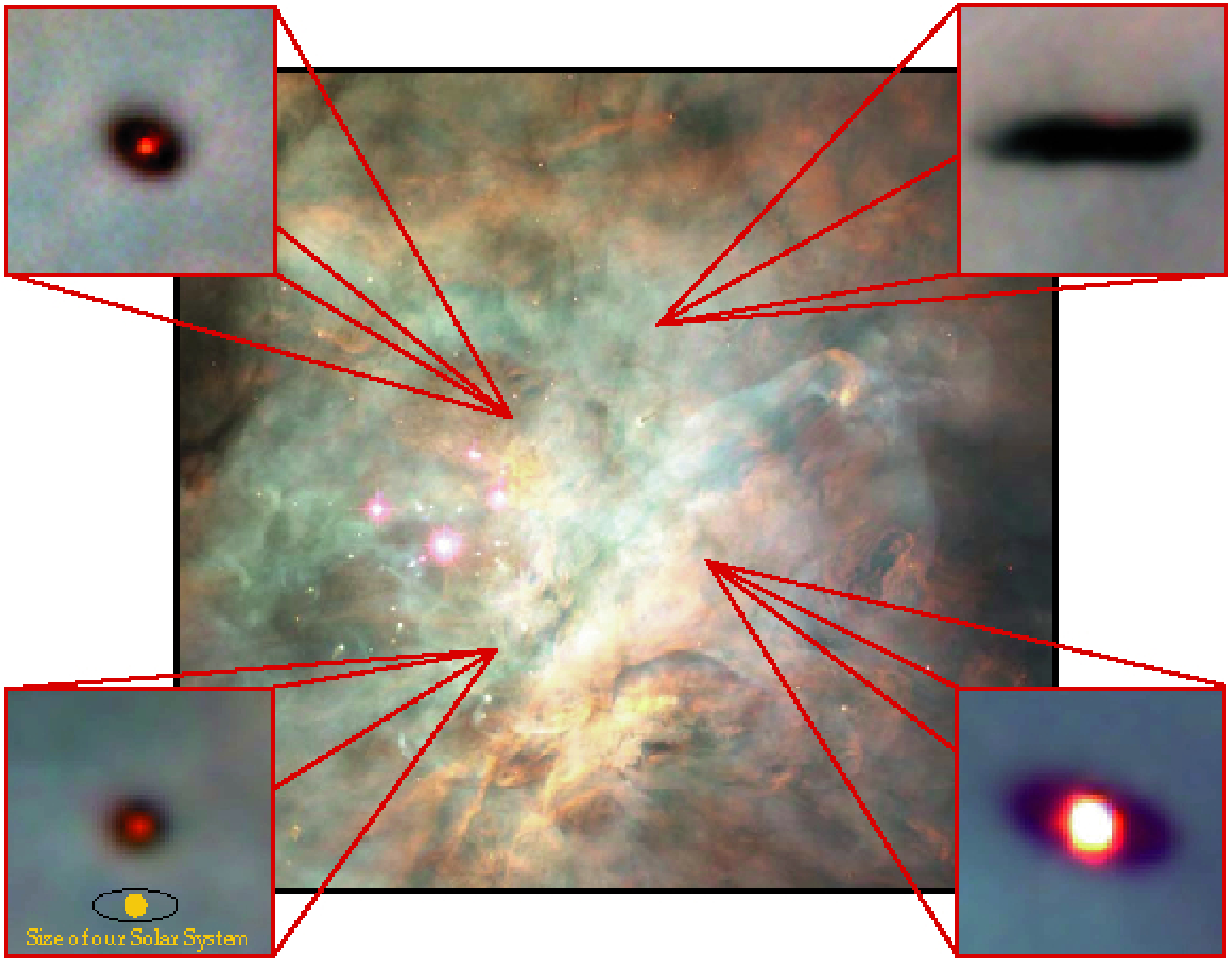
Zooming into planet-forming zones of disks with ALMA

Ewine F. van Dishoeck, Leiden Observatory / MPE

CSH colloquium Bern, October 18 2017

23 years ago: Iconic HST images of disks



0.05'' pixels

HST/NASA/ESA
O'Dell et al. 1994

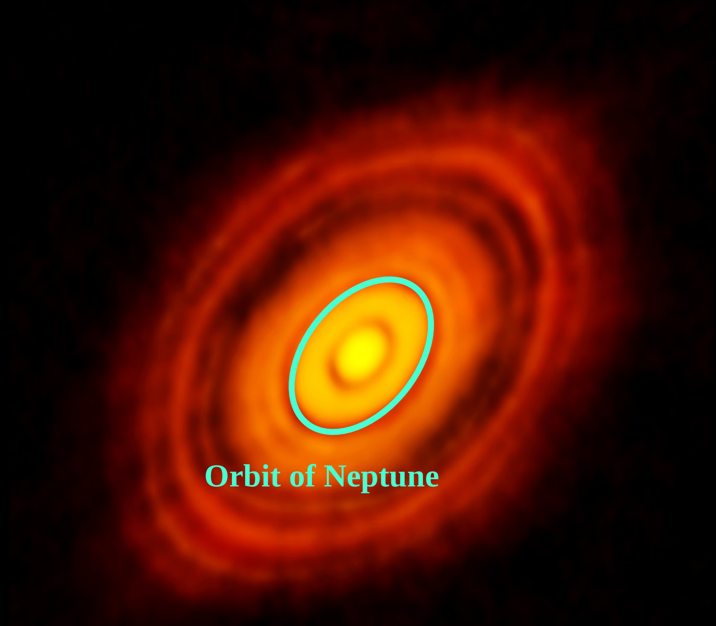
Iconic ALMA image of young disk
20 years later...

ALMA 20 milli-as
(few AU resolution)
HL Tau

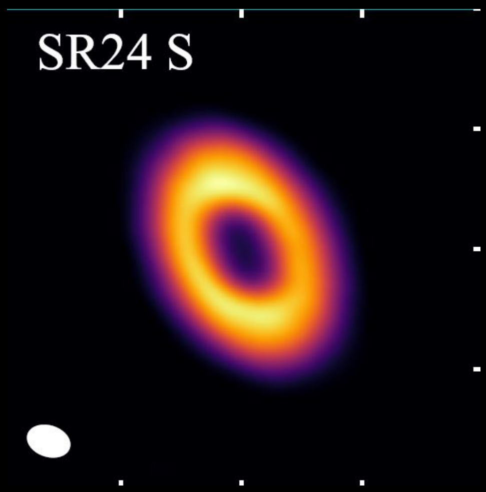
ALMA partnership,
Brogan et al. 2015

New era of observational planet formation

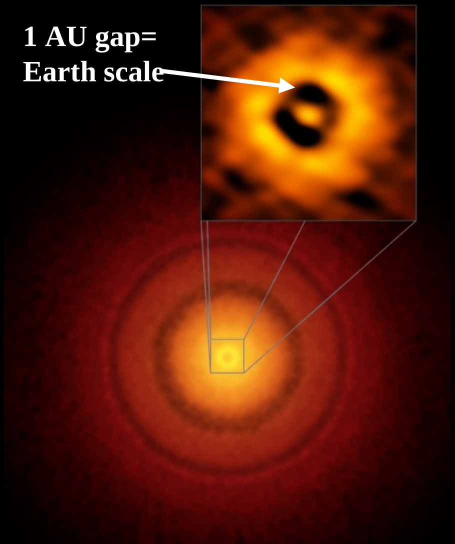
Not yet clear what is causing these rings, gaps, dust traps...



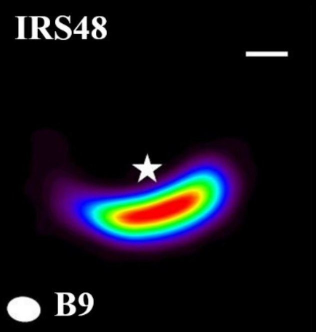
HL Tau young disk
ALMA partnership
et al. 2015



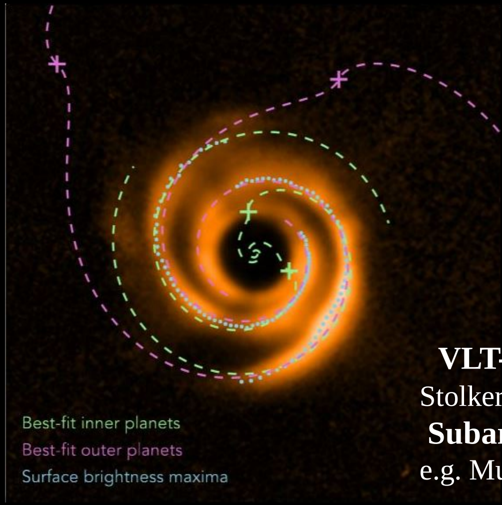
ALMA: Pinilla et al. 2017



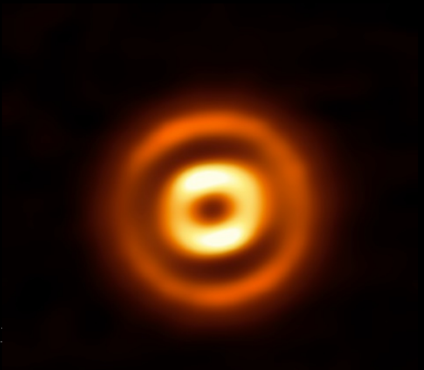
ALMA TW Hya
Andrews et al. 2016



ALMA: van der Marel et al. 2013, 2016

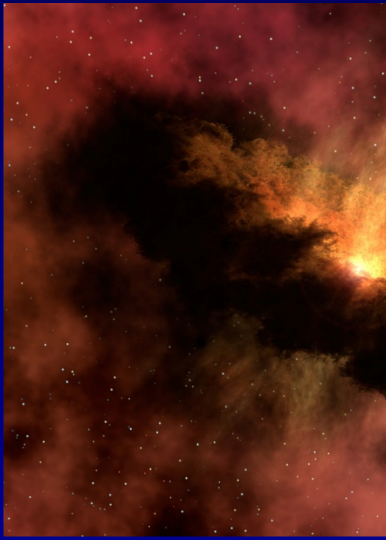


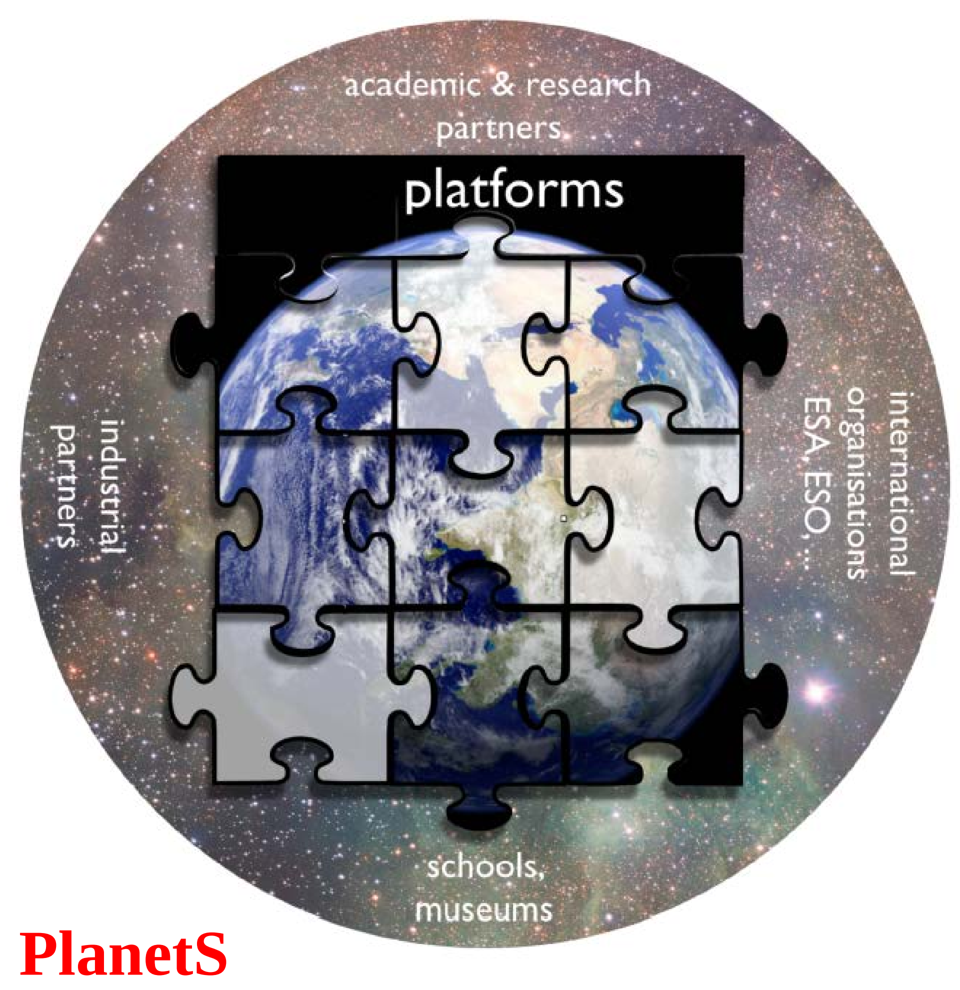
VLT-Sphere, Gemin
Stolker et al. 2016
Subaru-SEEDS
e.g. Muto et al. 2012



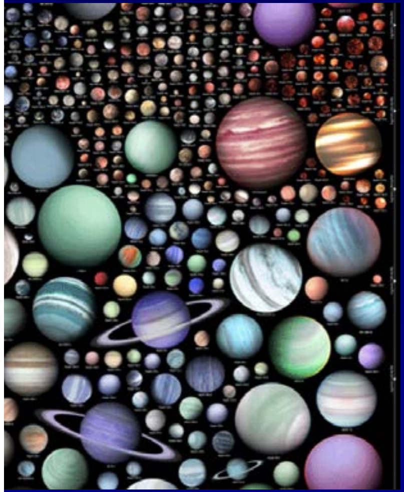
ALMA:
Fedele et al. 2017

From disks to planets

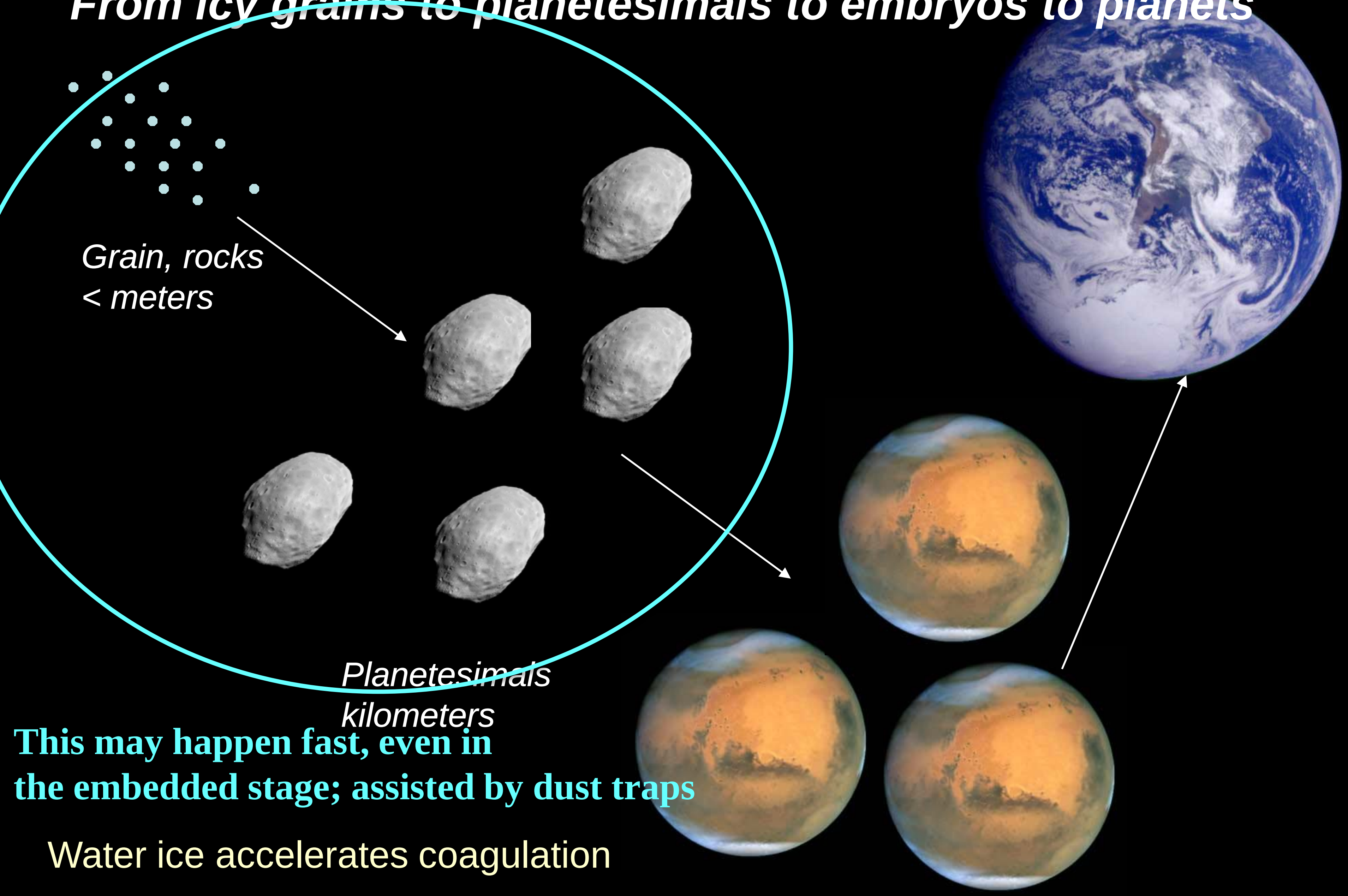




PlanetS



From icy grains to planetesimals to embryos to planets



Grain, rocks
< meters

Planetesimals
kilometers

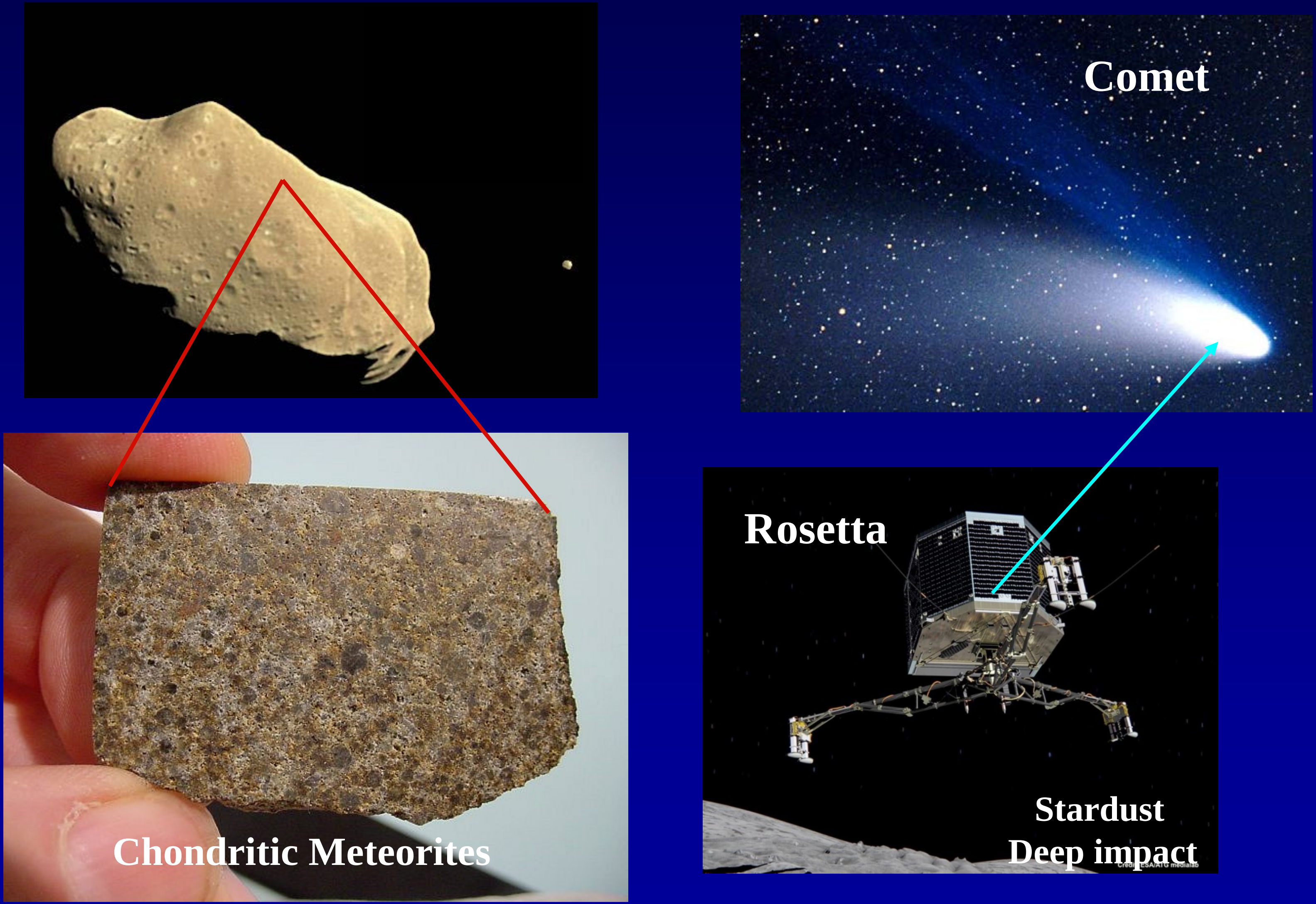
This may happen fast, even in the embedded stage; assisted by dust traps

Water ice accelerates coagulation

Planetary embryos
Lunar (1 AU)-to-Mars (2 AU) sized

J. Lunine

How were ‘we’ formed 4.5 billion years ago?



