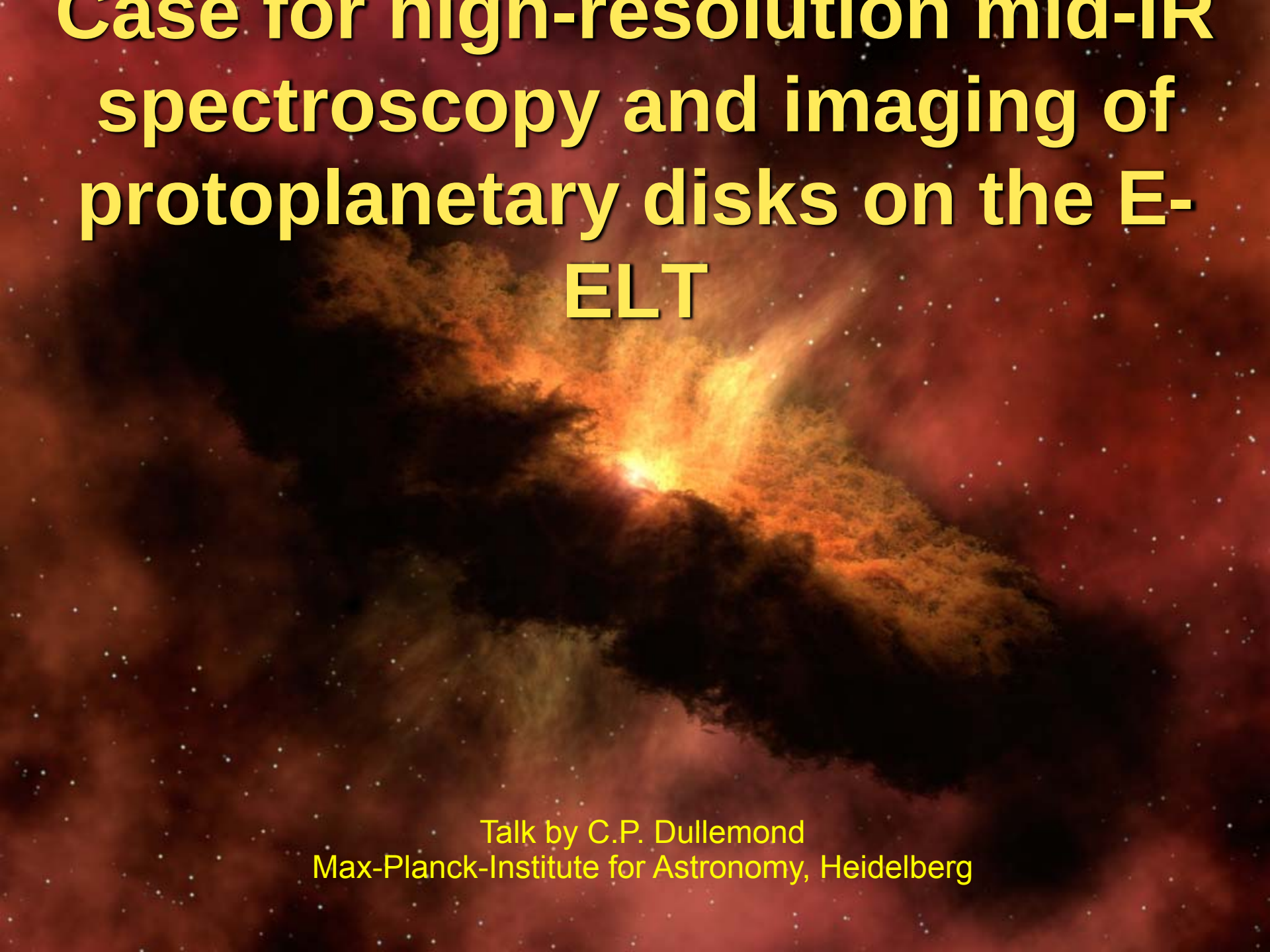
Case for high-resolution mid-IR spectroscopy and imaging of protoplanetary disks on the E-ELT

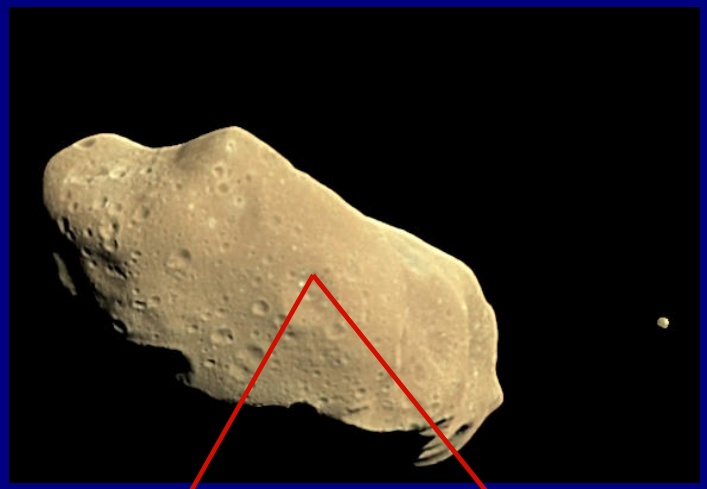


Talk by C.P. Dullemond
Max-Planck-Institute for Astronomy, Heidelberg

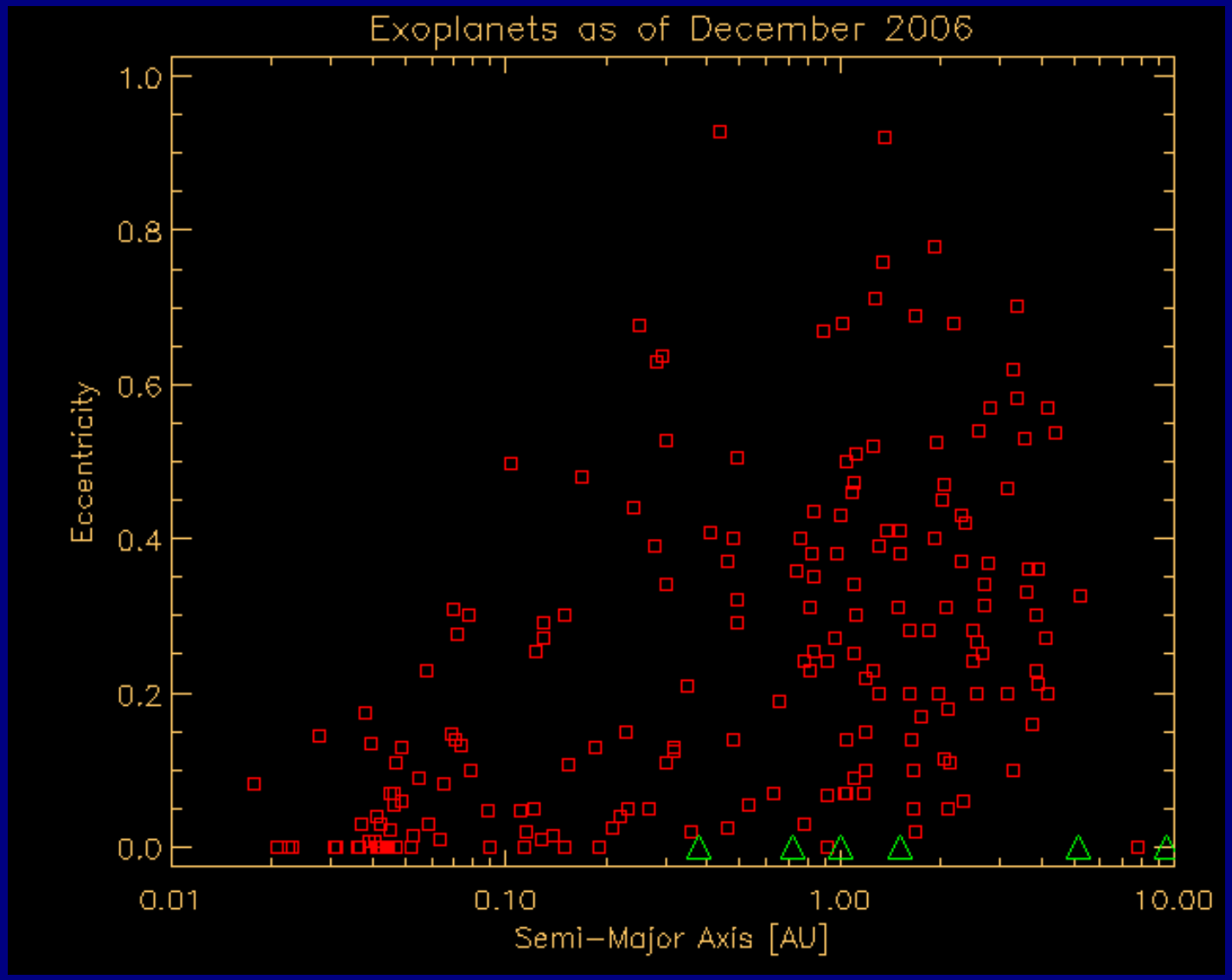
Billion-Dollar Question:

How were “we” formed 4.5 Billion years ago?

Messengers from the past



Extrasolar Planetary Systems



Study “proto-solar systems”

Probing the inner disk regions...

E-ELT spectro-astrometry

E-ELT imaging(!) and spectroscopy

T Tauri star

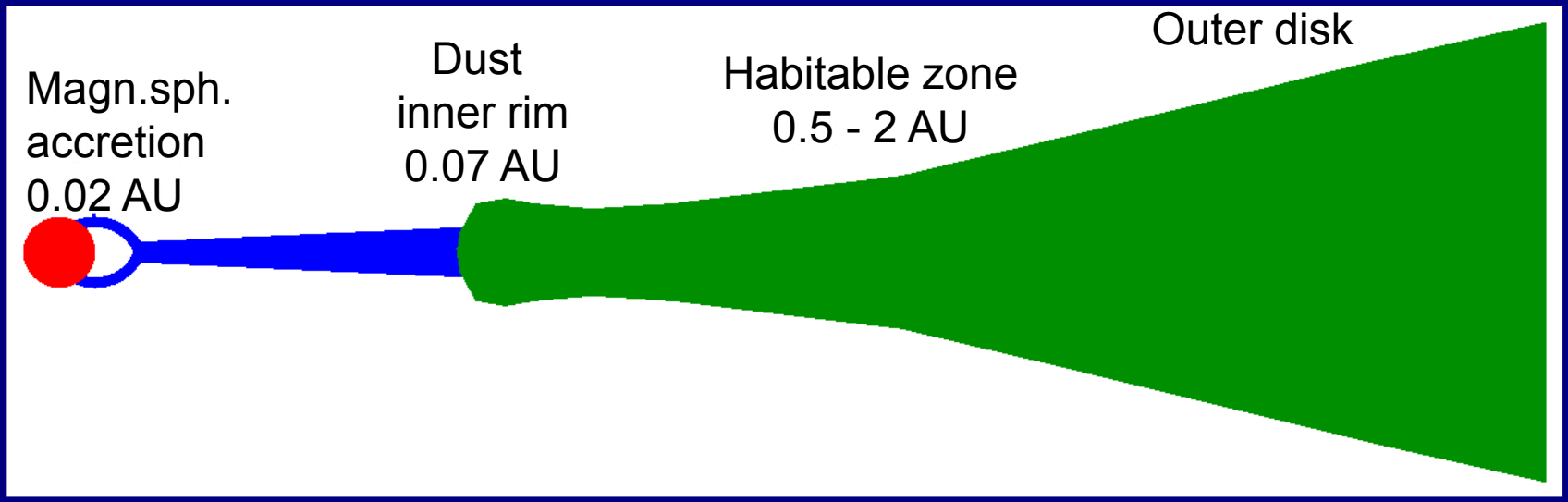
Near-IR VLT interferometry

(sub-)mm interfero

Mid-IR VLT interferometry

8-10 meter Telescope

Hubble Space Telescope



Probing the inner disk regions...

E-ELT spectro-astrometry

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Herbig Ae/Be star

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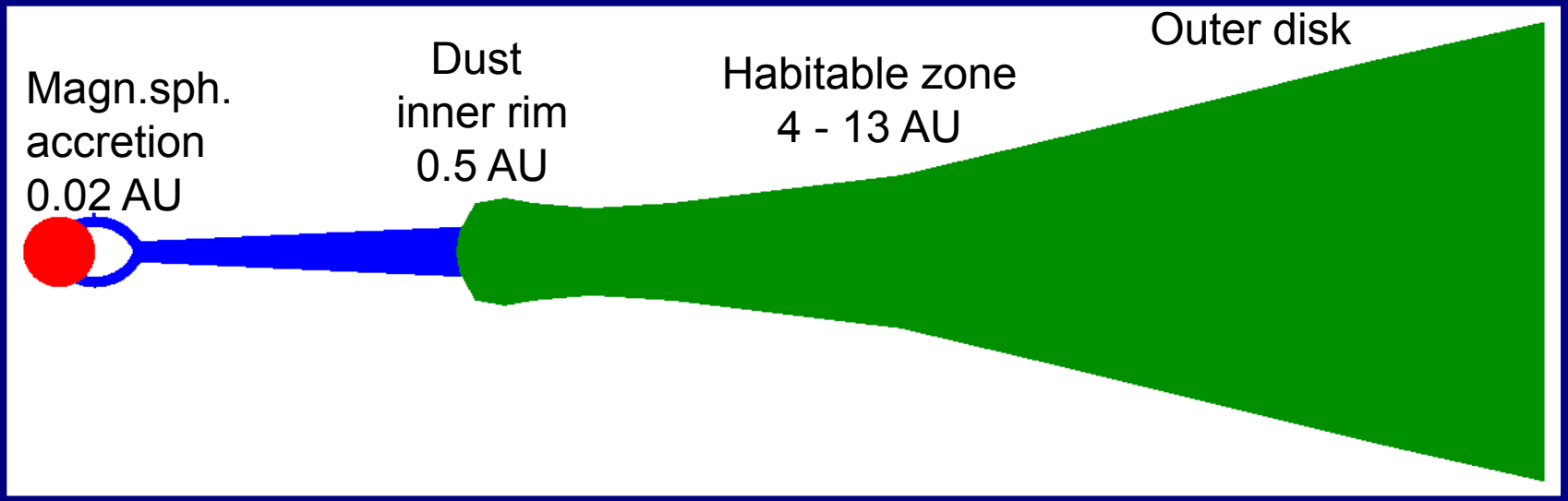


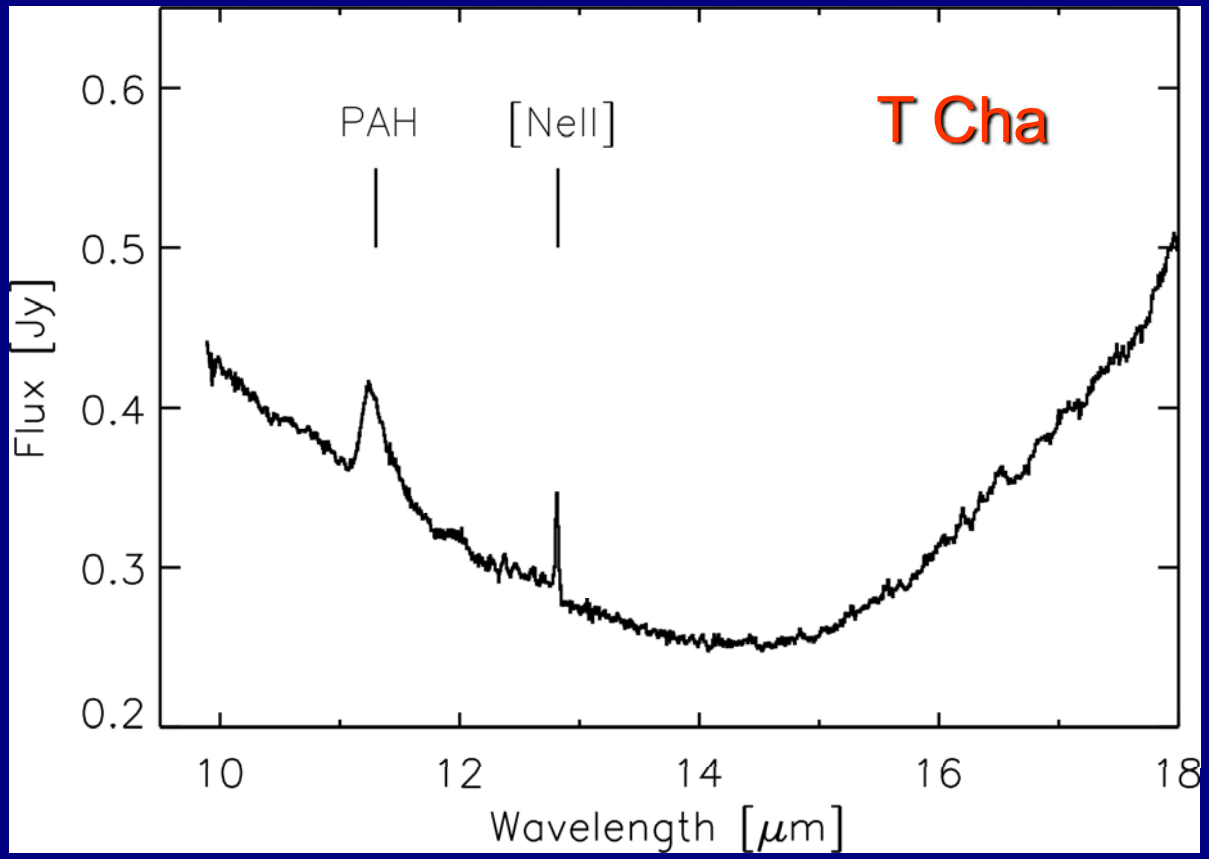
Major questions

- Structure, formation and evolution of protoplanetary disks?
- How and when is gas lost from disks => timescale for giant planet formation?
  - Mechanisms: photoevaporation, winds, …
- How and when is dust lost from disks?
- How and when are planets formed?
- How do planets affect their birth-disks?
- Chemical composition of material for forming planets (H_2O, biogenic molecules, …)?

