

# Imaging extended objects with ALMA – “Data Combination” (Tutorial “3b”)

Dirk Petry (ESO, ALMA Regional Centre), Jan 2026

## Outline

- Tutorial Overview
- Motivation: Spatial filtering in radio-interferometric imaging
- ALMA observations of extended objects are meant to use “data combination”
- Data Combination methods available under CASA

## TUTORIAL 3B - DATA COMBINATION

All sessions in room BW0.32, Total time: 4.5 h

11:00 - 12:30 h:

- Intro lecture: Imaging extended objects with ALMA
- Q&A

Slides: Leiden-DataCombinationIntro-dpetry-Jan2026.pdf

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13:30 h - 15:00 h::

- Setup for hands-on tutorial
- Joint deconvolution of TM and 7M MOUSs
- Start of Combination of interferometric and SD data

Slides: Leiden-DataCombinationHandsOn-dpetry-Jan2026.pdf

Leiden-DataCombination-sdintimaging-Jan2026.pdf  
(lecture during long exec times of sdintimaging/tclean)

Script: leiden-tutorial3b.py  
(up to launching second sdintimaging)

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15:30 h - 17:00 h:

- Combination of interferometric and SD data (continued)
- uv coverage assessment

Slides: Leiden-DataCombination-assess\_ms3-Jan2026.pdf

Scripts: leiden-tutorial3b.py  
(final steps: image analysis with imview, sdgain tests)

leiden-tutorial3b-supplement.sh  
(assess\_ms)

# Radio-interferometric imaging in a nutshell

## Relationship between Visibility $V(u,v)$ and Sky Brightness Distribution $T(l,m)$

$$V(u, v) = \int \int T(l, m) e^{-i2\pi(ul+vm)} dl dm$$

- Can *in principle* measure  $T(l,m)$  by measuring  $V(u,v)$  and then *applying inverse FT*
- But we cannot measure  $V$  on entire, infinite  $uv$  plane!
- We can only sample  $V$  at those  $(u,v)$  points where we have baselines (aperture synthesis)
- Reminder: single-dish telescopes sample  $uv$  space with good sample density!
  - but only cover  $uv$  plane from  $(0,0)$  out to  $u^2+v^2 < D^2$  ( $D$  = dish diameter)
  - sample  $T(l,m)$  directly but on a (relatively) coarse angular grid
  - angular resolution limited to  $\lambda/D$  , e.g. for 100 GHz,  $3\text{mm}/30\text{m} = 21$  arcsec

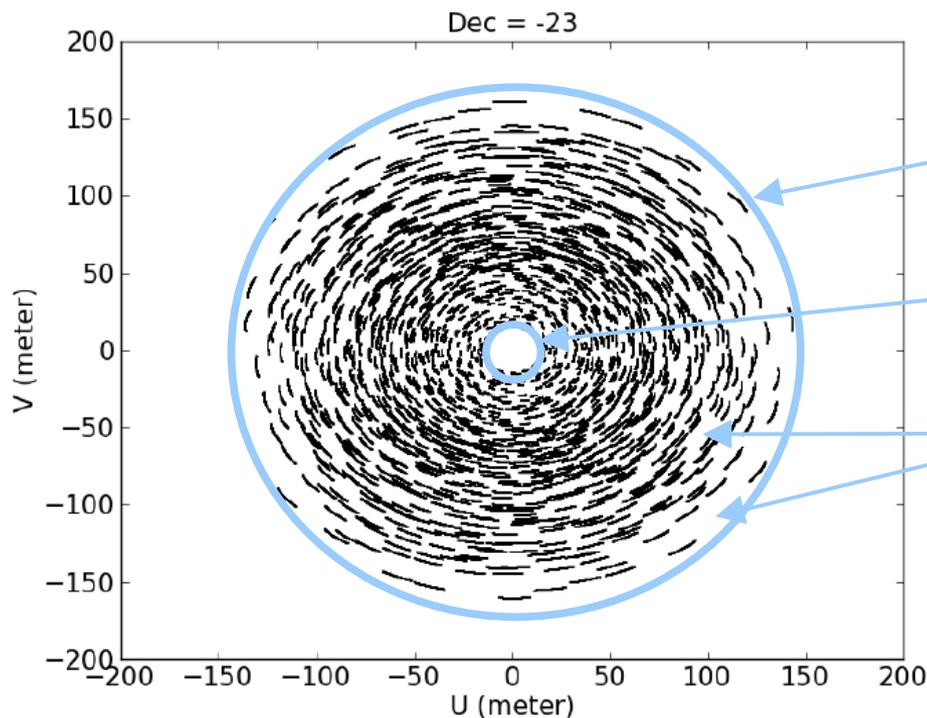
# Why data combination? - Spatial filtering!

High uv-coverage at high angular resolution is very expensive! Need excessive number of antennas!

Will always have some coverage holes and inhomogenous sensitivity!

Minimum possible baseline length  $\geq$  diameter of smallest antenna (shadowing!).

Smaller “spacings” can only be reached by including single-dish measurements!



Spatial filtering limits our knowledge:

- $r =$  longest baseline  $\Rightarrow$  smallest scale
- $r =$  shortest baseline  $\Rightarrow$  largest scale
- holes (incomplete coverage)

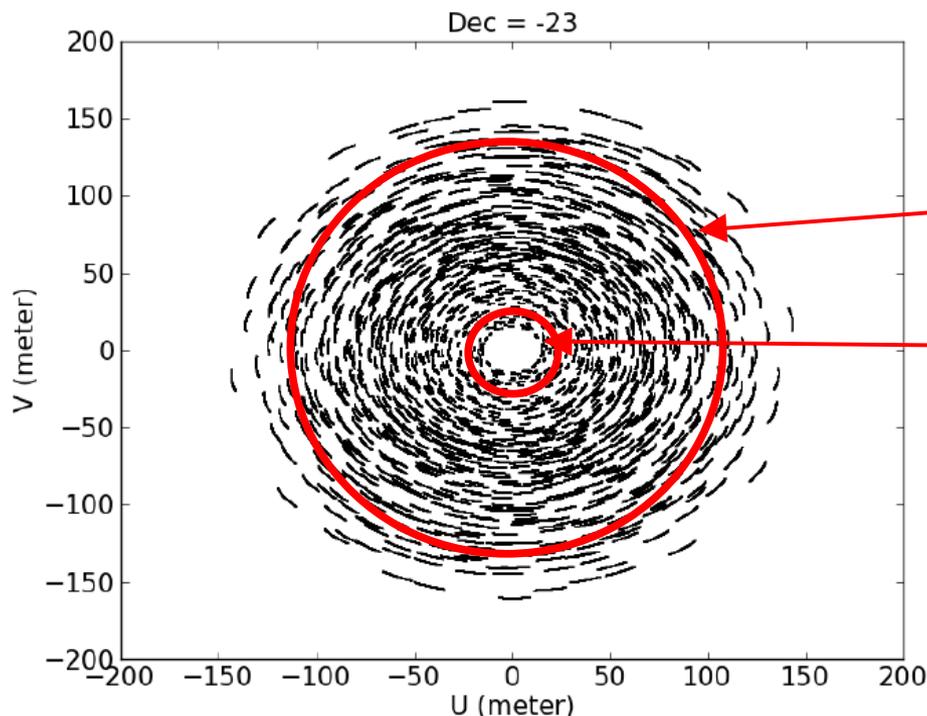
(UV coverage after one hour with ALMA 12M  
in config 1, 43 antennas, elevation near 90 deg)

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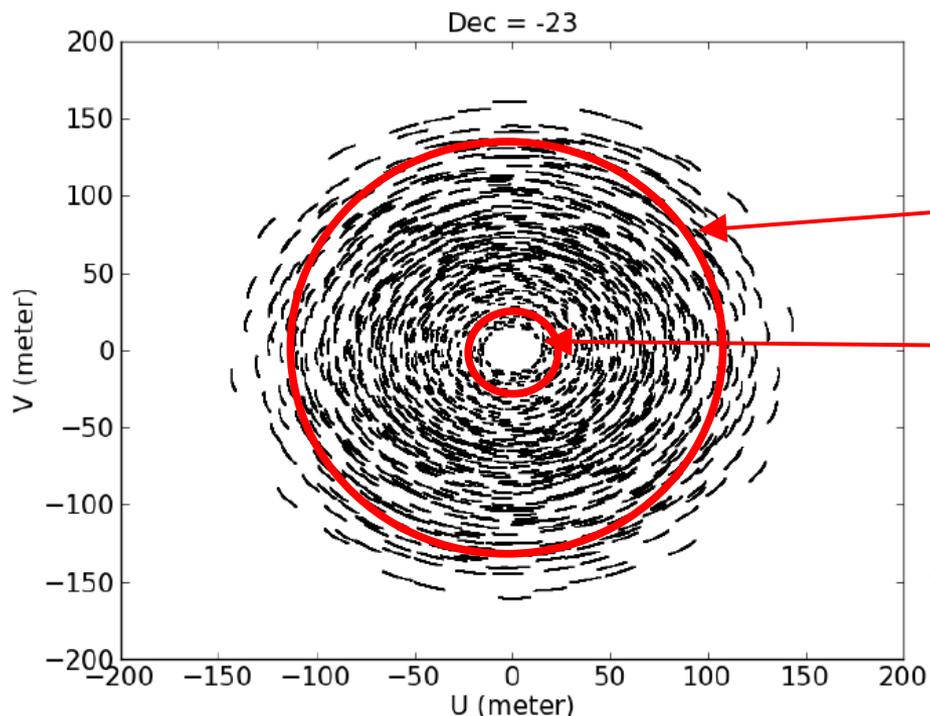
Spatial filtering limits our knowledge:

- $r$  = longest baseline  $\Rightarrow$  smallest scale  
min. recoverable scale  $\approx \lambda/L80$   
(need sufficient sensitivity)
- $r$  = shortest baseline  $\Rightarrow$  largest scale  
max. recoverable scale  $\approx \lambda/L05$   
(need sufficient sensitivity)

(UV coverage after one hour with ALMA 12M  
in config 1, 43 antennas, elevation near 90 deg)

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Remember: what counts is the projected baseline!  
 The uv coverage obtained with a given array  
 depends on the HourAngles of the observation!

