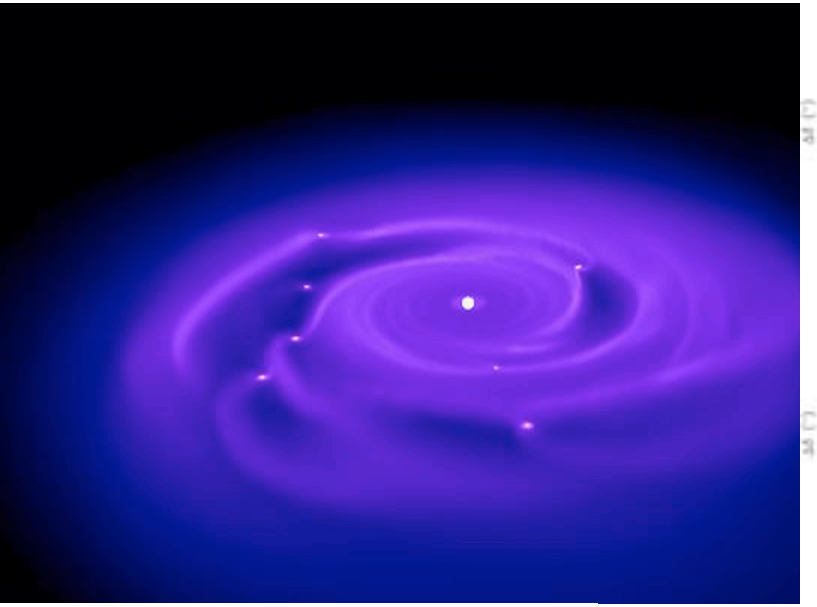
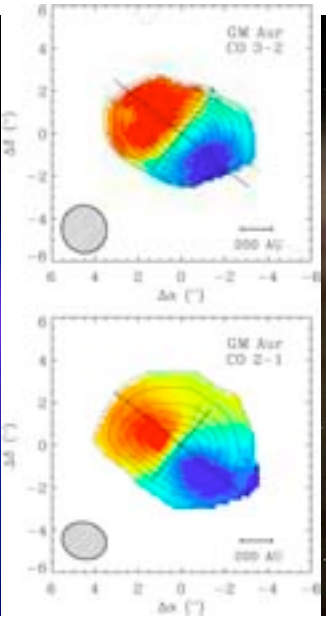
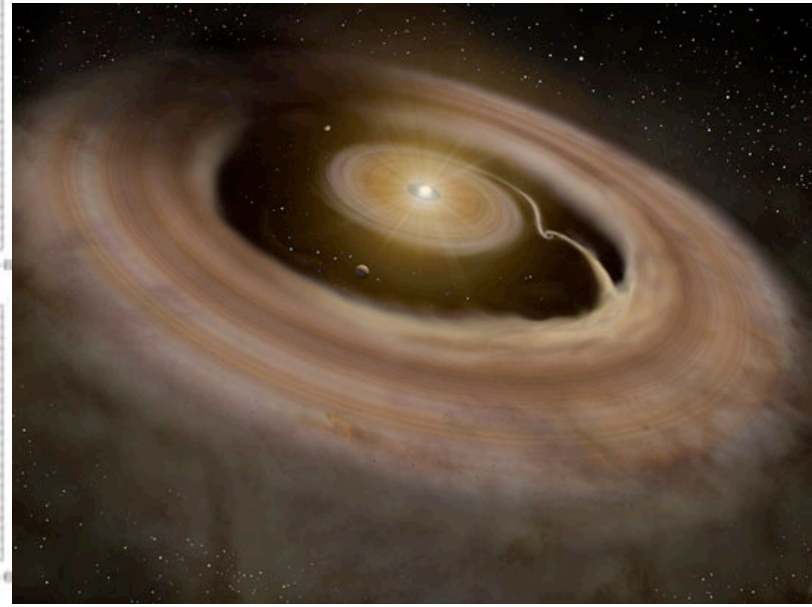
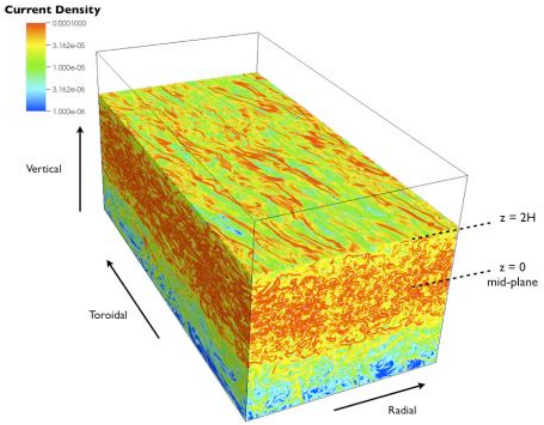
# Observations of Protoplanetary Disks: GAS

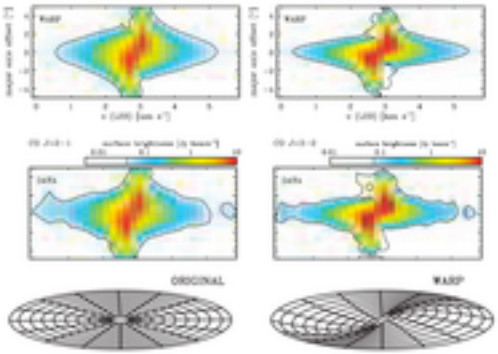






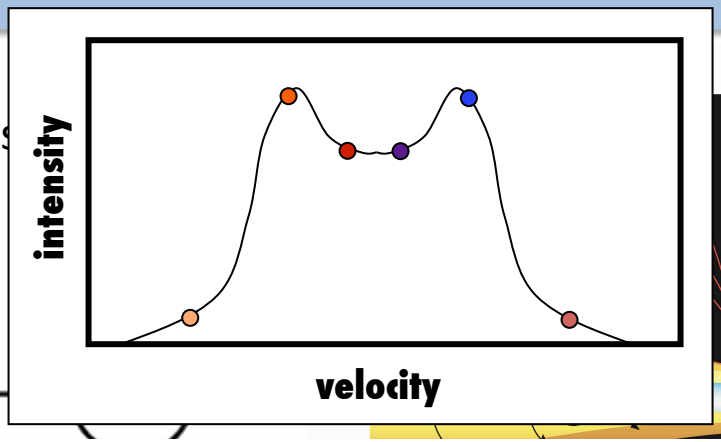

Meredith Hughes
Wesleyan University

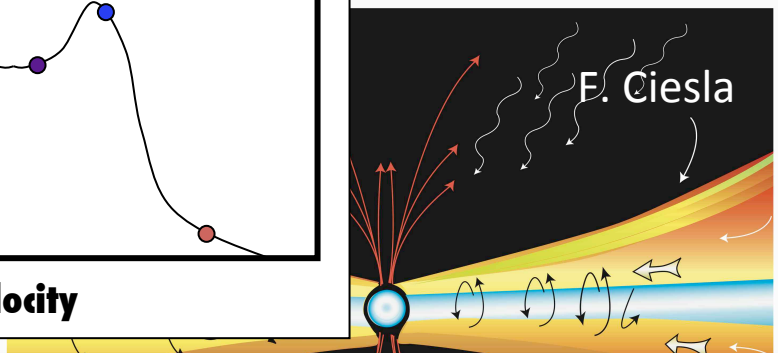


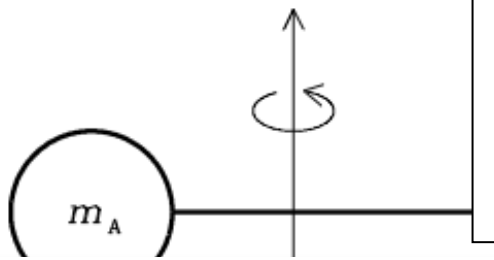
# Why gas?

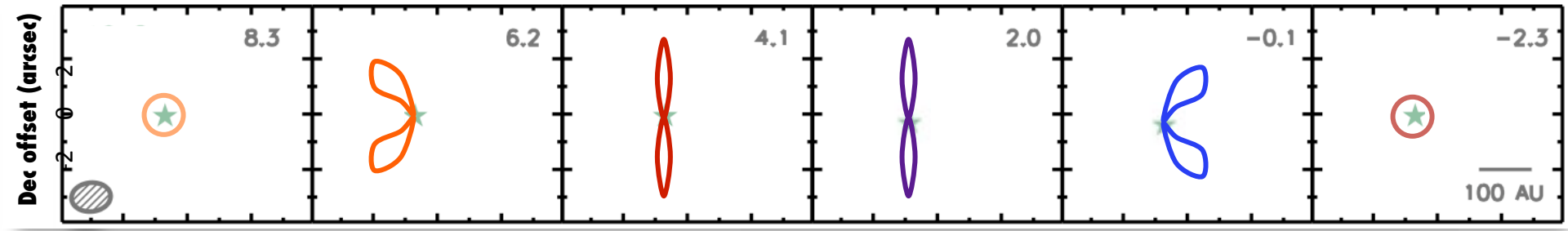
- 99% of the mass of a protoplanetary disk is in gas
- Gas dominates dynamics
- Provides access to kinematics
- Chemistry

