ALMA

The following slides have been produced by the ALMA staff, especially the support scientists at the Nordic ARC node.

http://www.nordic-alma.se/

INTERFEROMETRY

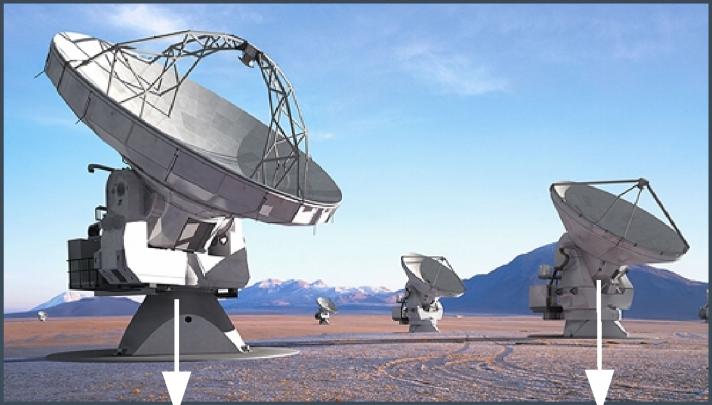
(A *LIGHT* INTRODUCTION)

Ivan Marti-Vidal (Nordic ARC)
Onsala Space Observatory

Interferometers

- The interference is computed as the *signal cross-correlation*.

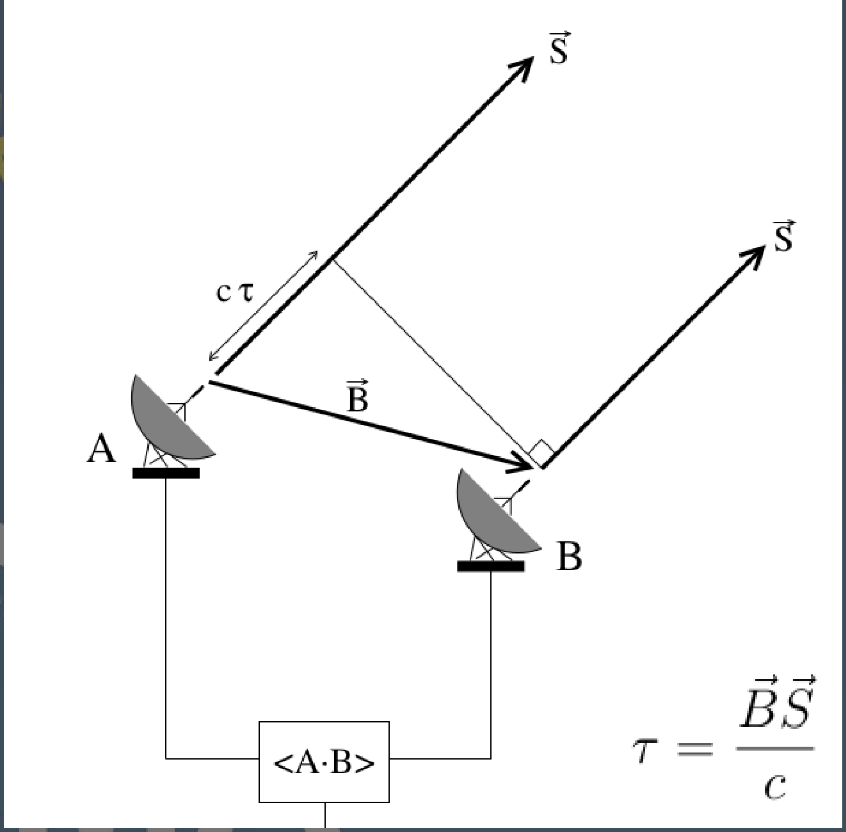
- A visibility is the coherent time average of this correlation.



$s_1(t_i)$ $s_2(t_i)$

$S_1(\nu_k)$ $S_2(\nu_k)$

$V_k = < S_1(\nu_k)\, S_2(\nu_k)^* >$

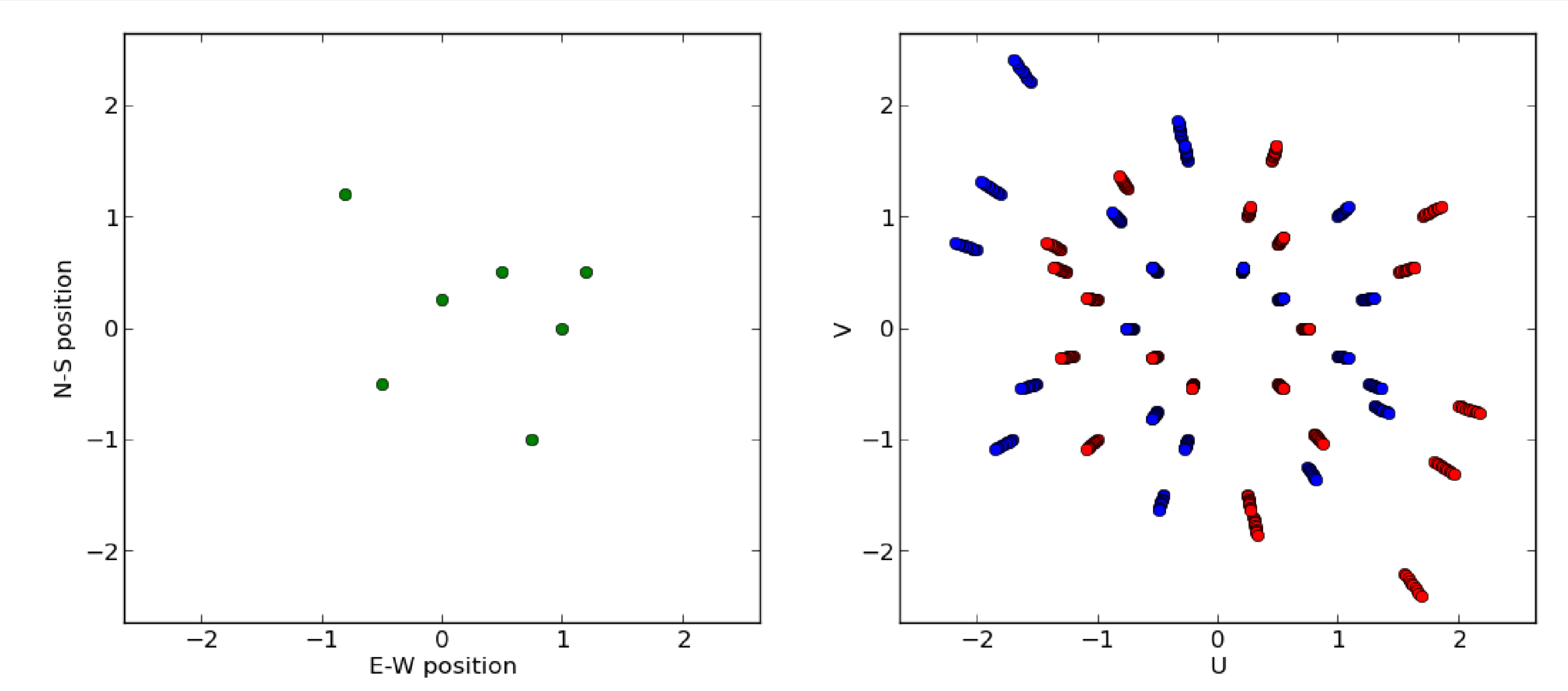


$$\tau = \frac{\vec{B}\vec{S}}{c}$$

$$Re = G_A G_B \frac{I}{2} \cos \omega\tau$$

$$Im = G_A G_B \frac{I}{2} \sin \omega\tau$$

Aperture Synthesis



Bandwidth of 10%

$$V\left(\frac{u}{\lambda},\frac{v}{\lambda}\right)=\mathcal{F}\left[I\left(x,y\right)\right]$$

Ivan Marti-Vidal. OSO (2013)

But reality is not that beautiful!

The measured visibilities are corrupted in many different ways.

- ATMOSPHERE:
  - Opacity (amplitude bias)
  - Water vapor (phase instabilities)

- INSTRUMENT:
  - Gain curve and pointing (varies with elevation and time)
  - Parallactic angle and leakage (affect polarization)
  - Bandpass (affects source spectrum)

- CORRELATOR & OTHERS:
  - Antenna positions (aberrating baseline-dependent effects).
  - Bandpass of digital filters (affects FDM ampl. calibration).
  - RFI.

Calibration

- Each undesired effect in the visibilities needs its own calibration strategy.

-There is a simple, elegant, and very powerful formalism that unifies all the calibration strategies in one single, and compact, formulation:

THE MEASUREMENT EQUATION

(e.g., Smirnov 2011, A&A, 527, 106)

OBSERVATIONS

$$V_{pq} = \begin{pmatrix} v_{XX} & v_{XY} \\ v_{YX} & v_{YY} \end{pmatrix} \text{ or } \begin{pmatrix} v_{LL} & v_{LR} \\ v_{RL} & v_{RR} \end{pmatrix}$$

