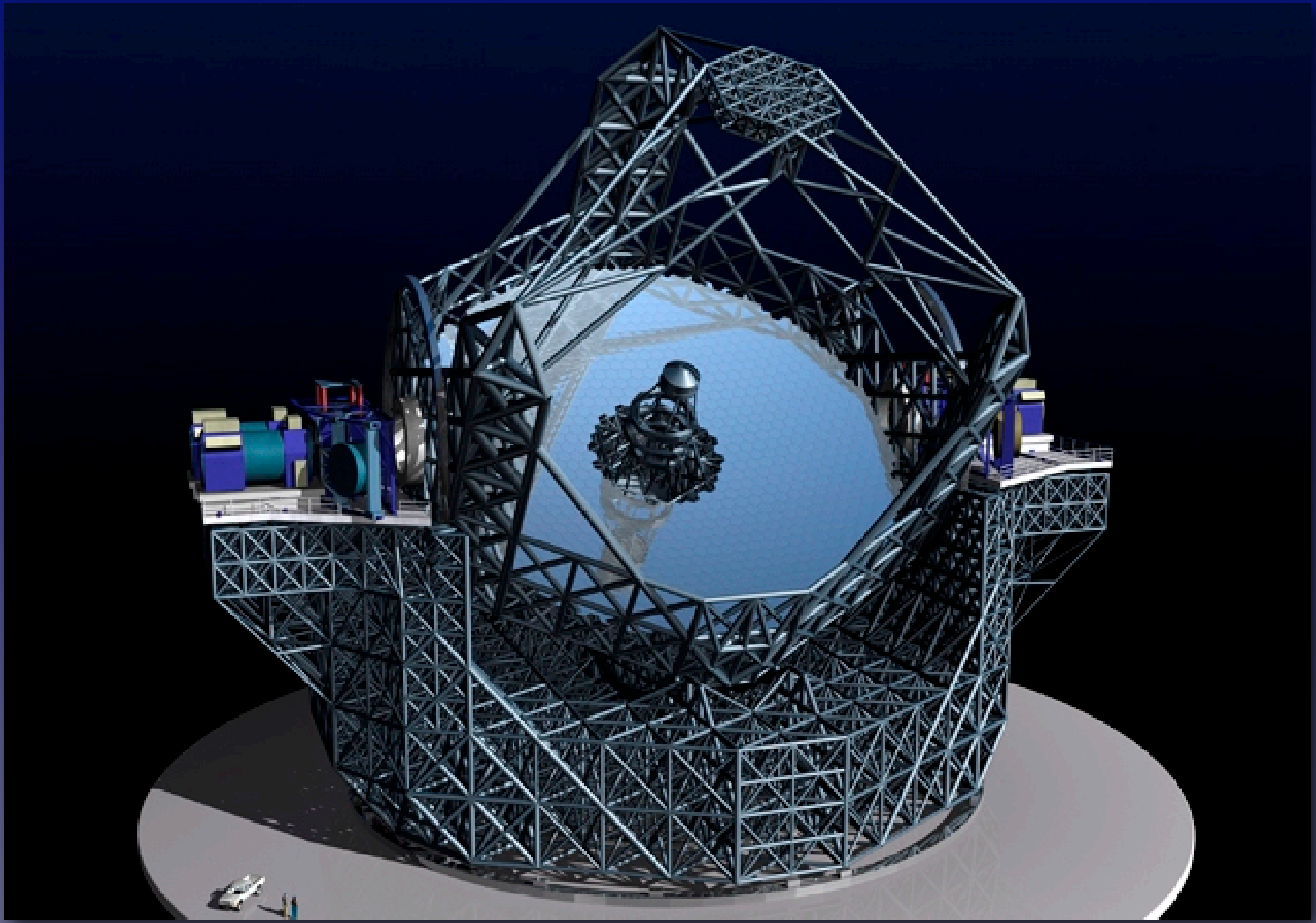
News flash: another 28 planets announced at AAS meeting today by Marcy group: now 236 total



Circumstellar disk science with the E-ELT

UNIVERSITY OF EXETER

Mark McCaughrean

Astrophysics Group, School of Physics

E-ELT SWG Design Reference Mission meeting, ESO Garching May 29-30 2007

With credit to science cases for:

- MIDIR (Brandl et al.)
- GSMT (Najita, Strom et al.)
- OWL

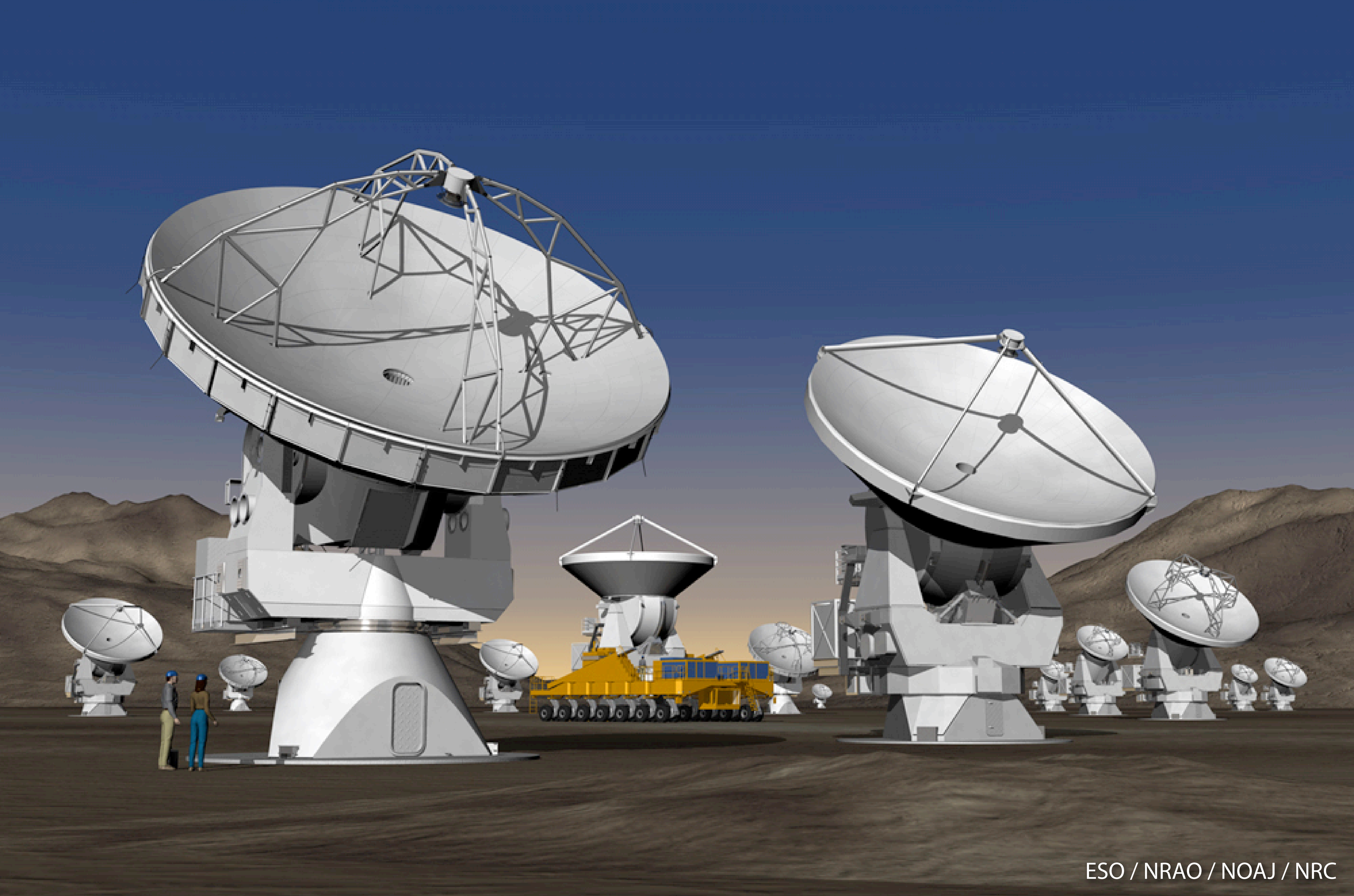
Artist’s representation of a protoplanetary disk

