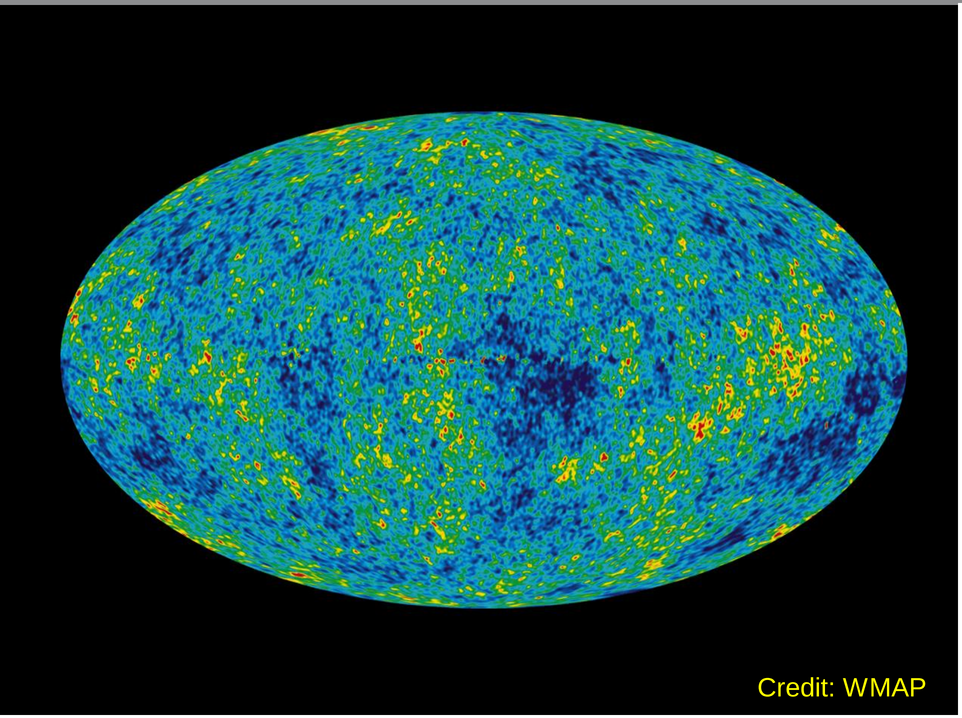
Overview of Herschel Calibration

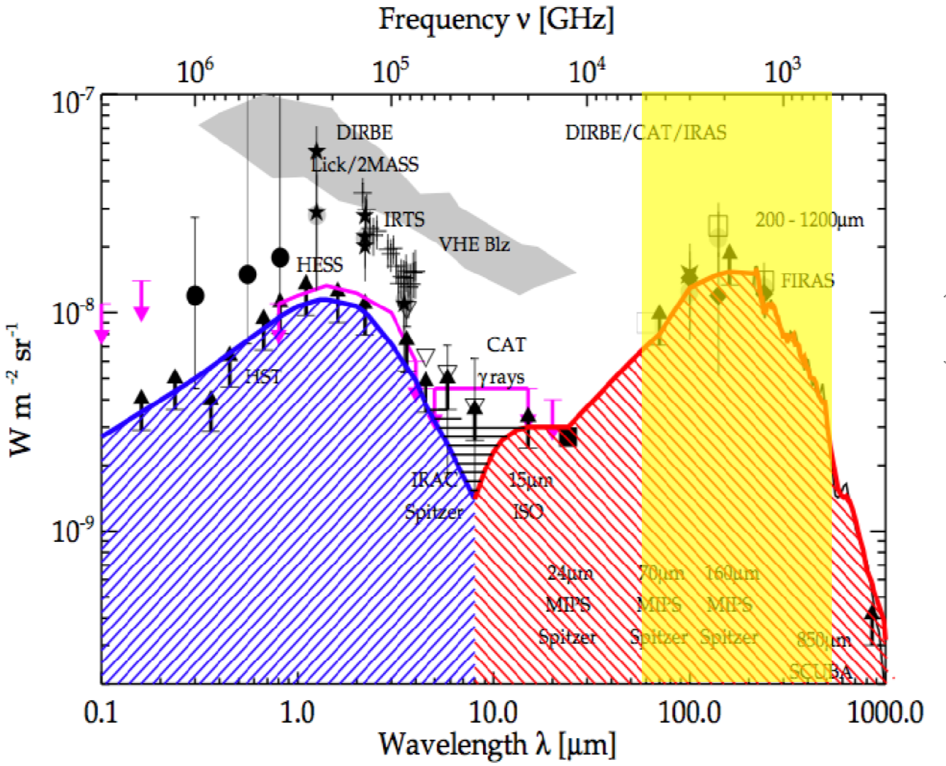
A.P.Marston,
Instrument and Calibration Scientist Team Lead,
Herschel Science Centre, ESAC, Spain.
&
the Herschel Calibration Steering Group.

Overview

- Herschel Basics.
  - Orbit and spacecraft
  - Instruments (SPIRE, PACS, HIFI) and their capabilities + Overall calibration
  - A few science results
- Models used in Herschel calibrations
  - Planets – prime calibrator for SPIRE (checked against PACS observations)
  - Stars – prime calibrator for PACS (checked against SPIRE observations)
  - Asteroids – secondary calibrator for PACS (checked against SPIRE observations)
- Cross-comparisons between instruments
- Calibration offsets for SPIRE photometer and using Planck observations.
- And for PACS photometer? Possibly in post operations.
- Conclusions.

Herschel Basics: Importance of the FIR & submm





– **Half of the energy created in the Universe since the CMB has been reprocessed into the IR**

– **Herschel covers the IR peak and pushes into the submillimetre**

Herschel – the machine

Large telescope

- 3.5 m diameter
- collecting area and resolution

'New' spectral window

- 55-671 μm – bridging the far infrared & submillimetre – the 'cool' universe

Novel instruments

- wide area mapping in 6 'colours'
- imaging spectroscopy
- heterodyne spectroscopy

Herschel objectives

- star formation near and far
- galaxy evolution over cosmic time
- ISM physics/chemistry
- our own solar system
- provide >3 yrs of routine observing time (expected up to Feb/Mar 2013 – 3.5yrs).

Herschel – the science instruments

__14-channel heterodyne receiver__

480 - 1250 GHz (625 - 240 μm)

HiFi

1410 - 1910 GHz (212 - 157 μm)

$\lambda/\Delta\lambda = 10^5 - 10^6$

Instantaneous BW: 4 GHz

__3-band camera__

250, 350, 500 μm (all simultaneous)

SPIRE

__Imaging FT spectrometer__

194 - 671 μm (simultaneously)

$\lambda/\Delta\lambda$ = 1300 – 370 (high-res)

= 60 – 20 (low res)

__3-band camera__

70 or 100, 160 μm (2 simultaneous)

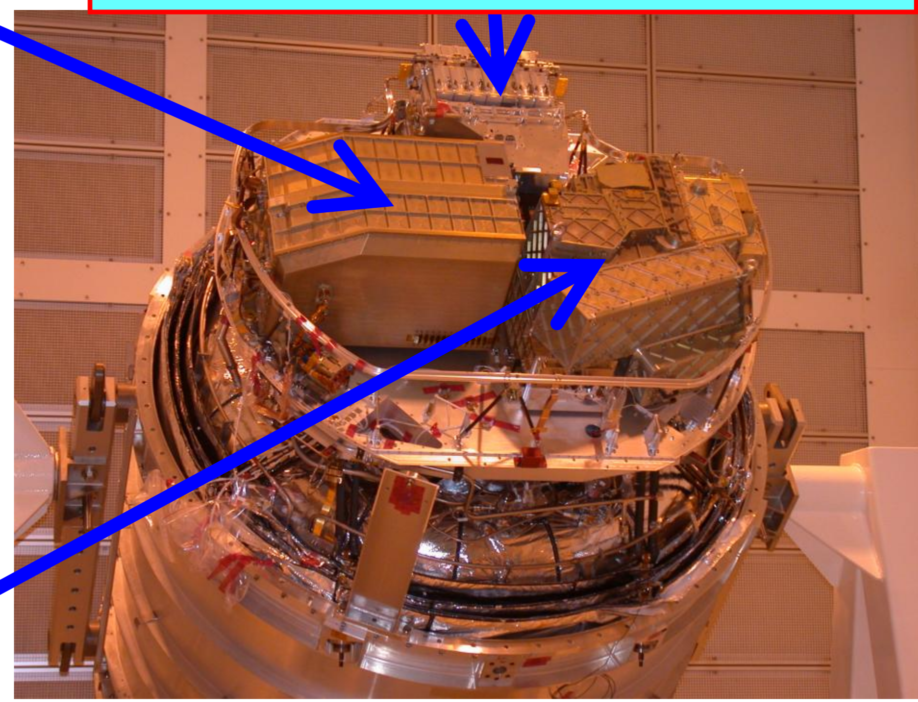
PACS

Photodetector Array Camera & Spectrometer

__Imaging grating spectrometer__

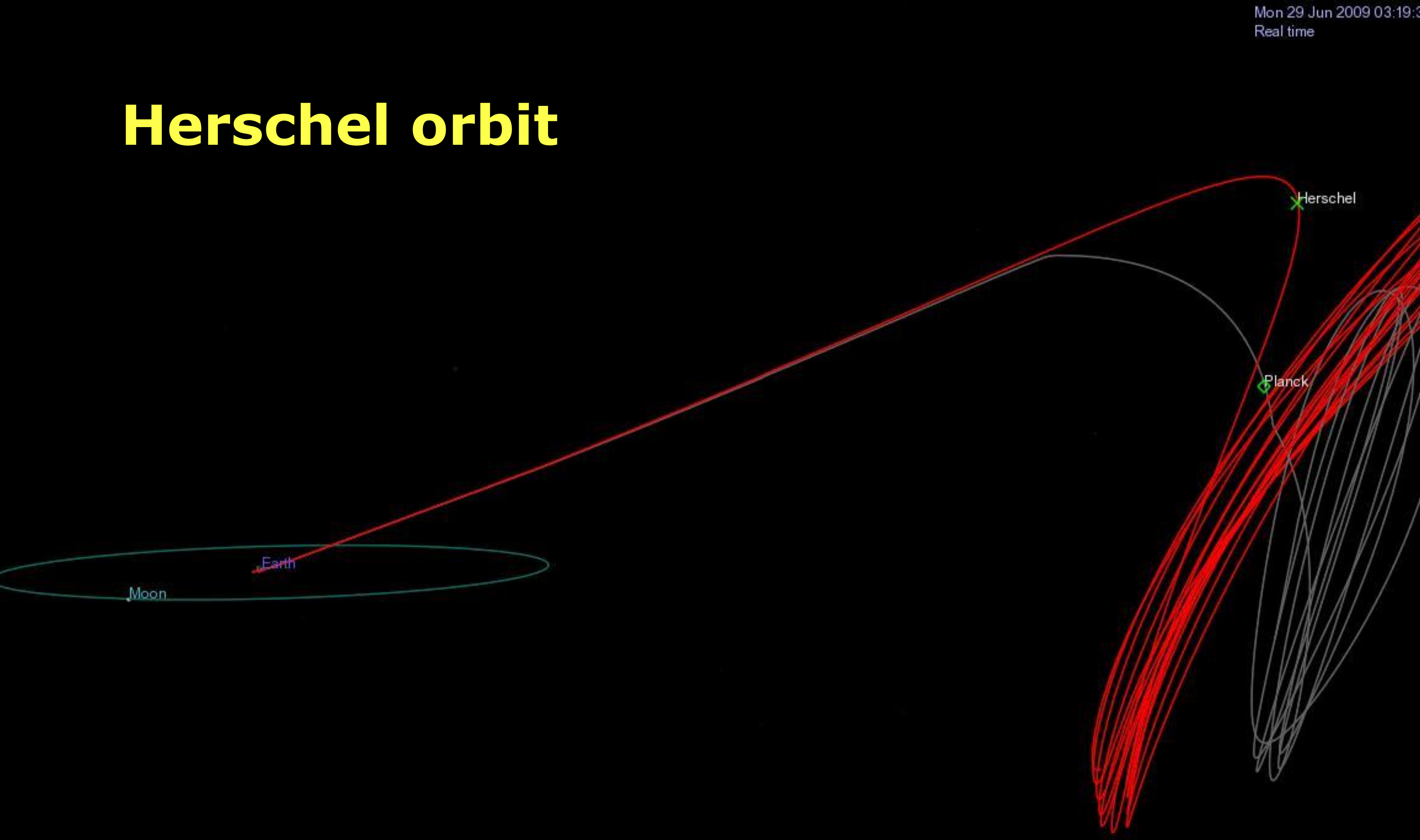
55 - 210 μm (3 orders)

