ASTROCHEMISTRY

FROM THE BIG BANG TO LIFE

Global Astrochemistry Lecture Series (GALS) 2024

ASTROCHEMICAL OBSERVATIONS: INSTRUMENTS

Rens Waters. *Radboud University and SRON Netherlands Institute for Space Research, The Netherlands*

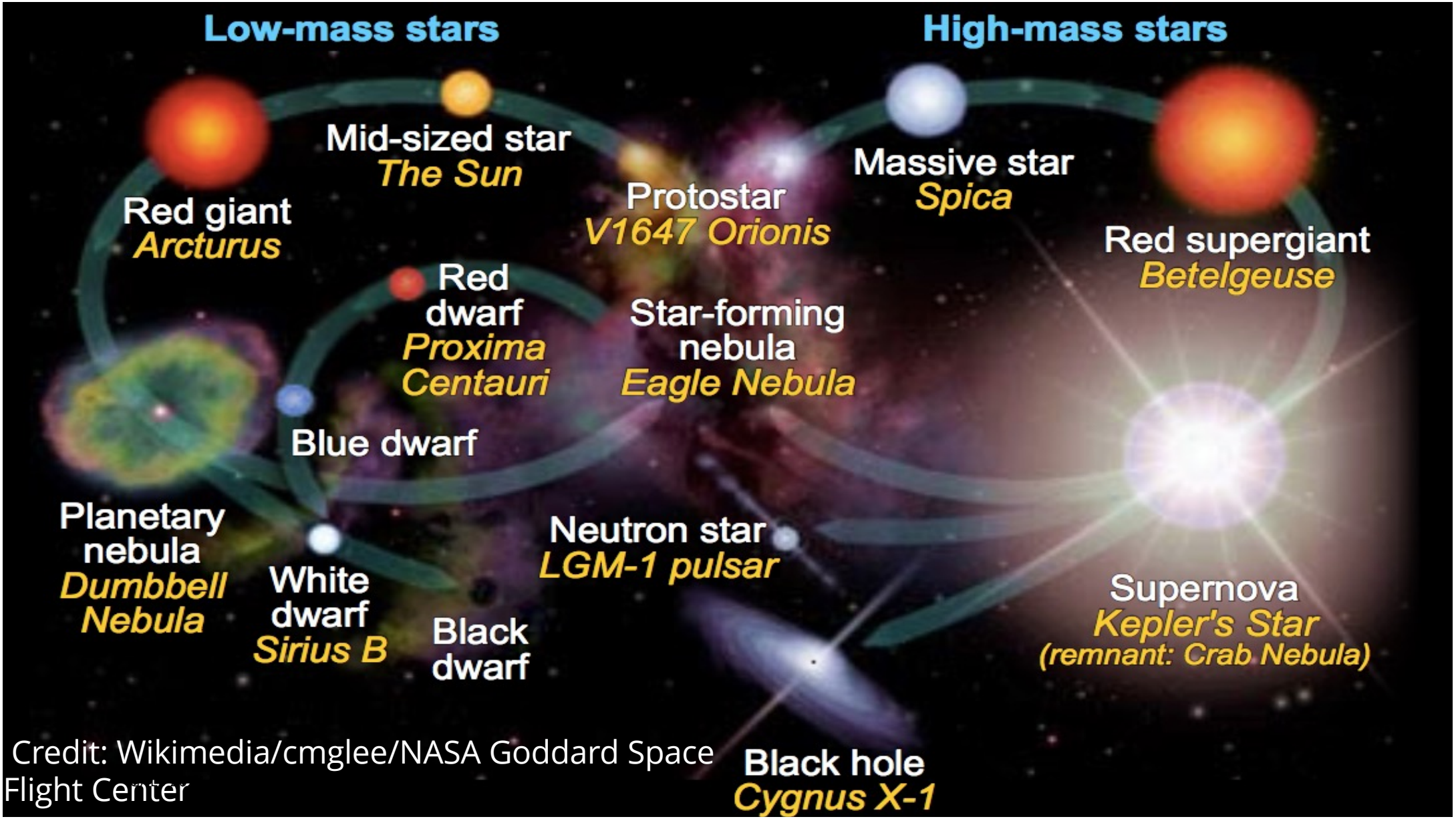
19.02.2024 | 15:00 - 17:00 CET

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY
NanoSpace
Funded by the European Union

Overview of lecture:

- **Introduction**
- Diagnostics of gas
- Telescopes: Spectroscopy
- Telescopes: Angular resolution, interferometry
- JWST
- ALMA
- solids in space (time permitting)

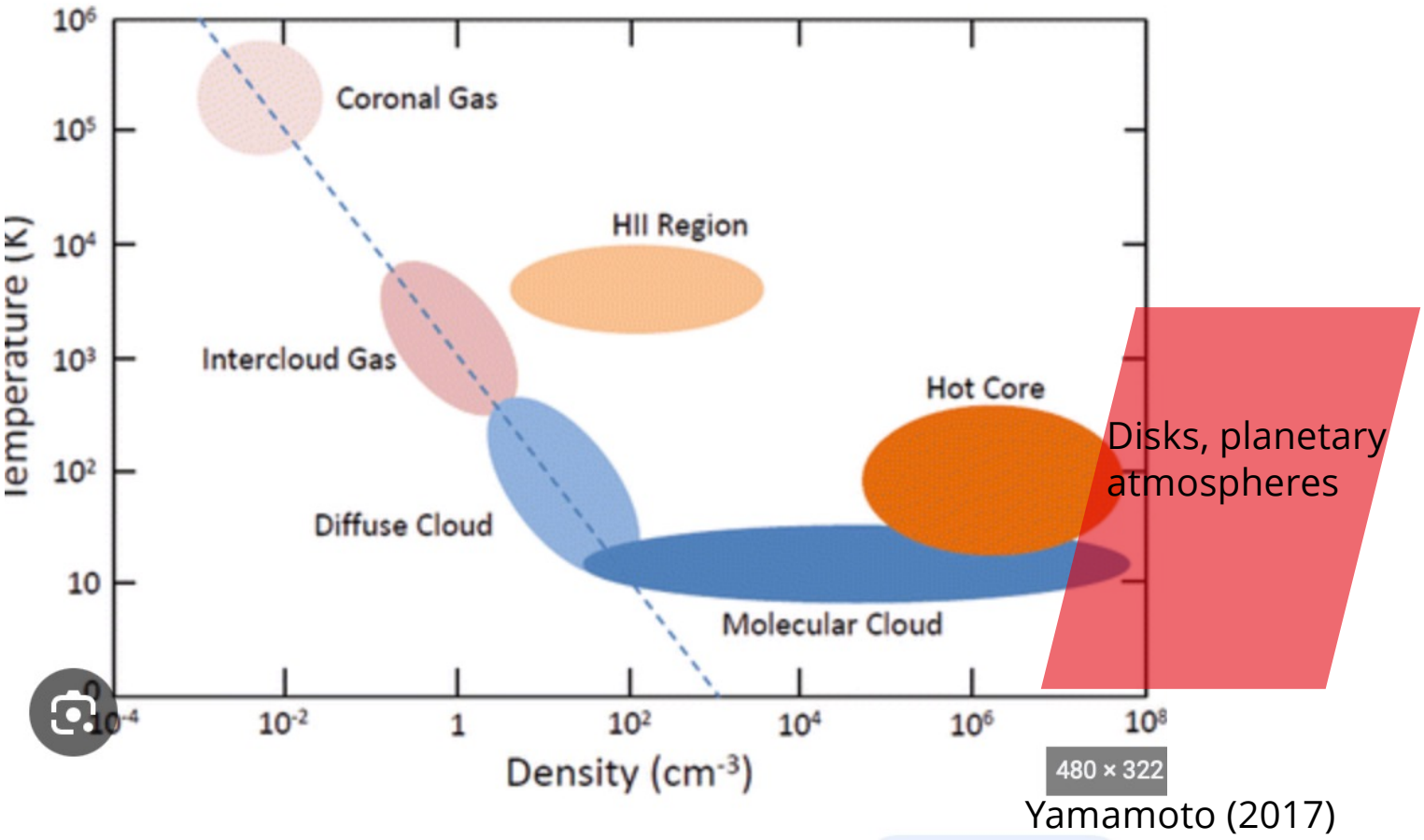
Bias: planet forming disks
Bias: JWST/MIRI



Credit: Wikimedia/cmglee/NASA Goddard Space Flight Center

THINGS WE WANT TO KNOW

- Temperature
- (column) density
- Abundance
- Spatial distribution
- Kinematics (gas lines)
- Mass and composition of solids



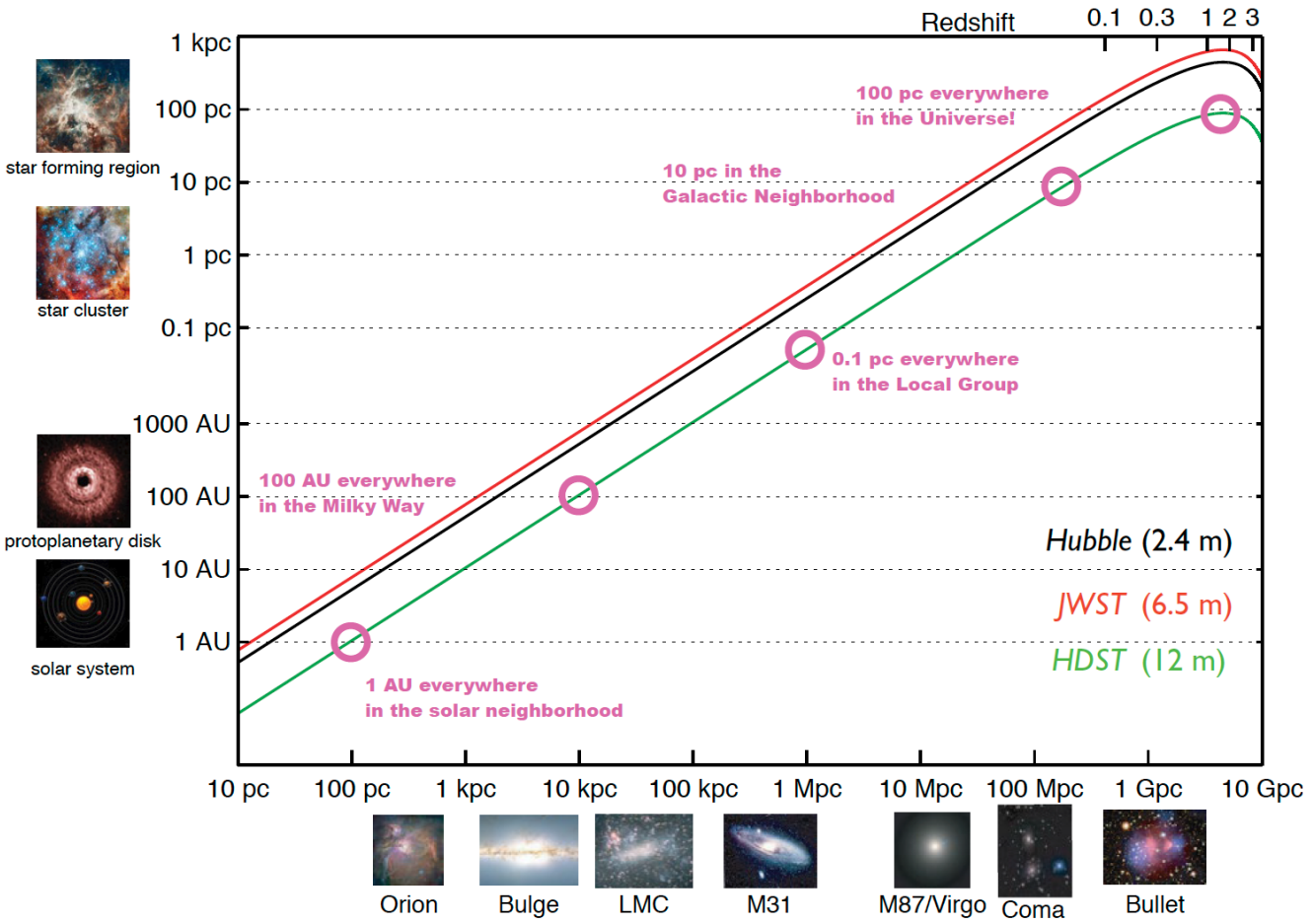
Yamamoto (2017)

We need telescopes and instruments to measure these quantities!

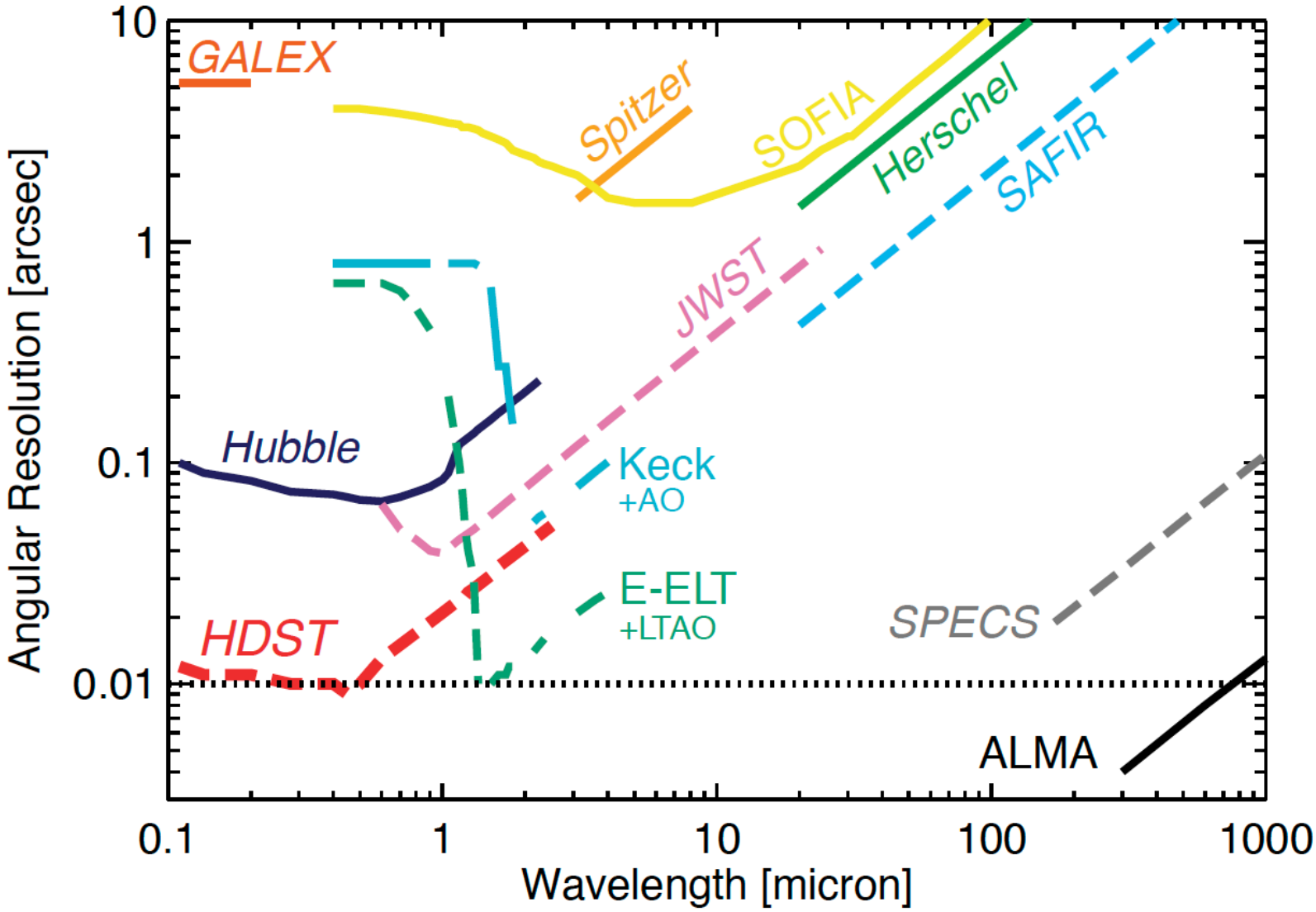


Source: J. menu (thesis)

Spatially resolving objects: bigger telescopes help



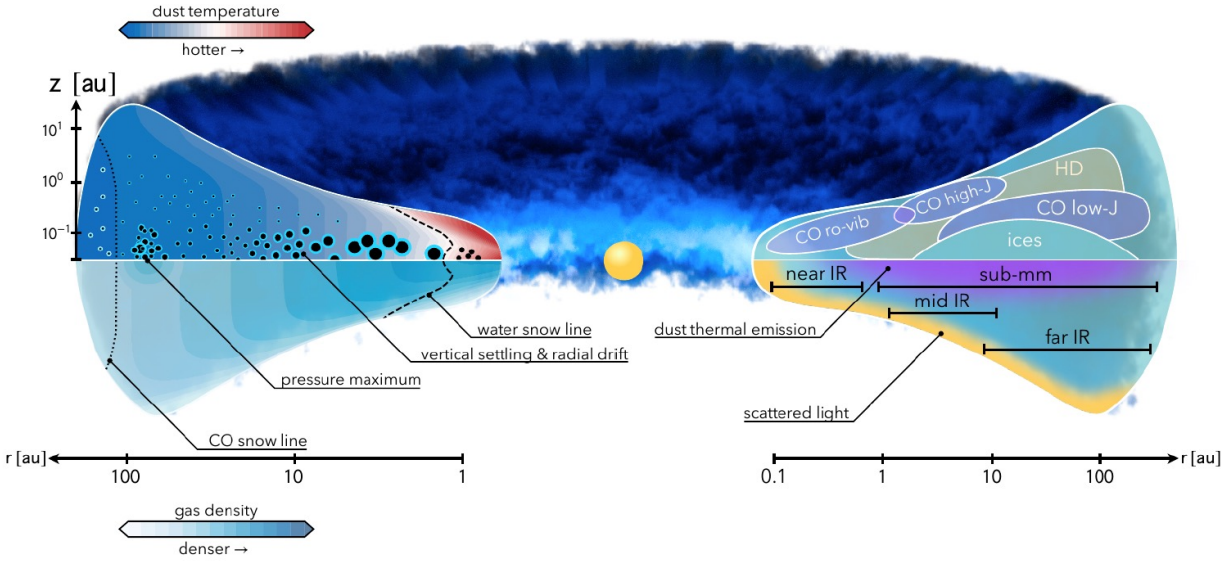
HDST study report (AURA)



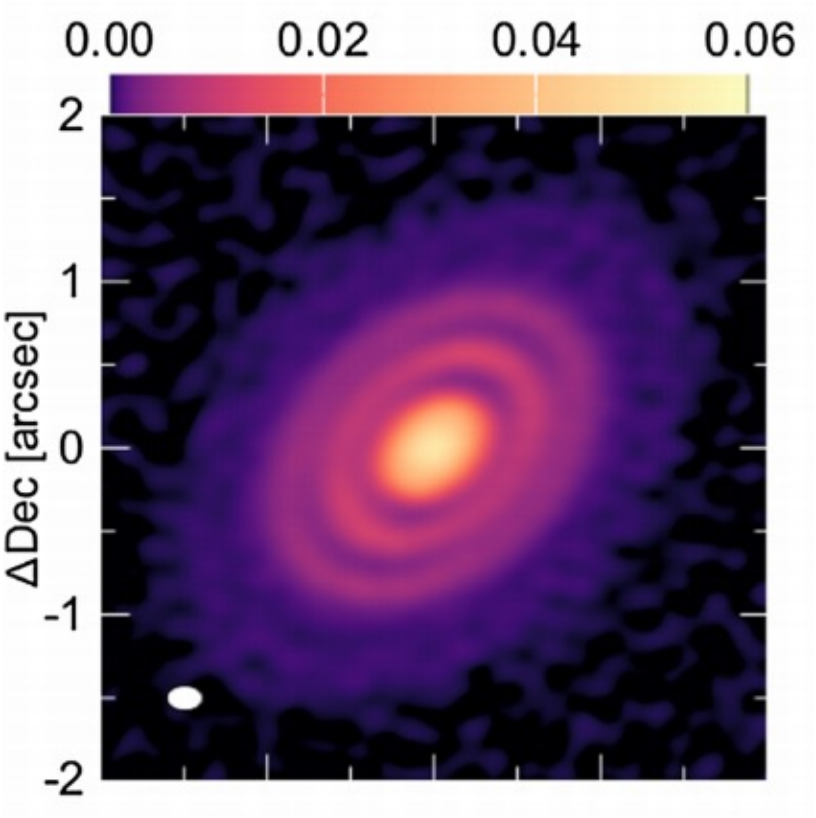
HDST study report (AURA)

SPATIALLY RESOLVING PLANET FORMING DISK

Sub-arcsec angular resolution needed



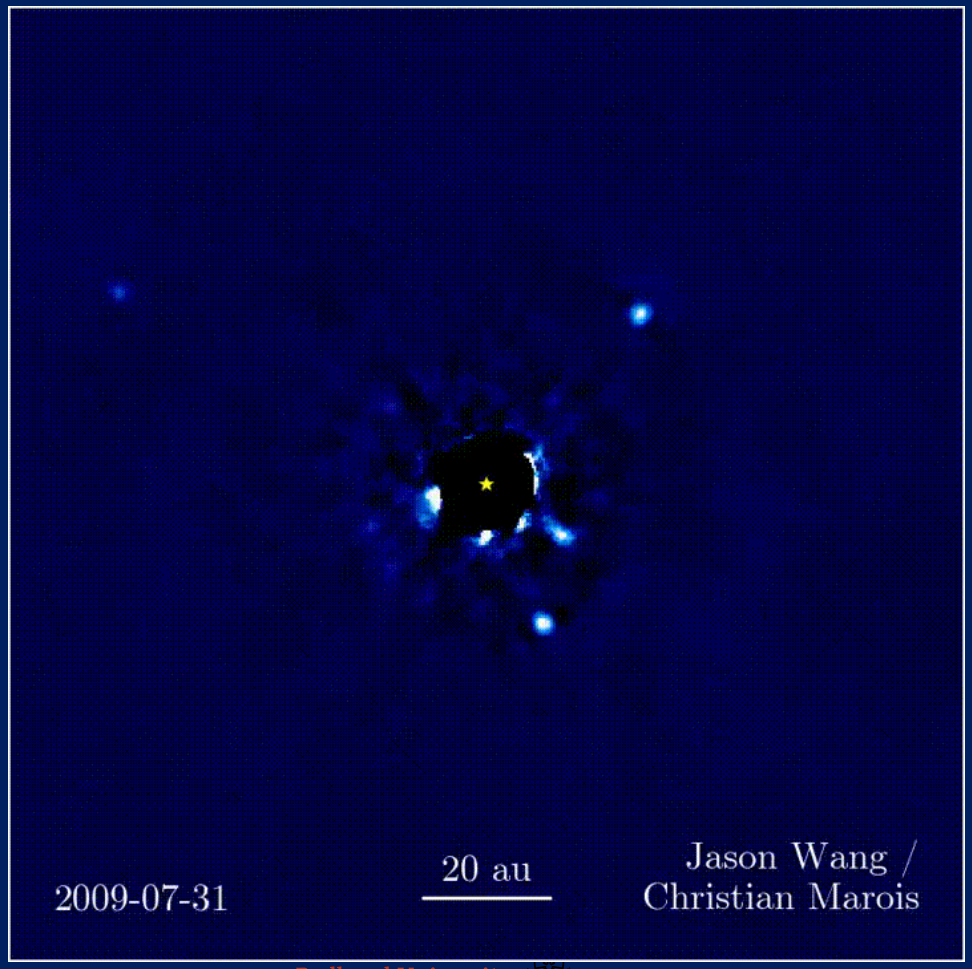
Miotello et al. (PPVII)



ALMA image Isella et al.

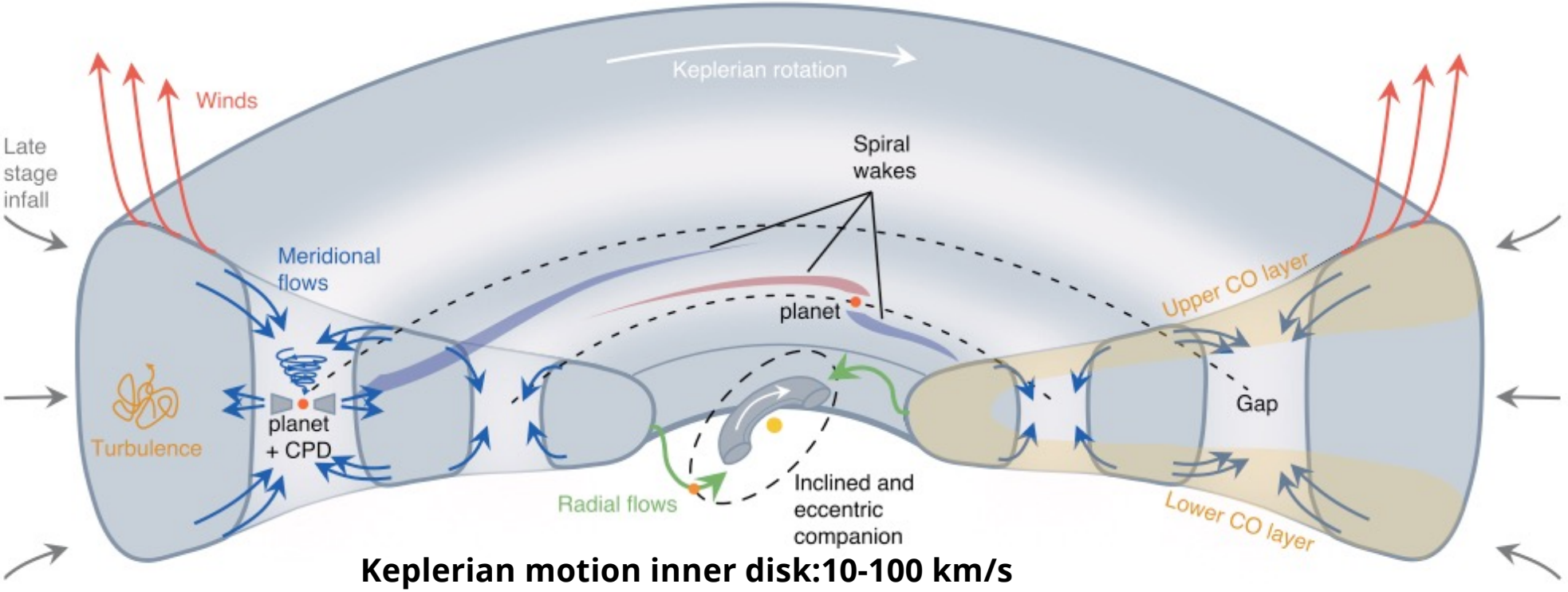
Distance 150-200 parsec

Coronographs to suppress starlight



Spectral resolution: kinematics of gas

Jets: 100-500 km/s **Outer disk, disk winds: 1-5 km/s**



Keplerian motion inner disk:10-100 km/s

Pinte et al., PP VIII

Overview of lecture:

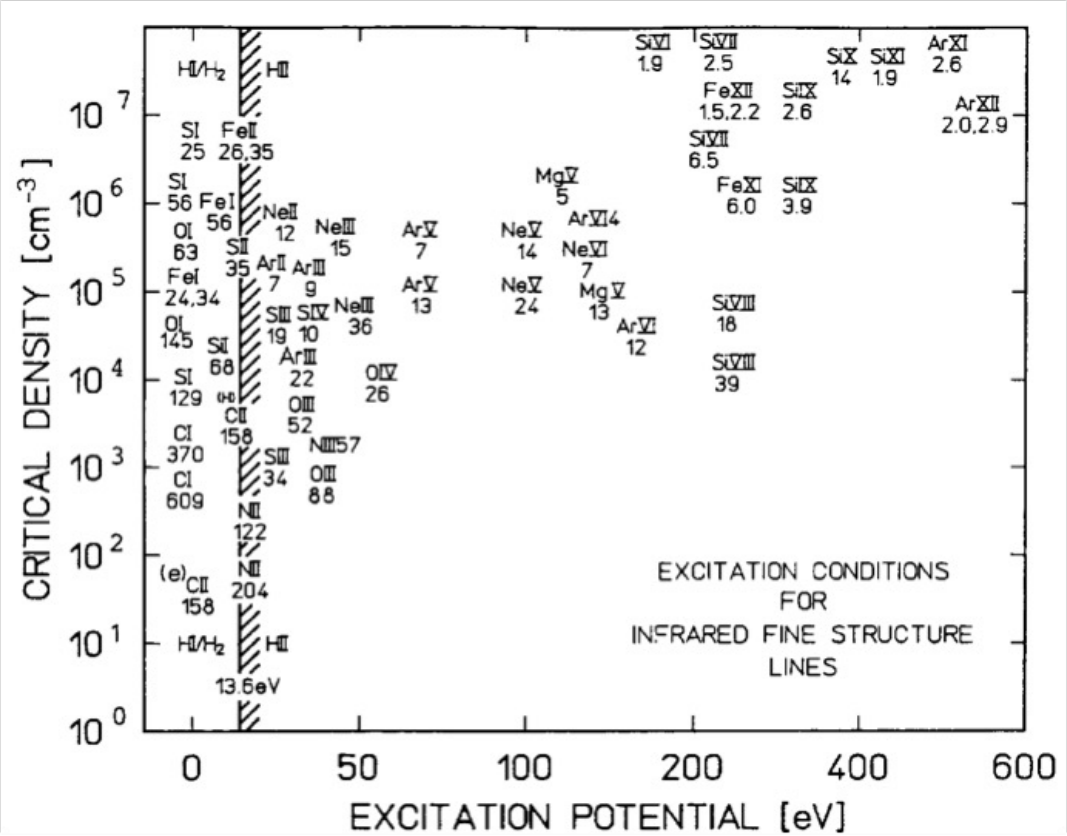
- Introduction
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- ALMA
- solids in space

PROBING ATOMIC AND ELECTRONIC, VIBRATIONAL AND ROTATIONAL MOLECULAR TRANSITIONS

- Forbidden lines: optical wavelengths
- Fine structure lines: IR spectral region
- Electronic transitions: UV or optical spectroscopy
- Vibrational bands: infrared spectral range, 1-20 μm
- Rotational lines: mid-IR to radio wavelengths

