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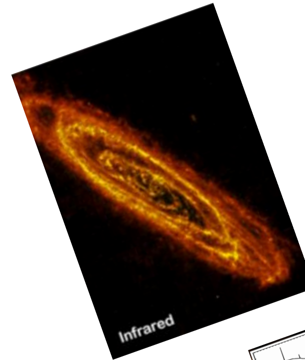
# SPICA-SAFARI calibration challenges and lessons learned from Herschel

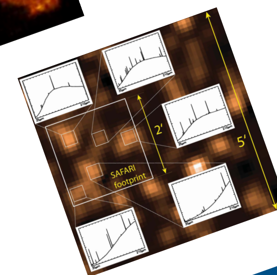
Bart Vandenbussche
on behalf of the SPICA-SAFARI consortium

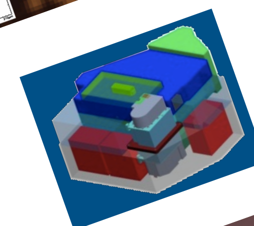
SAFARI

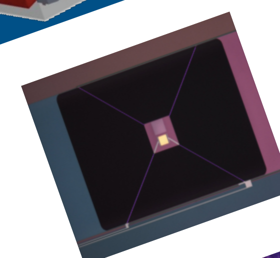
# Overview

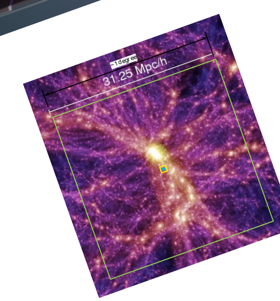
- SPICA mission
- Key science questions
- Safari instrument design
- Calibration challenges



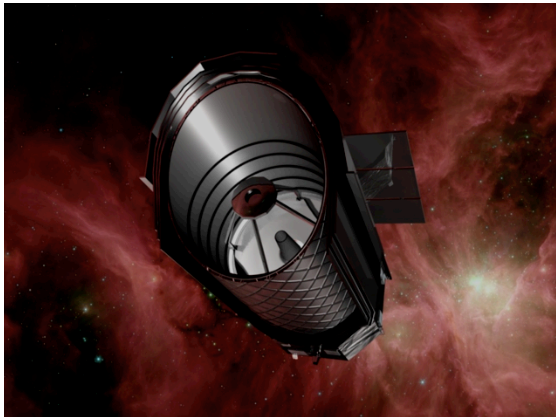



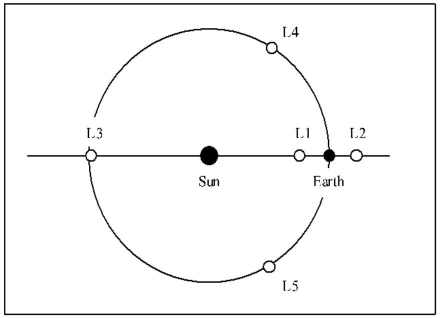





# SPICA – overview

- Telescope: 3.2m , cooled to 6K
  - Superior sensitivity
  - Spatial resolution
- Core wavelengths: 5-210um
  - MIR-instrument
  - Far-infrared instrument (SAFARI)
- Orbit: Sun-Earth L2
- Mission life 3 years nominal, 5 years goal
- Launch ~2022
- International mission: Japan, Europe, Korea, Taiwan



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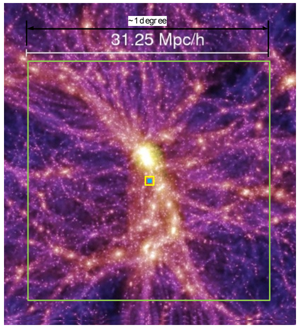
# SPICA – key science questions

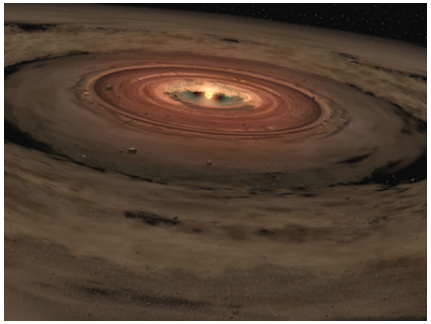
- *How do stars and galaxies form and evolve over cosmic ages?*

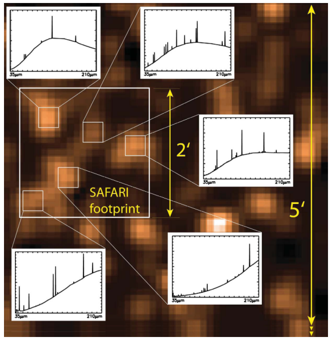
  Observe thousands of obscured, far away galaxies and determine what processes govern their evolution

- *How does our solar system relate to other planetary systems and could life evolve elsewhere?*

  Characterise exoplanet systems, characterise oxygen, water, ice and rock in young planet forming systems and study their relation to the rocks and ice in our own Solar System



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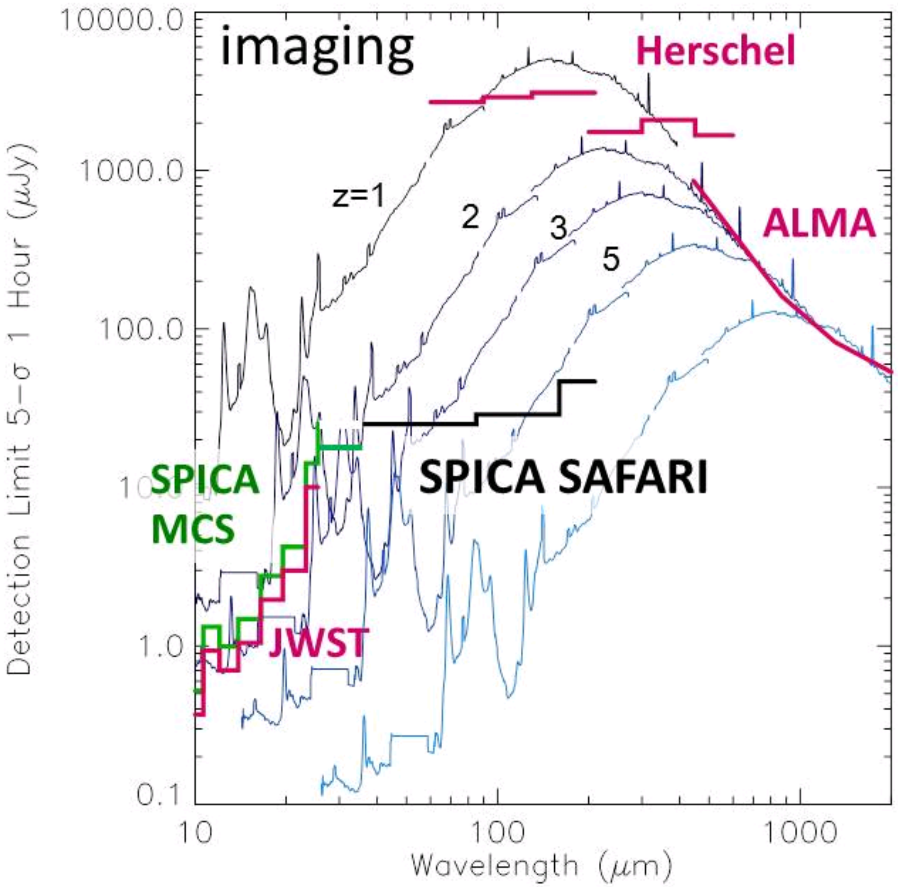
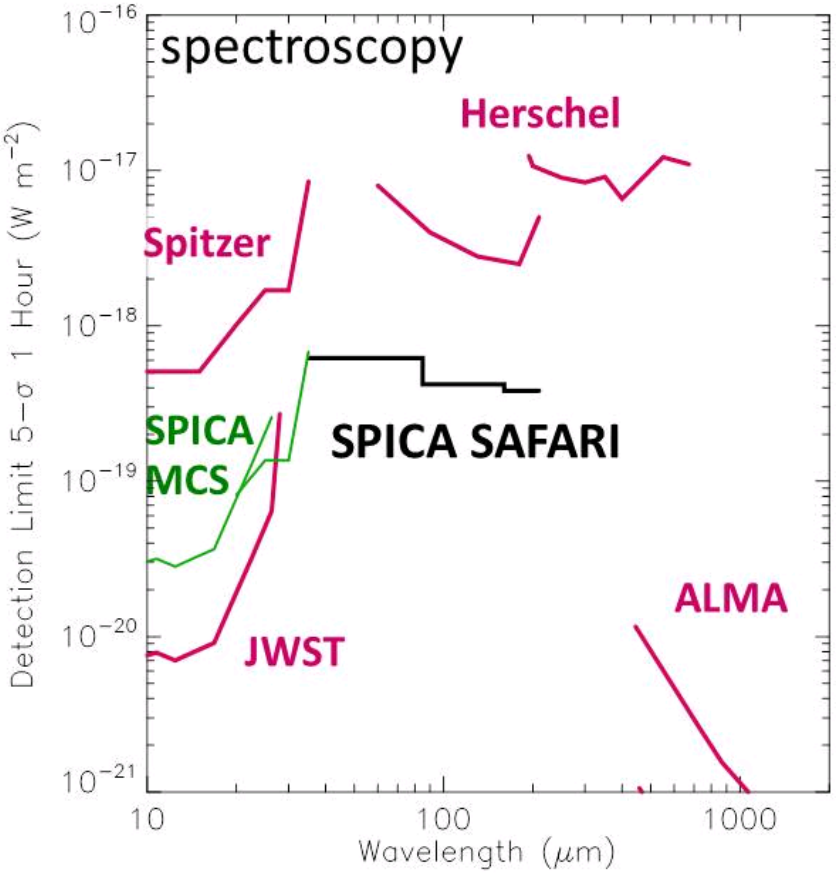
# SPICA – the next far-IR mission

