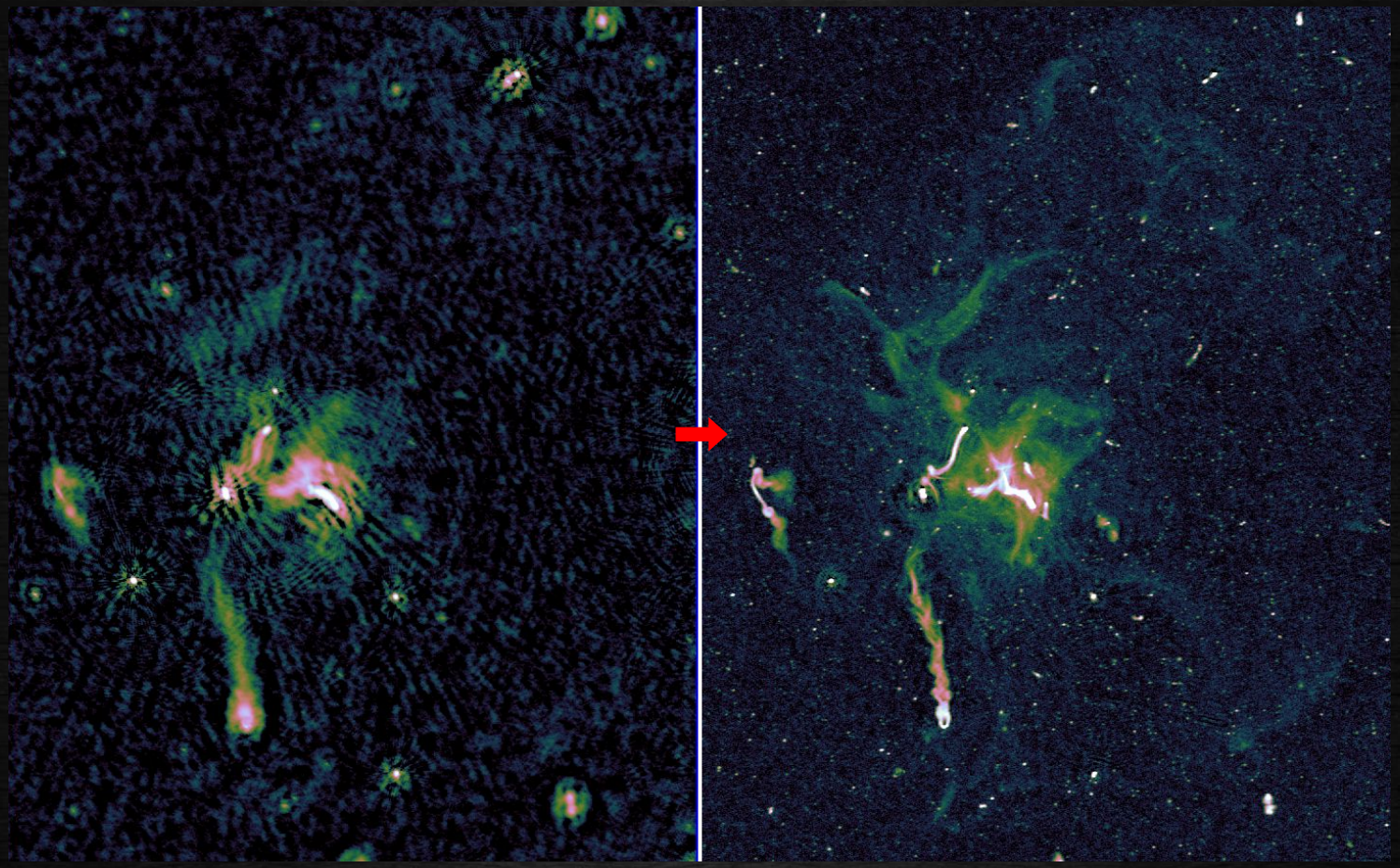
# Analysis techniques to characterize extended sources

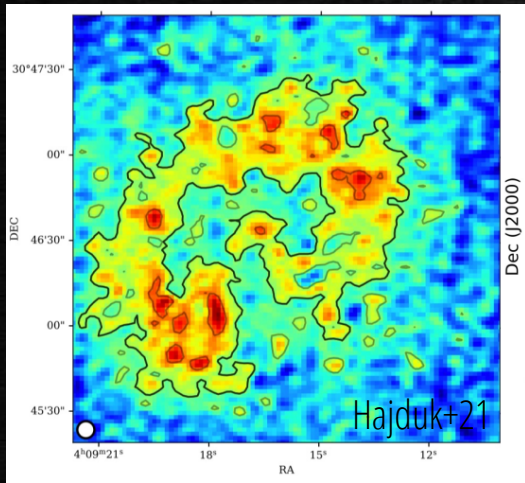


*Istituto Nazionale di Astrofisica (INAF)*
*Istituto di Radioastronomia (IRA)*

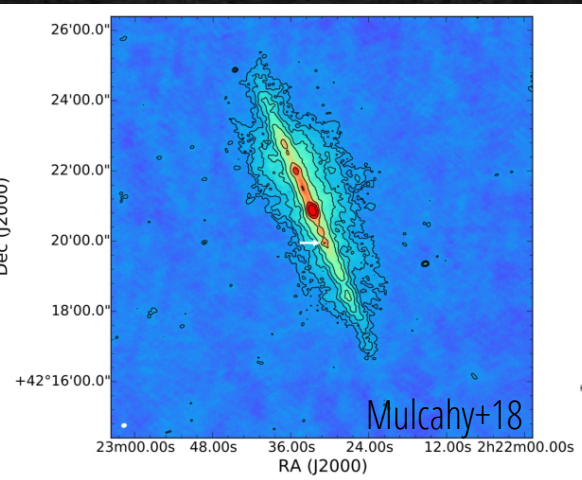
**Andrea BOTTEON**

September 18, 2026 – The eighth LOFAR Data School, Dwingeloo

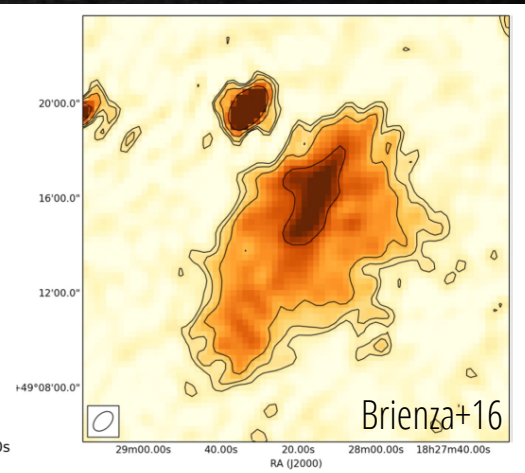
# Extended radio sources...



