Techniques, Observations, and Diagnostics of Protoplanetary Disks: Inner Disk

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2021 Sagan Summer Workshop

Who am I?

A research astronomer in Tucson, Arizona

- Study star and planet formation, the Milky Way, etc.
- Theory, observations, archival data, storytelling

Staff astronomer at an Observatory (NSF’s NOIRLab)

- NOIRLab is the unification of NOAO, Gemini Observatory, and Rubin Observatory, which is carrying out the Legacy Survey of Space and Time (LSST).
- At NOIRLab, we plan and deliver new facilities, initiatives, instruments, observing modes, data systems and analysis tools...to enable anyone with a good idea to pursue it using forefront capabilities.

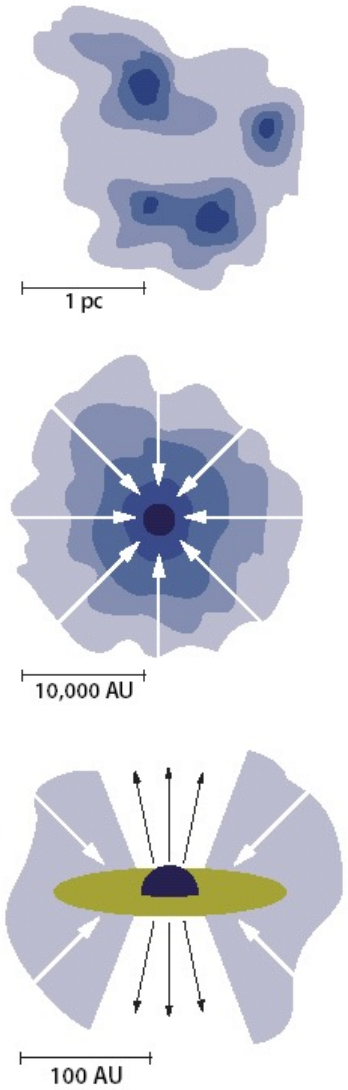
Welcome to contact me: joan.najita@noirlab.edu

UV/IR, Inner Disks, Planet Formation

Brief sampling of techniques, ideas, science:

- Stellar accretion
  - Inner disk lifetime
  - Nature of transition disks
- Disk structure and substructure
  - Inner gas disk radii
  - Orbiting gaseous circumplanetary disks
- Disk chemistry
  - Probe planetesimal formation (otherwise elusive)
- Disk dynamics
  - Possible accretion in action

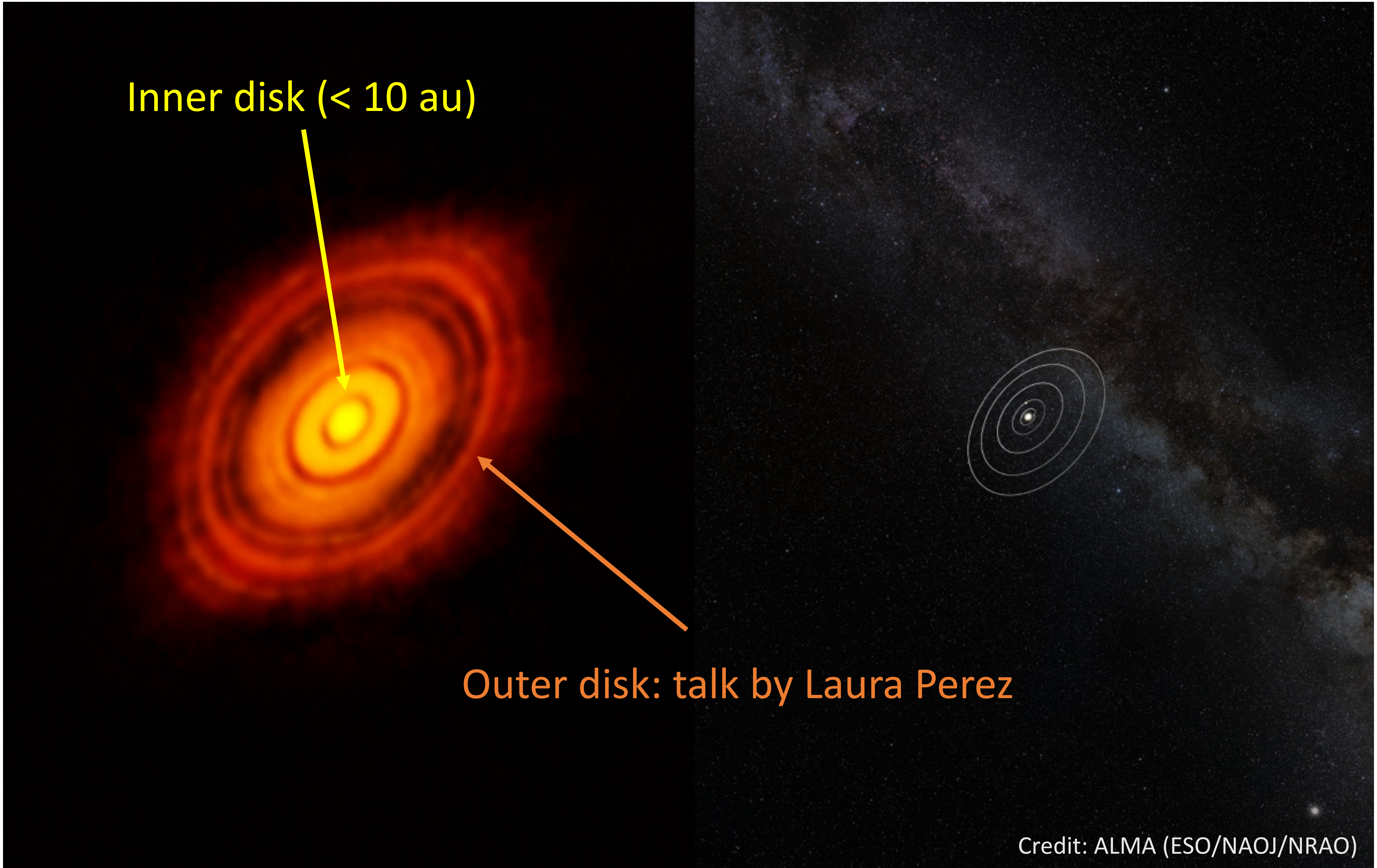
Disks in Star and Planet Formation



Molecular cloud cores have finite angular momentum.

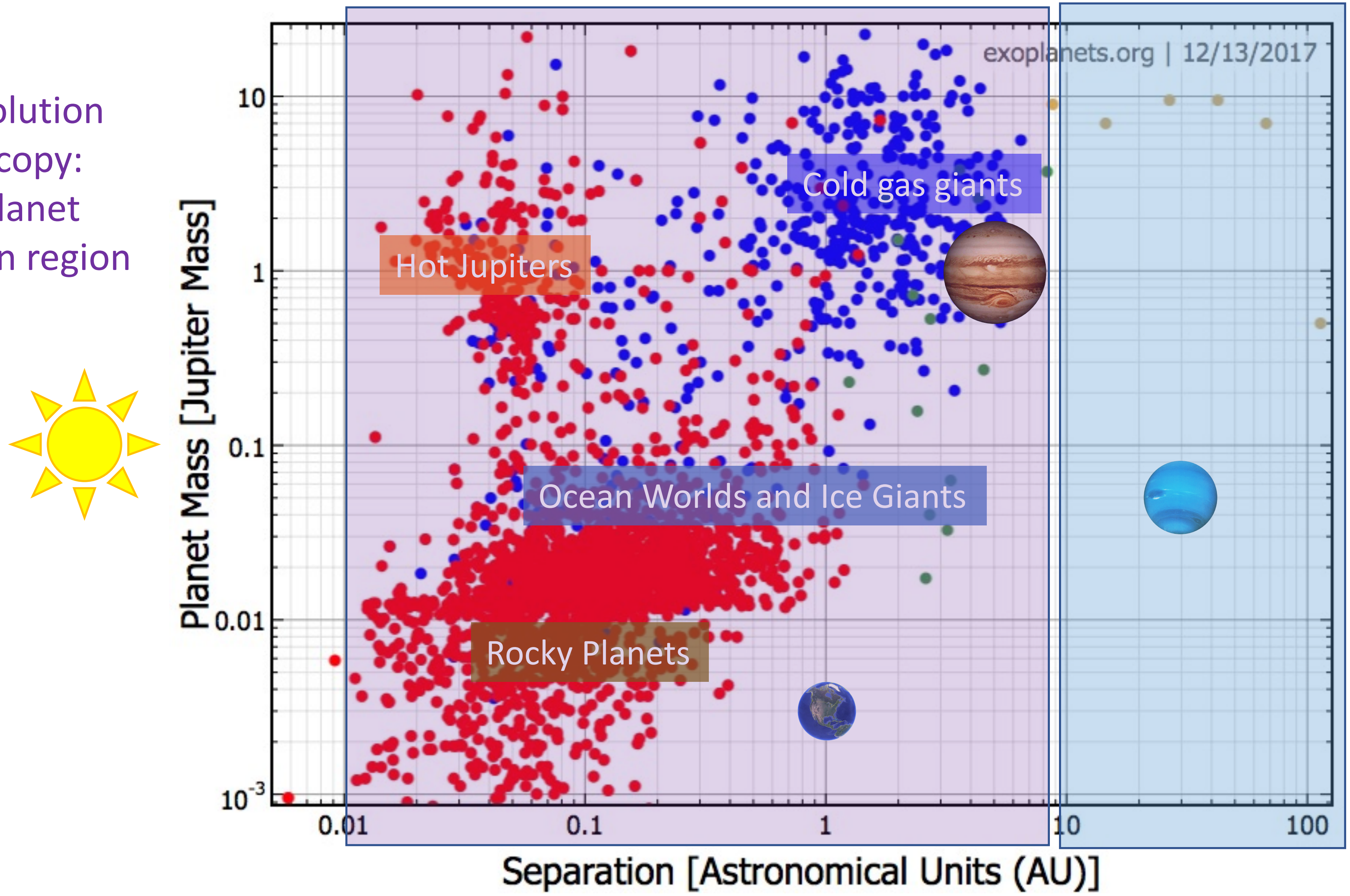
When they collapse, disks form.

Stars grow by accretion through disks.
Planets also form there.


Inner disk (< 10 au)
Outer disk: talk by Laura Perez
Credit: ALMA (ESO/NAOJ/NRAO)

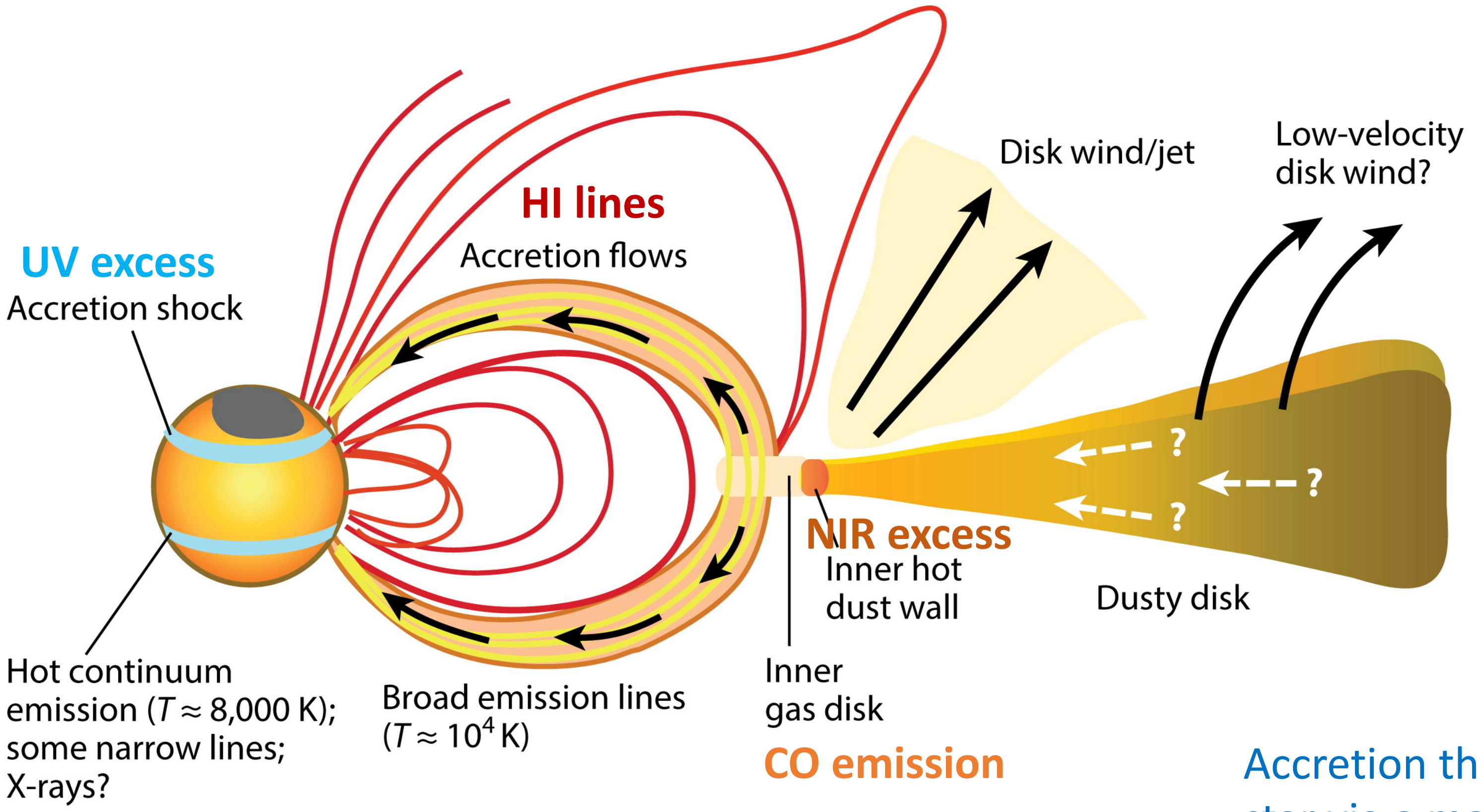
Exoplanet Populations

High resolution Spectroscopy: Probes planet formation region



Imaging: ALMA, high contrast NIR

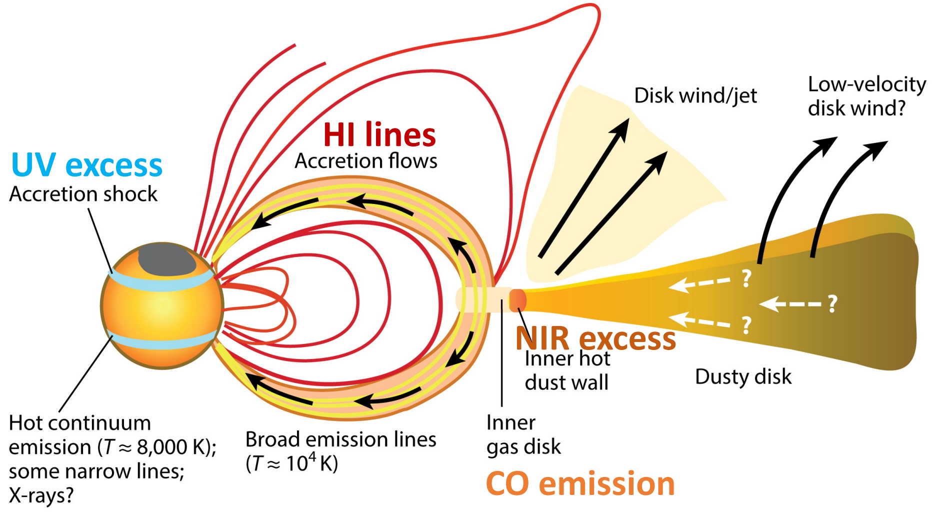
The near-stellar environment of T Tauri Stars

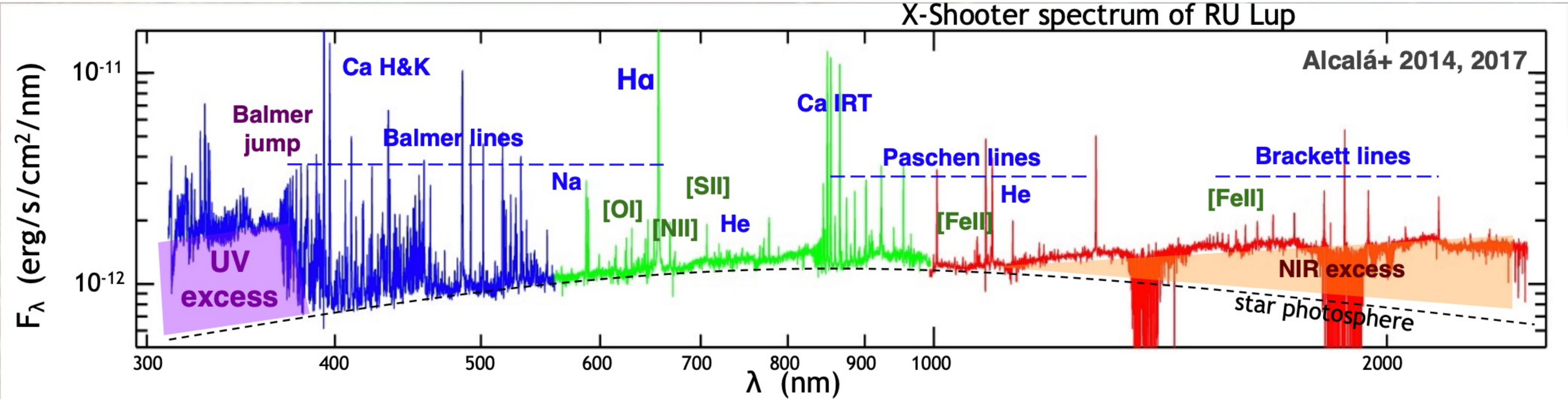


Accretion through disks and onto star via a magnetosphere

Hartmann et al. 2016

NUV/Optical Diagnostics





Credit: Alcala in "Accretion & winds/outflows in solar-type YSOs"

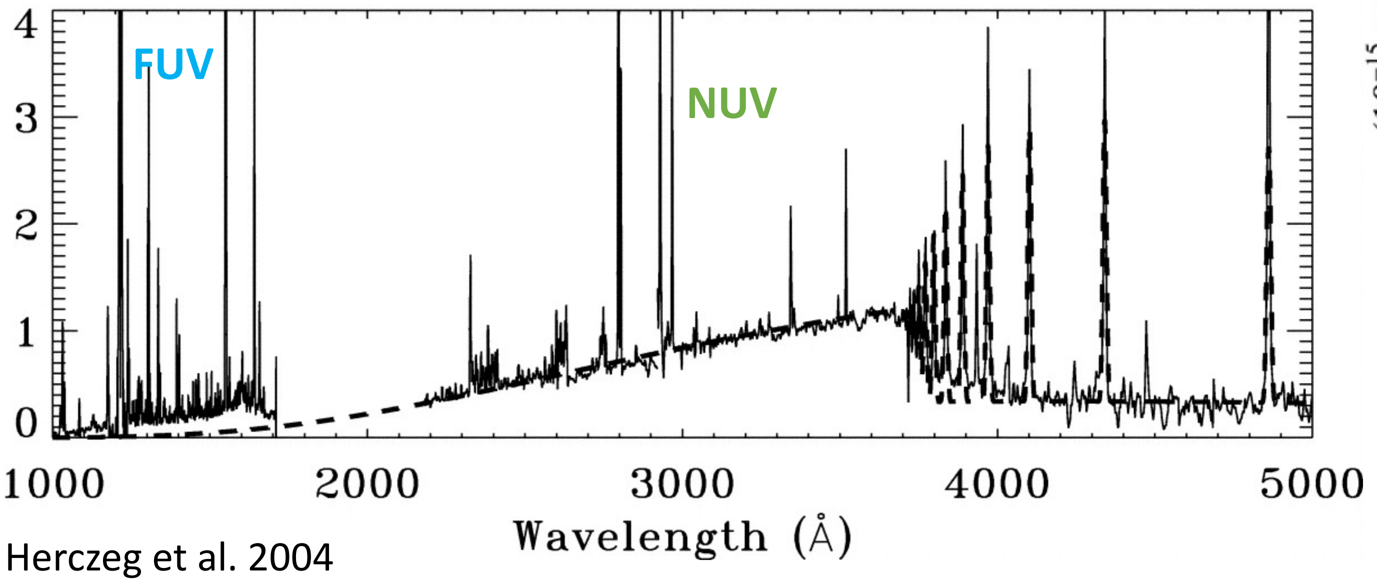
FUV Diagnostics

Atomic lines (e.g., CIV): diagnose accretion

Ly α: dominates FUV luminosity, affects disk chemistry

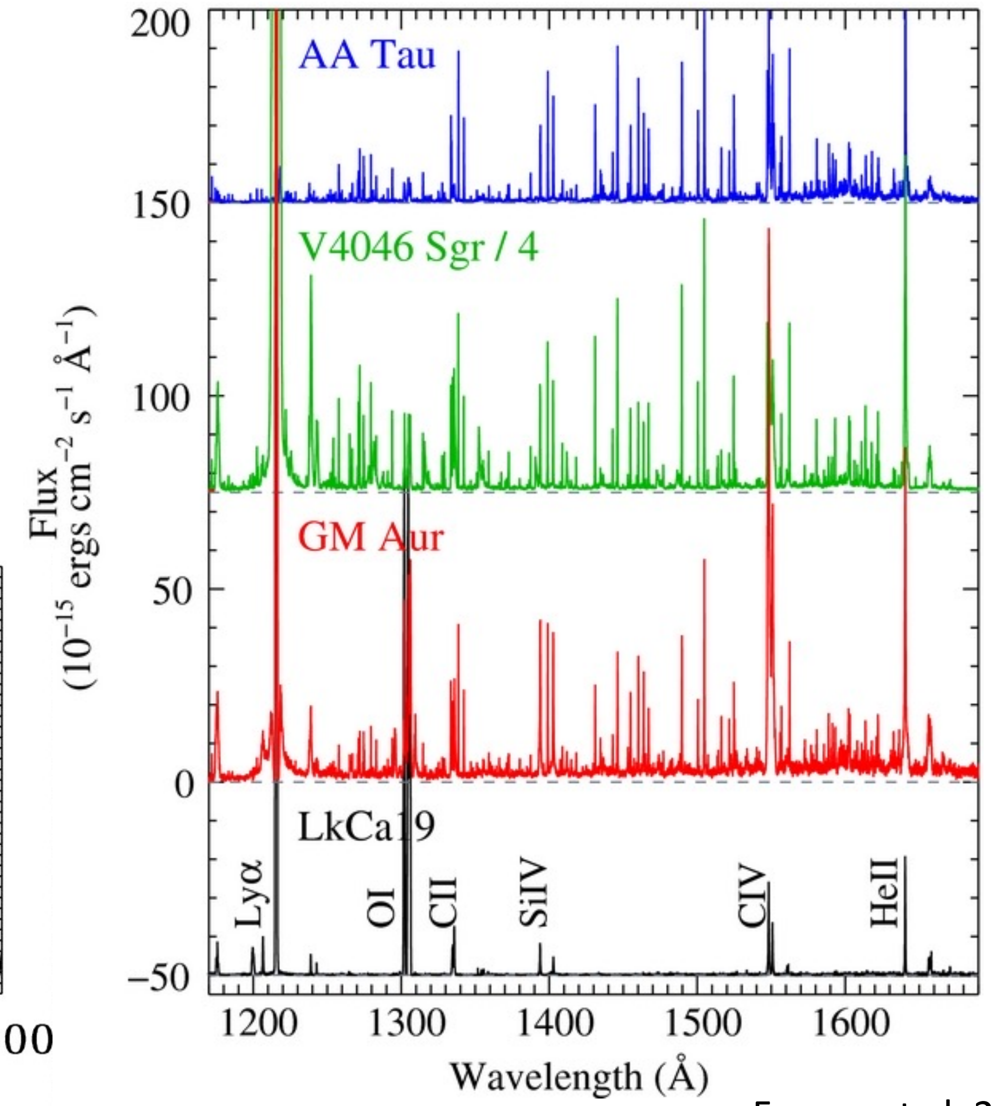
H_2 fluorescence: probes Ly α-irradiated disk

