Figure: Emil Ivanov, Sterne und Weltraum

Addressing the Mystery of Exozodiacal Dust

– Part I: Observations –

Steve Ertel – IPAG UJF Grenoble

(Part II: Theory – by Amy Bonsor – will follow in ~25 min)

ON BEHALF OF:

Jean-Charls Augereau
Philippe Thebault
Olivier Absil
Jean-Baptiste Le Bouquin
Denis Defrère
and the EXOZODI team

AGENCE NATIONALE DE LA RECHERCHE ANR

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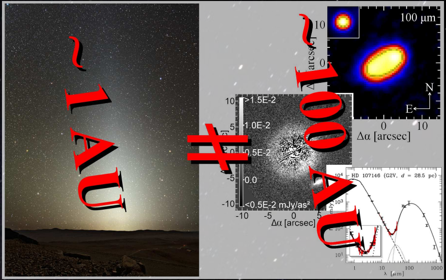
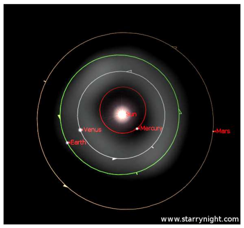
IPAG Institut de Planétologie et d'Astrophysique de Grenoble

What is exozodiacal dust?

- Dust around main sequence stars (~ 1 AU)
- **NOT** a typical debris disk (maybe related)
- Similar to our zodiacal disk



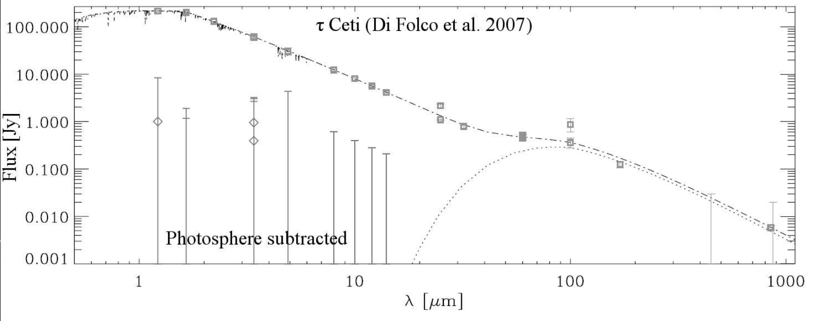
Why do we care?



- Dust in the habitable zone
- Structures might point towards planets
- **BUT:** Obstacle for imaging of earthlike planets

How to detect exozodiacal dust?

The problem:



- Our zodiacal dust would be too faint to be detected, e.g., by *Spitzer* (more than 100 times)
- Actually, the photometric calibration uncertainty is the problem (few percent of the **total** flux of the system)

How to detect exozodiacal dust?

Some very bright systems found with *Spitzer* (IRS/MIPS24)

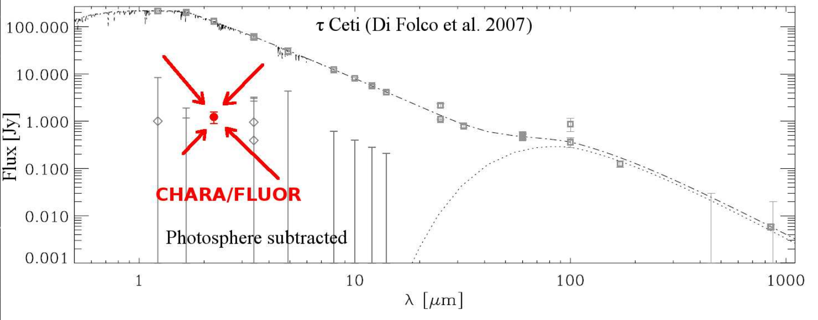
- Hundreds of stars surveyed, very low rate of excess detections at $\sim 10\,\mu$m (e.g., Lawler et al., 2009: $\sim 1\%$)
- BUT: Sensitivity “around 1000 times the zodiacal level” at $\sim 10\,\mu$m

Other technique: Keck Nuller (Millan-Gabet et al., 2011):

- 25 nearby MS stars surveyed, 3 excess detections
- Upper limits on others: “$\lesssim 150$ zodis”

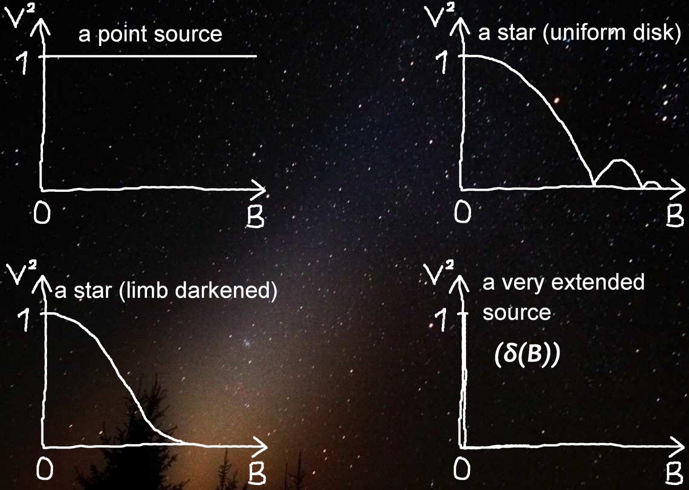
How to detect exozodiacal dust?

The solution:



- Dust emission alone would be detectable (10 mJy to 1 Jy)
  ⇒ disentangle stellar emission and dust emission
- Solution: (near) infrared interferometry

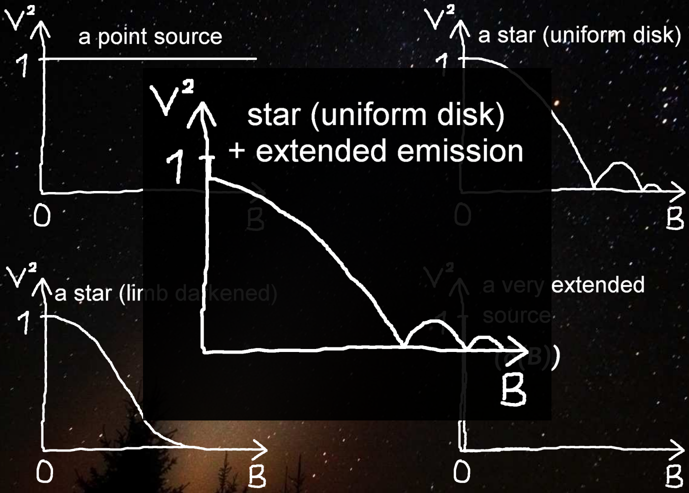
Near-infrared interferometry: Strategy



steve.ertel@obs.ujf-grenoble.fr

How to detect exozodiacal dust?

