(Star and) Planet Formation with the TMT

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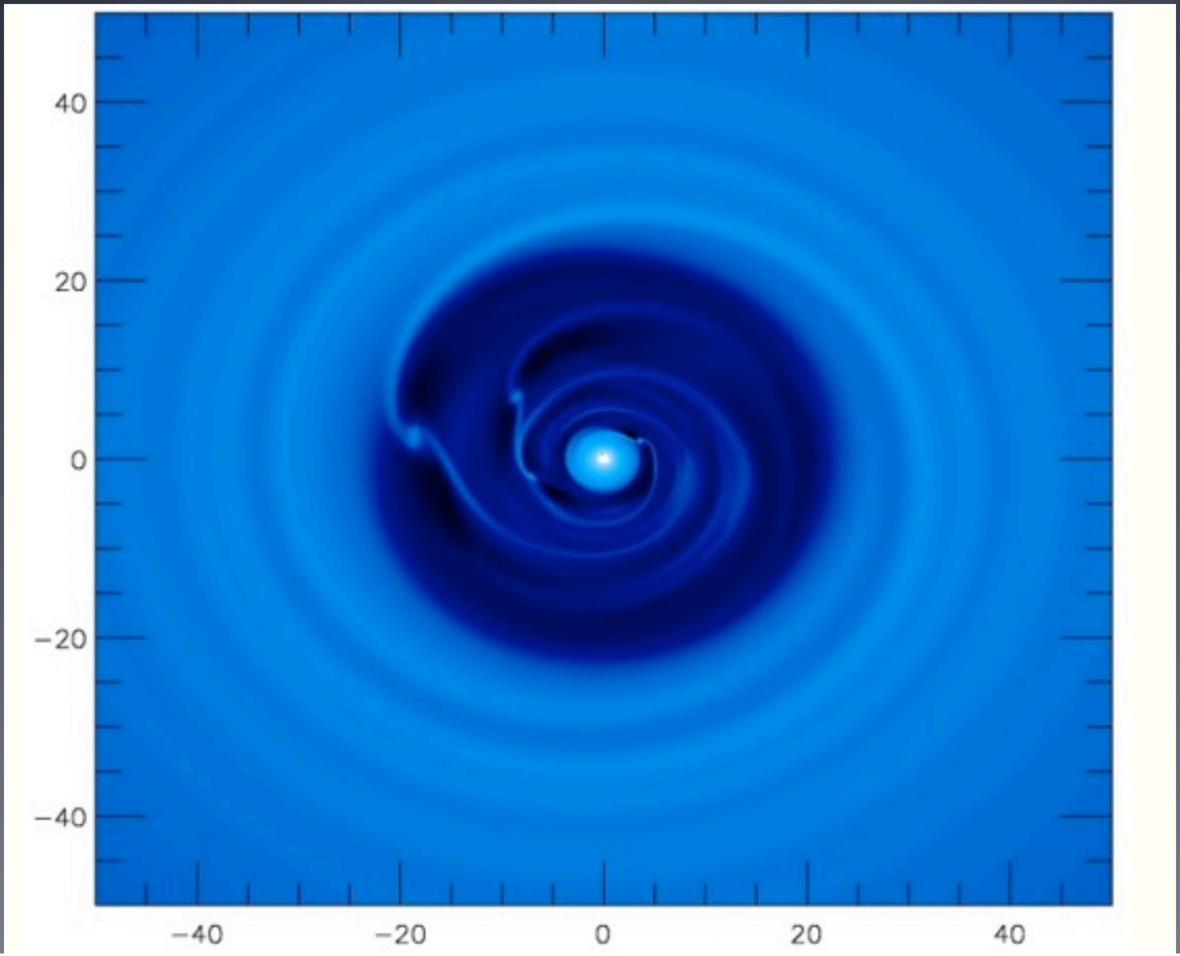
The last astrophysical step of our origins

Star and Planet Formation with the TMT

- **Initial Planet Mass Function for Stars in Diverse Environments**
  - **Disk survival timescales/planet formation**
- **The physics of planet formation at high resolution**
  - **Scattered light structures**
  - **Disk chemistry and planetary abundances**
  - **Directly detecting protoplanets in formation**
- **Direct detection of young exoplanets**
  - **(Exoplanet science case – all of the direct imagers are at a different conference!)**

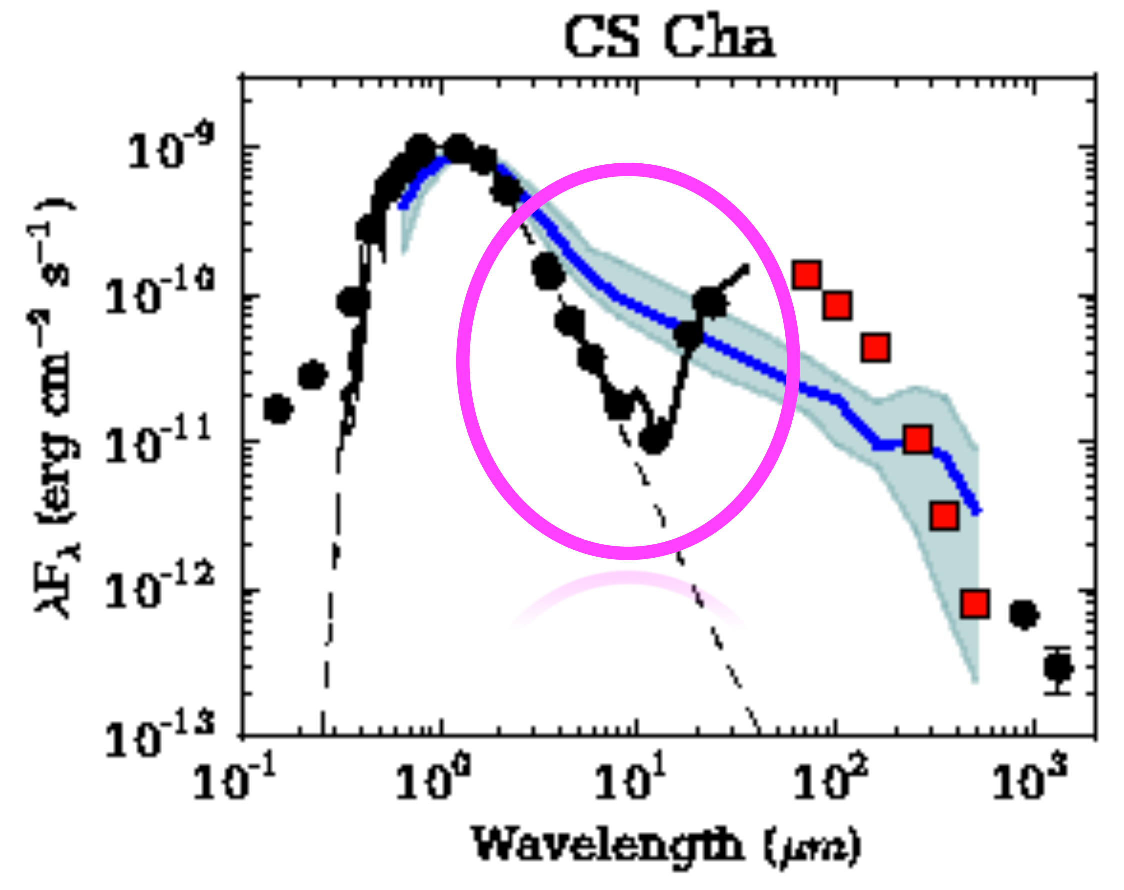
How would a forming planet affect a disk?

(e.g., Lin & Papaloizu 1986; Zhu+2011)



Competition between gas accretion; gap/hole formation

Transition disks and planet formation



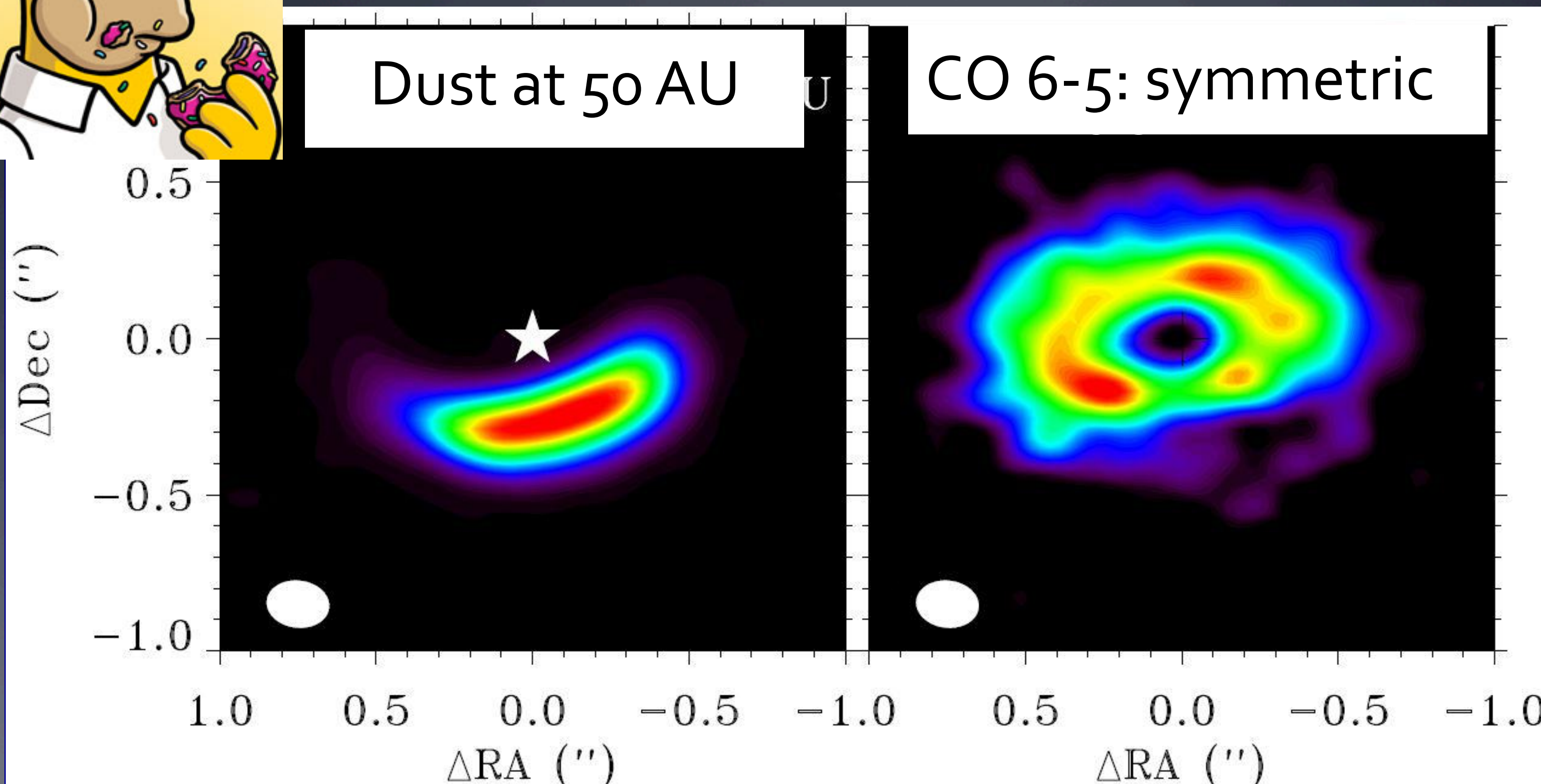
Spitzer legacy

- Lack of warm dust as absence of near-IR emission
- Ongoing accretion: hole in dust, gas still unclear

e.g., Strom+1989, Calvet+2002, D'Alessio+2005, Kim+2009, Merin+2010

Dust trap in a transition disks

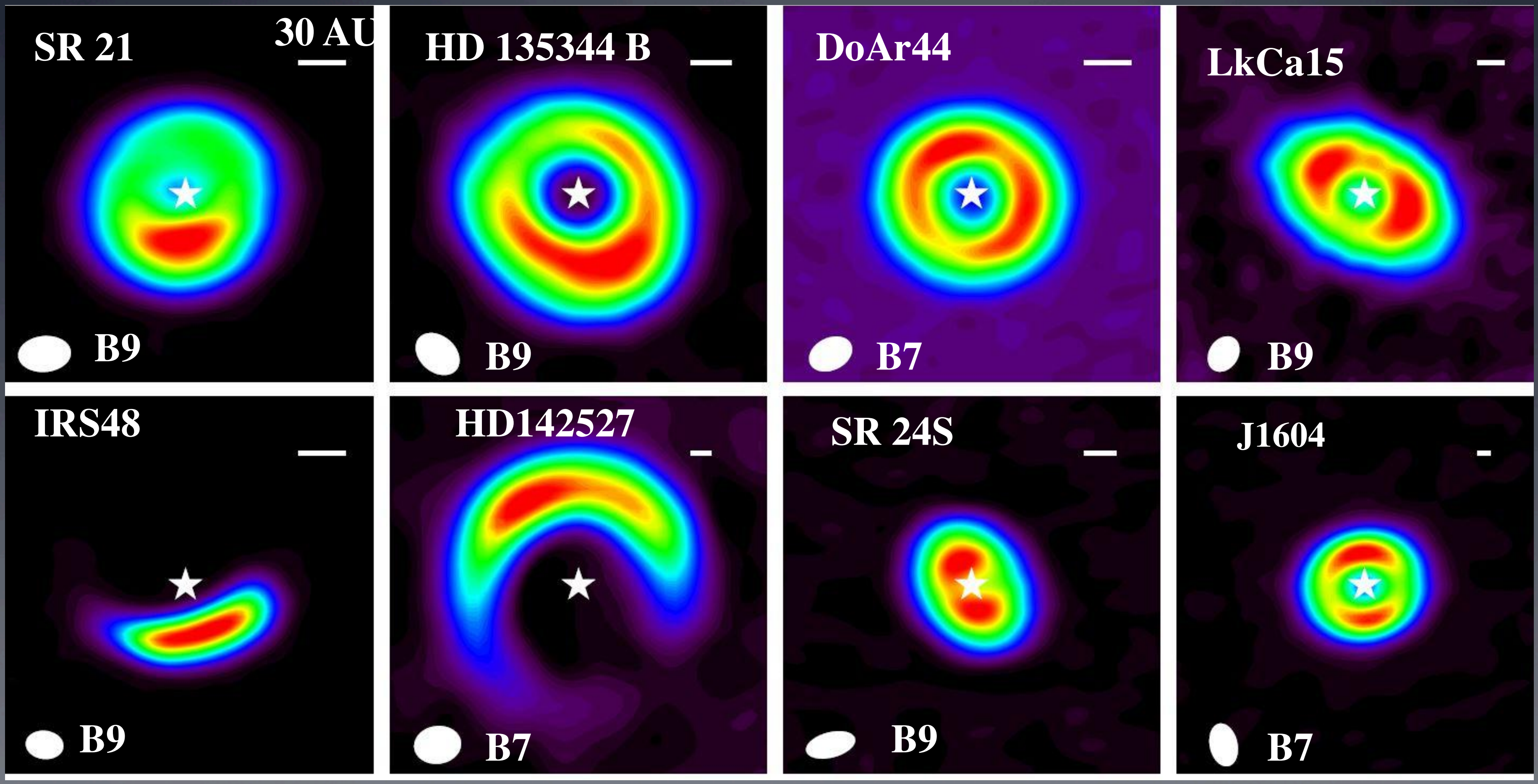
(van der Marel+2013, 2015)



