High Dynamic Range Imaging of EoR 3C196 Field

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(Astron & Kapteyn Institute)

(on behalf of the LOFAR EoR Group)

LOFAR Science Workshop

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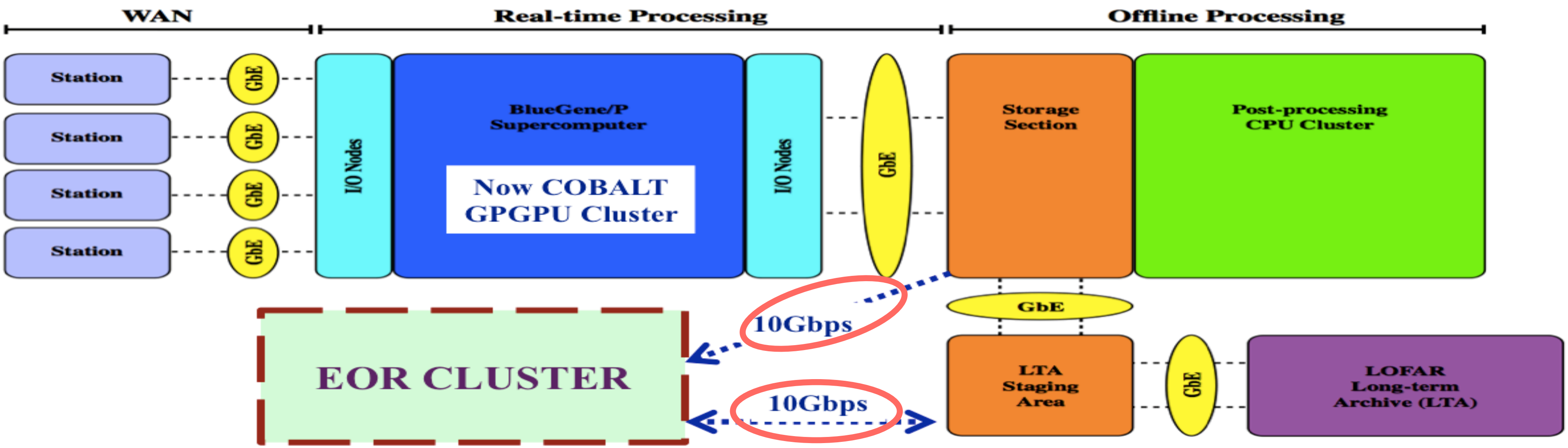
ASTRON RuG LOFAR

The LOFAR-EoR Project - Basic Numbers



Data Rate (8 times less)	~3.75 TB/hr 3KHz; 2s
Observation (115-185MHz)	3000 Hour
Total Raw Data	11.25 PB
already acquired (~1000hrs)	3.5 PB (Since Dec 2012)

After avg ~ 1PB; 12KHz, 2s (Further increase 3 times)
*Murphys law

LOFAR-EoR Cycle-1 Data; Acknowledgements

- *Wietze Albers (Target)*
- *Ger Strikwerda (Target)*
- *Robin Teerenga (Target)*
- *Eite Tiesinga (Kapteyn/EoR)*
- *Teun Grit (ASTRON)*
- *Arjen Koers (CIT)*
- *Adriaan Renting (ASTRON)*
- *Hanno Holties (ASTRON)*
- *Ger de Bruyn (EoR)*
- *V.N. Pandey (EoR)*
- *Michael Sipior(EoR/ASTRON)*
- *Maaijke Mevius(Kapteyn/EoR)*
- *Saleem Zaroubi(kapteyn/EoR)*
- *Yan Grange (ASTRON)*

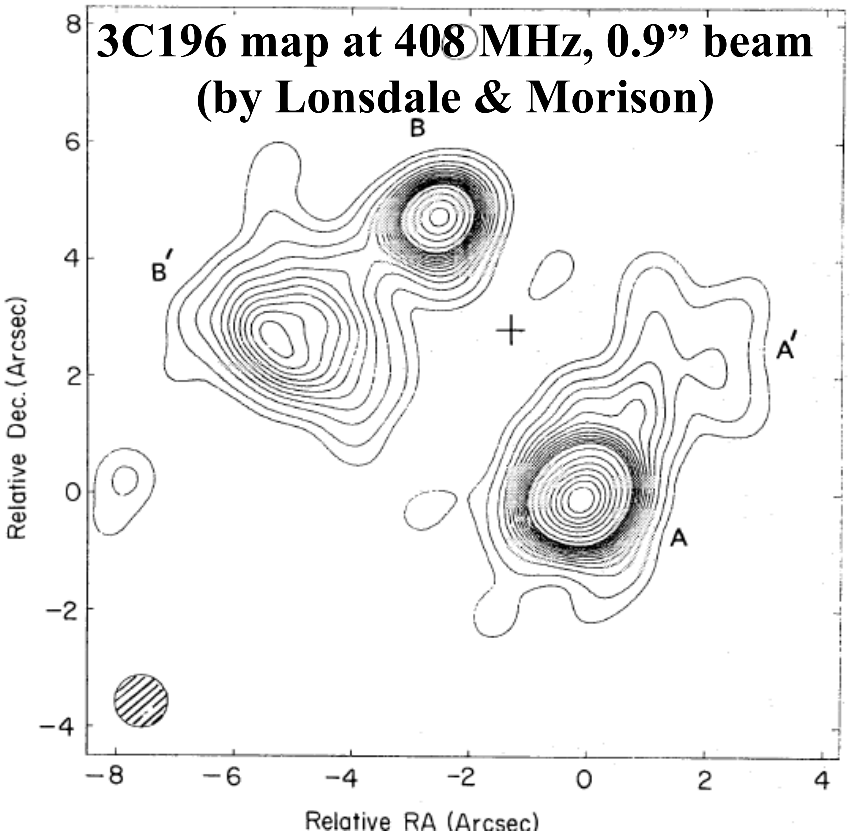
(not in order)

- **Sep 2014 - Oscar (DM) moves to new Job**
- **Nov 2014 – Target LTA offline**
- **2 Dec 2014 - Possibility of no EoR Data**
- **5 Dec 2014 – Storm; Meeting+skype;**
- **University closed 2PM (Thursday)**
- **9 Dec 2014 - EoR sysadmin -> Vacation**
- **Dec 8th 2014 – CEP2->EoR Connection**

- **ssh via mobile phones to test transfers**
- **Meterwave conf in India (Dec9-13, 2014)**
- **EoR Cluster reorganization**
- **severe ionoshperic activity**

~45 nights of EoR data in 100 days

The EoR 3C196 Field:- Overview



- ~ 5" x 5" in size
- Longest Dutch baseline ~120 Kms !!
- LOFAR resolution ~ 4"x5" (150MHz)
- Super Resolution – 3C196 model

- An 80Jy (140MHz), bright radio quasar, relatively! compact source.
- In one of the colder regions of galactic halo

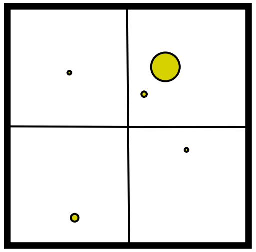
  - allows accurate direction independent calibration

  - solve for band-pass structure, one ionosphere pierce point

  - relative flux and noise scale down to KHz level

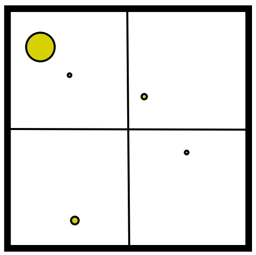
- Need Extremely High dynamic range (~70dB)
- Several 5-10Jy bright sources !

Dynamic Range: DR = peak flux / rms noise



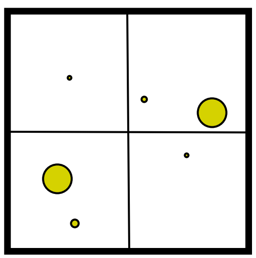
on-axis

point source

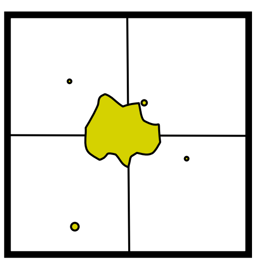


off-axis

point source



≥ two off-axis
point sources



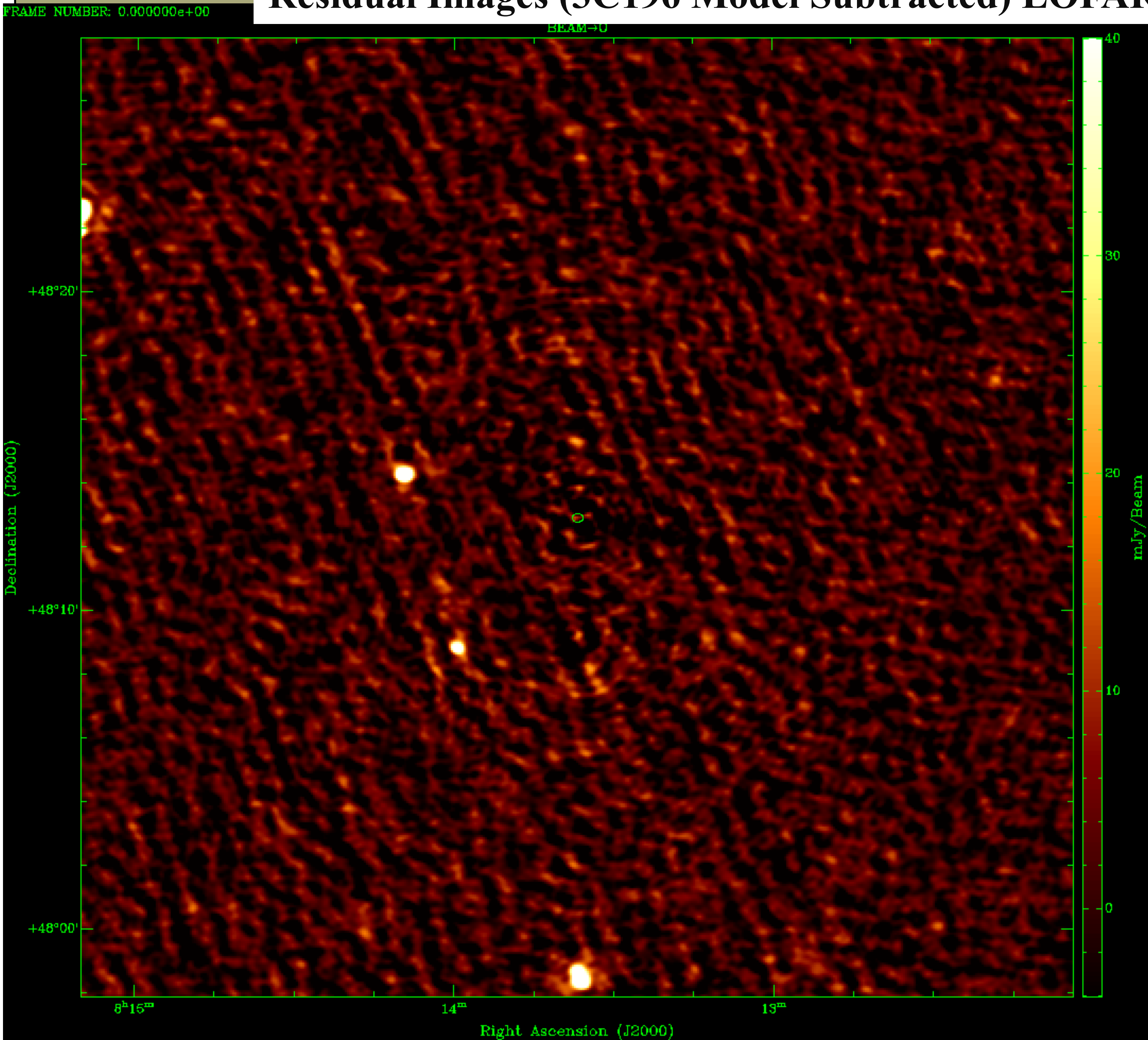
extended
source

source configurations and causes

✓	(mechanical) pointing	-	X	X	-
✓	non - isoplanatism (ionosphere)	-	-	X	-
✓	decorrelation (troposphere/ionosphere)	X	X	X	X
✓	closure errors (cross-talk, ...)	X	X	X	X
✓	non-linearity (RFI, ...)	X	X	X	X
✓	ghosts (Gibbs, image rejection..)	-	X	X	X
✓	polarization leakage instability	-	X	X	X
✓	deconvolution limitations	-	-	-	X
✓	variable sources	X	X	X	X
✓	software errors/deficiencies	X	X	X	X
✓	Inaccurate Model extended on axis source (when also used as Calibrator) – Exact Case of 3C196 Field	X	X	X	X

Slide from Ger's talk at CALIM 2006

Residual Images (3C196 Model Subtracted) LOFAR



Modelling 3C196

- 0.5^0 x 0.5^0
- 30λ-17Kλ
- (resolution 13")
- Briggs weights

(8hrs x 200KHz)

