Protoplanetary disks

Nienke van der Marel
January 26th 2017

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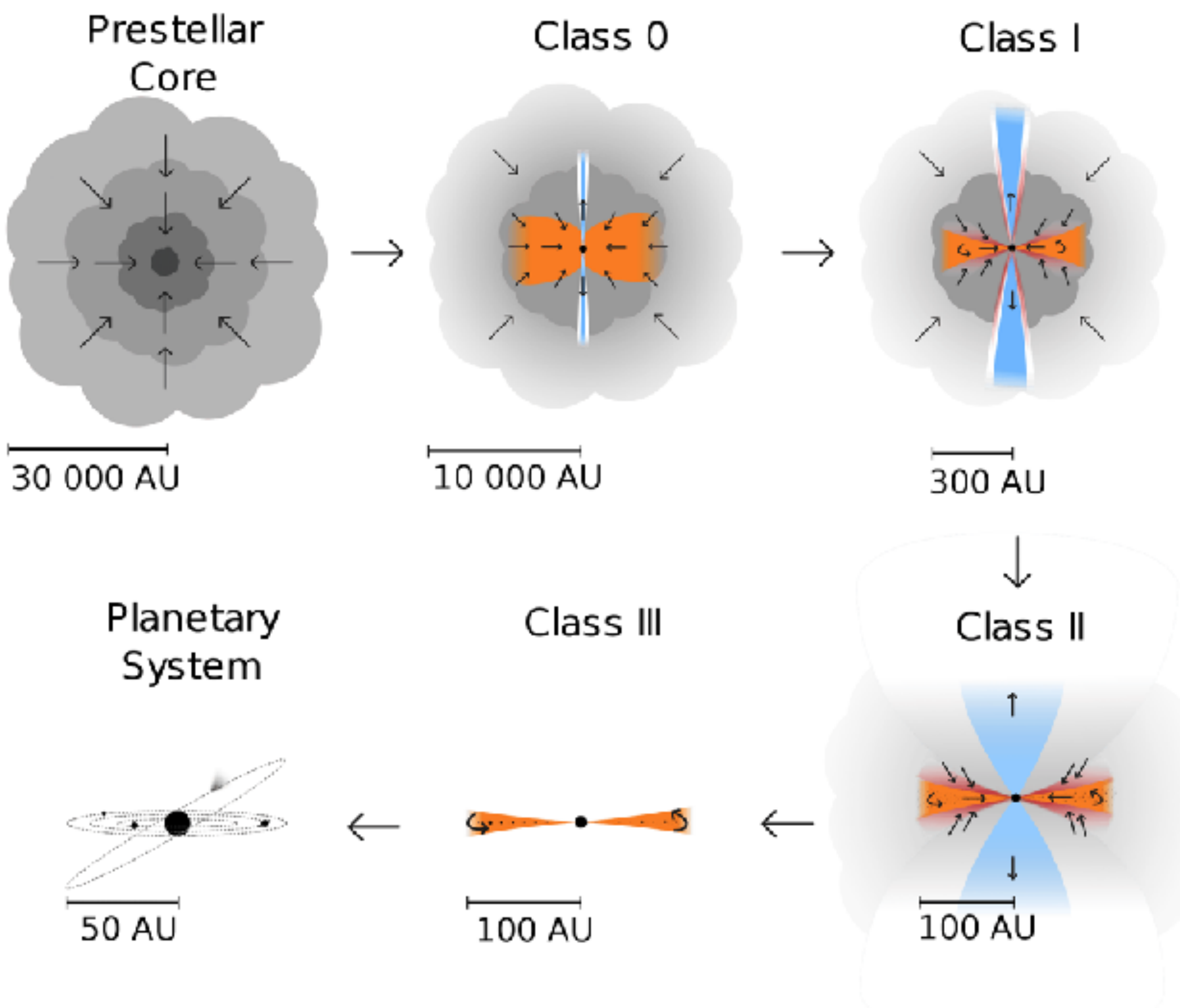
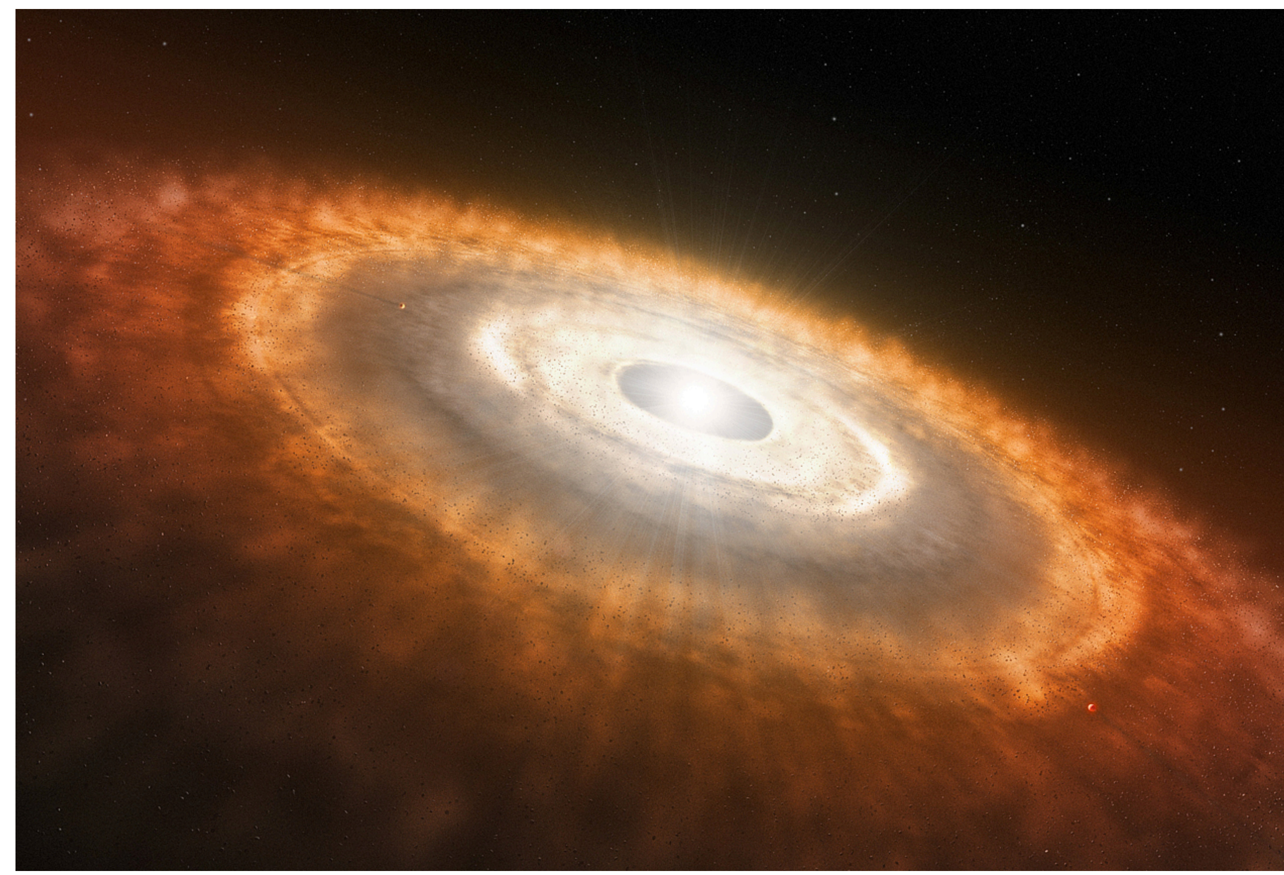
- Disk structure
- Outer disk vs inner disk
- Modeling
- Disk mass
- Disk processes

Star and planet formation



Disk structure

- Lifetime ~Myrs
- Keplerian motion
- Large density and temperature gradients:
  - n_{gas} ~ 10^4 - 10^{16} cm^{-3}
  - T ~ 10 - 10 000 K
- Vertical *and* radial structure: flaring
- Radiation field: young star! (incl UV, X-ray)
- Birth cradles of planets
- Size ~ arcseconds => importance interferometry!

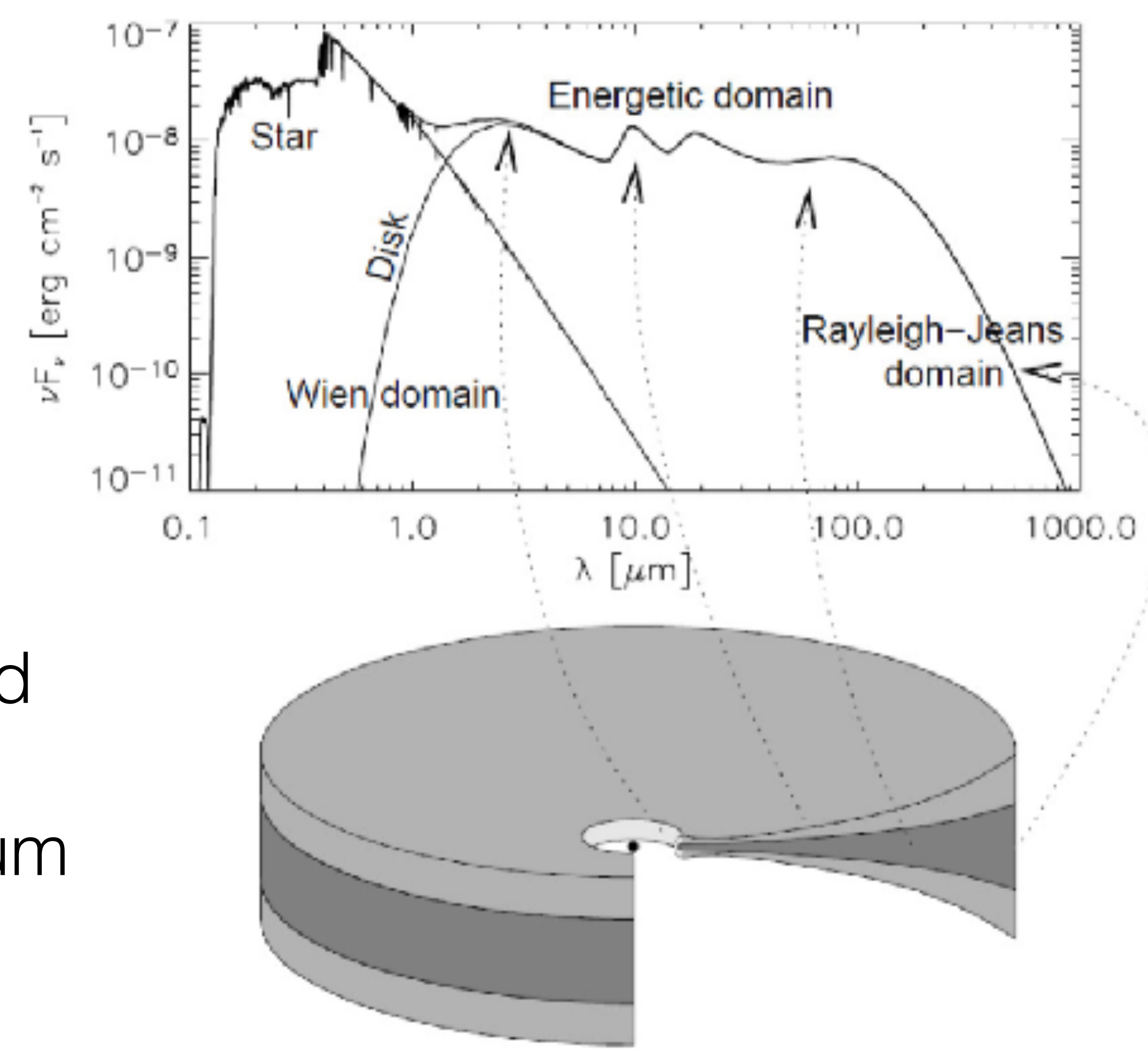


Disk structure

- History of “protoplanetary disks”
  systematically brighter stars in dark clouds with strong emission lines (50s)
  => pre-main sequence stars:
  no IR, so existence disk not yet known!
    - T Tauri stars (G-M) => strong UV excess (accretion) (Herbig 1957)
    - Herbig stars (A,F) => massive equivalent T Tauri (Herbig 1960)
- CTTS (classical) vs WTTS (weak-line): line strength
- Disk nature not understood until 70s: viscous accretion disk model (Lynden-Bell & Pringle 1974)
- Class II vs Class III: Lada classification: IR slope (1987)
- Debris disks (a.k.a. Class III, WTTS):
  very little dust (IR excess) and gas left, older systems => little chemistry

Disk structure

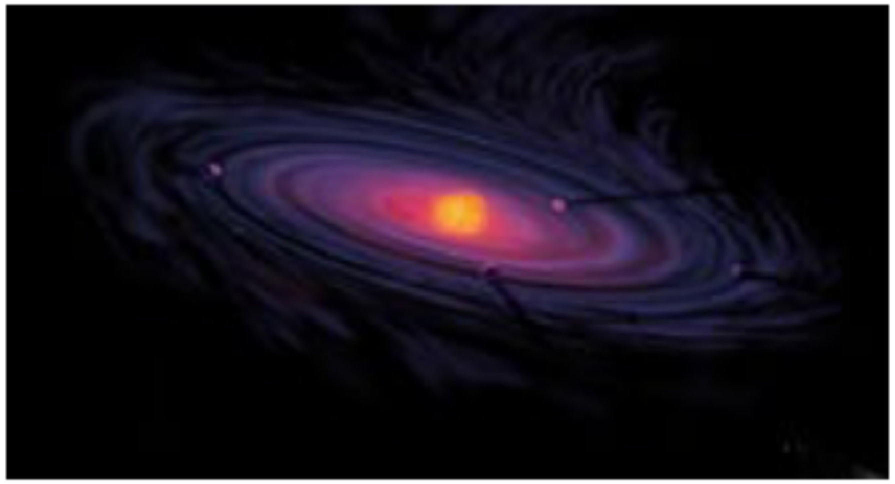
- Disk structure
- Spectral Energy Distribution (SED) provides information on the dust distribution
(easy to detect)
- Vertical structure (flaring) is reflected in SED and can be fit
=> alternative: hydrostatic equilibrium
- mm-slope:
dust grain size distribution
(in Rayleigh-Jeans limit)

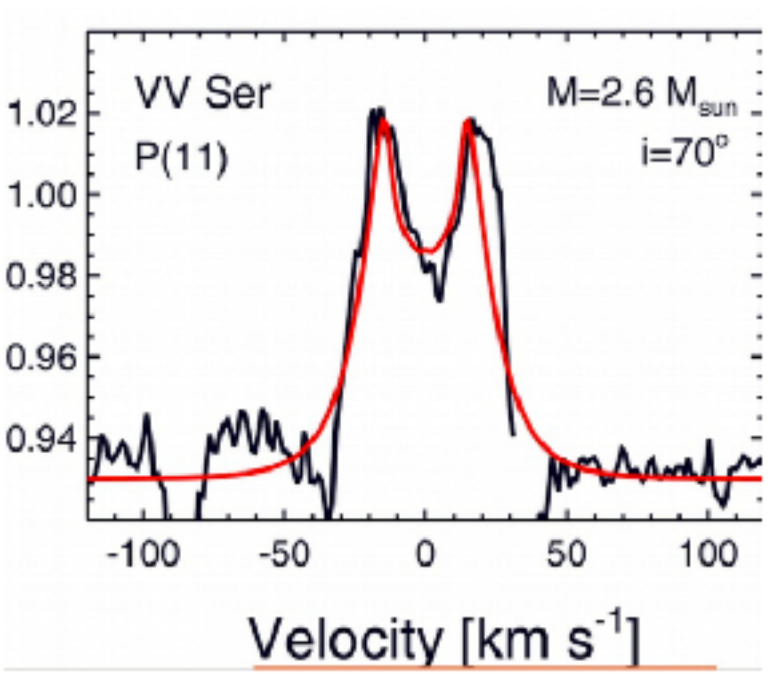


Cartoon C. Dullemond

Disk structure

- Gas observations in disks limited:
  - Accretion (optical lines)
  - Molecular lines challenging
    - sensitivity-limited
    - confusion cloud
    - spatial interpretation?