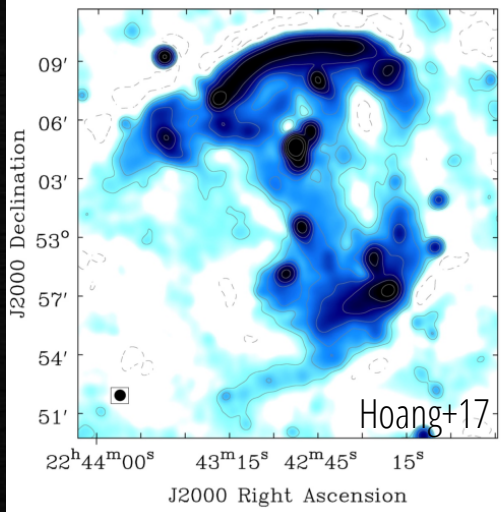

**Planetary nebula:** $D \sim 2'$



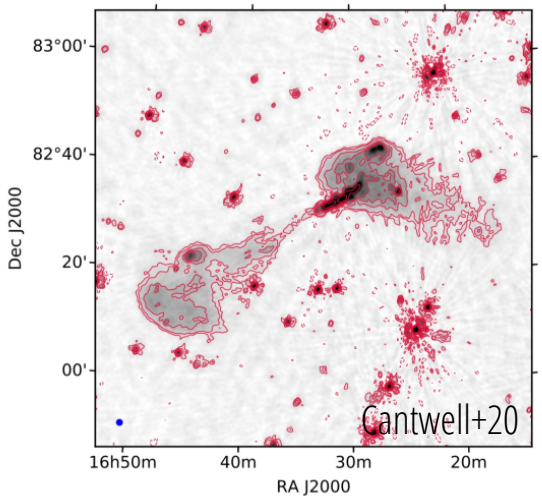

**Disk galaxy:** $D \sim 7'$



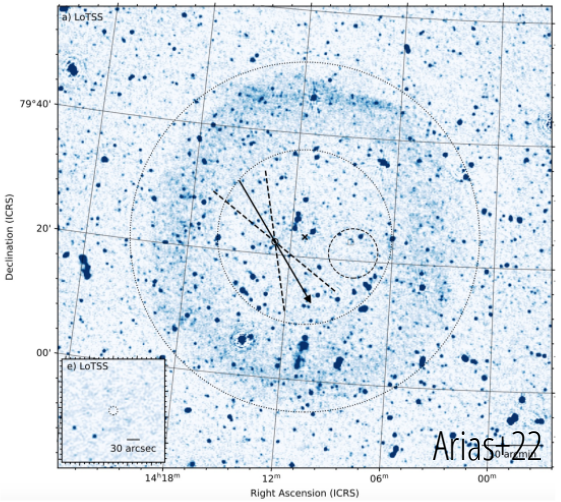

**Remnant radio galaxy:** $D \sim 12'$




**Galaxy cluster:** $D \sim 16'$



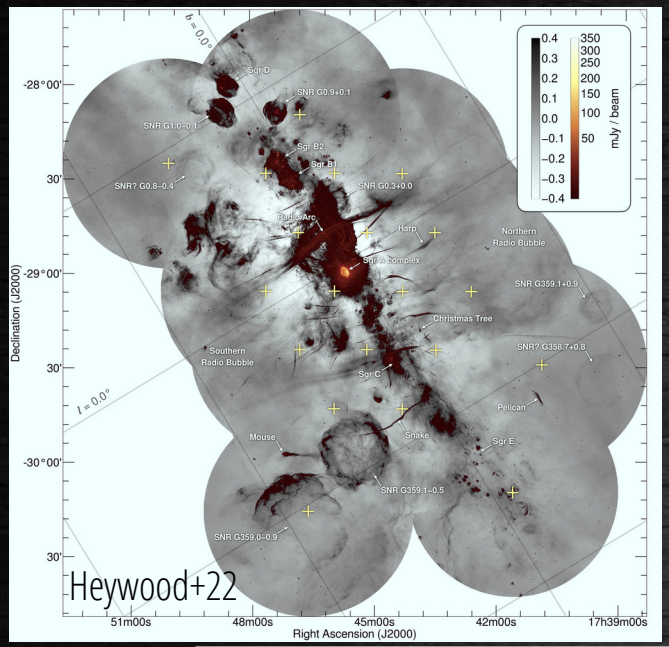

**Giant radio galaxy:** $D \sim 19'$

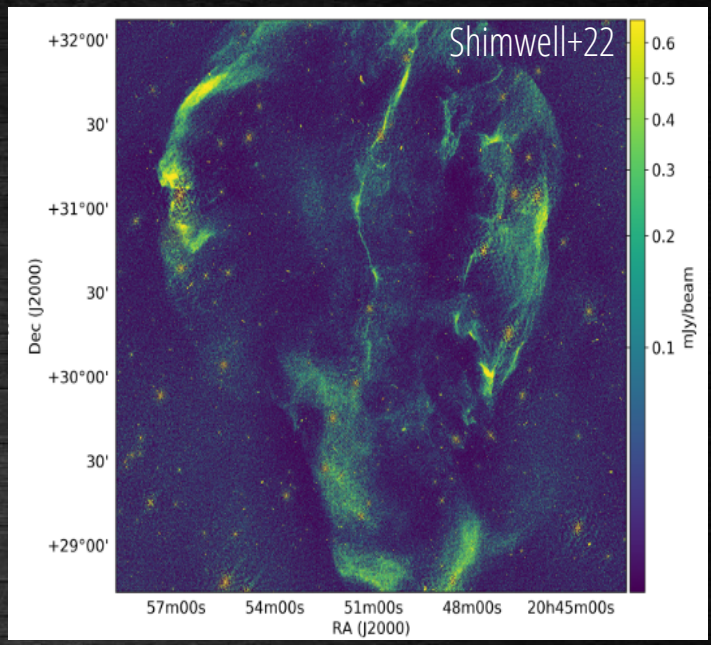


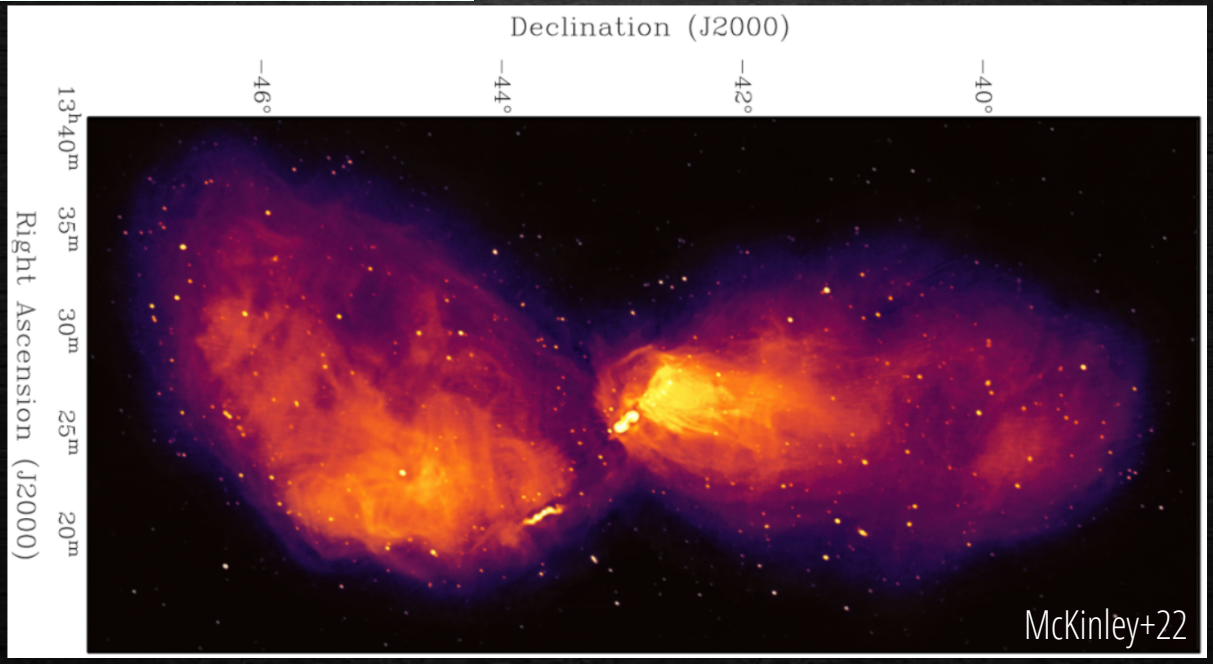

**Supernova remnant:** $D \sim 1°$

Diffuse radio sources can span a wide range of angular scales and can have very different origin (**galactic** and **extragalactic**)

