Combining Single Dish and Interferometric Data

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and for the tutorial:

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Goals

- Single Dish vs. Interferometry, and why combine?
- Learn techniques to combine
- How to measure success
  - Total Flux, of Flux(channel) “spectrum” plot
  - Noise
  - Image Fidelity (like a S/N map)
    - F = Model / (Model - Observed)
  - Image Properties (science driven?)
    - PDS
    - Mom0 (flux), Mom1 (mass), Mom2 (turbulence)
- Group Photo
- Lunch
- Tutorial
- ? B & B ?

Tutorial Session

2h + 1.5h or 1.5h + 2h ?

- 13:00 – 13:05 : git on github **“why git?”**
- 13:05 – 15:00 : common exercises **“repeat after me”**
  - Feather and tp2vis combination
- 15:30 – 17:00 : group exercices **“hack hour”**
  - What-IF Exploratory exercises
    - Scale factors
    - Weight factors
    - Influence of choice or arrays and dish sizes
    - Current Algorithms (feather, tp2vis, sd2vis, ssc)
    - New Algorithms (stani)

And then there was this....

- HDD:
  - **Data** for tutorials 1,3,4/5
    - Directories: CASA_SD,CLASS, CASA_QAC
  - **Papers** : ~40 papers in ~ 140MB
    - Note these are not on wiki, only on the HDD
- **Software** via SD2018 github
  - Instructions for CASA,QAC,tp2vis etc.
  - Python3 miniconda + radio-astro-tools / astropy / APLpy / ....
  - Fits viewers: ds9, casaviewer, QfitsView
- GIT?
  - Intro to git for beginners
  - “git pull request” (*I’ll just send you a PR*)

I'm going to skip....

van Cittert - Zernicke relation

$$\mathcal{V}(u,v) = \iint I(l,m) e^{-2\pi i(ul+vm)} dl dm$$

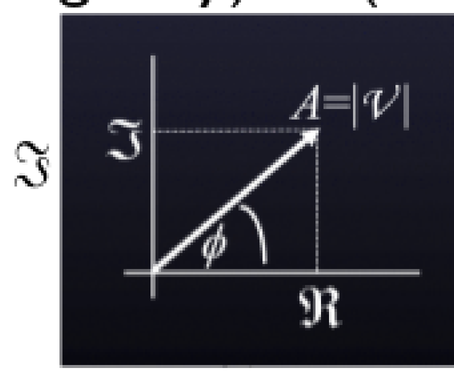
$$I(l,m) = \iint \mathcal{V}(u,v) e^{2\pi i(ul+vm)} du dv$$

$I(l,m)$ can be recovered from $V(u,v)$ via Fourier Transform

$V(u,v)$ expressed as (real, imaginary) or (amplitude, phase)

