Data Reduction IV:
Herschel spectroscopy

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European Space Agency

What I will not cover

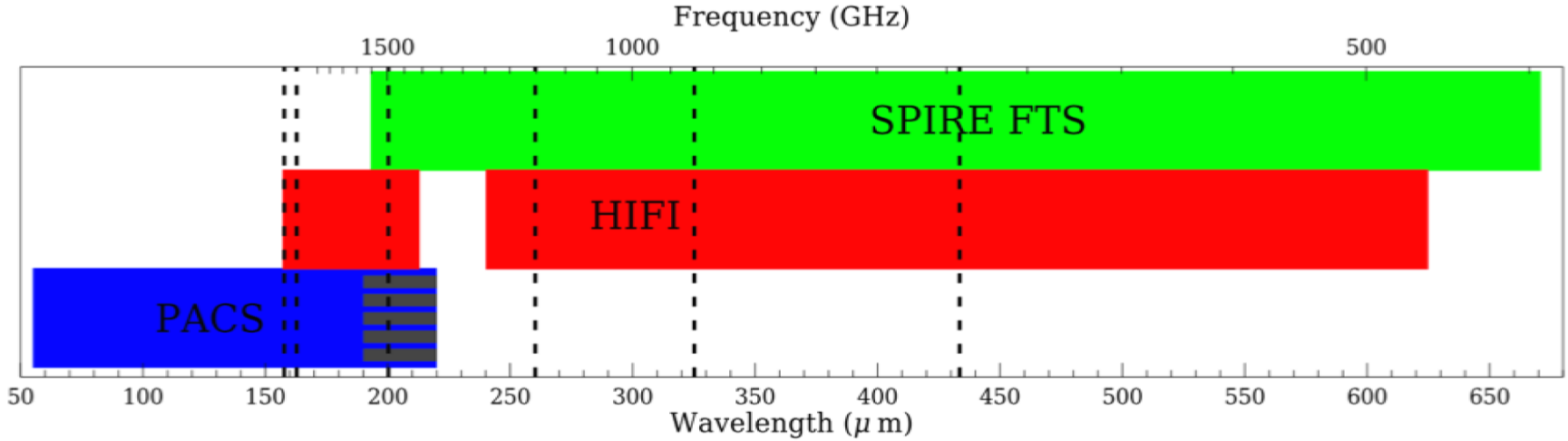
- Instruments/hardware
- Instrument pipelines

Read the Manuals!

Herschel spectrometers

- **HIFI:** Heterodyne Instrument For Infrared
  - single pixel heterodyne spectroscopy in 7 bands, dual polarisation: **157-212 & 240-625 µm,** LO sub-bands ➔ 14 bands
  - Resolving power: up to **10^7**
- **PACS:** Photodetector Array Camera and Spectrometer
  - Grating spectroscopy: **55-201 µm**
  - Integral Field Unit
  - Resolving power: 1000-4000
- **SPIRE:** Spectral and Photometric Imaging Receiver
  - Fourier-Transform Spectrometer, two overlapping bands: **191-318 µm** and **294-671 µm**
  - Hexagonal sparse bolometer array
  - Resolving power: 400-1000

Herschel spectrometers: coverage



The Herschel spectrometers: coverage

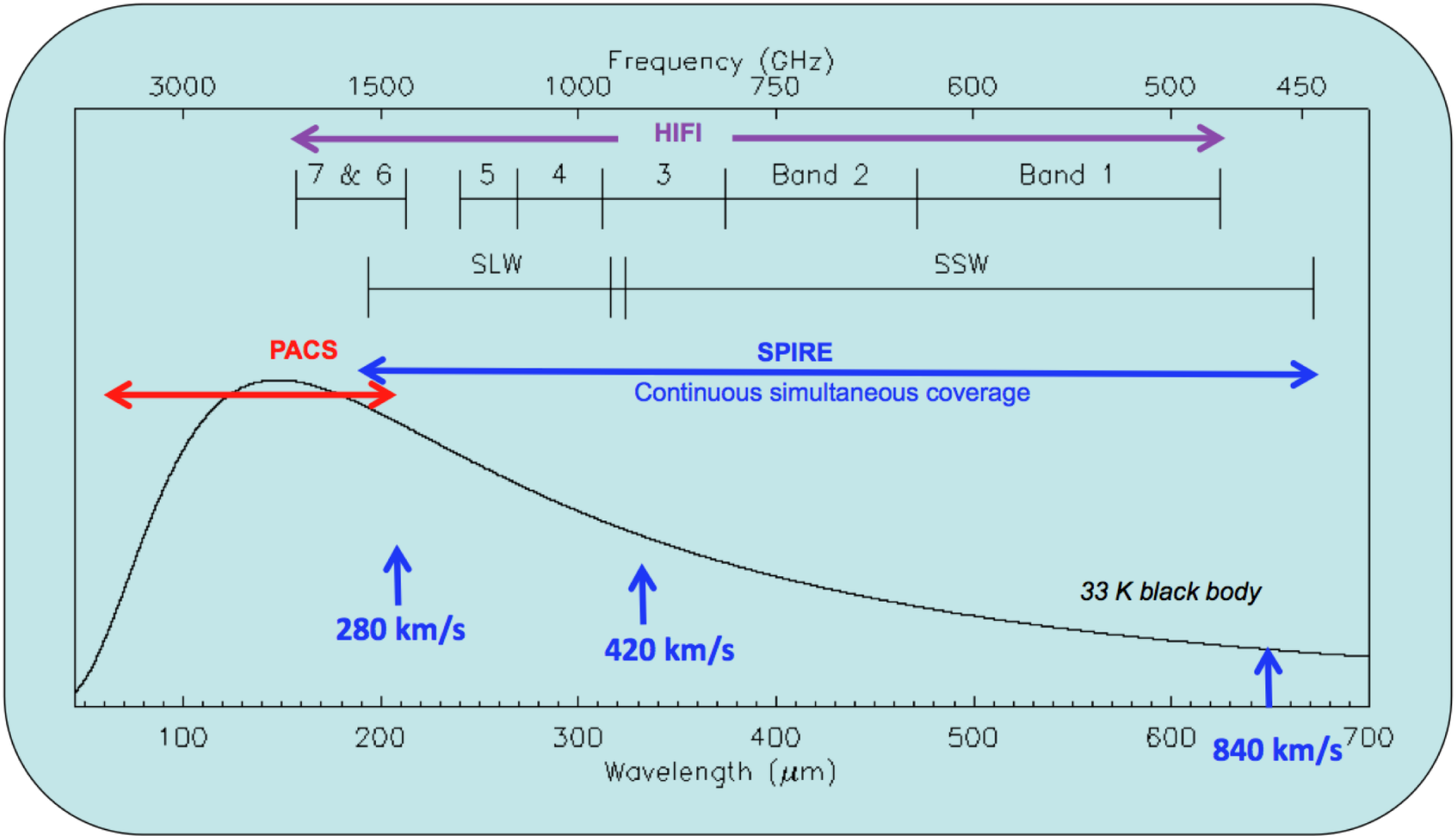
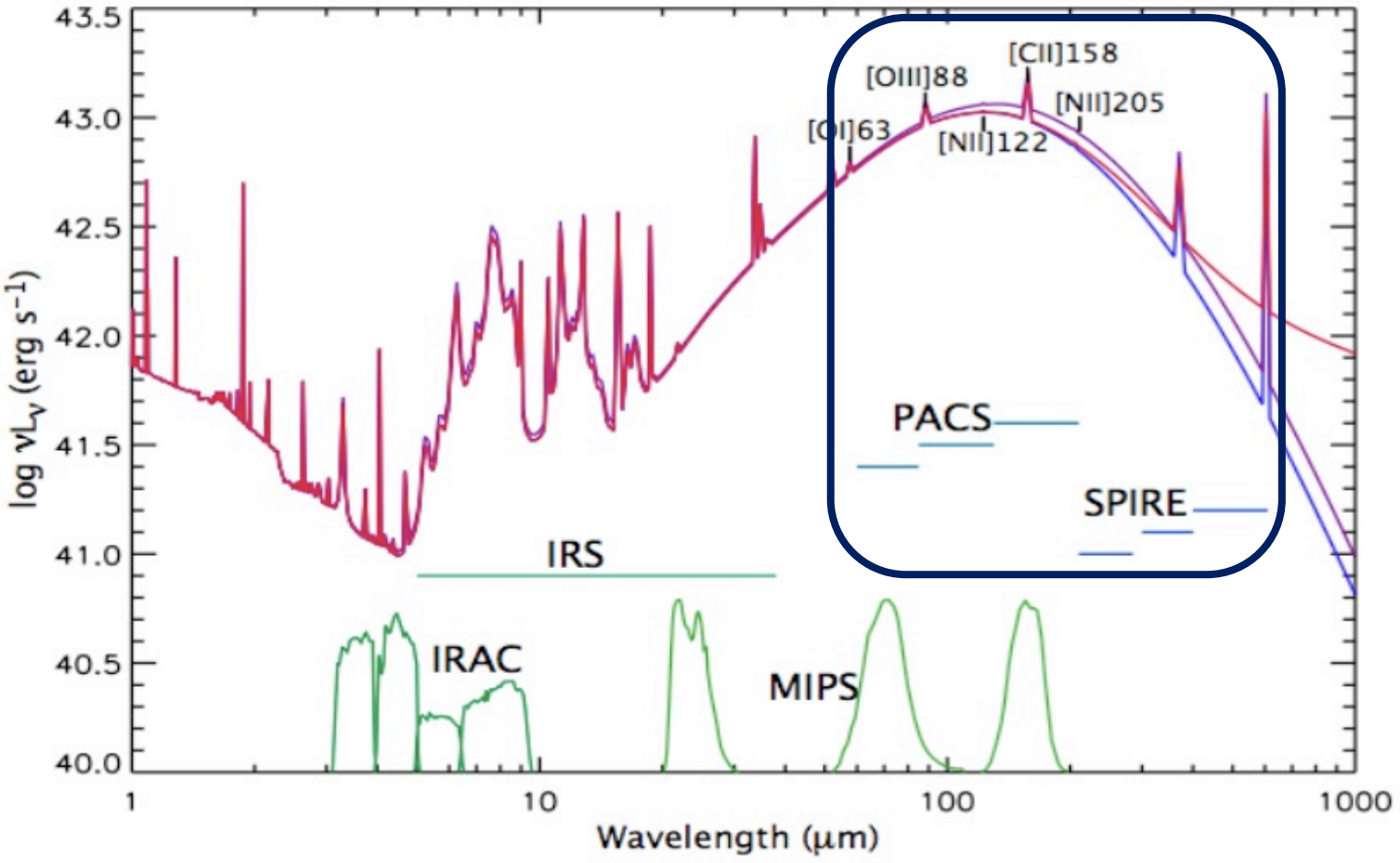


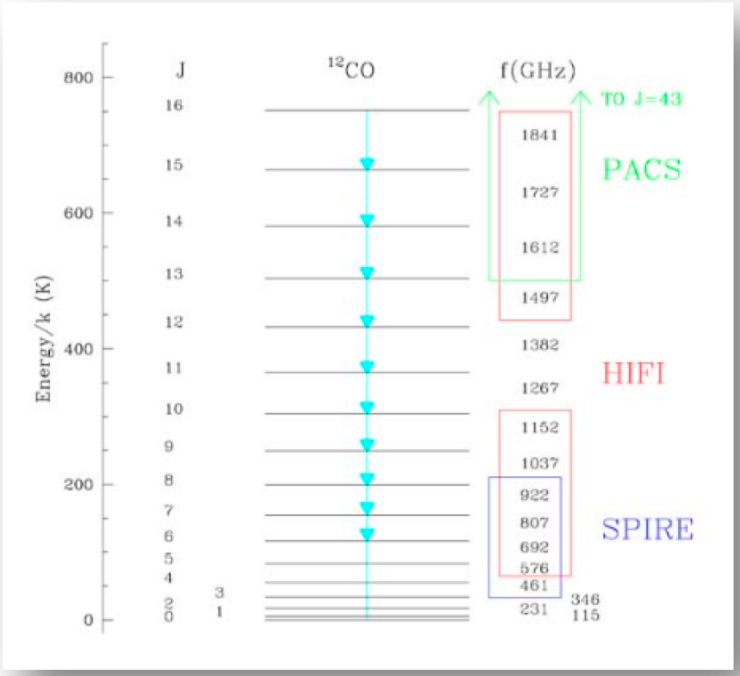
Image credit: C. Pearson (SPIRE ICC)

Spectroscopy for Herschel

- Many important atomic and molecular lines are in [55,700] μm.

