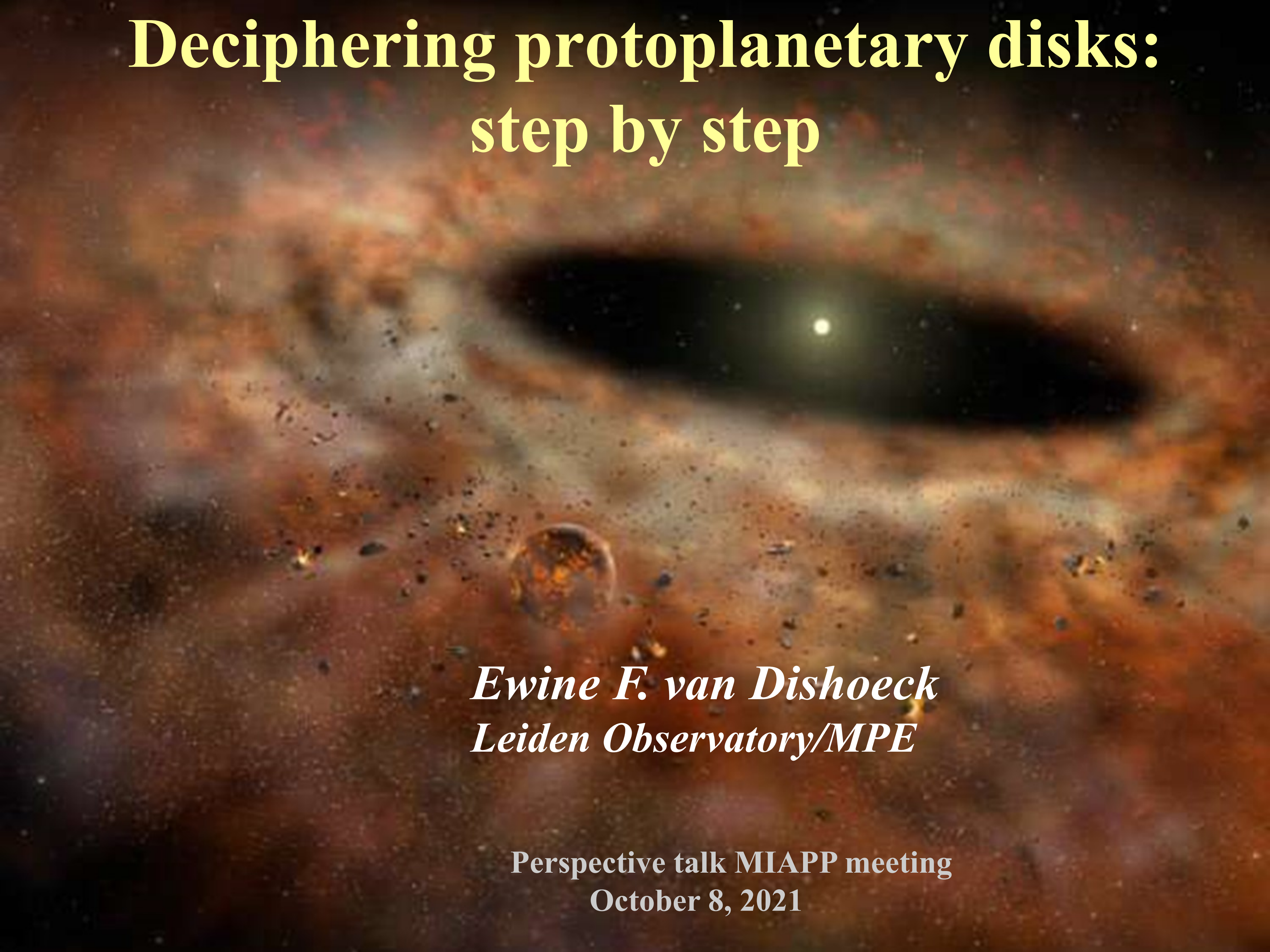
Deciphering protoplanetary disks: step by step

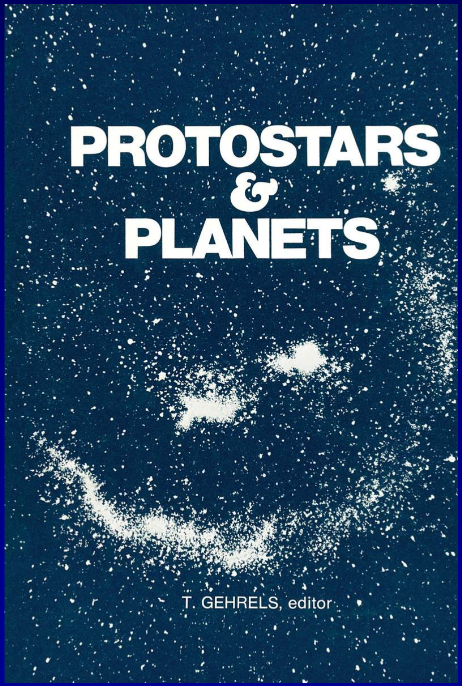


Ewine F. van Dishoeck
Leiden Observatory/MPE

Perspective talk MIAPP meeting
October 8, 2021

Caveats

- Biased perspective on part of the field
  - References highly incomplete
- Focus on gas rather than dust
- Look back but also forward
- Look beyond topic of disks

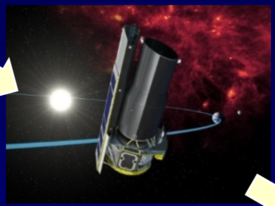


Thanks to all colleagues, postdocs, students for making this such an enjoyable journey

Thanks to Jane Huang for an excellent review and perspective

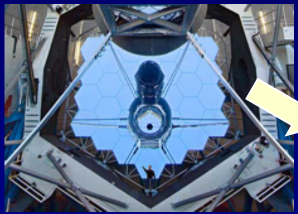
Progress in astronomy driven by new instrumentation

ISO
1995-1998



Spitzer
2003-2011

OVRO, BIMA,
IRAM, NRAO,
Nobeyama, VLA
CSO, JCMT,
SMA, ……
1987-



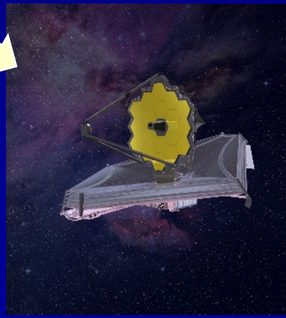
VLT-ISAAC,
CRIRES,
Keck-NIRSPEC
2007-2013

Herschel
2009-2013

ALMA
2012-

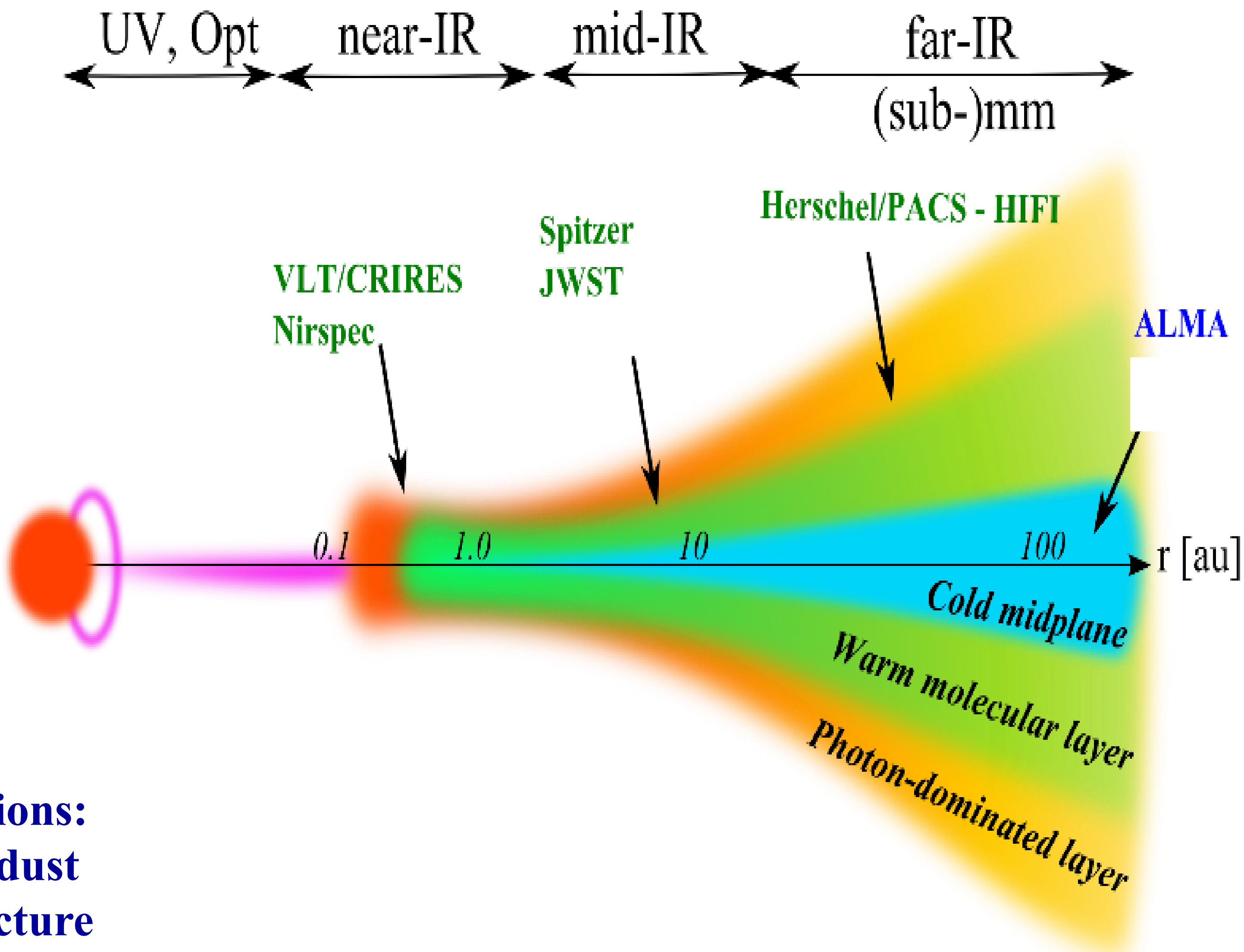
Rosetta
2014-2019

Solar system link



JWST
2022-

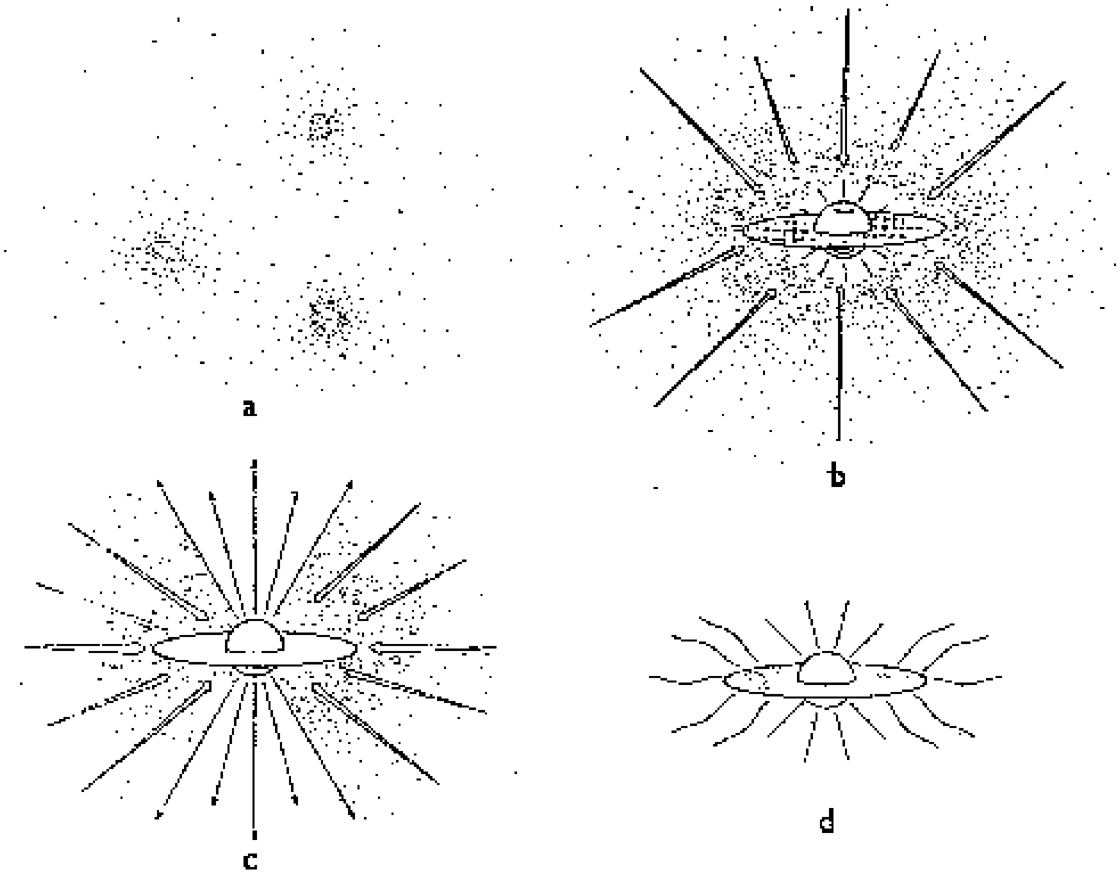
Every wavelength provides piece of puzzle



Questions:
- Gas/dust
- Structure
- Chemistry

D. Fedele

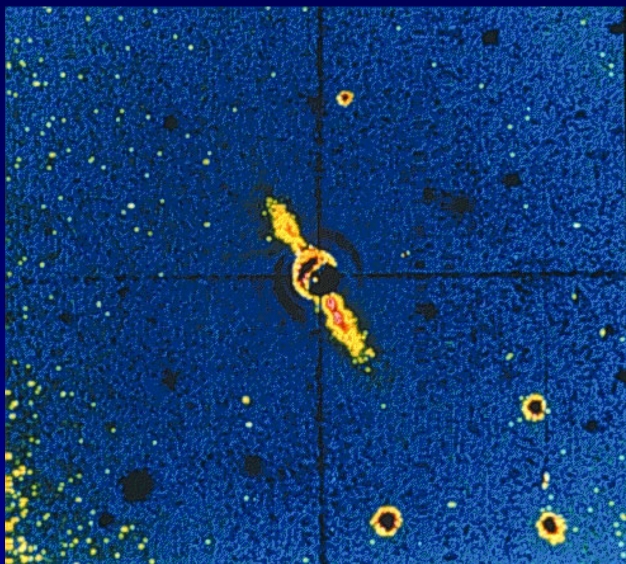
Scenario for low-mass star formation



Shu et al. 1987, 1993

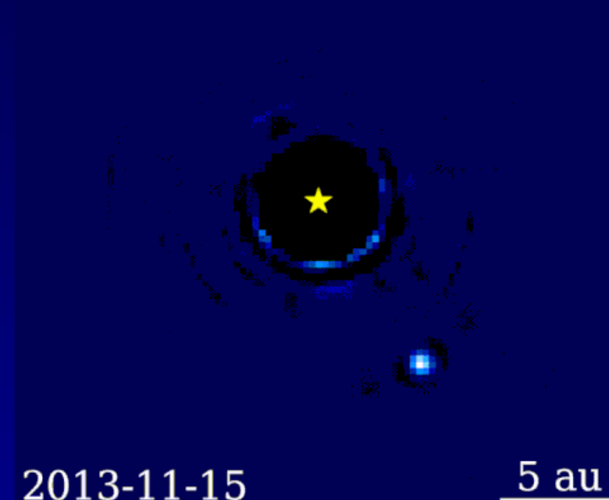
Disks: do they exist?

An image is worth a thousand words
(and a thousand SEDs….)



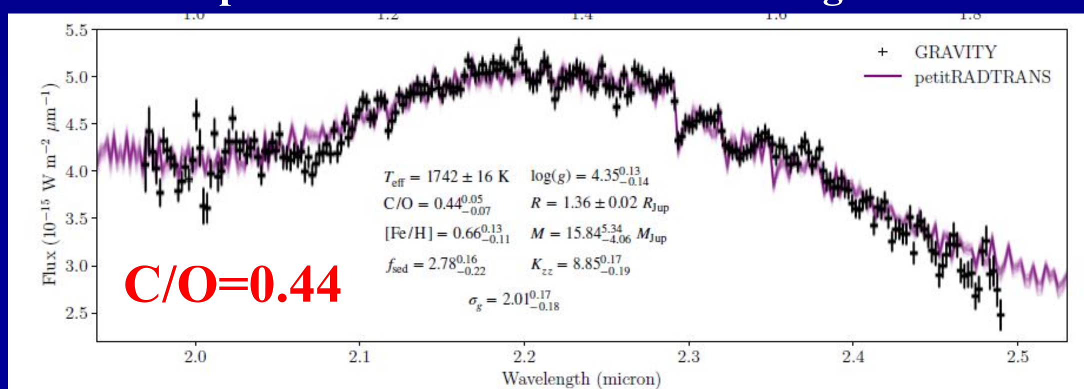
Smith & Terrile 1984

30 years later: planets!



Lagrange et al. 2013-2018

A spectrum is worth a thousand images….

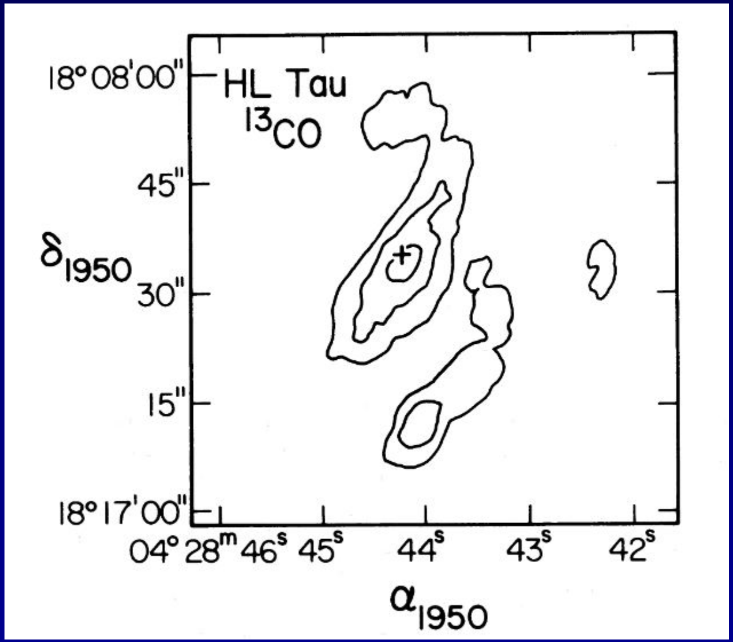


Beta Pic b
VLTI-Gravity
Spatially resolved
K-band spectrum

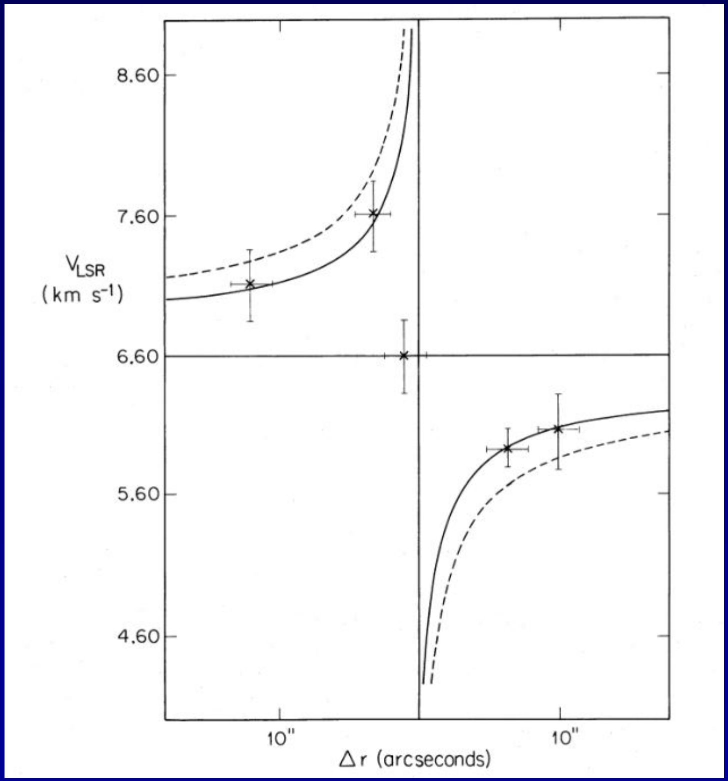
Gravity, Nowak, Lacours et al. 2019

Existence of protoplanetary disks?

It took some time to provide convincing evidence



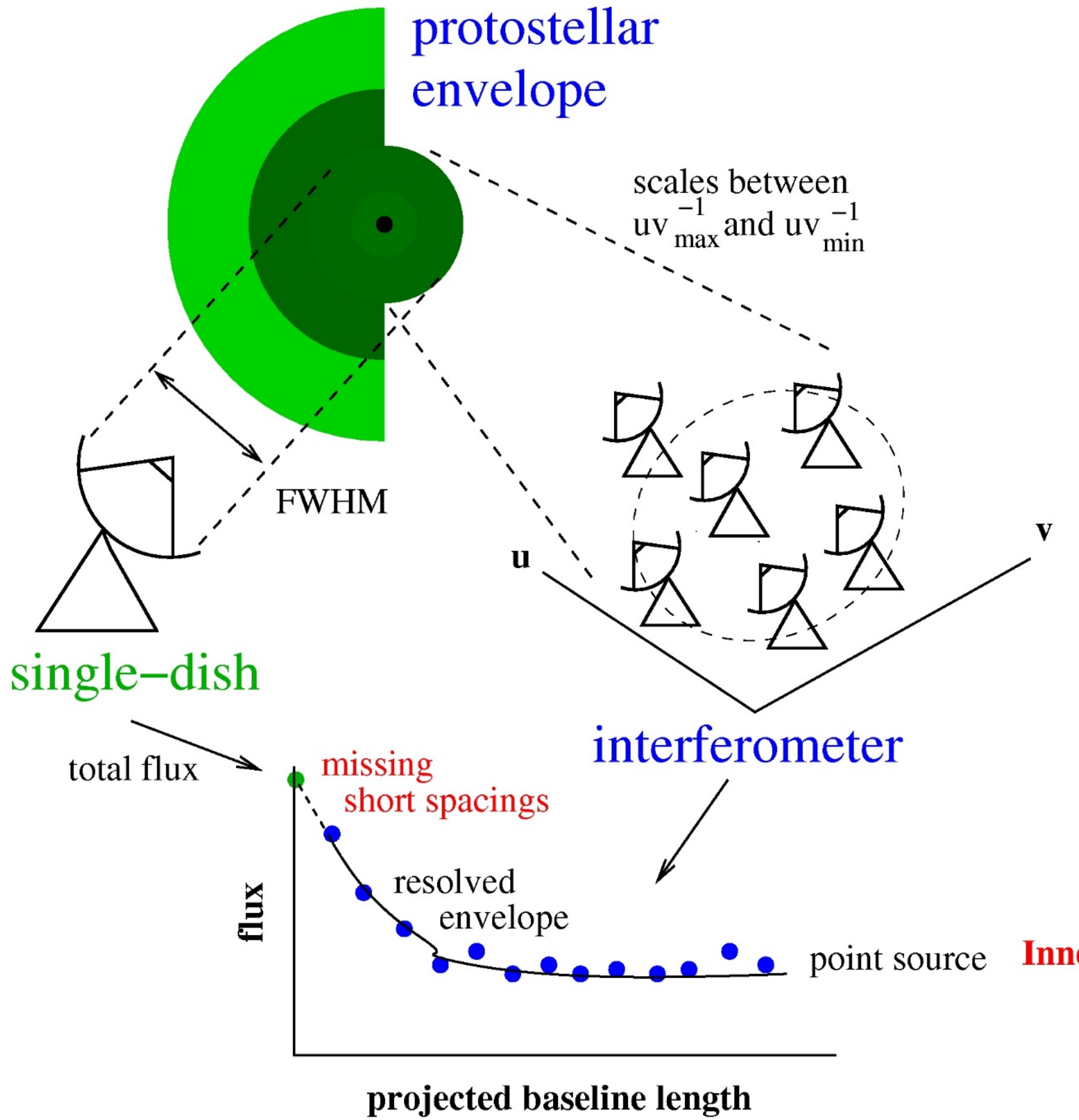
Sargent & Beckwith 1987, OVRO



Keplerian rotation or infall?

