The Herschel Legacy Calibration

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Instrument and Calibration Scientists Team lead

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European Space Agency

Outline

1. The POP Objectives from the Calibration Perspective
2. The Herschel Calibration Steering Group and its Legacy
3. Instrument Calibration Achievements during the POP
4. Science-readiness of the Data Products
5. Conclusions and Remaining Work in the POP

The Post-Operations Phase Calibration Plan

- *Following the HSC POP Plan (HERSCHEL-HSC-DOC-1987), the calibration effort in POPs is organised around the following pillars:*
  - Liaison between Instrument teams, NHSC, and Herschel SOC
  - Support to data product calibration improvement both via software and calibration model/files updates – includes software and product validation campaigns
  - Provision of reference documentation for the Legacy Phase (instrument handbooks and DP manuals, pocket guides, web pages, etc)
  - Community Support in the exploitation of the Herschel data (workshops, helpdesk, video tutorials, DP Interest Mailing Lists)
  - Improvement of the reconstructed attitude (pointing)
  - Coordination of cross-calibration efforts among Herschel instruments, and between Herschel and other observatories
  - Support to related calibration for other observatories (e.g. ALMA)
  - Validation of deliveries (products/scripts) from Herschel Key Projects (*User-Provided Data Products – UPDPs*) prior to ingestion into Archive

The Post-Operations Phase Calibration Plan

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Top priority

- Liaison between Instrument teams, NHSC, and Herschel SOC
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- Improvement of the reconstructed attitude (pointing)

Low priority

- Coordination of cross-calibration efforts among Herschel instruments, and between Herschel and other observatories
- Support to related calibration for other observatories (e.g. ALMA)

Basically de-scoped

- Validation of deliveries (products/scripts) from Herschel Key Projects (*User-Provided Data Products – UPDPs*) prior to ingestion into Archive

What is the Herschel Legacy Calibration ?

- *Prime and Secondary Calibrator models*
- *Calibration software and calibration files*
  - The combination of coded algorithms and instrument characterisation files (e.g. PSFs, spectral responses, photometer filter curves, etc) turned into the instrument pipelines
  - The set of interactive scripts and tools for *ad hoc* re- or post-processing of data products (from raw to final)
- *Calibration documentation*
  - Collection of peer-reviewed publications, instrument handbooks, relevant technical notes/reports, and software-related manuals/guides
- *Calibration as public outreach*
  - Various workshops organised for intra-Herschel (e.g. map-maker WS) or cross-observatory purposes (e.g. Herschel-ALMA synergies)
  - Regular Data Processing workshops targeting both advanced and novice users, and associated video tutorials

The Herschel Calibration Steering Group

- *The **HCalSG** was kicked off in 2004 with a group formed by ICC calibration experts, prime calibrator modellers and scientists from other observatories*
- *Main mandates pre-launch and in Operations:*
  - identify prime calibrators and support the generation of reference models at the required accuracy levels
  - Monitor progress in instrument calibration concepts and pipelines, via regular meetings and dedicated workshops
  - Coordinate calibration campaigns over the mission (CoP, PV, Routine) and optimise synergies between instruments for the allocated time
- *Main role during POPs*
  - Consolidate prime calibrator models, esp. by retro-feeding Herschel findings into existing models (mostly planetary calibrators)
  - Foster cross-calibration exercises between Herschel and other instruments using the wealth of data acquired over the mission
  - Monitor and support the work towards legacy documentation/ publication about calibration and the reference models

The HCalSG legacy: calibrator models

- *The HCalSG oversaw the production of a series of reference models, which have now reached a high level of maturity*

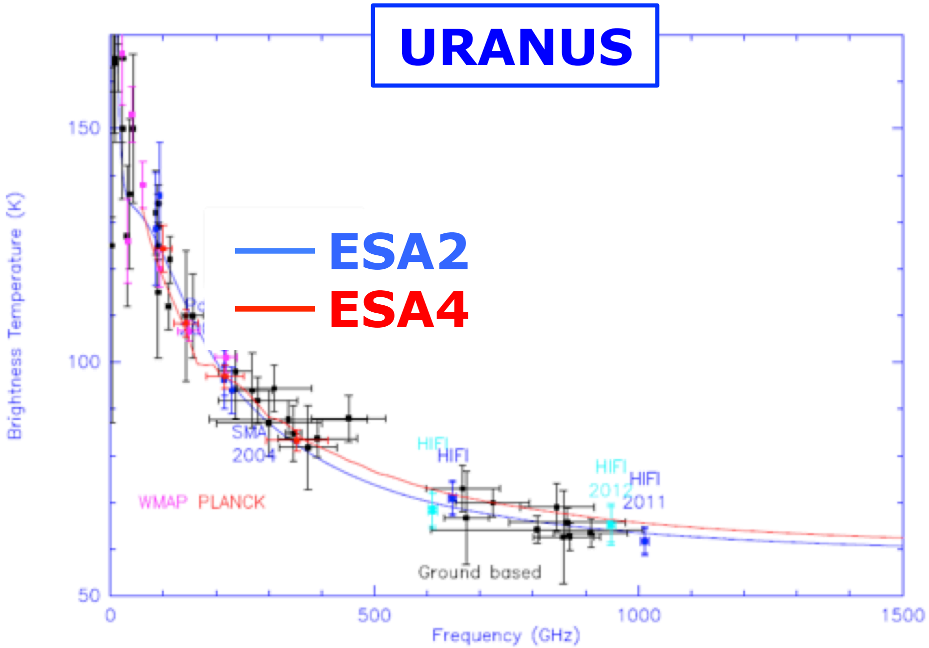
Overall accuracy ~ 5%

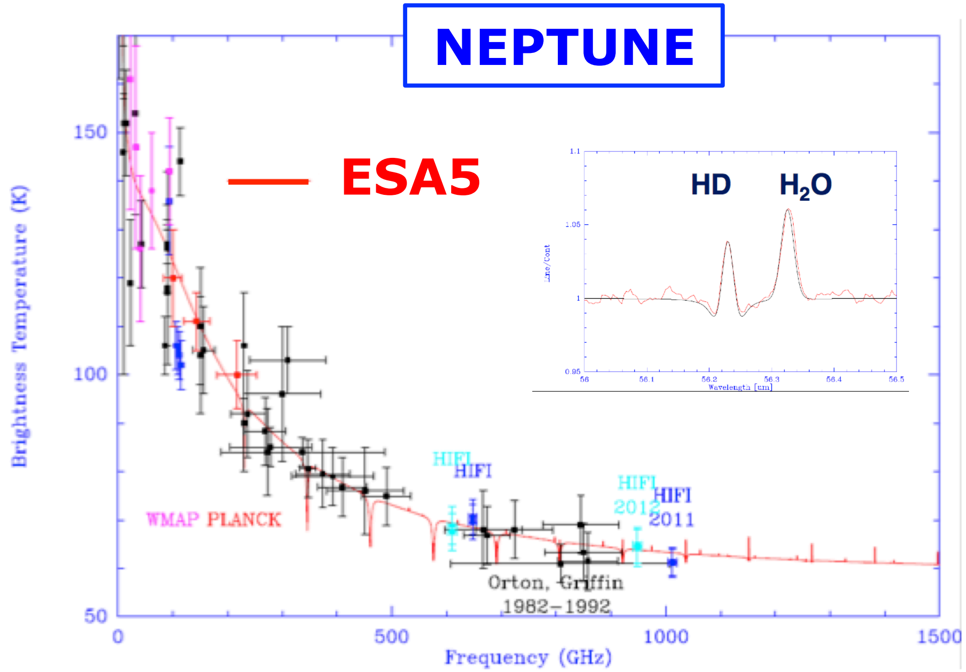
- **Mars** (Moreno & Lellouch): prime for HIFI
- **Uranus** (Moreno + Orton): prime for SPIRE-S, secondary for PACS-S
- **Neptune** (Moreno): prime for SPIRE-P, secondary for PACS-S
- **Stellar calibrators** (Decin & Dehaes): 5 prime/3 secondary calibrators for PACS-S and PACS-P – untouched since launch – strong heritage from Spitzer.
- **Asteroids** (Müller): secondary calibrators for PACS
  - 4 brightest ones now considered prime calibrators (5% accuracy)
  - note: Ceres and Pallas were used to derive time-dependent telescope background models, used in the PACS-S calibration
- **Others (Titan, Callisto, Ganymede):** not used directly by Herschel

- **All models available as Ancillary Data Products (via the HSA and web)**

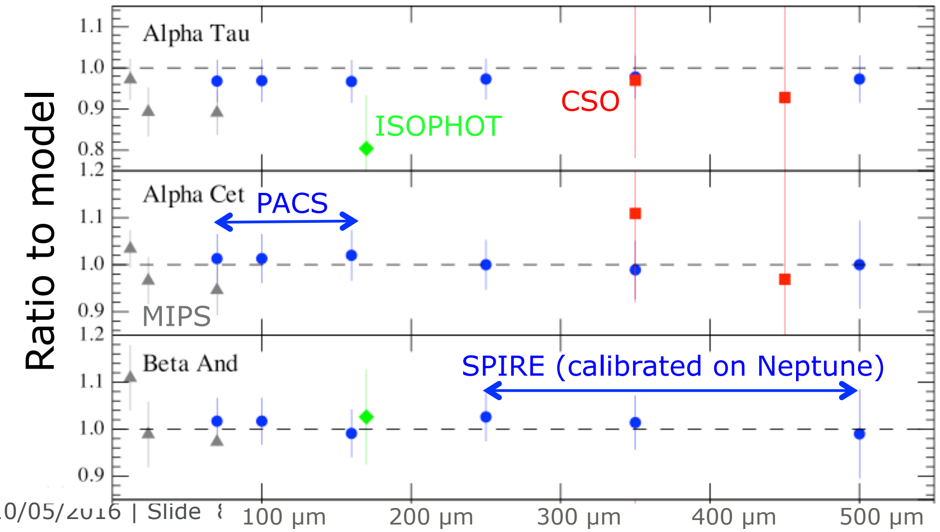
See also http://herschel.esac.esa.int/twiki/bin/view/HCalSG/NewCalSource