Requires different types of telescopes and receivers

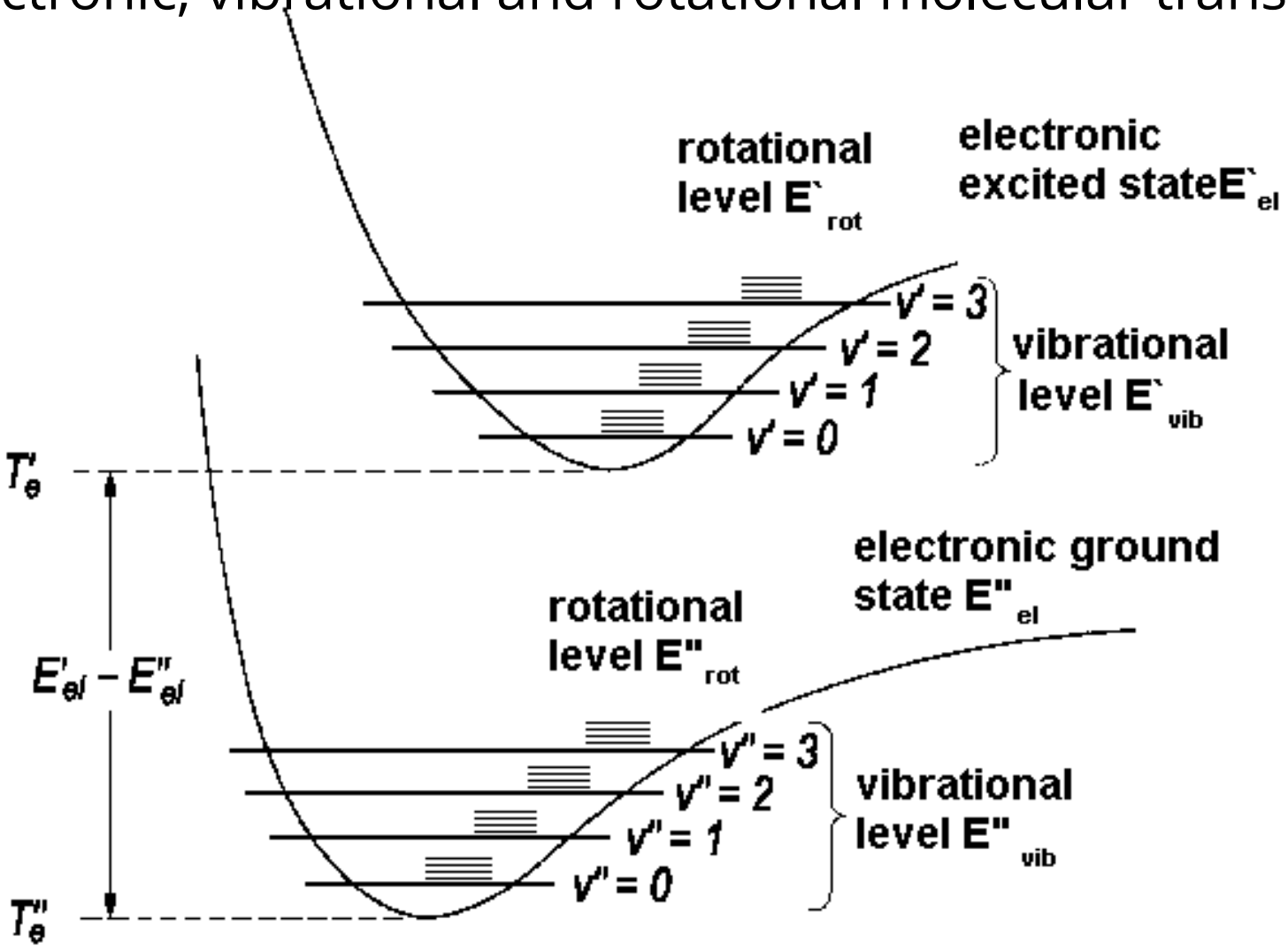
CRITICAL DENSITY OF ATOMIC/IONIC FINE STRUCTURE TRANSITIONS



$$n_{crit} = \frac{A}{q}$$

A = Einstein A coefficient
q = coll. probability

Electronic, vibrational and rotational molecular transitions



Wavelength range of important vibrational bands

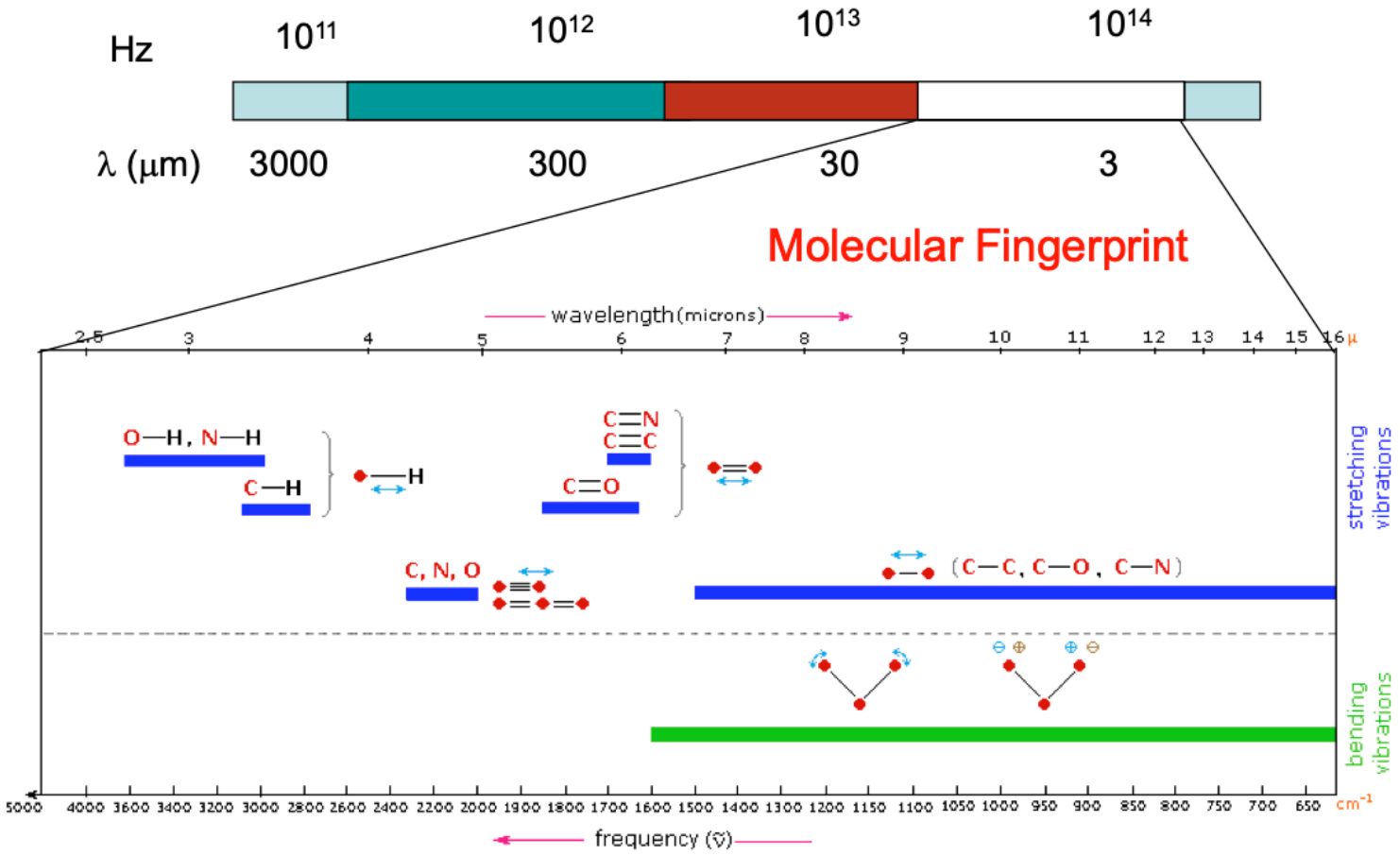
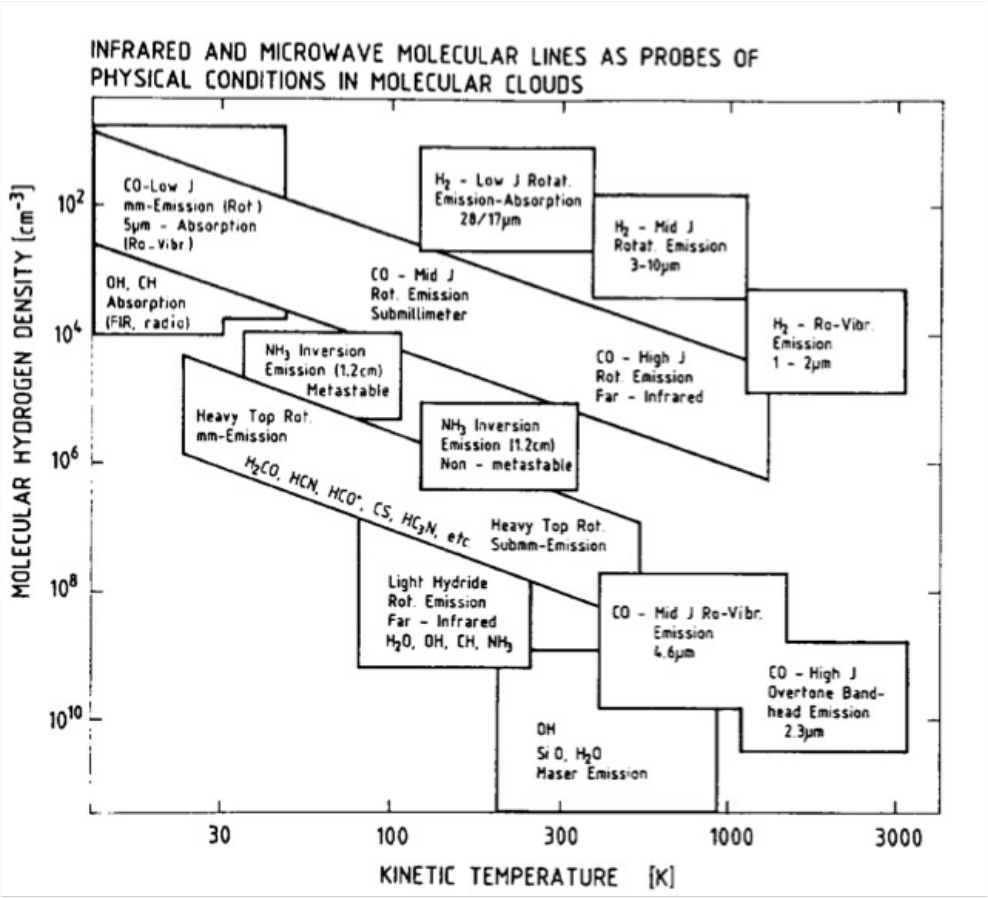


Figure: Redlich

DENSITIES AND TEMPERATURES PROBED BY MOLECULES



$$n_{crit} = \frac{A}{q}$$

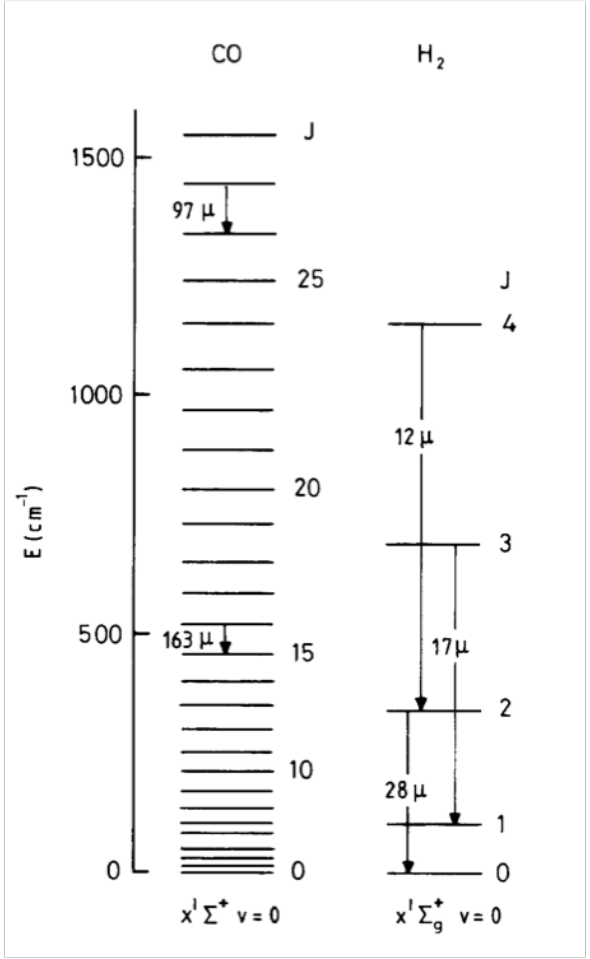
A = Einstein A coefficient
q = coll. probability

$$A \propto \mu^2 \nu^3$$

μ = electric dipole moment

Critical densities increase with frequency

- Rotational energy levels of H2 and CO
- Very different rotational constants
- H_2 lines weaker (forbidden, small Einstein A values)
- CO and H_2 probe very different temperature regimes



Ideally: high spectral and spatial resolution…

Overview of lecture:

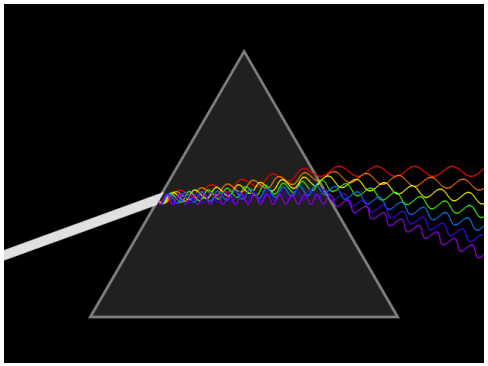
- Introduction
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SPECTRAL RESOLUTION

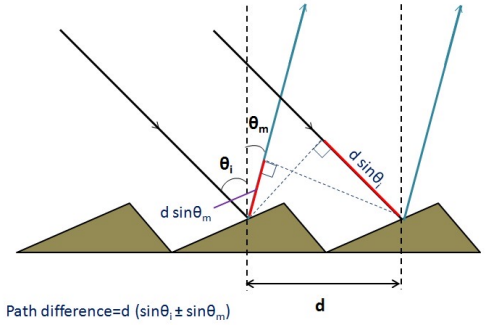
$$R = \frac{\lambda}{\Delta\lambda}$$



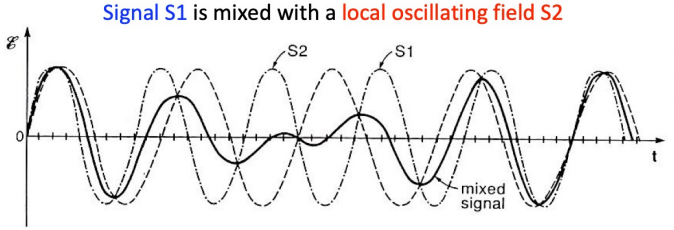
Prism
Modest spectral resolution
Wavelength dependent refractive index



Grating
Intermediate resolution
Wavelength dependent diffraction

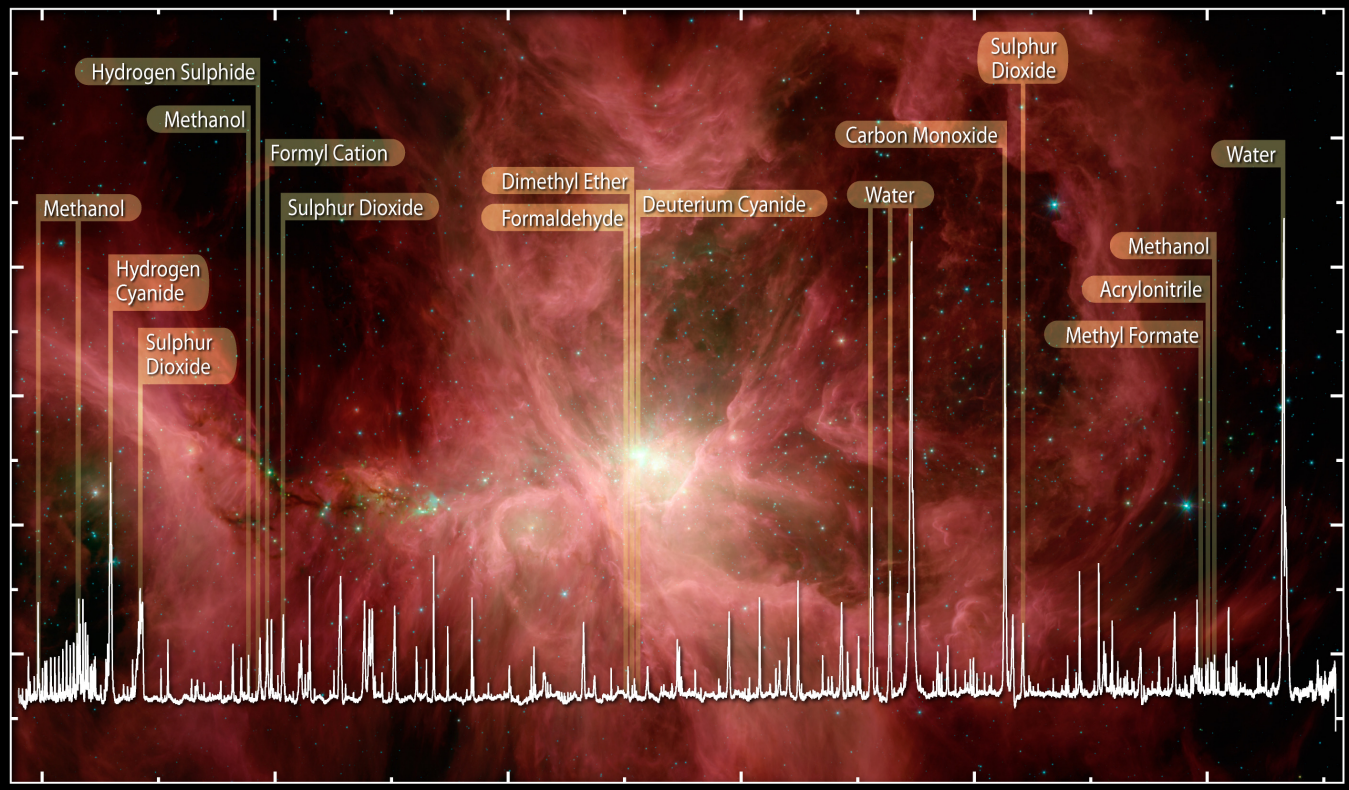


Heterodyne: very high spectral resolution
Mixing of signals



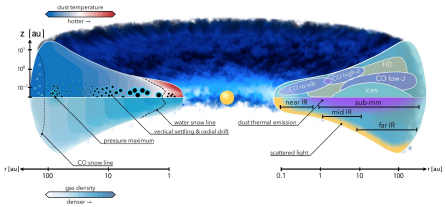
Lucas Vieira / Wikipedia/B. Brandl

HIFI/HERSCHEL: heterodyne spectrograph (single pixel)

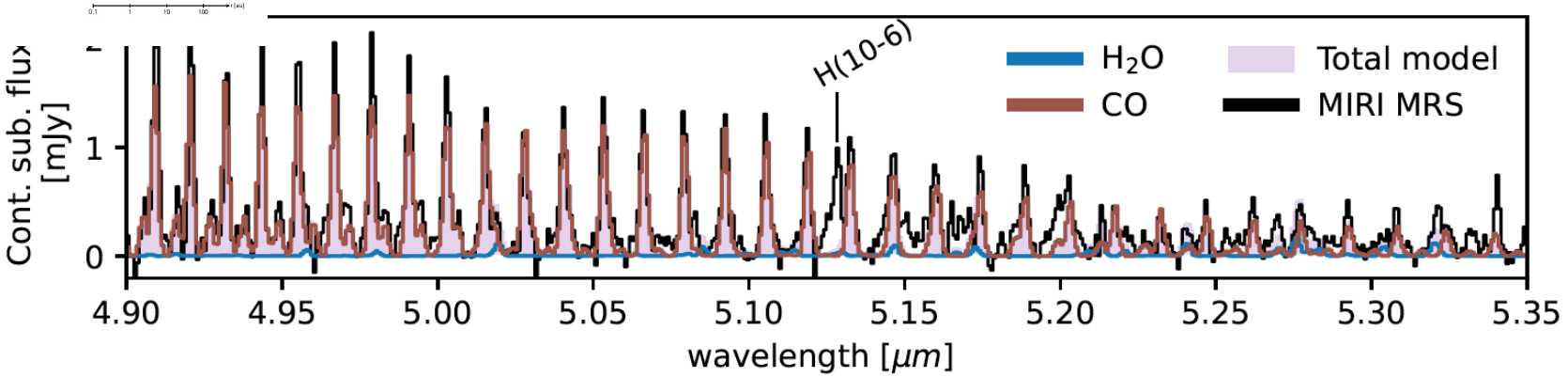


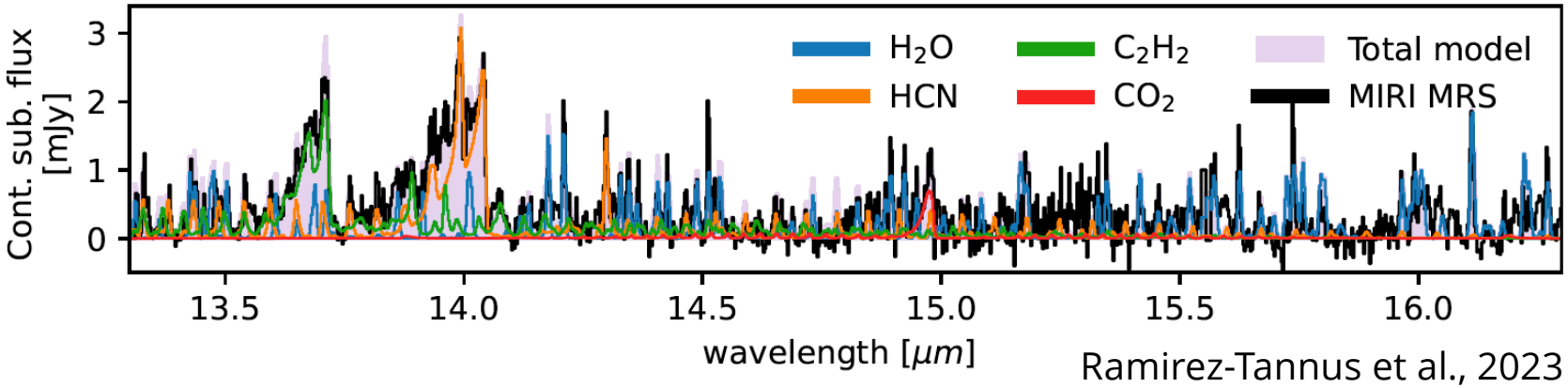
HIFI Spectrum of Water and Organics in the Orion Nebula

© ESA, HEXOS and the HIFI consortium
E. Bergin

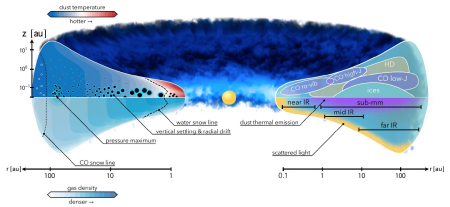


JWST MIRI: grating spectrograph





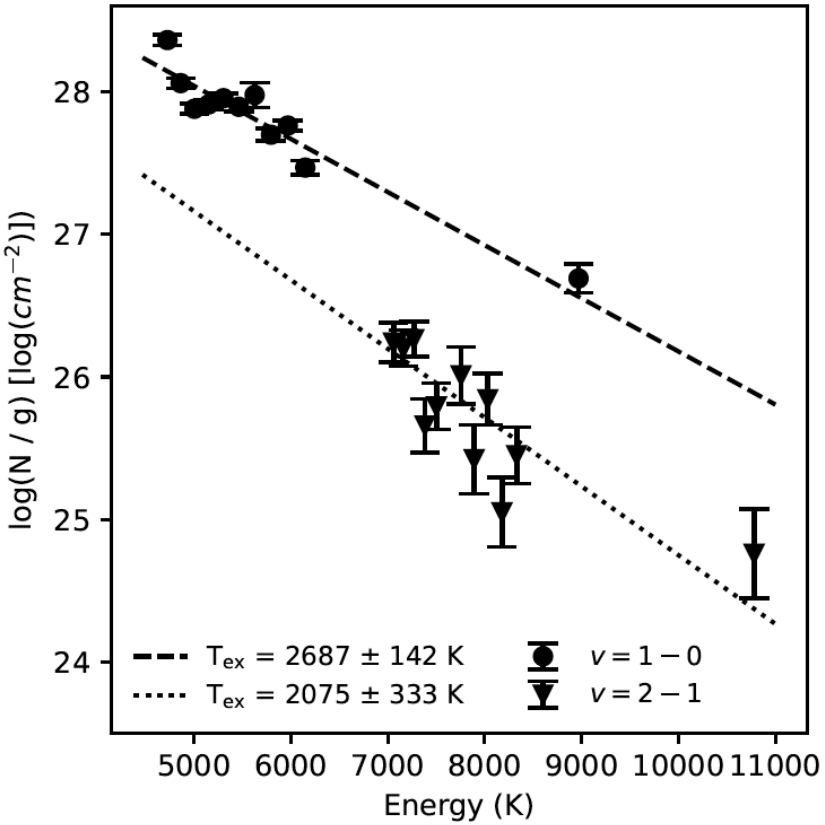
Ramirez-Tannus et al., 2023



Rotational diagram of CO ro-vibrational emission in planet forming disk

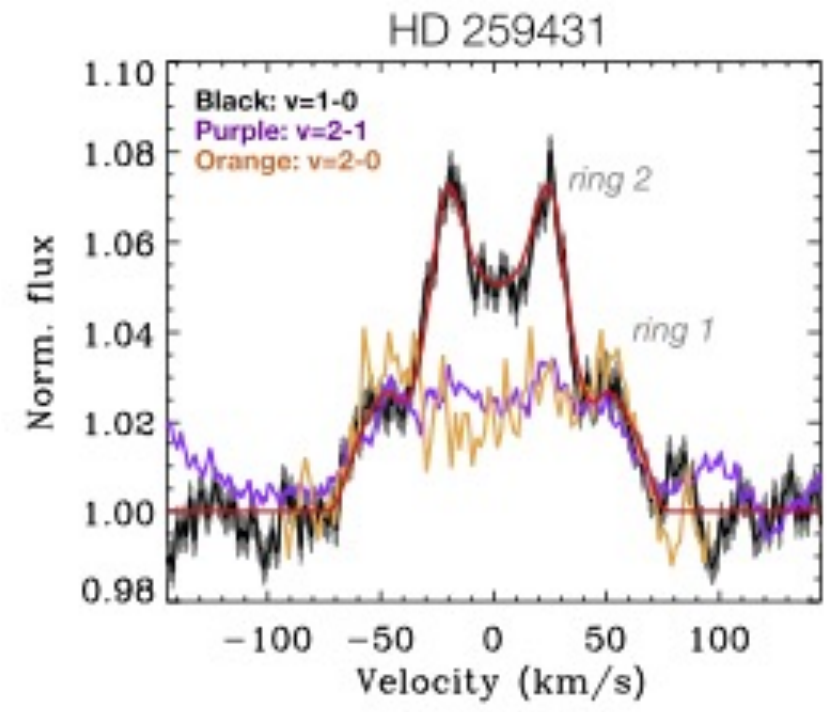
Slope: excitation temperature
Line flux: column of CO gas emitting surface

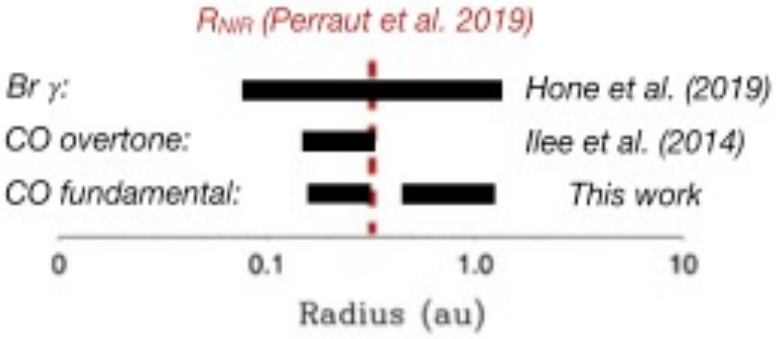
➔ Location of the gas (spatial information)

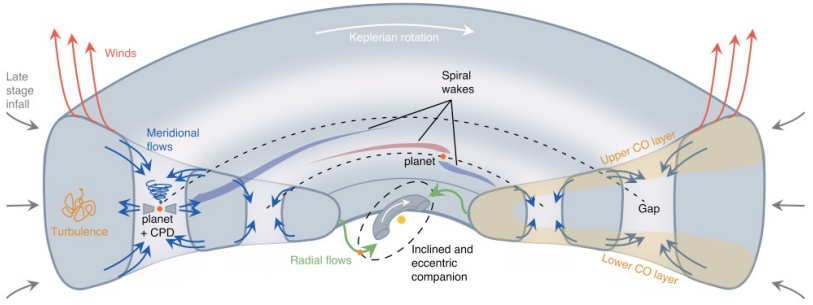


Ramirez-Tannus et al. 2023

Using high spectral resolution to find out about geometry







Banzatti et al. 2022 AJ 163

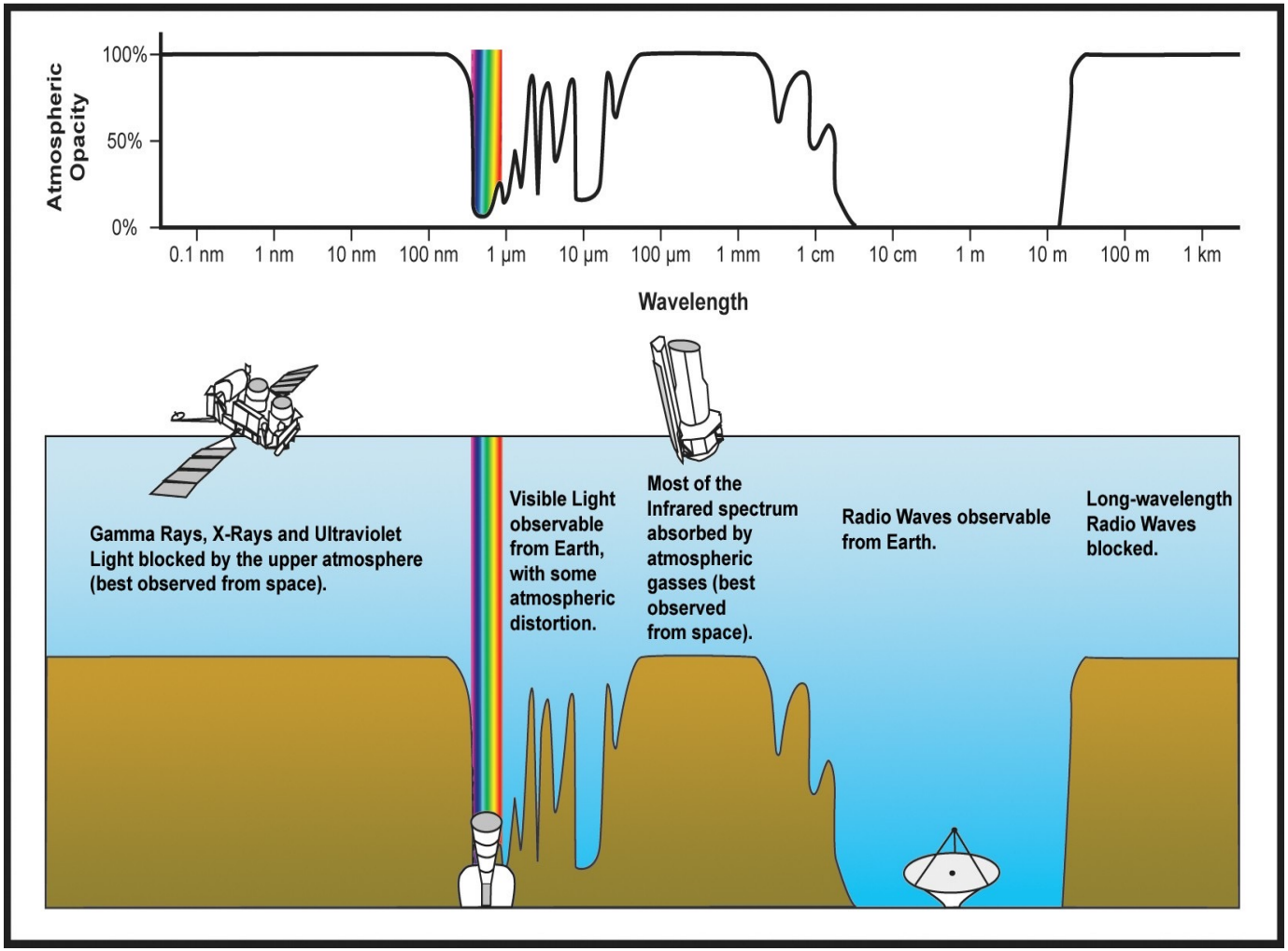


Why go to space?

