Herschel Spectrometers Cross Calibration

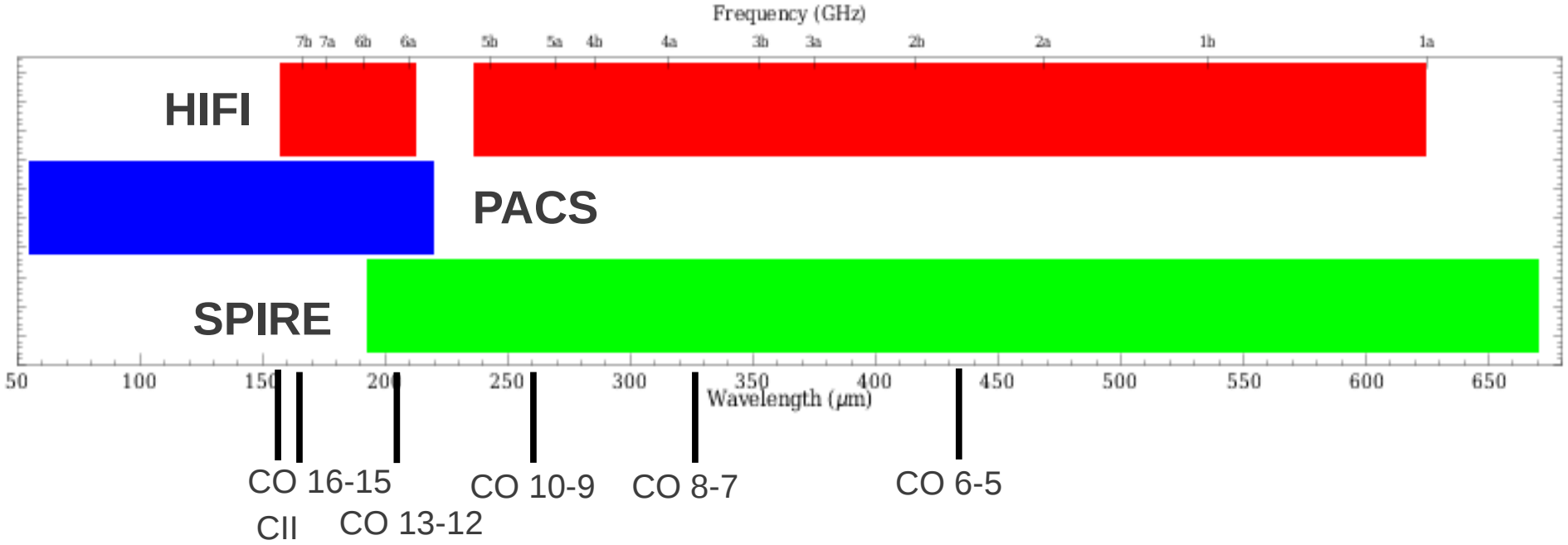
27th March 2013

E. Puga,
on behalf of the HSC Instrument Calibration Team

Outline

- Line Flux Comparison
  - Observational Program and object sample
  - Extraction of line fluxes
- Continuum Comparison
- Extended Emission Comparison
- Conclusions and future prospects

Herschel Spectrometers Cross Calibration

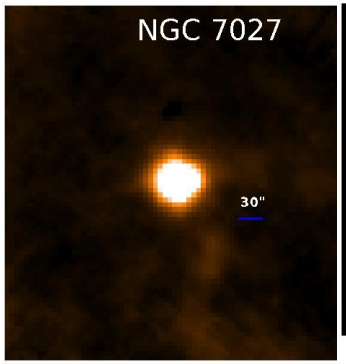


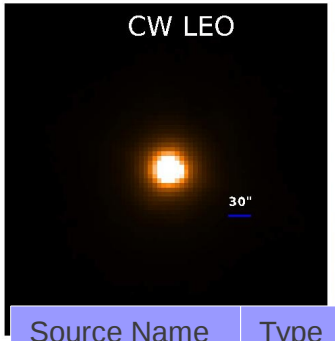
Mindset Change:

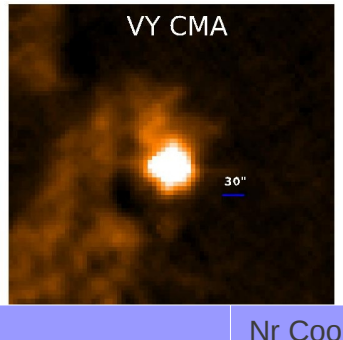
- This is wavelength/frequency accesibility, not necessarily coverage.
- HIFI spectral resolution is a factor 1000 higher than PACS and SPIRE. Lines fluxes obtained by line model fitting (PACS/SPIRE) and numerical integration.
- PACS Red Leak between 190-220 μm imposes some difficulties in the comparison in the past, but not anymore for line sources!

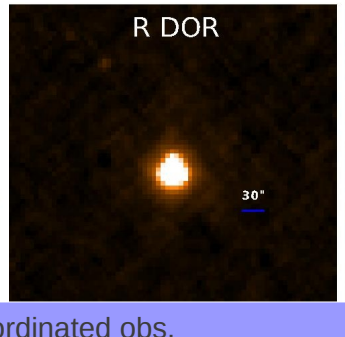
Line Flux Sources

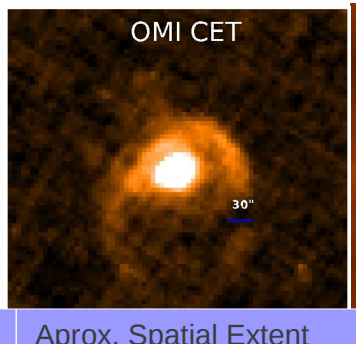
- Source Sample: Basis on the HIFI Calibration Monitoring Programme
- Spectrometers Cross Calibration Proposal (33 hrs): coordinated observations within a cycle by the three instruments between OD850-OD1360
- Detailed potential list of **science and calibration observations** in SpecXCal twiki (up to OD 1385)