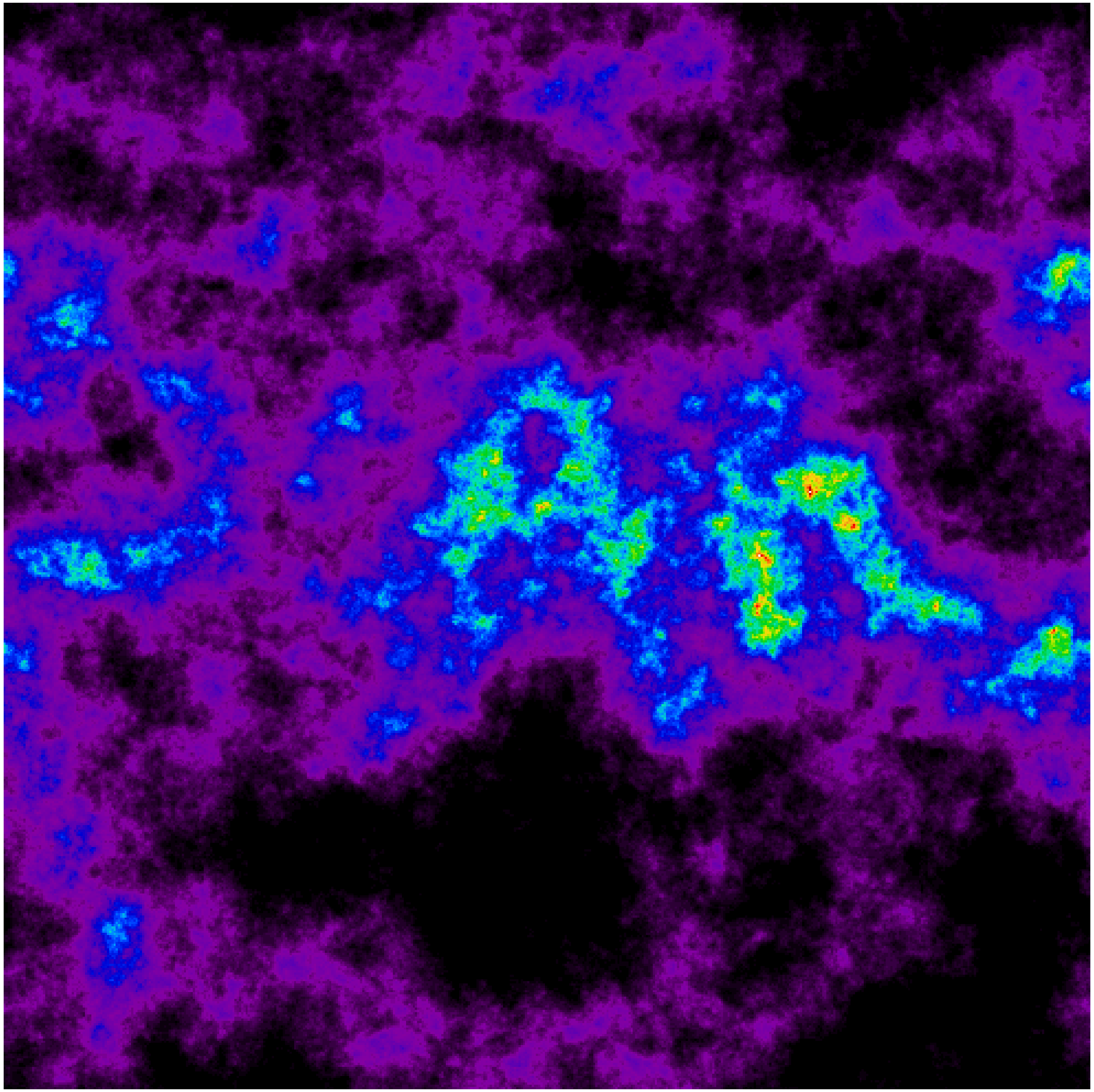
$$A = \sqrt{\Re^2 + \Im^2}$$

$$\phi = \tan^{-1}\left(\frac{\Im}{\Re}\right)$$

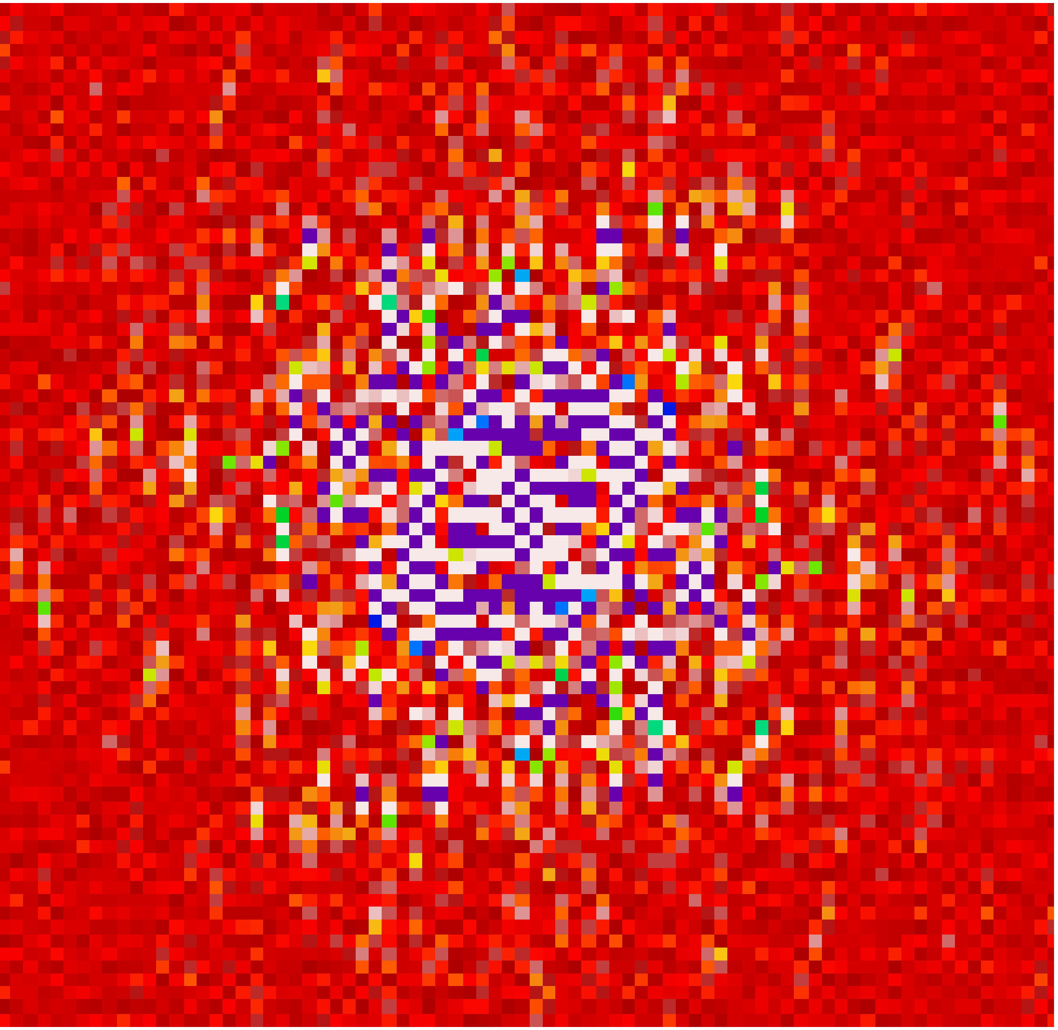


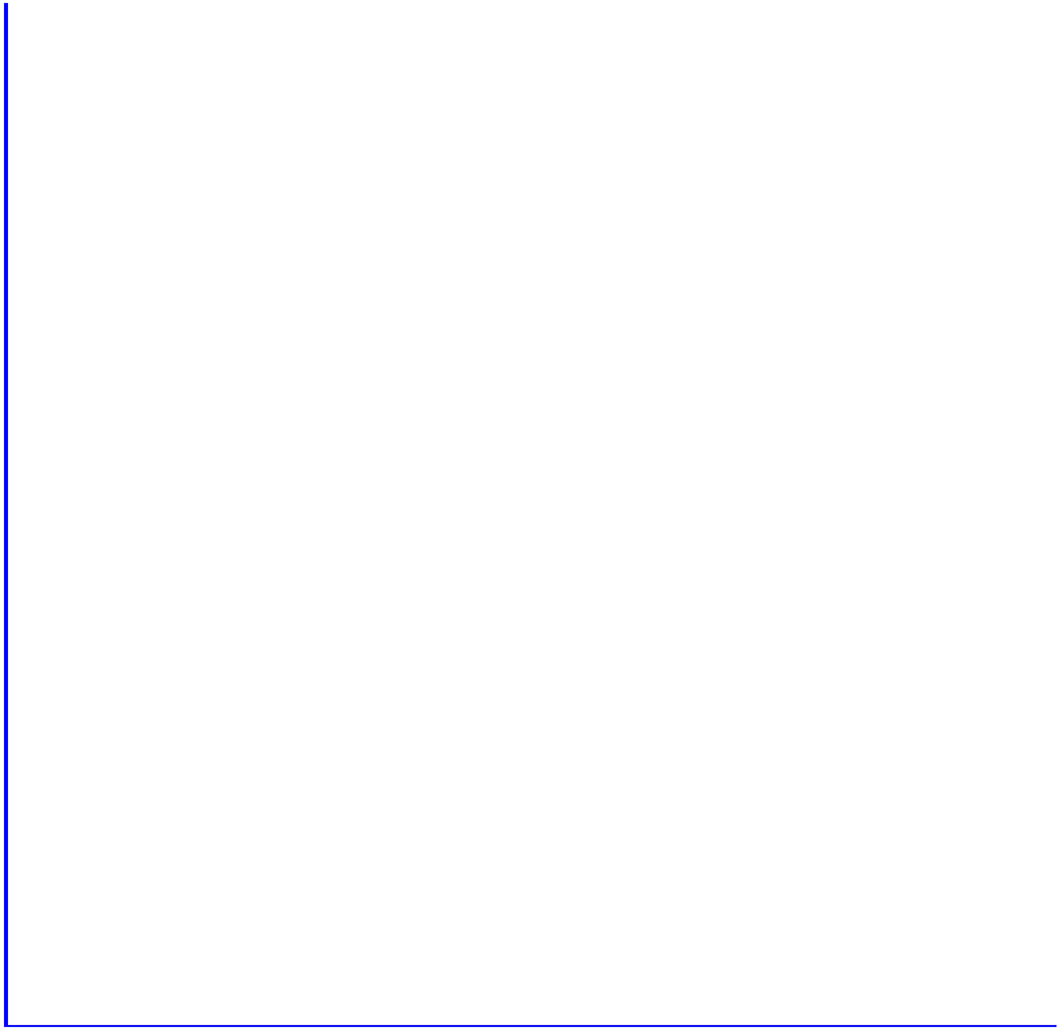
Carpenter – JAO lecture series (see your Papers/)

Let’s say we have a sky image



If only we had a regular UV grid of Amp and Phase





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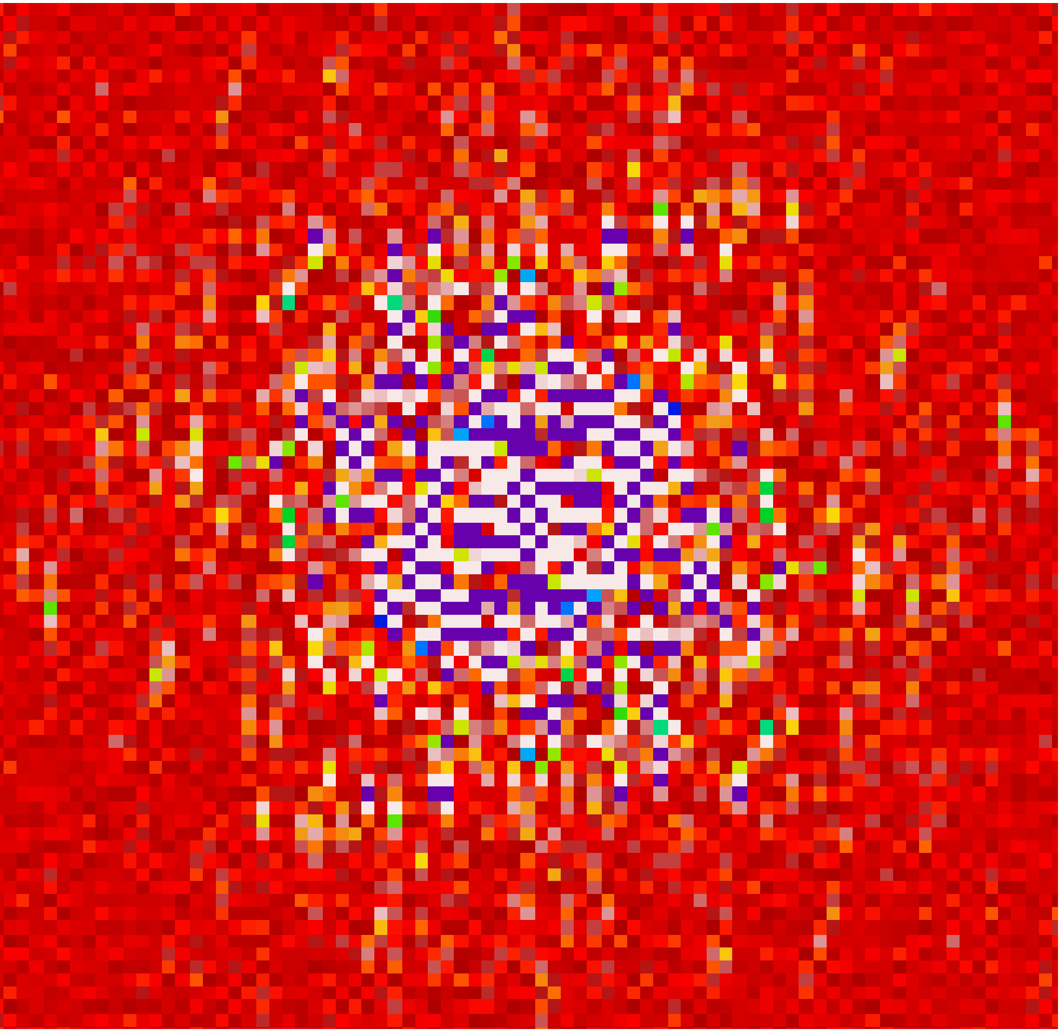
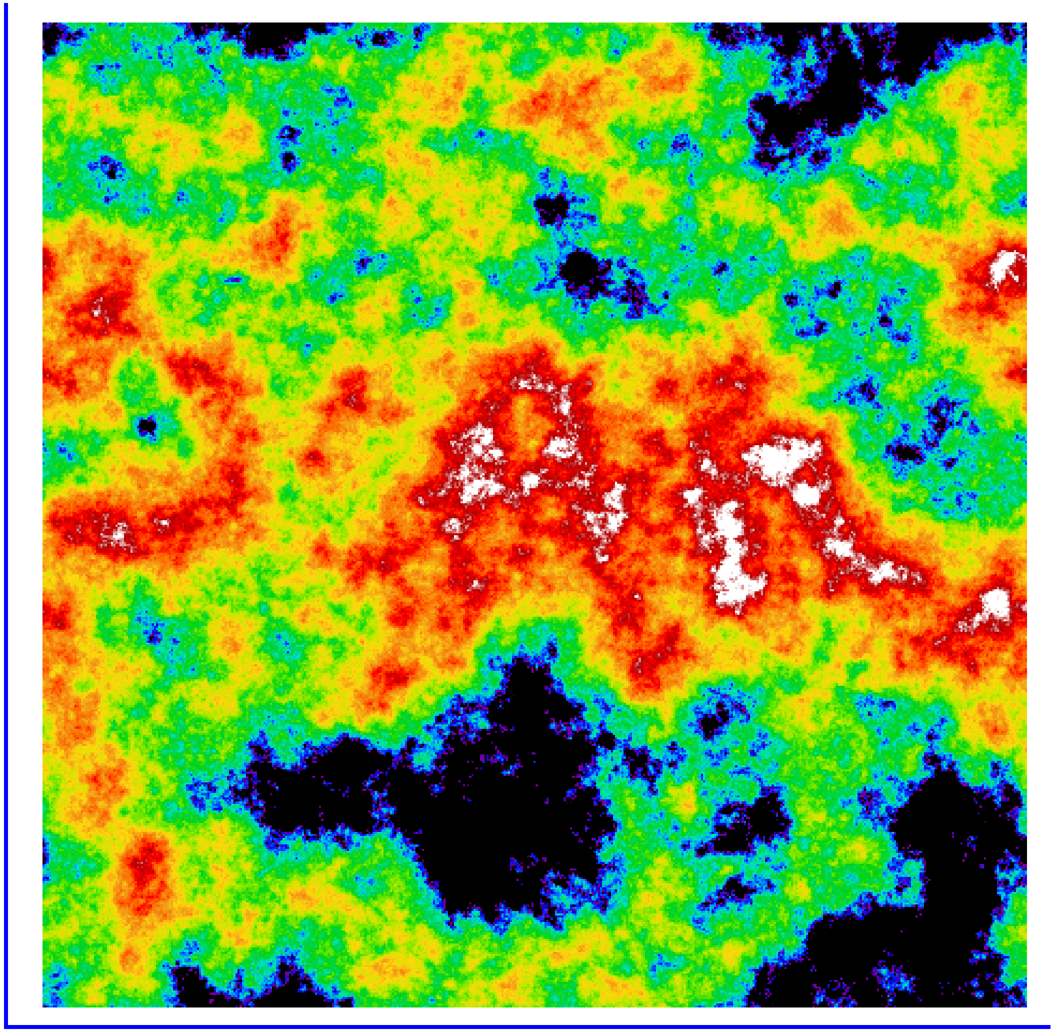
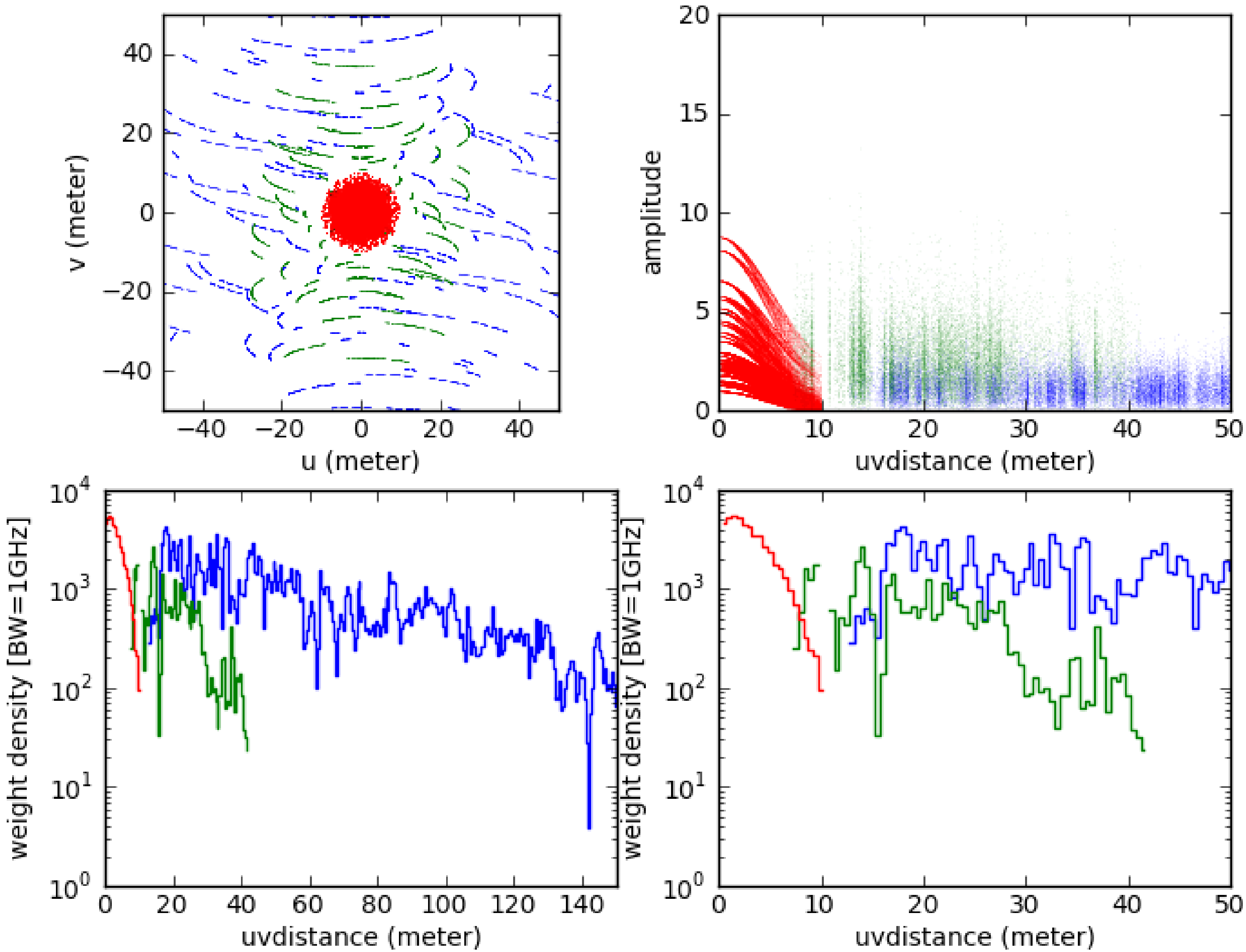




