

— ALMA Workshop 2018a — “ALMA-SOL-CDAW19”

TUTORIAL OF SOLAR IMAGE SYNTHESIS USING CASA

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2019/01/15 @ MTK/NAOJ

TODAY'S TOPICS

- How to obtain solar ALMA data from ALMA Archive?
- How to calibrate ALMA solar data?
- How to synthesize solar images from ALMA data?
- Advanced calibration (What is "self-calibration"?)
- To avoid the void located at the center of u-v plane...

BEFORE STARTING THE TUTORIAL

- Login to an ADC terminal front of you.
- Make your working directory under /work.
 - It is good that the directory name is your ID.
- Move your working directory.
- Executing the following command on the working directory.
 - `rsync -avz /lfs01/almasolcdaw19/tutorial/tutorial_datasets .`

ENVIRONMENTS FOR ALMA DATA REDUCTION AND IMAGE SYNTHESIS

- **Web applications**

- ALMA Archive, SnooPI (tracking the status of your projects), Helpdesk, etc.
- Recommend using the “**Firefox**” web browser because the ALMA observatory does not check the web applications on the other browsers.

- **Data reduction and image synthesis**

- CASA (Common Astronomy Software Applications)
 - Python/IPython-based application
 - OS: “Red Hat Enterprise Linux” or “macOS”
 - RedHat clones (Fedora/CentOS/Science Linux) are OK for CASA.
 - You can get the package from <https://casa.nrao.edu/> with free.
 - CASA is already installed to all ADC servers and terminals.
 - The requirement of “Disk I/O” is so serious. The data have to be located in local disks. **Never put the data on network file systems (NFS, samba, etc.).**

HOW TO OBTAIN SOLAR ALMA DATA FROM ALMA ARCHIVE?

Start "FireFox"

and

Go to "ALMA Science Portal"

<https://almascience.nao.ac.jp/>

LIST OF CYCLE4 DATASET

- Shimojo created the google spreadsheet of all ALMA solar data obtained in Cycle 4.

<https://docs.google.com/spreadsheets/d/1xVc0eSpd42hKjt5Gdv9IebfJRupdBTSbyYsYfhAkfe4/edit?usp=sharing>

- Shimojo might continue to create such a spreadsheet for future Cycles.

EXAMPLE: PROJECT 2016.1.00202.S

QUIET SUN BAND3 DATA

- Files

-rw-r--r-- 1 masumism adcusers 665 Jan 9 15:46 2016.1.00202.S.readme.txt

README file

-rw-r--r-- 1 masumism adcusers 77M Jan 9 15:47 2016.1.00202.S_uid___A001_X8a5_X3e_001_of_001.tar

The meta data of the interferometric observation

-rw-r--r-- 1 masumism adcusers 9.4G Jan 9 15:47 2016.1.00202.S_uid___A002_Xbfb22d_X56f4.asdm.sdm.tar

The raw data of the interferometric observation

-rw-r--r-- 1 masumism adcusers 274M Jan 9 15:47 2016.1.00202.S_uid___A002_Xbfb22d_X58cf.asdm.sdm.tar

The raw data of the single-dish observation

- After "untar"ing the meta and raw data of the interferometric observation.

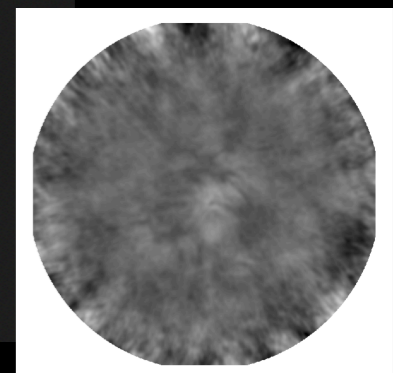
```
2016.1.00202.S
|-- science_goal.uid___A001_X8a5_X3c
|-- group.uid___A001_X8a5_X3d
|-- member.uid___A001_X8a5_X3e
|   |-- README
|   |-- calibration
|   |   |-- uid___A002_Xbfb22d_X56f4.calibration.plots
|   |   |-- uid___A002_Xbfb22d_X56f4.calibration.tgz
|   |-- log
|   |   |-- Imaging.log.tgz
|   |   |-- Solar_uid___A001_X8a5_X3e.log.tgz
|   |   |-- uid___A002_Xbfb22d_X56f4.log.tgz
|   |-- product
|   |   |-- uid___A002_Xbfb22d_X56f4.ms.split.cal.Sun_sci.spw5-7-9-11_100GHz.sf.12m7m.2D.cont.flux.fits.gz
|   |   |-- uid___A002_Xbfb22d_X56f4.ms.split.cal.Sun_sci.spw5-7-9-11_100GHz.sf.12m7m.2D.cont.mask.tgz
|   |   |-- uid___A002_Xbfb22d_X56f4.ms.split.cal.Sun_sci.spw5-7-9-11_100GHz.sf.12m7m.2D.cont.pbcor.fits
|   |-- qa
|   |   |-- uid___A002_Xbfb22d_X56f4__qa2_part1.png
|   |   |-- uid___A002_Xbfb22d_X56f4__qa2_part2.png
|   |   |-- uid___A002_Xbfb22d_X56f4__qa2_part3.png
|   |   |-- uid___A002_Xbfb22d_X56f4__textfile.txt
|   |-- raw
|   |   |-- uid___A002_Xbfb22d_X56f4.asdm.sdm
|   |-- script
|   |   |-- scriptForImaging.py
|   |   |-- scriptForPI.py
|   |   |-- sun_reduction_util.py
|   |   |-- uid___A002_Xbfb22d_X56f4.ms.scriptForCalibration.py
```

Image created by ARC staff

Information obtained at cal. in ARC

Raw data

Script of the calibration



HOW TO CALIBRATE ALMA SOLAR DATA?

WHAT IS THE CALIBRATION OF
VISIBILITY DATA?

電波干渉計とは？

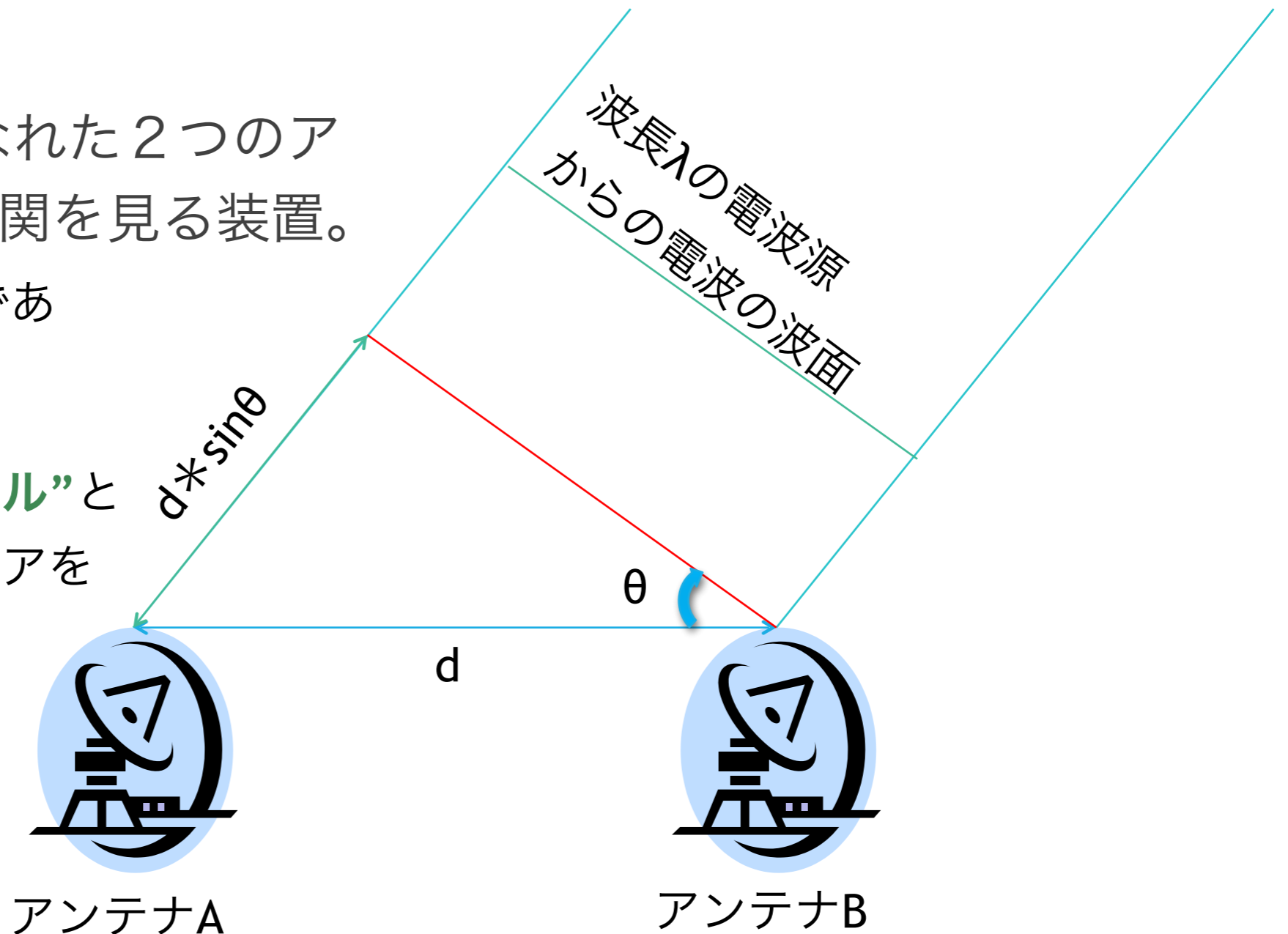


ある距離 d [基線長]はなれた2つのアンテナの出力変動の相関を見る装置。

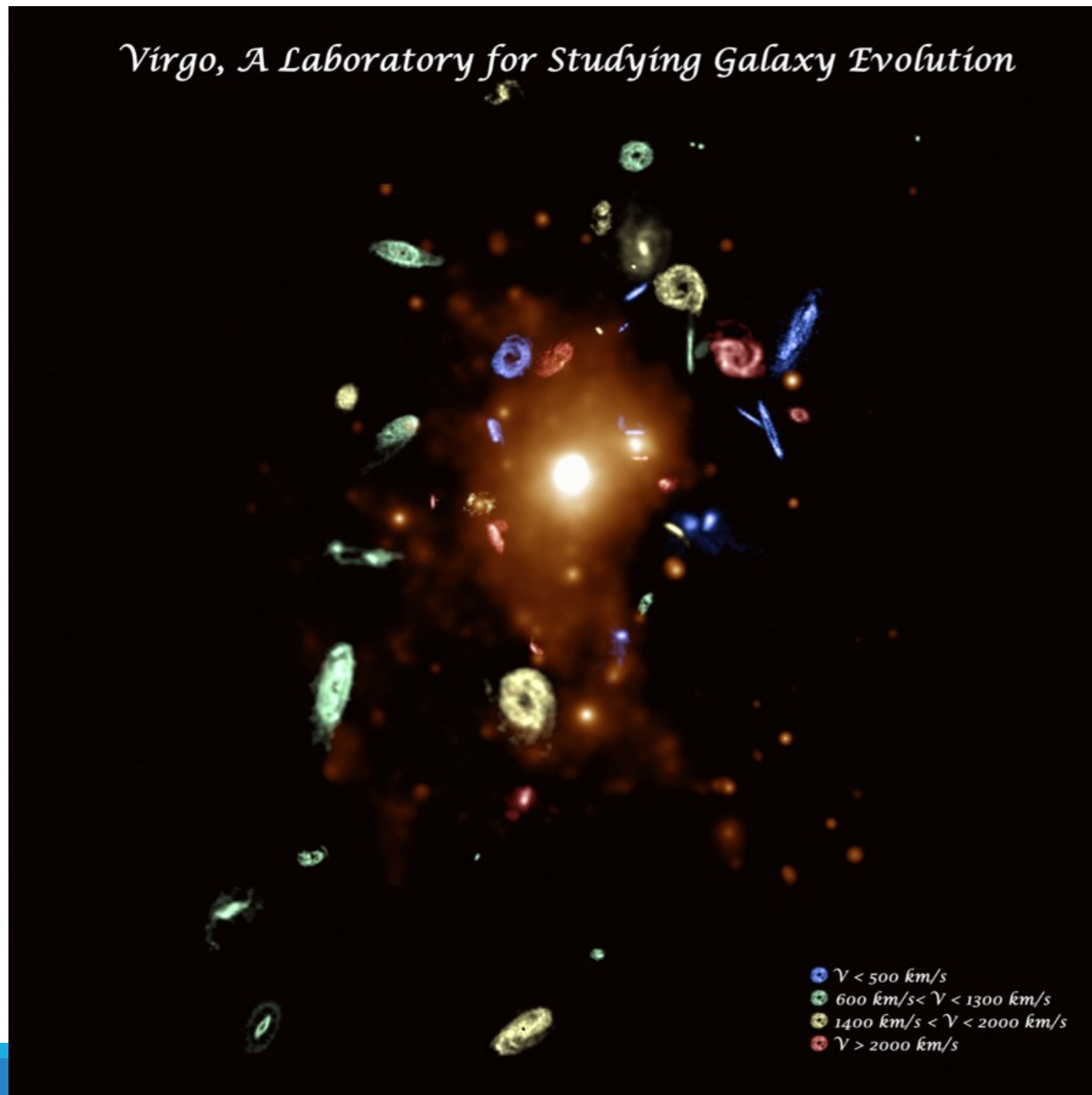
$d \cdot \sin\theta$ が波長 λ の整数倍であれば、干渉が発生。

d のベクトルを“**基線ベクトル**”と言い、2つのアンテナのペアを“**基線(Baseline)**”という。

d の長さは“**基線長**”