BUT… most of that gas is

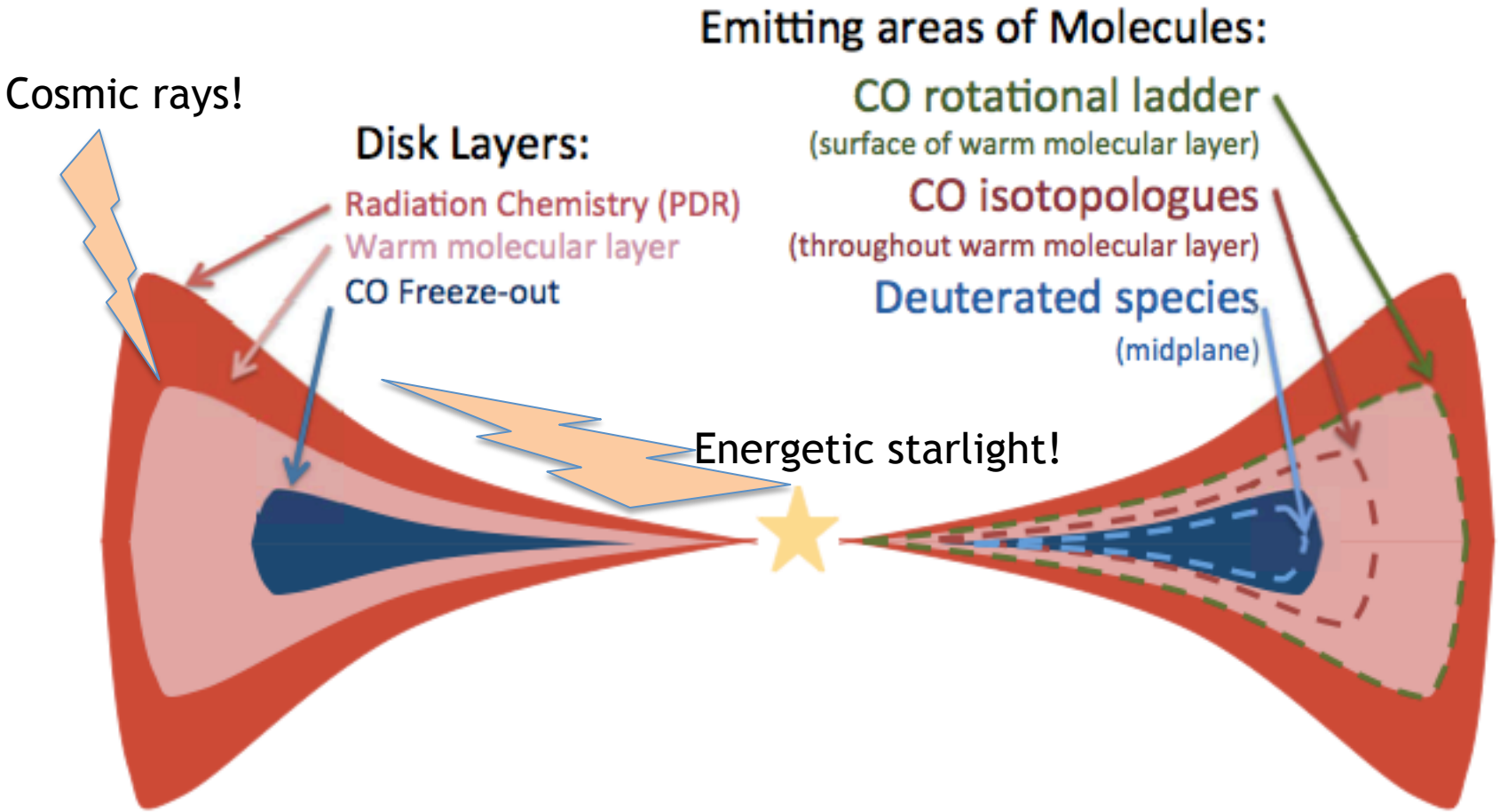


# Understanding the layered structure of a gas disk



# BIG QUESTIONS

## about gas

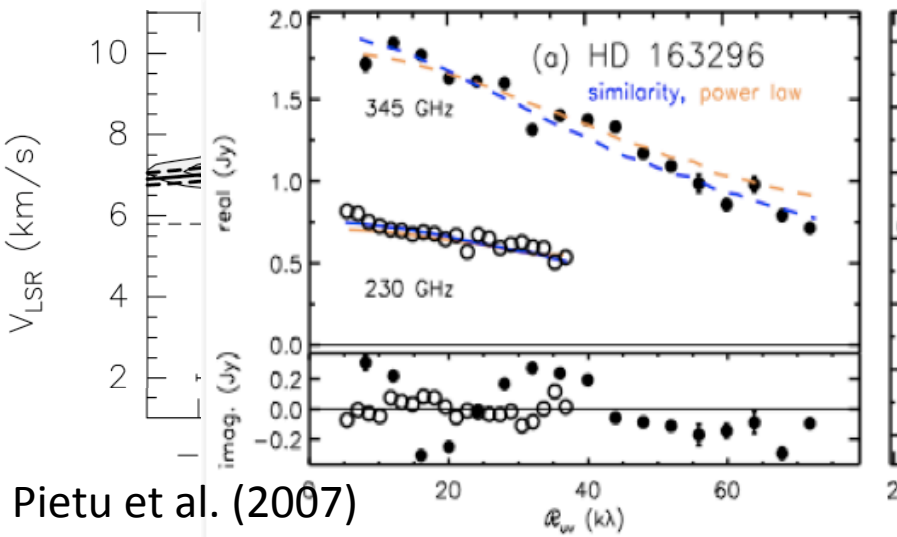
1. Does the gas trace the dust?
2. How does chemistry affect planet formation?
3. How does the gas move?
4. What is the deadline for giant planet growth?
5. What can gas tell us about planets?

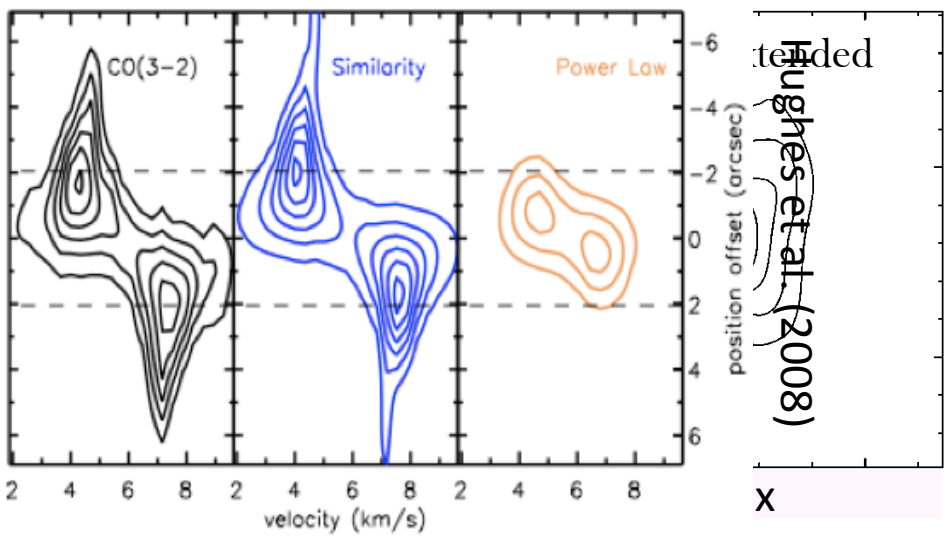
# 1. Does the gas trace the dust?

How good are disk mass estimates that use only dust?

*Once upon a time…*

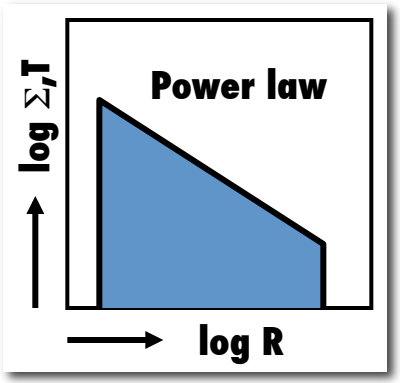
(The story of similarity solutions)

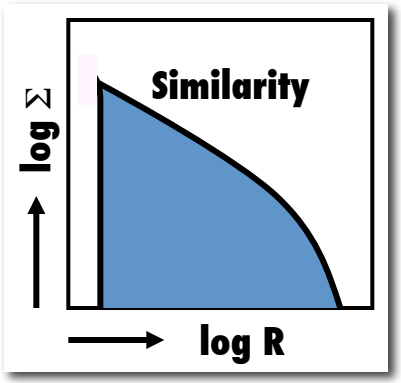



Pietu et al. (2007)

Isella et al. (2007)




tended

Hughes et al. (2008)

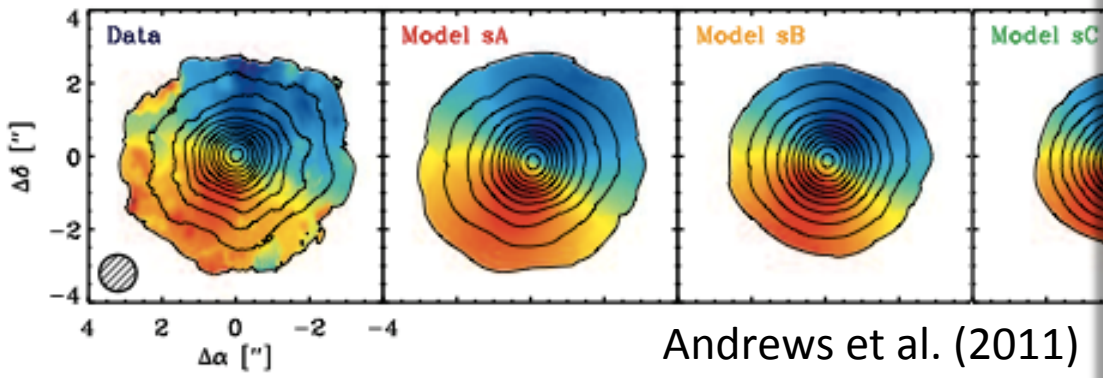
x

# 1. Does the gas trace the dust?

How good are disk mass estimates that use only dust?

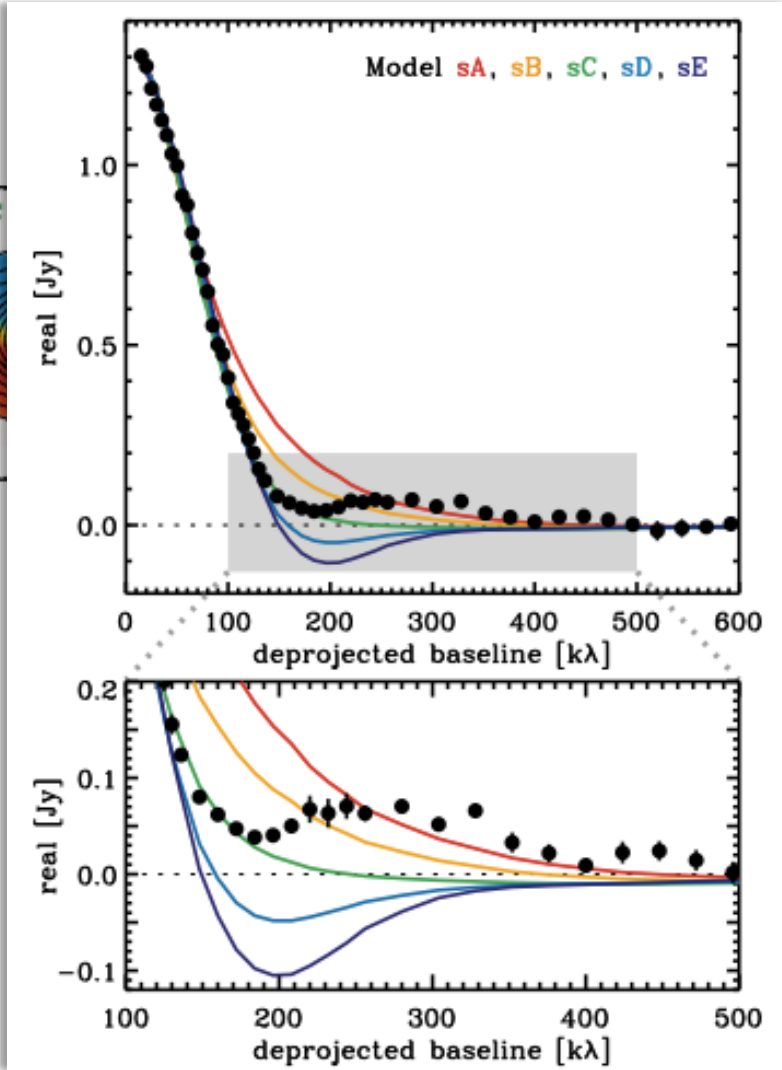
*But now…*

(The story of similarity solutions)