Hartmann

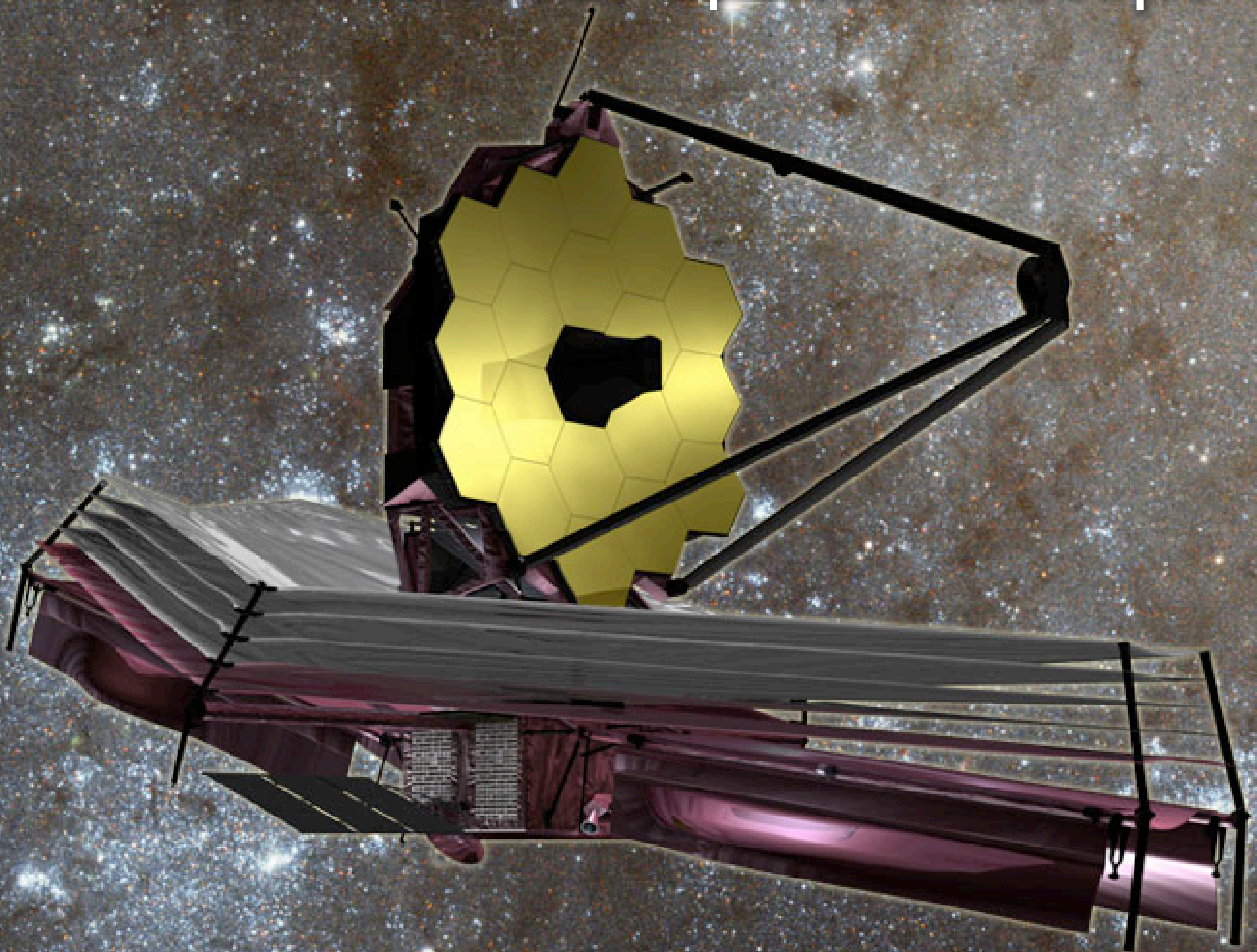
Circumstellar disks

- Play crucial role in star and planet formation
  - Provide conduit for accretion onto central star
  - Provide launch platform for collimated jets and outflows
  - Provide medium for agglomeration and accretion into planets
- Broad range of questions to be addressed by E-ELT
  - How is material funnelled onto star (magnetospheric accretion)?
  - What is the impact of the central protostar on the disk?
  - How are jets collimated and do they rotate?
  - Can we understand the formation of planetary systems?
- A large, filled-aperture E-ELT provides key tools
  - Broad optical, near-IR, and mid-IR wavelength coverage
  - High spatial resolution, filled u,v-plane imaging
  - High sensitivity for high resolution spectroscopy

