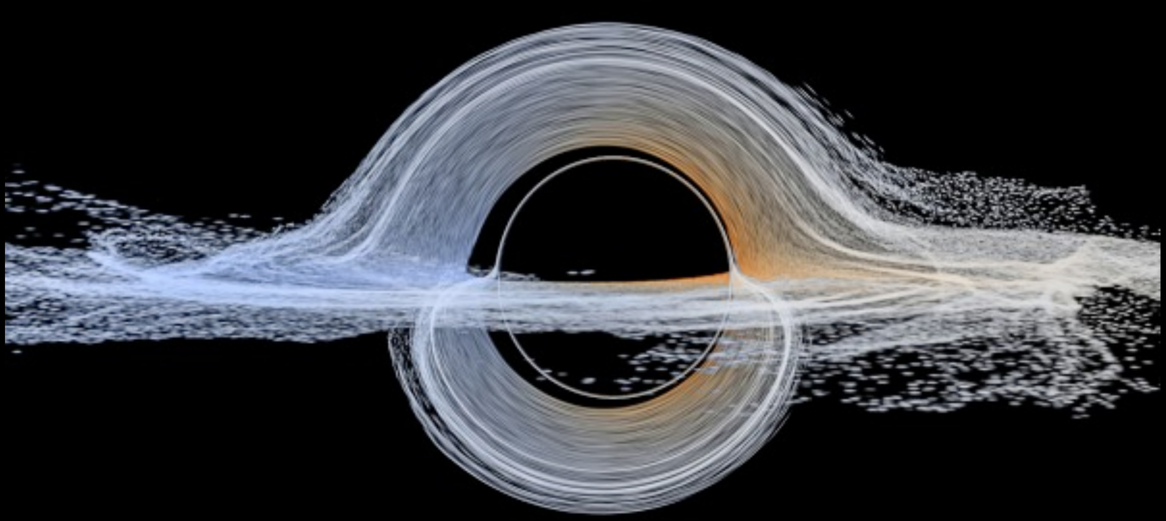
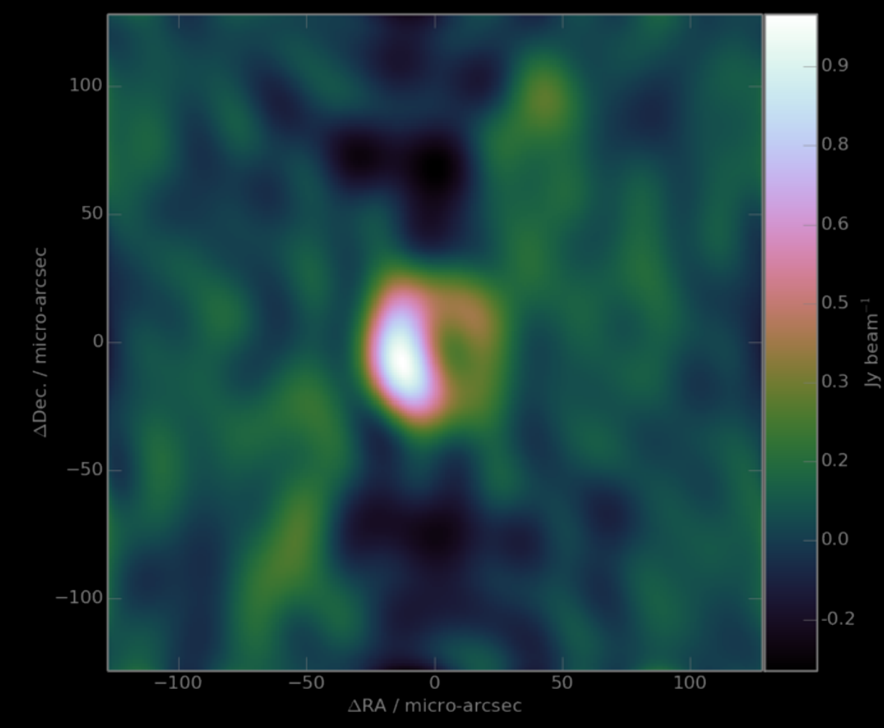
Meq Silhouette

mm-VLBI simulations and parameter estimation





Roger Deane
Rhodes University / SKA SA

outline

- MeqTrees: overview and past successes
- MeqSilhouette: mm-VLBI simulation pipeline (pre-alpha)
- Bayesian capabilities and plans

The Measurement Equation

- MeqTrees is (mostly) about building measurement equations, e.g.:

$$\mathbf{V}_{pq} = \overbrace{\mathbf{G}_p}^{\text{gain \& bandpass}} \underbrace{\left(\sum_s \overbrace{\Delta \mathbf{E}_p^{(s)}}^{\text{differential gain}} \overbrace{\mathbf{E}_p^{(s)}}^{\text{beam}} \overbrace{\mathbf{X}_{pq}}^{\text{source coherency}} \mathbf{E}_q^{(s)H} \Delta \mathbf{E}_q^{(s)H} \right)}_{\text{sum over sources}} \mathbf{G}_q^H$$

- An m.e. decomposes the observed visibility V_{pq} into intrinsic source properties and per-antenna Jones terms.

- Can describe an endless variety of (linear) physics.

can add pol. leakage, field rotation angle, etc.

MeqTrees

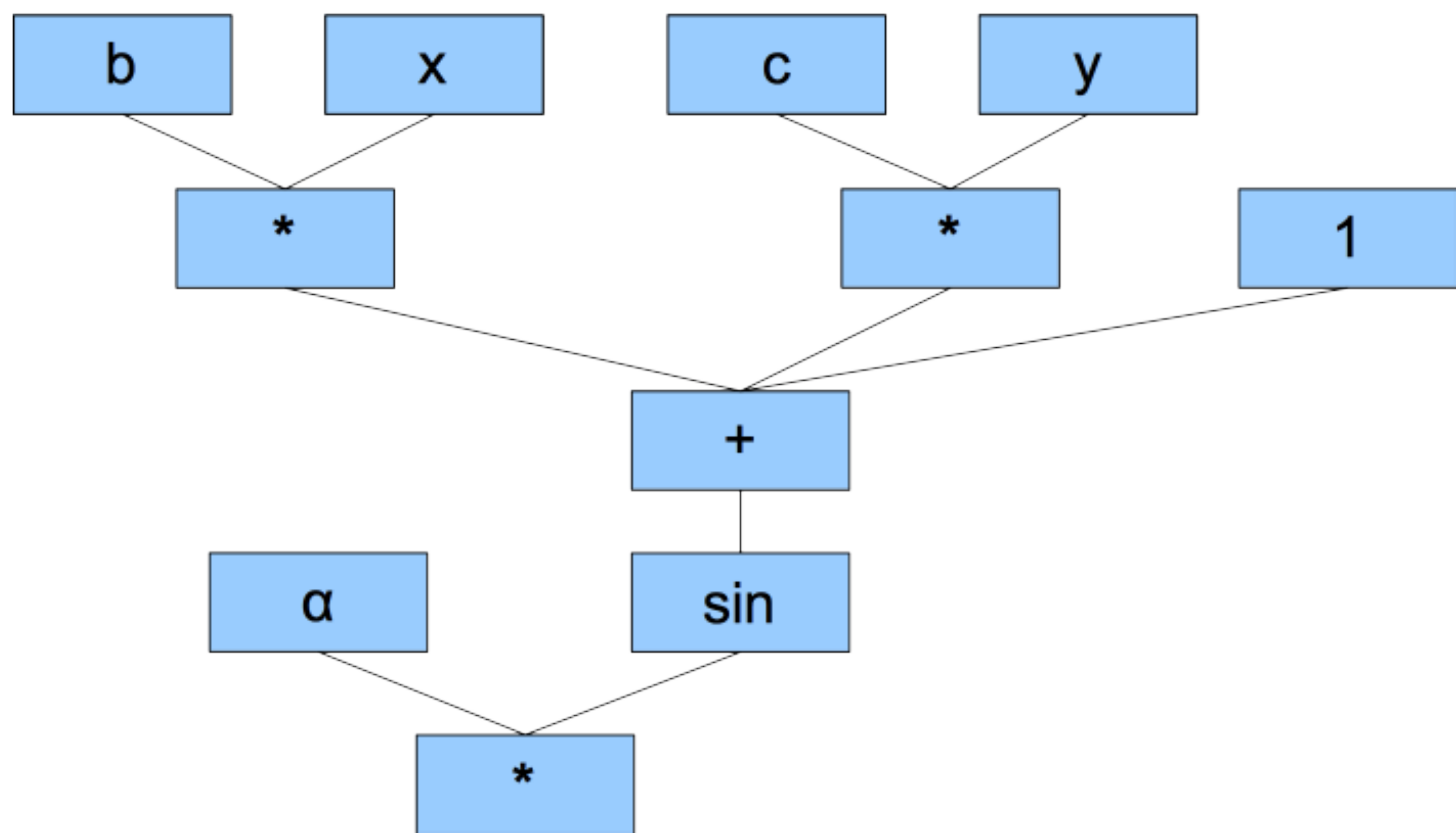
“Meq" = Measurement Equation

“Trees” = computational trees

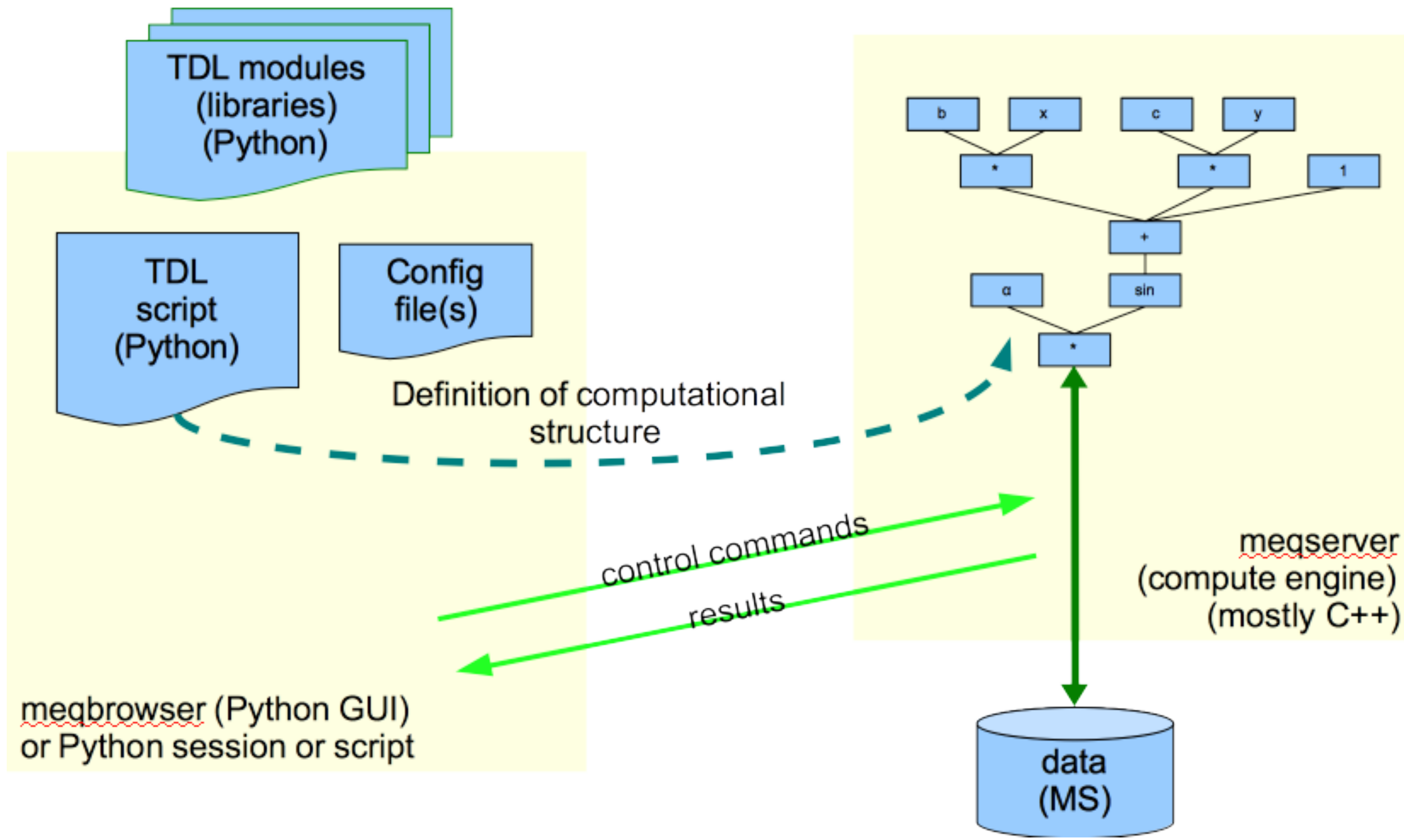
Trees = Expression Trees

- Any mathematical function can be represented by a tree:

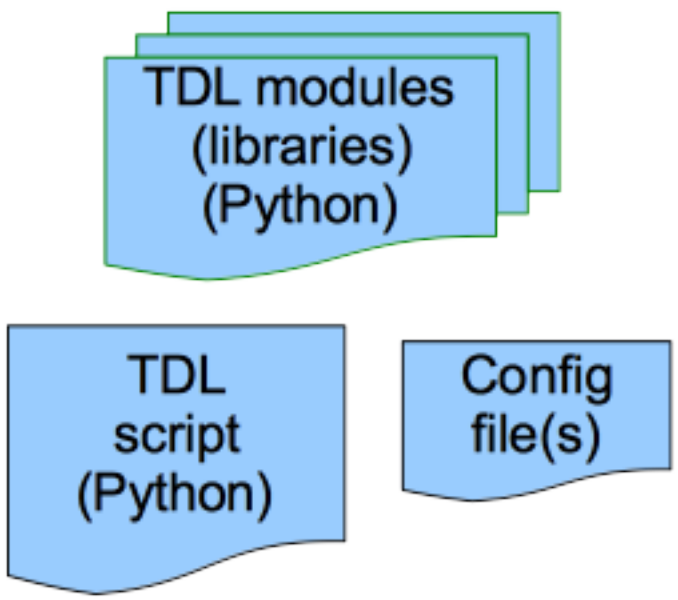
$$f = \alpha * \sin(b * x + c * y + 1)$$



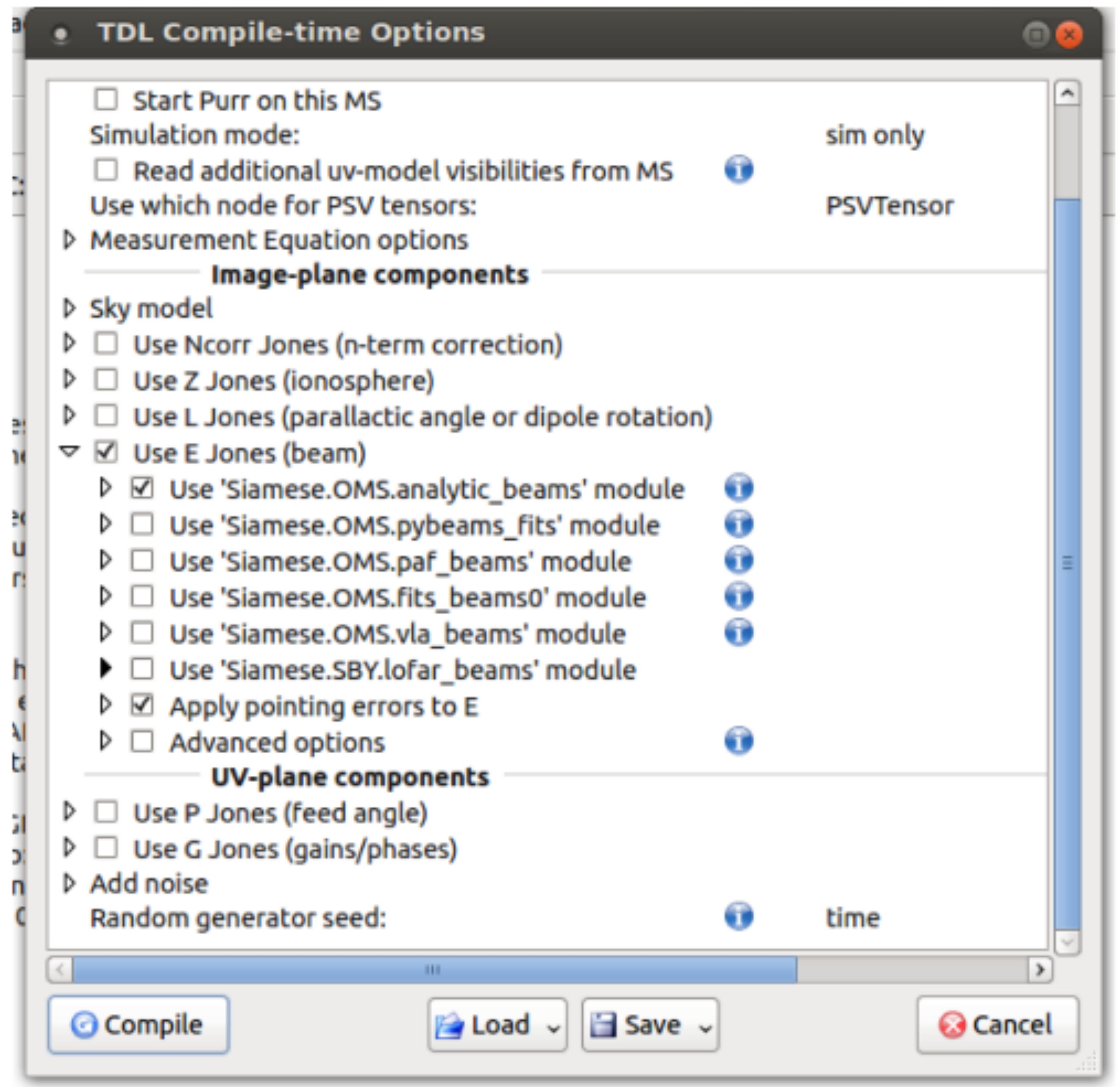
MeqTrees Architecture



A library of RIME components

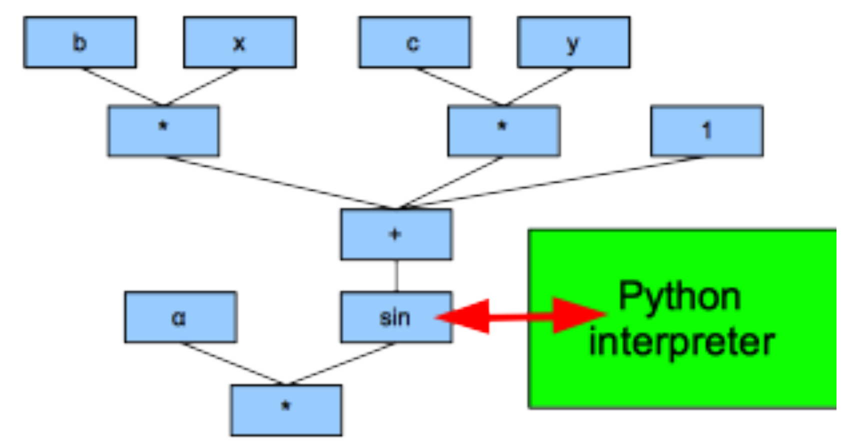


- TDL scripts essentially specify the structure of RIMEs on the meqserver side
- Modules provide many “pre-cooked” components



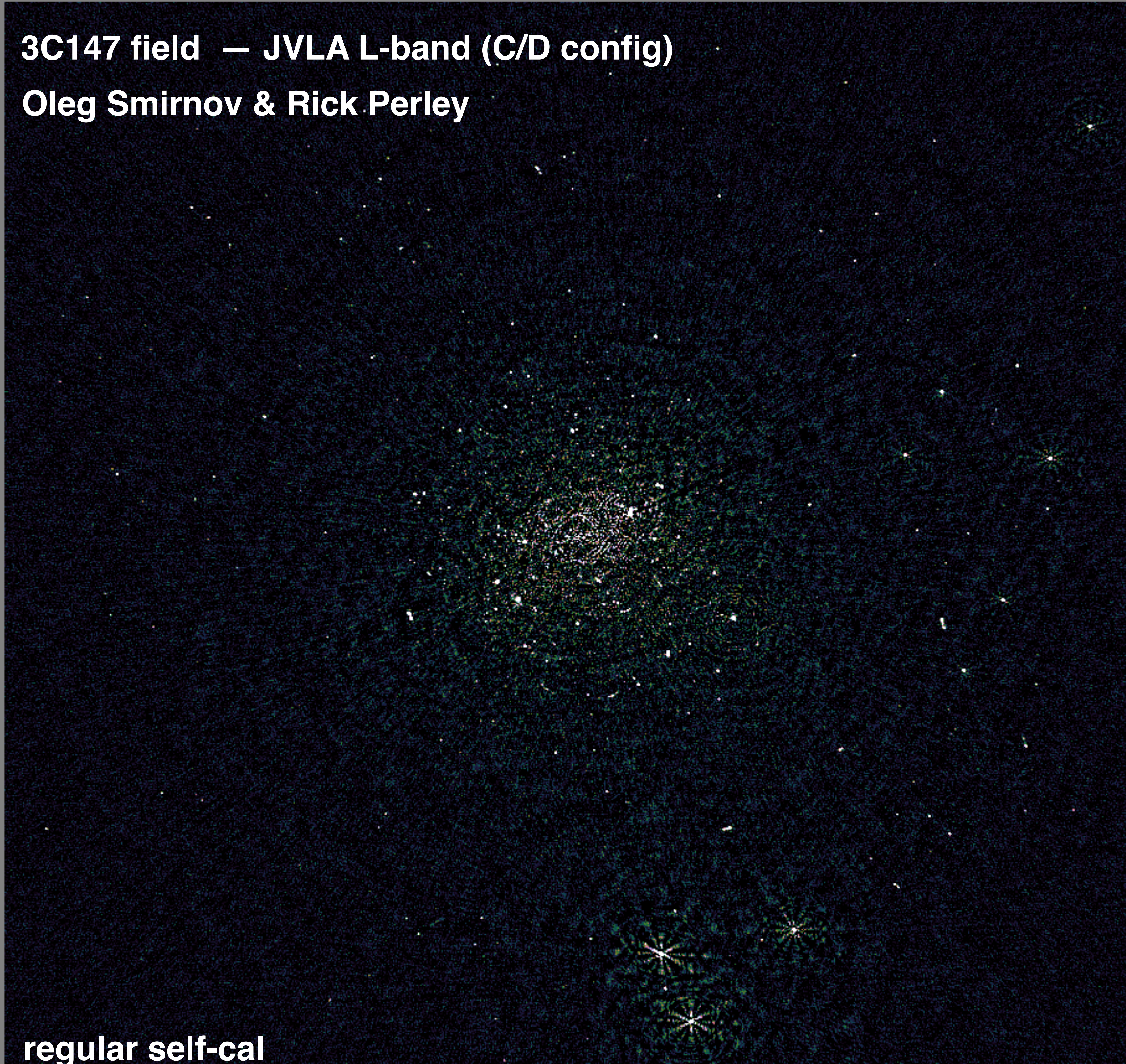
Performance / Flexibility

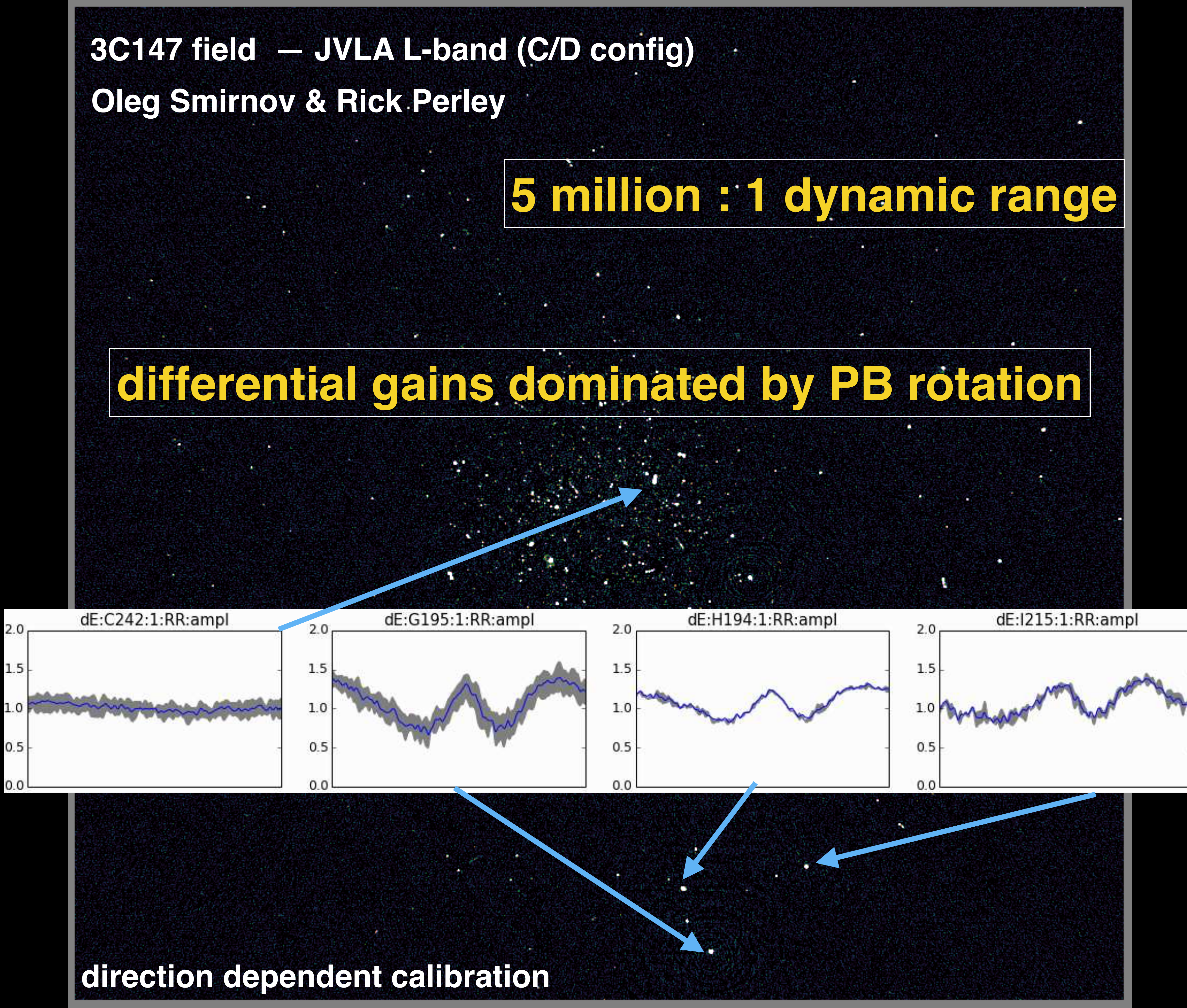
- Instrumental subtleties can be implemented very rapidly (10s of lines of Python vs. 100s of lines of C++)
- Without necessarily sacrificing performance
- For extra flexibility, particularly tricky nodes can be prototyped in Python
  - (and historically, none of these “prototypes” have ever needed to be rewritten)