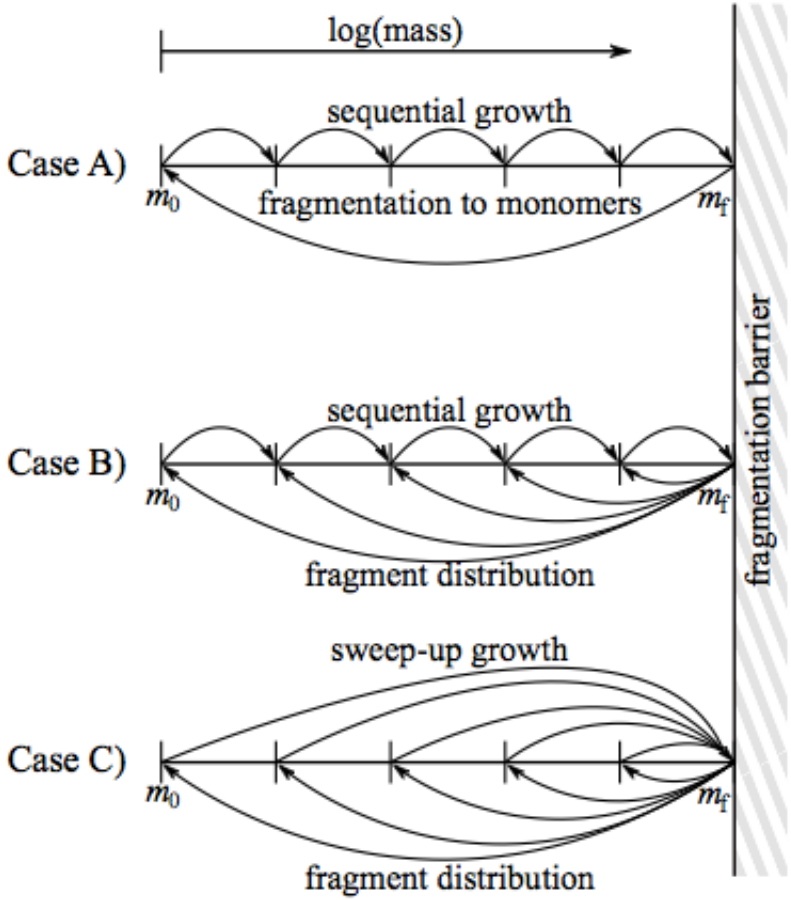

Andrews et al. (2011)

- Dust disks are at least sometimes smaller than gas disks.
- AND they appear to have sharp edges!
- Probably doesn't affect mass measurement much.
- Why? Fragmentation and drift



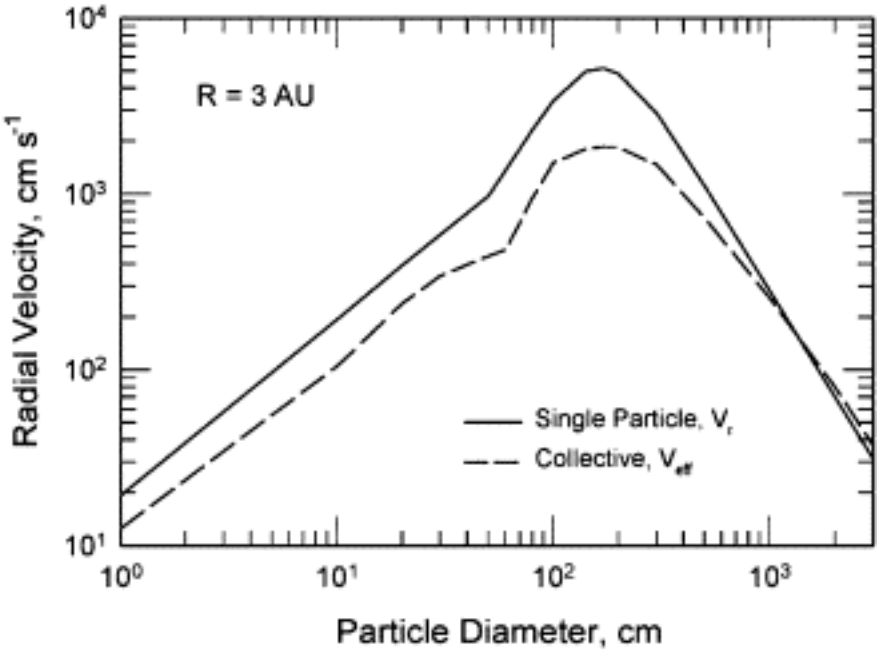
# 1. Does the gas trace the dust?

How good are disk mass estimates that use only dust?



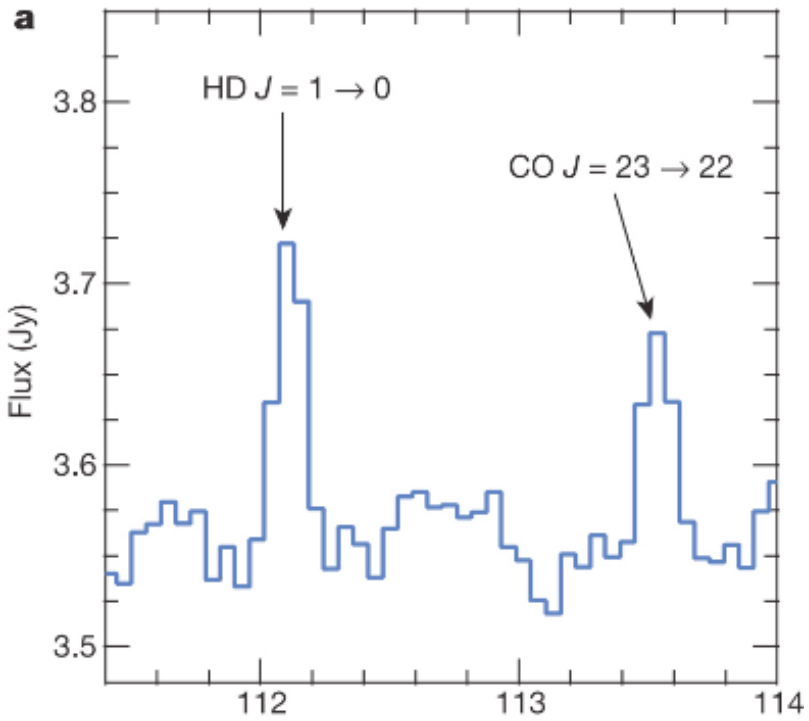

Birnstiel et al. (2011)

Weidenschilling et al. (2006)



# 1. Does the gas trace the dust?

How good are disk mass estimates that use only dust or CO?



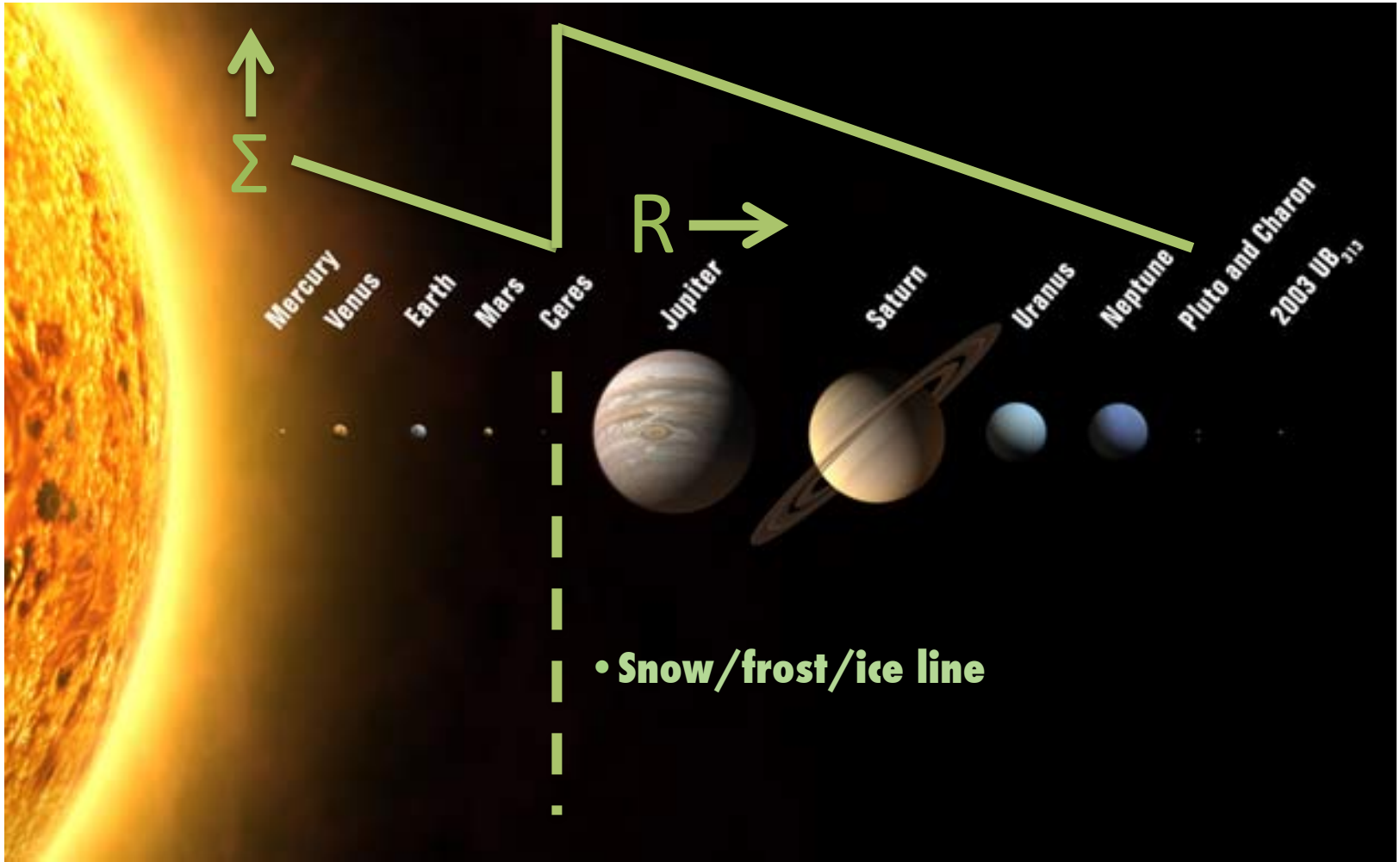

Bergin et al. (2013)