Sadly we have a "poorly" sampled UV plane



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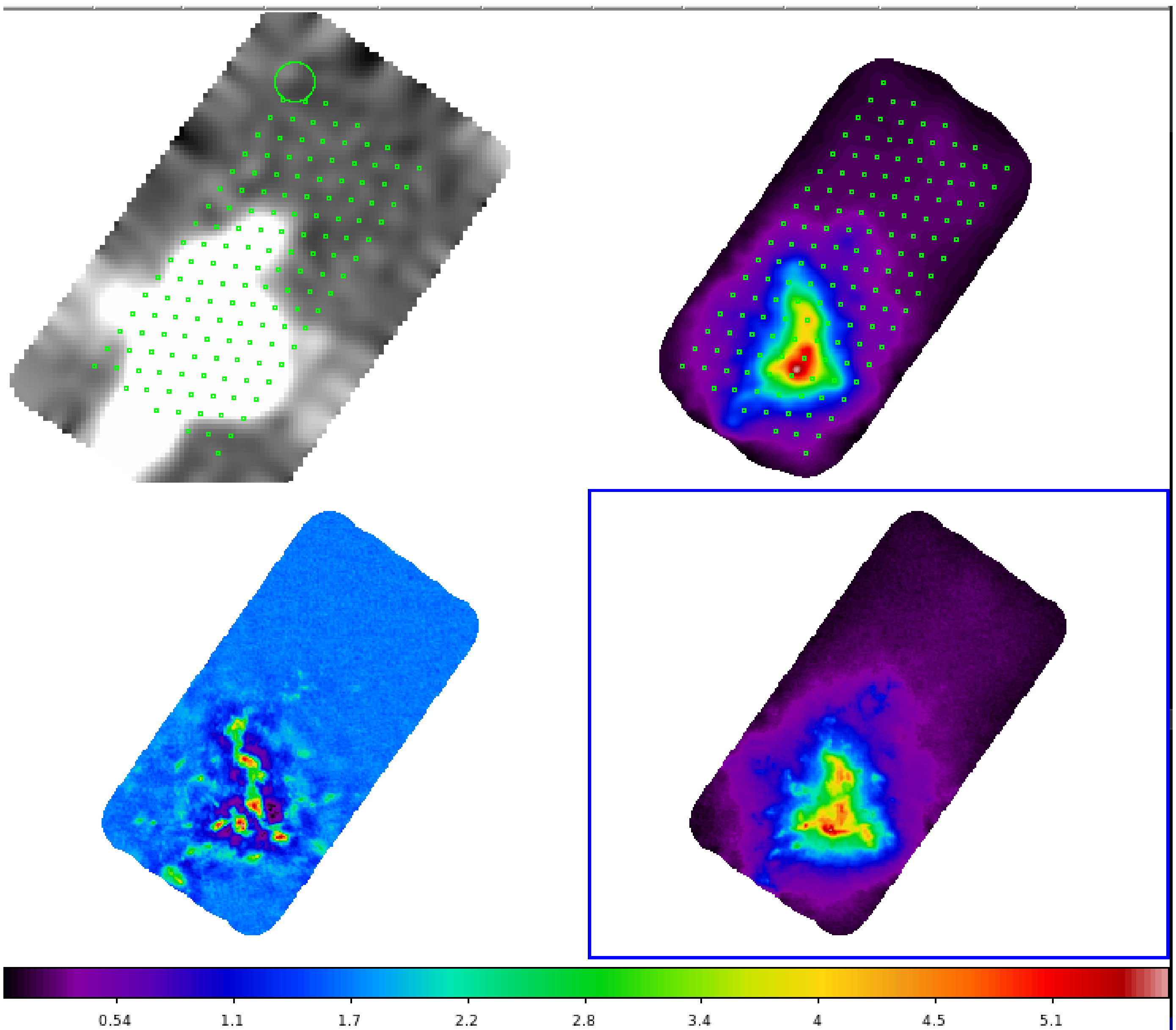


Missing Short Spacings

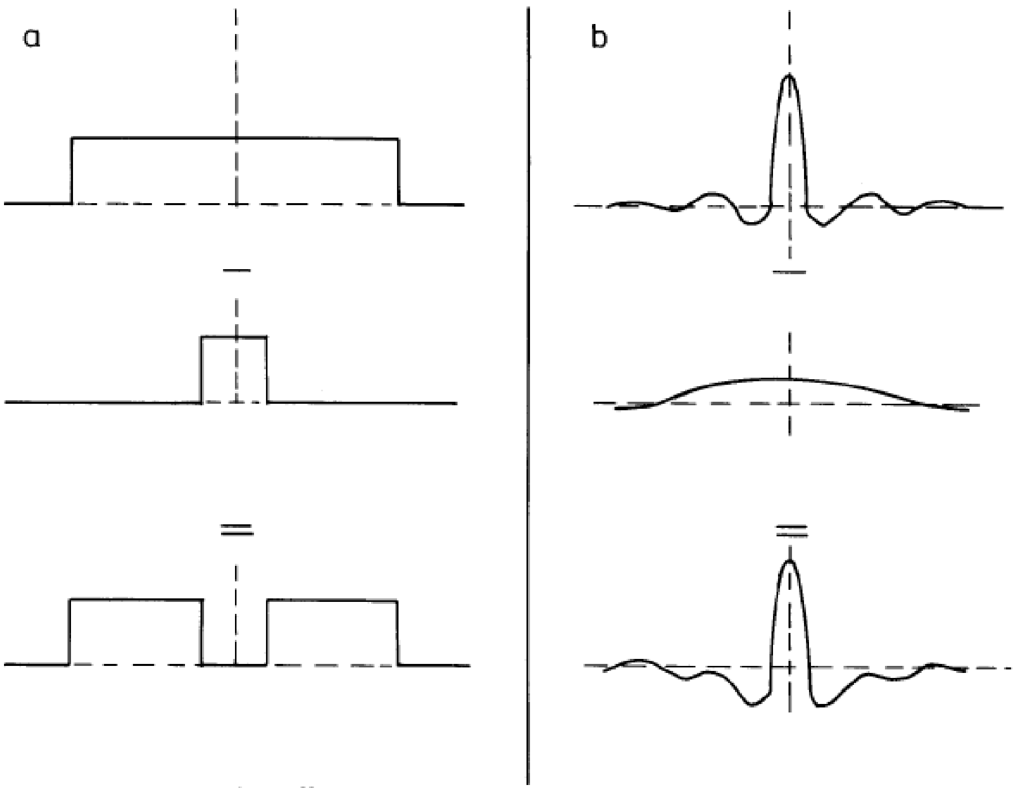
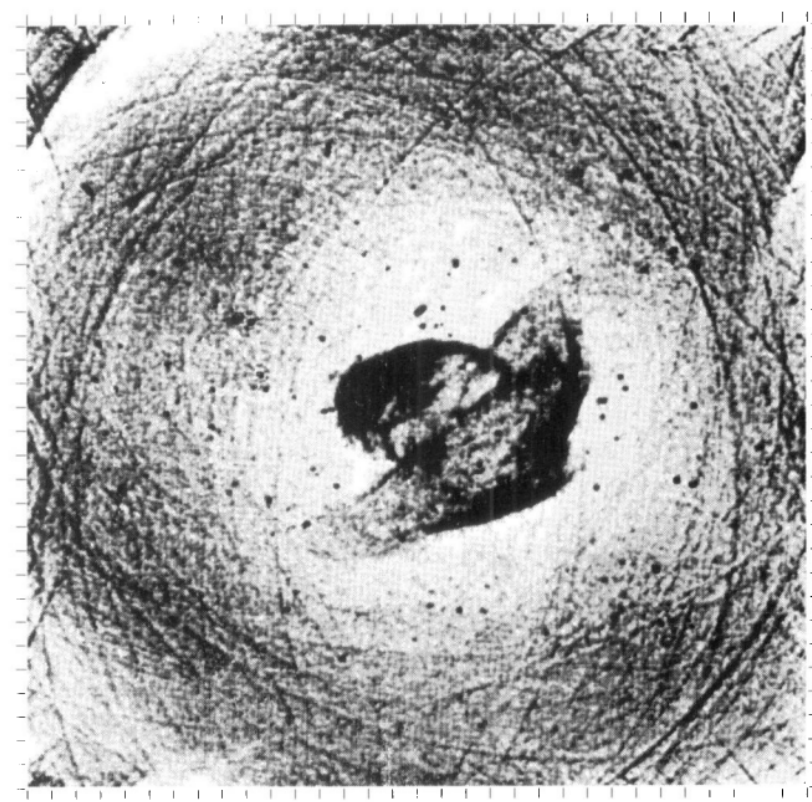