The HCalSG legacy: calibrator models





- *Consistency between stellar and planetary model calibration shown to be extremely good (1%!) –* ***significant achievement considering the very different and independent nature of the models***



The HCalSG legacy: workshops

- *Calibration workshops (none during POPs)*
  - Calibrator Models workshops (Dec 2004 and Feb 2008)
    - http://www.cosmos.esa.int/web/herschel/calibration-workshop-1
    - http://www.cosmos.esa.int/web/herschel/calibration-workshop-2
  - Instrument Flux Calibration workshops:
    - 2010: mostly dedicated to photometer calibration http://herschel.esac.esa.int/twiki/bin/view/HCalSG/CalibrationWorkshop
    - 2012: mostly dedicated to spectrometer calibration http://herschel.esac.esa.int/twiki/bin/view/Public/CalibrationWorkshop4
    - 2013: general wrap-up prior to POP start – led to a special topical issue of Experimental Astronomy (17 published papers) http://herschel.esac.esa.int/twiki/bin/view/Public/CalibrationWorkshop5
- *Photometer map-maker workshop (January2013)*

http://www.cosmos.esa.int/web/herschel/pacs-and-spire-map-making-workshop

  - Half a dozen map-makers were benchmarked against a set of metrics – led to selection of "best" PACS-P map-makers used in the pipeline

Some HCalSG success stories

- *Planck/HFI data in bands overlapping with SPIRE-P were used in order to assess accurate background reference levels for the photometric maps*
  - Despite a lengthy iteration process with Planck team (non-disclosure of early data), the payback of this effort was significant for both projects, allowing e.g. Planck/HFI to refine their beams
- *Cross-calibration of ext. emission between PACS-P and Spitzer MIPS at 160 μm*
  - Discrepancy of >30% at high end between the two instruments initially thought to be issue with the Herschel data and their calibration
  - Data from either instruments reconciled after correction for an overlooked non-linearity issue in the MIPS 160 μm data
- *Reference calibrator models*
  - Planetary and asteroid models used by Herschel have now become a reference for modern observatories such as ALMA and SOFIA
  - Heritage for a potential SPICA mission will also be very valuable

Instrument calibration achievements: Introductory remarks

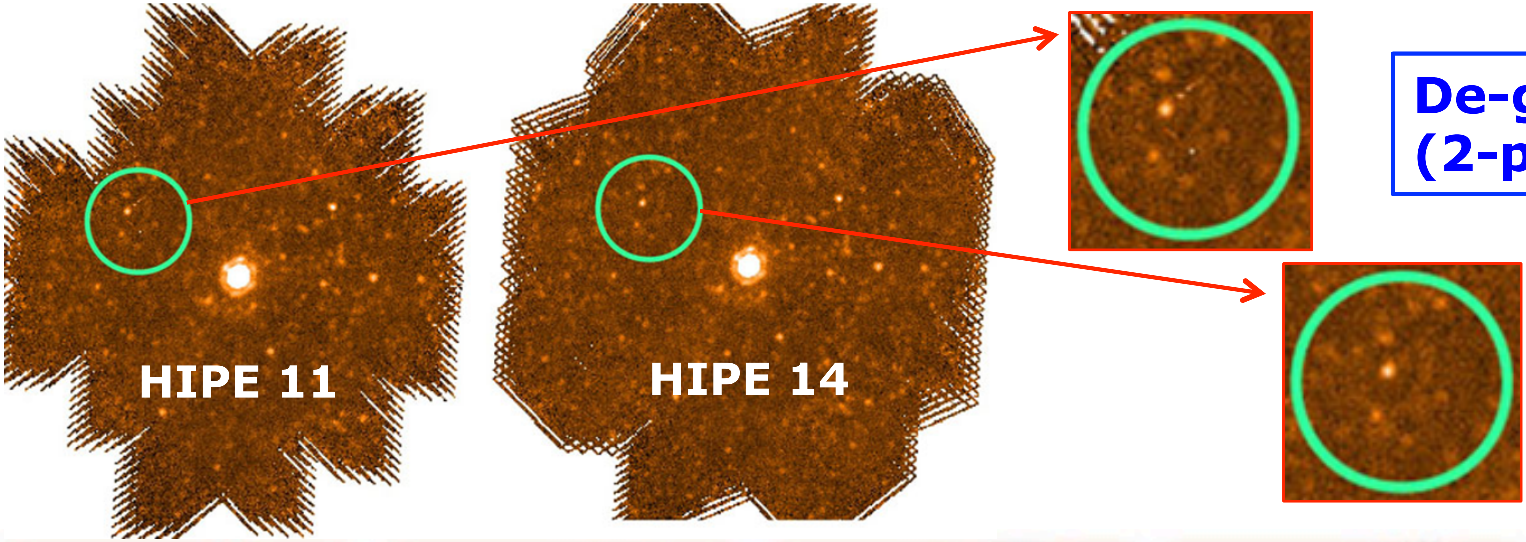
- *Most, if not all, improvements applying to the calibration effort have materialised in the products in a staging fashion, related to the regular bulk reprocessing campaigns associated to HCSS user release versions*
- *During the POP, the following landmarks are applicable (**see also the Legacy Software presentation**):*
  - HIPE 10: last HCSS release during Operations (Dec 2012)
  - HIPE 11: released July 2013
  - HIPE 12: released March 2014
  - HIPE 13: released April 2015
  - HIPE 14: 14.0 (released Dec 2015), 14.1 (released April 2016), 14.2 (planned for June 2016)
  - HIPE 15: Planned for December 2016

Instrument calibration achievements: SPIRE-P

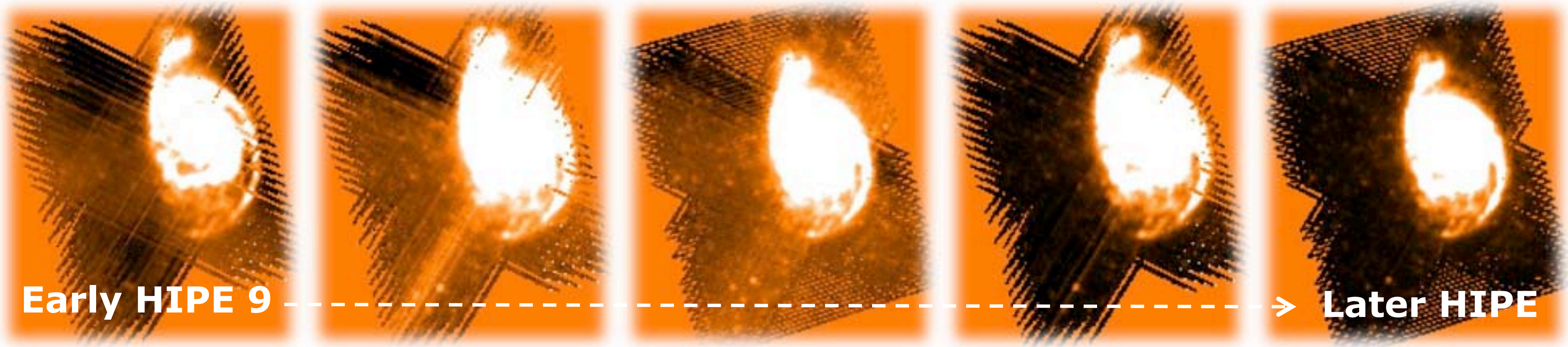
- *SPIRE-P products were already very close to science-ready when entering POPs*
- *Main Pipeline improvements:*
  - Two-pass pipeline: optimised deglitching and map destriper
  - Anomalous instrument behaviour mitigation (cooler burp, bolo jumps)
- *Introduction of new products:*
  - Level 2.5 (overlapping nominal and orthogonal scans) and level 3 products (mosaics of overlapping level 2 or 2.5 fields of view)
  - "High Resolution" (*HiRes*) maps – essentially a spatial deconvolution
  - Serendipity mode data
- *Main Calibration improvements:*
  - High accuracy instrument beam derived from *shadow observations,* allowing better extended source calibration maps
  - Extended calibrated maps zero level matched to Planck/HFI

Calibration considered final

Instrument calibration achievements: SPIRE-P - examples



De-glitching (2-pass pipeline)



