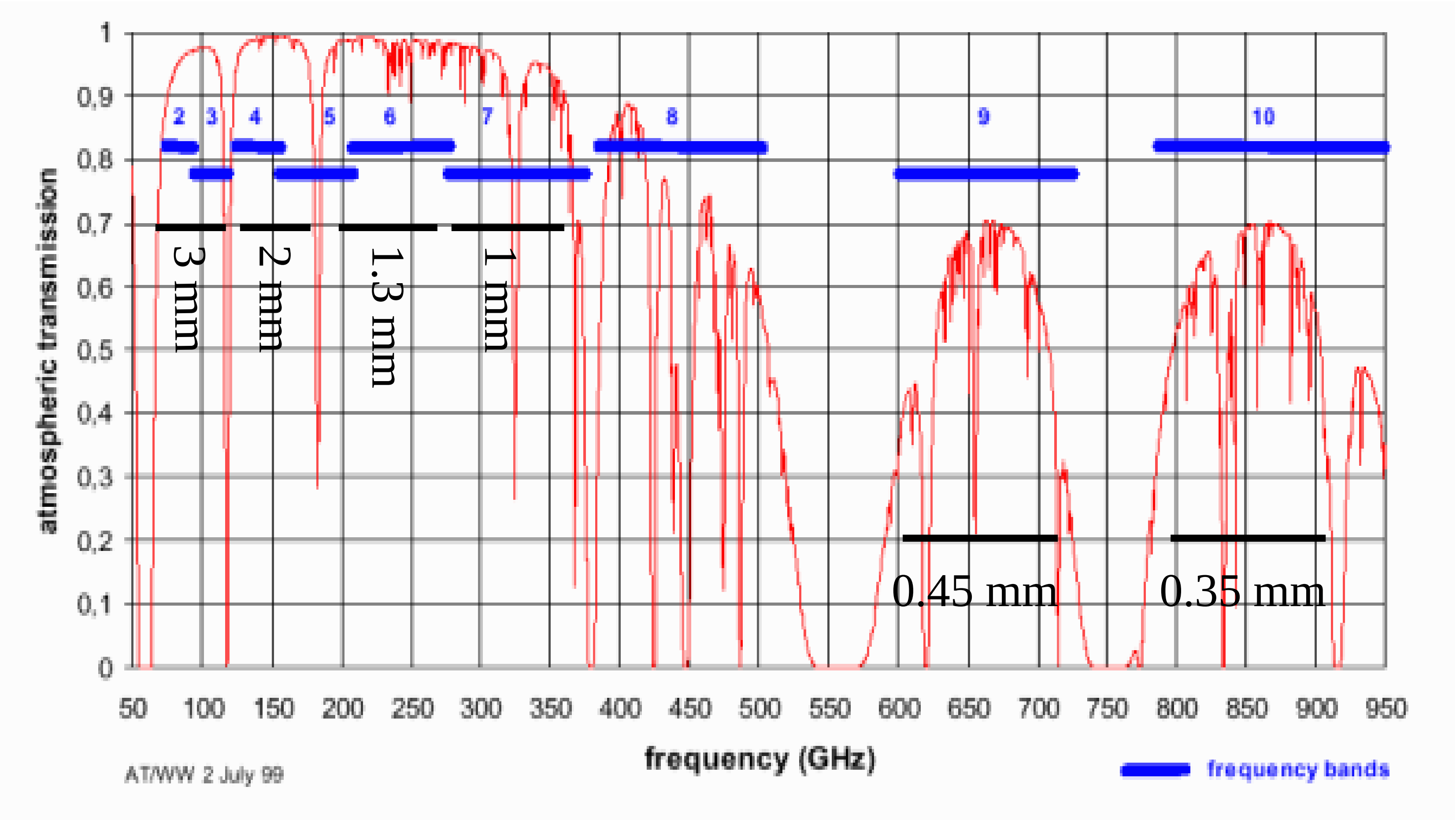
High-Frequency Radio-Interferometry

Frédéric Gueth
IRAM Grenoble

Mm / submm bands

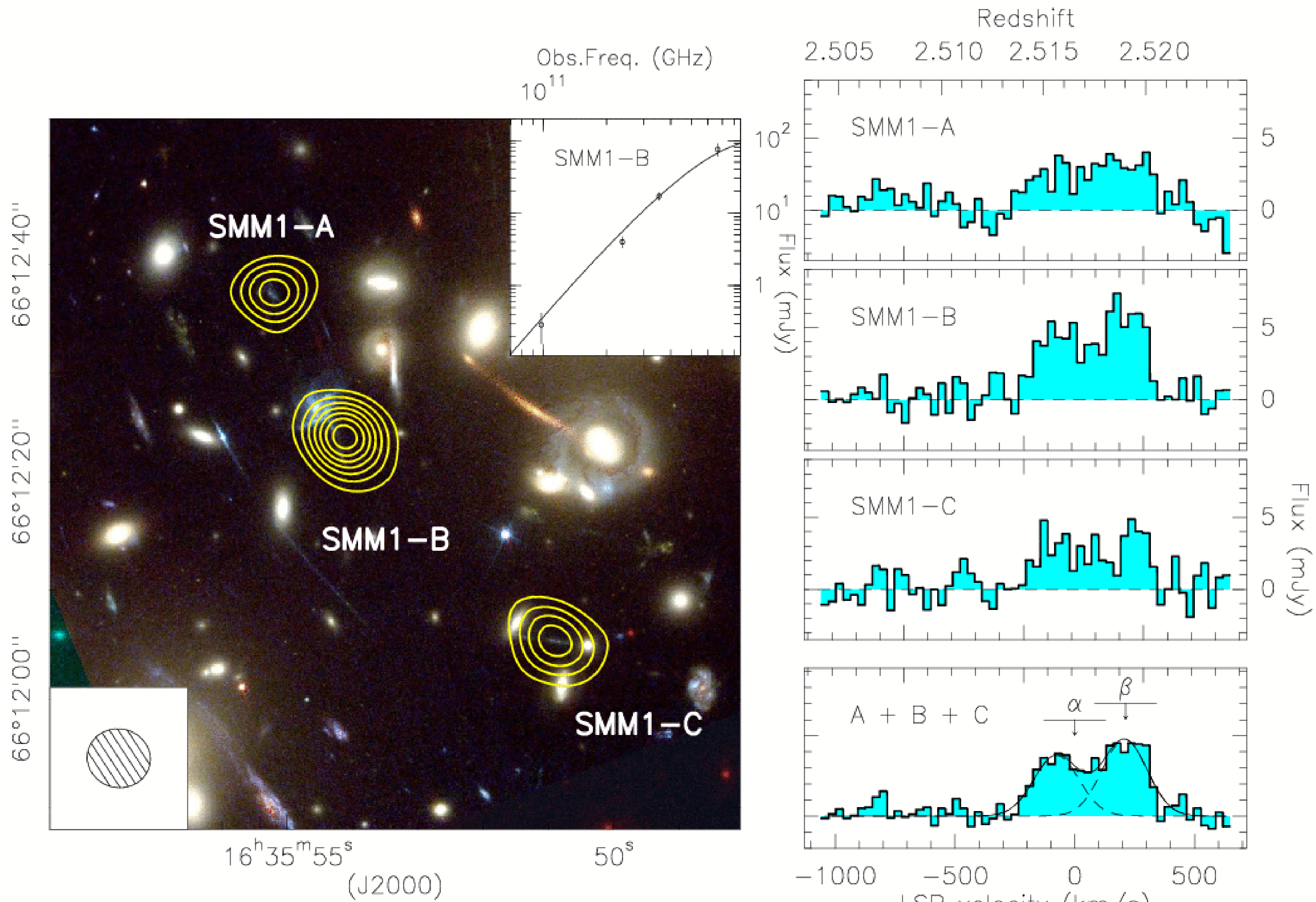


Science drivers

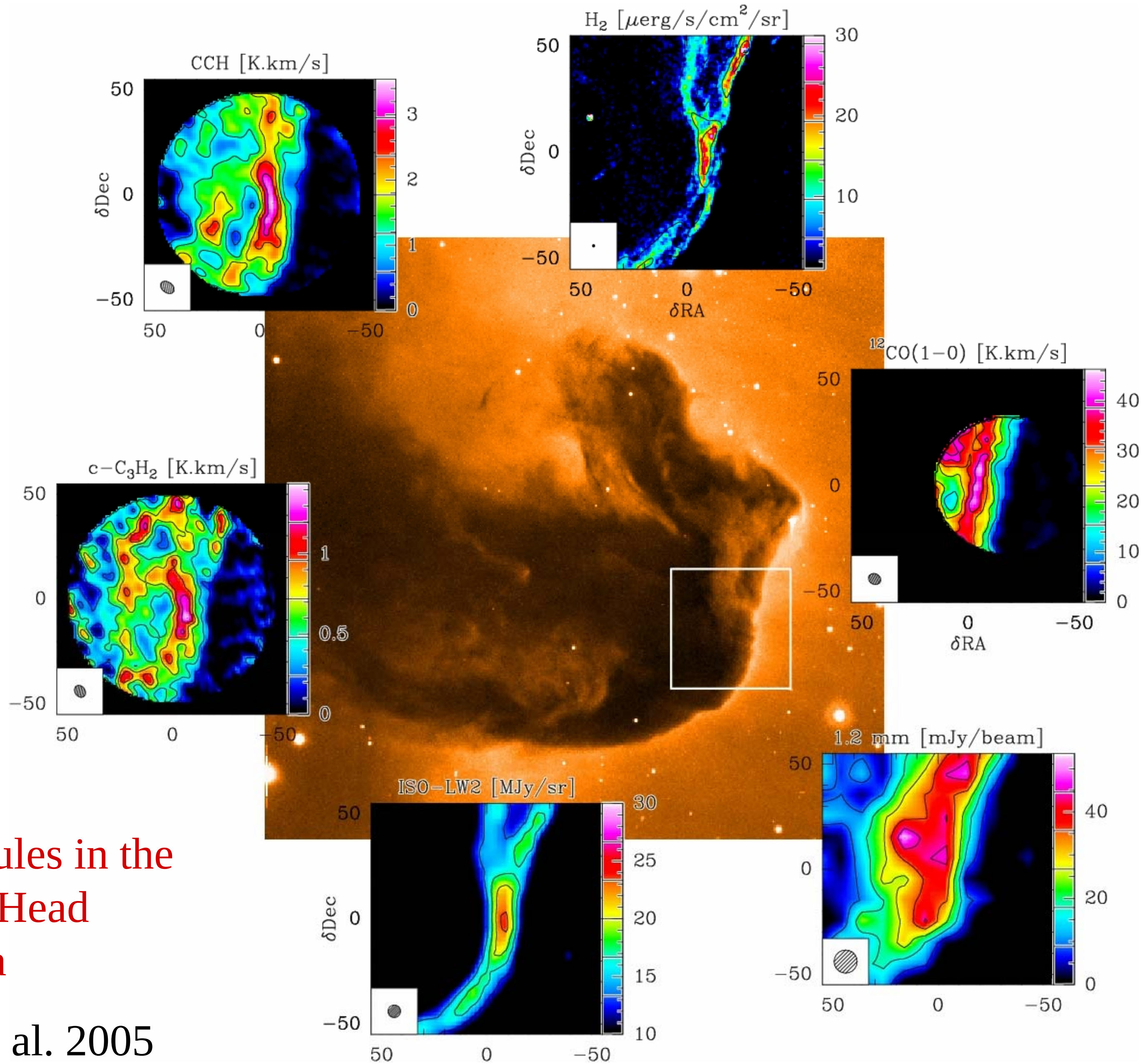
- The **cold universe**
  – Galaxy formation
  – Star formation

- Continuum → **thermal dust emission**
- Lines → **molecular rotational transitions**
- H2 has no rotational transitions, but CO does (abundance = 10^{-4} in ISM)

CO detection toward the multiply-imaged z=2.5 galaxy SMM J16359+6612

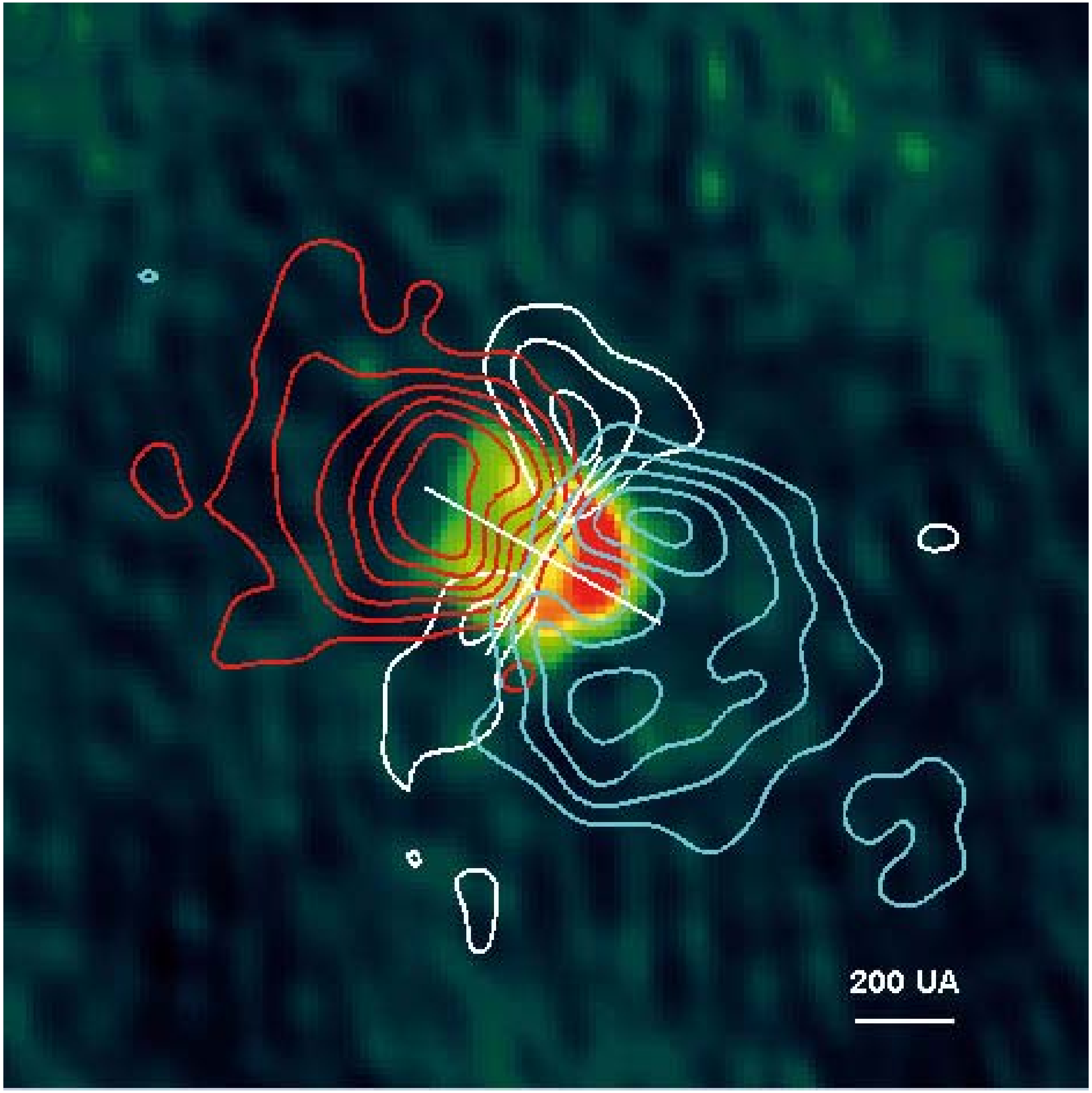


Kneib et al. 2005



Molecules in the Horse Head Nebula

Pety et al. 2005



The rotating circumstellar disk of the YSO AB Aurigae (1.3 mm + 13CO(2—1)

