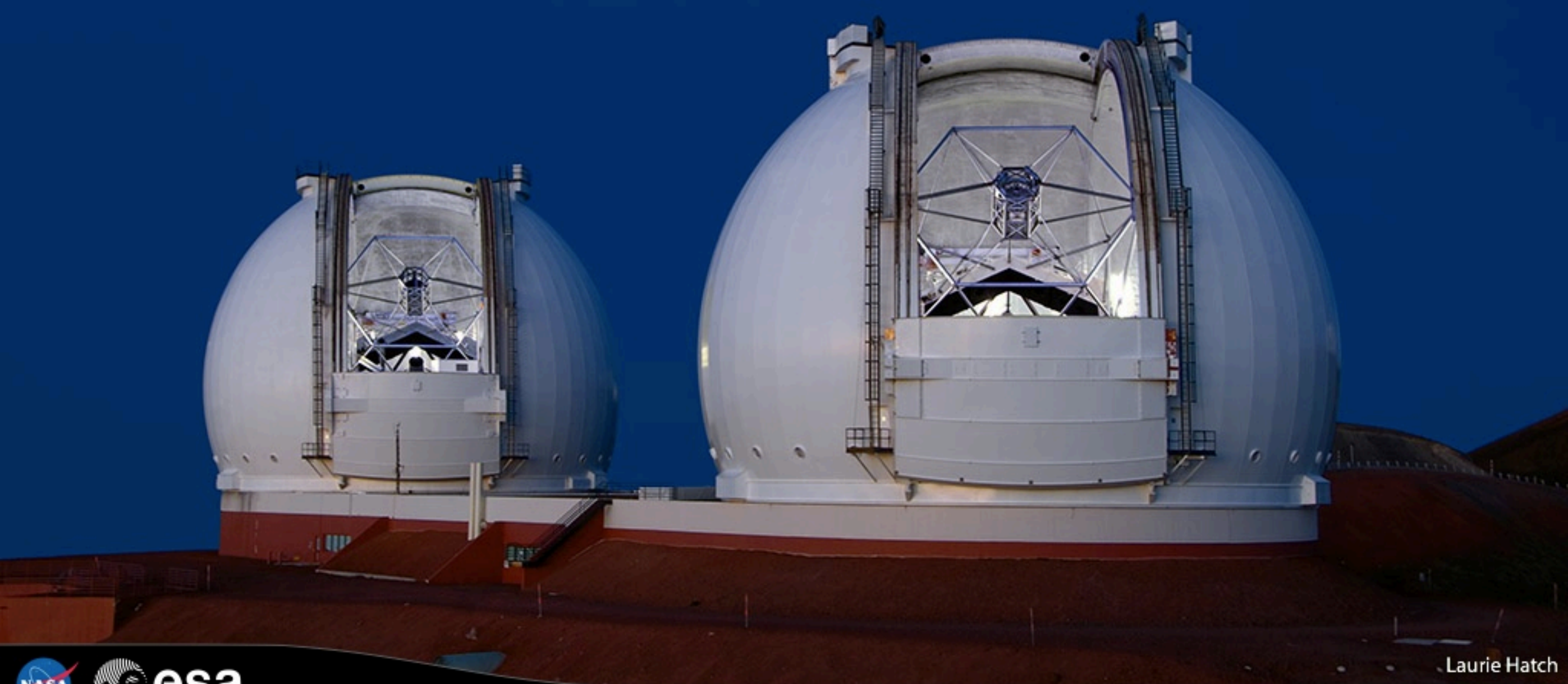
The HST–JWST–ELT connection

Mark McCaughrean
Research & Scientific Support Department, ESTEC
European Space Agency

Hubble Space Telescope

NASA / ESA

Keck telescopes

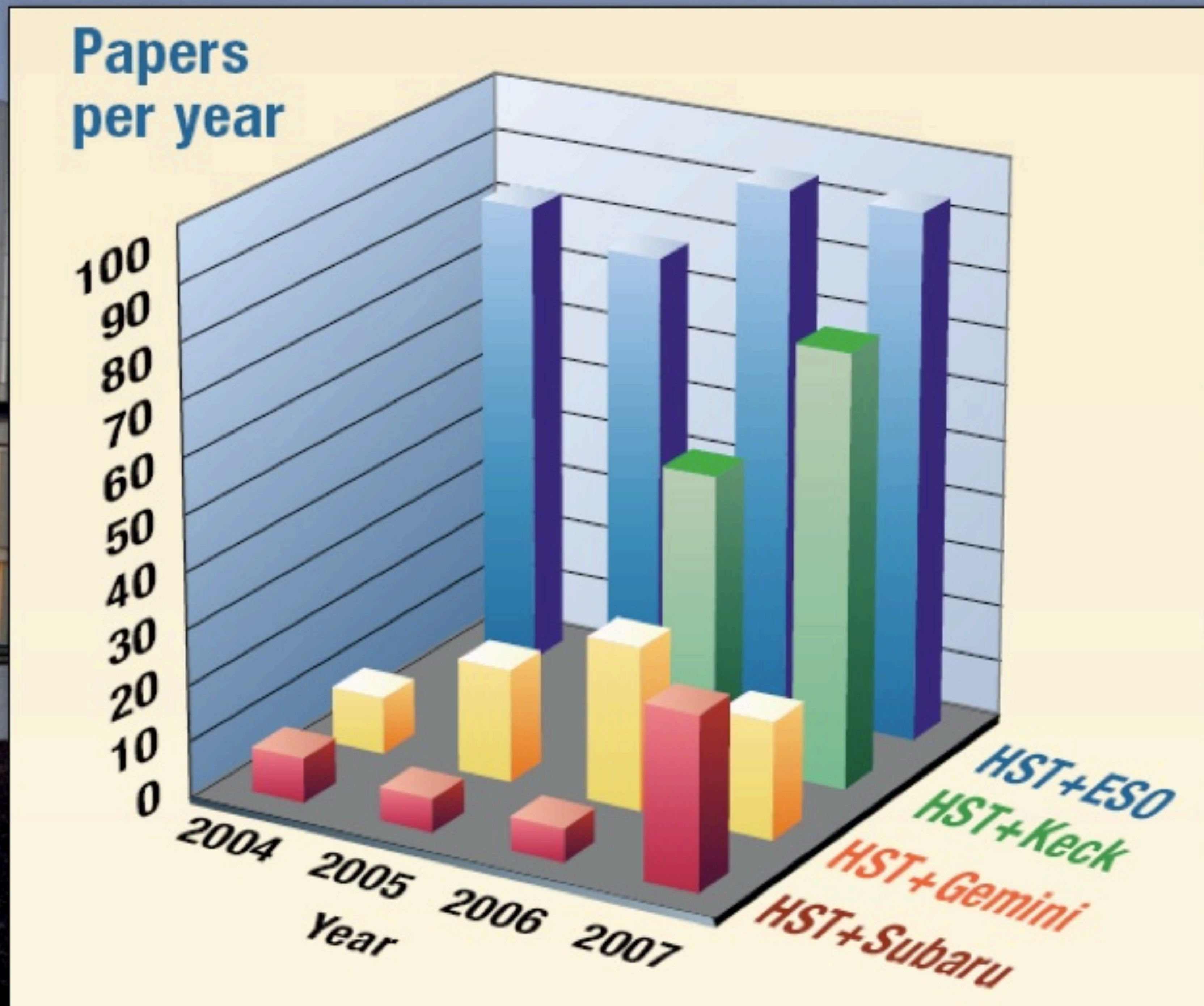


Laurie Hatch

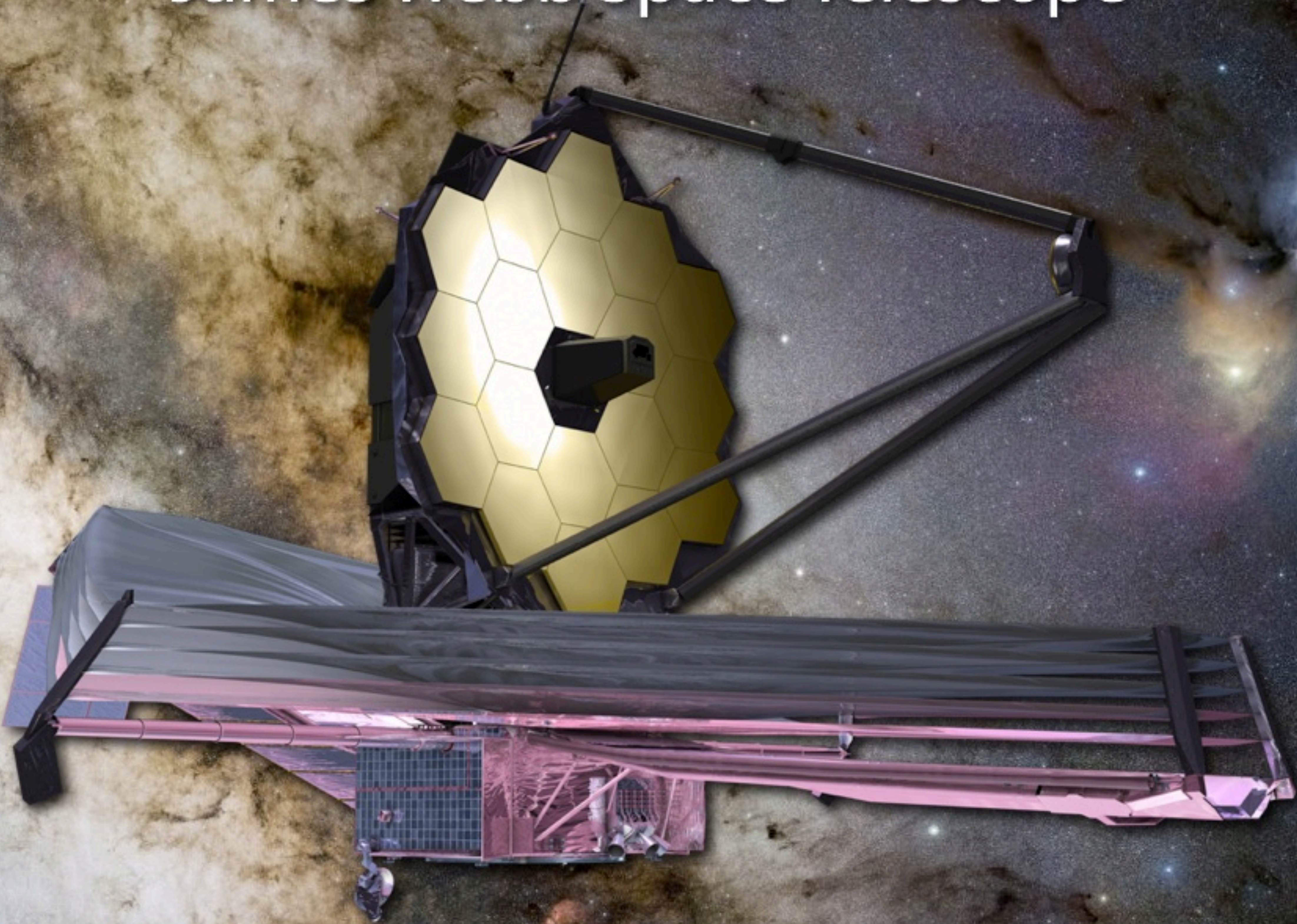
ESO Very Large Telescope

ESO

ESO Very Large Telescope



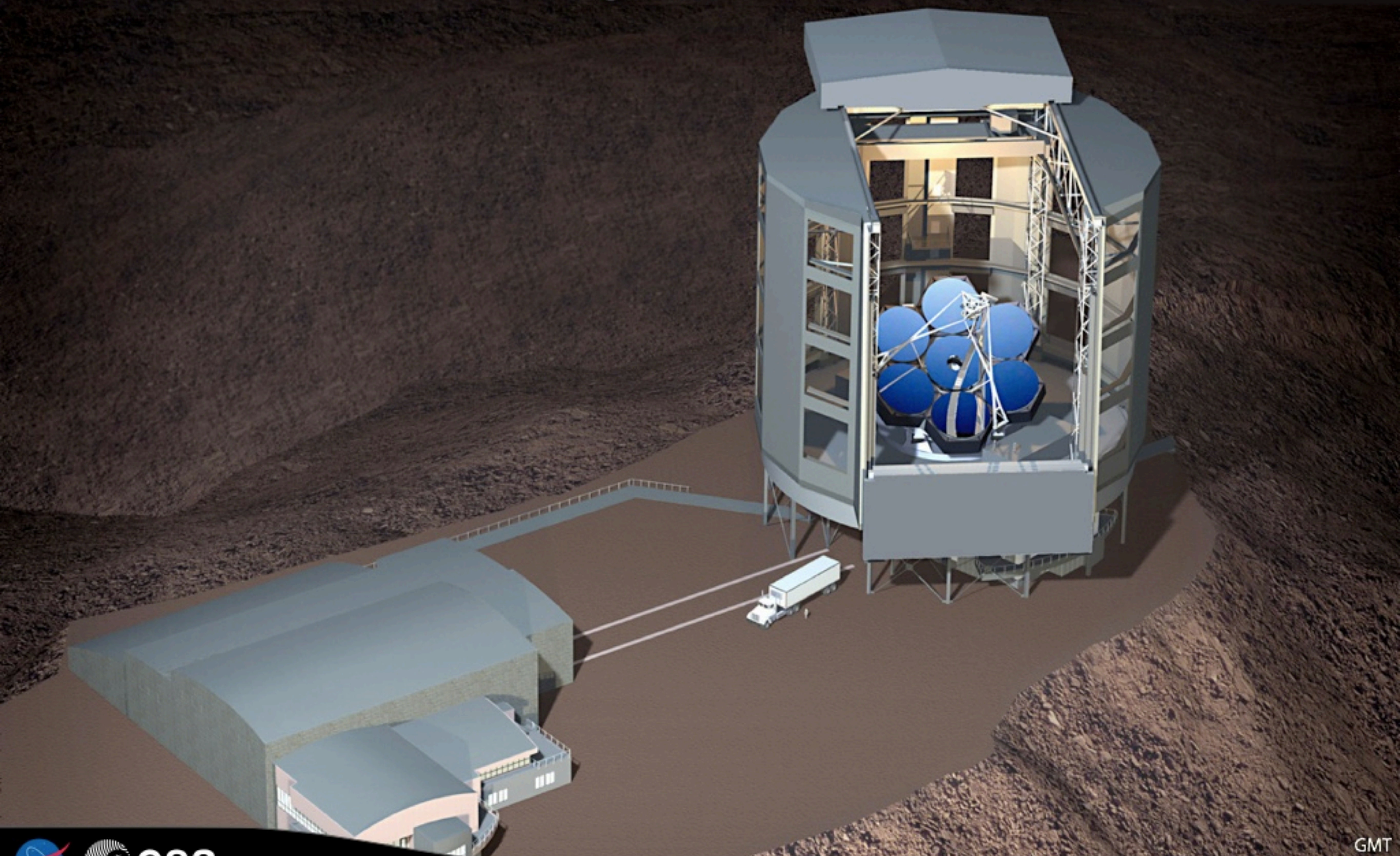
James Webb Space Telescope



Background: ESO/S. Guisard

NASA / ESA / CSA

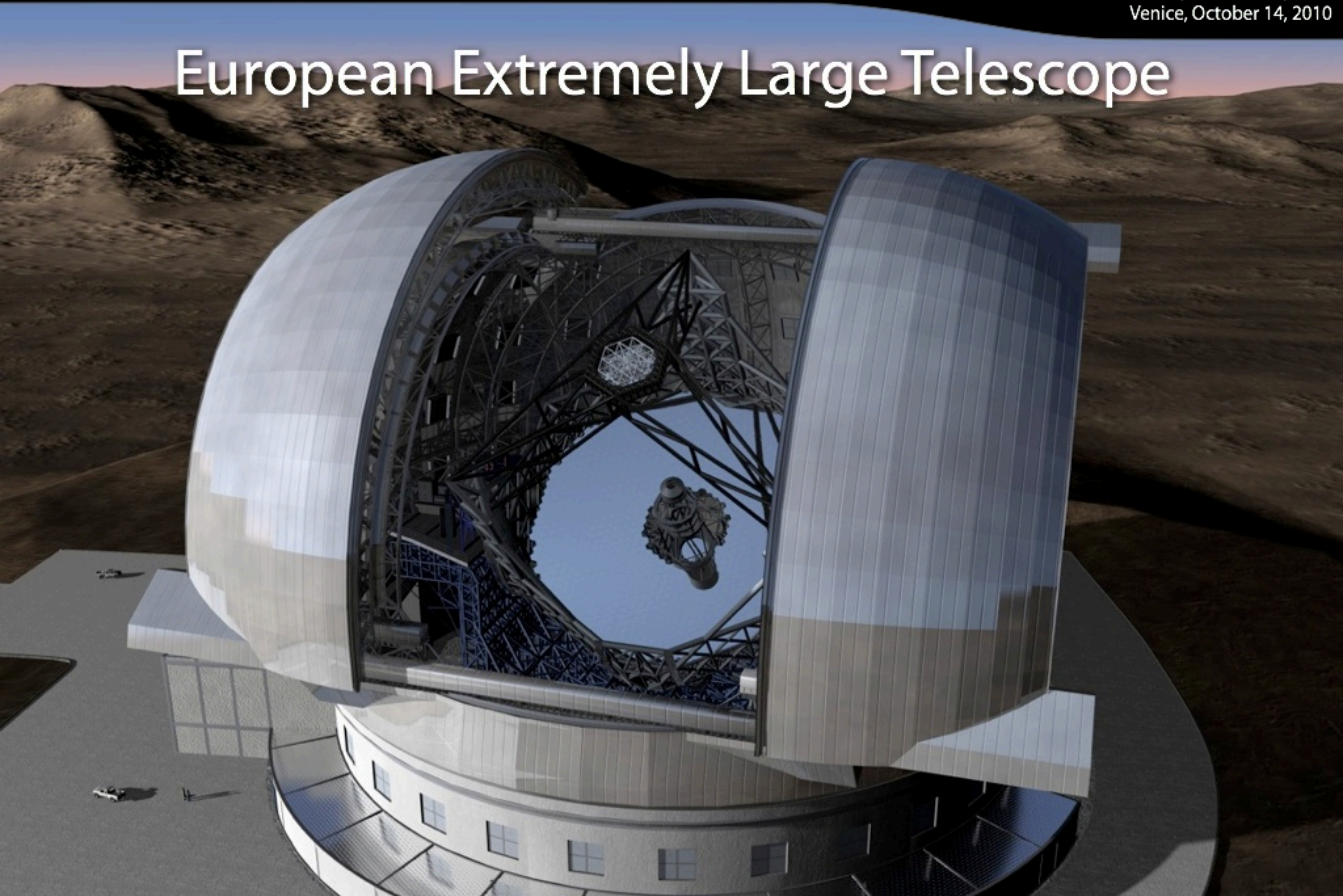
Giant Magellan Telescope



GMT

Thirty Meter Telescope

European Extremely Large Telescope



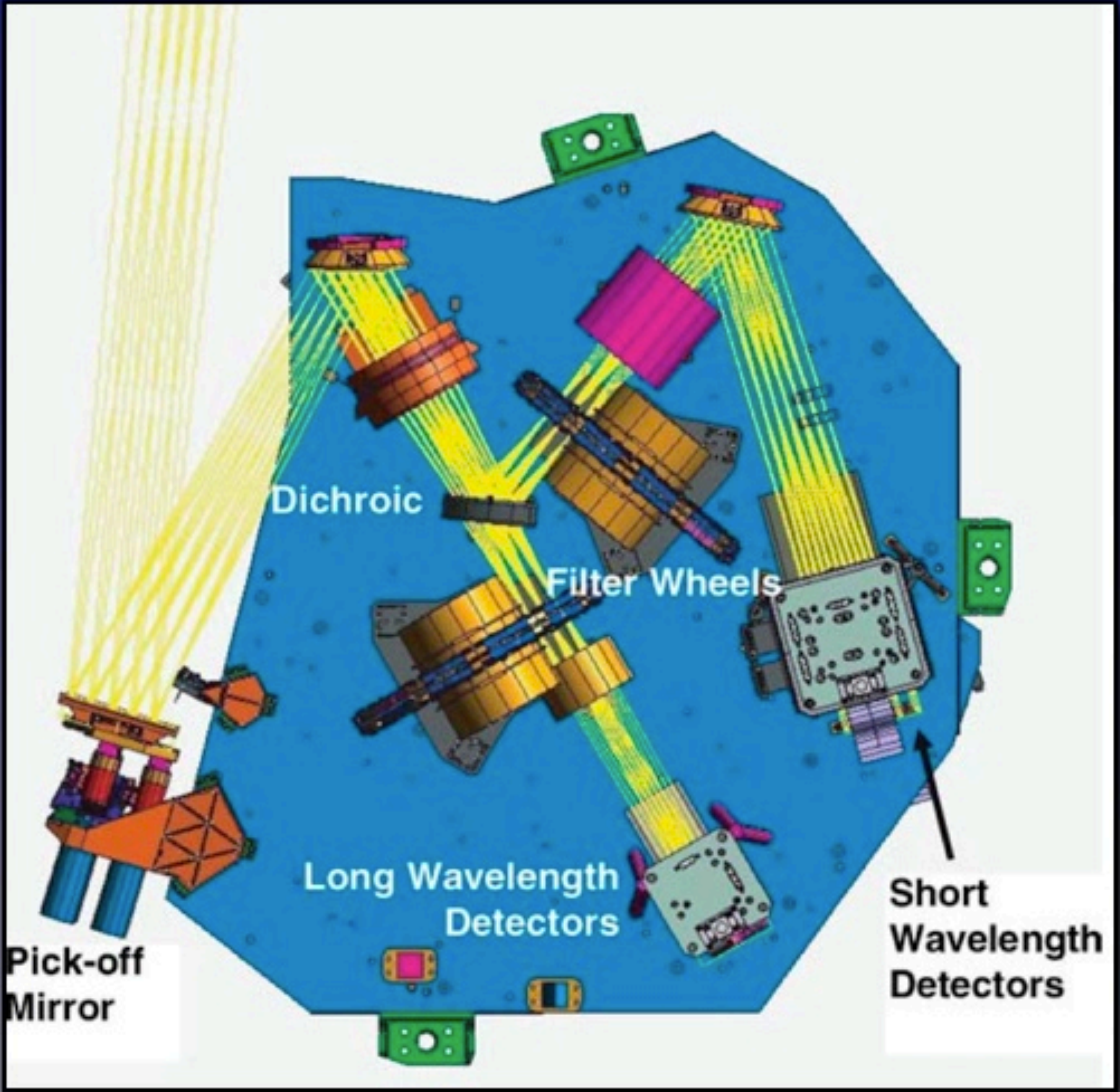
ESO

Complementary capabilities

	Wavelength coverage				Relative capabilities			
	UV	Opt	NIR	MIR	Imaging sensitivity	Spectro sensitivity	Spatial resolution	Areal coverage
 HST	✓✓✓	✓✓✓	✓	✗	✓✓	✓	✓✓	✓✓
 8-10m	✓	✓✓✓	✓✓	✓	✓✓	✓✓	✓✓	✓✓✓
 JWST	✗	✓	✓✓✓	✓✓✓	✓✓✓	✓✓	✓✓	✓✓
 ELTs	✓	✓✓✓	✓✓	✓	✓✓✓	✓✓✓	✓✓✓	✓