(UV coverage after one hour with ALMA 12M  
 in config 1, 43 antennas, elevation near 90 deg)

# Spatial filtering parameters of ALMA - AR and MRS

Basic ALMA 7M and 12M array configuration parameters (pointing at the Zenith):

Configuration	7-m	C43-1	C43-2	C43-3	C43-4	C43-5
Minimum baseline (m)	8.7	14.6	14.6	14.6	14.6	14.6
5th percentile or <b>L05</b> (m)	9.1	21.4	27.0	37.6	54.1	90.9
80th percentile or <b>L80</b> (m)	30.7	107.1	143.8	235.4	369.2	623.8
Maximum baseline (m)	45.0	160.7	313.7	500.2	783.5	1397.9
Configuration	C43-6	C43-7	C43-8	C43-9	C43-10	
Minimum baseline (m)	14.6	64.0	110.4	367.6	244.0	
5th percentile or <b>L05</b> (m)	148.6	235.2	427.3	746.9	1228.1	
80th percentile or <b>L80</b> (m)	1172.5	1673.1	3527.3	6482.6	8685.9	
Maximum baseline (m)	2516.9	3637.8	8547.7	13894.2	16194.0	

- **min. recoverable scale  $\approx \lambda/L80$**   
a.k.a. “angular resolution” (AR)
- **max. recoverable scale  $\approx \lambda/L05$**   
=: MRS

*More exact relationship to L05 and L80 depends on weighting scheme!*

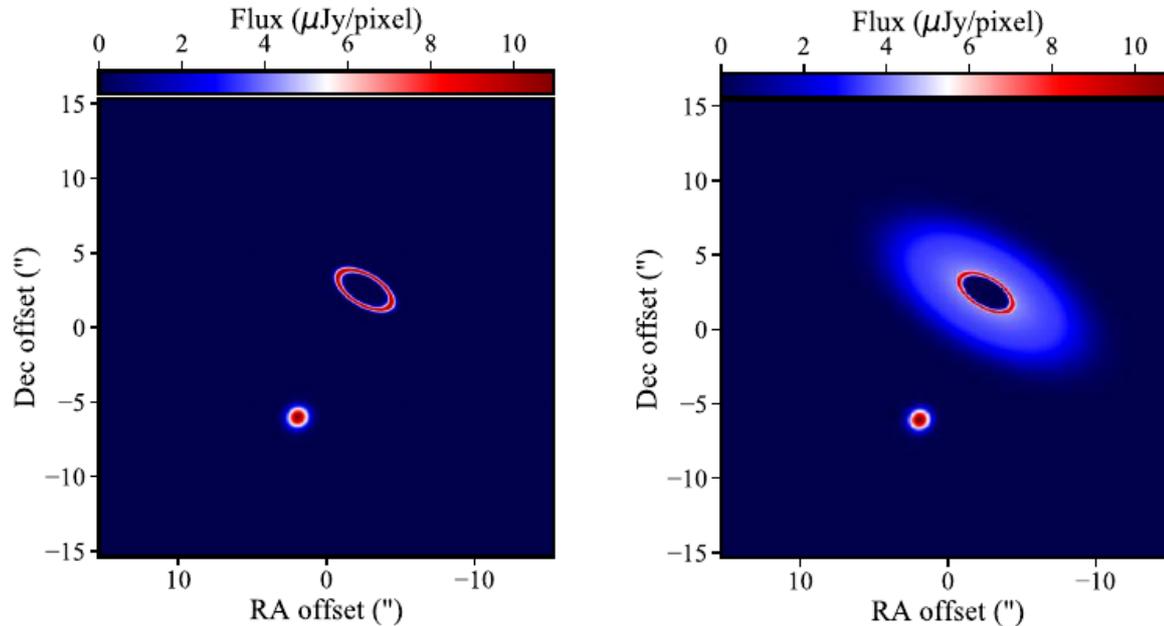
*All baseline lengths depend on elevation and hourangle!*

*See ALMA THB chapter 7.*

# Symptoms of missing “short spacings”

## Demonstration of the effect of missing short baselines:

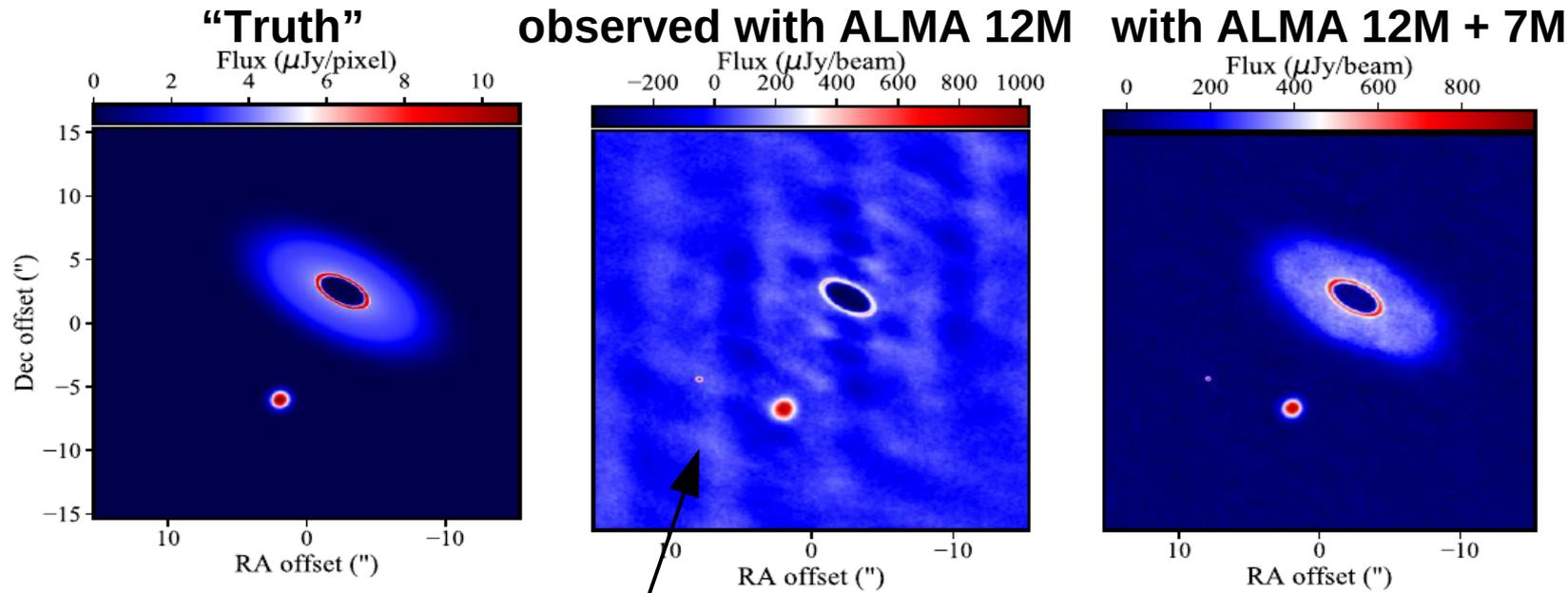
**Question:** *With the uv-coverage from slide 3, can we distinguish between these two sky brightness distributions?*



# Symptoms of missing “short spacings”

**Demonstration of the effect of missing short baselines:**

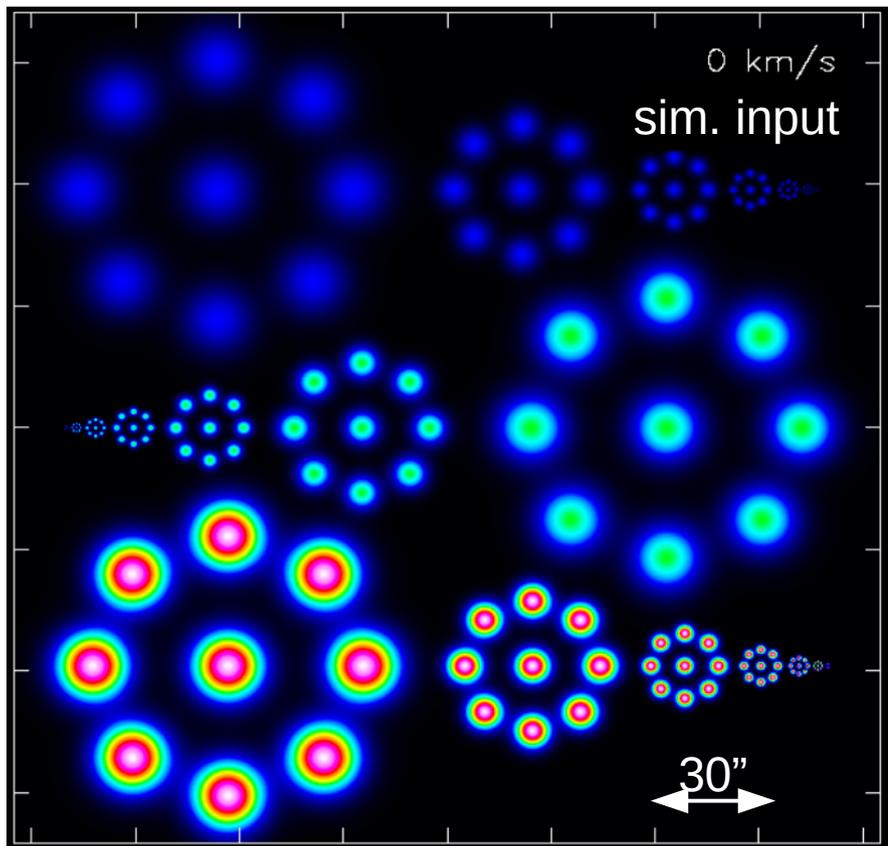
*Answer: no, not with ALMA 12M alone. We need to at least add ALMA 7M!*



Missing short spacings are also causing a larger noise RMS than would be expected!  
**Bad PSF increases noise correlation** (see Tsukui et al. 2023)

# Symptoms of missing “short spacings”

You can explore what you are missing by simulating the interferometer you are using ...



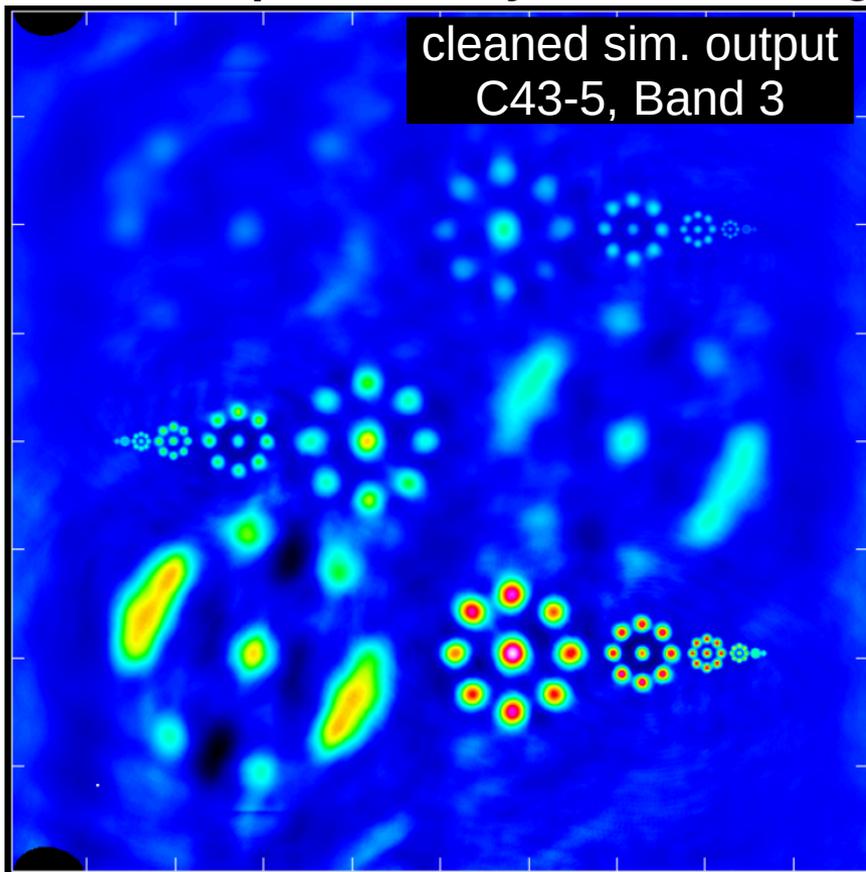
**Example** (from recent ALMA dev. study):  
Test image with 3 rows of 7 groups  
of 9 identical Gaussians each.  
From group to group, the FWHM doubles  
(range 0.15 arcsec to 10 arcsec).  
From row to row, the flux doubles.

Use CASA simulator to “observe” with  
a configuration as defined by the  
CASA ALMA templates at your  
frequency and DEC of interest.

For “observing”, this example at 115 GHz  
needs a 4 arcmin x 4 arcmin **mosaic** of 75 fields.

# Symptoms of missing “short spacings”

You can explore what you are missing by simulating the interferometer you are using ...



