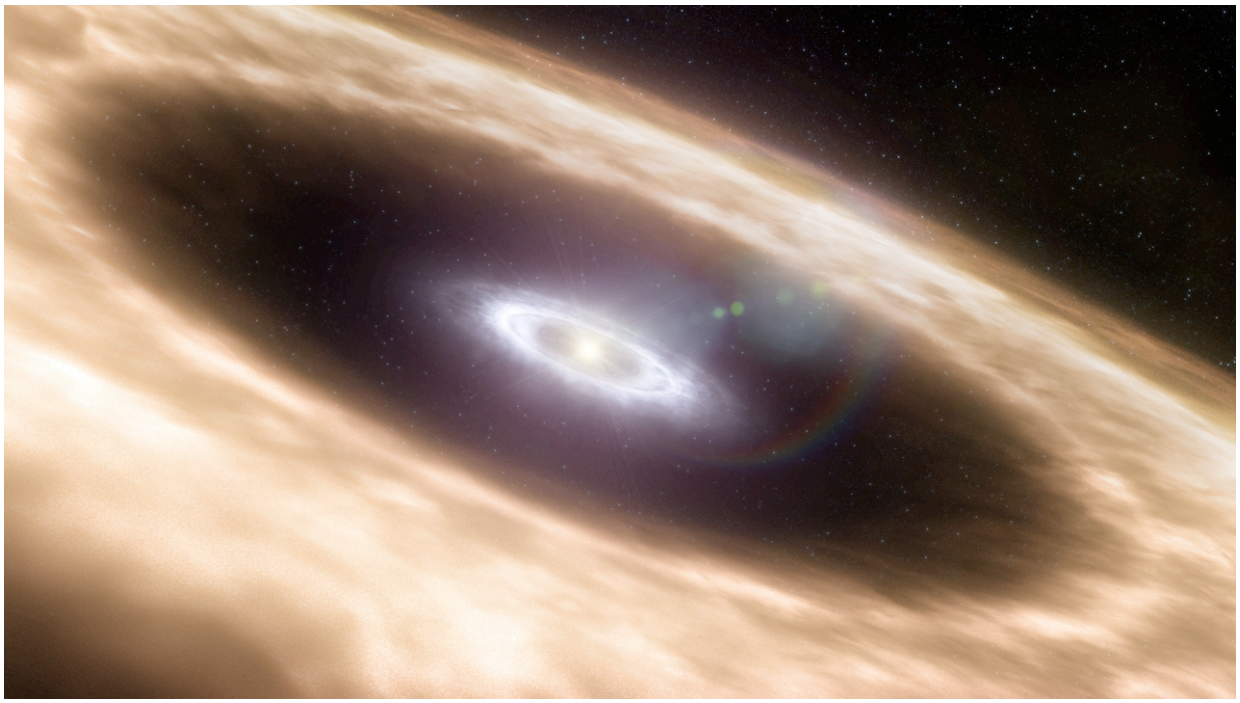

1 AU IMAGING OF GAS IN PROTOPLANETARY DISKS

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California Institute of Technology

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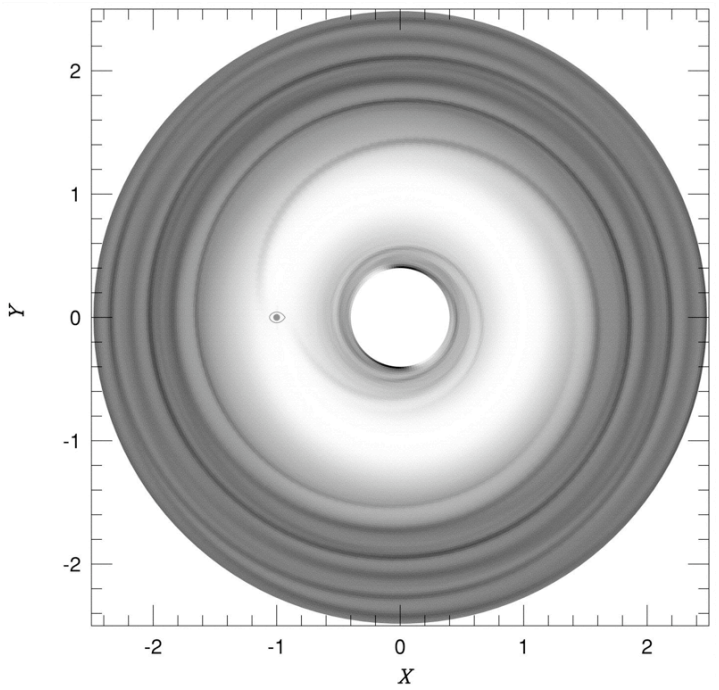
New light on young stars: Spitzer's view on circumstellar disks, October 2008