NIRCam: near-IR camera

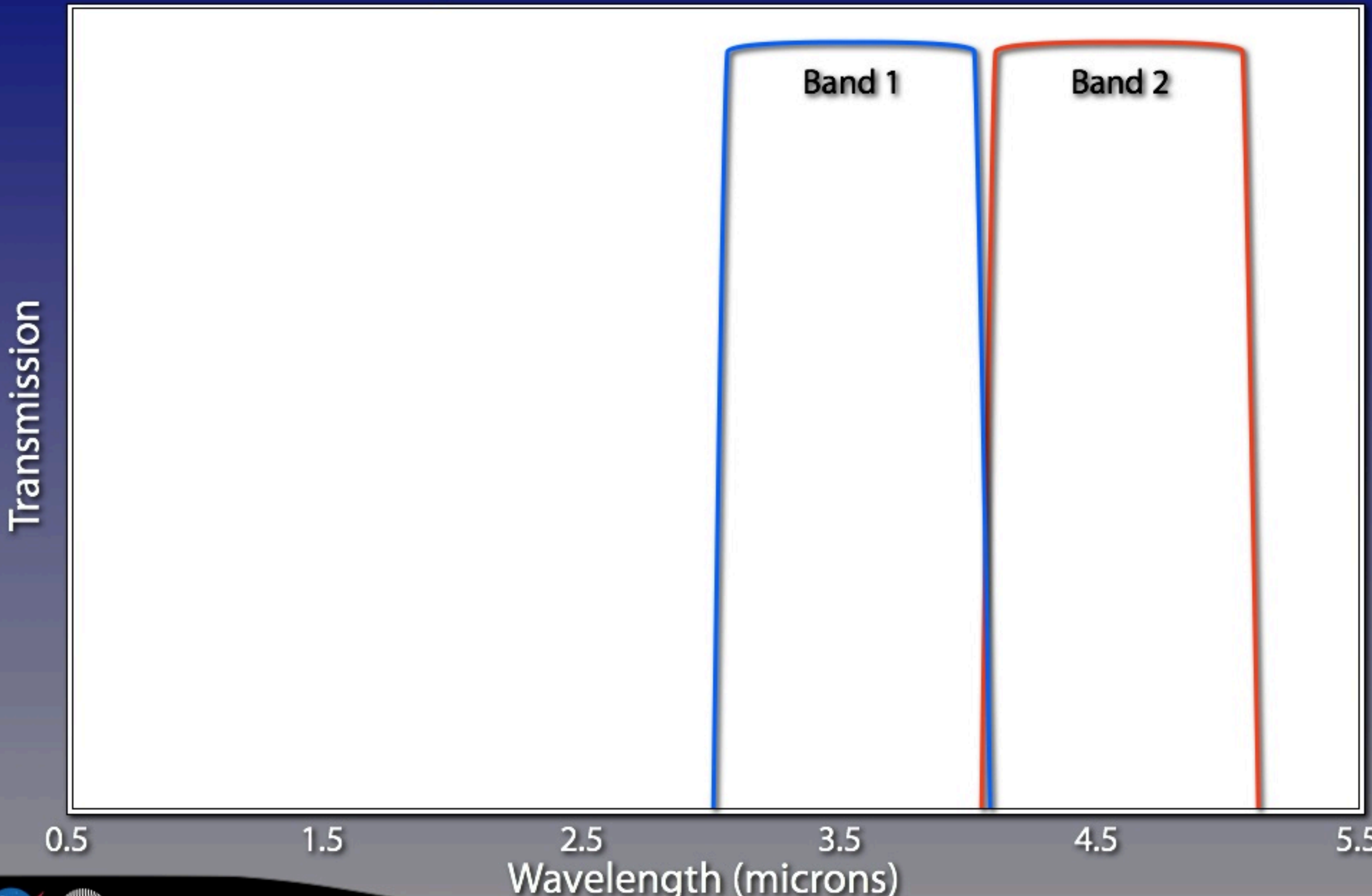
- Dual arm camera
  - Two contiguous fields on sky
  - Simultaneous SW & LW channels in each arm
  - Total FOV: 4.4 x 2.2 arcmin
- SW cameras:
  - 0.6–2.4 μm, 32 mas/pix
  - Diffraction limited at 1.7 μm
  - FOV of each: 2.2 x 2.2 arcmin
- LW cameras:
  - 2.4–5.0 μm, 65 mas/pix
  - Diffraction limited at 3.4 μm
  - FOV of each: 2.2 x 2.2 arcmin
- Wide range of filters
- Coronographic spots



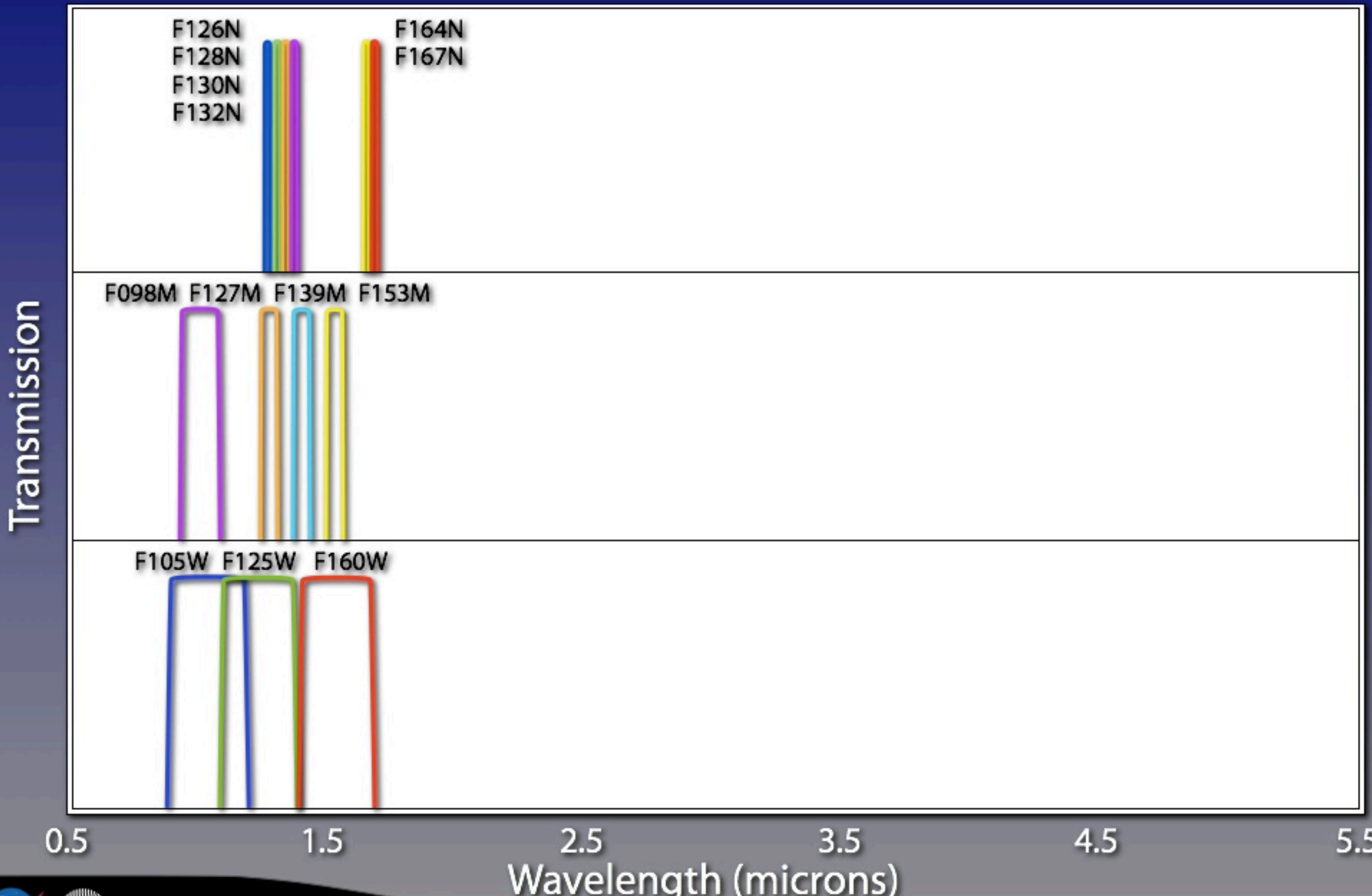
One of two near-identical, redundant arms on opposite sides of common baseplate simultaneously viewing adjacent fields

Univ Arizona / Lockheed Martin

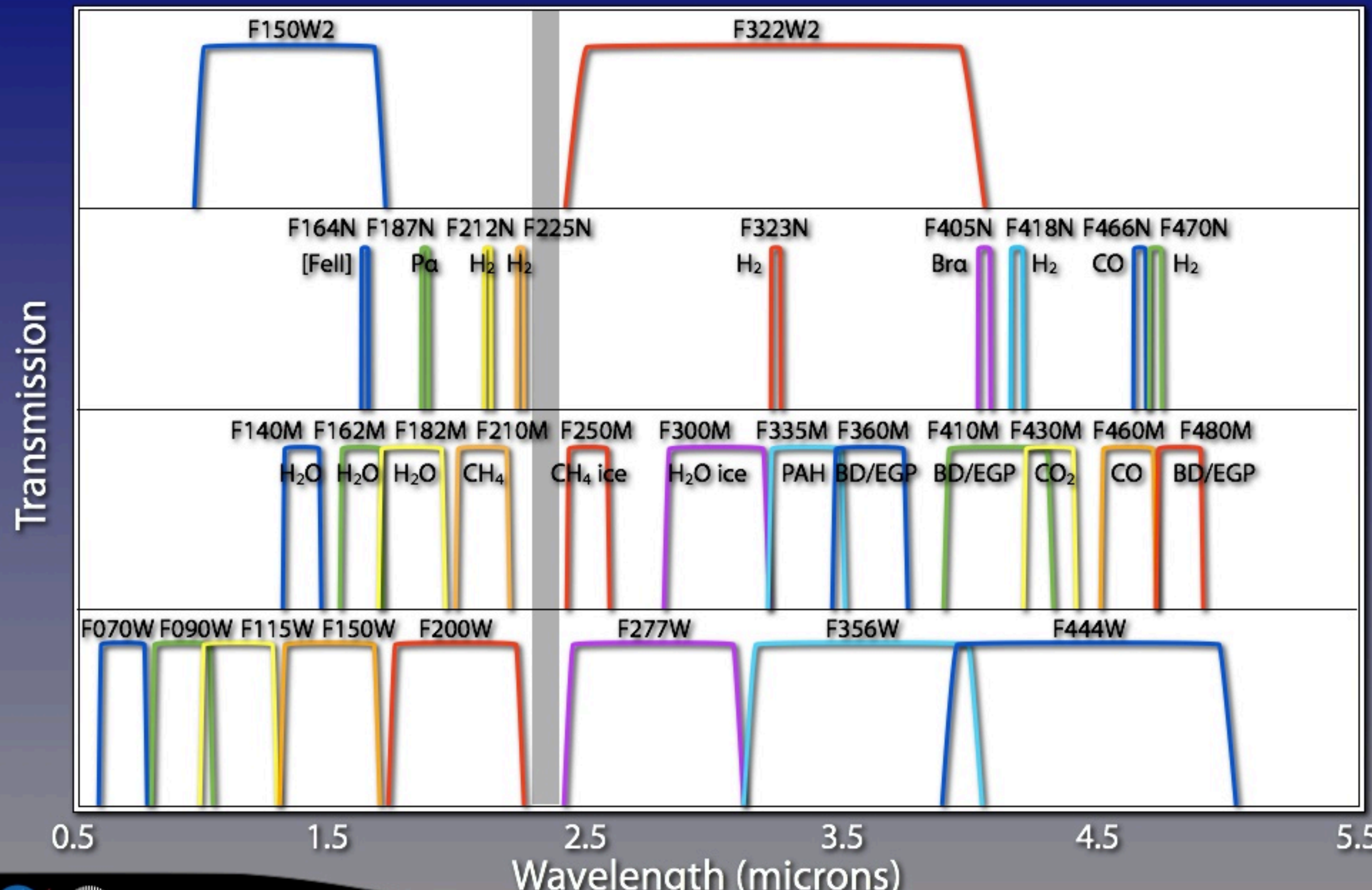
Spitzer IRAC filter set



HST WFC3-IR filter set

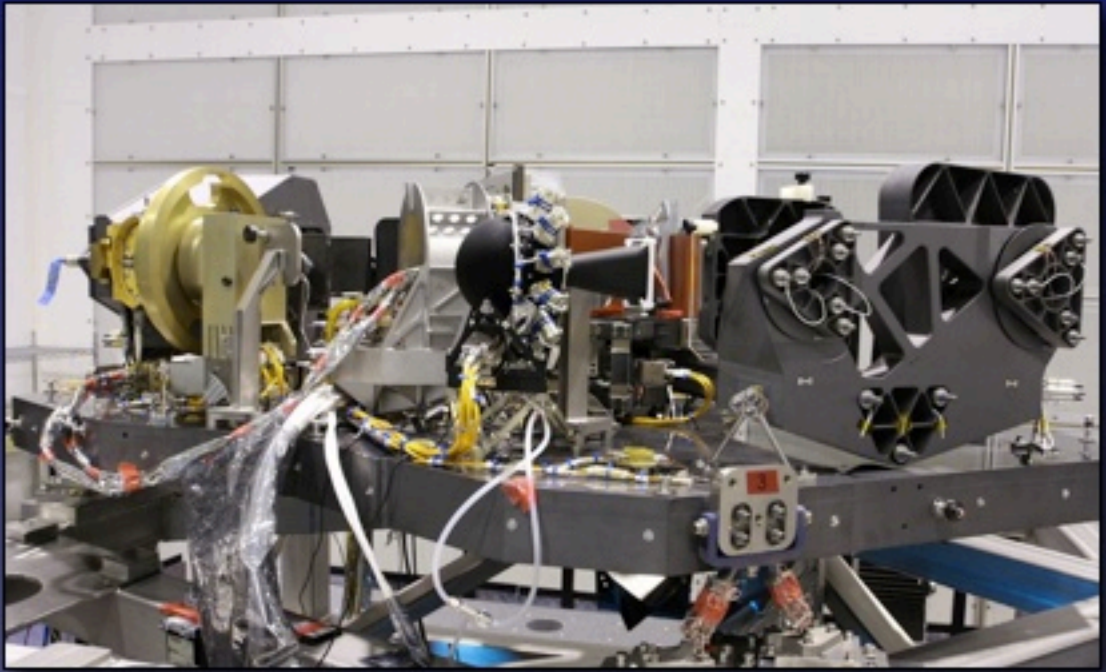


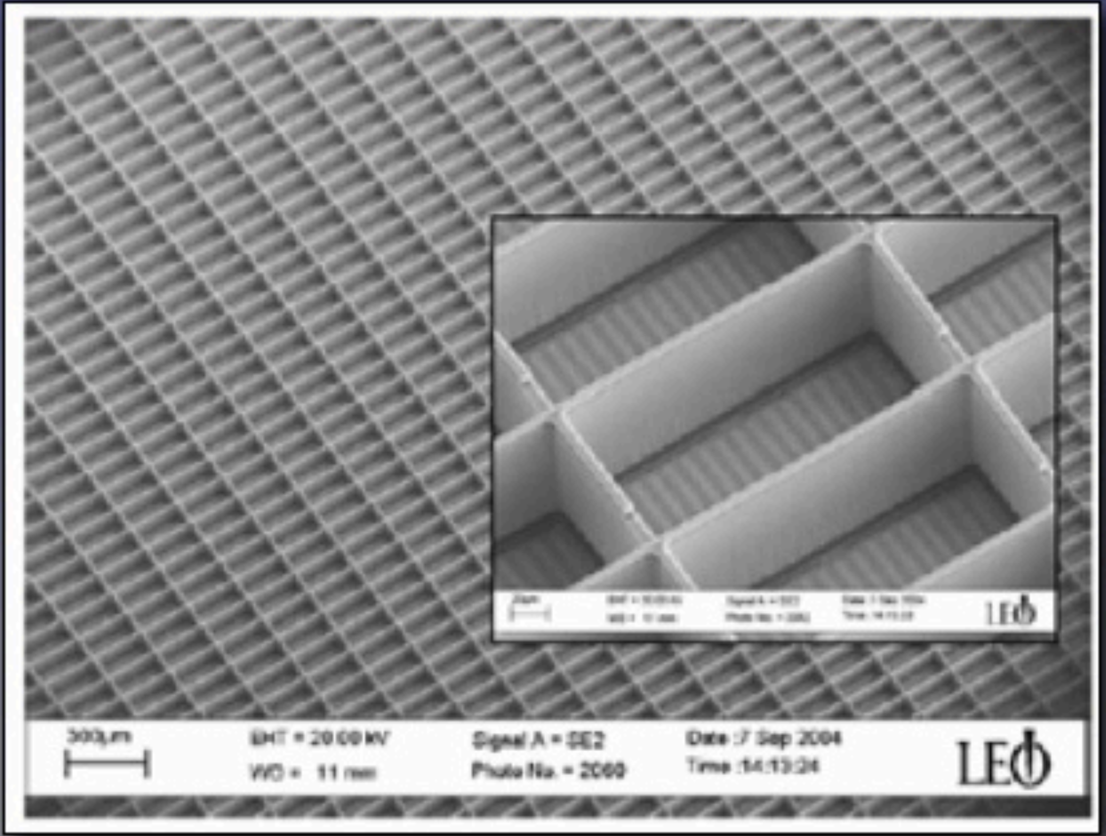
JWST NIRCam filter set



NIRSpec: multiobject spectrograph

- Dispersers
  - R=100 CaF_2 prism; 0.7–5.0 μm
  - R=1000 gratings; 1.0–5.0 μm
  - R=2700 gratings; 1.0–5.0 μm
- Microshutter array
  - 730 x 342 array of addressable shutters
  - Each slit: 203 x 463 mas
  - Total FOV: 3.4 x 3.6 arcmin
- Fixed slits
  - 5 fixed slits for high contrast observations of single objects
- Integral field unit
  - 3 x 3 arcsec IFU with 100 mas spaxels

