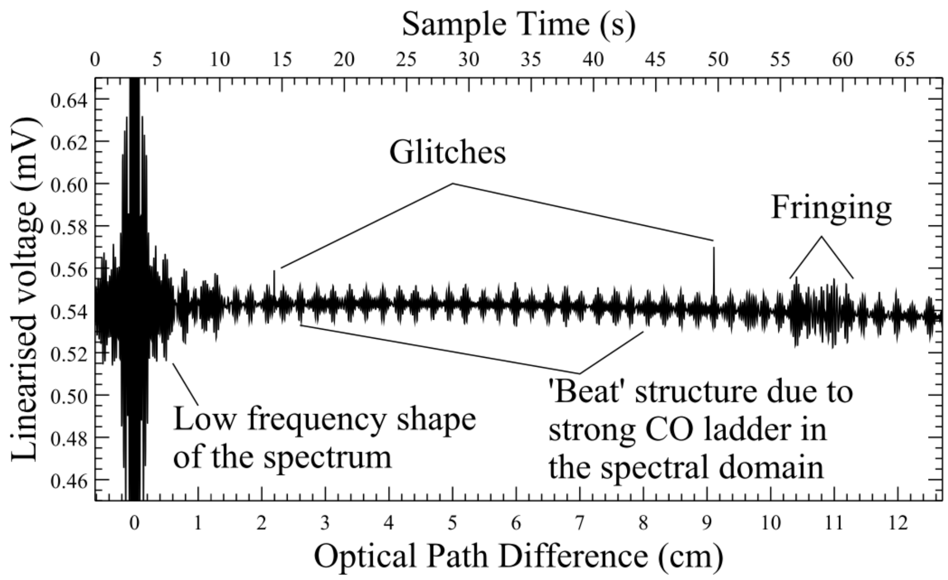
SPIRE Spectrometer: Pipeline Calibration

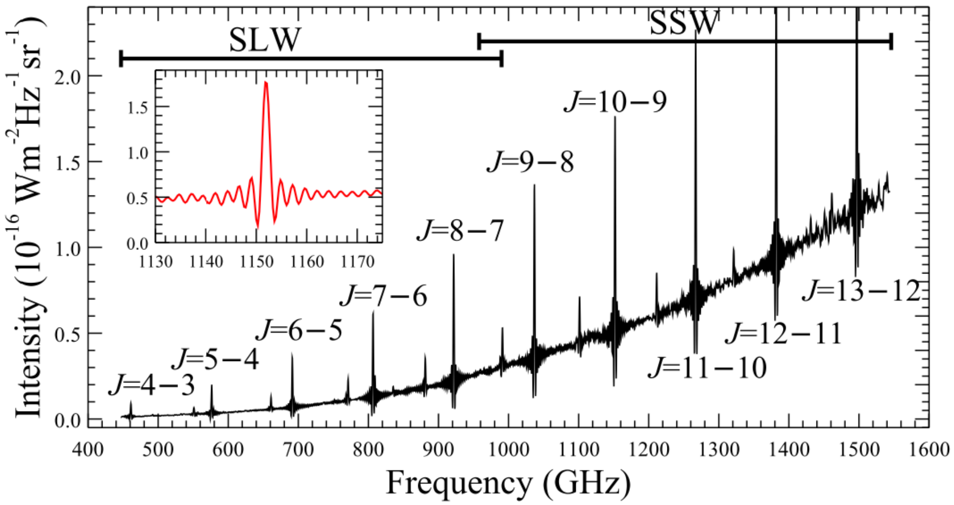
Nanyao Lu
NHSC/IPAC
(on behalf of the SPIRE ICC, HSC & NHSC)

SPIRE/FTS Interferogram



Pipeline with calibration products

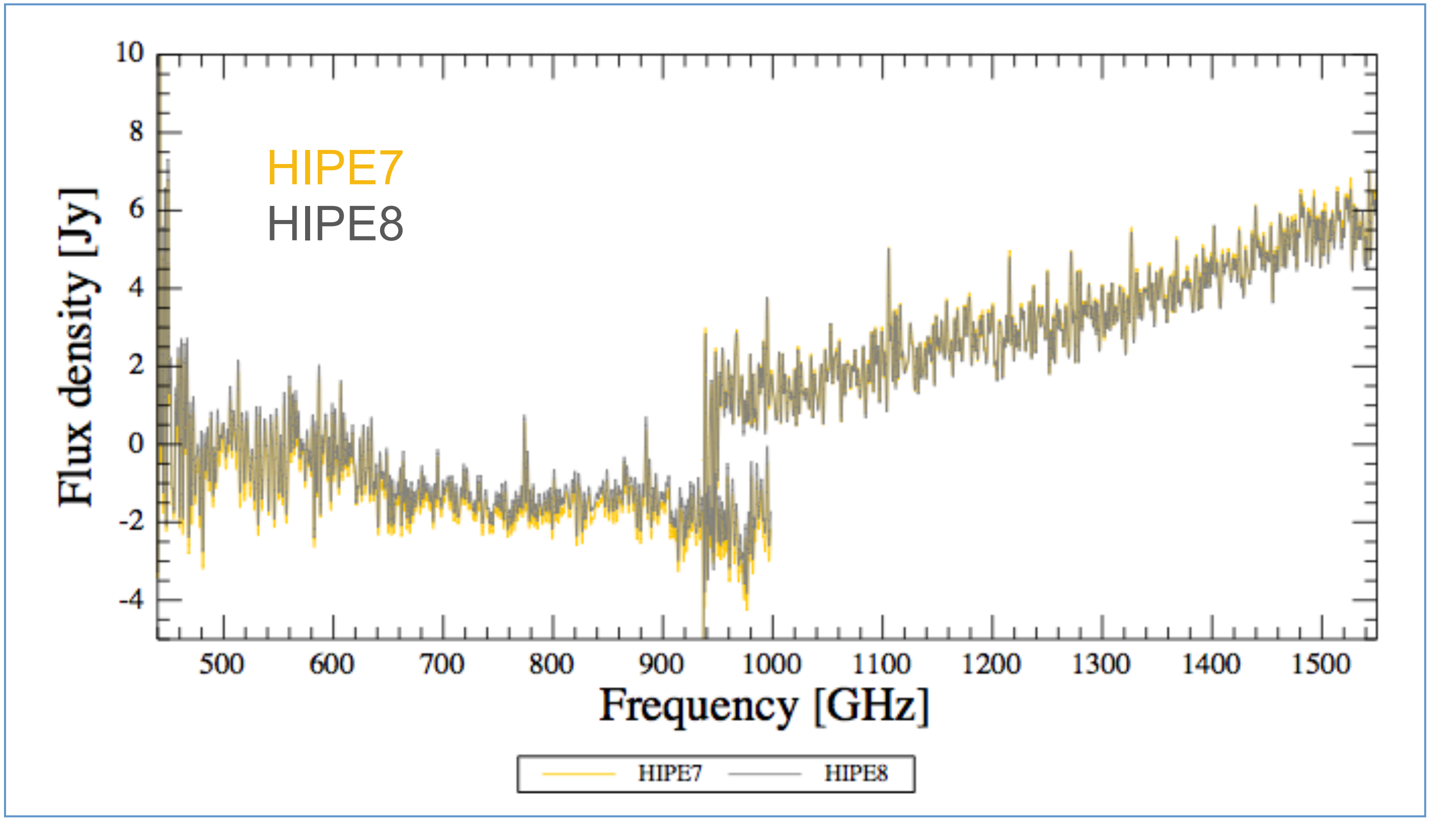
Spectrum



Probing molecular, atomic and ionized gases via spectral lines [e.g., CO ladder, [CI] 360 & 609 um, [NII] 205um, H_2O, HF(1-0)].