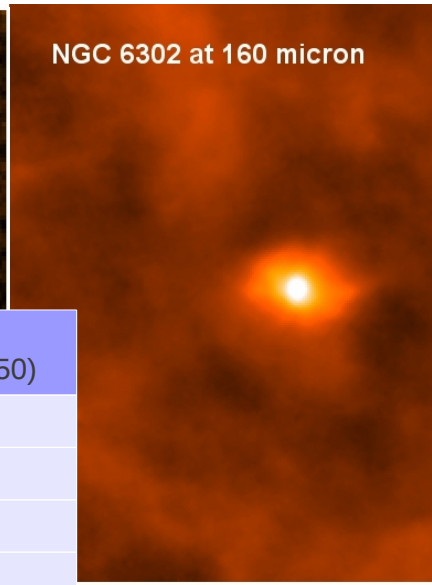


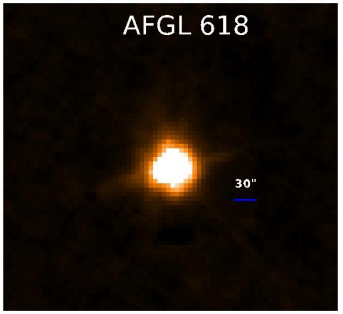


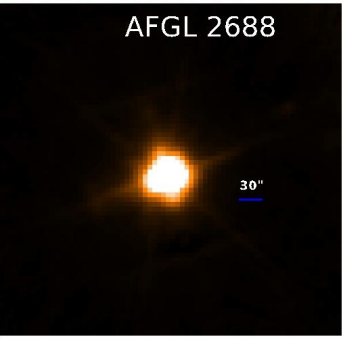




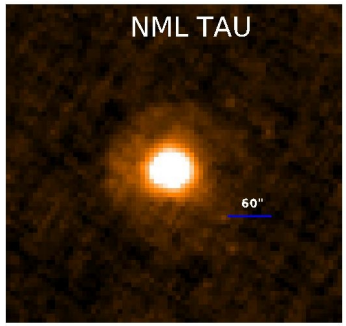








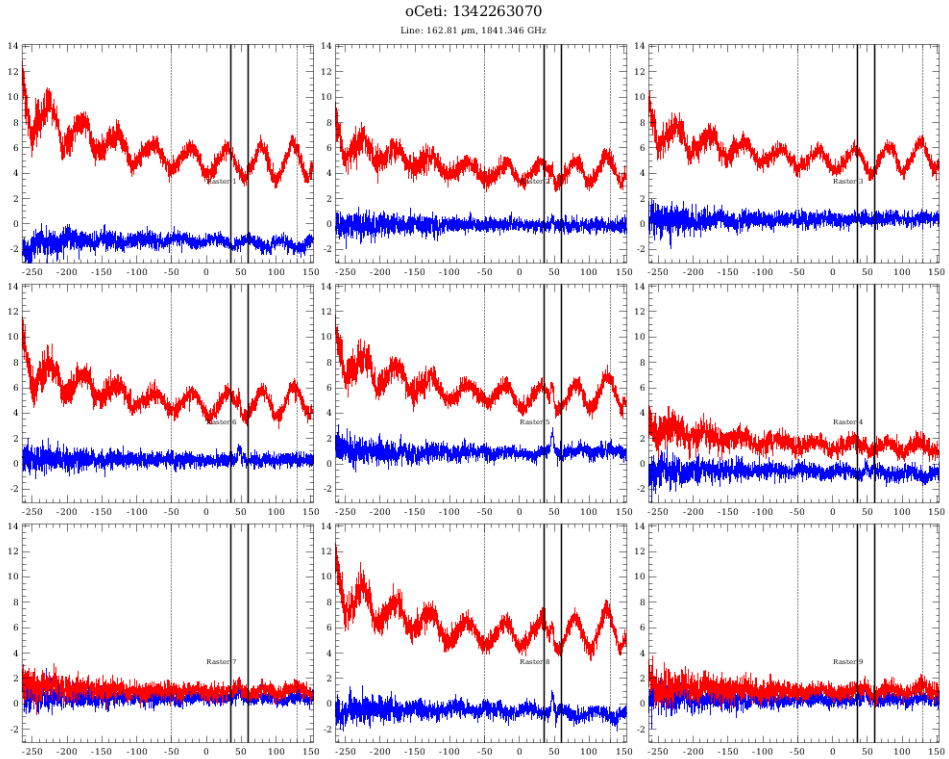
Source Name	Type	Nr Coordinated obs.	Aprox. Spatial Extent (PACS@60/SPIRE@250)
CRL 618	Point	3/3	8.17”/17.95”
AFGL 2688	Compact	3/3	10.13”/17.94”
NGC 6302	Compact	3/3+1 continuum peak	-/21.46”
NGC 7027	Compact	3/3	13.89”/21.05”
AFGL 4106	Point	1 (PACS, HIFI), regularly SPIRE	-/17.53”
IRC+10216	Compact/Extended Variable	3/3	11.39”/20.26”
VY CMa	Compact	1-2 HIFI, SPIRE continued, but not in PACS range	8.28”/-
IK Tau	Point		8.49”/19.12”
R Dor	Point	3/3	7.75”/-
o Cet	Point	3/3 HIFI and PACS	10.03”/-
W Hya	Compact		7.56”/-

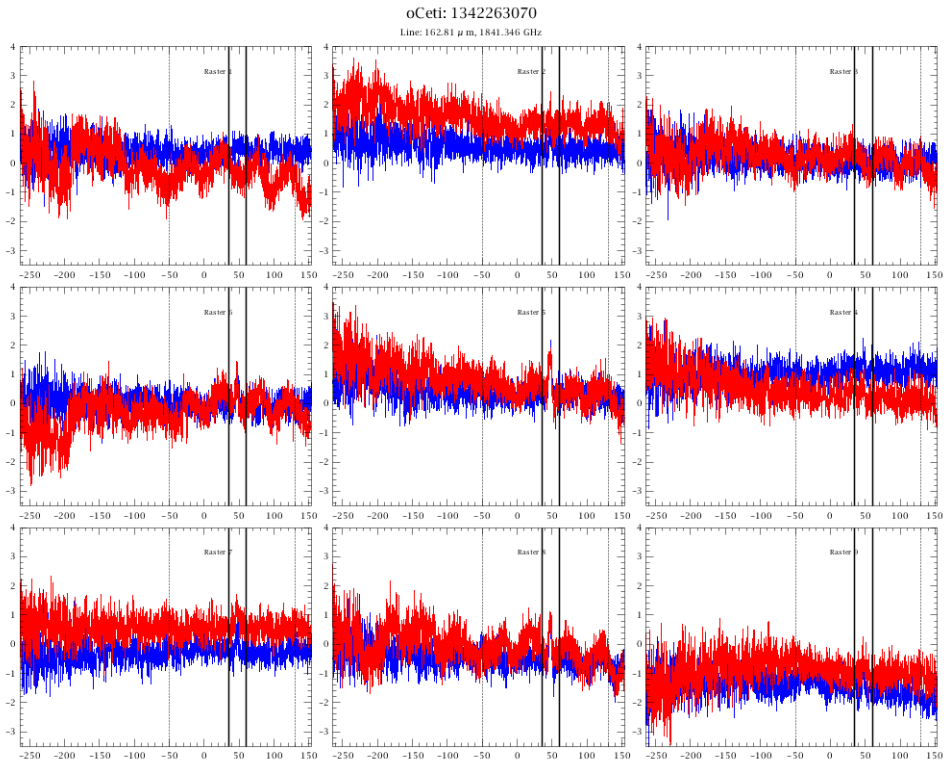


HIFI Line Flux Analysis

- SPG 9.1.0/ 10.0.0 and 30% of observations processed with HIPE11
  - Gain sideband Ratio (6% in band 5a that affects the CO 10-9 line at 1151 GHz)
- Electric Standing Wave mitigation in HEB bands 6/7 using matching technique script with a reference catalog for each band/line (see poster by Ian Avruch)

  Partially beating the 25% uncertainty....





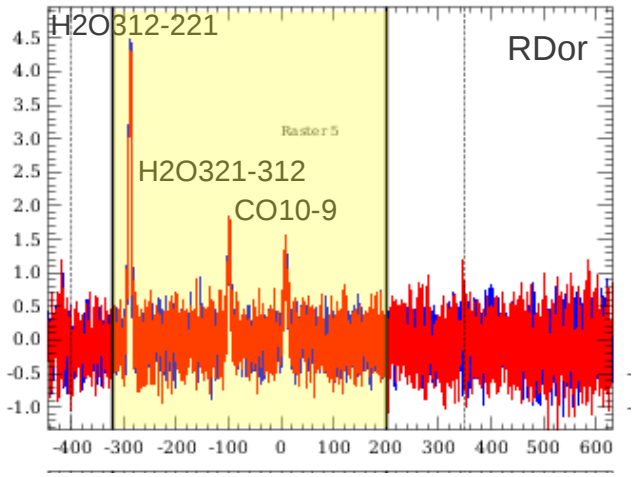
HIFI Line Flux Analysis

- Absolute intensity calibration uncertainties:
- Line flux extraction for each polarization orientation:
  - Integrated intensity via numerical integration after baseline subtraction (polyOrder=1) at native spectral resolution. Conversion to line flux for a point source:

$$F\left[\frac{W}{m^2}\right]=10^{-26}\cdot\frac{2\cdot 1.3806488\cdot 10^{-16}}{8.45\cdot 10^{-19}\cdot 2.99\text{x}10^{5}}\cdot\frac{1}{\eta_A}\cdot f[GHz]\cdot 10^{9}\cdot\eta_l\cdot T_A{}^{*}\cdot\Delta\upsilon[K\cdot km\cdot s^{-1}]$$

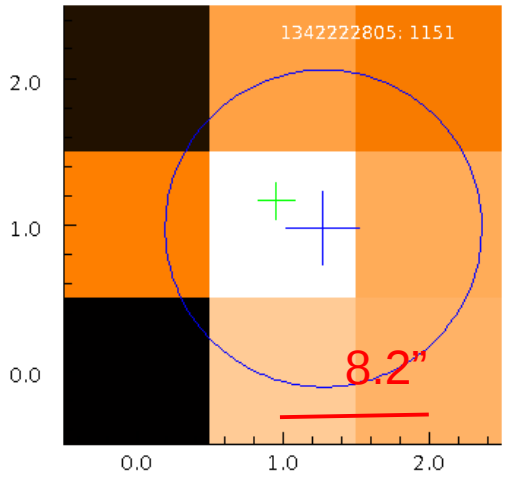
$$\eta_A=\eta_{A0}\cdot e^{-\left(\frac{4\cdot\pi\cdot\sigma}{\lambda}\right)^2}$$

  - Line flux error is determined from the baseline rms, multiplied by the velocity channel bandwidth and scaled with the square root of the number of integrated line channels.
  - Line contamination of HCN and H2O lines in the CO 10-9 line at 1151 GHz, or other sideband H2O



HIFI Line Flux Analysis

- Mispointing flux correction (~8%) using a symmetric 2D Gaussian fit in 3x3 raster maps
  - ~85% of HIFI XCal Observations are 3x3 raster maps.
  - Nyquist sampled maps (grid stepSize = HPBW/2.4)
  - Total line fluxes for the V and H polarizations averaged for the individual 9 raster positions which are distributed in an irregularly gridded collection of line fluxes according to the map rasters R.A. and Dec.
  - Fit of symmetric 2D Gaussian to this **irregularly gridded** map of line fluxes using their errors as weights to the fit (w_i=1./σ_i^2).
  - Initial fitting parameter values are R.A., Dec for the centre and the line flux at the closest raster position to R.A. and Dec for the Gaussian peak. Initial value for the width of the Gaussian is HPBW/(2*SQRT(2 ln 2)) in units of raster Stepsize. Position and width of the Gaussian are left as free parameters.
  - The line flux is recovered as the peak of the Gaussian while the error is the error of the fitted peak parameter.
  - Visualization of the result parameters uses the HIFI doGridding projection of the spectral cube. Baseline subtraction and numerical integration within the line limits.