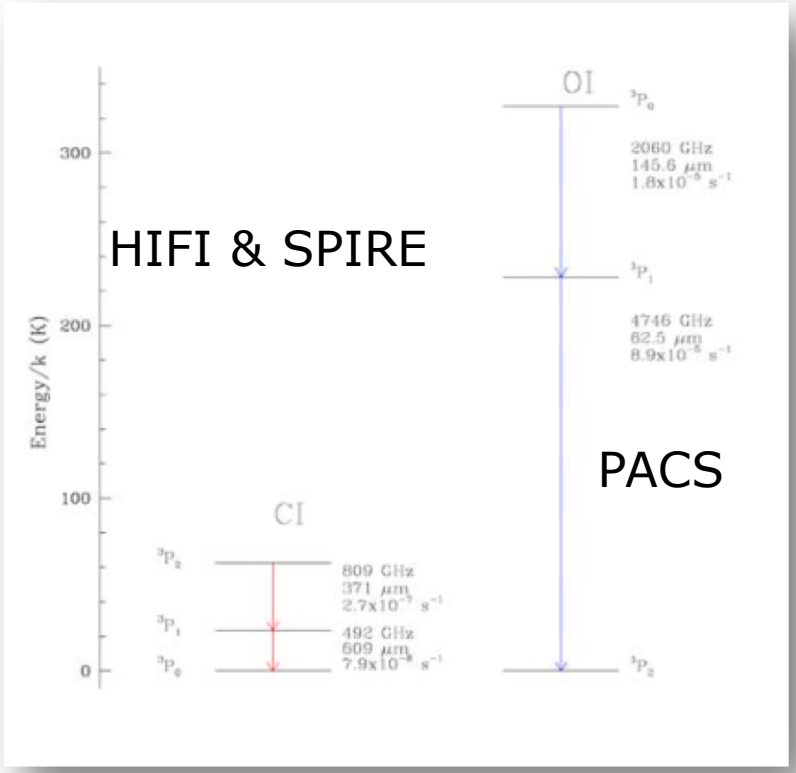


Spectroscopy with Herschel



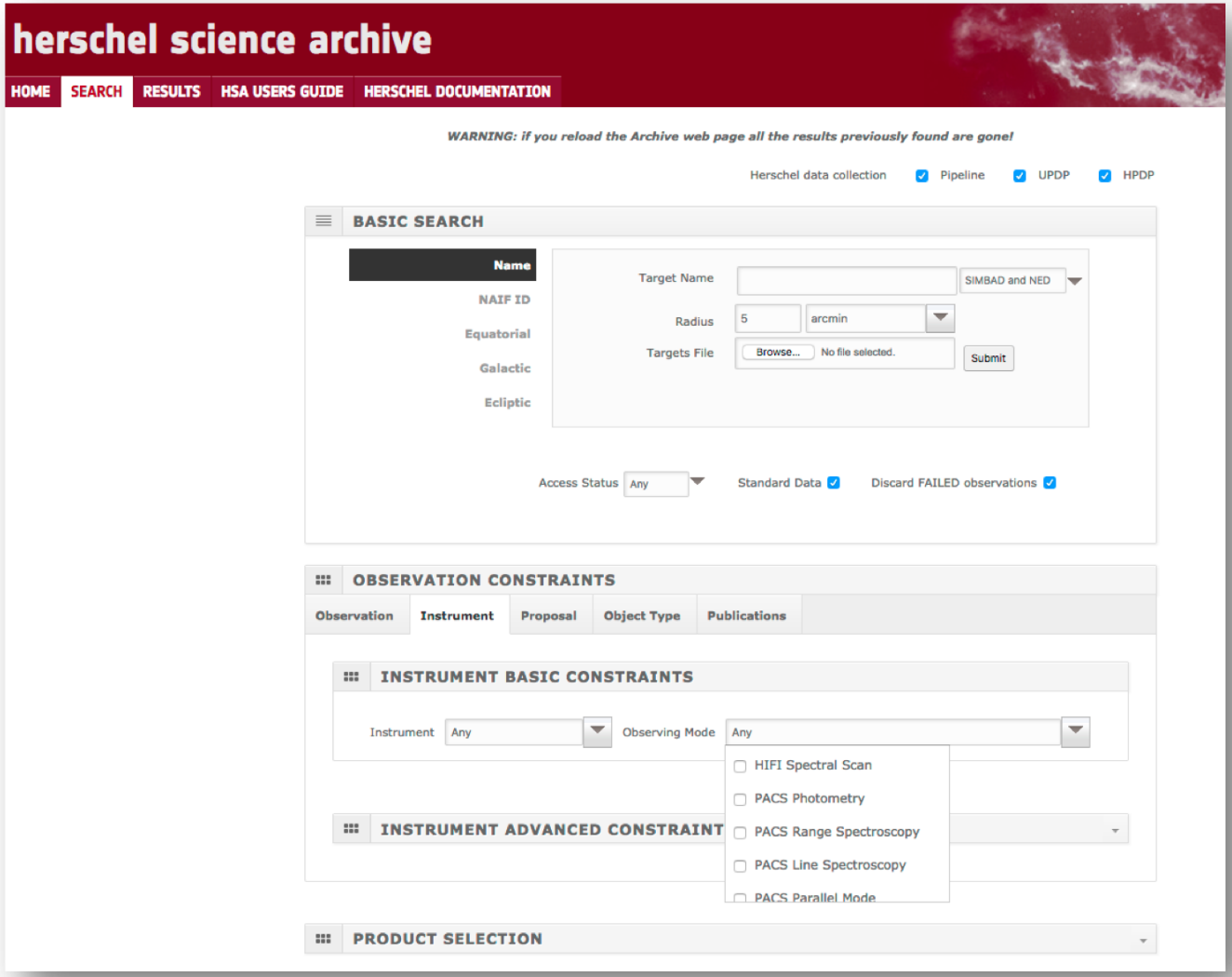
^{12}CO

[OI] and [CI]



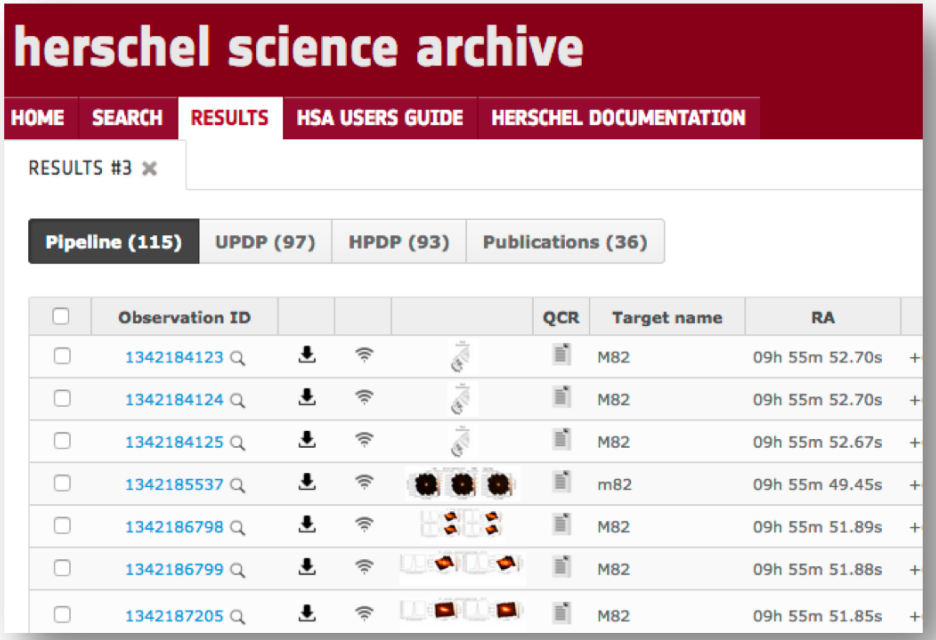
Goldsmith (2007)

Spectroscopy observations in HSA



Products in the Herschel Science Archive

1. Most **pipeline** products in the HSA are science ready
2. Some expert processed products are provided too: the so called Highly Processed Data Products (**HPDP**)
    a. Compared to the SPG: these are alternative or better products
    b. Always check the HPDPs and read the release notes for valuable information.
3. User Provided Data Products (**UPDP**)
    a. Careful! Read the release note.
4. Ancillary Data Products (**ADP**): not linked to any particular observation but of some use, e.g. Planetary, asteroid and stellar models, PSF maps, filter profiles etc.



Currently available HPDP/UPDP/ADP

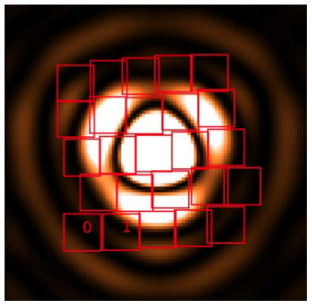
Observing modes

The PACS-S: observing modes

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

Pointing modes

1. Single pointing

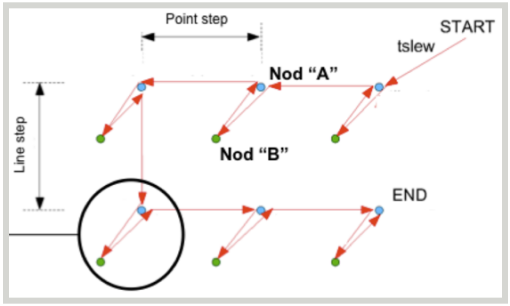


Snapshot observation

Under-sampled

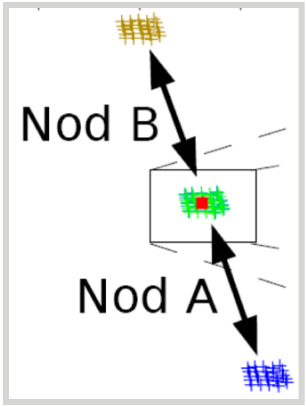
2. Raster mapping

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

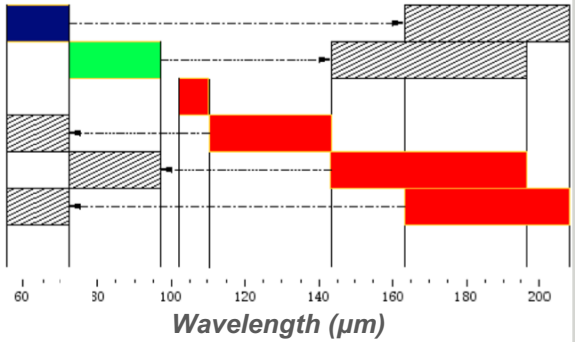
Best for extended objects

Best for bright lines

Uses an OFF position observed following a slew

Spectral coverage

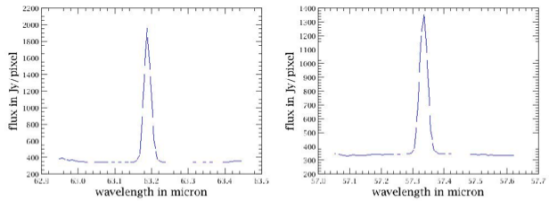
1. Range spectroscopy



Range scans or SED scans

Nyquist or high density sampling

2. Line spectroscopy



Special bright line mode

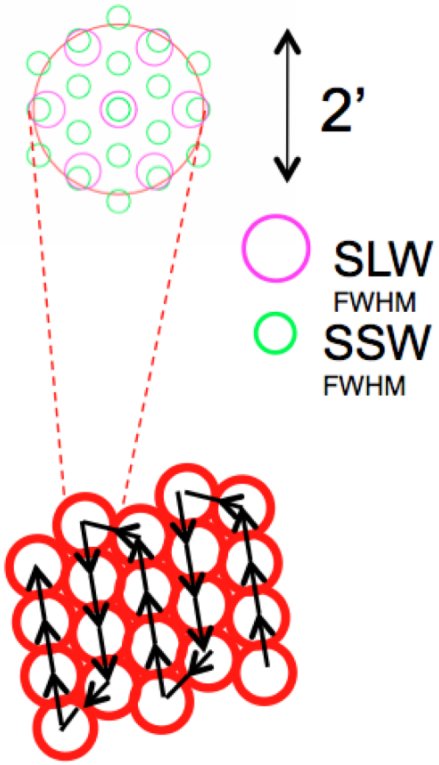
Two wavelength ranges possible: 1st+2nd orders, or 1st + 3rd orders

The SPIRE-S: observing modes

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

Pointing modes

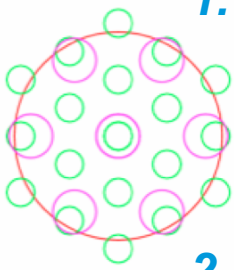
1. Single pointing



2. Raster pointing

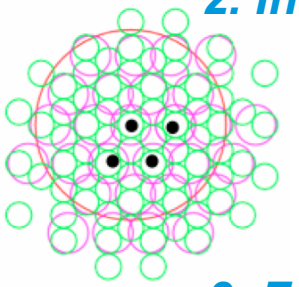
Image sampling

1. Sparse



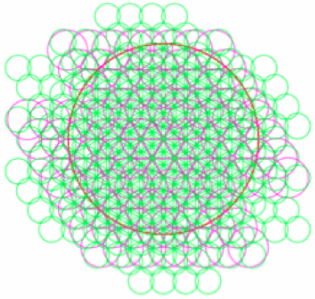
2 beam spacing

2. Intermediate



1 beam spacing (4 jiggle positions)