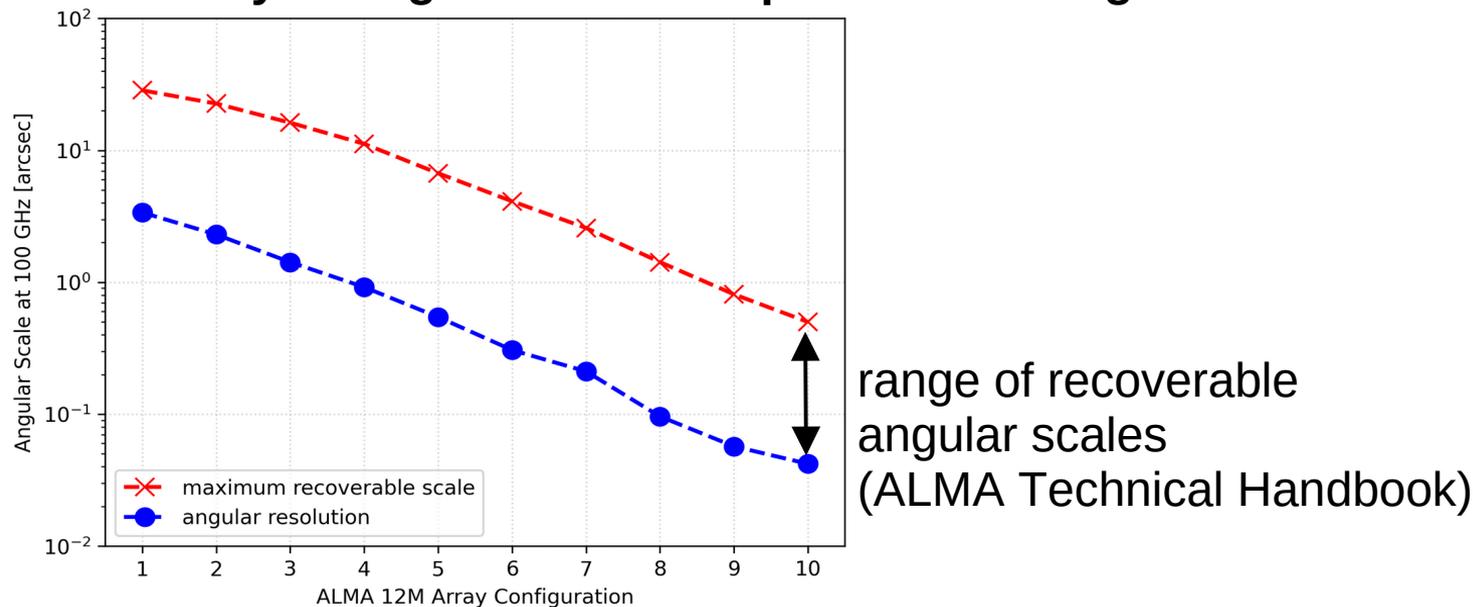
Example of multiscale tclean image from simulated observation with Array configuration “5”, 43 antennas, semi-extended

Result:

- obvious loss of flux
- some structures change their morphology
- some disappear entirely
- non-physical structures appear, some with negative emission

# ALMA's range of recoverable angular scales

Each ALMA array configuration corresponds to an angular scale “window”:



The nominal window is still modified by the Alt/AZ path which the observation takes!  
 Given the current array configuration, ALMA scheduling controls the uv coverage via choosing the *starting hour angle* of each EB

Later modification of uv coverage only via reweighting/flagging of visibilities offline!

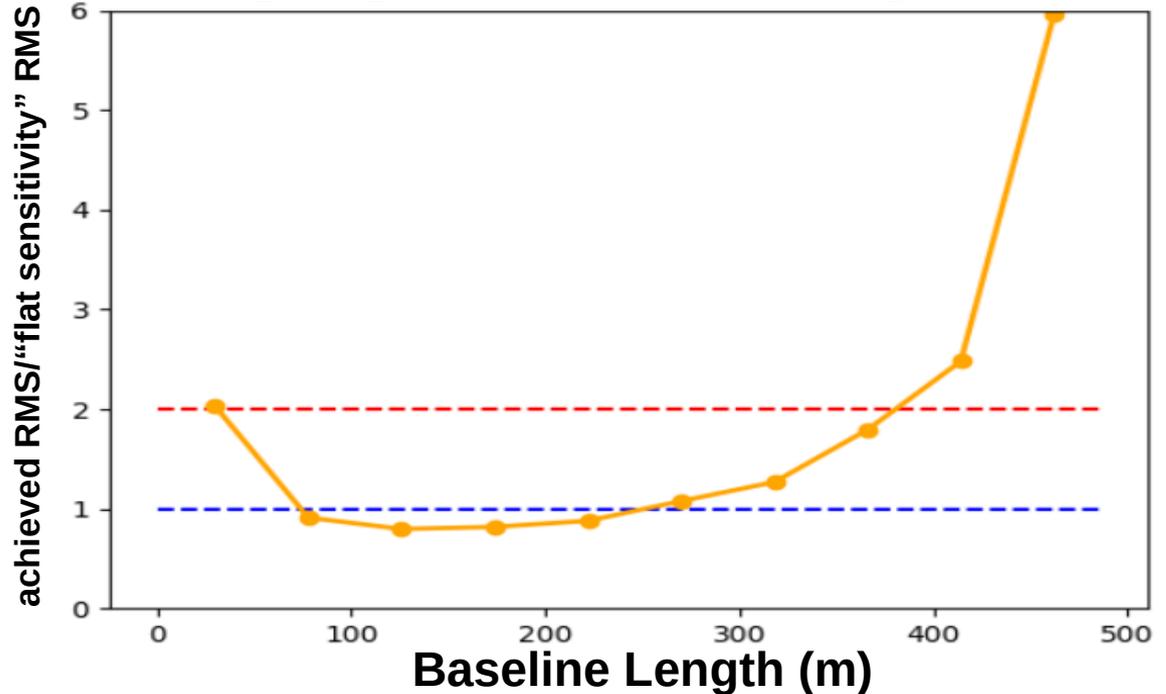
# Measuring the range of recoverable angular scales

The ALMA internal development study on uv coverage assessment and scheduling (Petry, Diaz Trigo, Kneissl et al. 2024) has developed a new method to define and measure the Angular Resolution (AR) and Maximum Recoverable Scale (MRS):

## *Plot (RMS/exp.RMS) vs. BL for assessing angular scale sensitivity*

*Shows in which BL range we are as sensitive as a "naive" PI would expect, i.e. if it were possible to have "flat sensitivity" (equal sensitivity in equal angular scale ranges).*

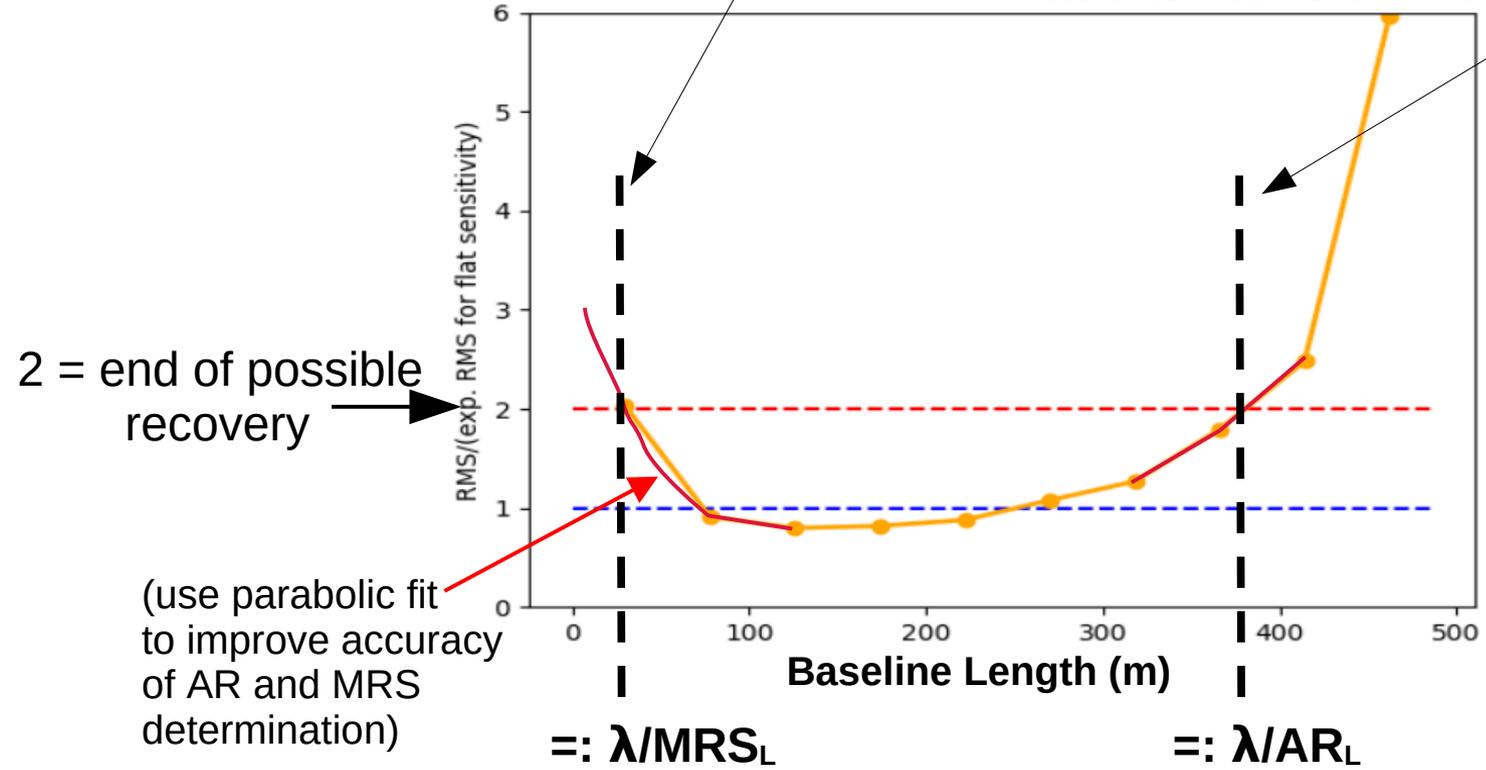
*(Similar methods are in use in CMB power spectrum analysis: e.g. Hobson & Masinger 2002)*