EUV and soft X-rays: disk photoevaporation



Herczeg et al. 2004

Rich H_2 fluorescence spectrum



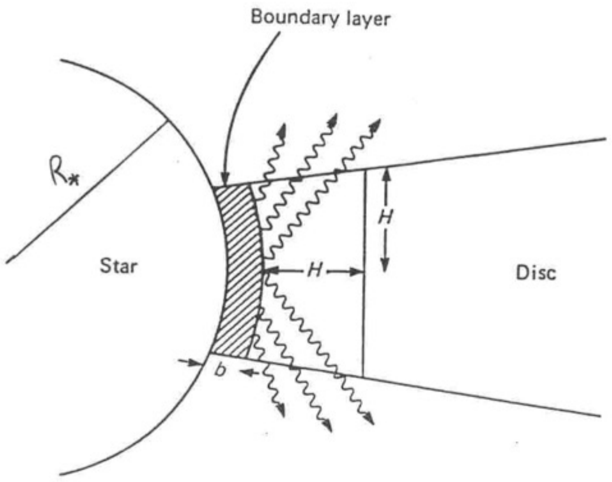
France et al. 2012

High res spectroscopy (line profiles)

Nature of stellar accretion (it’s magnetospheres)

Accretion onto Star

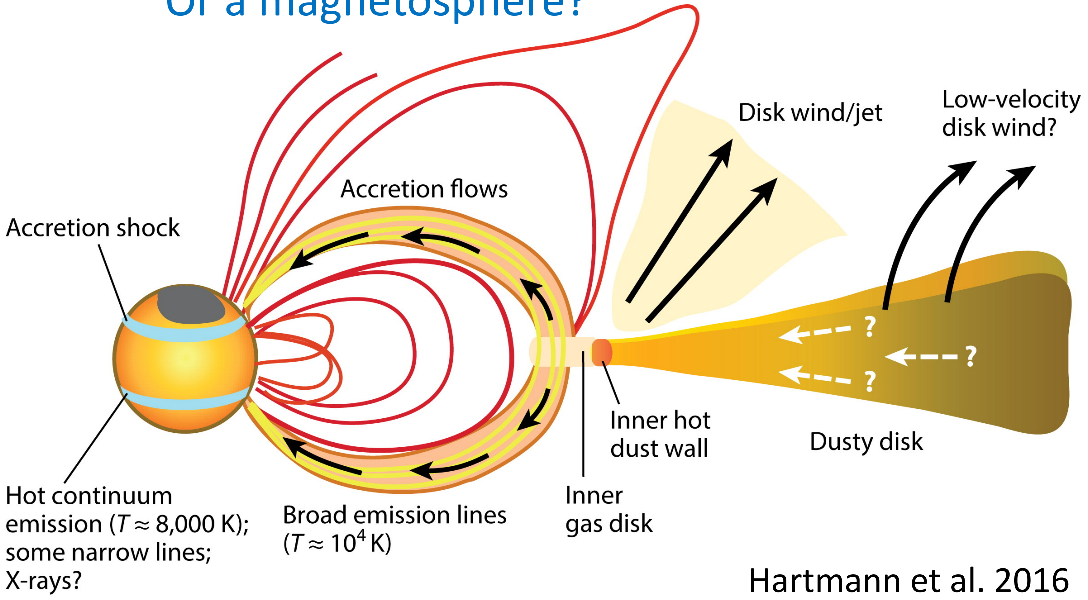
Via a boundary layer?



Credit: B. Ryden

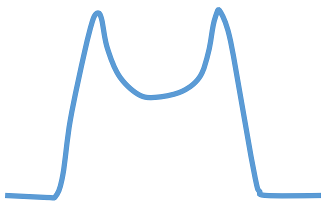
b < H < R*

Or a magnetosphere?



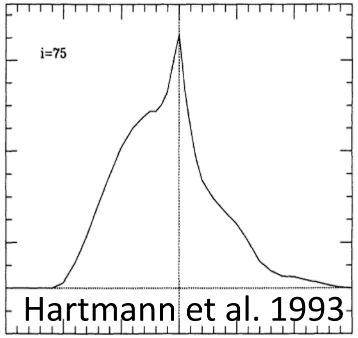
Hartmann et al. 2016

Double-peaked profile from a thin annulus

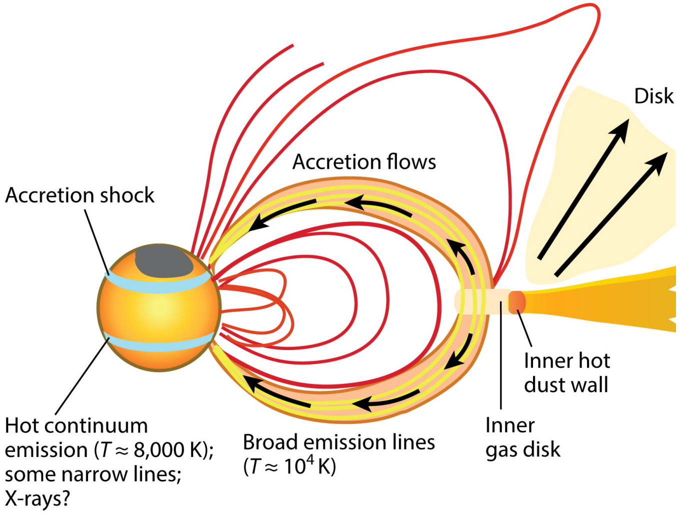


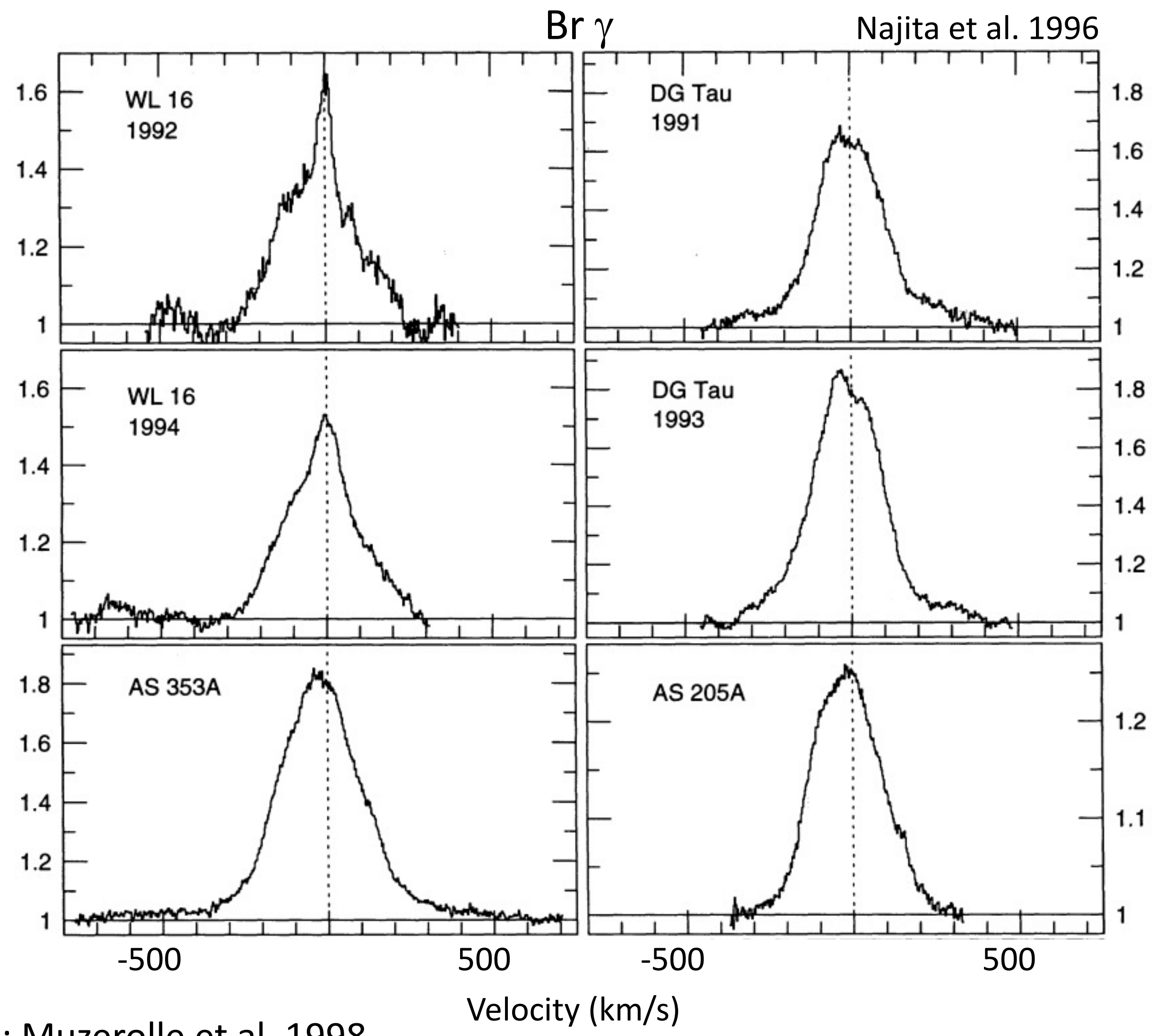
Stellar Accretion via Magnetospheres

Theoretical profiles



Hartmann et al. 1993





See also Calvet & Hartmann 1992; Hartmann et al. 1994; Muzerolle et al. 1998

Low res spectroscopy (line fluxes)

Measuring accretion

Measuring Accretion Rates

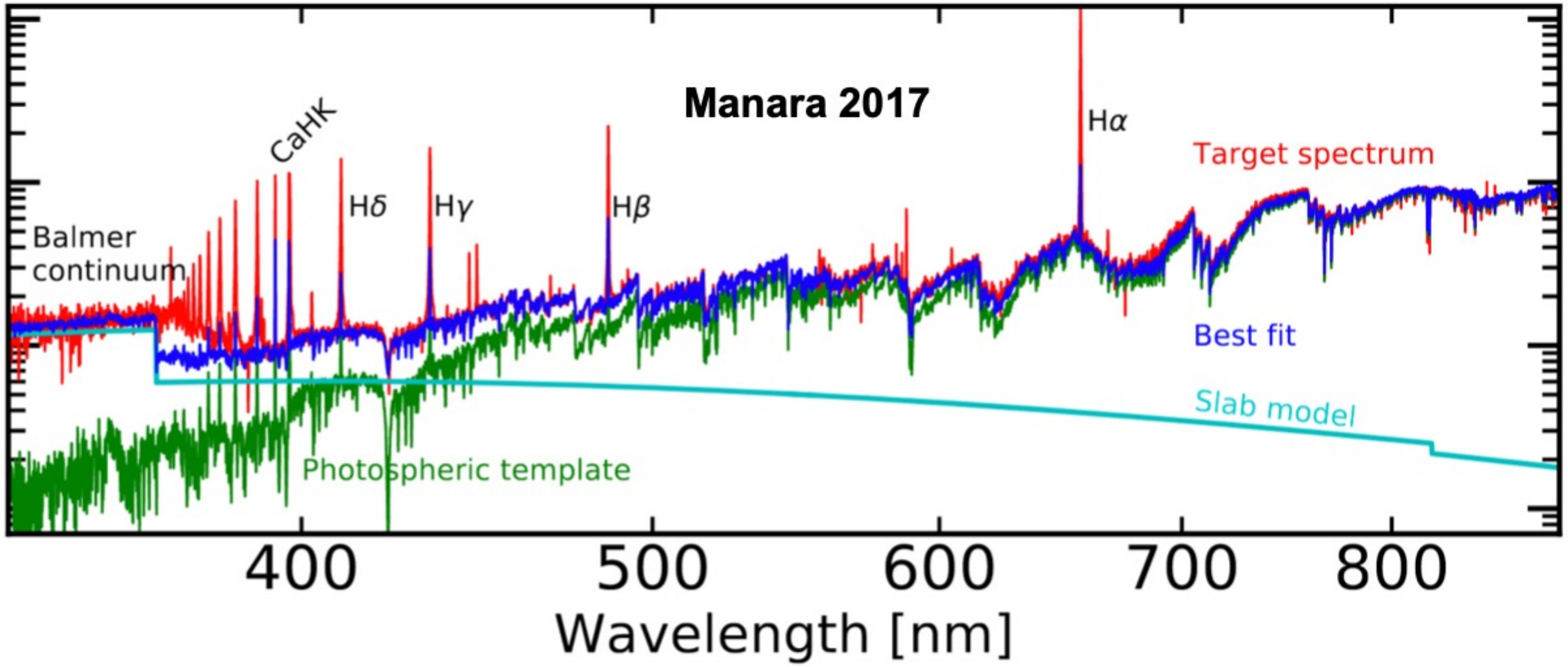
Luminosity method:

$$L_{acc} = \frac{G M_\star \dot{M}_{acc}}{R_\star}\left(1 - \frac{R_\star}{R_{in}}\right)$$

Credit: Alcala in "Accretion & winds/outflows in solar-type YSOs"

Primary indicator:
Measure UV continuum luminosity.

Secondary indicators:
Correlate UV flux with line fluxes (HI lines, CIV, etc)

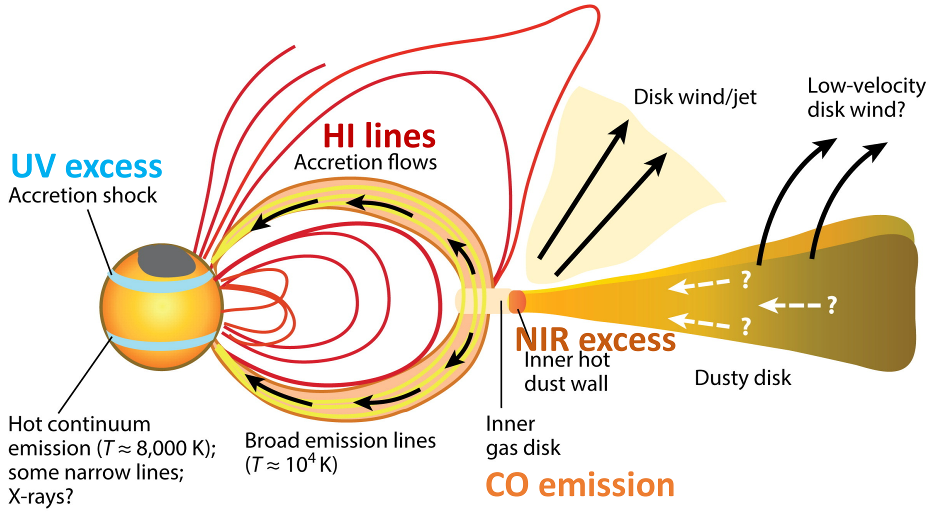


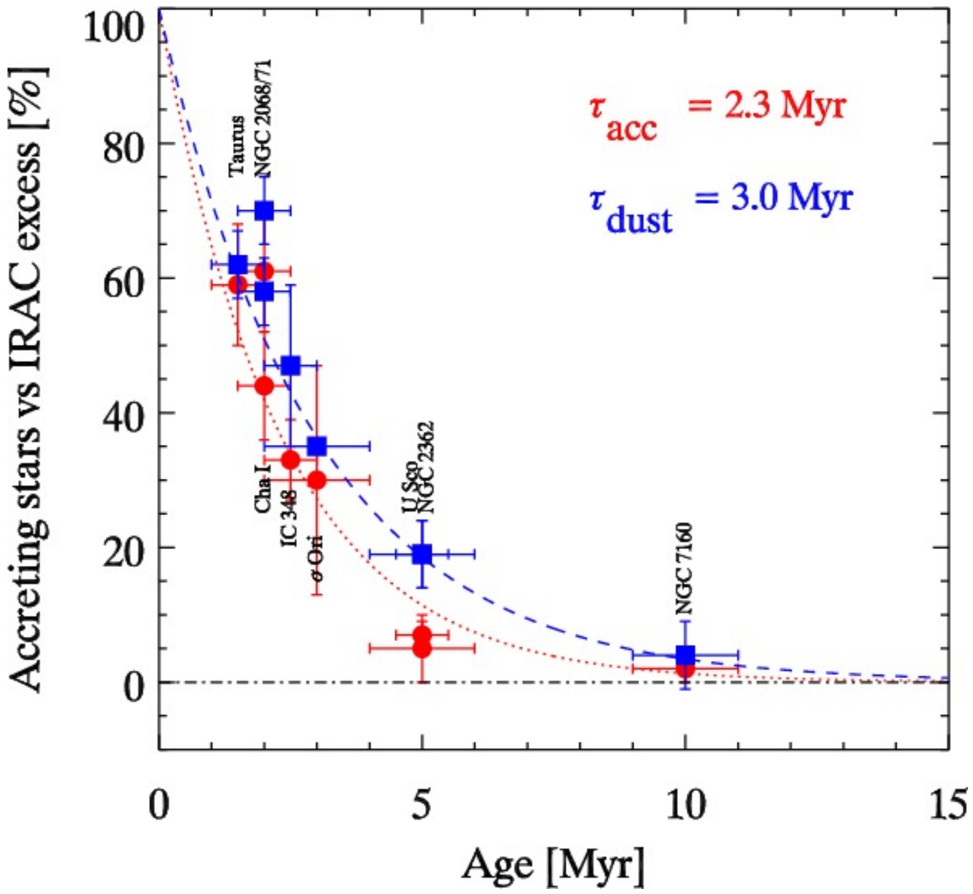
Accretion demographics

Gas disk lifetime, nature of transition disks

Accretion and gas disk lifetime

Fraction of accreting sources in clusters of different ages constrains gas dissipation time of inner disk



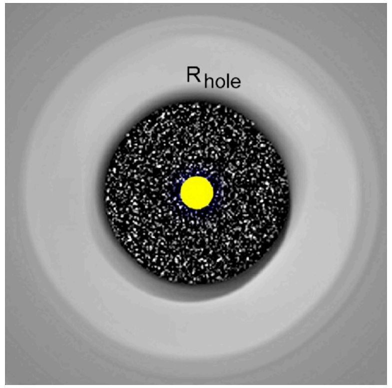


Fedele et al. (2010)

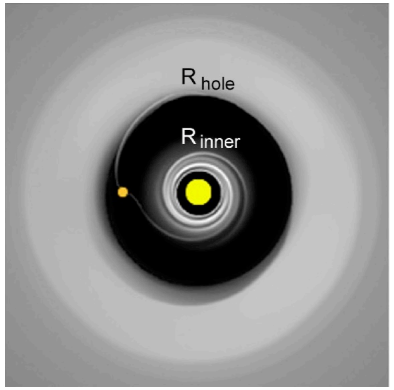
Accretion and nature of transition disks*

