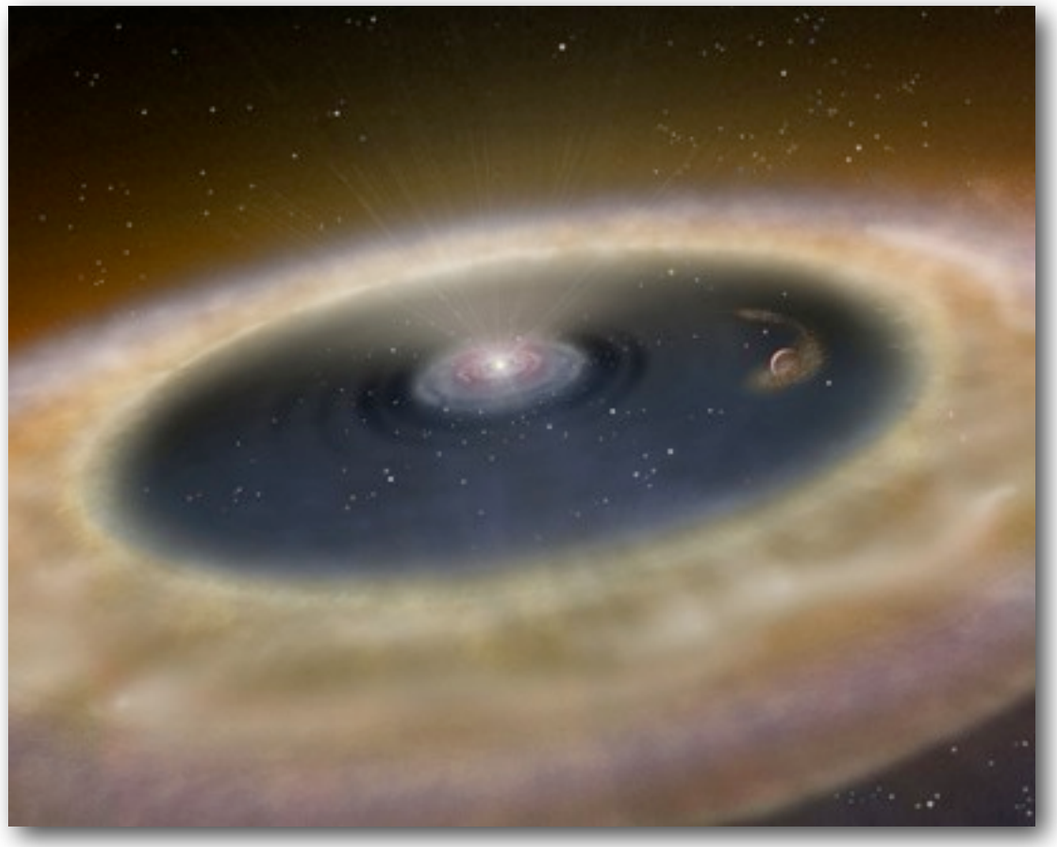
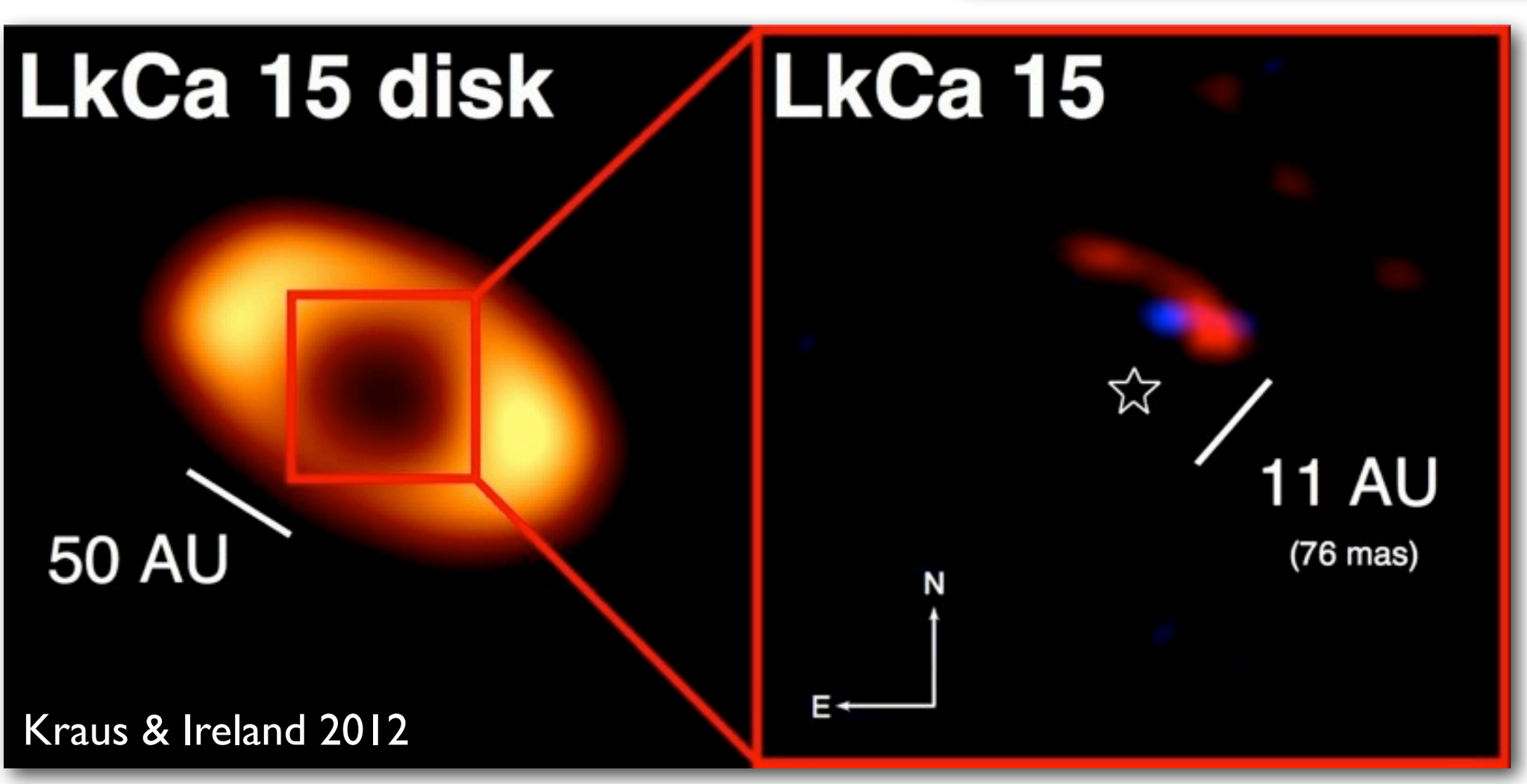
Herschel Observations of Protoplanetary Disks

Jonathan Williams
University of Hawaii

Herschel2012: "From atoms to pebbles", Grenoble 3/22/12

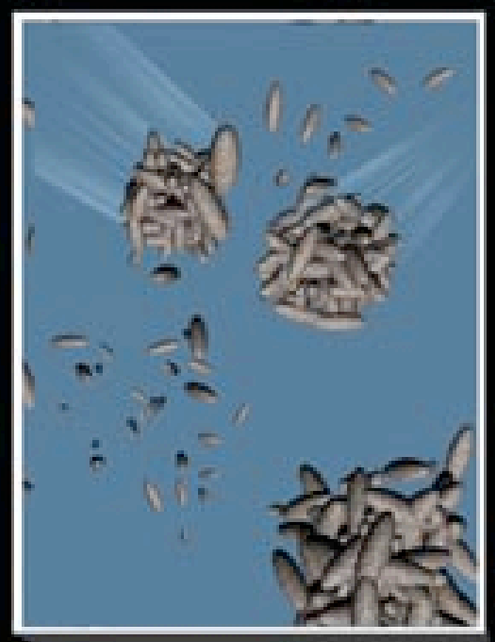
All stars form surrounded by disks, and at least some disks truly are protoplanetary!





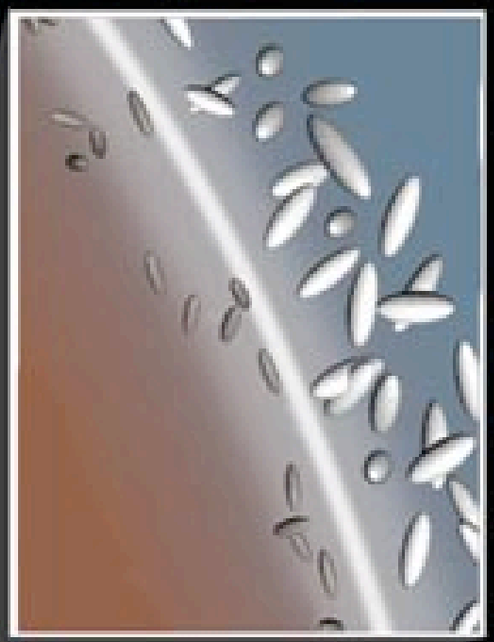
Disks are not like the ISM!

1 Grains collide, clump and grow.



2 Small grains are swept along by the gas, but those larger than a millimeter experience a drag force and spiral in.

3 At the snow line, local conditions are such that the drag force reverses direction. Grains tend to accumulate and readily coagulate into larger bodies called planetesimals.



2–4 AU

Protosun

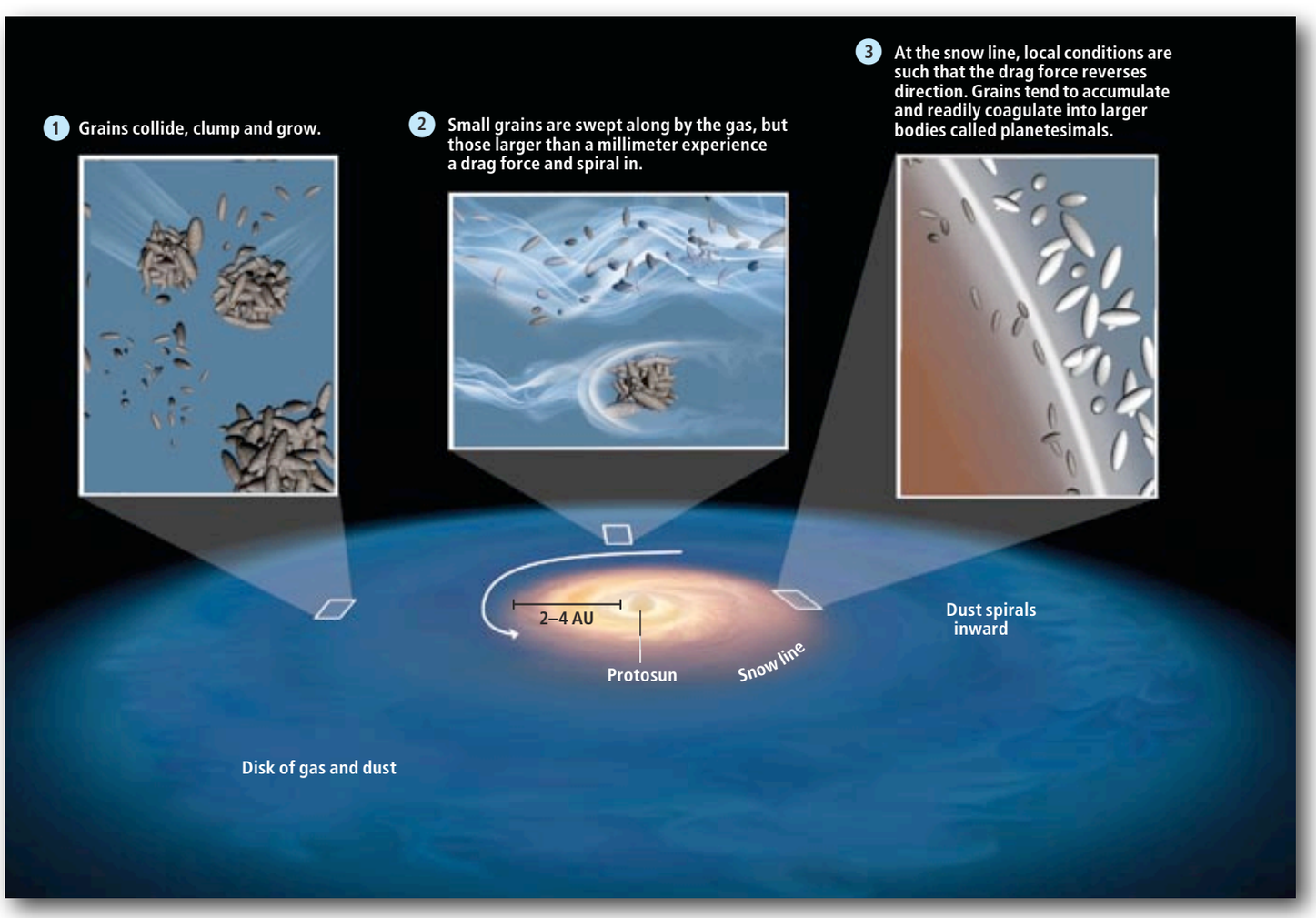
Snow line

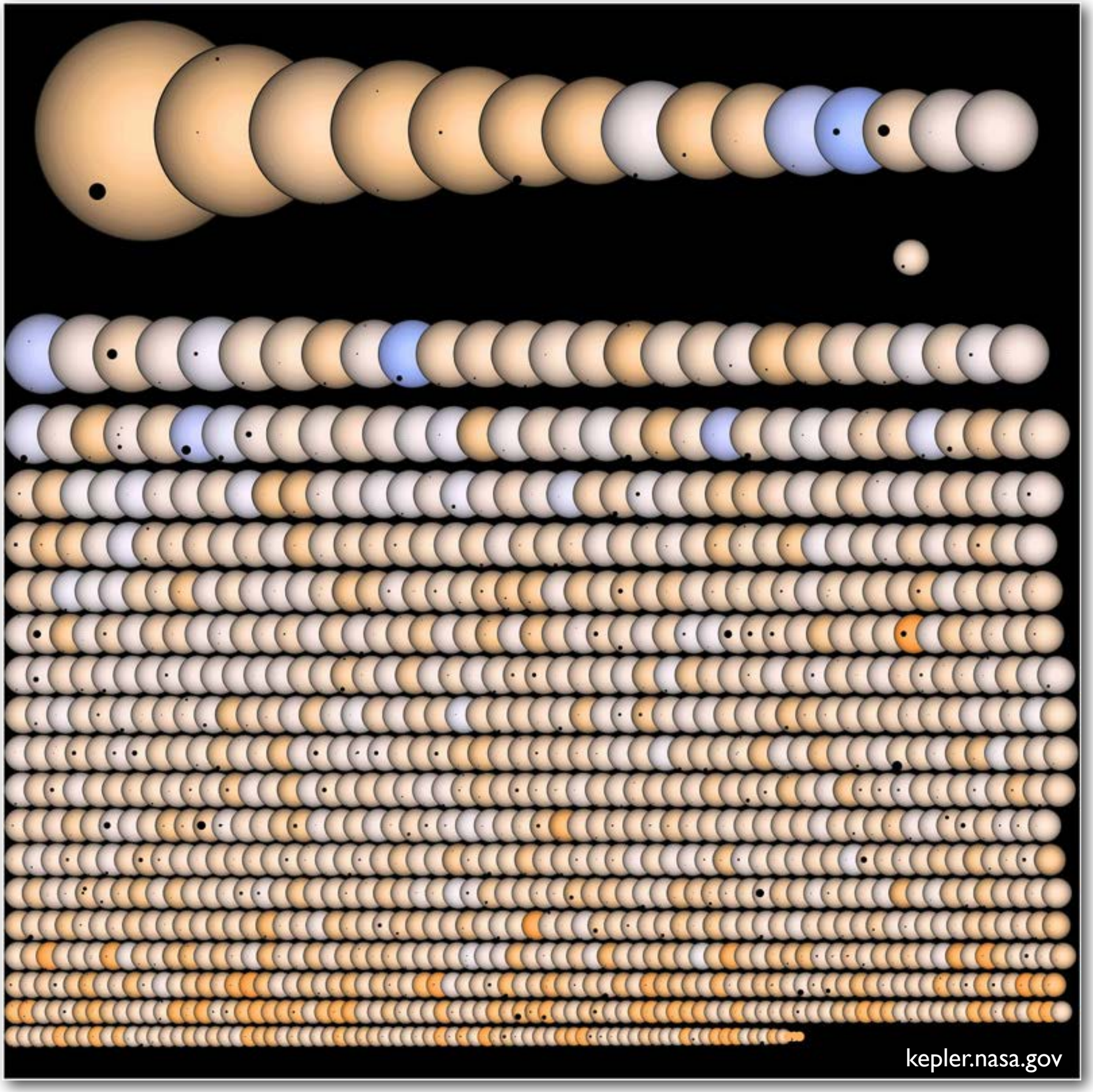
Dust spirals inward

Disk of gas and dust

How to make giant planets

- Grow dust, μm → km, in presence of gas...
- build ~10M_{Earth} cores for runaway accretion...
- while still having >1M_{Jup} of gas to make giant planets...
- then disperse gas quickly!





Kepler's new law

~1000 / 150000 stars have planetary candidates (Borucki+ 2011)

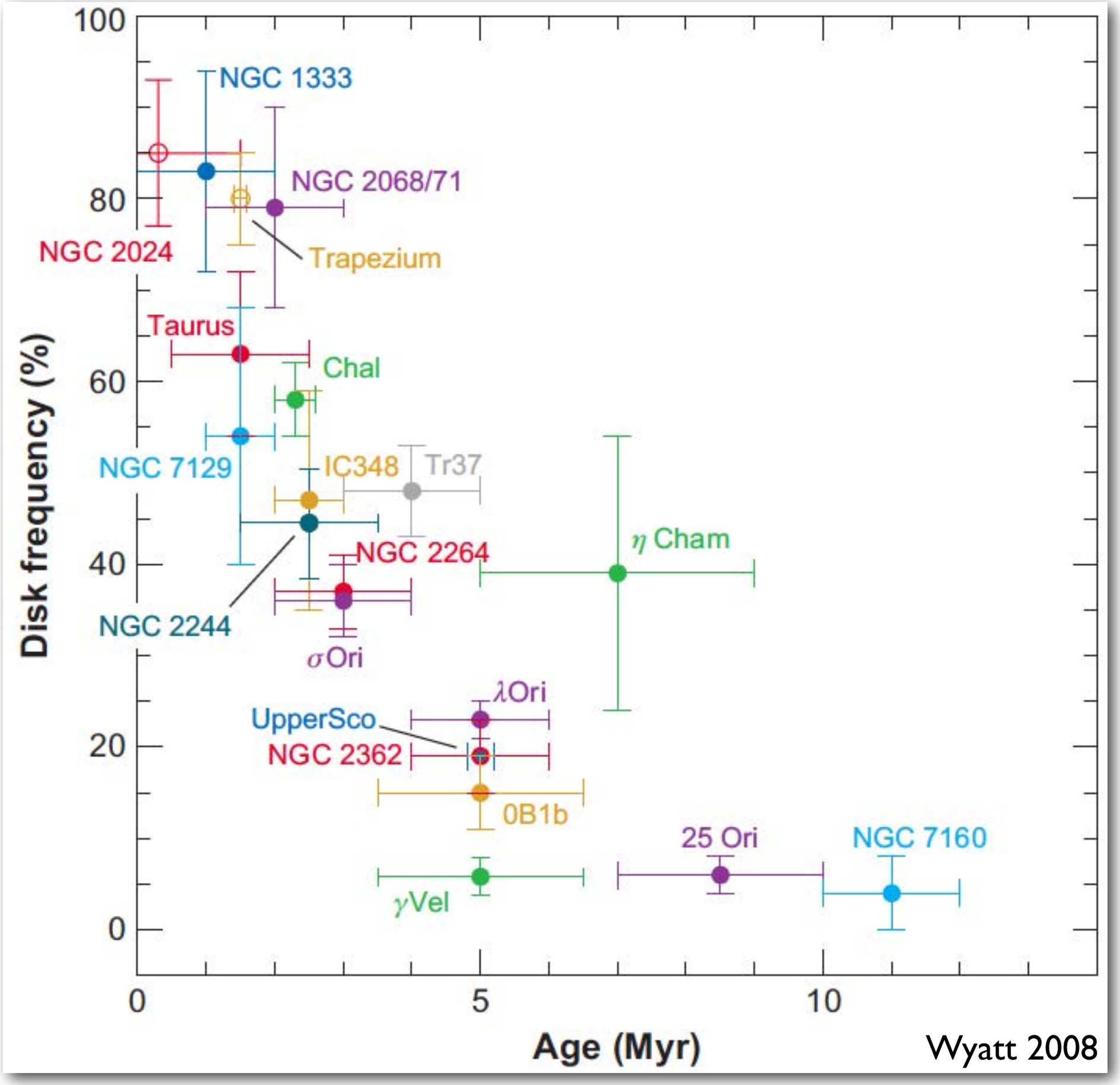
Planets are *very* common...

... and with a huge diversity

⋯▸ Initial conditions?

⋯▸ Disk evolution?

⋯▸ Stochastics?


100
80
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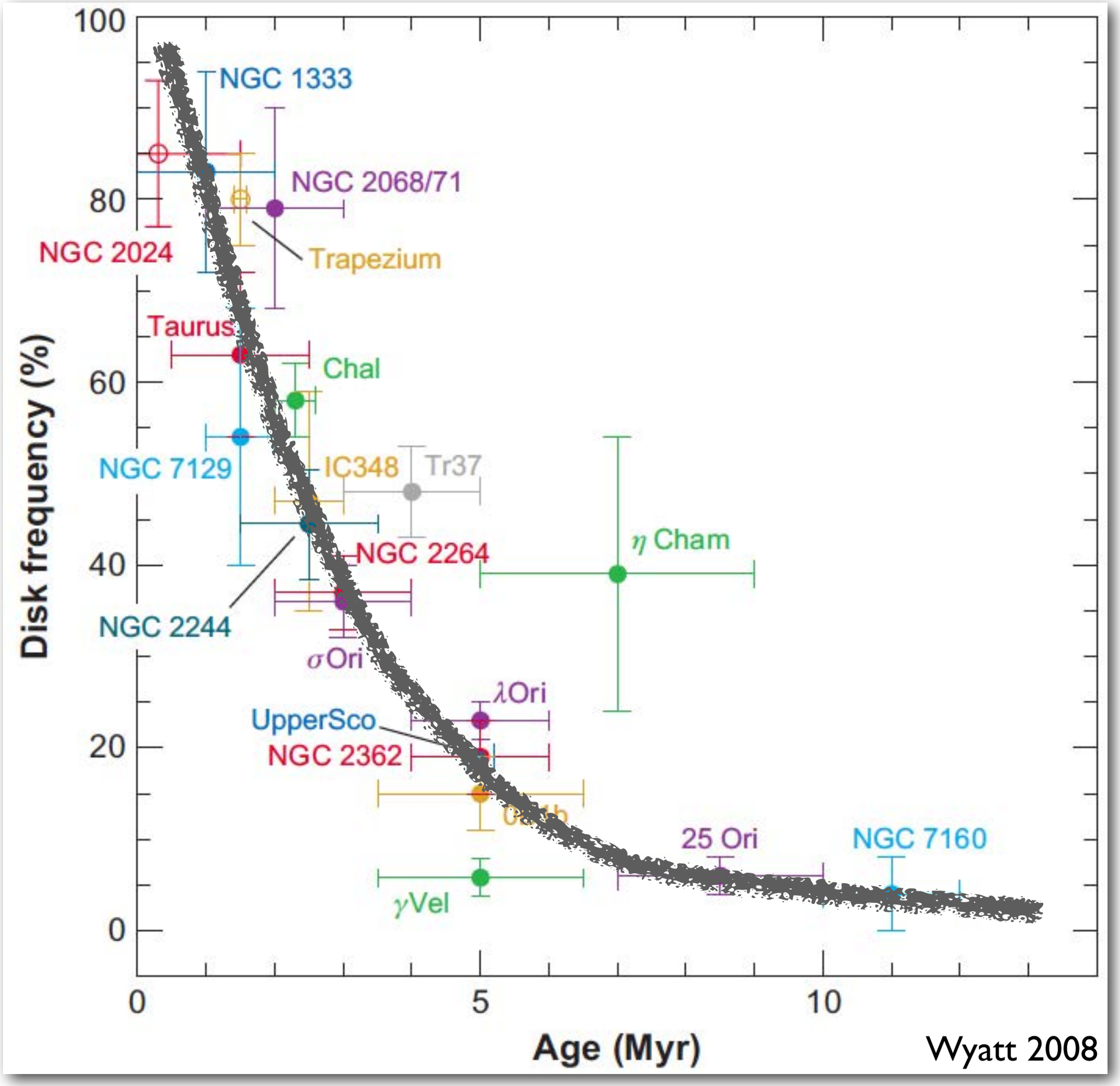
40
20
0
Disk frequency (%)
0
5
10
Age (Myr)
NGC 1333
NGC 2068/71
NGC 2024
Trapezium
Taurus
Chal
NGC 7129
IC348
Tr37
NGC 2264
η Cham
NGC 2244
σOri
λOri
UpperSco
NGC 2362
0B1b
25 Ori
NGC 7160
γVel