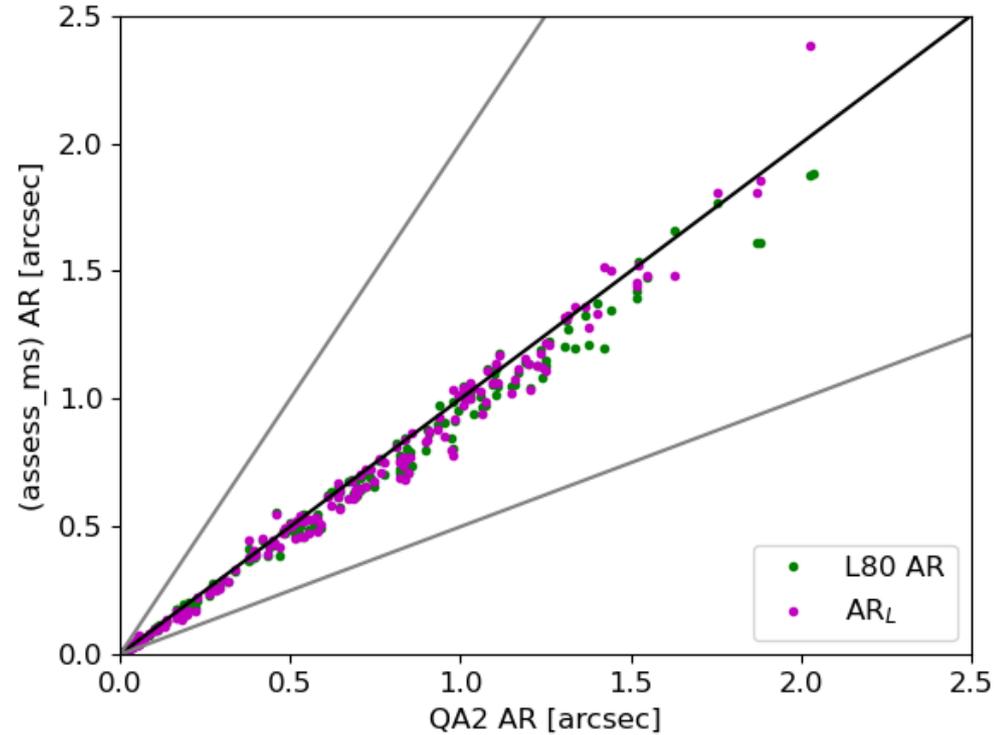
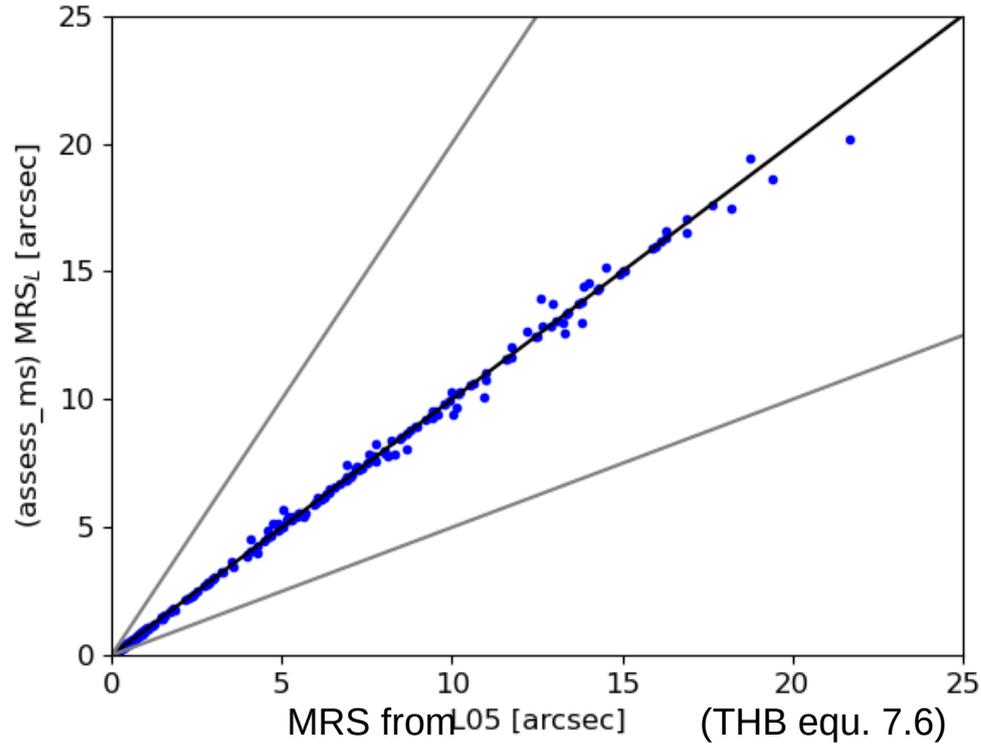
# Measuring the range of recoverable angular scales

Use the smallest BL  
where  $RMS < 2 \times$  flat expectation  
as *alternative definition of achieved MRS*.

Use the largest BL  
where  $RMS < 2 \times$  flat expectation  
as *alternative definition of achieved AR*.



# Measuring the range of recoverable angular scales



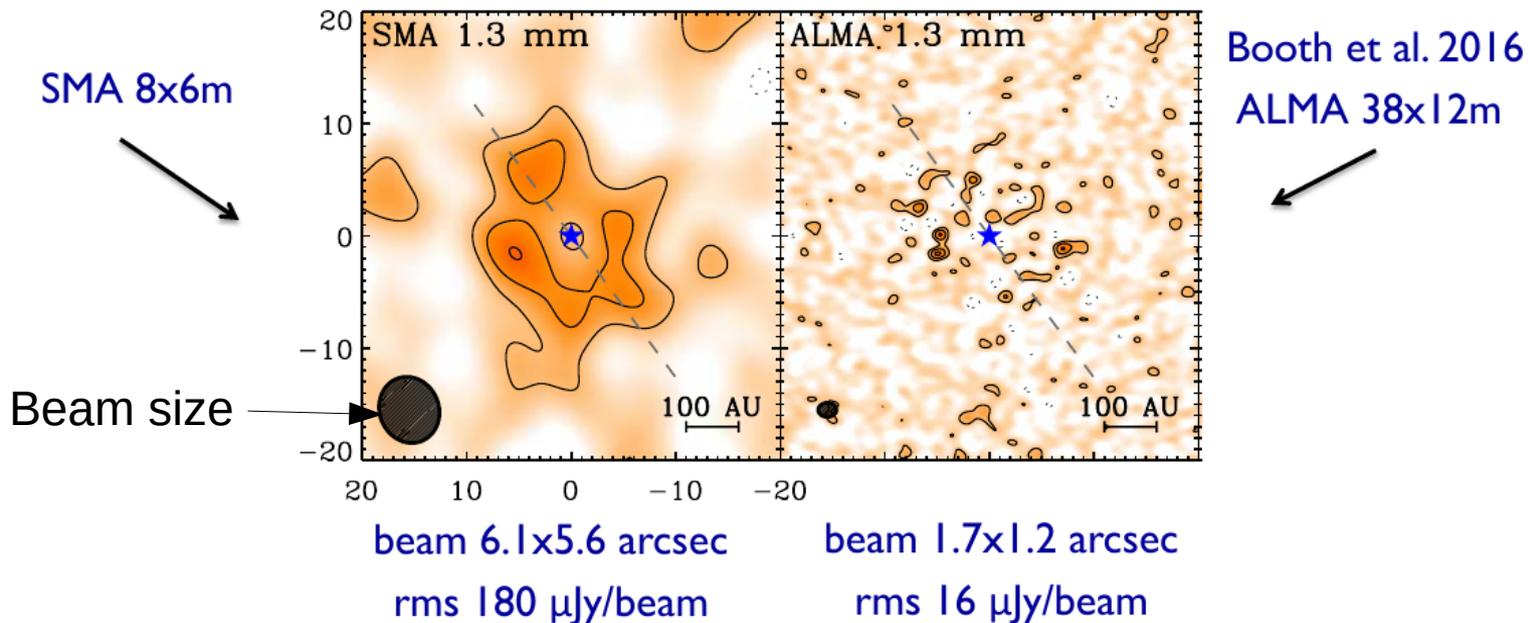
Plots based on representative sample of 214 TM1 MOUSs from Cycle 9.

# The extend of the danger (of not combining)

“Real data”  
example:

## Resolved Millimeter Observations of the HR 8799 Debris Disk

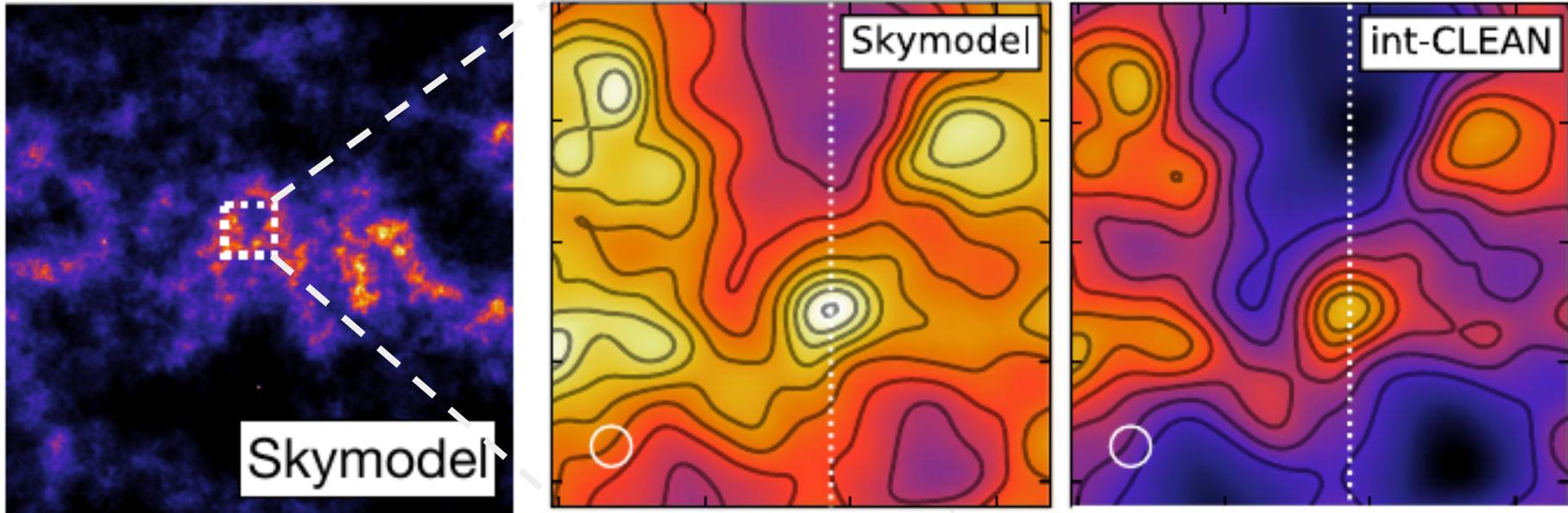
David J. Wilner<sup>1</sup>, Meredith A. MacGregor<sup>1,2,6</sup>, Sean M. Andrews<sup>1</sup>,  
A. Meredith Hughes<sup>3</sup>, Brenda Matthews<sup>4</sup>, and Kate Su<sup>5</sup>



While the low-resolution “SubMmArray” can see the disk, it is “resolved out” by ALMA.

# The extend of the danger (of not combining)

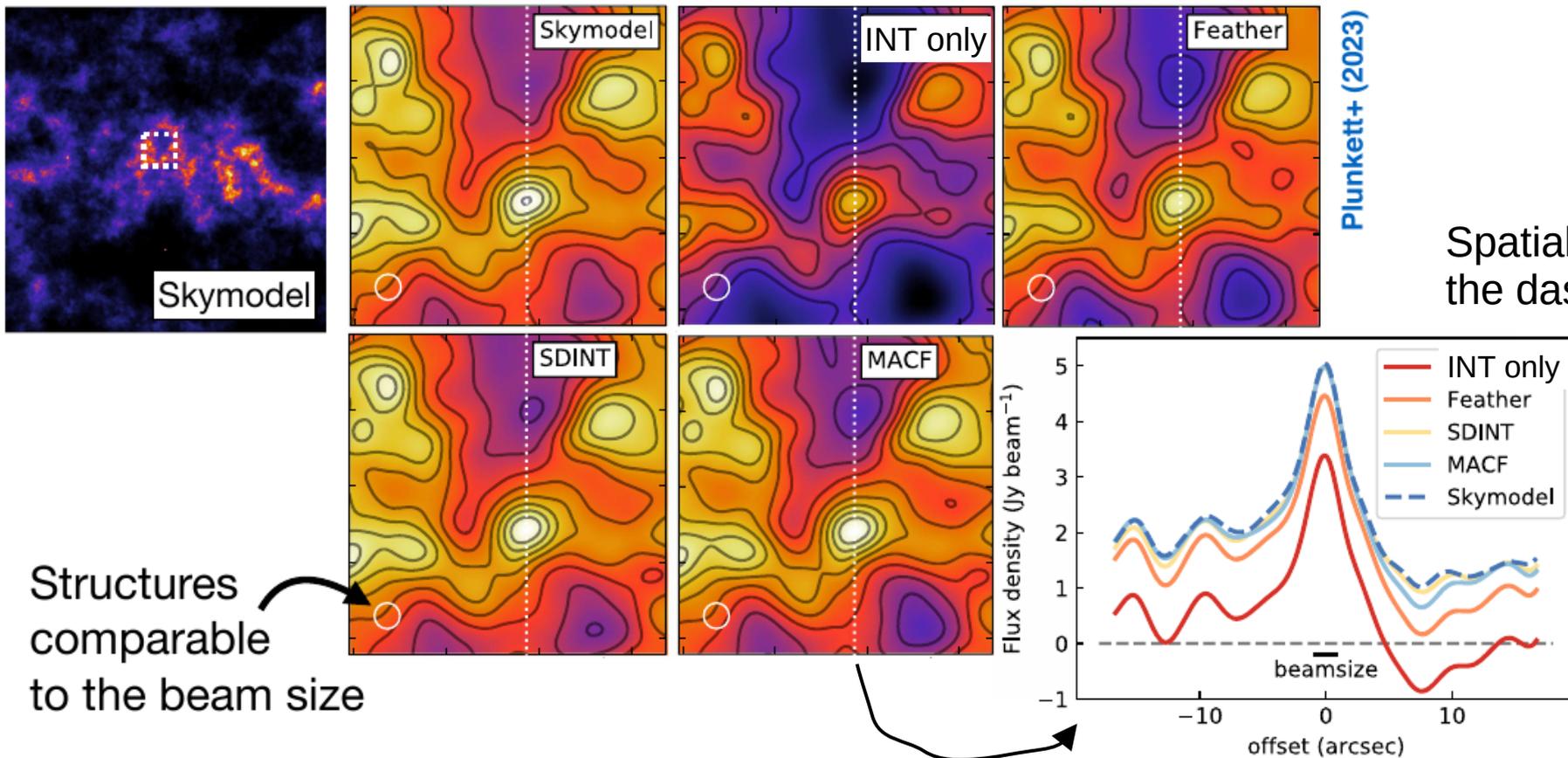
Example from Plunkett et al. 2023 (report from the 2019 Leiden Workshop on data combination):



The entire image loses flux, not just the extended structures!  
Also the flux of beam-sized objects can be reduced!