*Protoplanetary disk whose center is optically thin in continuum

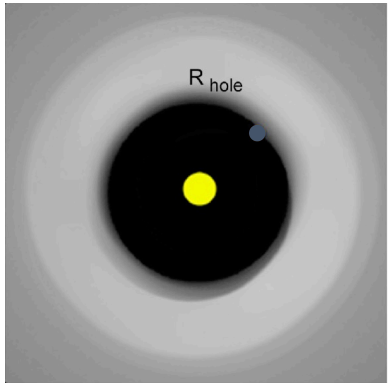
Planetesimal formation



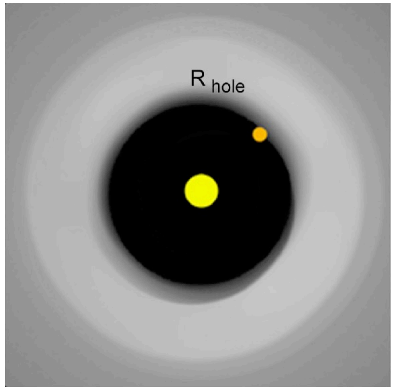
Low-mass gas giant

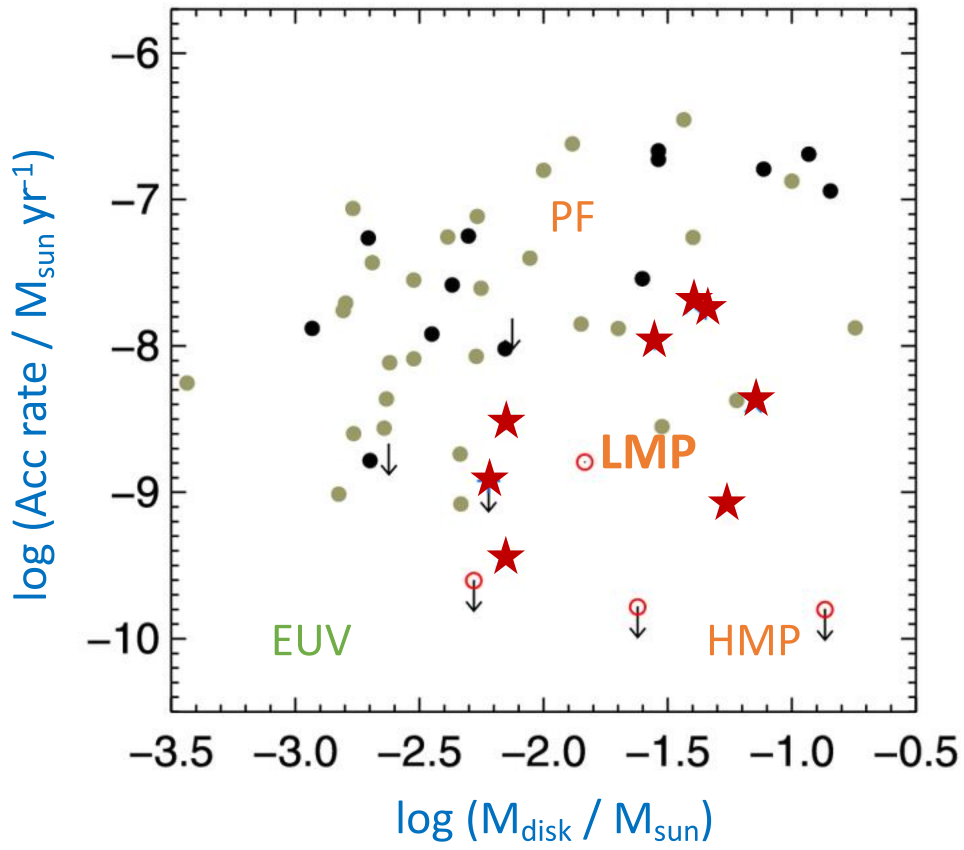


EUV Photoevaporation



High mass gas giant

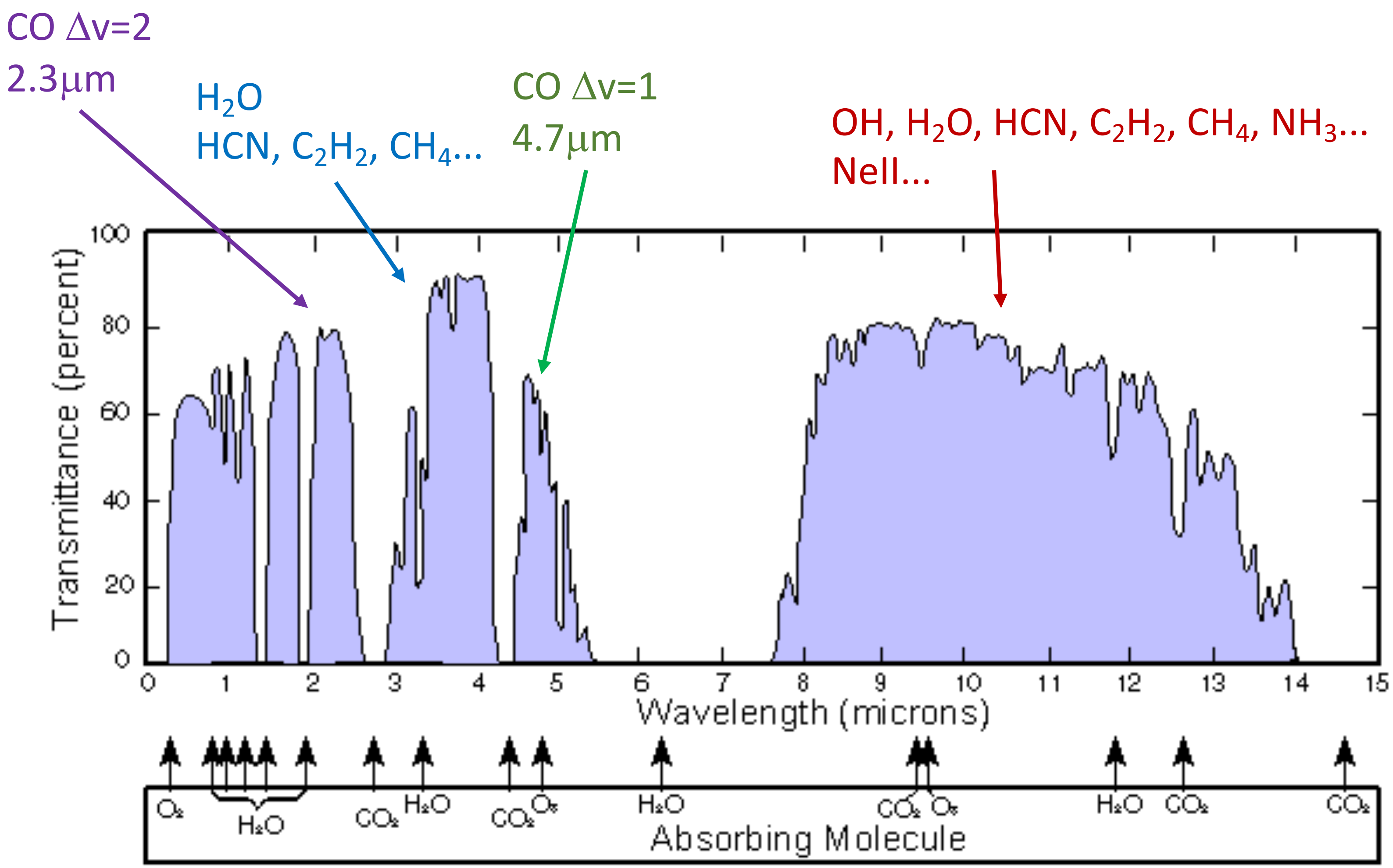




See Najita et al 2008, 2015; Kim et al. 2016

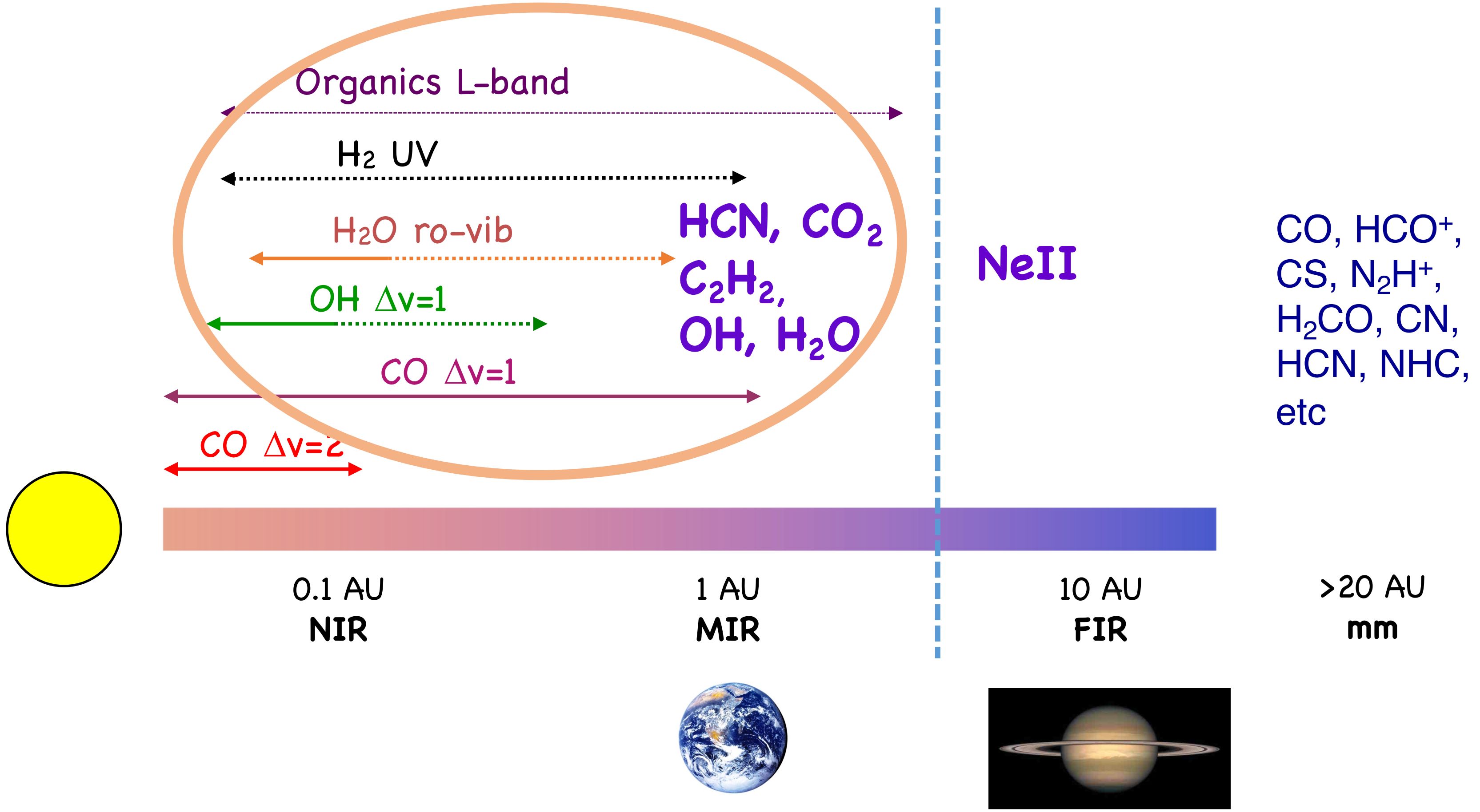
IR Spectroscopy and Disks

Probes of disk
- Dynamics
- Structure
- Chemistry



Gaseous Probes of Inner Disks

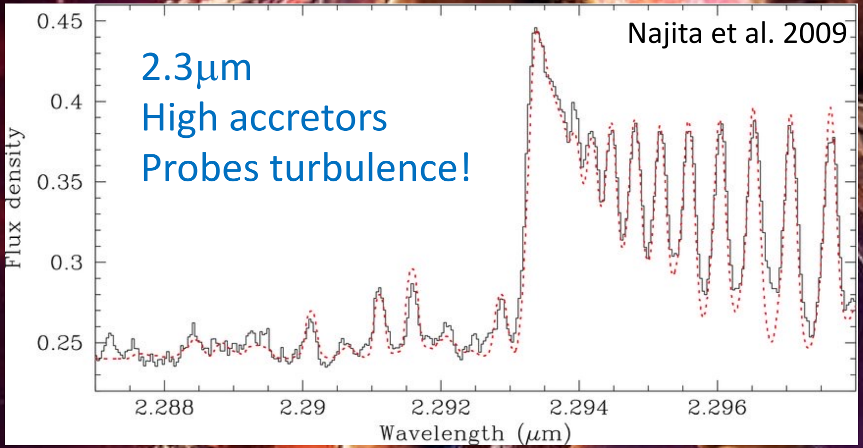
IR molecular diagnostics probe planet formation region within the snow line



CO Fundamental!

4.7μm
Probes disk (sub)structure!

CO Overtone!



MIR Water / Organics!

12-18 μm
Disk chemistry,
Planetesimal formation, solid migration
Disk surface accretion

UV/IR, Inner Disks, Planet Formation

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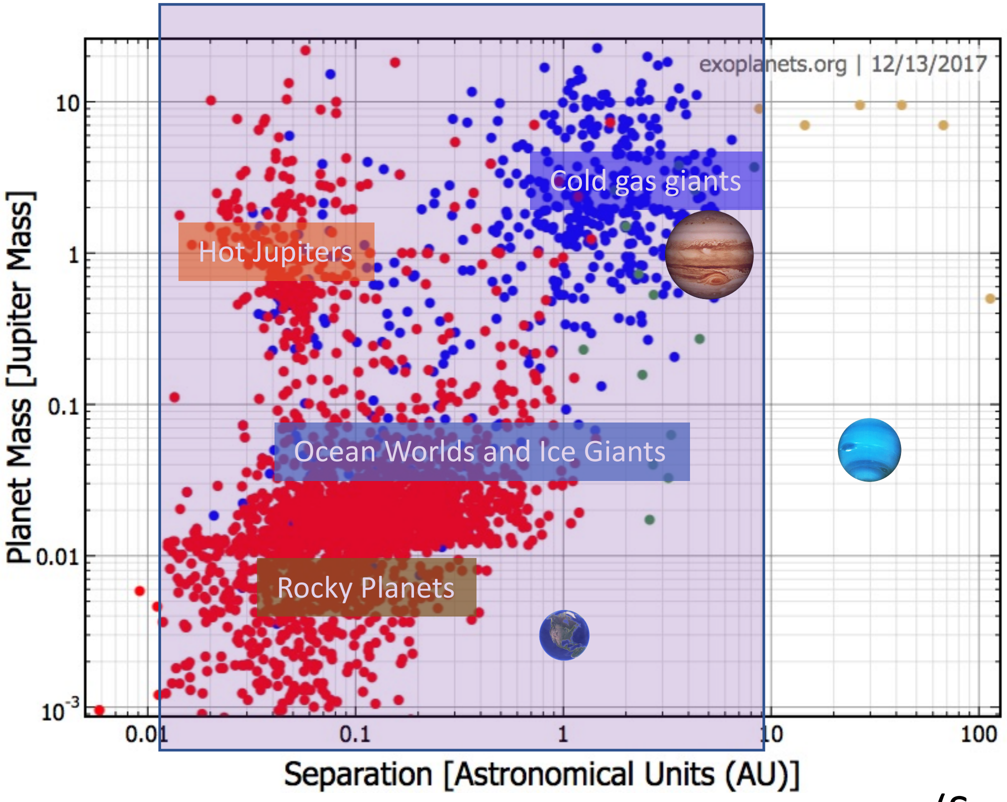
High res spectroscopy (line profiles)

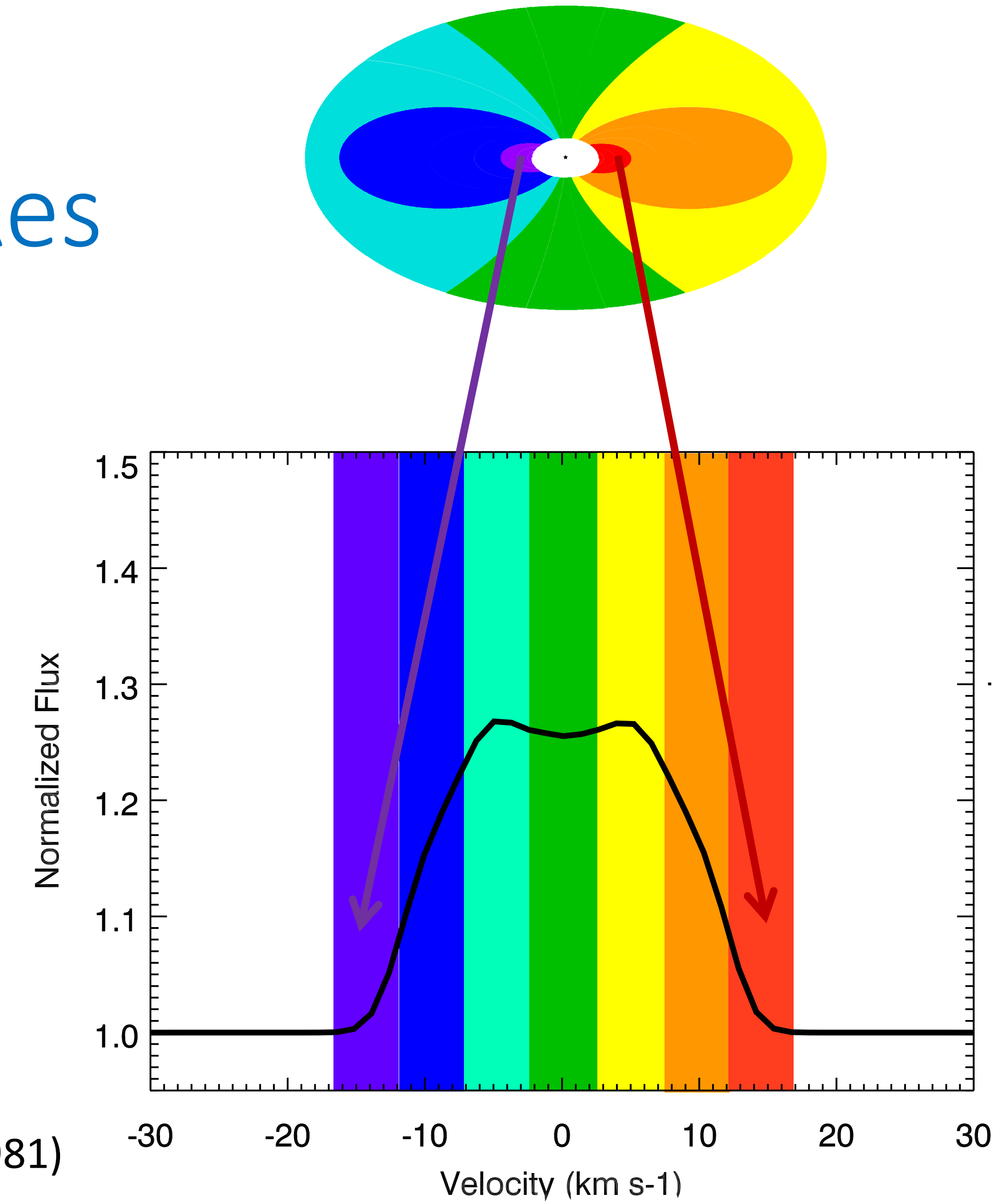
Studying inner disk structure

e.g., Carr 2007; Hoadley et al. 2015

High Spectral Res:
Surrogate for High Ang Res



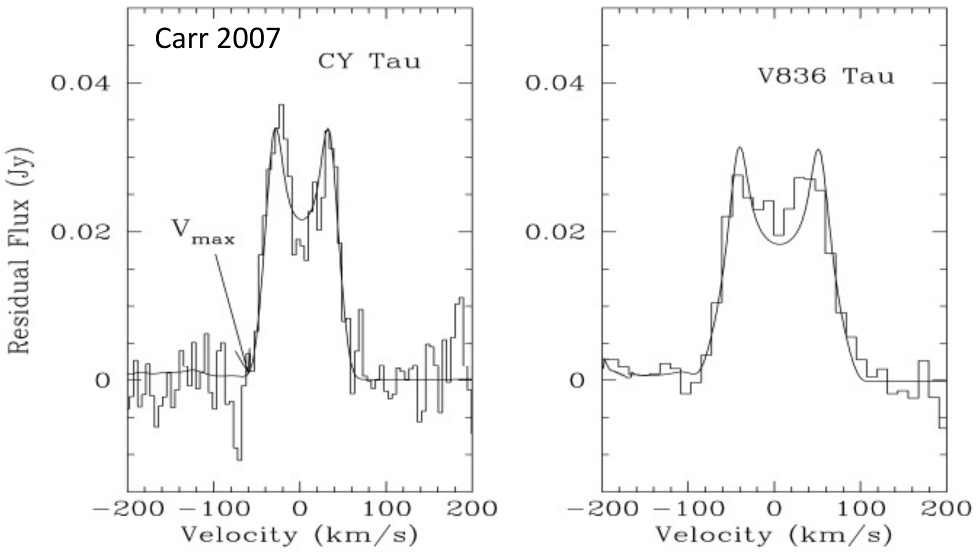
(See Smak 1981)

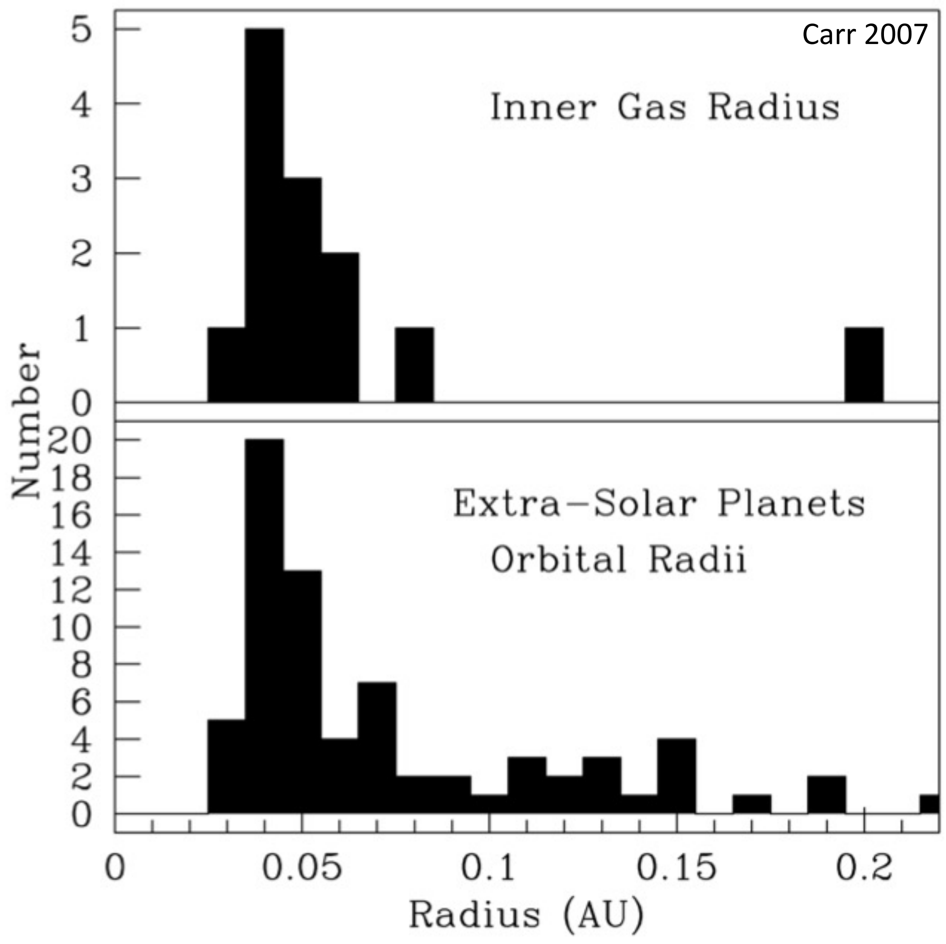


Graphics Credit: Sean Brittain

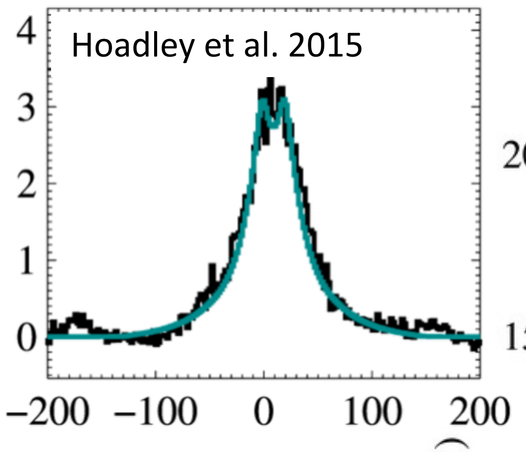
Inner Disk Radii and Exoplanet Orbital Radii