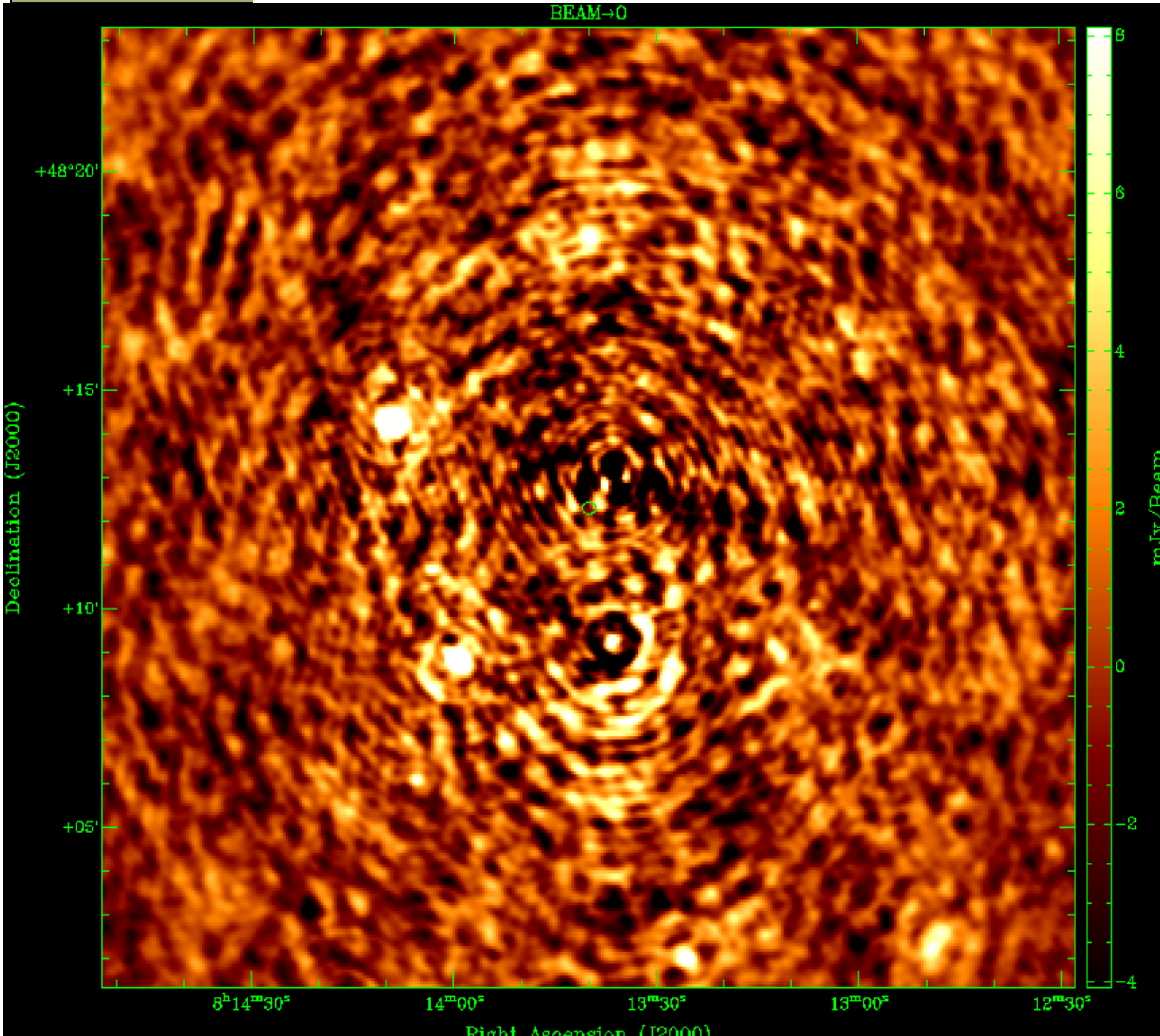
- rms noise 1.5-2mJy (In each frame)

movie along ν

- 21 frames
- 163-167MHz

3C196 (75Jy) subtracted (10mJy level)

Residual Images (3C196 Model Subtracted) LOFAR



Modelling 3C196

30λ-17Kλ (resolution 13”)
Briggs weights

(32hrs x 4MHz) rms noise ~0.3 mJy (9 time low rms)

~165MHz

3C196 (75Jy) subtracted (10mJy level)

EoR Project:
600hrs x 70MHz
~ 20 times deep

High Dynamic Range Imaging - History

1960ies Cambridge ~ 100 : 1

1970ies WSRT ~ 1000 : 1 (very G/ϕ - stable array)

~ 1977-1980 discovery/development of selfcal

1982 WSRT >10,000 : 1

(Noordam & de Bruyn, 1982; 3C84, redundancy)

1980ies WSRT, VLA ~1-400,000 : 1

(de Bruyn: 3C84/147, Perley: 3C273, Briggs - Cornwell: DA193)

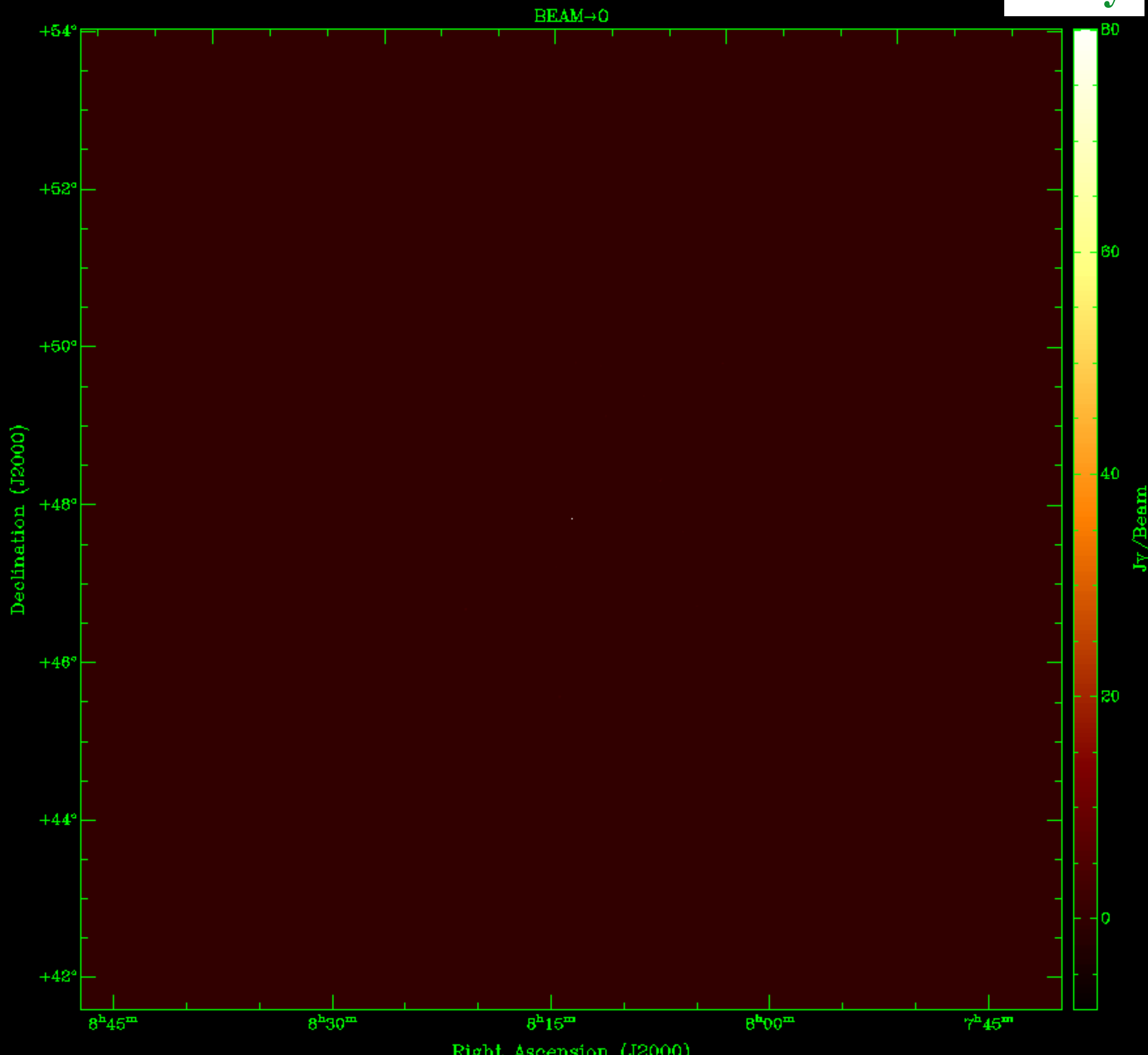
1990ies WSRT ~ 500,000 : 1

2000++ WSRT > 1,000,000 : 1 (debruyn, Brentjens)..

2013 JVLA ~ 2,500,000 : 1 (Perley & Oleg; 1.4GHz)

- With LOFAR at 150MHz - an order of magnitude lower from 1420MHz !
- For todays talk; all data under discussion is from LOFAR HBA
- All 3C196 data only calibrated with Black Board Selfcal System

80 Jy

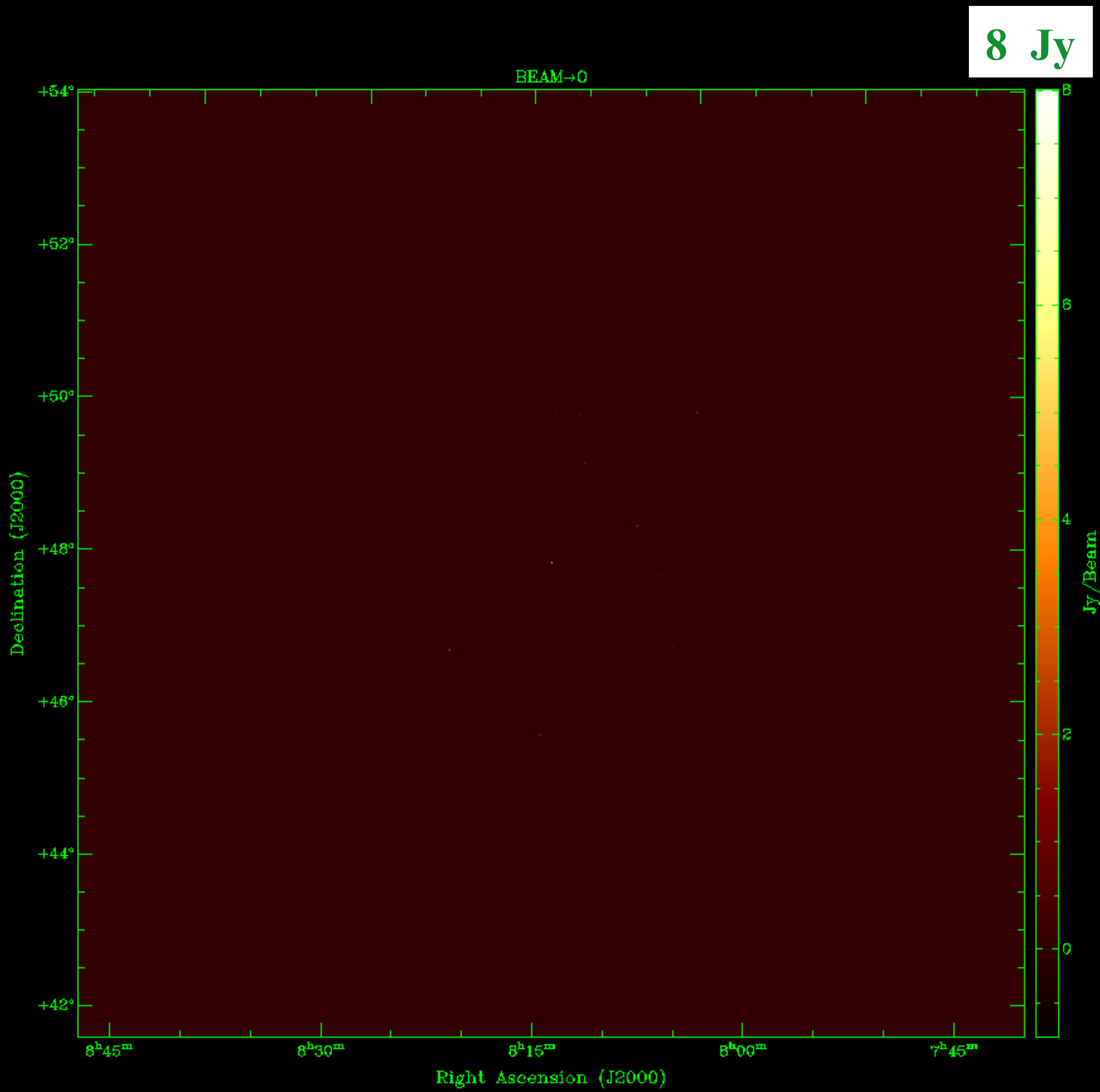


3C196 Field Image

- 145 MHz (~2m)
- 60MHz continuum
- 6 powers of 10

- 32 hours on 3C196 (8 hrs x 4 days)
- Dec 21,12-Feb08,13
- 30λ - 5000λ
- Resolution - 50”
- $12^0 \times 12^0$ Image