Fig. 1a and b. The effect on instrumental response of missing short spacings. **a** Observed spatial frequencies and **b** the corresponding instrumental response



Braun & Walterbos (1985)

See also: Ekers & Rots **1979**, Vogel et al. **1985**, Stanimirovic **1999**, Koda et al **2011**

Deconvolution

- CLEAN: Subtracting Dirty Beam components
  - Hogbom (1974)
  - Clark (1980)
    - Cotton-Schwab iterations : major and minor cycles
    - Minor cycle => deconvolution
    - Major cycle => imaging
  - **Schwarz** (1978) – 1D clean mathematical proof
  - Wakker & Schwarz (1988) – mrc – short spacings
  - Cornwell (2008) – multiscale clean
- MEM: Maximum Entropy
  - Cornwell & Evans (1985)

`scales=[0,5,15] smallscalebias=0.5`

Astron. Astrophys. 65, 345—356 (1978)

Mathematical-statistical Description of the Iterative Beam Removing Technique (Method CLEAN)

U. J. Schwarz

Kapteyn Laboratory, University of Groningen, Postbus 800, NL-8002 Groningen, T

Received October 13, 1976; revised July 15, 1977

Summary. The CLEAN method (Högbom, 1974), which is a deconvolution method, is analysed mathematically for the 1-dimensional case. It is shown that the method is equivalent to solving a system of linear equations by an iterative method (Temple, 1938). A criterion of convergence is given. In typical applications of the method the solution of the system of equations is *not* unique and the consequences for the CLEAN solution are discussed.

By applying the analysis to maps which are obtained from Fourier transformed data the convergence criterion is shown to be equivalent to the condition that all weights used for the Fourier transform have to be non-negative. It is proven that the method is in fact a statistically correct least-squares fit of sine functions to the observed data (the visibility function). The choice of clean beam and the effects of adding residuals are analysed.

An error analysis is given which allows the errors in interpolated and extrapolated information to be determined. Some numerical examples of error calculations are given.

The extension of the present analysis to 2 dimensional distributions is briefly discussed in an Appendix.

Key words: CLEAN — data-processing — Fourier transform — statistics — radio astronomy

Cheat Sheet
CASA-MIRIAD-GILDAS

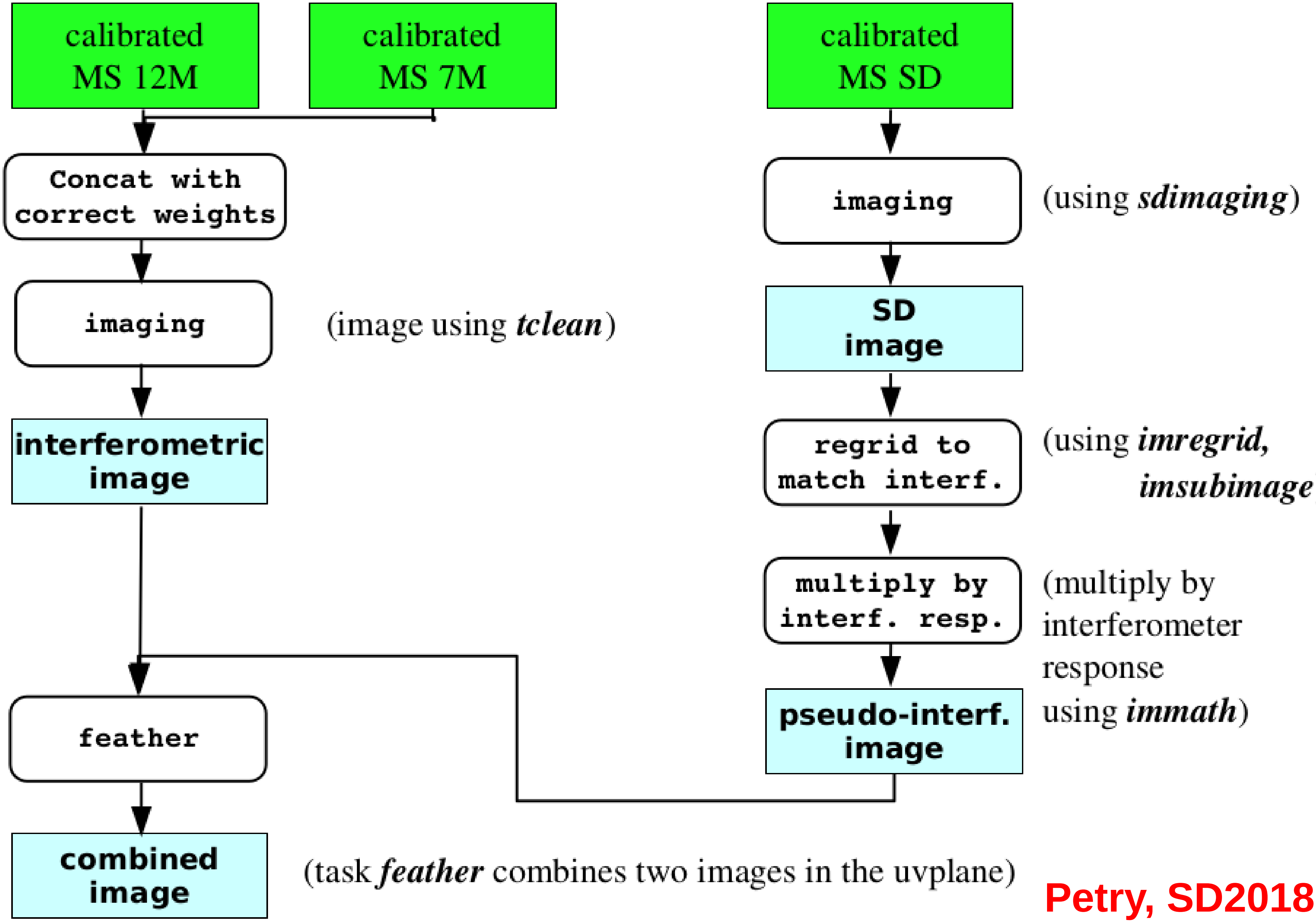
- tclean (*)
- feather
- tp2vis NEW
- tclean(scales=[])

- invert+clean+restor
- immerge
- [Koda’s scripts]
- “mrc” [Wakker]

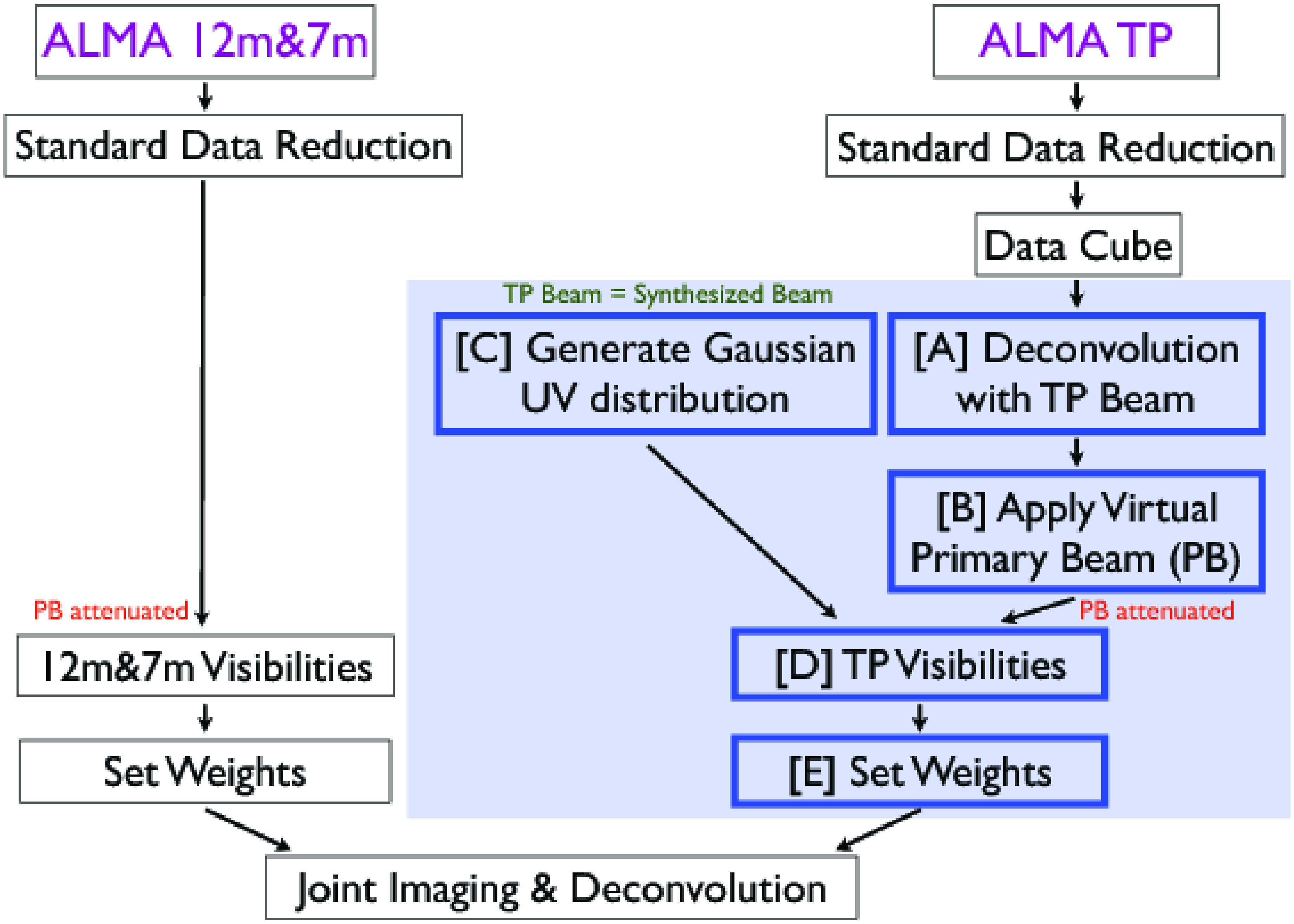
<u>* tclean see also:</u>

```
deconvolve()
im.restore()
```