# The extend of the danger (of not combining)

Adding single-dish observations gives significant improvement, no matter which method is used:



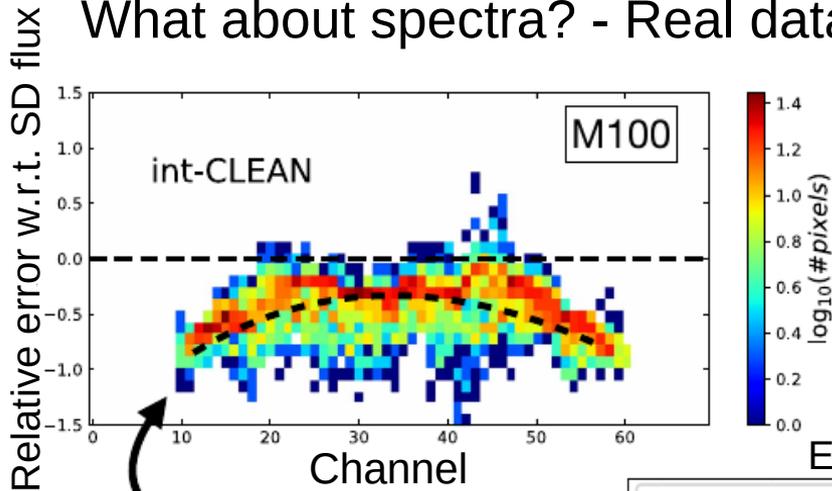
Plunkett+ (2023)

Spatial profile along the dashed line

Structures comparable to the beam size

# The extend of the danger (of not combining)

What about spectra? - Real data example (again from Plunkett et al. 2023)

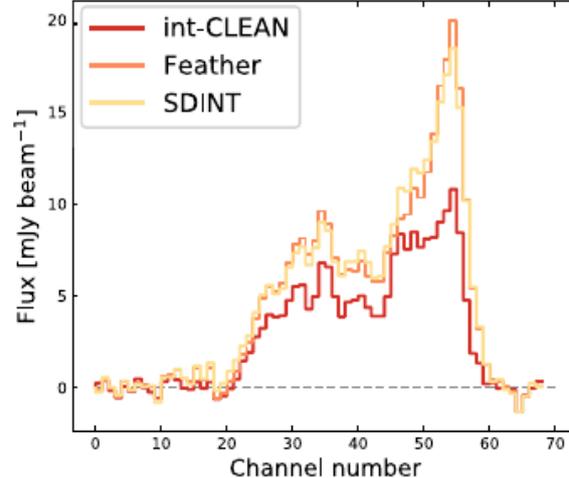


The effects of missing short spacings typically vary with spectral channel!

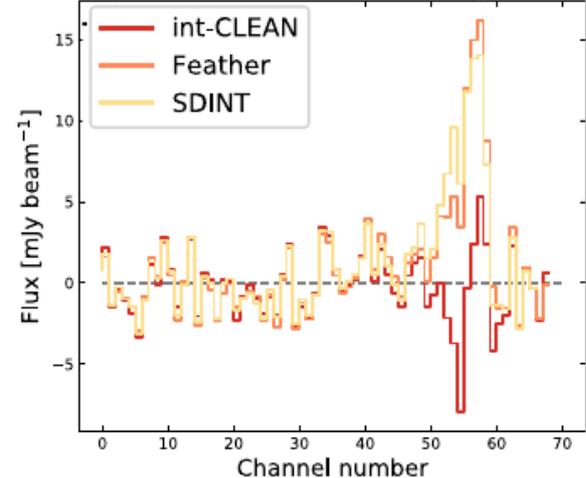
Spectra without short spacings are not scaled down but ***distorted!***

“banana-shaped” spectrograms

Example Region 1



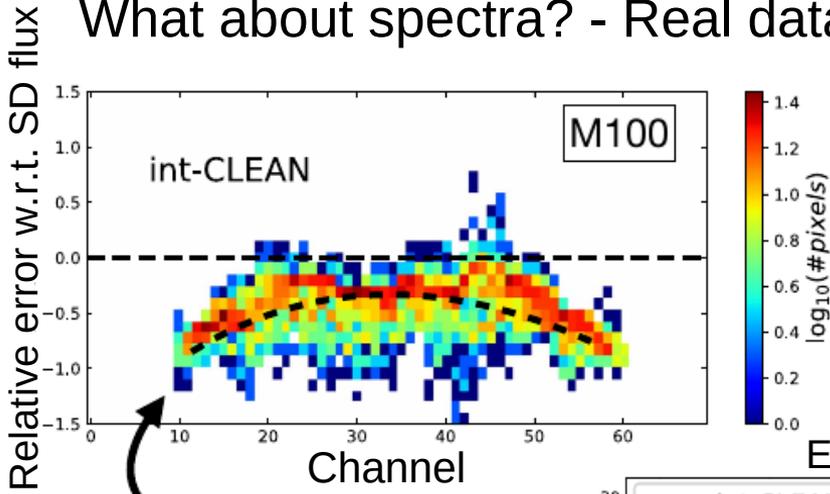
Example Region 2



Plunkett+ (2023)

# The extend of the danger (of not combining)

What about spectra? - Real data example (again from Plunkett et al. 2023)

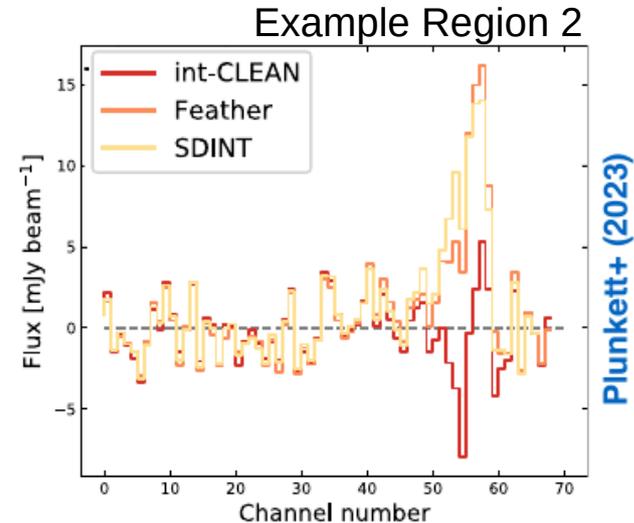
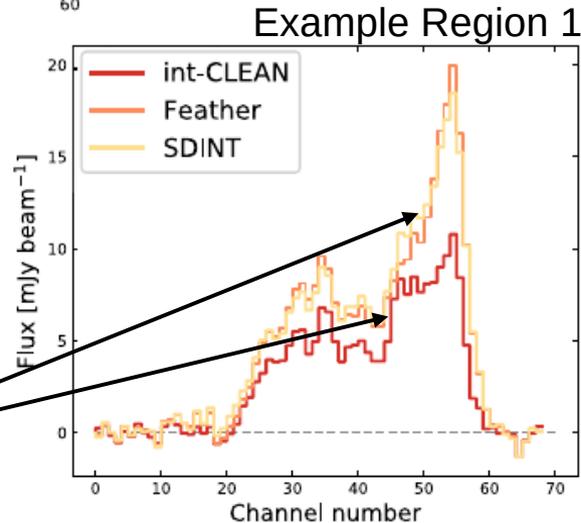


The effects of missing short spacings typically vary with spectral channel!

Spectra without short spacings are not scaled down but ***distorted!***

“banana-shaped” spectrograms

Two spectra from different regions *with* short spacings and *without*:



Plunkett+ (2023)

# Why data combination? - Summary

*If we cannot obtain information about all relevant angular scales with one instrument, we need to combine the data from different instruments into one image.*

Not as simple as it sounds!

Caveats:

- 1) requires good flux calibration of the individual instruments  
(at least relative to each other)
- 2) special care is needed *in the case of time-variable objects* if the different instruments were not observing at the same time!

ALMA therefore tries to deliver all necessary measurements with consistent calibration and small time-offsets.

# The ALMA arrays

In other words:

You need to adapt your interferometer to the object you want to observe in order to measure all relevant angular scales!

You may need to combine observations from different arrays and even single-dish telescopes!

**ALMA was designed to provide these possibilities *within a single observatory.***

ALMA PIs are asked to specify for a given target:

- AR (image angular resolution = smallest angular scale)
- LAS (image largest angular scale)
- Sensitivity (image noise RMS)
- Spectral Resolution and Ranges

The observatory then schedules the 3 arrays (TP, 7M, 12M) to achieve this.

# ALMA – operating since 2011

## The Atacama Large Mm/sub-mm Array

- a collaboration between America (US, Canada, Chile), Europe (ESO member states), and East Asia (Japan, Taiwan, Korea)

Located at the Atacama desert, Chile, 5000 m a.s.l.

Total cost approx. 1 Billion Euros

Main Array: 50 x 12m antennas

7M Array: 12 x 7m antennas

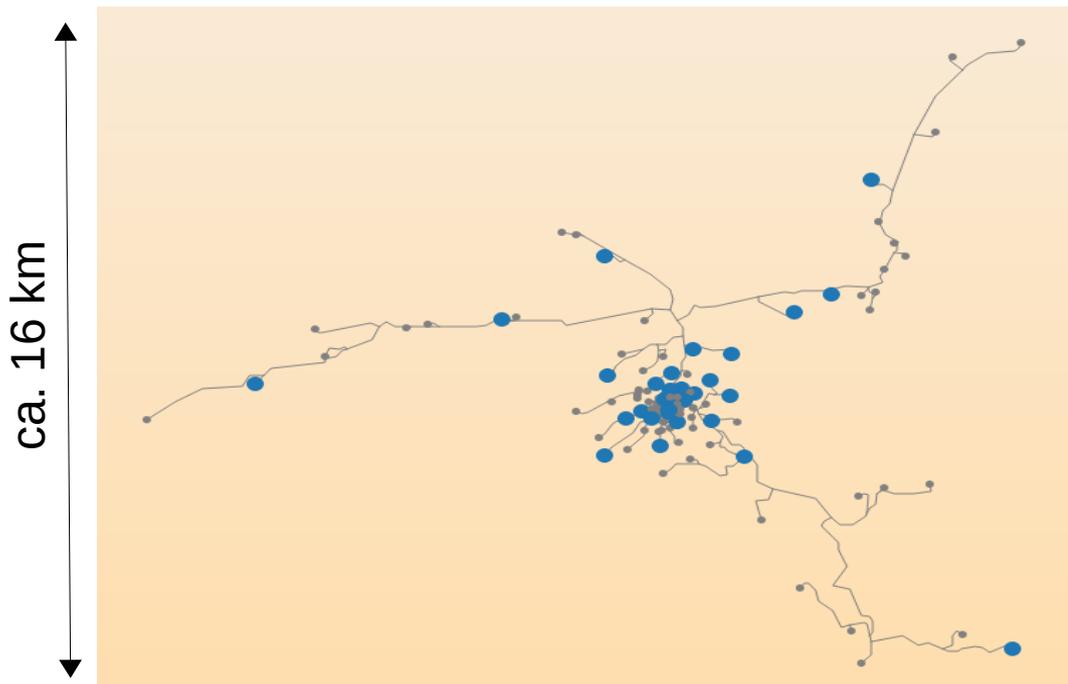
TP Array: 4 x 12m antennas

} together = the ACA



# The ALMA arrays

ALMA main array can be re-configured from very compact (C-1) to very extended (C-10)



Observations need to be scheduled in time such that array configuration matches PI requirements.

