EXOZODIACAL DUST AROUND NEARBY STARS

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and the **EXOZODI team**:
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and many others

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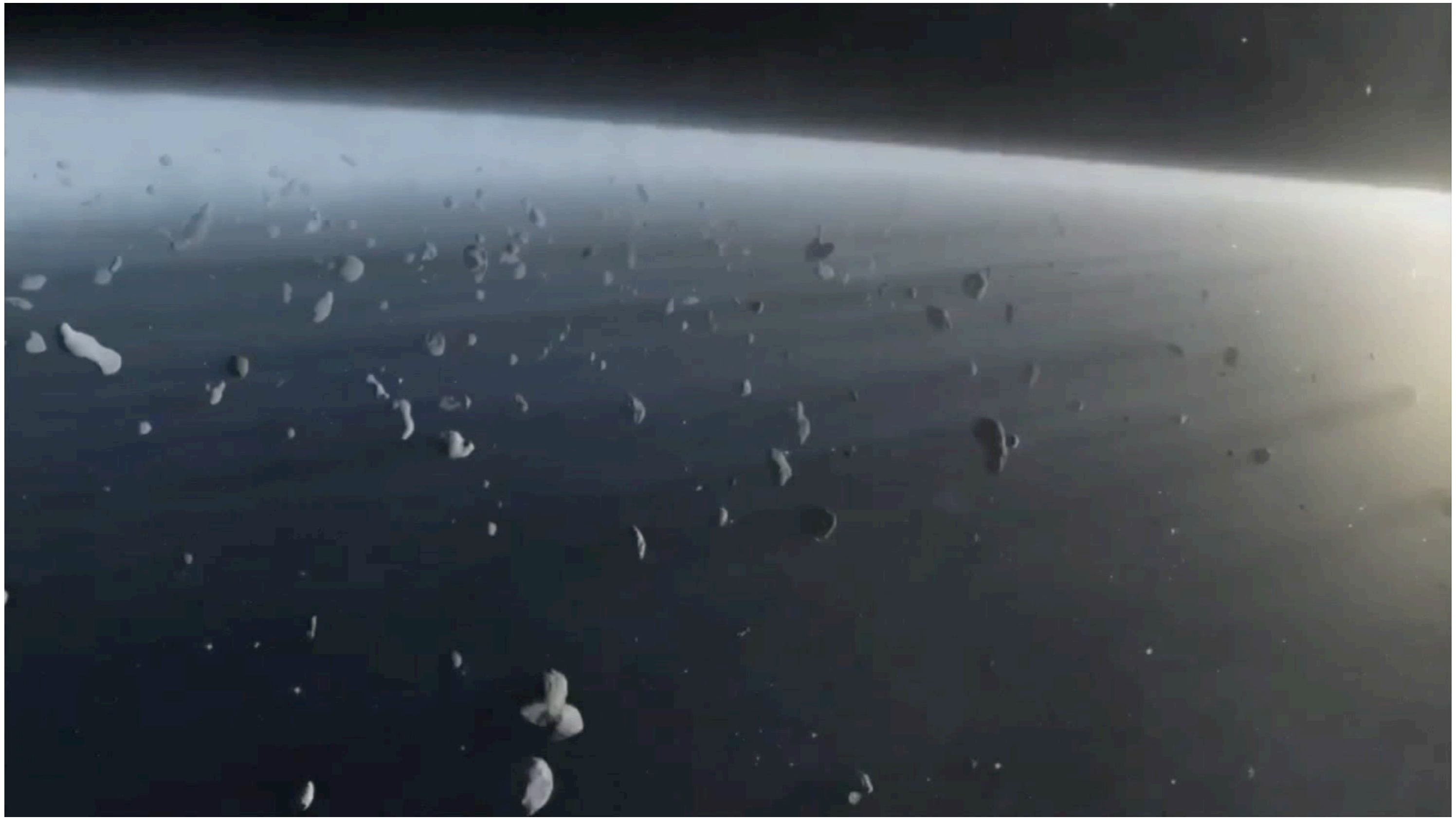
The solar system

- **Planets and small bodies (asteroids, comets)**

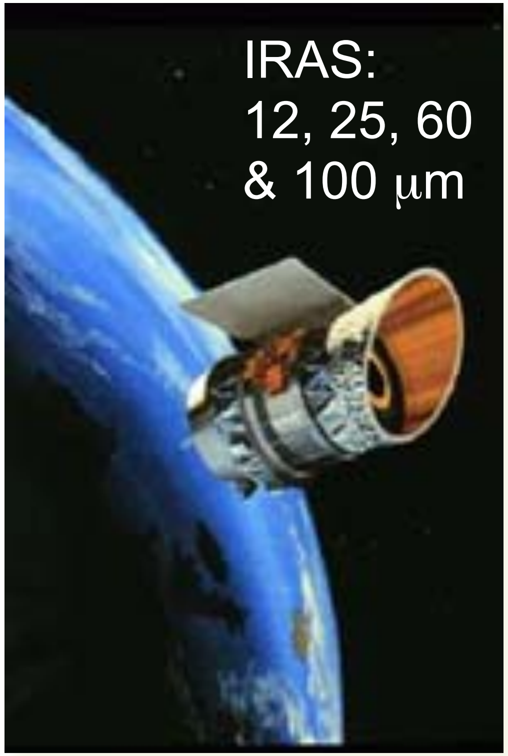
Extrasolar planetary systems

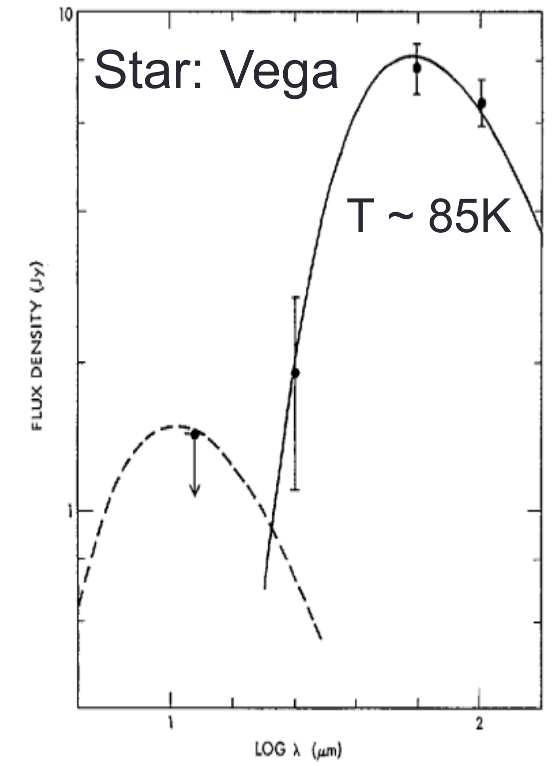
- **Extra-solar planets:** detected since the early 1990's
- **Exo-asteroids and exo-comets :** detected since the early 1980's
  - we don't see them directly
  - but they produce dust that can be detected : debris disks



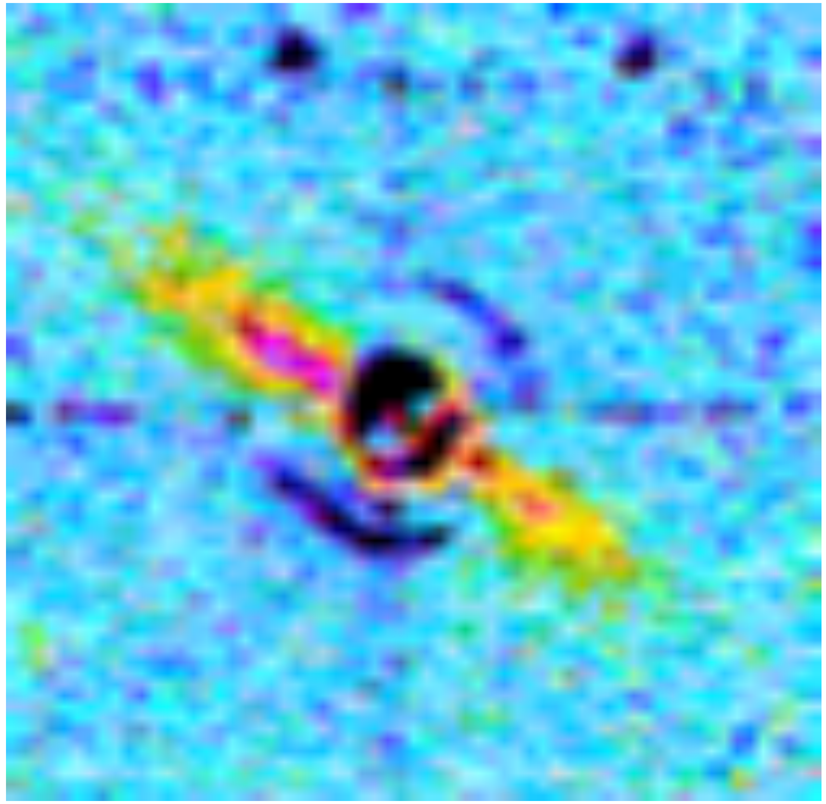
The discovery of debris disks

- Dust around main sequence stars has been discovered by accident in 1983
- At that time, these dust disks were thought to trace the last stages of planet formation





Star: Beta Pictoris

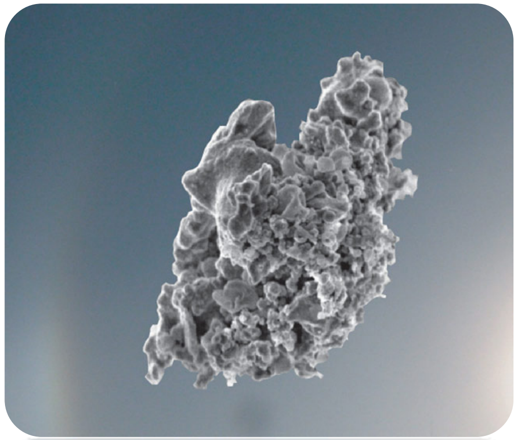


The origin of the dust in debris disks

- **Analysis of the dust emission in the mid-1980's:**
  - low-mass dust disks : not enough mass to form new planets
  - density is low : optically thin dust disks.
  - grains are small and short-lived : collisional replenishment

- **Debris disks = populations of extrasolar comets / asteroids**

Planet formation (protoplanetary disks)

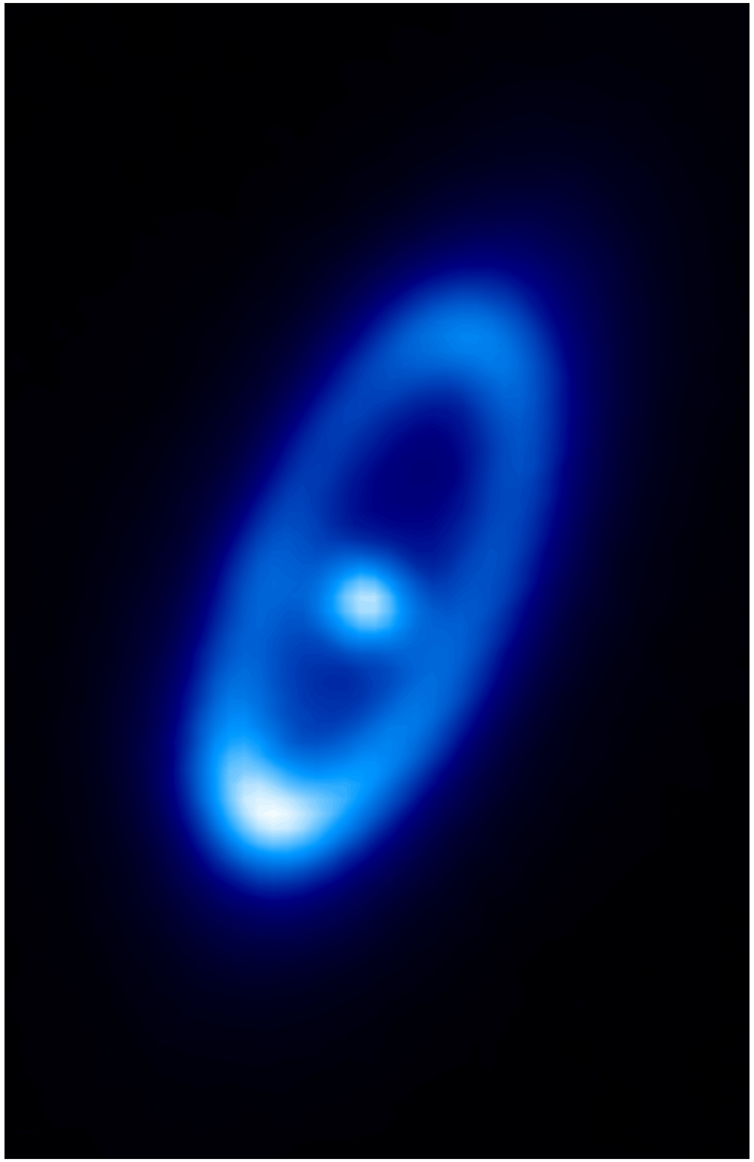


Collisional erosion (debris disks)

The incidence of debris disks

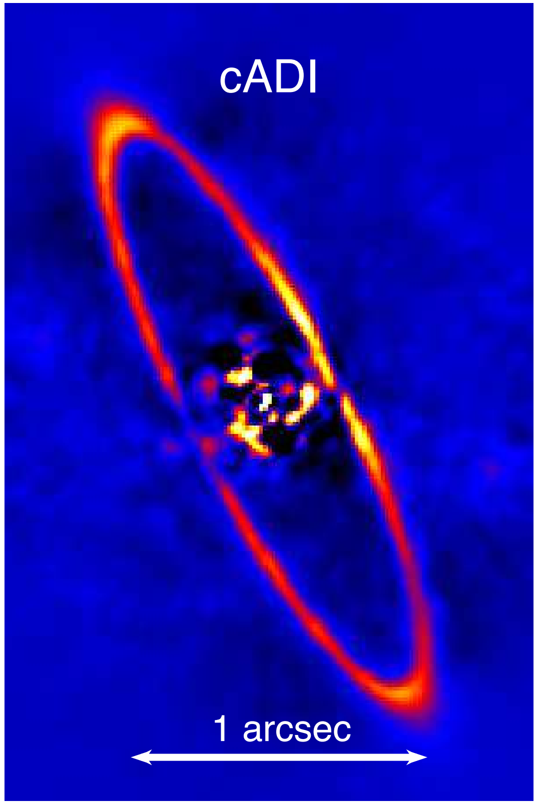
- **Herschel** Space Observatory (ESA):
  - 22% of nearby F, G, K stars have a debris disk
  - Stars from a few 10Myr to a few Gyr