CO fundamental line profiles of Classical T Tauri stars

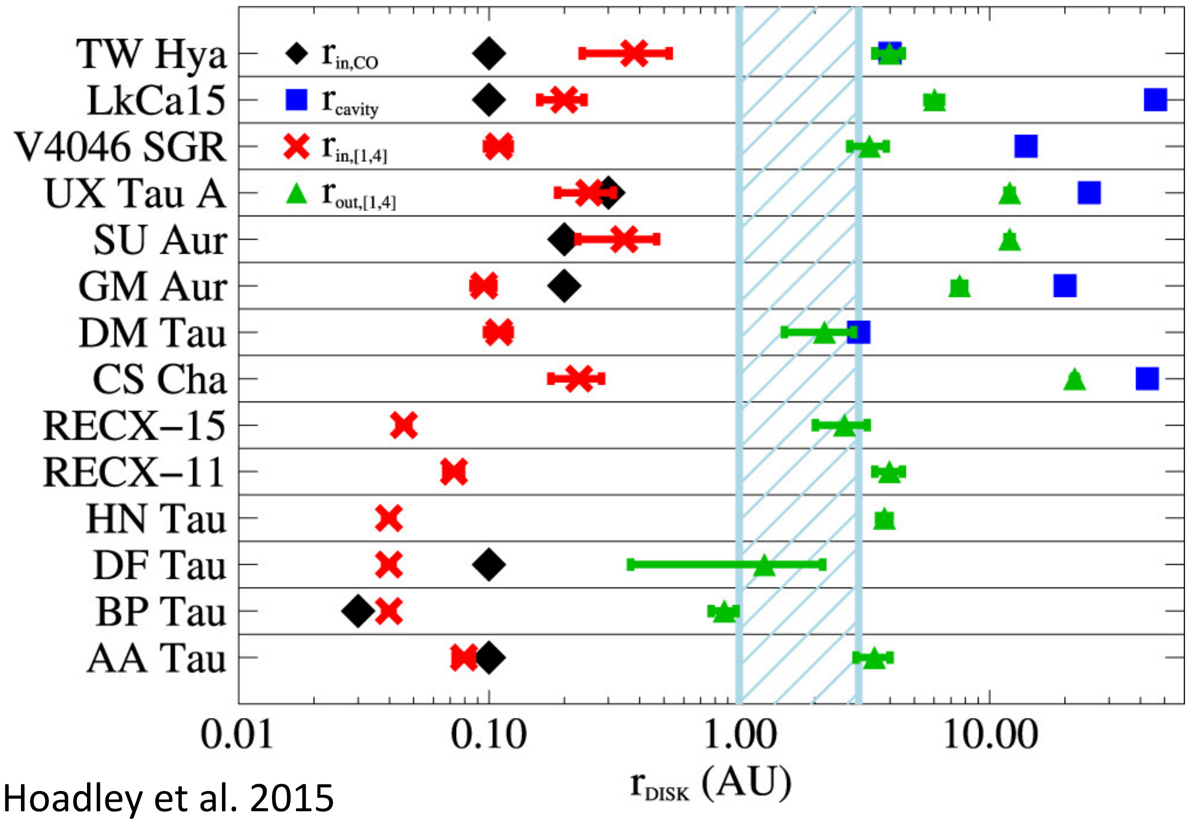




FUV H_2 emission

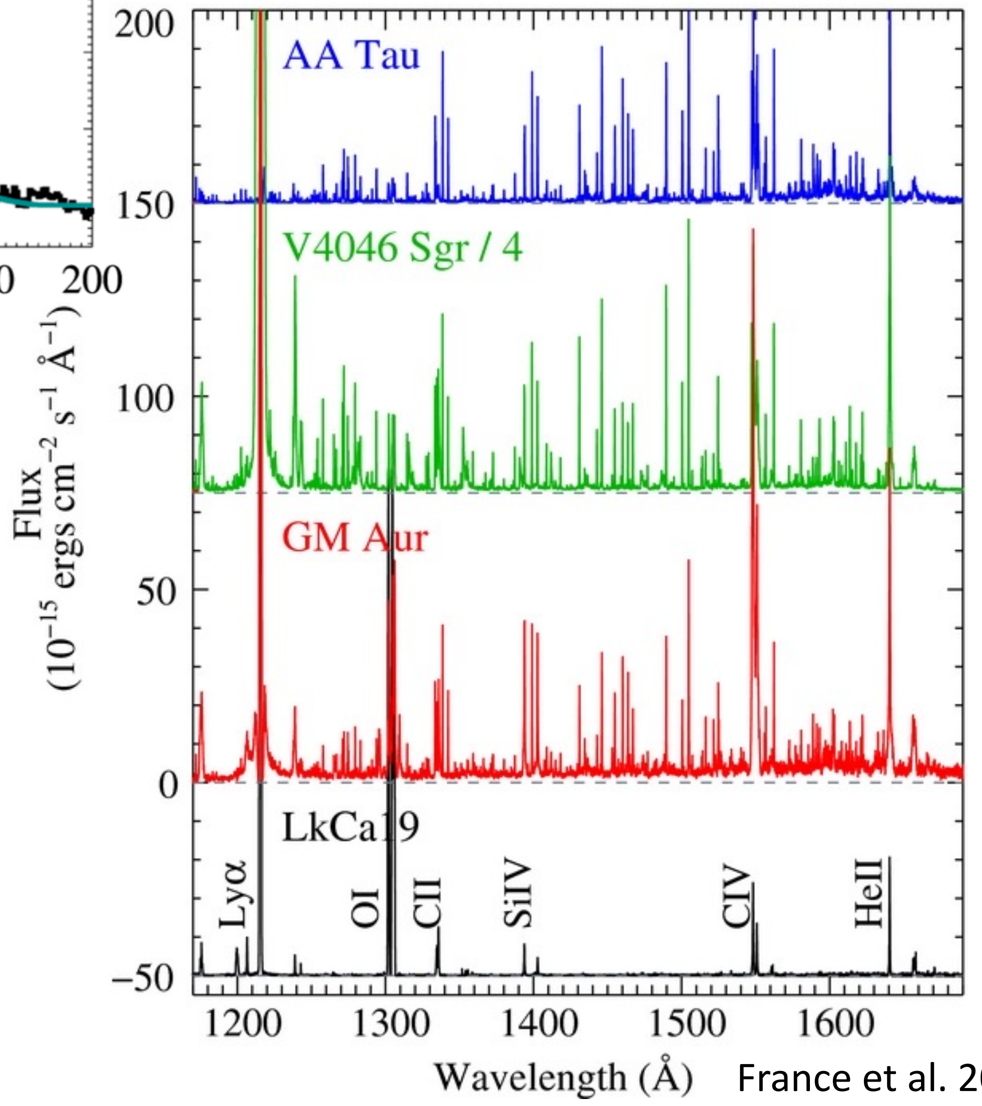


Inner and outer radii from H_2 line profiles



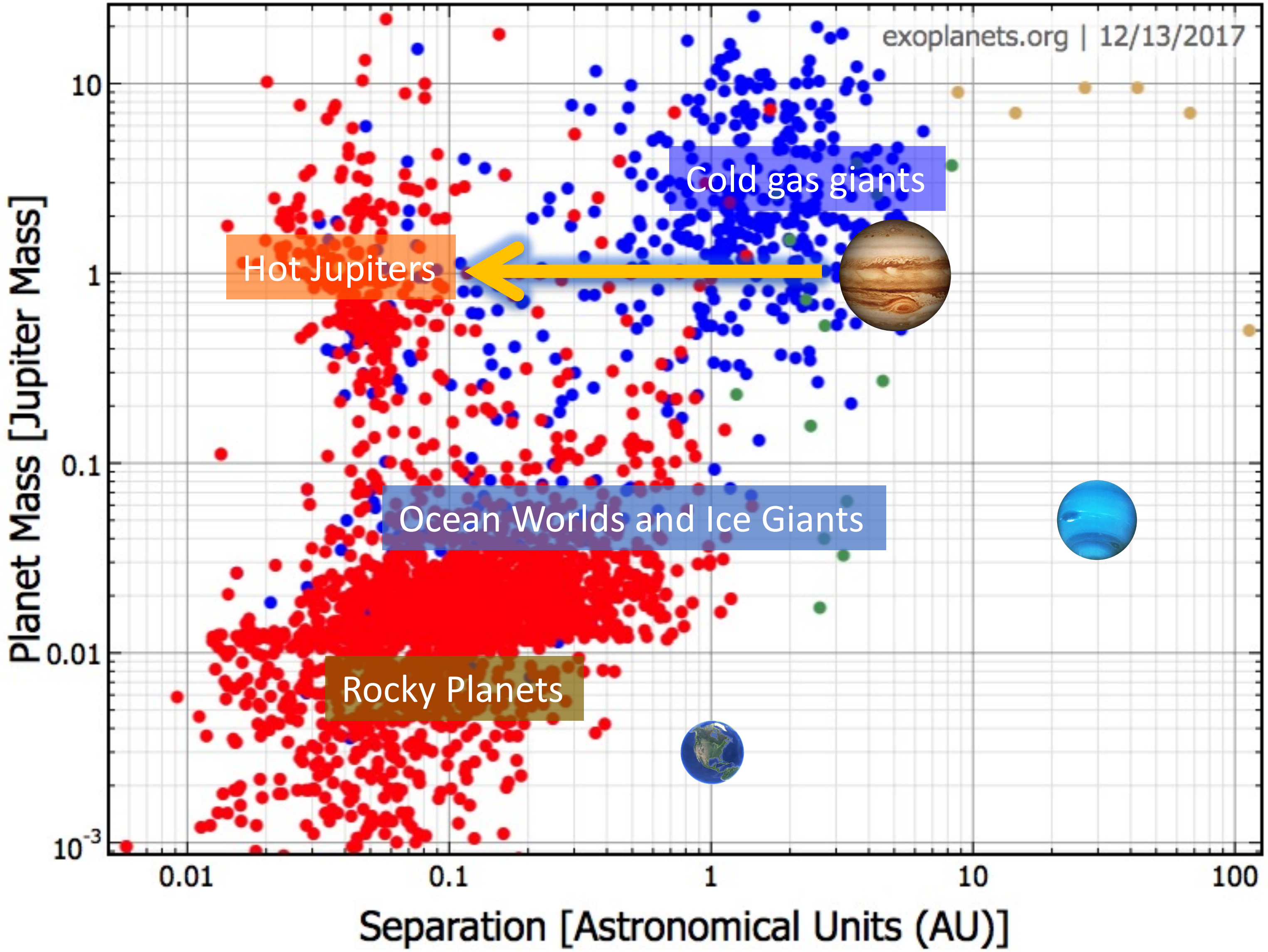
Hoadley et al. 2015

Rich H_2 fluorescence spectrum



France et al. 2012

Exoplanet Populations



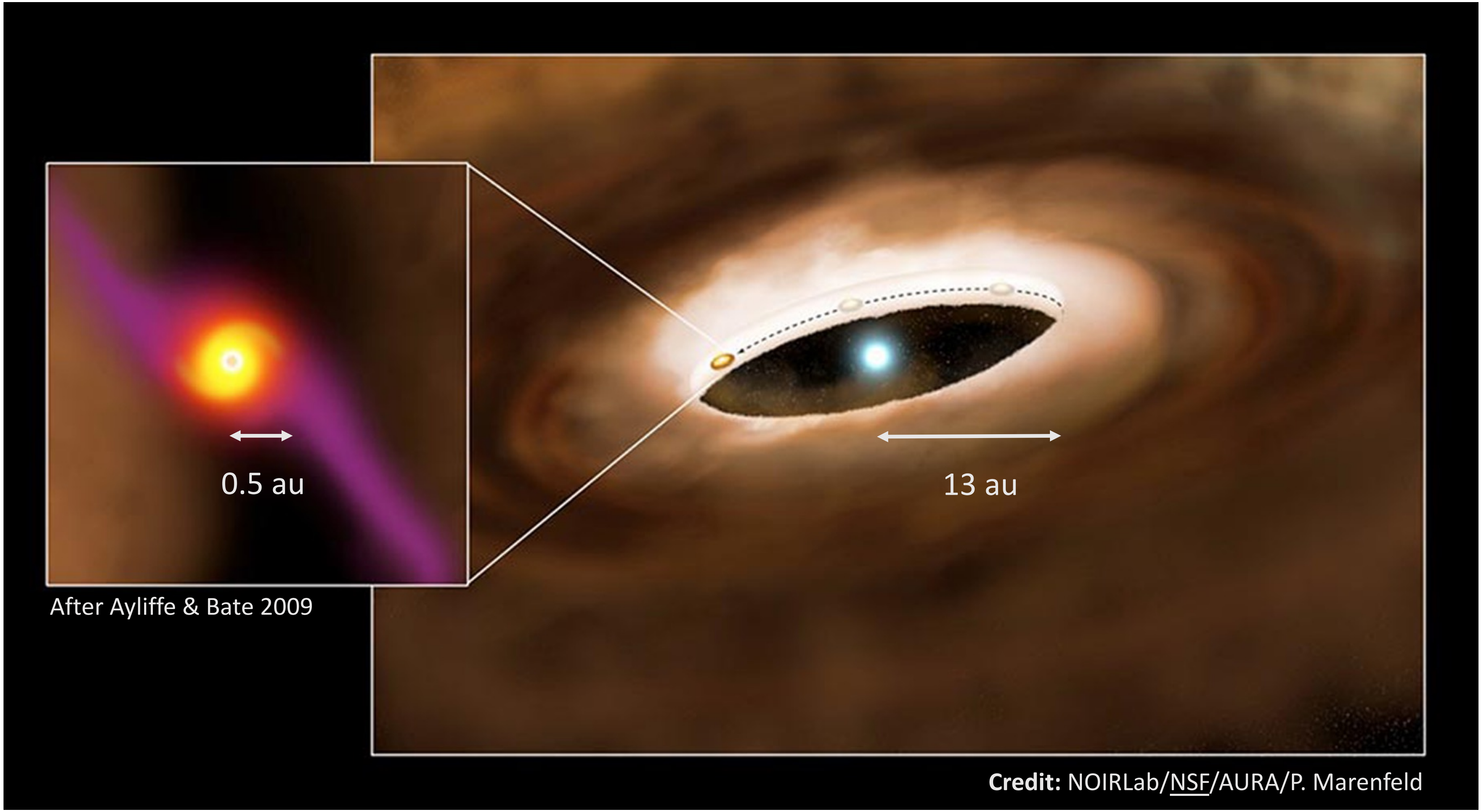
Gas giants can migrate into the inner disk edge

Spectroastrometry

Detecting forming planets and circumplanetary disks (birthplaces of moons)

Pontoppidan et al. 2008; Brittain et al. 2010, 2015, 2019; Whelan et al. 2021

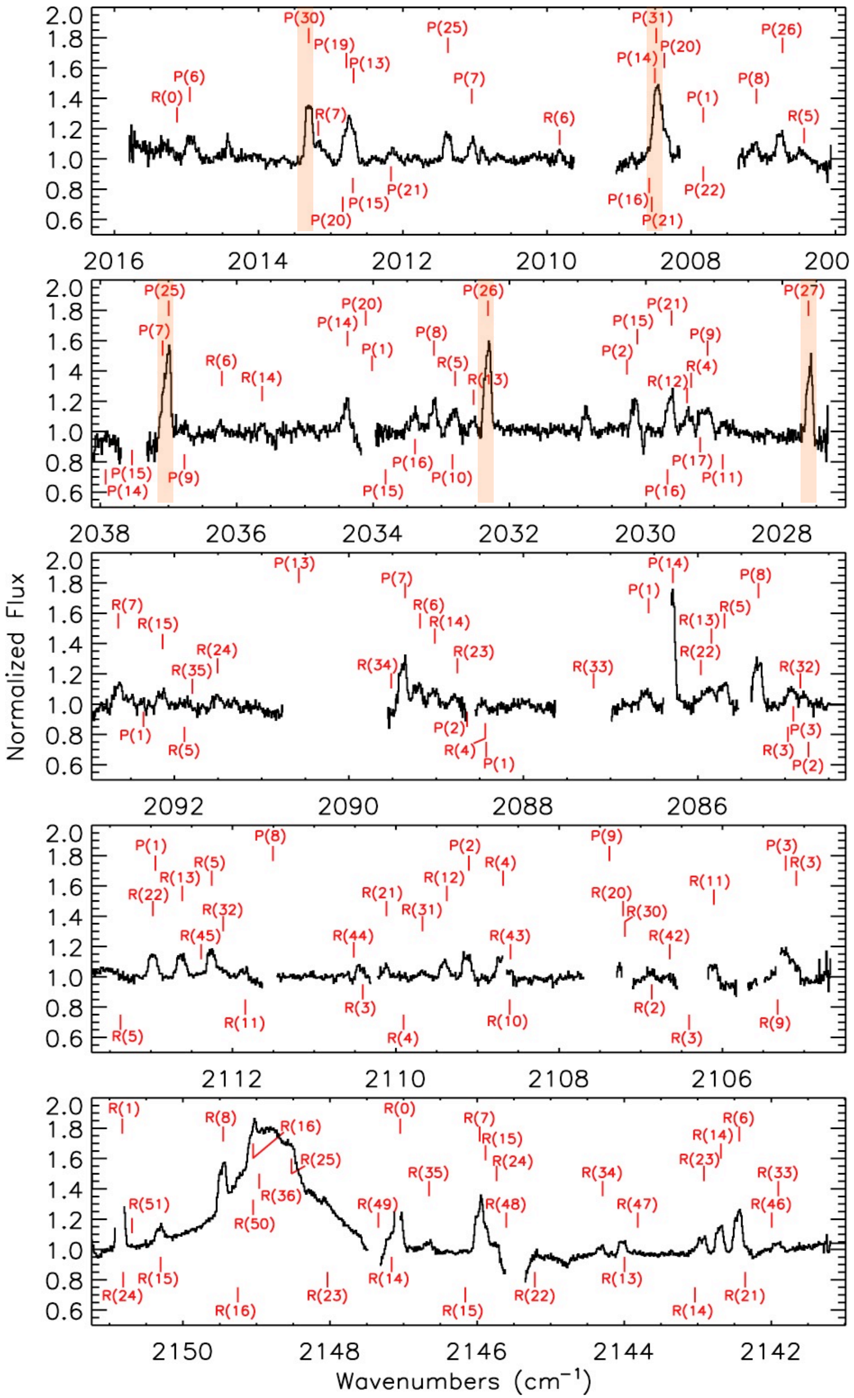
Circumplanetary Disk in HD100546



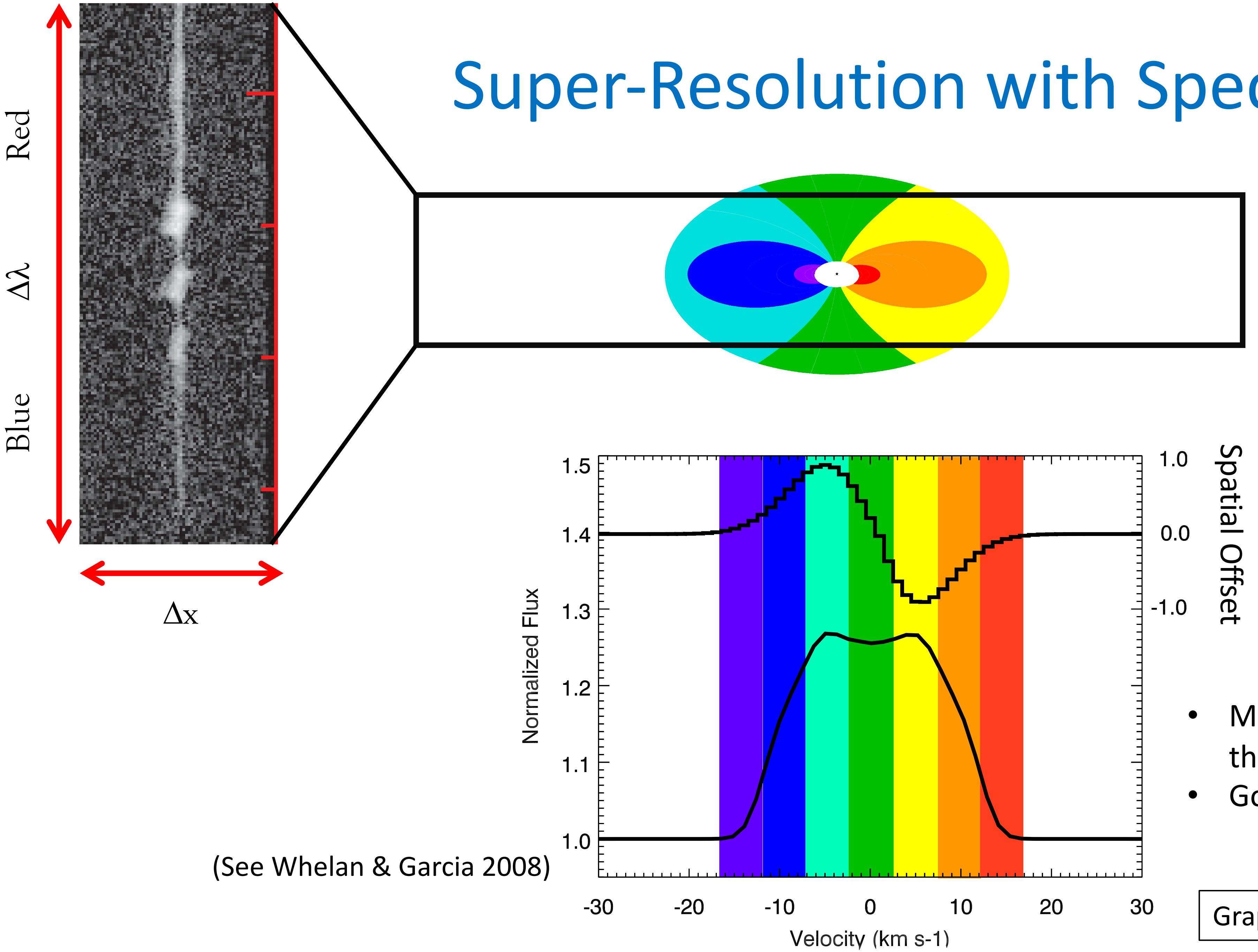
Fun with high s/n spectroscopy

CO fundamental emission from HD100546, a young intermediate mass star

Brittain et al. (2009): shows transitions of
CO v=1-0,...,7-6
^{13}CO v=1-0, 2-1
$C^{18}O$ v=1-0



Super-Resolution with Spectroastrometry

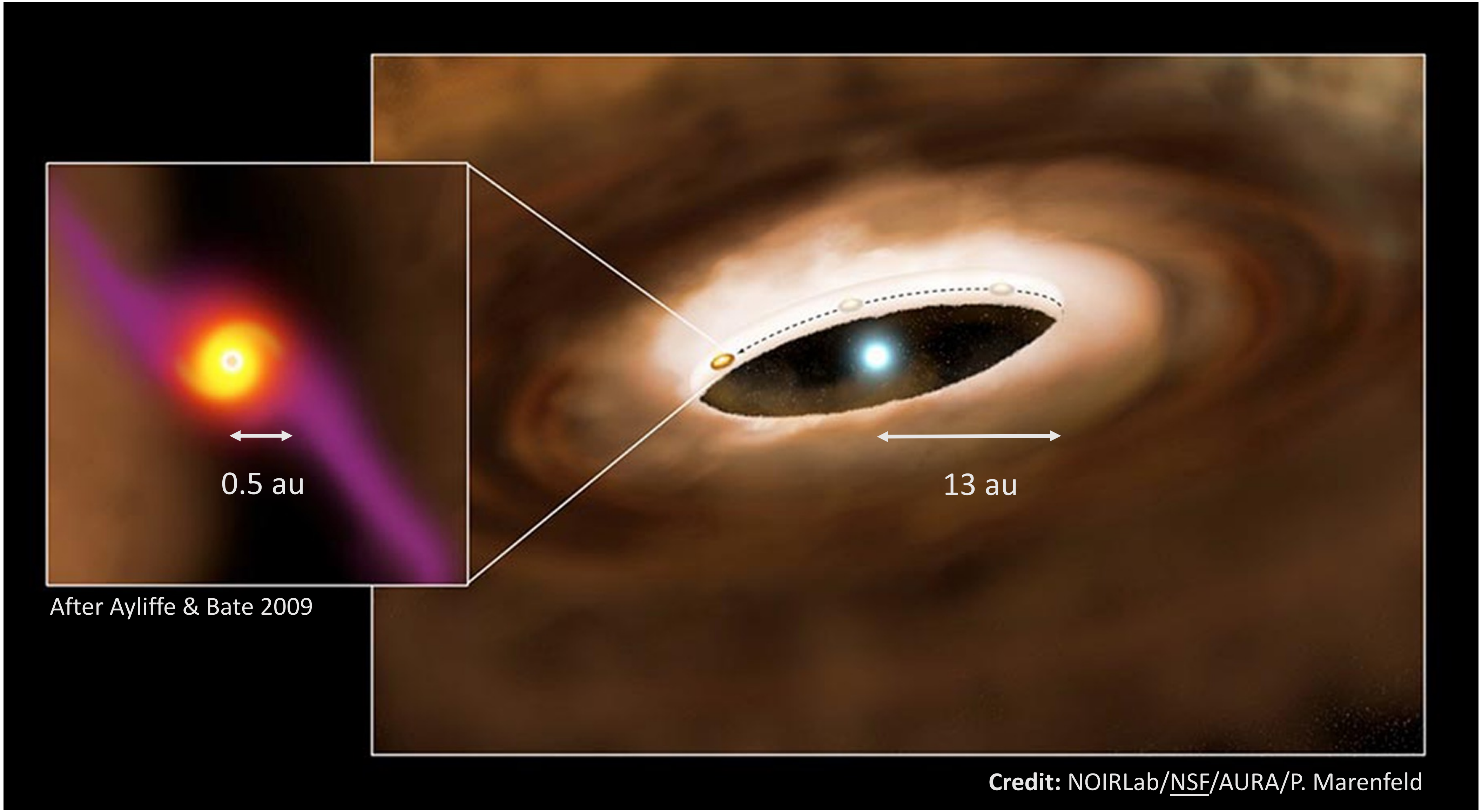


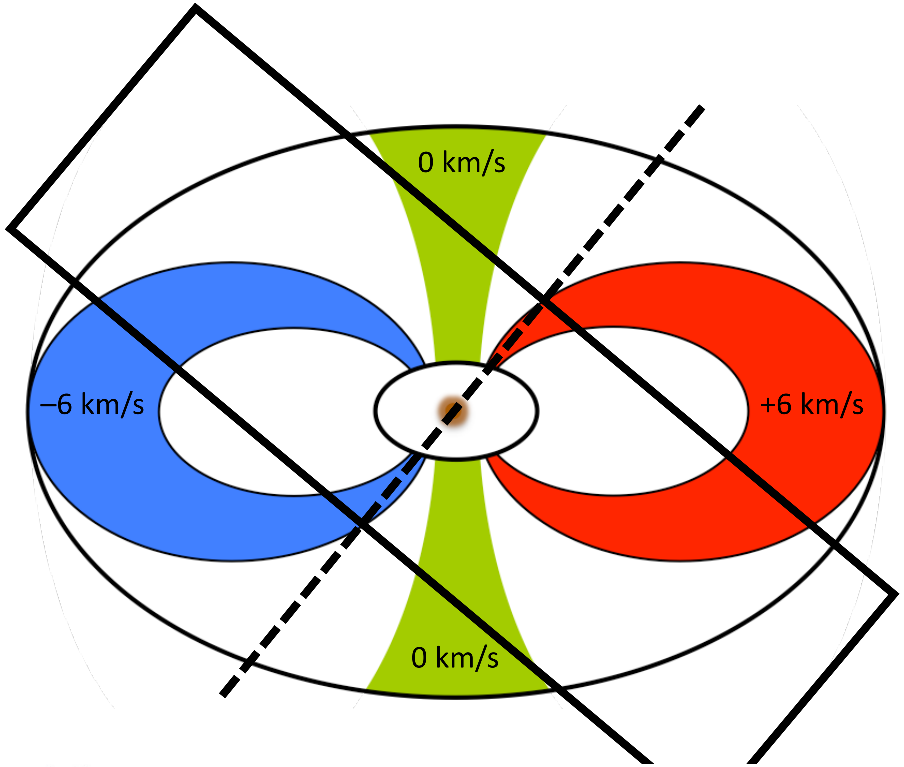
(See Whelan & Garcia 2008)