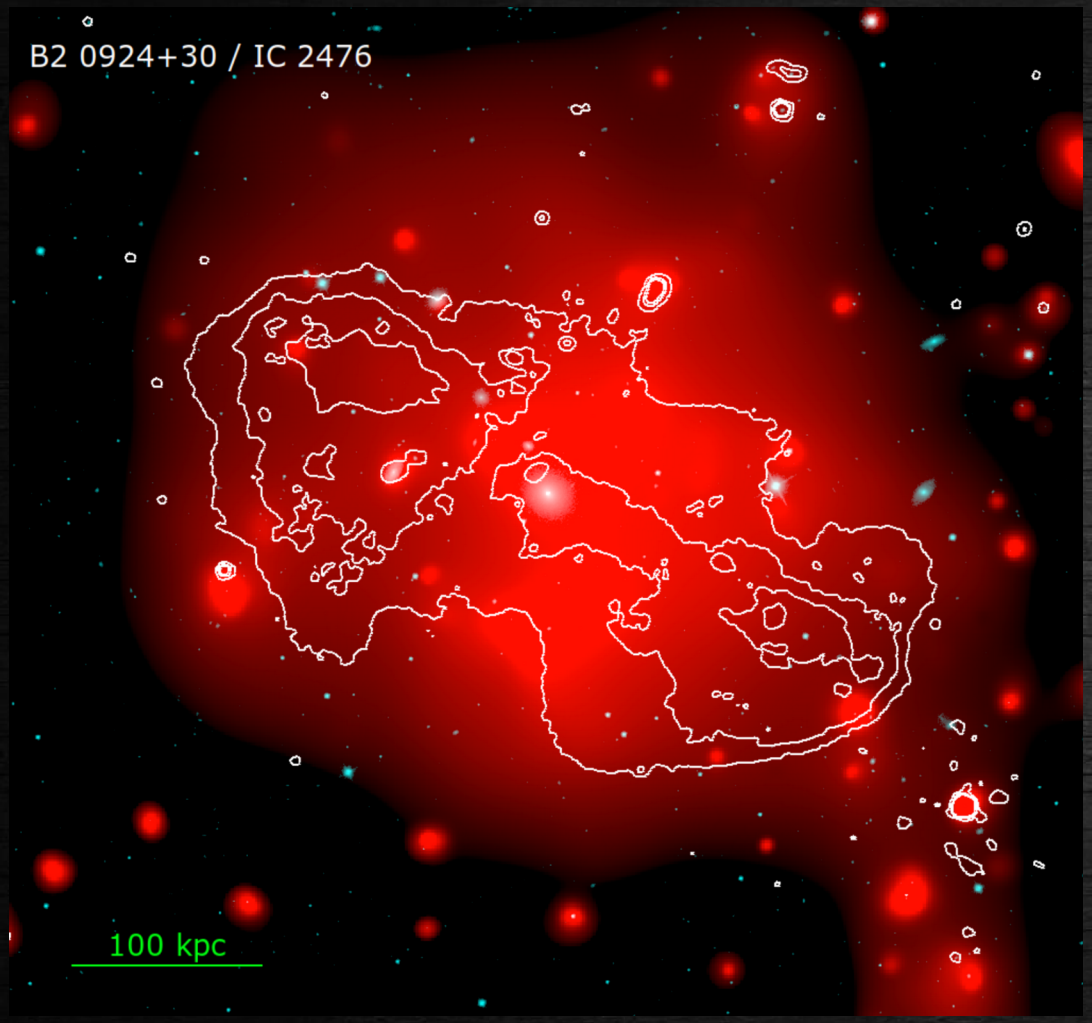
# ...and very extended radio sources

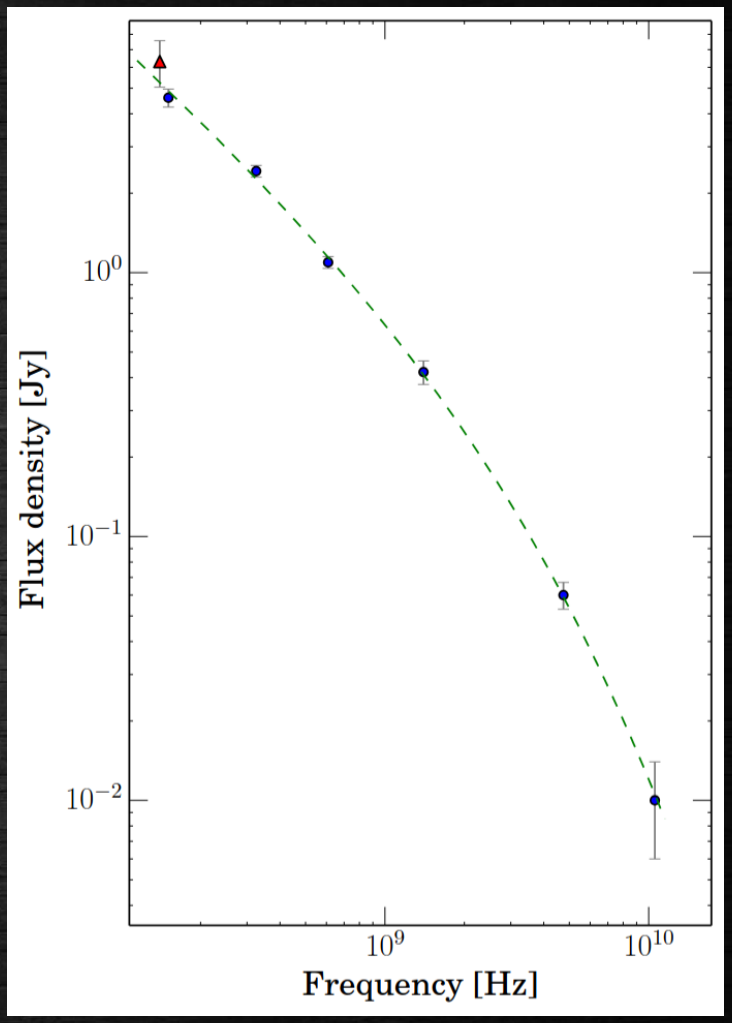


# Our target: IC 2476




**IC 2476** is a remnant radio galaxy at z=0.027 (1” = 0.536 kpc)

(e.g. Shulevski+17)

# Setup the environment

```
tar xzvf IC2476.avg.tar.gz

apptainer shell flocs_v6.2.2_[znver2_znver2|sandybridge_sandybridge].sif \
 --noprofile --norc
```

INFO: the FoV of the image is 24’x24’. The dataset has been “extracted” from LoTSS and “recalibrated” with facetselfcal.

```
This color will highlight the running time on my machine (12xCPU, 30GB RAM)
```

# Basic clean

```
wsclean -no-update-model-required \
 -minuv-l 80.0 -size 1200 1200 -scale 1.2arcsec \
 -weight briggs -0.5 \
 -mgain 0.8 -data-column DATA \
 -join-channels -channels-out 6 \
 -fit-spectral-pol 3 \
 -auto-mask 2.5 -auto-threshold 0.5 \
 -niter 100000 \
 -name IC2476_ROBUST-0.5 \
 IC2476.ms.avg

real    0m57.317s
```

Check image and residual.

```
ds9 IC2476_ROBUST-0.5-MFS-image.fits IC2476_ROBUST-0.5-MFS-residual.fits -scale log -scale limits -1e-4 5e-2 -cmap cubehelix0 -lock frame wcs -lock scale yes -lock colorbar yes
```

Do you notice the issue?

# Add multiscale

```
wsclean -no-update-model-required \
 -minuv-l 80.0 -size 1200 1200 -scale 1.2arcsec \
 -weight briggs -0.5 \