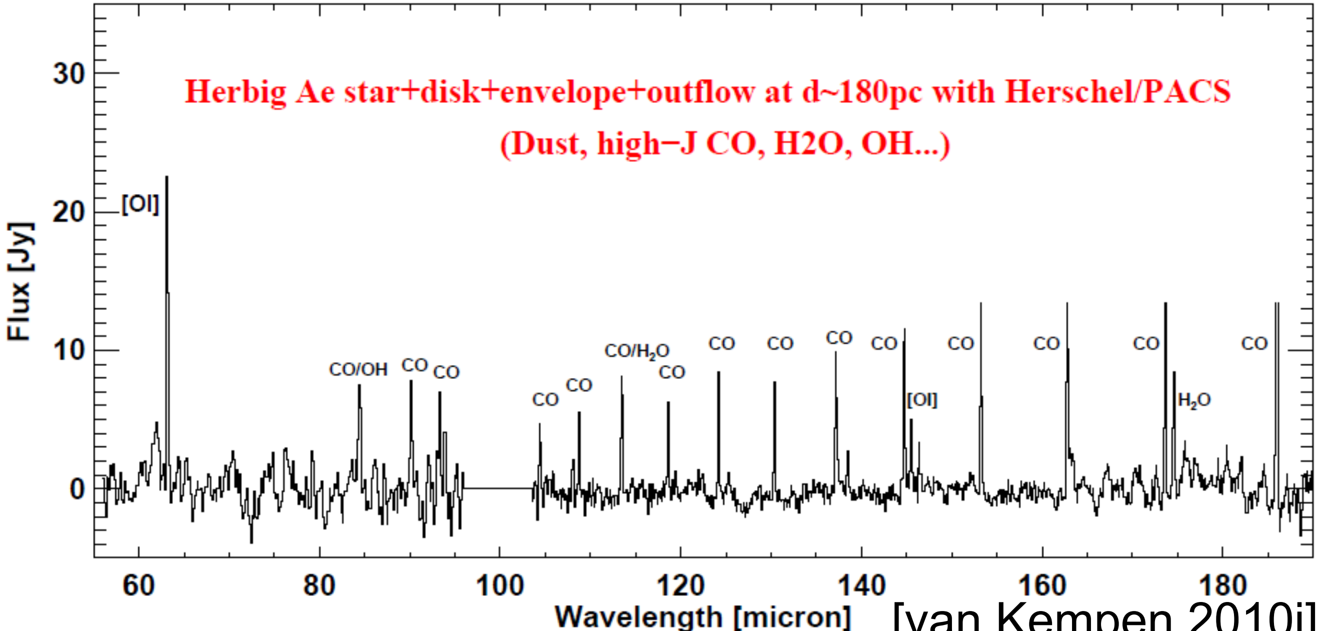
SPICA (< 5 K) → "Cooled Herschel":

- Much lower background → deep spectroscopy possible
- Closing the far-IR gap in the JWST – ALMA sensitivity ballpark



# Spectro-imaging of young stellar objects


[van Kempen 2010i]

Physical conditions, gas, dust & ice composition

- cold regions in our Milky Way & local group galaxies
- transition embedded -> protoplanetary disk

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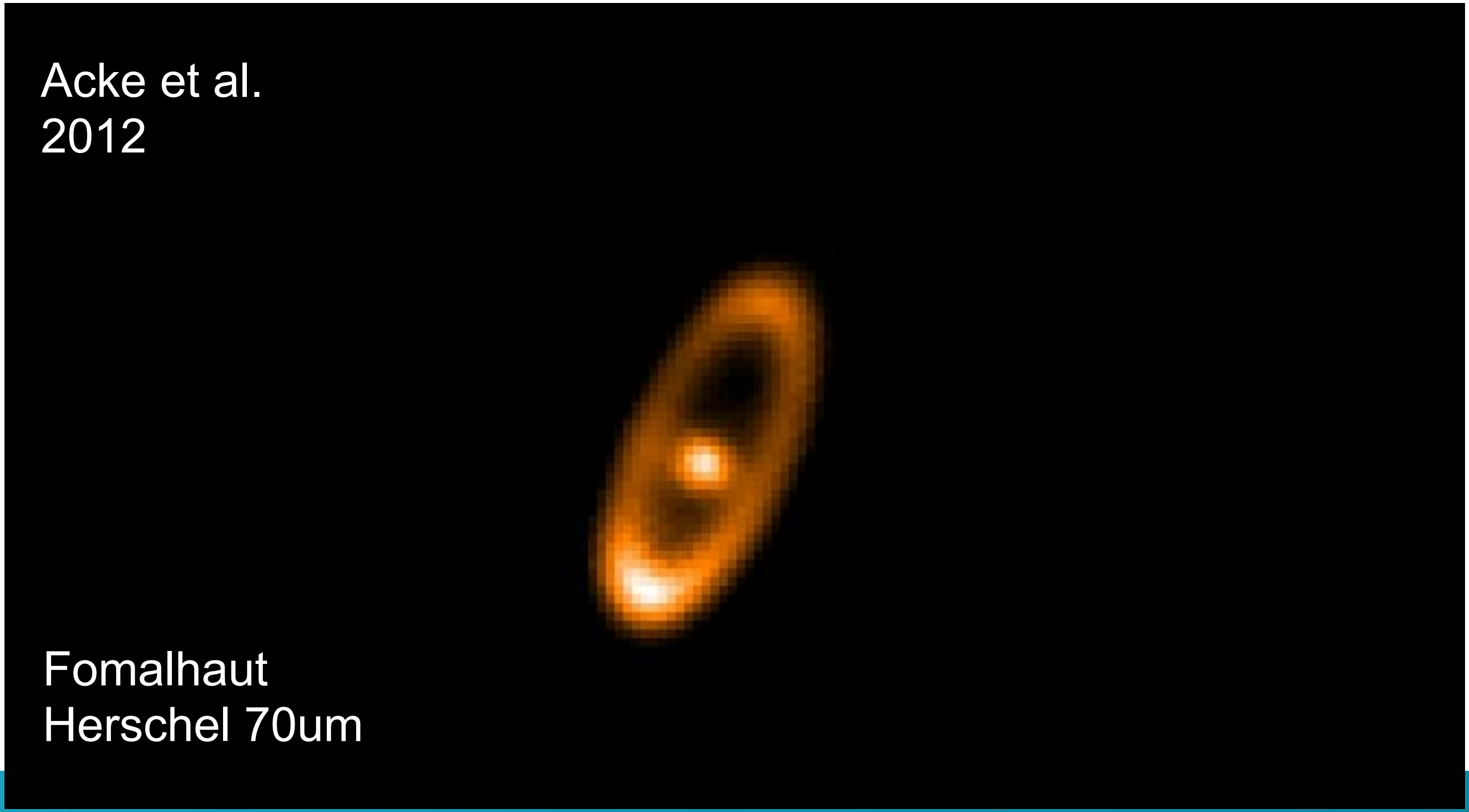
# SPICA – mineralogy of protoplanetery and debris disks

- Large surveys of faint protoplanetary disks
  - sensitivity to solid state features
  - gas lines ($H_2O$, OI, CII, ...)
- Spectral mapping of resolved objects → determine snow line in debris disks

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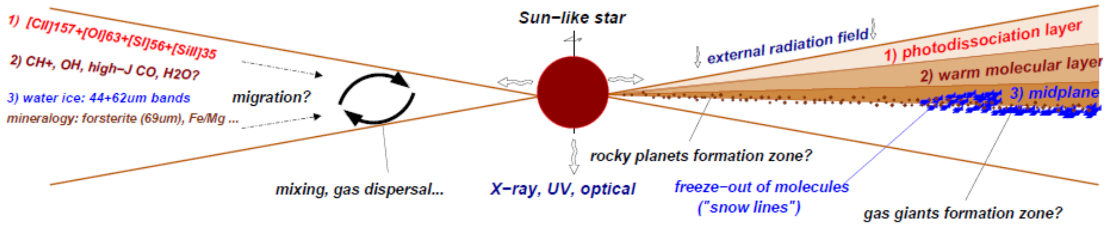
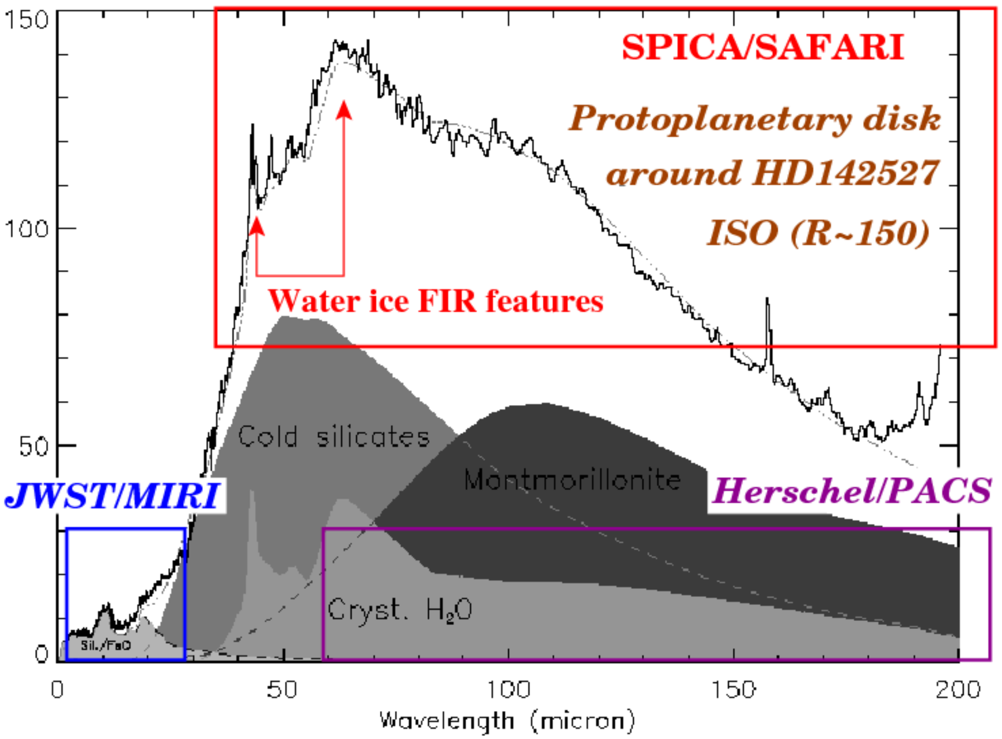
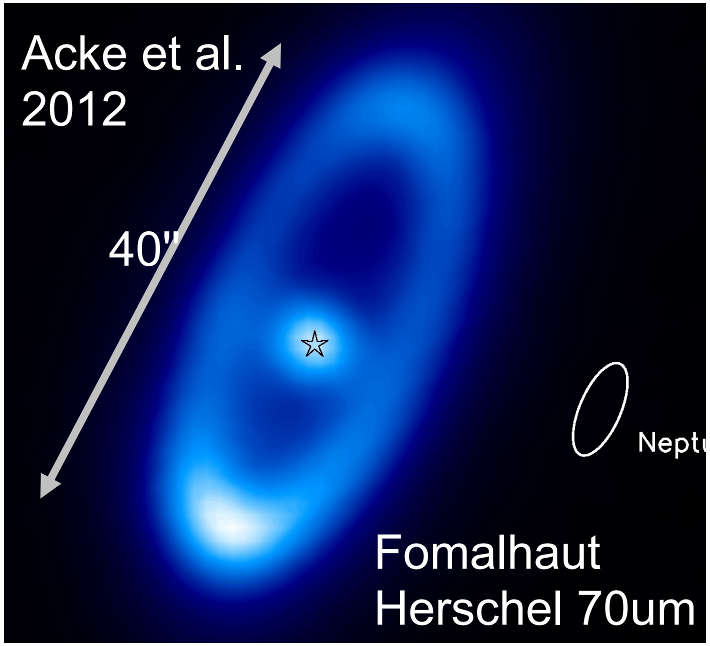
# SPICA – mineralogy of protoplanetery and debris disks