Wyatt 2008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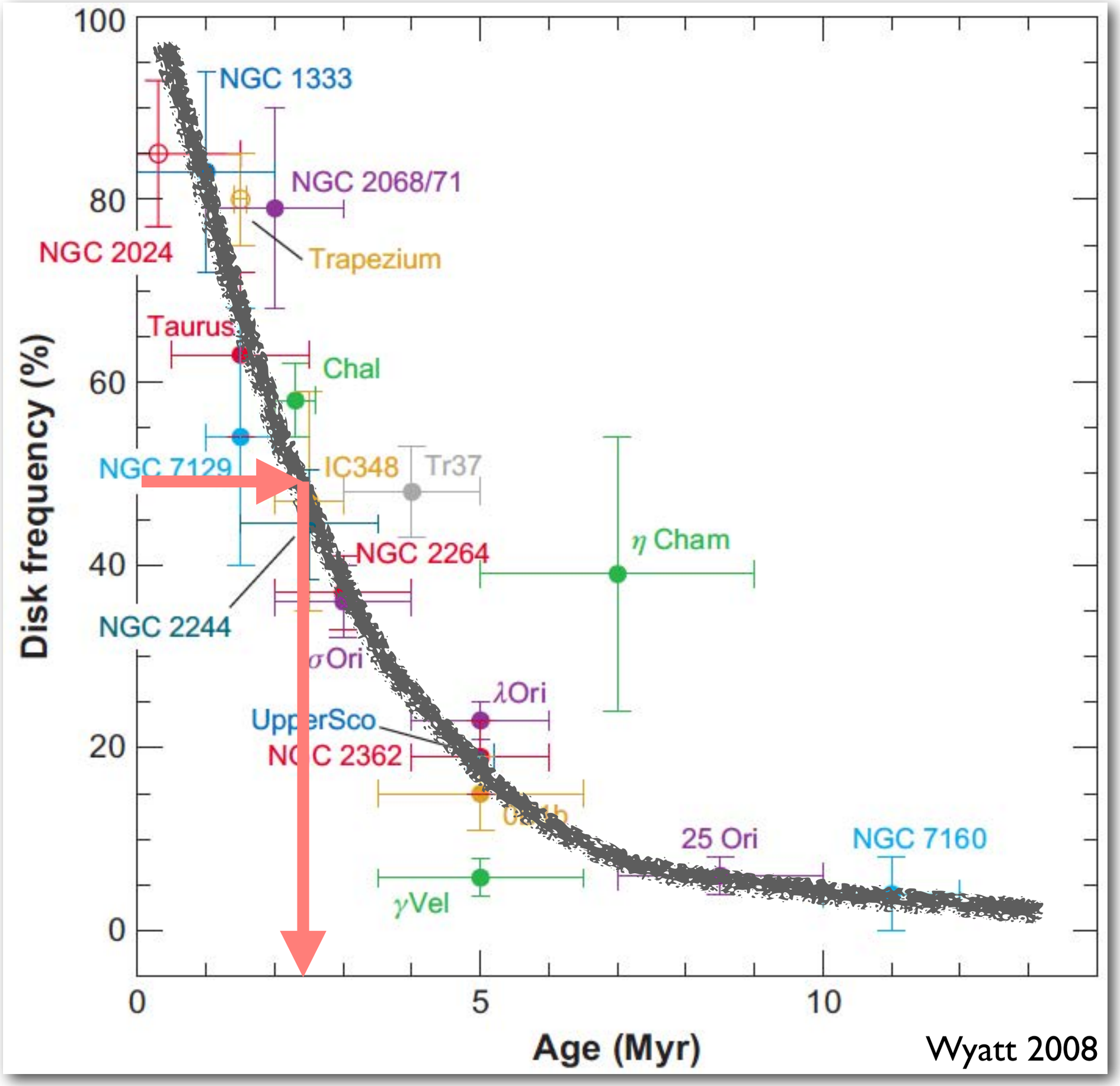
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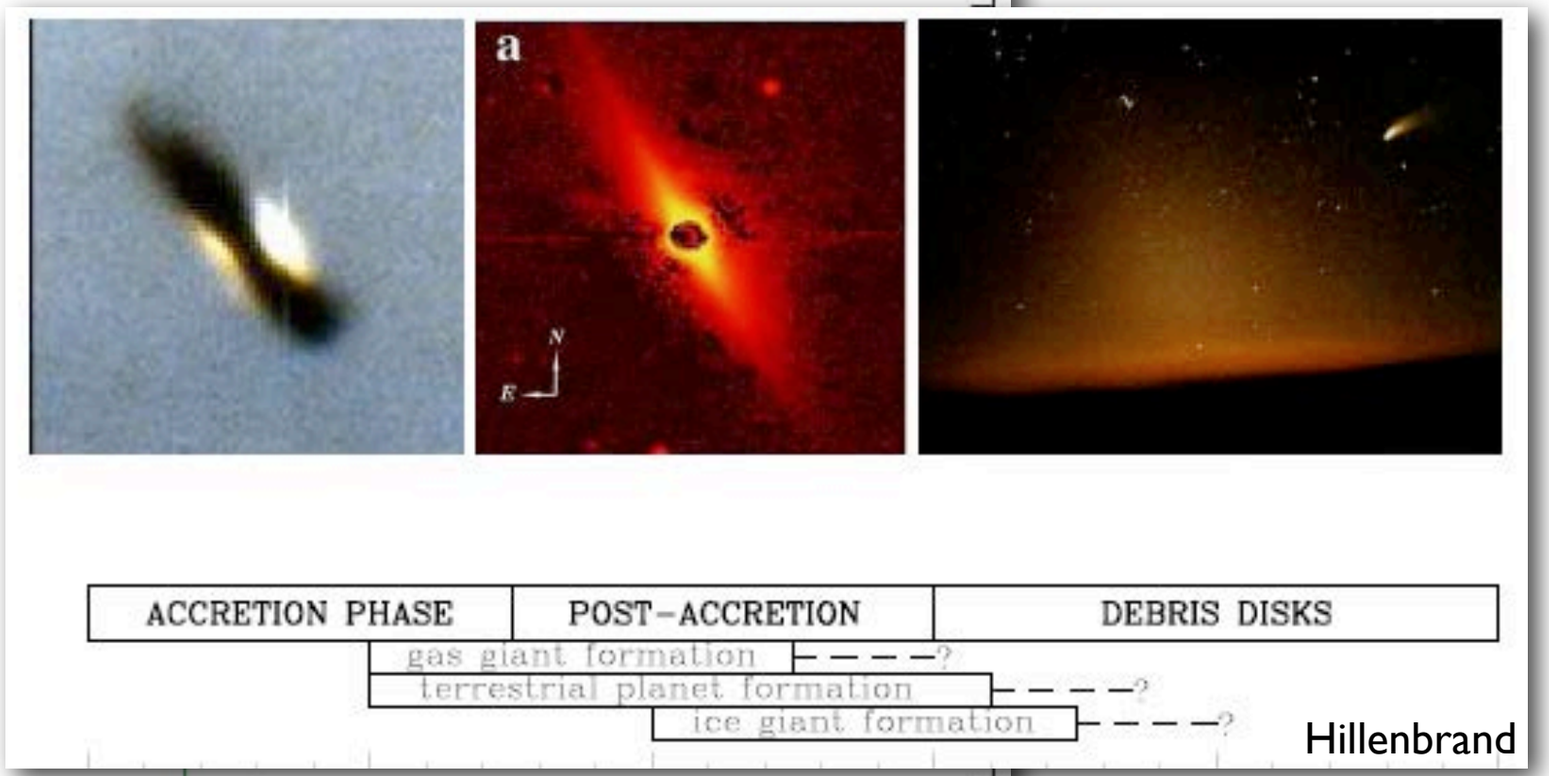
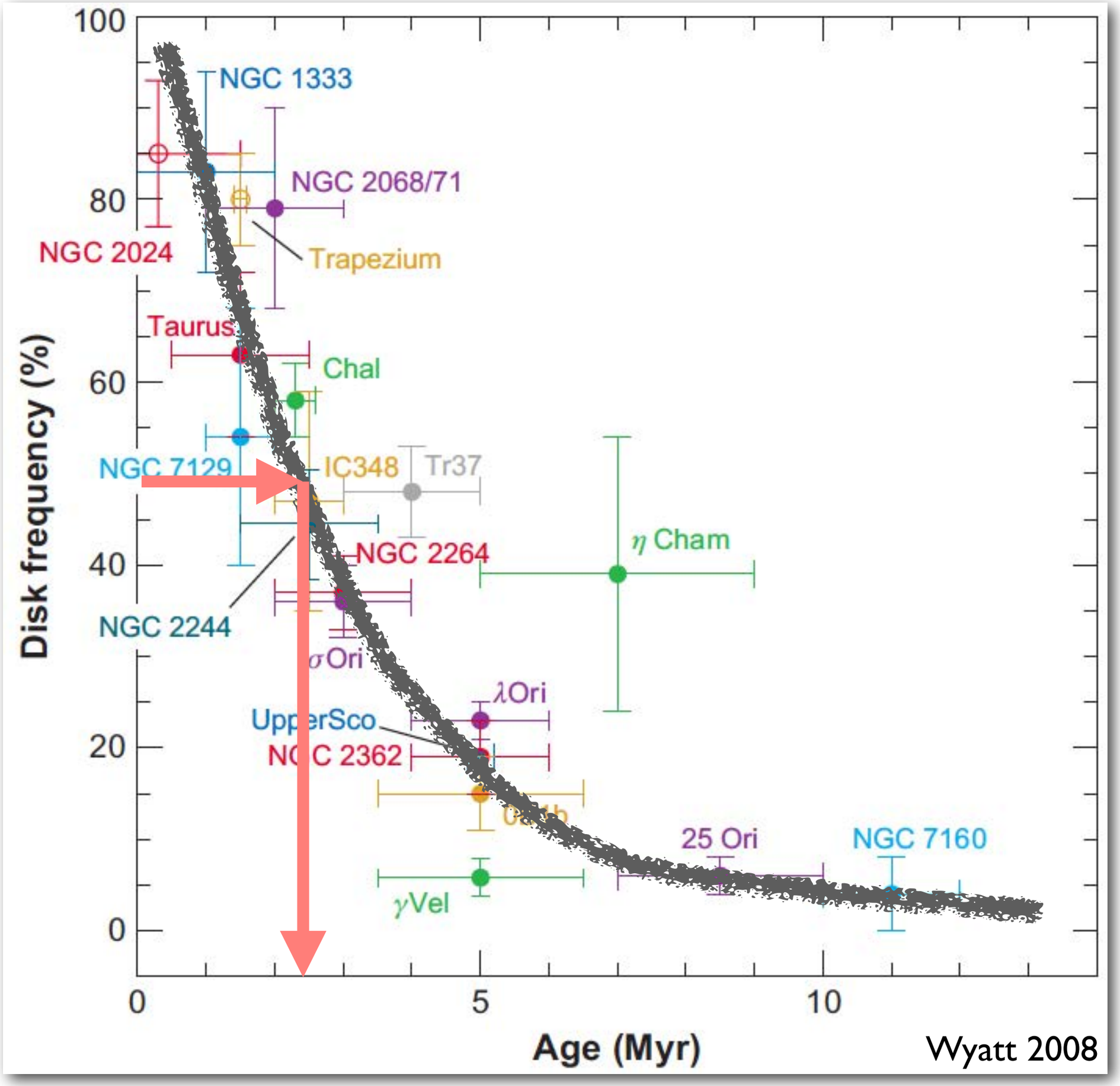


Hillenbrand

Wyatt 2008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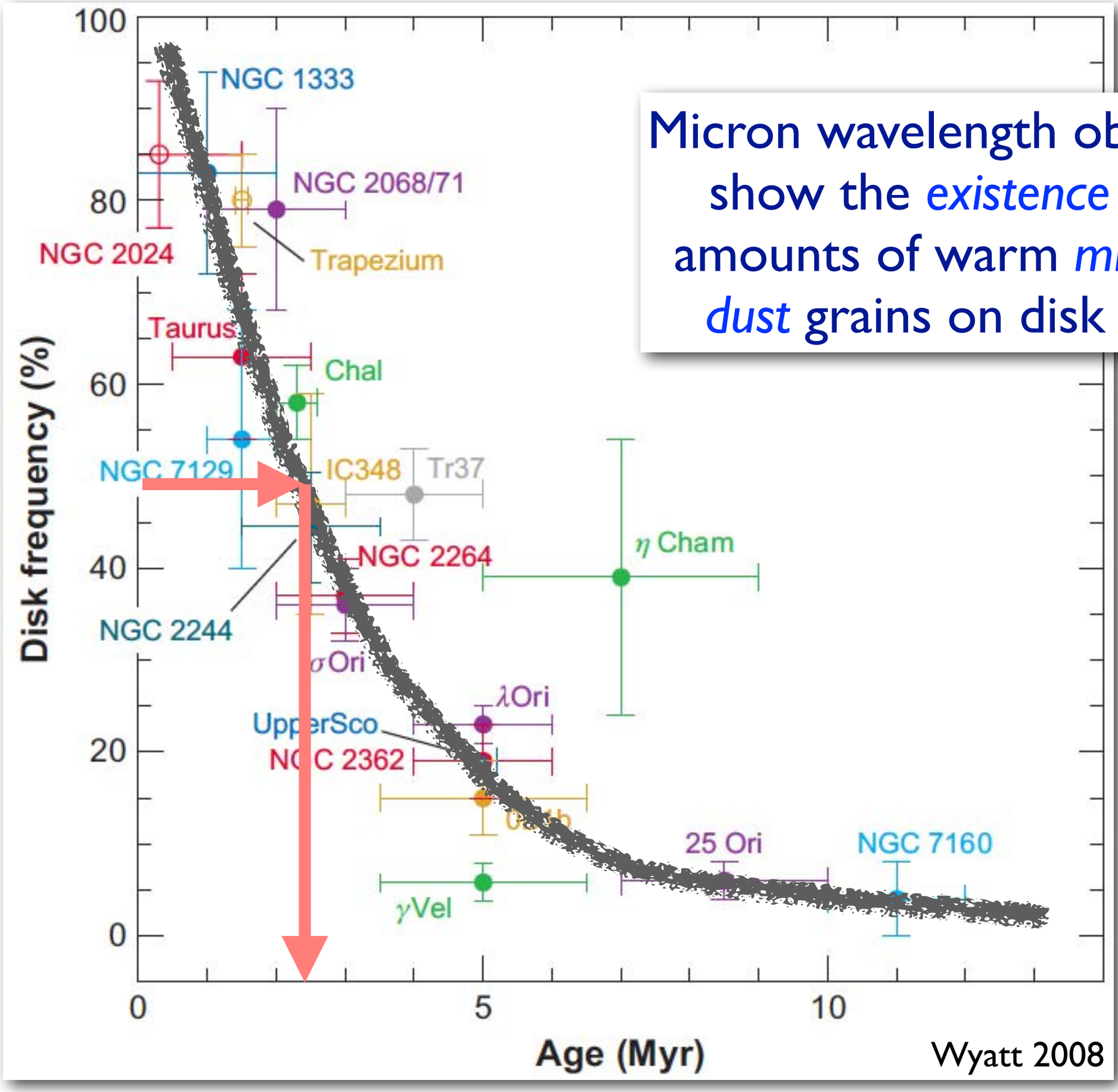
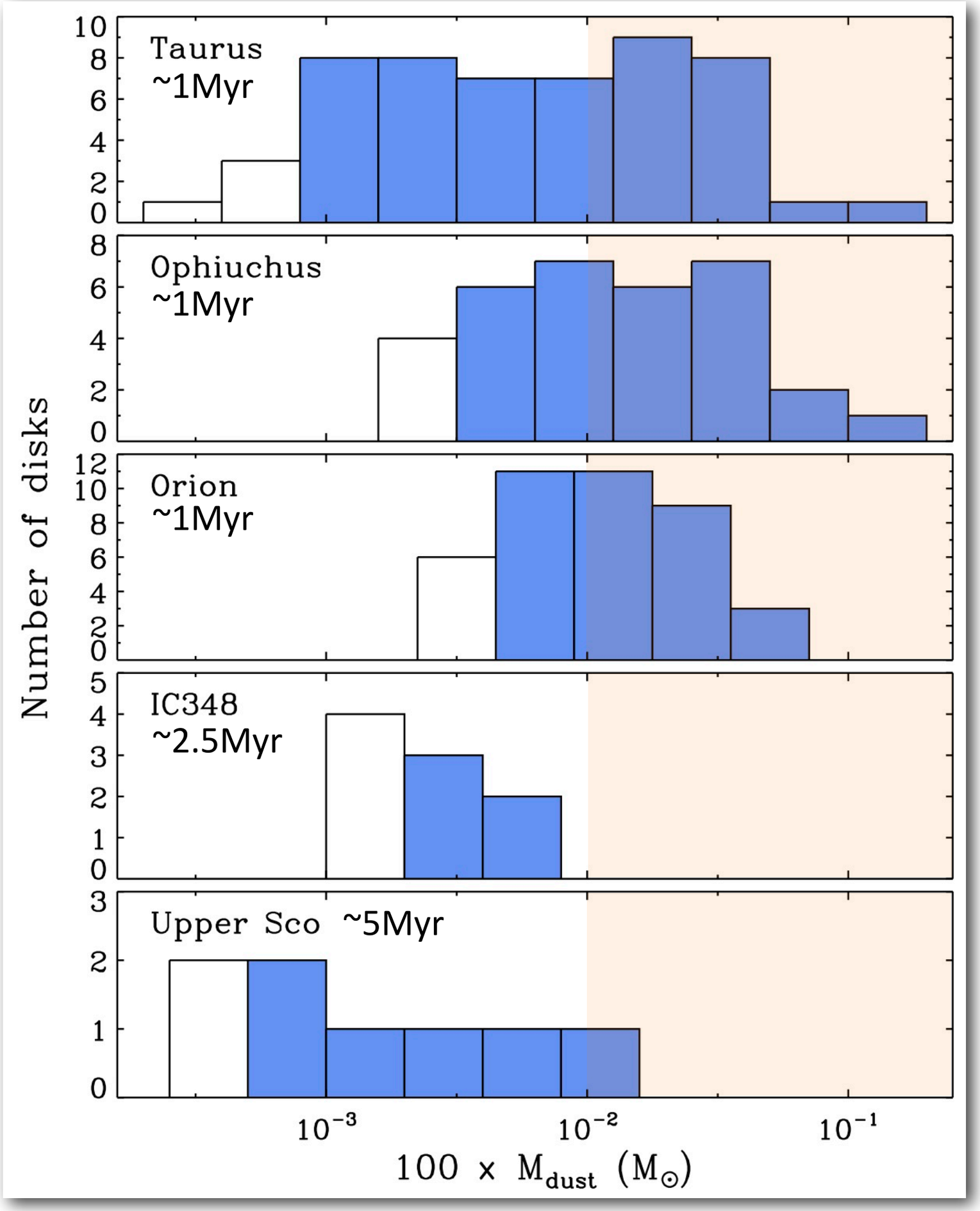
Wyatt 2008

Micron wavelength observations show the *existence* of small amounts of warm *micron sized dust* grains on disk surfaces



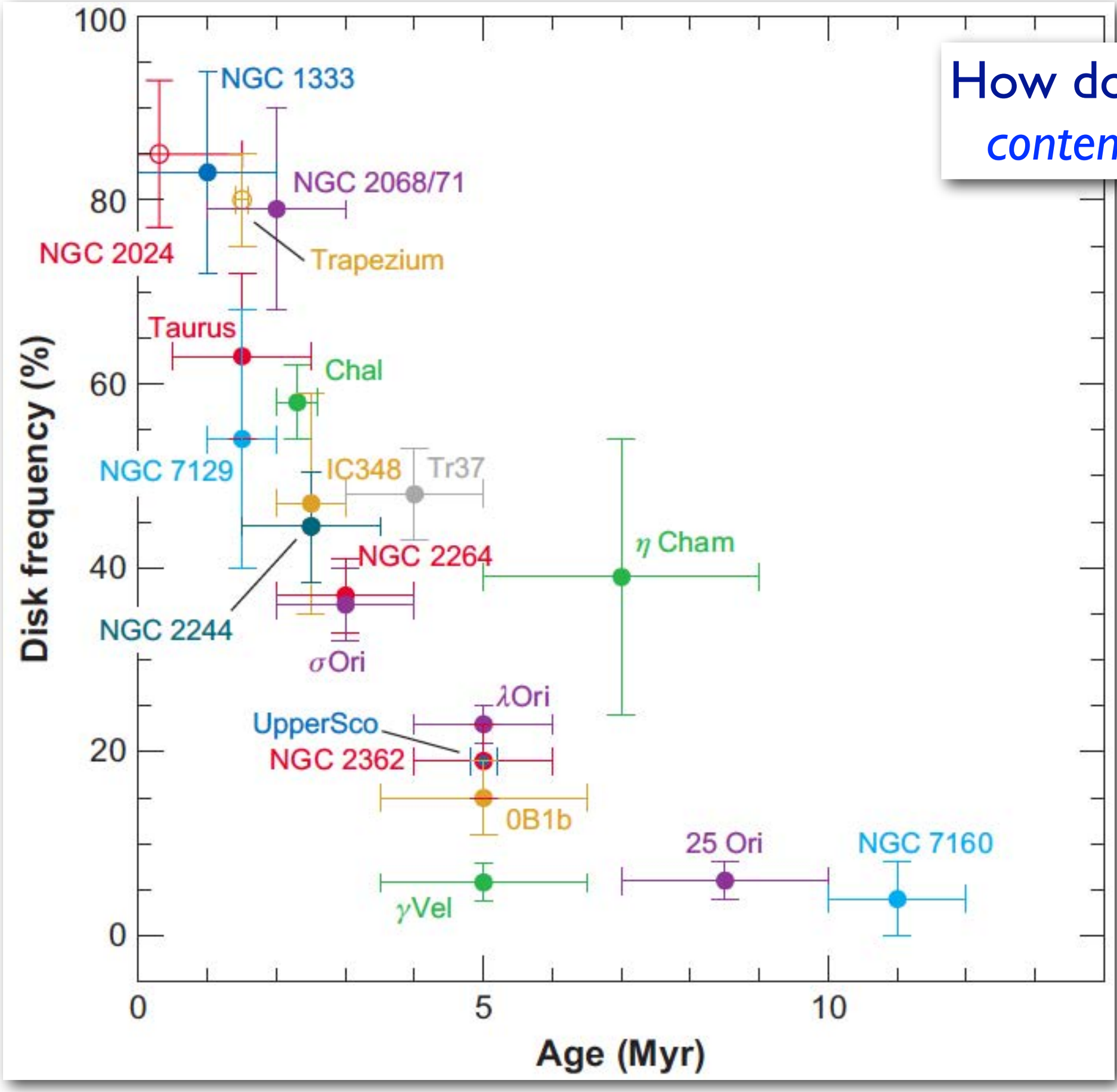
Wyatt 2008



Millimeter wavelength observations can measure *dust masses* of grains up to few mm in size, and show the *capacity* for planet formation, but are fairly insensitive (for now...)

Andrews & Williams 2005, 2007
Mann & Williams 2009
Lee+ 2011
Mathews+ 2012

How does the *gas content* evolve?



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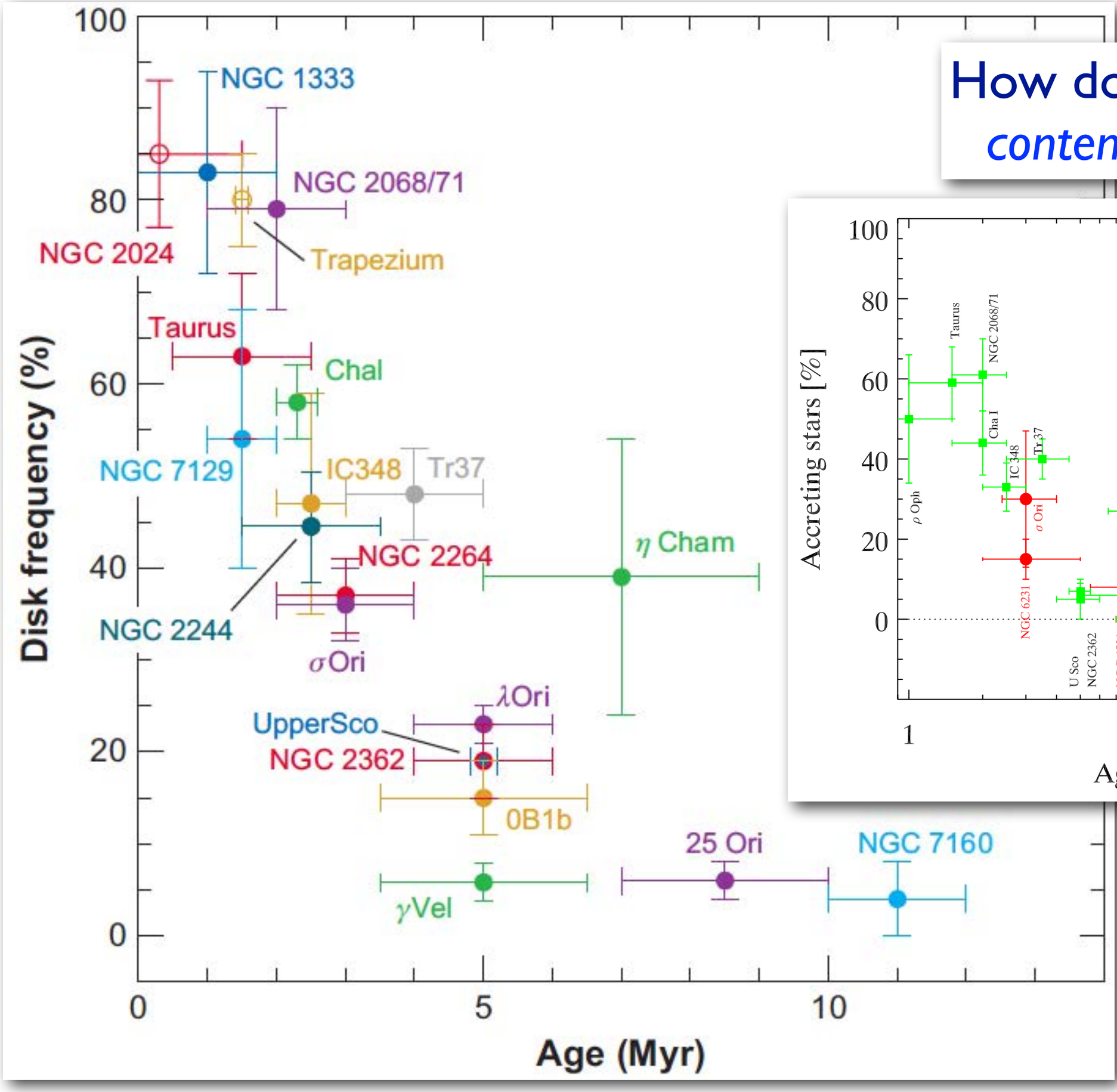
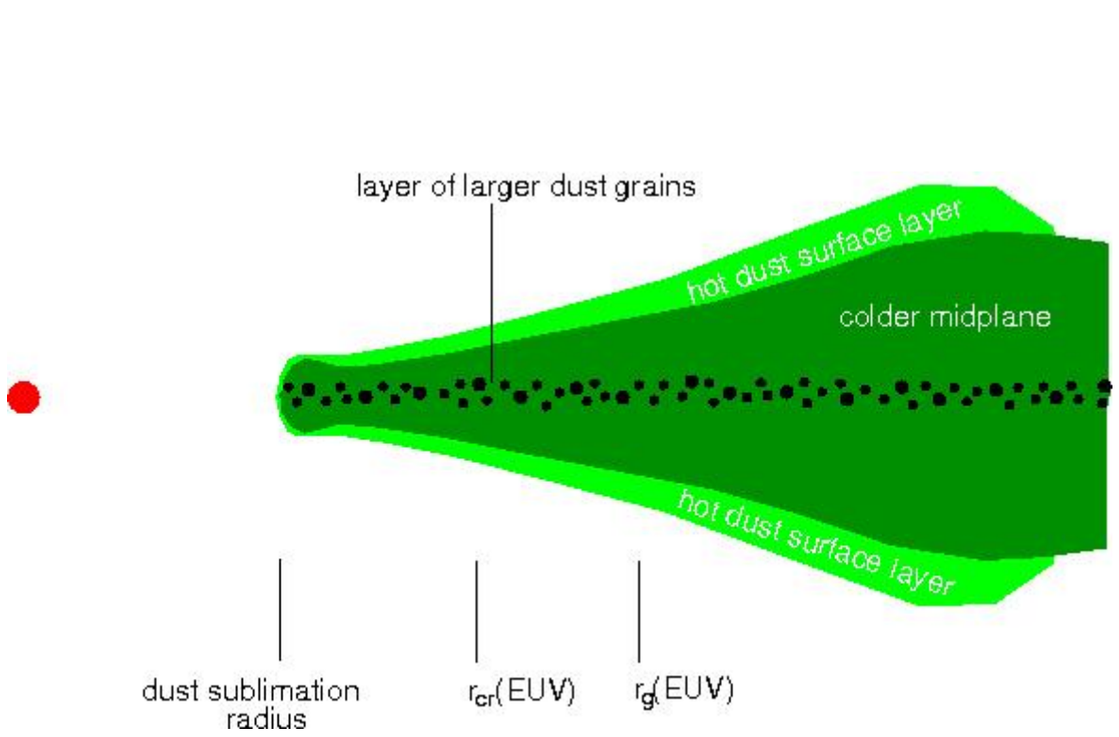
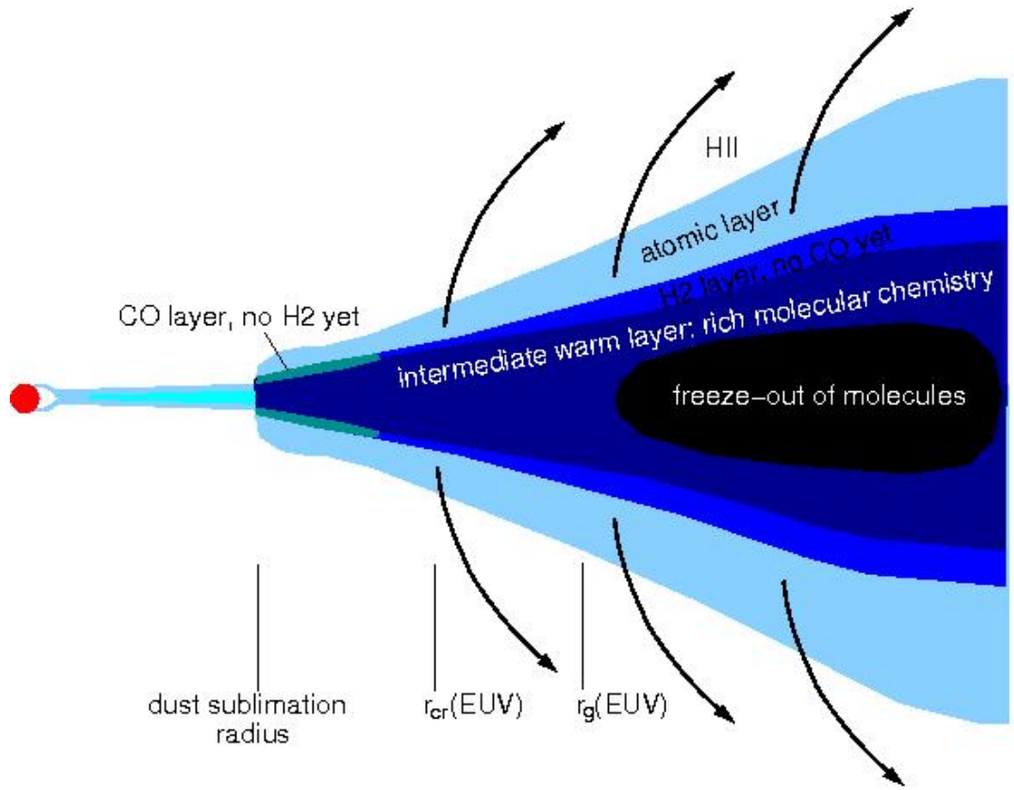