Line Flux per source and line

Combination of measurements taken with different observing modes and slightly different settings through weighted average:

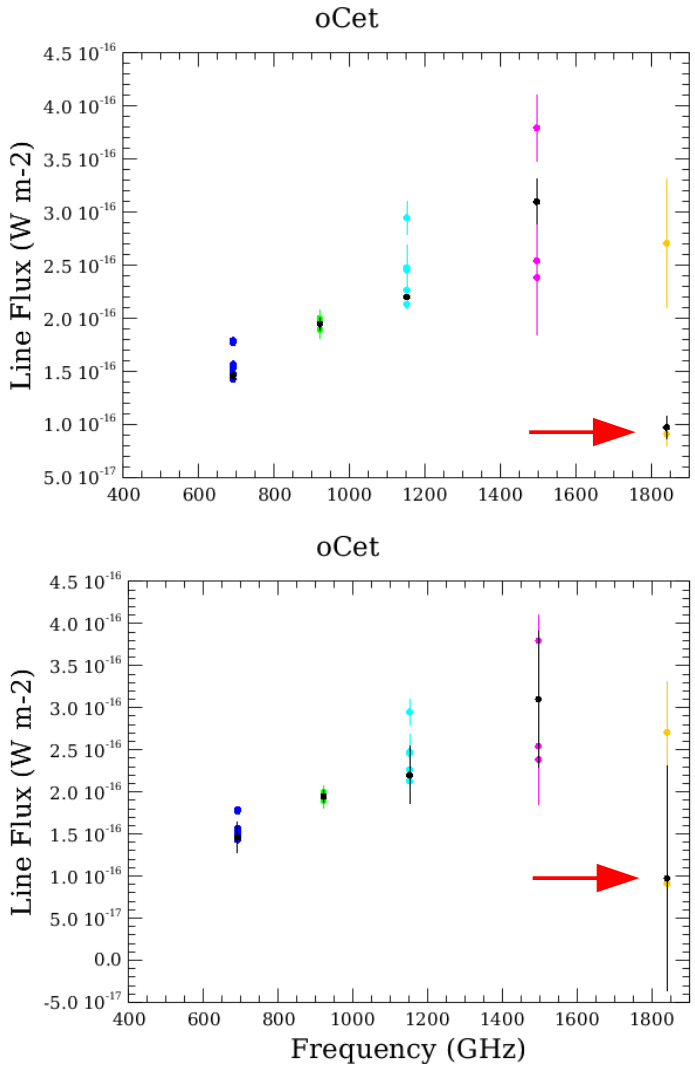
$$\bar{x} = \frac{\sum_{i=1}^{N} (x_i/\sigma_i^2)}{\sum_{i=1}^{N} (1/\sigma_i^2)}$$

variance of the weighted mean can be the biased weighted estimator of the sample variance

$$\sigma_{\bar{x}}^2 = \frac{1}{\sum_{i=1}^{N} (1/\sigma_i^2)}$$

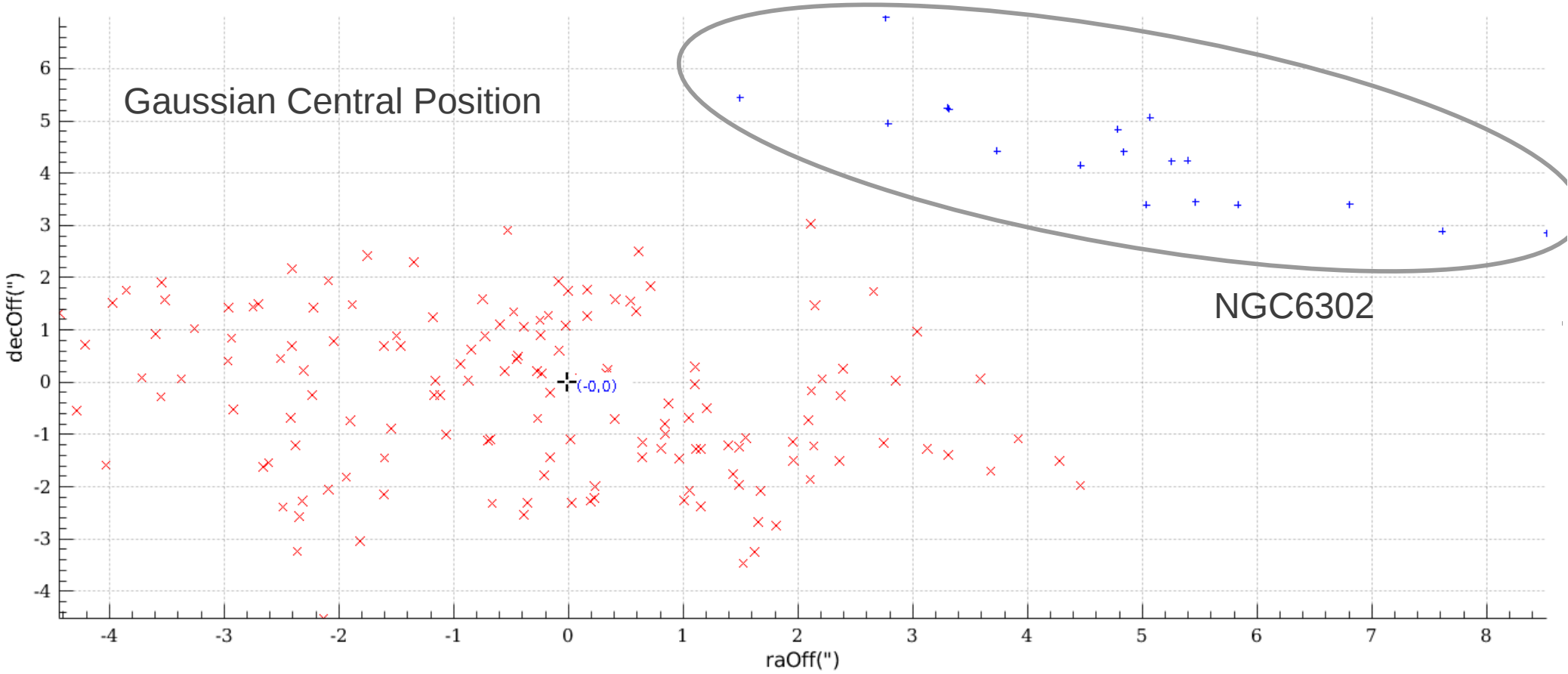
but for small sample measurements (>1), the unbiased estimator of a weighted population variance is given by

$$s^2 = \frac{\sum_{i=1}^{N} \omega_i}{\left(\sum_{i=1}^{N} \omega_i\right)^2 - \sum_{i=1}^{N} \omega_i^2} \cdot \sum_{i=1}^{N} \omega_i (x_i - \bar{x})^2 \qquad \omega_i = \frac{1}{\sigma_i^2}$$