Piétu et al 2005

EU mm arrays

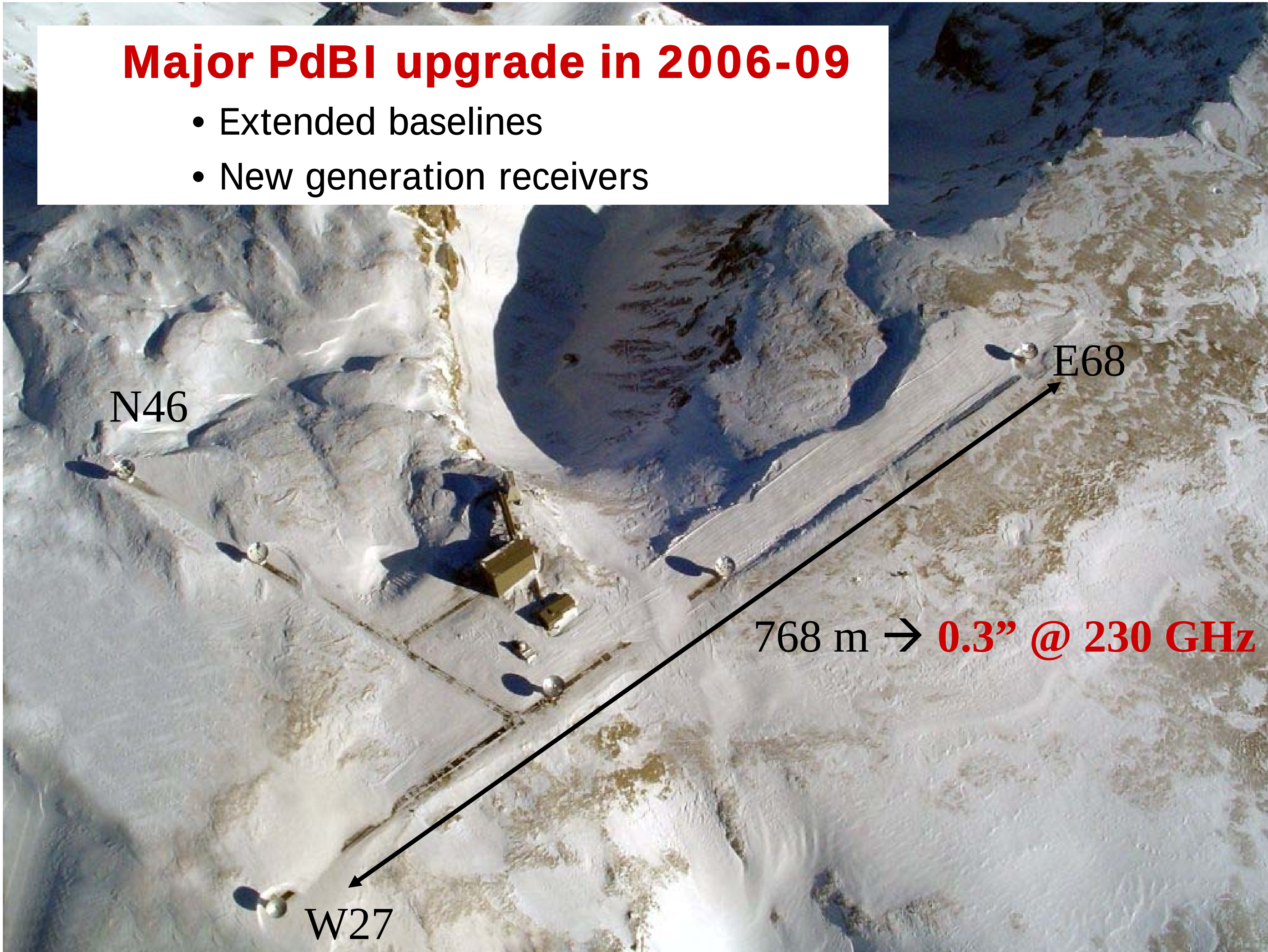
- **IRAM Plateau de Bure Interferometer** (PdBI)
  - Funded by France, Germany, Spain
  - **Open to all EU countries via RadioNet TNA**
  - 6 15 m antennas, baselines up to **~800 m**, dual polarization receivers (3 mm, 1.3 mm)
  - **New Generation Receivers**: four bands (3 mm, *2 mm*, 1.3 mm, *0.8 mm*), two polarizations, 4 GHz bandwidth

IRAM PdBI

IRAM PdBI

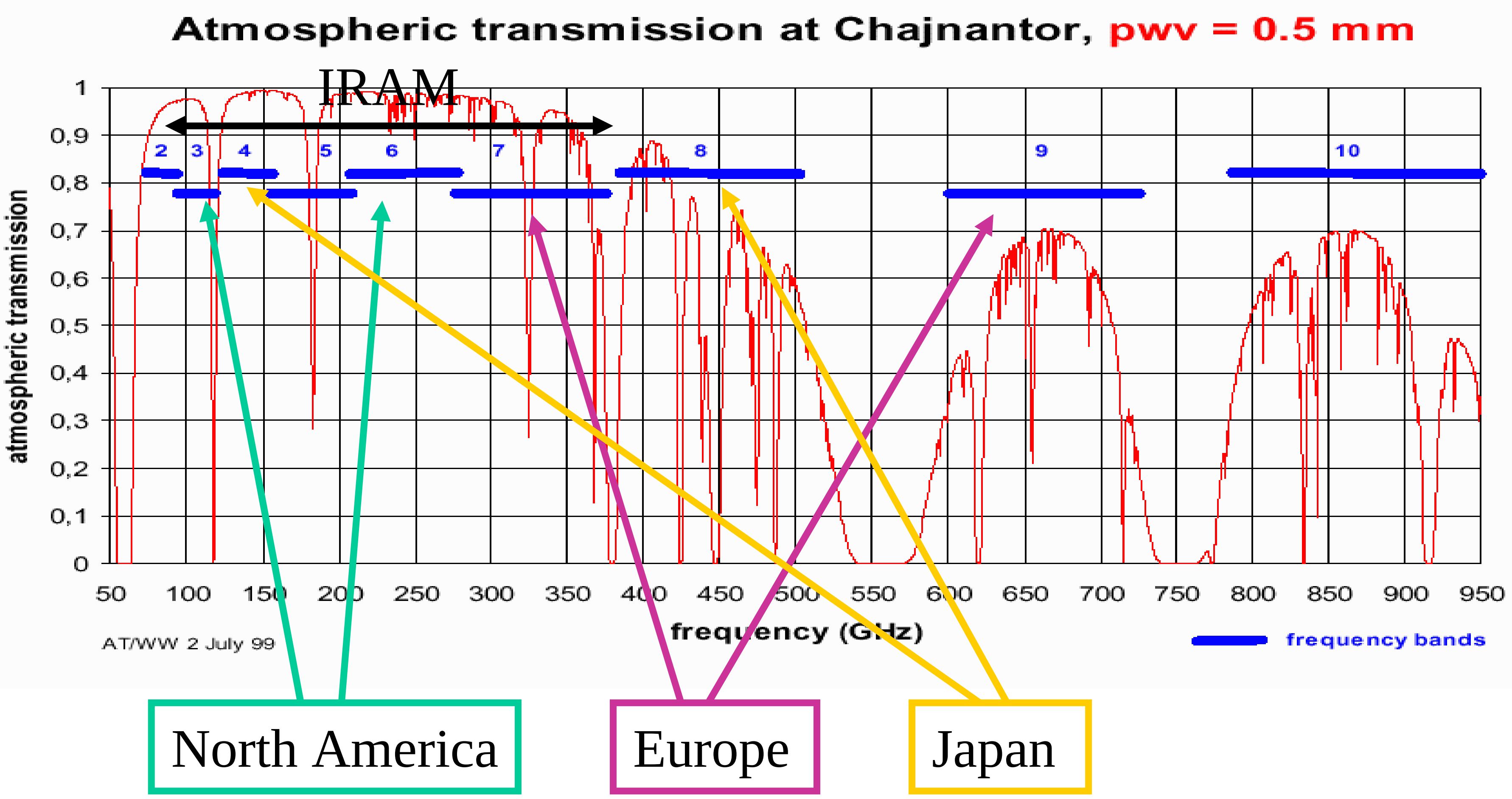
Major PdBI upgrade in 2006-09

- Extended baselines
- New generation receivers



EU mm arrays

- **ALMA (Atacama Large Millimeter Array)**
  - NA (US/NRAO+Canada) + EU (ESO) + Japan
  - Goal: 64 12 m antennas, 10 frequency bands, baselines up to 12 km
  - Funded: **50 12 m antennas, 6 bands**
  - ALMA Compact Array (**ACA**): 12 7-m antennas
  - First science 2010, full operations 2012



Atmospheric transmission at Chajnantor, pwv = 0.5 mm
IRAM
atmospheric transmission
frequency (GHz)
AT/WW 2 July 99
frequency bands
2
3
4
5
6
7
8
9
10
North America
Europe
Japan

ALMA

mm vs. cm domain

- **Hardware developments more challenging**
  - Antennas (surface accuracy << λ)
  - Receivers (SIS junctions cooled at 4 K)
  - Correlator (spectral line observations is standard → need thousands of spectral channels)

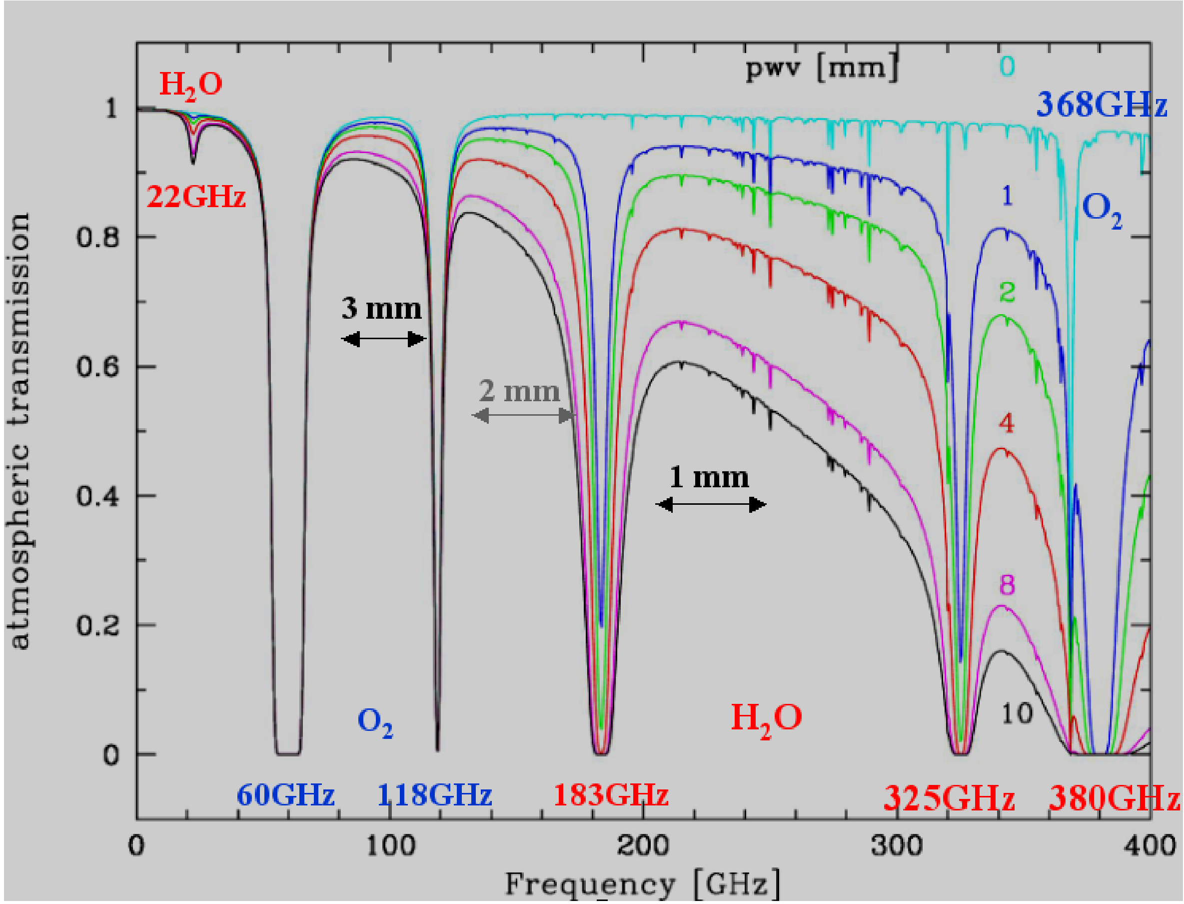
- New problems for the astronomer
  - **SNR much worst** (more noise, sources weaker)
  - **The atmosphere !**

The atmosphere

- Thermal emission → **noise**
- **Absorption of incoming signal** → attenuation
- Time- & position- dependant **phase error**
  → Amplitude decorrelation
  → Radio "seeing"

- Amount of **water vapor is highly variable** in time
  – Need real-time calibration of signal attenuation
  – Need real-time calibration of phase fluctuations

Atm. absorption



Atm. absorption calibration

- Goals

  1. Backend counts → Temperature (Kelvin)

  2. Correct for atmospheric absorption

- At mm wavelengths, this **must be done very often** (20 min) because
  - Receiver gain drift
  - Atmosphere fluctuations

Atm. absorption calibration

- Assume linear answer of receiving system

$$C = \alpha\,(Te^{-\tau} + T_{sys})$$

- Observe sky, cold (4K), and warm (273 K) loads
- Compute:
  - System temperature Tsys
  - Receiver gain α
  - Atmosphere opacity τ (using atm. model)

Atm. phase correction

- Timescale of phase fluctuations: seconds to hours
- **Need real-time correction** of fluctuations during basic integration time (< 1 min), to avoid
  - loss of amplitude (decorrelation)
  - "seeing" (phase $\leftrightarrow$position)
- This is conceptually similar to **adaptative optics** in optical/IR domain