The Atacama Large Millimetre Array



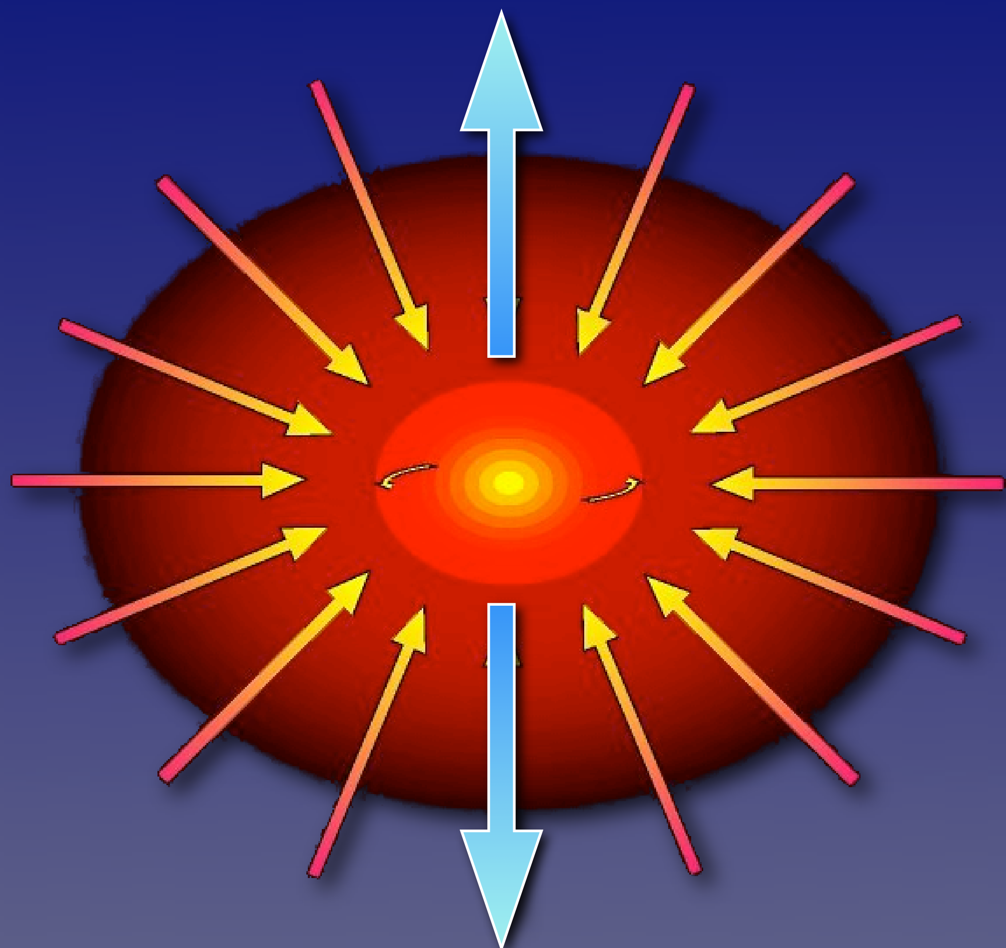
The James Webb Space Telescope



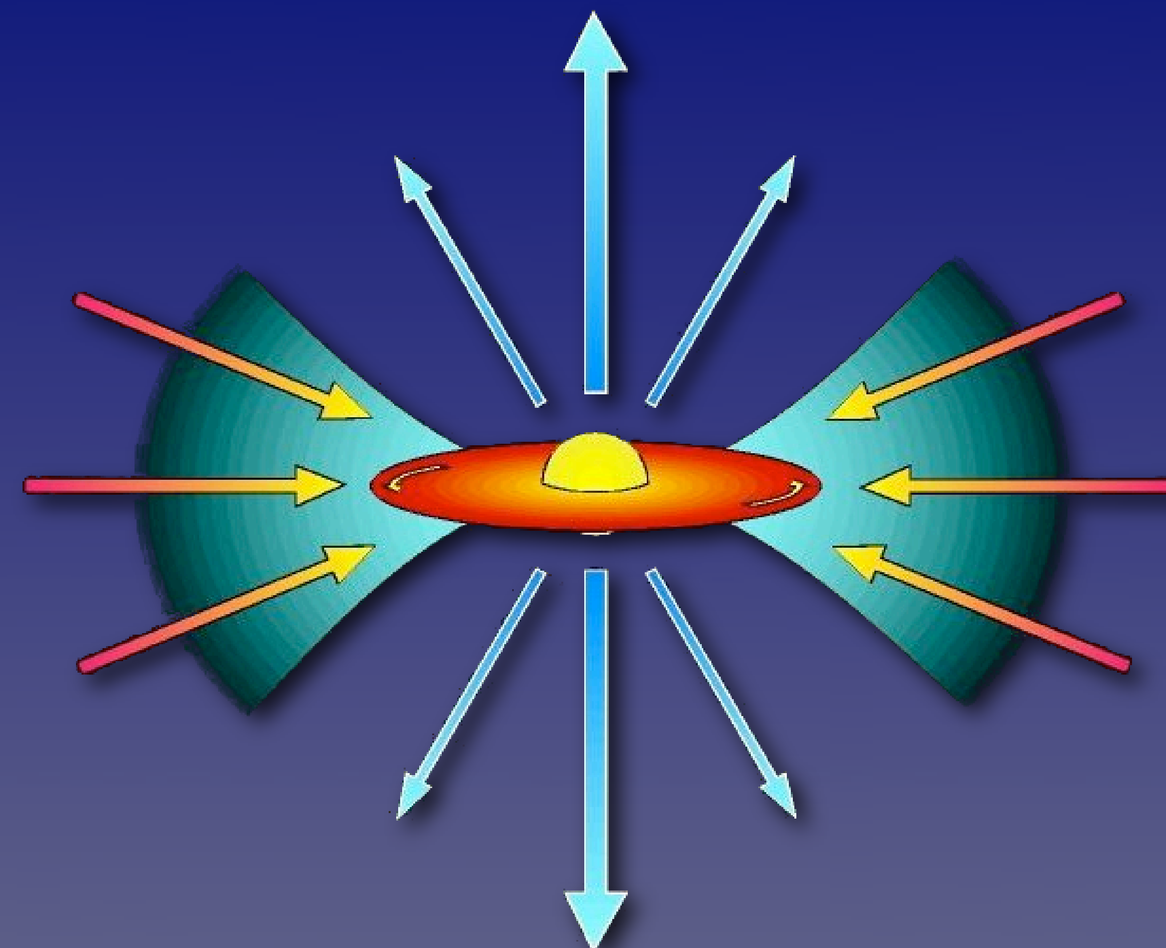
NORTHROP GRUMMAN
Space Technology

NASA esa CSA ASC

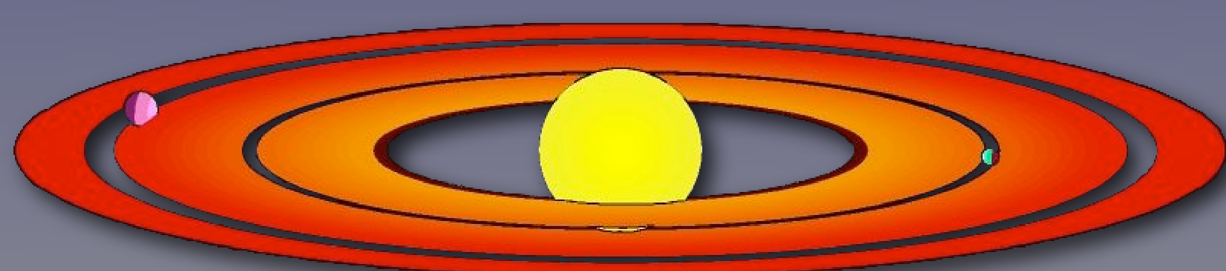
From cores to disks to planets



Class 0:
10^4 yrs; 10-10^4 AU; 10-300 K



Class I-II:
$10^{5\text{-}6}$ yrs; 1-1000 AU; 100-3000 K



Class II-III:
$10^{6\text{-}7}$ yrs; 1-100 AU; 100-5000 K

42m E-ELT diffraction-limited spatial resolution

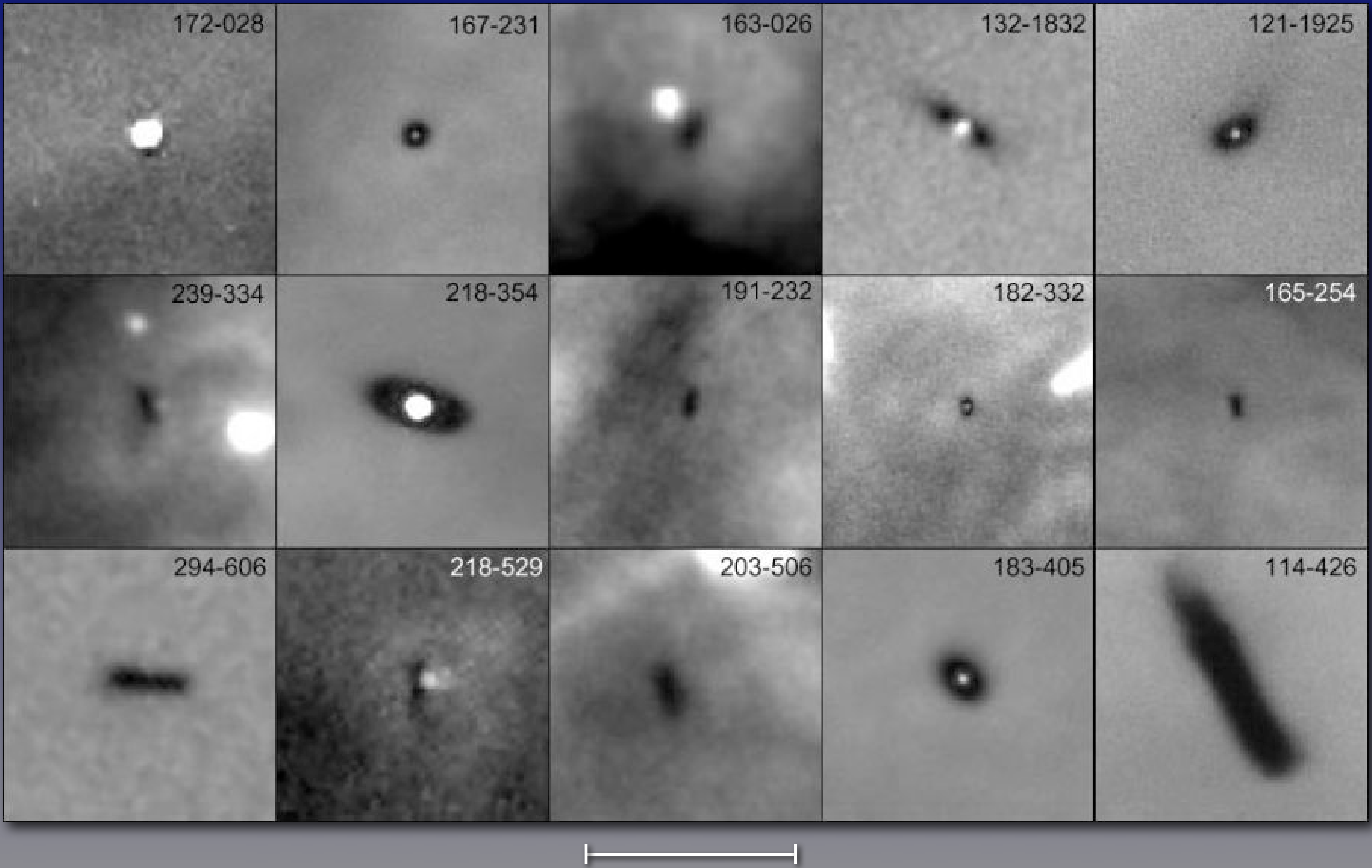
	Ang	20 pc	150 pc	500 pc
2 µm	12 mas	0.24 AU	1.8 AU	6 AU
5 µm	30 mas	0.6 AU	4.5 AU	15 AU
10 µm	60 mas	1.2 AU	9 AU	30 AU
20 µm	120 mas	2.4 AU	18 AU	60 AU

McCaughrean

Evolution of planetary systems in Orion

Orion 114-426 edge-on silhouette disk

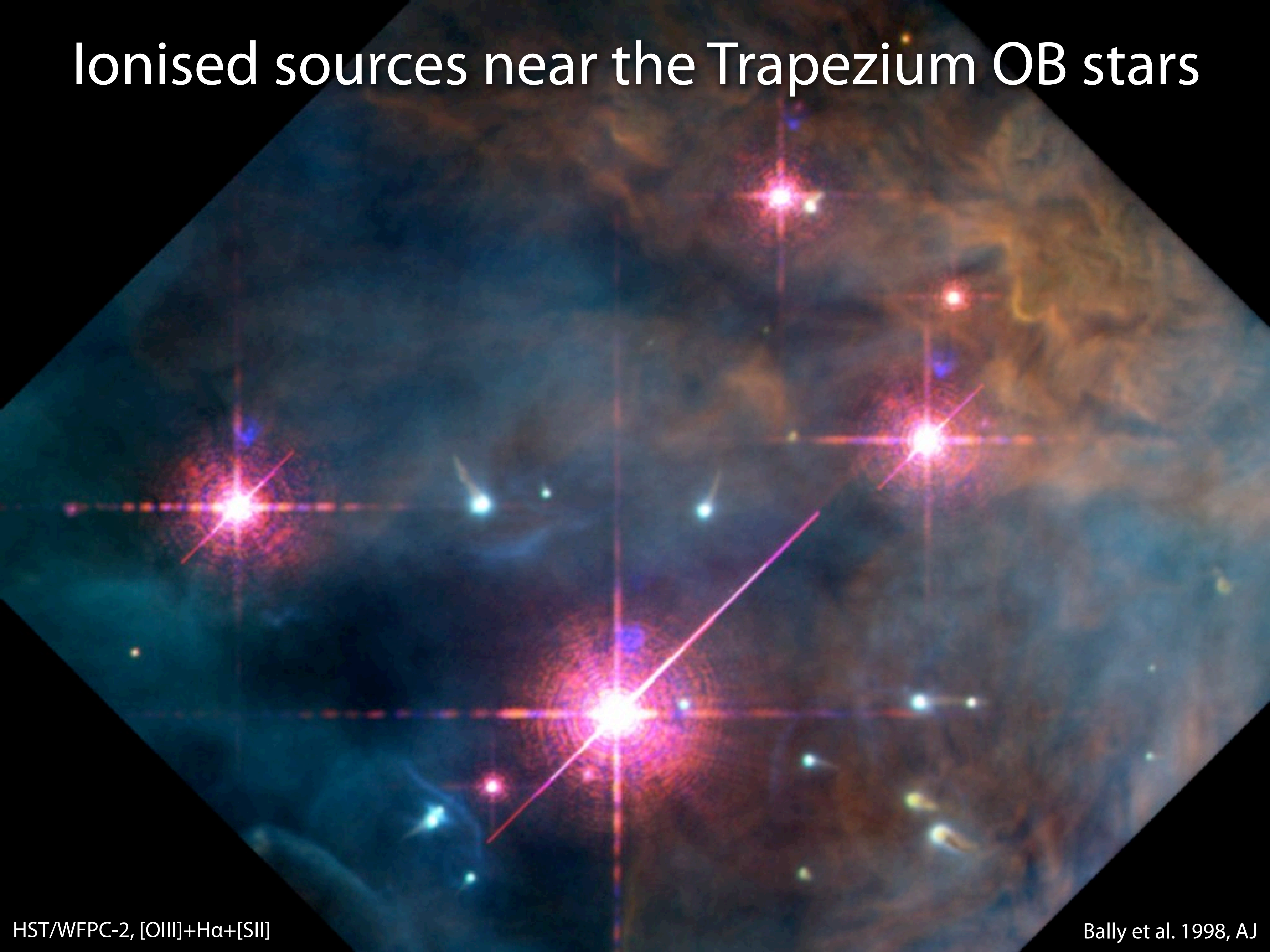
Pure silhouette disks in Orion



Orion silhouette disks: HST WFPC-2

Bally, O'Dell, & McCaughrean AJ (2000)