Also: Japanese Nobeyama

Young disks: Envelope vs disk

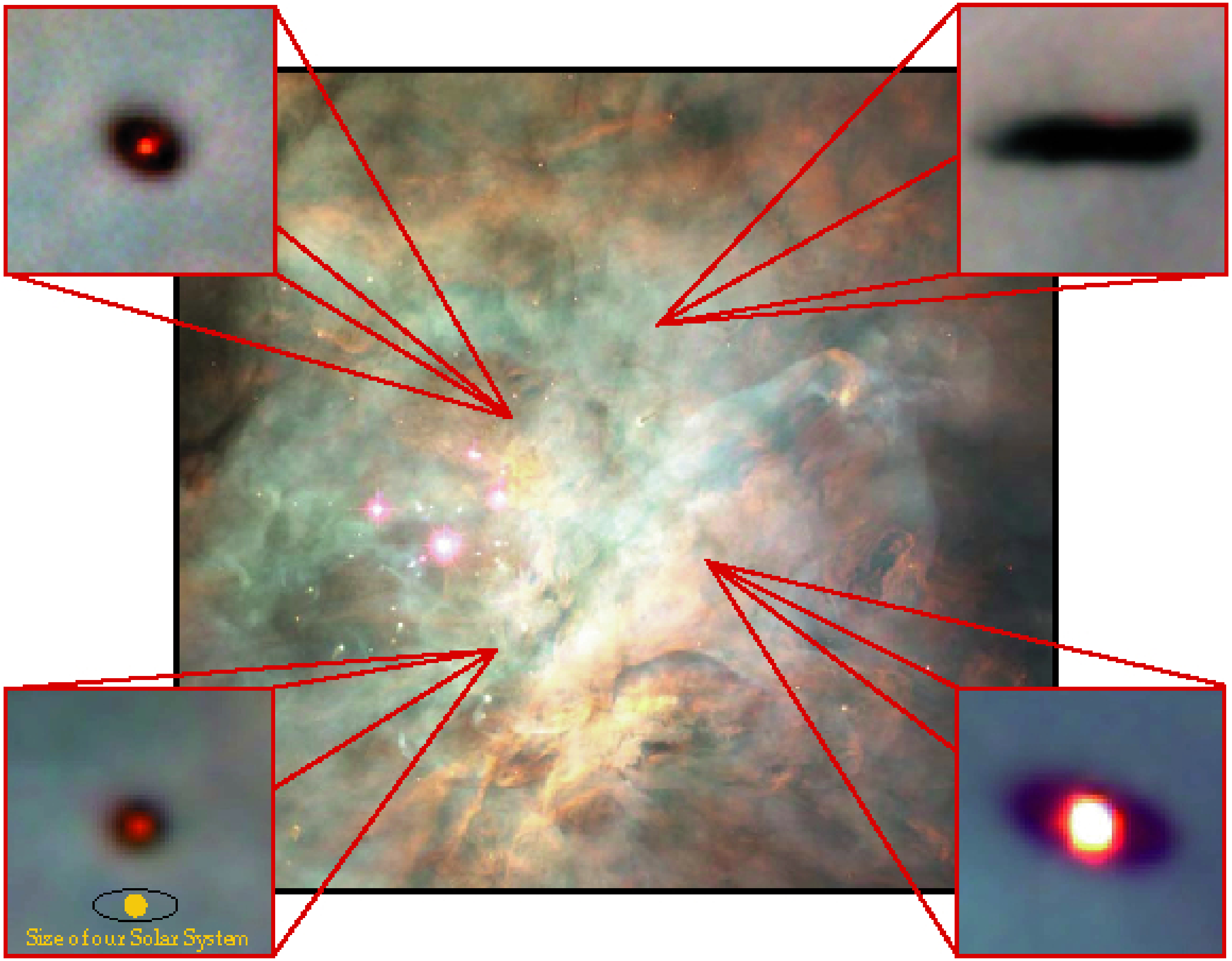


Inner envelope or disk?

Envelope overwhelms disks except on longest baselines

Keene & Masson 1990
Hogerheijde et al. 1998
Looney et al. 2000

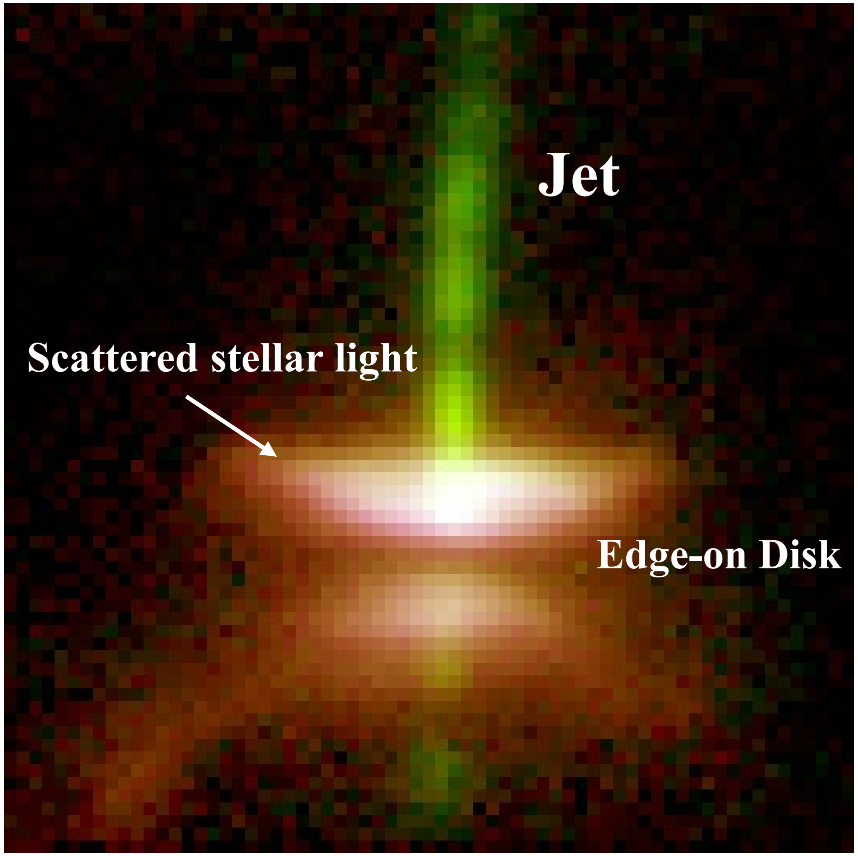
Again: images



HST/C. O'Dell et al. 1993-1995
VLA: Churchwell et al. 1987

HH 30 disk + jet

Optical image HST



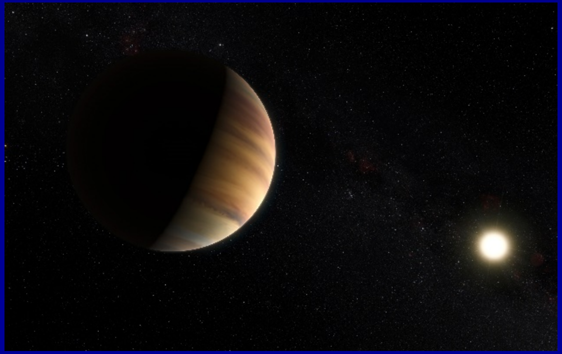
Green: [O III]
White: broadband

HST: C. Burrows et al. 1996

Some years are special: 1995-1996

- HST Orion disk images: disks exist
  - Also with mm interferometers
- Discovery of extrasolar planets: 51 Peg
- Bright comets: Hyakutake, Hale-Bopp

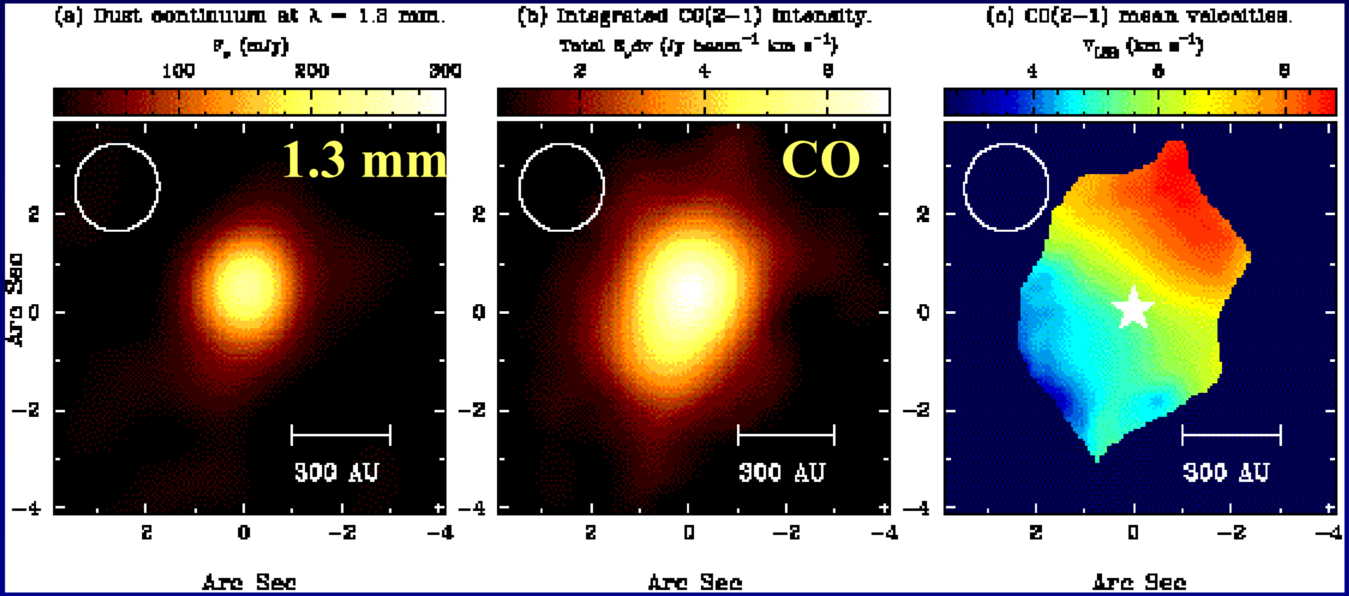
Exoplanets



Disks

Comets

Mm observations of young disks



MWC 480:
Herbig Ae intermediate mass young star
Progenitor of Vega-type star

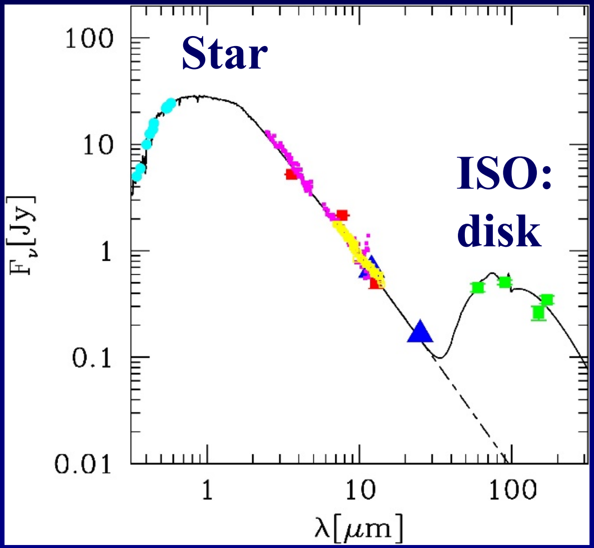
Mannings & Sargent 1997

Velocity pattern CO consistent with Keplerian rotation

Also: Lay et al. 1994 (JCMT-CSO), Guilloteau, Dutrey et al. 1994-1997 (IRAM PdBI)
Hayashi et al. 1993 (Nobeyama)

More observations of ‘debris’ disks

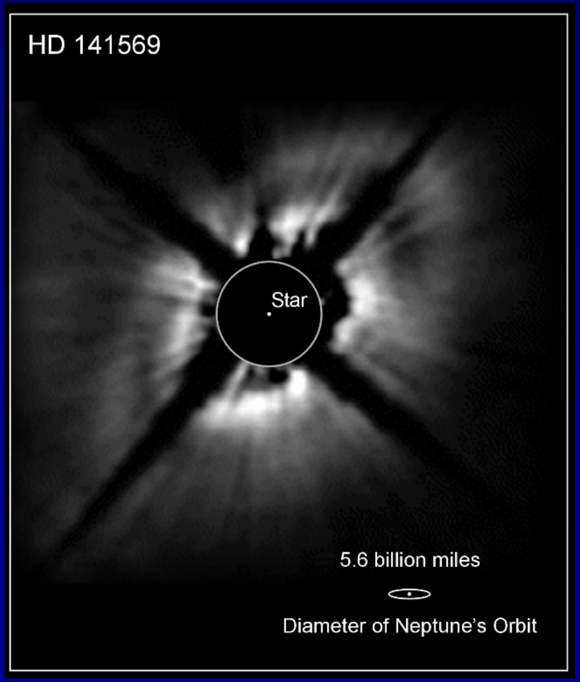
HD 207129 G0V, d=15.6 pc



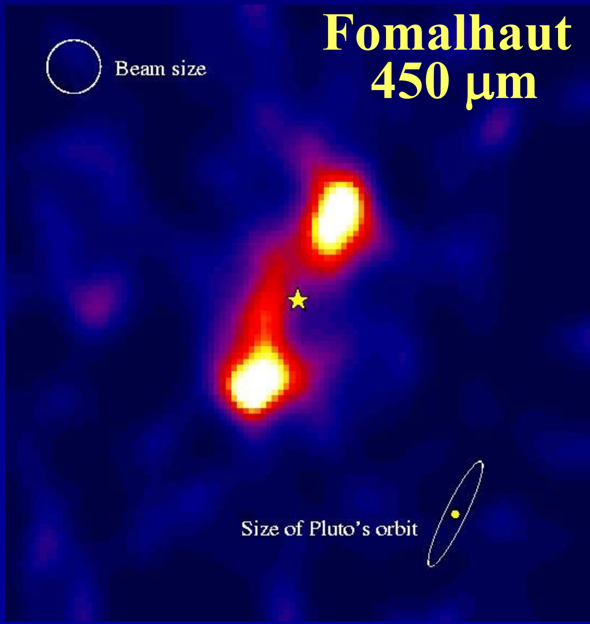
$M=0.01\ M_{Earth}$

Jourdain de Muizon et al. 1999

IRAS Vega FIR excess
Aumann et al. 1984



Weinberger et al. 1999



Holland et al. 2003, SCUBA

Also structured! Little discussion so far….

Initial chemistry studies

THE ASTROPHYSICAL JOURNAL, 391:L99–L103, 1992 June 1

CHEMISTRY IN CI… …RD HL TAURI

GEOFFREY … …I. SARGENT[3]

ASTRONOMY AND ASTROPHYSICS

…stron. Astrophys. 317, L55–L58 (1997)

Letter to the Editor

Chemistry of Proto…olar-like nebulae:

The molecular conten… …and GG Tau disks

A. Dutrey, S. Guilloteau, and …
Institut de Radio Astronomie Milli… …s, France

A&A 425, 955–972 (2004)
DOI: 10.1051/0004-6361:20040026

Organic molecules in pro… …etary disks around T Tauri and … stars⋆

W.-F. Thi[1,2,3], G.-J. van …

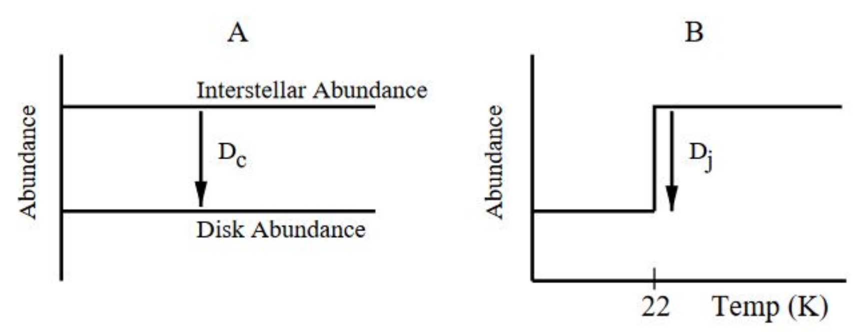
Astronomy & Astrophysics

A&A 377, 566–580 (2001)
DOI: 10.1051/0004-6361:20011137

Astronomy & Astrophysics

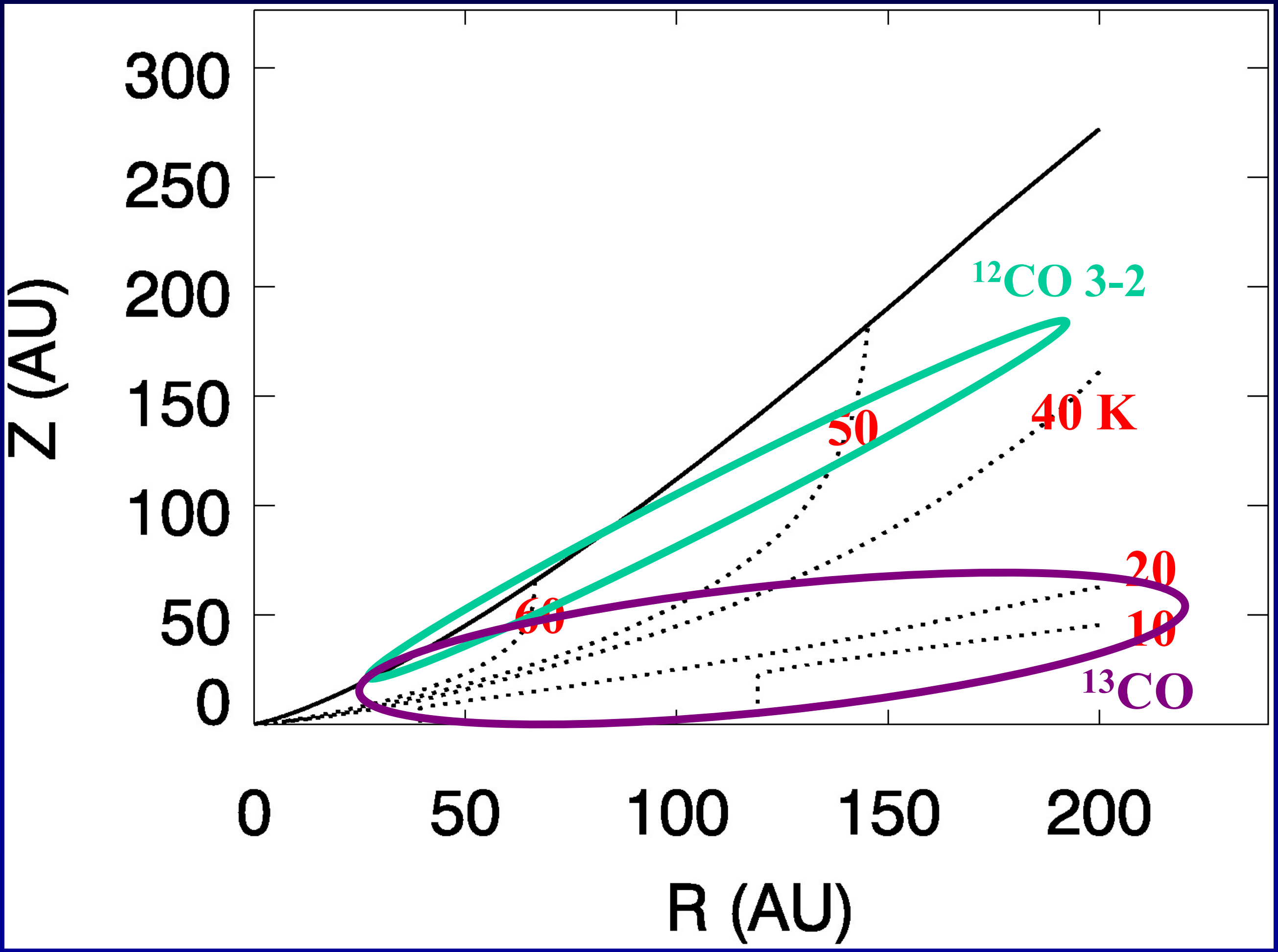
Submillimeter lines from circumstella… sequence star…