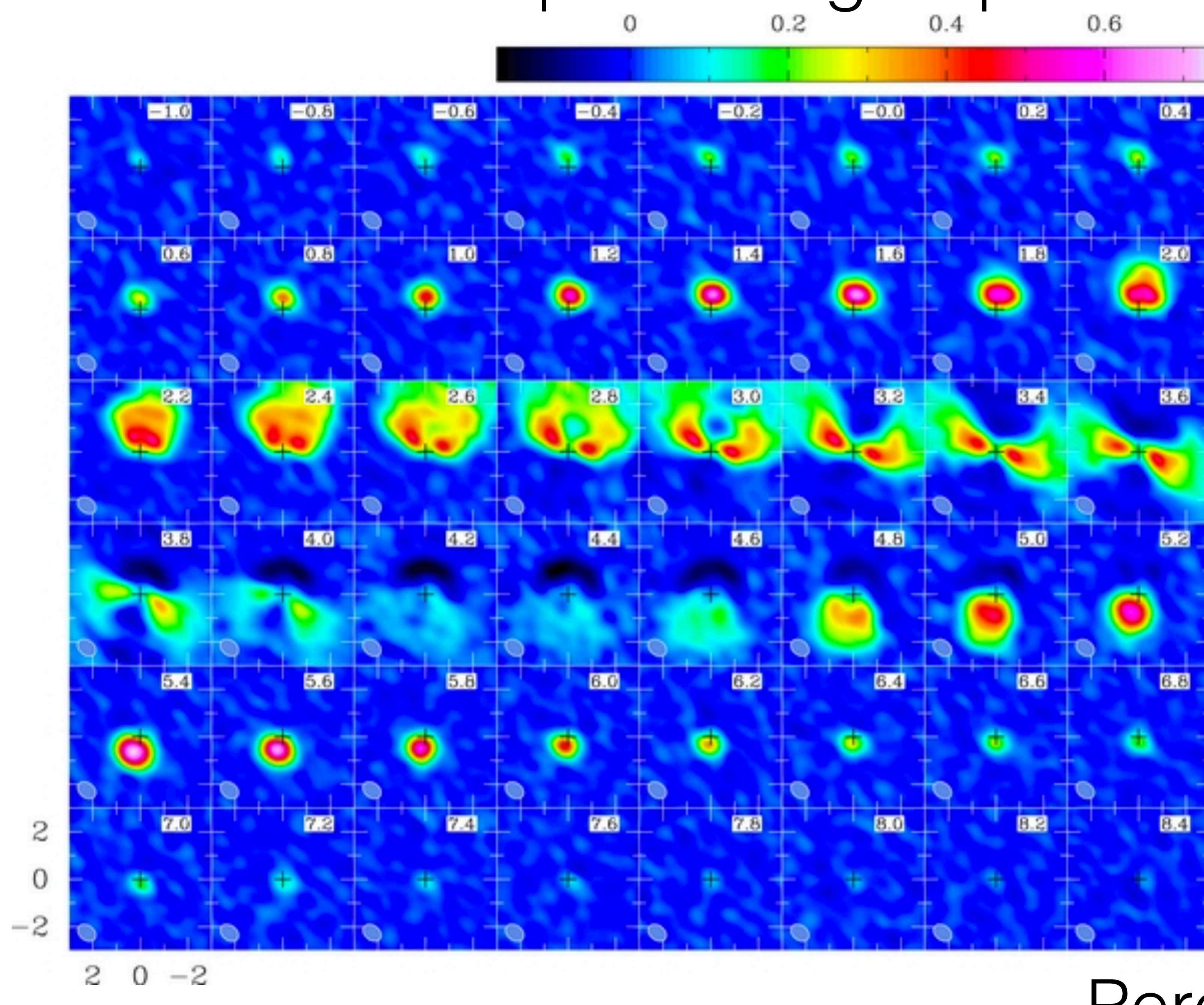




Disk structure

- ALMA: CO channelmap showing Keplerian motion

butterfly
pattern

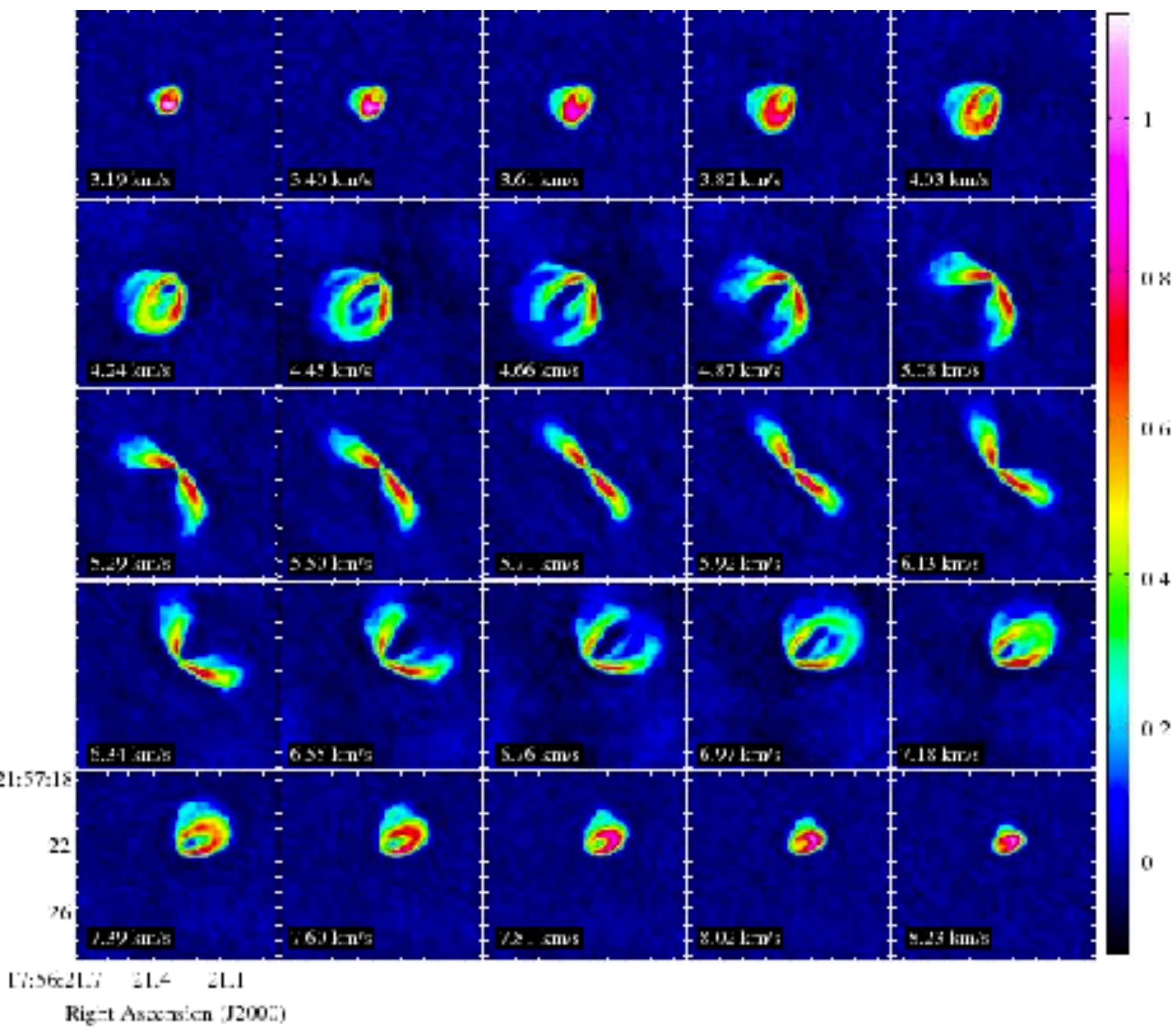


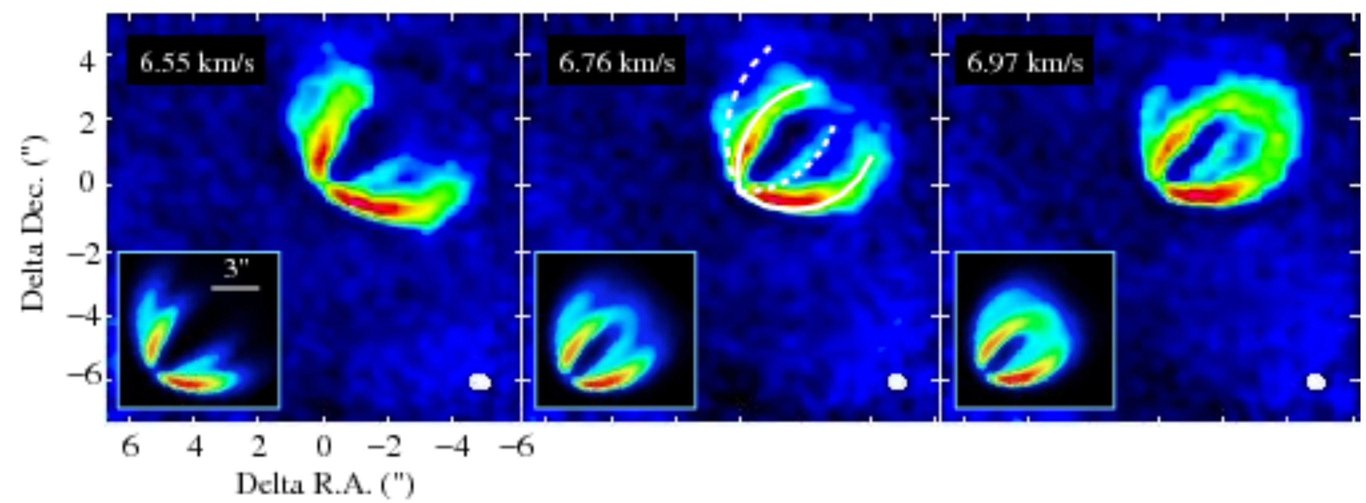
HD142527

Perez et al. 2015

Disk structure

- ALMA CO channel map following Keplerian motion





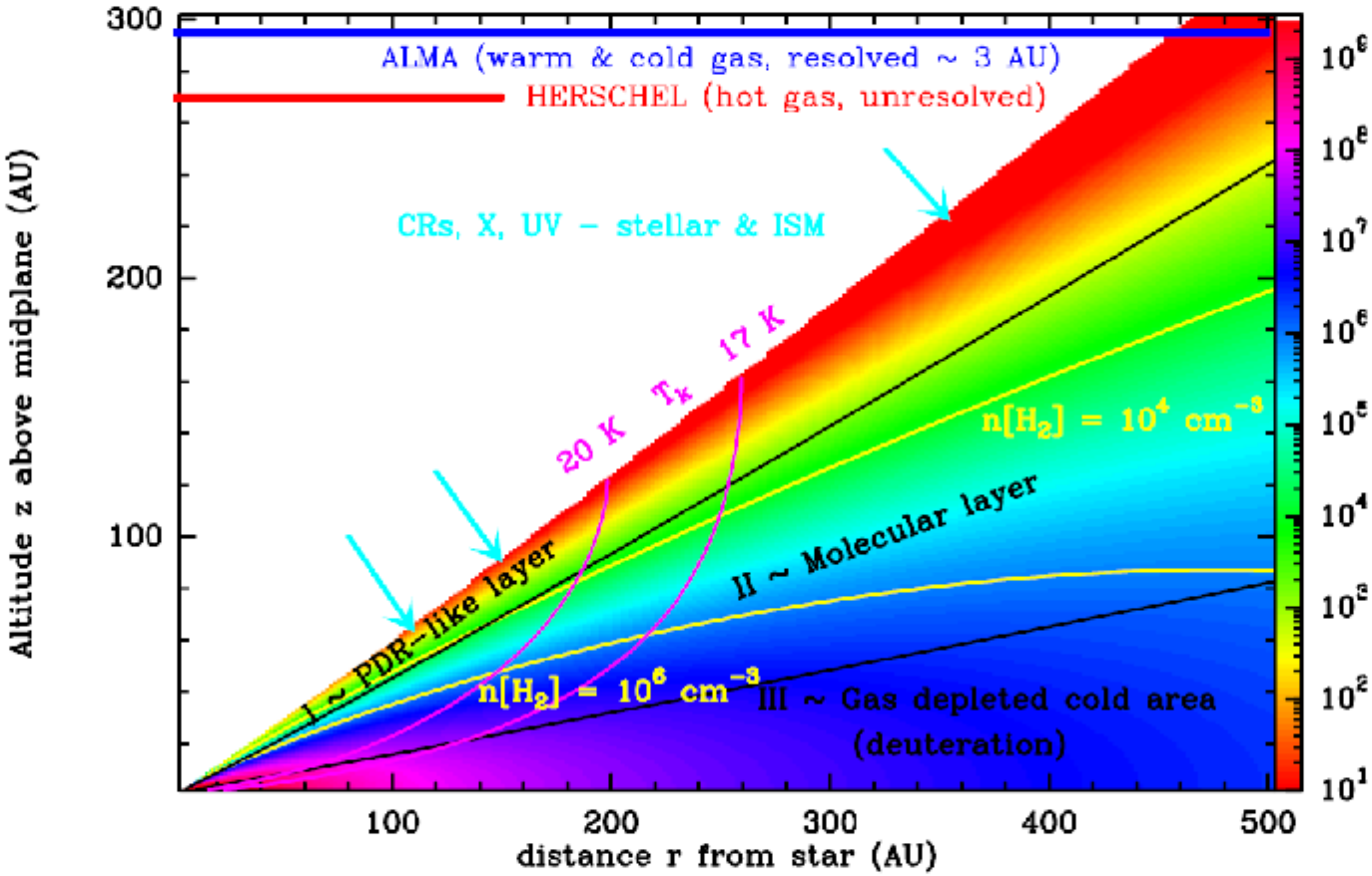
double butterfly?

HD163296

de Gregorio-Montsalvo et al. 2013

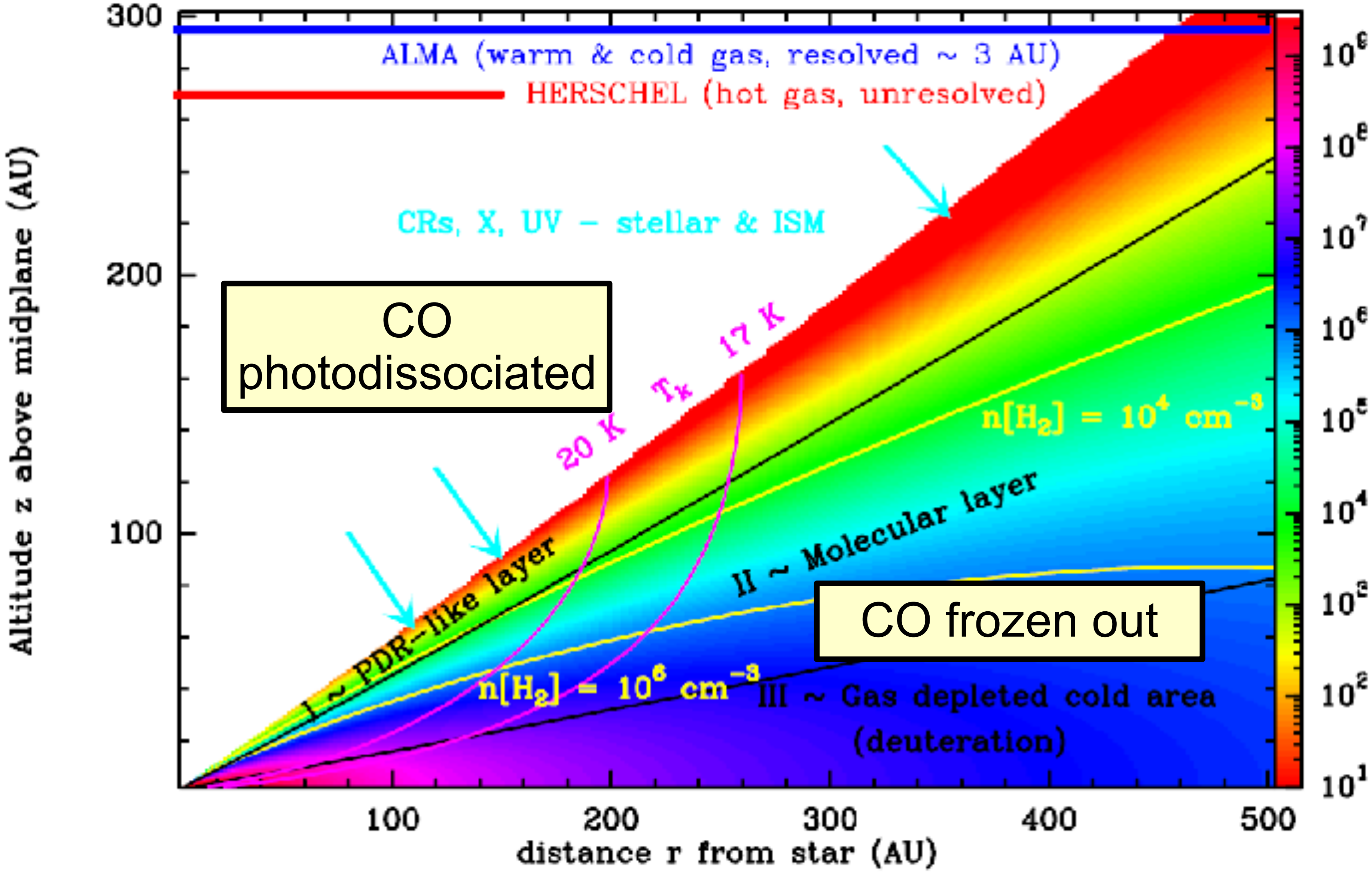
Disk structure

- Three main regions



Disk structure

- Three main regions: CO gas only in middle warm layer

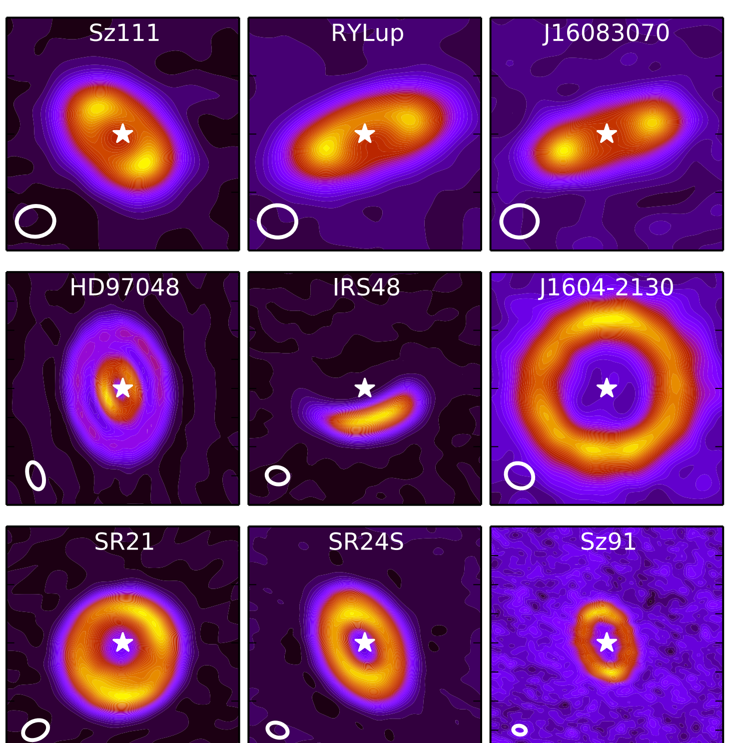


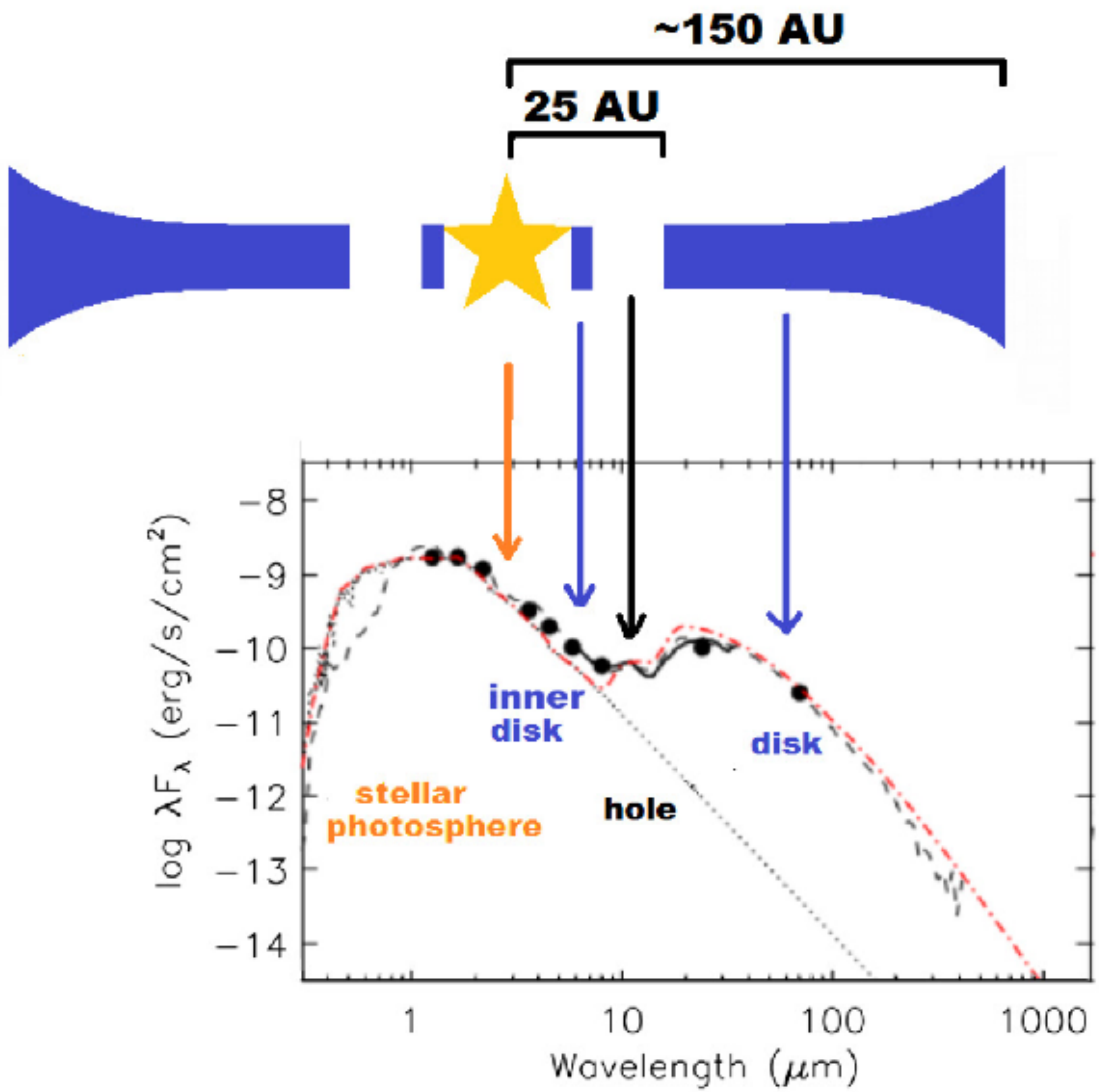
Transitional disks

Transitional disks

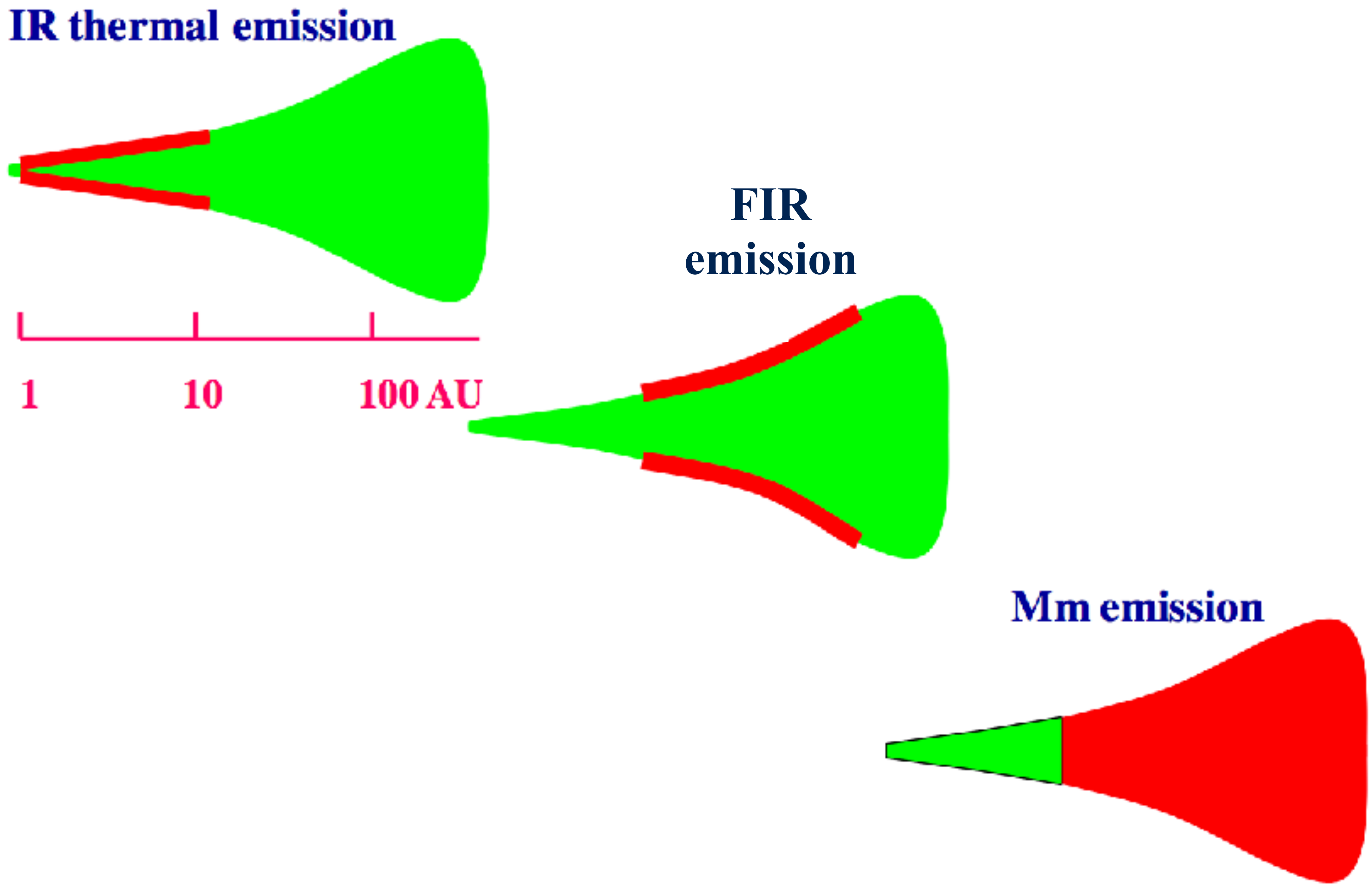
Not necessarily an evolutionary term!