Flux recovery for HIFI 3x3 rasters maps

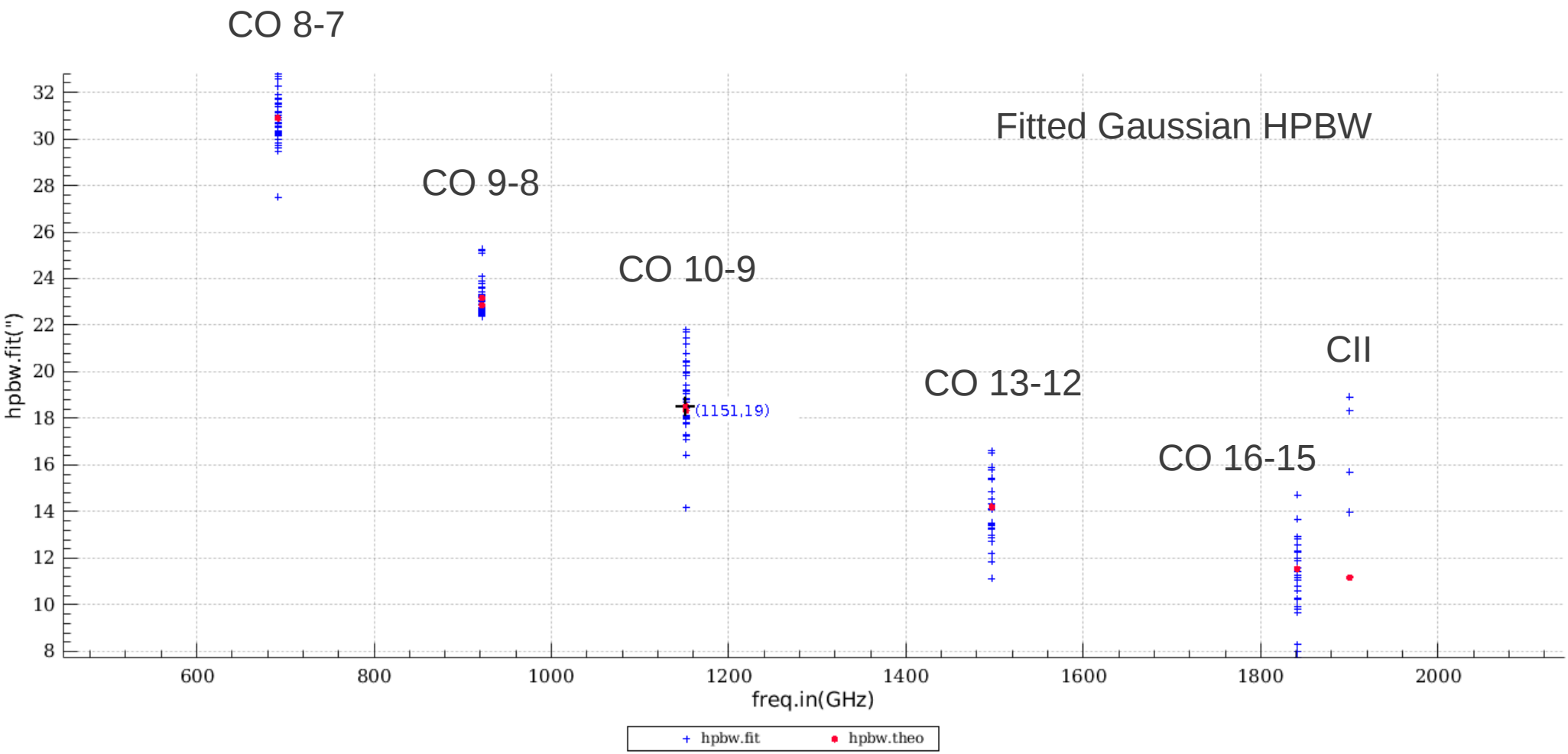
- Fitting results:



This is expected, as XCal observation coordinates for NGC6302 were offset ~6” from the continuum peak coordinates. There is one observation at continuum peak coordinates for All three instruments in OD1242-1248.

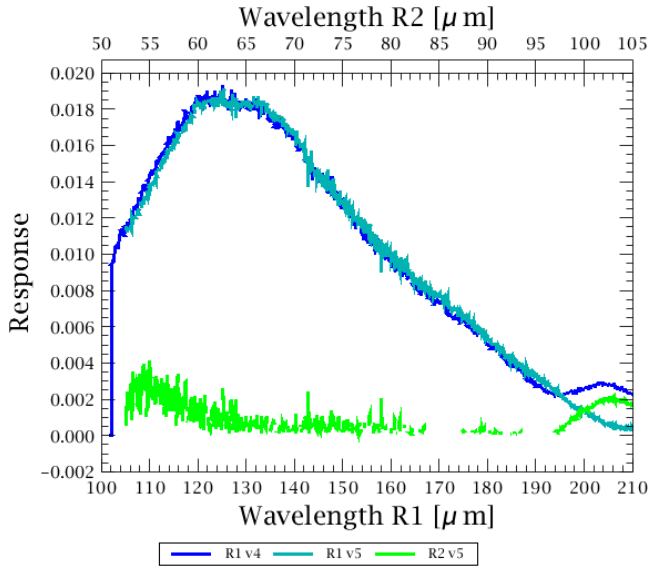
Flux recovery for HIFI 3x3 rasters maps

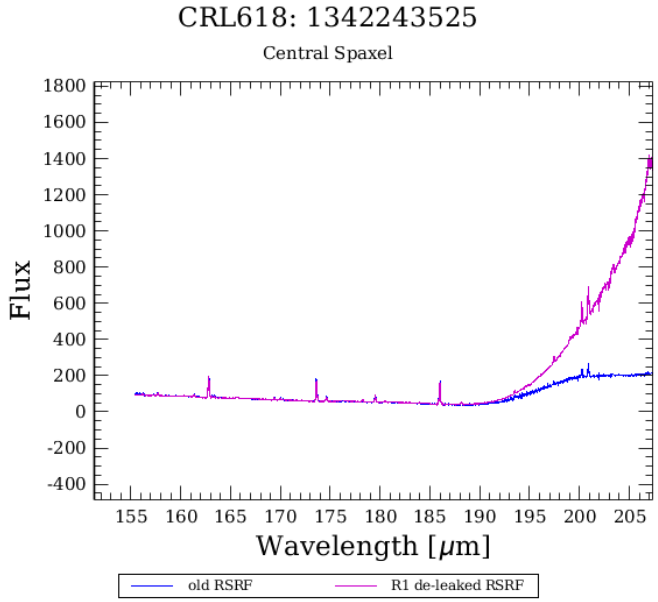
- Fitting results:



PACS Line Flux Analysis

- CalTree v49, HIPE 11
- Line and Range scans reprocessed with state-of-the-art ipipe scripts
- Absolute Flux Calibration scheme: Calibration Block + RSRF (Deleaked R1 RSRF version 4)

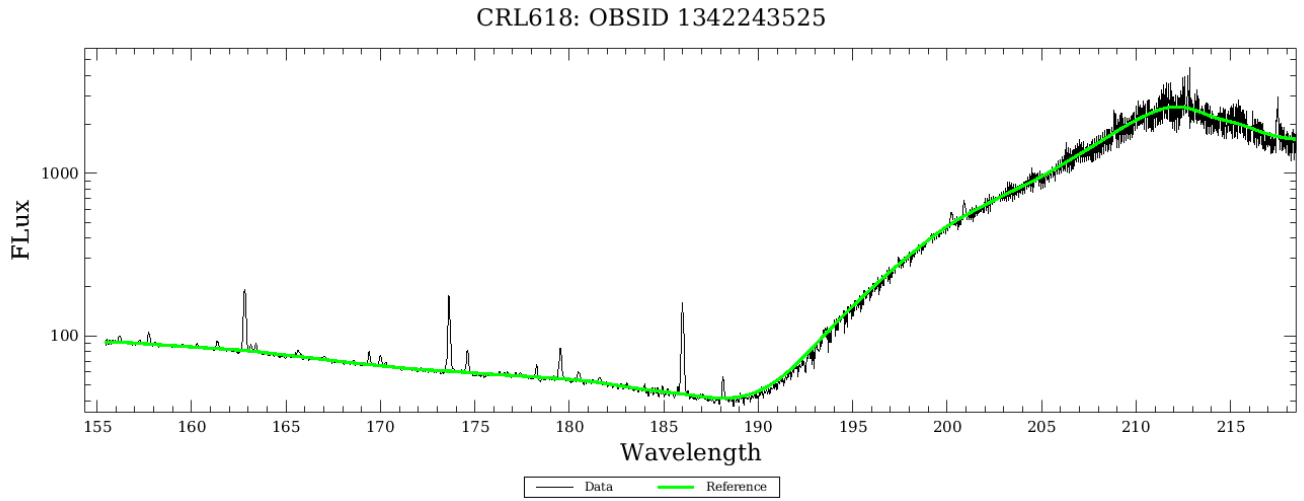




- At 200 μm, the leaked RSRF translated into a factor 2.5-3.5 smaller for PACS line fluxes.

PACS Line Flux Analysis

- SpecFlatFieldLine and (prototype by P. Royer) specFlatFieldRangeFF3 based on Wavelet decomposition.