Example applications:

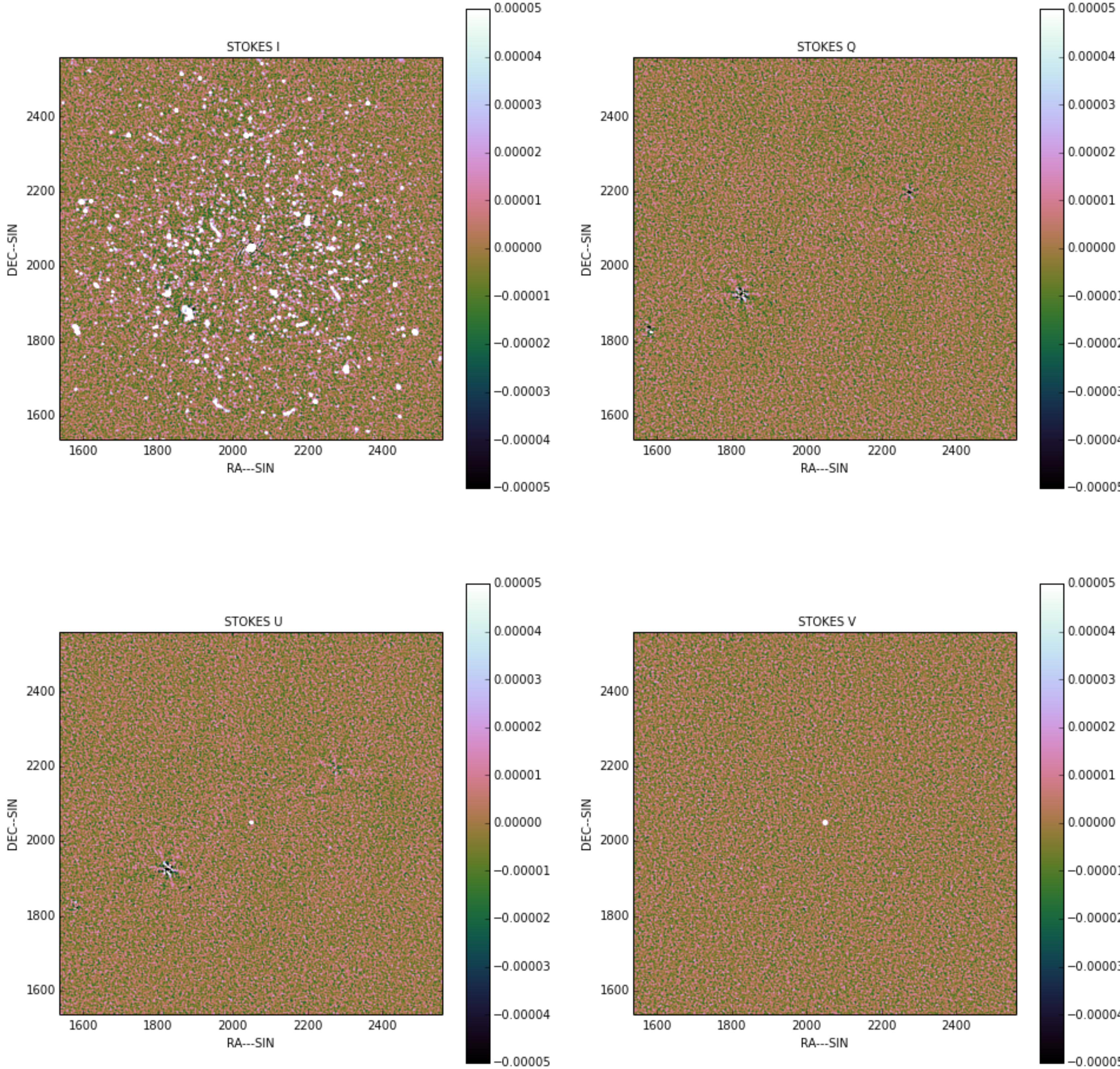
- High dynamic range calibration & imaging (direction dependent calibration, etc.)
- Evaluation of beam-related effects
- Prime focus vs offset Gregorian performance
- Element gain drifts in phased array feeds
- Fundamental sensitivity limits due to beam instability
- Ionosphere and Epoch of Reionization sims
- Weak lensing simulations (incl. SKA1)
- MC & Bayesian sampling
- Generating training data for machine learning


3C147 field — JVLA L-band (C/D config)
Oleg Smirnov & Rick Perley
regular self-cal


3C147 field — JVLA L-band (C/D config)
Oleg Smirnov & Rick Perley
5 million : 1 dynamic range
differential gains dominated by PB rotation
dE:C242:1:RR:ampl
dE:G195:1:RR:ampl
dE:H194:1:RR:ampl
dE:I215:1:RR:ampl
2.0
1.5
1.0
0.5
0.0
direction dependent calibration

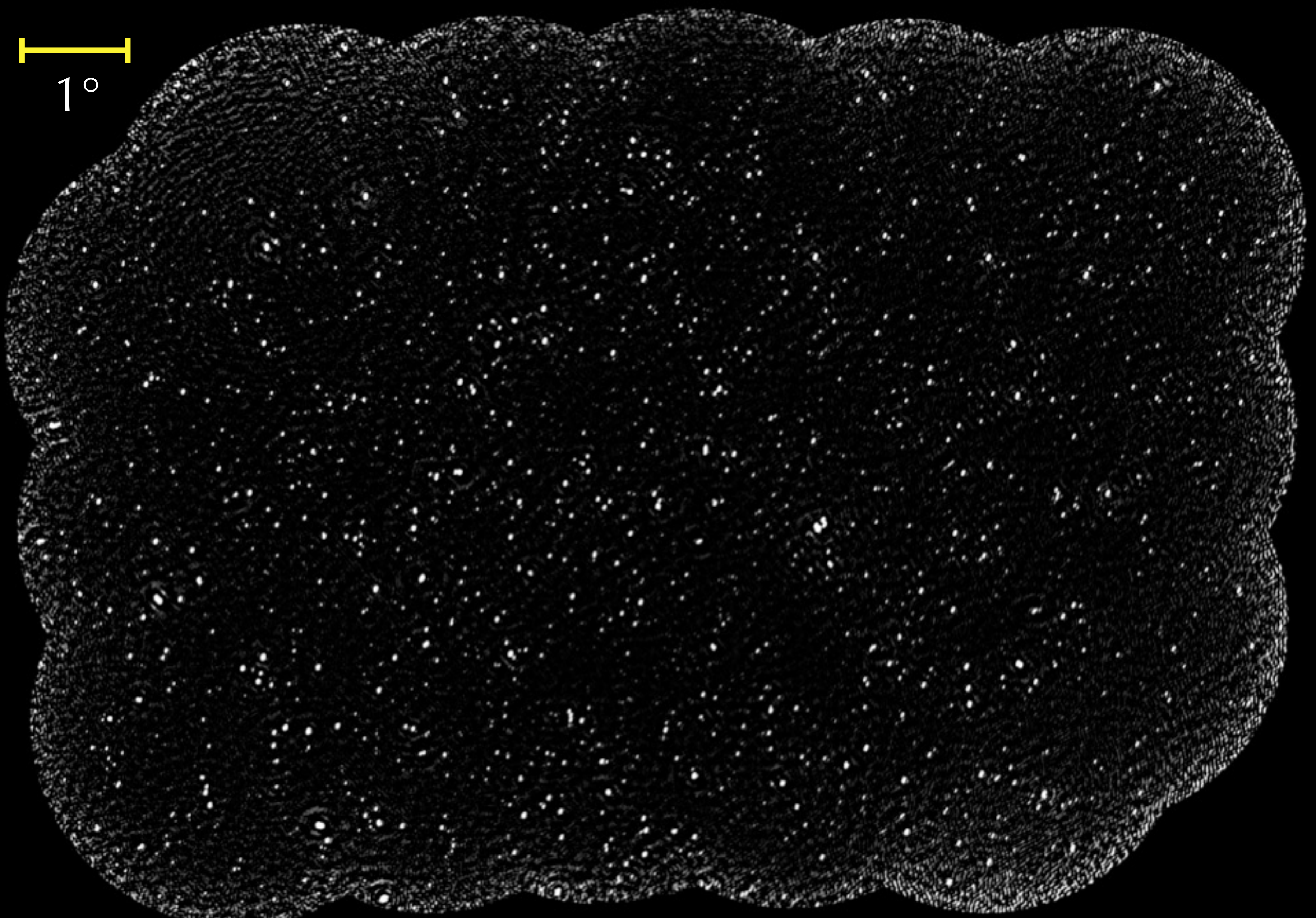
full stokes primary beam correction

(no more JVLA beam squint)



Phased array feed calibration

- 50 deg^2 with 2 pointings down to 0.5 mJy/beam with ASKAP/BETA
- fully automated MeqTrees pipeline employing differential gains
- ~2200 sources detected above 5σ

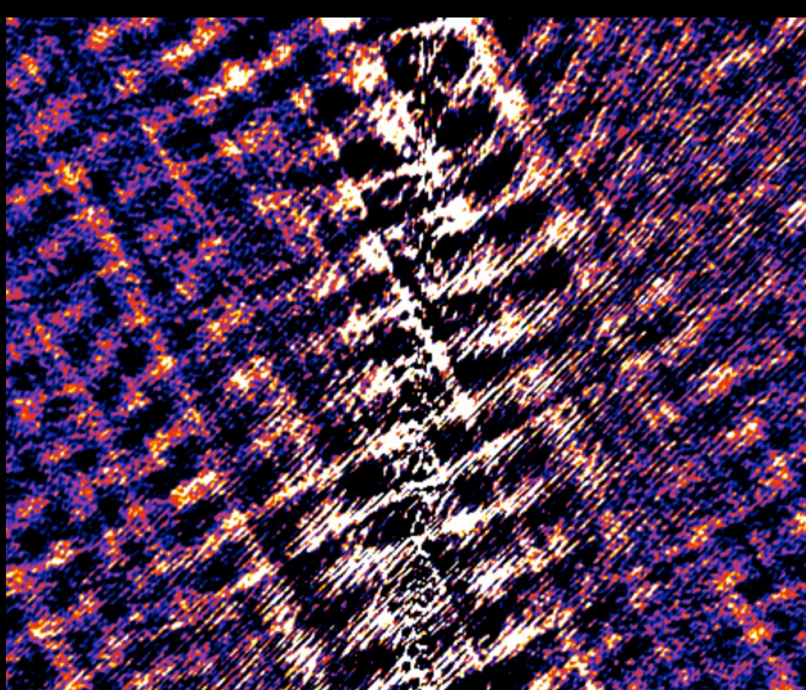


credit:
Ian Heywood

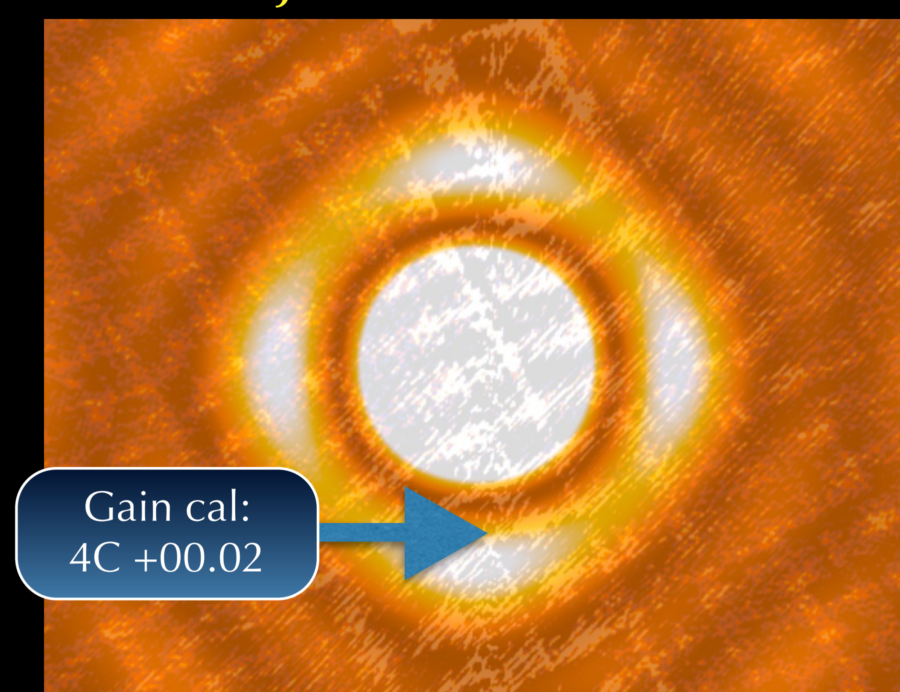
Direction-dependent gains for accurate bright source subtraction

- X-band JVLA observation of the WHT deep field
- bright source (4C +00.02, the phase calibrator) near the first primary beam null
- impossible to calibrate without MeqTrees differential gain solutions and accurate source subtraction.