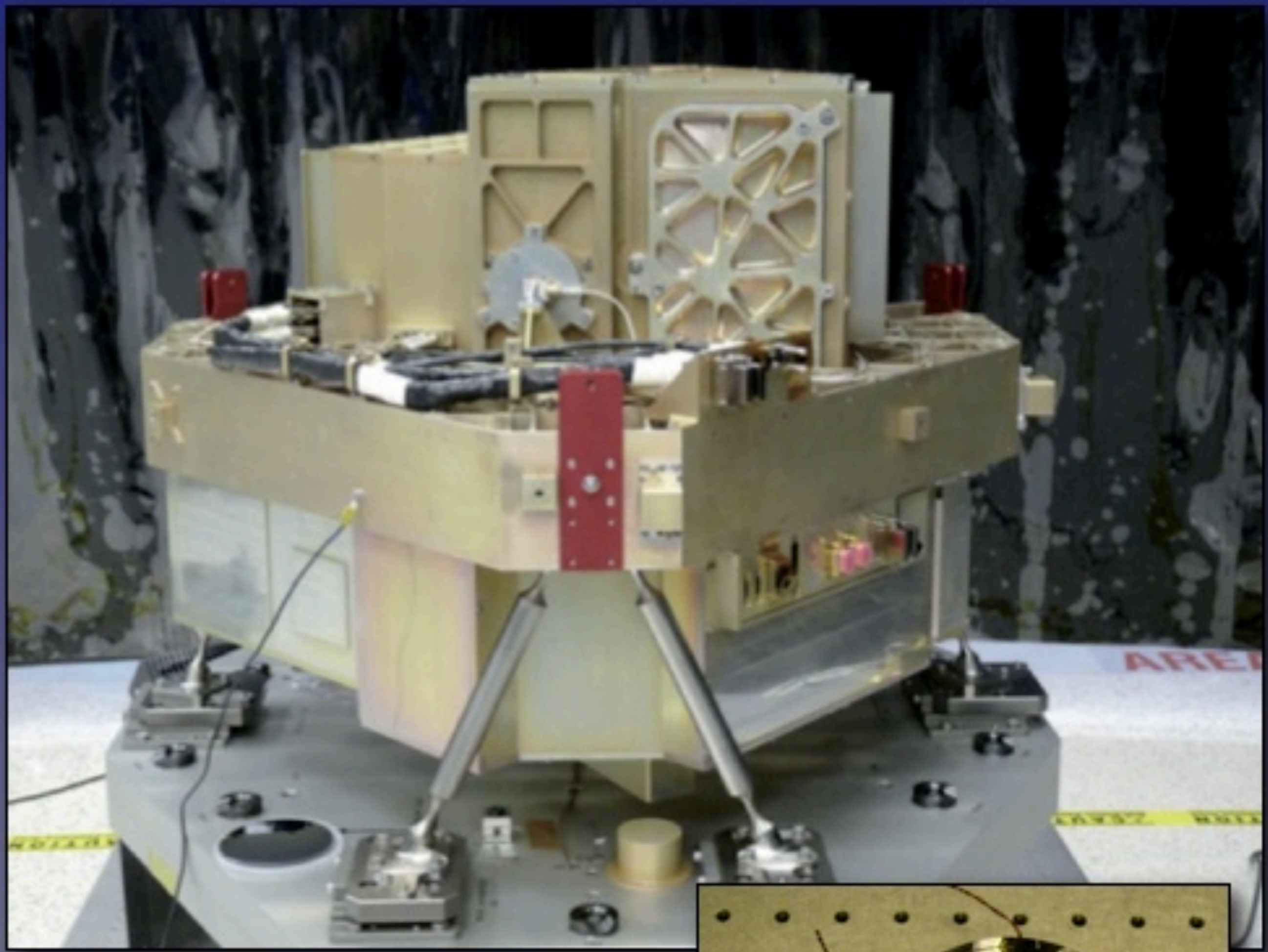


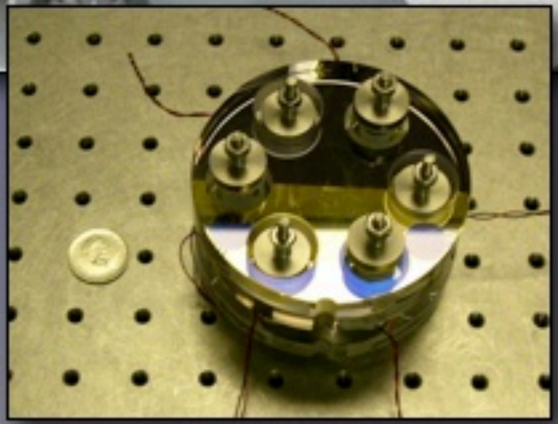


ESA / Astrium / NASA

TFI: Tuneable filter imager

- Narrow-band imager
  - Tuneable R~100 etalon filter
  - Range 1: 1.5–3.0 μm
  - Range 2: 3.5–5.0 μm
- Detector
  - Single 2048 x 2048 HgCdTe array
  - Pixel size 67 mas
  - Total FOV: 2.3 x 2.3 arcmin
- Coronographic spots
- Powerful complement / backup to NIRCam

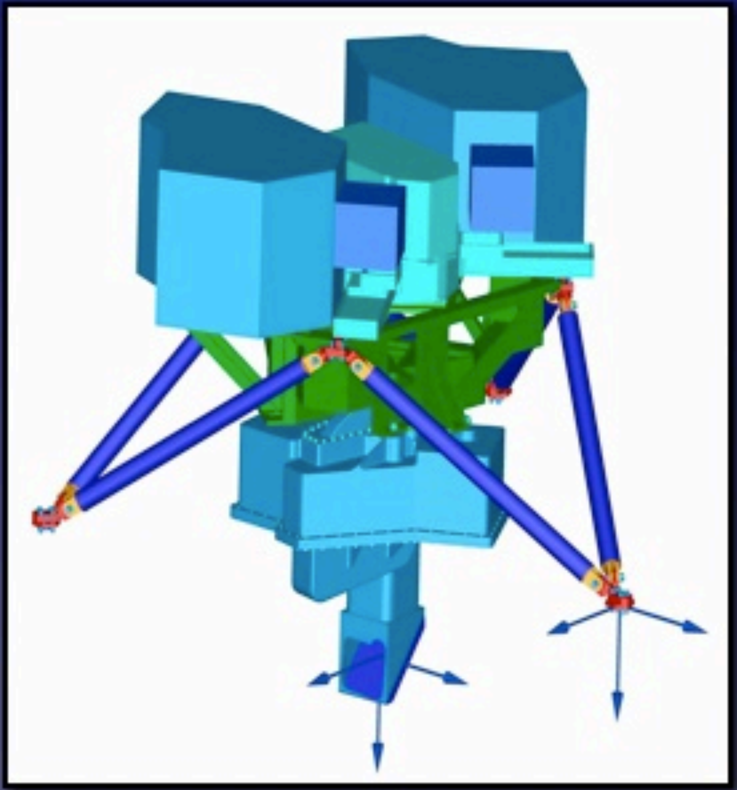


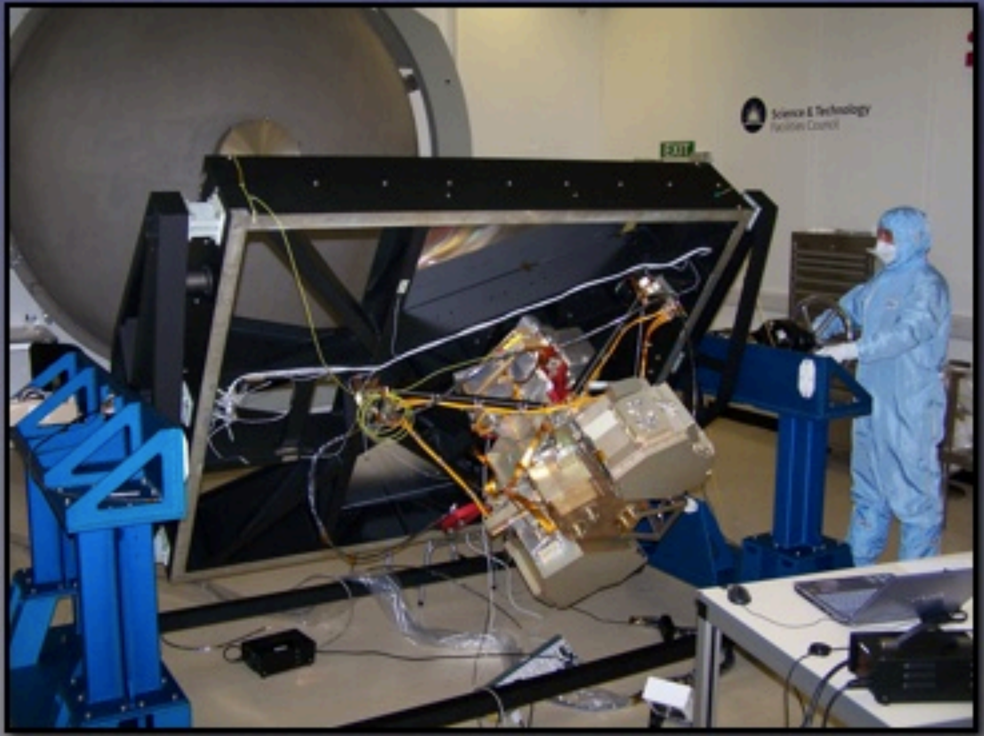


TFI sits on back side of the Fine Guidance Sensor

MIRI: Mid-IR imager & spectrometer

- Imager
  - 1024 x 1024 pixel Si:As IBC array
  - Broad-band imaging 5–28 μm
  - Pixel size 100 mas (diffn. lim. @ 5 μm)
  - Total FOV: 1.7 x 1.3 arcmin
- Coronograph
  - Fixed masks and 4QPM options
- Single object spectrograph
  - Slit with R=100 grism for 5–10 μm
- Integral field spectrograph
  - R=3000 gratings covering 5–28 μm
  - FOV 3 x 3 arcsec at 5 μm
  - FOV 8 x 8 arcsec at 28 μm
- Cryocooler used to reach 7 K





European Consortium / NASA

Reference JWST sensitivity figures

Instrument	λ (μm)	Resolution	Sensitivity
NIRCam	2.7	4	11.2 nJy, AB = 28.8
TFI	3.5	100	126 nJy, AB = 26.1
NIRSpec low	2.0	100	120 nJy, AB = 26.2
NIRSpec medium	2.0	1000	900 nJy, AB = 24.0
NIRSpec high	2.0	3000	3.3 μJy, AB = 22.6
MIRI imaging	10.0	4.2	700 nJy, AB = 24.3
MIRI imaging	21.0	5	8.7 μJy, AB = 21.6
MIRI spectroscopy	9.2	2400	1.0×10^{-17} erg s^{-1} cm^{-2}
MIRI spectroscopy	22.5	1200	5.6×10^{-17} erg s^{-1} cm^{-2}

10σ point source detections in 10^4 secs (~2.5 hrs) at North Ecliptic Pole

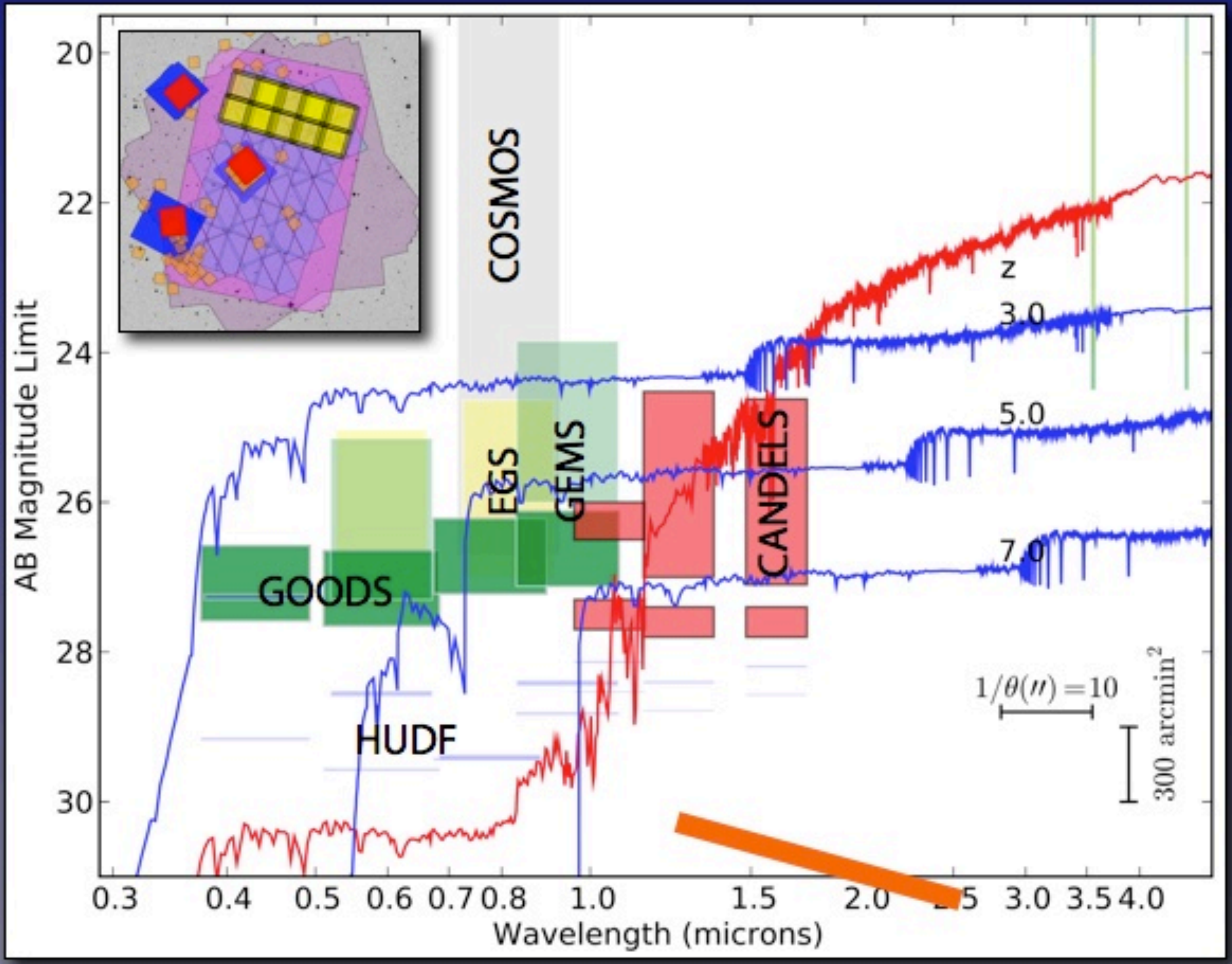
JWST science themes

Extragalactic deep fields

- Depth needed to detect first galaxies?
- Extrapolate HUDF z=6 LF to higher redshifts

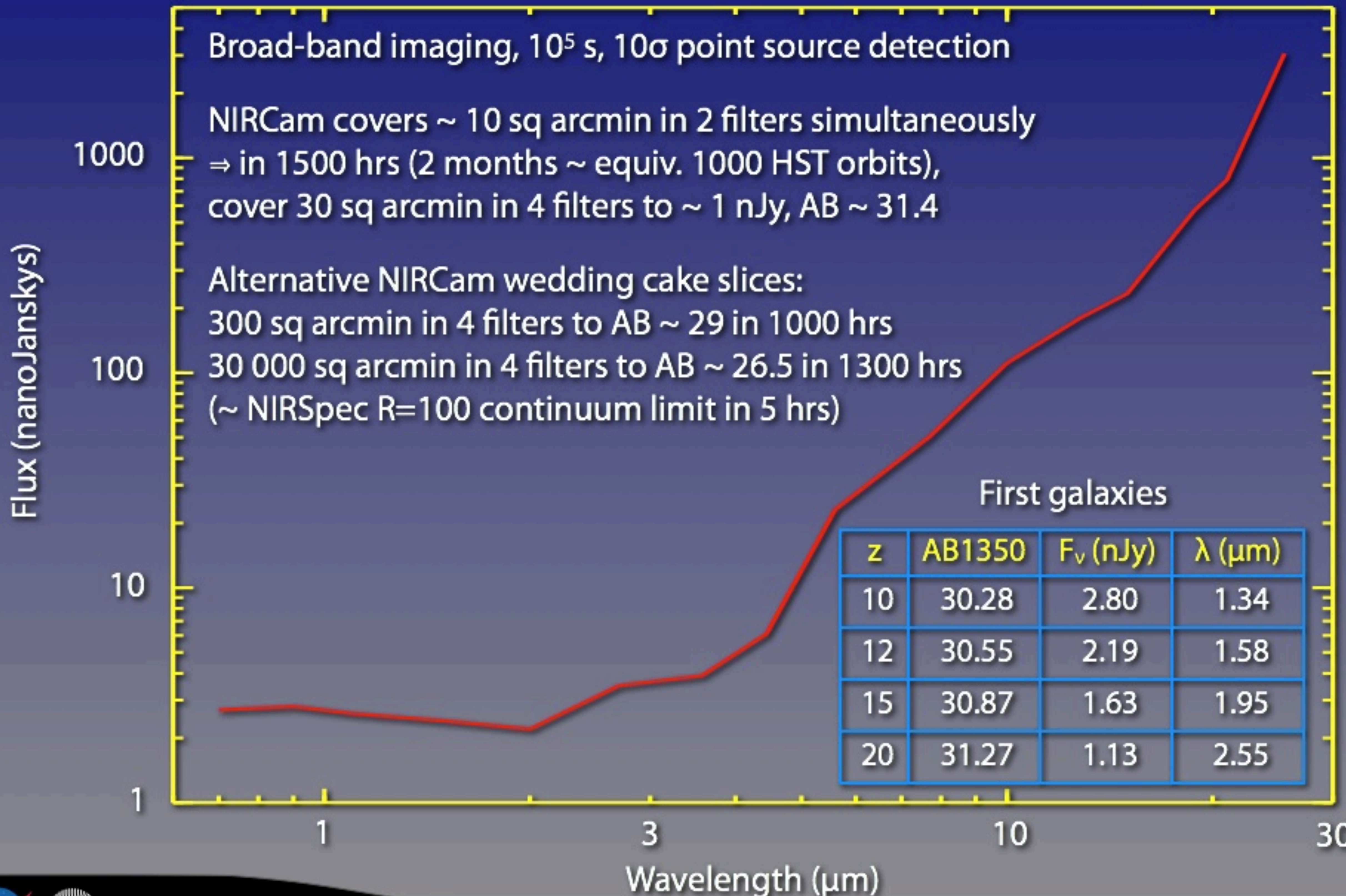
z	AB1350	F_ν (nJy)	λ (μm)
10	30.28	2.80	1.34
12	30.55	2.19	1.58
15	30.87	1.63	1.95
20	31.27	1.13	2.55

Trenti & Stiavelli 2006



⇒ Need imaging at λ=1–3 μm down to sensitivity of 1–3 nJy over tens of square arcminutes to be equivalent to HUDF

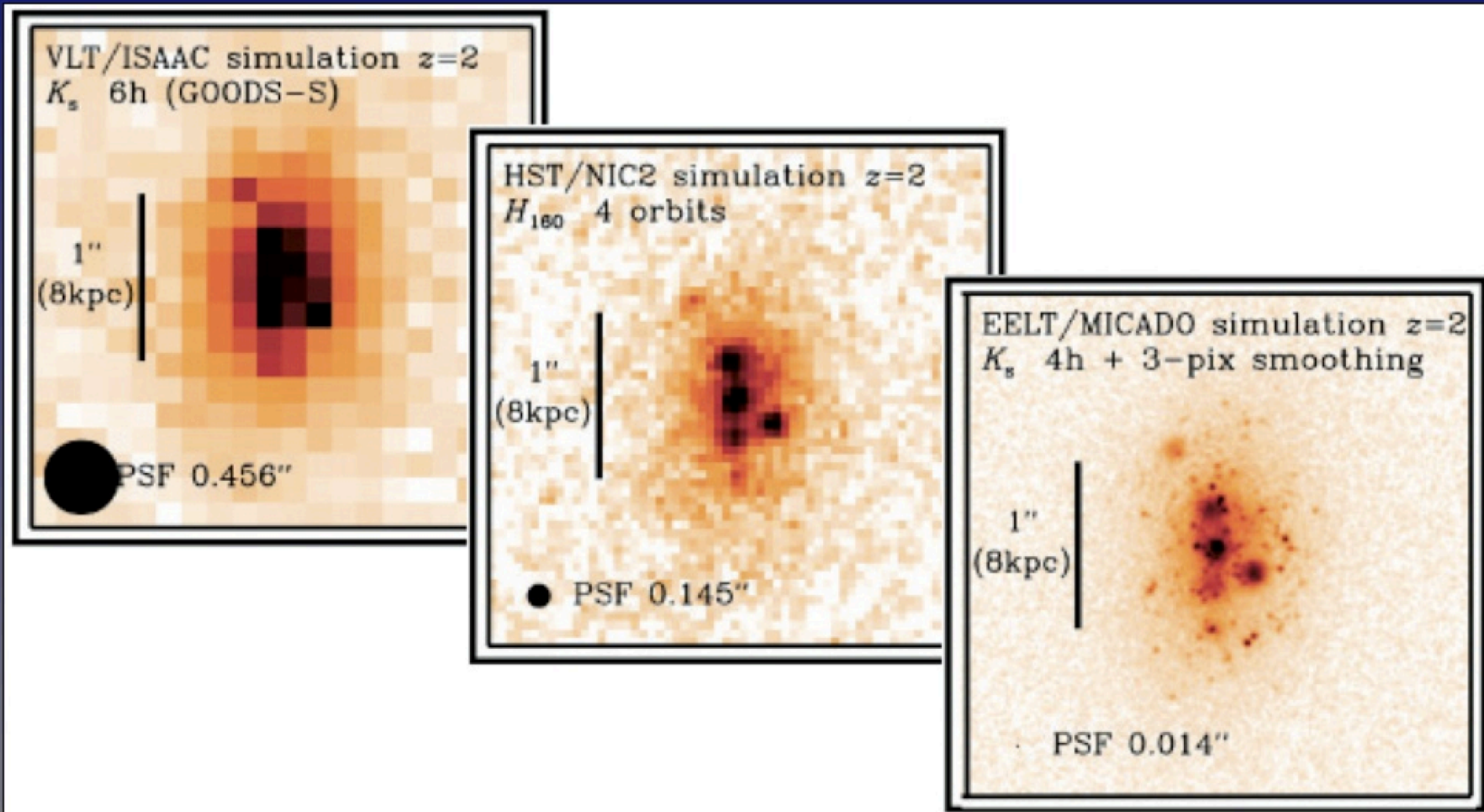
JWST deep imaging sensitivity



First galaxies

z	AB1350	F_ν (nJy)	λ (μm)
10	30.28	2.80	1.34
12	30.55	2.19	1.58
15	30.87	1.63	1.95
20	31.27	1.13	2.55