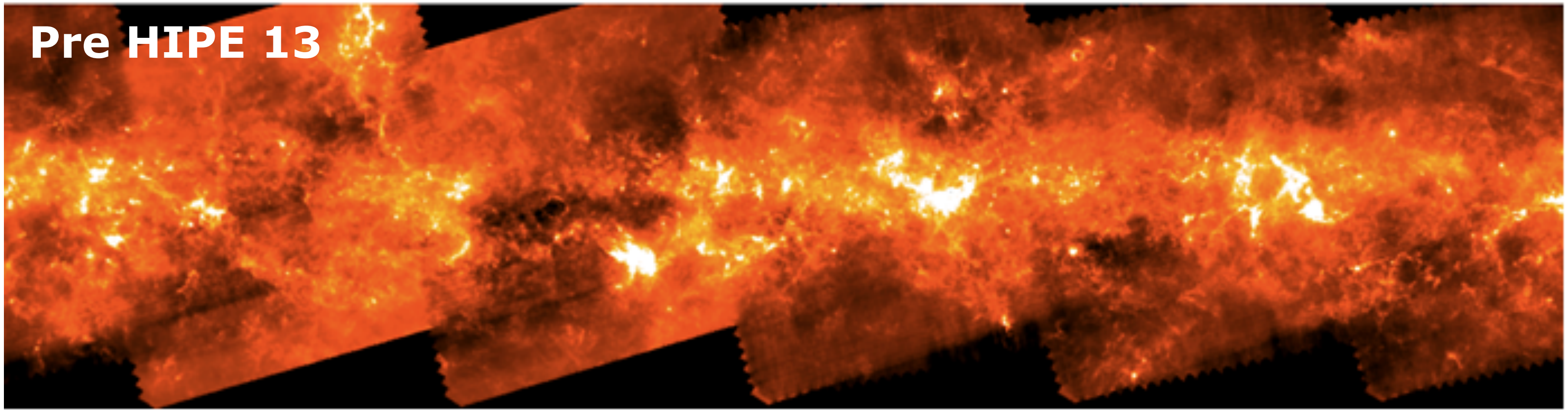
Naïve Map	Naïve Map + Destriper	Naïve Map + Destriper + Turnarounds	Naïve Map + Destriper + Extended Gain	Naïve Map + Destriper + Turnarounds + Extended Gain

SPIRE Destriper (2-pass pipeline)

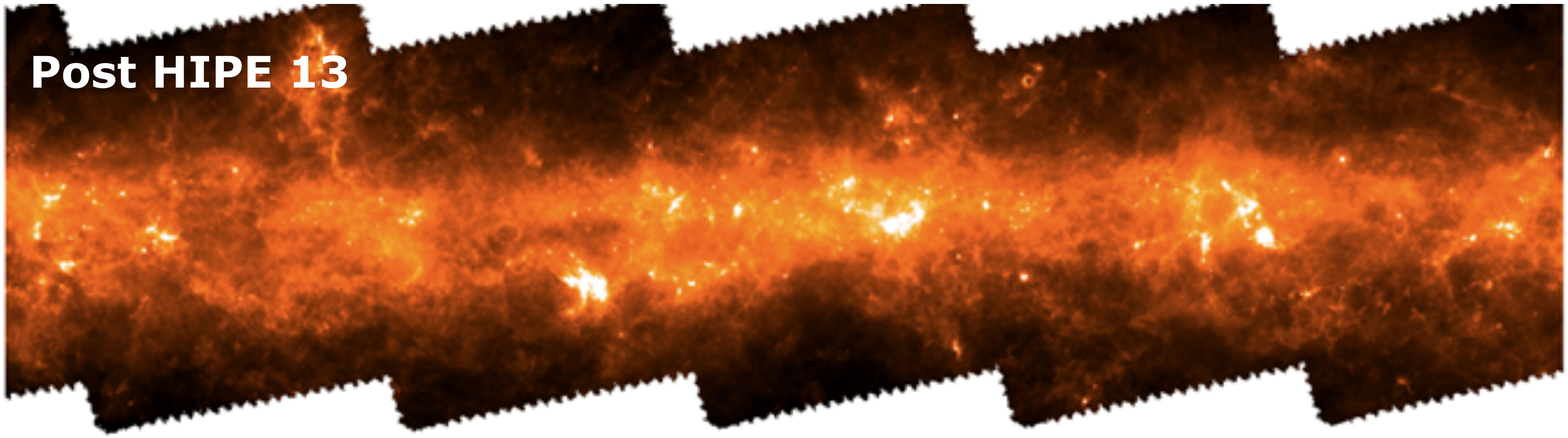
Instrument calibration achievements: SPIRE-P - examples

Level 3 products

Level 3 product created from Level 2



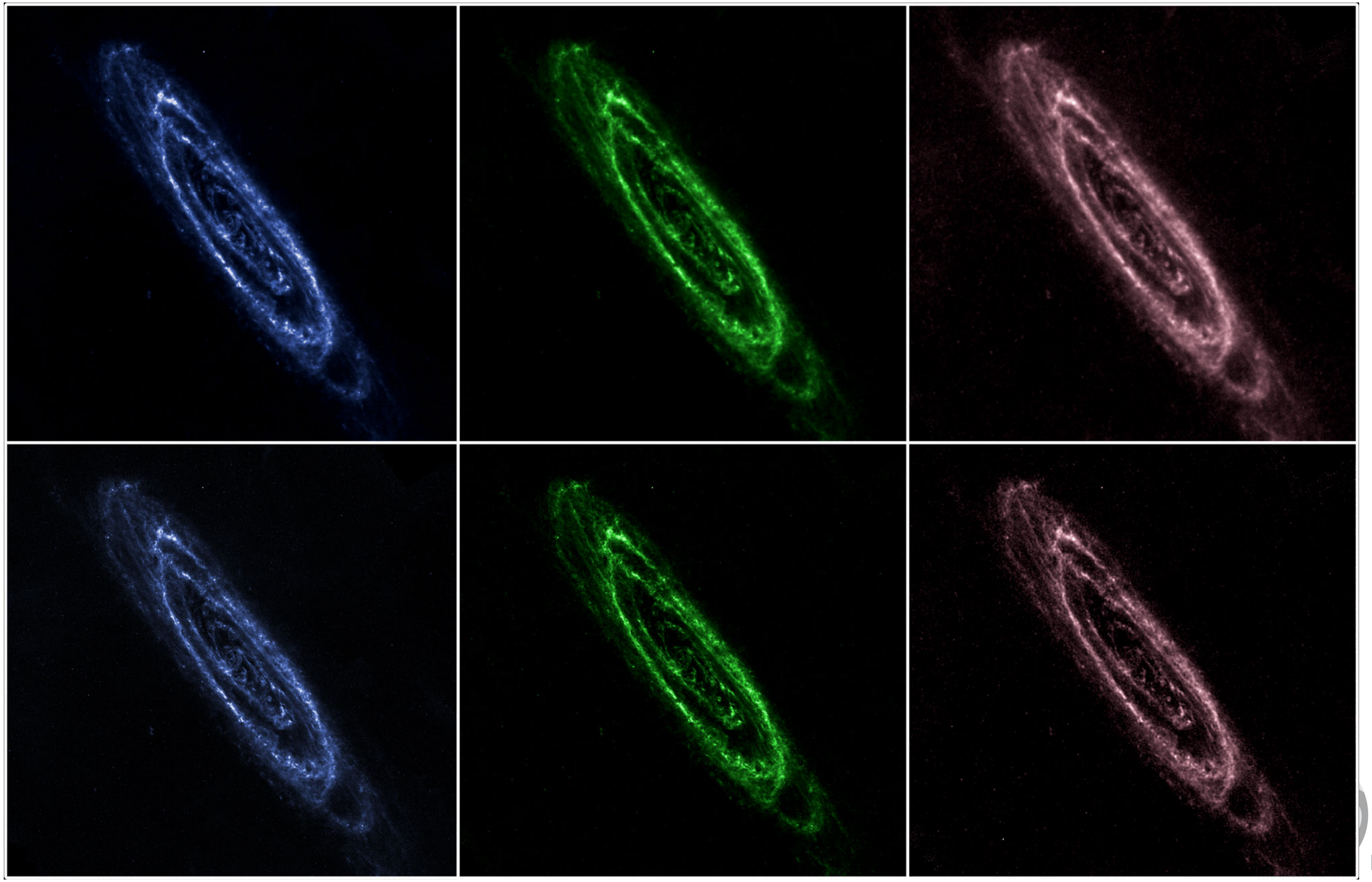
Level 3 product created from Level 2.5



Instrument calibration achievements: SPIRE-P - examples

HiRes maps

Products readily available from the pipeline for ~17% of SPIRE-P observations as level2/2.5