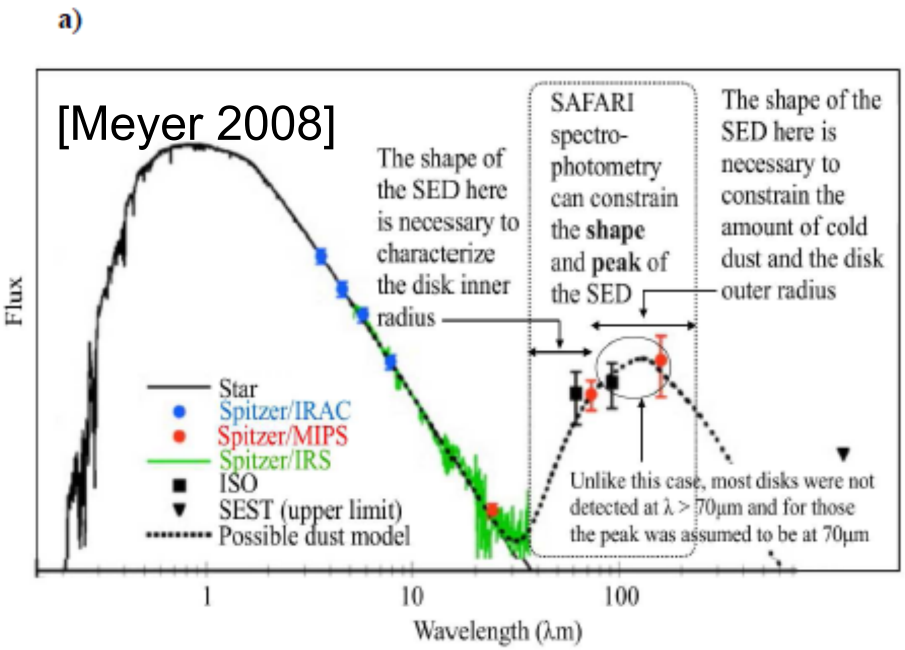


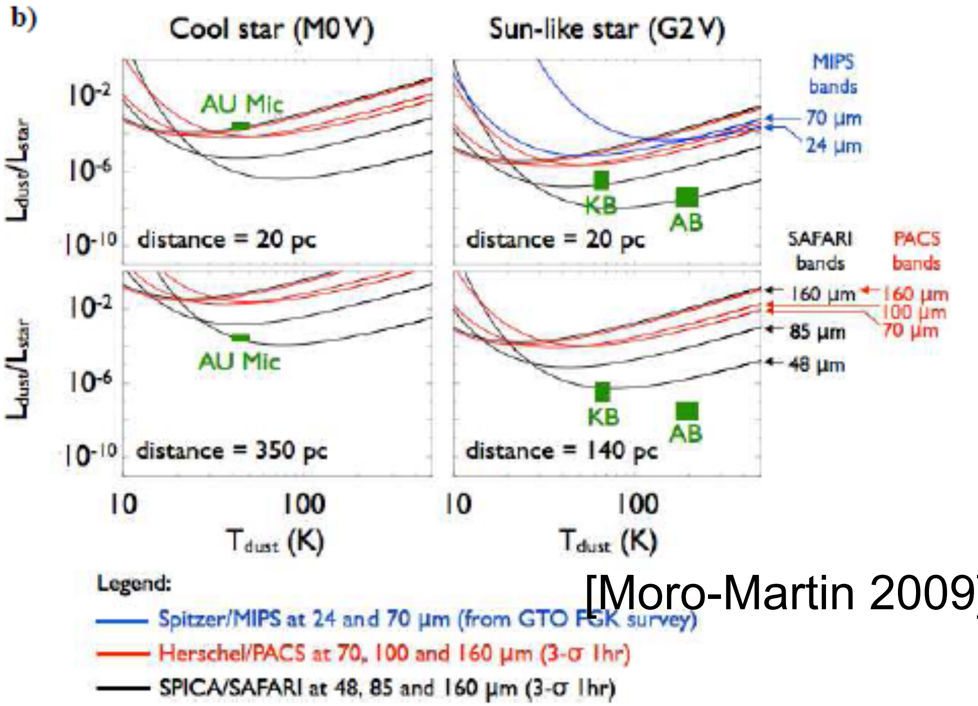




SAFARI FoV: 2”x2”



# Kuiper belt & asteroid belt analogs in exosolar systems

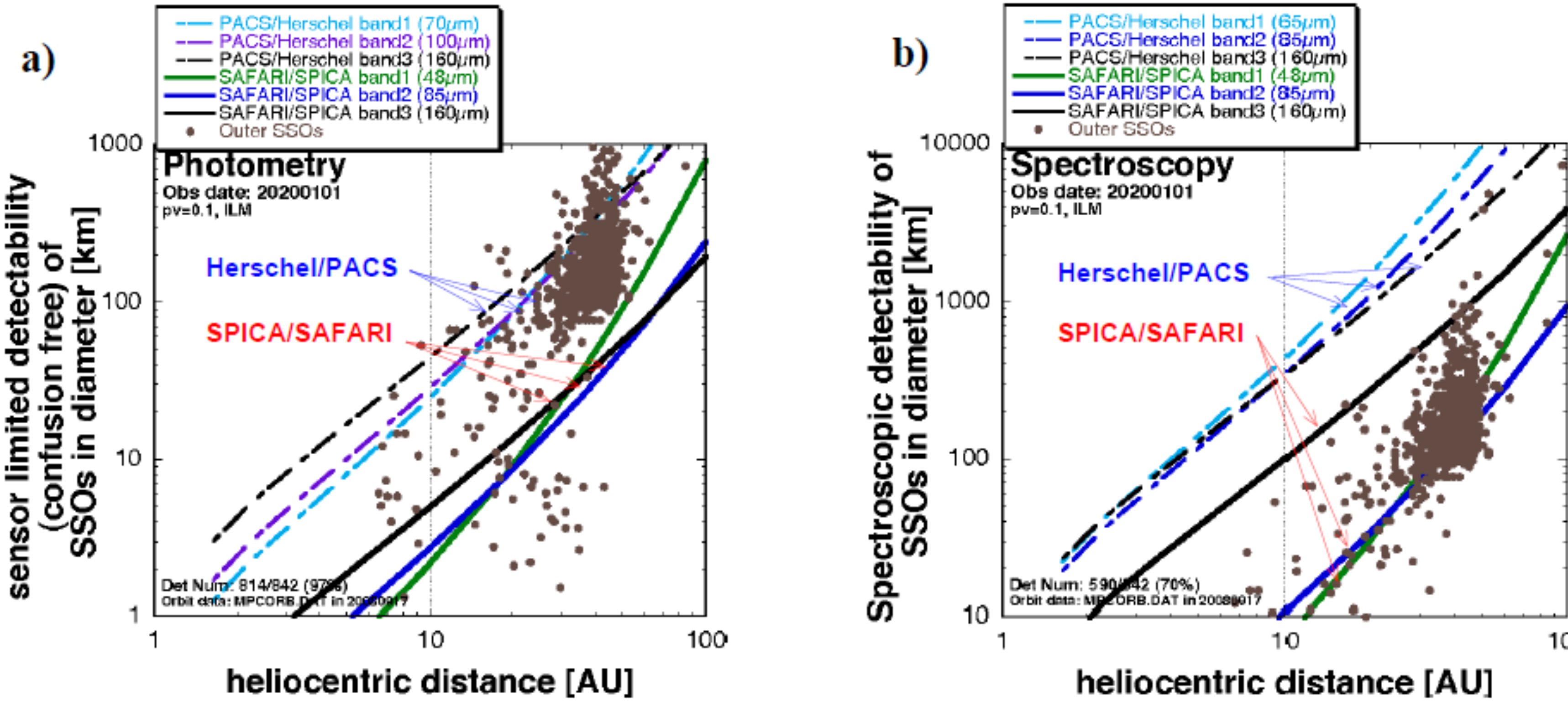



[Moro-Martin 2009]

- Detect asteroid belts around solar-type stars at d<20pc (n~400)
- Detect kuiper belts around solar-type stars at d<140pc (n~1.4E5)