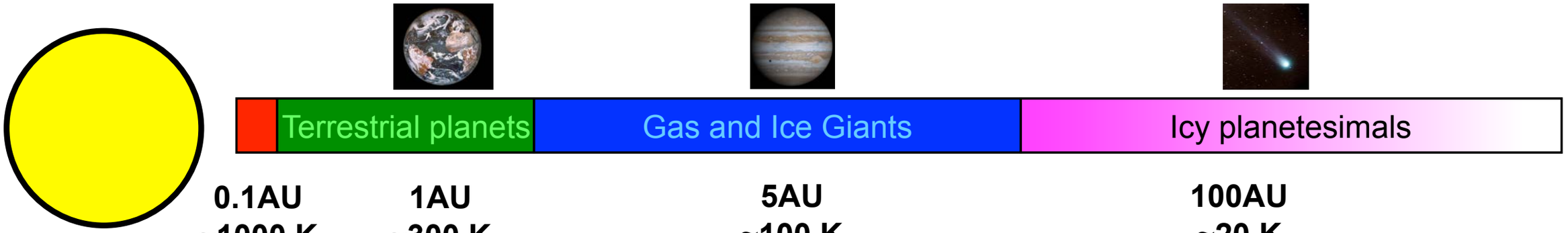
Dust and Gas Structures

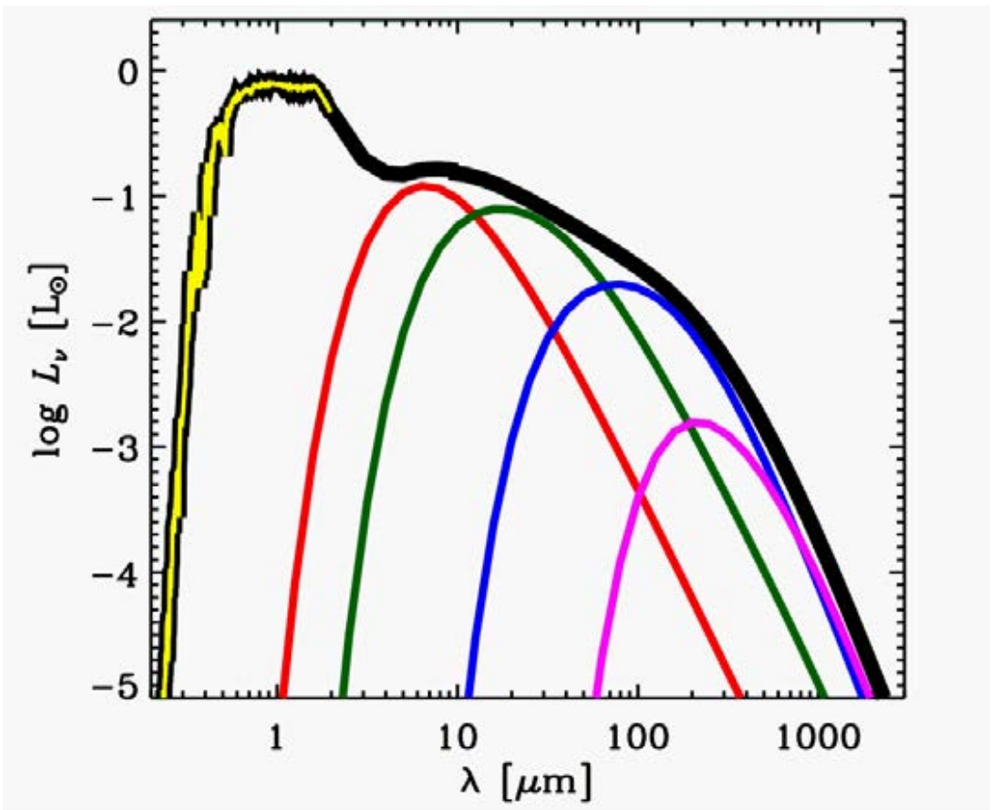




Dullemond+ 2005

Temperature structure





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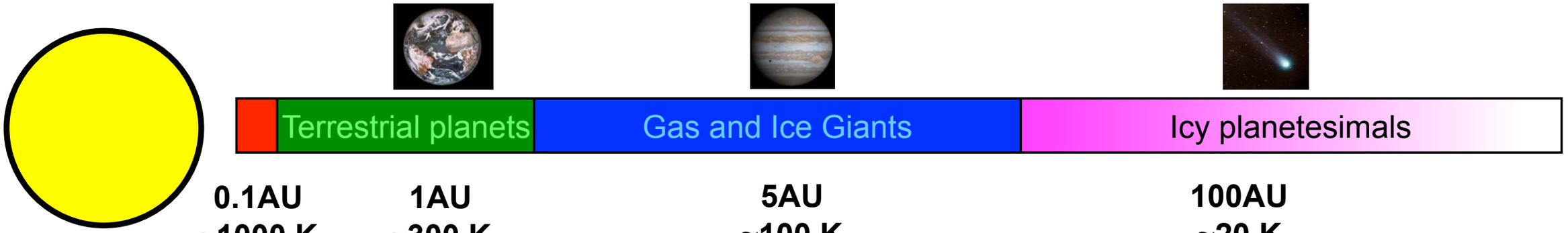
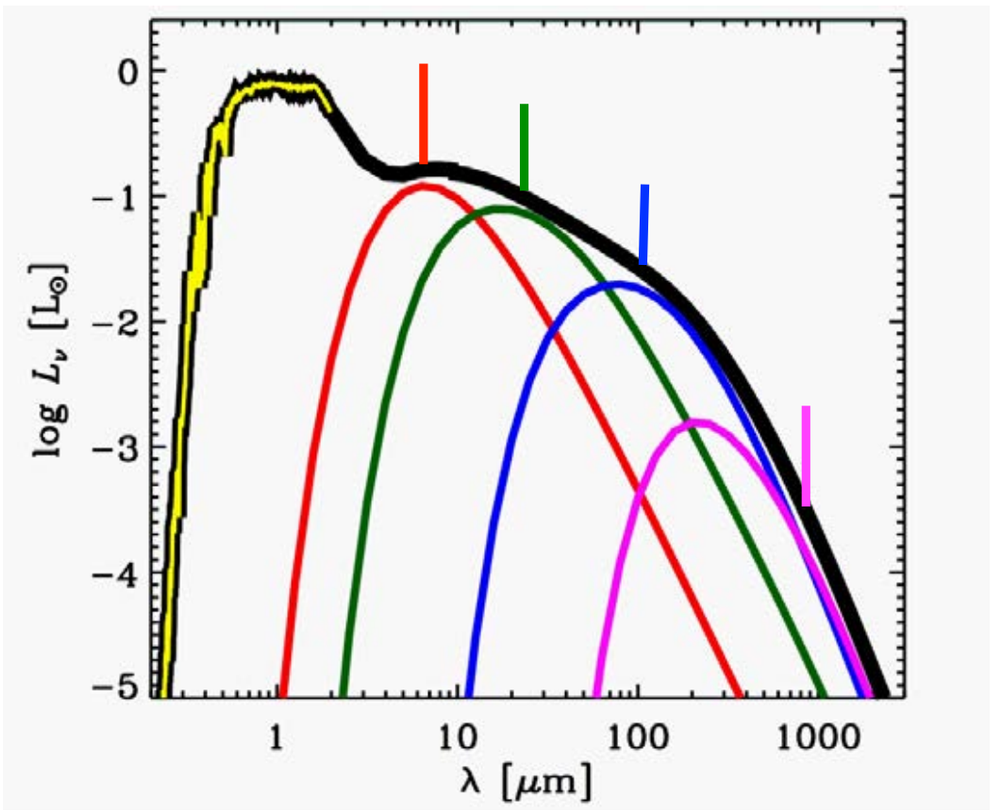
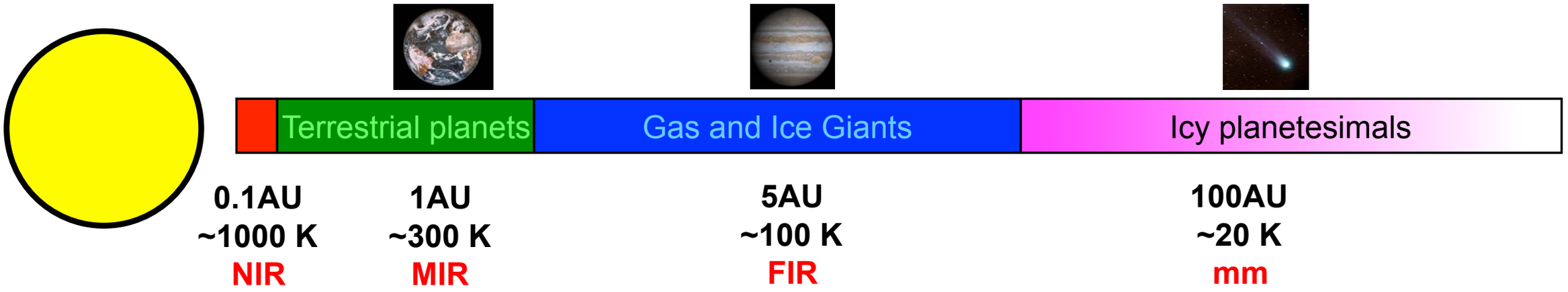
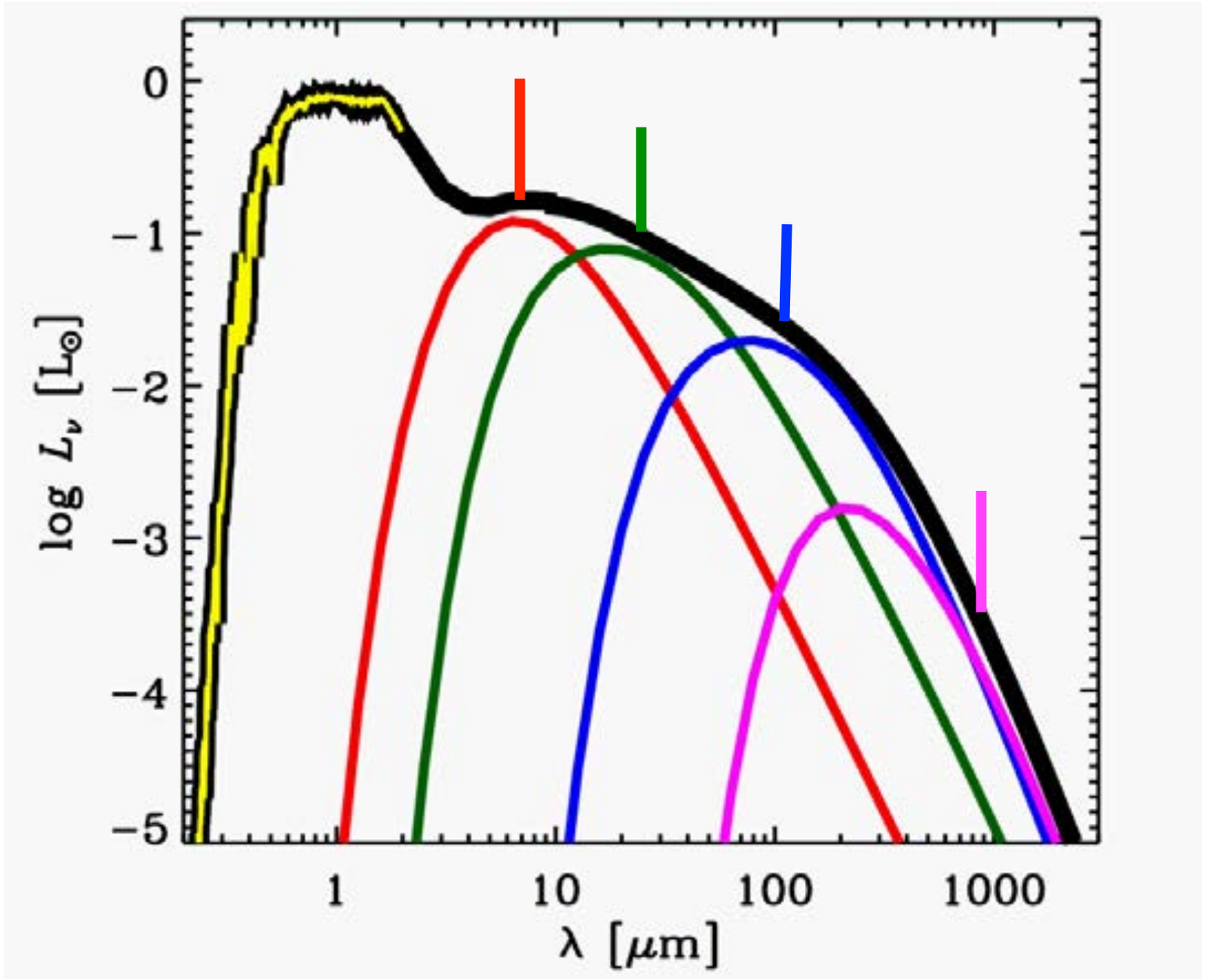




Spectral lines show the gas at the same *approximate* radius


Terrestrial planets
Gas and Ice Giants
Icy planetesimals
0.1AU
~1000 K
NIR
1AU
~300 K
MIR
5AU
~100 K
FIR
100AU
~20 K
mm


0
−1
−2
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−4
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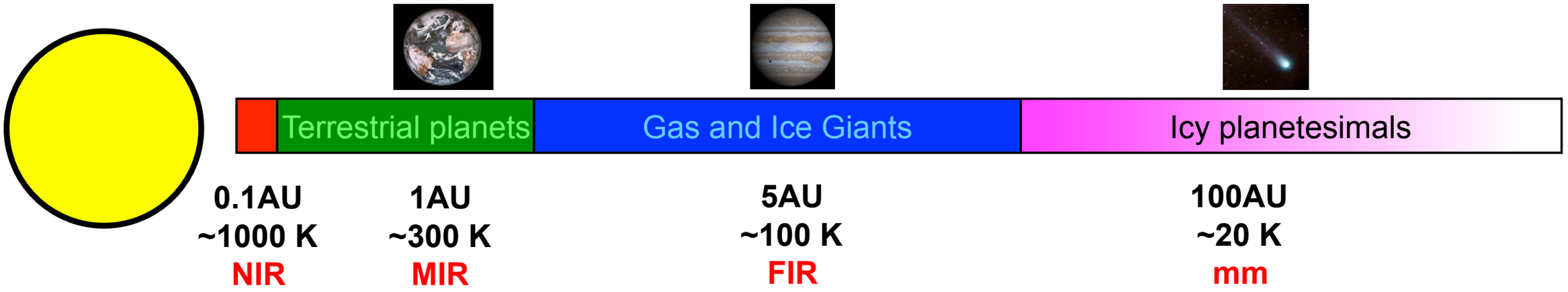
log L_ν [$L_\odot$]
1
10
100
1000
λ [μm]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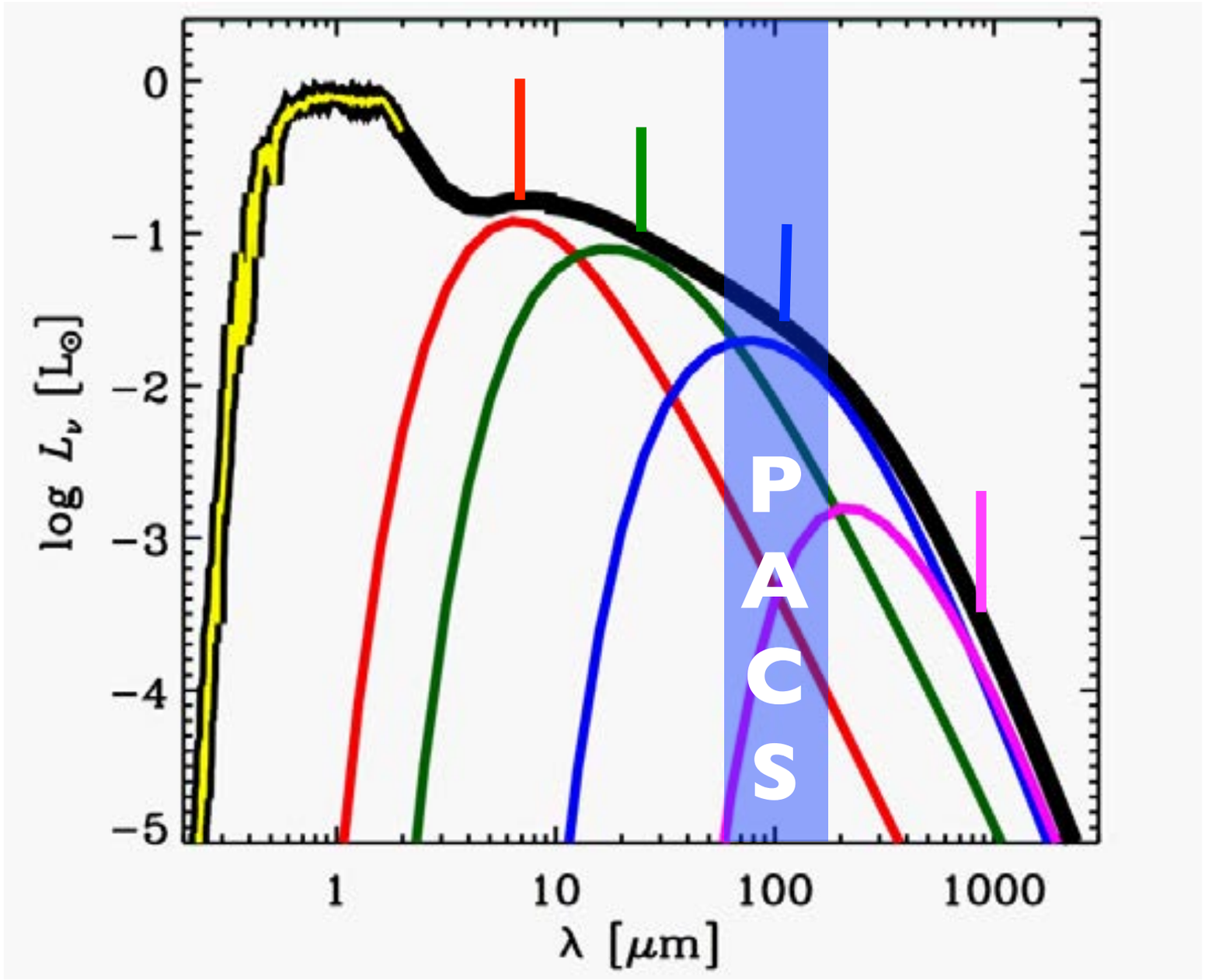
0
−1
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log L_ν [$L_\odot$]
1
10
100
1000
λ [μm]
PACS

Note: these are *global* measures

Spitzer and singledish millimeter observations only measure the *total* (spatially unresolved) disk continuum.

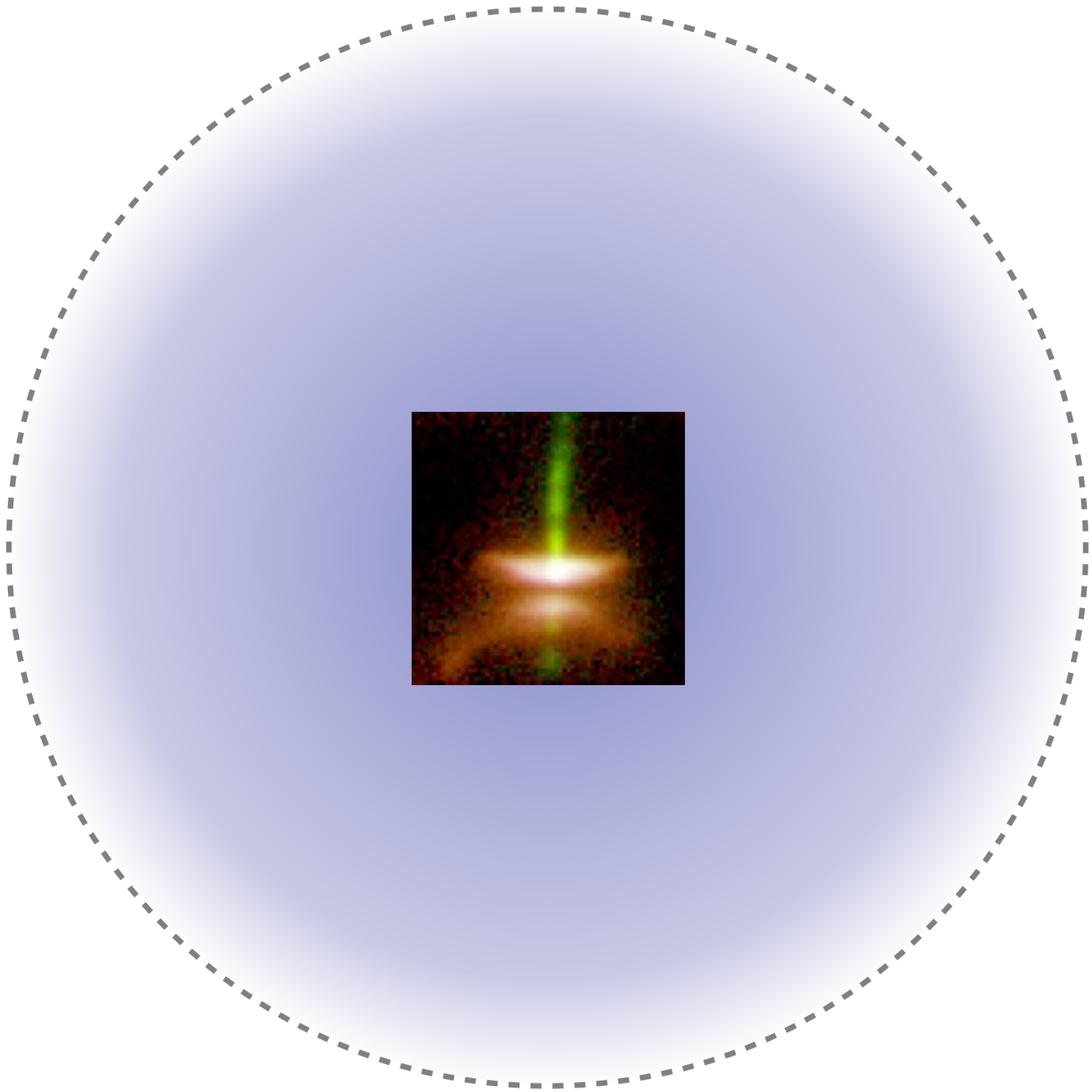
Similarly, Herschel does not resolve the disks *spatially, or spectrally.*

Model fits to the data may not be unique!

Herschel angular resolution
θ_{FWHM}~5” at 63μm

= 750AU at 150pc

>> R_{disk} ~100 AU

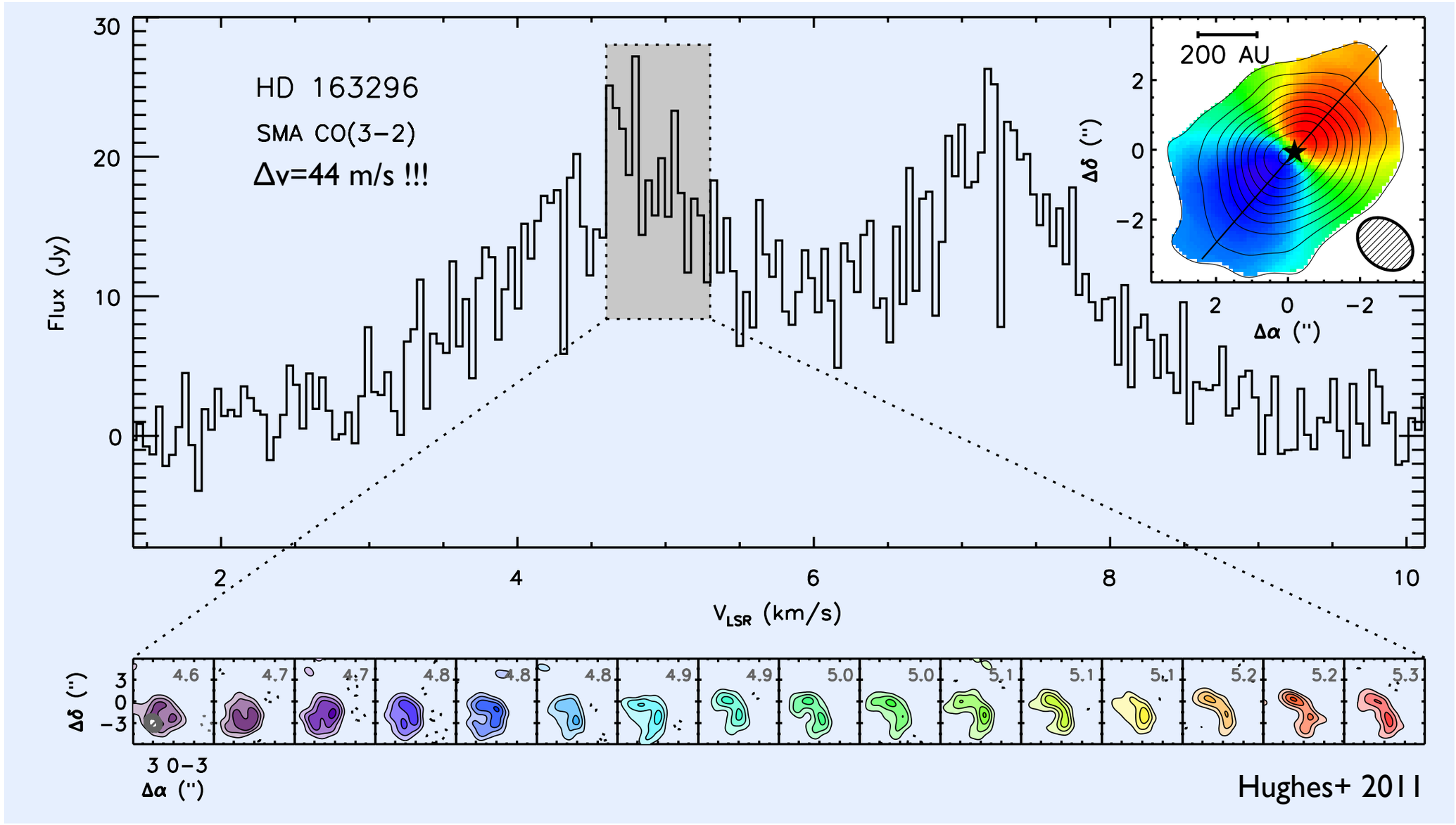


(and watch out for the outflows)