## Typical Configuration Schedule

Start date	Configuration	Longest baseline	AR, MRS (asec) at 100 GHz
1-Oct-19	C-4	0.78 km	0.92, 11.2
20-Oct-19	C-3	0.50 km	1.42, 16.2
10-Nov-19	C-2	0.31 km	2.30, 22.6
30-Nov-19	C-1	0.16 km	3.38, 28.5
20-Dec-19	C-2	0.31 km	2.30, 22.6
10-Jan-20	C-3	0.50 km	1.42, 16.2
1-Feb-20	No observations due to maintenance		
1-Mar-20	C-4	0.78 km	0.92, 11.2
20-Mar-20	C-5	1.4 km	0.55, 6.7
20-Apr-20	C-6	2.5 km	0.31, 4.1
20-May-20	C-7	3.6 km	0.21, 2.6
20-Jun-20	C-8	8.5 km	0.10, 1.4
11-Jul-20	C-9	13.9 km	0.06, 0.8
30-Jul-20	C-10	16.2 km	0.04, 0.5
20-Aug-20	C-9	13.9 km	0.06, 0.8

# The ALMA arrays

ca. 16 km



In addition to Main Array:  
Atacama Compact Array (ACA)

four 12M single-dishes + twelve 7M antennas



# ALMA – geared towards data combination

ALMA was designed from the start to let users image all relevant angular scales within one observing project.

PIs are asked to specify for a given target:

**AR** (image angular resolution), **LAS** (target largest angular scale)  
Sensitivity (image noise RMS), Spectral Resolution and Ranges

Based on this, the ALMA Observing Tool (OT) creates for each target a **Group of up to 4 Scheduling Blocks (SBs)**:

**TM1** - high-resolution 12M SB

**TM2** - low-resolution 12M SB

**7M** - the 7M array SB

**TP** - the single-dish SB (up to 4 antennas in parallel)

The resulting observations produce **one MemberOUS per SB**.

These MOUSs form the **GroupOUS**.

**So far, ALMA QA only delivers products on the MOUS level,  
not on the GOUS level! - Users need to do the combination.**

***ALMA delivers Groups of MOUSs which still need combination.  
Possible combinations are (ordered by angular resolution):***

***TM1 + TM2***  
***TM1 + TM2 + 7M***  
***TM1 + TM2 + 7M + TP***  
***TM1 + 7M***  
***TM1 + 7M + TP***  
***7M + TP***

***If ALMA TP not available, use SD data from other observatories!***

Two basic combination methods needed:

**A) Combination of interferometric data from different arrays**

Visibilities + Visibilities

**B) Combination of interferometric data with single-dish data**

Visibilities + Image

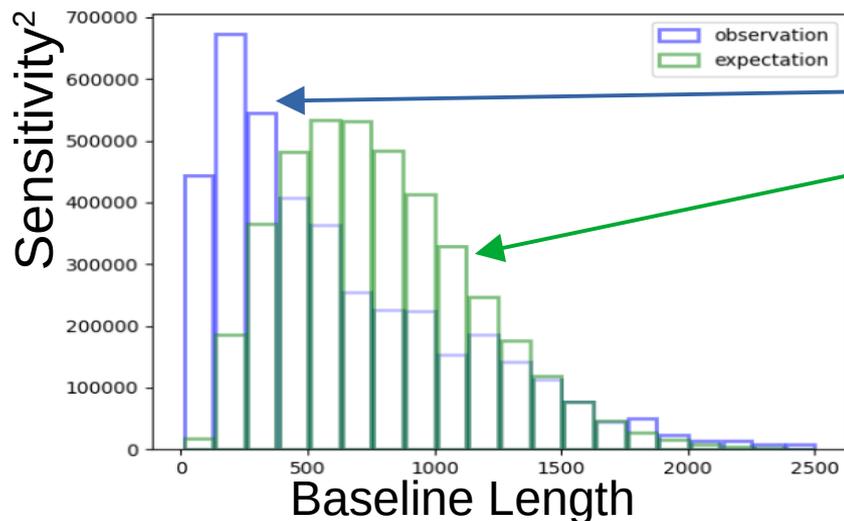
**or** Visibilities + Visibilities + Image (if there is more than one INT dataset)

# ALMA – data combination, uv coverage assessment

## A) Combination of interferometric data from different arrays

- relatively simple for the CASA user
- if all data uses same antenna diameter (e.g. ALMA TM1+TM2):  
just feed all calibrated data into CASA's CLEAN implementation "tclean" (**joint deconvolution**)
- heterogeneous arrays (e.g. ALMA 12M + 7M):  
need to use gridding "mosaic" (even for single pointing!)

**Beware: by combining different interferometric observations you can change the PSF shape!**



BLD = Baseline Length Distribution (histogram)

BLD shape for 2 h config 6 + 0.5 h of config 3

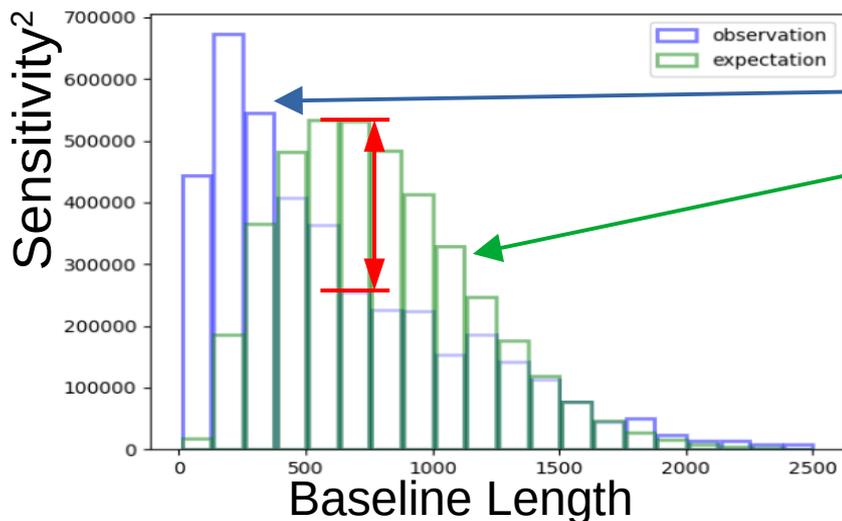
expected BLD shape for most Gaussian PSF for same angular resolution and sensitivity

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BLD = Baseline Length Distribution (histogram)

BLD shape for 2 h config 6 + 0.5 h of config 3

expected BLD shape for most Gaussian PSF for same angular resolution and sensitivity

**More Gaussian PSF means**

- less PSF sidelobes
- more reliable deconvolution
- less correlated noise in the image

# ALMA – data combination, uv coverage assessment

*What happens when sensitivity is missing in individual BL ranges?*

*What are the tolerable limits?*

ALMA development study 2020-2024 (Petry et al. 2024)

**Find that imaging is quite robust to azimuthally symmetric BLD defects.**

A sensitivity loss of 23% in a BL range (over all azimuths) **is tolerable**  
(systematic errors not larger than statistical)  
*- corresponds to 50% deficiency for a BLD bin*

*But what about azimuthally **asymmetric** defects?*

# ALMA – data combination, uv coverage assessment

For diagnosing uv coverage defects,  
introduced **4 x 10 uv coverage assessment matrix of “filling fractions”**  
**(FFs, Petry et al. 2024)**

$$FF = \text{observed \#visibilities (weighted)} / \text{expectation}$$

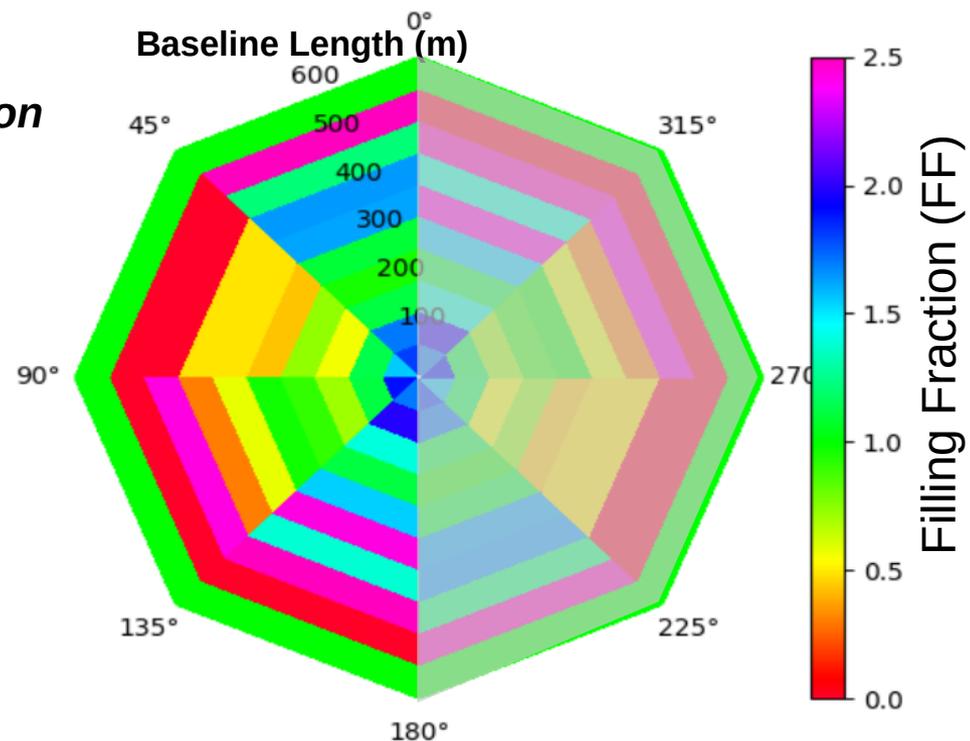
4 equidistant bins along azimuth,  
i.e. 4 sectors of 45 deg

10 equidistant bins along BL

Ideal result:  $FF = 1.0$  in all 40 bins.