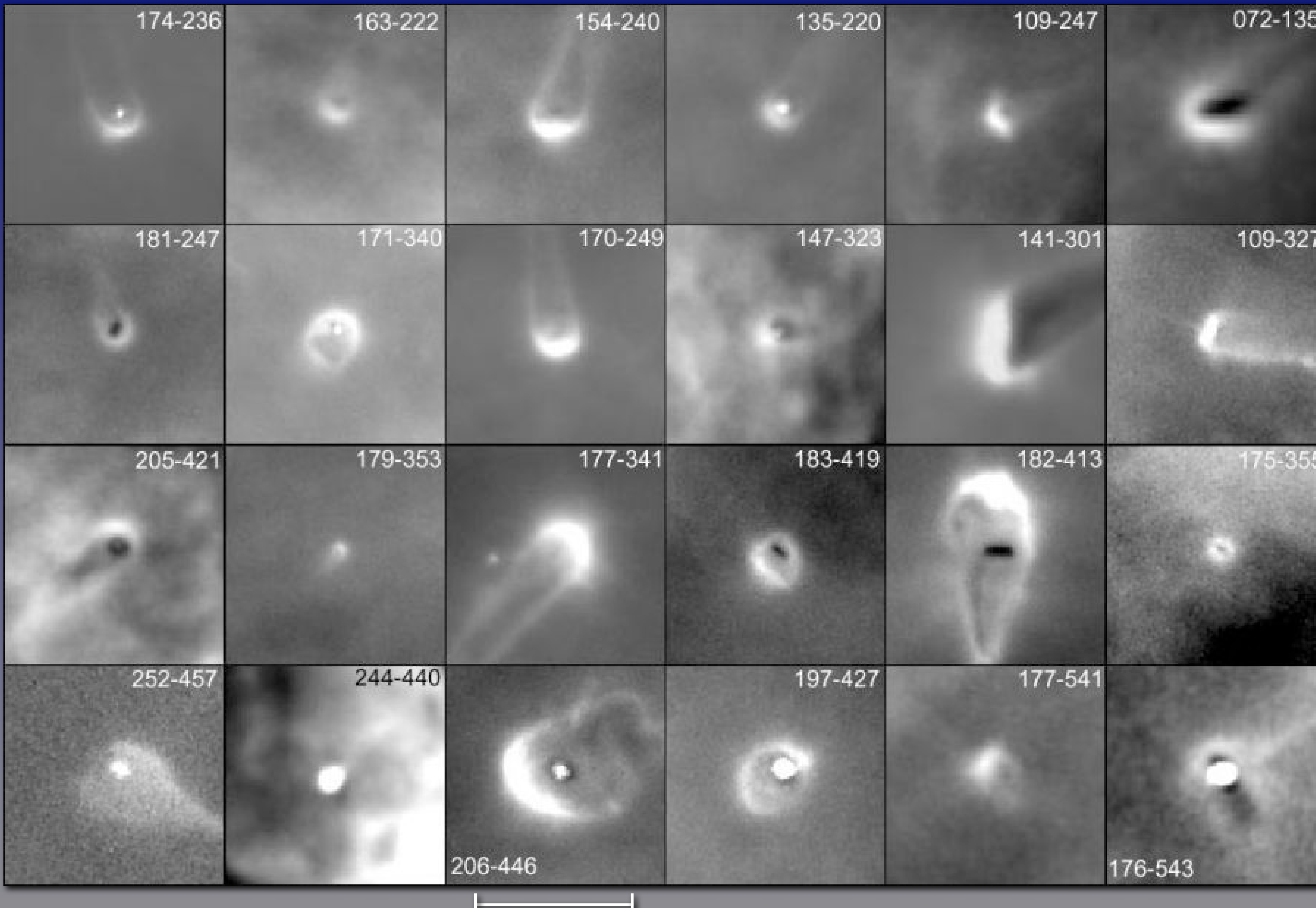
Ionised sources near the Trapezium OB stars



HST/WFPC-2, [OIII]+Hα+[SII]

Bally et al. 1998, AJ

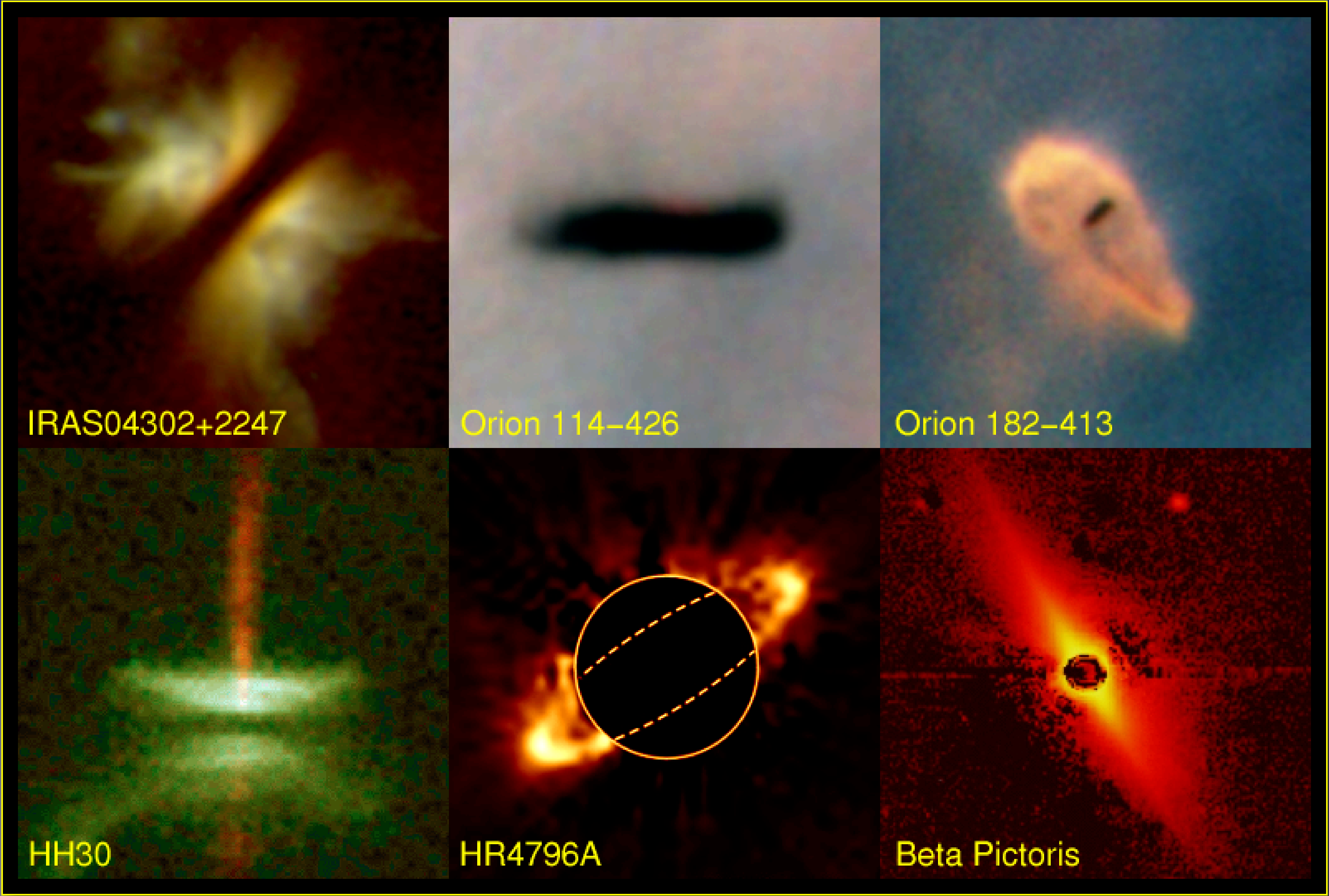
Ionised silhouette disks in Orion



Orion ionised disks: HST WFPC-2

Bally, O'Dell, & McCaughrean AJ (2000)