- ‘Noise’ < 75 μJy
- 3C196 - 79.97 Jy
- **DR: ~ 10^6:1**



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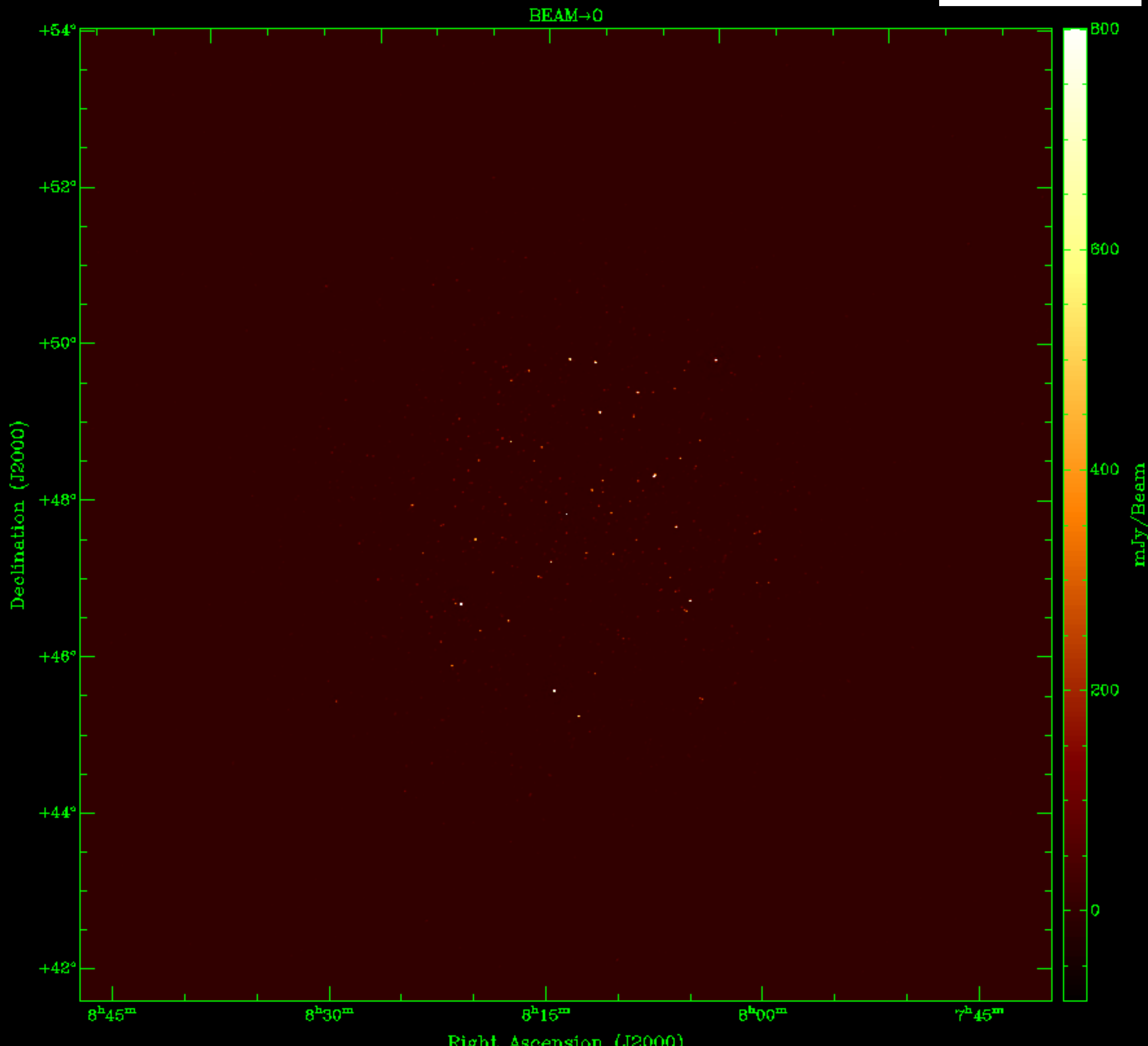
800 mJy



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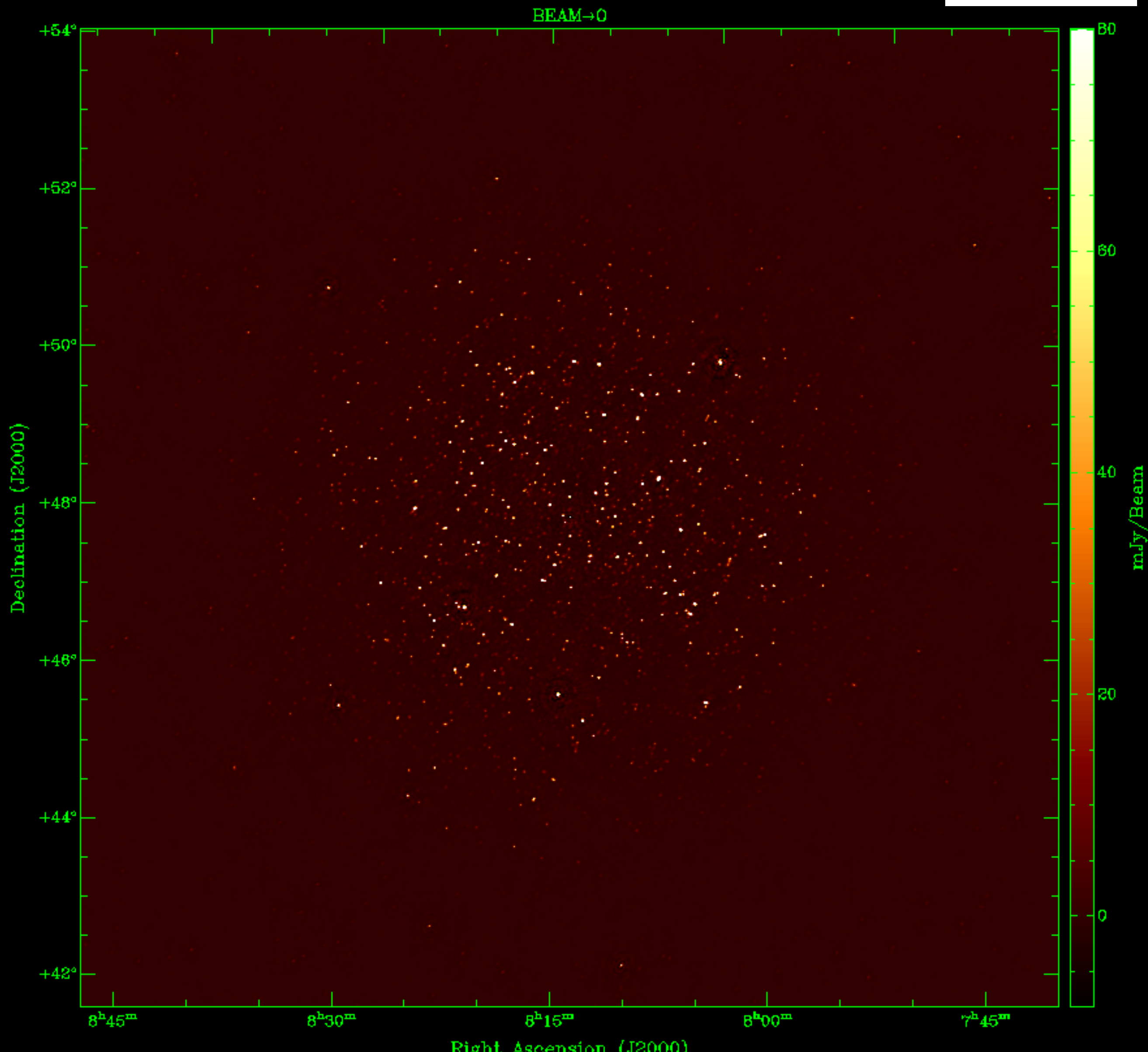

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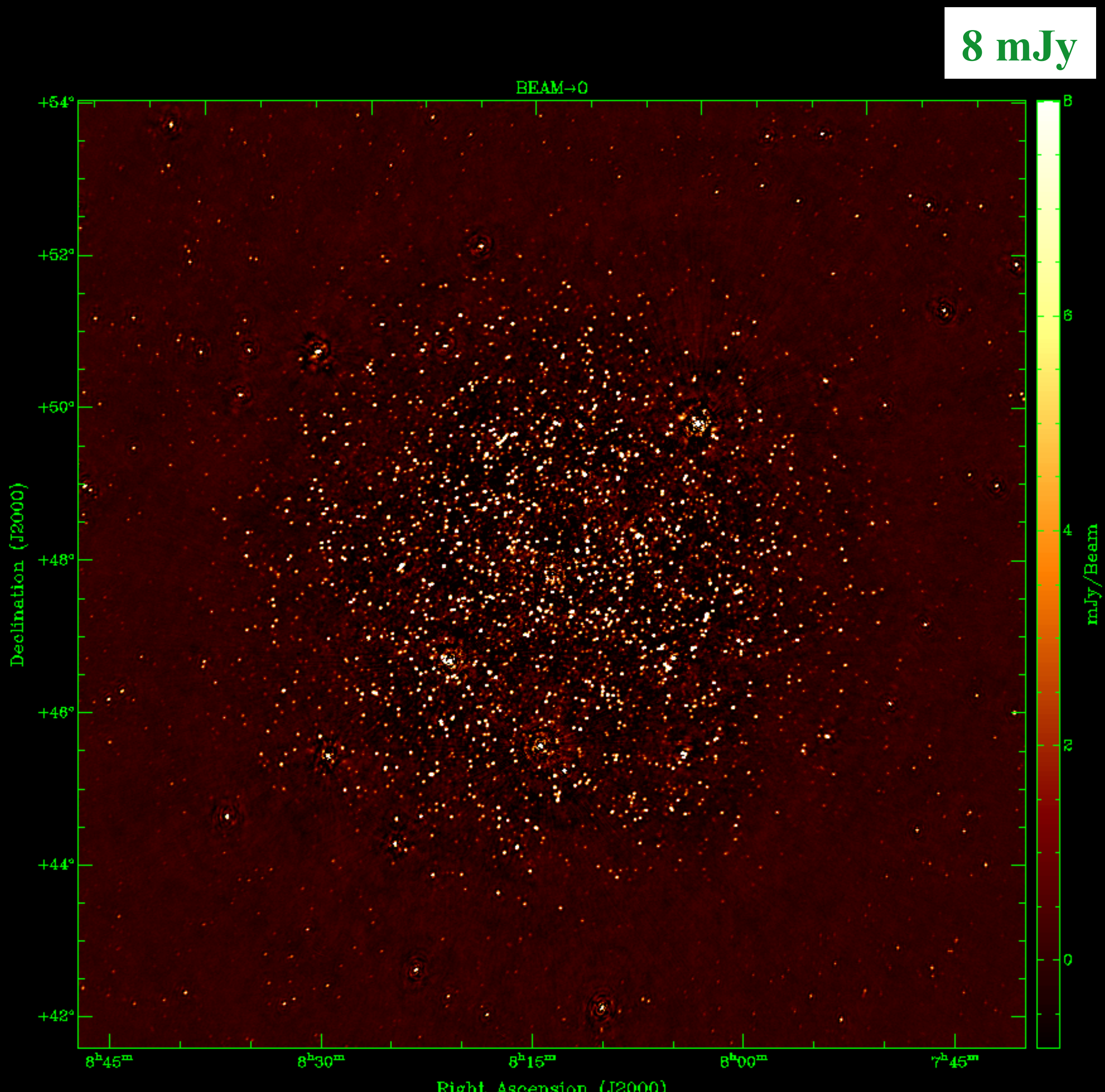

