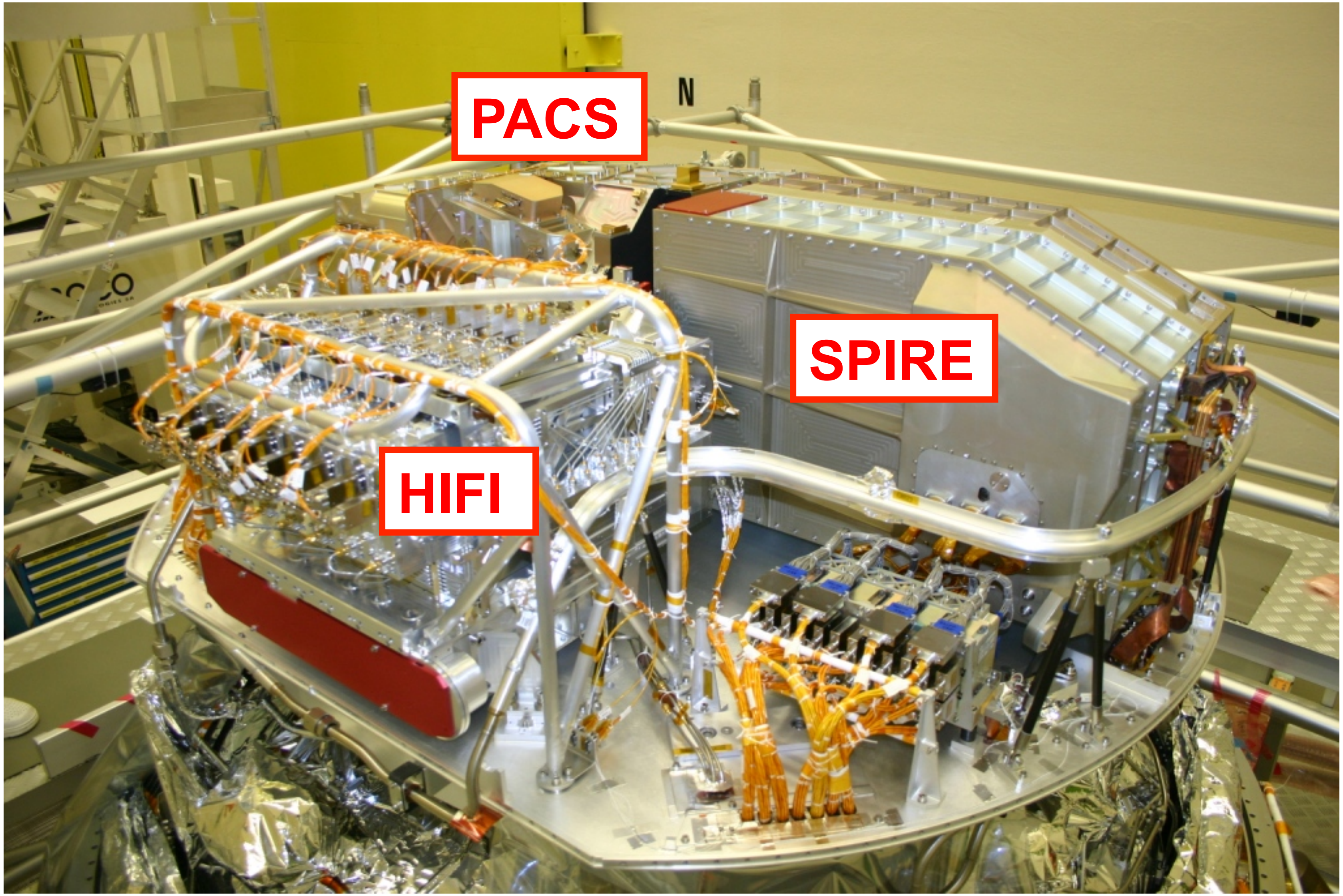
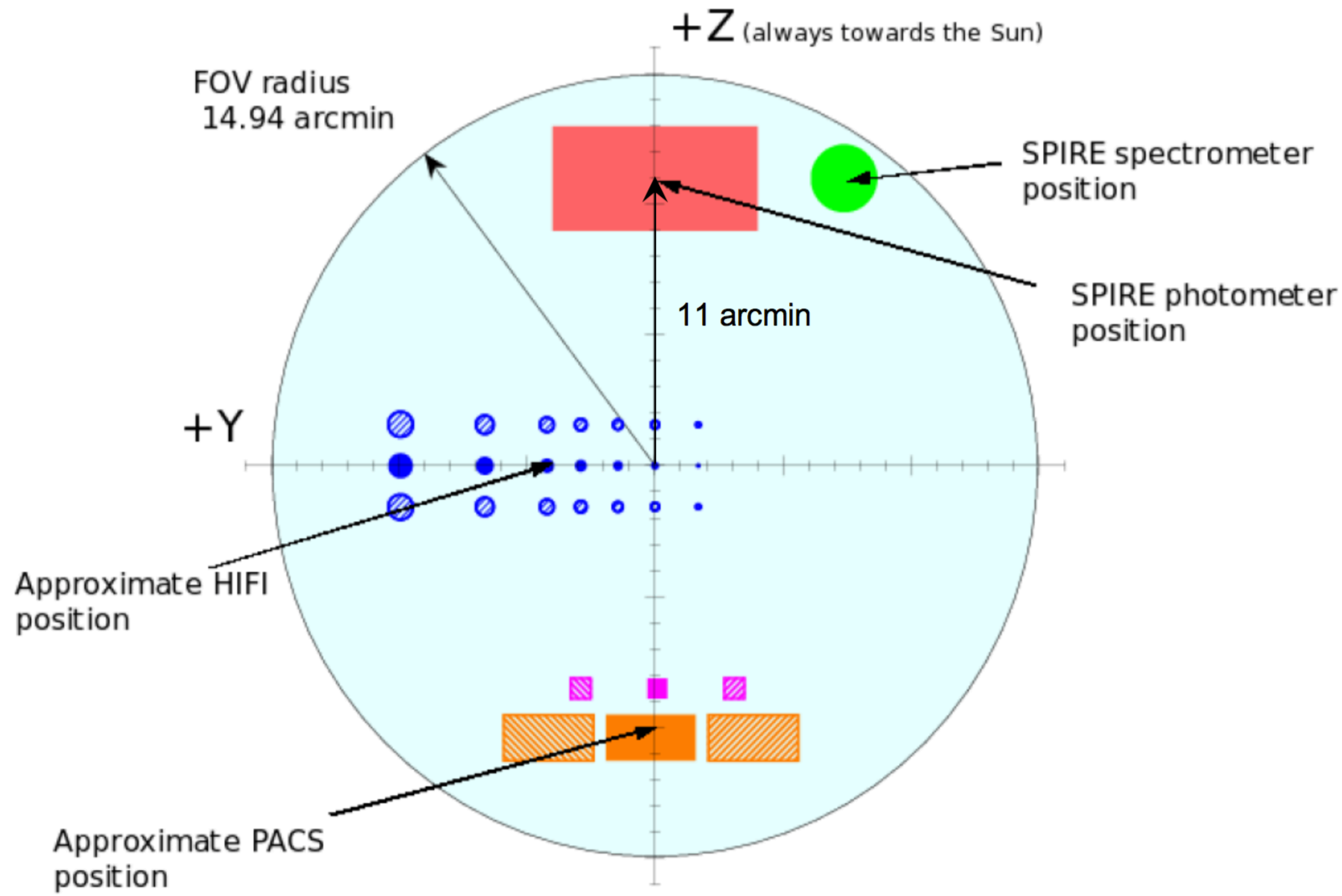
The Herschel Space Observatory instruments

Bruno Altieri (ESAC)

The Herschel instruments

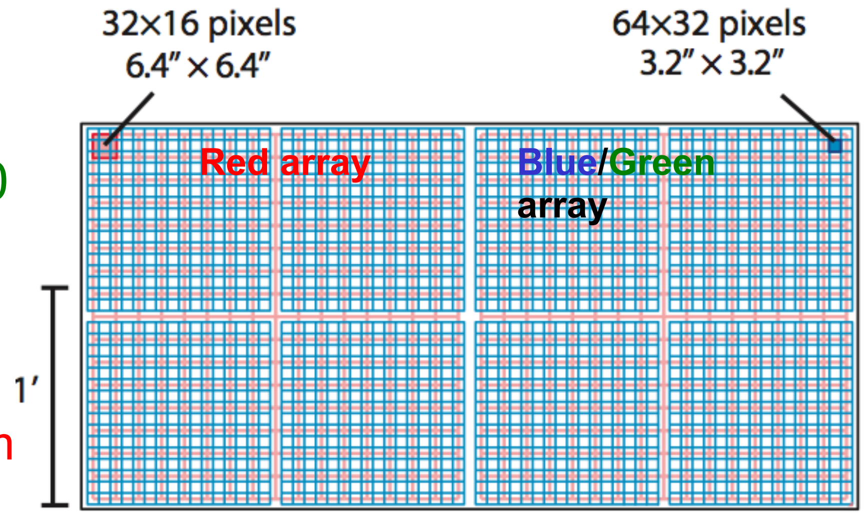


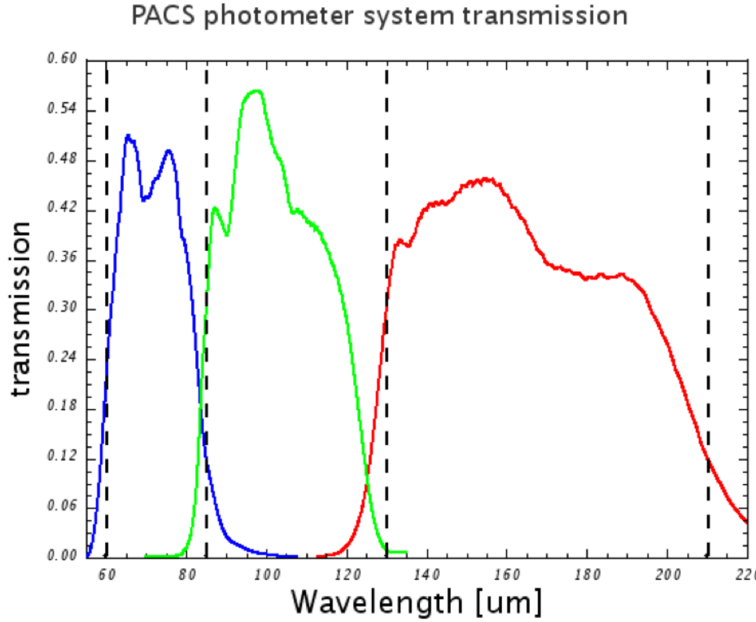
Herschel Focal Plane



The PACS Photometer

- The **PACS** photometer uses two filled *Si* bolometer arrays
- It offers 3 photometric colours (70, 100 and 160 μm), 2 of which being observed simultaneously over a common 1.75’ x3.5’ Filed of View
  - ***Red array***: 32x16 pixels in 125-210 μm
  - ***Blue***/Green array: 64x32 pixels in either 60-85 μm and 85-125 μm