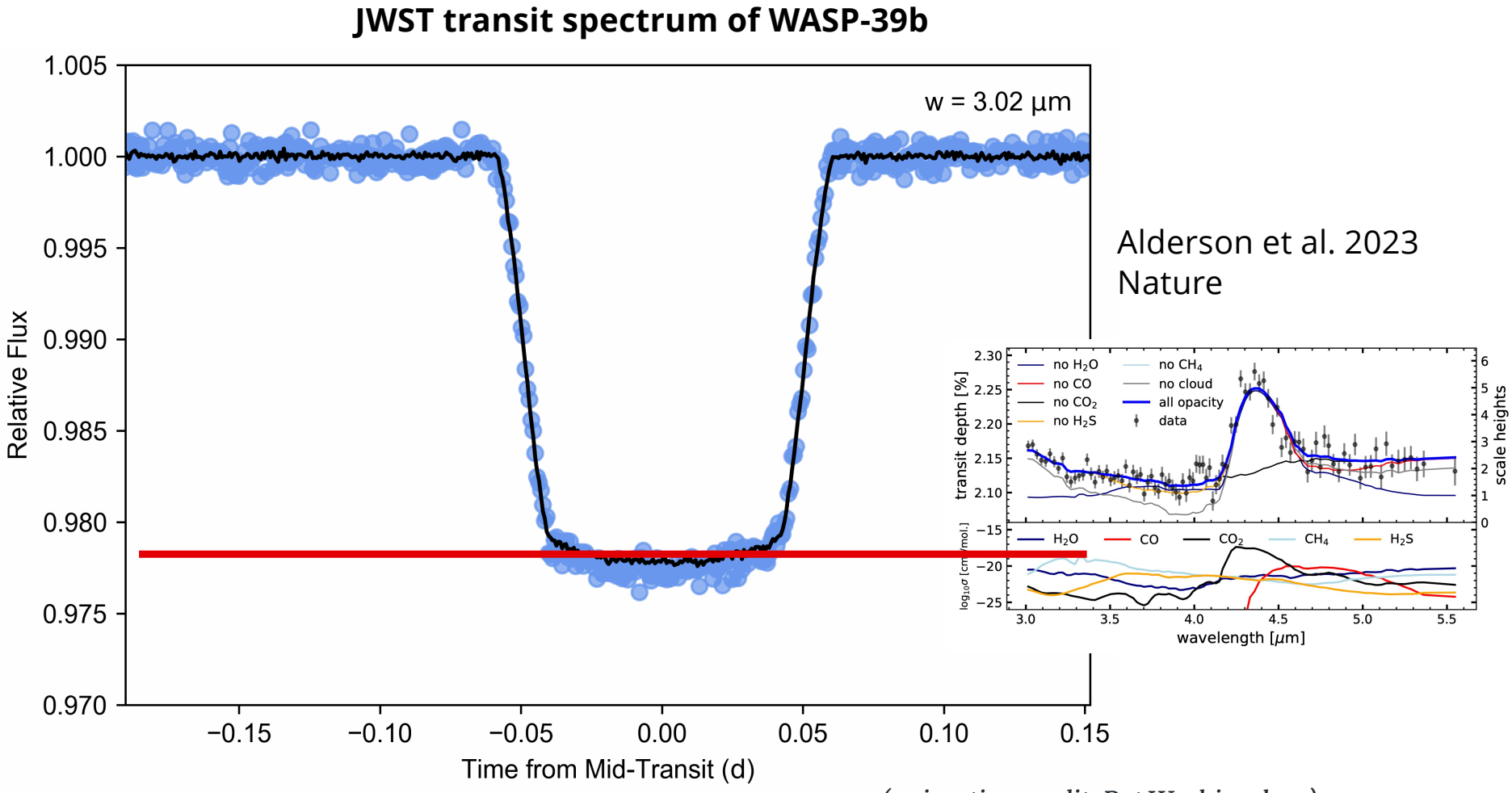
Separation of JWST from
last satge ARIANE V

Separation of JWST from Ariane 5 upper stage at 5 x speed / ESA, CNES, Arianespace, Réaltra Space

Why do we need space telescopes?



Amazing stability of telescopes in space!



Alderson et al. 2023
Nature

(animation credit, Pat Wachiraphan)

IRAS



ISO

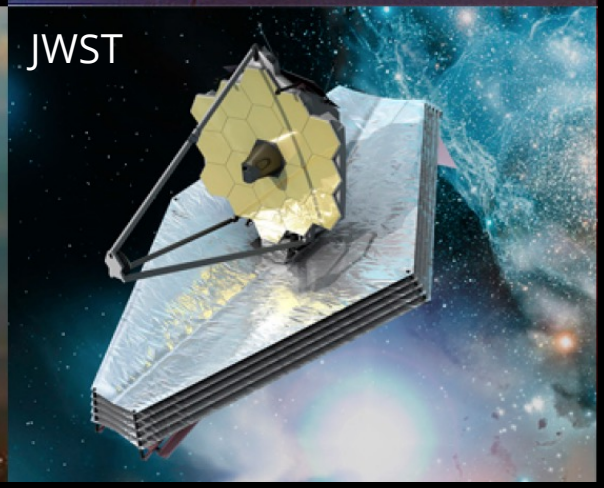


Spitzer





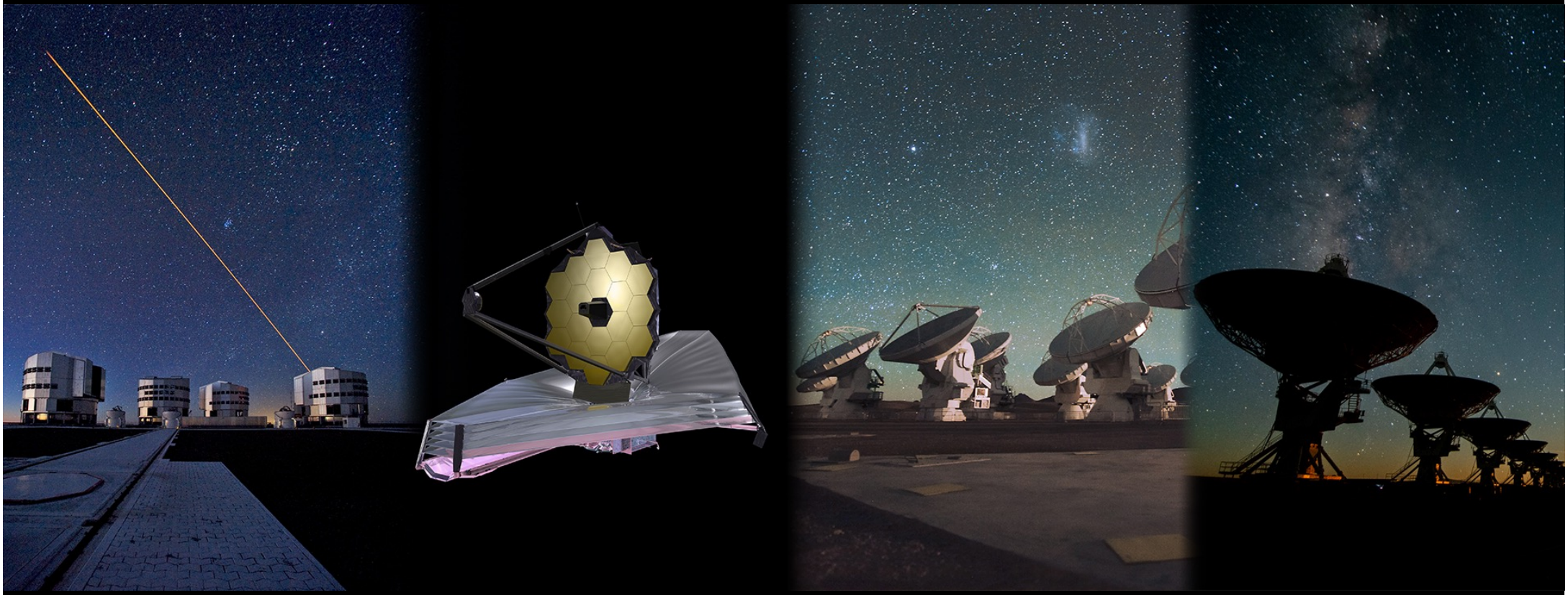
JWST



HST



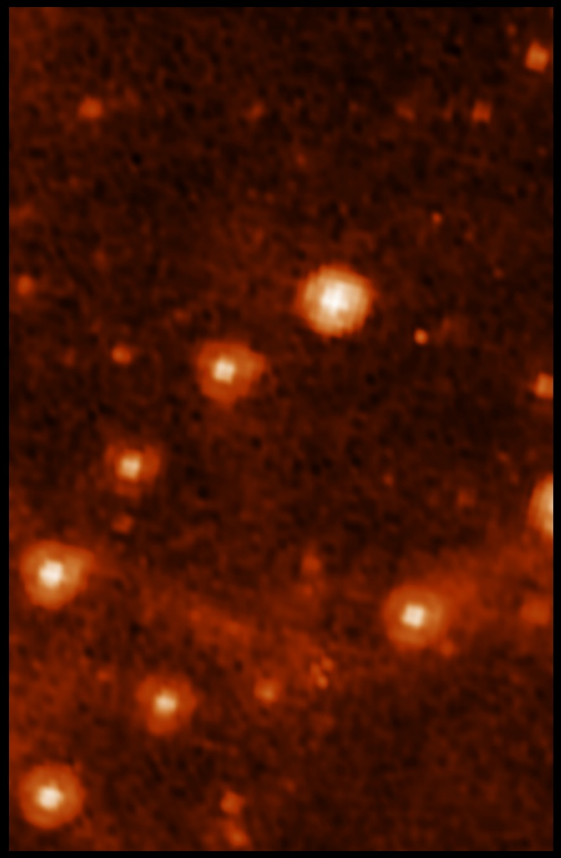
One observing proposal to use ALMA, JWST, VLT, VLA



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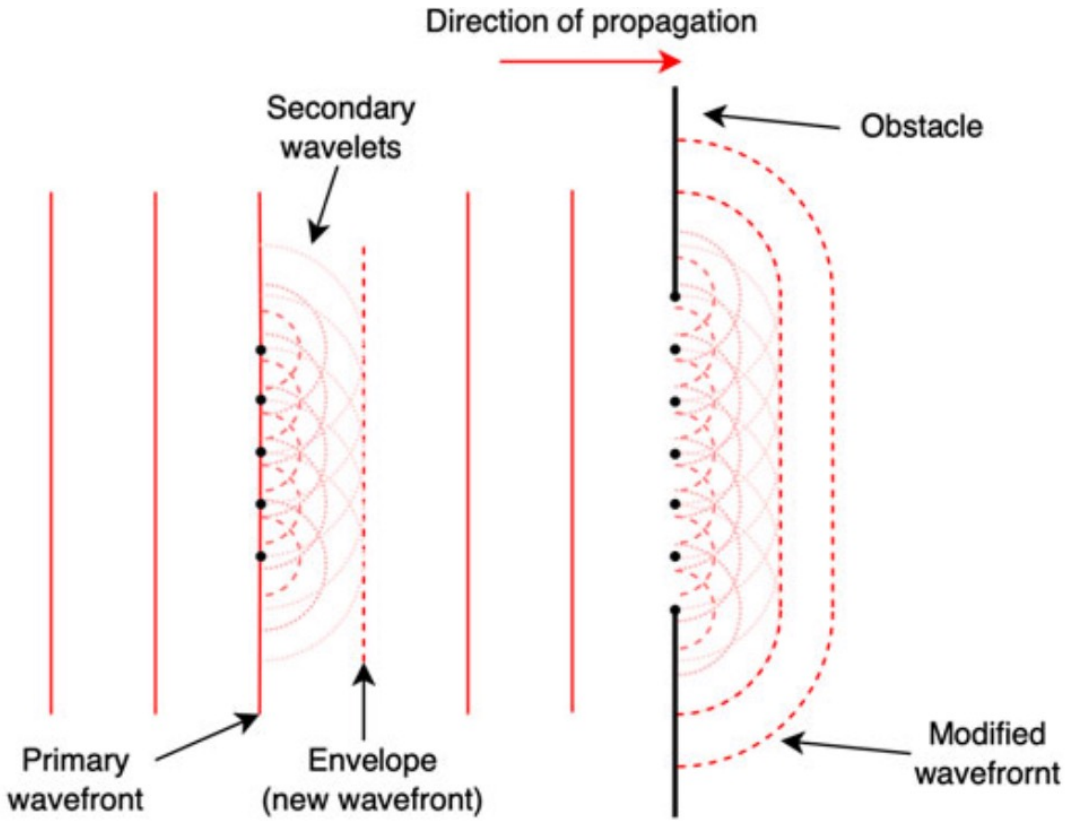
Angular resolution of telescope



SPITZER IRAC 8.0μ



WEBB MIRI 7.7μ



Liaudat et al.

AIRY DISK OF A TELESCOPE

Fraunhofer diffraction of a circular aperture, given by the squared modulus of the Fourier transform of the circular aperture.

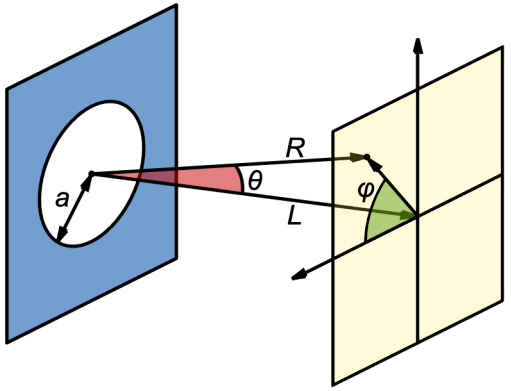
$$I(\theta) = I_0 \left[\frac{2\,J_1\,(x)}{x}\right]^2$$

J_1 = Bessel function

$$x = k\,a\,\sin\theta = \frac{2\,\pi\,a}{\lambda}\frac{q}{R}$$

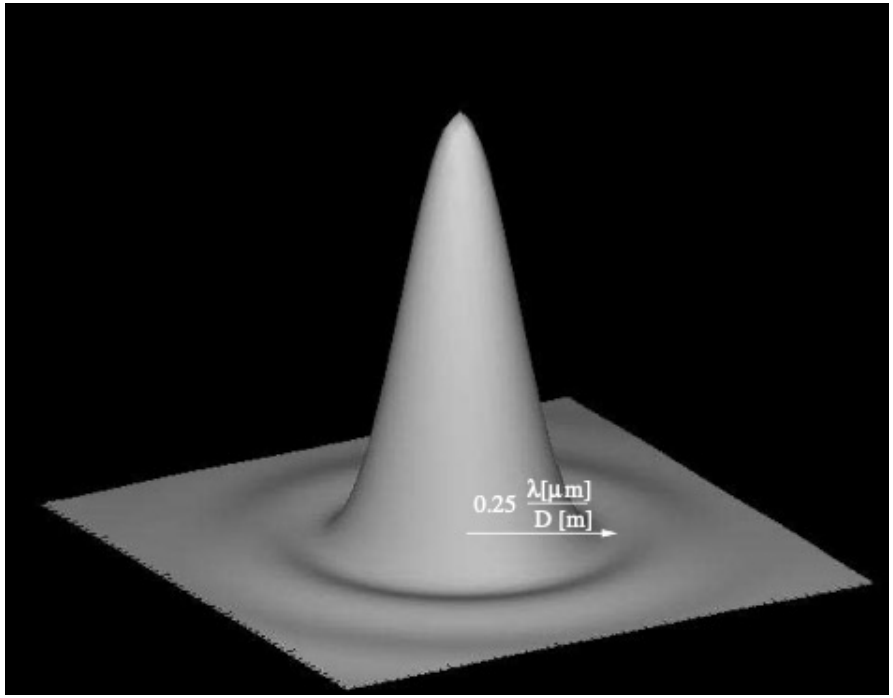
Zeros of J_1 are at x ≃ 3.83, ...

$$\sin\theta \simeq \frac{3.83\,\lambda}{2\,\pi\,a} = 1.22\,\frac{\lambda}{D}$$

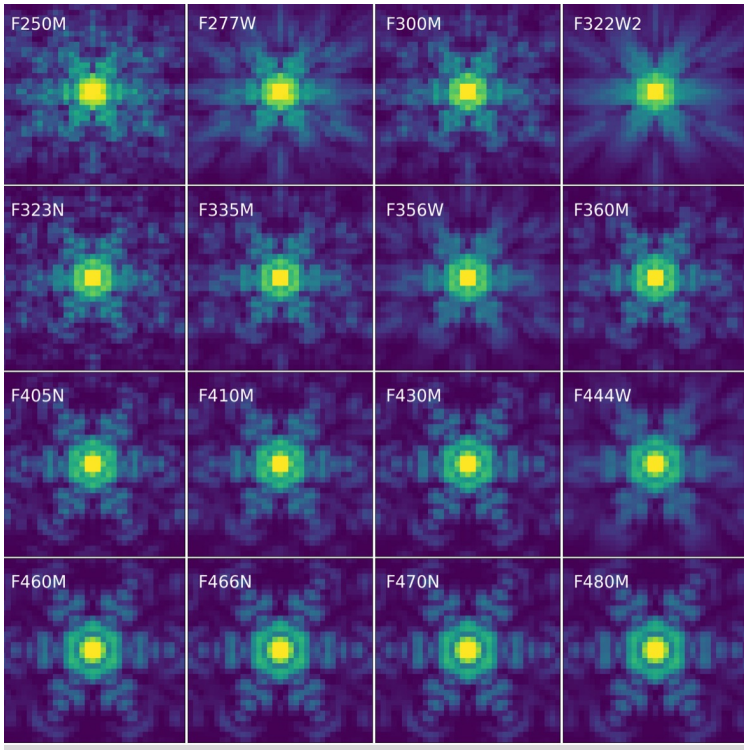


By Inductiveload - Own work

POINT SPREAD FUNCTION OF THE TELESCOPE DETERMINES ANGULAR RESOLUTION



Ideal PSF shape, Airy disk, fourier transform of a uniformly illuminated spherical aperture



JWST/NIRCAM (source:STScI)

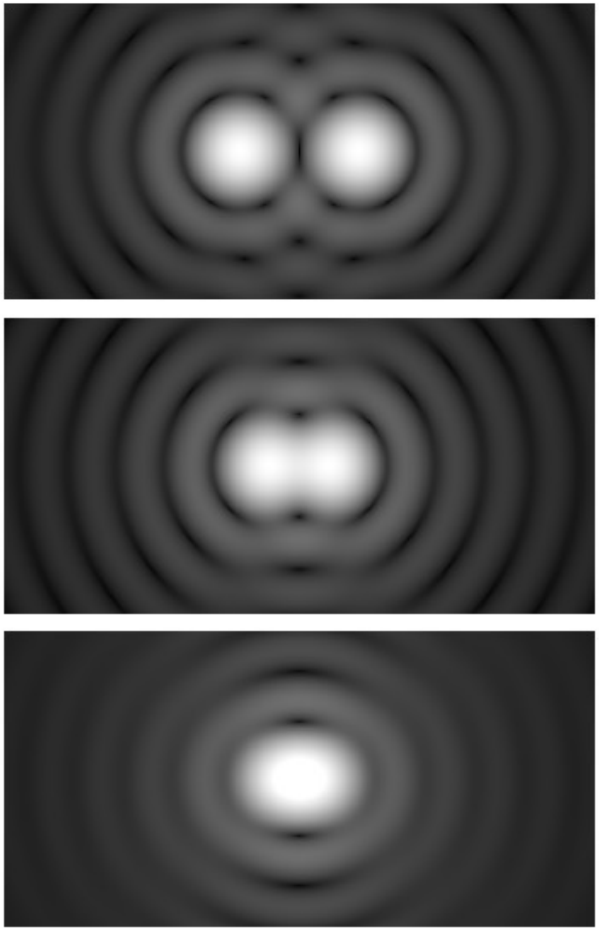
ANGULAR RESOLUTION OF A TELESCOPE

- Rayleigh: 2 point sources are just resolved when the center of Airy disk 1 coincides with the first minimum of Airy disk 2

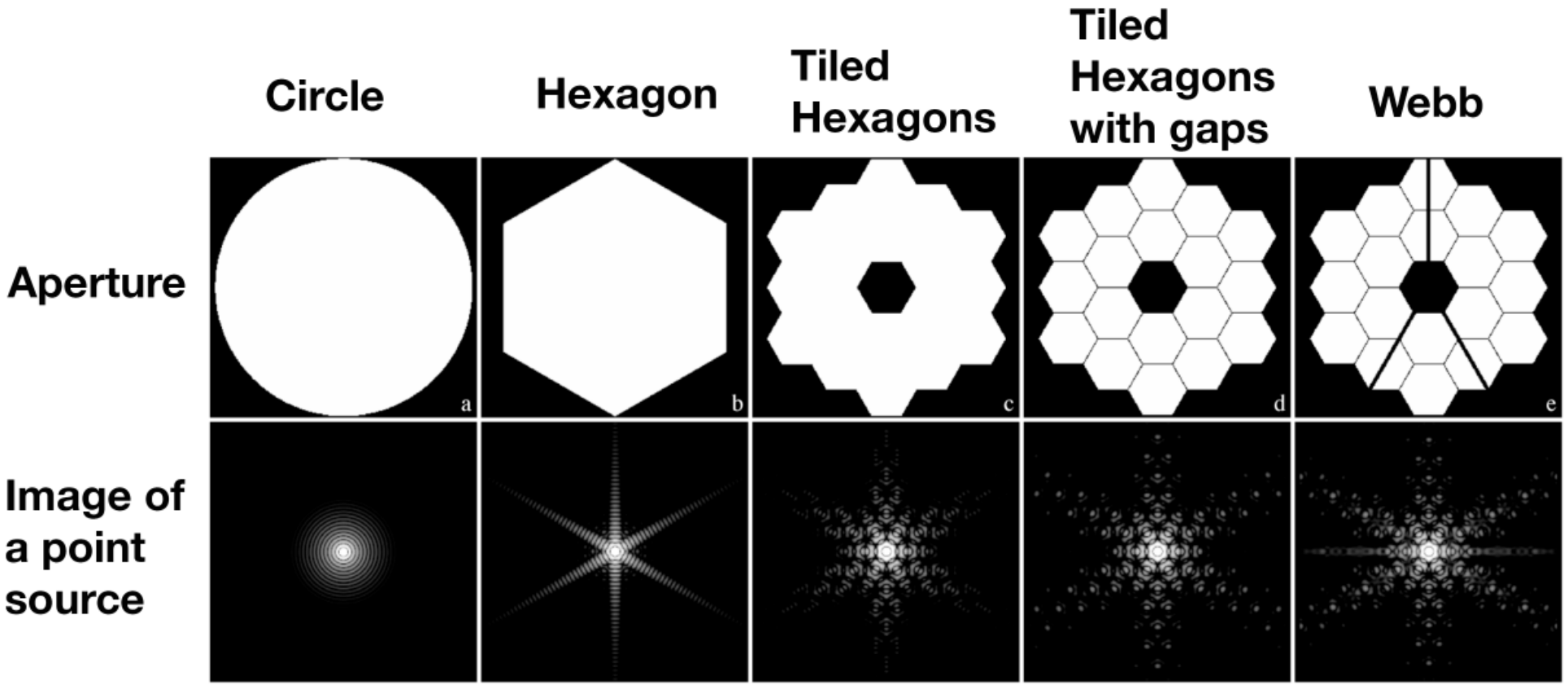
$$\theta \approx 1.22 \frac{\lambda}{D}$$

θ = angular resolution in radians
λ = wavelength of light
D = diameter of the aperture

Diffraction limit



Wikipedia, Spencer Blive


Circle
Hexagon
Tiled Hexagons
Tiled Hexagons with gaps
Webb
Aperture
Image of a point source
a
b
c
d
e

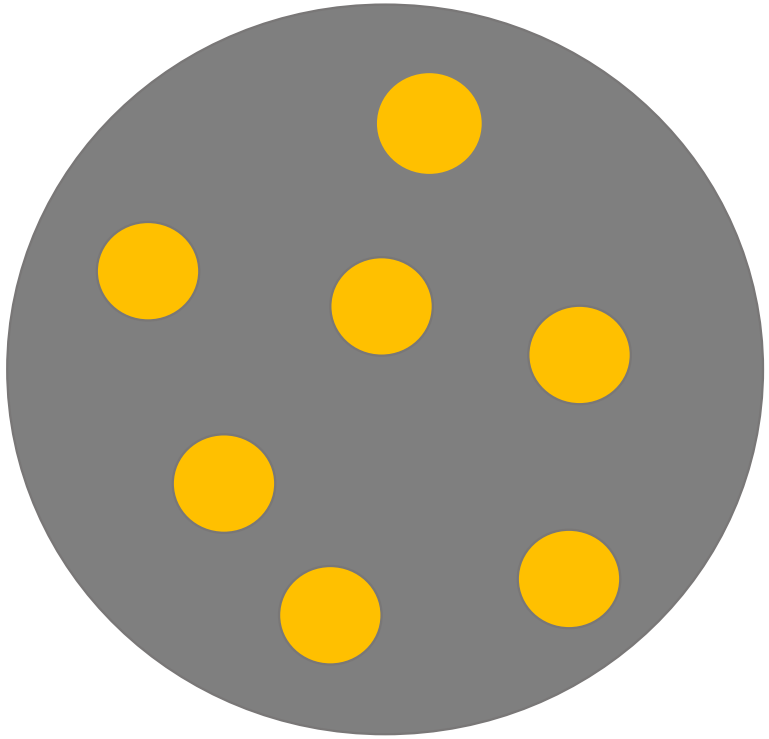
Wikipedia

Basic principles of interferometry



Source: J. menu (thesis)

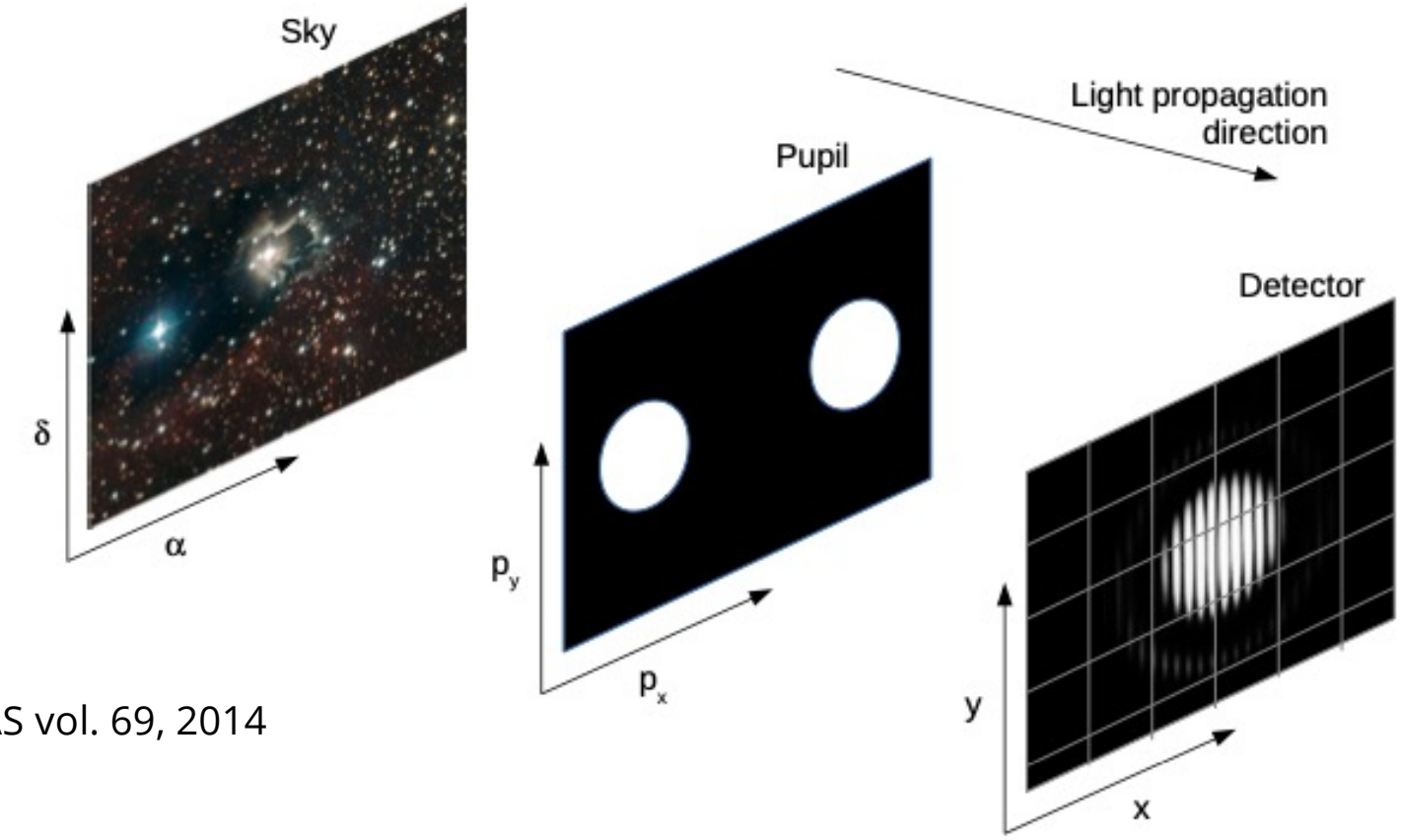
Interferometry: aperture-masked PSF



Angular resolution: largest telescope separation

Small collecting area

Can have limited image quality



Millour, EAS vol. 69, 2014

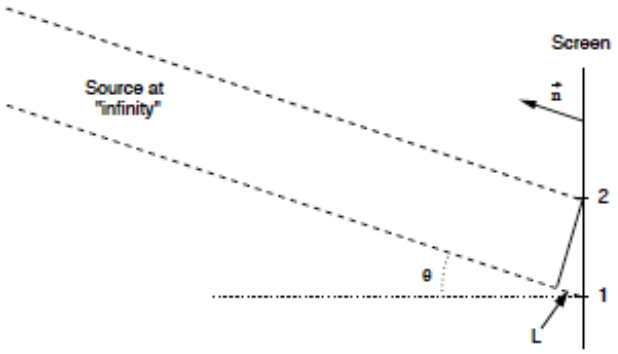
Van Cittert – Zernike theorem

$$\langle E_1^*(t) E_2(t) \rangle = \int A^*(n_x, n_y) A(n_x, n_y) \exp\left[-2\pi i \nu \left(\frac{n_x r_x + n_y r_y}{c}\right)\right] dn_x dn_y$$