First discovery:
Strom et al. 1989

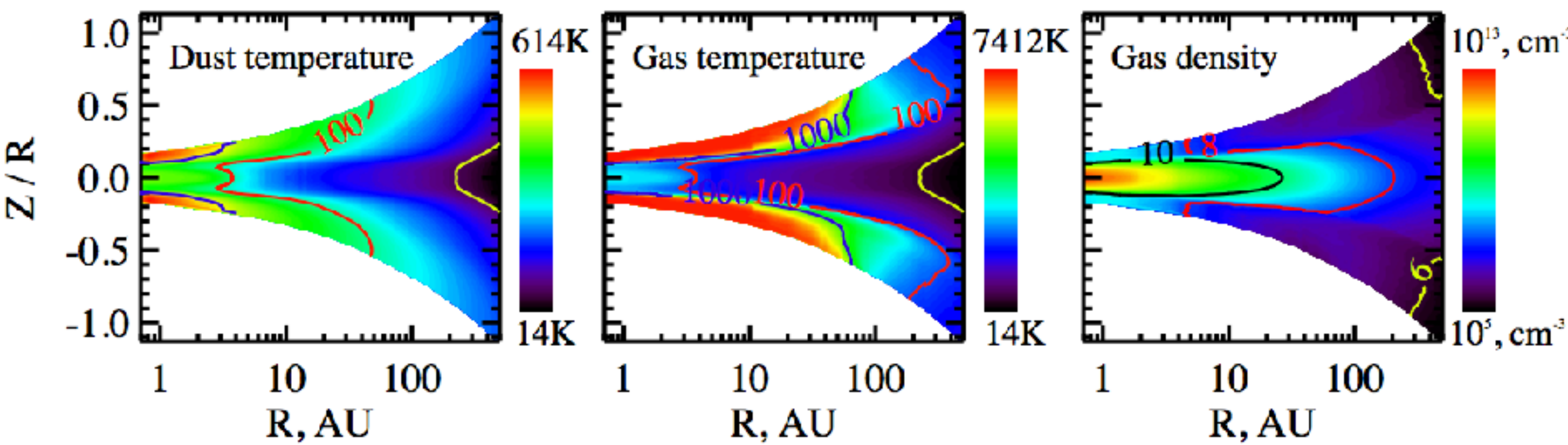




Outer disk vs inner disk



Outer disk vs inner disk

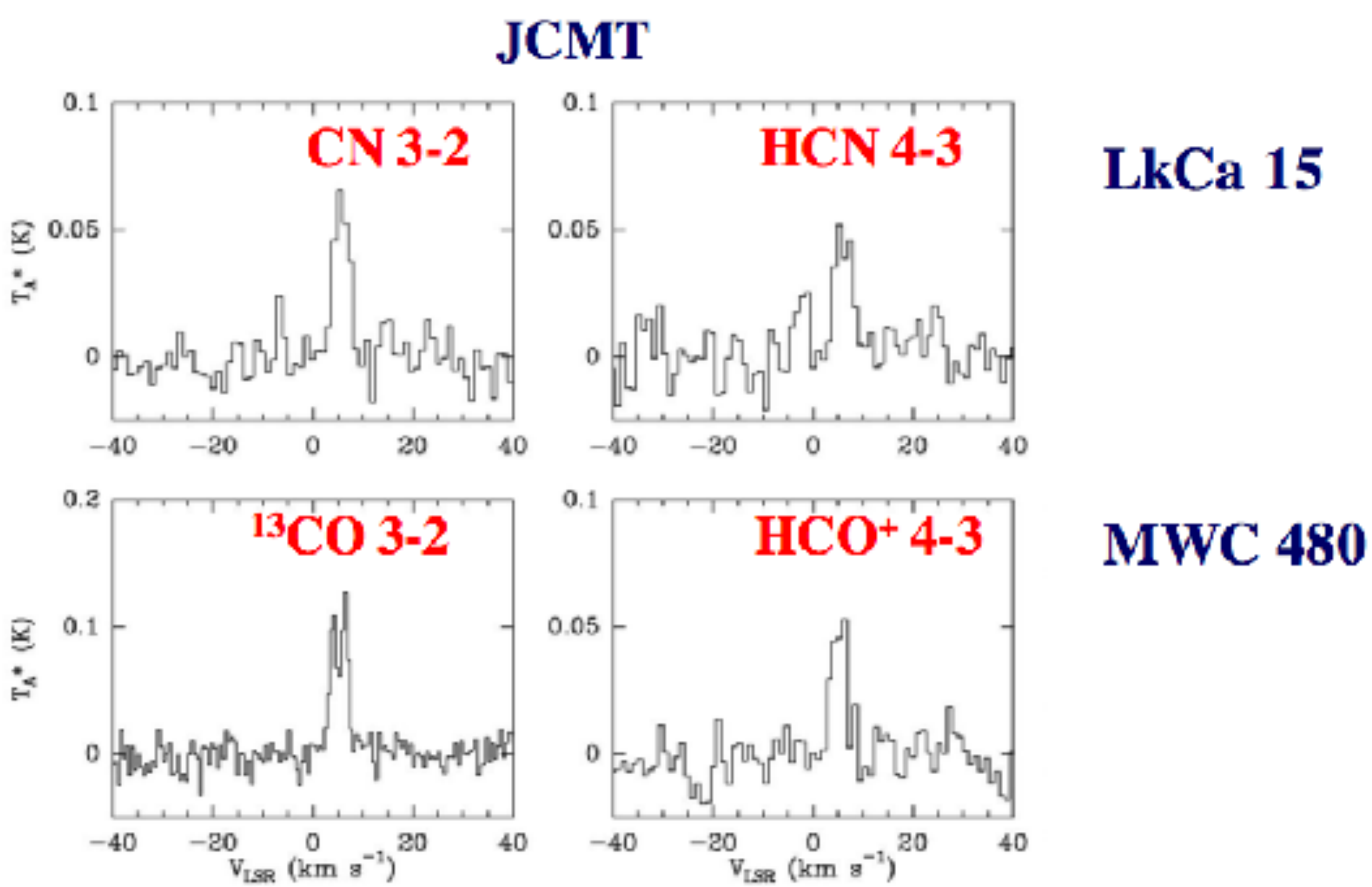


Henning & Semenov 2013

Outer disk (>20 AU)

- submm and mm emission: rotational lines of the cold gas in the bulk of the outer disk

- Examples:
  - CO
  - HCO^+
  - CN
  - HCN,HNC
  - $H^{13}CO^+$
  - DCO^+
  - H_2CO
  - CS
  - N_2H^+
  - C_3H_2

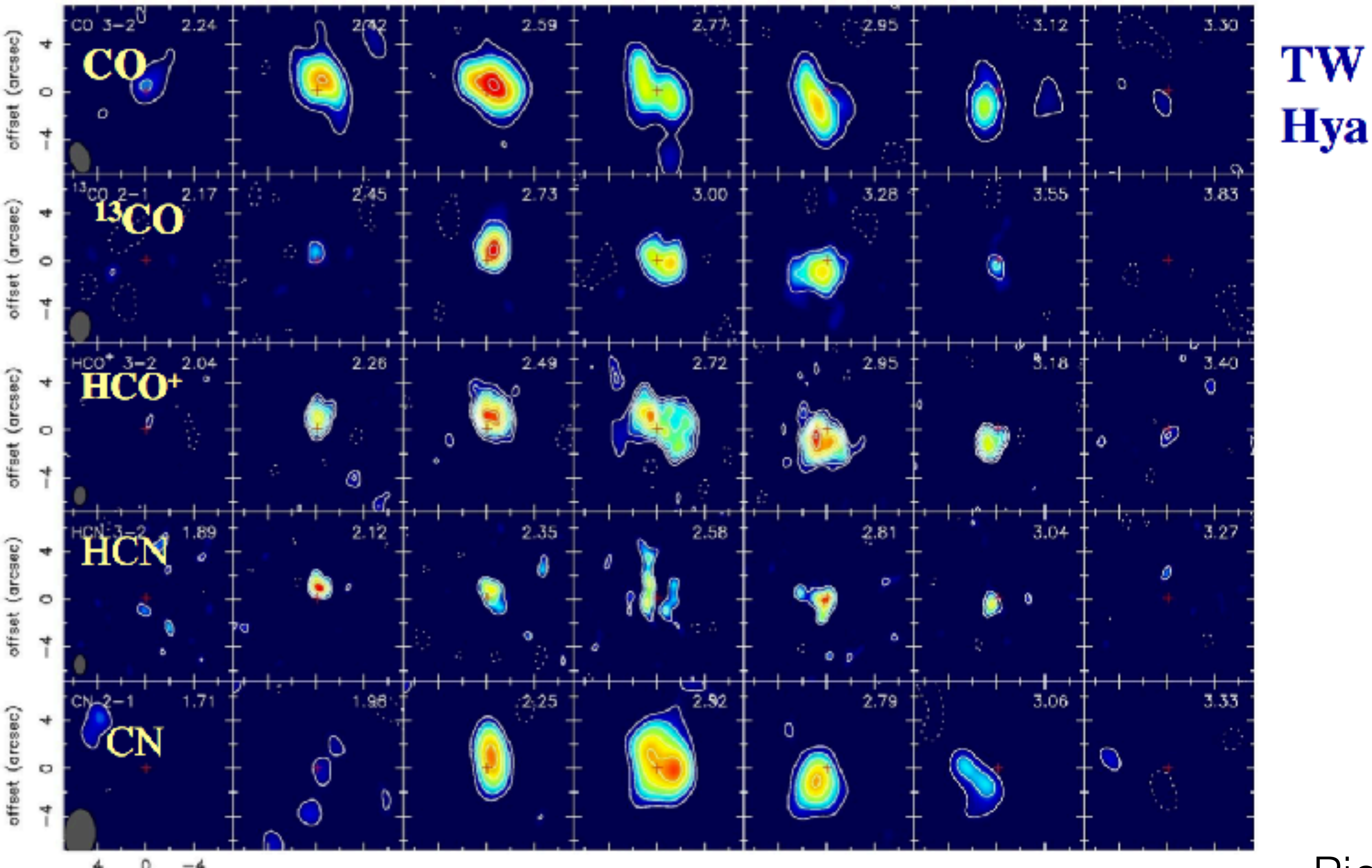


spatially unresolved: 15” beam!

Dutrey et al. 1997
Kastner et al. 1997

Outer disk

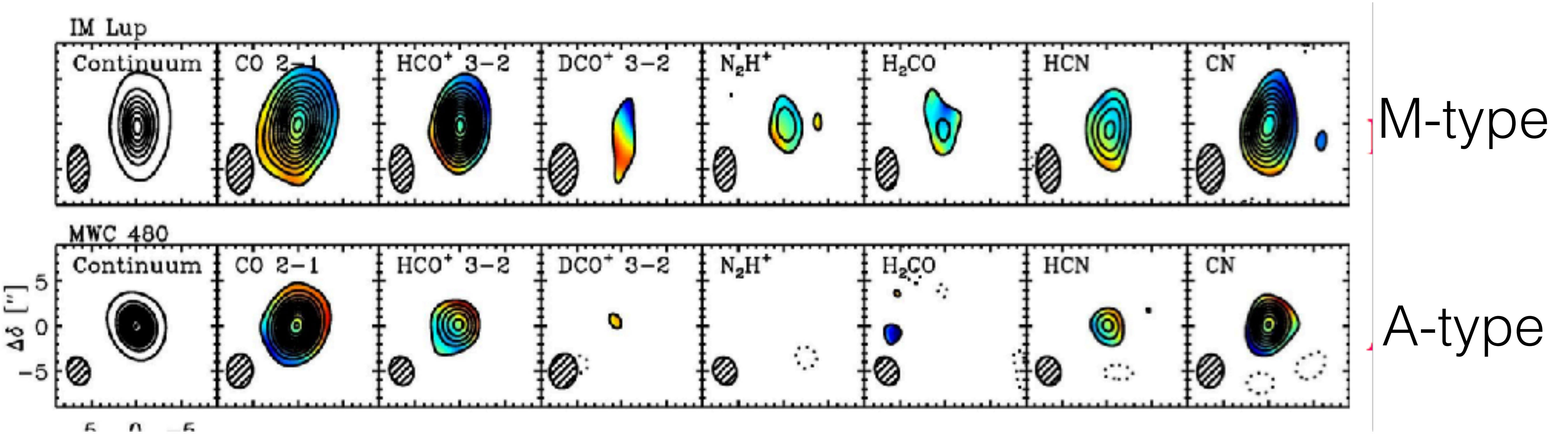
- First channel maps (PdBI)



Pietu et al. 2007

Outer disk

- SMA spatially resolved: DISCS survey (deep line integrations on the brightest disks)

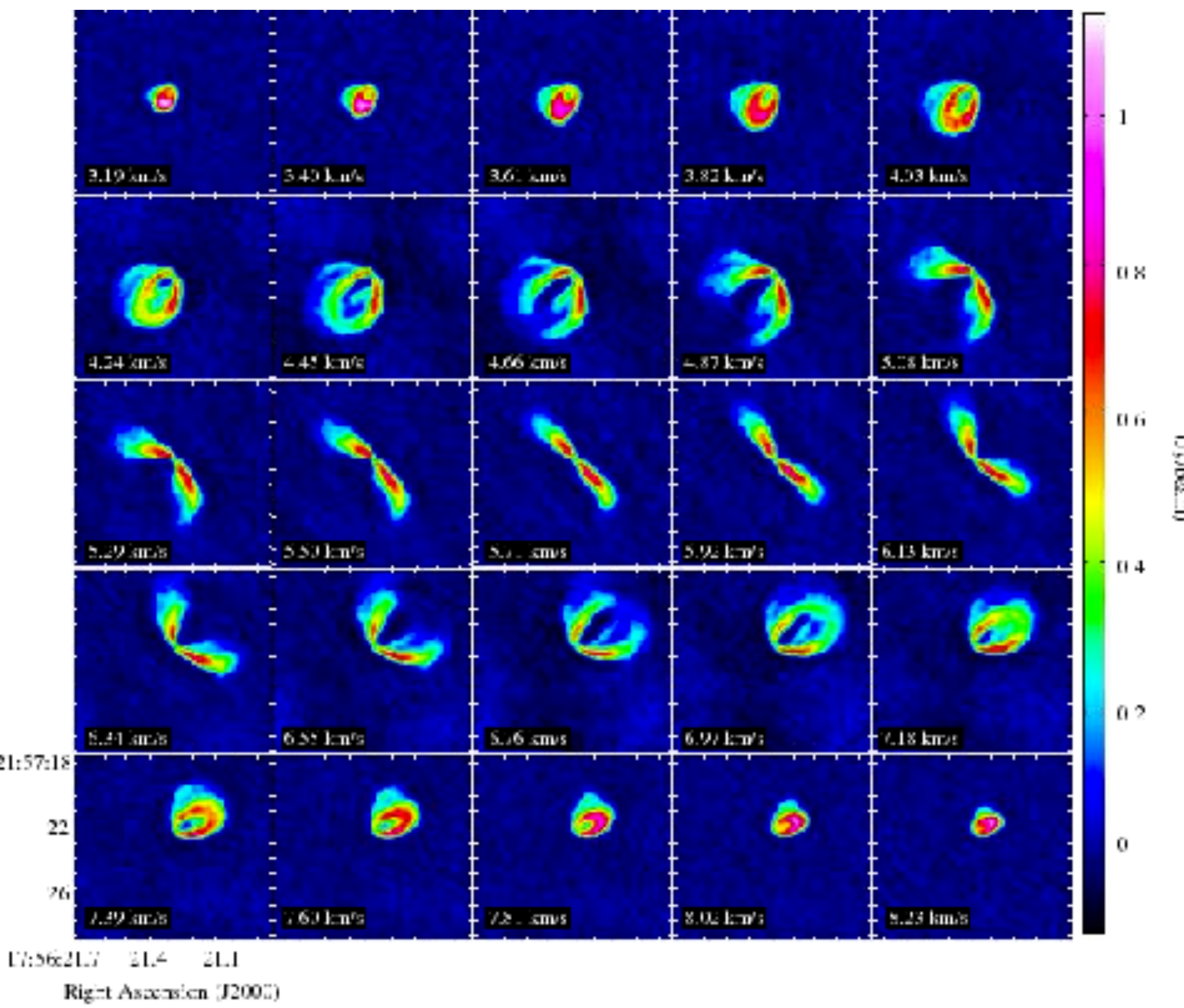


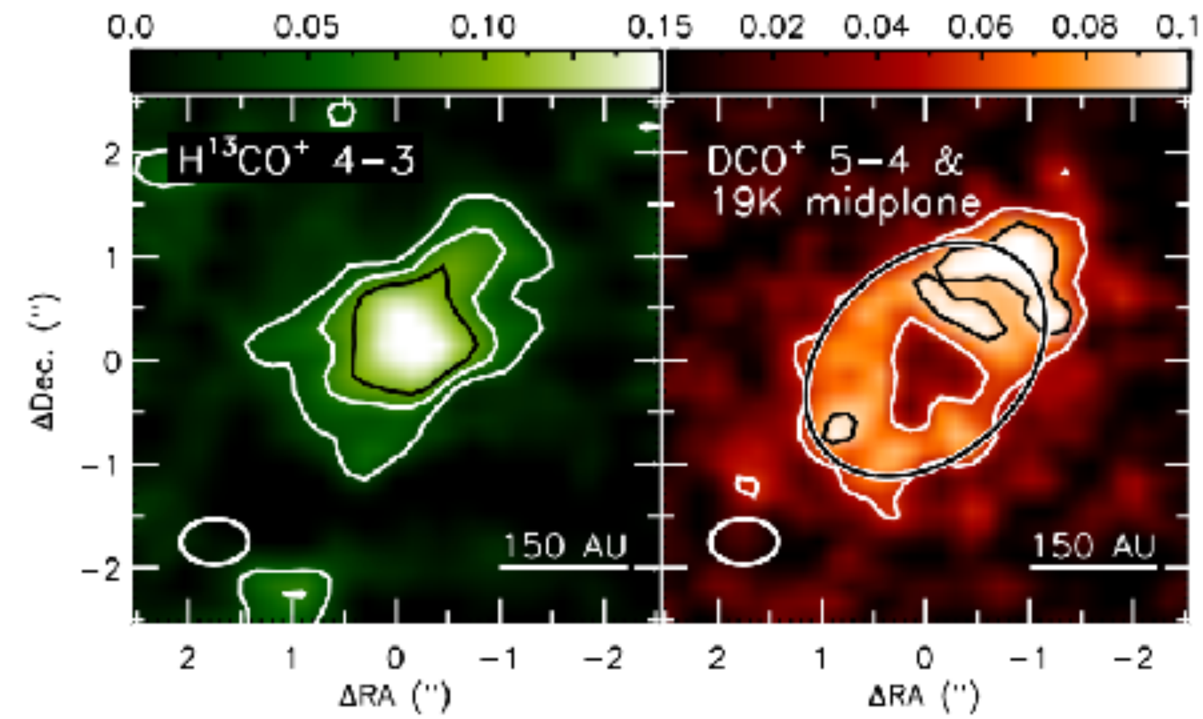
=> Complex molecules almost absent around Herbig stars!

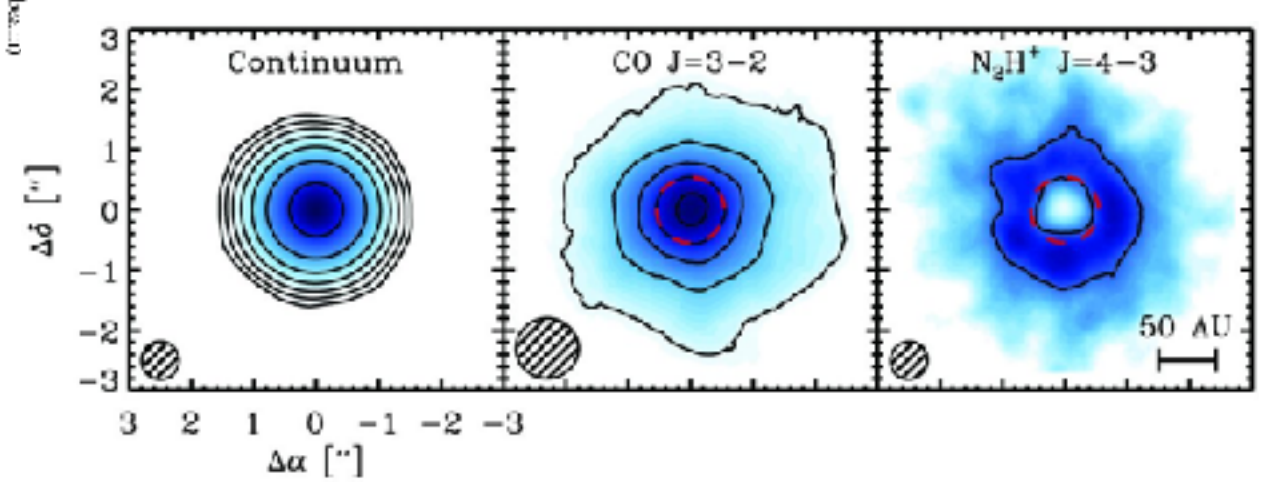
Oberg et al. 2010, 2011

Outer disk

- ALMA images (since 2013)