G.-J. van Zadelhoff[1], E. F. van Dishoeck[1], W.-…



Disk abundances much lower than in ISM

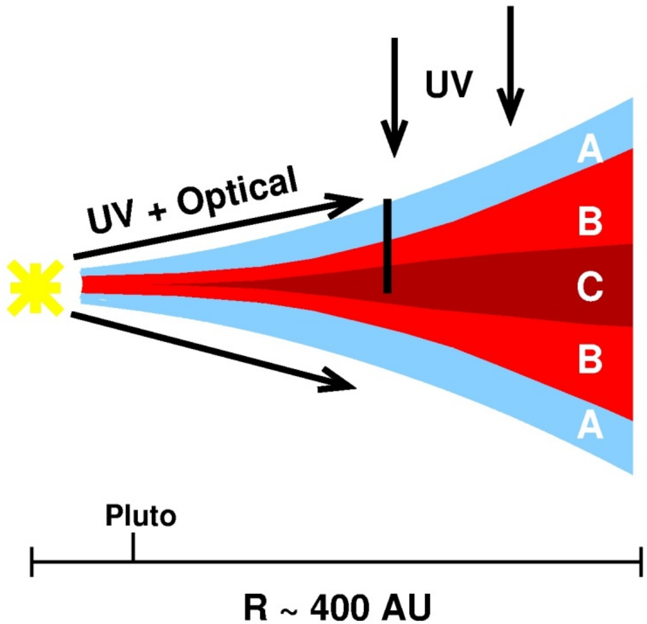
Vertical temperature structure

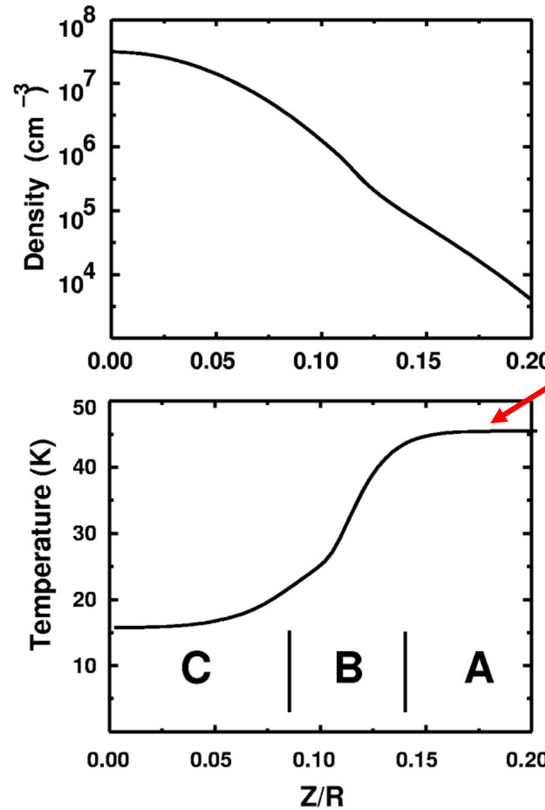


- ^{12}CO τ=1 surface near top of disk
- ^{13}CO emission from deeper in disk

Van Zadelhoff et al. 2001
Dartois et al. 2003

Three-layer chemical structure

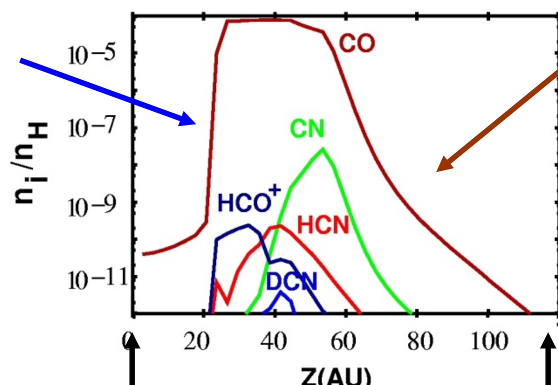




T_{gas} is larger

-Most emission comes from warm intermediate molecular layer

Freeze-out



Photodissociation

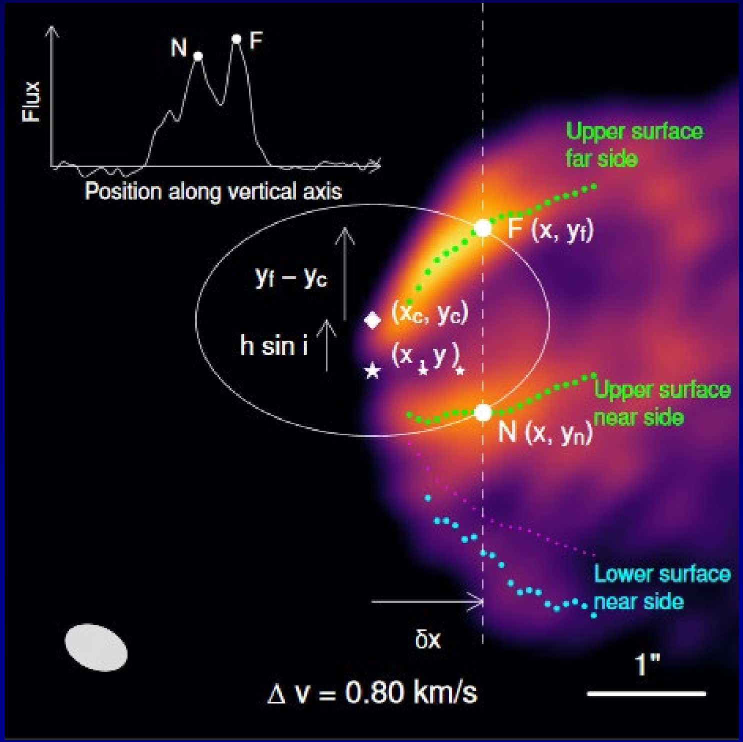
midplane

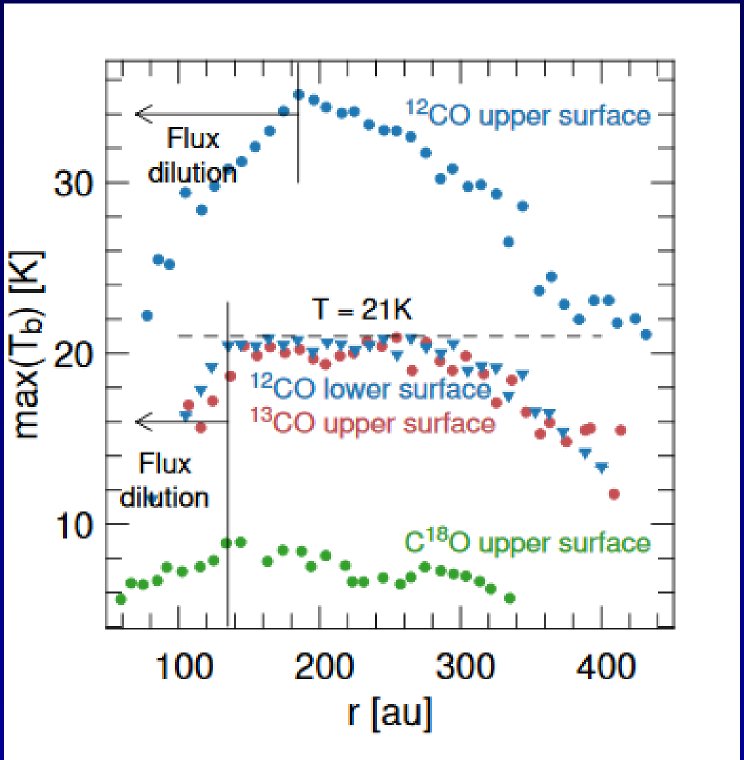
surface

Aikawa et al. 2002, Van Zadelhoff et al. 2003, Markwick et al. 2002, Millar, Nomura et al. 2003 Jonkheid et al. 2004, 2007, Semenov et al. 2006, 2008, …..

Temperature now measured directly!

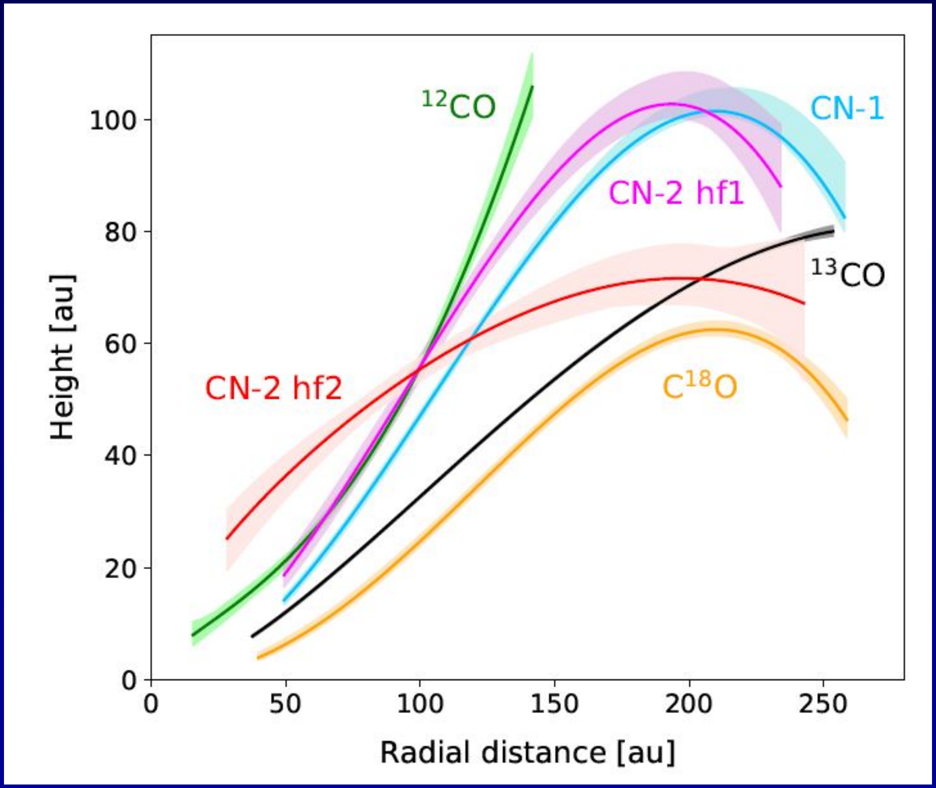
IM Lup





Pinte et al. 2018
Paneque et al.,
Izquierdo et al. modeling!

Vertical structure molecules



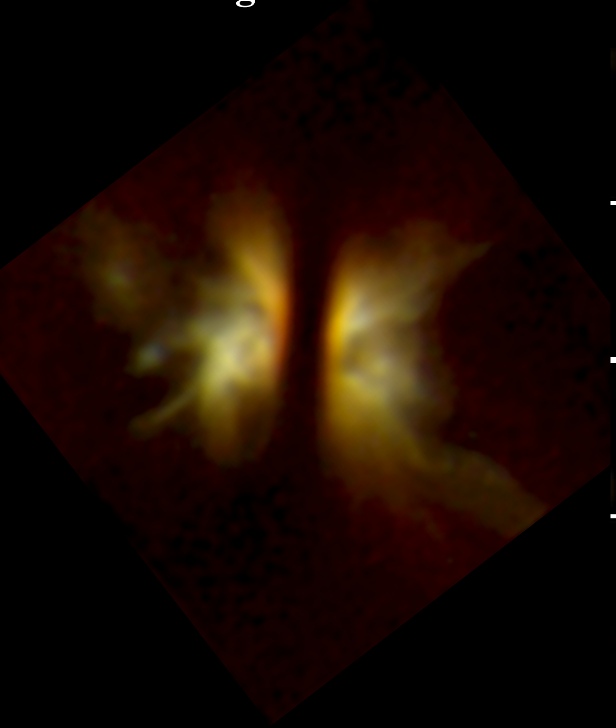
Elias2-27

Paneque et al. 2021, to be submitted

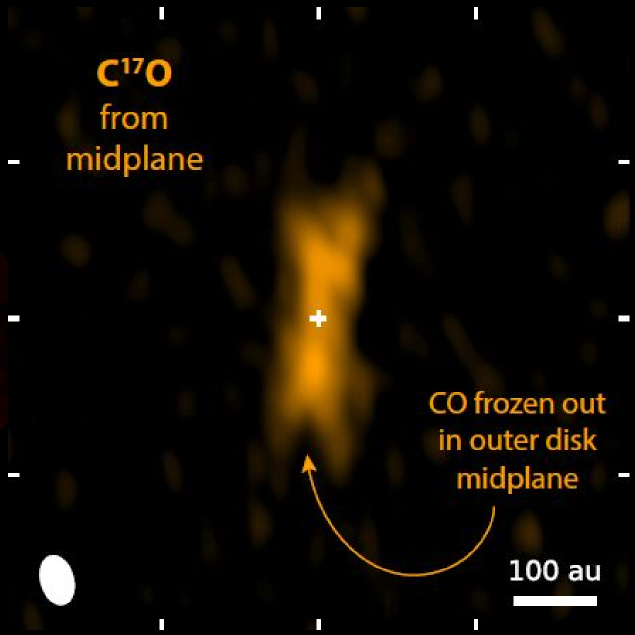
Probing vertical *T* structure

The textbook case of IRAS04302

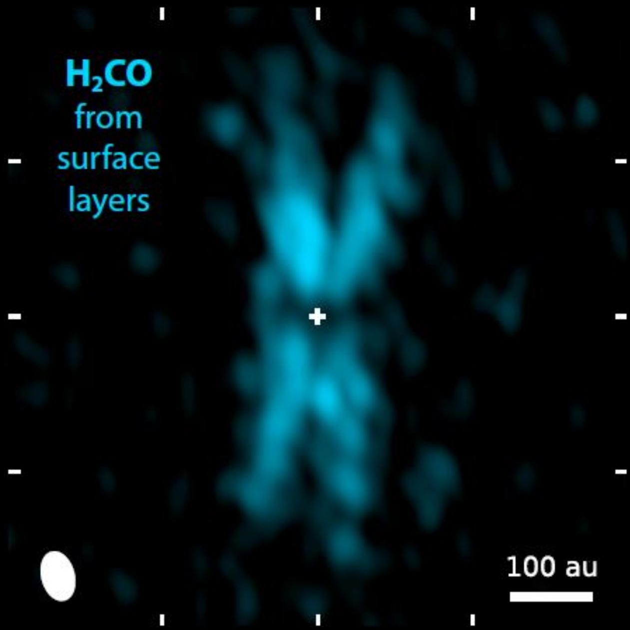
HST: edge-on disk



$C^{17}O$ (T_{sub}~20 K)



H_2CO (T_{sub}~50 K)

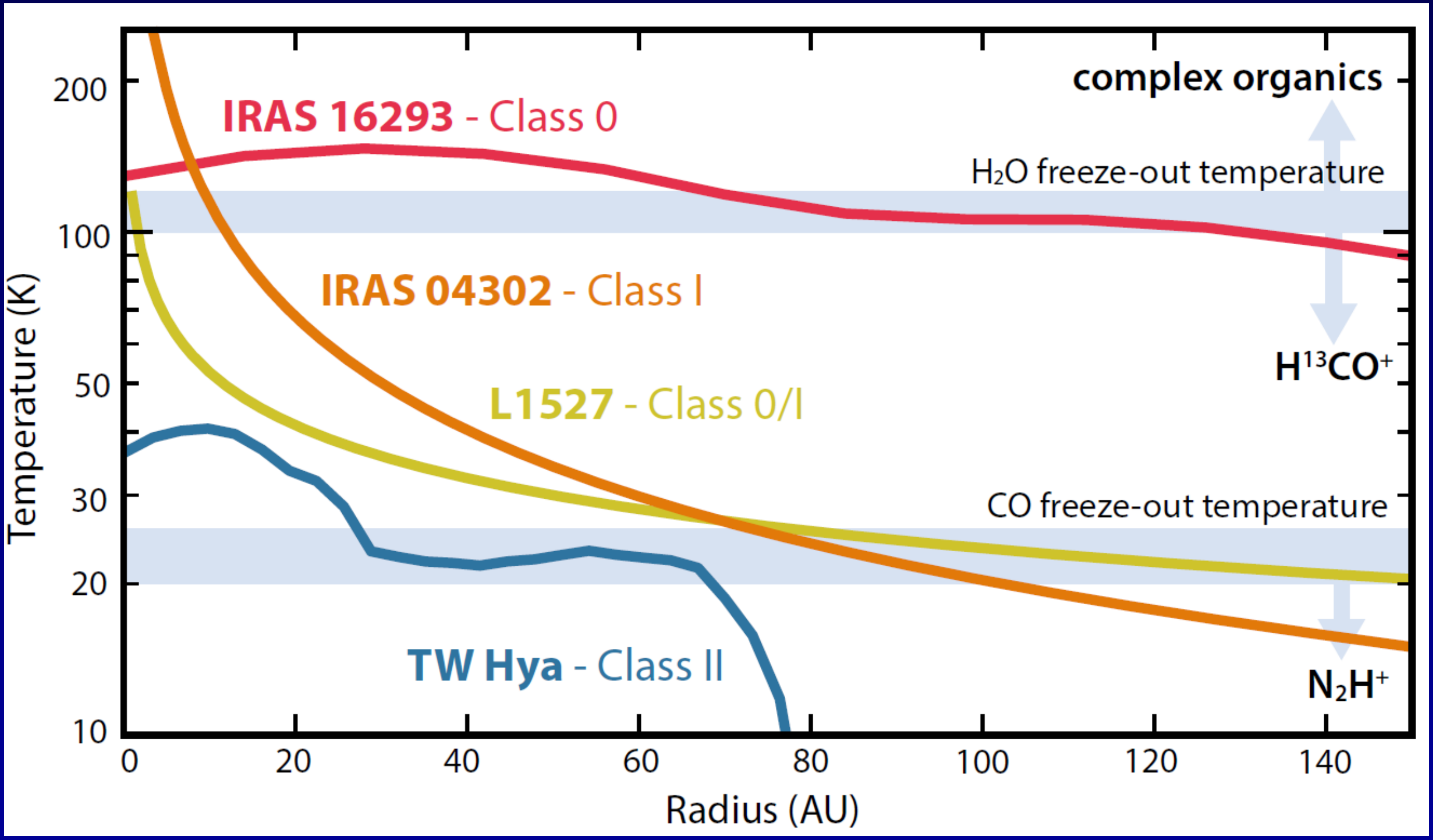


van 't Hoff et al. 2020
Podio et al. 2020

- CO not frozen out (except at very large radii)
- H_2CO frozen out in midplane but not surface layers

Young disks are warm, mature disks cold

Young disks are warm
Mature disks are cold

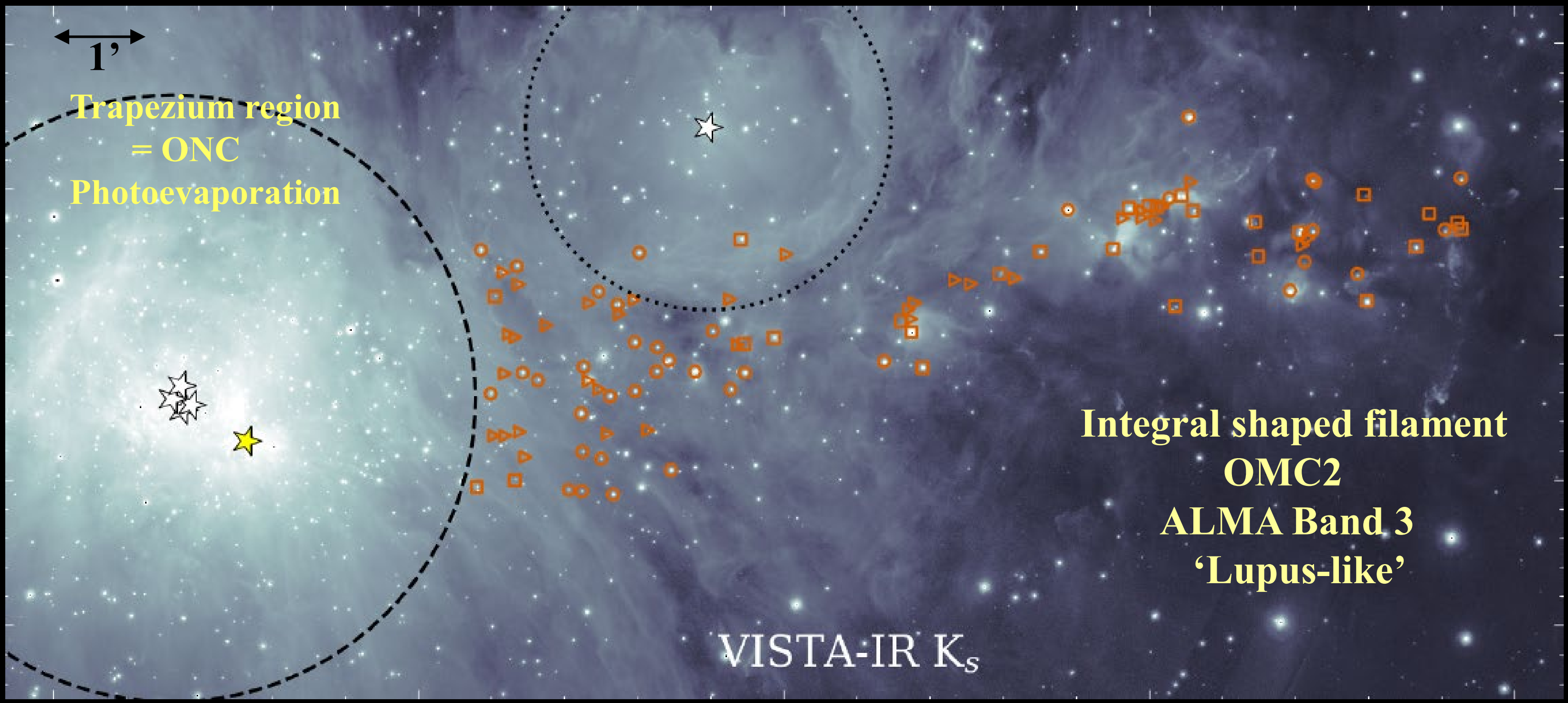


Van 't Hoff et al. 2020

Disk subthemes

- Disk surveys
- Disk chemistry
  - With gaps and cavities
- Inner disk structure

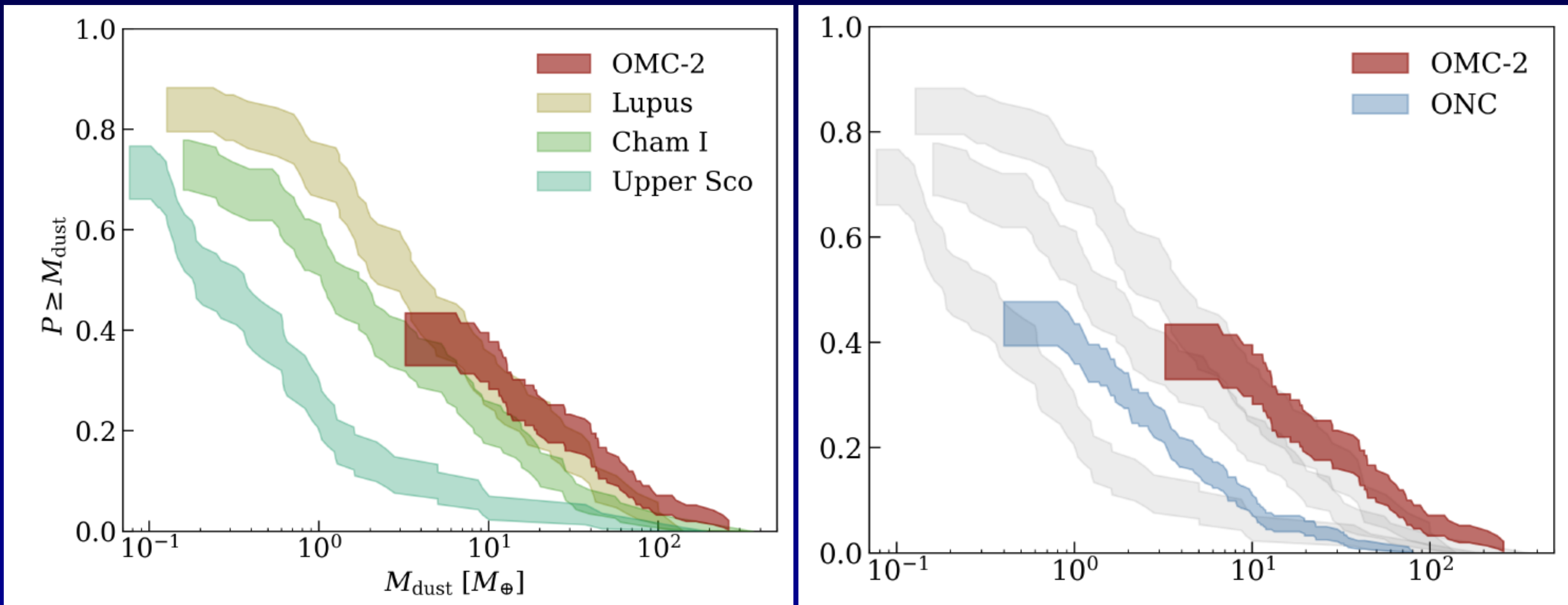
High-mass regions: Orion OMC2



Also: NGC 2024, L1641, …
van Terwisga et al. 2019, 2020
Grant et al. 2021, Otter et al. 2021

Unbiased survey of disks of around low-mass stars in high mass environment

High vs low-mass regions:
‘Environment’ (UV) matters



van Terwisga, Hacar, vD 2019

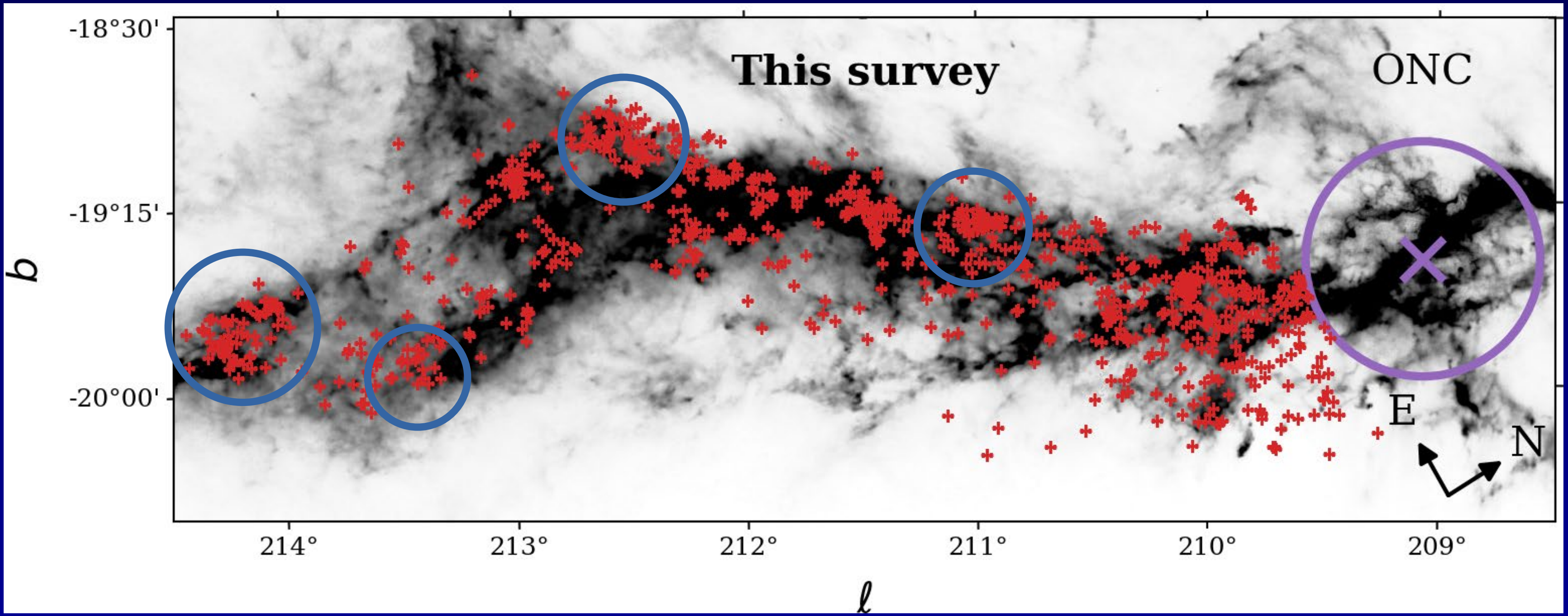
- **Disks in OMC2 (away from bright massive stars) similar to Lupus**
- **Disks in ONC (near massive stars) much lower masses → *photoevaporation***

dM/dt~8x10^{-8} M$_{sun}$/yr

Mann et al. 2014, Eisner et al. 2018 ONC, Ansdell et al. 2017 σ Ori

And now for something really big!