PACS spectral resolution

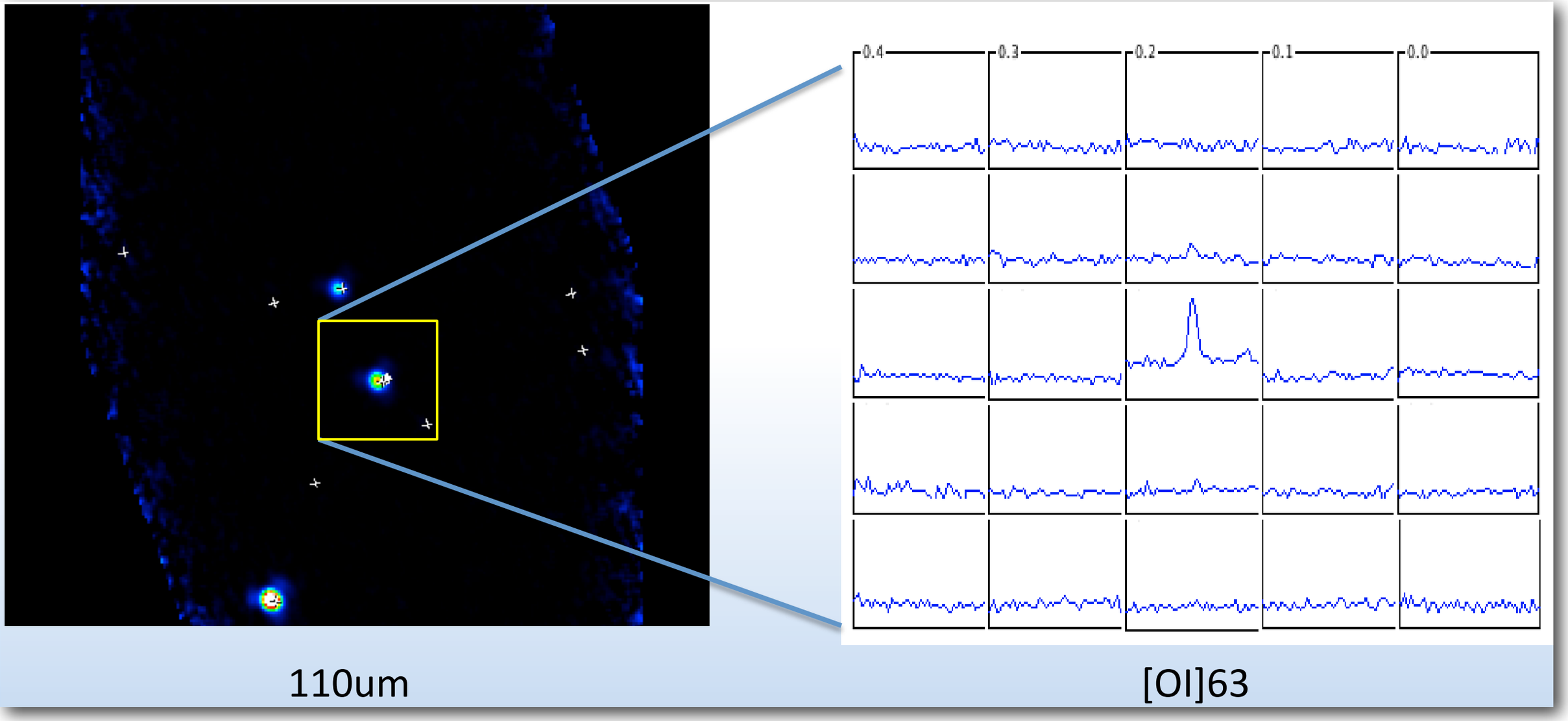
$\lambda/\Delta\lambda$~1000-4000

$\Rightarrow \Delta v$~88km/s at 63μm >> Δv_{disk} ~10km/s (need HIFI)



(and watch out for the outflows)

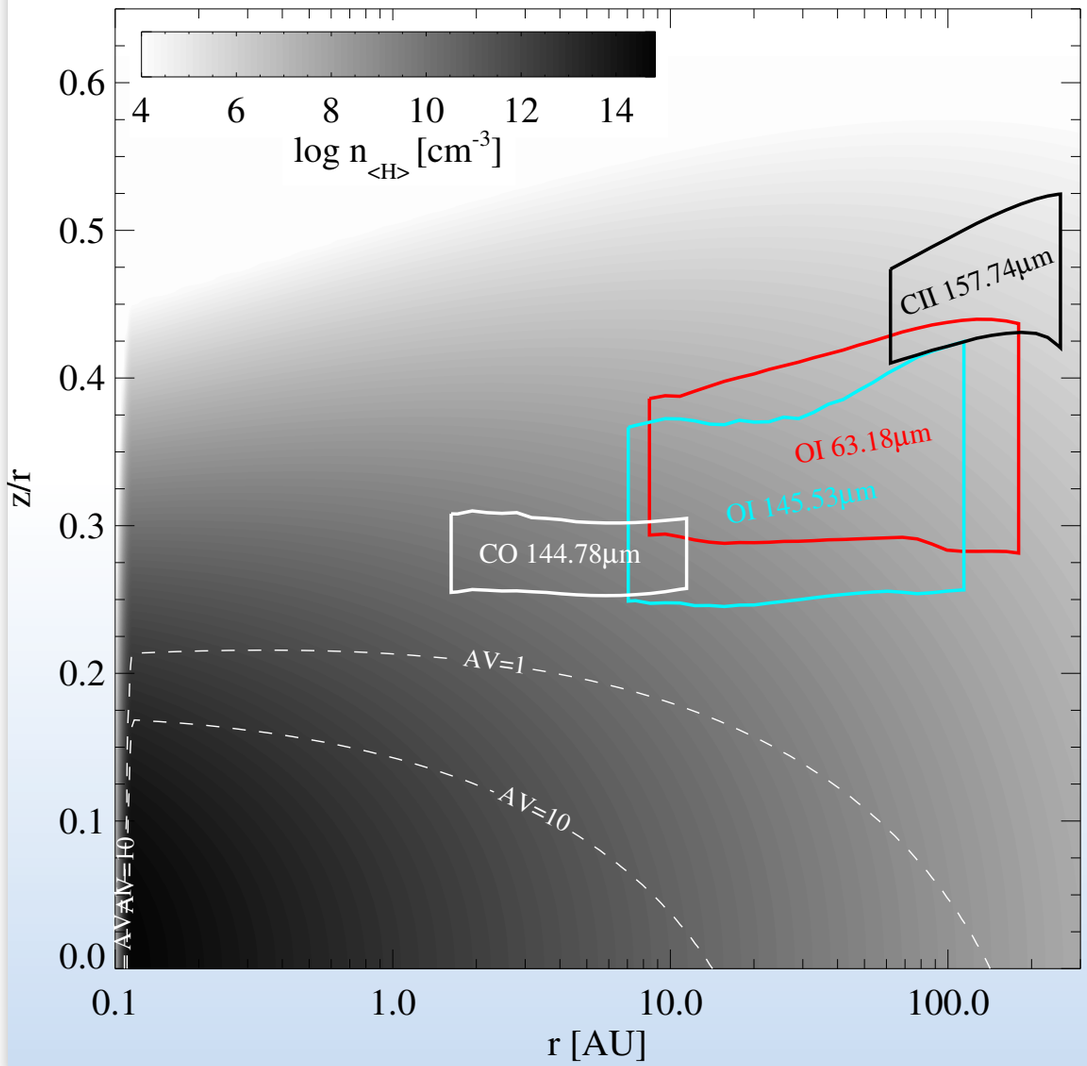
PACS line and continuum are unresolved

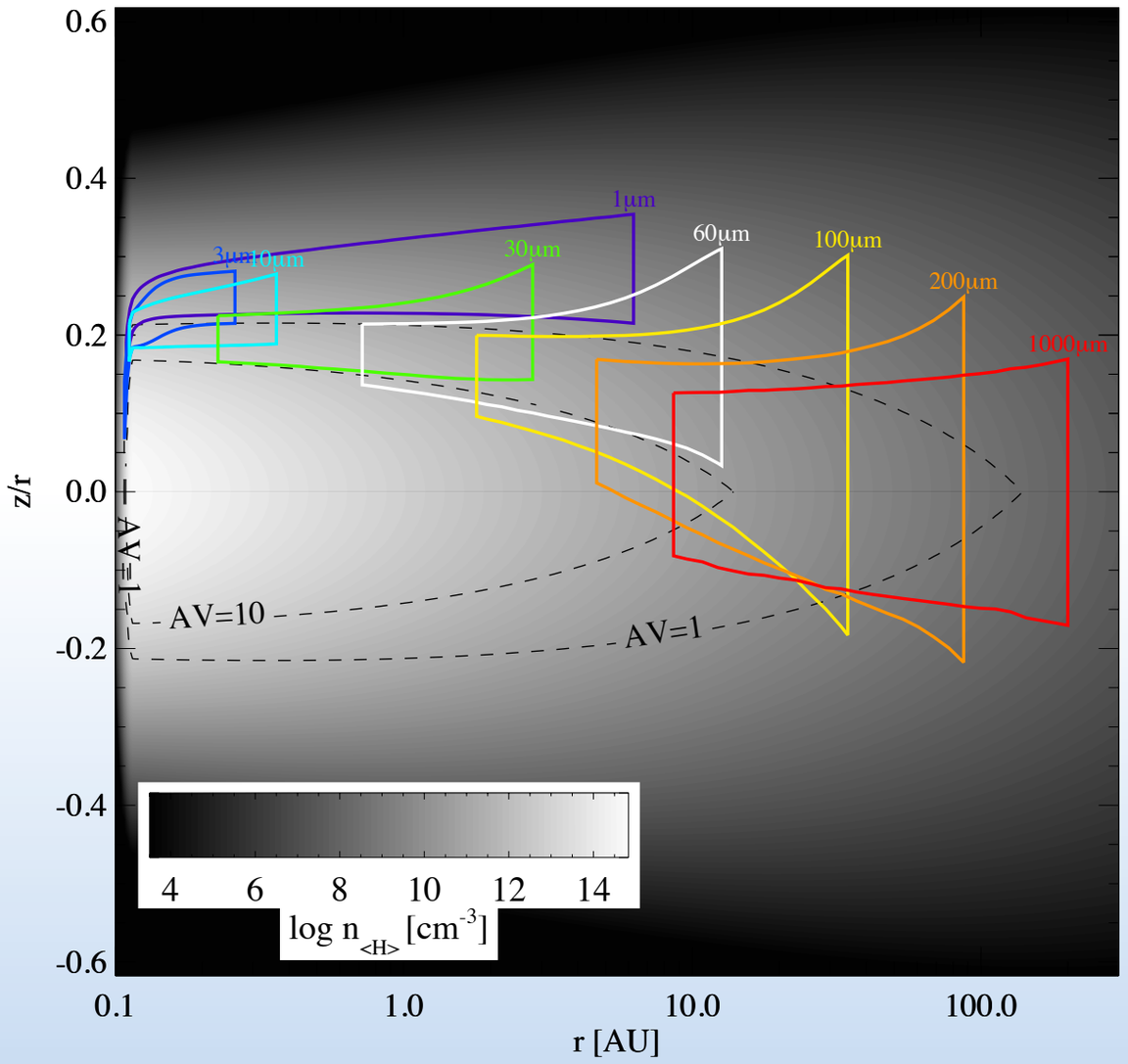


Detailed modeling is required, and ambiguities remain

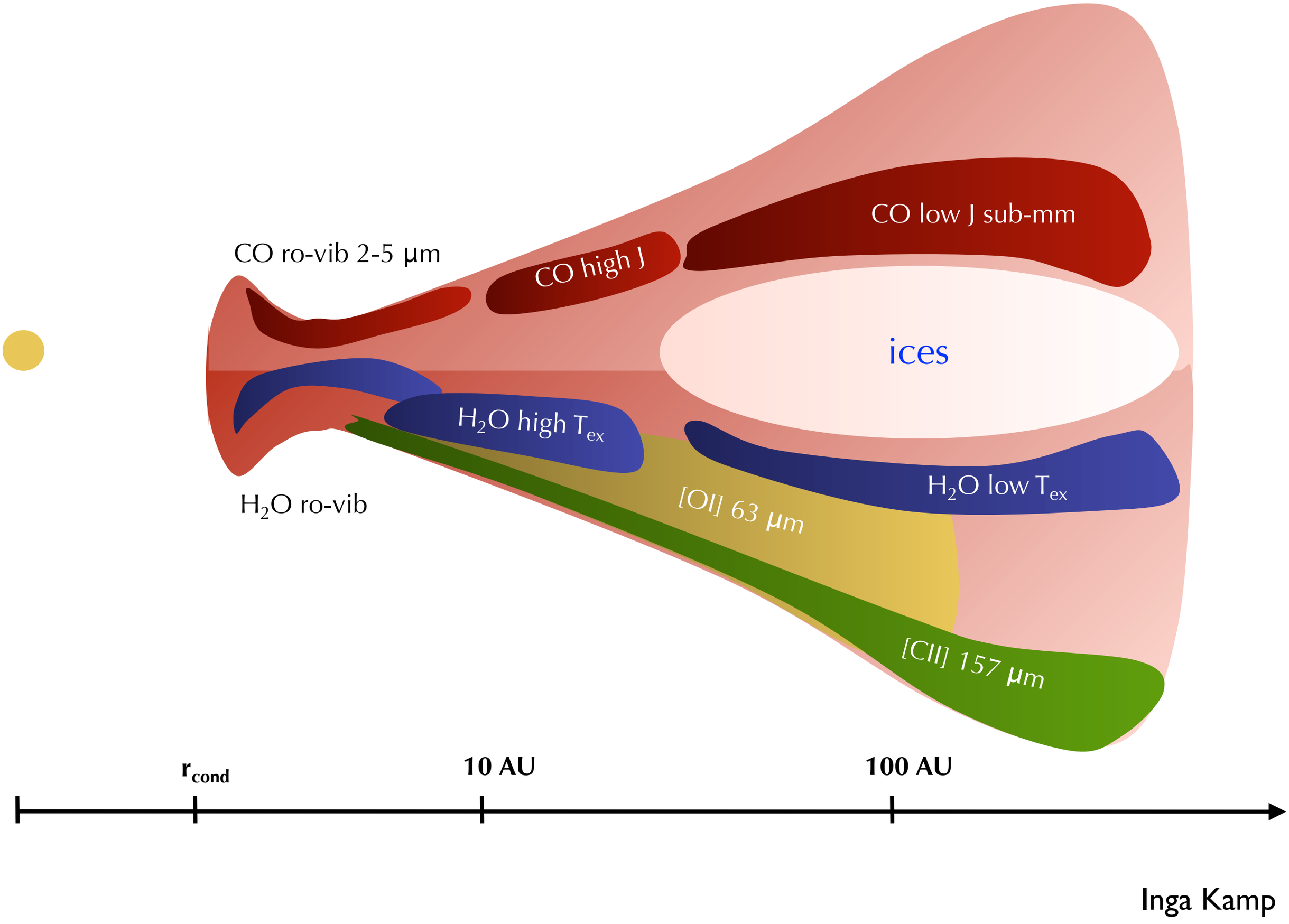
(see Peter Woitke talk this afternoon)

The DENT grid of disk models





Woitke+ 2009


CO ro-vib 2-5 μm
CO high J
CO low J sub-mm
ices
H_2O high T_{ex}
H_2O low T_{ex}
H_2O ro-vib
[OI] 63 μm
[CII] 157 μm
r_{cond}
10 AU
100 AU

Inga Kamp

Herschel protoplanetary disk programmes

- GASPS (Gas in Protoplanetary Systems)
- DIGIT (Dust, Ice, and Gas In Time)
- WISH (Water In Star forming regions with Herschel)
- + several individual programs

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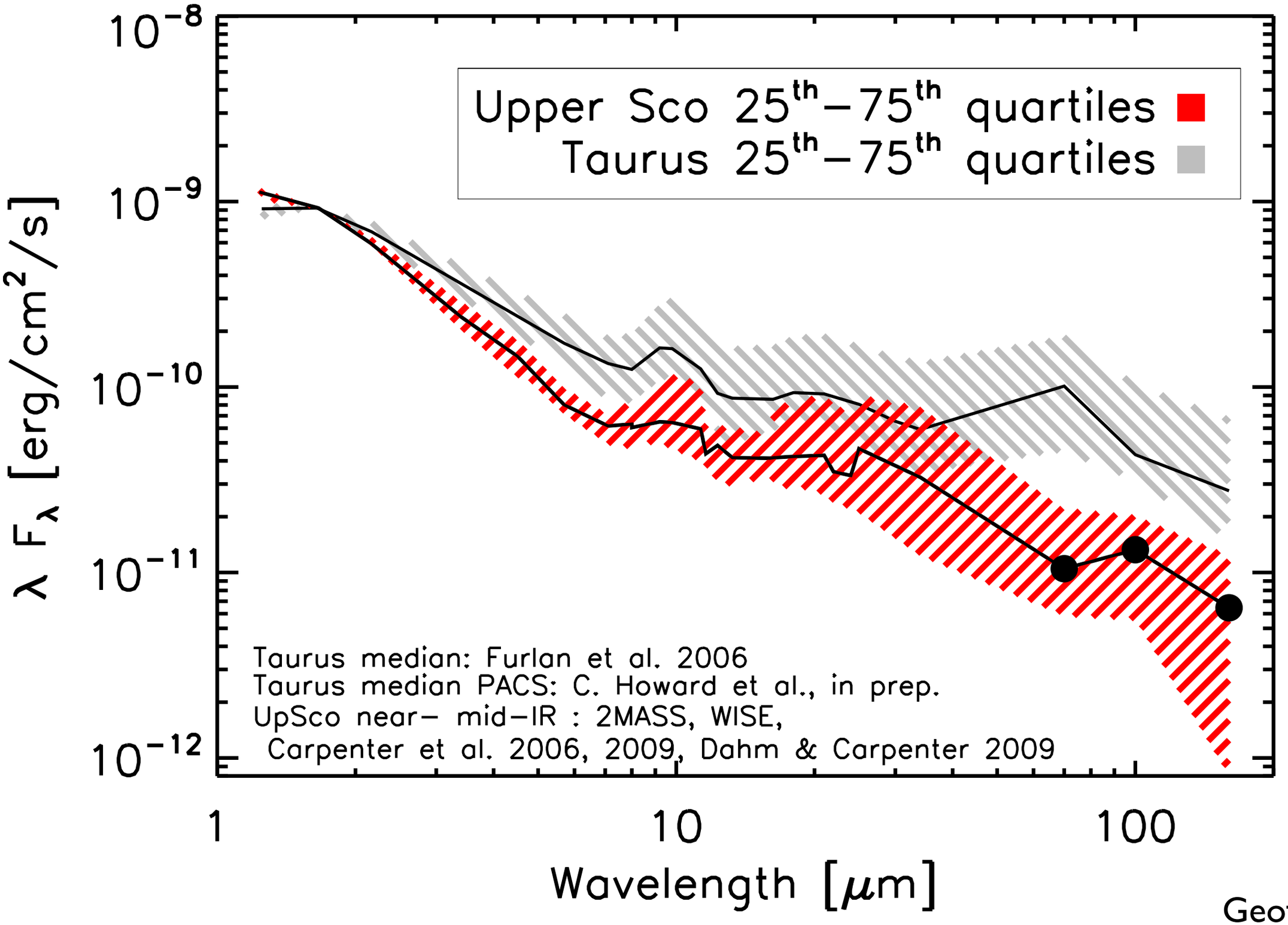
GASPS

- PACS 70/110/170μm photometry
- [OI]63/145μm, [CII]158μm, CO, H_2O, OH
- Class II / III / debris disks
- Nearby (<150pc), range of ages 1-30Myr
  - ★ Taurus, Cha II, Upper Sco, ηCha, βPic, TW Hya, TucHor
- T Tauri and Herbig Ae/Be stars

The GASPS Team

Sean Andrews
David Ardila
Giambattista Aresu
Jean-Charles Augereau
David Barrado Navascues
Sean Brittain
Nahuel Cabral
Andres Carmona
David Ciardi
Bill Dent (PI)
Jessica Donaldson
Gaspard Duchene
Carlos Eiroa
Davide Fedele
Carol Grady
Itziar de Gregorio-Monsalvo
Ana Heras
Christian Howard
Nuria Huelamo
Inga Kamp
Alexander Krivov
Jeremy Lebreton
Rene Liseau
Claire Martin-Zaidi
Geoff Mathews
Francois Menard
Pablo Riviere Marichalar
Gwendolyn Meeus
Ignacio Mendigutia
Benjamin Montesinos
Alcione Mora
Maria Morales-Calderon
Hideko Nomura
Eric Pantin
Ilaria Pascucci
Neil Phillips
Christophe Pinte
Linda Podio
Dieter Poelman
Suzie Ramsay
Aki Roberge
Veronica Roccatagliata
Lara Rodrigues
Goeran Sandell
Enrique Solano
Wing-Fai Thi
Ian Tilling
Bart Vandenbussche
Silvia Vicente
Helen Walker
Jonathan Williams
Glenn White
Peter Woitke

SED evolution



Geoff Mathews

Detected lines

- **[OI] 63μm**, 145μm
- [CII] 158μm
- H_2O 8 lines, E_{up}=115-1300 K
- CO 4 lines, J=18-17 to J=36-35
- OH, CH^+

(F_{63}/F_{145} > 10)

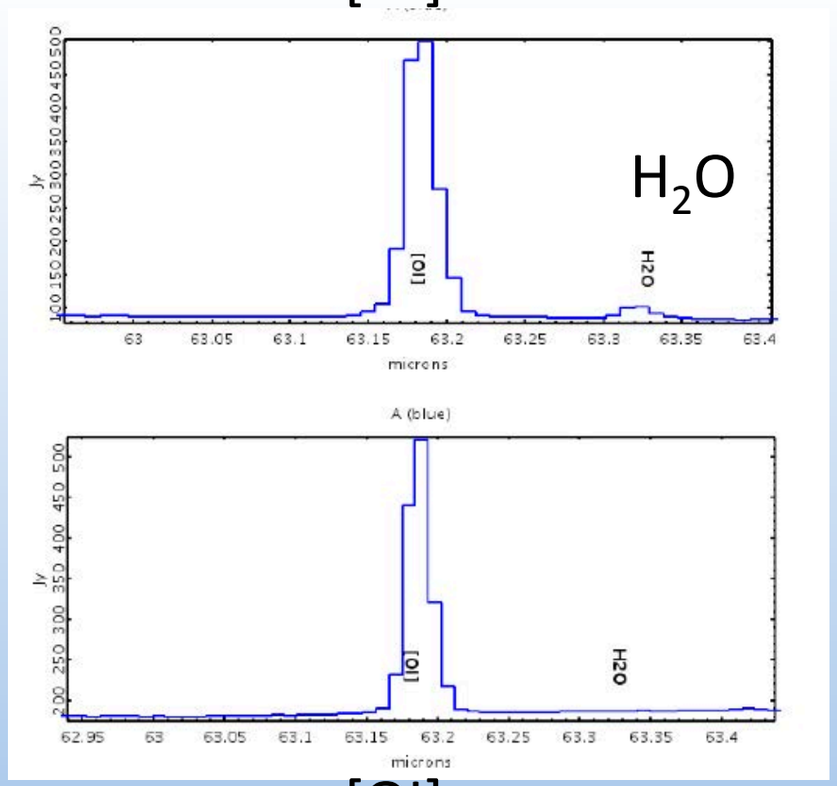
(envelope contamination?)

(mainly TTS, not HAeBe)

(warm disk atmosphere)

(two HAeBes only)

[OI]

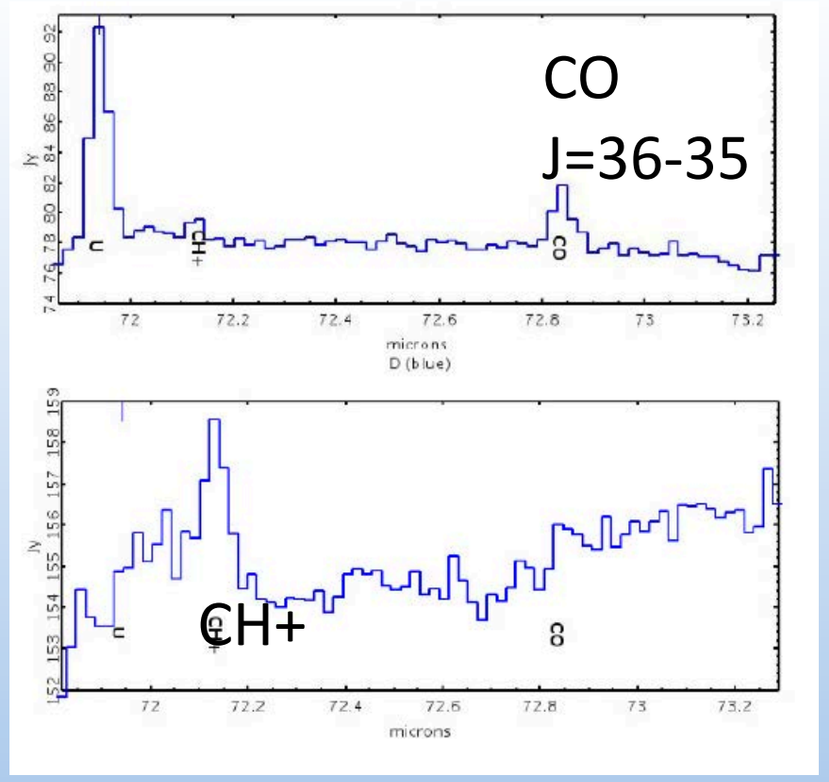


[OI]