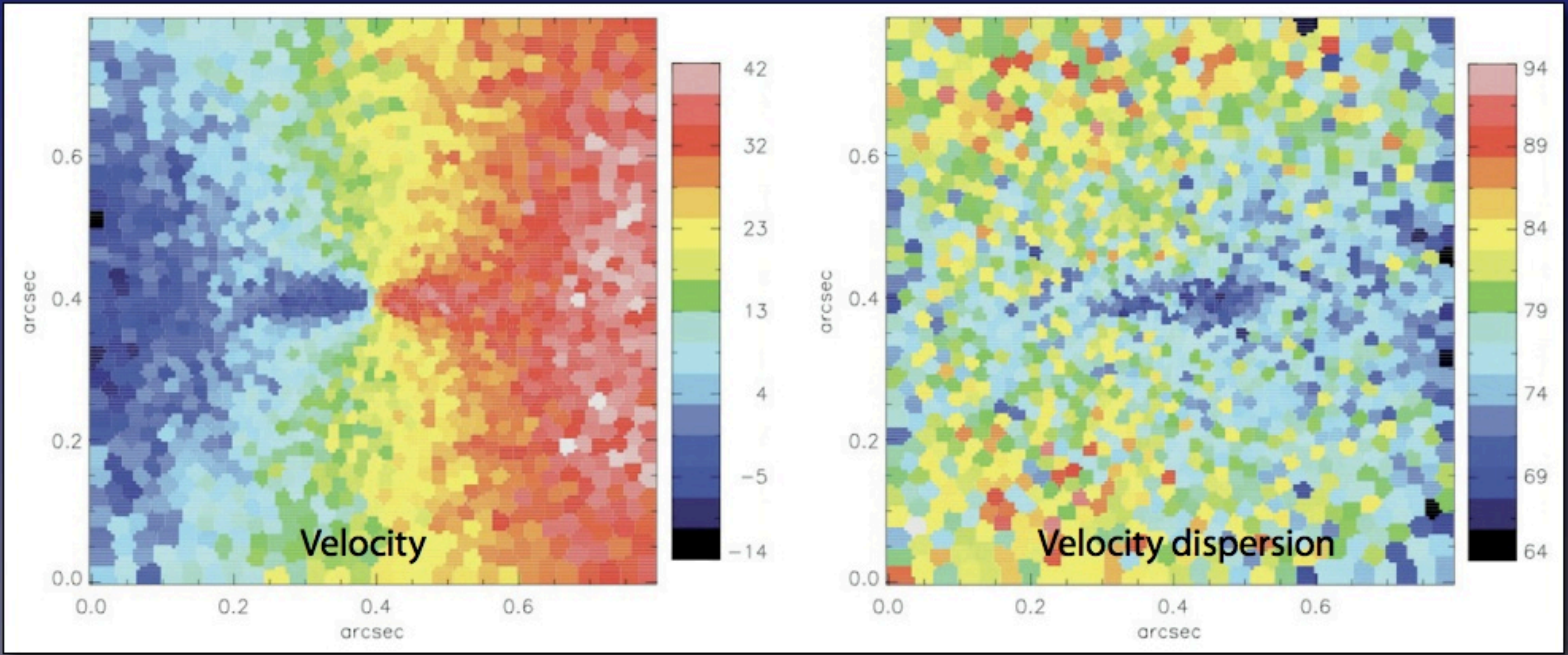
High-z galaxies at 100pc scale



E-ELT/MICADO simulation of mock disk galaxy at z=2.3, K_{AB} = 21.3; resolution of 100 pc at z ~ 2

Trippe et al. (2010), Forster-Schreiber et al. (2010) / JWST-ELT meeting, Garching, April 2010

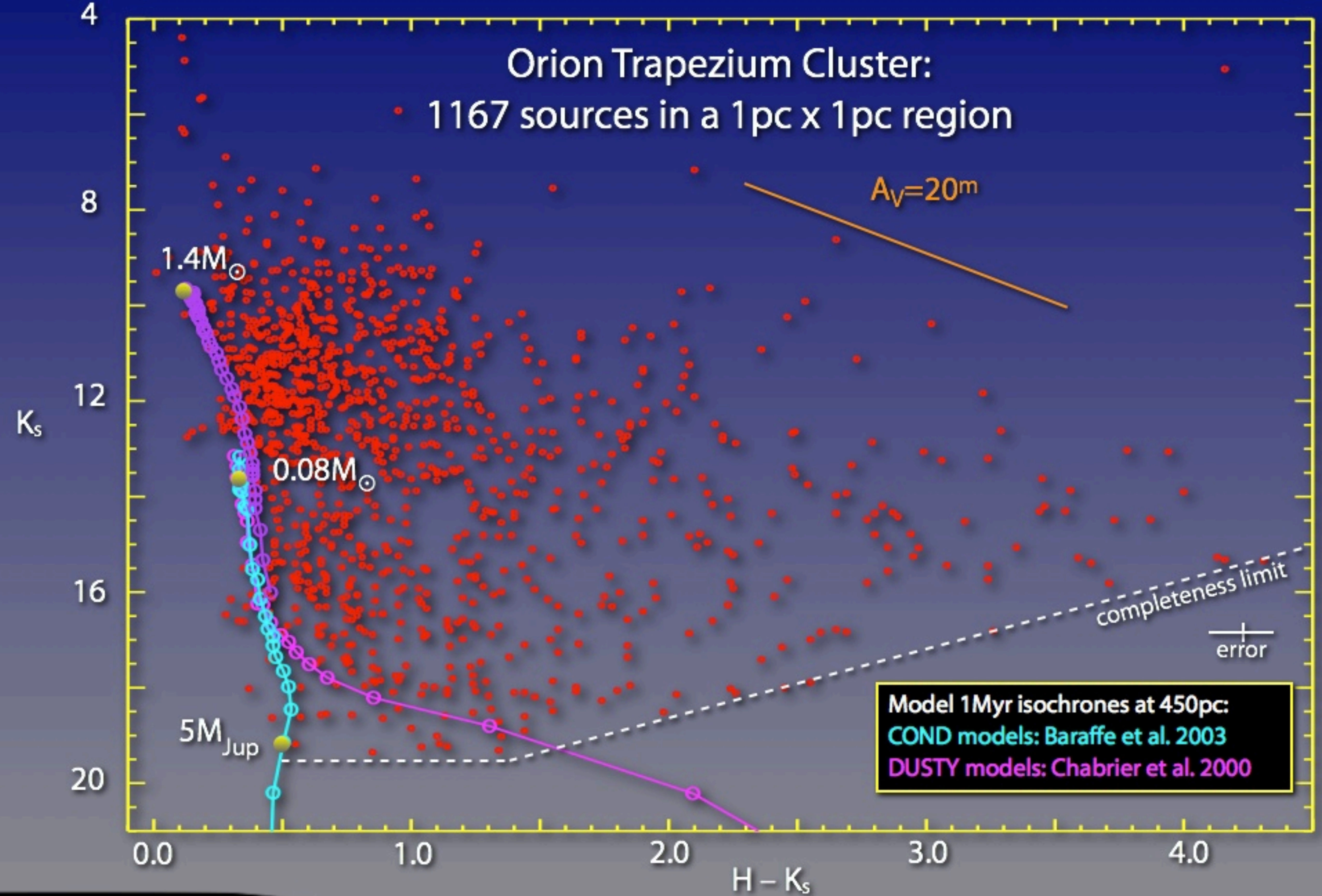
Kinematics near supermassive black holes

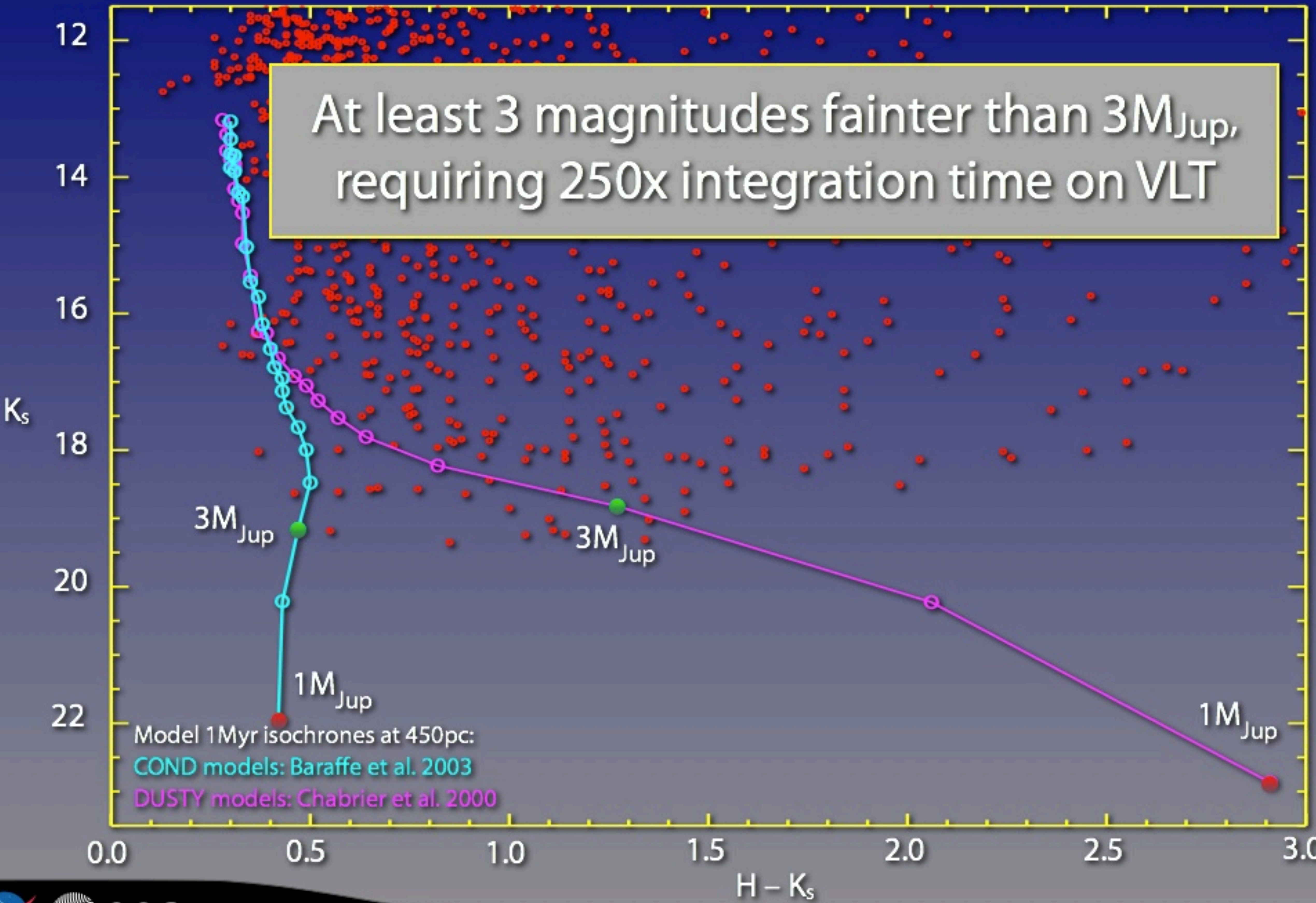


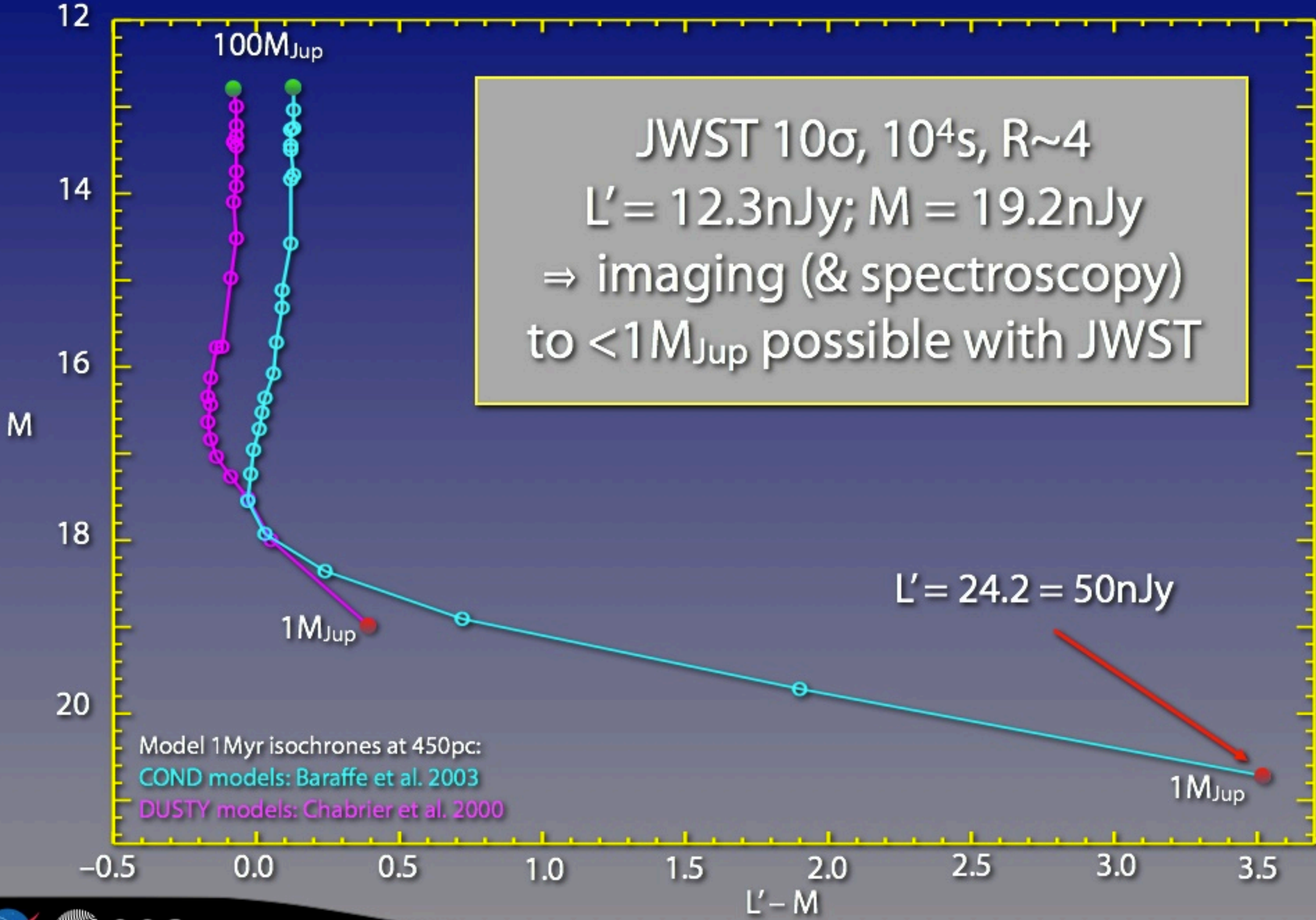
Simulated near-IR K-band IFU observations of NGC4486a hosting 1.25 x 10^7 $M_\odot$ SMBH
E-ELT/HARMONI with laser tomography adaptive optics, 5 mas/spaxel

Orion Nebula deep IR imaging

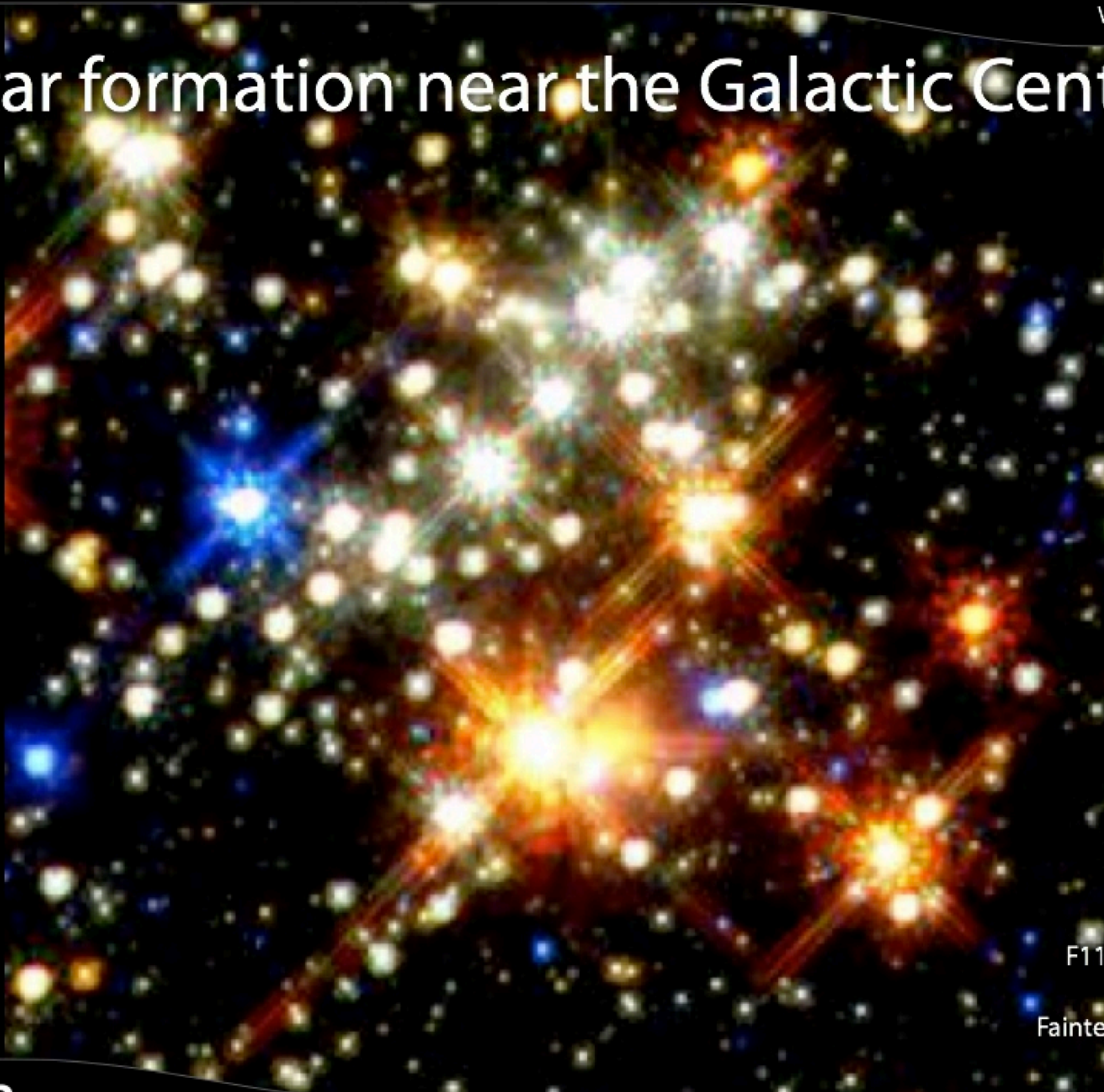
McCaughrean et al. / VLT ISAAC


Orion Trapezium Cluster:
1167 sources in a 1pc x 1pc region
A_V=20^m
1.4M$_\odot$
0.08M$_\odot$
5M$_{Jup}$
completeness limit
error
Model 1Myr isochrones at 450pc:
COND models: Baraffe et al. 2003
DUSTY models: Chabrier et al. 2000
K$_s$
H – K$_s$
4
8
12
16
20
0.0
1.0
2.0
3.0
4.0


At least 3 magnitudes fainter than 3MJup, requiring 250x integration time on VLT
12
14
16
18
20
22
Ks
3MJup
3MJup
1MJup
1MJup
Model 1Myr isochrones at 450pc:
COND models: Baraffe et al. 2003
DUSTY models: Chabrier et al. 2000
0.0
0.5
1.0
1.5
2.0
2.5
3.0
H – Ks


JWST 10σ, 10⁴s, R~4
L′ = 12.3nJy; M = 19.2nJy
⇒ imaging (& spectroscopy)
to <1MJup possible with JWST
100MJup
1MJup
L′ = 24.2 = 50nJy
1MJup
Model 1Myr isochrones at 450pc:
COND models: Baraffe et al. 2003
DUSTY models: Chabrier et al. 2000
12
14
16
18
20
M
−0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
L′ − M

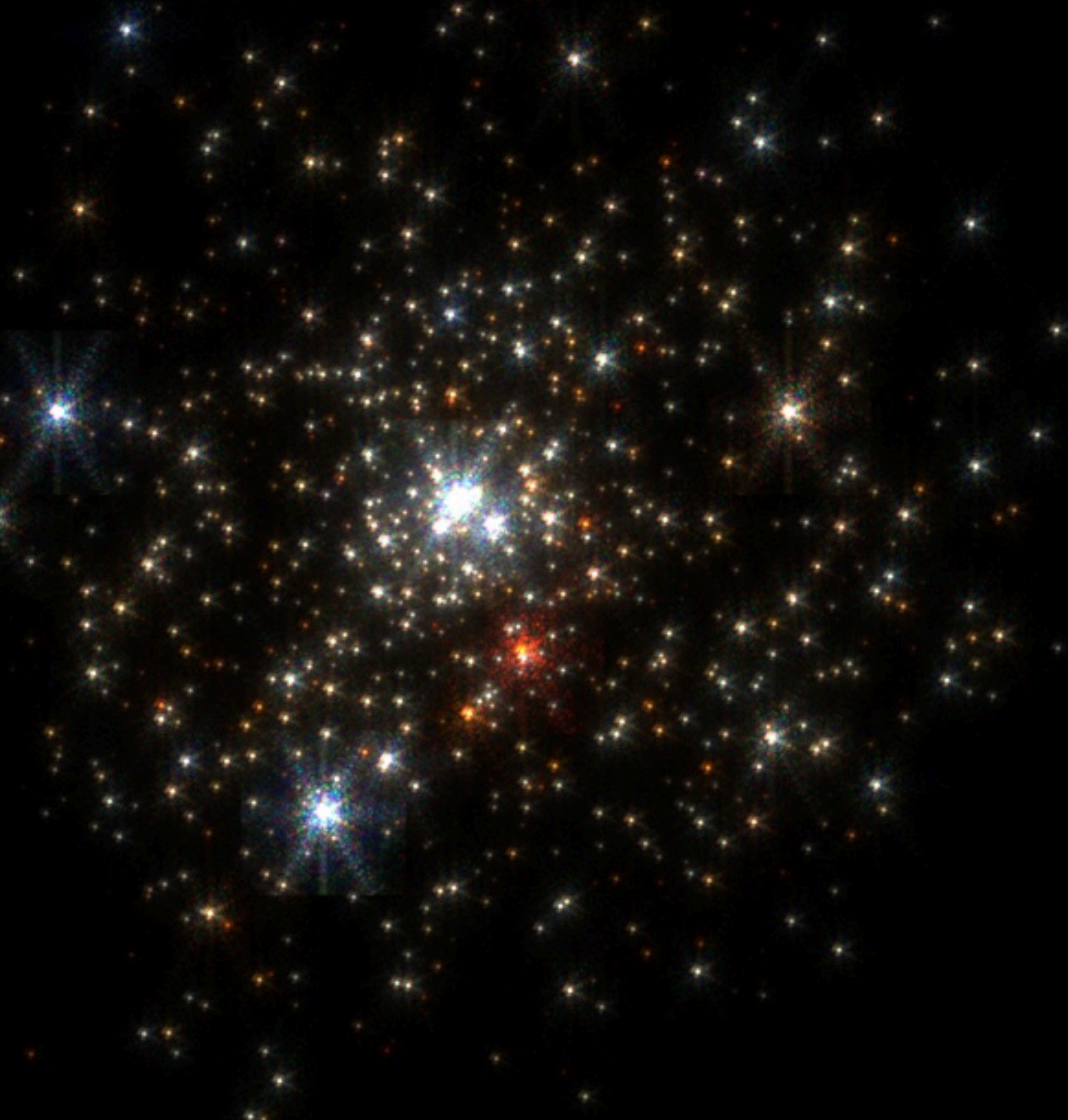
Star formation near the Galactic Centre



HST NICMOS
Quintuplet cluster
NIC2 76 mas pix^{-1}
26 x 26 arcsec field
F110W, F160W, F205W
~256 sec per filter
Faintest sources $K_{AB} \sim 22$
Figer et al. (1999)