- Magic: spatial centroid more accurate than ang res Δx ~ 0.4 FWHM / SNR
- Good for simple velocity fields

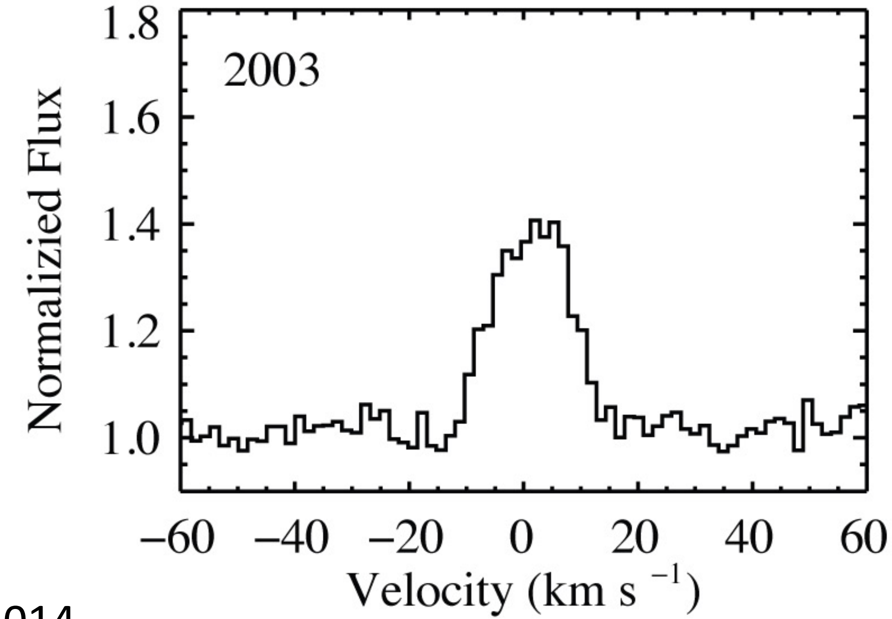
Graphics Credit: Sean Brittain

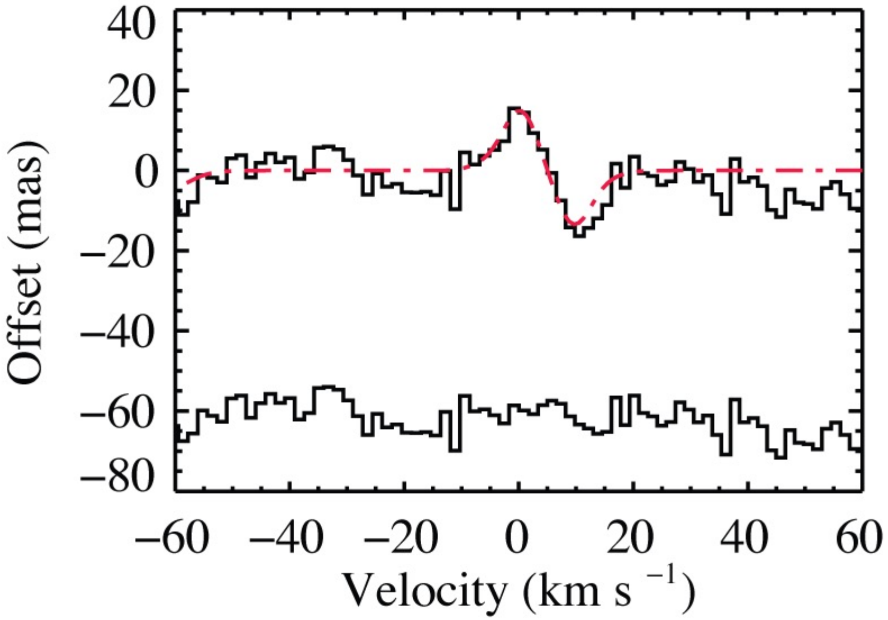
Circumplanetary Disk in HD100546





Spectroastrometry

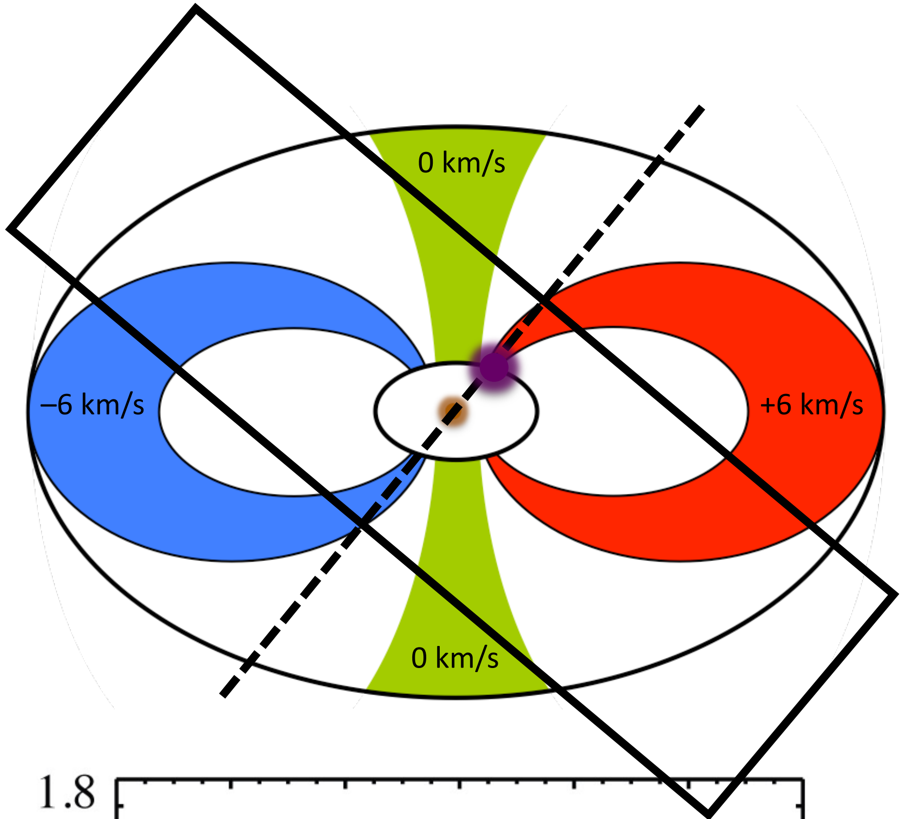


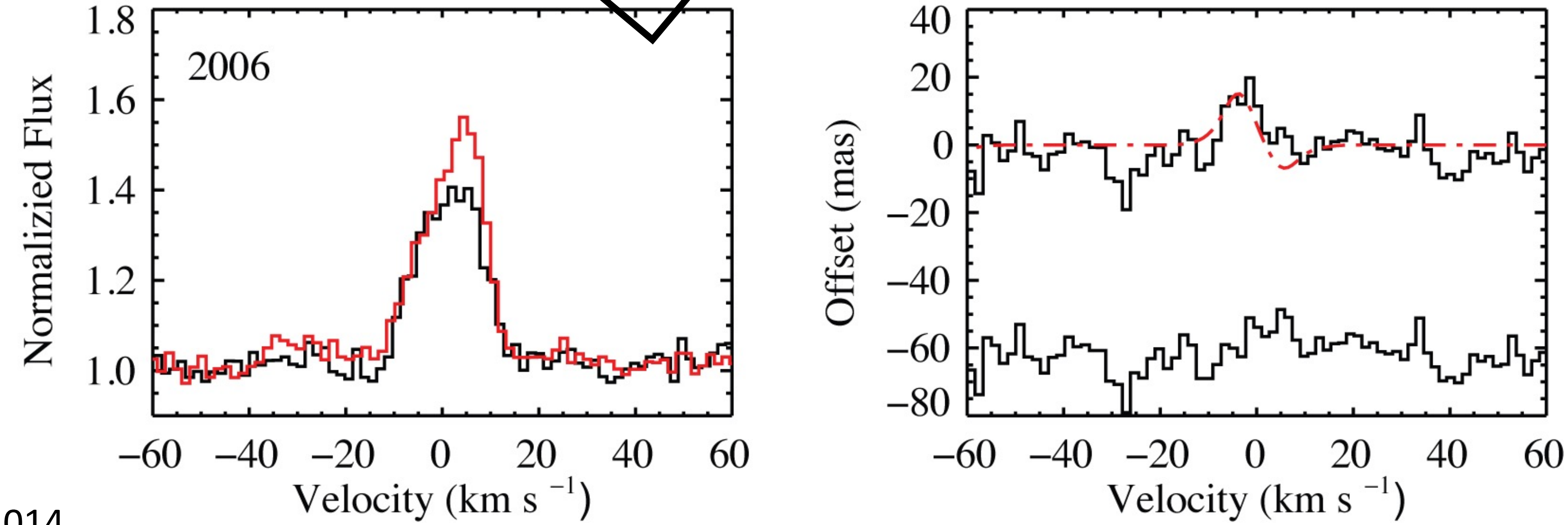


Brittain et al. 2014

Spectroastrometry

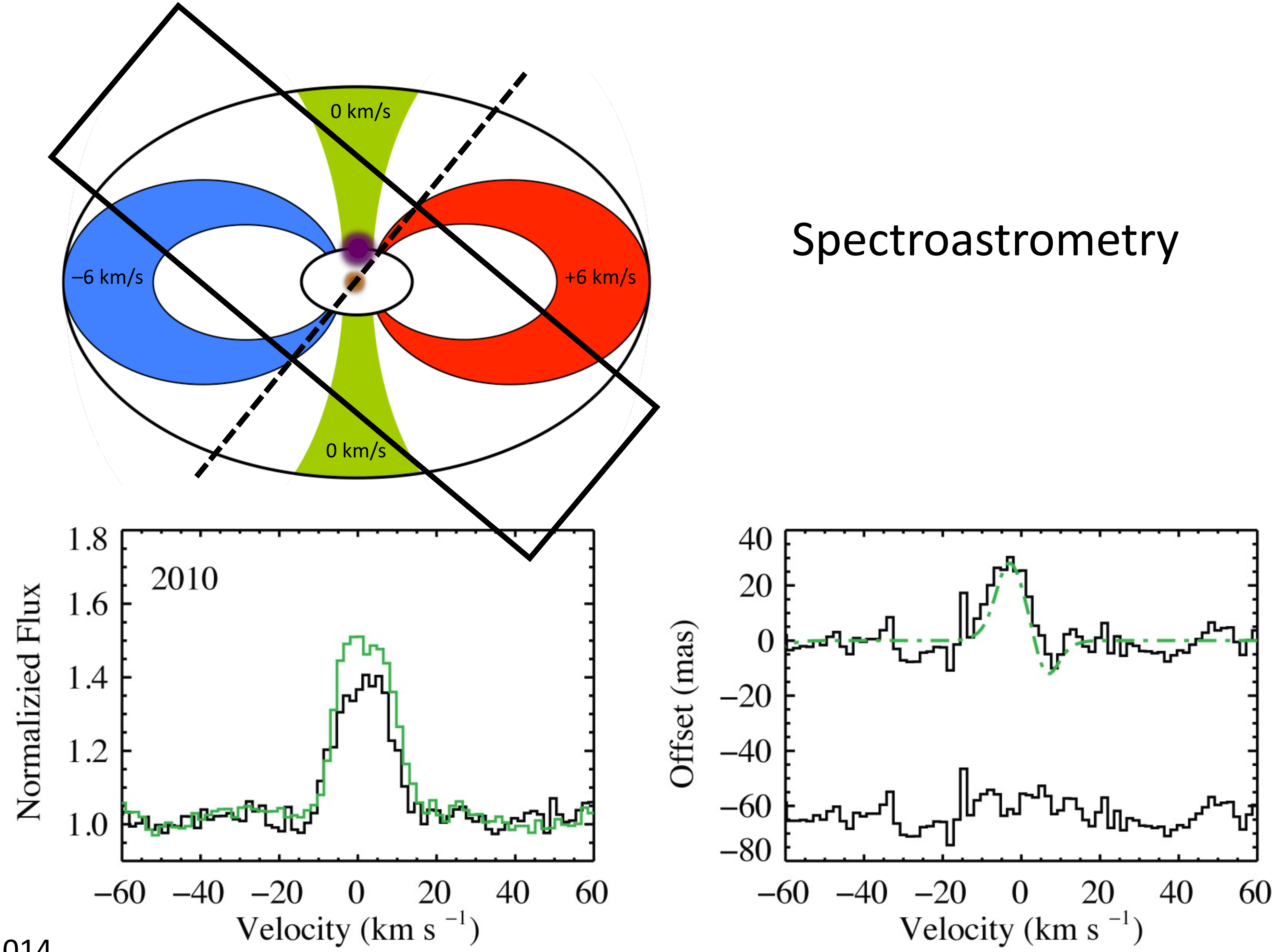
Excess emission consistent with size of CPD





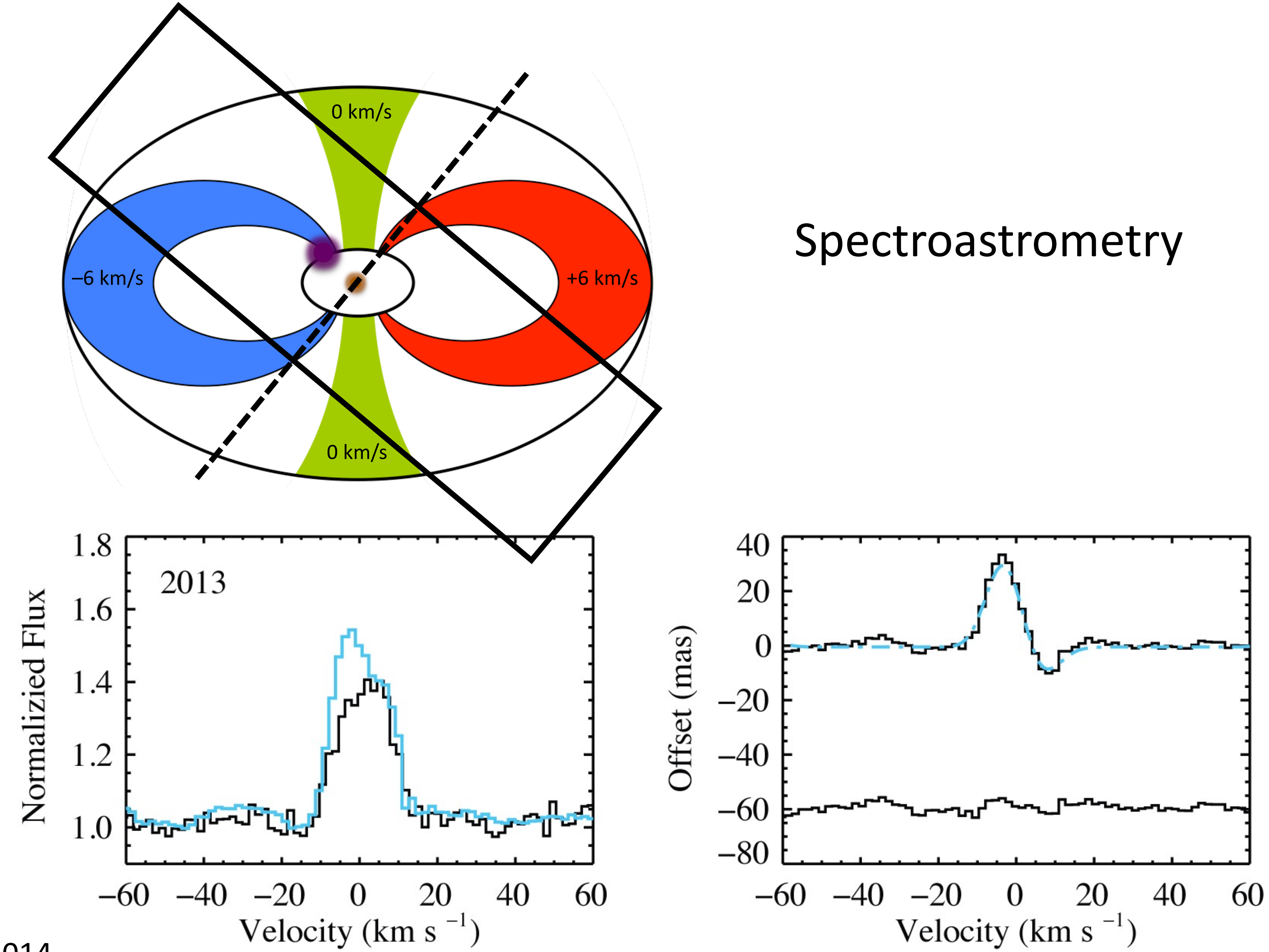
Brittain et al. 2014

Spectroastrometry



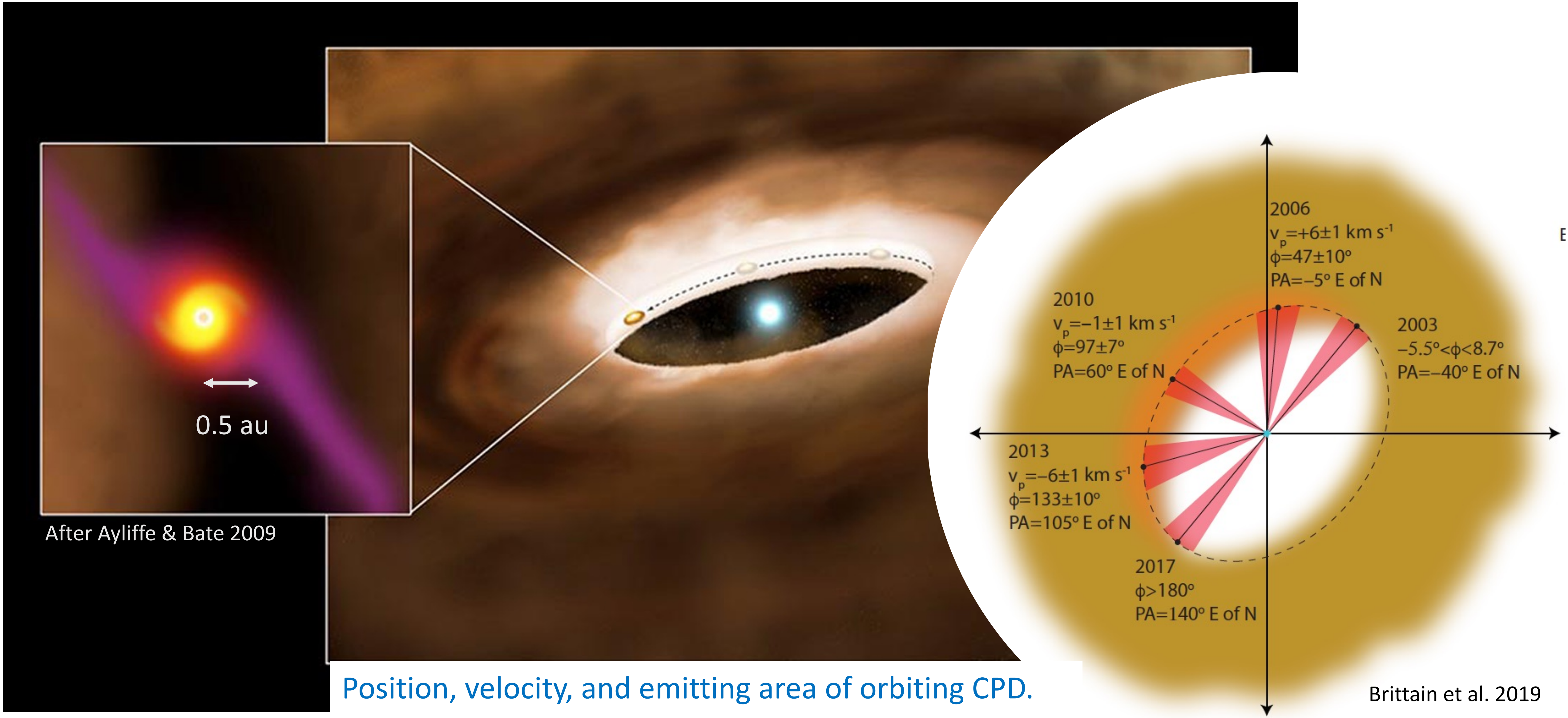
Brittain et al. 2014

Spectroastrometry



Brittain et al. 2014

Circumplanetary Disk in HD100546



After Ayliffe & Bate 2009

Position, velocity, and emitting area of orbiting CPD.