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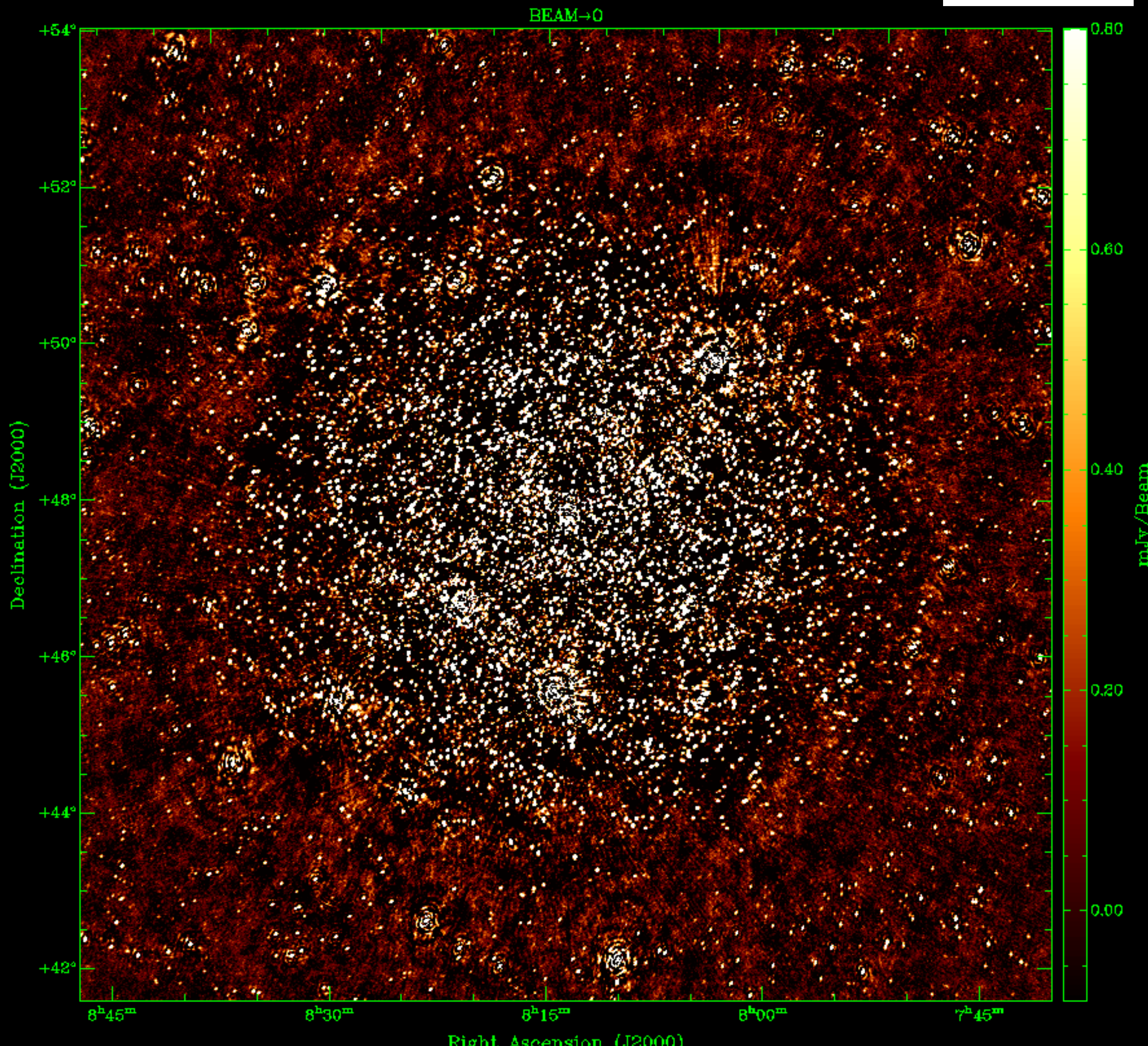

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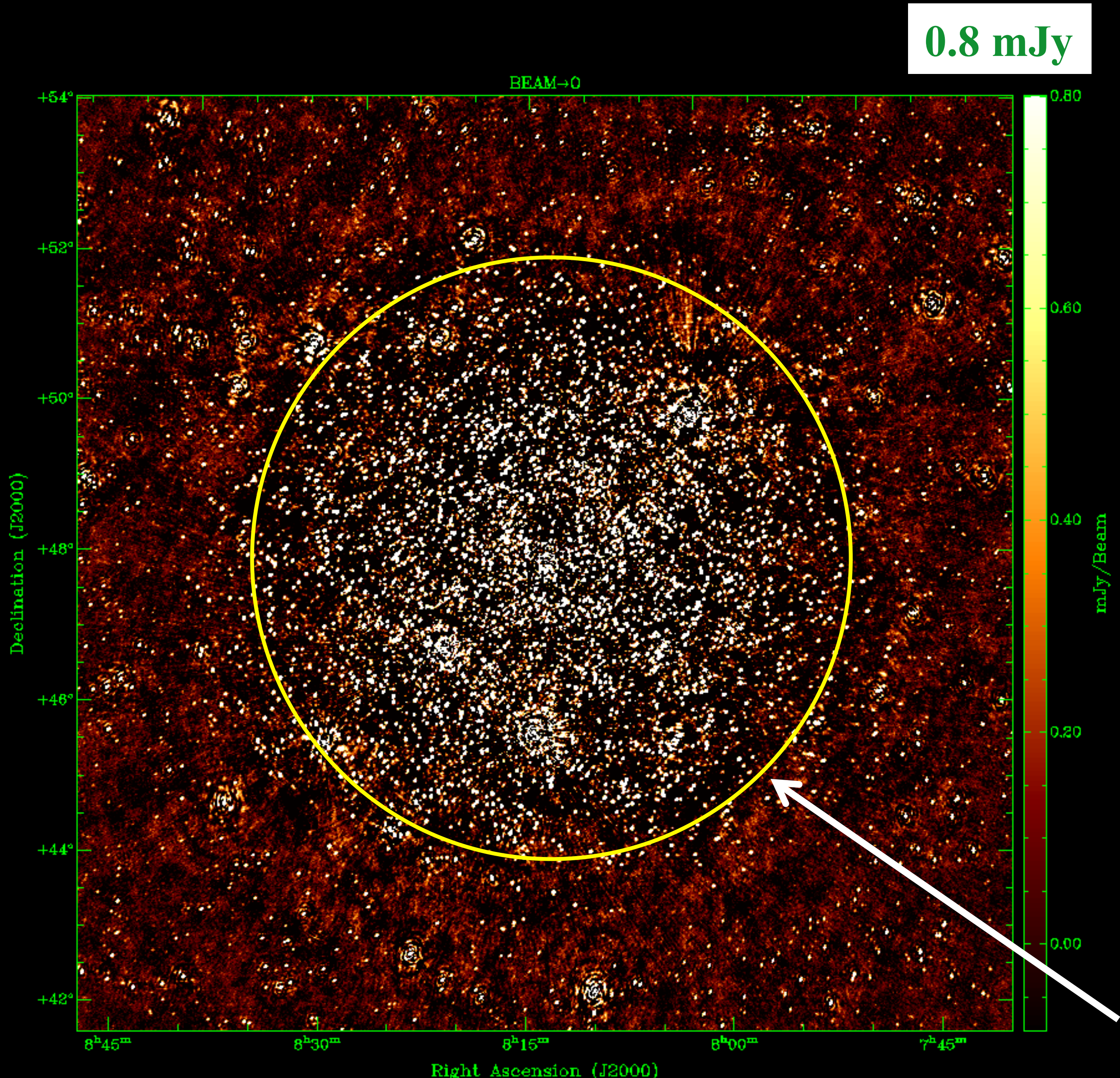

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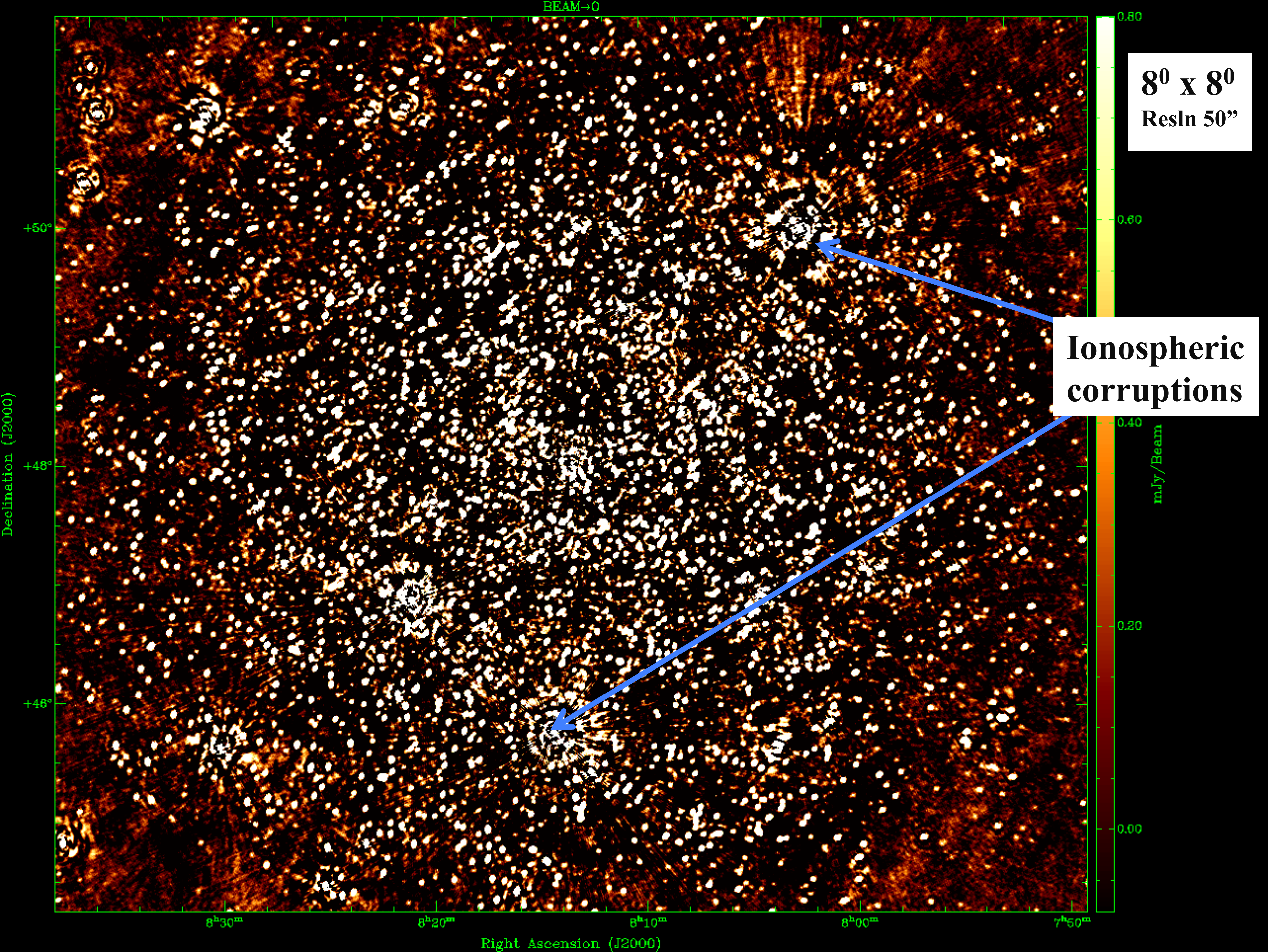
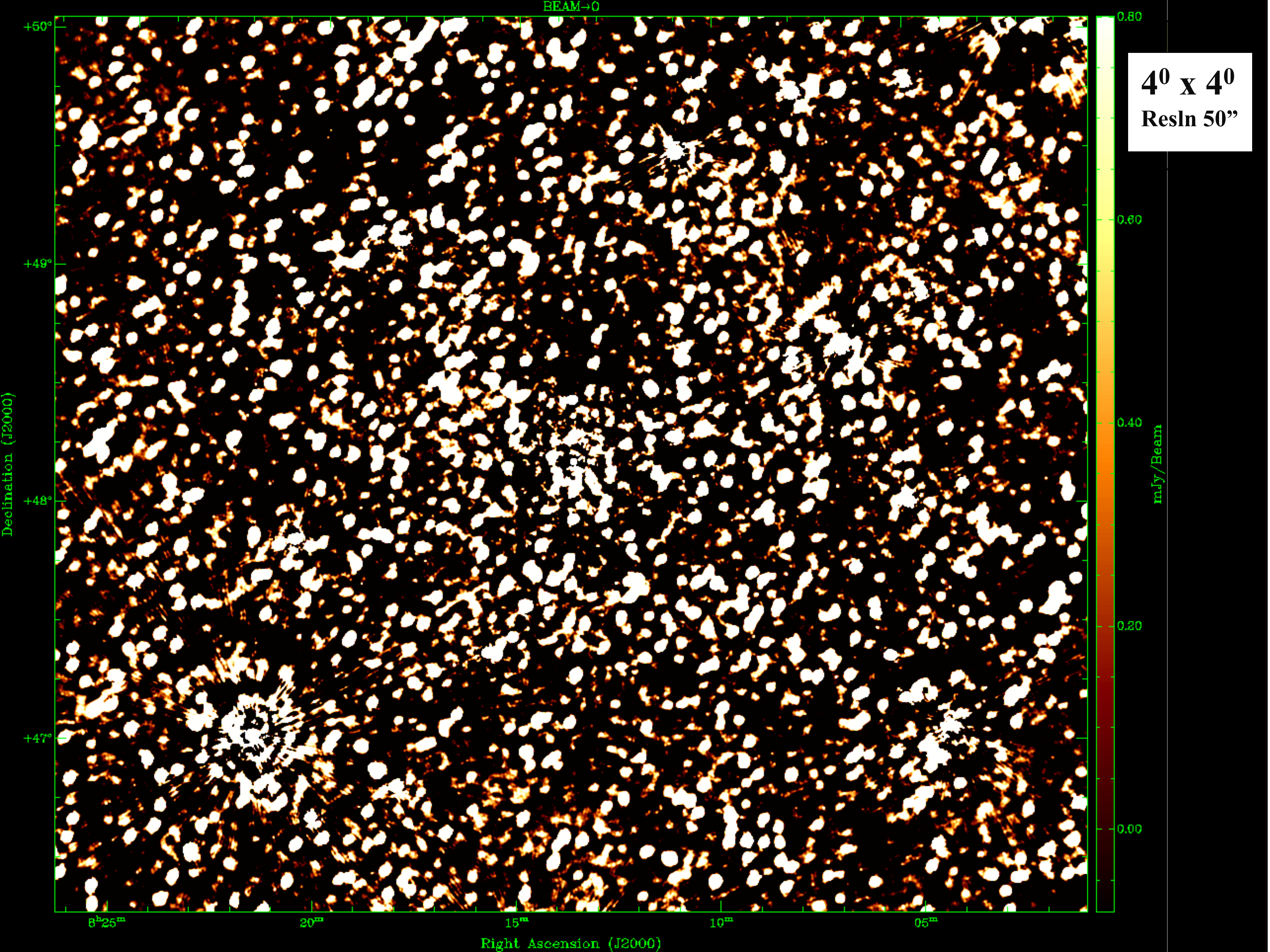
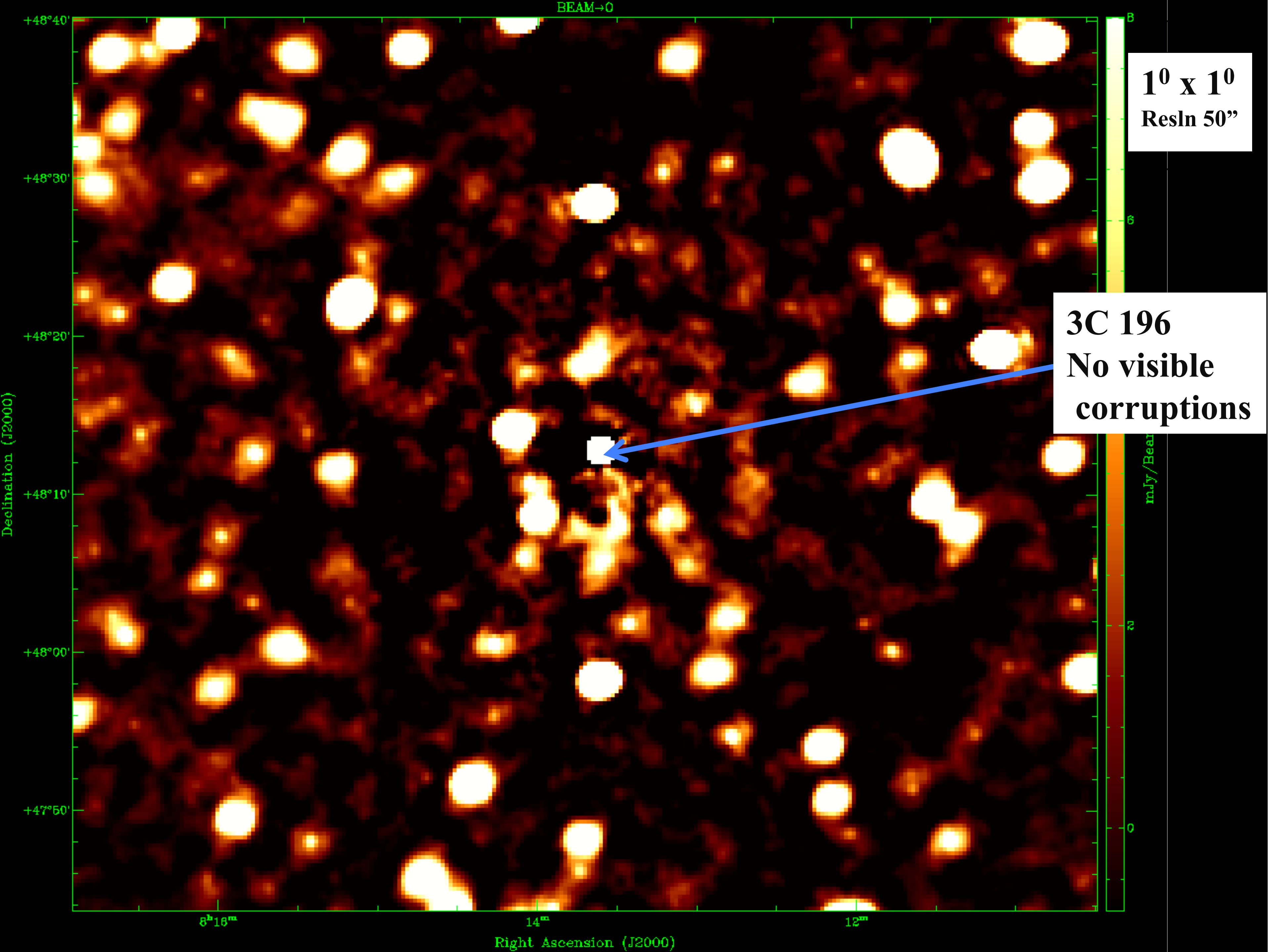
- **DR: ~ 10^6:1**