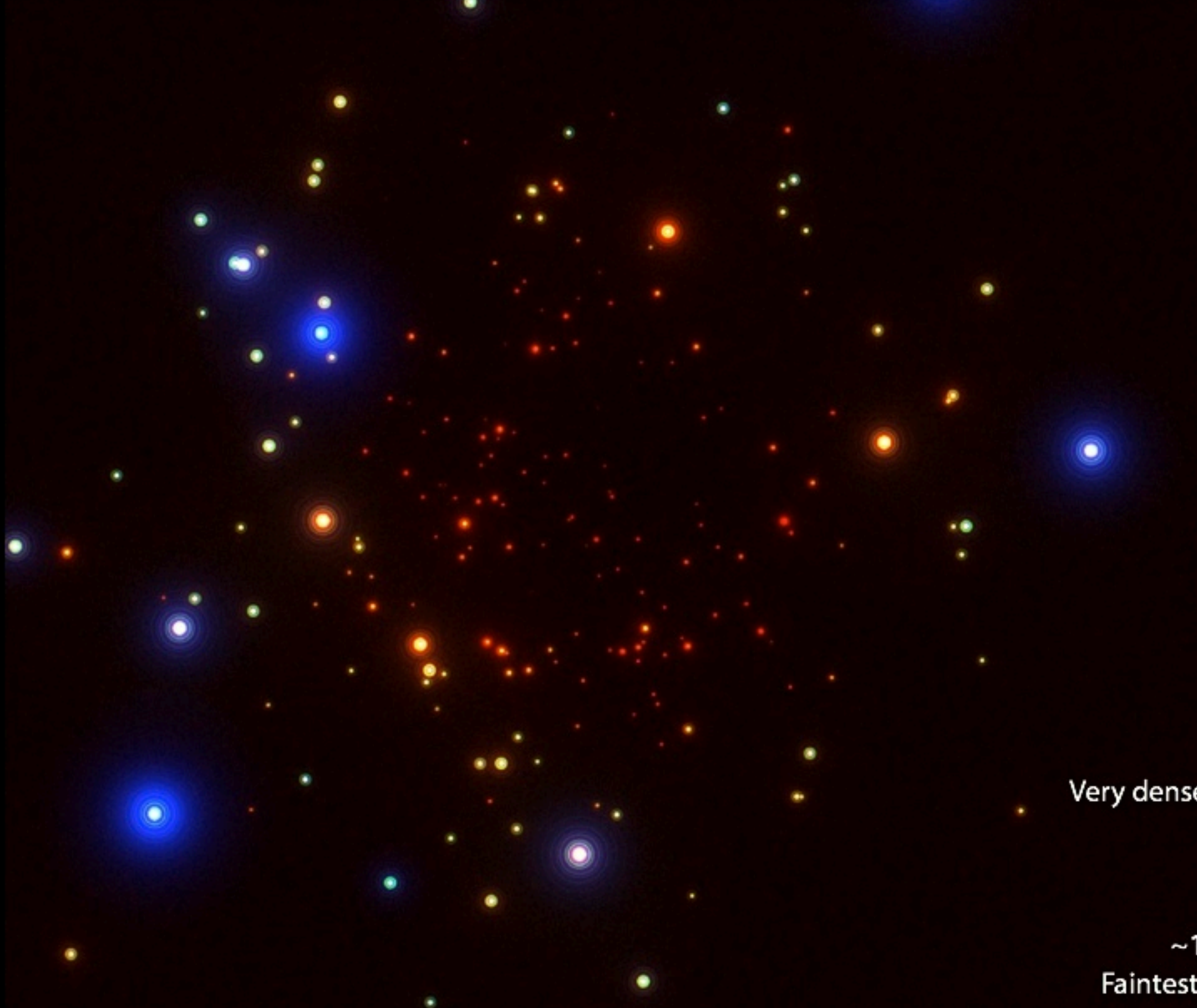
NASA esa

Star formation near the Galactic Centre



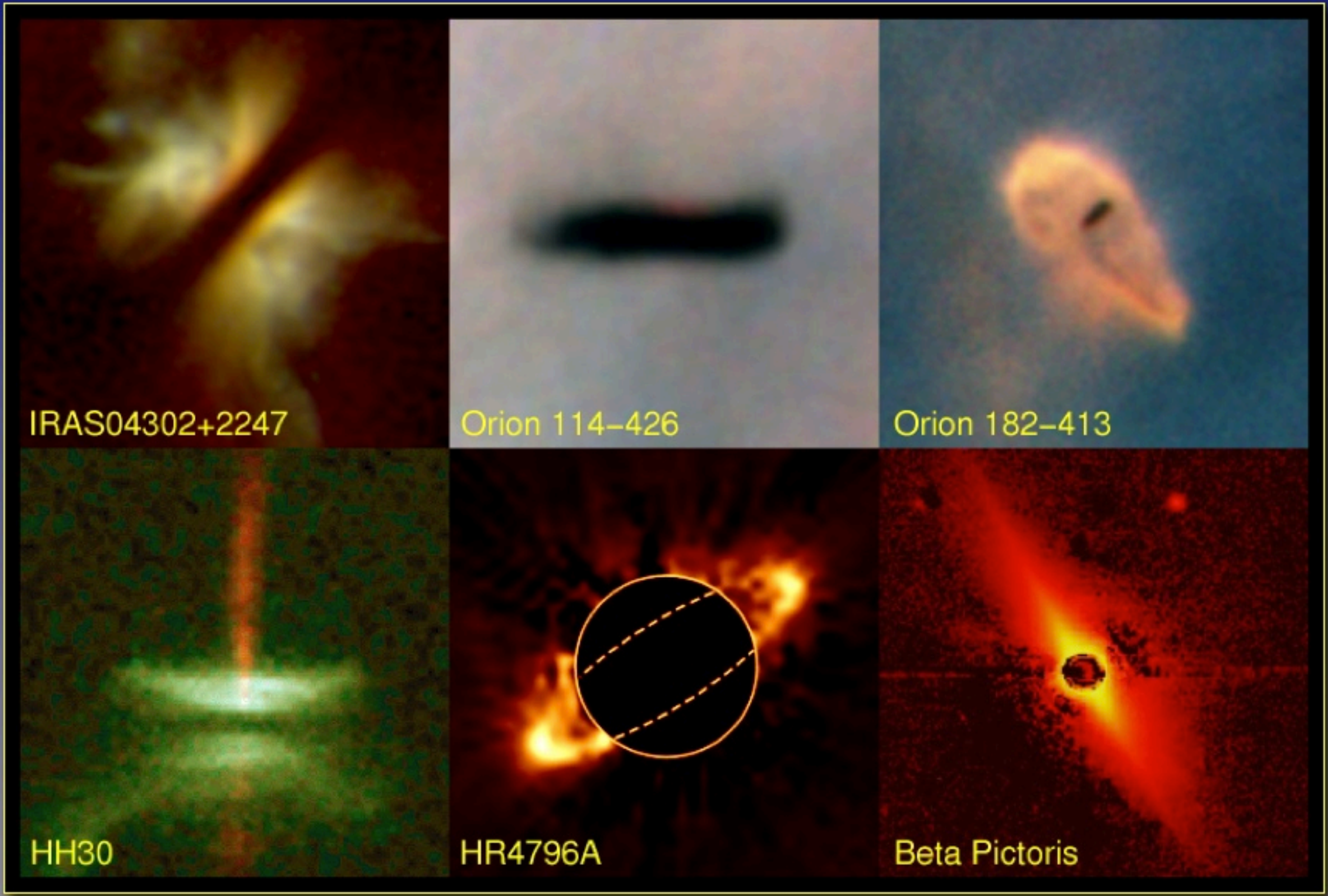
JWST NIRCam
Zeumiprat cluster
SW camera 32 mas pix^{-1}
26 x 26 arcsec field
Monochromatic PSFs 1, 1.5, 2μm
~1000 sec per filter
Faintest sources K_{AB} ~ 28

Star formation near the Galactic Centre



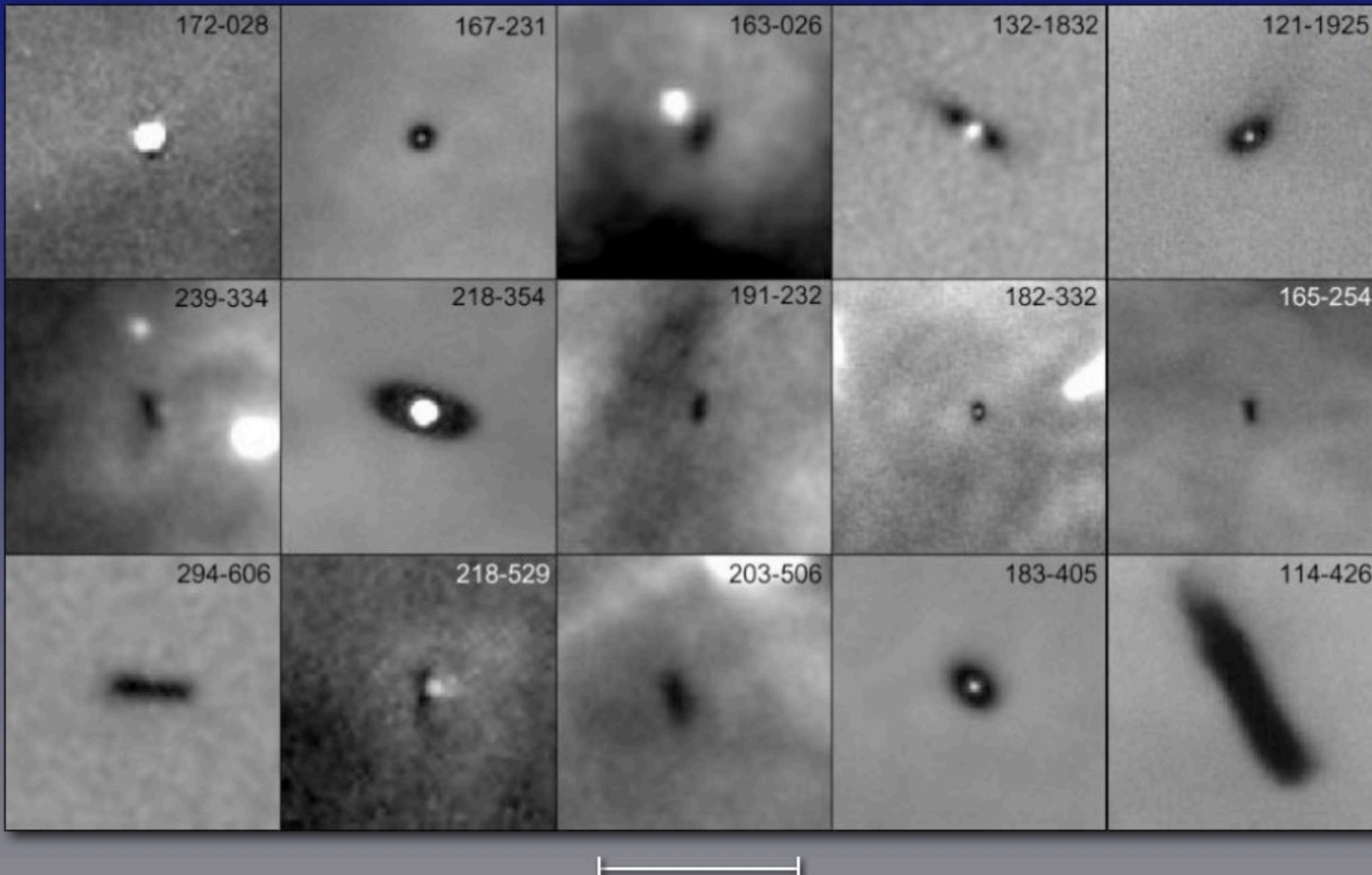
E-ELT MICADO
Very dense core, A_V up to 150
~ 5 mas pix^{-1}
6 x 6 arcsec field
K, L, M bands
~1 hr at K, 1 min at M
Faintest sources K_{AB} ~ 29.5
Calamida et al. , ESO

Evolution of disks to planetary systems



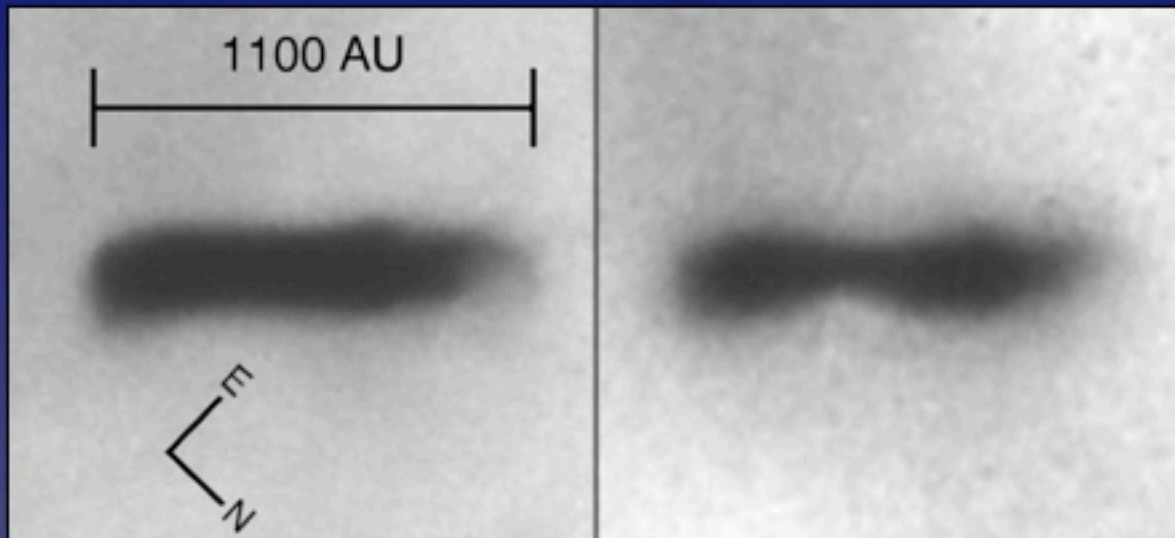
McCaughrean, Stapelfeldt, & Close 2000

Orion Nebula silhouette disks

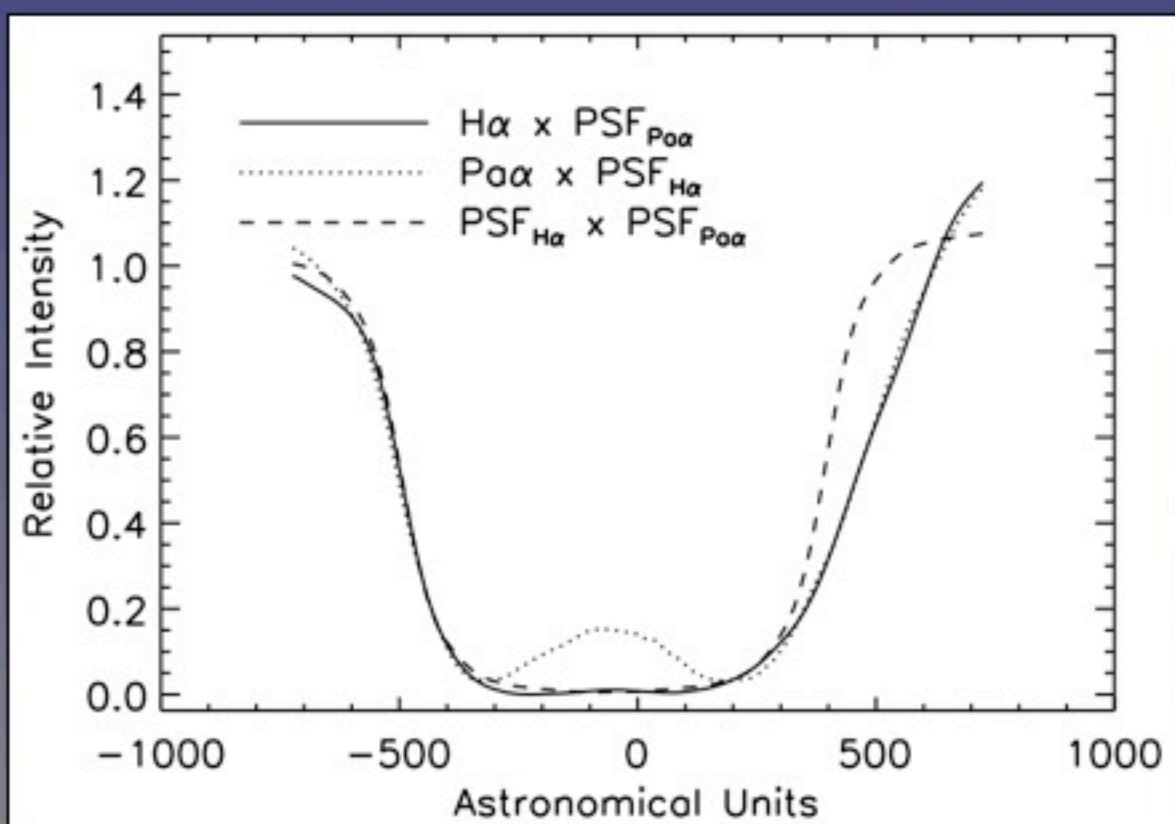


Baly, O'Dell, & McCaughrean (2000)

