FIR Surveyor Workshop, Caltech, 3-5 June 2015

Debris Disks in the 2020's

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Outline of talk

- What are debris disks?
- Now and the near future: surveys and ALMA
- The 2020’s: what are the key goals?
- The “perfect” mission and conclusions

What are debris disks?

- Originally discovered by IRAS in the 1980's – excess IR emission from a star brighter than the photosphere

- Observed around many main sequence stars as a disk (or ring…), implying the existence of larger bodies to replenish the material

- Detected in the optical to the mm from scattered light to the thermal emission of dust

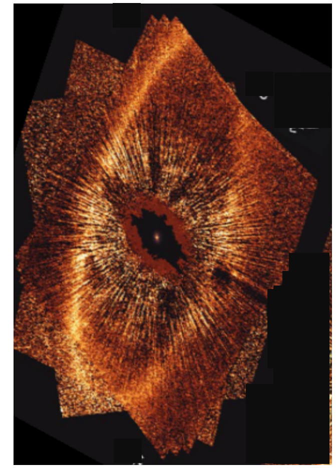
- ~15% of stars have known debris disks

- About 300 debris disks are known, with ~30 imaged in some detail

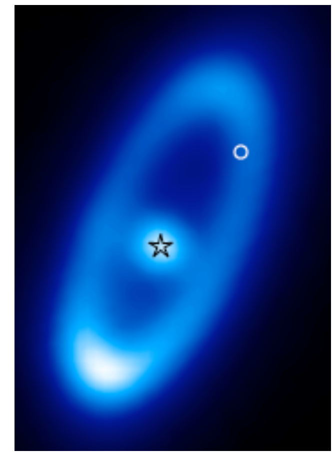
- Most have inner holes of order 40 – 100 AU in diameter

Observables

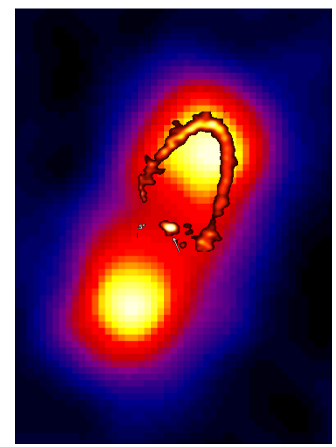
Optical
– scattered light
(Hubble)



Far-IR
– dust emission
(*Herschel*/PACS)

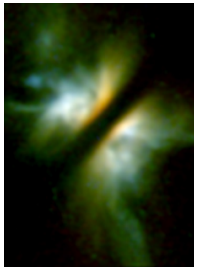


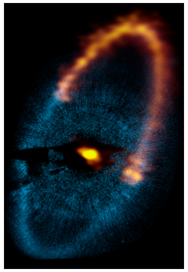
Submm
– dust emission
(JCMT/SCUBA-2
and ALMA)



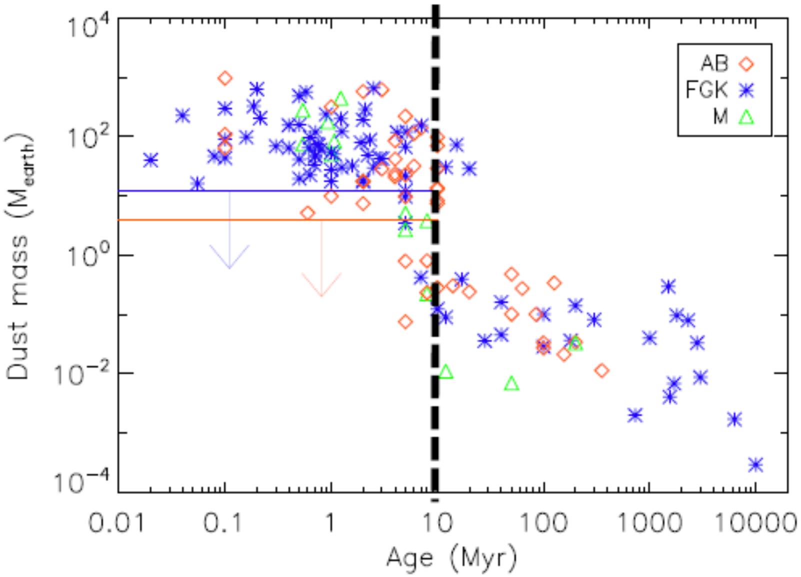
Fomalhaut

Descendant of proto-planetary disk





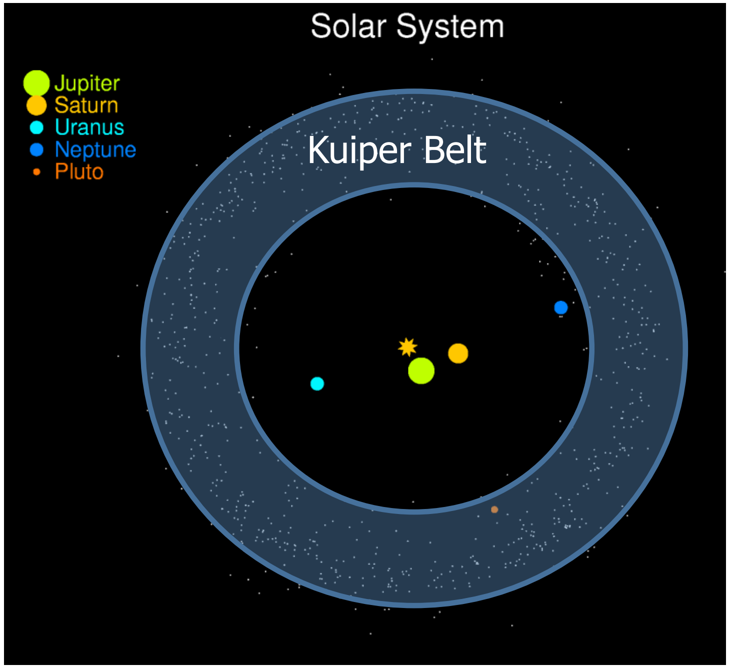
	Proto-planetary disk	Debris disk
Age	< 10 Myr	10 Myr – 10 Gyr
Optical depth	Optically thick	Optically thin
Dust mass	> 10 M_{Earth}	< 1 M_{Earth}
Gas mass	~100x dust mass	Very little (usually…)
Structure	Dust from 0.1 – 1000 AU	Confined to 30 – 100 AU ring
Dust origin	Primordial?	Secondary (short lifetime)

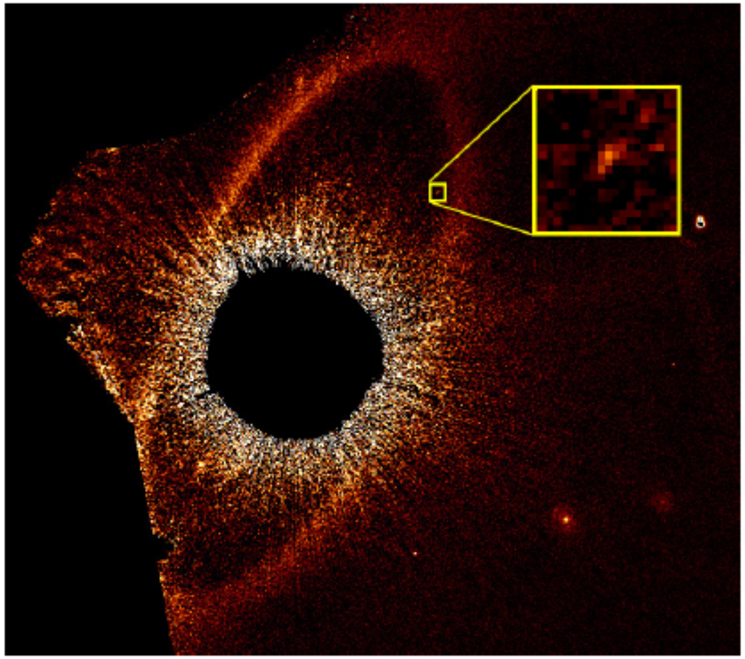


Onset of the debris phase
(Panić et al. 2013, MNRAS 435, 1037)

Debris disks and planets

- Structure provides indirect information on the architecture (and evolution) of a possible planetary system



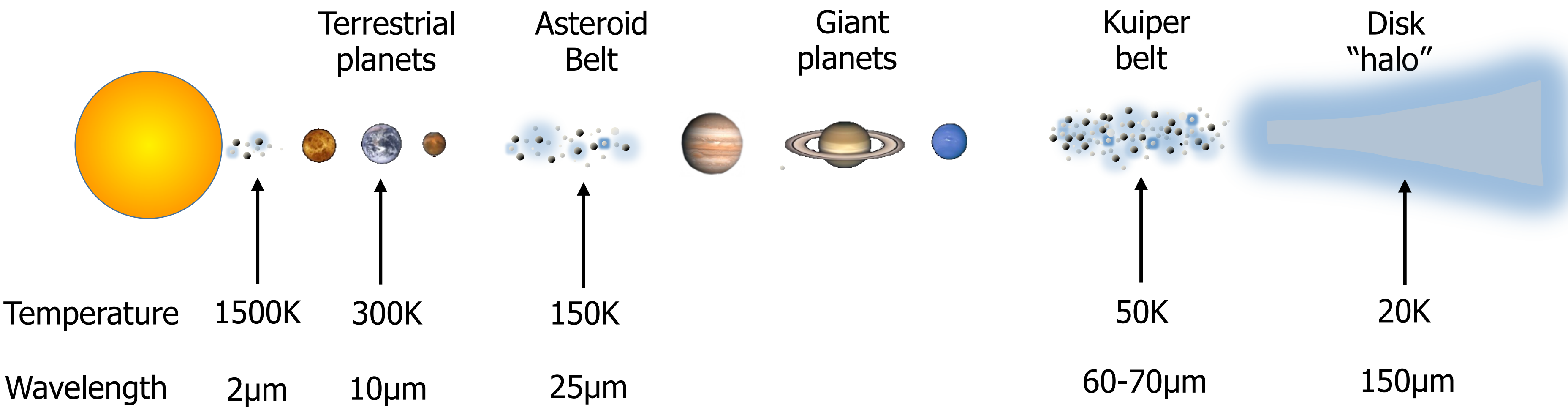


Fomalhaut (Kalas et al. 2013)