Star: Fomalhaut

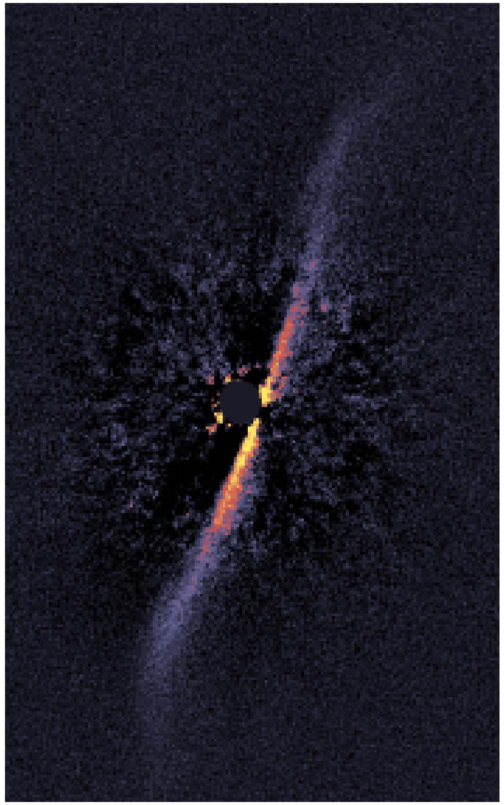


Direct imaging

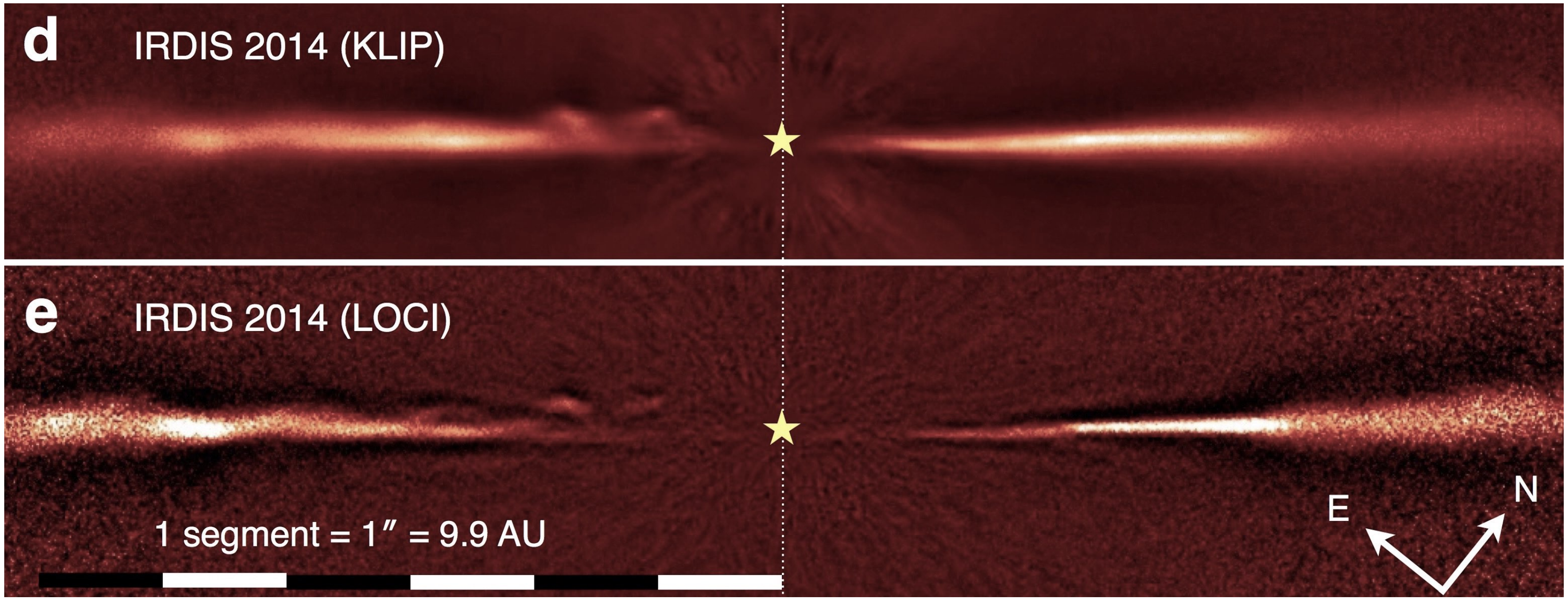
- **VLT/SPHERE** observations



Milli et al. 2016



Olofsson et al. 2016

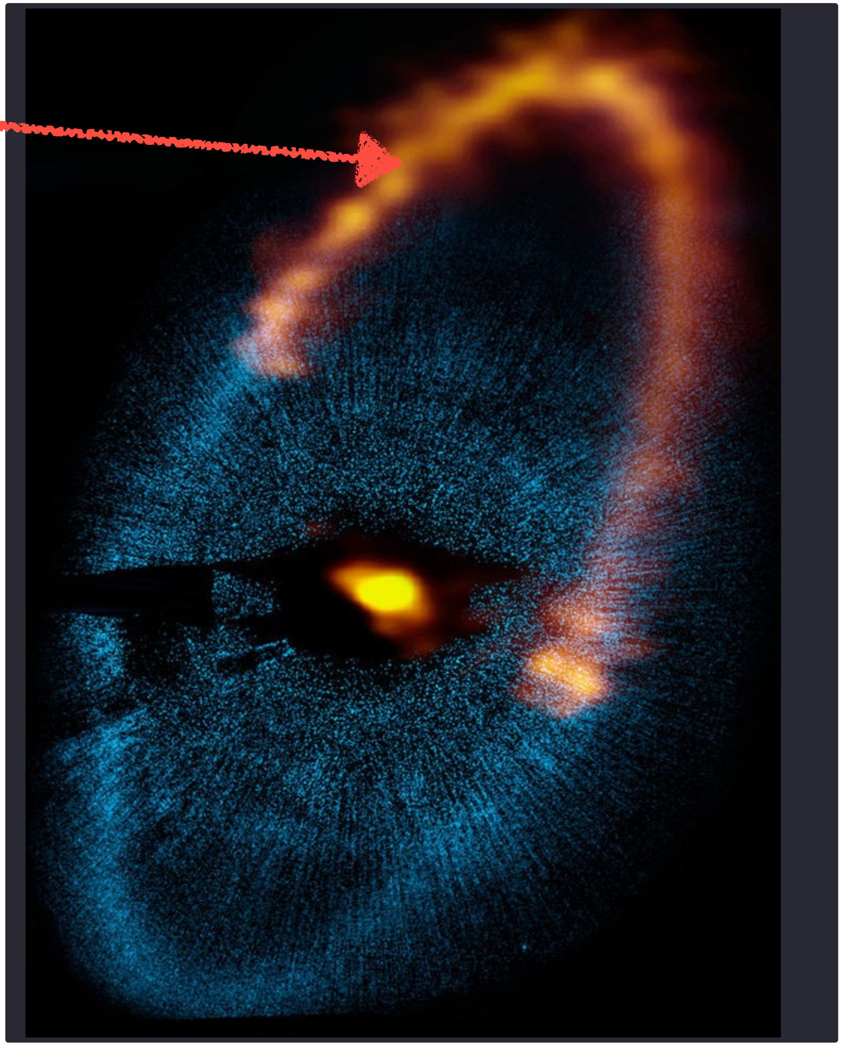


Boccaletti et al. 2015

Exozodiacal dust. What's that?

Star Fomalhaut : composite HST+ALMA image
Kalas et al. 2005, Boley et al. 2012

- **Cold, outer debris disks**
  — extrasolar Kuiper belts
  — discovered in the early 1980's
  — observed at almost all wavelengths,
  — rather well understood
  (but still a lot to learn)



Exozodiacal dust. What's that?

Star Fomalhaut : composite HST+ALMA image
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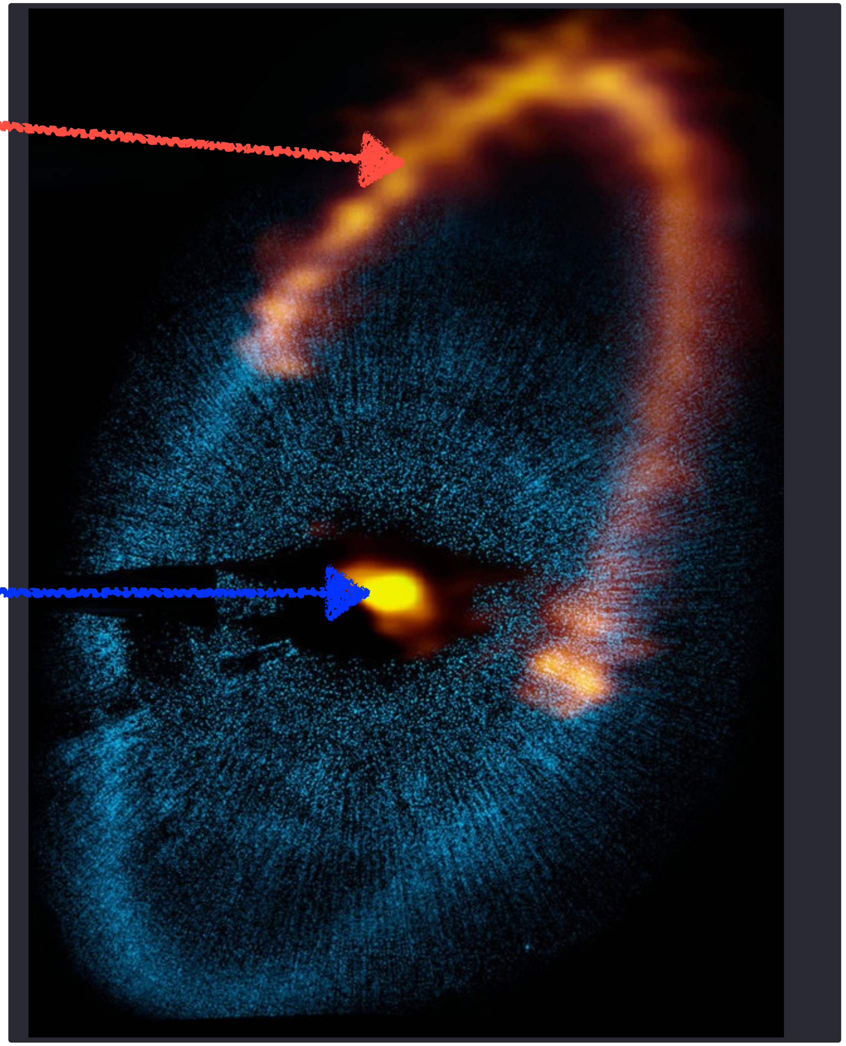


- **Cold, outer debris disks**
  — extrasolar Kuiper belts
  — discovered in the early 1980's
  — observed at almost all wavelengths,
  — rather well understood
  (but still a lot to learn)

- **Exozodiacal dust (or exozodi)**
  — extrasolar zodiacal clouds
  — discovered in the mid-2000's
  — refers to the hot and warm dust
  in the inner regions of planetary
  systems
  — poorly understood

Exozodis

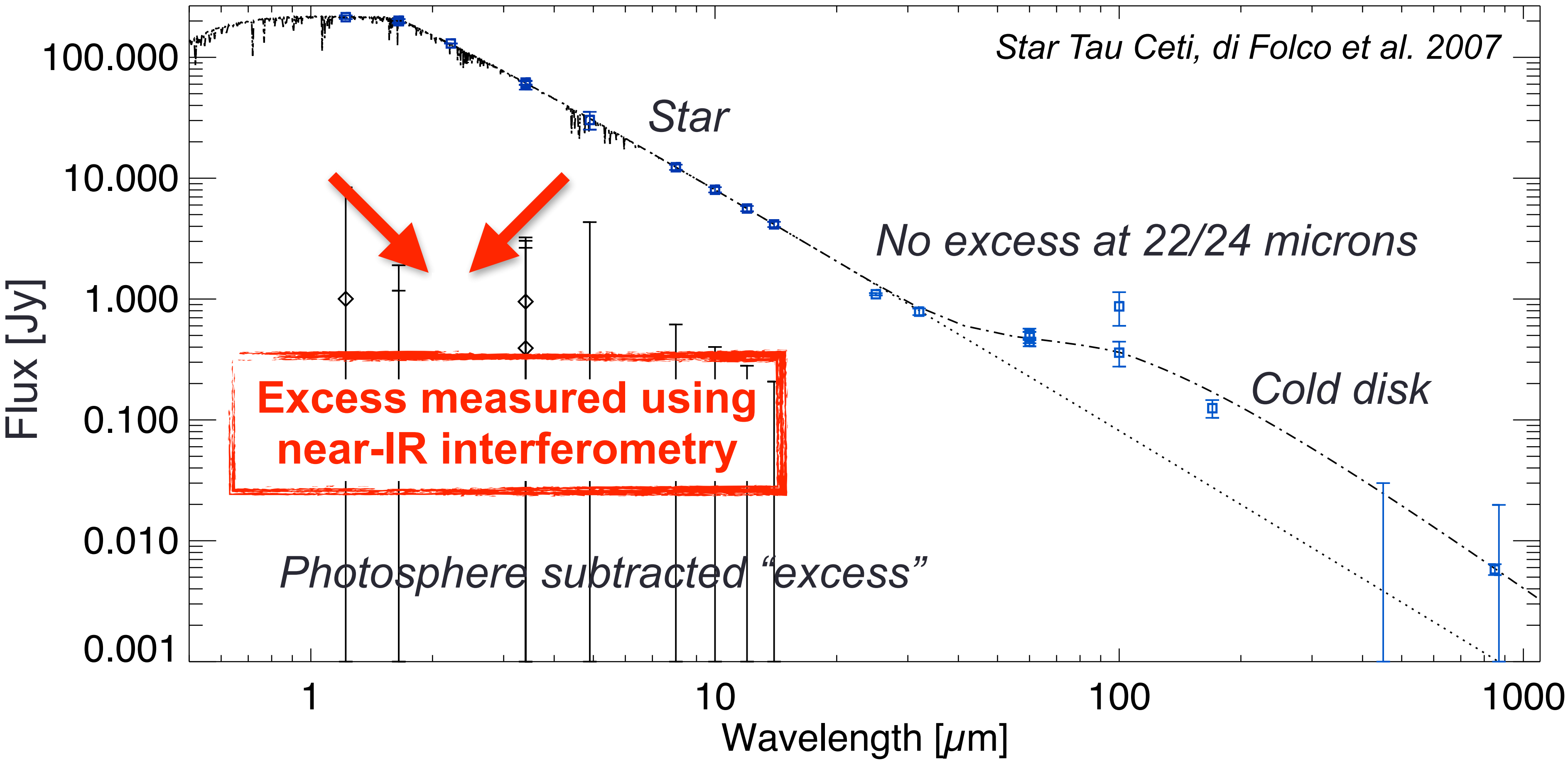
- **Zodiacal dust in the solar system:**
  - location : within a few AU
    (encompassing the habitable zone)
  - mass : tiny
    ($\sim 10^{-8} M_{Earth}$, or a medium-sized asteroid)
  - luminosity: high
    (most luminous circumsolar component)

- **Exozodiacal dust:**
  - how frequent?
  - basic properties?
  - origin?

- **The EXOZODI project:**
  1. near-IR interferometric surveys
  2. radiative transfer modelling
  3. N-body simulations
  4. New code: LIDT-DD (Kral et al. 2013/15)
     collisions AND dynamics in debris disks

1. Exozodi detection

- **How to detect exozodiacal dust?**
  - high contrast
  - high spatial resolution

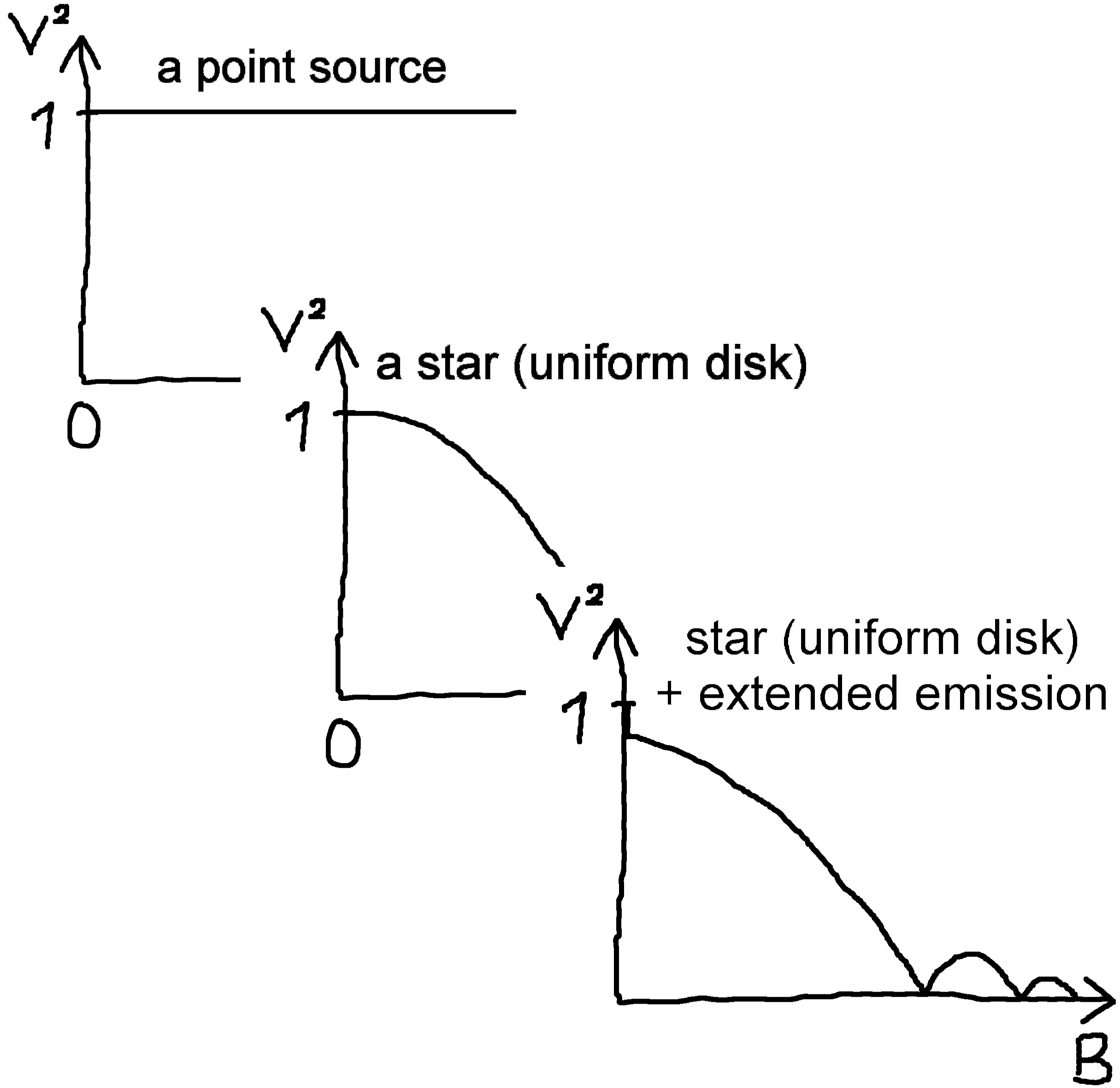


Exozodi detection

- V: Visibility = constrast of fringes
- B: Baseline = separation between 2 telescopes