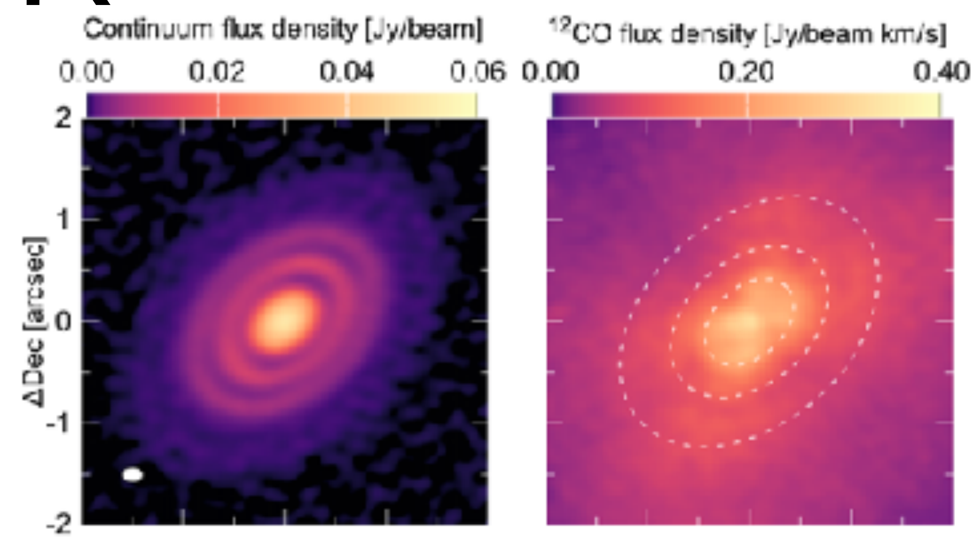


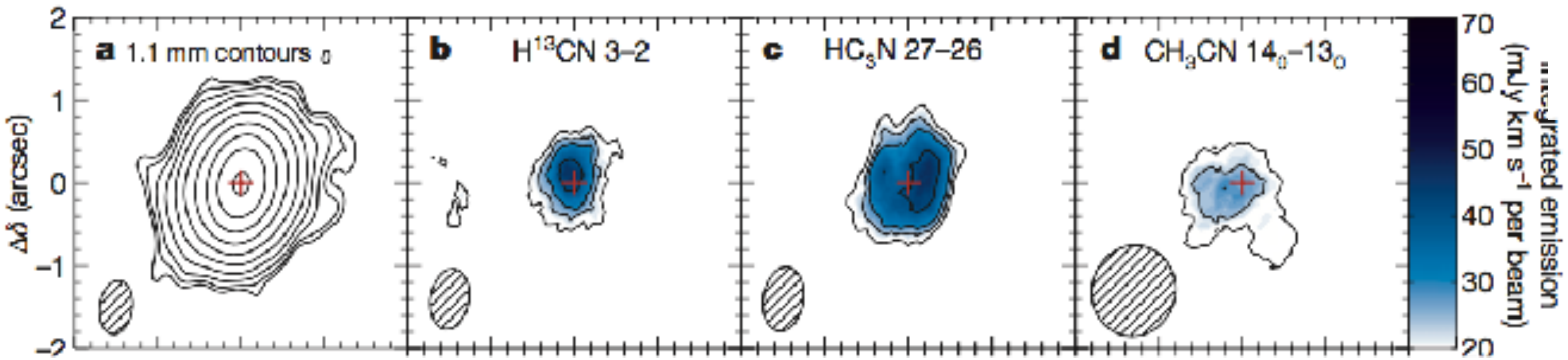


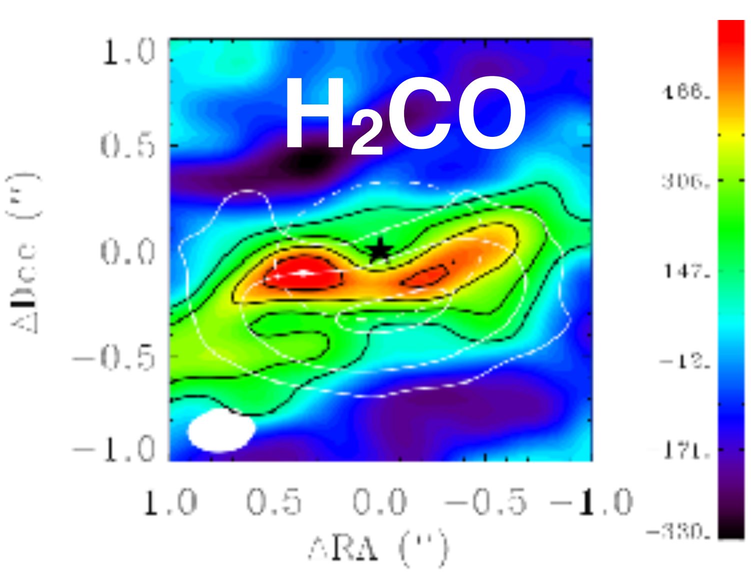
de Gregorio-Montsalvo et al. 2013
Mathews et al. 2013
Qi et al. 2013

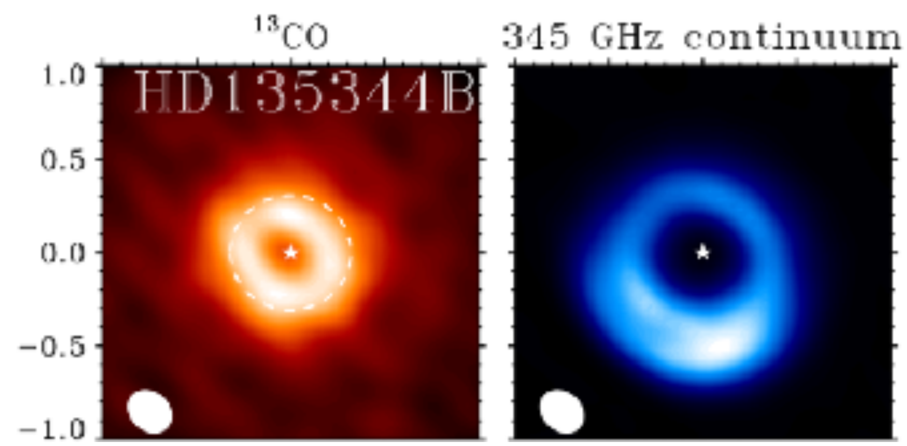
Outer disk

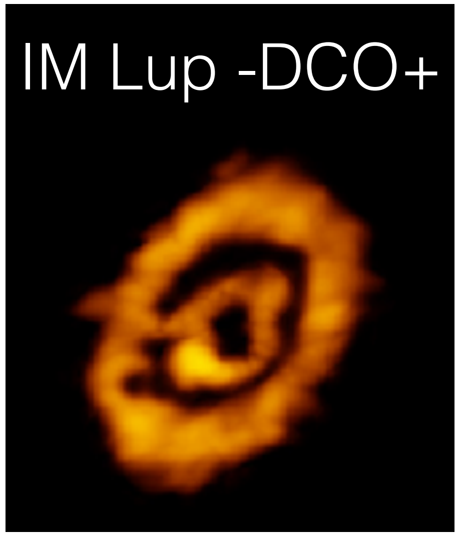
- ALMA images











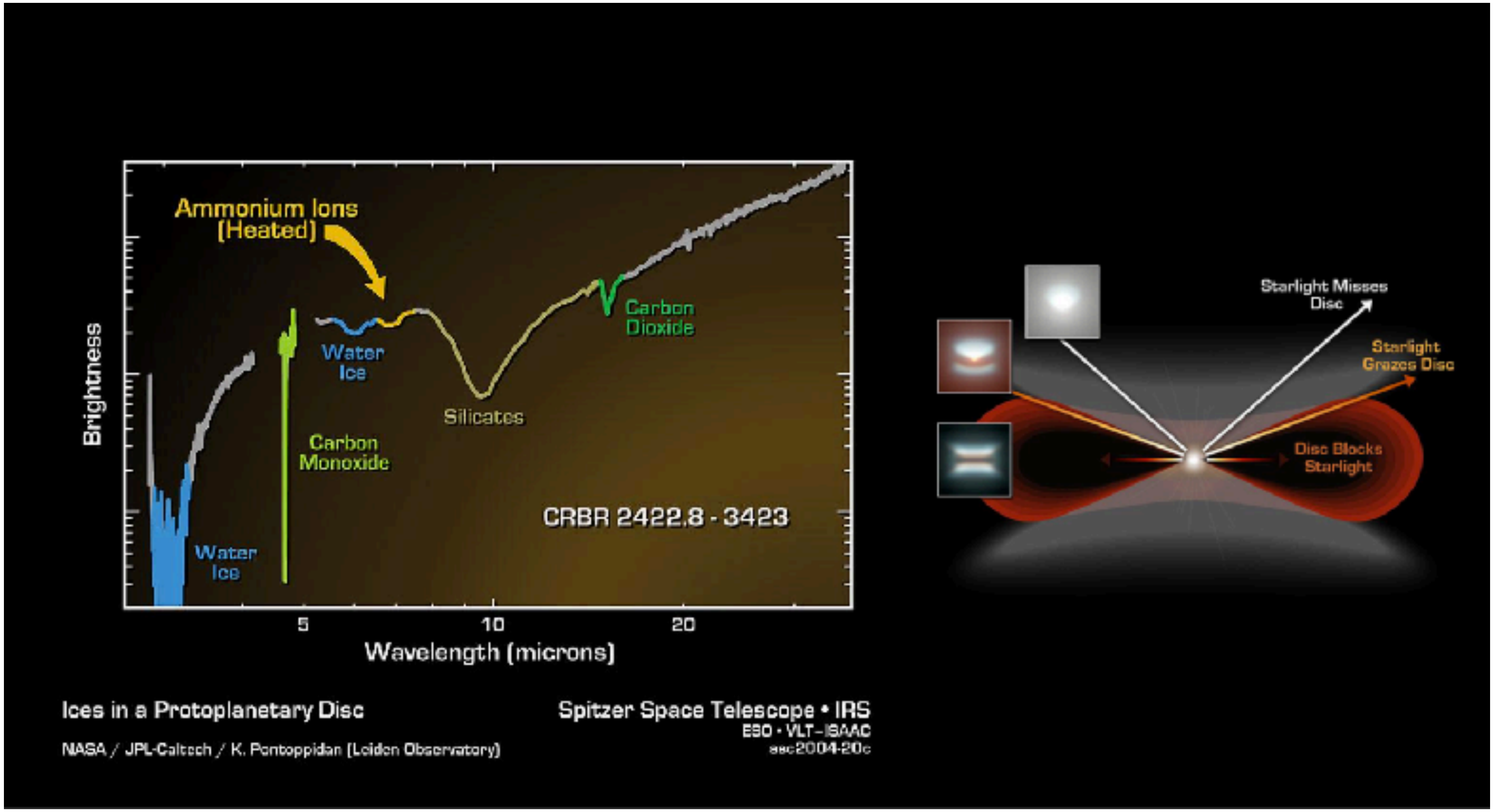
van der Marel et al. 2014,2016
Oberg et al. 2015a,b
Isella et al. 2016

Outer disk

- Chemistry in outer disk
  - heavy freeze-out especially at large radii: gas-grain chemistry
  - snow-lines
  - photodissociation in disk atmospheres (PDRs) by stellar UV and interstellar radiation field
    - stellar UV field ~ 10^5 x ISRF (Herbigs) and ~10^3-10^4 x ISRF (TTS) (origin UV?)
      => reason for difference chemical complexity
  - cosmic ray ionization: production ions => increase chemistry (why?)
  - X-ray radiation
    - generated by coronal activity by magnetic fields generated by a dynamo mechanism in convective stellar interiors: 1000x stronger than our Sun!
    - X-ray flux declines from T Tauri to Herbig (non-convective interior)
    - ionise He => He^+ destroys CO => rich hydrocarbon chemistry

Outer disk

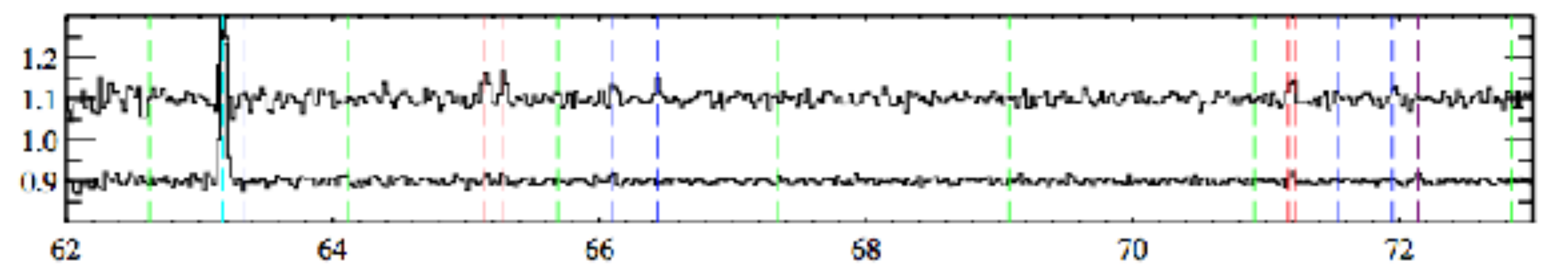
- Edge-on disks: ices => IR absorption

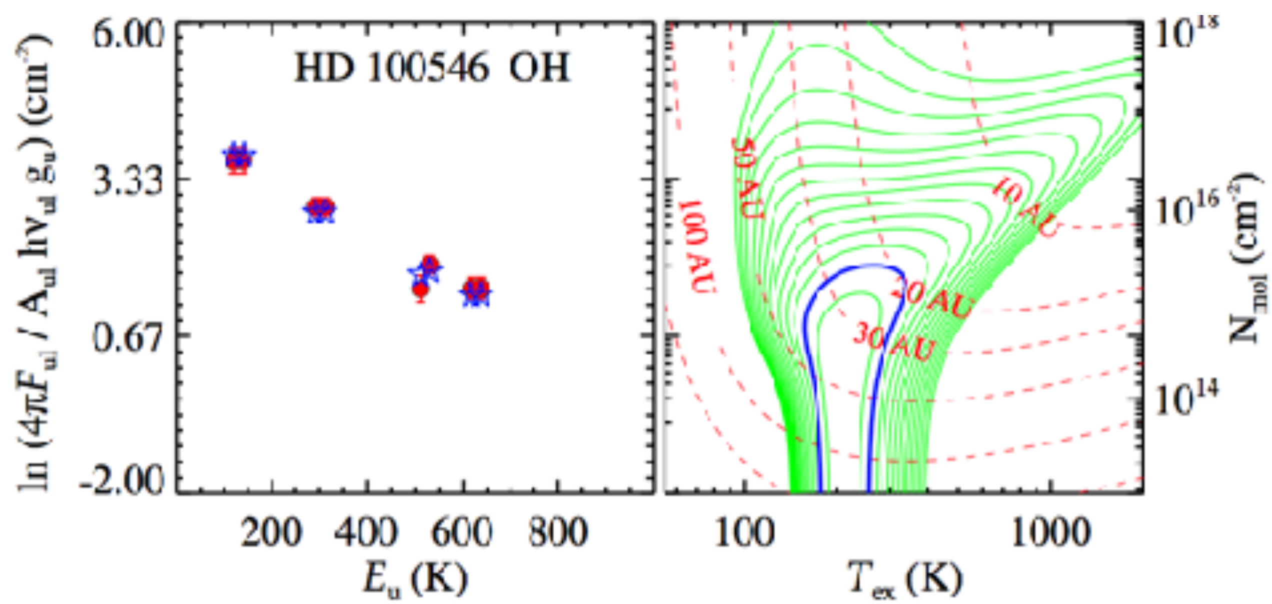


Pontoppidan, Dullemond et al. 2005

Outer disk

- Far infrared lines (Herschel!): disk atmosphere
    - CO ladder (J transitions >15)
    - [OI]: 63, 145 μm
    - [CI]: 370, 810 μm
    - [CII]: 158 μm
    - H_2O: e.g. 179, 78 μm
    - OH
    - CH+
- Approach: estimating excitation temperature (few 100 K), number of molecules using simple models => origin of the lines
- Disk Herschel surveys: GASPS (GAS in Protoplanetary Systems), DIGIT (Dust, Ice Gas In Time)

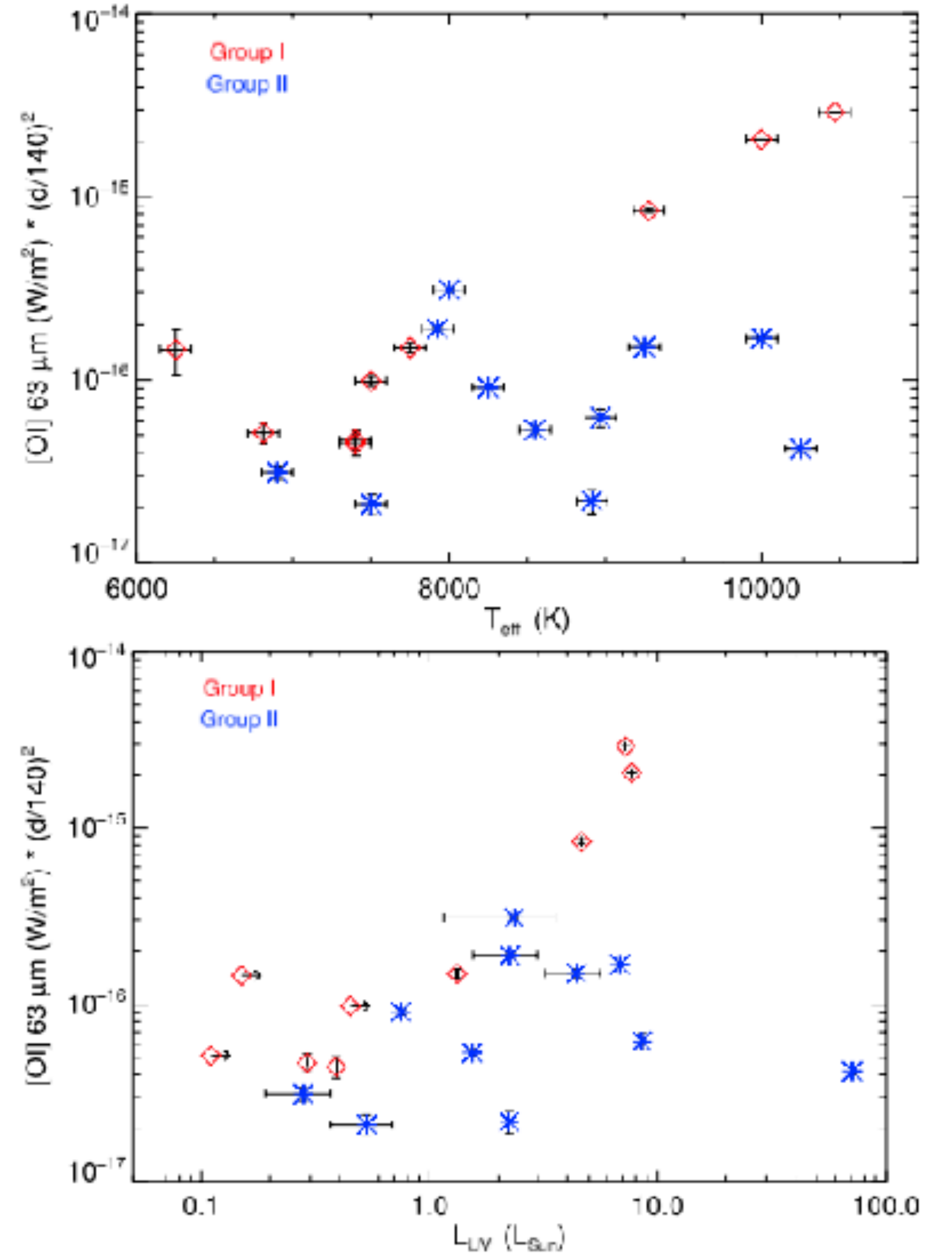




Meeus et al. 2010,2012
Fedele et al. 2013

Outer disk

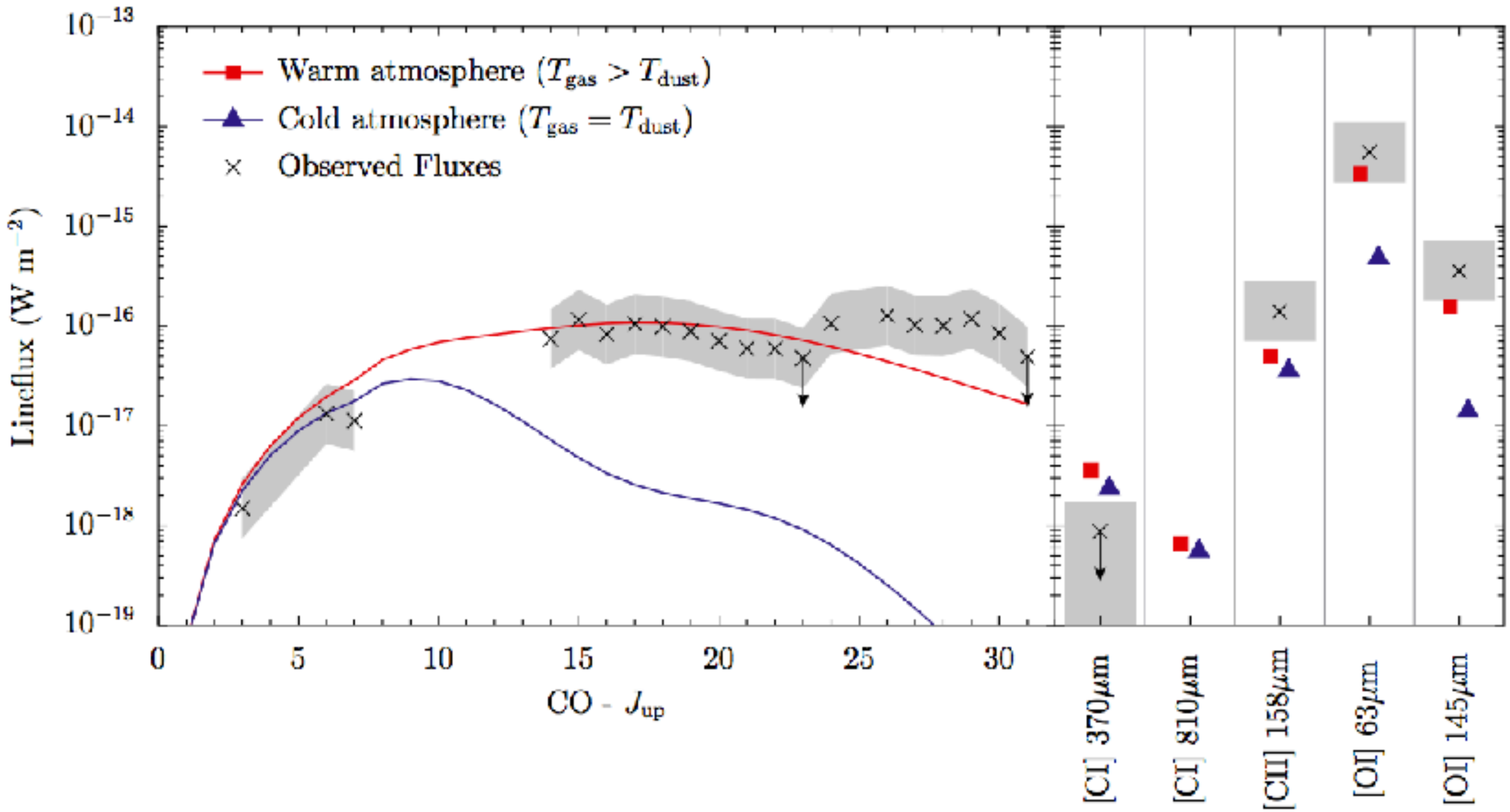
- Search for correlations between different lines and disk properties
- General conclusion: large variety of line strengths throughout sources, unclear origin