$\lambda/\Delta\lambda$ = 1000 – 4000

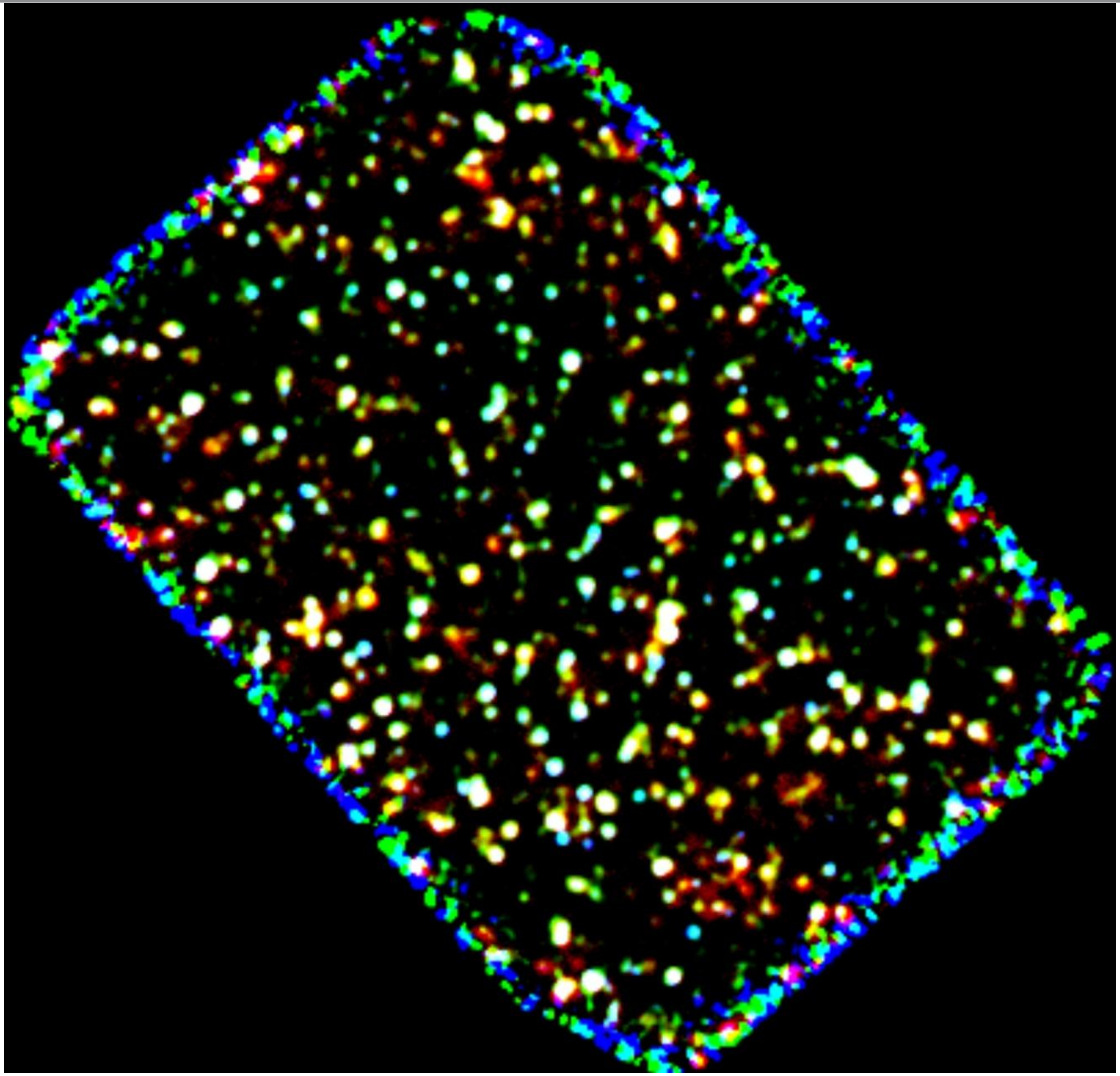



Herschel Launch:
14 May 2009

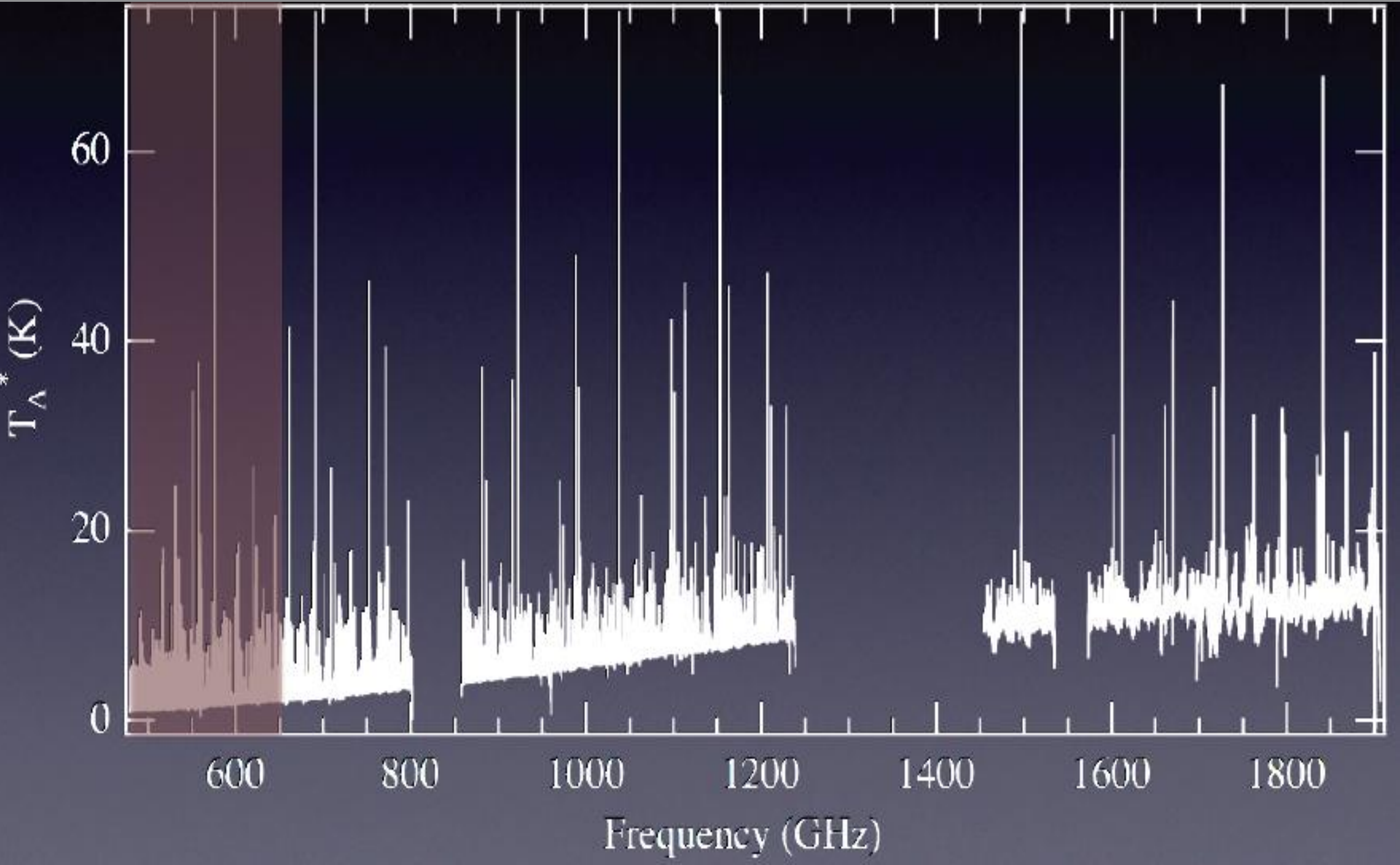
Herschel orbit



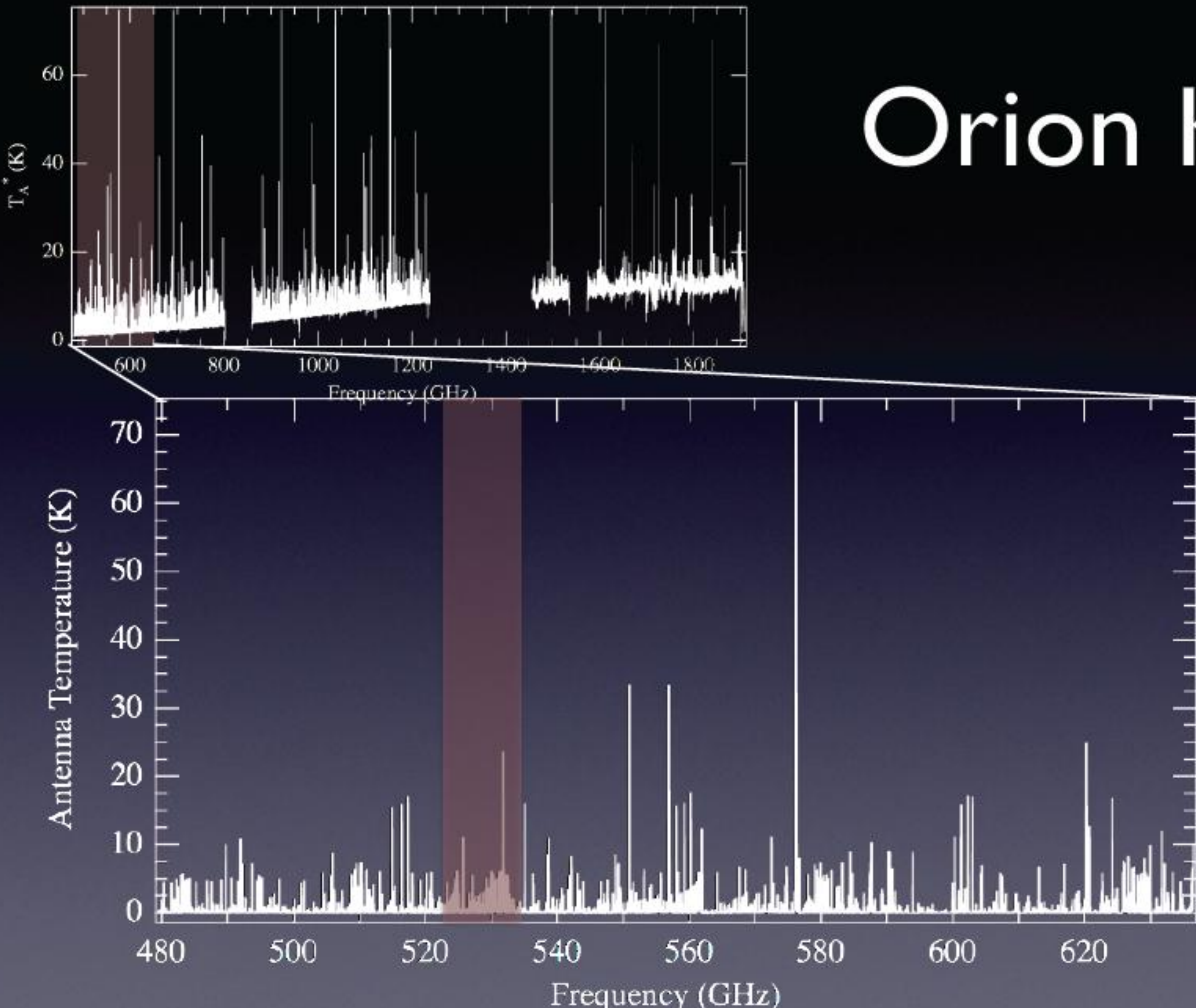
Herschel GOODS-S Field (70 – 100 -160 μm)