Combination of interf. and SD data workflow with CASA



Petry, SD2018


ALMA 12m&7m
Standard Data Reduction
PB attenuated
12m&7m Visibilities
Set Weights
ALMA TP
Standard Data Reduction
Data Cube
TP Beam = Synthesized Beam
[C] Generate Gaussian UV distribution
[A] Deconvolution with TP Beam
[B] Apply Virtual Primary Beam (PB)
PB attenuated
[D] TP Visibilities
[E] Set Weights
Joint Imaging & Deconvolution

Array Combination Methods

[that (can) work in CASA]

- Feather: combine image via fourier domain
- Pure JD in combination with tclean()
  - TP2VIS
  - SD2VIS (single pointing)
- Maximum Entropy “JD” of Hires and Lowres
- CBD – Linear Combination (Stanimirovic et al 1999)
- CDD tclean + startmodel=
  - TP map (scaled to Jy/pixel)
  - TP map deconvolved
  - Feather (scaled to Jy/pixel)
- CAD – SSCIM (Faridani et al. 2017)

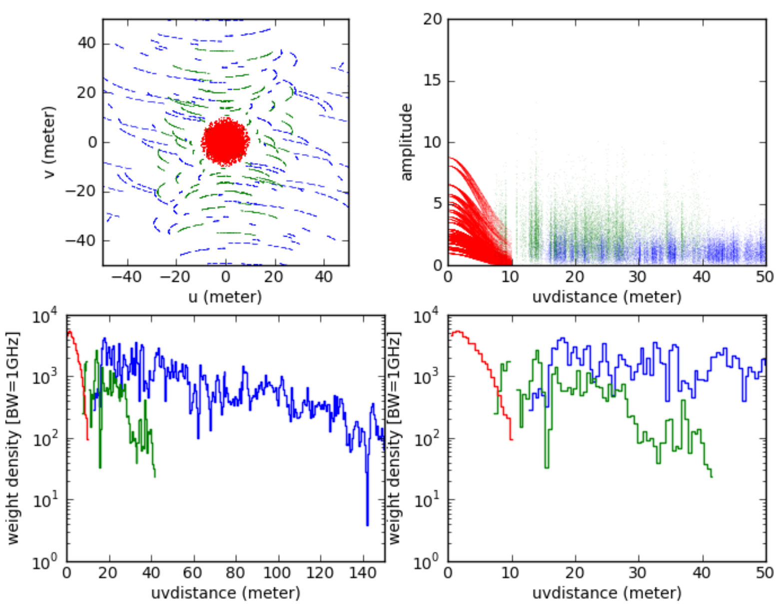
See also: Stanimirovic 2002

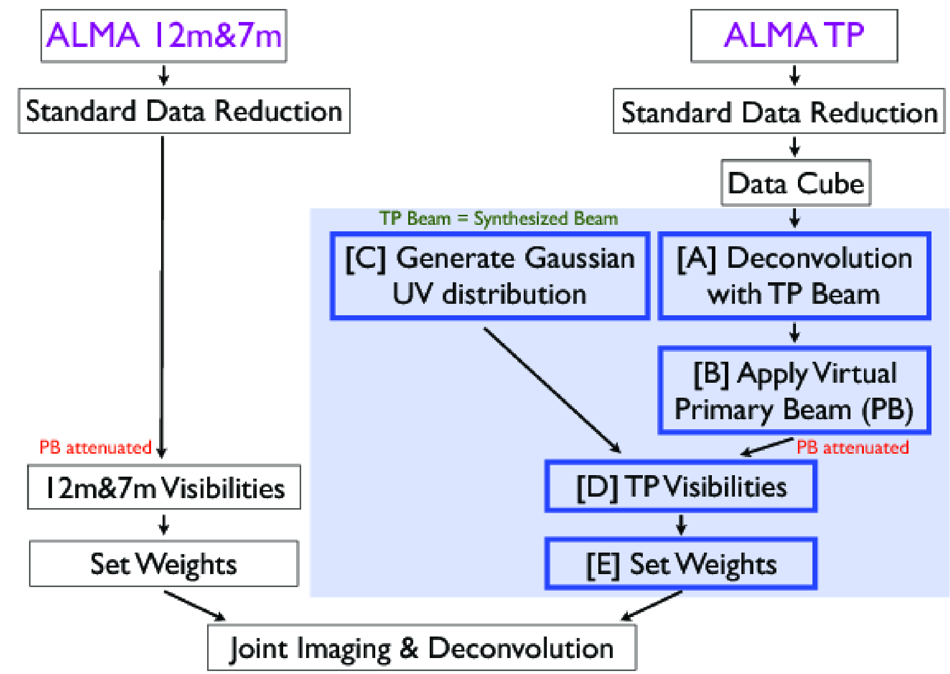
Feather (immerge)

- Get LoRes and HiRes image on same grid (imregrid)
- Ignore edges where PB < 0.2 (imsubimage)
- Use noise flat images:
  - LoRes = TP * .PB
  - HiRes = .image
- Run feather()
- Moments on this noise flat result
- MOM0/PB for fluxes, MOM1, MOM2

tp2vis
(Koda et al. , in prep.)

1) tp2vis(tpim, tpms, ptg, rms=0.15)
2) tp2viswt(tpms, mode='mult', value='0.1')
3) tp2vispl(tpms)
4) tclean([tpms,ms07,ms12],...)





SSCIM ("CAD")
(Faridani et al. 2017)

- Convolve INT map to SD resolution
- Subtract this from SD map => "missing flux"
- Scale missing flux by beam area ratio
- Add this back into the INT map => combined map

$$I_{combine} = I_{int} + \varepsilon * (I_{SD} - I_{int}^{conv})$$

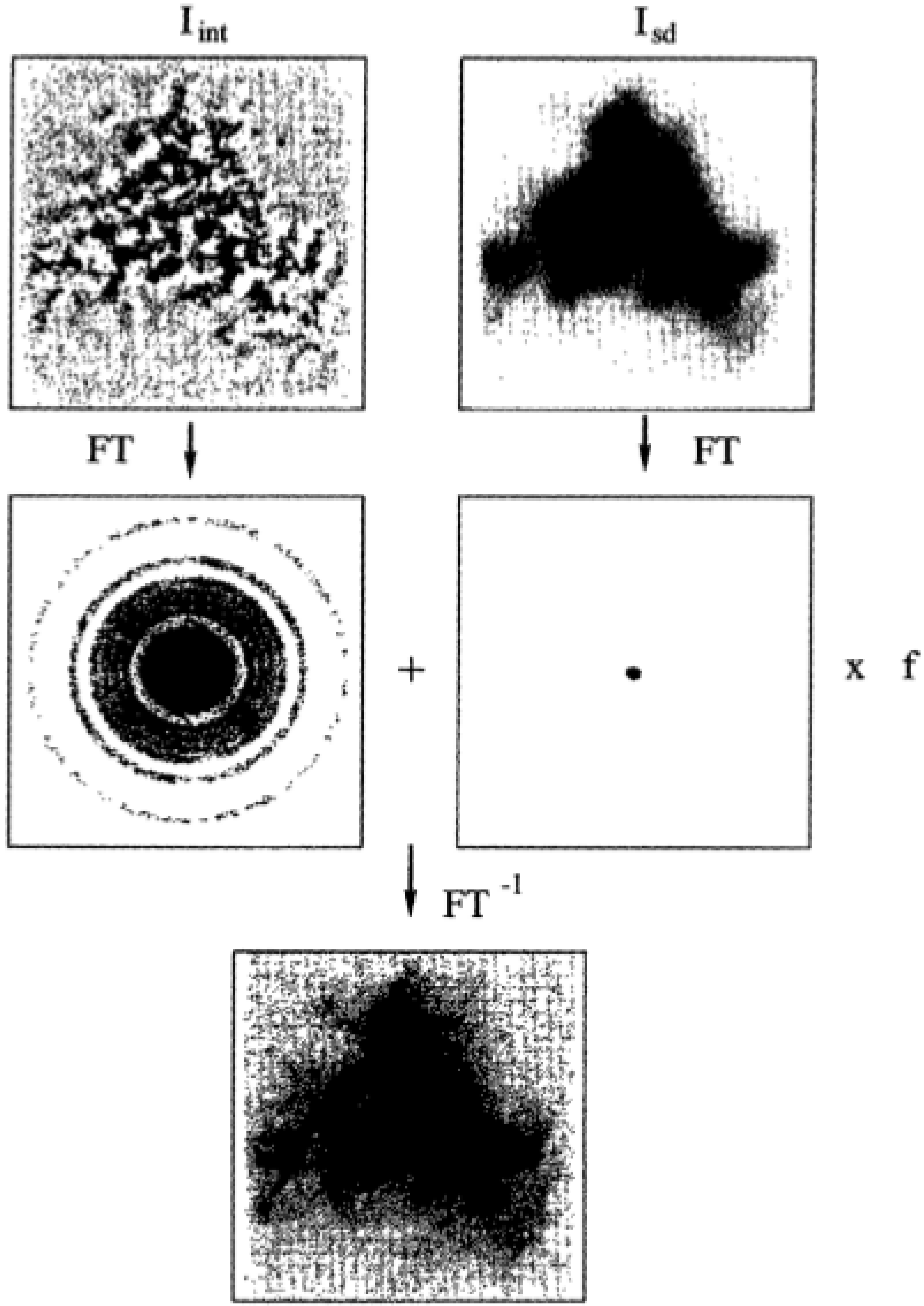
$$\varepsilon = \Omega_{int} / \Omega_{SD}$$