3. Full

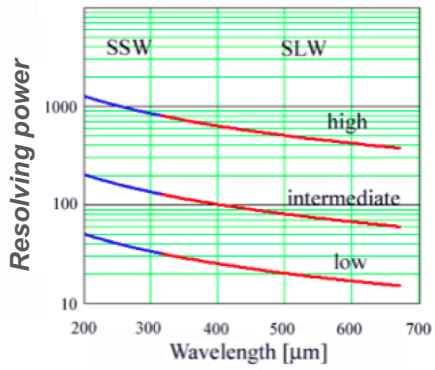


1/2 beam spacing

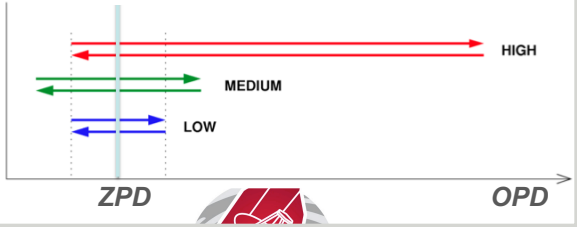
(16 jiggle positions)

Spectral resolution

1. *High (HR): 1.2 GHz*
2. *Medium (MR): 7 GHz*
3. *Low (LR): 25 GHz*
4. *HR+LR:*



FTS scan configuration



HIFI: observing modes (1)

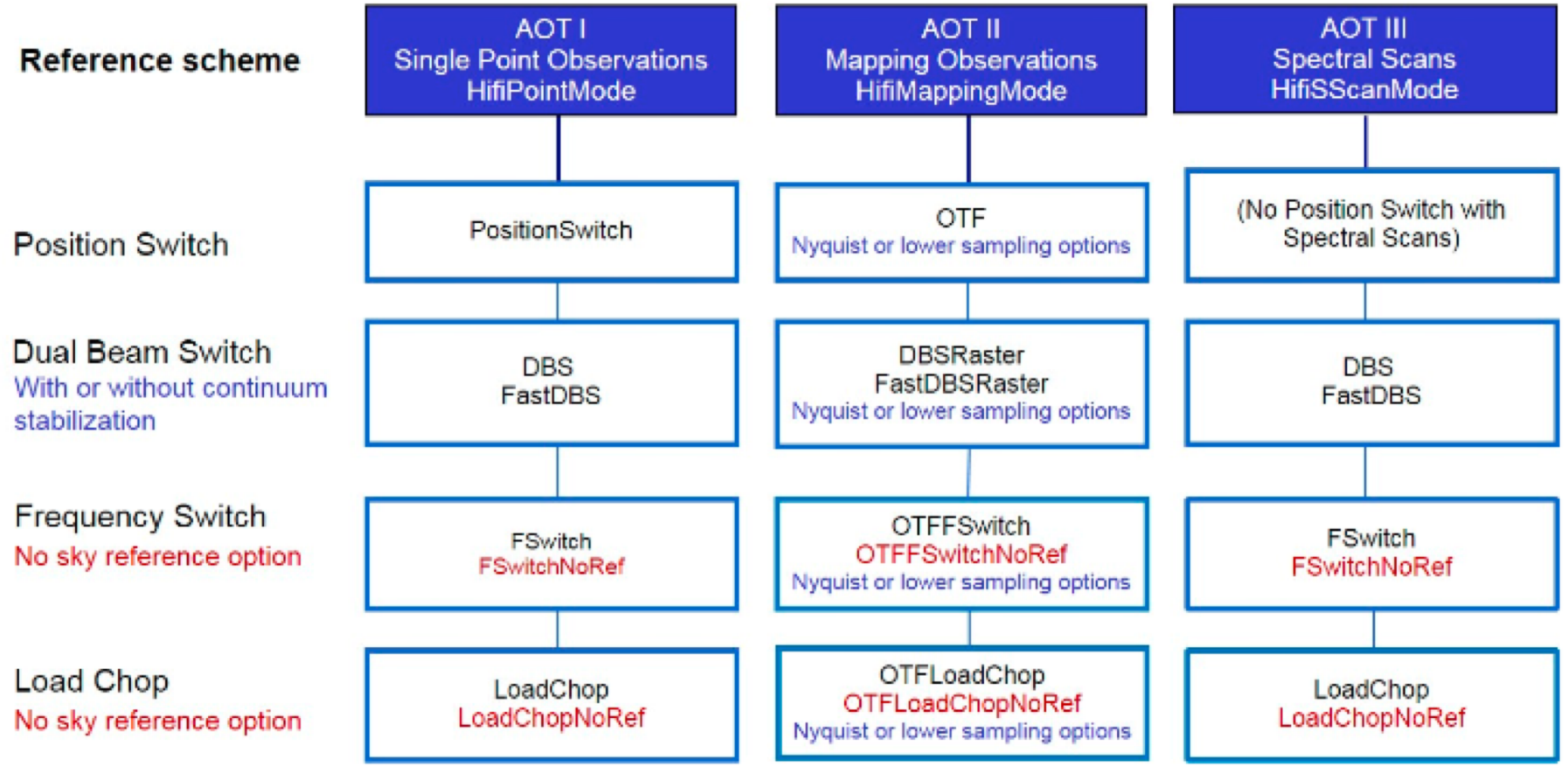
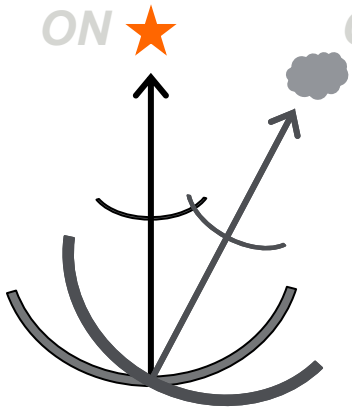


Figure 2: Overview of available AOT Observing Modes for HIFI.

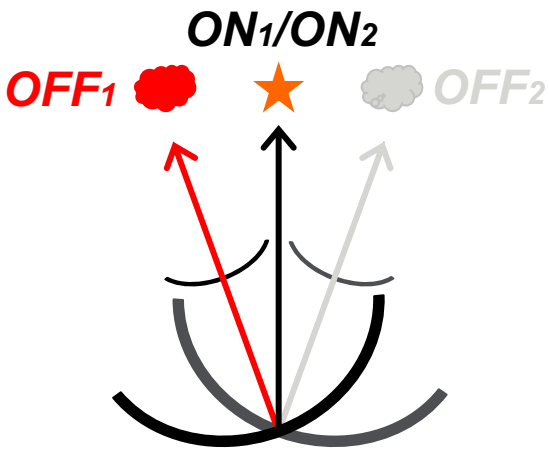
HIFI: observing modes (2)

Position Switch



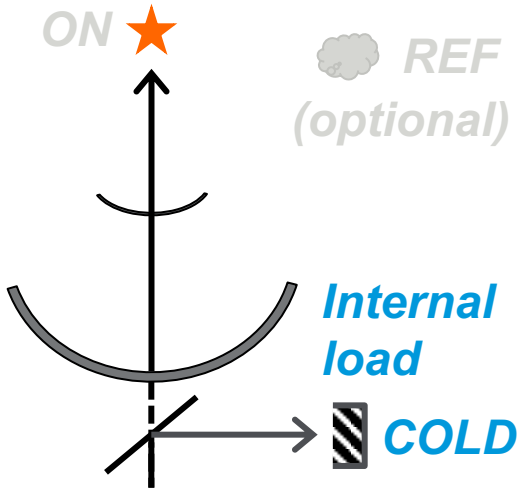
Telescope slewing

Double Beam Switch

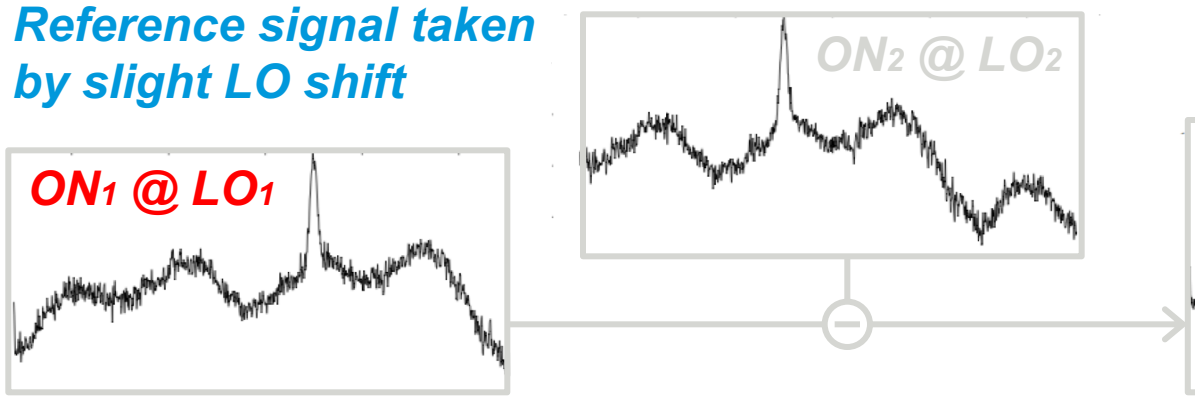


Chopping/nodding

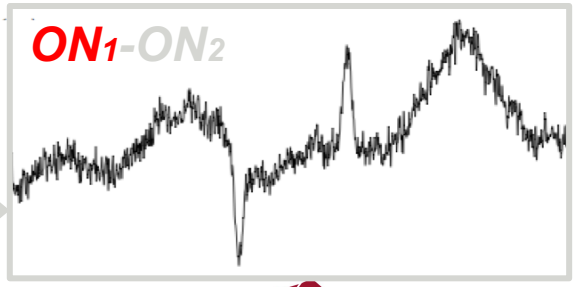
Load Chop



Reference signal taken by slight LO shift

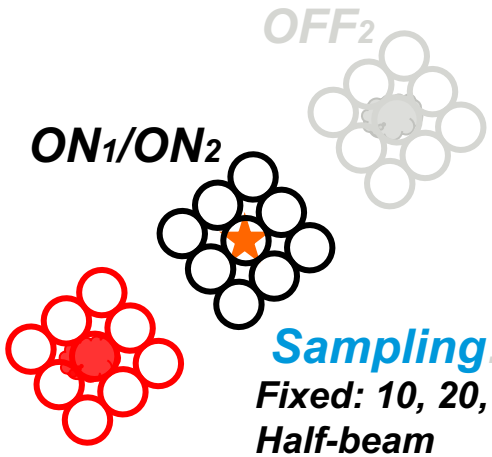


Frequency Switch



HIFI: observing modes (3)

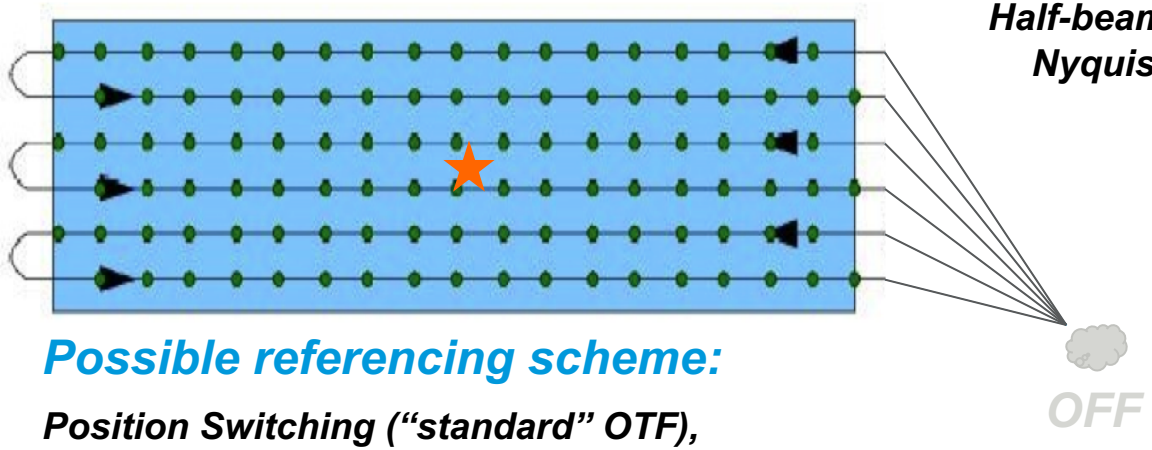
DBS raster map



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

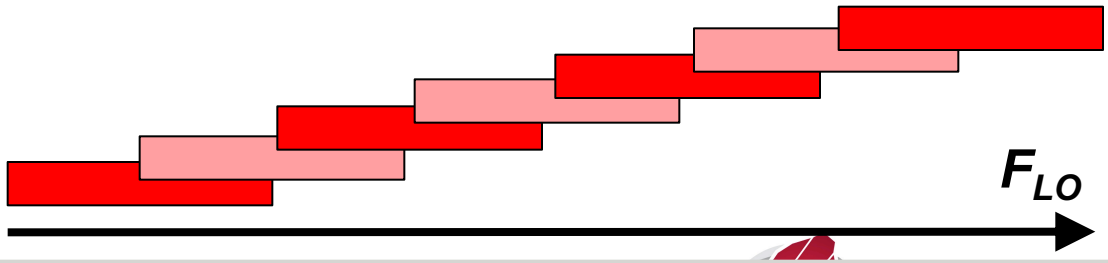
WBS (and HRS) stepped in overlapping chunks of 2.4-4 GHz