Brittain et al. 2019

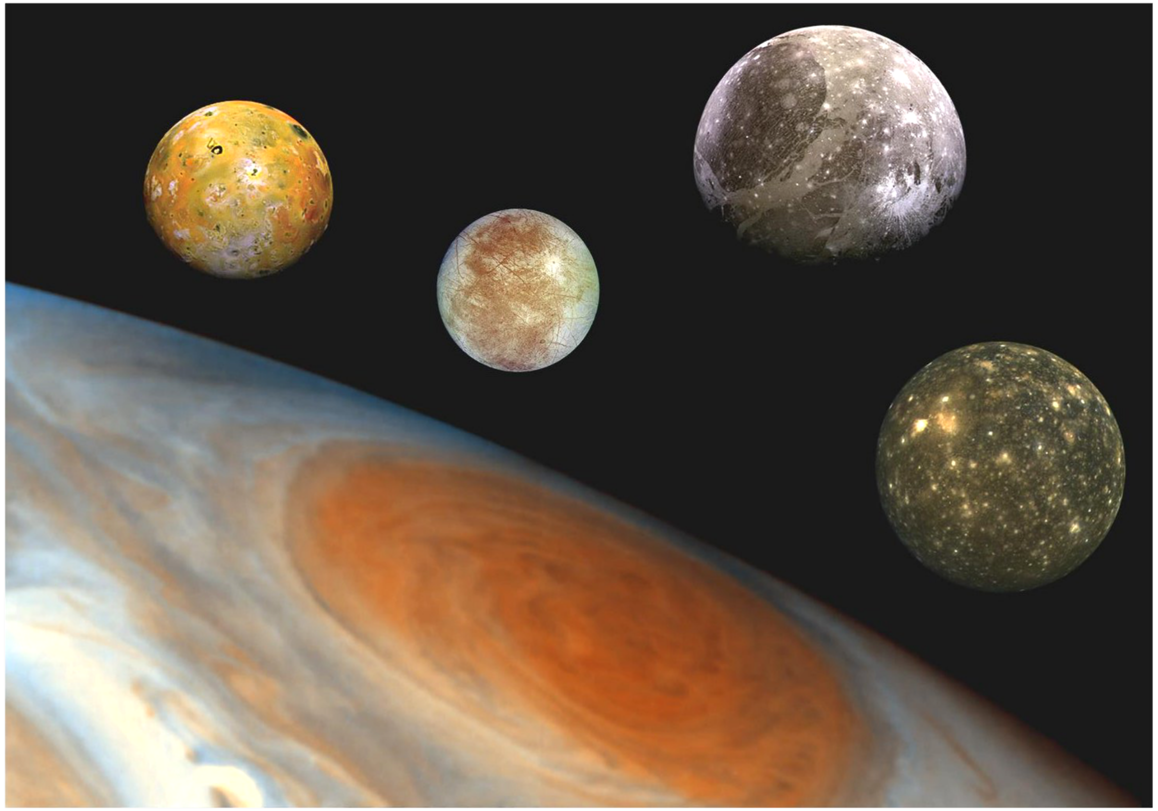
IR Spectroscopy: Structure and Sub-structure

High spectral resolution as a surrogate for high spatial resolution

- E.g., measure inner disk radii.

Spectroastrometry enables super-resolution

- E.g., detect orbiting gaseous circumplanetary disk.



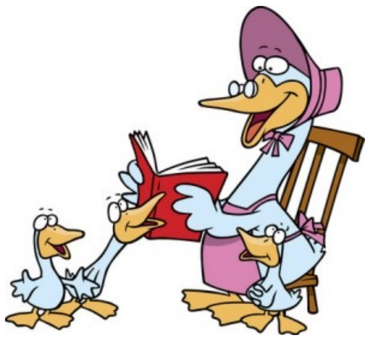
Credit: Galileo Project/Voyager Project/NASA's JPL

MIR molecular spectroscopy

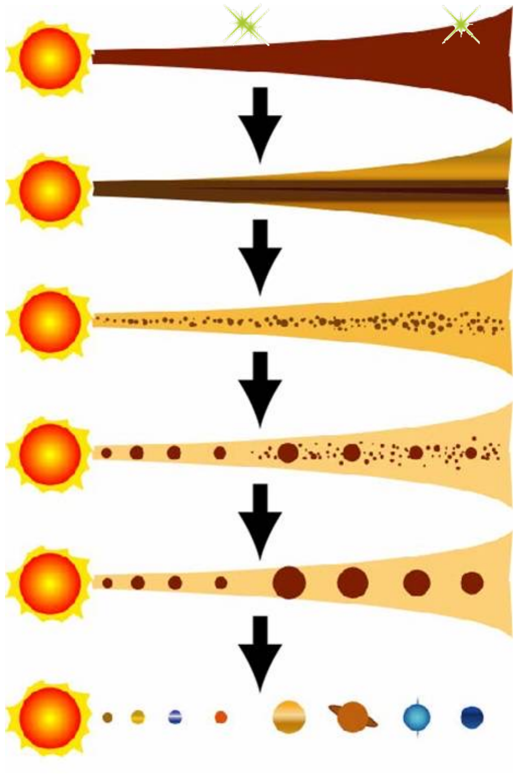
Chemical Fingerprint of Planetesimal / Protoplanet Formation

e.g., Carr et al. 2011; Najita et al. 2011, 2013; Banzatti et al. 2020

Story of Core Accretion



Once upon a time…



Grains (μm) grew…

Planetesimals (km) that grew…

Protoplanets (~1000s km) that grew…

Giant planets (10^5 km)

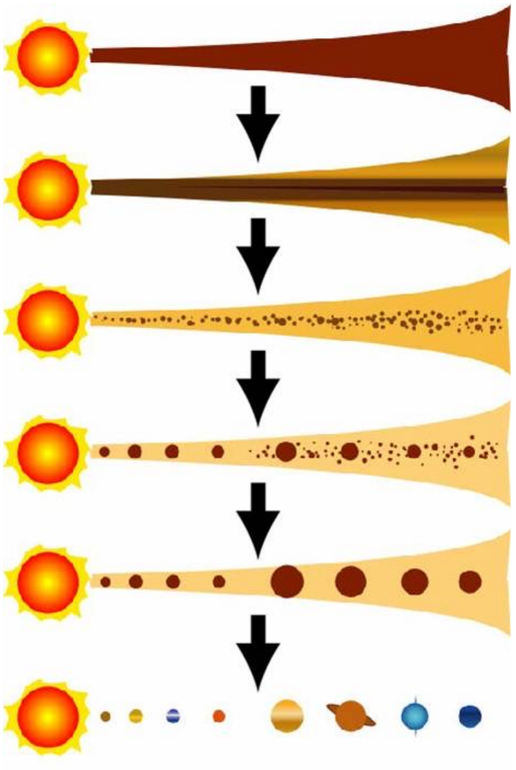
- 5-10 M_{Earth} core
- accretion of gaseous envelope

Remnant disk cleared…*The End*

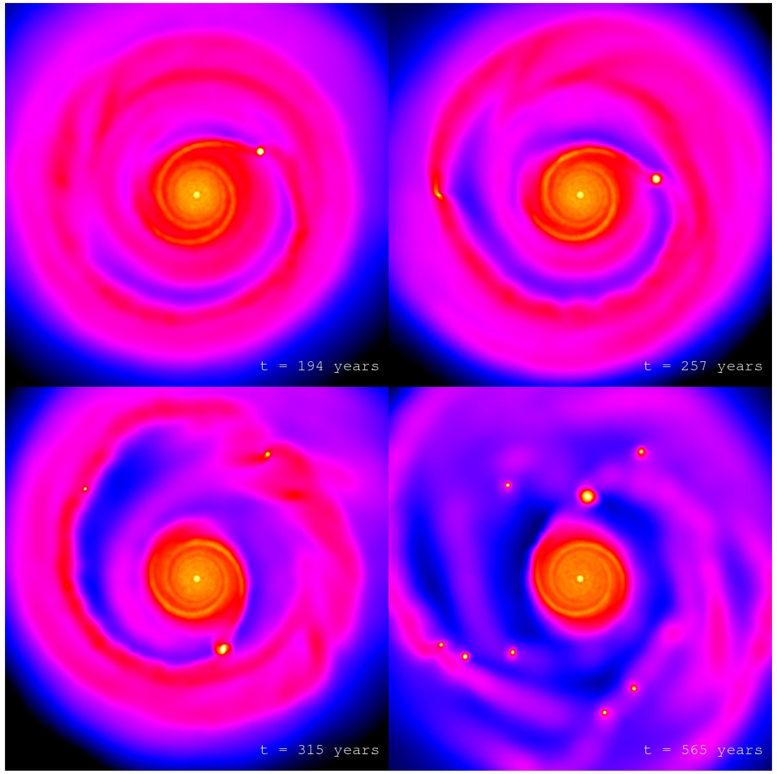
What is a signpost of core accretion?

- Core accretion makes planetesimals and protoplanets
- Are these abundant at epoch of planet formation?

Core Accretion



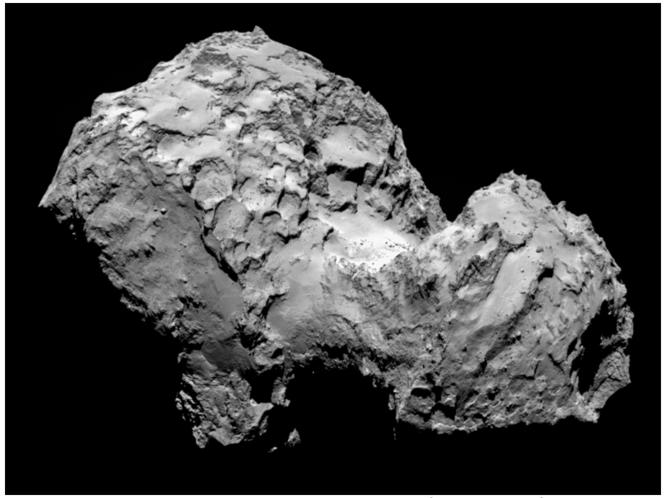
Gravitational Instability



Mayer et al. 2004

What do planetesimals look like?

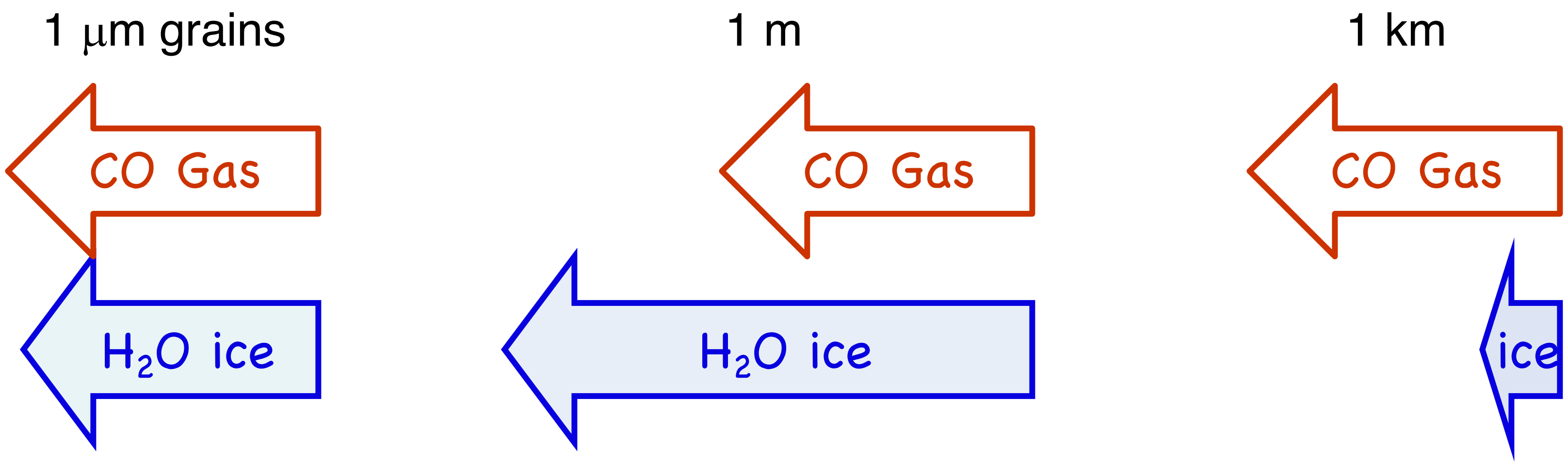
Hale Bopp: Wikimedia Commons



67P: ESA/Rosetta/NAVCAM

Solid aerodynamics and C/O of inner disk

Planetesimal (~1 km) and protoplanet (~M_{Mars}) formation dehydrates and enhances C/O of inner disk.



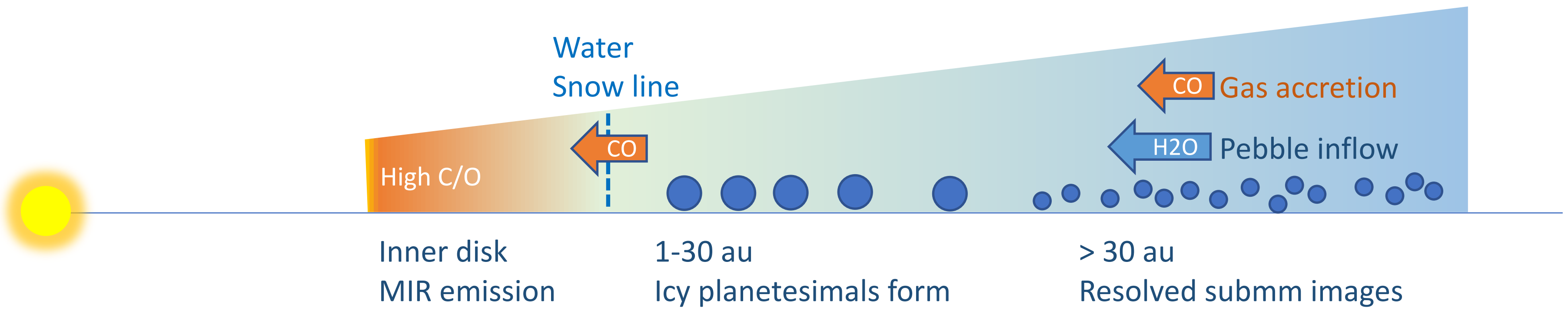
Gas, dust accrete together; no enhancement

Ice migrates faster than gas; super-hydrated inner disk, low C/O

Large bodies don't migrate; **dehydrated** inner disk, high C/O; **enhanced organics**?

Cf. Cuzzi & Zahnle 2004;
Ciesla & Cuzzi 2007

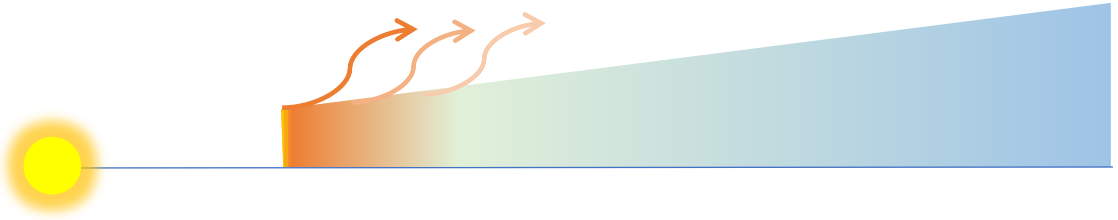
Planetesimals and C/O of Inner Disk



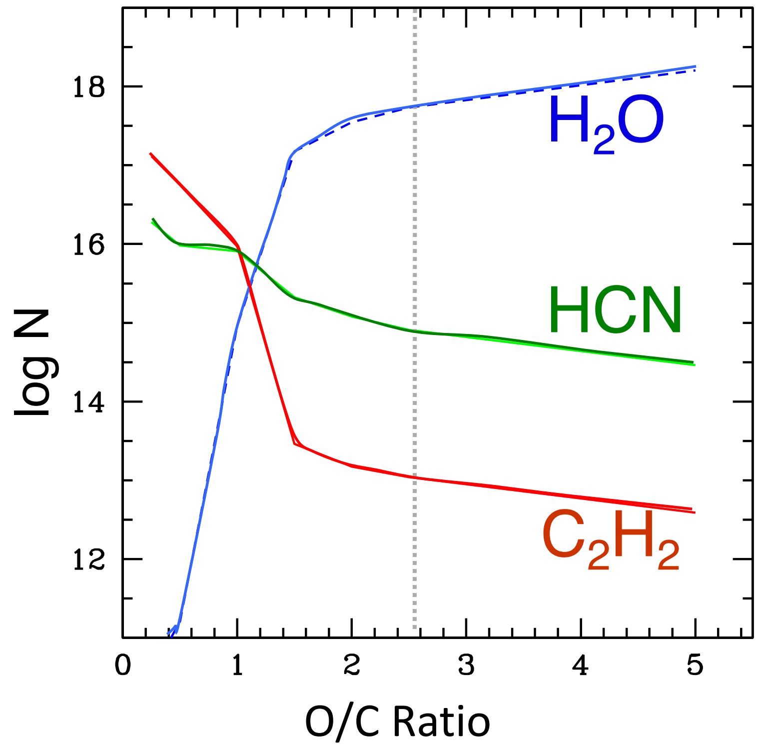
- Icy planetesimals sequester water and O beyond the snow line
- Efficient formation dehydrates inner disk, raises C/O ratio

Chemical signature of rising C/O

Warm molecular columns from thermal-chemical models of disk atmospheres at 1AU

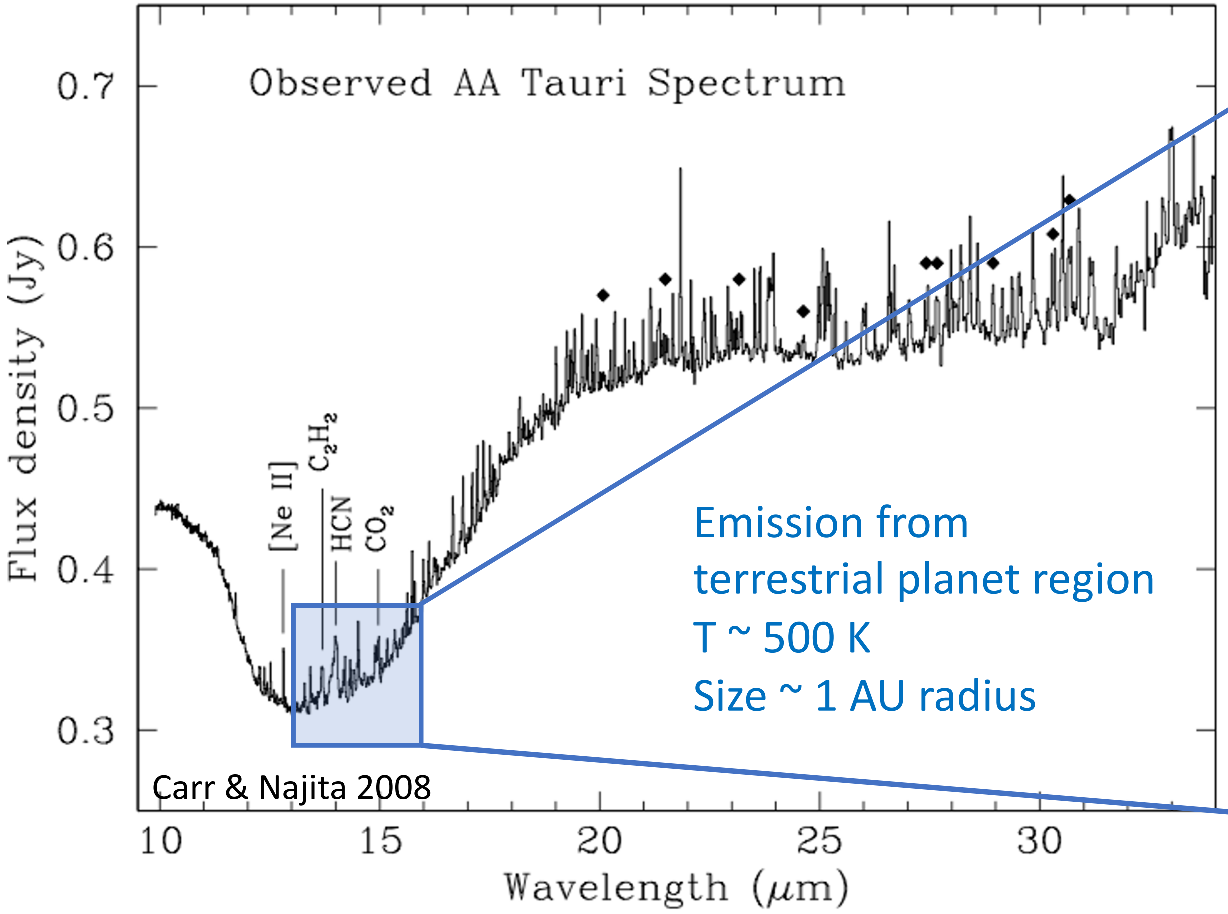


Najita, Adamkovics, Glassgold 2011



Doubling C/O produces 10 fold increase in HCN/H_2O warm column ratio

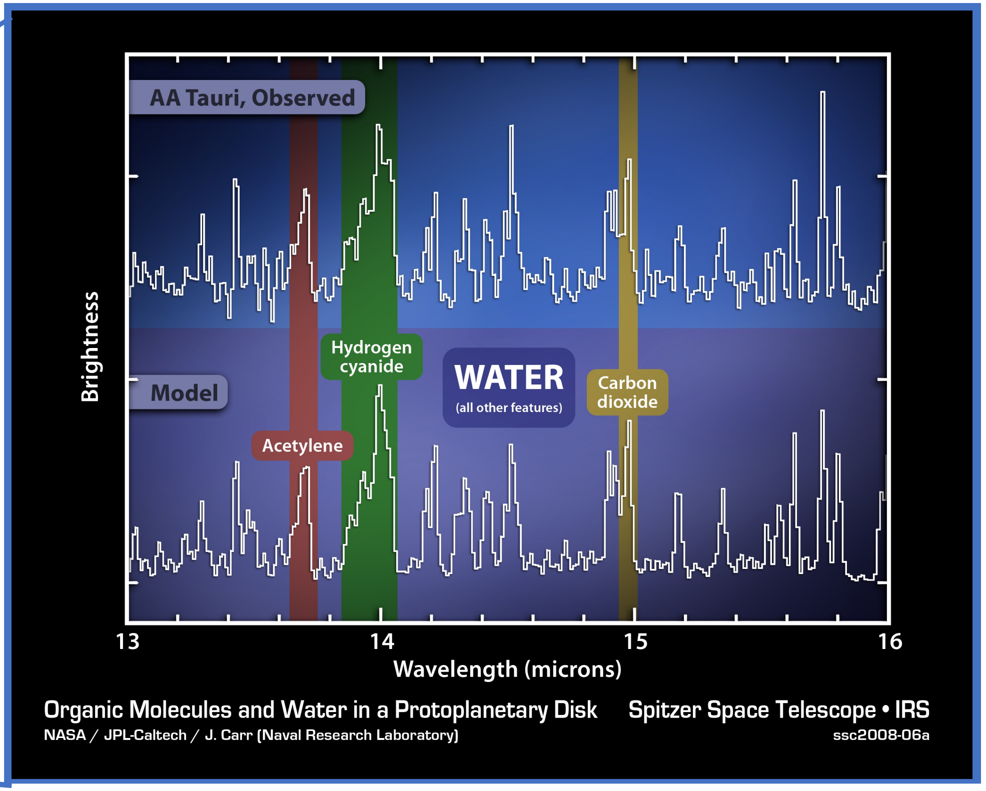
Inner Disk Molecules in Emission



Emission from terrestrial planet region

T ~ 500 K

Size ~ 1 AU radius



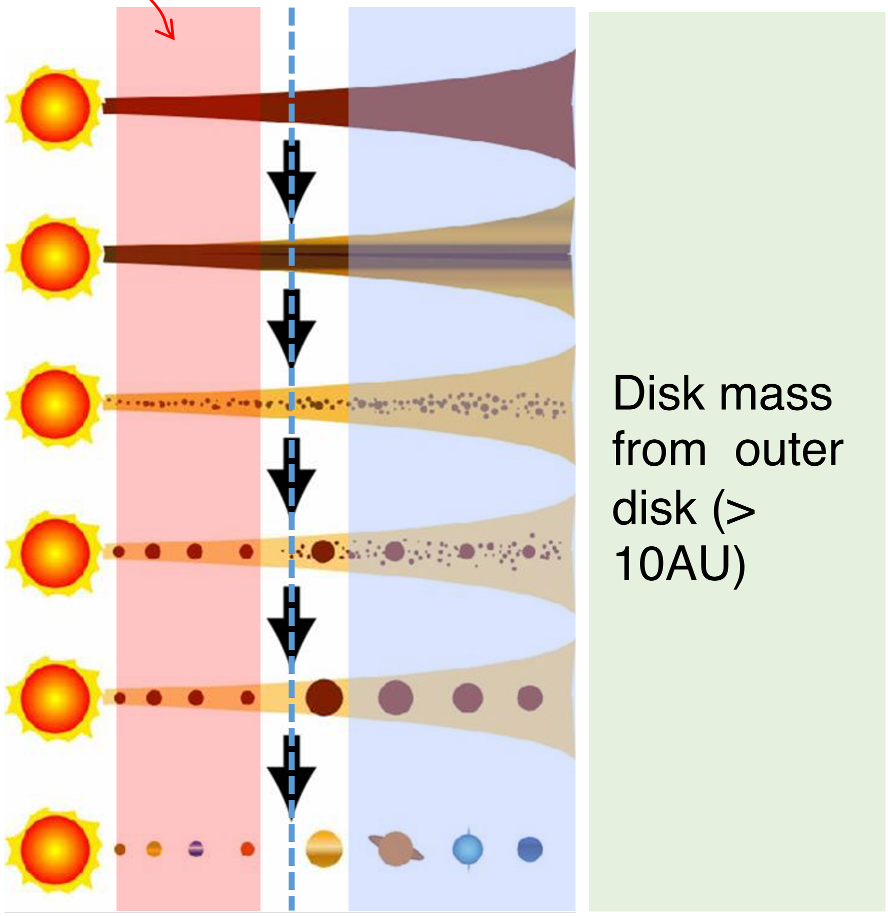
See also Carr & Najita 2011; Salyk et al. 2008, 2011; Pontoppidan et al. 2010