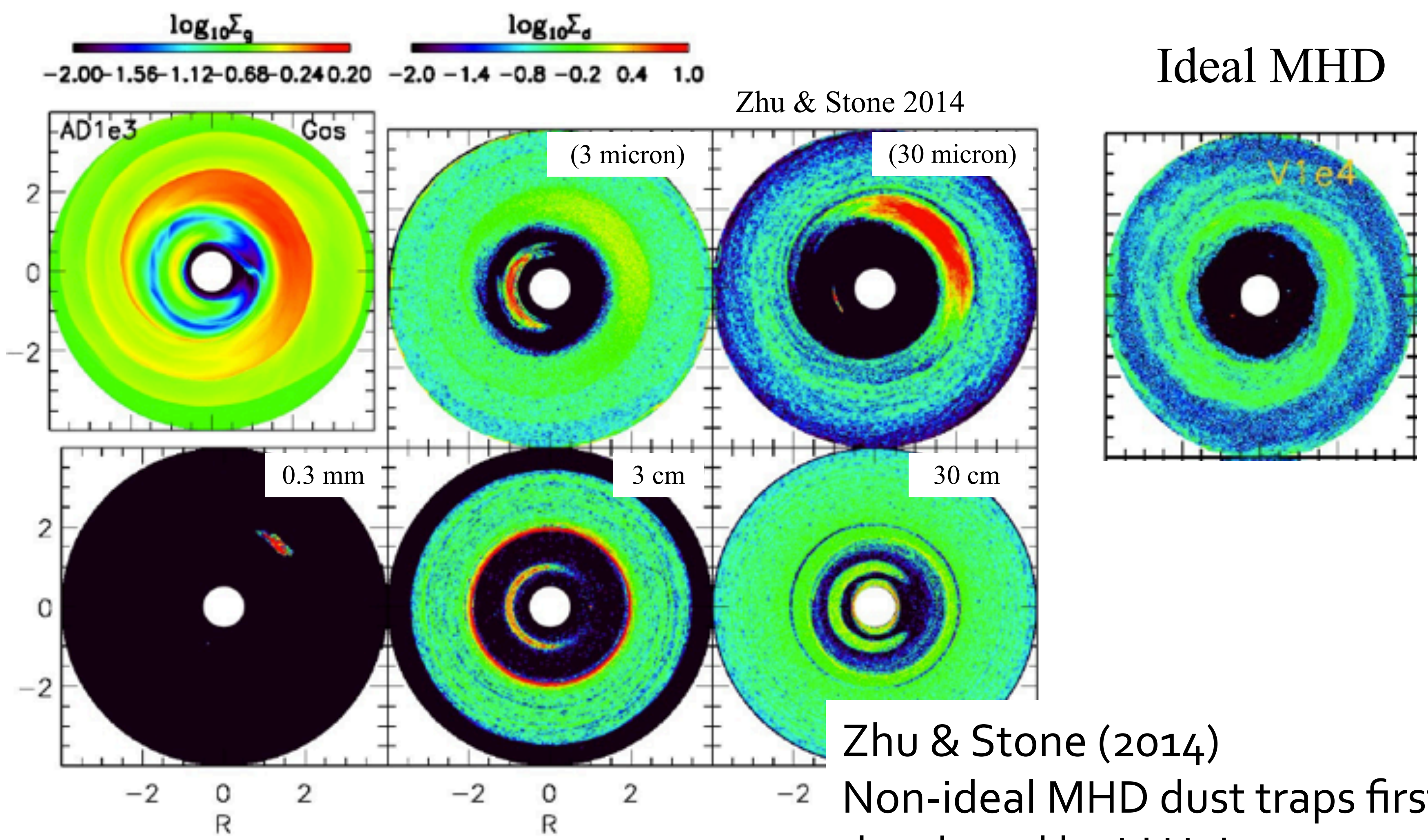
Vortex? Comet/KBO factory?

Dust traps with ALMA

(e.g., Perez+2014; van der Marel+2015; Pinilla+2015)

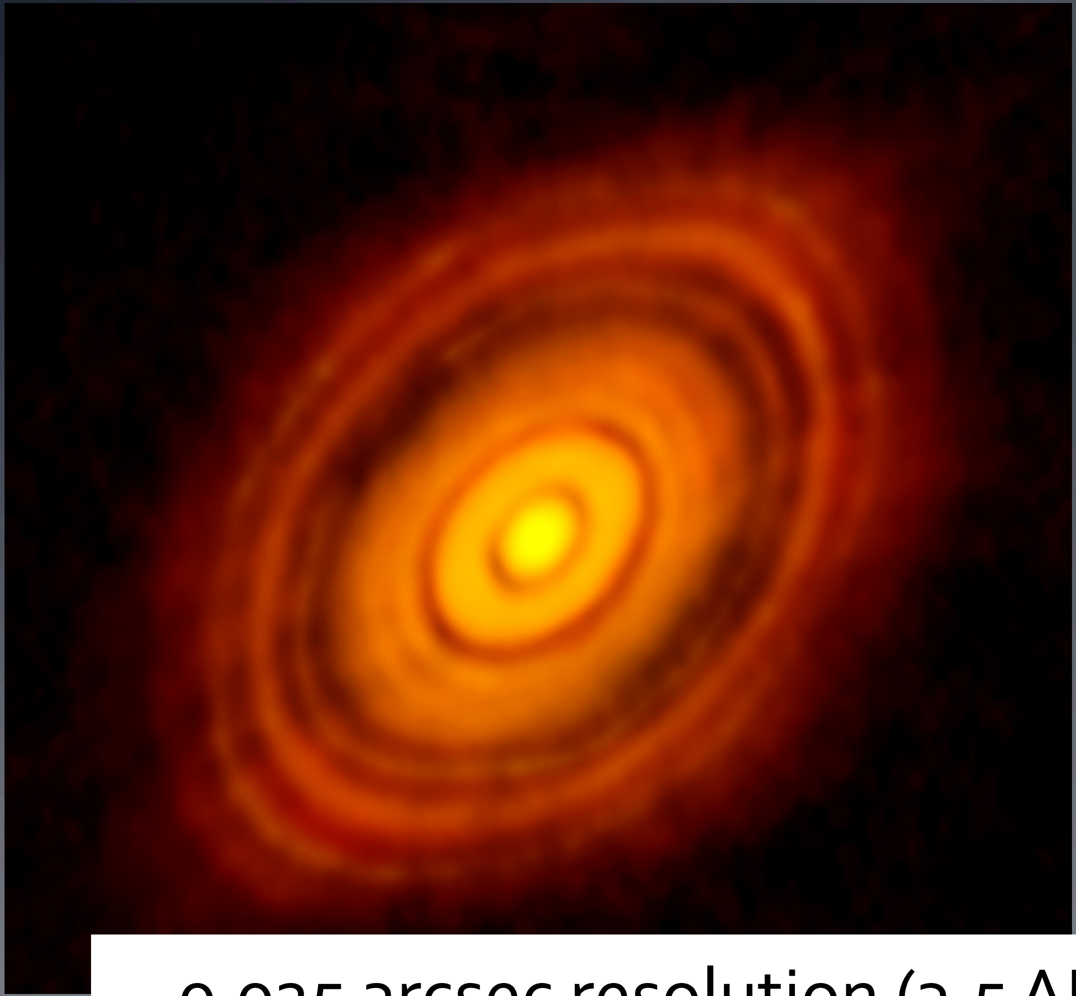


Dust traps in simulations of non-ideal MHD disk physics



Zhu & Stone (2014)
Non-ideal MHD dust traps first developed by Li Hui

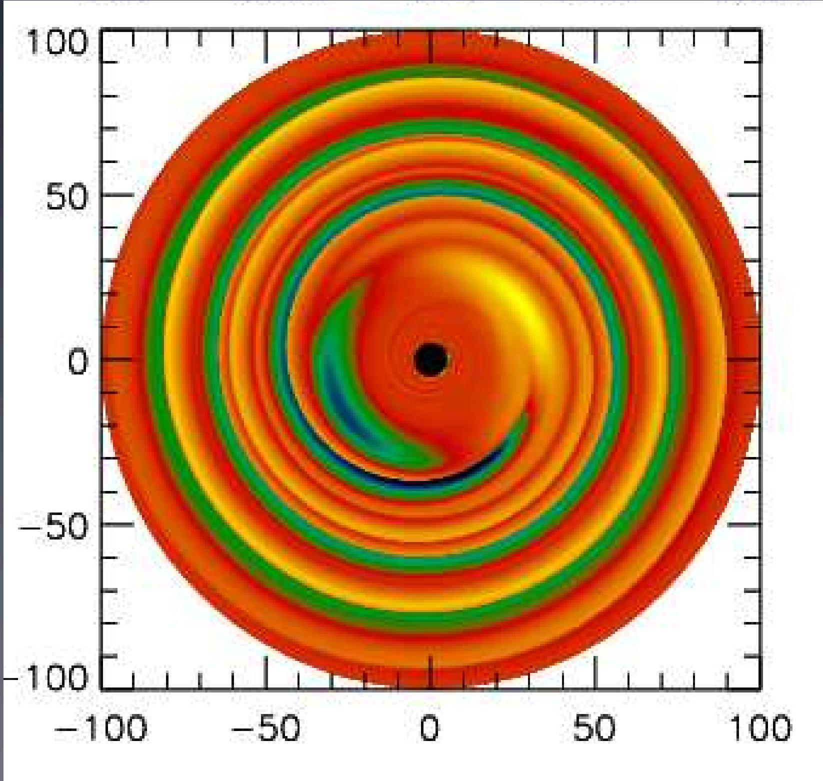
ALMA: Structure of the HL Tau disk

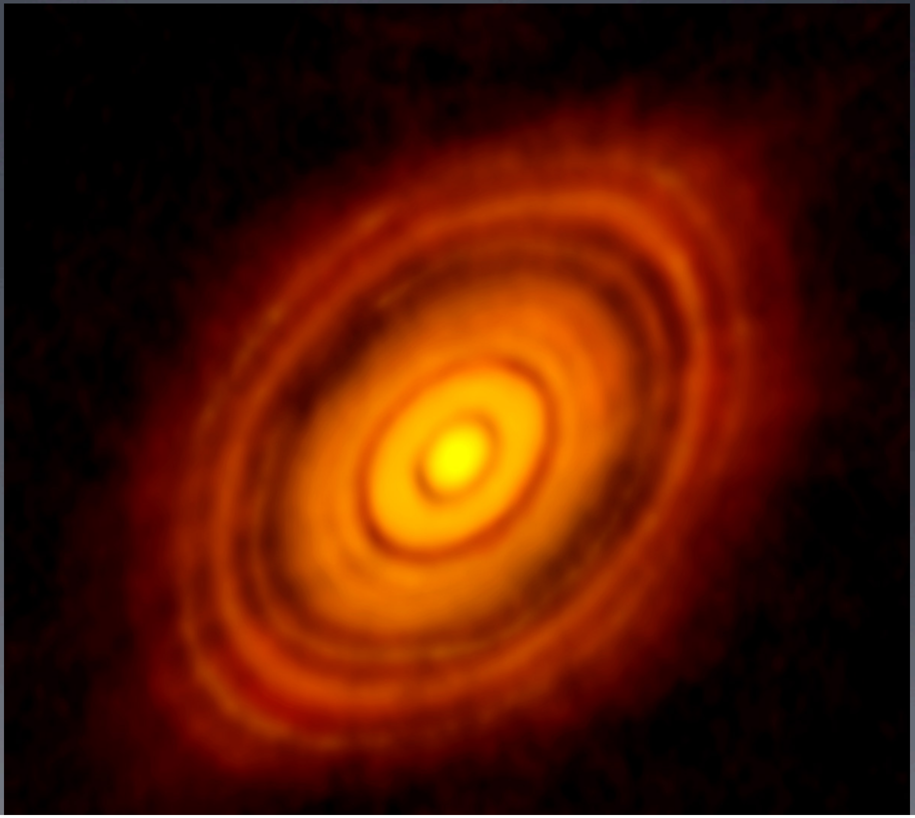


- Planets? Unlikely
- Chemistry of freeze-out/grain growth? (Zhang+2015)
- Rossby waves from infalling envelope (Bae+2015)