Detection of HD in TW Hya with *Herschel*

Previous mass estimates: 0.0005-0.06 $M_{sun}$
Using HD: 0.05 $M_{sun}$

# 2. How does chemistry affect planet formation?

Snow lines in circumstellar disks



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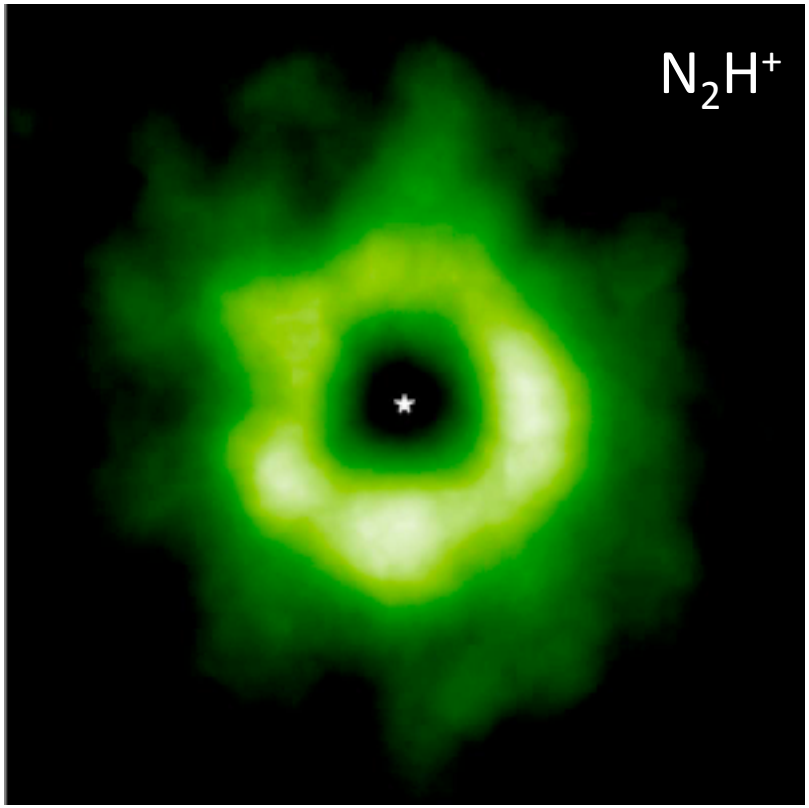
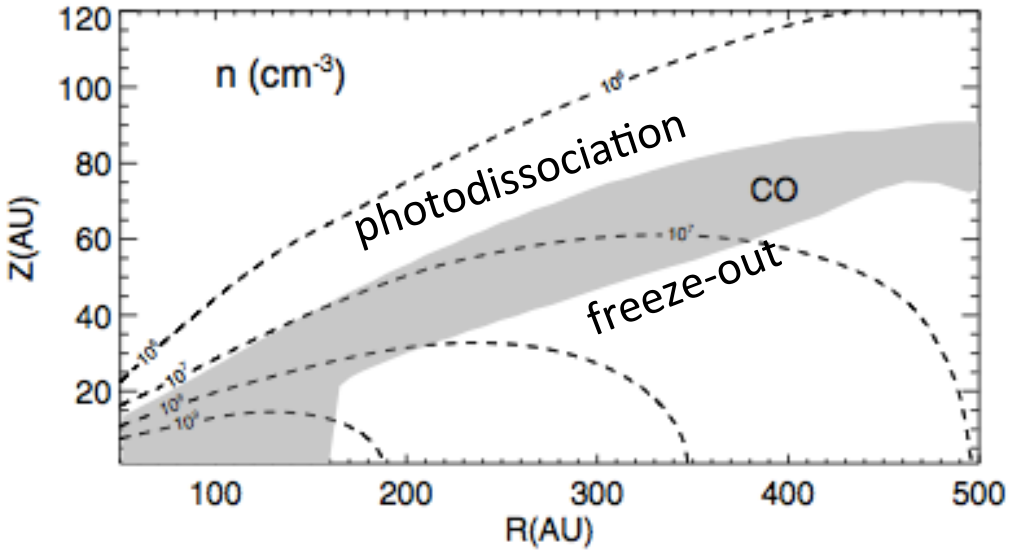
Snow lines in circumstellar disks

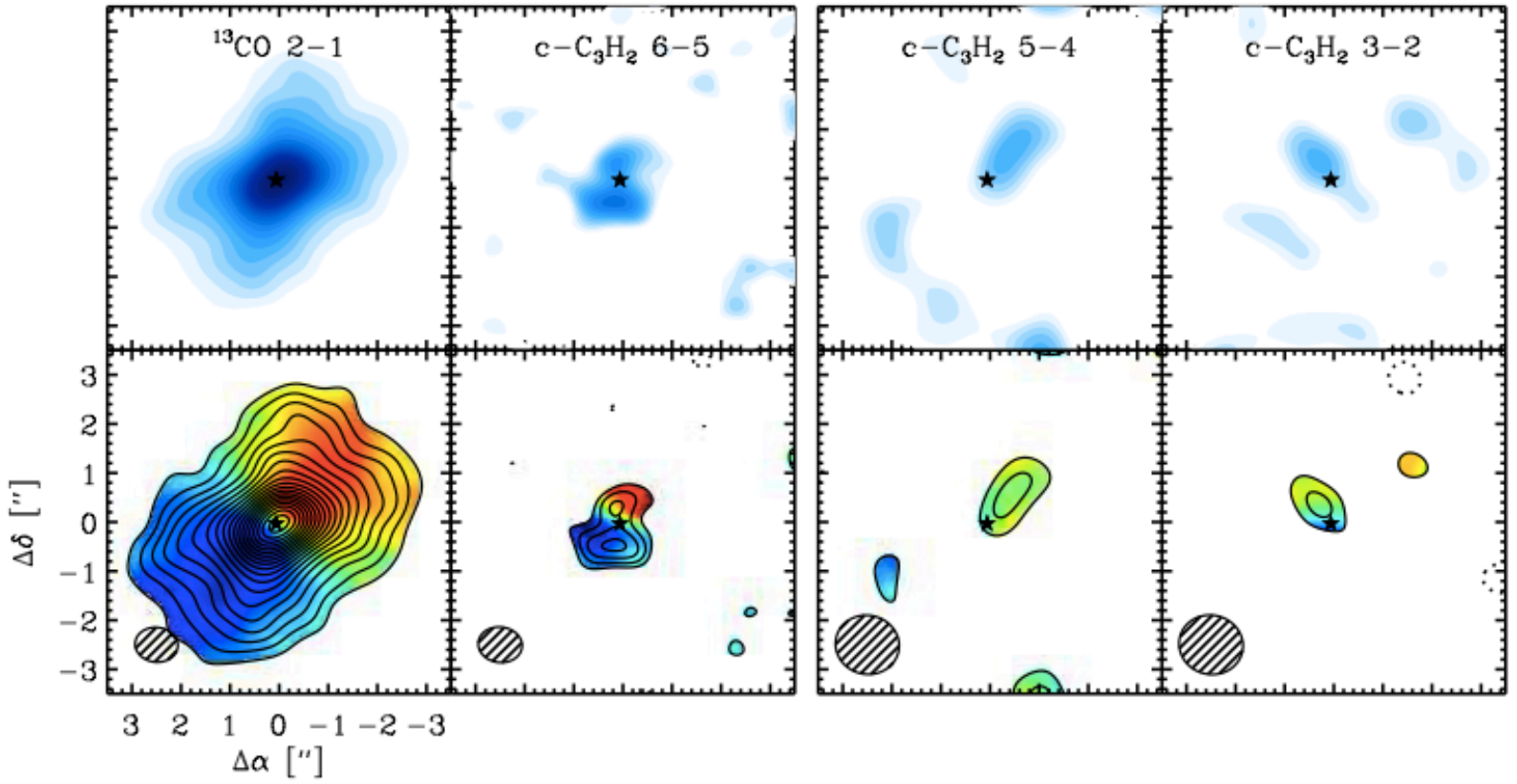



CO snow line – Qi et al. (2011, 2013a)

# 2. How does chemistry affect planet formation?

c-$C_3H_2$ as an excitation/turbulence tracer

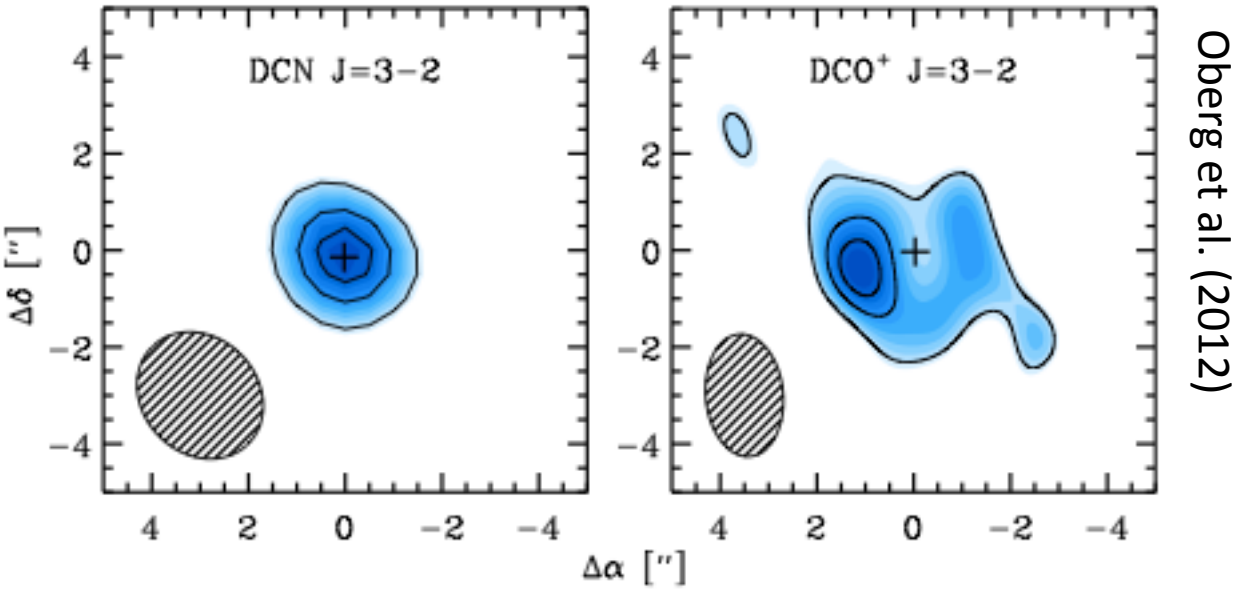



Qi et al. (2013b)

Sensitive to fractional ionization, penetration depth of X-rays and UV photons, turbulent mixing (relative to other hydrocarbons)