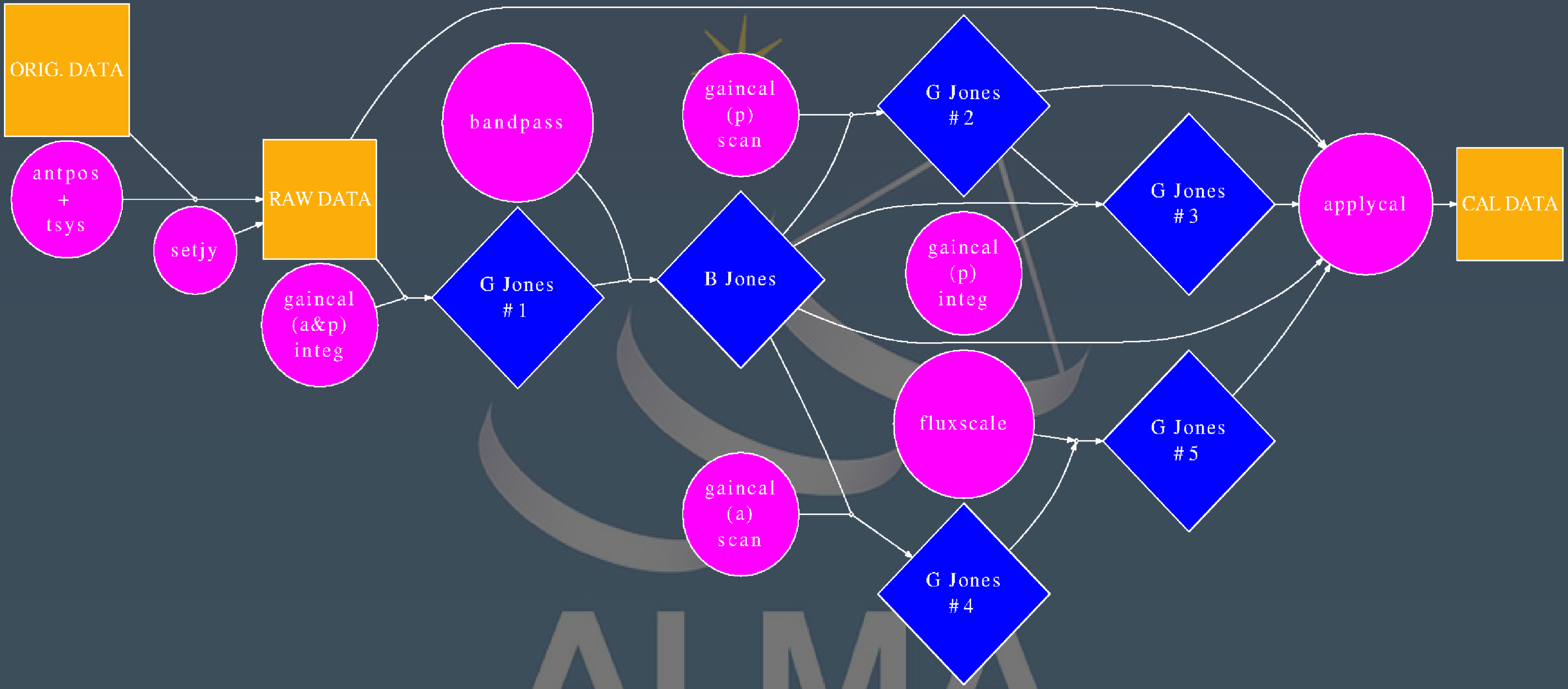
SCIENCE

$$\boldsymbol{X} = \begin{pmatrix} I+Q & U+\mathrm{i}V \\ U-\mathrm{i}V & I-Q \end{pmatrix} \text{ or } \begin{pmatrix} I+V & Q+\mathrm{i}U \\ Q-\mathrm{i}U & I-V \end{pmatrix}$$

$$\boldsymbol{V}_{pq} = \boldsymbol{B}_p\boldsymbol{G}_p\boldsymbol{P}\left(\sum_{k=1}^{N}\boldsymbol{E}_k\boldsymbol{K}_{pk}\boldsymbol{X}_k\boldsymbol{K}_{qk}^{\dagger}\boldsymbol{E}_k^{\dagger}\right)\boldsymbol{P}^{\dagger}\boldsymbol{G}_q^{\dagger}\boldsymbol{B}_q^{\dagger}$$

Calibration

- The calibration matrices are estimated from calibrator data (time stability of atmosphere and instrumentation between target and calibrator observations is assumed).



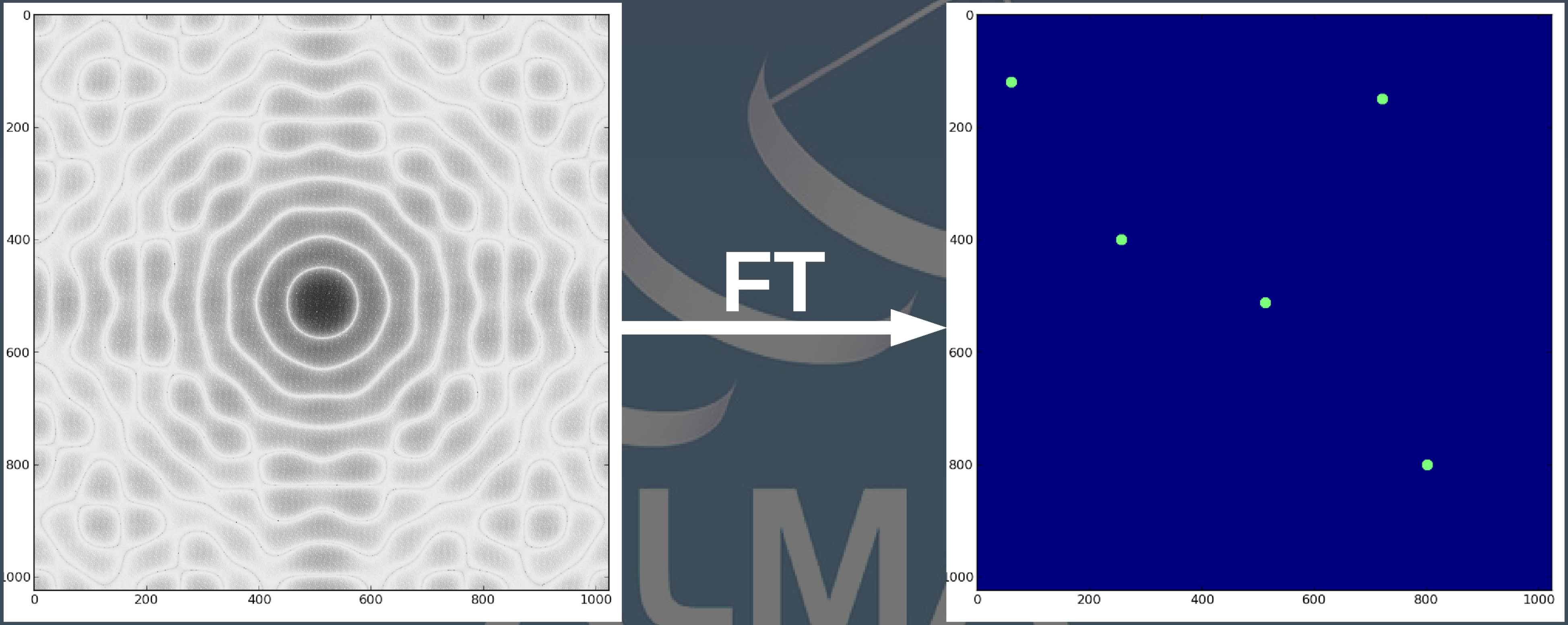
Ivan Marti-Vidal. OSO (2013)

Imaging

OK. I've got my calibrated visibilities. What do I do with them?

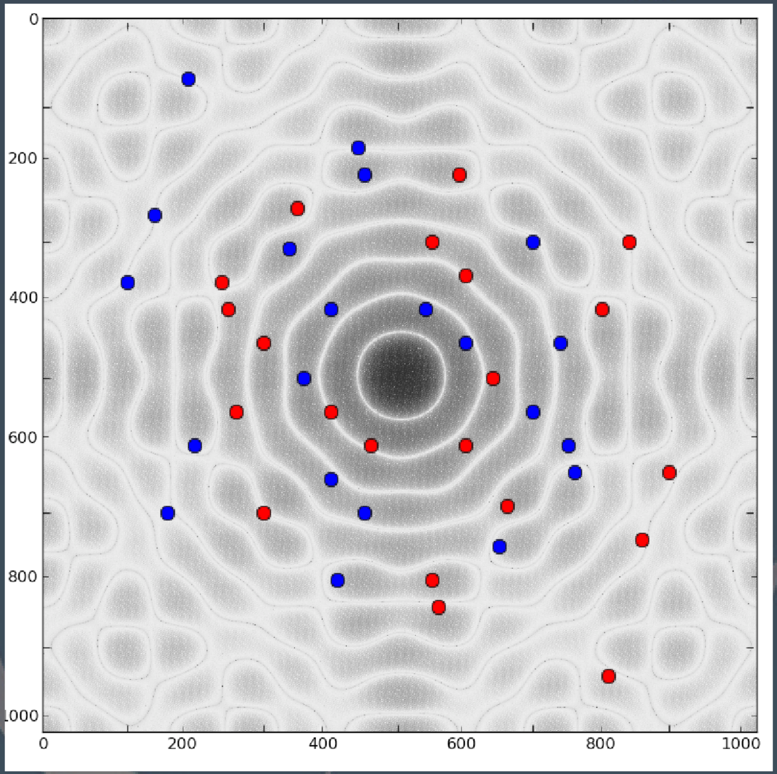
“JUST” INVERT THE FOURIER RELATION!

$$V\left(\frac{u}{\lambda},\frac{v}{\lambda}\right)=\mathcal{F}\left[I\left(x,y\right)\right]$$