- Structure also can be used to predict and identify perturbers, such as planets

Observations probe different zones

- Different wavelength observations probe multiple components of a disk



Observations probe different zones

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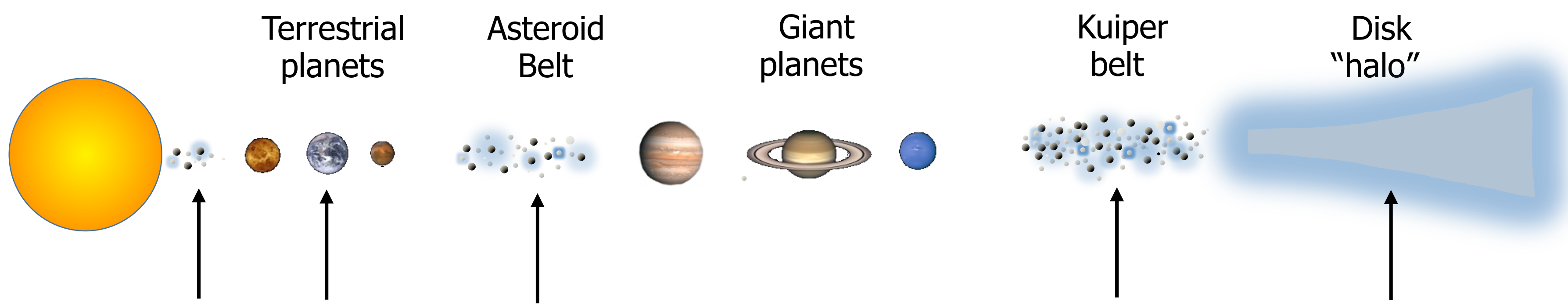
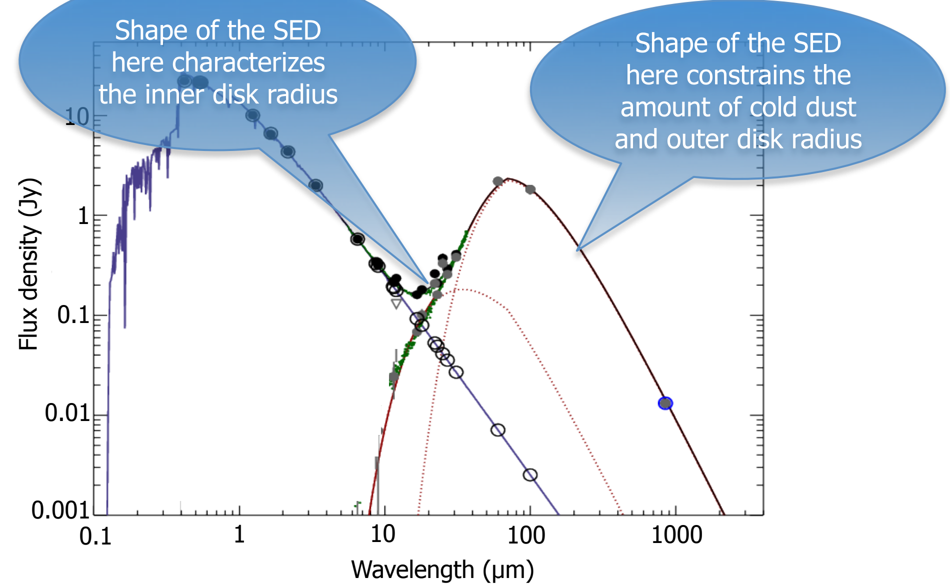


Temperature	1500K	300K	150K	50K	20K
Wavelength	2μm	10μm	25μm	60-70μm	150μm

If a single component dominates (such as a Kuiper belt) then multi-wavelength observations probe different grain sizes



State-of-the-art today

Statistics from surveys, resolved images, detection of gas and the possible discovery of new classes of object...

- IRAS, ISO, & SCUBA: photometry and "imaging" → early information on basic properties
- *Spitzer*: Surveys of A-stars → studying dust evolution
- *Herschel:* DUNES and DEBRIS → 50% of debris disks are resolved
- JCMT/single dishes: e.g. SONS → cold and massive disks

Key results so far

- Disk incidences are reasonably well measured by *Spitzer* and *Herschel*

	A stars	F, G and K stars	M stars
Incidence	26%	10-24%	Very few!
Main wavelengths	2, 24, 70, 100μm	24, 70, 100, 160μm	24, 70, 100, 850μm

Su et al. 2006, ApJ 653, 675
Chen et al. 2011, ApJ 738, 122
Absil et al. 2013, A&A 555, 104
Thureau et al. 2014, MNRAS 445, 5558

Hillenbrand et al. 2008, ApJ 677, 630
Carpenter et al. 2009, ApJS 181, 197
Eiroa et al. 2013, A&A 555, 11
Marshall et al. 2014, A&A 565, 15

Liu 2004, Science 305, 1442
Gautier et al. 2007, ApJ 667, 527
Lestrade et al. 2012, A&A 548, 86
Matthews et al. 2015, *in prep*

Key results so far

- Disk incidences are reasonably well measured by *Spitzer* and *Herschel*

Comparable to planet rate discovered by Kepler

	A stars	F, G and K stars	M stars
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Main wavelengths	2, 24, 70, 100µm	24, 70, 100, 160µm	24, 70, 100, 850µm

Generally good agreement at all wavelengths

Su et al. 2006, ApJ 653, 675
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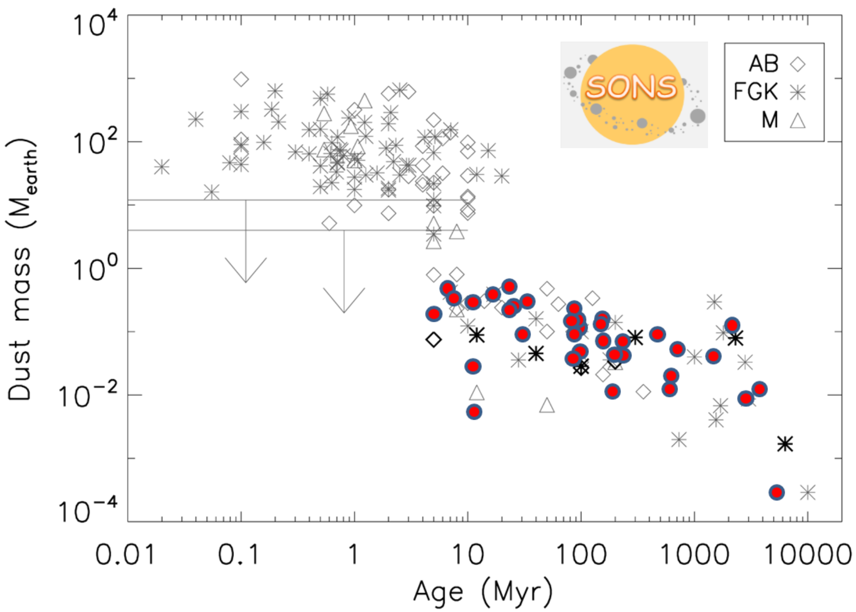
Liu 2004, Sci
Gautier e
Lestrad
Matthe

Except for very young M stars, these remain elusive!

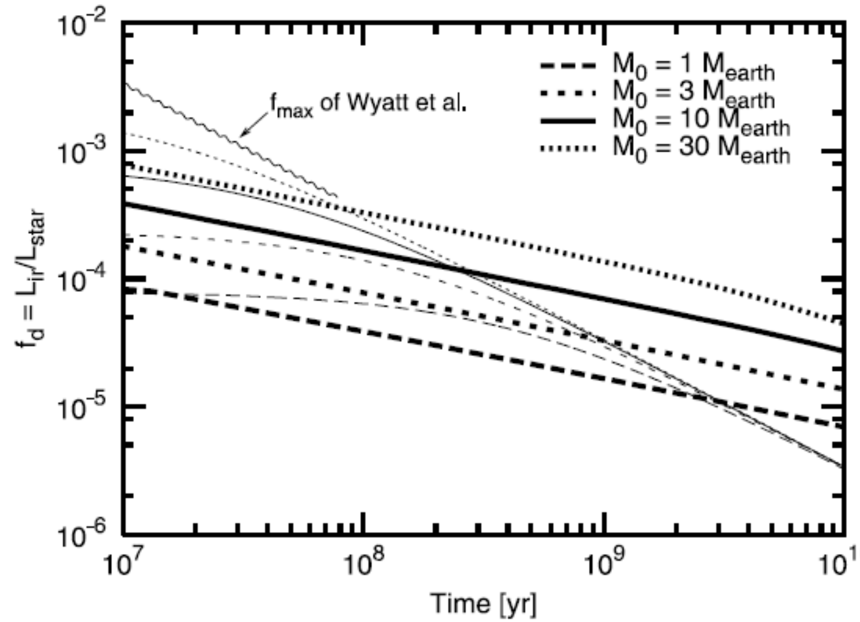
Tentative conclusion: Debris disks tend to be more prevalent around higher-mass stars

Key results so far

- Evidence of declining disk mass and luminosity over time



Panić et al. 2013, MNRAS 435, 1037
Holland et al. 2015 *in prep*

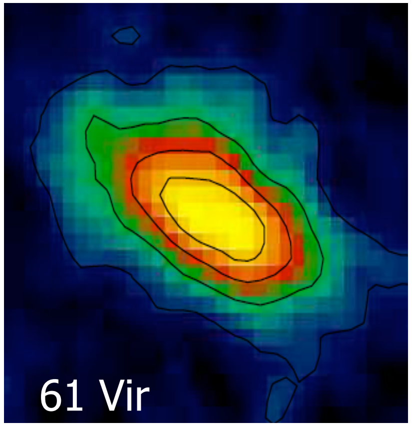


Wyatt et al. 2007, ApJ 663, 365

Key results so far

- Tentative correlation between low-mass planets and debris disks for Solar-type stars

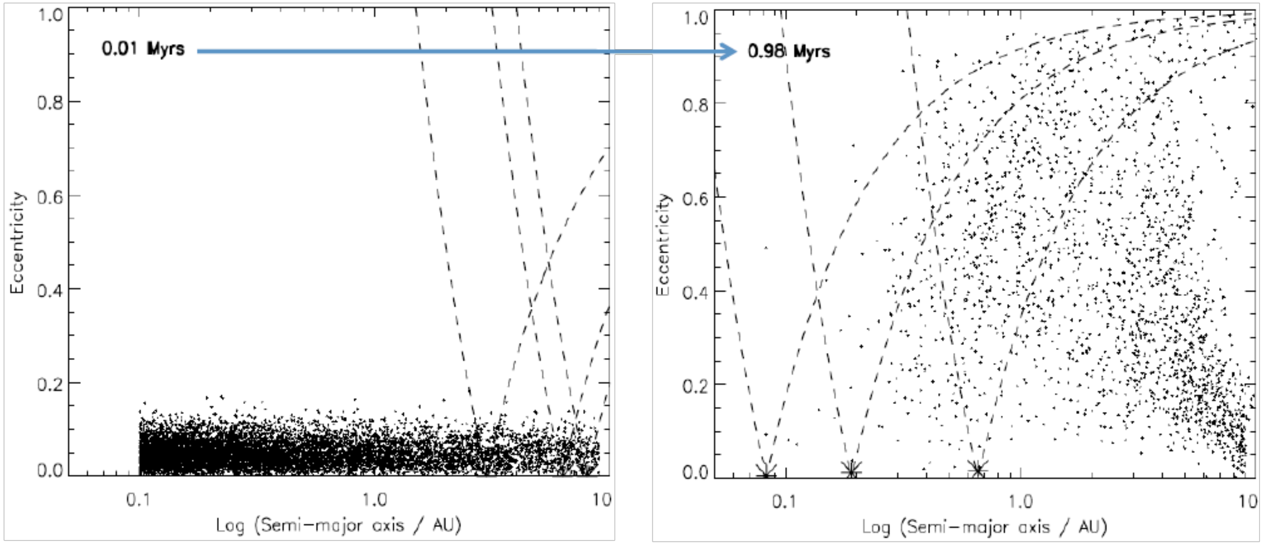
See also: Marshall et al. 2014
A&A 565, A15



4/6 with low-mass planets have debris

0/5 with high-mass planets have debris

Wyatt et al. 2012, MNRAS 424, 1206



Planets start off at 5-10 AU and migrate inwards → many planetesimals end up beyond the outermost planet in a dynamically stable system

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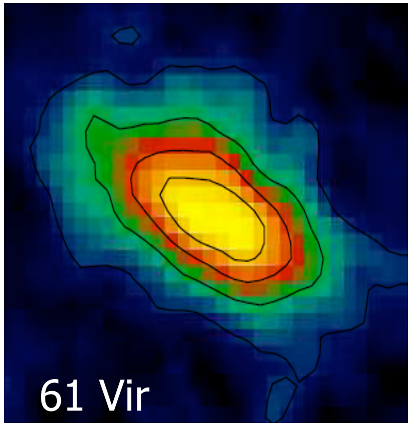