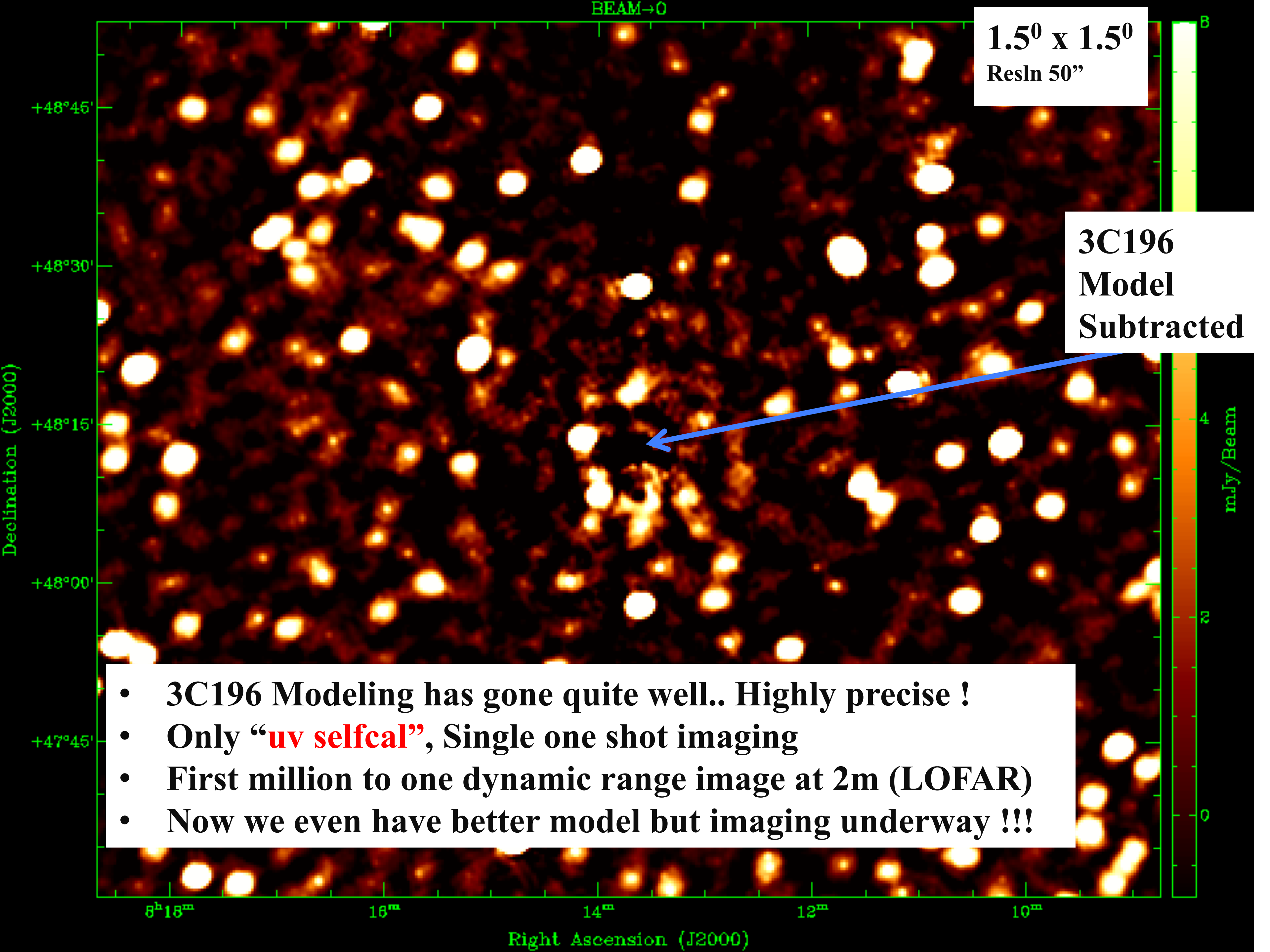
Station beam (~8^0)


BEAM→0
8⁰ x 8⁰
Resln 50"
Ionospheric corruptions
Declination (J2000)
+50°
+48°
+46°
Right Ascension (J2000)
8h30m
8h20m
8h10m
8h00m
7h50m
mJy/Beam
0.80
0.60
0.40
0.20
0.00


BEAM→0
4⁰ x 4⁰
Resln 50”
+50°
+49°
+48°
+47°
Declination (J2000)
8h25m
20m
15m
10m
05m
Right Ascension (J2000)
0.80
0.60
0.40
0.20
0.00
mJy/Beam

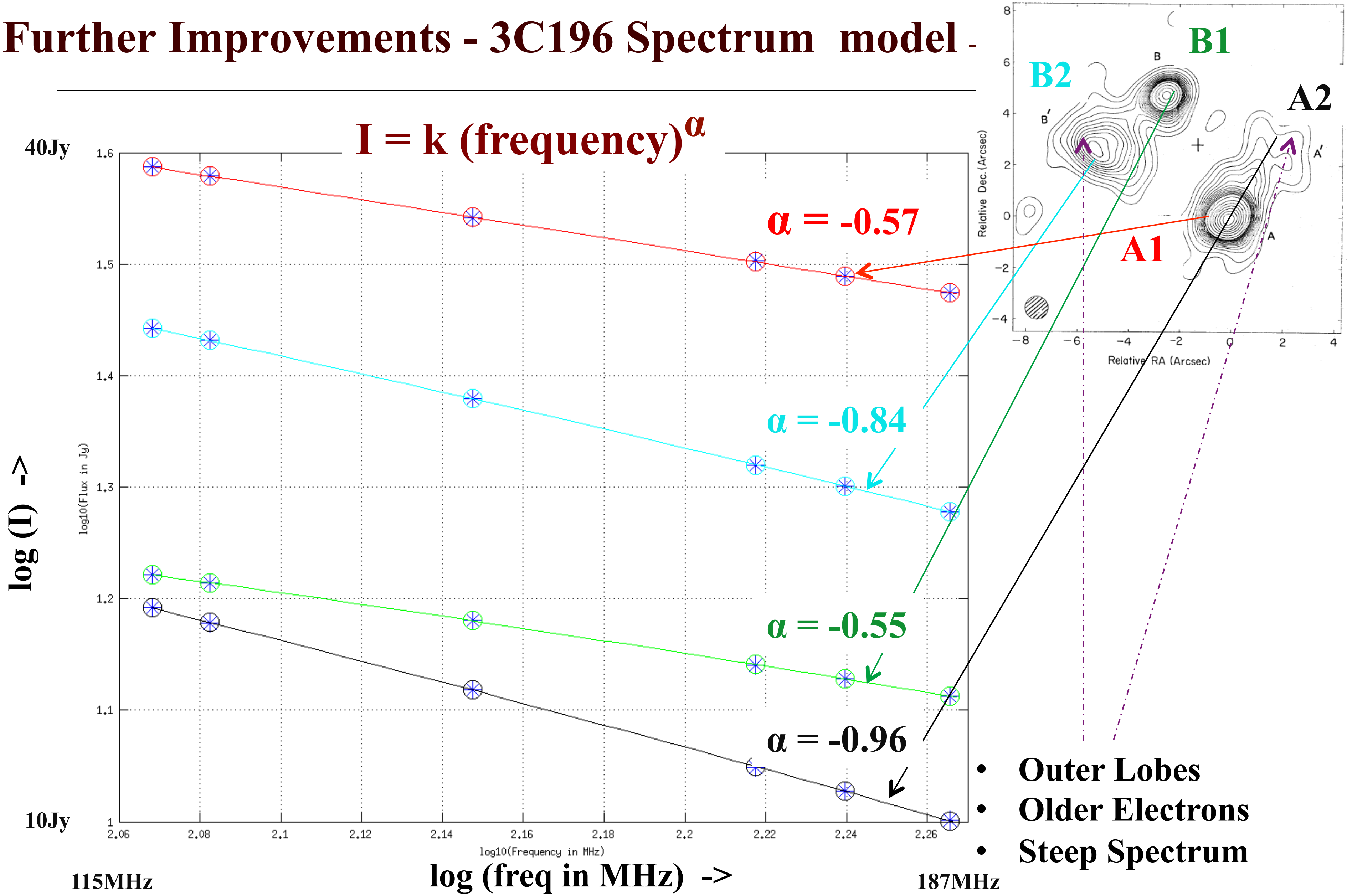


BEAM→0
1⁰ x 1⁰
Resln 50"
3C 196
No visible
corruptions
+48°40'
+48°30'
+48°20'
+48°10'
+48°00'
+47°50'
Declination (J2000)
8h16m
14m
12m
Right Ascension (J2000)
mJy/Beam