Transition from disks to planetary systems



McCaughrean, Stapelfeldt, & Close PPIV, 2000

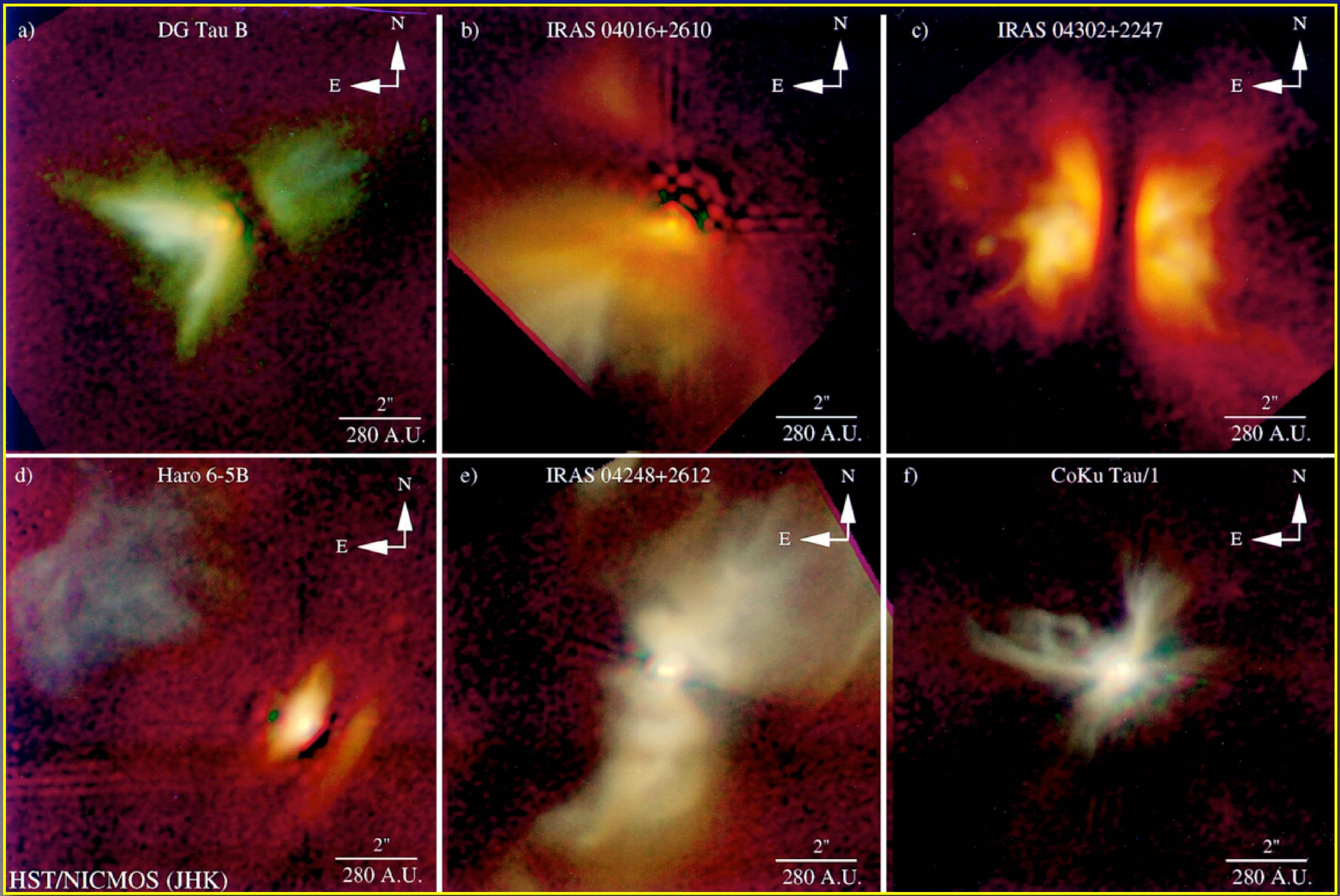
The formation of planetary systems

- A complex business
  - Wide wavelength range: X-ray to millimetre
  - Large range of spatial scales: 0.05-1000 AU
  - Physical, astrochemical, and dynamical processes at work
- How is the material assembled?
  - Dust agglomeration, gas accretion
- What are the time scales?
  - Influence of environment on formation of high/low-mass planets
- How do planets interact with disk and each other?
  - Gap formation, orbital migration, dynamical scattering
- Can we understand observed planetary systems?
  - Make predictions of mass, orbital radius, eccentricity distributions

Two core science cases for the DRM

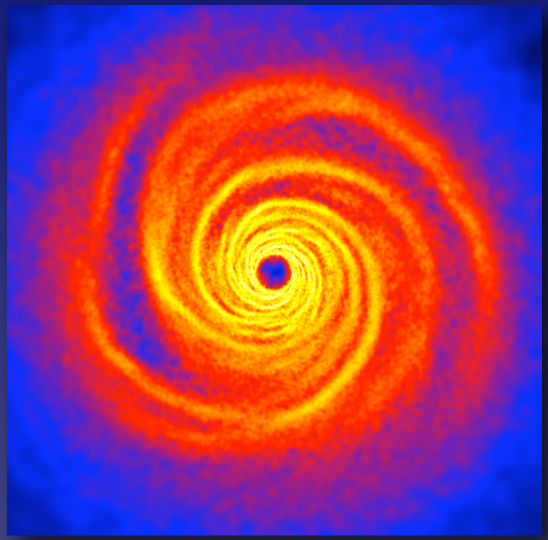
- **High spatial resolution imaging at 2-20μm**
  - Search for structures in disks indicative of ongoing or completed planet formation: gaps, rings, spiral density waves
  - Young, optically-thick disks in star forming regions
  - Older, optically-thin dust debris disks in solar neighbourhood
  - Diffraction-limited broad/medium/narrow-band imaging
  - Single object, small FOV
- **Spectroscopy of gas and dust at 2-20μm**
  - Tracing dynamics and physical/astrochemical evolution
  - Watching the transition to protoplanets at 1-100 Myr
  - R=300, 3000, 100 000 spectroscopy
  - High Strehl ratio useful to increase sensitivity
  - IFU spectroscopy useful to image differential structures in disk

Young disks in scattered light

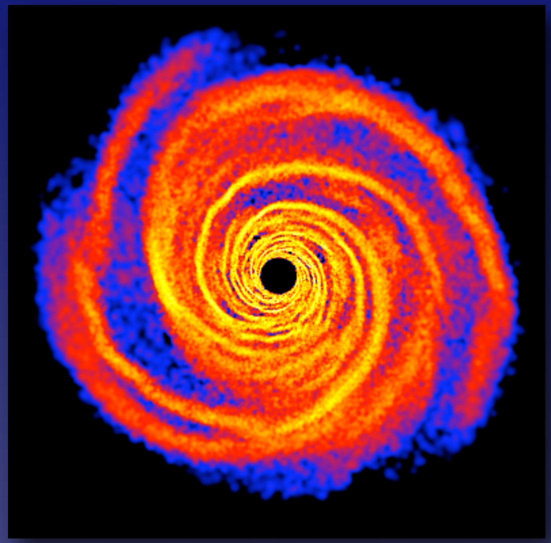


NICMOS imaging: Padgett et al. (1999)

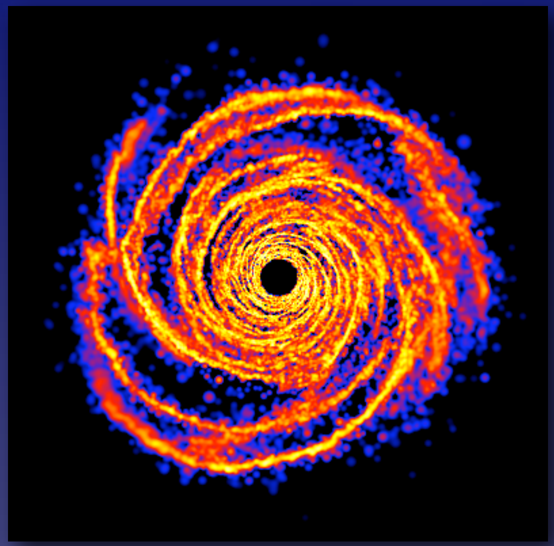
Planetesimal growth & structure formation