Near-infrared interferometry: Strategy



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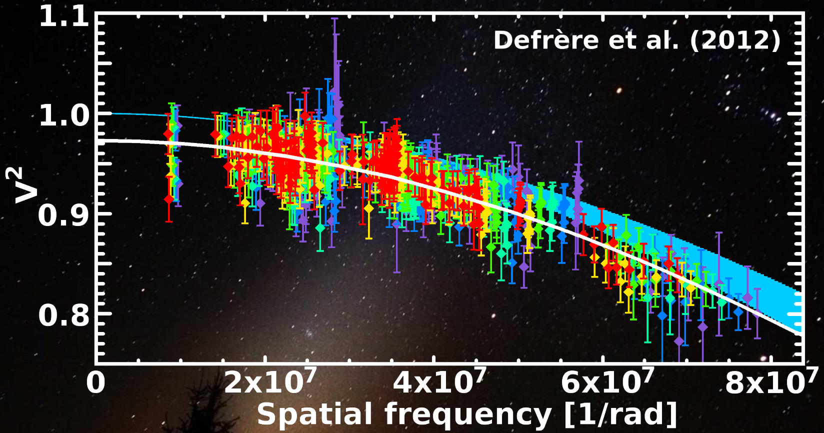
How to detect exozodiacal dust?

Example: β Pic



Several possible origins of exozodiacal dust, but all have problems (details: see Part II):

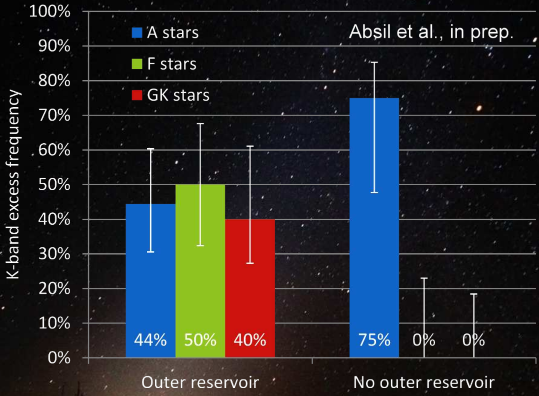
- Local collisions of large bodies
  - High amount vs. short lifetime of the dust
  - ⇒ **Statistics** of frequency/dust mass vs. age
- Recent planetary collision
  - Low probability vs. high detection rate?
  - ⇒ **Statistics** of frequency among stars in general
- Evaporation of comets from outer disk
  - Large number of comets required (LHB?)
  - ⇒ **Statistics** of correlation between exozodis and exo-Kuiper belts

The EXOZODI Project

The project:

- First **statistical** survey for exozodiacal dust
- Northern (CHARA/FLUOR) and southern hemisphere (VLTI/PIONIER)
- $\sim$ 100 stars ($K < 5$) with debris disks, same number of stars without (known) cold dust, unbiased sample
- Observation, statistics + detailed modeling & theoretical investigation (**see Part II of this talk**)
- Development of next-generation debris disk modeling tools
- Direct contribution to instrumentation (e.g., VLTI/PIONIER)

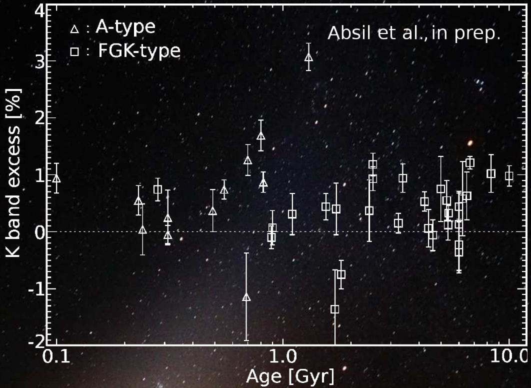
Statistics (CHARA/FLUOR survey, Absil et al., 2013 in prep.):



- So far 12 detections out of 41 stars (29^{+8}_{-6} %)
- Cold & hot dust seem to be correlated for late type stars
- Early type stars completely different?

 steve.ertel@obs.ujf-grenoble.fr

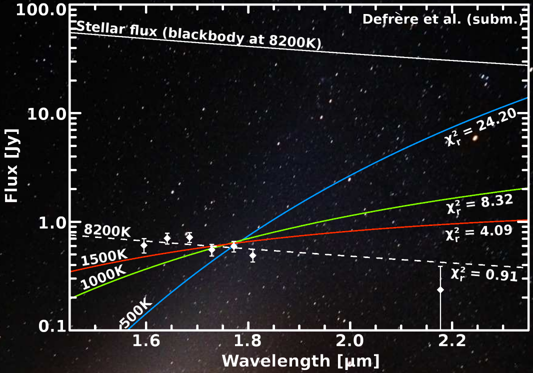
A particularly intriguing result:



- No age dependence for solar-type stars, excess increasing with age for A-type stars
- No circumstellar, but stellar phenomenon?
- But no stellar phenomenon known either ...

First results

A detailed study on β Pic (VLTI/PIONIER):



- Clear detection ($\sim 8.5\sigma$, 4 independent epochs)
- Companion ruled out to be responsible (closure phases)
- Emission very hot (sublimation relevant – Lebreton et al., in prep.) or dominated by scattering of stellar light

Observational work in progress

The southern survey with VLTI/PIONIER:

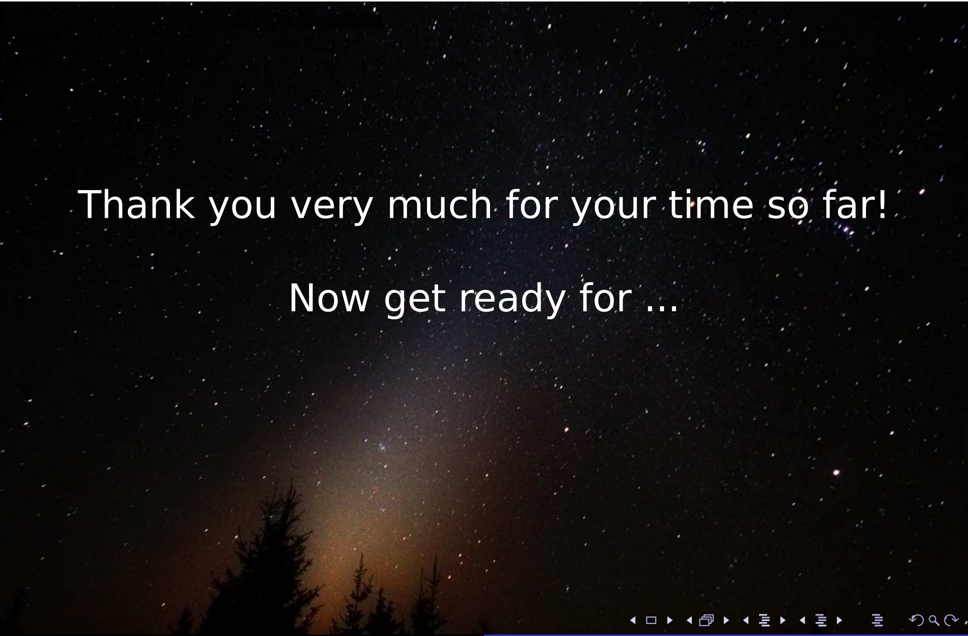
- 92 southern stars, unbiased sample, better statistics
- High efficiency, ~10 targets/night
- Observations just finished, reduction in progress
- So far lower detection rate (H vs. K expected?)

