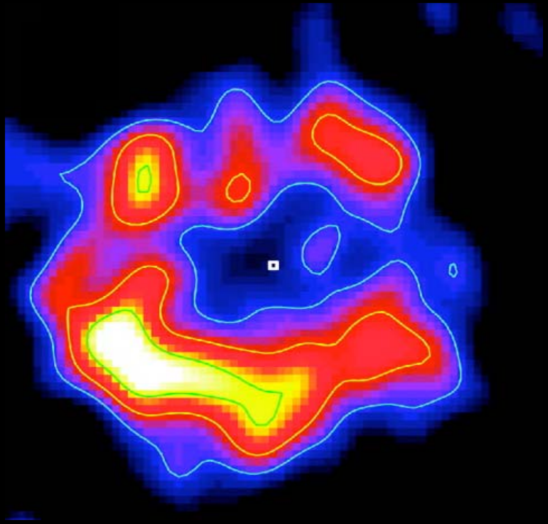
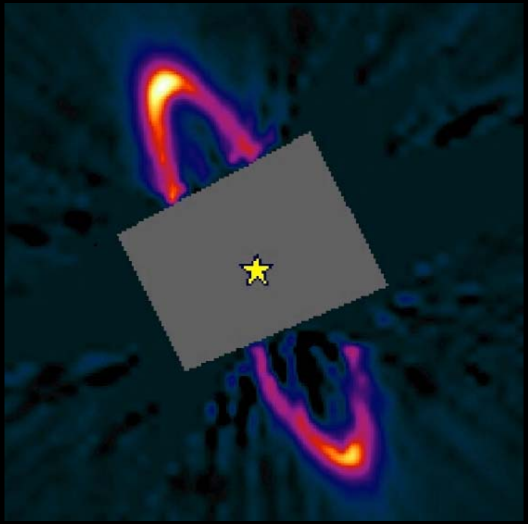
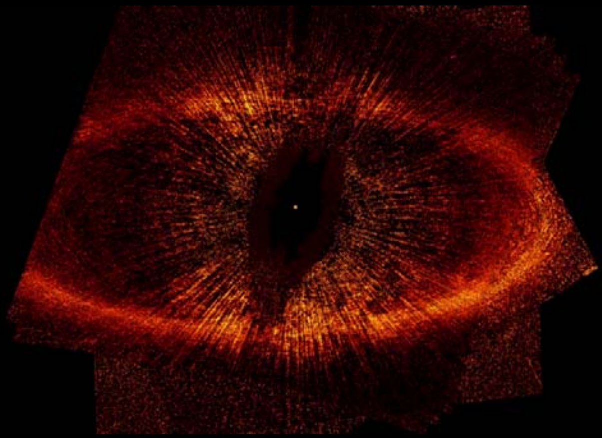
Debris Disks :

The Late Stages of Planetary System Formation

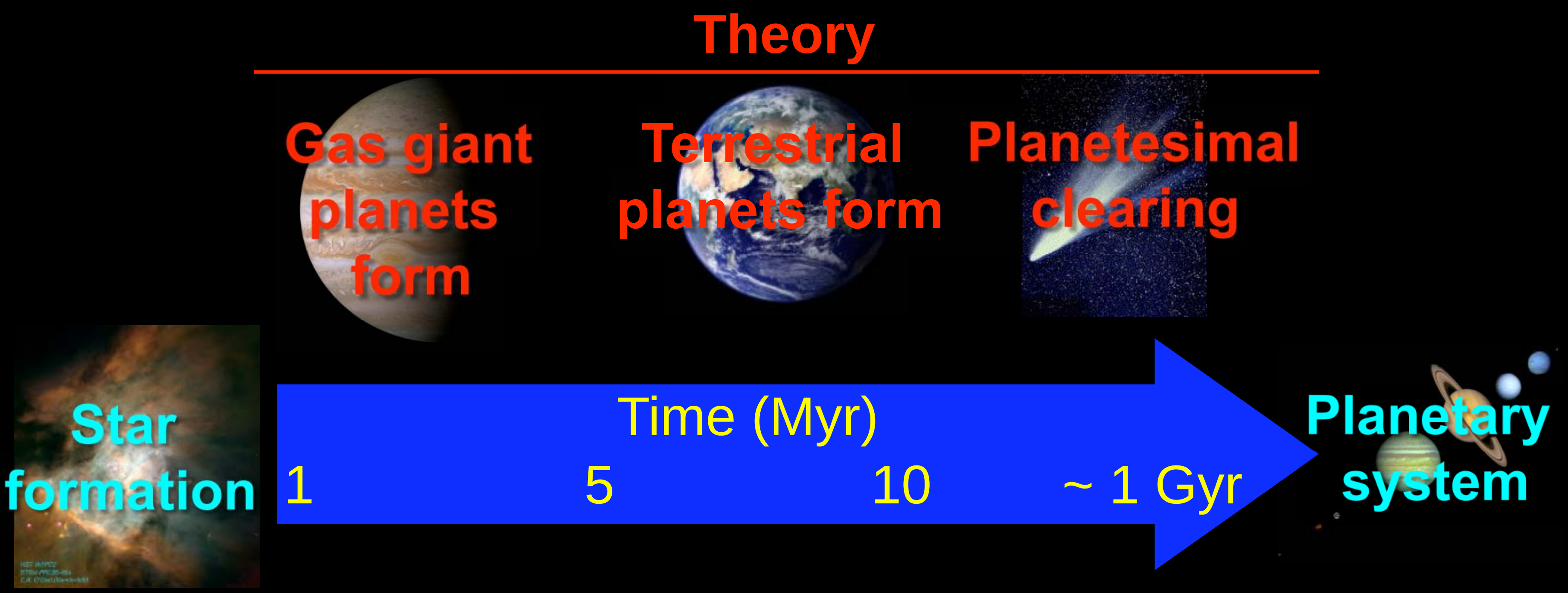
Aki Roberge (NASA GSFC)