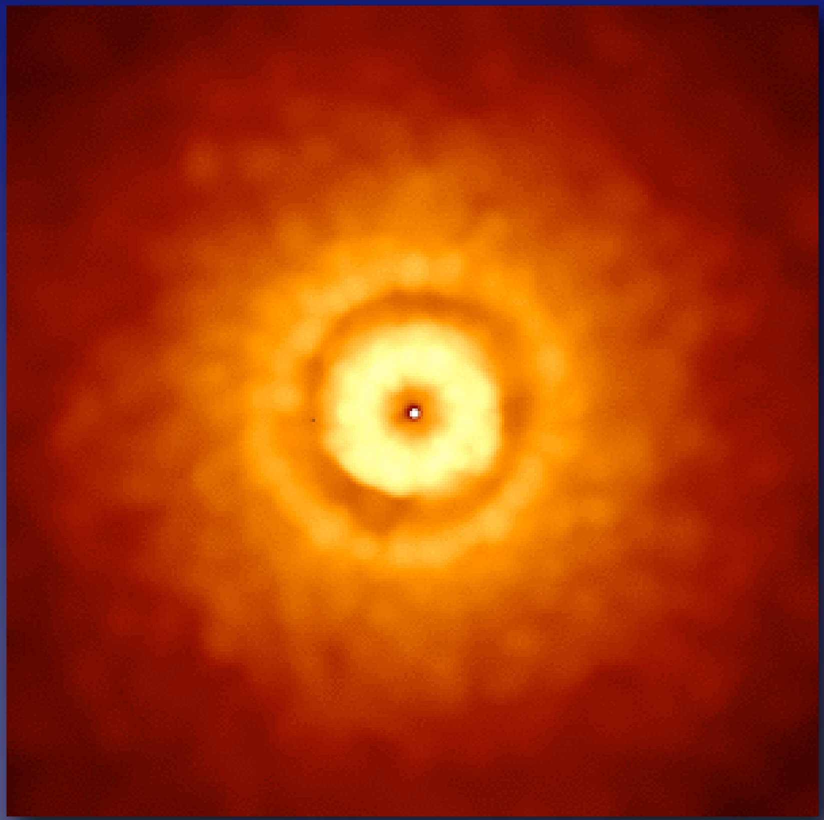
Gas density



10m particles follow gas density



50cm particles more concentrated in spiral density waves

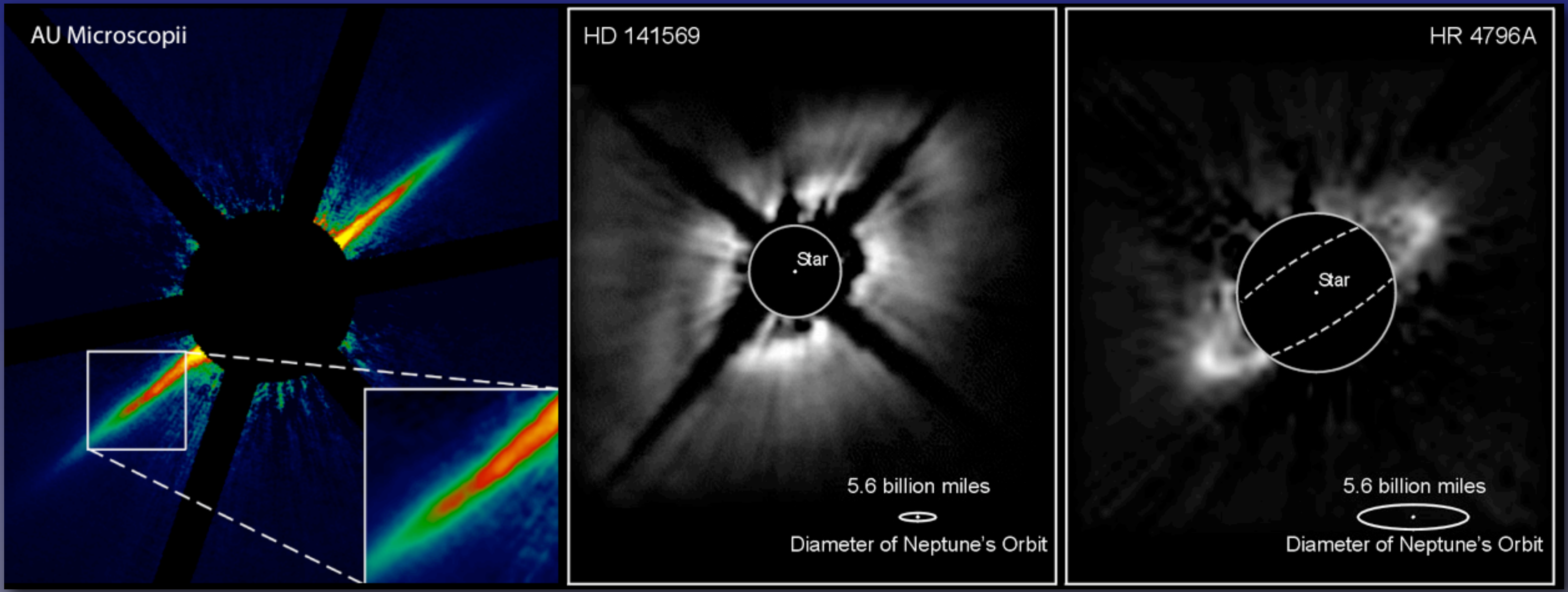


GM Aur: young disk with gap

- ★ **Dust agglomeration & processing**
  - Grain size distribution as a function of radius and time
  - Near-IR scattered/transmitted light, thermal-IR imaging/spectroscopy, all combined with ALMA
- ★ **Gaps, rings, spiral waves, warps due to planets**
  - Near-IR scattered light, thermal-IR dust in young and debris disks
  - SED decomposition → direct imaging of structures

SPH simulations Rice et al.

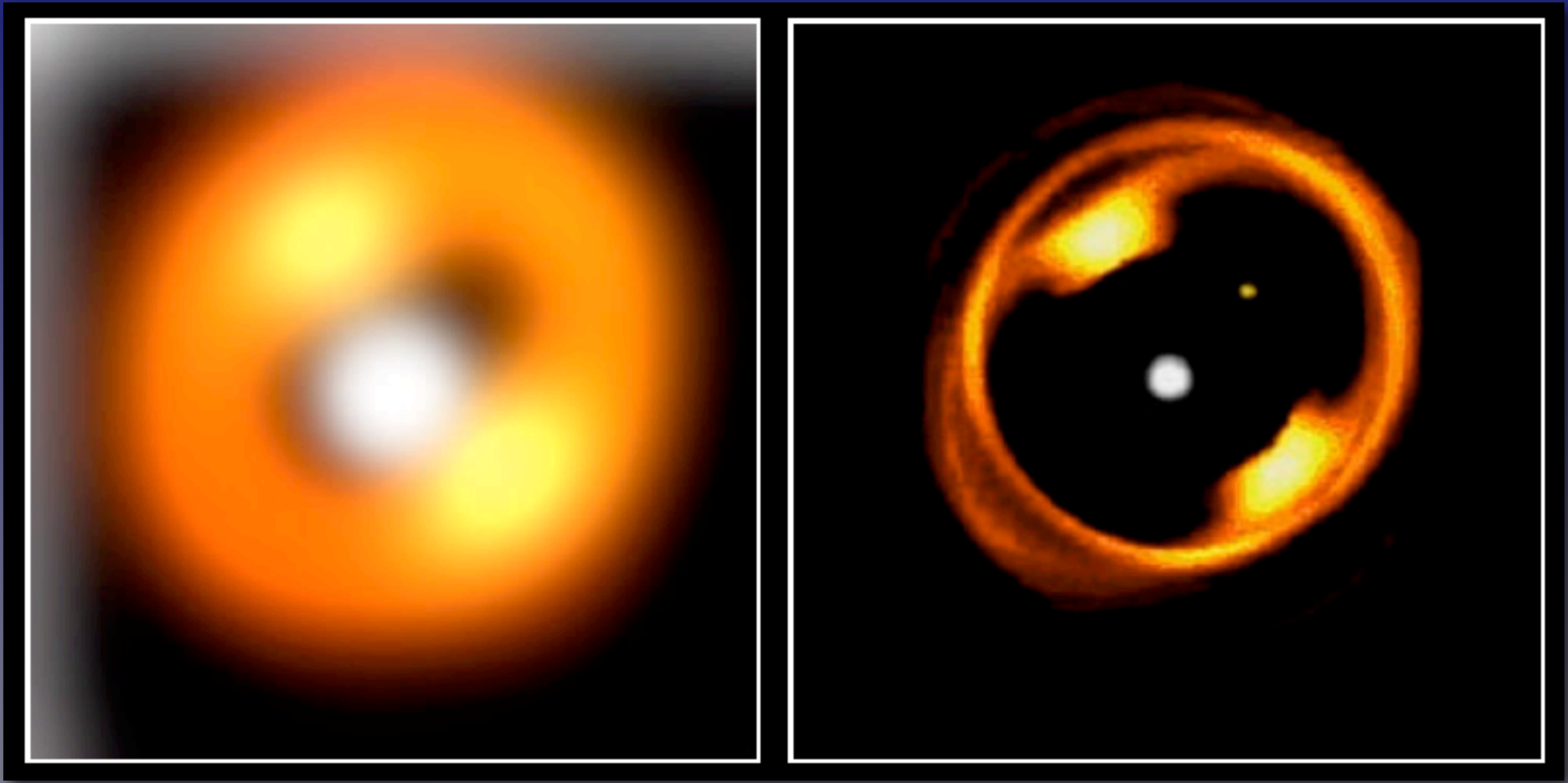
Scattered light imaging of debris disks



Keck (left) & NICMOS (centre, right) near-IR images of three nearby debris disks
(Kalas et al 2004; Weinberger et al. 1999; Schneider et al. 1999)