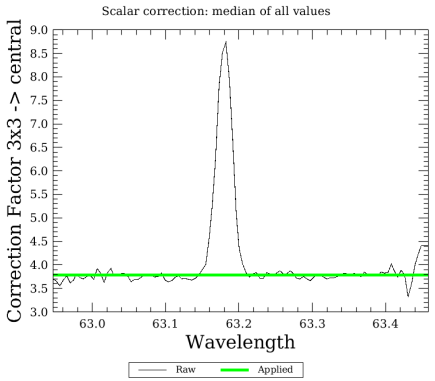


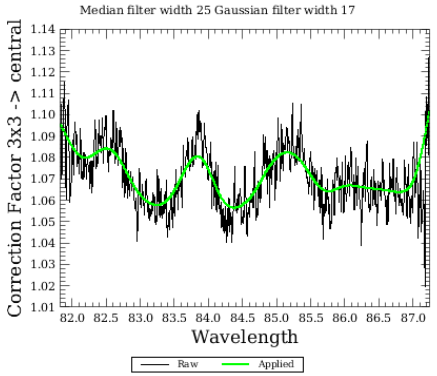
- Mispointing (pointing error/offset continuum peak):
  - Central to 3x3 Correction for point sources during post-processing.

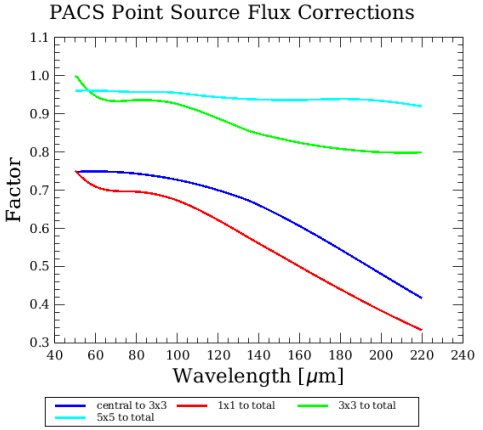
PACS Line Flux Analysis

Post-processing steps:

Wavelength Range	Point Source		Compact Source
In Band (140-190 μm)	Central to 3x3 Correction (up to ~5% flux loss due to pointing mishaps) + 1x1 to total beam PSC	**Line Scan:** extractCentralSpectrum (correct3x3=1, applyPSC=1, Width=0, smoothing="Wavelet", smoothLevel=6)	Sum of central 3x3 spaxels + 3x3 spaxels to total beam PSC
		Range Scan: extractCentralSpectrum (correct3x3=1, applyPSC=1, Width=25, smoothing="Wavelet", smoothLevel=6)	Task extractCentralSpectra.C9
In Leak (190-220 μm)	Continuum flux remains ucorrect in this range central spaxel extraction + 1x1 to total beam PSC Task extractCentralSpectrum (correct3x3=0, applyPSC=1, smoothing="Wavelet", smoothLevel=6)		Sum of central 3x3 spaxels + 3x3 spaxels to total beam PSC Task extractCentralSpectra.C9

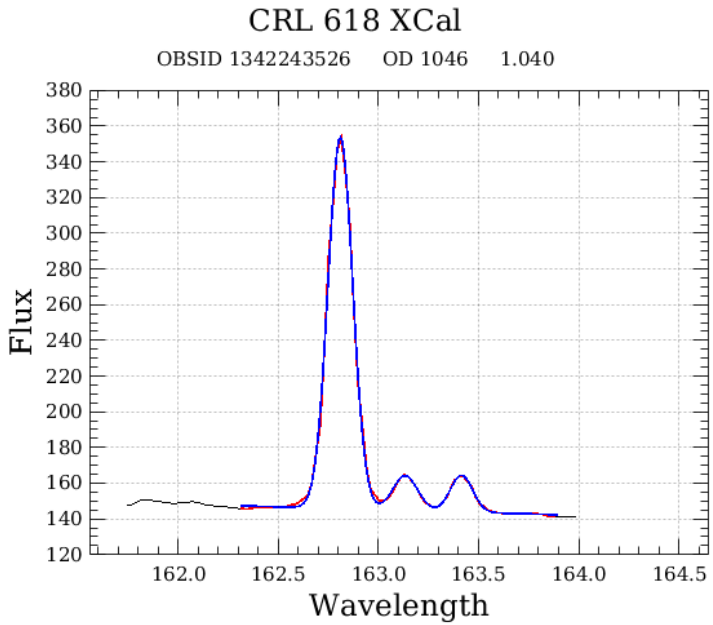






PACS Line Flux Analysis

- Absolute flux calibration uncertainties: 15% absolute flux calibration and 10% in-band accuracy.
- Line flux extraction:
  - Simultaneous fit of multiple Gaussians with a polynomial of order 1 for the continuum (widthFactor=4)



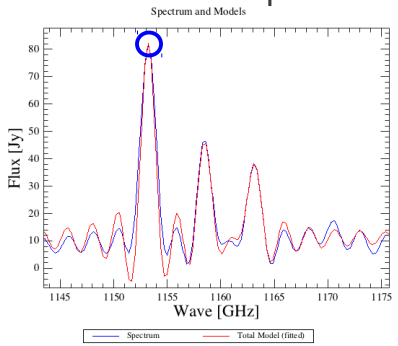
Line flux error is corresponds to the fitting error

- Final line fluxes per source and line are also computed as weighted average

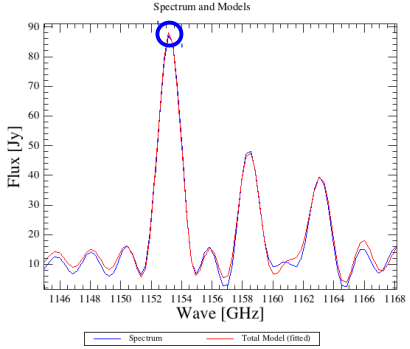
SPIRE Line Flux Analysis

- SPIRE Calibration for HIPE 11
- Absolute flux calibration accuracy: repeatability error 6%
- Line flux extraction:
  - The input 12CO lines (and nearby lines) are simultaneously fit with a Sinc models and a polynomial of order 2 for the continuum. The line width is kept fixed at the instrumental resolution, i.e. 1.2/π =0.38 GHz.
  - Line contamination at 1151 GHz: HCN and/or H2O lines. Simultaneous fit of 2 sinc functions for global line flux extraction. Line compound around the CO (10-9) feature.