Messengers from the early solar system

Atacama Large Millimeter Array (ALMA)

54x12 m + 12x7 m antennas
84-900 GHz; 0.3-3 mm

***Lines*: rotational transitions of molecules; *continuum*: cold dust**

Atacama Large Millimeter Array

Outline

- Introduction
- Disks around pre-main sequence stars
  - Surveys, dust statistics
  - Gas/dust ratios, carbon and oxygen depletion
  - Snowlines, rings
- Transitional disks
- Conclusions

Thanks to many students, postdocs, collaborators

Nienke van der Marel

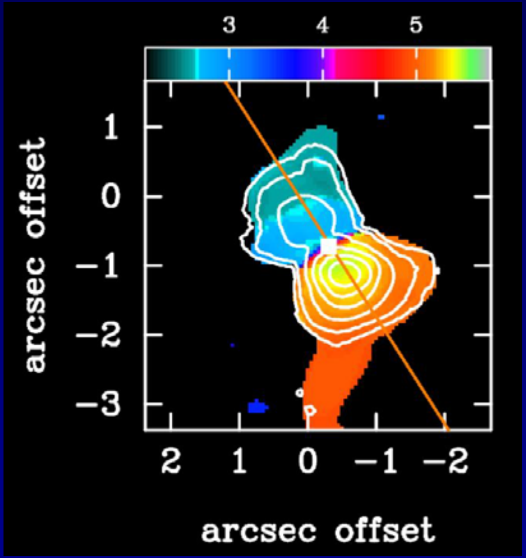
Megan Ansdell

Anna Miotello

What I will not talk about:

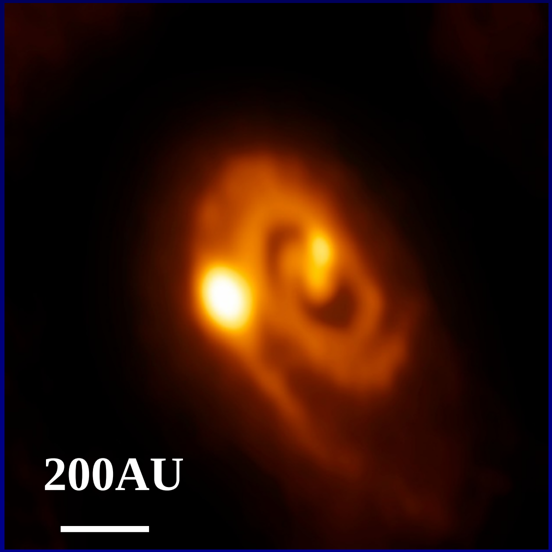
Disks in the embedded phase

VLA1623A



Murillo et al. 2013

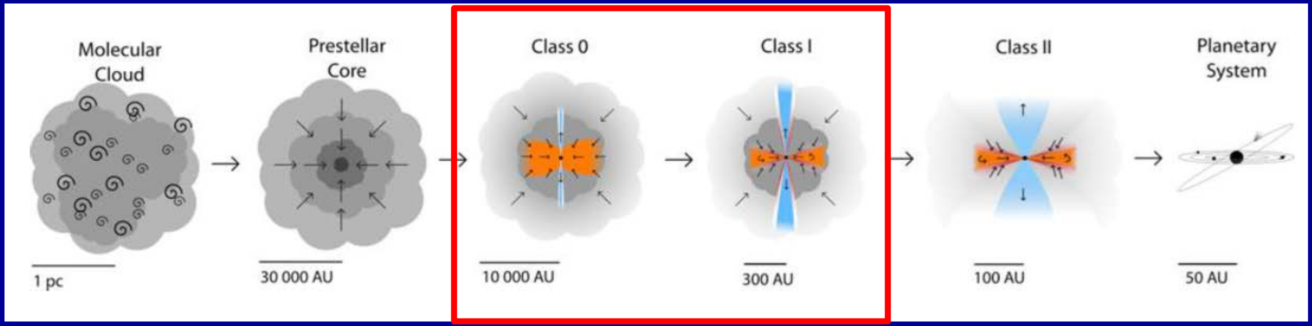
L1448 triple



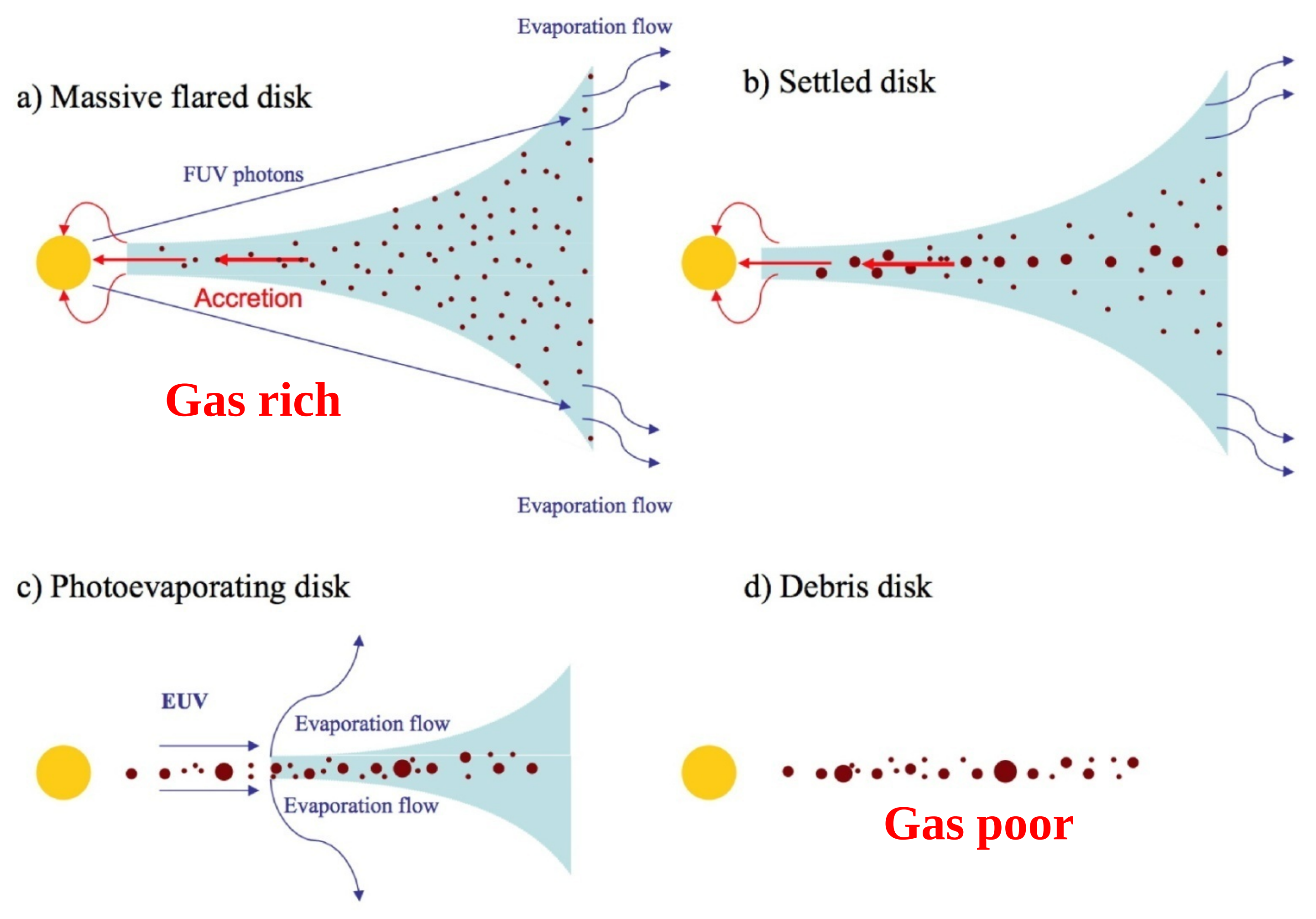
Tobin et al. 2016

Elias 2-29

L. Perez et al. 2016



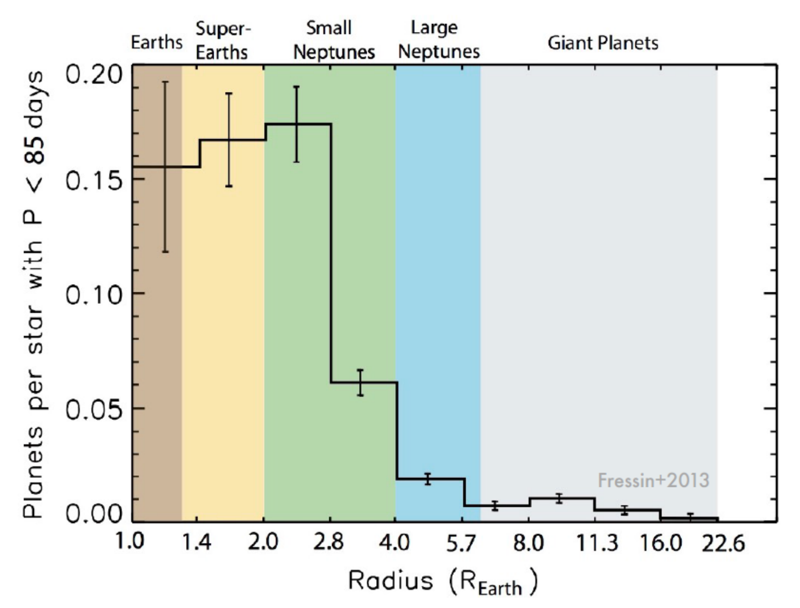
Disk evolution and planet formation



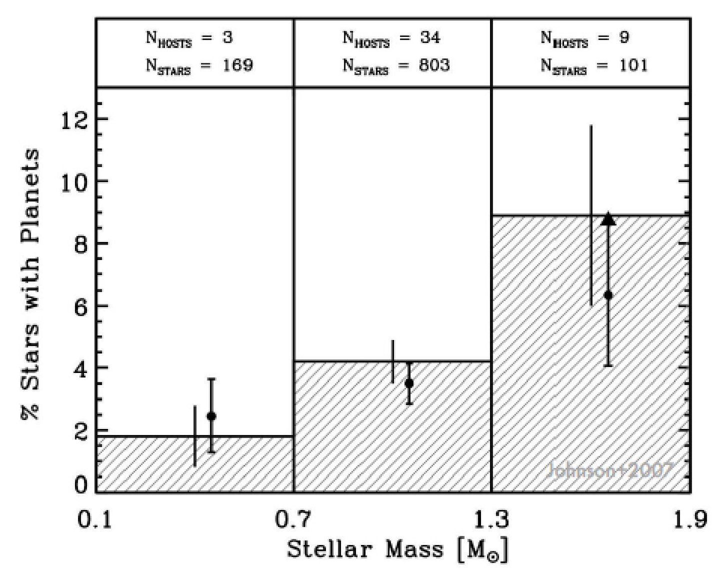
ALMA can characterize and quantify each of these steps

Williams & Cieza 2011

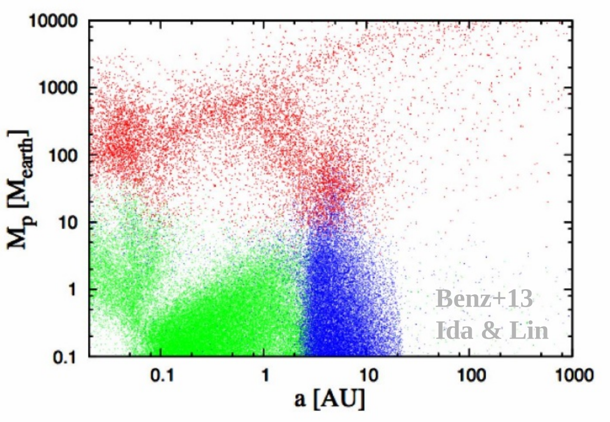
What sets exoplanet characteristics?



- Lots of SuperEarths
- Few giant planets

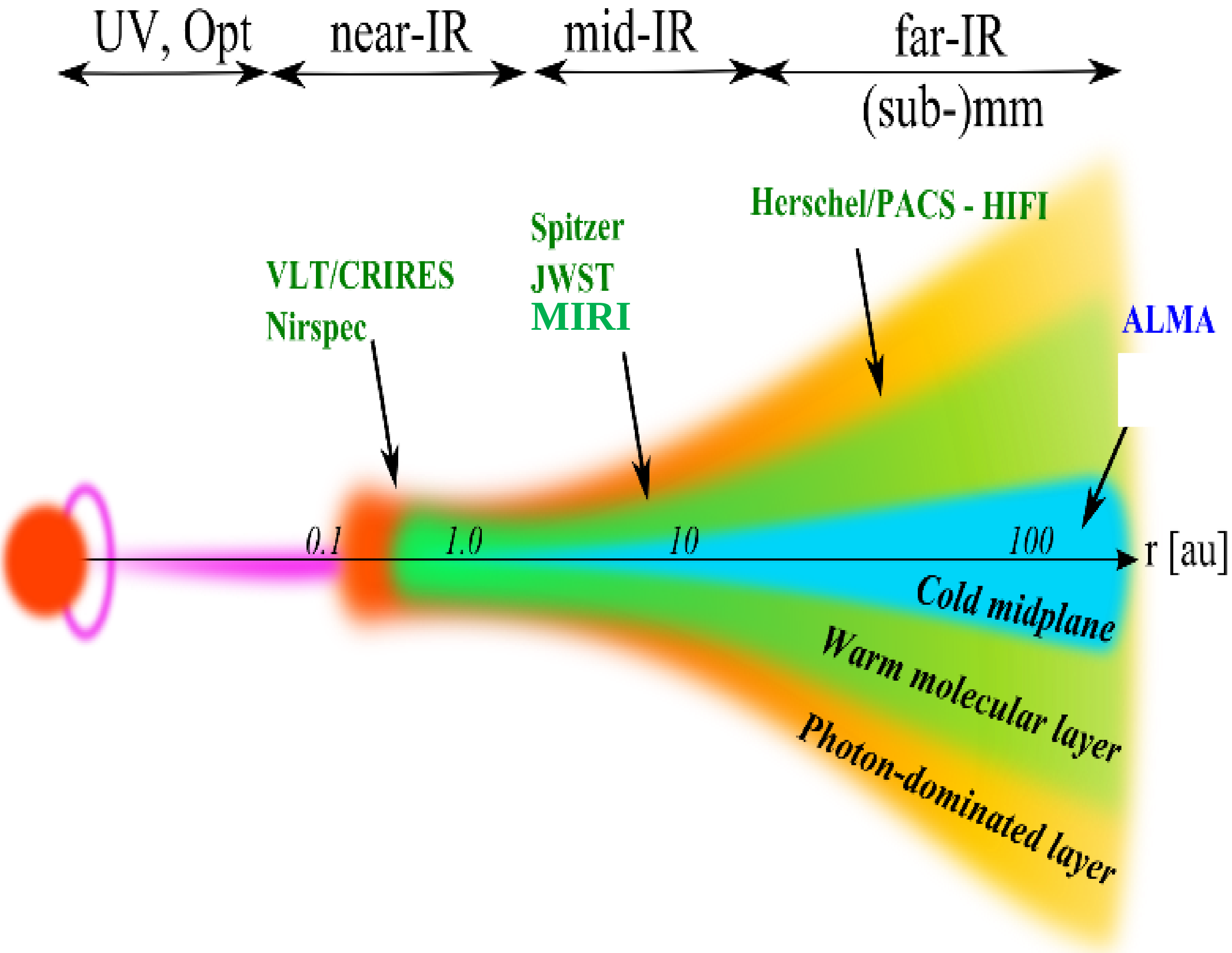


- Increase with stellar mass



Planet population synthesis

Probing protoplanetary disks

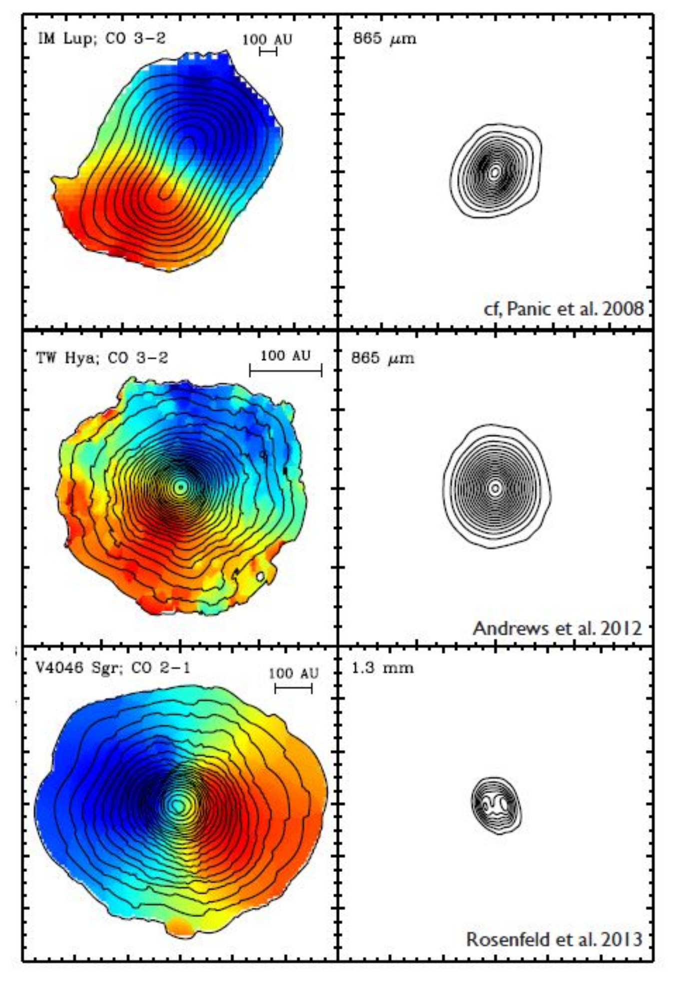


D. Fedele

ALMA measures the bulk of the gas and dust in disks and can observe bulk of molecules

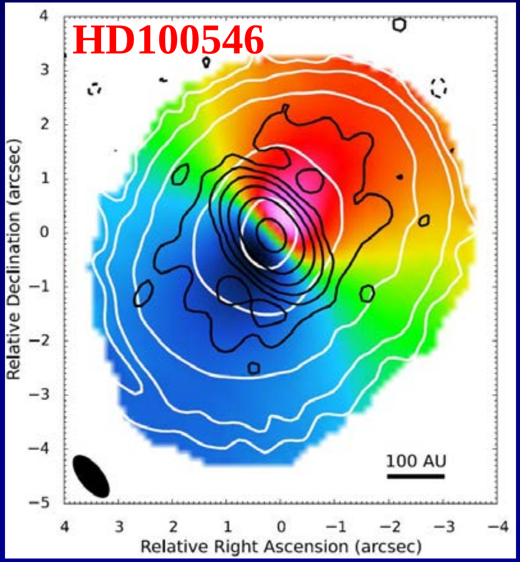
Pre-ALMA: handful of disks

Large gas **Small dust disk**



Andrews 2015

ALMA



Walsh et al. 2015, Facchini et al. 2017

Small dust disk naturally arises from low optical depth of continuum emission; Also evidence for grain growth and radial drift

From detailed studies of a few disks to large samples

PI: Jonathan P. Williams (IfA)

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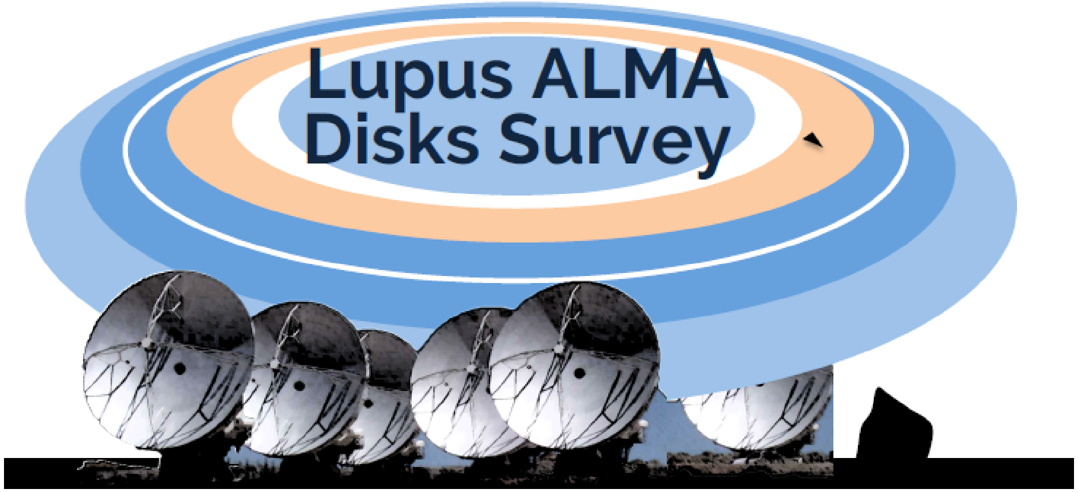
Stefano Facchini (MPE)
Greta Guidi (INAF),
Michiel Hogerheijde (Leiden Obs.),
Carlo F. Manara (ESA, ESO),
Geoff S. Mathews (IfA),
Anna Miotello (Leiden Obs., ESO),
Antonella Natta (INAF,DIAS),
Marco Tazzari (IoA),
Leonardo Testi (ESO,INAF), ★
Leon Trapman (Leiden Obs.),
Nienke van der Marel (IfA,UVic)
Ewine F. van Dishoeck (Leiden Obs., MPE), ★
Sierk van Terwisga (Leiden Obs.).