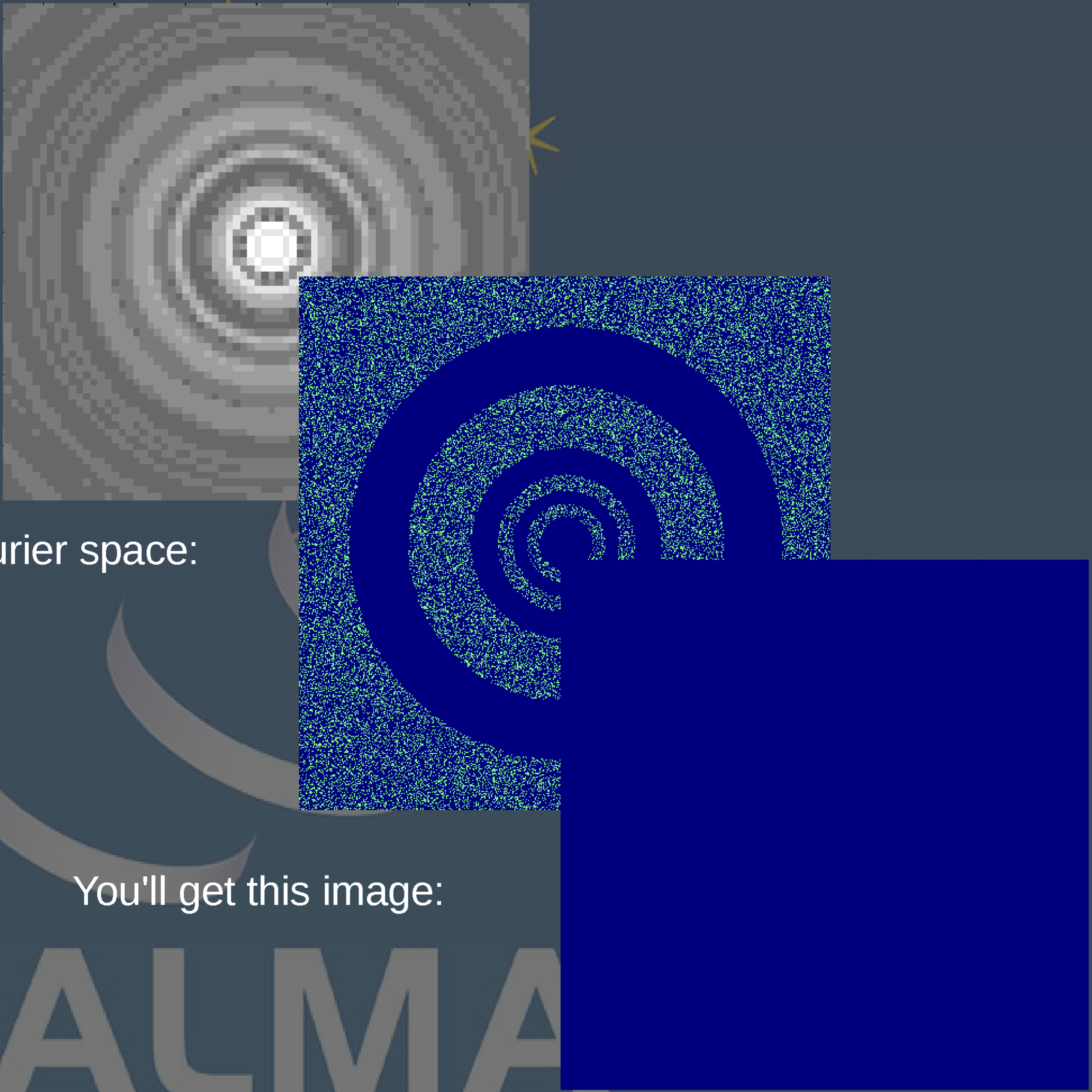
BUT !!!

There is ***A LOT*** of missing information in our sampling of Fourier space.



An interferometer is a ***filter of spatial frequencies.***

Imaging. “Special” example

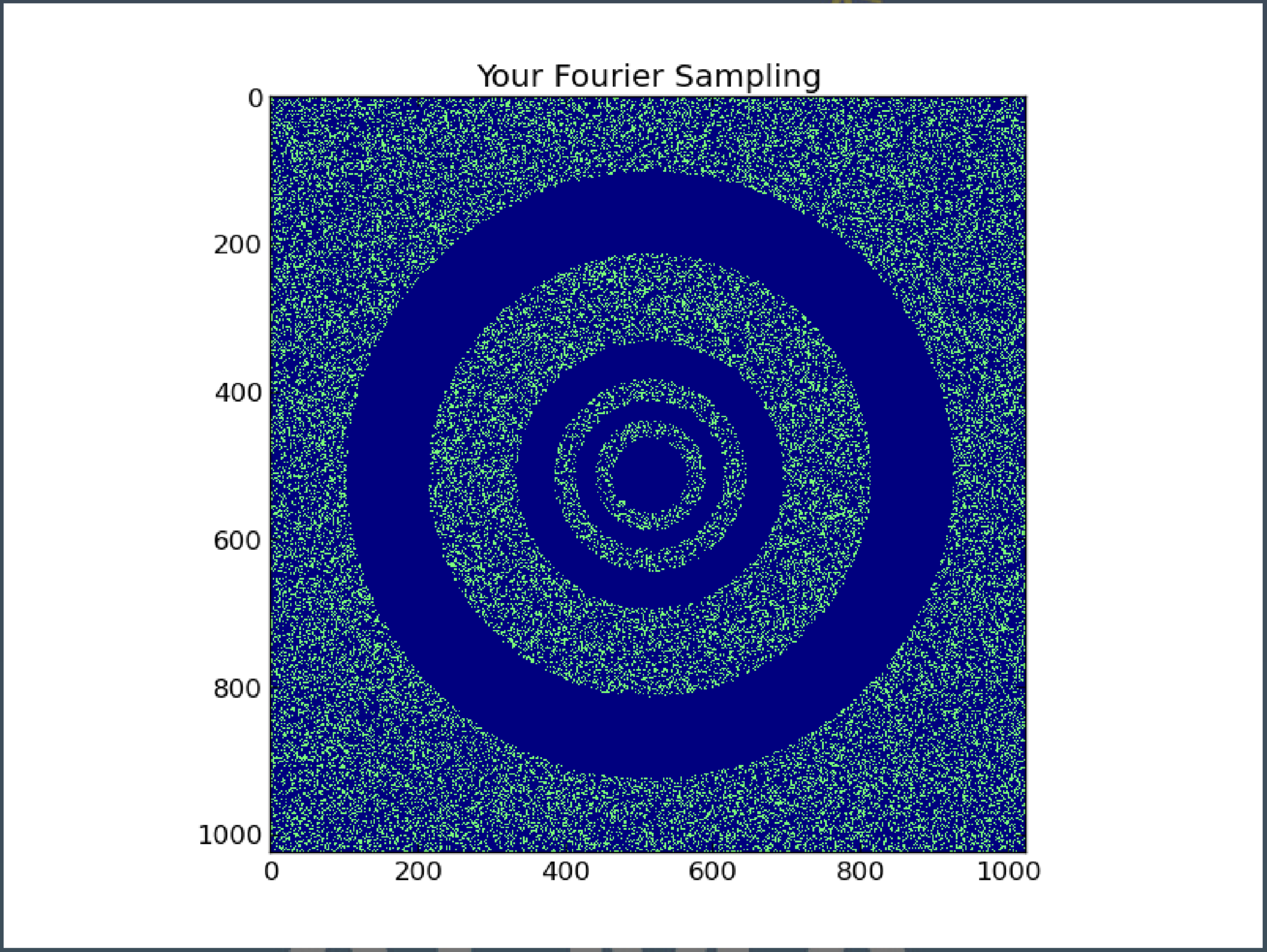


If you observe this source:

With this sampling of Fourier space:

You'll get this image:

Imaging. “Special” example
WHY?!



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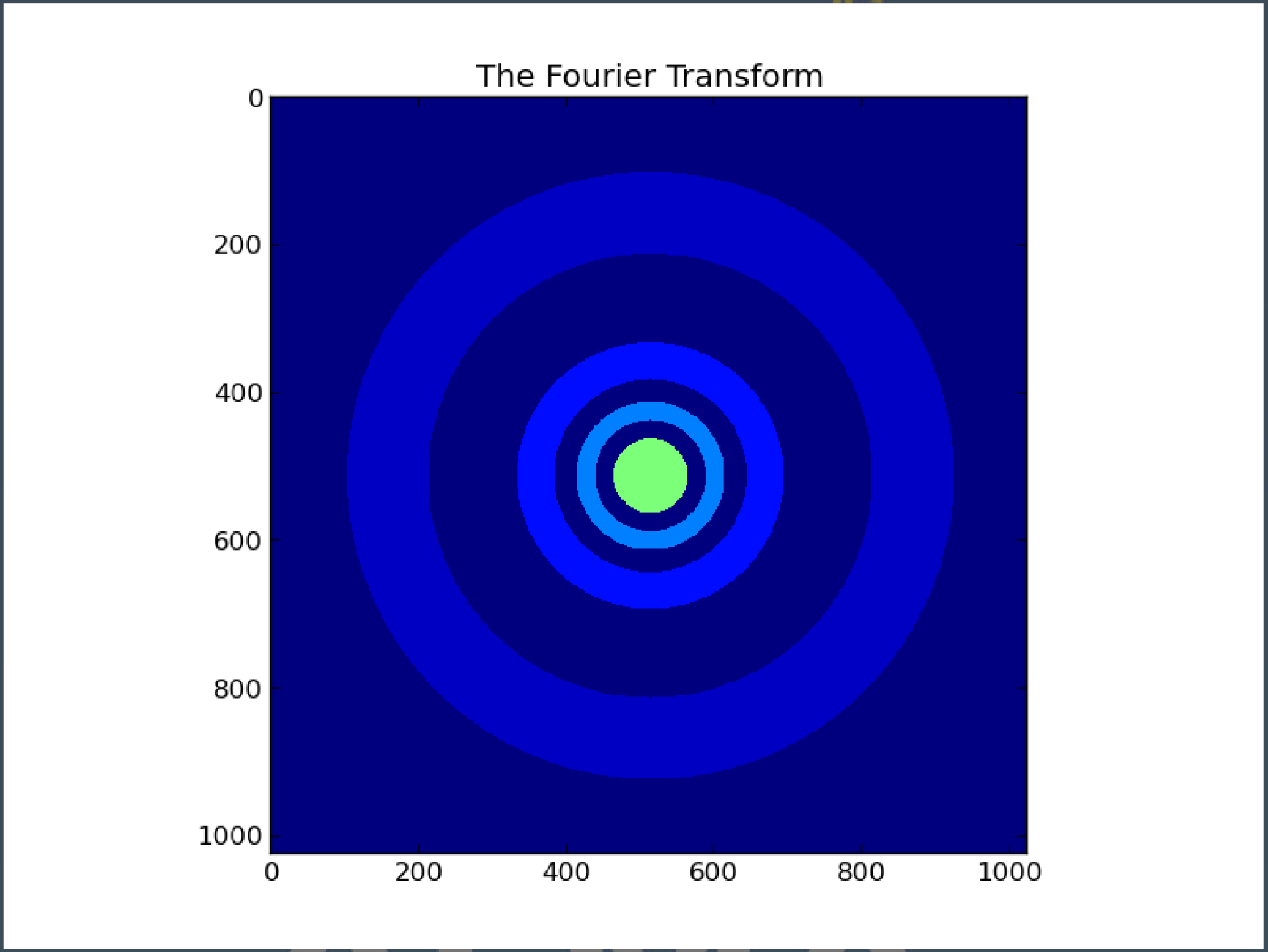


Imaging

- The interferometer only observes a *small* amount of all the spatial frequencies of the source structure. It *filters out a lot* of information of the source structure (fortunately, the image fidelity increases with the number of antennas, and ALMA is a ***huge*** interferometer!).