Pre-HIPE 13

HIPE 14

Instrument calibration achievements: SPIRE-S

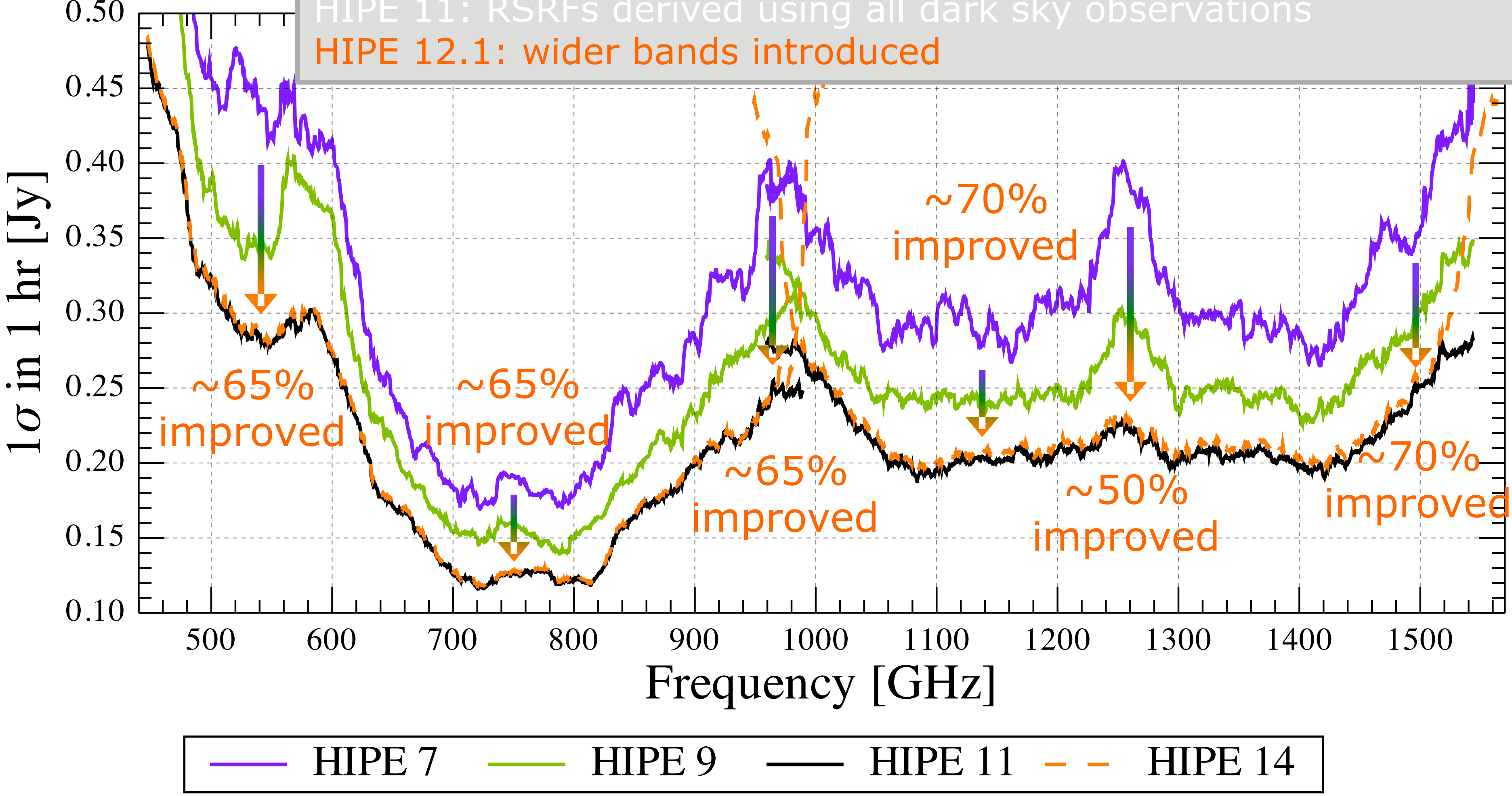
- *Main Pipeline improvements:*
  - Better characterisation of the telescope *Relative Spectral Response Function* (RSRF), resulting in improved sensitivity and spectral shape
  - Band spectral coverage extension at the edges
  - Correction for Low Res. data, improvements of the SLW spectral shape
  - Improved re-gridded cubes for fully sampled spectral maps
- *Introduction of new products:*
  - Spectra processed for all array pixels (originally: only central ones)
- *Main Calibration improvements:*
  - Improved extended source calibration based on SPIRE-P/SPIRE-S cross-comparison
  - Detailed characterisation of the FTS calibration accuracy based on secondary calibrators monitoring
  - Characterisation of the FTS beams and feedback into ad hoc correction tool for semi-extended objects

Calibration considered final (flux & frequency)

Instrument calibration achievements: SPIRE-S – examples

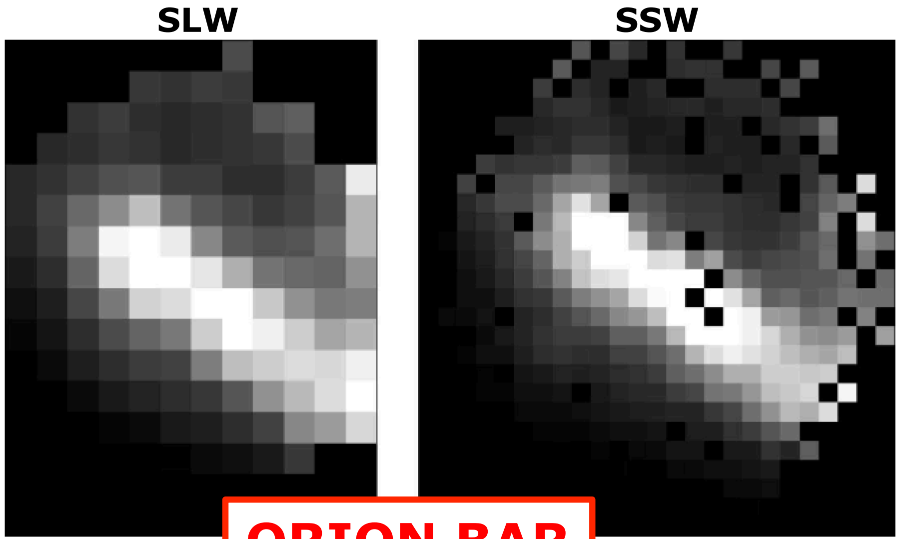
Telescope RSRF improvement: Sensitivity figures in HR mode

HIPE 7: telescope RSRF derived using a single dark sky observation
HIPE 9: mean telescope RSRF from many dark sky observations
HIPE 11: RSRFs derived using all dark sky observations
HIPE 12.1: wider bands introduced



Instrument calibration achievements: SPIRE-S – examples

Convolved cubes for fully sampled spectral maps



ORION BAR

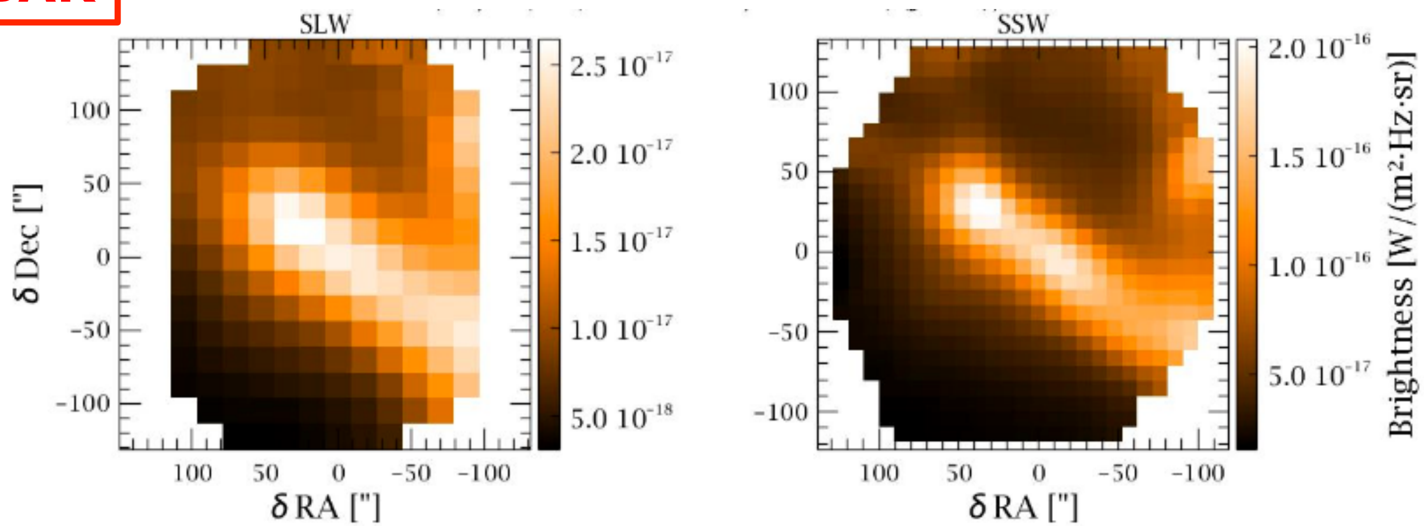
HIPE 13

Naïve projection cubes – leads to empty pixels at under-sampled sky positions (dead detectors)

(note also the improvements in the pipeline postcard)

HIPE 14

Cubes re-gridded using convolution kernel – assigns flux at every pixel of the grid