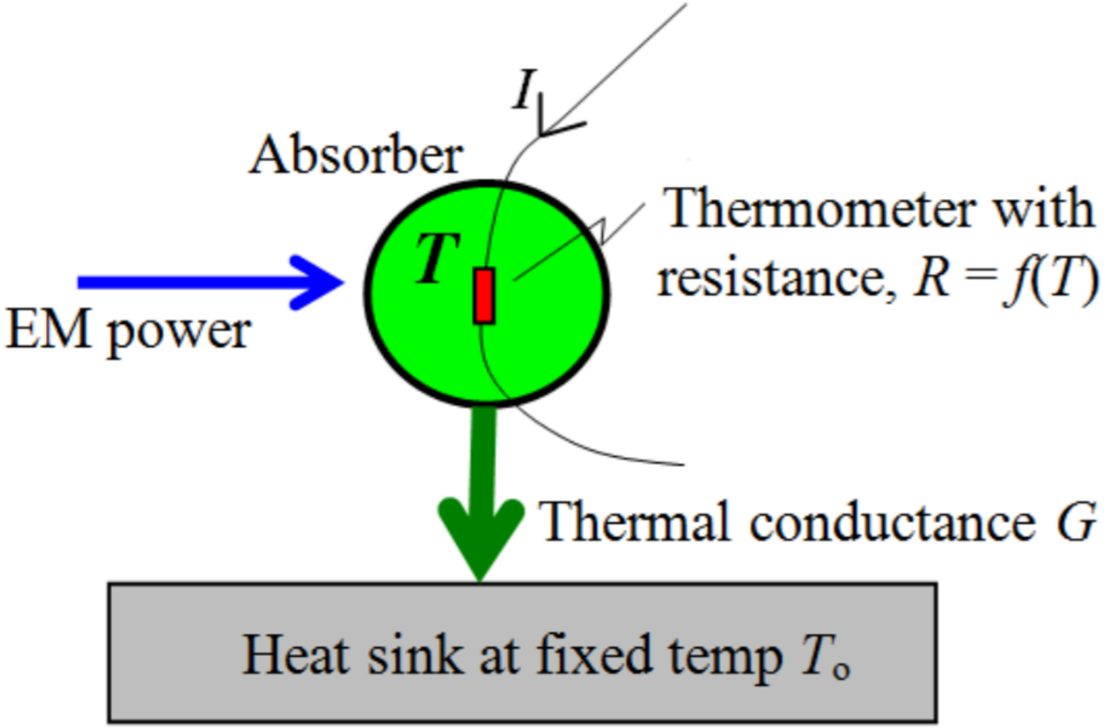
Saturation limits

Filter	Point source [Jy]	Extended source [GJy/sr]
Blue	220	290
Green	510	350
Red	1125	300

Sensitivity

Band	Uncertainty[a]	Point source[b] mode $5\sigma/1$ h	Scan map[b] $[10' \times 15']$ $5\sigma/30$ h
Blue	±10%	4.4 mJy	3.7 mJy
Green	±10%	5.1 mJy	5.0 mJy
Red	±20%	9.8 mJy	9.5 mJy

Bolometric Detectors



$$NEP_{\mathrm{phonon}} = \left(4kT_o^2 G\right)^{1/2}$$

- **Low NEP requires low *T* and low G**
- **Good speed of response requires low heat capacity (*τ* ~ *C*/*G*)**
  - **Which also reduces with temperature**
- **For PACS and SPIRE we need *T* ~ 0.3 K**

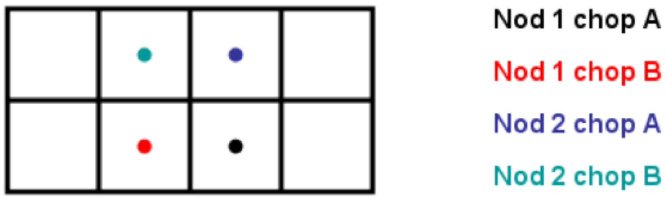
The PACS-P: observing modes

With optional setting dedicated settings for bright lines…

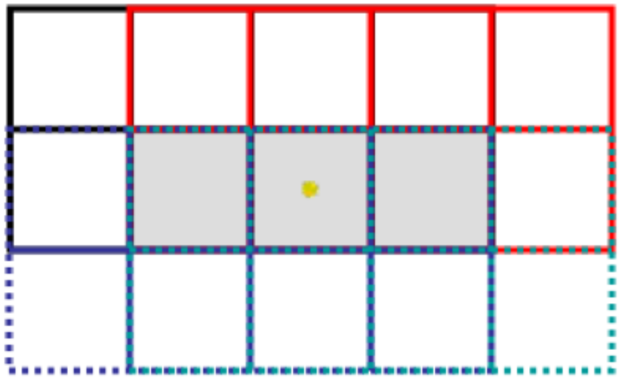
Pointing modes

1. Point source photometry

Uses a four point chop/ nod cycle

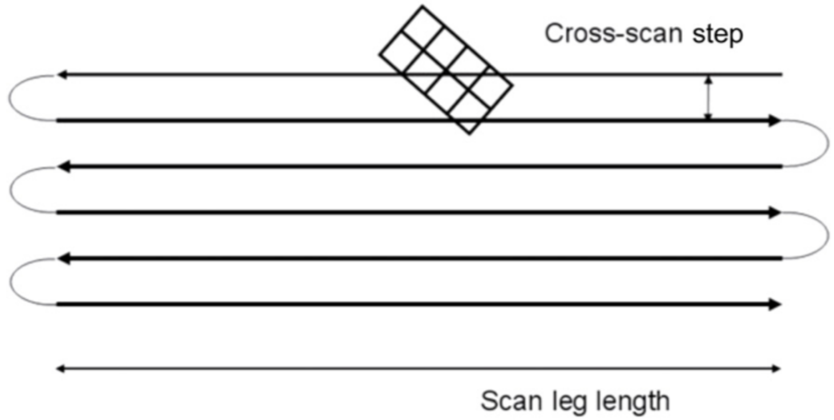


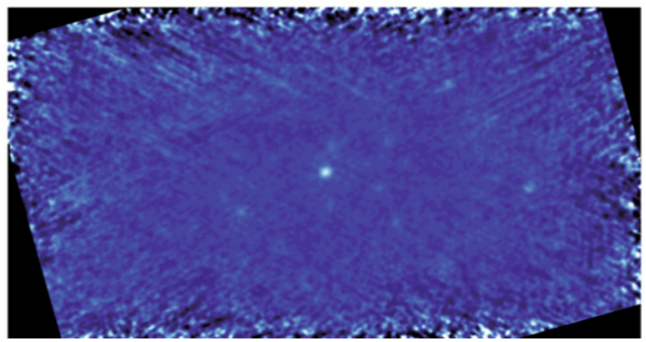
AOT footprint on the sky



2. Scan map

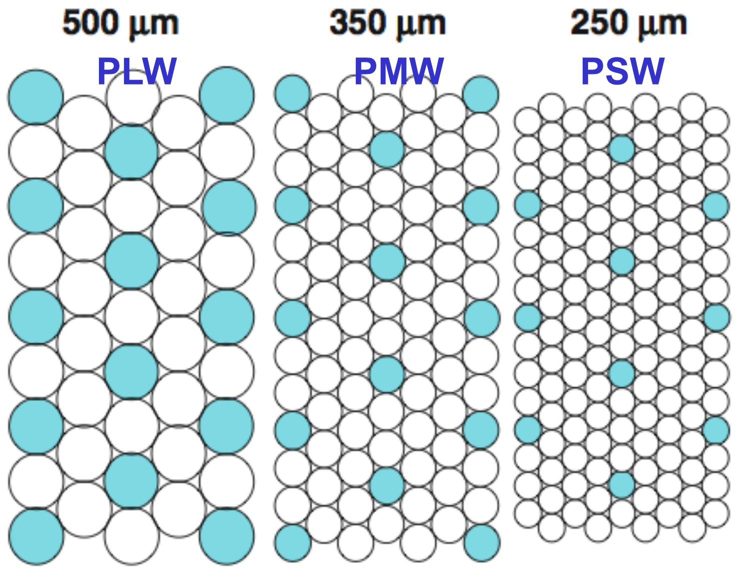
Scanning speeds 20 or 60 "/sec





The SPIRE Photometer

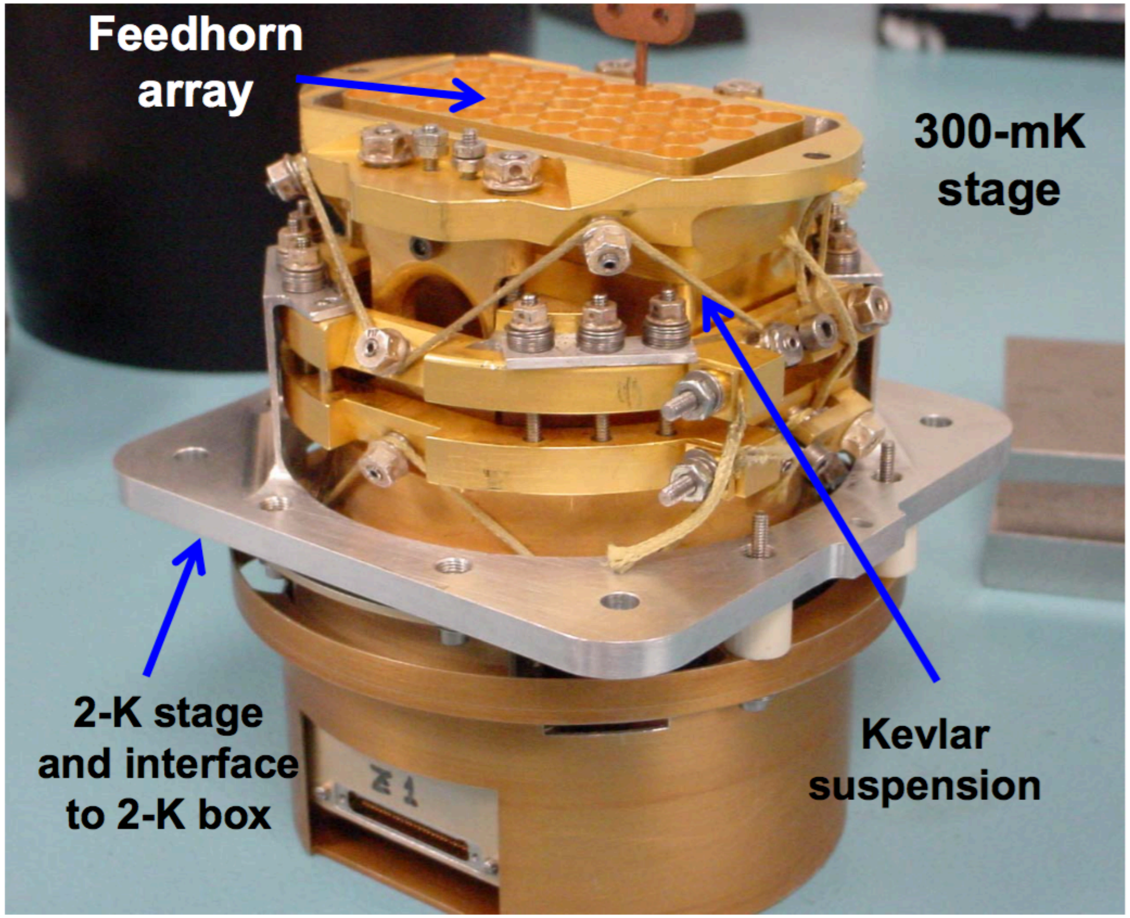
- The **SPIRE** photometer uses three feed-horn coupled bolometer arrays
- It offers 3 photometric colours (250, 350 and 500 µm), all observed simultaneously over a FoV of ~ 4’ x8’
  - ***PSW***: 139 pixels, 18.2” HPBW
  - ***PMW***: 88 pixels, 24.9” HPBW
  - ***PLW***: 43 pixels, 36.3” HPBW