# 2. How does chemistry affect planet formation?

Multiple pathways to deuterium enhancement in protoplanetary disks



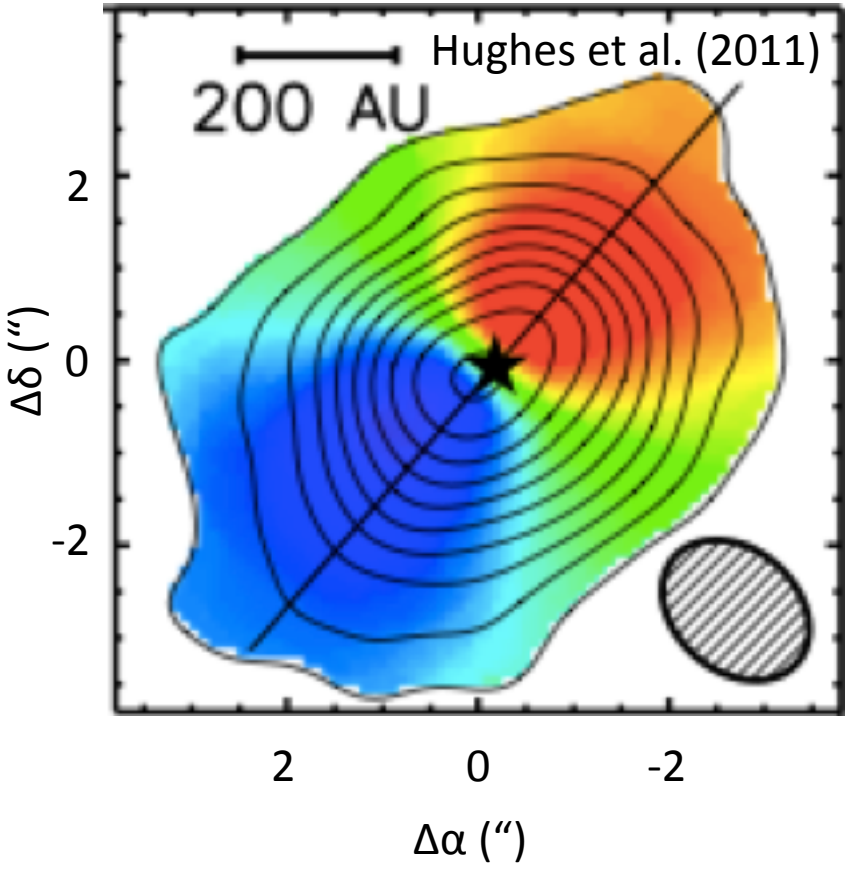

Oberg et al. (2012)

Some pathways to deuterated molecule formation are efficient at high temps and others at low temps: caution when looking at solar system deuteration!

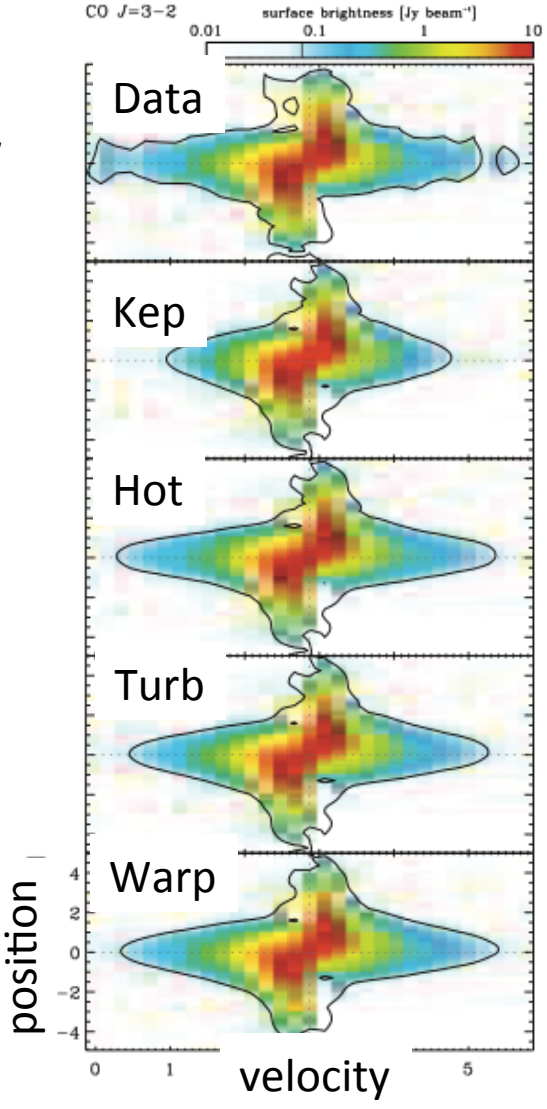
# 3. How does the gas move?

Observing the kinematic initial conditions for planet formation

At least to first order, these disks are so Keplerian it hurts.



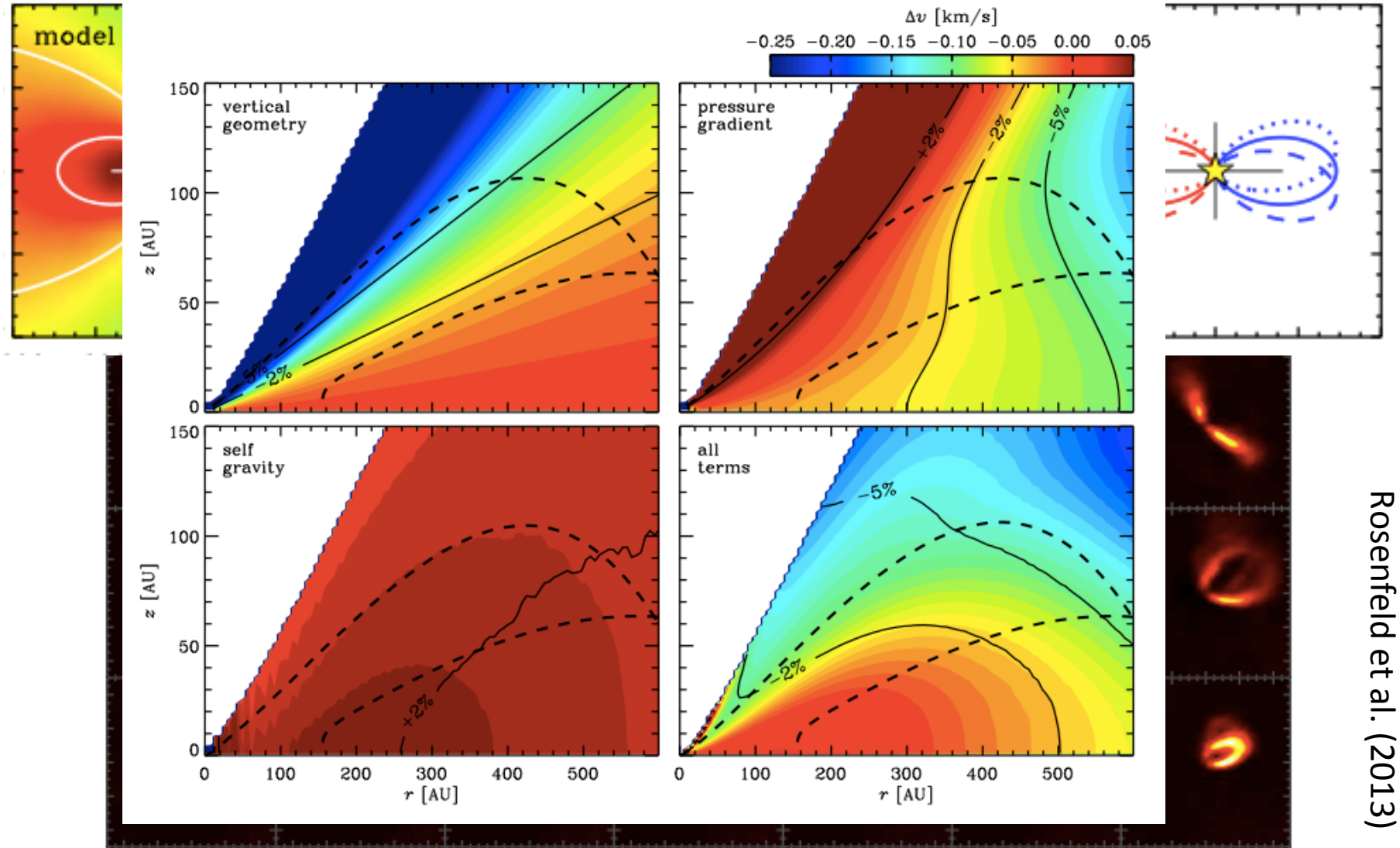

But recent technologies allow us to look closer…




Rosenfeld et al. (2011)

# 3. How does the gas move?

Observing the kinematic initial conditions for planet formation



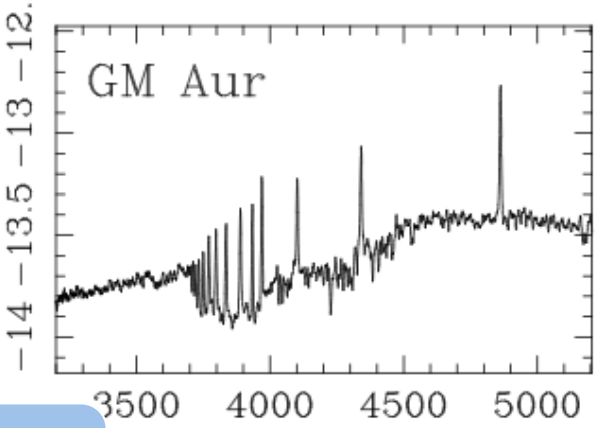

Rosenfeld et al. (2013)

# 3. How does the gas move?

Observing the kinematic initial conditions for planet formation

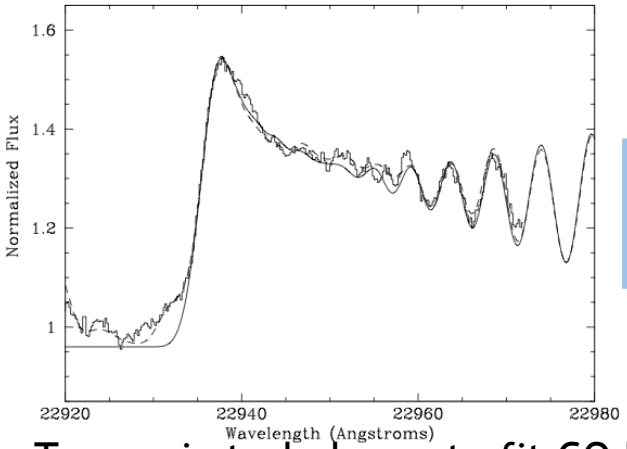
Observing turbulence…

## Accretion rate measurements




UV continuum excess
Gullbring et al. (1998)