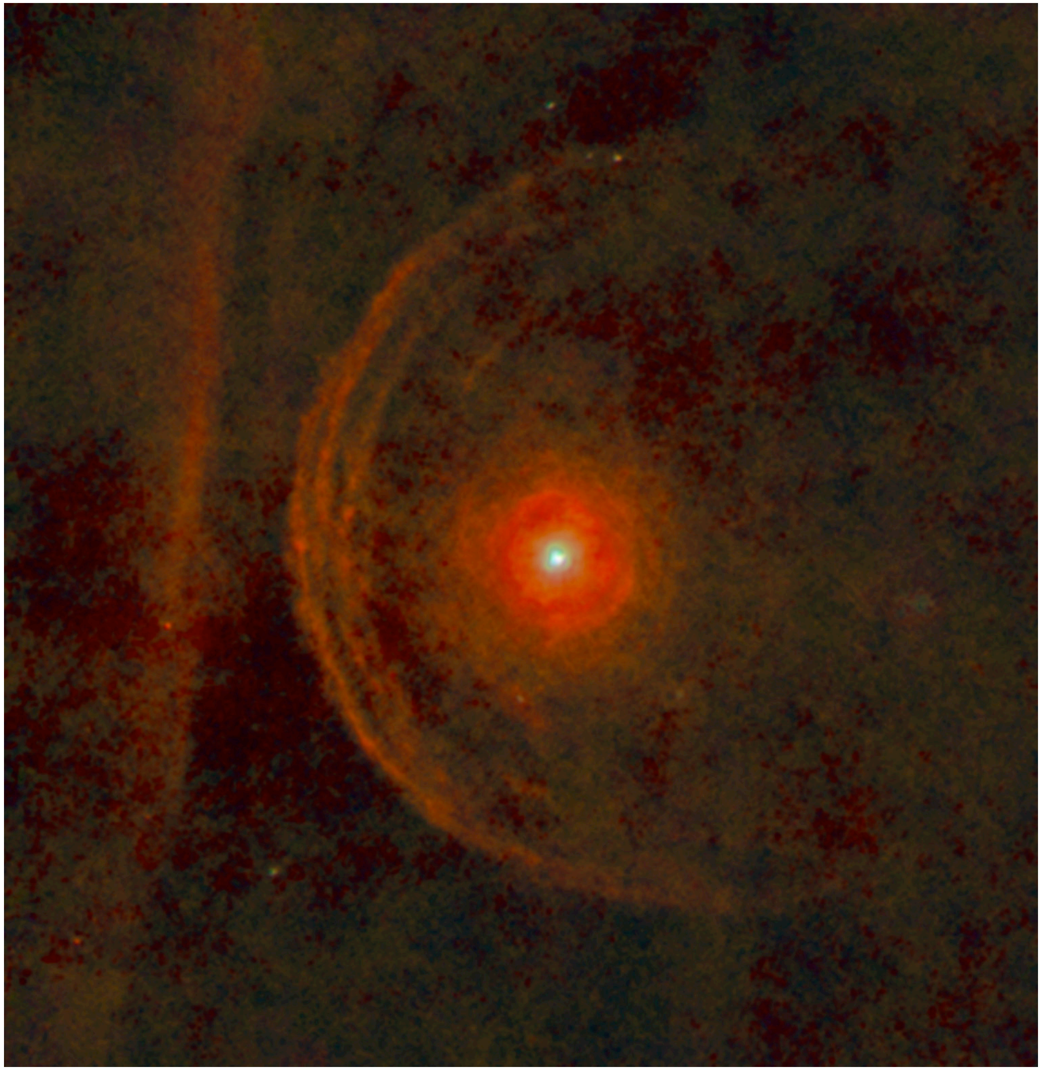
# Resolving our own Kuiper belt spectrally




[data: Hasegawa 2000]]

- Mineral and ice characterisation of significant sample of masses

# Evolved stars – the dust factories of the milky way dust cycle



Alpha Ori
Herschel/PACS
[Decin 2012]

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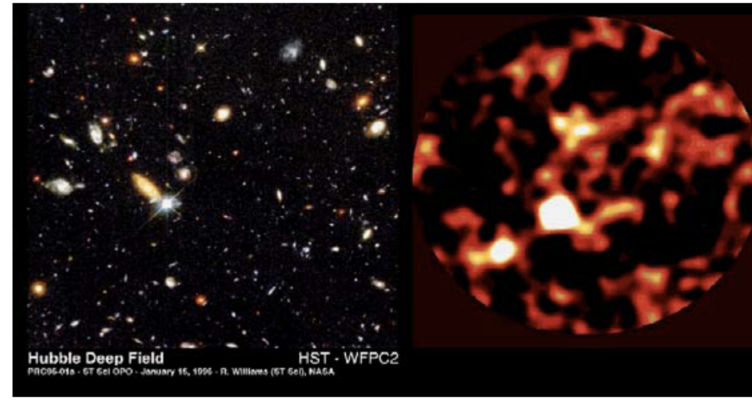
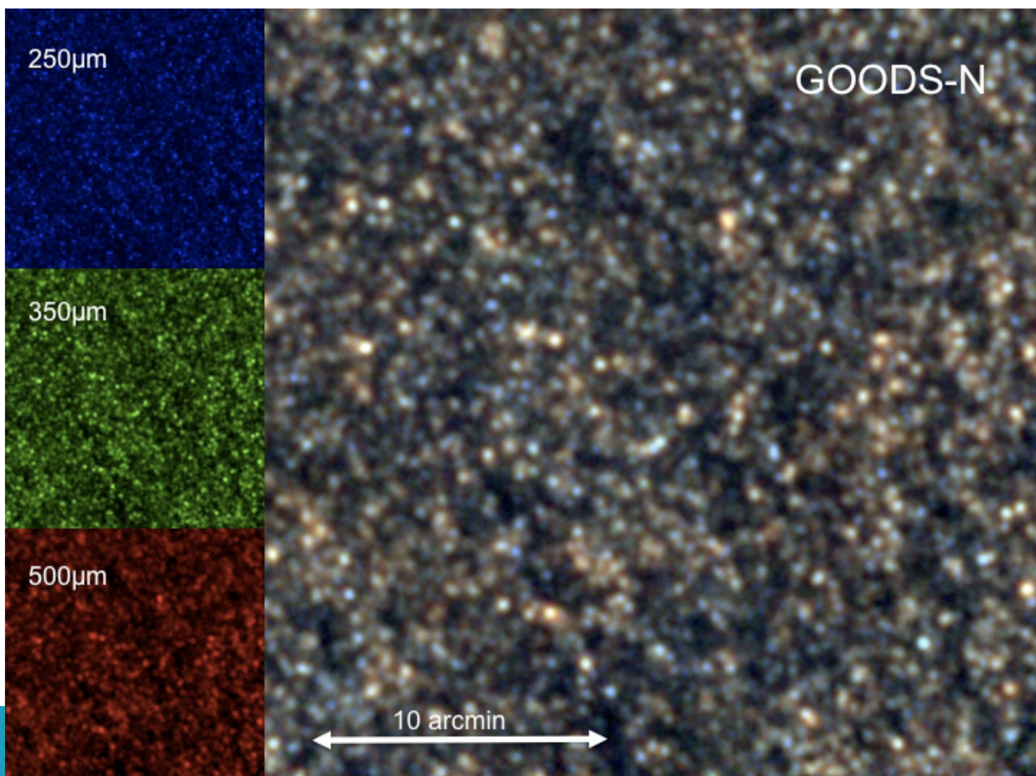
# The deep universe – the Herschel leap repeated spectrally

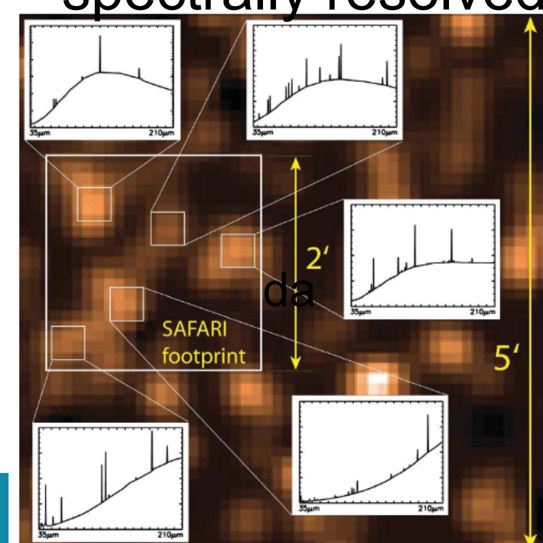
1998 – JCMT/SCUBA
Hubble Deep Field
5 sources detected in 20 nights