Band	250	350	500
1 σ extragalactic confusion noise (mJy in beam)	5.8	6.3	6.8
SPIRE-only scan map; 30″/s scan rate			
1 σ instrument noise for one repeat: i.e., two cross-linked scans, A+B (mJy in beam)	9.0	7.5	10.8
1 σ instrument noise for one repeat: i.e., one scan A or B (mJy/beam)	12.8	10.6	15.3
Point source (7-point jiggle)			
1 σ instrument noise for one repeat (mJy)	7	7	7
Source flux density up to 1 Jy (mJy)	6-8	6-8	6-8
Source flux density 1-4 Jy (mJy)	8-12	8-12	8-12
Source flux density $\geq$ 4 Jy	S/N $\sim$ 100		

Sensitivity

SPIRE Bolometer Detector Array



The SPIRE-P: observing modes

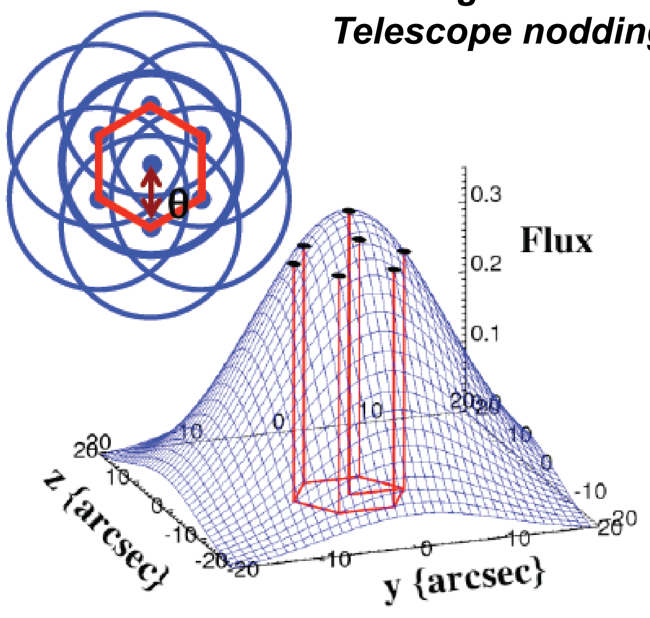
With optional setting dedicated settings for bright lines (above ~200 Jy)

Pointing modes

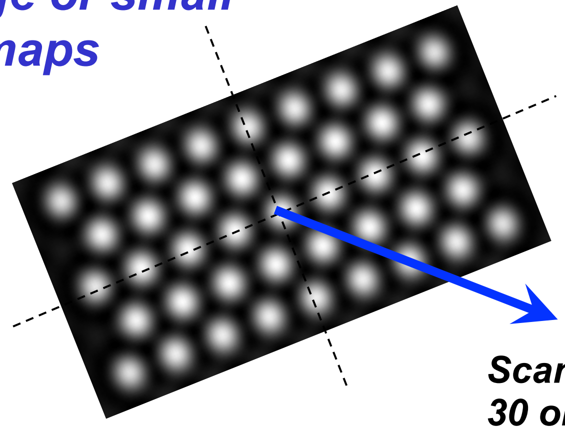
1. 7-pt jiggle maps

Best for point sources

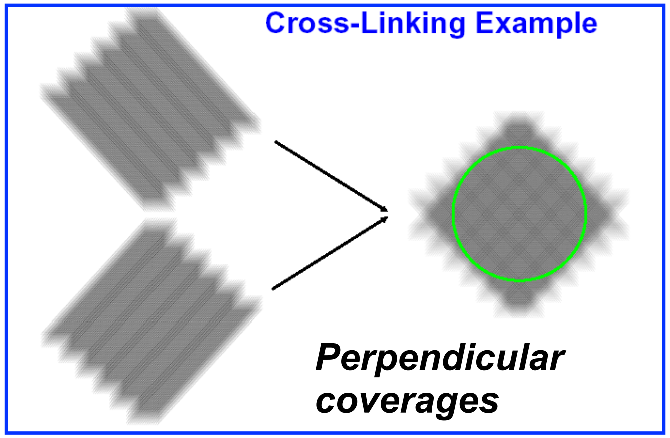
Chopping with SPIRE Beam Steering Mirror + Telescope nodding



2. Large or small scan maps

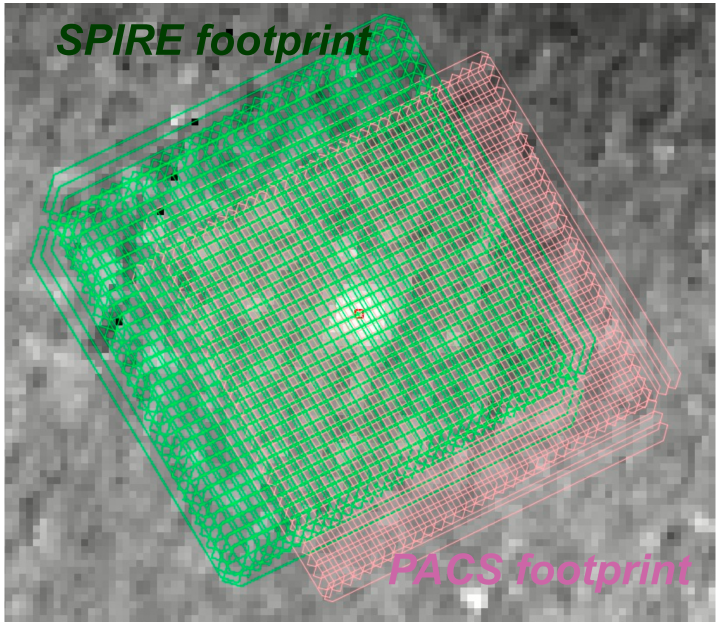


Scanning speeds 30 or 60 "/sec



The SPIRE-P/PACS-P parallel mode

- It allows to simultaneously observe with the 3 SPIRE-P colours, and 2 of the PACS-P ones (either 70+100 or 70+160 µm)
- Because the respective fields of view are at different locations on the sky, part of the map is only seen by either of the arrays – larger areas need to be covered to be seen by all 5 colours



SPIRE-PACS Parallel Mode; 20″/s (slow) scan rate			
1 σ instrument noise for one repeat: i.e., one scan A, nominal (mJy in beam)	7.3	6.0	8.7
1 σ instrument noise for one repeat: i.e., one scan B, orthogonal (mJy in beam)	7.0	5.8	8.3
SPIRE-PACS Parallel Mode; 60″/s (fast) scan rate			
1 σ instrument noise for one repeat: i.e., one scan A, nominal (mJy in beam)	12.6	10.5	15.0
1 σ instrument noise for one repeat: i.e., one scan B, orthogonal (mJy in beam)	12.1	10.0	14.4

Sensitivity

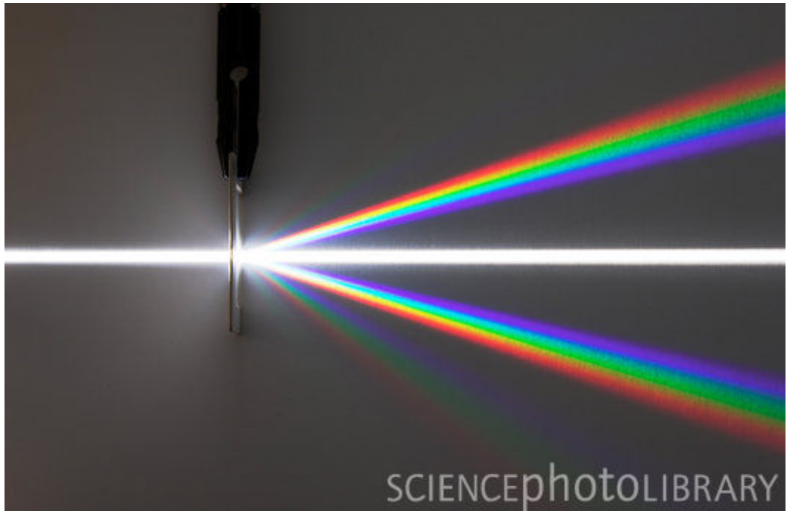
The PACS Spectrometer: concept (1)

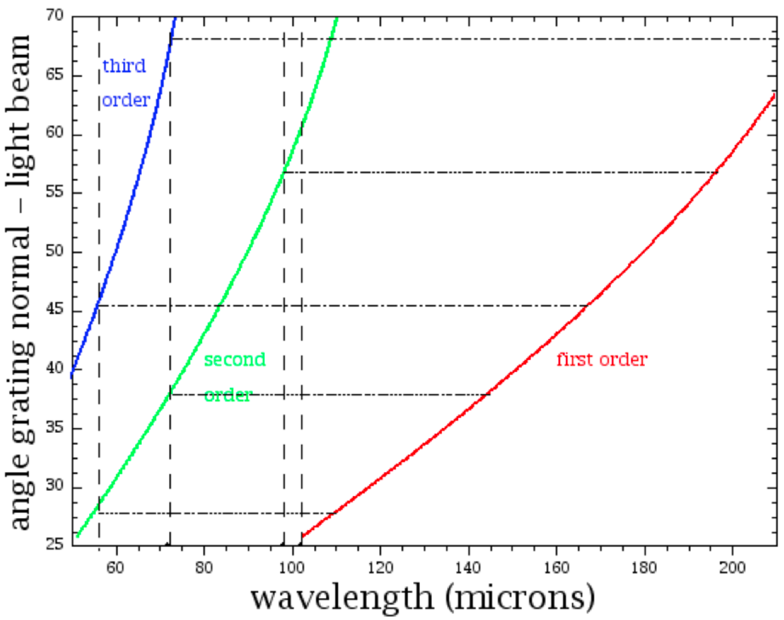
- The **PACS** spectrometer is an ***Integral Field Unit*** (***IFU***)
- It uses the principles of the ***Dispersing Grating Spectroscopy*** whereby light is diffracted by a slit along a different direction to spatially sample the wavelength components
- The dispersion angle ***θ*** follows the so-called ***grating equation***:

  $m\lambda = 2d \sin(\theta)$ *(Littrow config.)*

  (d: groove separation, m: order)

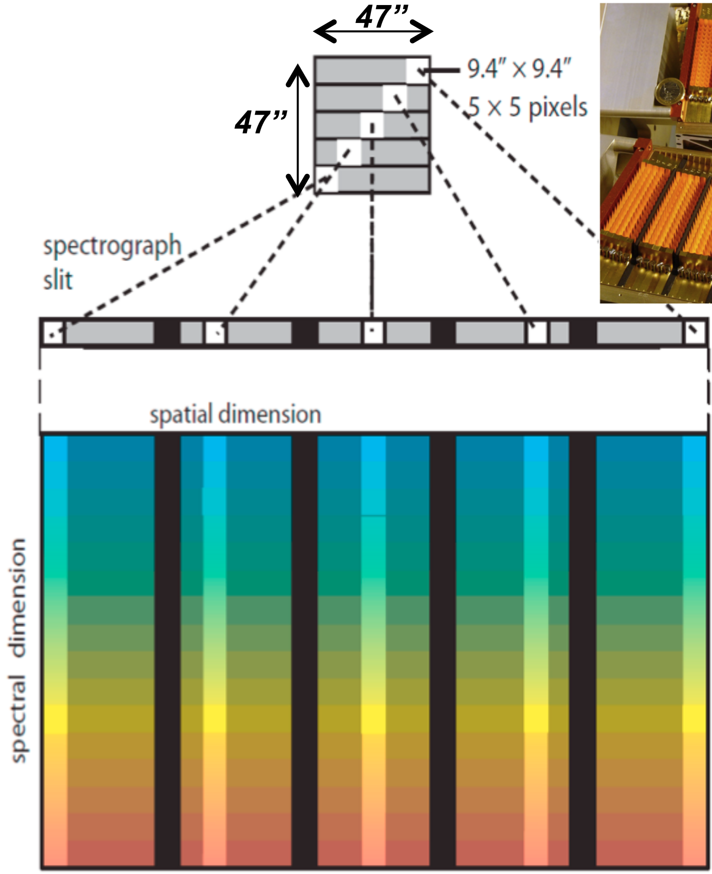
- Several wavelengths solve the equation at a given incident angle: these are called ***orders*** – PACS uses the first 3 to cover ***52-210 µm*** in total

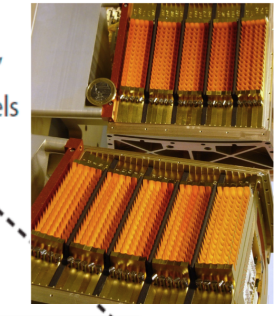


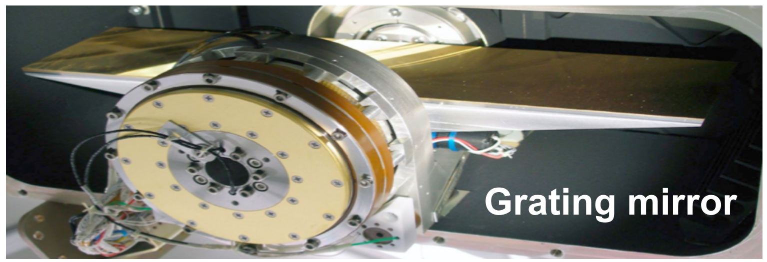


The PACS Spectrometer: concept (2)

- The PACS-S offers ***5x5 spaxels*** sliced on a slit, imaged in 2x five 5x16 arrays
- The various spectral ranges are covered as the grating mirror rotates, the # of positions defines the resolution
- The various orders are filtered over 2 arrays:
  - ***Red array***: 1st order only, 102-210 µm
  - ***Blue array***: 2nd (51-73 µm) and 3rd orders (70-105 µm)







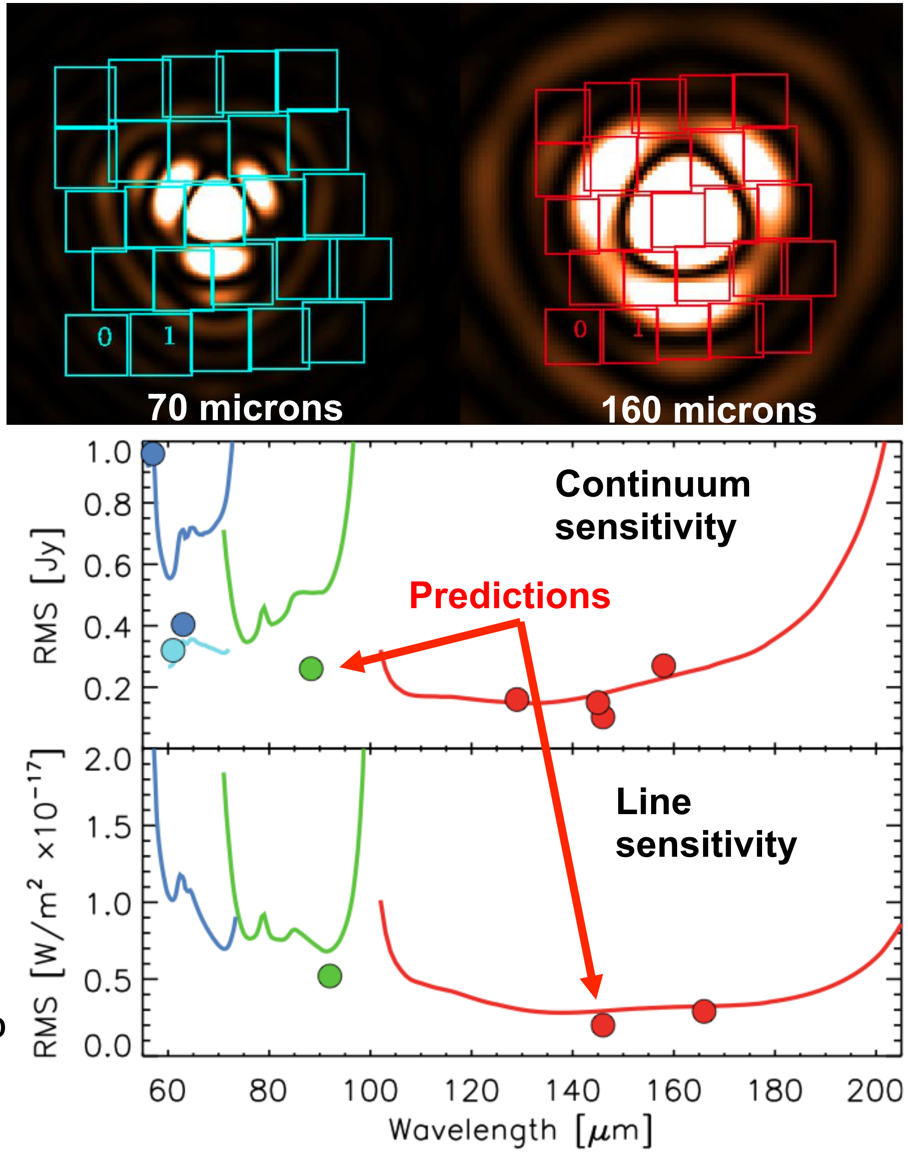
The PACS-S: Performance

Spatial response

- Substantial departure from a pure Gaussian profile due to telescope tripod
- The beam is ***under-sampled*** in the spaxels, leading to flux mis-calibration in compact sources
- The fraction of the beam seen depends on the wavelength

Sensitivity and accuracy

- Similar or better to pre-launch predictions
- Resolving power 1000-4000
- Cal. accuracy between 10 and 20%

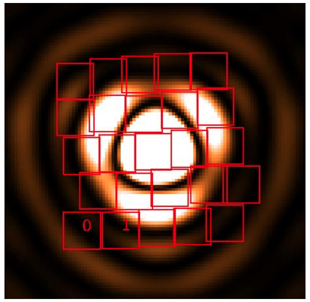


The PACS-S: observing modes

COMBINATIONS OF… with a configurable number of line/coverage repetition

Pointing modes

1. Single pointing

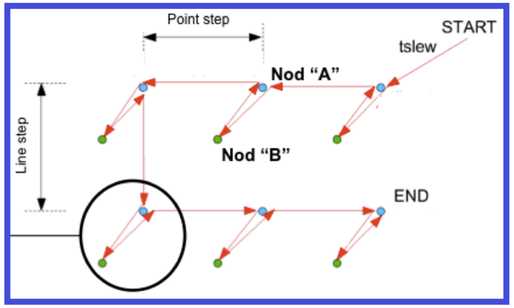


Snapshot observation

Under-sampled

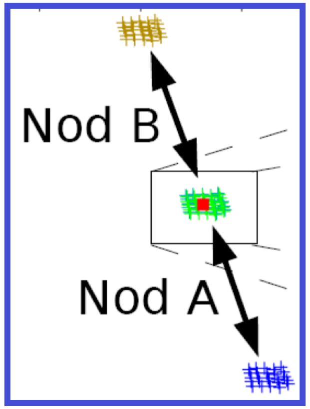
2. Raster mapping

Tiling (sub-Nyquist) or mosaicing (Nyquist)



Referencing

1. Chopping-nodding



3 chopping throws (1.5', 3', 6')