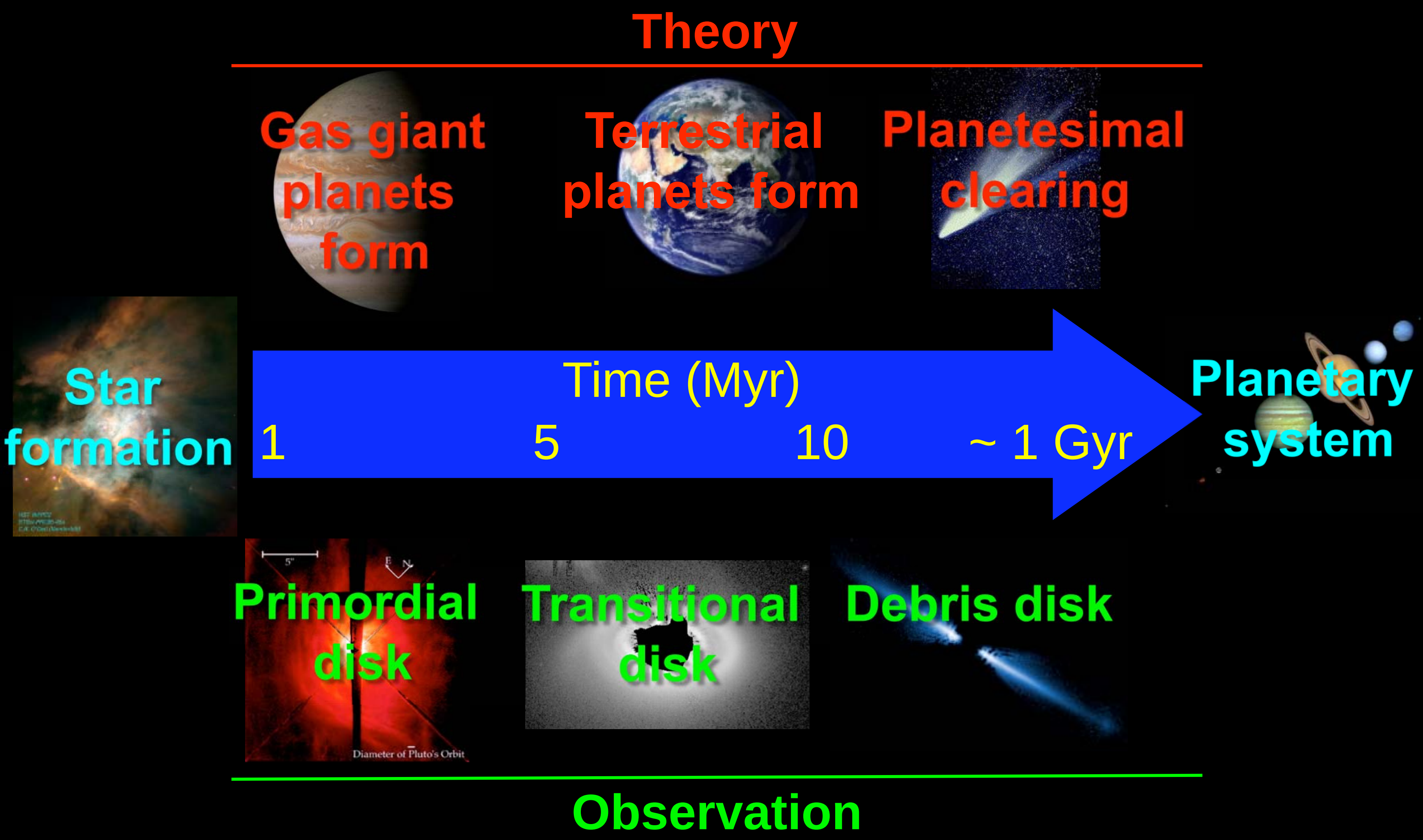




Formation of Planetary Systems



Disk Evolution



Disk Evolution

10 – 100 $M_{Jupiter}$ **few M_{Lunar} (dust)**

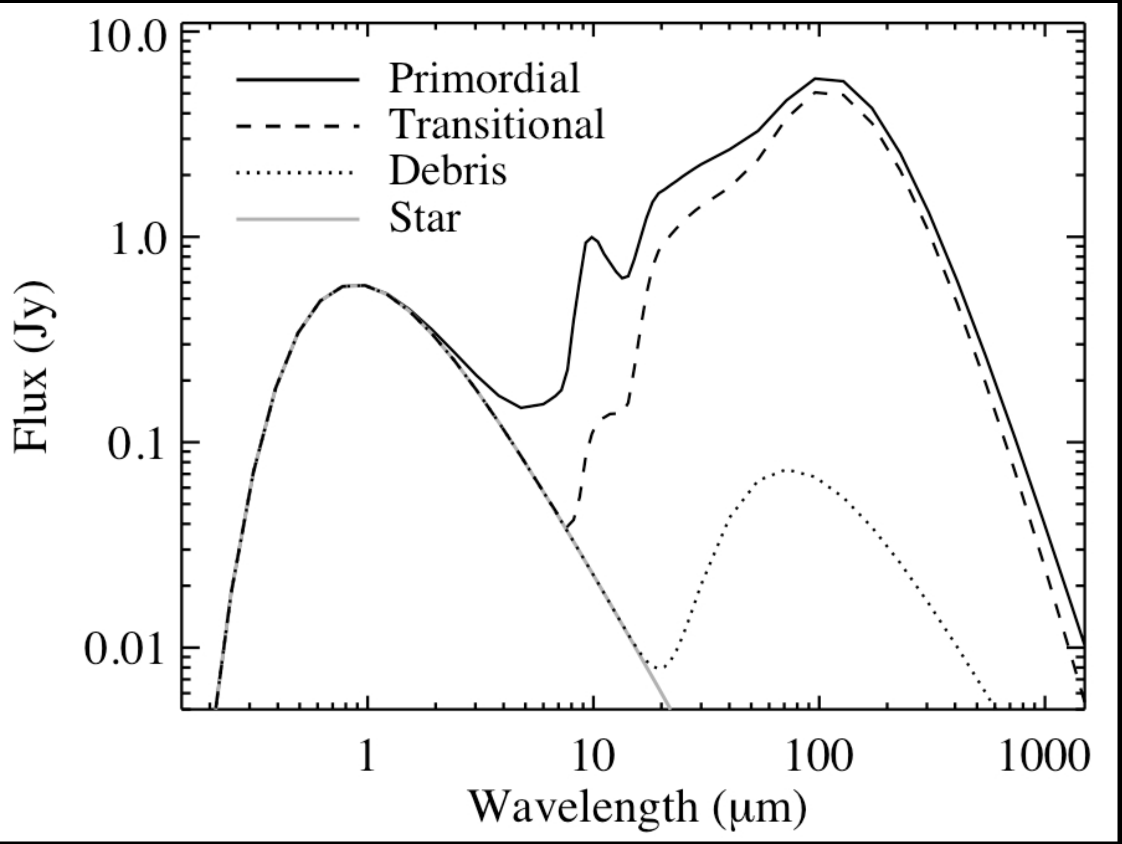
Total Mass

Time (Myr)

1 5 10 ~ 1 Gyr

Observation

Dust Evolution: Disk SEDs



Primordial & transitional models: CGPlus code (Dullemond et al. 2001)
Debris disk model: 70 K blackbody

- Debris disk L_{IR}/L_{star} < 10^{-5} to 10^{-3}

Gas Evolution

10 – 100 $M_{Jupiter}$ **few M_{Lunar} (dust)**

Total Mass

10 – 100 $M_{Jupiter}$ **?**

Gas Mass

Time (Myr)