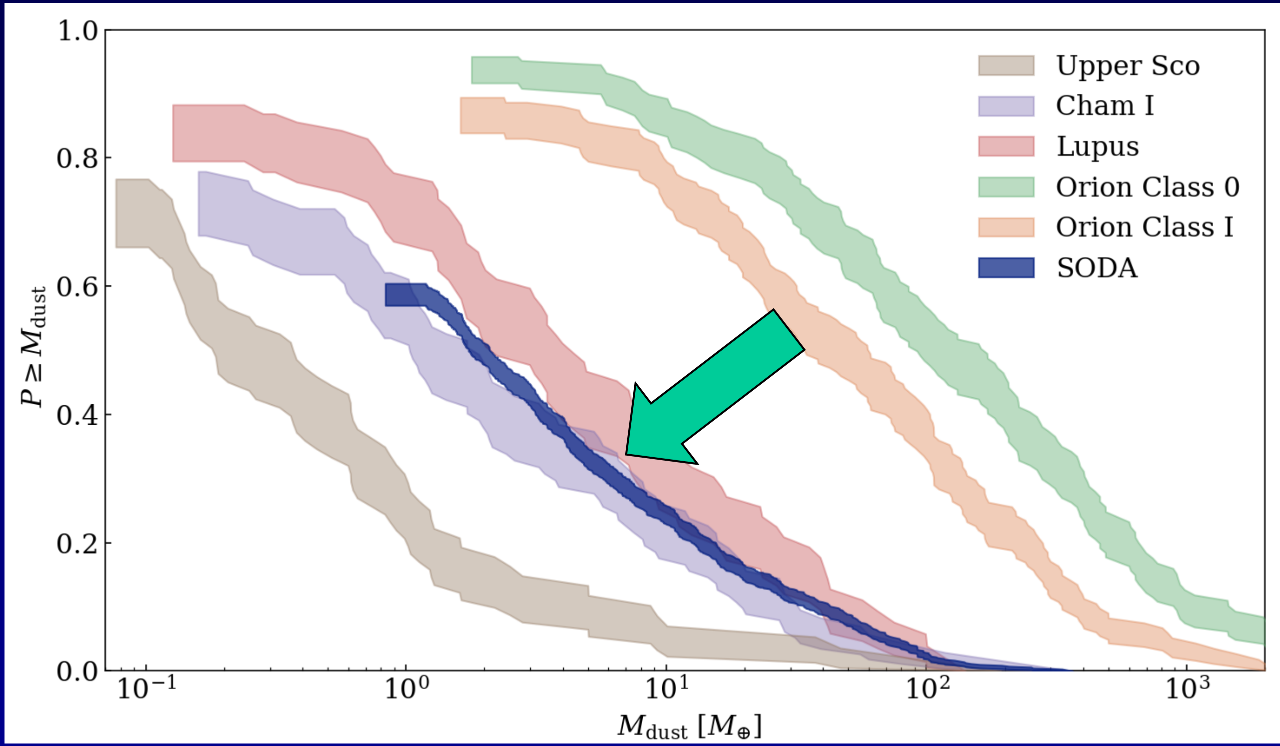
Survey of Orion's Disks with ALMA (SODA)



Van Terwisga, Hacar, vD
et al. subm

N = 872 disks across the length of Orion A, at 1.3" in ALMA B6

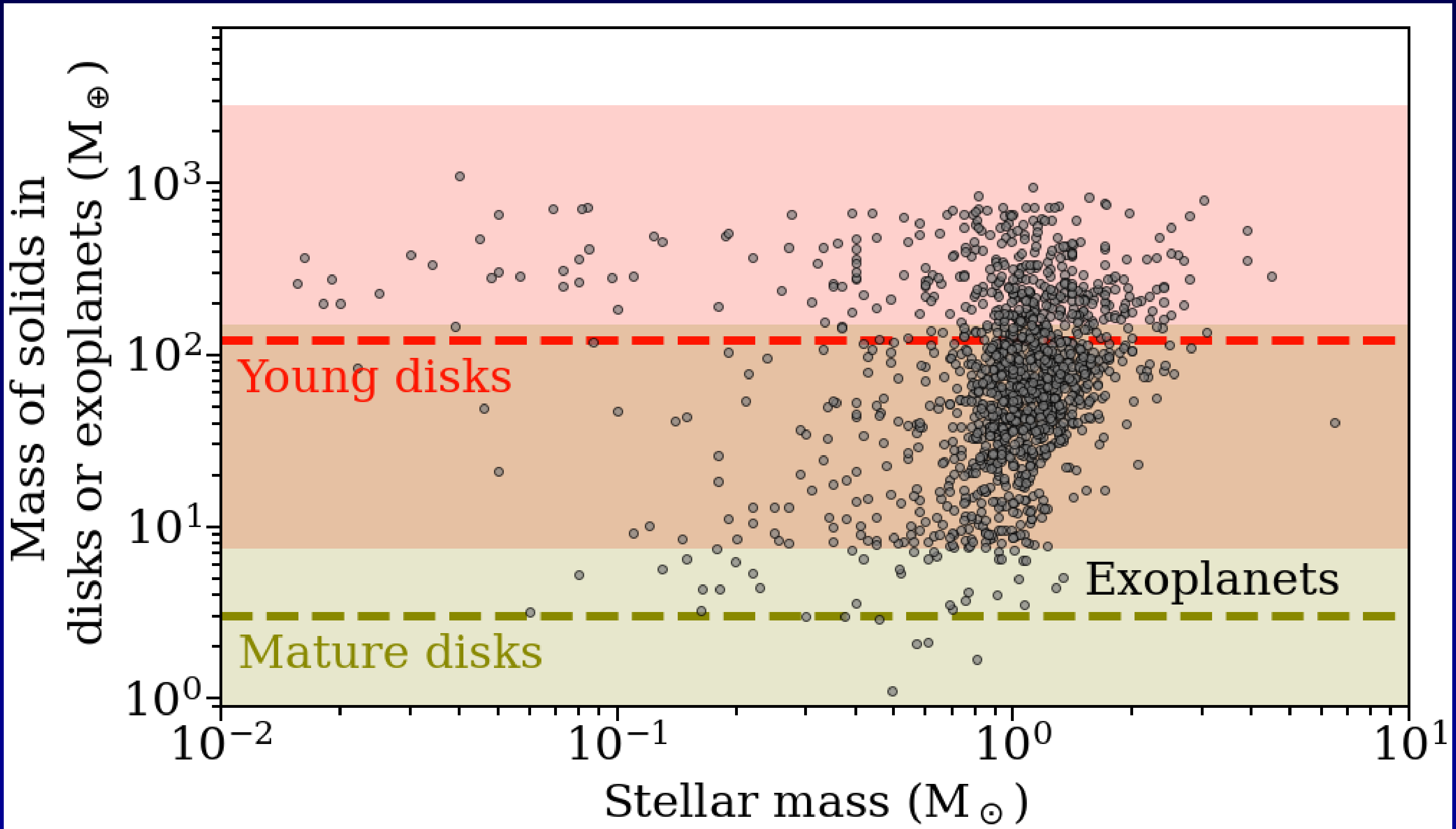
Orion disk mass distribution



van Terwisga et al. subm.

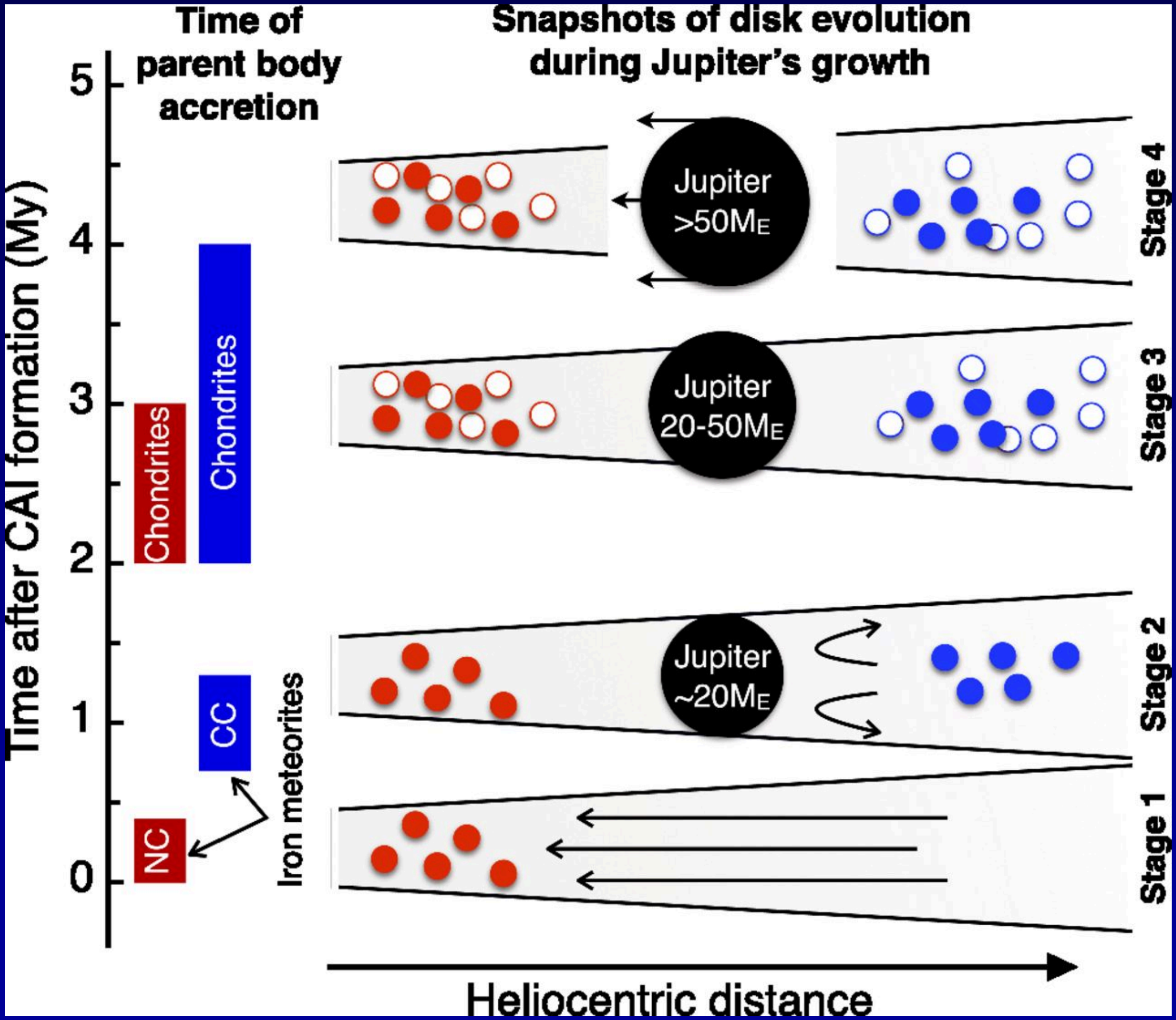
- **57% detected**
- **Similar distribution to Lupus, Cha I**
- **Direct comparison to Tobin et al. 2020: factor 50 flux loss vs Class 0**

Young disks are massive
Planet formation must start early



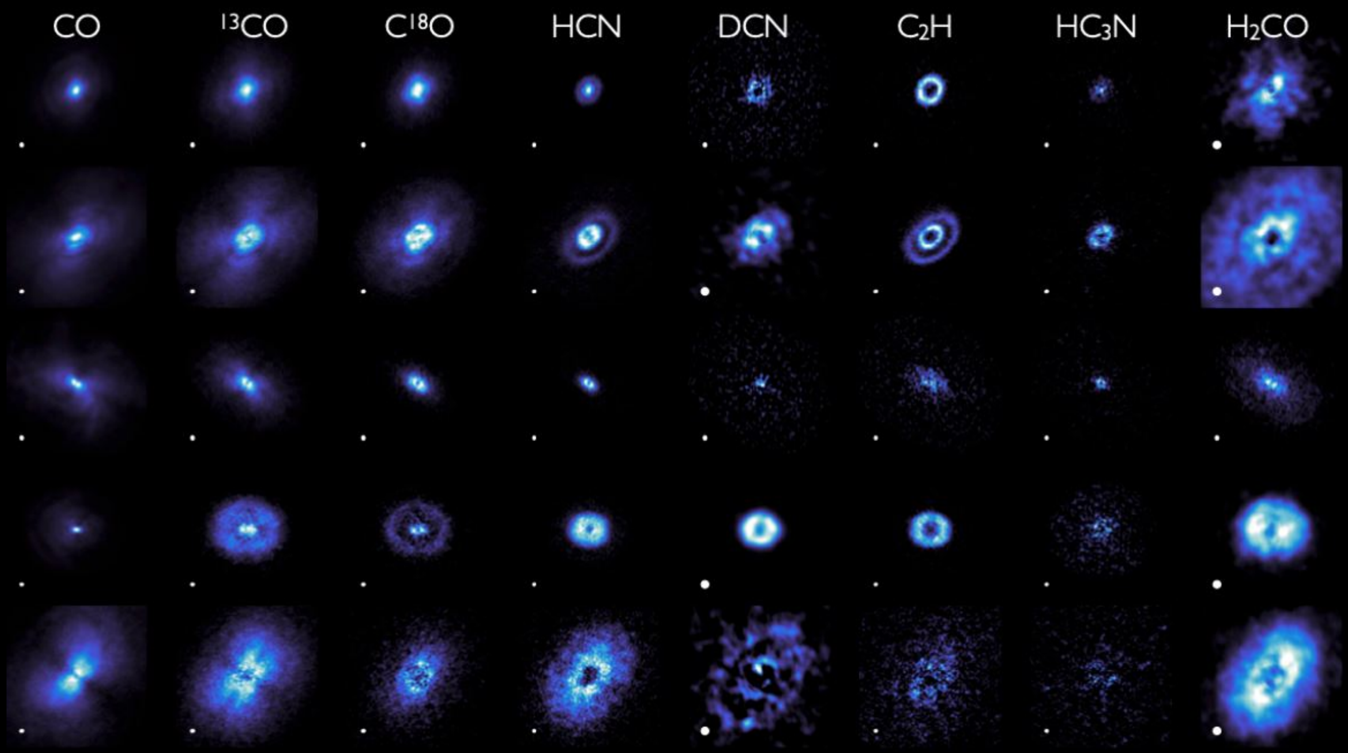
Tychoniec et al. 2018, 2020

Solar system:
evidence for early planet formation



Kruijer et al. 2017

Gas vs dust structures



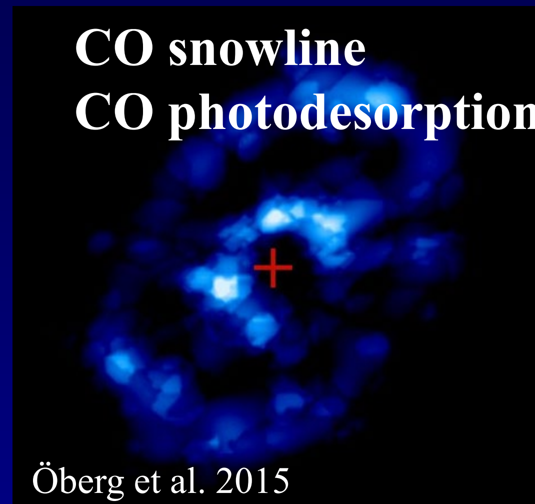
MAPS
Öberg et al. 2021
Guzman et al. 2021
Law et al. 2021

- **Many gas structures not related to dust structures**

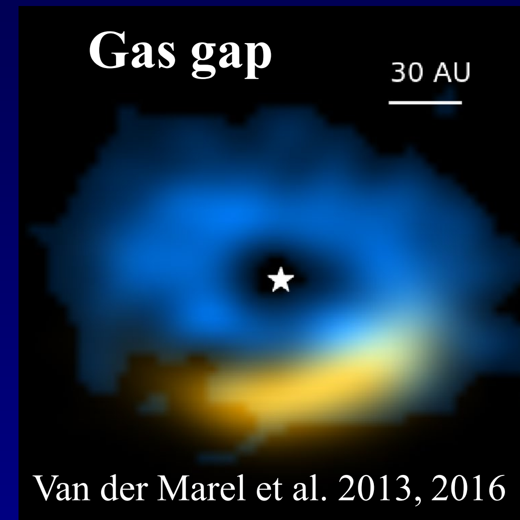
Every molecule tells its own story

TW Hya, N_2H^+ 4-3

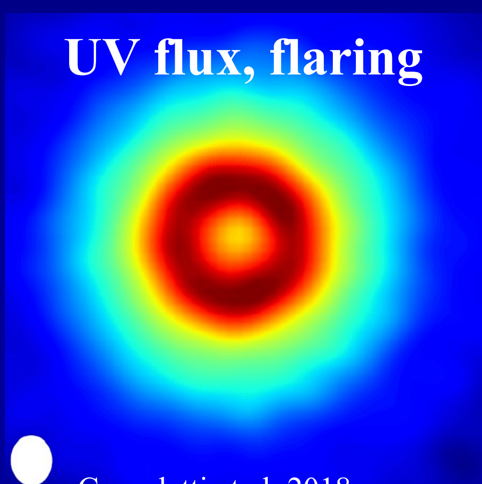
IM Lup, DCO^+ 3-2



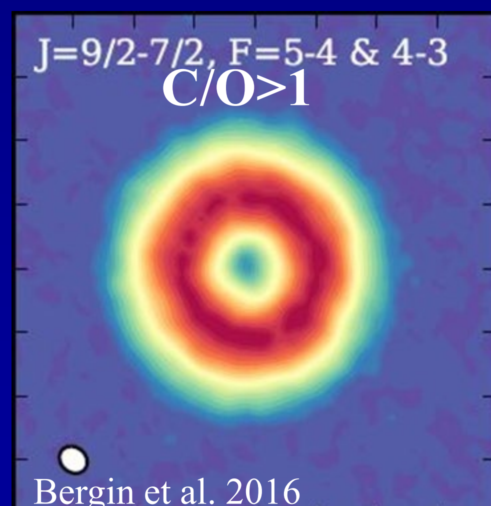
IRS48, ^{13}CO 3-2



TW Hya, CN 2-1



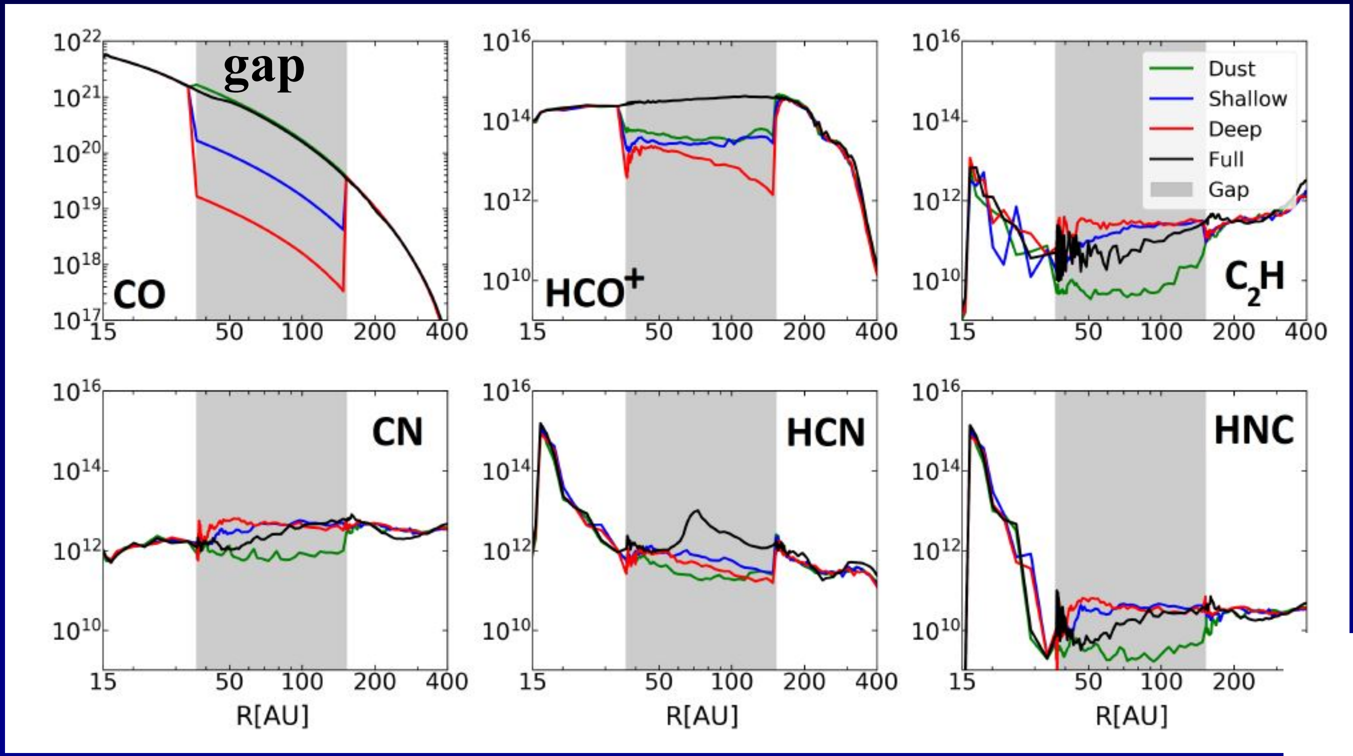
TW Hya, C_2H



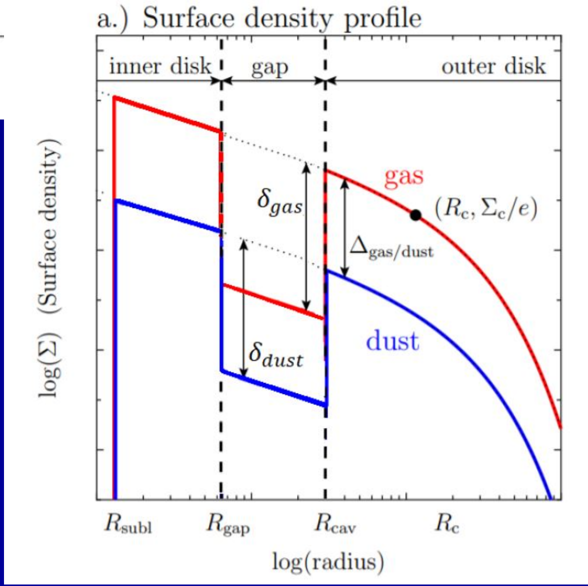
Miotello et al. 2019, Bergner et al. 2019

Much more data needed!