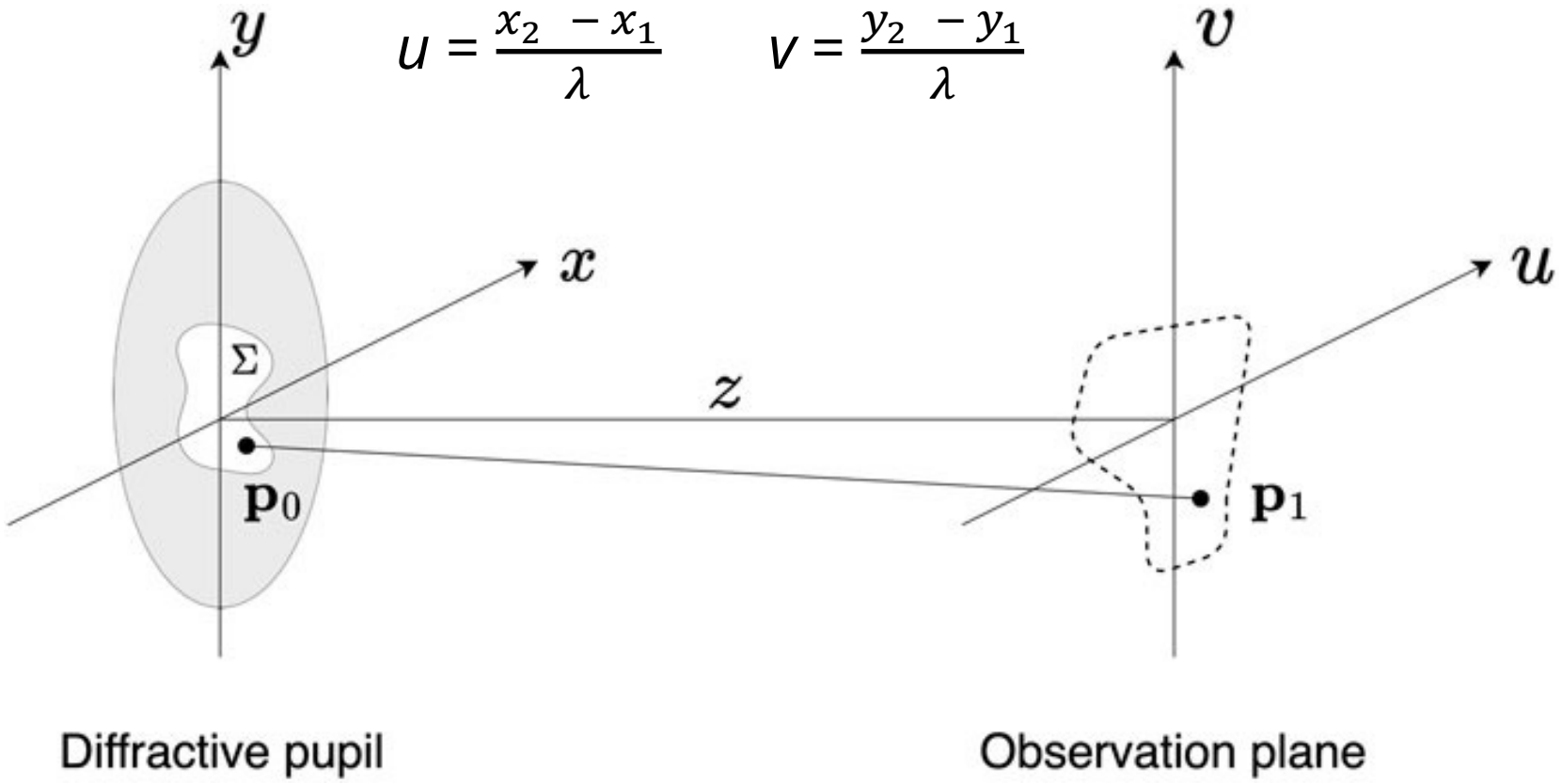
Coherence of radiation between two points = fourier transform of intensity

n_x and n_y : 2D angular position on the sky
r_x and r_y : 2D baseline on the image screen

Relative position of telescopes can be expressed in units of observing wavelength : u,v plane



$$u = \frac{x_2 - x_1}{\lambda} \qquad v = \frac{y_2 - y_1}{\lambda}$$



Liaudat et al, Astron. Space Science 2023

$$\langle E_1^*(t) E_2(t) \rangle =$$ Complex visibility of the signal

Complex visibility contains amplitude and phase information

Amplitude of visibility:
How strongly correlated are the two points?

Phase of visibility:
Geometry of the source

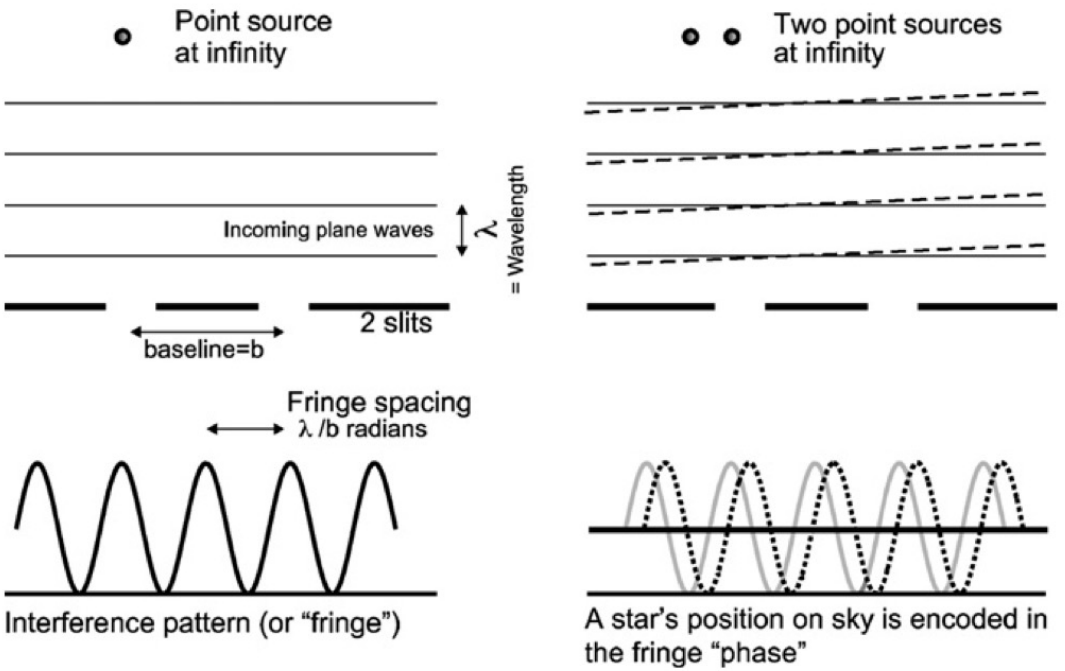
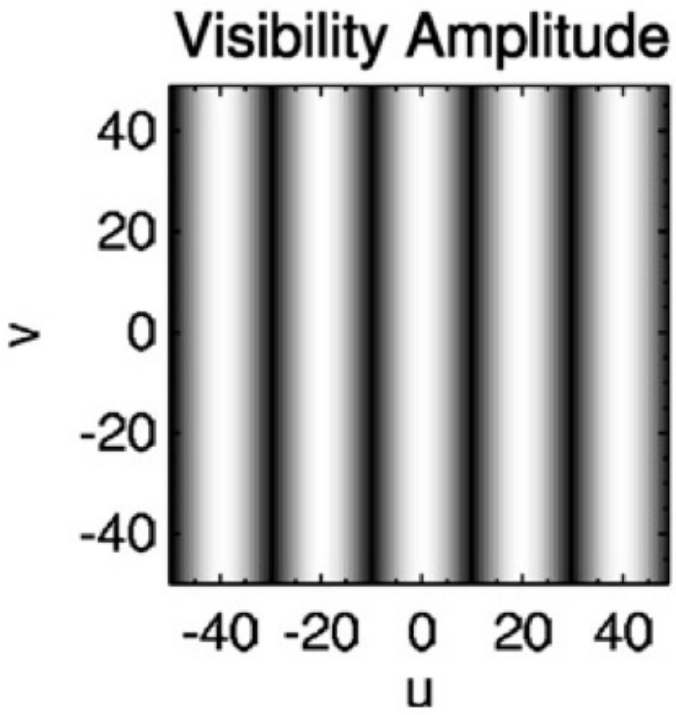
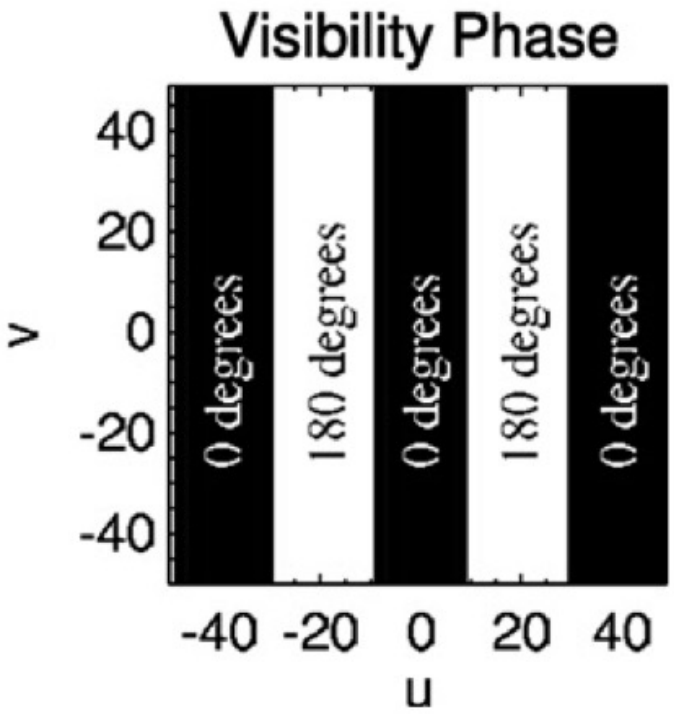


Fig. 1. The left panel shows a simple Young's two-slit interferometer response to a point source – the interference fringe can be characterized by an amplitude and phase. The right panels show how two different stars would produce fringes with different phase offsets, thus measurement of fringe phase is equivalent to a measurement of stellar position on the sky (in the absence of turbulence).

Monnier (New Astronomy Reviews 2007)

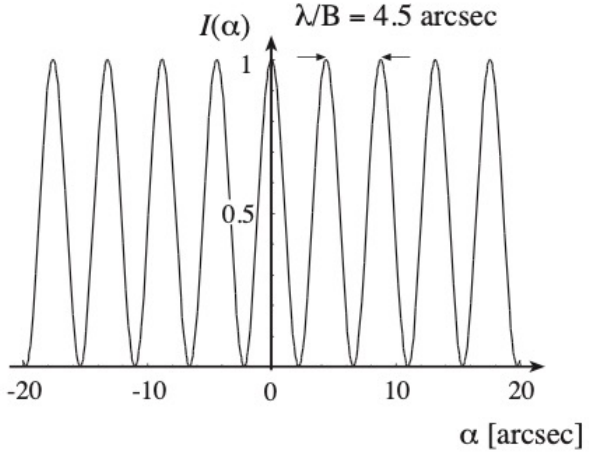




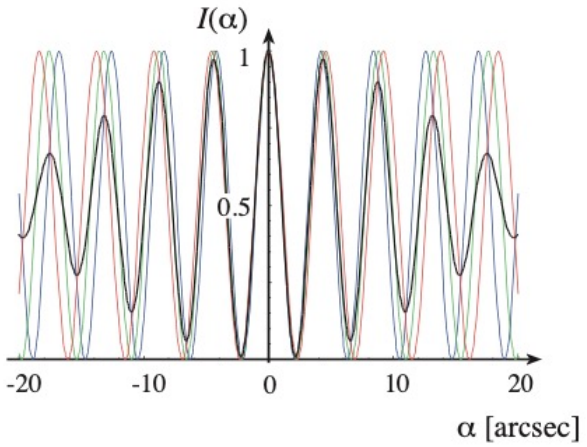
Monnier (New Astronomy Reviews 2007)

Fringe contrast decreases for extended sources and for non-monochromatic radiation

point source
monochromatic



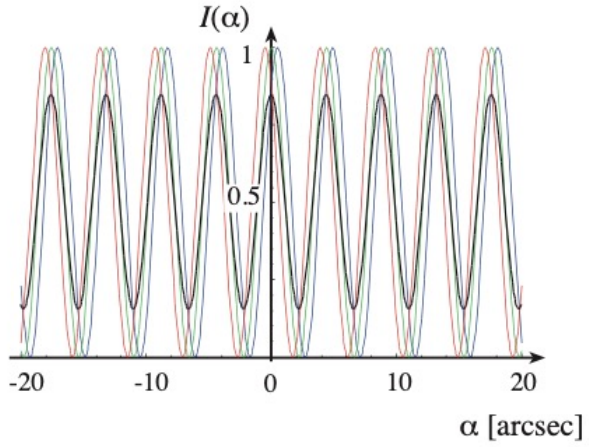
a) point source, monochromatic

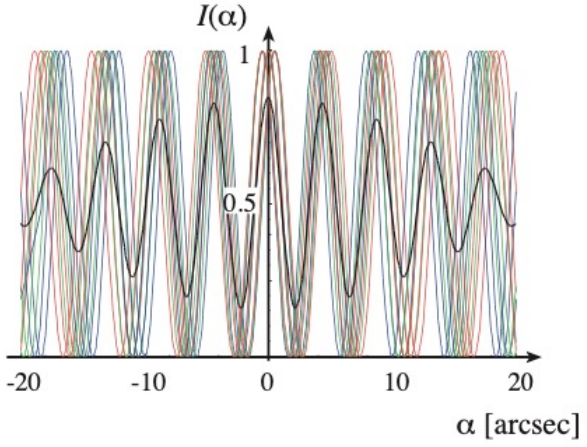


b) point source, K-band

point source
K band (2 μm)

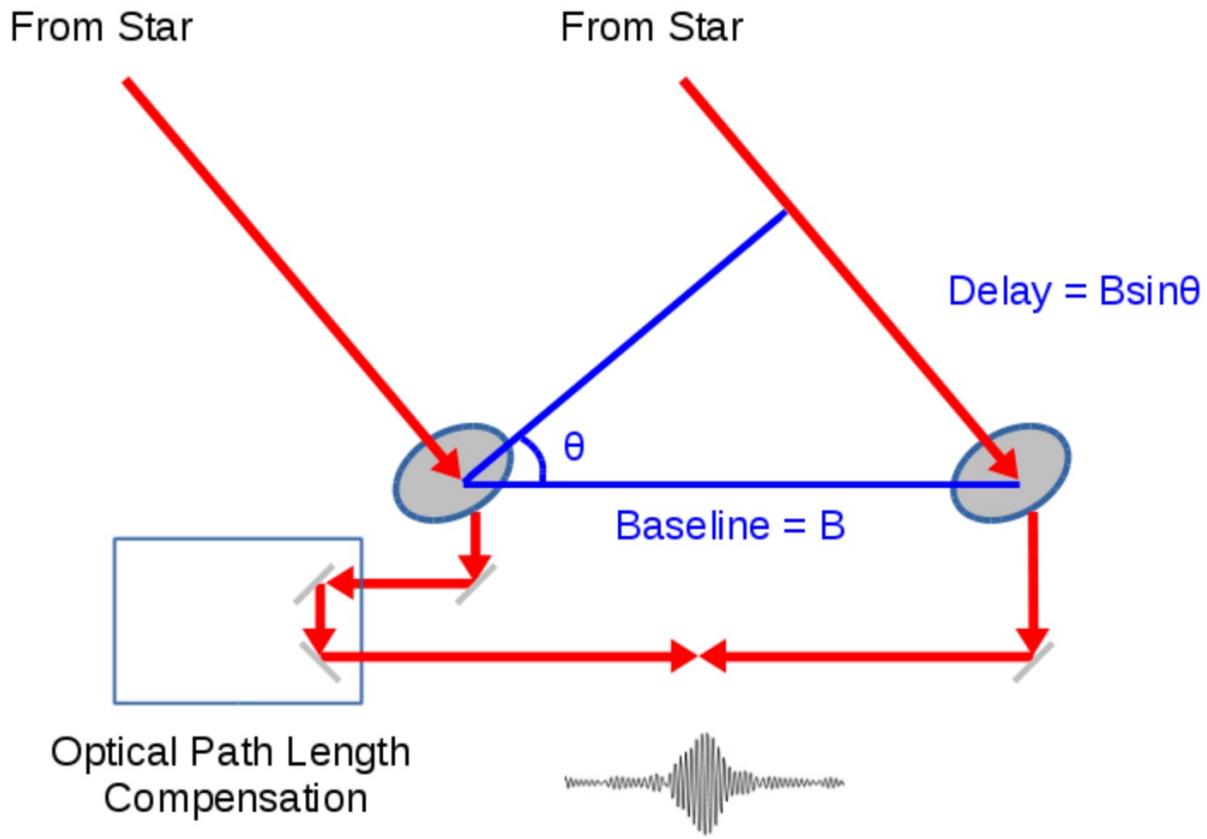
extended source
monochromatic





extended source
K band (2 μm)

Glindemann
Tutorial
interferometry



CHARA website

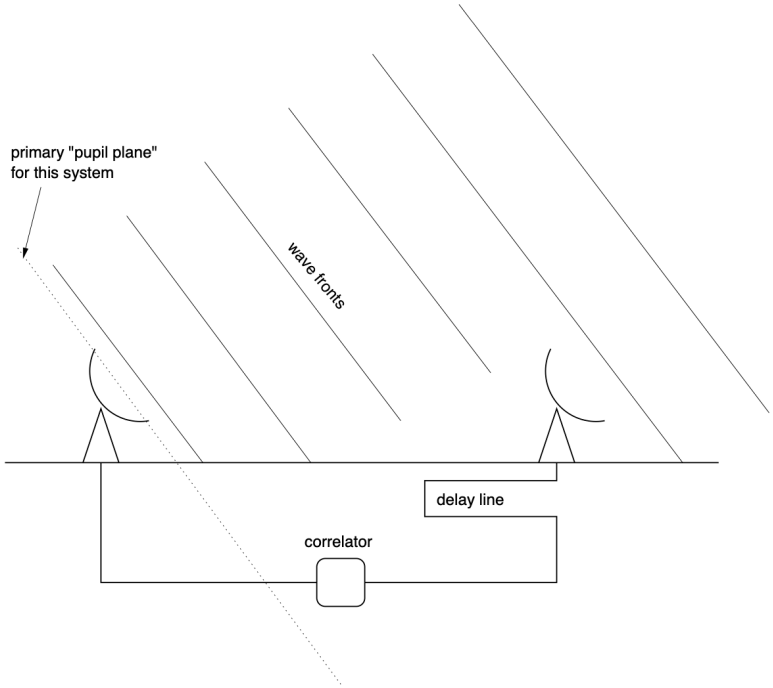
MEASURING AMPLITUDE AND PHASE OF THE COMPLEX VISIBILITIES

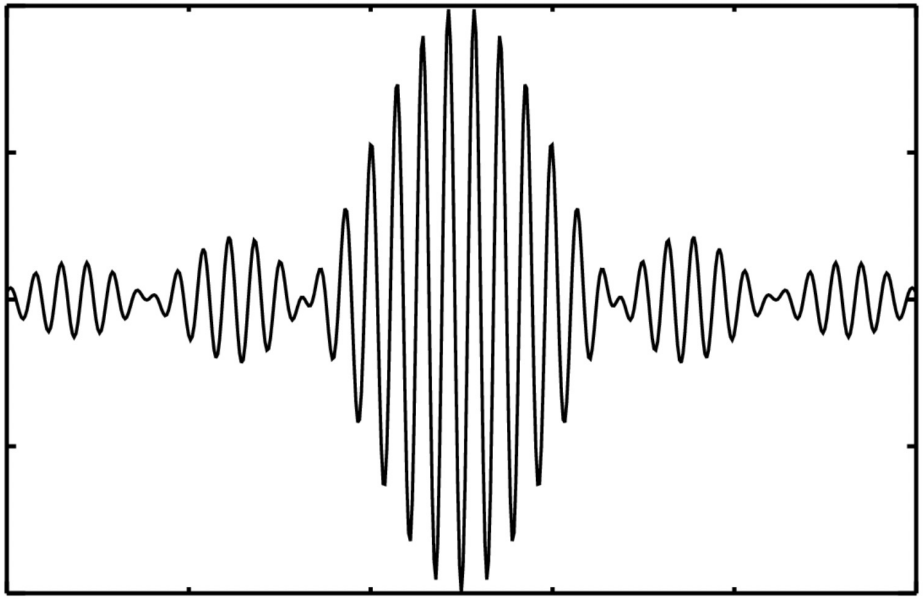
AMPLITUDE OF THE VISIBILITIES: VARY THE PATH DIFFERENCE TO MEASURE THE FRINGE CONTRAST

PHASE MEASUREMENT: A LOT HARDER BECAUSE OF ATMOSPHERE AND TELESCOPE PHASE SHIFTS

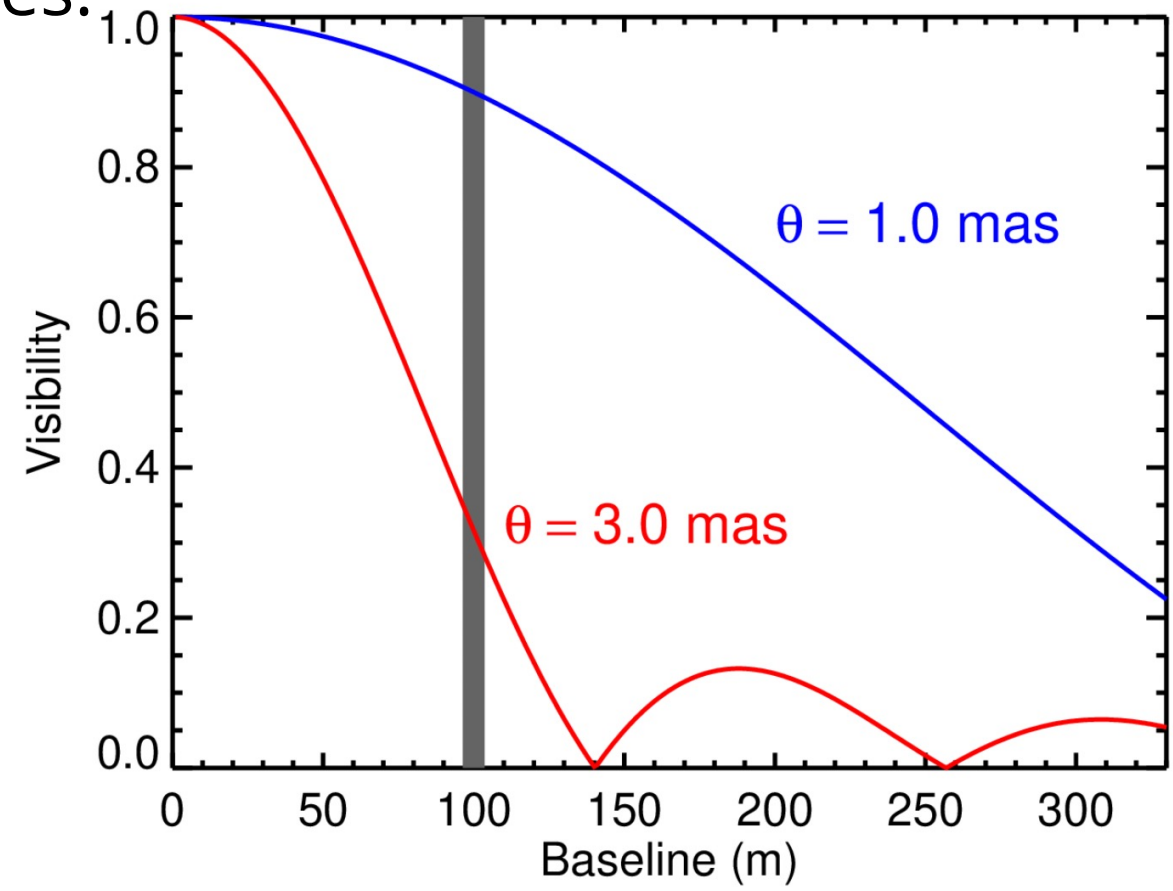
TRICK: USE THREE OR MORE TELESCOPES CLOSURE PHASES

Varying the path difference finds the visibility amplitude (or correlated flux)





Examples of visibility curves: uniform stellar disk



CHARA website

Examples of visibility curves: planet forming disk

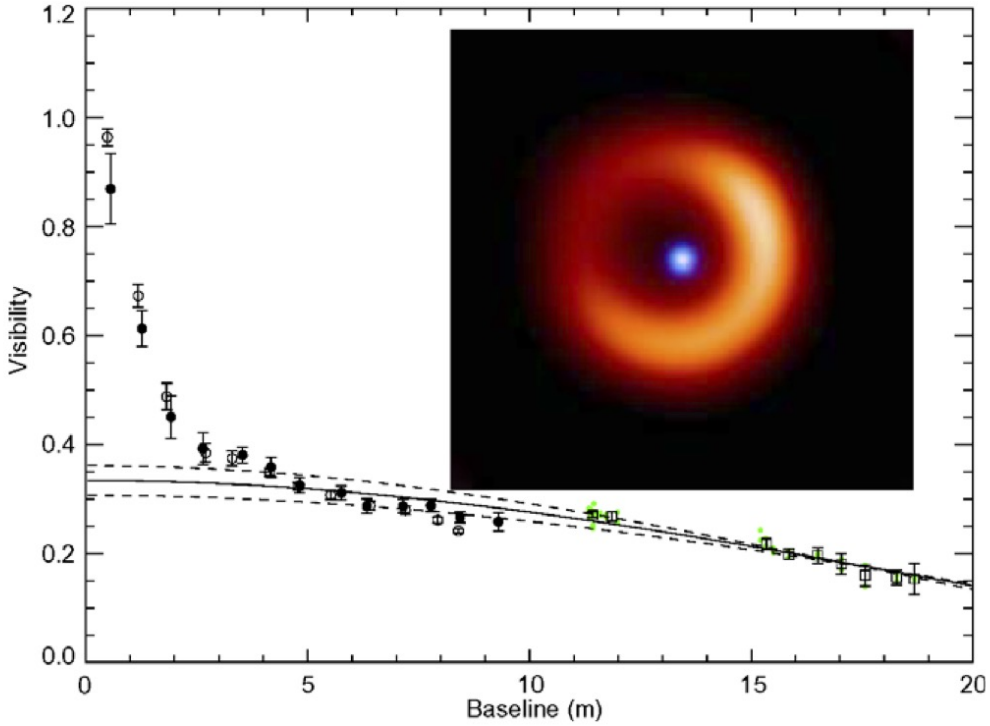
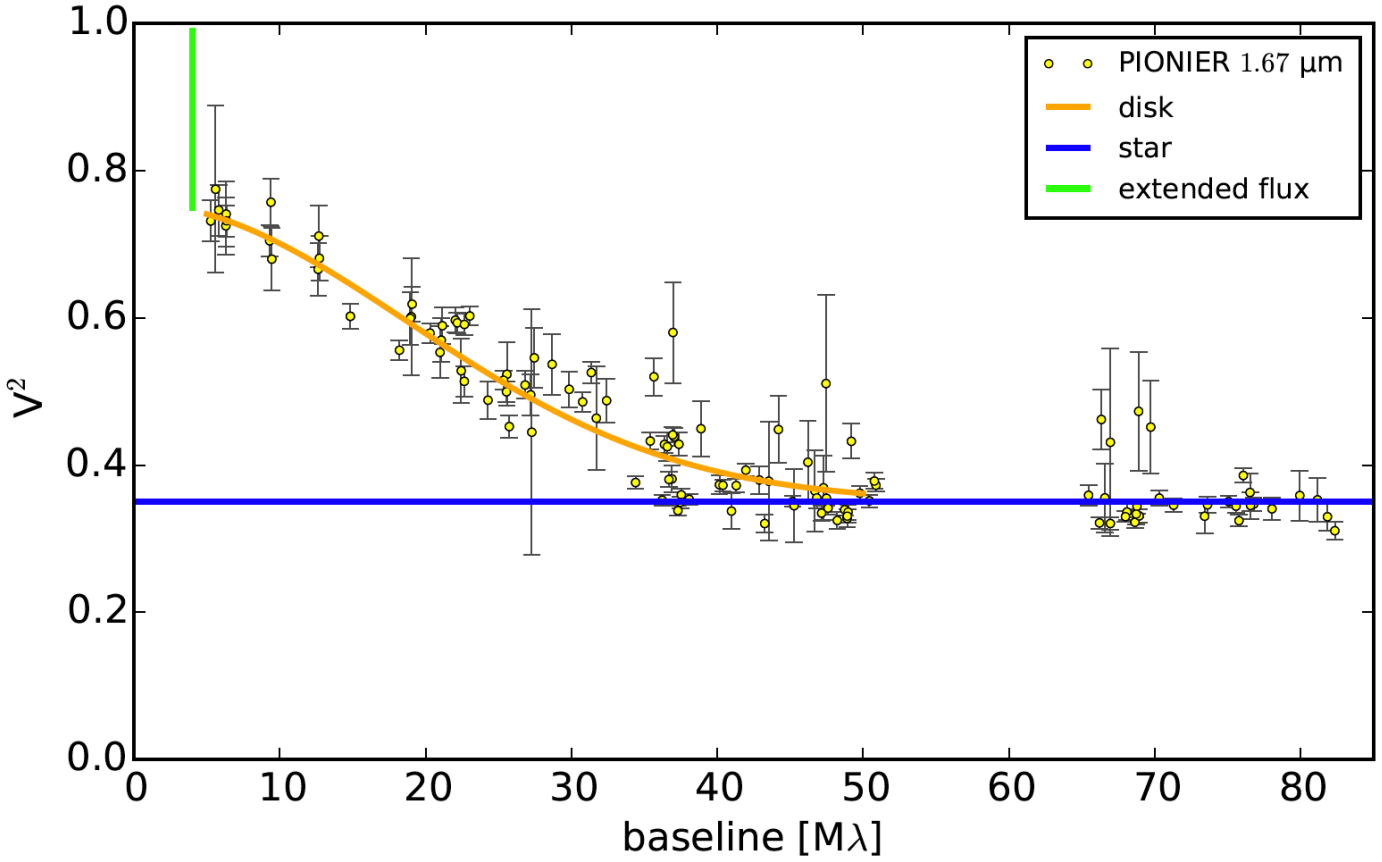


Fig. 10. A common case encountered in infrared interferometry is a star surrounded by a dust shell. This figure shows an example image and corresponding visibility curve. The important point is that the short baselines are probing the large scale structure of the object (the dust shell), while the long baselines resolve out the dust and only "see" the underlying star.