2009 – Herschel/SPIRE
15000 sources in 16 hours

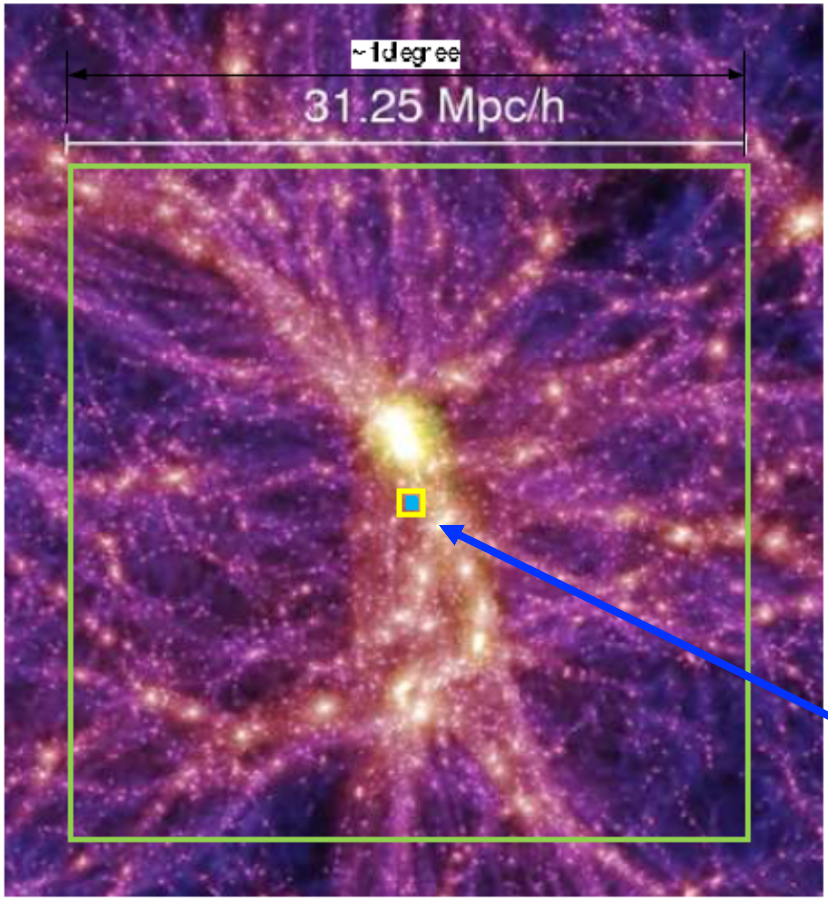



2022 – SPICA/SAFARI
spectrally resolved

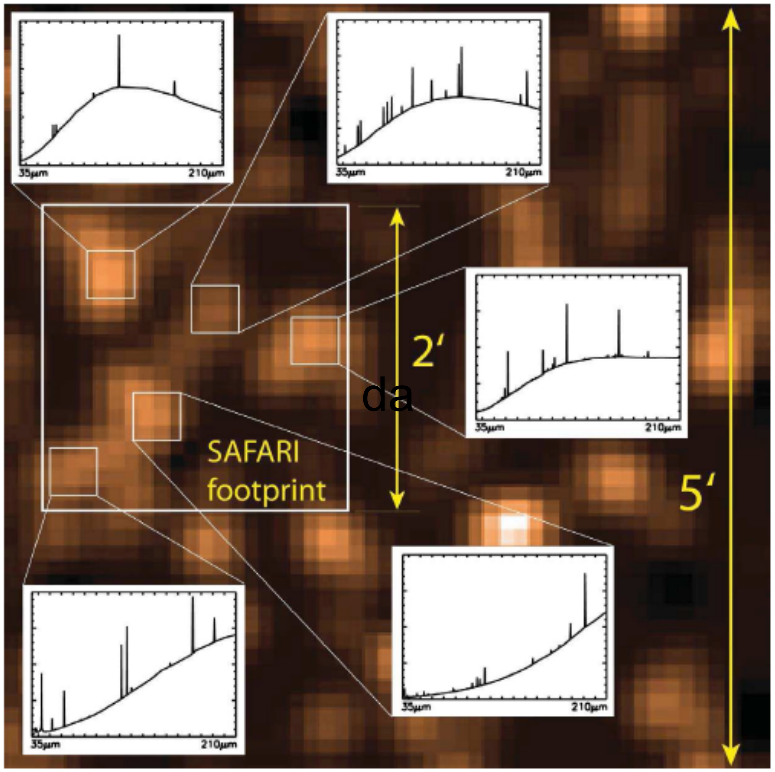


# SPICA – deep cosmological spectral surveys down to z=4

SPICA/SAFARI: Spectral survey of 1x1° in 900 hours down to 5E-19 W/m$^2$

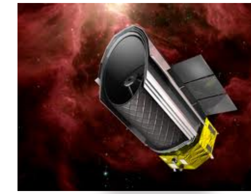



Millennium simulation z=1.4 (Springel et al 2006)



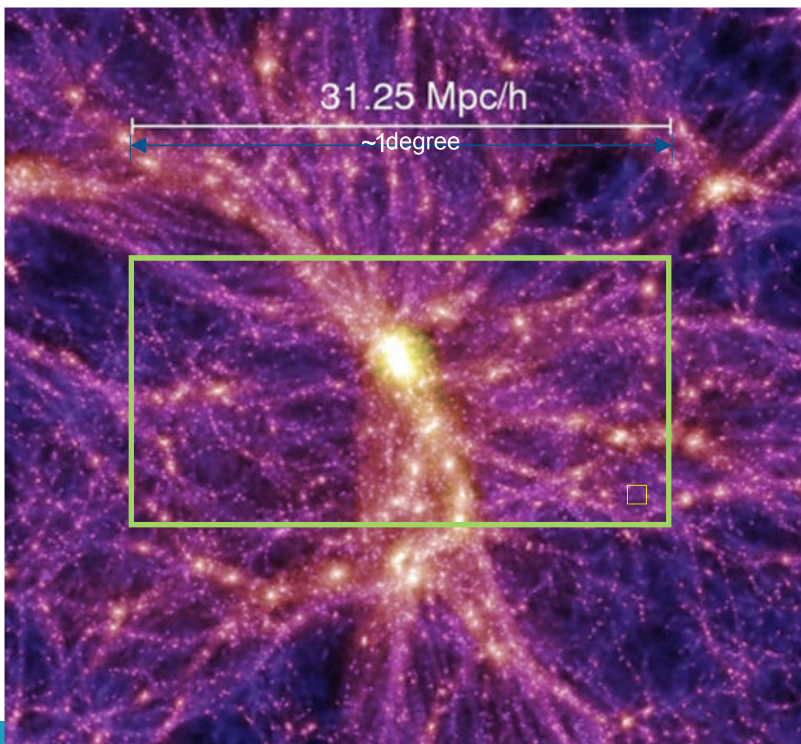

Herschel-SPIRE 250um – Hermes consortium

Compare: HERSCHEL-PACS : 1800 hours for 1'x1' to same depth



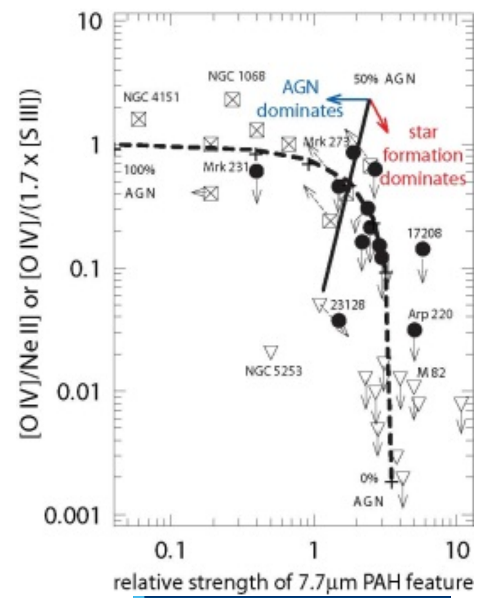
# High throughput surveys

Example Blind spectroscopic survey
0.5 square degrees, ~500 hours obsering time sigma few 10-19W/m2
Models predict 2000 sources in at least 4 lines




| Line | | # sources |
|---|---|---|
| PAH | | |
| | 11.25µm | 715 |
| [NeII] | 12.81µm | 228 |
| [NeV] | 14.32µm | 60.7 |
| [NeIII] | 15.55µm | 113 |
| [SIII] | 18.71µm | 55.8 |
| [NeV] | 24.32µm | 37.8 |
| [OIV] | 25.89µm | 232 |
| [SIII] | 33.48µm | 1753 |
| [SIII] | 34.81µm | 2713 |
| [OIII] | 51.81µm | 2983 |
| [NIII] | 57.32µm | 567 |
| [OI] | 63.18µm | 5611 |
| [OIII] | 88.35µm | 4274 |

AGN PDR HII region

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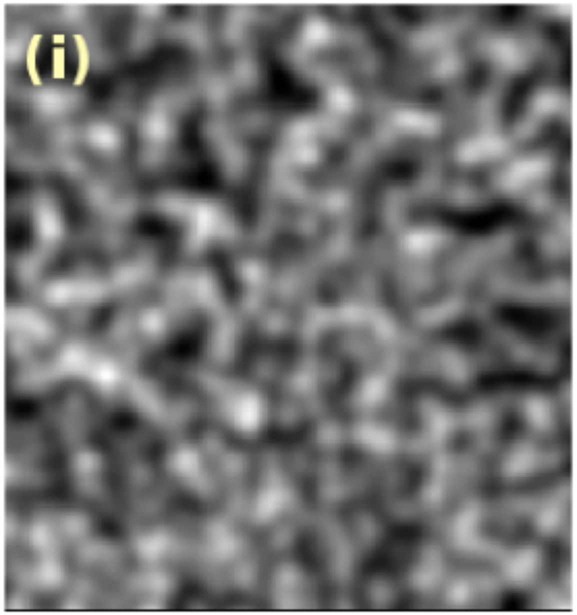
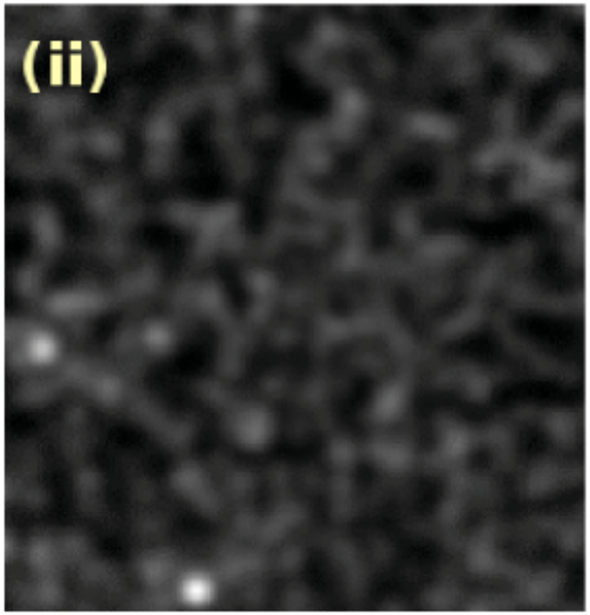
Millennium simulation z=1.4 (Springel et al 2006)