- Anyway, it is impossible to *completely recover* the source structure (it would violate the law of conservation of information :D).

- We can, however, *interpolate* the missing spatial frequencies of our Fourier sampling, based on several *criteria*.

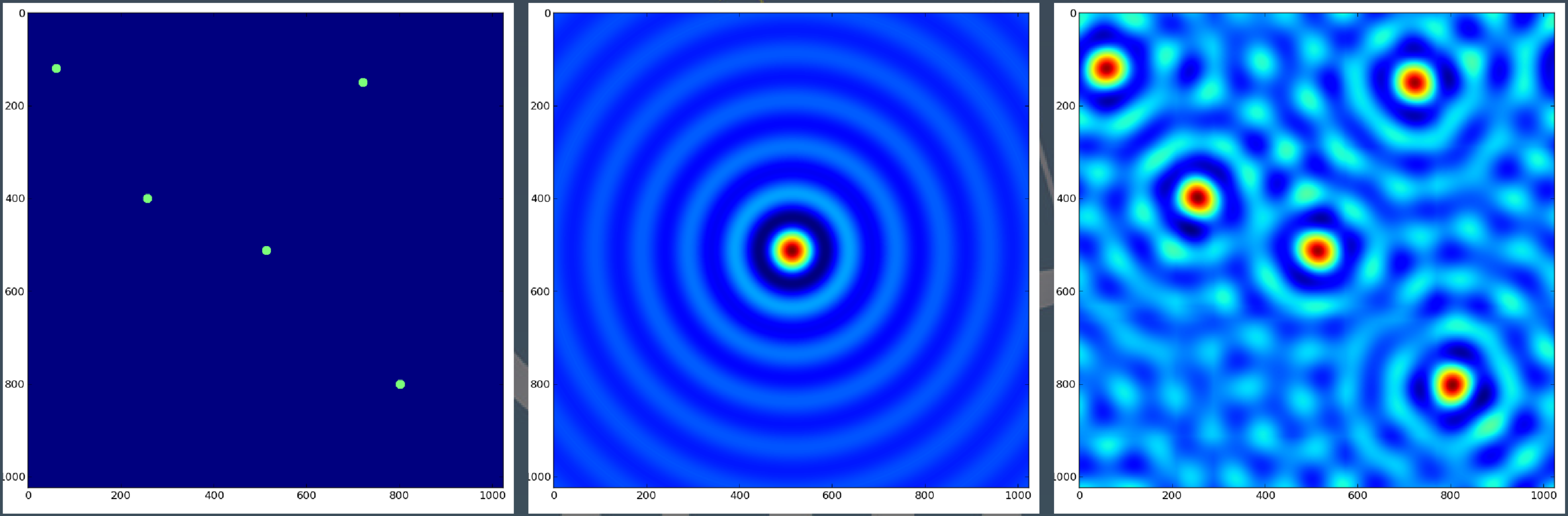
- We can thus, use realistic criteria to find out the ***most reliable*** image of the source structure, from all the different images that are compatible with our data.

THIS IS THE “ART” OF IMAGING!

Imaging criteria

THE CLEAN ALGORITHM

- Different imaging strategies are based on different criteria. The most commonly-used imaging algorithm (i.e., the CLEAN deconvolution) assumes that the source ***is made of compact components***.



Imaging criteria

THE CLEAN ALGORITHM

- If the source has extended components, ***CLEAN will make them clumpy***!

- You can use *multiscale CLEANing* to minimize this artificial *clumpiness,* or use alternative deconvolution algorirthms (e.g. MEM).

-In any case, if your source is expected to have extended emission, the best thing to do is to ***sample very well the lower spatial frequencies***.

THE ACA WILL HELP YOU *A LOT* IF YOU WANT TO IMAGE THE EXTENDED EMISSION OF YOUR SOURCE!

Imaging

CONLUSIONS

- An interferometer filters out a lot of information of the source structure (i.e., it is a filter of spatial frequencies).

- We can, though, estimate the missing information (i.e., interpolate in Fourier space), based on realistic criteria.

- Different deconvolution algorithms (e.g., CLEAN, MS-CLEAN, MEM) are based on different criteria. You should beware of how this may affect the image of your particular source.

- Although ALMA has a lot of antennas (i.e., the sampling of Fourier space is extremely good), the limitations of the different deconvolution algorithms (e.g., the CLEAN *clumpiness*) are still there. You will want the ACA to help you in the imaging, if there is extended emission in your source.

- The final image is not “data”. It is a “model” of the data. The actual data are the visibilities!

Working with ALMA data

THE COMMON ASTRONOMY SOFTWARE APPLICATIONS

- ALMA visibilities are arranged in a format called *ALMA Science Data Model* (ASDM).

- The standard tool to calibrate ALMA data is casacore. There is an enhanced/extended wrapper/API to casacore called CASA (by NRAO), which has a Python-based interface (**casapy**).

- CASA works with measurement sets (MSs), which are calibrated using the *Measurement Equation formalism* (via *Jones* matrices). The ASDM have to be imported into MS format.

- A measurement set is “just” a directory full of all the necessary and sufficient information that defines interferometric observables. Extremely versatile and flexible, compared to older formats (i.e., uvfits).

- The scripting capabilities of CASA, and a mastering of its main tasks and tools, gives the user full power over the data, with endless possibilities!

- LEARN A BIT OF PYTHON!

ALMA

ALMA: Atacama Large Millimeter/submillimeter Array


© AFP/GETTY IMAGES

- Observe the sky in the mm/submm window

- High sensitivity, high angular resolution, high image quality

- Located in the Andes, Chile, at 5000 m altitude

- Most expensive ground-based astronomical instrument

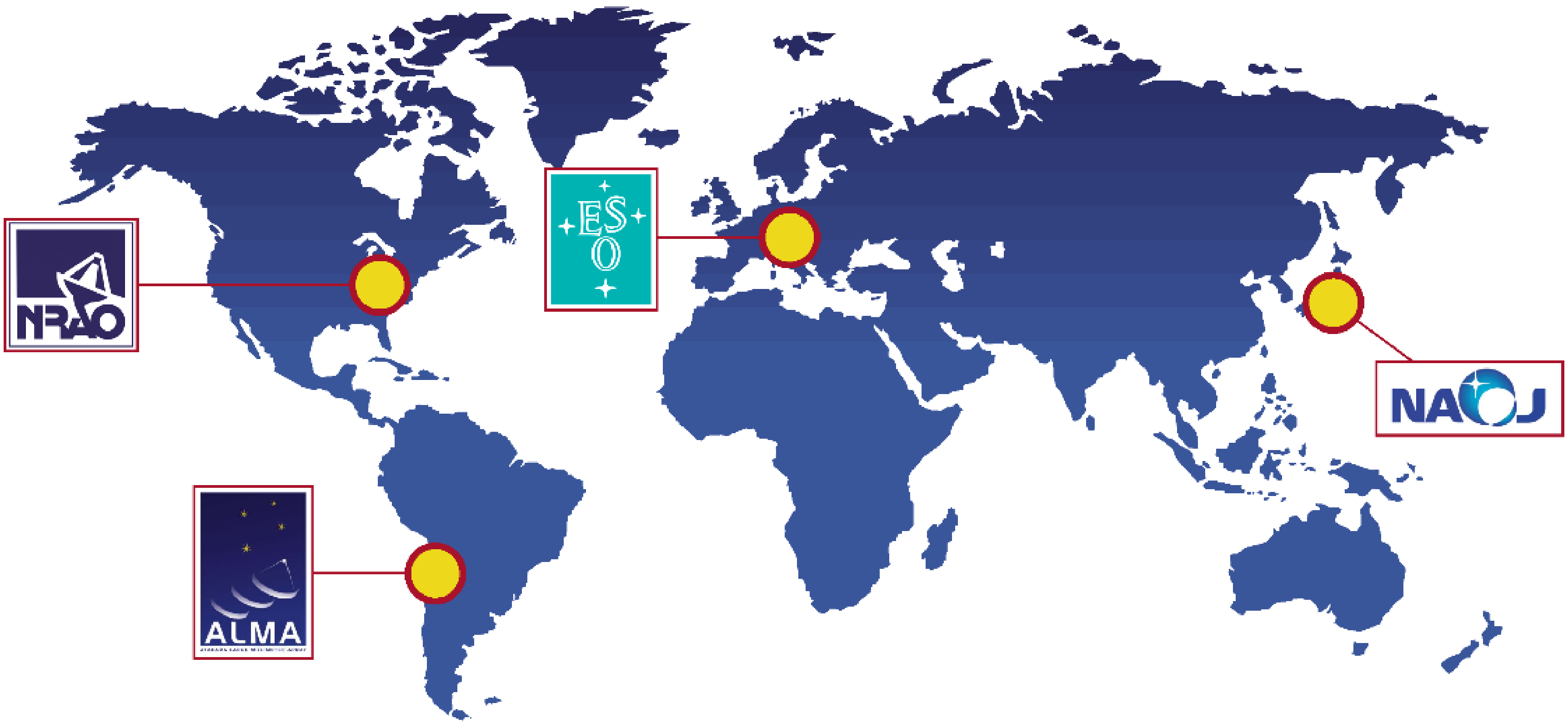
- International collaboration between

    Europe / North America / East Asia


© AFP/GETTY IMAGES

ALMA is international

ALMA Regional Centers



ALMA can observe nearly everything from:

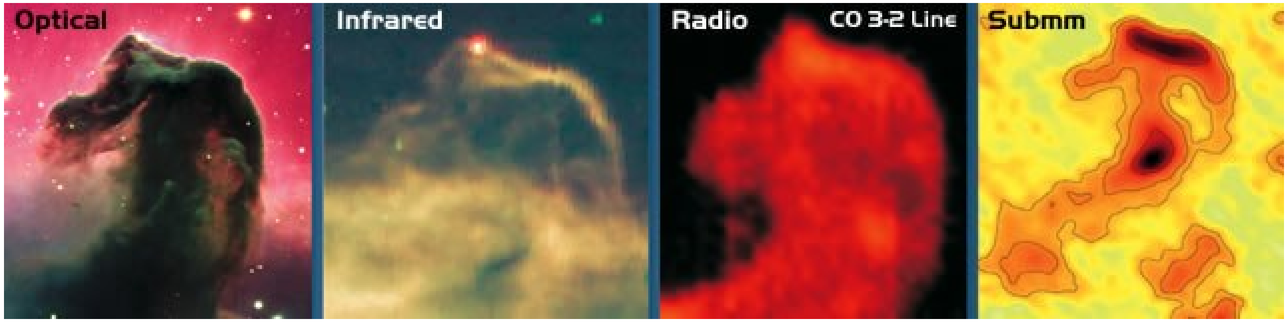
Solar System objects (comets, atmospheres),

To star formation regions, young stellar objects,

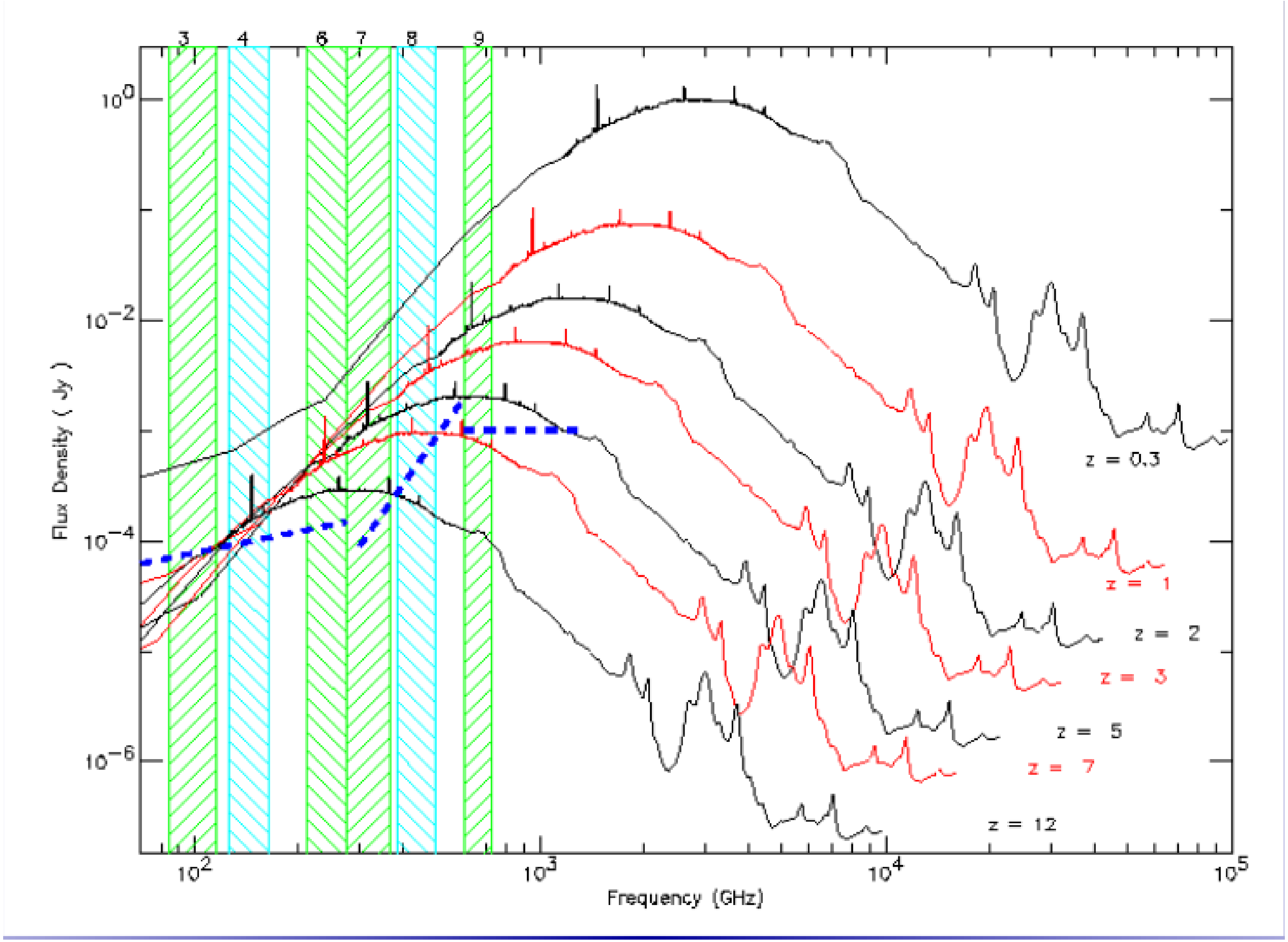
To evolved stars, giant molecular clouds, in the Milky Way

To nearby galaxies in the Local Universe

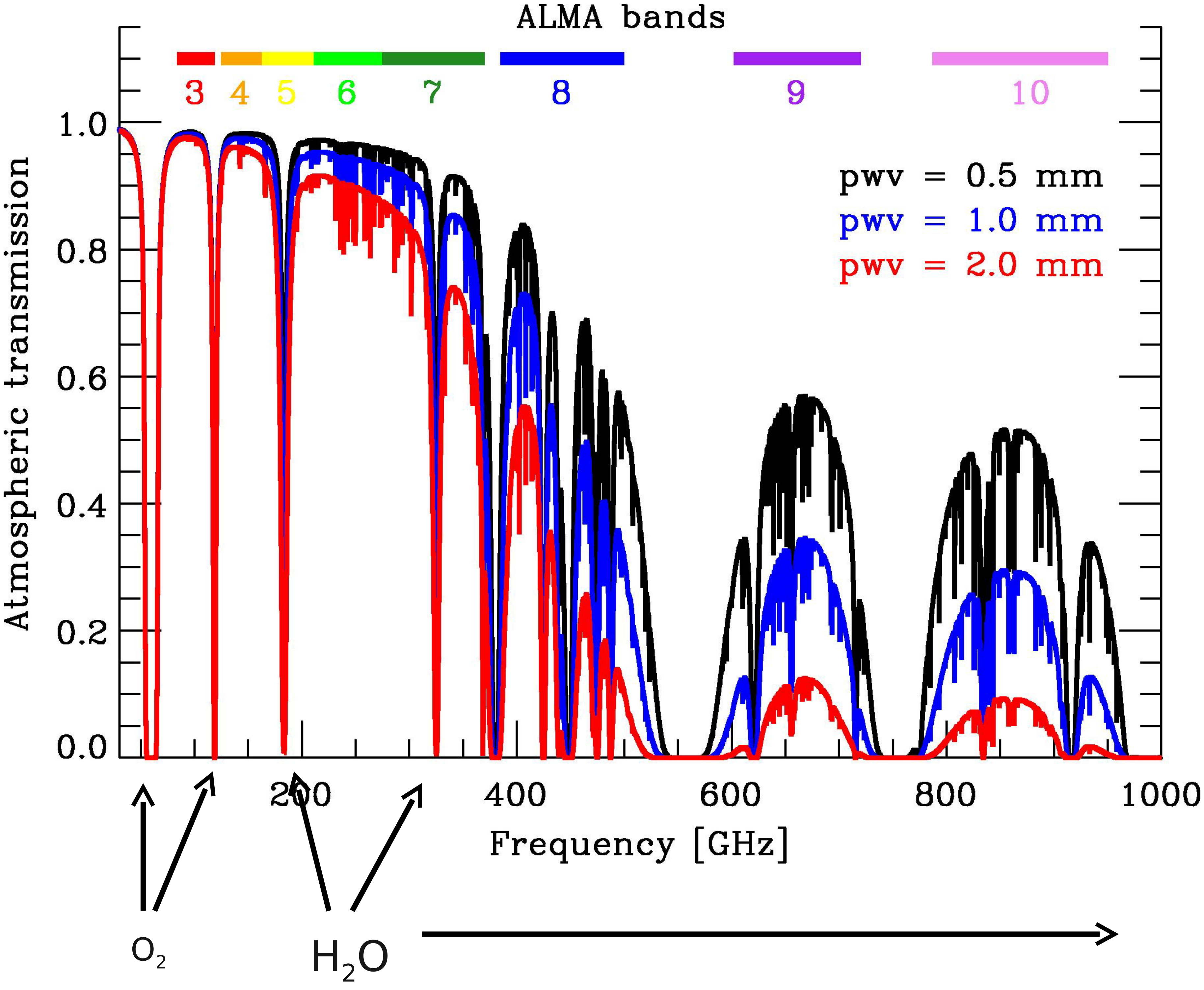
Up to remote galaxies in the distant Universe.