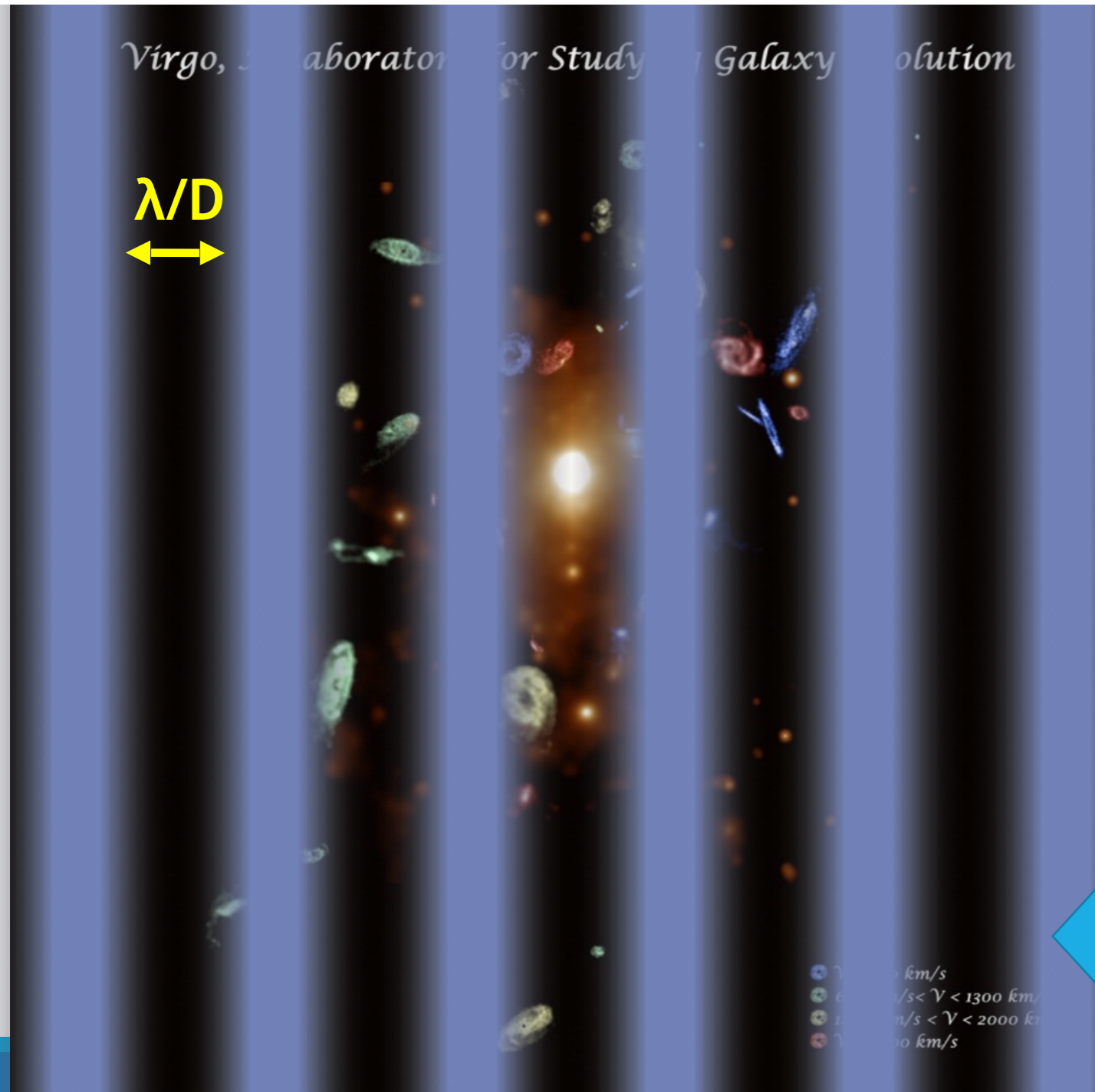


一つの基線で空を見ると？

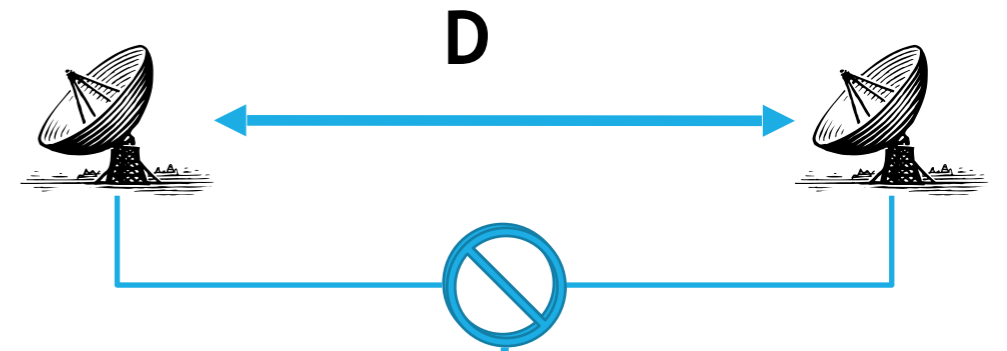


※厳密にはDは天体から見た射影長

一つの基線で空を見ると？



※厳密にはDは天体から見た射影長

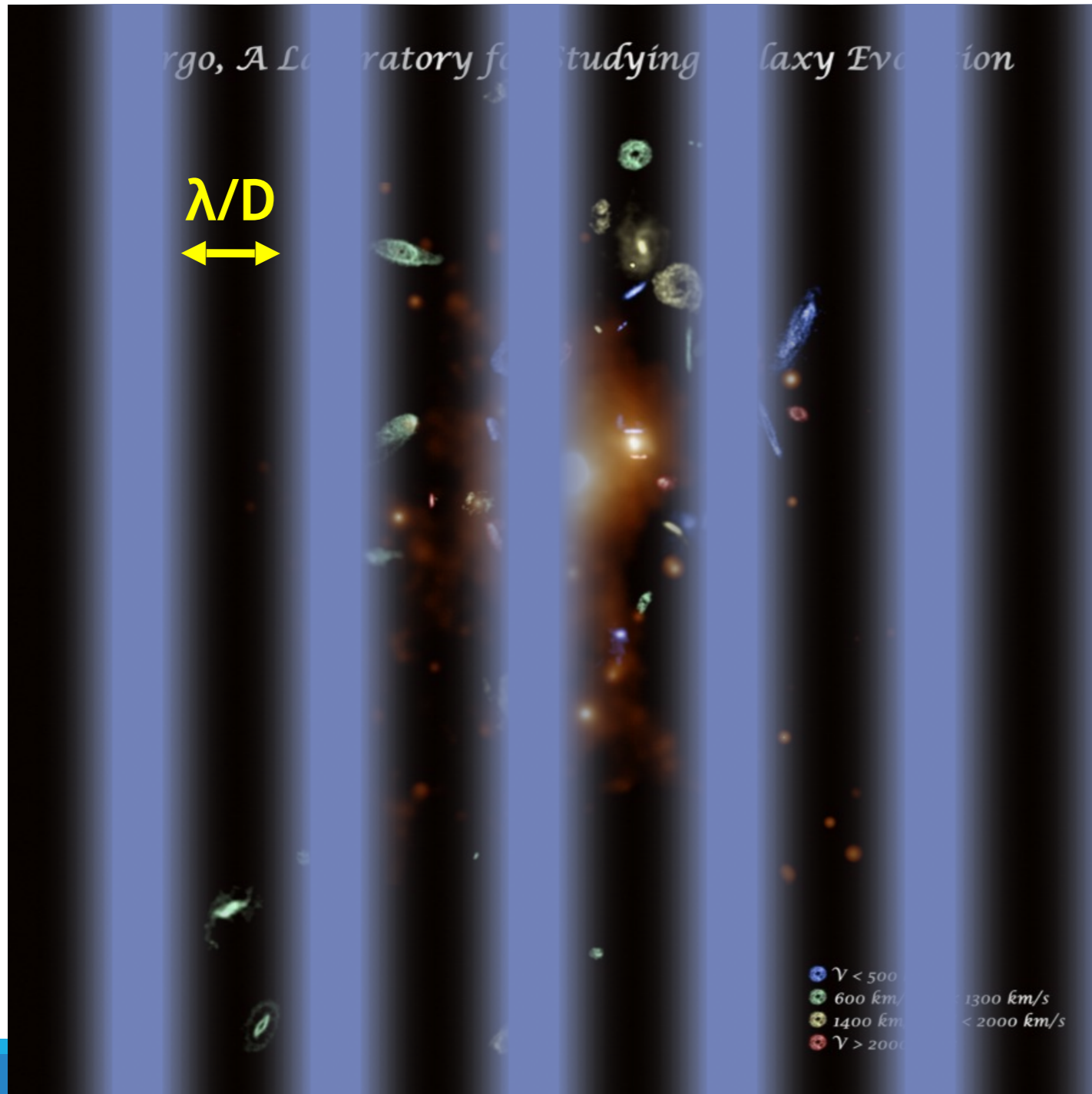


左のような縞々のフィルター
(cos関数フィルター)
を通した強度のようなもの

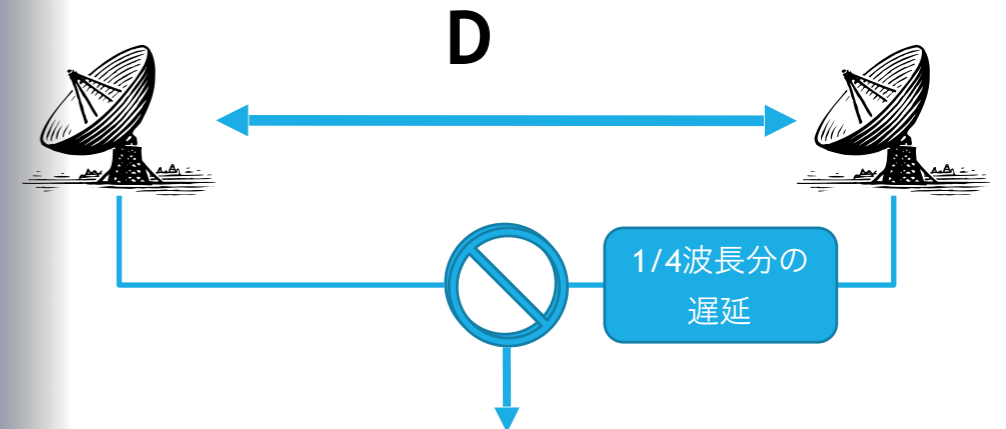
a_n

← 感度がない領域

一つの基線で空を見ると？



※厳密にはDは天体から見た射影長



左のような縞々のフィルター
(sin関数フィルター)
を通した強度のようなもの
 b_n

一つの基線で得られる情報 = 天空の輝度分布のフーリエ係数

$$f(x) = a_0 + \sum_{n=1}^{\infty} \left(a_n \cos \frac{D2\pi x}{\lambda} + b_n \sin \frac{D2\pi x}{\lambda} \right)$$

↓ ↓
干渉計はこの値を求める装置

観測されたフーリエ係数を**”Visibility”**と呼んでいる。

複素フーリエ級数にすると $f(x) = \sum_{n=-\infty}^{\infty} c_n e^{i\frac{2\pi D}{\lambda}x}$

は複素数なのでオイラー表記をすると、 $C_n = r e^{i\varphi}$

r を**”amplitude”**, φ を**”phase”**と呼んでいる

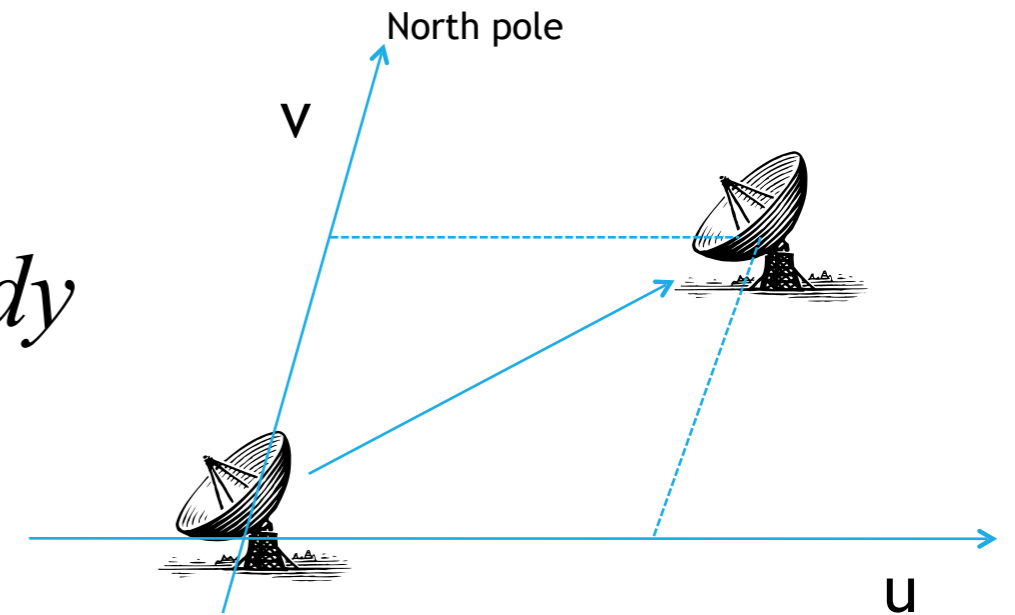
ALMAの生データ = 各基線での *amplitude* と *phase*

Visibility

干渉計の観測量Visibility

$$V(u, v) = \iint I(x, y) \exp(i(ux + vy)) dx dy$$

- u, v は投影基線長を波長で規格化 ()
 - 別名：空間周波数



※厳密には天体から見て常に同一平面にアンテナ群が存在しているわけではないので、空間周波数を表現するにはuv面に直交する軸wが必要になる。しかし、wの影響は微々たるものなので、無視をしても実際の観測にはほとんど影響しない