4/6 with low-mass planets have debris

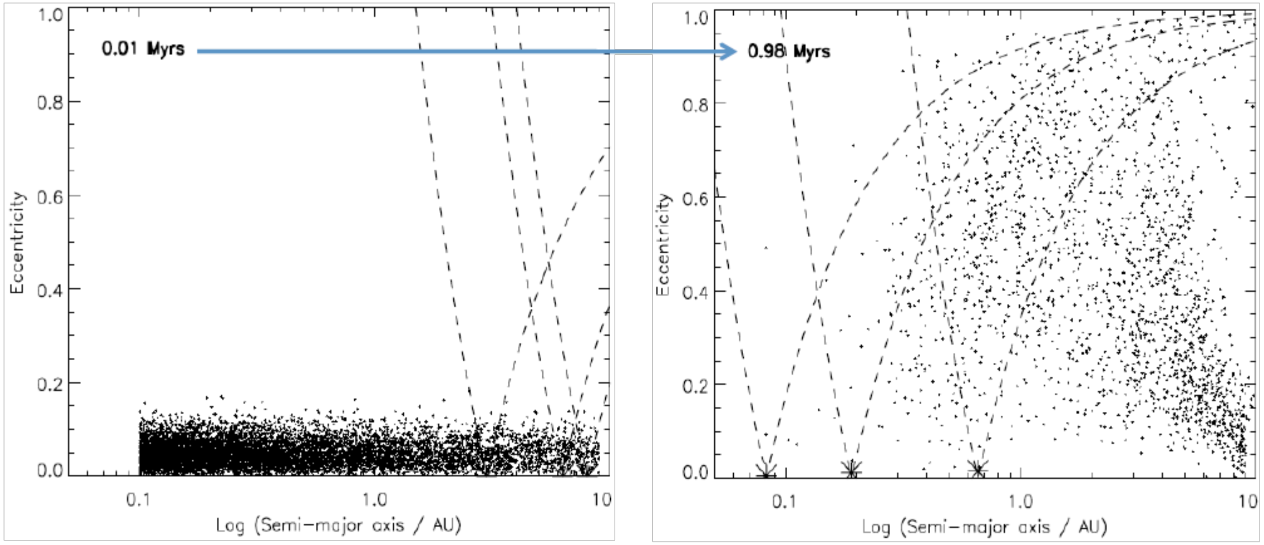
0/5 with high-mass planets have debris

Wyatt et al. 2012, MNRAS 424, 1206

HOWEVER…

Larger survey of ~200 FGK stars with *Herschel* (Moro-Martin et al. 2015) found NO correlation…

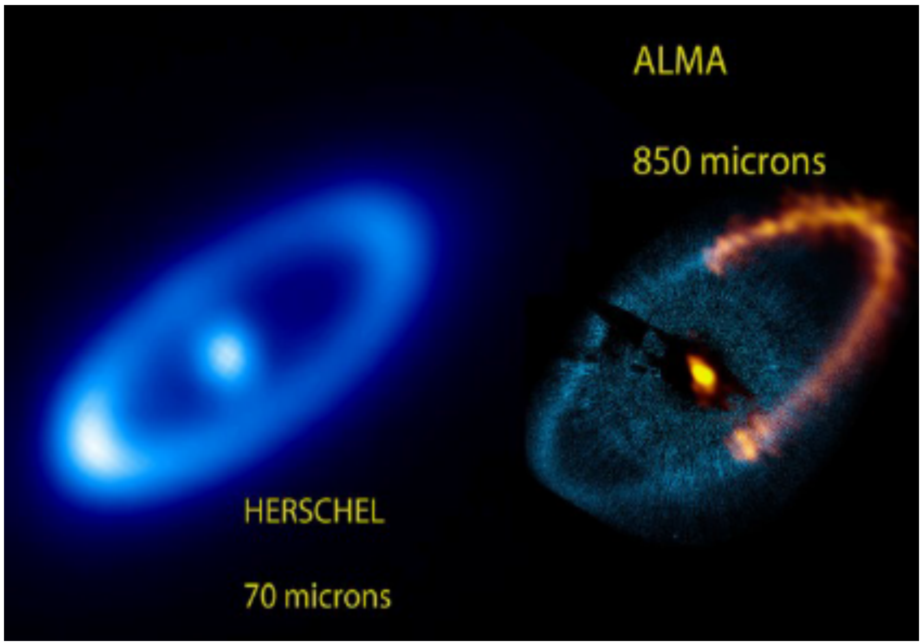
Diverse dynamic histories of such systems may account for the lack of correlations…



Planets start off at 5-10 AU and migrate inwards → many planetesimals end up beyond the outermost planet in a dynamically stable system

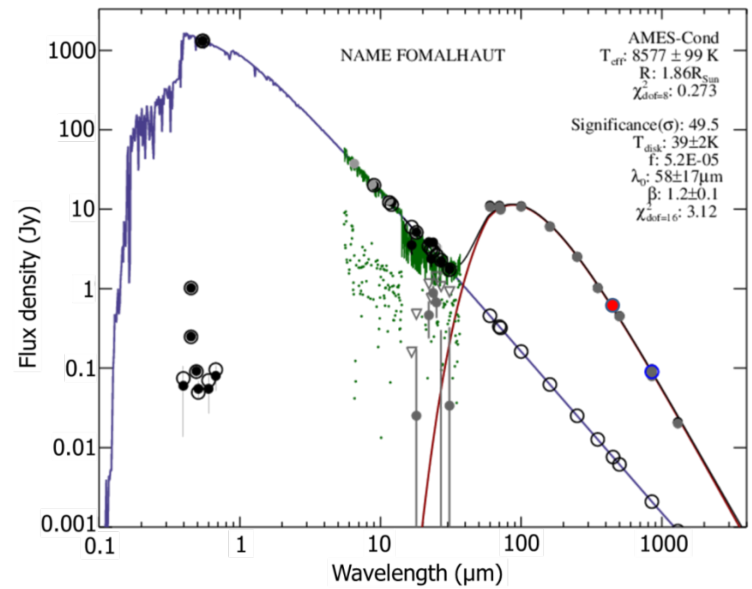
The role of ALMA

- Resolving disks is key to understanding the underlying structure of debris disks



Acke et al. 2012, AAp 540, A125; Kalas et al. 2013, ApJ 775, 56

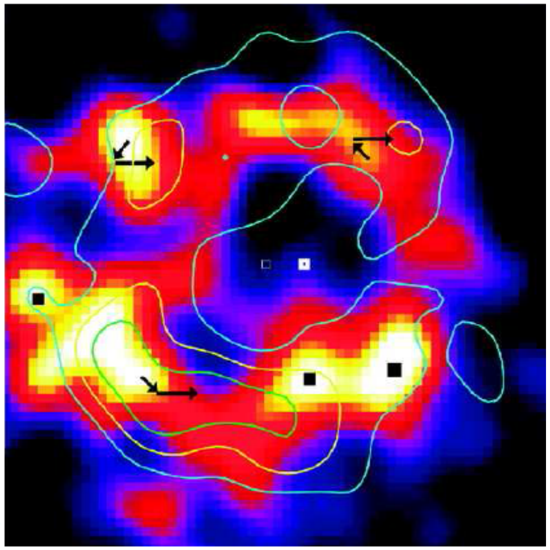
Spectral energy distribution
Fit for T_{dust}, r_{disk} and spectral slope



Can derive other physical parameters such as dust luminosity and mass, and information about dust grain sizes and composition.

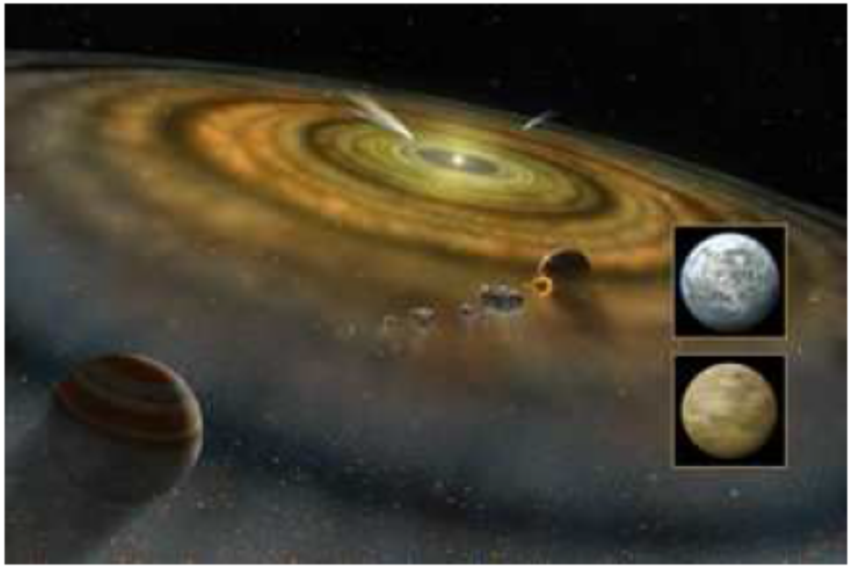
The role of ALMA

- Unambiguous identification of dust trapped in resonances with a planet



ε Eridani dust ring
(Greaves et al. 2005, ApJ 619, L187)

- Sensitivity to detect perturbations within disks on short timescales
e.g. rotation of ε Eridani clumps in 1 month!



…But deep spectroscopy will be important to study comet collisions that should produce H_20 and CO

- BUT, ALMA is not a disk finder, it is (and will be…) good at characterising disks

Next generation of missions in the 2020's…

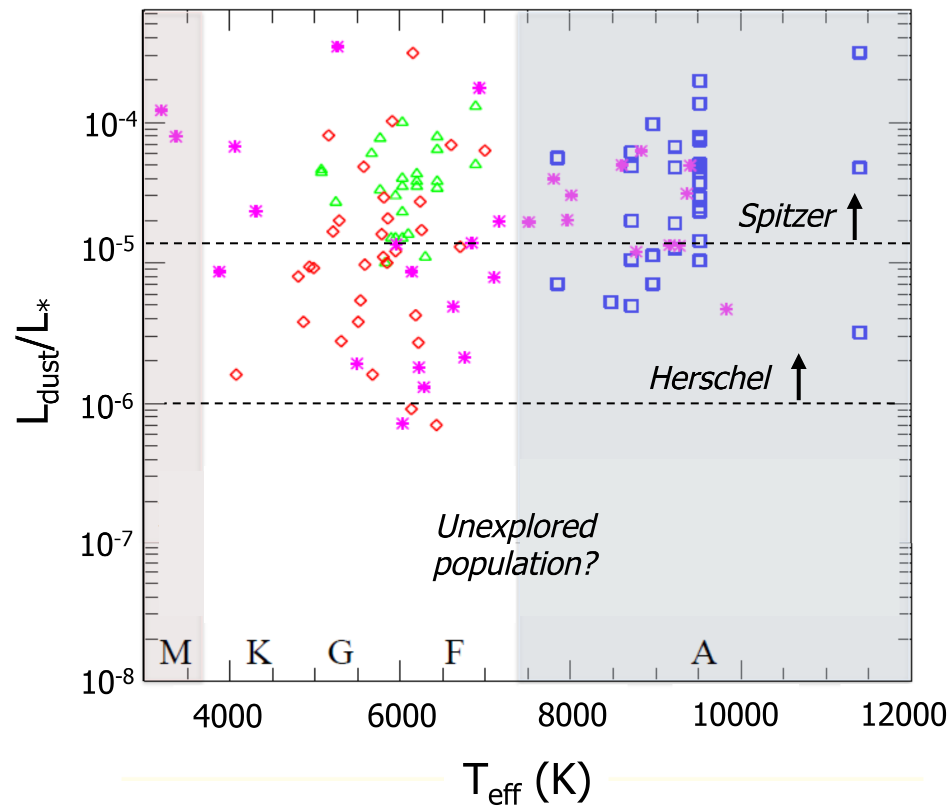
Need to address questions such as:

- Do all stars have debris disks?
- The planet/star connection: How do the properties of the star and any planets present influence the disk?
- Do asymmetries/clumps within debris disks mean planets have to be present?
- Are there Kuiper and asteroid belts around most stars? ("How common is our Solar System architecture?")
- What is the composition of the disk material (mineralogy), how did it originate and how does it evolve?
- What role does atomic and molecular gas play in the evolution of debris disks (and planetary systems)?