Spectrum Example from Early Calibrations

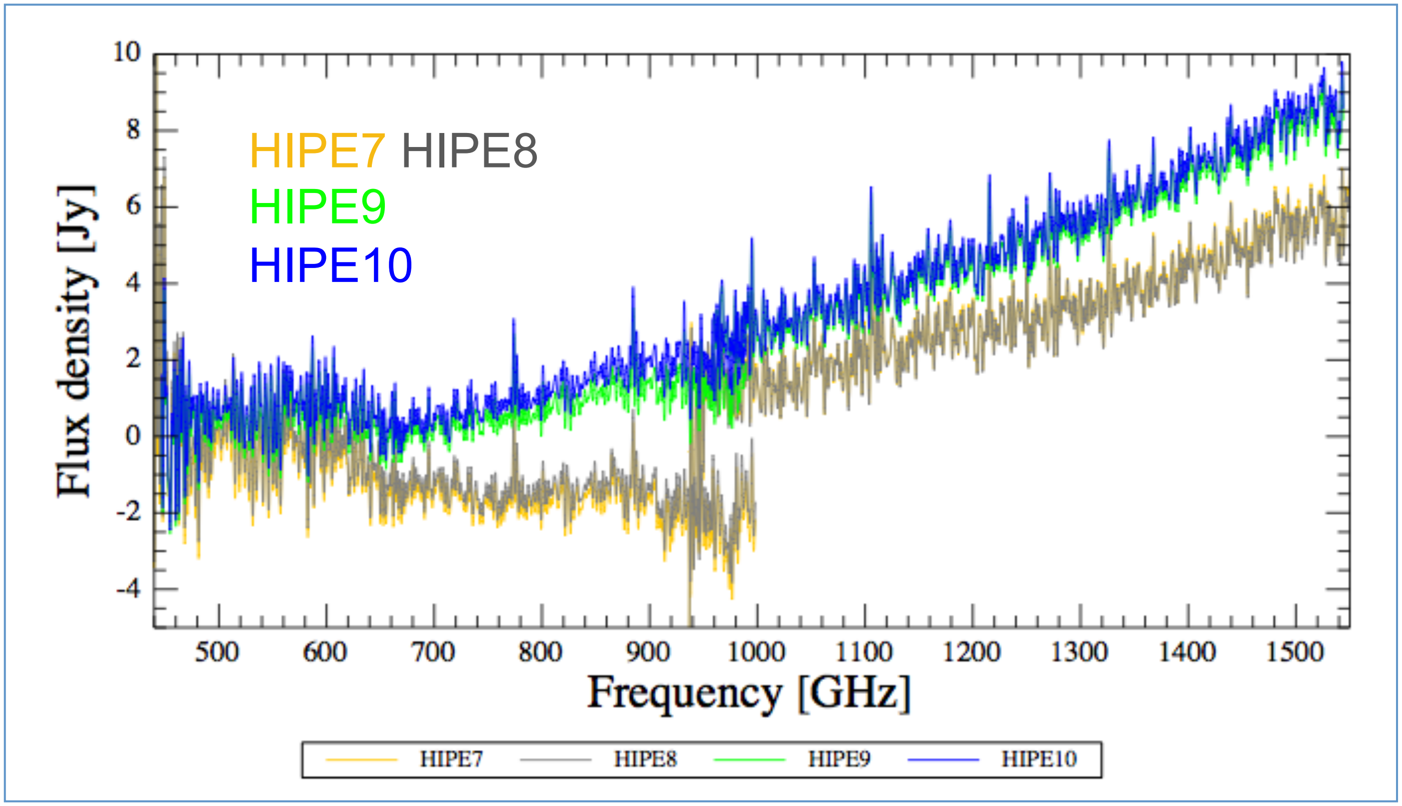
Mrk 231 observed on OD209



Standard pipeline Level-2 output

Calibration Got Better

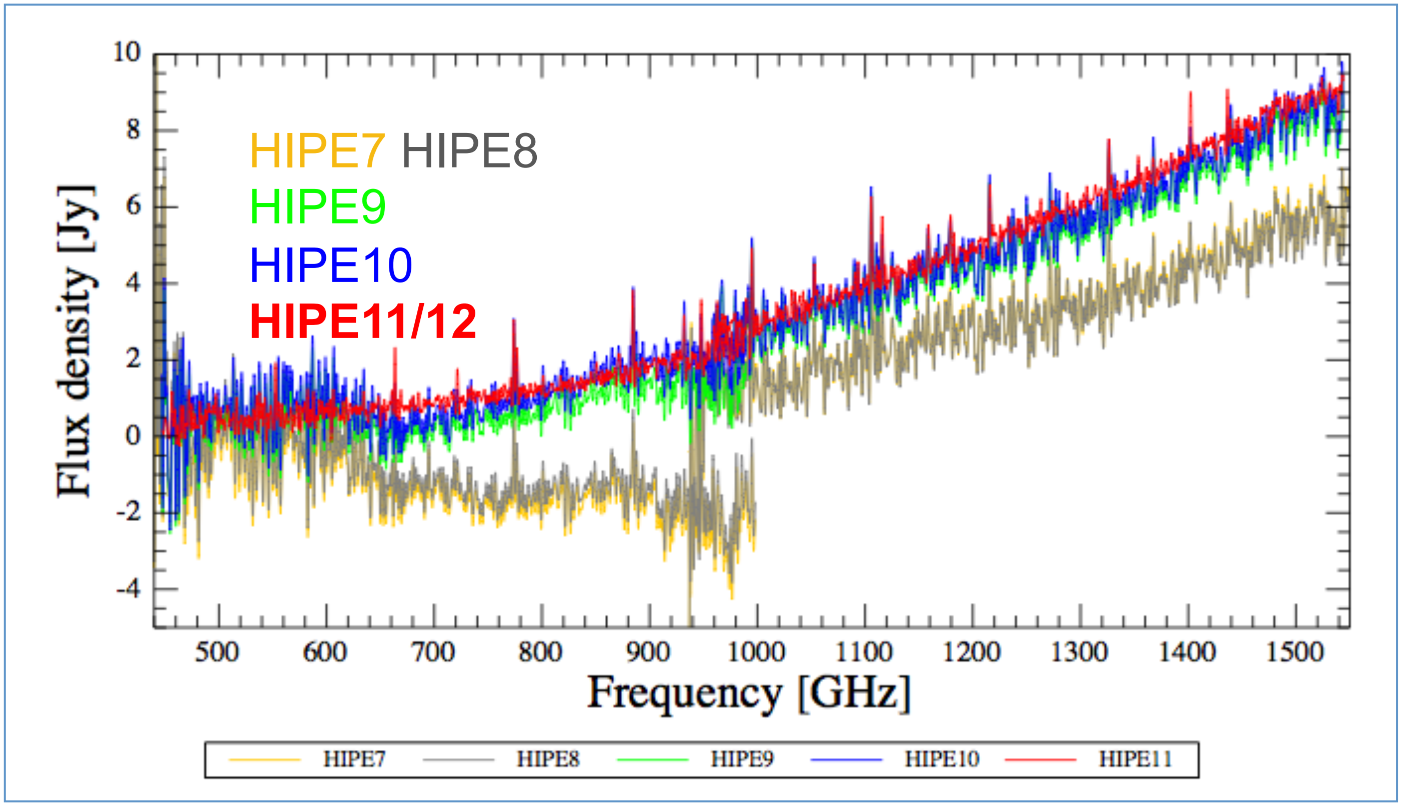
Mrk 231 observed on OD209



Standard pipeline Level-2 output

Current Calibration: HIPE 11/12

Mrk 231 observed on OD209



Standard pipeline Level-2 output

Calibration Documents

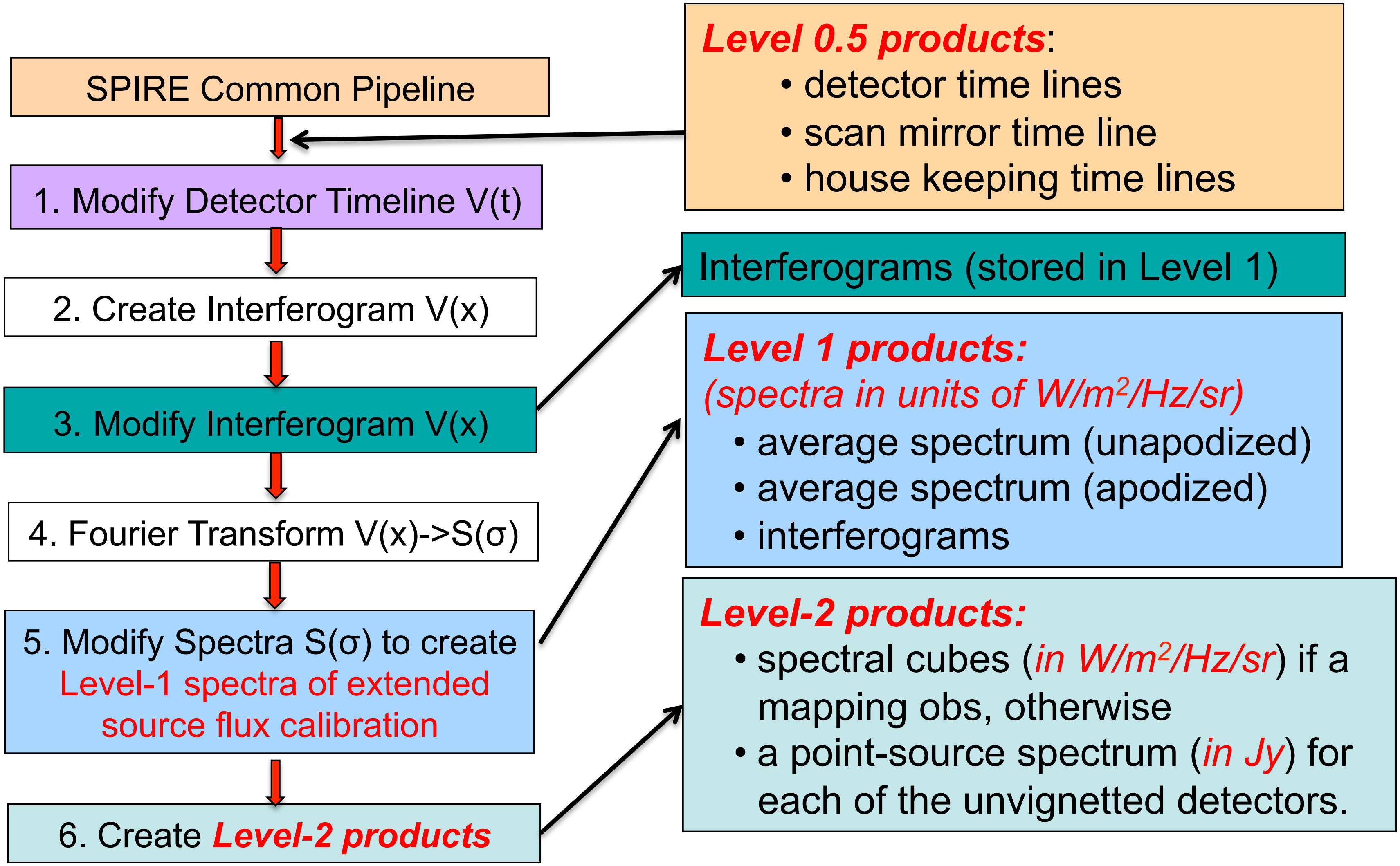
- **The SPIRE Data Reduction Guide** (DRG; data structure, processing, reprocessing, many details and cookbooks)
- **The SPIRE Handbook** (instrument observing modes, calibration…)

- Swinyard et al. 2014, MNRAS, 440, 3658 - **FTS calibration**
- Makiwa et al. 2013, Applied Optics, 52, 3864 - **FTS beams**
- Wu et al. 2013, A&A, 556, 116 - **Semi-extended sources**
- …

- Public wiki on SPIRE
http://herschel.esac.esa.int/twiki/bin/view/Public/SpireCalibrationWeb

The Pipeline

(cf. SPIRE DRG Sect. 7.3)