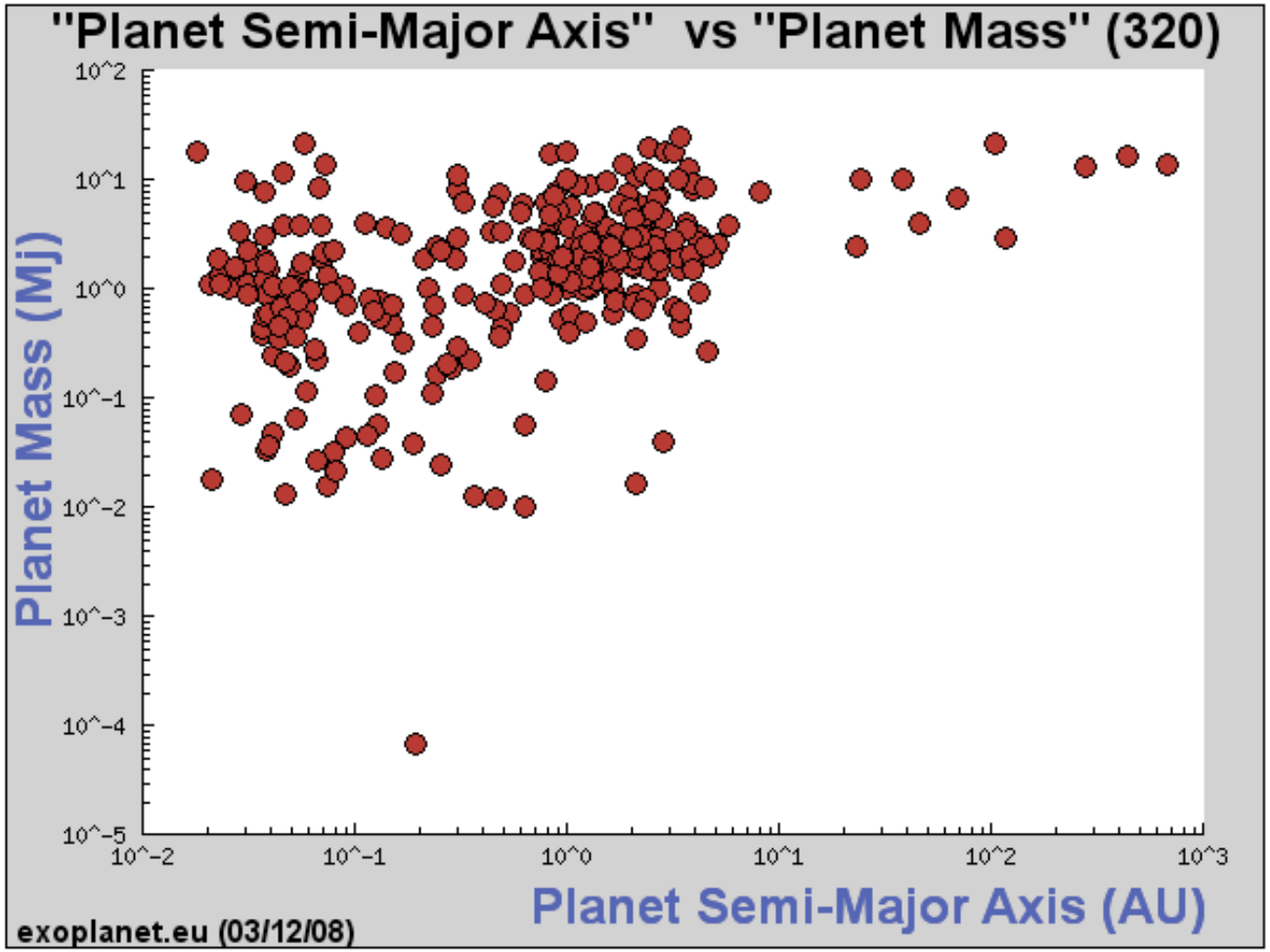
Evolution of the inner disk

- Dust and gas affected differently.
  - Opacity decrease through grain growth
  - Photo-processing - evaporation, chemistry
  - Planet-disk interactions and radial dust filtration
  - Stellar-mass companions causing complete clearing
- Observations of all phases needed to test models.