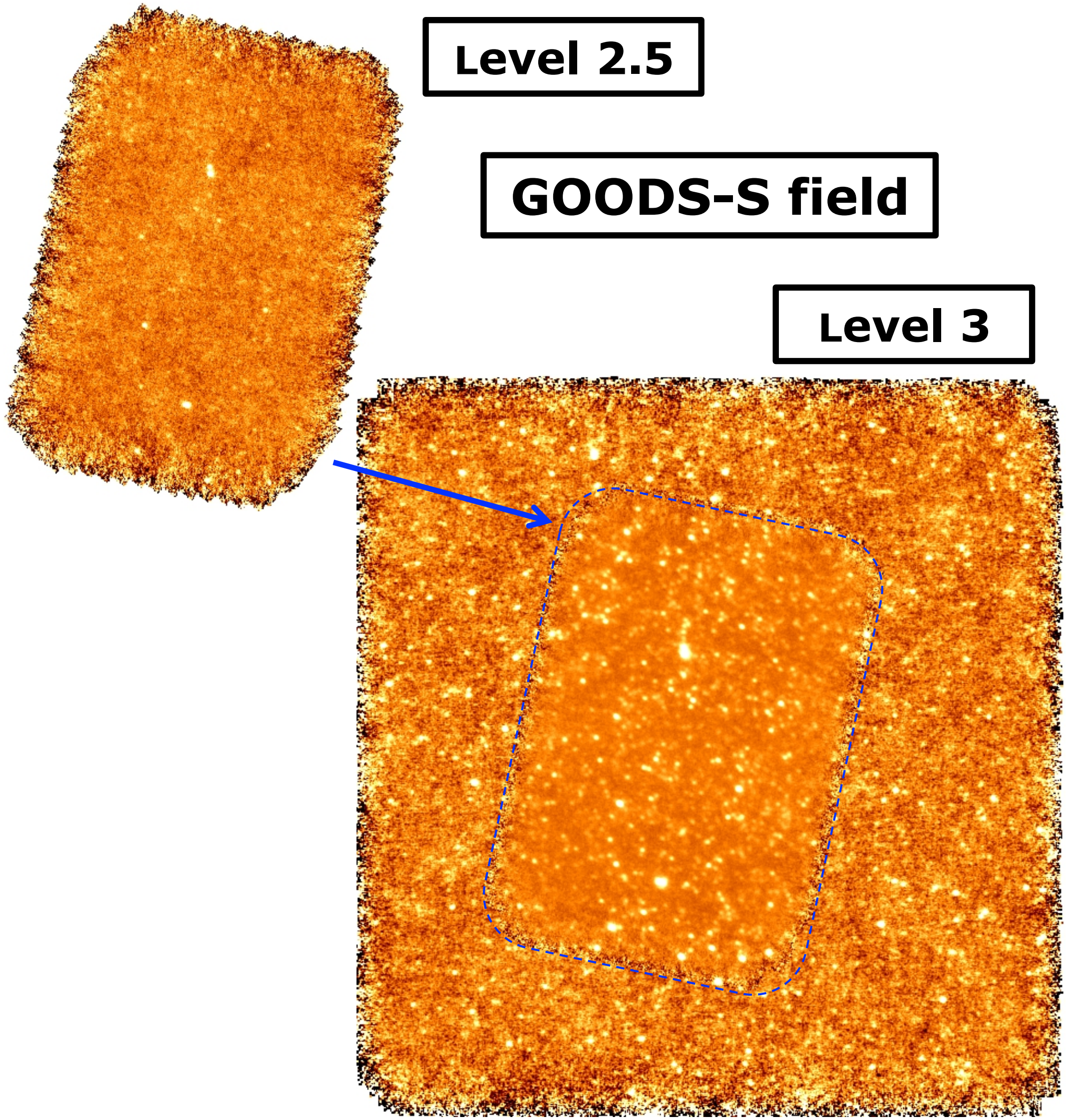
Instrument calibration achievements: PACS-P

- *PACS-P products were already very close to science-ready when entering POPs*
- *Main Pipeline improvements:*
  - Introduction of new GLS mapper *Unimap*, replaced *MadMap* in HIPE 13
  - Introduction of destriper code (*JScanam*) based on *Scanamorphos*
  - Calibration blocks detection and masking
  - *Interactive scripts capable to process any number of observations*
- *Introduction of new products:*
  - level 3 products (overlapping fields of view from level 2.5 products)
  - Level 2.5 products for Solar System Objects (in SSO co-moving frame)
- *Main Calibration improvements:*
  - PSFs and EEFs derived for various scan speeds and observing modes
  - Updated calibration corrections: projection of physical pixels onto sky, evaporator temperature correction, signal calibration for chopped observations

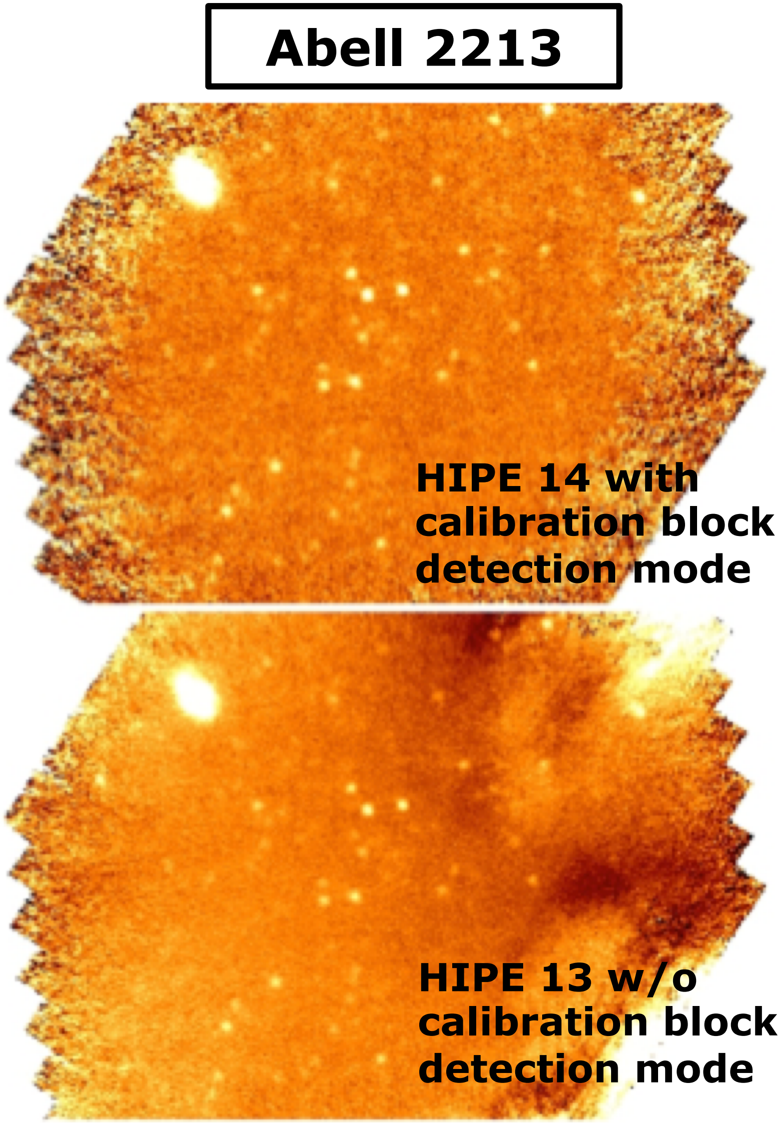
Calibration considered final

Instrument calibration achievements: PACS-P examples

Improved SNR in Level 3 products



Cal block masking



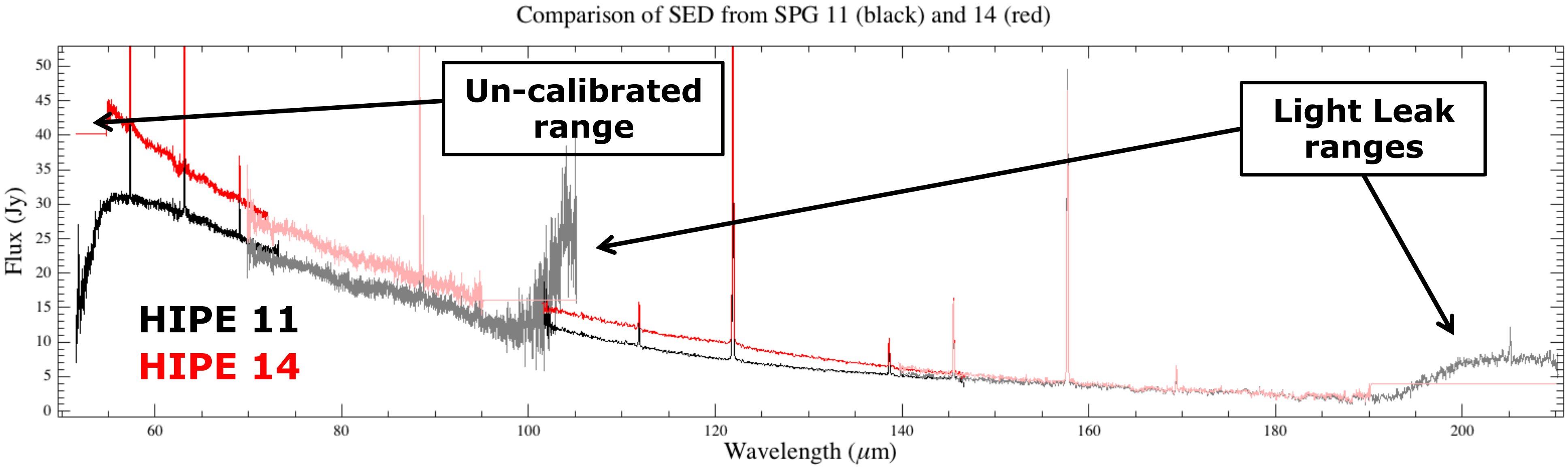
Instrument calibration achievements: PACS-S

- *Main Pipeline improvements:*
  - Transition from internal Calibrator-based scheme to Telescope background normalisation scheme (tracking response drift) – improvement esp. for broad band features and faint sources
  - Flat-fielding for range scan observations based on cubic splines
  - New flux calibration scheme for drizzled cubes
- *Introduction of new products:*
  - Cubes spectrally and spatially resampled on regular grids
  - Level 3 products (concatenation of spectral range of SEDs)
  - Point-source corrected spectra on top of that from central spaxel
- *Main Calibration improvements:*
  - Better beam characterisation (improved Point Source correction, and Extended Source calibration – recovery of up to 30% flux loss at low λ)
  - Instrument RSRF in leak region above 190 μm ("de-leaked" RSRF)