 -mgain 0.8 -data-column DATA \
 -join-channels -channels-out 6 \
 -fit-spectral-pol 3 \
 -auto-mask 2.5 -auto-threshold 0.5 \
 -niter 100000 \
 -name IC2476_ROBUST-0.5ms \
 -multiscale \
 IC2476.ms.avg

real    2m1.457s
```

Check image and residual

```
ds9 IC2476_ROBUST-0.5ms-MFS-image.fits IC2476_ROBUST-0.5ms-MFS-residual.fits -scale log -scale limits -1e-4 5e-2 -cmap cubehelix0 -lock frame wcs -lock scale yes -lock colorbar yes
```

Compare previous model with present model

```
ds9 IC2476_ROBUST-0.5-MFS-model.fits IC2476_ROBUST-0.5ms-MFS-model.fits -scale linear -scale limits 0 5e-5 -cmap cubehelix0 -lock frame wcs -lock scale yes -lock colorbar yes
```

# Taper!

```
wsclean -no-update-model-required \
 -minuv-l 80.0 -size 360 360 -scale 4.0arcsec \
 -weight briggs -0.5 \
 -mgain 0.8 -data-column DATA \
 -join-channels -channels-out 6 \
 -fit-spectral-pol 3 \
 -auto-mask 2.5 -auto-threshold 0.5 \
 -niter 100000 \
 -name IC2476_ROBUST-0.5msTAPER15 \
 -multiscale \
 -taper-gaussian 15.0 \
 IC2476.ms.avg

real    0m11.573s
```

Check image and residual

```
ds9 IC2476_ROBUST-0.5msTAPER15-MFS-image.fits IC2476_ROBUST-0.5msTAPER15-MFS-residual.fits -scale log -scale limits -1e-3 5e-1 -cmap cubehelix0 -lock frame wcs -lock scale yes -lock colorbar yes
```

Compare previous image with present image, what are the rms?