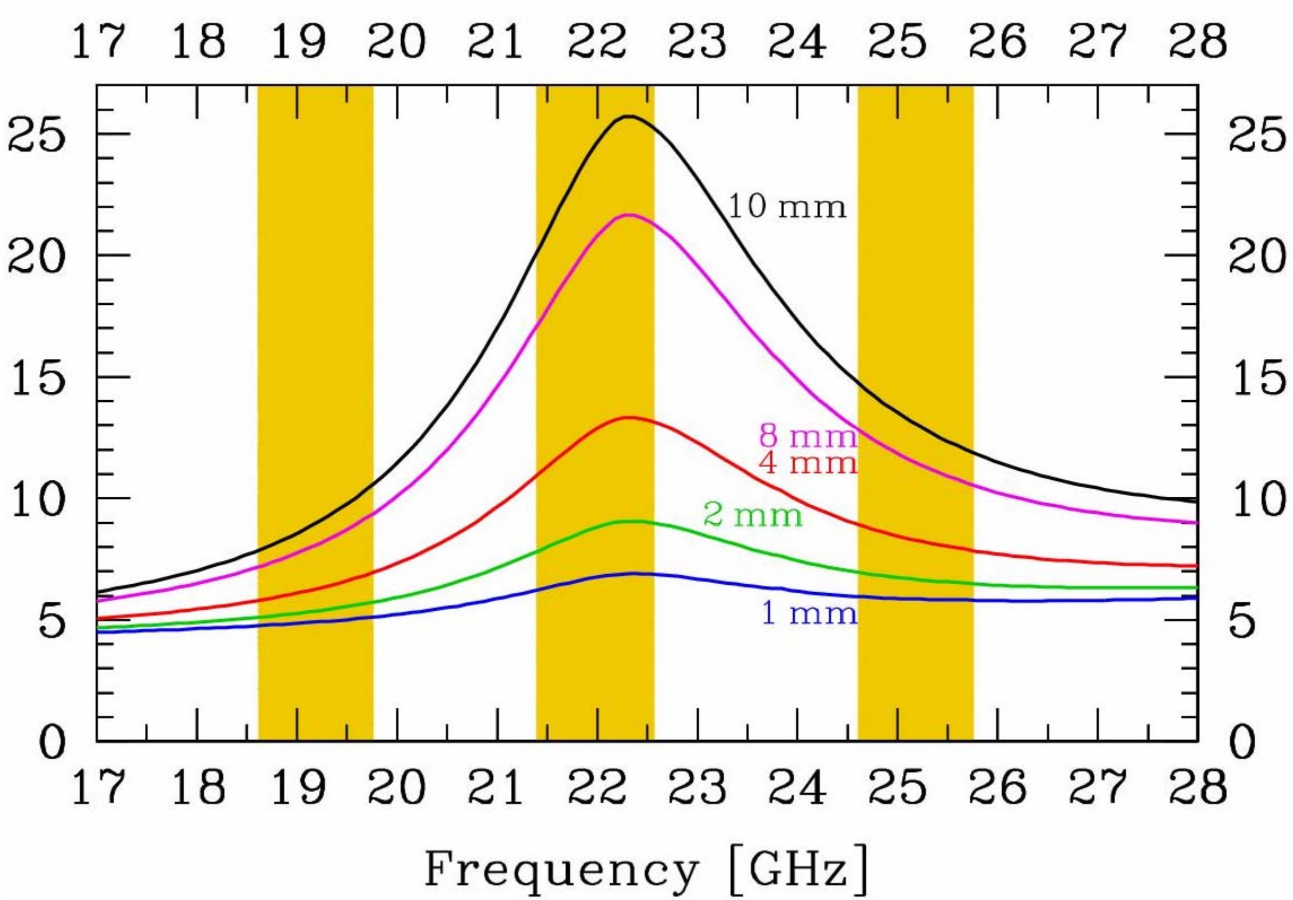
Atm. phase correction

- Predict amount of water from **water line at 22 GHz (PdBI) or 183 GHz (ALMA)** using dedicated receivers (WVR)

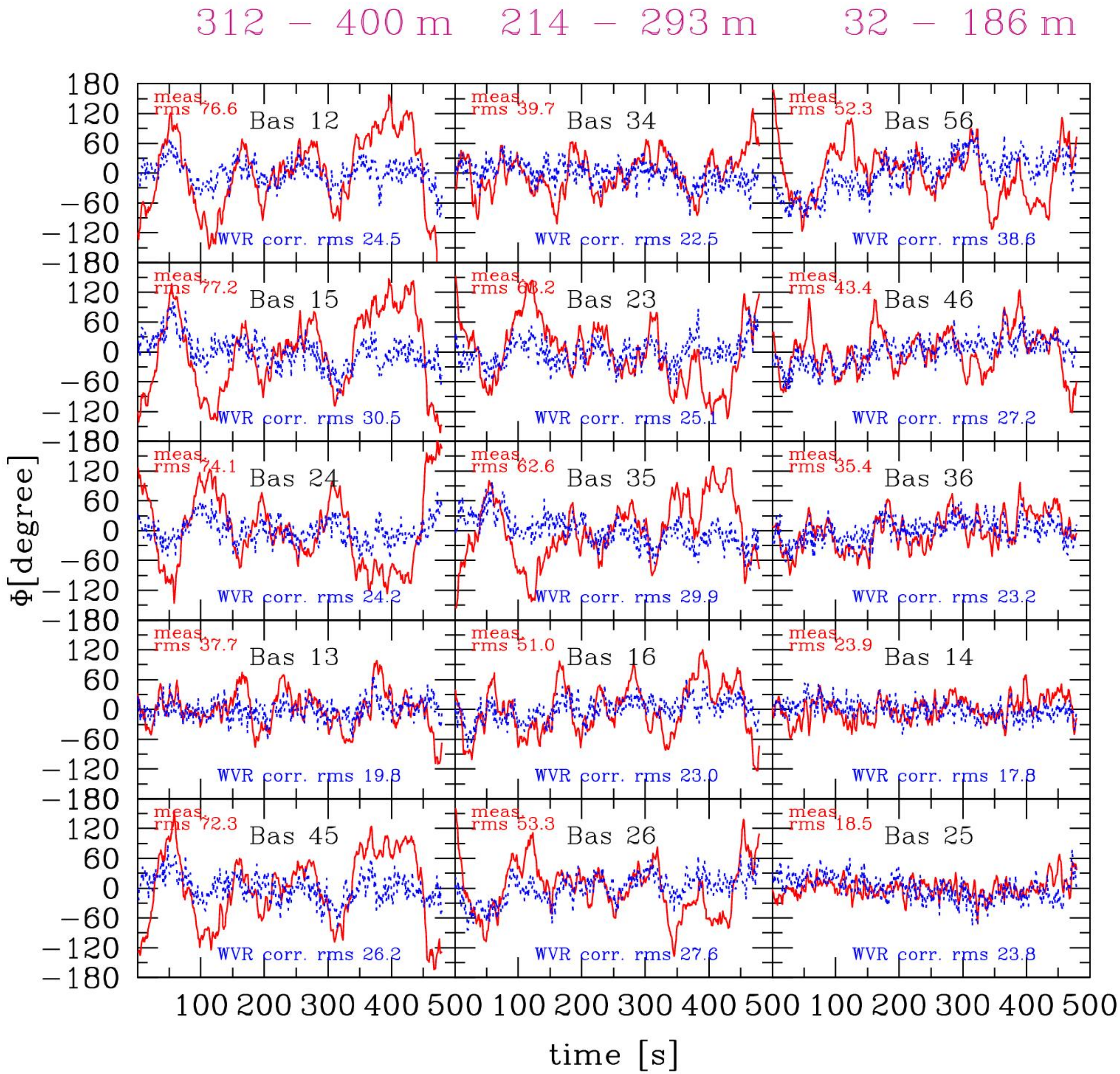
- Measurement → Atmospheric **model** → Water vapor content → Path delay → Atmospheric phase → Real-time correction

- Done **every second** at IRAM PdBI

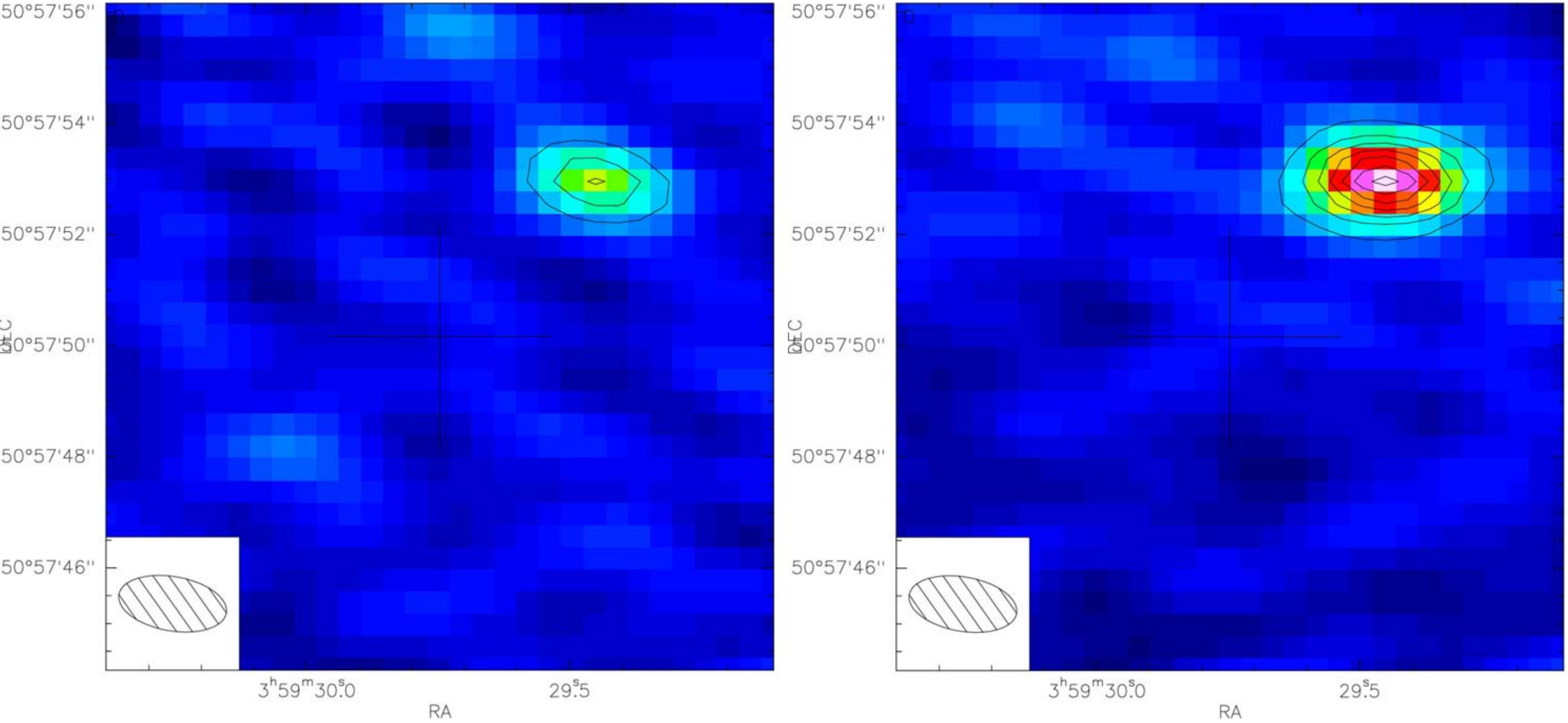
WVR at 22 GHz

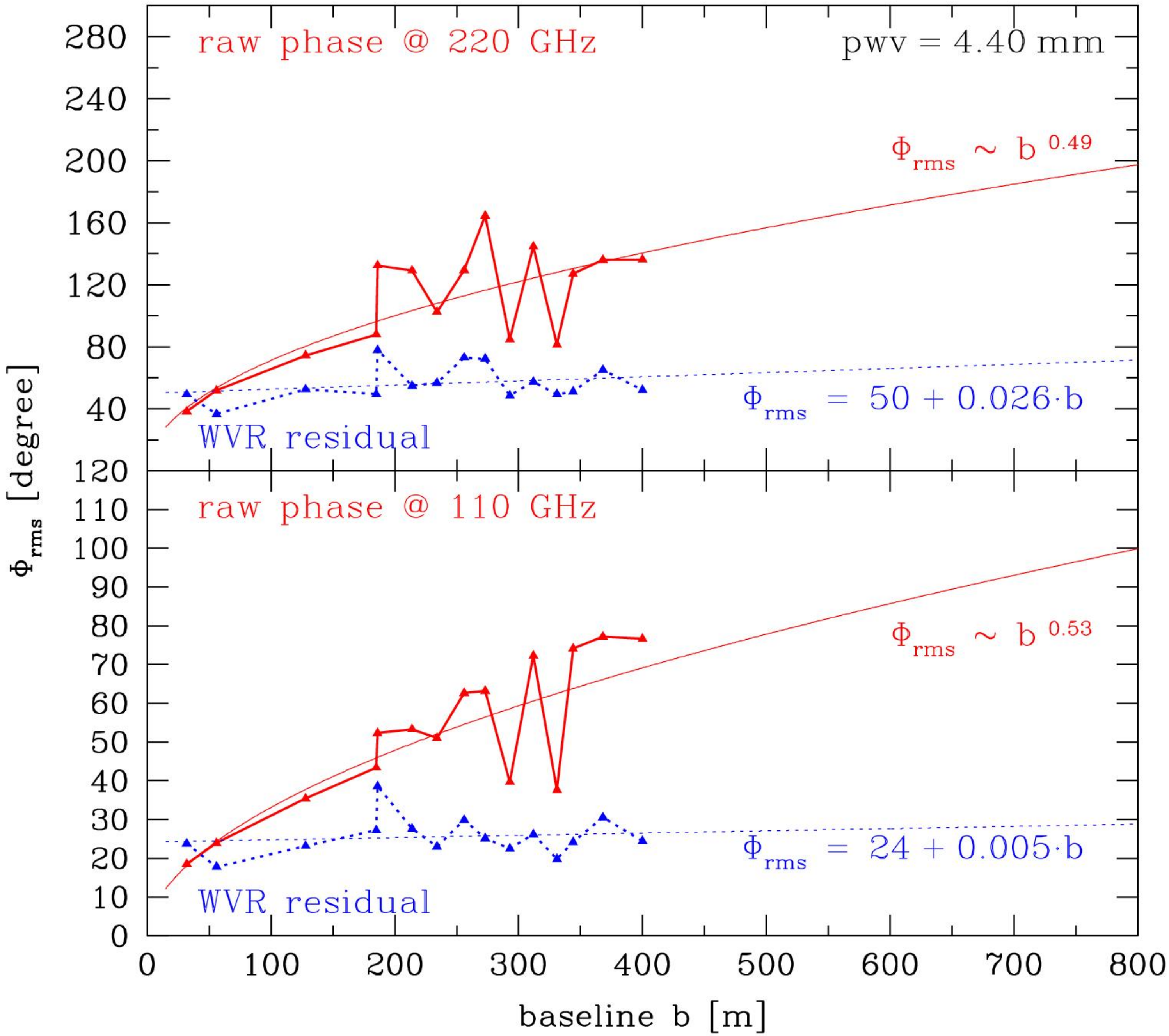


17 18 19 20 21 22 23 24 25 26 27 28
25
20
15
10
5
0
10 mm
8 mm
4 mm
2 mm
1 mm
Frequency [GHz]


312 – 400 m
214 – 293 m
32 – 186 m
Bas 12
meas. rms 76.6
WVR corr. rms 24.5
Bas 34
meas. rms 39.7
WVR corr. rms 22.5
Bas 56
meas. rms 52.3
WVR corr. rms 38.6
Bas 15
meas. rms 77.2
WVR corr. rms 30.5
Bas 23
meas. rms 63.2
WVR corr. rms 25.1
Bas 46
meas. rms 43.4
WVR corr. rms 27.2
Bas 24
meas. rms 74.1
WVR corr. rms 24.2
Bas 35
meas. rms 62.6
WVR corr. rms 29.9
Bas 36
meas. rms 35.4
WVR corr. rms 23.2
Bas 13
meas. rms 37.7
WVR corr. rms 19.8
Bas 16
meas. rms 51.0
WVR corr. rms 23.0
Bas 14
meas. rms 23.9
WVR corr. rms 17.8
Bas 45
meas. rms 72.3
WVR corr. rms 26.2
Bas 26
meas. rms 53.3
WVR corr. rms 27.6
Bas 25
meas. rms 18.5
WVR corr. rms 23.8
Φ[degree]
180
120
60
0
−60
−120
−180
100 200 300 400 500
time [s]

- Turbulent conditions, 4.4 mm pwv, A configuration
- NRAO150 (point source) → **gain of 2.5 in SNR**