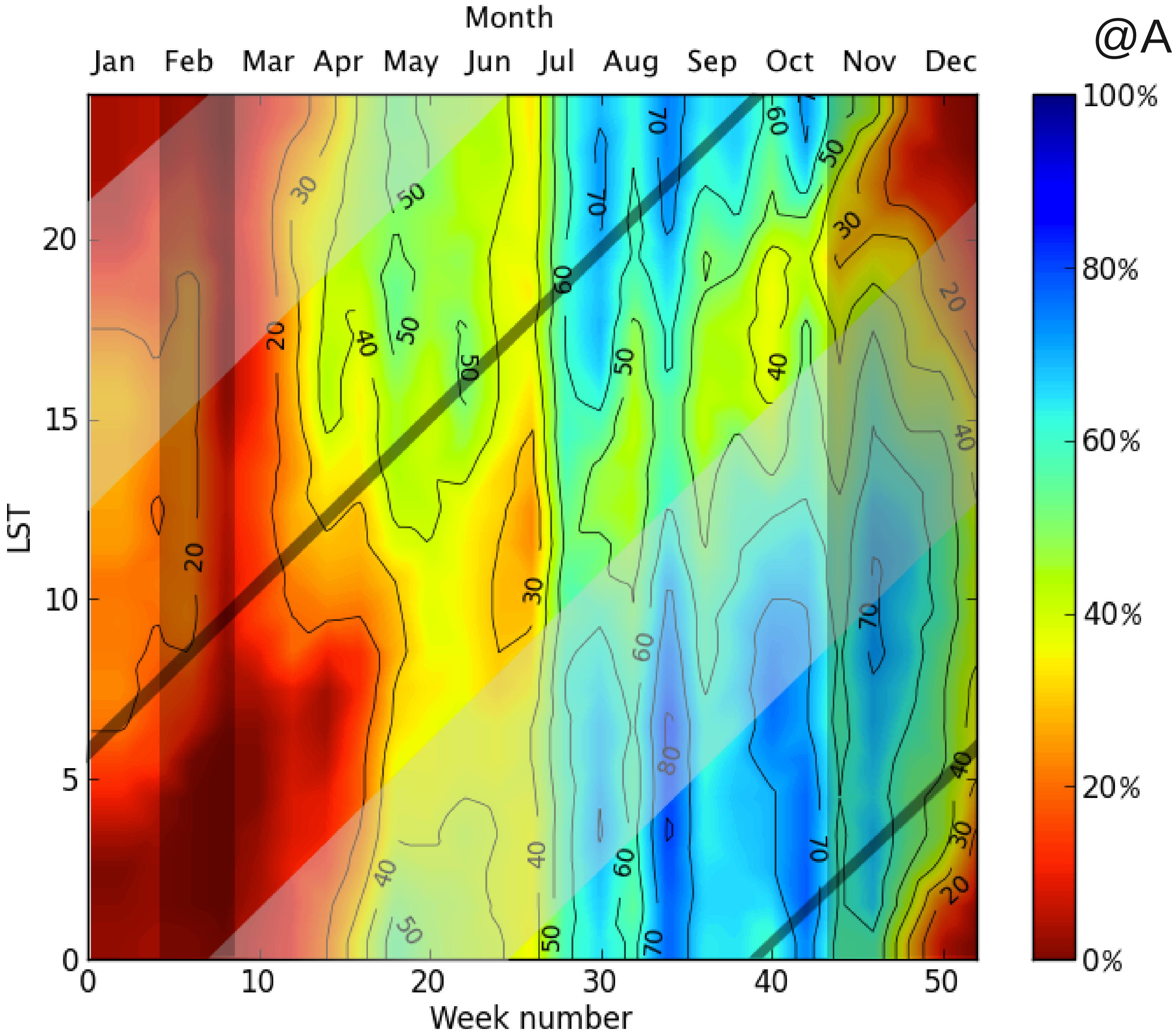
M82 redshifted Spectral Energy Distribution



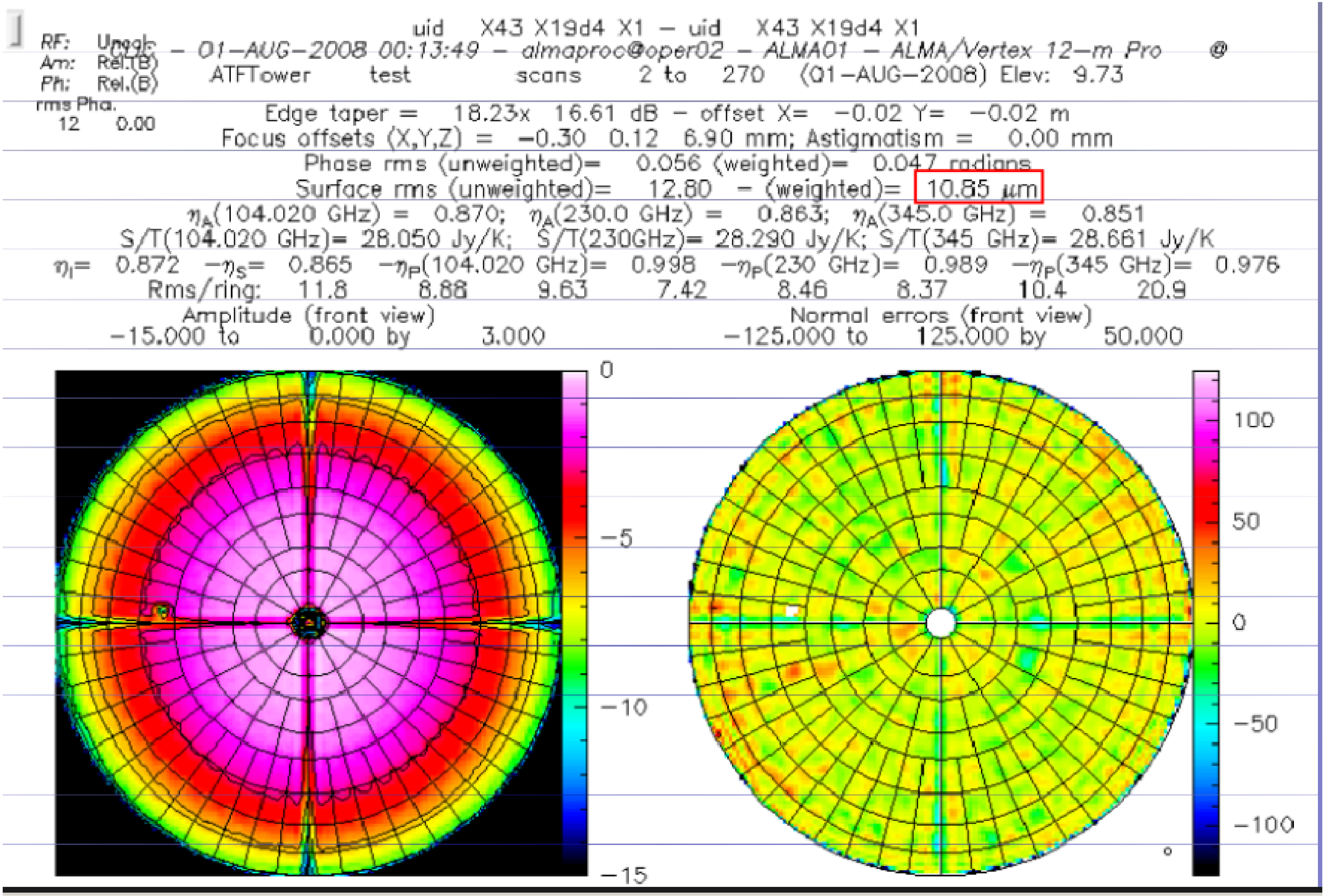
-> Mm/submm well adapted to detect and study high-z galaxies


ALMA bands
3
4
5
6
7
8
9
10
pwv = 0.5 mm
pwv = 1.0 mm
pwv = 2.0 mm
Atmospheric transmission
0.0
0.2
0.4
0.6
0.8
1.0
200
400
600
800
1000
Frequency [GHz]
O_2
H_2O

Fraction of time when PWV is below 1mm @ALMA site



Surface accuracy



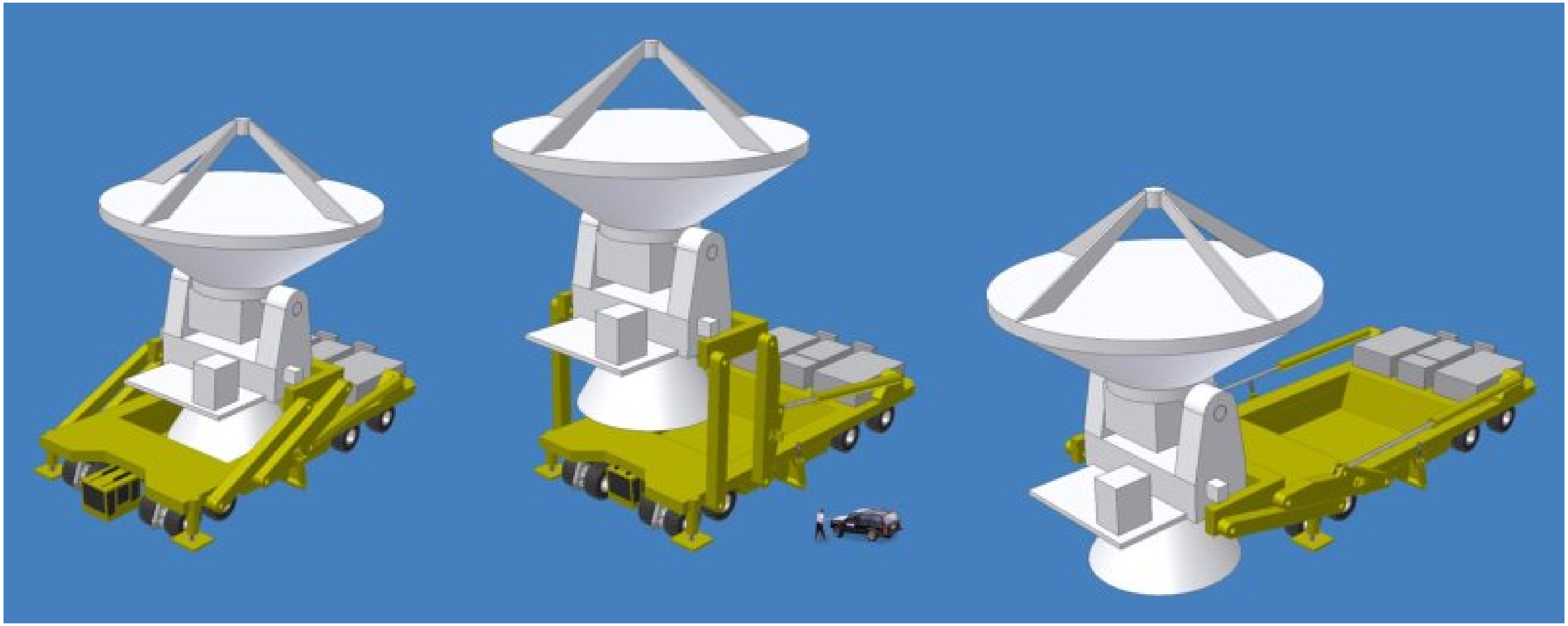
RF: Unagl:
Am: Rel.(B)
Ph: Rel.(B)
rms Pha.
12 0.00

uid X43 X19d4 X1 – uid X43 X19d4 X1
CLK – 01–AUG–2008 00:13:49 – almaproc@oper02 – ALMA01 – ALMA/Vertex 12–m Pro @
ATFTower test scans 2 to 270 (01–AUG–2008) Elev: 9.73