Possible referencing scheme:

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

Full or partial band coverage

Redundancy 2 to 12



HIFI observing modes in HSA

Mode	count
HifiPointModeDBS	3154
HifiPointModeFastDBS	2788
HifiPointModeLoadChop	968
HifiMappingModeOTF	504
HifiMappingModeLoadChopOTF	414
HifiPointModePositionSwitch	378
HifiMappingModeFastDBSRaster	368
HifiSScanModeDBS	296
HifiPointModeFSwitchNoRef	179
HifiSScanModeFastDBS	144
HifiPointModeFSwitch	107
HifiMappingModeDBSRaster	54
HifiSScanModeLoadChop	41
HifiMappingModeFastDBSCross	20
HifiMappingModeFSwitchOTF	14
HifiSScanModeFSwitch	13
HifiPointModeLoadChopNoRef	10
HifiMappingModeLoadChopOTFNoRef	6
HifiMappingModeDBSCross	4
HifiSScanModeFSwitchNoRef	2
HifiSScanModeLoadChopNoRef	2

Total: 9466 HIFI obs

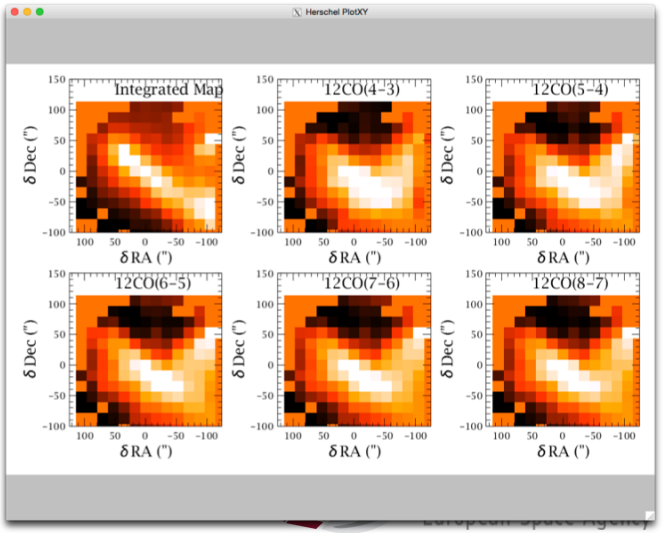
Unique obs modes: 21

Spectroscopy data analysis

- Measuring lines and/or continuum of individual sources
  - Radial velocity
  - Physical characteristics of the emitting region ← astro-chemistry
- Measuring lines and continuum over extended region: spectral cubes
  - Velocity structure of the region
  - Spatial distribution of lines ➔ morphology, temperature/density distribution, etc.
- Pre-requisite: the starting data sets are of high science quality

Tools: HIPE, Gildas, CASSIS, CASA, etc.

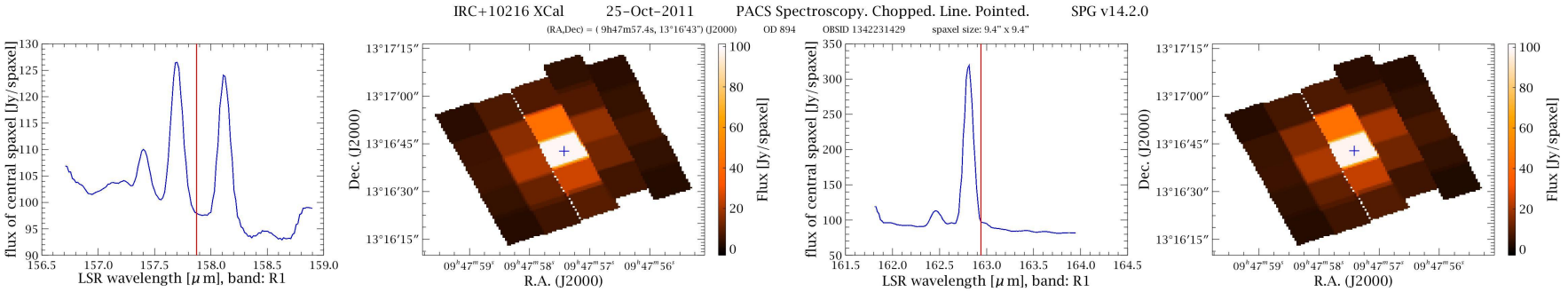
Some may need adapting the Herschel FITS files.



Examples

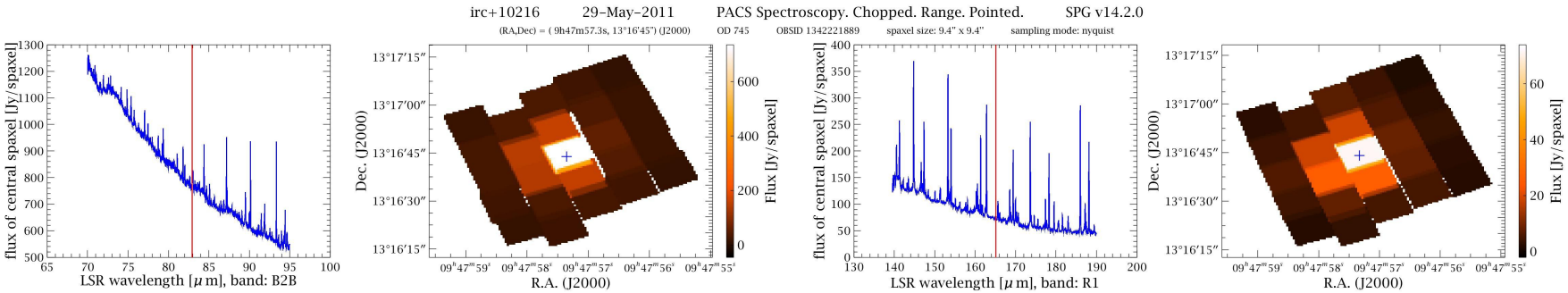
Examples of input data

PACS **line** spectroscopy ➔ IFU cube



Examples of input data: PACS

PACS **range** spectroscopy ➔ IFU cube



PACS spectroscopy considerations

- Cubes are extended source calibrated
- Pointed and tiled cubes undersample the PSF
- Instrumental line shape: ~Gaussian
- Poorly calibrated (>195 μm) or uncalibrated ranges (<55 μm)
    - Available data as HPDP

- A set of different spectral cubes are provided, depending on the obsMode
    - Rebinned cube, 5x5 with 9.4” pixels
    - Projected cube
    - Interpolated cube
    - Equidistant cube
    - Drizzled cube

PACS spectroscopy products in HSA

Folder	Sub-folder	Filename pattern	Description *AOT*
Level 2	HPS3D[B|R]/herschel.pacs.signal.PacsCube	hpacs<OBSID>_20hps3d[b|r]s_<##>_<NNN>	earliest cube *not for science*
	HPS3DR[B|R]/herschel.pacs.signal.PacsRebinnedCube	hpacs<OBSID>_20hps3dr[b|r]s_<##>_<NNN>	native/rebinned cube
	HPSTBR[B|R]/herschel.pacs.signal.PacsSpecTable	hpacs<OBSID>_20hpstbr[b|r]s_<##>_<NNN>	rebinned cube table
	HPS3DP[B|R]/herschel.ia.dataset.spectrum.SpectralSimpleCube	hpacs<OBSID>_20hps3dp[b|r]s_<##>_<NNN>	projected cube
	HPS3DI[B|R]/herschel.ia.dataset.spectrum.SpectralSimpleCube	hpacs<OBSID>_20hps3di[b|r]s_<##>_<NNN>	interpolated cube *(Nyquist+range-scan, all pointed and tiling)*
	HPS3DD[B|R] /herschel.ia.dataset.spectrum.SpectralSimpleCube	hpacs<OBSID>_20hps3dd[b|r]s_<##>_<NNN>	drizzled cube *(line-scan+ Nyquist and oversampled)*
	HPSSPEC[B|R]/herschel.pacs.signal.PacsCentralSpectrum	hpacs<OBSID>_20hpsspec[b|r]s_<##>_<NNN>	point-source table *(pointed)*
Level 2.5	HPS3DRBS[B|R]/herschel.pacs.signal.PacsRebinnedCube	hpacs_25HPS3DRBS[B|R]S_<RA>_<DEC>_<##>_v1.0_<NNN>	native/rebinned cube
	HPSTBRBS[B|R]/herschel.pacs.signal.PacsSpecTable	hpacs_25HPSTBRBS[B|R]S_ <RA>_<DEC>_<##>_v1.0_<NNN>	rebinned cube table
	HPS3DPBS[B|R]/herschel.ia.dataset.spectrum.SpectralSimpleCube	hpacs_25HPS3DPBS[B|R]S_<RA>_<DEC>_<##>_v1.0_<NNN>	projected cube
	HPS3DIBS[B|R]/herschel.ia.dataset.spectrum.SpectralSimpleCube	hpacs_25HPS3DIBS[B|R]S_<RA>_<DEC>_<##>_v1.0_<NNN>	interpolated cube *(Nyquist+range-scan, all pointed and tiling)*
	HPS3DDBS[B|R]/herschel.ia.dataset.spectrum.SpectralSimpleCube	hpacs_25HPS3DDBS[B|R]S_<RA>_<DEC>_<##>_v1.0_<NNN>	drizzled cube *(line-scan+ Nyquist and oversampled)*
	HPSSPECBS[B|R]/herschel.pacs.signal.PacsCentralSpectrum	hpacs_25HPSSPECBS[B|R]S_<RA>_<DEC>_<##>_v1.0_<NNN>	point-source table *(pointed)*
Level 3	HPSSPEC	hpacs_30HPSSPEC_<RA>_<DEC>_v1.0_<NNN>	point-source table (pointed+chop-nod+SED)