Publications

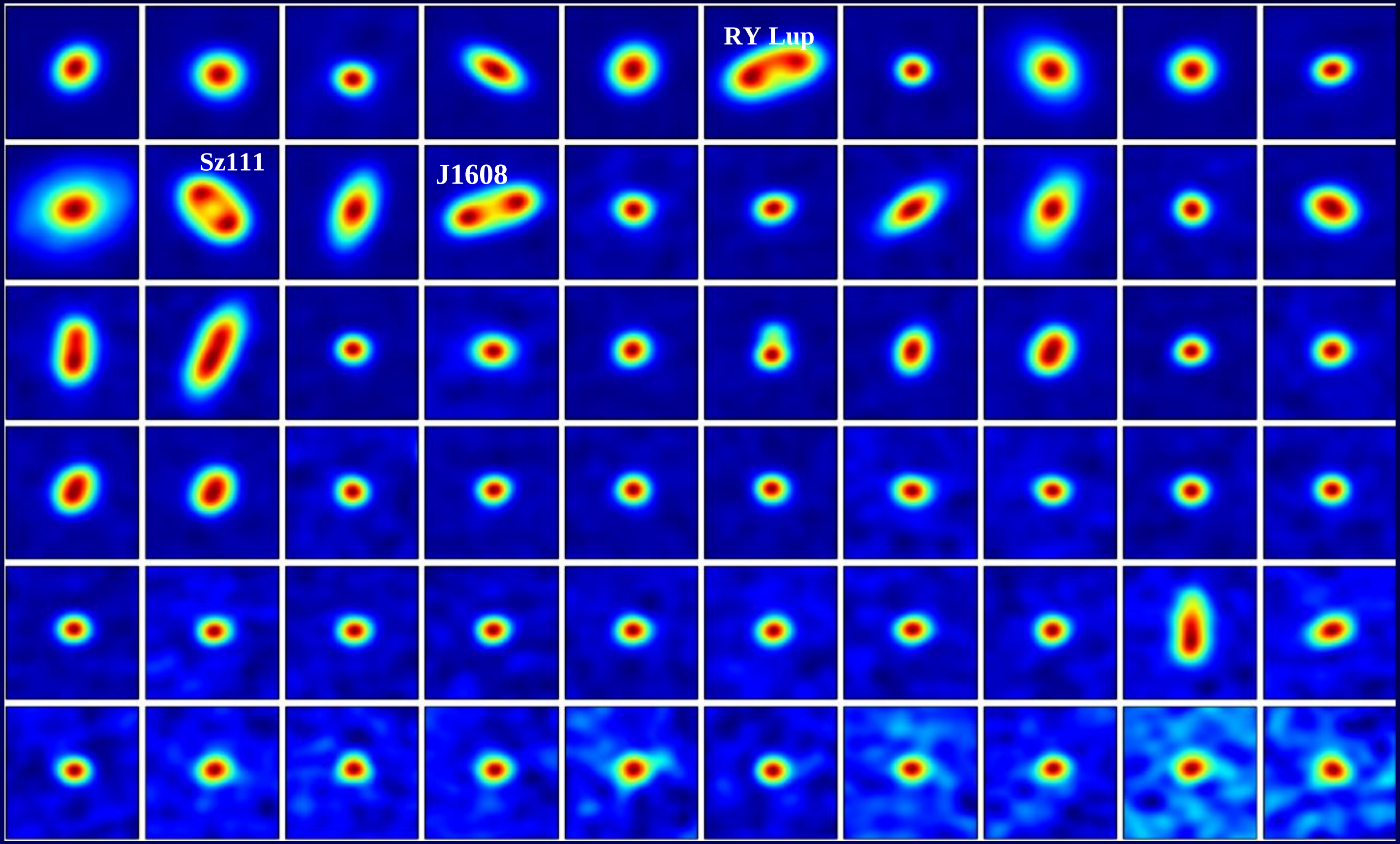
Ansdell et al. (2016)
Manara et al. (2016)
Miotello et al. (2017)
Tazzari et al. (2017)



Unbiased survey Lupus disks

J.P. Williams, PI

2”x2”



330 GHz
Cont

1-2 min
Each

20 AU
resolution

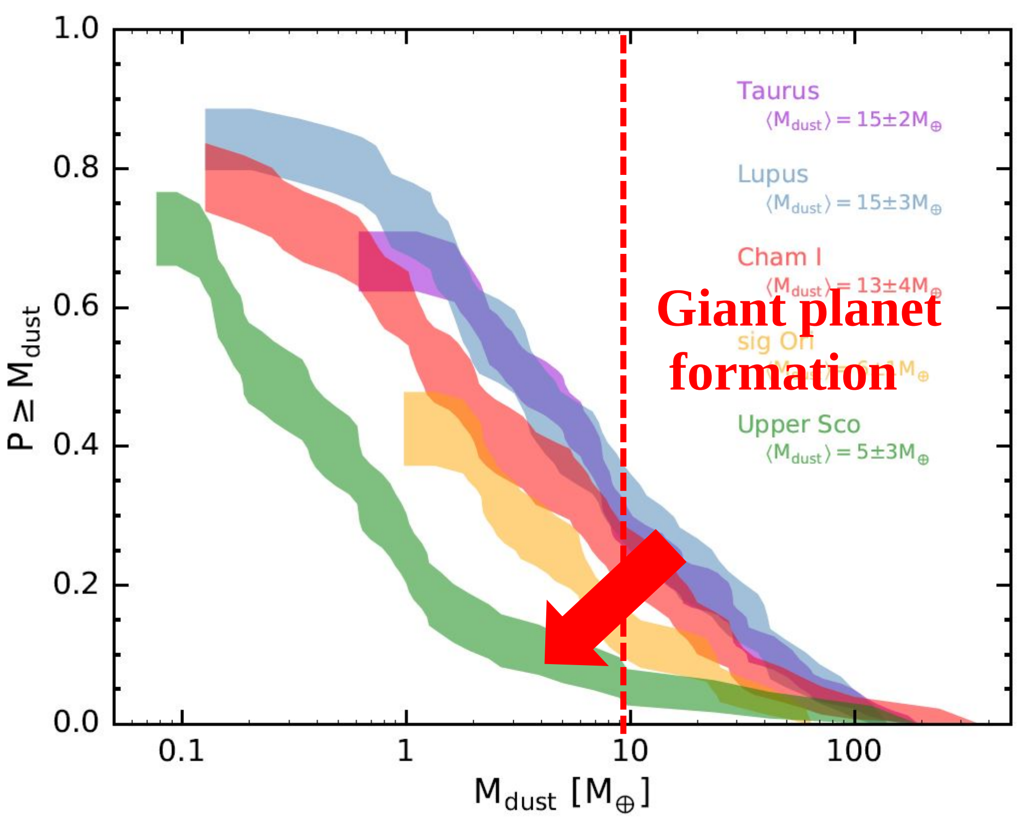
Gas + dust

Ansdell et al.
2016

65 / 98 sources detected in continuum, only 30 in ^{13}CO

- $F_\nu \sim M_d T_d \kappa_\nu$

Cumulative dust mass distribution



Giant planet formation

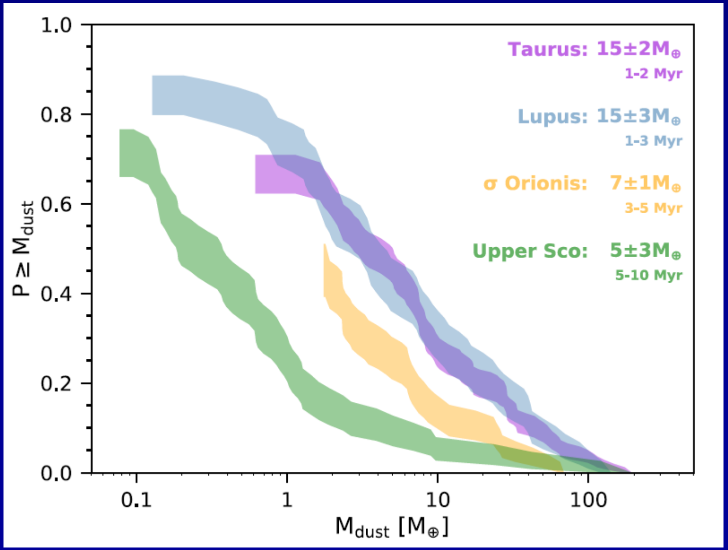
Ansdell et al. 2016, 2017
Barenfeld et al. 2016
Pascucci et al. 2016

Most disks do not have enough dust mass for core accretion model to form a giant planet

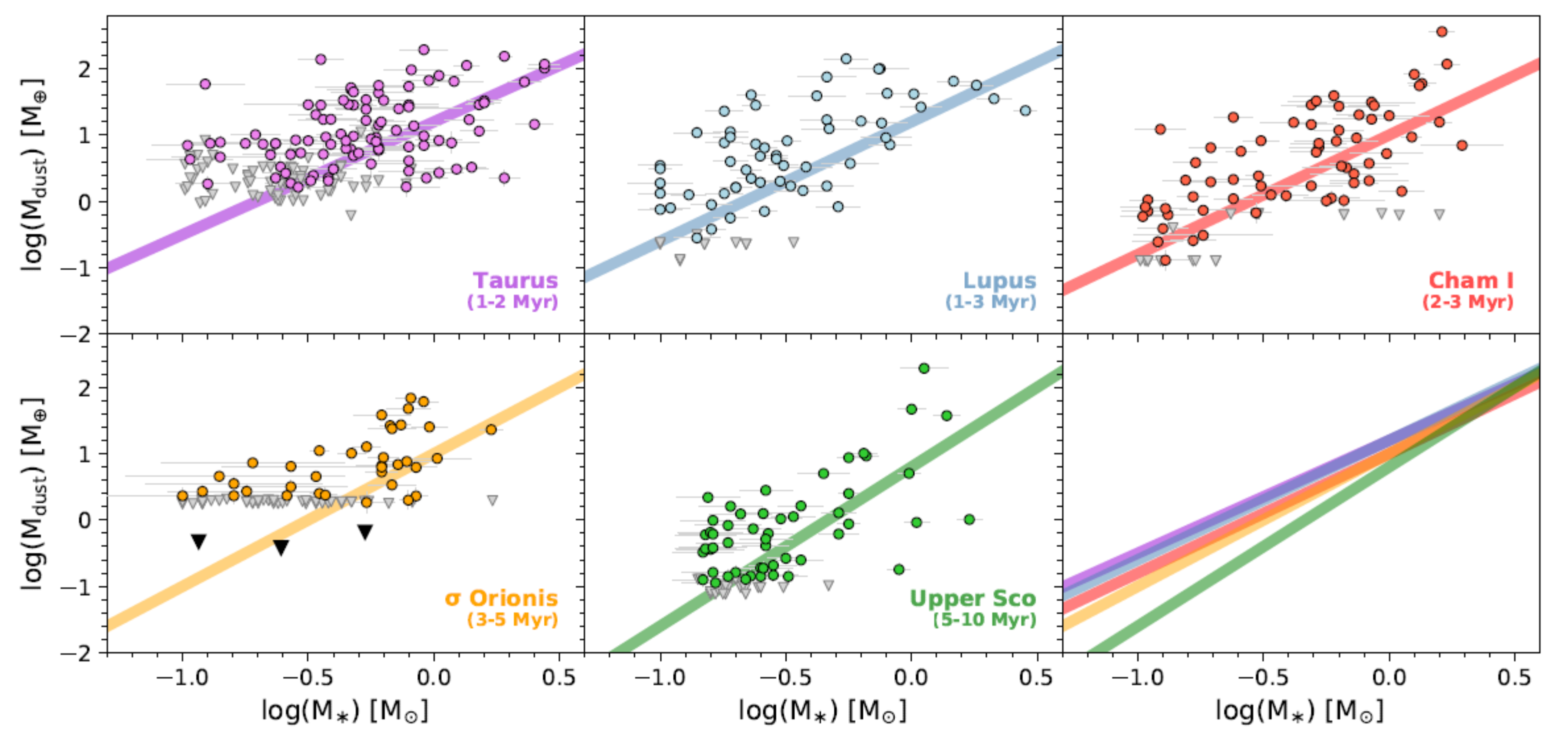
Assumes κ_ν^{dust}=100 cm^2 gr^{-1} at 1000 GHz, β=1

Declining dust distribution

- Disks that can form giant planet cores (10 M_{Earth})
  - 1-3 Myr: 25%
  - 3-5 Myr: 13%
  - 5-10 Myr: 5%
- Giant planet formation well underway early?
- Giant planet formation rare?
  - Most disks lack sufficient dust
  - Consistent with exoplanet statistics



Dust mass increases with M*

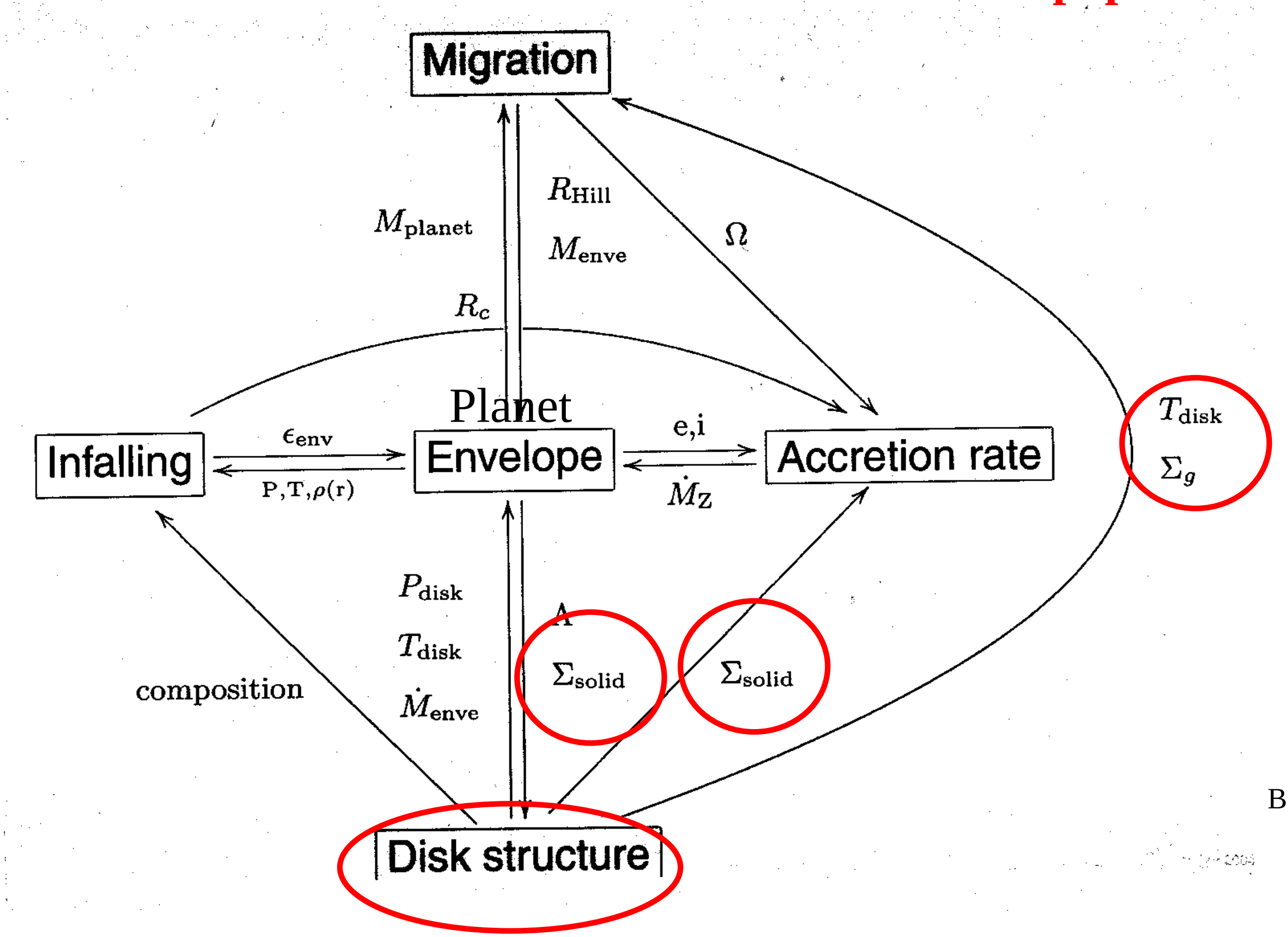


Ansdell et al. 2017

- Consistent with giant planets more frequent around higher-mass stars

Link planet formation theories with disk evolution

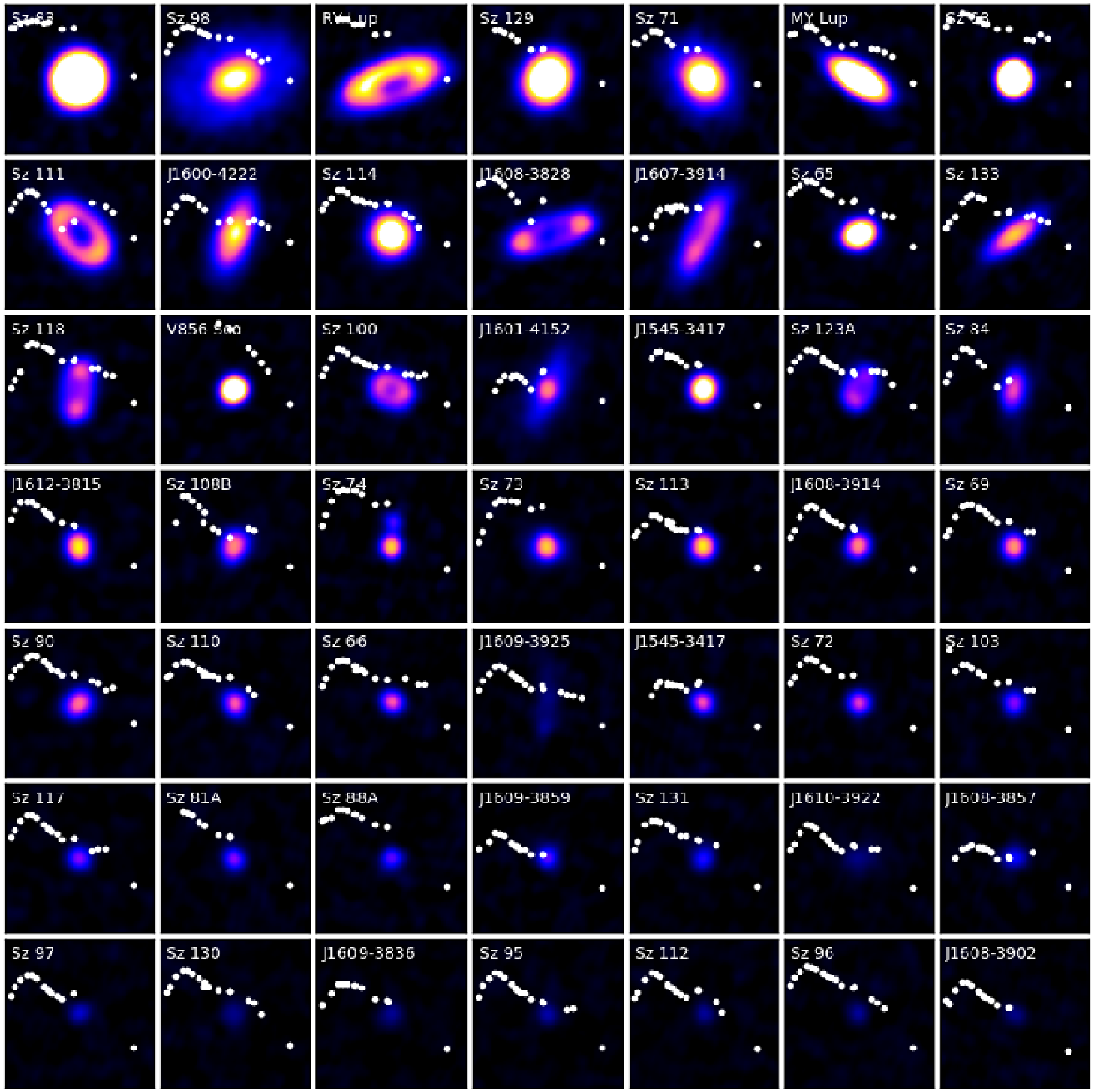
Planet population synthesis



Benz et al. 2014

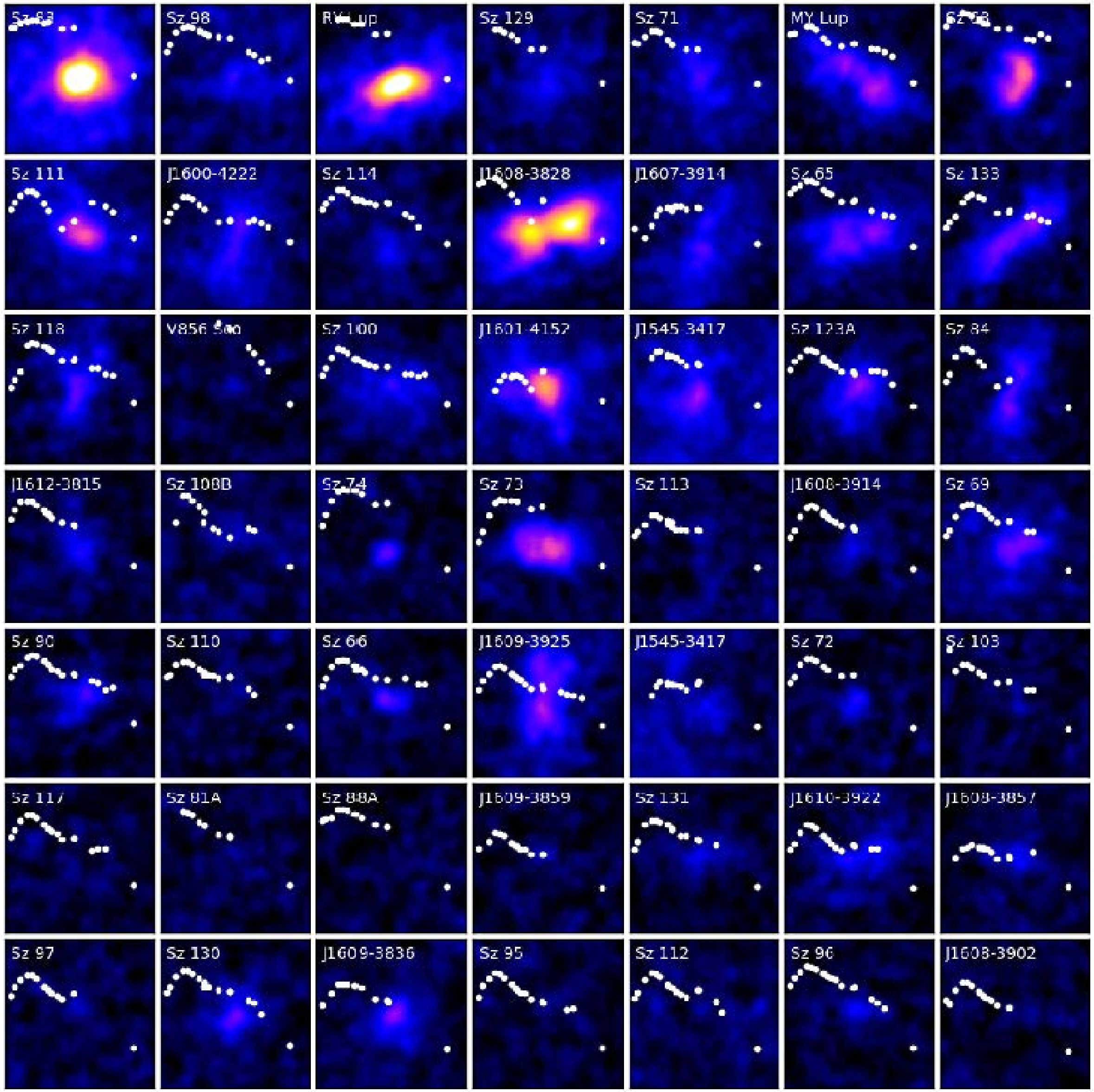
Lupus
1.3mm

Dust



Lupus
CO 2-1

Gas

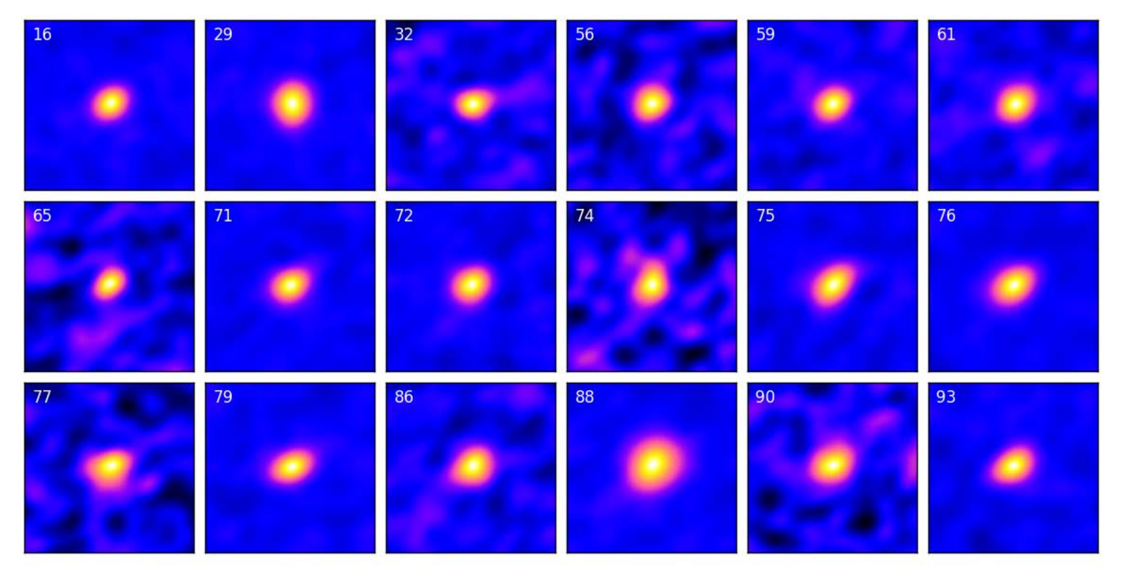


Ansdell
et al. 2016

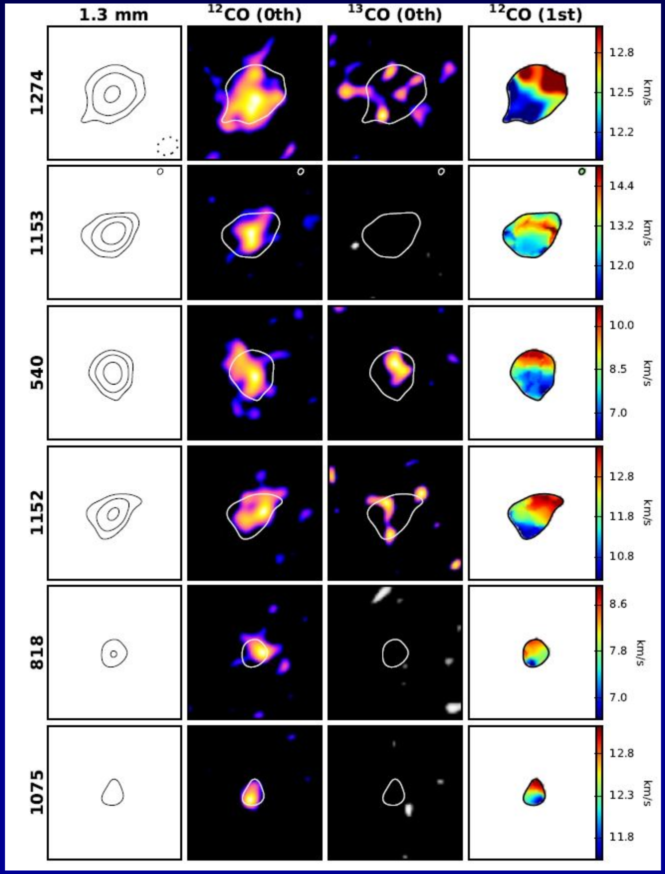
CO lines are weak, much weaker than expected