Best for faint lines

2. Un-chopped grating scan

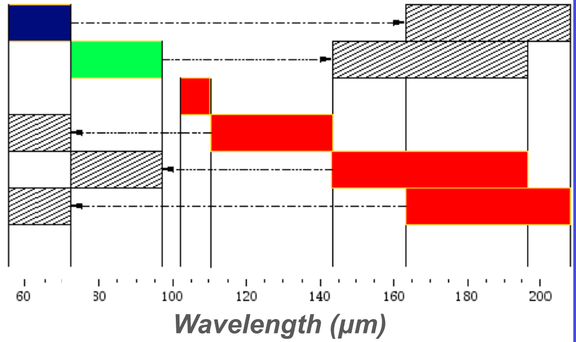
Best for extended objects

Best for bright lines

Uses an OFF position observed following a slew

Spectral coverage

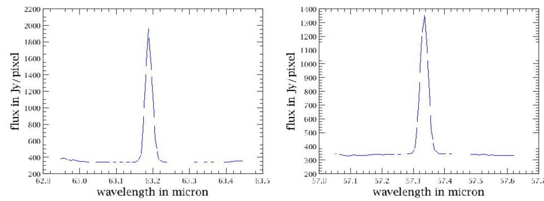
1. Range spectroscopy



Range scans or SED scans

Nyquist or high density sampling

2. Line spectroscopy

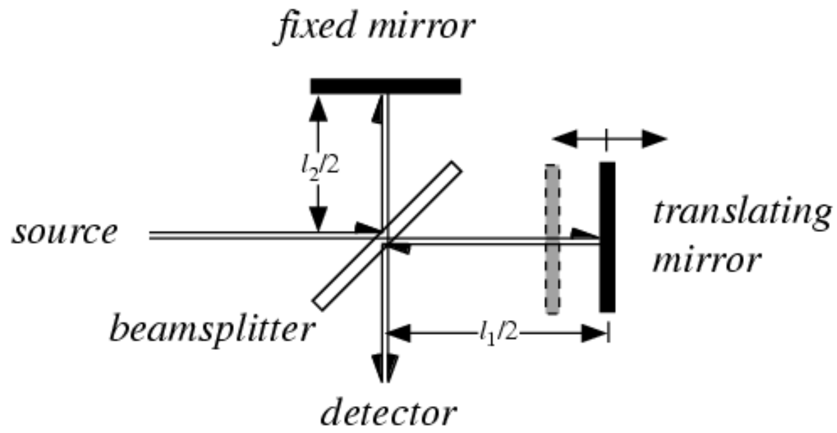


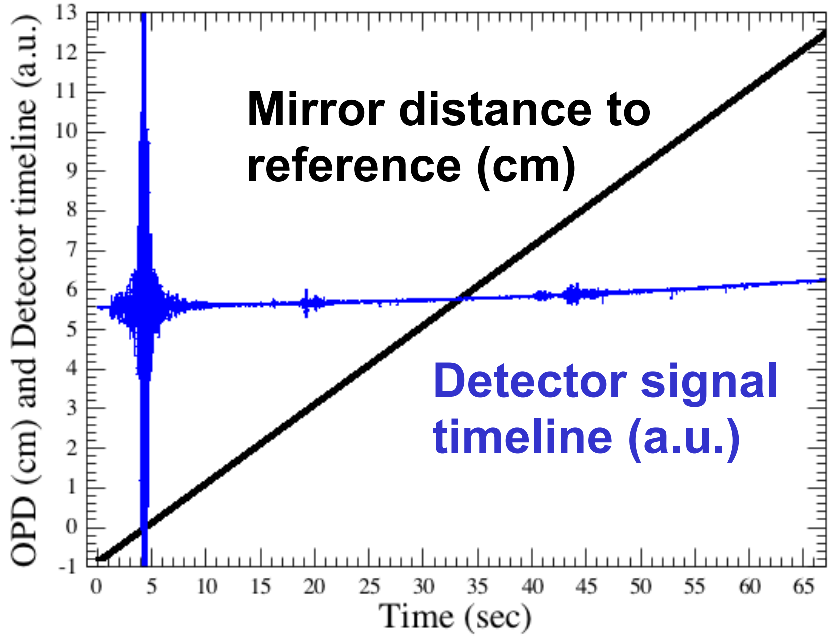
Special bright line mode

Two wavelength ranges possible: $1^{st}+2^{nd}$ orders, or $1^{st} + 3^{rd}$ orders

The SPIRE Spectrometer: concept (1)

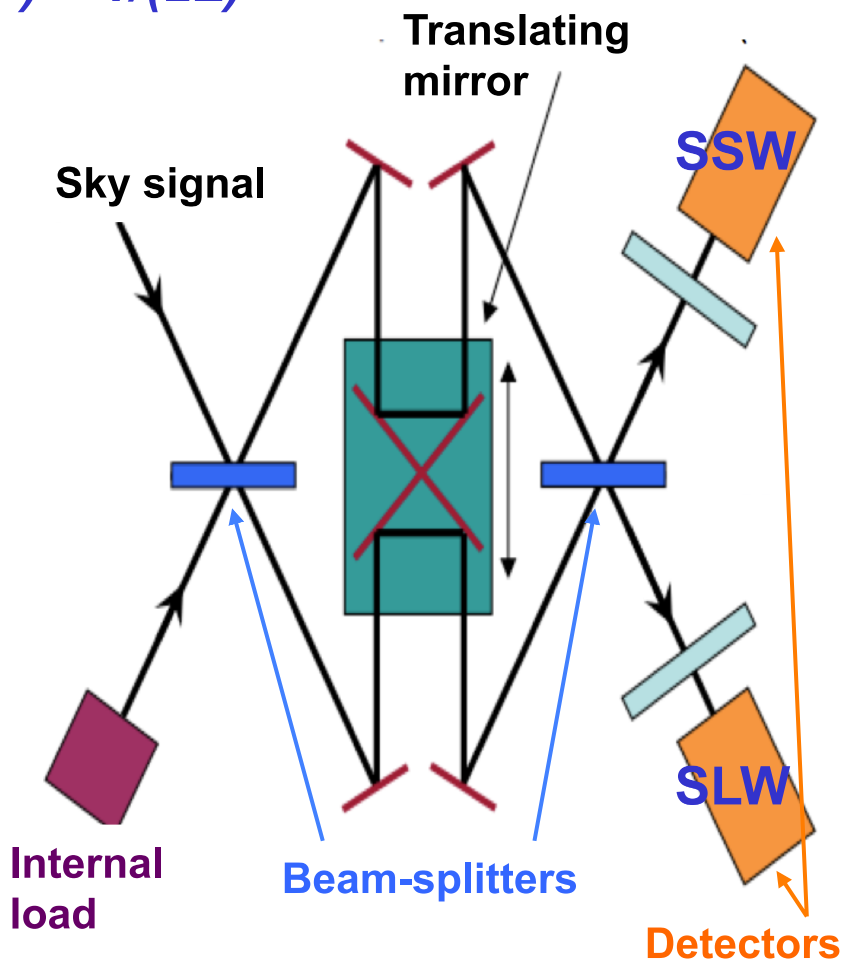
- The **SPIRE** spectrometer uses the principles of the ***Fourier Transform Spectroscopy***
- In an ***FTS***, a movable mirror creates a delay (i.e. a phase-shift) in part of the incoming signal
- When the phase-shifted signals are re-combined, they *interfere* with each other, transmitting certain wavelengths, whilst blocking others
- The series of signals collected at various (discrete) Optical Path Differences (***OPD***) forms an ***interferogram***, which is the Fourier transform of the signal spectrum





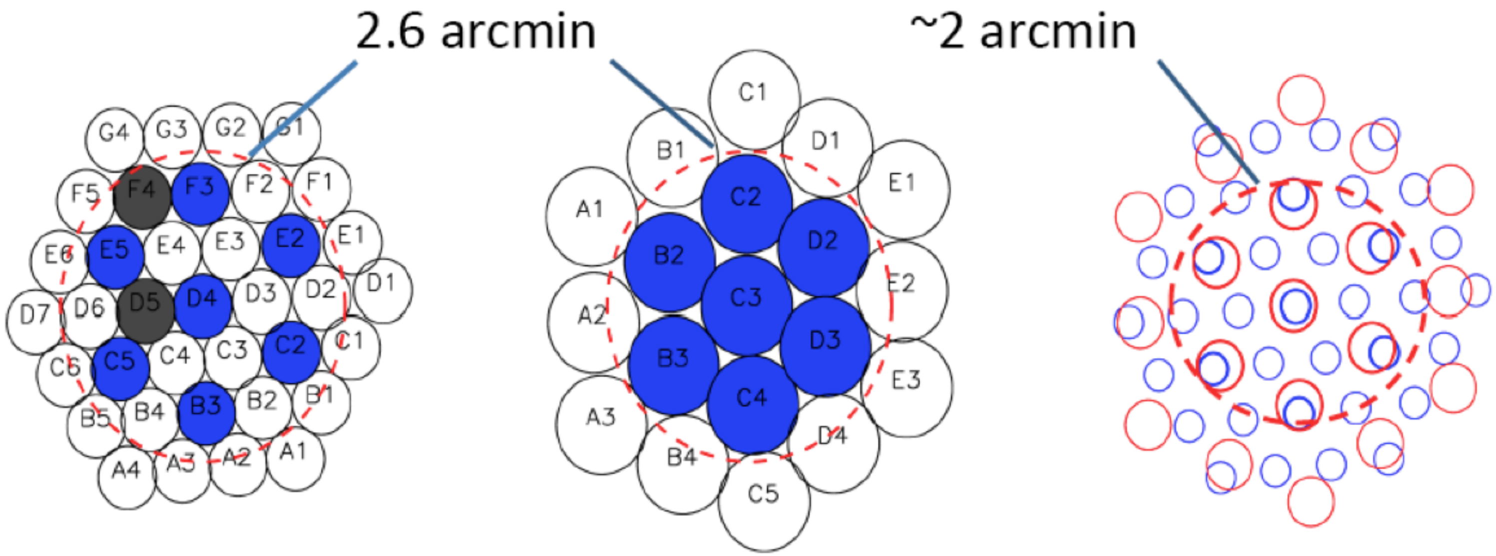
The SPIRE Spectrometer: concept (2)

- The ***spectral resolution*** of an FTS scales with the maximum OPD (L) achieved during a mirror scan: $\Delta\sigma\ (cm^{-1}) = 1/(2L)$
- In order to achieve long OPD within a compact configuration, the SPIRE-S uses a ***folded*** FTS design (so-called *Mach-Zehnder* configuration)
- This allows OPD 4x larger than the actual mirror displacement
- The maximum OPD achievable by SPIRE is ***12.8 cm*** ($\Delta\sigma$ = 0.04 cm-1, or 1.2 GHz), but lower resolution modes can be used by scanning over shorter OPD (more efficient since faster)



The SPIRE-S: characteristics

- The SPIRE-S offers *spectro-imager* capability onto a pair of bolometer detector arrays:
  - The ***SLW*** (at long wavelengths): 303-671 μm (*447-990 GHz*), *beam 29-42"*
  - The ***SSW*** (at short wavelengths): 194-313 μm (*960-1545 GHz*), *beam 17-21"*



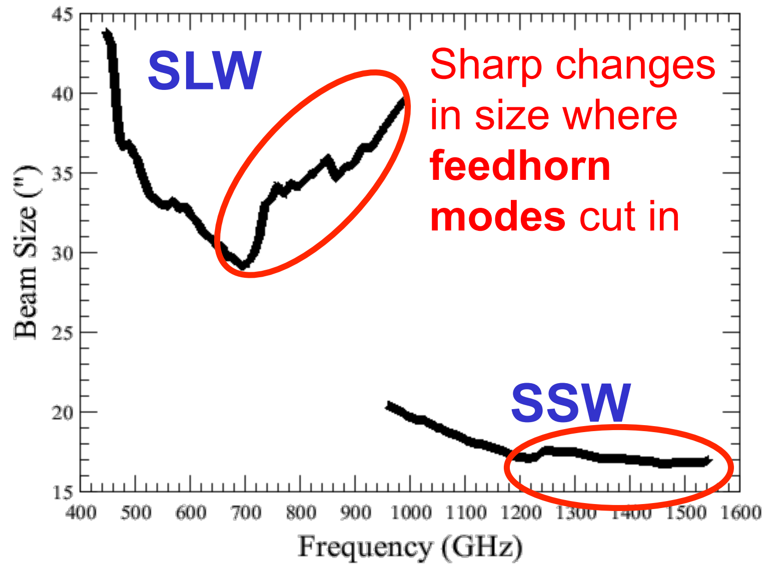
SSW (37 pixels) **SLW (19 pixels)** **Overlapping positions**