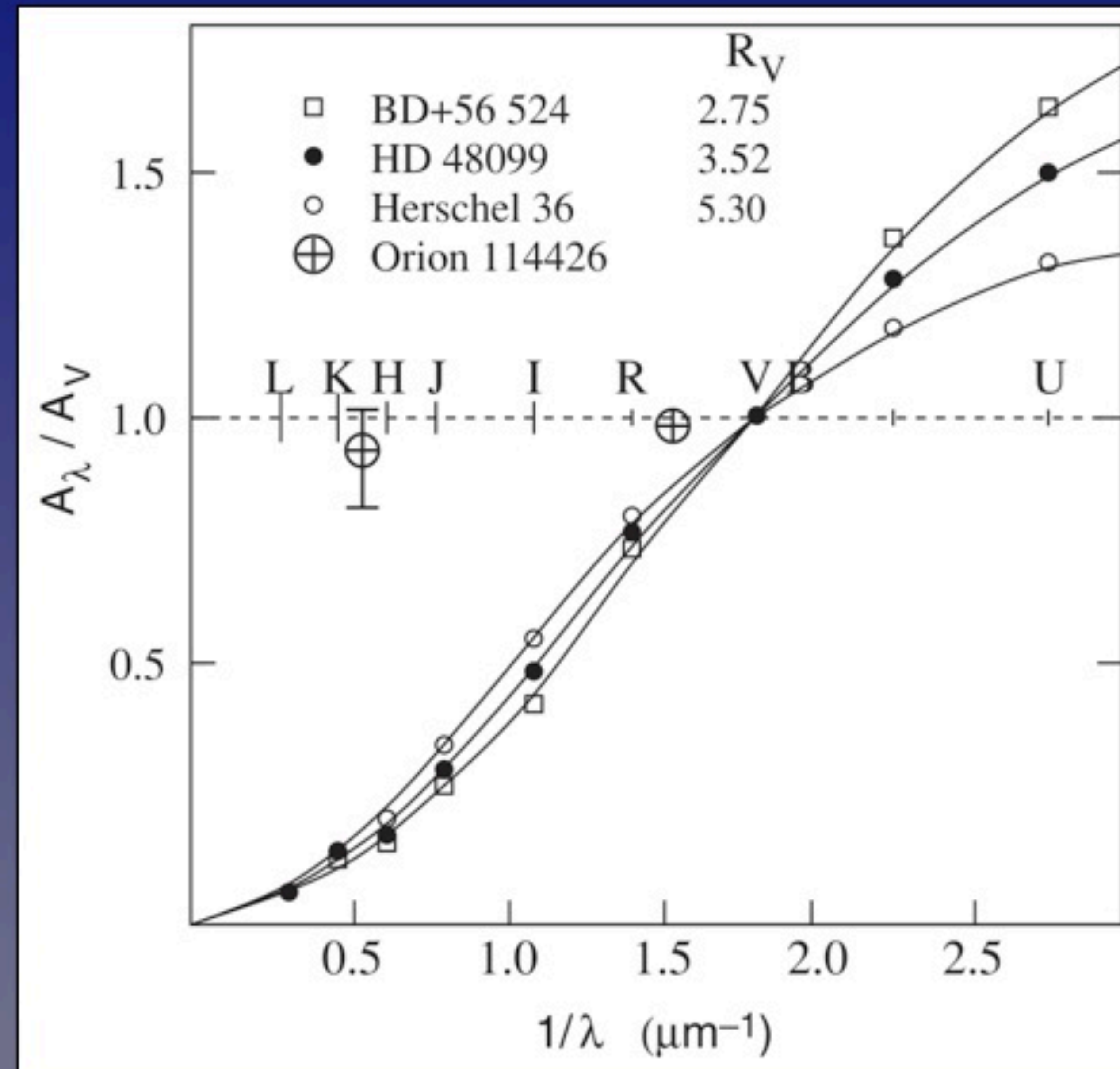
Grain growth in circumstellar disks



WFPC-2 F656N NICMOS F187N



Profiles along major axis of disk

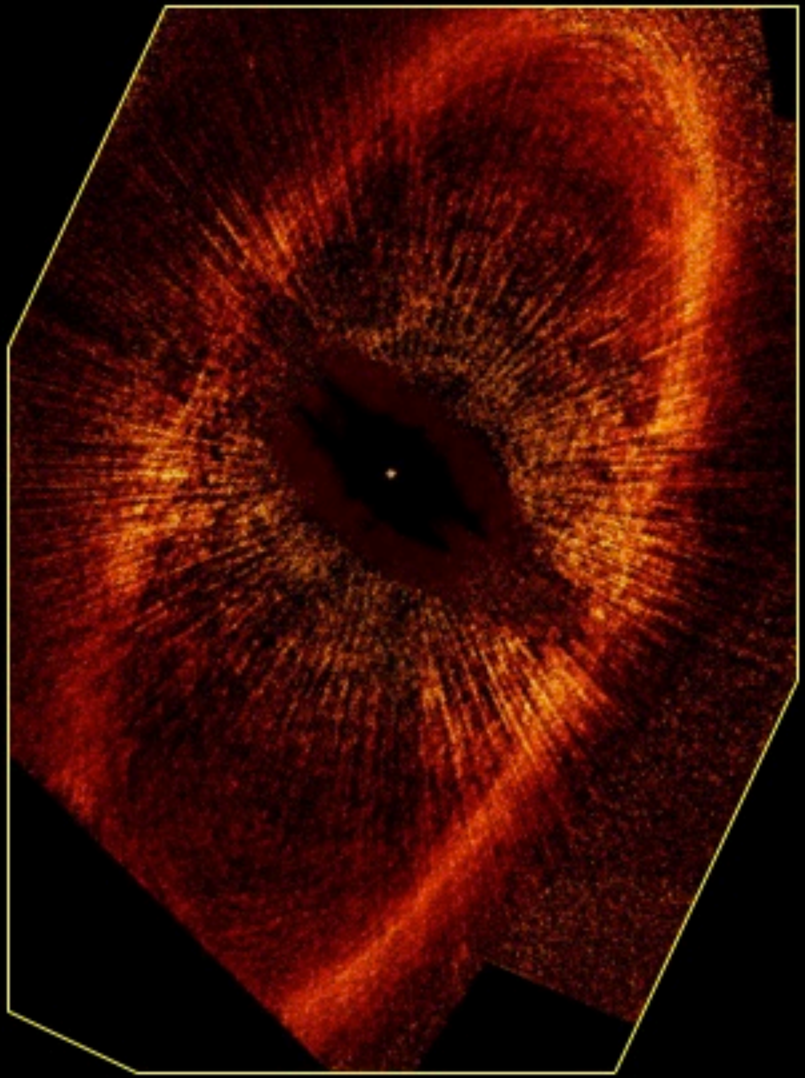


No change in disk size as function of wavelength: suggests >5 μm dust grains, much larger than ISM

Need JWST for better infrared images of the smaller silhouettes

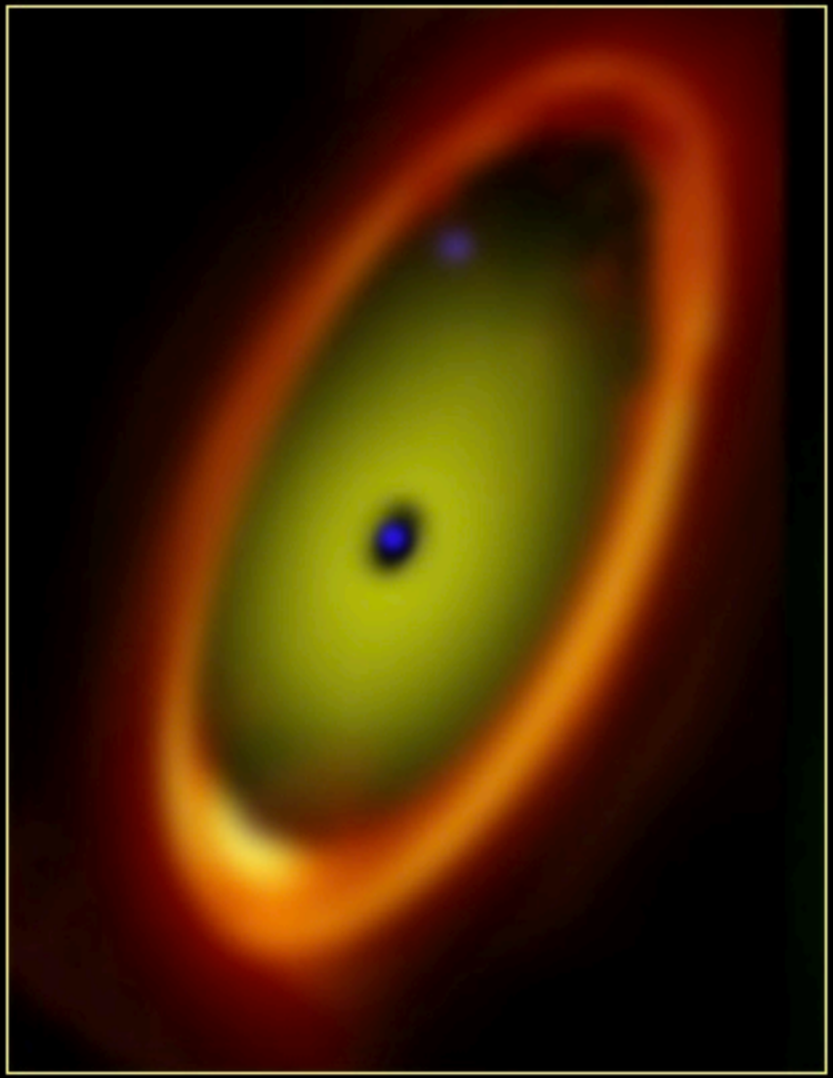
Throop et al. (2001)

Fomalhaut debris disk



HST ACS visible

Spitzer 24 μm

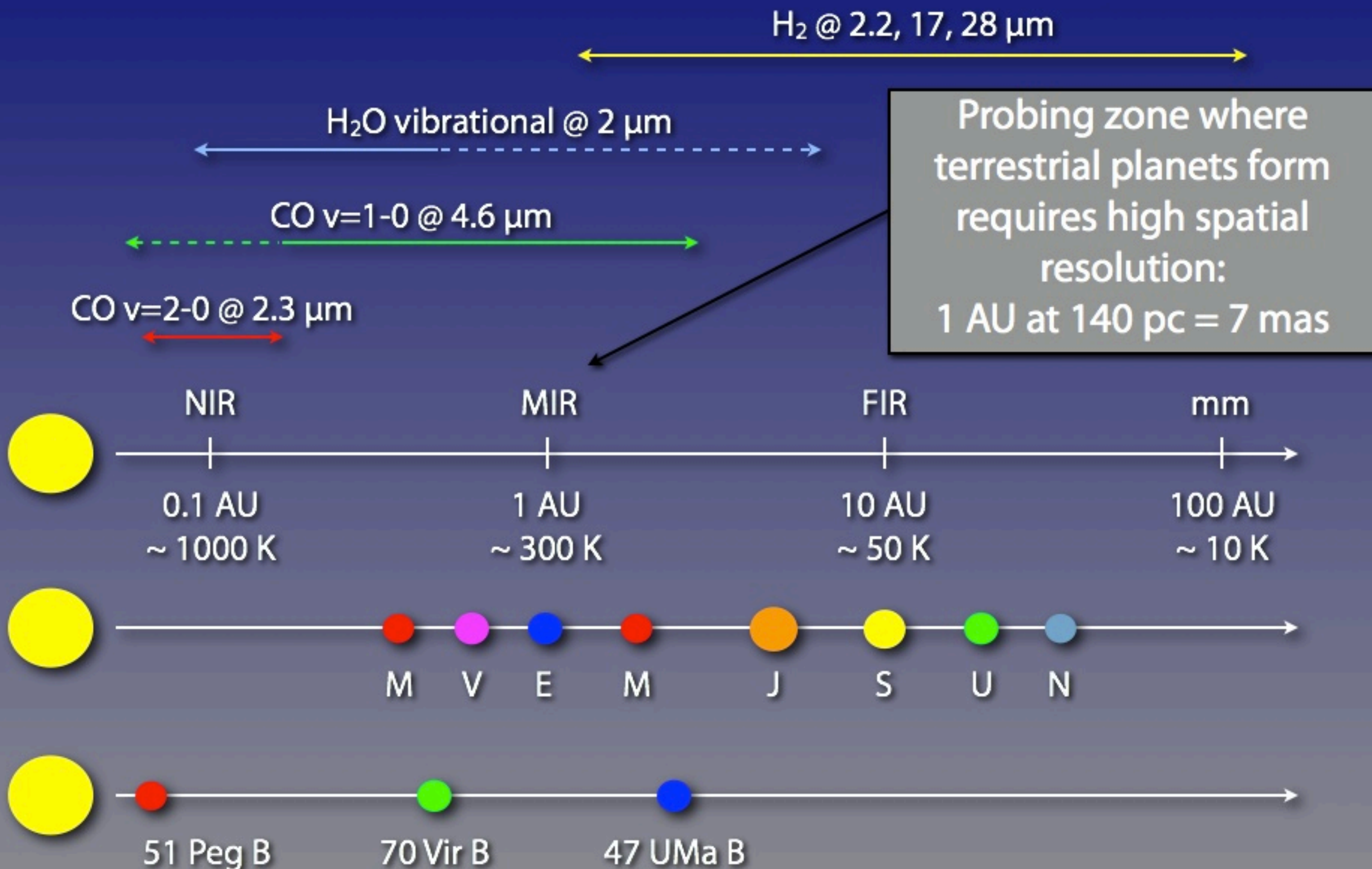


Simulated JWST MIRI 20 μm

Disk morphology: planet-induced gaps and rings

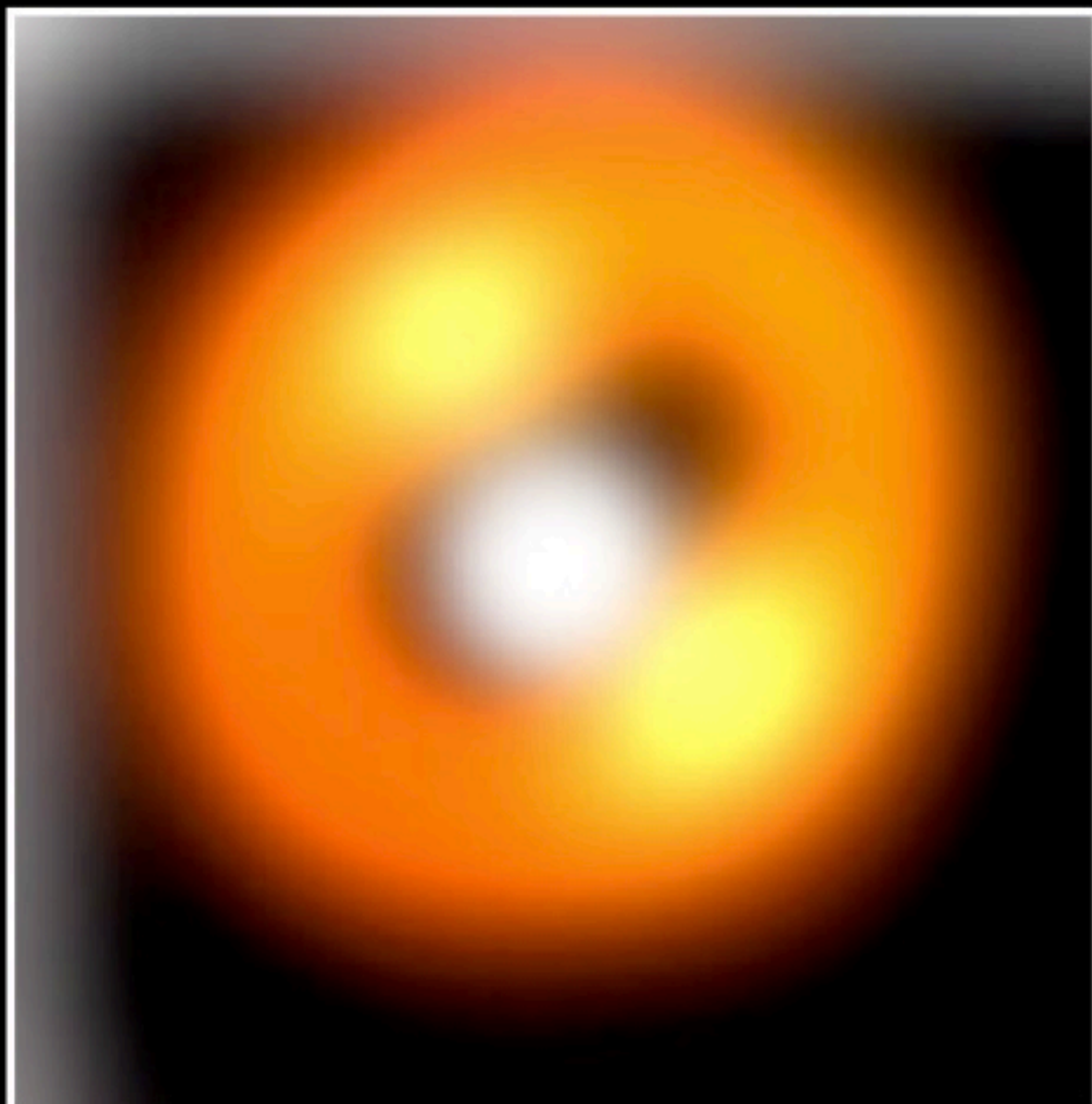
Courtesy Mark Clampin, Paul Kalas

Diagnostic scales in protoplanetary disks

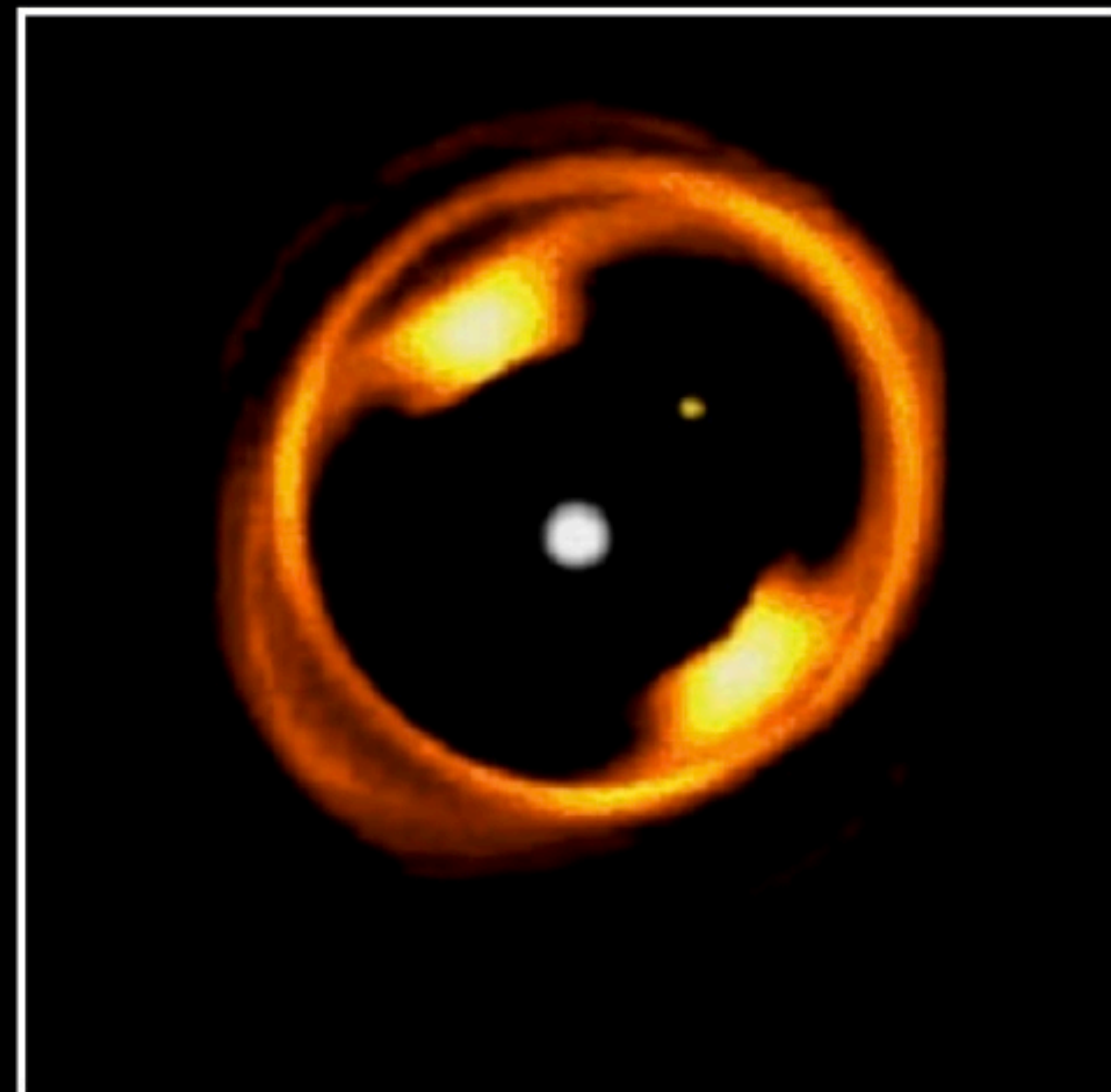


After Joan Najita

Moving out to 40 parsecs



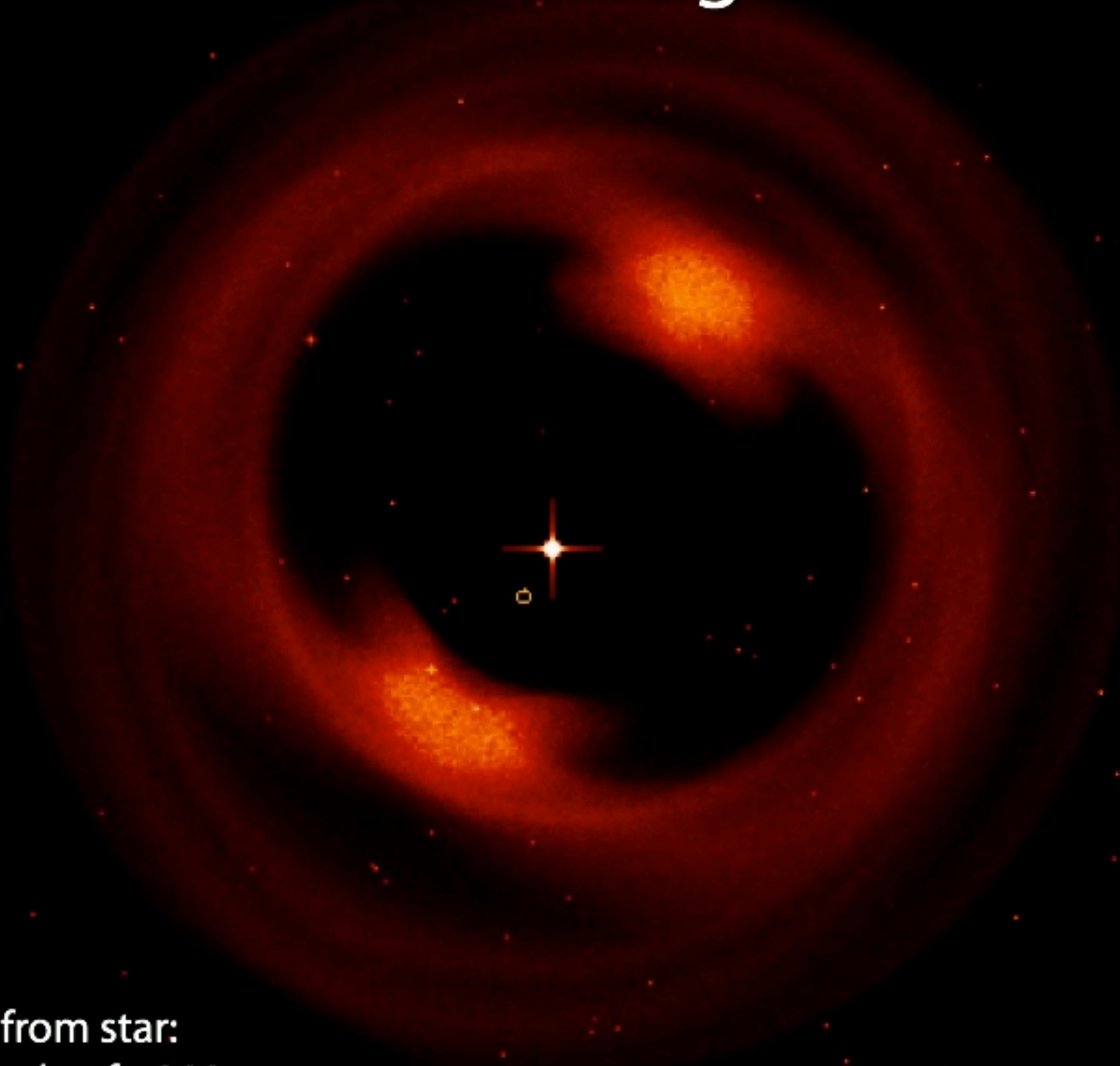
JWST MIRI diffraction-limited imaging at 10 μm, 0.4 arcsec FWHM