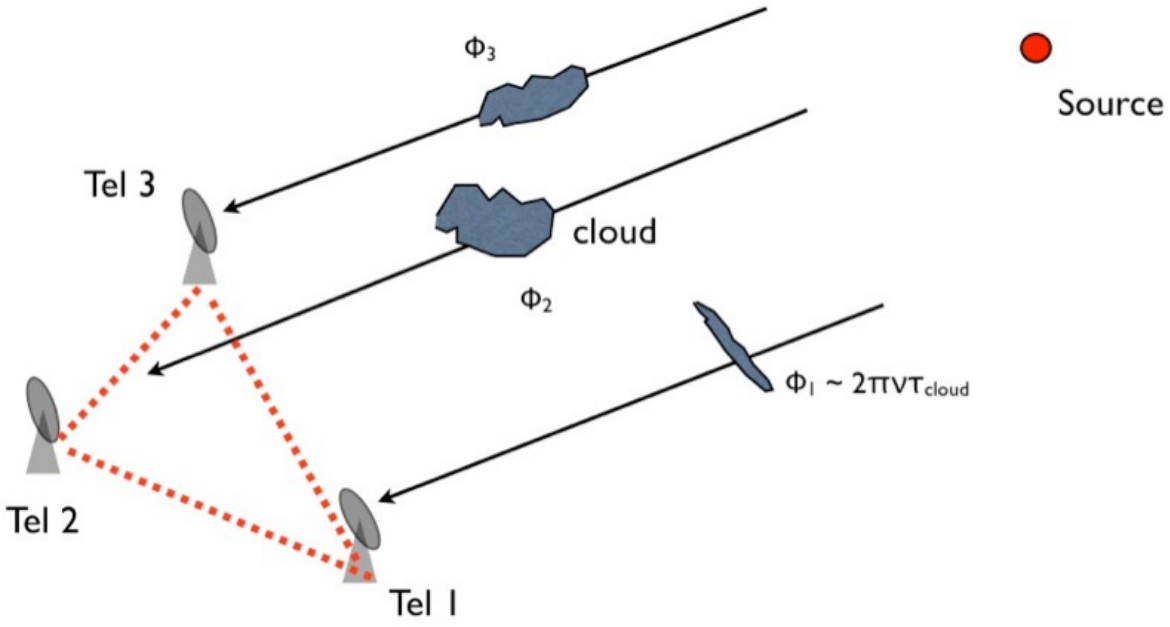
Monnier (New Astronomy Reviews 2007)



A. Corporaal (thesis, KU Leuven)

Closure phase cancels phase shifts caused by local atmospheric or instrumental effects

$$\Phi_{12} = \varphi_{12} + \phi_1 - \phi_2$$
$$\Phi_{23} = \varphi_{23} + \phi_2 - \phi_3$$
$$\Phi_{31} = \varphi_{31} + \phi_3 - \phi_1$$

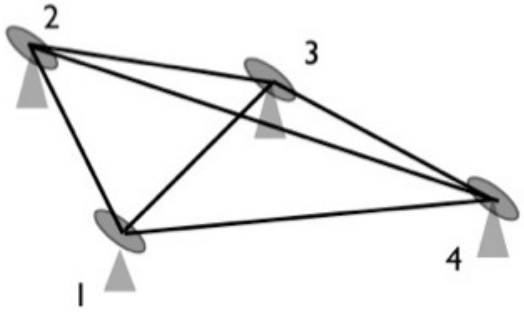


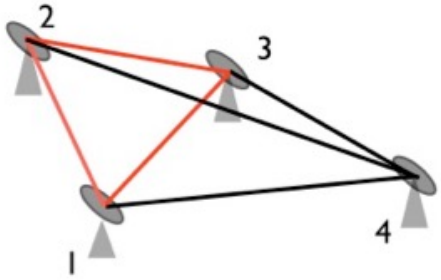
H.-R. Klöckner, IMPRS lecture notes

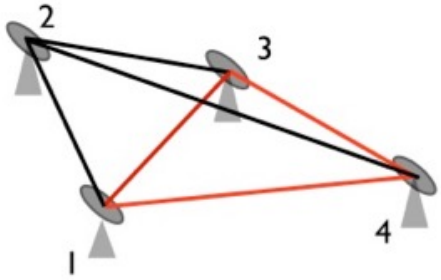
For a given array of N telescopes, there are:

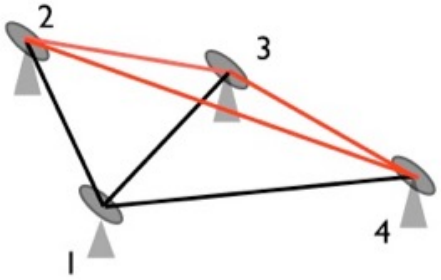
(N-1)(N-2)/2 independent closure phases [3]

e.g. for N=4 there are 3 *independent* closure relations.







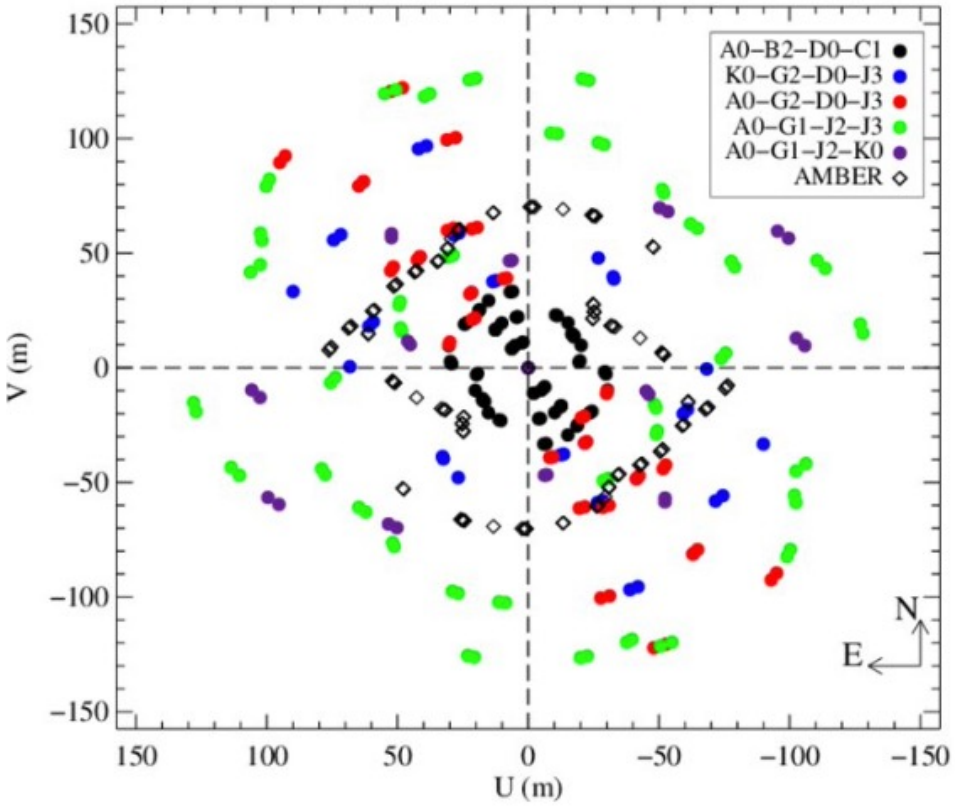


H.-R. Klöckner, IMPRS lecture notes

Fill the u,v plane by adding telescopes and use earth rotation

Example of uv coverage

ESO VLTI

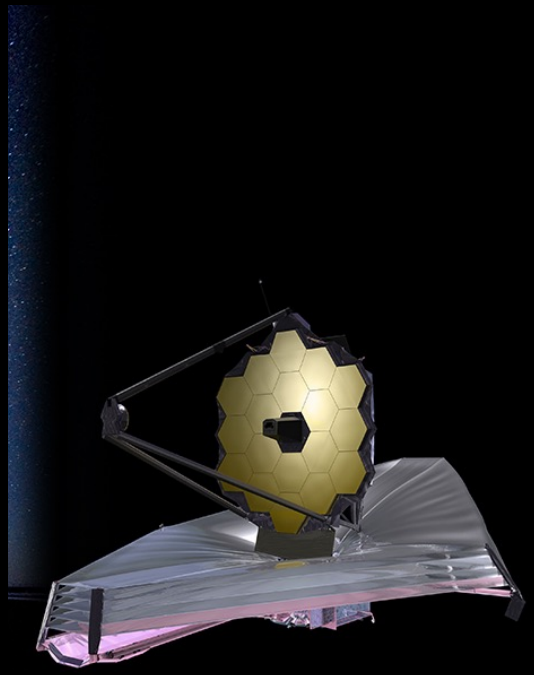


Koumpia et al. 2020 A&A 635

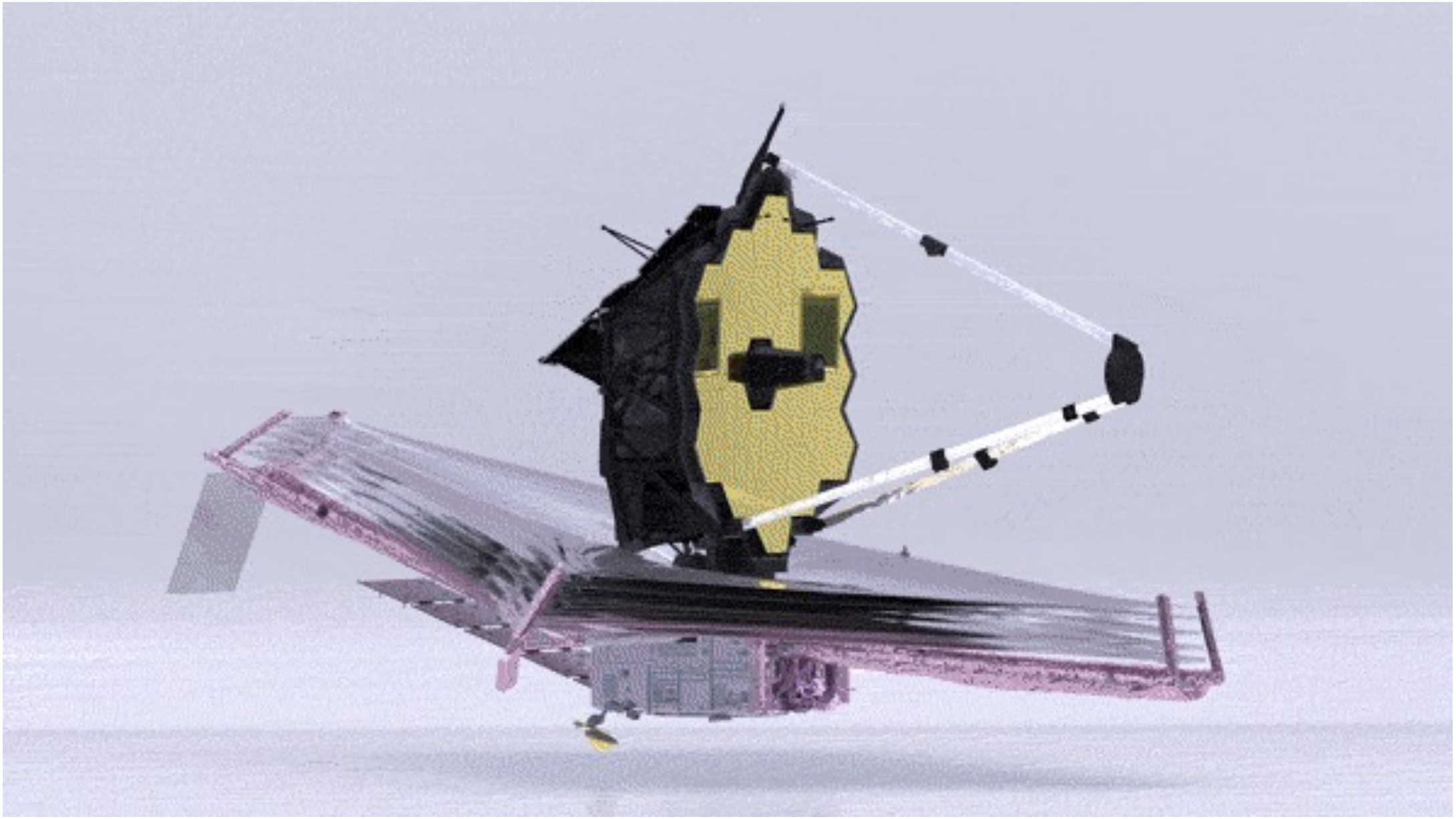
Overview of lecture:

- Introduction
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- Telescopes: Spectroscopy
- Telescopes: Angular resolution, interferometry
- **JWST**
- ALMA
- solids in space

JWST and ALMA: groundbreaking telescopes for astrochemistry



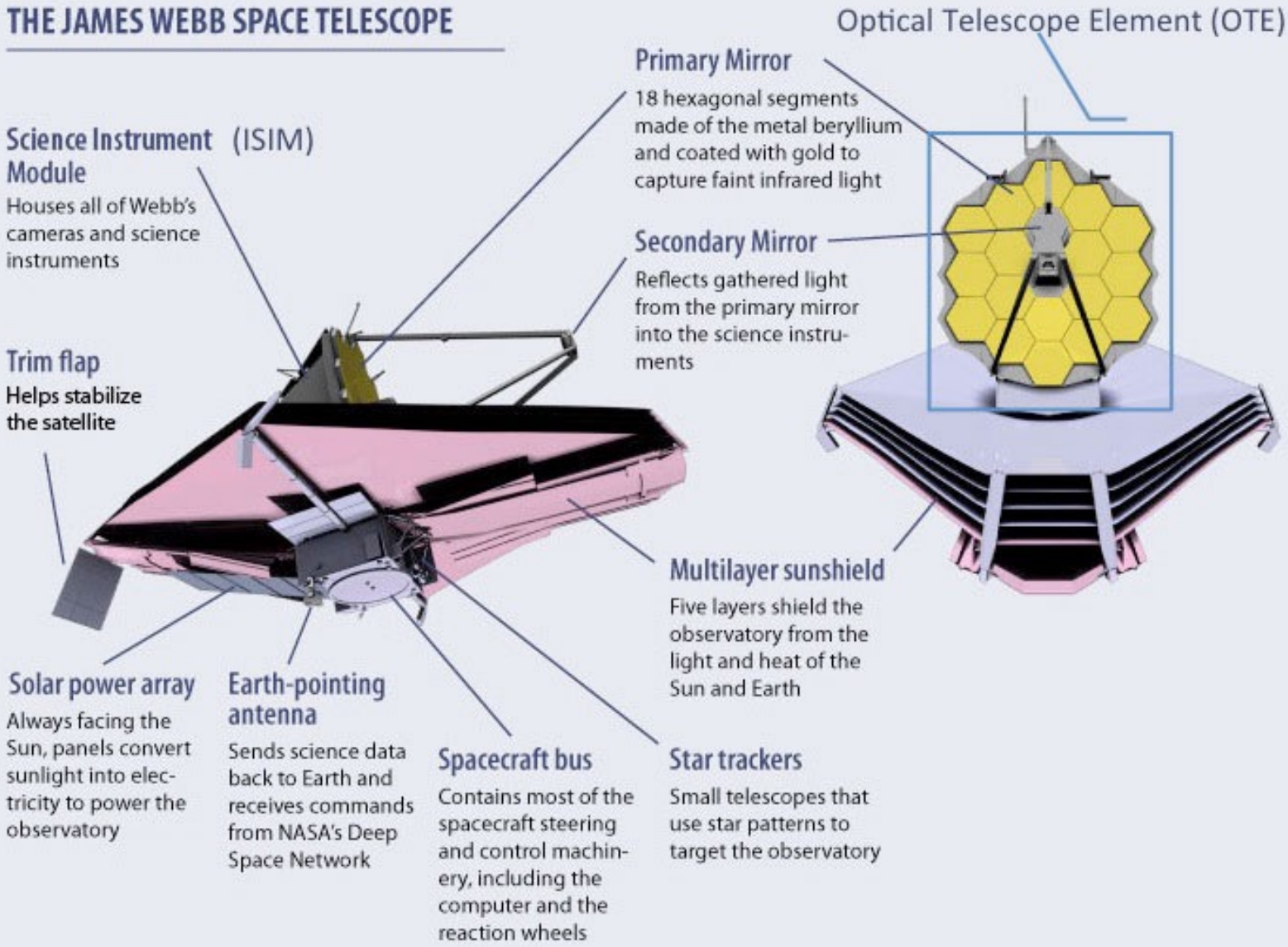


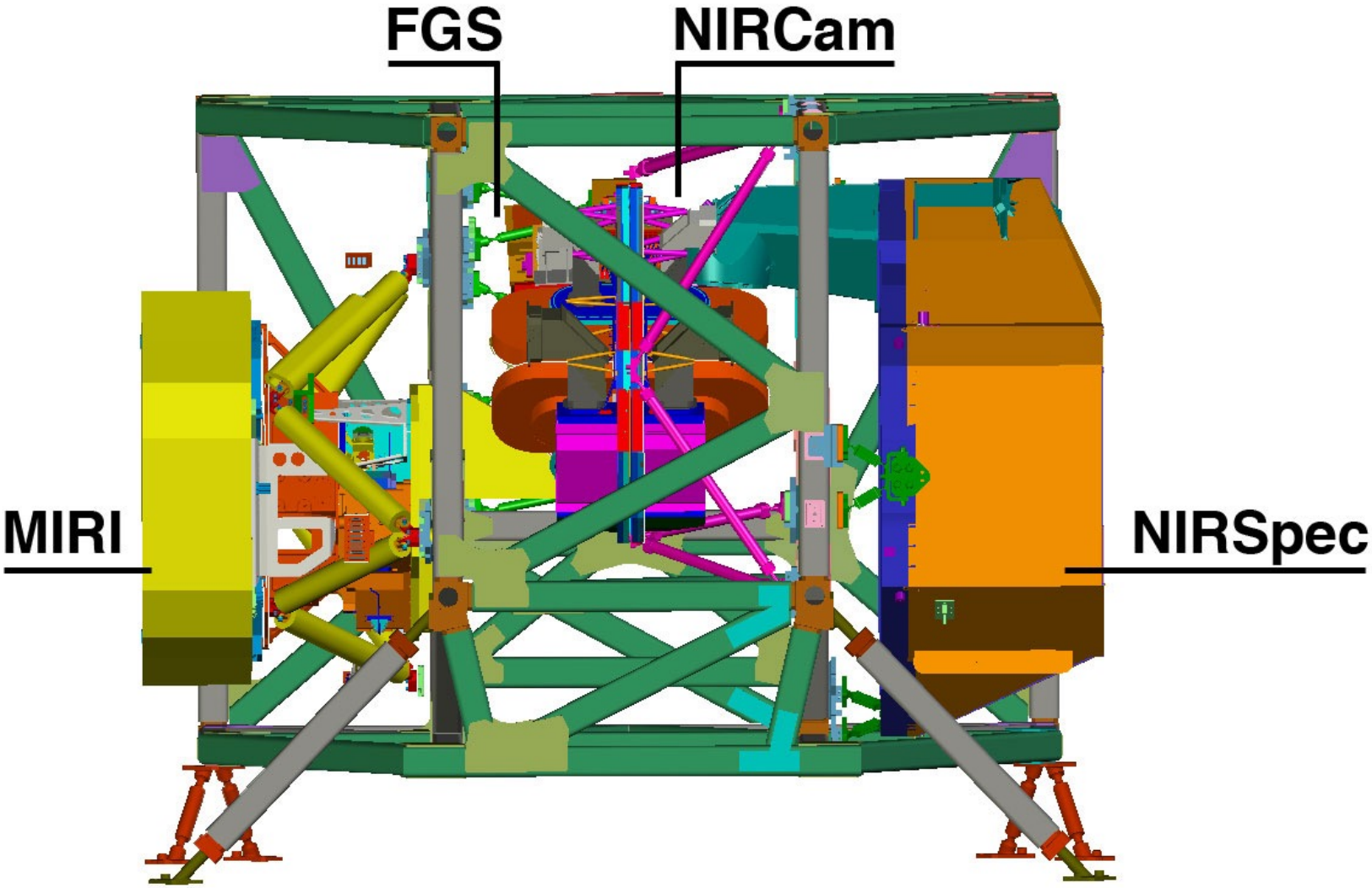


Webb fact Sheet (NASA)

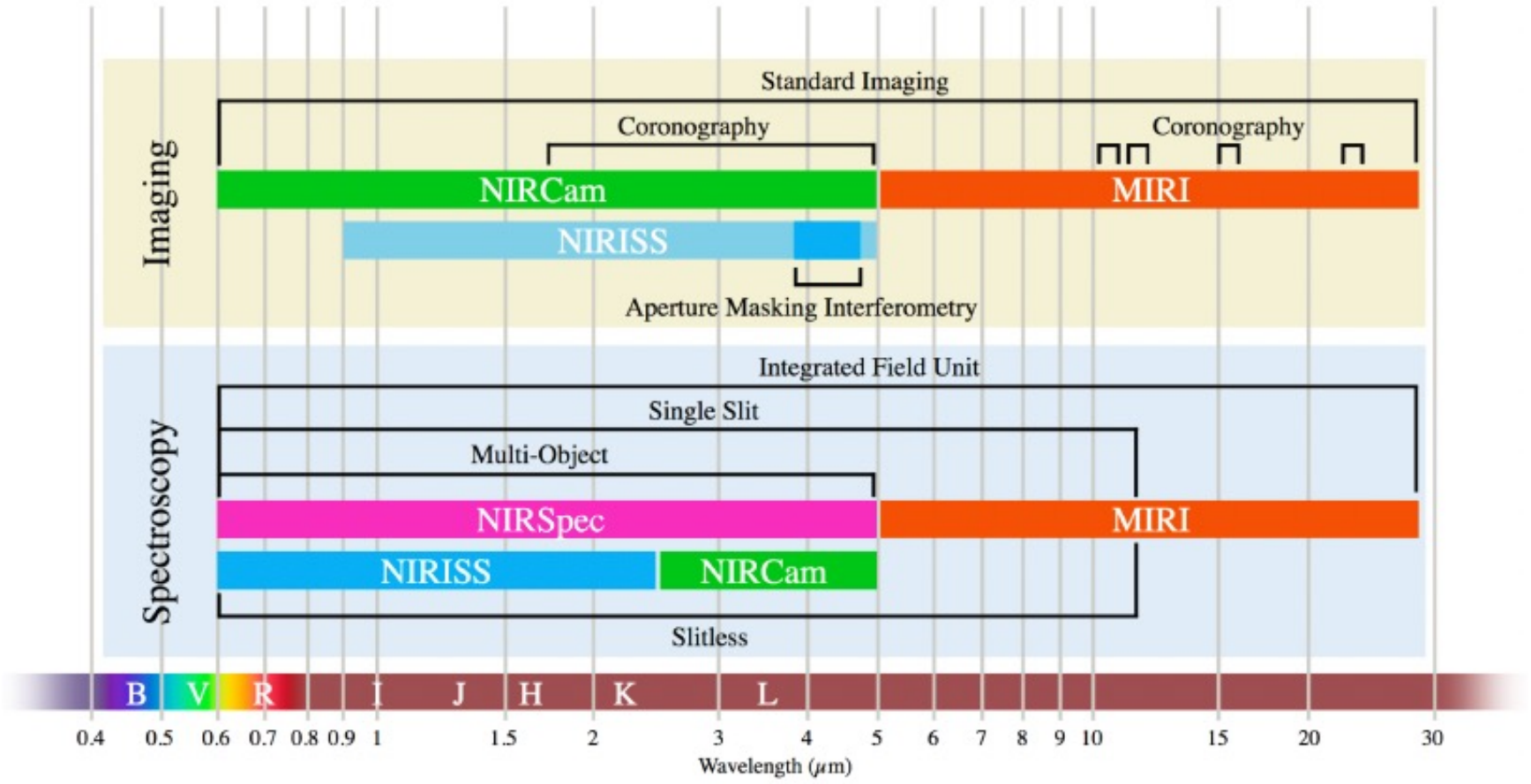
Diameter of primary Mirror:	6.5 m (21.3 ft) approximately
Clear aperture of primary Mirror:	25 m^2
Primary mirror material:	beryllium coated with gold
Mass of primary mirror:	705 kg
Mass of a single primary mirror segment:	20.1 kg for a single beryllium mirror, 39.48 kg for one entire primary mirror segment assembly (PMSA).
Focal length:	131.4 meters
Number of primary mirror segments:	18
Optical resolution:	~0.1 arc-seconds
Wavelength coverage:	0.6 - 28.5 microns
Size of sun shield:	21.197 m x 14.162 m (69.5 ft x 46.5 ft)
Temp of sun shield layers:	Layer 1: Max temperature 383K = approx 231F Layer 5: Max temperature 221K = approx -80F Min temperature 36K = approx -394F
Orbit:	1.5 million km from Earth orbiting the L2 Point
Operating Temperature:	under 50 K (-370 °F)
Gold coating:	Thickness of gold coating = 100 x 10^{-9} meters (1000 angstroms). Surface area = 25 m^2. Using these numbers plus the density of gold at room temperature (19.3 g/cm^3), the coating is calculated to use 48.25g of gold, about equal to the mass of a golf ball. (A golf ball has a mass of 45.9 grams. Note mass does not equal size!)