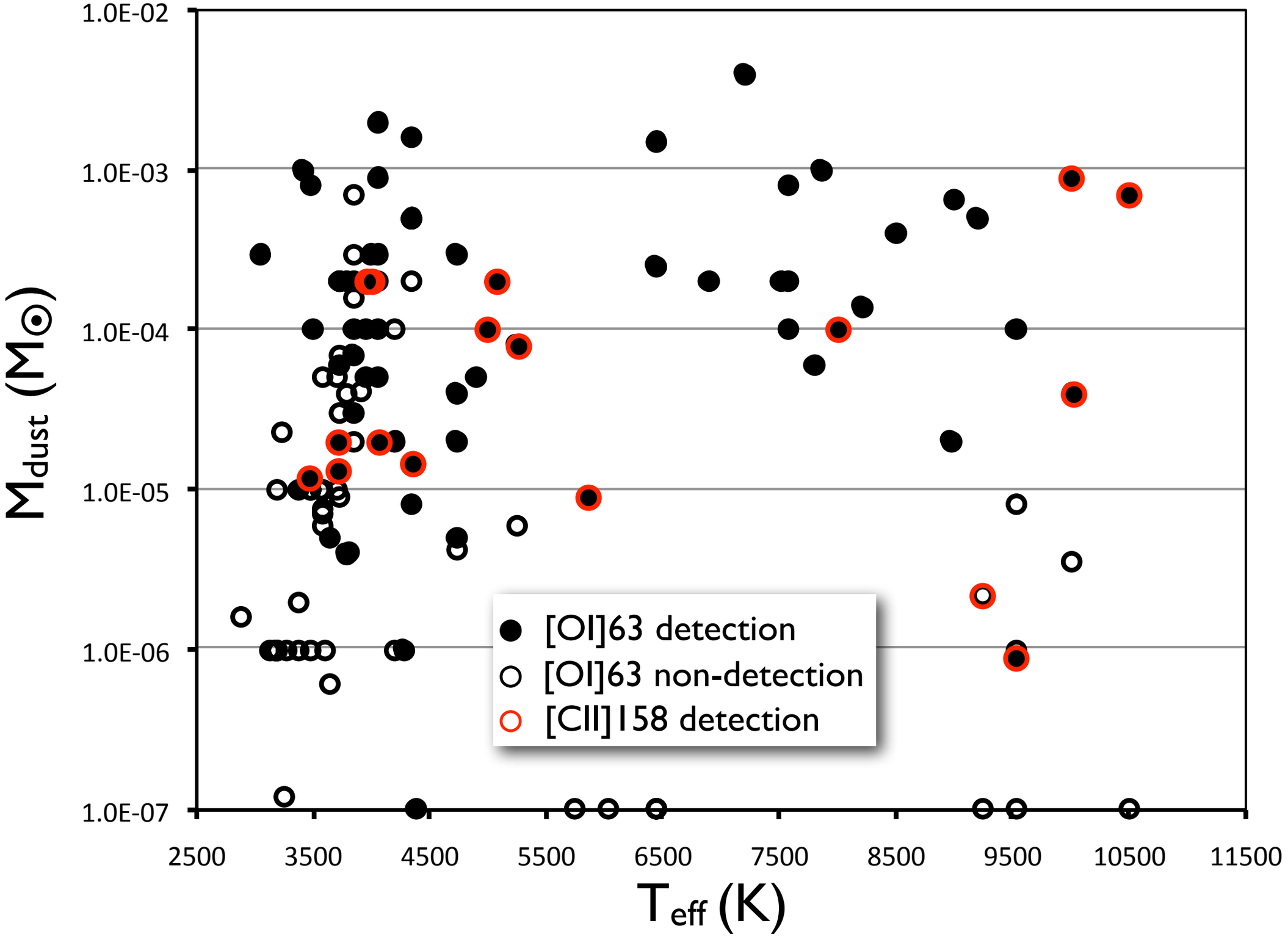
H_2O

T Tauri

HD100546



Detection statistics



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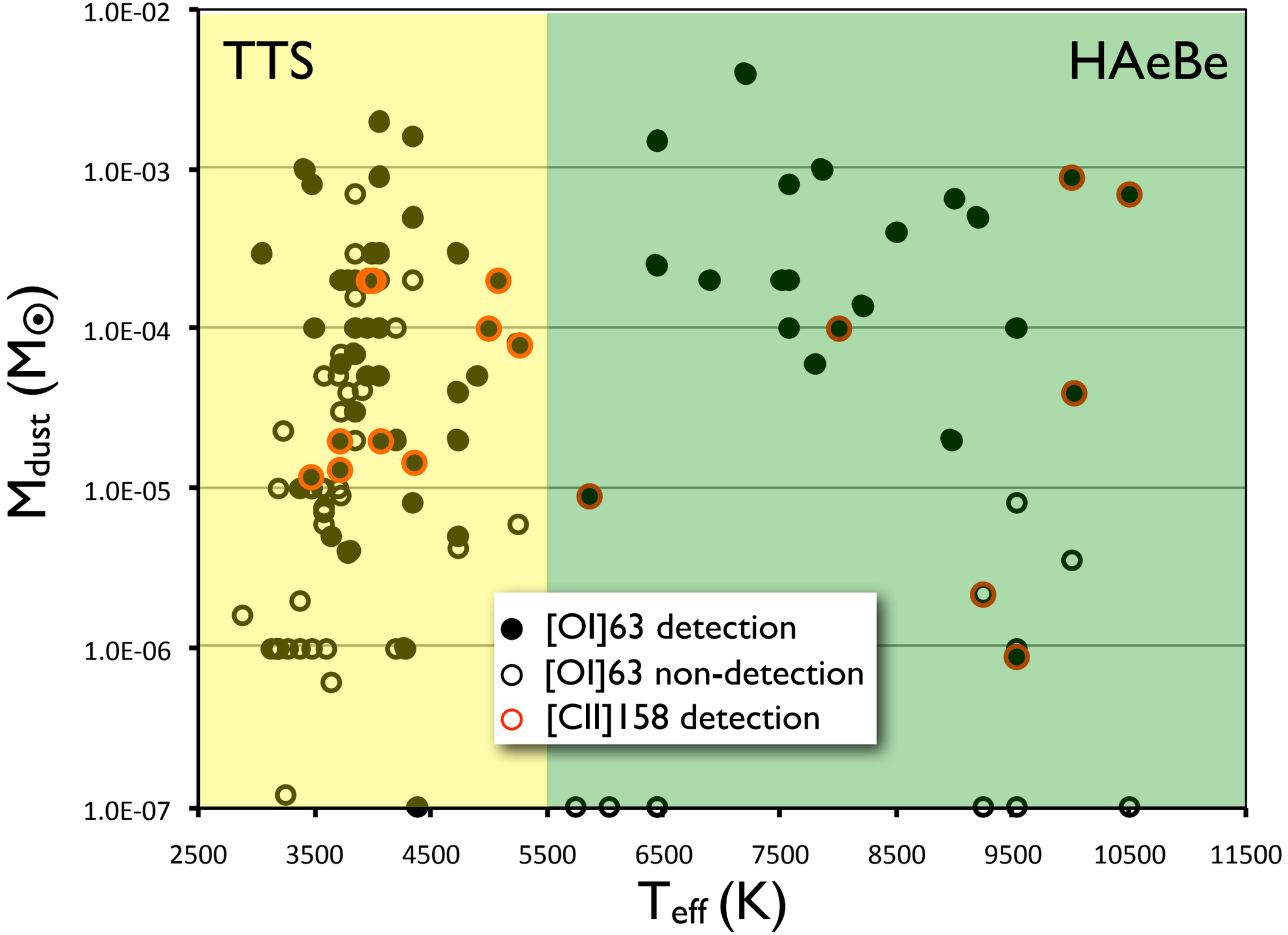

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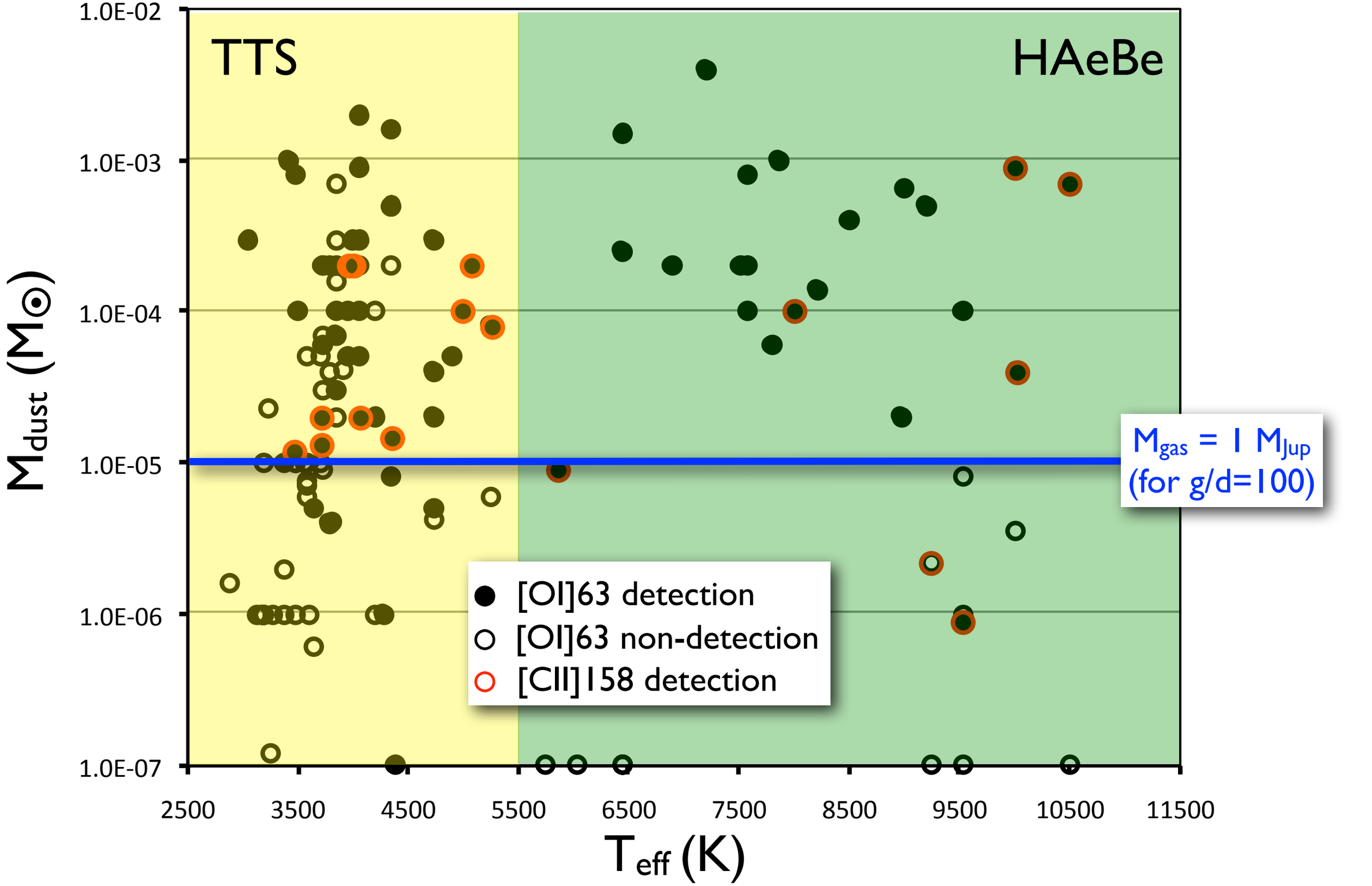
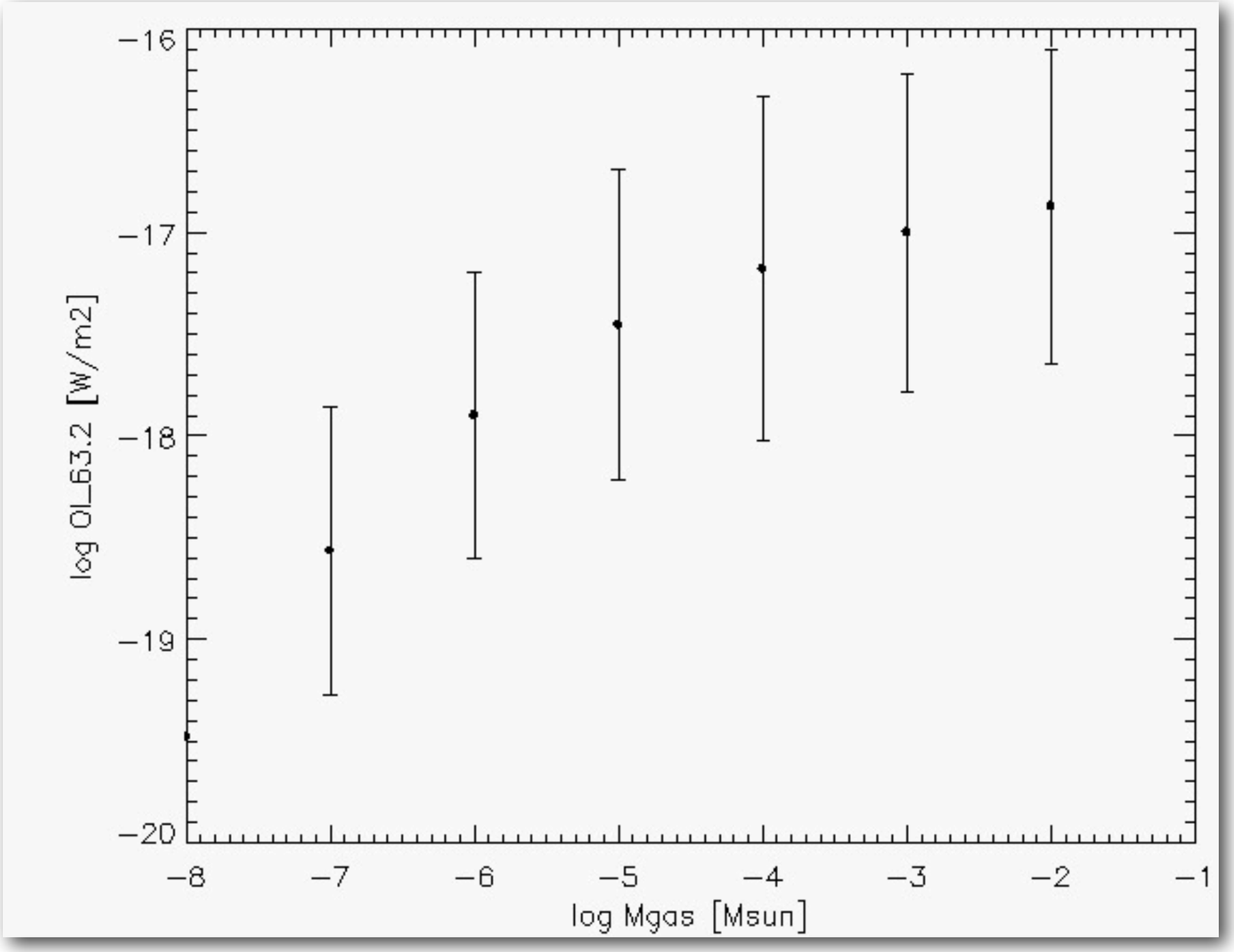


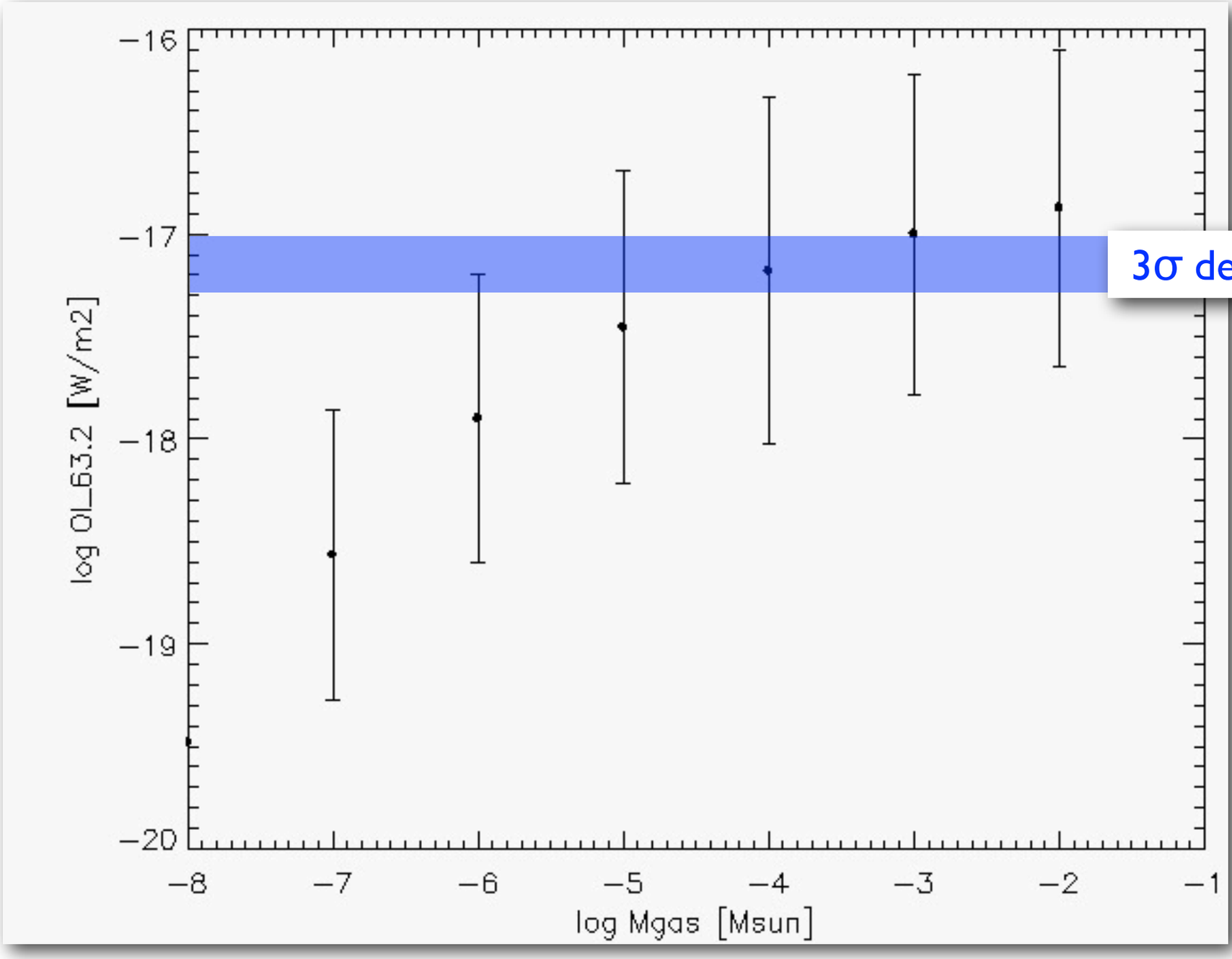
Detection limits



[OI]63μm correlates with gas mass, but with *an order of magnitude* dispersion

Survey mass sensitivity is ~1 M_{Jup}

Detection limits



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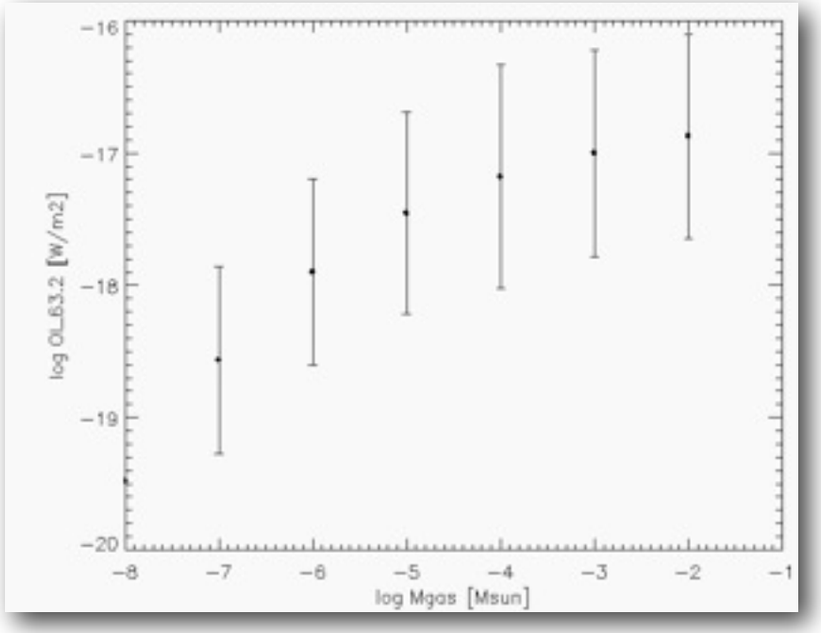
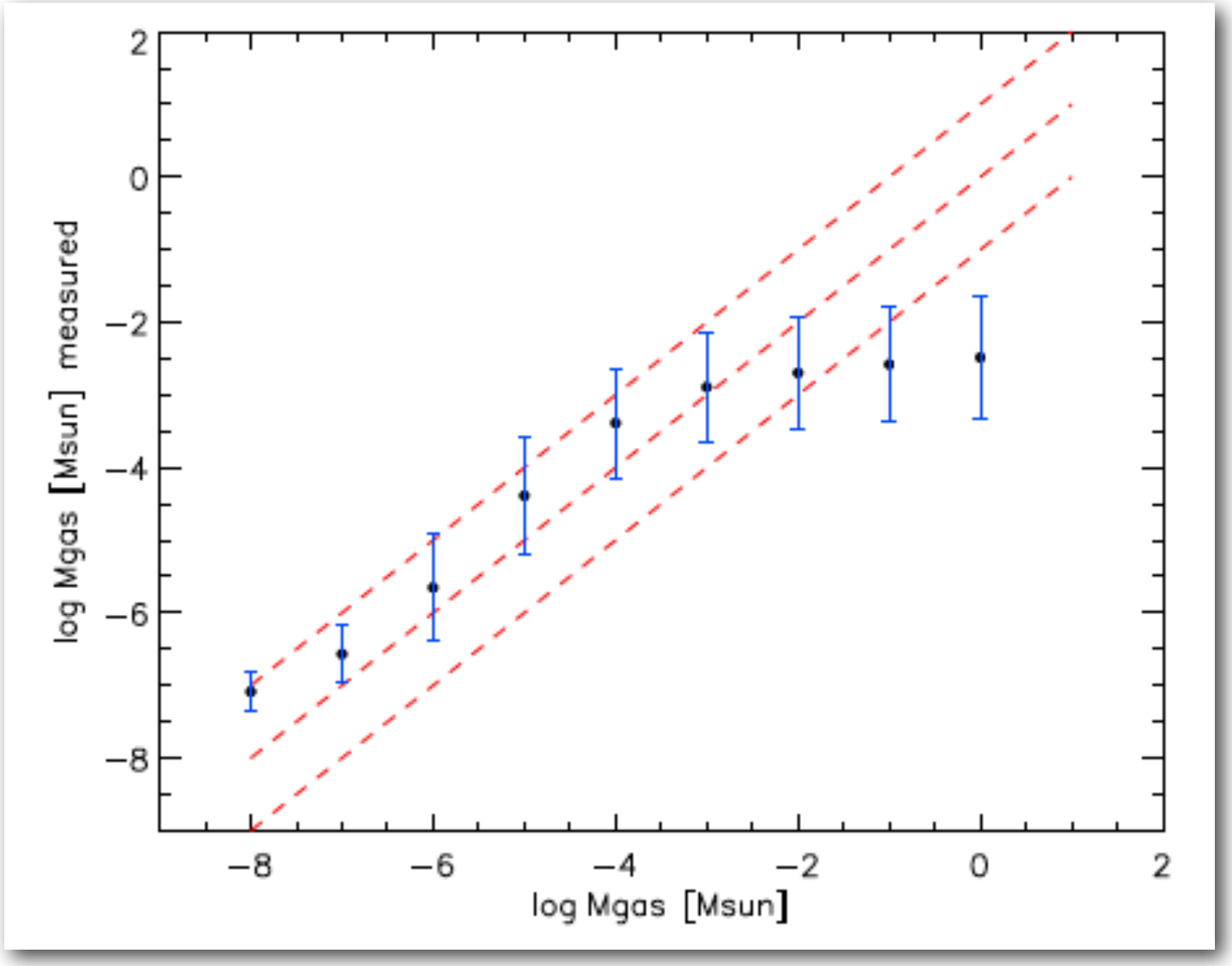
Determining gas masses

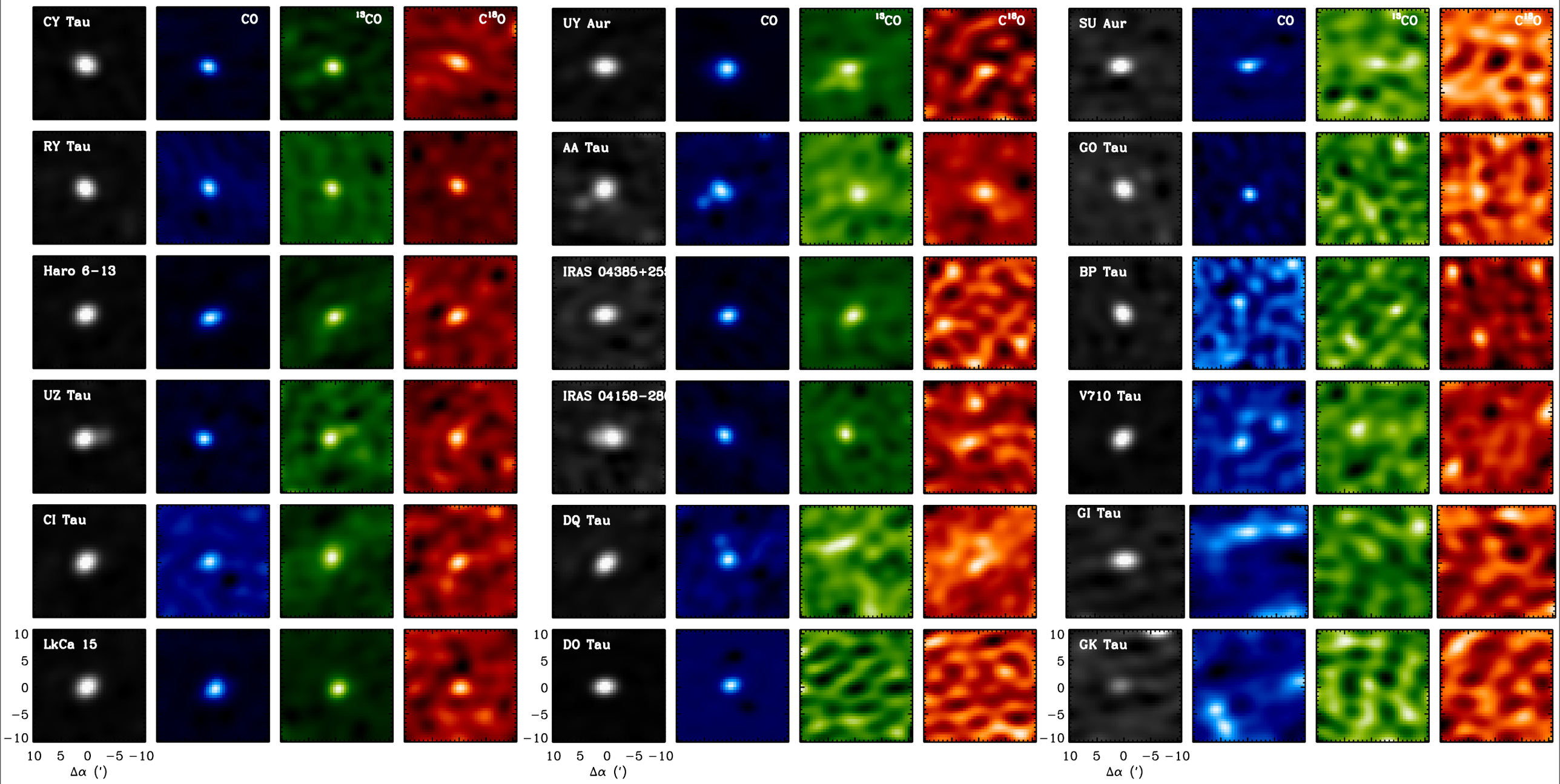


The *combination* of [OI]63μm and CO J=2-1 provide a more precise and robust measure of gas mass



Kamp+ 2011

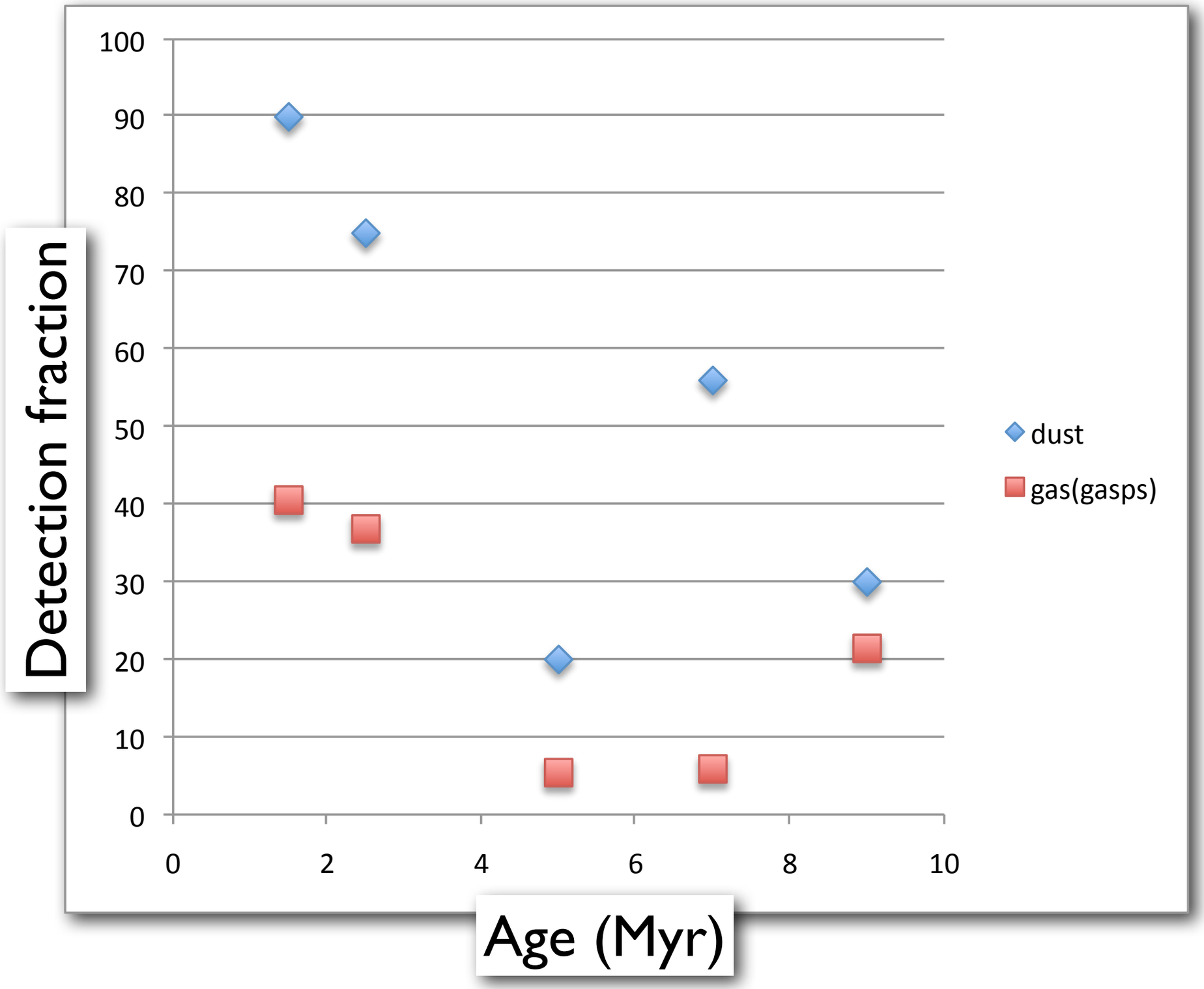
The more lines the better...