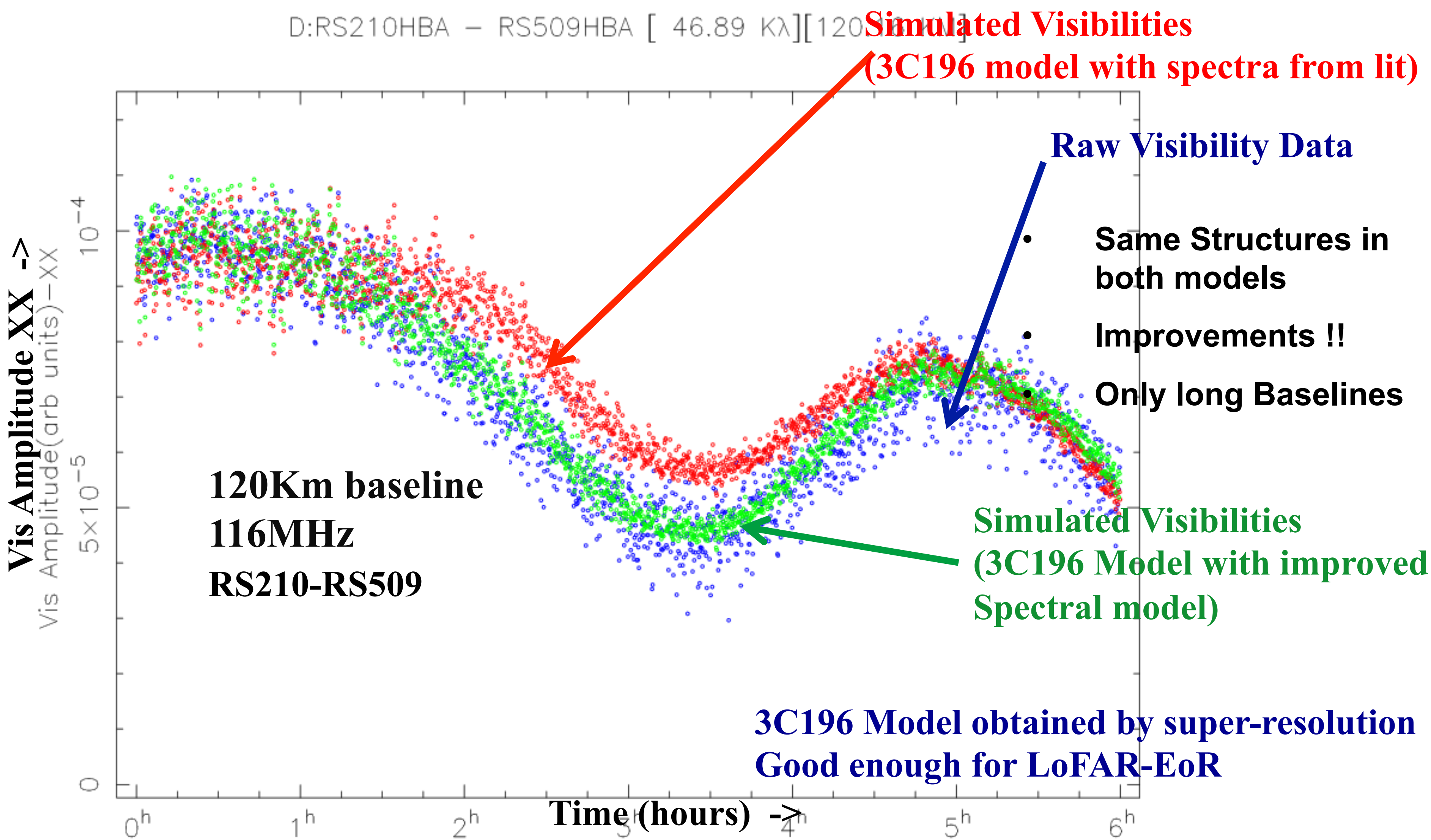
- 3C196 Modeling has gone quite well.. Highly precise !
- Only “uv selfcal”, Single one shot imaging
- First million to one dynamic range image at 2m (LOFAR)
- Now we even have better model but imaging underway !!!