Kley et al. 2001

PLANETS FORM AT RADII OF 1-10 AU

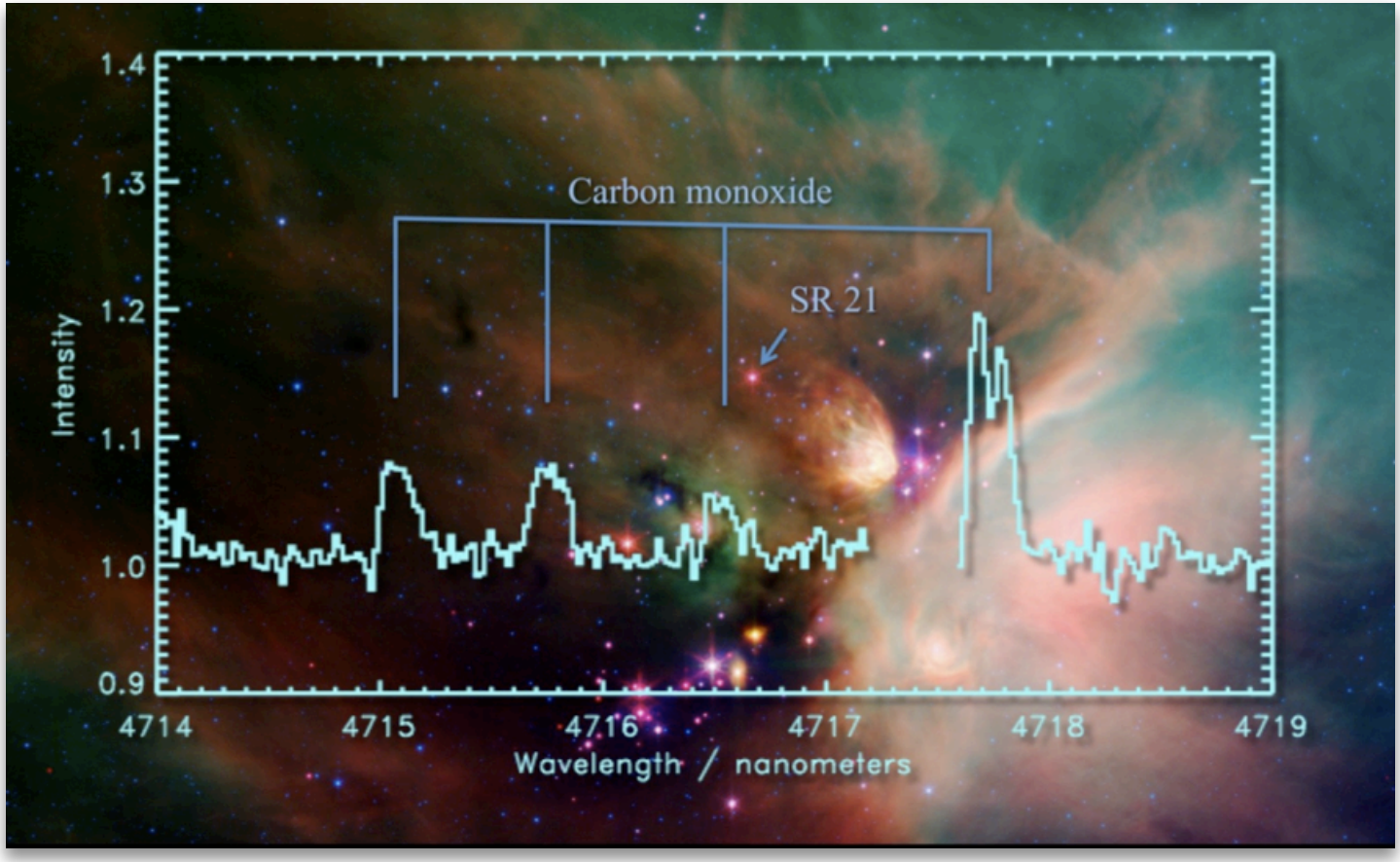


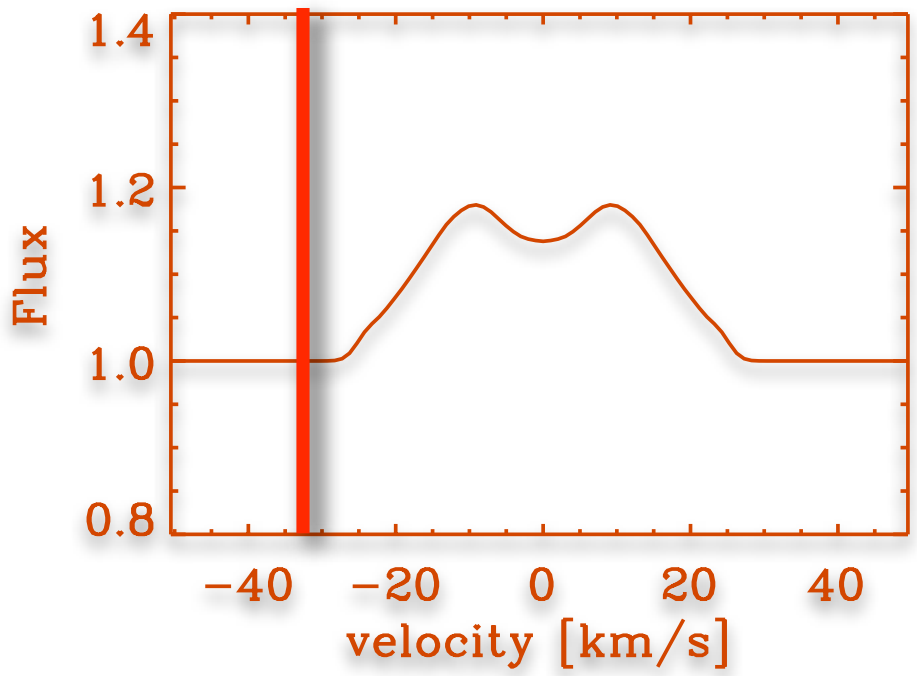
How can the planet-forming region be observed?