1.2mm continuum, CO, ^{13}CO, C^{18}O *SMA Reconnaissance of Taurus*

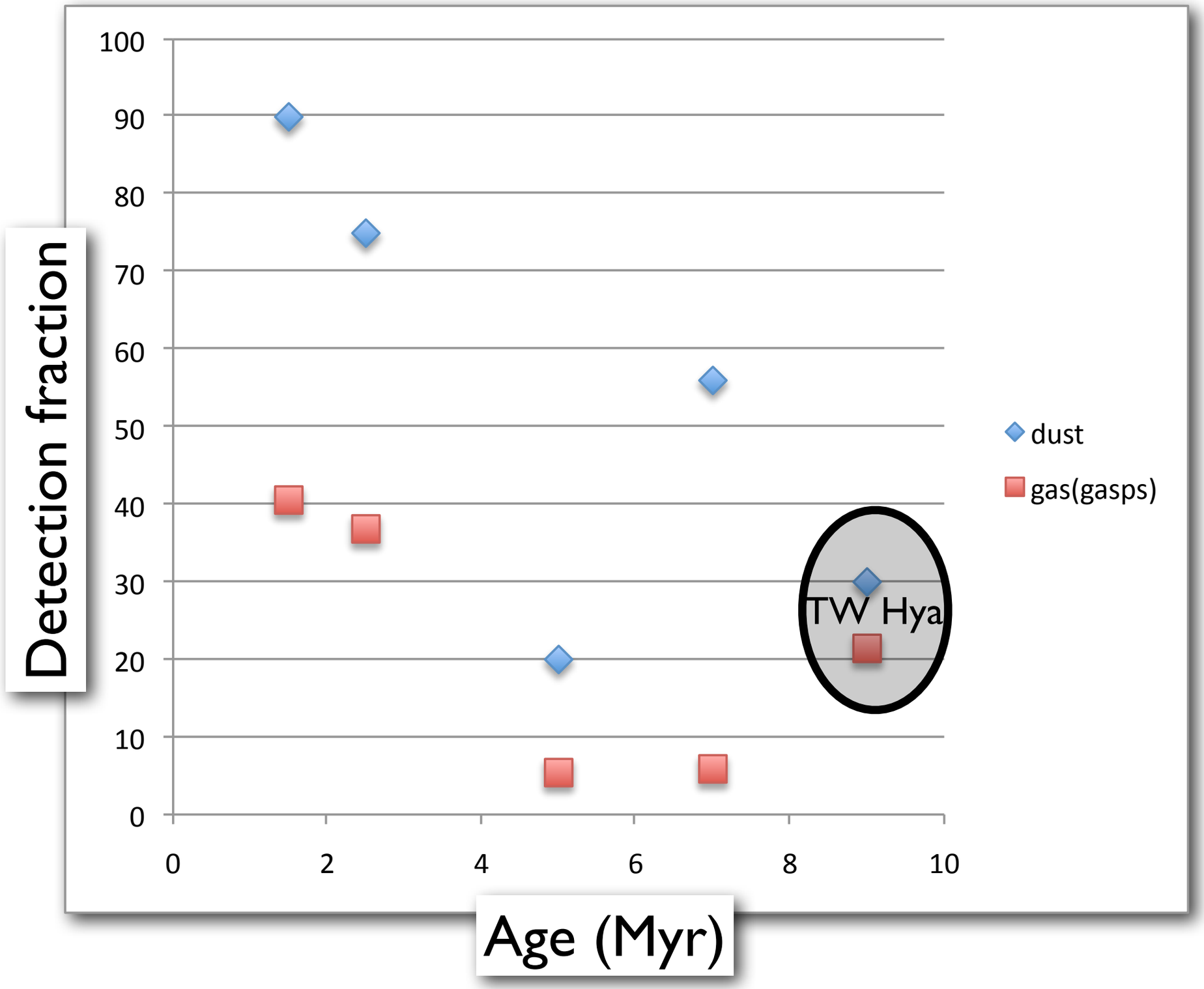
Gas lifetimes

(preliminary!)



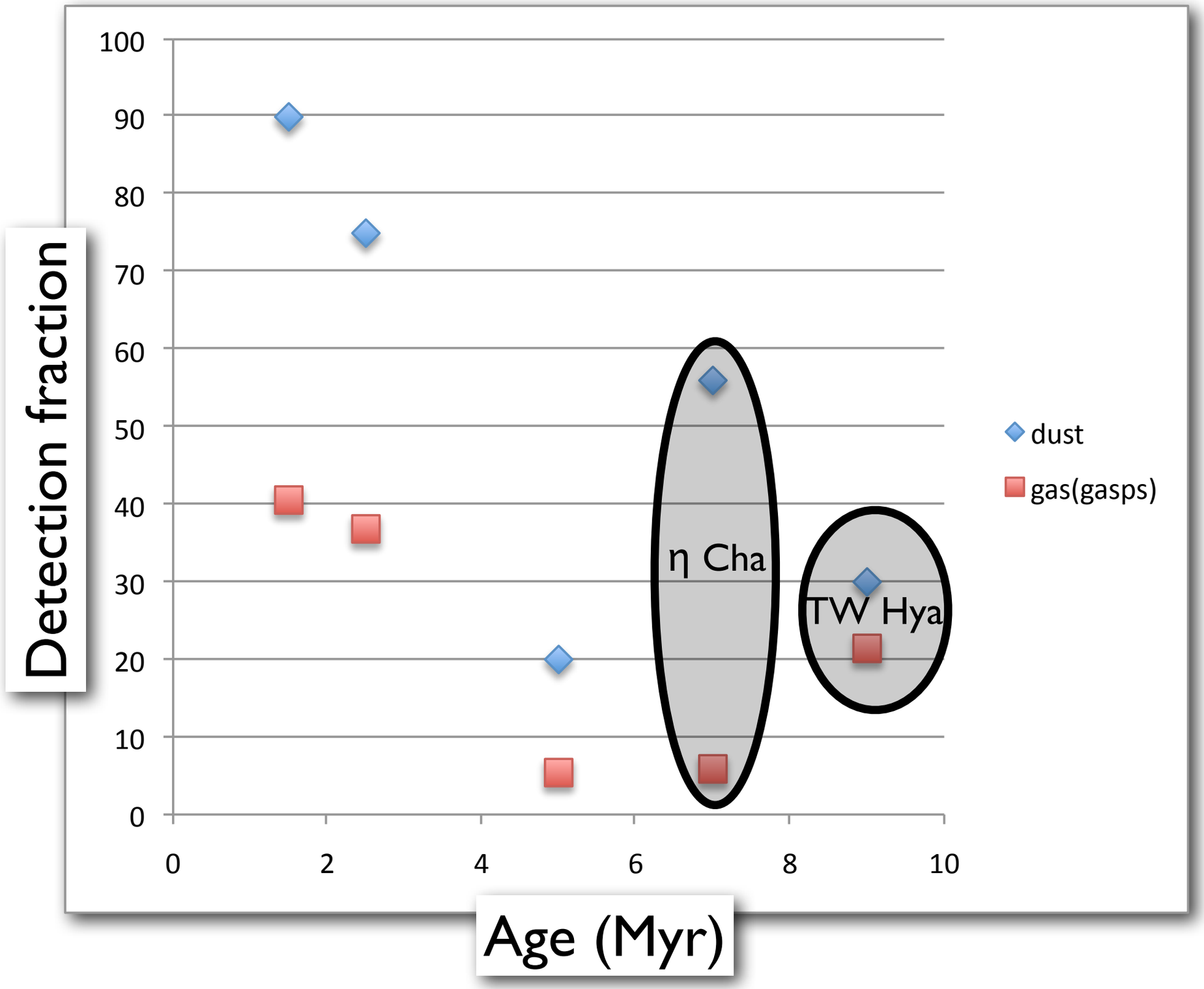
Gas lifetimes

(preliminary!)



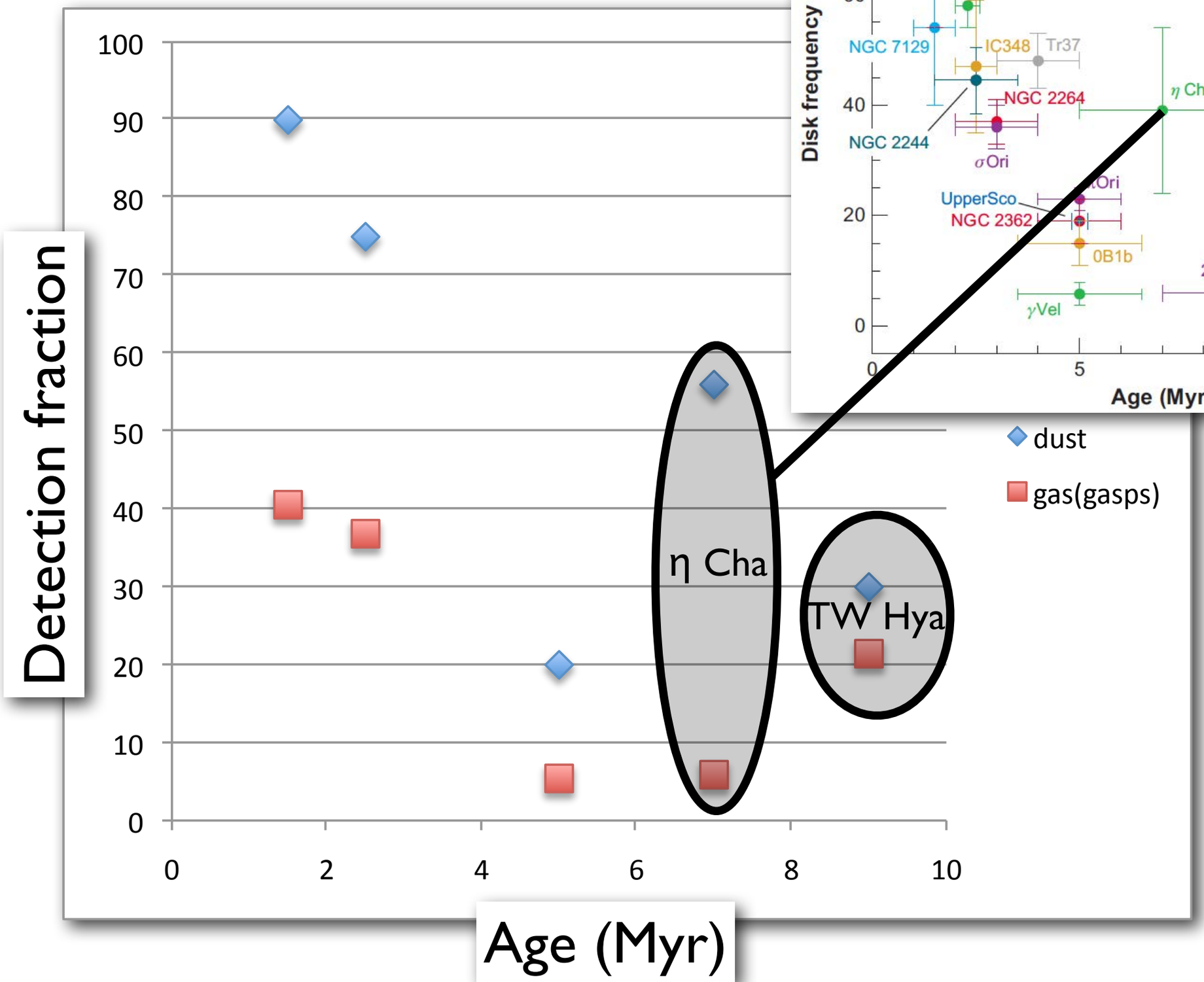
Gas lifetimes

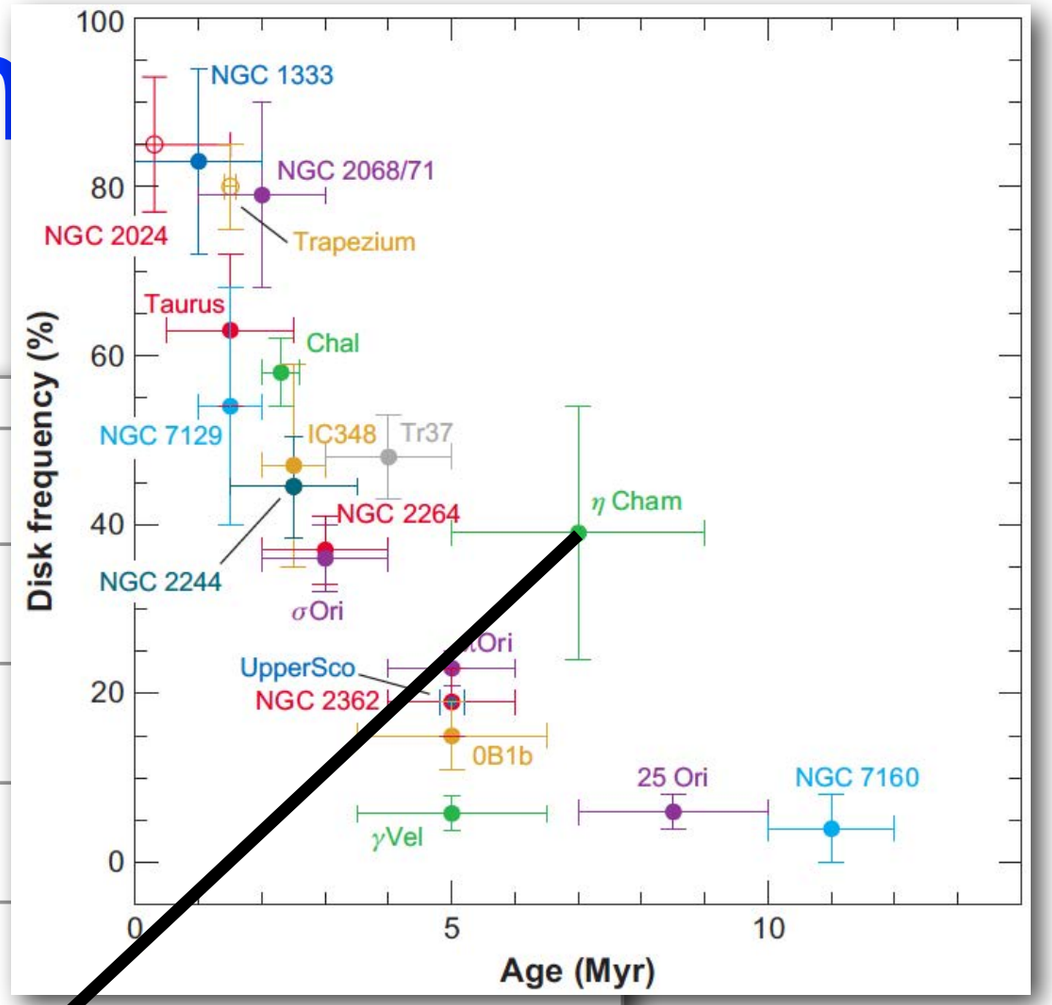
(preliminary!)



Gas lifetin

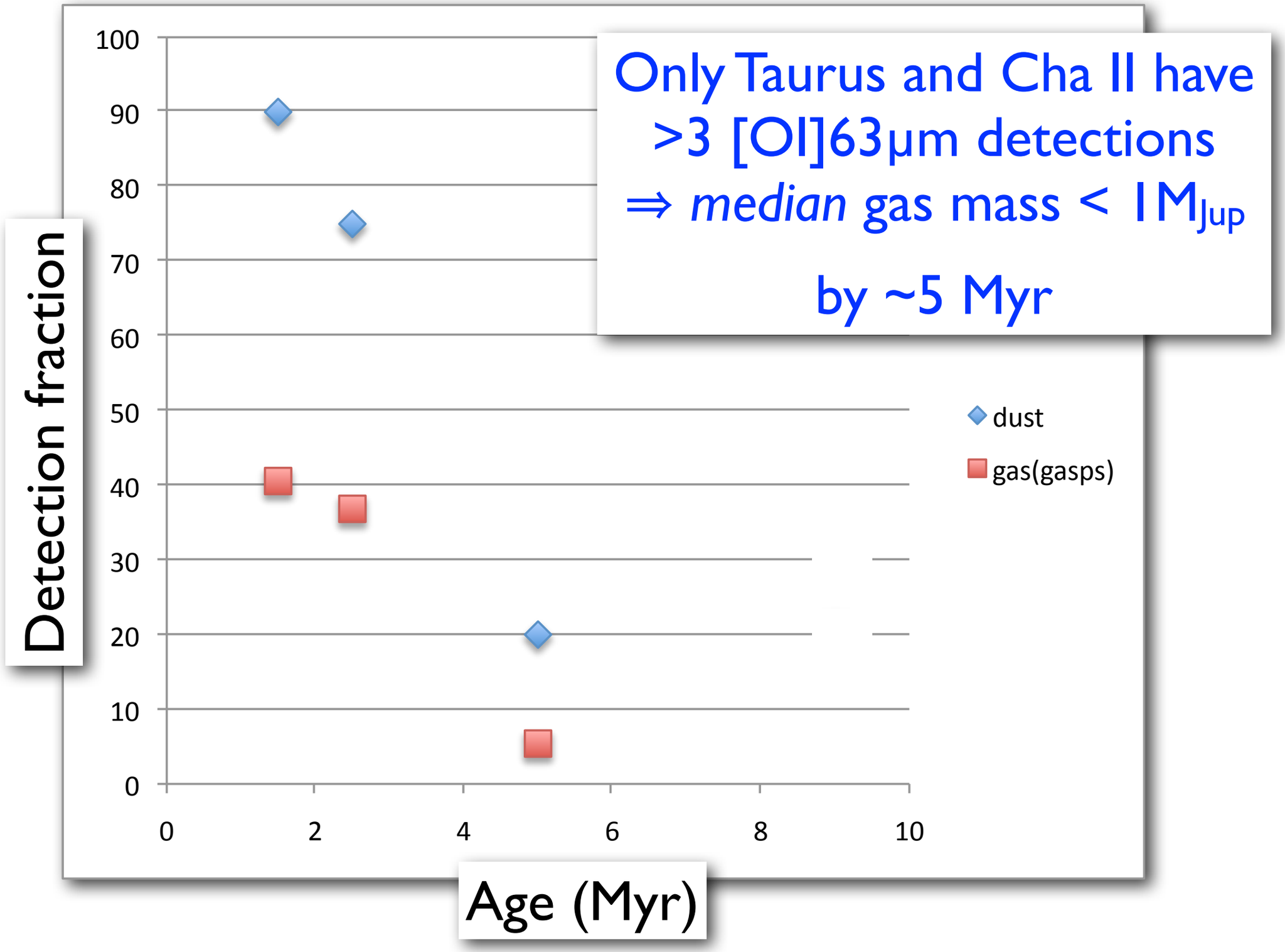
(preliminary!)





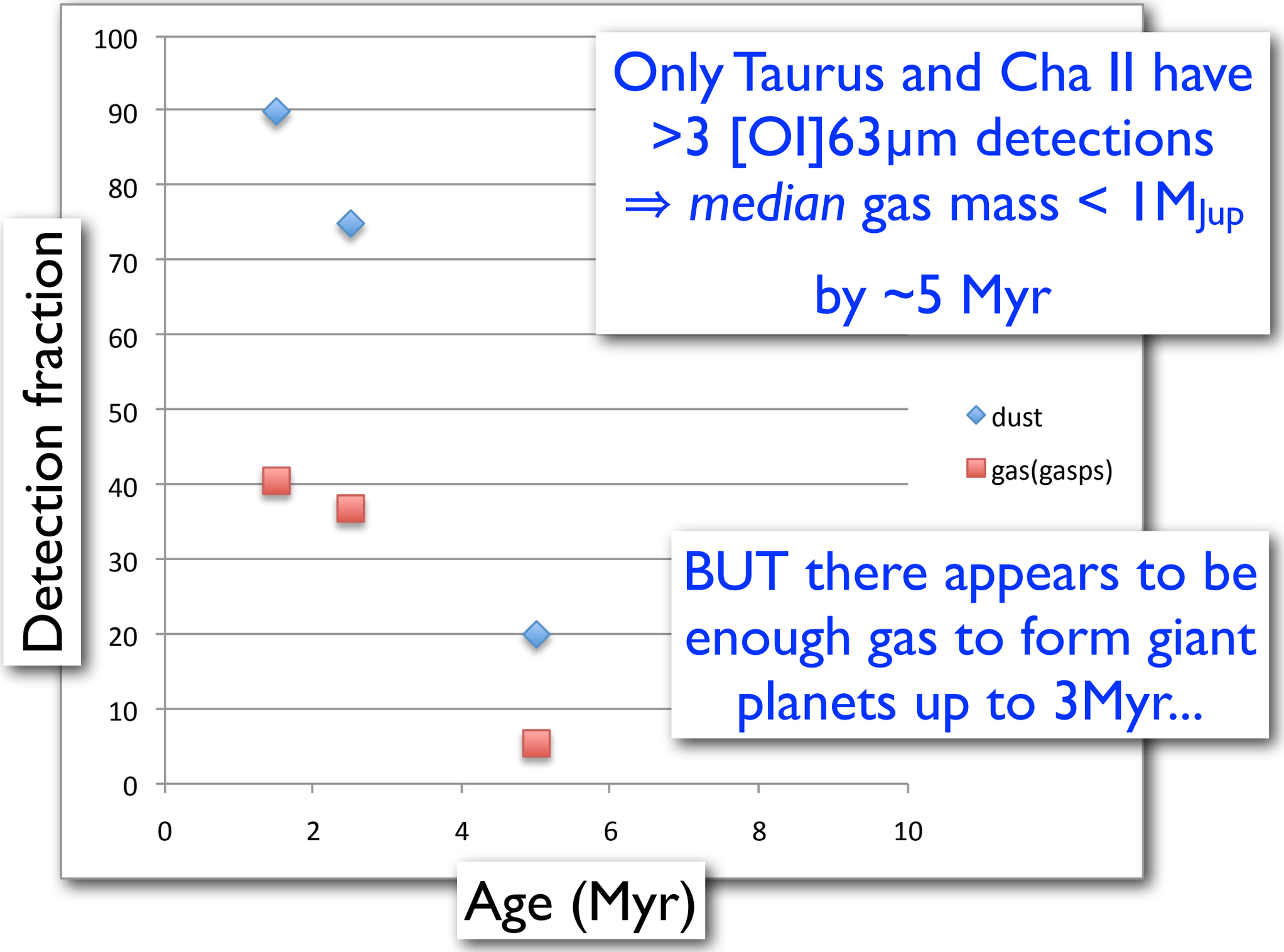
Gas lifetimes

(*preliminary*!)



Gas lifetimes

(preliminary!)



Only Taurus and Cha II have >3 [OI]63μm detections

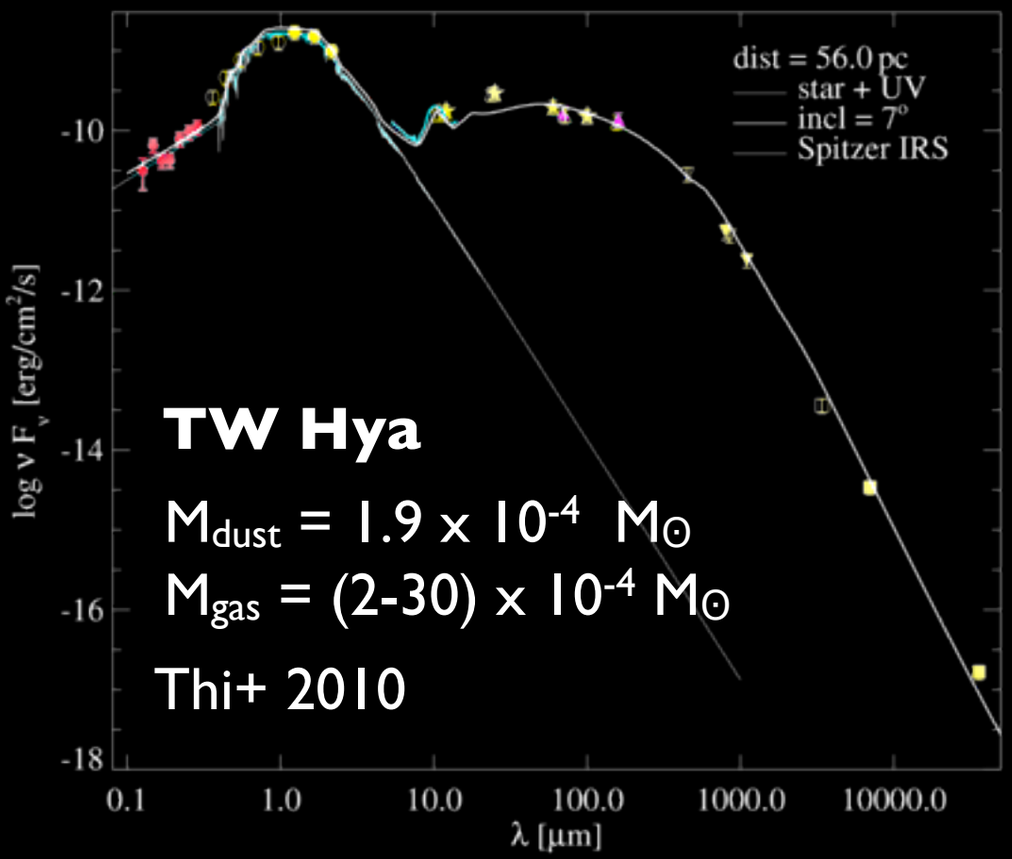
⇒ *median* gas mass < $1M_{Jup}$

by ~5 Myr

BUT there appears to be enough gas to form giant planets up to 3Myr...