0.025 arcsec resolution (3.5 AU) at 0.87 mm

Disk structure/planet formation is instability physics

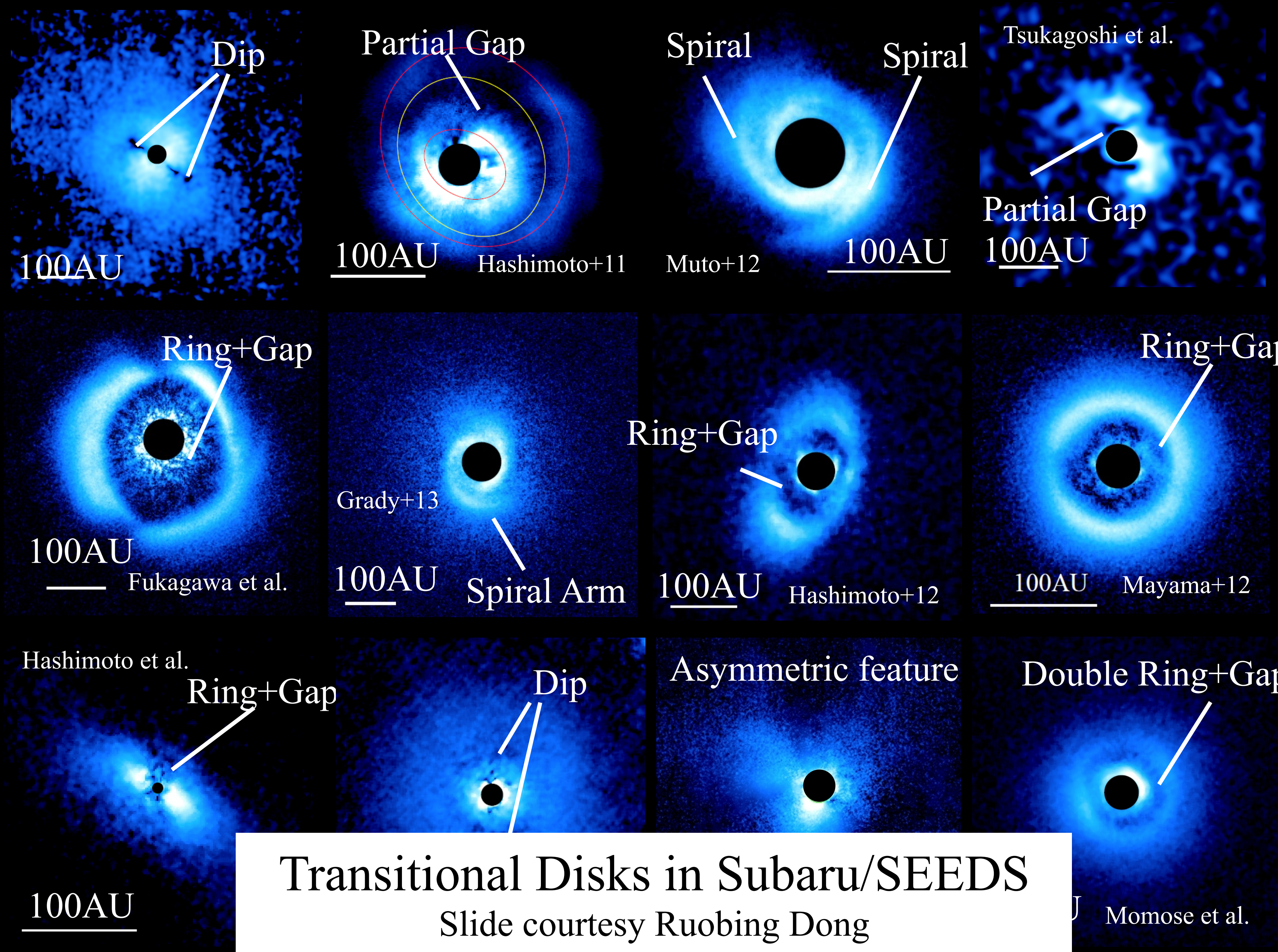




Rossby waves from infalling envelope? Bae+2015

Transitional Disks in Subaru/SEEDS

Slide courtesy Ruobing Dong

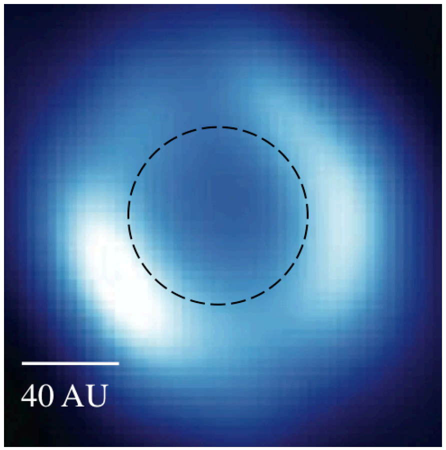


SEEDS: Decoupling of mm-sized, micron-sized

Dong et al. 2012, slide courtesy Ruobing Dong

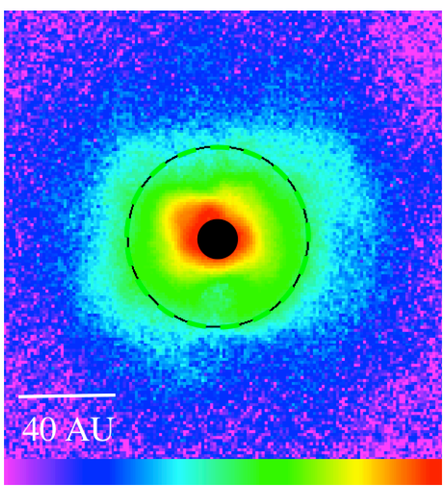
SR 21, SMA 0.88 mm Image

Andrews et al. 2011, Williams & Cieza 2011

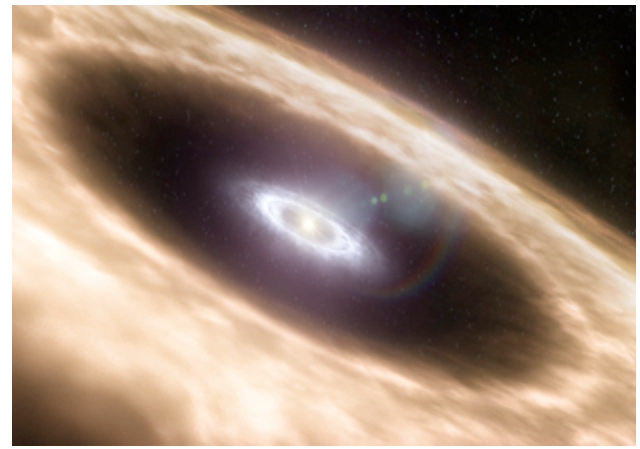


SR 21, Subaru H-band Image

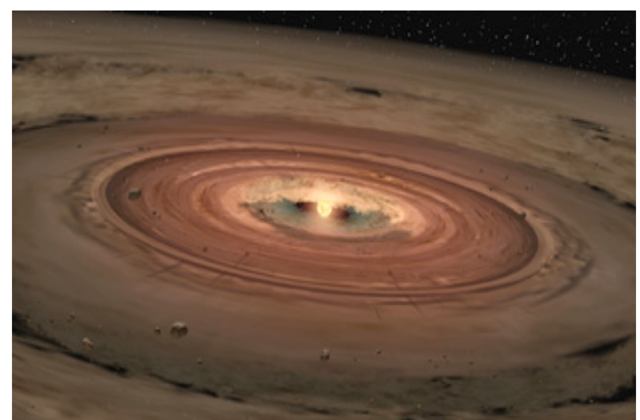
Follette et al. 2013



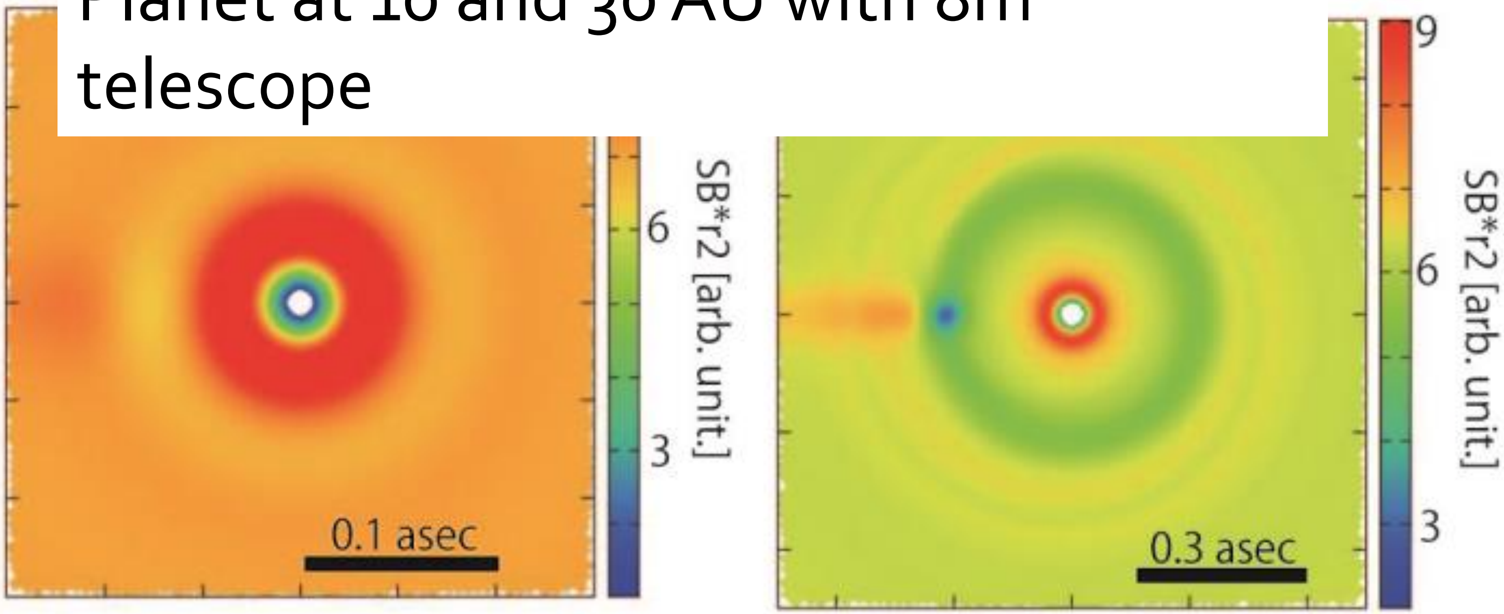
~mm-sized grains



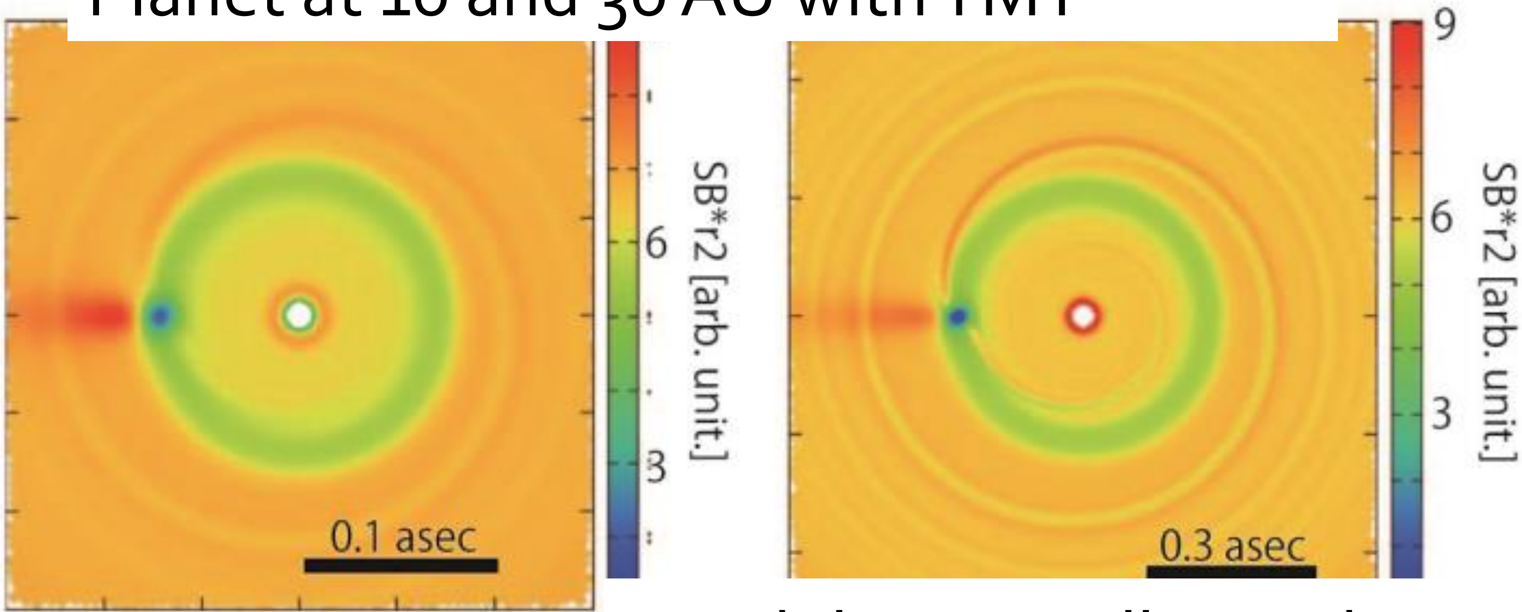
~sub-micron-sized grains



Planet at 10 and 30 AU with 8m telescope

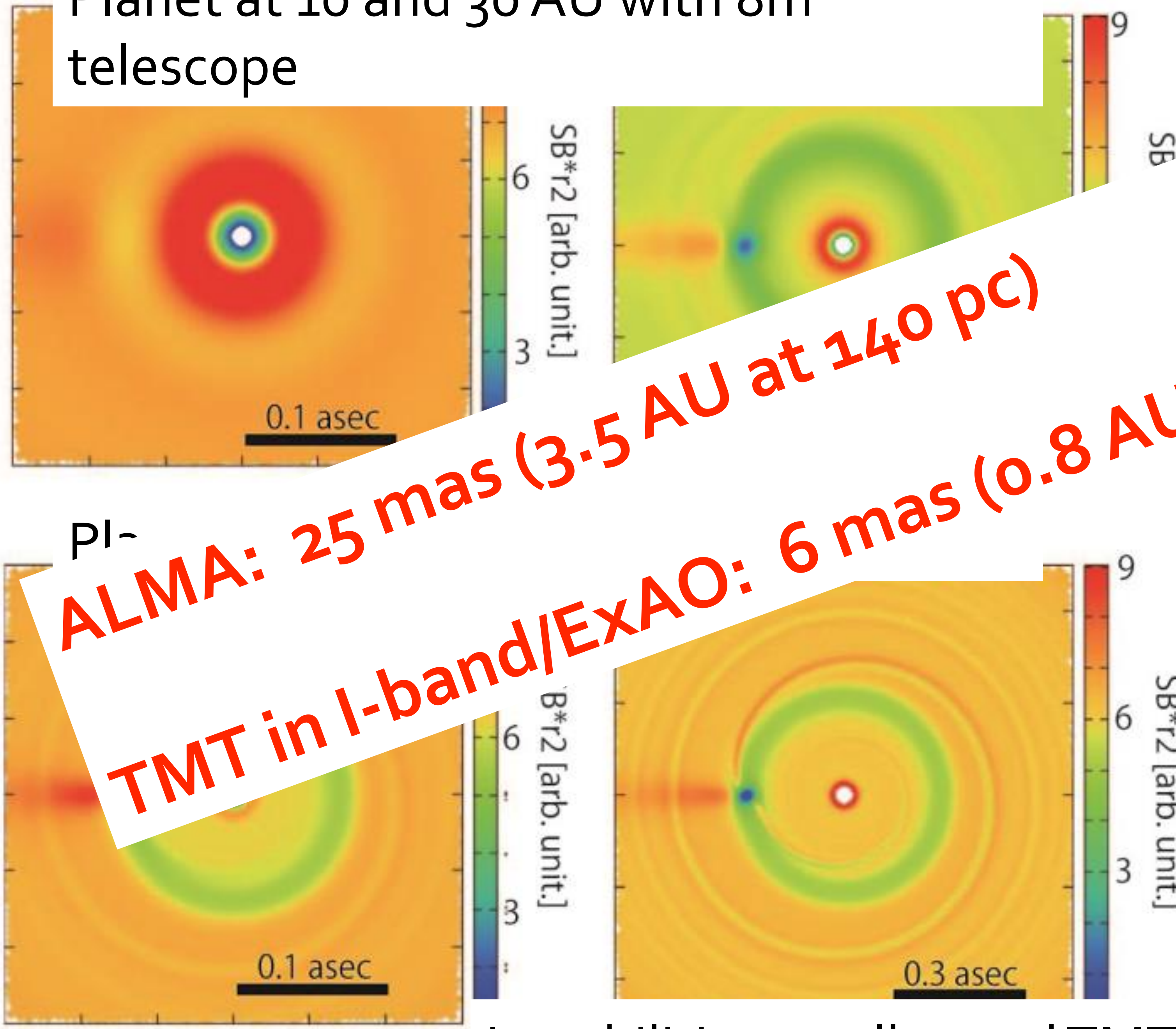


Planet at 10 and 30 AU with TMT



Instabilities small; need TMT to resolve!

Planet at 10 and 30 AU with 8m telescope

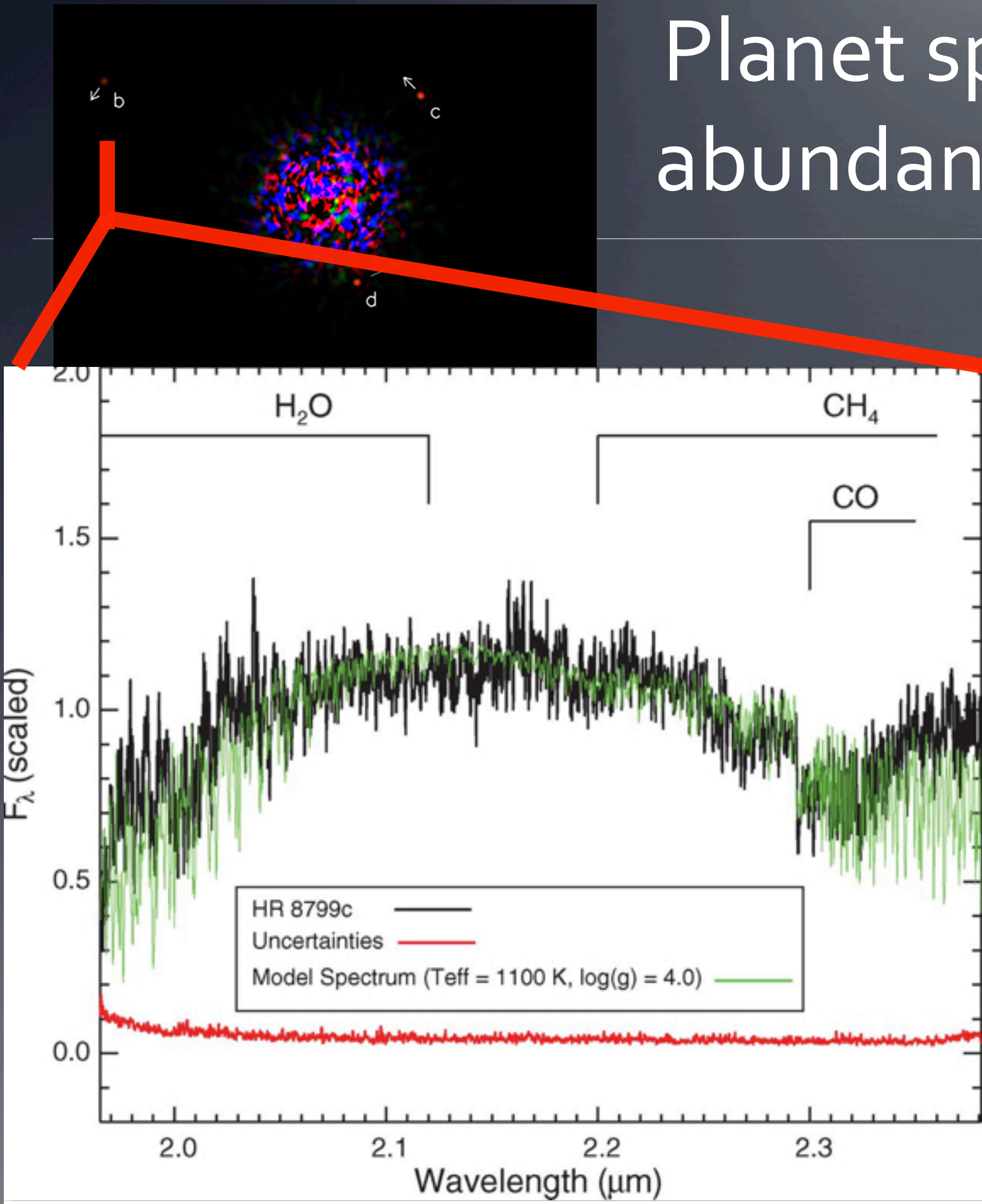


ALMA: 25 mas (3.5 AU at 140 pc)

TMT in I-band/ExAO: 6 mas (0.8 AU)

Instabilities small; need TMT to resolve!