RDor: SPIRE 1 sinc component fit

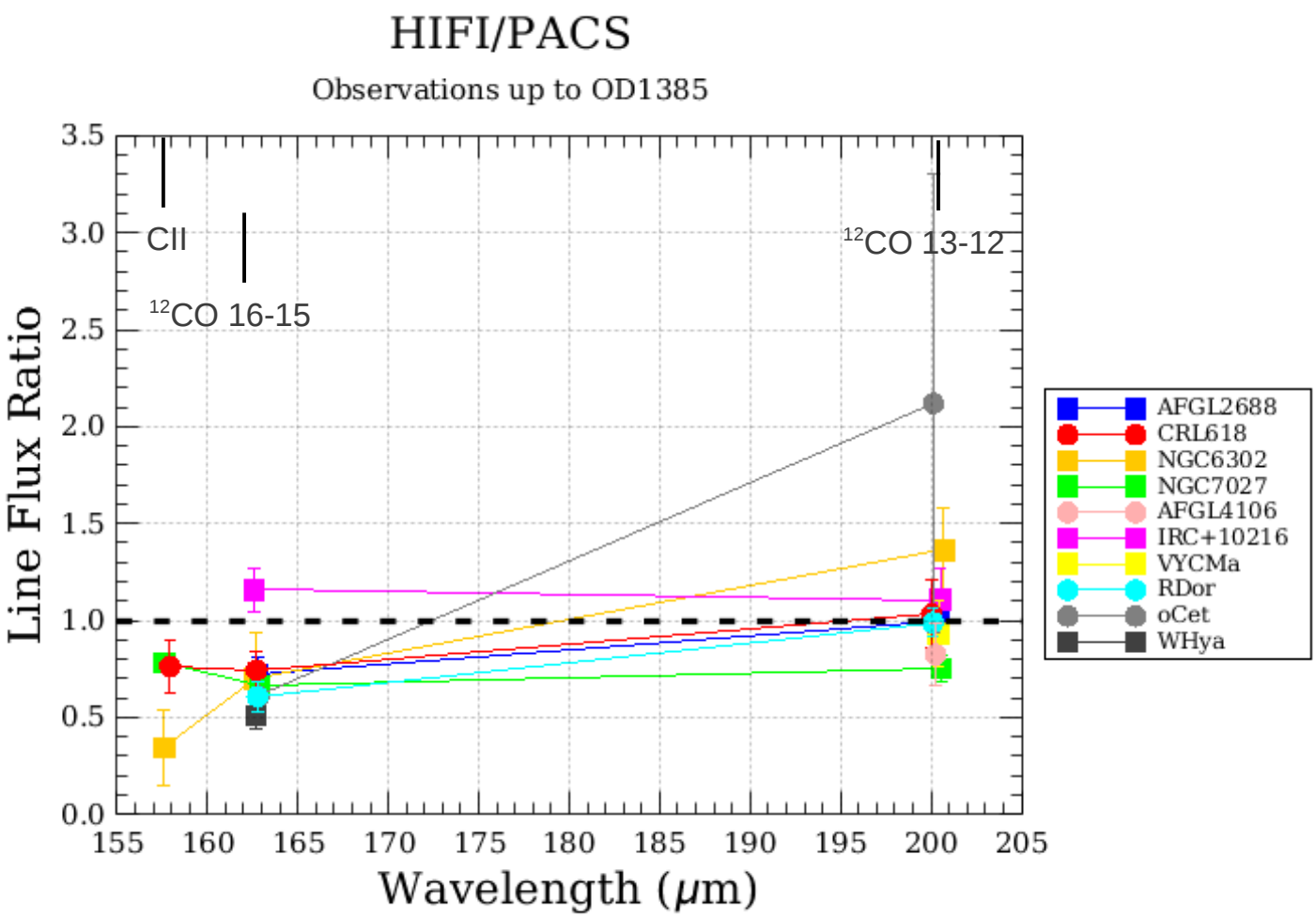


SPIRE 2 sinc component fit



- Final line fluxes per source and line are computed as the average, the error is given by the standard deviation of the sample.

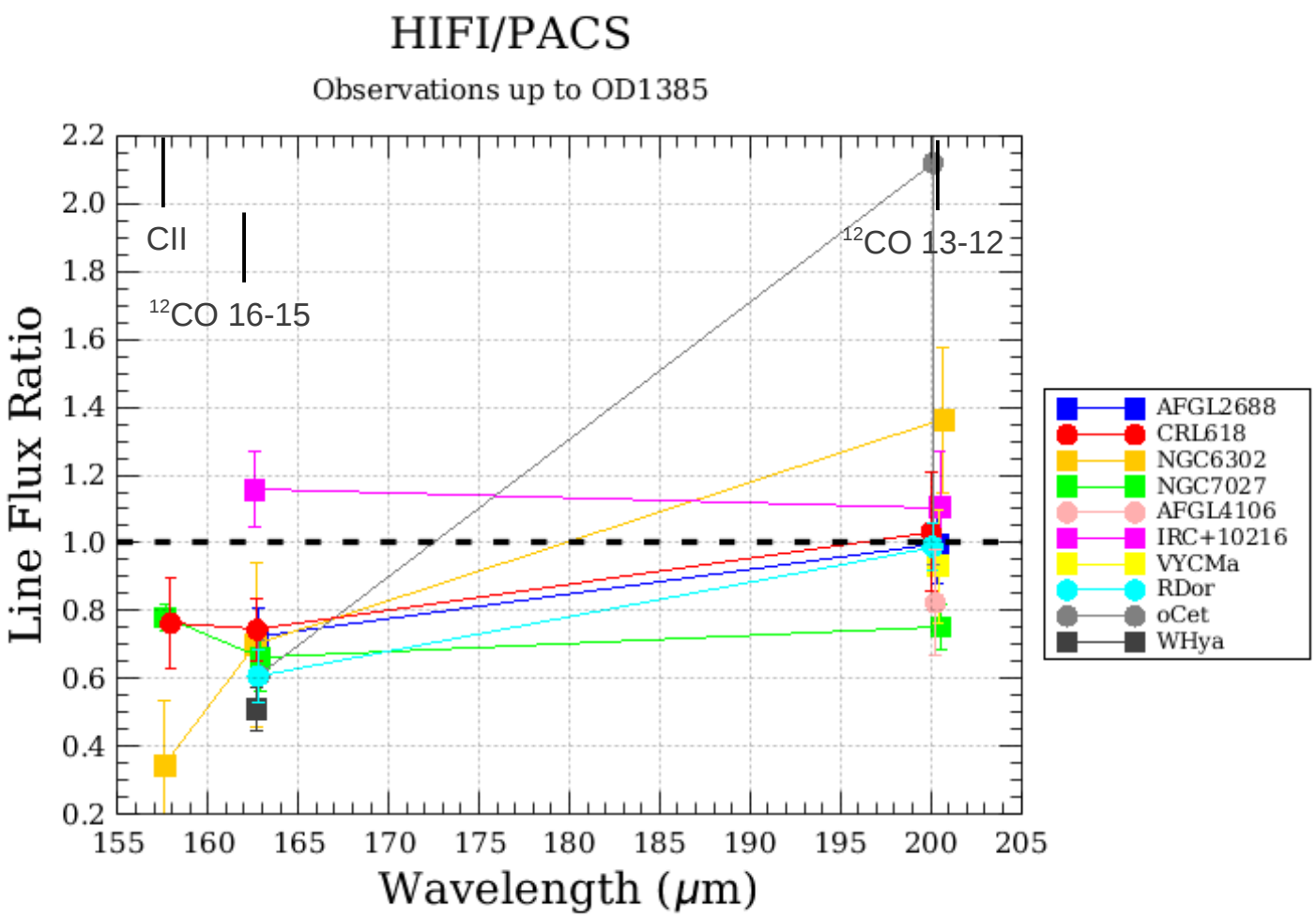
HIFI-PACS Line Flux Comparison



- AFGL4106, WHya and oCet (PACS) have only one measurement
- IRC+10216 is extended and variable in some lines
- CII line is extended

(*) Values are artificially slightly shifted in wavelength for visualization purposes