Do all stars have debris disks?

- Debris disks are faint so need very sensitive telescopes and instruments (M-star disks within 100pc might be as faint as 100μJy...)

- Must survey as many targets as possible (big sub-samples!)
  - Prevalence of planets
  - Spectral type
  - Age
  - Metallicity of star…



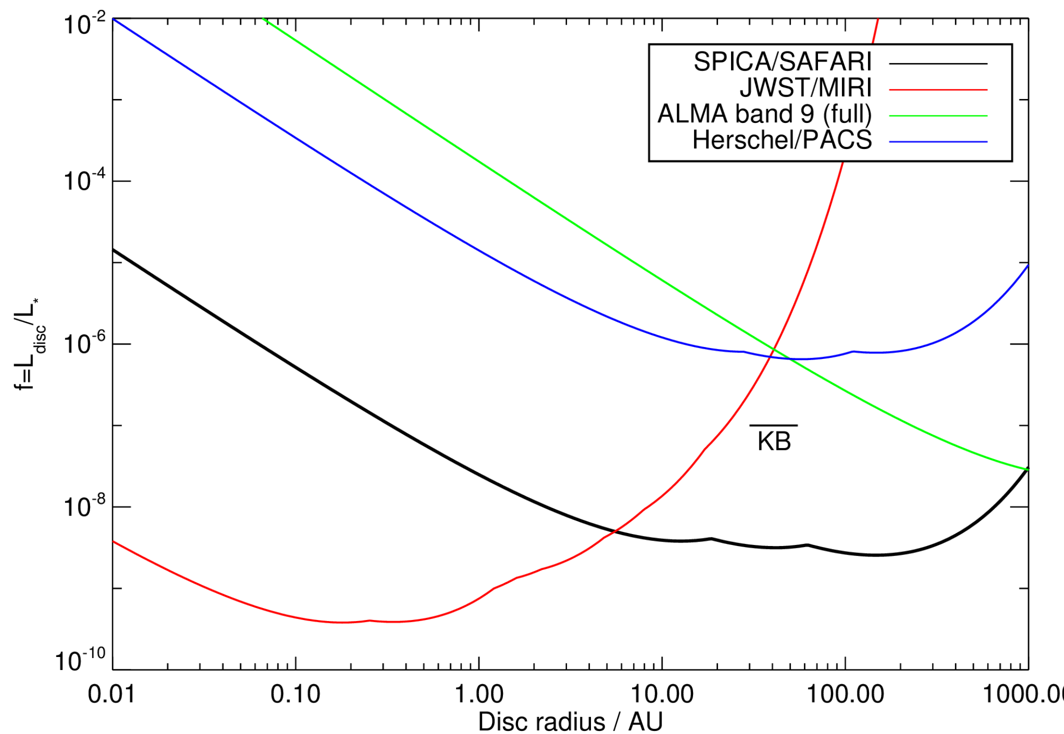
It is quite possible that **ALL** stars have a debris disk at some level (below current detection thresholds)

Sensitivity to reach very low dust masses

- Need to go at least 10x deeper than any planned facility to properly resolve a Kuiper Belt

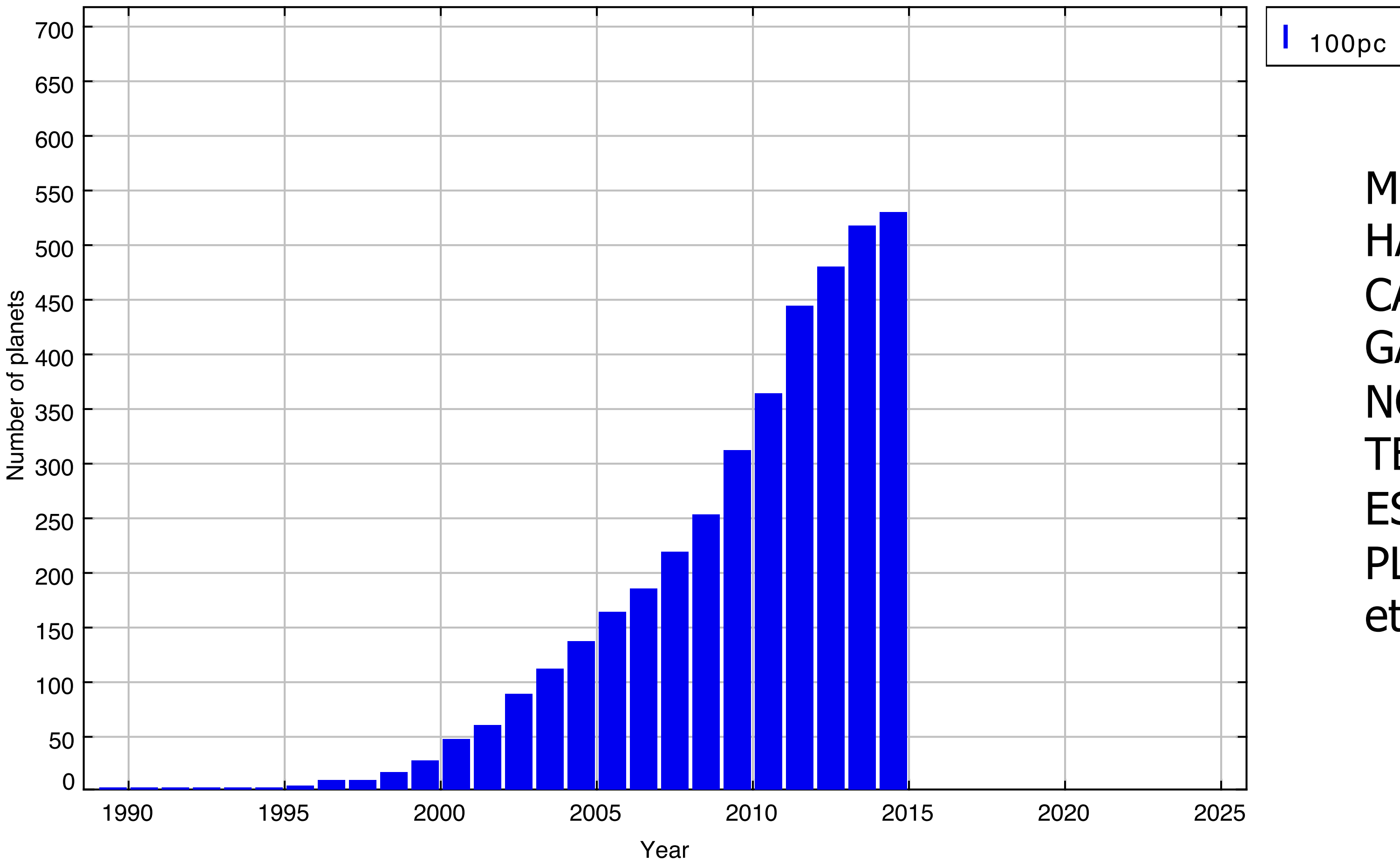
- SPICA, CALISTO or a Far-IR space Interferometer type mission could achieve these levels…

- But confusion and calibration uncertainties may limit the achievable sensitivity (need an interferometer?)



Fractional luminosity versus disk radius for blackbody emission around a star at 10pc, based on the sensitivities of selected missions for 1 hour integration time. Note this applies to resolved systems only. Plot kindly provided by Bruce Sibthorpe.

The planet connection



Plot by Grant Kennedy (data from exoplanets.org)

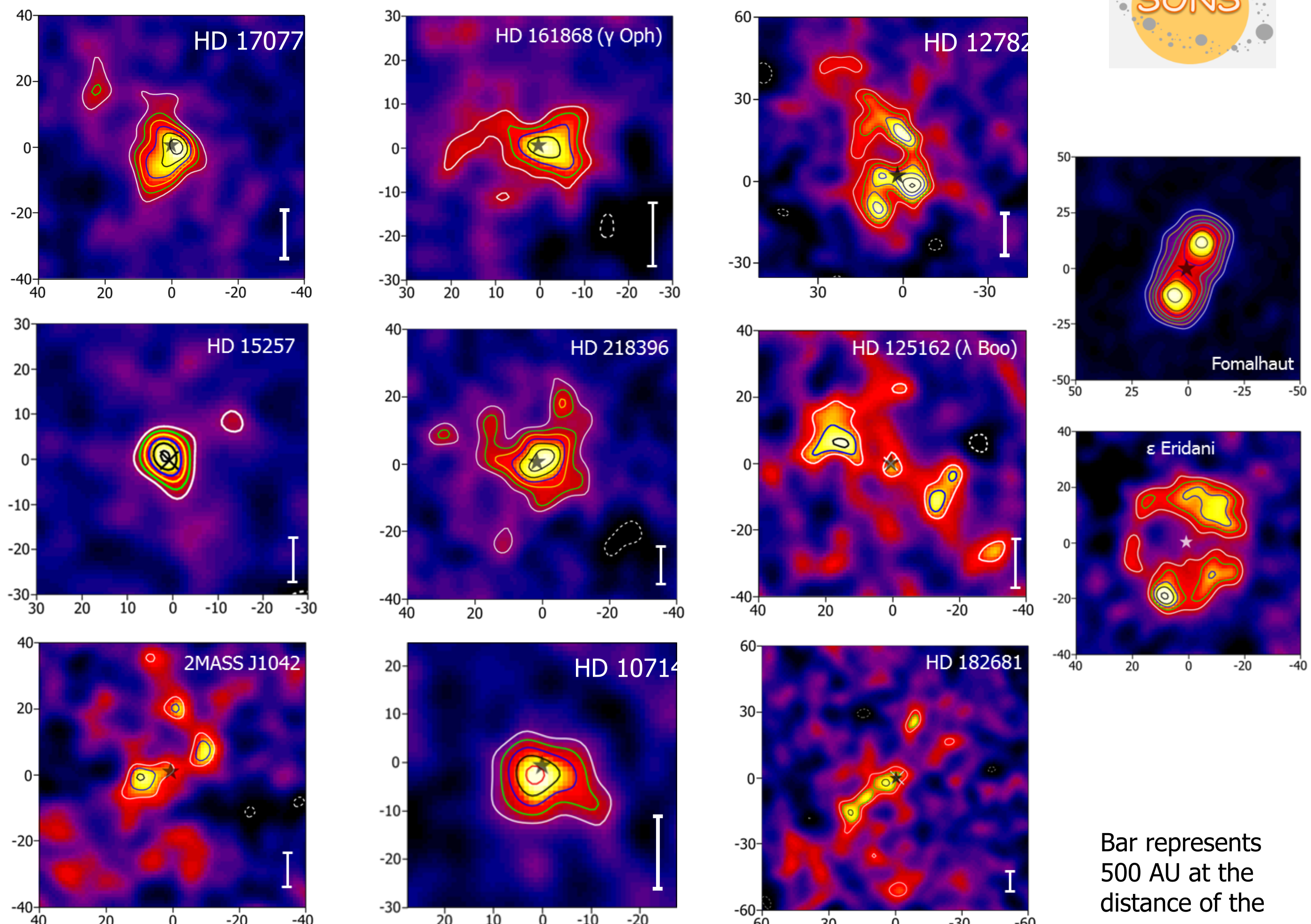
MEARTH
HARPS (N)
CARMENES
GAIA
NGTS
TESS
ESPRESSO
PLATO
etc...