σ Orionis disk survey

Older region



Ansdell et al. 2017



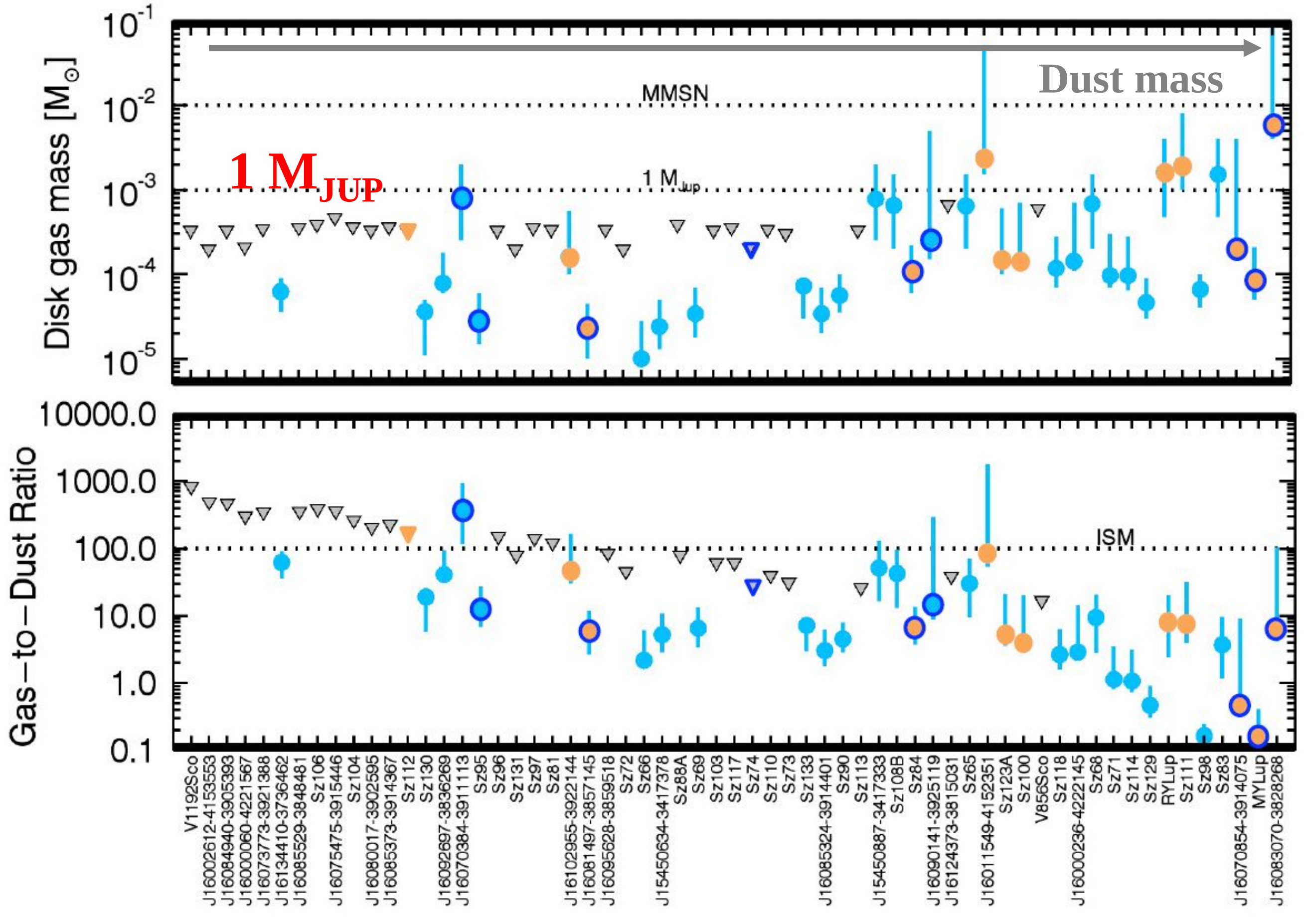
Only 37 / 92 disks detected in continuum
Only 6/92 detected in lines

Weak CO emission is common

O9 star
3-5 Myr
d=388 pc

Pascucci et al. 2016 (Cha), Barenfeld et al. 2016 (upper Sco), Eisner et al. 2016 (ONC1), Cazzoletti et al. (R Cra)

Determining gas masses



- Most disks not enough gas to form Jupiter
- Most disks gas/dust <<100 assuming [C]/[H]=10^{-4}

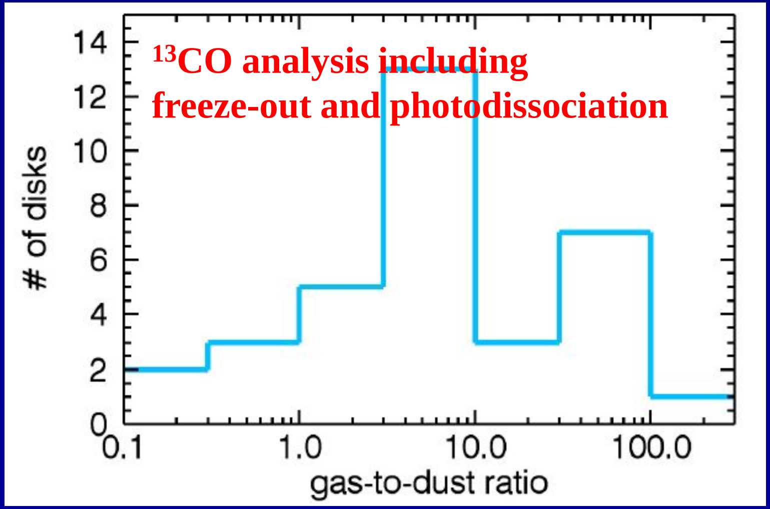
Ansdell et al. 2016
Miotello et al. 2017

Weak CO emission: Low gas/dust ratios or low volatile carbon?

- Gas removed quickly from disk (<few Myr)?
  → *SuperEarths*

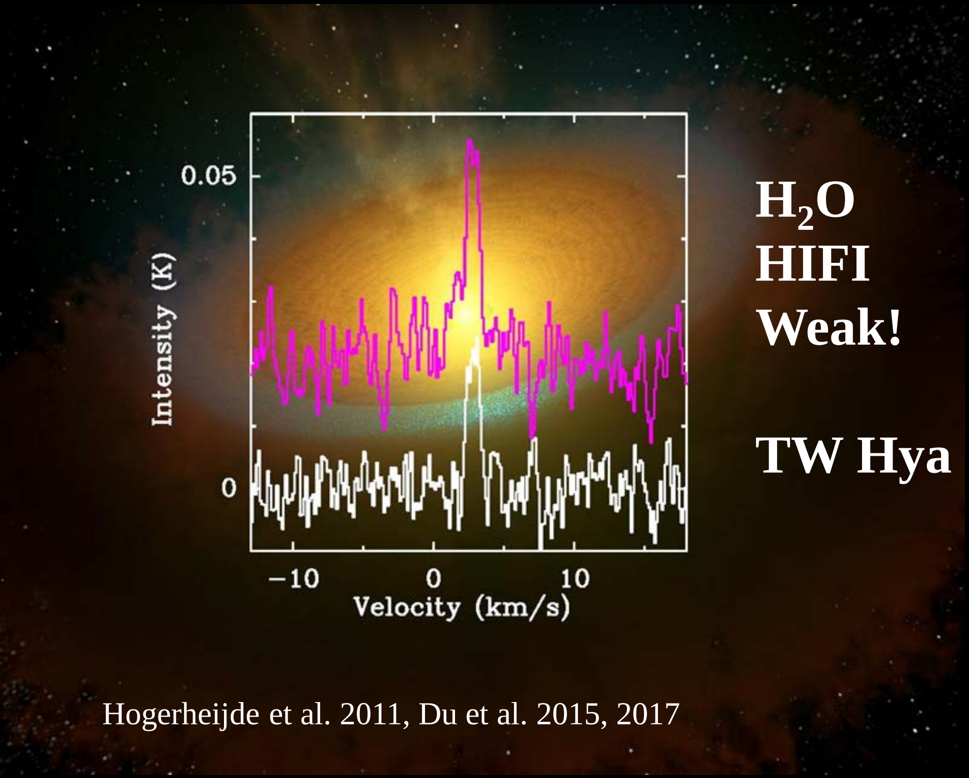
- CO transformed to other species?
  (CO_2, CH_3OH, hydrocarbons)

- CO and other volatiles locked up quickly in large bodies in midplane?



Miotello et al. 2017 Lupus
Long et al. 2017 Cha

Where is the volatile oxygen and carbon?

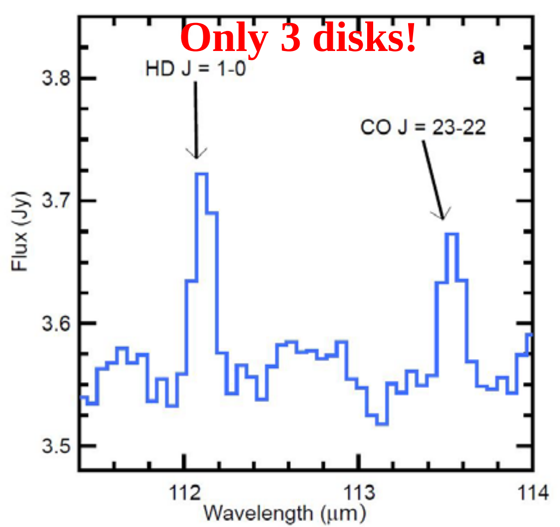


H_2O
HIFI
Weak!

TW Hya

Hogerheijde et al. 2011, Du et al. 2015, 2017

Disk mass from *Herschel*-PACS:
HD J=1-0 112 μm



Only 3 disks!

Gas mass from HD factor 100 higher than from CO

Points to carbon and oxygen depletion, not low gas/dust

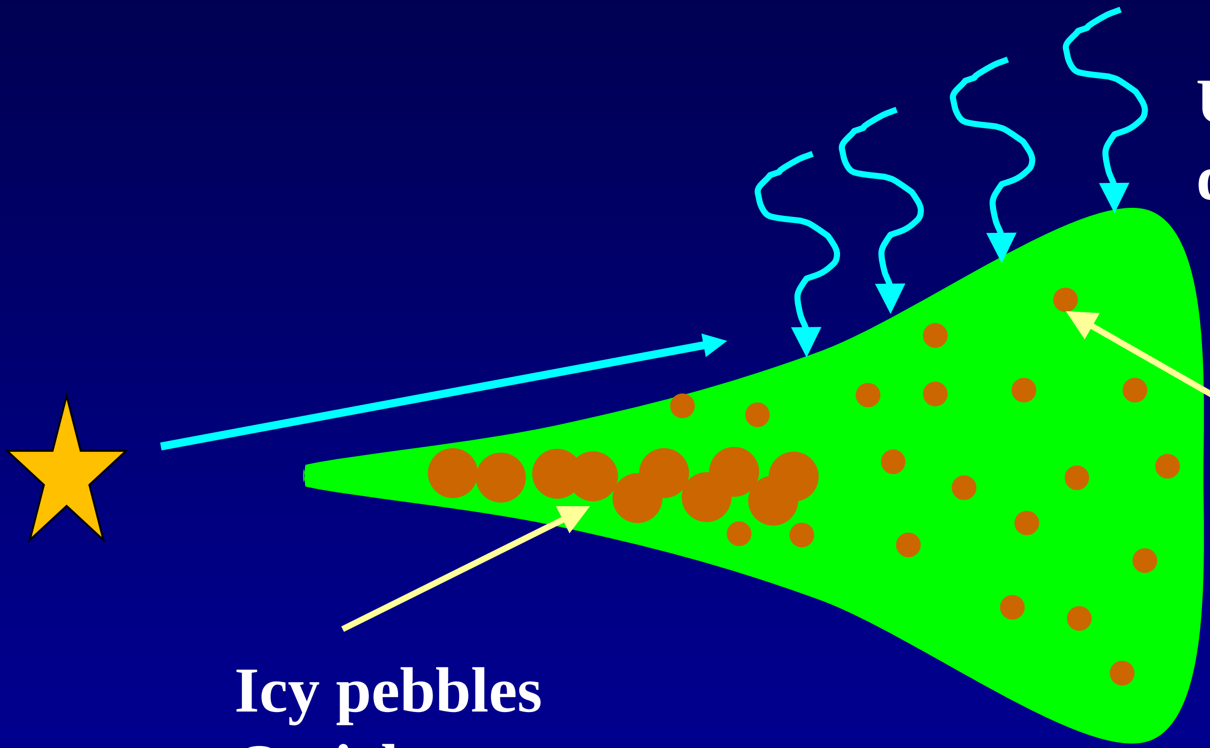
Bergin et al. 2013, McClure et al. 2016

Favre et al. 2013, Schwarz et al. 2016,
Trapman et al. 2017

SOFIA
SPICA

Bergin et al. 2014, Kama et al. 2016, Miotello et al. 2017

Chemistry as tracer of gas and dust evolution



UV penetrates deep into disk

Small bare grains

Icy pebbles
O-rich

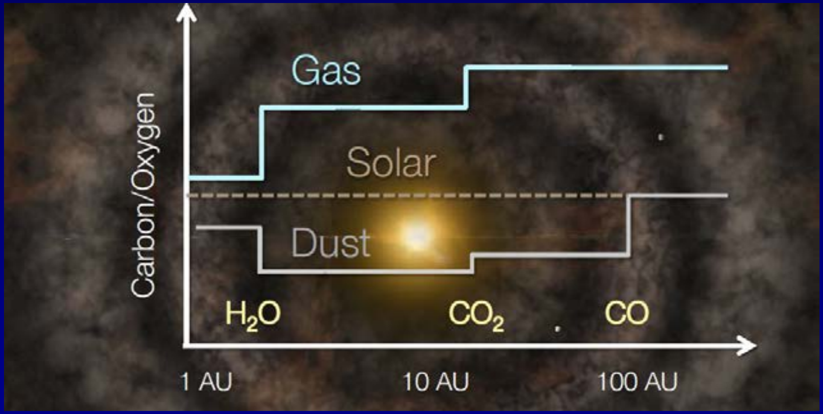
Gas with
C/O >1
(but overall C
depleted)

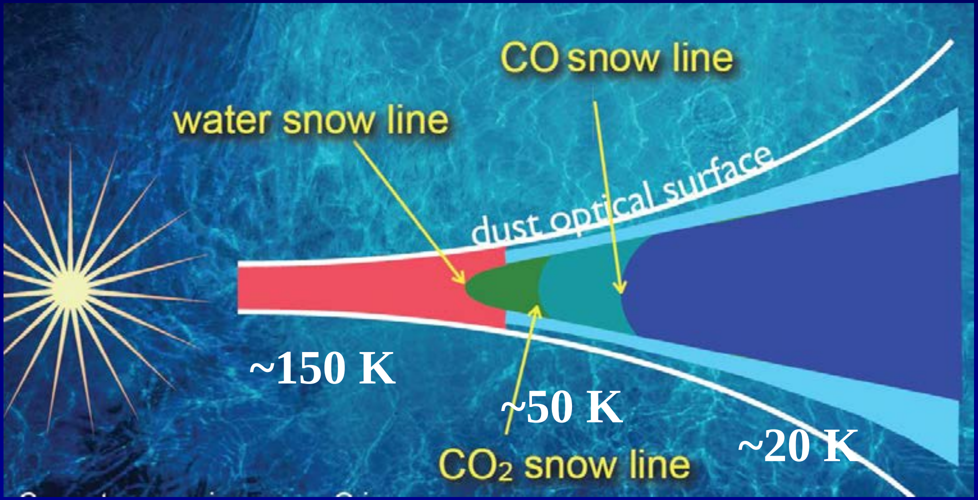
Is most of the chemistry of planet formation hidden from our view?

Bergin et al. 2016
Birnstiel et al.
Kama et al. 2016
Cleeves et al. 2016
Facchini et al. 2017

Disk structure and snowlines

Snowlines

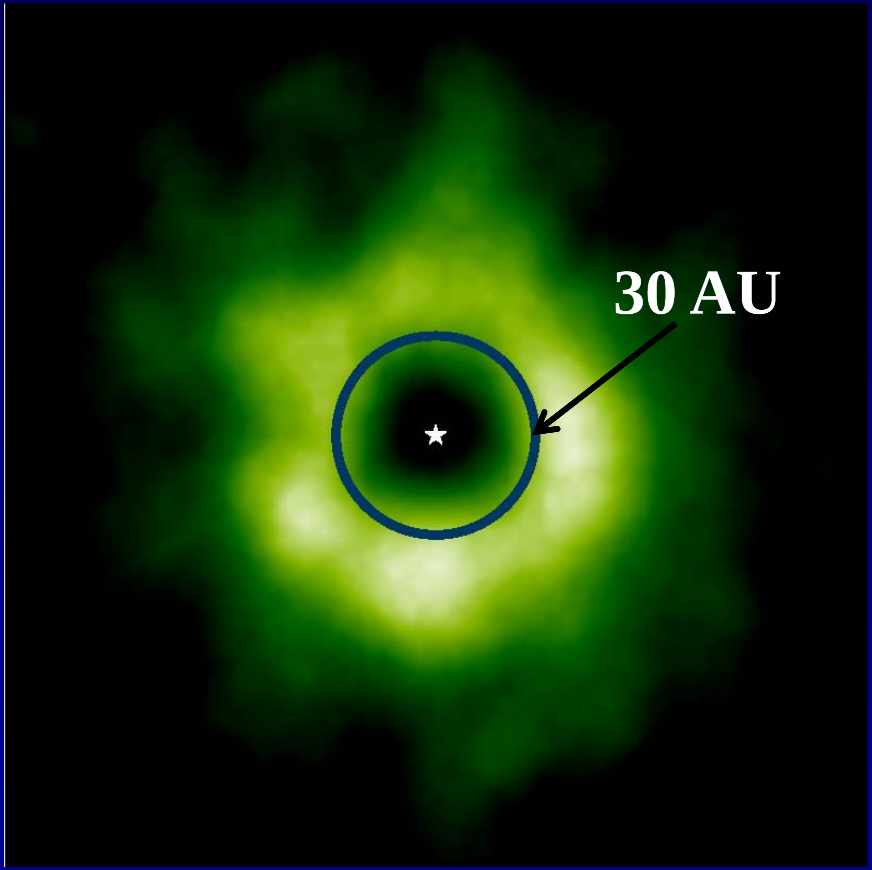




Öberg, Bergin et al. 2011

- Snowline enhances mass of solids → *planet formation*
- Freeze-out changes C/O ratio gas and ice → *planet atmosphere*