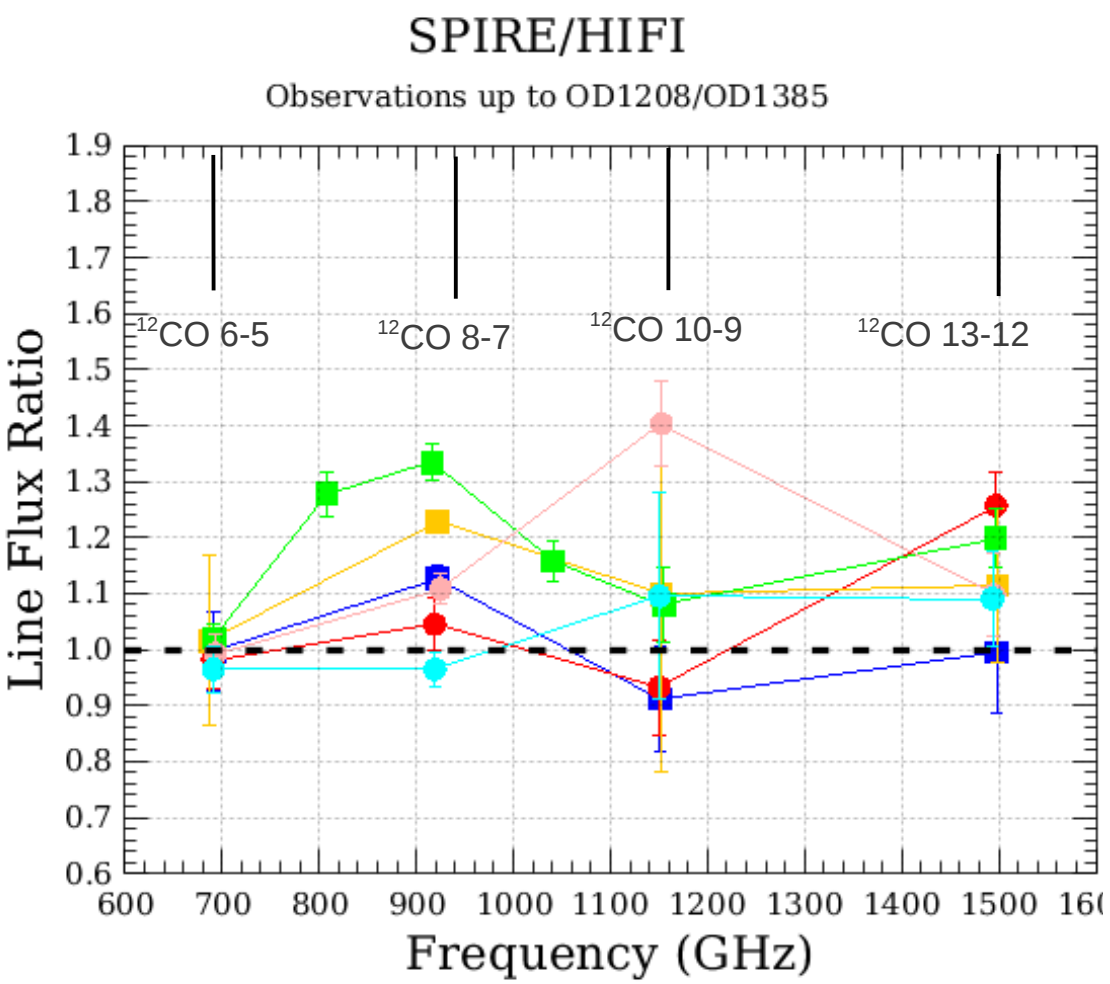
HIFI-PACS Line Flux Comparison



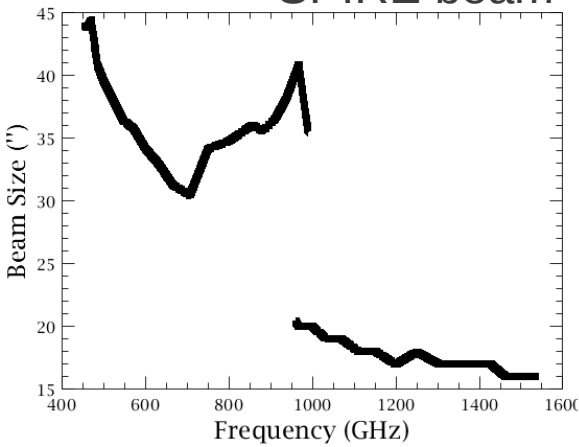
- AFGL4106, WHya and oCet (PACS) have only one measurement
- IRC+10216 is extended and variable in some lines
- CII line is extended

(*) Values are artificially slightly shifted in wavelength for visualization purposes

SPIRE-HIFI Line Flux Comparison



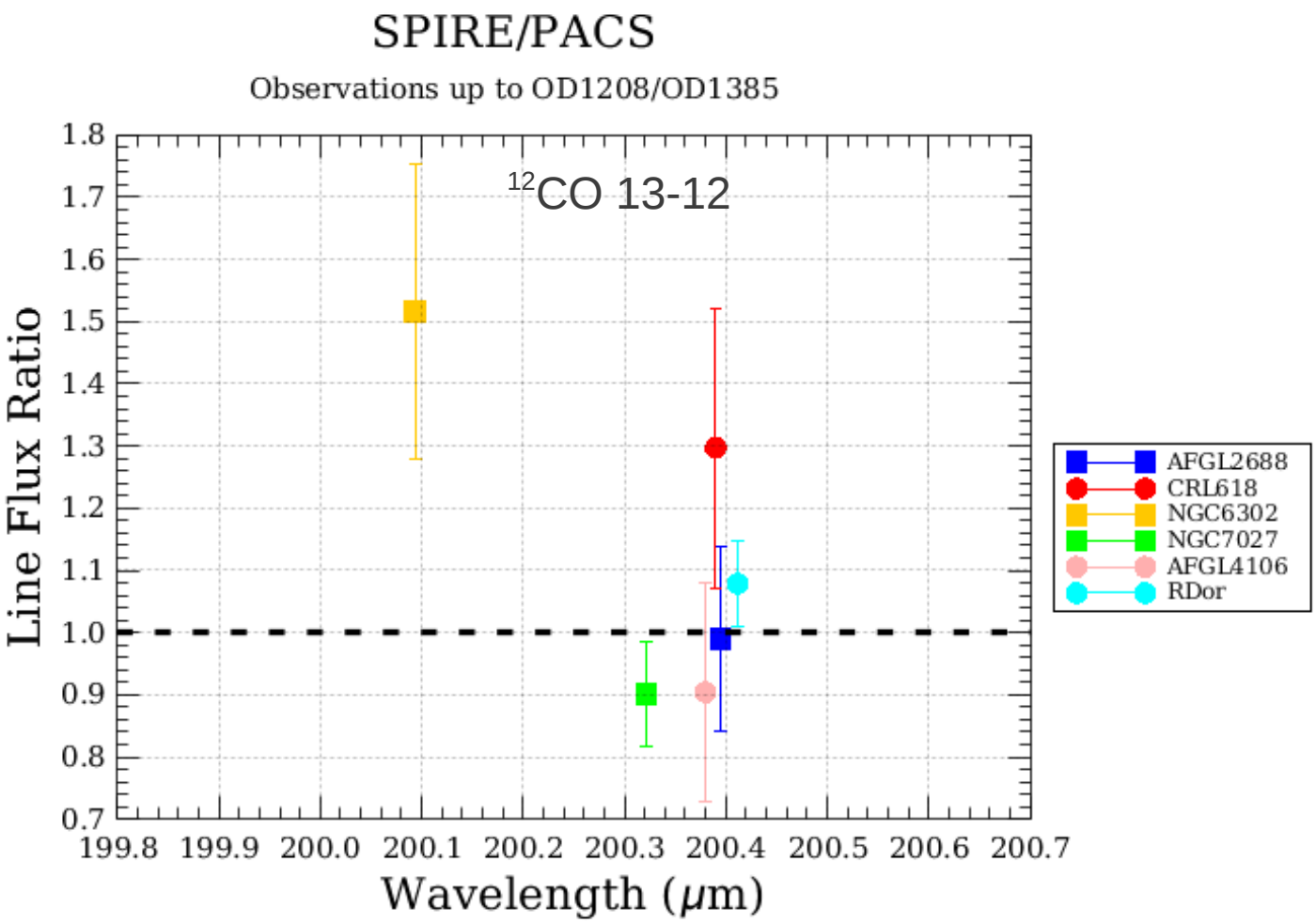
SPIRE beam



AFGL4106 was visited only once by PACS

(*) Values are artificially slightly shifted in frequency for visualization purposes

SPIRE-PACS Line Flux Comparison



AFGL4106 was visited only once by PACS

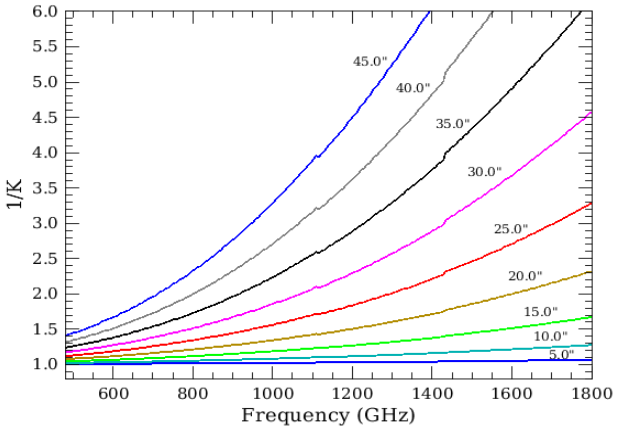
(*) Values are artificially slightly shifted in frequency for visualization purposes

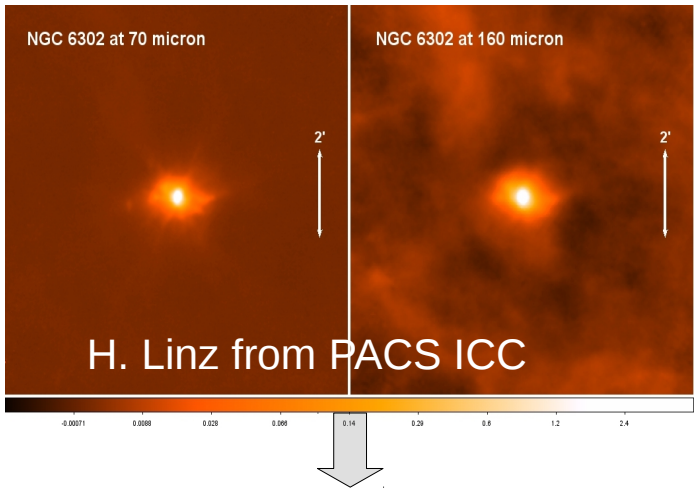
Treatment of Compact Sources

$$S[Jy] = \frac{2 \cdot k_B}{A_{geom} \cdot \eta_A} \cdot \frac{1}{K} T_A'[K]$$

Coefficient for a reduction in antenna temperature when observing a source of non-negligile diameter

$$K = \frac{1 - e^{-x^2}}{x^2} \qquad x = \sqrt{(\ln 2)} \cdot \frac{\theta_s}{\theta_B} \qquad \theta_B = \sqrt{\frac{4 \cdot ln2}{\pi} \Omega_{MB}} \qquad \Omega_{MB} = \frac{\eta_B \cdot \lambda^2}{\eta_A \cdot A_{geom}}$$