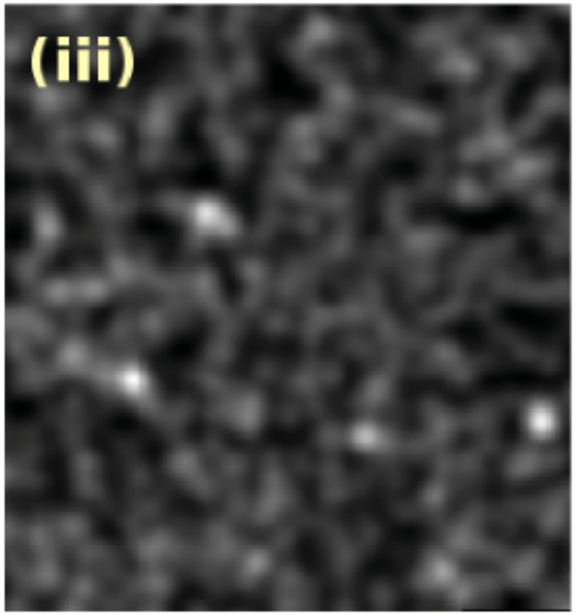
# Breaking the confusion limit




SAFARI photometry
at 120 micron




SAFARI imaging spectroscopy
at 63.2 micron




SAFARI imaging spectroscopy
at 58.3 micron

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# Science case summary

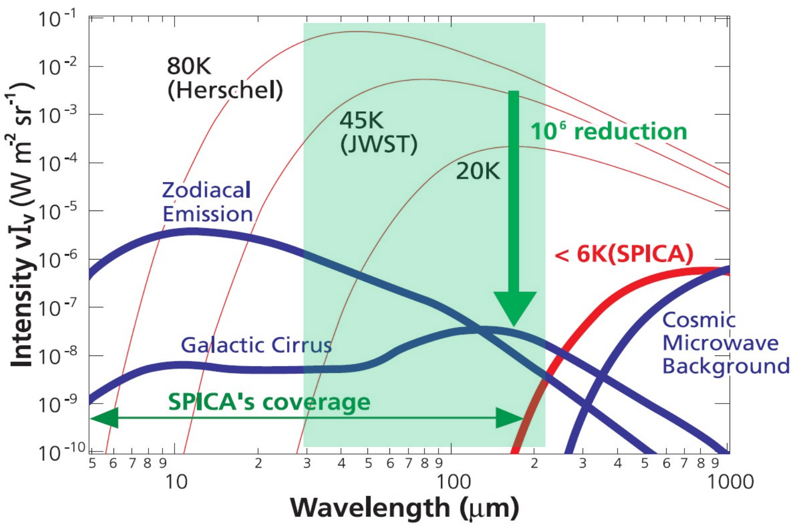
- Solar system formation
  - our solar system
  - exosolar systems in all development phases
- Dust cycle, our milky way & local universe
- Spectrally resolving the cosmological background
- All this requires Imaging spectroscopy

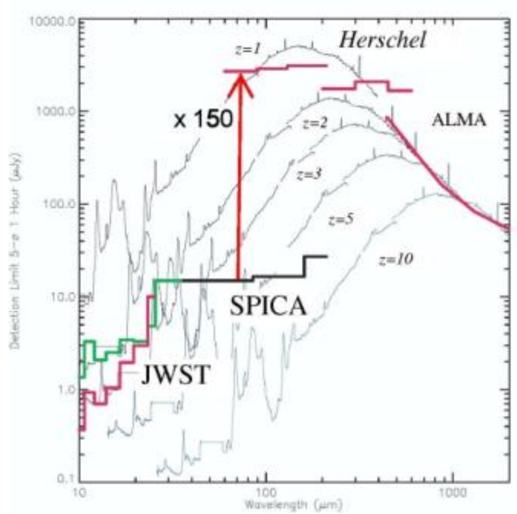
# The limits in Infrared sensitivity

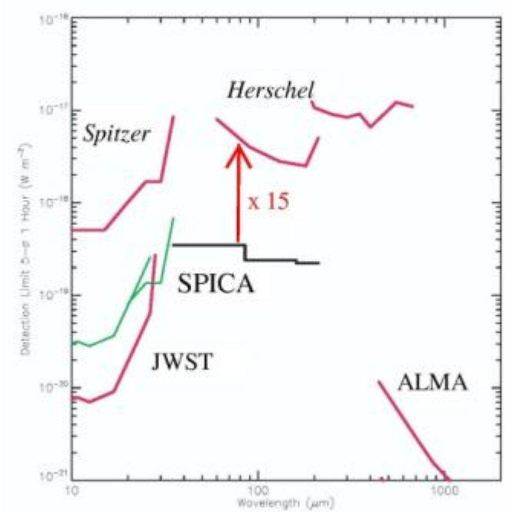
- *All starlight* is “recycled” to Infrared by the dust and the gas
  → we only see the complete picture by observing the Infrared
- We want to be limited *only by the natural background* in the universe
- For signals in the FarInfrared this means a telescope colder than ~6K

SPICA provides the low background…

…and SAFARI has to provide the extreme sensitivity

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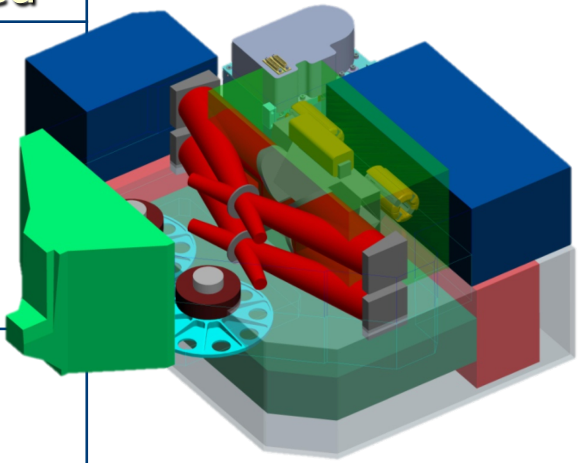
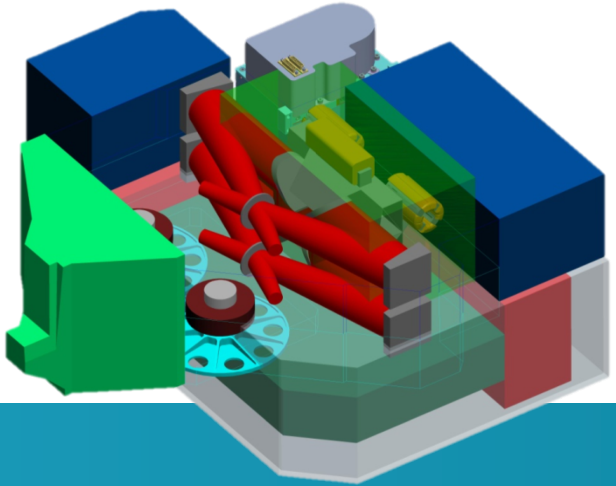
# Scientific instrument requirements

| | |
|---|---|
| Field of view | 2' x 2' (close to) Nyquist sampled |
| modes: | |
| photometry | $\lambda/\Delta\lambda \sim 3$ |
| SED mode | $\lambda/\Delta\lambda \sim 150 - 200$ |
| spectroscopy | $\lambda/\Delta\lambda \sim 2000$ |
| line sensitivity | few x $10^{-19}$ W/√Hz (5σ-1h) |
| continuum sens. | <20 μJy (5σ-1hr) |
| bright sources | up to 1 Jy without ND filter |
| 3 bands: | |
| SW, 34-60 μm | 43x43 |
| MW, 60-110 μm | 34x34 |
| LW, 110-210 μm | 18x18 |



# SAFARI instrument summary

- Scanning Fourier Transform Spectrometer with 2’x2’ FoV
- Simultaneously observing in 3 bands (34-210μm)
- Ultra sensitive TES detectors/SQUID read out at 50 mK
  → almost ***200 times*** more sensitive than Herschel
- Frequency Domain Multiplexing
- To be built by an NL-led consortium – PI Peter Roelfsema
  - ~15 institutes in Europe, Canada, Japan - cost ~170M€



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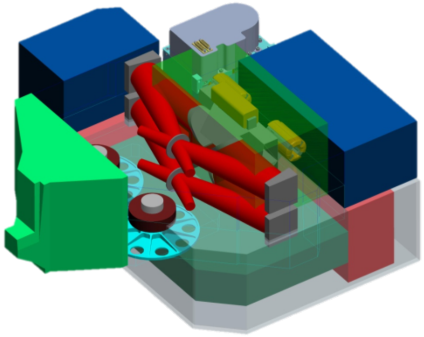
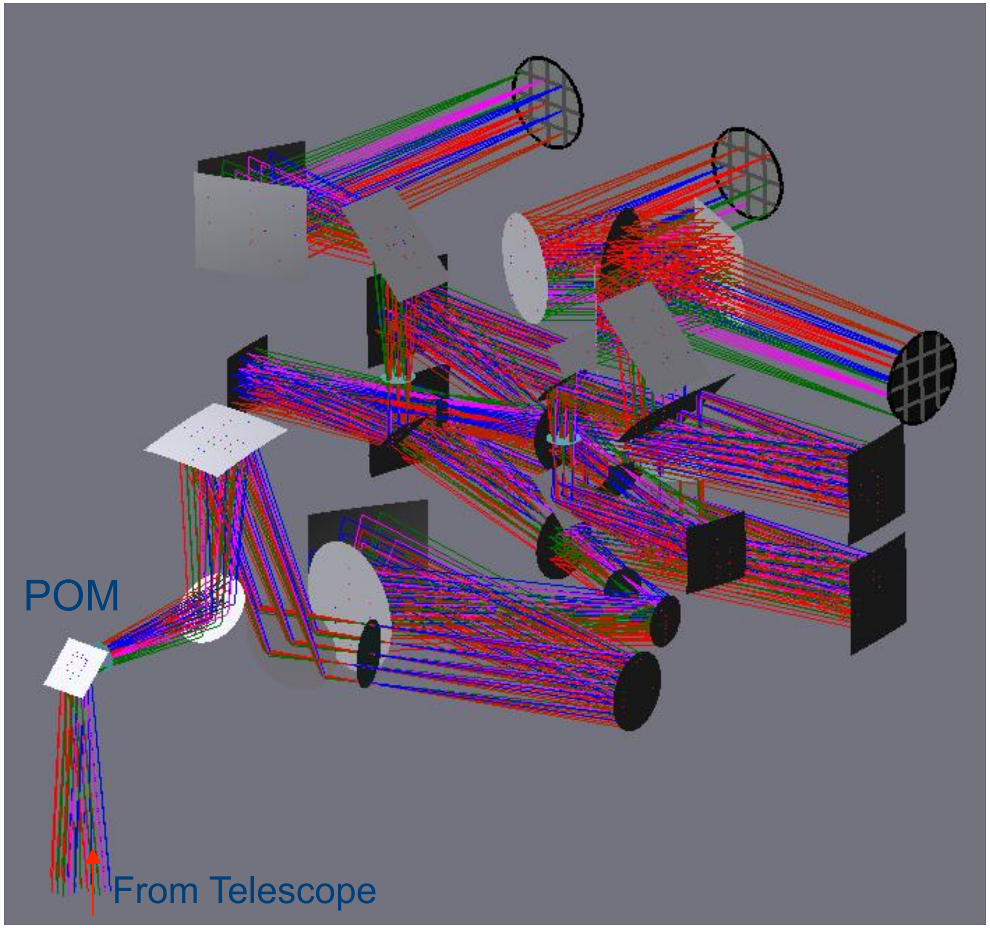
# The SAFARI optics