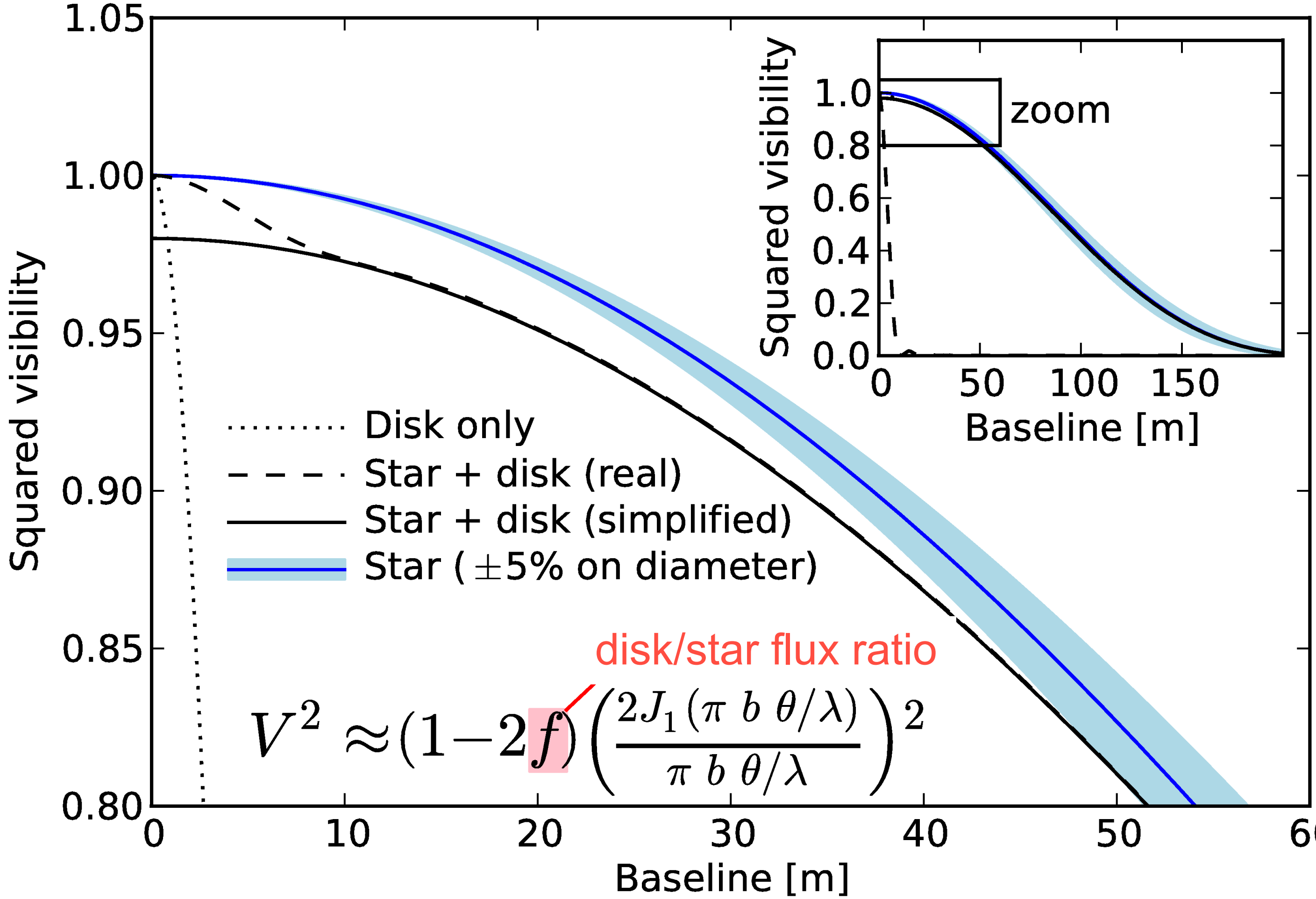
Courtesy: Steve Ertel

- Principle of exozodi detection with near-IR interferometry



Exozodi detection

- Principle of exozodi detection

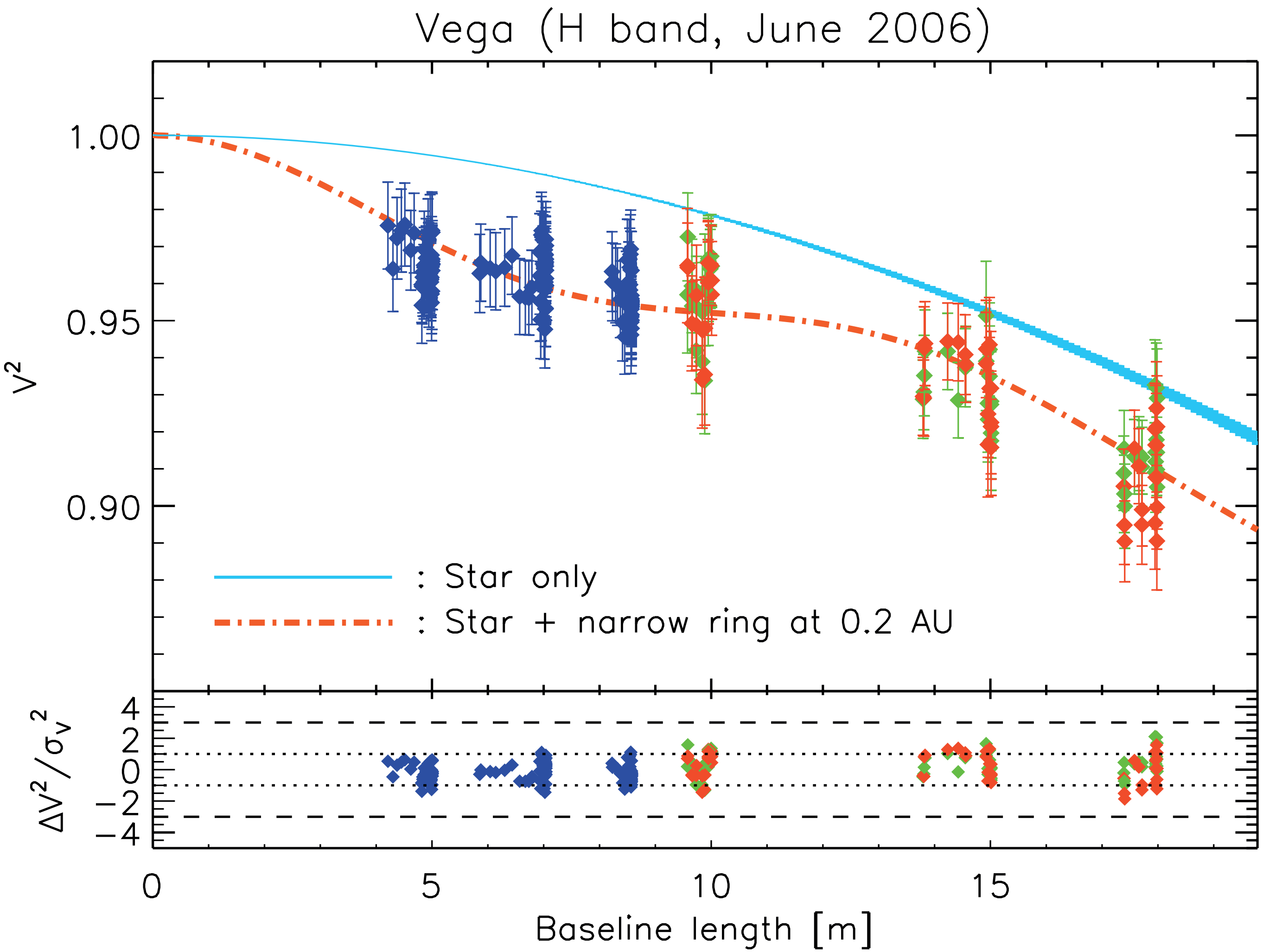


Courtesy: Steve Ertel

A real case example: Vega

Exozodi detection

- IOTA interferometer
- H-band

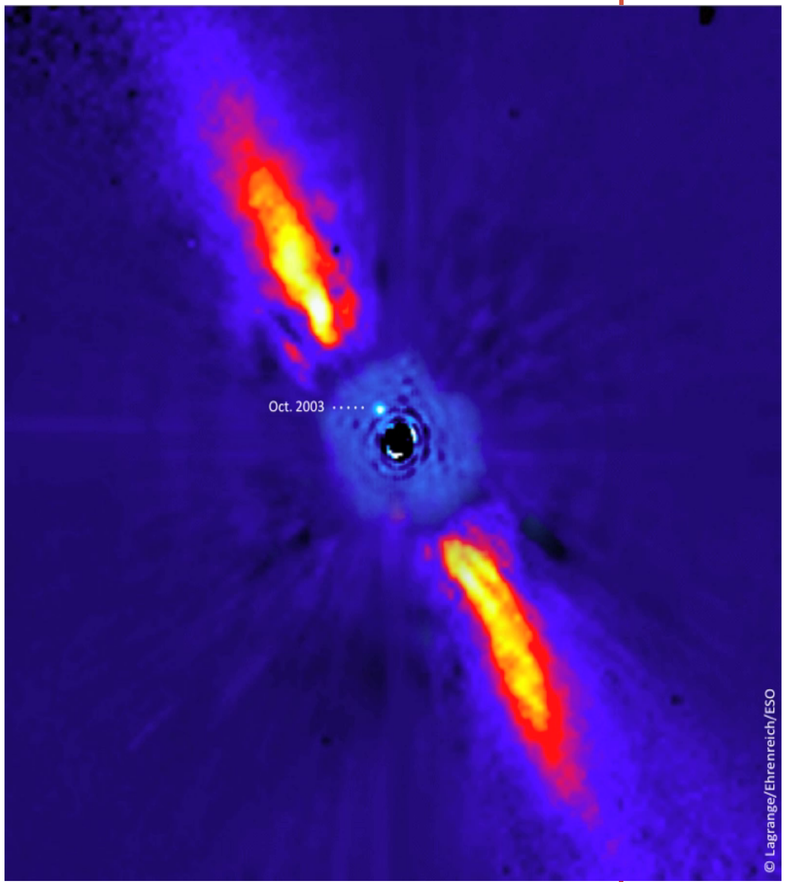


Defrère et al. 2011

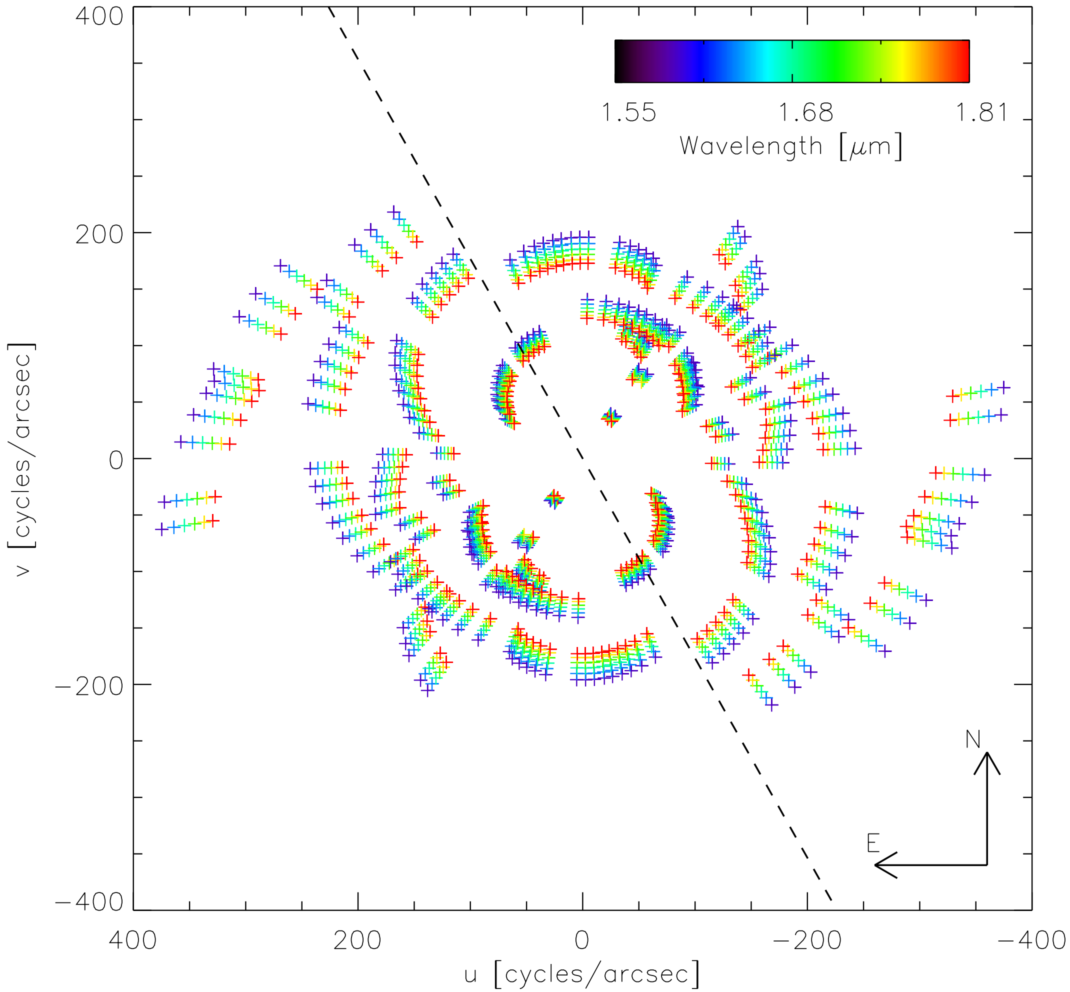
Beta Pictoris with PIONIER

- sampling of the uv plane

Exozodi detection



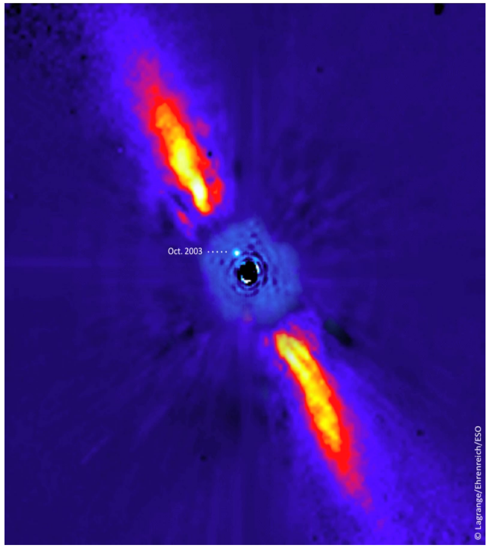
Defrère et al. 2012

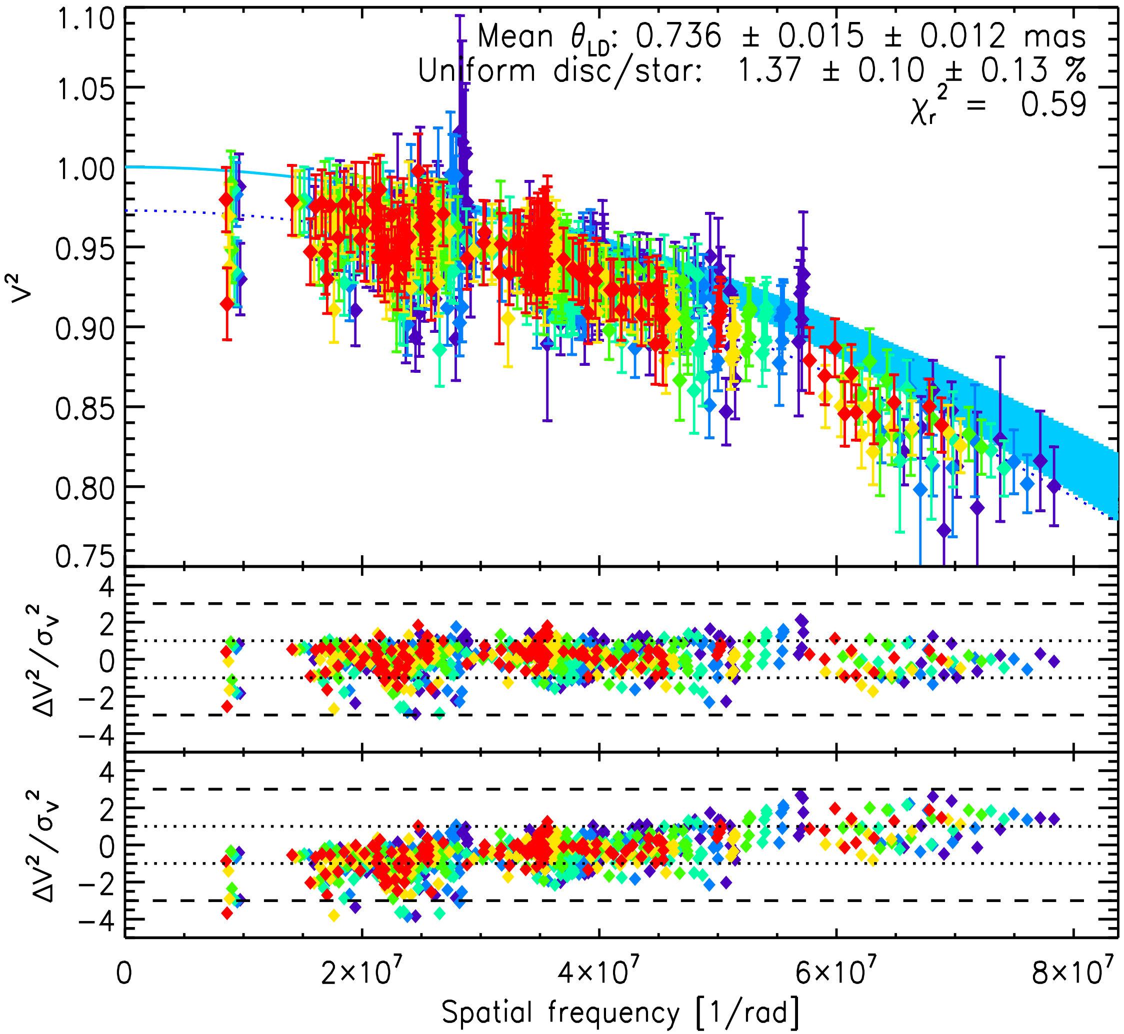


Beta Pictoris with PIONIER

Exozodi detection