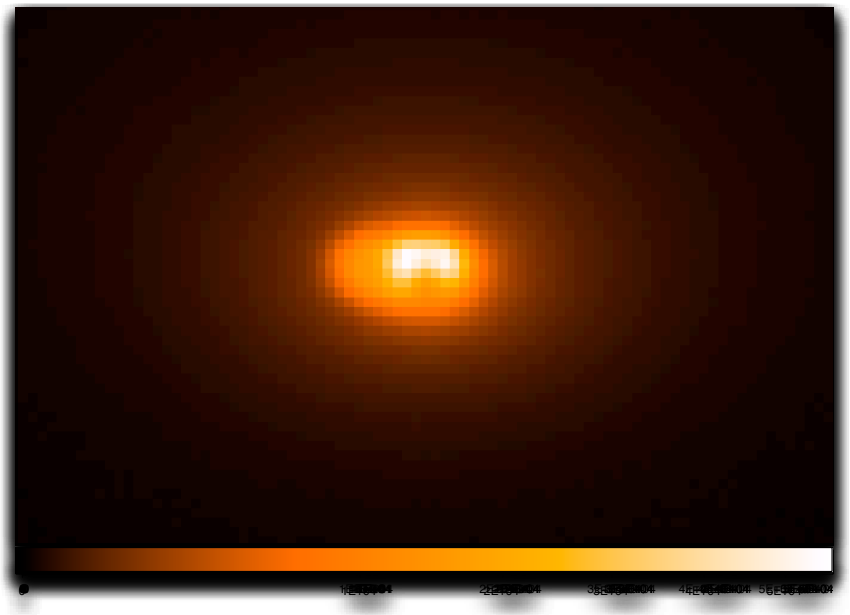
- 1-10 AU = 7-70 milli-arseconds @ Taurus.
- Spatially resolved tracers: gas or dust.
  - Scattered light - visible/NIR (e.g., Roberge et al. 2005).
    - 100 mas
  - Thermal dust emission - NIR/MIR interferometry (e.g. van Boekel et al. 2004)
    - 10 mas
  - Gas continuum emission - NIR interferometry (e.g. Akeson et al. 2005, Eisner et al. 2008, Tannirkulam et al. 2008)
    - 1 mas
  - Atomic lines - OI – visible (Acke & Ancker 2006).
    - 10 mas
  - Molecular lines - IR/submm/mm (Goto et al. 2006)
    - 150 mas
- Spectro-astrometry of CO – ***<1 mas*** imaging of lines with ***kinematic information.***

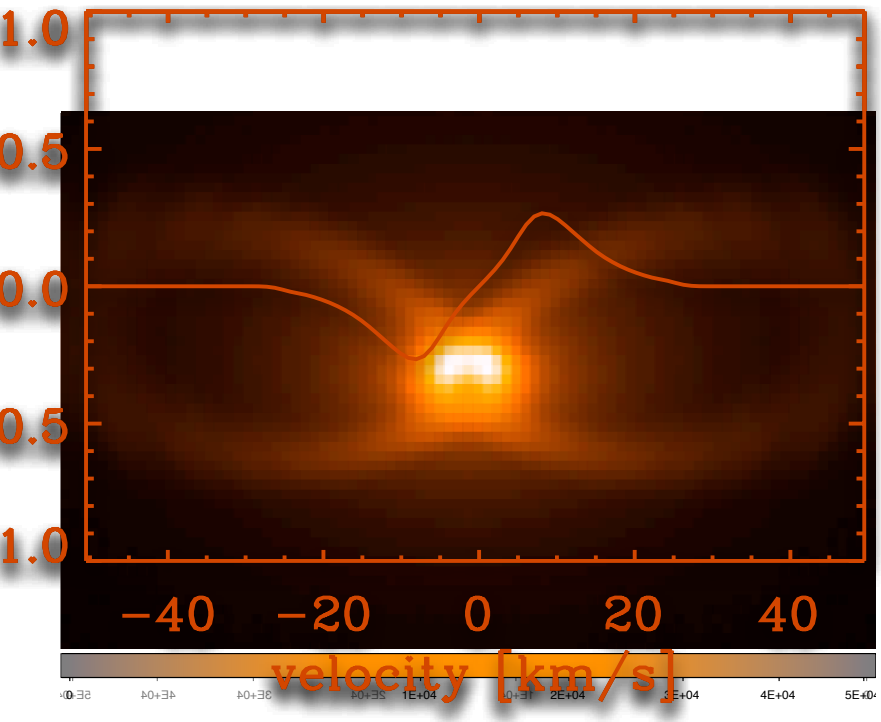
INFRARED MOLECULAR LINES AS TRACERS OF INNER DISKS

VLT-CRIRES



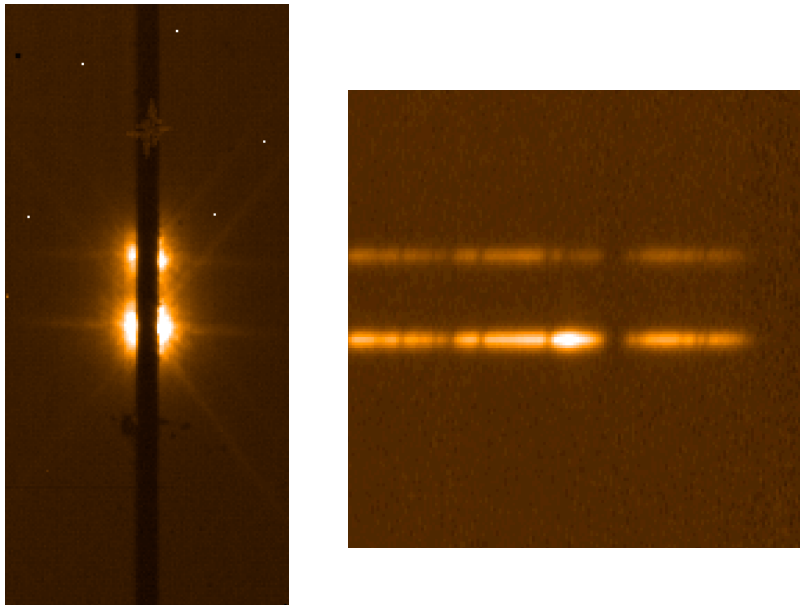

1.4
1.2
1.0
0.8
Flux
−40
−20
0
20
40
velocity [km/s]