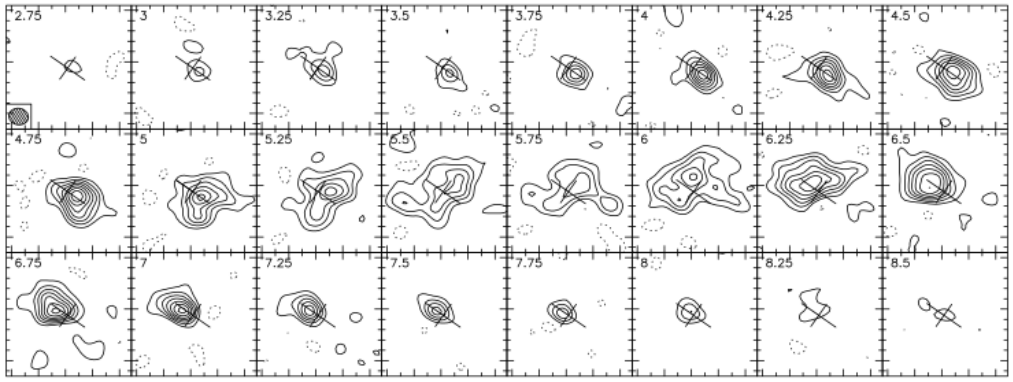
## Rovibrational lines




Transonic turbulence to fit CO band head
Carr et al. (2004)

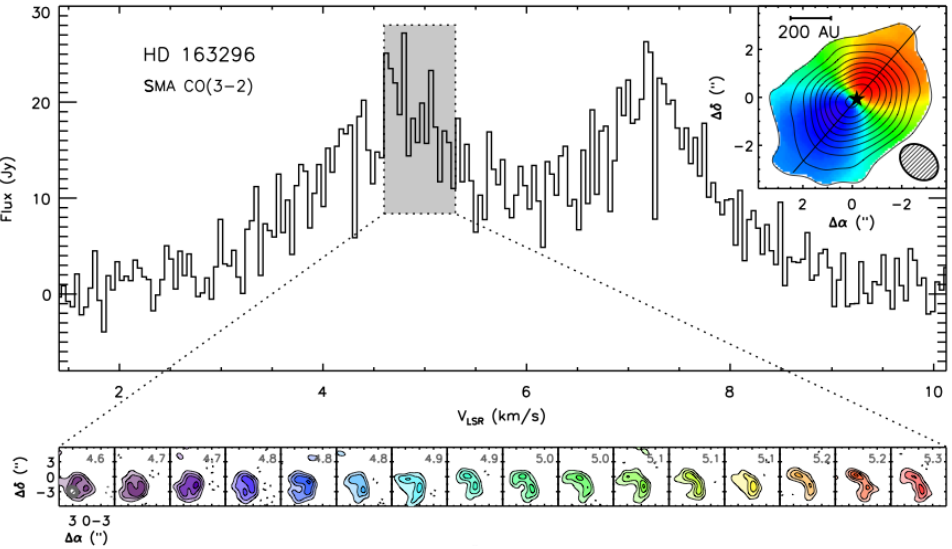
Fitting models to low-res CO spectra
Dutrey et al. (1998)

## Millimeter observations

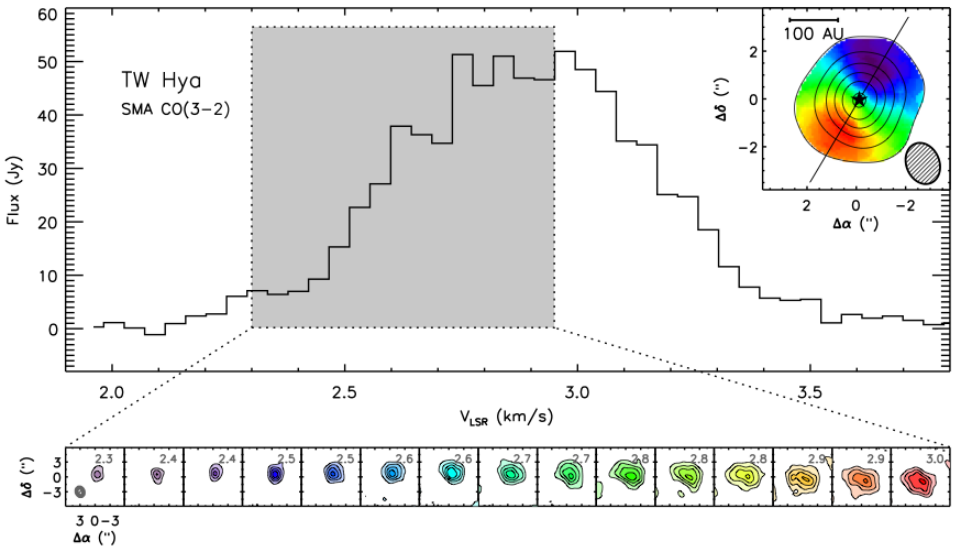


# 3. How does the gas move?

Observing the kinematic initial conditions for planet formation




Turbulence ~40% of local sound speed




Turbulence <10% of local sound speed

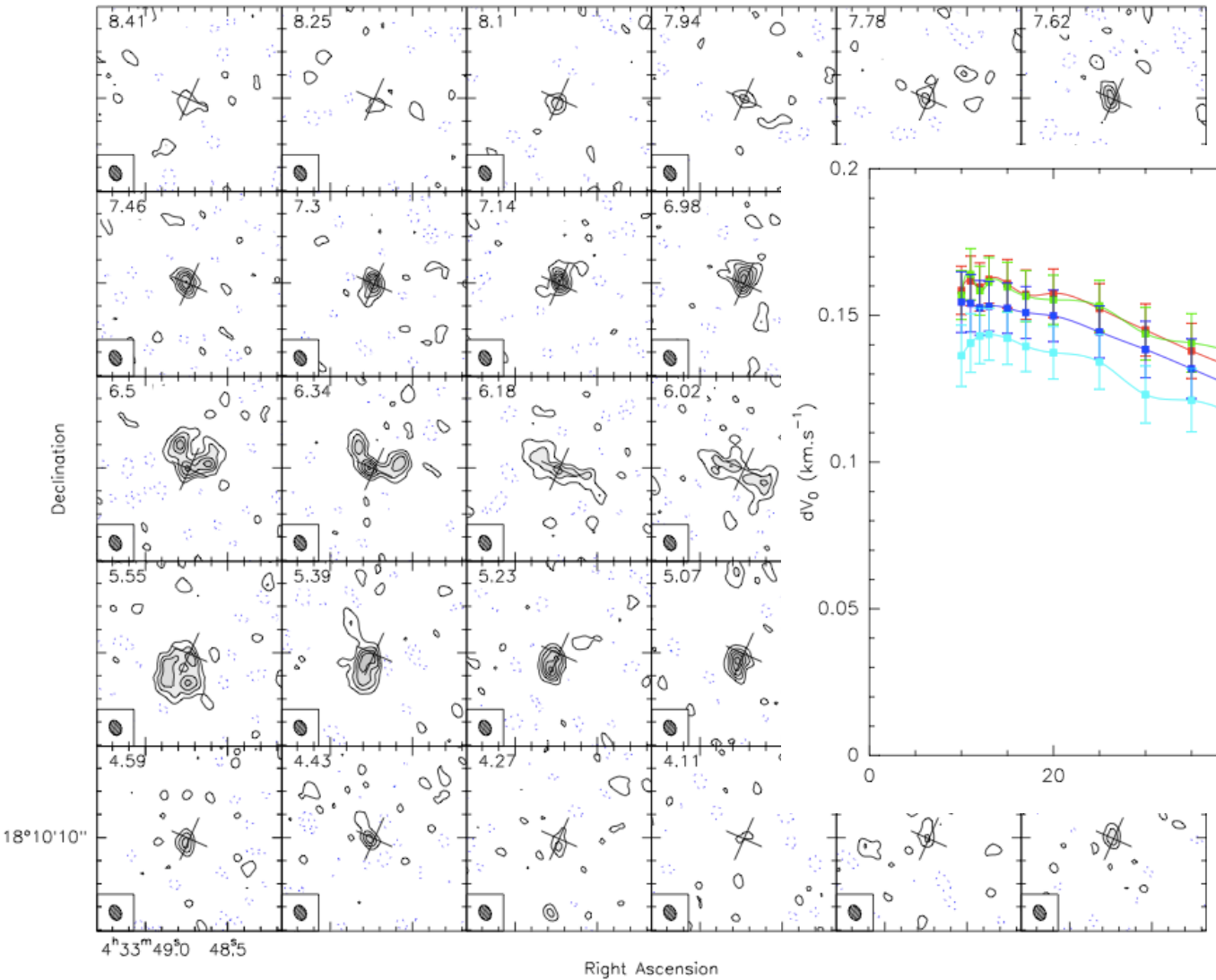
Challenge is to disentangle turbulence from other broadening (rotational, thermal, τ, …)

Tools: RATRAN/Lime

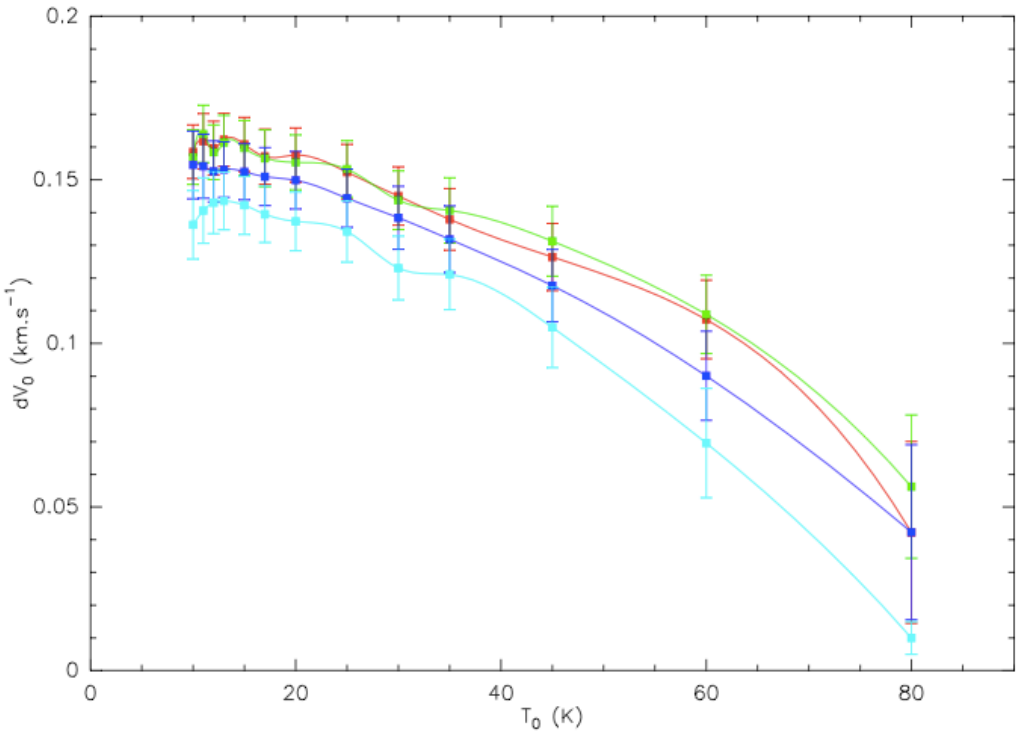
Hughes et al. (2011)