実際の観測では有限の (u, v) データ点(=有限の基線長=有限のアンテナ)で、Visibilityをサンプリングする

$$\Rightarrow V_{\text{obs}}(u, v) = \underline{S(u, v)} V(u, v)$$

Visibilityのサンプリング関数 → アンテナの数とその配置に依存

なぜ“Calibration”が必要か？

観測量Visibility $V(u, v) = \iint I(x, y) \exp(i(ux + vy)) dx dy$

理想的には、

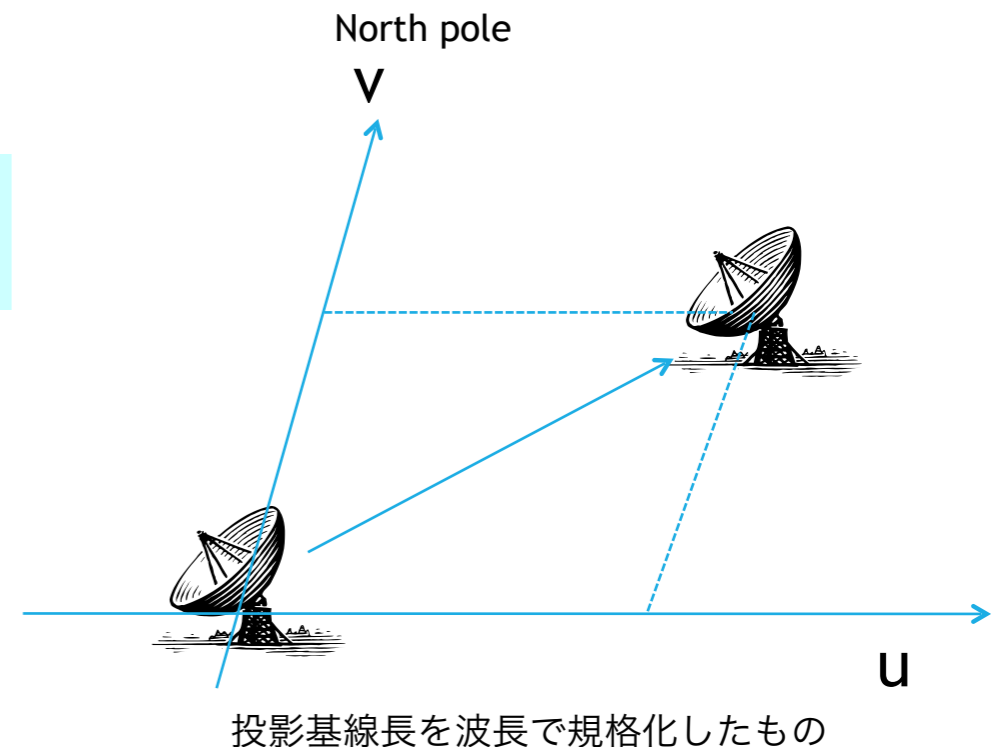
$$V_{obs} = V_{real}$$

実際には、

$$V_{obs} \neq V_{real}, \quad V_{obs} = GV_{real}$$

- 大気・装置起因で“G”(ゲイン)が加わる
- Gは複素量（振幅と位相）

Gを解く作業が“Calibration”



Gの主要なファクター

大気の影響、特に水蒸気

- 水蒸気による吸収：電波強度が変化
- 水蒸気量の変化：電波の位相が変化

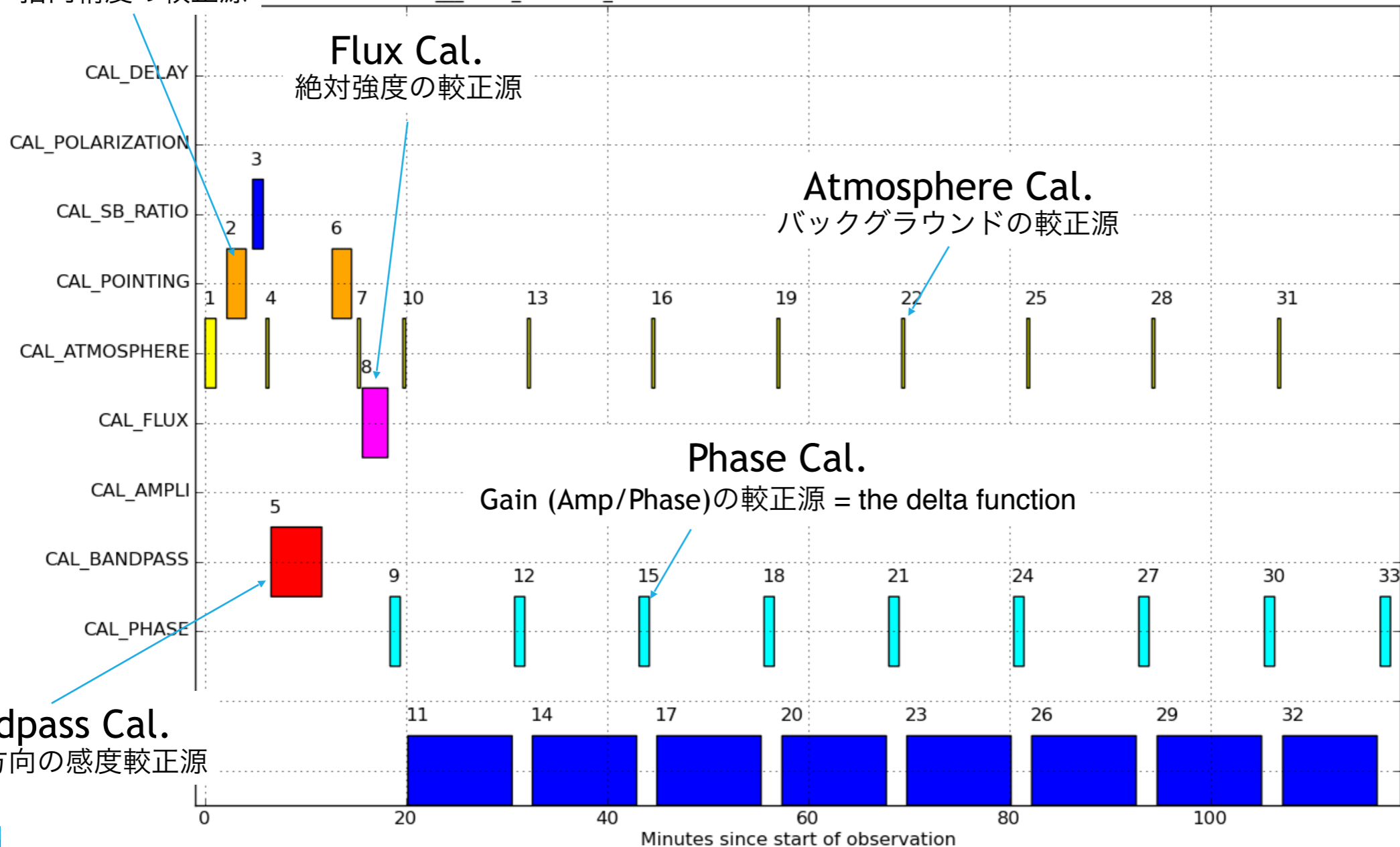
装置の影響

- 装置のimperfectness/stability：強度・位相が変化（e.g., アンテナの熱変形・重力変形）
- 基線長測定エラーによる位相変動
- 受信帯域全体の応答は必ずしもフラットではない：帯域特性を生む
- etc

実際の観測シーケンス

Pointing Cal.

指向精度の校正源 measurement set = uid__A002_Xbbadbe_X5c89.ms - Start time = 2016-12-13T13:25:50 - End time = 2016-12-13T15:23:41



HOW TO DO THE CALIBRATION?

1. Move to the "script" directory that is located under the "untar" directory.

2. Start CASA

- [Caution] The usable version of CASA for calibrating the dataset obtained in each Cycle is determined!
- Cycle 4: CASA 4.7.2
 - [command on MDAS] /usr/local/casa/casa-release-4.7.2-el7/bin/casa
- Cycle 5: CASA 5.1.0
 - [command on MDAS] /usr/local/casa/casa-release-5.1.0-el7/bin/casa
- Current version CASA 5.4.0
 - [command on MDAS] casa
 - [To synthesize images, we use the current one \(5.4.0\) in this workshop.](#)

3. Execute the calibration script

- CASA <2>: `execfile('scriptForPI.py')`

4. Wait one night. (In case of MDAS)

EXAMPLE: PROJECT 2016.1.00202.S QUIET SUN BAND3 DATA

- Files

-rw-r--r-- 1 masumism adcusers 665 Jan 9 15:46 2016.1.00202.S.readme.txt

README file

-rw-r--r-- 1 masumism adcusers 77M Jan 9 15:47 2016.1.00202.S_uid___A001_X8a5_X3e_001_of_001.tar

The meta data of the interferometric observation

-rw-r--r-- 1 masumism adcusers 9.4G Jan 9 15:47 2016.1.00202.S_uid___A002_Xbfb22d_X56f4.asdm.sdm.tar

The raw data of the interferometric observation

-rw-r--r-- 1 masumism adcusers 274M Jan 9 15:47 2016.1.00202.S_uid___A002_Xbfb22d_X58cf.asdm.sdm.tar

The raw data of the single-dish observation

- After "untar"ing the meta and raw data of the interferometric observation.

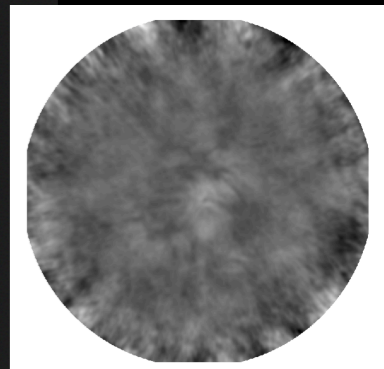
```
2016.1.00202.S
|-- science_goal.uid___A001_X8a5_X3c
|-- group.uid___A001_X8a5_X3d
|-- member.uid___A001_X8a5_X3e
|   |-- README
|   |-- calibration
|   |   |-- uid___A002_Xbfb22d_X56f4.calibration.plots
|   |   |-- uid___A002_Xbfb22d_X56f4.calibration.tgz
|   |-- log
|   |   |-- Imaging.log.tgz
|   |   |-- Solar_uid___A001_X8a5_X3e.log.tgz
|   |   |-- uid___A002_Xbfb22d_X56f4.log.tgz
|   |-- product
|   |   |-- uid___A002_Xbfb22d_X56f4.ms.split.cal.Sun_sci.spw5-7-9-11_100GHz.sf.12m7m.2D.cont.flux.fits.gz
|   |   |-- uid___A002_Xbfb22d_X56f4.ms.split.cal.Sun_sci.spw5-7-9-11_100GHz.sf.12m7m.2D.cont.mask.tgz
|   |   |-- uid___A002_Xbfb22d_X56f4.ms.split.cal.Sun_sci.spw5-7-9-11_100GHz.sf.12m7m.2D.cont.pbcor.fits
|   |-- qa
|   |   |-- uid___A002_Xbfb22d_X56f4__qa2_part1.png
|   |   |-- uid___A002_Xbfb22d_X56f4__qa2_part2.png
|   |   |-- uid___A002_Xbfb22d_X56f4__qa2_part3.png
|   |   |-- uid___A002_Xbfb22d_X56f4__textfile.txt
|   |-- raw
|   |   |-- uid___A002_Xbfb22d_X56f4.asdm.sdm
|   |-- script
|   |   |-- scriptForImaging.py
|   |   |-- scriptForPI.py
|   |   |-- sun_reduction_util.py
|   |   |-- uid___A002_Xbfb22d_X56f4.ms.scriptForCalibration.py
```

← "An" Image created by ARC staff

← Information obtained at cal. in ARC

← Raw data

← Script of the calibration



AFTER ONE NIGHT

```
2016.1.00202.S
|-- science_goal.uid___A001_X8a5_X3c
  |-- group.uid___A001_X8a5_X3d
    |-- member.uid___A001_X8a5_X3e
      |-- README
      |-- calibrated
      |   |-- uid___A002_Xbfb22d_X56f4.calibration
      |   |-- uid___A002_Xbfb22d_X56f4.ms.split.cal
      |-- calibration
      |   |-- uid___A002_Xbfb22d_X56f4.calibration.plots
      |   |-- uid___A002_Xbfb22d_X56f4.calibration.tgz
      |-- log
      |   |-- Imaging.log.tgz
      |   |-- Solar_uid___A001_X8a5_X3e.log.tgz
      |   |-- uid___A002_Xbfb22d_X56f4.log.tgz
      |-- product
      |   |-- uid___A002_Xbfb22d_X56f4.ms.split.cal.Sun_sci.spw5-7-9-11_100GHz.sf.12m7m.2D.cont.flux.fits.gz
      |   |-- uid___A002_Xbfb22d_X56f4.ms.split.cal.Sun_sci.spw5-7-9-11_100GHz.sf.12m7m.2D.cont.mask.tgz
      |   |-- uid___A002_Xbfb22d_X56f4.ms.split.cal.Sun_sci.spw5-7-9-11_100GHz.sf.12m7m.2D.cont.pbcor.fits
      |-- qa
      |   |-- uid___A002_Xbfb22d_X56f4__qa2_part1.png
      |   |-- uid___A002_Xbfb22d_X56f4__qa2_part2.png
      |   |-- uid___A002_Xbfb22d_X56f4__qa2_part3.png
      |   |-- uid___A002_Xbfb22d_X56f4__textfile.txt
      |-- raw
      |   |-- uid___A002_Xbfb22d_X56f4.asdm.sdm
      |-- script
      |   |-- scriptForImaging.py
      |   |-- scriptForPI.py
      |   |-- sun_reduction_util.py
      |   |-- uid___A002_Xbfb22d_X56f4.ms.scriptForCalibration.py
```

Created directory by "scripyForPI.py"

← **Calibrated data**

HOW TO SYNTHESIZE SOLAR
IMAGES FROM ALMA DATA?