Sp.-Type	A	F	GK	total
w/ cold dust	14	16	15	45
w/o cold dust	17	18	12	47
total	31	34	27	92

Observational outlook

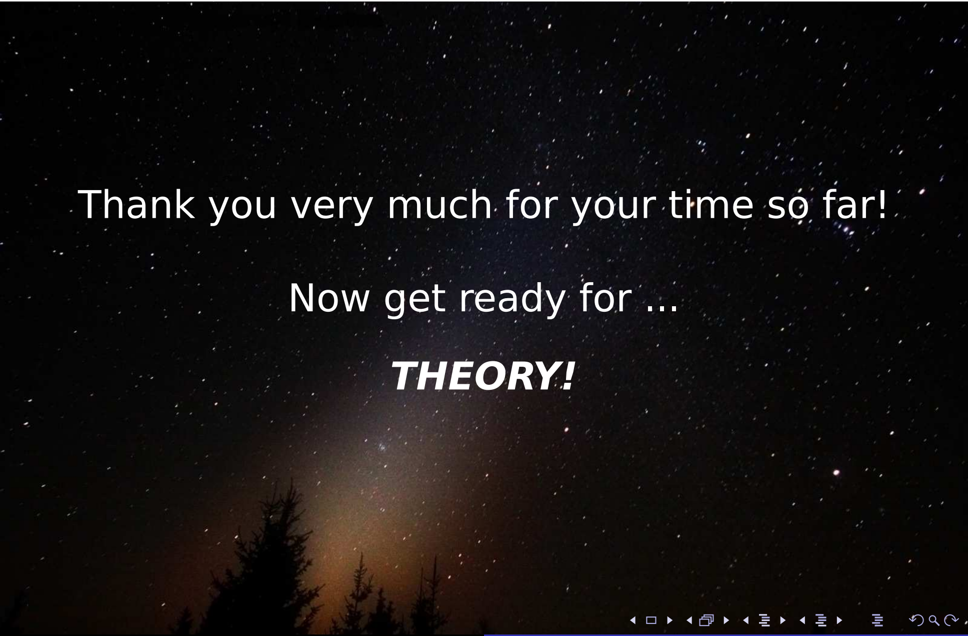
Future plans with PIONIER and future VLTI:

- More detailed studies like β Pic accepted for P91
- Color studies with PIONIER (H, K band)
- Variability survey just started
- 5 nights in P91 for color studies and variability survey
- Variability study to be continued with GRAVITY, color studies to be extended with MATISSE



Thank you very much for your time so far!

Now get ready for ...



Thank you very much for your time so far!

Now get ready for ...

THEORY!

Addressing the Mystery of Observations of Exozodiacal dust Part 2: Theory

Amy Bonsor
IPAG, Grenoble
Collaborators: Jean-Charles Augereau, Philippe Thébault, Sean Raymond, Hervé Beust, Jérémy Lébreton, Virginie Faramaz, Steve Ertel and the EXOZODI team

Exozodiacal dust has a short lifetime

Collisions grind down small grains on timescales ~yr and even large km bodies (located at the position of the exozodi and dense enough to produce the observed dust) on <Myr

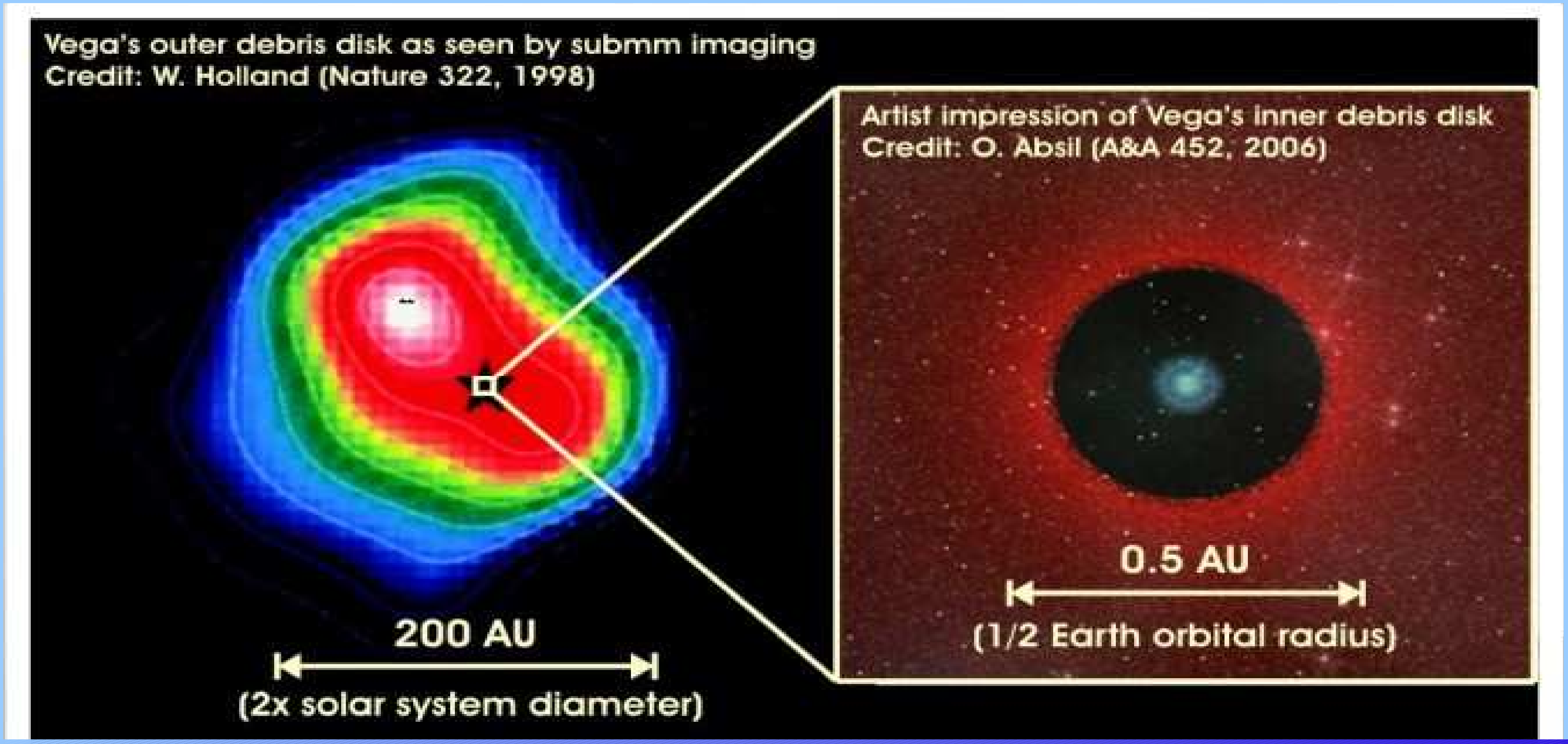
Radiative forces remove observed small grains on <yr timescales

How do we explain the observations of such high levels of dust around such a high proportion of systems?

One explanation could be that the hot dust is associated with an outer planetary system?