- 1.37% excess in the H-band within 4 AU (200mas)

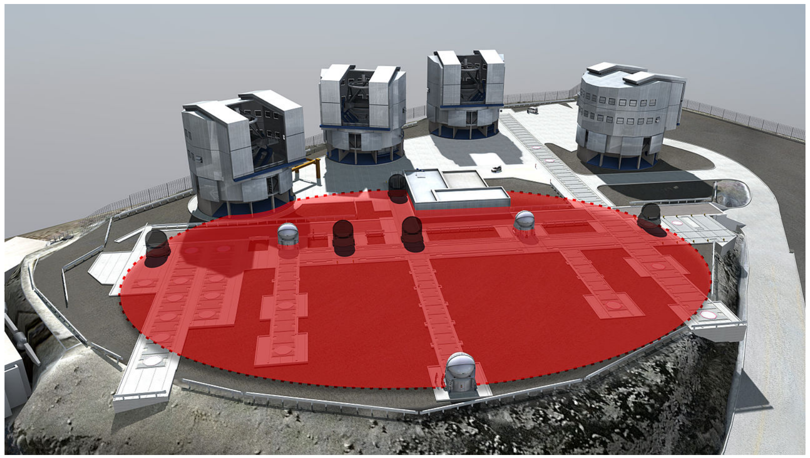




Defrère et al. 2012

2. Surveys for exozodiacal disks

- **The EXOZODI survey:**
  - **CHARA/FLUOR**
    - started in 2005
    - K-band
    - Northern hemisphere (California)
  - **VLTI/PIONIER**
    - executed in 2012
    - H-band
    - Southern hemisphere (Chile)

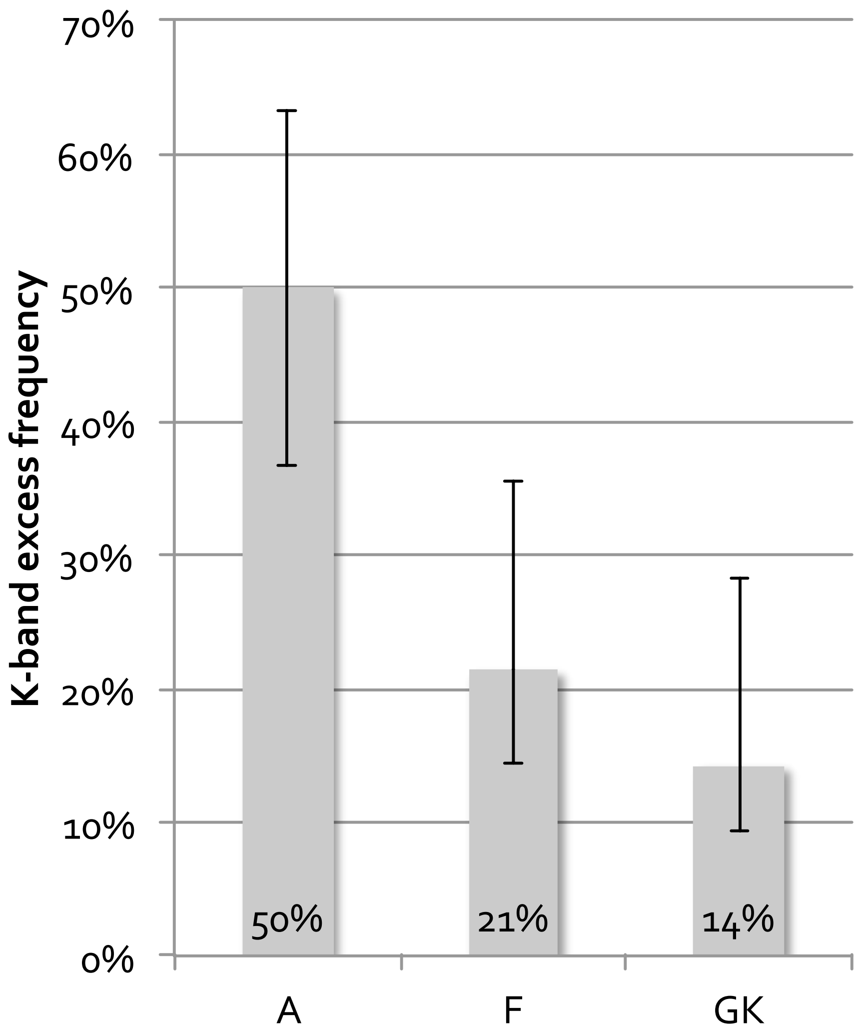


Surveys for exozodiacal disks

- CHARA/FLUOR interferometer
- K-band
- 42 stars
- 8 year survey

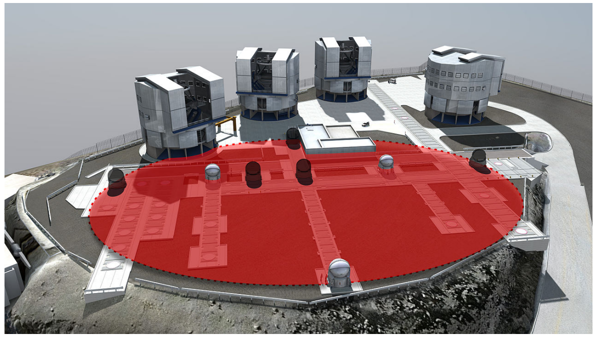
Absil et al. 2013

- **Exozodi detection frequency (K-band)**
  - ~ 30% for A-, F-, and GK-type stars
  - ~ 15-20% for solar type stars