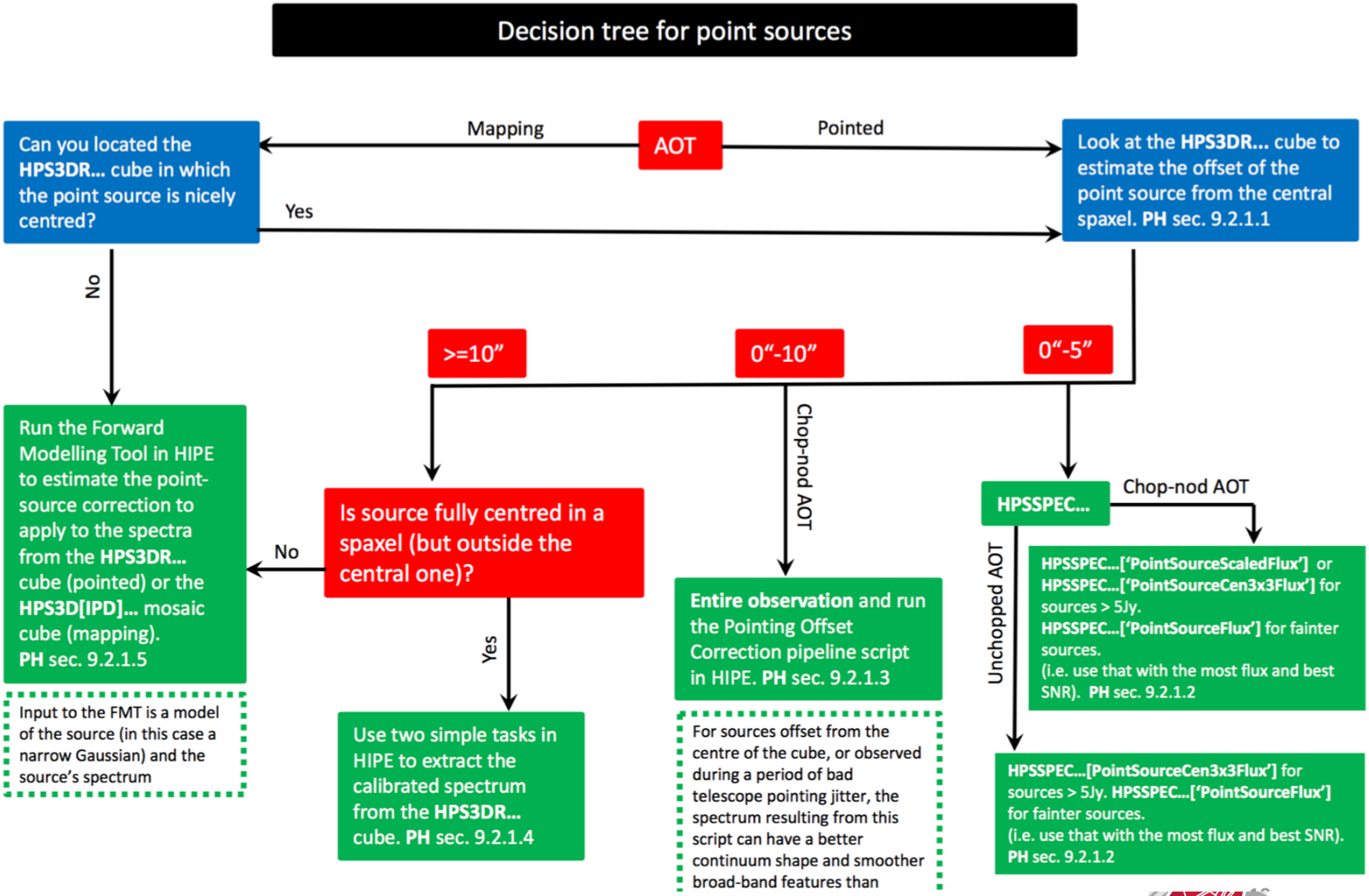
PACS spectroscopy products

Folder	Sub-folder	Filename pattern	Description *AOT*
Level 2	HPS3D{BR}/herschel.pacs.signal.PacsCube	hpacs<OBSID>_20hps3d{br}s_<##>_<NNN>	earliest cube *not for science*
	HPS3DR{BR}/herschel.pacs.signal.PacsRebinnedCube	hpacs<OBSID>_20hps3dr{br}s_<##>_<NNN>	native/rebinned cube
	HPSTBR{BR}/herschel.pacs.signal.PacsSpecTable	hpacs<OBSID>_20hpstbr{br}s_<##>_<NNN>	rebinned cube table
	HPS3DP{BR}/herschel.ia.dataset.spectrum.SpectralSimpleCube	hpacs<OBSID>_20hps3dp{br}s_<##>_<NNN>	projected cube
	HPS3DI{BR}/herschel.ia.dataset.spectrum.SpectralSimpleCube	hpacs<OBSID>_20hps3di{br}s_<##>_<NNN>	interpolated cube *(Nyquist+range-scan, all pointed and tiling)*
	HPS3DD{BR} /herschel.ia.dataset.spectrum.SpectralSimpleCube	hpacs<OBSID>_20hps3dd{br}s_<##>_<NNN>	drizzled cube *(line-scan+ Nyquist and oversampled)*
	HPSSPEC{BR}/herschel.pacs.signal.PacsCentralSpectrum	hpacs<OBSID>_20hpsspec{br}s_<##>_<NNN>	point-source table *(pointed)*
Level 2.5	HPS3DRBS{BR}/herschel.pacs.signal.PacsRebinnedCube	hpacs_25HPS3DRBS{BR}S_<RA>_<DEC>_<##>_v1.0_<NNN>	native/rebinned cube
	HPSTBRBS{BR}/herschel.pacs.signal.PacsSpecTable	hpacs_25HPSTBRBS{BR}S_<RA>_<DEC>_<##>_v1.0_<NNN>	rebinned cube table
	HPS3DPBS{BR}/herschel.ia.dataset.spectrum.SpectralSimpleCube	hpacs_25HPS3DPBS{BR}S_<RA>_<DEC>_<##>_v1.0_<NNN>	projected cube
	HPS3DIBS{BR}/herschel.ia.dataset.spectrum.SpectralSimpleCube	hpacs_25HPS3DIBS{BR}S_<RA>_<DEC>_<##>_v1.0_<NNN>	interpolated cube *(Nyquist+range-scan, all pointed and tiling)*
	HPS3DDBS{BR}/herschel.ia.dataset.spectrum.SpectralSimpleCube	hpacs_25HPS3DDBS{BR}S_<RA>_<DEC>_<##>_v1.0_<NNN>	drizzled cube *(line-scan+ Nyquist and oversampled)*
	HPSSPECBS{BR}/herschel.pacs.signal.PacsCentralSpectrum	hpacs_25HPSSPECBS{BR}S_<RA>_<DEC>_<##>_v1.0_<NNN>	point-source table *(pointed)*
Level 3	HPSSPEC	hpacs_30HPSSPEC_<RA>_<DEC>_v1.0_<NNN>	point-source table (pointed+chop-nod+SED)

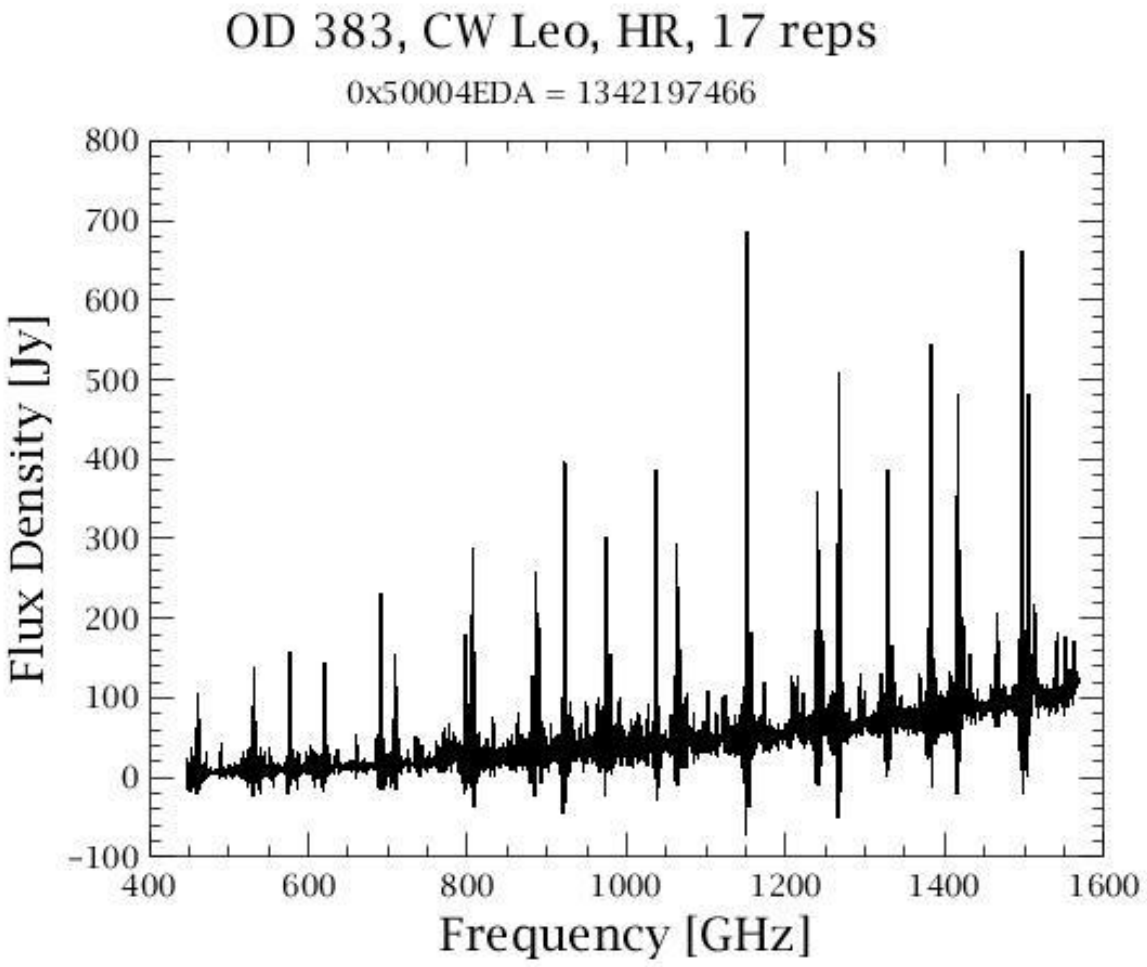
Which products to use?