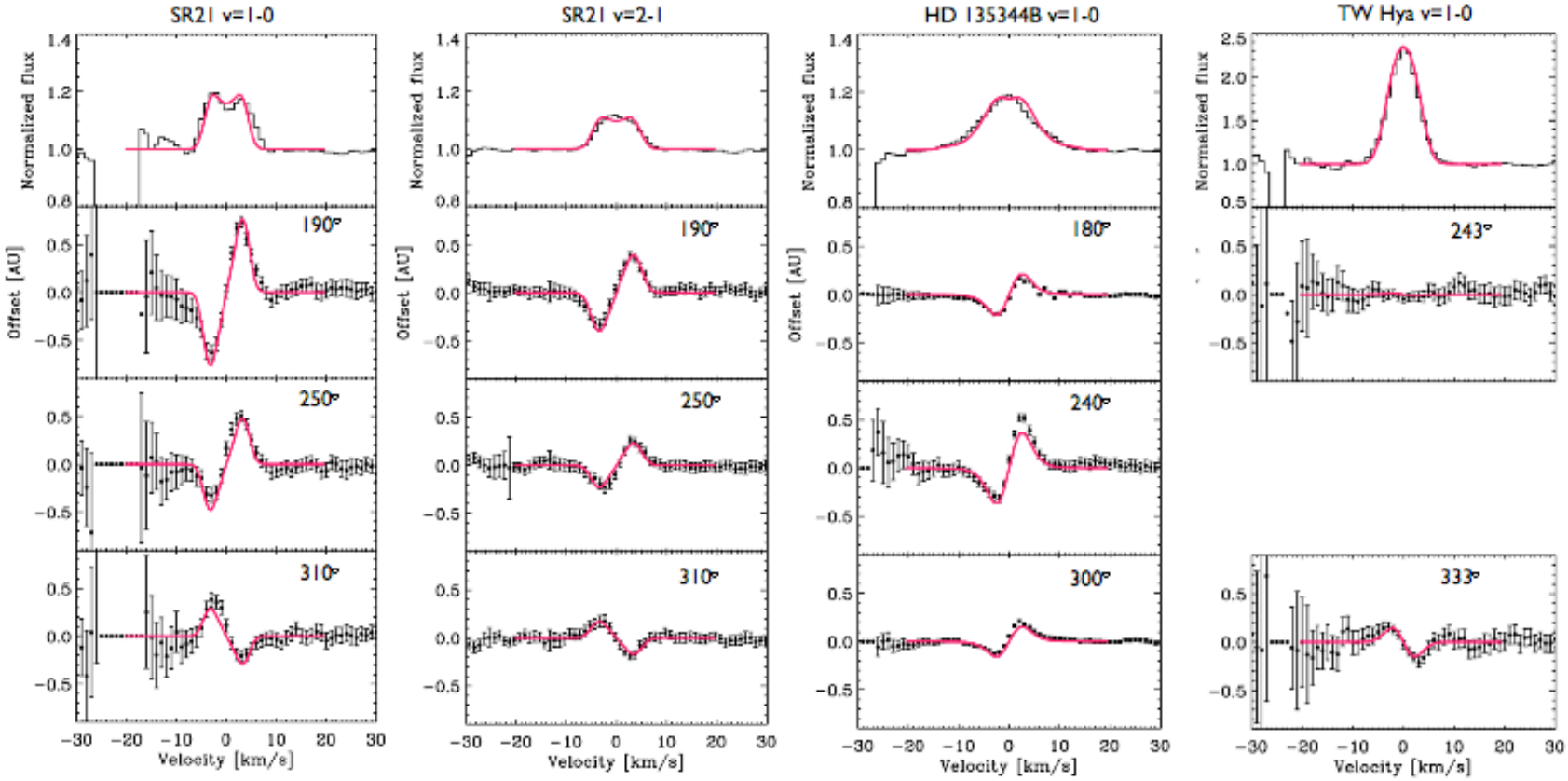

1.0
0.5
0.0
−0.5
−1.0
position [AU]
−40
−20
0
20
40
velocity [km/s]

SUPER-RESOLUTION WITH VLT-CRIRES SPECTRO-ASTROMETRY

- R=100,000 @ 1-5 micron.
- AO-fed.
- Photo-center offsets measured to ~200 micro-arcseconds.
- Data shown part of large program survey of protoplanetary disks (27 VLT nights).
- CRIRES spectro-astrometry now offered to community.