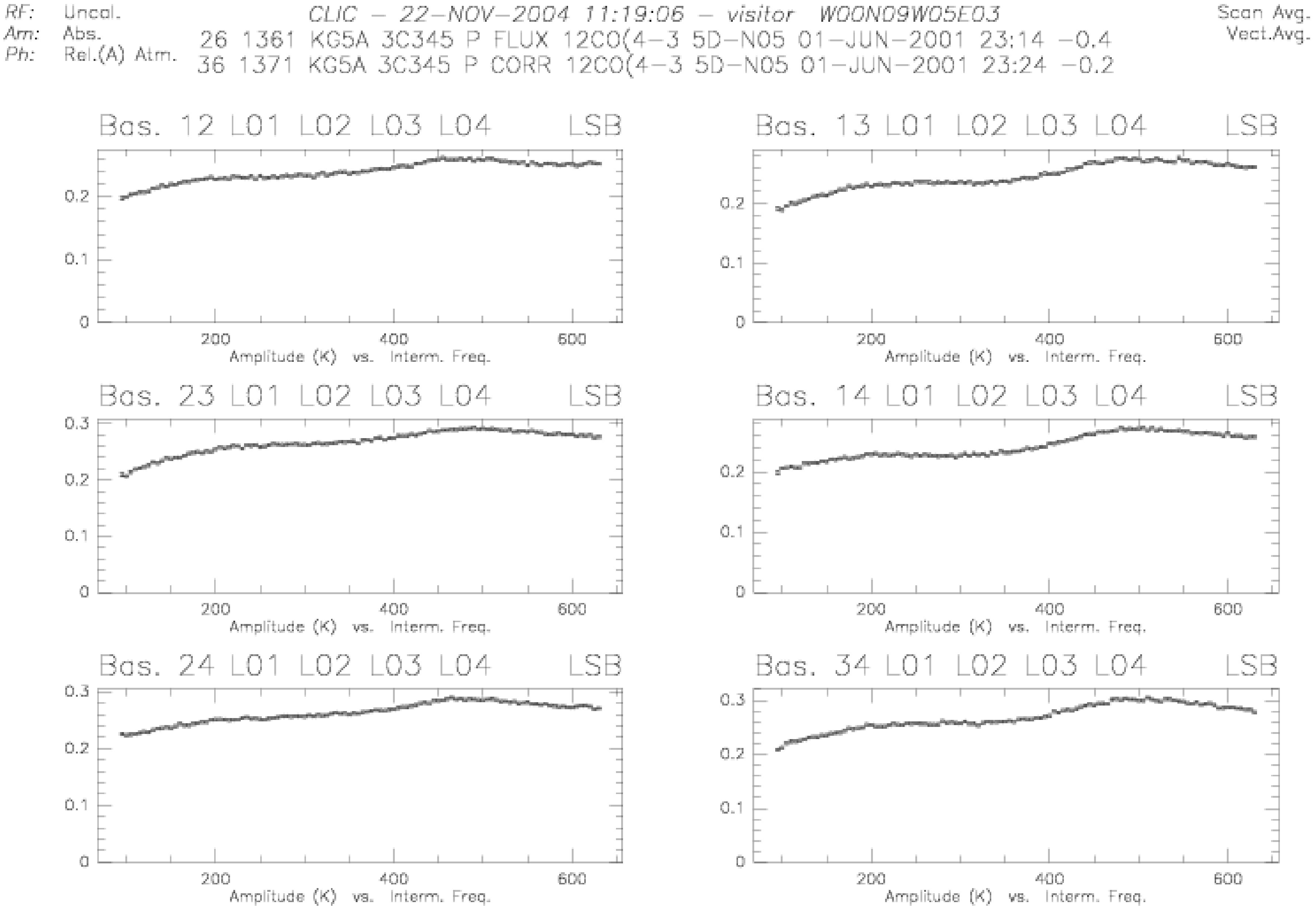


raw phase @ 220 GHz
pwv = 4.40 mm
$\Phi_{rms} \sim b^{0.49}$
$\Phi_{rms} = 50 + 0.026 \cdot b$
WVR residual
raw phase @ 110 GHz
$\Phi_{rms} \sim b^{0.53}$
$\Phi_{rms} = 24 + 0.005 \cdot b$
WVR residual
Φ_{rms} [degree]
baseline b [m]

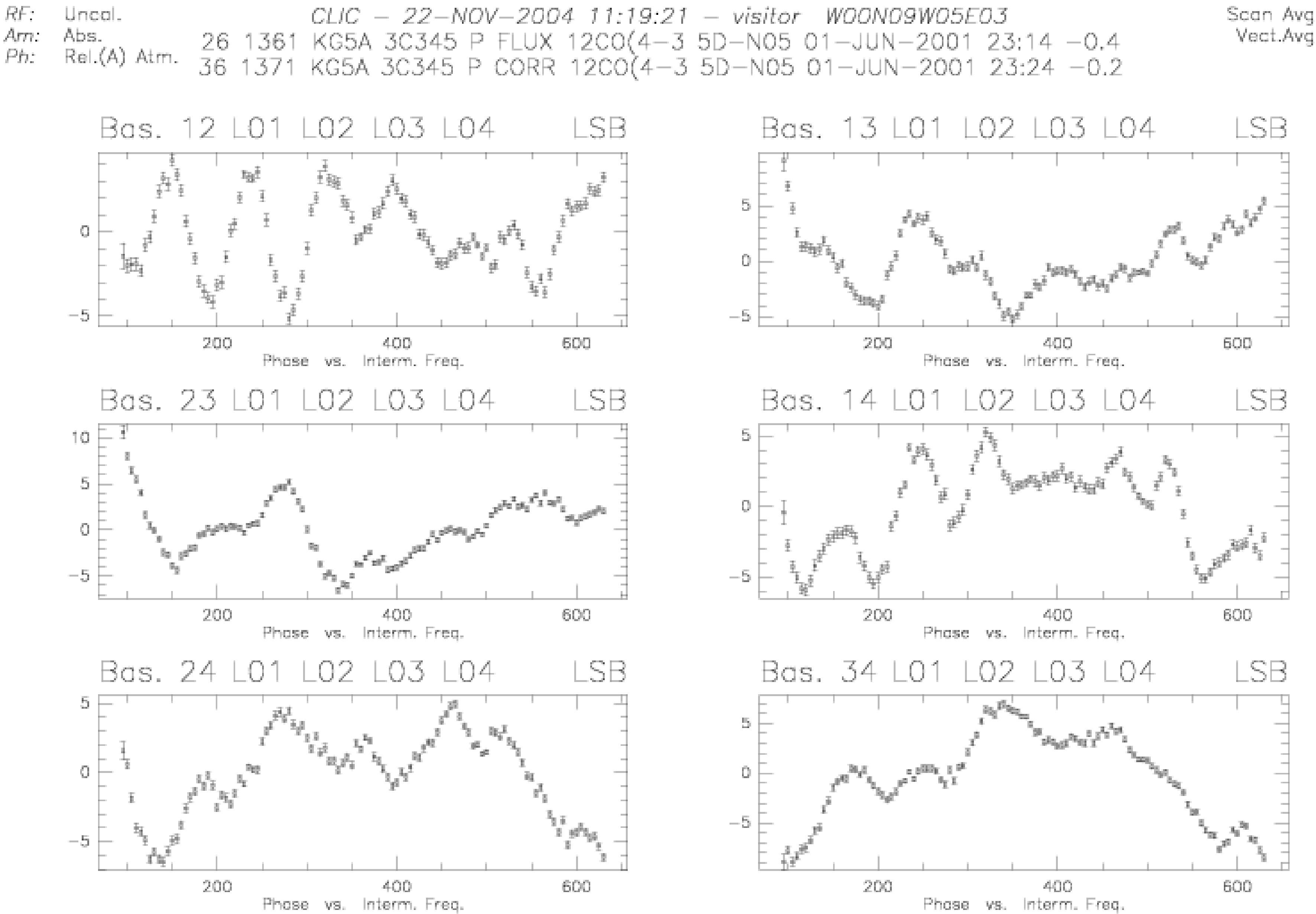
Off-line calibration
1. Bandpass

- Assumption: **frequency- and time- variations are independent**
- Calibration
  - A strong quasar is observed at the beginning of each project
  - **Its phase must be zero, its amplitude must be constant** → fit a gain vs. frequency curve
  - Correct all subsequent data for this bandpass

Amplitude vs Frequency for each baseline



Phase vs Frequency for each baseline

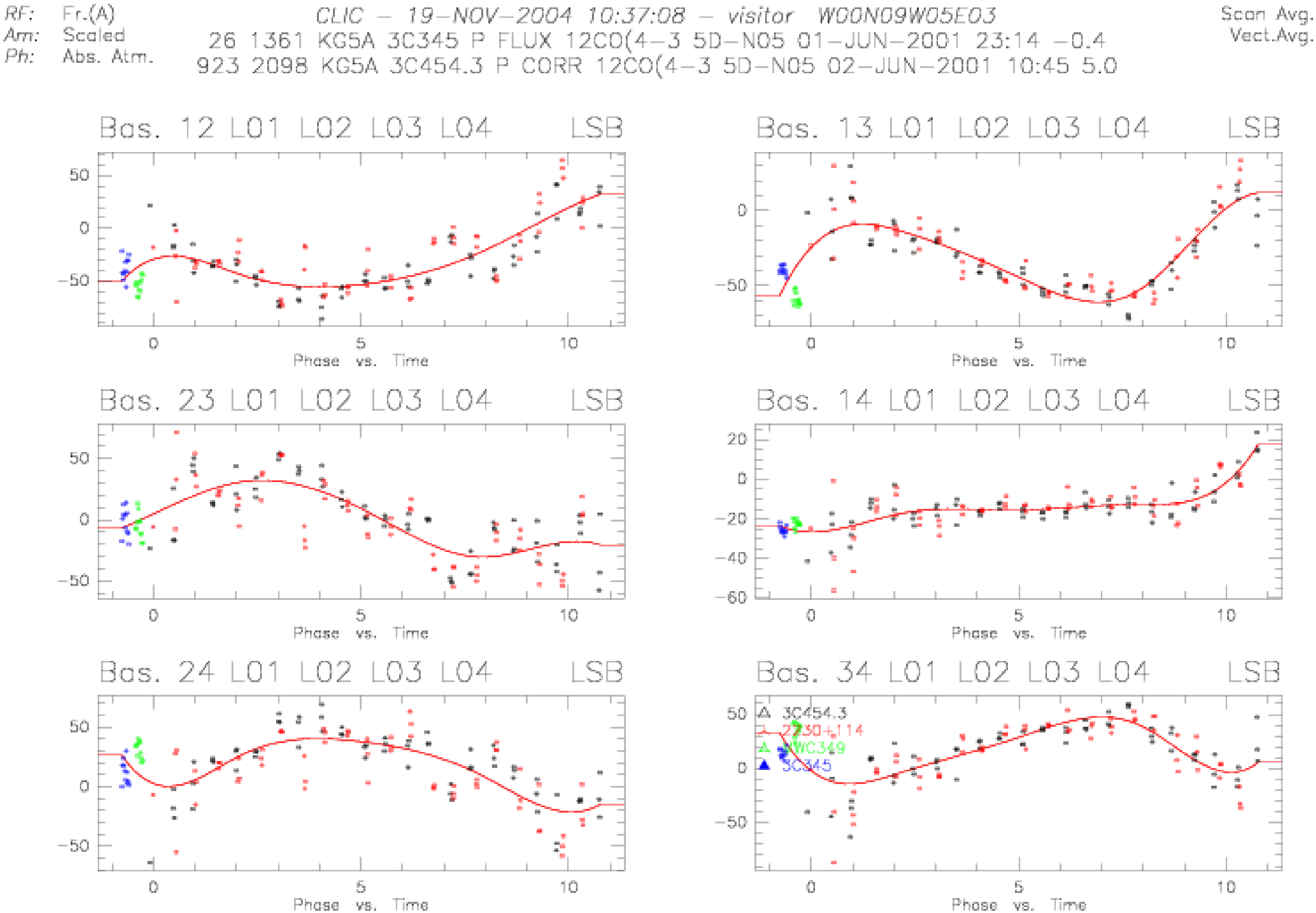


Off-line calibration
2. Phase

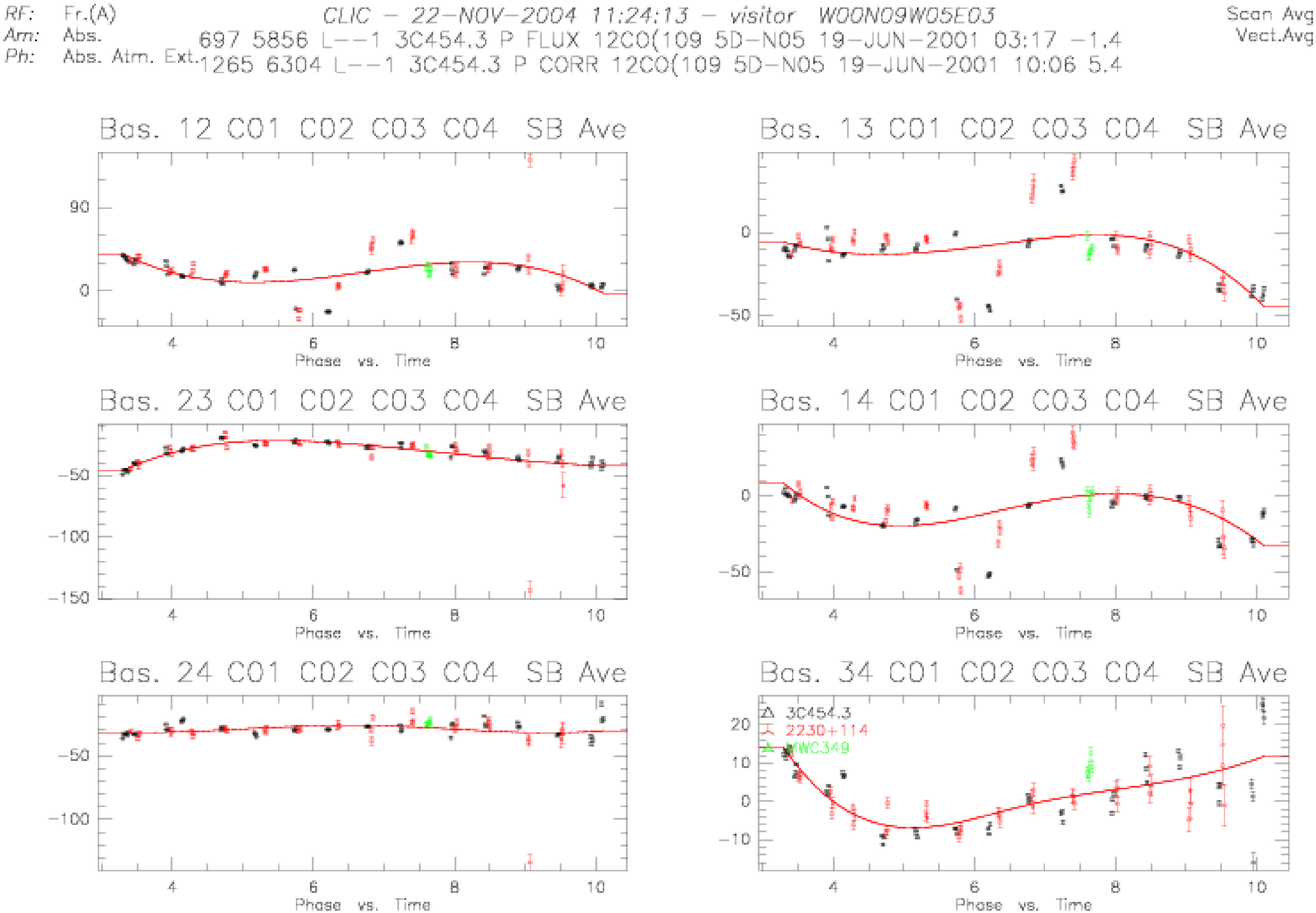
- **Long-term time dependence** of the phase is caused by the atmosphere and the instrumental drifts

- Calibration
  - A point source (quasar) is observed every ~20min
  - **Its phase must be zero** → fit a gain vs. time curve to estimate the phase variations
  - Better: use two calibrators