SPIRE Common Pipeline

1. Modify Detector Timeline V(t)

2. Create Interferogram V(x)

3. Modify Interferogram V(x)

4. Fourier Transform V(x)->S(σ)

5. Modify Spectra S(σ) to create Level-1 spectra of extended source flux calibration

6. Create ***Level-2 products***

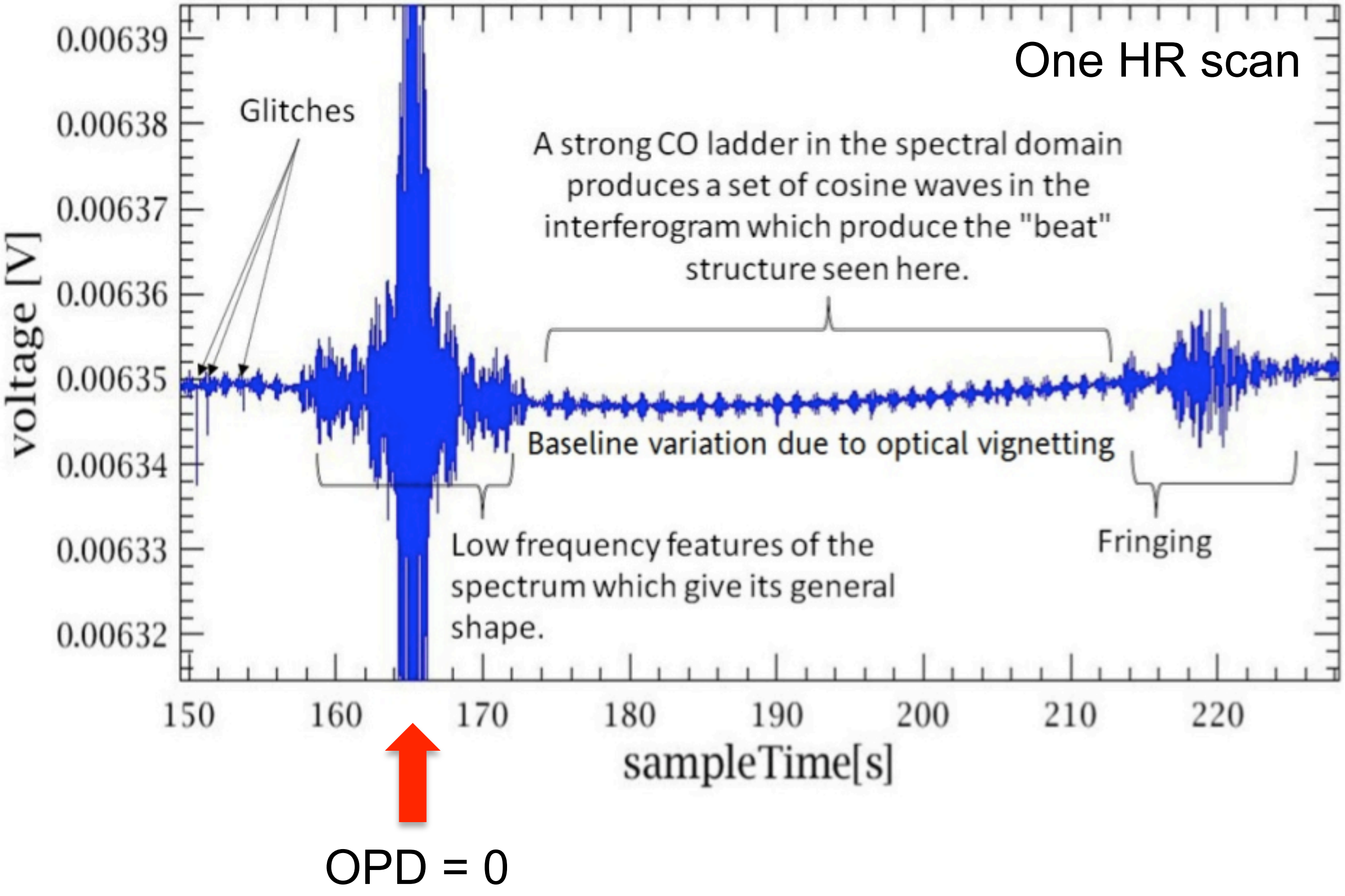
Level 0.5 products:
- detector time lines
- scan mirror time line
- house keeping time lines

Interferograms (stored in Level 1)

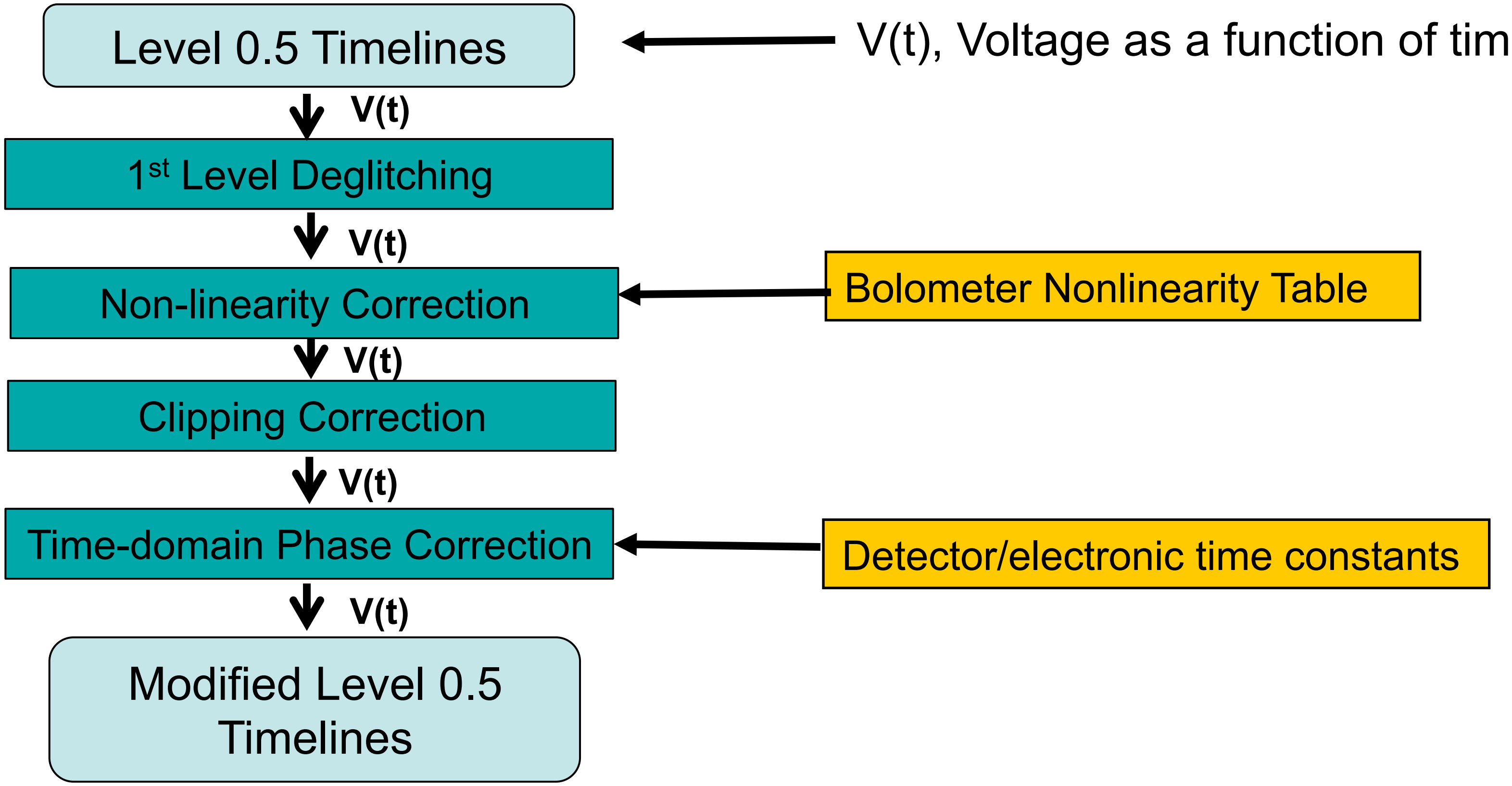
Level 1 products:
(spectra in units of $W/m^2/Hz/sr$)
- average spectrum (unapodized)
- average spectrum (apodized)
- interferograms

Level-2 products:
- spectral cubes (*in $W/m^2/Hz/sr$*) if a mapping obs, otherwise
- a point-source spectrum (*in Jy*) for each of the unvignetted detectors.