Some of the observed systems also have an outer planetesimal belt, e.g. Vega

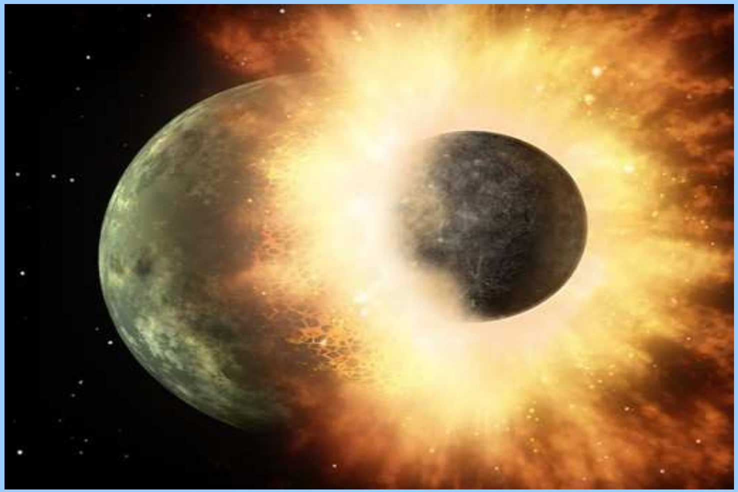
Absil et al, 2006



How do we transport material from the outer belt inwards?

Scattering by planets? - steady state or large collision between two bodies

e.g. Lisse et al 2009



Poynting-Robertson drag (radiative forces), such as in the Solar System or as suggested Epsilon Eridani

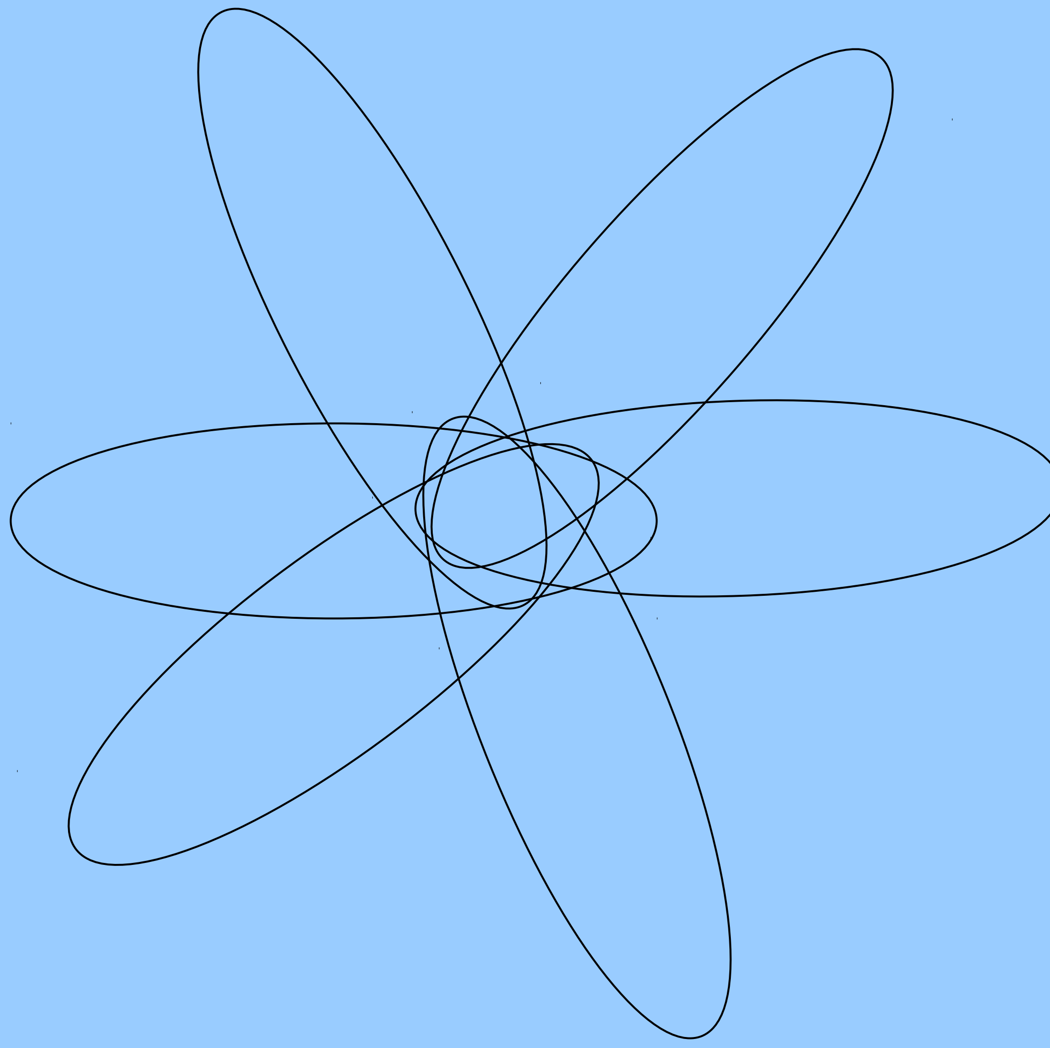
e.g. Riediemeister et al, 2010

Alternative explanations?

A population of two bodies on highly eccentric orbits

Wyatt et al 2010

This only works for a LARGE population of particles on HIGHLY (e>0.9) eccentric orbits



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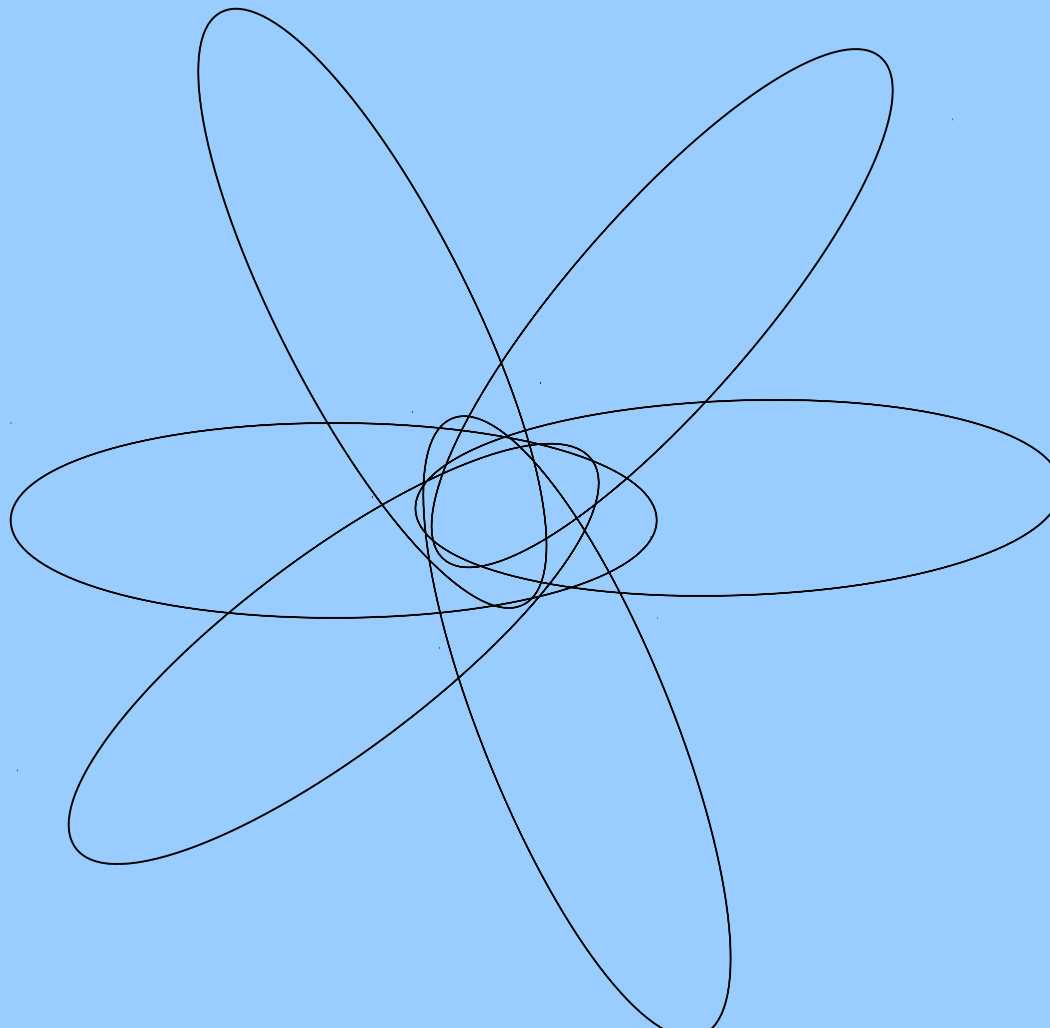