Planetesimal Formation and C/O

Icy protoplanets form beyond the snowline

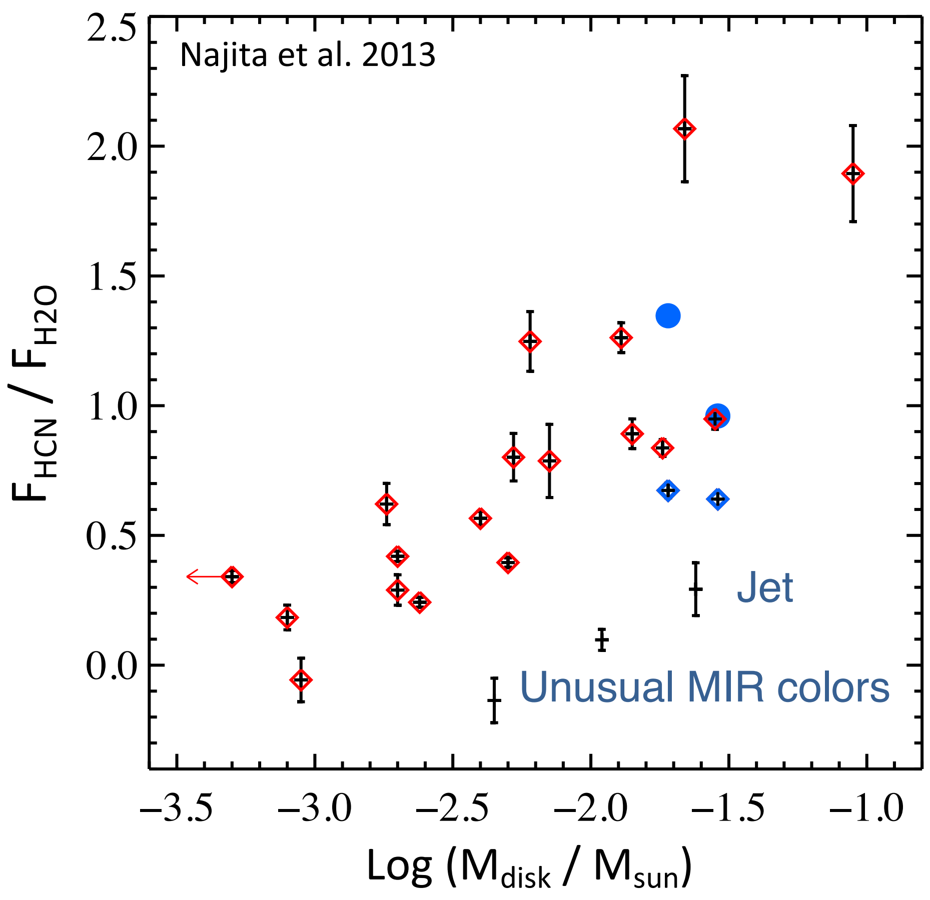
MIR molecular emission from here

Raises C/O, org/H_2O ratios within snowline



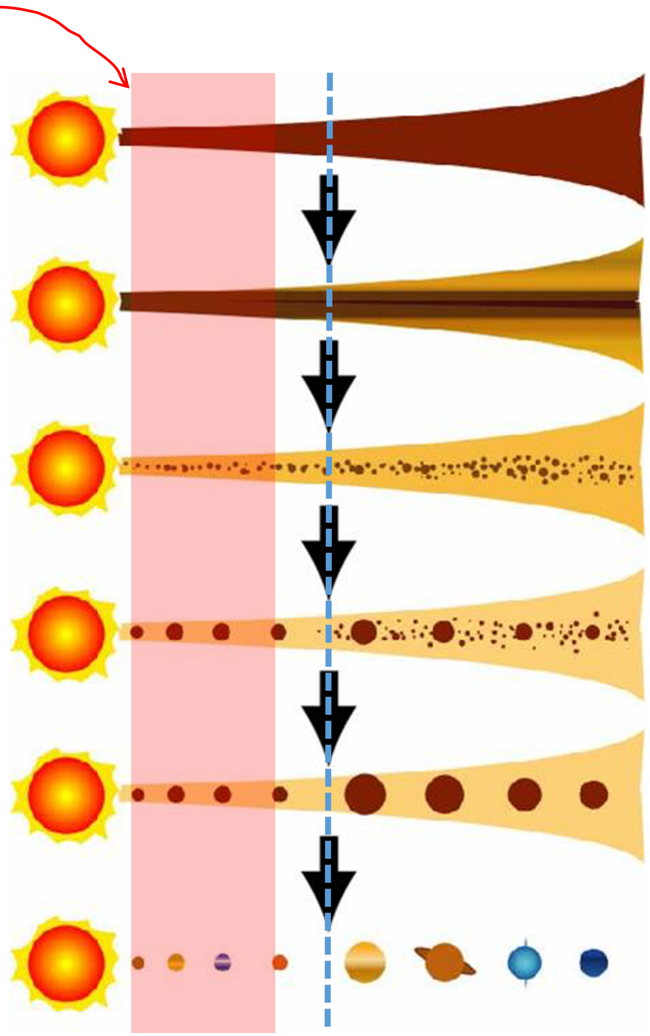
More massive disks form protoplanets quicker, have higher C/O ratio?

HCN/H2O Ratio vs. Disk Mass



Single T Tauri Stars in Taurus; disk masses from Andrews & Williams

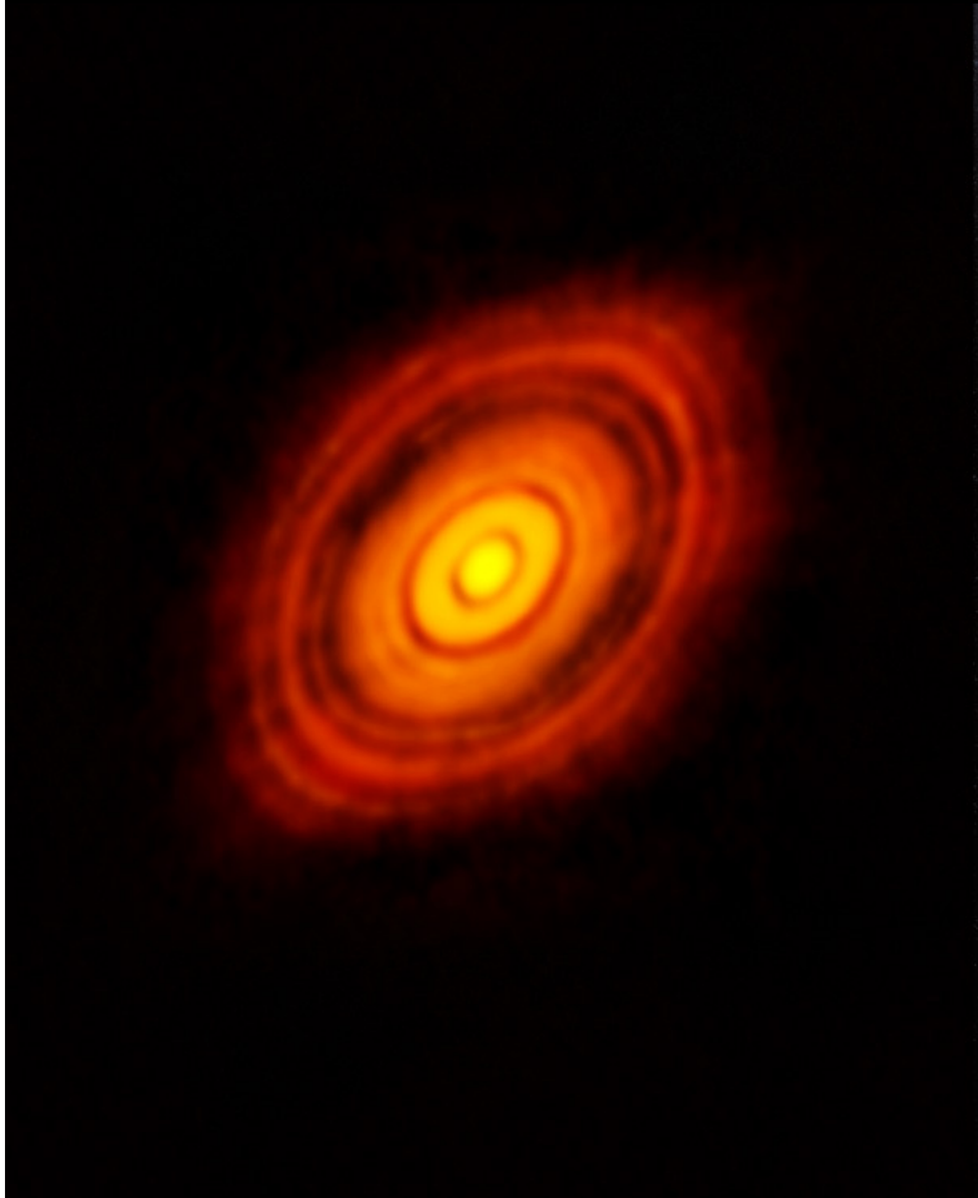
Chemical signature of planetesimal formation



Molecular message from 2013:

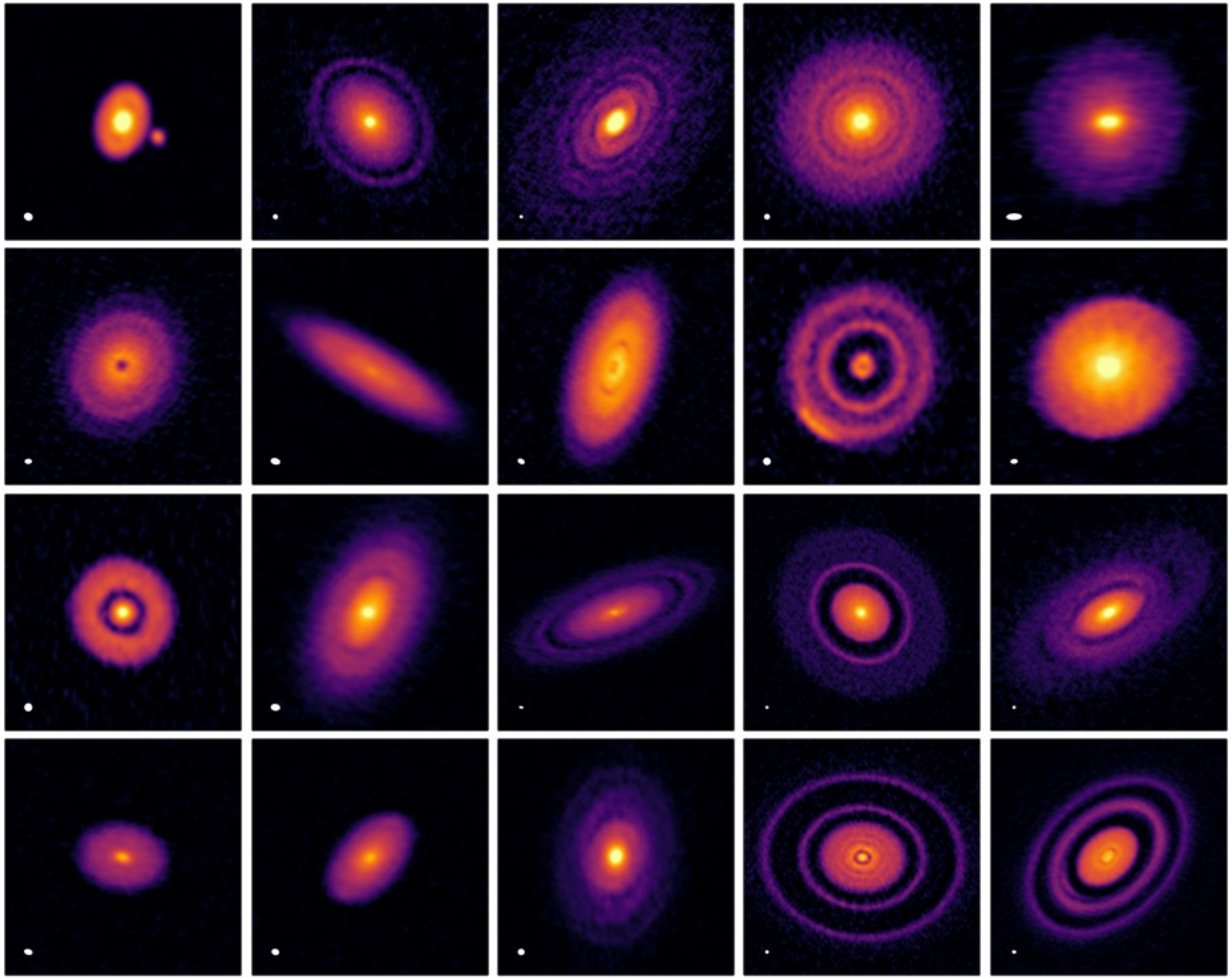
Disks are not primordial –
they have formed planetesimals or protoplanets
– a chemical signature of core accretion in action!

ALMA Observes HL Tau



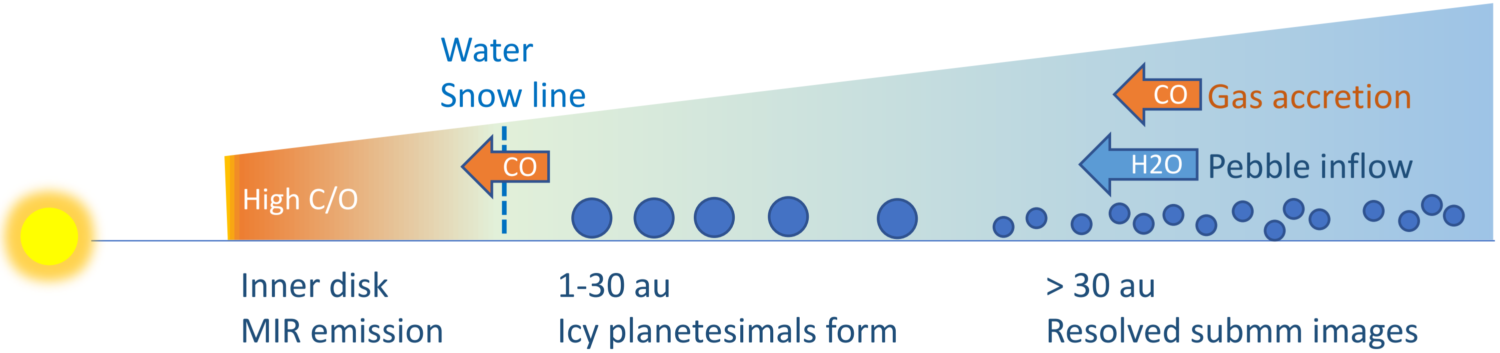
Credit: ALMA (ESO/NAOJ/NRAO)

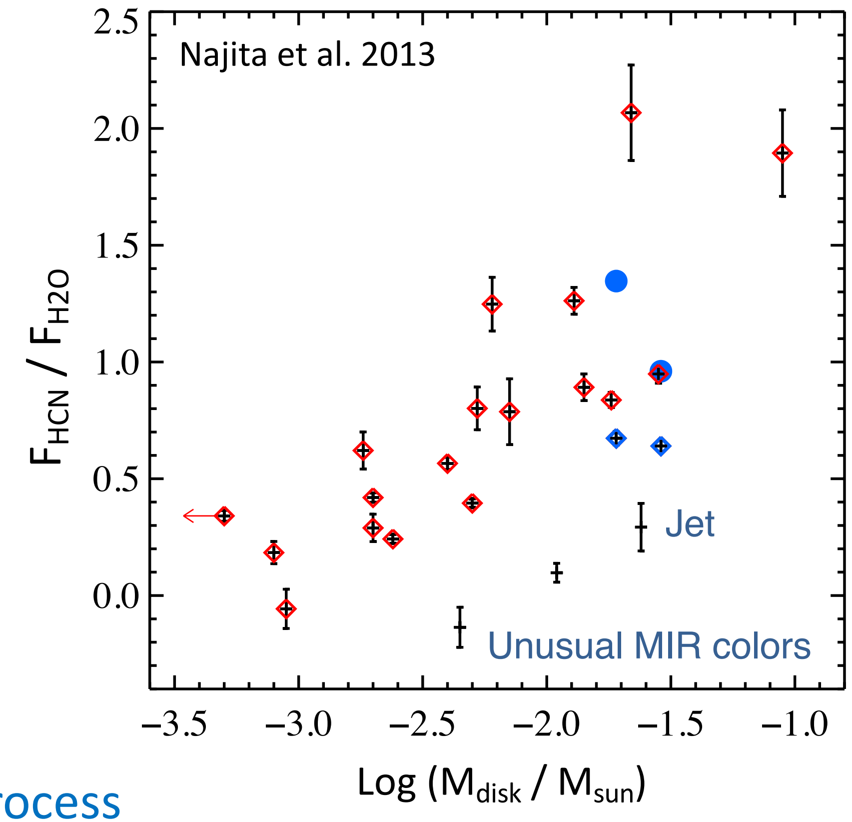
Rings and Spirals in DSHARP



Andrews et al. 2018

Chemical signature of planetesimal formation?





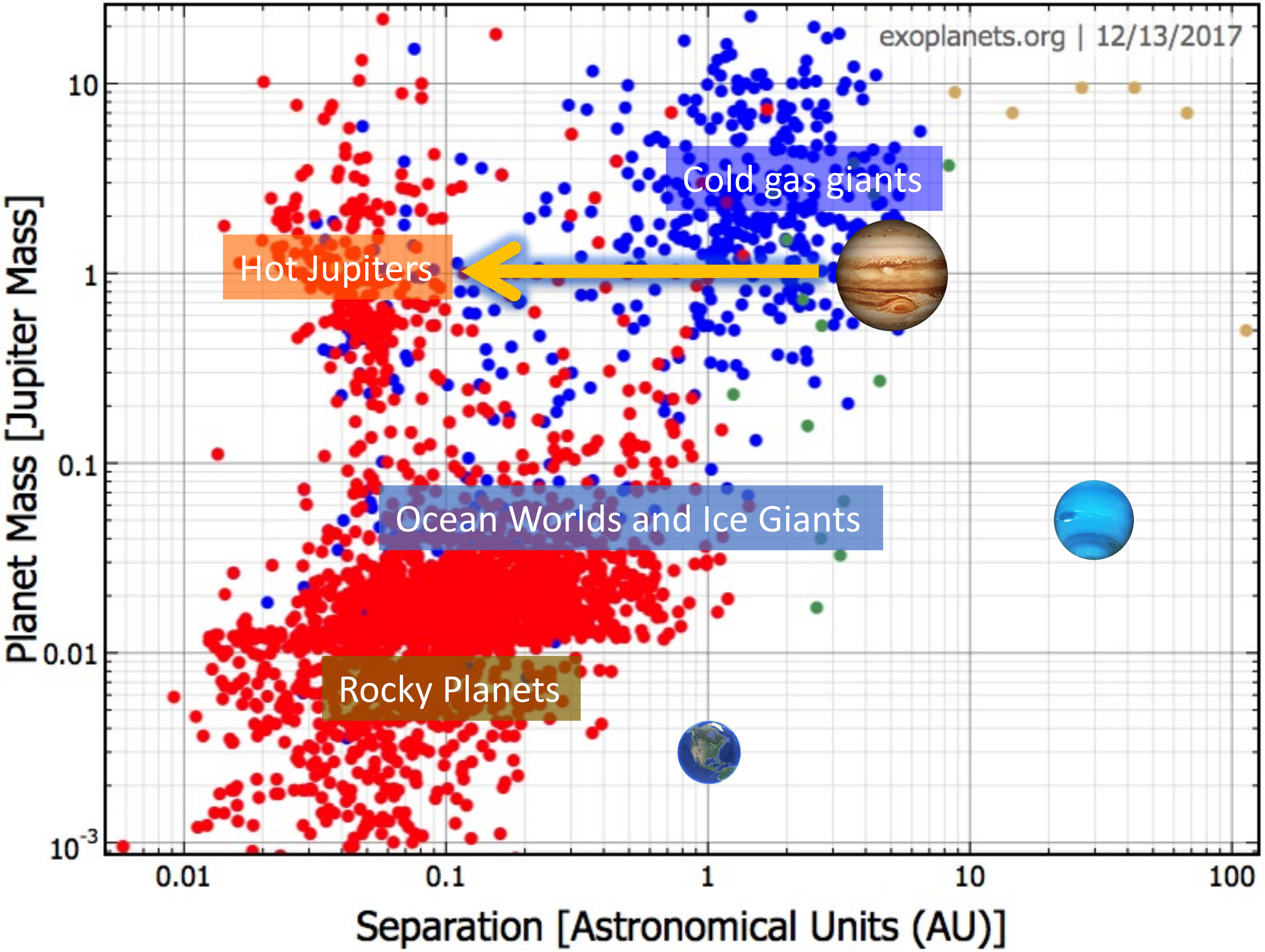
- Possibly we're onto something!
- Chemistry can uniquely illuminate an elusive planet formation process

High resolution MIR spectroscopy

Observing disk accretion in action?