- Mach-Zehnder interferometer
- Two symmetrical sets of FTS ports
  - Input port 1 → sky
  - Input port 2 → calibrator
  - Output port 1 → LW band
  - Output Port 2 → MW/SW bands



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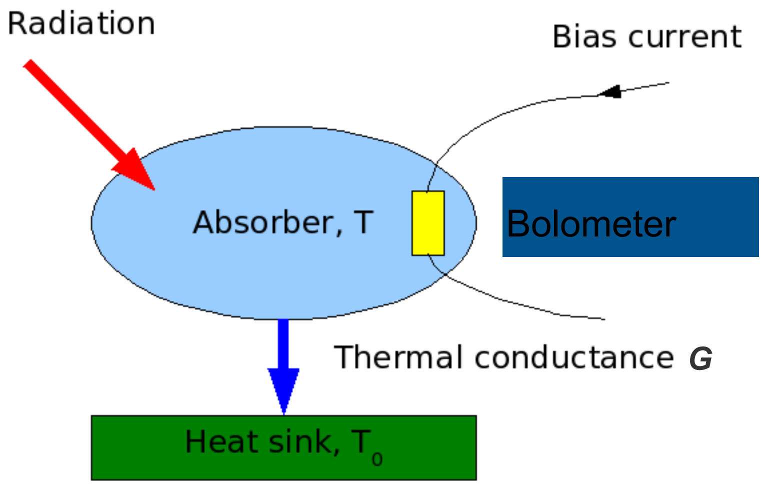
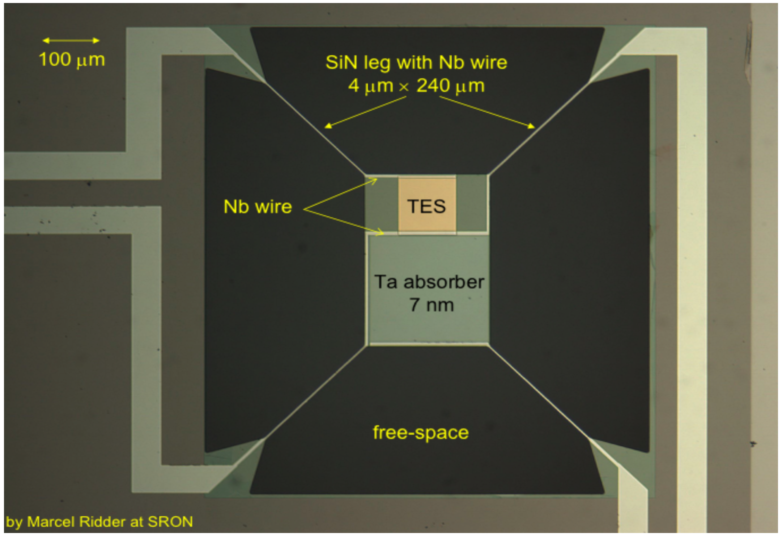
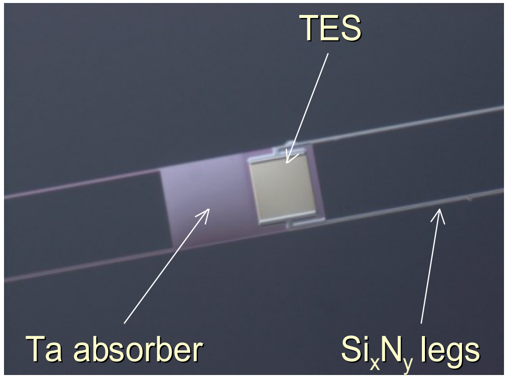
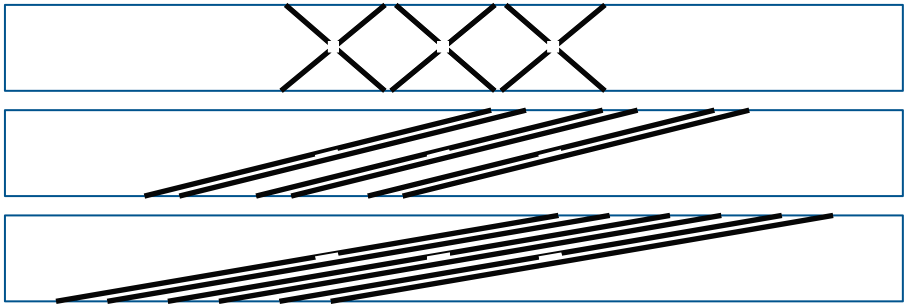
# Transition Edge Sensors - TES




- Phonon-noise NEP=$\sqrt{(4\gamma k_B T^2 G)}$ Watt/√Hz
- Small pixels (480 μm) → low G is difficult
  → make layout with 'long legs'



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# Calibration challenges

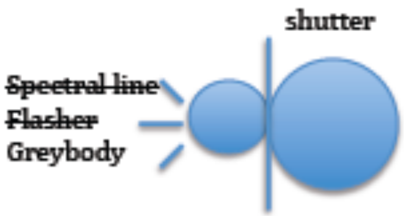
- Sub-Jy flux standards
- Detector drift monitoring
- Linearity, TES speed with flux
- Beam characterisation
- Pointing jitter and broadband spectral shape

# Sub-Jy flux standards

- SAFARI will saturate on point sources of ~1Jy (brighter sources accessible via neutral density filters)
- Primary standards for Herschel are too bright for SPICA
- New network of spectrophotometric stellar standards is being established for JWST-MIRI and SPICA
- Small asteroids
- Cross-calibration with Herschel via PACS faint star observations (Calibration programme and archive search)

# Detector response

- TBD: High frequency modulation TES bath temperature
- <15min – use of redundant data (sky scans, overlapping scan legs & rasters, FTS up&down, …) and blind pixels
- ~15min – internal flasher
- ~day – internal response flat, cold shutter
- ~week – reproducibility flux sources
- ~mission – dozens of absolute flux calibrator measurements, systematic error SQRT(n)

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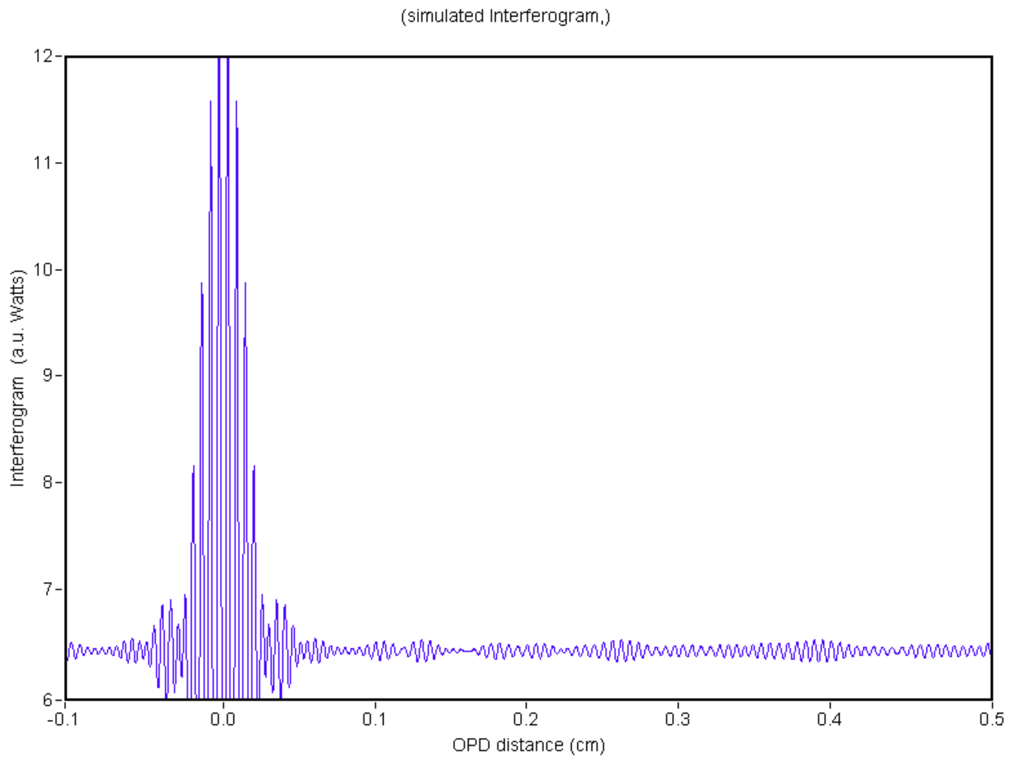
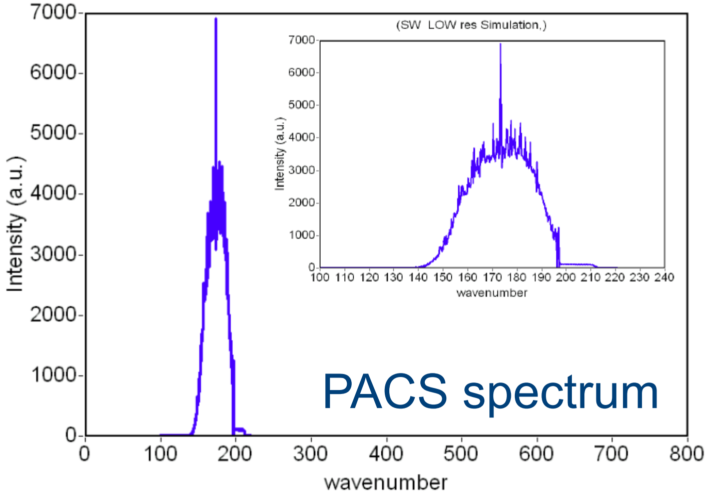
# Linearity & flux dependent time constant