# 3. How does the gas move?

Observing the kinematic initial conditions for planet formation




CS as a turbulence tracer

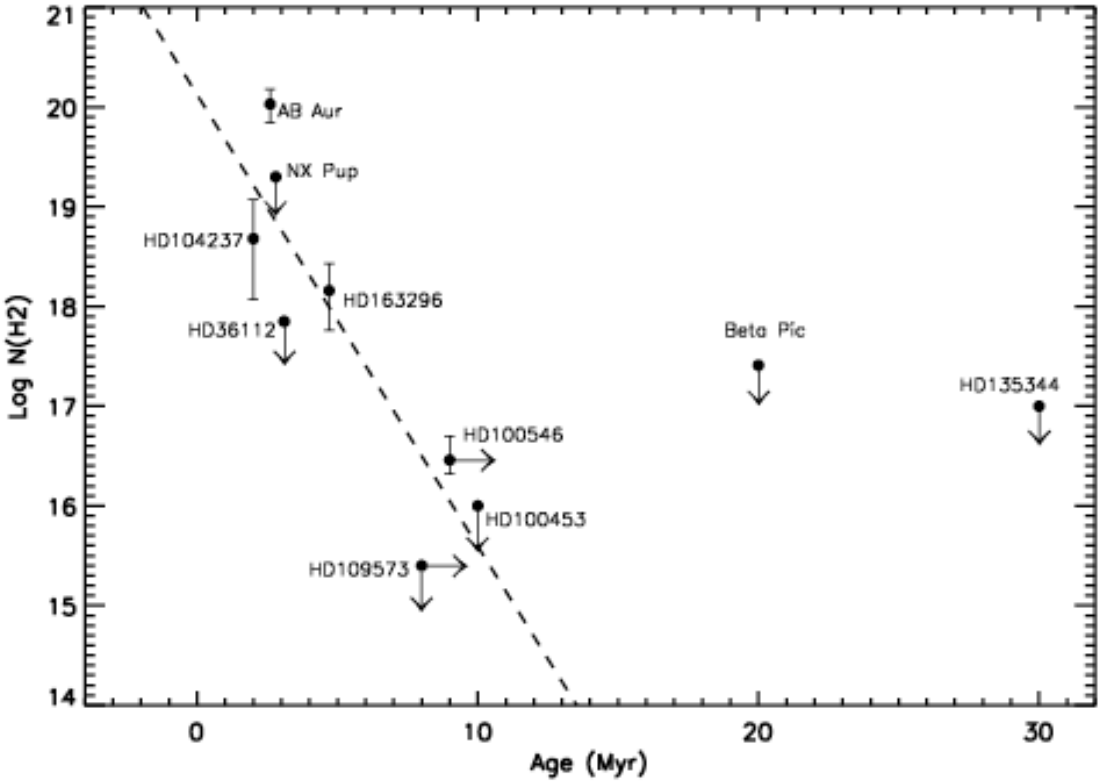



Guilloteau et al. (2012)

# 4. What is the deadline for giant planet formation?

Understanding gas disk dissipation and its timescales

Dust is much better characterized; this is the best we have for gas (possibly until the *Herschel* GASPS team publishes.)



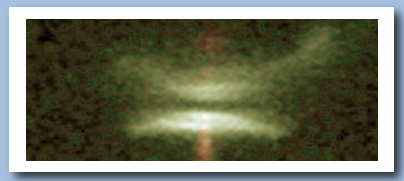

Martin-Zaidi et al. (2008)

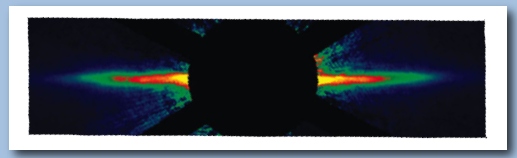
# 4. What is the deadline for giant planet formation?

Understanding gas disk dissipation and its timescales

## The standard story

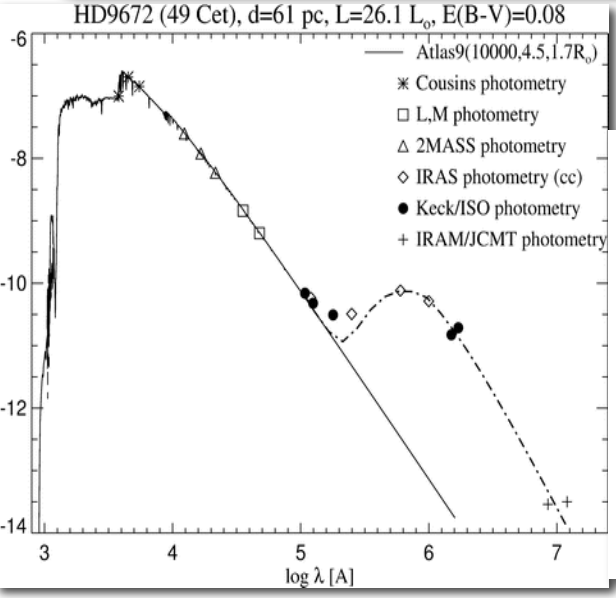
Lots of gas/dust left over from SF





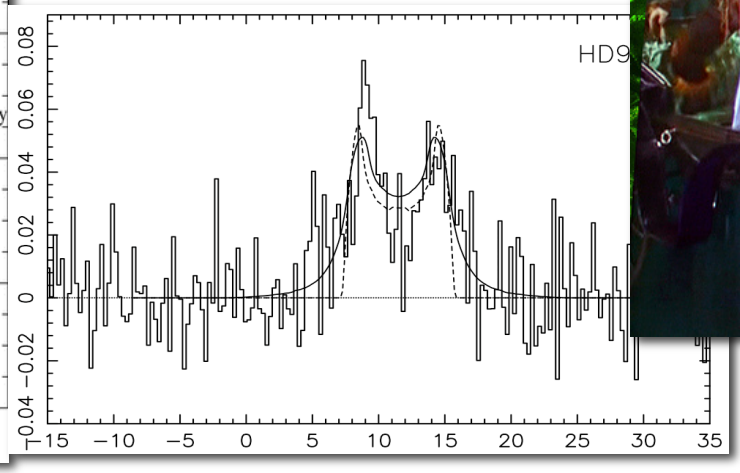
Debris dust only

Gas/dust disappear (~10Myr)




Dust looks like a debris disk…

Then what is this?



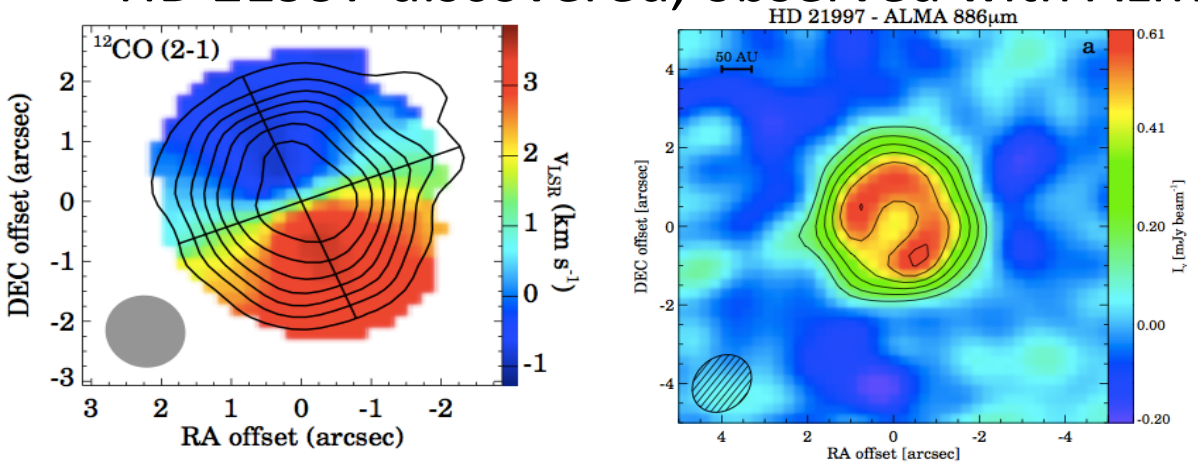


But still has lots of molecular gas!

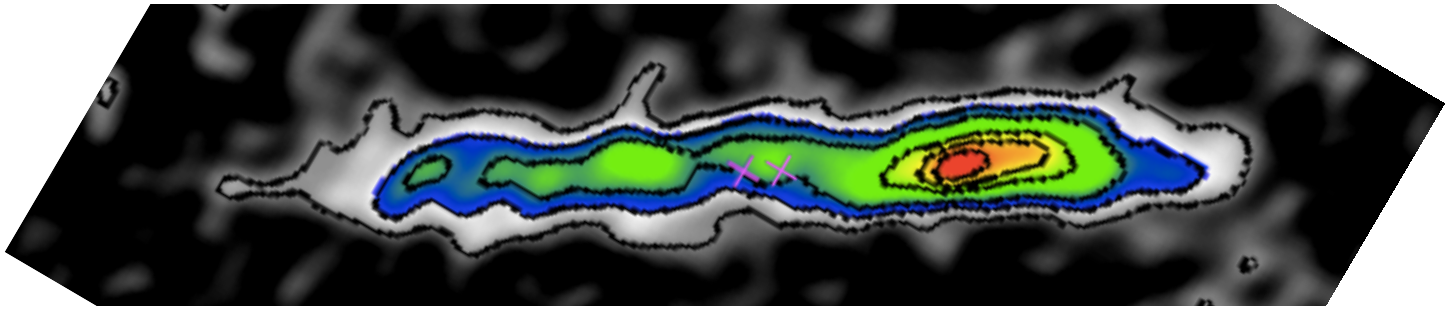
# 4. What is the deadline for giant planet formation?