Edge taper = 18.23x 16.61 dB – offset X= –0.02 Y= –0.02 m
Focus offsets (X,Y,Z) = –0.30 0.12 6.90 mm; Astigmatism = 0.00 mm
Phase rms (unweighted)= 0.056 (weighted)= 0.047 radians
Surface rms (unweighted)= 12.80 – (weighted)= 10.85 μm
η_A(104.020 GHz) = 0.870; η_A(230.0 GHz) = 0.863; η_A(345.0 GHz) = 0.851
S/T(104.020 GHz)= 28.050 Jy/K; S/T(230GHz)= 28.290 Jy/K; S/T(345 GHz)= 28.661 Jy/K
η_I= 0.872 –η_S= 0.865 –η_P(104.020 GHz)= 0.998 –η_P(230 GHz)= 0.989 –η_P(345 GHz)= 0.976
Rms/ring: 11.8 8.88 9.63 7.42 8.46 8.37 10.4 20.9

Amplitude (front view)
–15.000 to 0.000 by 3.000

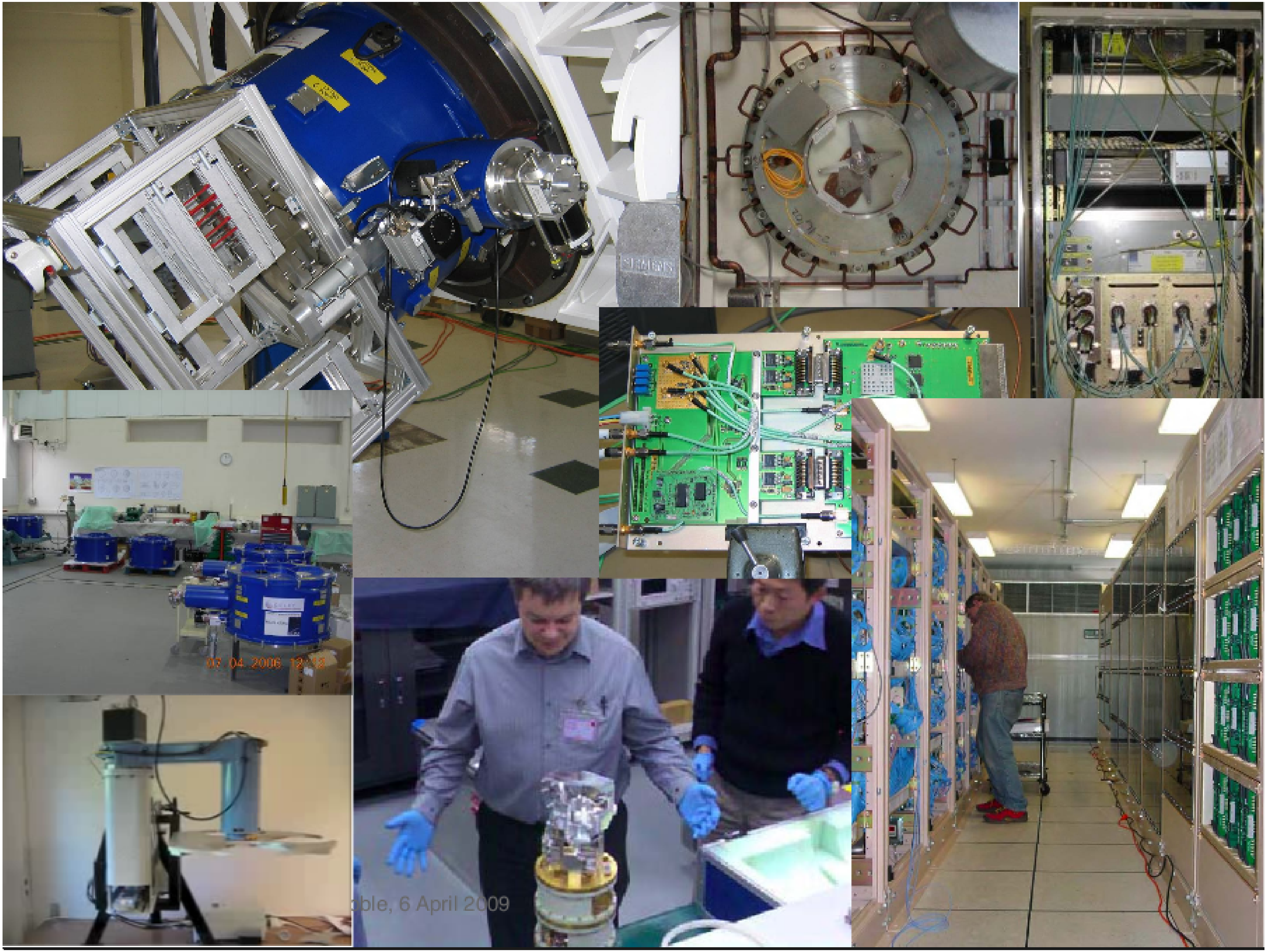
Normal errors (front view)
–125.000 to 125.000 by 50.000



The ALMA Antenna Transporter

ESO Press Photo 45b/07 (5 October 2007)


SCHEUERLE
SCHEUERLE


SIEMENS
07 04 2006 12:13

Receivers

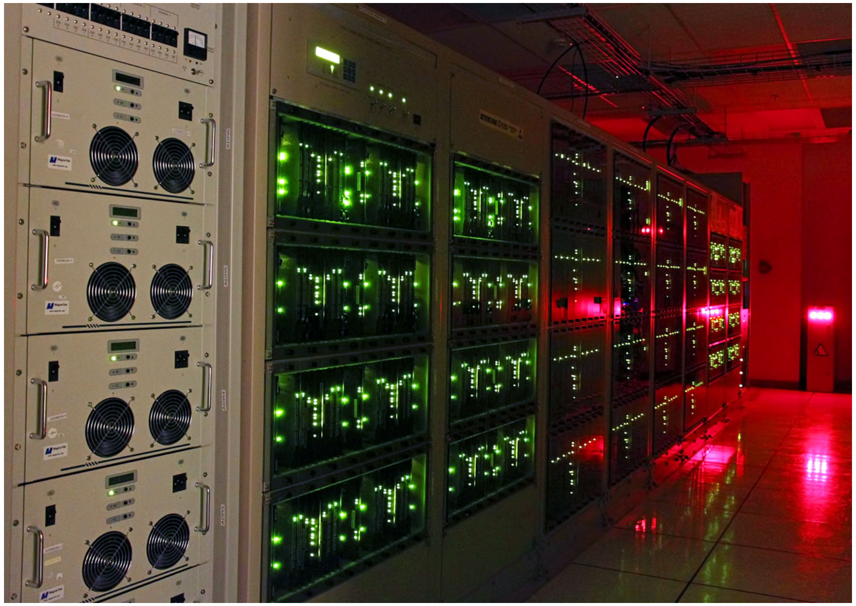
Bands 3 (84-116 GHz), 6 (211-275 GHz), 7 (275-373 GHz), and 9 (602-720 GHz) SIS “cartridges”