- By about 2025 all Sun-like stars within 100pc will have been observed in the search for planets (perhaps gaining information on rotation periods, space motions, asteroseismology...) – so, lots of targets!

Mega-surveys?

- Must survey as many targets as possible (big sub-samples!)

- Prevalence of planets
- Spectral type
- Age
- Metallicity of star…



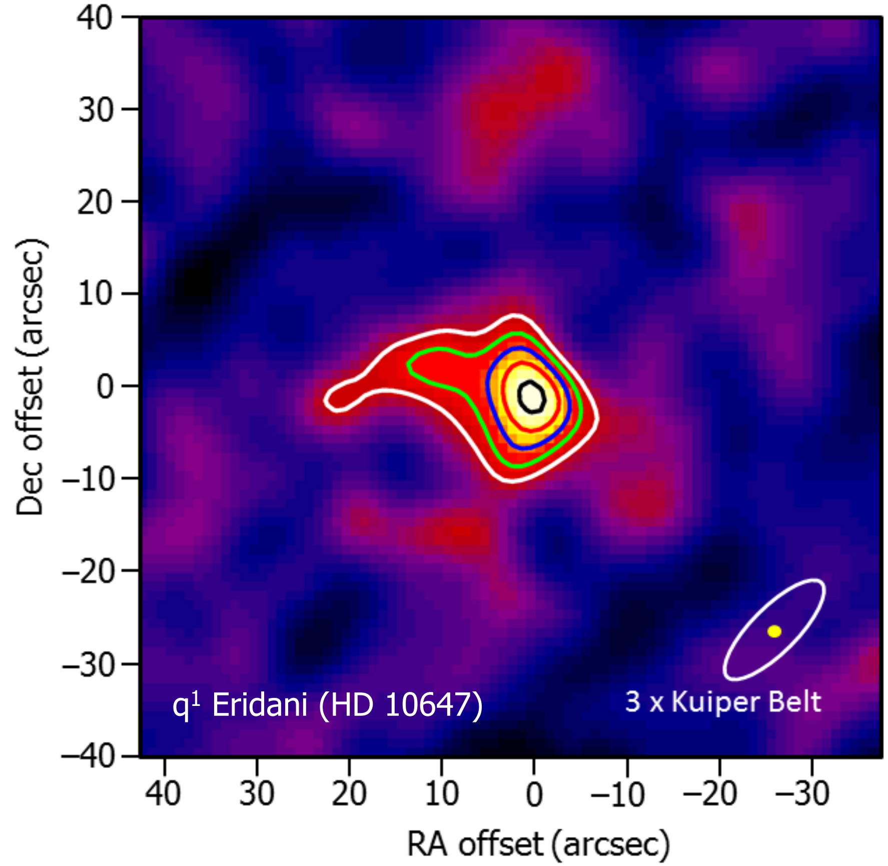
Bar represents 500 AU at the distance of the star

Clumps and asymmetries?

- Asymmetries and clumps within debris disks have been modelled to (usually) suggest the presence of one or more perturbing planets

- Is this the most plausible and only explanation?

Massive disk at around 300 AU from the star, but perhaps with an inner edge as close as 25 AU?

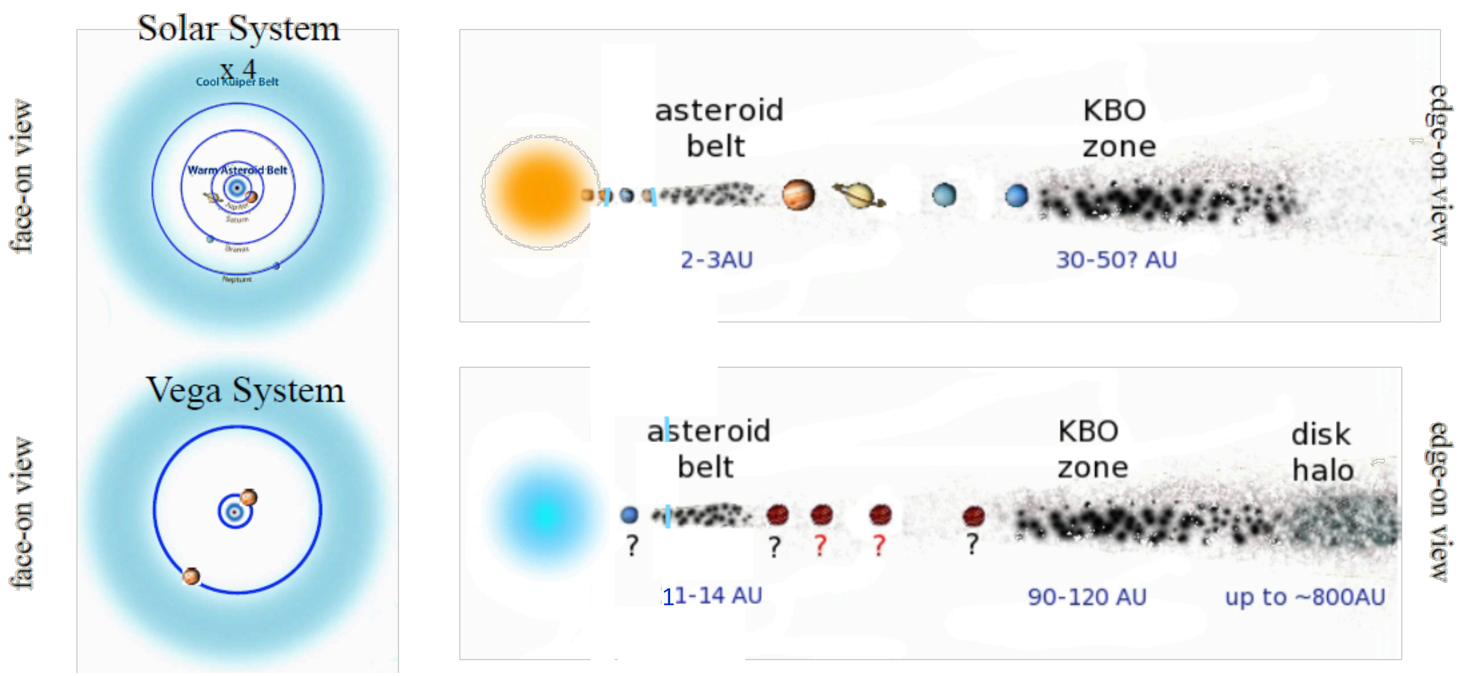


An outer planet or just a large, massive Kuiper Belt?

Need better angular resolution to improve constraints on models…

Kuiper and asteroid belts

- Sub-arcsec resolution in the far-IR allows exploration of the warmer inner regions, but also the range to characterise systems with multiple dust belts



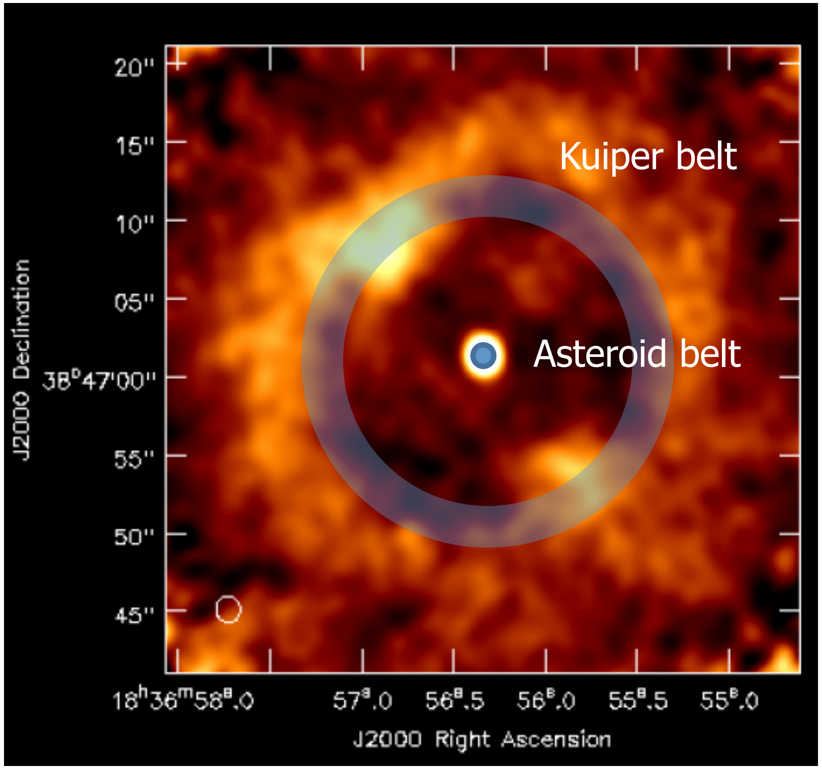
- Information on zodiacal and asteroid belt dust – regions that could affect the evolution of habitable planets, but need sub-arcsec resolution

Sub-arcsec observations in the mid/far-IR

- What are the requirements?

The angular resolution to resolve structure in Kuiper and asteroidal belts around other stars

For example, an asteroid belt at 10pc has a diameter of ~1 arcsec – so a facility like a FIRI at 40μm would be perfect