THE JAMES WEBB SPACE TELESCOPE

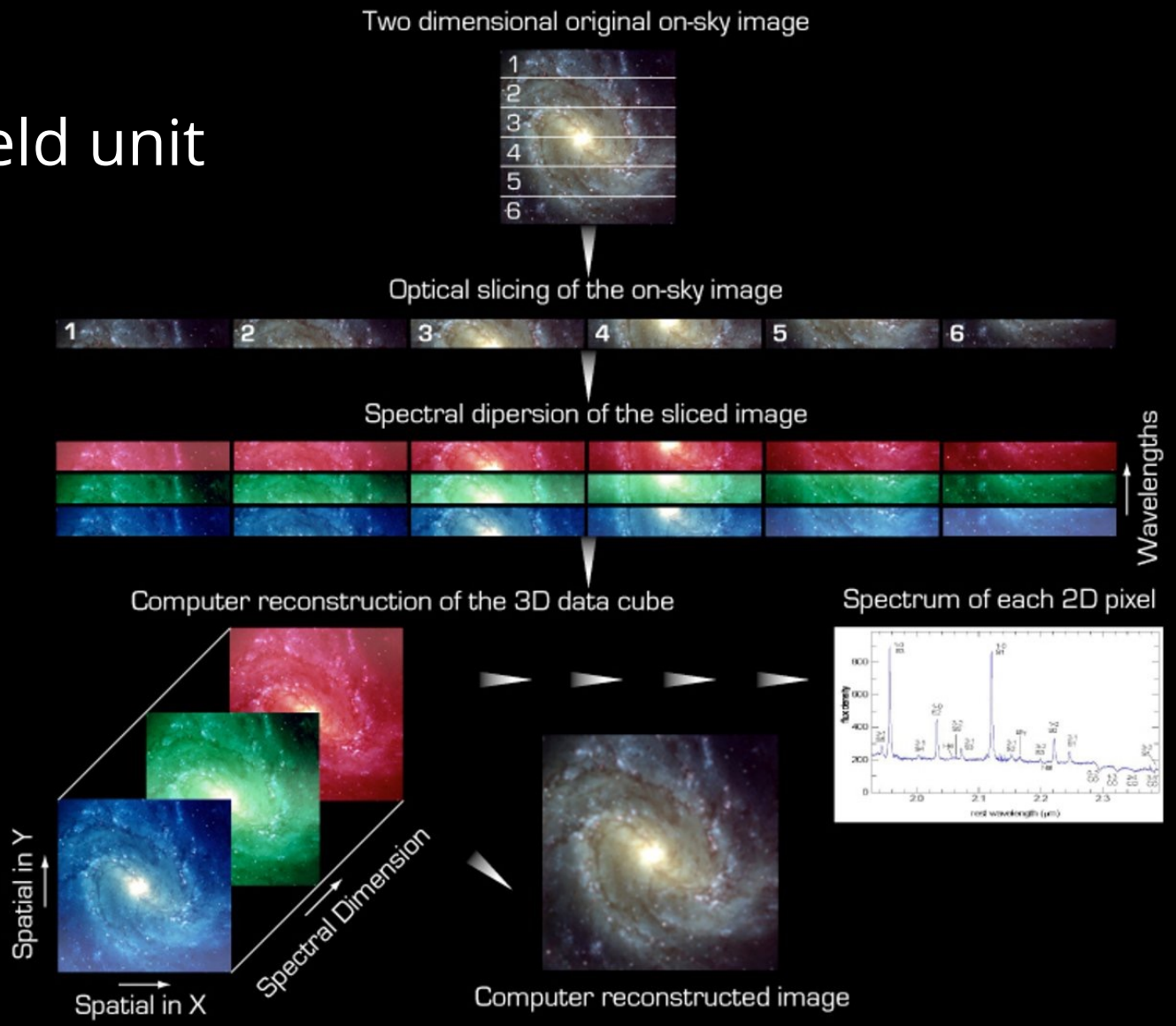



FGS
NIRCam
MIRI
NIRSpec

Overview of JWST capabilities



Integral field unit

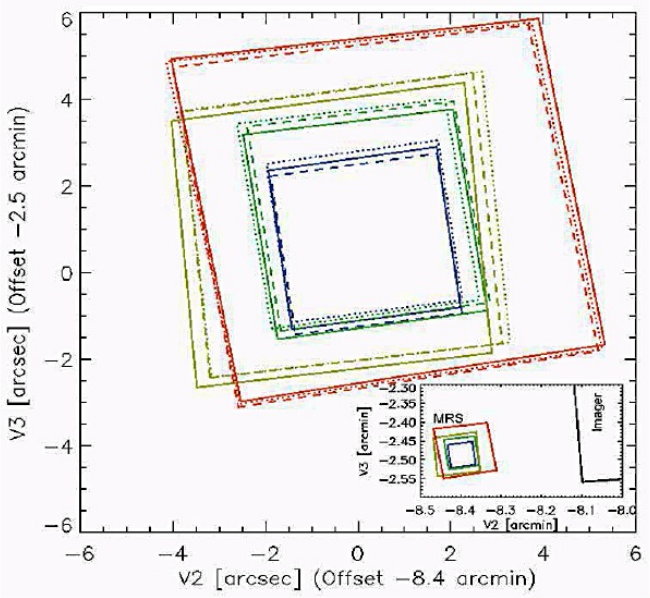


Source: ESO

MIRI capabilities interesting for PPDs

Spectroscopy:

- 5-28.5 μm, R~1300-3700, four channels and three dichroic settings to obtain full spectral coverage
- nested FoV of 3.7" to 7.7"
- line sensitivity ~0.5-100 x 10^{-20} Wm^{-2} (10σ, 2.77hr)



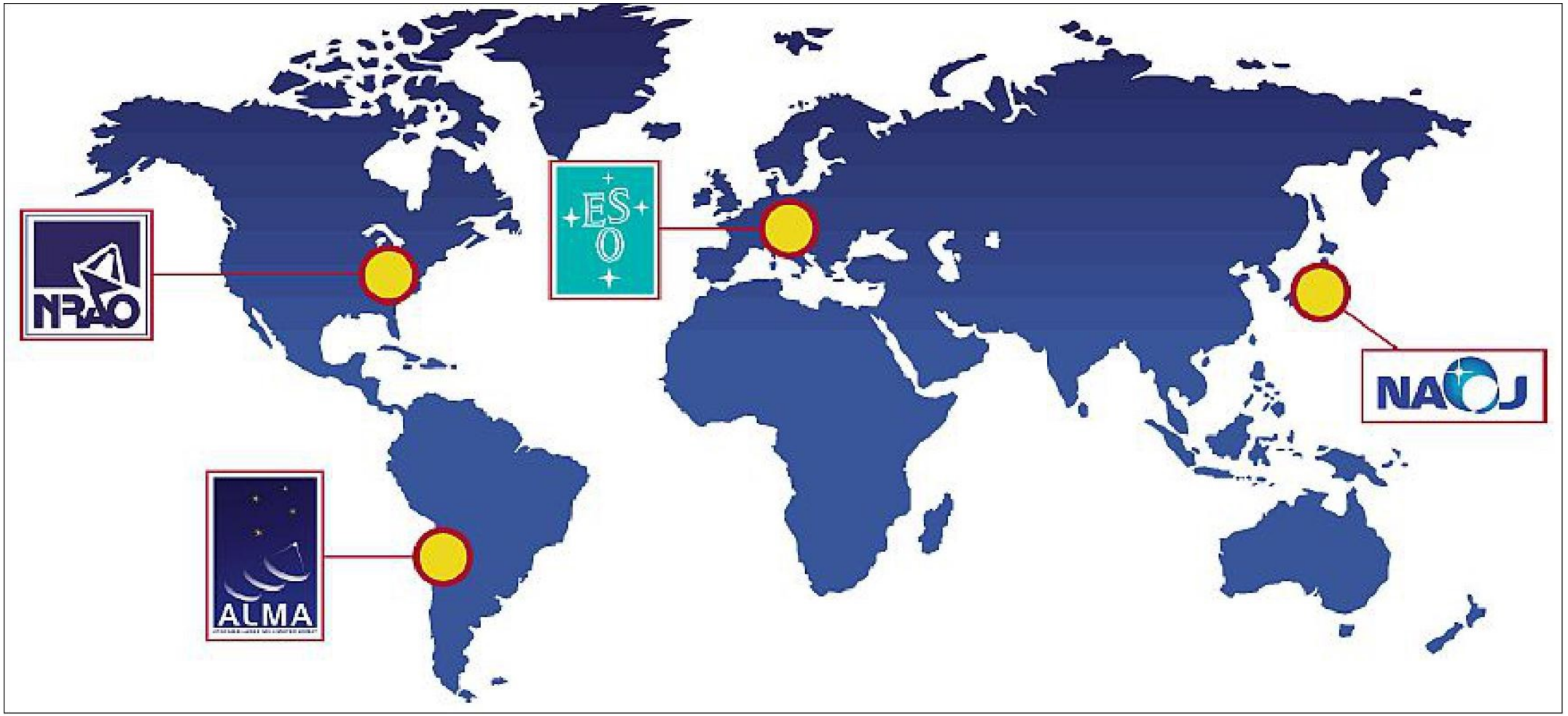
Imaging:

- IFU (FoV 3.7”x7.7”), 0.176”-0.82” spatial resolution
- @140 pc FoV ~520 au x ~1100 au, ~25 au resolution @ 5 μm
- coronagraph IWA 0.33”-0.49” (10.6, 11.3, 15.5 μm), 0.11” resolution

Overview of lecture:

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- JWST
- ALMA
- solids in space


The ALMA site
Credit: ALMA (ESO/NAOJ/NRAO)/L. Calçada (ESO


NRAO
ES
O
NAOJ
ALMA

ALMA TELESCOPE

- Large array: 12m antennas with baselines up to 16 km: highest angular resolution
- Compact array: 12 7m antennas and 4 12m antennas: larger spatial scates
- Spatial resolution: huge range, from 0.5 arcsec to 20 milli-arcsec
- Observing frequencies: receiver bands 1 to 10 (35 – 950 GHz)
- Spectral resolution: up to 0.01 km/s, depends on receiver channel widths

Atmospheric transmission at ALMA site

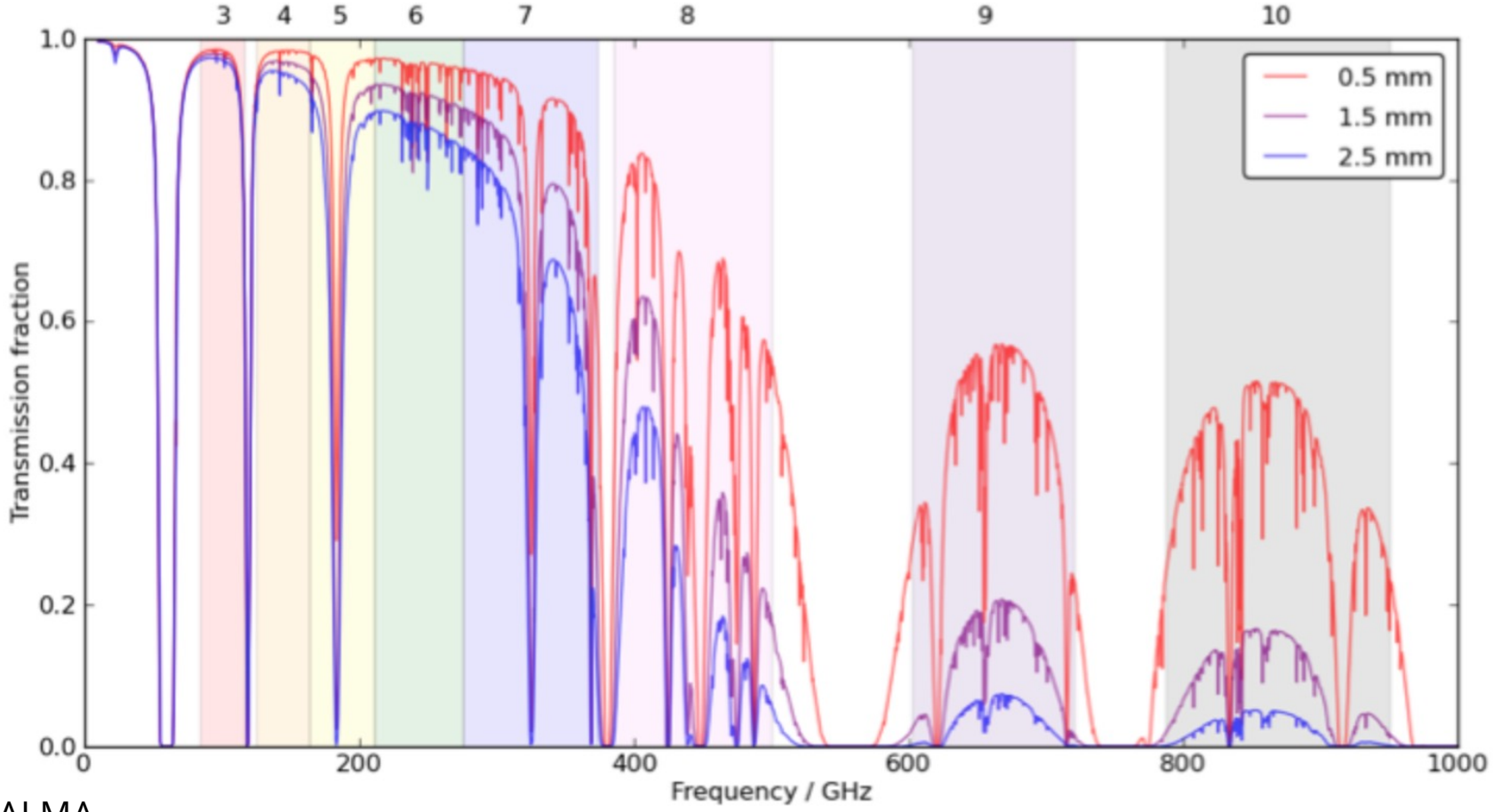
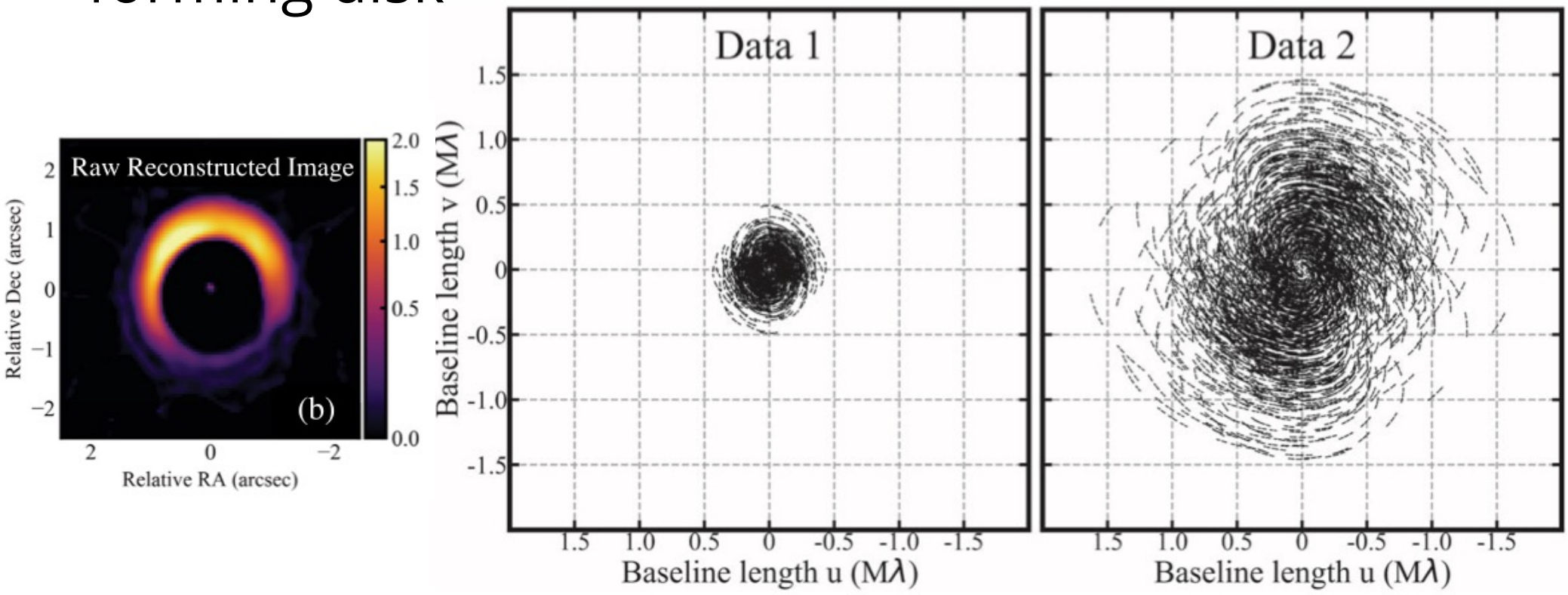


Figure: ALMA

ALMA u,v coverage and image of a planet forming disk



Yamaguchi et al., 2020 ApJ 895

Overview of lecture:

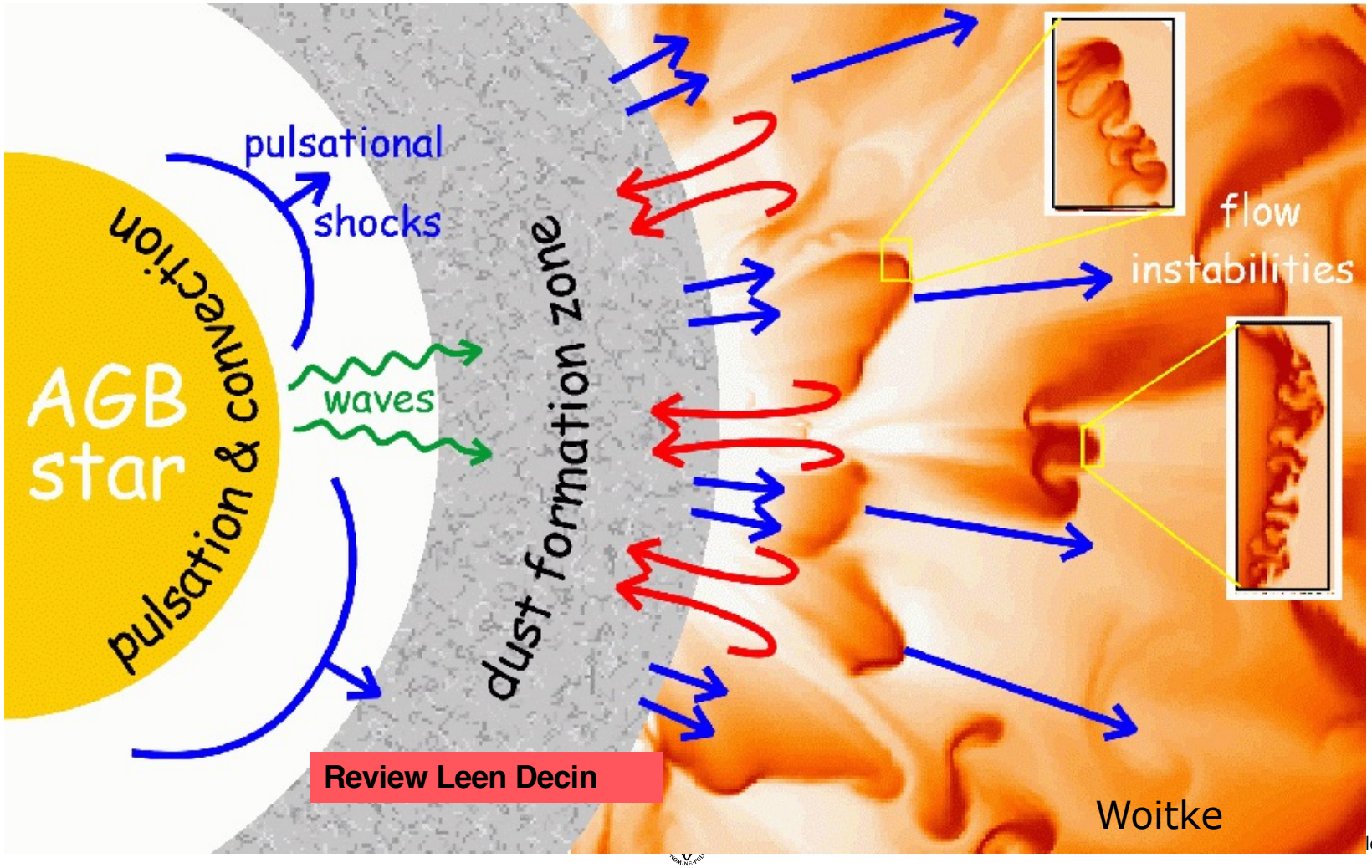
- Introduction
- Diagnostics of gas
- Telescopes: Spectroscopy
- Telescopes: Angular resolution, interferometry
- JWST
- ALMA
- **solids in space**

Solids in space

- Source of opacity: thermal balance of the ISM, molecular clouds, proto-planetary disks
- Provides surface: crucial for the formation of molecules
- Example: formation of H_2 in interstellar clouds
- Building blocks of planets

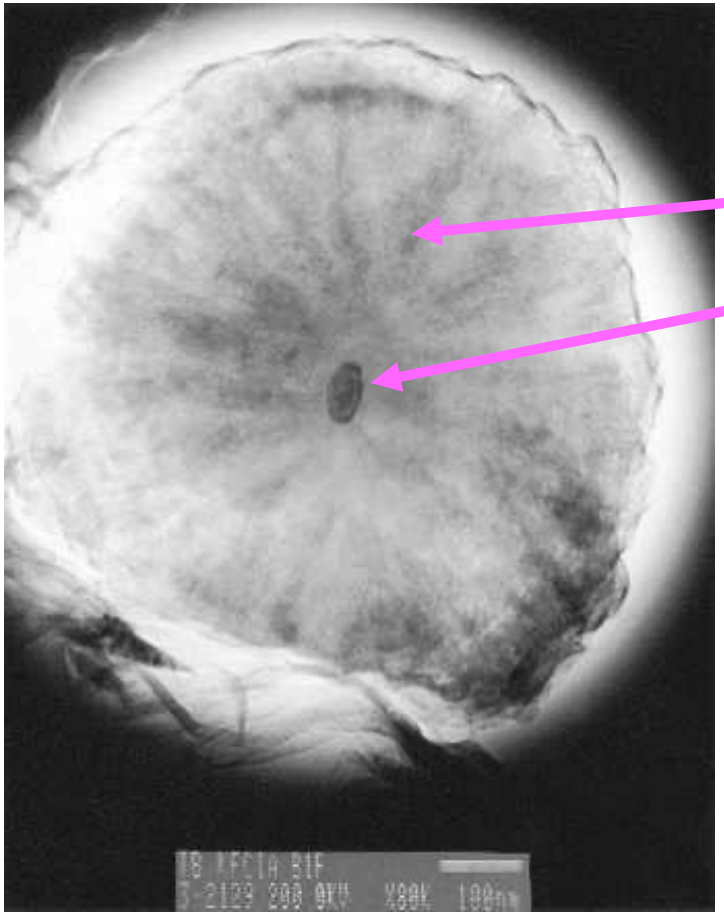
- About 1 % of atoms in interstellar space are locked up in dust
- Dominant species: oxygen-rich and carbon-rich dust
- Main sources of dust: evolved stars (AGB, RSG, WR) , supernovae, novae
- Dust budget problem: dust gets destroyed in the ISM at higher rate than produced by dust factories
- Dust formation in the ISM must occur (molecular clouds)

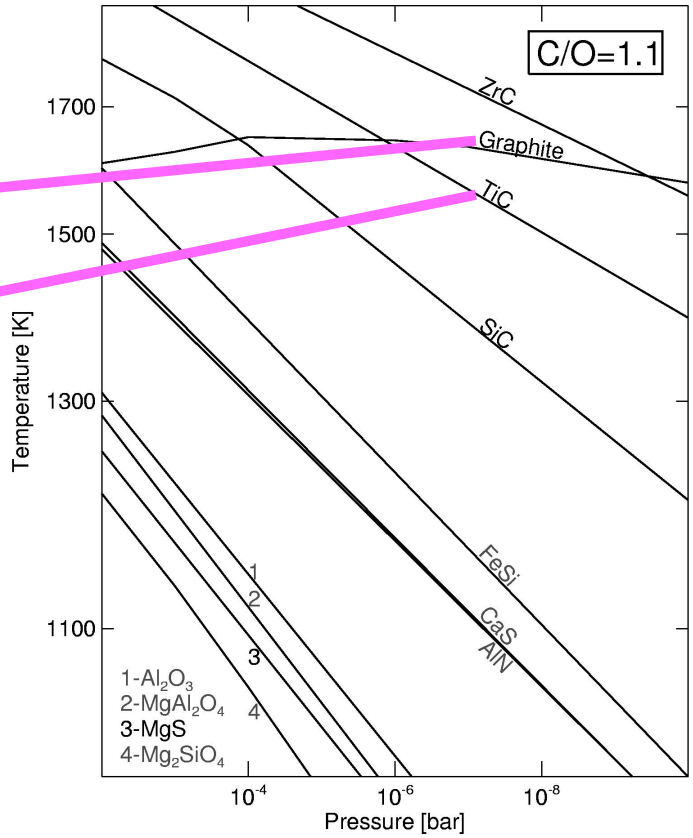
DUST PRODUCTION IN RED GIANT WINDS



lecture

C-RICH CONDENSATION SEQUENCE





Bernatowicz et al.

Lodders & Fegley

Planetary nebula



NGC6543/Cat's Eye Nebula

Space Telescope/Corradi

Supernova Remnant



Cas A Supernova Remnant

De Looze et al.

Relative contribution of evolved stars and massive stars to dust production?

Sources of stardust in the interstellar medium

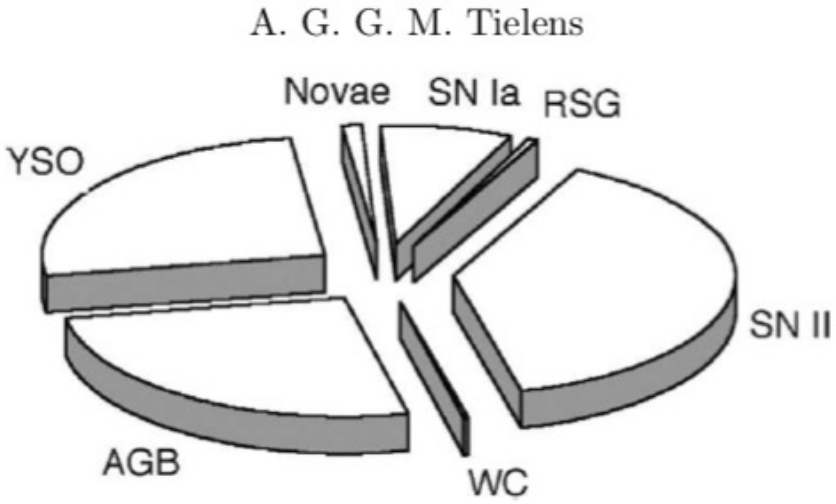
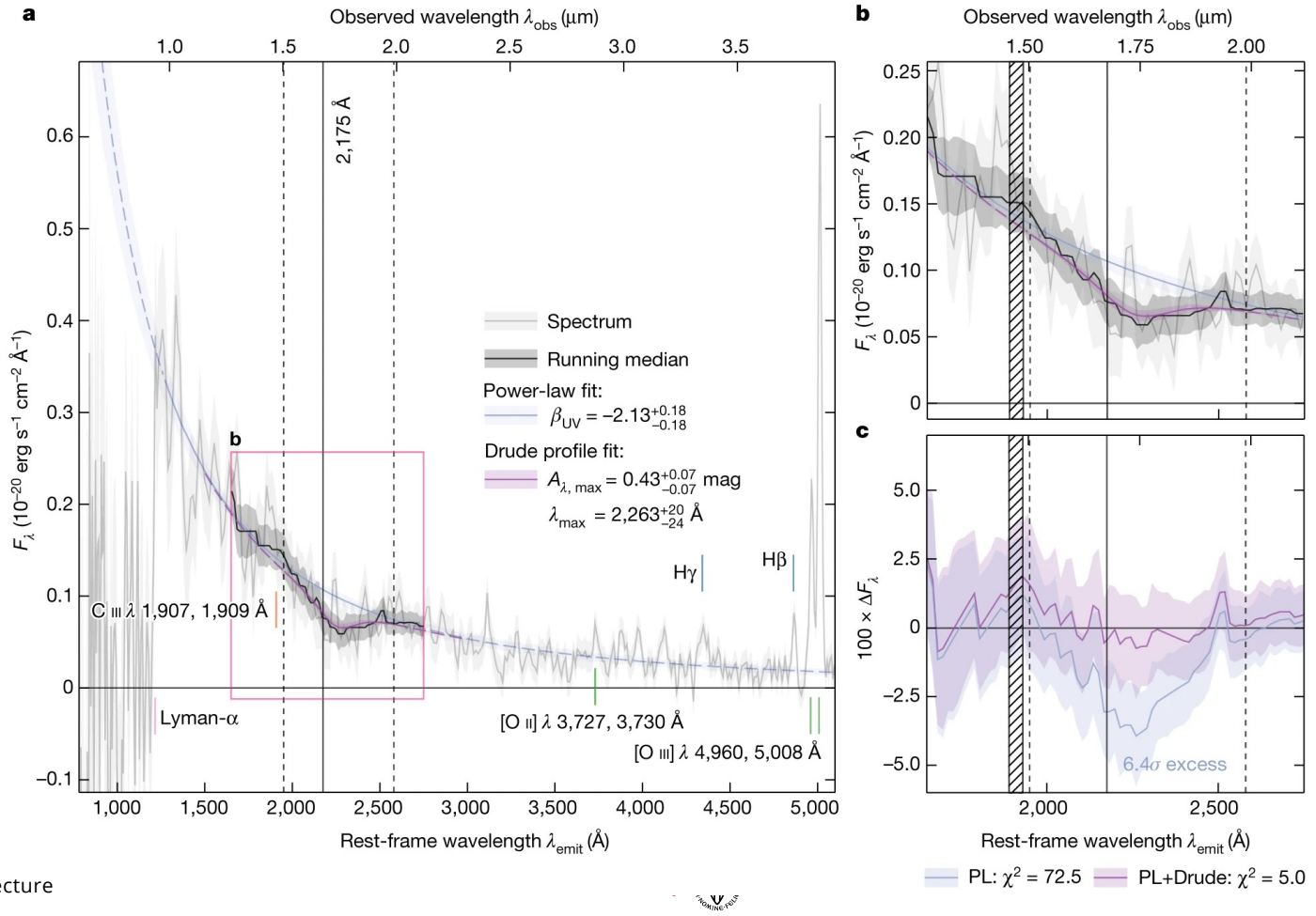


Figure 2. The contribution of different stellar sources to the interstellar dust budget. For details, see § 3. Note that all these values are very uncertain. (Taken from Tielens 2001).