Understanding gas disk dissipation and its timescales

HD 21997 discovered, observed with ALMA




Kospal et al. (2013), Moor et al. (2013, submitted)



CO observed in the debris disk around β Pictoris

Dent et al. (2013, submitted)

# 4. What is the deadline for giant planet formation?

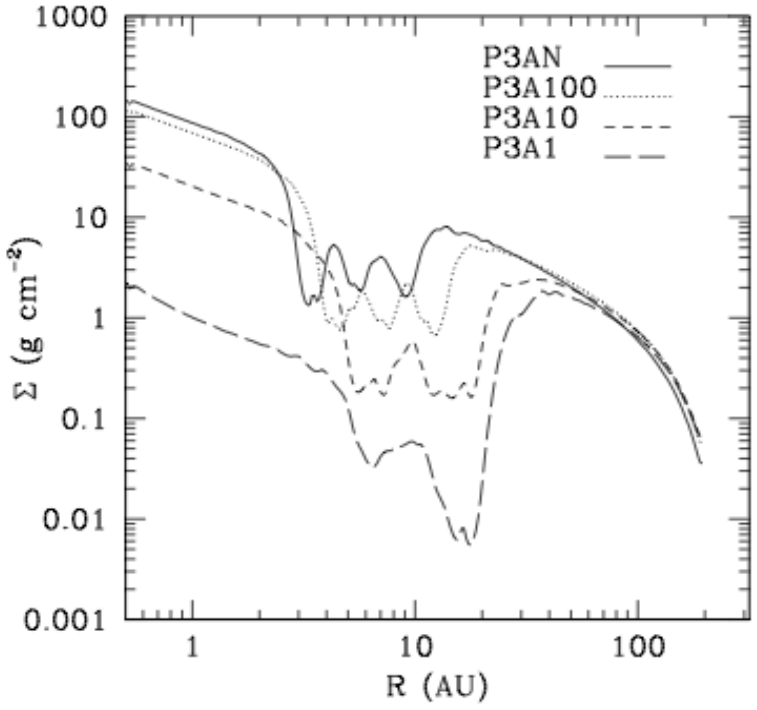
Understanding gas disk dissipation and its timescales

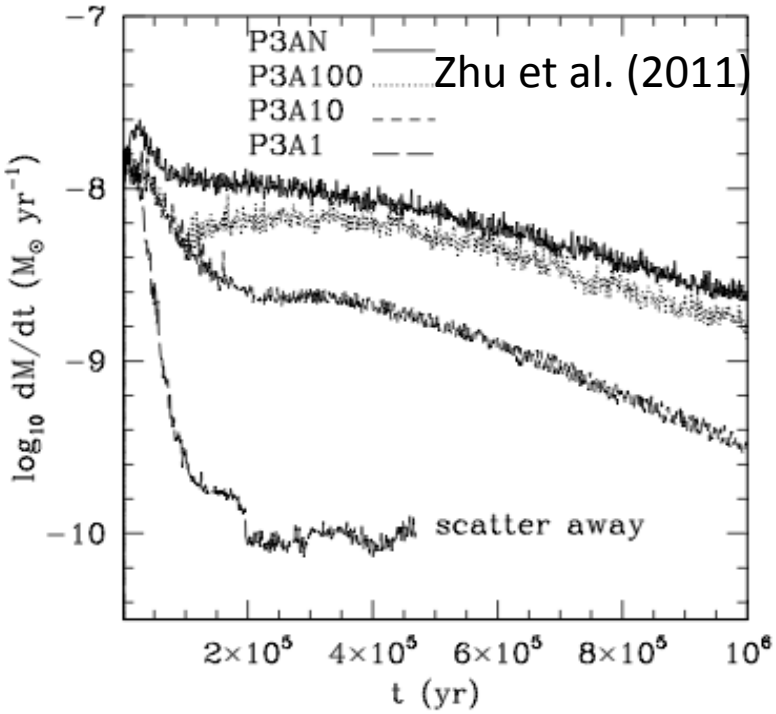
Is the gas primordial (Peter Pan disks) or second-generation (evaporating comets)?

# 5. What can gas tell us about planets?

Problem: Must decrease surface density by 4 dex, but accretion rate by only 1 dex, stable for ~0.1Myr

Solution: Multiple planets?



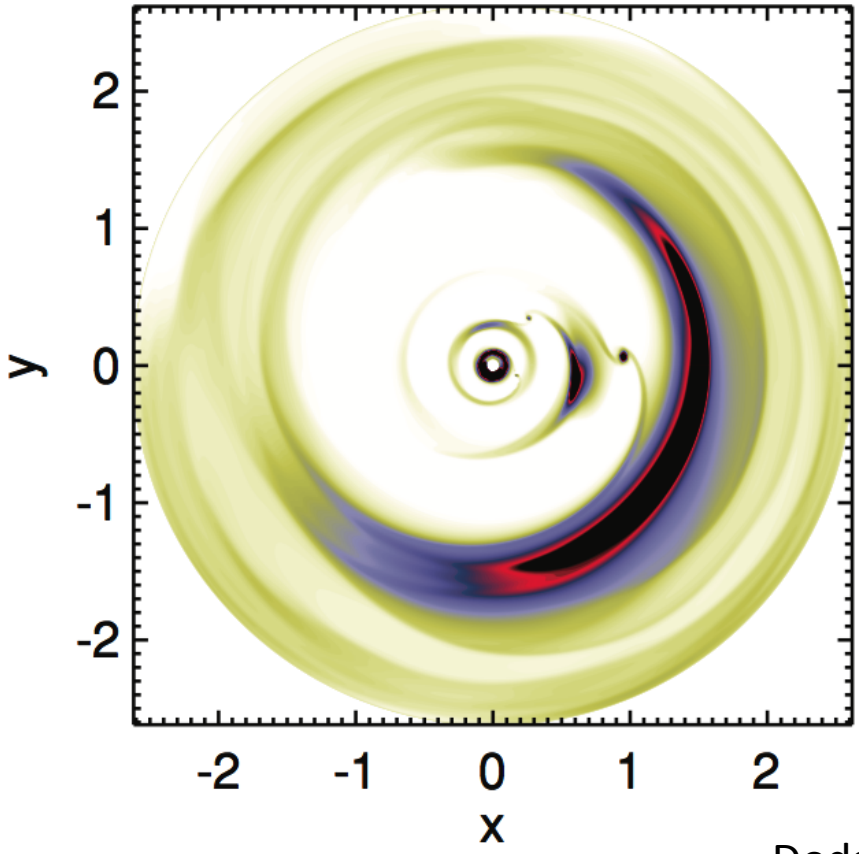

Zhu et al. (2011)

"Carefully comparing our simulations with observations indicates that the pre-transitional/ transitional disk systems require substantial reduction in dust opacities within the gaps…"
(i.e., "Not quite")

# 5. What can gas tell us about planets?

Problem: Must decrease surface density by 4 dex, but accretion rate by only 1 dex, stable for ~0.1Myr

Solution: Multiple planets?

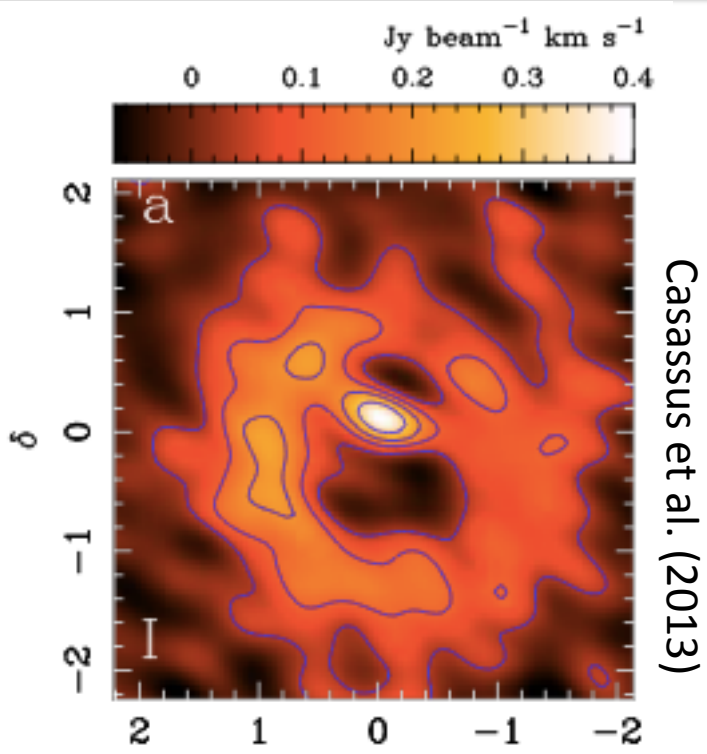



Dodson-Robinson & Salyk (2011)

# 5. What can gas tell us about planets?

Transition disk disambiguation

Have we already observed gap-crossing streamers?




Casassus et al. (2013)

# BIG QUESTIONS

## about gas

1. Does the gas trace the dust?
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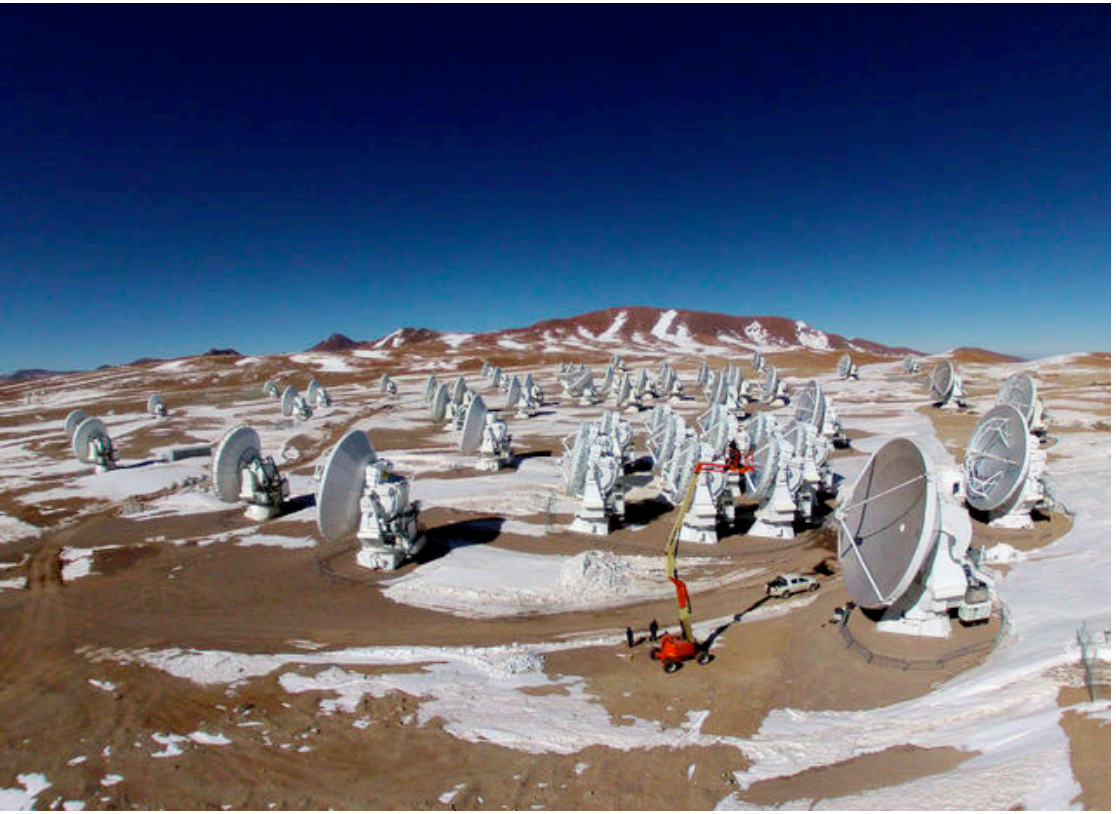
# ALMA

## Cycle 2 deadline this fall!



Cycle 2 will ramp up to nearly all the sensitivity and resolution of full ALMA – hugely impressive!

Lots of exciting planet-formation science to be done

Interested? Intimidated? I love talking about technical feasibility.