Planet spectro-archeology: abundances from formation

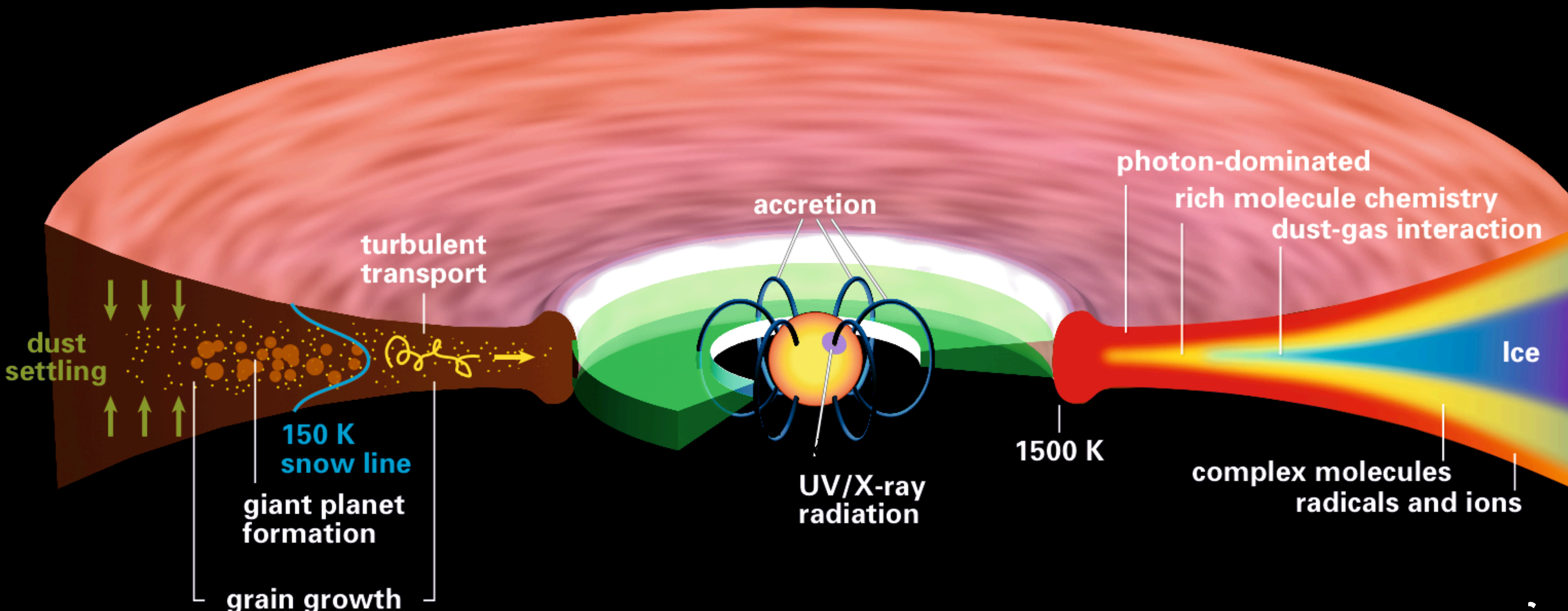


Konopacky+2013.: spectra versus models for HR 8799b

Birkby Talk

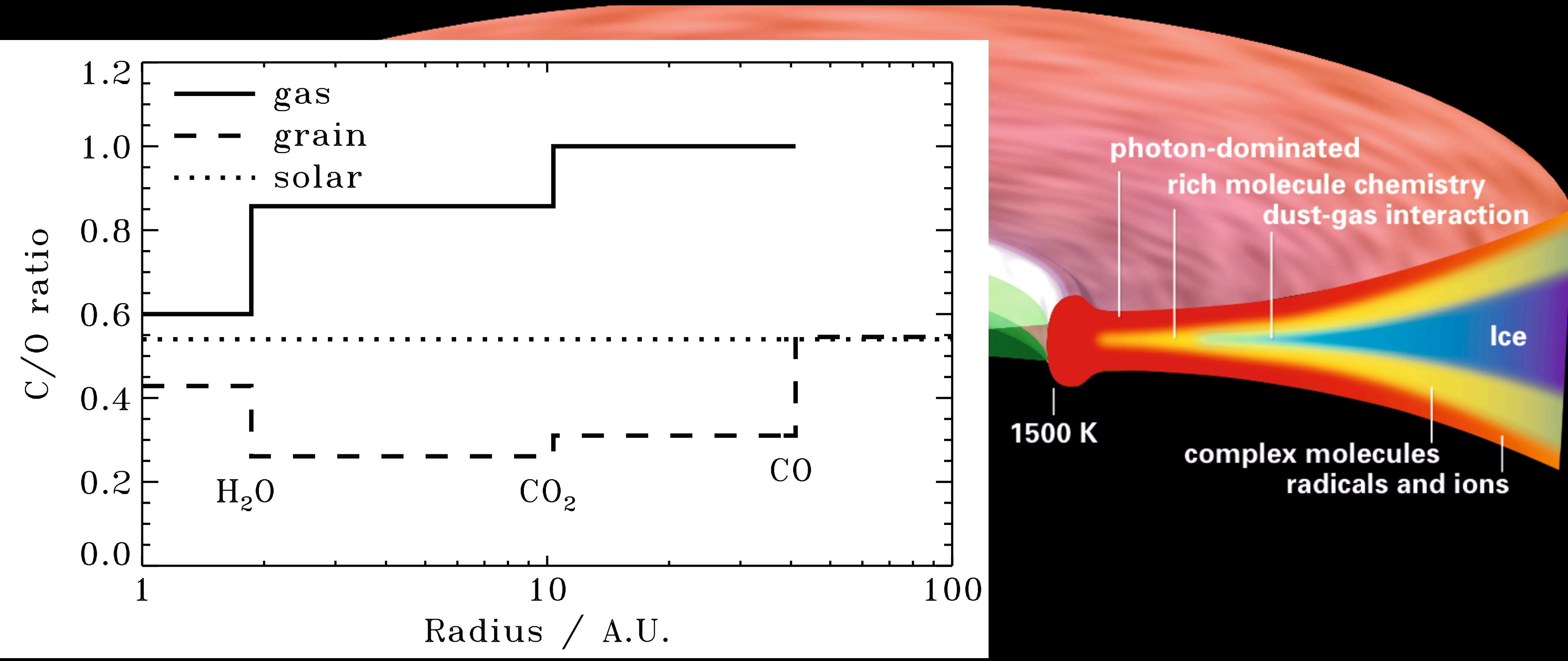
- C/O ratios from direct imaging, transits (e.g., Madhusudan+2012; Line +2012)
- Still in infancy for directly imaged planets (e.g., Lockwood +2014; Snellen+2014)

Abundance of giant planets: set at protoplanetary disk phase



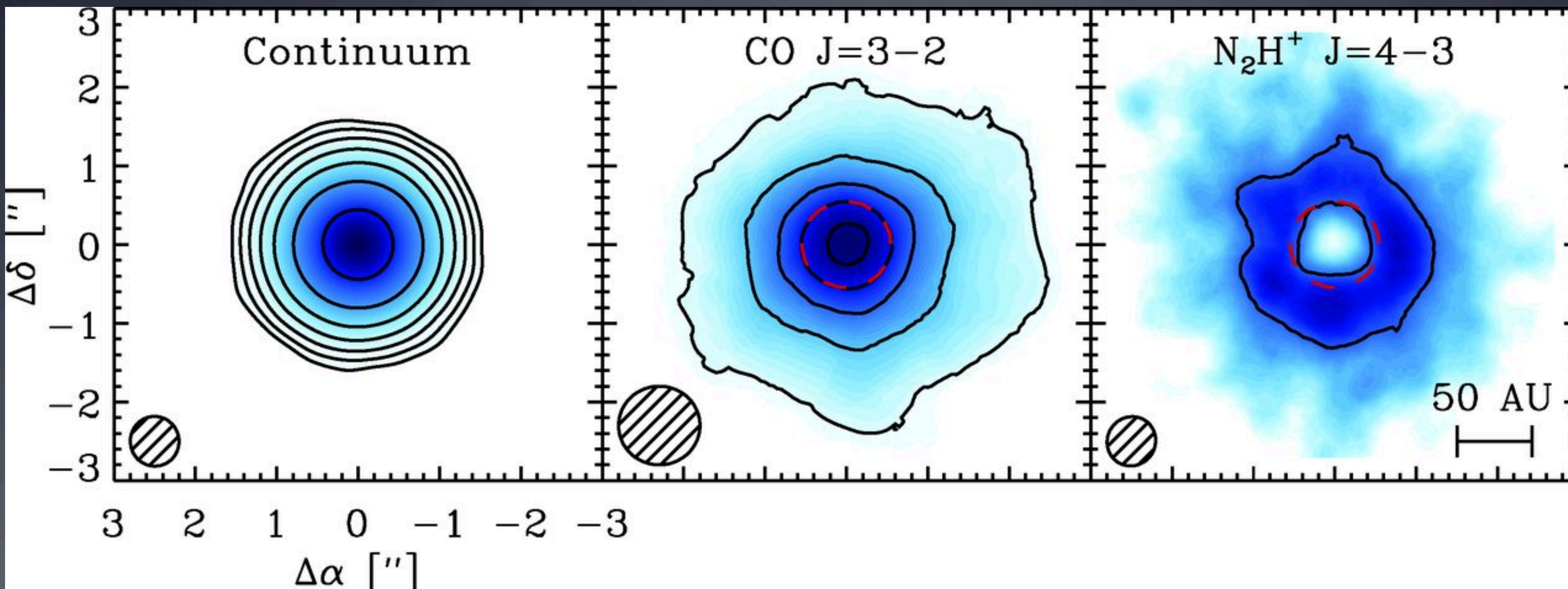
Cartoon from Semenov & Henning 2014 review

Abundance of giant planets: set at protoplanetary disk phase



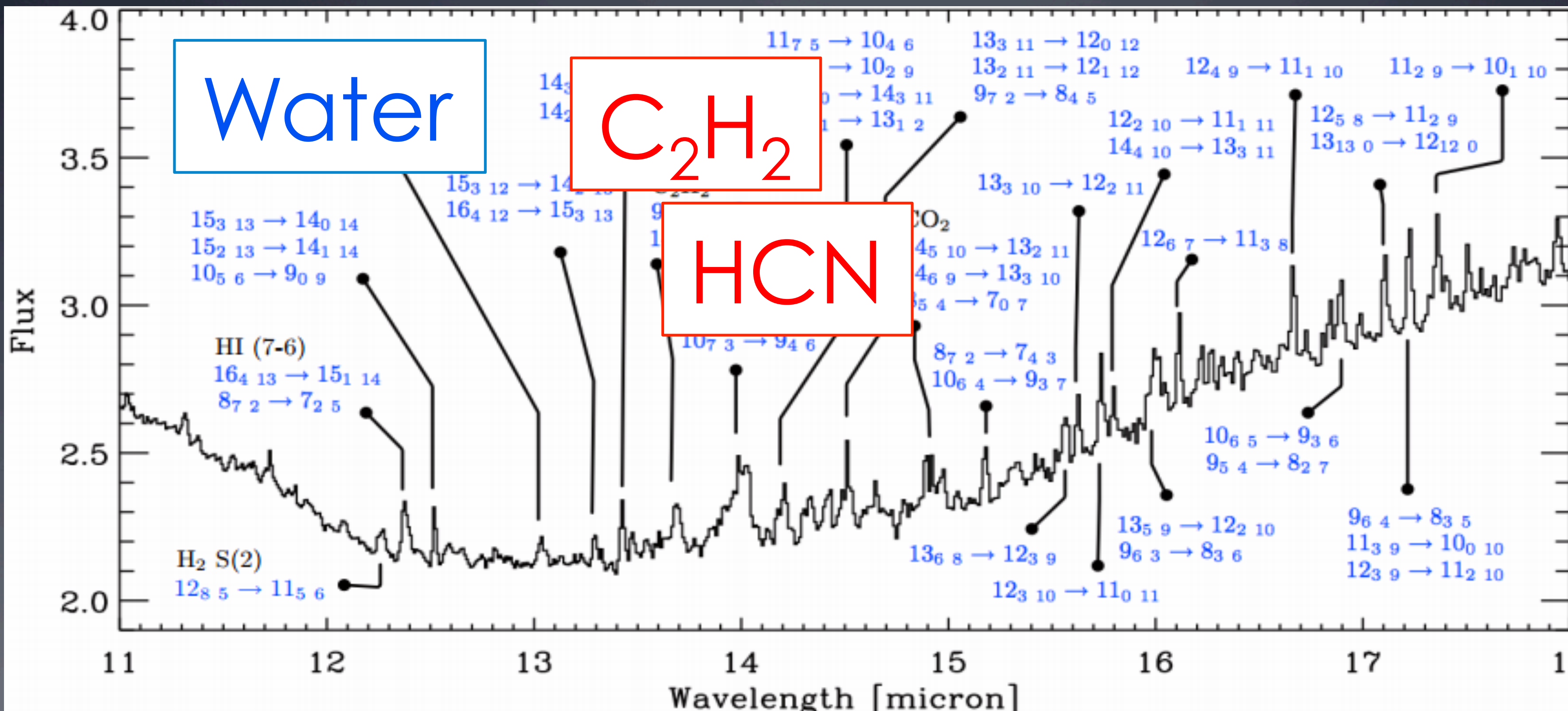
Öberg et al. 2011: superstellar C/O could be enhanced explained by accretion of C-rich gas near ice lines

Observing H2O and CO snow lines



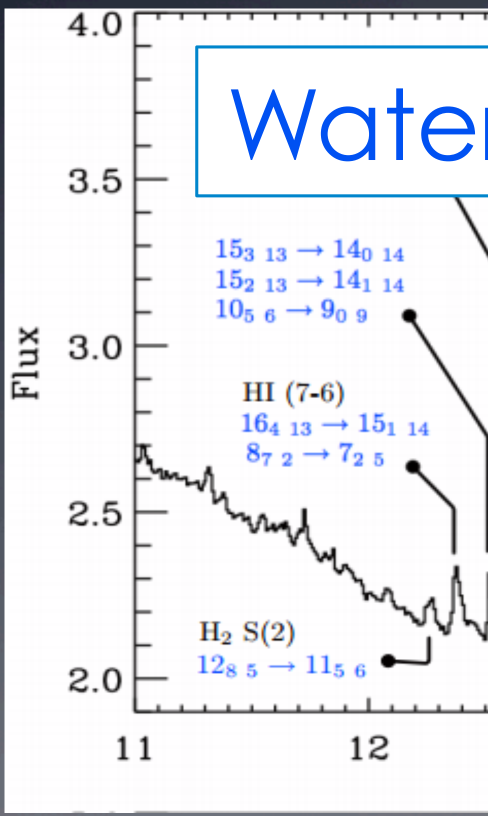
Qi+2014: CO snow line detected for a disk with ALMA, but what about H2o snow line?