E-ELT METIS diffraction-limited imaging at 10 μm, 0.06 arcsec FWHM

Simulation of dust density in Vega-like system: Wilner et al. 2002

Resonant structures in Vega-like debris disk



Planet at few arcsec from star:
clump orbital time scale of ~300 yrs

Simulated near edge-on circumstellar disk

Young ~solar type star (IM Lup) T_{eff}=3900K, R=3$R_\odot$

Optically-thin disk M=0.1$M_\odot$; radii: inner 0.8AU; outer 400AU

Inclination=81°; I, K, L composite; log scaling; pixel size 5 mas

Courtesy Christophe Pinte

Simulation convolved with E-ELT LTAO PSFs

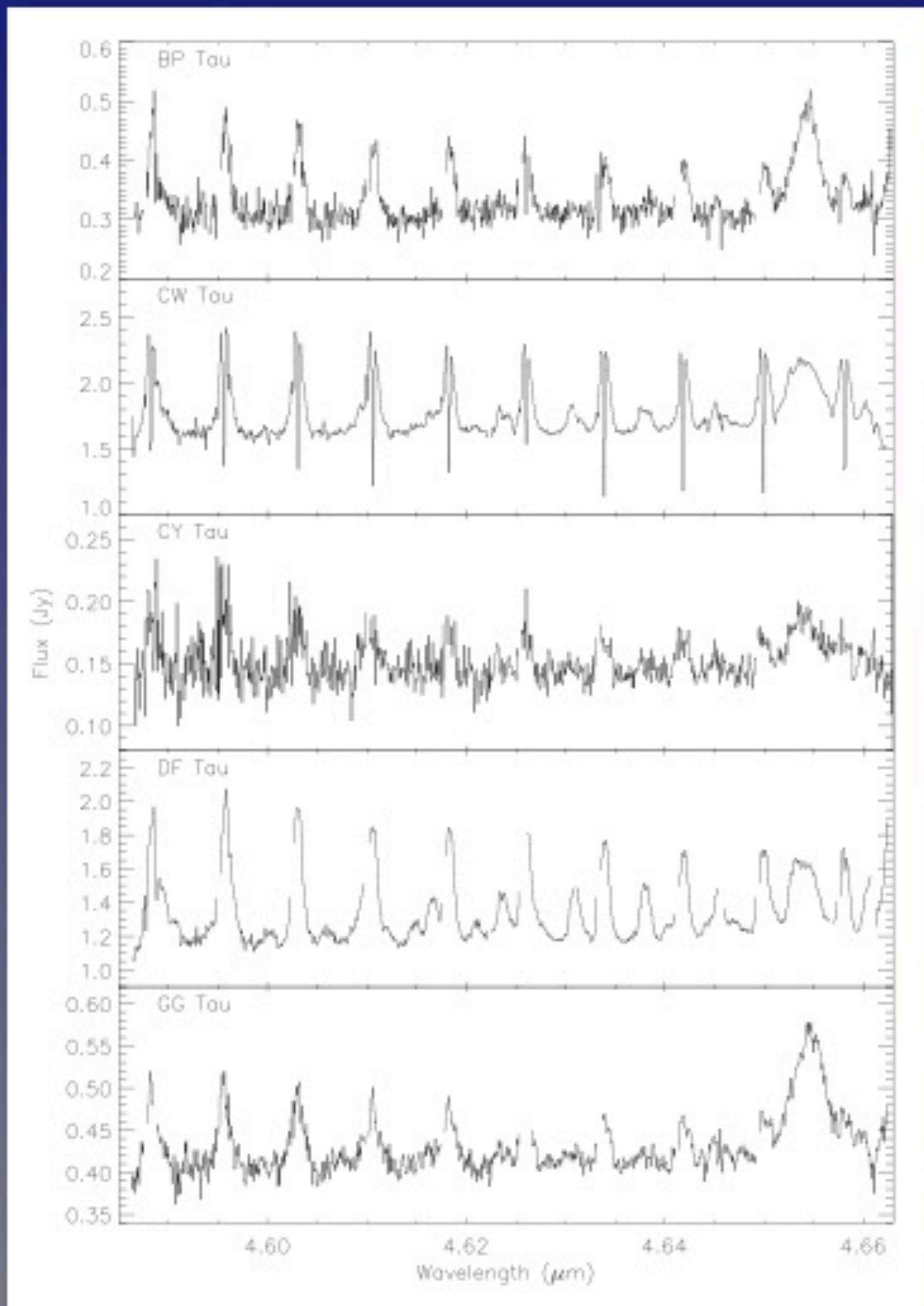
Young ~solar type star (IM Lup) T_{eff}=3900K, R=3$R_\odot$

Optically-thin disk M=0.1$M_\odot$; radii: inner 0.8AU; outer 400AU

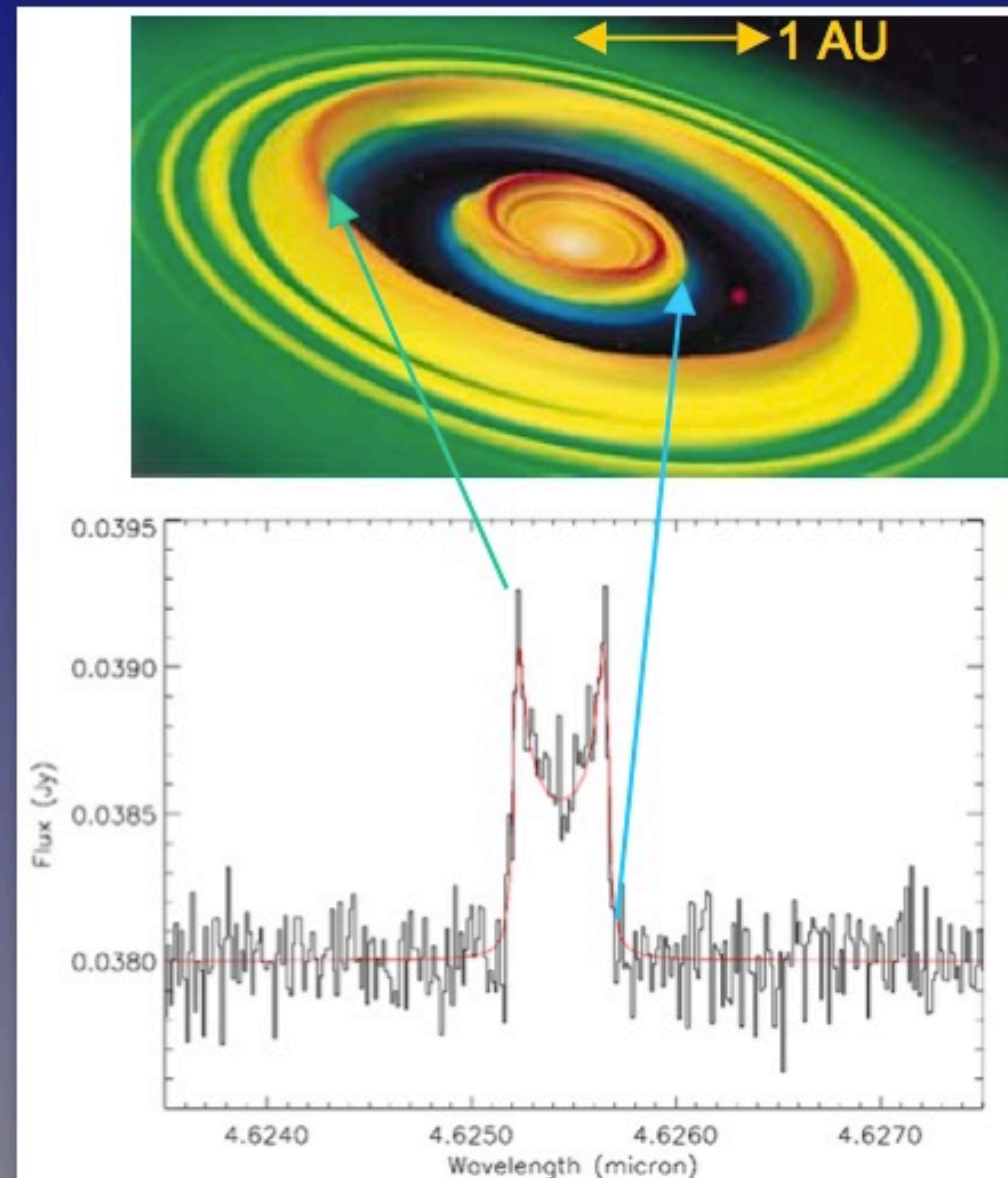
Inclination=81°; I, K, L composite; log scaling; pixel size 5 mas

Courtesy Christophe Pinte

Dynamical studies of the inner disk



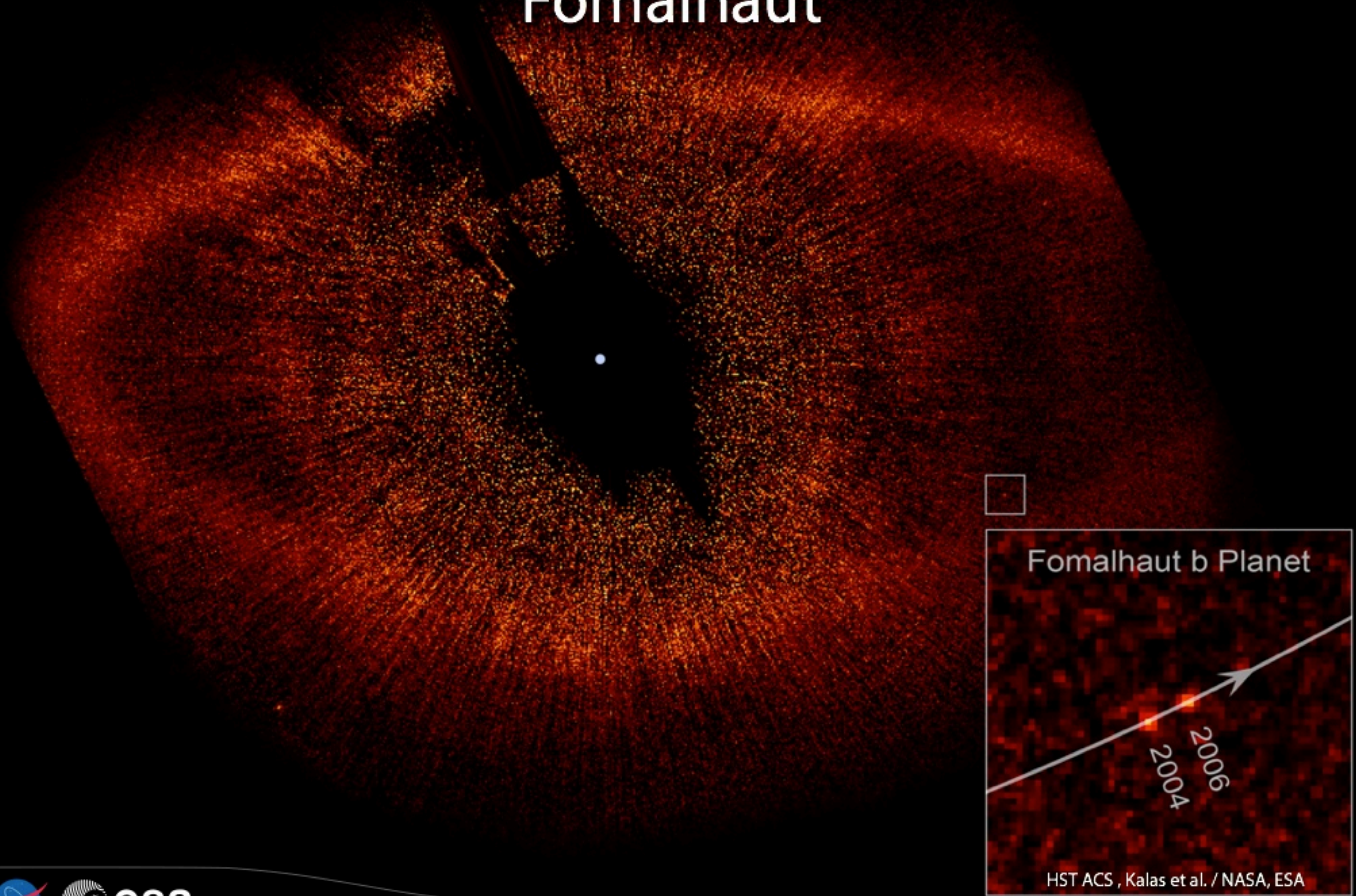
CO v=1–0 spectra of T Tauri stars



Model CO v=1–0 line profile for emission from gap induced at 1AU by Jupiter-mass planet
R=100 000 spectrum, 8 hr, 30m GSMT

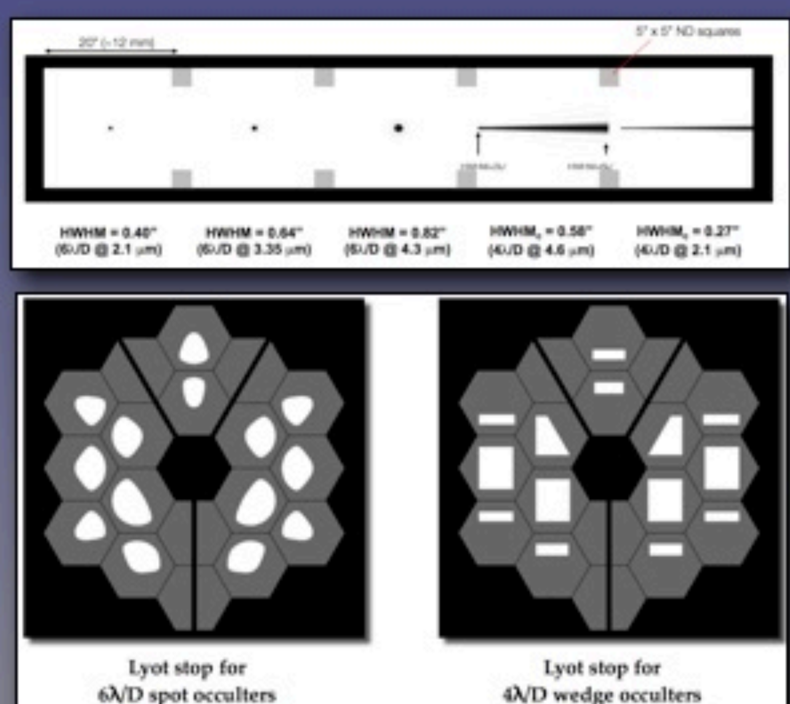
Data: Najita et al. / Simulation: Bryden & Najita

Fomalhaut

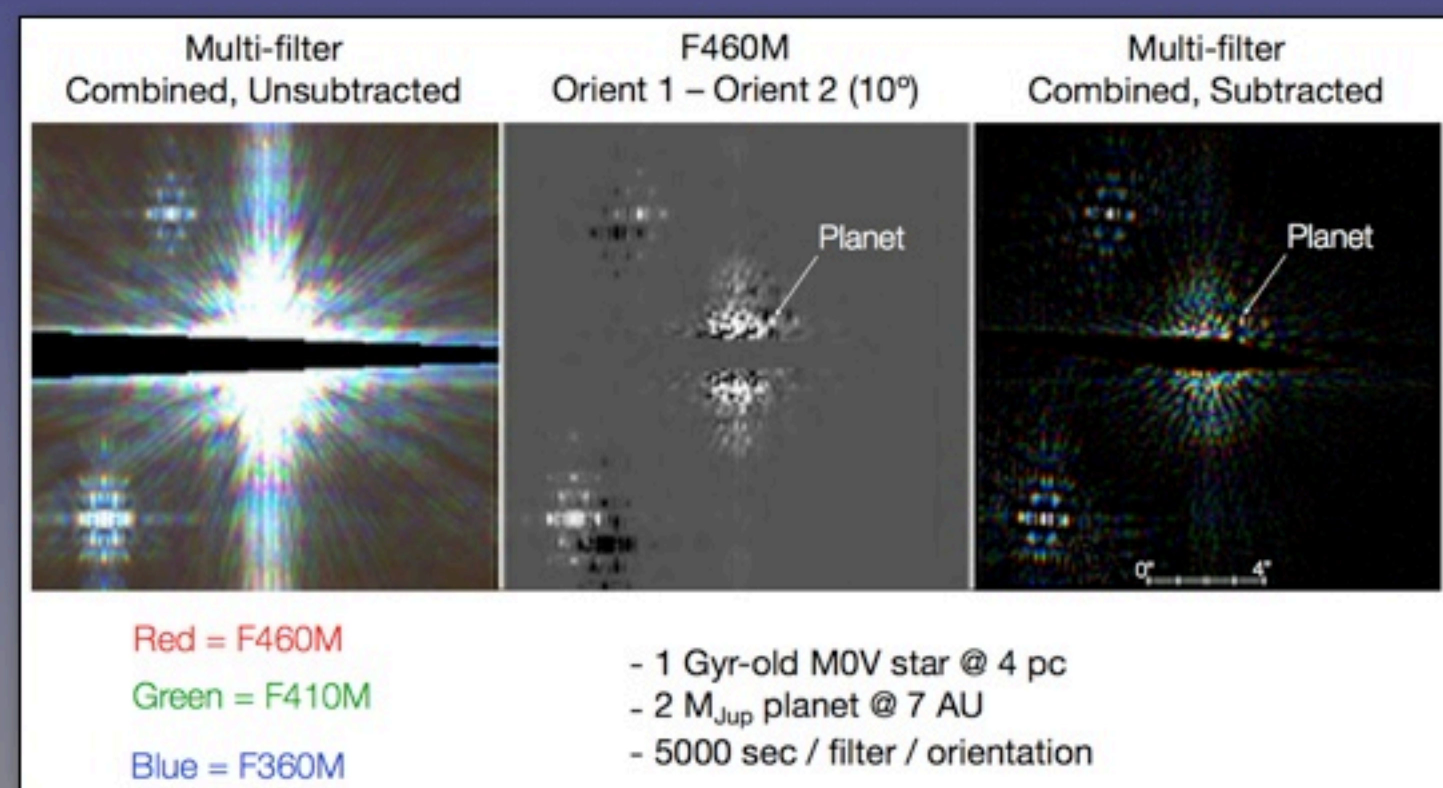


JWST exoplanet imaging

- Direct imaging and spectroscopy
  - NIRCam: Short-λ Lyot coronograph: λ=0.6–2.3 μm, R=4, 10, 100
  - NIRCam: Long-λ Lyot coronograph: λ=2.4–5.0 μm, R=4, 10, 100
  - TFI: Lyot coronograph: λ=1.2–4.8 μm, R=100
  - MIRI: 4QPM coronographs: λ=10.65, 11.4, 15.5 μm, R=20
  - MIRI: Lyot coronograph: λ=23 μm, R=5