E-ELT versus JWST at 40 parsecs

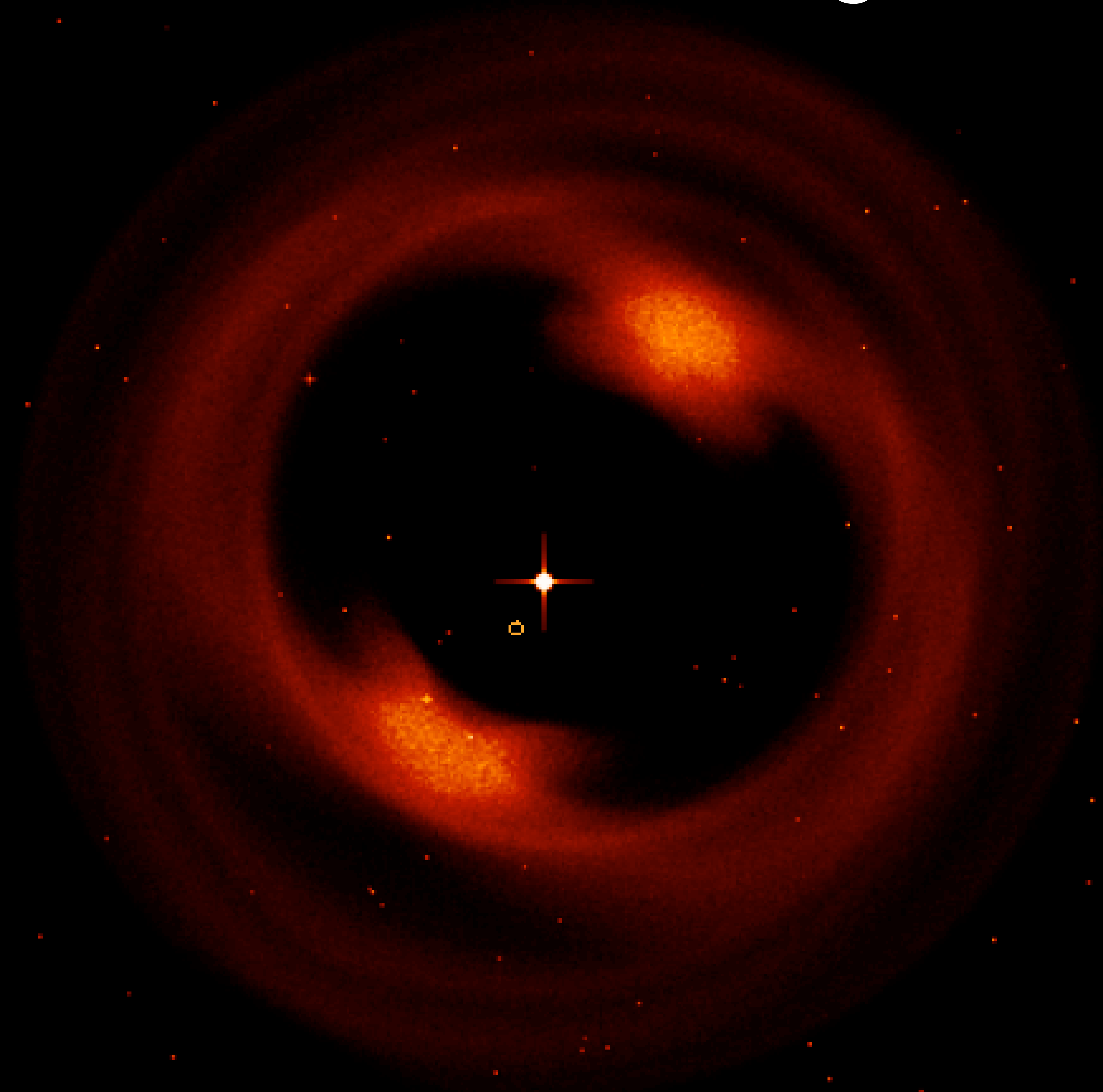
Simulation of dust density in Vega-like system (Wilner et al. 2002)



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

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

Resonant structures in the Vega debris disk



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

Animation due to Marc Kuchner

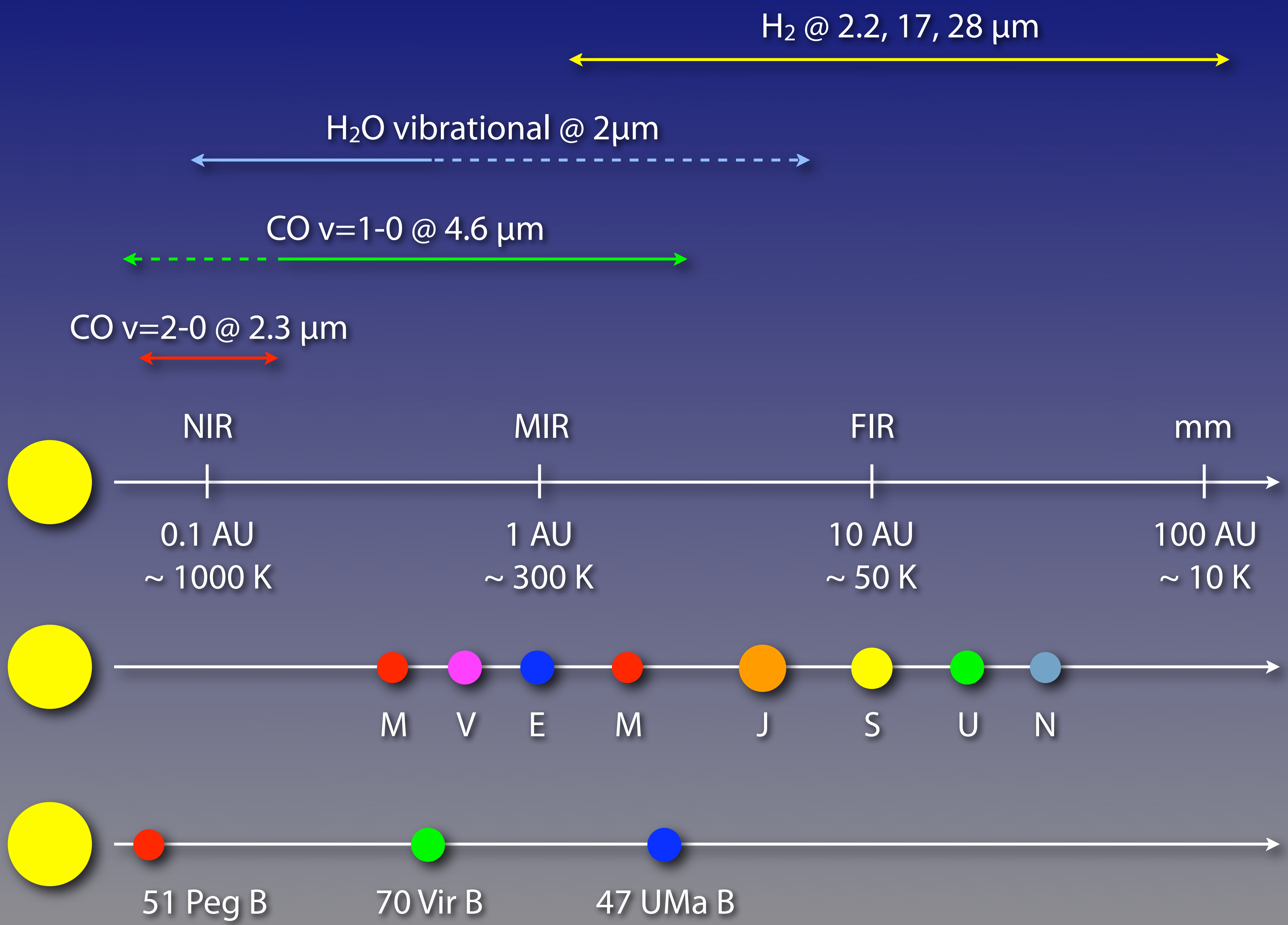
Sensitivity and sample size

- Circumstellar disks exhibit a very large range of sizes and surface brightnesses
  - Difficult to make simple estimate of exposure time
  - (Range of numbers contained in DRM proposal)
  - Typically likely to be only minutes in near-IR, ~1 hr in mid-IR
  - Crudely estimate total elapsed time of 5 hr/disk for 5 filters
- Total time required dominated by sample size
  - 10s of known resolved nearby debris disks
  - Likely 100s with known IR excess resolvable with E-ELT
  - 100s of resolved disks in nearby star-forming regions
- Take 40 debris disks, 60 young disks
  - Probe range of ages, stellar masses, environments
  - Total elapsed time ~500 hr / 50 nights