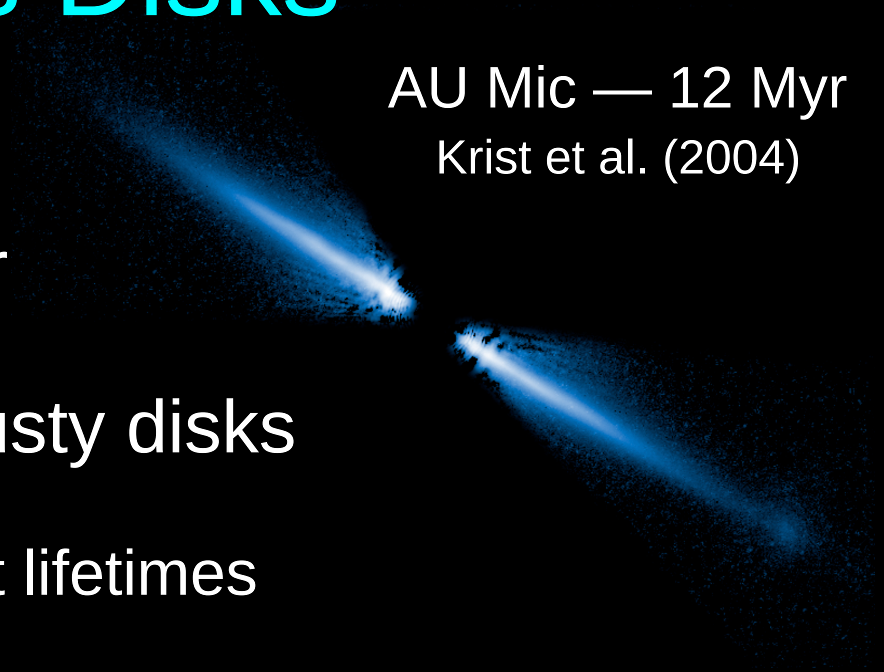
1 5 10 ~ 1 Gyr

Observation

Debris Disks

- Wide age range :

  5 - 10 Myr   to   > 1 Gyr

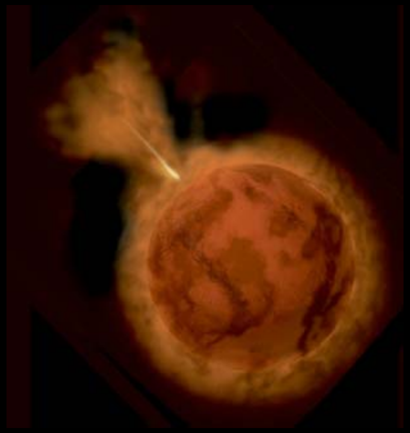


AU Mic — 12 Myr
Krist et al. (2004)

- Gas-poor, low-mass dusty disks
  - Optically thin, short dust lifetimes
- Secondary material from asteroids & comets
- Delivery of volatiles to

  terrestrial planet surfaces

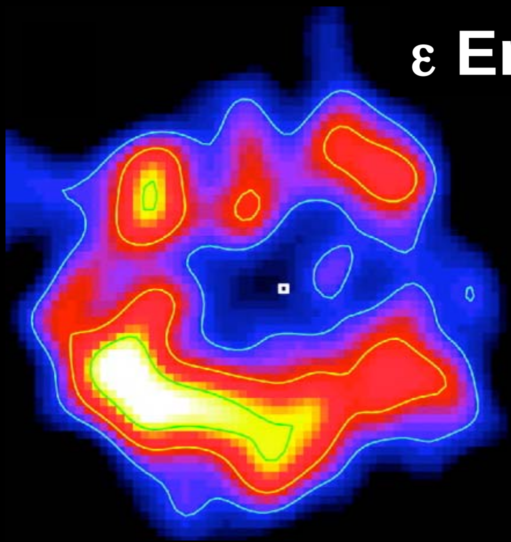
  (e.g. Morbidelli et al. 2000)



Dust Structures

Clumps

ε Eridani @ 850 μm

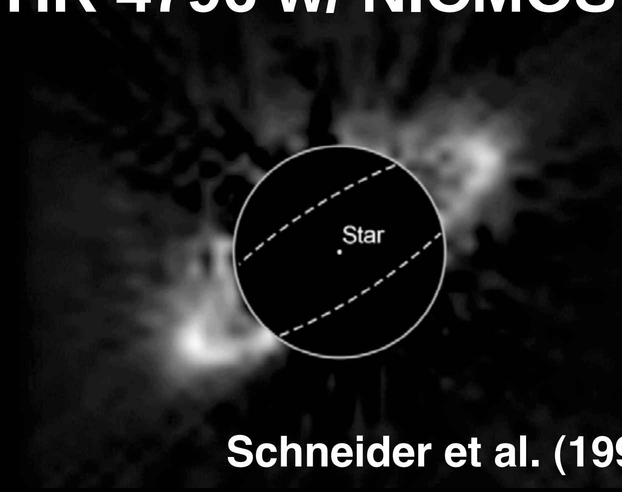


Greaves et al. (2005)

Caused by planets

Rings

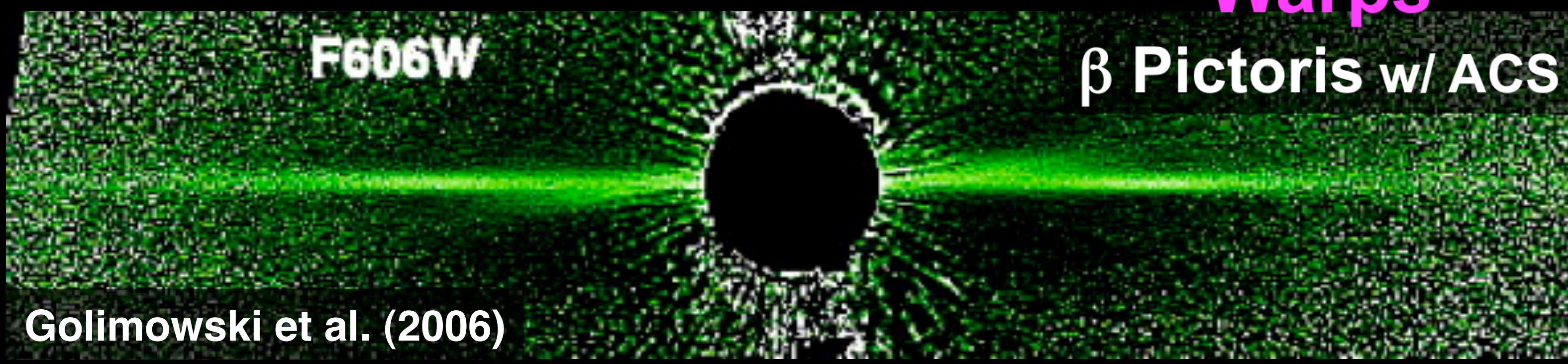
HR 4796 w/ NICMOS



Schneider et al. (1999)