Some highlights of recent protoplanetary disk observations

Rich features in NIR/MIR
both in dust and in gas

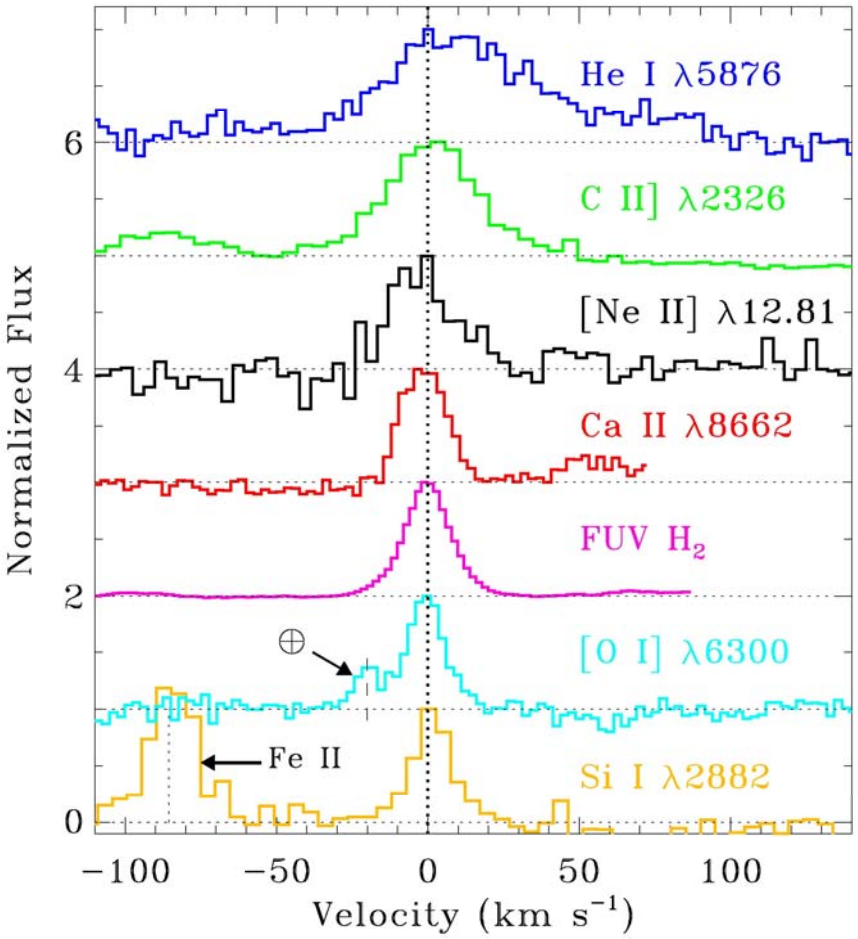
PAH & [Ne II] in disks: tracers of X-ray/EUV radiation



Detected in at least 20% of sources.
Fluxes consistent with recent models of X-ray irradiated disks.

Geers et al. 2006
Lahuis et al. 2007
Pascucci et al. 2007

[Ne II] at high spectral resolution



TW Hya

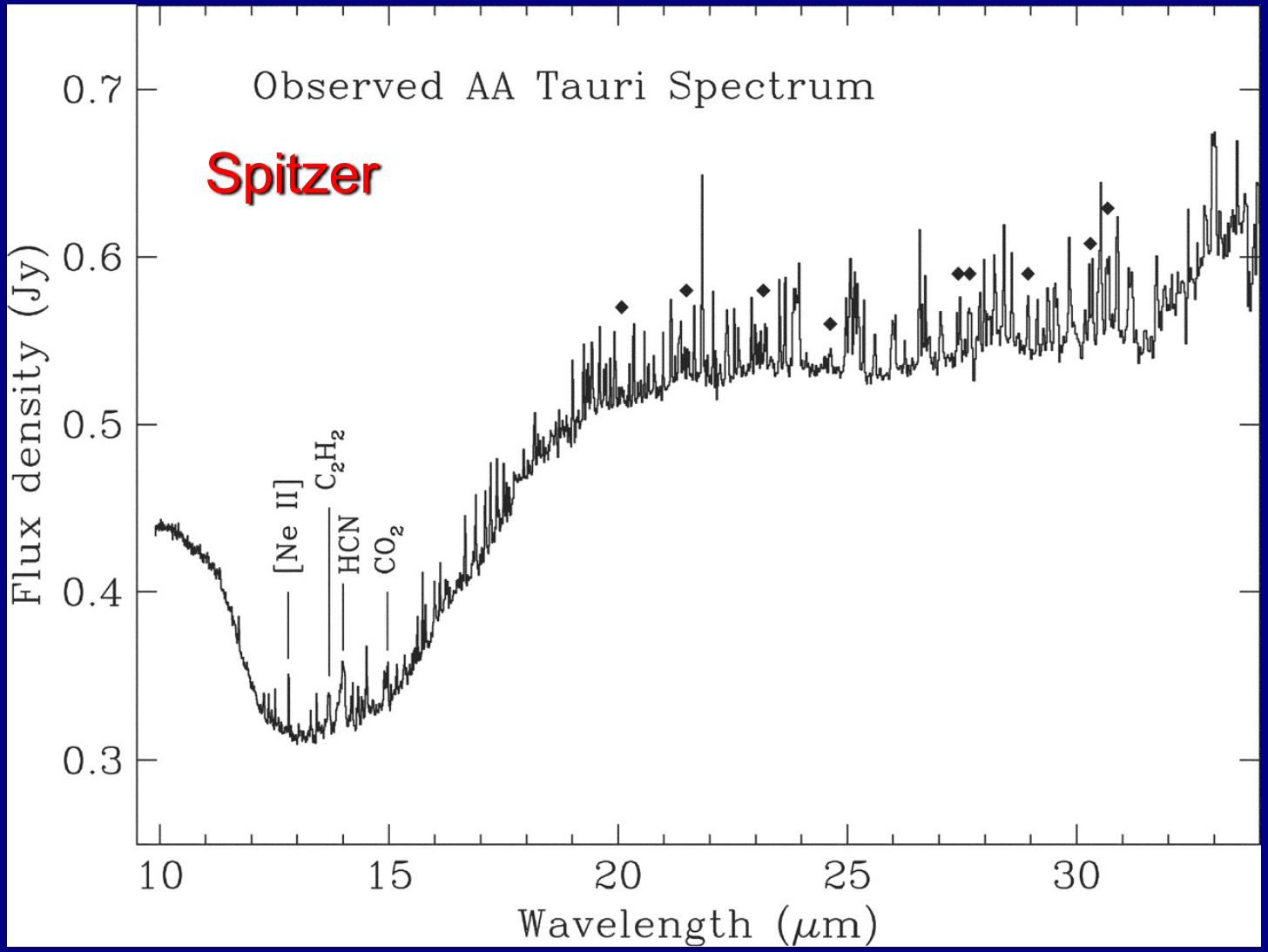
FWHM=21 km/s, broader than other narrow lines =>

- Keplerian rotation at 0.1 AU?
-Photoevaporative flow?

Herczeg et al. 2007

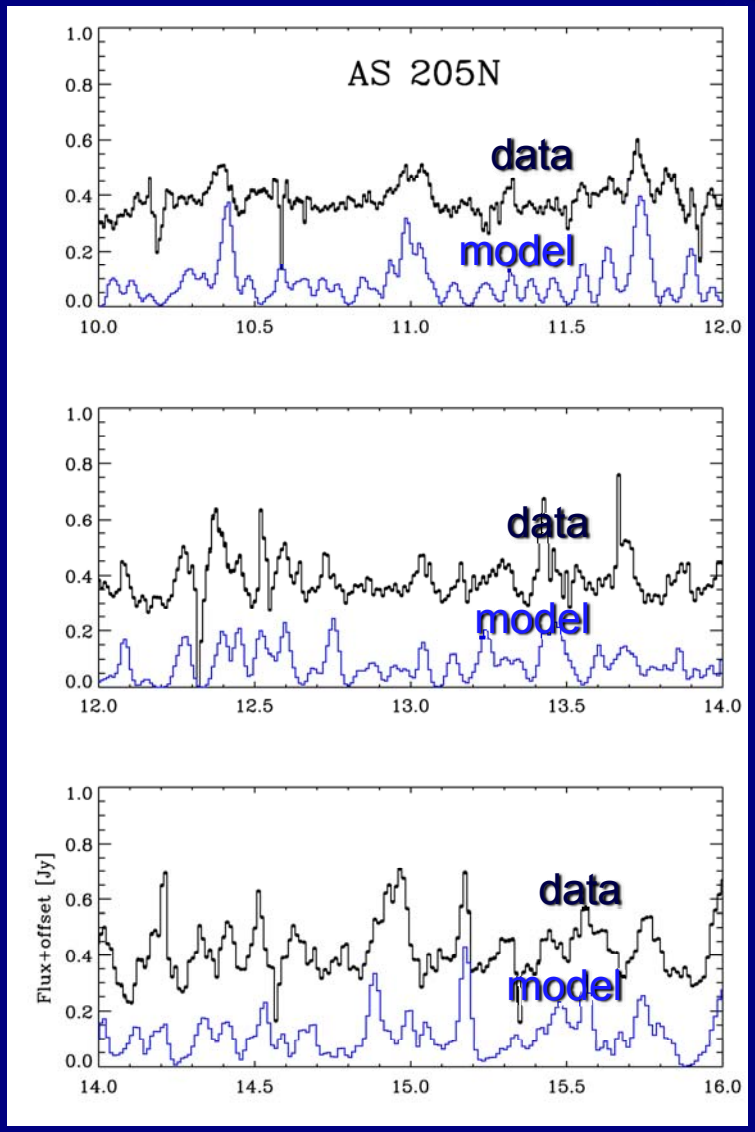
Water and organics !

Water and organics in AA Tau



Carr & Najita 2008

Water and organics in AS 205



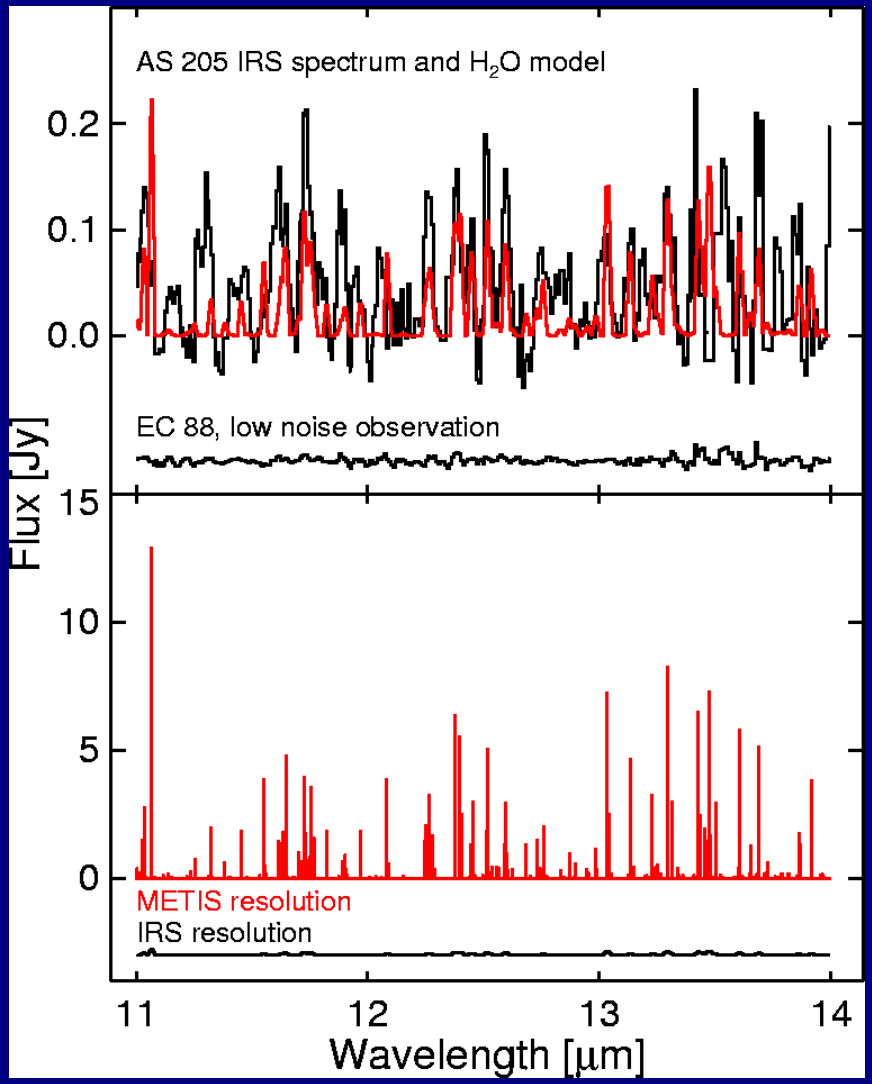
AS 205 Disk in Oph

H_2O spectral features barely seen at R=600; should have booming line/cont at high R

ELT can image emission and kinematics at few AU spatial resolution

Salyk et al. 2008

What would we gain from METIS?



R=10^5

Implications

- Water gas is found well inside the 'snow' line (estimated at ~3 AU)
- Water is expected to disappear in ~10^5 yr $\Rightarrow$ replenishment needed
- Inward radial migration or upward mixing of icy planetesimals, followed by evaporation?
- Might be able to characterize the snow line with ELT by direct spatially resolving

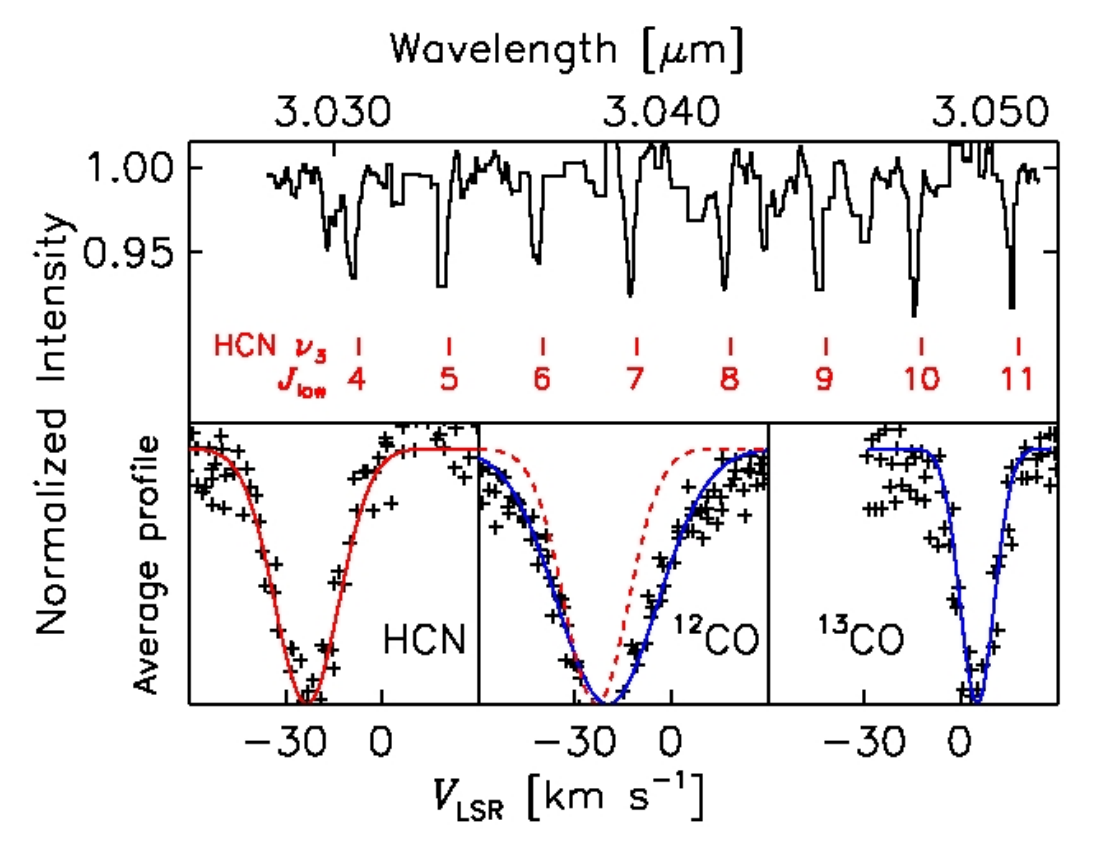
This is extremely important for planet formation theories!