Few molecules trace gas cavity



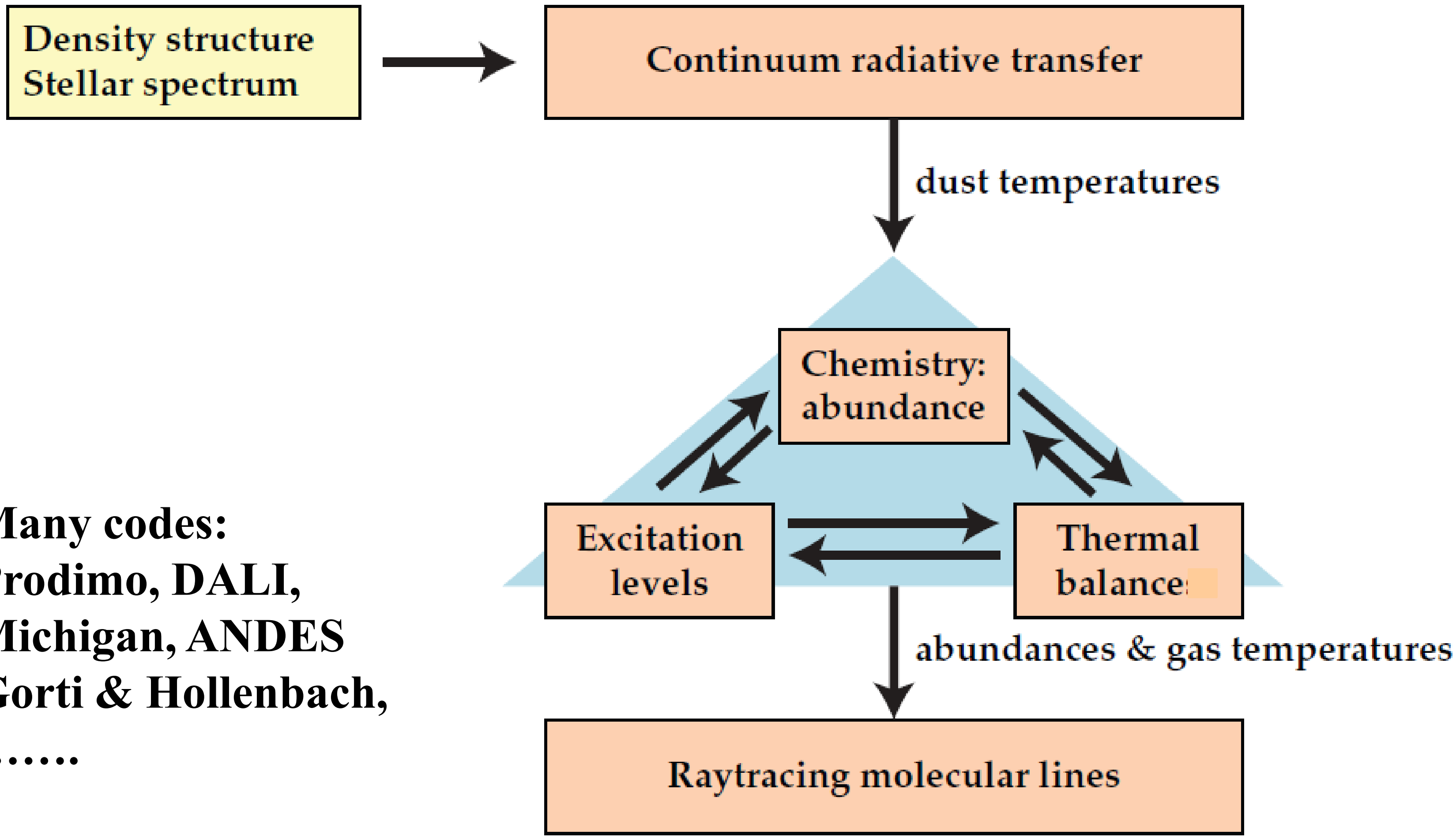
DALI model



Booth, Natoewal, Leemker et al. in prep.

- Model with gap in dust and varying depths in gas
- UV penetrates deeper in cavities → affects chemistry

Physical-chemical disk models

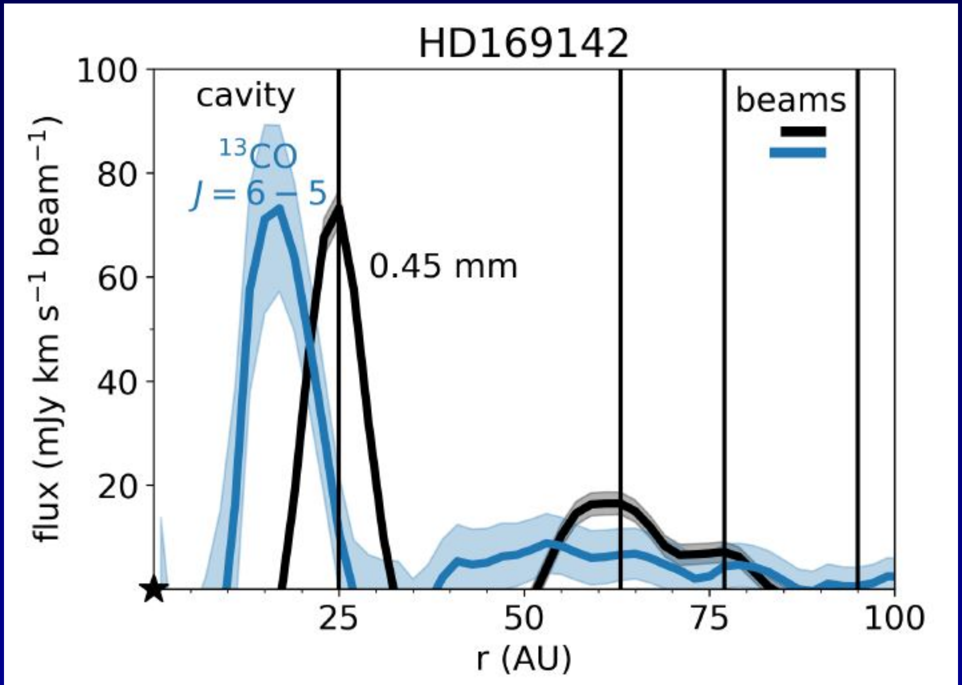


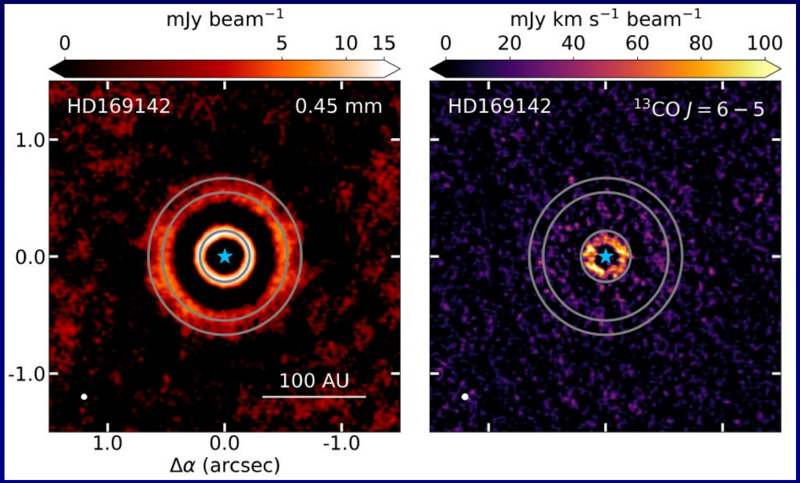
Many codes:
Prodimo, DALI,
Michigan, ANDES
Gorti & Hollenbach,
…….

Challenge to maintain them!

Bruderer et al. 2012, 2013, 2014
Miotello et al. 2014, 2016 CO isotopologs
Facchni et al. 2017 grain growth + drift

Gas cavity < Dust cavity



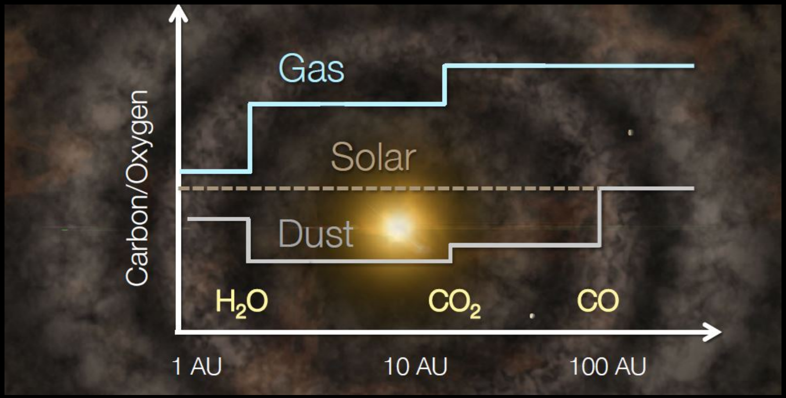


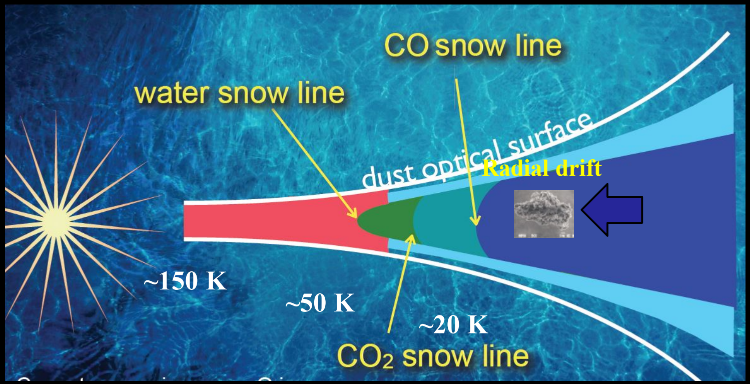
Leemker et al., in prep.

- **Deep gas cavities (drop factor 100 or more) point to companions**
- **Need $C^{18}O$ (^{12}CO, ^{13}CO temperature sensitive)**

Bruderer et al. 2014, Perez et al. 2014, Van der Marel et al. 2015, 2016,, Fedele et al. 2017, …

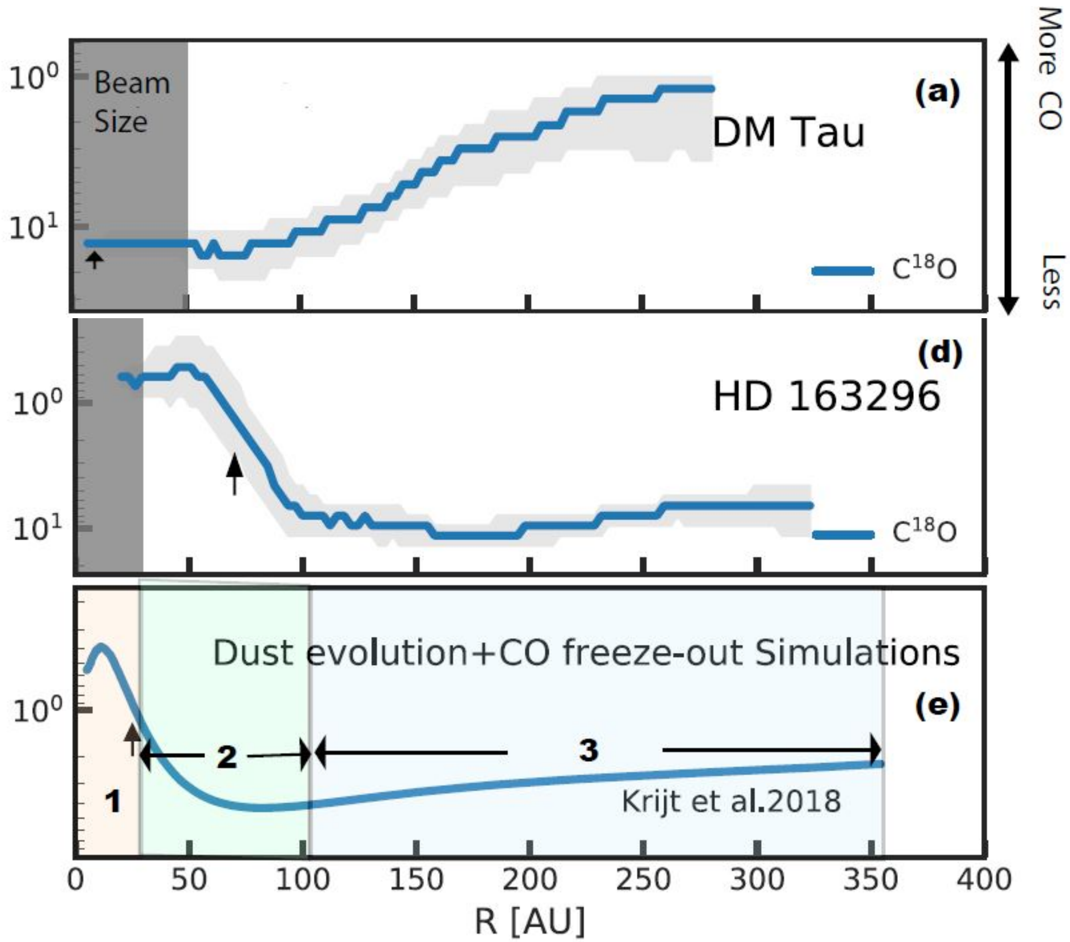
Snowlines and dust traps change C, O, N, … abundances in gas vs ice





Öberg, Bergin et al. 2011, 2021
Vvn Dishoeck & Bergin 2021

CO abundance profile:
enhancements vs depletions inner disk

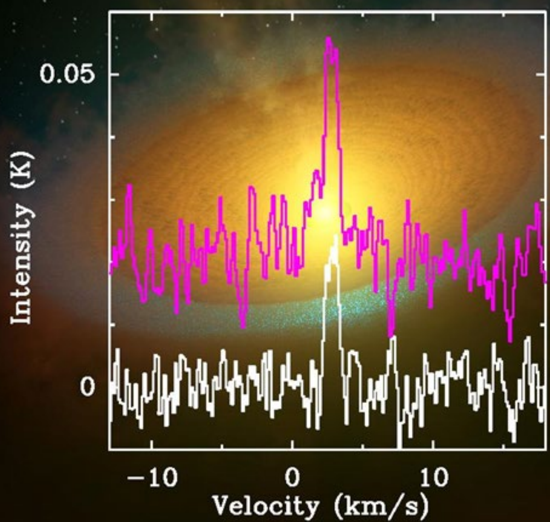


Schwarz et al. 2016
Zhang et al. 2019
Booth et al. 2019
Sturm et al. 2021

Krijt et al. 2020 models

- **Enhancement: radial drift icy pebbles**
- **Depletion: dust trap beyond CO iceline**

Where is the volatile oxygen?

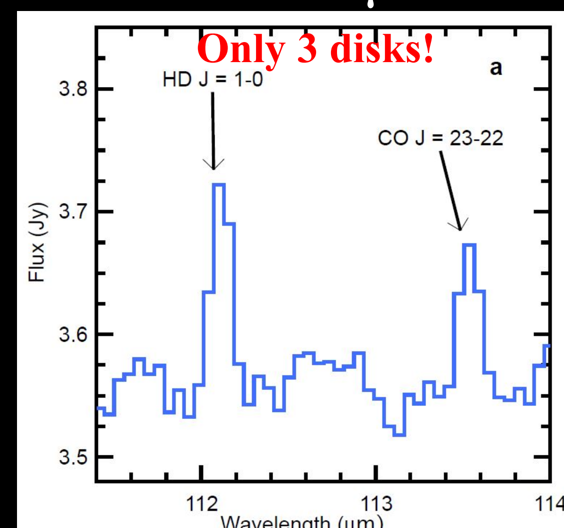


H_2O
HIFI
Weak!

TW Hya

Hogerheijde et al. 2011, Du et al. 2015, 2017

Disk mass from *Herschel*-PACS:
HD J=1-0 112 μm



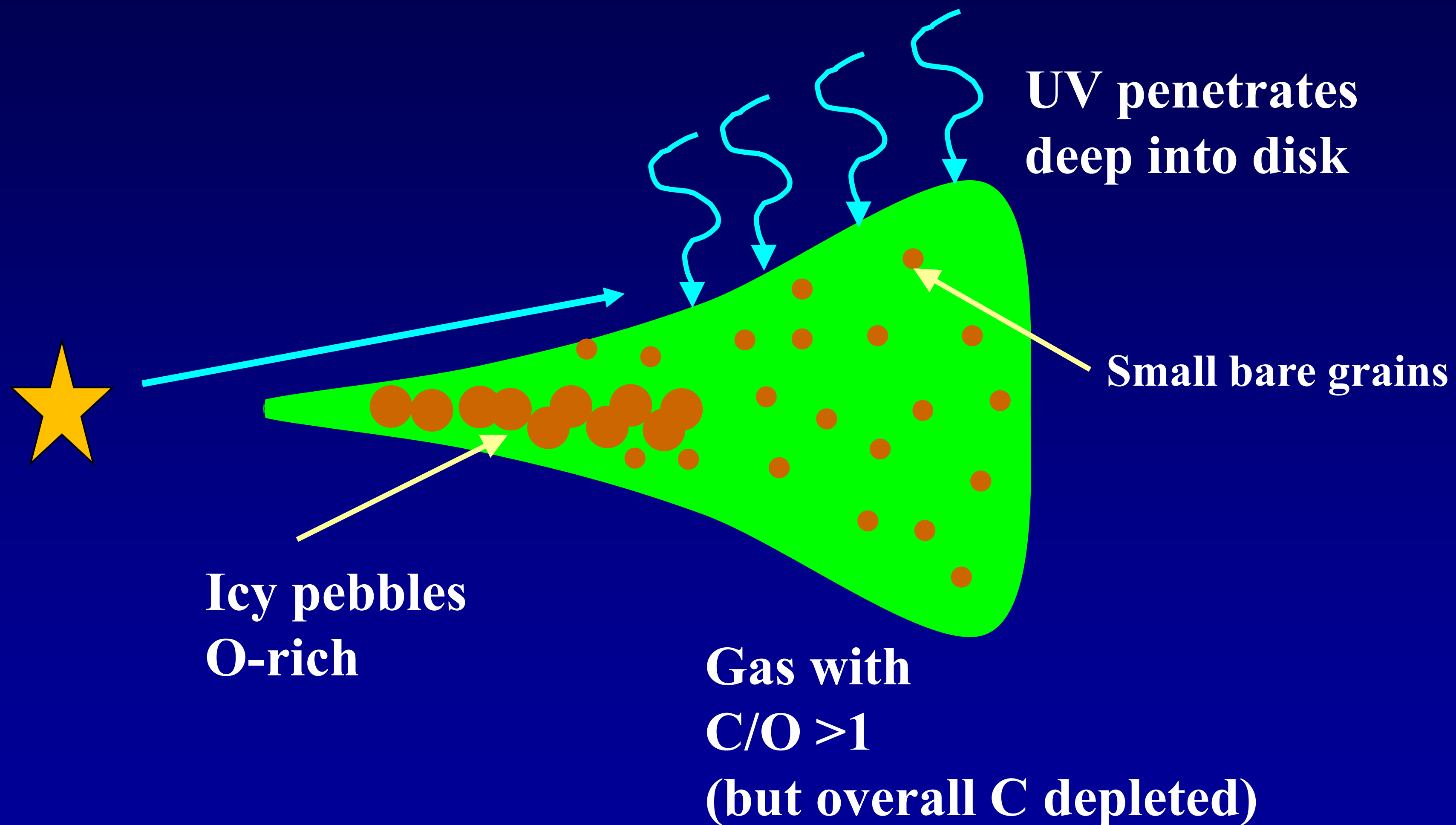
Bergin et al. 2013, McClure et al. 2016

Gas mass from HD factor 100 higher than from $C^{18}O$

Bergin et al. 2014, Kama et al. 2016, Miotello et al. 2017

Favre et al. 2013, Schwarz et al. 2016, Trapman et al. 2017, Kama et al. 2020

Chemistry: importance of disk structure and dust evolution



Bergin et al.
Birnstiel et al.
Krijt et al.