Further Improvements - 3C196 Spectrum model -

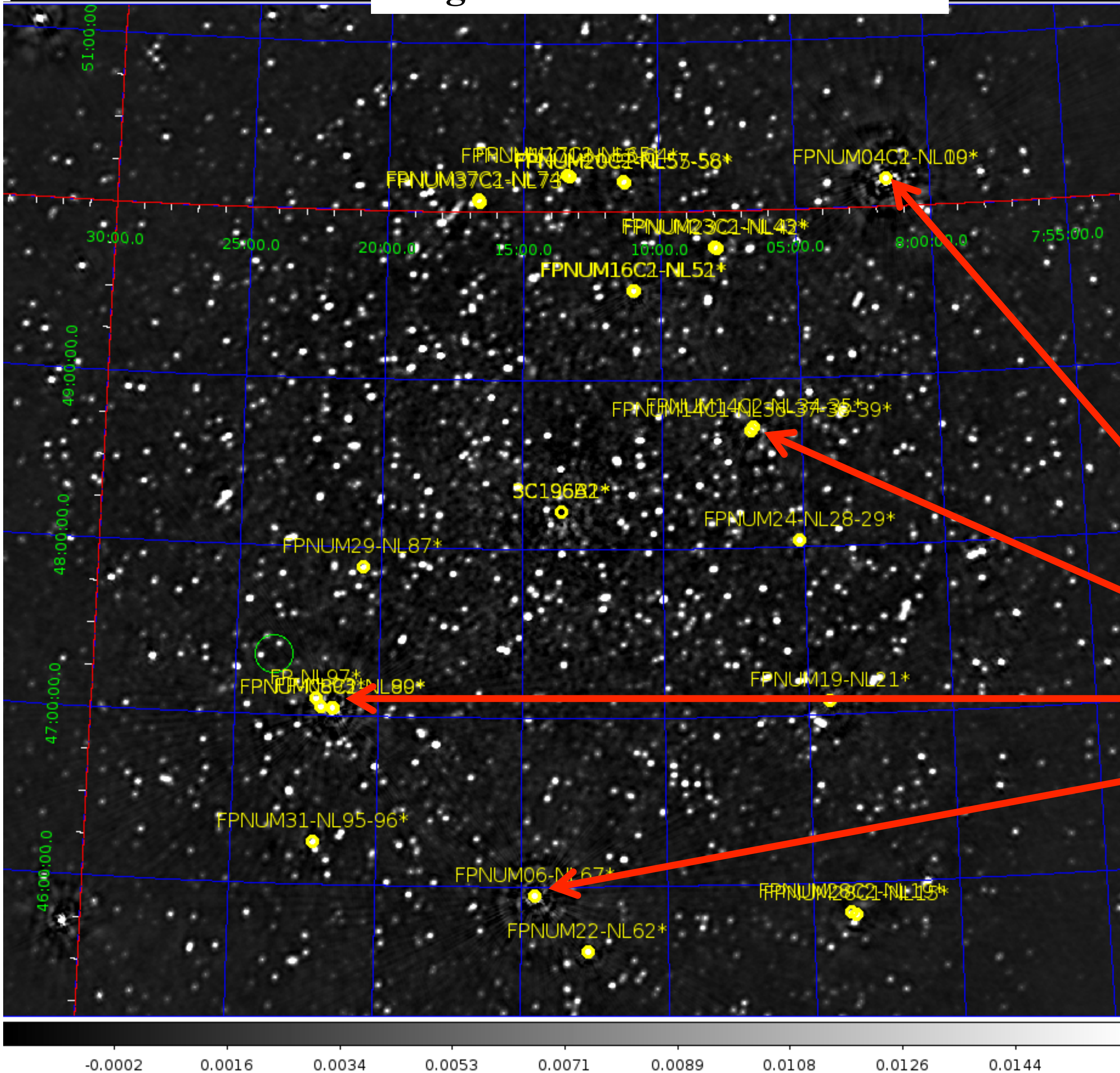


- Outer Lobes
- Older Electrons
- Steep Spectrum

Accurate 3C196 Spectrum model - RESULTS



Bright Sources in 3C196 Field



Modelling Bright sources

- About 40 bright sources
- Parametric modeling issues

6.6, 4.2 Jy

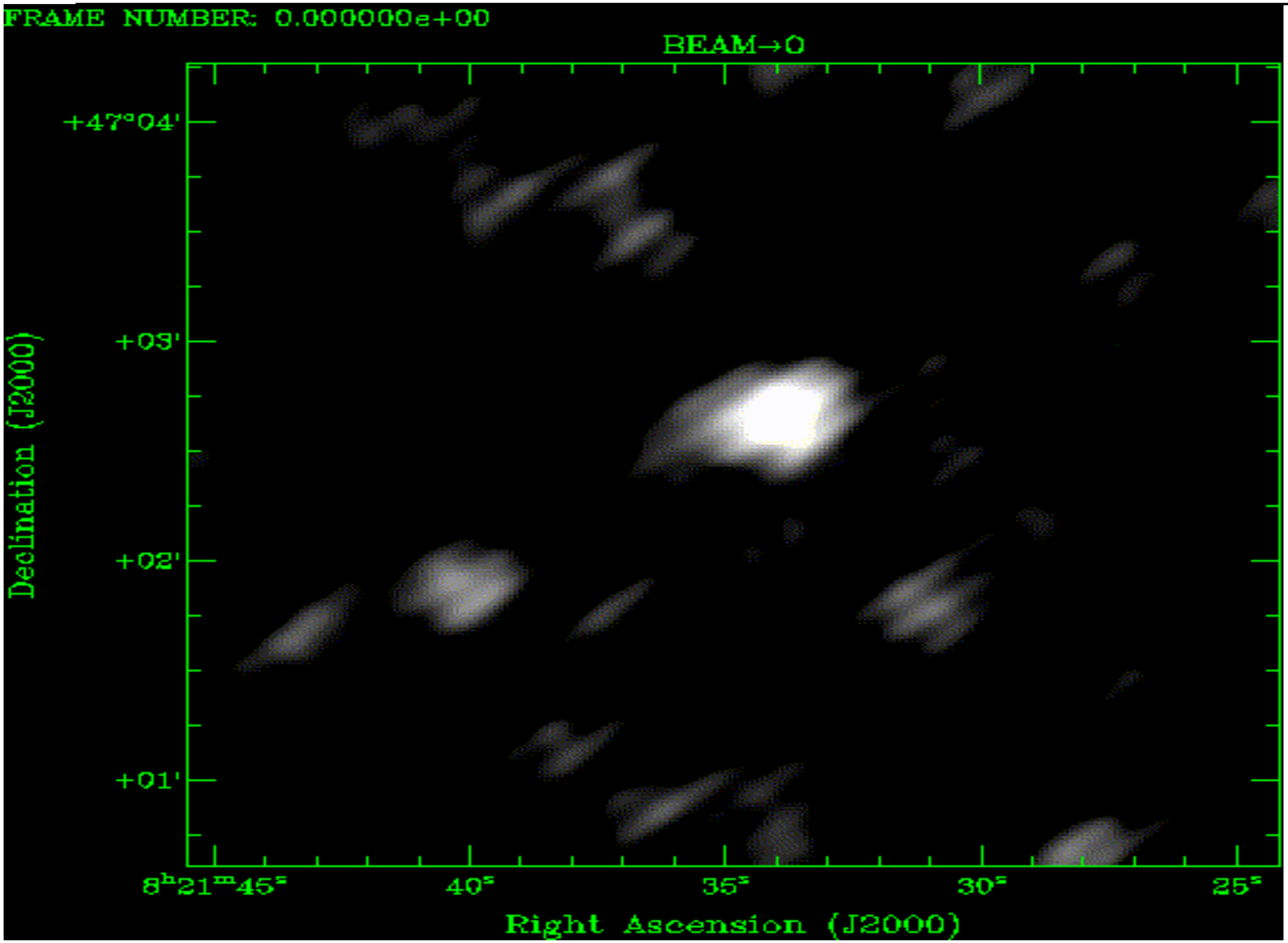
3.8, 2, .. Jy

4.5, 4.8 Jy

9.2 Jy

- Ionospheric corruptions

Bright sources parametric model fitting-Challenges



At arc sec resolution Nothing like quiet ionosphere

Source ~2^{0} away From phase center

4' x 4' image

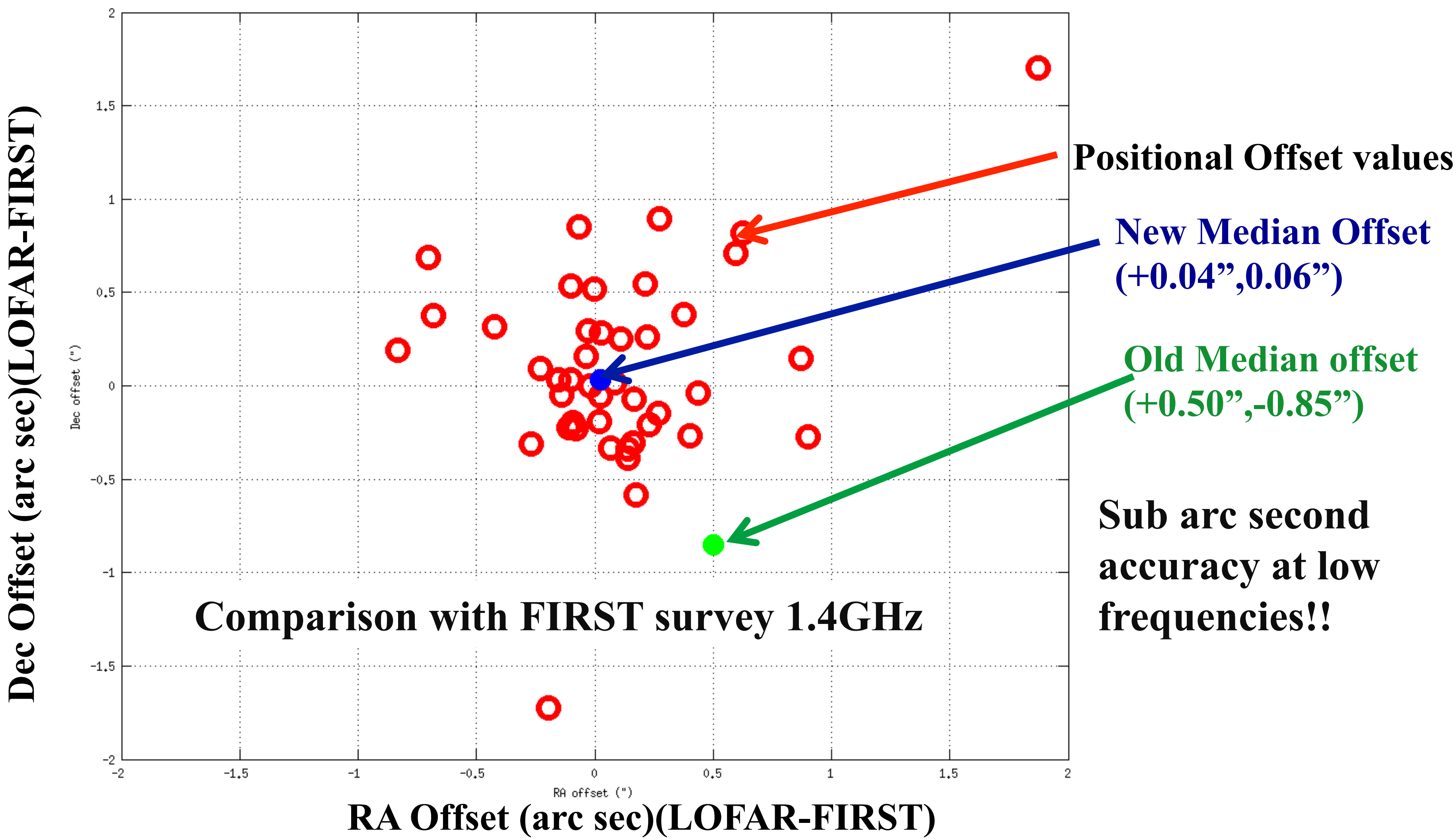
Resolution ~15"

Amplitude and Position variation with time (15" PSF; 1m Frames)

(M. Mevius)

Sub arc second Positional Accuracy -RESULTS

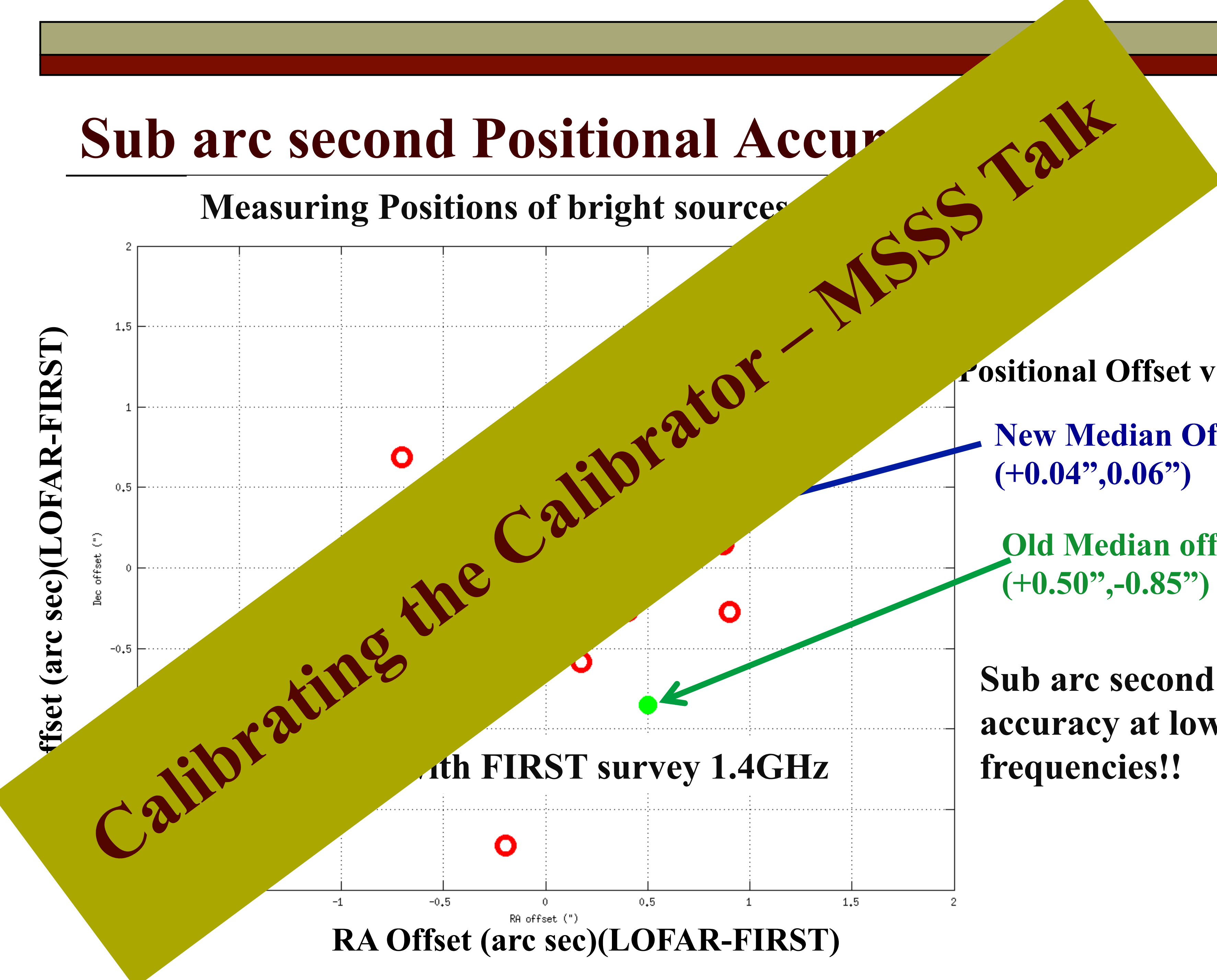
Measuring Positions of bright sources (and 3C196 itself)



Sub arc second accuracy at low frequencies!!

Sub arc second Positional Accur

Measuring Positions of bright sources



Positional Offset values

New Median Offset (+0.04”,0.06”)

Old Median offset (+0.50”,-0.85”)

Sub arc second accuracy at low frequencies!!

ffset (arc sec)(LOFAR-FIRST)

RA Offset (arc sec)(LOFAR-FIRST)

Conclusions

- **Million to One dynamic range possible at 150MHz**
- **3C196 parametric Model – has done remarkably well**
  - **Super resolution on observed data !!**
  - **Spectral Index measurements consistent**
- **High resolution model of bright sources in presence of ionospheric disturbances obtained**
- **Sub arc sec positional accuracy for bright sources**

  mean offsets ~ 1/100th of highest resolution lofar beam
- **Ionospheric calibration - 2D Phase screen approach(M.Mevius)**

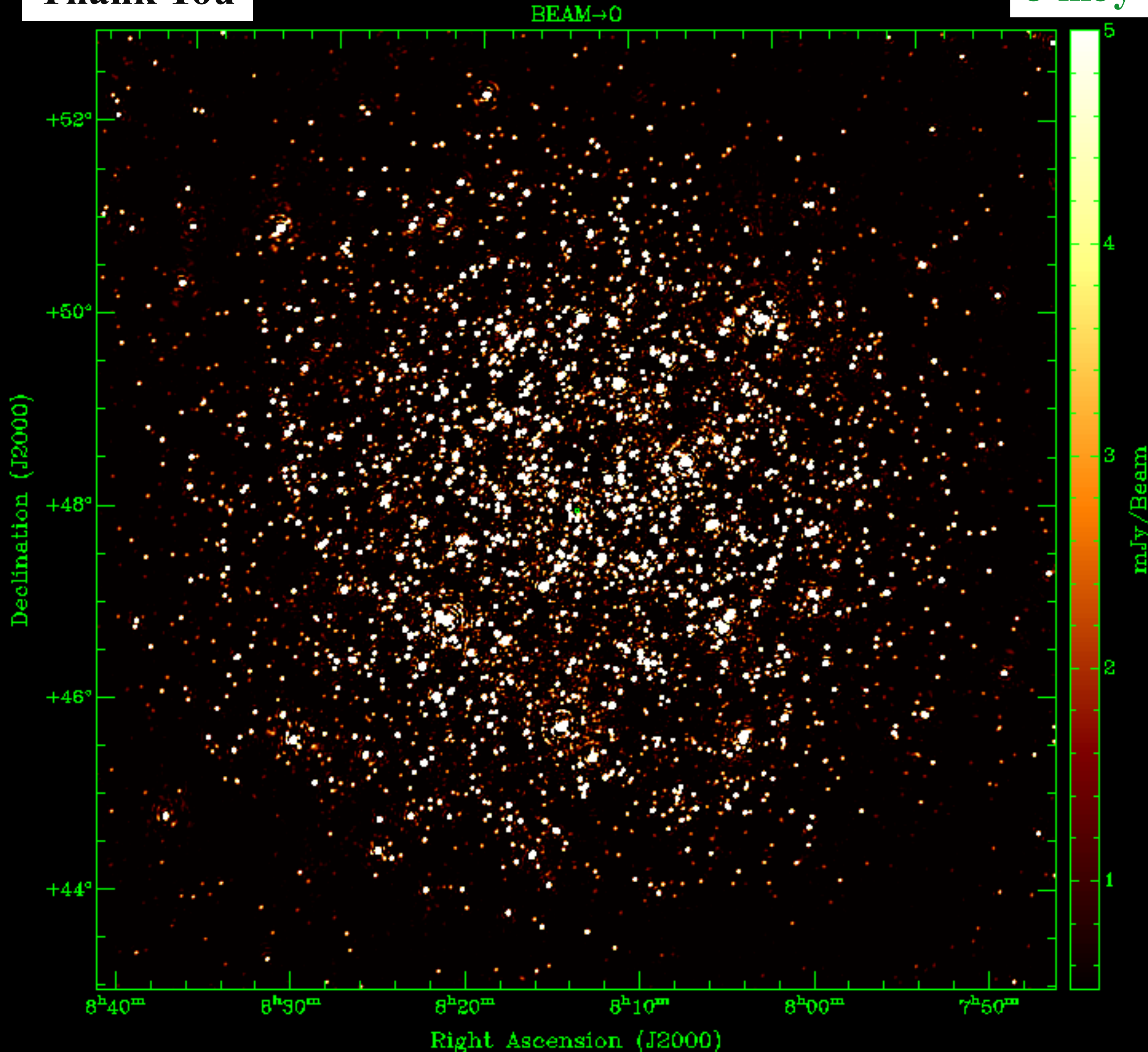
  - 3D tomography (S. Soobash)
- **Ongoing work – Direction Dependent Effects**