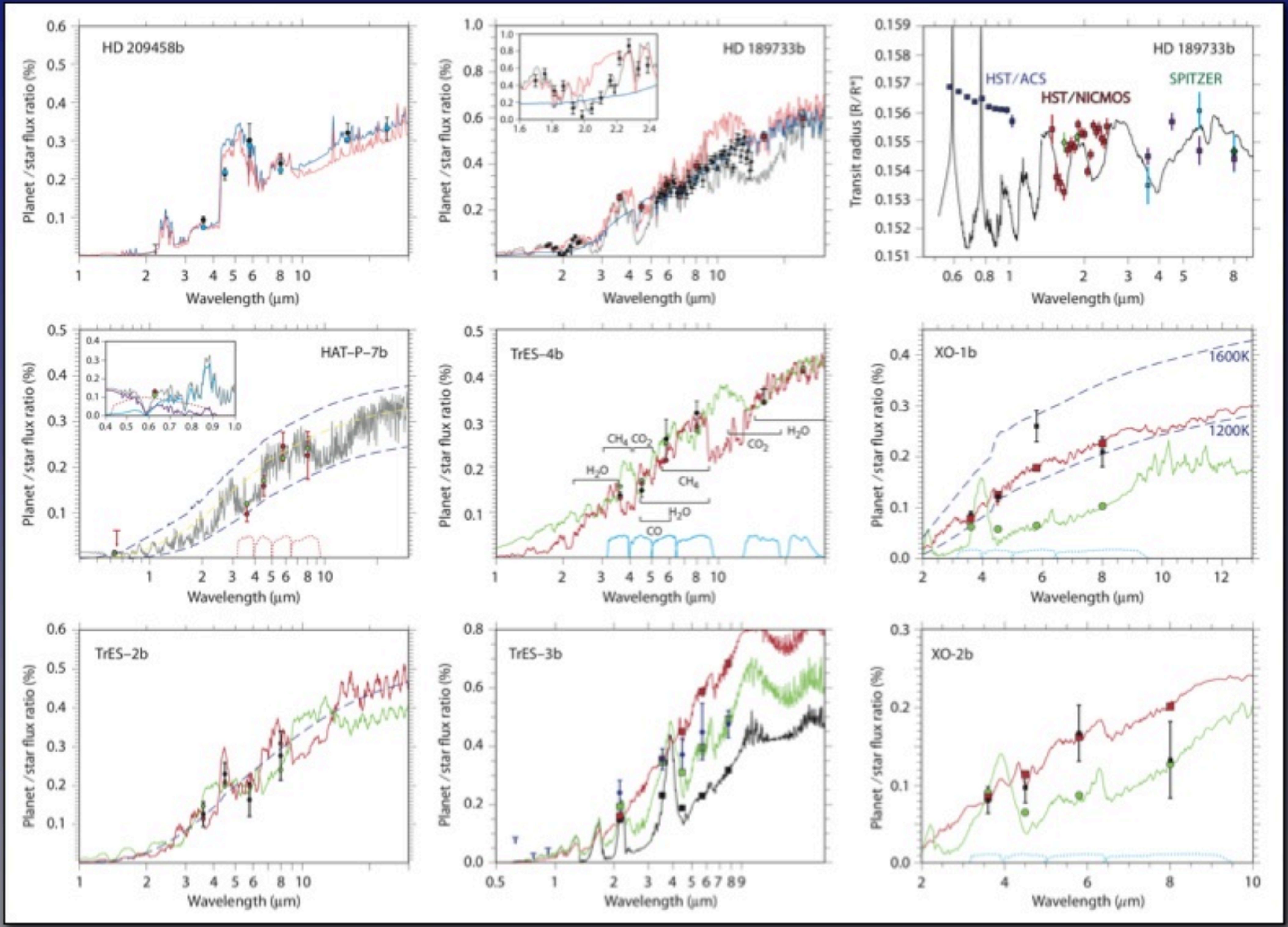


NIRCam radial and wedge occulters and corresponding Lyot stops



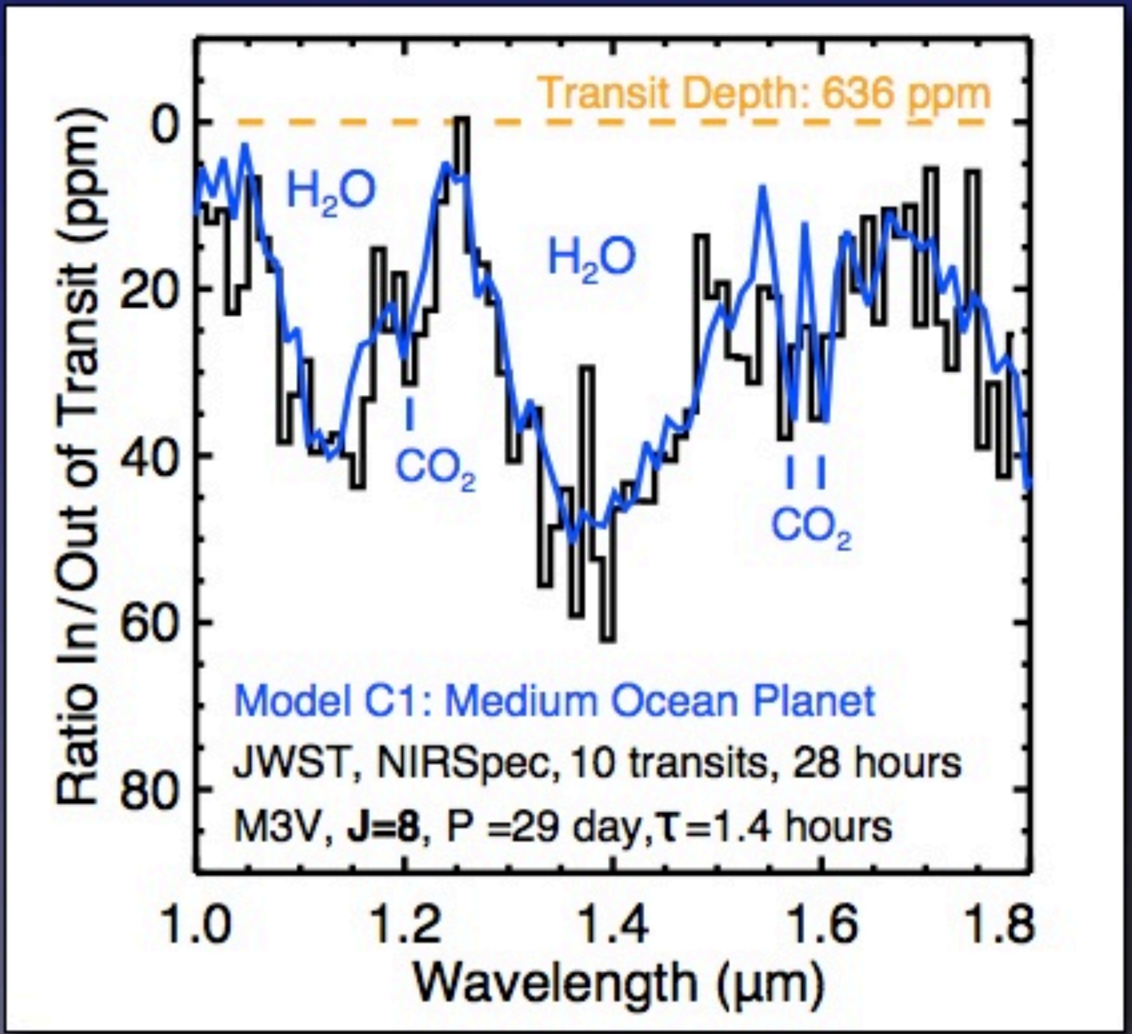
NIRCam coronographic simulations

Transit spectroscopy with Spitzer & HST

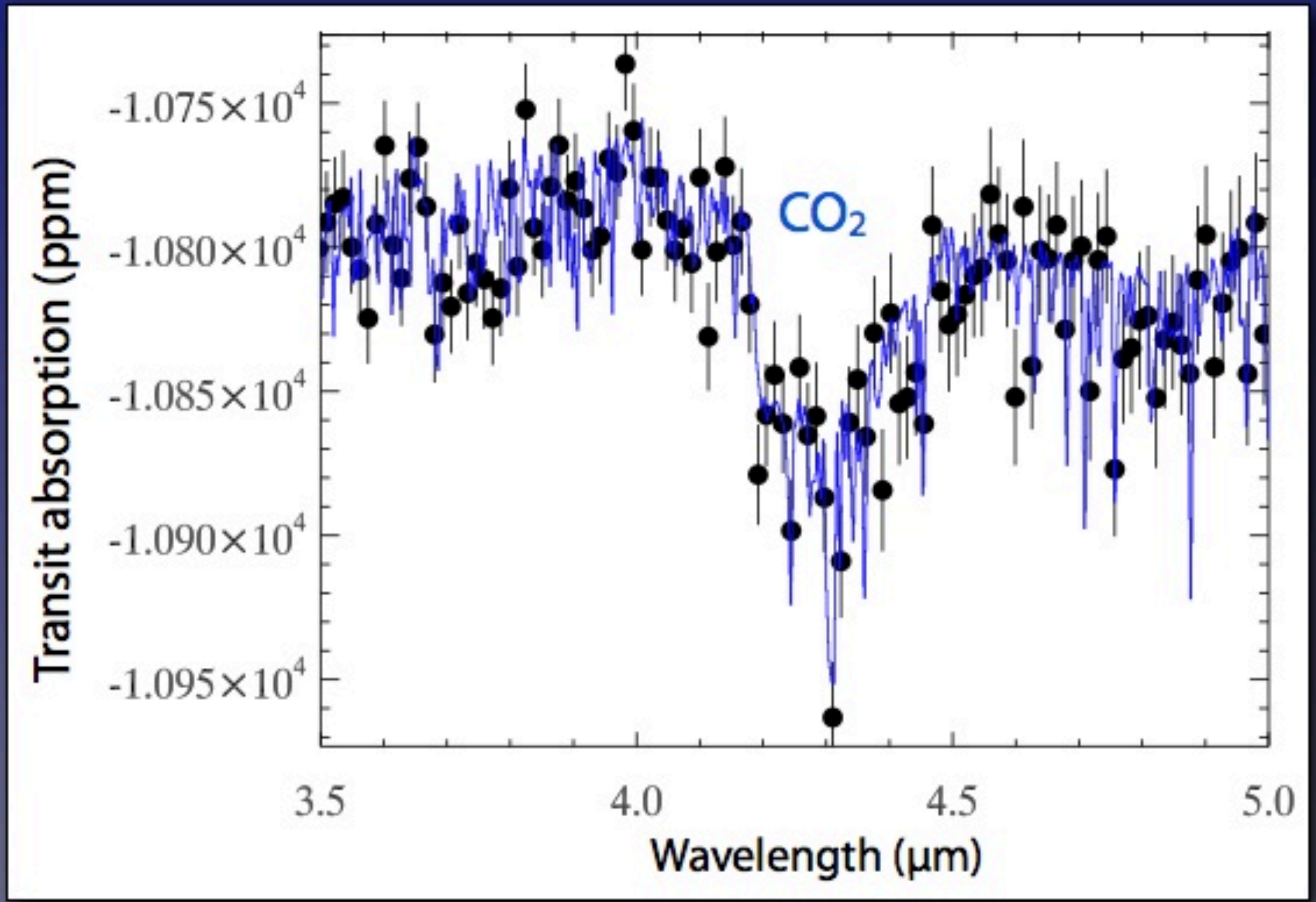


Collation by Seager & Deming (2010), ARA&A

NIRSpec transit simulations

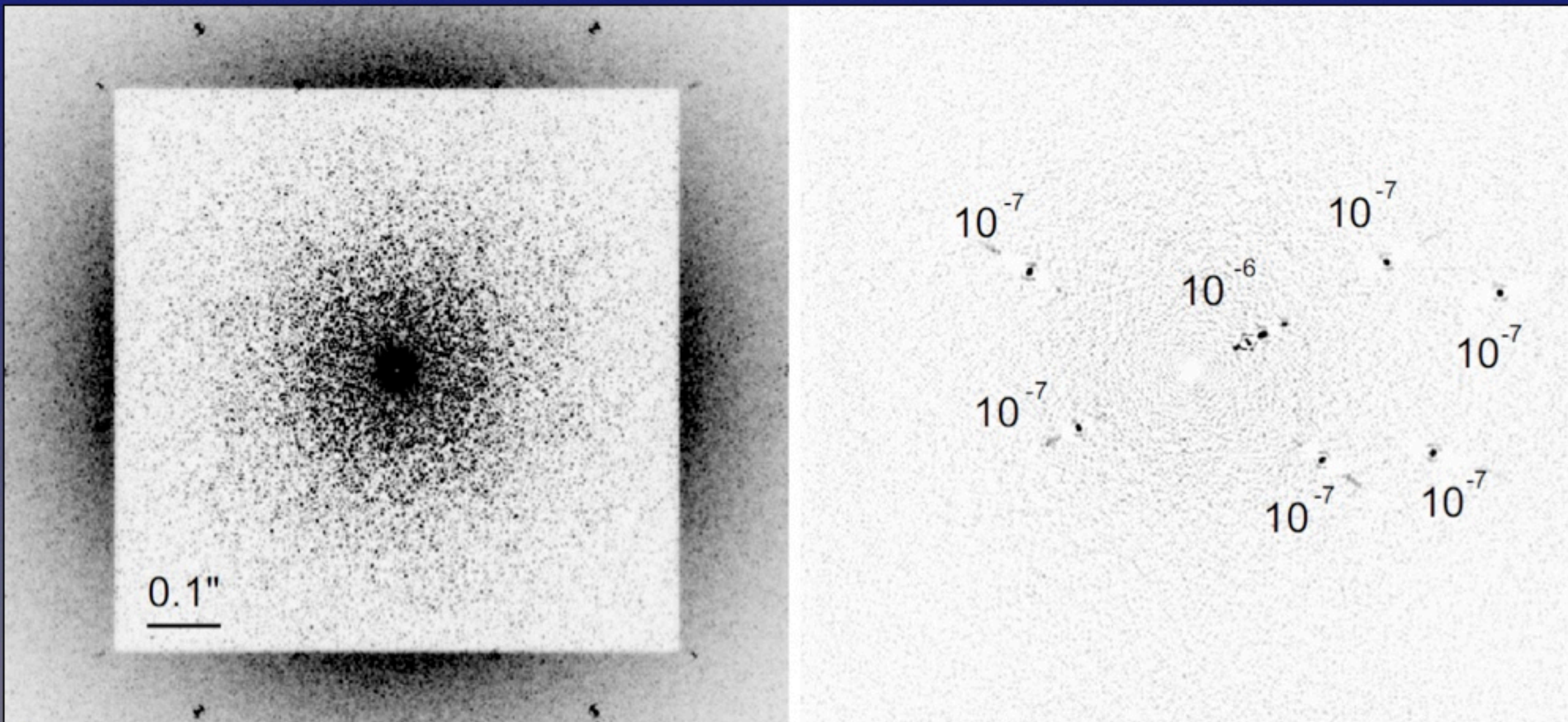


Transmission spectrum of Earth-sized ocean planet around J=8 M3V star
In-transit observing time: 14 hours
Total observing time: 28 hours
Simulation: Valenti et al.



Transmission spectrum of habitable super-Earth $T = 308K$, $R = 2.3R_\oplus$ around M dwarf at 22pc
In-transit observing time: 85 hours
Total observing time: 170 hours
Simulation: Deming et al.

Limits to extreme AO imaging of exoplanets

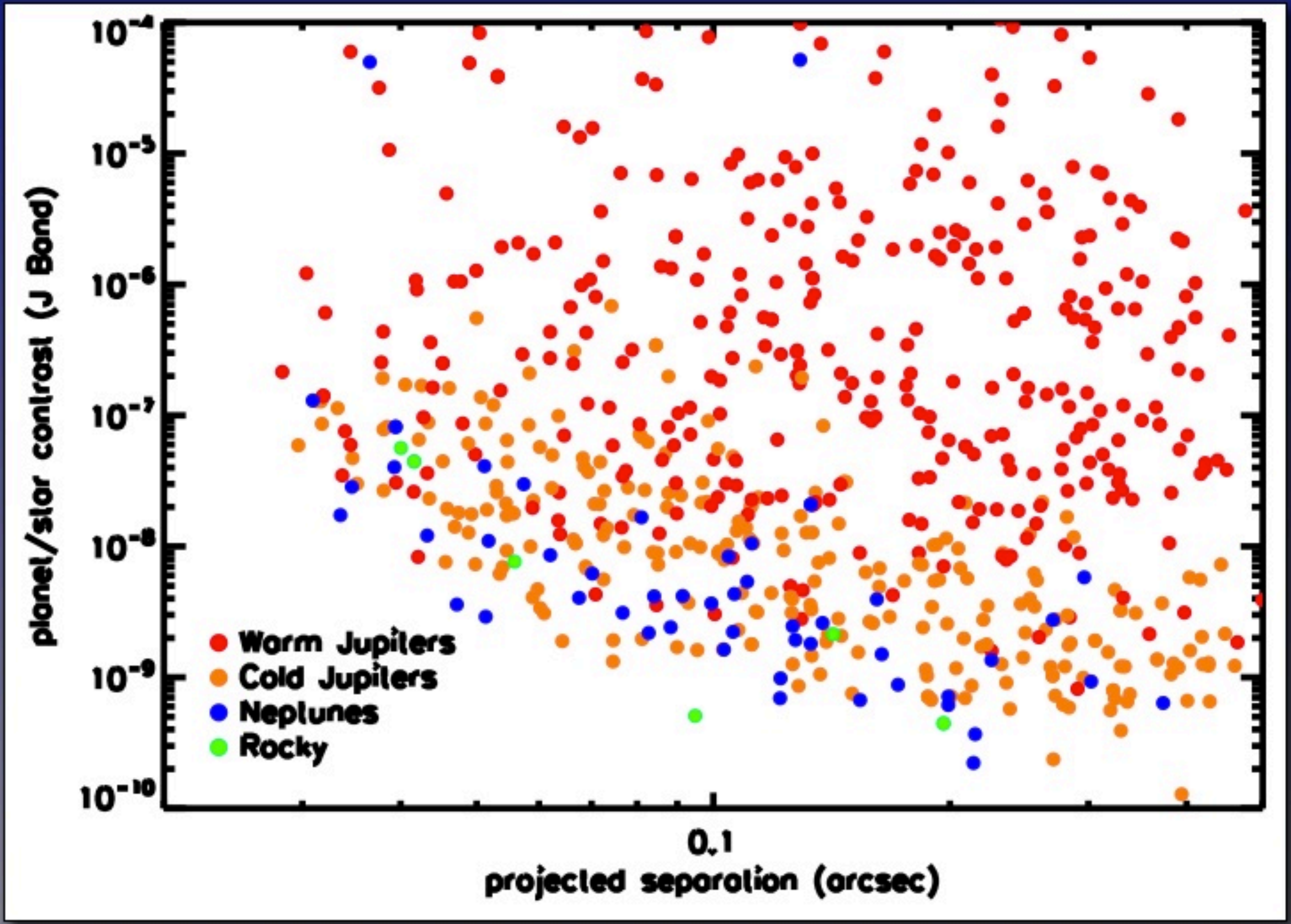


G2V star at 10 pc ($m_V = 4.7$) with E-ELT, 2 mas pix^{-1}, single 60 s exposure at 0.9 µm IFU spectrograph + "perfect" coronograph

Result after spectral deconvolution and recollapsing to form image. Exoplanet contrast w.r.t. star shown: extrapolates to 10^{-9} in ~ 10 hrs

Gladysz et al. (2010), submitted

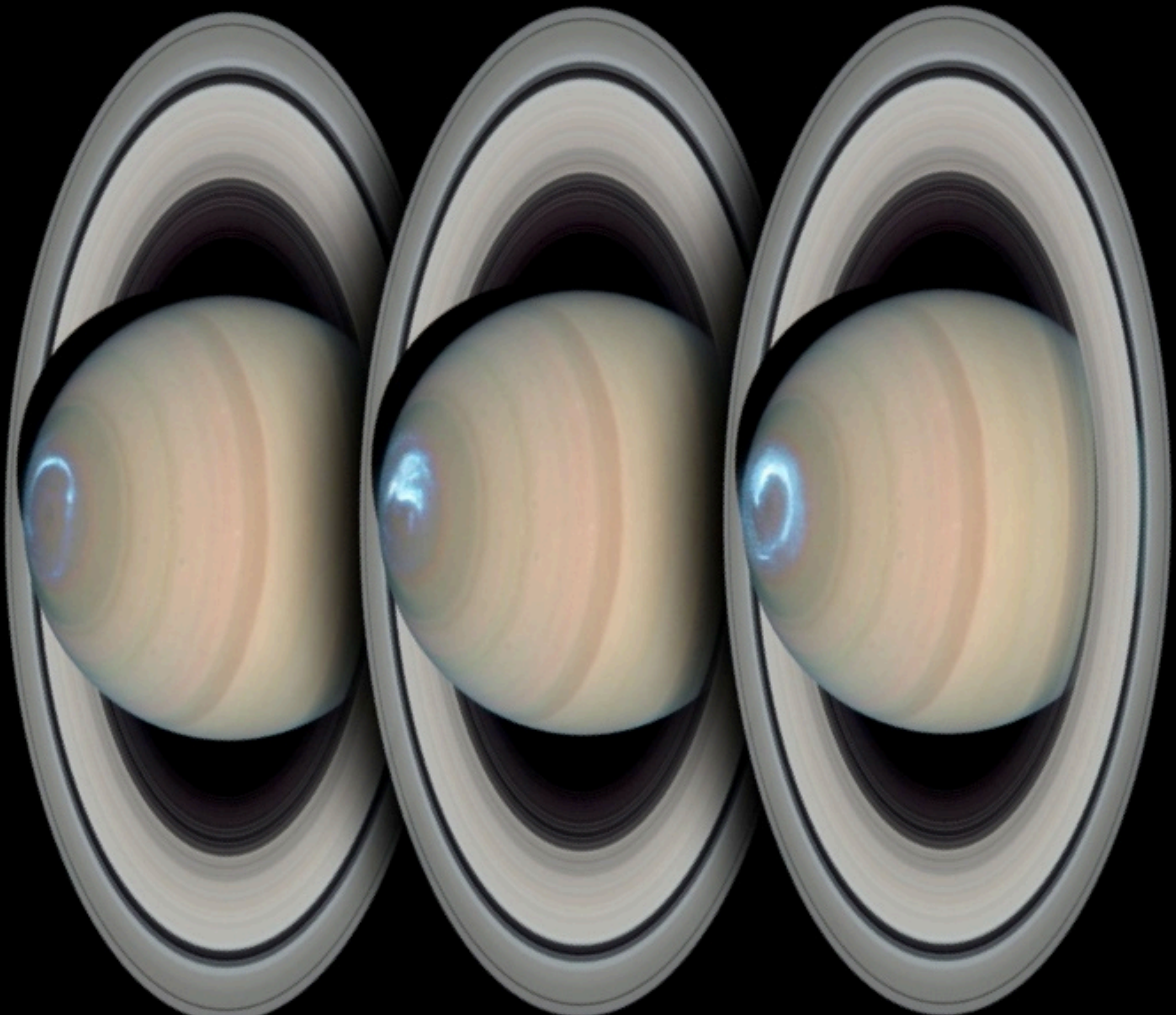
Direct exoplanet imaging



E-ELT EPICS extreme-AO + IFS simulated exoplanet detections, each 20 hours
Planets drawn from population simulation by Mordasini et al. (2009)

Courtesy E-ELT EPICS science team

Aurorae on Saturn



2004 images from HST ACS + STIS / NASA, ESA, Clarke, Levay, Karkoschka

Aurorae on Saturn in the infrared

Cassini VIMS
Blue: reflected sunlight at 2–3μm
Green: hydrogen ions at 3–4μm
Red: thermal emission at 5μm

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