OTHERS?

OUTLINE

1)Can steady-state scattering of planetesimals inwards explain exozodi?

2)The example of Vega

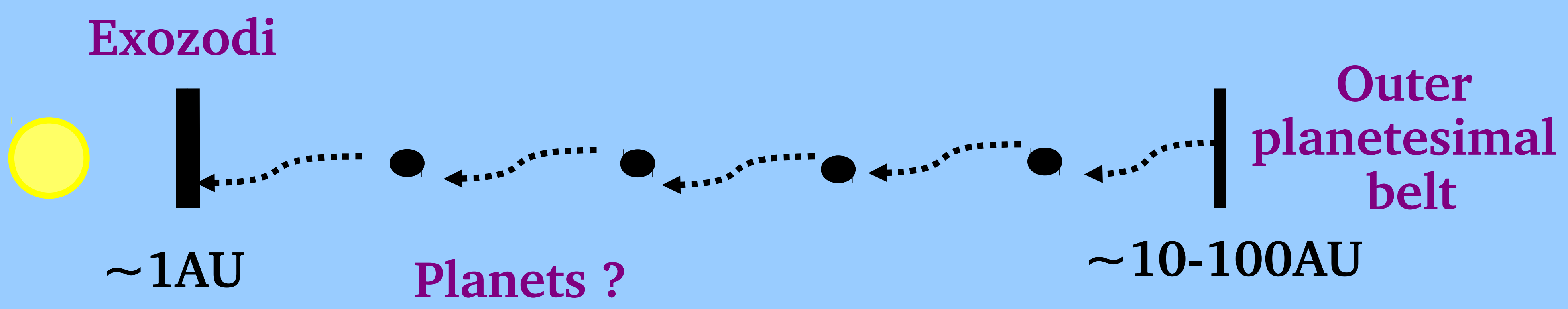
3)The example of Fomalhaut

4)Can scattering of material inwards following a dynamical instability explain exozodi?

Steady-state scattering

Make the hypothesis that the material is scattered inwards by a stable chain of planet that orbit between the inner and outer belts

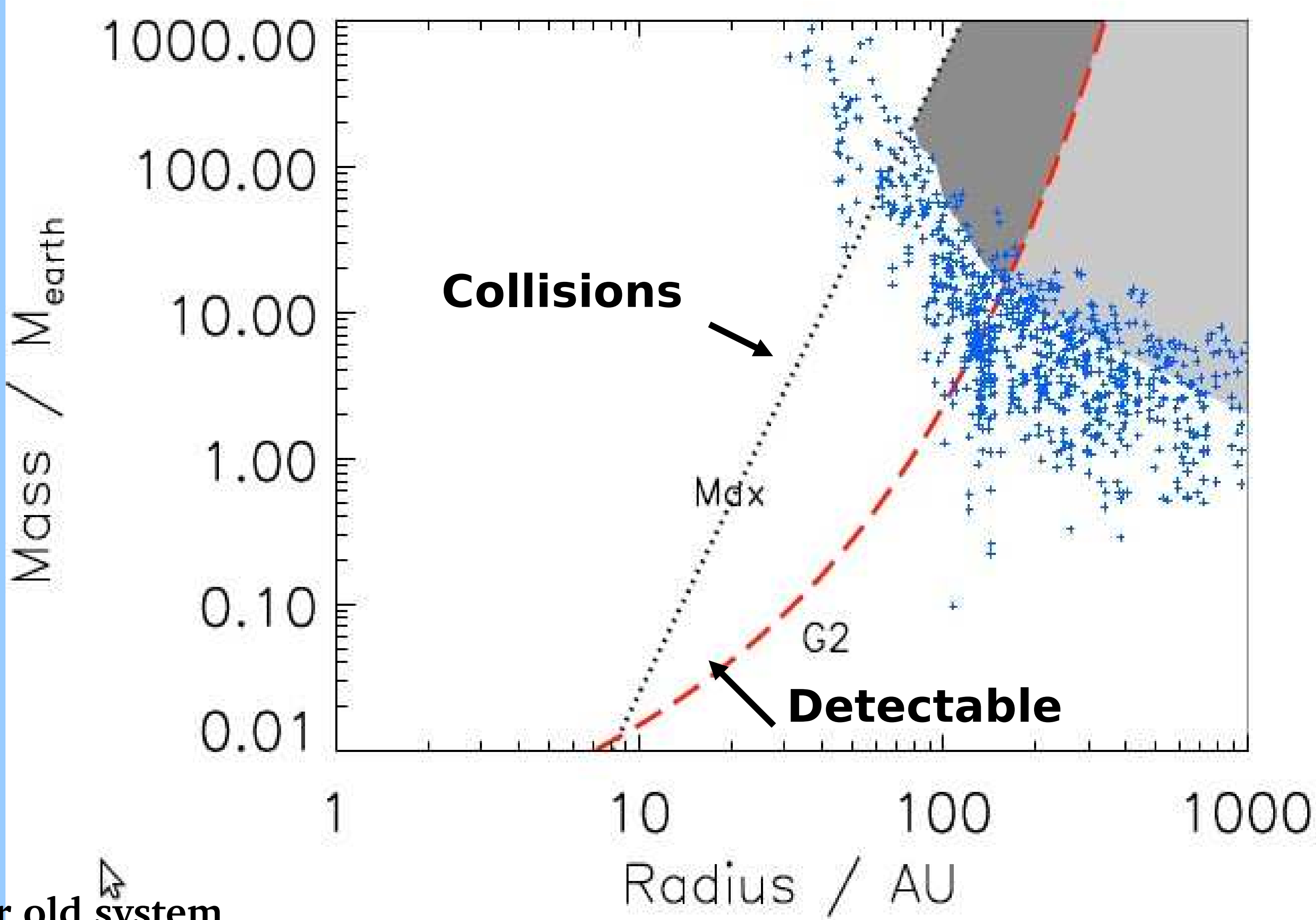
In a similar manner the Kuiper belt and JFCs are thought to be the origin of 90% of the Solar System's zodiacal cloud Nesvorny et al 2010



Use N-body simulations to determine how much material can be scattered inwards for a sample of representative planetary systems Bonsor et al 2012, A&A, submitted