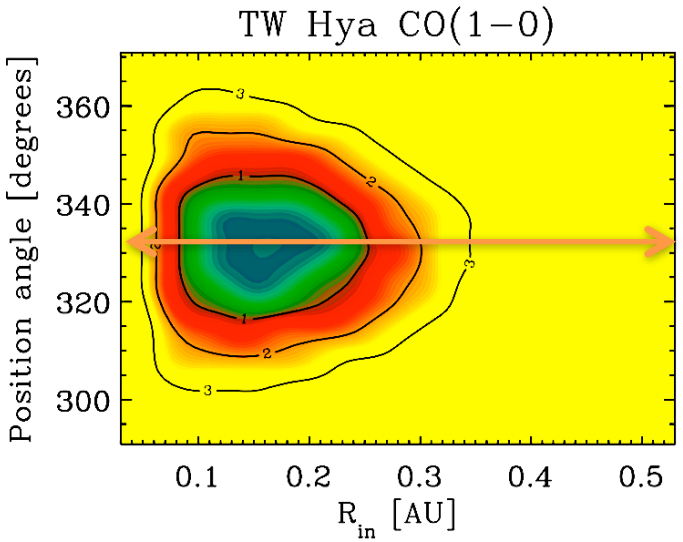
SPECTRO-ASTROMETRY DATA

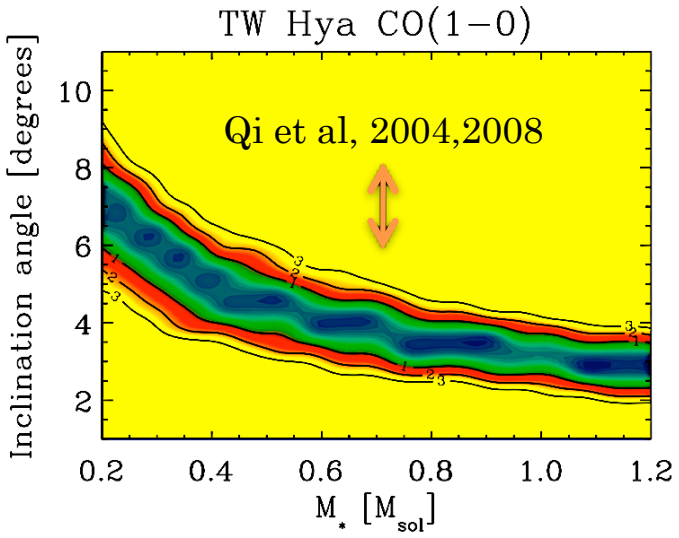


Pontoppidan et al., 2008, ApJ, 684, 1323

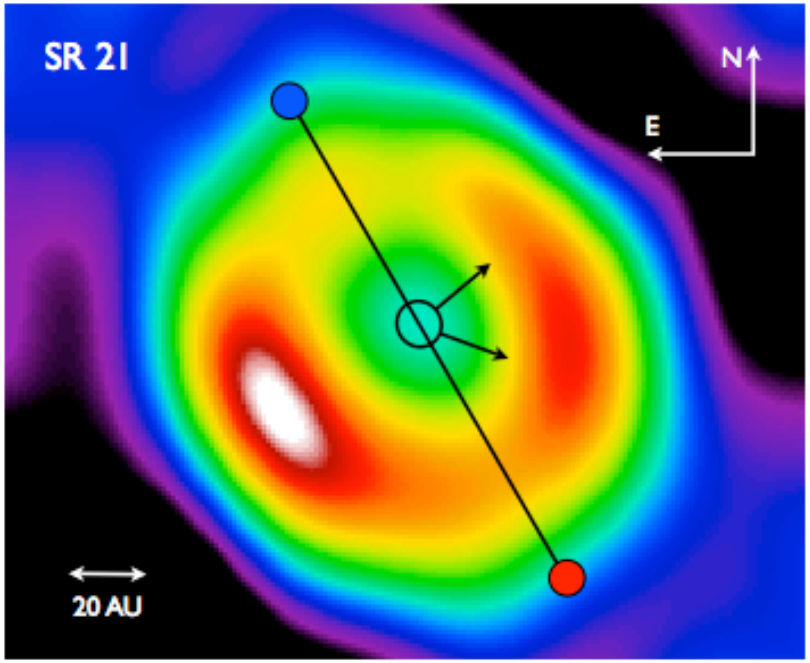
Determination of disk inclination, position angles and size

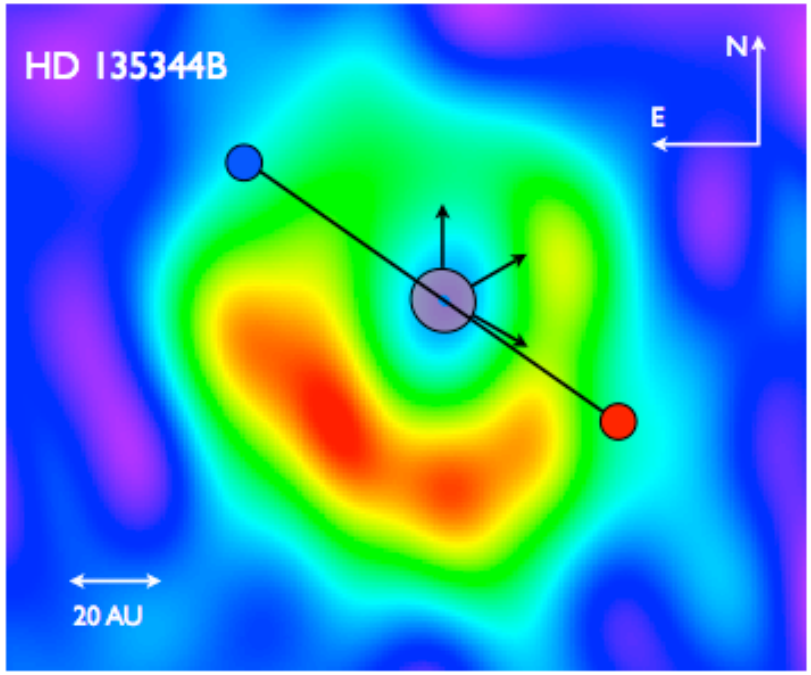
- Best-fit inner edge at 0.15+/-0.07 AU.
- Best-fit inclination: 4+/-1^{o}
- Spectro-astrometric imaging matches the outer disk!
- A difference in inclination between inner (4 degrees) and outer (7 degrees) disk may indicate a warp.