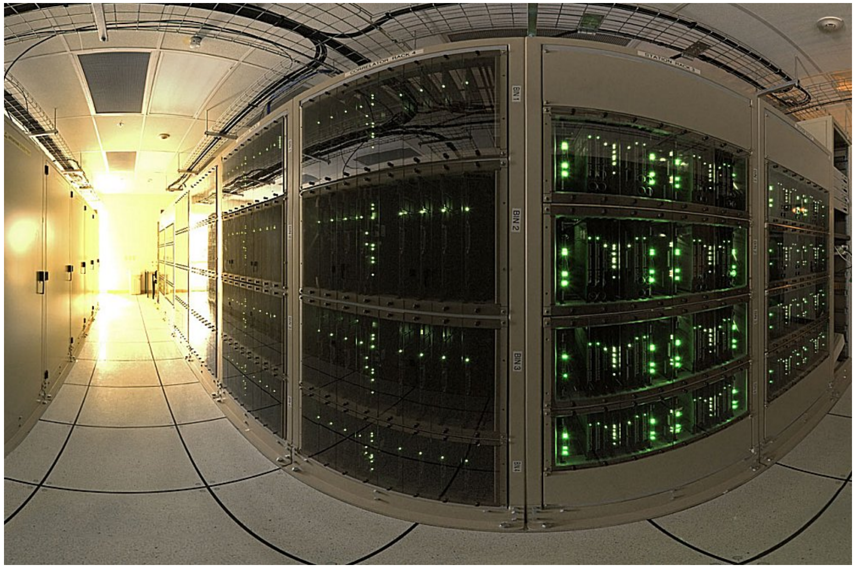
ALMA Correlator

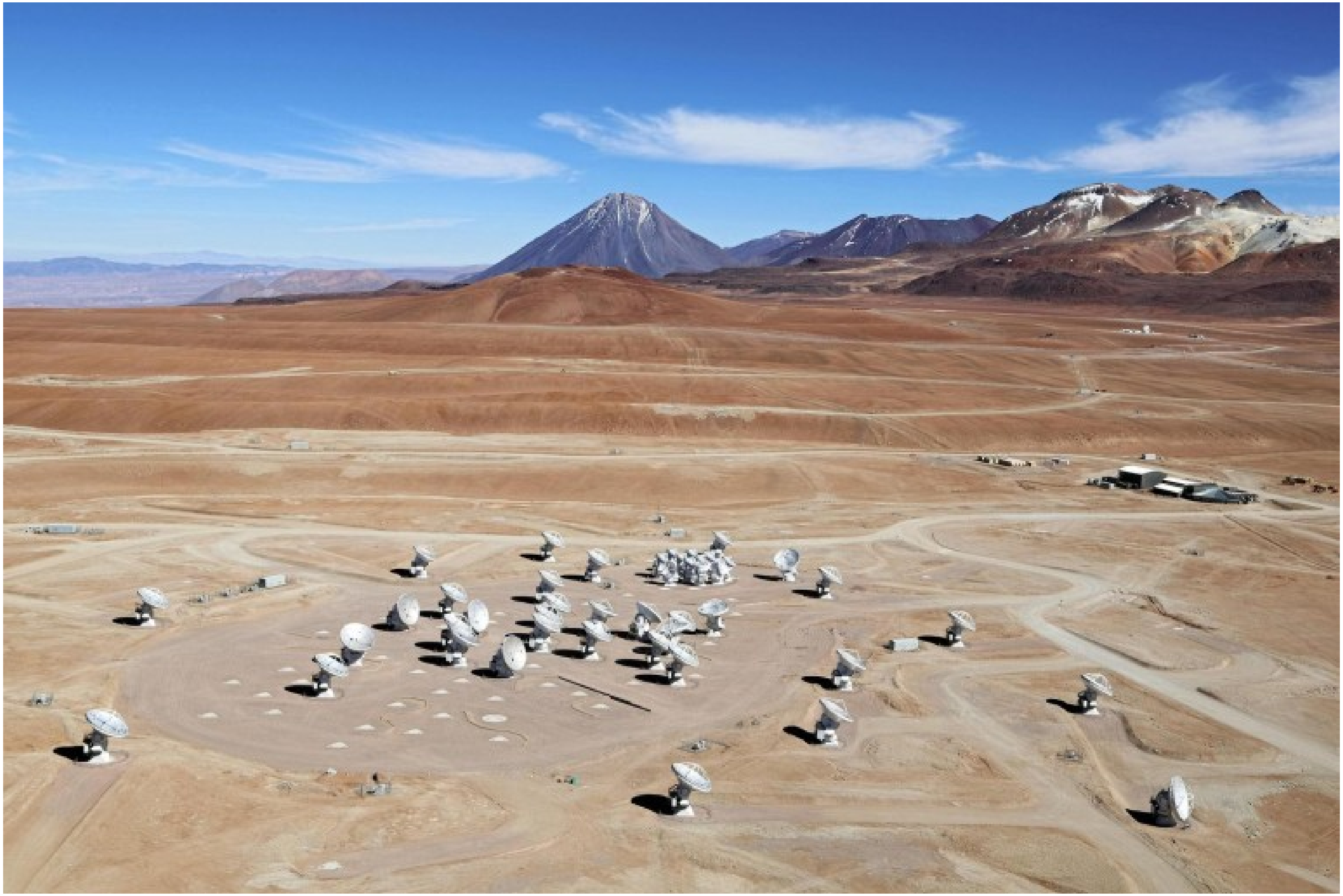
“MessageToEagle.com - One of the most powerful calculating machines known to the civilian world has been installed and tested in a remote, high-altitude site in the Andes Mountains of northern Chile - the ALMA Correlator.

(...)

It has to perform 16 quadrillion (16,000,000,000,000,000) operations per second - this is faster than the Department of Defense's best supercomputer! “







General advices for proposal writing

ALMA Cycle 2

Resources

-> ALMA Science Portal *almascience.eso.org*

- Call for Proposals
- Documents
  - Cycle 2 capabilities
  - Proposers Guide
  - Technical Handbook
- Observing Tool
- Helpdesk

-> ARC Nodes -> Nordic ARC nordic-alma.se

- Face-to-face support
- Local expertise
- General advices

Before starting (brief checklist)

Can the source(s) be observed at all ?

ALMA can see sources up to Dec~+50 deg

Is the required angular resolution achievable ?

Is the line (redshifted) in one of the offered ALMA band ?
What about the atmospheric transmission ? (atmospheric lines)

Is the source extended ? Is a mosaic required ?

ALMA 12m-array FOV = 21" x 300/ Frequency (GHz)

If the source is ~ half the FOV, it is extended

Is the required sensitivity achievable ?

Point source -> use Jansky unit $1\ \mathrm{Jy} = 10^{-26}\ \mathrm{W\ m^{-2}\ Hz^{-1}}$

Extended source -> Use brightness temperature $T_B(K)=c^2/2k\upsilon^2\, I_\upsilon$

ALMA Tools

- Observing Tool preparation and submission of proposals
- ALMA simulator in CASA
- ALMA Observation Support Tool almaost.jb.man.ac.uk
- Sensitivity Calculator (Science Portal, OT)
- Atmospheric transmission (Science Portal)
- Splatalogue Database for spectroscopy
- Archives Avoid duplication
  Data mining

Guidelines

Proposals must be written in English

Include the following sections:

- Science case
- Figures, tables, references (optional)
- A brief statement of likely potential for publicity

Format PDF < 20 MB for the whole proposal

Total length limited to 4 pages (A4 or US Letter format, font > 11pt)

Can use the ALMA proposal template .tex form

Proposals must be self-contained
Consultation of external documents should not be required for understanding the proposal

Technical justifications (to be entered directly in the OT)

Technical justifications

To be entered directly in the OT (dedicated text box, < 4000 char.)
Any associated figures must be included in the science case PDF

Should address (if relevant):

- Sensitivity (signal-to-noise ratio, dynamic range, ...)
- Imaging requirements (uv-coverage, extended sources, ...)
- Correlator setup (total bandwidth, spectral resolution, ...)
- Calibration (additional calibration request, user-defined calibration, ...)
- Bandpass accuracy (spectral response of up to 1000 at B3,4,5,6, and 500 for B7,8,9)
- Scheduling / time constraints
- Data rate (max data rate 60 MB/s, average 6 MB/s
  justification needed if data rate is > 12 MB/s)
- Special constraints on standard observing modes
  large overheads ratio, > 30%
  very short (<2 min) or lenghty (continuously >40 min) on-source observations
  Continuous observations of > 2h at best weather (best quartile) will be rejected

Exploiting the ALMA archive

Iván Martí-Vidal

Nordic Node of the European ALMA Regional Center
Onsala Space Observatory (Sweden)

October 24, 2013

Why do you want to use the archive?

- ALMA is a telescope with a high time pressure. Getting observing time is not so easy.
- There is a huge database, the ALMA Archive, with already public observations. This database is rapidly (and continuously) growing.
- Your science goal may be compatible with other science goals (or combinations of them!) related to data publicly available, e.g.
  - Continuum signal from a line-oriented SG.
  - Other lines covered in the observed bands.
  - Improvement of already-published results (refine calibration, advanced data analysis, ...).
  - Calibrator science.

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  - Other lines covered in the observed bands.
  - Improvement of already-published results (refine calibration, advanced data analysis, ...).
  - Calibrator science.
  - Unpublished data results!

The ALMA Archive

- Located at `http://almascience.eso.org/alma-data/archive`
- Data are publicly available one year after the product delivery to the PI.
- Access to the archive is free for public data and restricted for unpublic data.
- In the latter case, the archive is accessed by the PI (and/or delegated users) through the Science Portal at: `http://www.almascience.eso.org`

The ALMA Archive

- The user can provide source name/coordinates, frequency band(s), resolution, PWV, epoch range(s), project code, ...
- Each dataset is downloaded as a set of `tar` archives. Each `tar` archive can be untarred independently.
- Once all archives are untarred, the user will find a standard directory tree structure with all the data products for that EB.

The ALMA data products

We need to clarify some concepts first:

- Scheduling Block (SB): The "atomic" unit of observations (ca. 30 min). It is self-contained, in terms of calibration, and is related to a given Science Goal (SG) and Observation Unit set (OU).
- Execution Block (EB): A particular realization of an SB. One single SB can be observed many times (depending on the required RMS) and each one of these times produces a different EB.
- Observation Unit (OU) set: The set of all SBs (and/or other OUs) needed to achieve a given SG.

Notice that the results from the Archive query are based on EBs; not on SBs!

The ALMA data products

- sg_ouss_id / group_ouss_id / member_ouss_id. Will be useful when the pipeline is fully operative (already used in Cycle I).
- log. The set of log files generated by CASA during the calibration.
- product. FITS image cubes of (a selection of) frequency channels in the measurement set, ms.
- qa. Several diagnostic plots, related to the data calibration.
- script. All the scripts used for the data calibration.
- calibration. All the calibration tables (and plots).
- calibrated. The calibrated measurement set(s) of the EB(s). These are named `*.split.cal`.
- raw. The measurement set(s) after a basic a-priori calibration (antenna positions, T_{sys}, and PWV). These are named `*.split`.
- README. Some useful information.

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EUROPEAN ARC
ALMA Regional Centre || Nordic

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- log. The set of log files generated by CASA during the calibration.
- product. FITS image cubes of (a selection of) frequency channels in the measurement set, ms.
- qa. Several diagnostic plots, related to the data calibration.
- script. All the scripts used for the data calibration.
- calibration. All the calibration tables (and plots).
- calibrated. The calibrated measurement set(s) of the EB(s). These are named `*.split.cal`.
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- The content of the product directory is *limited*. A more complete (and careful!) imaging should be performed by the scientist, to extract as much information as possible from the data.
- The calibrated and raw directories will **not** be provided in the future packages. The user must download the raw data and calibrate them from scratch, using the scripts provided in the package.
- The calibration directory contains subdirectories for each EB (named `*.calibration` and `*.calibration.plots`).
  - These directories are compressed in `tar.gz` format.
  - The user must put all the tar's content into the same directory as the raw measurement set. Then, the calibration script must be run by defining the right "mysteps" variable.
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The ARC node is here to help you!

PLEASE, ASK THE **ARC NODE** FOR HELP!

We will be very happy and glad to help you, not only for proposal preparation, but also for Archive data mining, calibration optimization, advanced data analysis, etc.