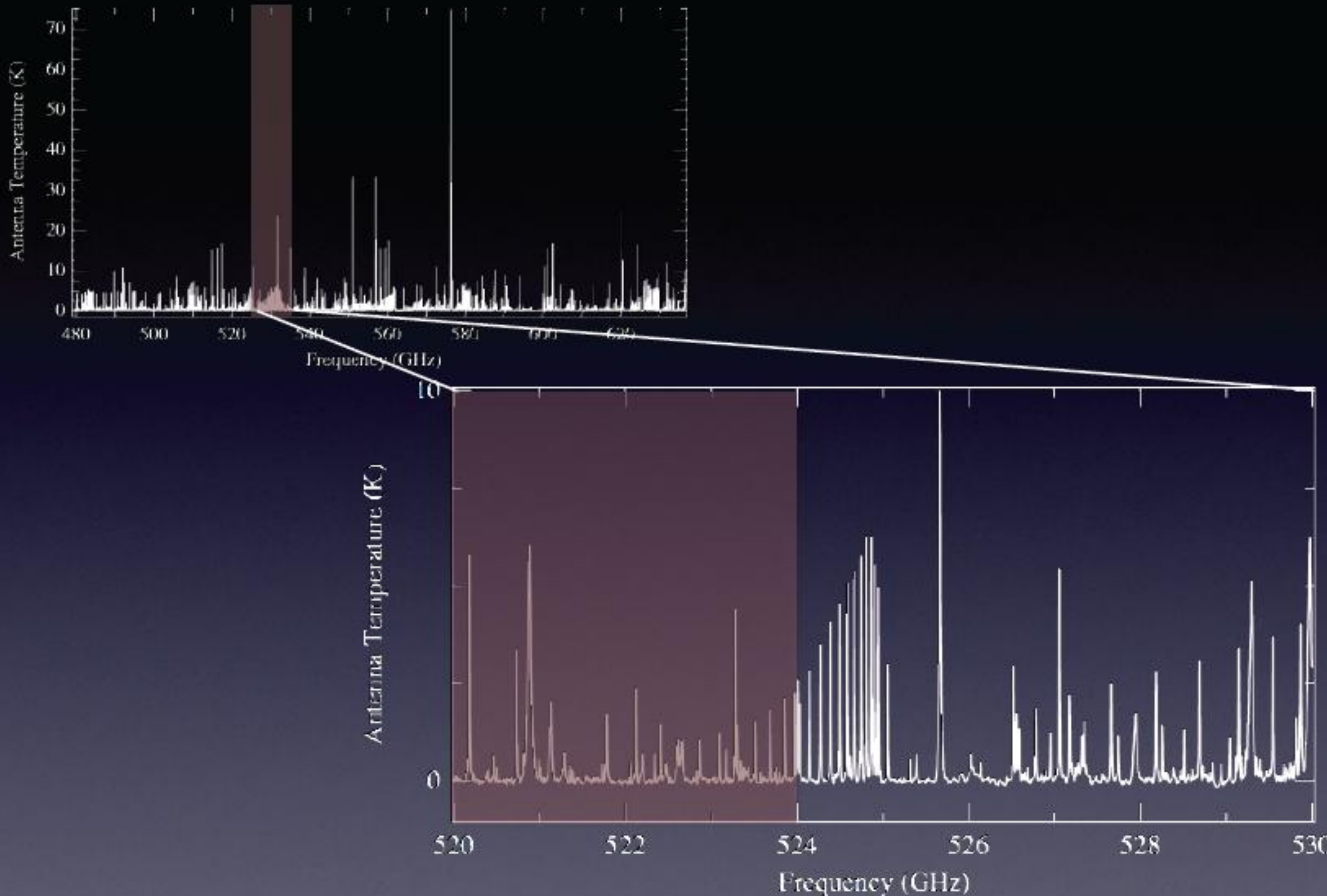
➤HIFI – Orion KL spectral survey



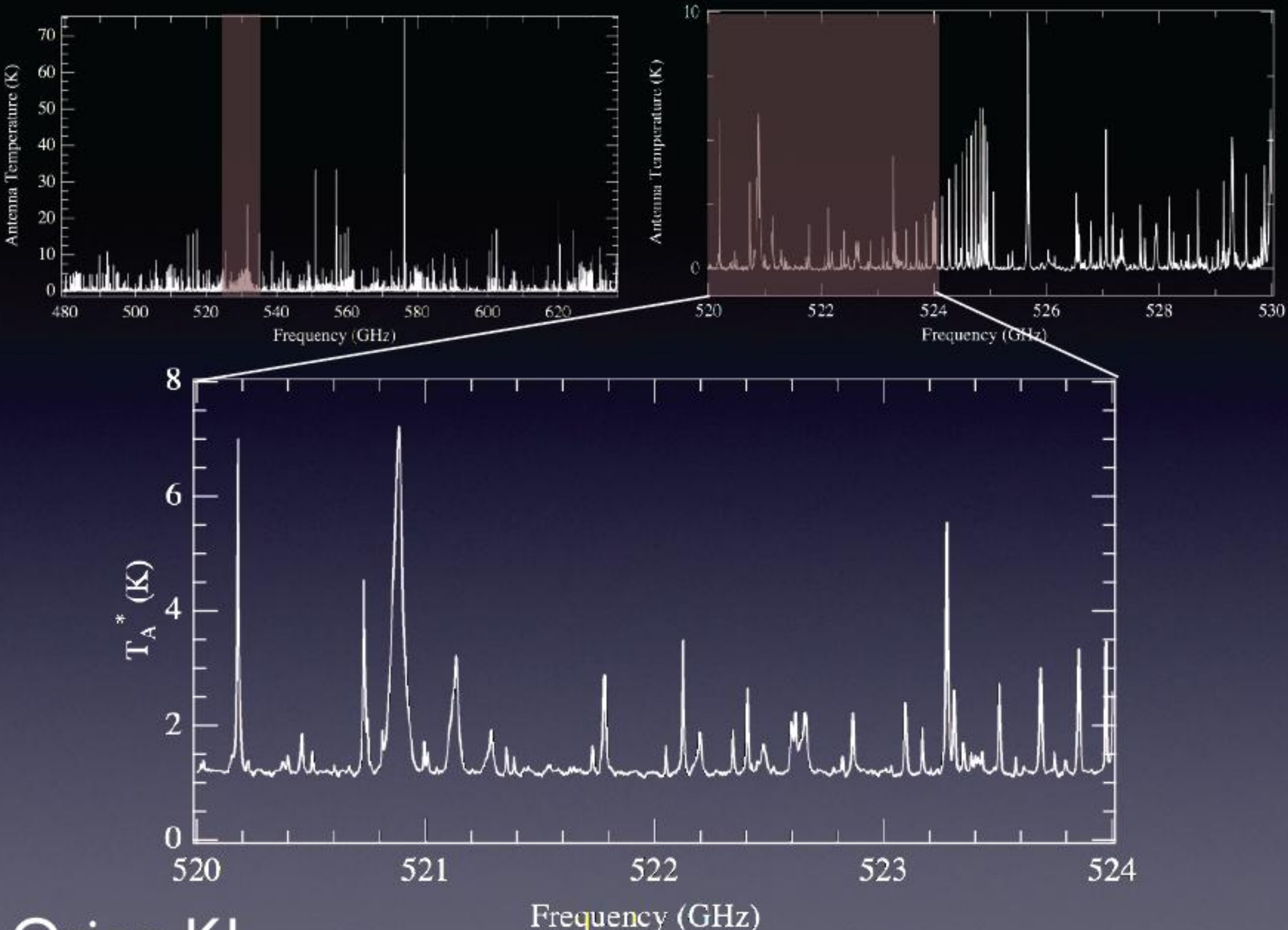
Orion KL



T_A^* (K)
0
20
40
60
600
800
1000
1200
1400
1600
1800
Frequency (GHz)
Antenna Temperature (K)
0
10
20
30
40
50
60
70
480
500
520
540
560
580
600
620
Frequency (GHz)



Orion KL - Band 1



Antenna Temperature (K)
Frequency (GHz)
Antenna Temperature (K)
Frequency (GHz)
T_A^* (K)
Frequency (GHz)

Orion KL

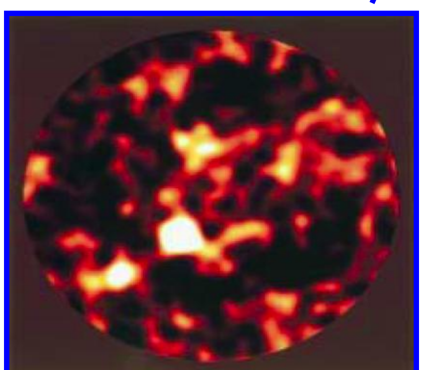
➢Progress in submm observations

1998

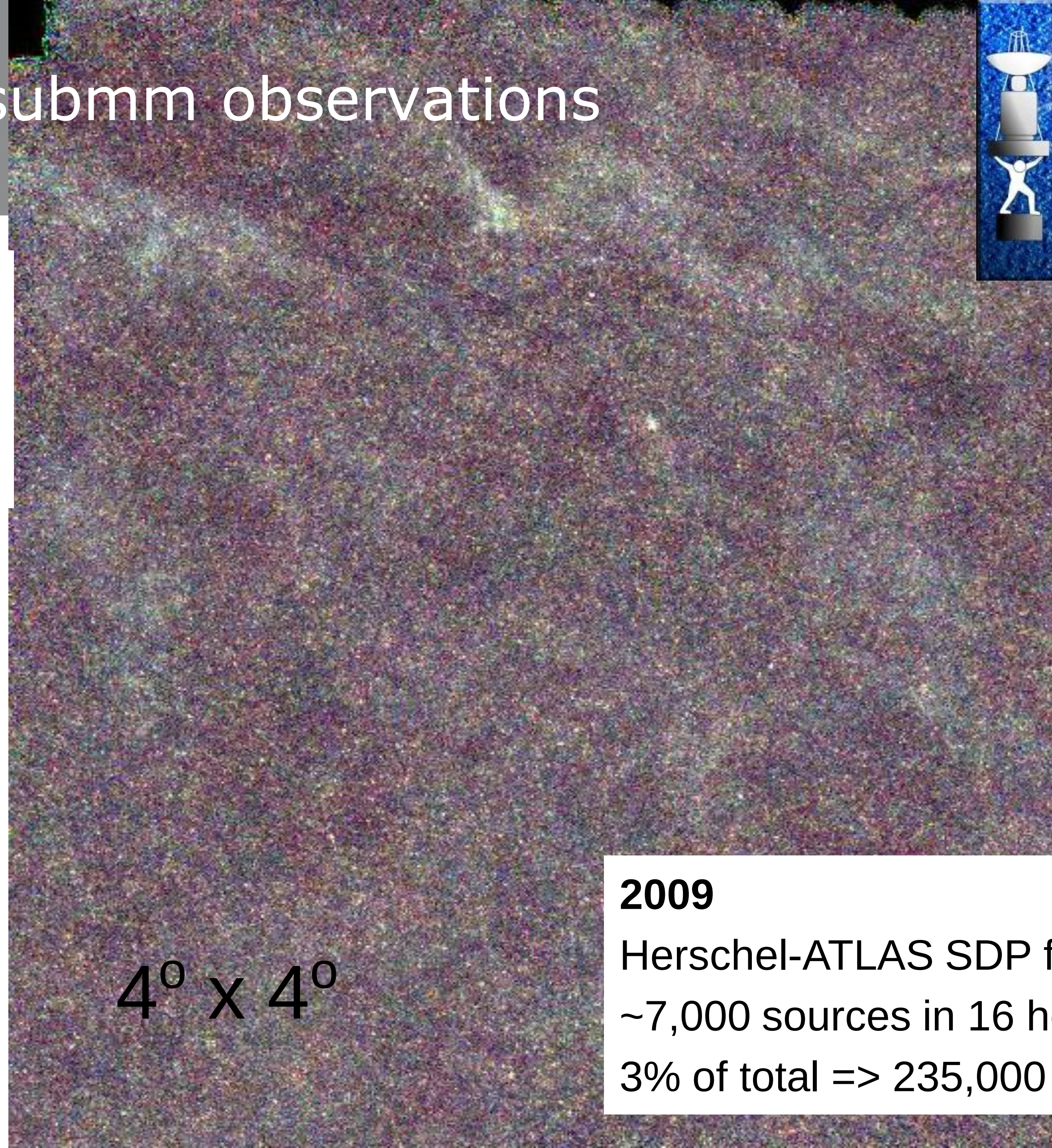
SCUBA HDF:

5 sources after 20 exceptional nights

To scale!



~3 arcmin



2009

Herschel-ATLAS SDP f

~7,000 sources in 16 h

3% of total => 235,000

ESLAB 2010 … and 'impact'

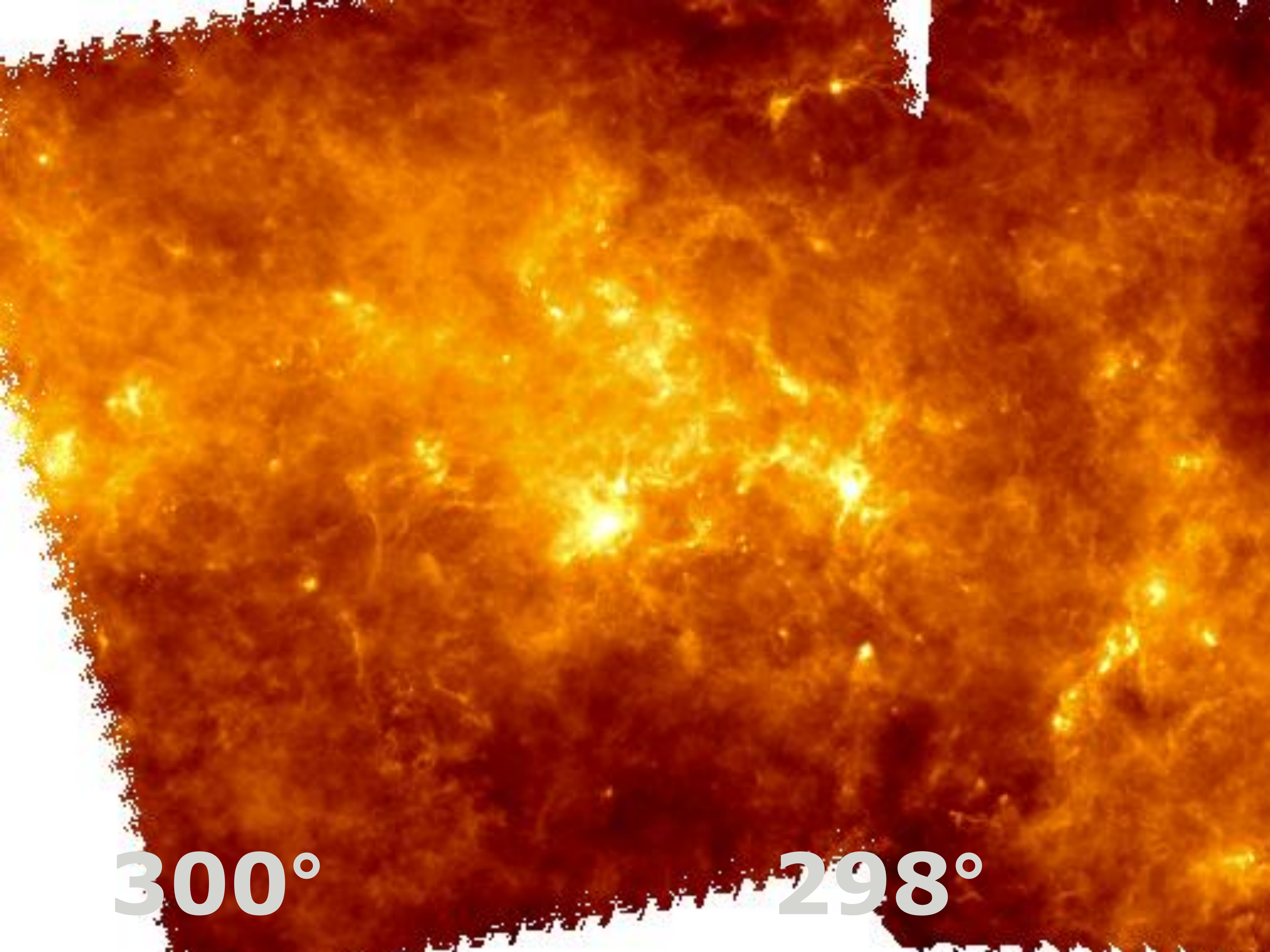
Conferences

- SDP Results, Madrid, 17-18 Dec 2009
- AAS#215, Wash DC, 3-7 Jan 2010
- ESLAB, ESTEC, 4-7 May 2010
- AAS#216, Miami, 23-27 May 2010
- SPIE, San Diego, 27 June-2 July 2010
- COSPAR, Bremen, 19-24 July 2010
- Göteborg/Särö, 6-9 Sep 2010
- JENAM 2010, Lisbon, 6-10 Sep 2010
- Zermatt, 19-24 Sep 2010
- Herschel/ALMA, 17-19 Nov 2010
- Planck, Paris, 10-14 Jan 2011
- RAS, London, 14 Jan 2011
- UCI, Irvine, 12-14 May 2011
- Toledo, 30 May- 3 Jun 2011
- JENAM 2011, St Petersb 4-8 Jul 2011
- FIR2011, London 14-16 Sep 2011
- MW2011, Rome, 19-23 Sep 2011
- Planck, Bologna, 13-17 Feb 2012
- Pebbles, Grenoble, 19-23 March 2012