Carr & Najita 2011
Salyk et al. 2011
Meeus et al. 2012

Outer disk

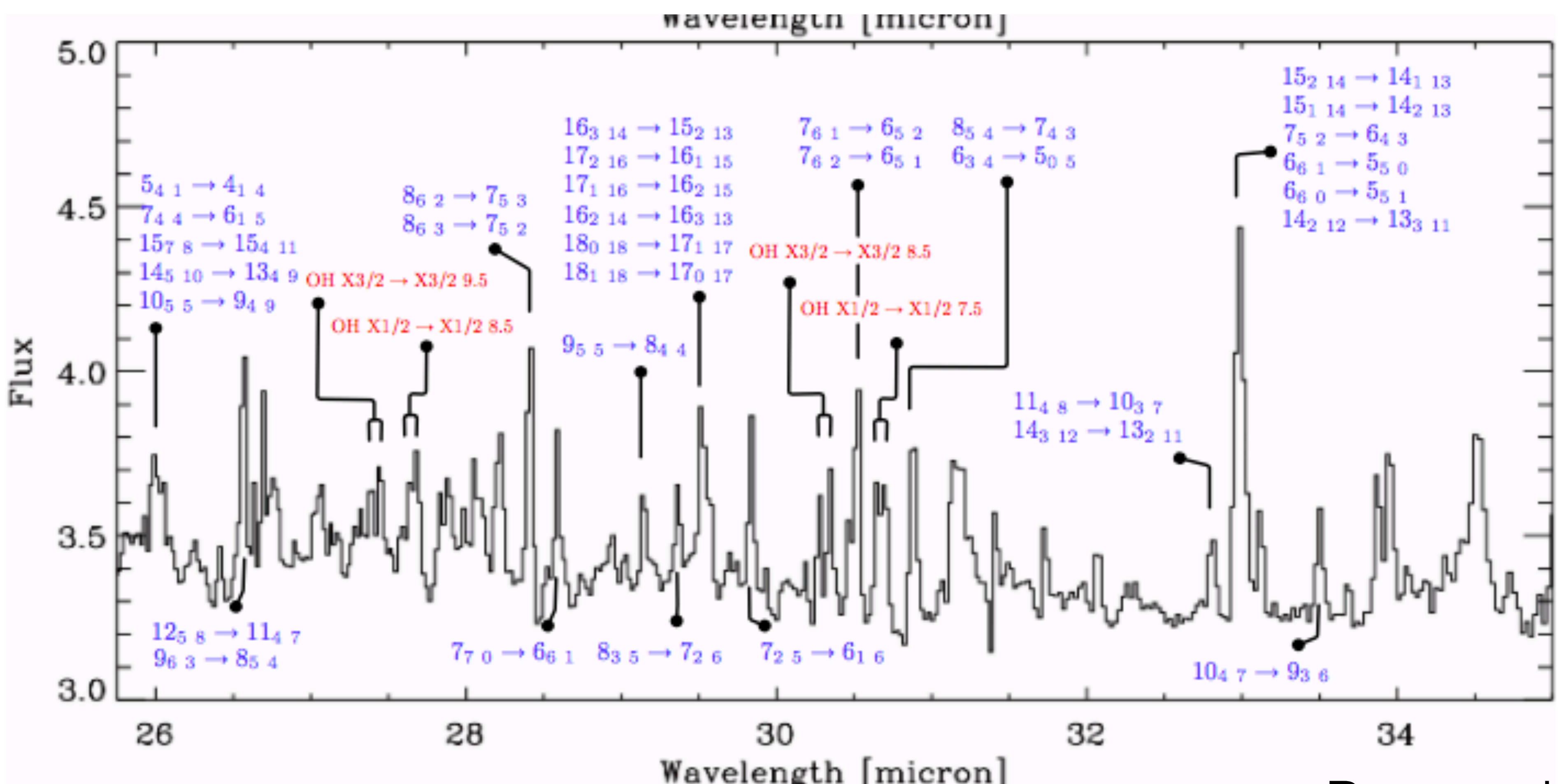
- Full disk model of HD100546



Bruderer et al. 2012

Inner disk

- Mid infrared (Spitzer) and near infrared (Keck-NIRSPEC, VLT-CRIRES) lines: rovibrational
- CO, H2O, OH, HCN, C_2H_2, …



Pontoppidan et al. 2010

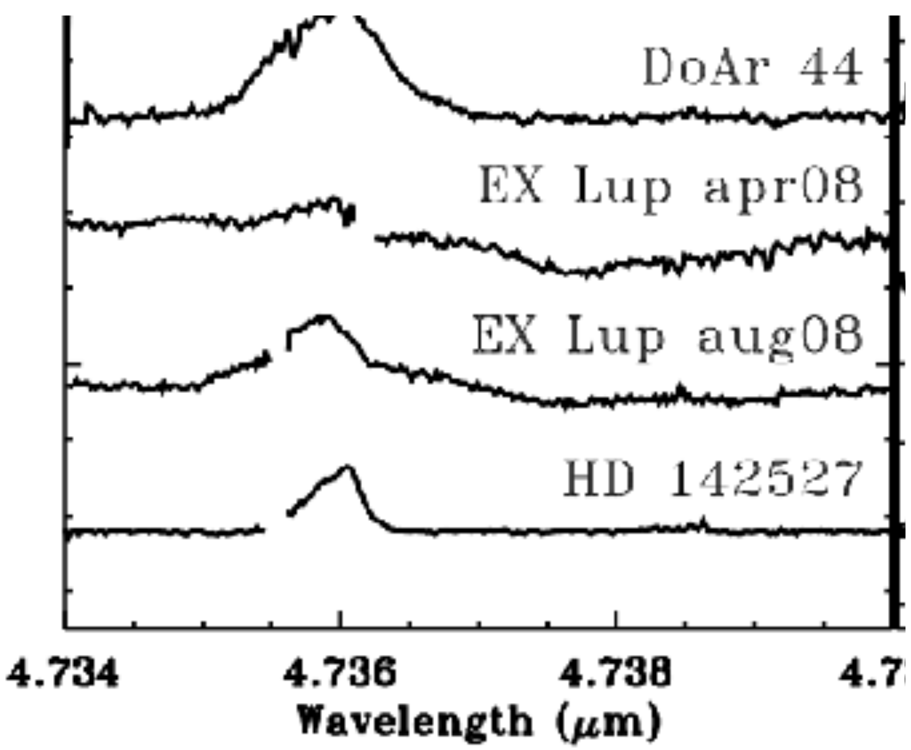
Inner disk

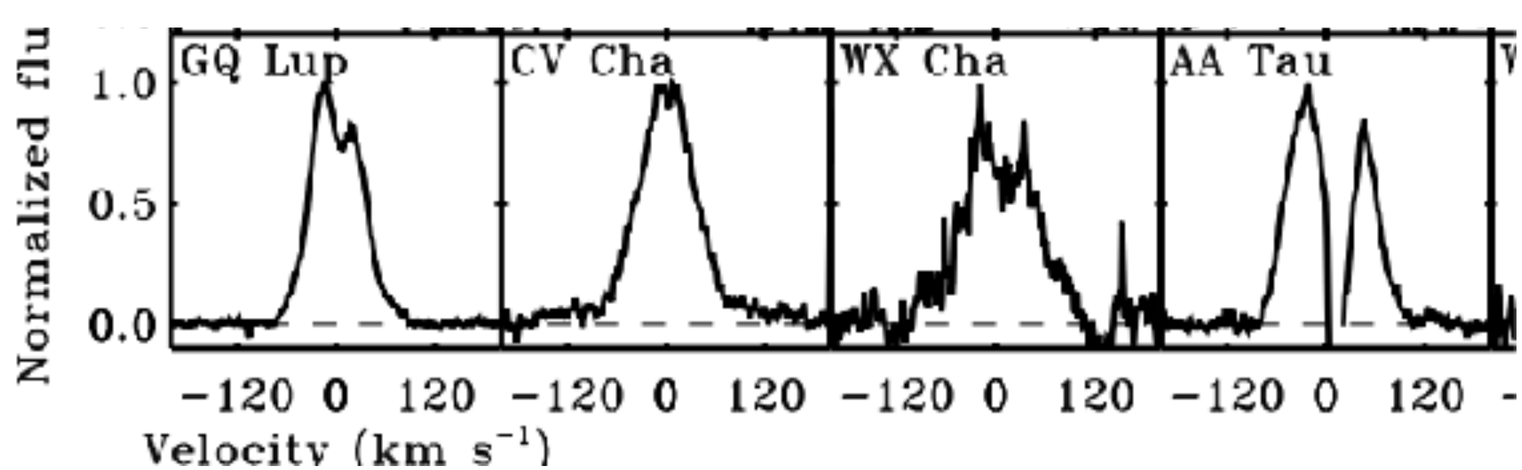
- Rovibrational CO lines: excitation temperatures >1000 K
  - originating from inner few AU
  - excitation through a combination of collisional excitation, infrared pumping and UV fluorescence
  - for high spectral resolution (e.g. NIRSPEC: R~25 000 or 12.5 km/s, or CRIRES: R~95 000 or 3.2 km/s) lines are spectrally resolved => proxy for spatial location

Salyk et al. 2009, 2011
Brown et al. 2012, 2013
Pontoppidan et al. 2008, 2011

Inner disk

- CO lines used to estimate inner radius gas (line wings!)
  - full disks: ~ dust sublimation radius
  - transitional disks: ~ several AU, but within dust cavity radius
  - spectroastrometry: flux-weighting technique, using spatial information along slit

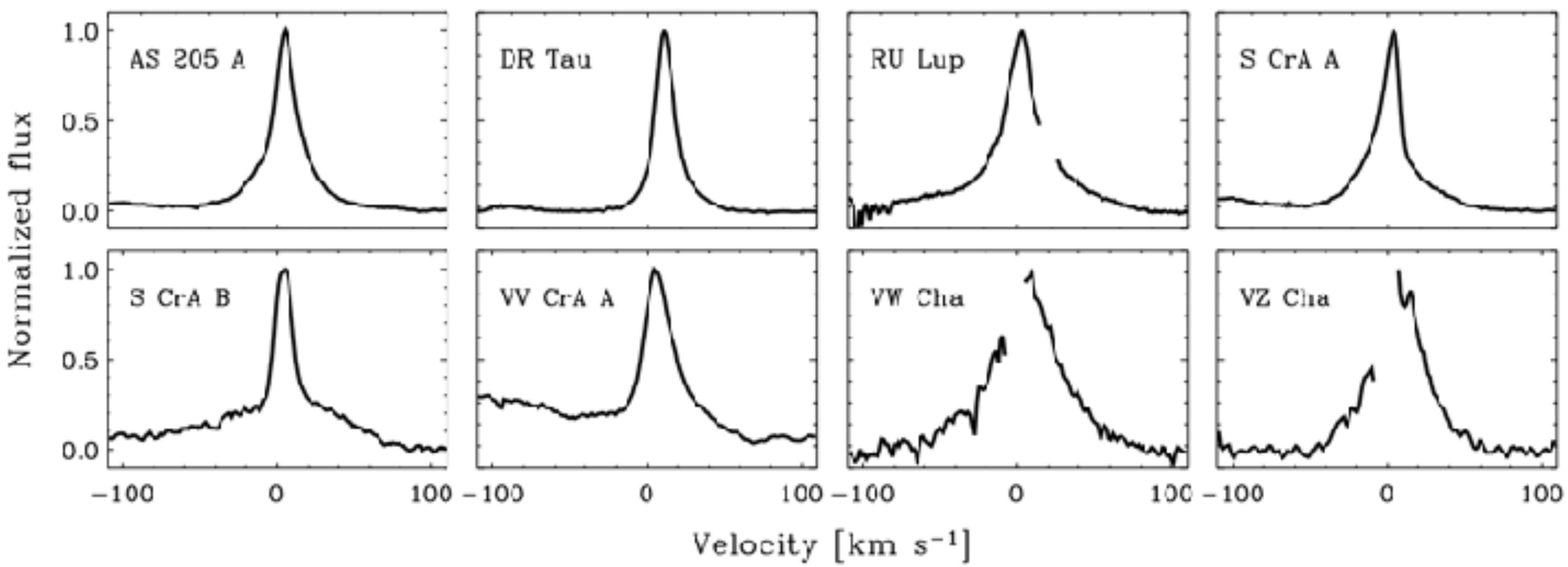




Brown et al. 2013

Inner disk

- CO line profiles: many disks with broad-base single peaks => does not look like Keplerian profile!



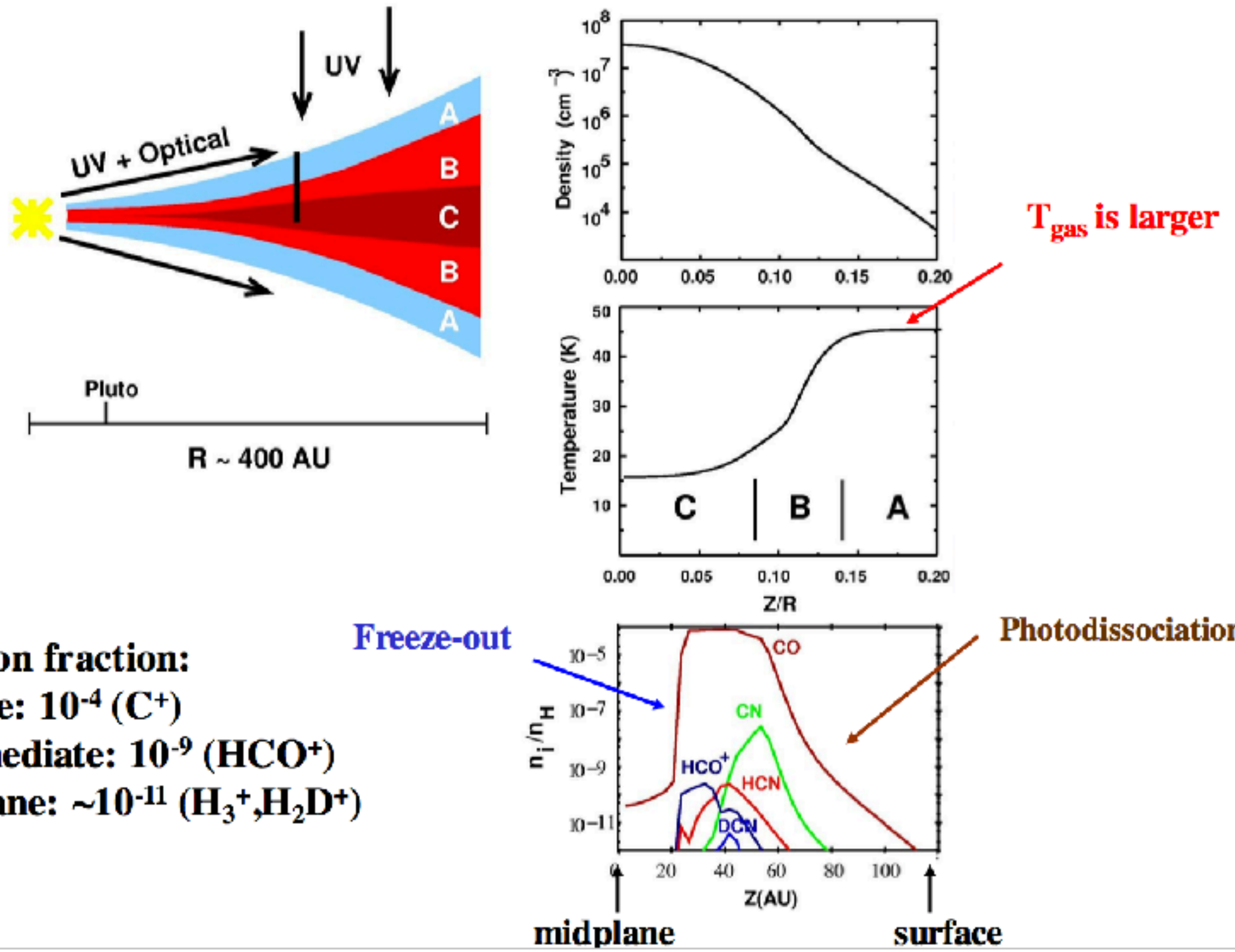
- Combination of disk emission and strong evaporative wind, but largely unknown

Bast et al. 2011

Modeling

- Line analysis:
  - inversion methods: retrieve e.g. T_{ex} and N_{mol} (cm^{-2}) directly from observations without the need of a full model
  - forward modeling: full disk model trying to reproduce observations
- Chemistry modelling:
  - fundamental approach, not to reproduce observations but to check the effects/significance/trends when including different chemistry/physics
    => usually single point calculations as the chemical network contains 1000s of reactions => slow in a full disk model

Modeling



Ionization fraction:
- Surface: 10^{-4} (C^+)
- Intermediate: 10^{-9} (HCO^+)
- Midplane: ~10^{-11} (H_3^+,H_2D^+)

Modeling

- Typical disk model: 2D (radial r and vertical scale height h)
- Gas temperature:
  - decoupled from dust temperature: additional heating mechanisms (e.g. UV, photoelectric heating, etc.)
  - $T(r) \sim r^{-q}$ and isothermal (no vertical gradient) e.g. Dutrey et al. 1994
  - $T(r,z) \sim r^{-q} * f(z)$ (vertical gradient), e.g. Qi et al. 2011, Rosenfeld et al. 2012, Williams & Best 2014
  - T(r,z) from dust radiative transfer using a radiation field from a star (e.g. RADMC, MCFOST), e.g. Dullemond 2012, Pinte et al. 2009
  - T(r,z) from combination chemistry, heating/cooling and radiative transfer (e.g. DALI, Prodimo), e.g. Bruderer et al. 2013, Woitke et al. 2015

Modeling

- When based on a dust surface density model (and radiative transfer):
  - fitting to the SED (degenerate and largely optically thick)
  - settling: large grains sink towards the mid plane
  - dust opacity (size distribution, composition)
  - gas-grain chemistry (limited)
  - dust shielding

Modeling

- Density
  - Surface density power-law Σ(r) with potential radial variations (transition disk)

$$\Sigma_{\rm gas} = \Sigma_c \left(\frac{R}{R_c}\right)^{-\gamma} \exp\left[-\left(\frac{R}{R_c}\right)^{2-\gamma}\right]$$

  - Scale height:

$$h = h_c (R/R_c)^{\psi}$$

    - parametrized:
    - hydrostatic equilibrium => puffed up rim (dynamical?)

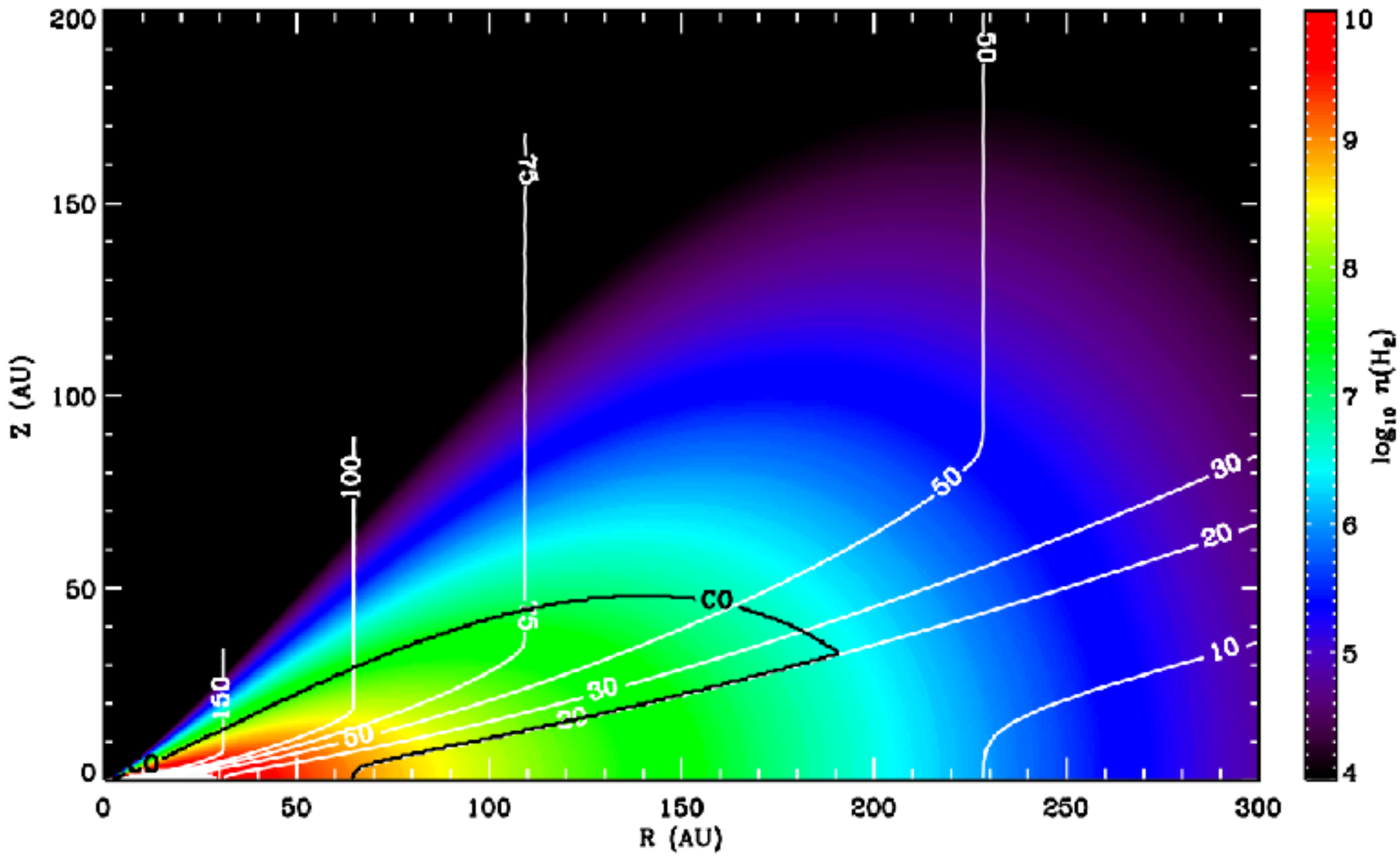
$$H(r) = \sqrt{\frac{2kr^3T(r)}{GM_* m_0}} = \sqrt{\frac{2k}{m_0}} \frac{r}{V_{\rm K}(r)} \sqrt{T(r)} = \sqrt{2} c_s/\Omega,$$

Modeling

- Molecular abundances:
  - parametrised
  - chemical network
  - physical-chemical network (e.g. freeze-out, photodissociation, radiation fields)
- Excitation:
  - LTE and non-LTE excitation, especially in inner disk