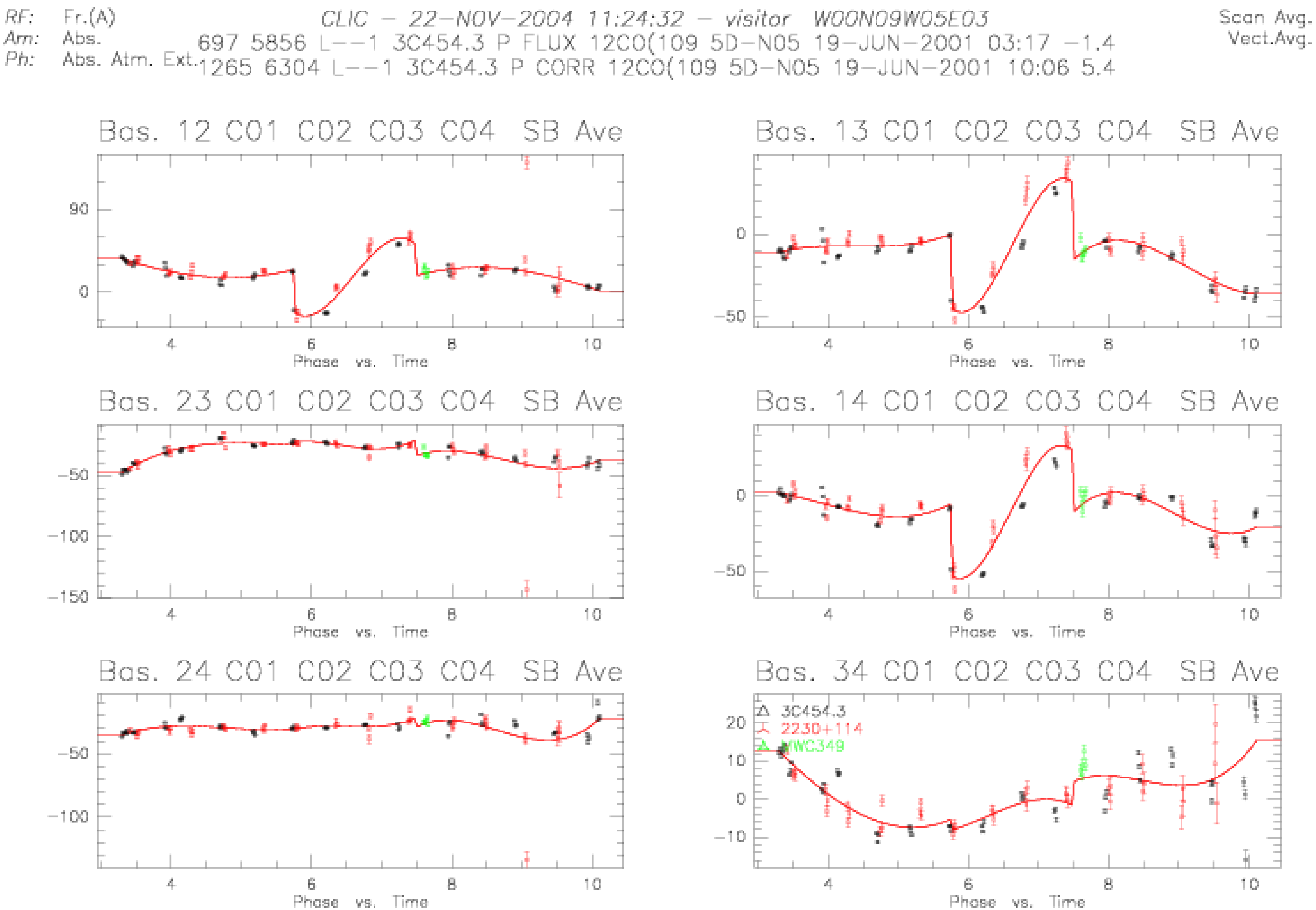
Phase vs. time for each baseline



Phase vs. time for each baseline



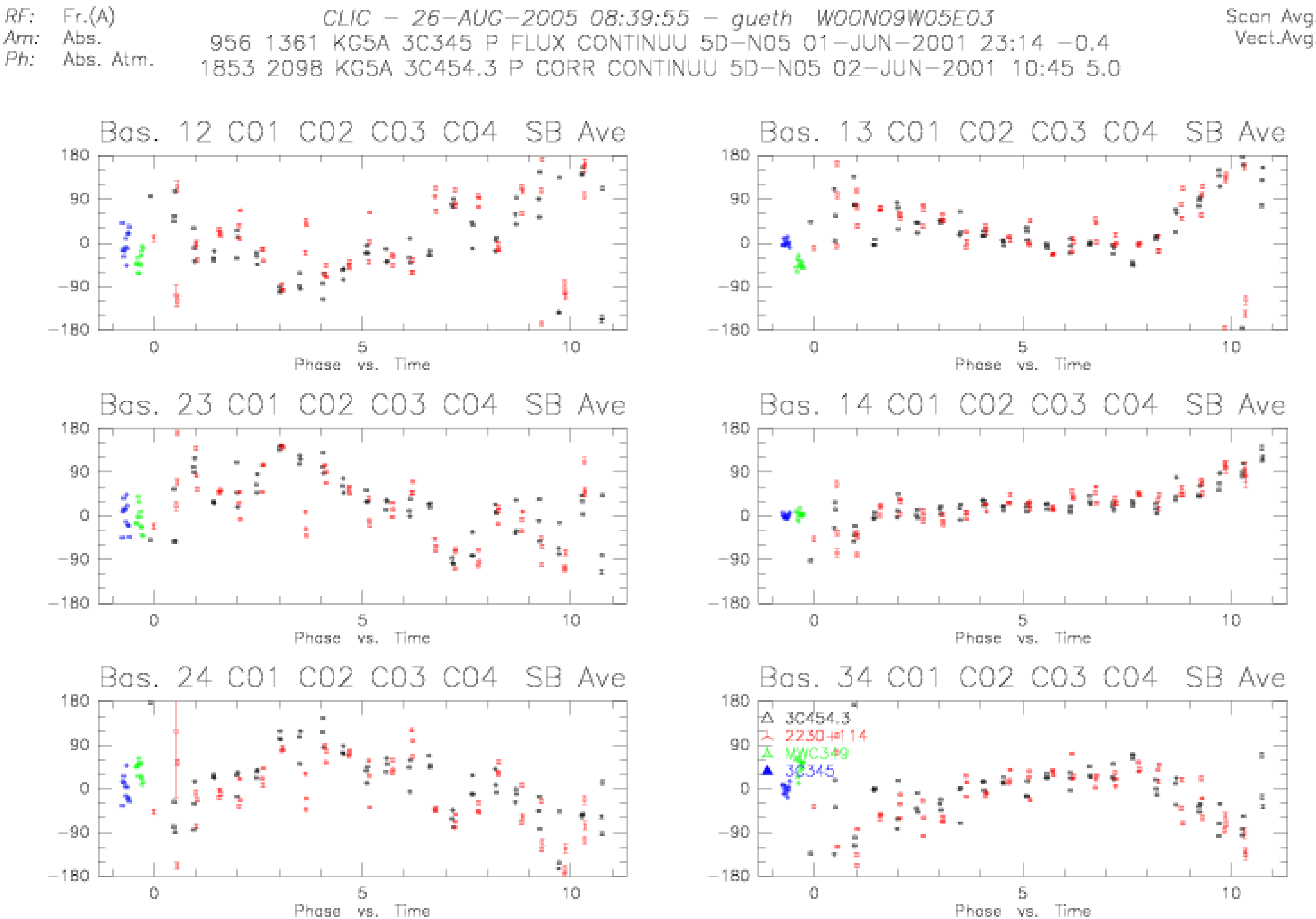
Phase vs. time for each baseline



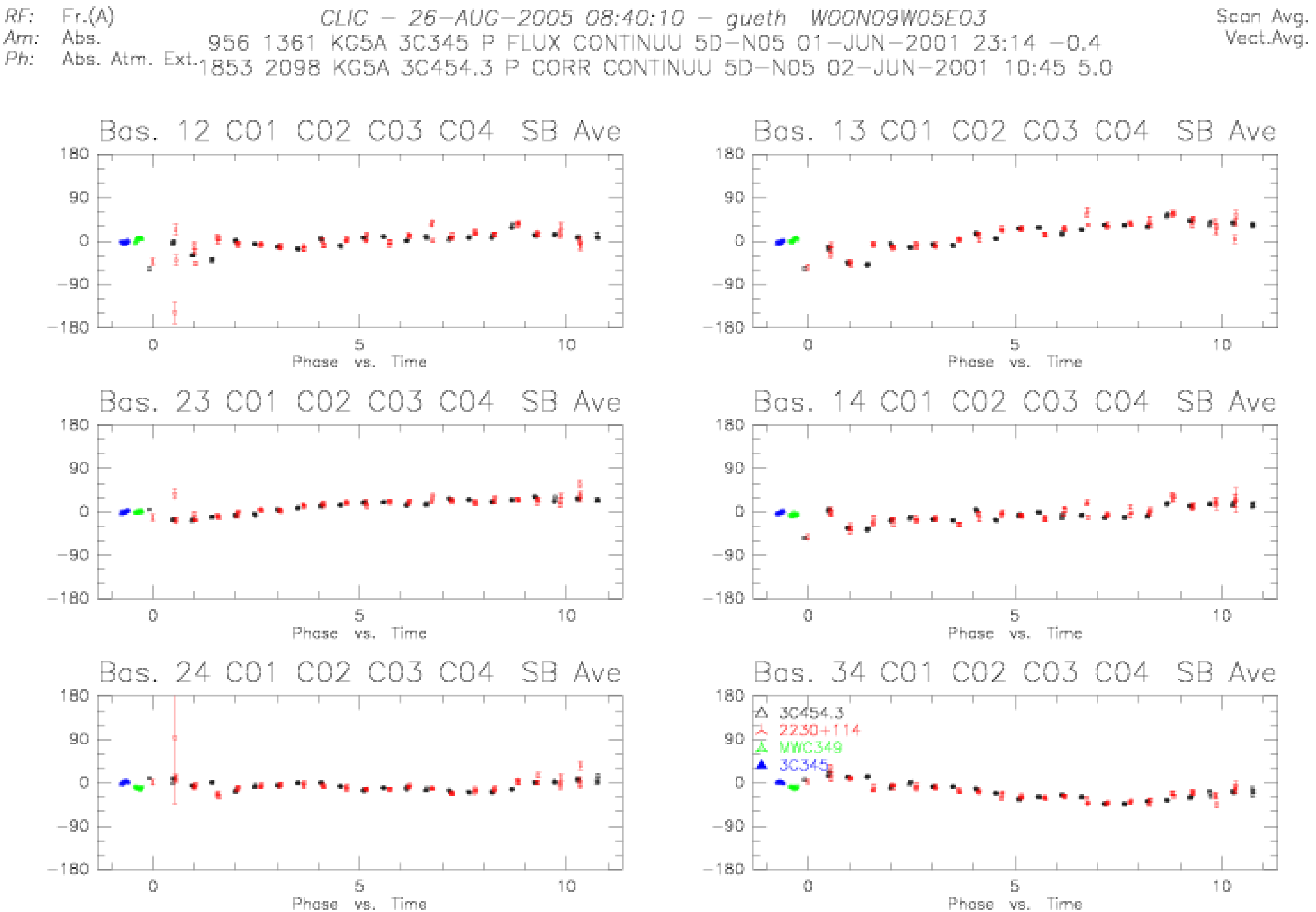
Off-line calibration
2. Phase

- **Phase transfer**
  - Atmospheric and most of the instrumental fluctuations should **scale with frequency**
  - **Use 3mm curve (highest SNR) to correct the 1mm data**
  - The residual fluctuations at 1mm must still be calibrated

230 GHz data, no phase transfer



230 GHz, with phase transfer



Off-line calibration
3. Amplitude

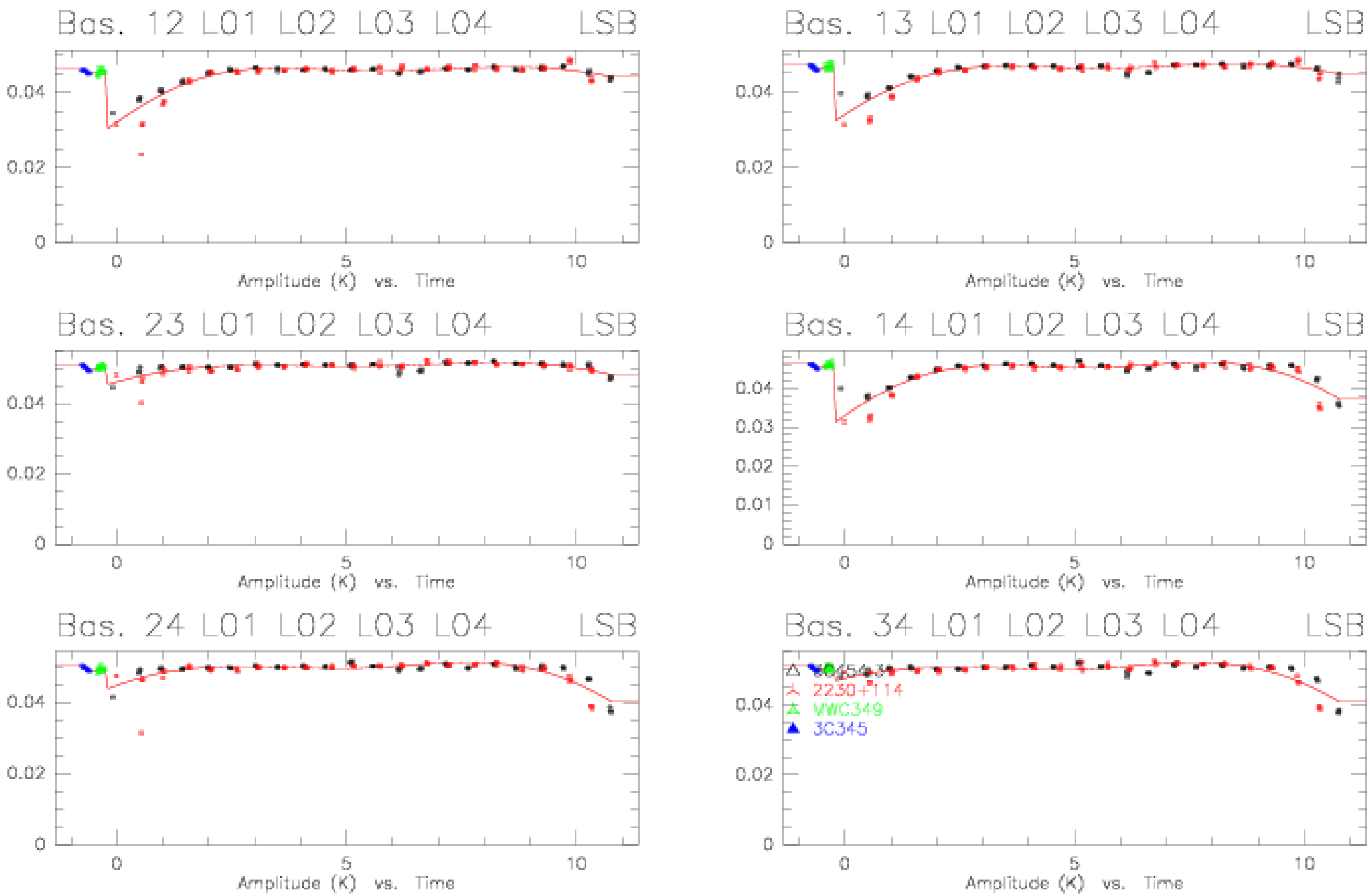
- Temperature (K) → Flux (Jansky)
  - Scaling by **antenna efficiency** (Jy/K)
  - **Not enough for mm-interferometers** because
    - Amplitude loss due to decorrelation
    - Variation of the antenna gain (pointing, focus)

- Need **amplitude referencing to a point source** (quasar) to calibrate out the temporal variation of the antenna efficiency – just like phase calibration

RF: Fr.(A)
Am: Scaled
Ph: Rel.(A) Atm.