Hi-GAL montage

300°

298°

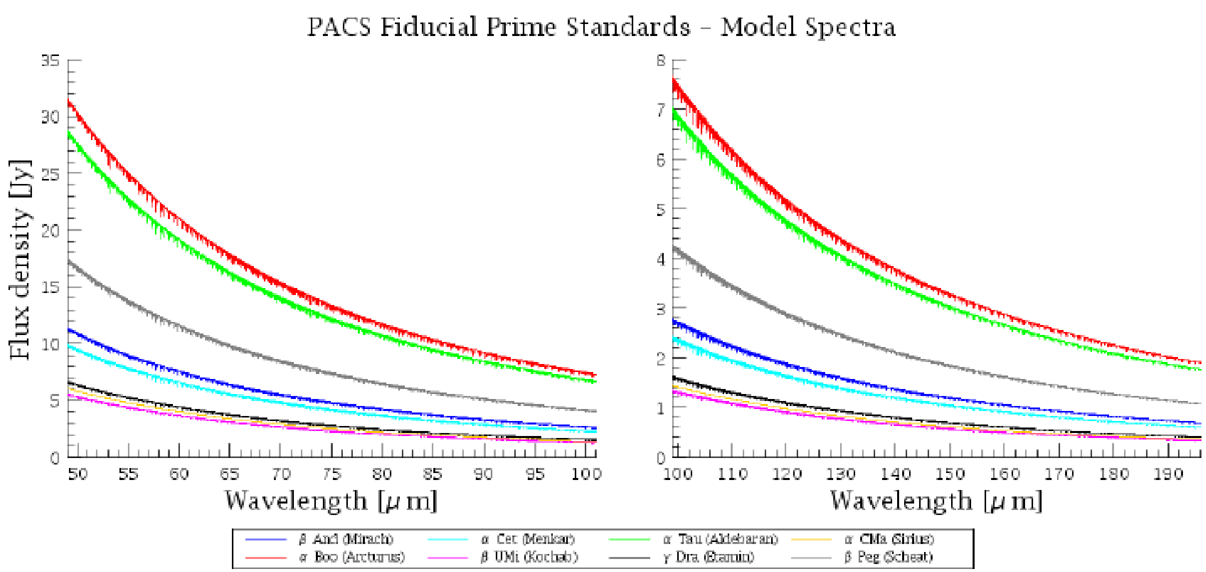

300°
298°

Overview of Herschel calibration

- Internal calibrations to all instruments in one form or another, e.g. hot and cold loads in the HIFI heterodyne instrument.
- Three elements in this presentation:
  - Reproducibility and linearity
  - Celestial models for full astronomical flux calibration
  - Cross-calibration
- NOT covering,
  - Variations with mode and reference schemes
  - Wavelength calibration of spectrometers.
- Three sets of celestial standards and associated models.
  - Planetary models
  - Stellar models
  - Asteroid models

Stellar models

- Based on pre-launch stellar models (Dehaes et al, 2011; A&A, 533, 107 and 2011yCat..35339107D).
- The stellar atmosphere model and theoretical spectrum are generated using the MARCS theoretical stellar atmosphere code (Gustafsson et al. 2003,A&A, 400, 709) and the TURBOSPECTRUM synthetic spectrum code (Plez et al., 1992, A&A, 256, 551).
- Absolute flux based on Selby K-band photometry (Selby, 1988).

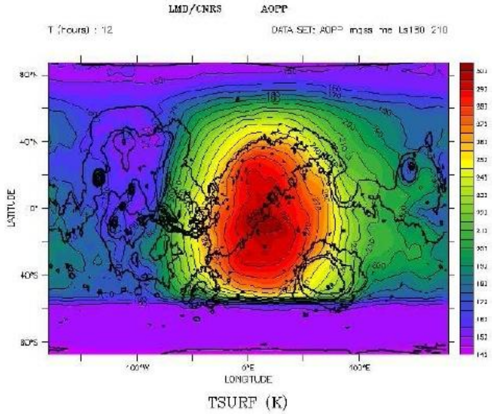


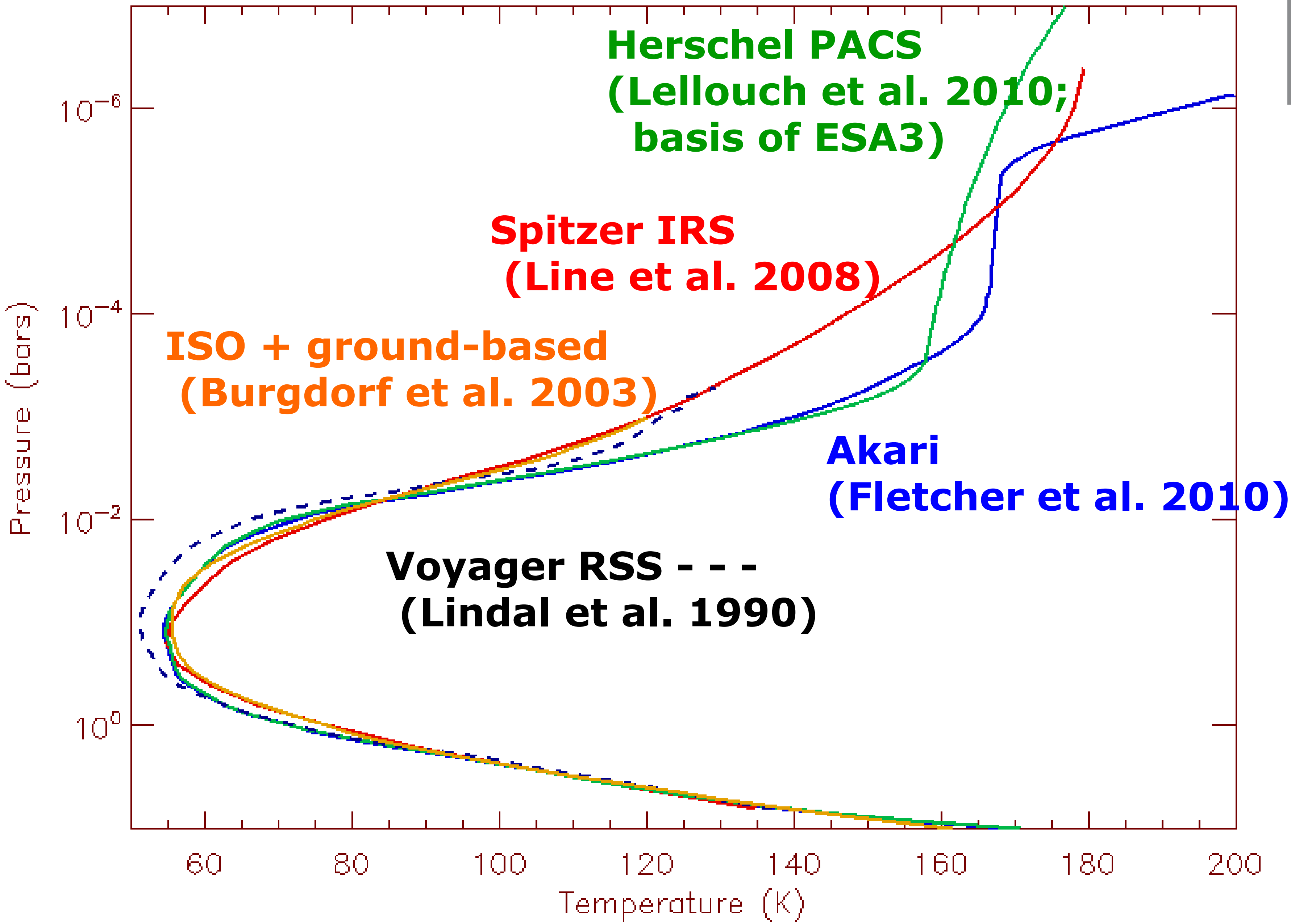
Planet models (R. Moreno & G. Orton)

- Based on physical atmospheric models of the outer planets (particularly Neptune and Uranus for SPIRE calibration).
- Data used for initial models based on physical flyby information, ground based radio to optical measurements (recent possible inclusion, full modeling based on Spitzer spectral data [Orton] – calibrated against standard stars). Everything within few percent.
- Comparison to Mars models also made (see later) – Amri & Lellouch

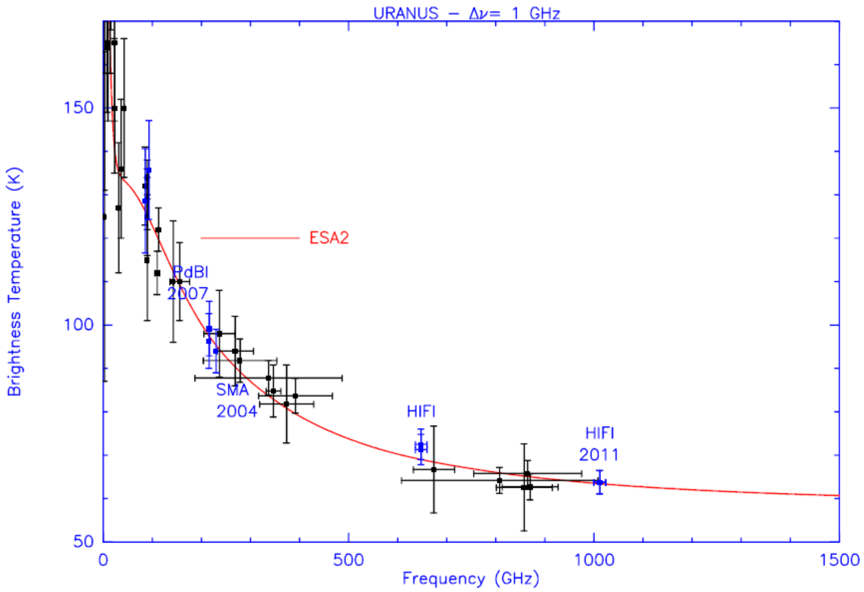
http://www.lesia.obspm.fr/perso/emmanuel-lellouch/mars/

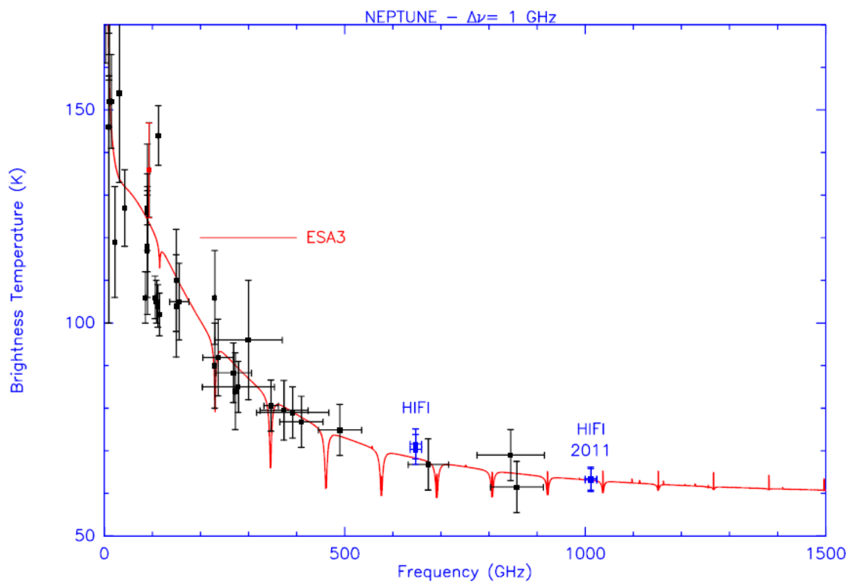
Based on surface and sub-surface temperatures from EMCD experiment (Forget et al).