Imaging the CO snowline



TW Hya

Face-on disk
d=68 pc

N_2H^+ 4-3

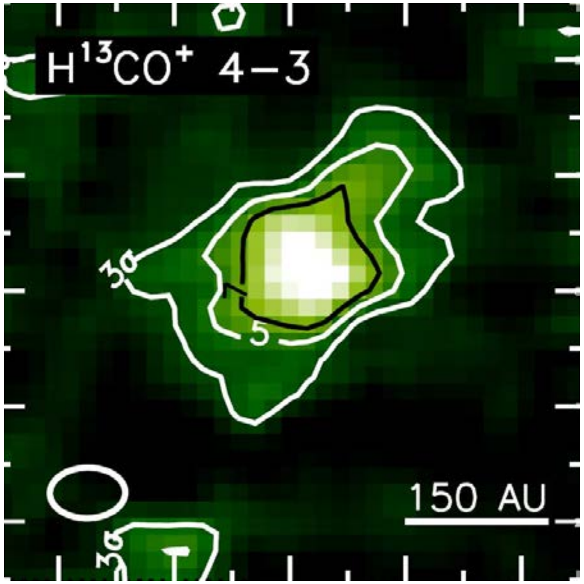
$N_2H^+ + CO \rightarrow$
$N_2 + HCO^+$

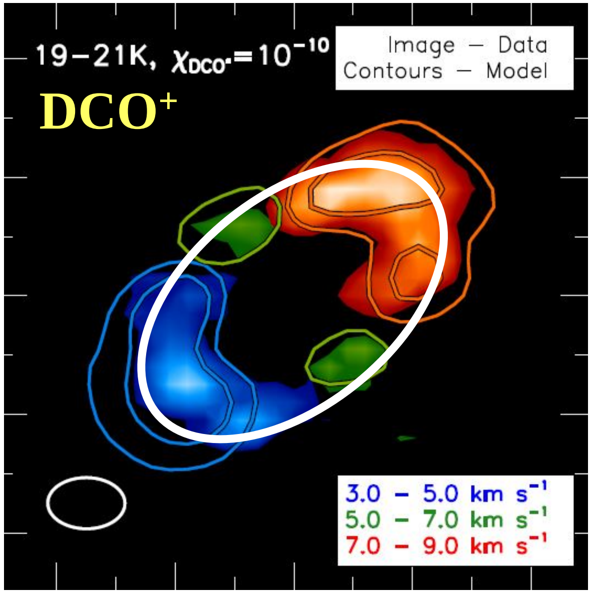
Qi, Öberg et al. 2013

N_2H^+ appears when CO freezes out
→ Tracer of snowline

Another example resolved CO snow line

HD 163296 Herbig star ALMA





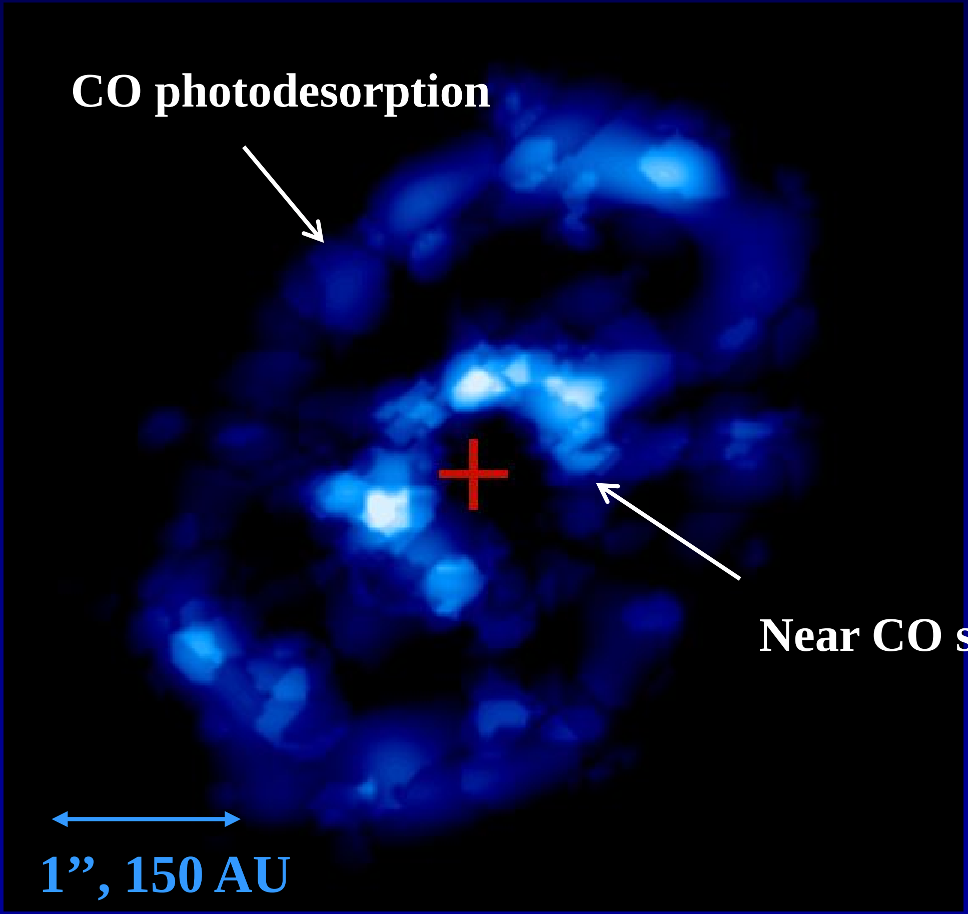
20 K
radius

G. Mathews et al. 2013
Qi et al. 2011 SMA

- CO freezes out at ~20 K ⟺ 145±15 AU

‘Disk tomography’

DCO$^+$ as tracer CO snowline



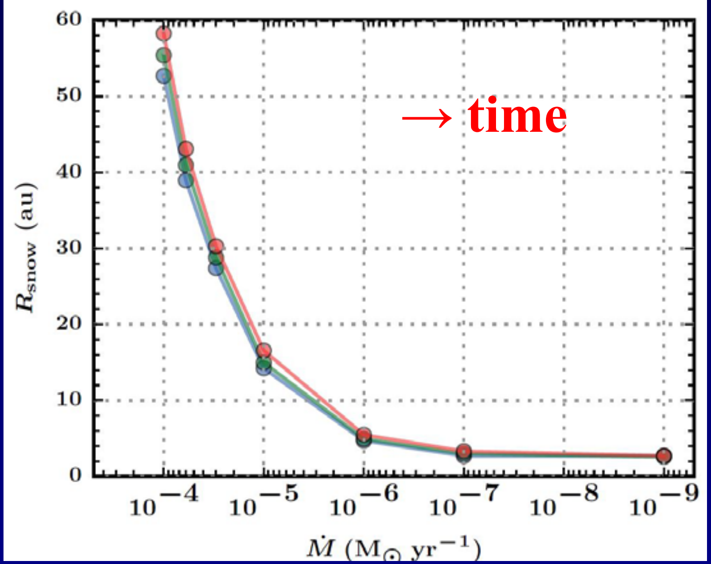
IM Lup
ALMA DCO$^+$

Double rings!

Öberg et al. 2015
Huang et al. 2017

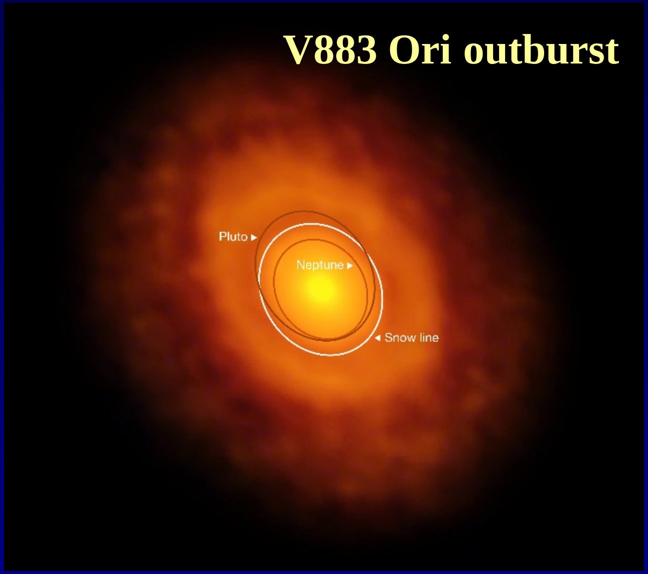
Snowlines move

Water snowline vs dM/dt

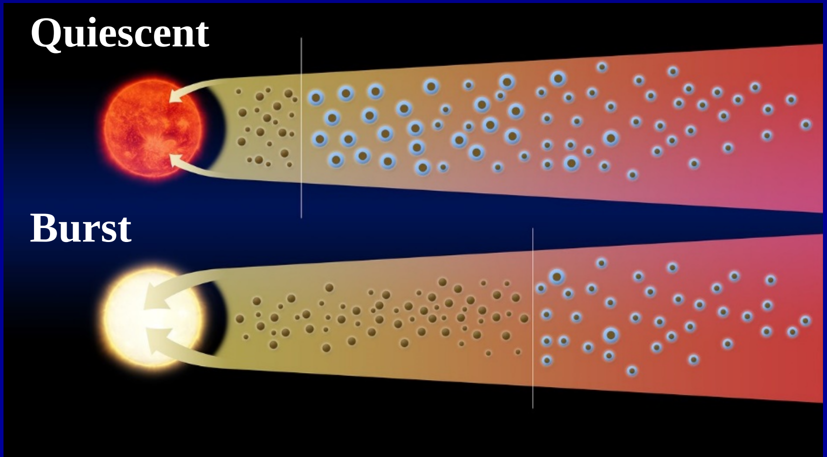


Harsono et al. 2015

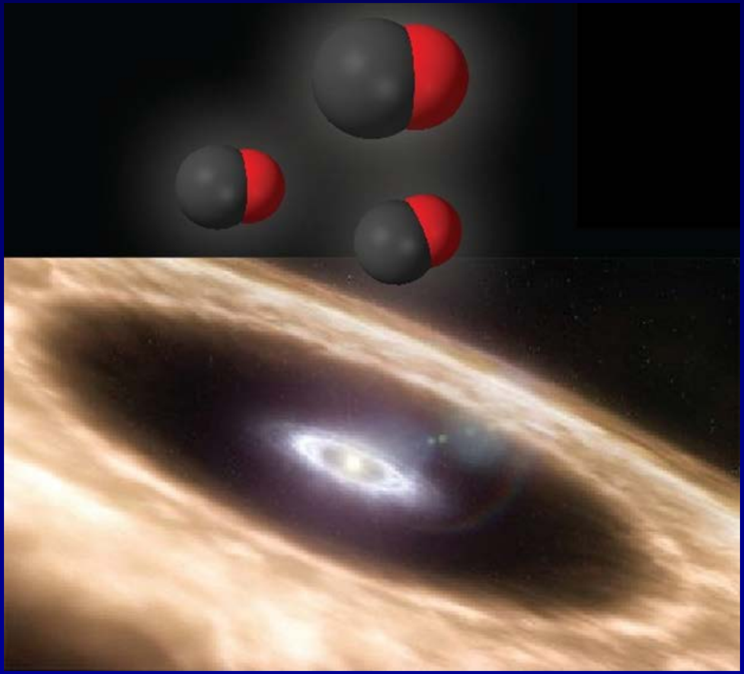
Imaging water snowline (indirect)



Cieza et al. 2016



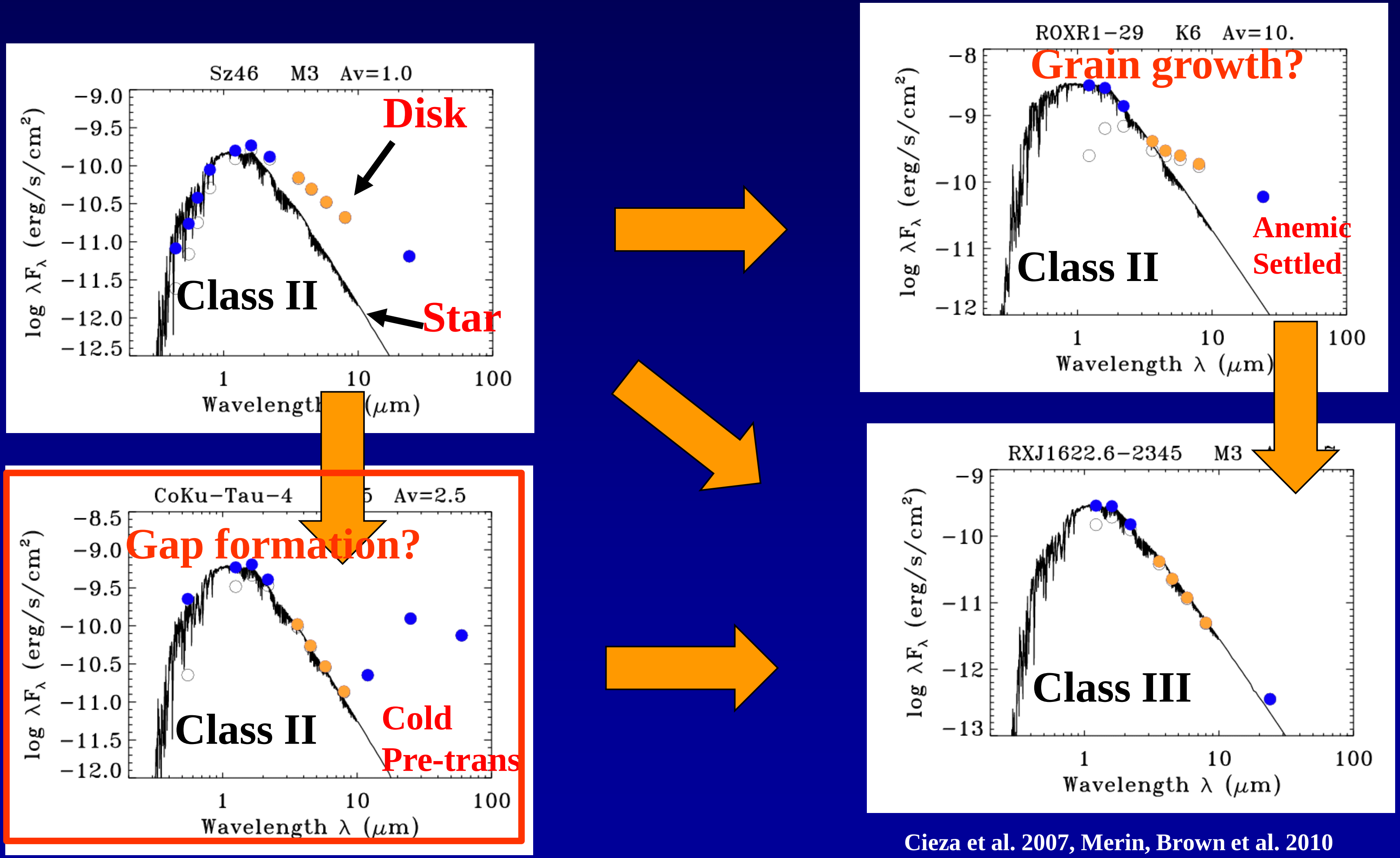
Transitional disks



‘Planet formation in action’

Disk evolution

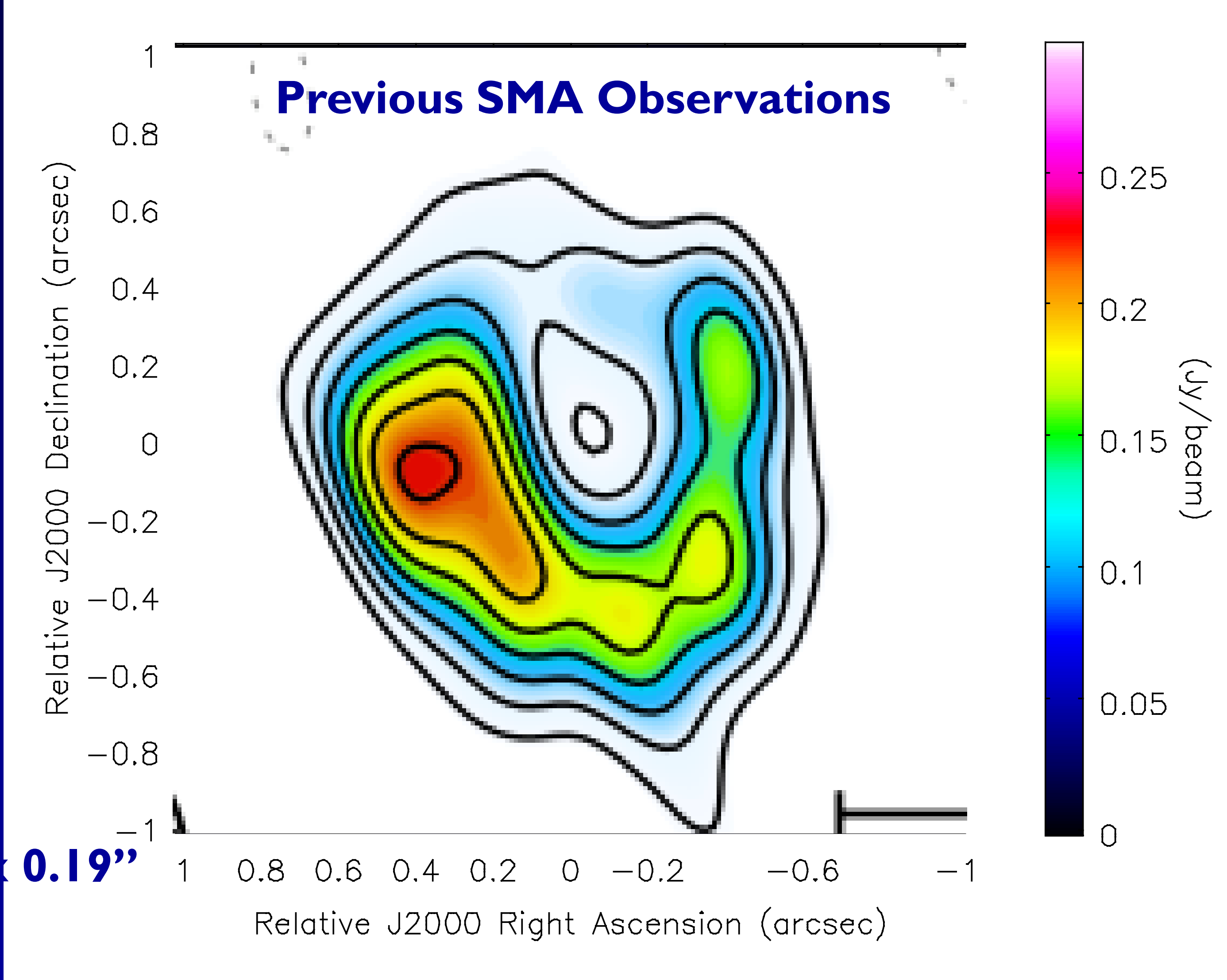
There are multiple paths from protoplanetary to debris disks



Cieza et al. 2007, Merin, Brown et al. 2010
Espaillat et a;. 2014

Transitional disk– dust continuum

SAO206462
=
HD135344B



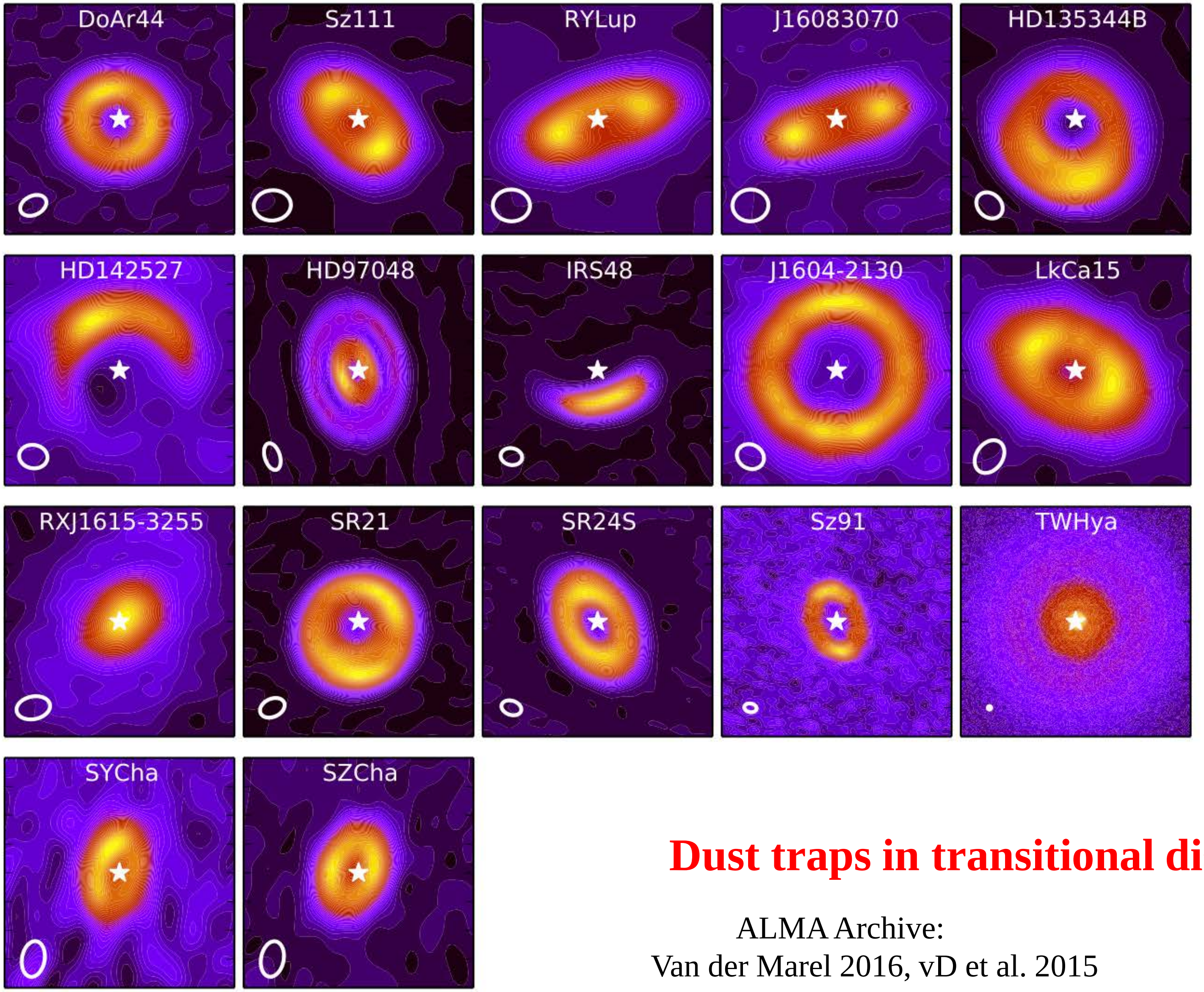
Just 24 min with ALMA!