Line profiles, P/V diagrams:

Kinematics of the disk (and wind?)

Resolving the lines

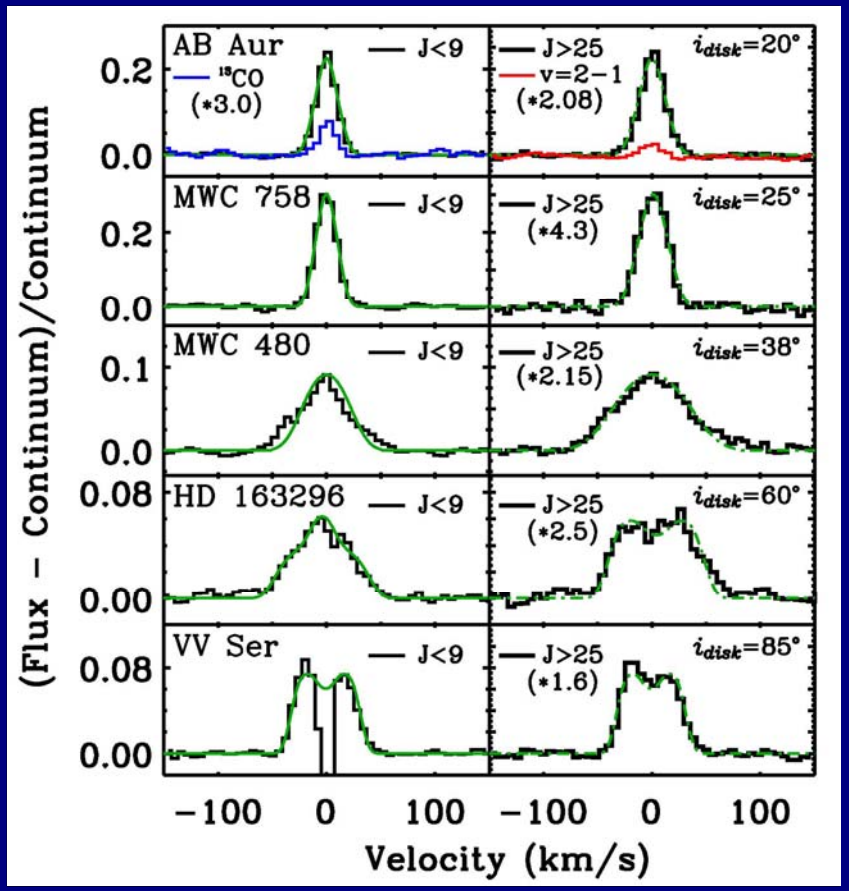
Keck HCN 3 μm and CO 4.7 μm



Hot HCN and CO blue-shifted by 25 km/s =>
-Base of MHD wind?

High R: Dynamics from line profiles

Cold gas Hot gas



Blake & Boogert 2004

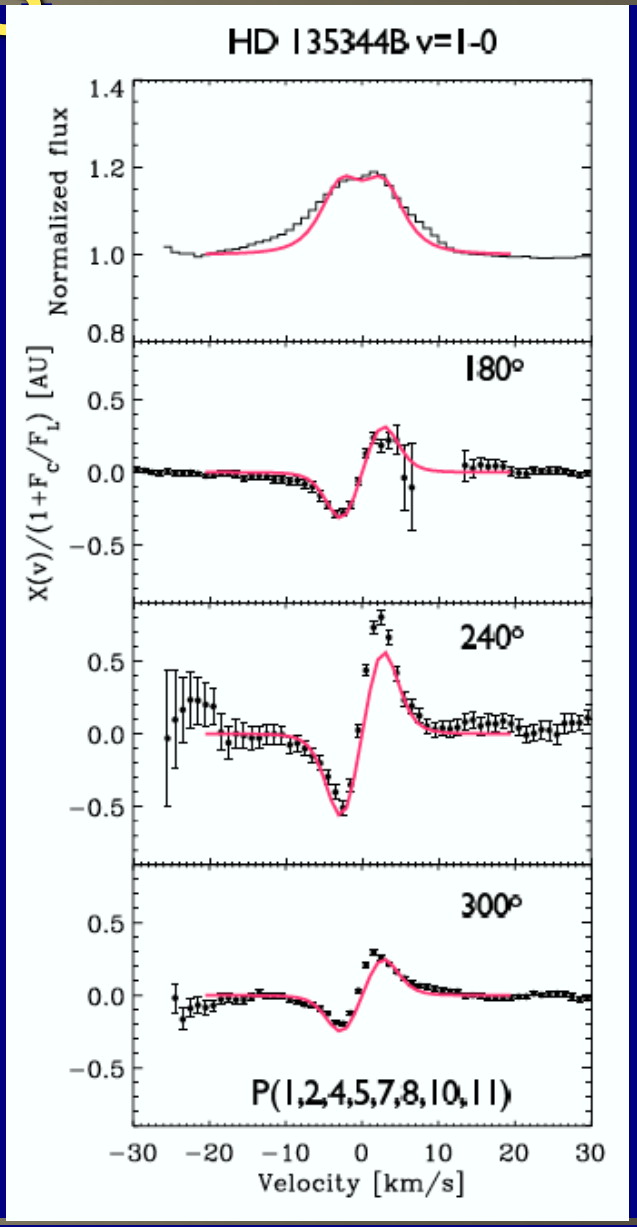
CO v=1-0 band at 4.7 μm in protoplanetary disks

Spectro-astrometry with CRIRES

- Slit spectrum
- At each wavelength fit Gauss to spatial emission
- Plot centroid of Gauss as a function of wavelength

↓

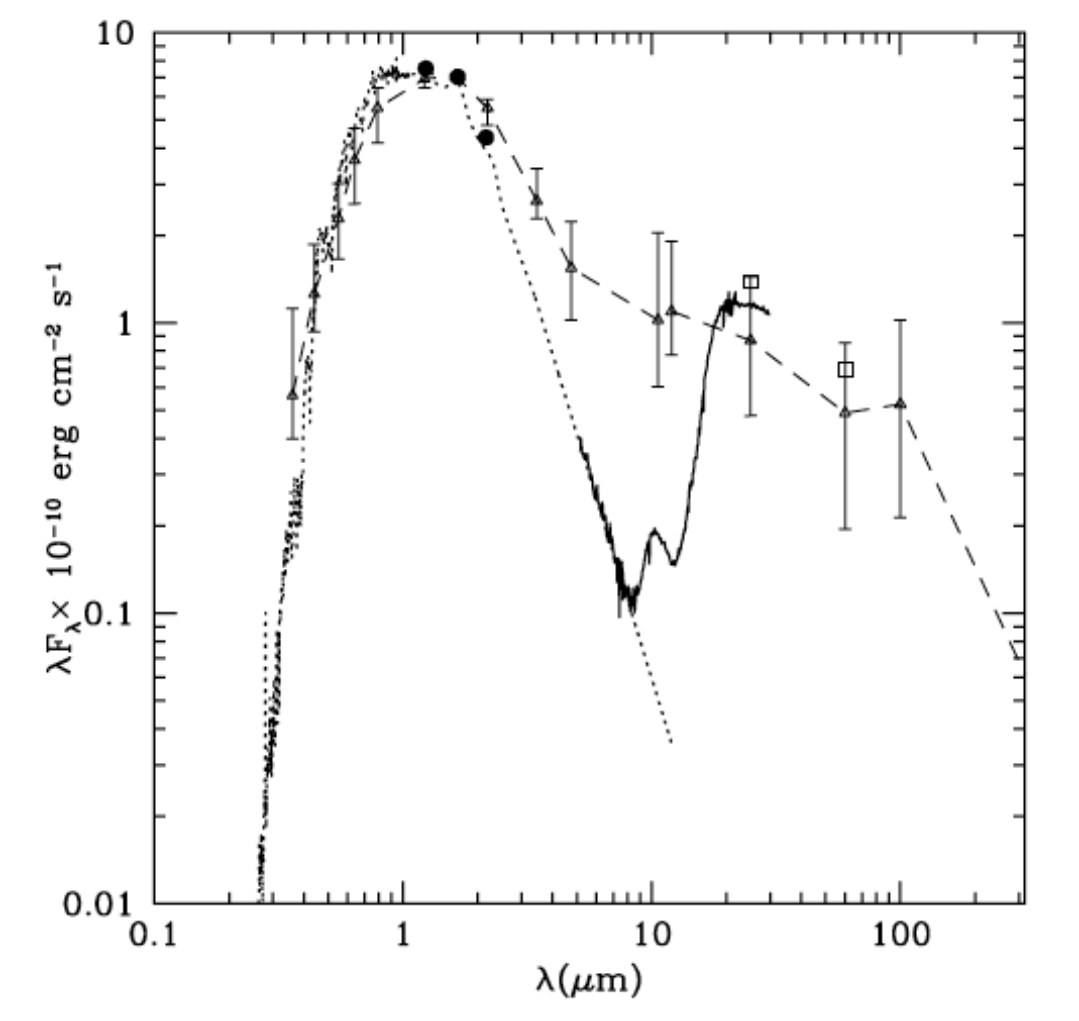
- Acquires spatial resolution well in excess of PSF!
- But only for 0th Moment
- For ELT: Huge resolution!



Pontoppidan et al. 2008

Large inner holes...

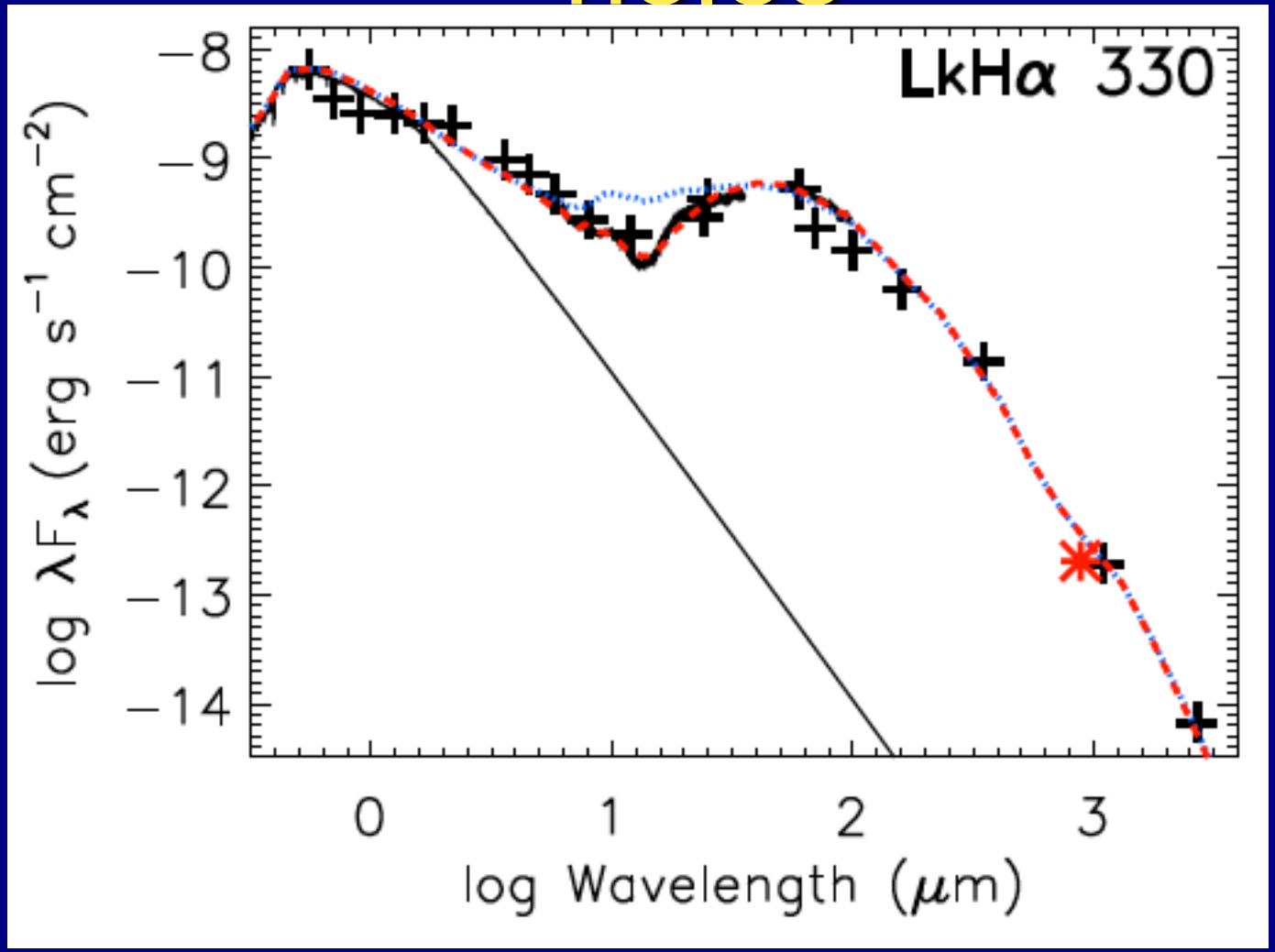
Transition disks : Huge inner holes



CoKu Tau 4

D'Alessio et al. 2005, Forrest et al. 2004

Transition disks : Huge inner holes



Brown et al. 2008

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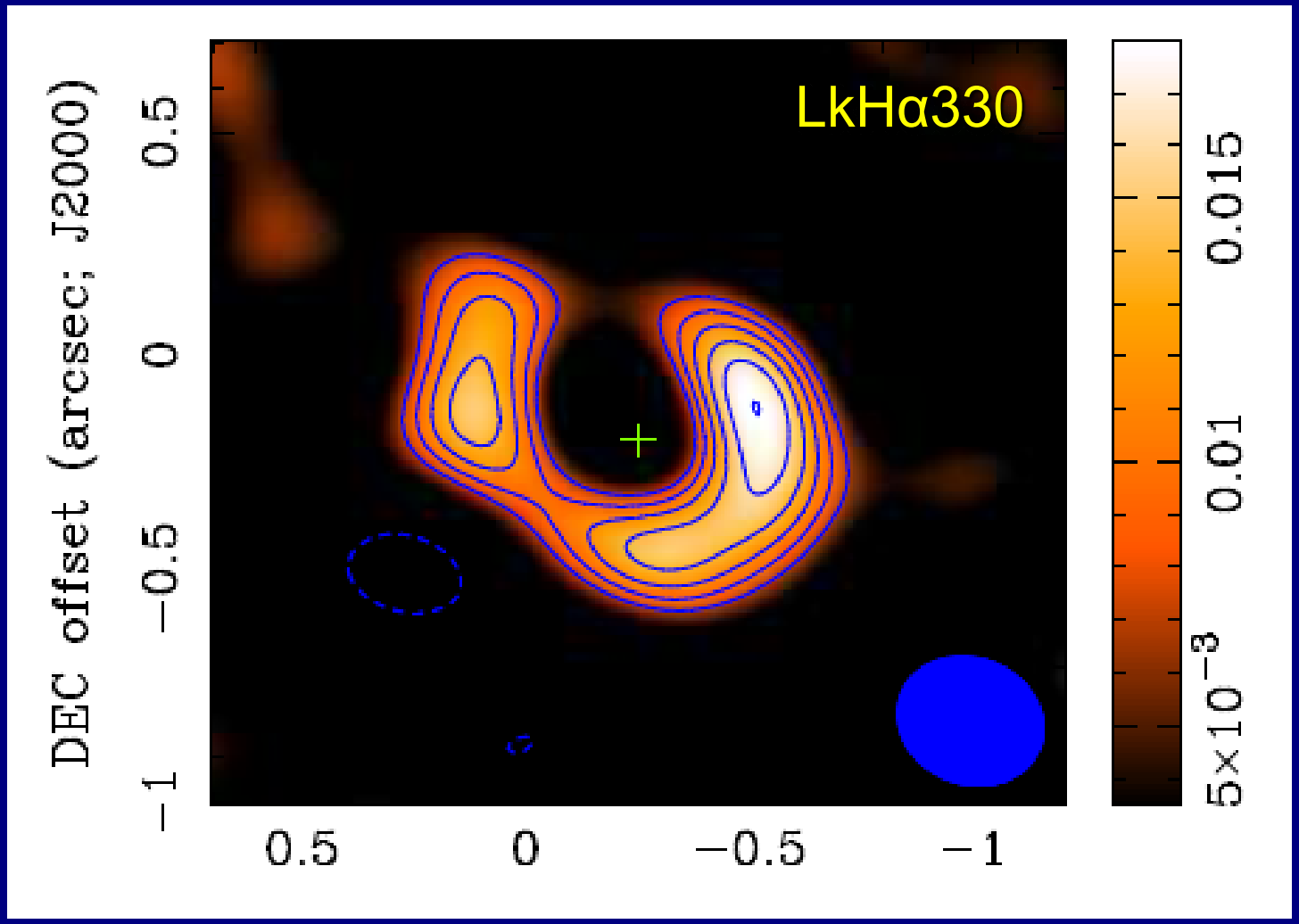