Linear Combination "CBD"
(Stanimirovic et al. 1999)

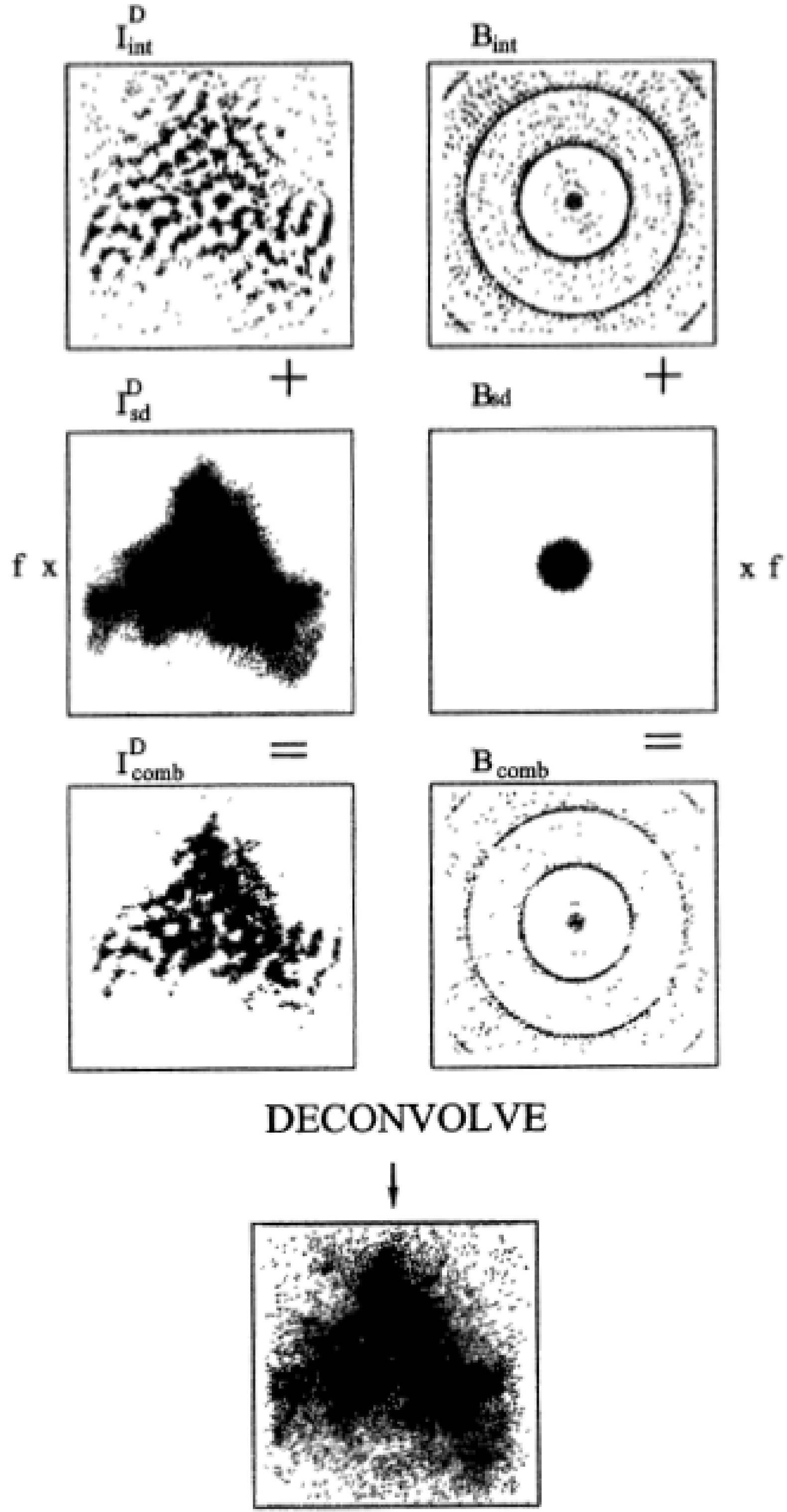
- Create dirty image (tclean niter=0)
- Define weights and flux factor
- Combine dirty image and beam
- Deconvolve

$$I_{comb} = I_{int} + f\,\varepsilon\, I_{SD}$$
$$B_{comb} = B_{int} + f\,\varepsilon\, B_{SD}$$

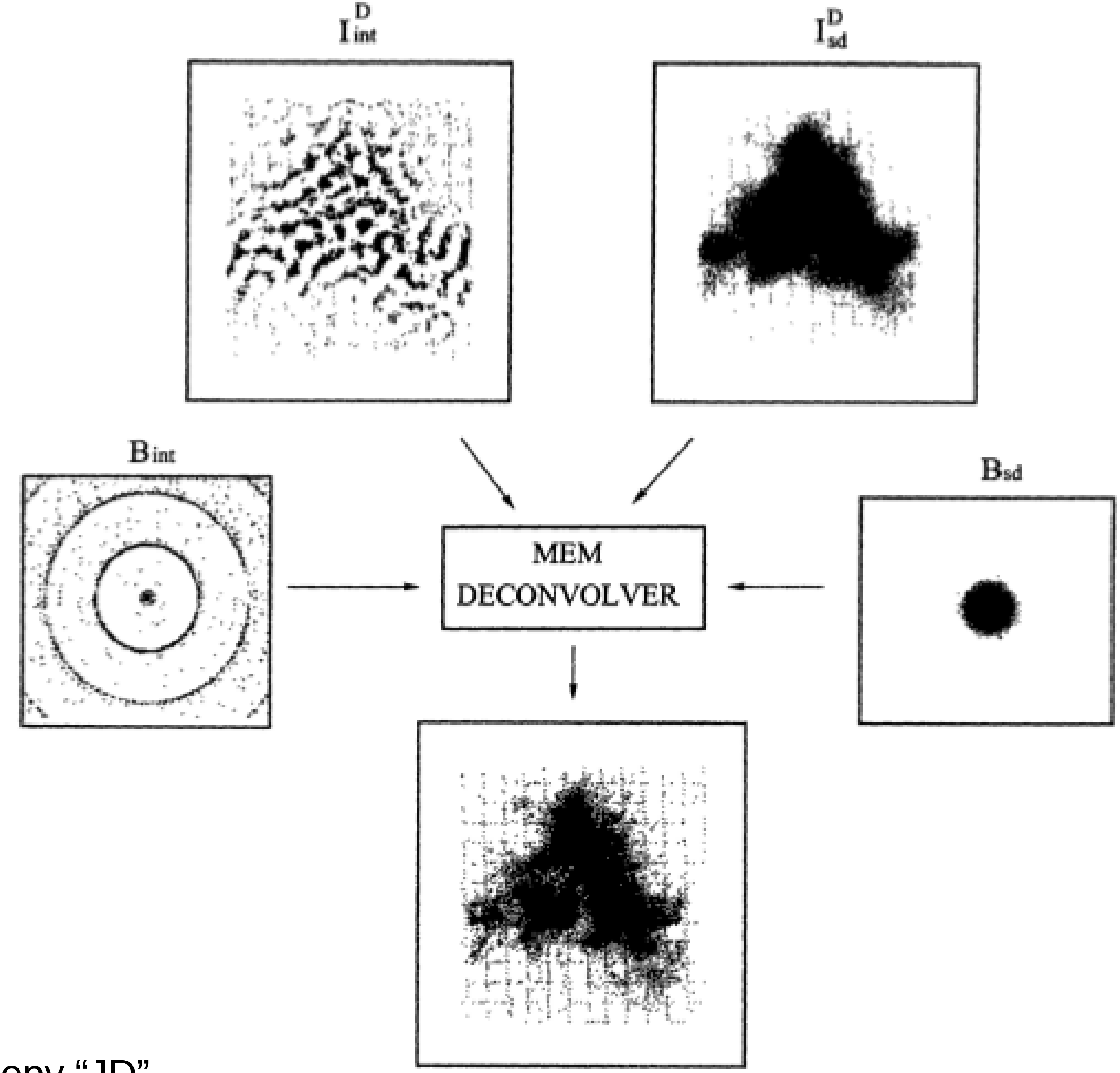
$$\varepsilon = \Omega_{int} / \Omega_{SD}$$



IMMERGE



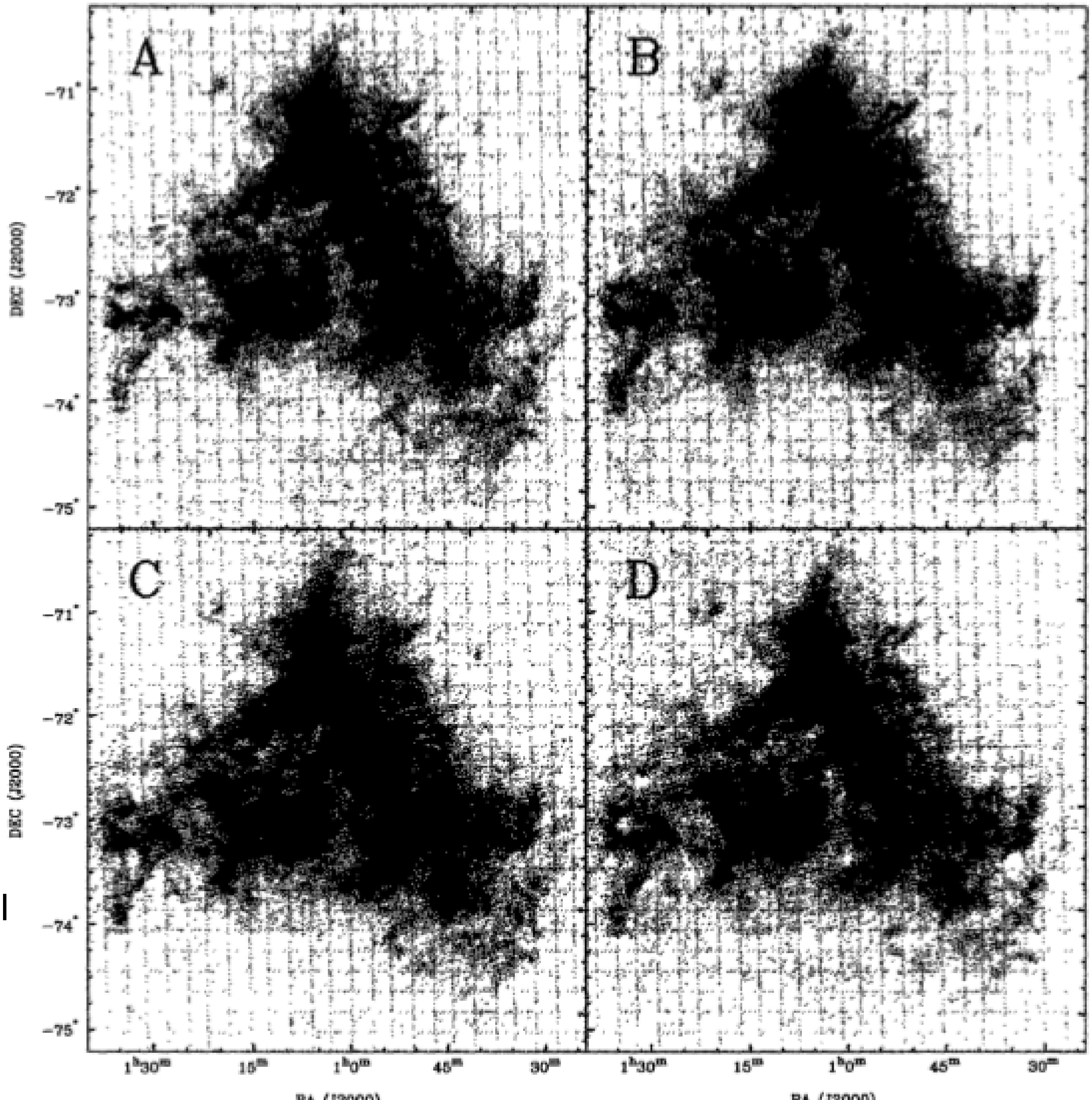
Linear Combination
(Stanimirovic 1999)