Gas in the inner disk

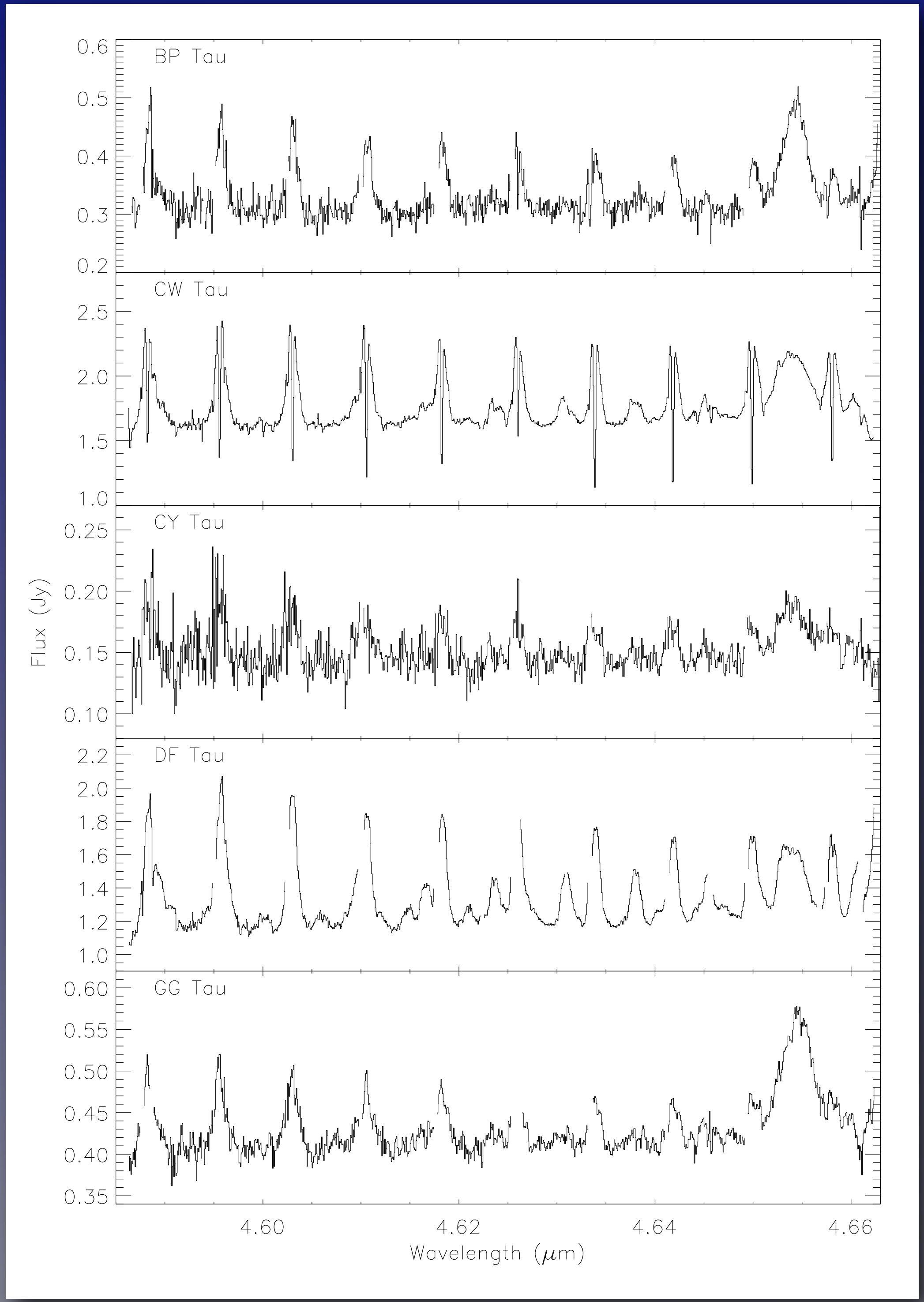
- Planet-forming region is inner 10 AU
  - Barely resolve with E-ELT at 150pc at 5μm: 4.5 AU diff. limit
- Use high resolution spectroscopy of gas to velocity resolve structures in inner disk
  - R = 100 000 yields 3 km s^{-1} cf. 30 km s^{-1} of Earth at 1 AU
- Different probes useful at different radii
  - CO v=2-0 overtone band at 2.3μm: denser, warmer gas
  - CO v=1-0 fundamental band at 4.6μm: lower density, cooler; best probe of terrestrial planet forming region
  - H_2 (2, 17, 28μm) and H_2O (2, 10, 20μm) also abundant: many transitions to probe density, temperature in disk: use to trace mass of gas in disk as a function of stellar mass, age, environment

Gas diagnostics in protoplanetary disks

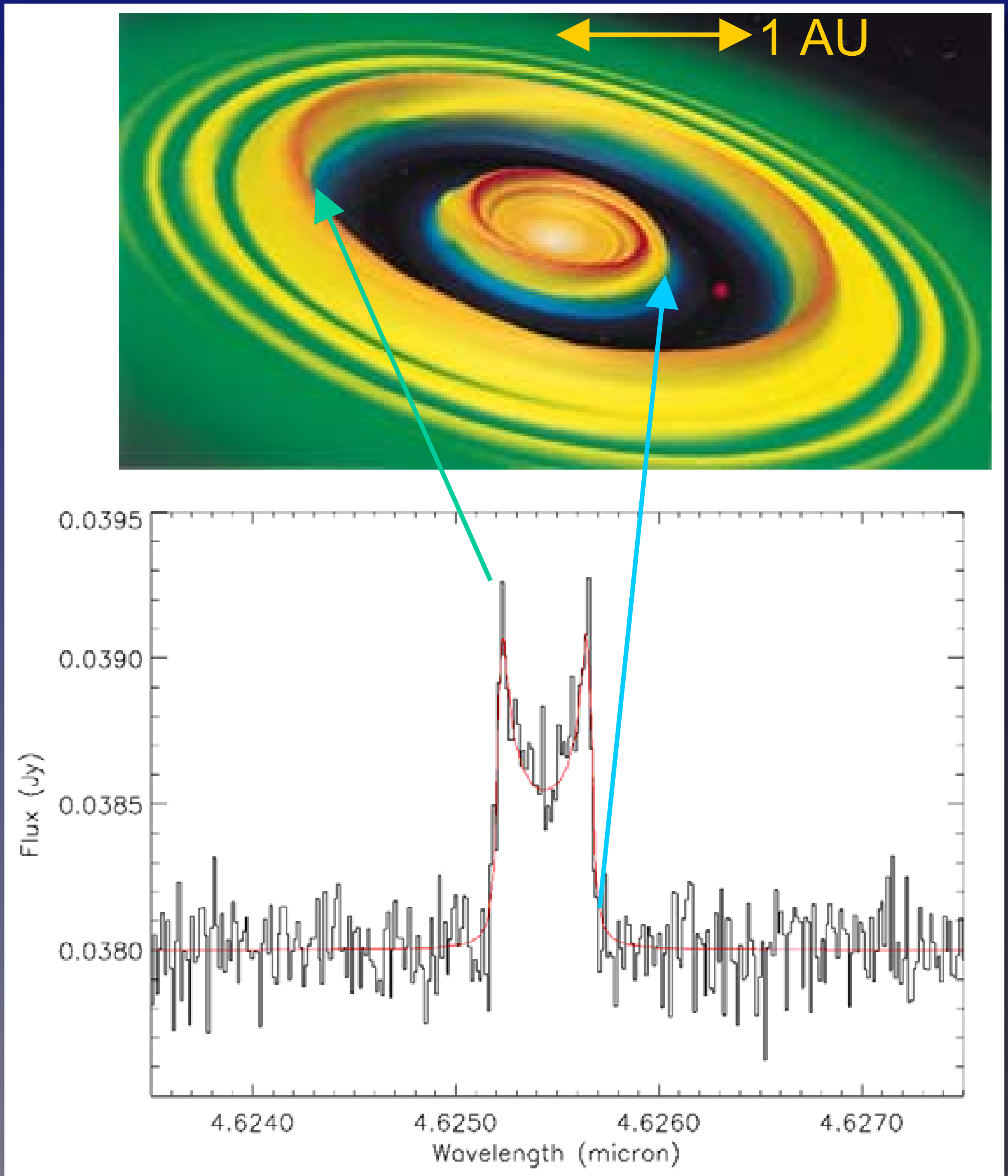


After Najita

CO fundamental spectroscopy at 4.6μm



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

Sensitivity and sample size

- Crude scaling from GSMT calculations (Najita et al.)
- CO v=1-0 4.6μm to detect planet gaps in young disks
  - Classical T Tauri star at 450 pc (Orion)
  - 0.3 AU gap opened at 1 AU by 1 Jupiter mass planet
  - S/N = 300 achieved in <10 minutes with 42m E-ELT
  - Including set-up, overheads, calibration, assume 30 min/source
  - Assume only 5-10% of sources form Jupiters
  - Thus need ~1000 sources (hence Orion) in order to yield 50-100
  - Total elapsed time then ~500 hr / 50 nights
- H_2O in disks at 10 & 20μm to gauge gas mass in disks
  - S/N~20 at both wavelengths takes ~1 night/source elapsed
  - 30 sources/cluster, 5 clusters for evolution vs time, environment
  - Thus total of ~150 nights required here

Summary: key drivers for the E-ELT

- Telescope size important but not fundamental (!)
  - Information content ∝ D or perhaps D^2 but key is > 5x JWST
- Site considerations ironically perhaps not crucial
  - JWST will be more sensitive in any case
- High spatial resolution at 2-20μm
  - Diffraction-limited imaging over 5-10 arcsec FOV
  - 6 mas/pixel at 2μm yields detector size of ~2k x 2k
  - High Strehl ratio important to maximise image "fidelity"
- Low, medium, high spectral resolution at 2-20μm
  - Resolutions 300 & 3000 at 2-20μm, 100 000 at 5μm
  - Single object: either slit or IFU (5 arcsec FOV?)
- Total time requirements:
  - Imaging: 50 nights; spectroscopy: 50 (200) nights

Things to be done

- Need proper E-ELT ETC calculations
  - ETC presently stops at K
  - Need thermal-IR extensions for both imaging and spectroscopy
- Sources are structured, not just smoothly extended
  - Ideally need imaging spectroscopy exposure time calculations
- Need proper disk models for meaningful results
  - Ideally need radiative transfer models of realistic gas and dust density distributions from SPH and other calculations
  - Need to engage modellers (Wolf, Harries, Dominik, Pinte, Wood)