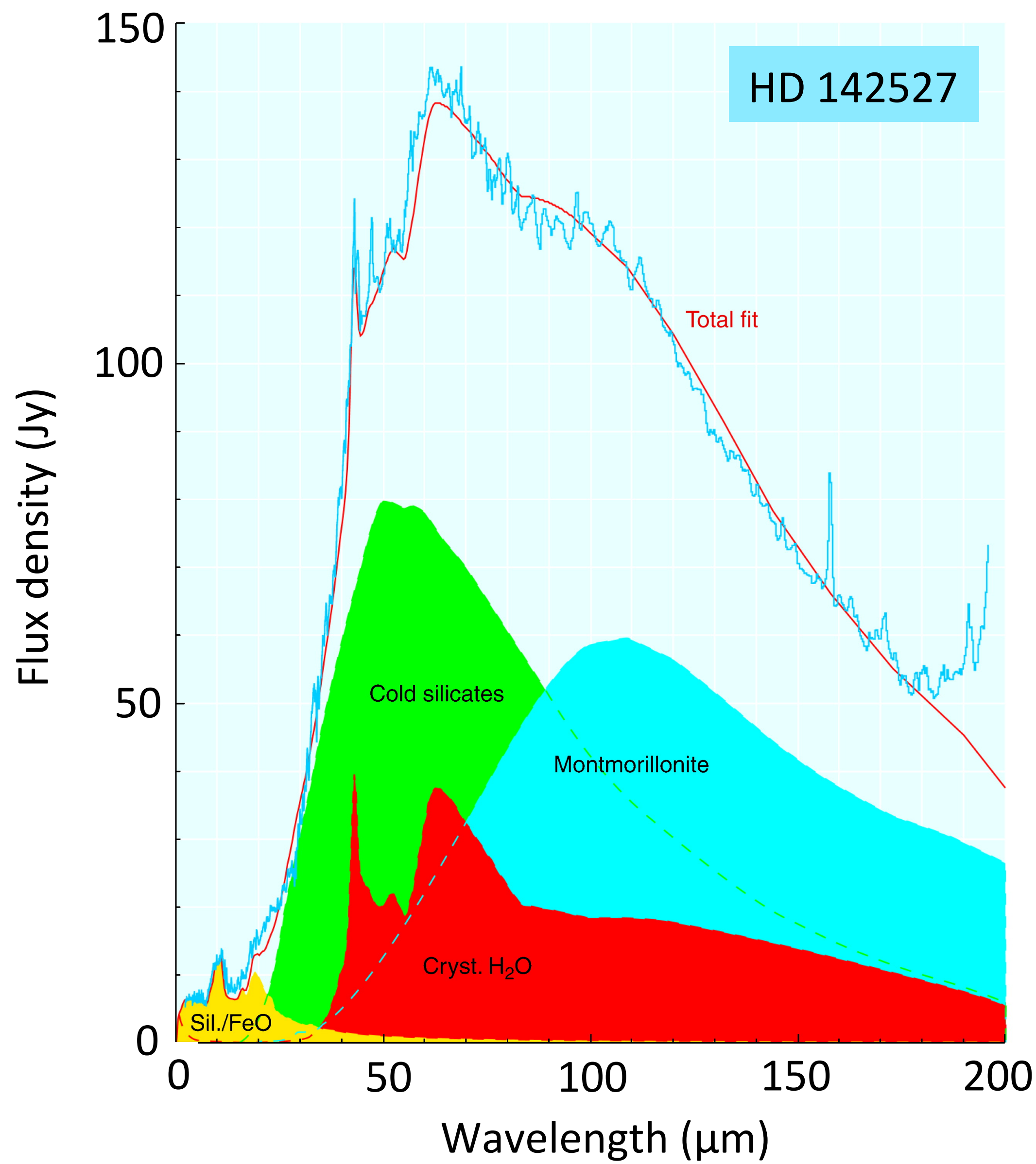
Simulation of the Vega disk with 1” resolution (Rob Reid)

FIRI (100m baseline)	30μm	40	100	200
FWHM beam (arcsec)	0.07	0.1	0.25	0.5

Dust composition

- ISO showed that for at least pre-main-sequence stars silicate emission dominated the warm dust component

The cold component tended to be dominated by O-rich dust (hydrous silicates and crystalline water)



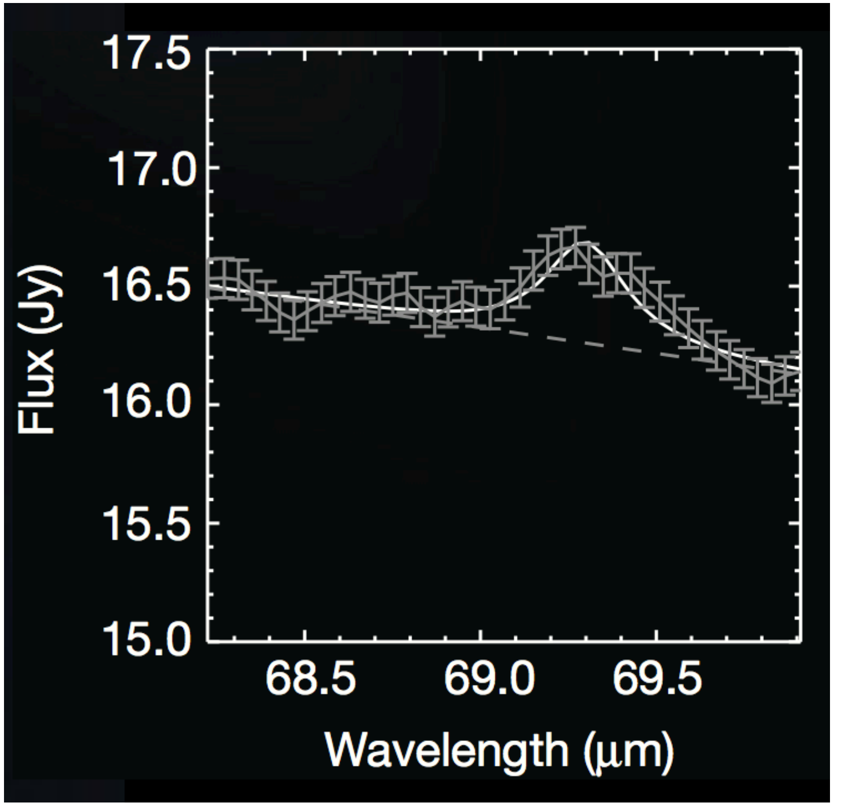
Adapted from Malfait et al. 1999

Dust composition

- For β Pic Herschel/PACS observations of the olivine feature at 69μm indicated the presence of cold dust at 15 – 45 AU that is Magnesium rich and makes up 3.6% of the total dust mass

Grain crystallization and size are inferred from the shape of the emission feature

This means that to characterize the cold silicate a spectral resolution of at least 1000 is needed (niche for SOFIA?)



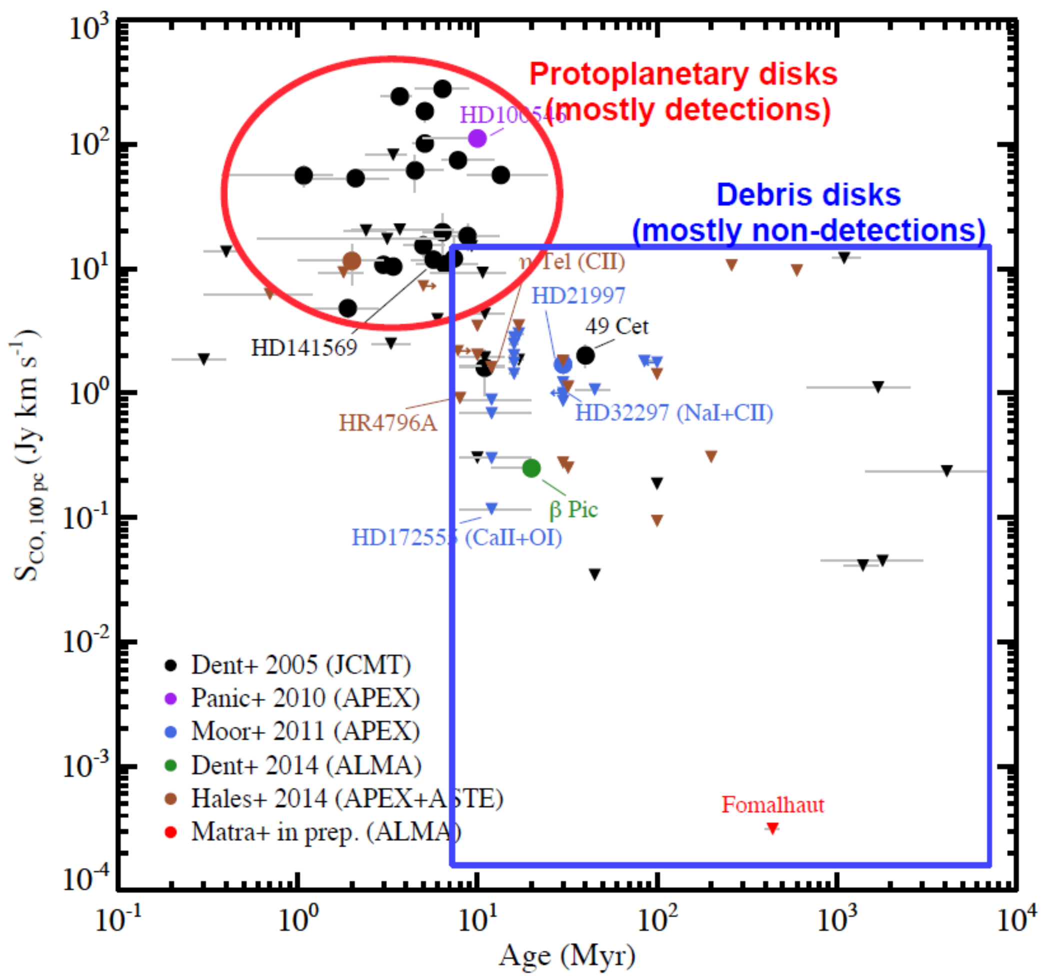
De Vries et al. Nature 490, 7418, 2012

How common is atomic and molecular gas?

- Gas is common in earlier proto-planetary disks, but only 3 debris disks have CO detections (all young systems 10 – 30 Myr)

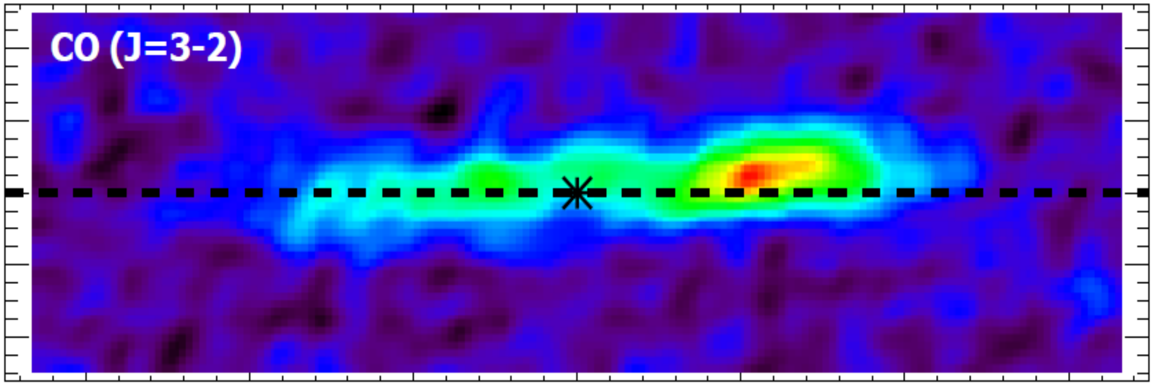
- Presumed that primordial gas would disperse early (end of story…) but becoming a hot topic

- Studies of gas provide a new window on **disk structure** (velocity information), planetesimal composition and proto-planetary disk dispersal



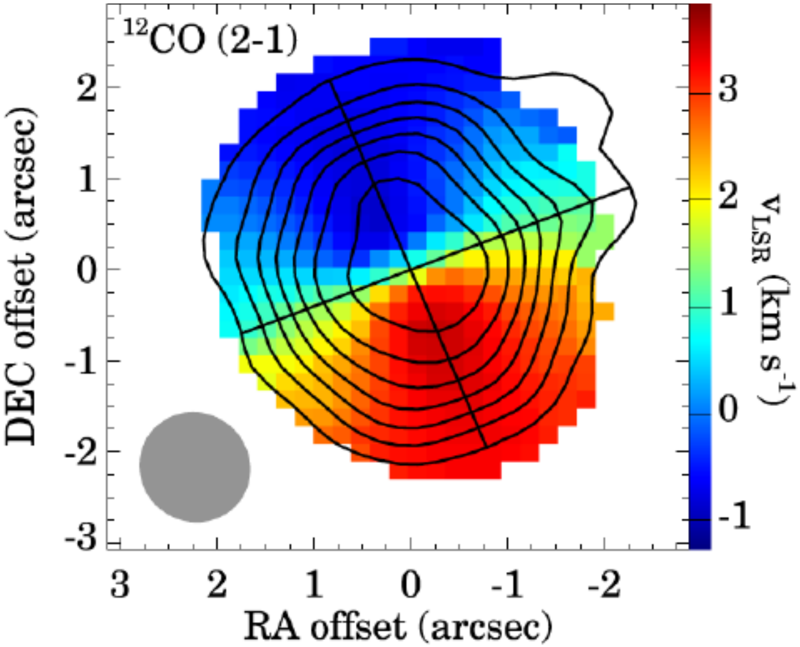
Primordial versus secondary gas

- ForβPictoris the CO must come from the break-up of planetesimals (as it has a 100 yr lifetime and is coincident with the dust)