*2D FF plot*

$$= \text{observed 2D BLD} / \text{ideal 2D BLD}$$

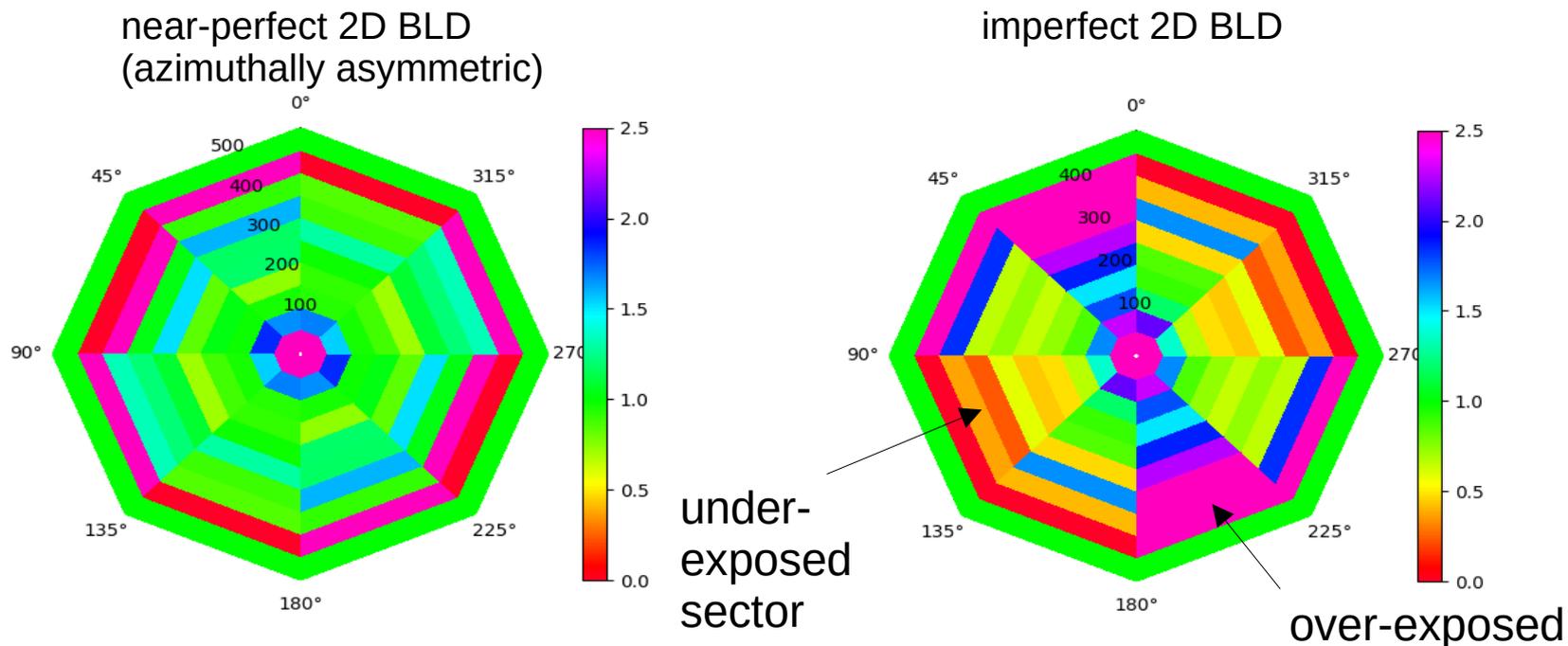


**Baseline Orientation Angle**  
(0 – 180 deg, other mirrored half plotted only by convention)

# ALMA – data combination, uv coverage assessment

What happens when the sensitivity is **azimuthally inhomogenous** in a BL range?  
 What are the tolerable limits?

Azimuthally asymmetric defects are **more disruptive** than symmetric ones!



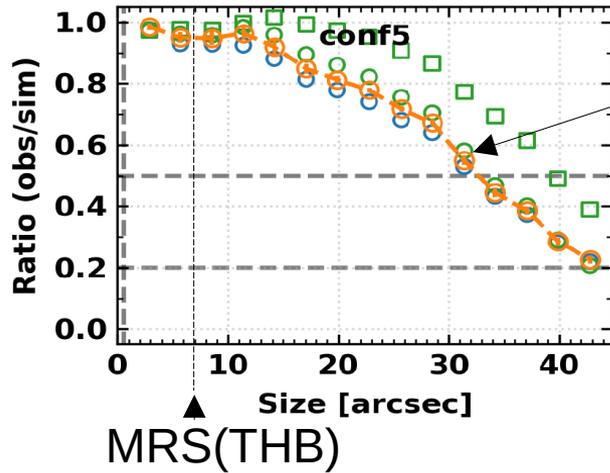
# ALMA – data combination, uv coverage assessment

**Azimuthally asymmetric defects also have a different name: incomplete tracks!**

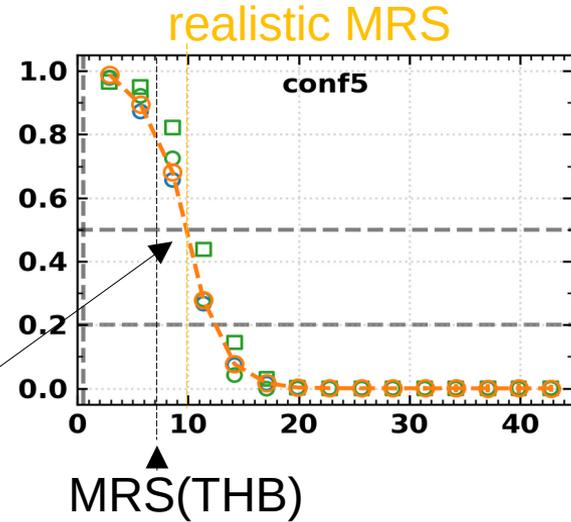
**At the shortest baselines, incomplete tracks *are particularly problematic!***

Example of flux recovery of Gaussian blobs of given size (FWHM) with an ALMA snapshot in C43-5:

*Inhomogeneous azimuthal coverage at short BLs results in strong image artifacts when the target becomes very extended, causes fake flux*



When incomplete tracks at the shortest baselines are **flagged**, the image artifacts disappear and the flux recovery behaves normally!



# Excursion: Impact of BLD defects on image properties

## Conclusions w.r.t. the interferometric component of your data:

- Have a look at the individual and combined BLDs in 1D and 2D!
- If you see (in 1D)  $> 50\%$  deviations from a reasonably smooth pseudo-Gaussian, then consider obtaining more data to fill the deficits, and/or flagging some data to eliminate too large excesses.
- If you see (in 2D)  $45^\circ$  sectors with drop-outs worse than  $75\%$  below expectation, you definitely need more data to fill the deficit.
- If the azimuthal drop-outs (incomplete tracks) are at the shortest baselines (lower  $10\%$  of the BLD), consider flagging all baselines of that length.
- Use our **new uv coverage assessment tool “`assess_ms`”!**  
(See talk during the last session of this tutorial.)

# Data combination under CASA

## Methods for combining interferometric data with single-dish data

### 1) Feather (CASA task “feather”)

- combination of two images in the Fourier plane
- assumes overlap in the spatial scales covered by the images
- main parameters: ***sdfactor*** controls SD flux scale,  
***effdishdiam*** controls SD weight

### 2) Model-Assisted Clean and Feather (MACF)

- use SD image as initial model in tclean, then Feather

### 3) SDINT (CASA task “sdintimaging”)

- joint deconvolution of visibilities and SD image via CLEAN
- uses Feather internally before every CLEAN minor cycle to combine SD and INT(erferometric) residual
- main parameter: ***sdgain*** controls *relative* SD weight

### 4) tp2vis (package for CASA <https://github.com/tp2vis/distribute>)

- convert SD image to pseudo-visibilities
- then use tclean to do joint deconvolution (heterogenous array)
- main parameter: *RMS\_tp estimate*
- *no longer maintained! Good idea, but presently no working implementation!*

# Data combination under CASA

## 1) Feather (CASA task “feather”)

- combination of two images in the Fourier plane
- assumes overlap in the spatial scales covered by the images
- main parameters: ***sdfactor*** controls SD flux scale  
***effdishdiam*** controls SD weight (must be < true dishdiam)

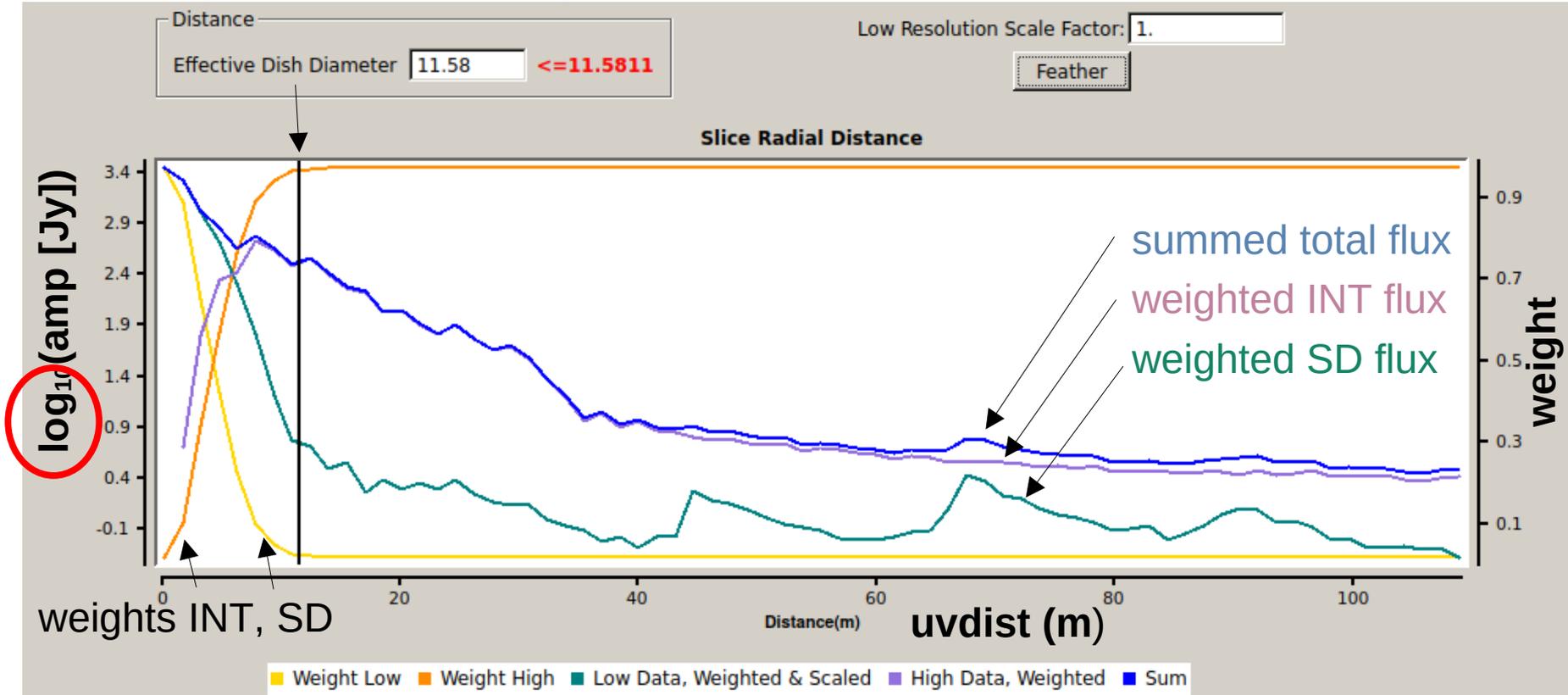
Typical procedure:

- i. **tclean** all interferometric MSs using **gridder='mosaic'**, **pbcor=True** to create the INT image or cube
- ii. Prepare the SD image or cube to have
  - a) the "**restoringbeam**" set to the size of the SD primary beam (**imhead**)
  - b) the same **flux units** as the INT image, typically Jy/beam (**imhead**, **immath**)
  - c) the same **axisnames and axisunits** as the INT image (**imhead**), typically ['Right Ascension', 'Declination', 'Stokes', 'Frequency'], ['rad', 'rad', '', 'Hz']
  - d) the same **spectral grid** as the interferometric image (**imregrid**)
- iii. **feather** the INT with the SD image

```
feather(highres='myinterferometric.image.pbcor',
        lowres='mysingledish.image',
        sdfactor=1., effdishdiam=-1, # (default values)
        imagename = 'myfeather-combined.image')
```