Brown et al. 2008

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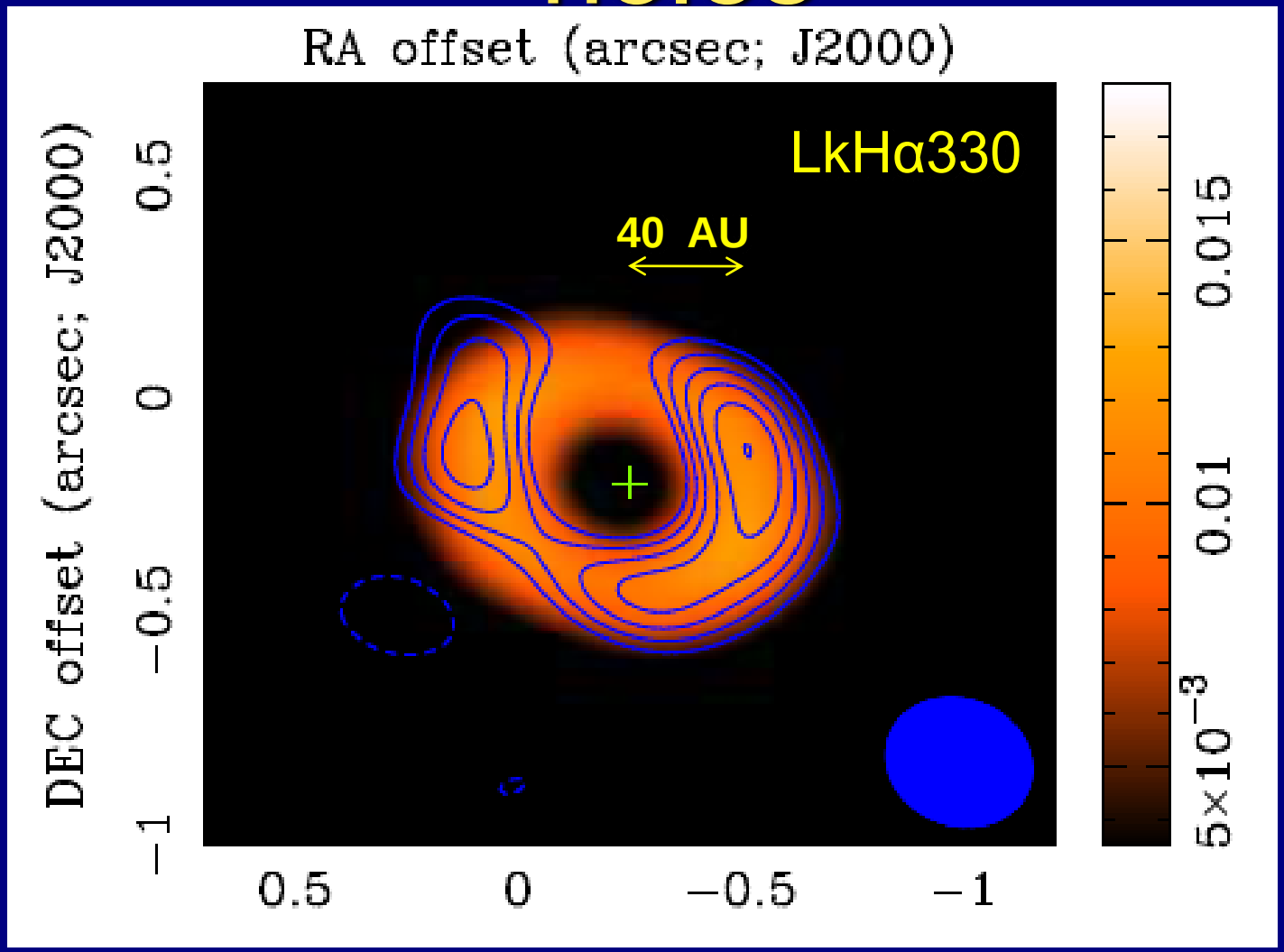
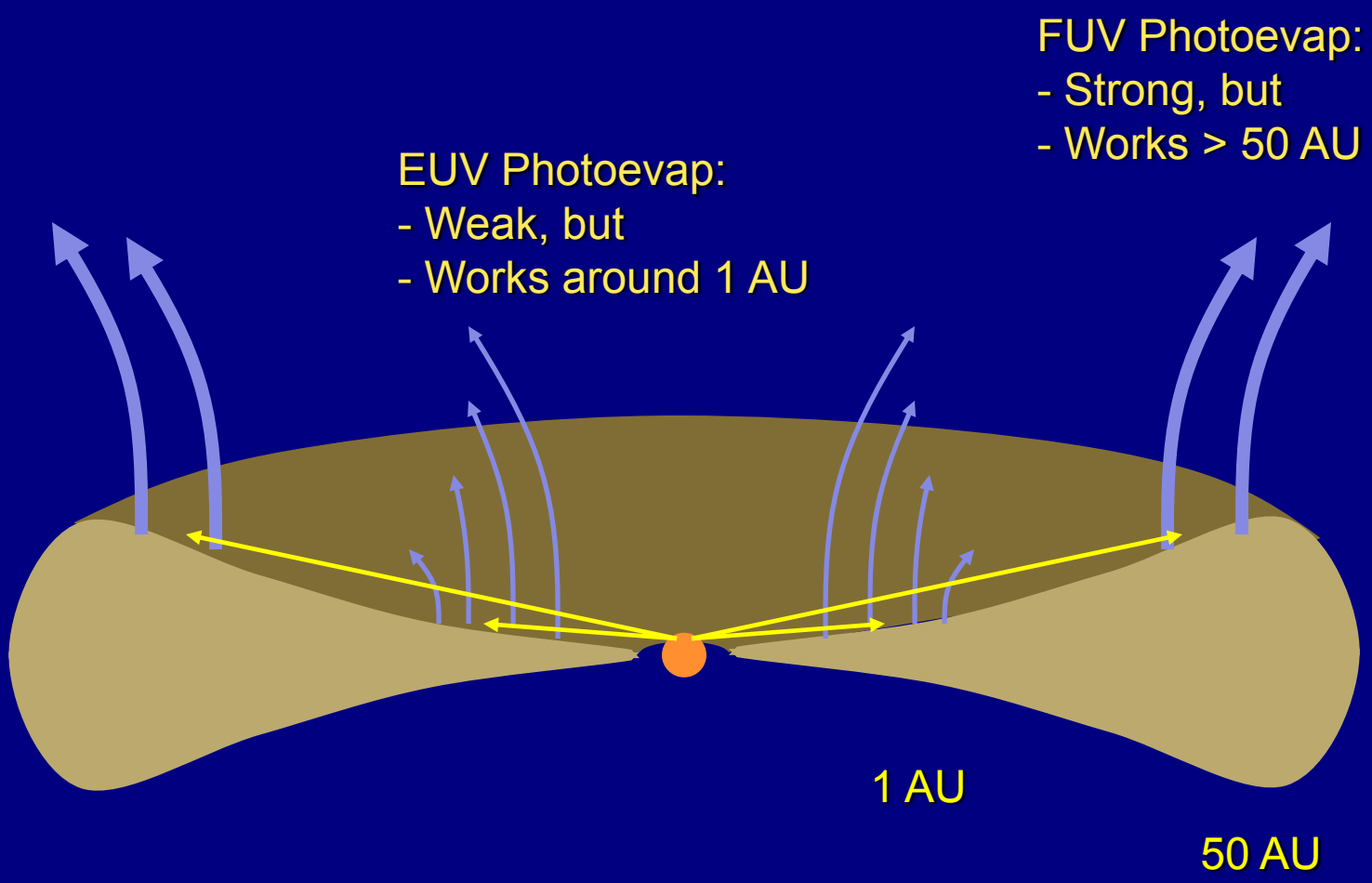


Brown et al. 2008

Can photoevaporation explain cavities?



Hollenbach et al. 1994
Gorti & Hollenbach 2007

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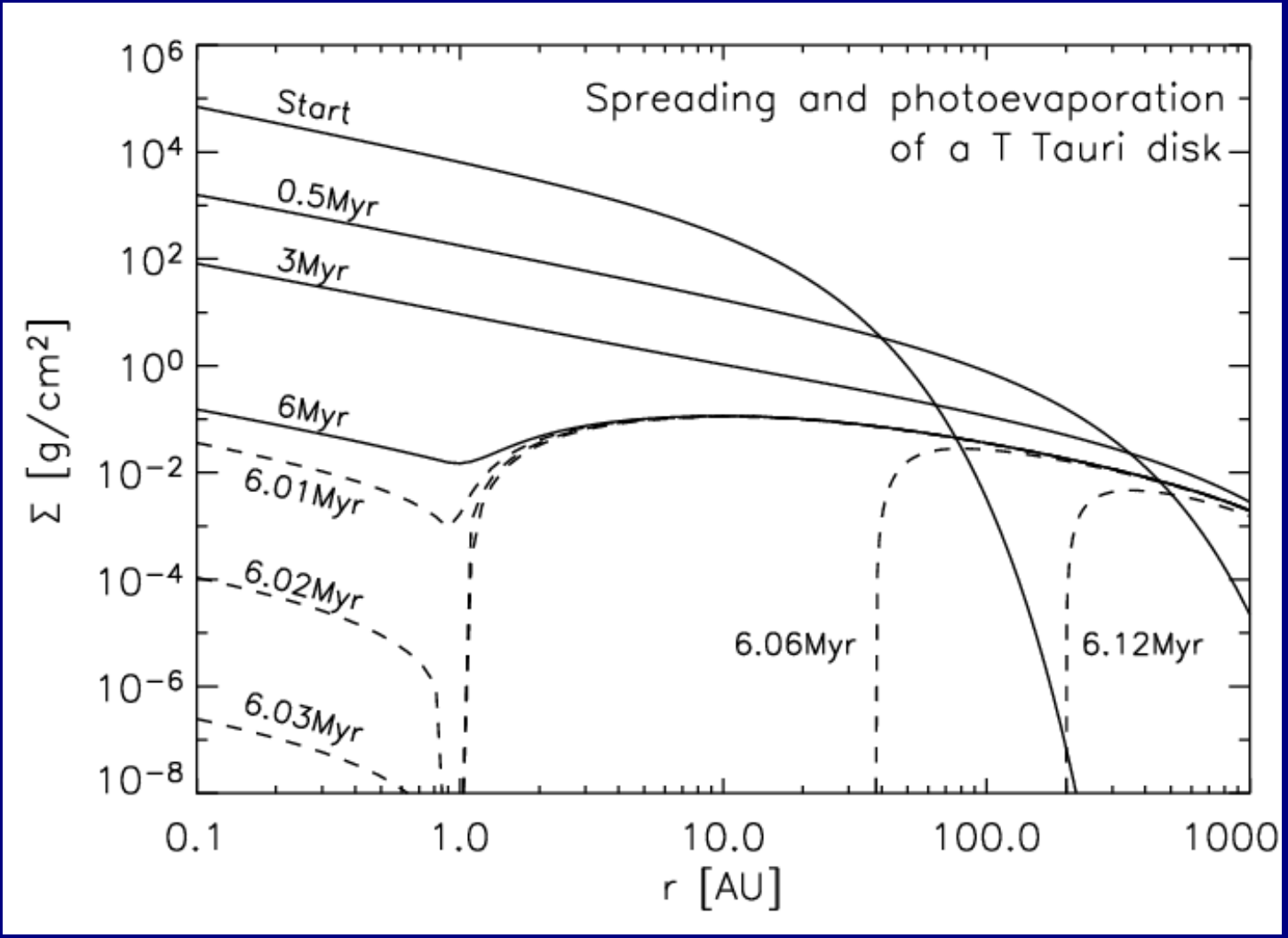


Hollenbach 1994; Clarke et al. 2001
Alexander, Clarke & Pringle 2006

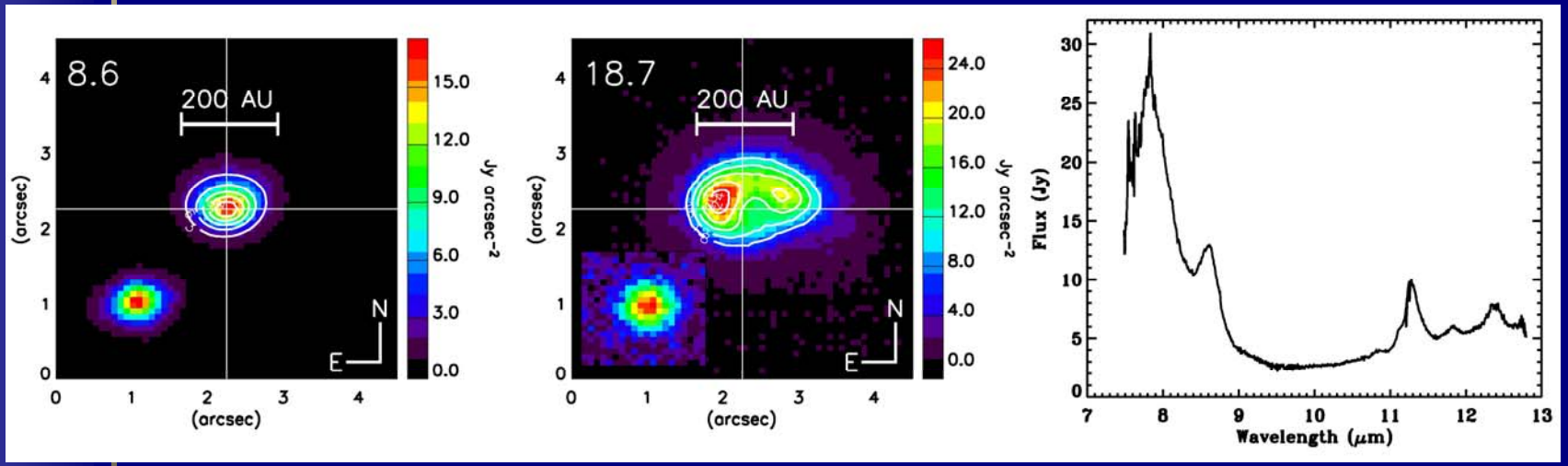
Spatial separation small and large grains