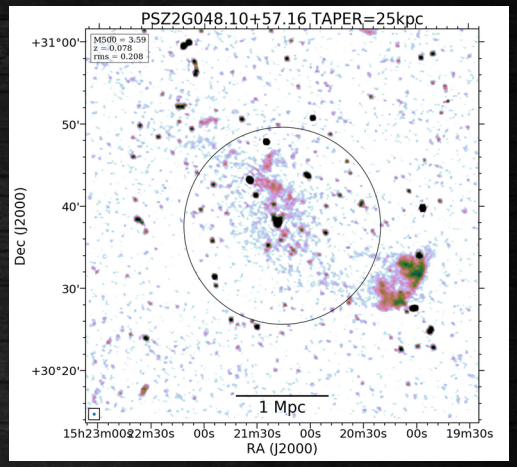
```
ds9 IC2476_ROBUST-0.5ms-MFS-image.fits IC2476_ROBUST-0.5msTAPER15-MFS-image.fits -scale log -scale limits -1e-4 5e-2 -cmap cubehelix0 -lock frame wcs -lock scale yes -lock colorbar yes
```

# Subtraction of discrete sources

Discrete sources (mainly AGN) **contaminate** the extended emission

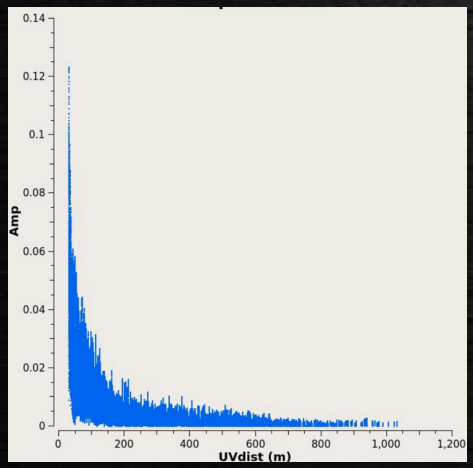
## Image-plane subtraction:

the contribution of the contaminating sources is subtracted a posteriori, in the **final image**. Fast but can be problematic (e.g. when your image has a low resolution)

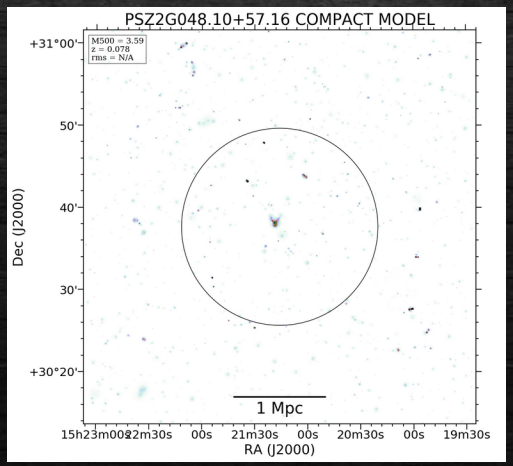



## uv-plane subtraction:

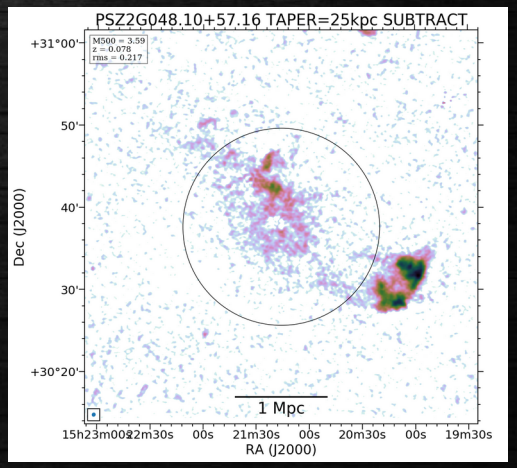
clean components of discrete sources are directly subtracted from the **visibility data**. Powerful but more time consuming




-

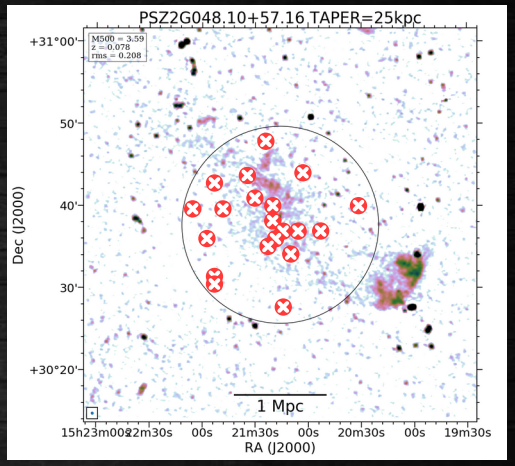



=



# Subtraction of discrete sources

Discrete sources (mainly AGN) **contaminate** the extended emission

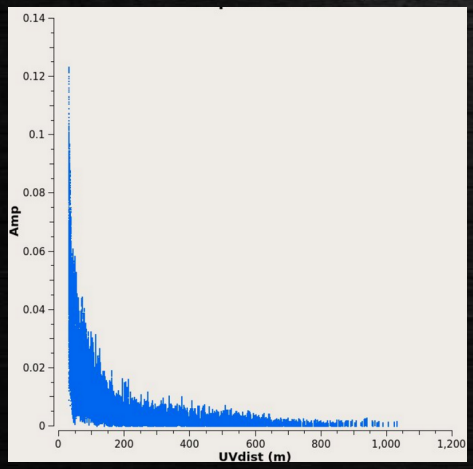



## Image-plane subtraction:

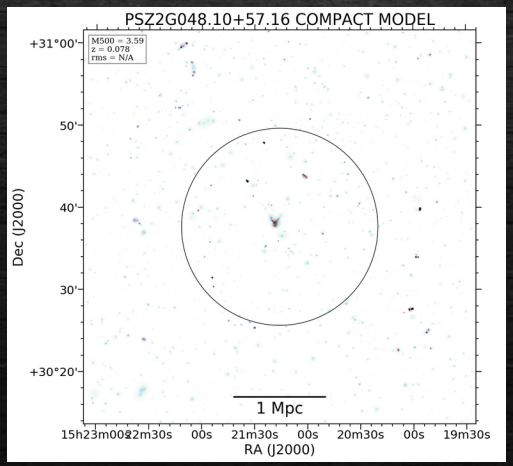
the contribution of the contaminating sources is subtracted a posteriori, in the **final image**. Fast but can be problematic (e.g. when your image has a low resolution)