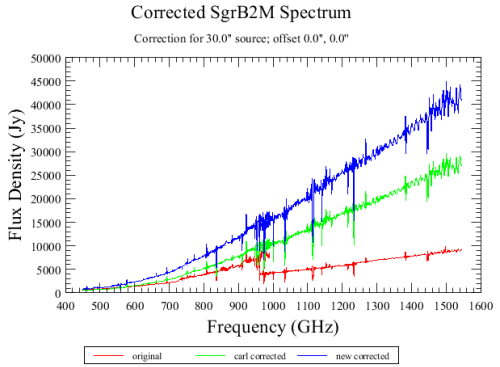


Initial spatial model

HIFI: convertKtoJy task

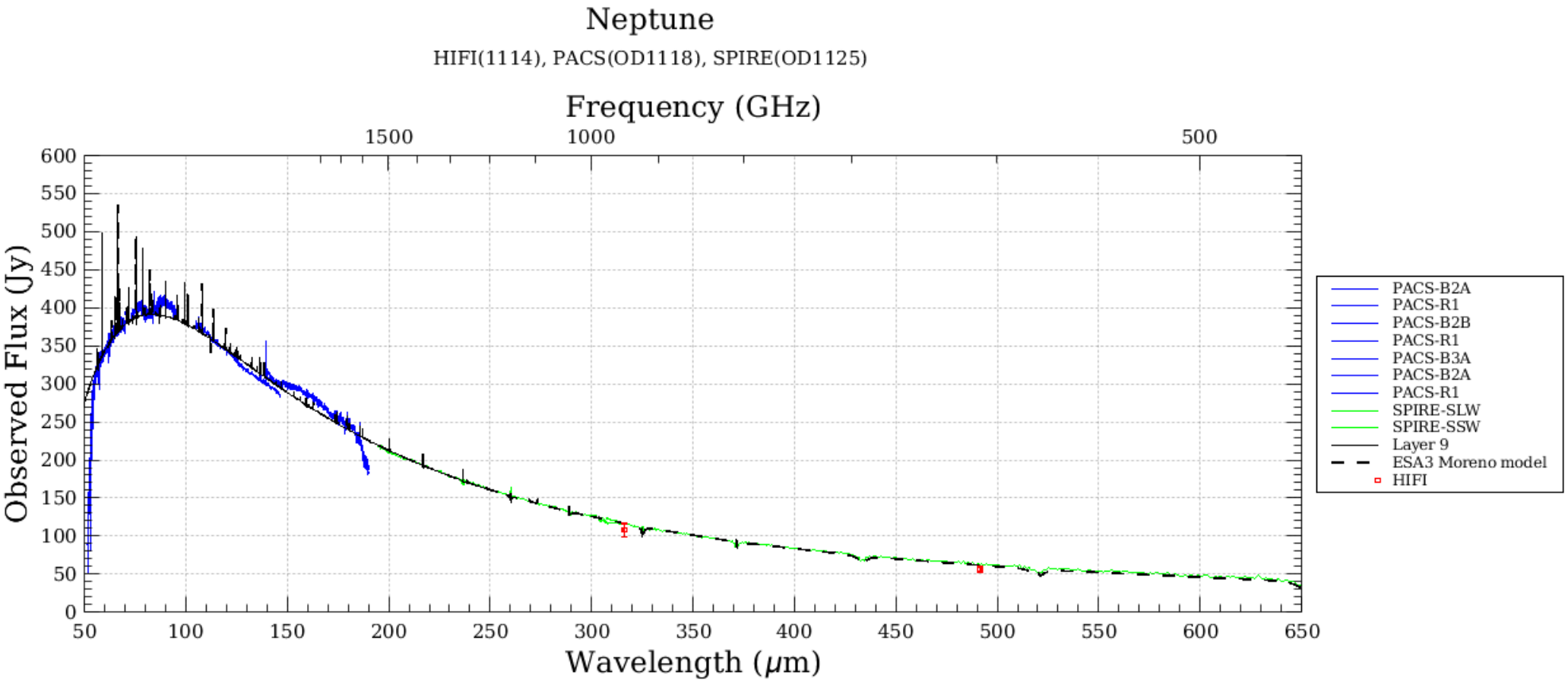
SPIRE Semi-extended Tool to refine source parameters

PACS: TBC



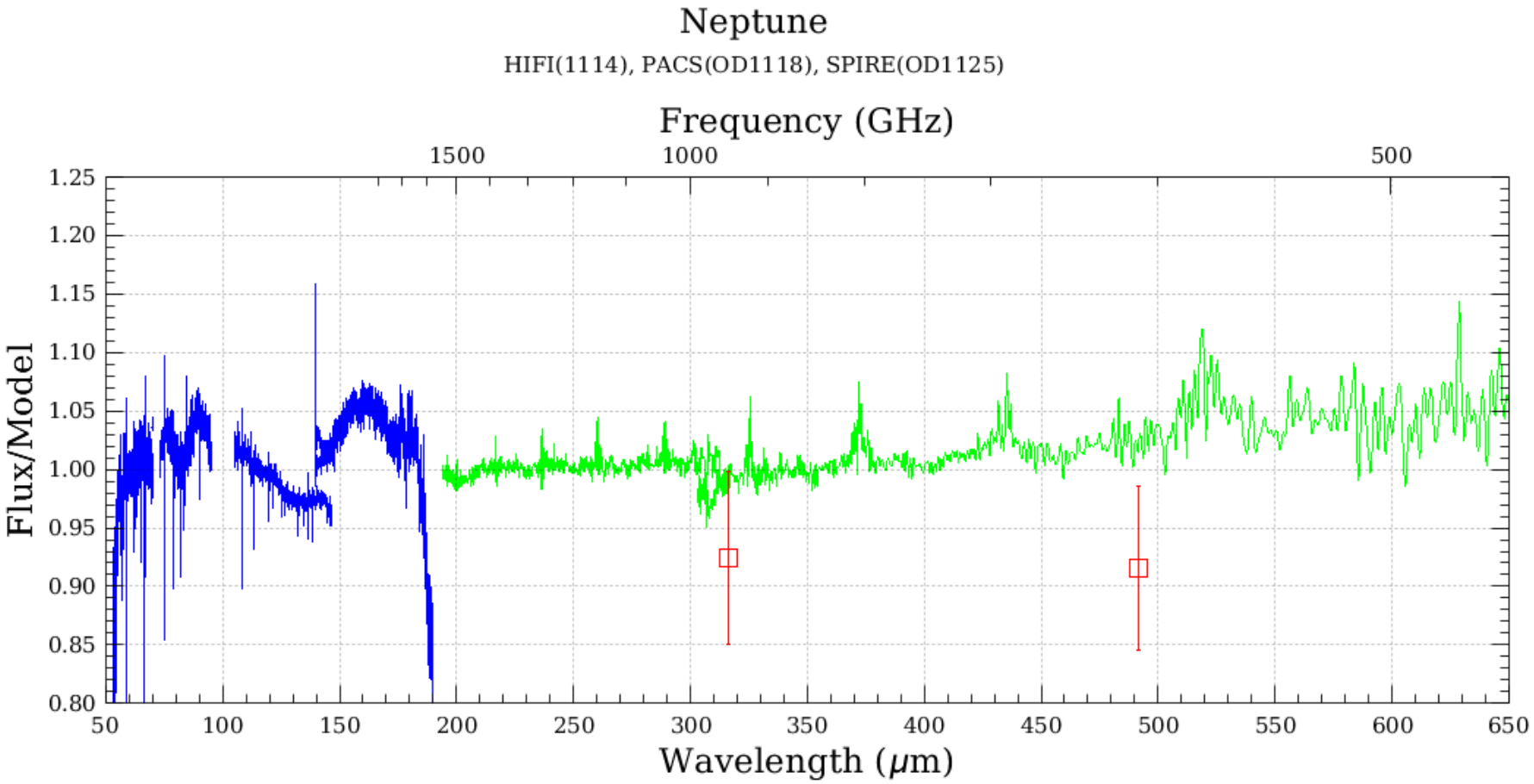
Continuum Source: Neptune

- Coordinated observations of Neptune to have flux variations within the model uncertainty



Continuum Source: Neptune

- Observations/Neptune Model (ESA3 Moreno)



Extended Source

- NGC 7023
- Beams characterization
- Line Integrated intensity comparisons

Conclusions

- PACS de-leaked red RSRF has brought CO13-12 line into the cross-comparisons.
- Mispointing corrections (PACS, HIFI) are definite improvements, more advanced corrections schemes are yet to come
- Correction for the electric standing wave decreases significantly the scatter for line fluxes at larger frequencies
- Proper treatment of compact sources will still improve the comparisons.
- Inter-spectrometer continuum comparison is within 10%
- Extended source comparison for some lines will come in the future.
- From here, to cross-calibration with space and ground-based observatories.

- Special thanks to ICCs representatives and many ICC people genuinely interested in cross-calibration