CLIC – 26-AUG-2005 08:40:56 – gueth W00N09W05E03
26 1361 KG5A 3C345 P FLUX 12CO(4-3 5D-N05 01-JUN-2001 23:14 -0.4
923 2098 KG5A 3C454.3 P CORR 12CO(4-3 5D-N05 02-JUN-2001 10:45 5.0

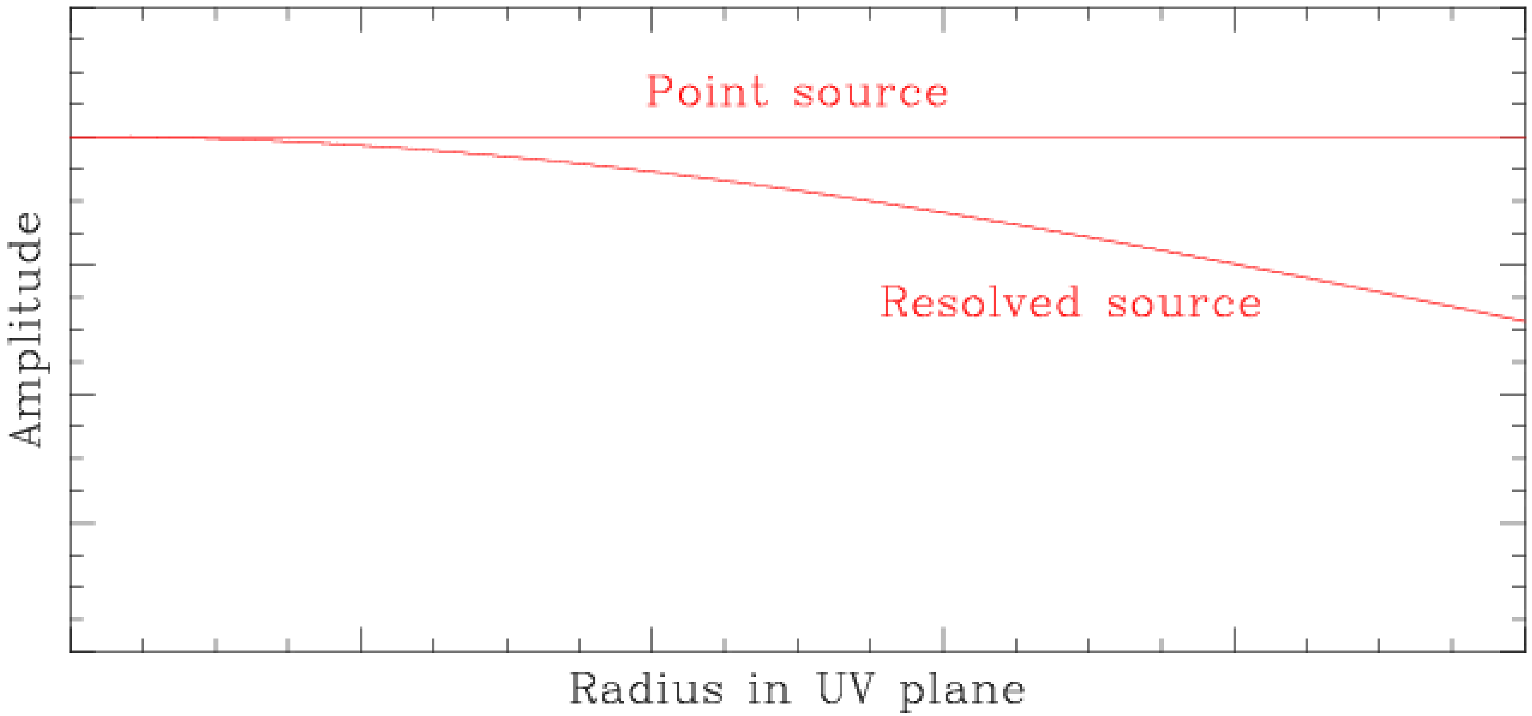
Scan Avg.
Vect.Avg.



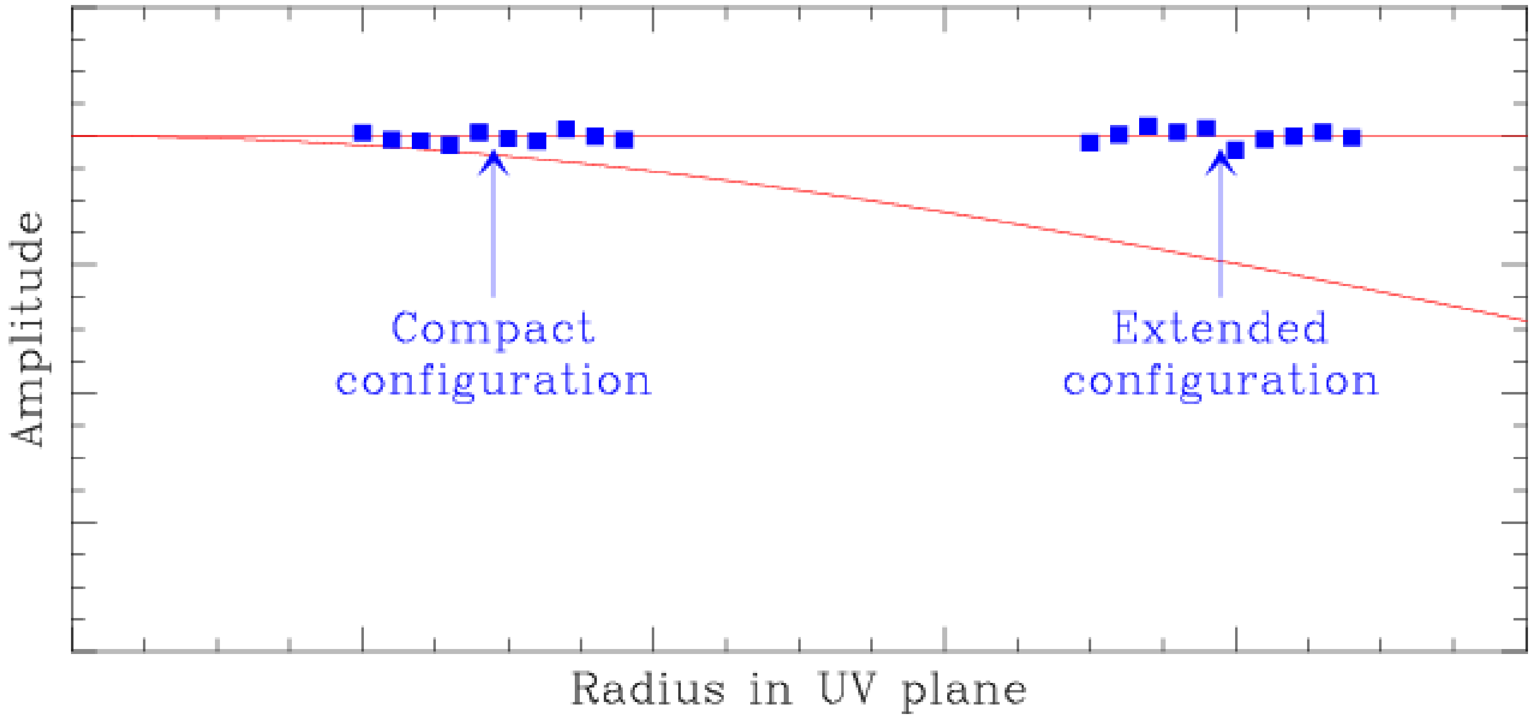
Off-line calibration
4. Flux scale

- Problem: **all quasars have varying fluxes** (several 10% in a few months) and spectral indexes
- **Cannot rely on a priori antenna efficiency** to measure their fluxes (decorrelation...)
- Need to measure the quasar fluxes against
  - Planets
  - Strong quasars (RF)
  - MWC349, CRL618, ...
- Can be **difficult** if a good accuracy is required