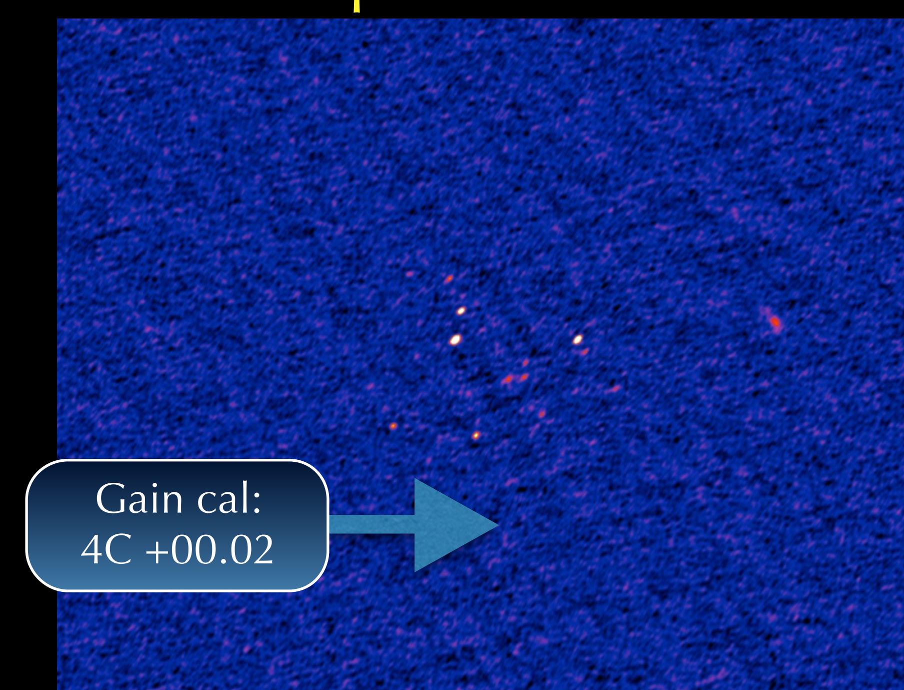
traditional calibration



JVLA Stokes I beam



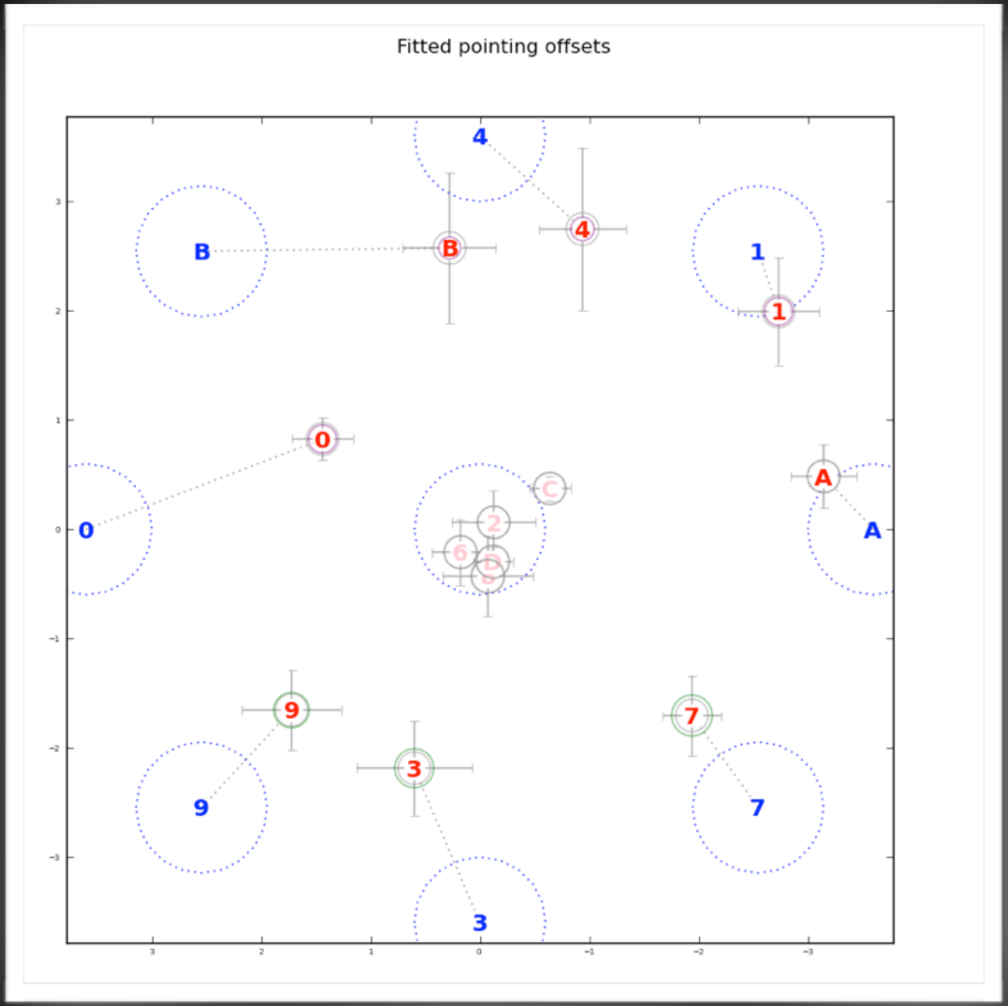
MeqTrees calibration



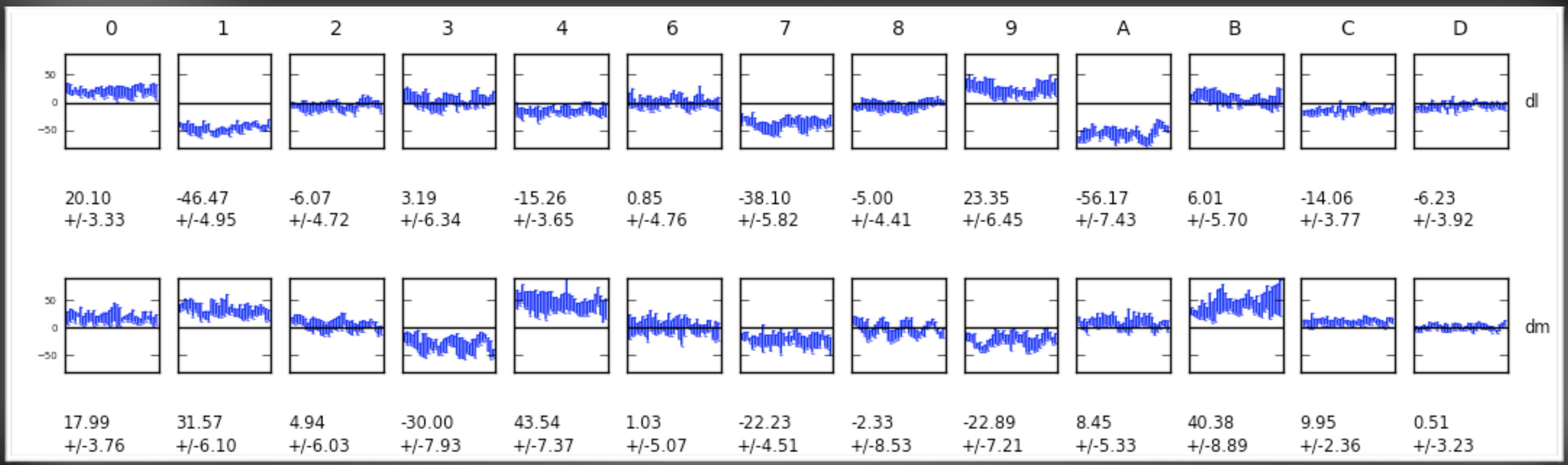
CASSBEAM software, Walter Brisken, NRAO

Heywood et al., *MNRAS*, 428, 935, 2013

Antenna pointing error solutions



- subset of antennas in the WSRT deliberately mis-pointed **(shown in blue)**
- MeqTrees was able to determine to reasonable accuracy the precise offsets from the intended pointing **(shown in red)**
- resulting pointing offset solutions (as a function of time) revealed a regular pointing **'wobble'** on some antennas that was not previously known



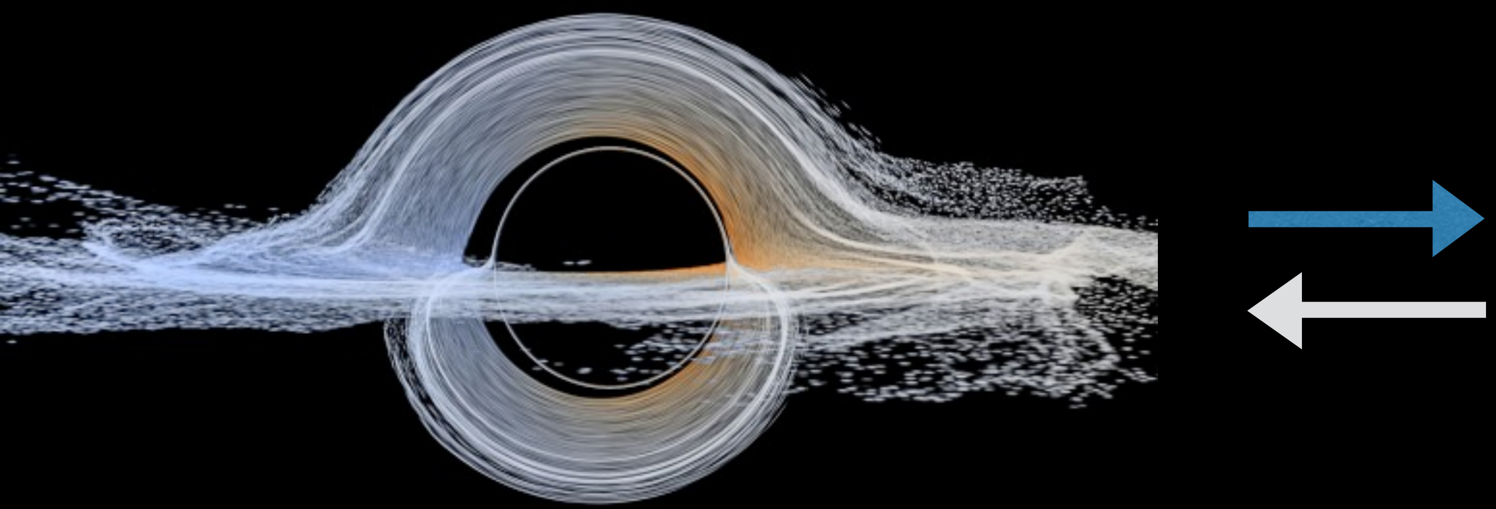
- MeqTrees is focussed on “niche” problems
- pushing interferometers to their limits by parameterising very subtle effects and solving for them
- recently made a big push towards Bayesian methods
- **KEY POINT:** parameters can (and should!) be a combination of source and instrument if this impacts the inferences that are made

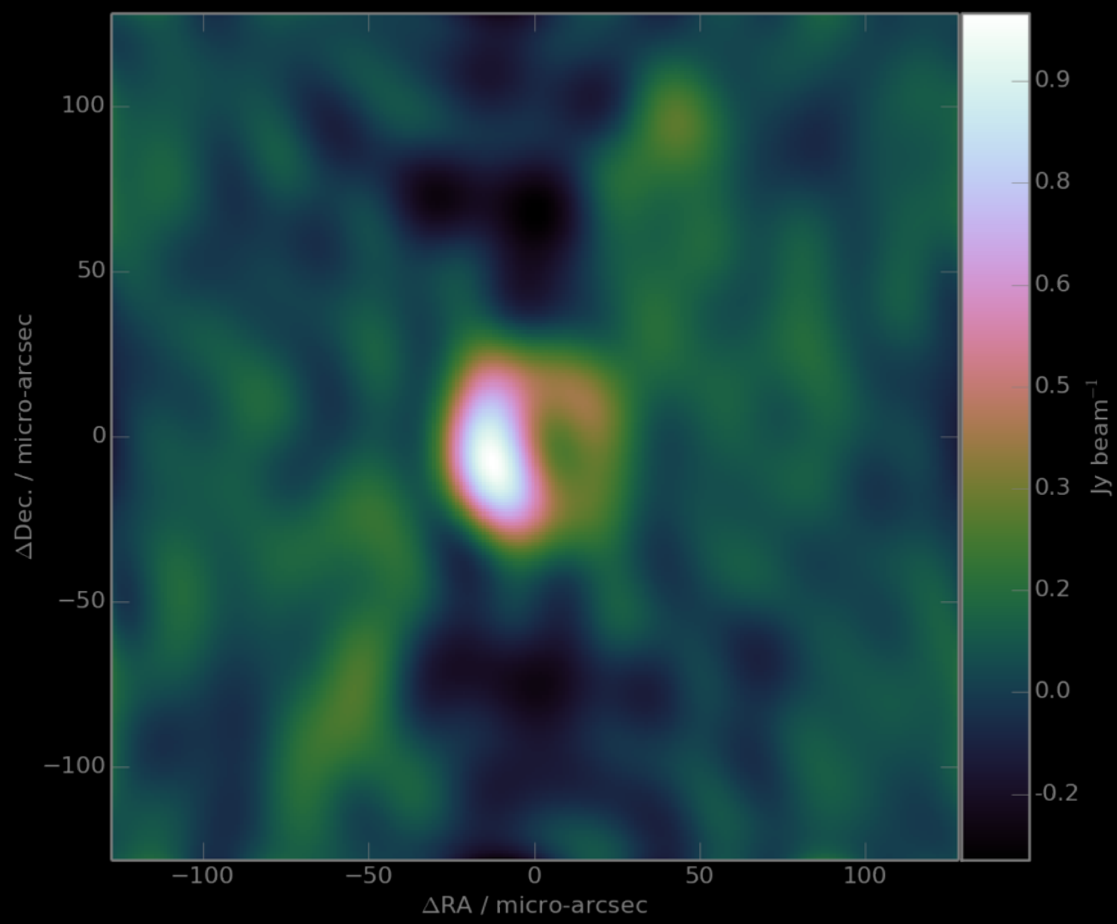
simulating (and solving for) these effects is all in place for connected element, cm-wave radio interferometry

all that we need to do is tailor it to mm-VLBI

Meq Silhouette

robust, repeatable measurements





joint fitting of instrumental and science parameters

in the visibility domain

interferometric simulations

Richard Feynman's dictum

“What I cannot create I do not understand”