Modeling

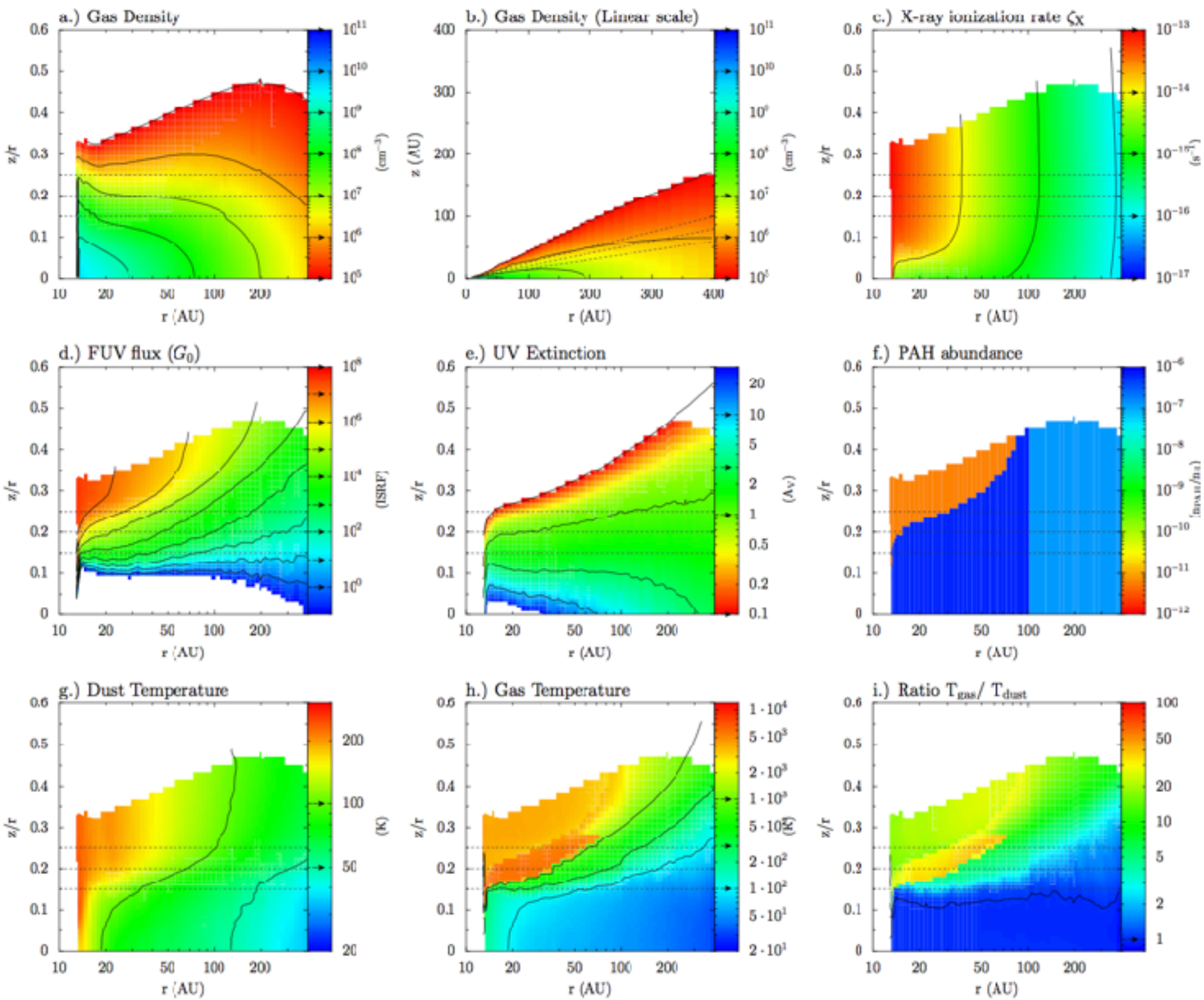
- Example (parametrized)



Williams & Best 2014

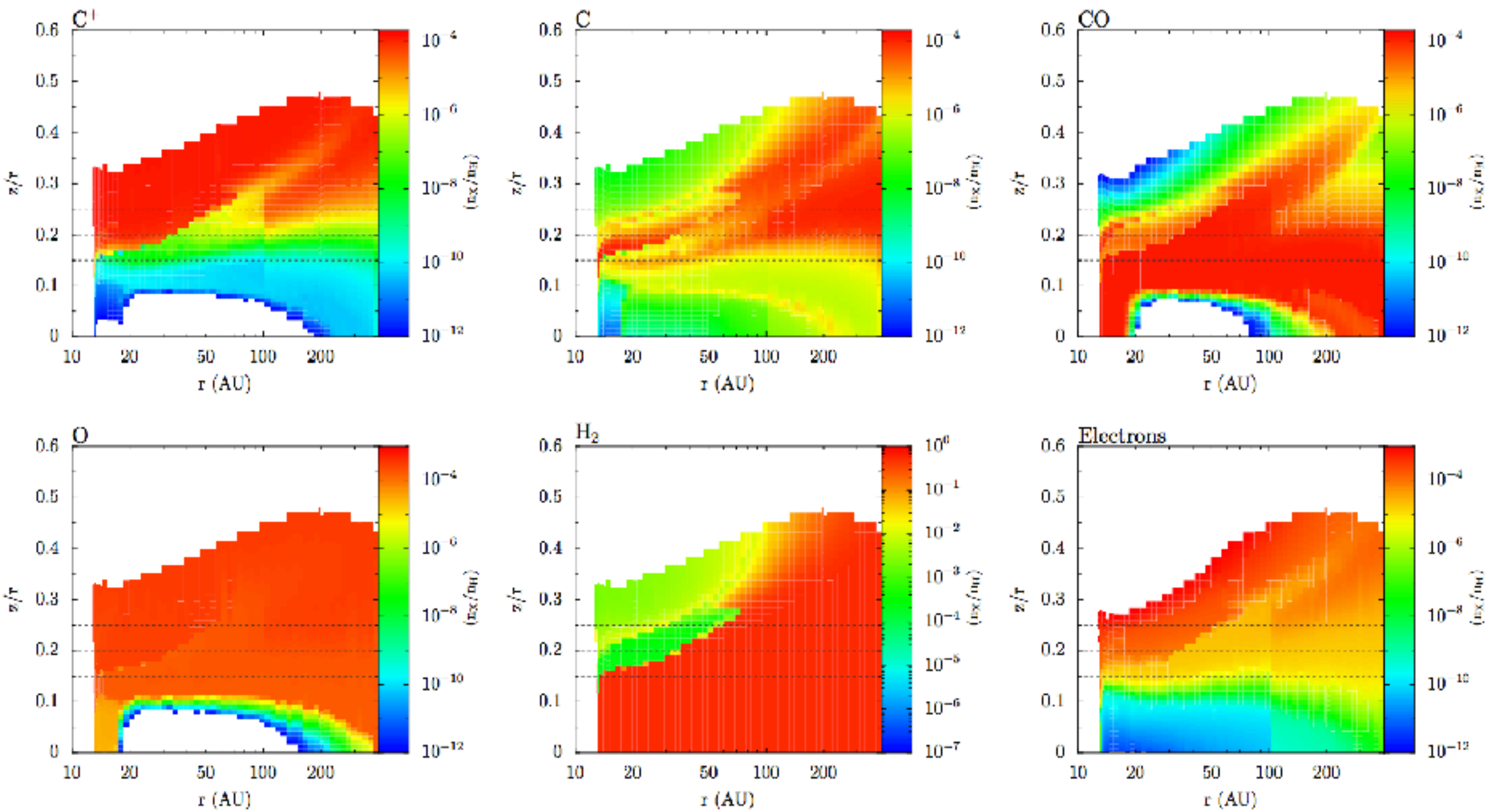
Modeling

- Example: physical-chemical model DALI



Bruderer et al. 2012

Modeling



Bruderer et al. 2012

Modeling

- Chemical modeling: checking the influence of a parameter on an abundance column
  - a_g = mean grain size
  - a_h = accretion heating

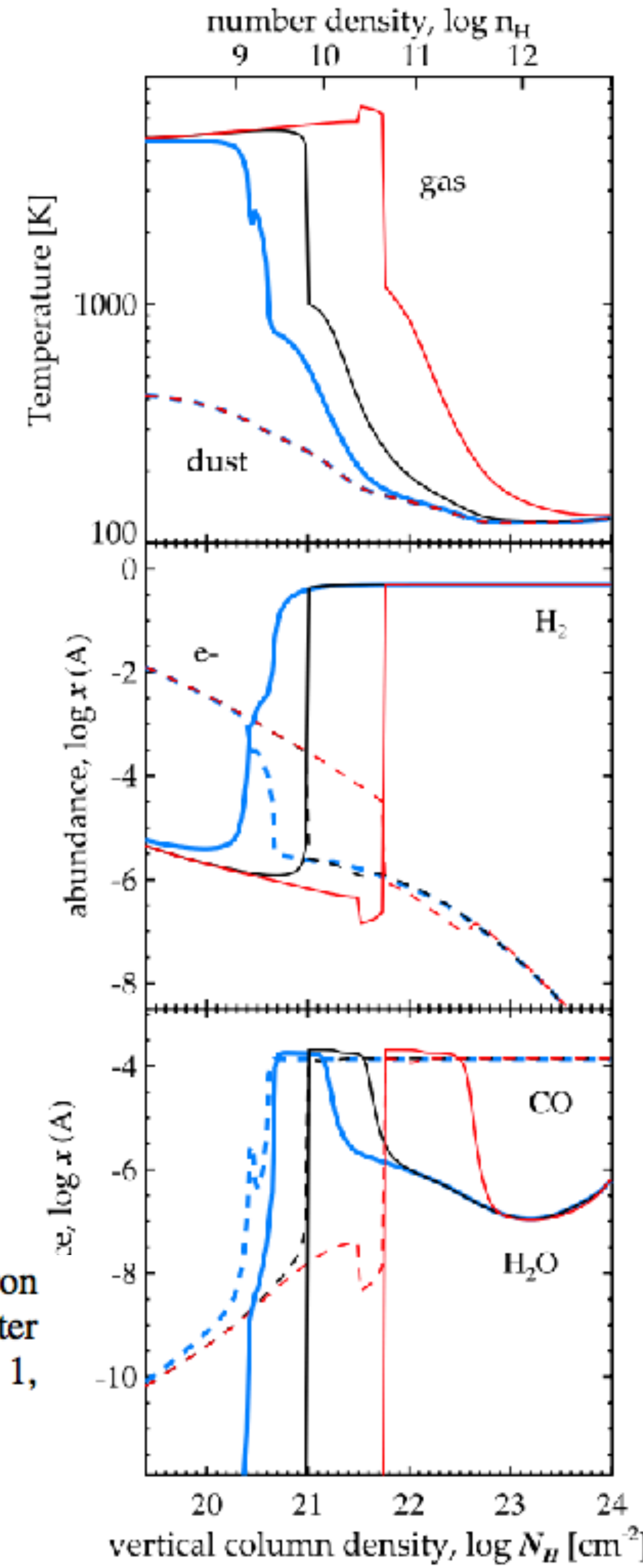
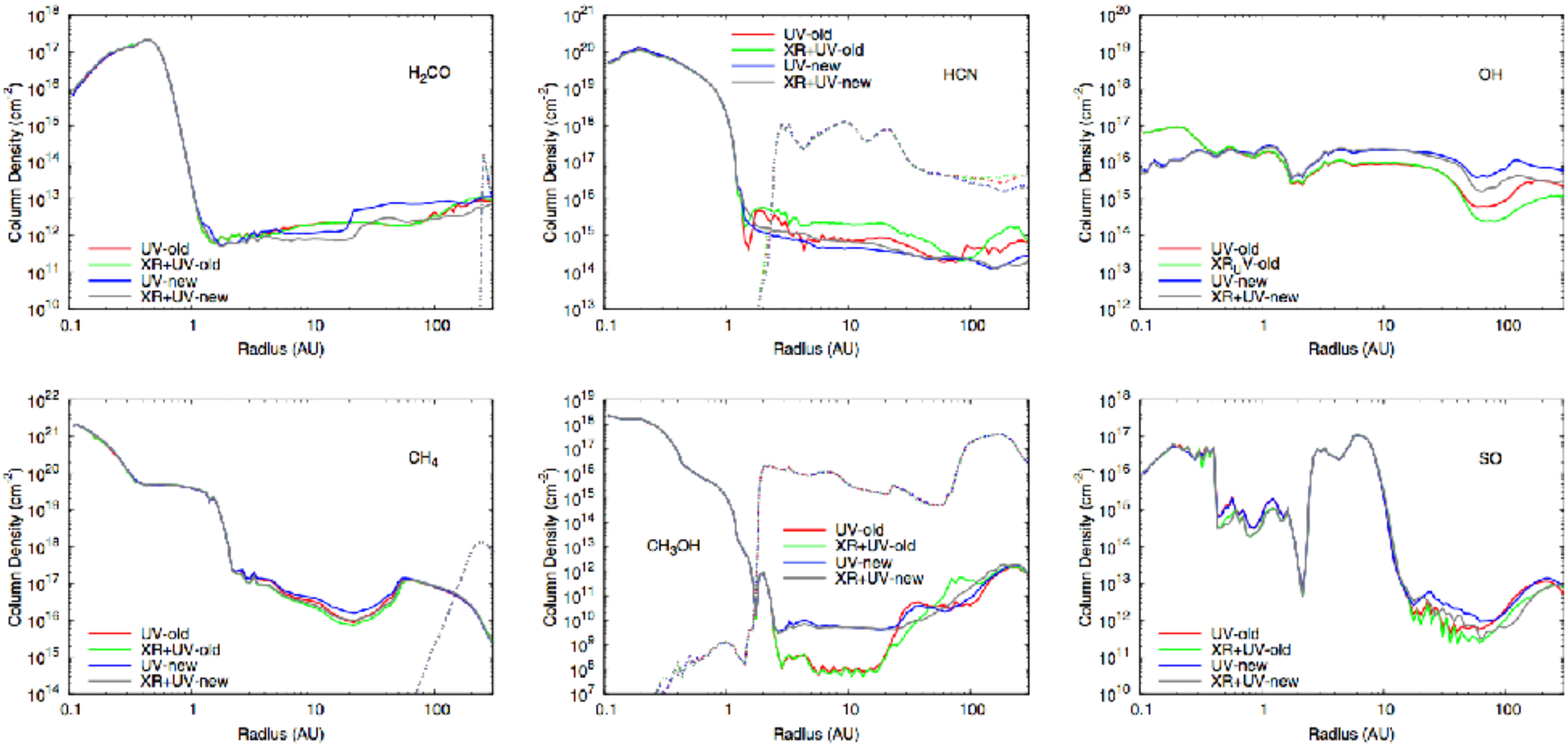


Figure 4. Gas (solid) and dust (dashed) temperatures (top panel), electron (dashed) and H_2 (solid) abundances (middle panel), and CO (dashed) and water (solid) abundances (bottom panel) in the reference case (black), and for $\alpha_h = 1$, $a_g = 7.07$ (red) and $\alpha_h = 0.01$, $a_g = 0.707$ (blue).

Najita et al. 2011

Modeling

- Influence of UV and X-ray ionisation



Walsh et al. 2012

Disk mass

- Traditional assumption:
  disk gas mass = GDR x dust mass
- GDR (gas-to-dust ratio) in ISM: 100
- dust mass for optically thin emission:
  $M_{dust} \sim F_{mm}$ (mJy), T_{dust}
- No consideration for disk structure (vertical/radial/size/radiation/settling/etc.)

Disk mass

- Why relevant?
  - Evolutionary parameter: disk dissipates with time
  - Capability to form (giant) planets
  - Planet-disk interaction (migration)
  - Gravitational stability/fragmentation
  - Input parameter for modeling of many disk processes
  - Densities determine chemistry: explanation of detection molecular lines

Disk mass

- H_2 emission not available in most of the disk (why?):
  => use CO emission instead

- Problems with CO?

Dutrey et al. 1997
Zadelhoff et al. 2001

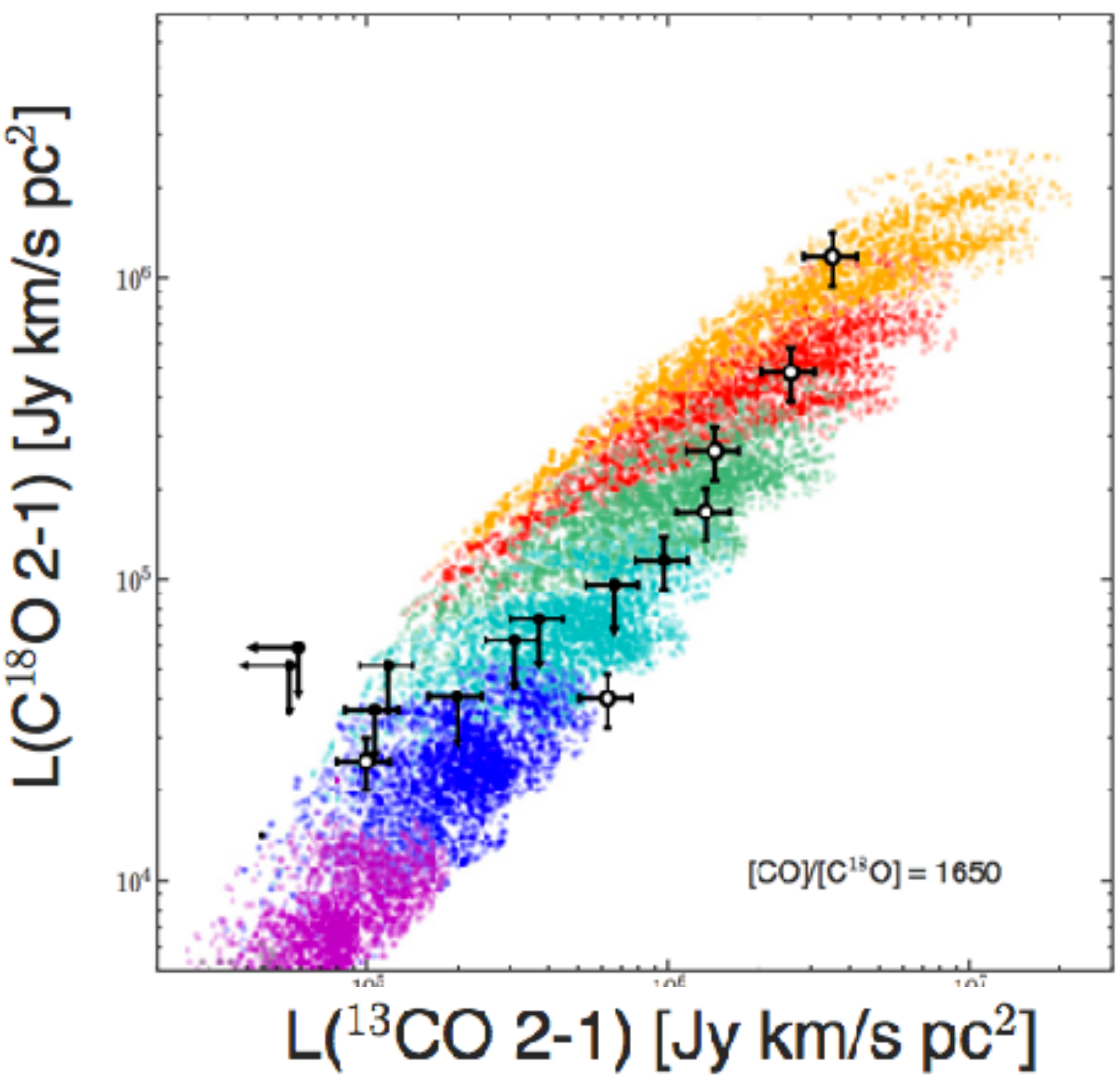
Disk mass

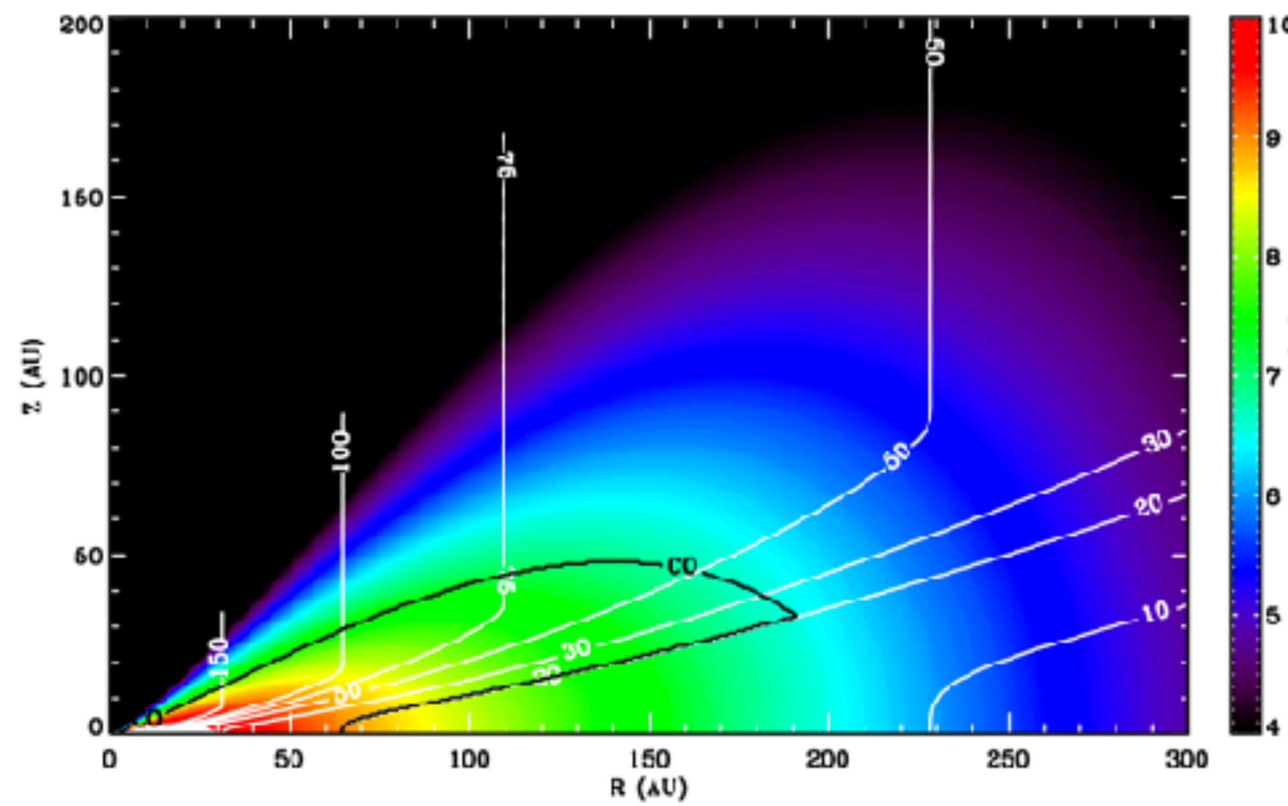
- H_2 emission not available in most of the disk (why?):
  => use CO emission instead
- Problems with CO?
  - optically thick => use CO isotopologues (^{13}CO, $C^{18}O$, $C^{17}O$)
  - photodissociation => model/parametrize
  - isotope-selective photodissociation => model/parametrize
  - freeze-out => model/parametrize
  - temperature
    => assume T_{gas}=T_{dust} (radiative transfer well understood)
    => decouple T_{gas} and T_{dust} (vertically: T_{gas}=T_{dust} in dense mid plane) with either modelling or parametrisation power-law (T(r,z))
    => use multiple CO transitions for proper constraints on temperature

=> In older studies (pre~2001) most of these effects not taken into account!