- Part of the pixels suffer from *vignetting* (due to their off-axis location), and are currently not properly calibratable

The SPIRE-S: characteristics (2)

Spatial response

- FTS beam size measured on Neptune
- Good approximation by 2-D Gaussian
- Not diffraction-limited over the whole range due to multi-mode feedhorns



FTS sensitivity: line and continuum

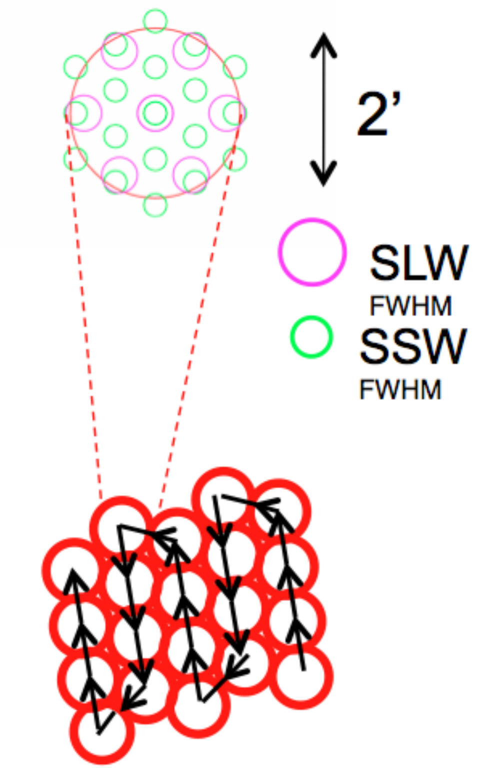
λ (μm)	Line (5σ, 1h, $Wm^{-2}x10^{-17}$)	Continuum (5σ, 1h, Jy)		
	HR	HR	MR	LR
194	2.15	1.79	0.28	0.083
214	1.56	1.30	0.22	0.063
282	1.56	1.30	0.22	0.063
313	2.04	1.70	0.28	0.082
392	0.94	0.77	0.13	0.037
671	2.94	2.20	0.37	0.106

The SPIRE-S: observing modes

ANY COMBINATION OF… with the addition of a dedicated BRIGHT source setting

Pointing modes

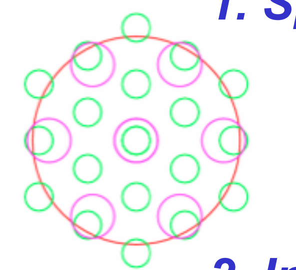
1. Single pointing



2. Raster pointing

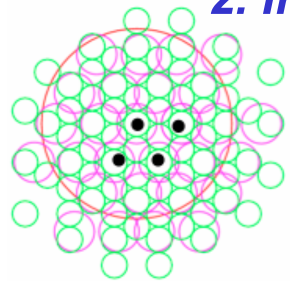
Image sampling

1. Sparse



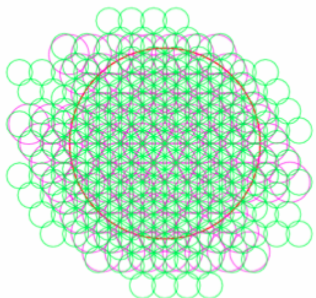
2 beam spacing

2. Intermediate



1 beam spacing (4 jiggle positions)

3. Full

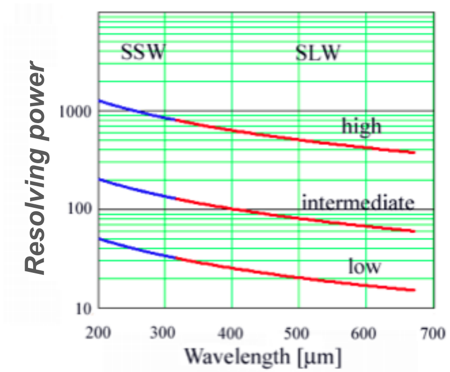


1/2 beam spacing

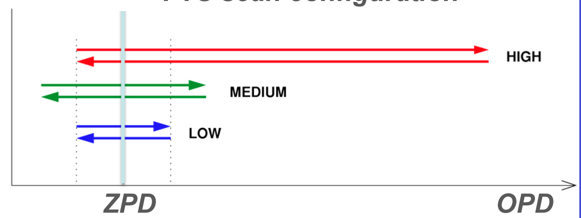
(16 jiggle positions)

Spectral resolution

1. *High (HR): 0.04 cm^{-1}*
2. *Medium (MR): 0.24 cm^{-1}*
3. *Low (LR): 0.83 cm^{-1}*
4. *HR+LR: 0.04/0.83 cm^{-1}*

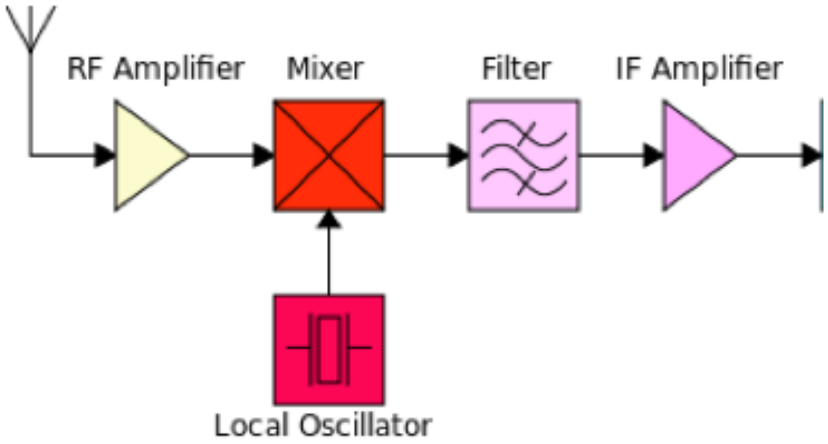


FTS scan configuration



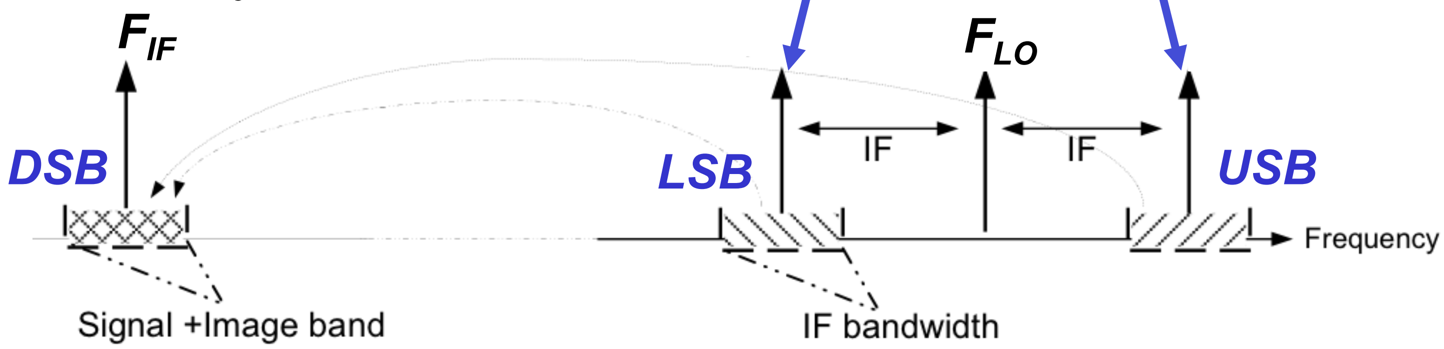
The HIFI Spectrometer: concept (1)

- The **HIFI** instrument uses the principles of the ***super-heterodyne*** detection
- In such a system, the sky signal (***RF***) is combined to that of a synthetic source (the ***Local Oscillator – LO***) tuned to a very nearby frequency, in a non-linear electronic device (the ***mixer)***
- The mixing of the two signals creates a *beat* of the two frequencies, that pulses at a much lower frequency (the ***Intermediate Frequency*** – ***IF***), but holds the amplitude and phase of the original signal (*coherent detection*)
- This operation is called *down-conversion*, and is used in numerous domestic devices (radio, TV, etc)



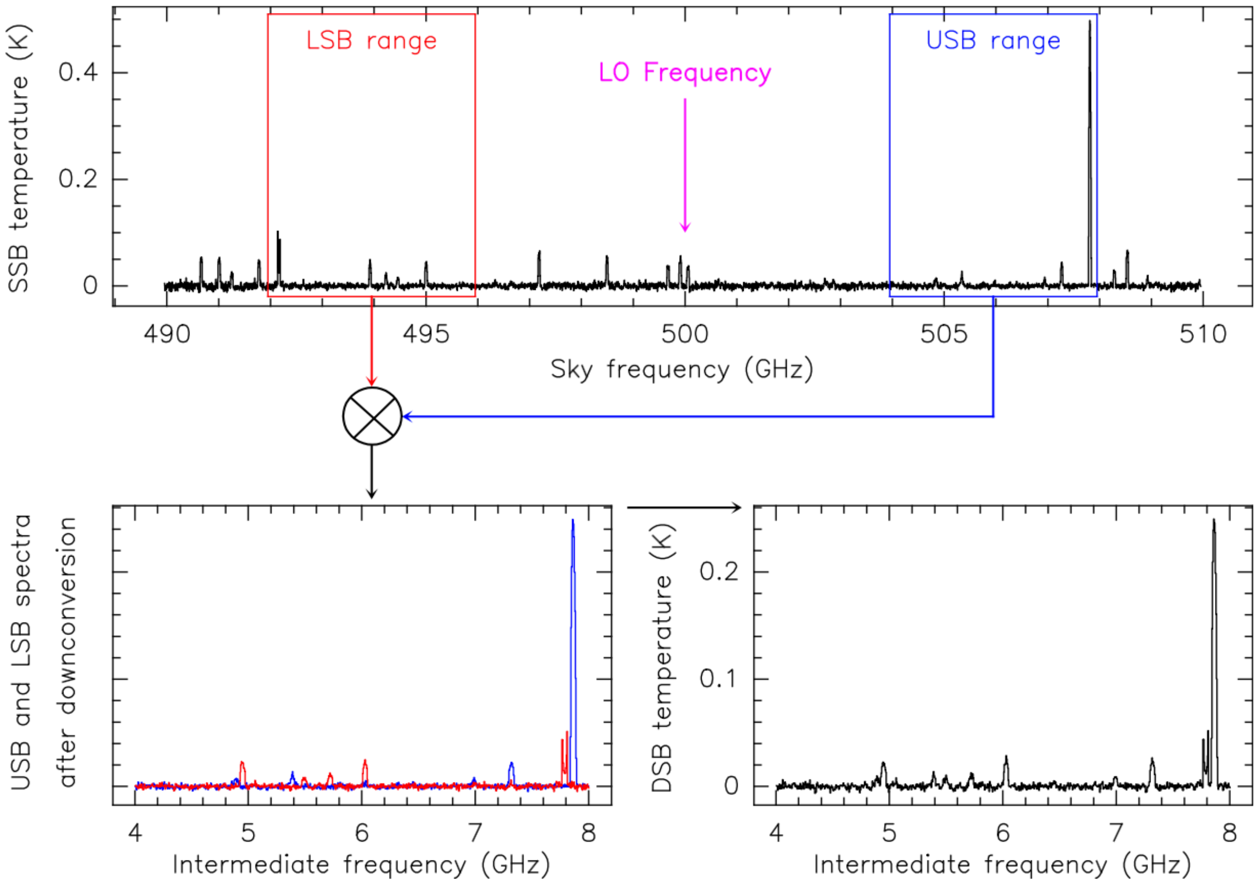
The HIFI Spectrometer: concept (2)