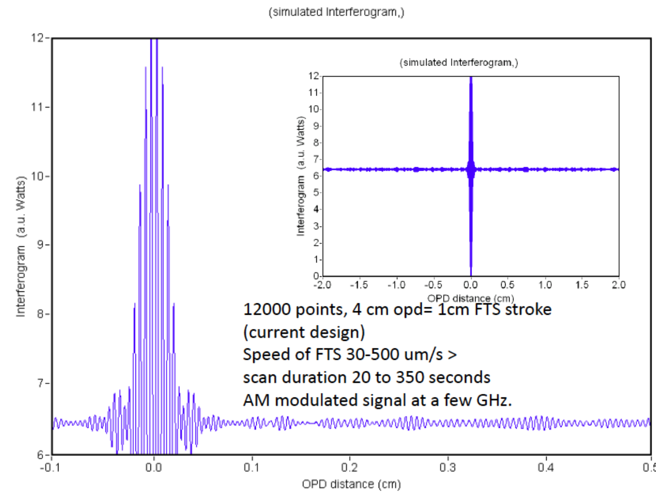
- Non-linearity of the detectors translates into harmonics in the spectrum
- The TES becomes slower with higher flux



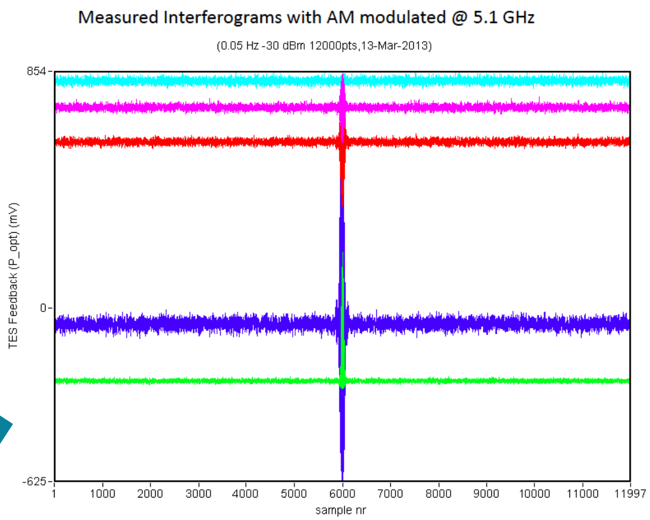
# AM modulated RF FTS / TES simulator



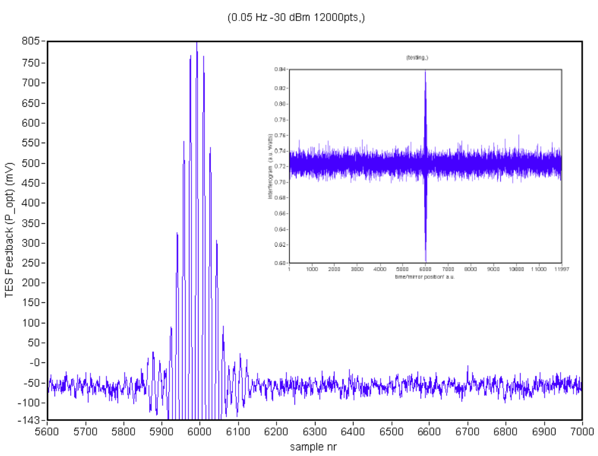

FTS software Simulator (D. Naylor)




AM modulation RF (5.1Ghz) TES + SQUID + readout + sampling

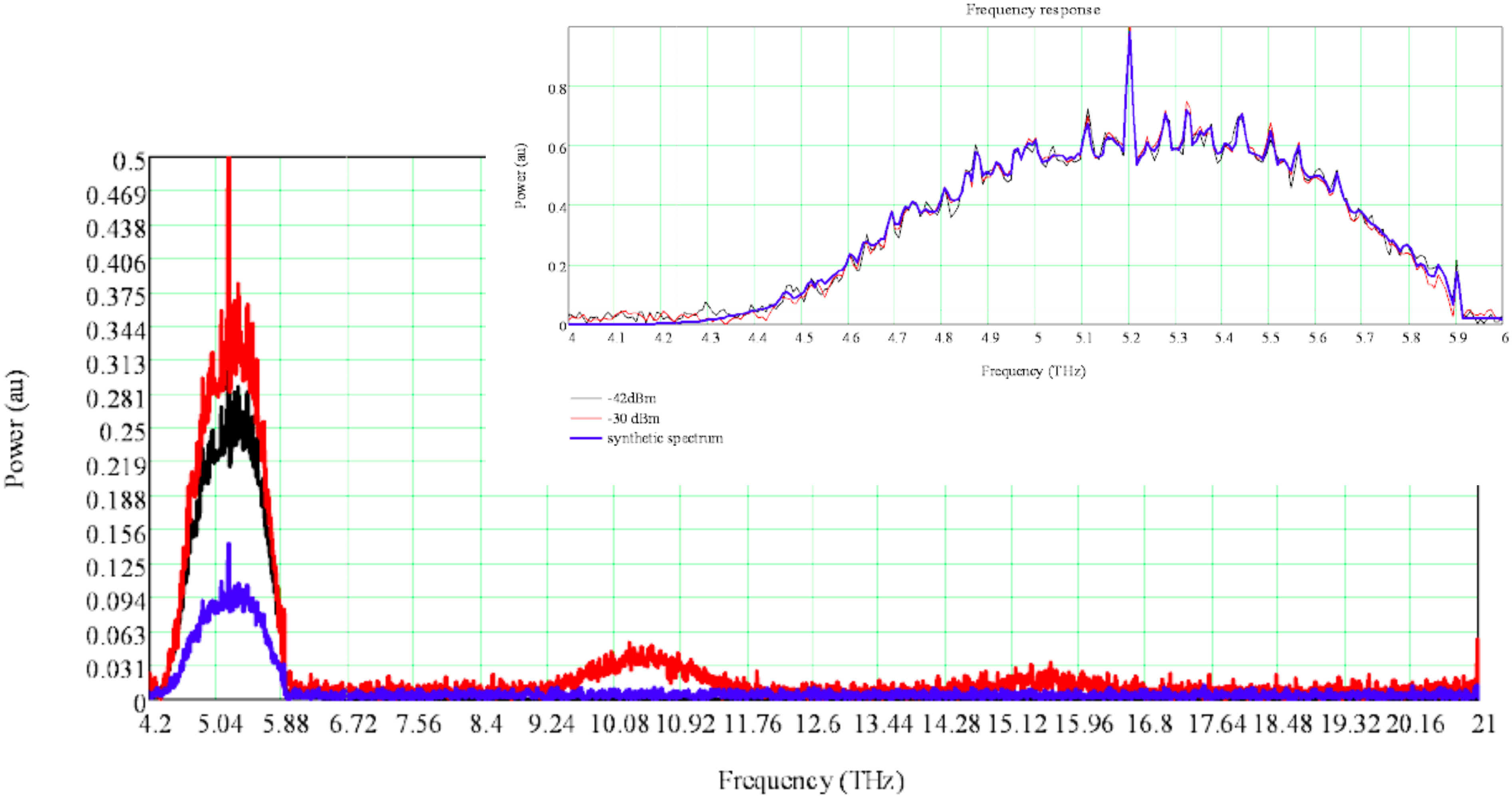



Sample-> OPD




Gert De Lange, Bruce Sibthorpe

# IFFT



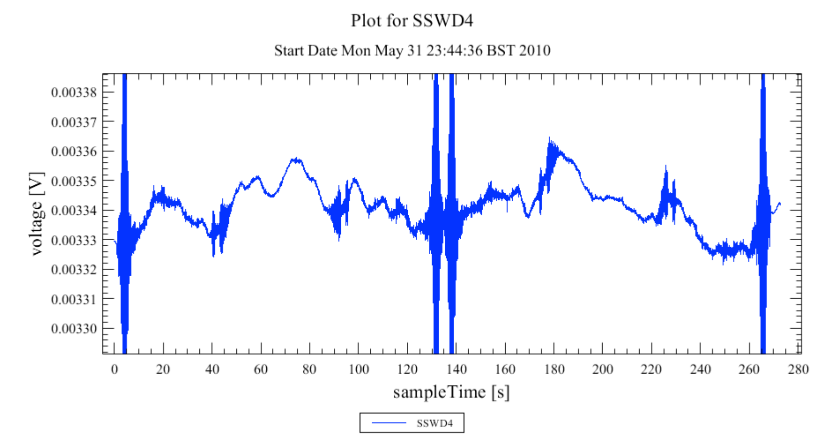
Frequency response
Power (au)
Frequency (THz)
-42dBm
-30 dBm
synthetic spectrum
Power (au)
Frequency (THz)

# Beam characterisation

- In-orbit full beam characterisation over the entire field of view on point source not feasible:
  - FTS scan ~15min
  - 2'x2' field nyquist sampling ~ 120 x 120 raster positions ~ 150 days
- Detailed characterisation on instrument level, using multi-hole image plane mask, cryogenic x-y-z stage
- Translate to in-orbit (with SPICA telescope) through spot-checks across the field + modeling

# Pointing jitter

- Modulation over the beam due to pointing jitter introduces a baseline modulation in the interferogram.
- In the spectral domain, this can lead to spectral slope / broadband features
- Control pointing jitter (cfr risk mitigation phase JAXA), keep jitter frequency out of critical frequency
- Detailed beam characterisation
- Prepare for ground reconstruction from raw gyro data



# Conclusions

- SPICA/SAFARI brings the far-infrared sensitivity into the JWST – ALMA ball park
- This leap in sensitivity brings specific calibration challenges
- These challenges are
  - Difficult enough to be exciting
  - Sufficiently under control not to panic (yet)

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