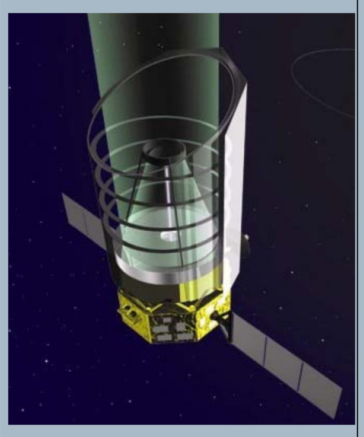


Yasuo Doi, U.Tokyo
Bruce Swinyard, RAL
Kate Isaak, Cardiff
Javier Goicoechea, CAB-CSIC
Doug Griffin, RAL
Mitsunobu Kawada, Nagoya U.
Shuji Matsuura, JAXA
Kentaroh Watanabe, JAXA

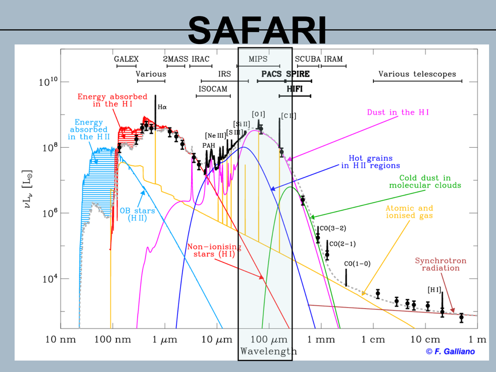
On behalf of the SAFARI consortium: **UK:** RAL, Cardiff, Imperial College, Sussex, UCL, MSSL, OU, ATC /Edinburgh, Oxford, UCLAN, Strathclyde, Durham, Hertfordshire; **Belgium**: MEC/RMA, KUL; **France:** CEA-Saclay, IAS, CEA-Grenoble, Bordeaux,LERMA, OAMP, CESR, GEPI; **Germany:** MPE, MPIA, MPIK, PTB-Berlin; **Netherlands:** SRON, Utrecht, TNO-Delft, Leiden; **Italy:** IFSI, INAF, La Sapienza, ISAF-Rome, TAS; **Spain:** IAC, CSIC; **Austria:** UVienna; **Canada:**Lethbridge, HIA/NRC, UBC, UWO, Calgary; **Japan:** ISAS, JAXA, UTokyo, NagoyaU, NAOJ; **USA:** Cornell, JPL

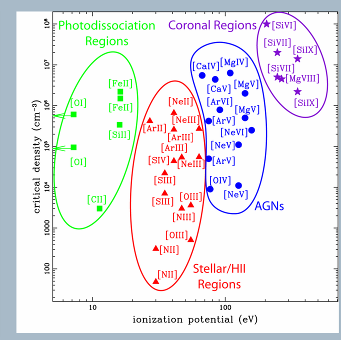
SAFARI -- a FIR Imager/Spectrometer for SPICA

We present an outline of a study that is being undertaken by a consortium of European, Canadian and Japanese institutes, along with JPL, for a FIR instrument for the proposed JAXA-led Japanese-ESA mission, **SPICA** (to be launched in ~2017). SPICA is one of a small number of missions that have been **selected** to go to the next stage of the recent **ESA's Cosmic Vision** process. **SAFARI** – **S**pic**A** **FAR**-infrared **I**nstrument -- is an imaging spectrometer with both spectral and photometric capabilities covering the ~33-210μm waveband. We highlight the core science justification for the instrument working, a possible conceptual design; its predicted performance and the technical challenges that need to be met in order to realise the full potential of the instrument.