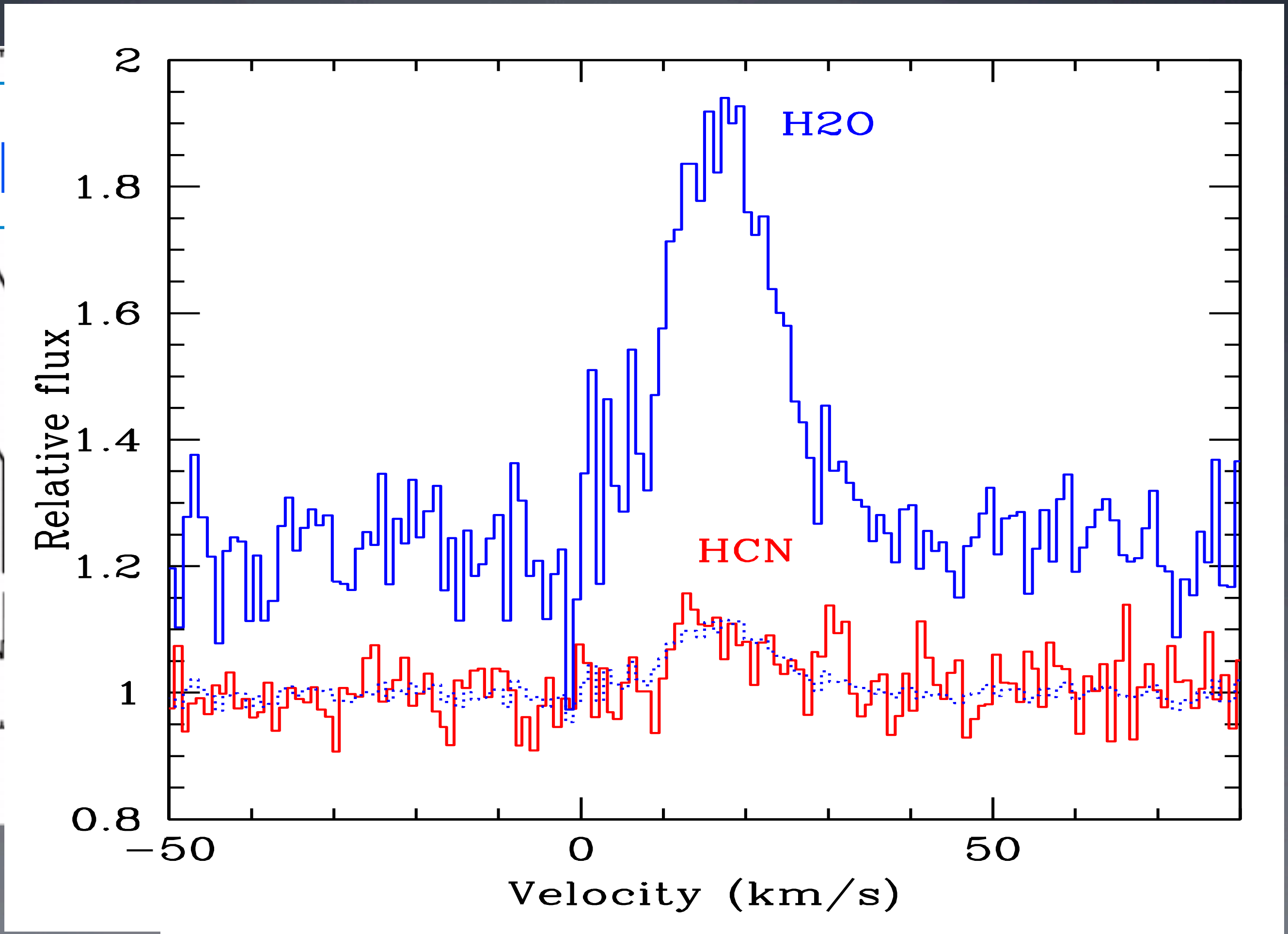
H_2O snow line from fluxes+chemical models; probably depends on stellar mass



Spitzer/IRS: Carr & Najita 2008; Salyk+2008

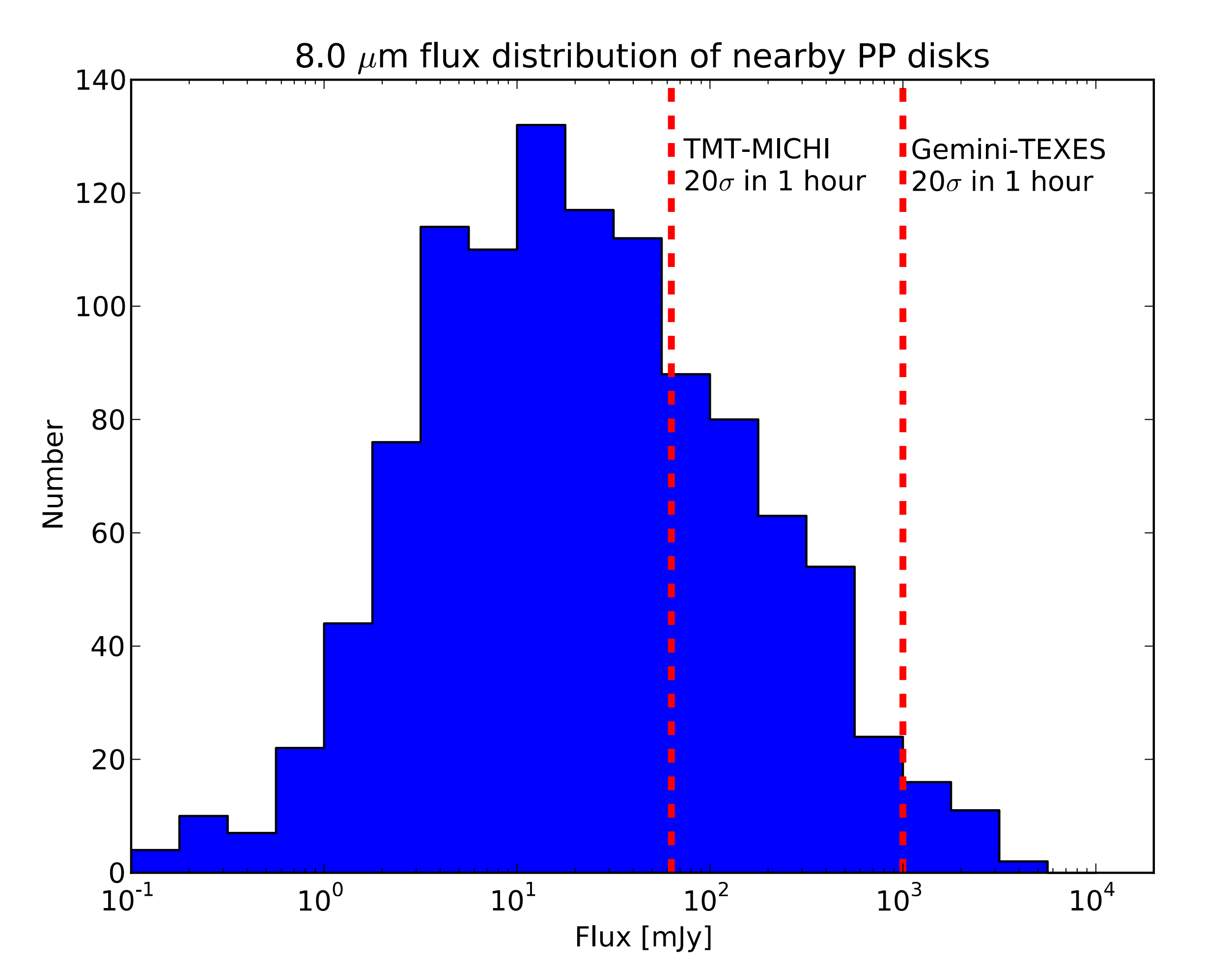
High resolution follow-up needed to measure the location of the snow line!





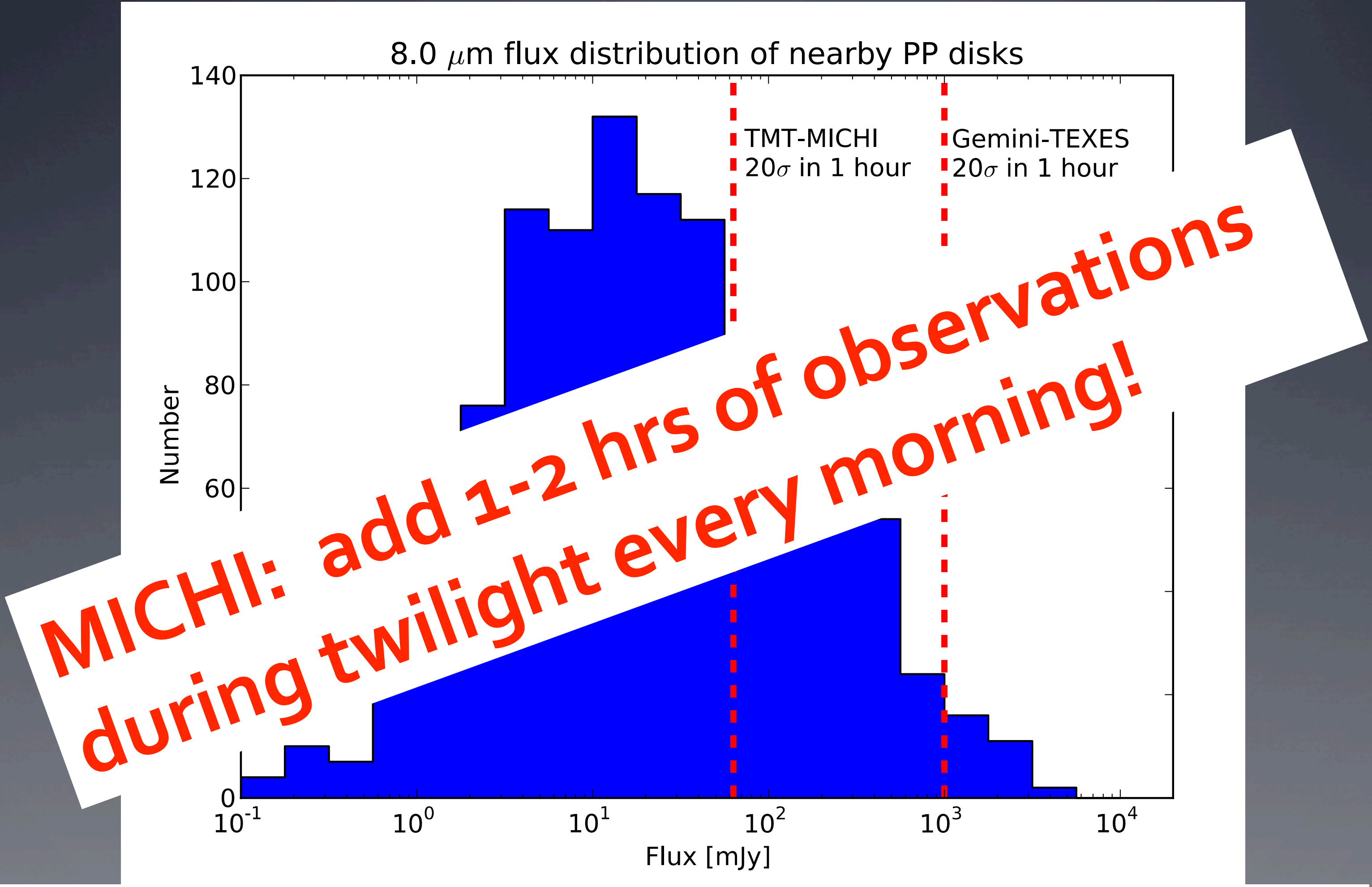
Gemini North/TEXES: Najita+ in prep

TMT: will open up the mid-IR at high spectral/spatial resolution



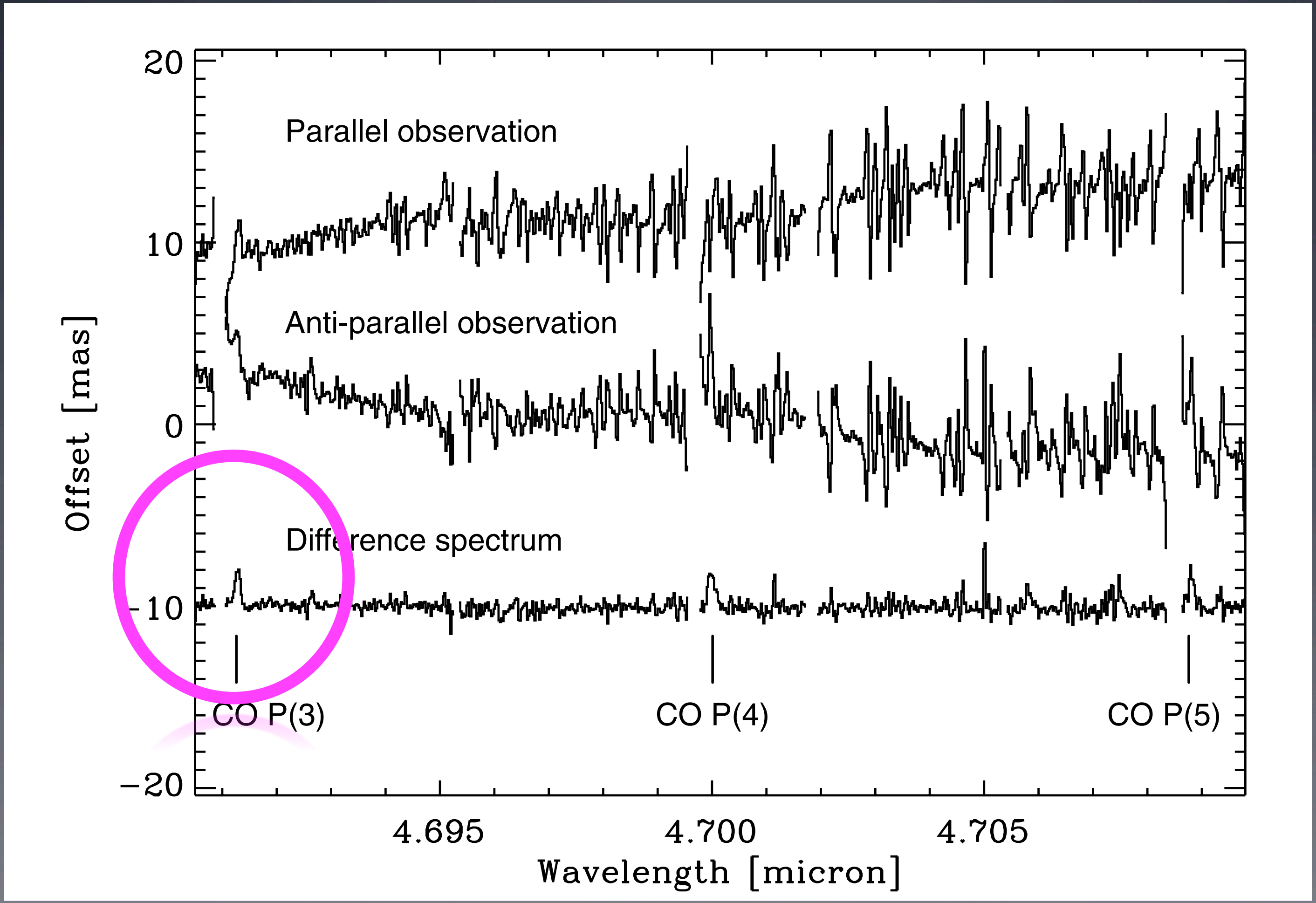
From TMT Star/Planet Formation Science Case