Spectrometer Detector Time Line



Pipeline Step 1: Modify Timelines



Level 0.5 Timelines ← V(t), Voltage as a function of time

V(t)

1st Level Deglitching

V(t)

Non-linearity Correction ← Bolometer Nonlinearity Table

V(t)

Clipping Correction

V(t)

Time-domain Phase Correction ← Detector/electronic time constants

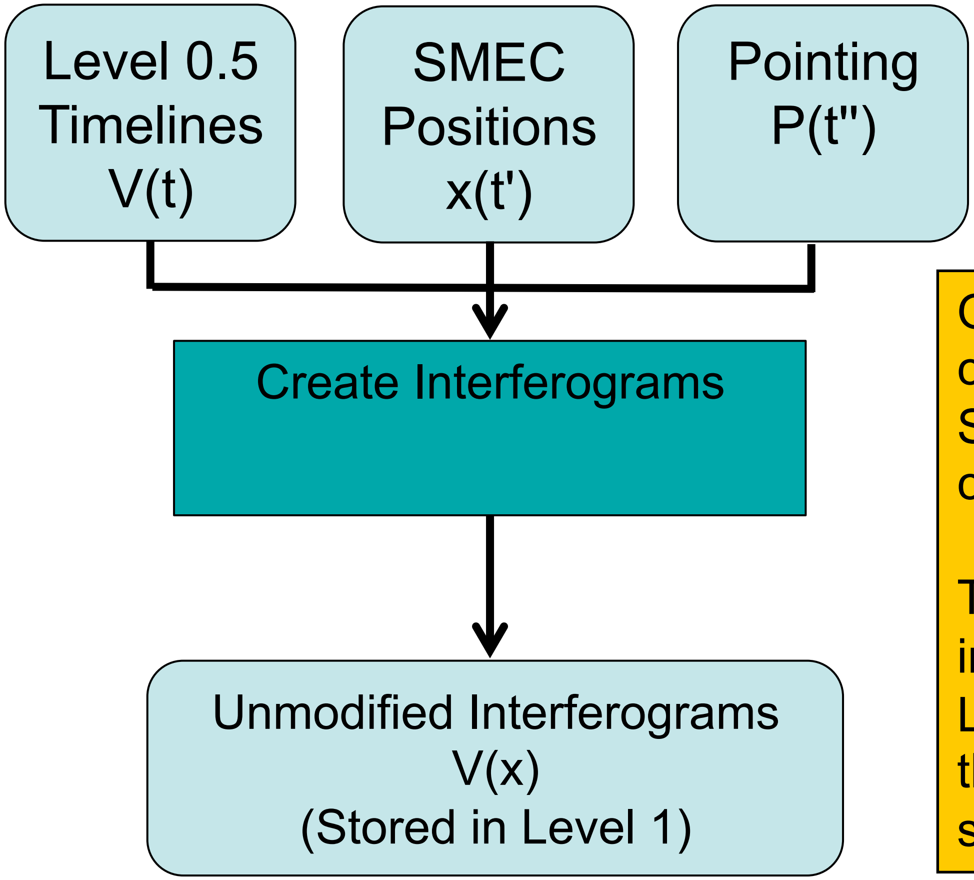
V(t)

Modified Level 0.5 Timelines

(cf. SPIRE DRG Sect. 7.3)

(cf. SPIRE DRG Sect. 7.3)

Pipeline Step 2: Create Interferograms



Level 0.5 Timelines V(t)

SMEC Positions x(t')

Pointing P(t'')

Create Interferograms

Unmodified Interferograms V(x) (Stored in Level 1)

Once time domain processing is complete, the detector signals and SMEC positions can be merged to create interferograms.

The created “unmodified” interferograms are also stored in Level 1 in case users want to do their own interferogram-to-spectrum process.

x = The difference between the 2 optical paths in the interferometer

Pipeline Step 3: Modify Interferograms

(Level 1) Interferograms

V(x)

Baseline Removal

V(x)

2^{nd} Level Deglitching

V(x)

Phase Correction

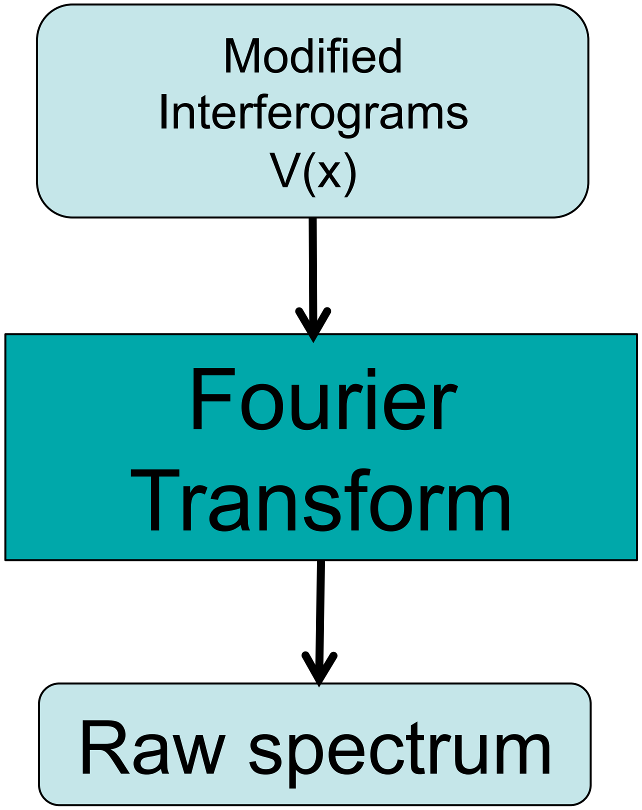
Correct for asymmetry between the two optical paths in the interferometer

V(x)

Modified Interferogram Products
(both unapodized and apodized)

(cf. SPIRE DRG Sect. 7.3)

Pipeline Step 4: Fourier Transform



Modified Interferograms V(x)

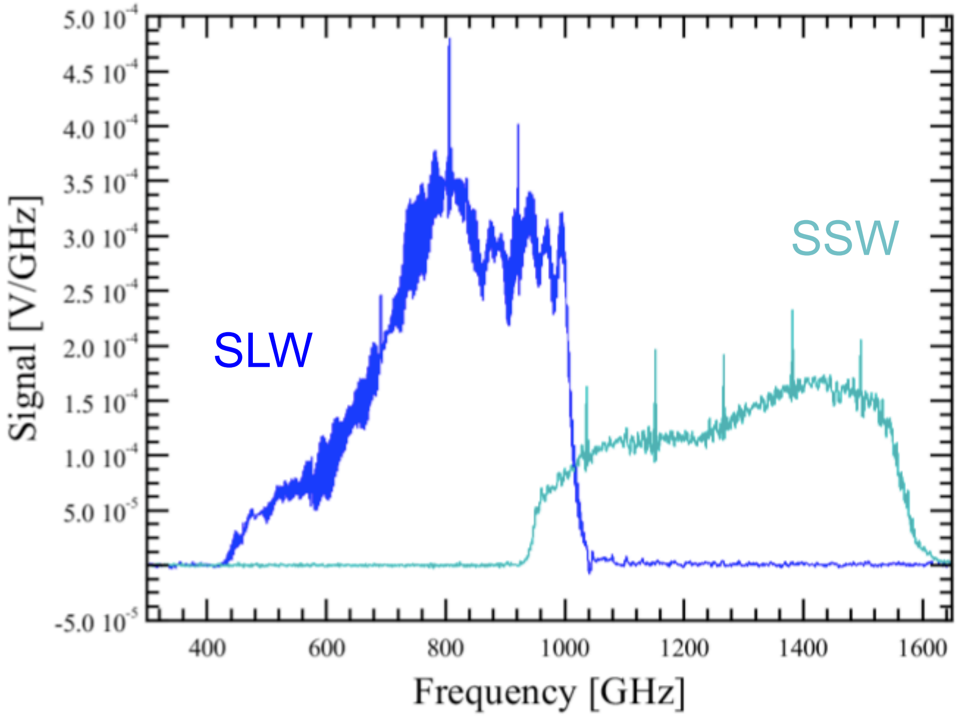
Fourier Transform

Raw spectrum

Apply the Fourier Transform to each interferogram to create a set of spectra for each spectrometer detector. The spectra are in units of V/GHz, not yet flux calibrated.