Maximum Entropy “JD”

Immerge

stani99



SD startmodel

JDmem

Performance

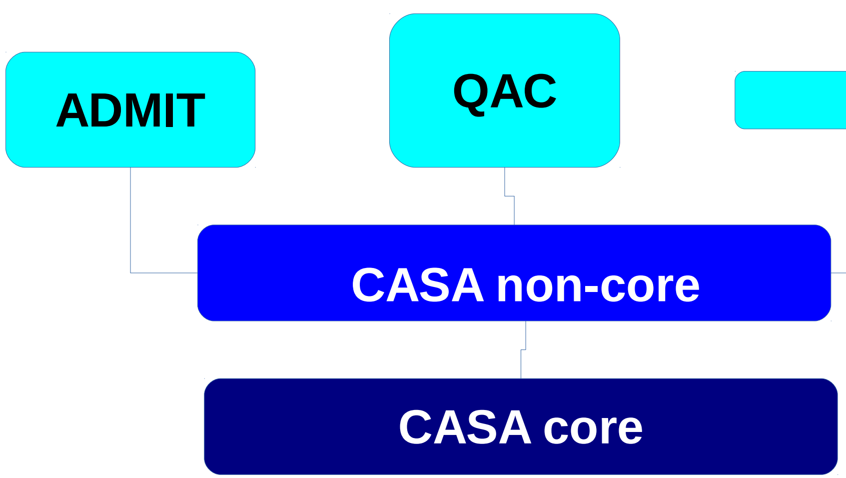
- CASA::tclean - lots of FFT
- CASA::feather – needs one FFT
- SSC – needs smooth (=FFT?)
- tp2vis – needs np.fft.fft2() and sm.predict()
-

Extending CASA
[could change in future CASA revisions]

- CASA uses the **~/.casa/init.py** and **prelude.py** much like your **.bashrc**
- **This is where you can automatically add new functionality**
- Several methods are available, each with caveats
  - Python's sys.path.append()   [e.g. au]
    - this is not part of CASA yet
  - CASA's buildmytask() procedure [e.g. SD2VIS]
    - The manual claims this might become deprecated, but is widely used in Nordic Tools
  - Python's execfile() [e.g. tp2vis]
    - The **execfile(filename)** command does not exist in python3
    - It would be **exec(compile(open(filename, "rb").read(), filename, 'exec'))**
  - ADMIT's "casarun" and $PATH/$PYTHONPATH shell approach that allows for "import admit"

QAC
(Quick Array Combination)

- Why QAC when you have CASA?
  - Simple layer to CASA, but....
  - Write shorter scripts, but...
  - Easy to use in unix shell, but...
  - Organize Data, Comparison & Regression, but...



CASA Tasks & Tools

CASA Tasks and Tools

TASK:

```
CASA> imhead('ngc1234.fits')
```

TOOL:

```
CASA> ia.open('ngc1234.fits')
CASA> ia.summary()
CASA> ia.close()
```

CASA tasks/tools vs. QAC functions

```
CASA:
 immath([a,b],'evalexpr',c,'IM0+IM1')


QAC:
 qac_math(c,a,'+',b)
```

QAC
scripting: calling as a unix command

```
% casa -c sky1.py plot=1 maxcfg=4
```

```
% casa -c sky1.py test='"test2"'
      alma=1 plot=1
      niter='[0,100,300,1000,3000]'
      maxcfg=8 grid=10.0 dish=30.0
      > sky1a.log 2>&1
```

QAC – Creating data

- qac_alma(P, PIM, cfg, ptg)
- qac_tp_vis(P, PIM, ptg)
- qac_sd_vis(P,...)
- qac_tp_otf(P, PIM)

CASA::simobserve()

P   = Project Directory
PIM = pixel image (jy/pixel)
cfg   = array configuration
ptg   = pointing grid (mosaic)

QAC – Cleaning Data

- qac_clean1(P, [ms],niter=[1,10,100],**line)
- qac_clean(P, tpms, [ms],niter=[1,10,100],**line)

P = Project Directory
PIM = pixel image (jy/pixel)
cfg = array configuration
ptg = pointing grid (mosaic)
[ms] = MS list
tpms = TP ms from tp2vis

QAC – Combining Data

- qac_combine(P, TPdata, INTdata)
- qac_clean(P, tpms, [ms], niter=[1,10,100],**line)
- qac_feather(P, hires, lores)
- qac_ssc(P, hires, lores)

QAC – Plotting Data

- qac_plot(cim)
- qac_plot_grid([cim], diff=10.0)
- qac_beam(psf)
- qac_psd(cim)
- qac_flux(cim)
- qac_stats(cim, test=)

P = Project Directory
PIM = pixel image (jy/pixel)
cfg = array configuration
ptg = pointing grid (mosaic)
[ms] = MS list
tpms = TP ms from tp2vis
cim = image

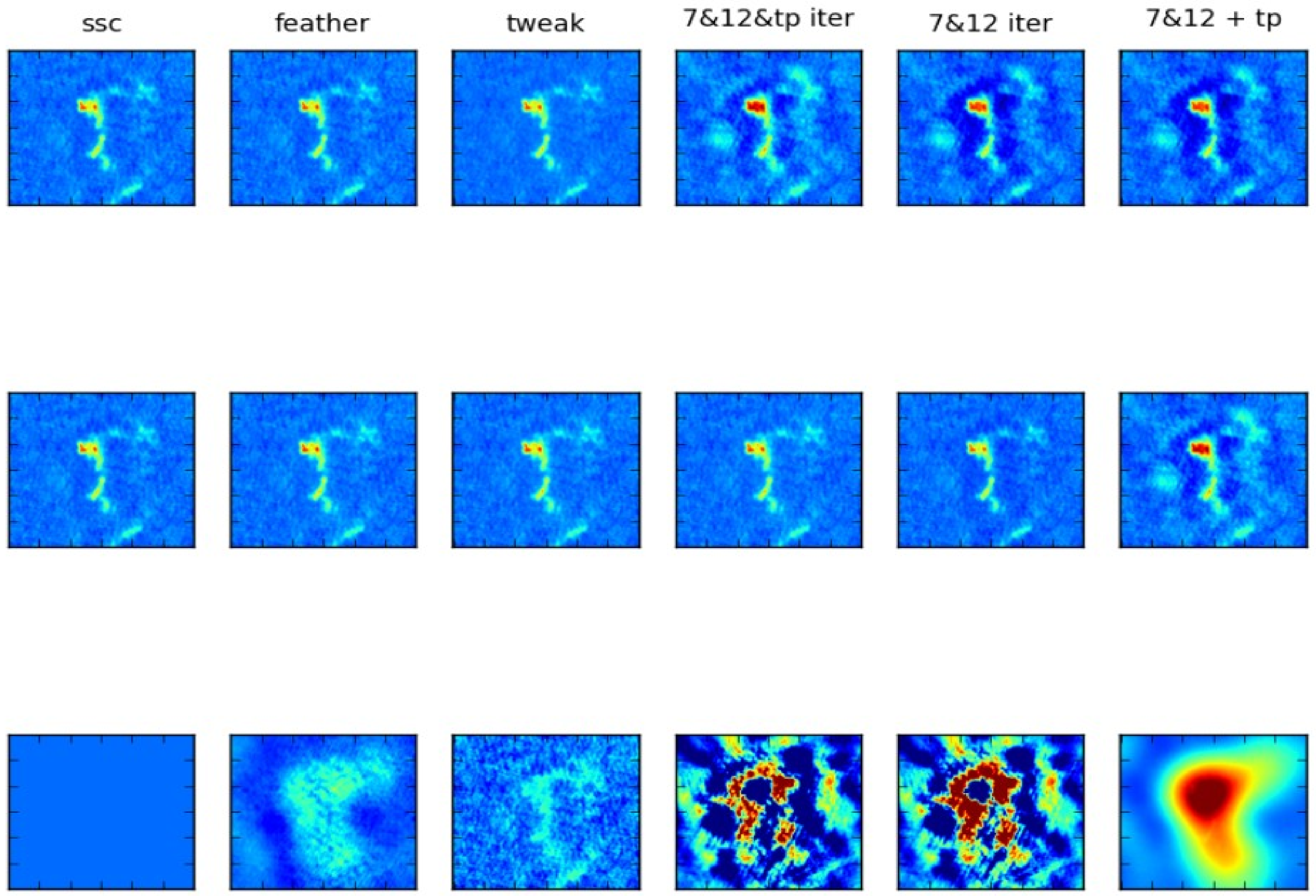
QAC – Analysis/Misc

- qac_mom(cim)
- qac_smooth(P, ...)
- qac_math(out,in1,oper,in2)
- qac_stats(cim, test=)