Warps

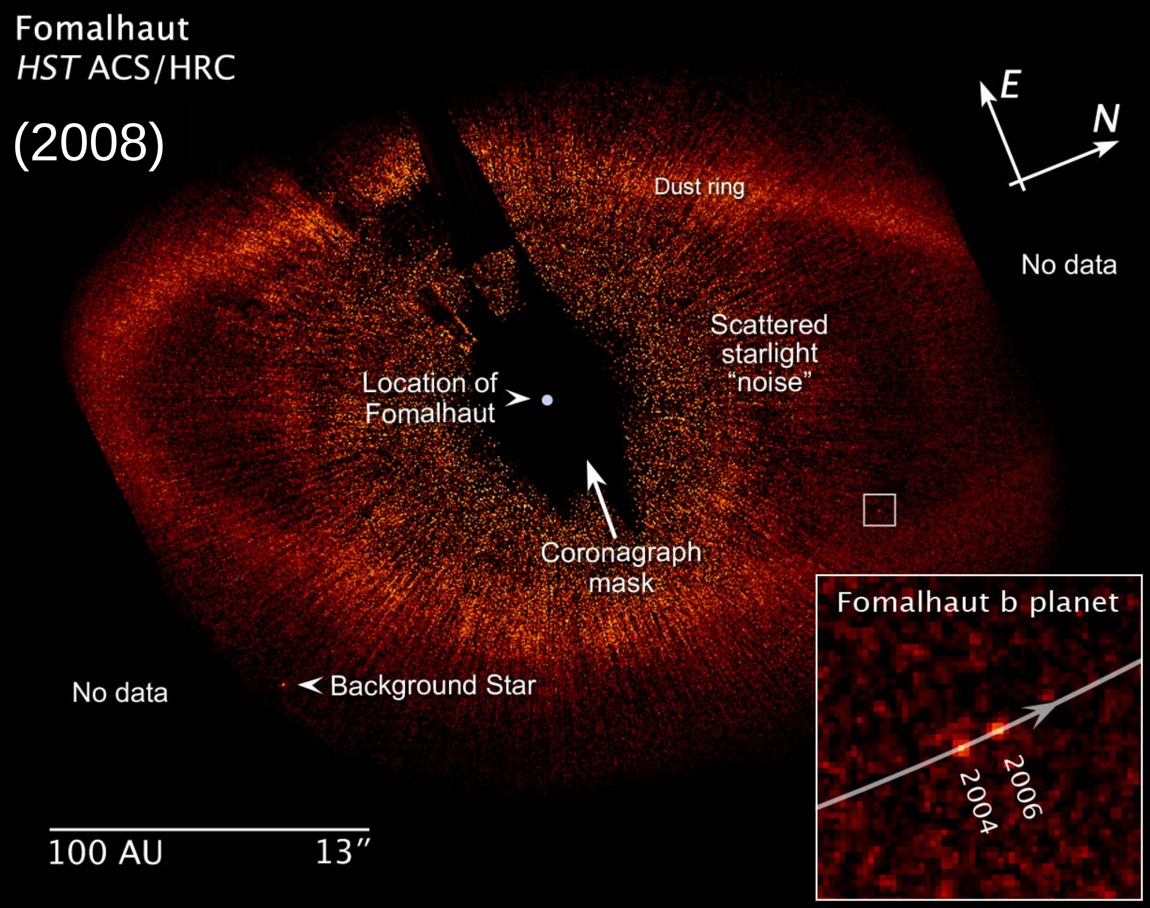
β Pictoris w/ ACS



Golimowski et al. (2006)

Fomalhaut b

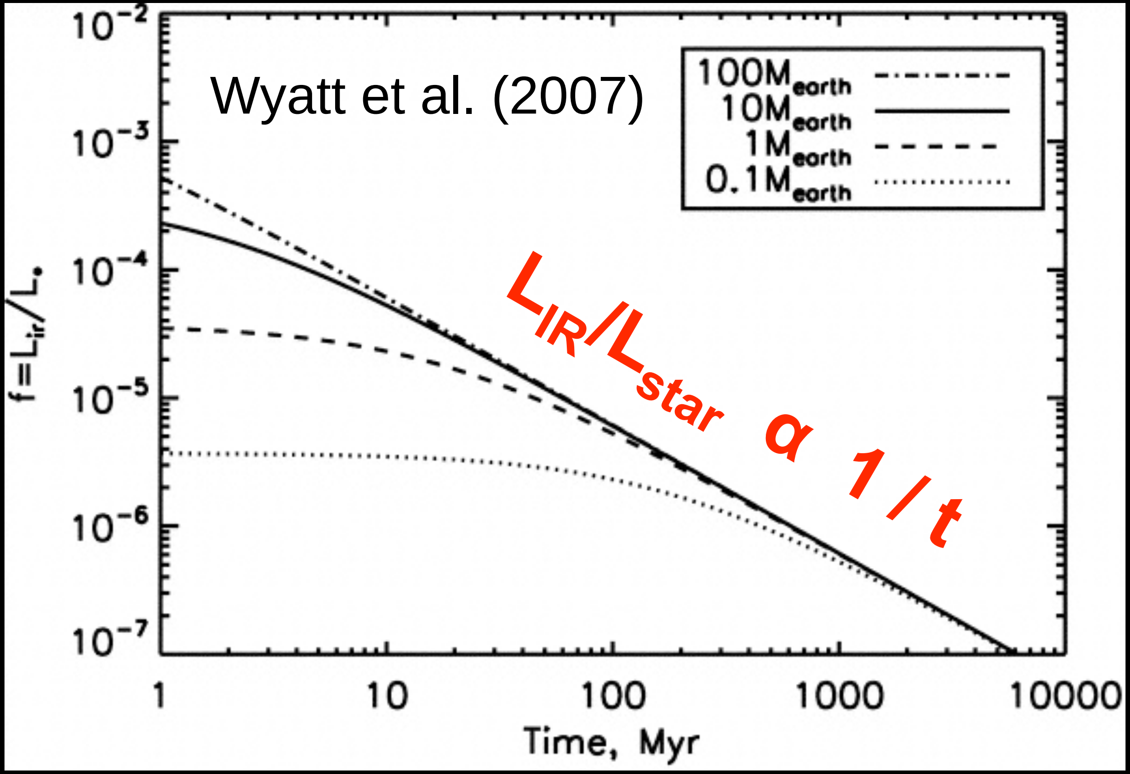
Kalas et al. (2008)



Debris ring morphology indicates $M_{planet} < 3\ M_{jupiter}$

(Chiang et al. 2008)

Debris Dust Evolution Theory



- Collisional cascade between planetesimals
- General behavior broadly consistent with debris disks surveys (e.g. Najita & Williams 2005, Su et al. 2006)

Primordial Gas in Debris Disks?