(cf. SPIRE DRG Sect. 7.3)

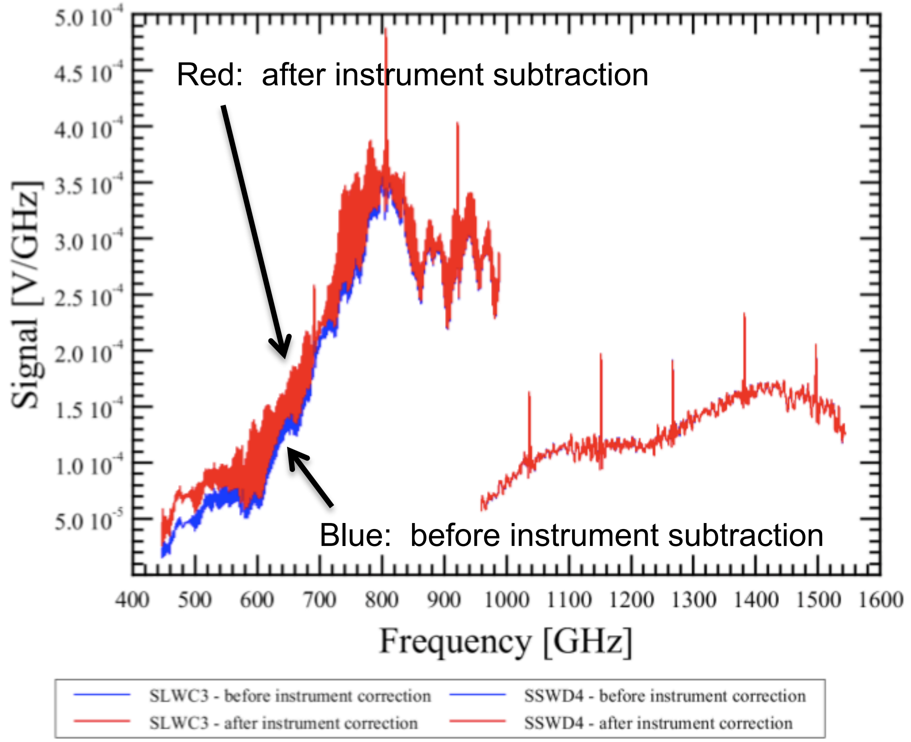
What is in the Raw Spectrum?



$$V_{Measured}(\sigma) = V_{Source}(\sigma) + V_{Telescope}(\sigma) + V_{Instrument}(\sigma)$$

@80K @4-5K

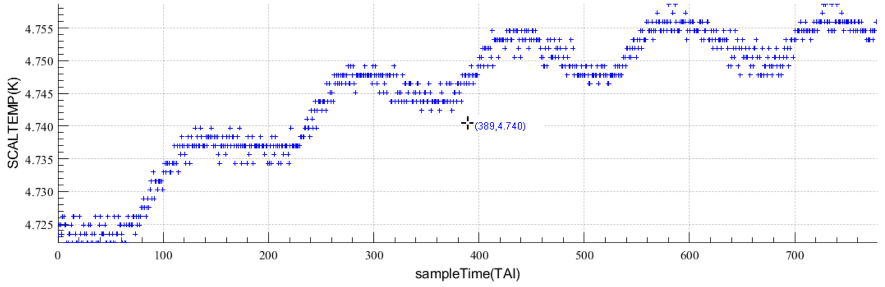
Instrument Background Emission


Red: after instrument subtraction

Blue: before instrument subtraction

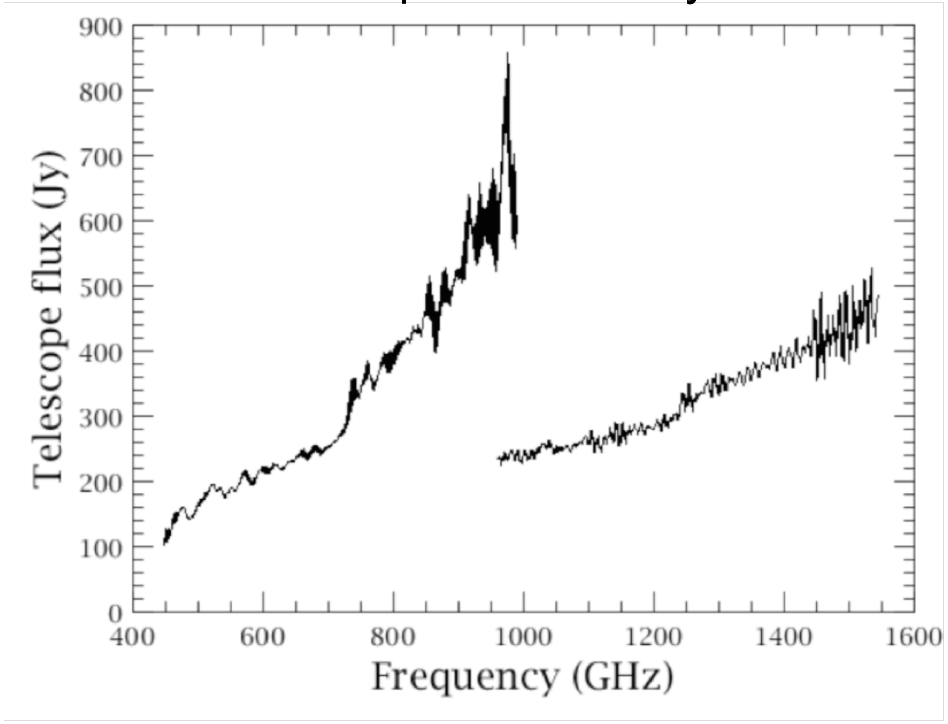
At about 4-5K, instrument emission is only significant at the long wavelength end of SLW.