Individual regions/sources

- Taurus (see Christian Howard's talk)
- transitional disks (see Francois Menard's talk)
- detailed modeling of individual sources
  - dust/gas ratio
  - warm H_2O
  - C^+, CO, OH, CH^+

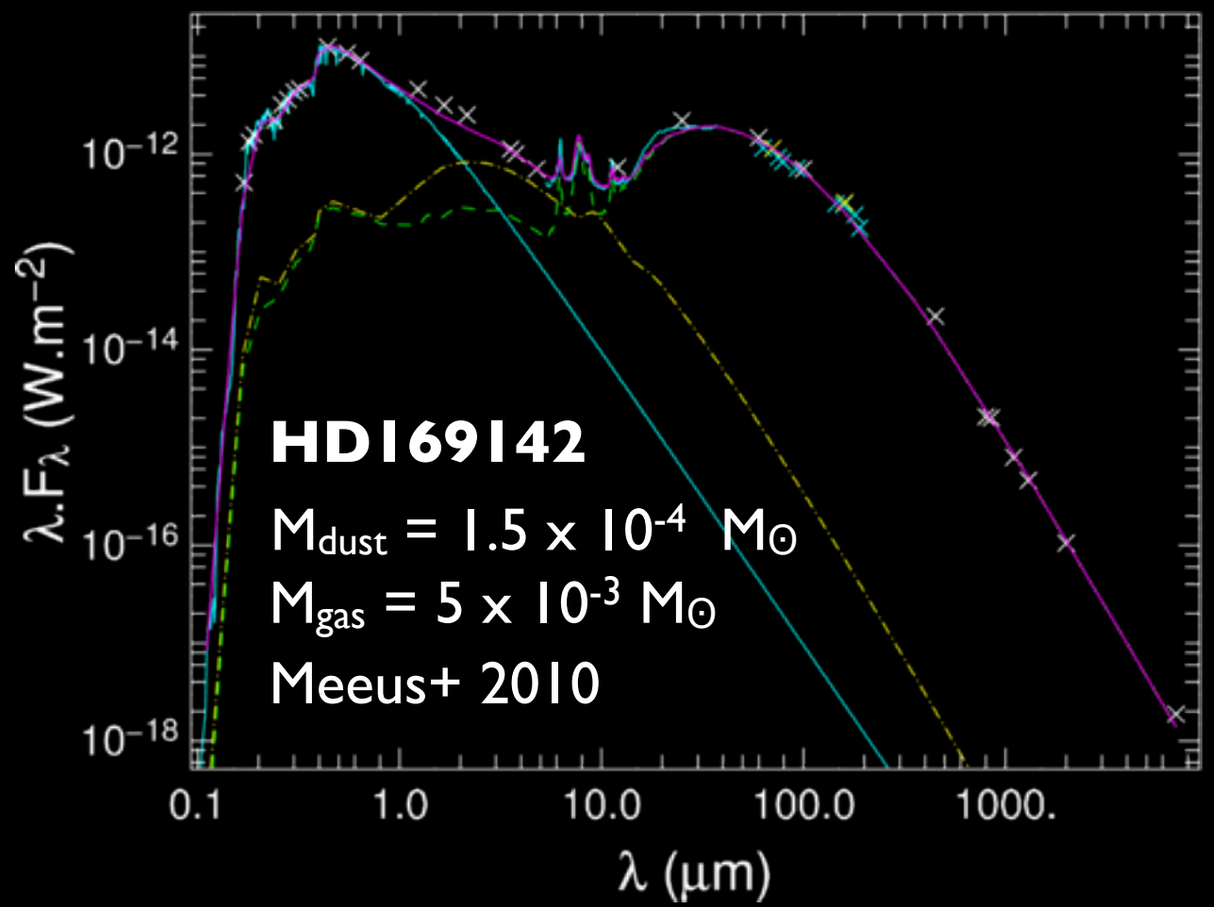


TW Hya

M_{dust} = 1.9 x 10^{-4} $M_\odot$

M_{gas} = (2-30) x 10^{-4} $M_\odot$

Thi+ 2010

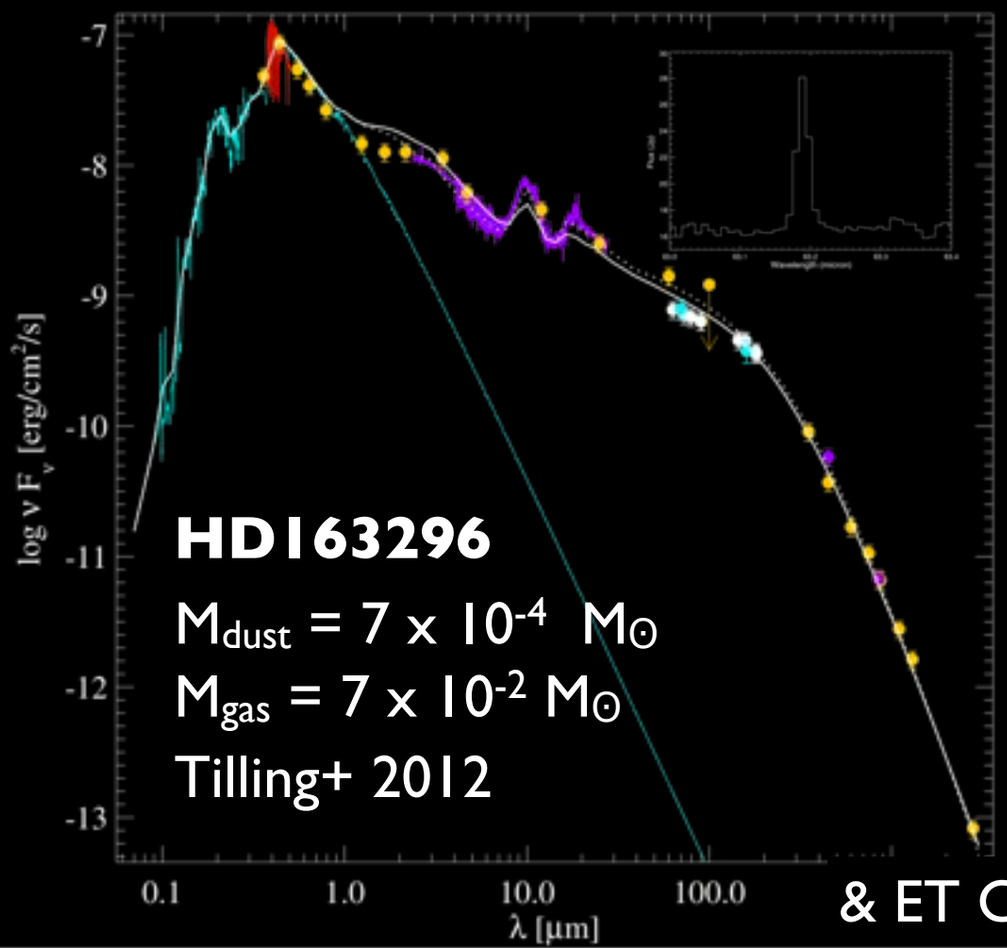


HD169142

M_{dust} = 1.5 x 10^{-4} $M_\odot$

M_{gas} = 5 x 10^{-3} $M_\odot$

Meeus+ 2010

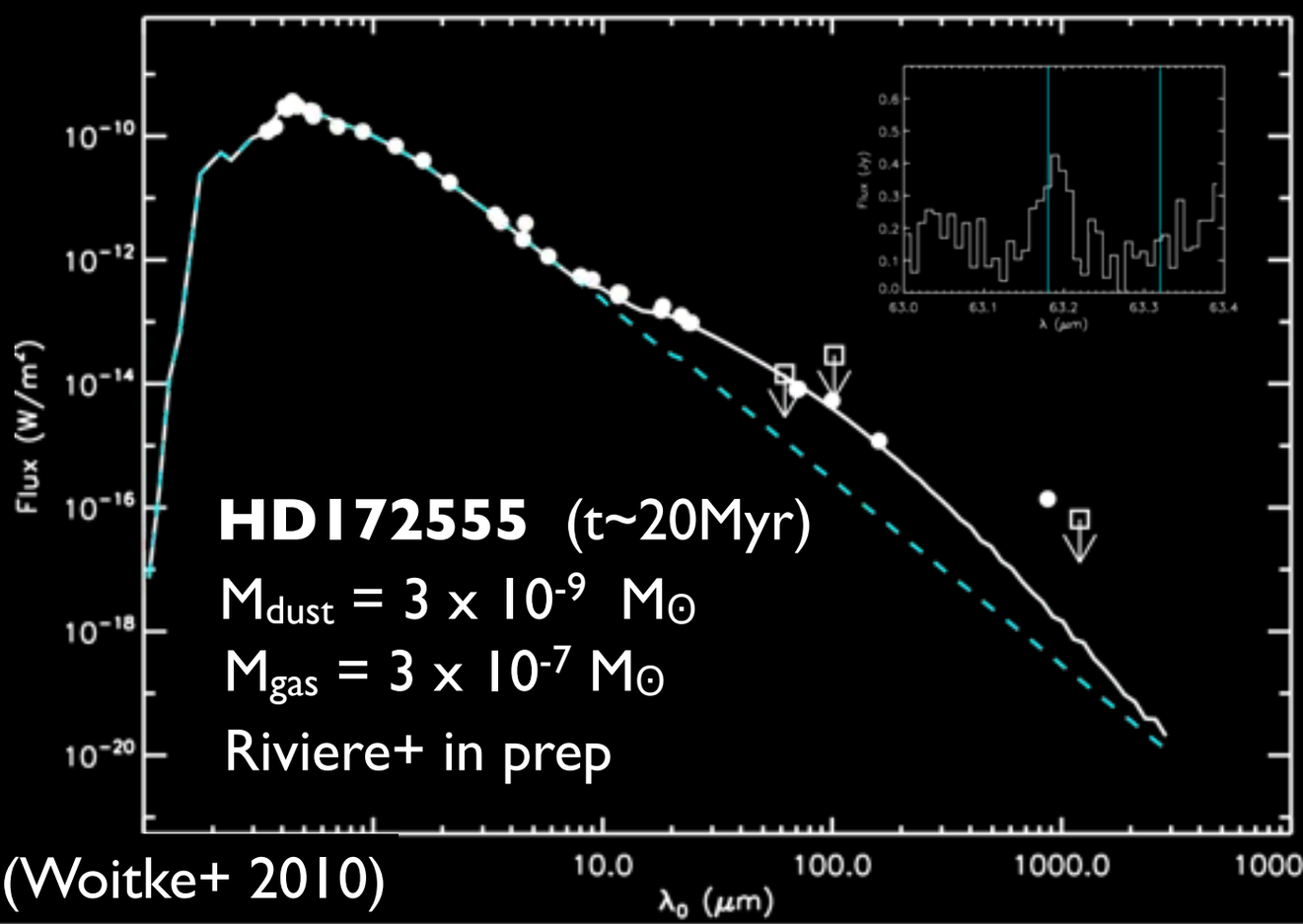


HD163296

M_{dust} = 7 x 10^{-4} $M_\odot$

M_{gas} = 7 x 10^{-2} $M_\odot$

Tilling+ 2012



HD172555 (t~20Myr)

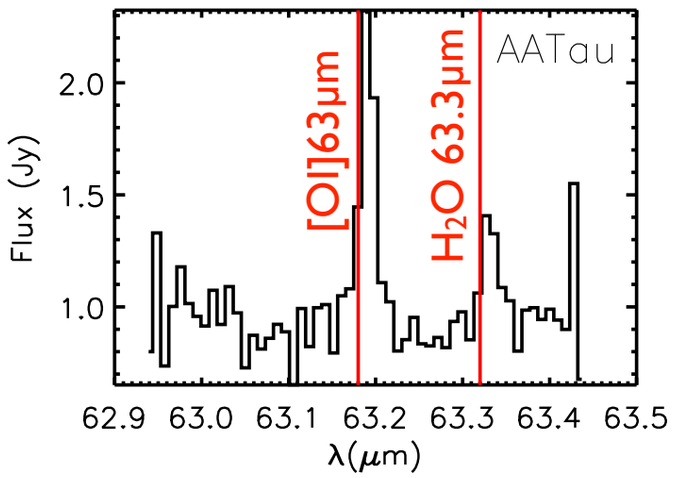
M_{dust} = 3 x 10^{-9} $M_\odot$

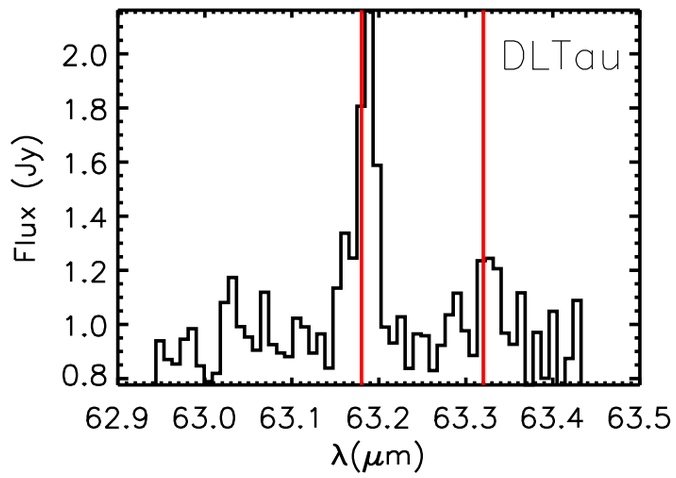
M_{gas} = 3 x 10^{-7} $M_\odot$

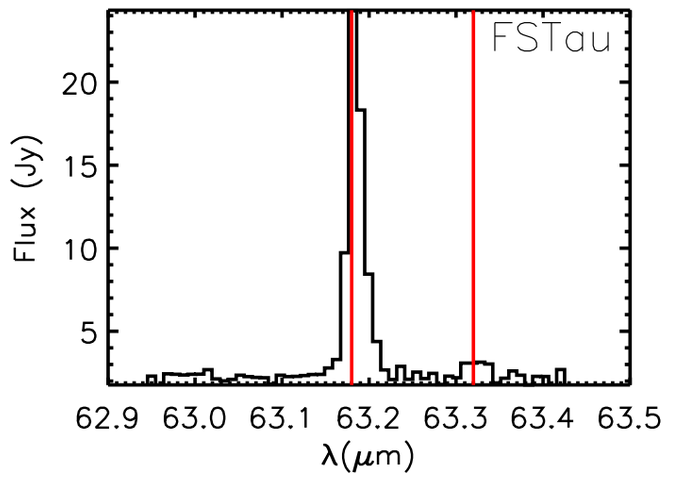
Riviere+ in prep

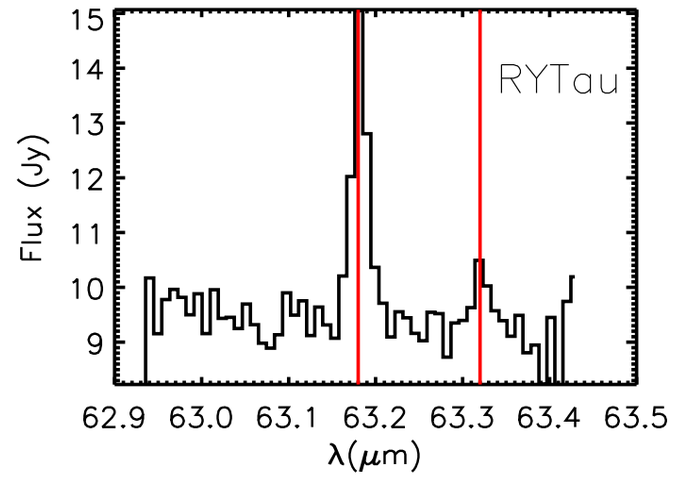
& ET Cha (Woitke+ 2010)

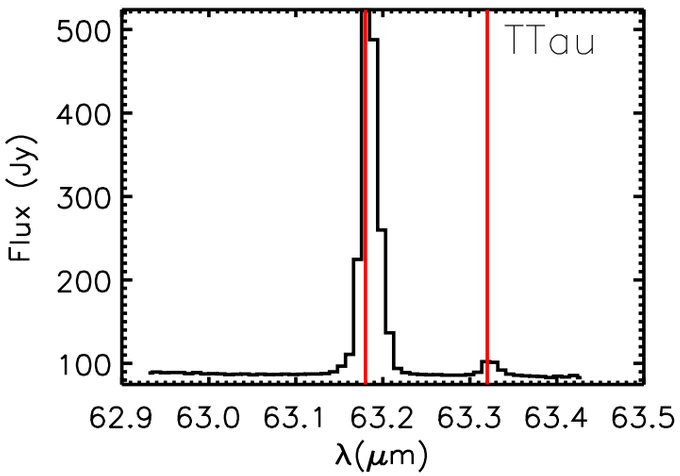
Warm water in disks

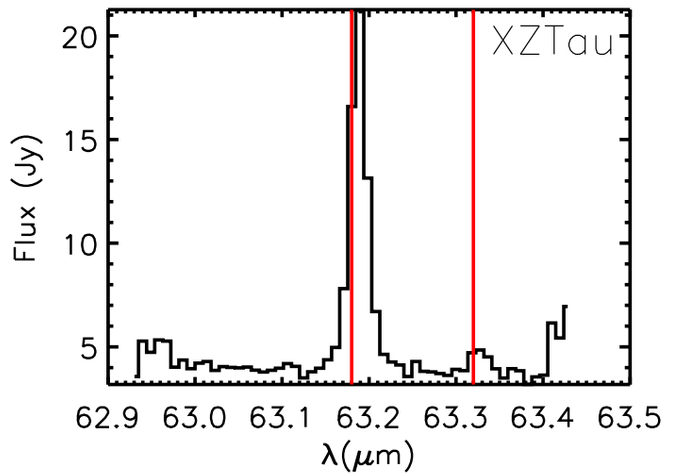


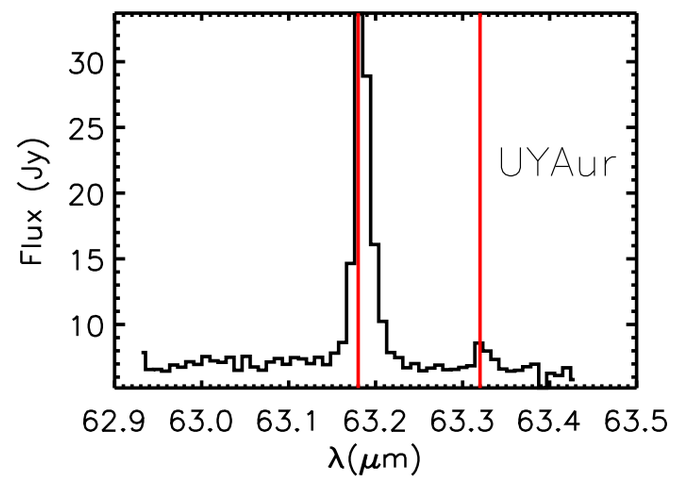


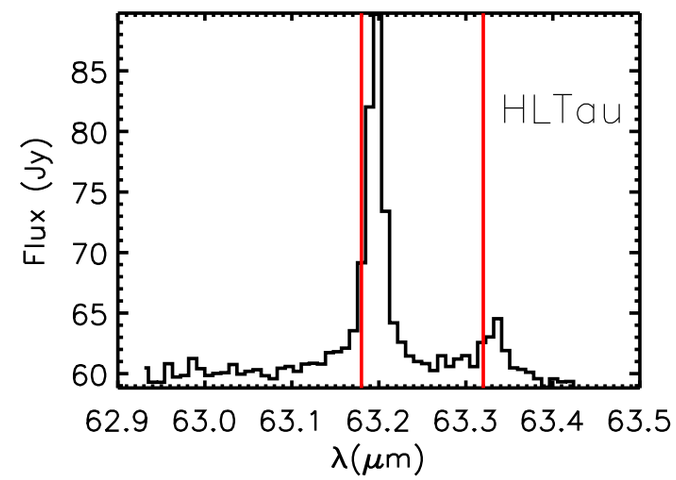










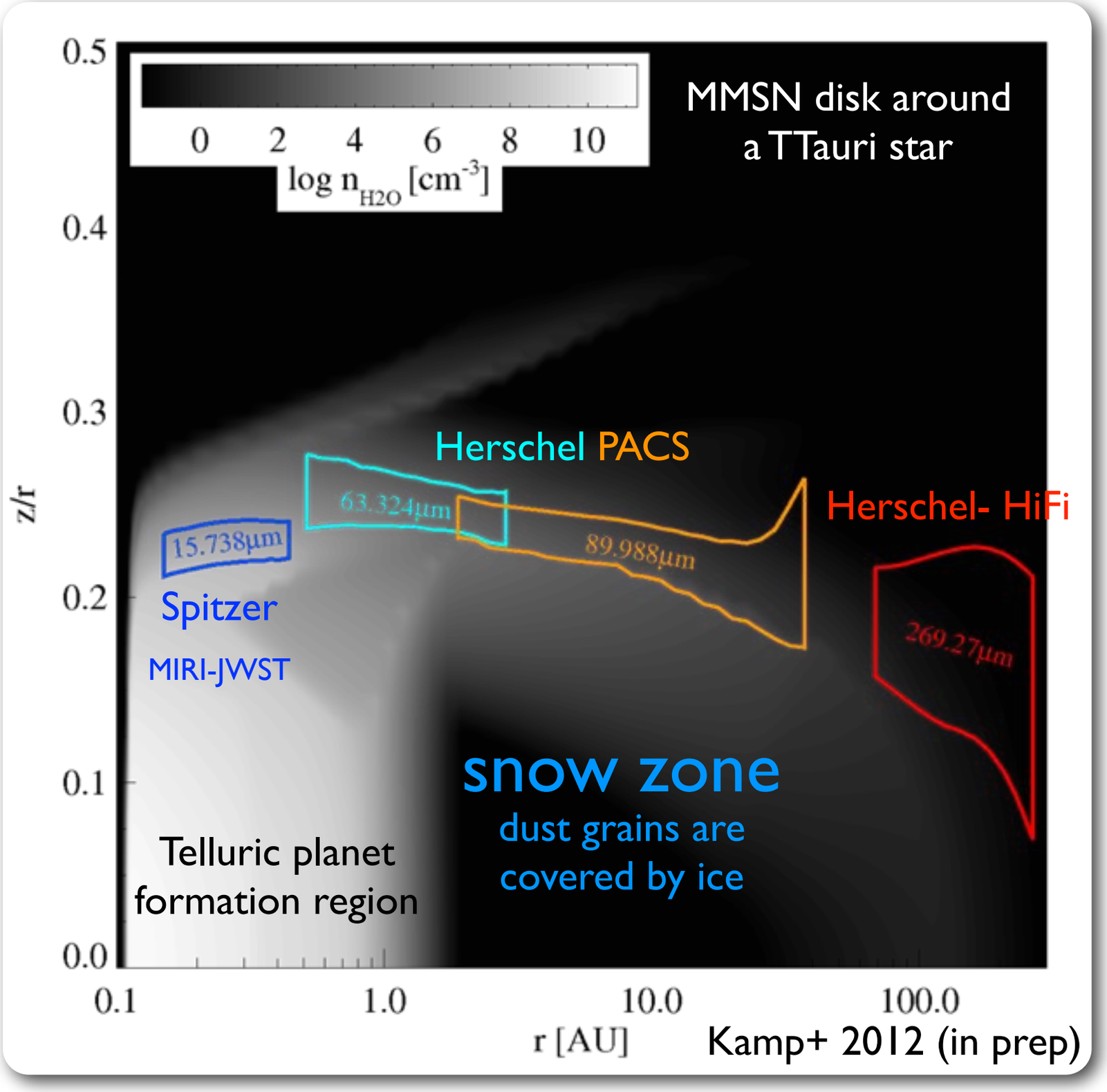


o-H_2O 8_{17}-7_{07} E_u=1070K

detected in 8/33 (24%)
of disks with [OI]63

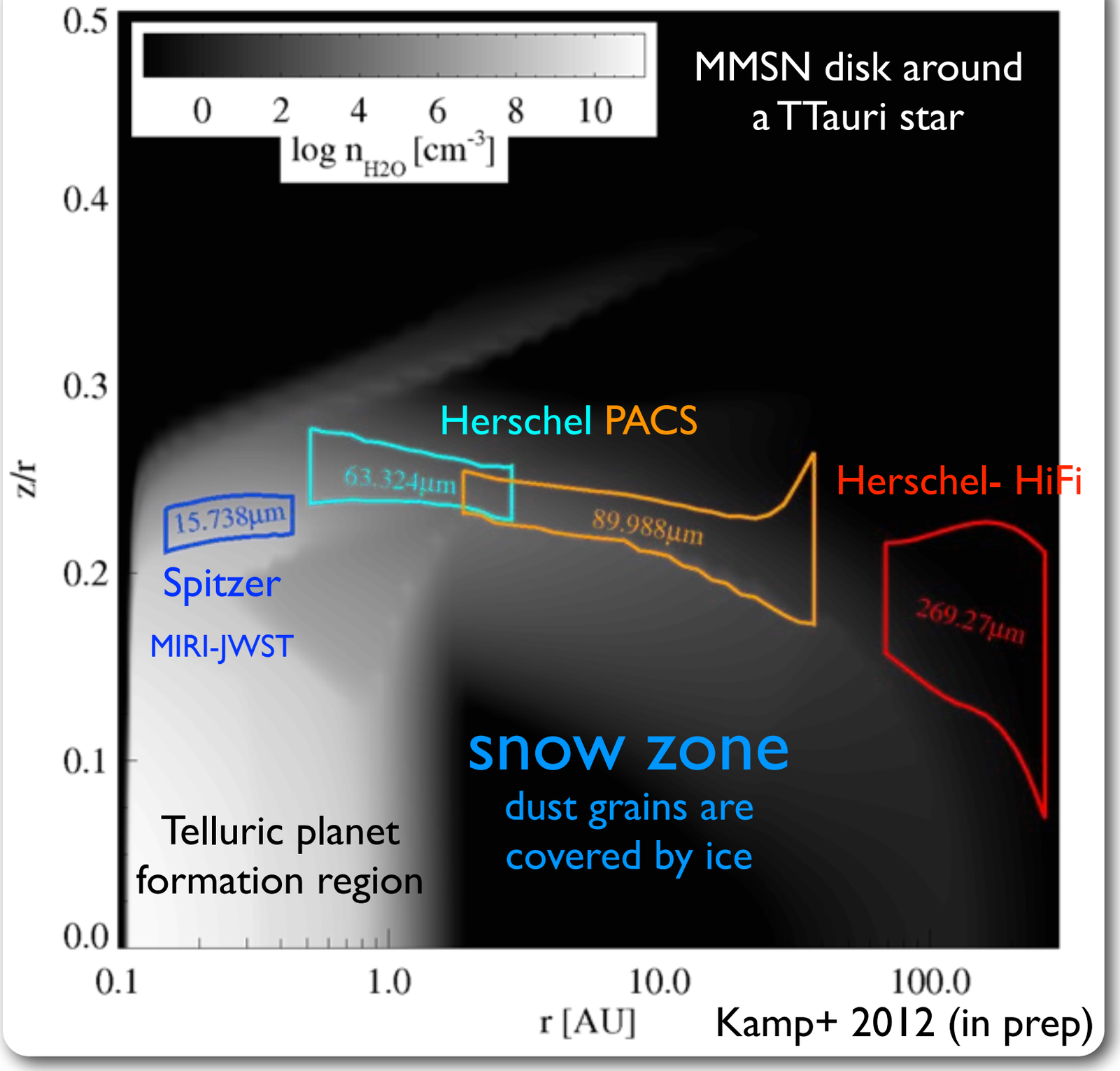
Riviere+ 2012

The 63.32μm water line



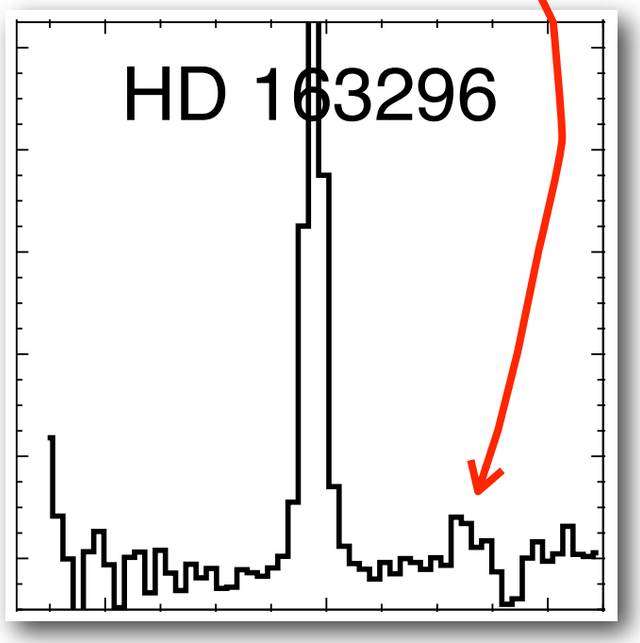
The H_2O 63.3μm line is seen in 8 TTauri disks but only 1 HAeBe

The 63.32μm water line



Kamp+ 2012 (in prep)

The H_2O 63.3μm line is seen in 8 TTauri disks but only 1 HAeBe



Meeus+ 2012

DIGIT

- PACS and some SPIRE photometry
- full PACS spectroscopy 52-210μm
- embedded protostars and protoplanetary disks
- Close (<350pc), young (~1 Myr) regions