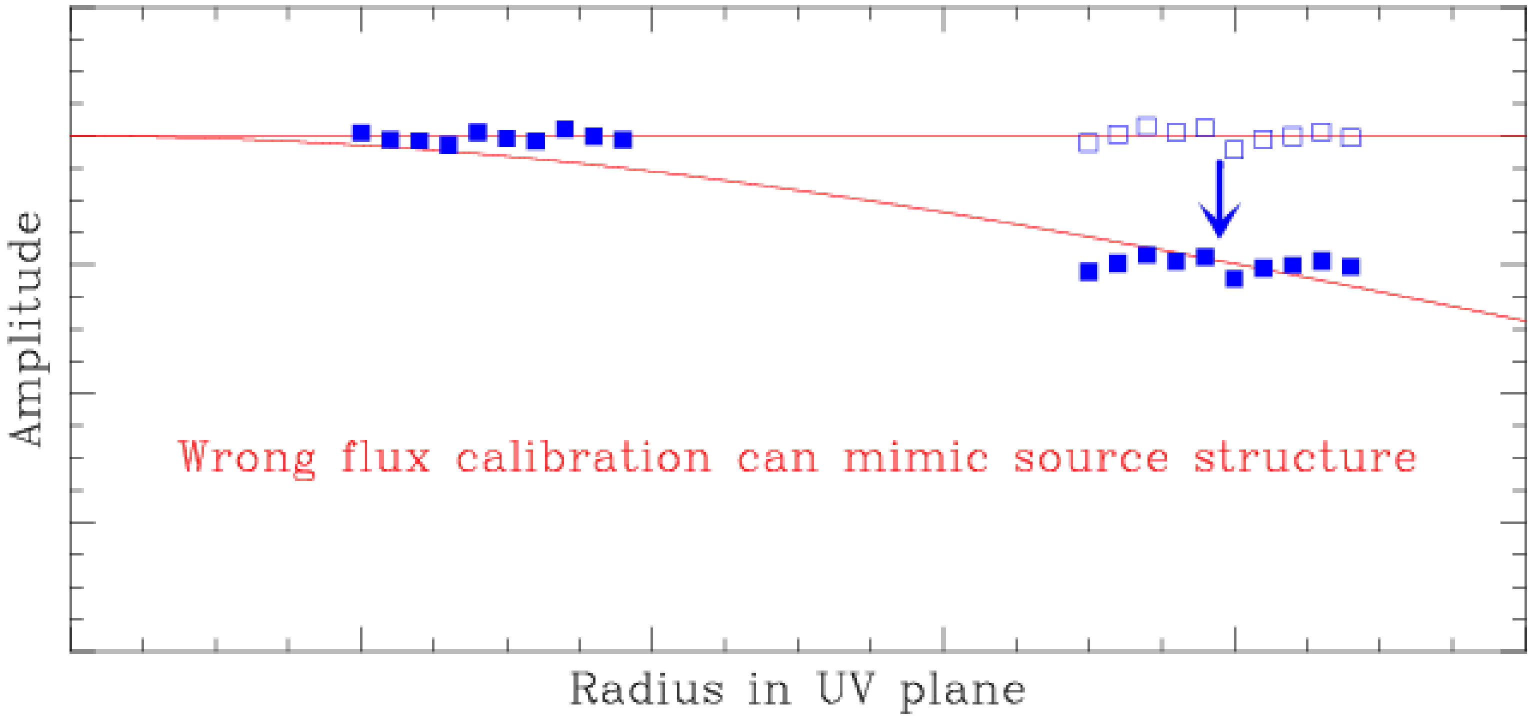
Off-line calibration
4. Flux scale



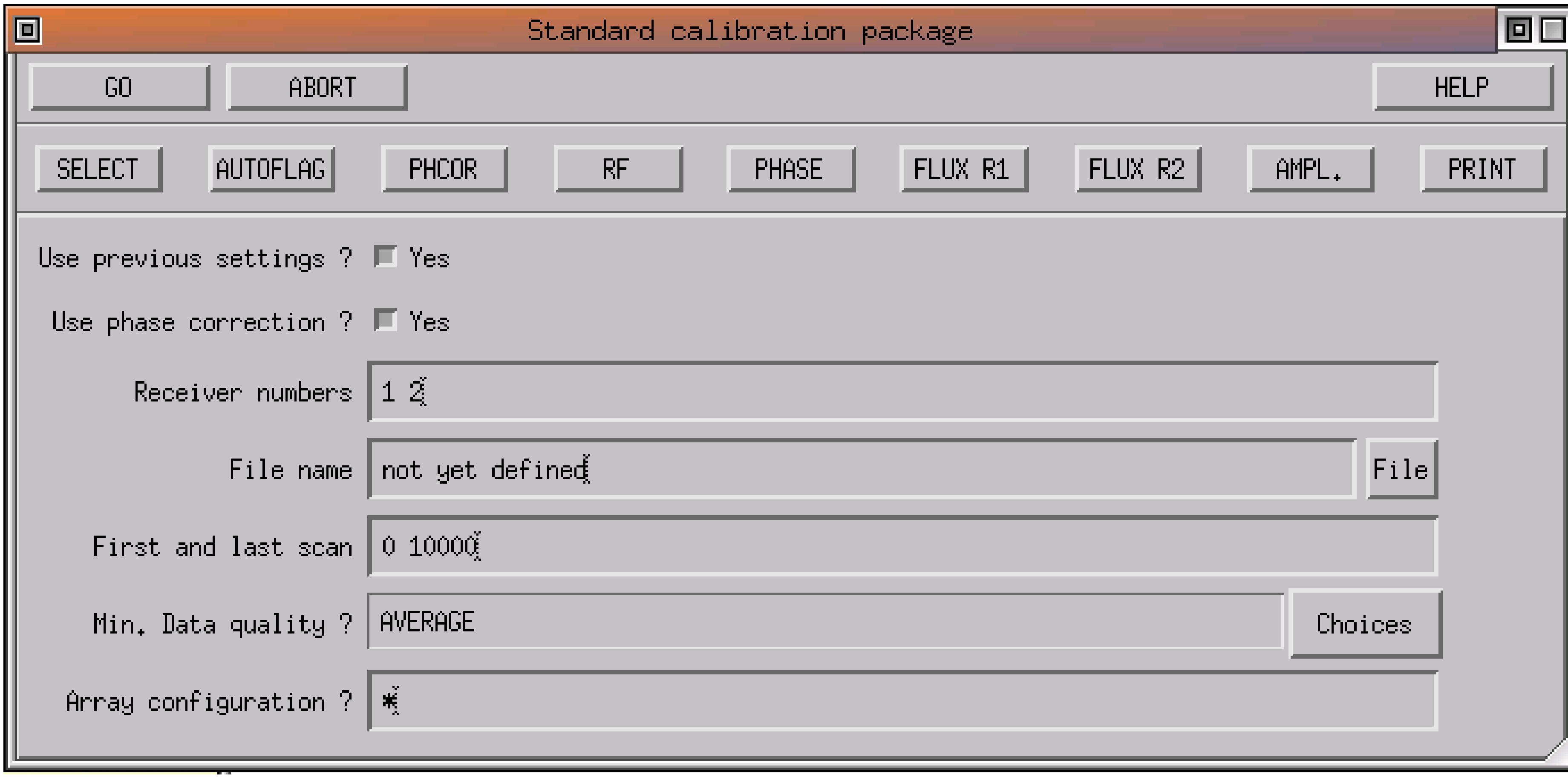
Off-line calibration
4. Flux scale



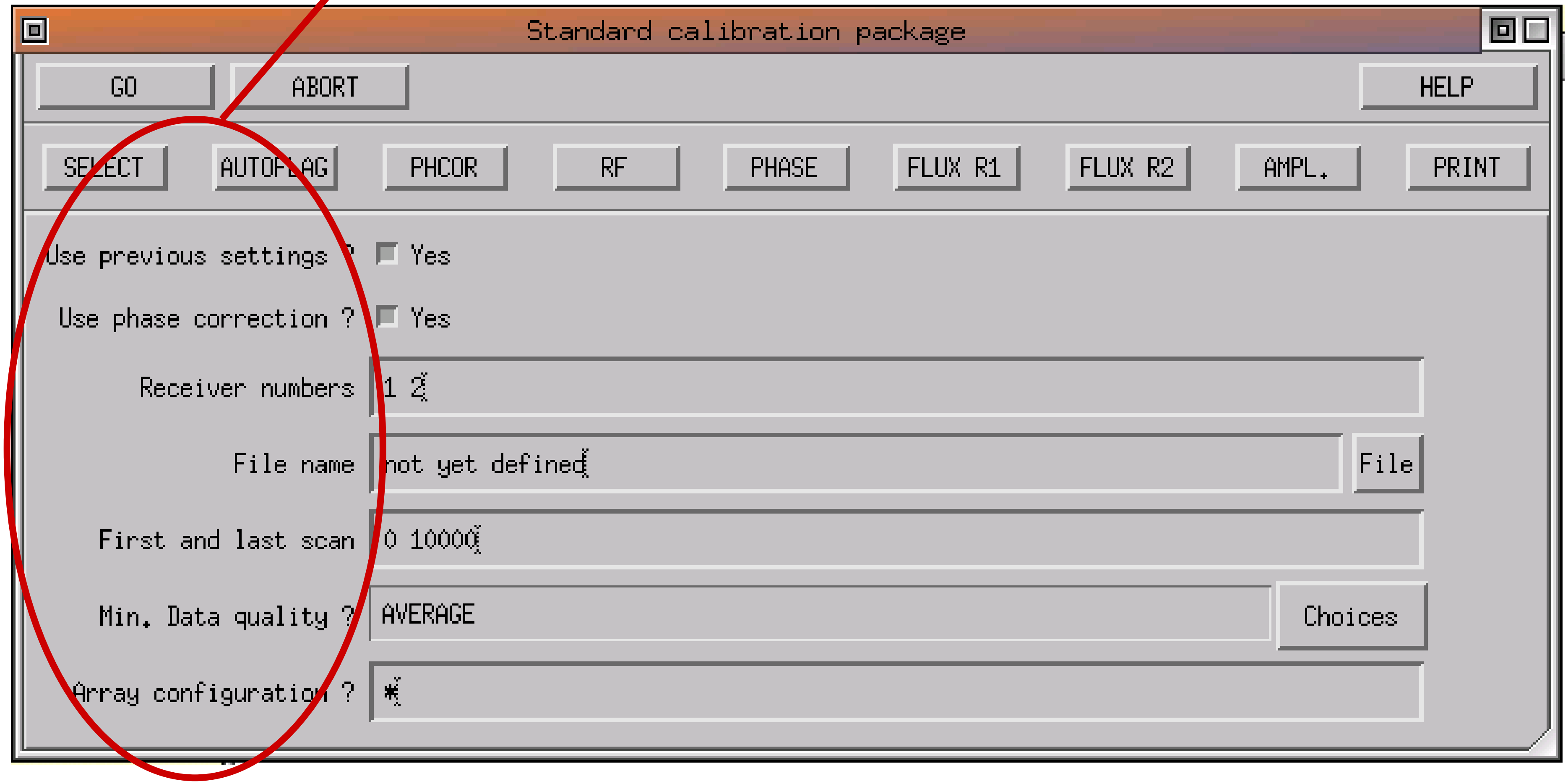
Off-line calibration
4. Flux scale



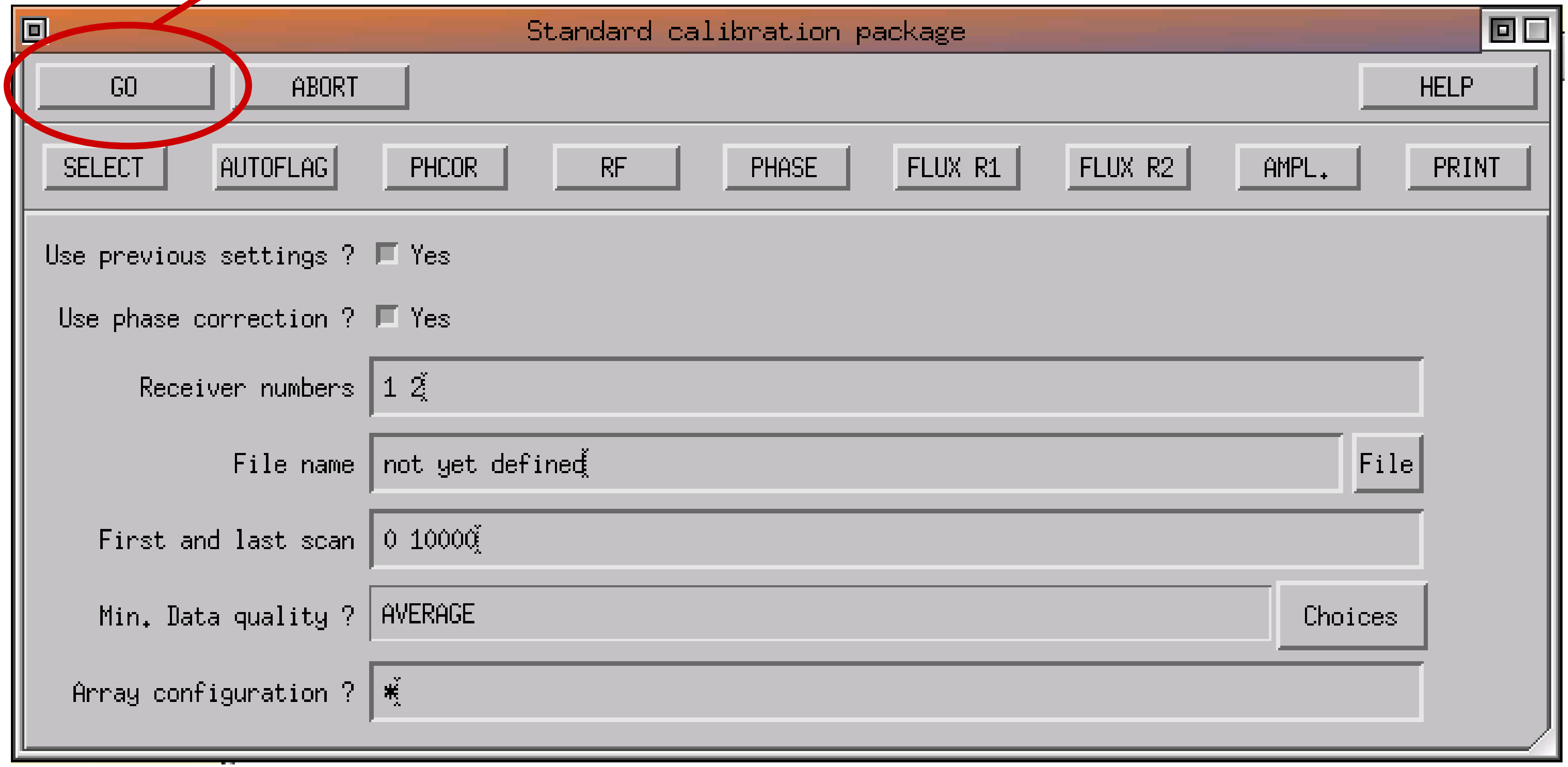
PdBI off-line data reduction



Input parameters to reduce an observation

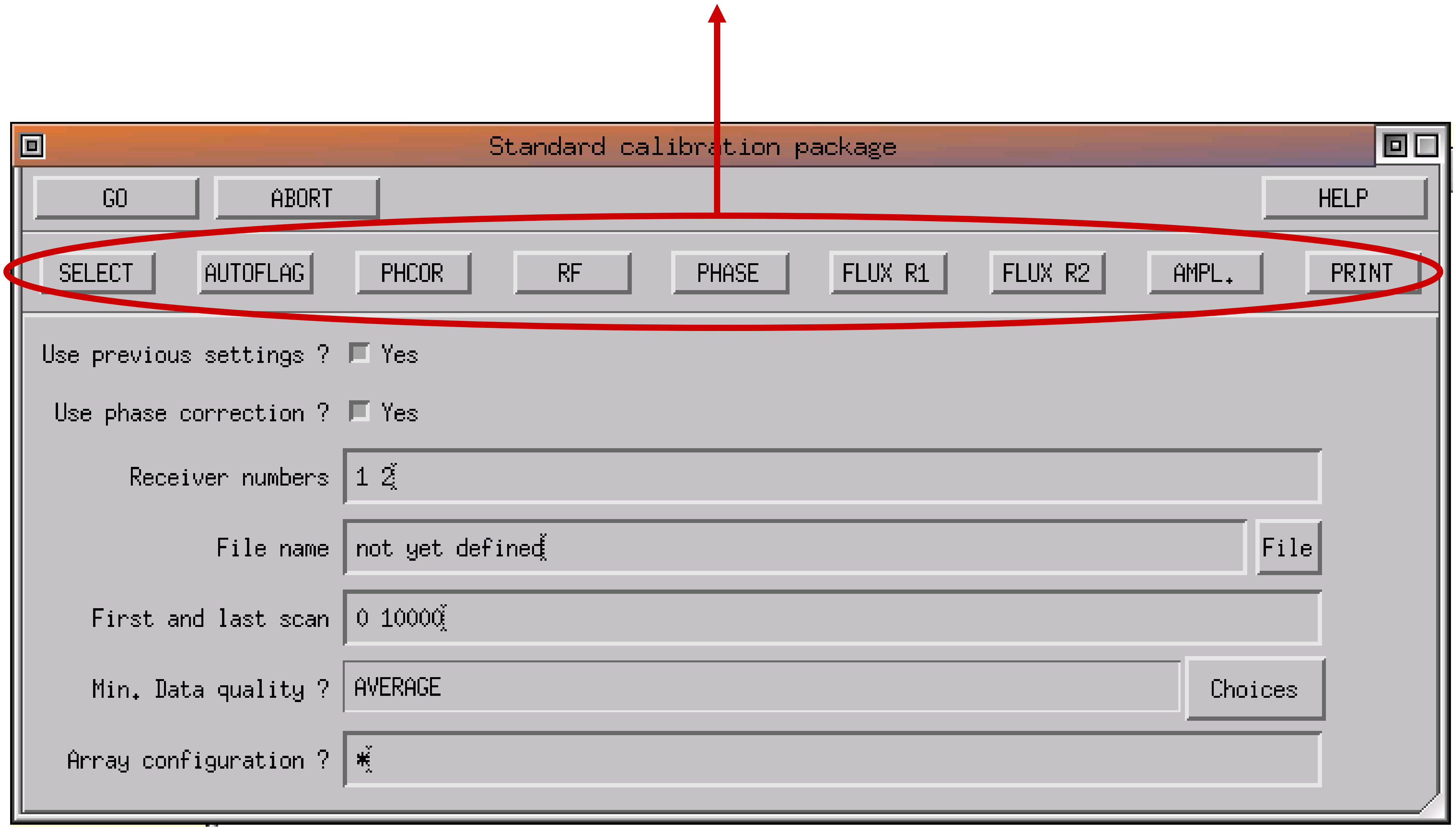


All calibrations in a row (pipeline)



One button per calibration step

The user can check/modify the results



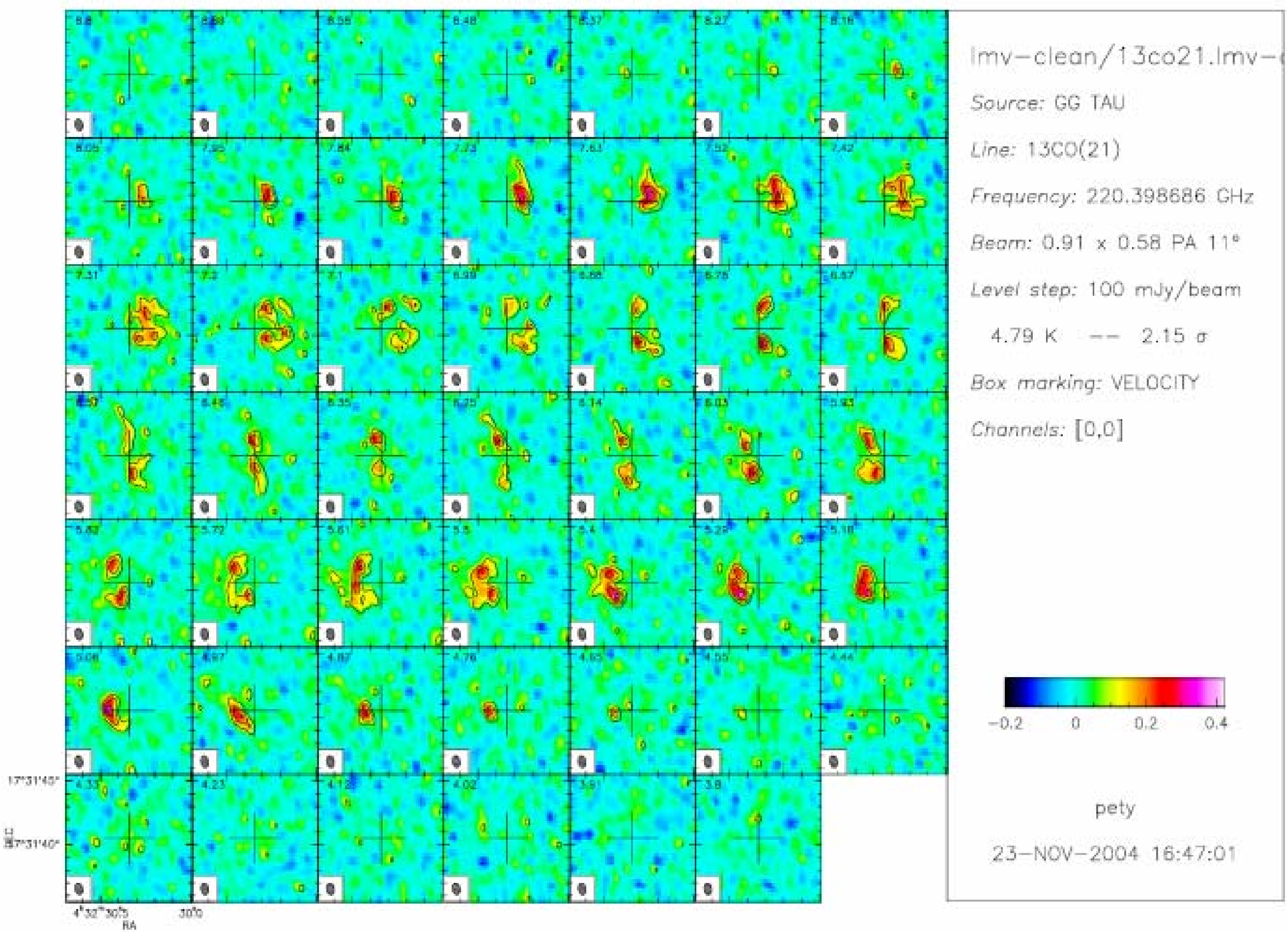
Imaging

mm vs. cm domain	Science	Imaging
- Resolution (~λ/B)	☹	☺
- FOV (~λ/D) smaller	☹	☺
- Much less pixels in image	☹	☺
- Much more spectral channels	☺	☹
- SNR much worst	☹	☹