Why another FIR mission

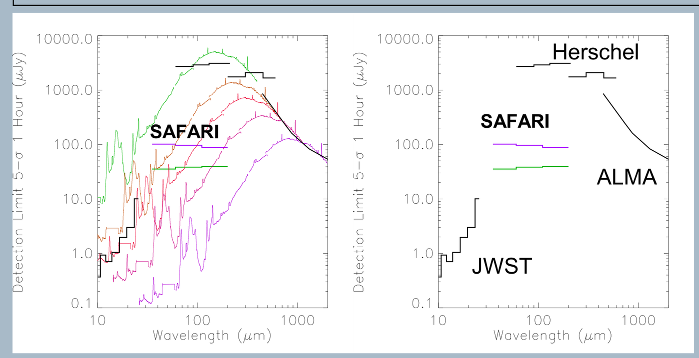
- **Key waveband**
  - Unique and extensive spectroscopic toolkit of key diagnostic lines (FIR&redshifted MIR) + thermal continuum
- **Long lineage of very successful FIR missions**
  - IRAS,KAO,ISO,Spitzer,AKARI (+SOFIA,Herschel…)
- **Herschel?**
  - Confusion-limited at λ>100um, detector-limited below
  - 1000s of distant,FIR sources, but what are they? Deep spectroscopy to characterize: eg. AGN vs. starburst
- **ALMA?**
  - *complementary* science
  - FIR: undetectable λ's from ground
- **SPICA → Cooled Herschel:**
  - Much lower background → deep spectroscopy
  - Imaging vs. point-source → determines science capabilities/sensitivities/instrument design
  - Facility vs. single science case





Above: A synthetic spectrum of a typical galaxy undergoing modest star formation.

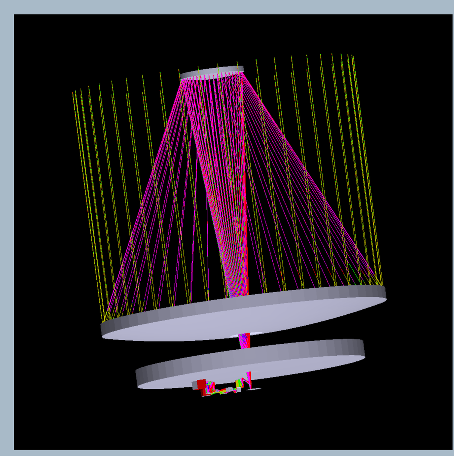
Right: A selection of redshifted MIR/FIR emission lines accessible with SPICA, plotted as a function of critical density ionization potential. Between them, they cover a wide range of physical and excitation conditions



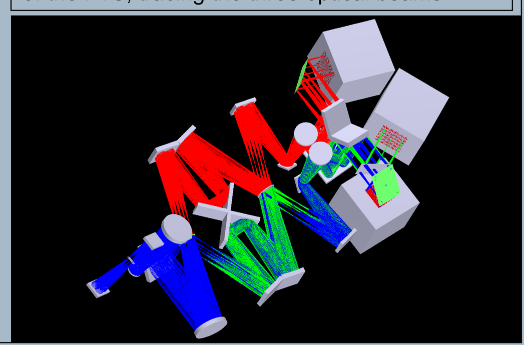
Left panel: A plot of the spectral sensitivity of SAFARI and Herschel, overlaid on redshifted (z=1-5) M82 SED+line fits; **Right panel:** photometric sensitivity of SAFARI relative to other facilities

Instrument concept:

- Imaging Fourier Transform Spectrometer (background higher than for grating, but imaging straight forward)
- Wavelength coverage of ~33-210μm (using 3-4 detector arrays, Fλ/2 sampling)
- Field of view of 1' x 1', with goal of 2' x 2'
- Spectroscopy (10<R<10 000) & photometry (R~3)
  5σ-1hr: few x 10^{-19} W/m² at R~2000 5σ-1hr: <50μJy
- Detector sensitivity required of 10^{-19} W/√ Hz
  - photoconductors (cf. Herschel-PACS/Spitzer) at 1.7 - 4.5K
  - TES bolometers operating at < 100mK
  - Silicon bolometers, also operating at sub-K temperatures
  - KIDs