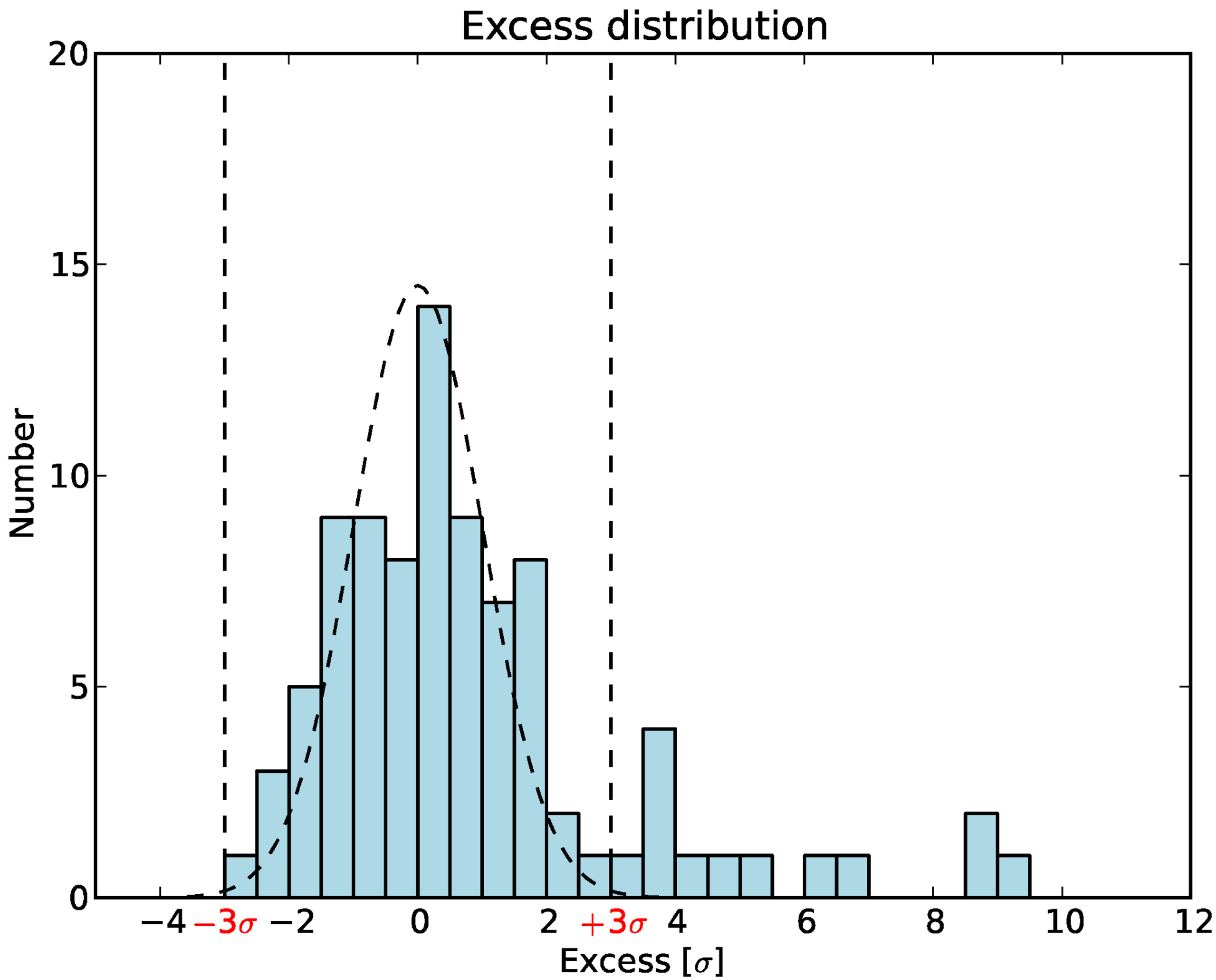
Excess distribution

Surveys for exozodiacal disks

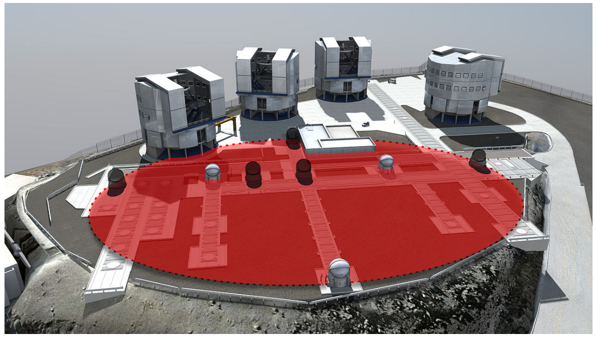


- VLTI/PIONIER interferometer
- H-band
- 88 stars
- 1 year survey

Ertel et al. 2014



Surveys for exozodiacal disks

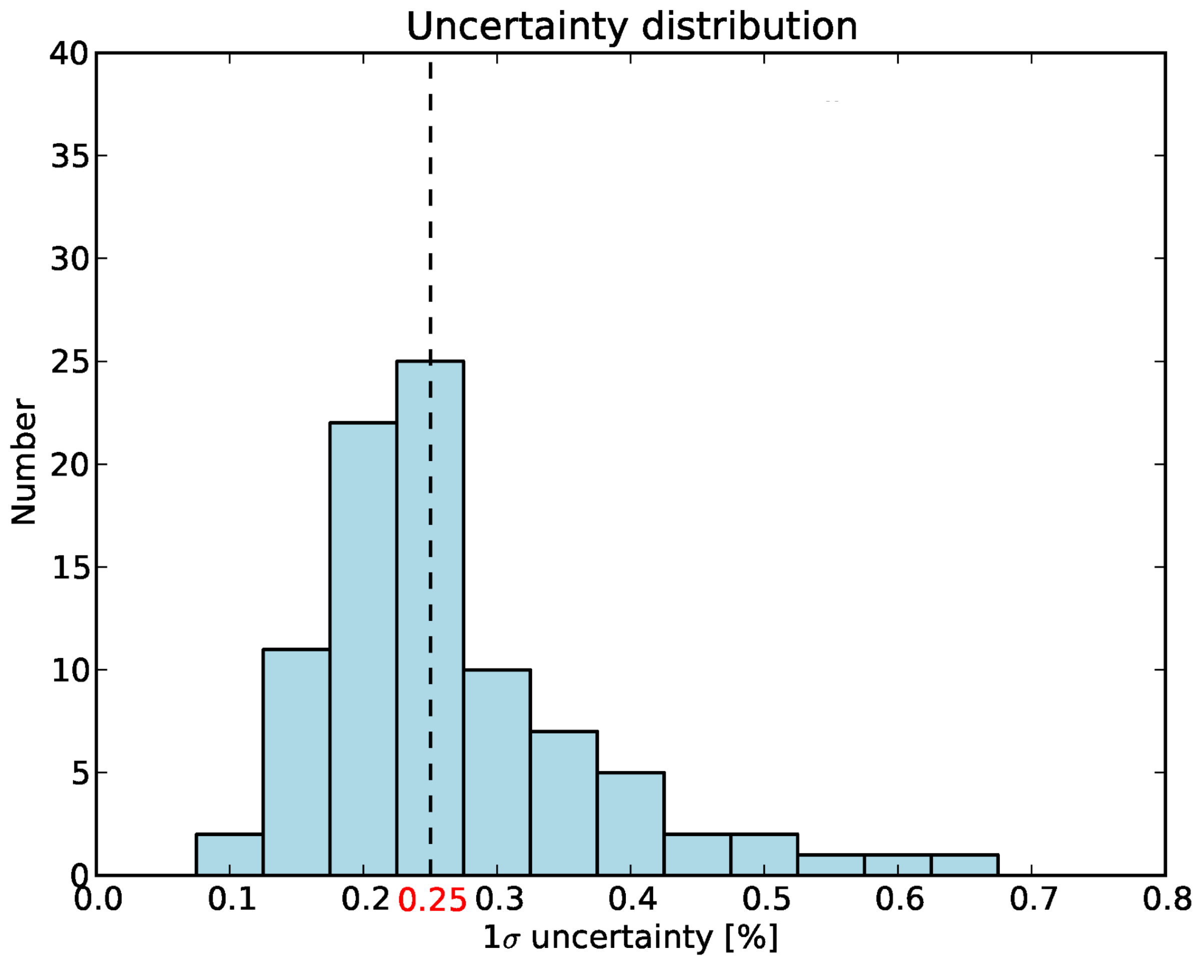


- VLTI/PIONIER interferometer
- H-band
- 88 stars
- 1 year survey

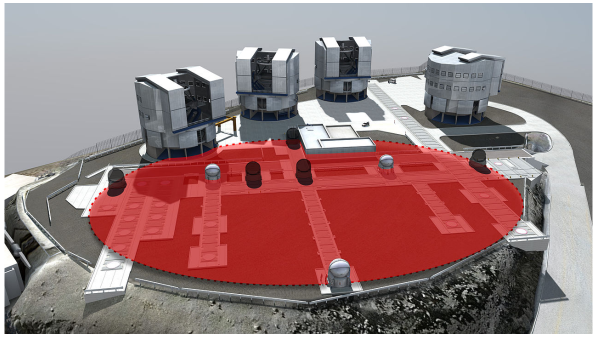
Ertel et al. 2014

Excess distribution

- 1 sigma median excess uncertainty: 0.25% of the stellar flux



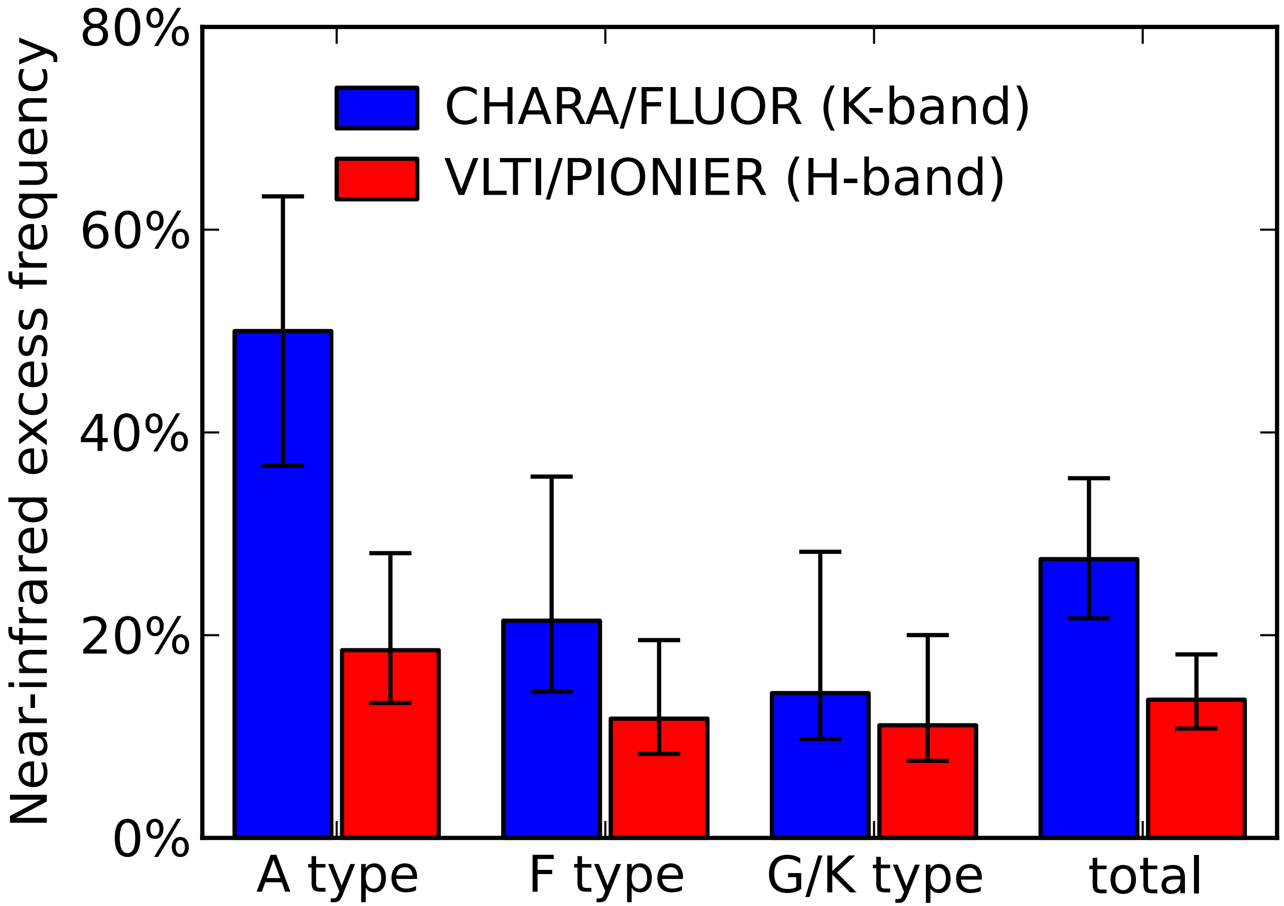
Surveys for exozodiacal disks



- VLTI/PIONIER interferometer
- H-band
- 88 stars
- 1 year survey

Ertel et al. 2014

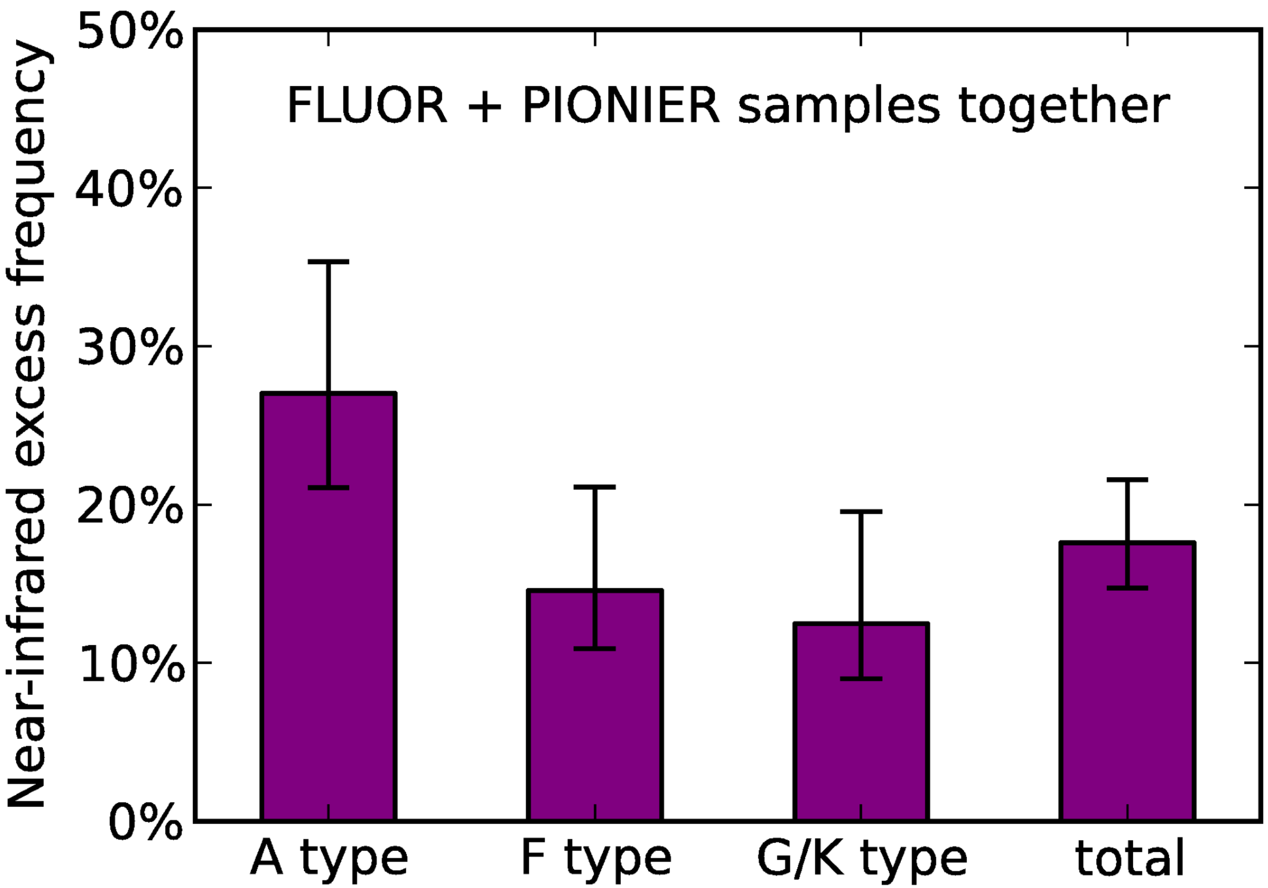
- **Exozodi detection frequency with PIONIER**
  - ~ 15% for A, F, and GK stars
  - ~ 12% for solar type stars