Band 9

Brown et al. 2009

L. Perez et al. 2014

Gallery of potential planet-forming disks

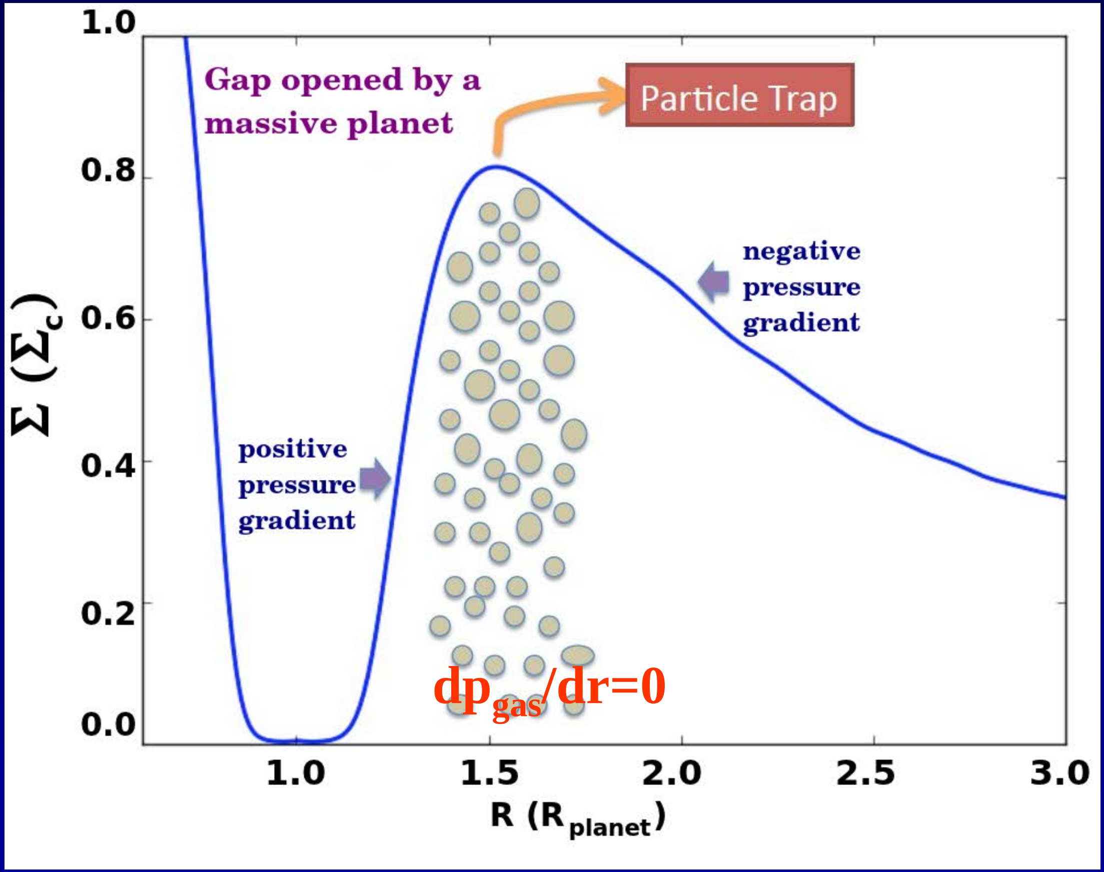


Dust traps in transitional disks

ALMA Archive:
Van der Marel 2016, vD et al. 2015

Dust trapping

- Companion generates a radial pressure bump in gas
- Large dust will be trapped and no longer migrates inward
- Dust hole much larger than gas hole $\Rightarrow$ massive companion

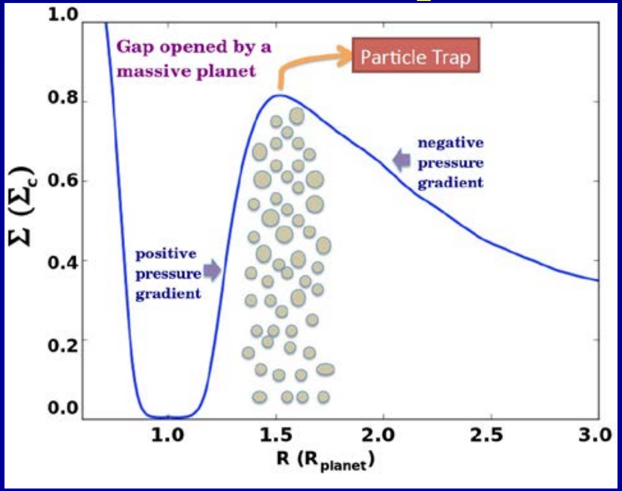


Whipple 1972
Pinilla et al. 2012
+ many others

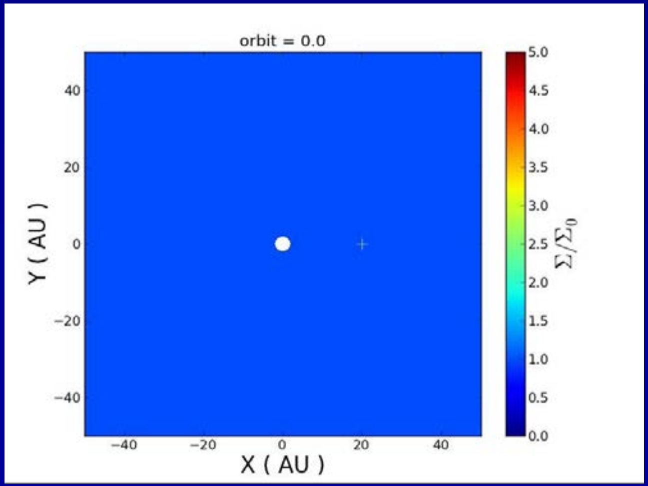
Radial and azimuthal dust traps

- For massive planets (>5 M_{Jup}), radial dust trap located at ~twice R_{planet}
- If overdensity at edge high + viscosity α low →Rossby unstable→long-lived vortex (10^5 yr)
  - Azimuthal asymmetry
- Gas edge < dust edge (~5 vs 10 R_{Hill})

Radial trap



Azimuthal asymmetry

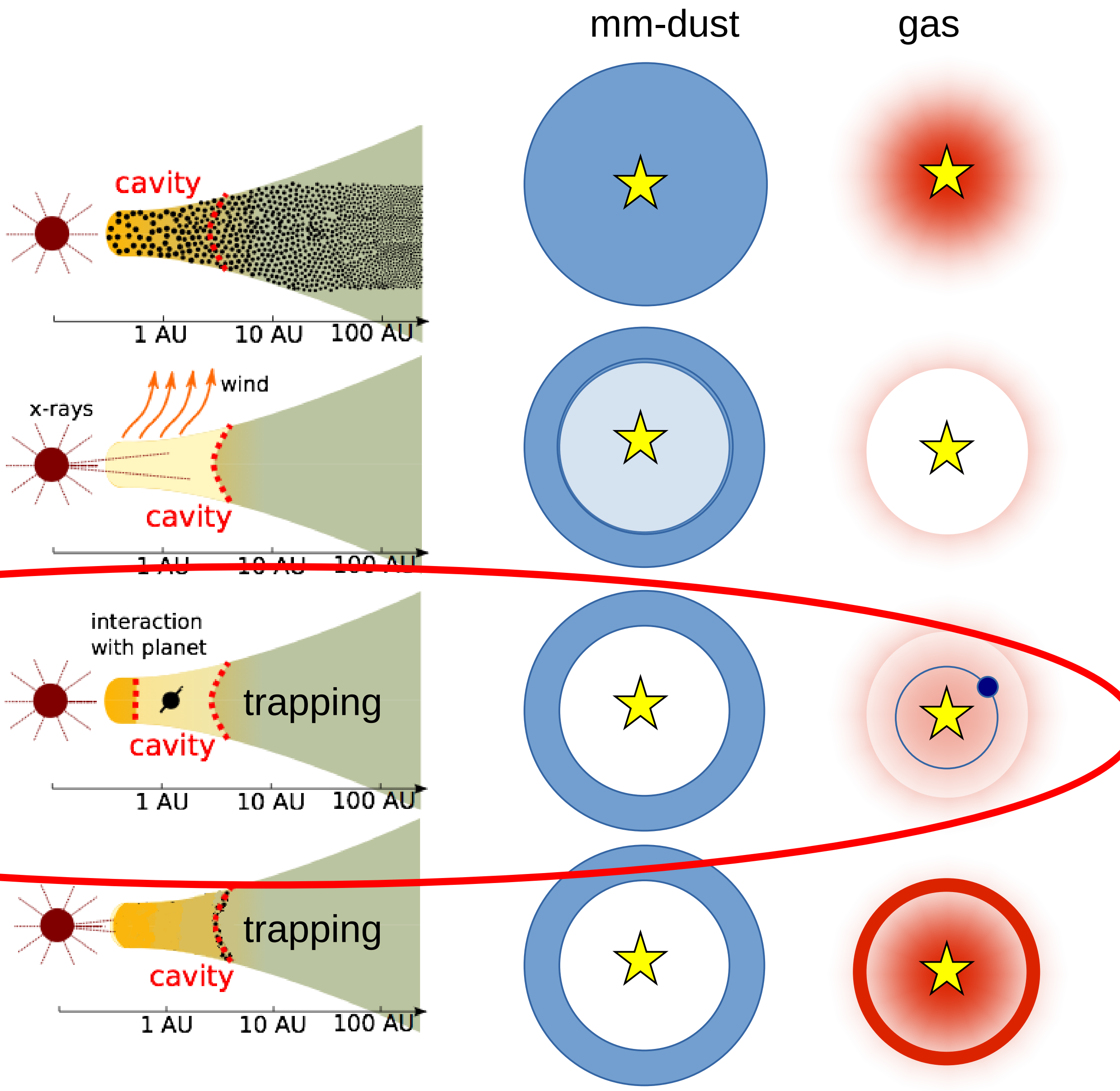


Pinilla, Birnstiel et al. 2013
Couple FARGO output with dust evolution code

Barge & Sommeria 1995
Klahr & Henning 1997
Wolf & Klahr 2002
Meheut et al. 2013,
Birnstiel et al. 2013
Facchini et al. 2017 ……

Dust ring and cavity clearing mechanisms

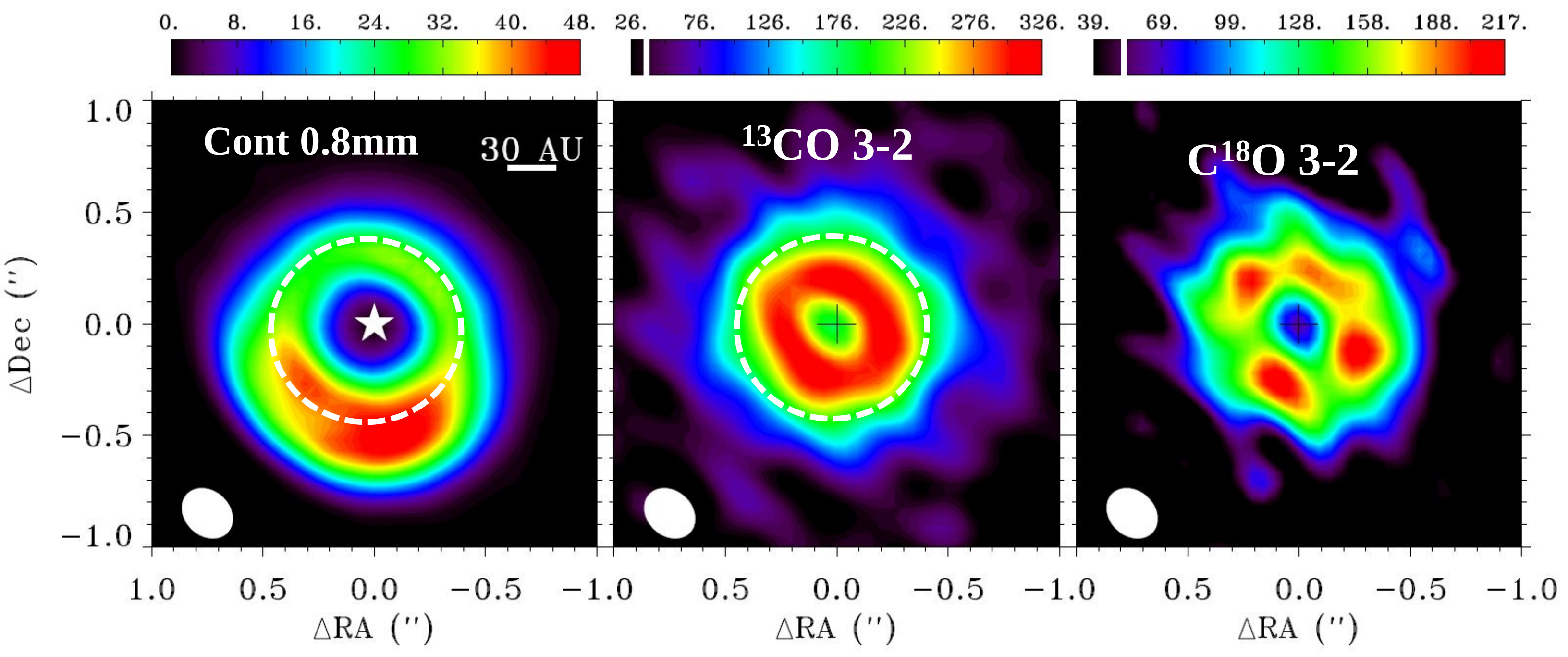
- Grain growth
- Photoevaporation
- Companion
- Dead zones



→ **Need to know the gas and dust distribution inside cavity**

Gas cavity smaller than dust cavity

HD135344B / SAO206462



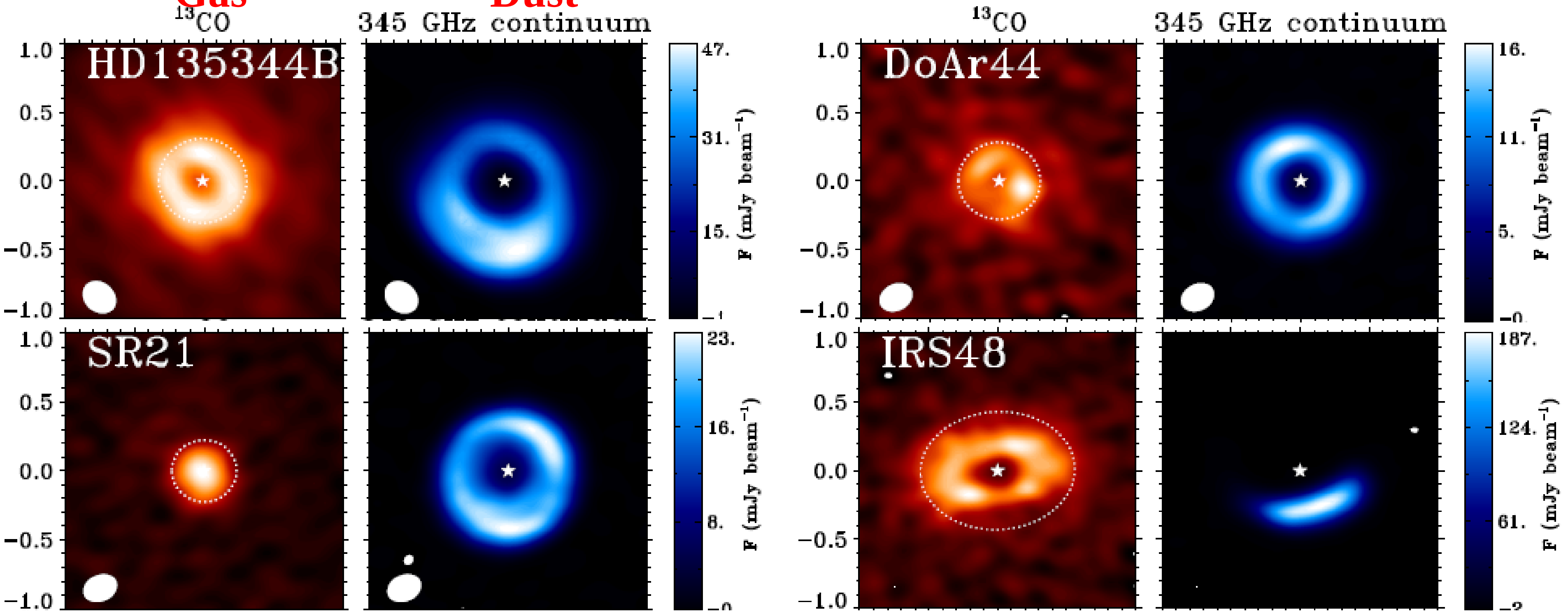
van der Marel et al. 2015, 2016

- Gas present inside dust hole
- Gas cavity smaller than that of dust

Gas and mm dust do not follow each other

Gas cavity < dust cavity

Gas **Dust**



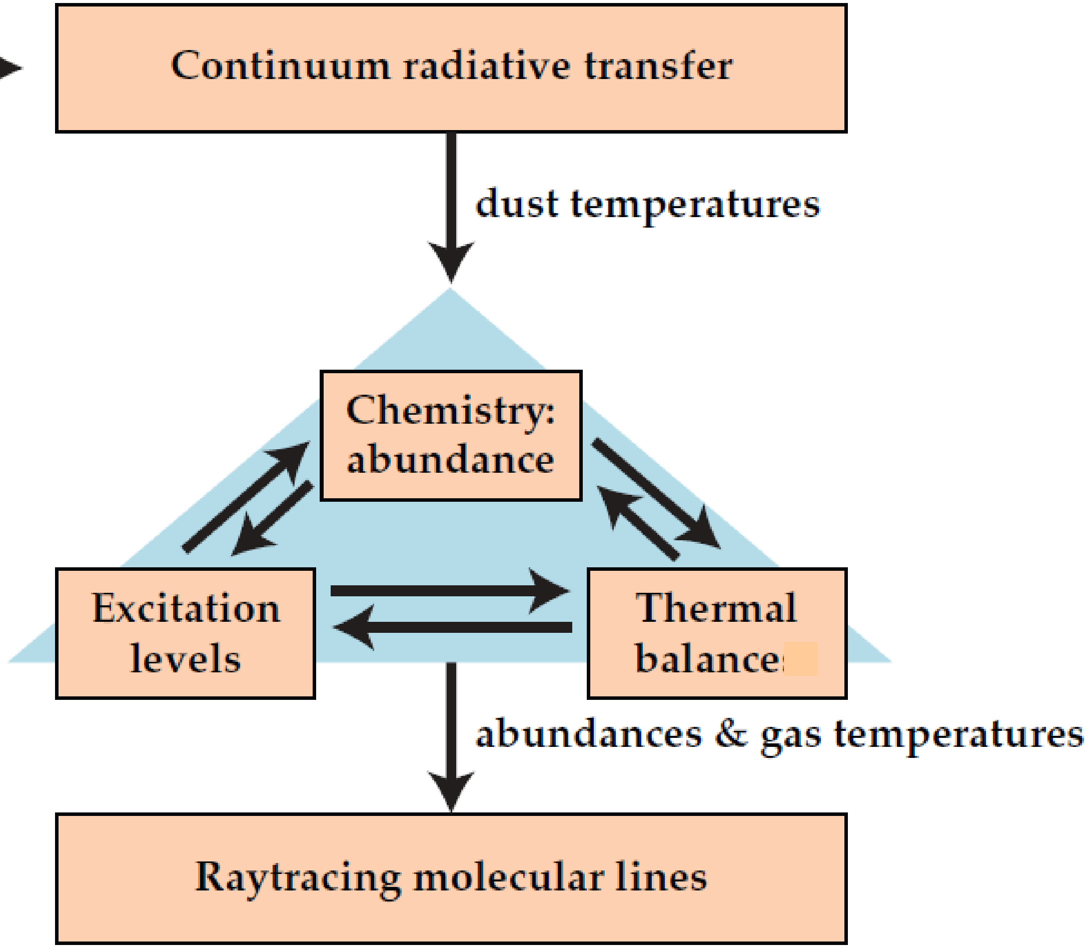
van der Marel et al. 2016

Press release December 16, 2015

Deep gas drops (factor 100-1000) point to young embedded planets

Quantitative CO analysis→ Gas mass + surface density

Density structure
Stellar spectrum



Continuum radiative transfer

dust temperatures

Chemistry: abundance

Excitation levels

Thermal balance

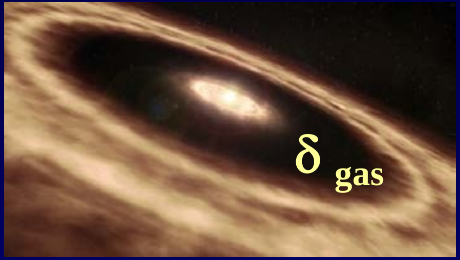
abundances & gas temperatures

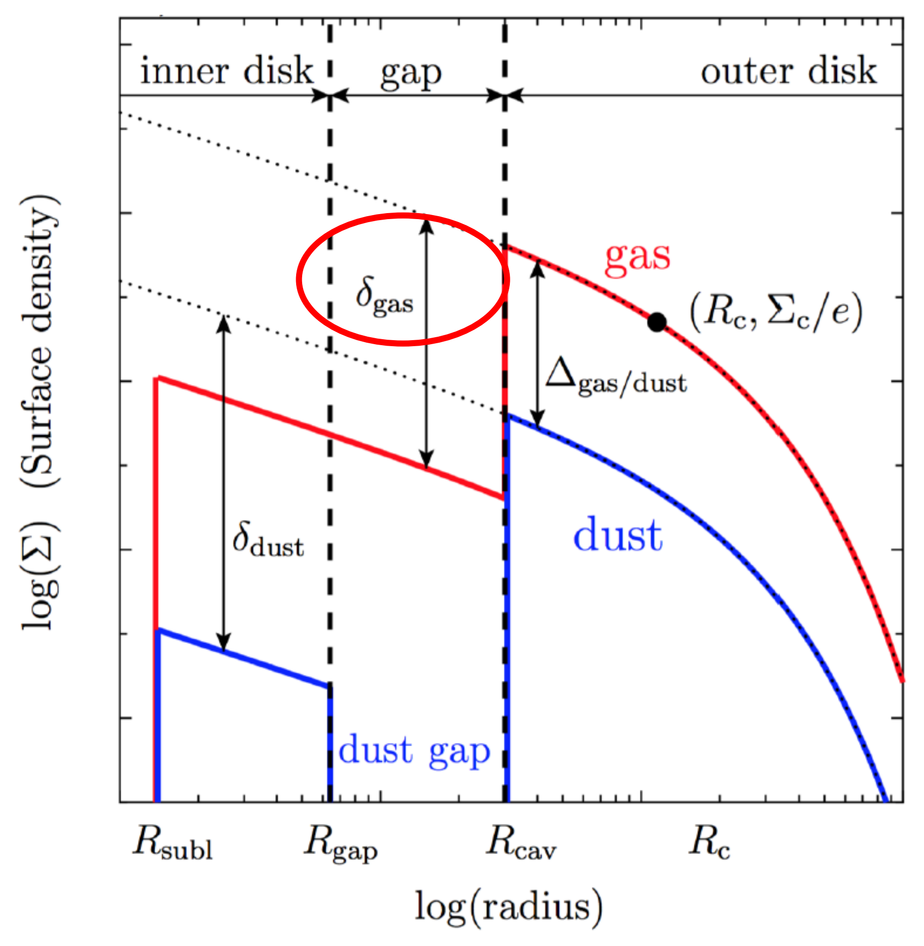
Raytracing molecular lines

DALI

Bruderer et al. 2012, 2013, 2014
Miotello et al. 2014

Gas mass and surface density





Factor 100 (TBD)

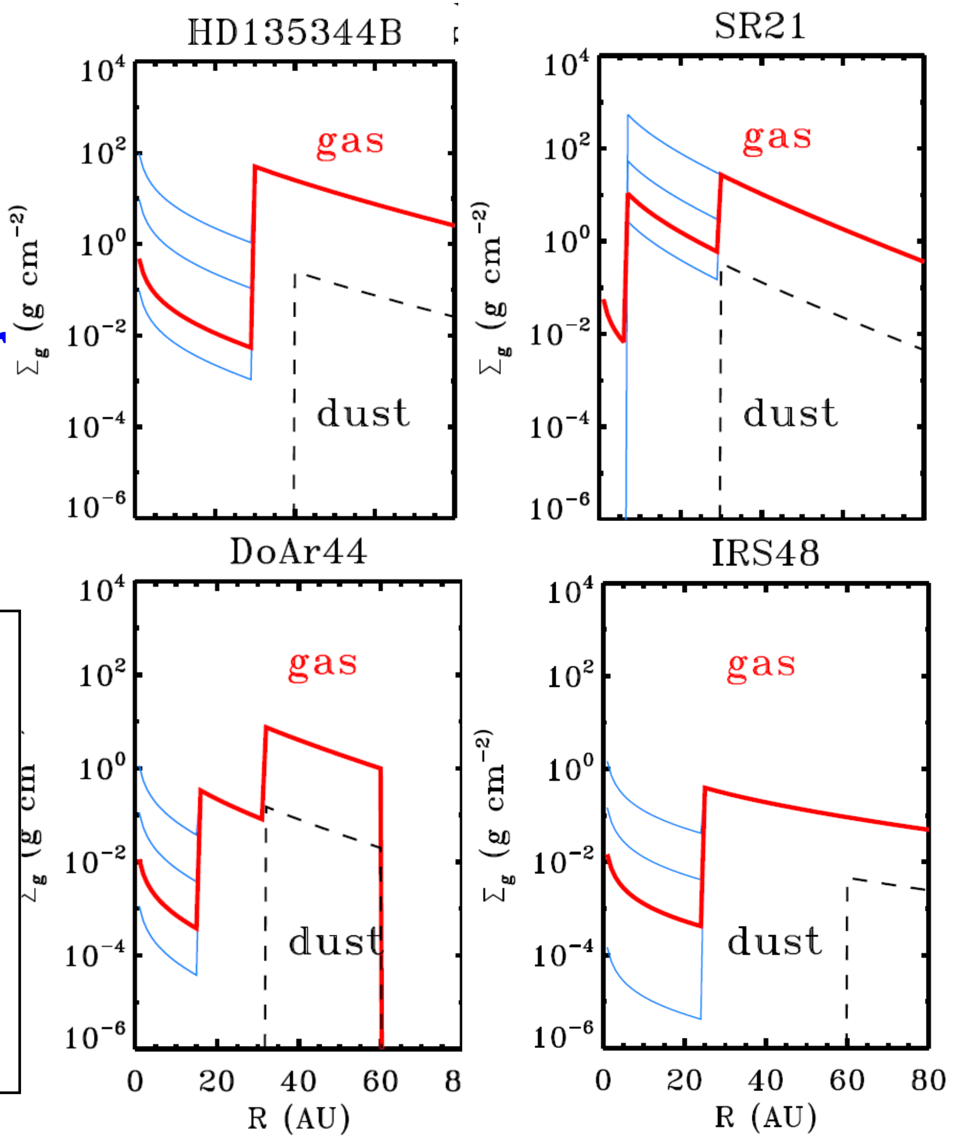
Bruderer 2013
Van der Marel et al. 2015
Facchini et al. 2017

- CO survives in dust-free cavity
- ALMA can probe gas masses down to 1 M_{Earth} in 1 hr!