(Dent et al. 2014)

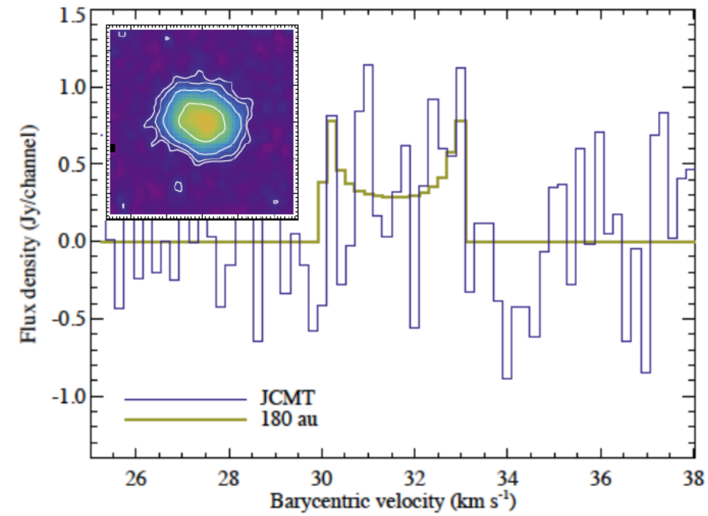
- However, for HD 21997 at least some of the CO must be primordial (as it isn't co-located with the dust)



(Kospal et al. 2013)

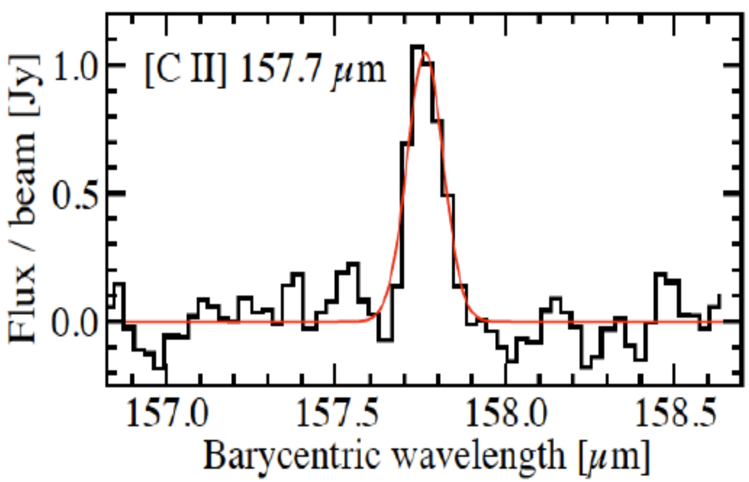
Need for a large, ultra sensitive survey?

- Programme on JCMT to search for CO emission has uncovered new gas around nearby 1Gyr, G4V star HD 38858, which has a debris disk and a radial velocity detected planet



(Kennedy et al. 2015)

(Brandeker et al. 2014)



- Young disks such as β Pic show clear atomic lines, but sensitivities needed are in the 10^{-19} W/m^2 range for other targets…

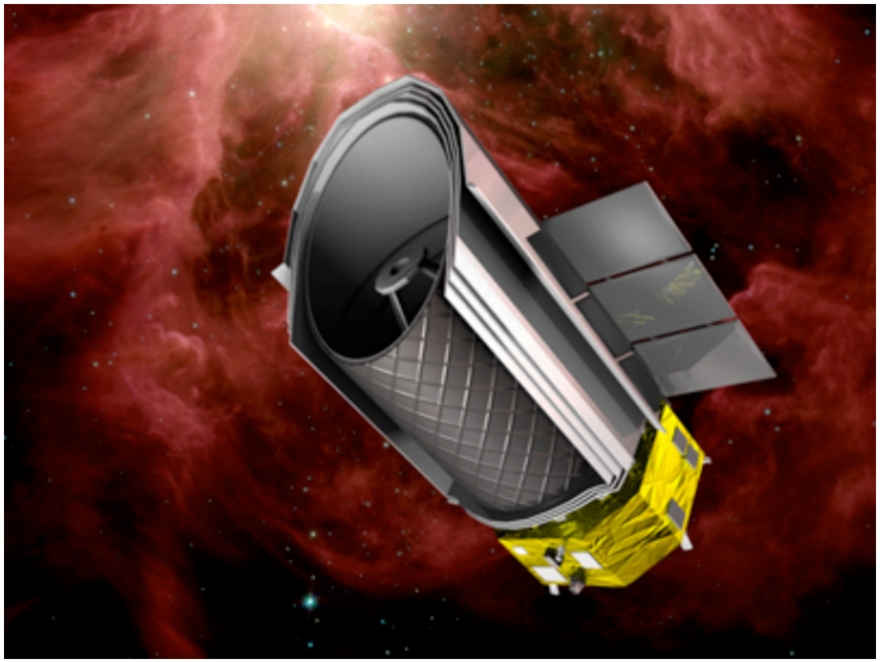
- Large, unbiased, atomic and molecular gas survey: (a) considerable unexplored parameter space, (b) poorly constrained physics, (c) target higher CO transitions, HCN, CII, OI, etc.

Summary of requirements

Parameter	Value or range
Wavelength	25 – 250μm
Angular resolution	0.1’’ at 40μm
Spectral resolution	5 – 5000 (imaging, SED; mineralogy…) 10^5 – 10^6 (molecular gas…)
Continuum sensitivity	10 μJy (1σ, 1hr)
Spectral line sensitivity	10^{-19} W/m^2 (1σ, 1hr)
Mapping/imaging speed	1 object field per hour?
Number of targets/fields	1000?
Instantaneous field-of-view	1-arcmin sq (2-arcmin goal)

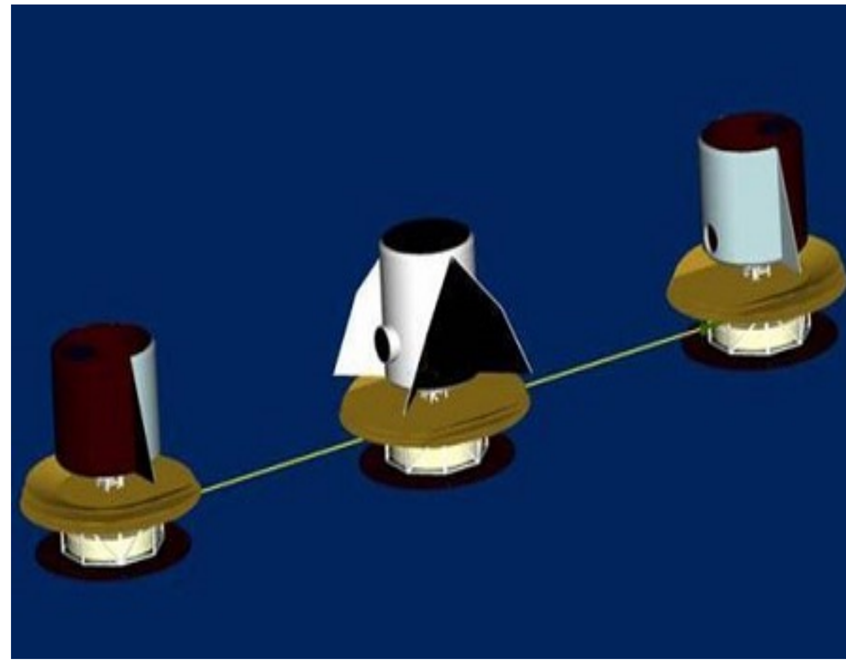
The perfect mission? (or isn't there one?)

Cooled single aperture
(SPICA, CALISTO…)



Great for detection surveys
Good spectral resolution and excellent continuum sensitivity
But limited angular resolution (relatively quickly confusion limited…)

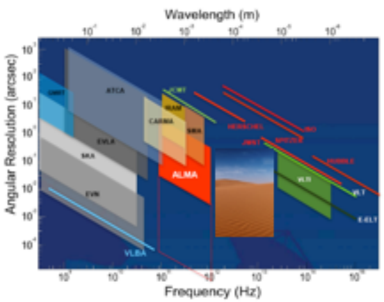
Far-IR Space Interferometer
(FIRI, SPIRIT etc.)



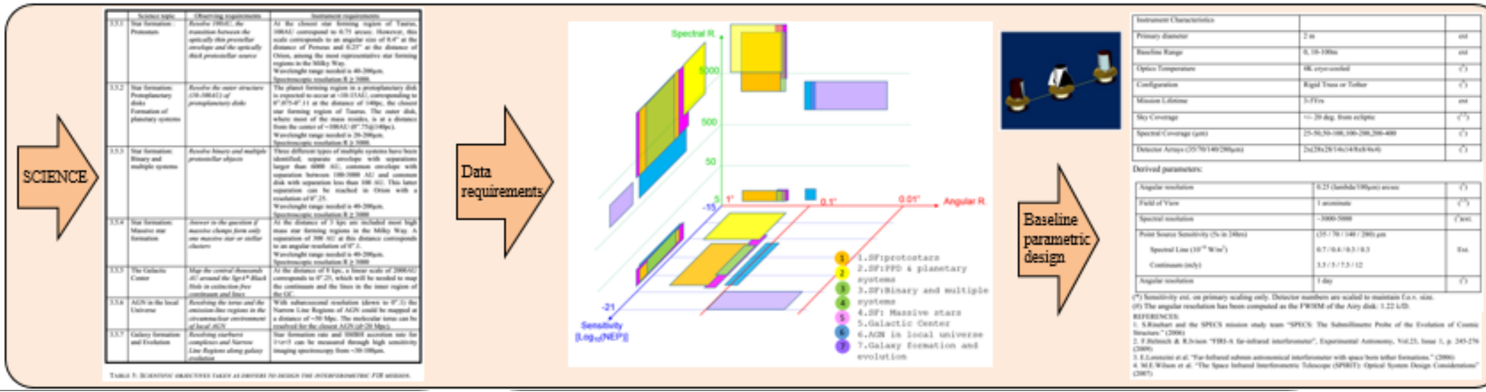
Great for probing the inner regions of disks
Good spectral resolution, but limited sensitivity?
But not a survey machine…