Read the Product Decision Trees document

Example of PACS-S decision diagram

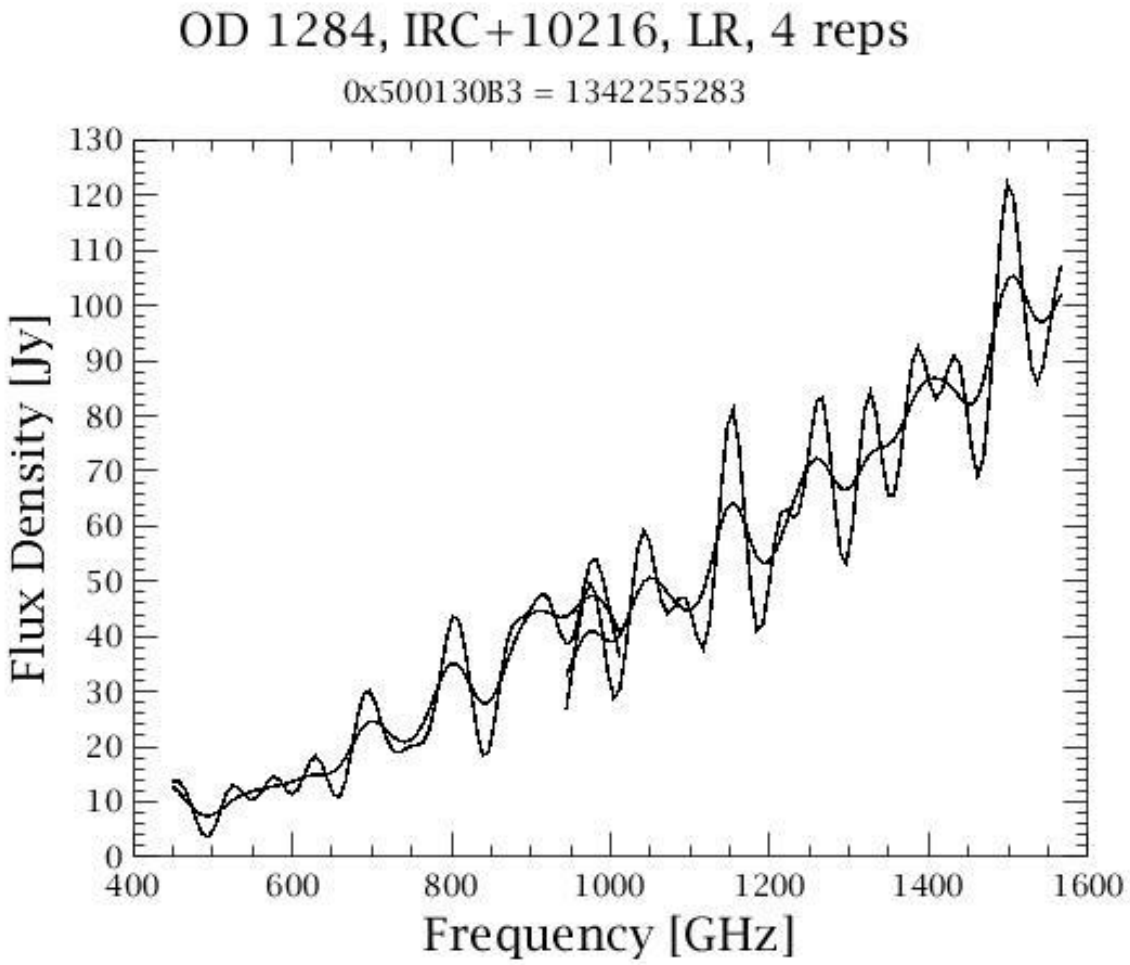


Examples of input data: SPIRE FTS



SPIRE **sparse** mode

Examples of input data

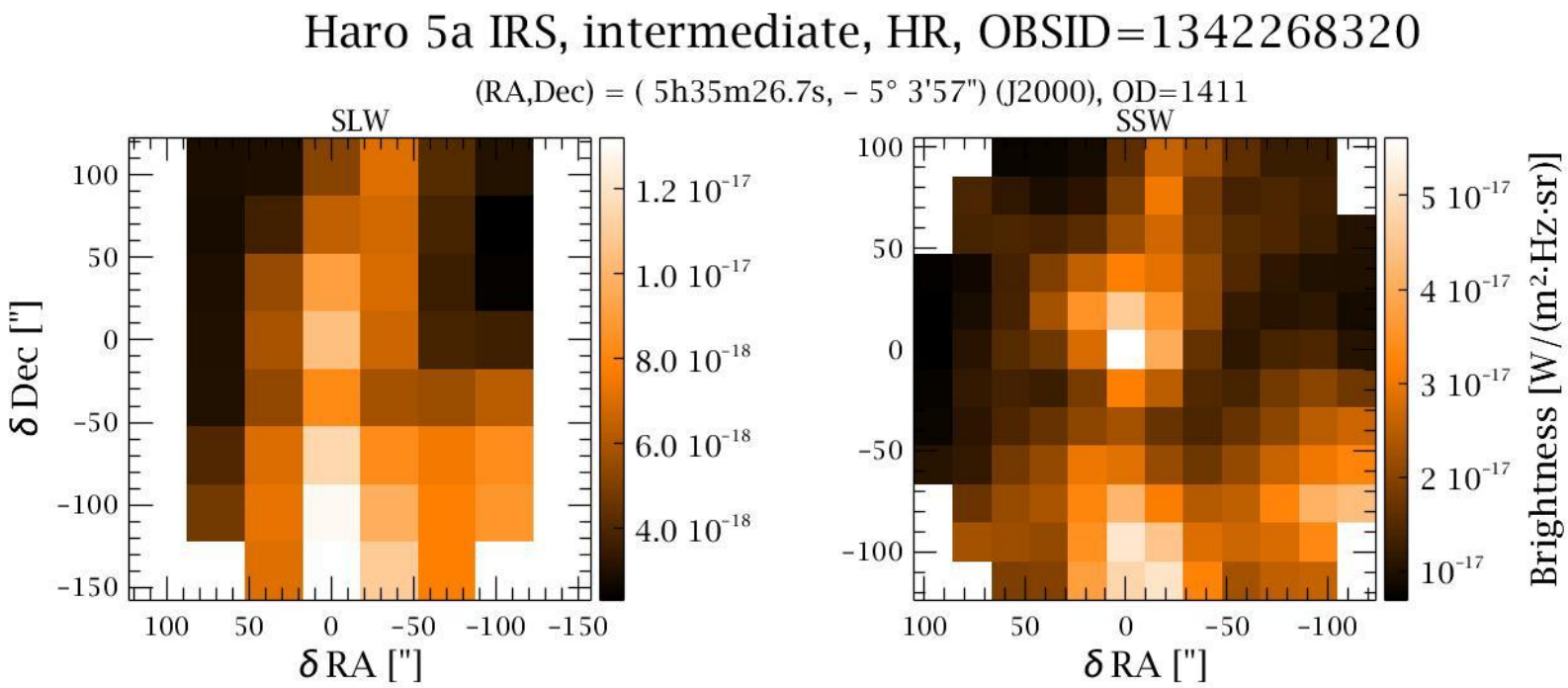


SPIRE **sparse** mode

Low Resolution

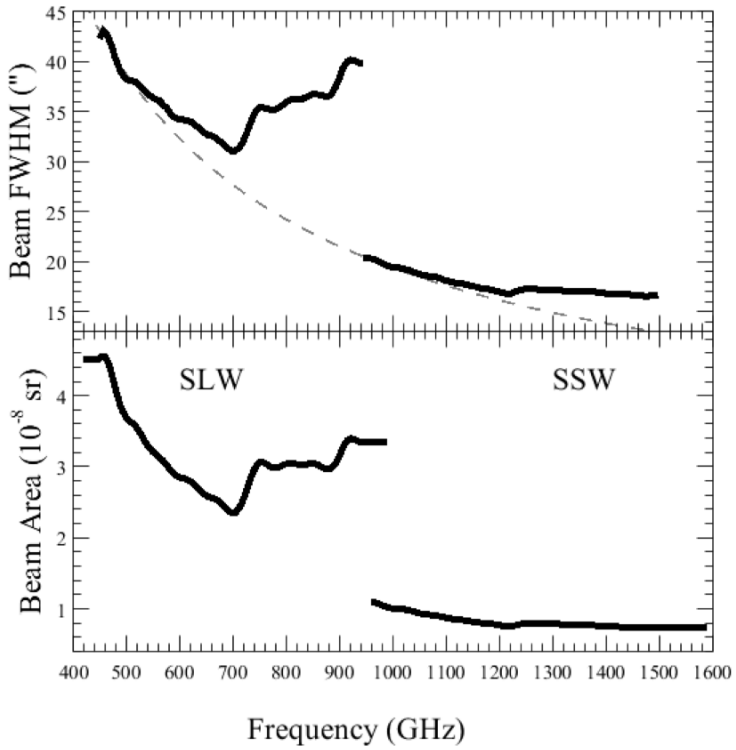
Examples of input data

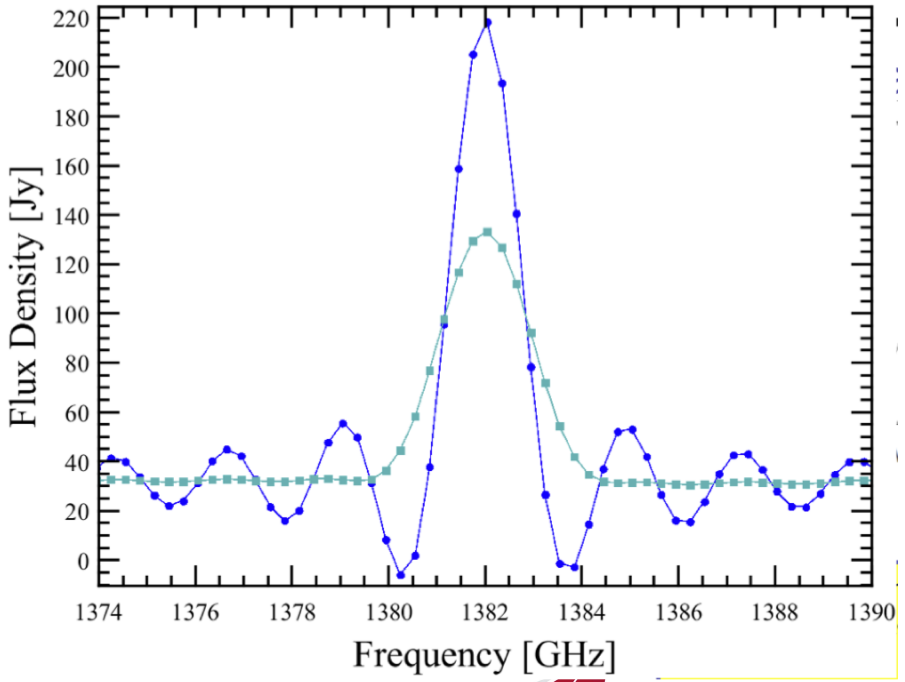
SPIRE **mapping** mode
Two hyper-spectral cubes



SPIRE spectroscopy considerations

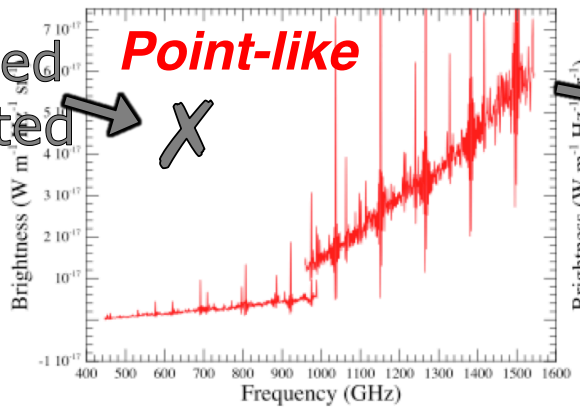
- Two calibrations: point-source (Jy) and extended source (W/m2/Hz/sr)
- Beam variations with frequency
- Instrumental line shape: sinc function, f= sin(x)/x





SPIRE calibrations

Extended calibrated



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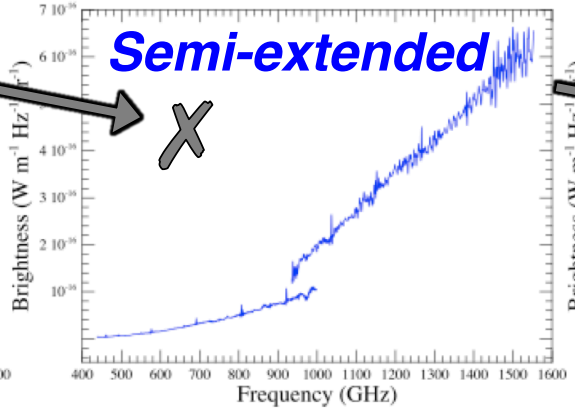

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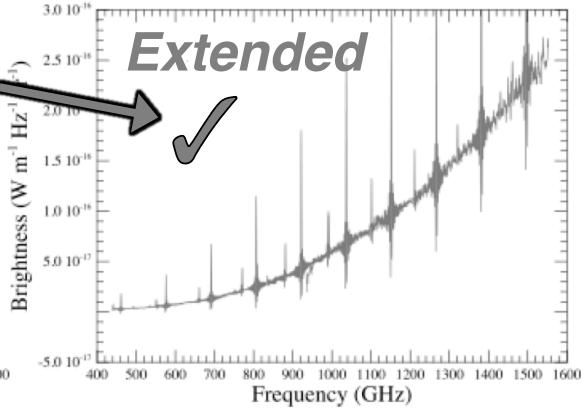
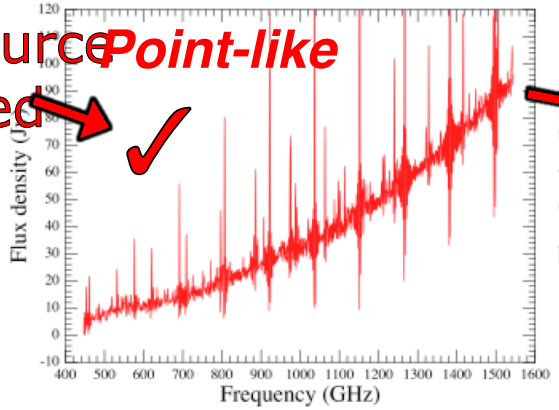


✓

Point-source calibrated



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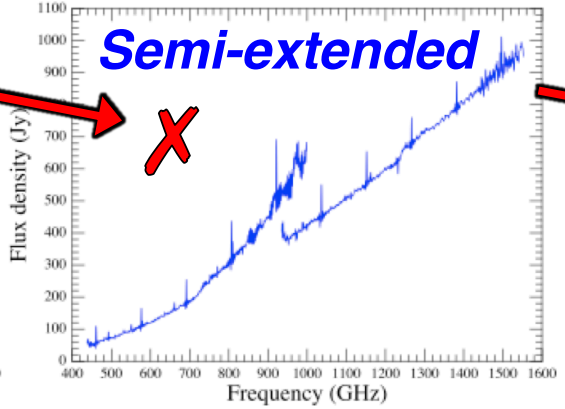
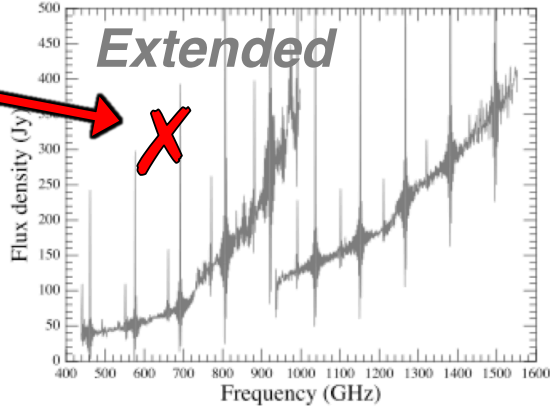


✗



✗

SPIRE spectroscopy products

Folder	Sub-folders	Filename pattern
level0	*BuildingBlockProduct	hspire<OBSID>_<BBID><NNNN>_00rst_<ID>
level0_5	*EdpBlockContext	hspire<OBSID>_a107<NNNN>_05level05blockcontext_<ID>
level1	Point_<NR>_Jiggle_<NJ>_<RES>/interferogram/	<prefix><OBSID>_a106<NNNN>_10sdi_<ID>
level2 (mapping)	<RES>_<ARR>_cube	<prefix><OBSID>_spg_<ARR>_<RES>_20ssc_<ID>
	<RES>_<ARR>_cube_convol	<prefix><OBSID>_spg_<ARR>_convol_<RES>_20ssc_<ID>
	<RES>_<ARR>_spectrum2d	<prefix><OBSID>_spg_<ARR>_<RES>_20spc_<ID>
	<RES>_<ARR>_cube_apod	<prefix><OBSID>_spgApod_<ARR>_<RES>_20ssc_<ID>
	<RES>_<ARR>_cube_convol_apod	<prefix><OBSID>_spgApod_<ARR>_convol_<RES>_20ssc_<ID>
	<RES>_<ARR>_spectrum2d_apod	<prefix><OBSID>_spgApod_<ARR>_<RES>_20spc_<ID>
level2 (sparse)	<RES>_spectrum_ext	<prefix><OBSID>_a1060001_spg_<RES>_20sds_<ID>
	<RES>_spectrum_point	<prefix><OBSID>_a1060001_spg_<RES>_20spss_<ID>
	<RES>_spectrum_ext_apod	<prefix><OBSID>_a1060001_spgApod_<RES>_20sds_<ID>
	<RES>_spectrum_point_apod	<prefix><OBSID>_a1060001_spgApod_<RES>_20spss_<ID>

Two types of cubes and individual spectra.
Apod = apodized = smoothed.