Instrument temperature varies with time:

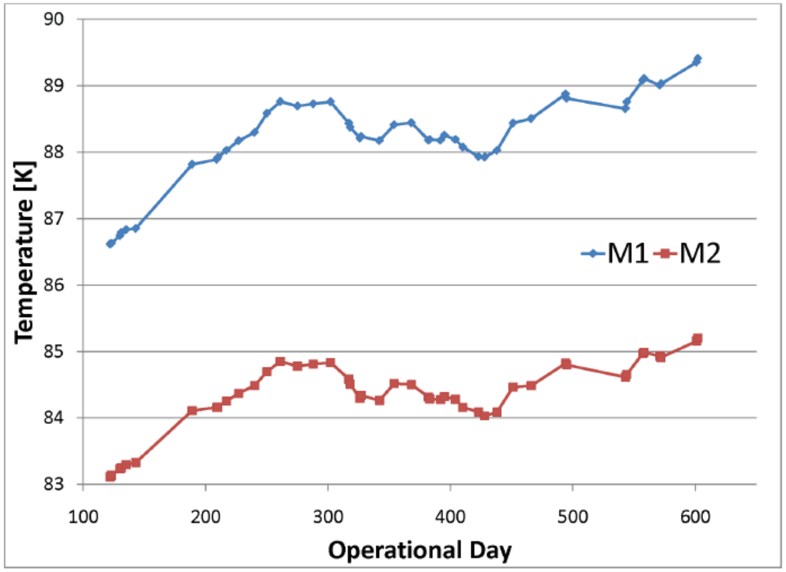


Warm Telescope Background Emission

Point source-equivalent telescope model in Jy:

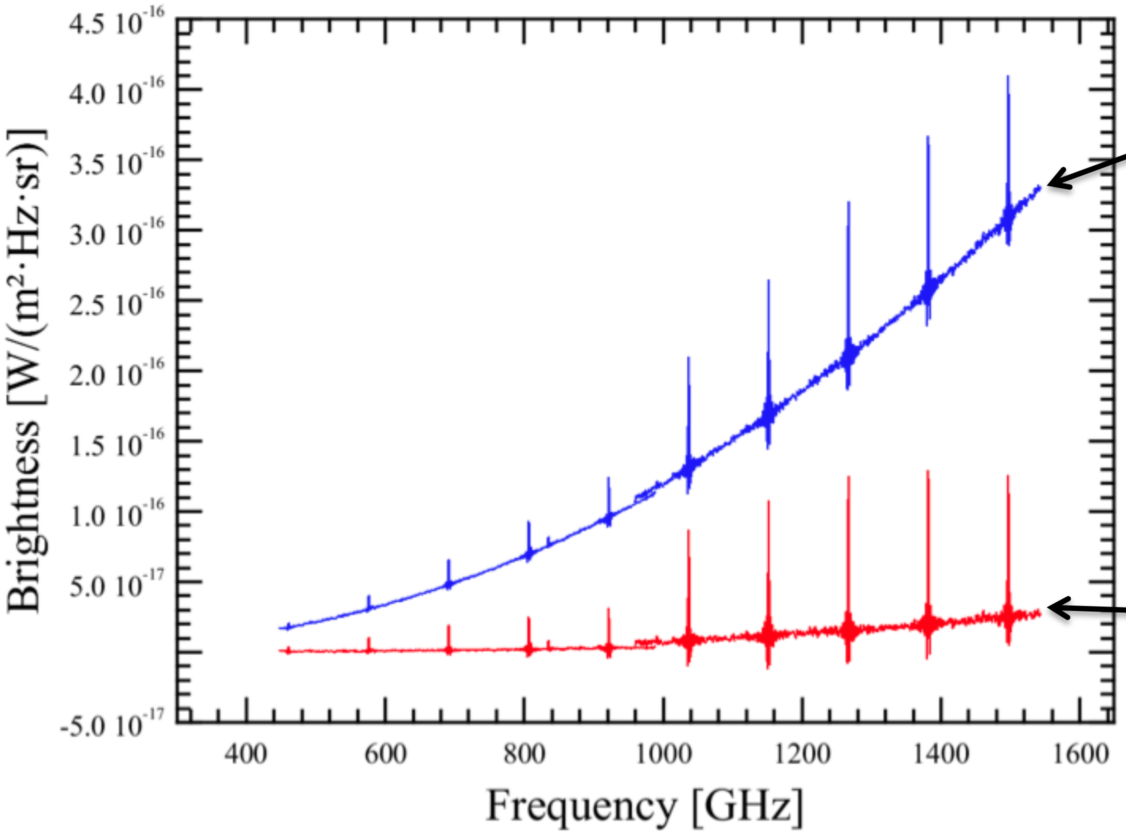


Telescope temperatures vary with time:



Telescope Background: A Typical Case

Your observations are most likely dominated by the telescope emission!



Telescope + Source

Telescope model is good to ~ 0.1%, or ~0.5 Jy (as of HIPE 11)

Source only

Flux Calibration Scheme

Level-1 spectrum

Brightness in W/m^2/Hz/sr
assumes extended emission

$$I = \frac{1}{R_{tel}} [S - R_{inst} M_{inst}] - M_{tel}$$

Telescope RSRF

Raw spectrum

Instrument model and RSRF important for SLW (T ~ 4-5 K)

Telescope model

Level-2 spectrum

Flux Density in Jy
assumes point-like emission

$$f = C_{point} I$$

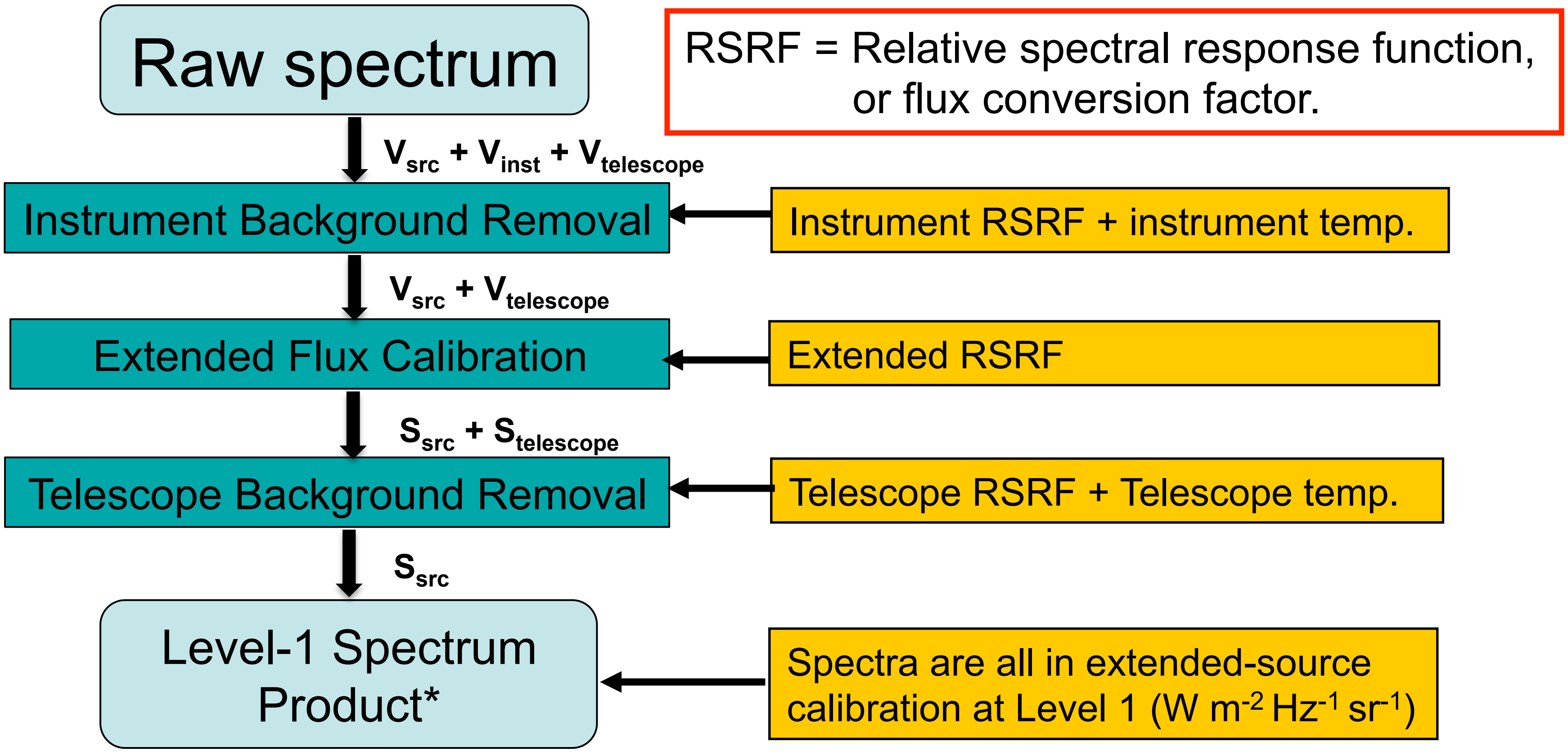
Point source conversion factor (= R_{tel}/R_{point})