Inner Disk: IR

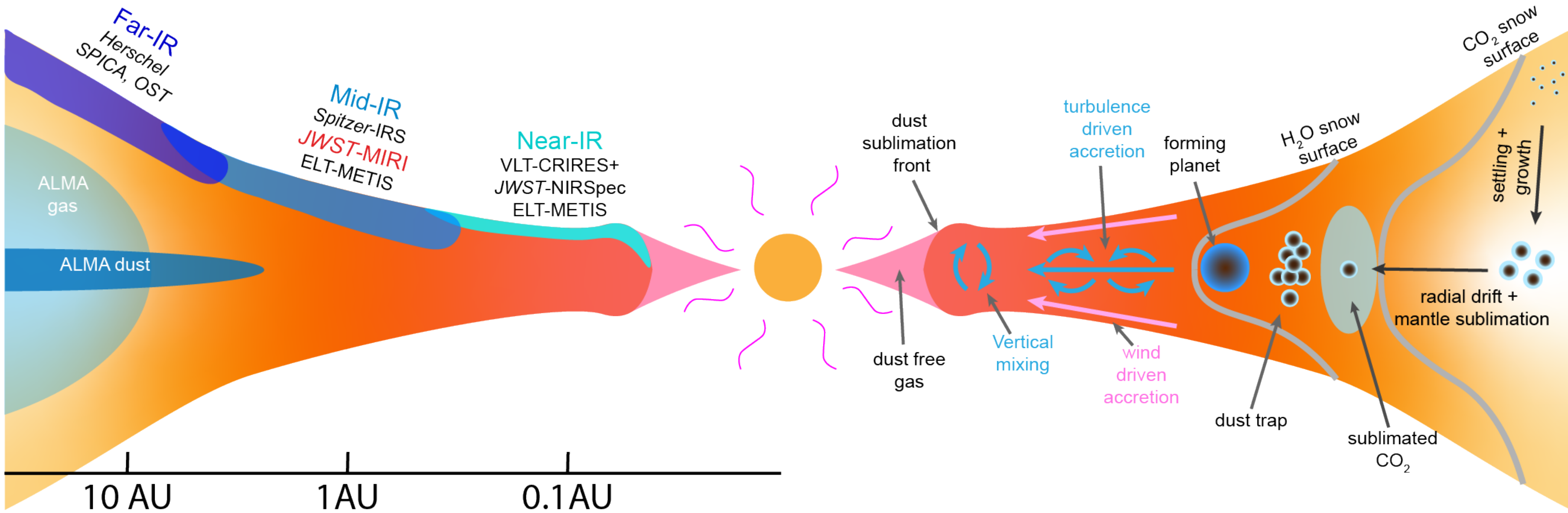
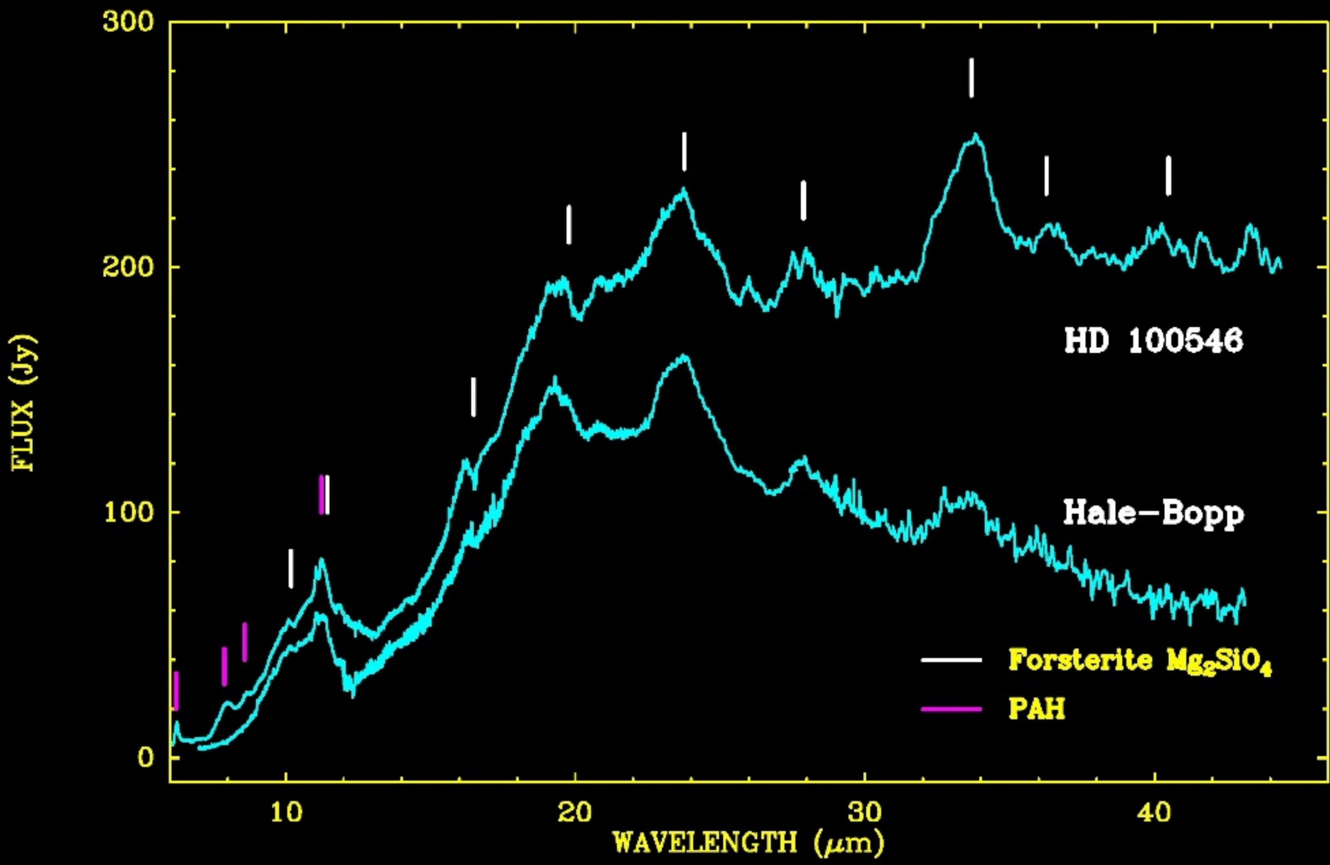


Figure by A. Bosman

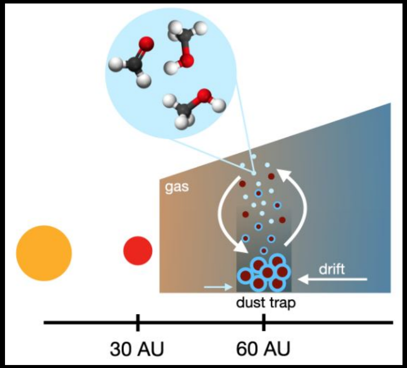
- IR: gas: major species, including without dipole moment H_2, CO_2, CH_4
  solids: silicates, ices, PAHs
  atomic lines, e.g. [Ne II], [S I], …
- Mm: gas: also minor species
  dust: continuum

Silicates: disks vs solar system



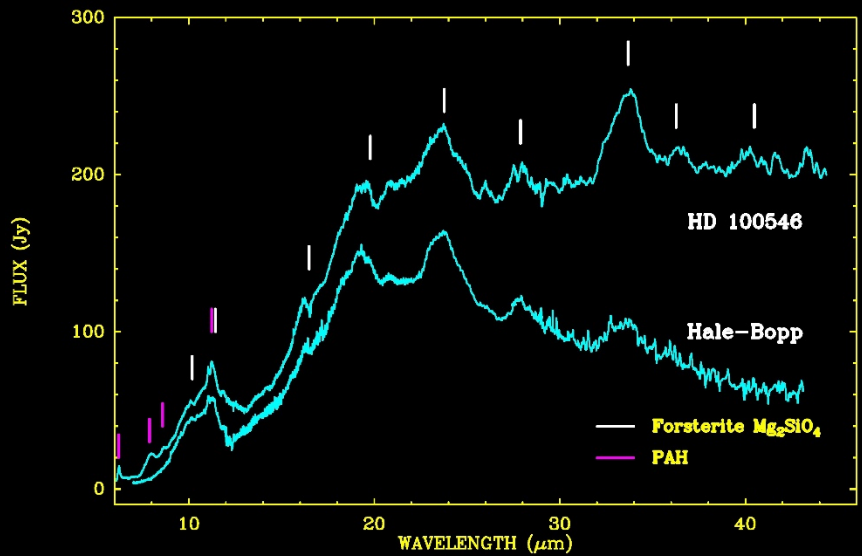
Malfait, Waelkens, Waters et al. 1998

ISO: Herbig stars



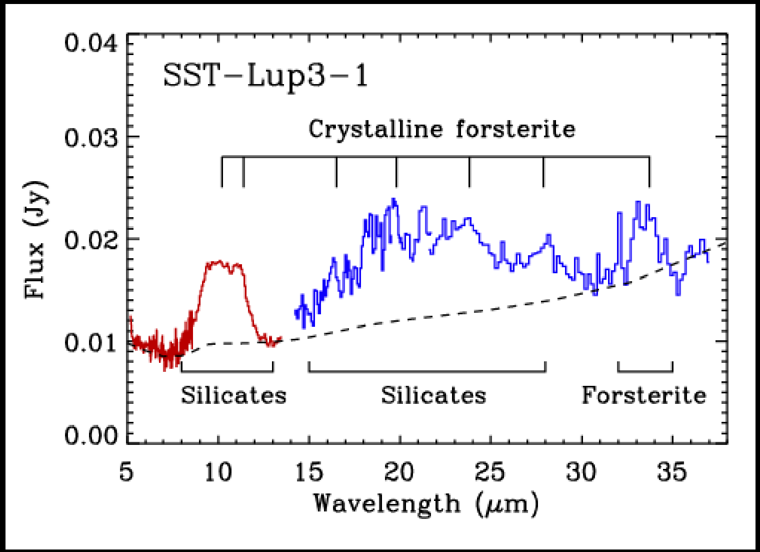
Crystallinity

ISO: Herbig stars



Malfait, Waelkens et al. 1998

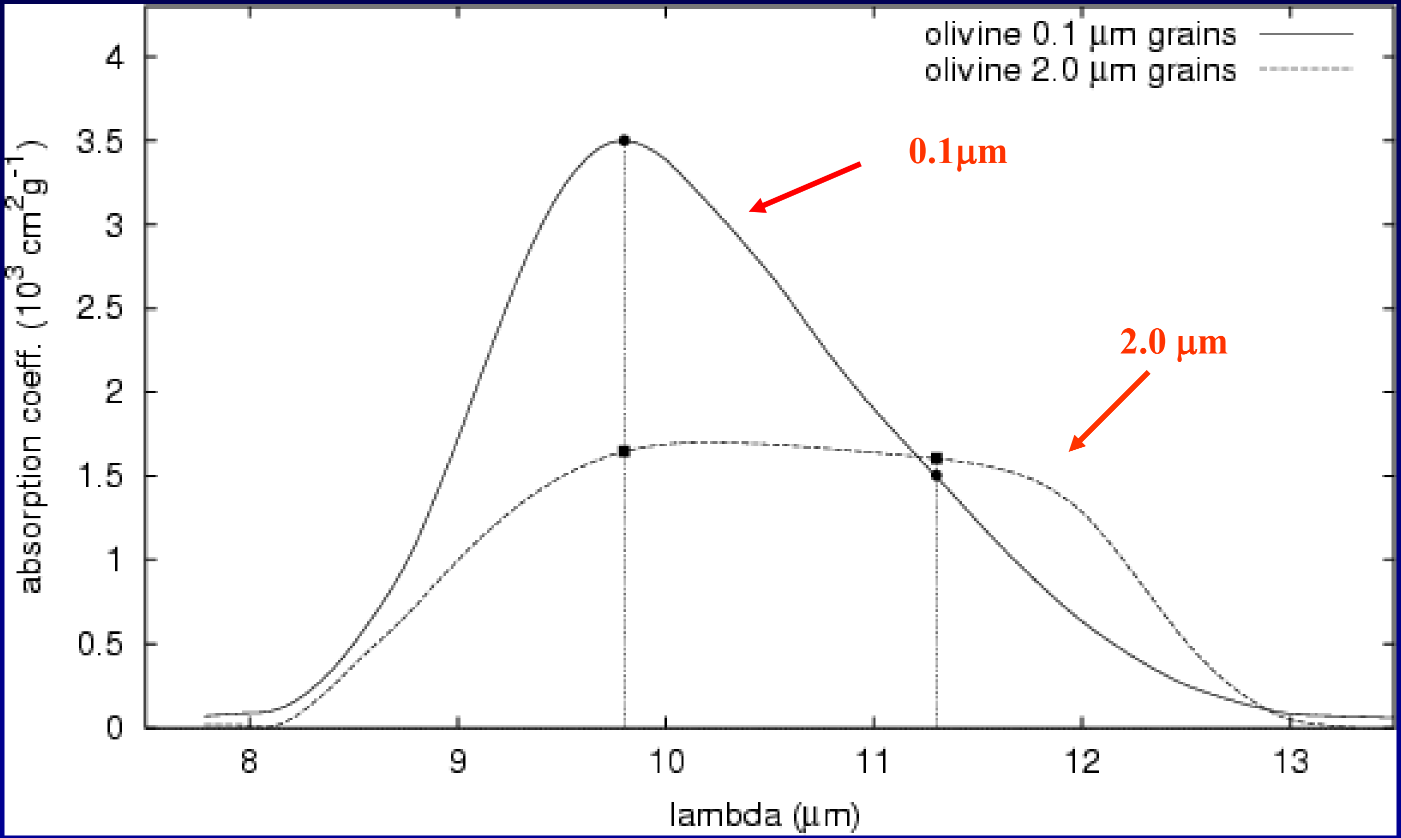
Spitzer: T Tauri stars and Brown Dwarfs



Merin et al. 2007
Apai et al. 2005

- Crystallinity seen in large fraction of T Tauri + BD disks (>50%)
- Interstellar silicates amorphous => crystallization at > 800 K must have occurred in inner disks
  => provides constraints on efficiency of heating and mixing processes
- Also seen in comets => mixing in our solar system was more significant than thought before

Silicate line profiles
(continuum subtracted)



- Ratio of 11.3/9.7 µm fluxes is measure of flatness of profile

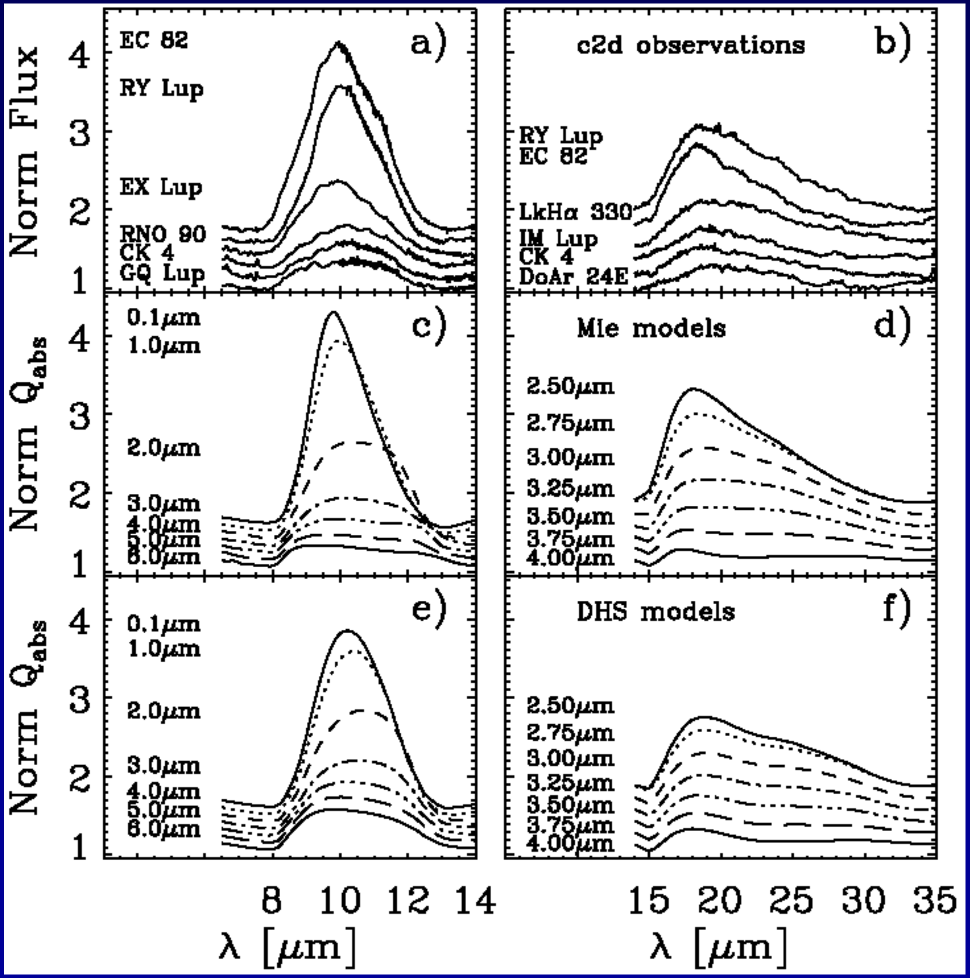
Bouwman et al. 2001
Van Boekel et al. 2003
Przygodda et al. 2003

Silicates in T Tauri disks

- Indication of grain growth to a few μm in most sources
- No correlation with age, accretion rate; weak trend with stellar type
  - Disks around M-stars show more grain growth than A stars

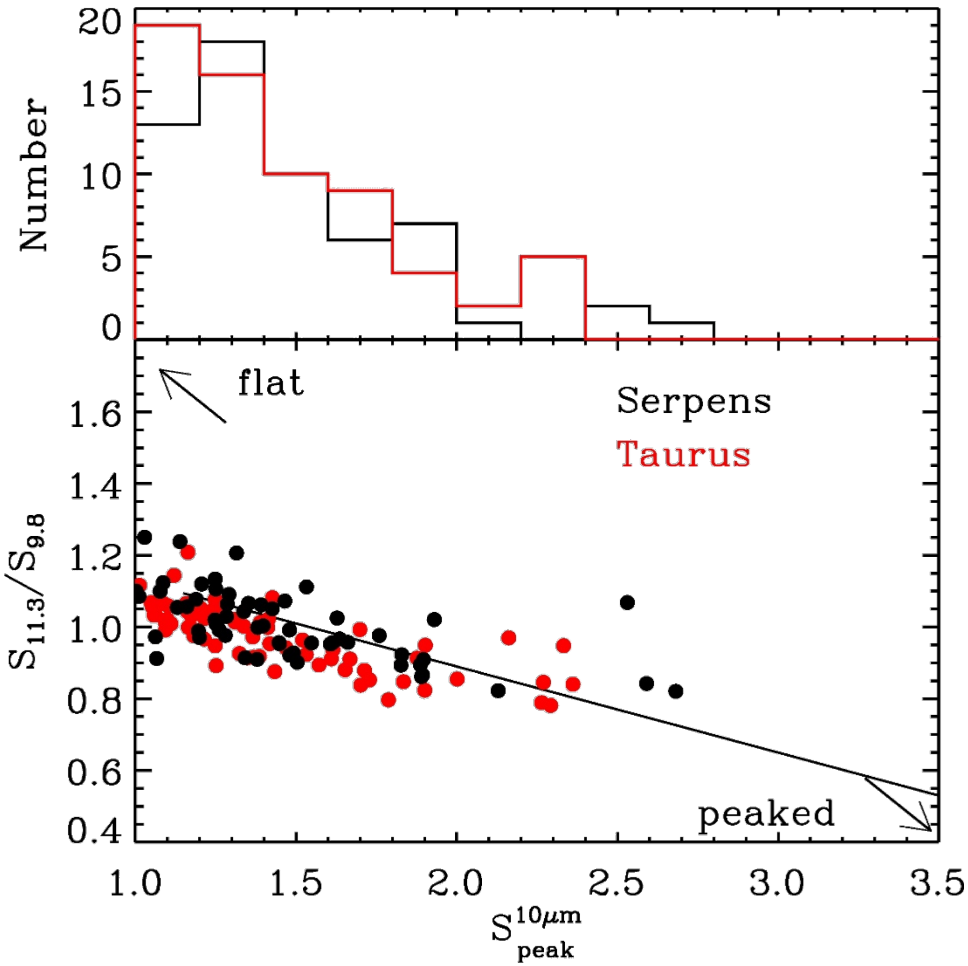
10μm

20μm



Kessler-Silacci et al. 2006, 2007

Statistics 10 μm feature

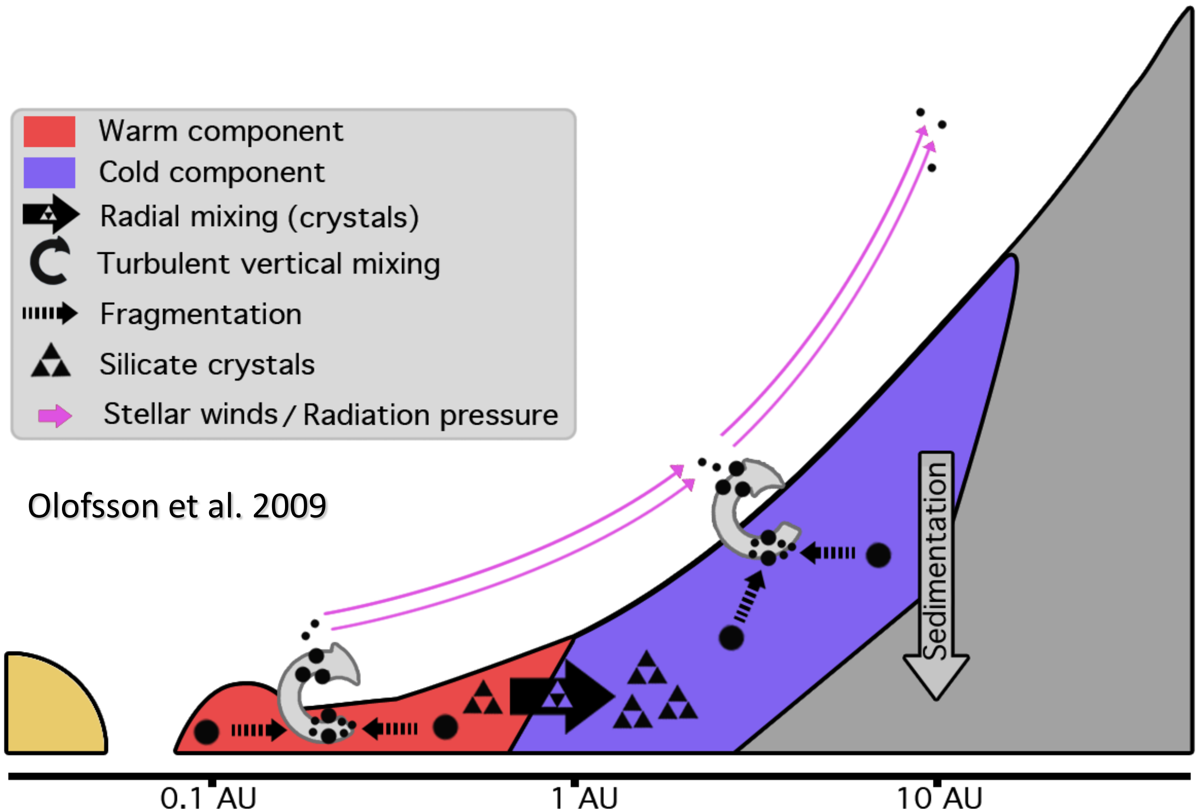


Remarkable similarity
(even though individual disks are very different)

Balance between dust *growth* and *fragmentation* that is maintained over a few million years independent of the population studied

Kessler-Silacci et al. 2006, 2007
Oliveira et al. 2010, 2011

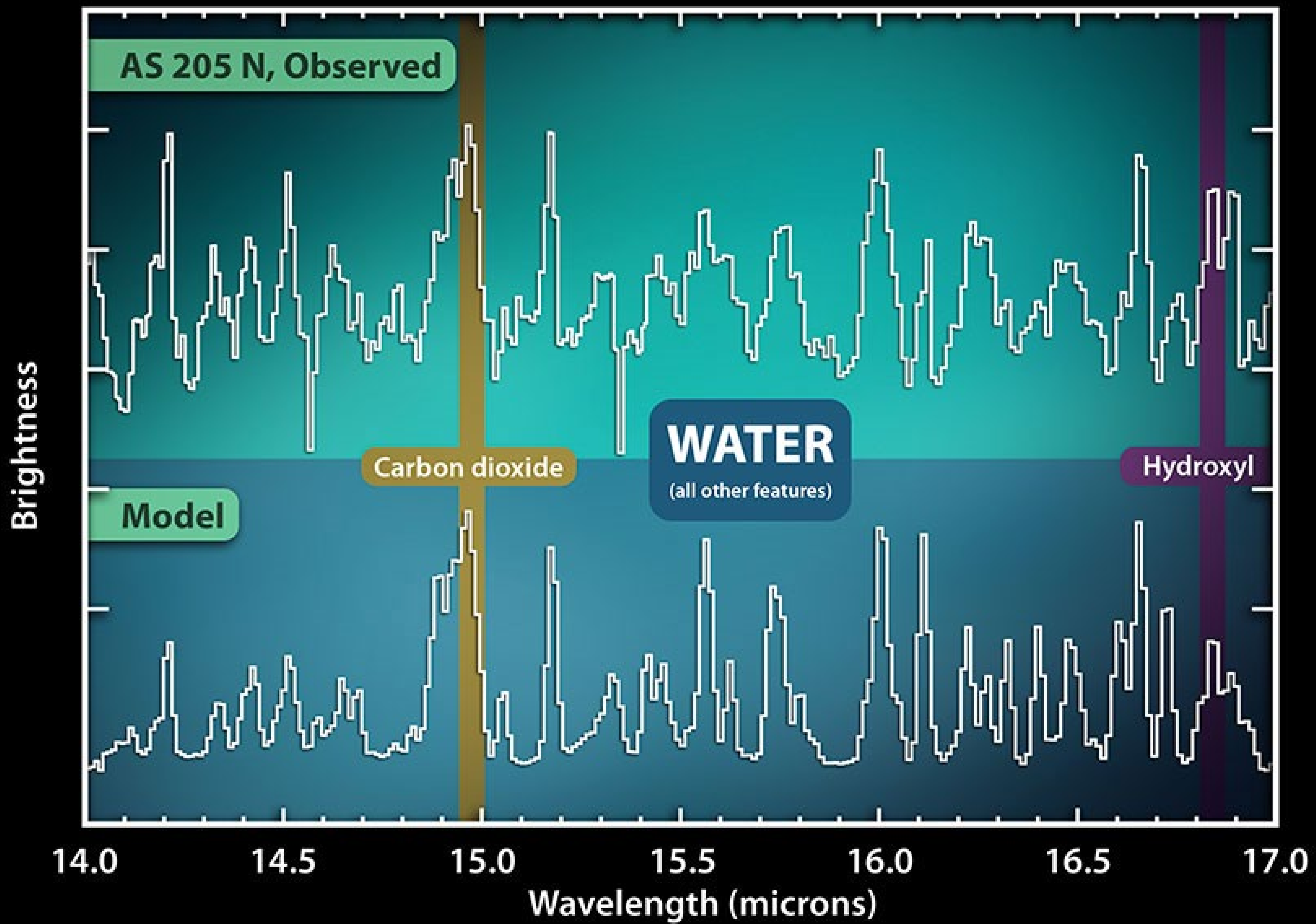
The Picture



- **Dust growth and sedimentation**
- **Bigger particles in midplane collide (fragmentation/boun-cing) producing smaller particles**
- **Turbulent mixing keeps a small dust population in upper layers at all times**
- **Different processes may be responsible for small dust at a given time**