Richard Feynman's dictum:

“What I cannot create I do not understand”

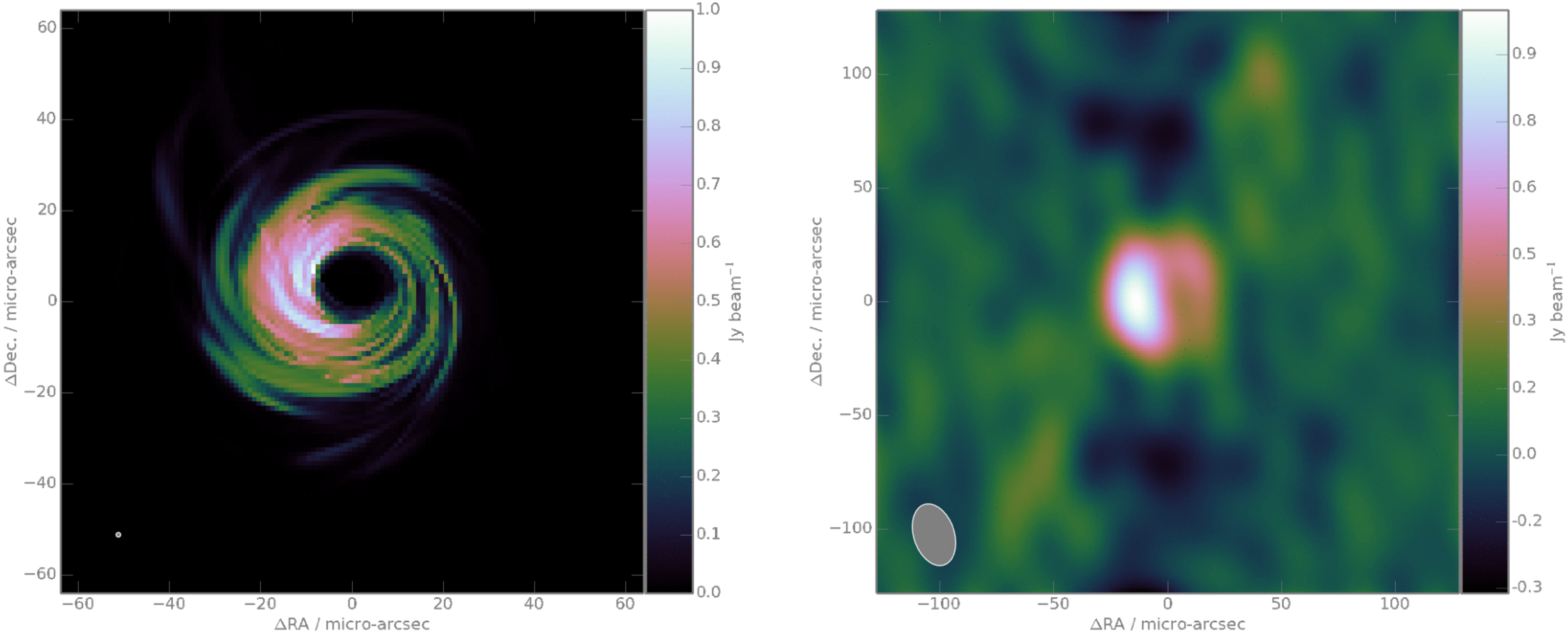
“If you can simulate it,
you can solve for it”

— Oleg Smirnov

an end2end simulator

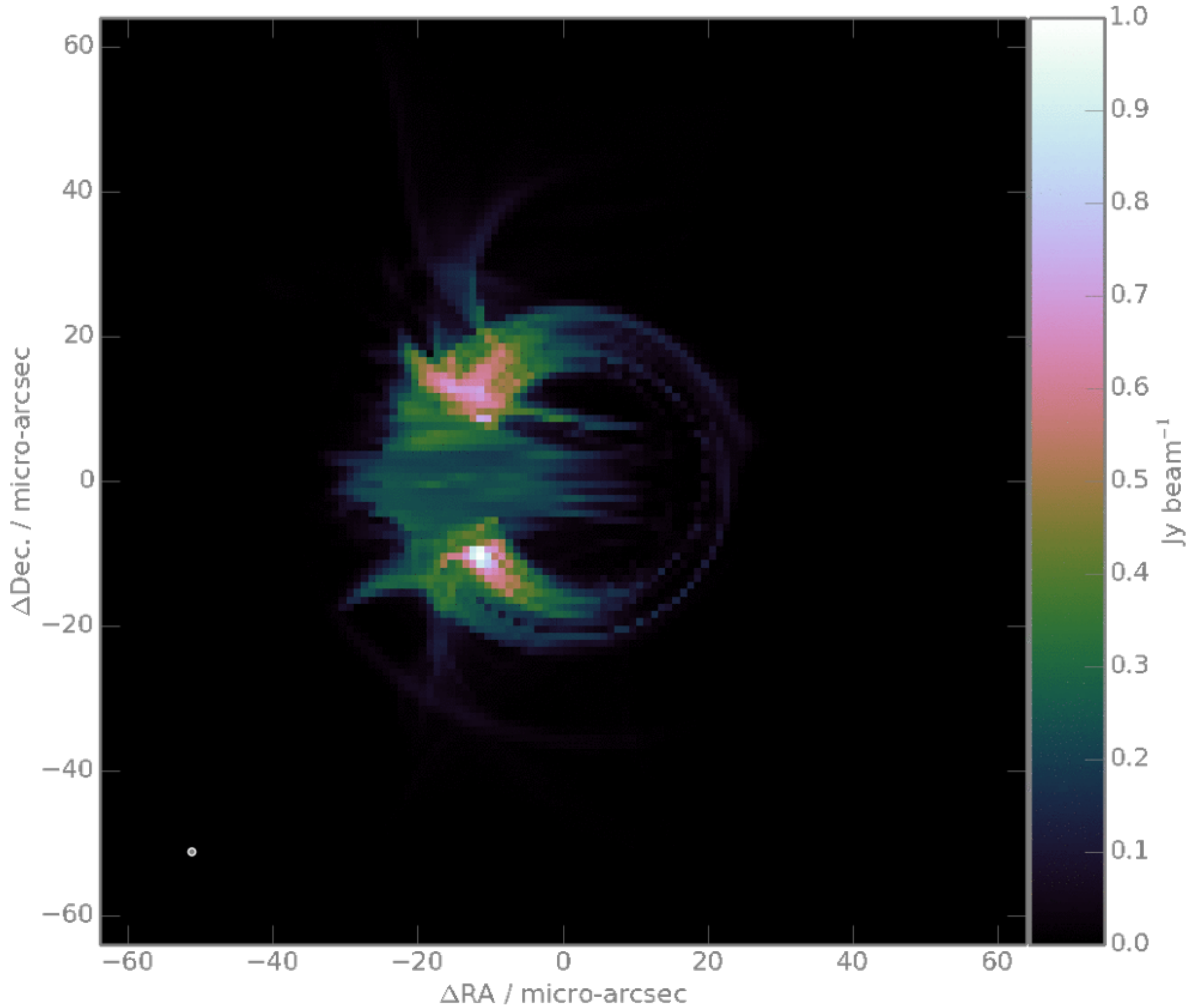
- form your measurement equations (python script, GUI, html interface)
- **inputs:** GR-MHD images, point srcs, etc. (full Stokes)
- **add corruptions** of choice (gain errors, polarization leakage, tropospheric model, pointing error, etc.)
- **simulate and image** (with a range of imaging algorithms)s
- **automated metrics** (e.g. polarization ratios, Radon transform, etc.)
- **parameter estimation** (MCMC and Bayesian model selection)

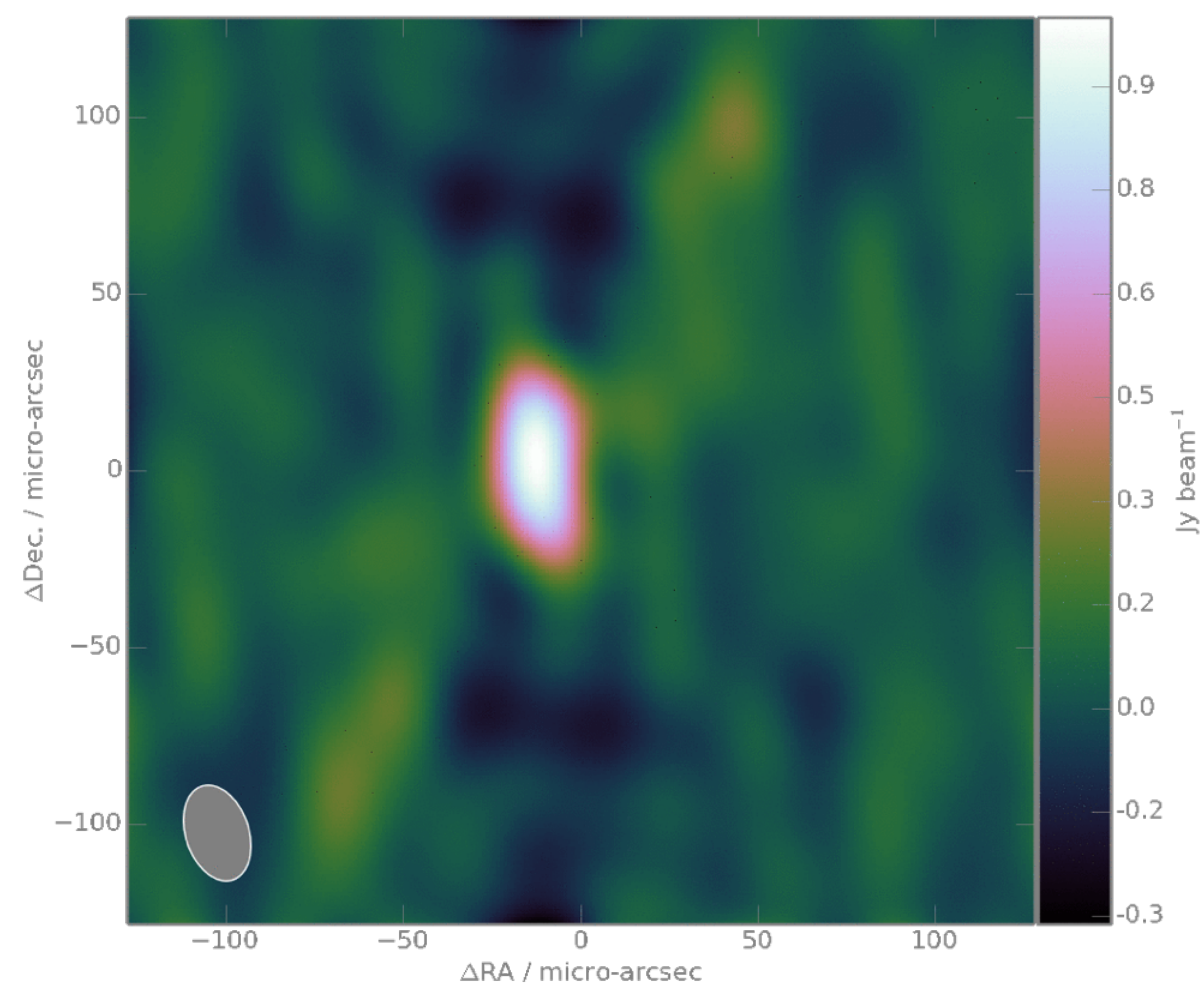
Monika's GR-MHD simulation
jet at inclination = 30 deg; RA,Dec = M87



stations: SMA, LMT, CARMA, SMT, Pico Veleta, PdBI, ALMA, GLT
12 hour track, elevation > 15 degrees

Monika's GR-MHD simulation
jet at inclination = 90; RA,Dec = M87





stations: SMA, LMT, CARMA, SMT, Pico Veleta, PdBI, ALMA, GLT

12 hour track, elevation > 15 degrees

…just add ~~water~~
corruptions

troposphere

- lots of work in MeqTrees on this for ionosphere (by Ilse, Pimm to continue(?))
- must be physical
- easily understand your risks (if *N* stations not participating due to weather)
- we have a lot of information on the sites already (and can envision each site having PWV radiometers in the future)

pointing errors

- seems more of problem than I originally thought
- substantial fractions of primary beam
- can calibrate out in station-dependent complex gains, but then there is dynamic pointing error