CO SPECTRO-ASTROMETRY FINDS GAS INSIDE THE DUST GAPS OF TRANSITION DISKS

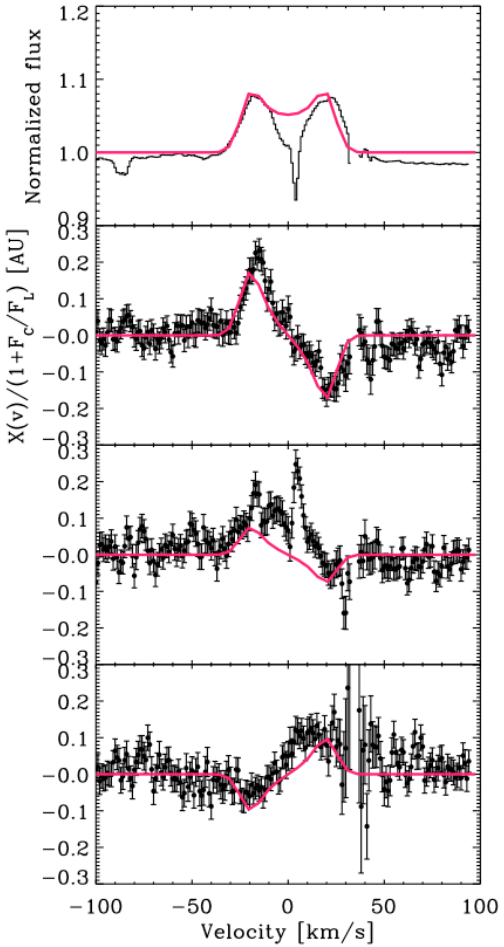


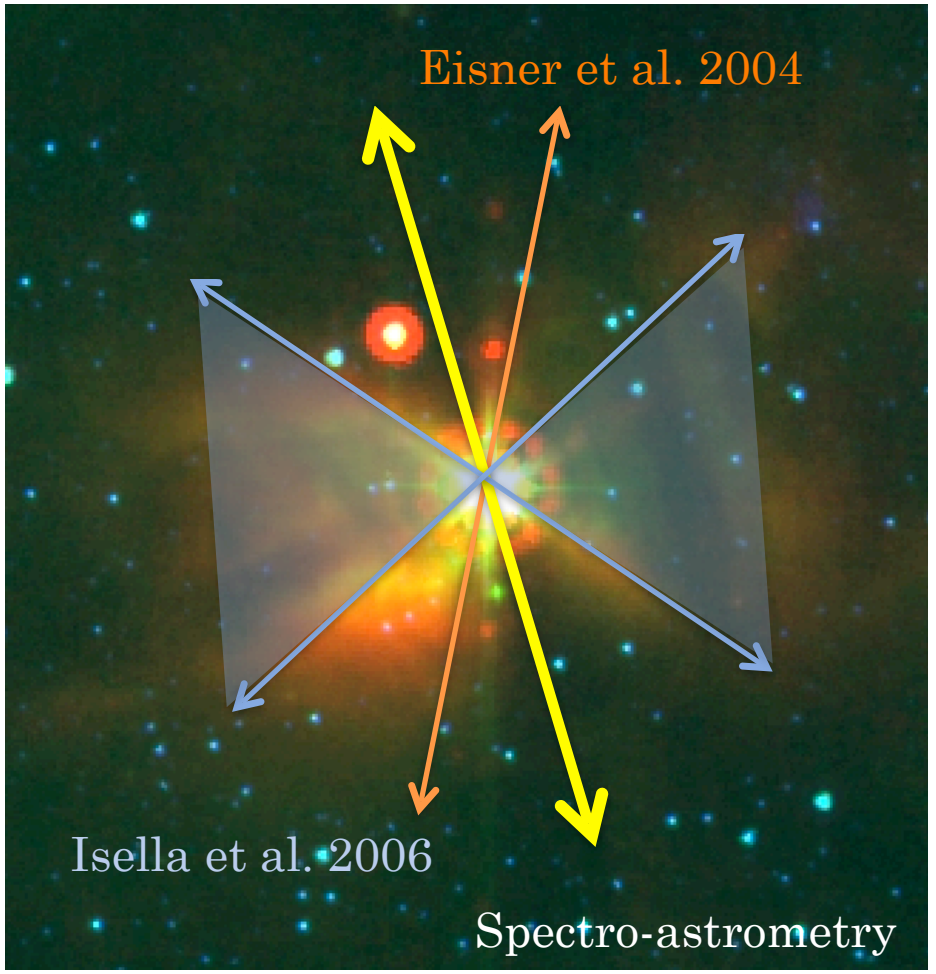


Pontoppidan et al. 2008, Brown, PhD Thesis, 2007

- Dust gaps between ~1 and ~20 AU.
- CO gas inside the gap: 7 AU for SR 21, 0.5-10 AU for HD135344B.