VLT VISIR image + spectra

8.6 PAH

19.8 μm large grains

7-13 μm spectrum



IRS48 in Oph

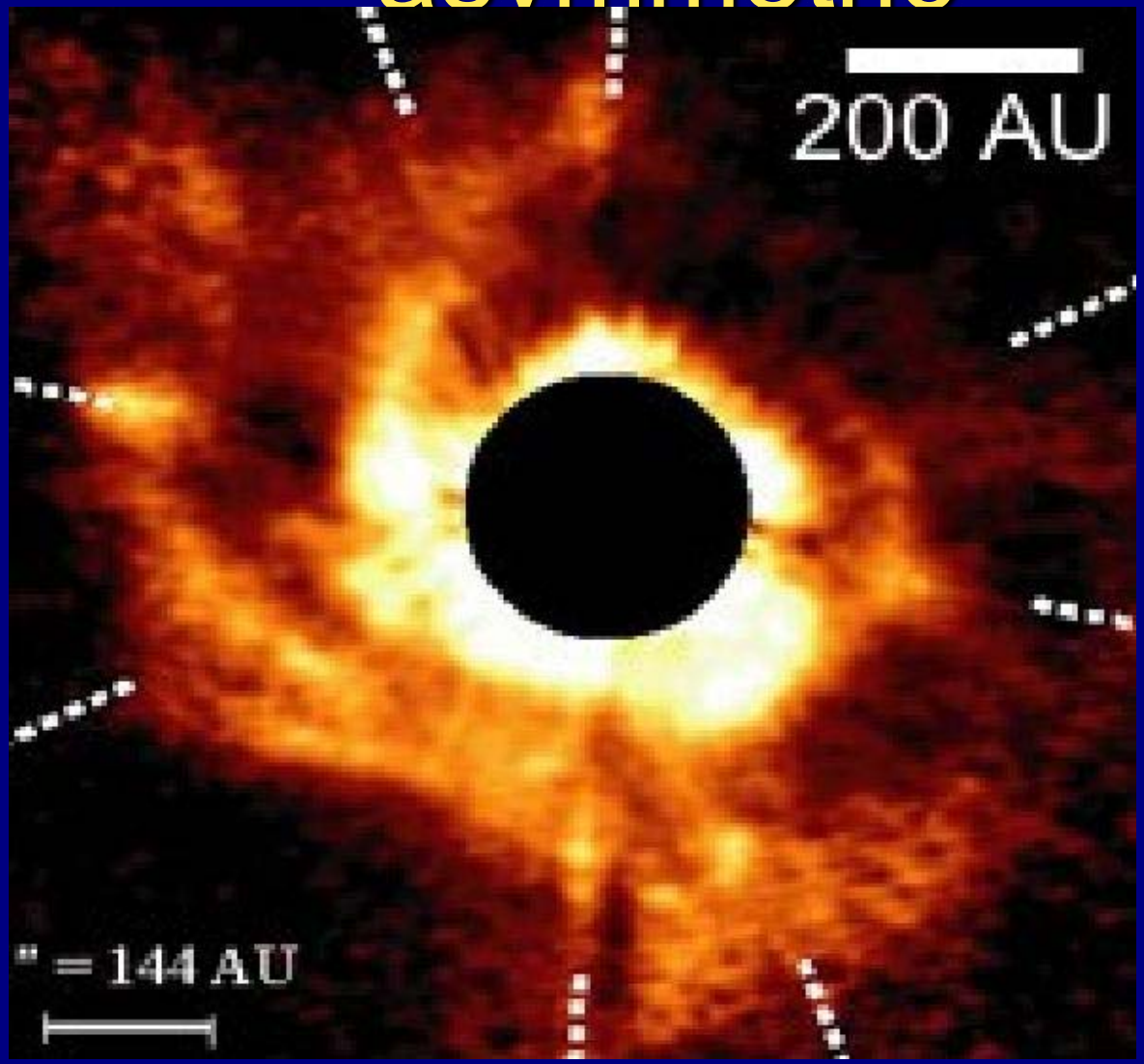
- 60 AU radius gap seen in large grains, but NOT in PAHs

Geers et al. 2007

Prospects for mid-IR imager/spectrometer for E-ELT

Clumpiness and asymmetries in protoplanetary disks

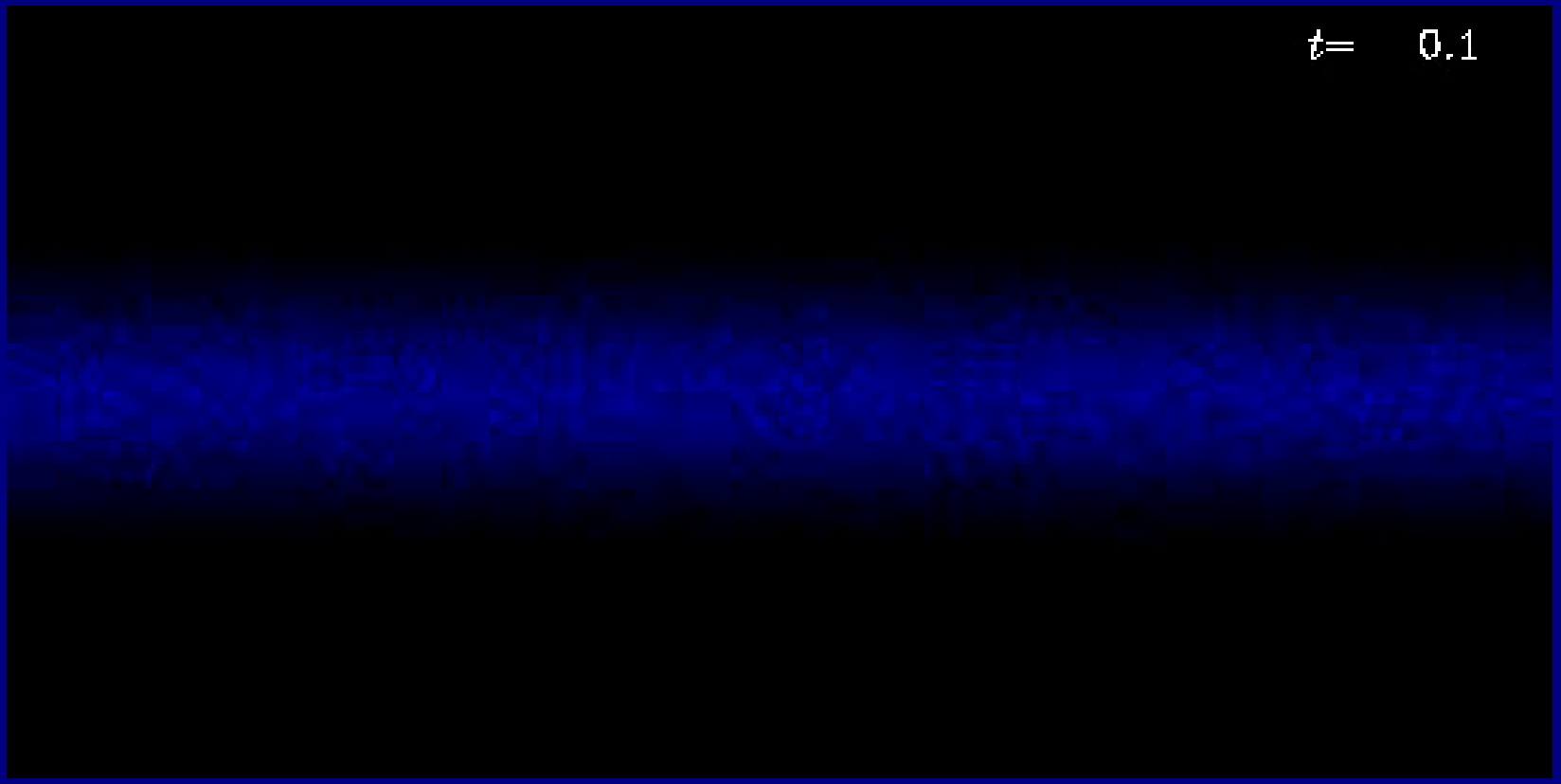
Disks are clumpy / spiraly / asymmetric



AB Aurigae

Fukagawa et al. 2004

Formation of planets: clumps, waves



Johansen et al. 2006

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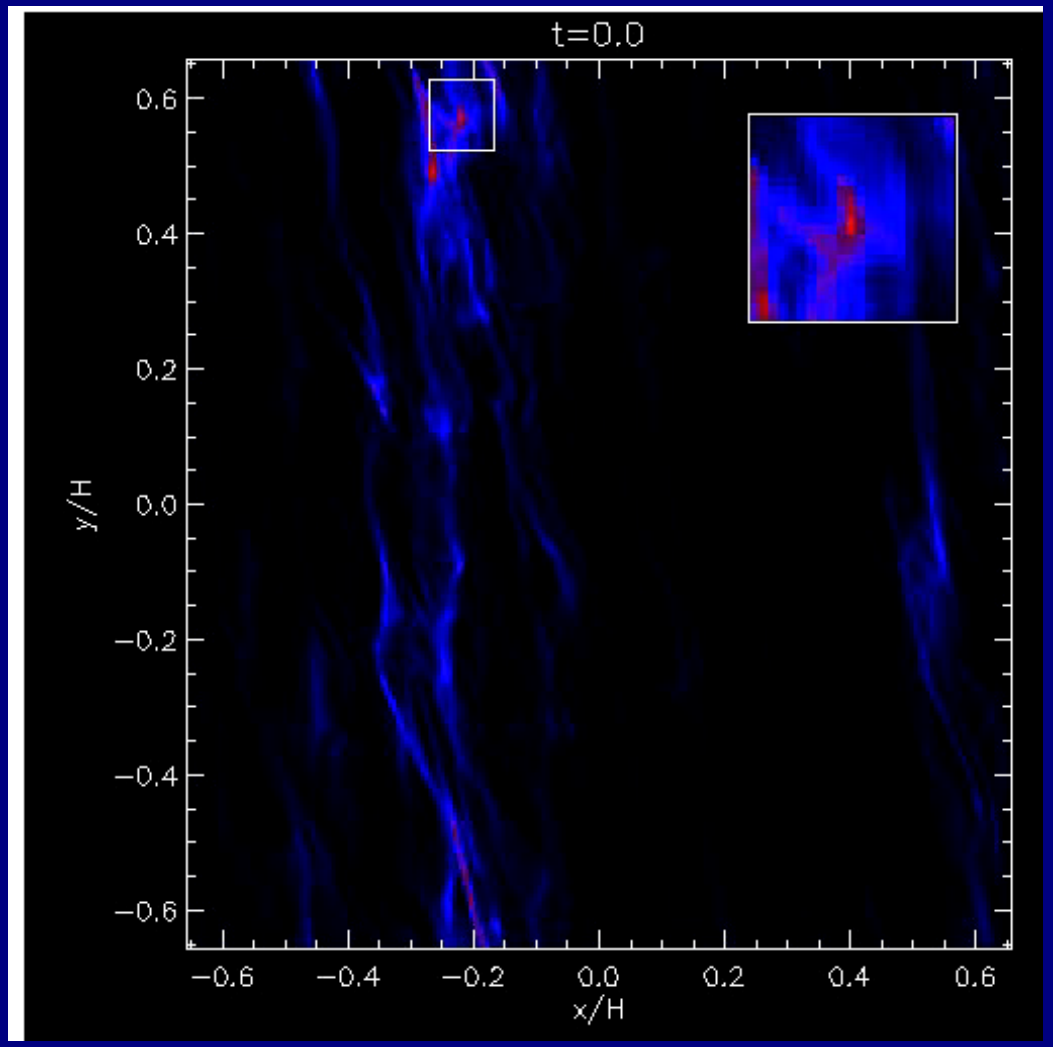

Johansen et al. 2007

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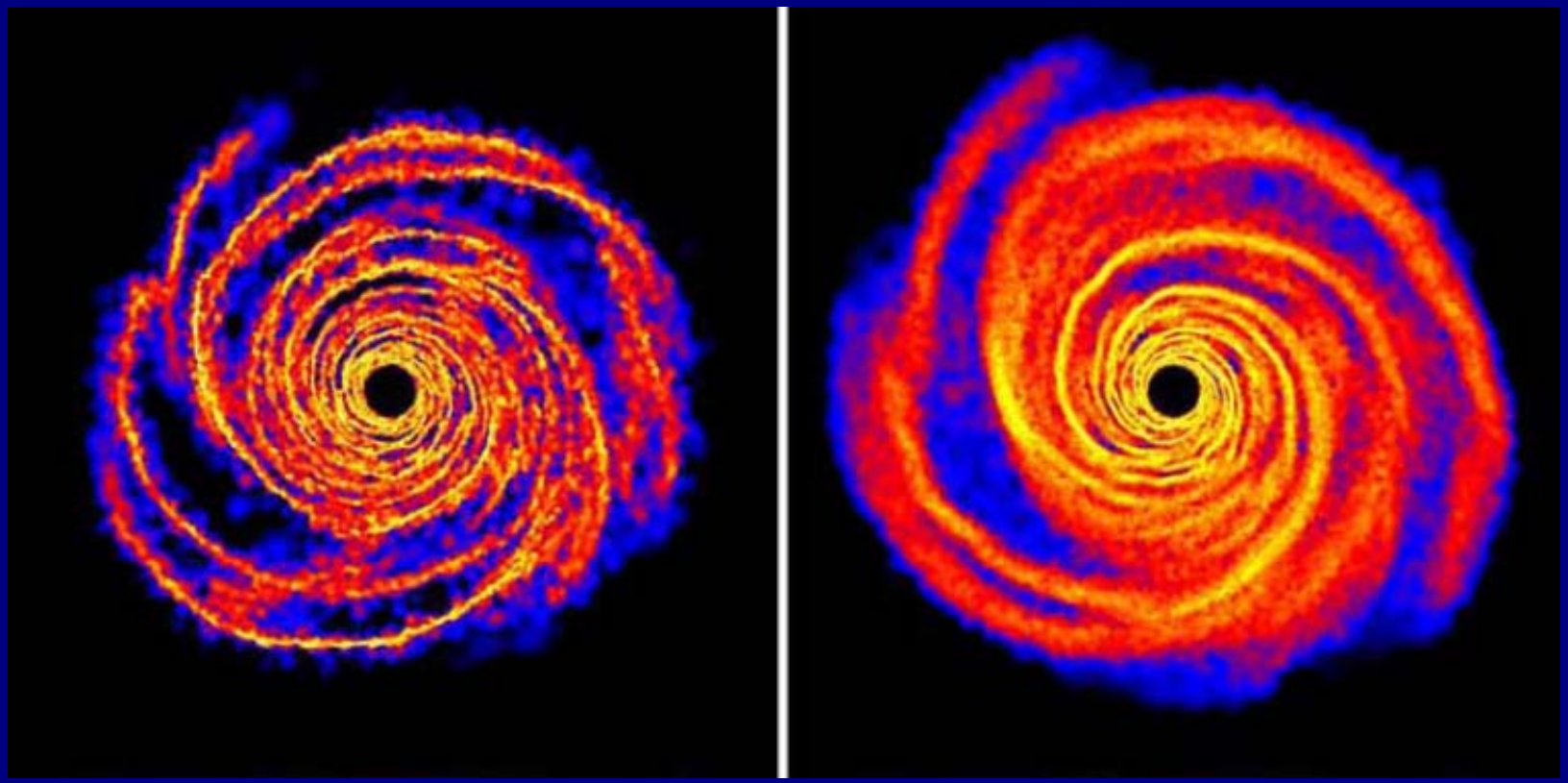
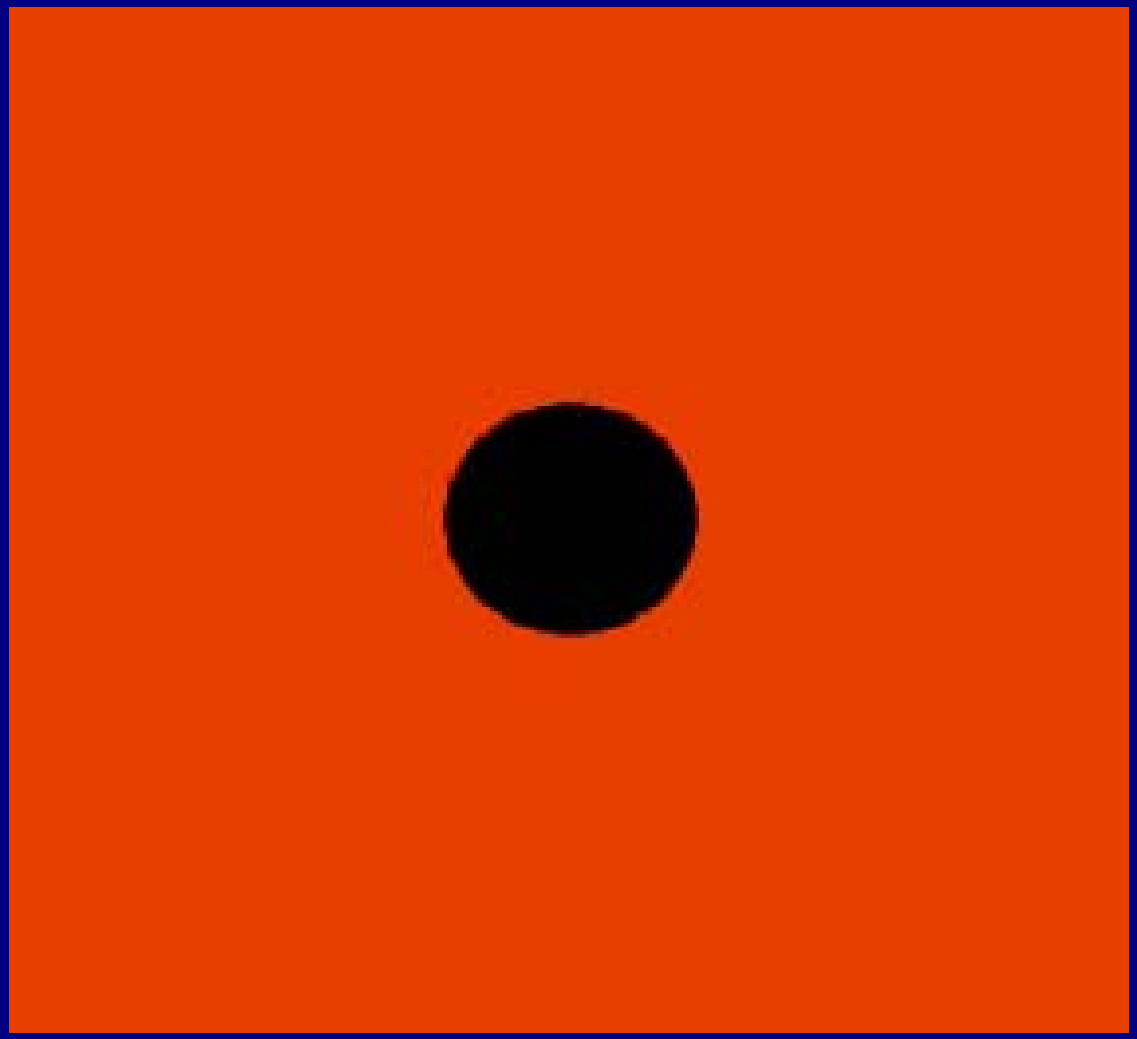