IMAGE SYNTHESIS

- At first, Inverse Fourier Transfer
 - $V_{\text{obs}}(u,v) = S(u,v)V(u,v)$
 - $S(u,v)$: Sampling function depended on the location and number of antennas...
 - The quality of images created only by Inverse Fourier Transfer is not good.
 - Deconvolution
 - CLEAN \Rightarrow [Kameno-sensei Lecture Note.](#) @ Kagoshima-U.
 - MEM
 - Sparse Modeling
 - etc...

RSYNC PROCESS FINISHED?

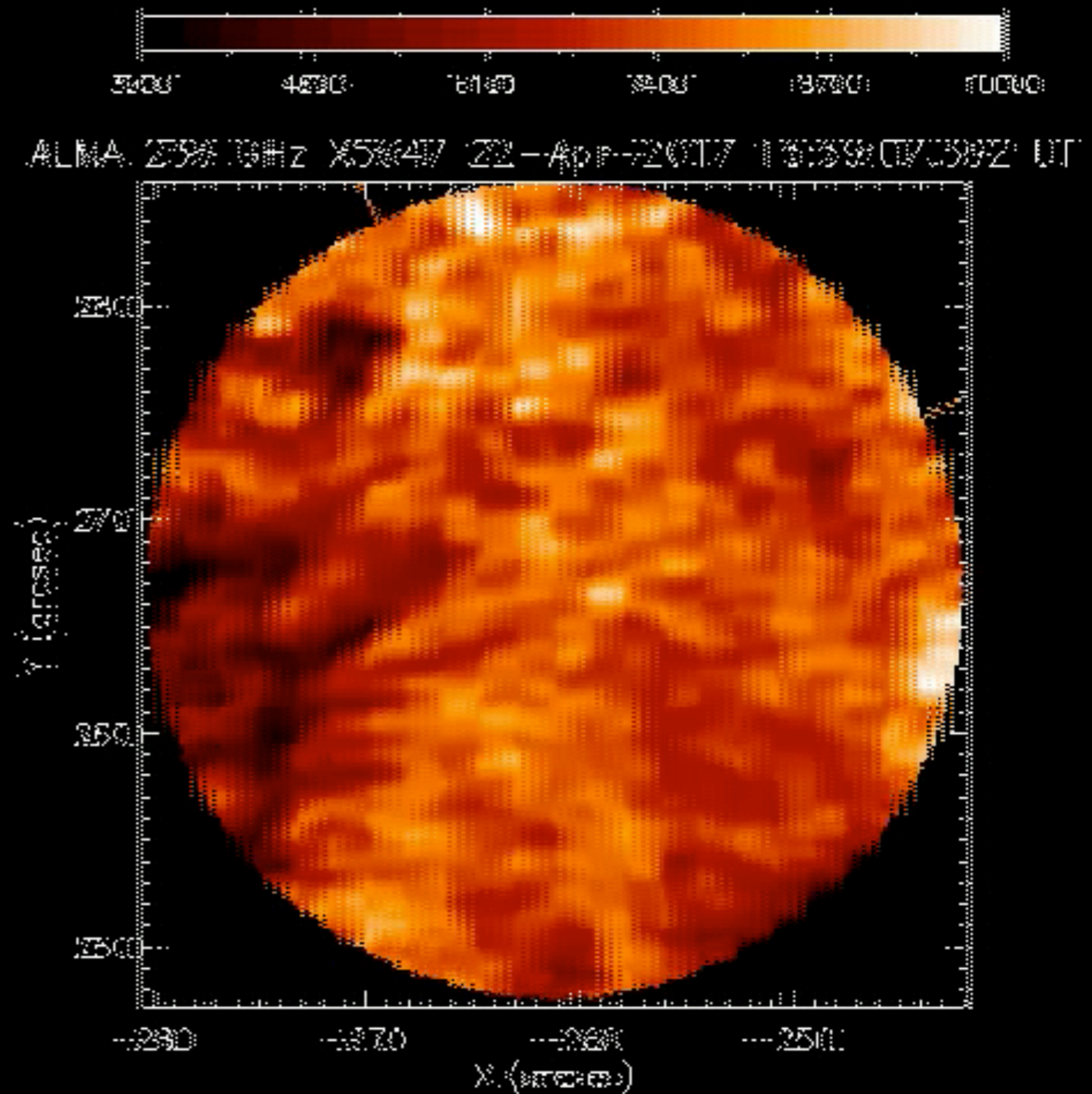
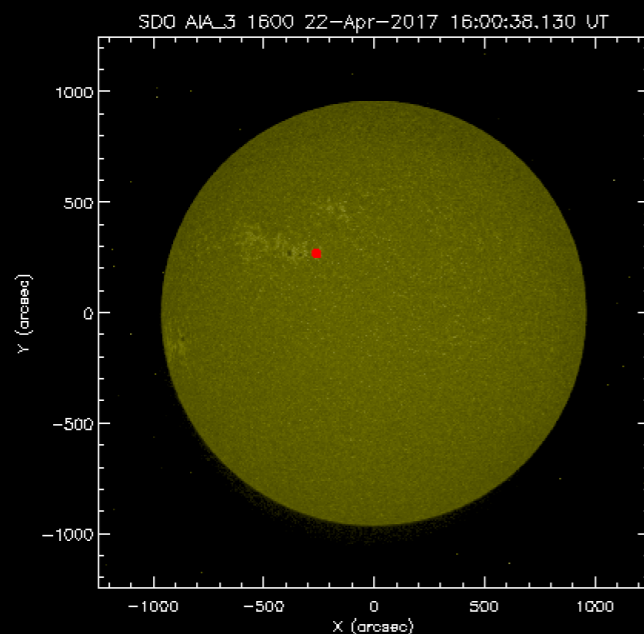
- Let's try the image synthesis using CASA

```
tutorial_datasets/  
|-- TP  
|-- X5647_11_normcal.ms  
|-- X5647_F  
|-- X5647_scriptForSelfCal_Mov_moduse.py  
|-- feather_pro.py  
|-- qa  
`-- scriptForImaging.py
```

PLAGE WITH BAND6

- Project ID: 2016.1.00050.S
- PI: Bart De Pontieu
- Single-Pointing
- Observing Period:
2017-04-22 15:58:58 - 16:43:34
- Size of the synthesized beam
 - Major: 0.91 arcsec
 - Minor: 0.72 arcsec
- Time cadence: ~2 seconds

IDL 0



RESULT OF IMAGE SYNTHESIS

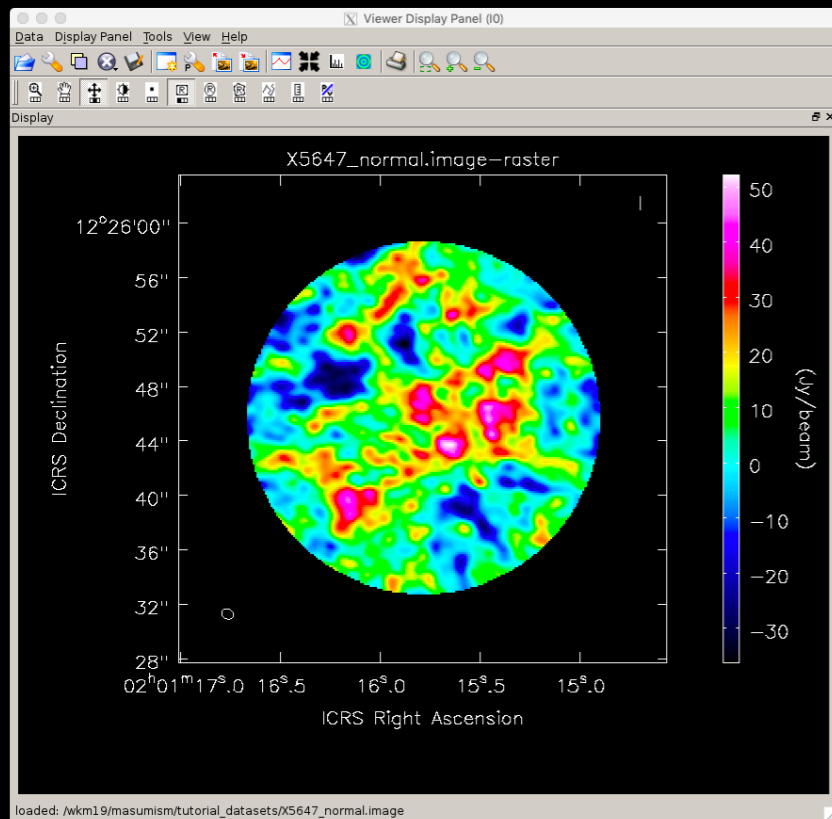
Depending on the operation being run, a subset of the following output images will be written to disk.

imagename = 'try'

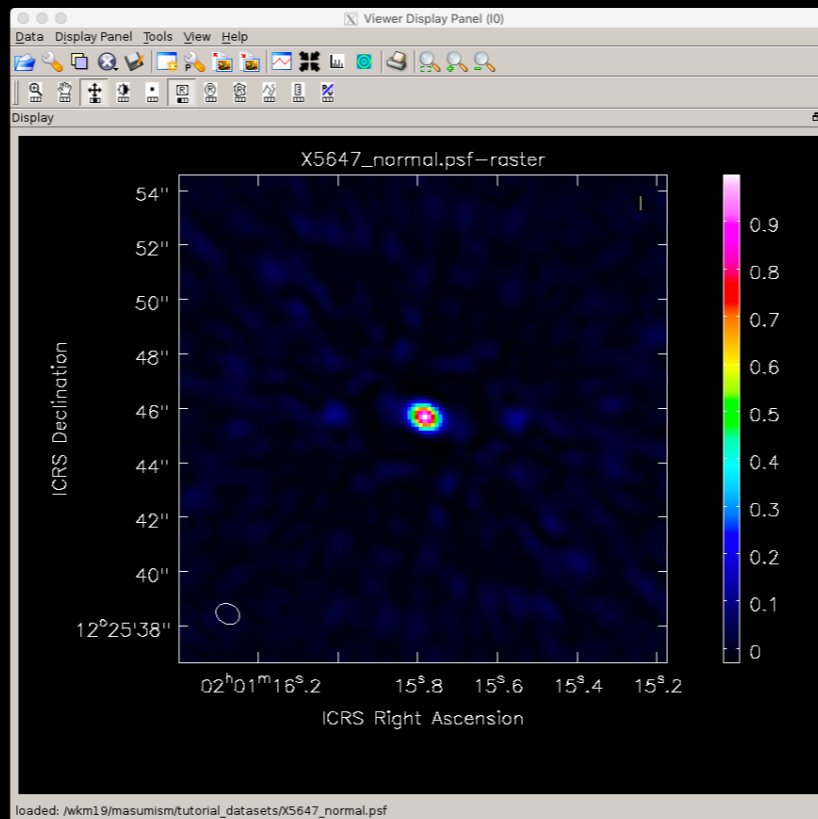
try.psf	Point Spread Function
try.pb	Primary Beam
try.residual	Residual Image (or initial Dirty Image)
try.model	Model Image after deconvolution
try.image	Restored output image
try.image.pbcor	Primary Beam corrected image
try.mask	Deconvolution mask
try.sumwt	A single pixel image containing sum of weights per plane
try.weight	Image of un-normalized sum of PB-square (for mosaics and A-Projection)