Only high mass, large radii belts capable of scattering at sufficiently high rates to explain exozodi around old (>100Myr) systems

This takes the maximum scattering rates, assumes a solar mass star and a typical required replenishment rate for an exozodi of $10^{-9} M_{earth}\ yr^{-1}$



100Myr old system

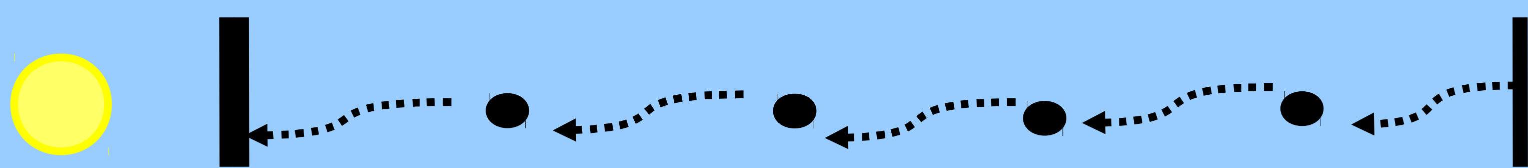
The example of Vega

Exozodi : CHARA/FLUOR Absil et al 2006 IOTA/IONIC
Defrère et al 2011

Cold, outer belt : IRAS, Aumann 1984, Spitzer, Herschel, etc

Exozodi

Outer planetesimal belt



~1AU

Needs $\sim 10^{-9} M_{earth}\ yr^{-1}$

Defrère et al 2011

Planets ?

~62-140AU

Muller et al (2010)

We can hypothesise any planets between the belts...

Even the most efficient scattering is not sufficient to sustain the observed dust!

What mass is required in the outer belt to retain the dust at its currently observed levels, as a function of time?

Vega

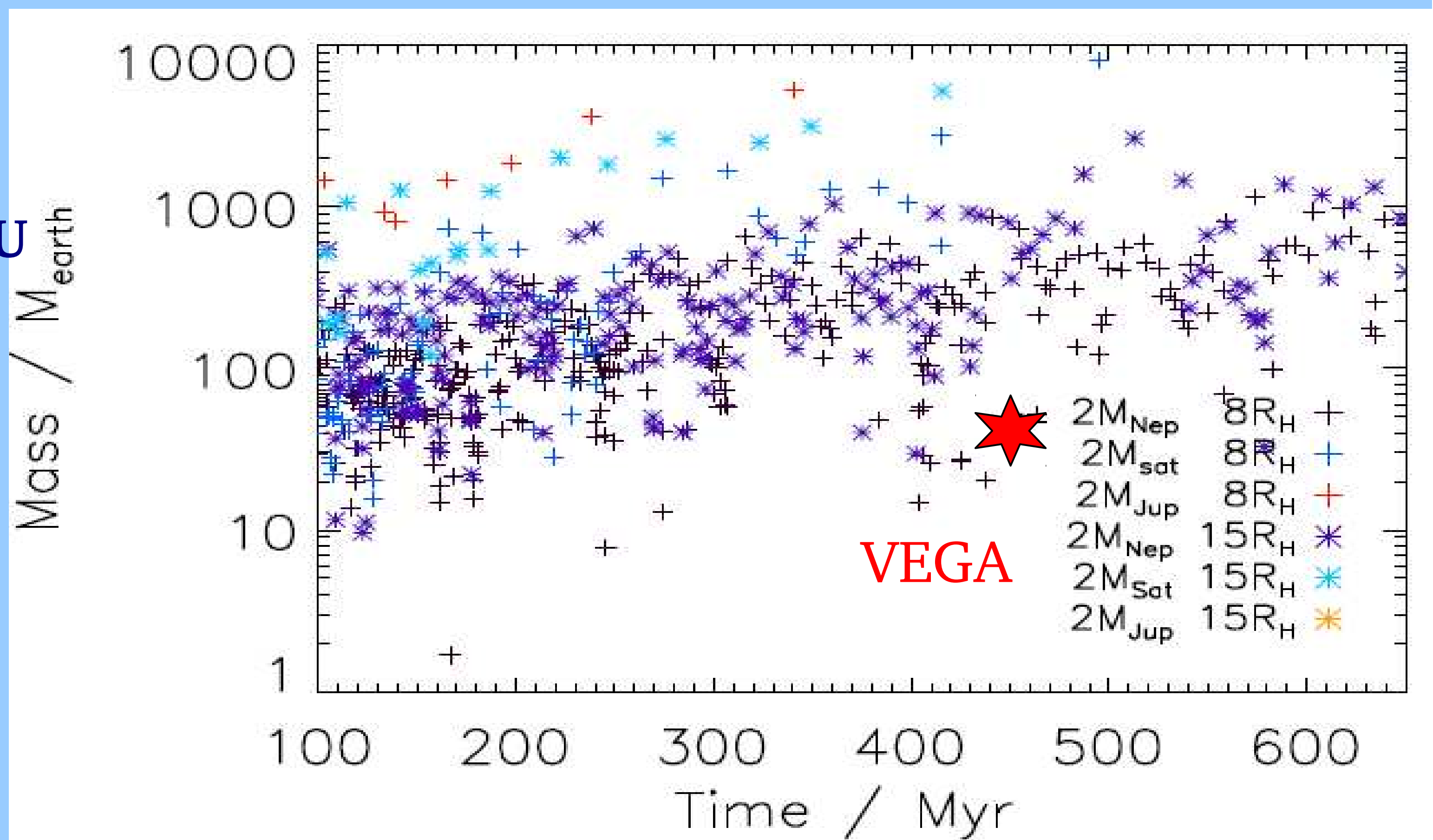
Exozodi: ~1AU

Outer belt: 62-130AU

Dust mass: $10^{-9}M_{earth}$

Lifetime ~ 1year

Defrère et al (2011)



The example of Fomalhaut

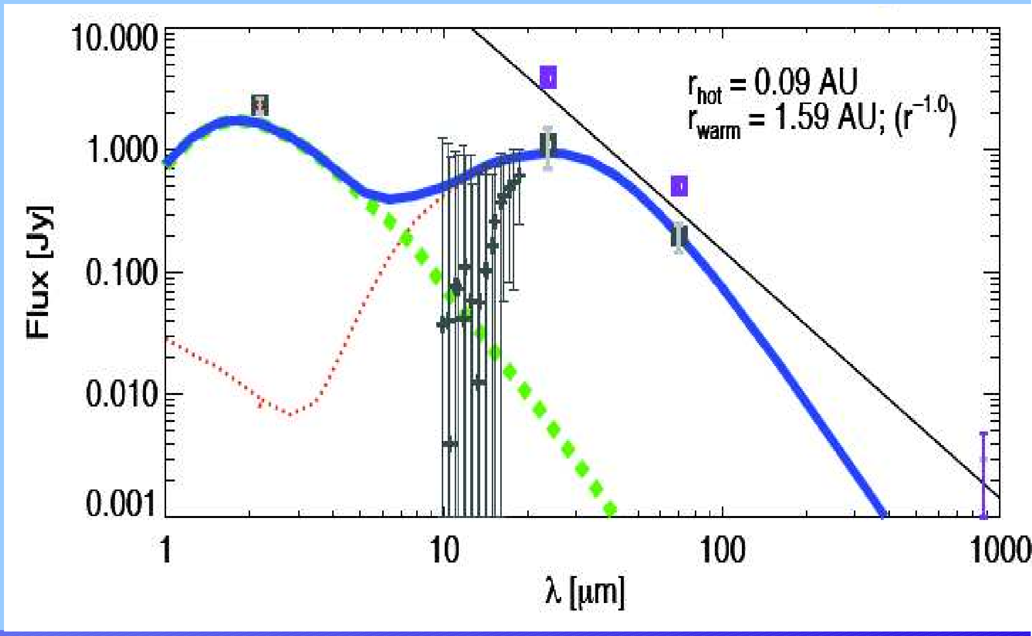
Detailed study as part of ANR Exozodi by Jérémy Lébreton, A&A, 2013, submitted