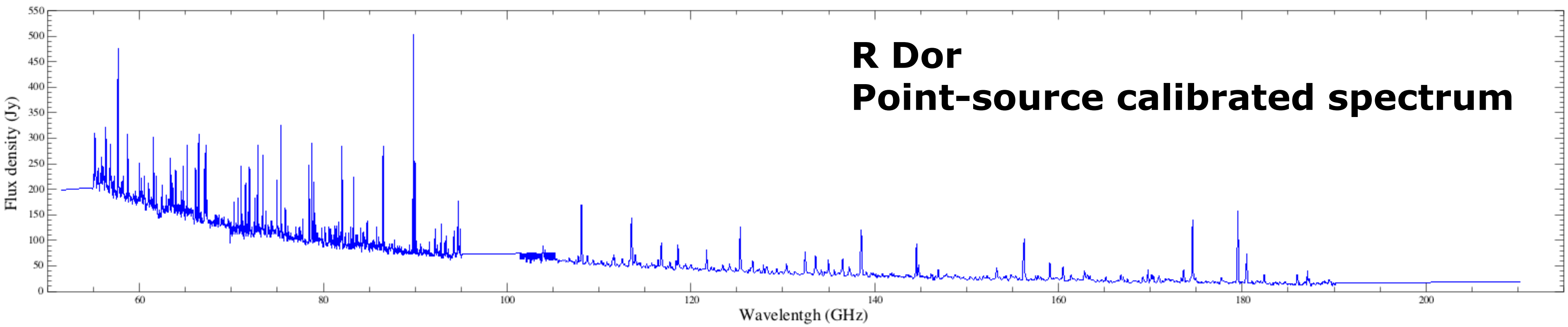
Flux Calibration not yet considered final – last update will take place in the HIPE 14.2 release (June 2016)

Instrument calibration achievements: PACS-S examples

Telescope Background Normalisation scheme



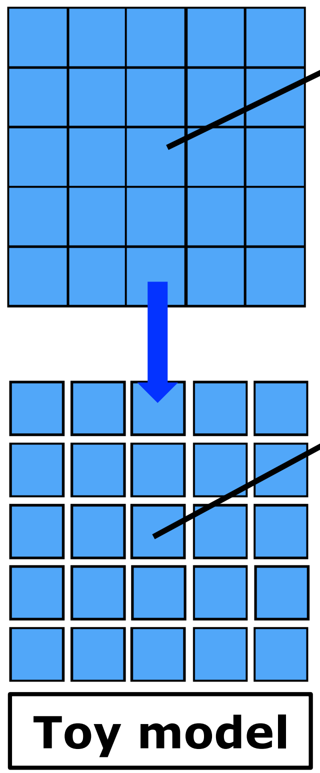
New level3 concatenated SED for range spectroscopy

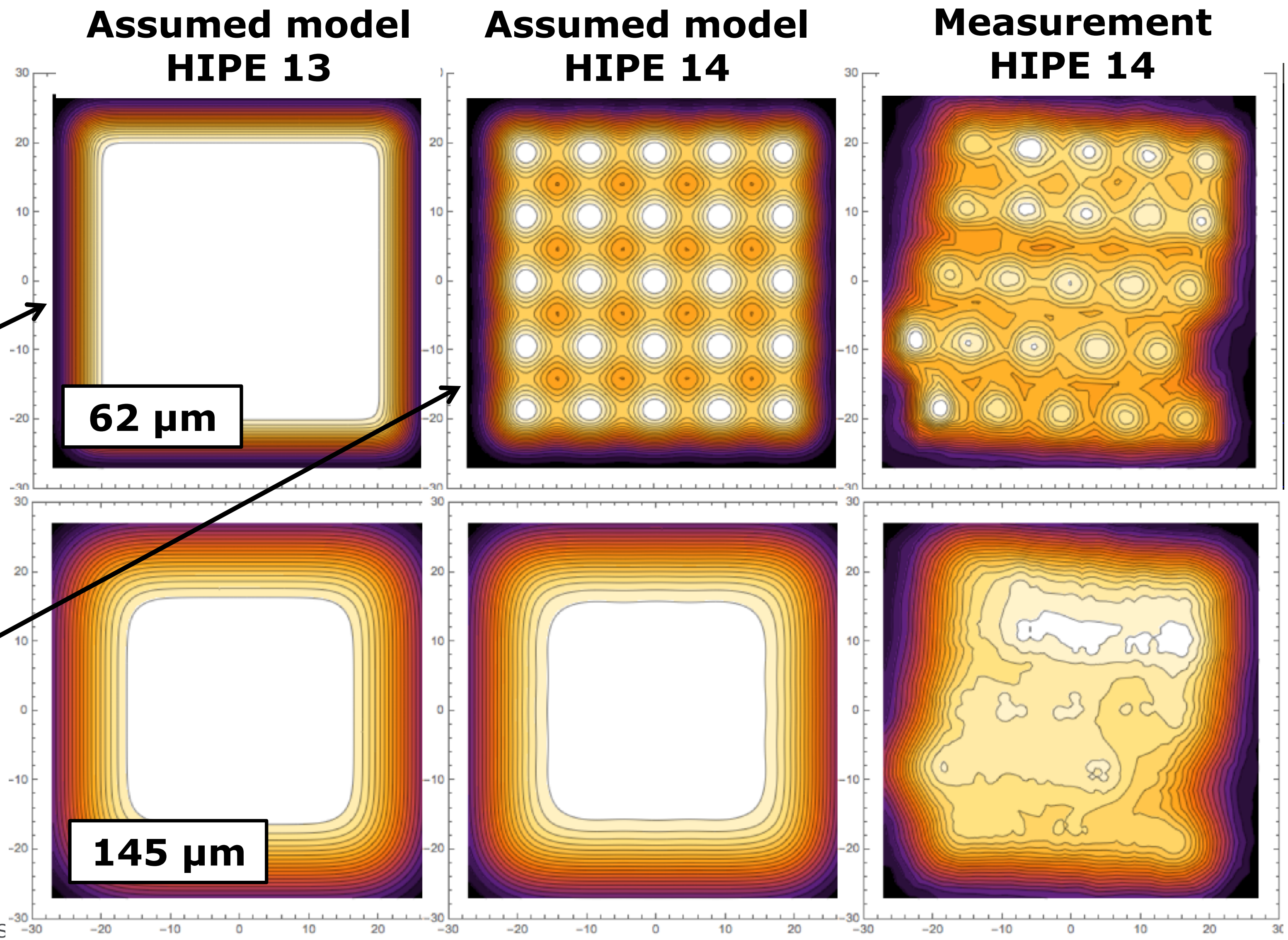


Instrument calibration achievements: PACS-S examples

Non-uniform illumination of PACS-S FoV

IFU Illumination effectively implies non-fully filled FoV by spaxels array





PACS improvements in 14.2: heads-up

- ***PACS-P:***
  - Newest version of Unimap 6.4.3
    - Introduction of error maps
    - New noise cancellation option to be activated in certain fields (e.g. Galactic Plane)
- ***PACS-S:***
  - Region in red leak (above 190 µm) will not be offered in the end product (filled with NaNs instead)
    - Necessary calibration table (‶de-leaked″ RSRF) present in calibration tree, allowing manual processing through ipipe
    - Shall be generated as HPDPs
  - New transient correction algorithm will not be implemented in SPG – results from new flat-field approach are of similar quality
  - Improvement of postcards
- ***General:***
  - *Tiding up headers and interactive scripts*

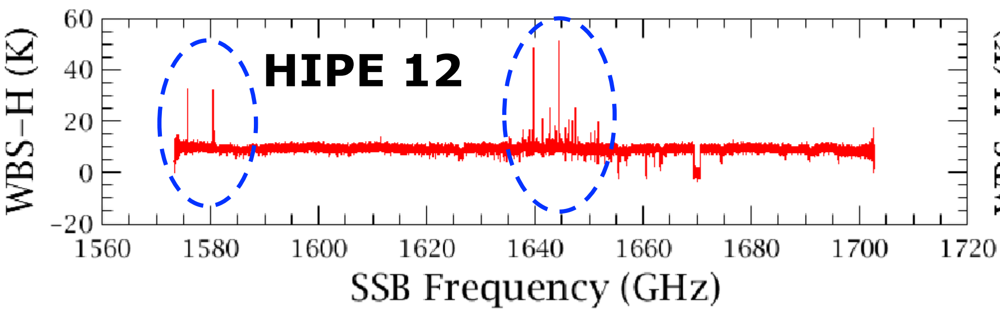
Instrument calibration achievements: HIFI

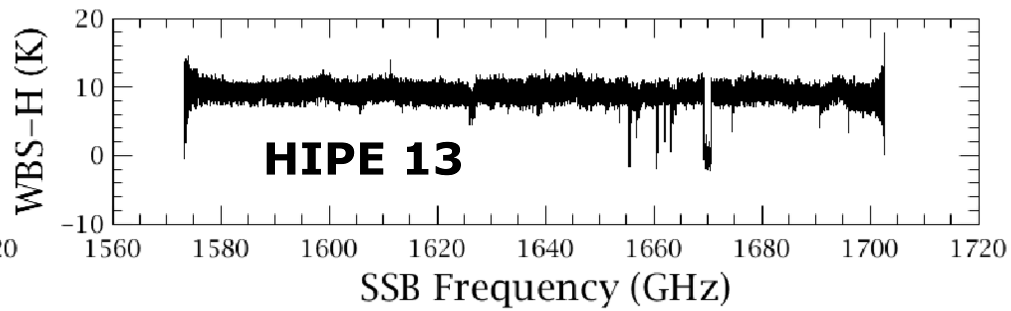
- *Main Pipeline improvements:*
  - Electrical Standing Wave automatic corrections in Bands 6 and 7
  - Generation of Flux Calibration Uncertainty tables applicable to the observing frequency
- *Introduction of new products:*
  - Level 2.5 simplified products for single point observations
  - Generation and provision of OFF position spectra for all modes
- *Main Calibration improvements:*
  - Better instrument PSF characterisation via bottom-up modelling of beam maps at all epochs, bootstrapped to ILT Far-Field beam data
  - Detector mixer sideband gain ratio estimated on a fine frequency grid, based on a combination of in-flight and pre-flight measurements
  - Masking of all spurious spectra features in Spectral Scan observations via a manually-populated calibration file

Calibration considered final (flux & frequency)