- Intrinsically, the sky frequency domain down-converted from ***RF*** to ***IF*** is not unique: two spectral ranges at [F_{LO}-F_{IF}] and [F_{LO}+F_{IF}] are covered simultaneously



- The two ranges are called the *Lower Side-Band* (***LSB***) and the *Upper Side-band* (***USB***) and the information they contain are folded onto each others, merged into what is called a *Double-Side-Band* (***DSB***) spectrum. *Single-Side Band* systems can be designed by *rejecting* one side-band
- The spectral resolution is ultimately limited by the ***LO*** stability, but in practice it is defined by the spectrometer (*backend*) used to sample the signal at the IF. It can be as high as $R \sim 10^7$ (λ/Δλ)
- The backend also sets the instantaneous spectral coverage

Heterodyne mixing on HIFI spectrum



HIFI: characteristics(1)

- ***Single pixel*** on the sky, in ***two polarizations***
- **7 mixer** bands (**14 LO** sub-bands) covering the ***480-1270 GHz*** (236-625 μm) and ***1430-1910 GHz*** (157-210 μm) ranges

F_{LO} (GHz)

480 640 800 960 1120 1270 // 1430 1700 1910

Band 1	*Band 2*	*Band 3*	*Band 4*	*Band 5*	*Band 6*	*Band 7*

SIS mixers

IF bandwidth: 4 GHz
Beam: 17" – 44"

HEB mixers

IF bandwidth: 2.4 GHz
Beam: 11" – 15"

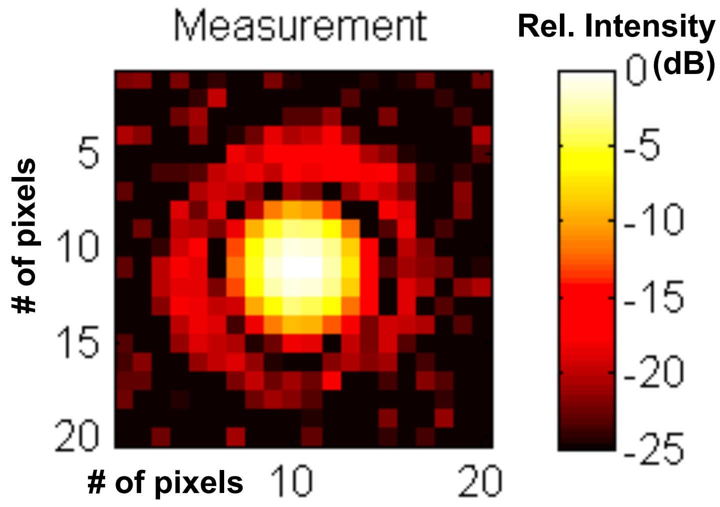
- *Two types of **spectrometers**, available simultaneously*

Wide- Band Spectrometer (WBS)	***High-Resolution Spectrometer (HRS)***
Covers the whole IF (2.4 or 4 GHz) ***Spectral resol.: 1.1 MHz (0.2–0.8 km/s)***	***Variable spectral resol.: 0.125, 0.25, 0.5 and 1 MHz (0.02–0.8 km/s)*** ***IF coverage from 0.25 to 2 GHz***

HIFI: characteristics(2)

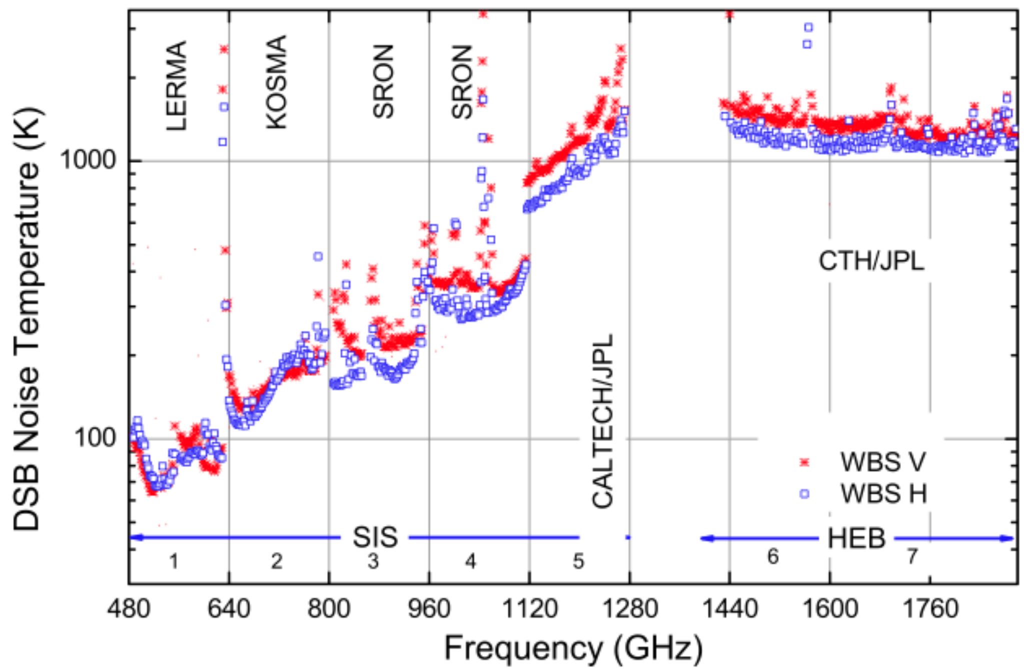
Spatial response

- HIFI beam size measured on Mars
- Good approximation by 2-D Gaussian, secondary side-lobes ~ -18 dB
- Diffraction-limited over the whole range



HIFI sensitivity

- Measured in units of *System noise Temperature* (***T***$_{sys}$)
- Near-quantum noise limit sensitivity
- Sporadic narrow ranges of degraded or null sensitivity (high T_{sys})

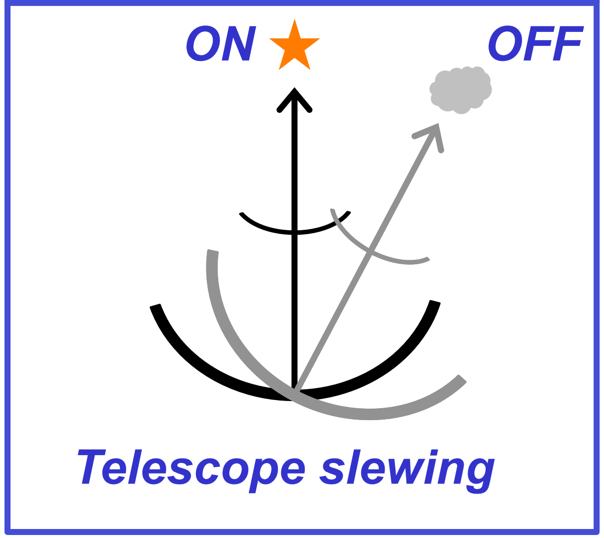


HIFI: observing modes (1)

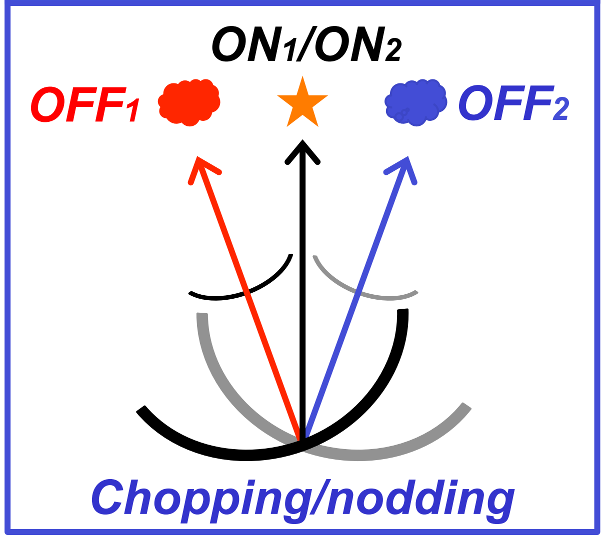
Referencing scheme	AOT I Single Point Observations	AOT II Mapping Observations	AOT III Spectral Scan
1 – Position Switch	Mode I – 1 Point-PositionSwitch	Mode II – 1 OTF	
2 – Dual Beam Switch ***Optional continuum optimisation***	Mode I – 2 DBS FastChop-DBS	Mode II – 2 DBS-Raster FastChop-DBS-Raster DBS-Cross FastChop-DBS-Cross	Mode III – 2 SScan-DBS SScan-FastChop-DBS
3 – Frequency Switch ***Optional sky ref measurement***	Mode I – 3 FSwitch FSwitch-NoReference	Mode II – 3 OTF-FSwitch OTF-FSwitch-NoReference	Mode III – 3 SScan-FSwitch SScan-FSwitch-NoReference
4 – Load Chop ***Optional sky ref measurement***	Mode I – 4 LoadChop LoadChop-NoReference	Mode II– 4 OTF-LoadChop OTF-LoadChop-NoReference	Mode III– 4 SScan-LoadChop SScan-LoadChop-NoReference

HIFI: observing modes (2)