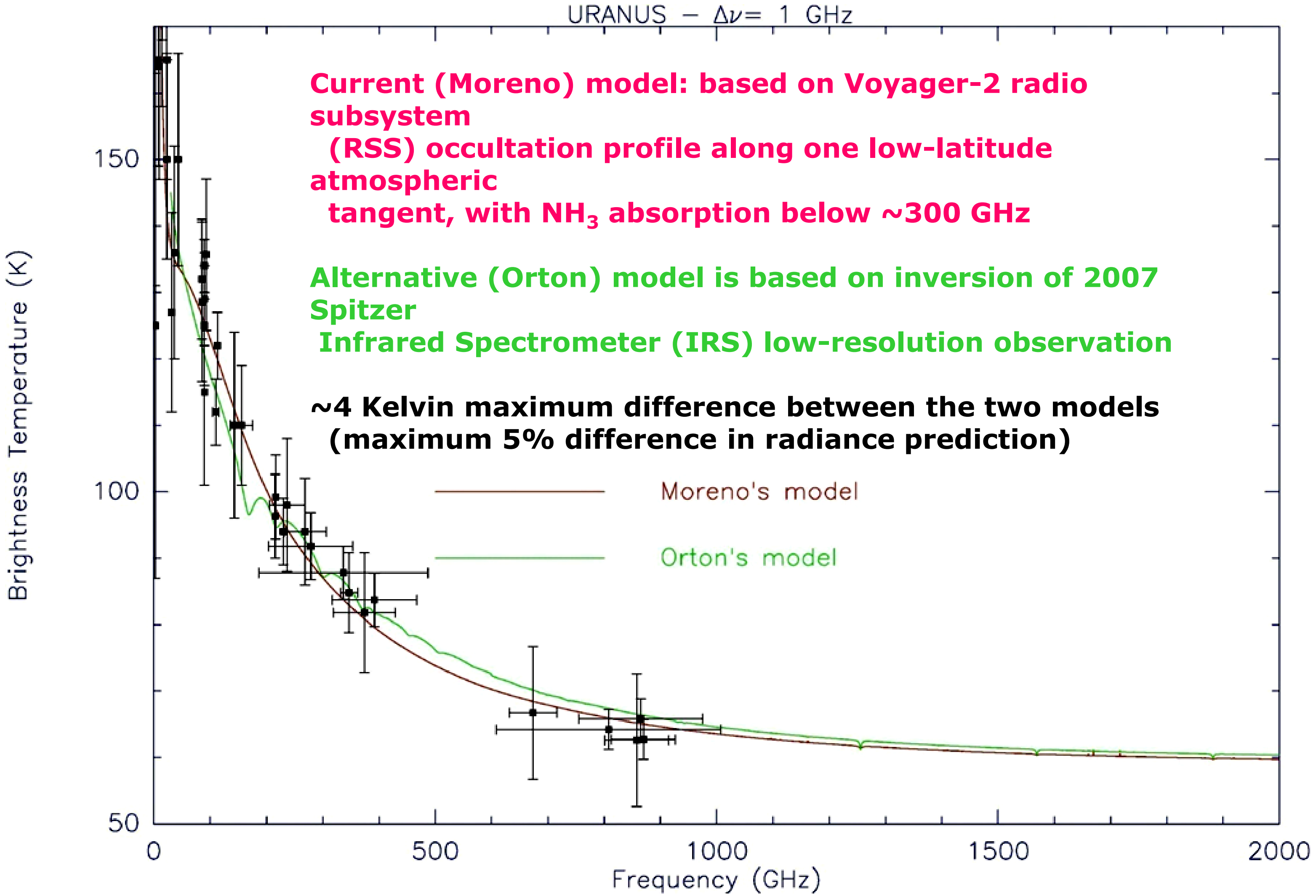

Herschel PACS
(Lellouch et al. 2010;
basis of ESA3)
Spitzer IRS
(Line et al. 2008)
ISO + ground-based
(Burgdorf et al. 2003)
Akari
(Fletcher et al. 2010)
Voyager RSS - - -
(Lindal et al. 1990)
10^{-6}
10^{-4}
10^{-2}
10^{0}
Pressure (bars)
60
80
100
120
140
160
180
200
Temperature (K)

Uranus and Neptune models





Model Updates Coming (June 2012; TBC)

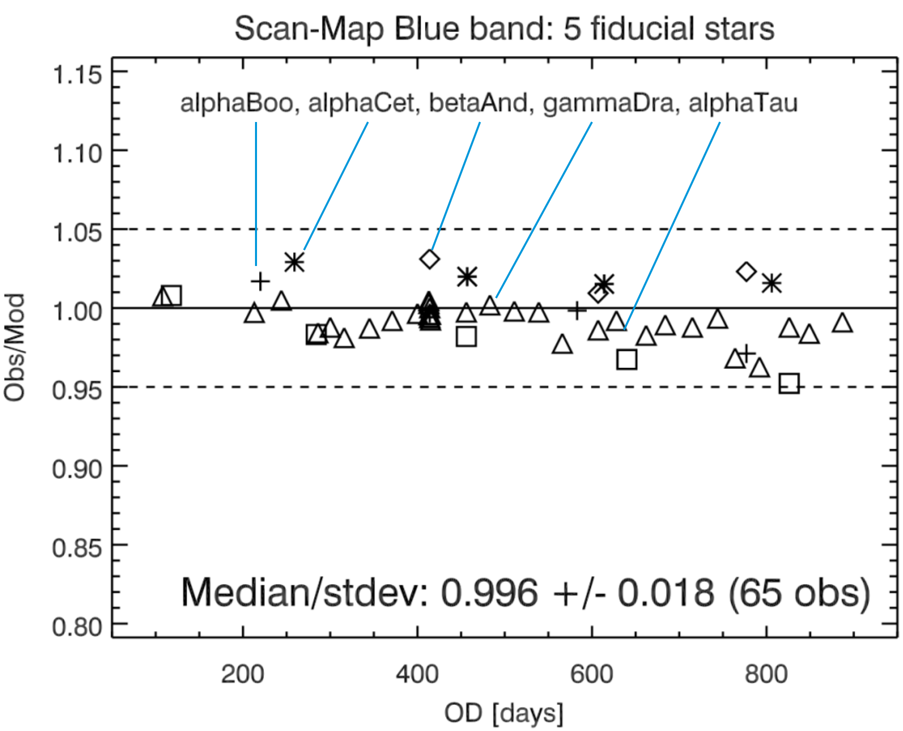


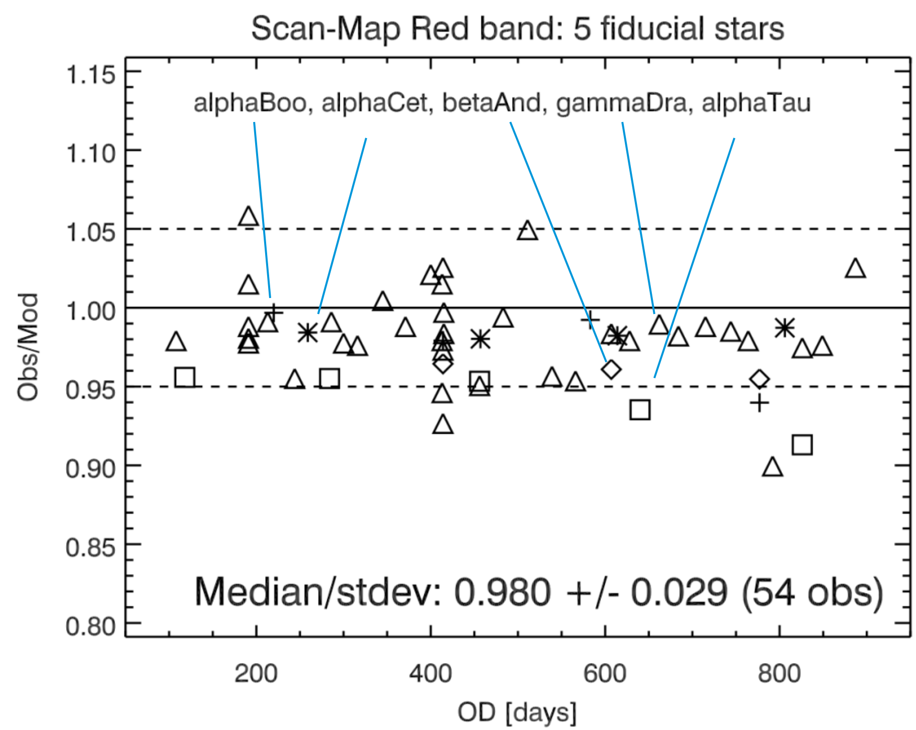
Abbreviated Modes of Photometer Data Taking

esa

- All photometers take data in scan modes (70, 100, 160, 250, 350, 500 μm).
- Multiple pixel arrays → mean each point in sky covered by many pixels in one or more scans.
- Following timeline of signals of bolometer pixels → interpolate onto sky position on a preset pixel array for final map.
- Various mapping routines being used – test comparisons still being performed.
  - Pointed emission
  - Extended emission – linear response of bolometers.
- Background is main source of flux due to warm (80+K) mirror.
- Absolute calibration
  - PACS (70 – 160 μm). Uses stellar model standards.
  - SPIRE (250 – 500 μm). Uses Neptune model.

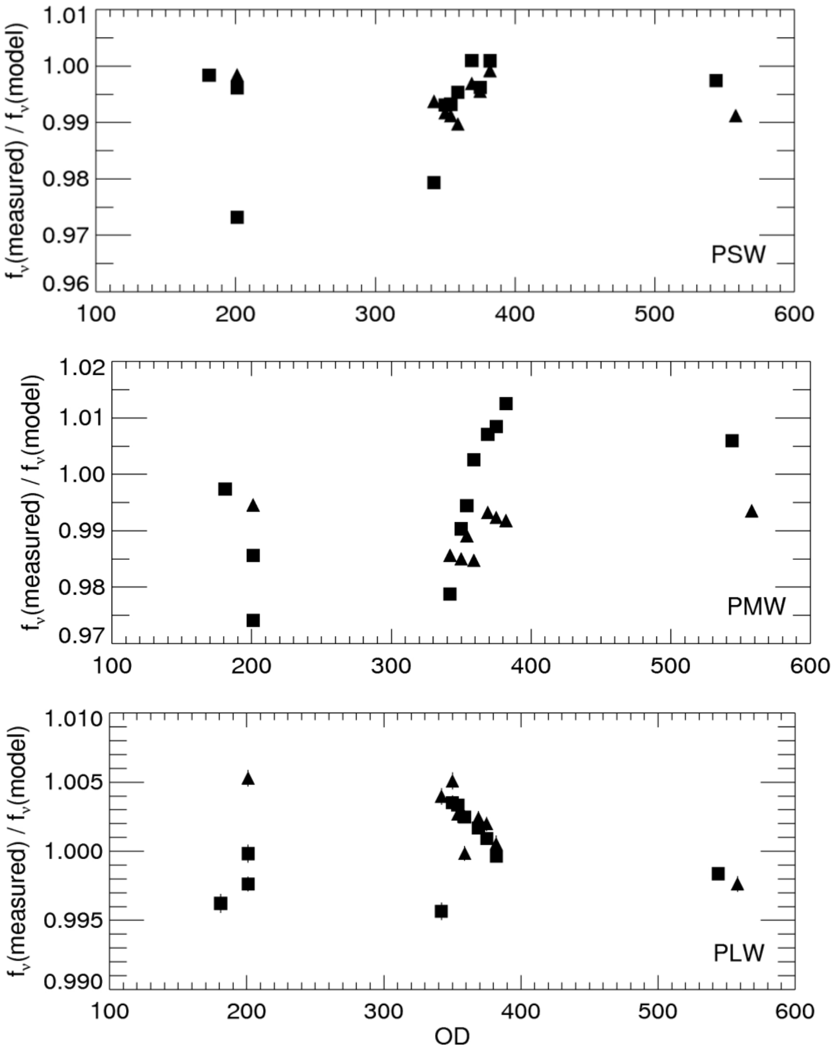
PACS calibration consistency



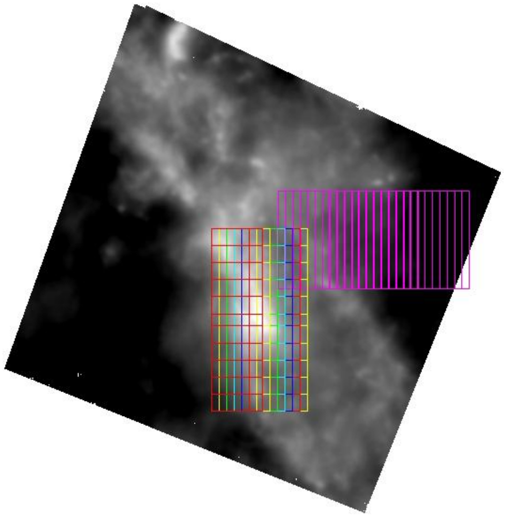


Consistency within 3-5% across PACS range – 160 fluxes may be ~2% underestimated.
Flux calibration uncertainties for PACS-P scan-map observations: 3%, 3%, 5% at 70, 100, 160 μm