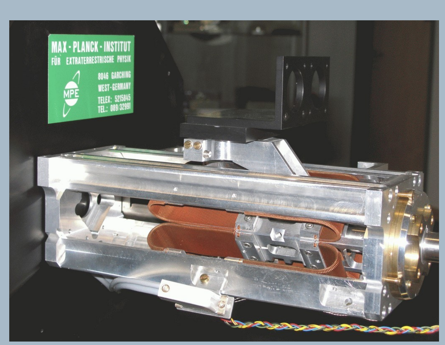


Above: Optical layout of the FTS concept, to scale with the 3.5m telescope; **Below:** Model of the FTS, tracing the three optical beams

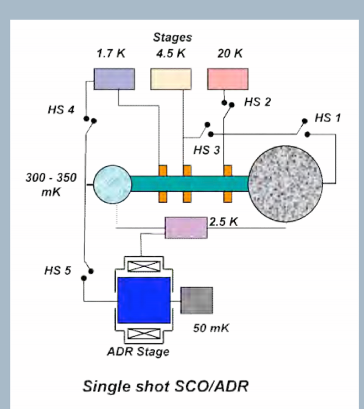


Technical challenges and solutions:

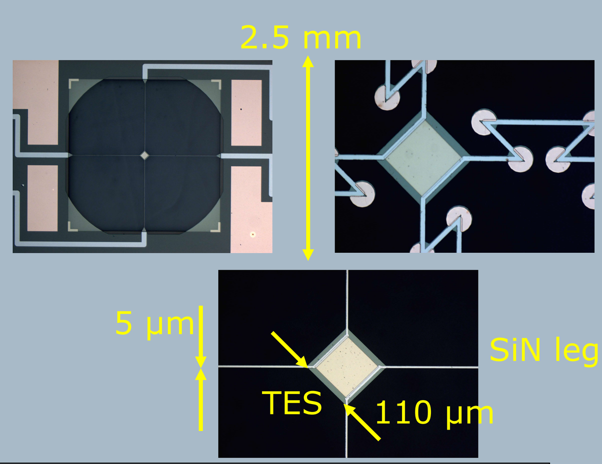
- Detector sensitivity, dynamic range and complexity
- Cooler technology: a full multi-stage ADR and a hybrid sorption cooler/ADR are under consideration
- Broadband beamsplitters and filters: ~3 octave bandwidth required
- FTS cryo-mechanisms: space-qualified mechanisms exist



A photo of the FTS scanner mechanism developed for the GIRL (German Infrared Laboratory) spectrometer. This friction-free mechanism has a scan length of 100mm and is fully space-qualified.



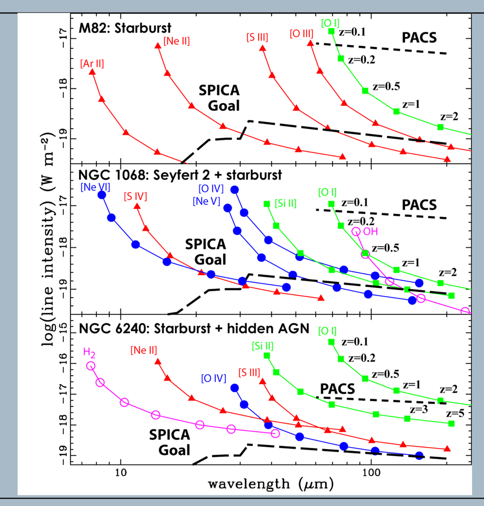
Schematic of one of the CEA-Grenoble (SBT) cooler designs under consideration for SAFARI



Prototype TES detectors under test and development at Cardiff/SRON/Cambridge with a parallel development programme at JPL