Rice, Lodato et al. 2004

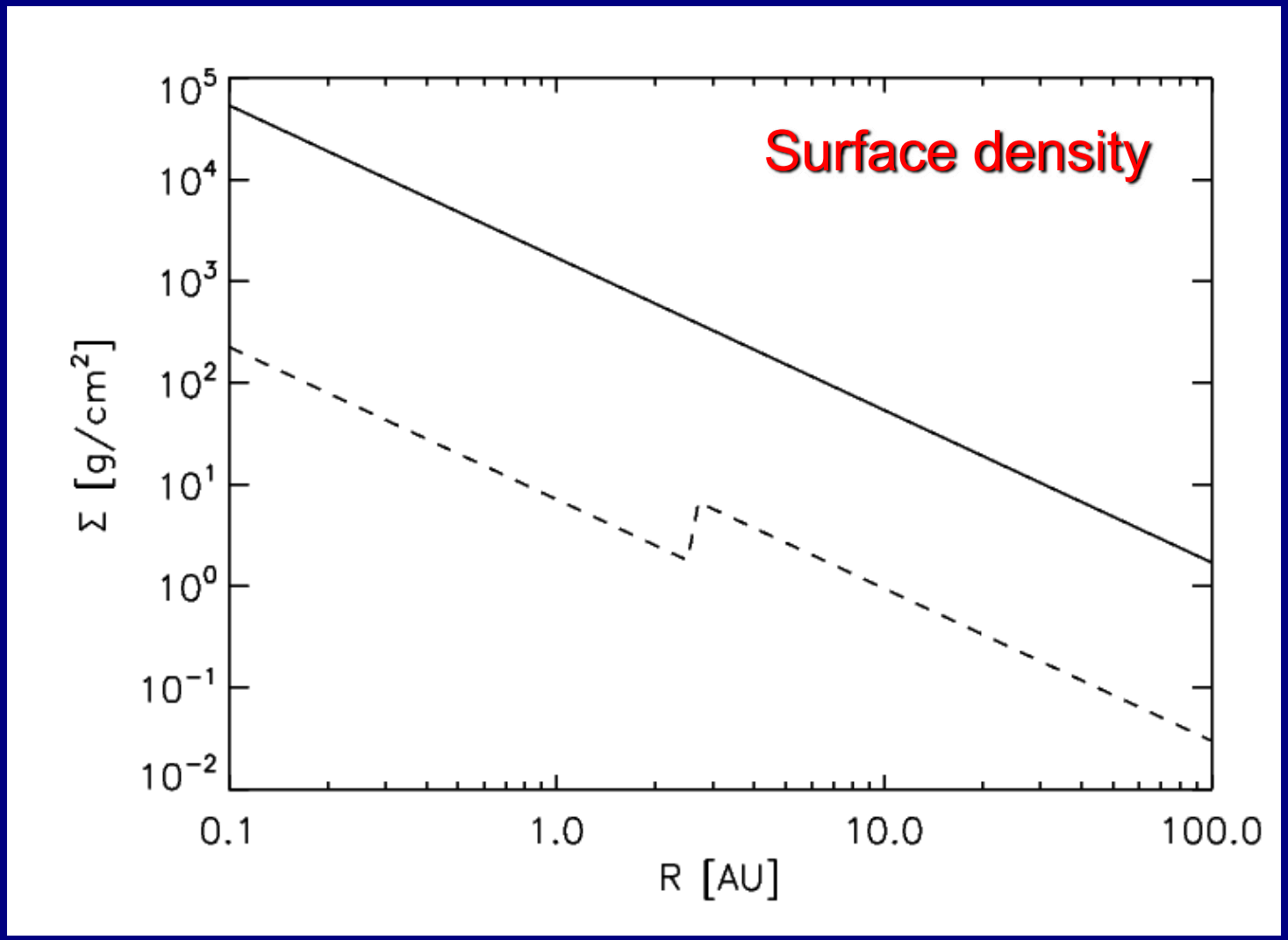
Planetary gaps and deviations from Kepler

Planet gap opening



Credit: Frederic Masset

Is the gap really empty?



Minimum Mass Solar Nebula

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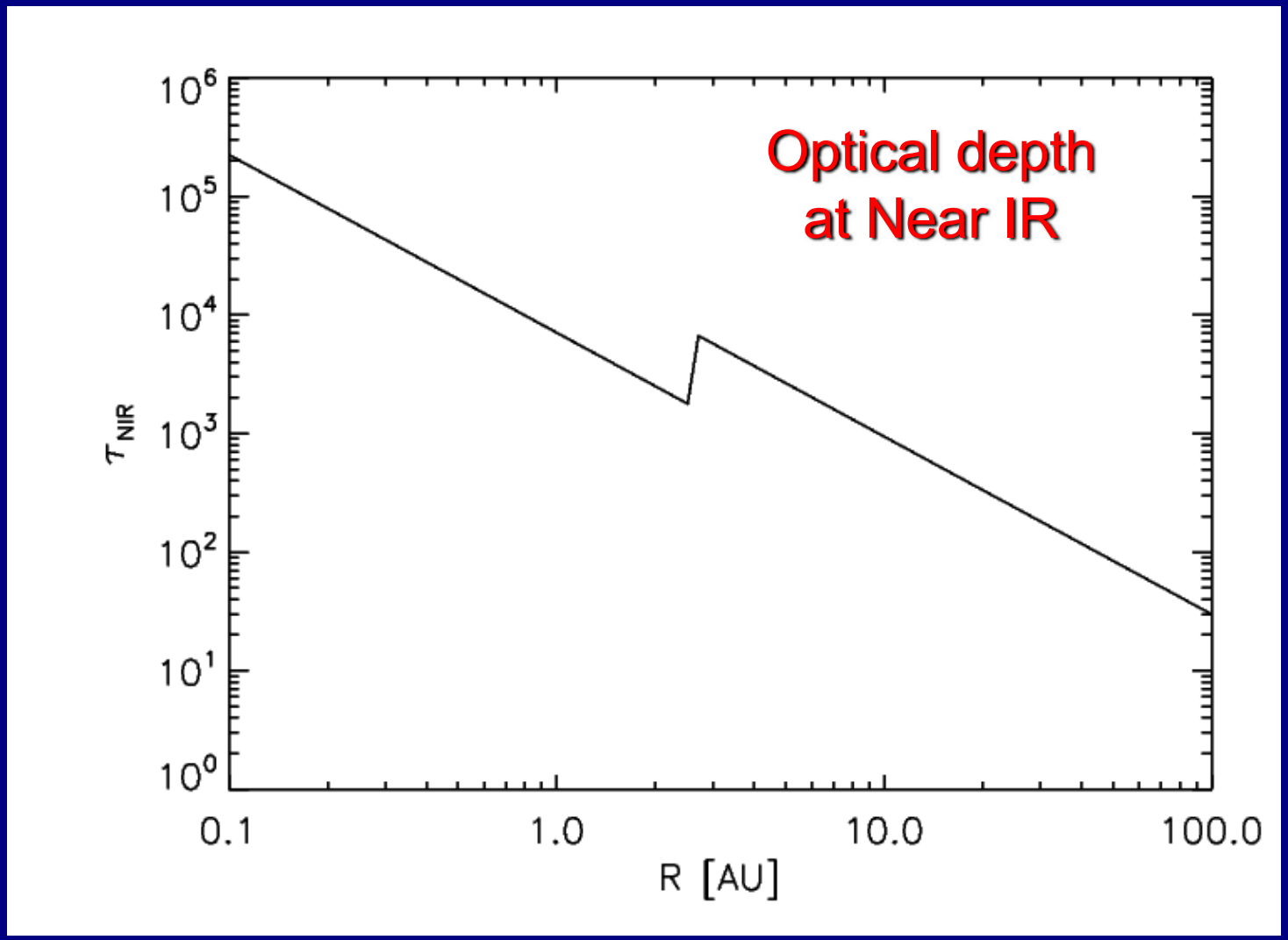

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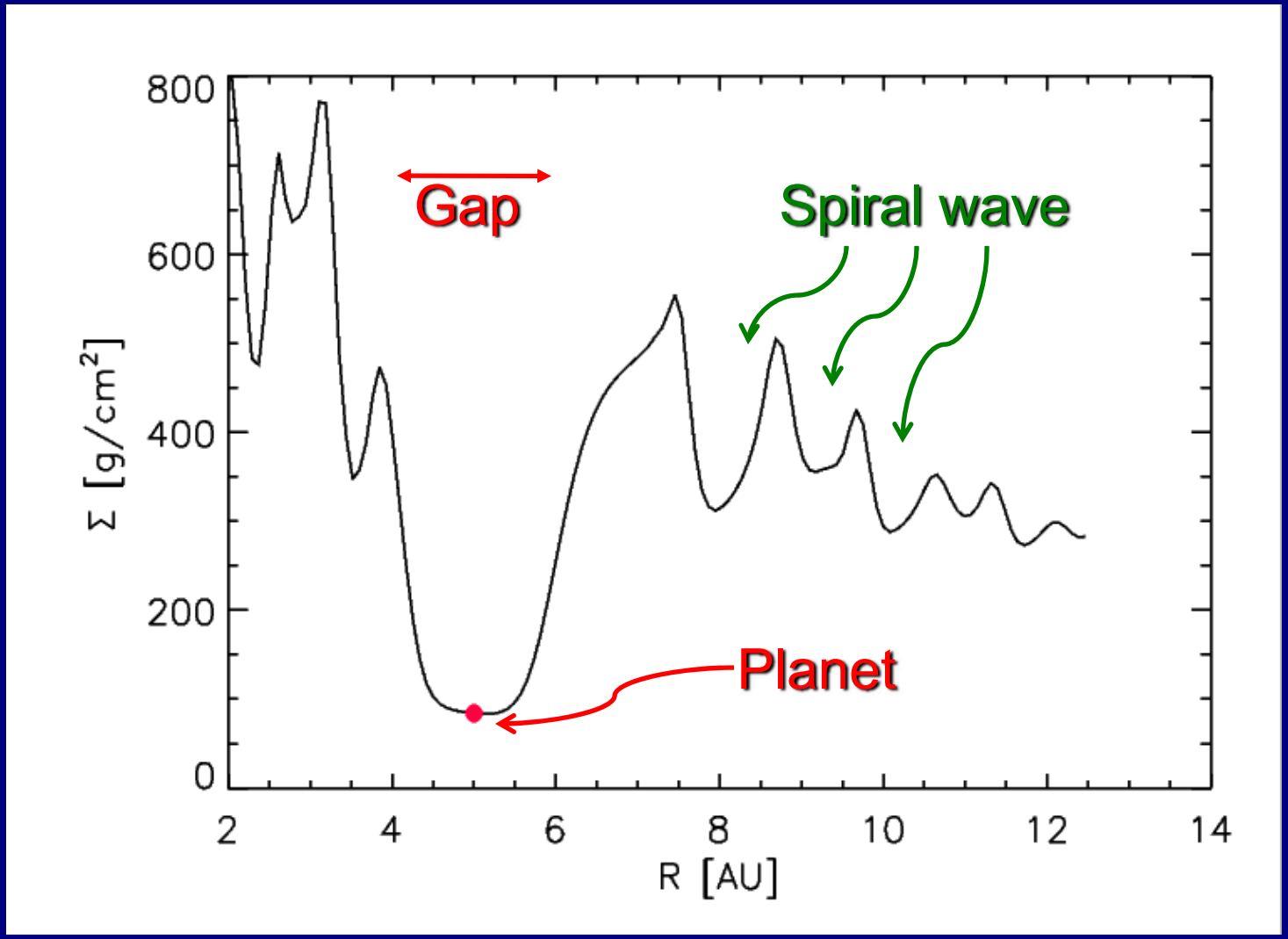
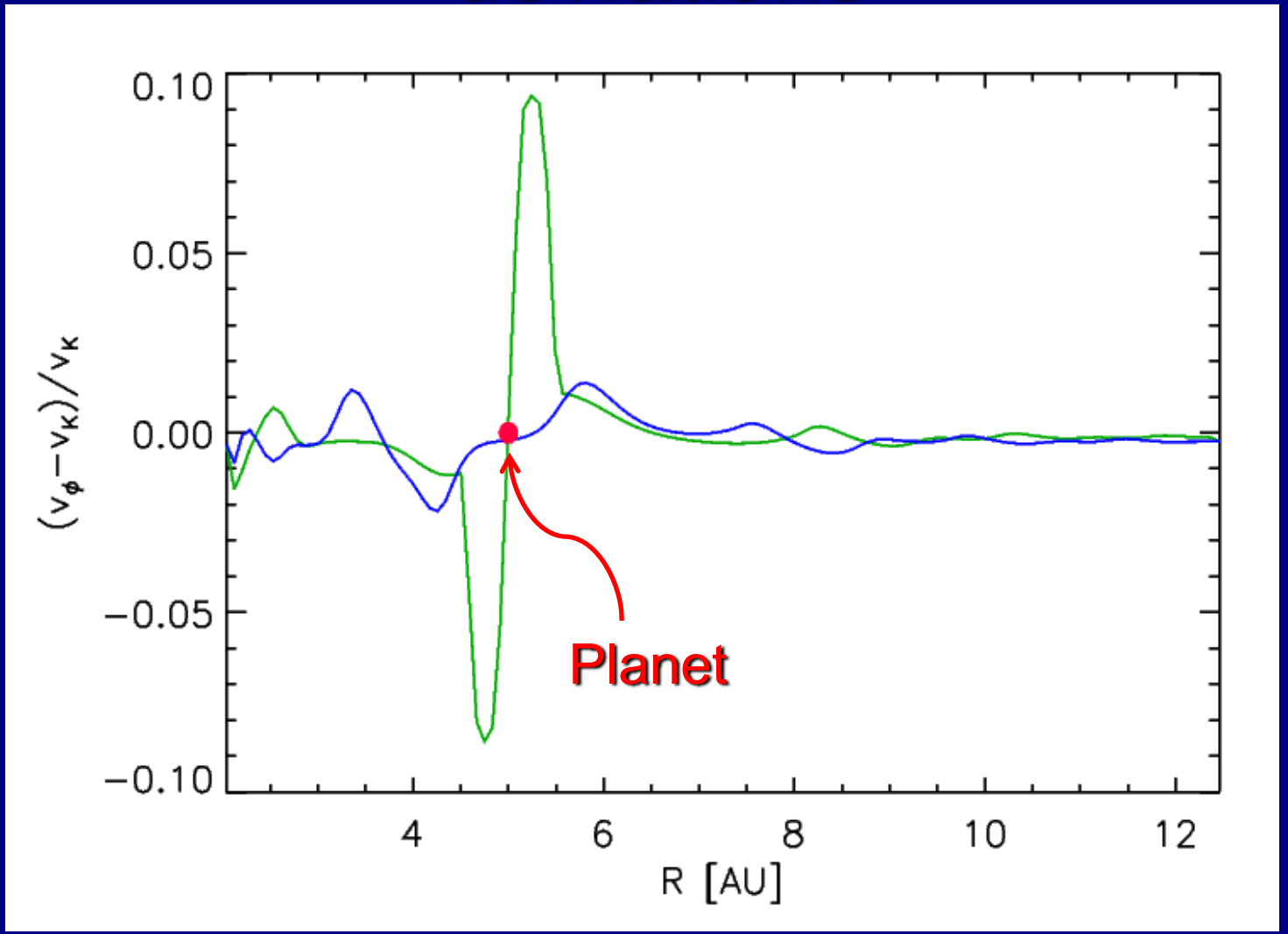
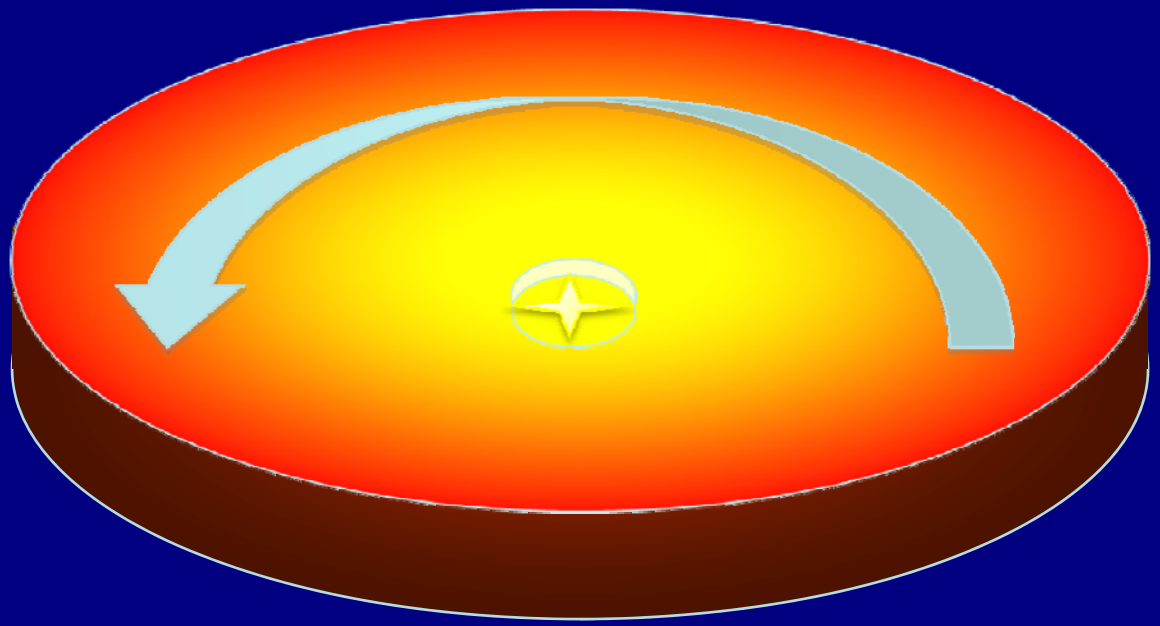