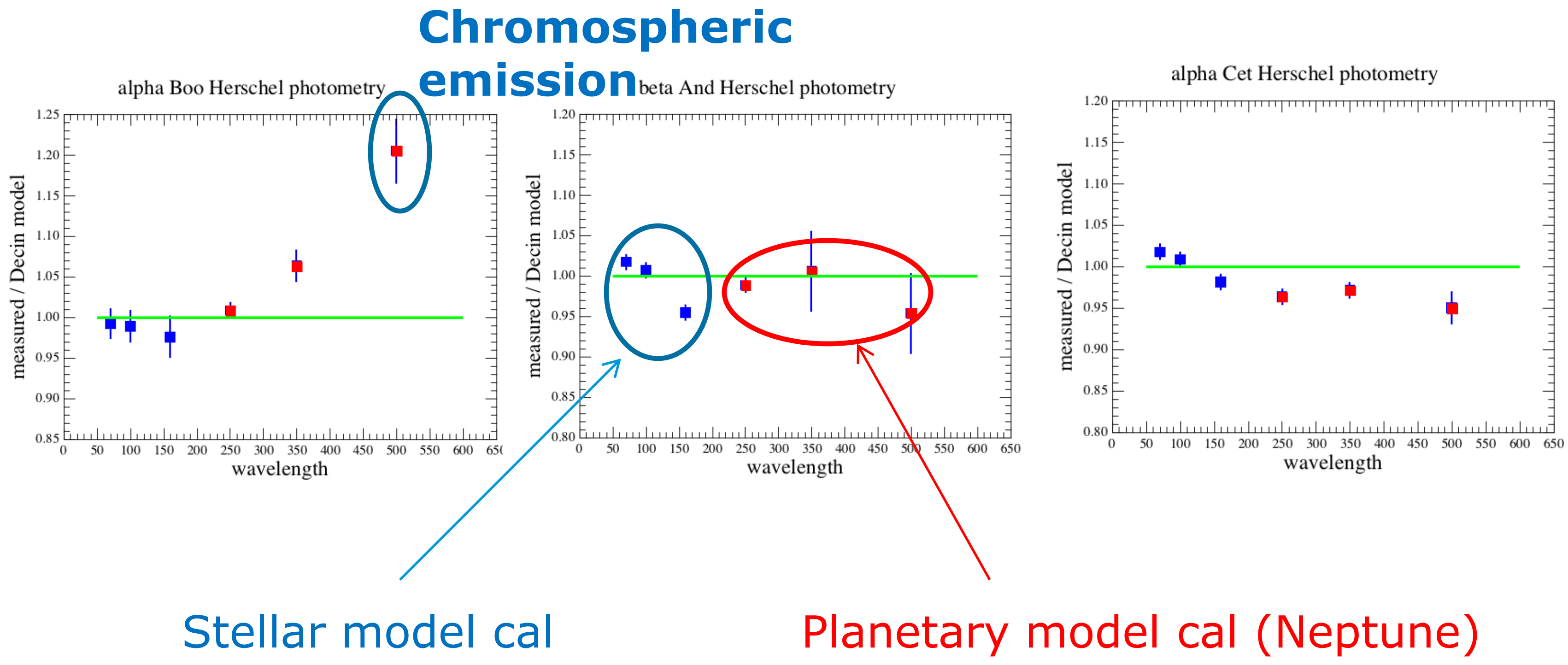
SPIRE photometry



- Initial measurements of bolometers with Pcal flashes measured on extended emission.
- Flux calibrated against scans of Neptune.
- Reproducibility: < 2%

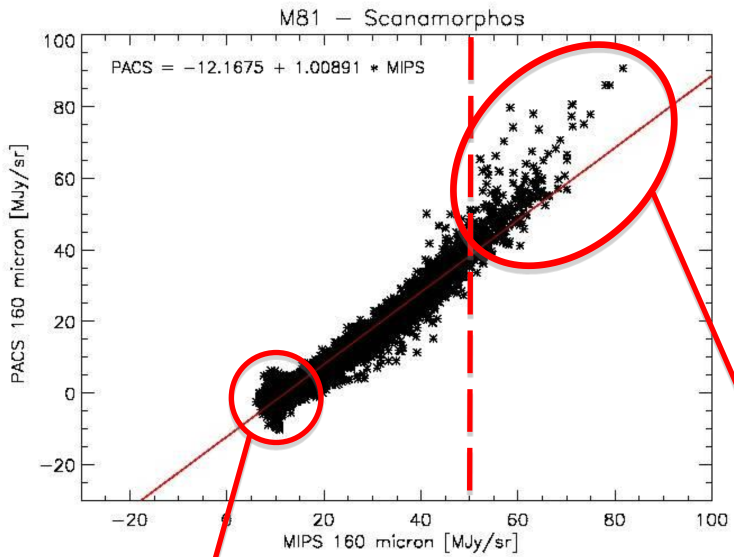


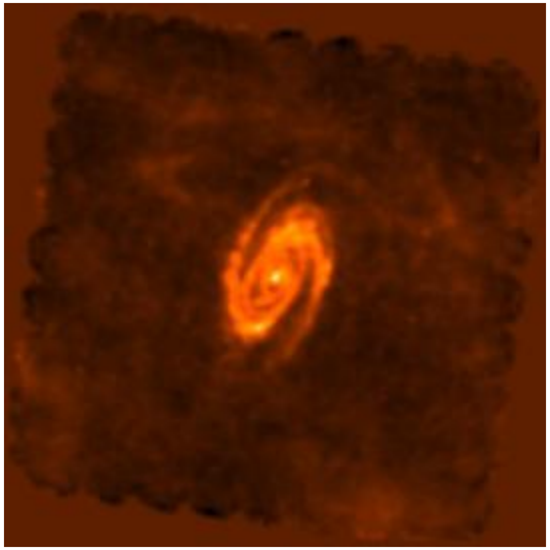
Photometer flux standard measurements



- PACS and SPIRE photometry – based on two different model sets agree with each other within few per cent.

Extended Emission – PACS/MIPS comparison





MIPS 160μm
non-linearity: ~ 50 MJy/sr !

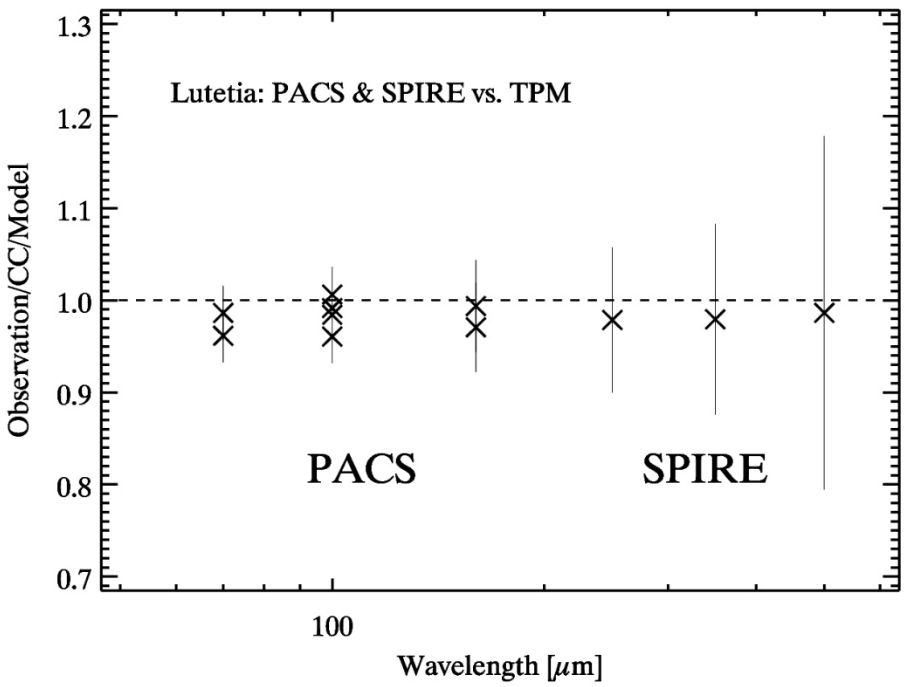
Background -> some of this is
"garbage"

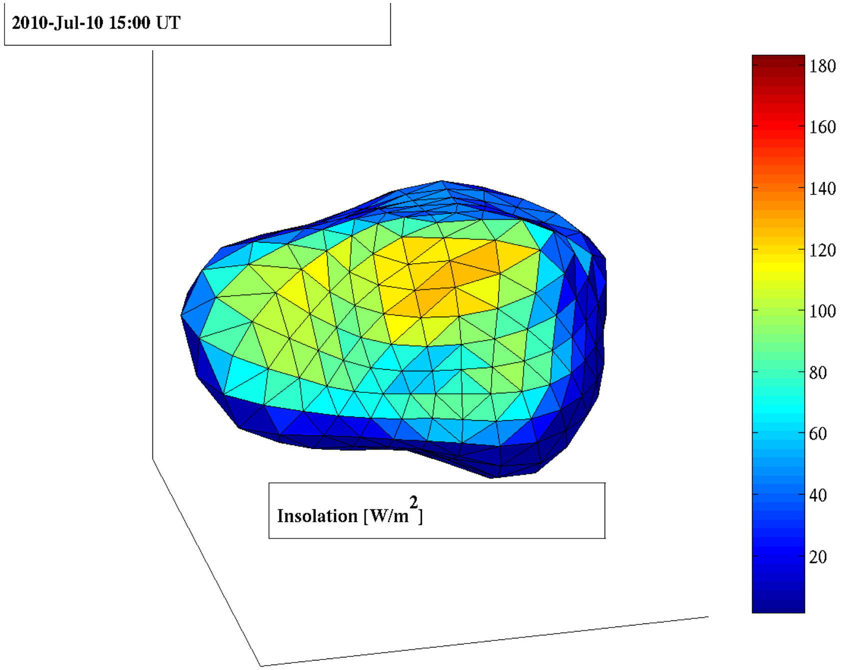
Asteroid models (Thomas Mueller)

- TPM: Müller & Lagerros (1998 & 2002).
  - *Key input parameters: D_{eff} & p_V; P_{sid}, epoch for true observing & illumination geometry*
- Shape model, rotation period from lightcurve inversion technique and adaptive optics
- There is an assumption of a low conductivity regolith on the surface
- TPM input parameters are derived from a large sample of thermal observations.
- Starting list:
  - *all known large main-belt asteroids with diameters >100 km*
  - *with high quality, smooth,*
  - *low amplitude lightcurves (visible)*
  - *good quality spin vector and rotational properties,*
  - *availability of "Kaasalainen" shape models (lightcurve inversion complemented by radar, adaptive optics, occultations, HST, ...) or at least high-quality ellipsoidal shape models, independent diameter and albedo information (occultation, speckle, HST, flybys, ...)!*

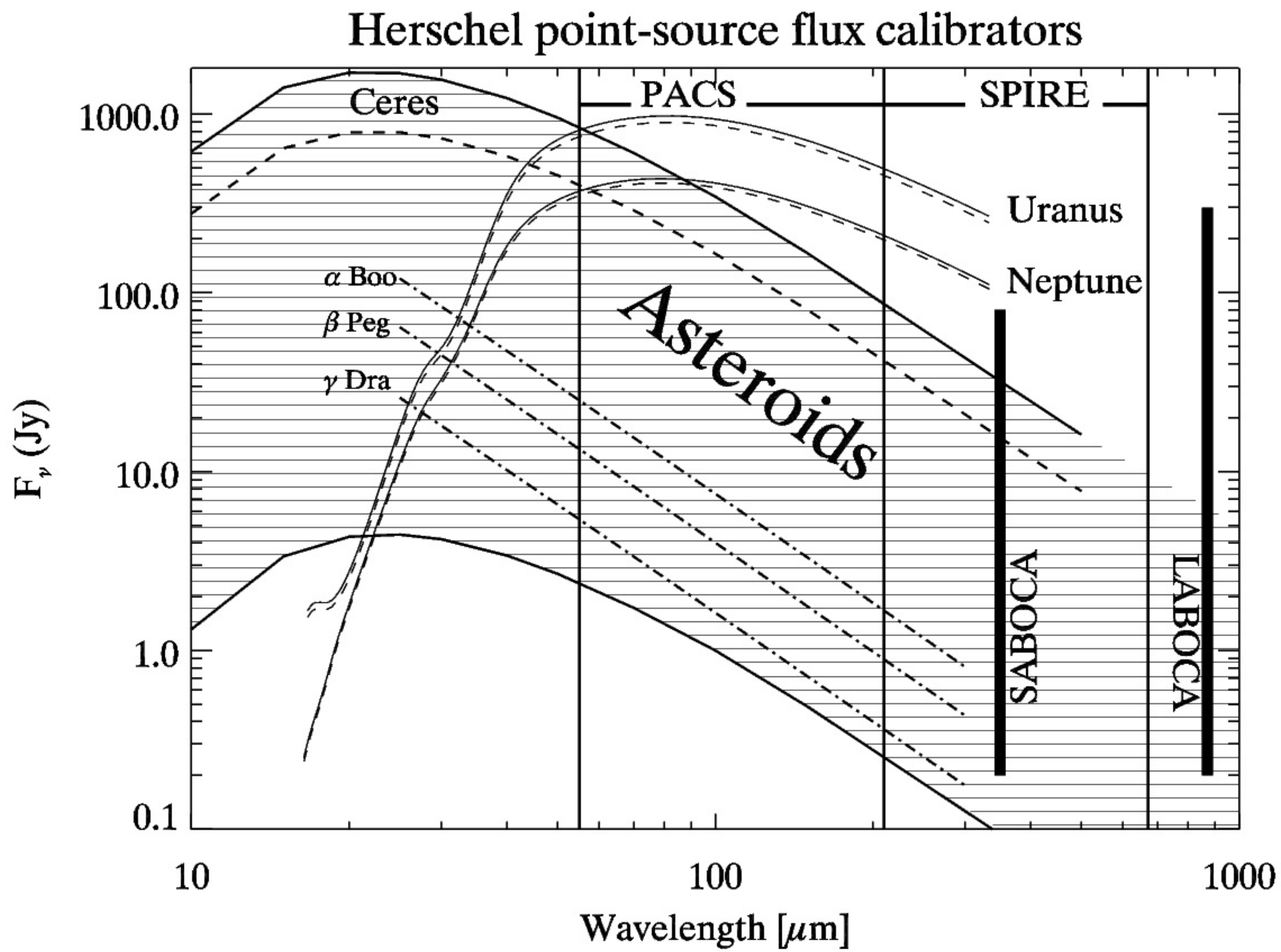
21 Lutetia example (Rosetta flyby)