Gas vs dust density structures

- **Gas cavity < dust cavity**
  <u>in all cases</u> studied to date

- **Gas density drops by factor 100-1000 → embedded planets**

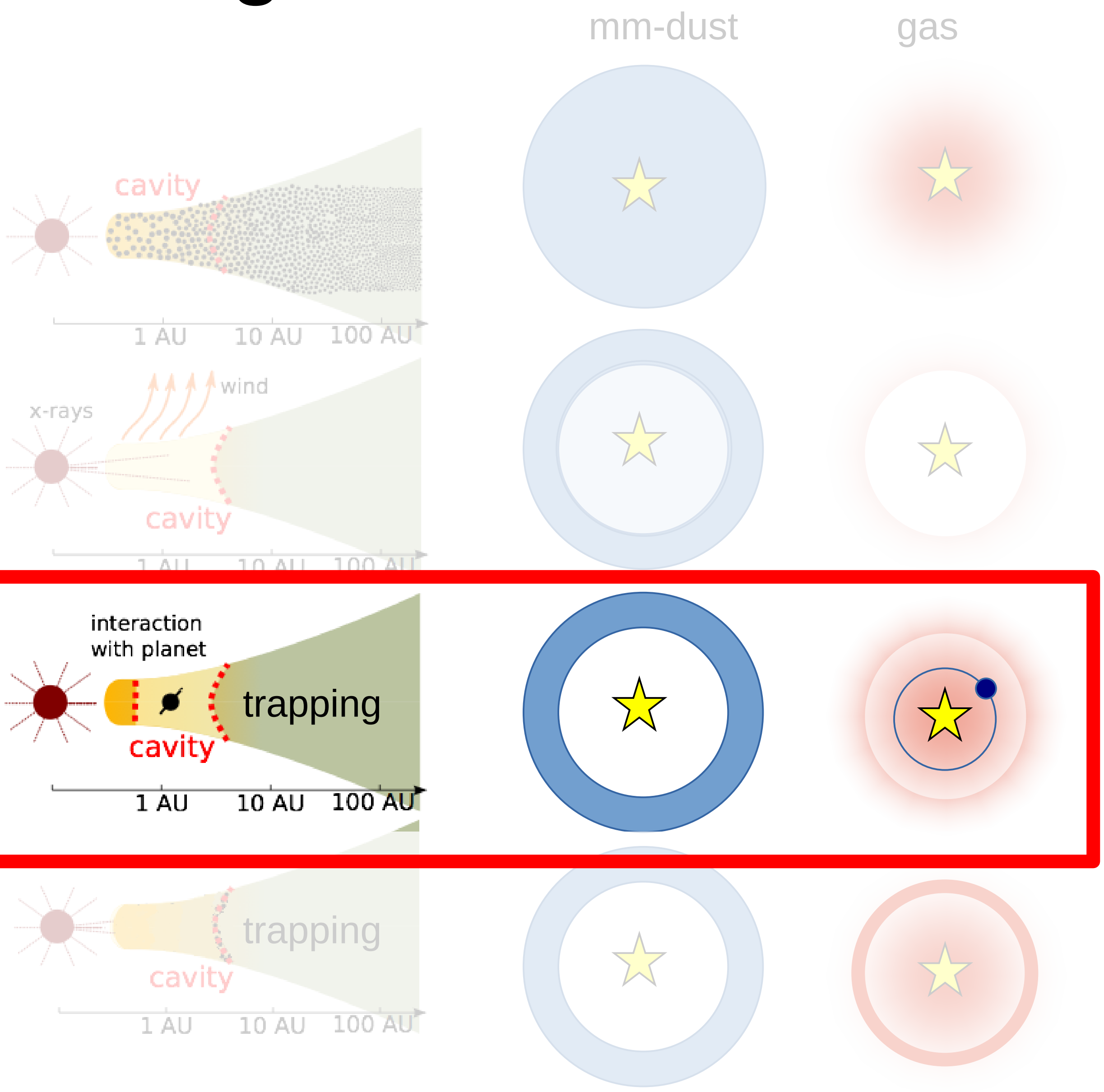


Other disks: Zhang et al. 2014, Perez et al. 2014, 2015

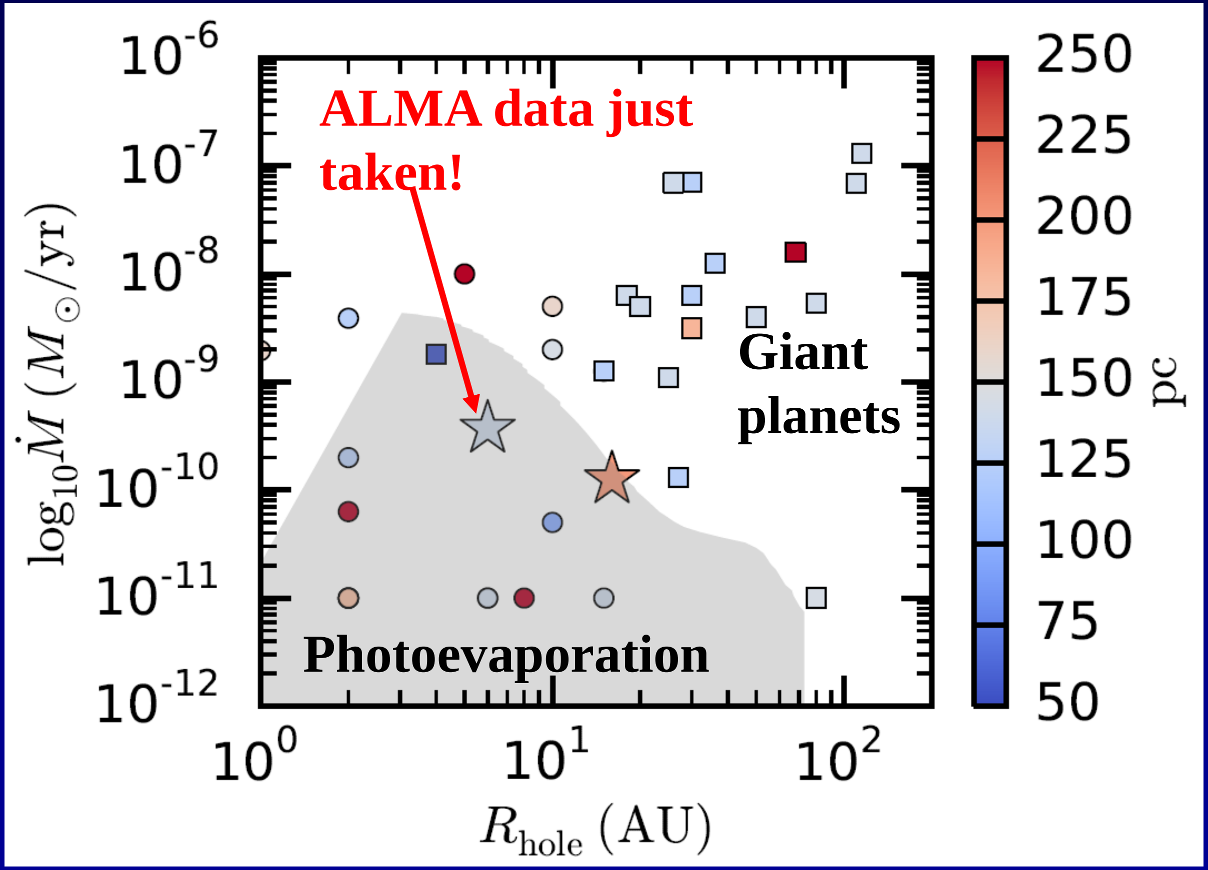
van der Marel et al. 2015, 2016; Bruderer et al. 2014

Cavity clearing mechanisms

- Grain growth
- Photoevaporation
- **Companion**
- Dead zones



Two regimes of TDs?

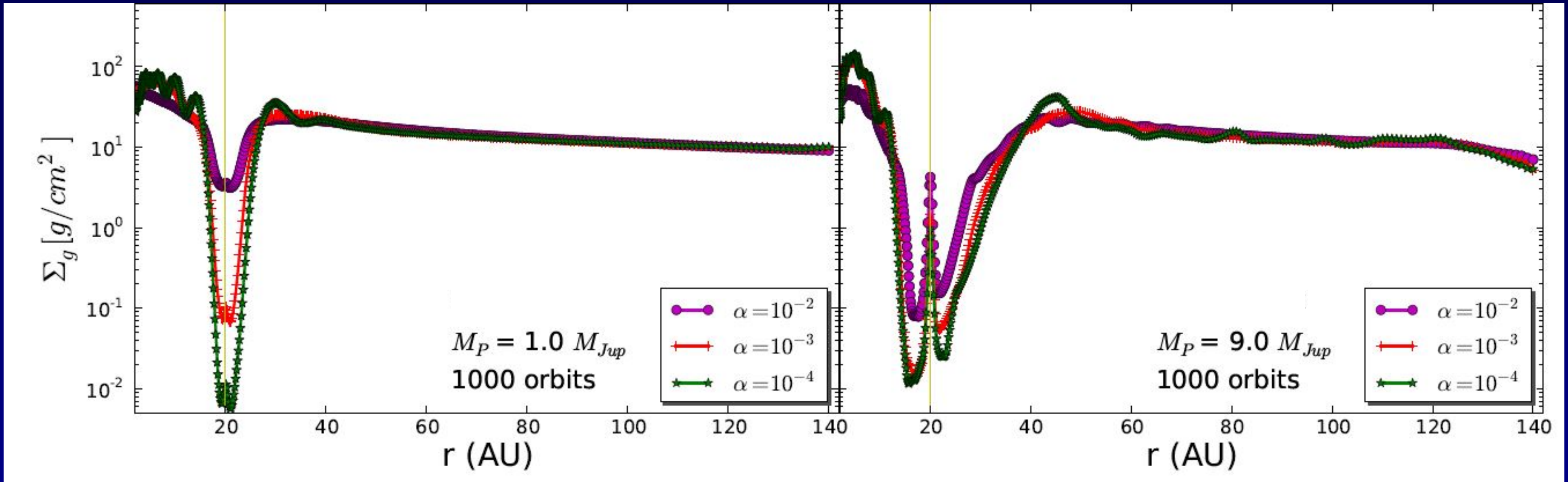


Owen & Clarke 2012
Facchini et al. 2017

- Test photoevaporation scenario with a few disks

Can we constrain planet mass?

Hydro-simulations

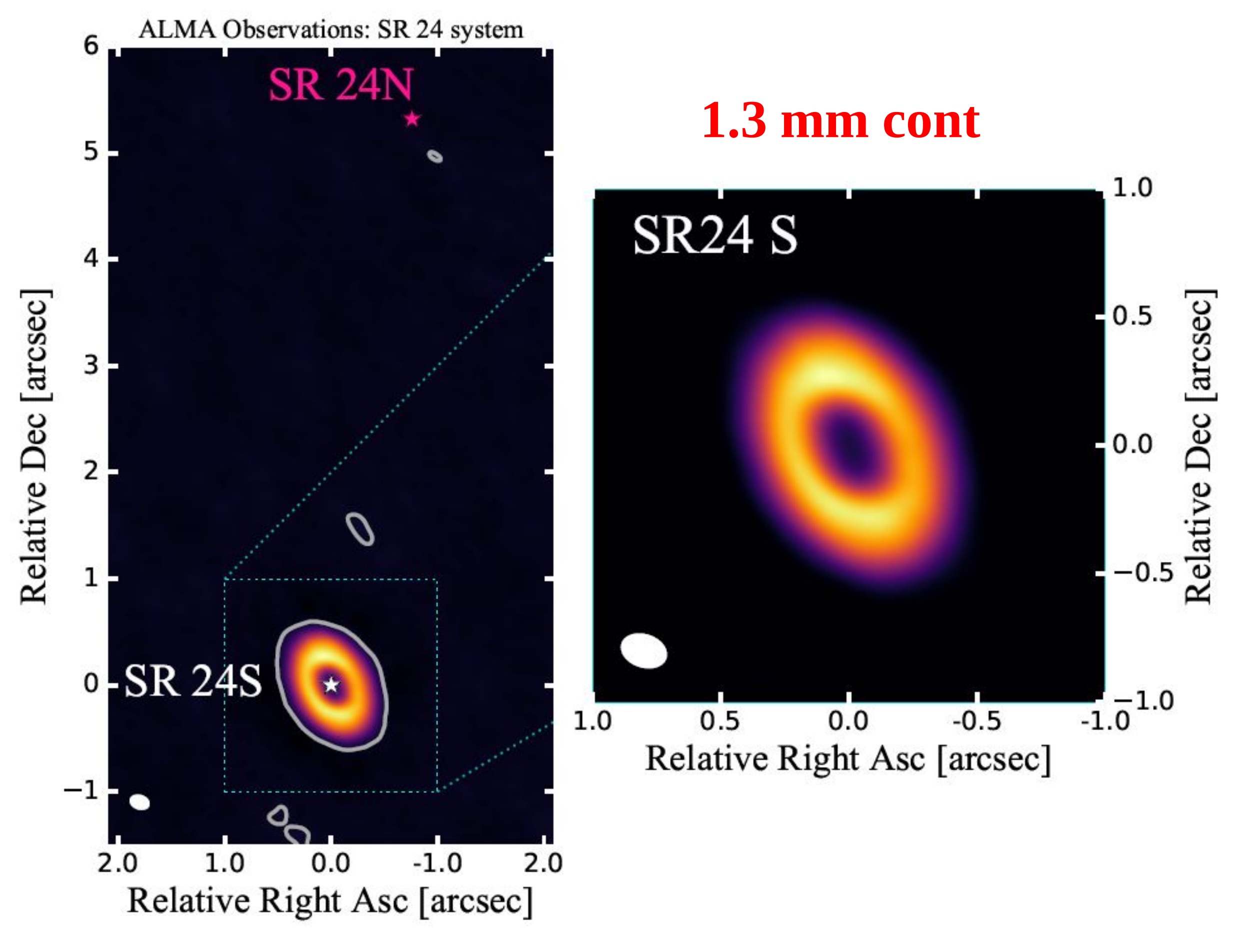


Pinilla et al. 2012
+ many other groups

- **Depth of gap depends on mass of planet *and* viscosity α**

Need to spatially resolve gaps! → <0.1”

Recent work
SR24 binary: large variations

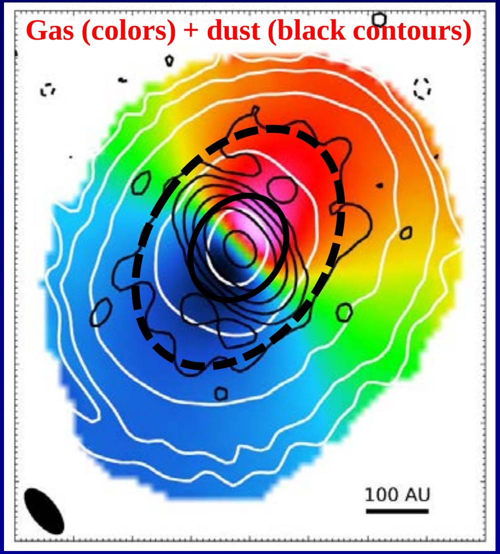


Pinilla et al. 2017

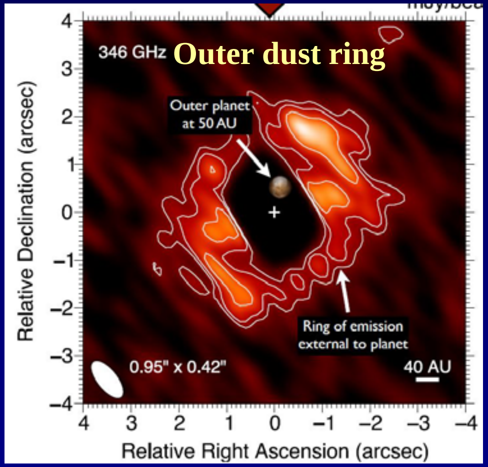
No disk seen in mm around SR 24N, factor >300 weaker than S

Double dust rings HD 100546

Outer gas disk > dust disk



Gas (colors) + dust (black contours)



Outer dust ring

Outer dust ring

Main dust disk subtracted
1% of peak flux

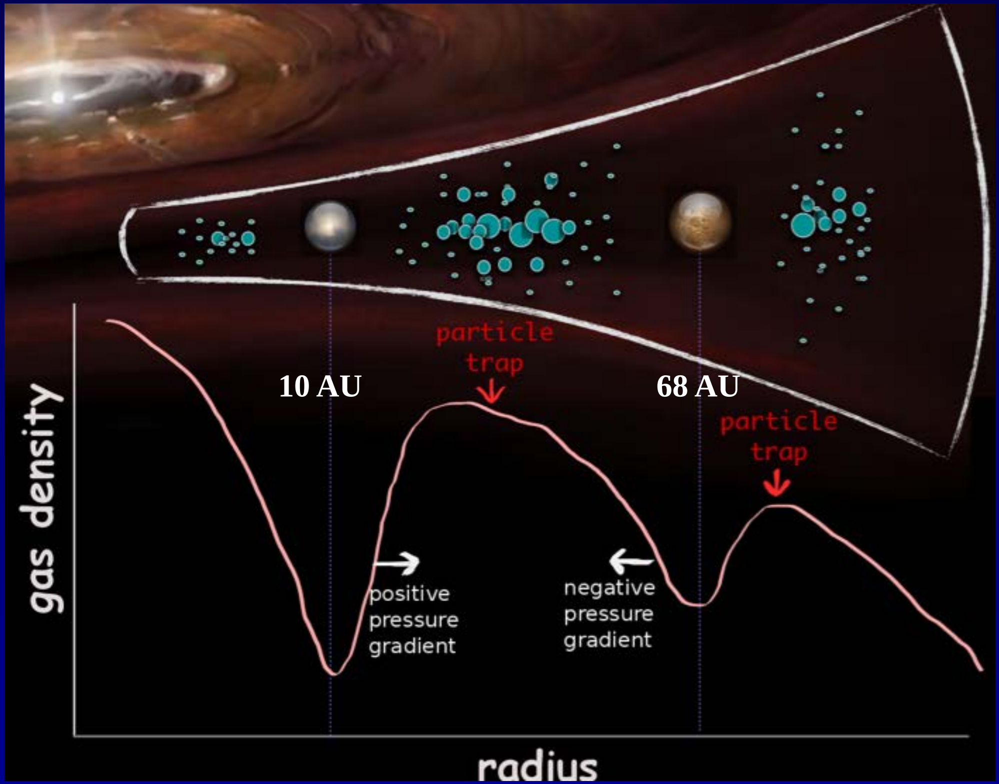
Inner dust ring

Inner dust ring
No circumplanetary disk

Walsh et al. 2014, 2017
C. Wright et al. 2015

ALMA long baselines
Pineda, Szulágyi+ in prep.

Evidence of multiple (sequential?) planet formation?



