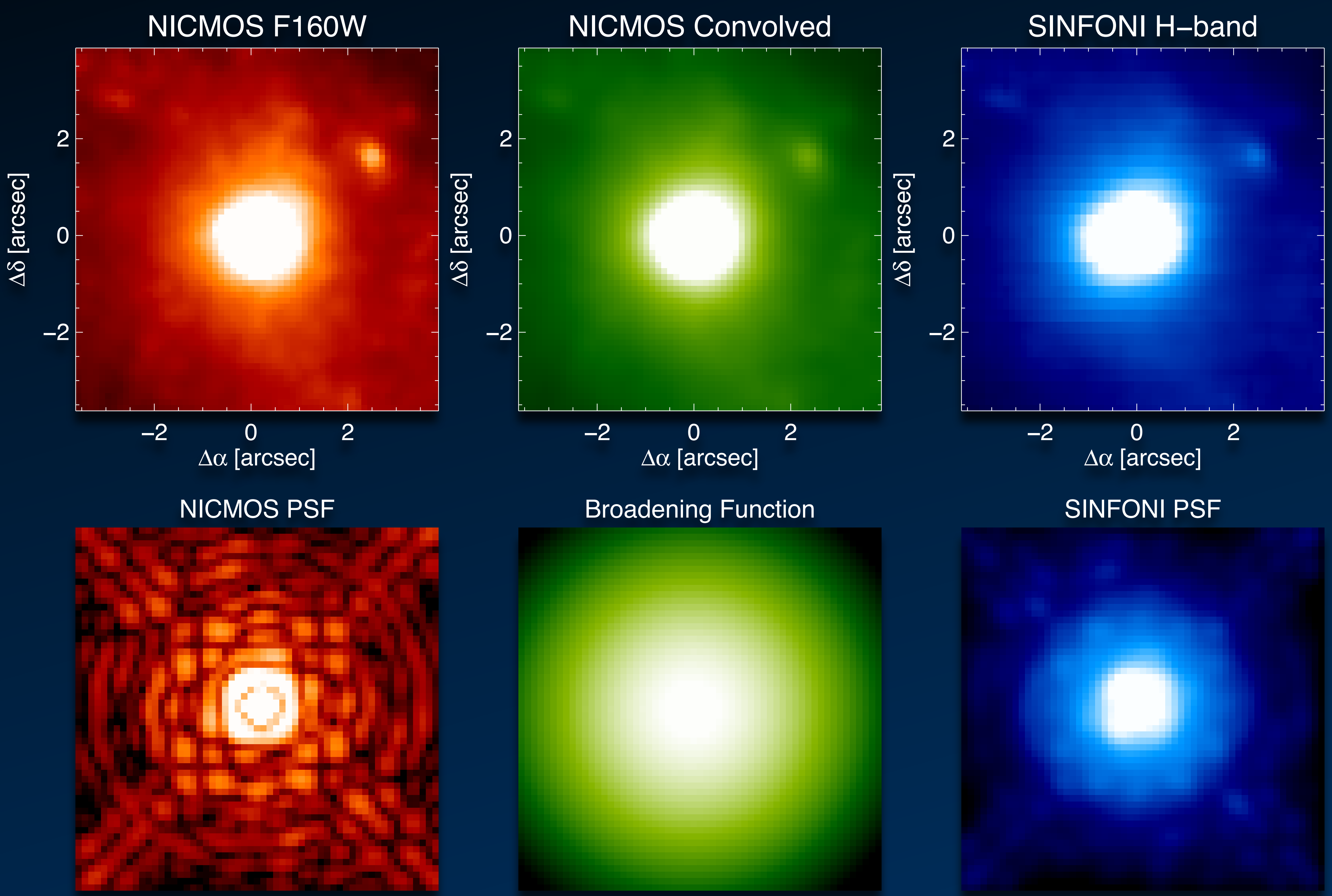


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