Disk mass

- Example: grid of models by Williams & Best 2014 based on a parametrised model of CO





Application:
Ansdell et al. 2016, 2017 modeling of Lupus and Sig Orionis disks

Disk mass

- Example: TW Hya (closest disk): disk mass ~ 0.0005 and 0.05 M_{Sun} depending on model/assumptions:

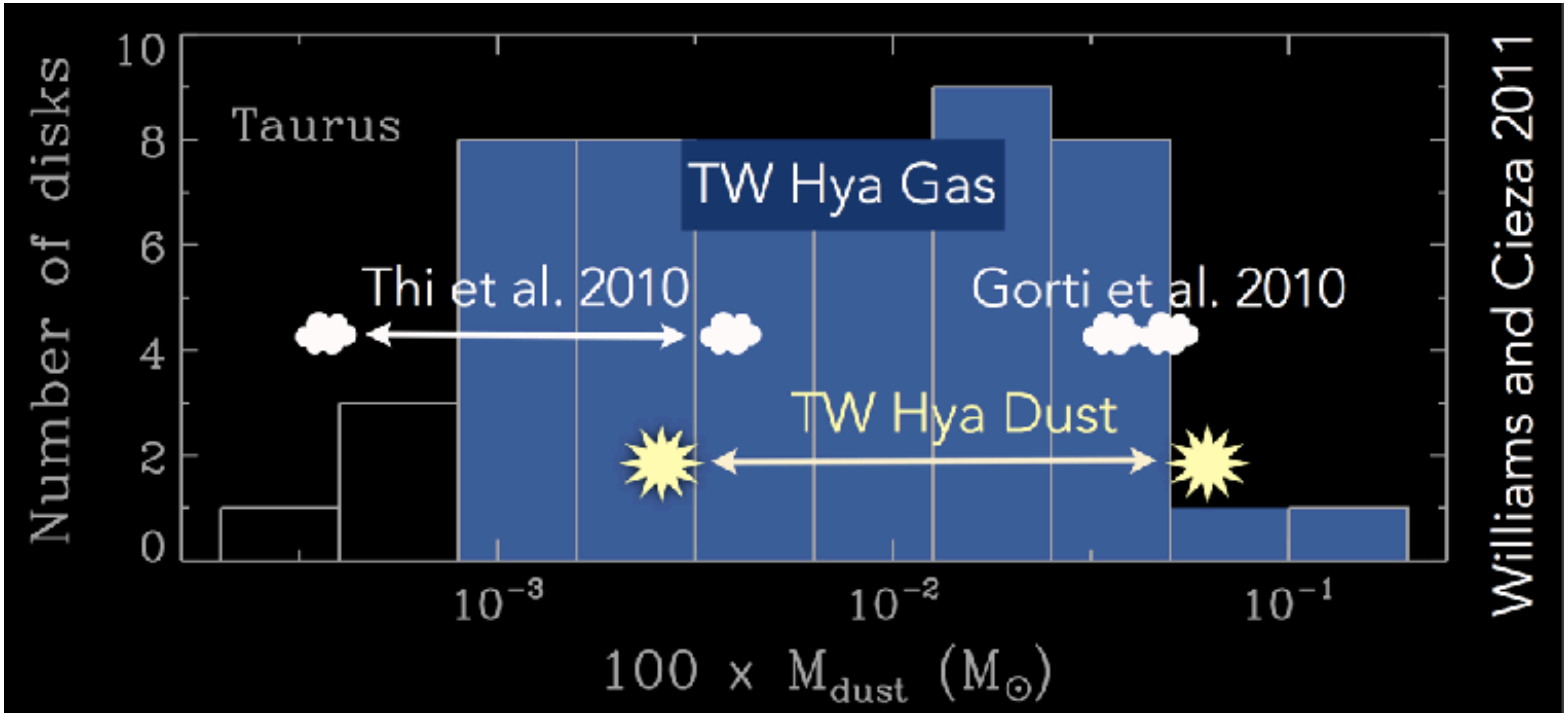


figure by Bergin

Disk mass

- Solution: use HD line (FIR: Herschel) for direct measurement disk mass:
  for TW Hya, Bergin derived 0.06 M_{Sun}

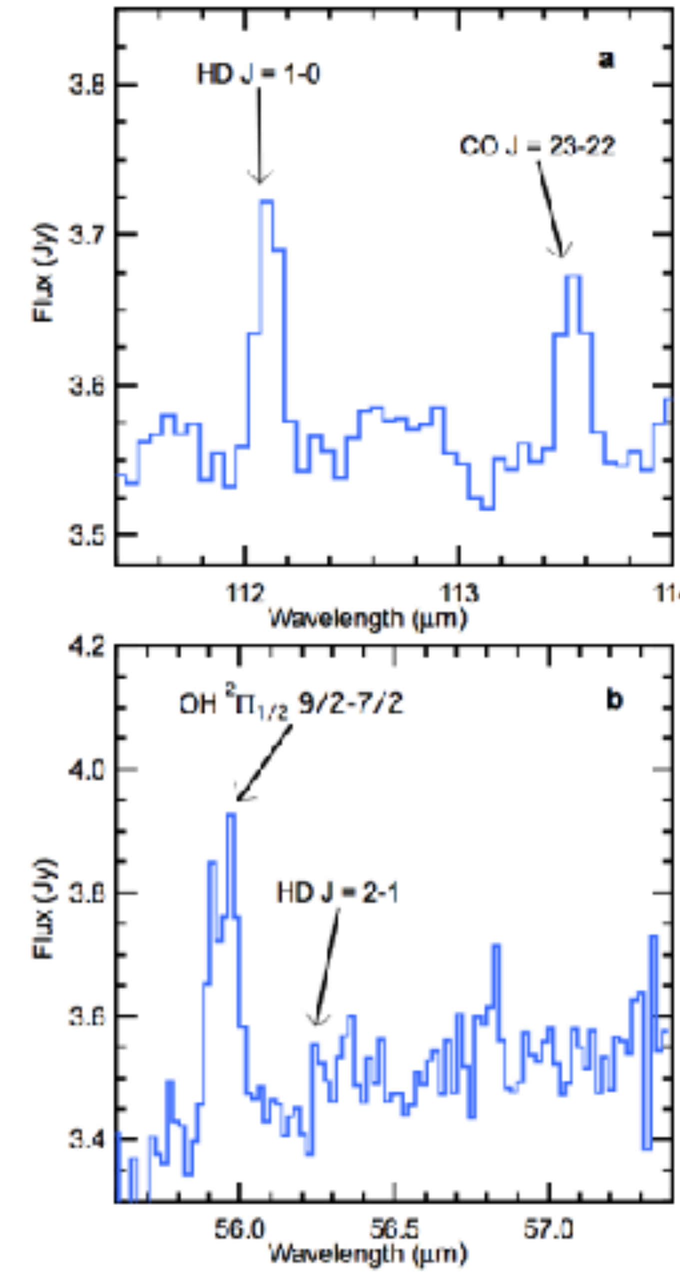
- Problems:

  - strong dependence on temperature (structure) and other model parameters

  - mass quite high for a 10 Myr old system

  - only a handful disks bright enough to be (barely) detectable

  - no more Herschel…



Bergin et al. 2013
McClure et al. 2016

Disk mass

- New modelling of $C^{18}O$ and [CI] emission: carbon underabundant in TW Hya
  => [C]/[H]~10^{-6} rather than 10^{-4} (ISM)
  => remove carbon from disk atmosphere

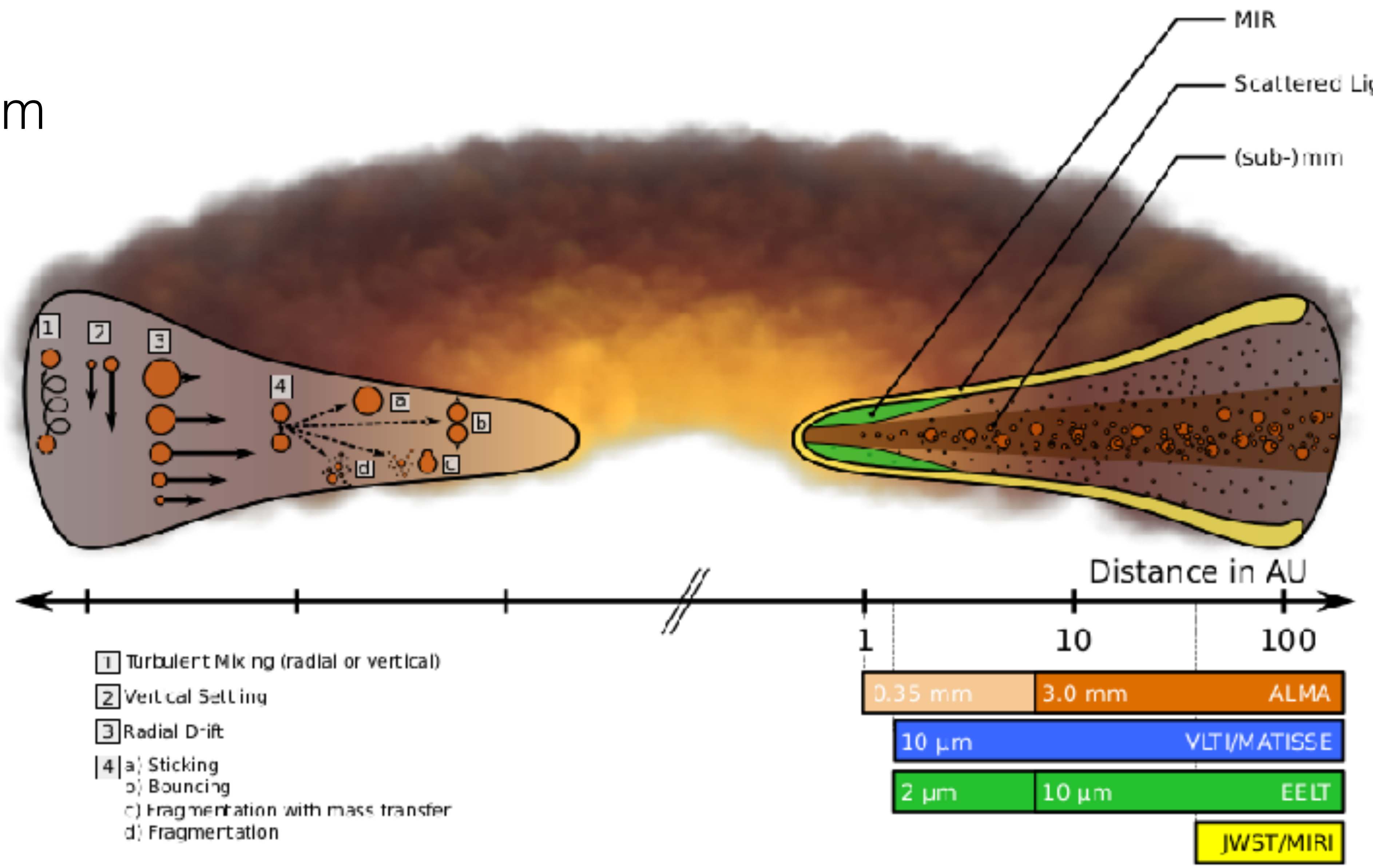
  - lock up of CO in complex organic molecules (e.g. C_2H and C_3H_2)

  - possibly explanation low CO abundance in other disks and derived low disk masses?

Favre et al. 2013
Kama et al. 2016
Miotello et al. 2016, in prep.
Ansdell et al. 2016

Disk processes

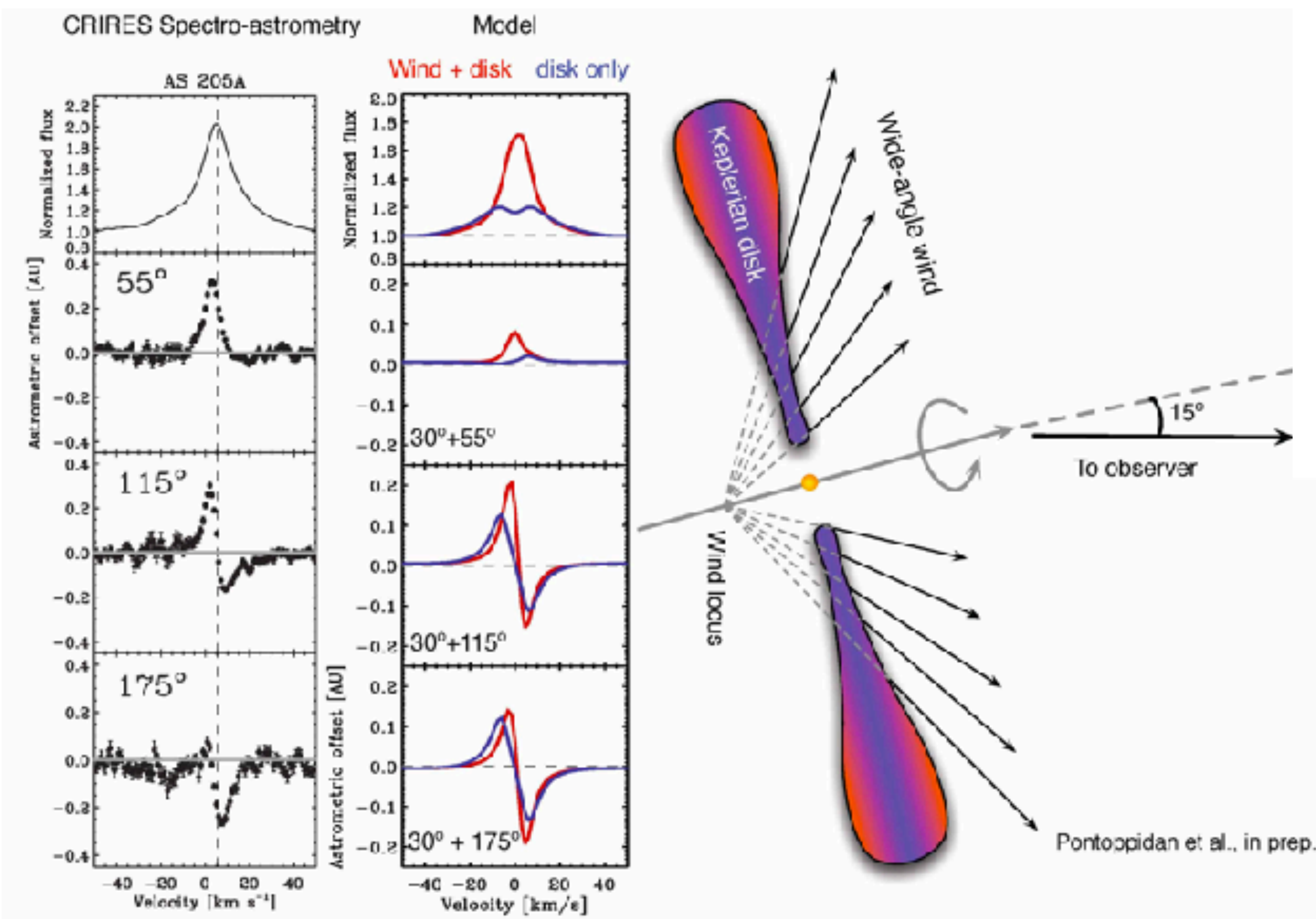
- Keplerian (and non-Keplerian?) motion
- Viscous evolution
- Hydrostatic equilibrium
- Dust growth
- Radial drift
- Settling/mixing
- Accretion
- Photoevaporation
- Dissipation
- Turbulence
- Planet formation
- Planet-disk interaction
- Ionization
- Gravitational and other instabilities

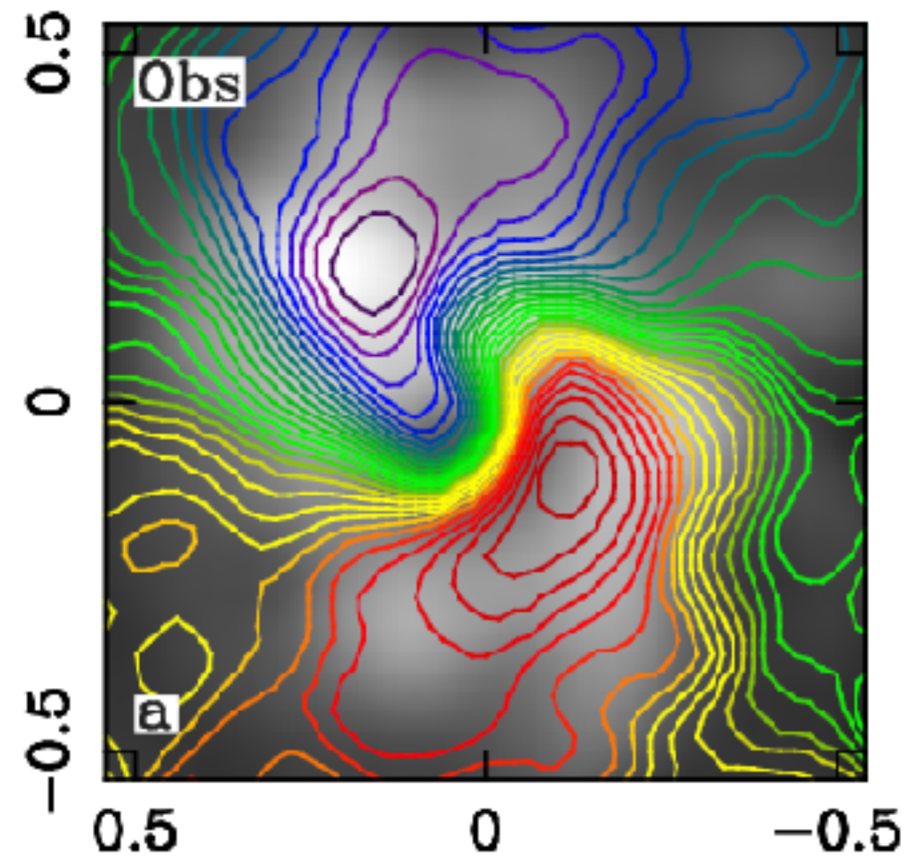


Testi et al. 2015

Disk processes

- Non-keplerian motion?

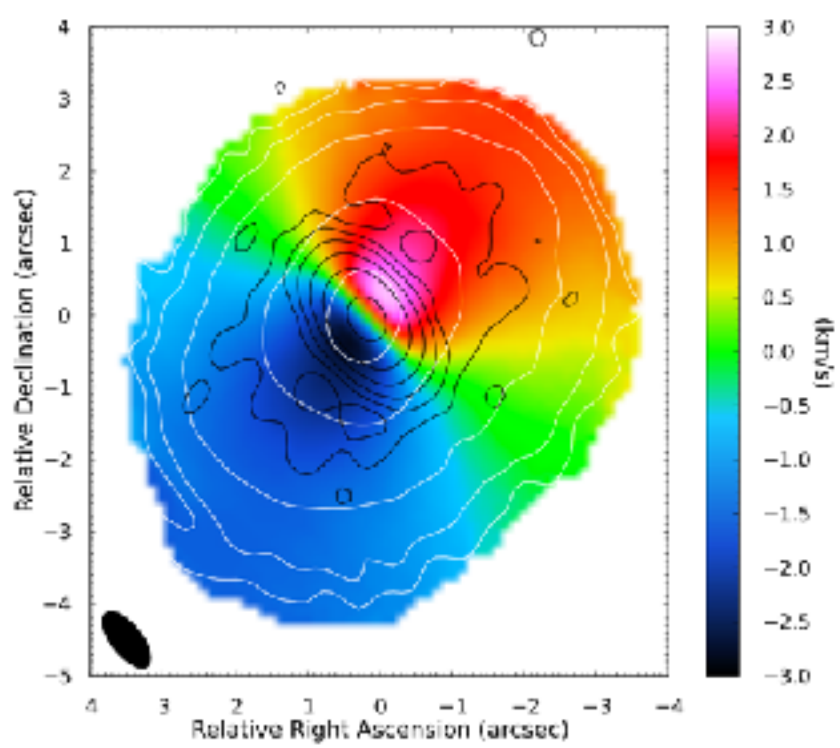


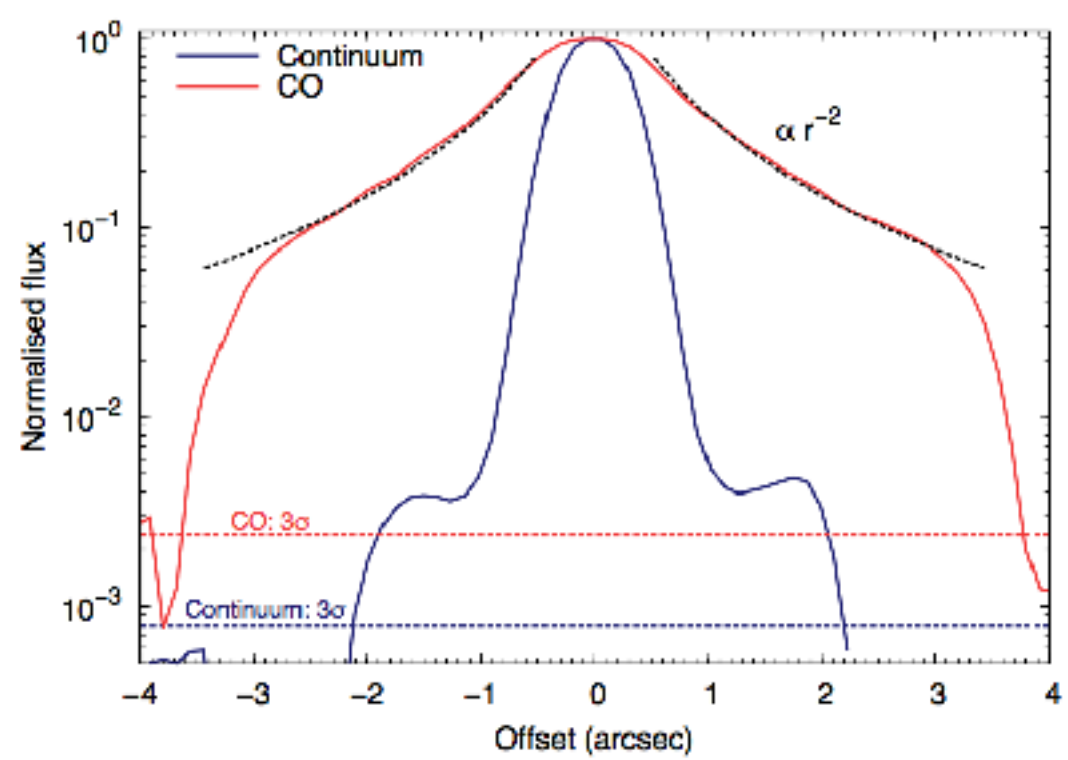


Pontoppidan et al. 2011
Casassus et al. 2015

Disk processes

- Radial drift and dust growth
- Due to drag forces, larger dust particles move towards pressure maxima (center of the disk in absence of gaps) => dust size < gas size
- Consequences: dust-gas segregation: cooling, shielding, chemistry?