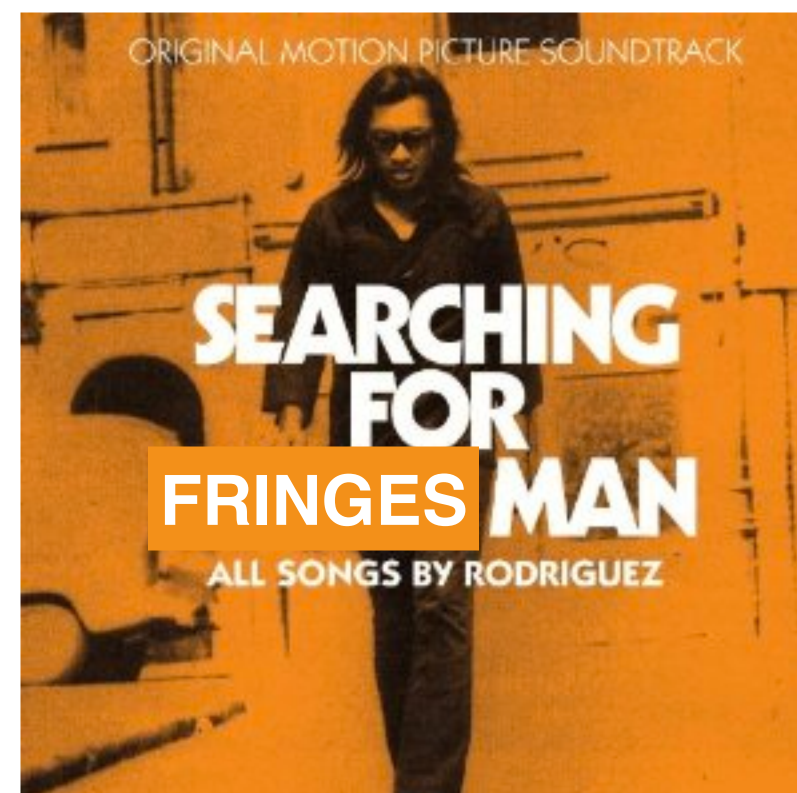
further effects

- intrinsic source variability
- ISM scattering

a point-and-click
end-2-end simulator

RODRIGUES

RATT Online Deconvolved Radio Image Generation
Using Esoteric Software

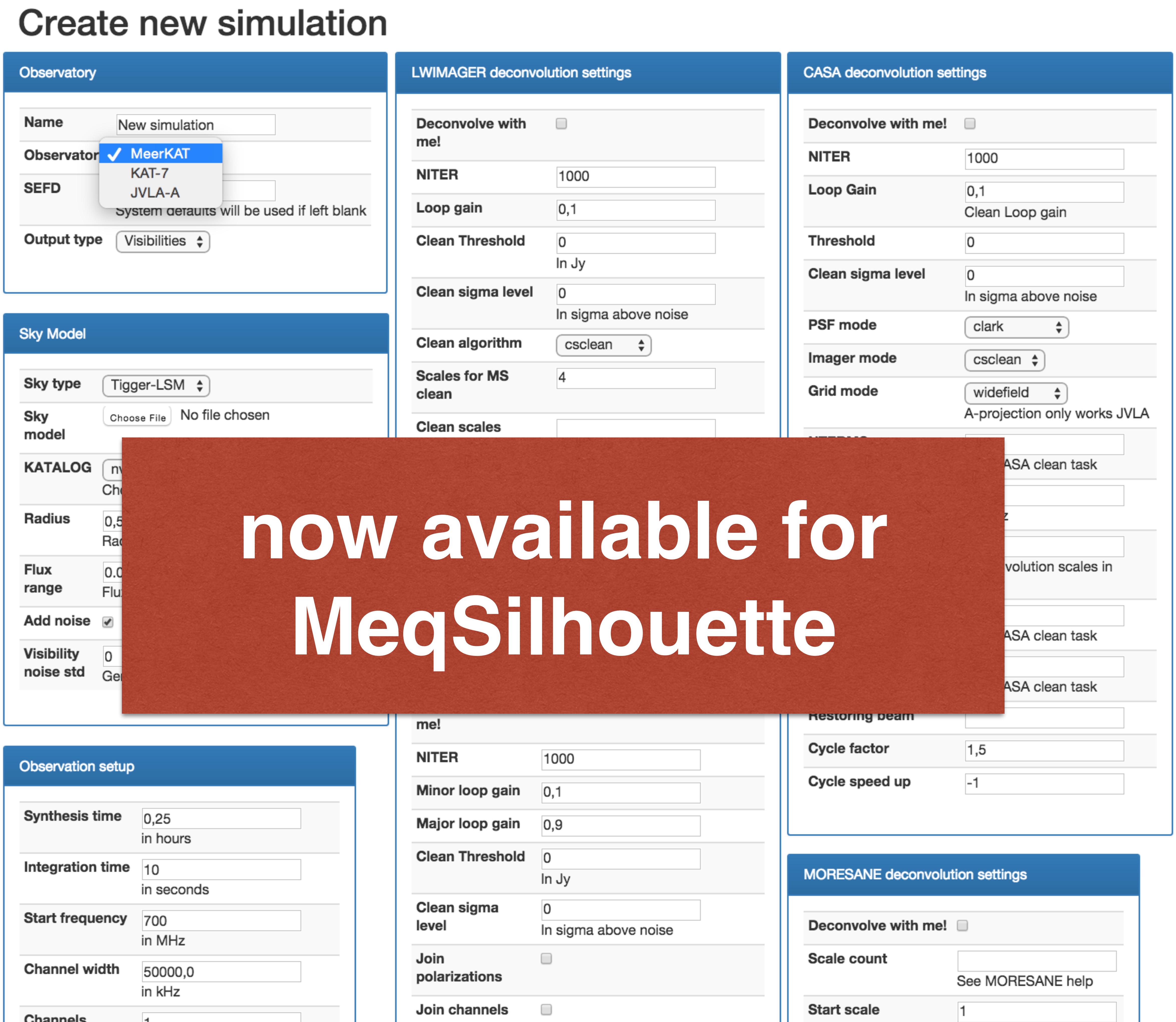


created by:
Sphesihle Makhathini
Gijs Molenaar
Oleg Smirnov

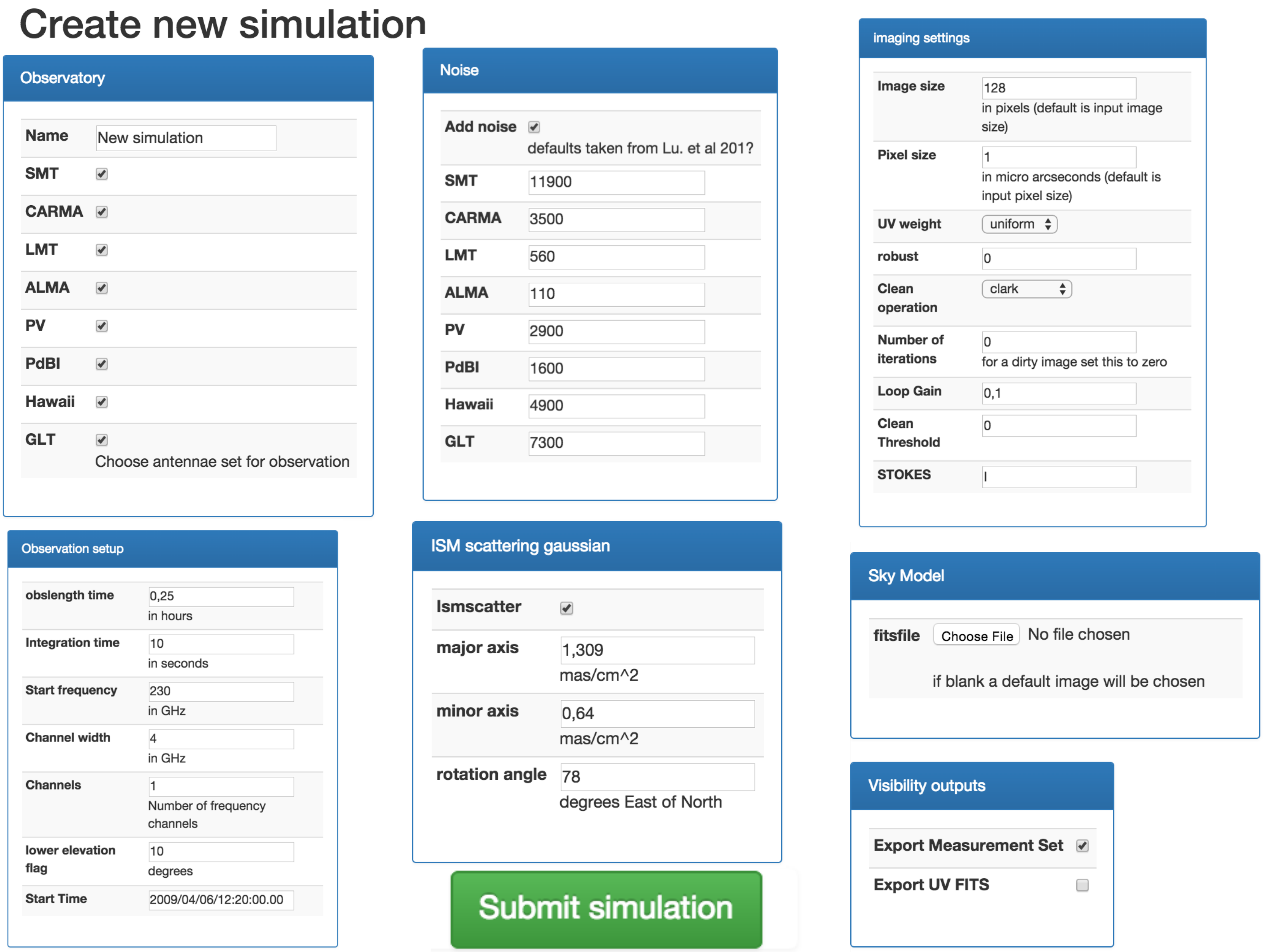
RODRIGUES

- browser-based, pipeline running on backend of GCE or HPC centre in Cape Town
- parametrised, platform independent scheduler
- Can be deployed on a laptop, cluster, cloud (Google Compute Engine, Amazon Web Services)
- Offers a standardised framework for comparing data reduction techniques (calibration, imaging, source finding, etc.)

http://rodrigues.meqtrees.net https://github.com/ska-sa/rodrigues



Create new simulation
Observatory
Name
New simulation
Observator
MeerKAT
KAT-7
JVLA-A
SEFD
System defaults will be used if left blank
Output type
Visibilities
Sky Model
Sky type
Tigger-LSM
Sky model
Choose File
No file chosen
KATALOG
Radius
Flux range
Add noise
Visibility noise std
0
Observation setup
Synthesis time
0,25
in hours
Integration time
10
in seconds
Start frequency
700
in MHz
Channel width
50000,0
in kHz
LWIMAGER deconvolution settings
Deconvolve with me!
NITER
1000
Loop gain
0,1
Clean Threshold
0
In Jy
Clean sigma level
0
In sigma above noise
Clean algorithm
csclean
Scales for MS clean
4
Clean scales
me!
NITER
1000
Minor loop gain
0,1
Major loop gain
0,9
Clean Threshold
0
In Jy
Clean sigma level
0
In sigma above noise
Join polarizations
Join channels
CASA deconvolution settings
Deconvolve with me!
NITER
1000
Loop Gain
0,1
Clean Loop gain
Threshold
0
Clean sigma level
0
In sigma above noise
PSF mode
clark
Imager mode
csclean
Grid mode
widefield
A-projection only works JVLA
ASA clean task
volution scales in
ASA clean task
ASA clean task
Cycle factor
1,5
Cycle speed up
-1
MORESANE deconvolution settings
Deconvolve with me!
Scale count
See MORESANE help
Start scale
1
now available for
MeqSilhouette


Create new simulation
Observatory
Name
New simulation
SMT
CARMA
LMT
ALMA
PV
PdBI
Hawaii
GLT
Choose antennae set for observation
Noise
Add noise
defaults taken from Lu. et al 201?
SMT
11900
CARMA
3500
LMT
560
ALMA
110
PV
2900
PdBI
1600
Hawaii
4900
GLT
7300
imaging settings
Image size
128
in pixels (default is input image size)
Pixel size
1
in micro arcseconds (default is input pixel size)
UV weight
uniform
robust
0
Clean operation
clark
Number of iterations
0
for a dirty image set this to zero
Loop Gain
0,1
Clean Threshold
0
STOKES
I
Observation setup
obslength time
0,25
in hours
Integration time
10
in seconds
Start frequency
230
in GHz
Channel width
4
in GHz
Channels
1
Number of frequency channels
lower elevation flag
10
degrees
Start Time
2009/04/06/12:20:00.00
ISM scattering gaussian
Ismscatter
major axis
1,309
mas/cm^2
minor axis
0,64
mas/cm^2
rotation angle
78
degrees East of North
Submit simulation
Sky Model
fitsfile
Choose File
No file chosen
if blank a default image will be chosen
Visibility outputs
Export Measurement Set
Export UV FITS

pipelined output:

R.O.D.R.I.G.U.E.S. List jobs Create job logged in as deane Log out

Results for job #8 (defaults-test)

Job properties

- **status:** FINISHED
- **start:** April 16, 2015, 3:13 p.m.
- **finished:** April 16, 2015, 3:15 p.m.
- **duration:** 0:01:26.051622
- **docker_image:** skasa/simulator
- **results_dir:** 8-qqysnq9y