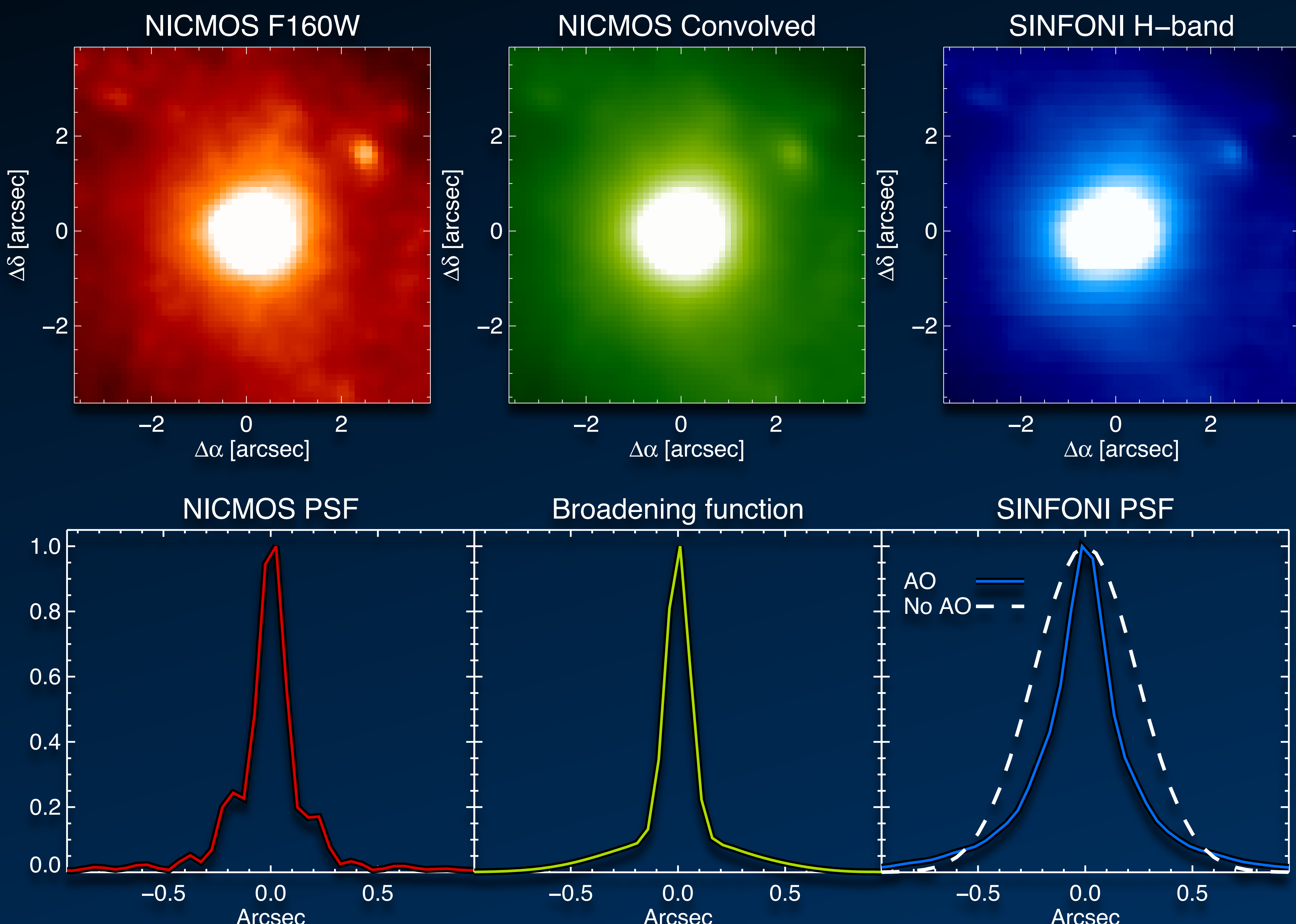


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# Science with near-IR IFS data