Walsh et al. 2014

Disk processes

- Snow line => radius (temperature) where volatiles (low condensation temperature, e.g. H_2O, NH_3, CO_2, CH4, etc.) freeze out

- Giant planets form outside of snow line due to enhanced particle growth

- Solar system: H_2O snow line at 2-3 AU

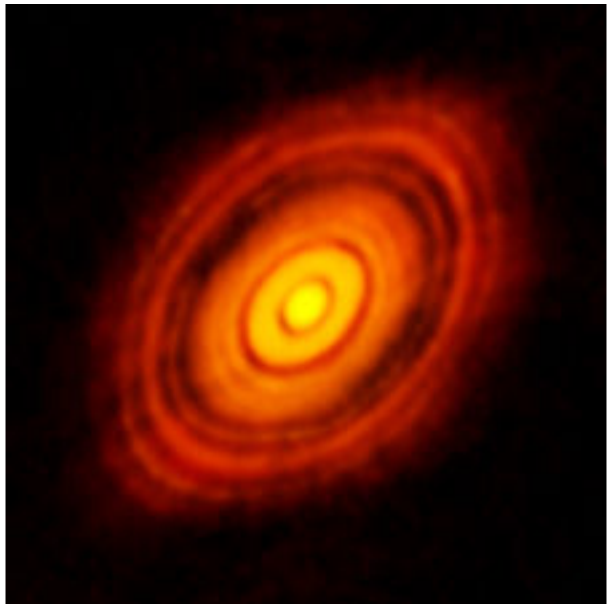
    - fits with giant planets being outside

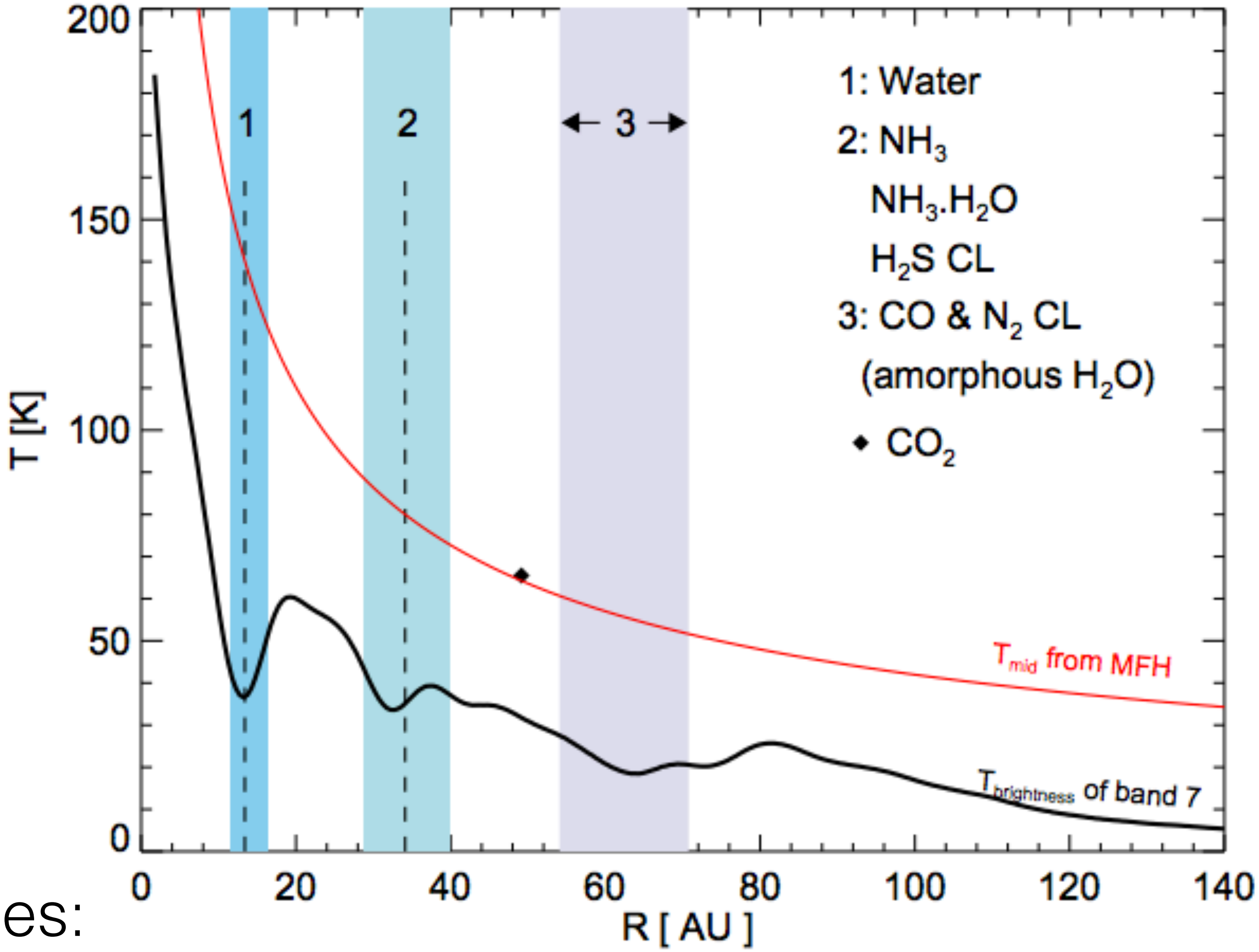
    - systems with hot Jupiters => migration?

    - Jupiter, Saturn, Uranus, Neptune: enriched in volatiles vs Sun => volatiles trapped in molecular ices?

Disk processes

- Dust growth: condensation fronts (snowlines)



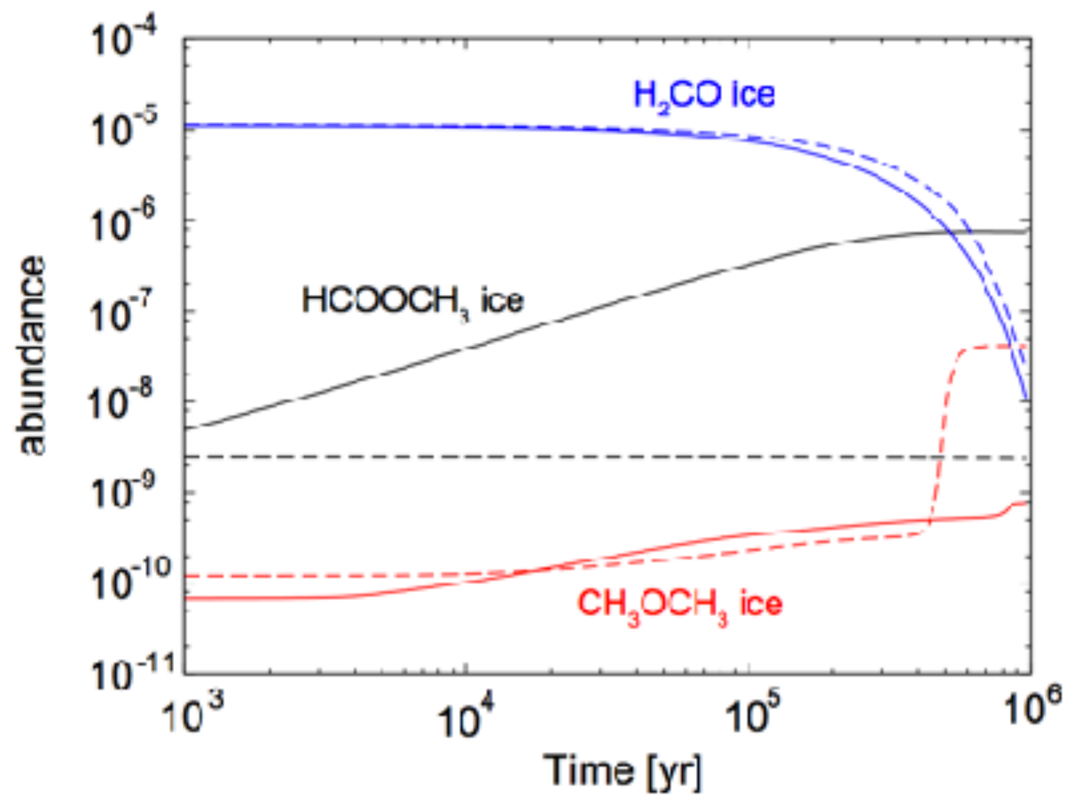


Growth to decimeter sizes:
no longer observable

Zhang et al. 2015

Disk processing

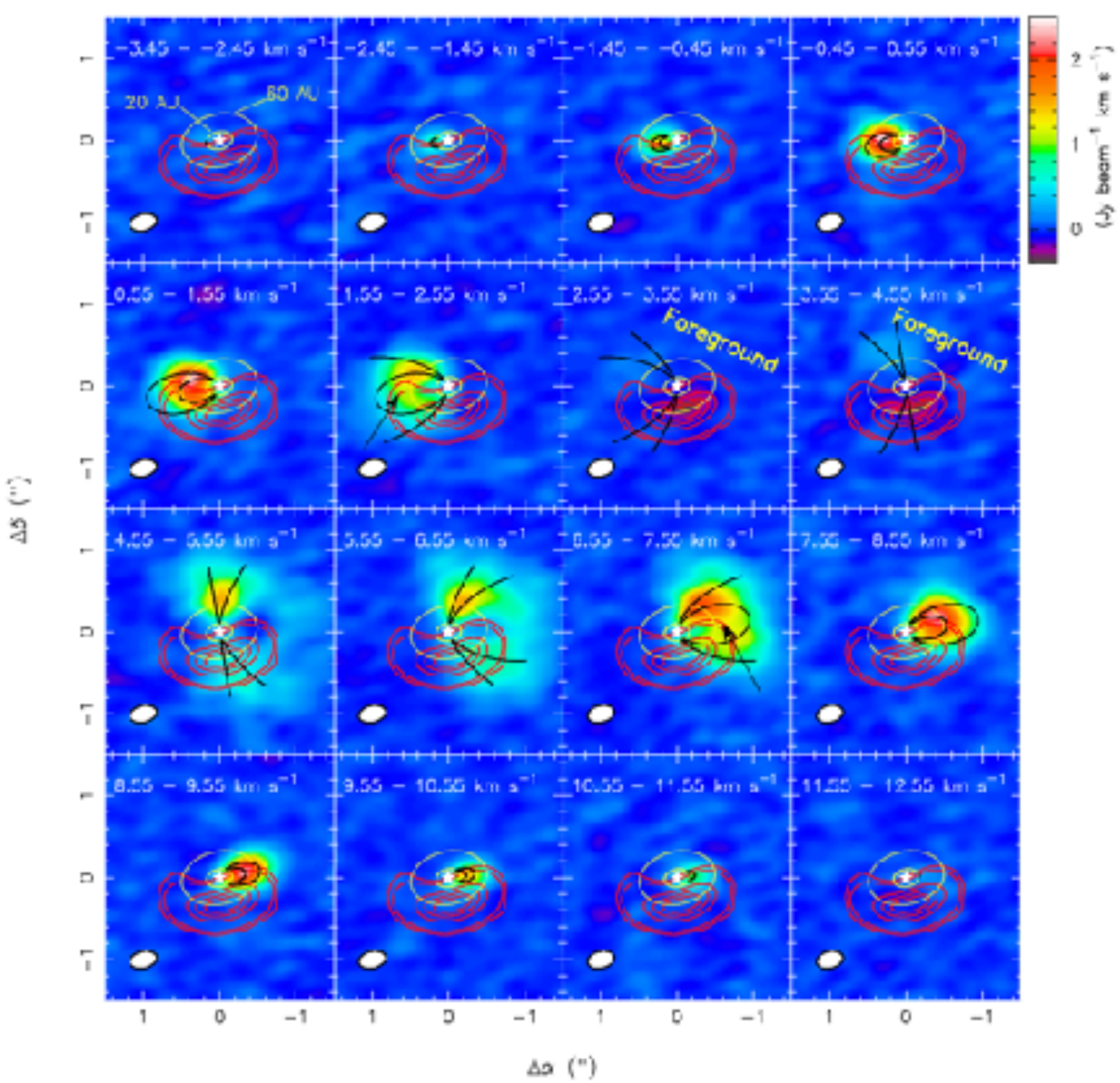
- Settling
  - large grains towards the mid-plane => small grains most important for chemistry/cooling => settling height relevant for molecular line emission
- Mixing
  - turbulent mixing can transport particles from the cold mid plane to higher warmer layers (enrichment COMs)

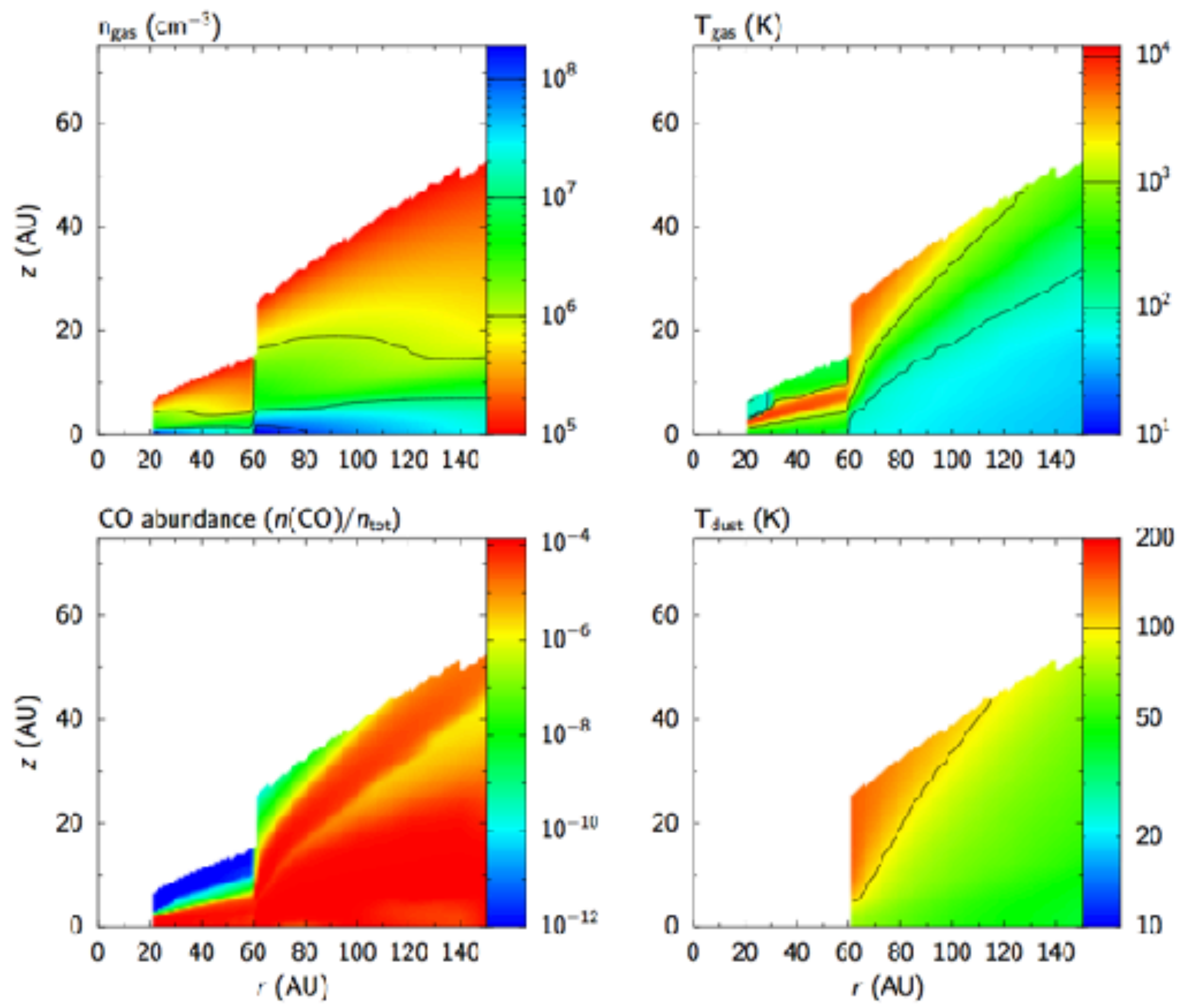


Furuya & Aikawa 2014

Disk processing

- Planet-disk interaction: gaps in transition disks => directly irradiated walls

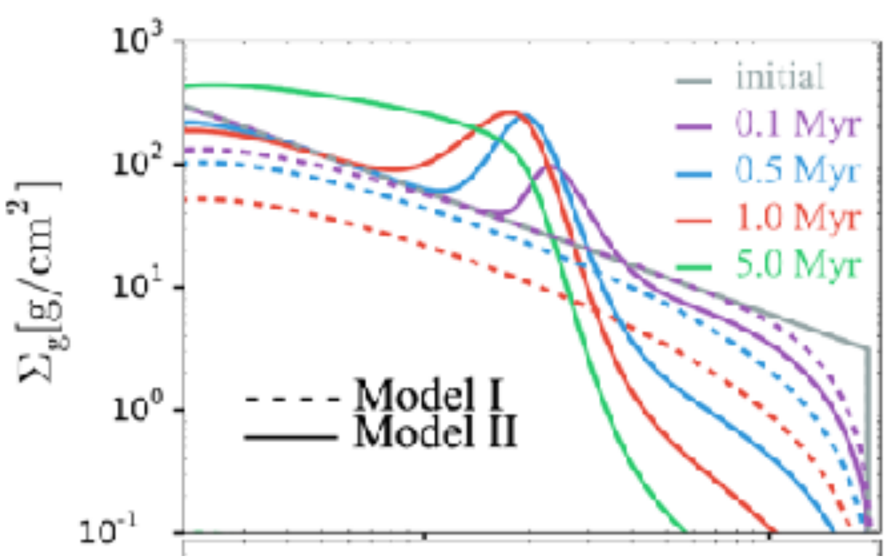


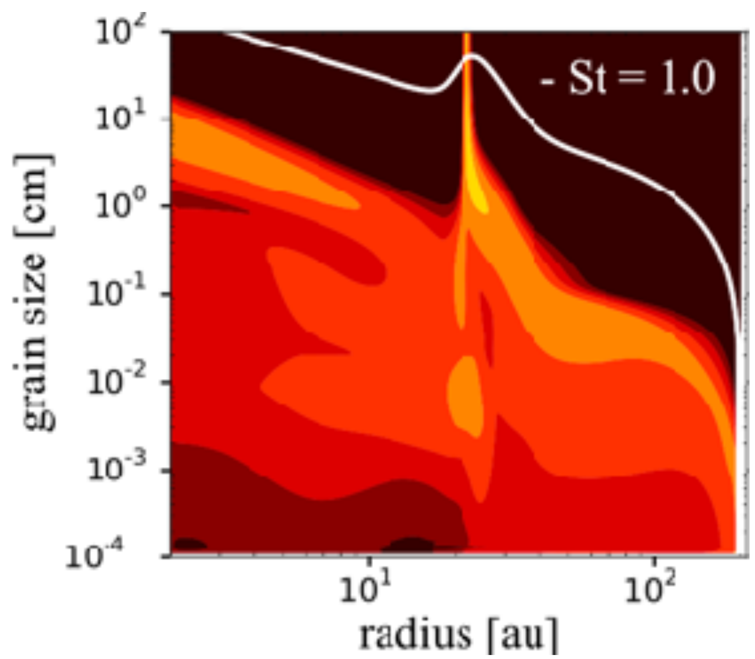


Bruderer et al. 2014
Cleeves et al. 2011

Disk processing

- Ionization (UV, X-ray, photo and cosmic ray):
  - MRI => driver viscosity and disk evolution
  - source of chemical enrichment
  - dead zone => region of low ionisation in between radiative ionised upper layer and collisionally ionised mid-plane layer





dust pile up => transition disk?

Cleeves et al. 2013,2014
Regaly et al. 2012
Pinilla et al. 2016

Disk processes

- Keplerian (and non-Keplerian?) motion
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- **Hydrostatic equilibrium**
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- Radial drift
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}

(Local) effects on temperature/density => thus on chemistry!

Next week: Ice chemistry

- Ice mantles
- Observational features
- Desorption
- Environments
- Comets