TMT: will open up the mid-IR at high spectral/spatial resolution



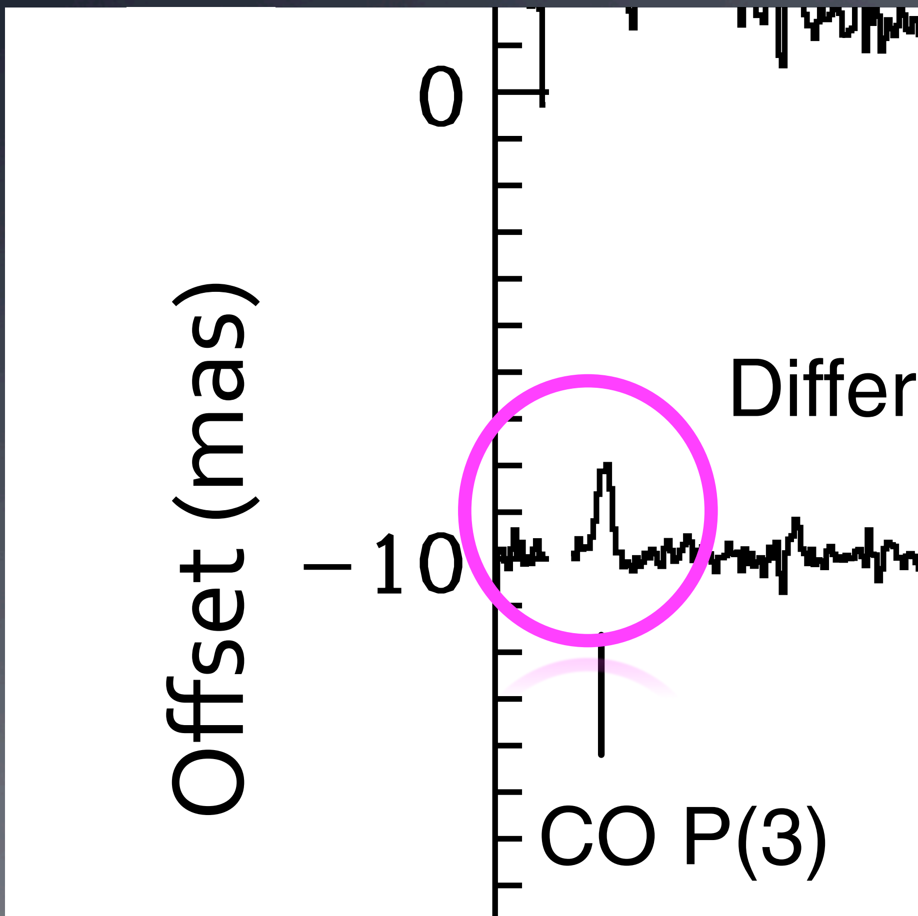
From TMT Star/Planet Formation Science Case

Spectroastrometry: improving the spatial resolution of TMT



Pontoppidan+2008/2011

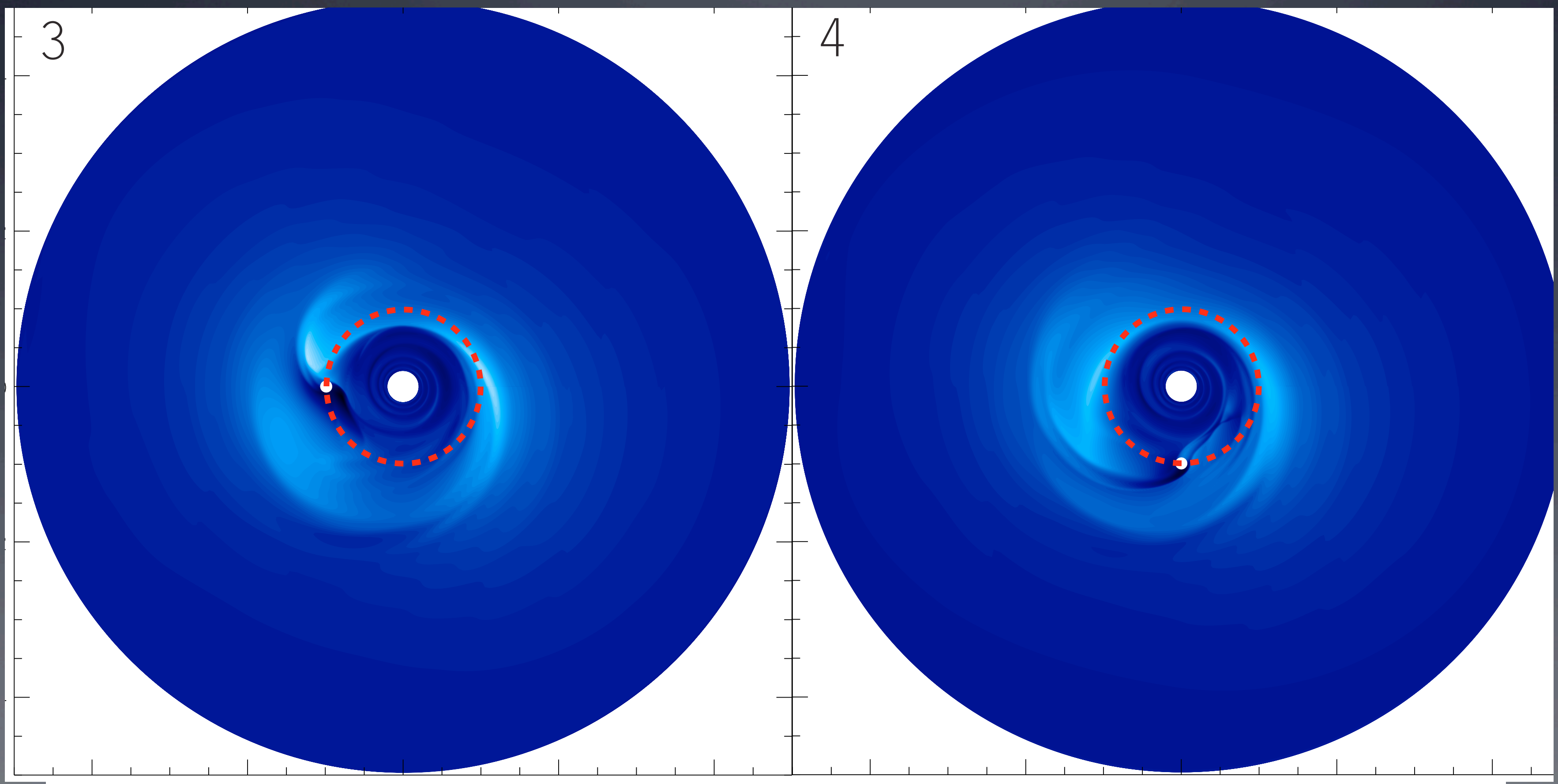
Spectroastrometry: improving the spatial resolution of TMT



- Median spatial centroid of emission in cross-dispersion direction
- 0.5 mas noise measured with VLT/CRIRES (AO, R=100,000)

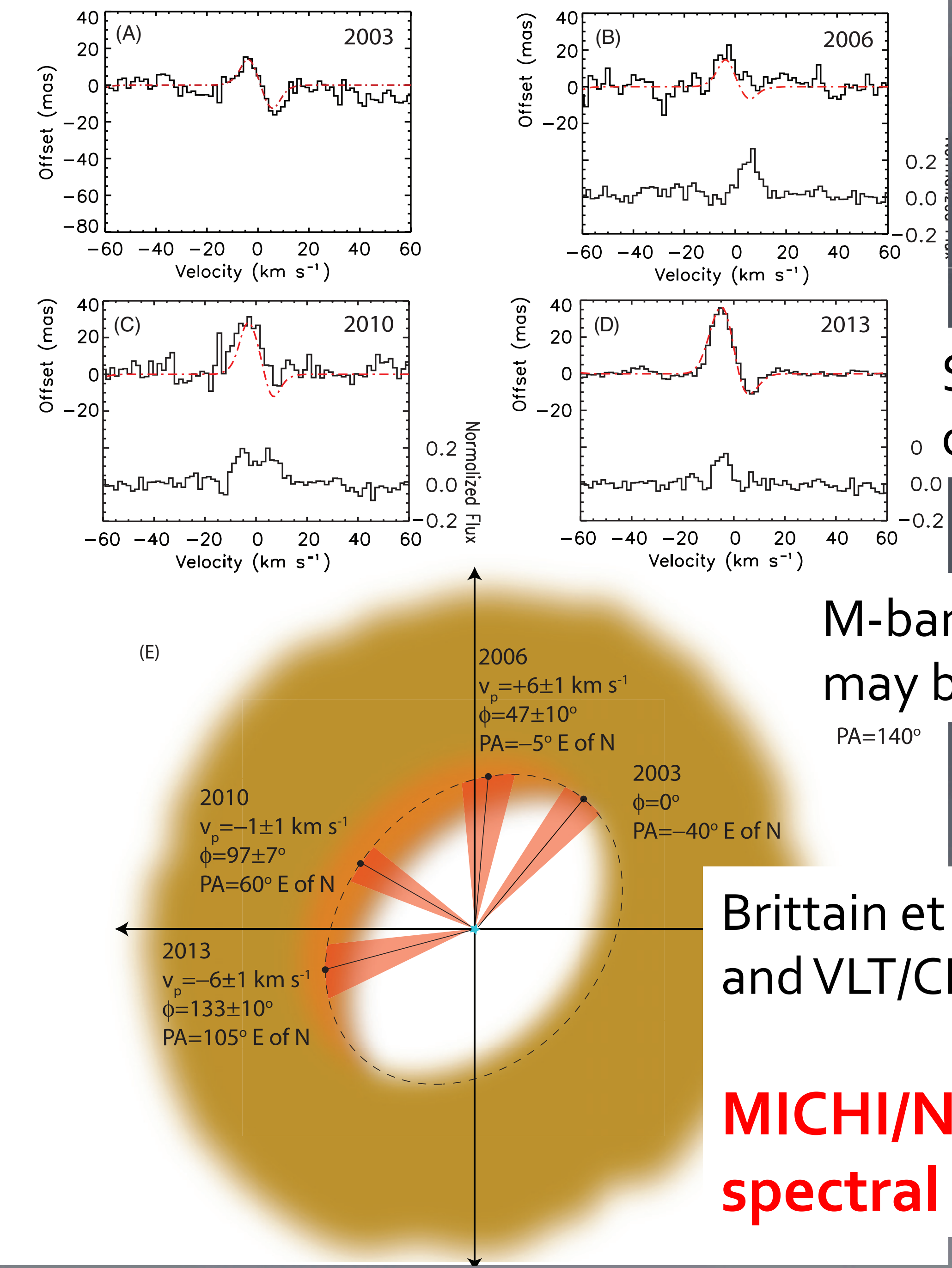
Pontoppidan+2008/2011

Gas asymmetries induced by planet should rotate



Regaly+2010 simulations of CO emission

Asymmetries in CO emission



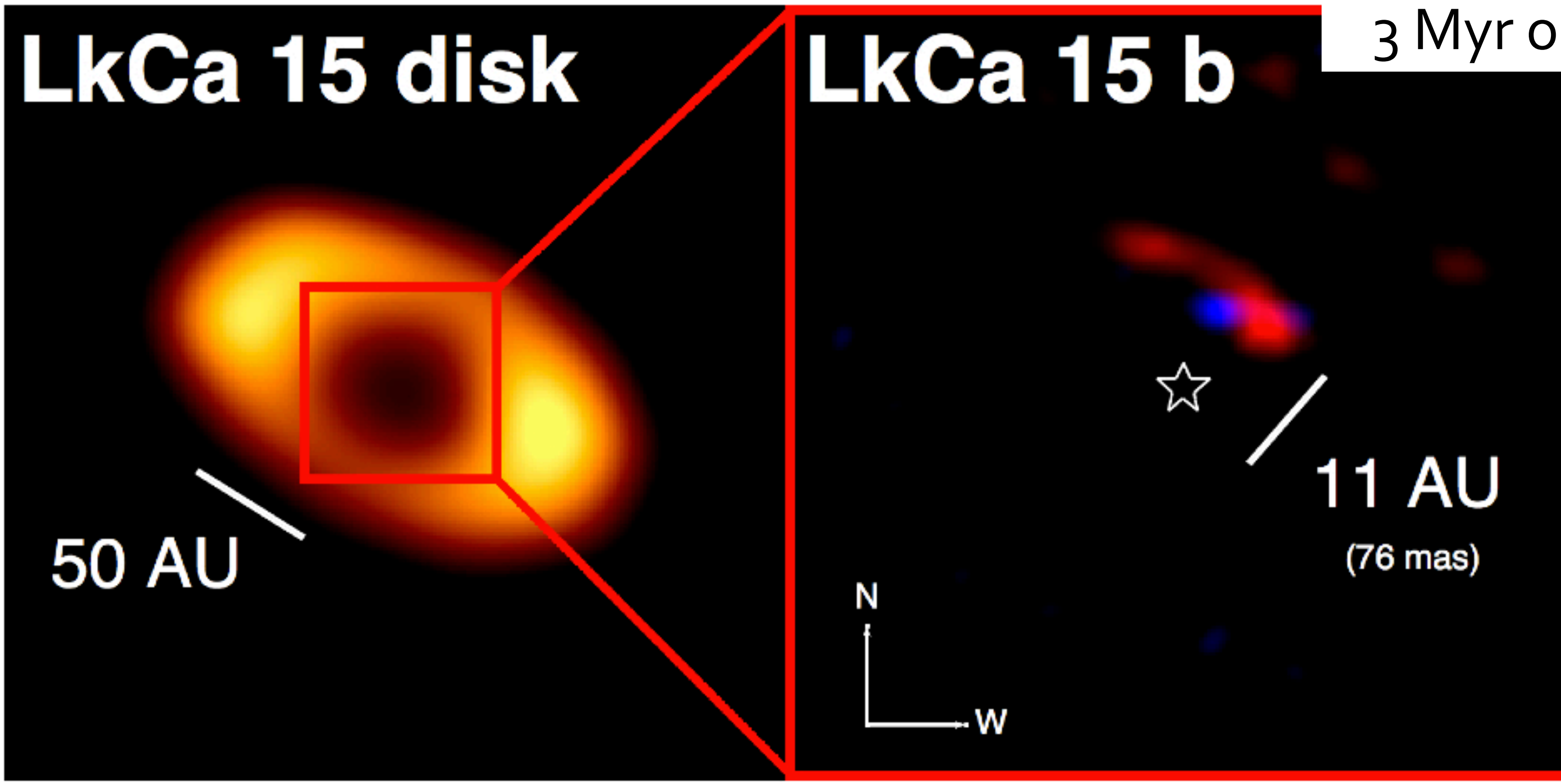
Spectroastrometry of CO emission

M-band CO emission asymmetry may be rotating? Planet?