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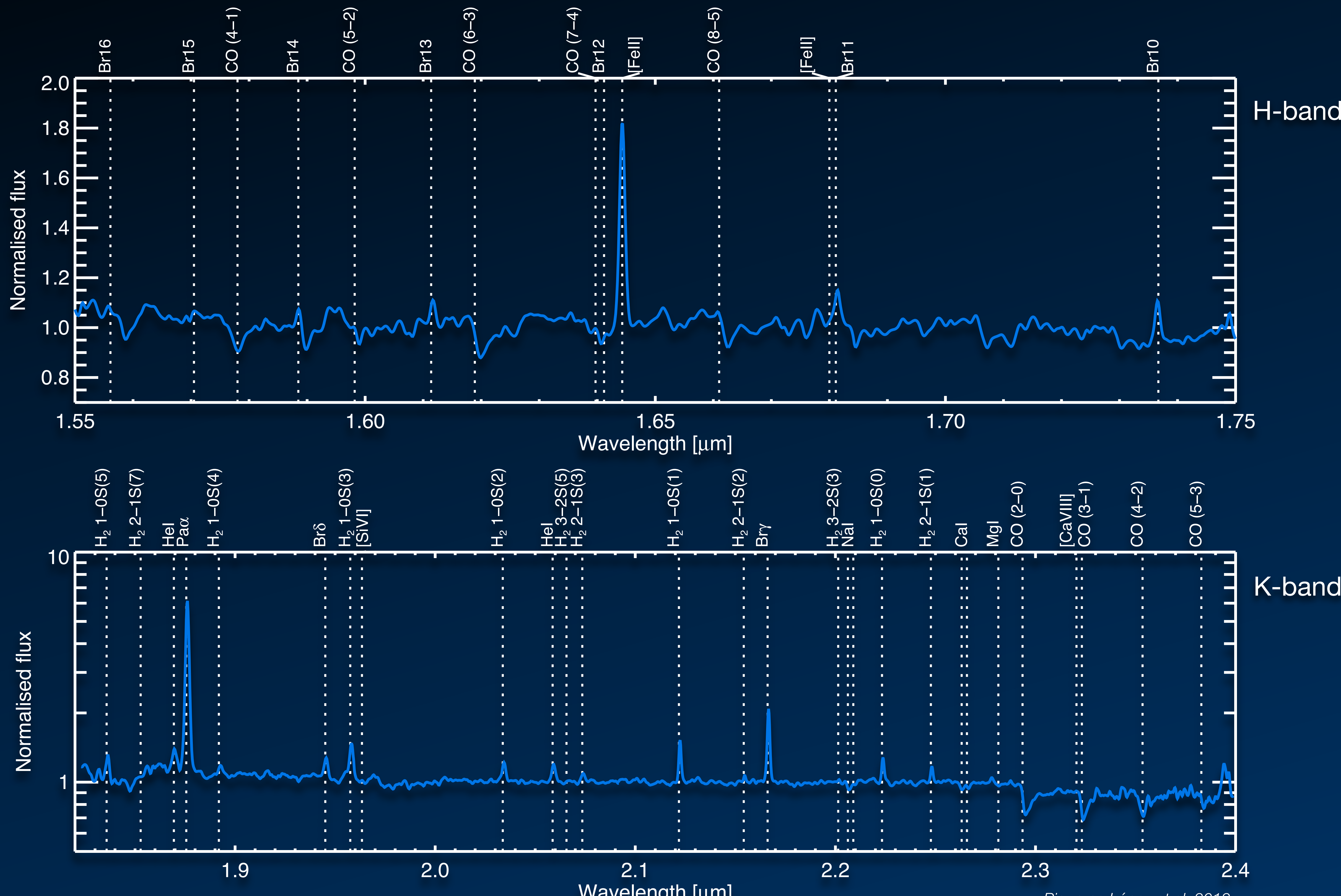
- Ionised gas and star-formation
  - Paβ λ1.282 μm, Paα λ1.876 μm, Brδ λ2.166 μm, Brγ λ2.166 μm, primary indicators of the star-formation rate
  - HeI λ2.059 μm associated to very young star-forming complexes
  - [FeII] λ1.257 μm, [FeII] λ1.644 μm: supernova rate in starbursts and constrain the age of the stellar populations
- Extinction measurements: Brγ/Brδ and Paα/Brγ line ratios
- Warm molecular gas: $H_2$ excitation mechanisms
- Ionisation mechanisms: 2D BPT near-IR diagrams, [FeII]/Paβ and $H_2$/Paβ ($H_2$/Brγ) line ratios
- Tracers of obscured AGNs: [SiVI] λ1.963 μm and [CaVIII] λ2.321 μm as AGN indicators
- Stellar populations: absorption features, CaI, NaI, CO (2-0), CO(3-1)…
- Multi-phase gas and stellar kinematics, outflows signatures in different phases of the ISM