## uv-plane subtraction:

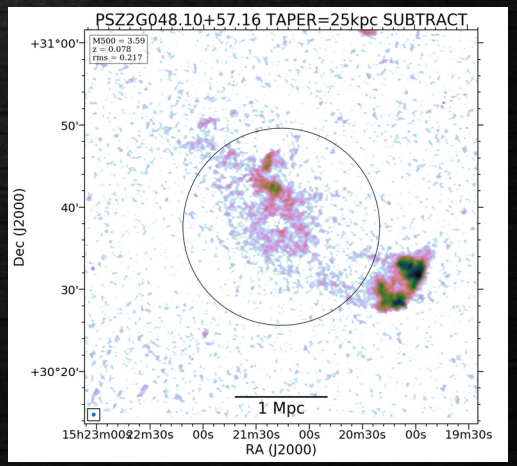
clean components of discrete sources are directly subtracted from the **visibility data**. Powerful but more time consuming




-



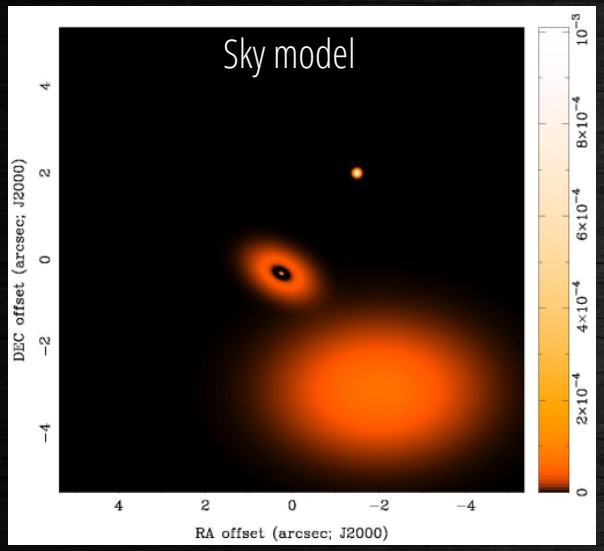

=

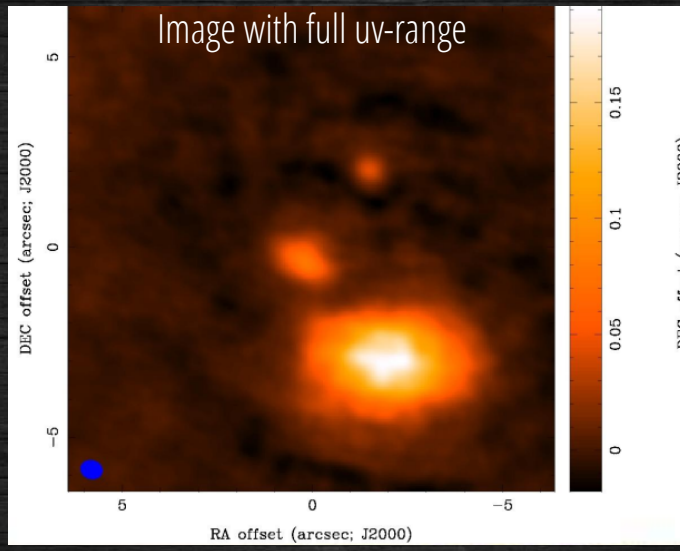


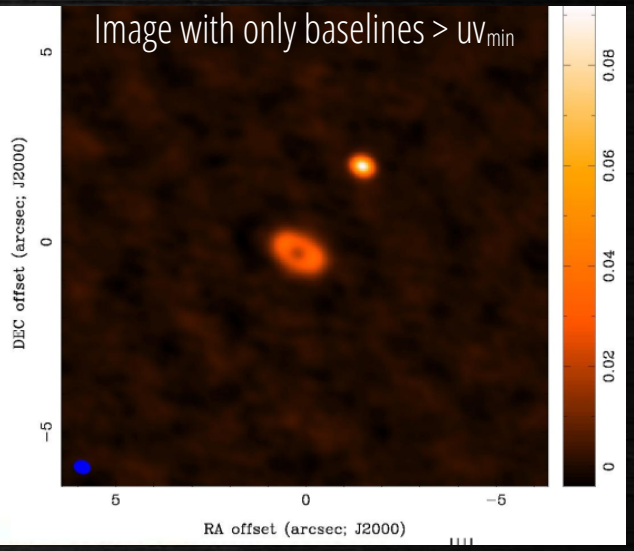
# uv-plane subtraction

How to make the model for the subtraction?

1) High resolution + high $uv_{min}$ imaging $\theta_{\max} = \lambda/B_{\min} = 206265/uv_{\min}$ [arcsec]
2) Subtract from the visibility data the model obtained
3) Reimage the residual visibilities




The extended emission disappeared because it can be recovered only by baselines **shorter than $uv_{min}$**

→ we can use this to our advantage to **filter out** the extended emission and image **only** the discrete sources that we want to subtract

# Source subtraction

Discrete sources contaminate the diffuse emission: we want to subtract them

Let's make an image containing only discrete sources, then we subtract the corresponding model from the visibilities.