- Lifetime of primordial gas limits the timescale for giant planet formation, controls planet migration
- Only one debris disk w/ sub-mm CO detection (49 Ceti ; e.g. Dent et al. 2005)
- Sensitive upper limits on H_2 (e.g. Lecavelier des Etangs et al. 2001, Roberge et al. 2005)
- Gas giant formation no longer possible

Herschel Open Time Key Project

- "Gas in Protoplanetary Systems" (GASPS)

  PI: W. Dent (UKATC / ALMA JAO)

  – 400 hours for about 250 late B to M stars, ages = 1 – 30 Myr

  – Primordial through young debris disks

- [C II], [O I], H_2O + ProDiMo code to get disk gas masses

  (Woitke, Kamp, & Thi 2009)

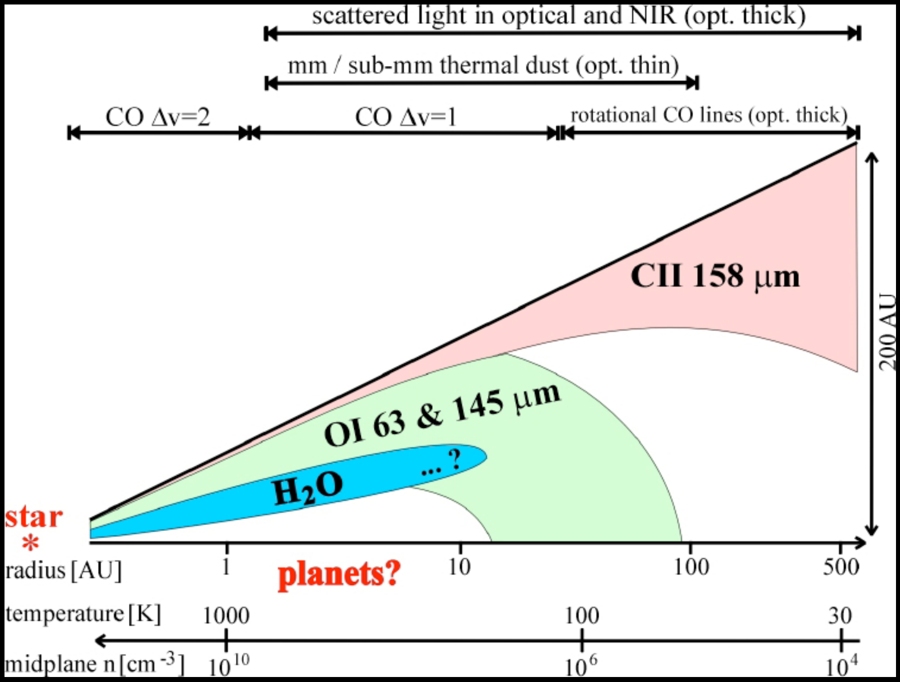
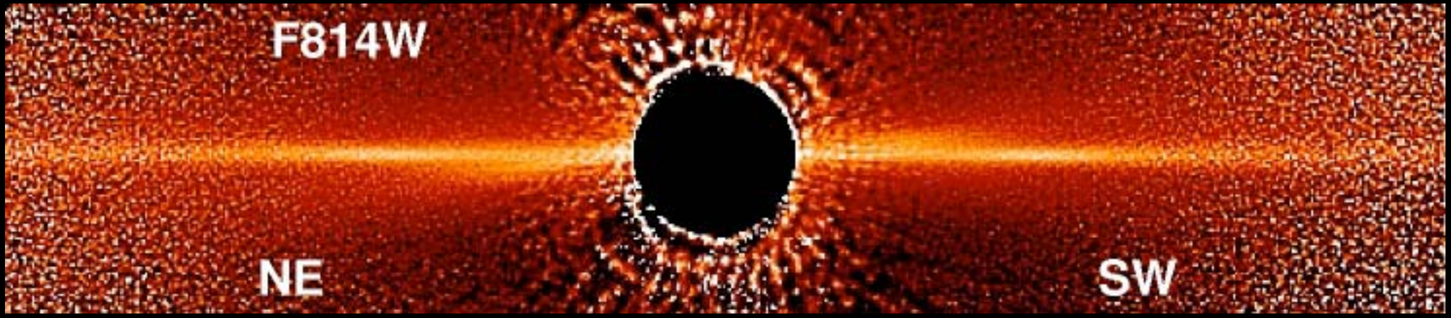


Image credit : I. Kamp

Secondary Gas in Debris Disks

- Debris disks w/ gas : Beta Pic, Sig Her, 51 Oph, 49 Cet, HD32297, HD118232, HD158352, HD21620
  - Mostly atomic & ionic
  - Secondary gas from planetesimals
  - Usually detected with UV/optical absorption spectroscopy of edge-on disks

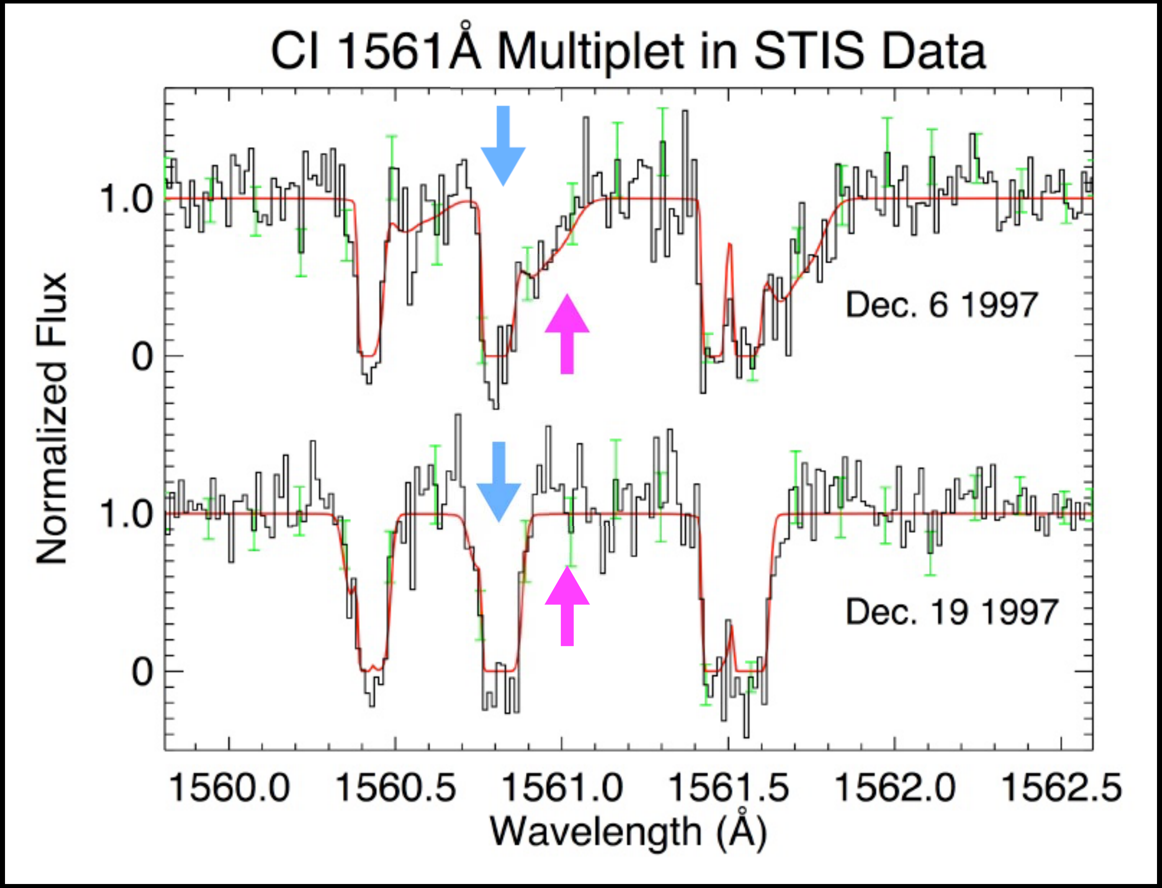
Beta Pictoris Golimowski et al. (2006)