# Science with near-IR IFS data




*Piqueras López et al. 2012*

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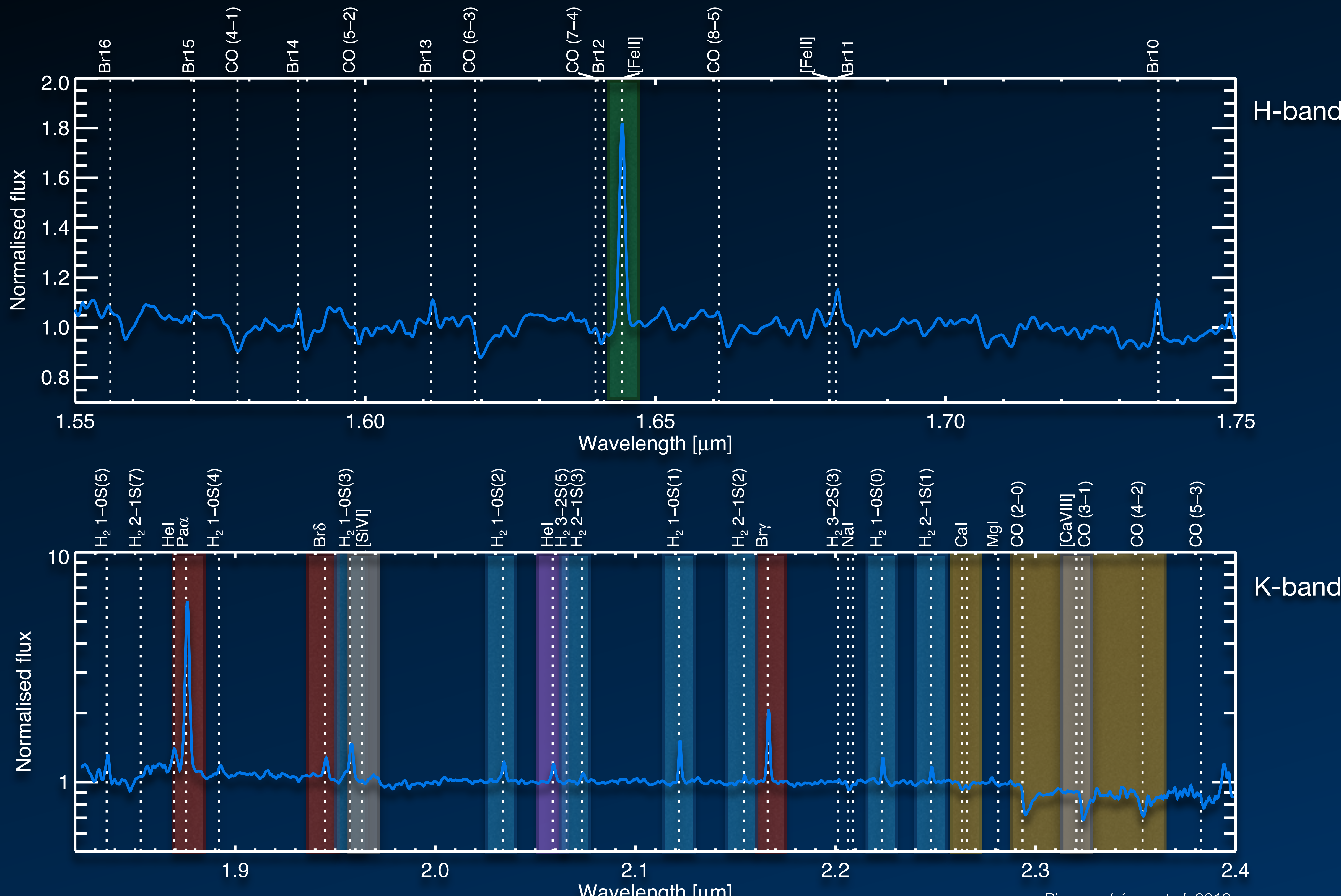