Reschedule Refresh Delete

Result files

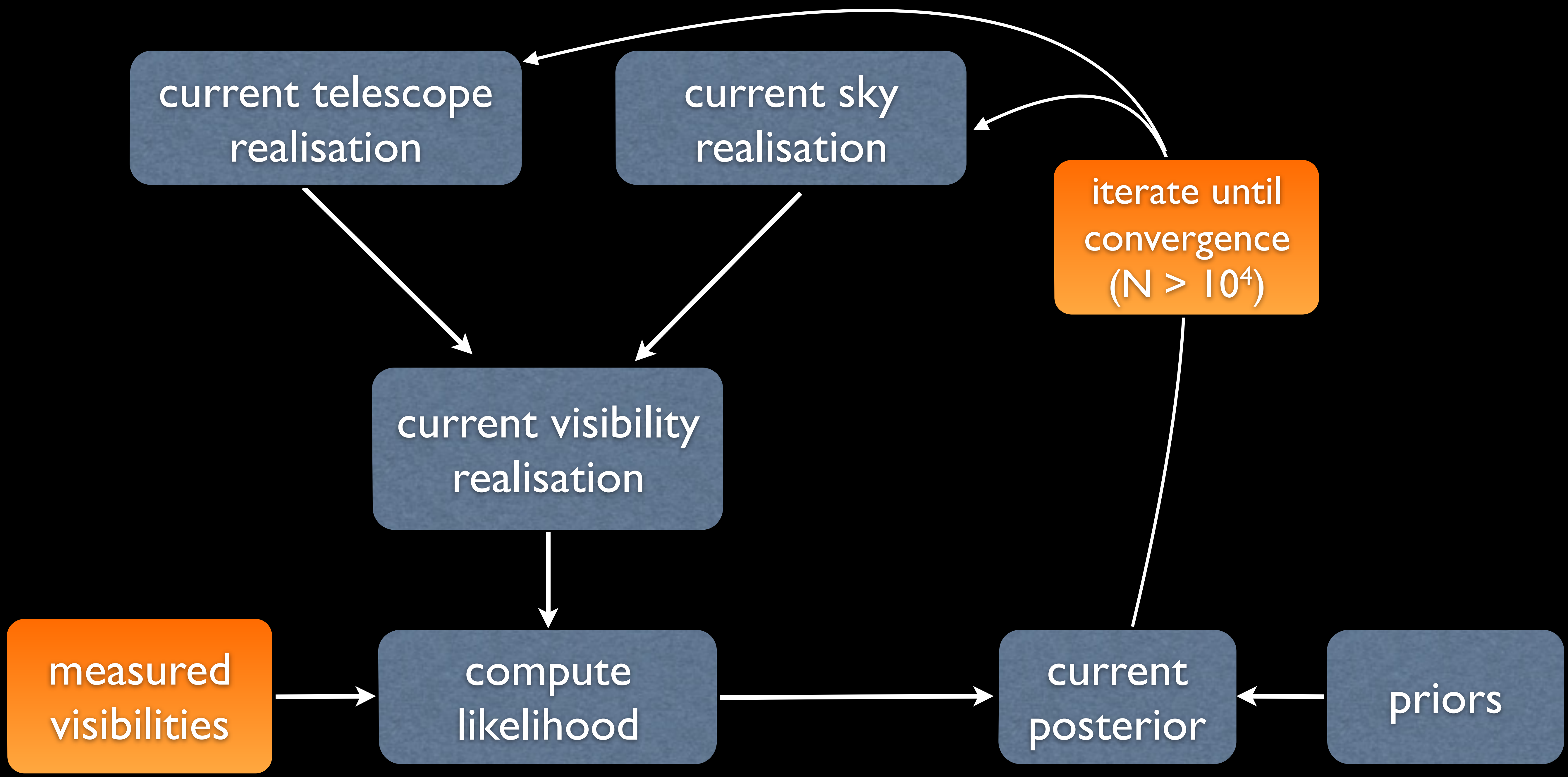
name	type	size	modified	actions
input/parameters.json	ASCII text, with very long lines, with no line terminators	2.2 KB	Thu Apr 16 15:13:57 2015	view download
output/log-ska1sims.txt	ASCII text	5.8 KB	Thu Apr 16 15:14:10 2015	view download
output/results-psf.fits	FITS image data, 32-bit, floating point, single precision	16.0 MB	Thu Apr 16 15:15:22 2015	view download
output/results-dirty.fits	FITS image data, 32-bit, floating point, single precision	16.0 MB	Thu Apr 16 15:15:17 2015	view download
output/results-uvcov.png	PNG image data, 1500 x 1500, 8-bit/color RGBA, non-interl...	178.0 KB	Thu Apr 16 15:14:11 2015	view download
output/plots-smakh1429190037.661782/log-smakh1429190037.661782.txt	ASCII text, with very long lines	12.4 KB	Thu Apr 16 15:15:22 2015	view download

pipelined output:

more from Tariq tomorrow

Bayesian Inference / Parameter Estimation

the problem with MCMC methods in interferometry

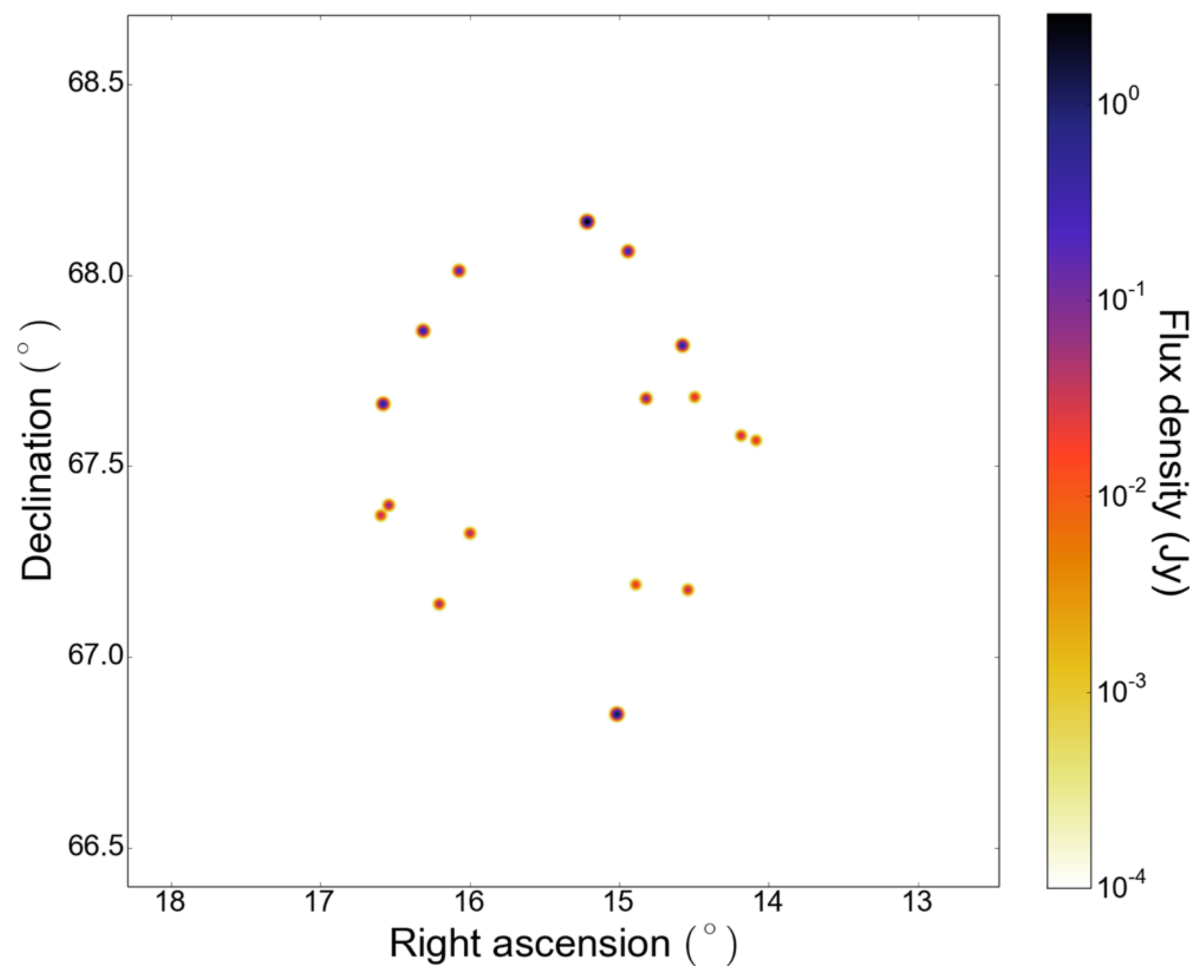


mm-VLBI (Bayesian) advantages

- relatively few stations
- required FoV is very small
- low dynamic range, not much cleaning (if needed)
- no clear direction-dependent effects

= rapid simulate-image-likelihood compute cycle time

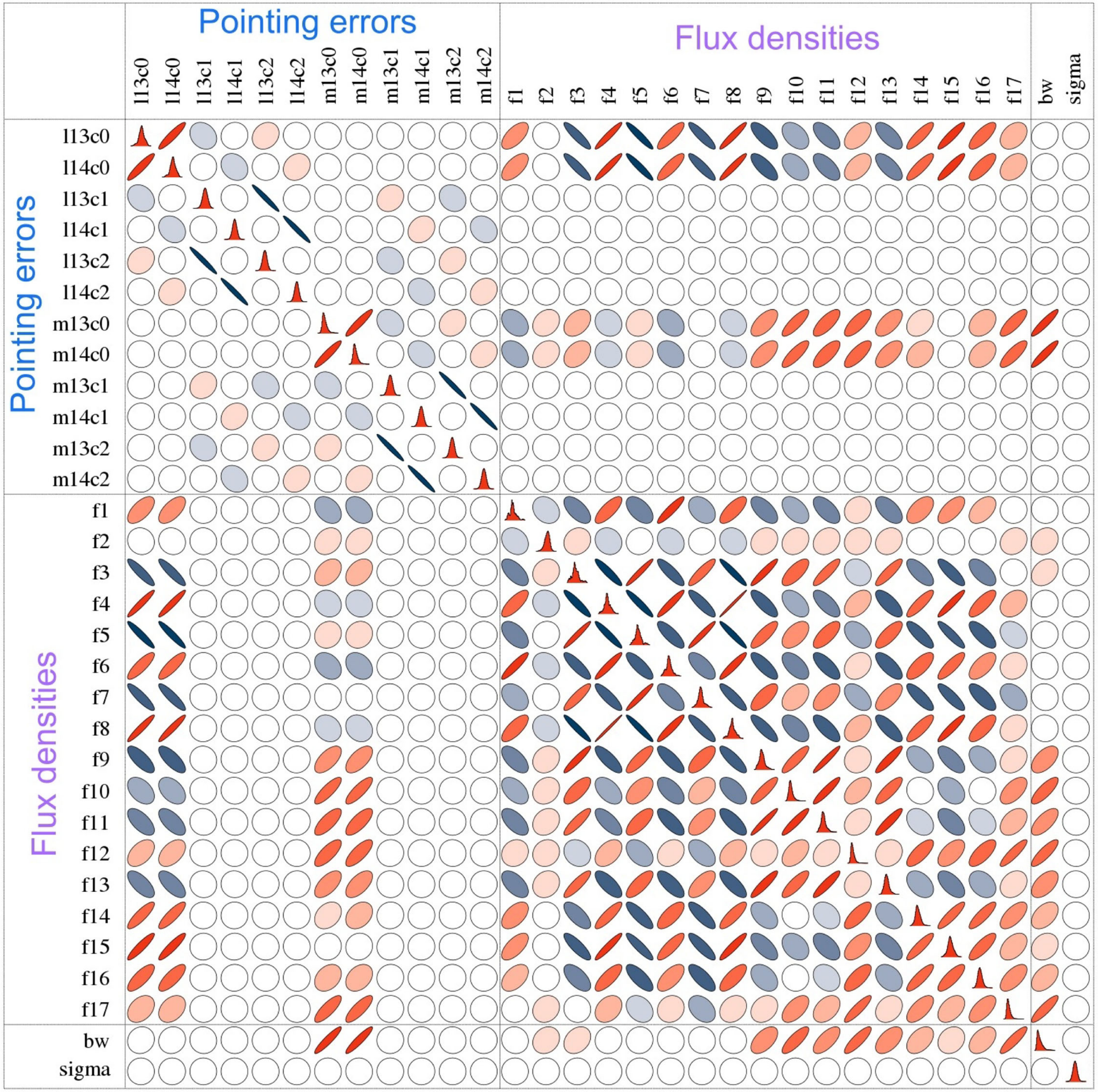
an example:



- simultaneously solve for pointing error and source flux
- covariance matrix with both instrumental and source parameters