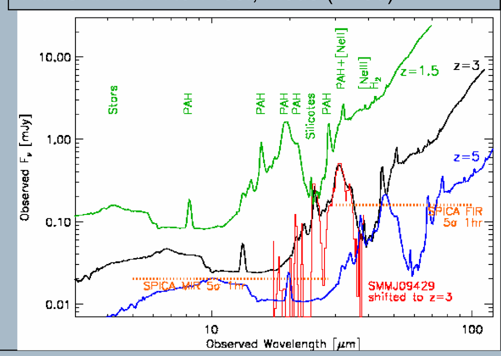
Galaxy evolution, near and far

- **The AGN-starburst connection at high-z**
  - Through deep spectroscopy, characterise the distant MIR/FIR galaxy population out to z~4 and beyond, and start to disentangle the interplay between AGN and starburst
- **Deep cosmological surveys:**
  - Through deep, confusion limited surveys at 70μm complete a census on (i) star formation down to MW/4 @z~1, 90% of the CIRB over 80% of Hubble time (ii) massive black-hole growth by unveiling the missing dust-obscured, Compton-thick AGN population responsible for the 30keV peak in the x-ray background
- **Punching through the traditional confusion limit:**
  - Break confusion through deep,spectral imaging of "blank" sky
- **Cosmology at low spectral resolution:**
  - Deep surveys using redshifted PAH features
- **Local galaxies: proxies for the distant Universe**



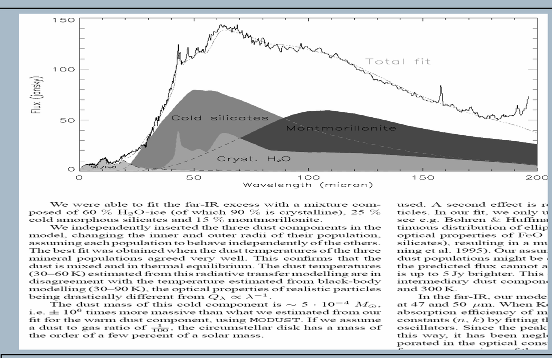
Above: Intensity vs. wavelength of key MIR/FIR lines in three archetypical objects -dashed line represents 5-σ 1hr sensitivity of SPICA

Below: Detectability of redshifted PAH features with SAFARI in low-res., mode (R~50)

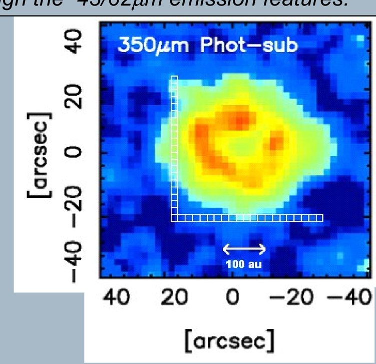


From gas and dust to planets

- **Protoplanetary disks: from ices to oceans**
  - Tracing the presence of stellar FIR photometric excesses (due to circumstellar disks) out to the edge of the galaxy
  - Providing a comprehensive inventory of stars with circumstellar disks for future planet imaging facilities
  - Resolving the "snow line" (water ice) in nearby "Vega" disks
  - Access to the main gas coolants & key chemical species (eg. water, oxygen, organics) in proto-planetary disks
  - Searching for FIR signatures of transiting exoplanets (water?)
- **Building blocks of the Solar System:**
  - Determining the chemical history of the Solar nebula by detection & characterisation of 100s of asteroids, TNOs and KBOs
- **The dust life-cycle:**
  - Tracing the evolutionary cycle of dust through spectral& photometric imaging of the faint,,extended medium where dust grains are formed (eg. evolved stars) and reprocessed (SNe remnants & the diffuse ISM), before incorporation into star-forming clouds



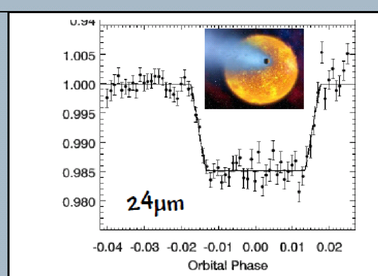
The ISO spectrum towards the young star HD142527 (Malfait et al.) showing the model components of the MIR/FIR disk emission. Water ices can be directly detected through the 43/62μm emission features.