*Piqueras López et al. 2012*

# Present and future of near-IR IFS

# Present & future: Ground 8-11m

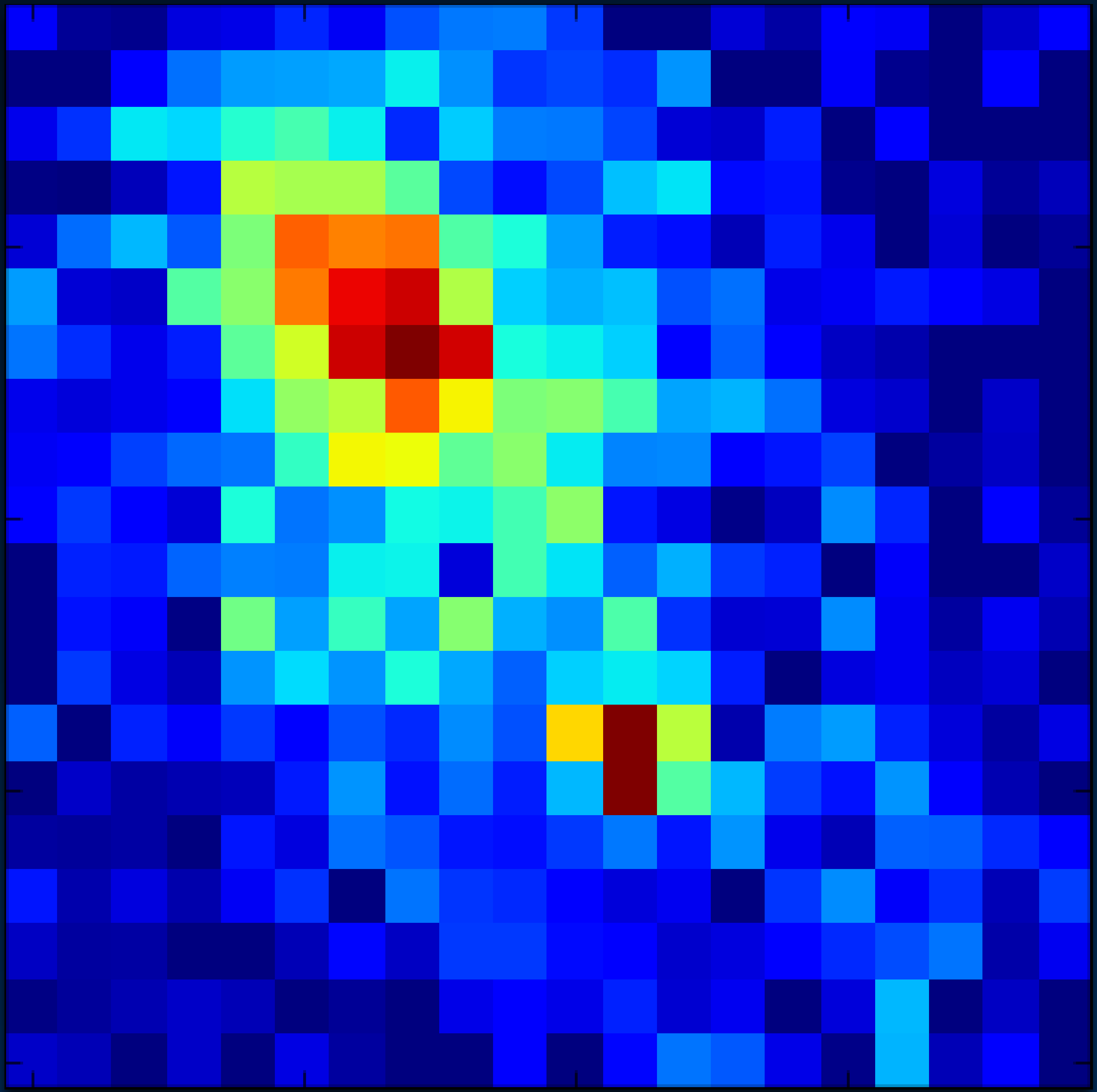
| | Type | FoV | Scale | R | λ range |
|---|---|---|---|---|---|
| OSIRIS *(Keck)* | Lenslet | 0.32”x1.28” to 3.2”x6.4” | 20, 35x50, 100 mas | 2.7k-4.0k | 1.0-2.4 μm |
| NIFS *(Gemini N)* | Slicer | 3”x3” | 40x100 mas | 5.0k | 0.95-2.4 μm |
| SINFONI *(VLT)* | Slicer | 0.8”x0.8” 3”x3”, 8”x8” | 25, 100, 250 mas | 1.5k 2.0-4.5k | 1.1-2.45 μm |
| KMOS *(VLT)* | Slicer | 2.8”x2.8” (x24) | 200 mas | 2.0k 3.5-4.2k | 0.8-2.5 μm |
| FRIDA *(GTC)* | Slicer | 0.65”x0.65” 2.6”x2.6” | 10-40 mas | 1.5k, 4.5k, 30k | 0.9-2.5 μm |