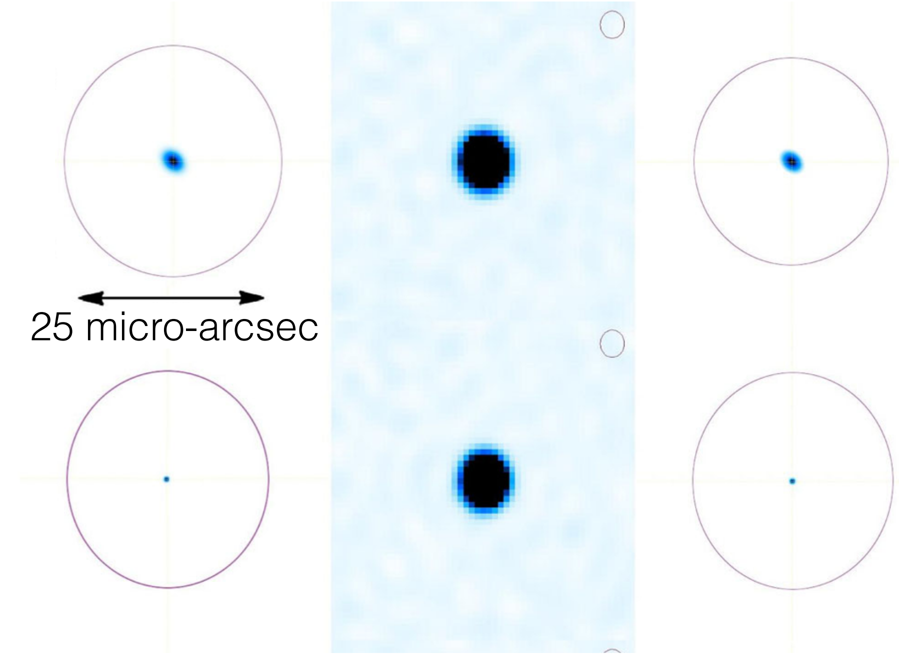
Lochner+2015

jointly solved flux densities and pointing errors

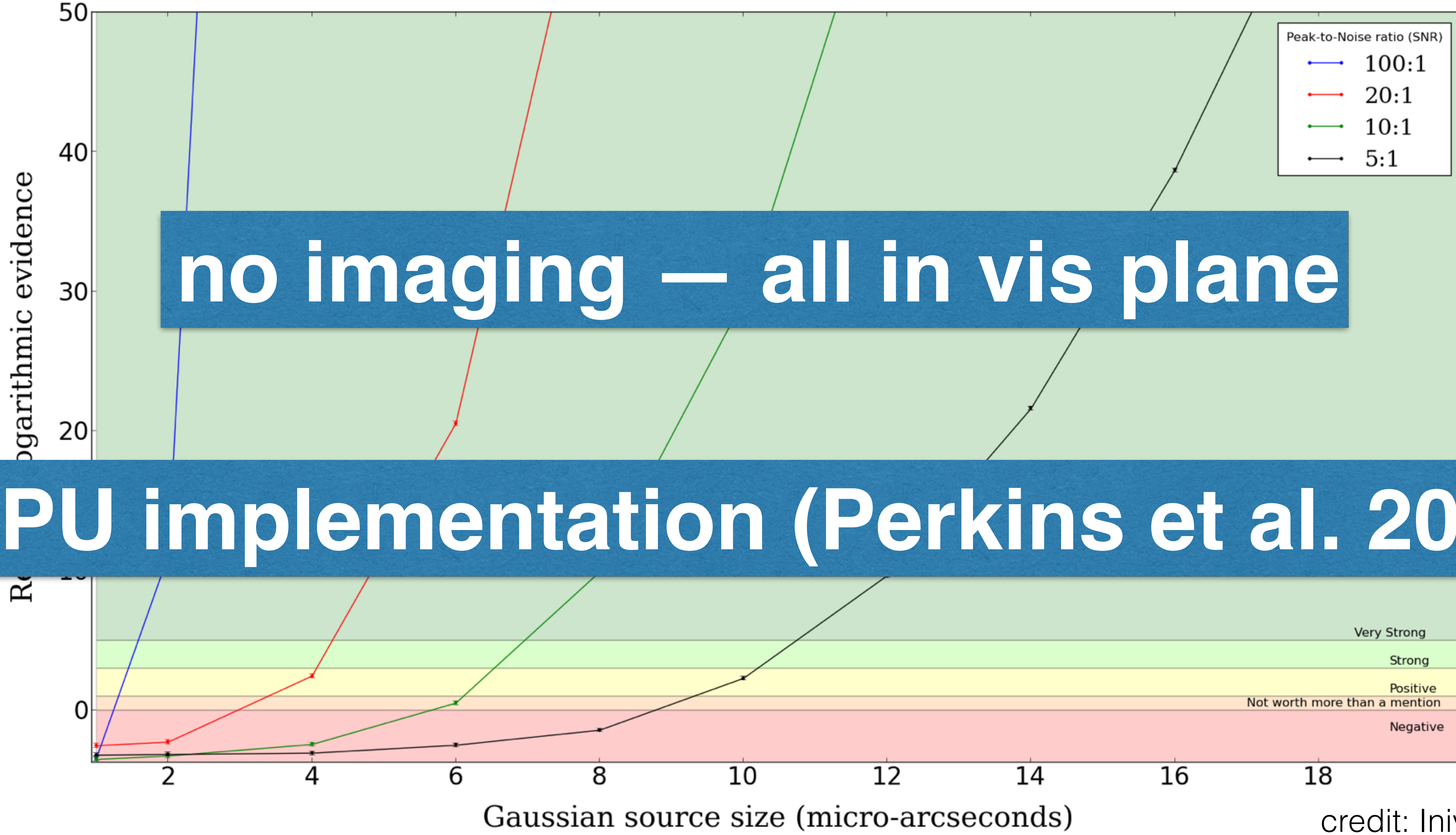


Lochner+2015

model selection



Gaussian vs Point Source



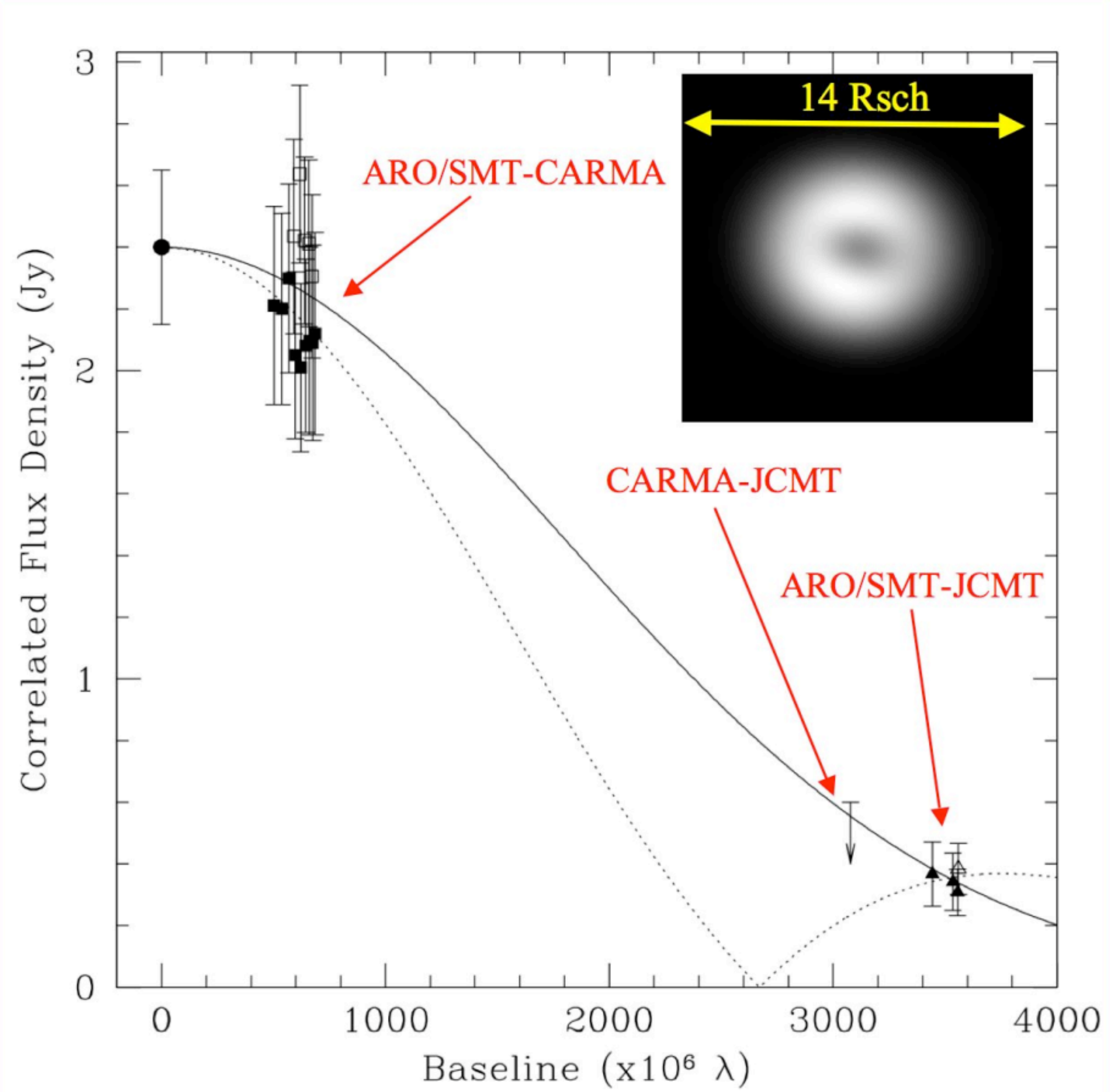
no imaging — all in vis plane

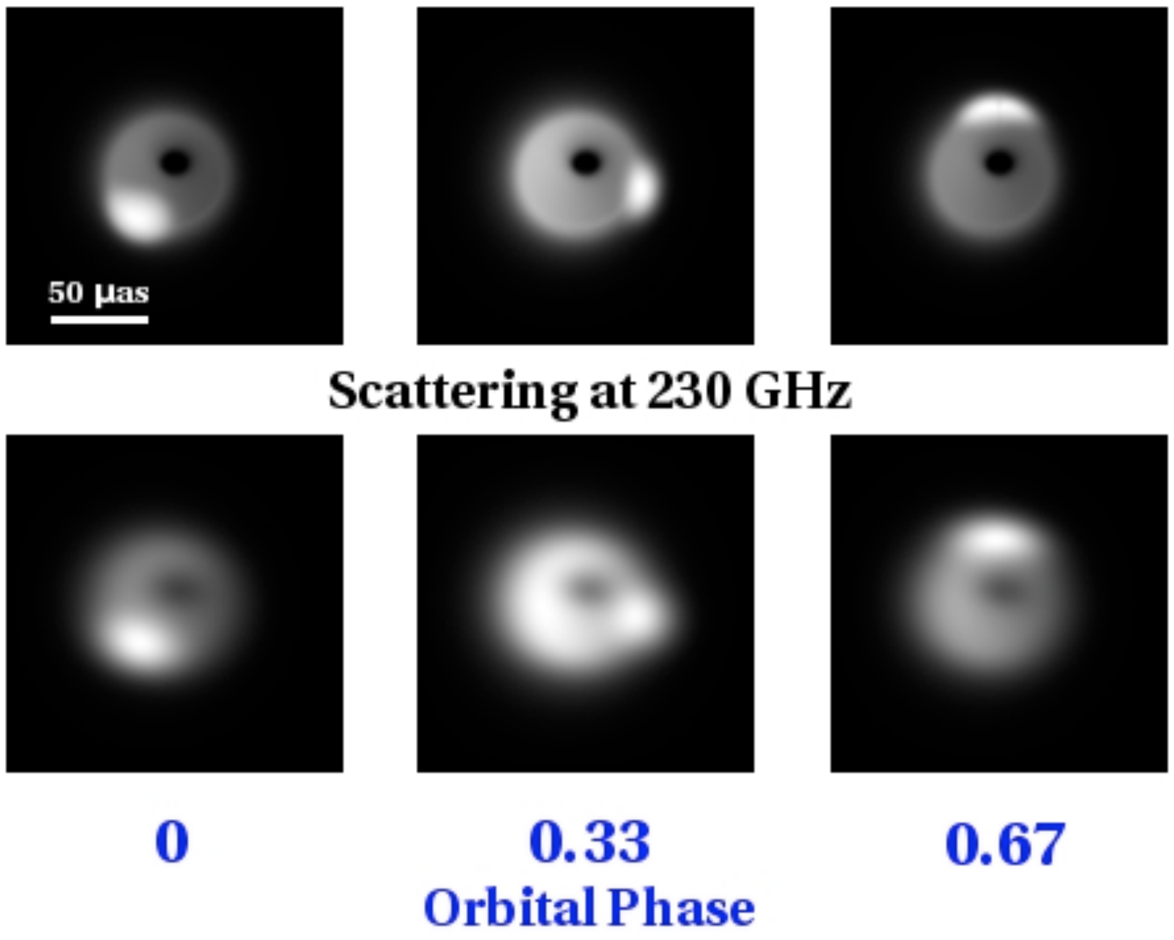
GPU implementation (Perkins et al. 2015)

credit: Iniyan Natarajan

model selection

that includes calibration systematics





Doeleman+2009

…but not just post-processing and parameter estimation

- plenty of priors available:
    - typical weather patterns
    - PWV measurements
    - typical pointing accuracy rms

future advantages

- MeqTrees development is “complete”
(~10 years development by Oleg Smirnov and others)

- Now the focus is on simulation (and calibration) pipelines; as well as Bayesian techniques

- Large team, primarily focussed on MeerKAT, HERA/PAPER, SKA1

- MeqSilhouette will benefit directly from any development in MeqTrees (e.g. RODRIGUES, GPU acceleration, imaging algorithms) so watch this space, but

COMMENTS / REQUESTS / SUGGESTIONS

would be most welcome at this point

more information

http://meqtrees.net

https://github.com/ska-sa/meqtrees