To make a image containing only discrete sources we need:
1) high resolution
2) filter out the diffuse emission

# Make discrete sources model

```
wsclean -no-update-model-required \
 -minuv-l 4000.0 -size 1440 1440 -scale 1.0arcsec \
 -weight briggs -1.0 \
 -mgain 0.8 -data-column DATA \
 -join-channels -channels-out 6 \
 -fit-spectral-pol 3 \
 -auto-mask 2.5 -auto-threshold 0.5 \
 -niter 100000 \
 -name IC2476_ROBUST-1.0uvmin4kl \
 IC2476.ms.avg

real    0m15.389s
```

Check image and residual

```
ds9 IC2476_ROBUST-1.0uvmin4kl-MFS-image.fits IC2476_ROBUST-1.0uvmin4kl-MFS-
residual.fits -scale log -scale limits -1e-4 5e-2 -cmap cubehelix0 -lock frame
wcs -lock scale yes -lock colorbar yes
```

What does the model tell us?

```
ds9 IC2476_ROBUST-1.0uvmin4kl-MFS-model.fits -scale linear -scale limits 0 5e-5
-cmap cubehelix0
```

# Guide the clean with a mask

```
MakeMask.py --RestoredIm=IC2476_ROBUST-1.0uvmin4kl-MFS-image.fits \
 --Th=3.0 \
 --Box=100,2
```

Check the generated mask

```
ds9 IC2476_ROBUST-1.0uvmin4kl-MFS-image.fits IC2476_ROBUST-1.0uvmin4kl-MFS-
image.fits.mask.fits -scale log -scale limits -1e-4 5e-2 -cmap cubehelix0 -lock
frame wcs -lock scale yes -lock colorbar yes
```

Clean with mask

```
wsclean -no-update-model-required \
 -minuv-l 4000.0 -size 1440 1440 -scale 1.0arcsec \
 -weight briggs -1.0 \
 -mgain 0.8 -data-column DATA \
 -join-channels -channels-out 6 \
 -fit-spectral-pol 3 \
 -auto-mask 2.5 -auto-threshold 0.5 \
 -niter 100000 \
 -name IC2476_maskROBUST-1.0uvmin4kl \
 -multiscale -multiscale-max-scales 2 \
 -fits-mask IC2476_ROBUST-1.0uvmin4kl-MFS-image.fits.mask.fits \
 IC2476.ms.avg

real    0m40.263s
```

# Model prediction

Compare previous model with present model

```
ds9 IC2476_ROBUST-1.0uvmin4kl-MFS-model.fits IC2476_maskROBUST-1.0uvmin4kl-MFS-model.fits -scale linear -scale limits 0 5e-5 -cmap cubehelix0 -lock frame wcs -lock scale yes -lock colorbar yes
```

Satisfied?

Fill the MODEL_DATA column

```
wsclean -predict \
 -channels-out 6 \
 -name IC2476_maskROBUST-1.0uvmin4kl \
 IC2476.ms.avg

real    0m5.558s
```

Now we will make a new column “DIFFUSE_SUB”, by subtracting the MODEL_DATA column to the DATA column

# Subtraction

Add a new column to the ms:

```
DP3 msin=IC2476.ms.avg msout=. steps=[] msin.datacolumn=DATA
msout.storagemanager=dysco msout.datacolumn=DIFFUSE_SUB

real    0m2.025s
```

Subtract the model of discrete sources from the data:

```
taql "UPDATE IC2476.ms.avg SET DIFFUSE_SUB = DATA - MODEL_DATA"

real    0m2.041s
```

# Imaging only the diffuse emission 1/2

```
wsclean -no-update-model-required \
 -minuv-l 80.0 -size 1200 1200 -scale 1.2arcsec \
 -weight briggs -0.5 \
 -mgain 0.8 -data-column DIFFUSE_SUB \
 -join-channels -channels-out 6 \
 -fit-spectral-pol 3 \
 -auto-mask 2.5 -auto-threshold 0.5 \
 -niter 100000 \
 -name IC2476_subROBUST-0.5ms \
 -multiscale \
 IC2476.ms.avg

real    2m18.729s
```

Compare with non-subtracted image

```
ds9 IC2476_ROBUST-0.5ms-MFS-image.fits IC2476_subROBUST-0.5ms-MFS-image.fits -
scale log -scale limits -1e-4 5e-2 -cmap cubehelix0 -lock frame wcs -lock scale
yes -lock colorbar yes
```

# Imaging only the diffuse emission 2/2

```
wsclean -no-update-model-required \
 -minuv-l 80.0 -size 360 360 -scale 4.0arcsec \
 -weight briggs -0.5 \
 -mgain 0.8 -data-column DIFFUSE_SUB \
 -join-channels -channels-out 6 \
 -fit-spectral-pol 3 \
 -auto-mask 2.5 -auto-threshold 0.5 \
 -niter 100000 \
 -name IC2476_subROBUST-0.5msTAPER15 \
 -multiscale \
 -taper-gaussian 15.0 \
 IC2476.ms.avg

real    0m10.800s
```

Compare with non-subtracted image

```
ds9 IC2476_ROBUST-0.5msTAPER15-MFS-image.fits IC2476_subROBUST-0.5msTAPER15-
MFS-image.fits -scale log -scale limits -1e-3 5e-1 -cmap cubehelix0 -lock frame
wcs -lock scale yes -lock colorbar yes
```

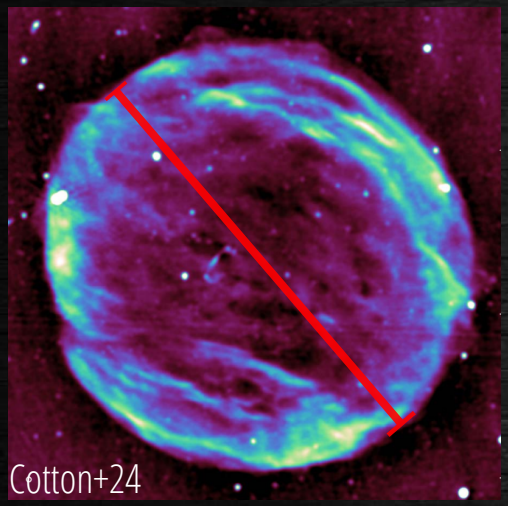
Now you are ready to measure the properties of the diffuse emission.