Scenario consistent with evidence from primitive chondrites in our own Solar System

Hot water in the planet-forming zones of disks



Water Vapor and Other Gases in AS 205 N

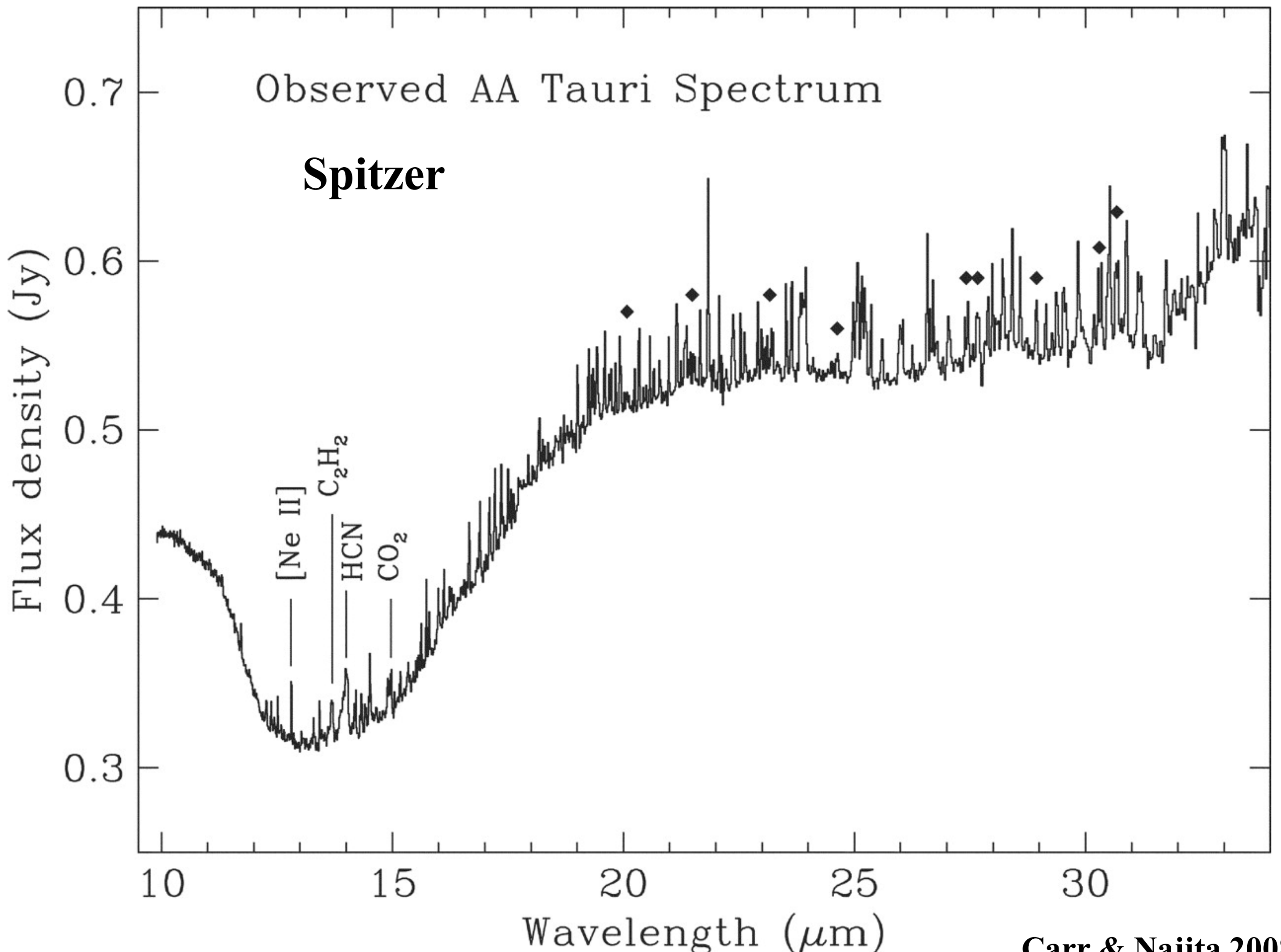
Spitzer Space Telescope • IRS

NASA / JPL-Caltech / C. Salyk (Caltech)

Salyk, Pontoppidan et al. 2008

ssc2008-06b

Water and organics in AA Tau



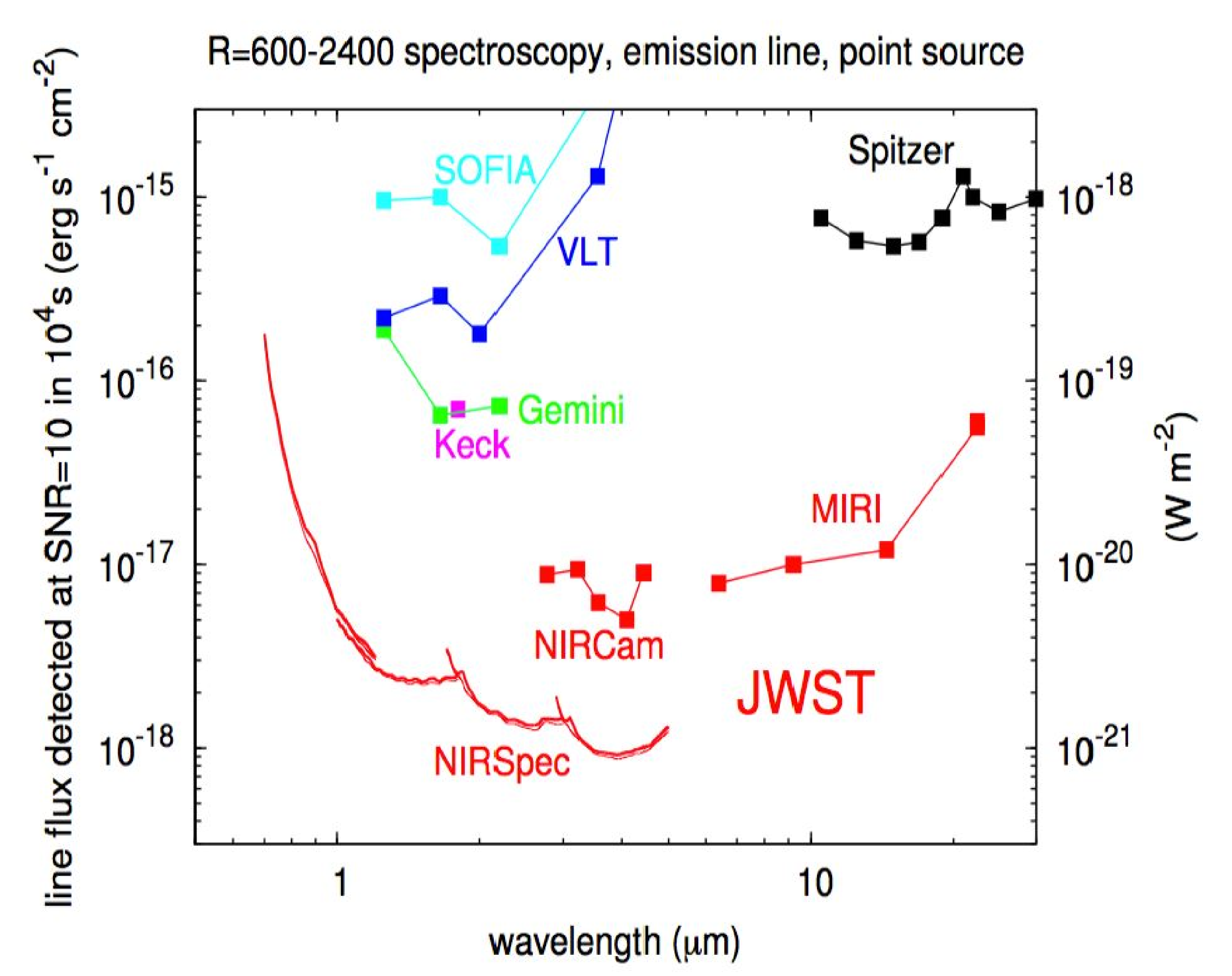
Carr & Najita 2008

- Deep new observations: such rich spectra are common for T Tauri disks

Revival of IR spectroscopy
after 8 yr drought (>2013)

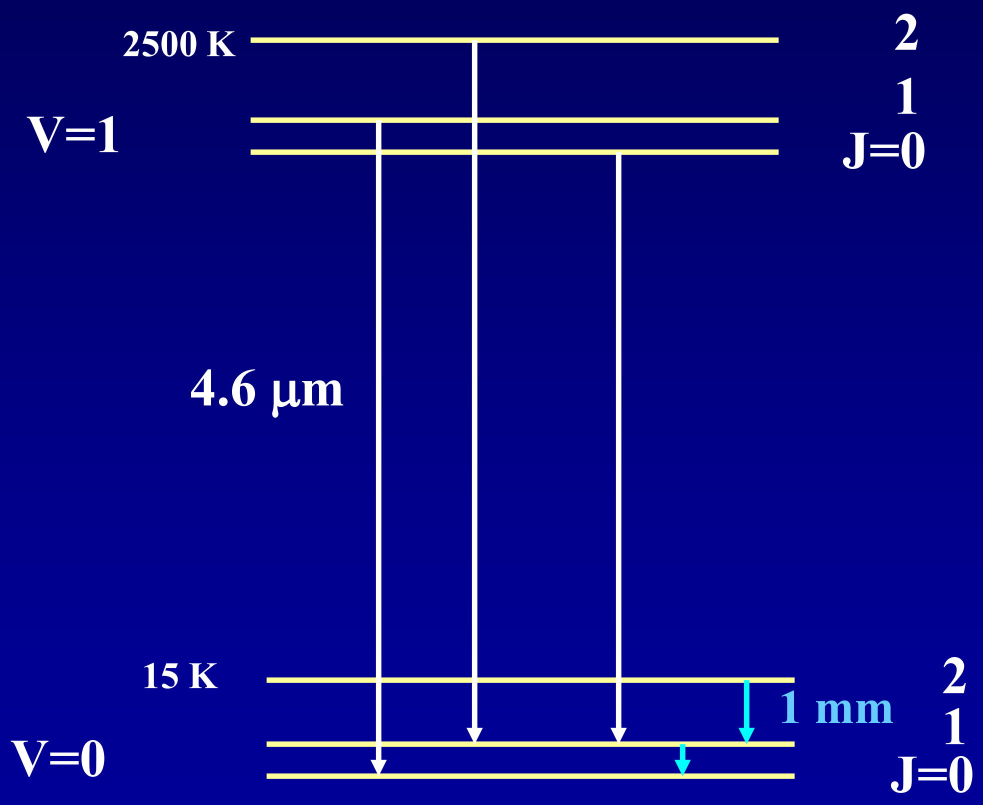
- **VLT-CRIRES+, Keck-NIRSPEC:** *high spectral res*
  - **1-5 μm R~10^5**
- **JWST-MIRI, NIRSPEC:** *sensitivity, full λ range*
  - **1-28 μm R~3000 IFU**
- **VLTI-Gravity(+) :** *spatial resolution 1 milliarcsec*
  - **2μm R~3000**
- **ELT-METIS ~2027:** *spatial + spectral resolution*
  - **1-5 μm R~10^5, IFU**

JWST spectral sensitivity



Ro-vibrational energy levels of CO

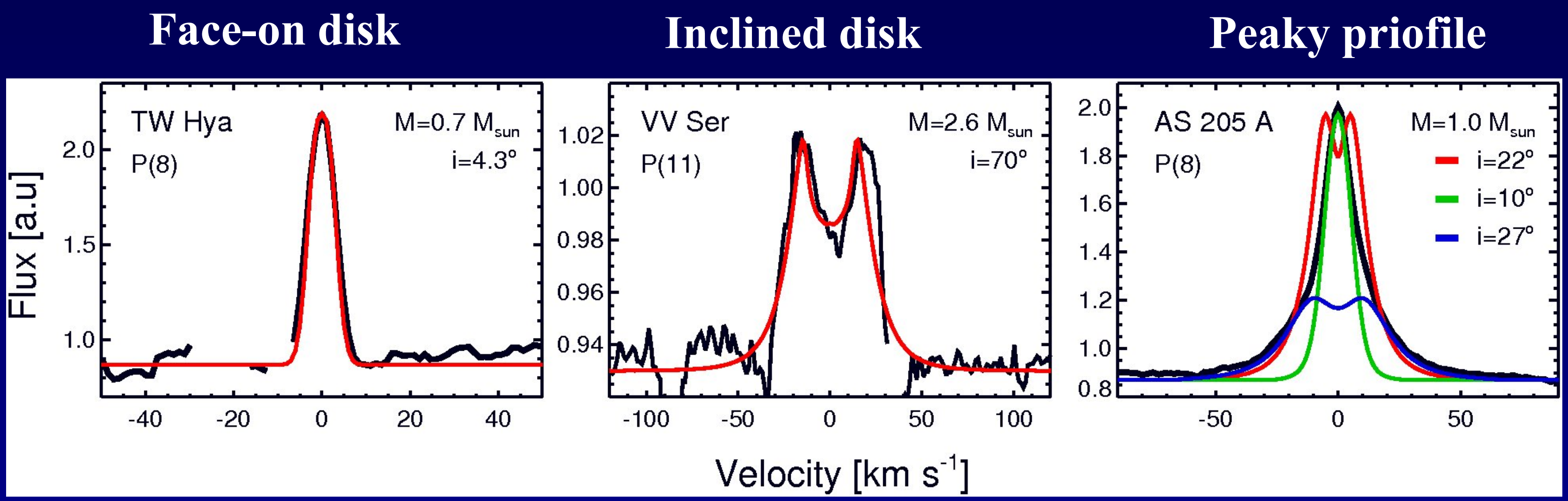
V=1-0: M-band 4.6 μm
V=2-0: K-band 2.3 μm



Not to scale

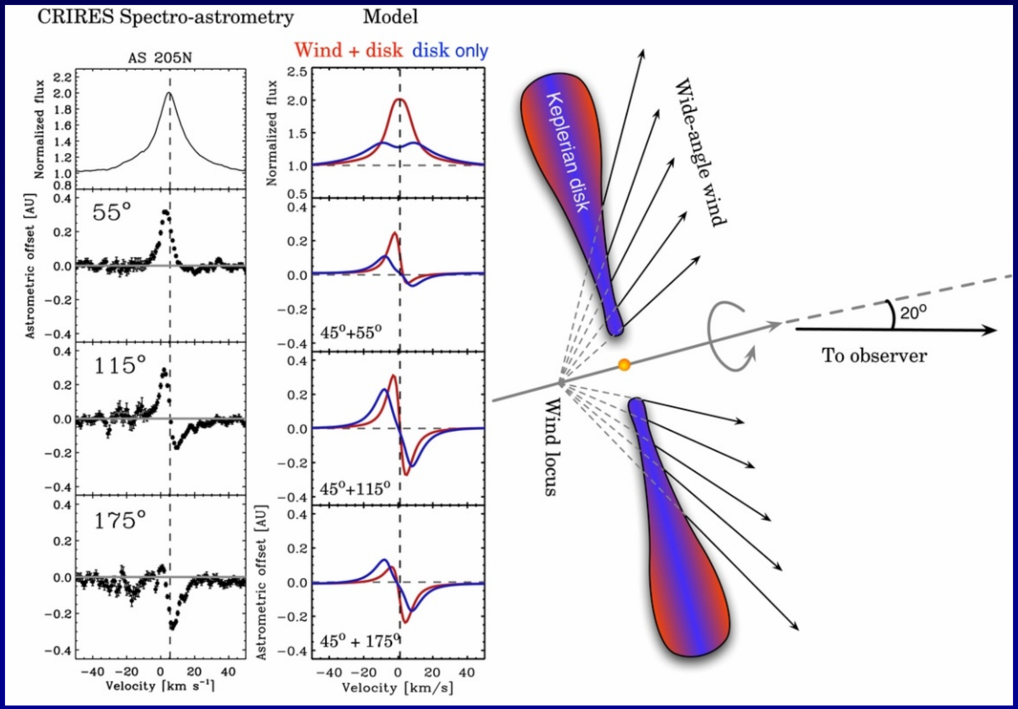
- Lines probe warm gas in inner few AU of disks
- Many lines in a few spectral settings

CO Profile



- Kepler's law => Inner radius R_{CO}
- Evidence for disk and in many cases a slow disk wind

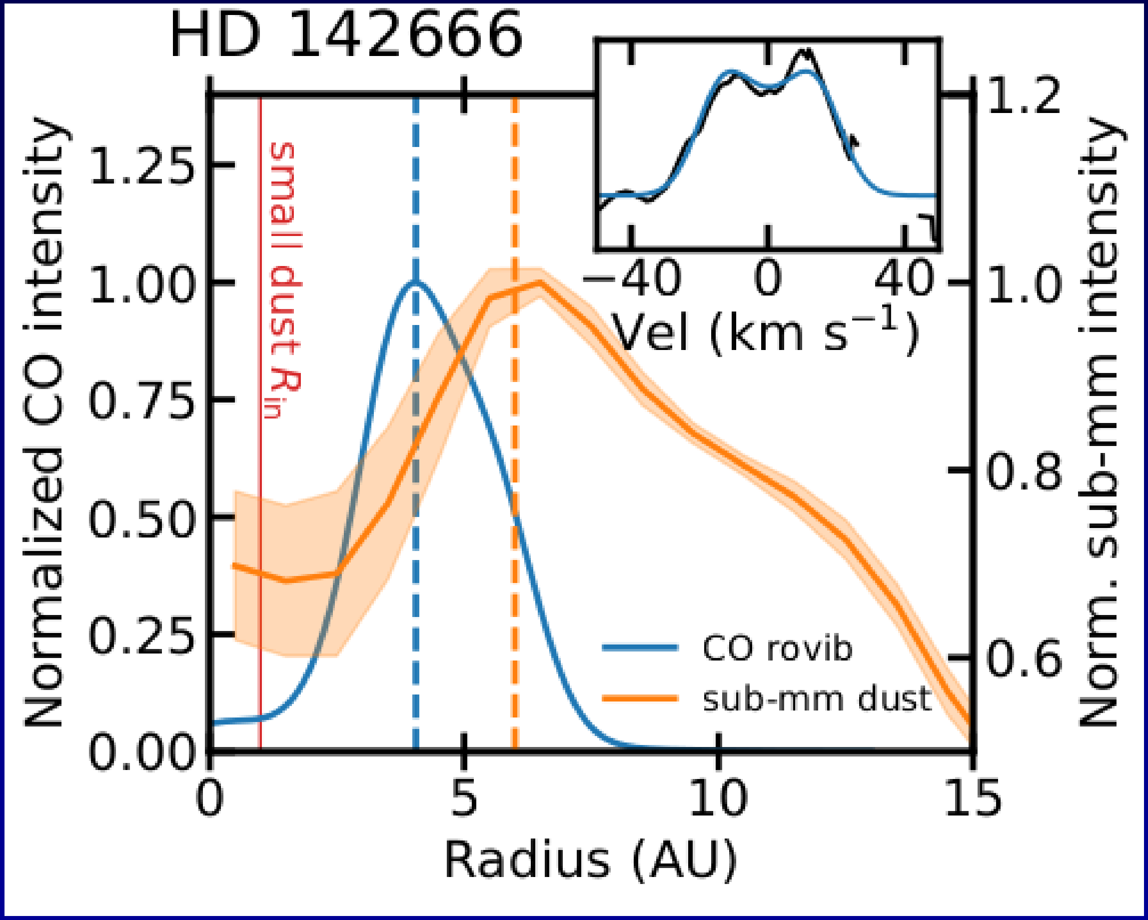
Probing disk + *slow* disk wind



Pontoppidan et al. 2011
Brown et al. 2013
Banzatti & Pontoppidan 2015

- Use spectro-astrometry to locate emission within a few au
- Slow molecular disk wind moving at few km/s w.r.t. stellar velocity

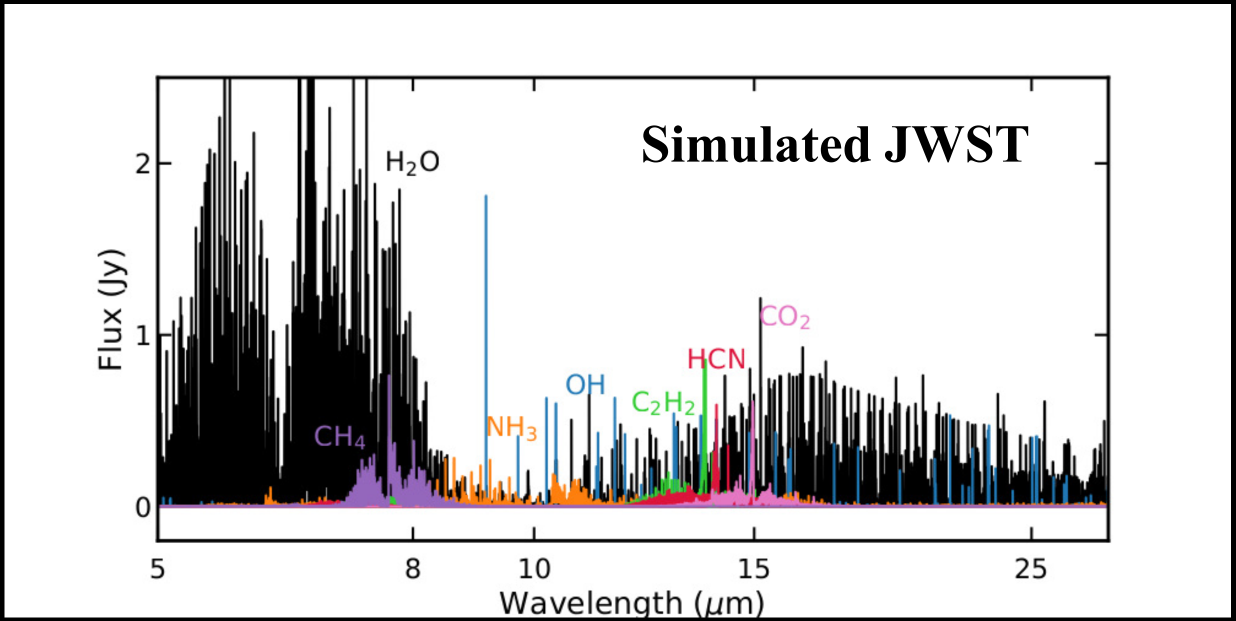
Probing inner disk gas structure



Bosman et al. 2019

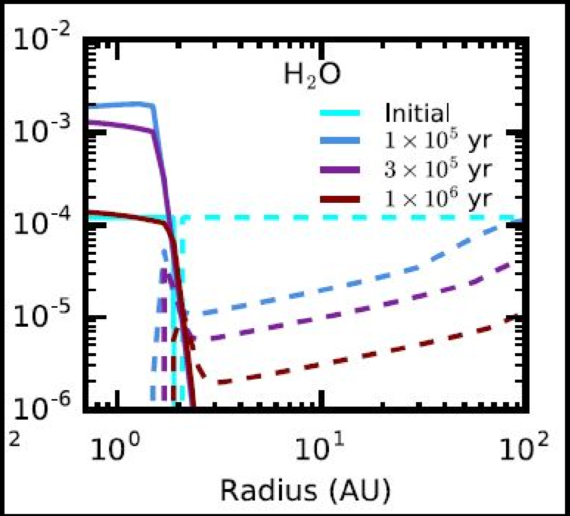
Invert line profile to get gas structure on few au scales!