SUPERNOVAE LIKELY DOMINATE DUST PRODUCTION IN THE EARLY UNIVERSE



Witstok et al 2023 nature 621, 267

Overview of lecture:

- Introduction
- Diagnostics of gas
- Telescopes: Spectroscopy
- Telescopes: Angular resolution, interferometry
- JWST
- ALMA
- **solids in space: scattering, absorption, emission**

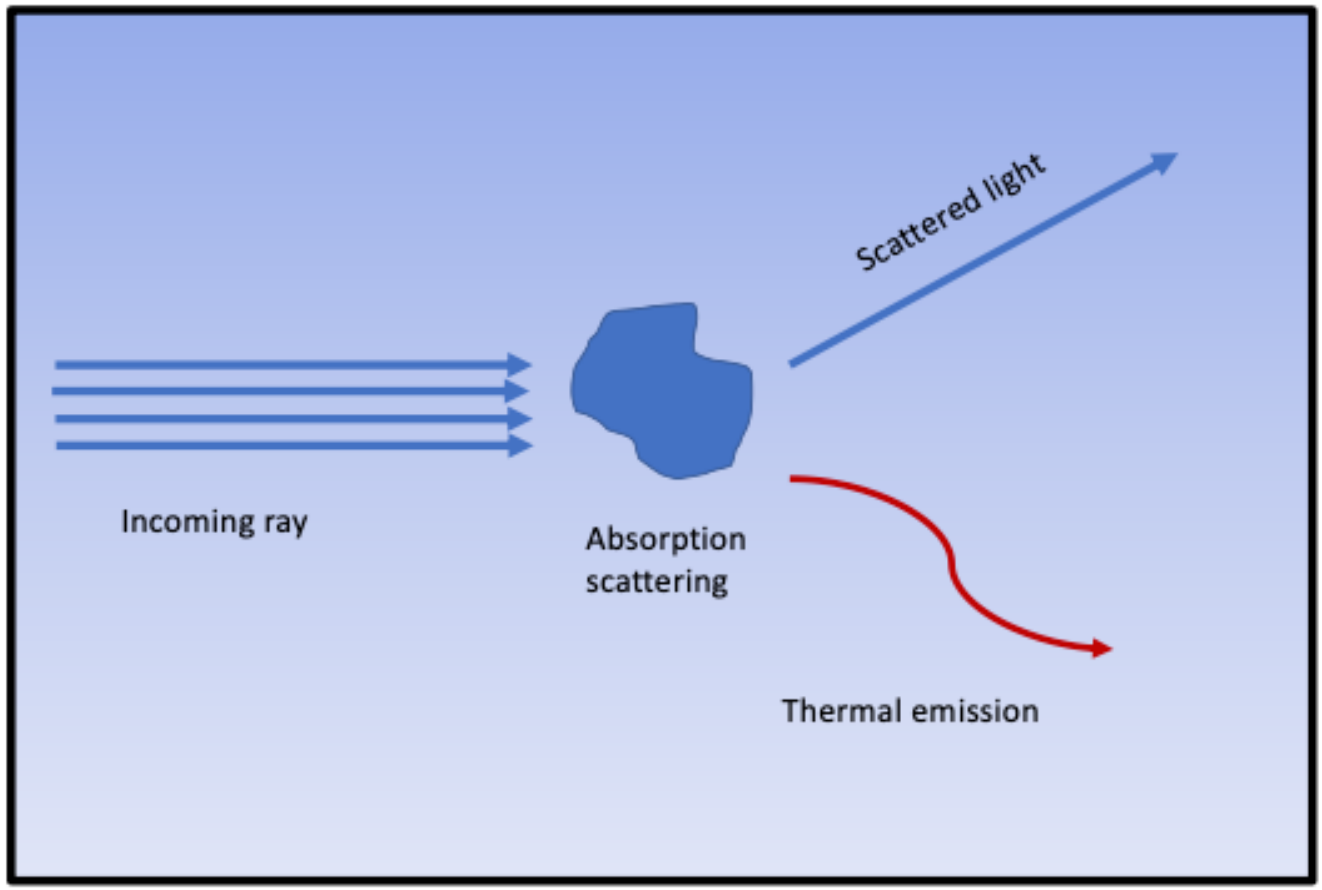

Scattered light
Incoming ray
Absorption
scattering
Thermal emission



Figure: Scattering and absorption in the Horsehead Nebula

Scattering of small Dust grains

thermal emission of large cold dust grains

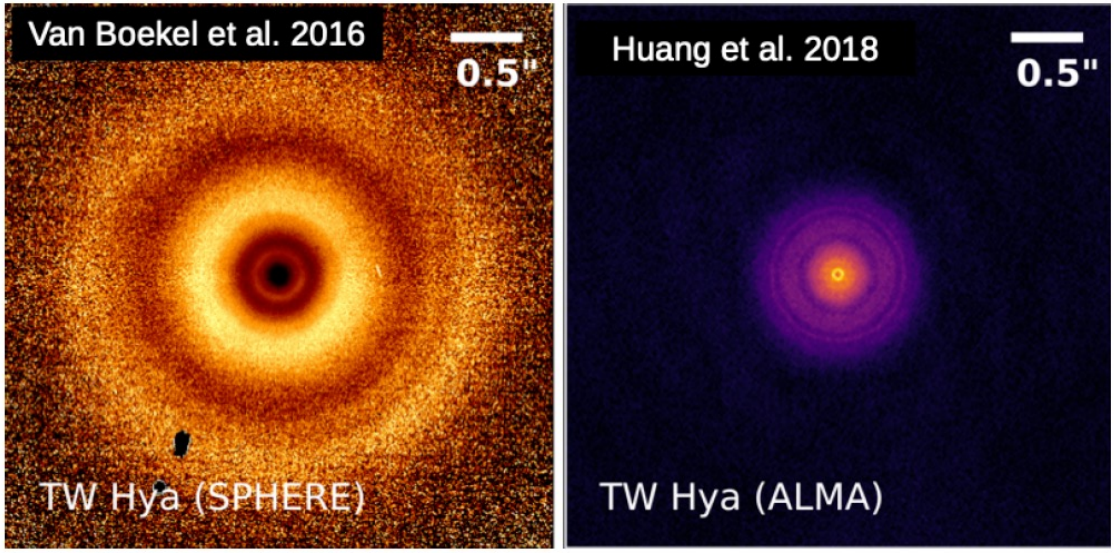
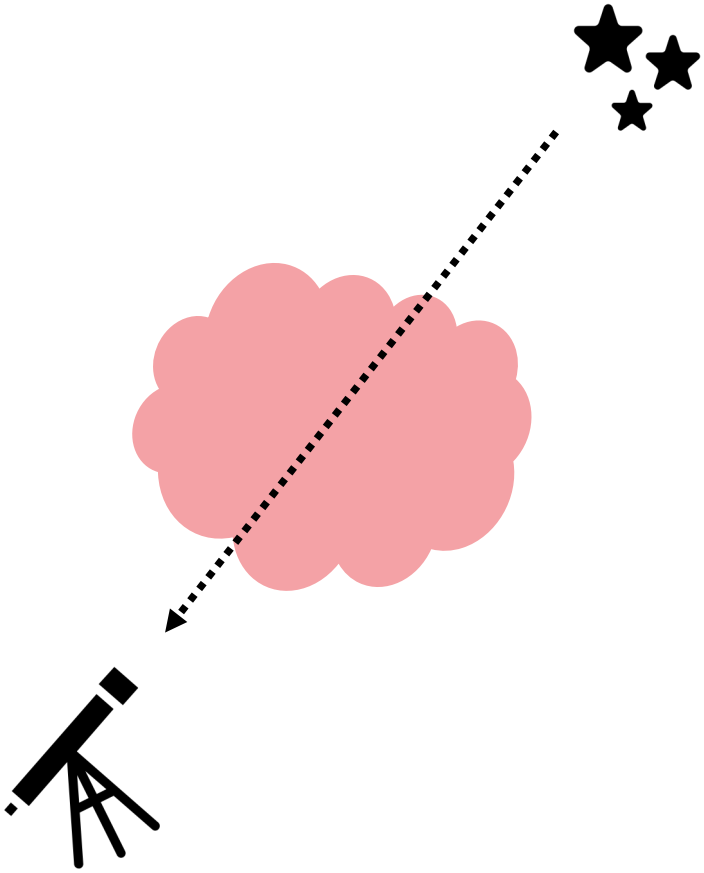


Figure: near-IR scattering and mm wave emission from the disk of TW Hya

$$I_\nu = I_\nu^0 e^{-\tau(\nu)} + B_\nu (T_{cloud}) (1 - e^{-\tau(\nu)})$$

$$\tau(\nu) = n\ L\ \kappa(\nu) = N\ \kappa(\nu)$$

I_ν = intensity observed
I_ν^0 = intensity emitted
$B_\nu (T_{cloud})$ = source function of gas or dust species in cloud
n = particle density in cm^{-3} or g cm^{-3}
L = line of sight length in cm
$\kappa(\nu)$ = opacity in cm^2 or cm^2/g



Assume spherical grains with radius a and number density $n_{\rm d}$ cm^{-3} along line of sight with length L.

$$\mathrm{d}I_\nu \;=\; -I_\nu n_{\rm d} C_{\rm ext} \mathrm{d}L \qquad (1)$$

$C_{\rm ext}$ extinction cross-section:

- absorption
- scattering

Integration of equation 1 gives:

$$I_\nu \;=\; I_{\nu 0}\; e^{-\tau} \qquad (2)$$

with $I_{\nu 0}$ the intensity of the light emitted by the star I_ν near the star ($L = 0$), and

$$\tau \;=\; n_{\rm d} C_{\rm ext} L \;=\; N_{\rm d} C_{\rm ext} \qquad (3)$$

τ: optical depth due to extinction

We introduce:

$$Q_{\rm ext} \;=\; Q_{\rm abs} \;+\; Q_{\rm sca} \;=\; \frac{C_{\rm ext}}{\pi a^2} \tag{4}$$

extinction efficiencies Q depend on:

- a dimensionless size parameter x

$$x \;=\; \frac{2\pi a}{\lambda} \tag{5}$$

- a parameter describing the composition of the particles: the complex refractive index of the grain material;
- the shape of the particle (sphere, ellipsoid, irregular);

$$m(\lambda) \;=\; n(\lambda) \;-\; ik(\lambda) \tag{6}$$

$n(\lambda)$ and $k(\lambda)$: optical constants.

$$x = \frac{2\pi a}{\lambda} \tag{7}$$

- x $<<$ 1: Rayleigh regime, particle much smaller than the wavelength: *Rayleigh* scattering
- x $\sim$ 1: no simple solutions possible
- x $>>$ 1: Geometric optics regime

$$m(\lambda) = n(\lambda) - ik(\lambda) \tag{8}$$

- Real part $n(\lambda)$: scattering
- Imaginary part $k(\lambda)$: absorption

Consider wave traveling through a medium with a complex refractive index $m(\lambda)$. In vacuum:

$$A = A_0 exp\{i(\omega t - \hat{k}x)\} \tag{9}$$

In medium with complex refractive index m:

$$A = A_0 exp\{i(\omega t - \hat{k}xn)\} exp\{-\hat{k}kx\} \tag{10}$$

Second term in equation 10: absorption, related to the imaginary part k of the complex refractive index.
for isolators: field cannot easily penetrate particle, so $k \approx 0$, and in approximation:

$$m = n \approx c_1 + c_2\lambda^{-2} \tag{11}$$

Mie theory

- interaction of EM radiation with **spherical** dust particle
- solution to boundary value problem, EM field must be continuous across boundary
- Mie theory: series expansion in size parameter x = 2 π a/ λ
- Rayleigh scattering is retrieved for small values of x:

$$Q_{abs} = 4xIm\frac{(\epsilon - 1)}{(\epsilon + 2)} \tag{14}$$

$$Q_{sca} = \frac{8}{3}x^4|\frac{(\epsilon - 1)}{(\epsilon + 2)}|^2 \tag{15}$$

where ϵ = di-electric constant

$$\epsilon = \epsilon_1 + i\epsilon_2 = m^2 \tag{16}$$

$$\epsilon_1 = n^2 - k^2 \tag{17}$$

$$\epsilon_2 = 2nk \tag{18}$$

Simple recipe to remember:

$$Q_{\mathrm{abs},\nu} \simeq \begin{cases} 1 & \text{for} \quad \lambda \leq 2\pi a \\ \frac{2\pi a}{\lambda} & \text{for} \quad \lambda > 2\pi a \end{cases} \quad , \quad Q_{\mathrm{scat},\nu} \simeq \begin{cases} 1 & \text{for} \quad \lambda \leq 2\pi a \\ \left(\frac{2\pi a}{\lambda}\right)^4 & \text{for} \quad \lambda > 2\pi a \end{cases}$$

Ivezic et al., MNRAS 291, 121; (lecture notes C. Dullemond)

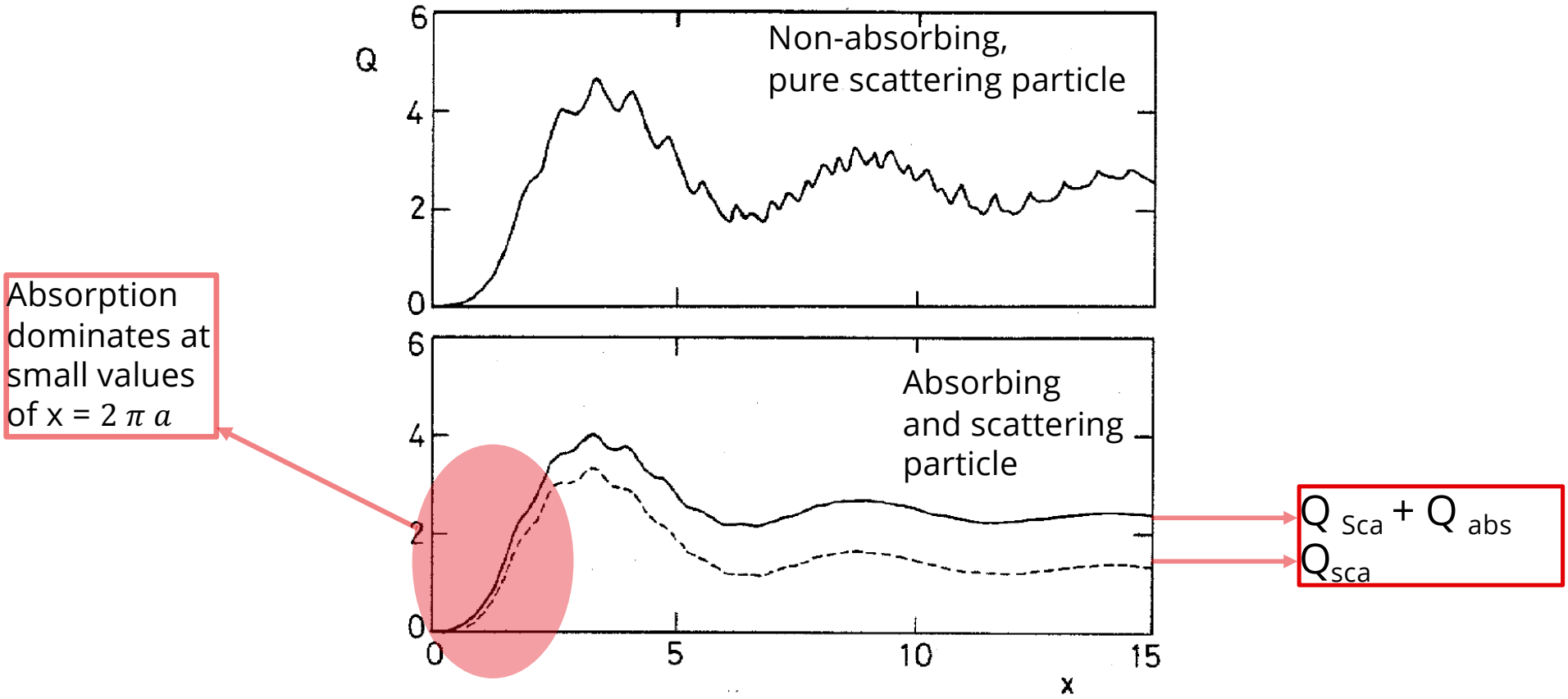


Figure: *The efficiency factors Q_{ext} and Q_{sca} are plotted against x for spherical grains. Top panel: m = 1.6-0.0i, so $Q_{ext} = Q_{sca}$. The lower panel: m = 1.6 - 0.05i; the solid line represents Q_{ext}, the dashed line gives Q_{sca}.*

Example of dust opacities, mixture of carbon and silicate

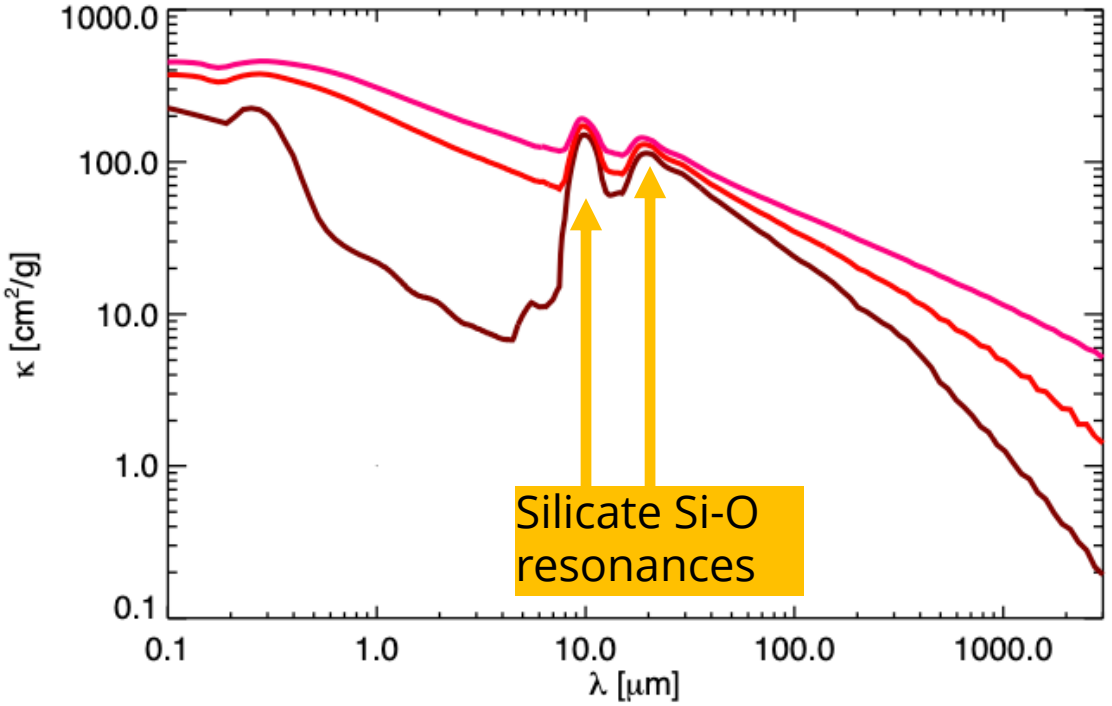


Figure: M. Min (DIANA lectures)

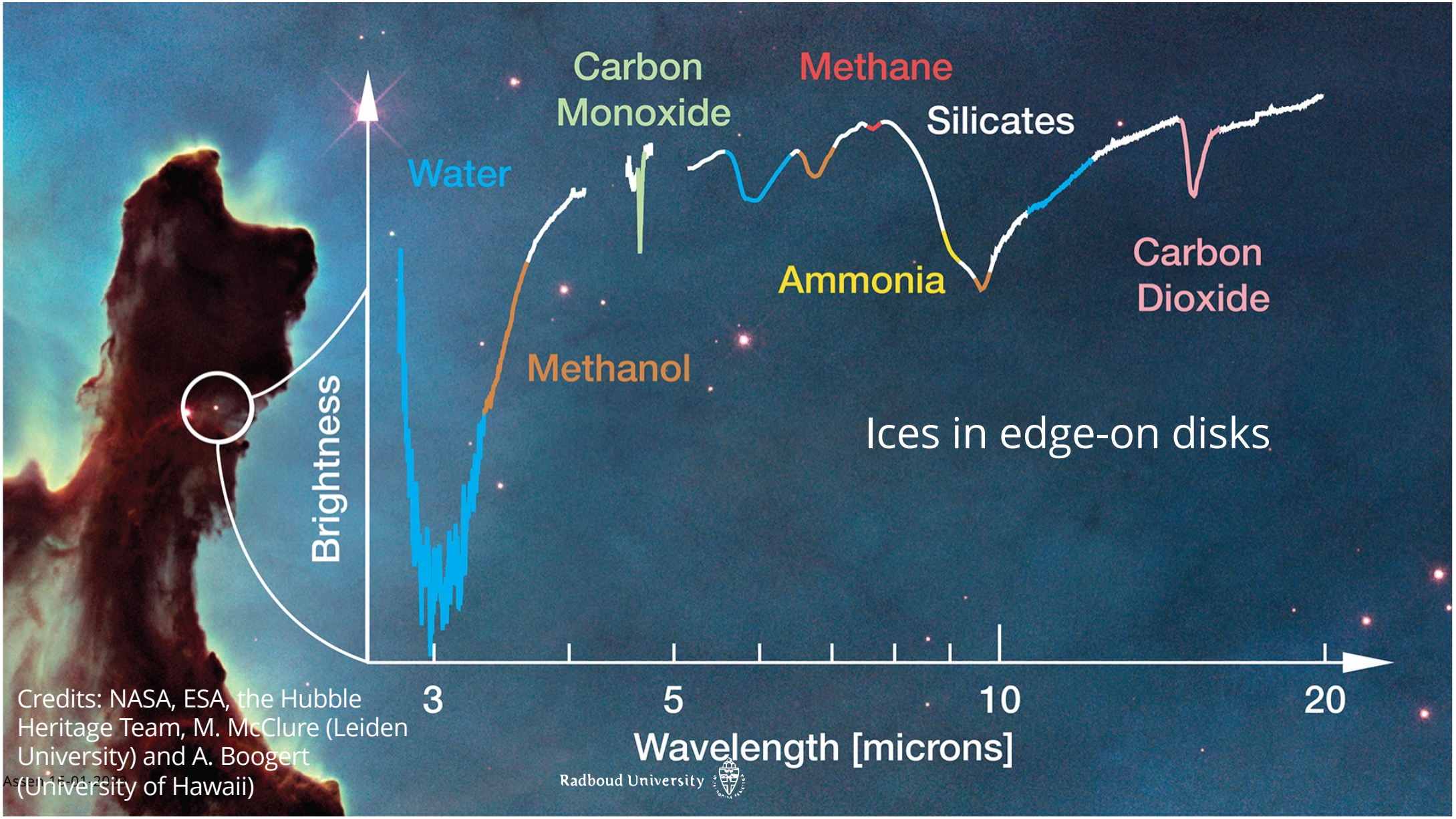
Measuring dust masses

- Assume dust is cold → Rayleigh-Jeans tail of black body
- Assume dust is optically thin
- Assume dust grains are optically thin
- Guess the dust opacity κ_ν (depends on where you are!)

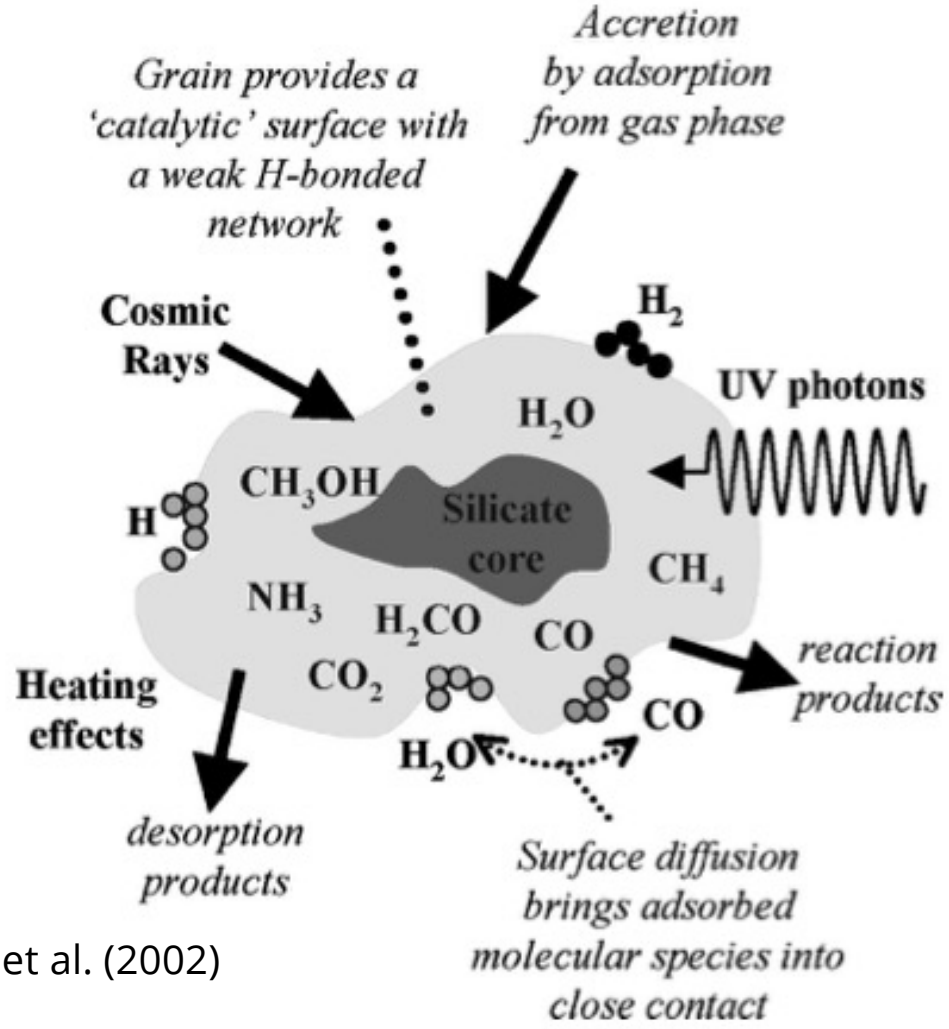
$$\text{Flux} = \frac{B_\nu\,(T_{dust})\,\kappa_\nu\,M_{dust}}{D^2}$$

Overview of lecture:

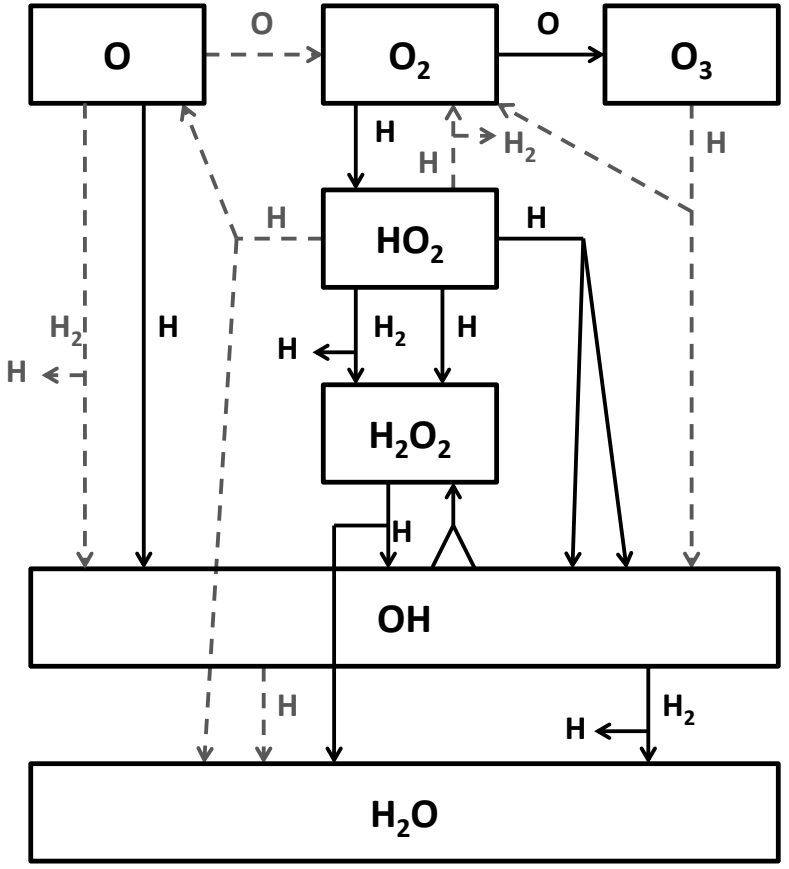
- Introduction
- Diagnostics of gas
- Telescopes: Spectroscopy
- Telescopes: Angular resolution, interferometry
- JWST
- ALMA
- **solids in clouds and disks: ices and refractory dust**


Carbon Monoxide
Methane
Silicates
Water
Ammonia
Carbon Dioxide
Methanol
Brightness
Ices in edge-on disks
3
5
10
20
Wavelength [microns]
Credits: NASA, ESA, the Hubble Heritage Team, M. McClure (Leiden University) and A. Boogert (University of Hawaii)
Radboud University

Interstellar ice chemistry



Fraser et al. (2002)



Cuppen et al. (2010)