SPIRE data analysis

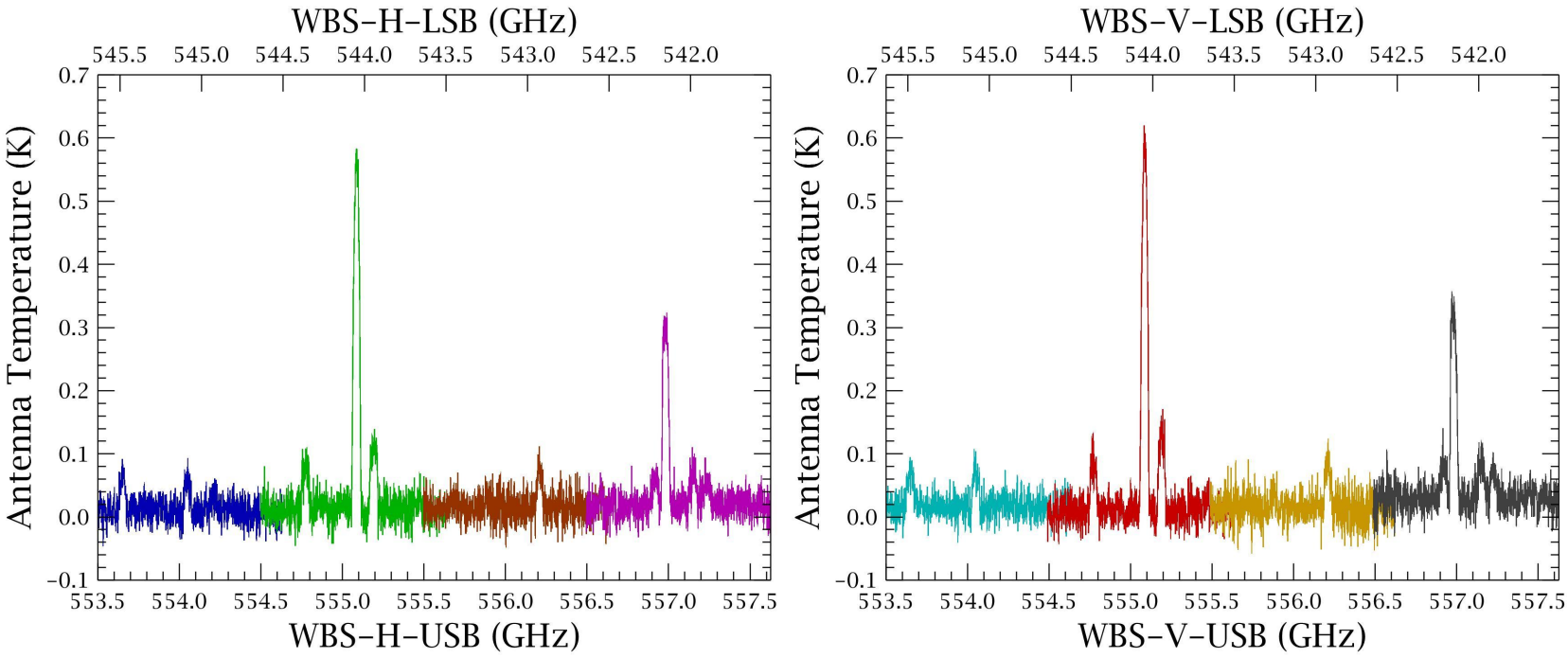
- Footprint plot
- Examining the spectra
- Background subtraction
- Partially extended sources
- Spectral line fitting
- Spectral cubes

Examples of input data: HIFI

HIFI point dual beam switch

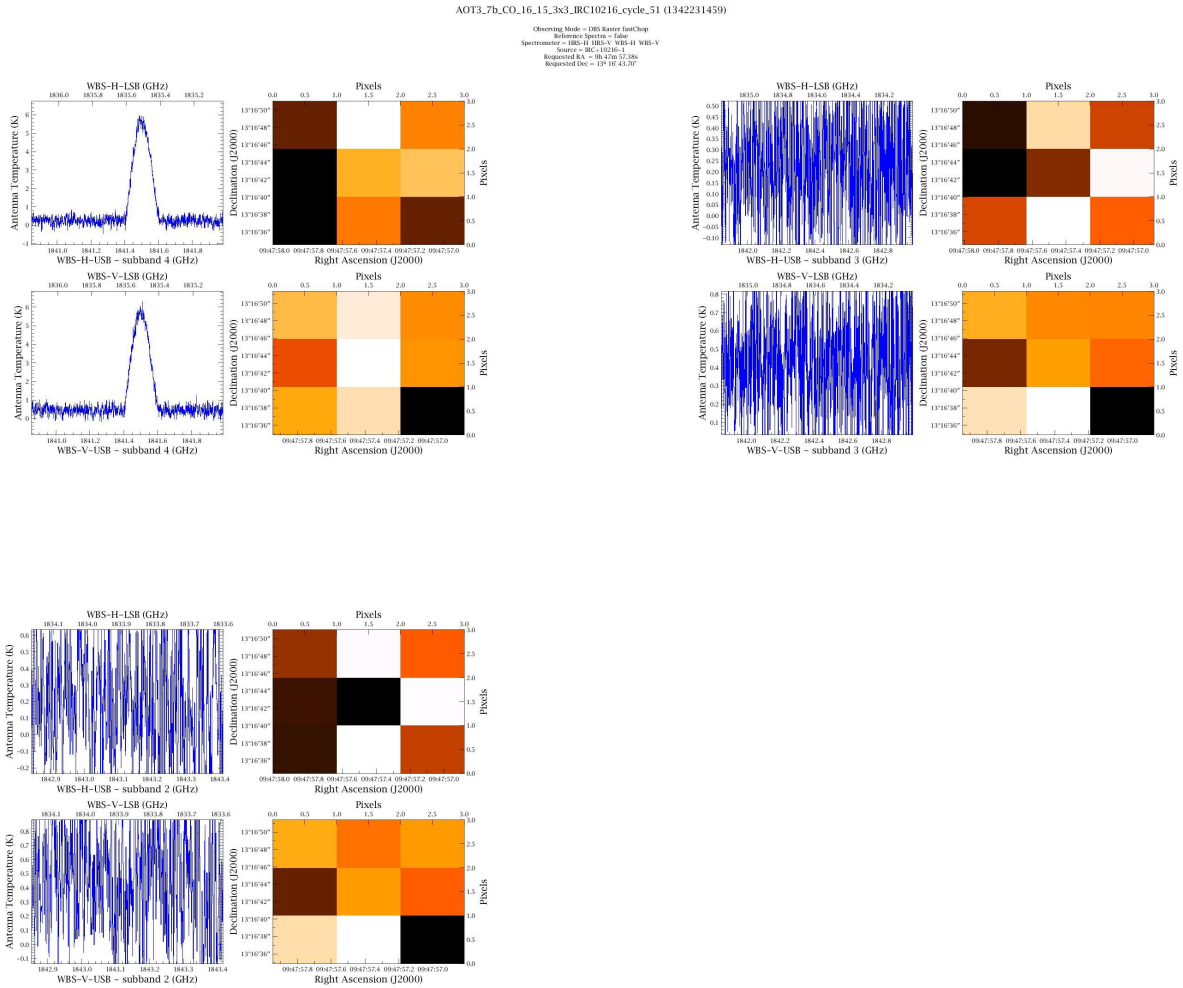
TV_HNC_6L-epoch_2 (1342253785)

Observing Mode = DBS
Reference Spectra = false
Spectrometer = HRS-H HRS-V WBS-H WBS-V
Source = irc+10216
Requested RA = 9h 47m 57.41s
Requested Dec = 13º 16' 43.60"