★ Taurus, Ophiuchus, Cha, Perseus, Serpens, Lupus

The DIGIT Team

Jean-Charles Augereau
Ted Bergin
Geoff Blake
Jeroen Bouwman
John Carr
Lucas Cieza
Carsten Dominik
Cornelis Dullemond
Neal J. Evans II (PI)
Al Glassgold
Manuel Guedel
Paul Harvey
Thomas Henning
Michiel Hogerheijde
Dan Jaffe
Jes Jørgensen

Simon Bruderer
John Lacy
Jeong-Eun Lee
Sebastien Maret
Bruno Merin
Lee Mundy
Joan Najita
Klaus Pontoppidan
Ewine van Dishoeck
Christoffel Waelkens
Rens Waters
Ruud Visser
Umut A. Yildiz
Odysseas Dionatos
Lars Kristensen
Koen Maaskant

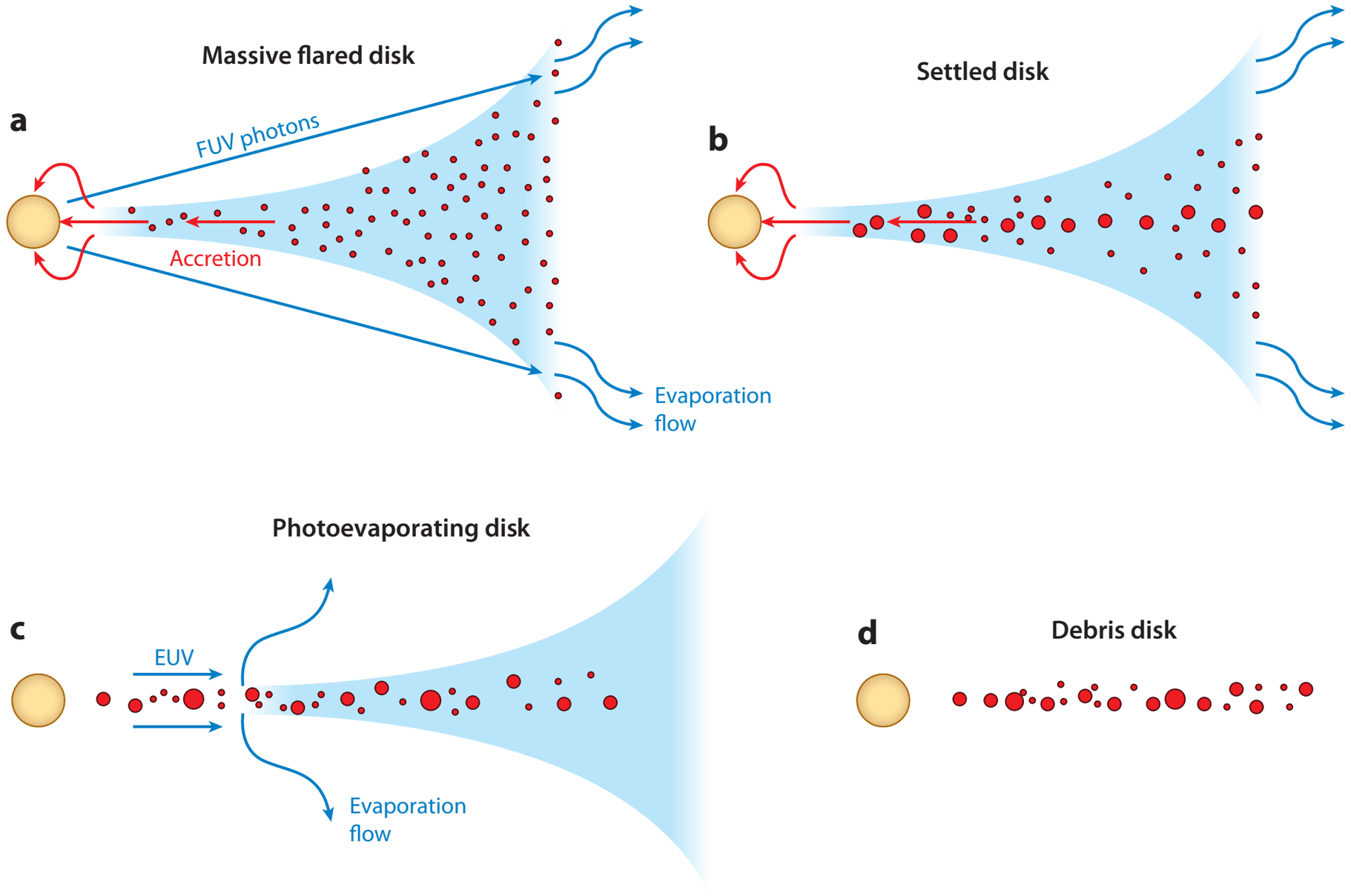
Joel Green
Gwendolyn Meeus
Bram Acke
Rowin Meijerink
Joanna Brown
Greg Herczeg
Tim van Kempen
Mate Adamkovics
Colette Salyk
Jo-hsin Chen
Mike Dunham
Hyo-Jeong Kim
Johan Olofsson
Bernhard Sturm
Ke Zhang
Gijs Mulders

Some DIGIT disk highlights

(reviewed yesterday by Bouwman)

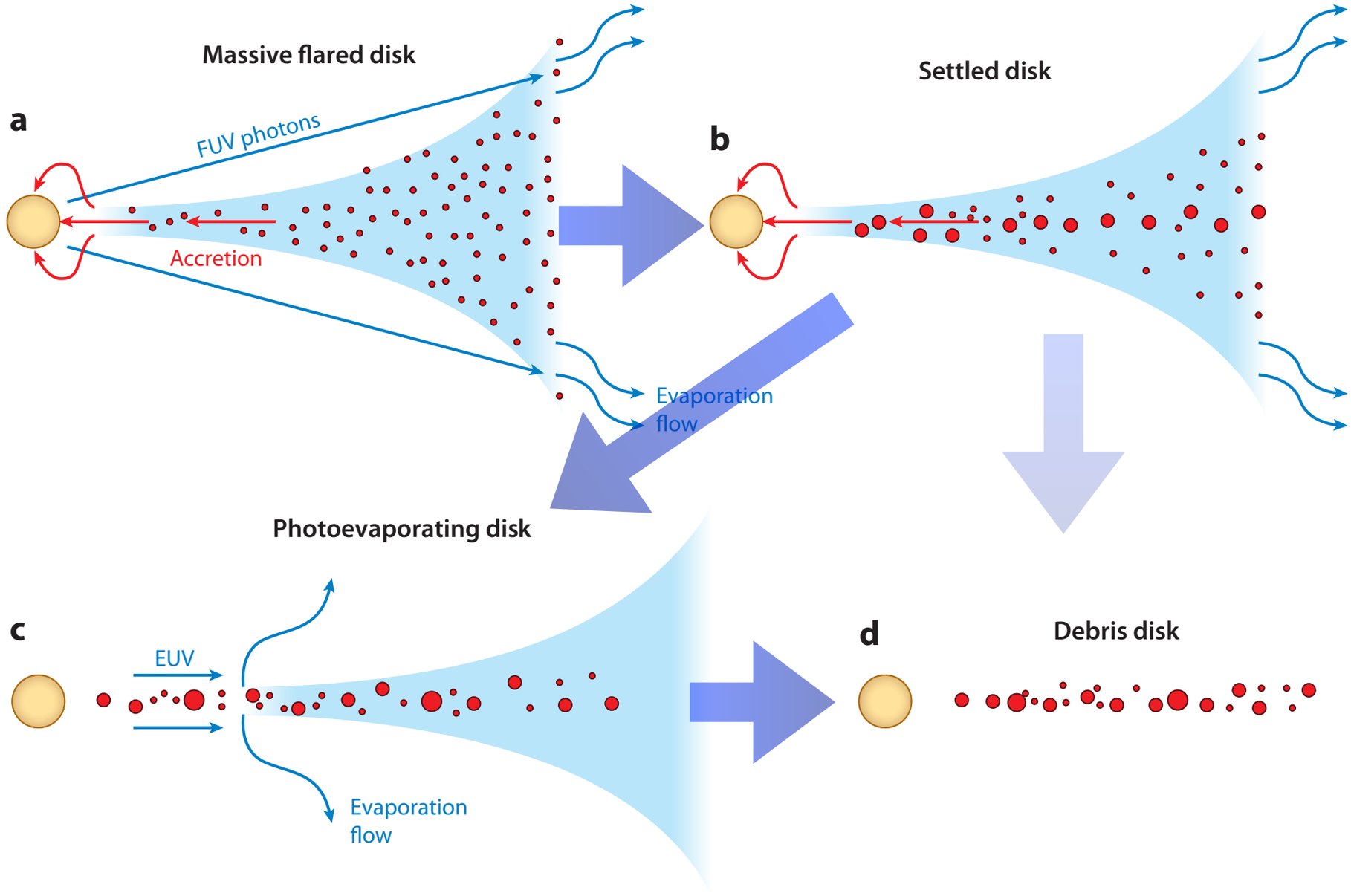
- Forsterite 69μm feature (Mulders)
- Warm disk atmospheres (Bruderer)
- WTTS structure

The transition from protoplanetary to planetary debris



Williams & Cieza 2011

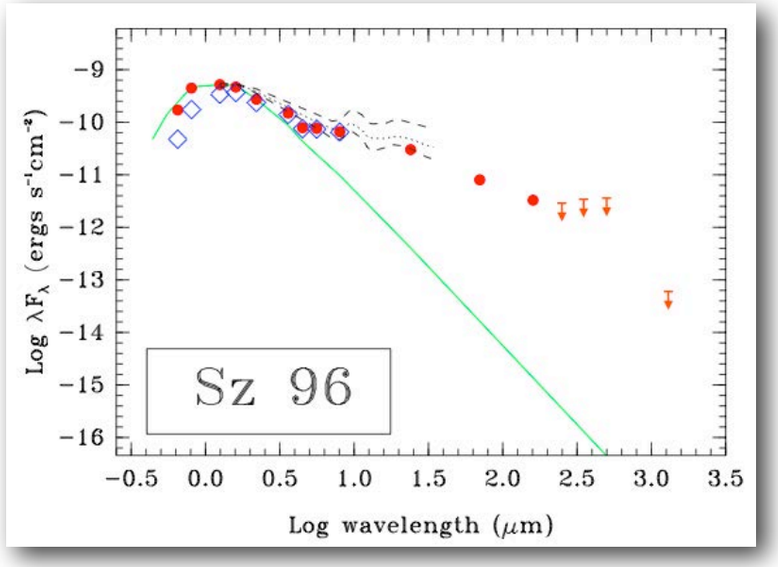
The transition from protoplanetary to planetary debris

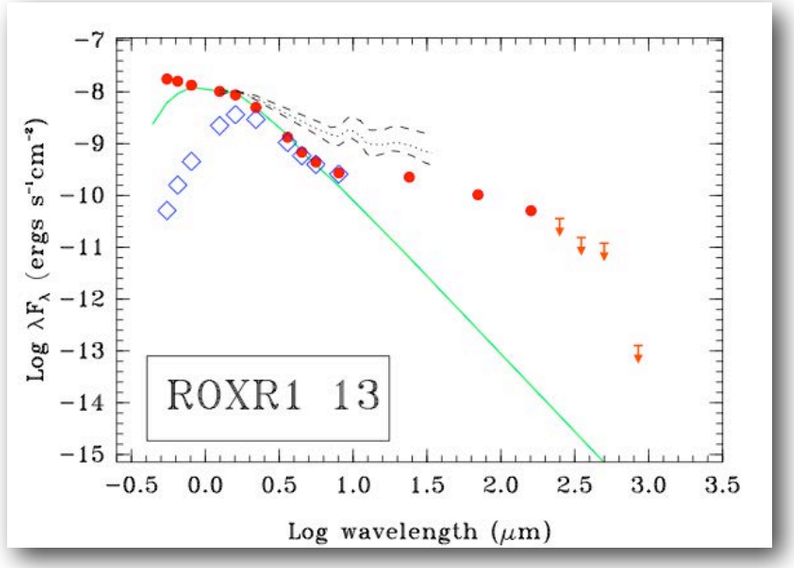


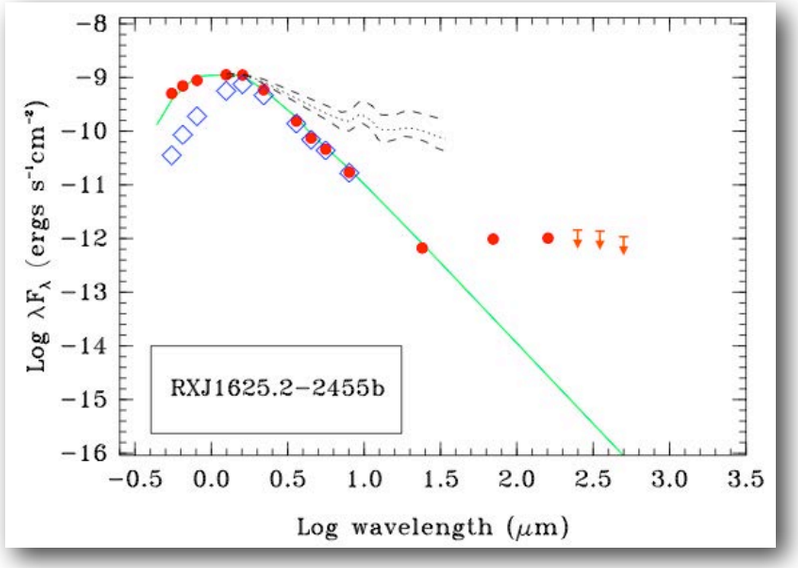
Williams & Cieza 2011

PACS/SPIRE photometry of WTTS

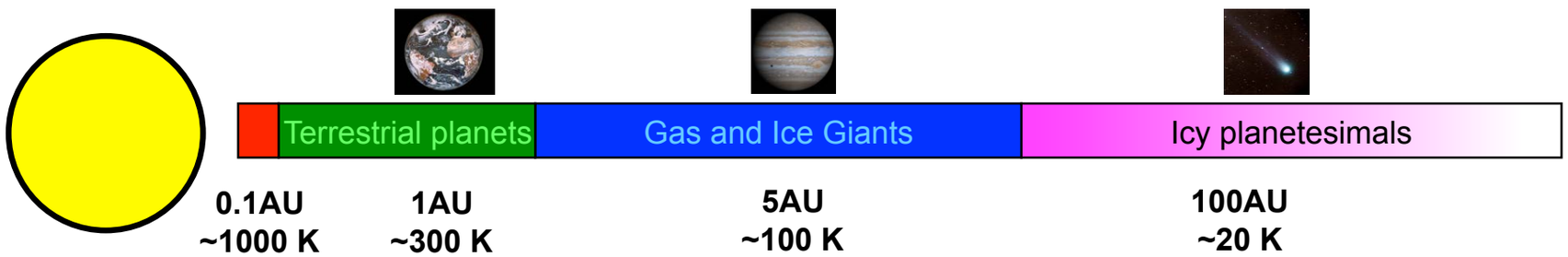
new constraints on outer disk structure

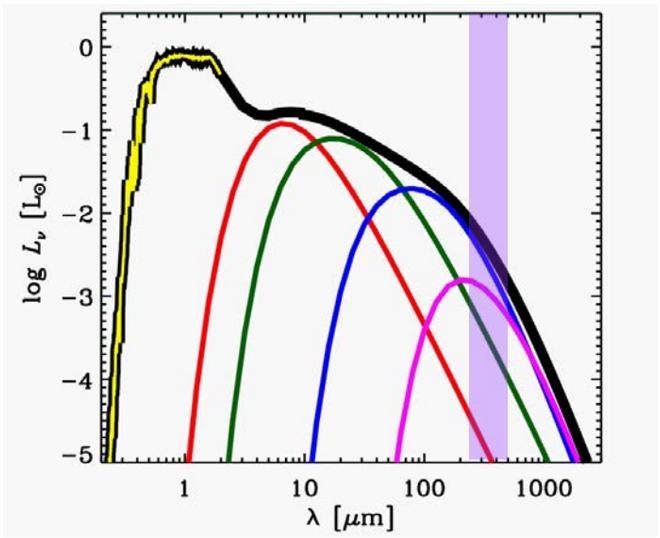




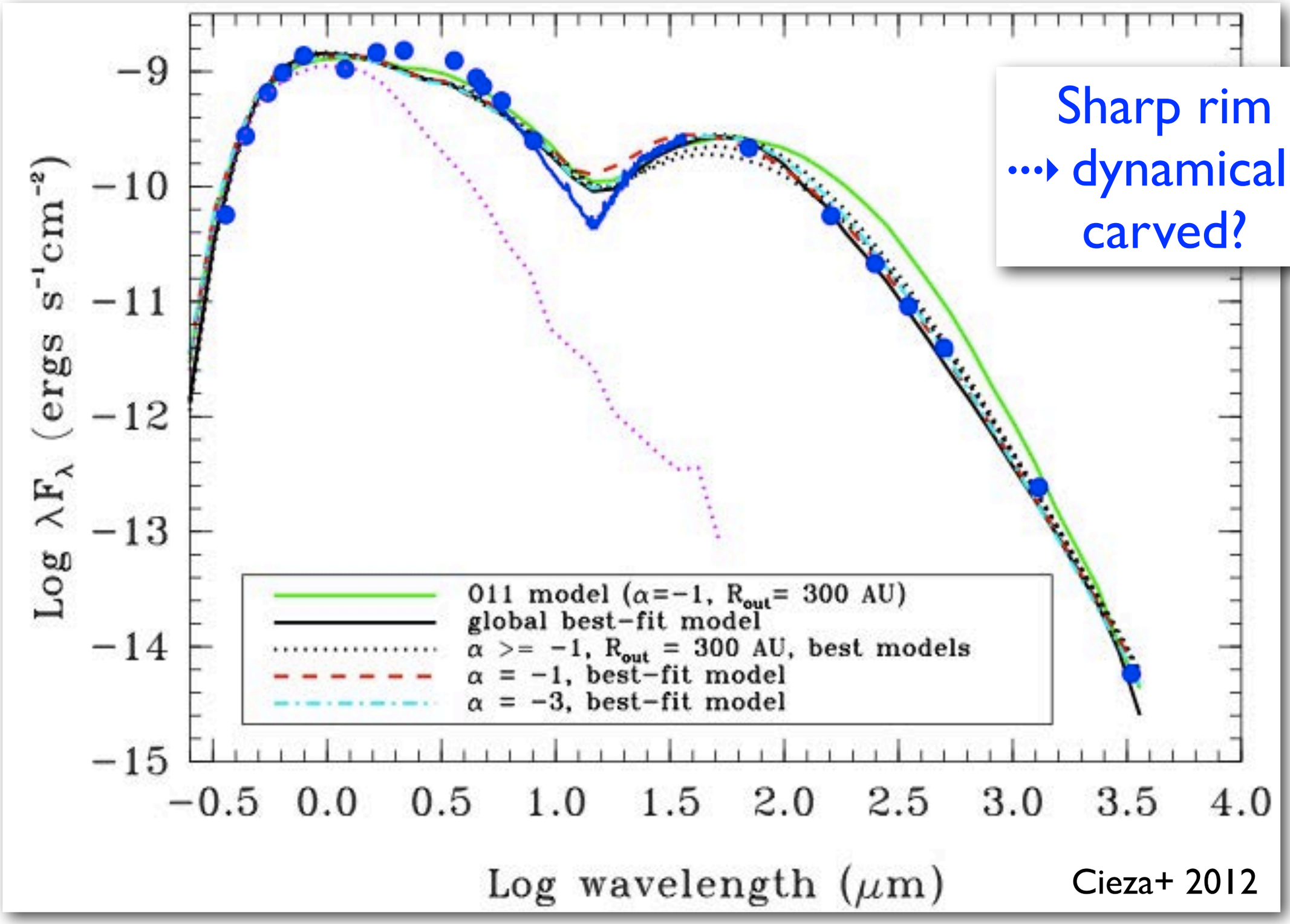


Lucas Cieza





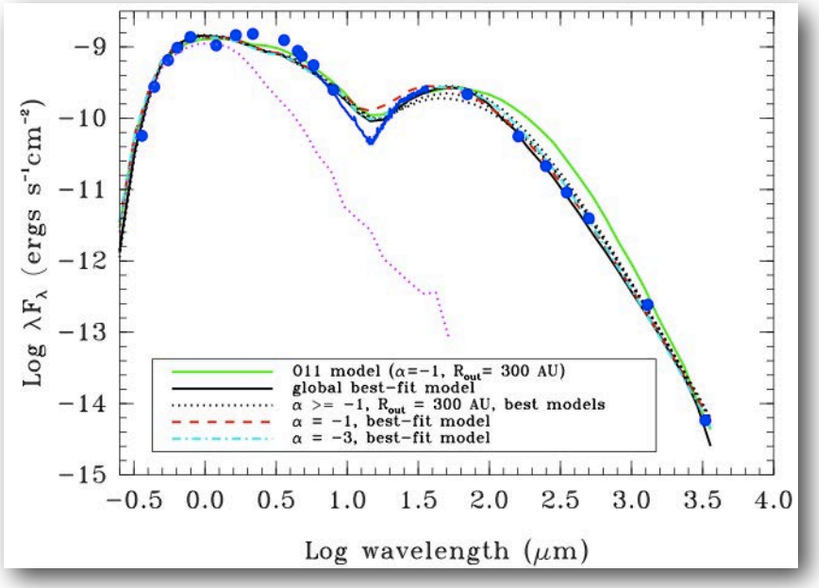
T Cha: a planet forming disk?

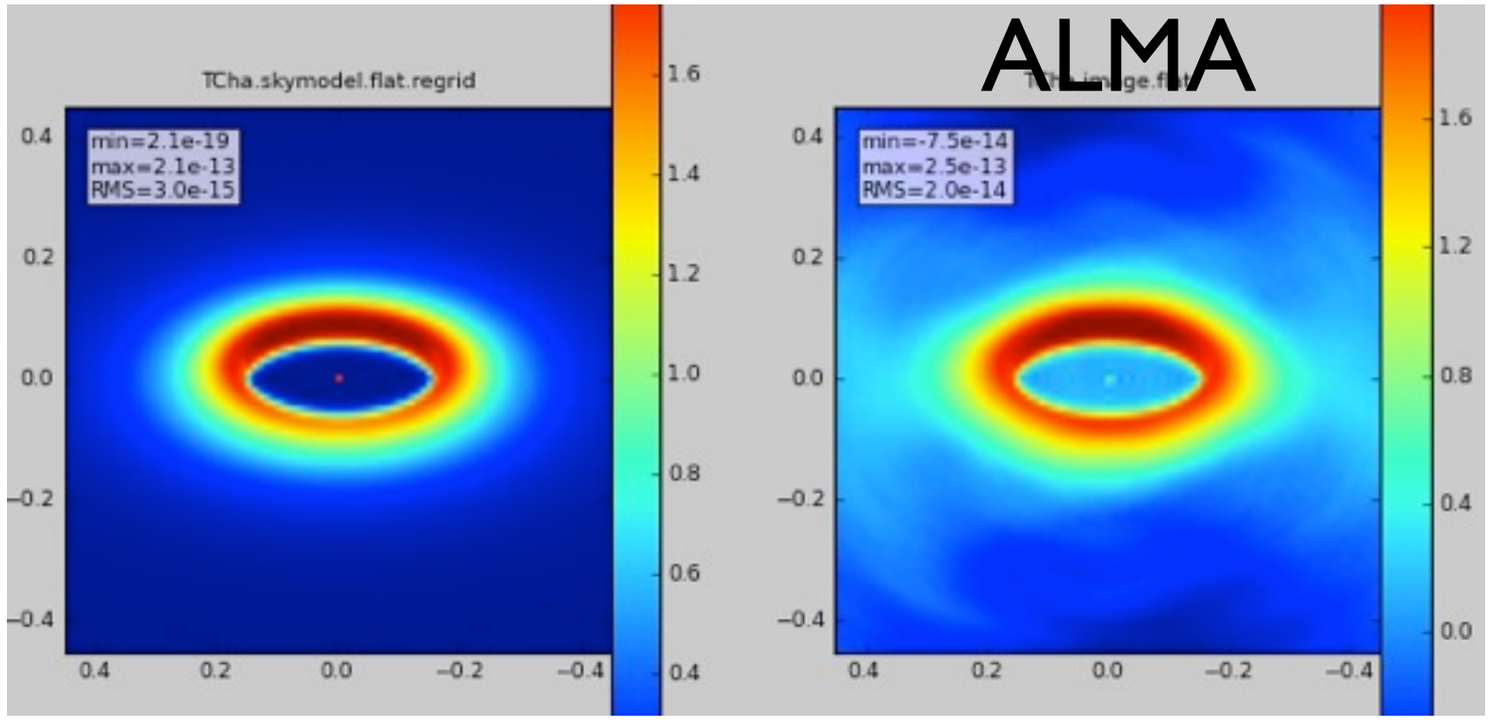


Sharp rim
⋯▸ dynamically carved?

Cieza+ 2012

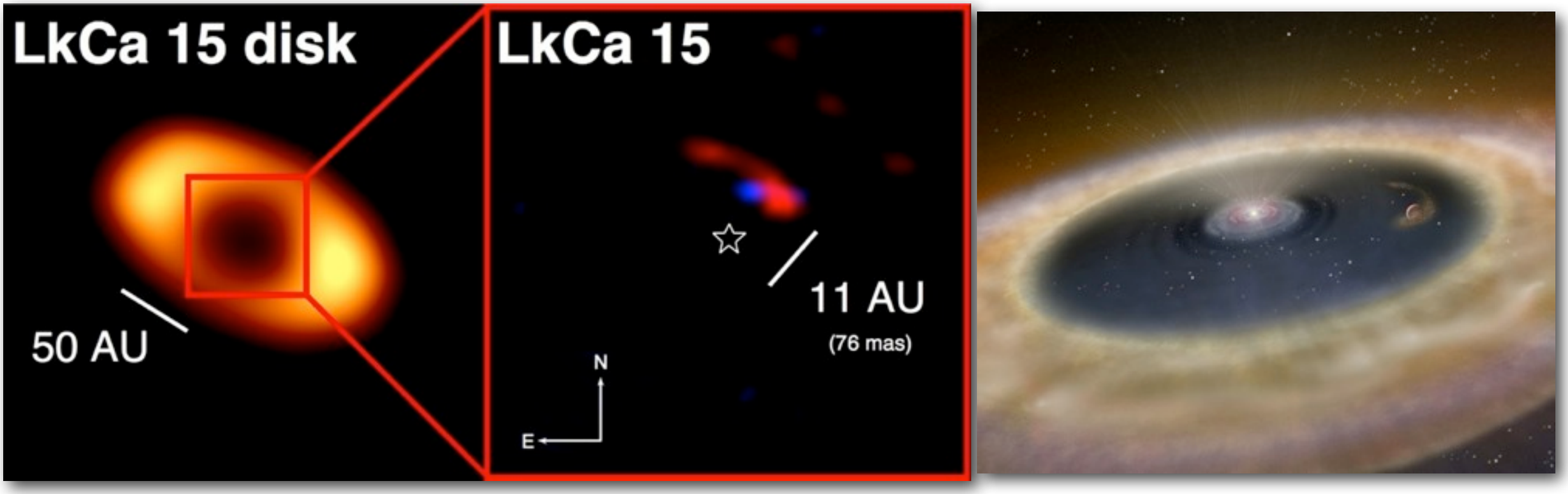
T Cha: a planet forming disk?





Transition disks caused by planets are great candidates for direct imaging

Disks ⋯▸ Planets



Kraus & Ireland 2012

Merci ESA!

Herschel Observations of Protoplanetary Disks

- Herschel spectra reveals the *gas* in the gas giant planet forming zone of disks!
- Herschel photometry constrains dust properties and disk structure in the outer parts of protoplanetary disks
- M_{gas} > 1M_{Jup} for >40% of Class II disks in Taurus and Cha II (~1-3 Myr)
- dust/gas ratio varies by (at least) an order of magnitude
- warm H_2O from disk surface at R~ few AU is found in many T Tauri disks

➡ **disks are diverse...**

...how does this relate to the diversity of exoplanets?