Scripts

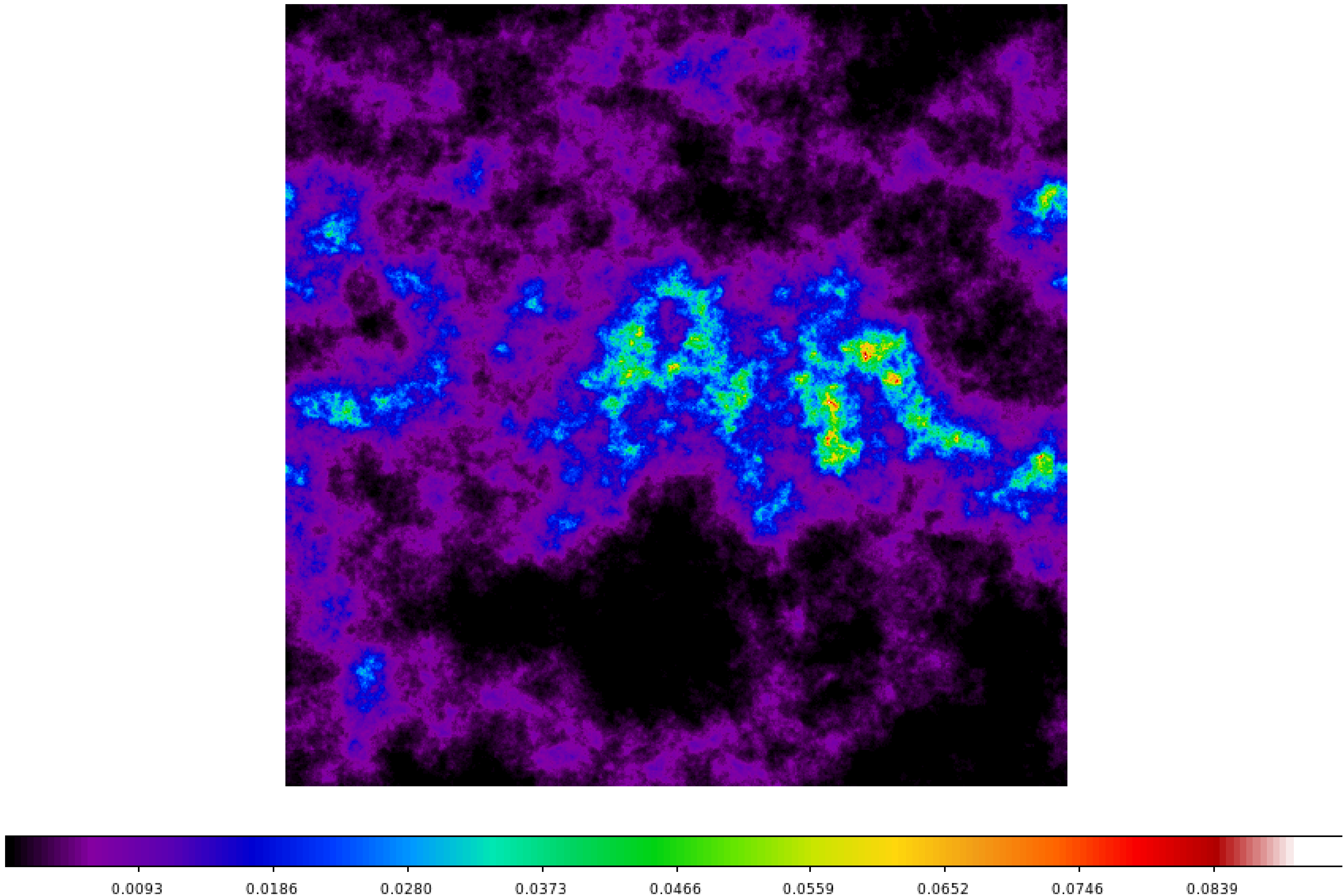
- SD2018/casa
  - `M100Band3Combine5.1.py` [NOT WORKING YET]
- QAC/test
  - `bench.py` - std M100 bench w/ 5 channels – talkes ~ 3 mins
  - **`bench0.py`** - tinker toy M100 w/ 1 channel
  - `sky1.py` – tinker toy skymodel.fits
- QAC/workflows [used for tp2vis project, most use QAC]
  - `workflow4.py` ~30 min
  - `workflow6a.py` (CASA Guide fixed for casa5) : ~60 min
  - `workflow6.py` ~70 min

    `example1.py` (no QAC, vanilla CASA)
-


ssc
feather
tweak
7&12&tp iter
7&12 iter
7&12 + tp

Preparations (prevent data avalanche, YMMV)

- Combining data means
  - Selecting spatially
    - split(ms1,ms2,field='M100',spw='3,5',datacolumn=)
  - Spatial match
    - imregrid(input, template, output)
  - Spectral match
    - mstransform(spw=, outframe='LSRK',**line)


0.0093
0.0186
0.0280
0.0373
0.0466
0.0559
0.0652
0.0746
0.0839

Tutorial Session

2h + 1.5h   or   1.5h + 2h
?

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    - New Algorithms (stani)

Common Exercises

- First: bench0.md   (i.e. bench0.py)
  –
- Workflow6a (M100 casaguide on feather)
  –
- Workflow6 (M100 with tp2vis joint deconvolution)
  –
- Workflow4 (skymodel jy/pixel)
  –

Possible Exercises

- Workflow6a:
  - Convert clean to tclean
  - Use tclean's new automasking
  - Use tclean's multi-scale
  - Play with Briggs' robust weighting
  - Use qac_mom() and study mom0, mom1 and mom2
    - Mom0=flux Mom1=dynmass Mom2=turbulence
- Workflow6 (Example1)
  - Play with weights and watch different beams, influence on total flux
  - Are tweak maps between different niters' similar?

Possible Exercises

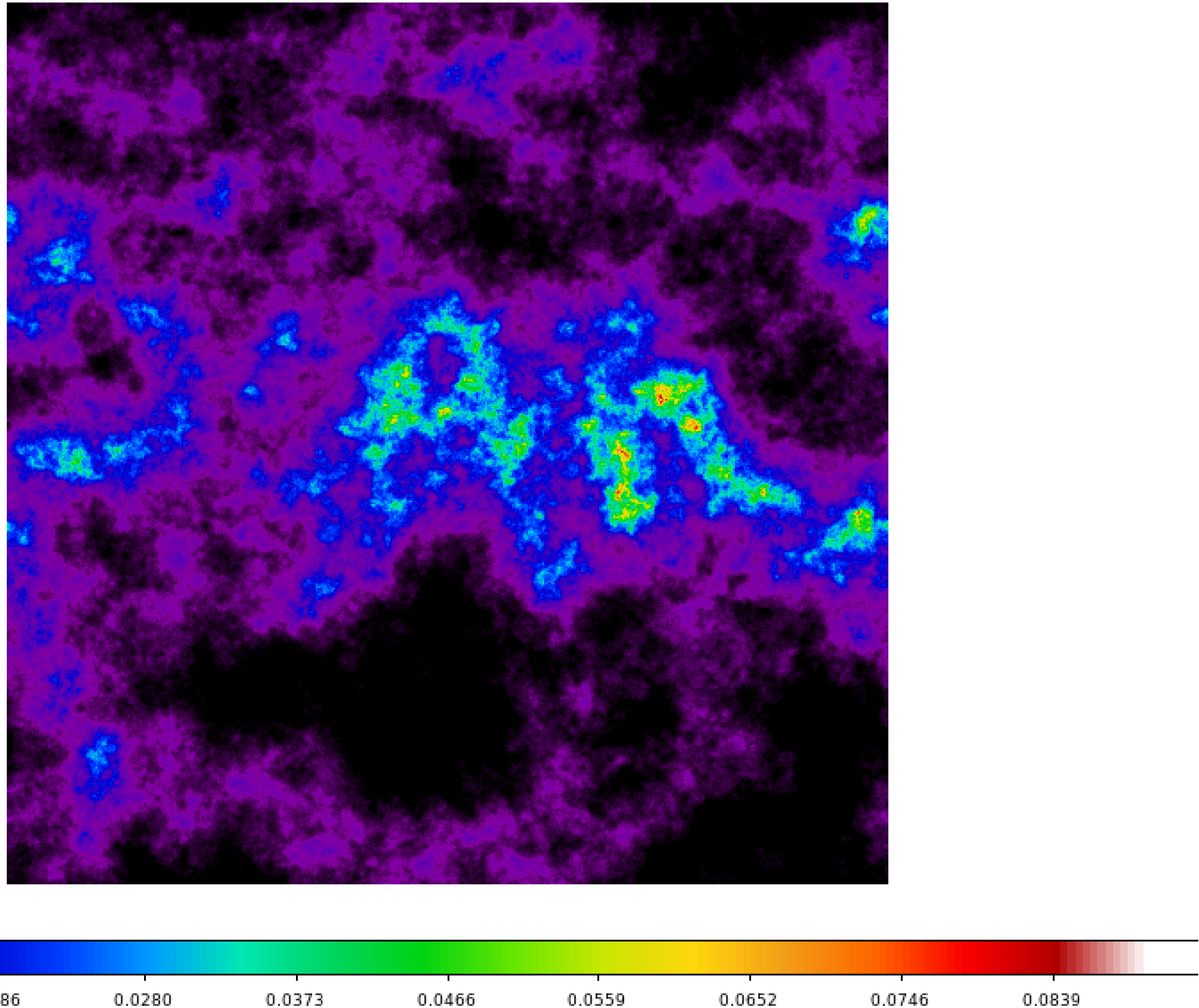
- Workflow4:
  - Compare AMPS on different arrays (tpvispl), what happens if we scale the TP by 10 or 20 %
    - The parameter **tp_scale** can be played with
- Compare qac_feather() with qac_ssc()
- Add bigger SD?   (cf. ATLAST)
- Can we combine without the 7m?
  - cf. GILDAS
- Can we scale down the 7m by factor 2 ?
  - It “seems” the 7m amplitudes too high?

Possible Exercises

- QAC @todo
  - Add a mom2 option to qac_mom()
  - Use radialProfile in qac_beam()   [cf. qac_psd()]
  - Implement qac_stani()

Neat Tricks

- If you have enough memory on linux, use /dev/shm/$USER
  - See sd2018/casa/qac_bench.txt
  - How to do this on mac?


0.0093
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0.0373
0.0466
0.0559
0.0652
0.0746
0.0839