Surveys for exozodiacal disks

- Merging the CHARA/FLUOR and VLTI/PIONIER samples

- CHARA/FLUOR + VLTI/PIONIER data
- 130 stars in total

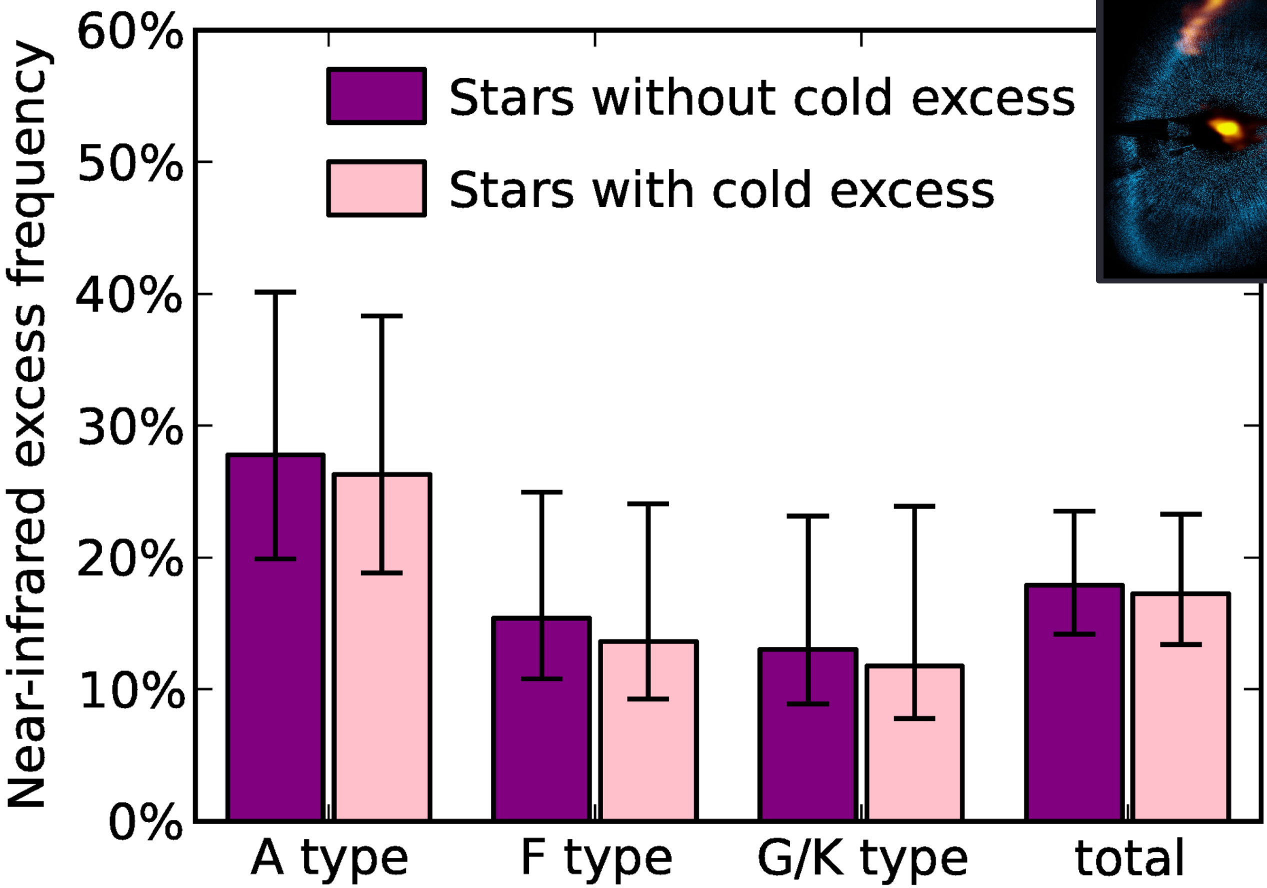


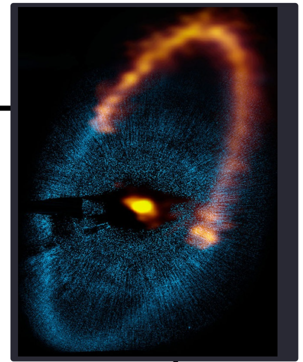
Ertel et al. 2014

Surveys for exozodiacal disks

- Hot and cold dust : no correlation

- CHARA/FLUOR + VLTI/PIONIER data
- 130 stars in total





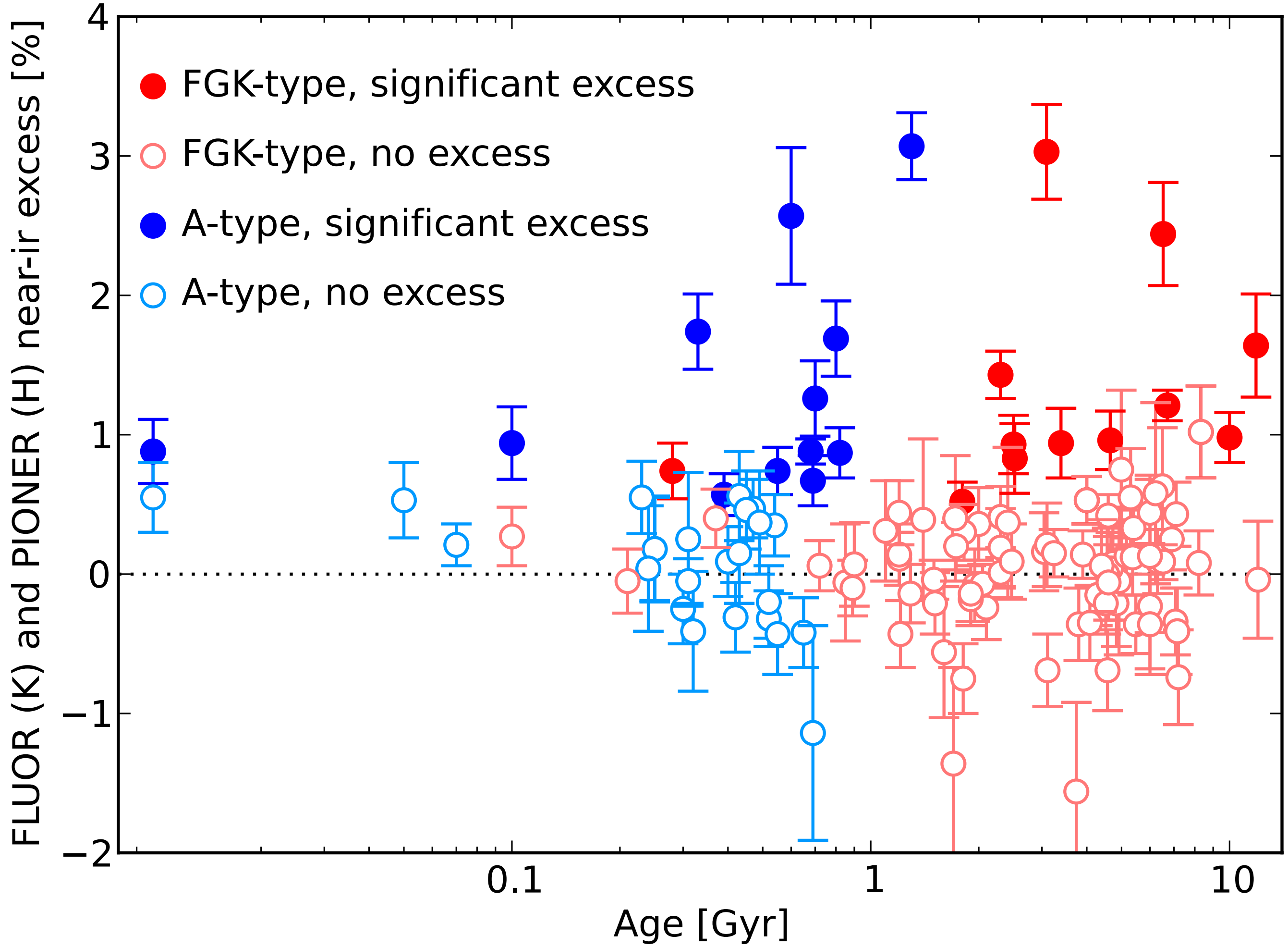
Ertel et al. 2014

Surveys for exozodiacal disks

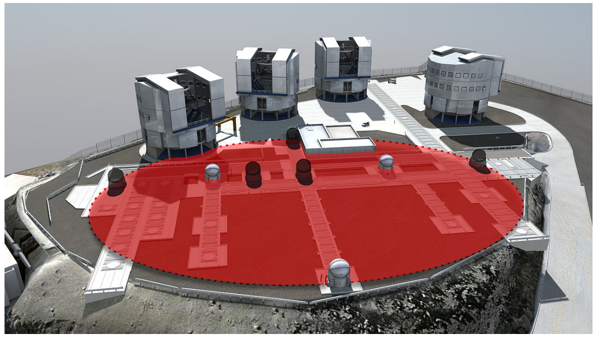
- CHARA/FLUOR + VLTI/PIONIER data
- 130 stars in total

Ertel et al. 2014

- **No clear age dependence seen**
  - increasing detection rate with increasing age?



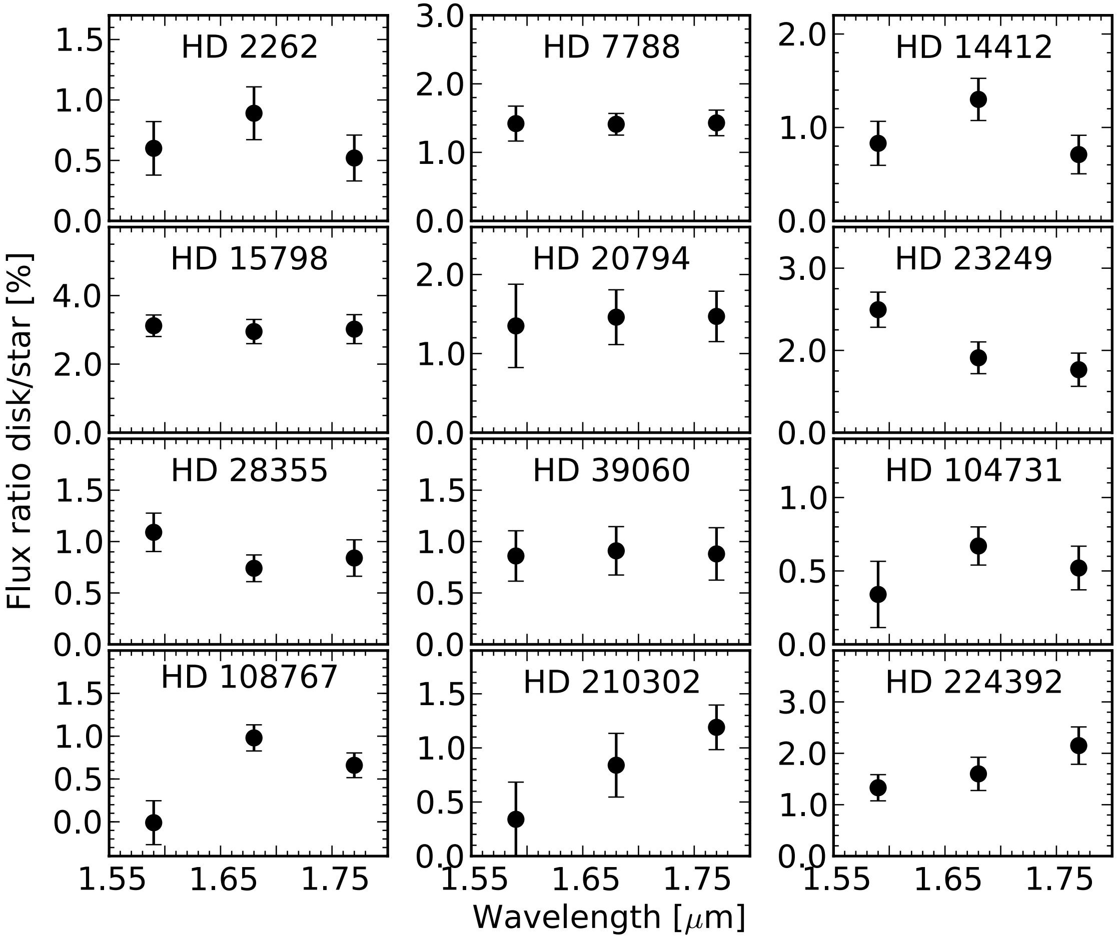
Surveys for exozodiacal disks



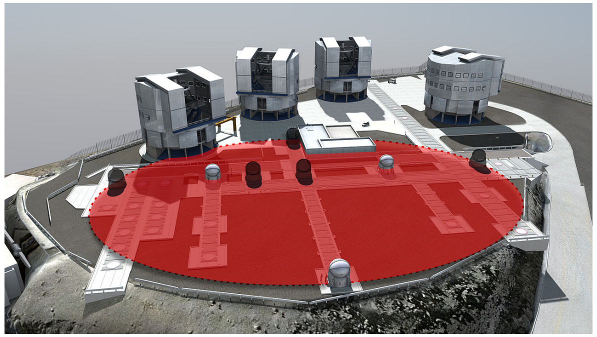
- VLTI/PIONIER interferometer

Ertel et al. 2014

- **Color of the excess across the H-band**
  - flat disk to star contrast: suggests important contribution from scattered light



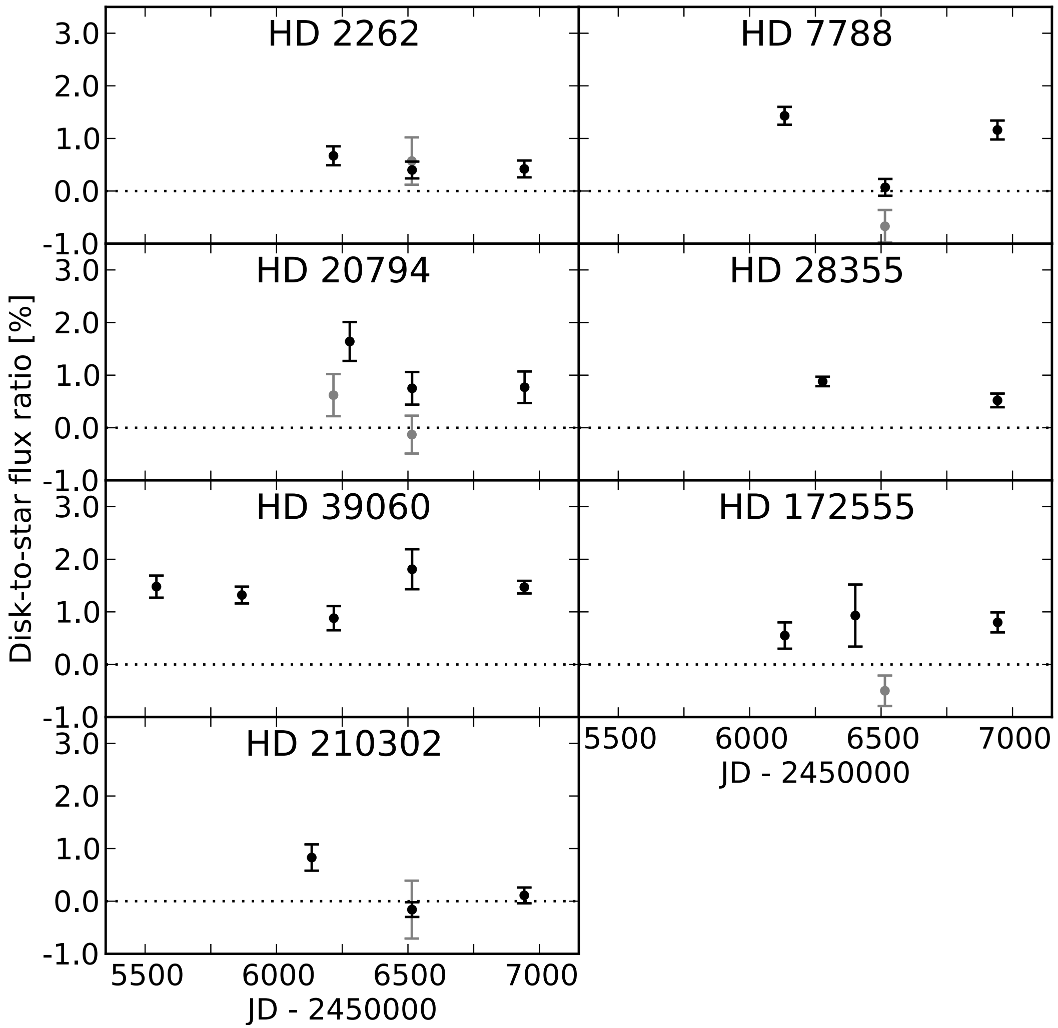
Surveys for exozodiacal disks



- VLTI/PIONIER interferometer

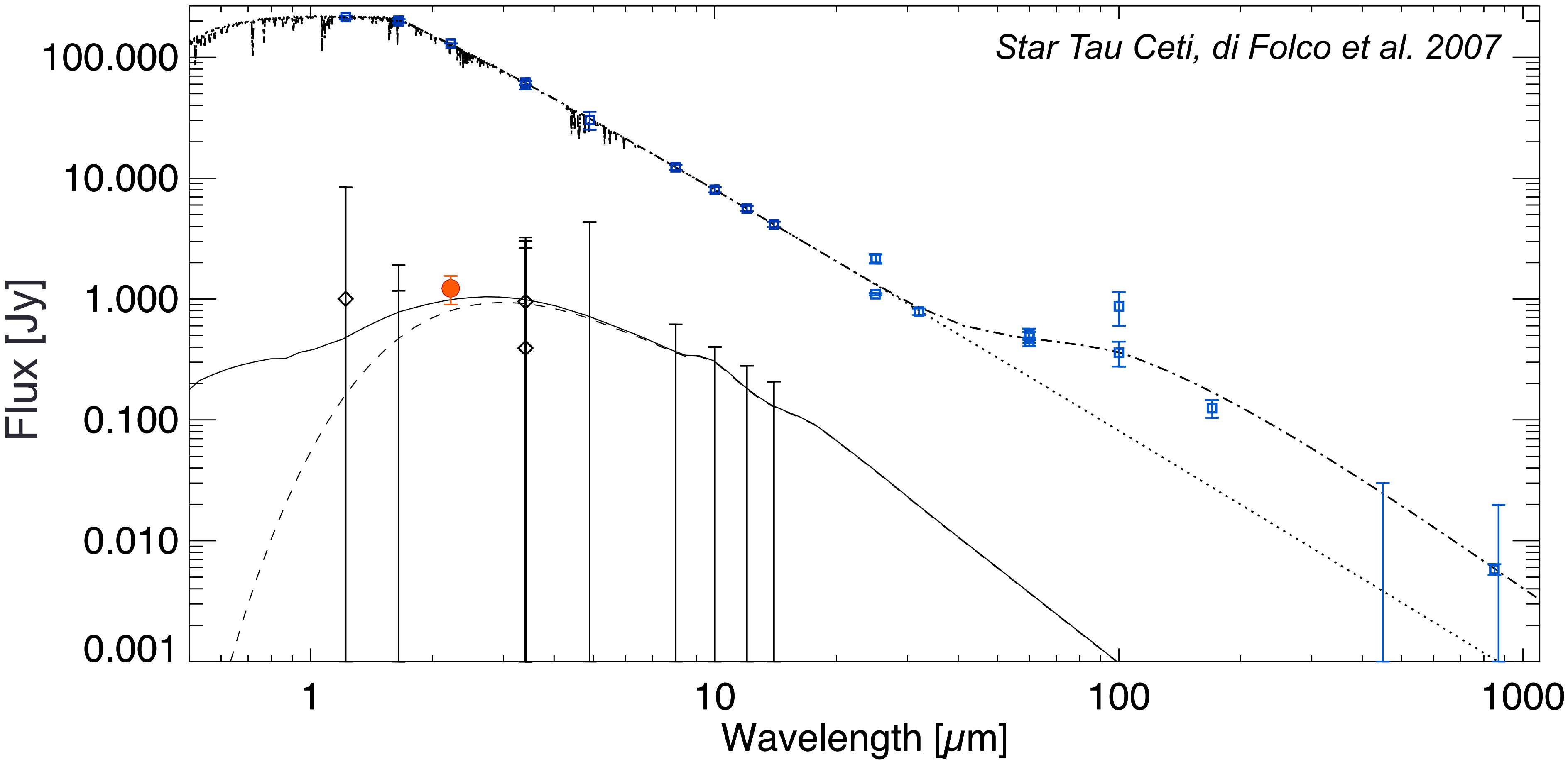
Ertel et al. 2016, submitted

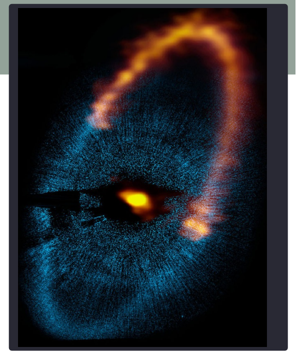
- **Time series of near-IR excess**
  - many excesses persist over timescales of a few years
  - possible variability for some objects



3. Radiative transfer modelling

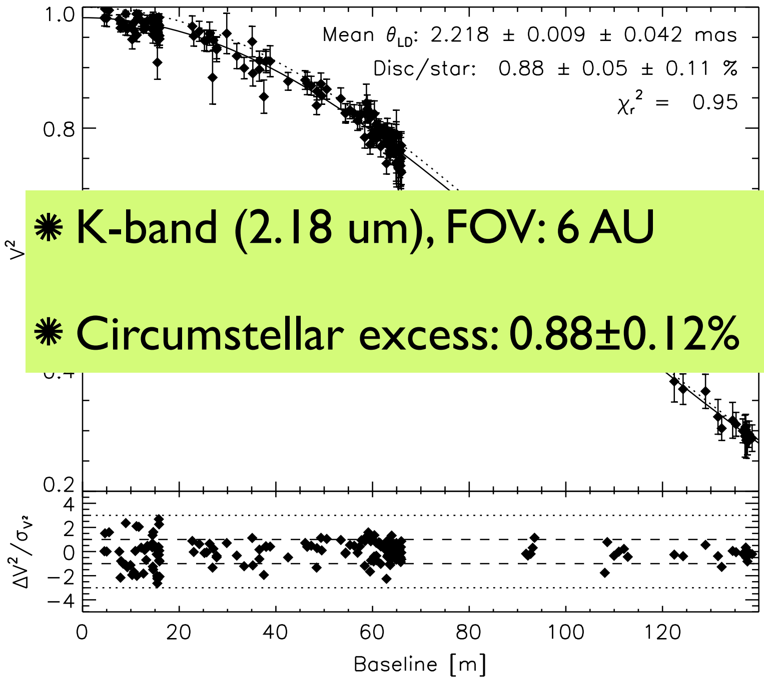
- **Methodology:**
  - radiative transfer code GRaTer (Augereau et al. 1999, Lebreton et al. 2012)
  - disk properties around the sublimation distance (Lebreton et al. 2013)
  - grids of models, bayesian analysis