Example: TPM input parameters for Lutetia: D_{eff}=102 km, p_V =0.22,
Shape model: Carry et al. (2010), P_{sid}=8.16827108 h
Herschel photometry: OD221/400 (PACS) OD423 (SPIRE)
Rosetta flyby: 2010-Jul-10 (OD 422)

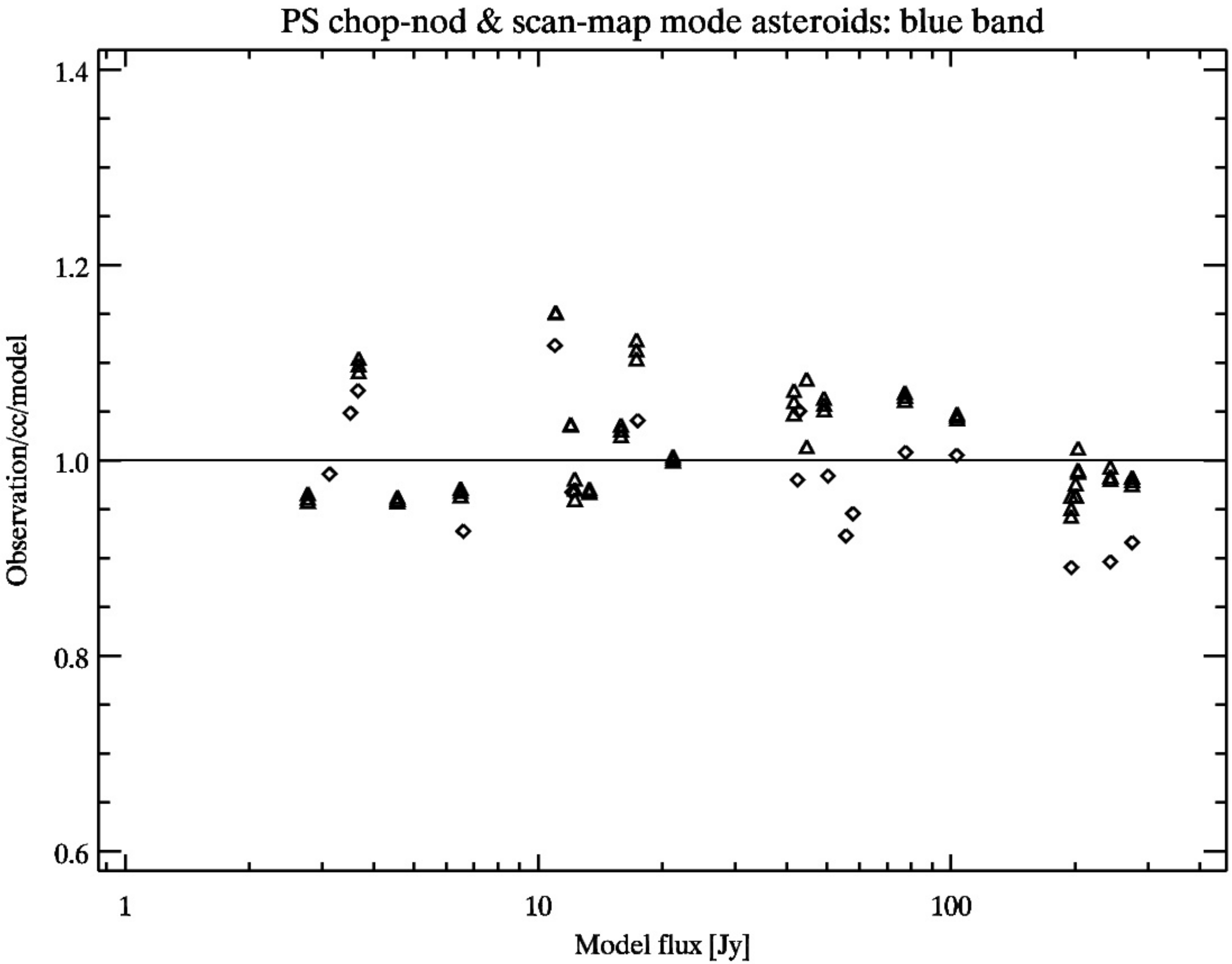




Range of flux calibrators



Consistency of asteroid measurements



- *Extra point:* No evidence of mid- or near-IR leaks.
- As a group good to ~1-2%.

PACS asteroid measurements – cross-check

- Models continue into the PACS photometer range
  - → 70, 100 & 160 microns fluxes.

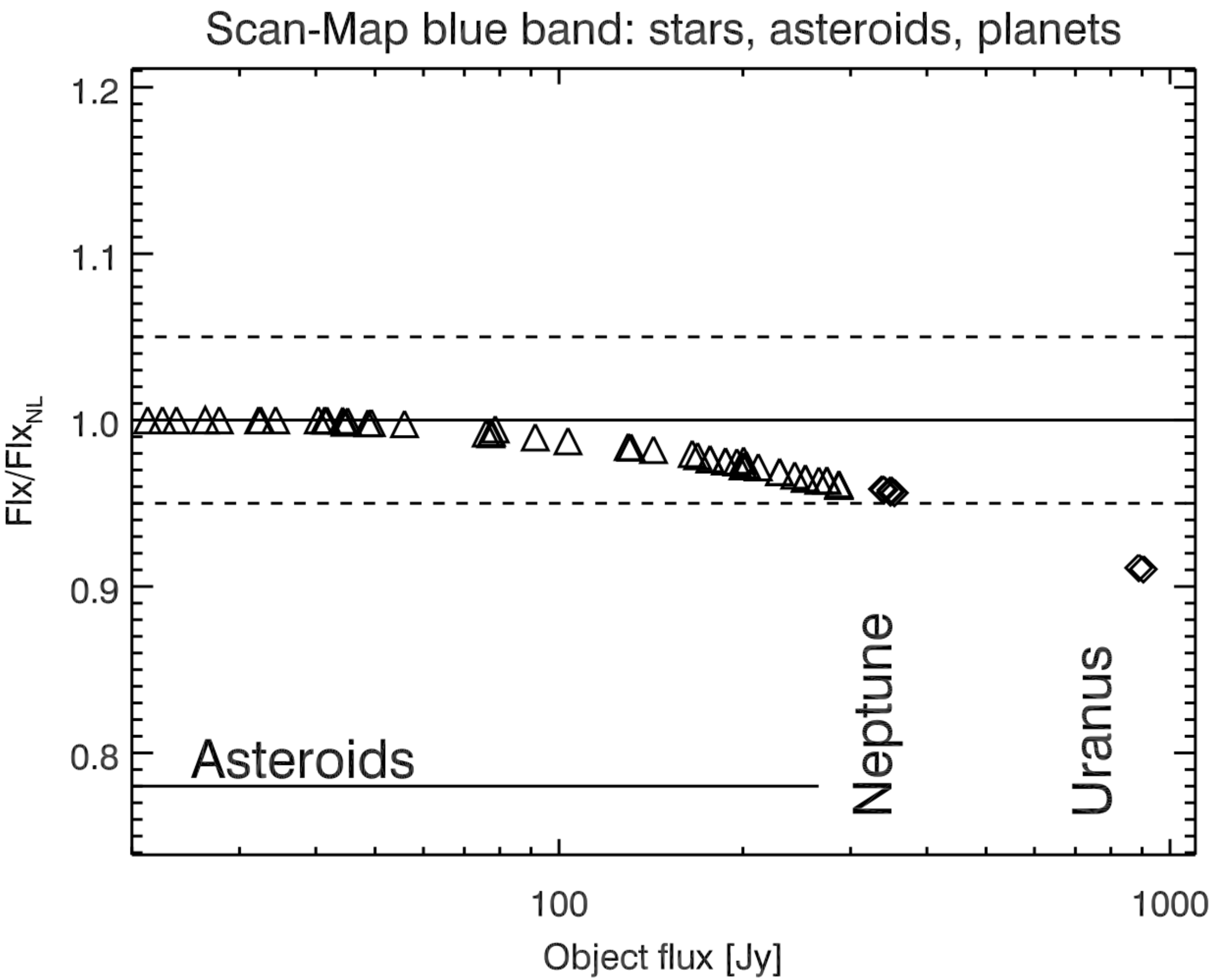
No. of asteroids	blue obs/model				green obs/model				red obs/model			
	no.	med.	mean	stdev	no.	med.	mean	stdev	no.	med.	mean	stdev
all 18 ast.	79	1.006	1.003	0.068	83	0.988	0.994	0.059	184	0.995	0.995	0.058
without 423	76	1.009	1.011	0.059	80	0.992	1.001	0.046	177	0.997	1.001	0.050
high quality ast.	53	1.012	1.014	0.036	53	0.999	1.003	0.036	119	0.997	0.996	0.042

SPIRE asteroid calibration

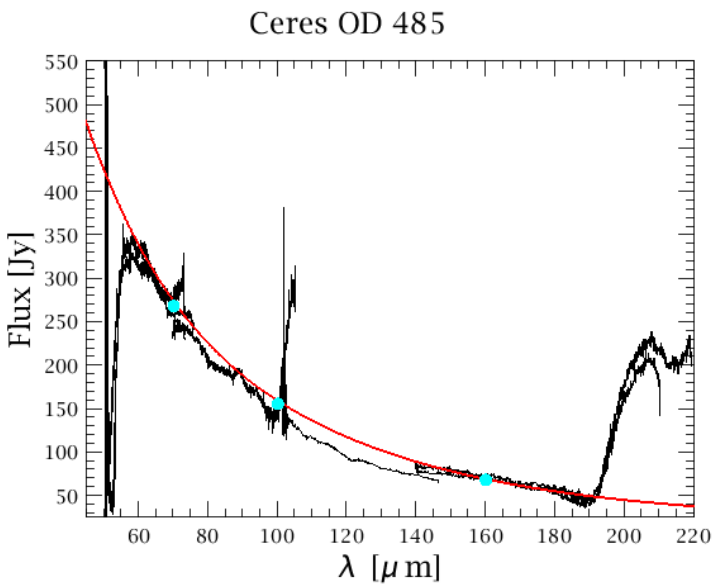
1 Ceres	13	13	36.60	**1.00**	**1.01**	**1.00**	0.03	0.02	0.03
4 Vesta	15	15	15.51	**1.07**	**1.11**	**1.09**	0.02	0.02	0.02
2 Pallas	9	9	10.45	**1.09**	**1.10**	**1.10**	0.03	0.03	0.03
10 Hygiea	6	6	7.64	**1.03**	**1.01**	**1.02**	0.04	0.11	0.09
3 Juno	9	9	5.89	**0.99**	**0.96**	**0.95**	0.03	0.03	0.03
52 Europa	6	6	4.58	**1.02**	**1.02**	**1.03**	0.03	0.03	0.02
7 Iris	2	2	4.27	**0.88**	**0.88**	**0.86**	0.11	0.12	0.14
6 Hebe	6	6	3.86	**1.03**	**1.01**	**0.98**	0.09	0.09	0.09
8 Flora	1	1	3.16	**1.03**	**1.03**	**1.02**			
704 Interamnia	3	3	2.29	**0.95**	**1.00**	**1.01**	0.18	0.10	0.06
29 Amphitrite	3	3	1.80	**0.94**	**0.91**	**0.88**	0.07	0.07	0.08
511 Davida	3	3	1.61	**1.03**	**1.10**	**1.01**	0.05	0.08	0.07
88 Thisbe	2	1	1.44	**1.07**	**1.07**	**1.07**	0.15	0.15	0.11
19 Fortuna	1	1	1.43	**0.84**	**0.85**	**0.71**			
65 Cybele	3	3	1.41	**0.98**	**0.98**	**0.97**	0.18	0.19	0.20
372 Palma	1	1	1.25	**0.84**	**0.85**	**0.84**			
173 Ino	2	2	1.12	**0.75**	**0.75**	**0.78**			
54 Alexandra	1	1	1.07	**1.25**	**1.27**	**1.29**	**0.37**	**0.38**	**0.33**
20 Massalia	1	1	0.74	**0.98**	**1.00**	**1.05**			
93 Minerva	2	2	0.55	**0.91**	**0.91**	**0.94**			
47 Aglaja	2	2	0.41	**1.20**	**1.21**	**1.18**	0.07	0.11	0.08
21 Lutetia	1	1	0.26	**1.00**	**1.01**	**0.94**	0.06	0.04	0.08
253 Mathhilde	1	1	0.25	**1.26**	**1.31**	**1.41**			
				1.01	**1.02**	**1.01**			

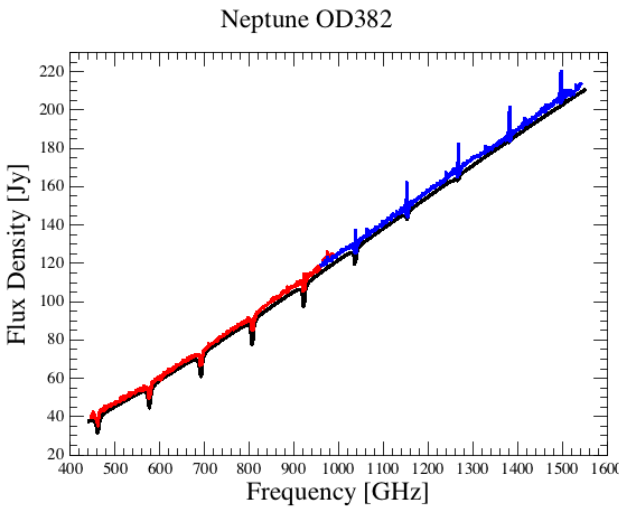
- No updates since launch – Herschel data can improve some of these models → make some into primary calibrators (calibration legacy).