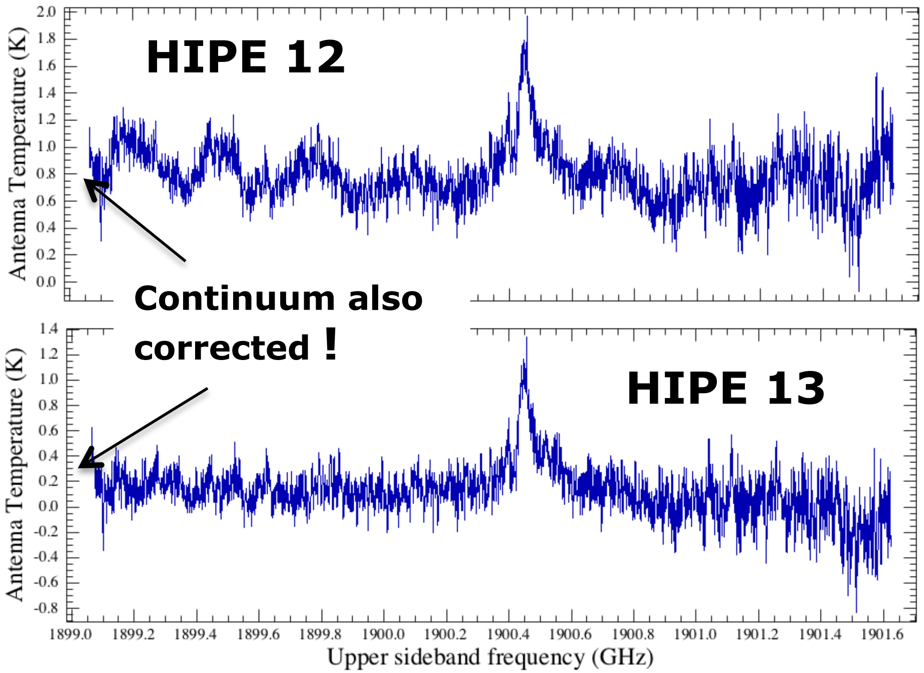
Instrument calibration achievements: HIFI – examples

Spur mask tables for Spectral Scans

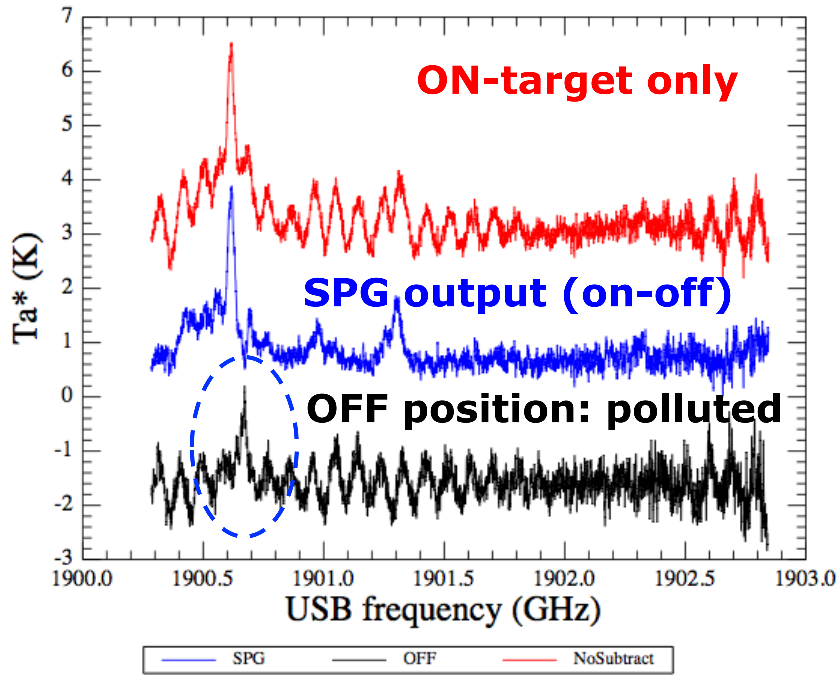




Electrical Standing Waves

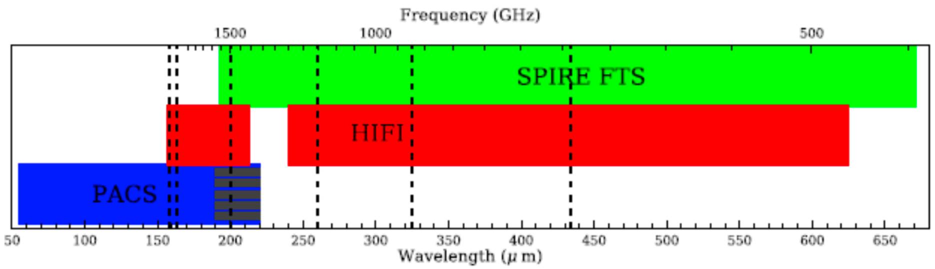


Reference position spectra



Instrument cross-calibration

- *With other observatories*
  - SPIRE-P/Planck HFI: successfully used for SPIRE absolute background level calibration – good to 10%
  - PACS-P/Spitzer MIPS: very good match once MIPS non-linearity understood and corrected
- *Intra-instrument*
  - PACS-P/PACS-S continuum calibration match very well by construction
  - SPIRE-P/SPIRE-S continuum discrepancy by up to 80% led to revision of SPIRE-S extended calibration scheme
- *Across instruments: the spectrometers*
  - HIFI/SPIRE flux intensities on AGB sample agree within 10%
  - HIFI/PACS flux intensities on AGB sample agree within 30%



  - Discrepancy for the latter was factor of 3 in red leak area (@200 μm), at the time when de-leaked RSRF was not yet available

Attitude reconstruction achievements (pointing)

- *At start of POPs, the pointing accuracy was already exceeding the pre-launch specification (Absolute Pointing Error – APE – of 1"-1.6" vs a specified 2")*
- *Main Pipeline improvements during POPs:*
  - HIPE 12: Correction for improper STR focal length for OD 321-761 range introduced in pipeline (was previously ingested manually)
  - HIPE 13: introduction of Gyro-based attitude reconstruction, allowing to track high-frequency changes in the S/C attitude (too heavily filtered) – esp. efficient to deal with pointing jitter.

→ offers the most homogeneous pointing performance over the mission

  - HIPE 14: Treatment of interlacing (use of 18 stars instead of 9 in the Star Tracker system – STR), and special correction for contingency events of the STR operations (e.g. switch-over to redundant STR)
  - **Reconstruction now considered final in the pipeline products**
- *Remaining work in POPs*: investigation of pointing drift in observations under so-called *warm attitude*, leading to thermo-elastic deformation of the STR – objective is to provide report and recipe on first order correction (not pipeline)

Attitude reconstruction performance (pointing)

OD range	Raw APE [(a)]	AME [(b)] HIPE 12	AME [(b)] HIPE 13	AME [(b)] HIPE 14
32-320	1.9″-2.2″	1.4″	1.4″	1.4″
321-761 [(c)]	2.4″	1.6″	1.2″	1.2″
762-865	1.45″	1.3″	1.2″	1.2″
866-1010	1.1″	N/A	No data	N/A
1011-1452	0.9″	N/A	1.2″	0.9″

Adapted from Sanchez-Portal et al. 2014

[(a)] Attitude accuracy from raw Spacecraft Telemetry

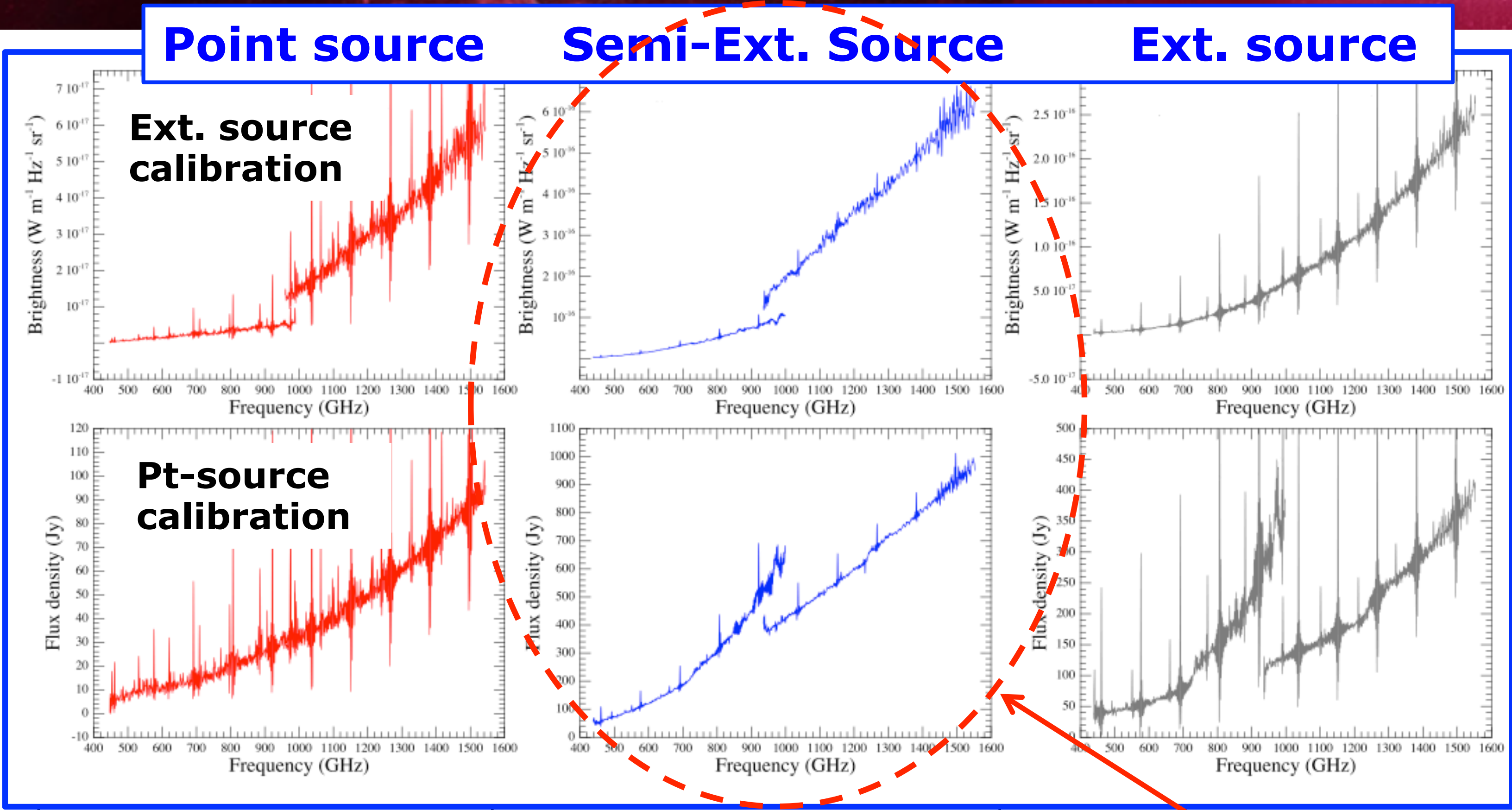
[(b)] Absolute Measured Error: in contrast with the APE, applicable at the time of observation, the AME is the accuracy of the *a posteriori* reconstructed attitude