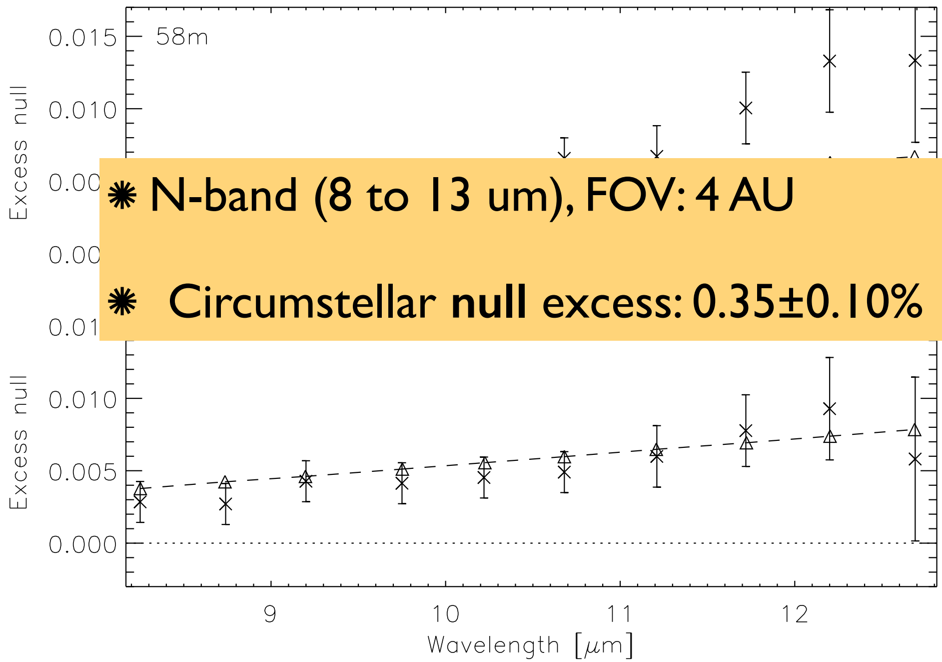


Radiative transfer modelling

- **Fomalhaut**

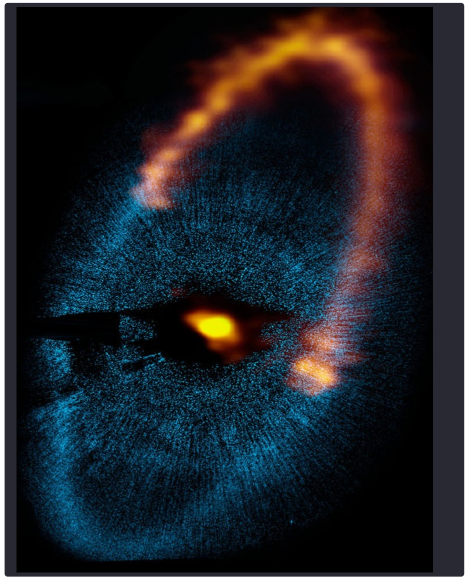


- K-band (2.18 um), FOV: 6 AU
- Circumstellar excess: 0.88±0.12%



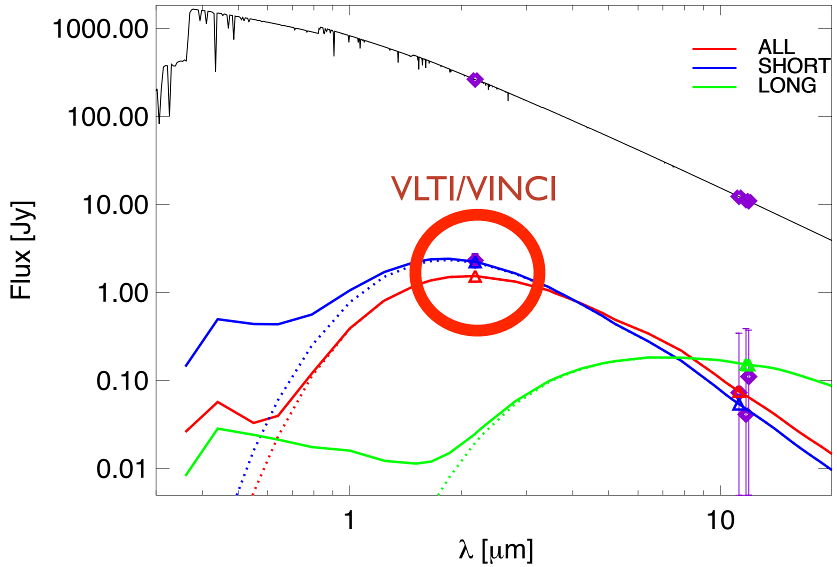
- N-band (8 to 13 um), FOV: 4 AU
- Circumstellar **null** excess: 0.35±0.10%

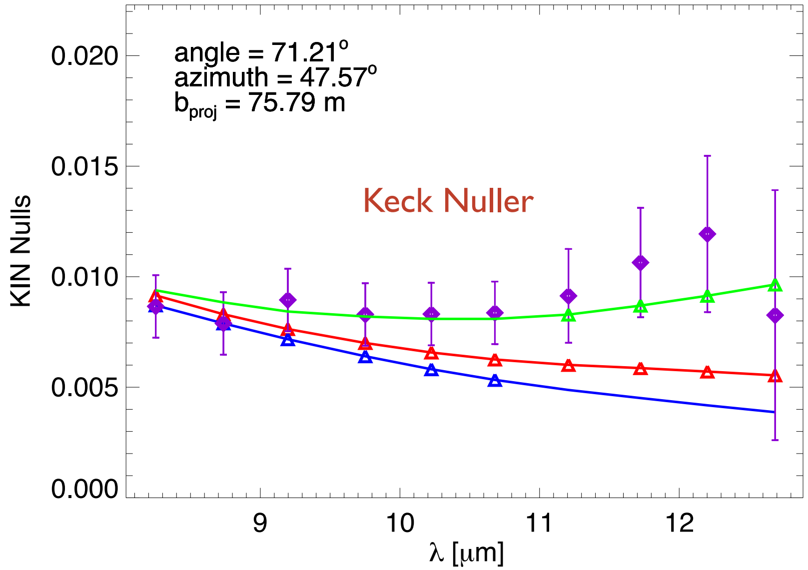
Radiative transfer modelling



Mennesson et al. 2013
Lebreton et al. 2013

- # Fomalhaut
  - a single dust population fails to reproduce everything together





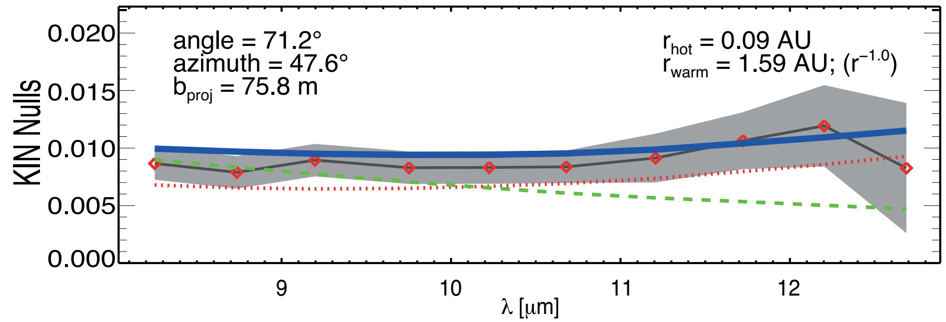
Lebreton et al. 2013

Radiative transfer modelling

• Fomalhaut

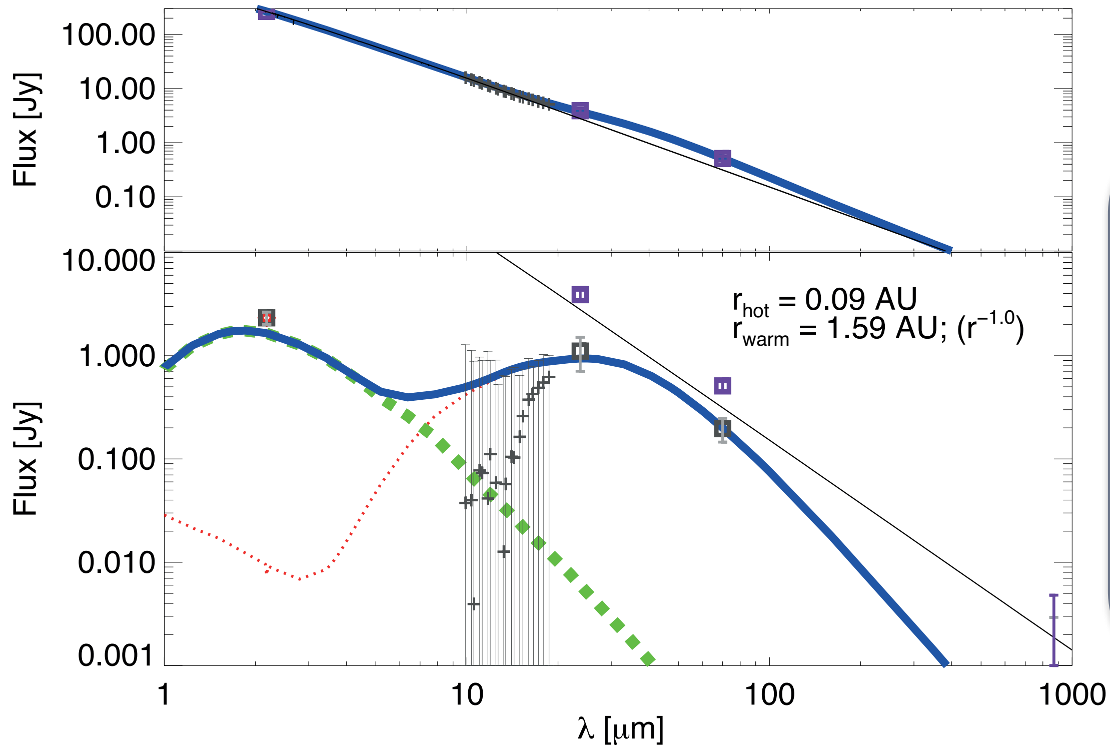
- two dust populations

KIN excess null depths



Spectral Energy Distribution

VLTI/VINCI, MIPS 24, Herschel 70 μm, (ALMA 870 μm)

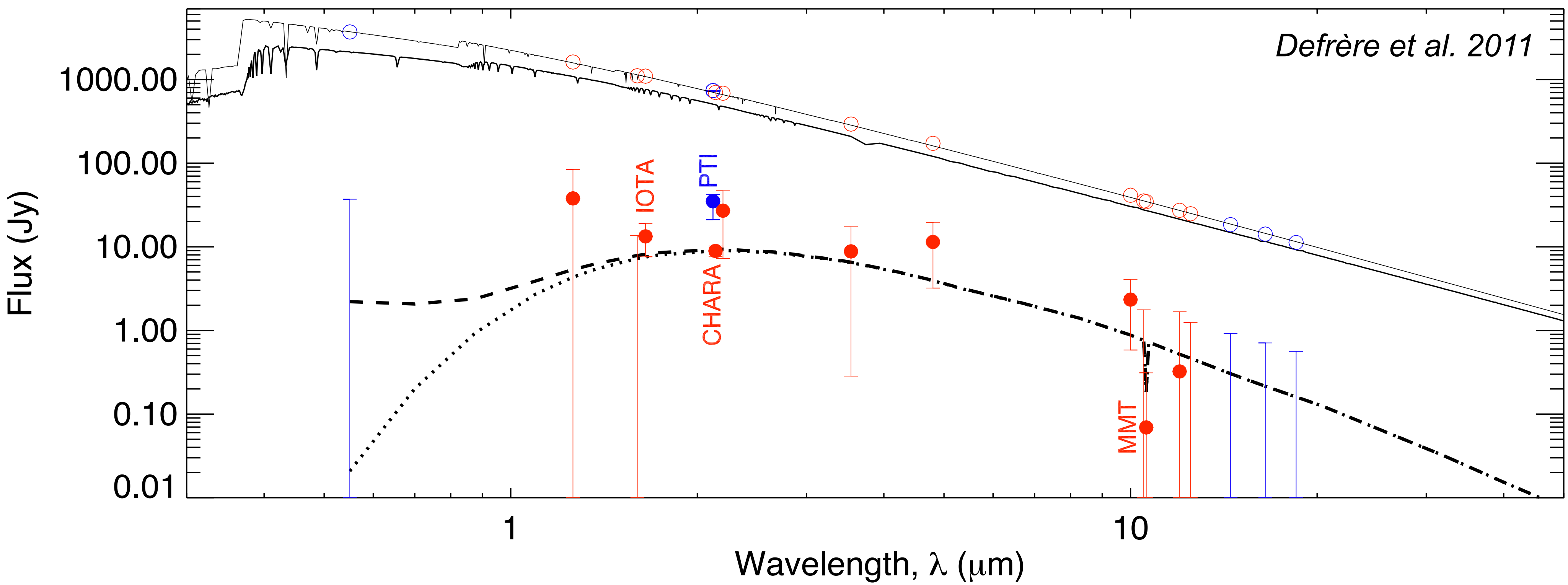


	HOT	WARM
Material	C	C+Si
Size (μm)	> 0.02	> 3
Distance (AU)	0.09-0.23	[1.5, 2.5]
Mass (M_{Earth})	2.5×10^{-10}	2×10^{-6}

$\chi^2_r = 1.6$ *(dof=30)*

Radiative transfer modelling

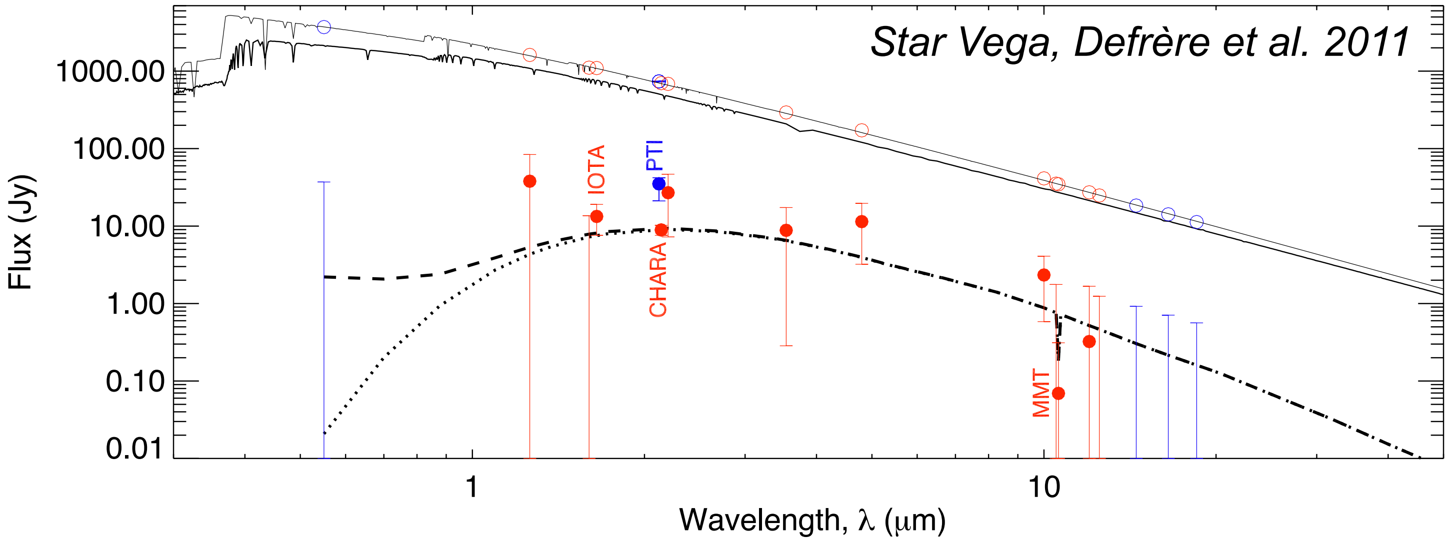
- **Vega:**
  - H- and K-band interferometry
  - N-band nulling interferometry (MMT-BLINC)
  - archival near- and mid-IR spectro-photometry