The answer is: often not! Only for very massive planets

Detecting gap by probing Kepler-deviations



forming zone

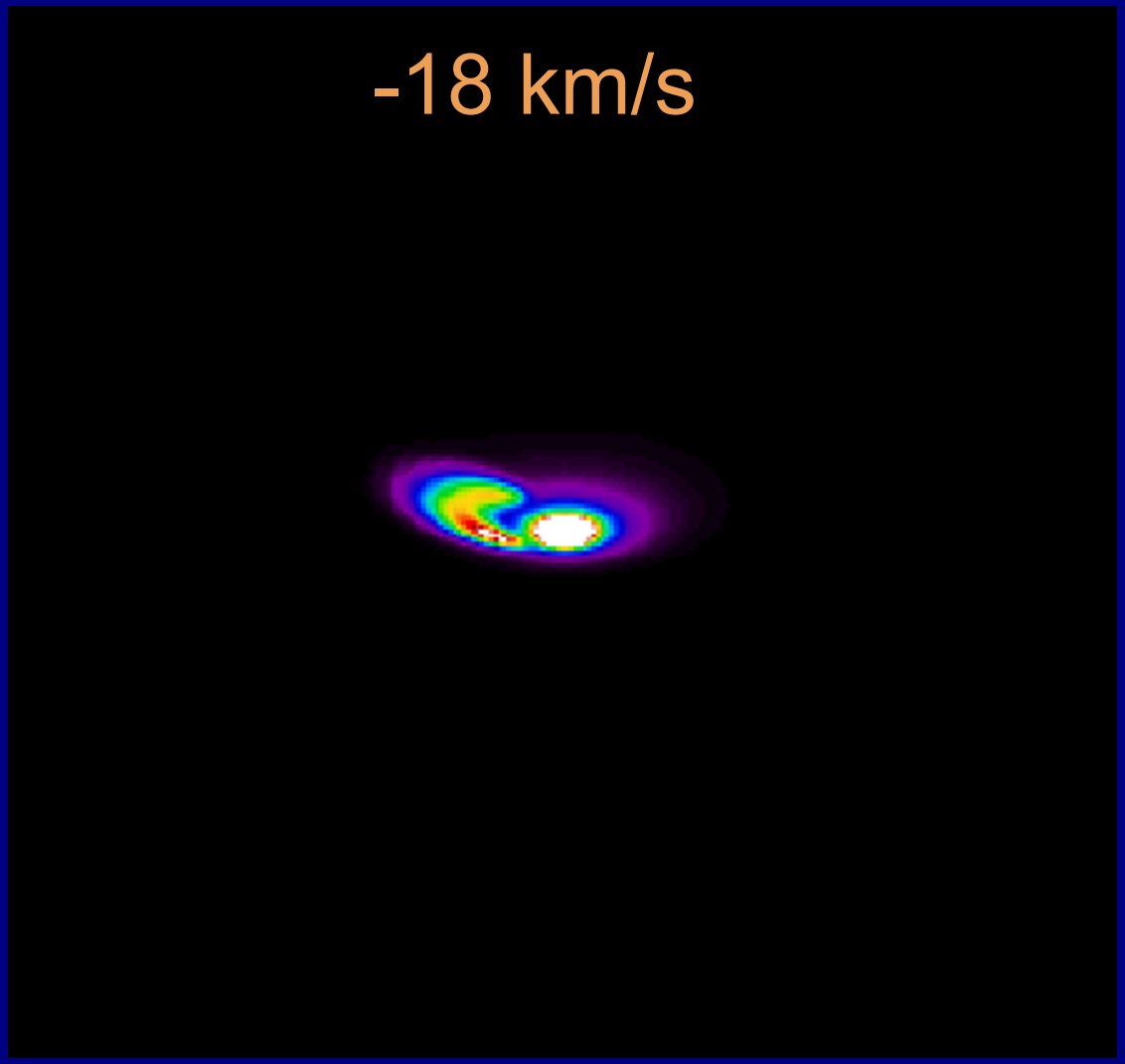


forming zone

3 ❍m H_2O hot band lines, 1 $M_\odot$ star

Model made with RAD-Lite by Klaus M. Pontoppidan and Cornelis P. Dullemond

Includes gas lines *and* dust continuum



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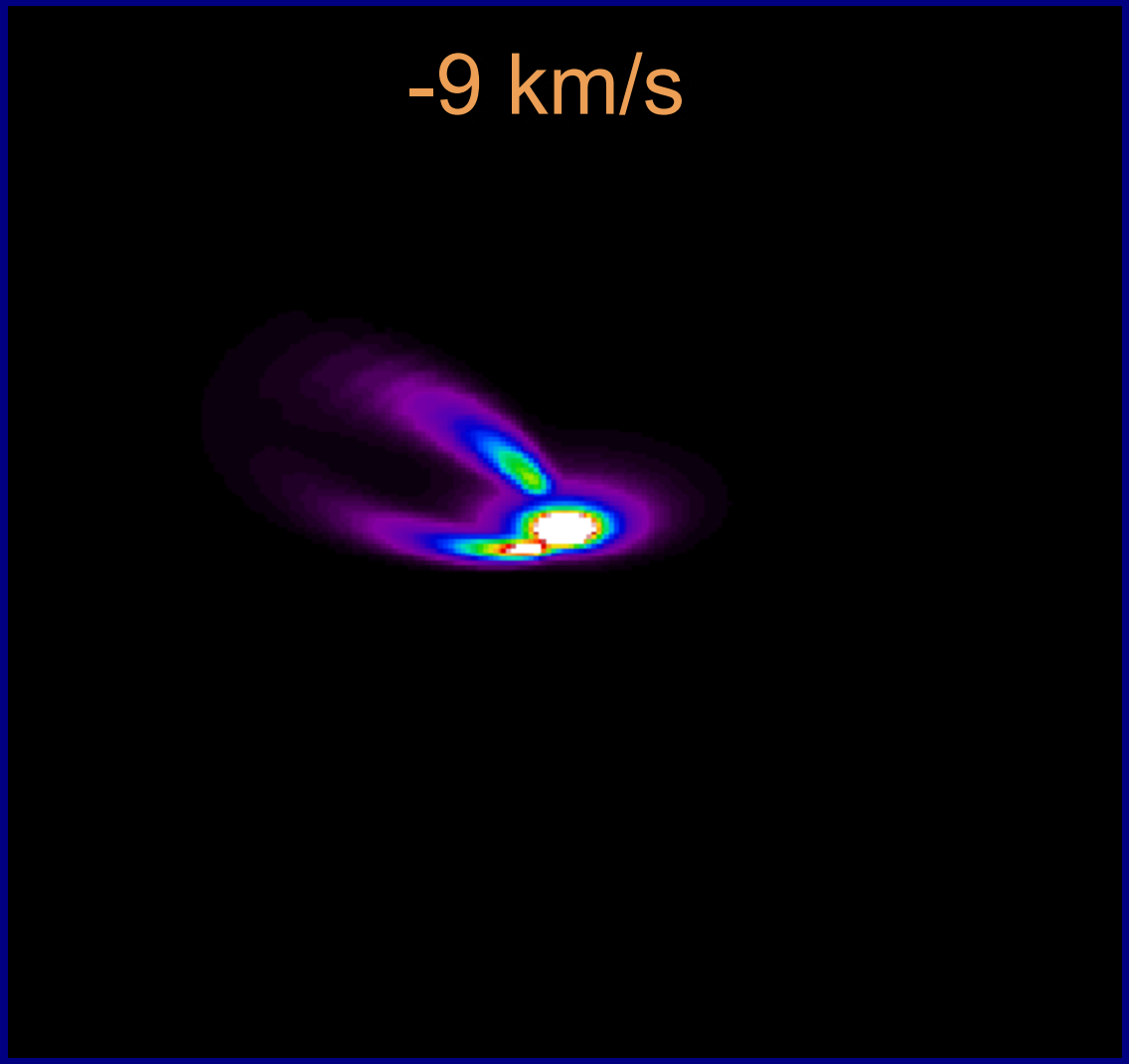

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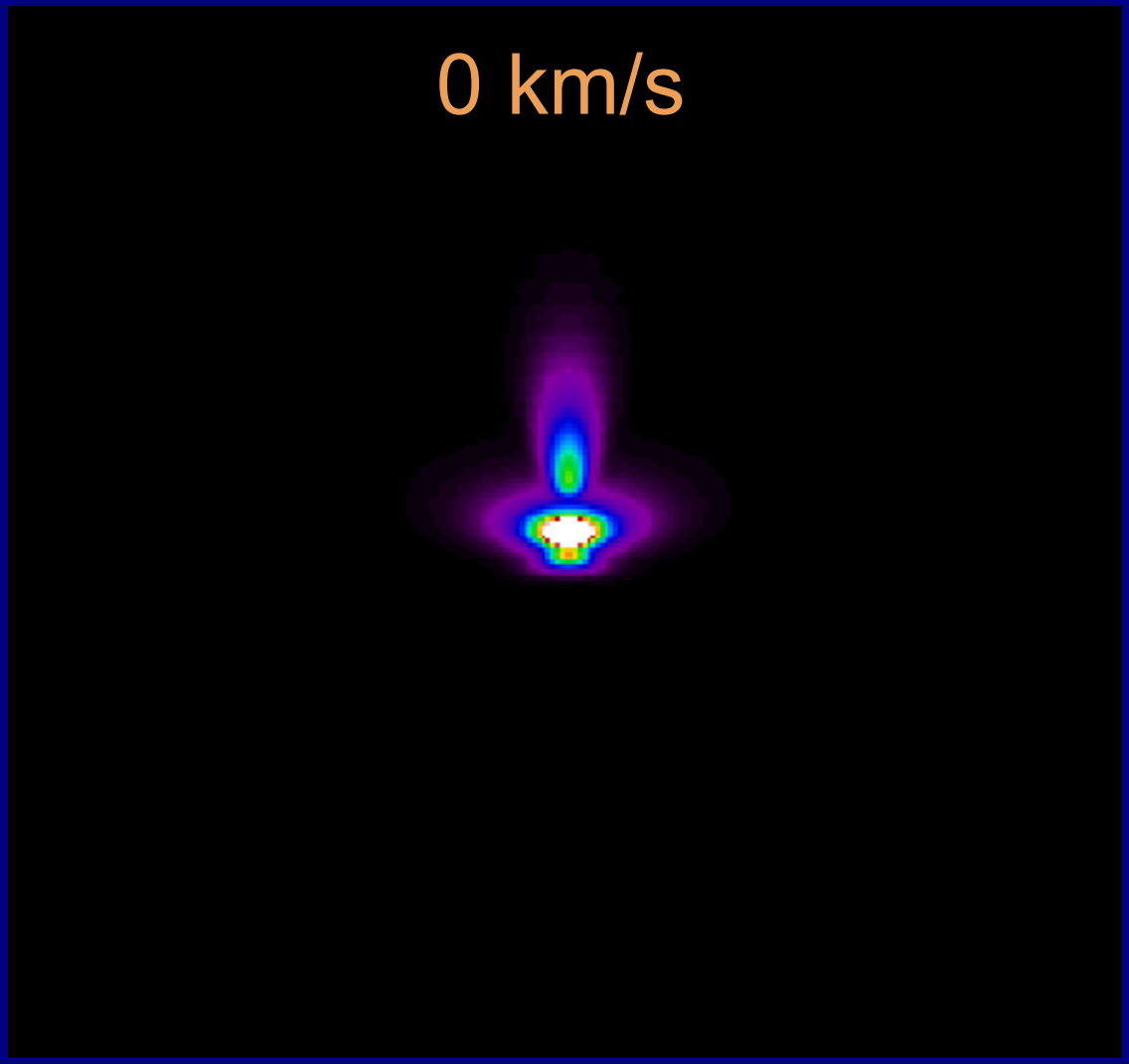

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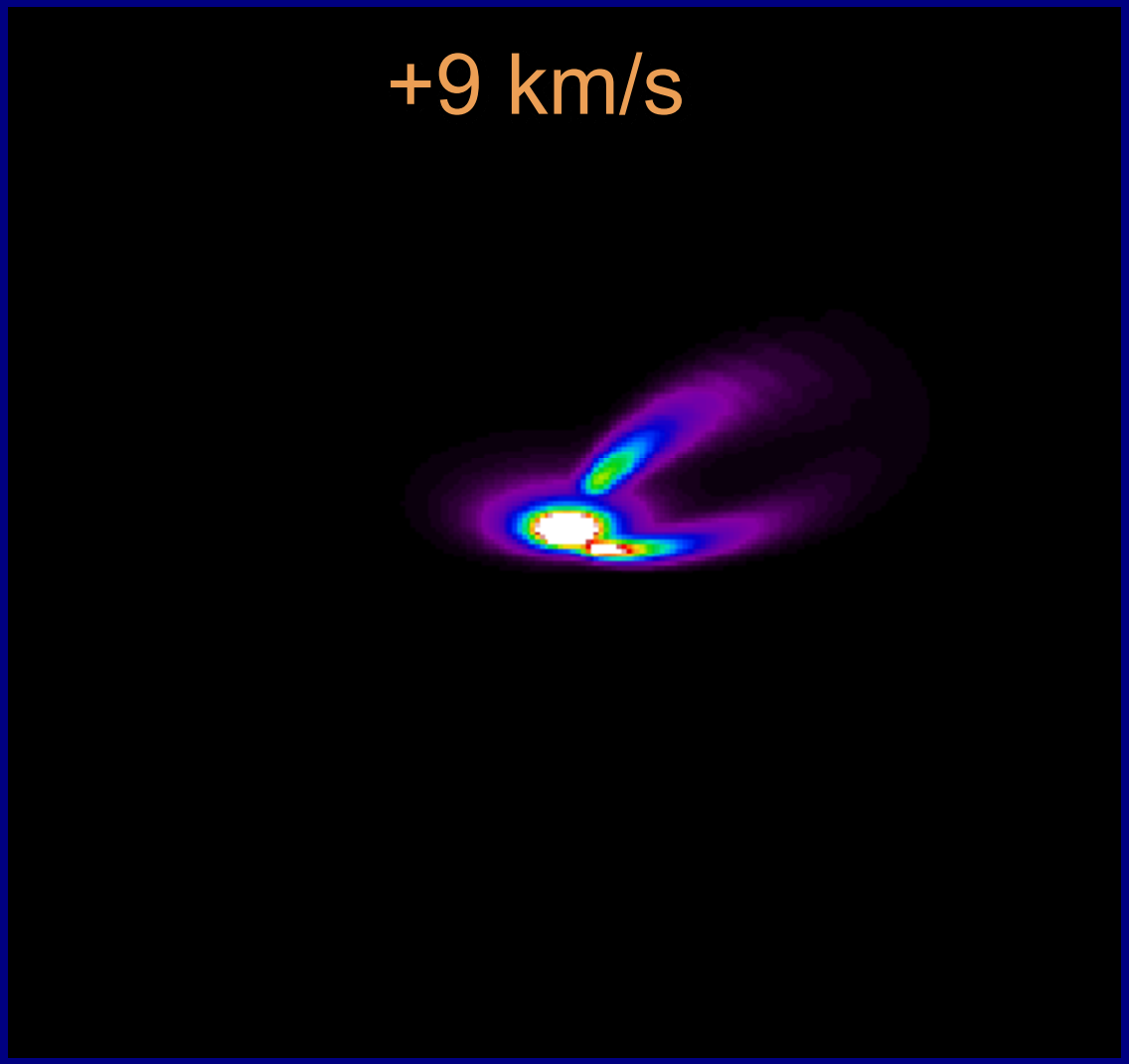