Secondary Gas in Debris Disks

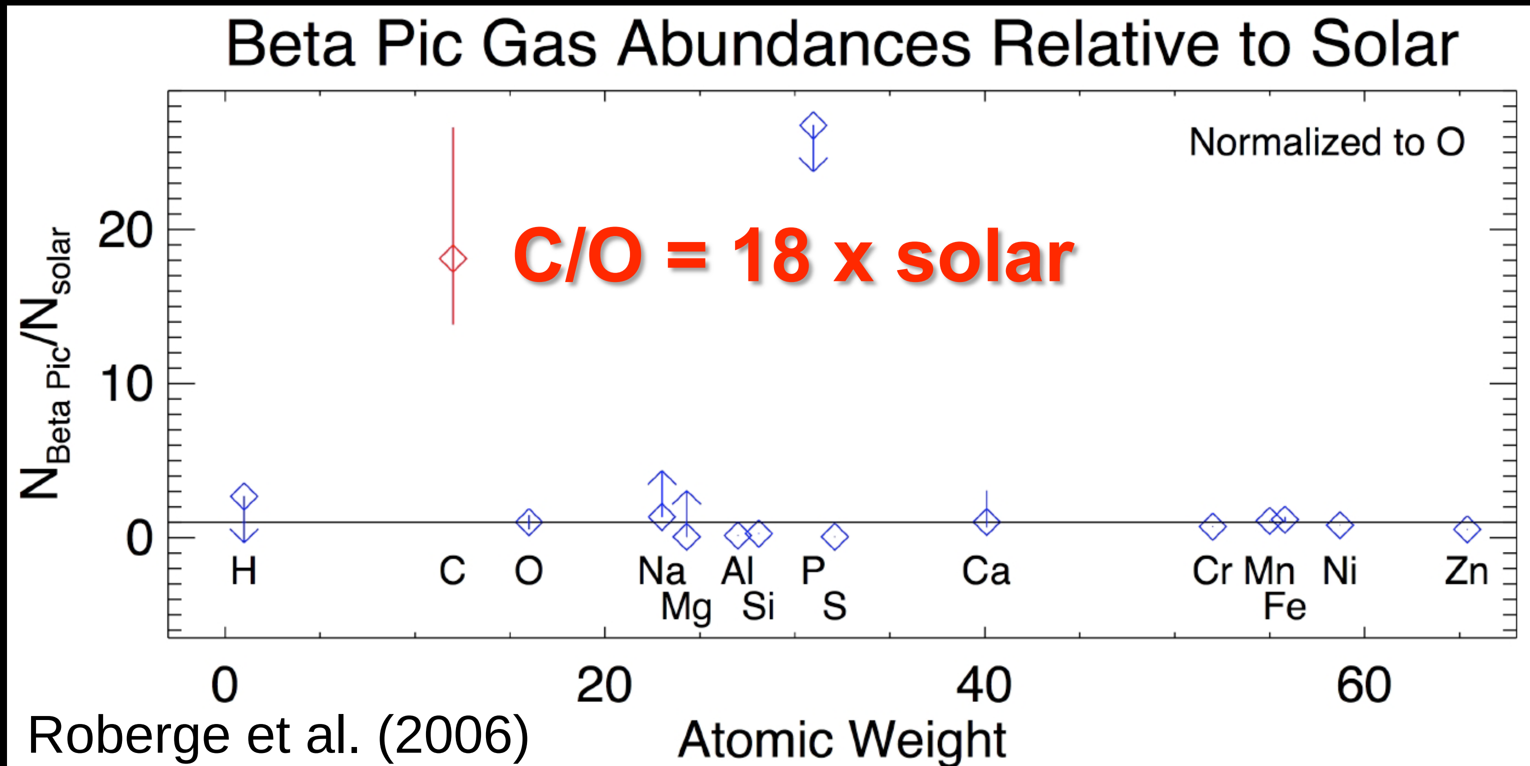
Narrow unvarying features at $v = v_\star$: stable gas

Variable redshifted features : star-grazing planetesimals



Roberge et al. (2000)