- Viewer command of CASA is "viewer"
- casa<?> : viewer

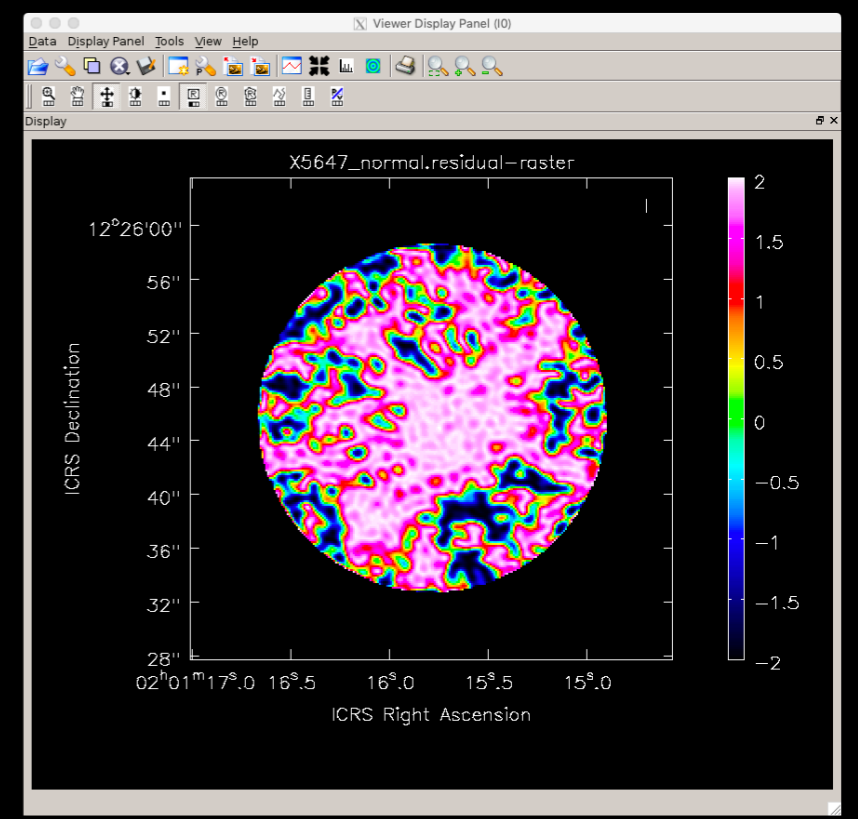
*.image (image)



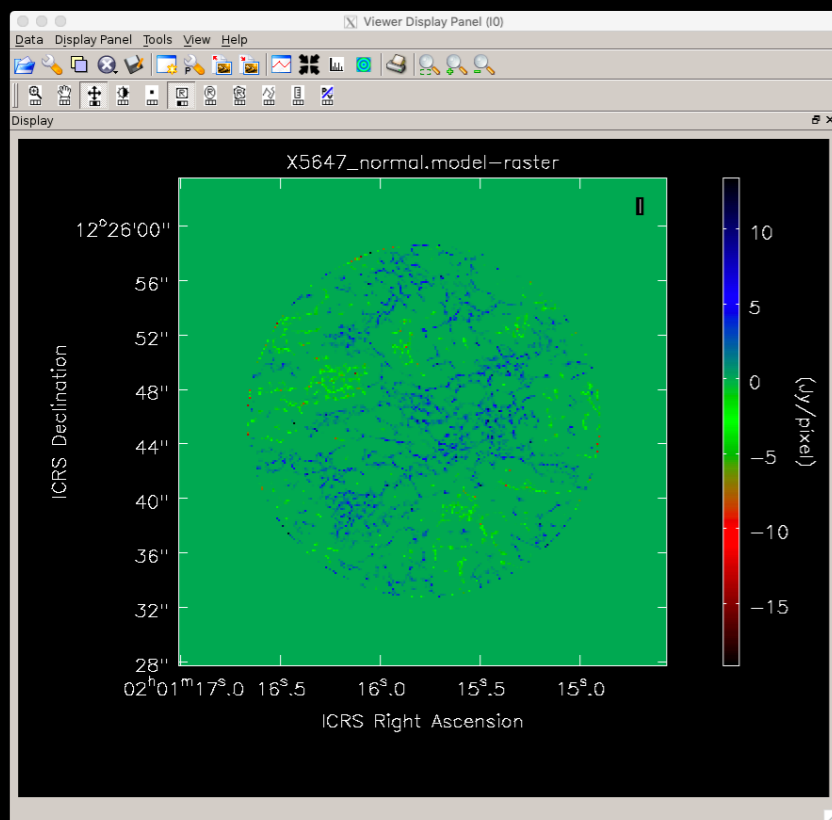
*.psf (Synth.Beam)



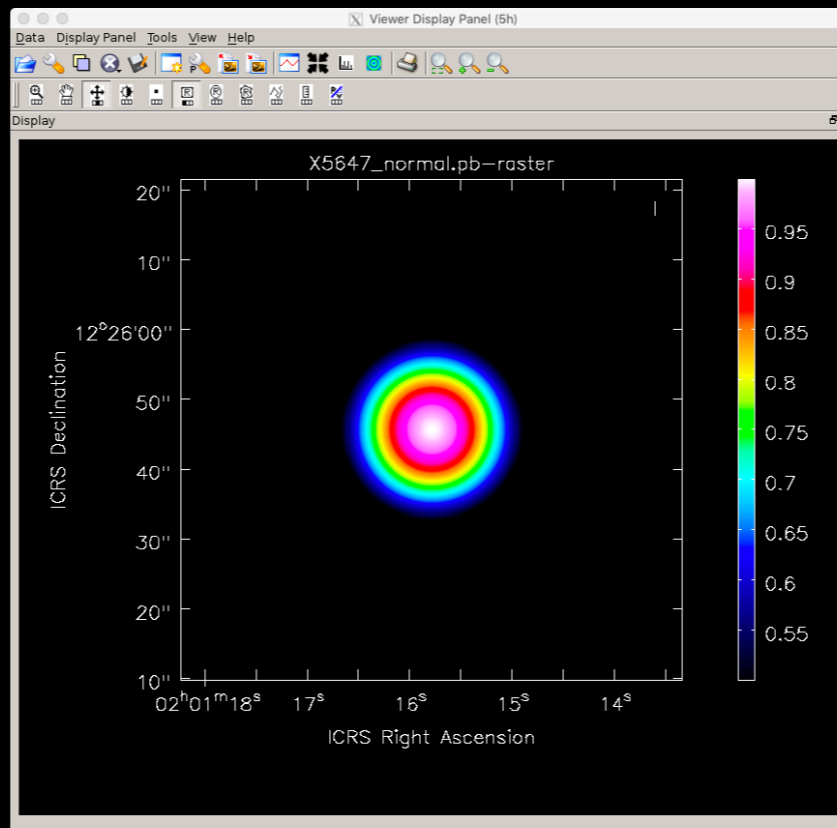
*.residual (Residual)



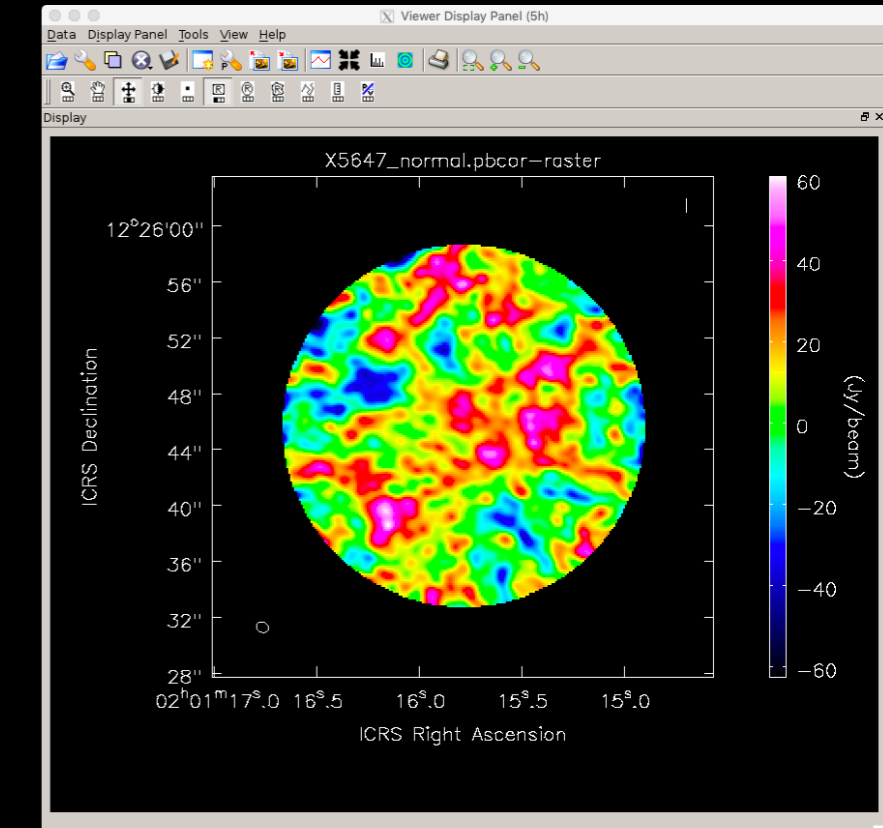
*.model (CLEAN components)



*.pb (Primary Beam)

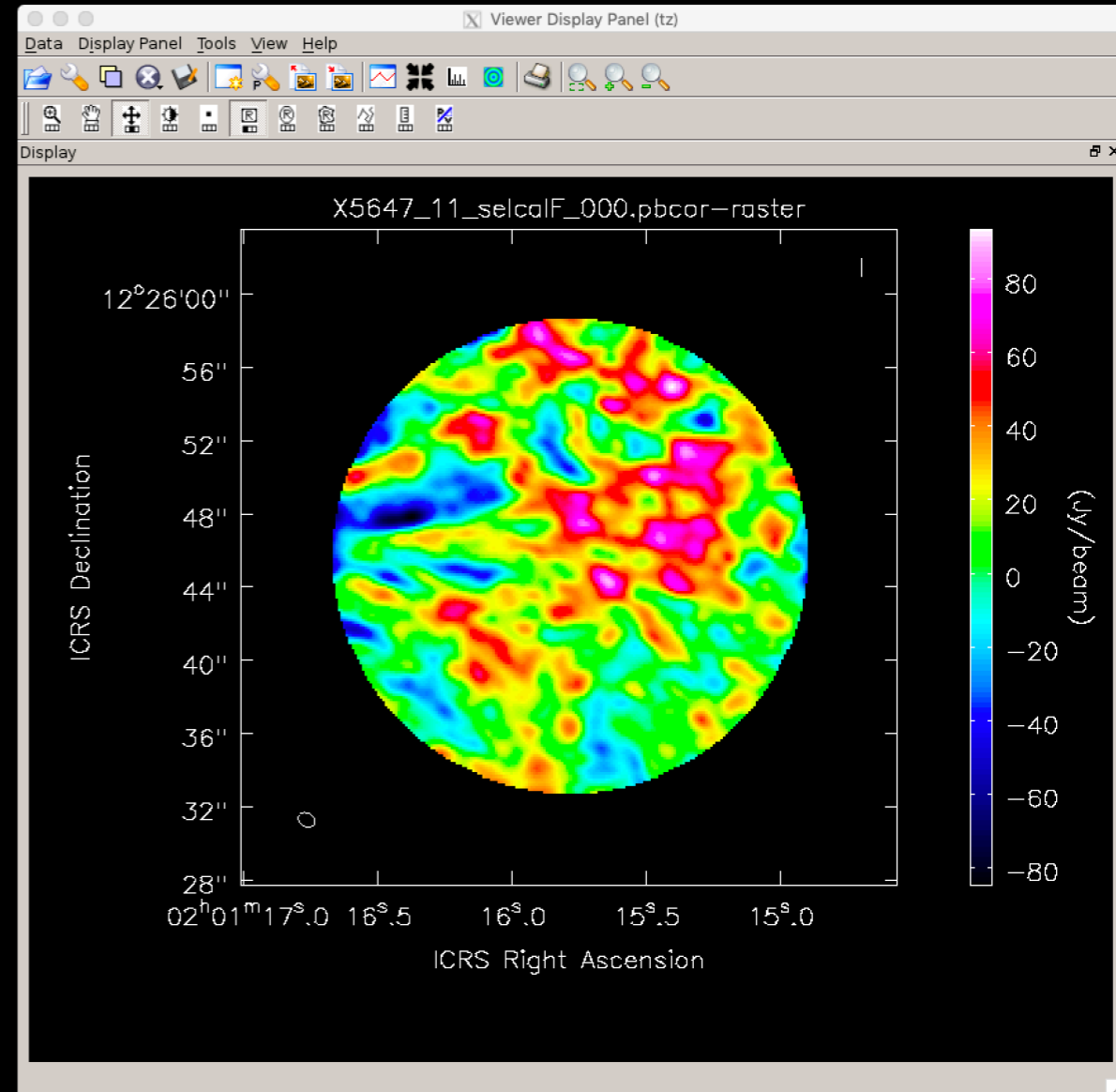
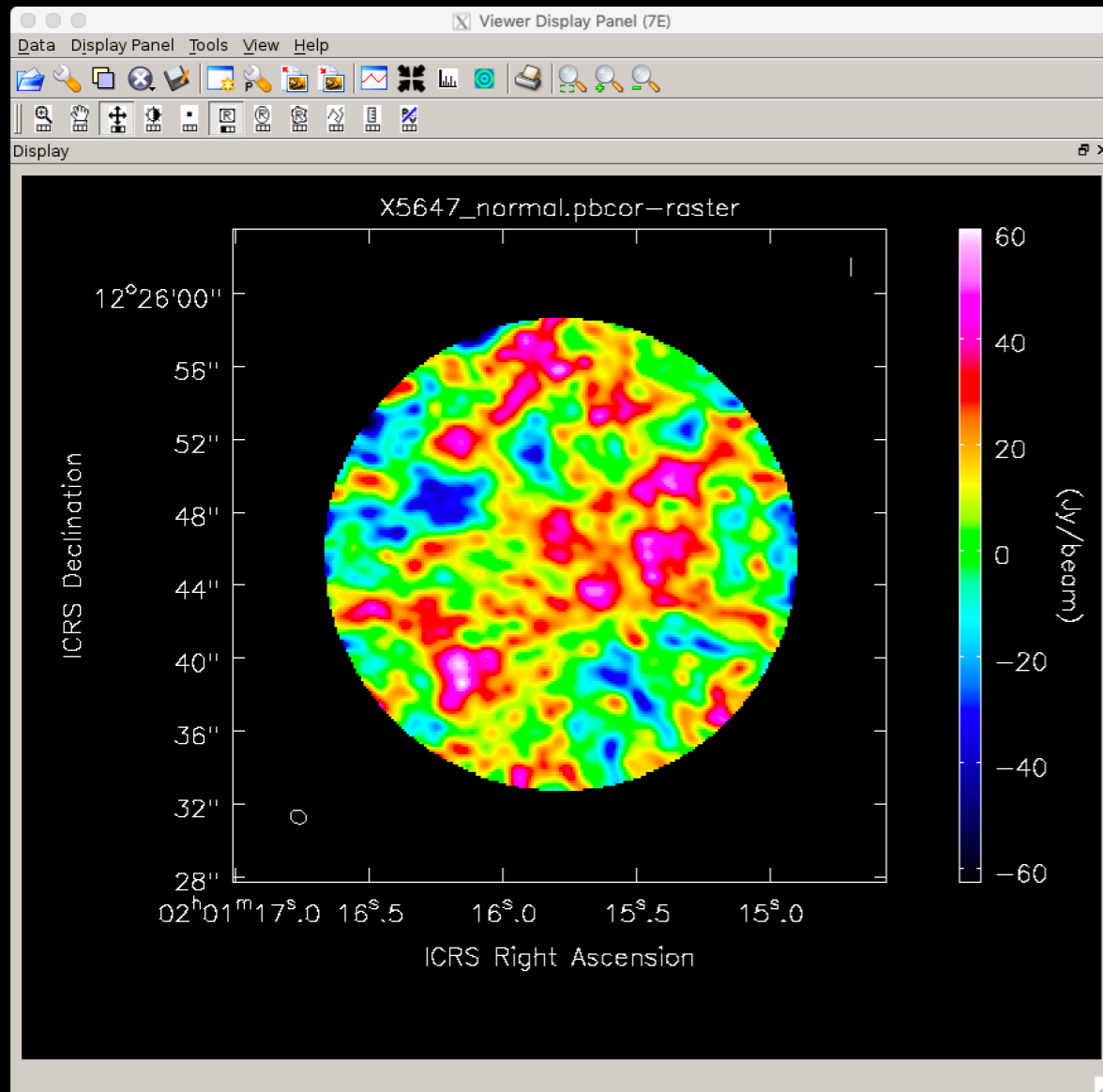