Brittain et al. 2014: Gemini South/Phoenix and VLT/CRIRES

MICHI/NIRES: more accurate spectral imaging at smaller scales

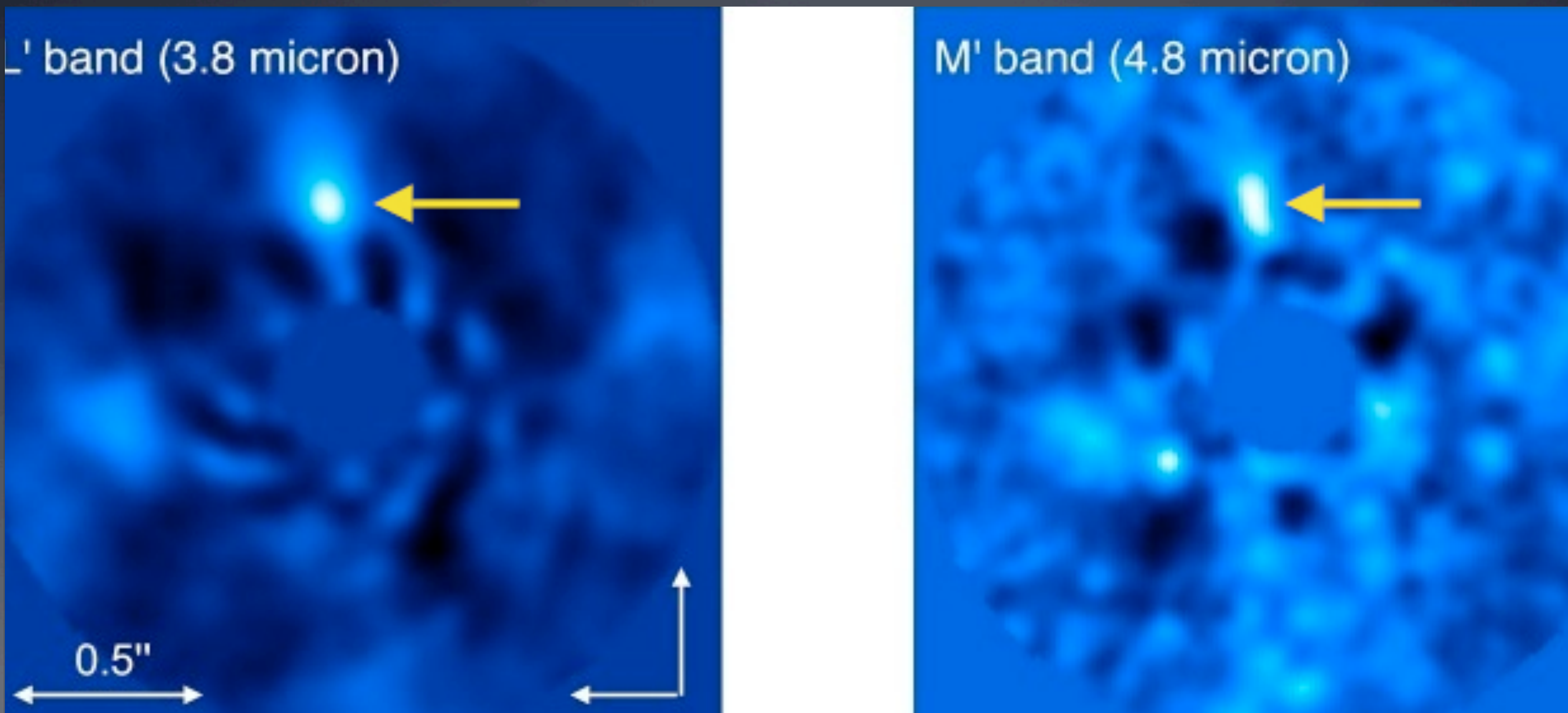
(Proto?)-planet detection in a disk hole



3 Myr old

Kraus & Ireland 2012: Keck AO with non-redundant aperture masking

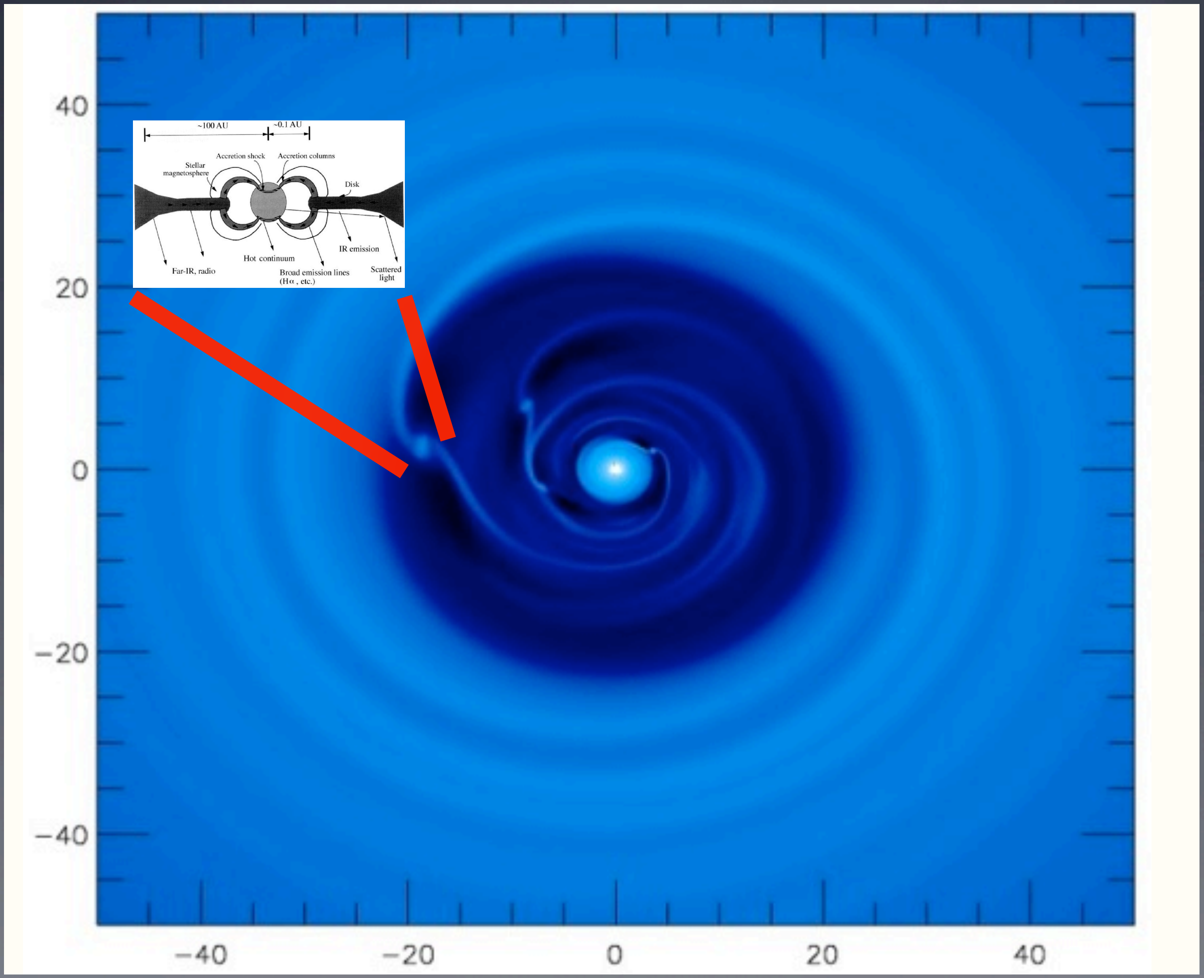
A (proto)-planet around HD 100546b
(Quanz+2014)



3 Myr old; compact object with some spatial extent!

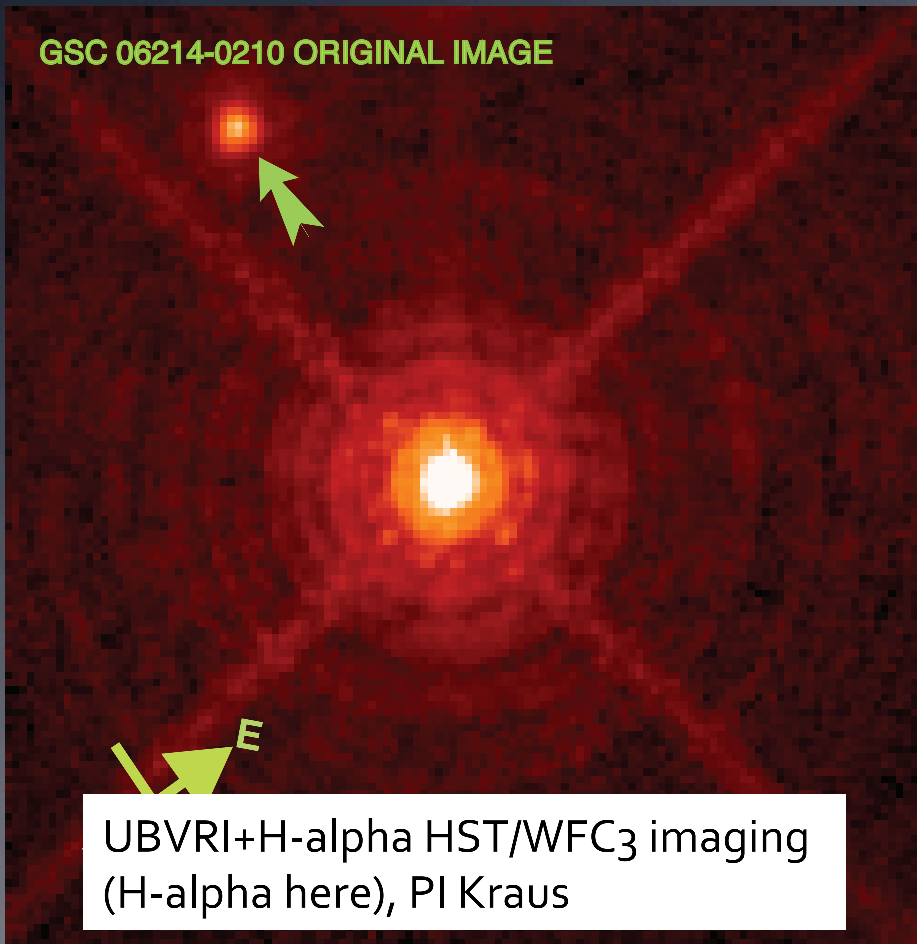
A protoplanet as a young star

(e.g., Bowler+2012; Zhou+2014; Zhu 2014)

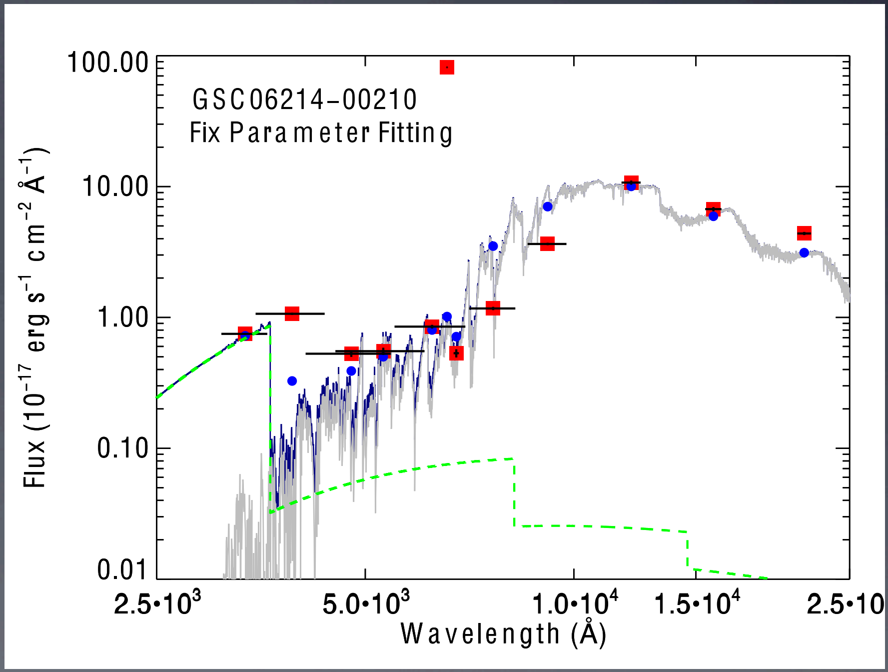


Formation of protoplanets in progress

(Zhou, Herczeg, et al. 2014; Bowler+2013)



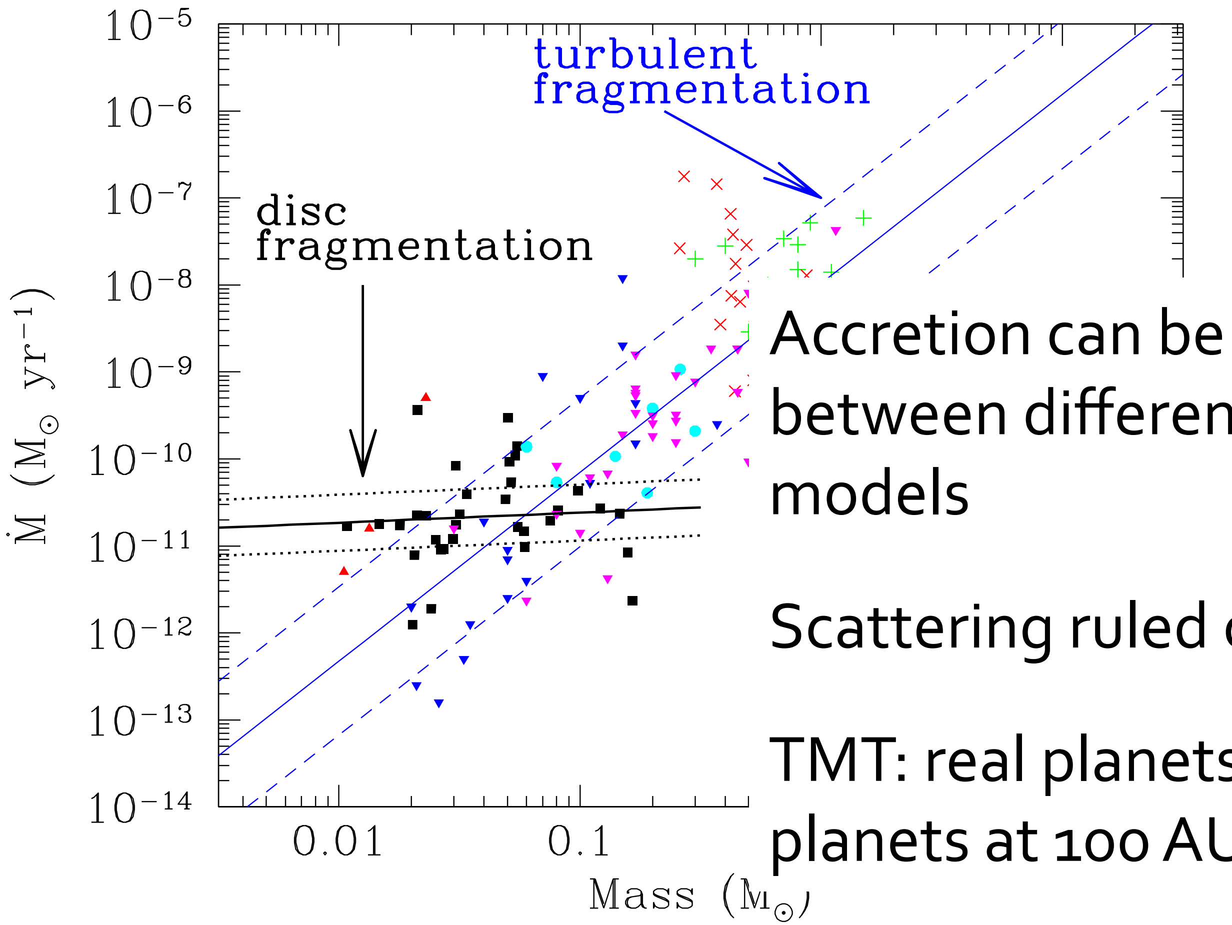
UBVRI+H-alpha HST/WFC3 imaging (H-alpha here), PI Kraus



Also being pursued with MagAO optical light AO, Follette+

Measure accretion onto planet mass companions

Predictions for accretion rates: disk fragmentation or failed binary?