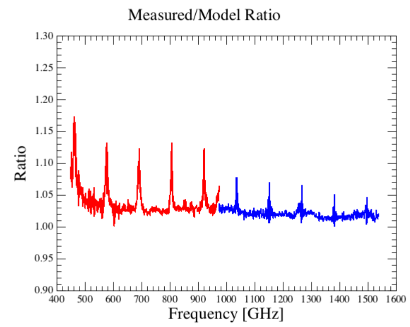
PACS nonlinearity



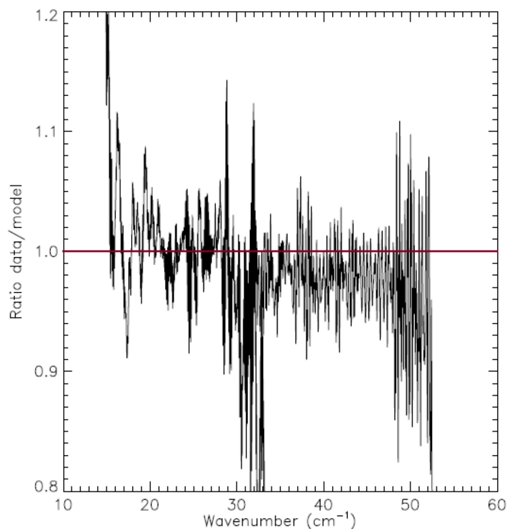
PACS and SPIRE spectra







Above left: PACS spectrum with phot (dots) points & compared to Ceres spectrum and model (in red).
Above right: Early SPIRE model versus calibrated spectrum.
To right: Model versus measurement of telescope emission.



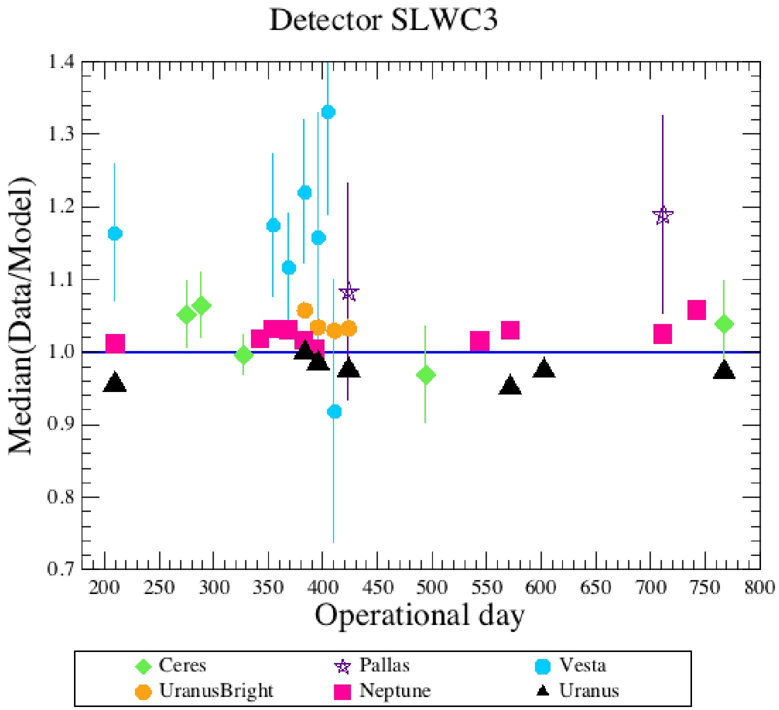
PACS and SPIRE spectroscopy

PACS:

- PACS 10-20% absolute flux accuracy depending on mode.
- Leak regions – possible to calibrate?
- Major component to reduce is the effect of pointing. Being addressed.

SPIRE:

- Repeatability – 6% for planets and 15% for asteroids.
- Line flux ~1.5-4%.

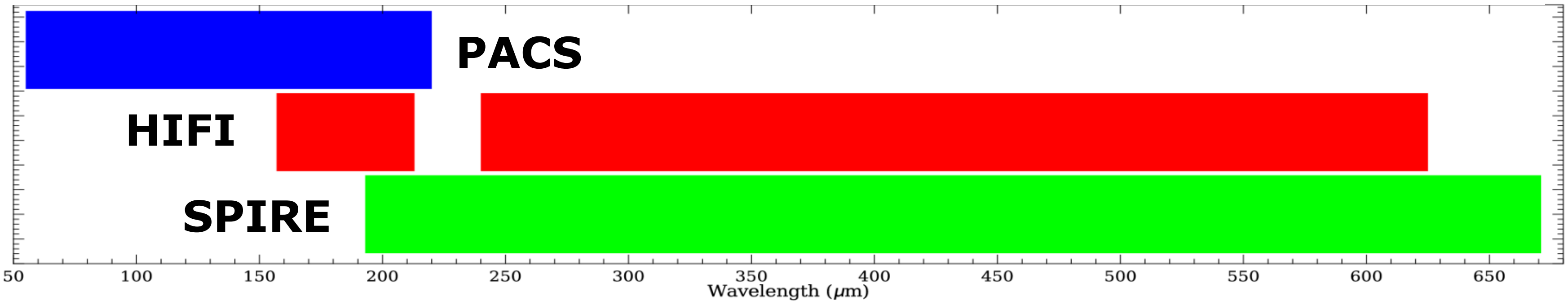


HIFI – high resolution spectrometer

- Uses internal loads to determine sensitivity for each frequency setting.
- Very accurate frequencies established by local oscillator (cross-cal).
- Most observations use double differencing to remove ripples in spec baselines.
- Mars used to determine beam and coupling coefficients.
- Neptune (esa3) used for flux calibration.
  - Biggest single issue is the side band ratio (dual sideband instrument).
  - Also standing waves (optical and electrical)

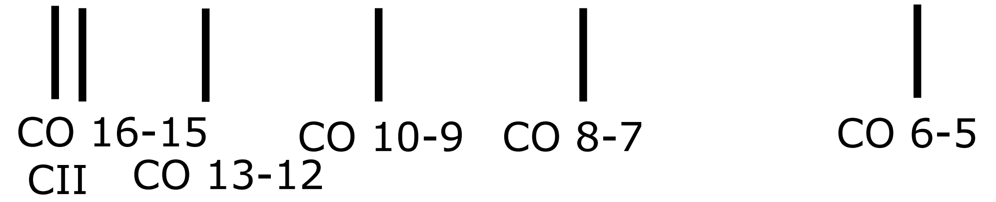
Spectral Overlaps

HIFI – PACS: 1360-1900 GHz. Red leakage 1360-1550 GHz
PACS – SPIRE: 1360-1550 GHz
SPIRE – HIFI: 1400-1550 GHz & 490-1250 GHz

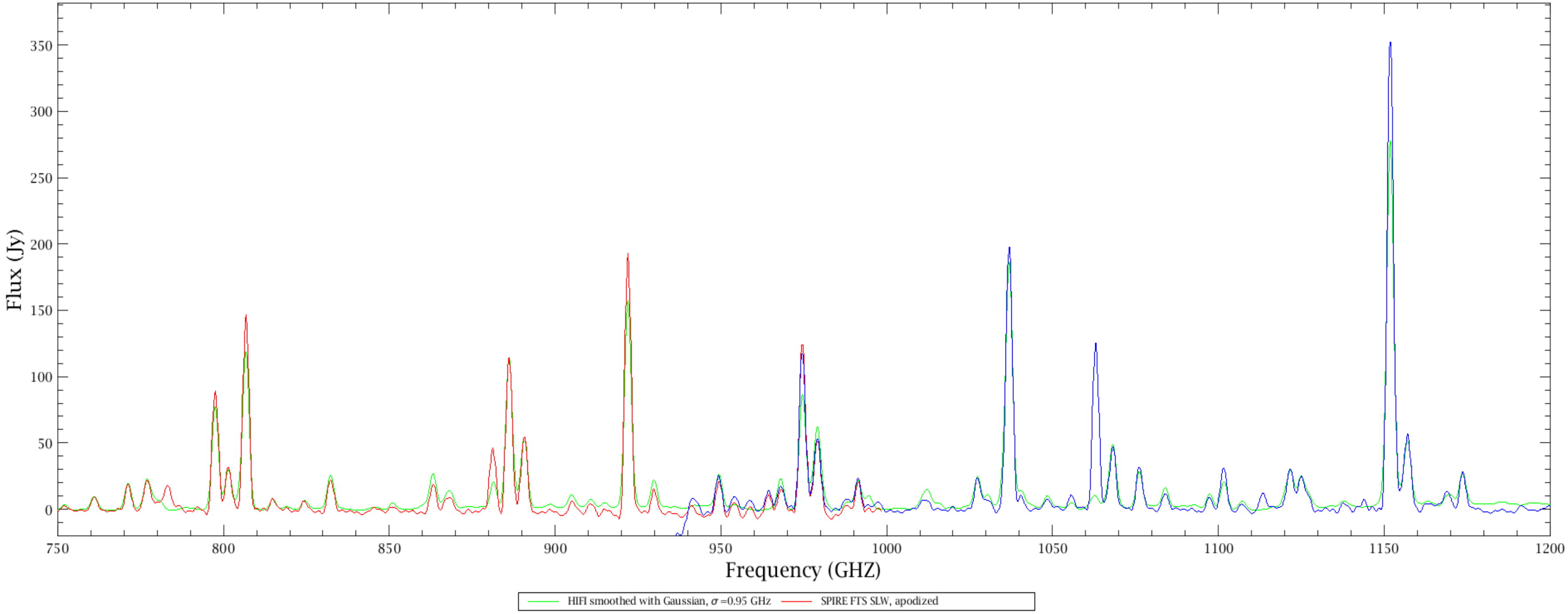


HIFI – PACS: 157-220 μm. Red leakage 190-220 μm
PACS – SPIRE: 193-220 μm
SPIRE – HIFI: 193-213 μm & 240-616 μm

Diagnostic lines in routine cross-calibration programmes



SPIRE/HIFI cross-calibration



HIFI (green) spectral scan and SPIRE (blue and red modules) FTS spectra overlaid.

Conclusions

- Calibration of Herschel overall uses models (initially produced pre-launch) of three completely different object types – planets, stars, asteroids.
- Data in the models comes from flyby missions, accurate near-infrared and sub-mm ground-based observations, space-based observations, radar measurements, known planetary atmosphere and stellar atmosphere conditions.
- Herschel data can be used and is being used to improve the models → *bootstrapping.*
- SPIRE uses planets Uranus and Neptune as prime calibrators, but observations of stellar model stars are in excellent agreement. PACS uses stars – the PACS/SPIRE photometer agreements are striking. Reproducible to a few percent. Limited by models.
- Asteroid models being updated → a set of prime calibrators.
- Cross-calibration work shows that the consistency between the spectrometers is already very good (within 20%) and will be improved.
- Updates to Uranus/Neptune models → ~3% absolute error (instead of 5%).

Some Herschel website references.

- Herschel Science Centre website:

http://herschel.esac.esa.int/conferences.shtml#Science

- Latest Herschel calibration workshop (Jan 2012).

http://herschel.esac.esa.int/twiki/bin/view/Public/CalibrationWorkshop4

- Science meetings based on Herschel

http://herschel.esac.esa.int/conferences.shtml#Science

- Online showcase of Herschel images

http://oshi.esa.int/

Herschel Calibration Steering Group

- Anthony Marston (Chair)
- Ulrich Klaas (MPIA)
- Markus Nielbock (MPIA)
- Bernhard Schulz (Caltech)
- Michael Olberg (Chalmers)
- Tanya Lim (RAL)
- Raphael Moreno (Obs. Paris)
- Thomas Müller (MPE)
- Joris Blommaert (KU Leuven)
- Göran Sandell (NASA Ames)
- Göran Pilbratt (ESA)

- Inputs from: Leen Decin (KU Leuven), Glenn Orton (JPL)