*.pbcor (PB corrected img.)



WAHT'S HAPPEN?

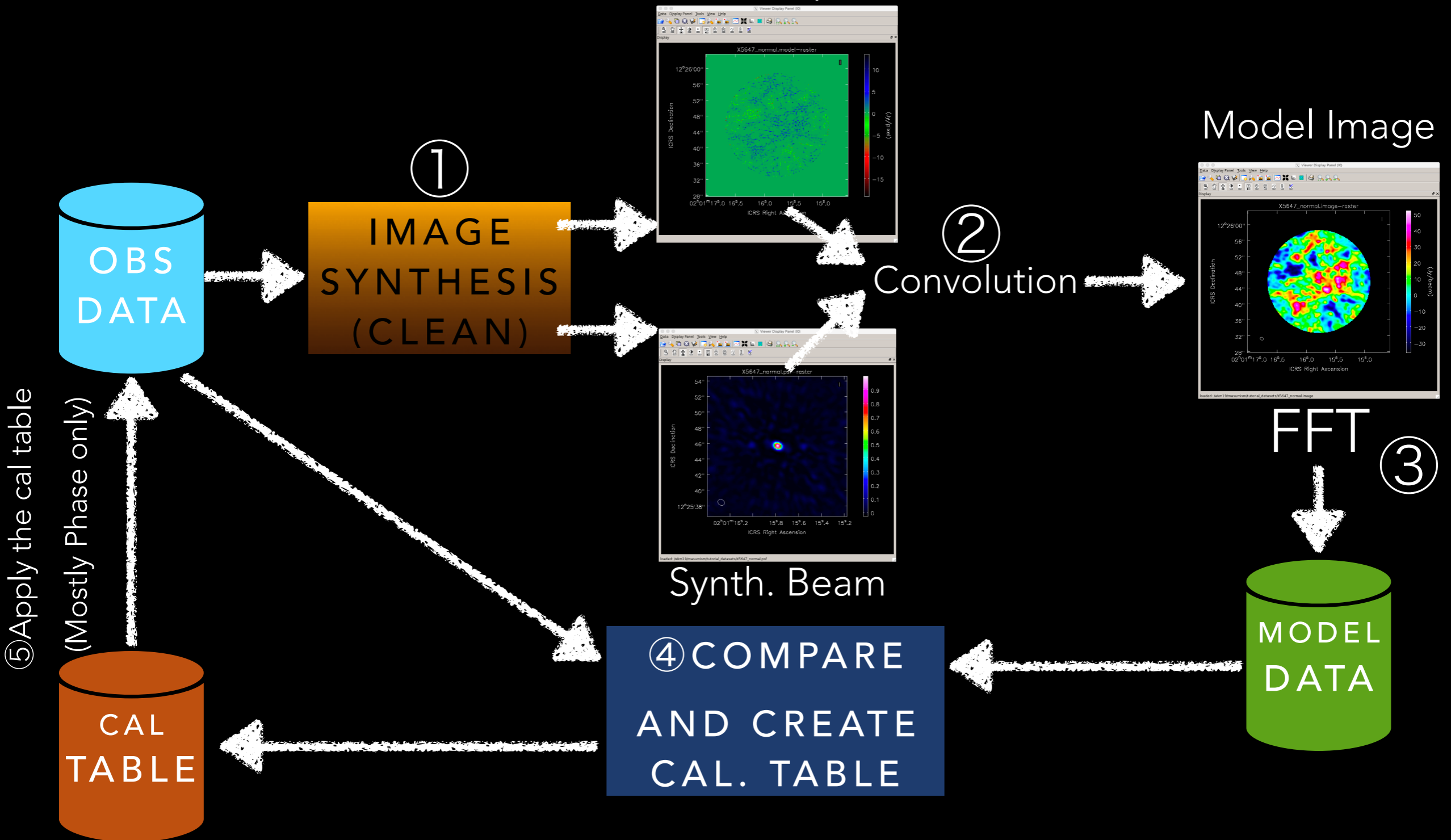
➡ MULTI-STEPS SELF-CALIBRATION!!



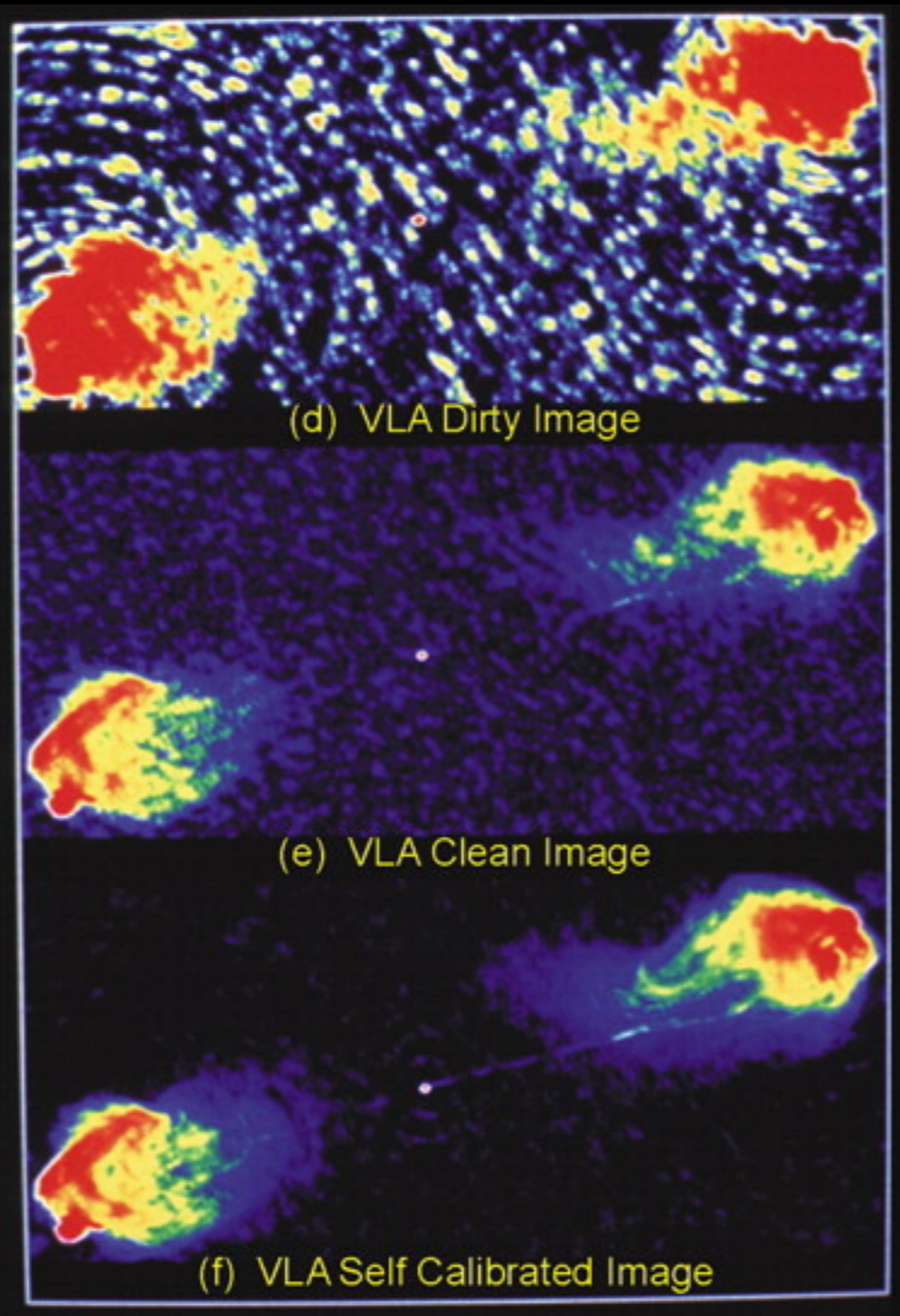
The both images are originated from the same data...

WHAT IS THE SELF-CALIBRATION?

CLEAN components



-AN EXAMPLE OF SELF CALIBRATION-
CYGNUS "A" OBSERVED WITH VLA



Dirty map (Only Inverse FT)

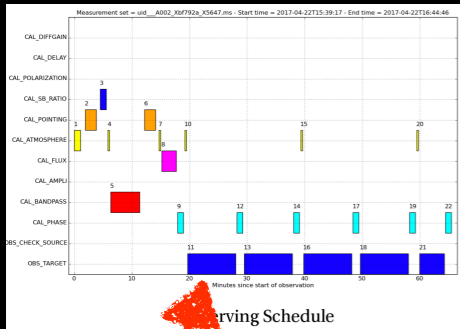
CLEAN deconvolution

Self-Cal. + CLEAN

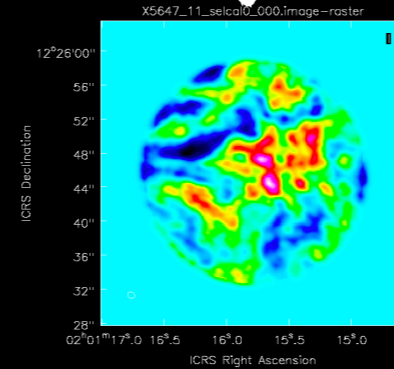
Kellermann, K. I. & Moran, J. M. 2001

MULTI-STEP SELF-CALIBRATION FOR SOLAR DATA (SHIMOJO VERSION)

1 scan data (~8mins@Band6)



SELF CAL



"X5647_scriptForSelfCal_Mov_moduse.py" in the "tutorial_datasets" directory is the CASA-Python script for the process