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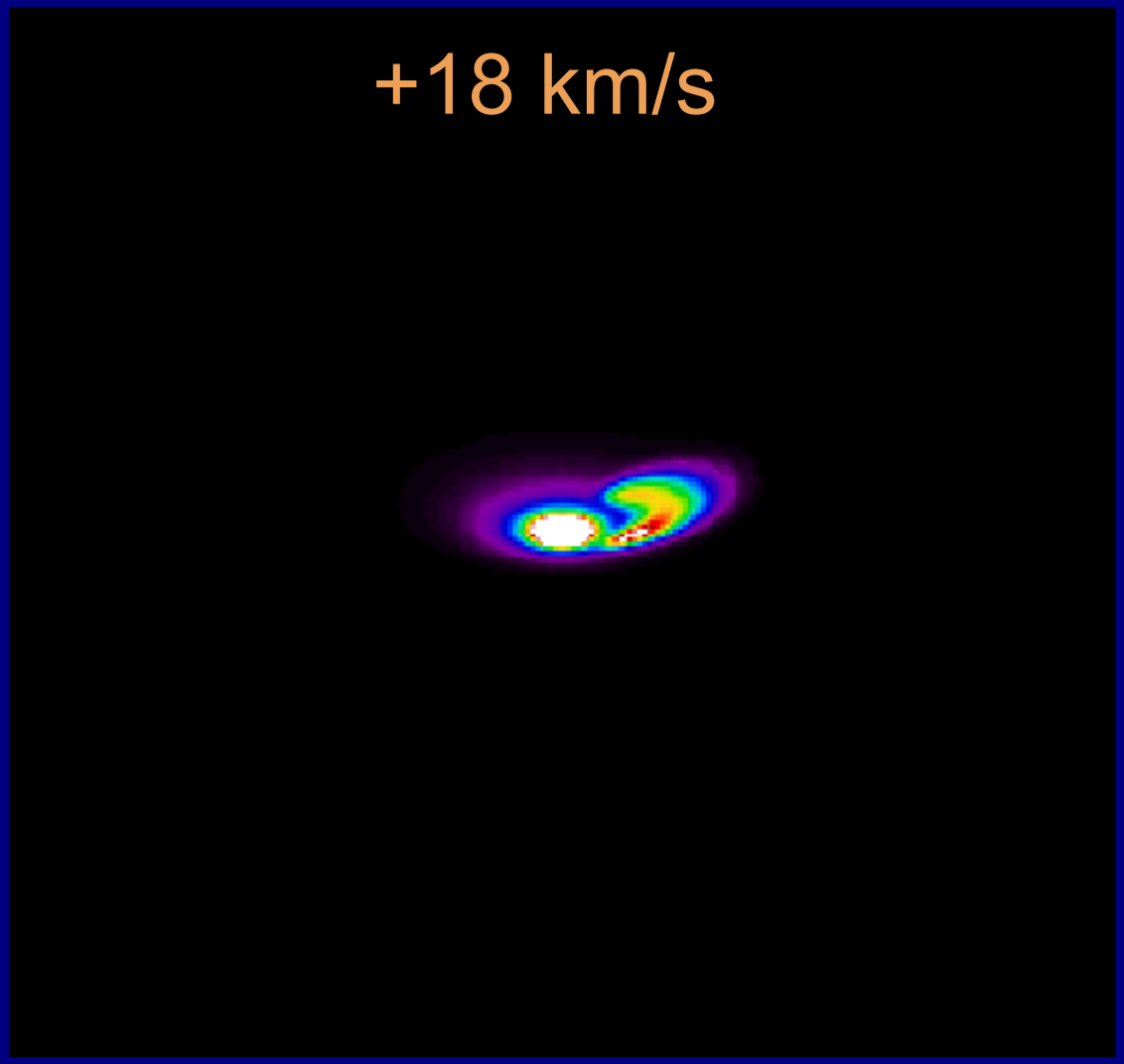

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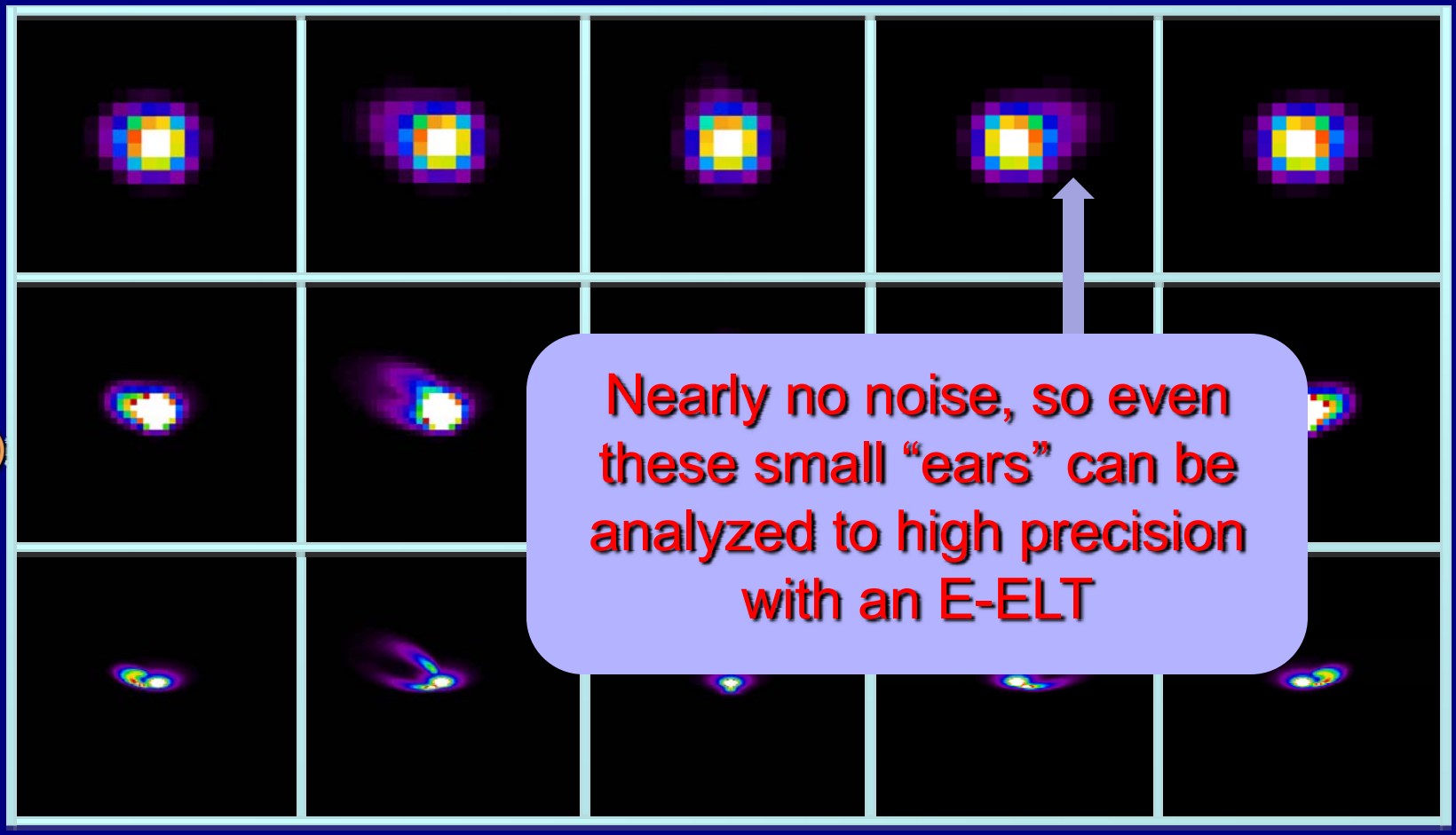


Resolution: E-ELT 42 meter

3 ❍m H_2O hot band lines

Probing mixing and turbulence

Crystallinity: Measuring Prandtl number

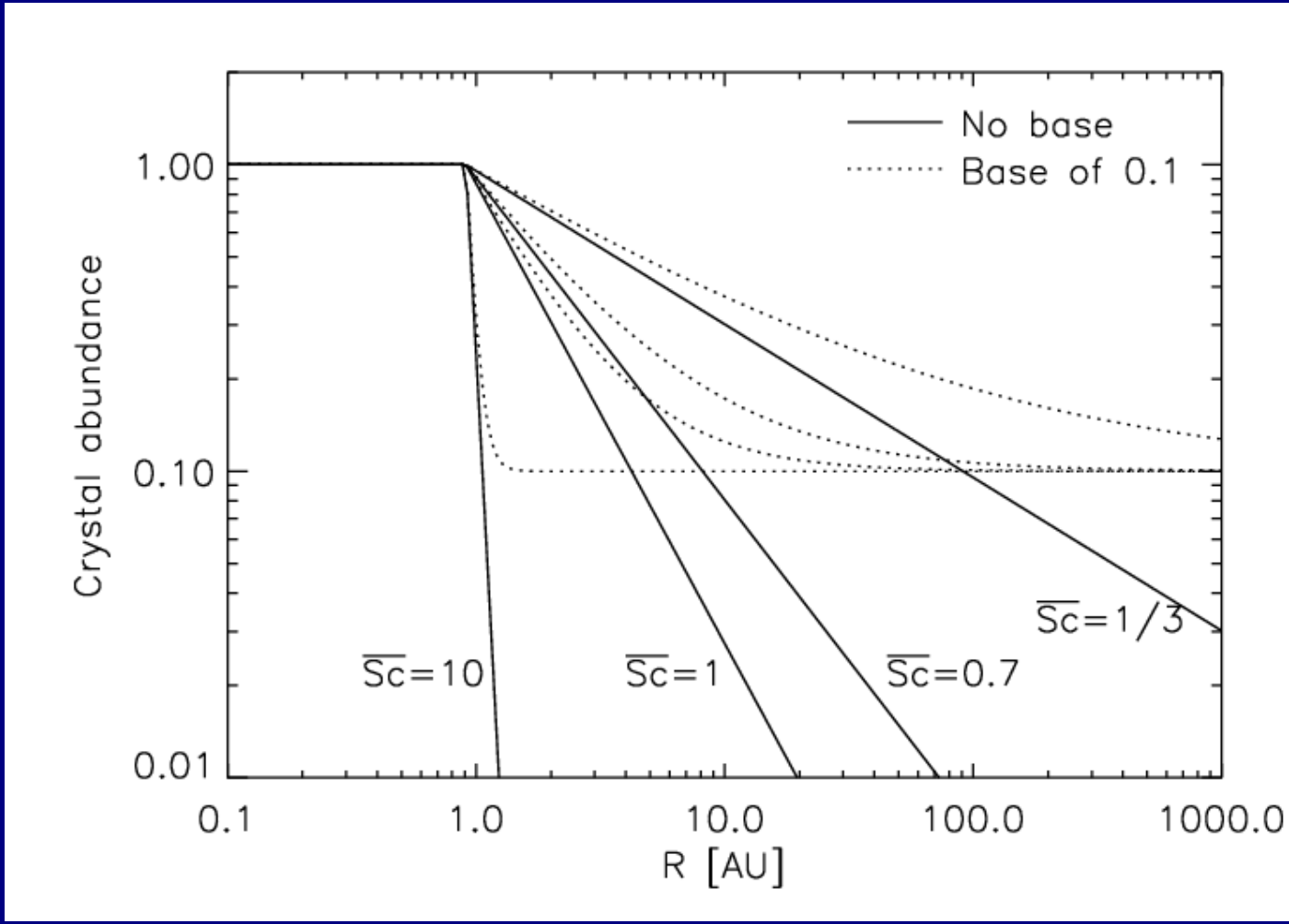
Prandtl number (or better: “Schmidt number”) is:

$$Sc = \frac{\nu_{viscosity}}{D_{turb-mixing}}$$

One of the most crucial, but completely unknown parameters in the theory of planet formation!

Links mixing and coagulation to the (measureable) accretion rate in the disk.

Crystallinity: Measuring Prandtl number



Pavlyuchenkov & Dullemond, 2007

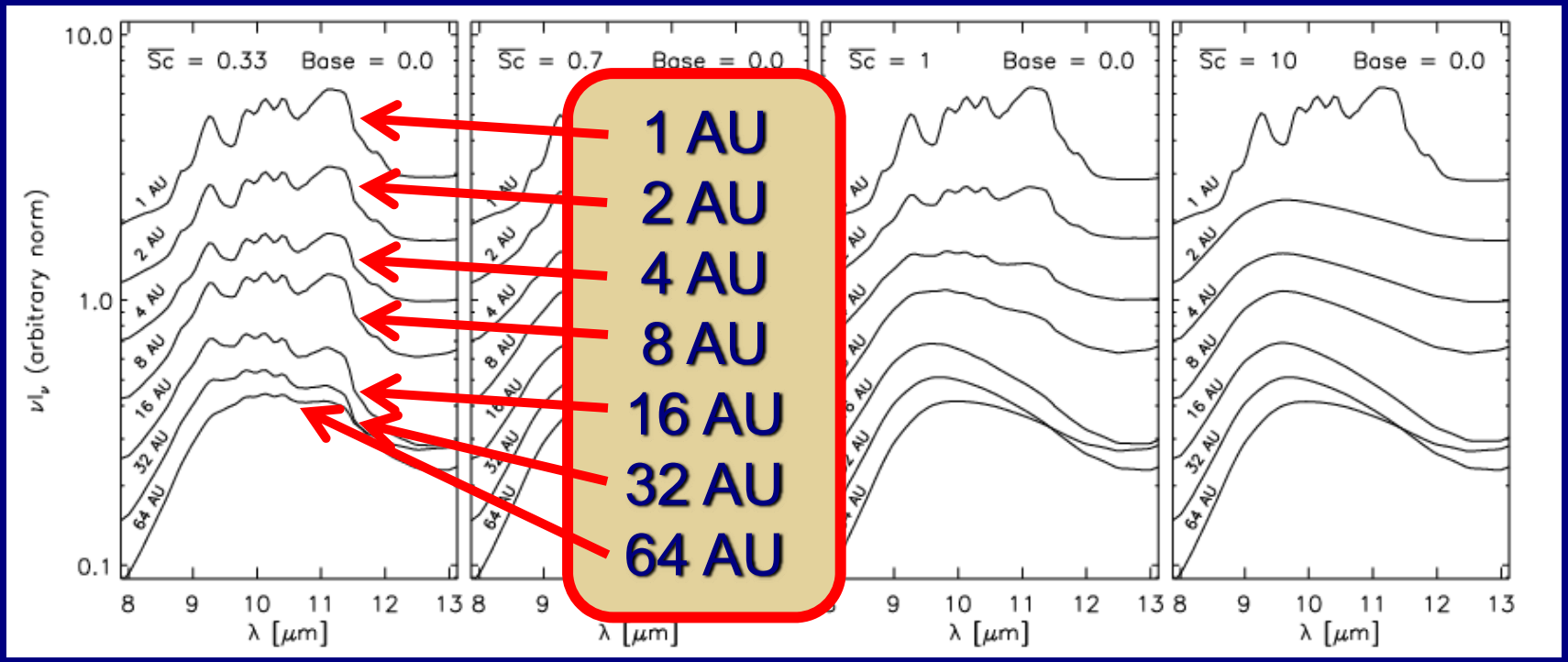
Crystallinity: Measuring Prandtl number

Predicted N-band spectra as a function of R-coordinate:

Strong mixing ⟷ Weak mixing

Inner Disk

Outer Disk



Pavlyuchenkov & Dullemond, 2007

Conclusions

- Near- and Mid-Infrared are bonanzas of diagnostics of protoplanetary disks:
  - Dust composition in earth-forming region
  - Rich set of atomic / rovib gas lines. [NeII], Water, Organics!
  - Kinematics of earth-forming region. Can we see planet formation in progress!?
- ELT with METIS provides:
  - Much higher sensitivity than VLT-I, plus true imaging capability (as opposed to VLT-MIDI / MATISSE)
  - Same resolving power as ALMA, but much higher sensitivity
  - Higher spatial resolving power than NGST