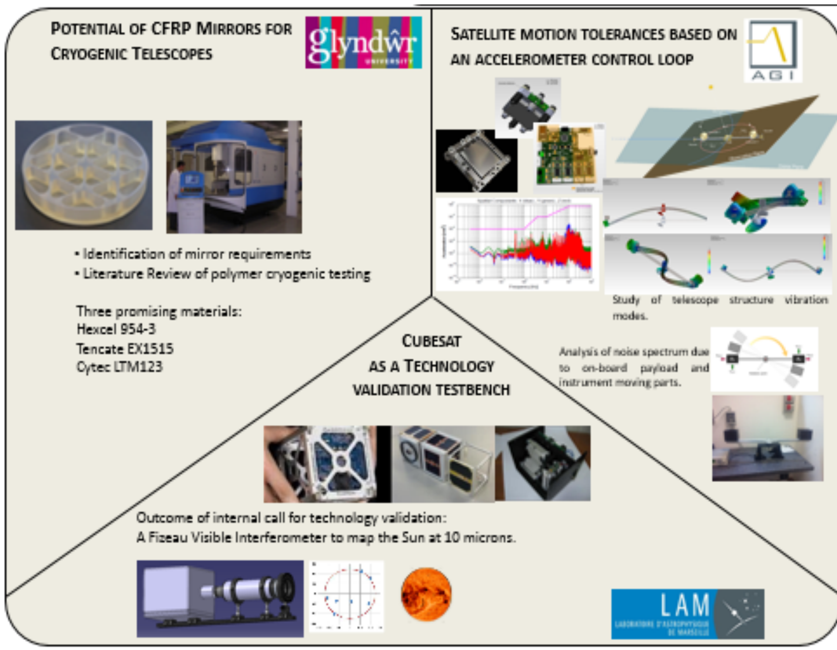
Far Infrared Space Interferometer Critical Assessment

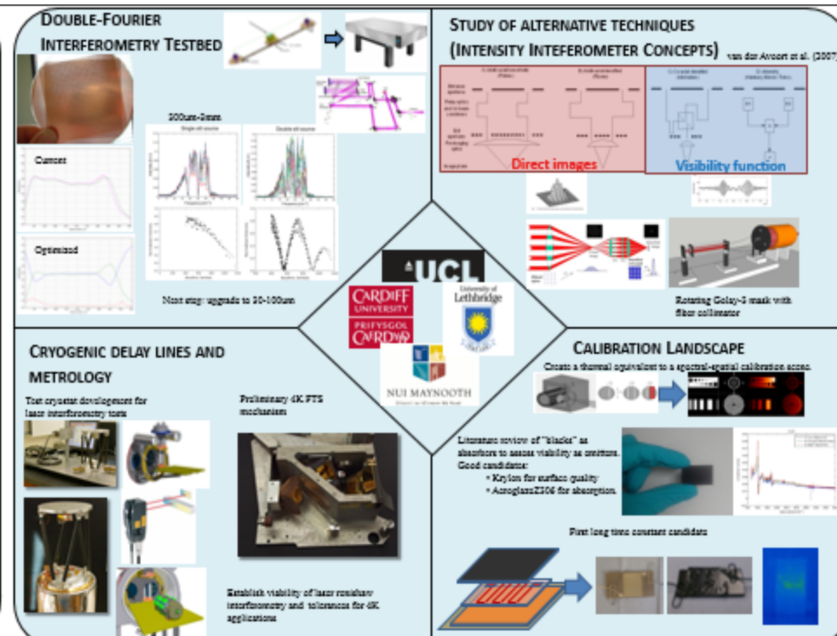
FISICA is re-visiting far-IR space interferometry in terms of the science and instrument and specific requirements, as well as technology development of key hardware, in view of a future far-IR mission



The Far Infrared desert. An obvious lack of facilities to provide high-angular resolution in the range 28-300 microns. (from Th.DeGraaw)







SEVENTH FRAMEWORK PROGRAMME

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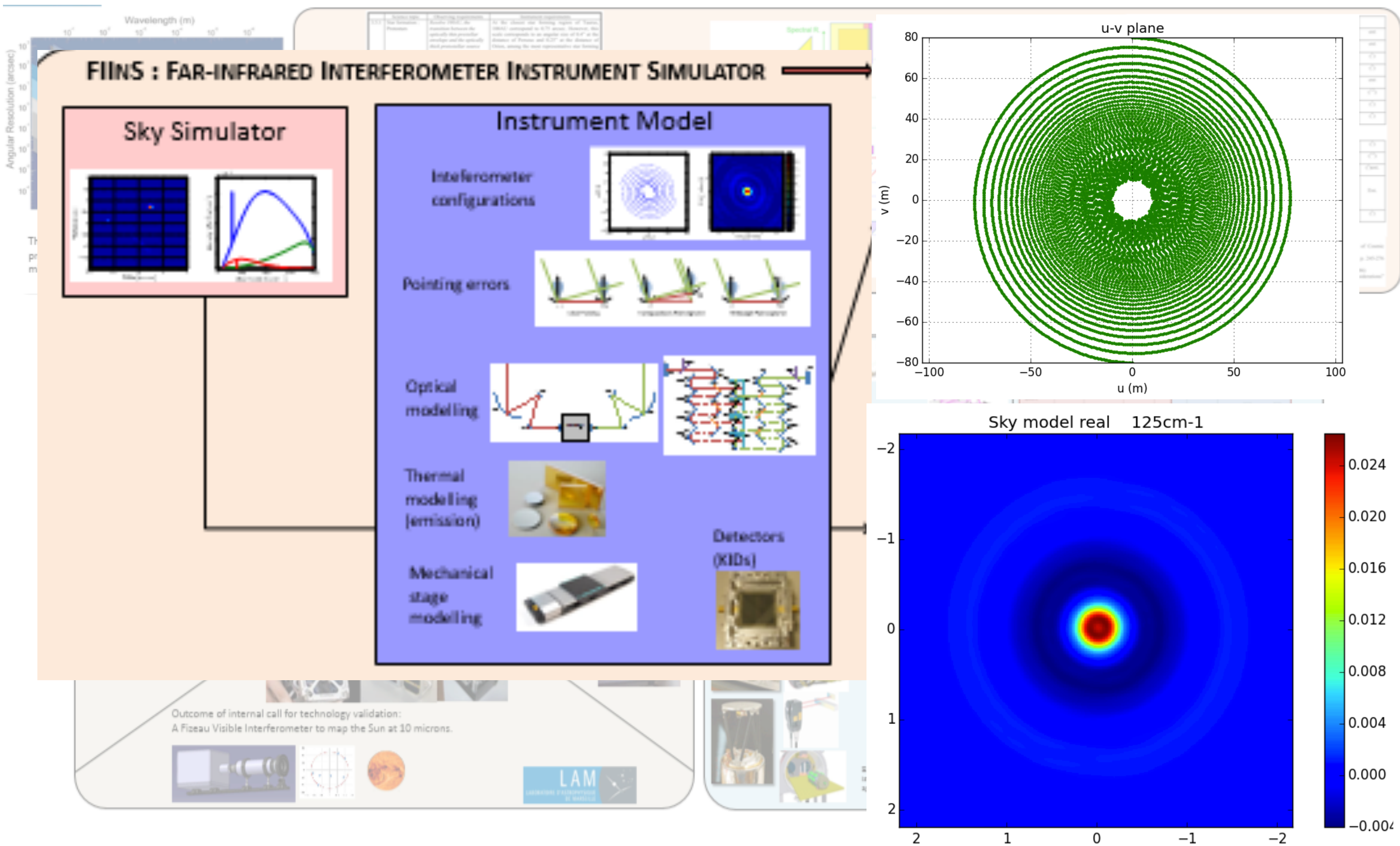
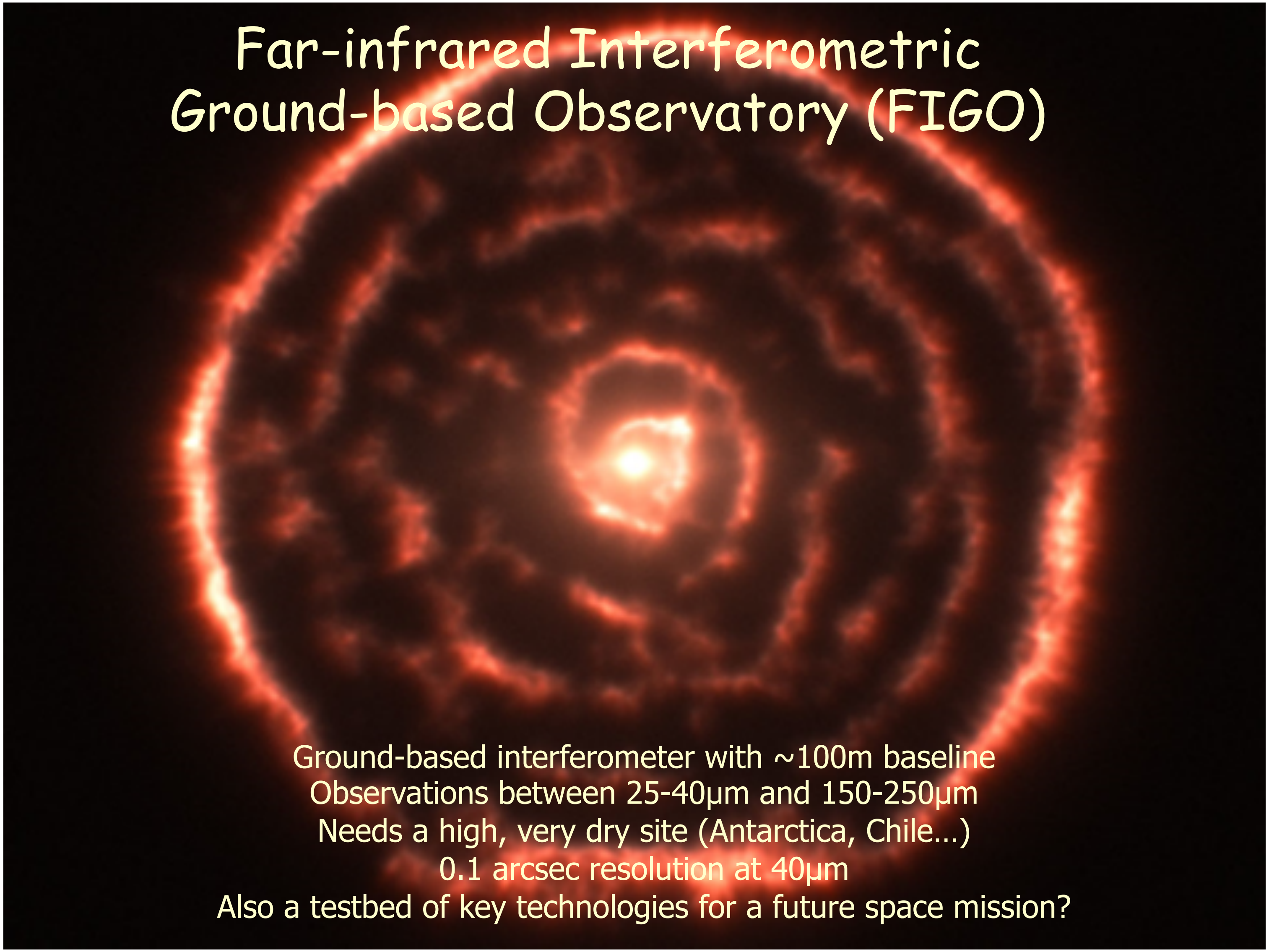


Can we do anything from the ground?



Summary

- Studying debris disks can provide a unique insight into the structure and evolution of a planetary system

- Observations (and theory...) have led to an enormous increase in our understanding of such systems over the past decade

- Whether dusty debris implies a planetary system must exist remains an open question...

- ALMA and JWST in the near future will target (most likely) individual objects

- An ultra-sensitive far-IR mission in the 2020's would be highly complementary and address unique science questions

Next generation of missions in the 2020's…

Need to address questions such as:

- Do all stars have debris disks?
- The planet/star connection: How do the properties of the star and any planets present influence the disk?
- Do asymmetries/clumps within debris disks mean planets have to be present?
- Are there Kuiper and asteroid belts around most stars? ("How common is our Solar System architecture?")
- What is the composition of the disk material (mineralogy), how did it originate and how does it evolve?
- What role does atomic and molecular gas play in the evolution of debris disks (and planetary systems)?