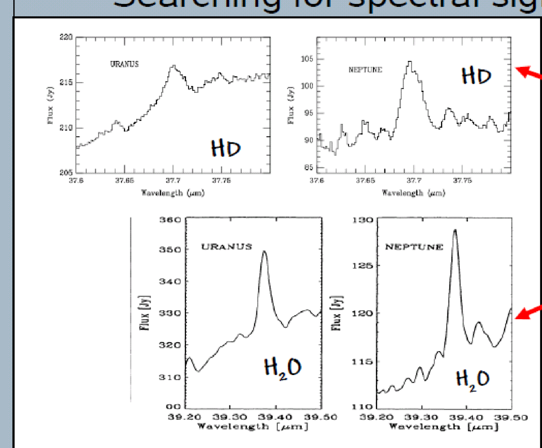
The CSO SHARCII 350μm image of Vega (Marsh et al.), onto with SAFARI pixel scale at 43-62μm overlaid. Spatial resolution equivalent to ~23 AU will be possible, enough to detect the expected snow-line region at 42 AU.

Exoplanet research in the far-IR

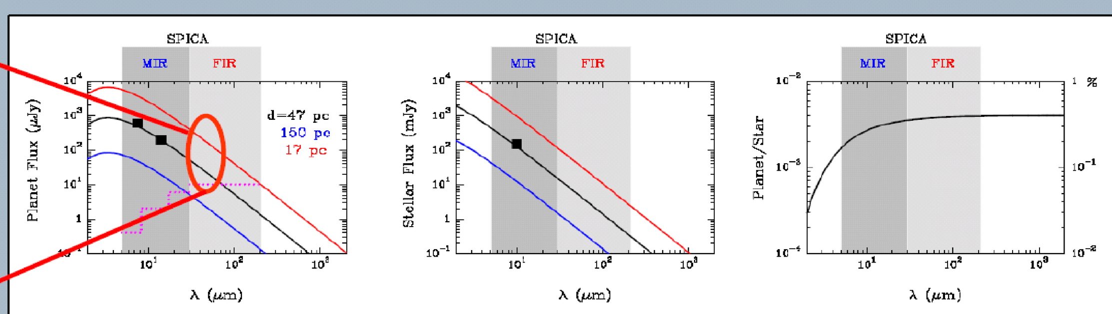
- 2 orders of magnitude higher sensitivity than Herschel/PACS to detect and characterize zodiacal backgrounds in a statistical sample of stars (~10^5 Sun-like stars at d<180 pc).
- Key to prioritising Earth-like candidates for long-term TPF missions.
- Very stable detectors and efficient, high cadence and high S/N observations to perform transit photometry and spectroscopy in the far-IR.
- Searching for spectral signatures of transiting exoplanets (water?, HD?, ice?)



HD 209458b primary eclipse with *Spitzer* (Richardson et al). Transit studies possible in the far-IR



Example of far-IR HD and H2O lines towards Uranus & Neptune (Fouchet; Feuchtgruber et al.)



Left: Fit to HD 209458b *hot Jupiter* (Teff~1000 K) mid-IR from Spitzer/IRS observations (Swain et al. 2008) during its secondary transit around a G0 star (d~47 pc, Teff ~6000 K) and estimations for different distances (blue and red). The magenta lines show the estimated photometric sensitivity of SPICA with GOAL detectors (5σ-1hr). **Middle:** Expected flux from the host star. **Right:** Resulting planet-to-star contrast ratio as a function of wavelength. The shaded regions represent the 2 main wavelength domains of SPICA instruments: "MIR" for the coronagraph and mid-IR instruments and "FIR" for the SAFARI spectrum.

Japanese contribution: provision of 64x64 Ge:Ga monolithic detector array

Direct Hybrid Ge:Ga Detector – 5 x 5 Test Model

Testing Items:

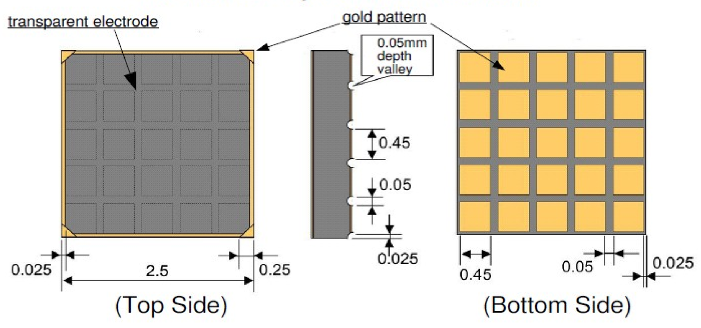
- Transparent Electrode (Hamamatsu Photonics)
- Anti-Reflection Coating (Optical Coatings Japan / option)
- Au bumping (Mitsubishi Heavy Industory)
- Readout Electronics (IMEC)

estimation of photo-current

$$P=\epsilon I_\nu d\nu S \Omega = 3.4\times10^{-16} \quad [W/pix]$$
$$I_p = P/R = 3.4\times10^{-15} \quad [A]$$

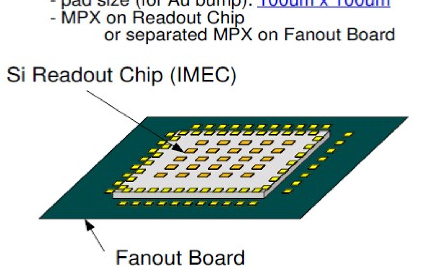
ϵ : optical efficiency (ϵ/0.2)
I_ν : sky brightness (I_ν/10[MJy/sr])
$d\nu$: band width ($d\nu/3\times10^{12}$[Hz]=50−100 μm)
S : telescope area (S/(3.5m φ))
Ω : solid angle of one pixel (Ω/(5×5 $arcsec^2$))
$1.2\lambda/D = 3.4\times^{-5}$[rad] ~ 7 arcsec @ 100 μm
R : responsivity (R/10[A/W])

5x5 Ge:Ga Crystal with Electrode



Readout Unit

- pad size (for Au bump): 100um x 100um
- MPX on Readout Chip or separated MPX on Fanout Board



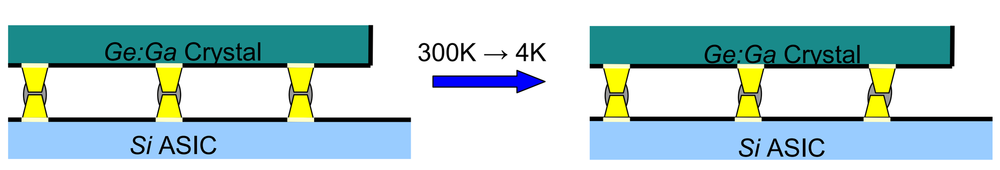
Au Stud Bump Technology

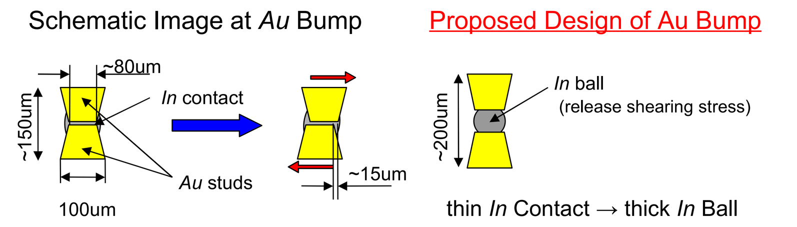
EXPERIMENTAL PROOF of Fundamental Technologies for Large Format *Ge:Ga* Array Detector

Verification Point: thermal stress at Au bump

difference of thermal contraction between Ge and Si: dL/L ~ 10^{-3} (300K → 4K)
Array size: 15mm x 15mm ==> strike slip= ~15um(max) @ *In* contact

Established Design of Au stud bump: Au stud with In contact





experimentally proofed for small size (about 2mm x 2mm)

thin *In* Contact → thick *In* Ball

Fabricate Test Pieces
(pure *Ge* + *Si* with electrode)

- bump type: both conventional and new ones
- array size: 15mm x 15mm (full size of largest *Ge:Ga* array)
  - bump pitch: 0.5mm pitch
  - number of bumps: 30 x 30 = 900
- test point: electric conductivity at bumps after thermal cycles

AR-coat for better transmission: free from spectrum fringes