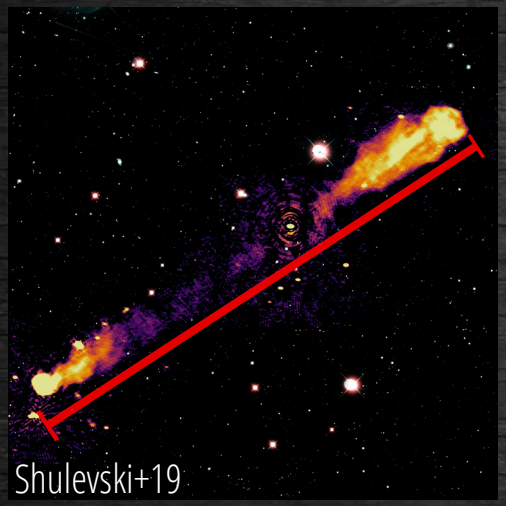
# Properties of extended sources

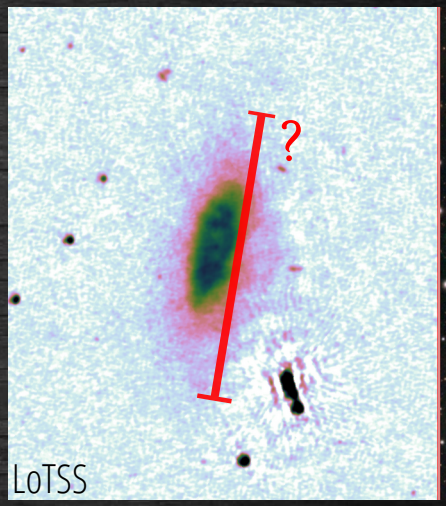
Now that you have images at multiple resolutions, with/without discrete sources removed, you are ready to measure the **source properties**

- **Largest-angular size** (LAS) and **largest-linear size** (LLS):

→ probably the *easiest* property that you can derive…but pay attention that often diffuse sources do not have sharp boundaries!


Cotton+24


Shulevski+19



LoTSS


PanSTARRS

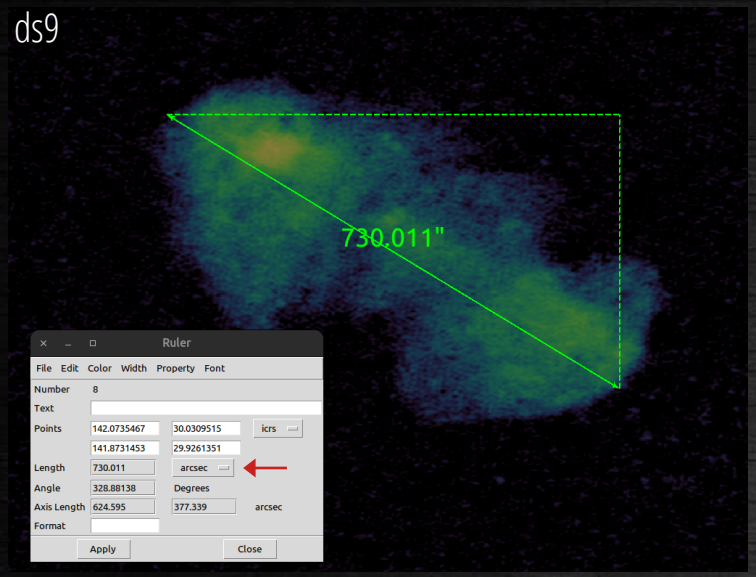
- **Volume** (V):

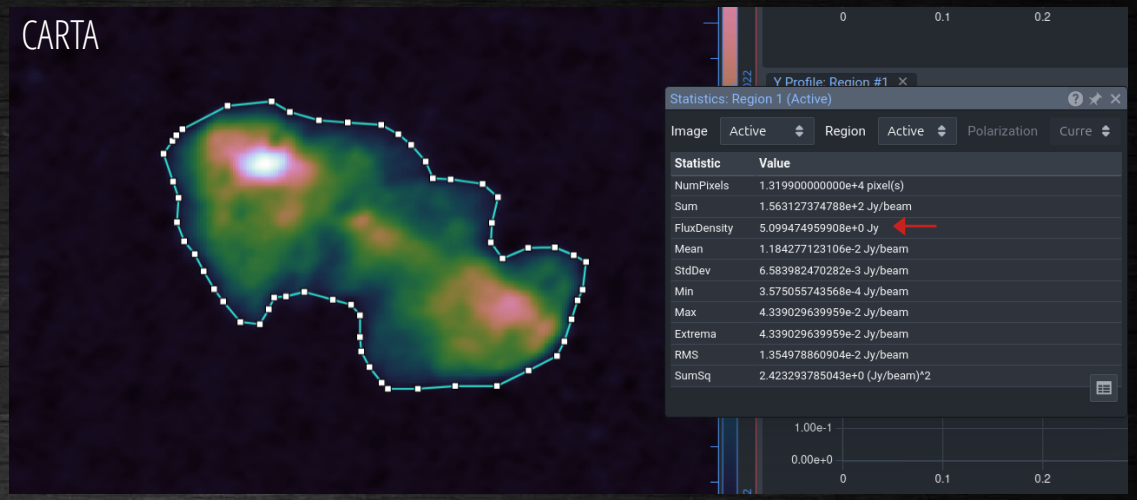
→ a real problem in astronomy due to the missing 3$^{rd}$ dimension: usually *spherical/ellipsoidal/cylindrical* geometries are assumed

- **Flux density** ($S_\nu$):

→ probably *the most relevant* property that you can derive: with $S_\nu$ you can derive the *power* ($P_\nu$), with $P_\nu$ + V you can derive the *emissivity* ($\varepsilon_\nu$)

# Let's measure LAS and $S_\nu$




$$\Delta S_{\rm diffuse} = \sqrt{\sigma^2_{\rm stat} + \sigma^2_{\rm sys}}$$

$$= \sqrt{\left(\sigma_{\rm rms} \times \sqrt{\frac{A_{\rm s}}{A_{\rm b}}}\right)^2 + (\delta_{\rm cal} \times S_{\rm diffuse})^2}$$

$\sigma_{rms}$ is the image noise

$A_s$ is the area of the source (NumPixels in CARTA)

$A_b$ is the area of the beam ($A_{b,arcsec} \sim 1.13 \times \theta_{max} \times \theta_{min} \rightarrow A_{b,pix} = A_{b,arcsec}$ / pixel$^2$)

$\delta_{cal}$ is the systematic uncertainty on the flux scale (10% for LoTSS)

# Data challenge: Abell 665



1) Find out what kind of object this is
2) Produce images at different resolutions (the FoV of the observation is 20'x20')
3) Subtract emission of discrete sources
4) Measure the properties of the diffuse emission (angular/linear size, flux density, power, emissivity, etc.)...and compare them with similar objects?

For point 2: explore different robust values and/or taper
For point 3: explore different -minuv-l in the creation of the model of the discrete sources to subtract. How does this impact the final measurement?

**Main suggestion:** follow what we have done during the tutorial...