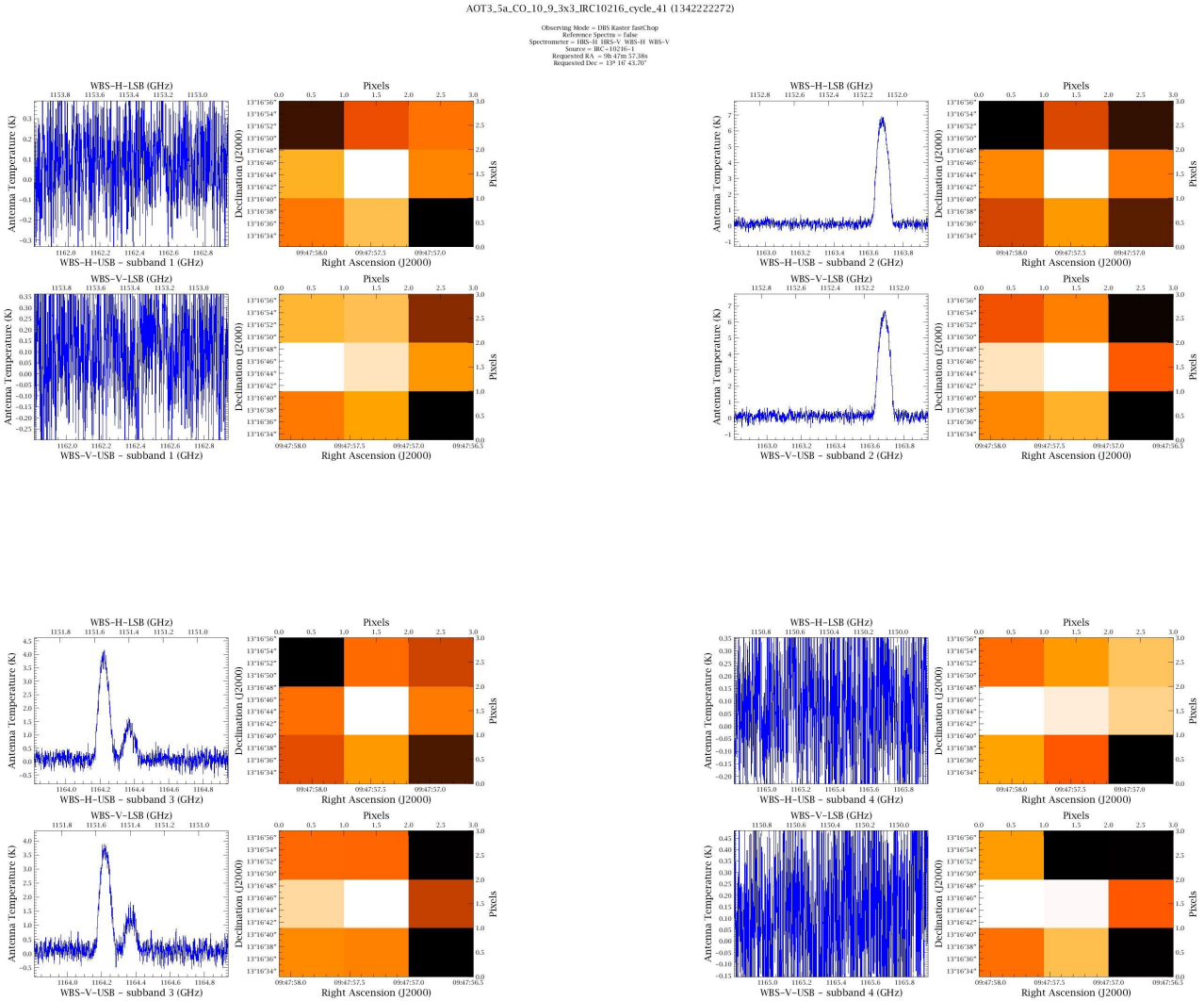
Examples of input data

HIFI mapping dual beam switch



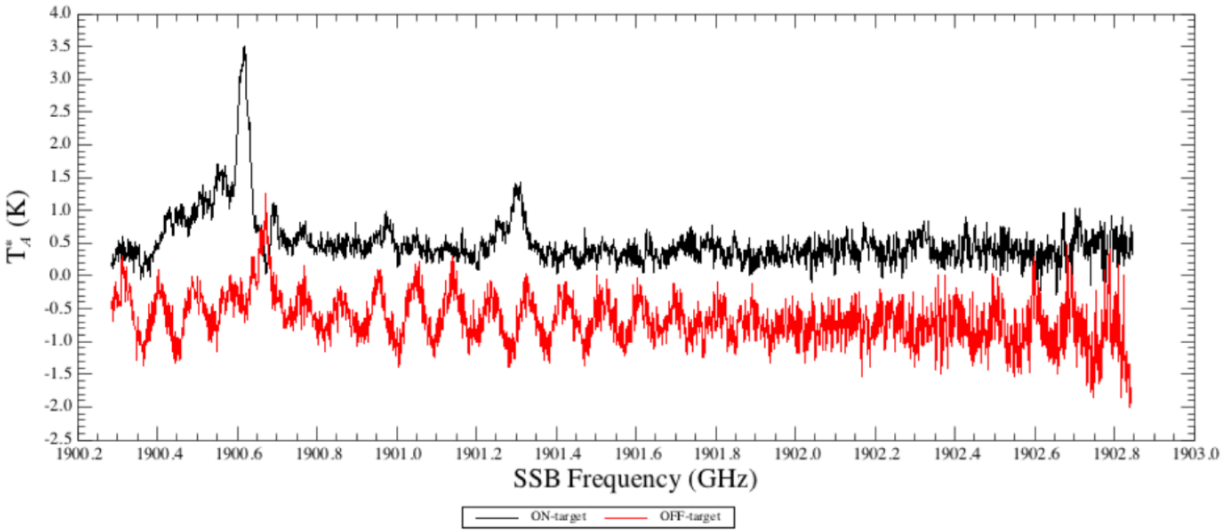
Examples of input data

HIFI mapping mode raster dual beam switch

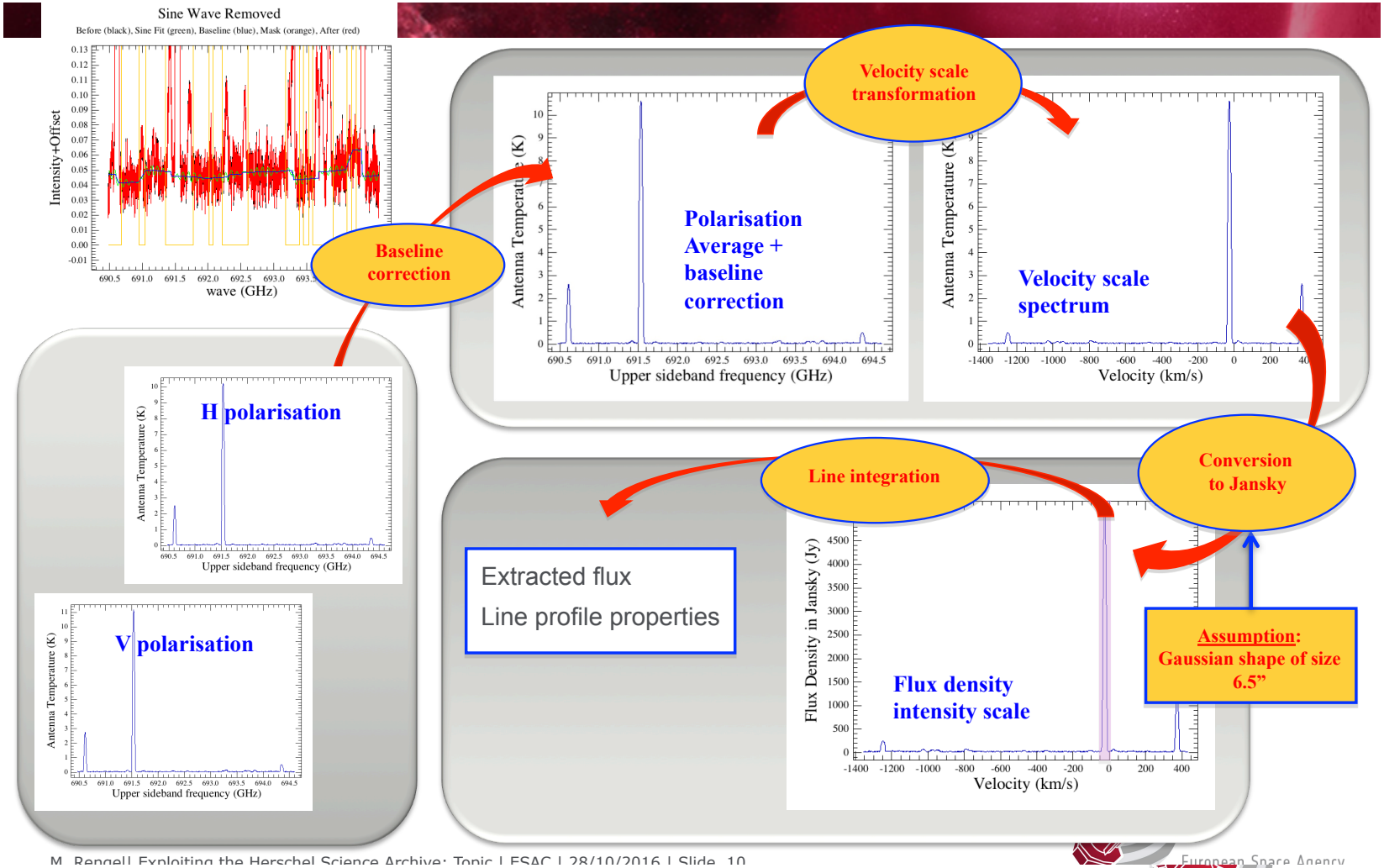


HIFI considerations

- Two polarisations
- Units of T_A^* (K)
- Resolved lines ← very high spectral resolution
- DSB deconvolution for spectral scans with many lines
- Data artefacts:
  - Baseline variations: optical and electrical standing waves
  - Baseline distortions: near IF edges
  - Platforming
  - Spurious spikes ➔ flagged.
  - OFF position contamination



Typical HIFI workflow on isolated line

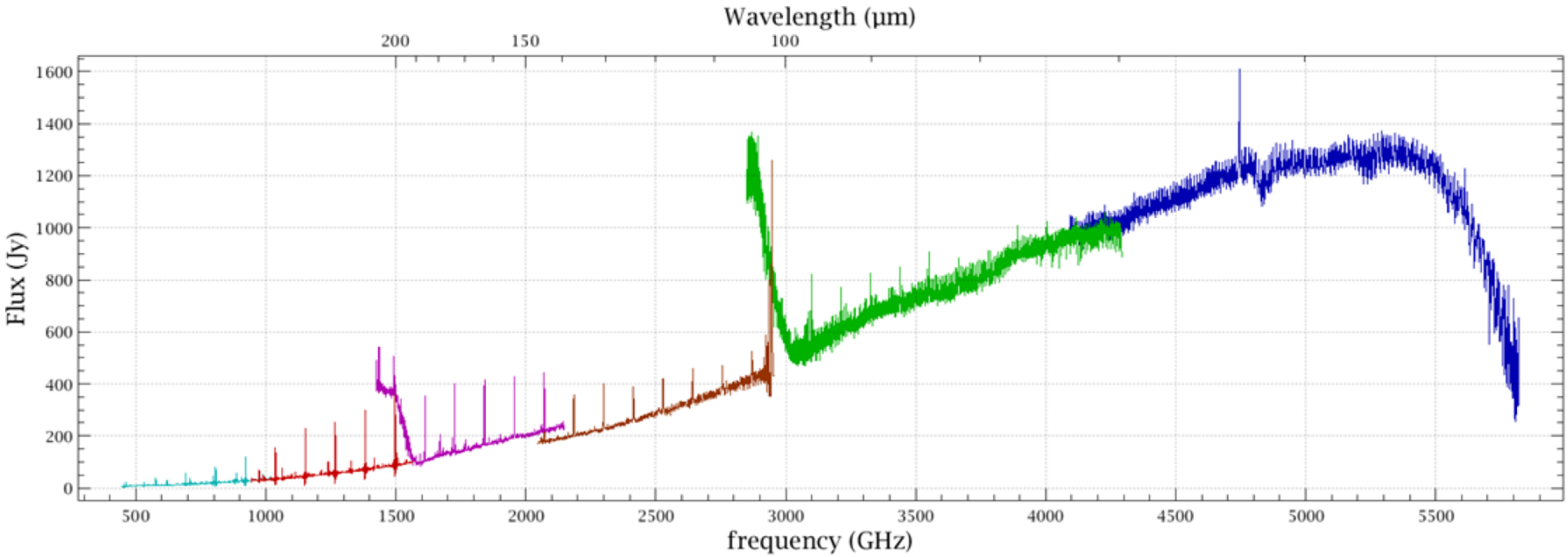


HIFI data analysis

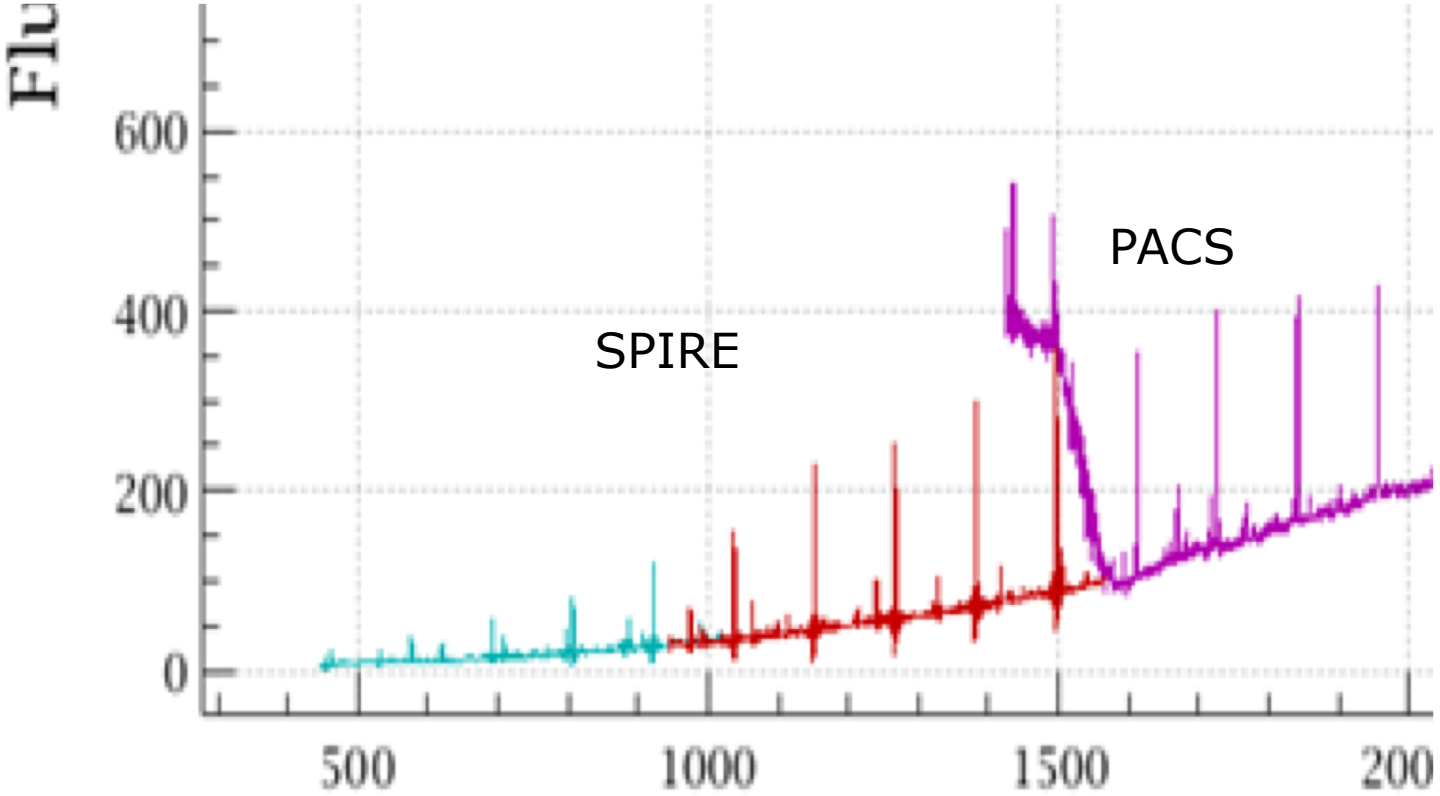
- Average H and V polarisations
- Scale/unit conversion: T_A^* ➔ T_{mb} ➔ S(Jy)
  - Unresolved sources
  - Compact sources with a model or user provided brightness distribution
- Line flux:
  - Unresolved lines via fitting
  - Resolved lines: direct integration
- Continuum

SPIRE and PACS

CRL618



SPIRE and PACS



Data analysis: hands on

From simple to more difficult analysis

1. Line measurements (in HIPE)
    1. Units, conversions, etc.
    2. Baseline/continuum subtraction
2. Simple cube analysis (in HIPE):
    1. Extracting line maps
    2. Velocity maps
    3. …

3. Science analysis:
    1. Radial velocity and velocity structure
    2. Physical conditions (T, density, G_0, …)
    3. …