Calibrated each scans

~2mins data

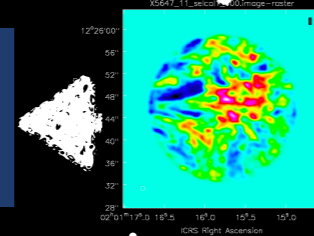
~2mins data

~2mins data

~2mins data

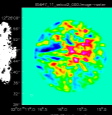
As a initial model

SELF CAL



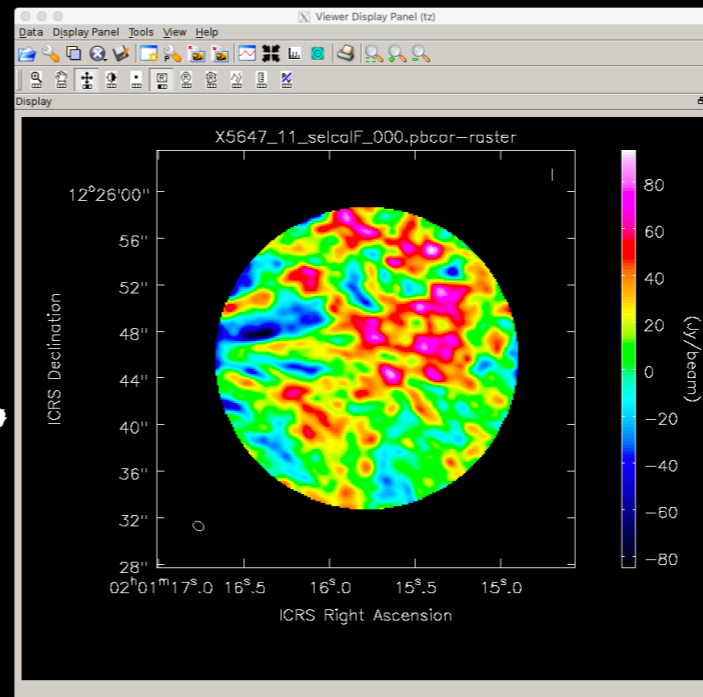
32sec

SELF CAL

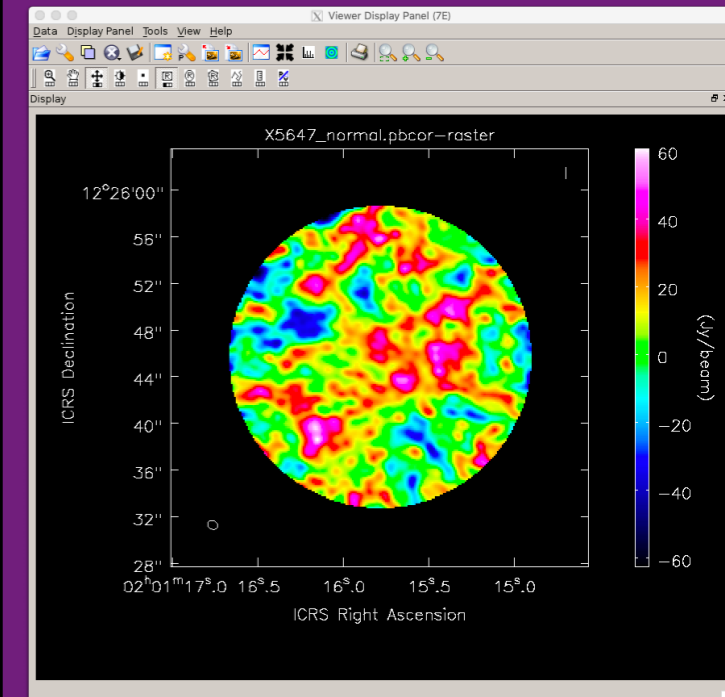


2s

Final Result



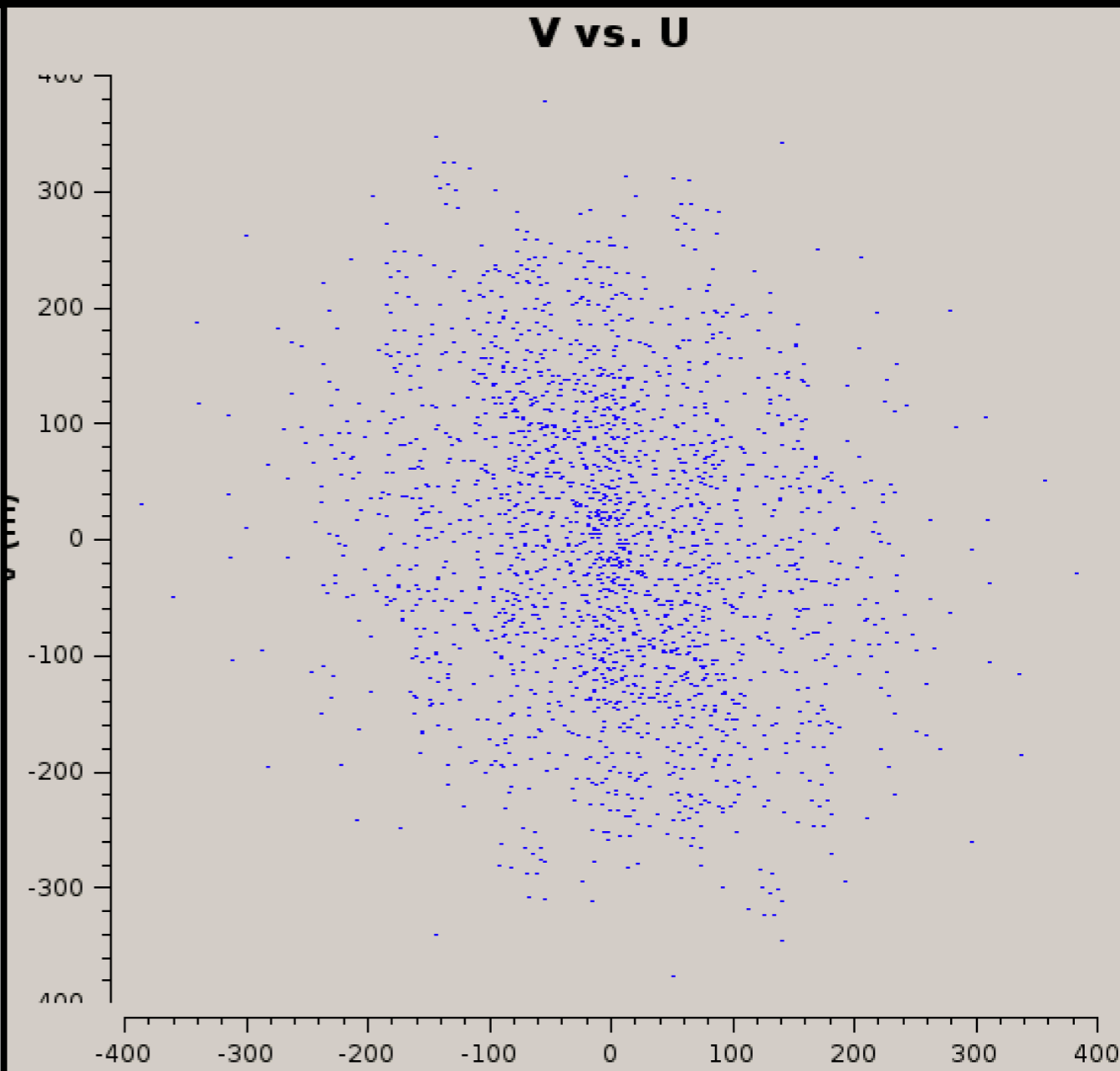
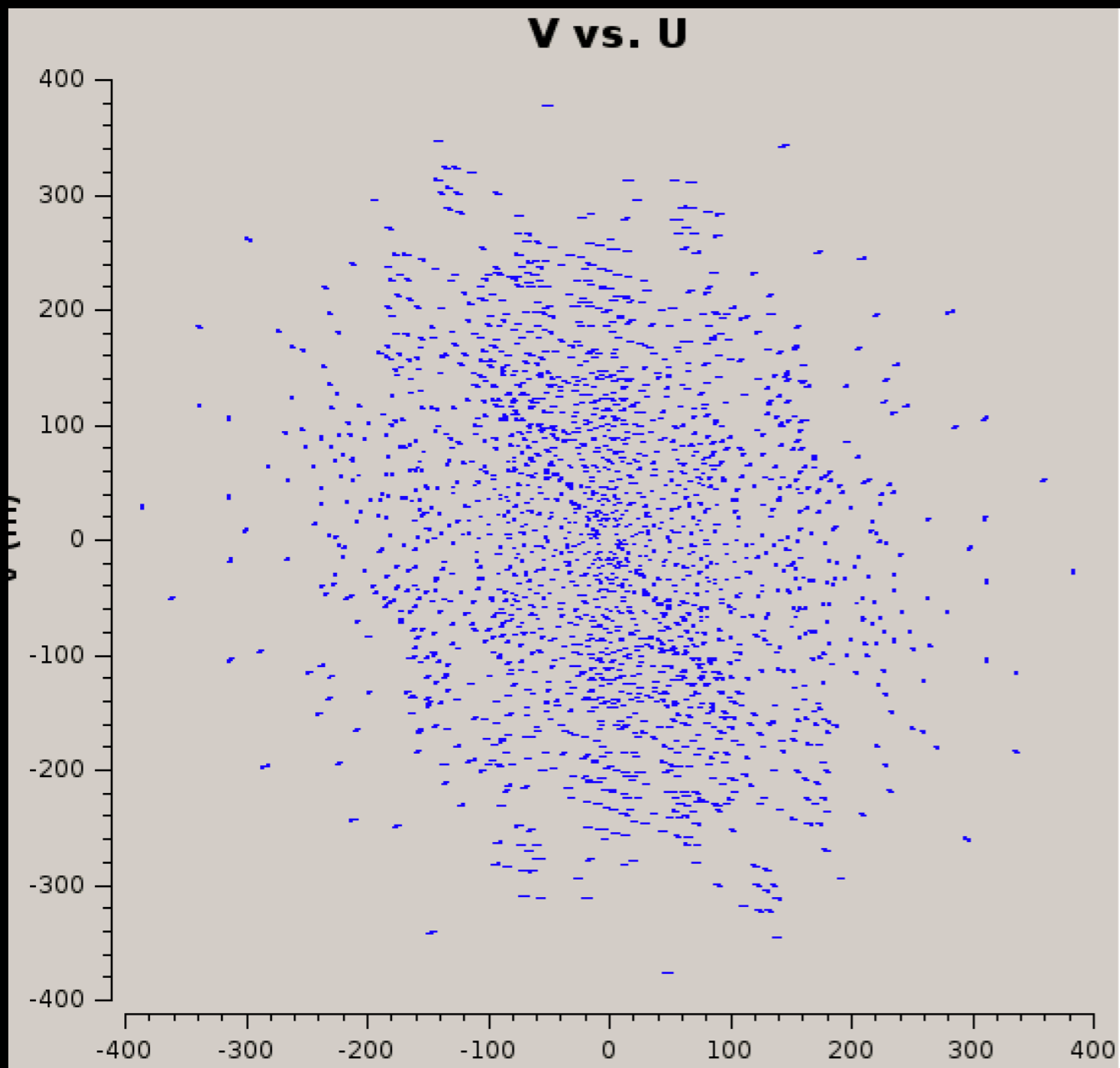
Non-SelfCal



DIFFERENCE OF DATA POINTS OBTAINED FROM ONE SCAN AND 2 SEC

Data points on u-v plan (1 scans: 8mins)

Data points on u-v plan (2 seconds)

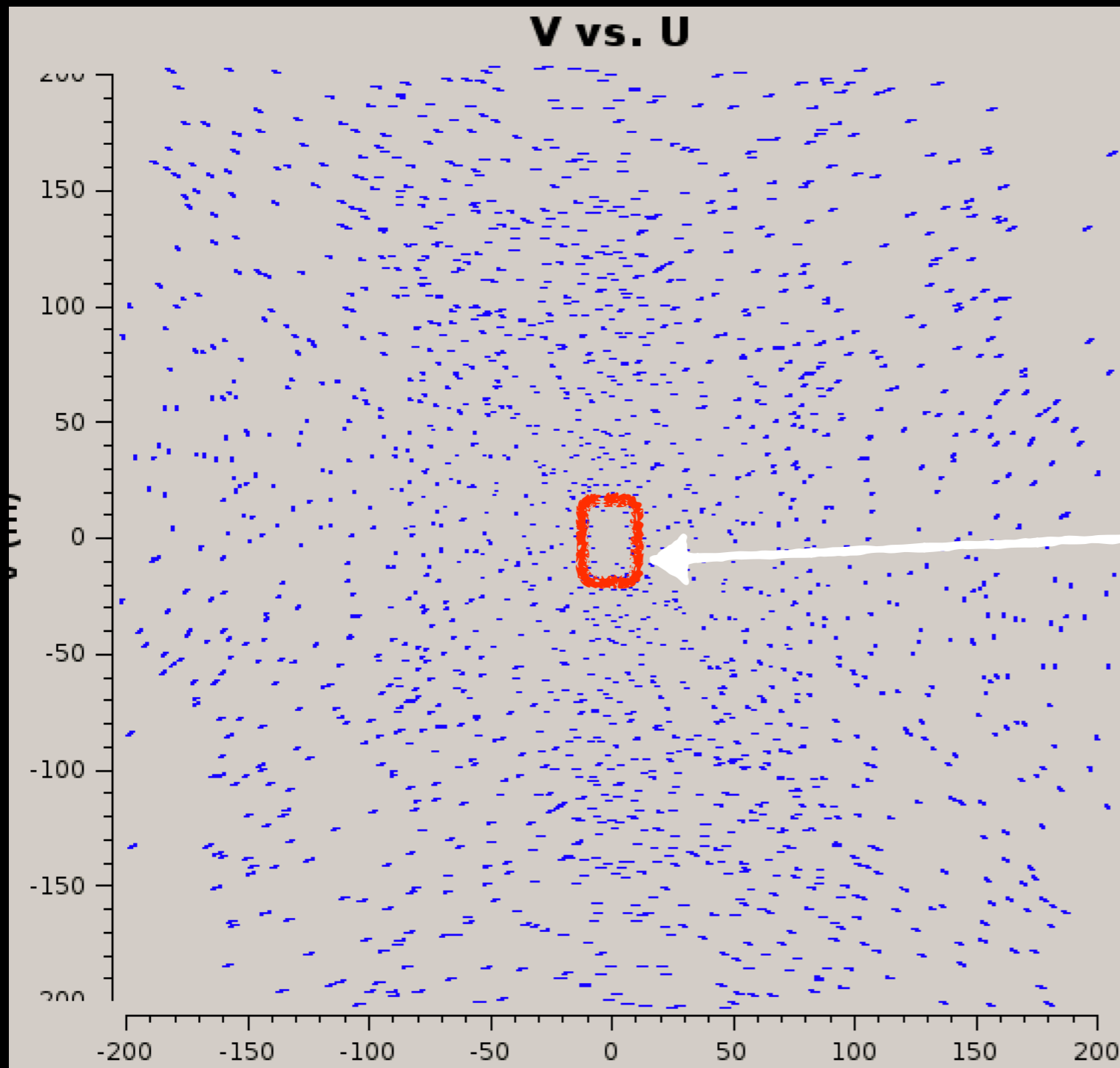


ISSUES OF SELF CALIBRATION

- The self-calibration does not work well for MOSAIC observations, because the time cadence of the MOSAIC maps is not high (> 1 mins).
- The "multi-steps" self-calibration does not work well for limb observations, because the signals from the limb are too strong and cleans the fine structures above the limb caused by the multi-step method.
 - I used the normal self-calibration for the limb data analyzed in the workshop.
- The effect of the self-calibration for Band3 data is not so large because the phase of Band3 data is already good in most cases.