# Present & future: Ground 20-40m

| | Type | FoV | Scale | R | λ range |
|---|---|---|---|---|---|
| IRIS *(TMT)* | Lenslet or slicer | 0.18”x0.35” to 2.2”x4.4” | 4, 10, 24, 50 mas | 2.0-4.0k | 0.8-2.5 μm |
| HARMONI *(E-ELT)* | Slicer | 0.6”x0.9”<br>1.5”x2.1”<br>3.0”x4.3”<br>6.4”x9.1” | 4x4 mas<br>10x10 mas<br>20x20 mas<br>60x30 mas | 0.5k, 3.5k, 8.0k, 20.0k | 0.47-2.5 μm |
| GMTIFS *(GMT)* | Slicer | 0.3”x0.5” to 2.25”x4.4” | 6,12, 25, 50 mas | 5.0 - 10.0k | 0.84-2.4 μm |

# HARMONI at the E-ELT

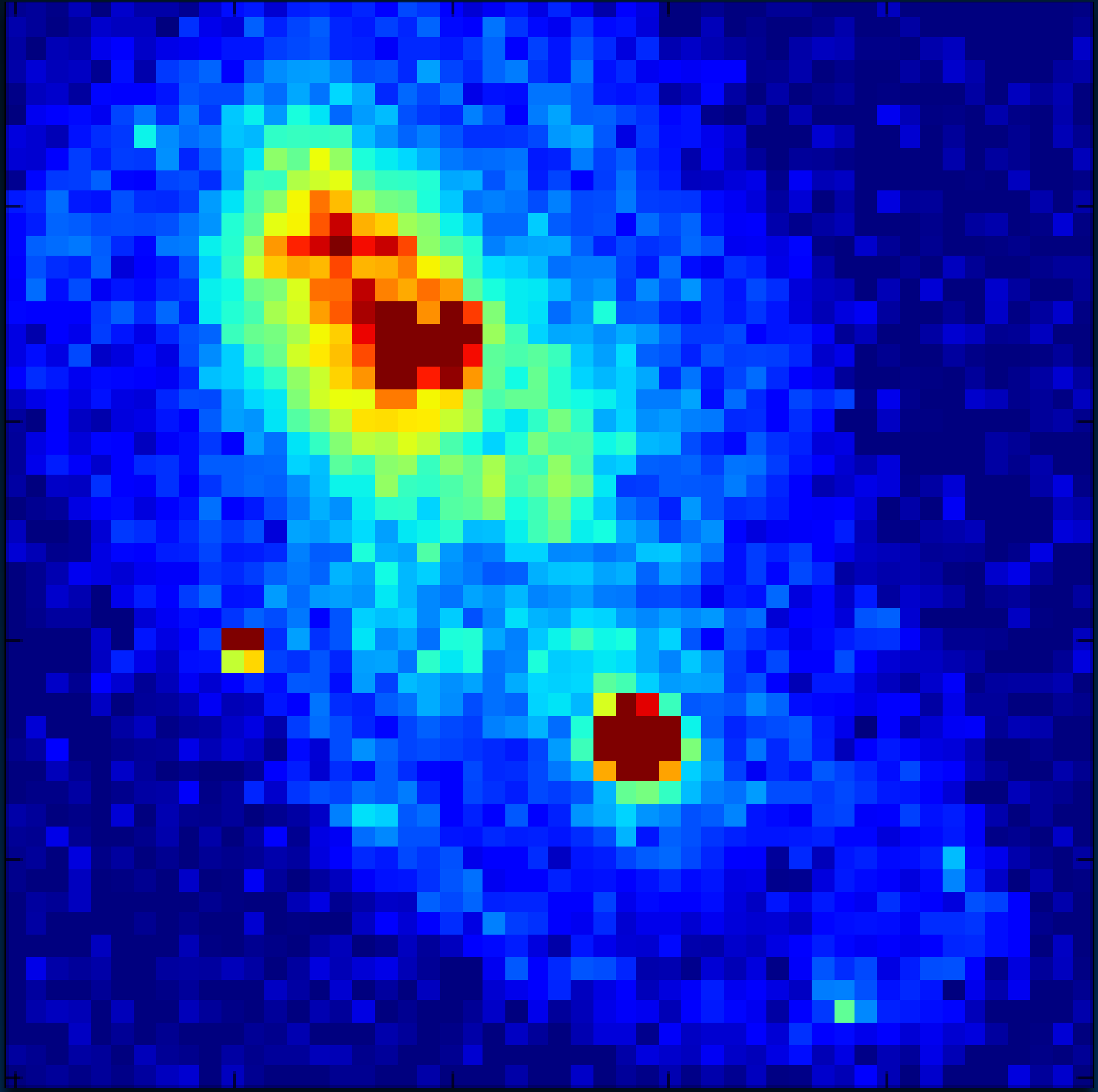
Hα, z~2 ULIRG   100 mas, VLT



*Thatte et al. 2012*

# HARMONI at the E-ELT

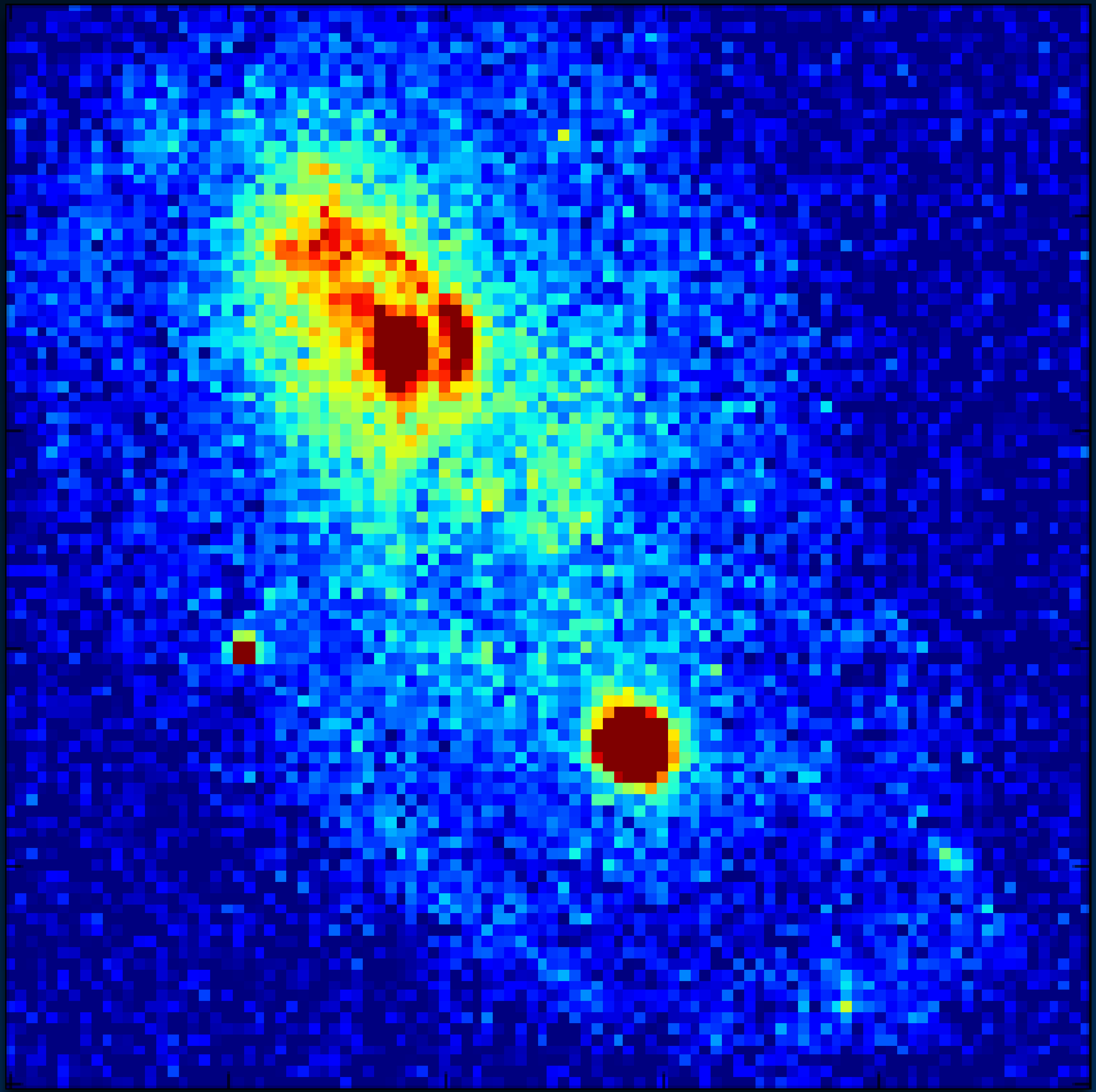
Hα, z~2 ULIRG 40 mas



*Thatte et al. 2012*

# HARMONI at the E-ELT

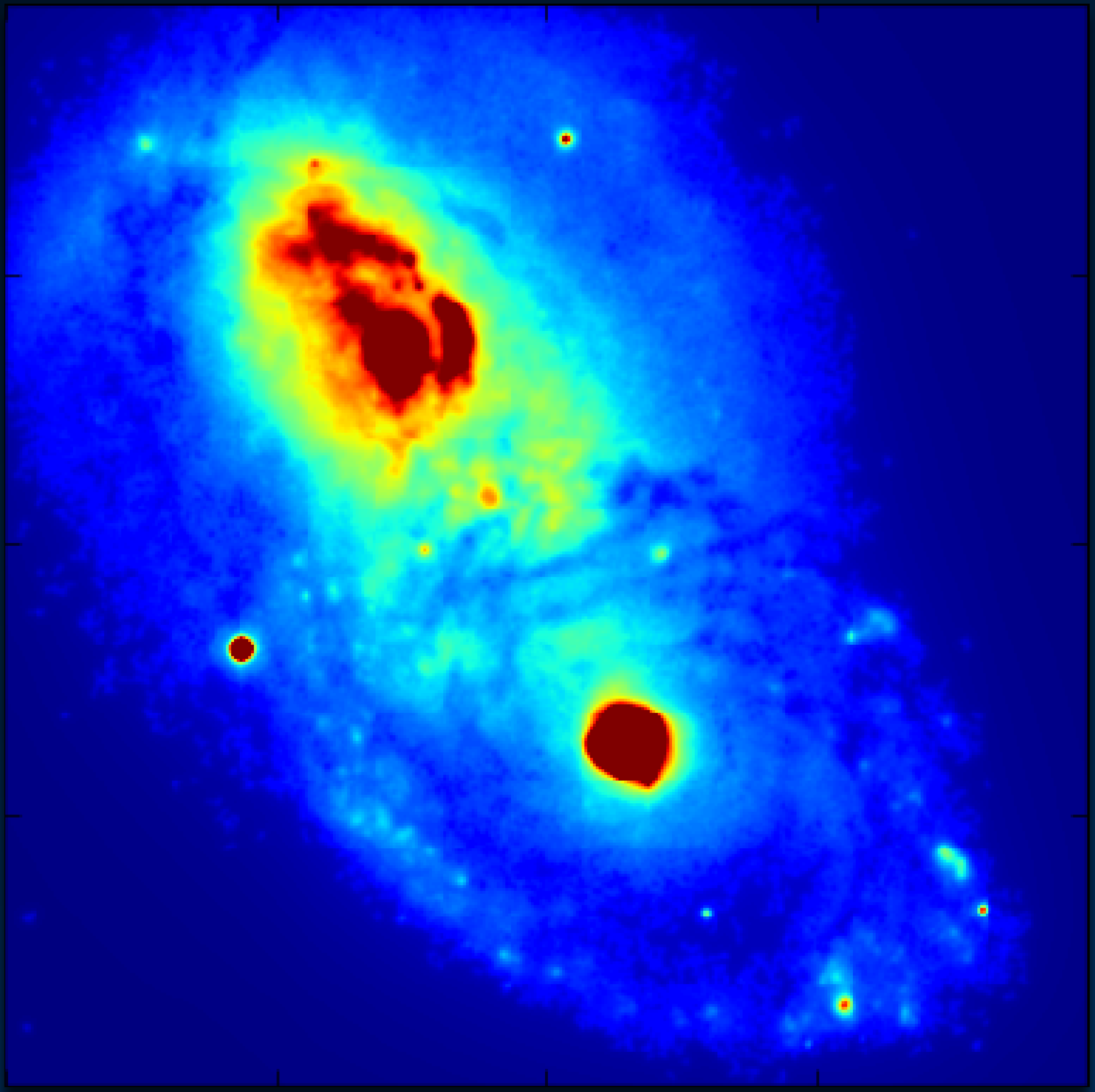
Hα, z~2 ULIRG 20 mas



*Thatte et al. 2012*

# HARMONI at the E-ELT

Hα, z~2 ULIRG 5 mas



*Thatte et al. 2012*

# Present & future: Space

| | Type | FoV | Scale | R | λ range |
|---|---|---|---|---|---|
| NIRSpec | Slicer | 3”x3” | 75 mas | 0.1k-2.7k | 0.6-5.0 μm |
| MIRI | Slicer | 3.0”x3.9” to 6.7”x7.7” | 170 to 640 mas | 2.2k to 3.0k | 5-28 μm |