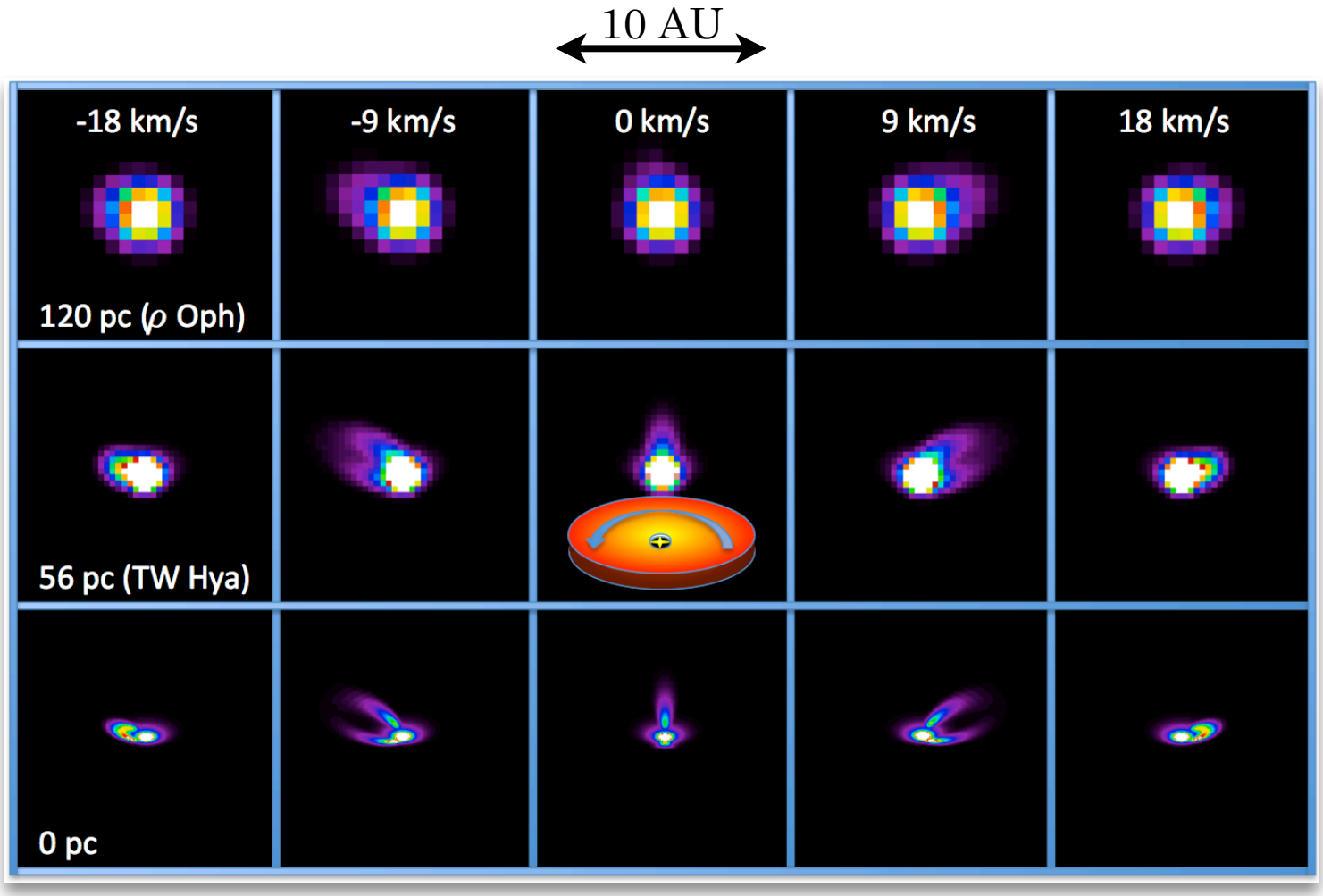
KINEMATIC IMAGING CAN BE MORE ROBUST THAN CONTINUUM IR INTERFEROMETRY





Pontoppidan et al. 2008

Imaging H_2O water vapor in the planet-forming zone with the ELTs



LTE model – non-thermal excitation makes it even better!!

CONCLUSIONS

- Very high resolution IR spectroscopy is a very powerful probe of inner protoplanetary disks.
- Allows imaging of molecular gas on AU-scales.
- Finds molecular gas in dust-depleted regions of transition disks.
  - evidence for strong grain growth/dynamical clearing by planetary-mass companions
- Spectro-astrometry highly complementary to NIR interferometry.
  - using kinematics derives much less ambiguous geometries.
- The ELTs will provide ***easy imaging*** of molecules in planet-forming zones ---- highly complementary to ALMA!
- Near future work includes spectro-astrometry of other molecular and atomic species.
  - See also poster by Gerrit van der Plas - CRIRES spectro-astrometry of Herbig Ae stars - comparison of CO and OI.