VLTI/VINCI (Absil 2010 K-band excess 0.8\pm 0.12%)
KIN (Mennesson et al 2013, detection in N-band, FOV 2AU)

Hot belt- ~0.09AU (sublimation radius), very small carbon grains

Warm belt ~0.5AU, classical debris disc

Cold belt ~140AU



The example of Fomalhaut

Both hot and warm belts are too bright to be explained by steady-state collisional evolution- could we replenish them from the outer belt?

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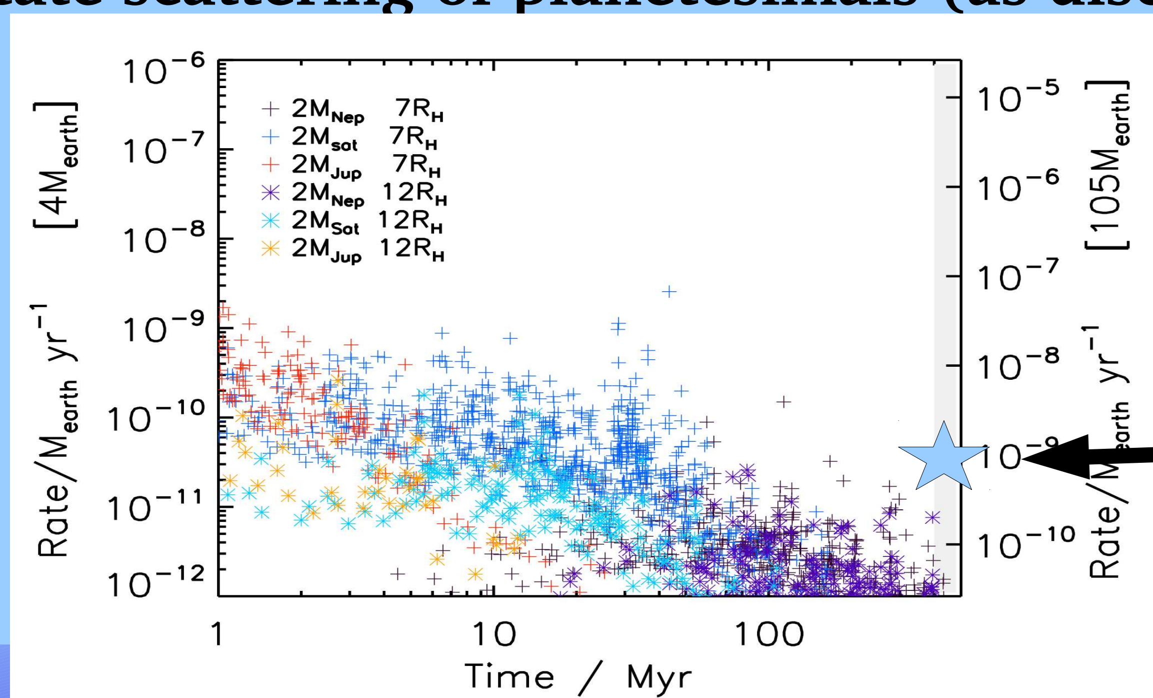

Warm belt needs at least this much material

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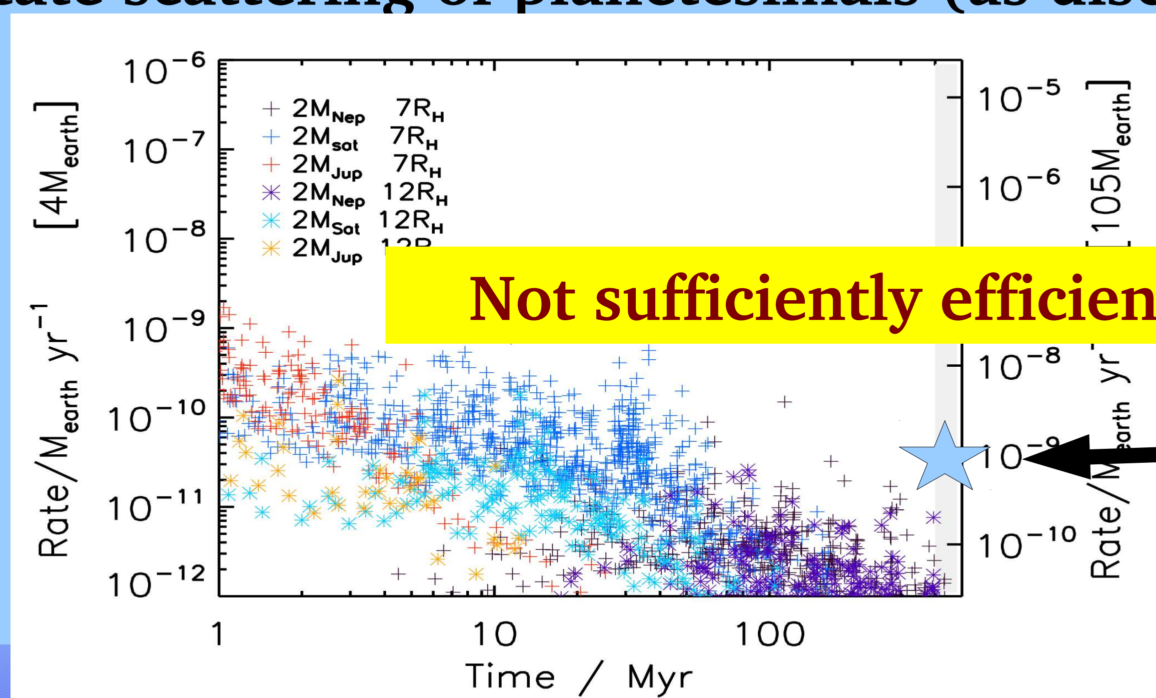

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Maybe?

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4) **Scattering of planetesimals at rates increased following a dynamical instability or planetesimal driven migration**

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Fom b could be evidence of this?

OUTLINE

1) Can steady-state scattering of planetesimals inwards explain exozodi?