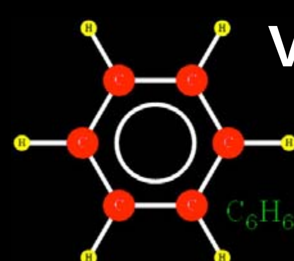
Beta Pic Gas Composition



Comet Halley Dust

C/O ~ 1.8 x solar

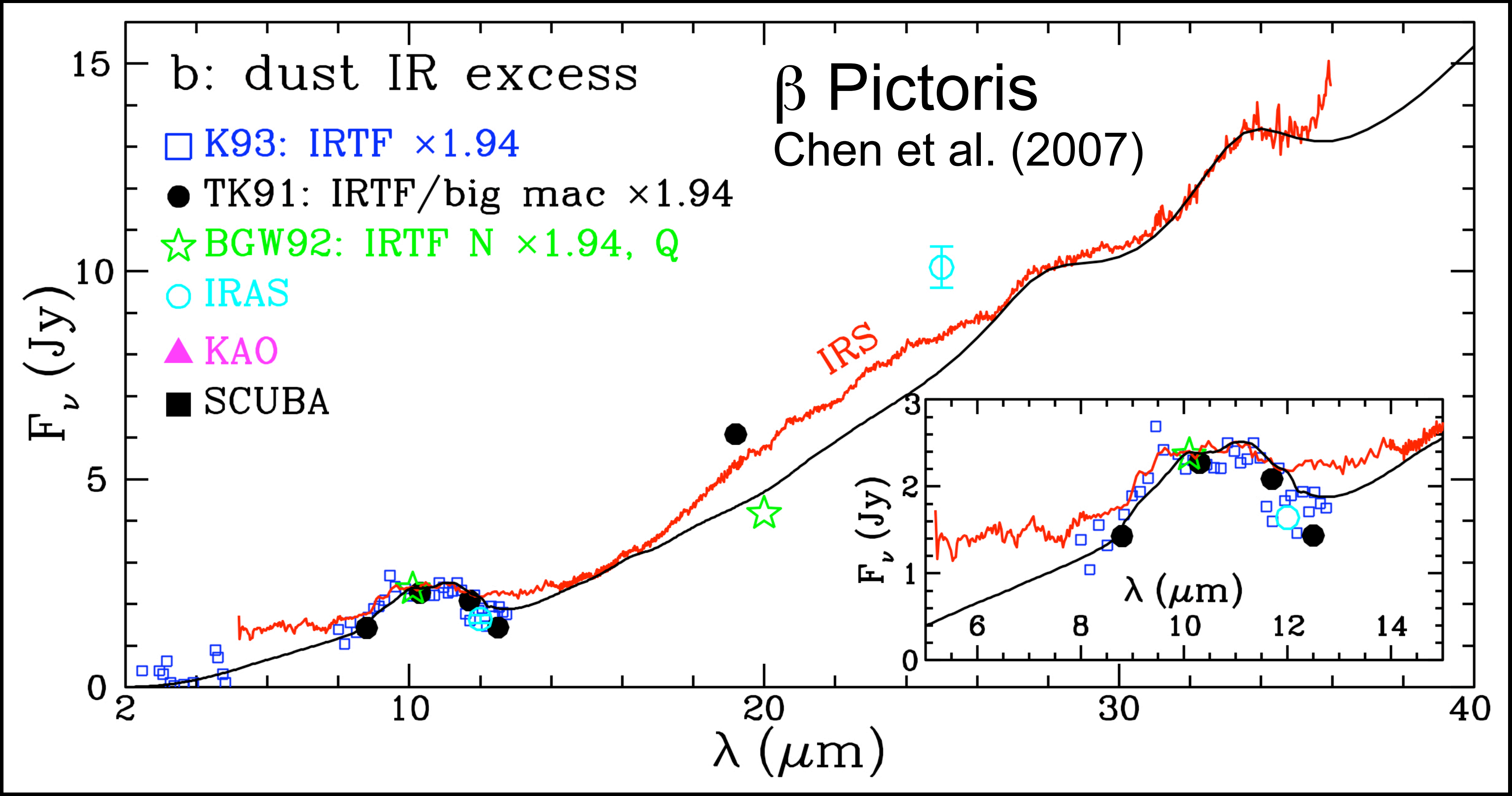
(Jessberger et al. 1988)



Volatile organics?

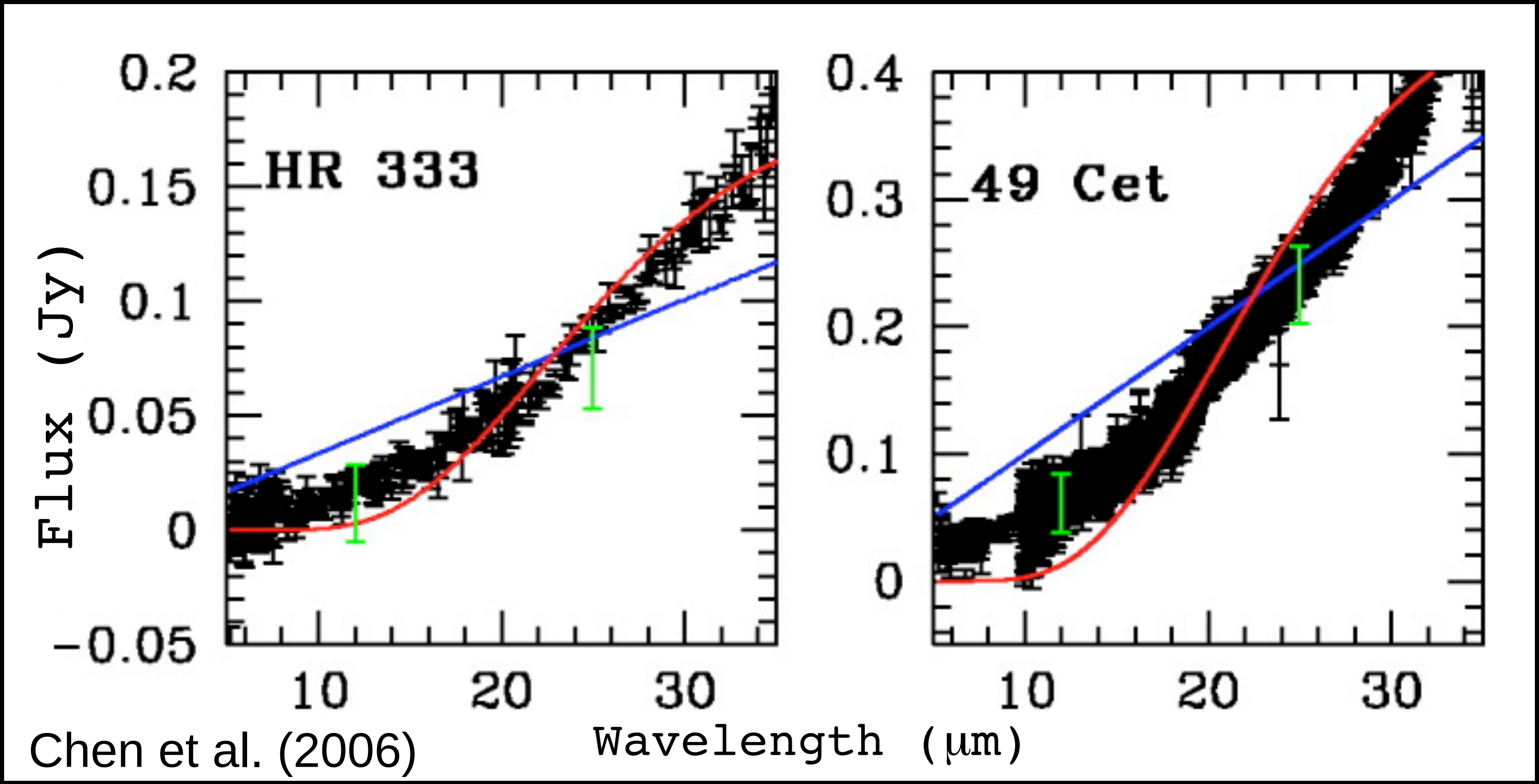
Carbon-rich planetesimals?

Dust Composition from Mid-IR Spectra



Small, warm amorphous & crystalline silicates

Dust Composition from Mid-IR Spectra

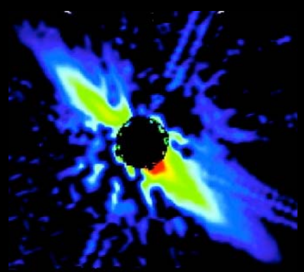


Cold grains, large grains ➙ featureless spectra

➙ no composition info.