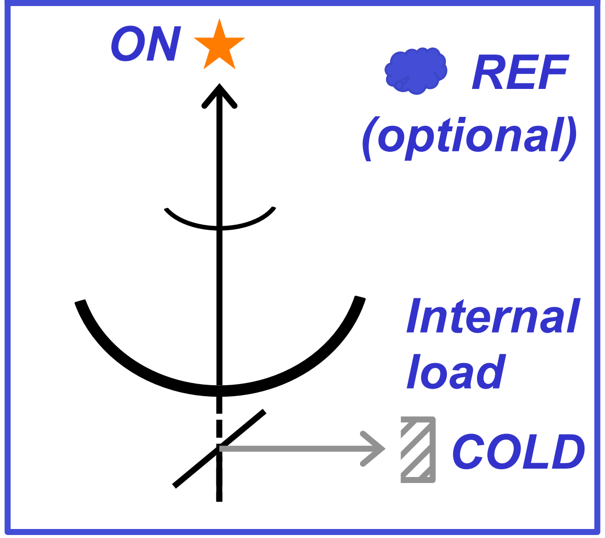
Position Switch



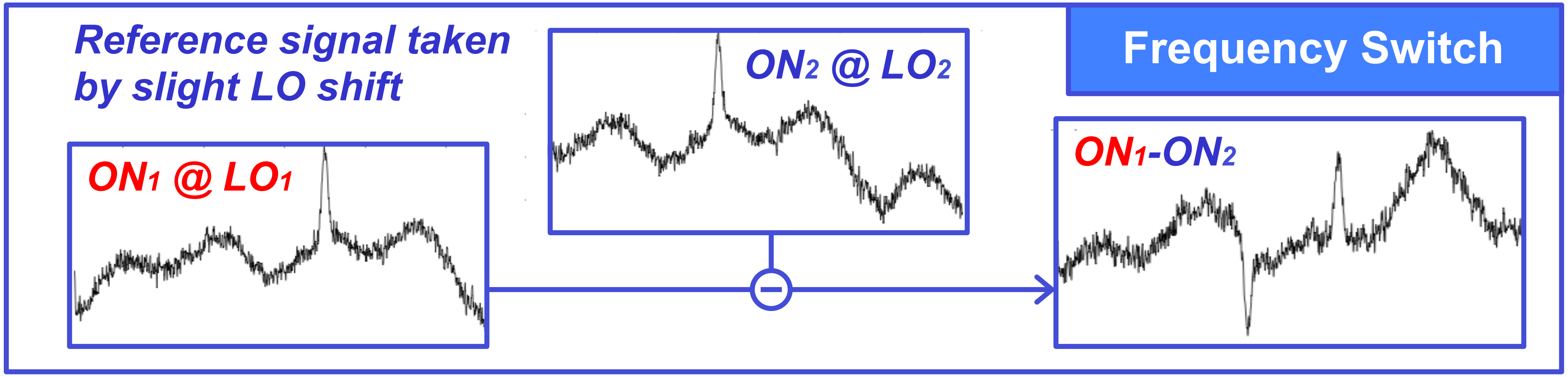
Double Beam Switch



Load Chop

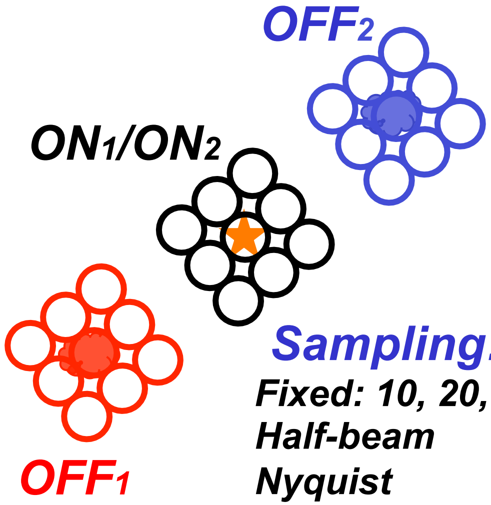


Frequency Switch



HIFI: observing modes (3)

DBS raster map



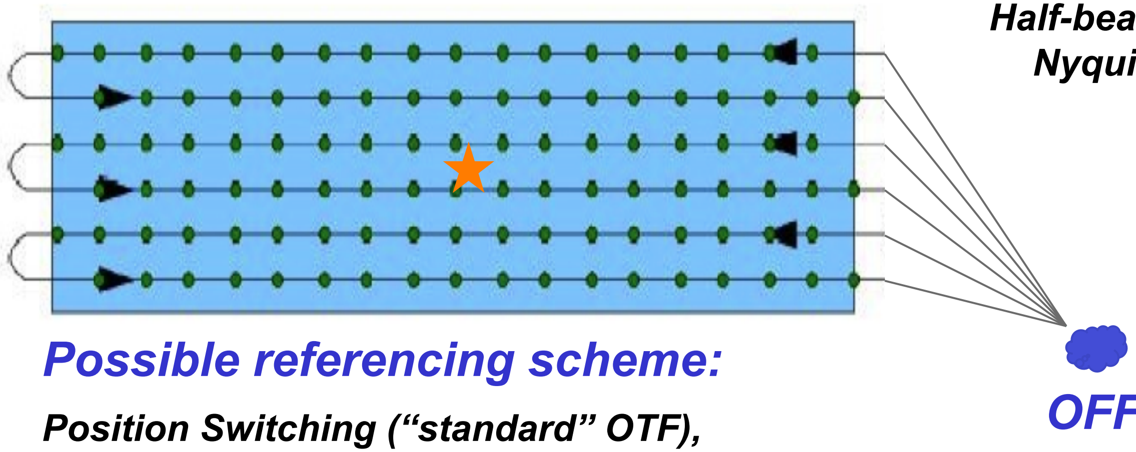
Sampling:

Fixed: 10, 20, 40"
Half-beam
Nyquist

On-the-fly Mapping

Sampling:

Fixed: 10, 20, 40"
Half-beam
Nyquist



Possible referencing scheme:

Position Switching ("standard" OTF),
Load-Chop, Frequency Switch (Sky REF optional)

Spectral Scan

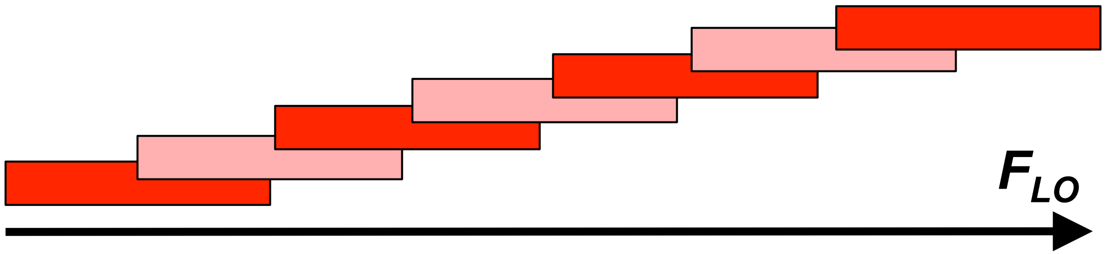
<u>WBS (and HRS) stepped in overlapping chunks of 2.4-4 GHz</u>

Possible referencing scheme:

Dual Beam Switching, Load-Chop,
Frequency Switch (Sky REF optional)

Full or partial band coverage

Redundancy 2 to 12



The Herschel spectrometers: coverage

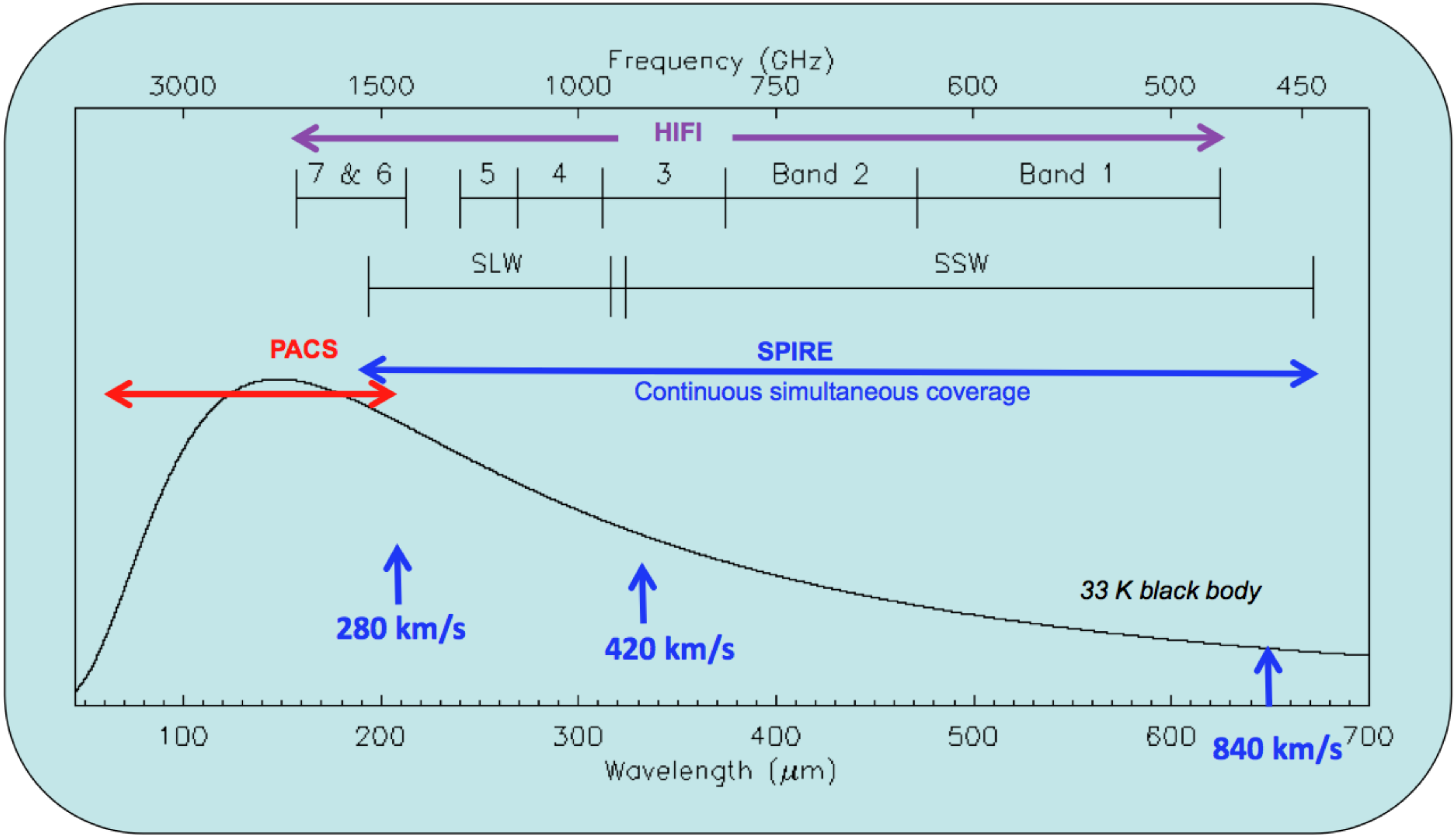


Image credit: C. Pearson (SPIRE ICC)