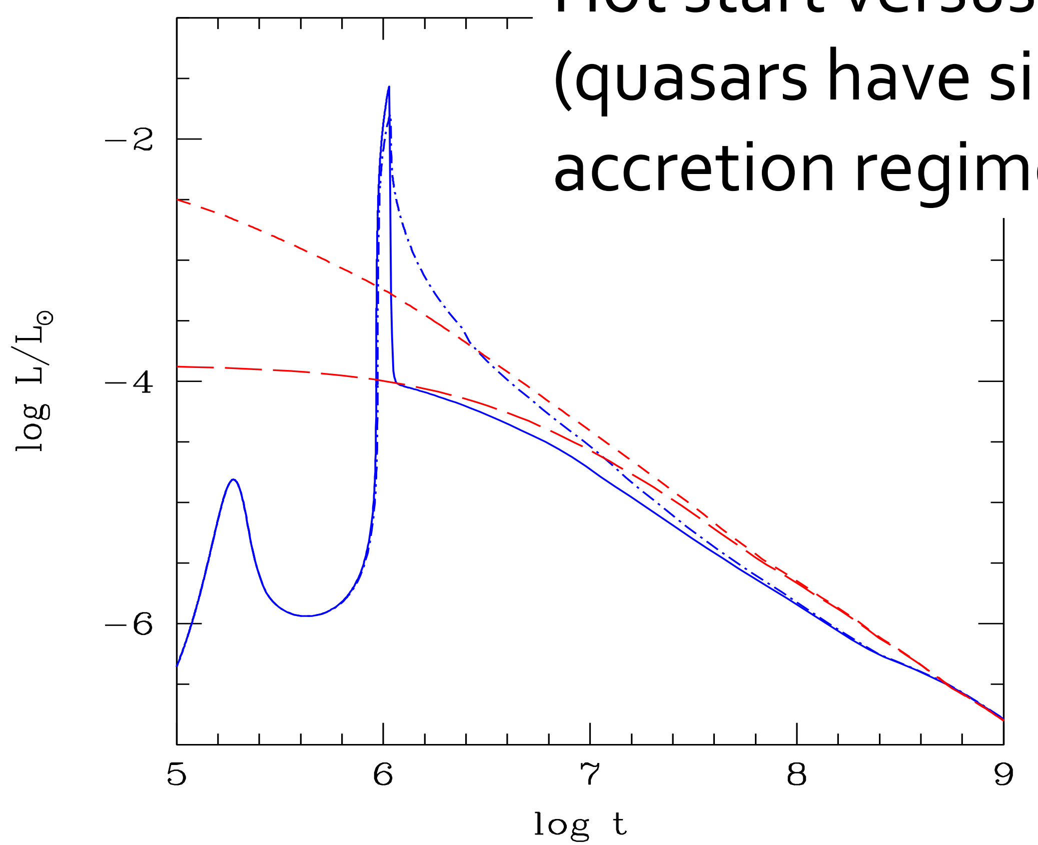
Accretion can be used to test between different formation models

Scattering ruled out

TMT: real planets (instead of planets at 100 AU!)

Stamatellos & Herczeg 2015

Formation history has lasting affect on luminosity (=mass estimates)

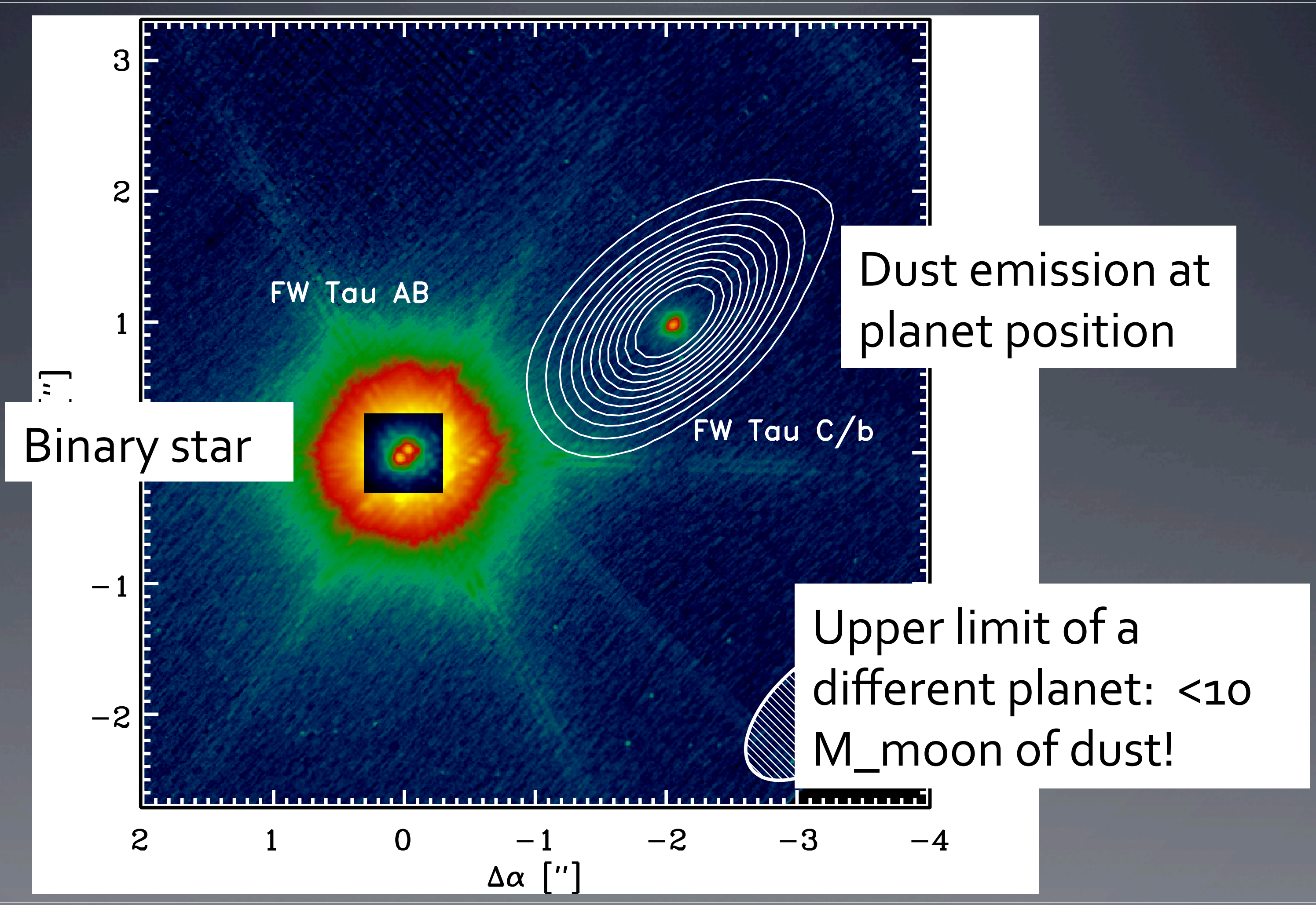


Hot start versus cold start (quasars have similar accretion regimes)

Chabrier+2014 review; see also Marley+2007; Spiegel & Burrows 2009

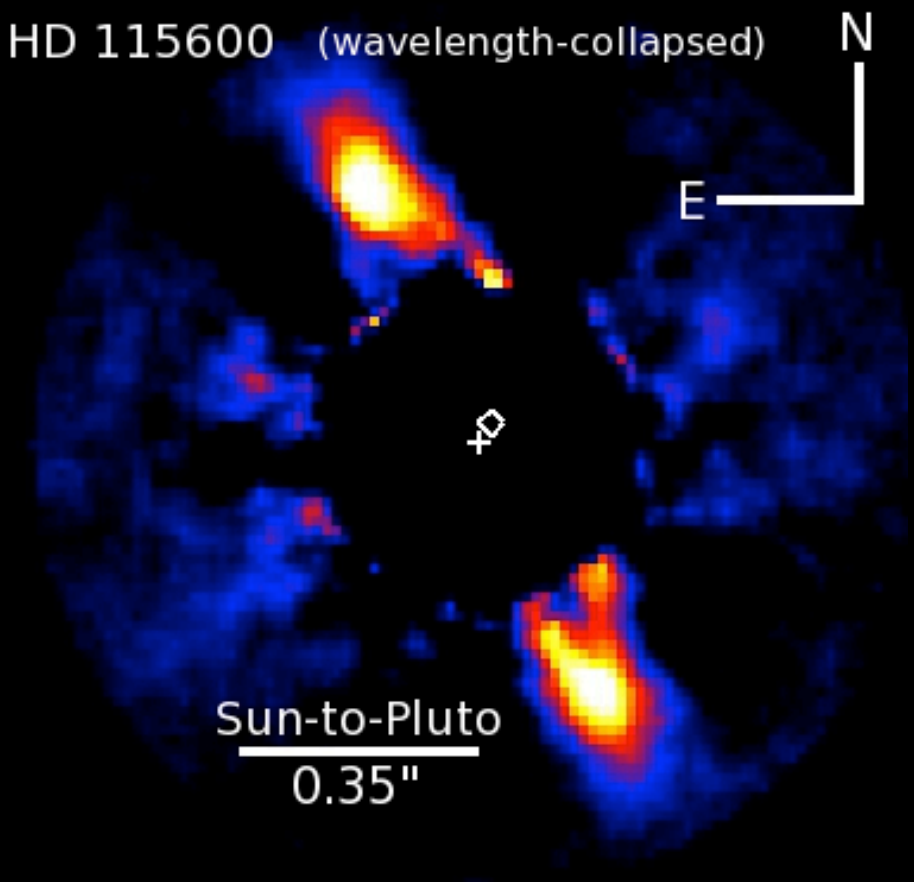
Exomoon formation and ALMA protoplanets

(Kraus+2015; Bowler+2015)

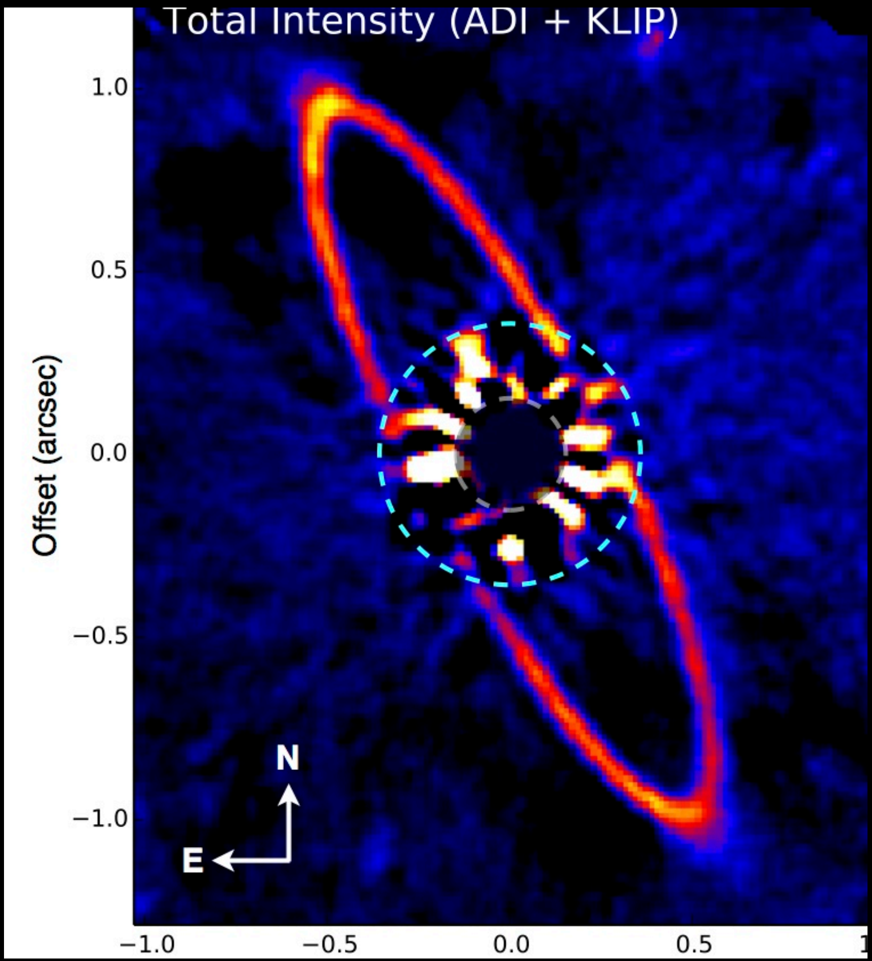


Planet Formation with TMT
(and 2nd generation instruments)

- Planet formation is the physics of disk instabilities, which needs high spatial resolution
- Snow lines for different molecules may lead to instabilities and affect final abundances of giant planets
- Planet growth/moon formation may be directly detectable at very small inner working angles (H-alpha, CO)
- ALMA and ExAO systems are revolutionizing this field (as will JWST); inner working angle and high resolution mid-IR are unique to TMT
- Direct detection of extrasolar planets (everyone at Lyot conference; many exciting Extreme AO results very soon)

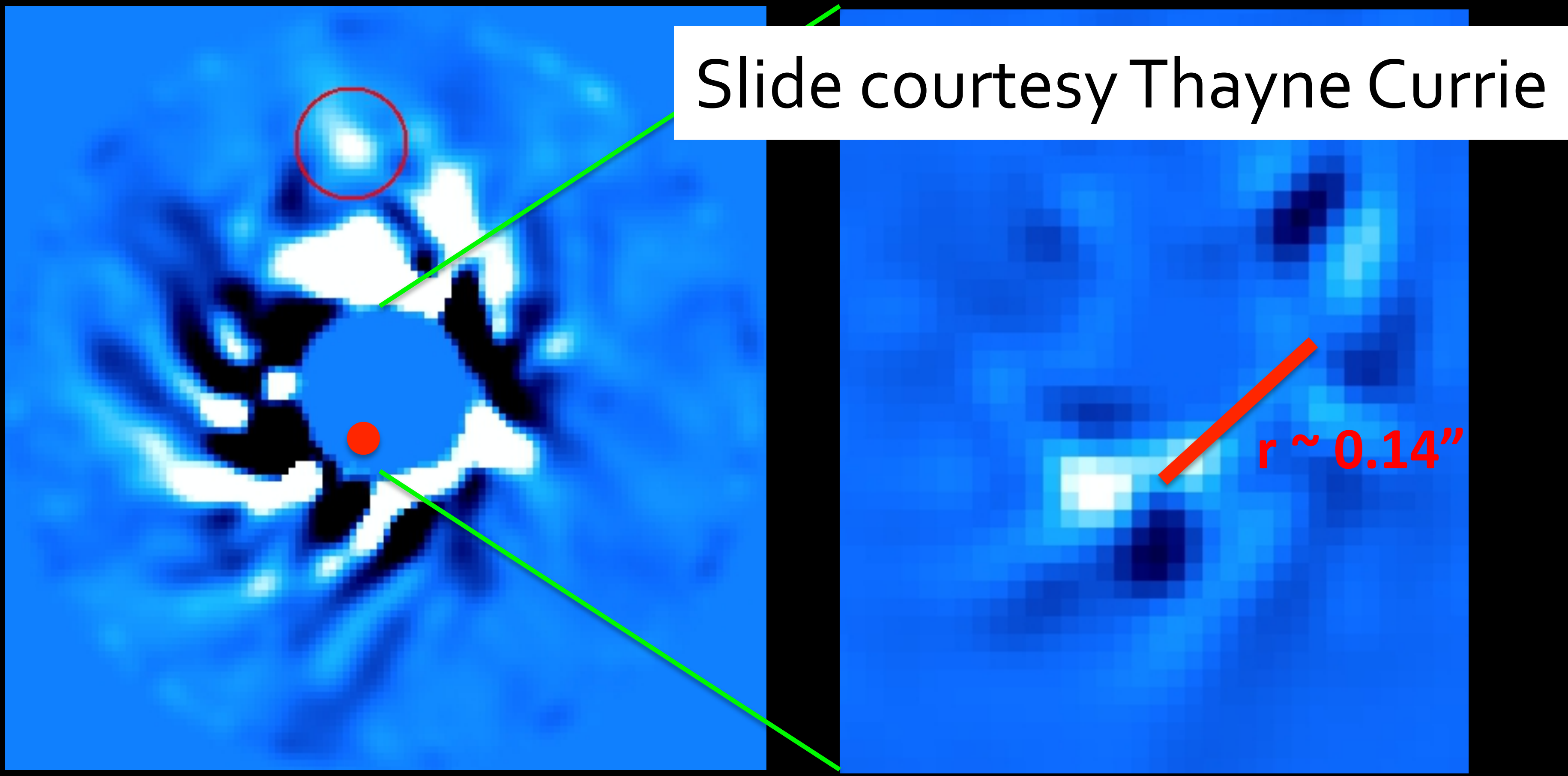


Currie+2015



Perrin+2015

GPI Images of HD 100546 at Small Separations: A Candidate 2nd Protoplanet (NEW!)



7-sigma point source-like feature (< 15 Mj)

- Almost perfectly consistent with predicted position of second planet: "HD 100546 c" (Brittain et al. 2014)
- protoplanet, disk hot spot/inner wall?

GPI: Twitter embargo fail

2 M_{Jup} at 13 AU; 20 Myr