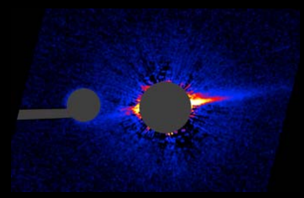
Scattered Light Colors

HD 32297
Blue
Schneider et al. (2005)

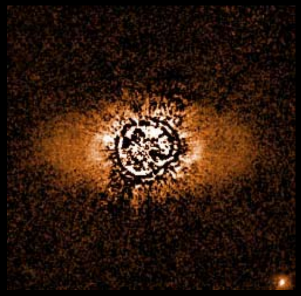


AU Mic
Blue
Krist et al. (2005)

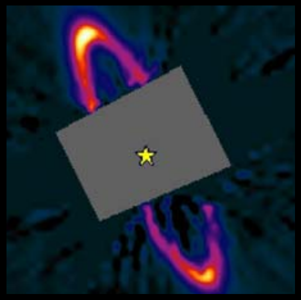
HD 15115
Blue
Kalas et al. (2007)



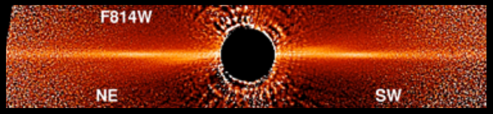
HD 92945
Neutral
Golimowski et al., in prep.



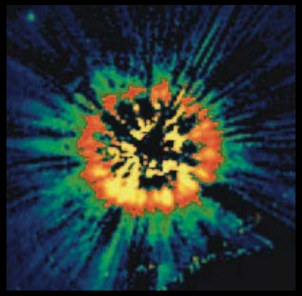
HR 4796A
Red
Schneider et al., in prep.



Beta Pic
Red
Golimowski et al. (2006)



HD 181327
Red
Schneider et al. (2006)



HD 107146
Red
Ardila et al. (2004)

Zodi and Exozodi

- Sun has a debris disk
  - Zodiacal dust comes from comets & asteroids
- Solar System now : 1 zodi
  - $L_{IR}/L_{star} = 10^{-7}$ for dust interior to asteroid belt
- Solar System over last 100 Myr : 0.5 – 2 zodis (Kuchner & Farley 2010)

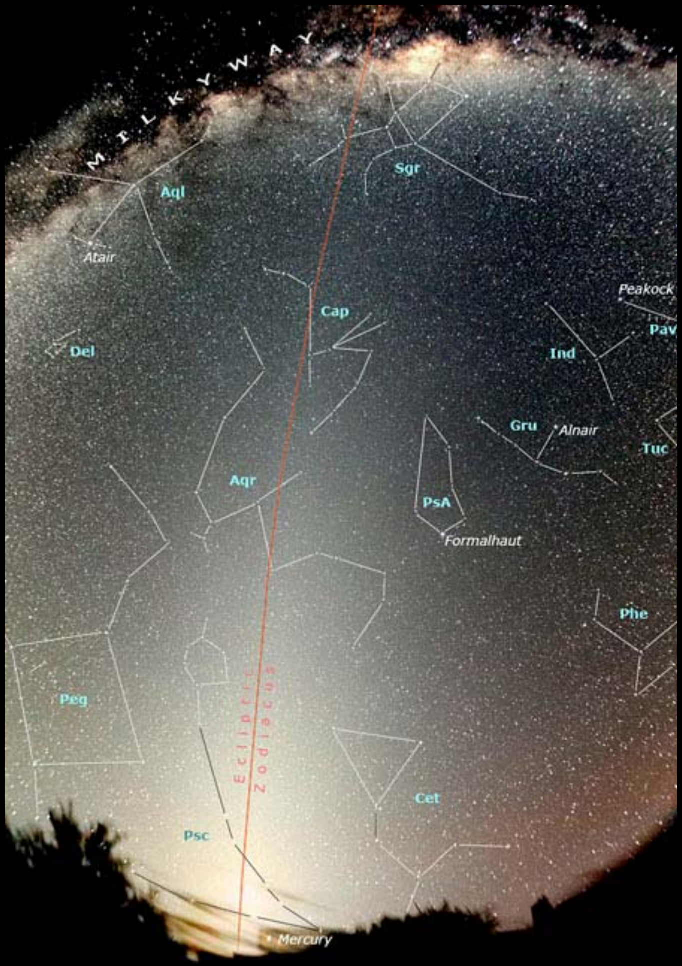
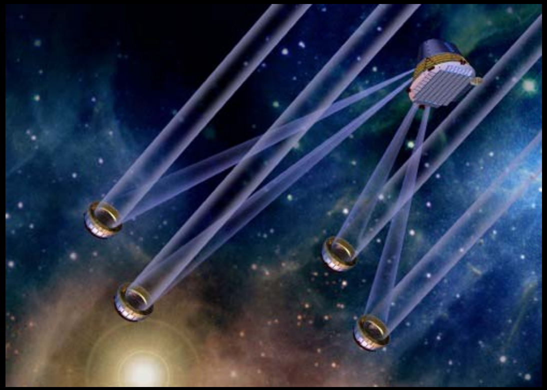
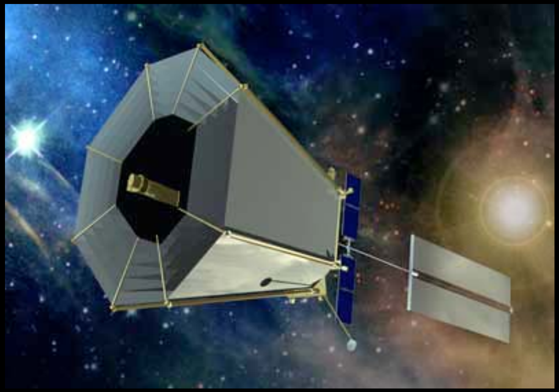


Image credit: Stefan Seip

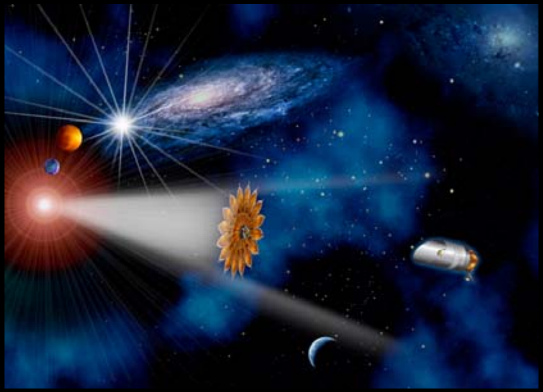
Imaging Habitable Planets



Interferometer
(near-IR)



Internal Coronagraph
(optical)



External Occulter
(optical)

- $F_{Earth}/F_{Sun} \sim 10^{-10}$, $r < 100$ mas at 10 pc
- Interferometer needs < 15 zodis (Defrere et al. 2009)
- Detection limit : > 1000 zodis in habitable zone (Beichman et al. 2006)
- Confusion: "Is that a planet or a dust clump ?"