RSRFs are empirically derived by observing a source with a known spectrum and dividing by a model:

R_{tel}: *Dark Sky (= the telescope)*
R_{point}: *Uranus*

(See *Swinyard et al. 2014, MNRAS, 440, 3658*)

Pipeline Step 5: Modify Spectra



RSRF = Relative spectral response function, or flux conversion factor.

Raw spectrum

$V_{src} + V_{inst} + V_{telescope}$

Instrument Background Removal ← Instrument RSRF + instrument temp.

$V_{src} + V_{telescope}$

Extended Flux Calibration ← Extended RSRF

$S_{src} + S_{telescope}$

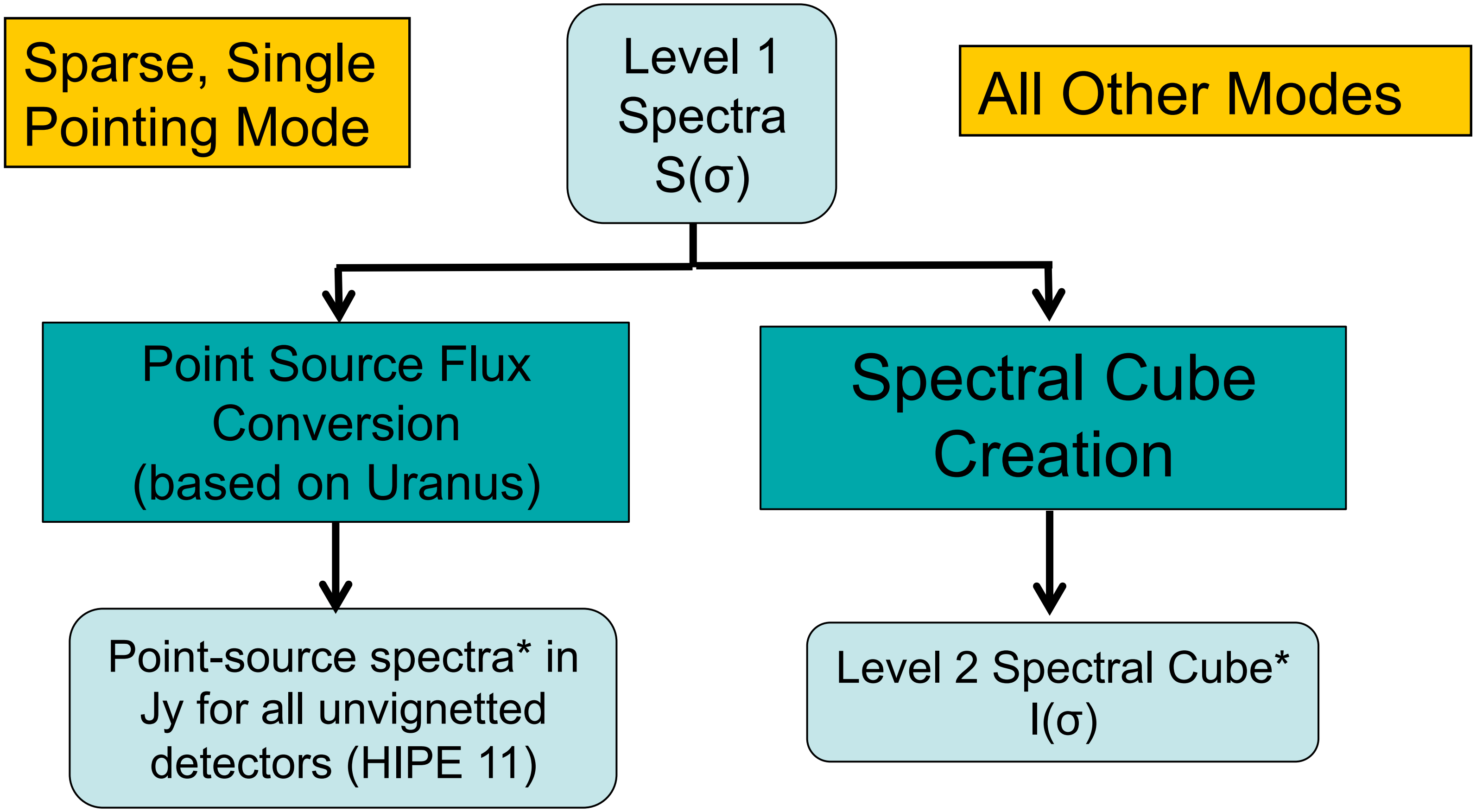
Telescope Background Removal ← Telescope RSRF + Telescope temp.

S_{src}

Level-1 Spectrum Product* ← Spectra are all in extended-source calibration at Level 1 (W m^{-2} Hz^{-1} sr^{-1})

* Both unapodized and apodized spectra [using the default apodization func. NB(1.5)]

Pipeline Step 6: Create Level-2 Products



Sparse, Single Pointing Mode

Level 1 Spectra S(σ)

All Other Modes

Point Source Flux Conversion (based on Uranus)

Spectral Cube Creation

Point-source spectra* in Jy for all unvignetted detectors (HIPE 11)

Level 2 Spectral Cube* I(σ)

* Both unapodized and apodized data [using the default apodization func. NB(1.5)]

Calibration Uncertainties (HIPE 11 onward)

- **Point sources observed on the centre detectors** (SSWD4 and SLWC3):
  - Absolute uncertainty **±6%**, with the following contributions:
    1. Systematic uncertainty in Uranus model: ±3%
    2. Statistical repeatability (pointing corrected): ±1%
    3. Uncertainties in the instrument and telescope model - additive continuum offset error of 0.4 Jy for SLW and 0.3 Jy for SSW
    4. The effect of the *Herschel* APE.
- **Sparse observations of significantly extended sources:**
  - Absolute uncertainty **±7%,** with the following contributions:
    1. Uncertainty comparing telescope and Uranus calibration: ±3%
    2. Systematic uncertainty in Uranus model: ±3%
    3. Systematic reproducibility of telescope model: 0.06%;
    4. Statistical repeatability estimated at ±1%
    5. Additive continuum offset of 3.4×10^{-20} W/m^2/Hz/sr for SLW and 1.1×10^{-19} W/m^2/Hz/sr for SSW.
- **Mapping mode:**
  - Overall repeatability **±7%**

- **Wavelength calibration:**
  - 5 - 7 km/s for line velocity.

(See *Swinyard et al. 2014, MNRAS, 440, 3658*)