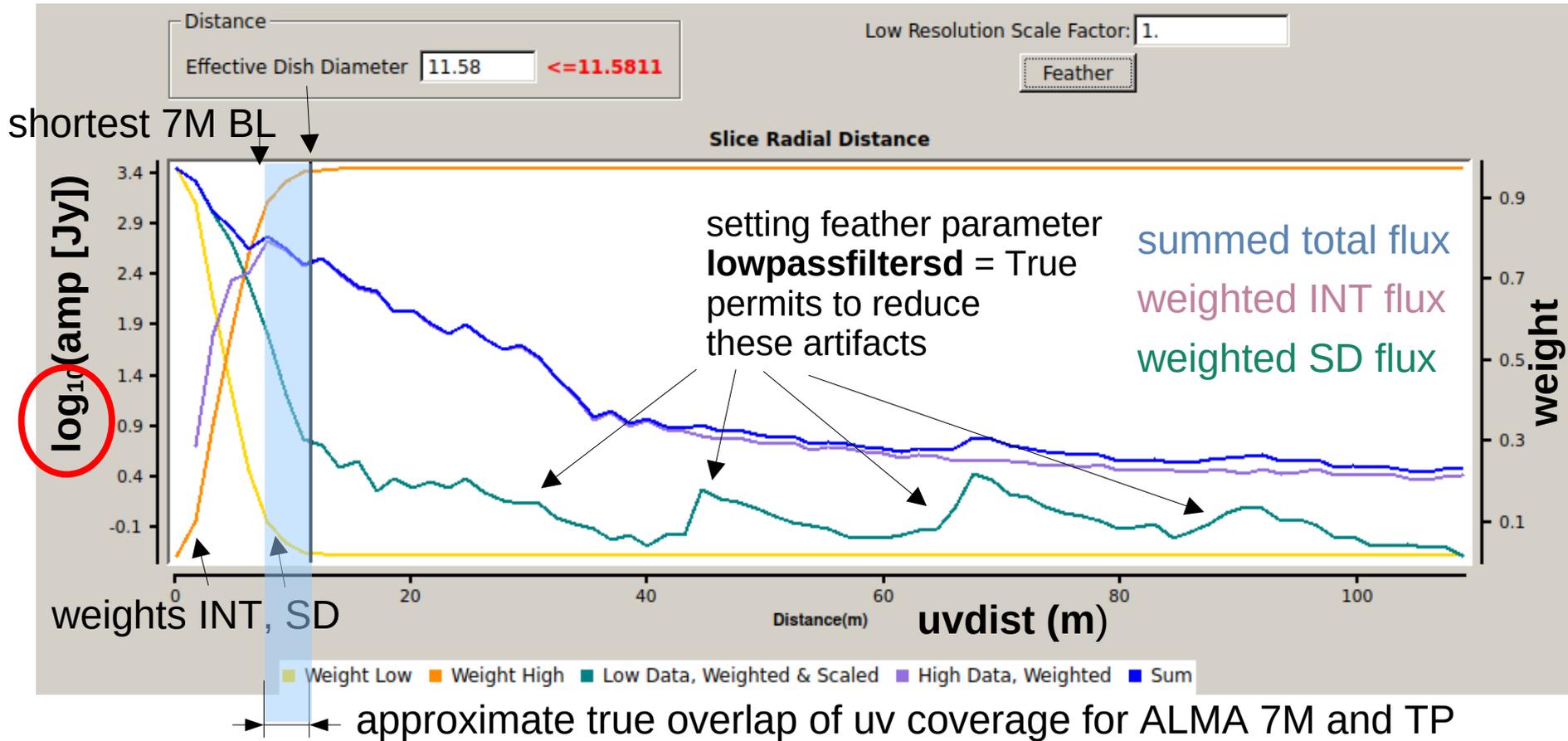
# Data combination under CASA - Feather

1) Feather (CASA task "feather"): Understand the parameters by playing with GUI tool "casafeather"



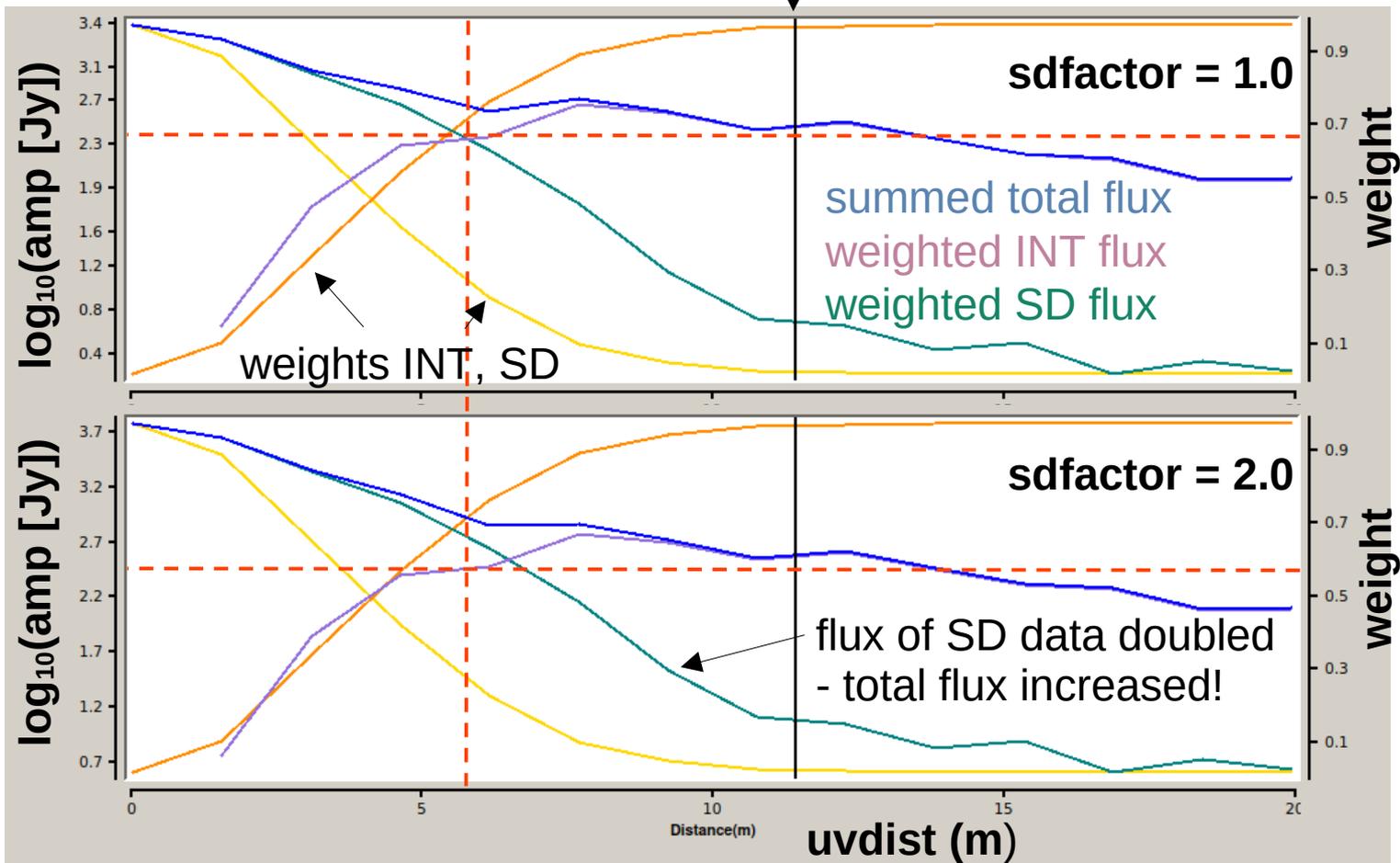
# Data combination under CASA – Feather, lowpassfiltersd

1) Feather (CASA task “feather”): Understand the parameters by playing with GUI tool “casafeather”



# Data combination under CASA – Feather, sdfactor

effdishdiam (weights reach ca. 5%, 95%)



# Data combination under CASA – MACF

## 2) Model-Assisted Clean and Feather (MACF)

(also called "Hybrid" in Plunkett et al. 2023)

- use SD image as initial model in Clean
- then Feather

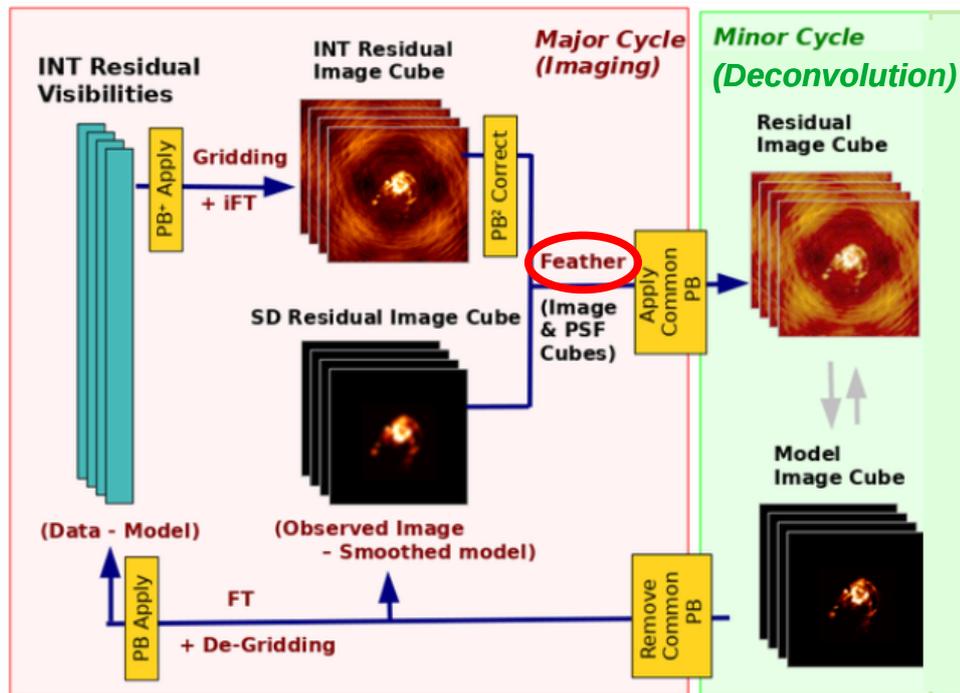
Typical procedure:

- i. Decide on `tclean` parameters to create INT image and produce dirty test image to get exact image parameters
- ii. Prepare SD image as for Feather
- iii. **`tclean`** as for Feather but setting **`startmodel=<SDimage>`** to obtain INT image (NOTE: you need to set `nterms=1` if you use deconvolver 'mtmfs')
- iv. Feather SD image and INT image

# Data combination under CASA – sdintimaging

## 3) SDINT (CASA task “sdintimaging”, algorithm: Rau, Naik & Braun 2019)

- joint deconvolution of visibilities and SD image via CLEAN
- uses Feather internally before every CLEAN minor cycle to combine SD and INT residual
- main parameter: ***sdgain*** controls *relative* SD weight in feather step



*More about this during the hands-on session!*

# Data combination under CASA – sdintimaging

## 3) SDINT (CASA task “sdintimaging”, algorithm: Rau, Naik & Braun 2019)

- joint deconvolution of visibilities and SD image via CLEAN
- uses Feather internally before every CLEAN minor cycle to combine SD and INT residual
- main parameter: ***sdgain*** controls *relative* SD weight

Typical procedure:

- Decide on `tclean` parameters to create INT image and produce dirty image to get exact image parameters
- Prepare SD image as for Feather
- Run **sdintimaging**:  
input data: `vis` = <the INT MSs (as a list)>  
`sdimage` = <the SD image>

*More about this during the hands-on session!*

# ALMA – data combination summary

- As users of interferometers you should **verify if you need to improve the angular scale coverage!** Improvement is possible using “**data combination**” with shorter-spacing visibilities or with SD-images
- ALMA often already provides the necessary components in **GroupOUSs with up to 4 members**. SD images can also be taken from other observatories.
- Combination of data from different interferometer arrays (especially TM1+TM2+7M) is called “**joint deconvolution**” and can be done using tclean with gridder "mosaic"
- For ALMA/CASA users, the easily available methods for data combination with SD-data are **Feather** and the feather-based **MACF** and **SDINT**
- Another promising approach is **tp2vis**: generation of pseudo-visibilities with simulated array. A version for CASA 6 will hopefully be developed some time in the future.
- **Plunket, Hacar, Moser-Fischer et al. (2023)** found that MACF and SDINT are the methods which perform best in terms of image fidelity.
- **Petry, Diaz Trigo, Kneissl et al. (2024)** (the ALMA internal dev. study on uv coverage assessment and scheduling) have developed tools and criteria to measure the quality of the uv coverage of your interferometric data. Use **assess\_ms 3.0** ! Pay special attention to azimuthal coverage!