[(c)] In this period, a colder STR baseplate operation temperature was not taken into account in the on-board focal length parameter of the STR system, leading to a poorer performance – the effectively achieved accuracy could be as bad as 8″

Science-readiness and calibration uncertainty: SPIRE

Flux Uncertainty		Science Readiness of Standard Products
Absolute	**Repeatability**	
Photometer – goal 10%, baseline 15% (rel.: 5%, 10% resp.)		
Pt-source calib.: ~ 5%	< 2% for S>100mJy <10% for S<100 mJy	Ready to use as is – background reference level accurate to 10% **Isolated artefacts not dealt with by pipeline in ~4% of obs.**
Spectrometer – goal 10%, baseline 15%		
Pt-source calib.: ~ 4%	6%, reduced to 3% if pointing can be corrected	Pt-source calibrated data and extended-source calibrated data ready to use as is for purely point and extended sources respectively. **Not science-ready for any source morphology in-between, or point-source embedded in an extended background (~55% of sparse mode obs.)**
Extended calib.: 4% or > if not fully extended	7%	

Science-readiness and calibration uncertainty: SPIRE



		of
		resp.)
		kground to 10%
		not dealt 4% of obs.
		a and ted data rely point espectively.
Extended calib.: 4% or > if not fully extended	7%	**Not science-ready for any source morphology in-between, or point-source embedded in an extended background (~55% of sparse mode obs.)**

Science-readiness and calibration uncertainty: PACS

<table>
<tr><th colspan="2">Flux Uncertainty</th><th rowspan="2">Science Readiness of Standard Products</th></tr>
<tr><th>Absolute</th><th>Repeatability</th></tr>
<tr><td colspan="3">Photometer – goal 10%, baseline 20% (rel.: 3%, 5% resp.)</td></tr>
<tr><td>5-7% - main contributor is abs. calibrator – rest is non-linearity corr.</td><td><1 % at 70 µm and 100 µm
<3% at 160 µm</td><td>Ready to use as is, although background reference level is un-calibrated (can be derived from differential photometry of course)</td></tr>
<tr><td colspan="3">Spectrometer – goal 10%, baseline 20% (rel.: 3%, 5% resp.)</td></tr>
<tr><td colspan="2">Uncertainty at key wavelengths</td><td rowspan="4">Pt-source calibrated data and extended-source calibrated data ready to use as is for purely point and extended sources respectively.

Not science-ready for any source morphology in-between Beside, continuum unreliable in un-chopped obs. and in red leak (λ > 190 µm)</td></tr>
<tr><td>Pt-source calib.: 6-12 %
Ext. calibration:15 %</td><td>4 % 1-sigma rms
15% peak-to-peak</td></tr>
<tr><td colspan="2">In-band relative uncertainty</td></tr>
<tr><td colspan="2">Un-chopped: 10%
Chop-nod: 5% below 150 µm, 10% above</td></tr>
</table>

Science-readiness and calibration uncertainty: HIFI

Flux Uncertainty		Science Readiness of Standard Products
Absolute	**Repeatability**	
Bands 1 to 5 (SIS mixers) – goal 3%, baseline 10%		
2-4% internal instrumental error (random) + 5% (syst.) Planet model	3-6% (pt-source), reduced to 3% if pointing offset can be corrected	HIFI data intrinsically in an instrument-internal scale (T_A*) – beam coupling losses to source need to be assessed by user Majority of HIFI products are science-ready (modulo the above conversion) **Main residual artefacts are baseline distortion (mostly standing wave), affecting ~20% of the standard products (2/3 being from point-mode observations)**
Bands 6 to 7 (HEB mixers)		
5-6% internal instrumental error (random) + 5% (syst.) Planet model	11% (pt-source), reduced to 9% if pointing offset can be corrected	

Conclusions (1)
Post-Operations: the data mining era

- *The POP is the first moment when instrument experts can look back at the wealth of the mission delivery as a whole – it is the data-mining era !*
- *For a cryogenic mission such as Herschel, this aspect is fundamental and the significant amount of resources and time allocated to it is/was essential*
- *Some unique outputs of such "big data" approach have been possible in this period – just to name a few (from previous slides):*
  - Assessment of flux calibration repeatability figures for all instruments
  - Creation of merged data products among several overlapping observations
  - HIFI beam modelling combining data collected at all epochs + ILT
  - Telescope RSRF for SPIRE-S based on all dark sky measurements collected in-flight
  - Corrected SPIRE-S extended source calibration based on systematic cross-calibration between SPIRE-S and SPIRE-P continua
  - Etc.

Conclusions (2)
Legacy Calibration in the Science Products

- *Herschel is a mission with no previous observatory to specifically pave its calibration road*
  - Very early work on absolute calibrator models, pursued throughout all mission phases, proved an extremely successful enterprise
- *Legacy calibration in the Herschel science products*
  - Photometer absolute flux accuracy (~5-7%) virtually turns any point source detected by Herschel into a calibrator for future FIR missions
  - Spectrometer data offer high accuracy calibration (<10%) for well-defined source morphology (typically: point-like or fully extended)
  - Tools to derive more accurate fluxes for intermediate cases are available in HIPE
    - Calibration uncertainty for those cases is strongly dependent on user's assumption on the source morphology knowledge
    - **The access to those tools in the long term is essential – ideally as independent tasks outside of HIPE (e.g. Python) or within a virtualisation of HIPE**

Conclusions (3)
Status of Legacy Calibration deliverables

Deliverable	Status	Where
Calibrator models	Planets + stars compiled in Feb 2016. Asteroids TBD in May 2016	HSA + FTP through HELL (Cosmos)
Calibration Software	Final for HIFI and SPIRE as of HIPE 14.1 (April 2016) Final version for PACS still pending (HIPE 14.2 – June 2016)	HIPE
Calibration Files		HSA
Calibration documentation[a]	Handbooks exist with un-even completion state among instruments. Explanatory Library component populated to a large extend. Instr. webpages geared towards Ops	HELL (Cosmos) + respective journal repositories for refereed publications
Cal. Workshops	Material is final on twiki pages – needs migration to Cosmos	HELL (Cosmos)
Video tutorials	Exist for already held Workshops	Youtube

[a] **See also Documentation presentation for HELL schedule**

Conclusions (4)
Remaining calibration work in POPs

Workpackage	When	Priority	Where/Remarks
Documentation – see also Documentation presentation for HELL schedule			
Handbooks	Until June 17	1	HELL (Cosmos)
Pocket Guides	June/Oct 16	1	HELL (Cosmos)
Instr. web pages	Dec 2016	1	HELL (Cosmos)
Publications	Best effort basis	3	HELL (Cosmos), but only until end of POPs
X-calibration report	July 2016	1	HELL (Cosmos)
Software – see also Legacy Software presentation			
Calibration Pipeline (HIPE 14.2)	June 2016	1	HIPE – VM for long term
Interactive tools (HIPE 15)	Dec 2016	2	HIPE – VM for long term
Python external library	Voluntary basis	3	Large fraction curated outside of HSC – central storage unclear

Priority 1: Mandatory, Priority 2: Highly-desirable, Priority 3: Nice to have

Conclusions (4)
Remaining calibration work in POPs (cont'd)

Workpackage	When	Priority	Where/Remarks
Provision of Legacy Data Products – see also next presentation			
Expert-curated Data Products with improved calibration	Between now and June 2017	1	HSA and FTP via HELL (Cosmos)
Added-value Data Products	Between now and June 2017	2	HSA and FTP via HELL (Cosmos)
Ancillary Data Products	Between now and Dec 2016	2	HSA and FTP via HELL (Cosmos)
Video Tutorials – see also Community Support presentation			
Collection of short tutorials on how to use functionalities of the Legacy SW	From Jan to June 2017	1	HELL (Cosmos) + Youtube

Priority 1: Mandatory, Priority 2: Highly-desirable, Priority 3: Nice to have

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