JWST: inner disk chemistry
Probing the gas that makes planets



Inventory
C, O, N

Bosman et al. 2017, Bosman, priv. comm.



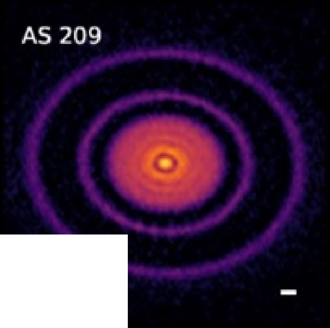
Bosman et al. 2018

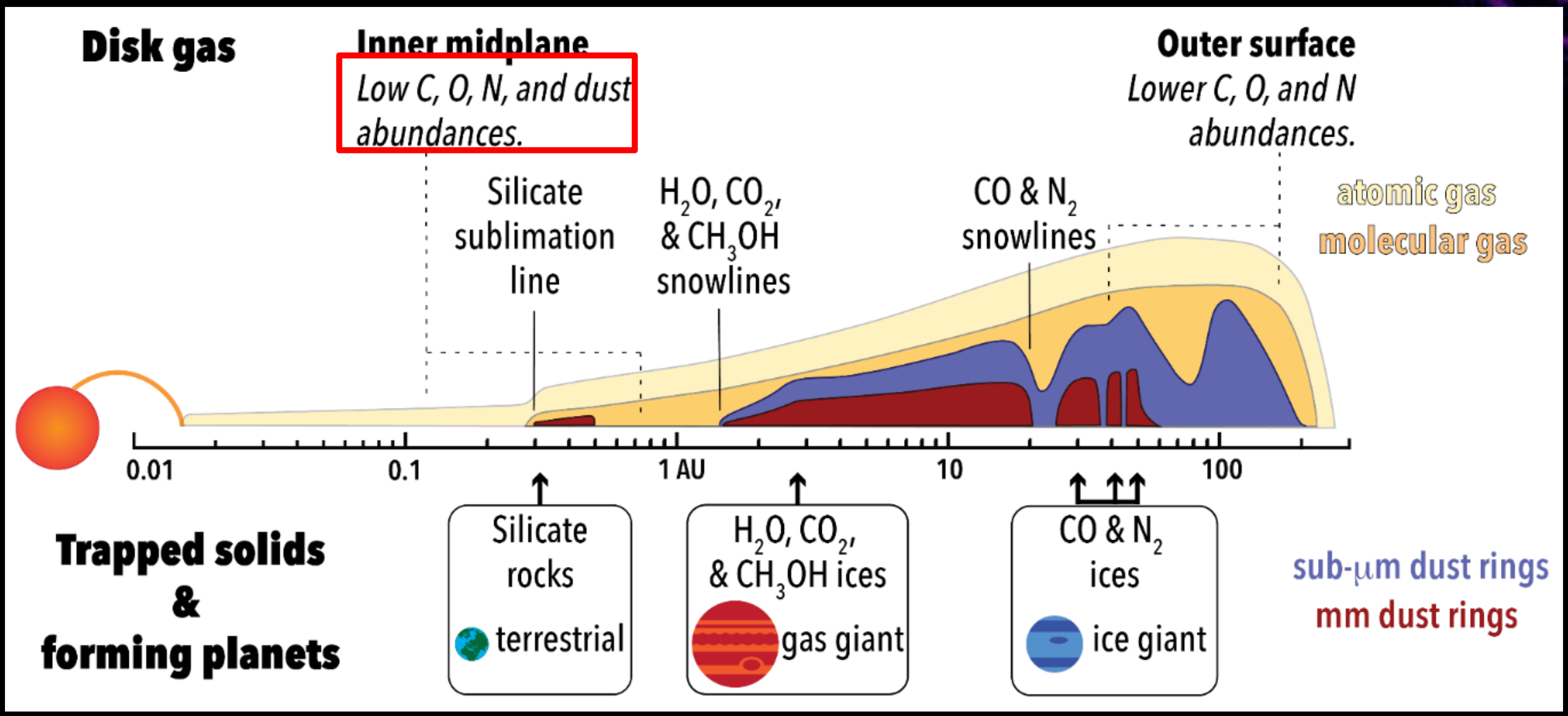
Pebble drift enhances
H_2O in inner disk

But…. Dust traps!

Locking up volatiles in dust traps

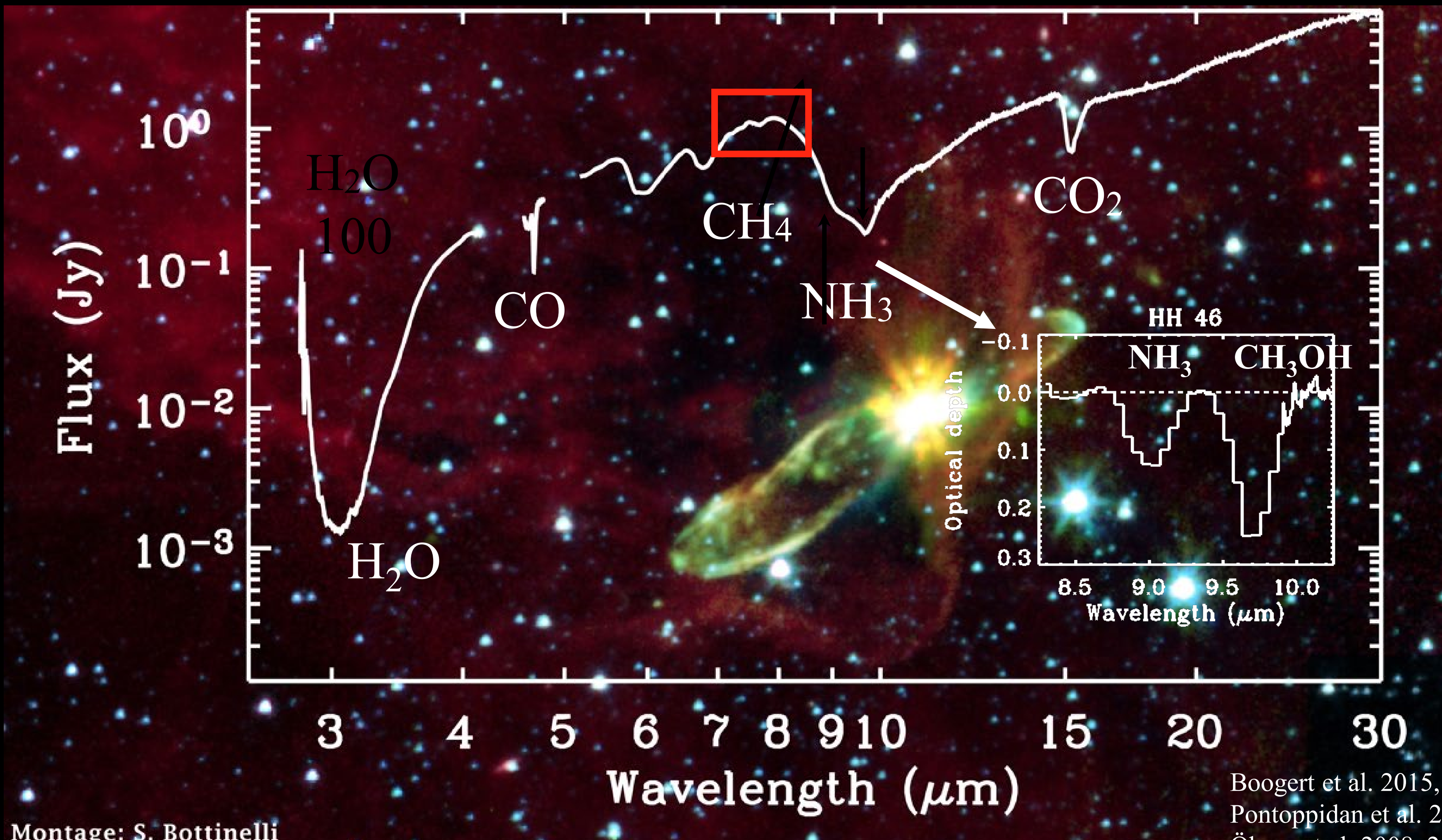
Linking inner and outer disk





McClure et al. 2019, 2020
Bosman & Banzatti 2019

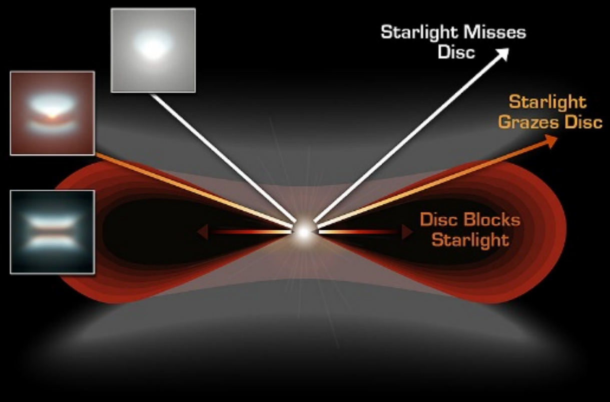
Ice features: simple to complex



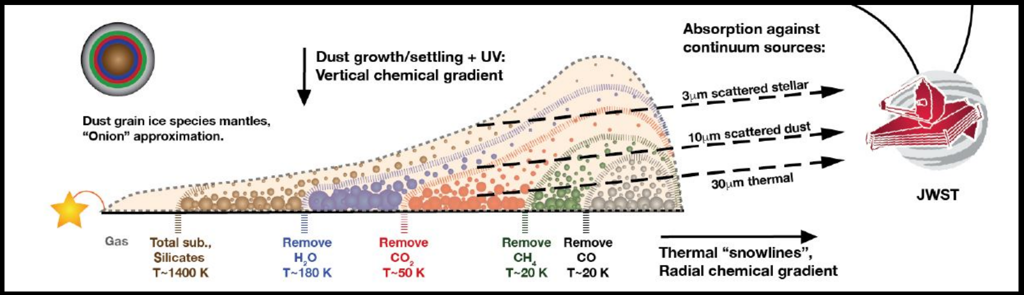
Boogert et al. 2015,
Pontoppidan et al. 2008,
Öberg et al. 2008, 2011
Gibb et al. 2004

- Ices can contain significant fraction (>50%) of heavy element abundances
-

JWST: ices, even spatially resolved!



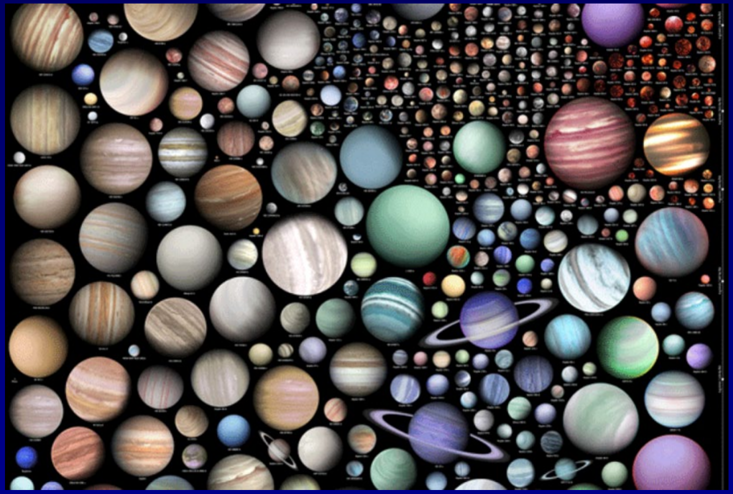
Pontoppidan et al. 2005



McClure et al. ERS, GO
van Dishoeck et al. GTO, GO
Henning, Kamp , EvDet al. GTO

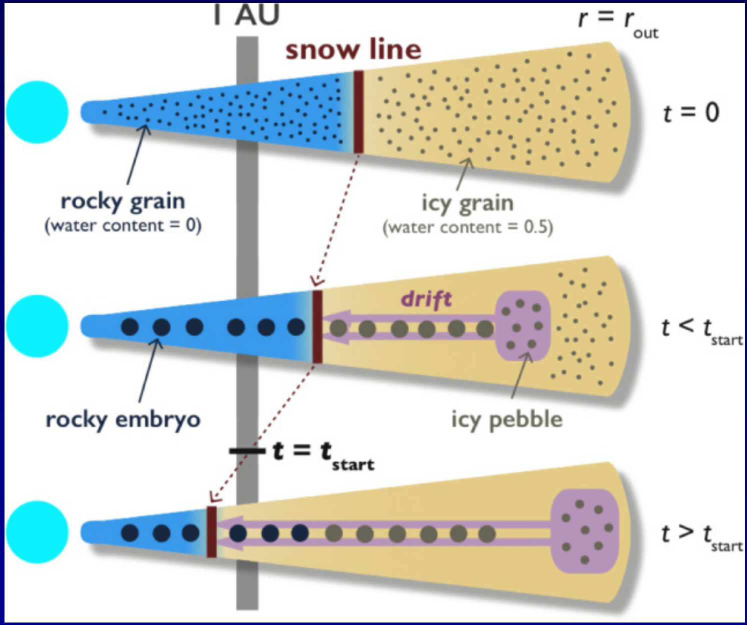
CO_2, CH_3OH ice enhanced in disks? (CO transformation)

From disks to comets, planets

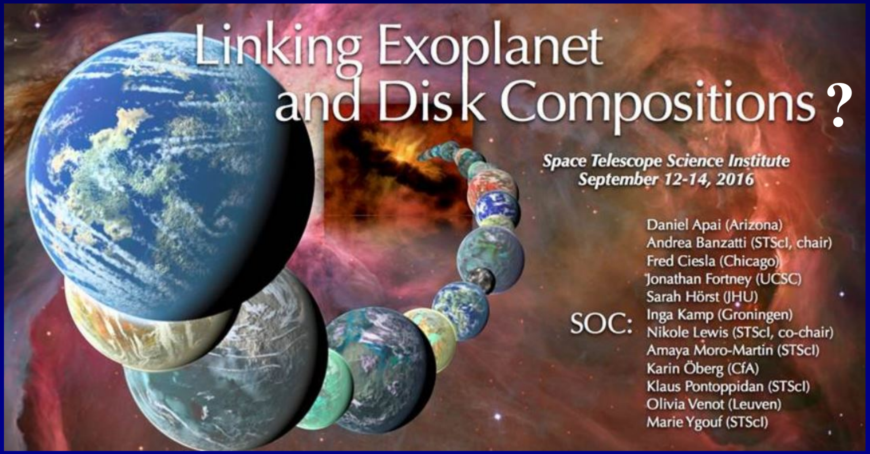


Can we link planetary atmosphere composition with its formation location / history?

Key question: are most heavy elements accreted from gas or ice?



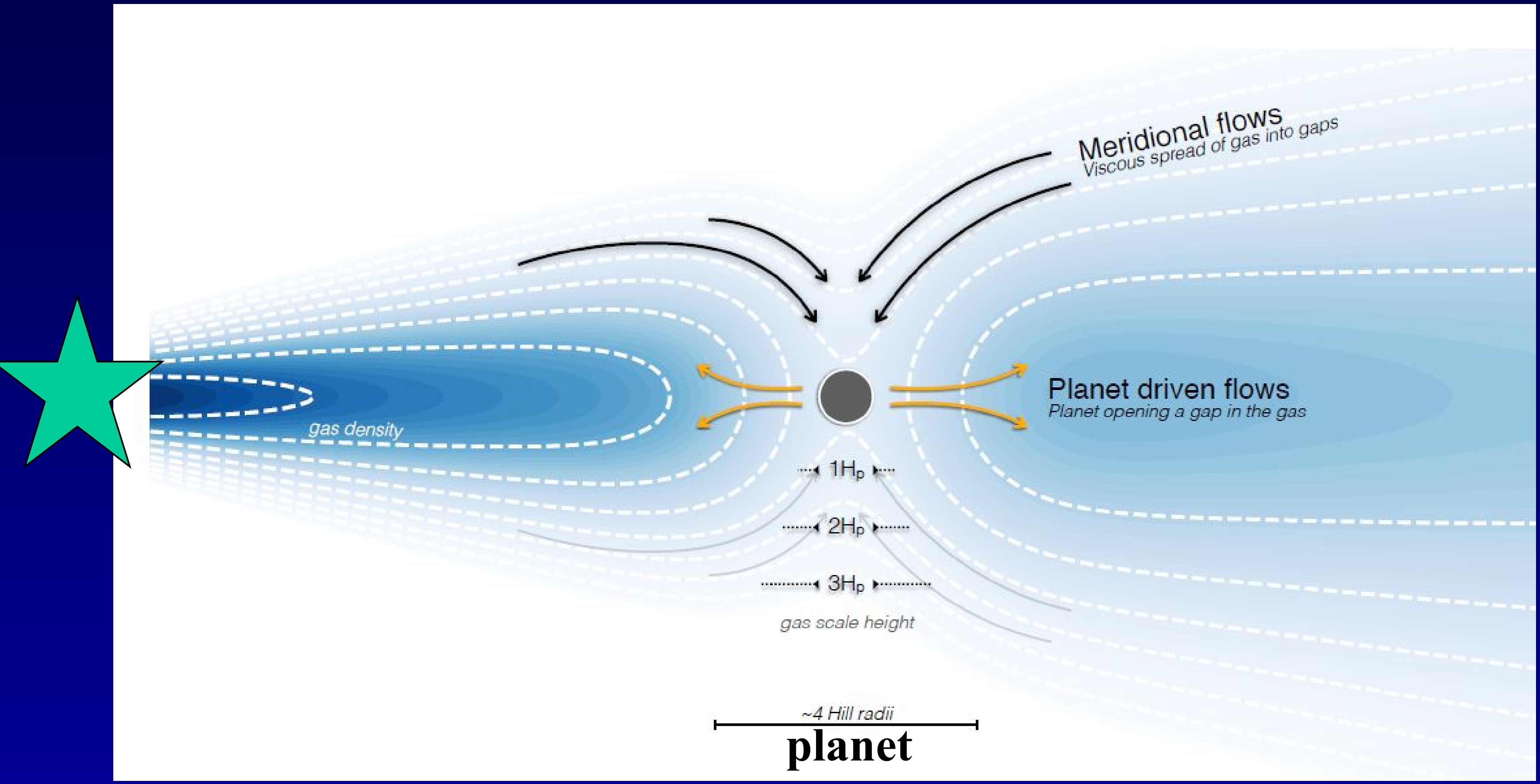
Sato et al. 2016, Piso et al. 2015, 2016



Complicated by:

- Radial drift pebbles, dust traps, diffusive mixing
- Migration planets
- Reset chemistry in inner disk (inside snow lines)
- Reset chemistry in planetary atmospheres→ preserve C/O, C/N?

Vertical accretions: Meridional flows

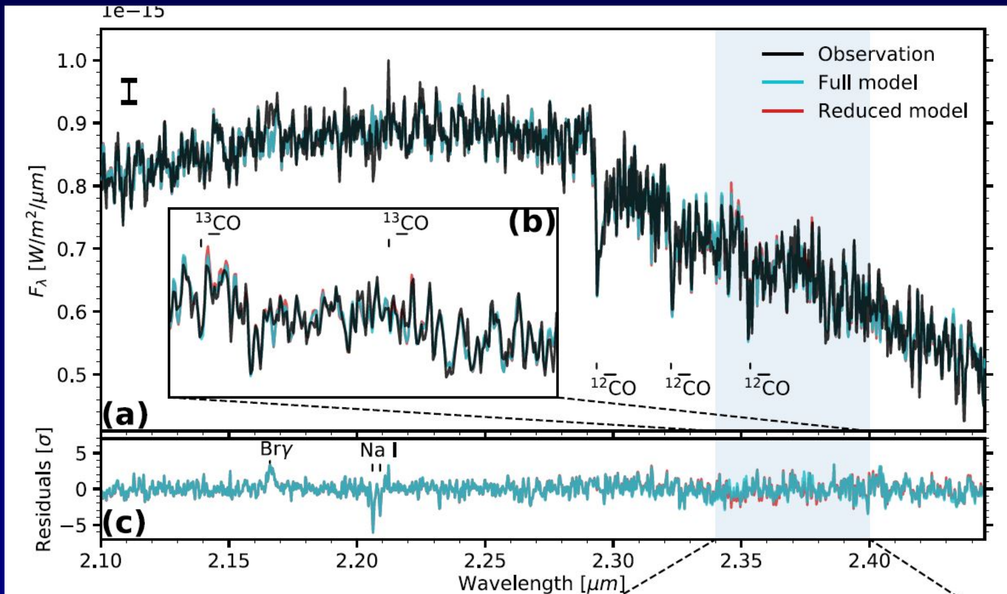


Teague et al. 2019, Nature
Cridland, Bosman & vD 2020
Facchini, Cridland et al. in prep

Chemistry in upper layers is relevant for planet formation → JWST!

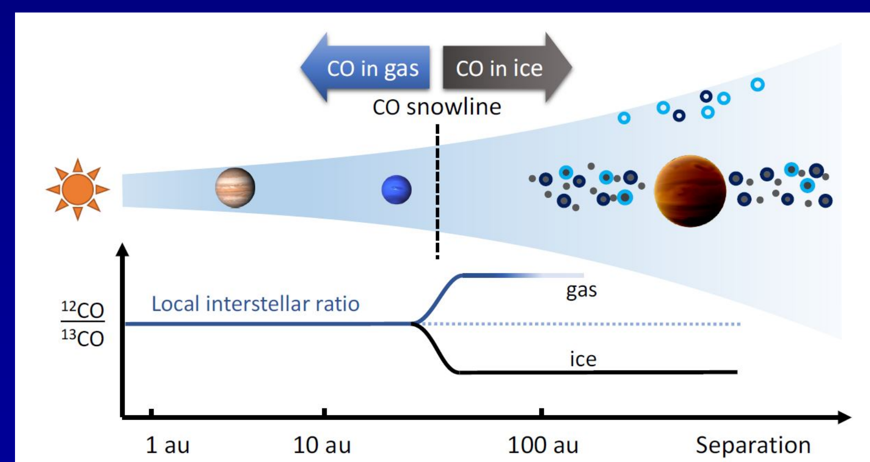
PDS70b,c disk + planets!

Direct spectroscopy exoplanets



Isotopes!

Low ^{12}CO/^{13}CO=31 +17-10!



Zhang, Snellen et al. 2021

Accelerating to the future

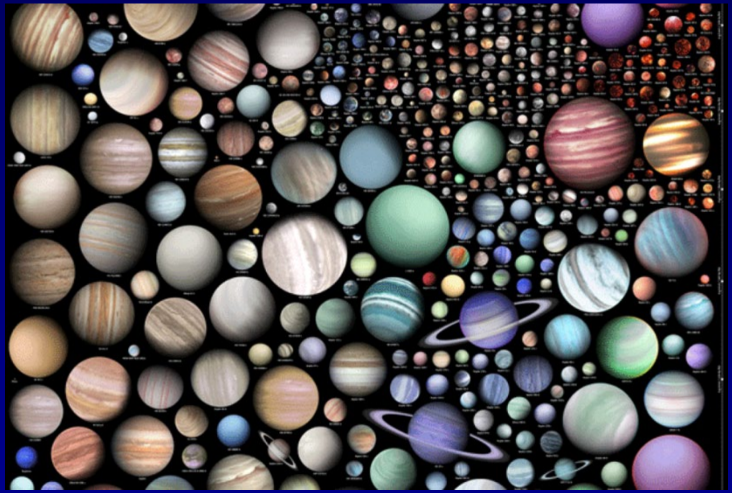
Extremely Large Telescope ESO
~39m diameter
~ 2027

METIS mid-IR instrument

Ariel

And hopefully more…..

From disks to comets, planets



A bright future, step by step!