Molecules in ices show vibrational bands, no rotation

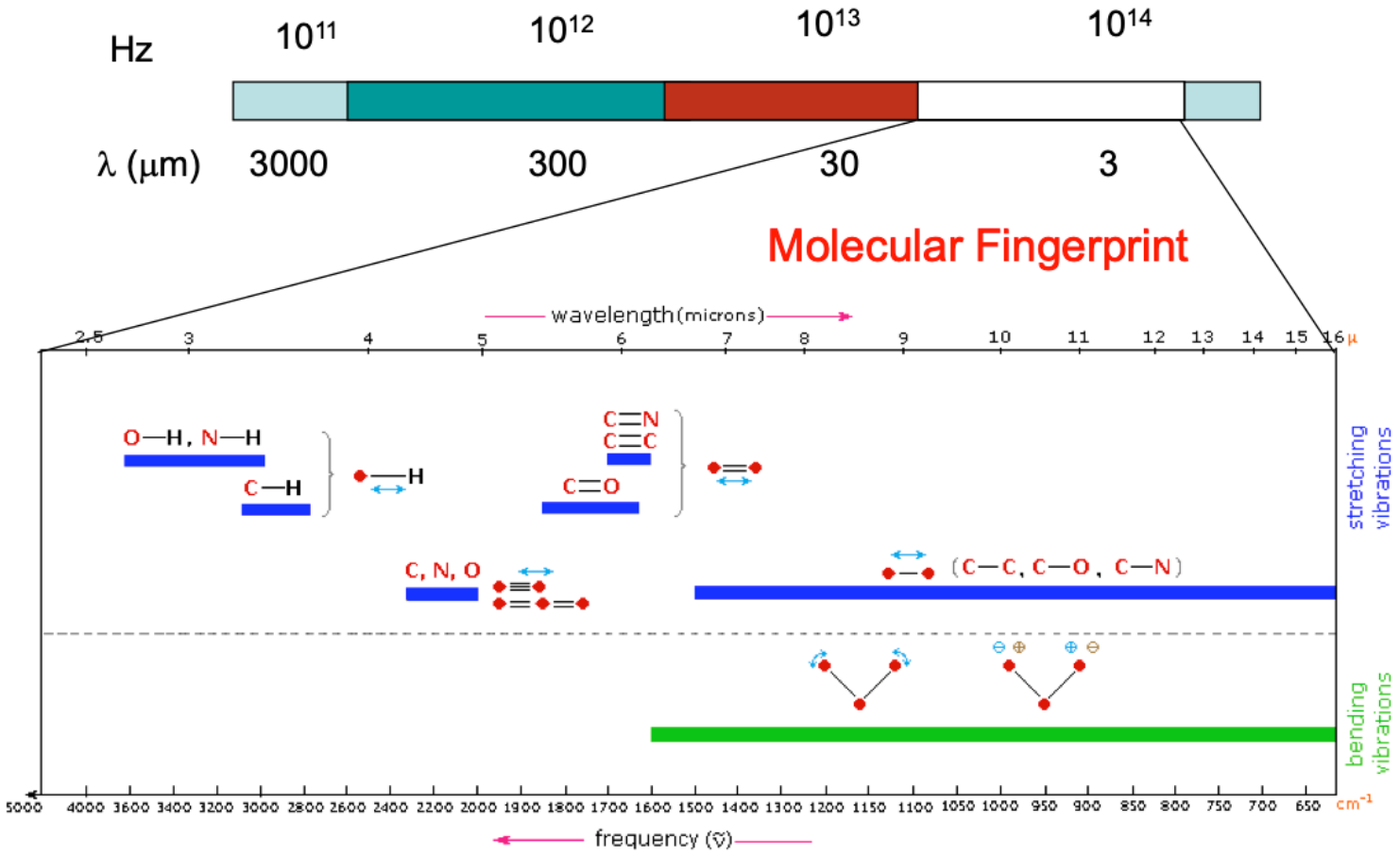
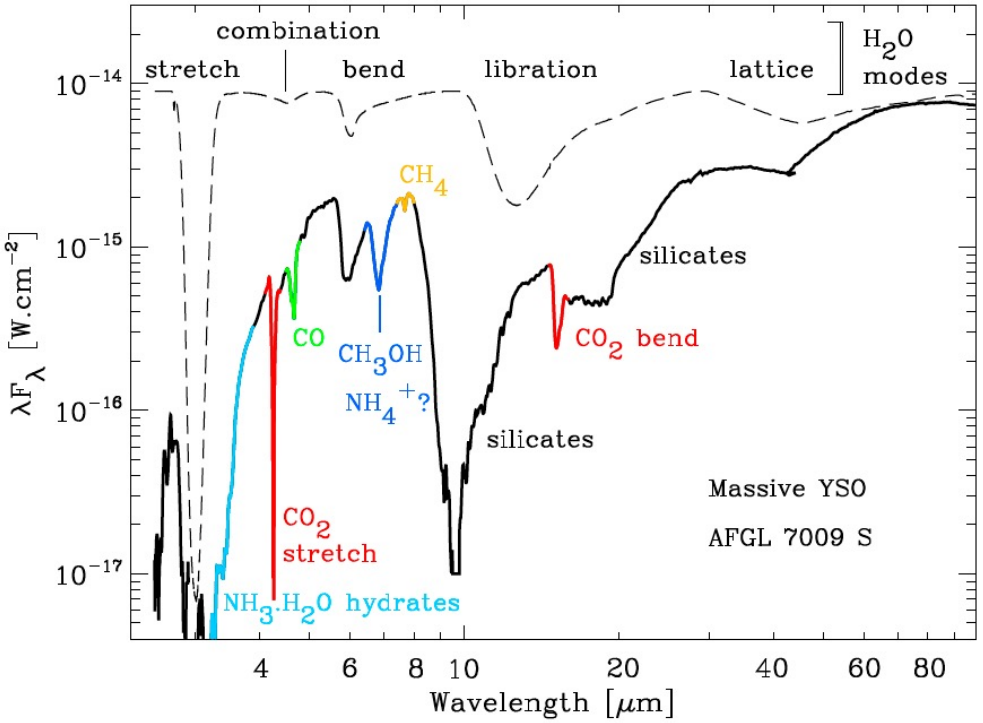
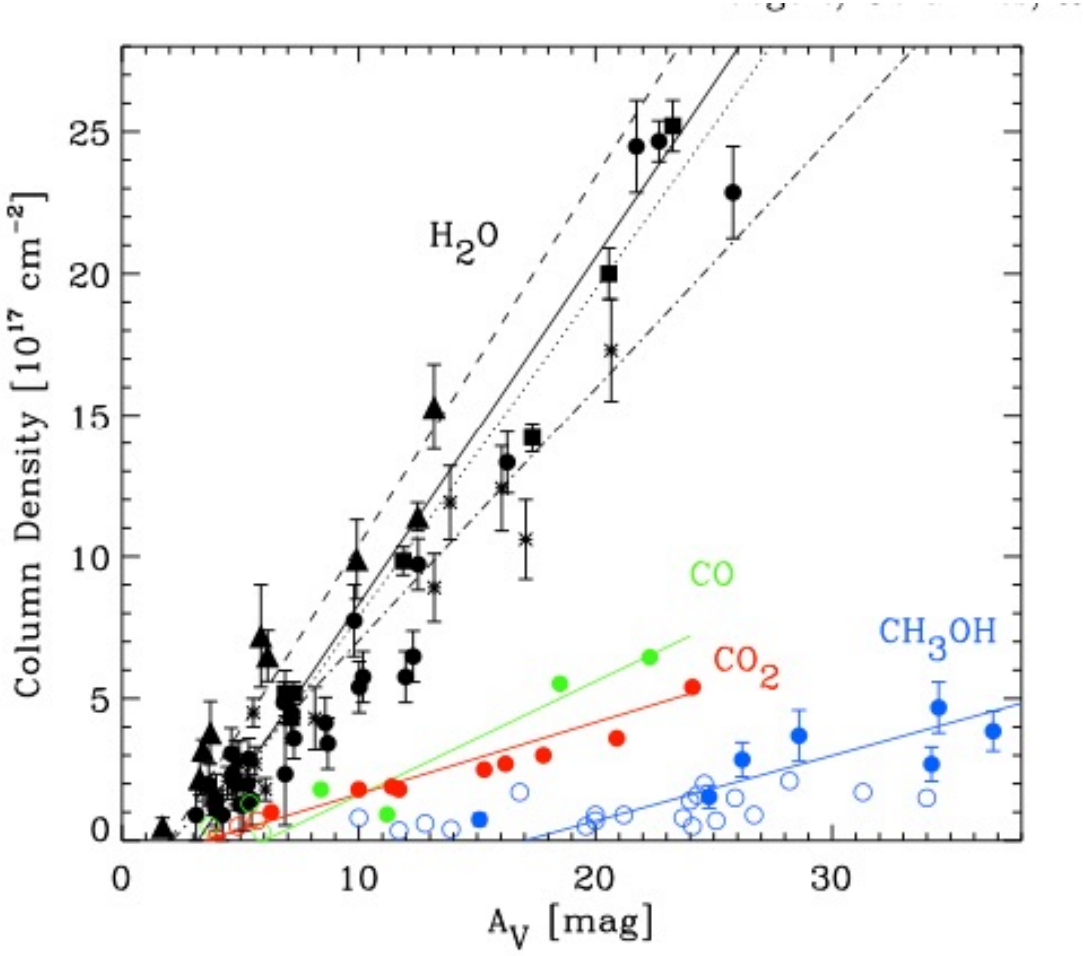


Figure: Redlich

Interstellar ices



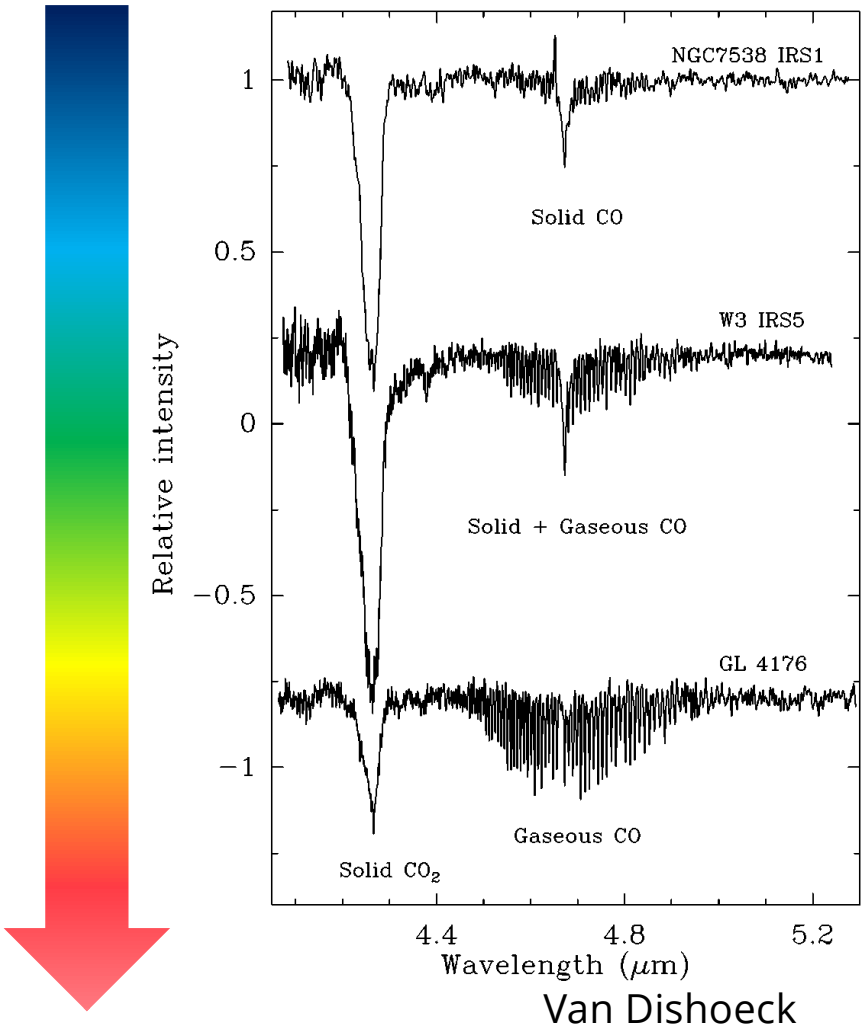


Boogert et al. 2015

From clouds to protostars

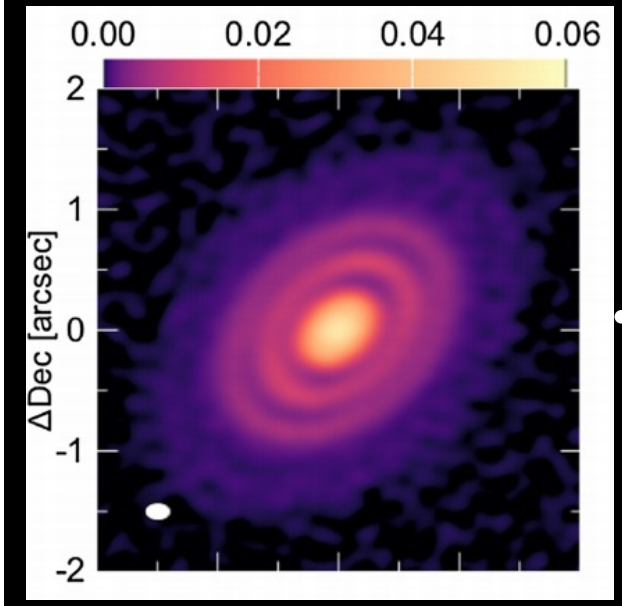
Increase in temperature

Ices evaporate

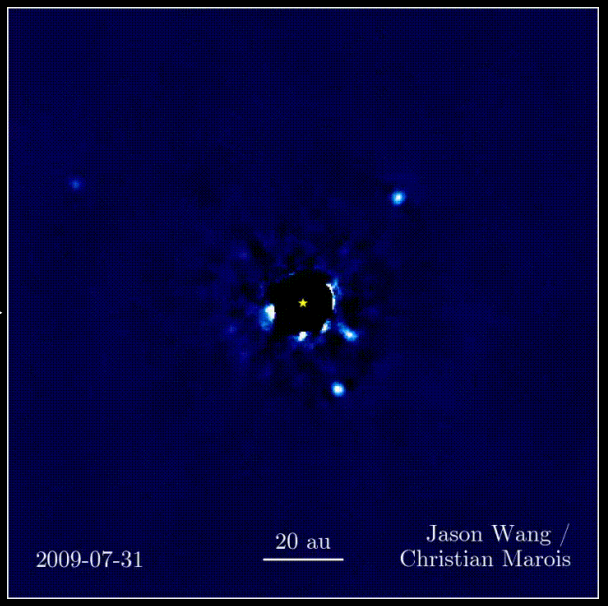


Van Dishoeck

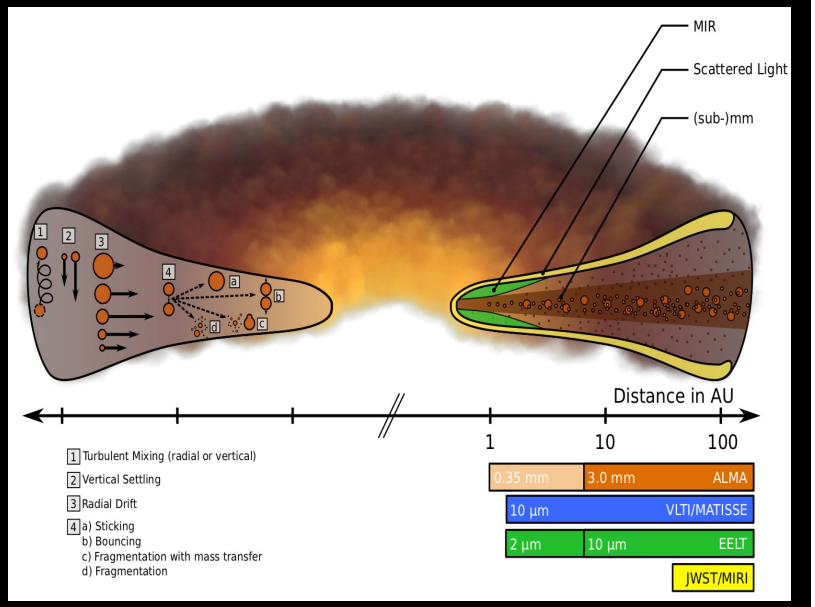
PLANET FORMING DISKS



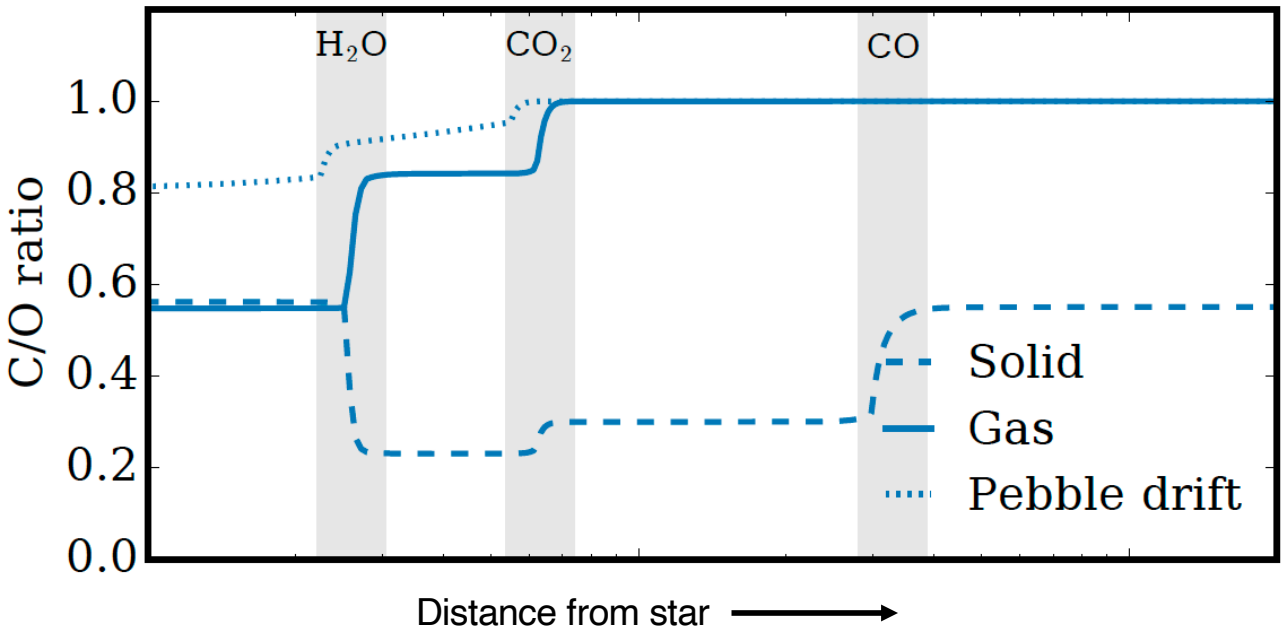
Isella et al. 2016



HR 8799



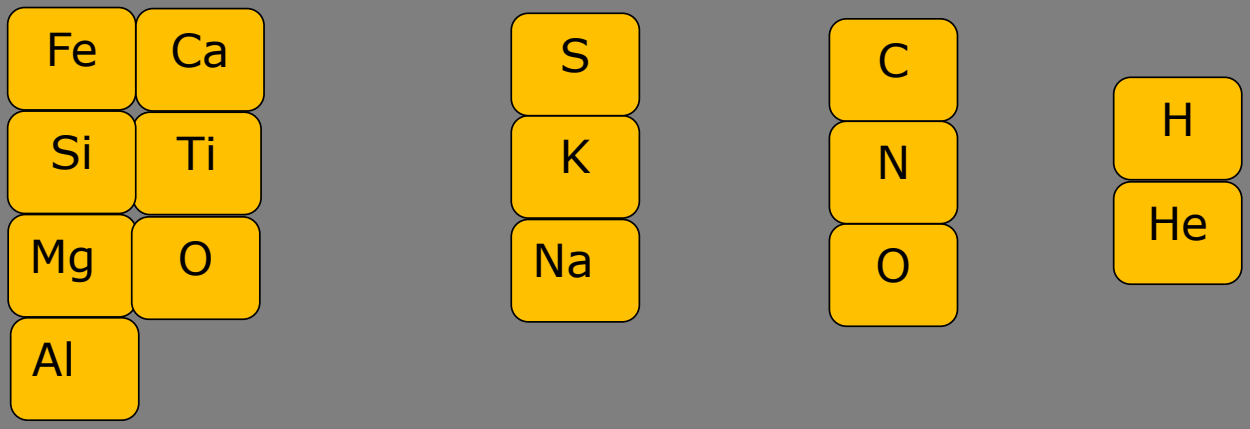
Chemical composition of atmosphere depends on where planet is formed



Oberg; figure from Madhusuthan (2020)

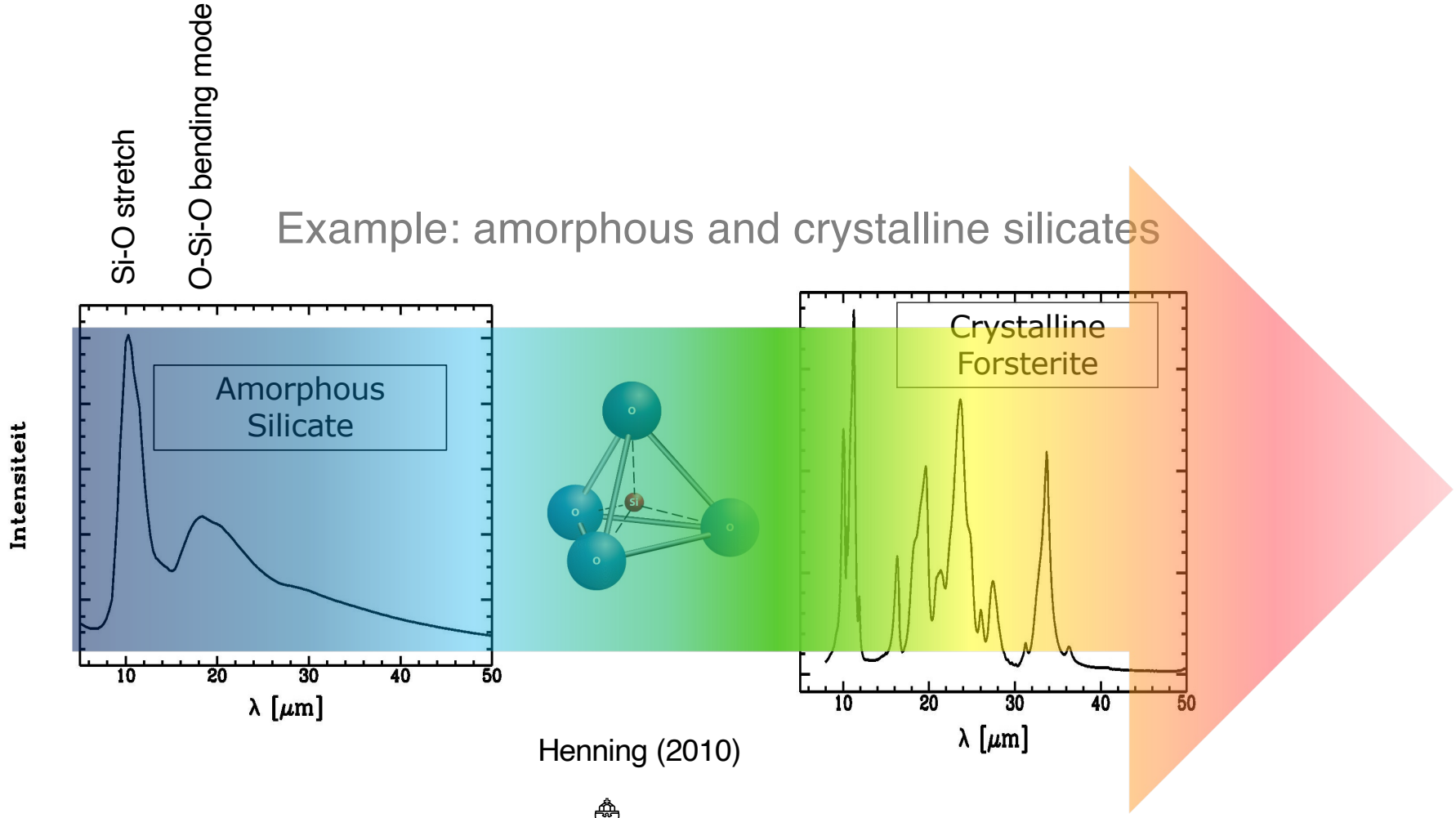
Rock-forming elements, in rocky planets or core of gas giants

Volatile elements, envelope of gas giants

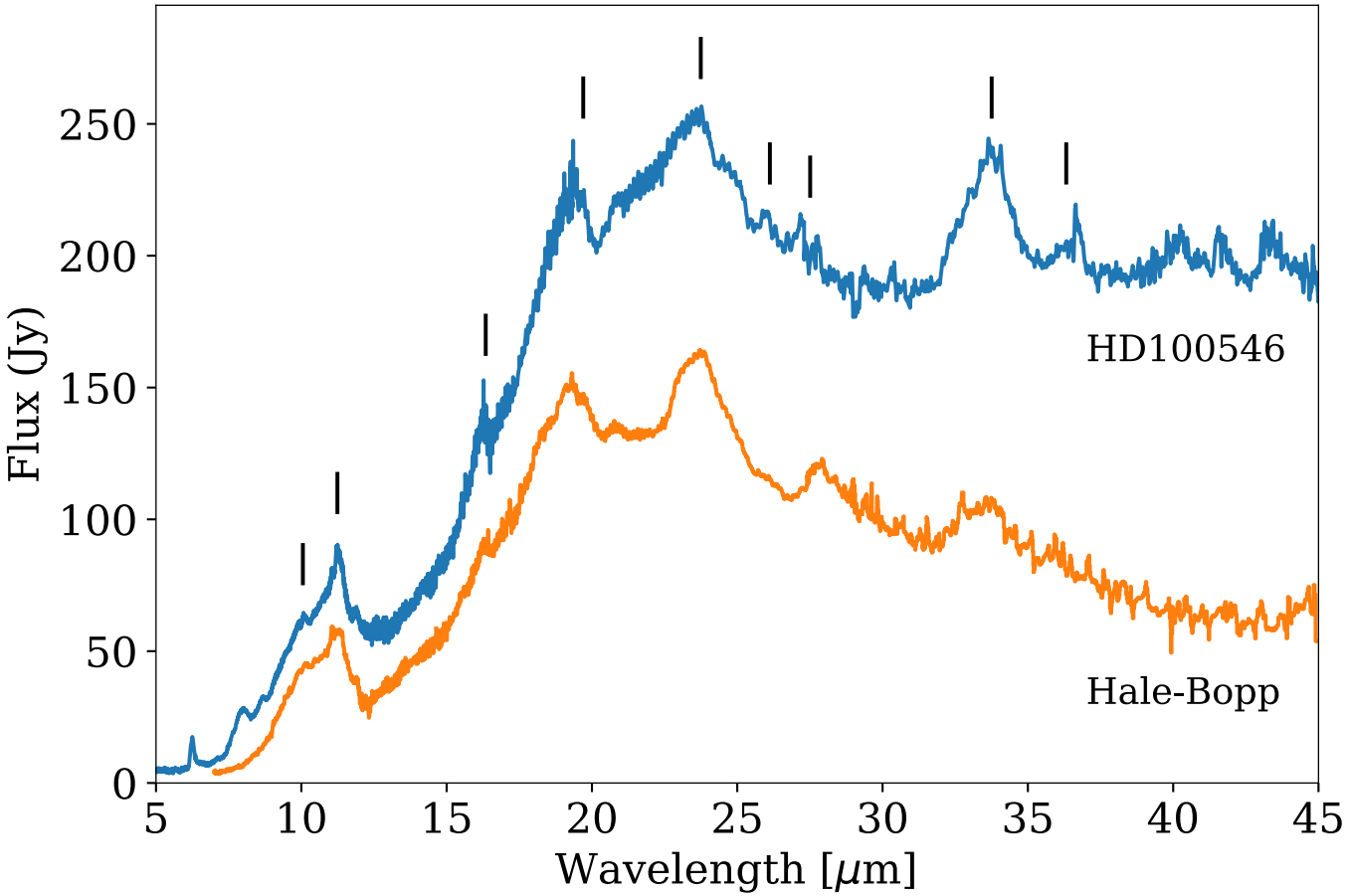


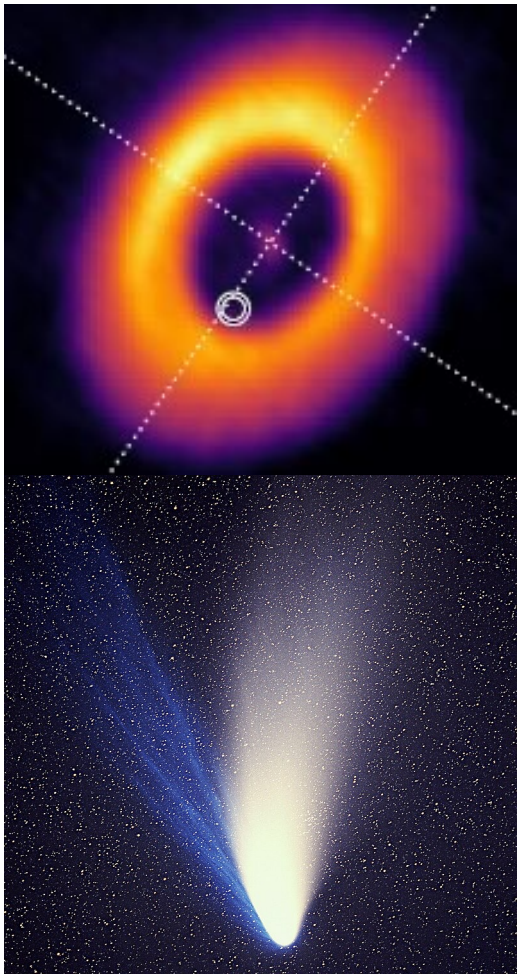
gas giant atmospheres get ”polluted” by the accretion of pebbles and planetesimals, traces formation history

CRYSTALLINE SILICATES TRACE DUST THERMAL HISTORY



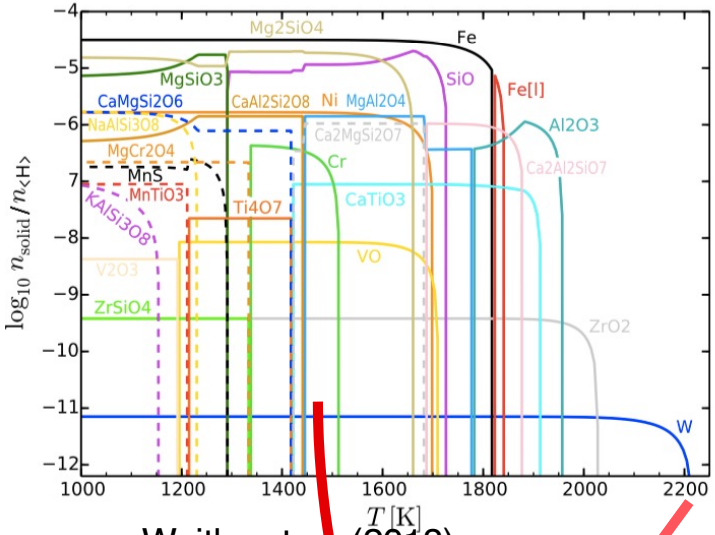
CRYSTALLINE SILICATES IN COMETS AND DISKS





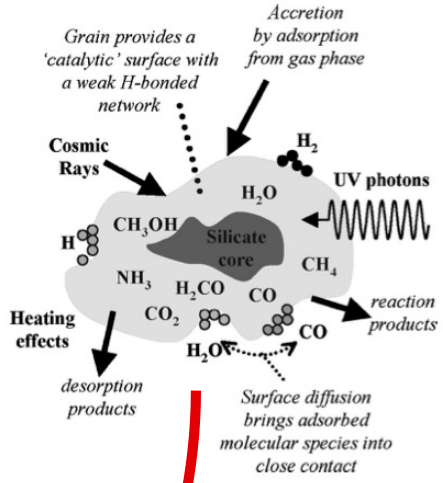
Hale-Bopp image: By E. Kolmhofer, H. Raab; Johannes-Kepler-Observatory, Linz, Austria; HD100546: Pineda et al. 2019

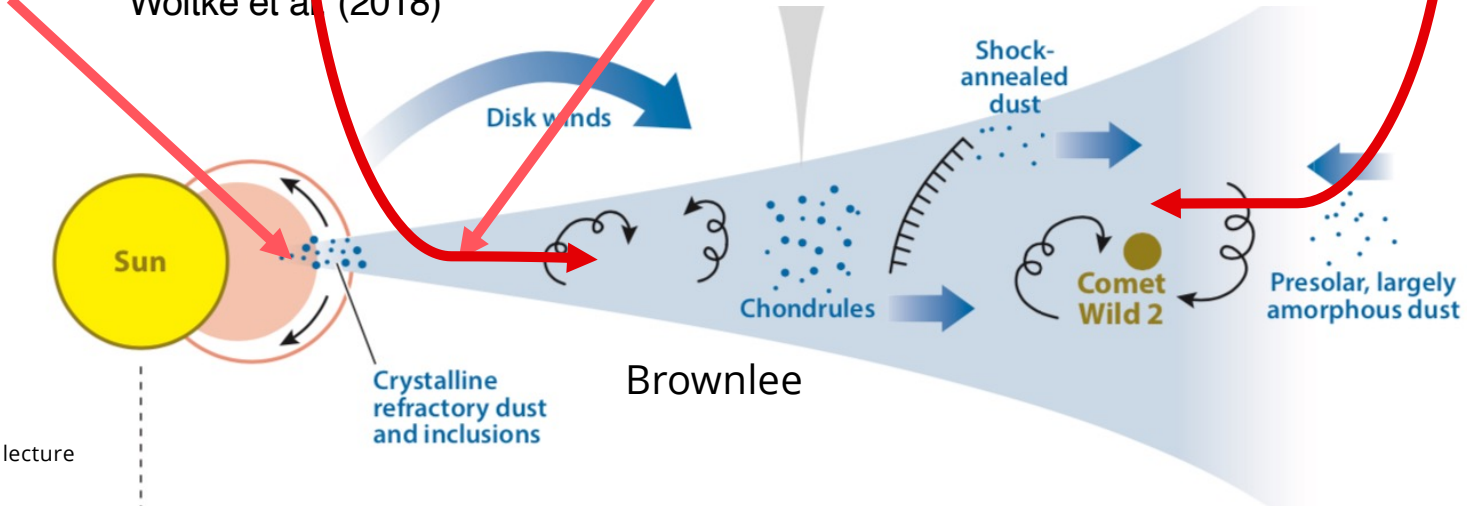
chemical equilibrium in the inner disk



Woitke et al. (2018)

inherited volatile ices from molecular cloud





Brownlee

SOLIDS IN DISKS

- Strongly mixed solid reservoir in disks
- Mix of gas-phase condensation and “Interstellar” (icy) solids
- Most (refractory) solids may be formed in the planet forming disk
- What about the ices: indigenous or inherited?


Questions?
GALS 2024 lecture