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4) **Can scattering of material inwards following a dynamical instability explain exozodi?**

Scattering after a dynamical instability

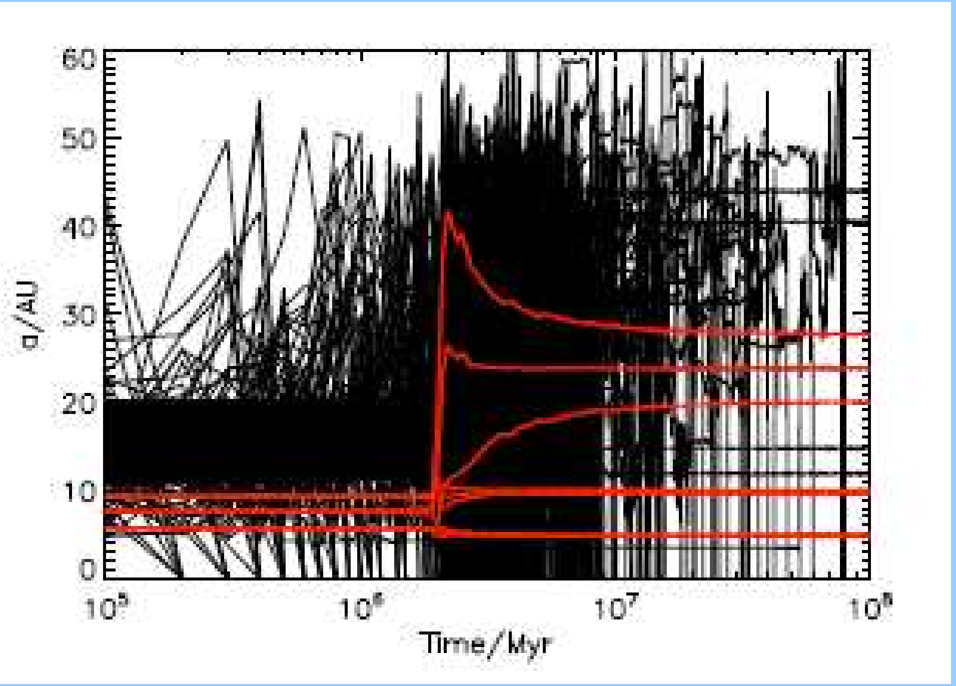
Many planetary systems are unstable…

After some period of time, planets may scatter one another

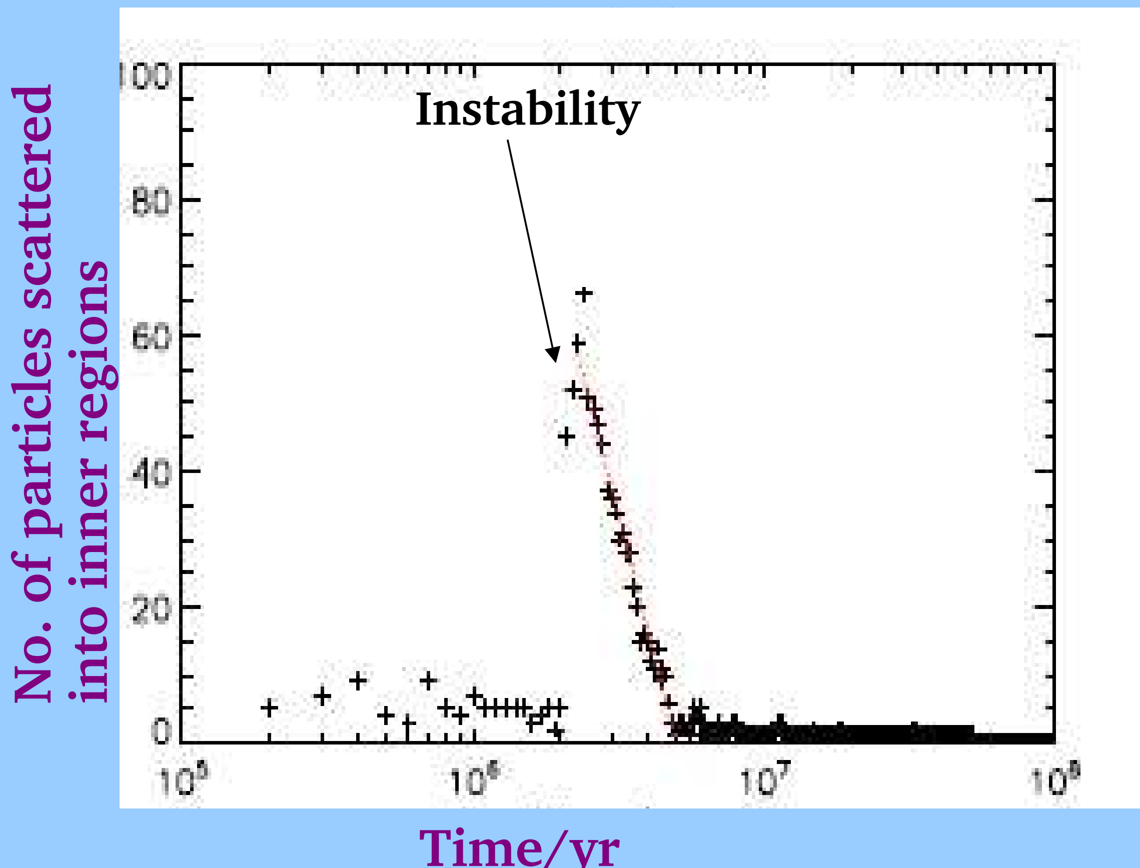
If a planet is scattered into (towards) a planetesimal belt, many planetesimals are scattered out of the belt

Such scattering may lead to the production of an exozodi

An example of a dynamical instability



Scattering after a dynamical instability



Directly following the instability, many particles are scattered, but this number falls off rapidly with time..

Can instabilities explain the high fraction of stars with exozodiacal dust?

- Between 4 and 30% of stars are observed with exozodiacal dust (Absil et al 2013, in prep, Millan-Gabet, 2011)

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- Between 4 and 30% of stars are observed with exozodiacal dust (Absil et al 2013, in prep, Millan-Gabet, 2011)
- Each star could have a maximum of one dynamical instability that increases the rate at which material is scattered inwards
- Increase in material scattered inwards into the inner regions only lasts for a short time period (maximum ~40Myr)

Can instabilities explain the high fraction of stars with exozodiacal dust?

- Between 4 and 30% of sun-like stars are observed with exozodiacal dust (Absil et al 2013, in prep, Millan-Gabet, 2011)
- Each star could have a maximum of one dynamical instability that increases the rate at which material is scattered inwards
- Increase in material scattered inwards into the inner regions only lasts for a short time period (maximum ~40Myr)
- Therefore, if a random sample of stars is observed, maximum percentage that could have material in the inner regions, i.e. be within 40Myr of an instability is 40Myr/tMS ~40Myr/5Gyr (typical main-sequence lifetime) ~0.8%

Can instabilities explain the high fraction of stars with exozodiacal dust?

Dynamical instabilities are an unlikely explanation for the 4-30% of sun-like stars observed with exozodi, and with current sample sizes, it is improbable that we observe any stars in the aftermath of an instability

Bonsor & Raymond, 2013, in prep

Conclusions

- Observations of a large fraction of systems with exozodiacal dust are mysterious, as this dust has a short lifetime against collisions/radiative forces

Hypothesis: Exozodiacal dust originates in an outer planetesimal belt and is scattered inwards by planets

- Steady-state scattering only occurs at very low rates, at the age of the observed systems

- Dynamical instabilities cannot occur sufficiently frequently to explain the large number of systems

- Other explanations? Planetesimal-driven migration? Watch this space!