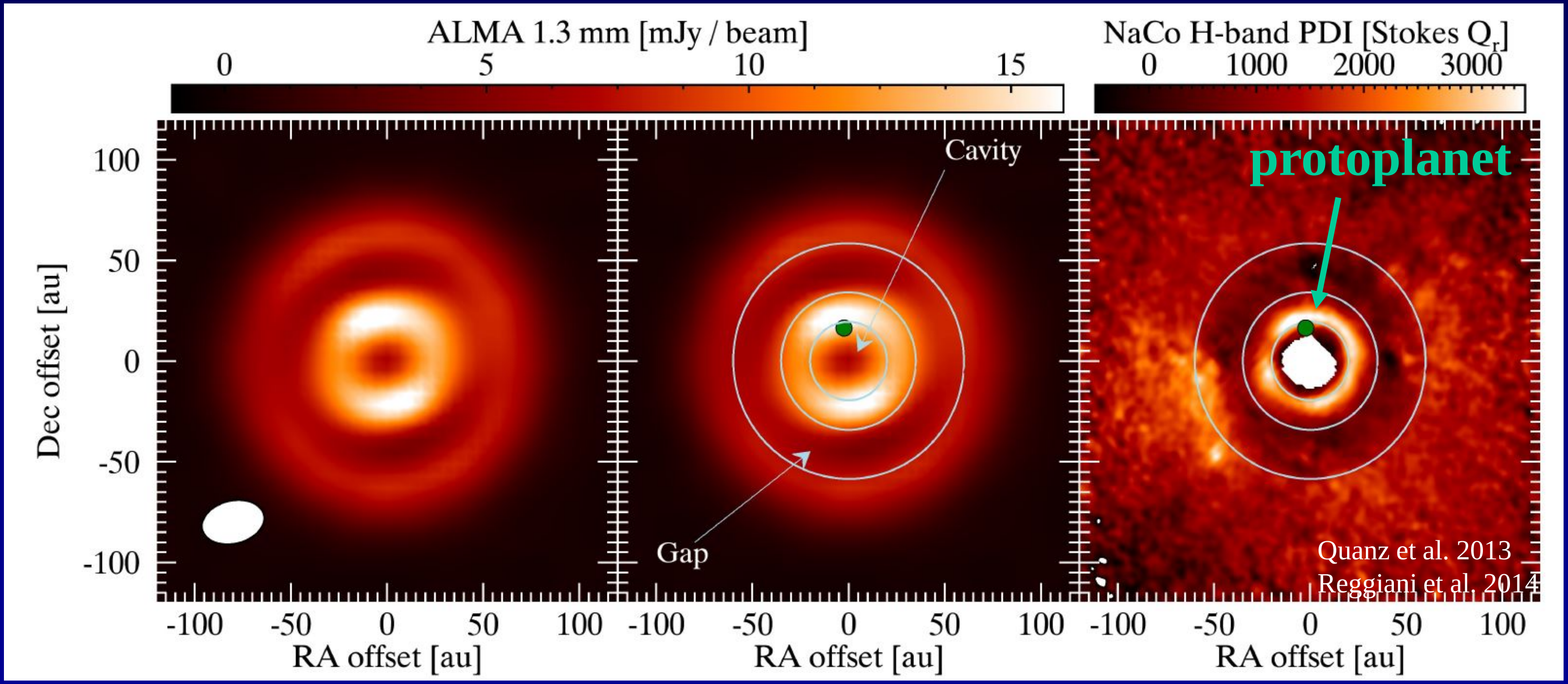
Pinilla et al. 2015

- Radial drift alone nor a single planet at 10 AU can reproduce the emission from millimeter-sized dust grains + scattered light

- Outer planet must be significantly younger than the inner planet (by > 2.5 Myr)

Double ring in planet-forming disk HD169142

Dust mm continuum **Scattered light**

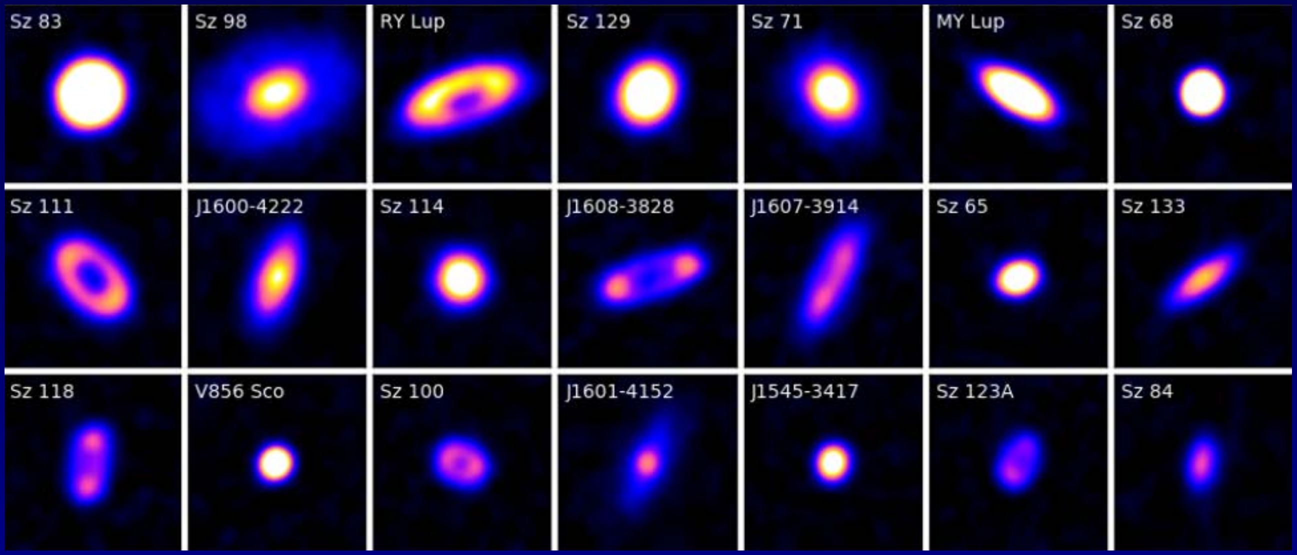


Quanz et al. 2013
Reggiani et al. 2014

Fedele et al. 2017

`- Deep gas drops in rings point to planets
- But presence protoplanet now being disputed?

Back to Lupus: TDs



**van der Marel et al.
2017 in prep.**

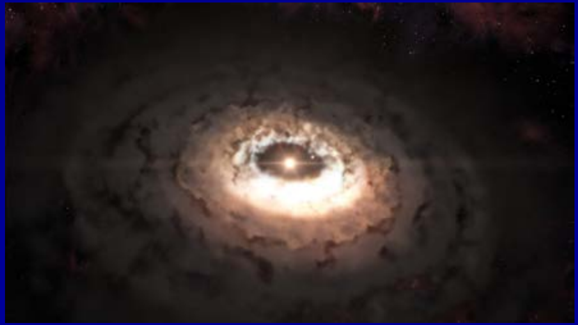
- **10% of disks in Lupus are TDs with >20 AU cavity**
- **TDs among most massive and largest disks**

Problems:
- ***Fraction too high compared with exoplanet statistics***
- ***No circumplanetary disks detected yet with ALMA***
- ***Embedded planets not found by direct imaging***

Summary

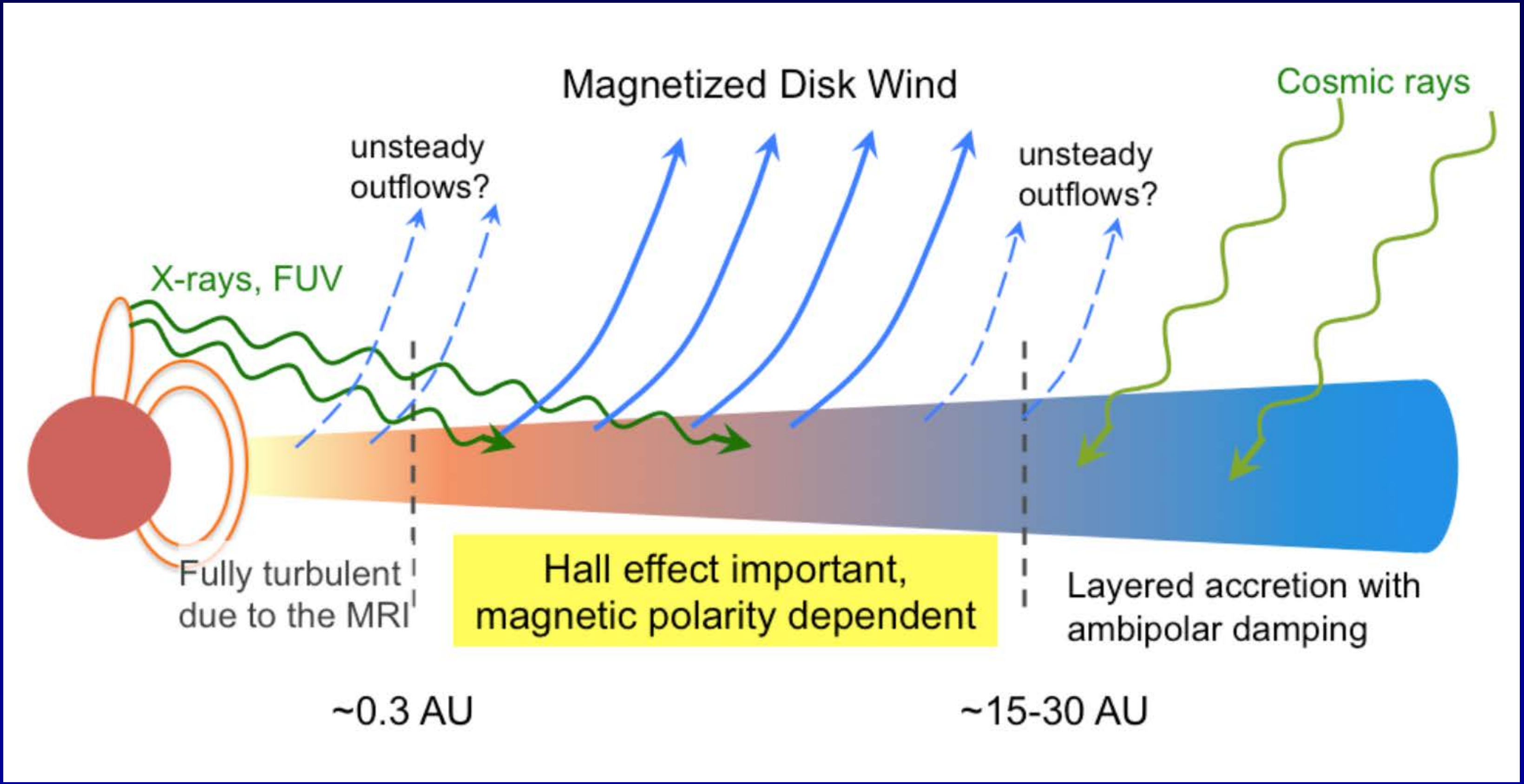
- Structure of protoplanetary disks being unravelled by ALMA
  - Gas and mm dust do not follow each other
  - Depletion of dust with age 1-10 Myr
  - Weak CO emission: low gas/dust vs carbon depletion
  - Few disks have enough dust or gas to build giant planet
  - Snowlines directly imaged
- Transitional disks as sites of giant planet formation?
  - Dust traps and gas cavities point to young giant planets
  - Tension with exoplanet statistics?

Next steps: $\Sigma_{gas}(R)$ large samples
chemistry
multi λ



Extra slides

Disk transport and evolution

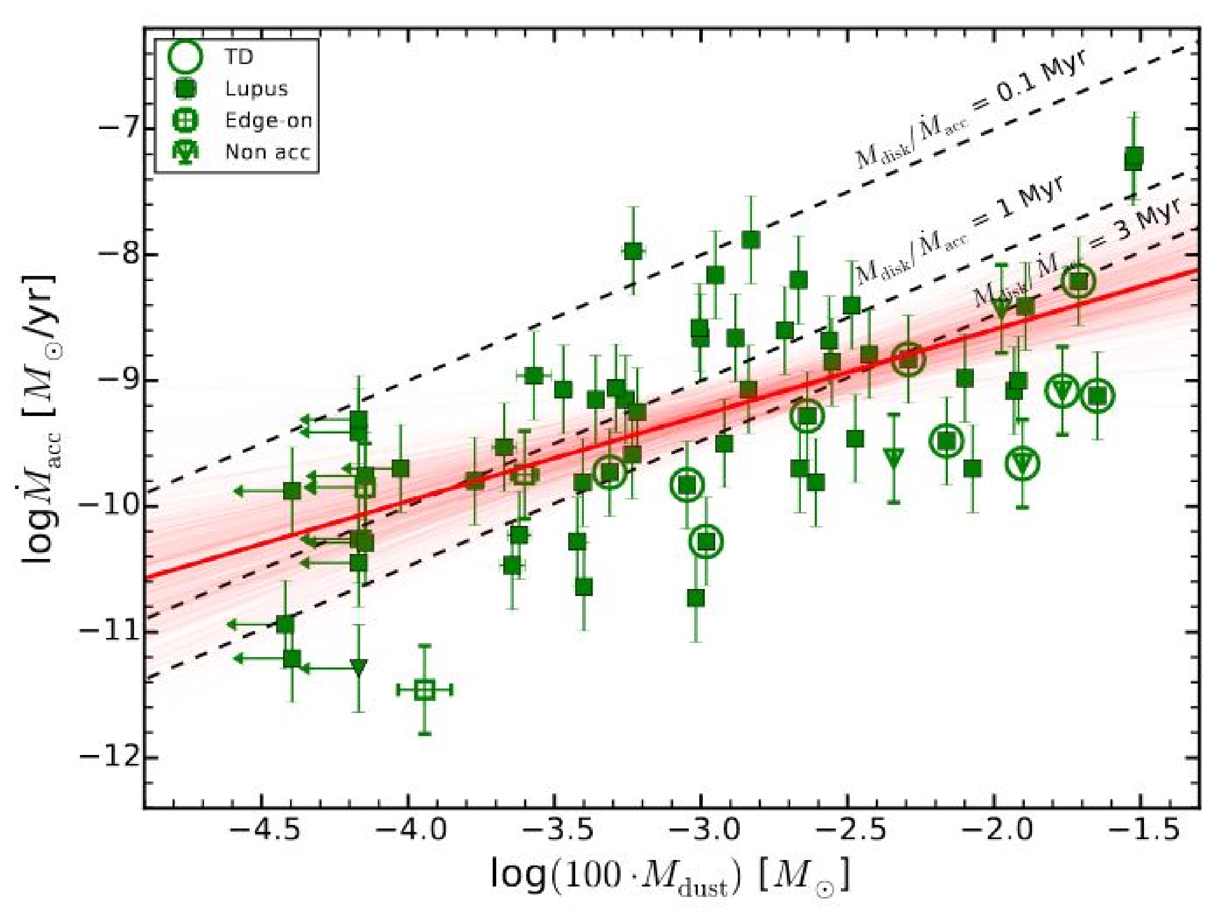


Disk winds more important than MRI?

Bai & Stone
Gressel et al.
Armitage

Accretion rate vs disk mass

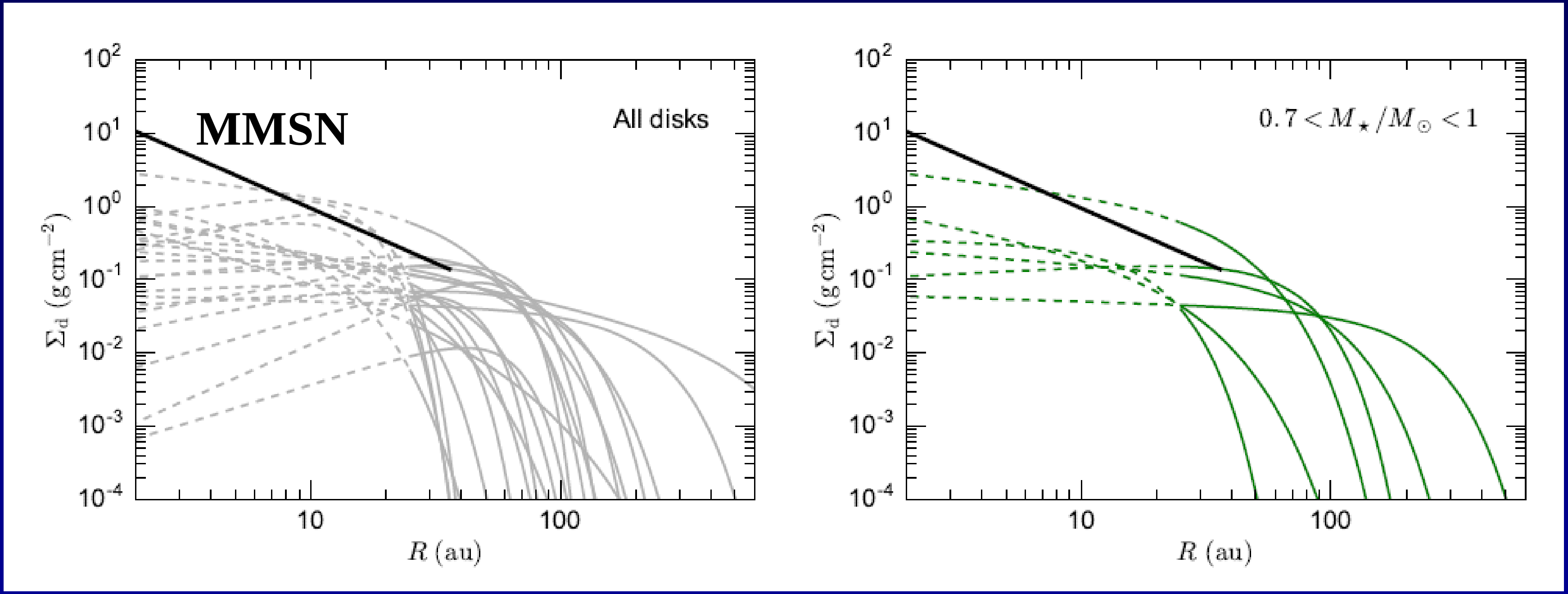
testing viscous evolution



Manara et al. 2016

100xM_{dust} agrees well with viscous evolution for ~3 Myr lifetime (with considerable scatter)

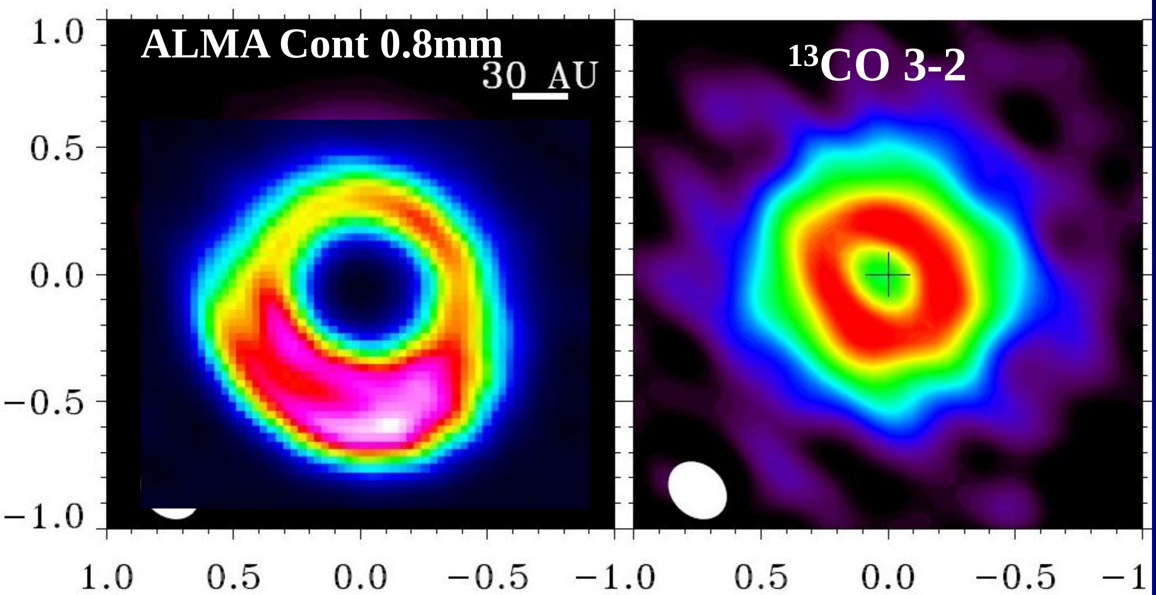
Lupus dust surface density profiles



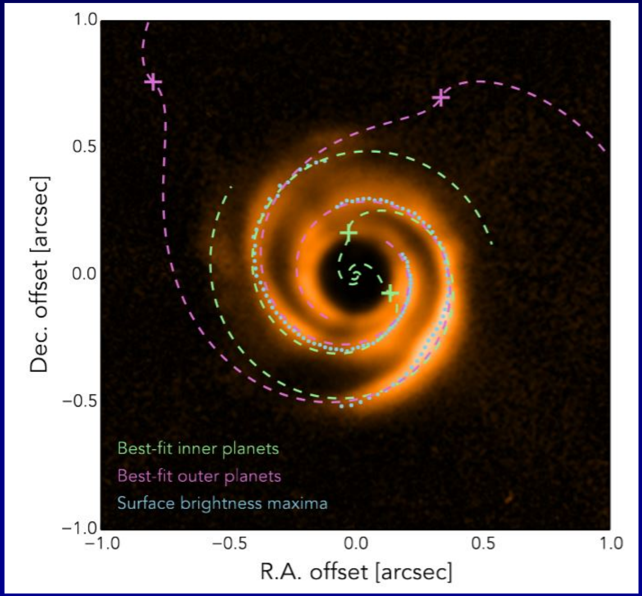
Tazzari et al. 2017

Disks structures: what do they imply for planets?

HD 135344B ALMA: van der Marel et al. 2016b

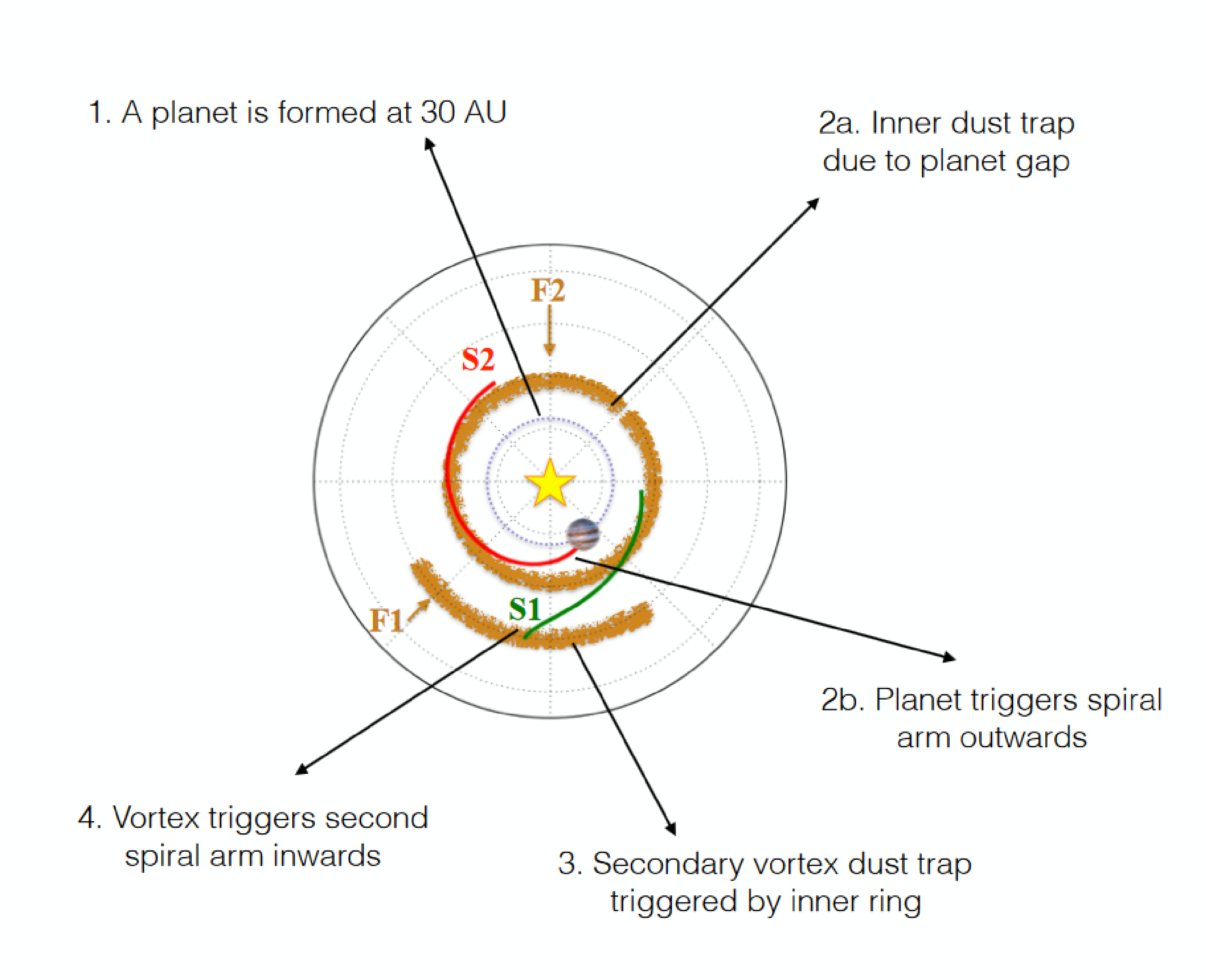


VLT-Sphere: Stolker et al. 2016
Scattered light image



- **Mm emission is ring + asymmetric trap**
- **Structures point to giant planet(s), but in different ways**
  - **Muto, Garufi, Stolker: 2 planets: inner and outer**
  - **Dong: 1 planet at ~100 AU**
  - **vdM: 1 planet at ~30 AU**

HD135344 spiral scenario



1. A planet is formed at 30 AU

2a. Inner dust trap due to planet gap

2b. Planet triggers spiral arm outwards

3. Secondary vortex dust trap triggered by inner ring

4. Vortex triggers second spiral arm inwards