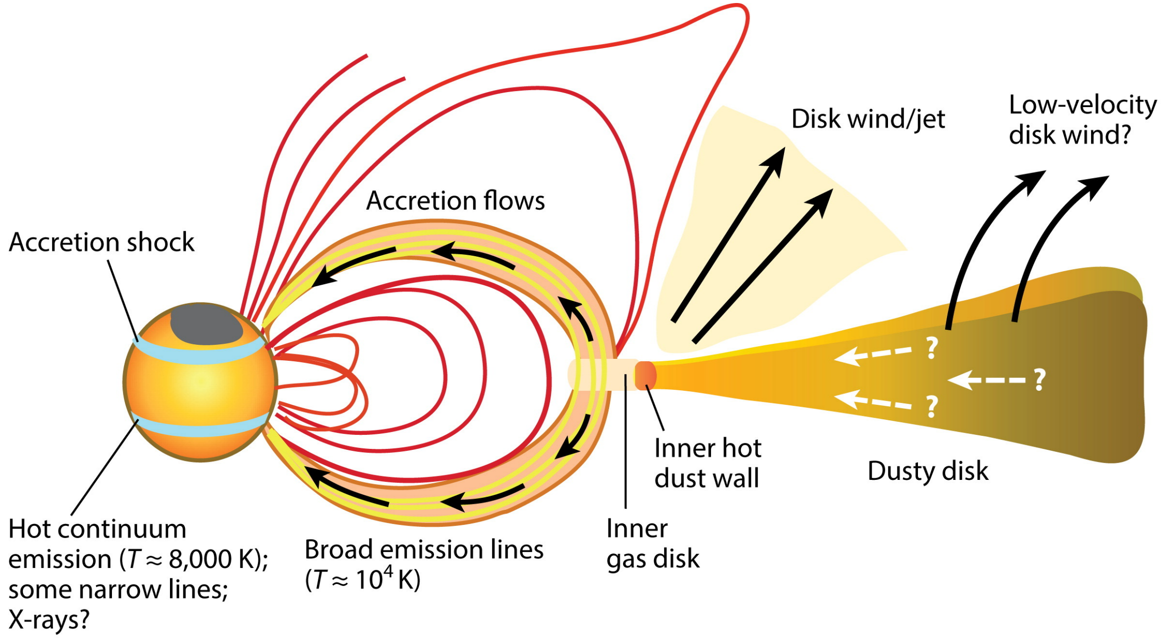
e.g., Najita et al. 2021

Exoplanet Populations



Migration is important

How does matter reach the magnetosphere?

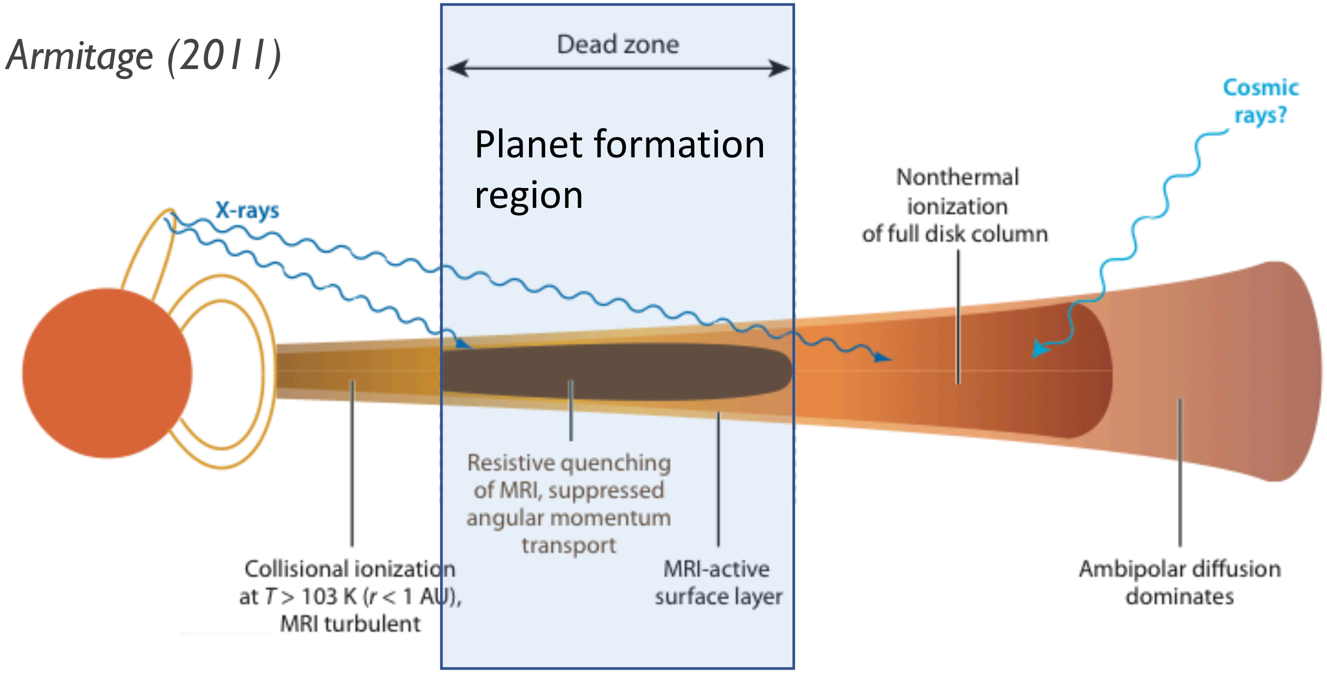


Stars accrete via magnetospheres and transport angular momentum to the inner disk, which is removed in a wind/jet from inner disk.

But how does accreting matter reach the magnetosphere?

How do disks accrete?

Armitage (2011)

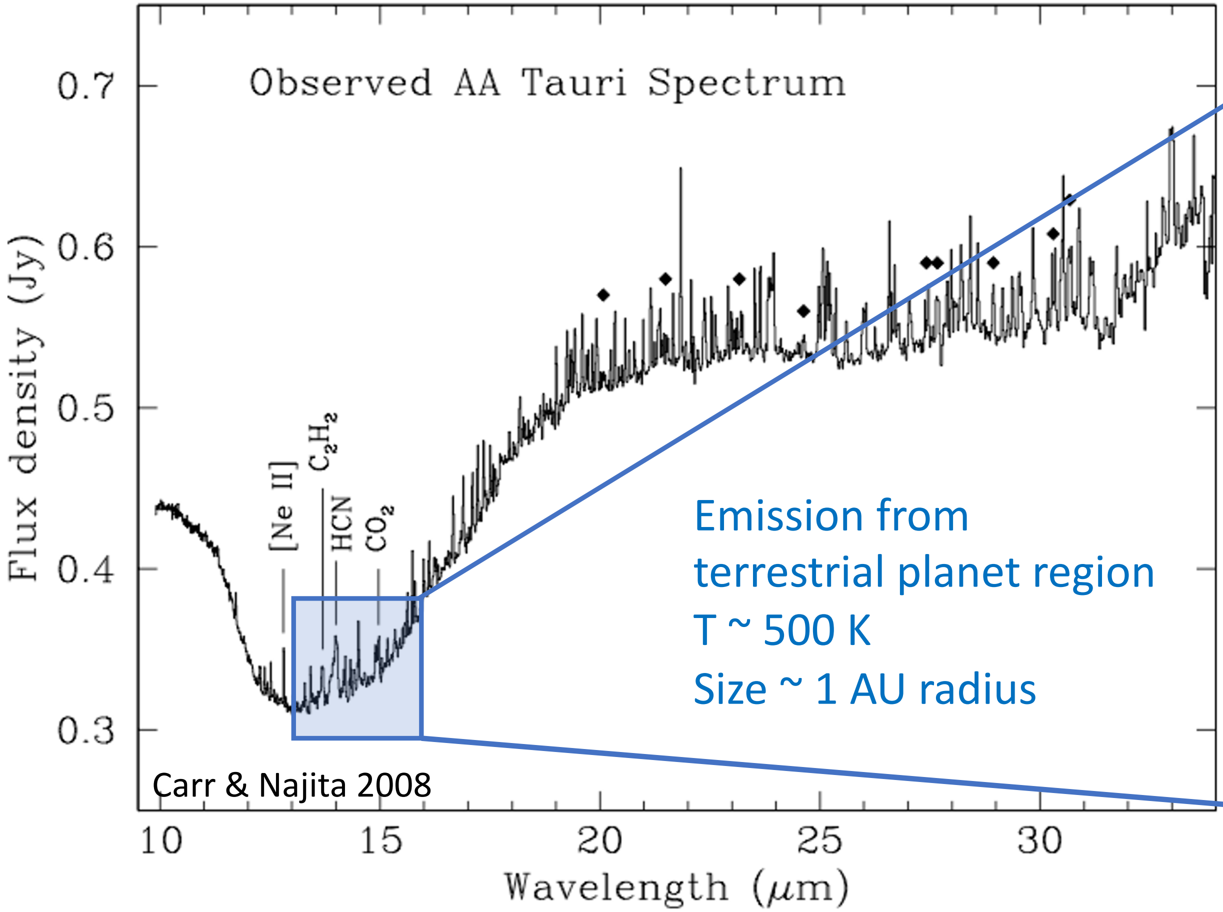


Thermal ionized
MRI

Layered accretion
Disk winds?
Something else?

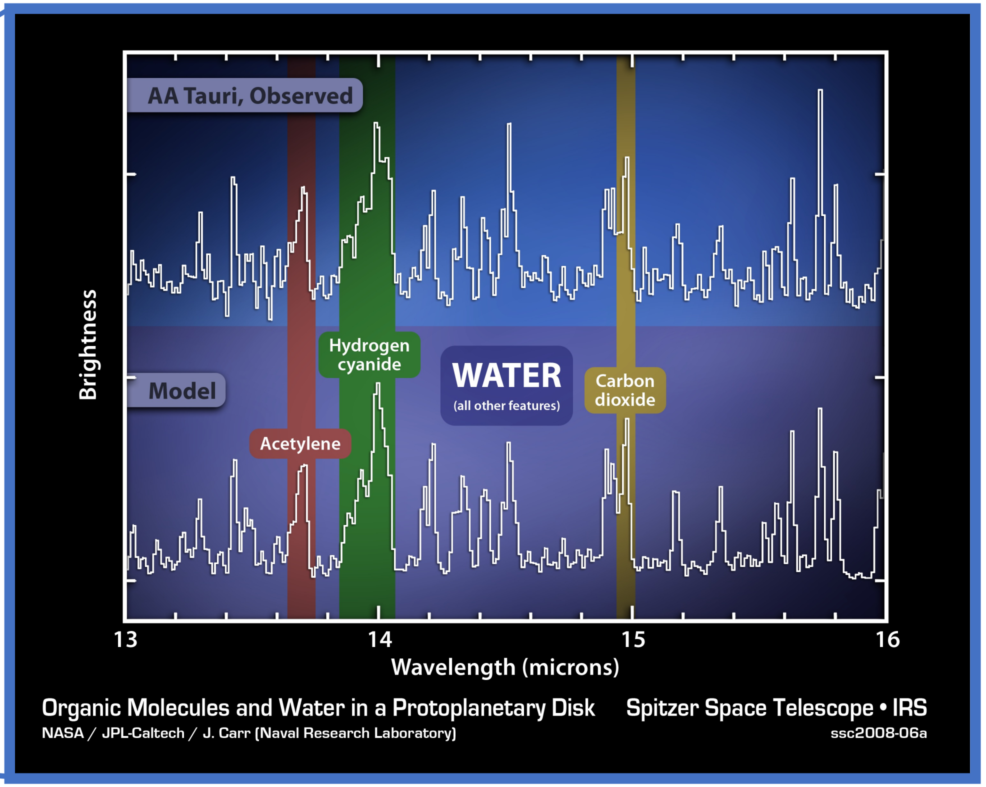
Non-thermal ionized
MRI

Inner Disk Molecules in Emission

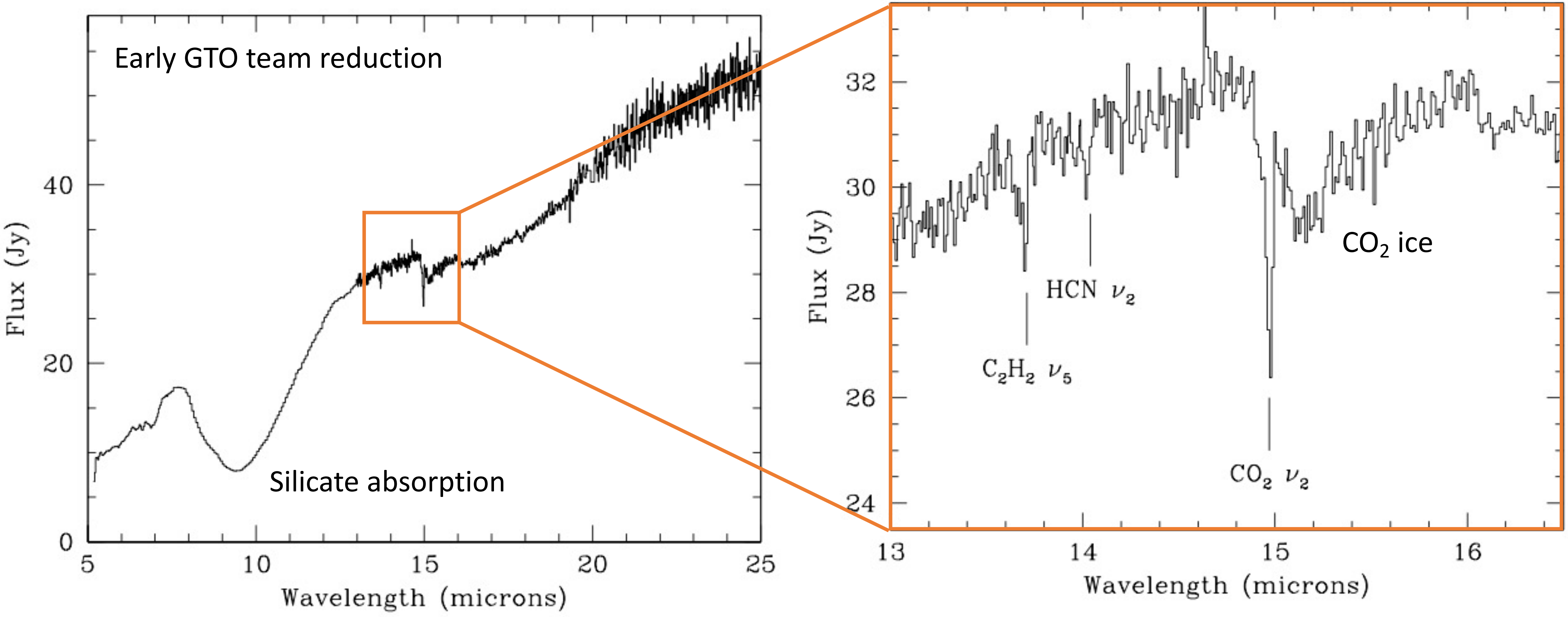


Carr & Najita 2008

Emission from
terrestrial planet region
T ~ 500 K
Size ~ 1 AU radius



GV Tau N: Spitzer/IRS molecular absorption



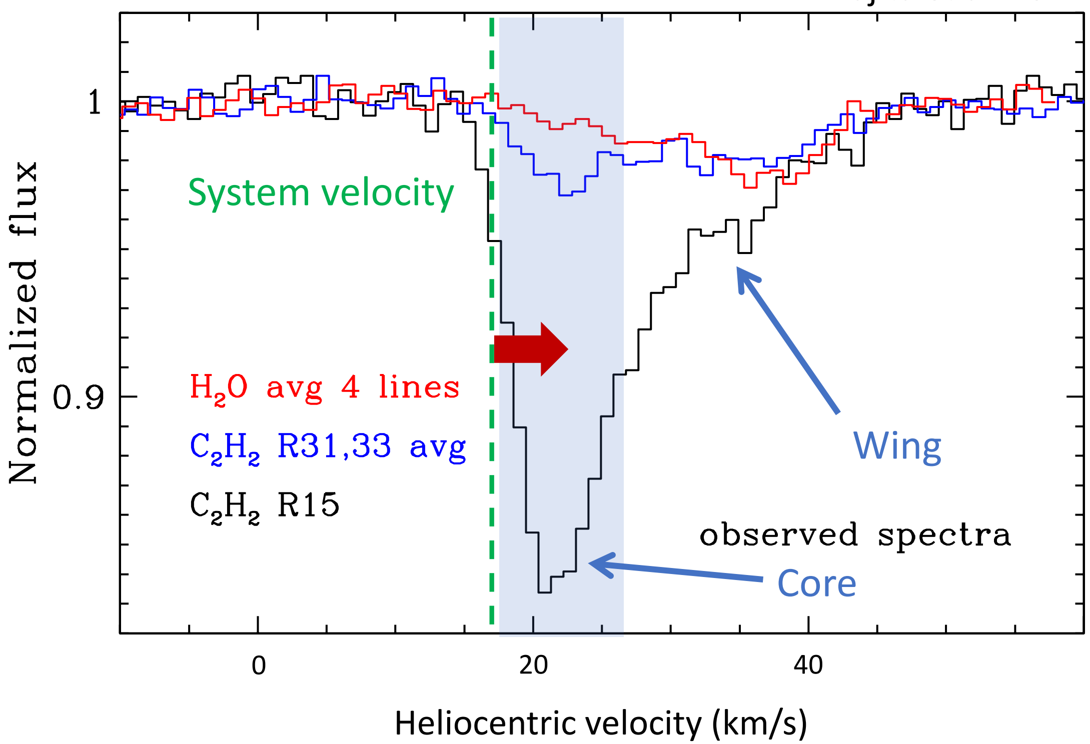
GV Tau N: high resolution line profiles

Redshifted line profiles

- 4-20 km/s
- C2H2, HCN, NH3, H2O
- TEXES/Gemini R=100,000

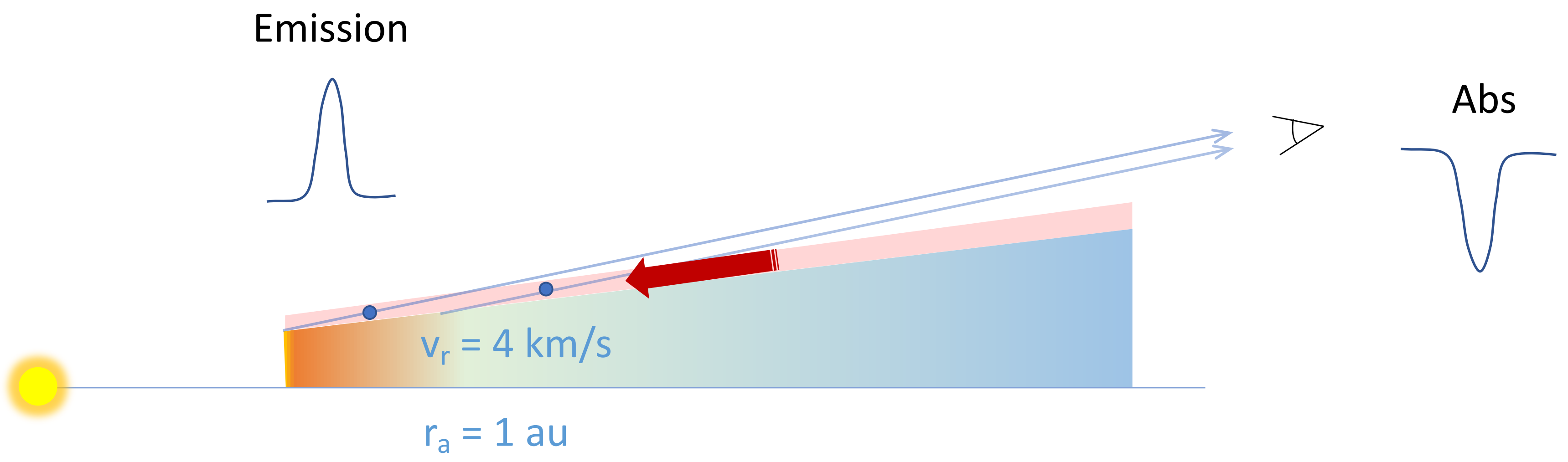
Measure component equivalent widths and infer
- Temperature T
- Absorption column density N
- Intrinsic line width Δv
- Filling factor f

Najita et al. 2021



- Molecular abundances, temperature of inner disks at ~ 1 au
- High column density → disk atmosphere viewed edge on
- Supersonic inflow velocities

Inner disk atmosphere seen edge on



Disk accretion in action through disk atmosphere?

Accretion rate ~ TTS:

10^{-8} - 10^{-7} M_{sun}/yr

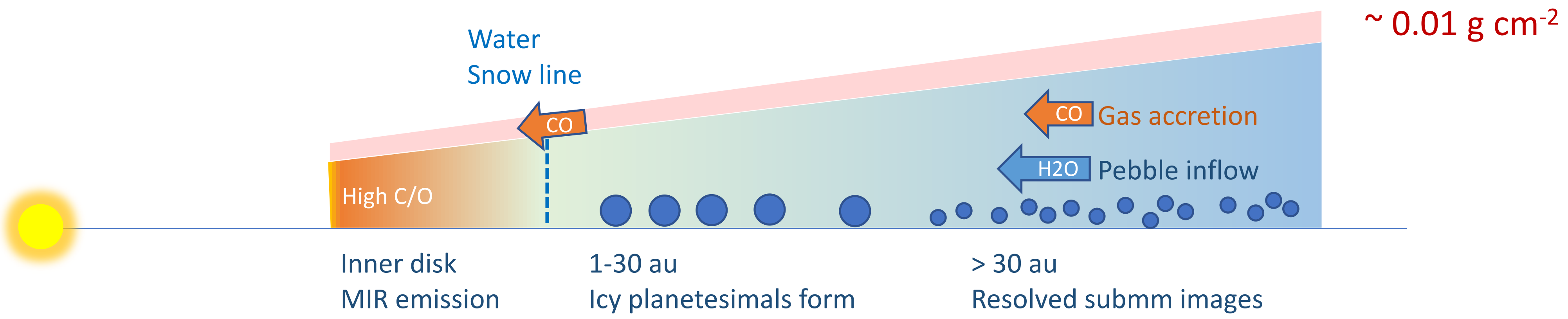
i.e.,

Mdot = $2\pi r_a m_H v_r N_{perp}$

$N_{perp} \sim 0.1\ N_{abs} / x_{mol}$

Disk accretion in a thin atmosphere

Fast current...overlying a “deep ocean” of the disk...hospitable to planet formation?



Summary: UV/Optical Spectroscopy

Rich UV-optical spectrum, long history, well studied

Diverse questions/issues:

- How stars accrete
  - Via magnetospheres not boundary layers
- Demographics of stellar accretion rates bear on:
  - Gas dissipation timescale of inner disk (planet formation, migration)
  - Nature of transition disks (due to planets or not?)

Summary: Infrared Spectroscopy

Many diagnostics available, much less well studied

Fun, powerful techniques (e.g., spectroastrometry)

Diverse questions/issues

- Disk structure and substructure
  - Measure inner gas disk radii (planetary orbital radii)
  - Identify orbiting gaseous circumplanetary disks (birthplaces of moons)
- Disk chemistry
  - Probe planetesimal formation, an otherwise elusive process?
- Disk dynamics
  - Do disks accrete through their atmospheres?