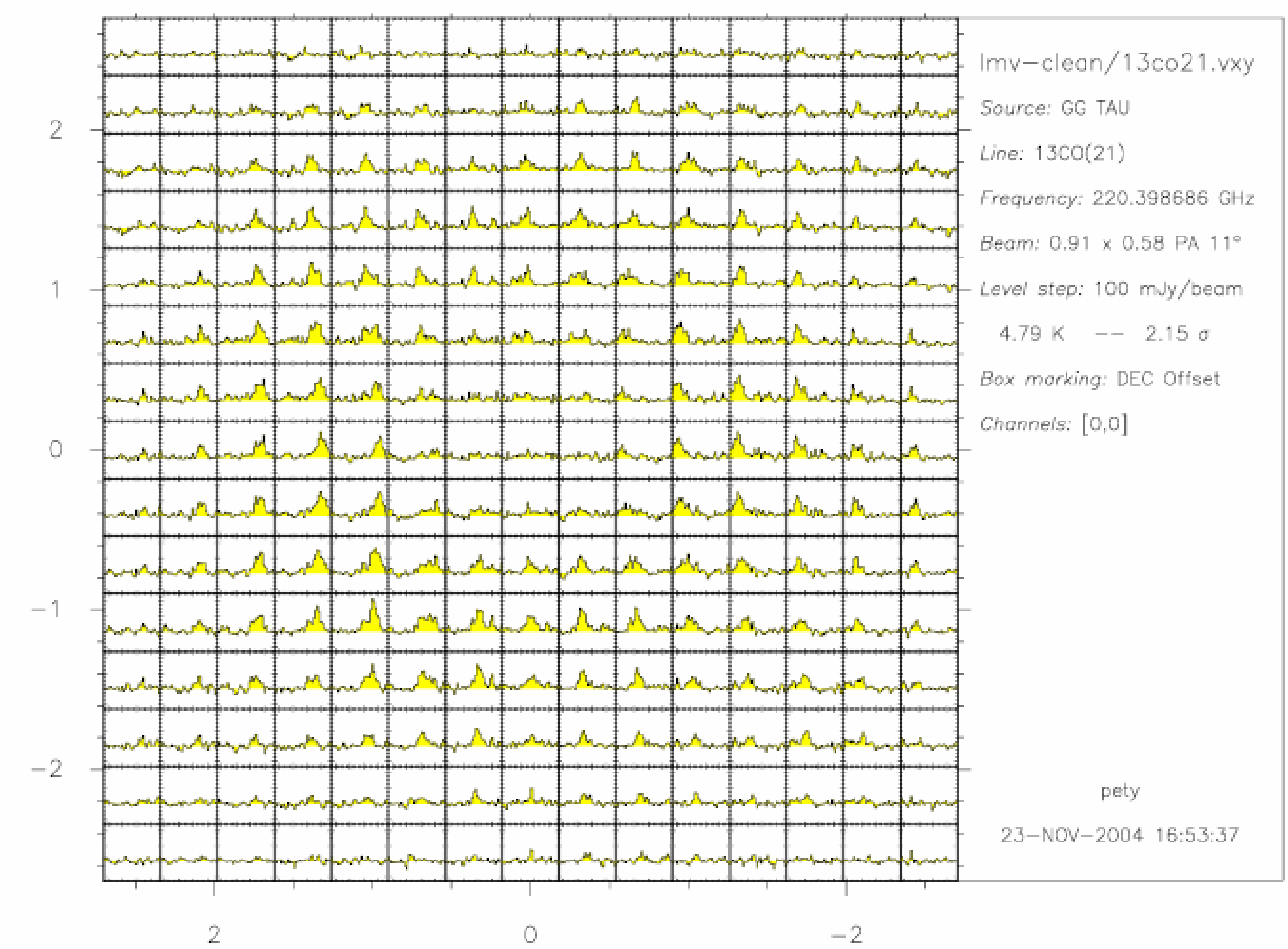
Visualization

- Large data cubes → **visualization** can be an issue
  - Plot all channel maps, movies
  - Position-velocity plots
  - Extract spectra at selected positions
  - Integrated spectra over map areas
  - Emission moments
  - ...
- **Extracting the information from large data cubes is not trivial**

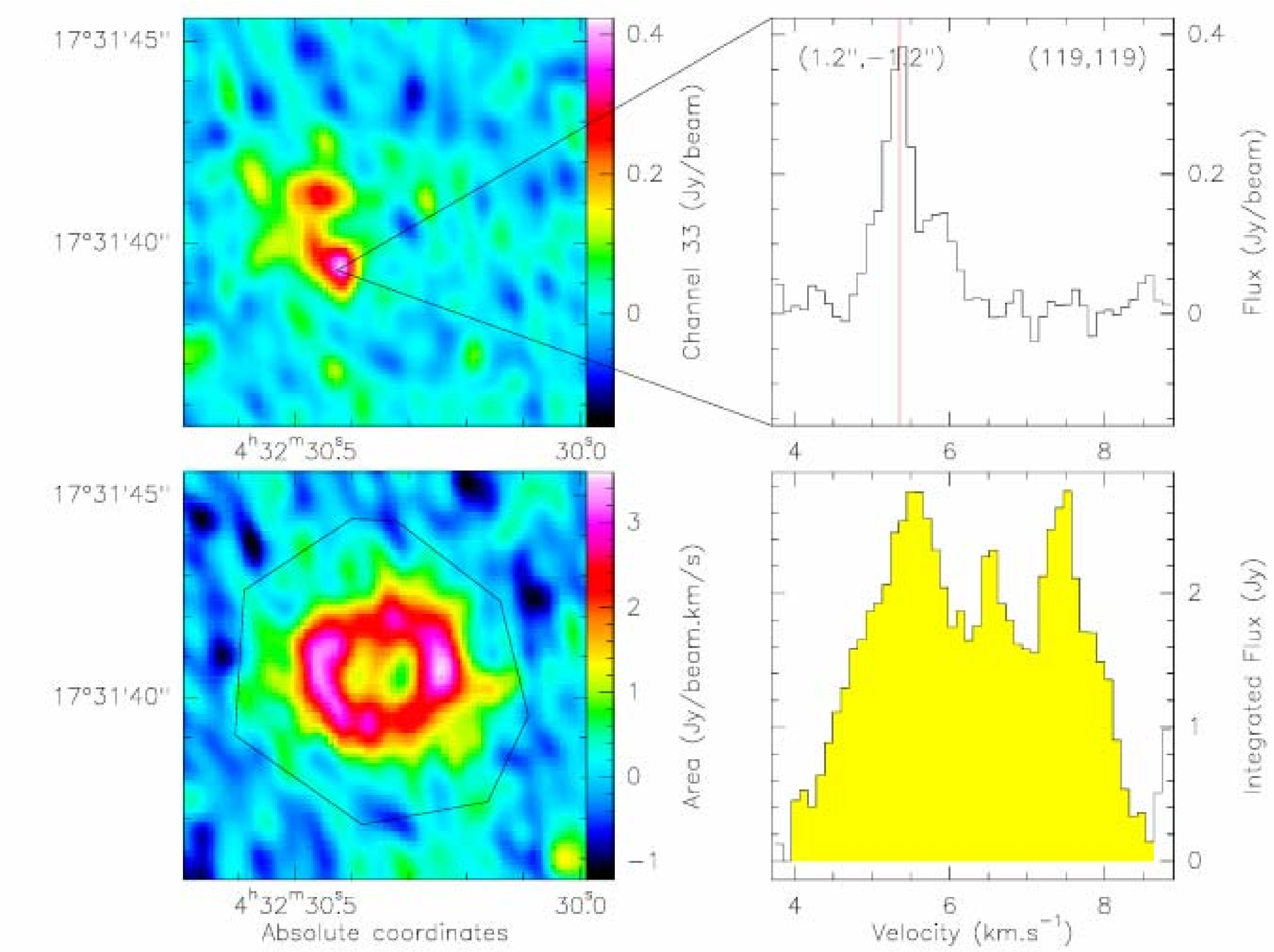
Channel maps (GO BIT)

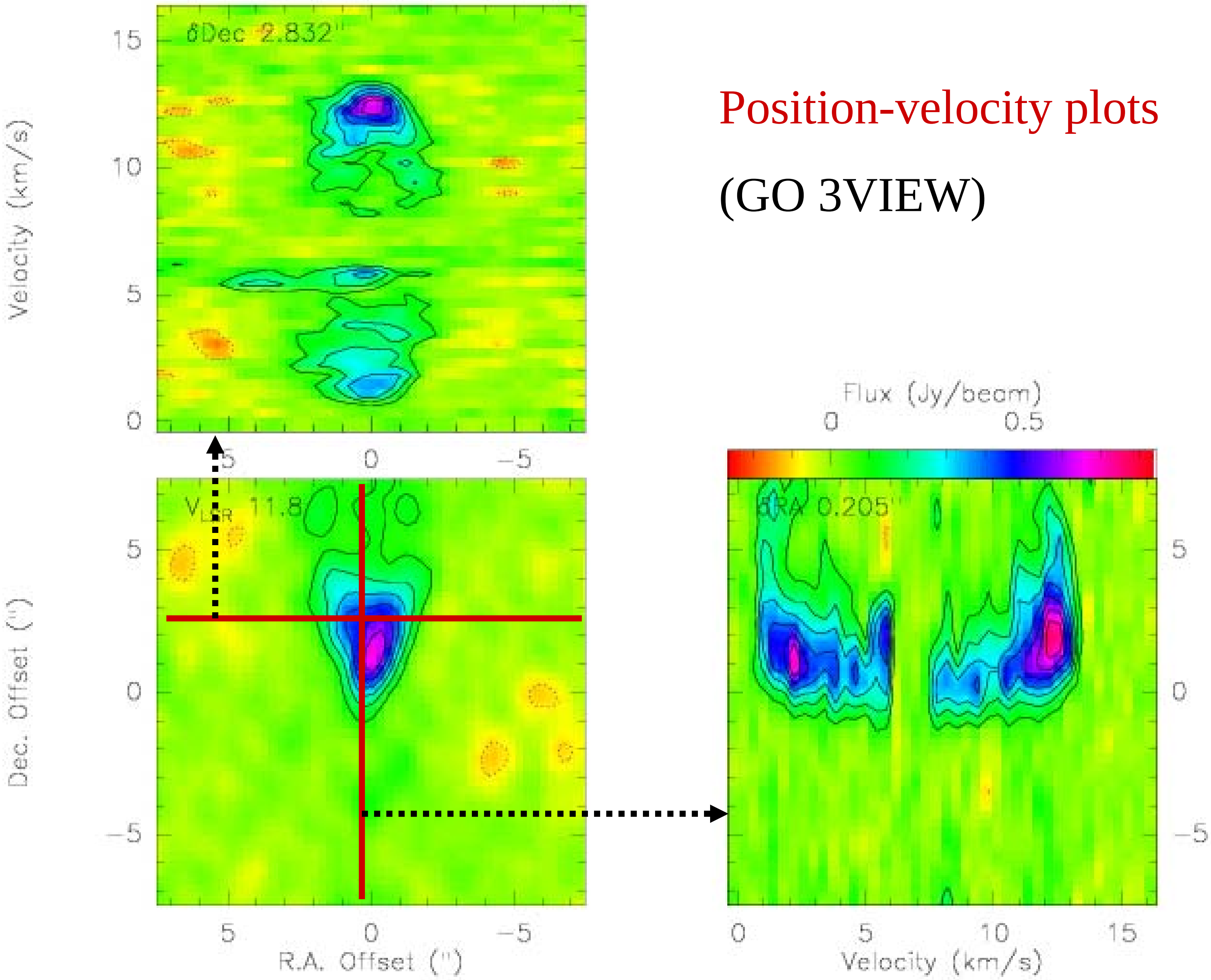


Spectra (GO SPECTRUM)



Spectra at selected positions/integrated (GO VIEW)





Position-velocity plots

(GO 3VIEW)

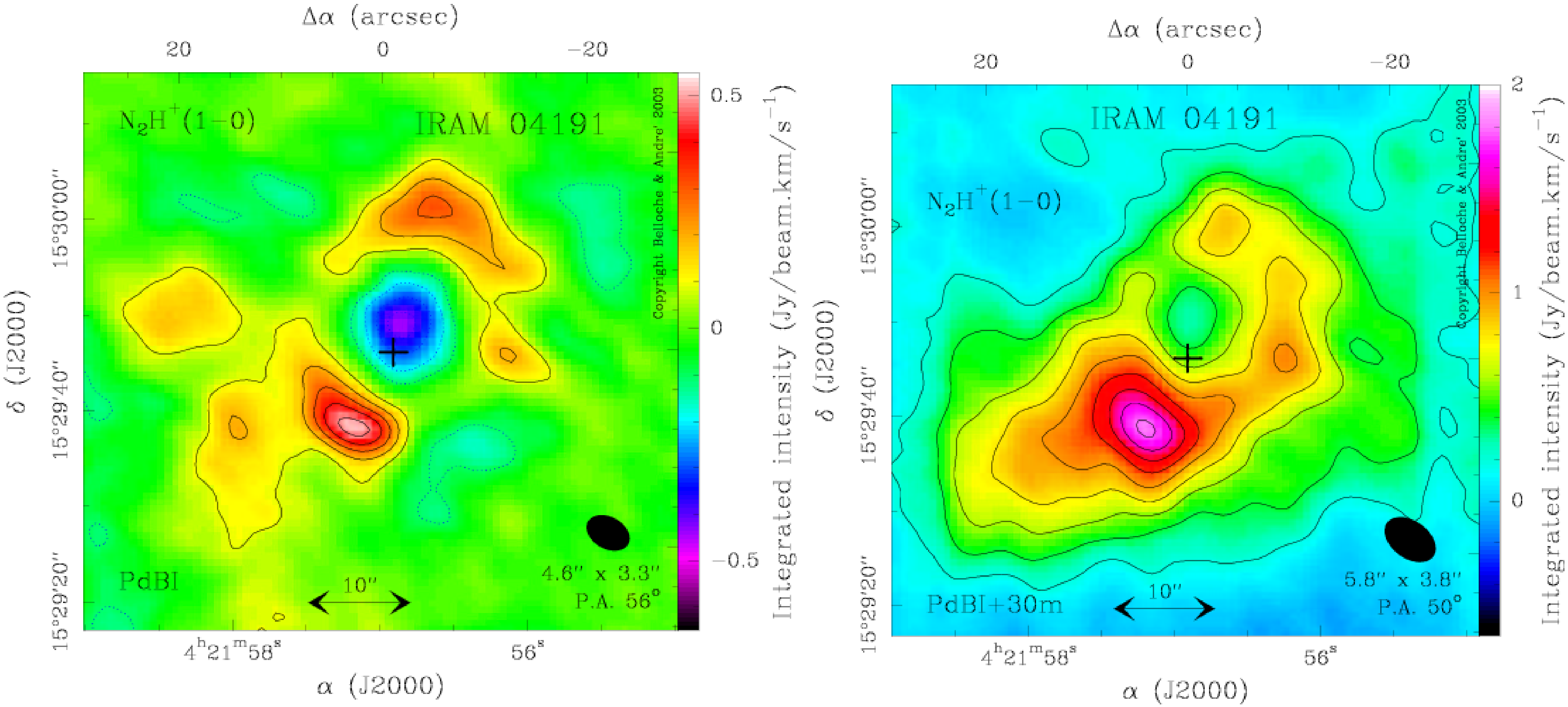
Advanced techniques

- **Polarization**
  - Not yet standard
  - Will be available soon (PdBI+NGRx, CARMA)
- **Snapshot observations**
  - Not possible because of poor SNR and uv coverage
  - Track-sharing between ~5 sources possible

Advanced techniques

- **Self-calibration**
  - Possible only on strong sources
  - In practice: absorption lines in front of quasars
- **Mosaicing**
  - Standard observing mode at PdBI (up to 50 fields)
- **Inclusion of short-Spacings**
  - (Almost) standard with IRAM PdBI + 30-m

Short-spacings



Belloche et al. (2004)

More on mm-interferometry?

- IRAM: **www.iram.fr**
- ALMA@ESO: **www.eso.org/projects/alma**

- IRAM mm-interferometry school series
  - Proceedings available on-line and in printed form (to be updated this autumn)
  - School #5 in October 2006
  - **School #6 in 2008** – co funded by RadioNet