Radiative transfer modelling

- Vega:
  - Absil et al. 2006
  - Defrère et al. 2011
- Tau Ceti:
  - Di Folco et al. 2007
- Fomalhaut:
  - Absil et al. 2009
  - Mennesson et al. 2013
  - Lebreton et al. 2013

- **General properties:**
  - very small grains (sub micron-sized < blow out size)
  - carbon-rich
  - accumulated next to the sublimation distance (0.1-0.5 AU)
  - dust mass (M_{dust}) : ~10^{-10} - 10^{-9} M_{Earth}
  - replenishment rate (dM_{dust}/dt): ~10^{-10} - 10^{-9} M_{Earth}/year



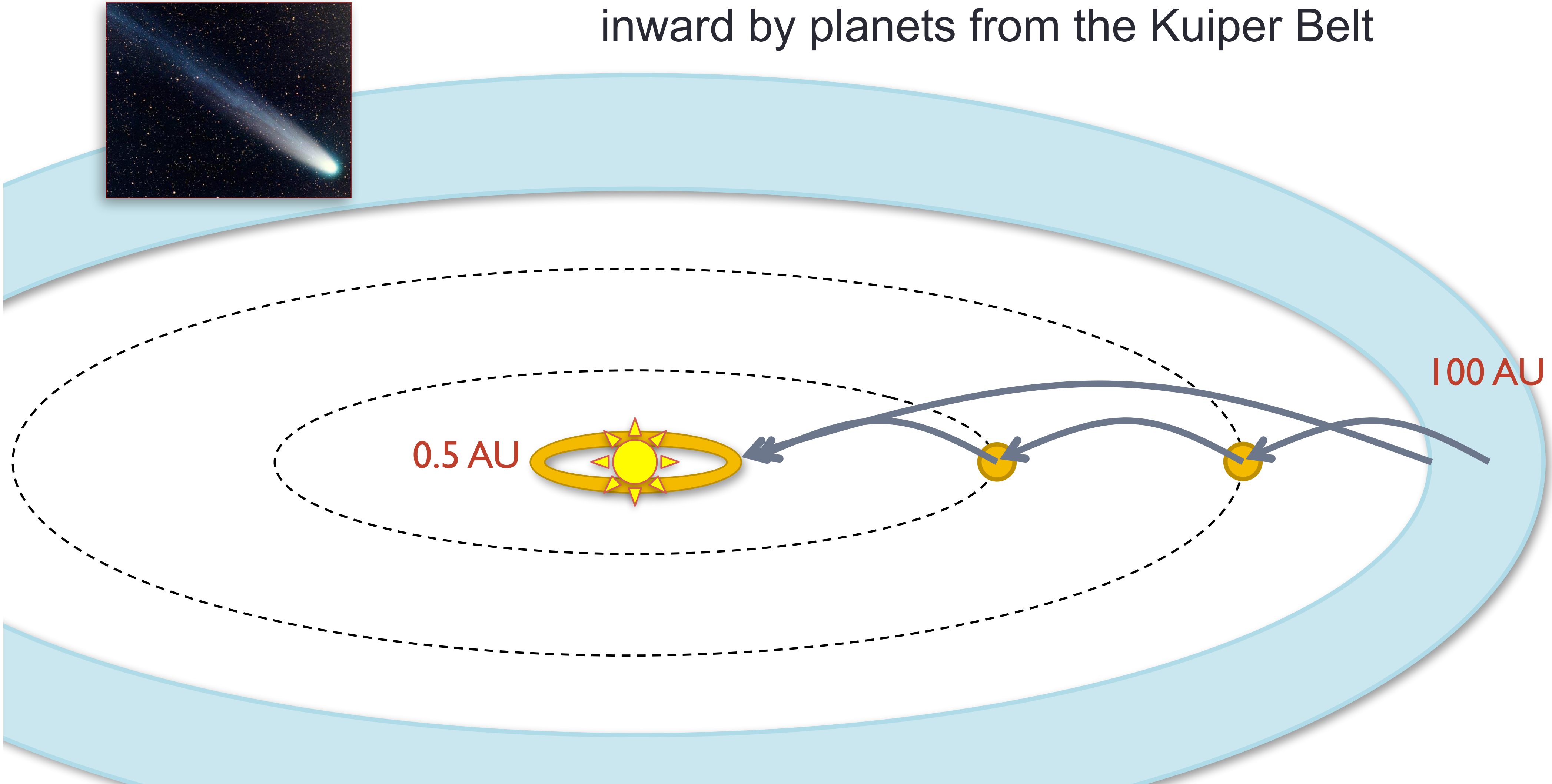
4. Origin of the exozodiacal dust

- **The conundrum:**
  replenishment in steady-state by collisions between planetesimals does NOT work for exozodiacal debris disks.

- **Possible solutions:**
  - **dynamical instabilities (e.g. LHB)**:
    unlikely to explain our statistics : *<0.1% chance to observe a system in the aftermath of a dynamical instability, Bonsor et al. (2013)*
  - **link with the outer planetary system**
  - **something else…?**

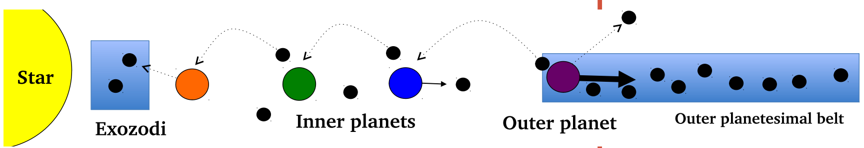
Origin of the exozodiacal dust

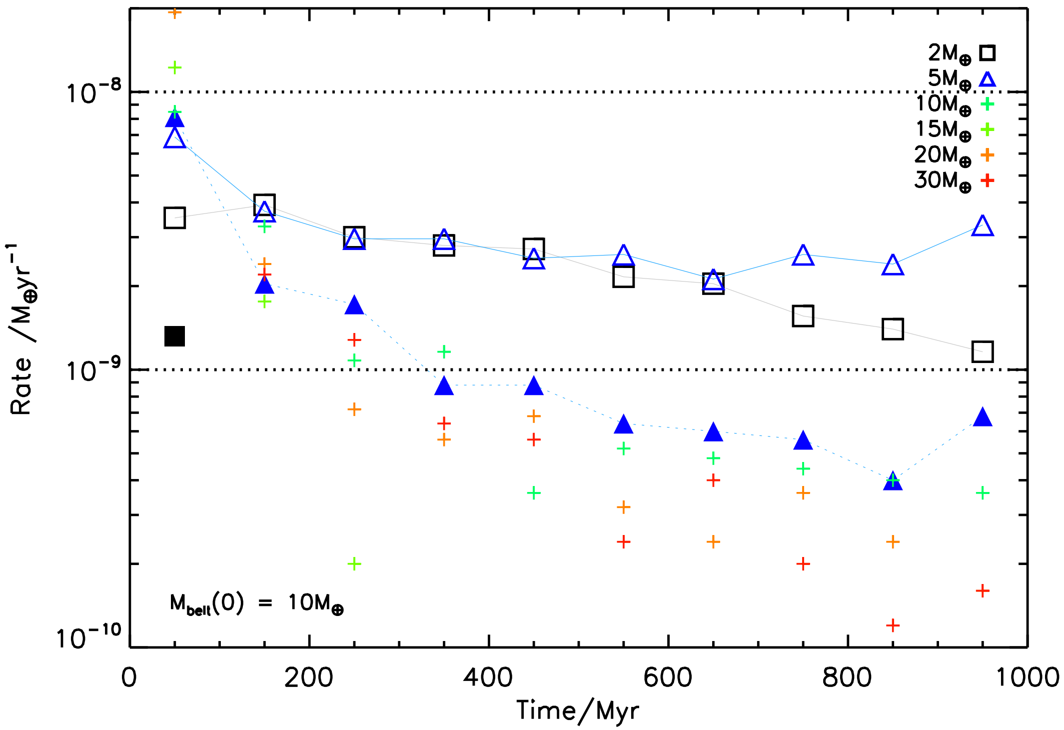
- **Steady-state scattering by a chain of (unseen) planets**
  - Solar System's zodiacal cloud is thought to originate from Jupiter Family comets scattered inward by planets from the Kuiper Belt



Origin of the exozodiacal dust

- **Steady-state scattering by a chain of (unseen) planets**
  - mass flux is insufficient to sustain Vega's exozodi for example

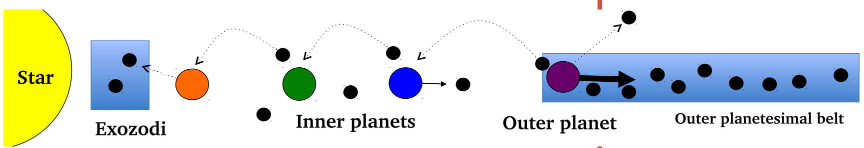


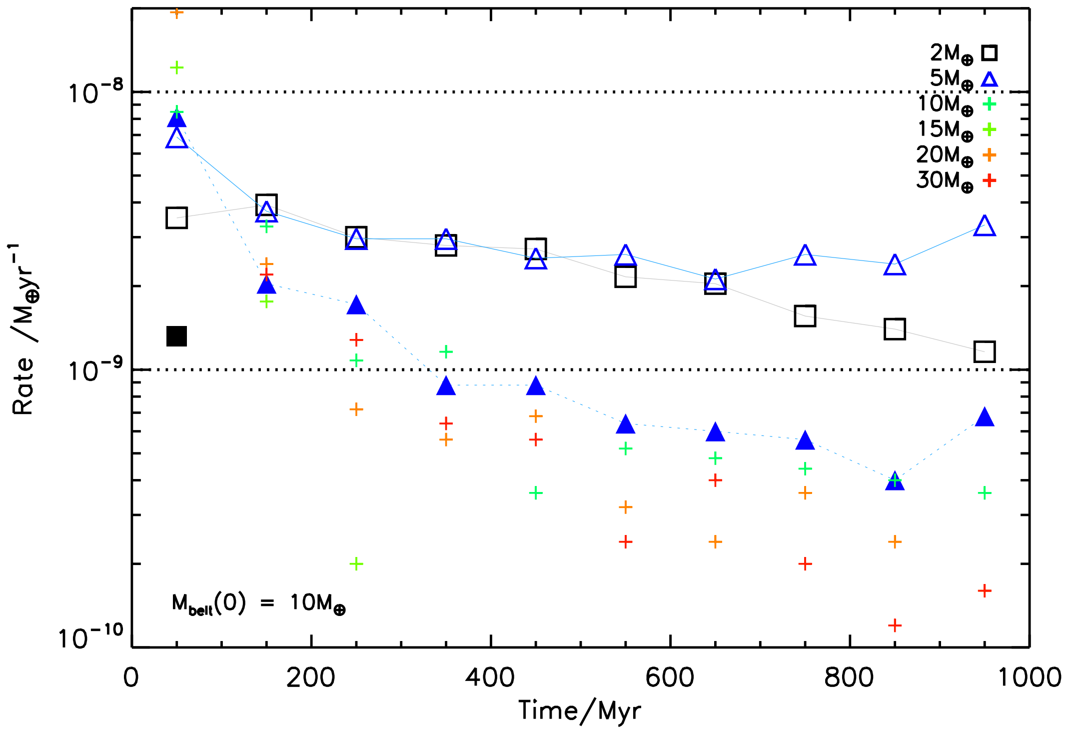


Bonsor et al. 2012
Bonsor et al. 2014

Origin of the exozodiacal dust

- **Steady-state scattering by a chain of (unseen) planets**
  - mass flux is insufficient to sustain Vega's exozodi for example
  - With planetesimal driven migration: mass flux might be sustained long enough





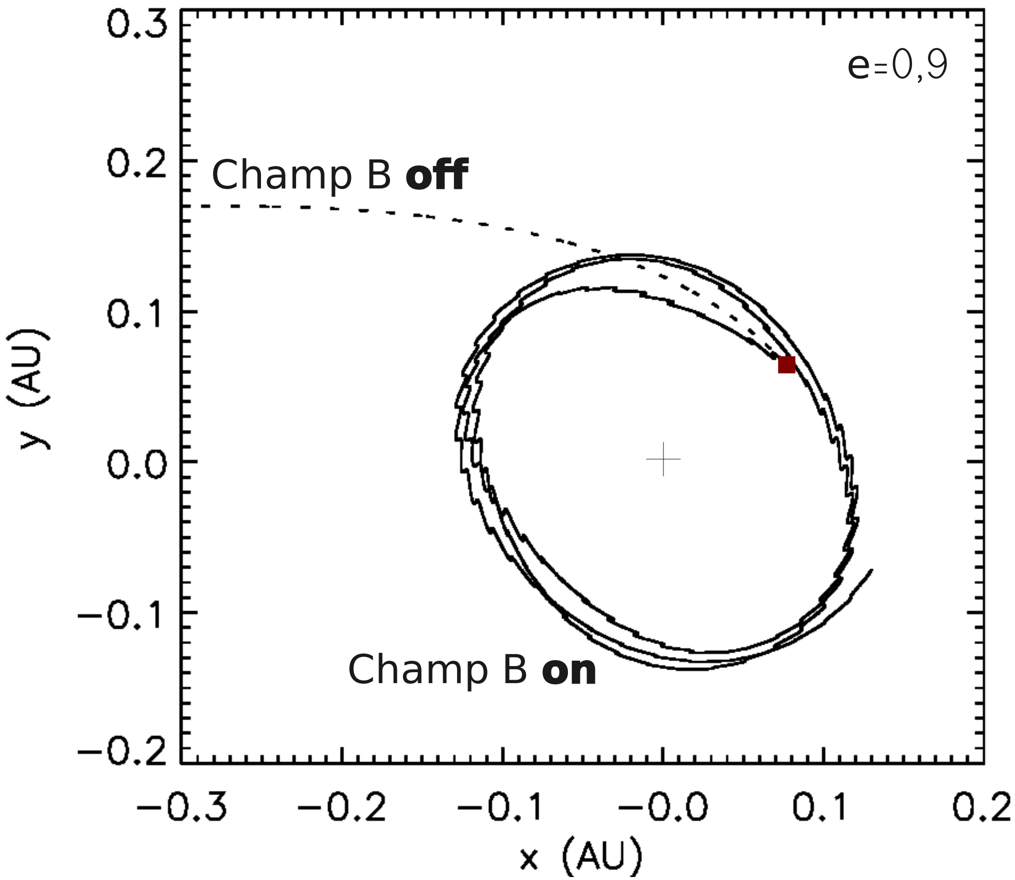
Bonsor et al. 2012
Bonsor et al. 2014

Something else?

- **Magnetic trapping**
  - increases the grain lifetime
  - relaxes the replenishment rate

Conditions initiales

- $e = 0.9$
- $i \simeq 0°$
- $q = 0.10$ UA
- $v_{ph} = v_{kep}\sqrt{1+e}$
- Grain relâché au périhélie q
- $Q/m = 3.10^{-6}\ e/m_p$



Concluding remarks

Publications by the EXOZODI team:

- Absil et al. 2006
- Di Folco et al. 2007
- Absil et al. 2008
- Absil et al. 2009
- Defrère et al. 2011
- Bonsor et al. 2012
- Defrère et al. 2012
- Olofsson et al. 2013
- Mennesson et al. 2013
- Lebreton et al. 2013
- Absil et al. 2013
- Bonsor et al. 2013
- Bonsor et al. 2014
- Ertel et al. 2014
- Marboeuf et al. 2016
- Ertel et al. 2016, sub.

+

- Thébault 2012
- Thébault et al. 2013
- Kral et al. 2013
- Kral et al. 2015
- Beust et al. 2013
- Faramaz et al. 2015

- PIONIER + FLUOR : Hot, exozodiacal dust is found around 15-20% of solar-type stars. They appear randomly (e.g. no correlation with age or presence of cold dust)
- Grains seen in the near-IR are very small, carbonaceous, and close to the sublimation distance
- Spectrally dispersed interferometric data are essential in the near-IR to mid-IR
- Their origin is still quite mysterious. Our preferred scenario involves a link with the outer planetary system