TO AVOID THE VOID LOCATED
AT THE CENTER OF U-V PLANE...

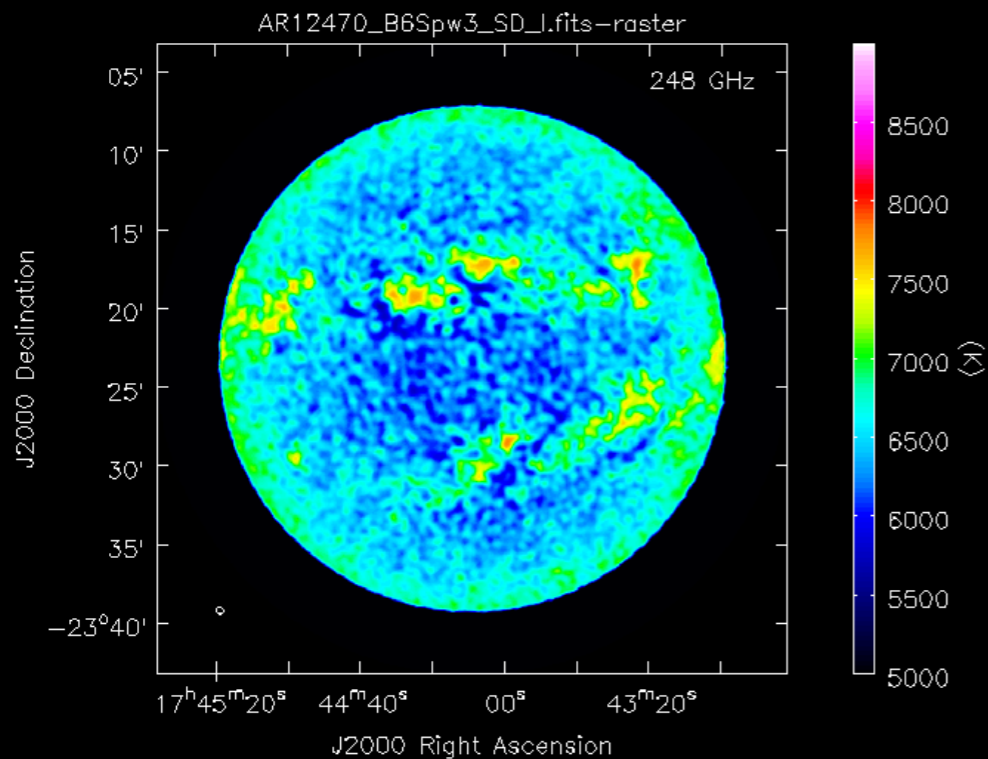
VOID OF THE DATA POINTS ON U-V PLANE



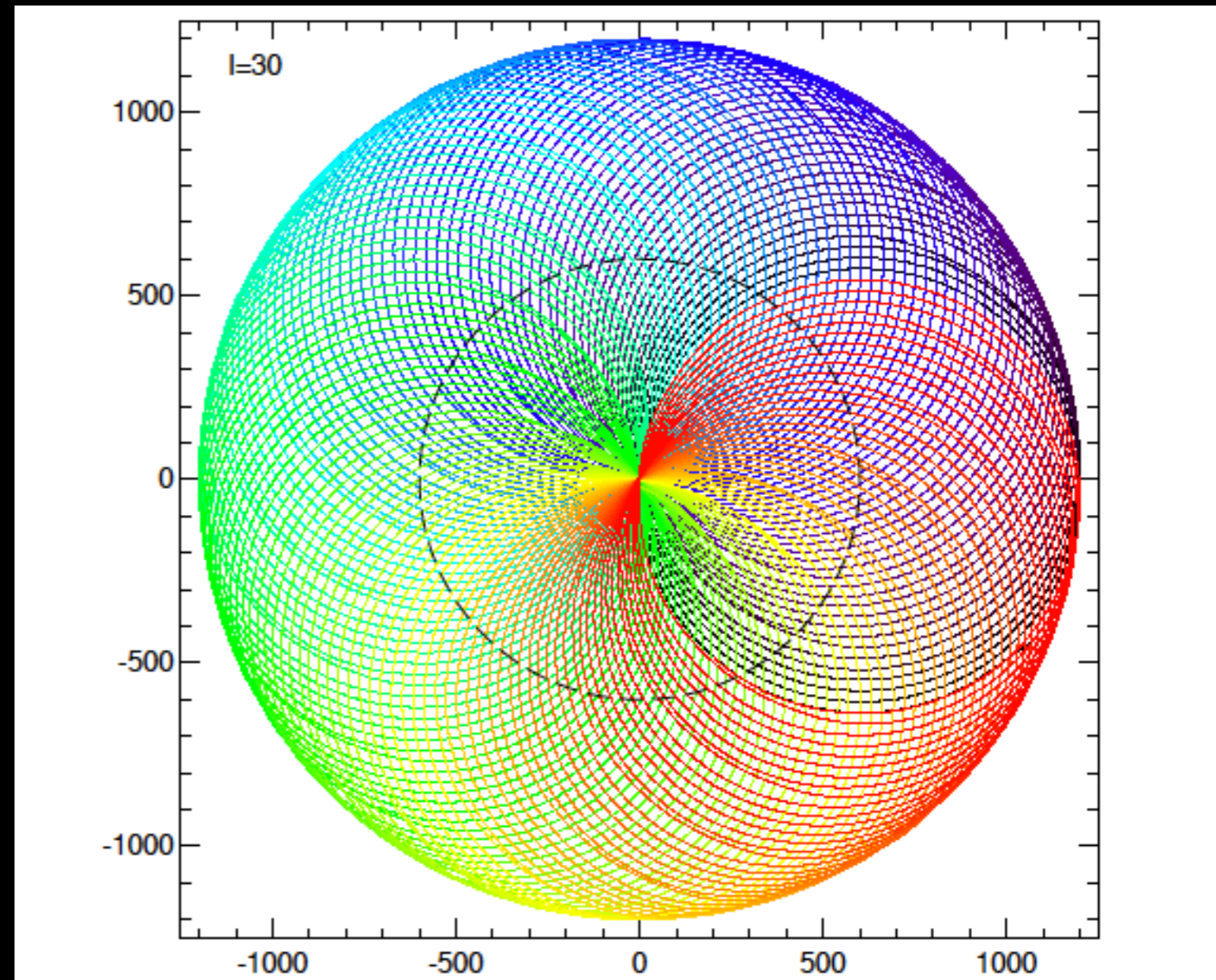
- Antennas cannot approach closer than 7m (ACA), physically.
- The limitation causes the void of the data point at the center of u-v plane.

SINGLE-DISH SOLAR OBSERVATIONS WITH ALMA

- Fast-scan imaging
 - double-circle pattern
 - FoV: $2400'' \phi$
 - One map per ~ 7 mins

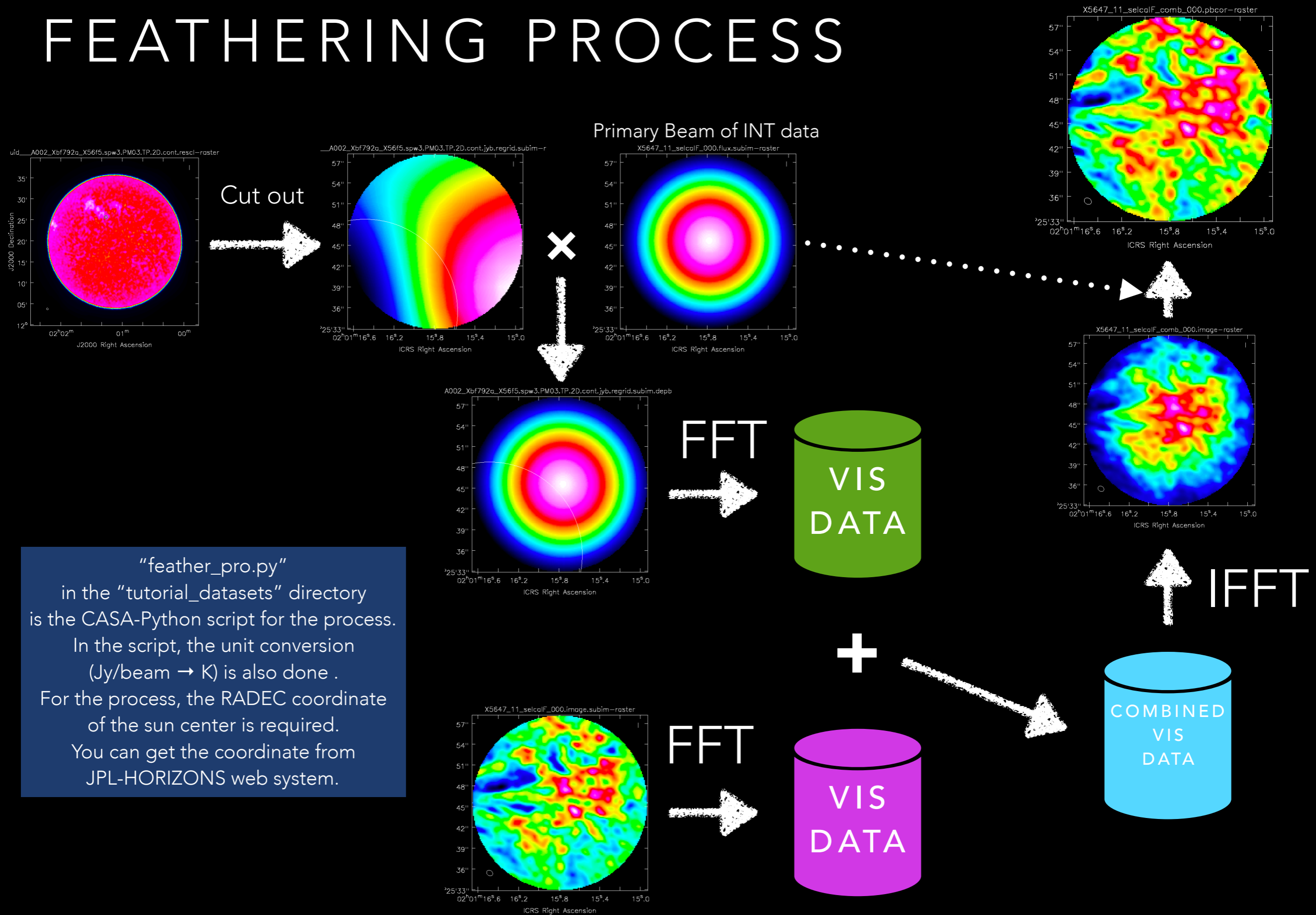


Double Circle Pattern



White et al. 2017

FEATHERING PROCESS



"feather_pro.py"
 in the "tutorial_datasets" directory
 is the CASA-Python script for the process.
 In the script, the unit conversion
 (Jy/beam → K) is also done .
 For the process, the RADEC coordinate
 of the sun center is required.
 You can get the coordinate from
 JPL-HORIZONS web system.

COORDINATE OF THE FITS FILES

- The coordinate of the FoV center in the ALMA FITS is written using "RA/DEC" coordinate system.
- To convert from RA/DEC to Heliocentric (XCEN/YCEN) , we can use the following web page.
 - <http://celestialszenes.com/alma/convert/>
 - The RA/DEC coordinate of the FoV center can be obtain from the FITS header.
 - The "reference time" is needed. The time can be seen in the google spreadsheet.
- The image have to be rotated using P angle. P angle can be estimated using IDL-SSW routine "get_rb0p" and the reference time.

END