  – Polarization (Vibor)

ASTRON

Thank You

5 mJy



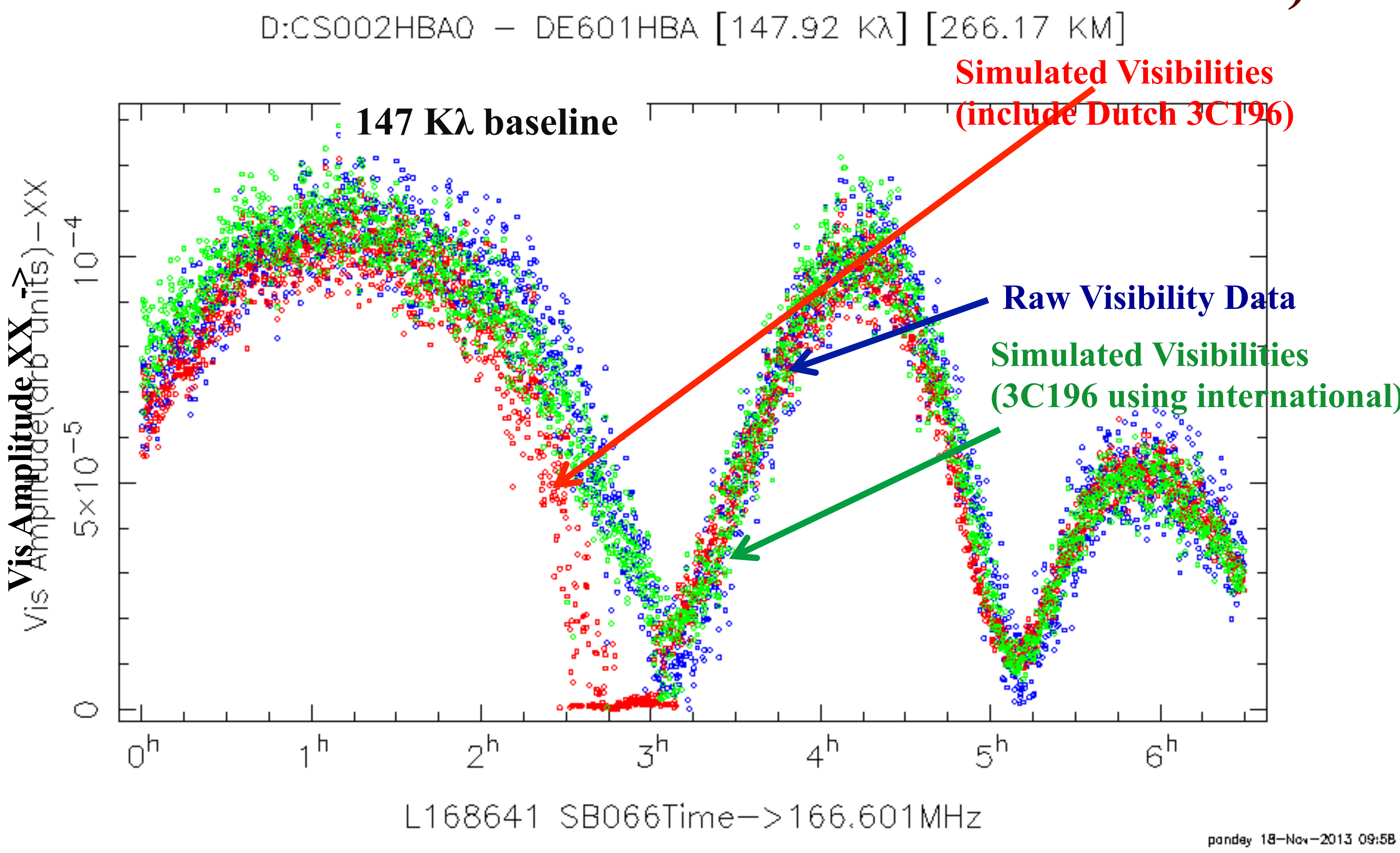
3C196 Field Image

- **145 MHz (~2m)**
- **60MHz continuum**

- **32 hours on 3C196**
  (8 hrs x 4 days)
- **Dec 21,12- Feb08,13**
- **30λ - 1200λ**
- **Resolution – 2.2'**
- **10^0 x 10^0 Image**

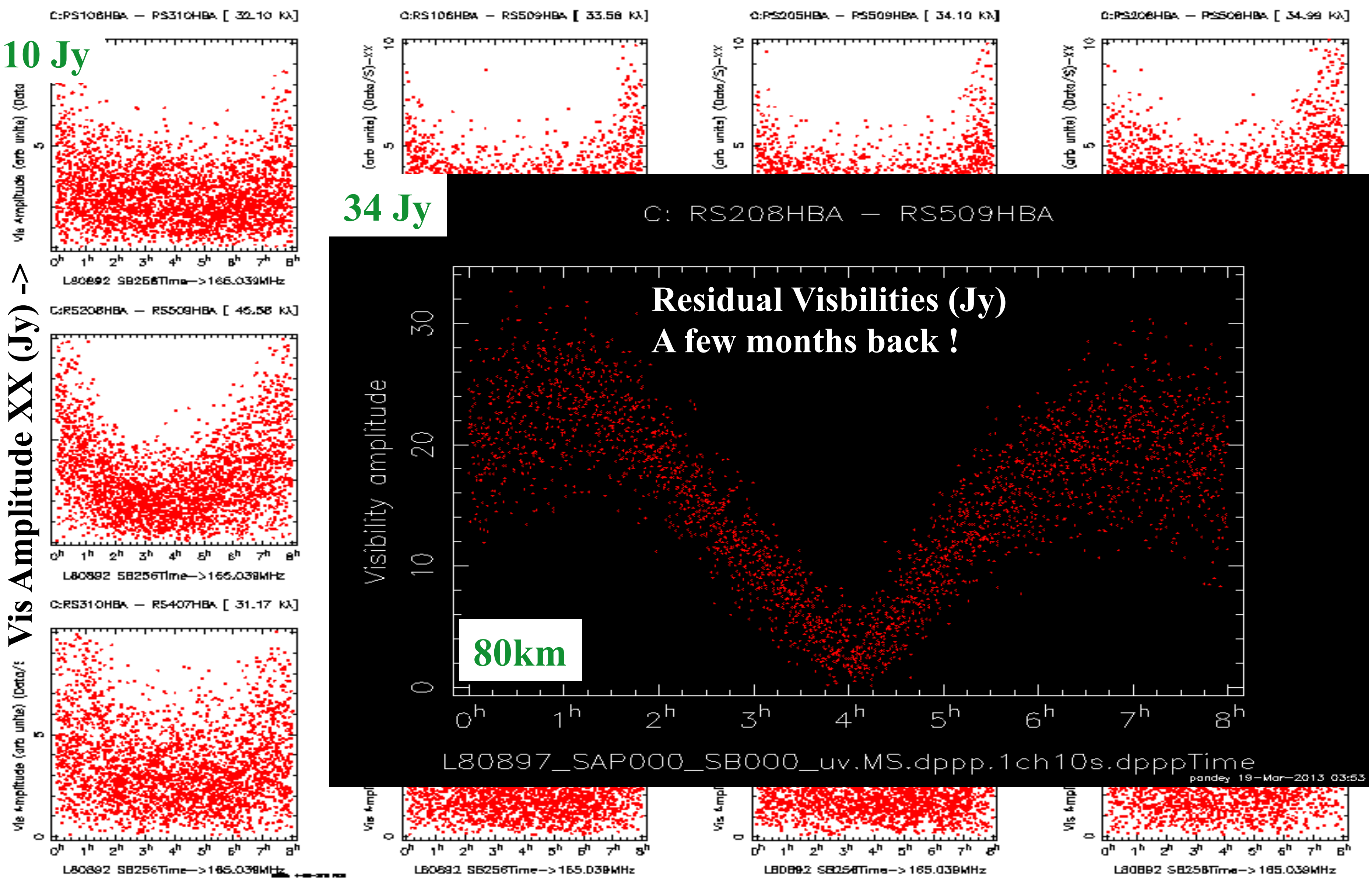
- **'Noise' ~ 150 μJy**
- **3C196 - 79.97 Jy**
- **DR: ~ 500000:1**

Test the model at International baselines → Then what we used to build model 45Kλ)

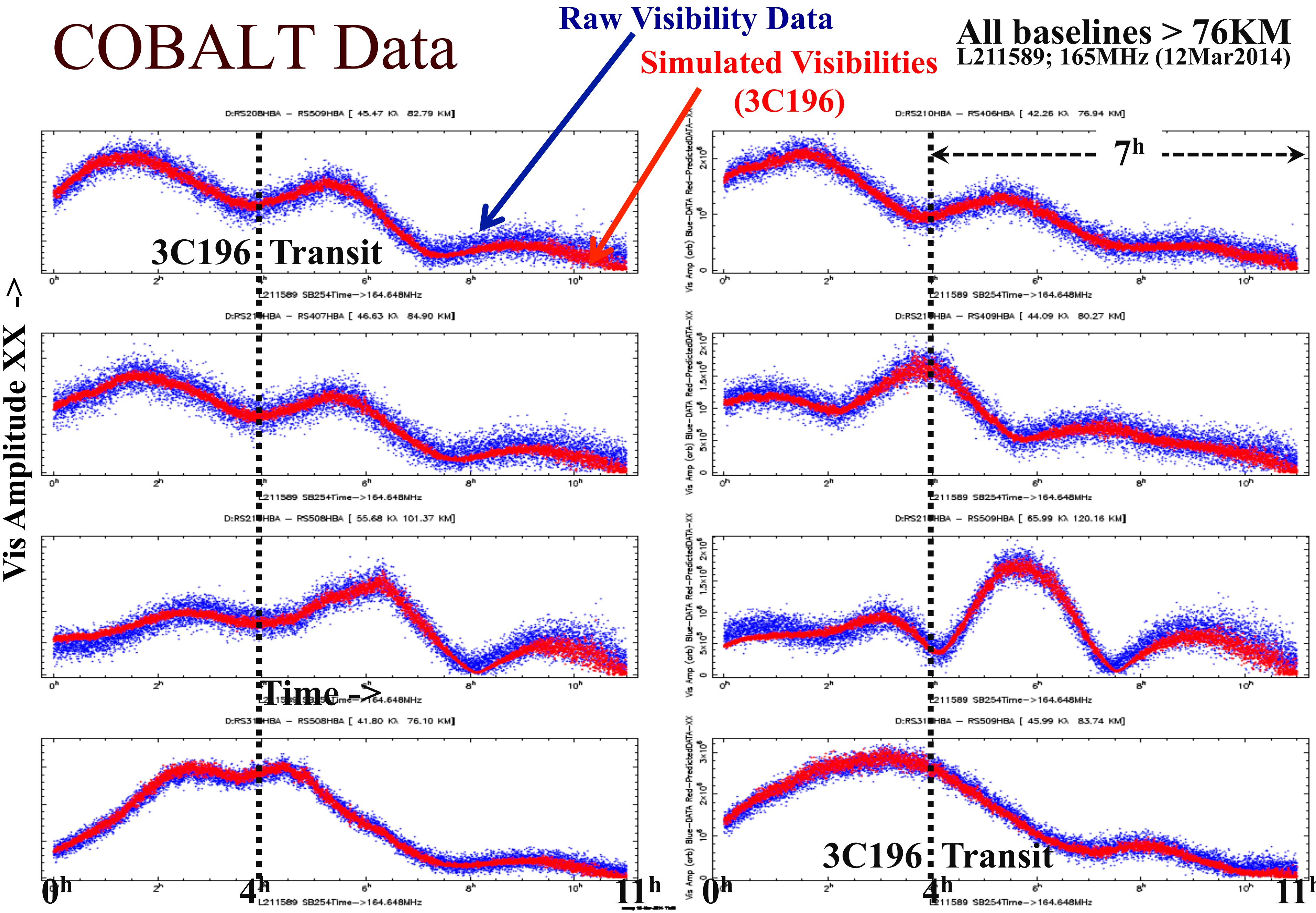


Improving Calibration !

Residual Visibilities in Jy (After Subtracting 3C196) Baselines > 30KL

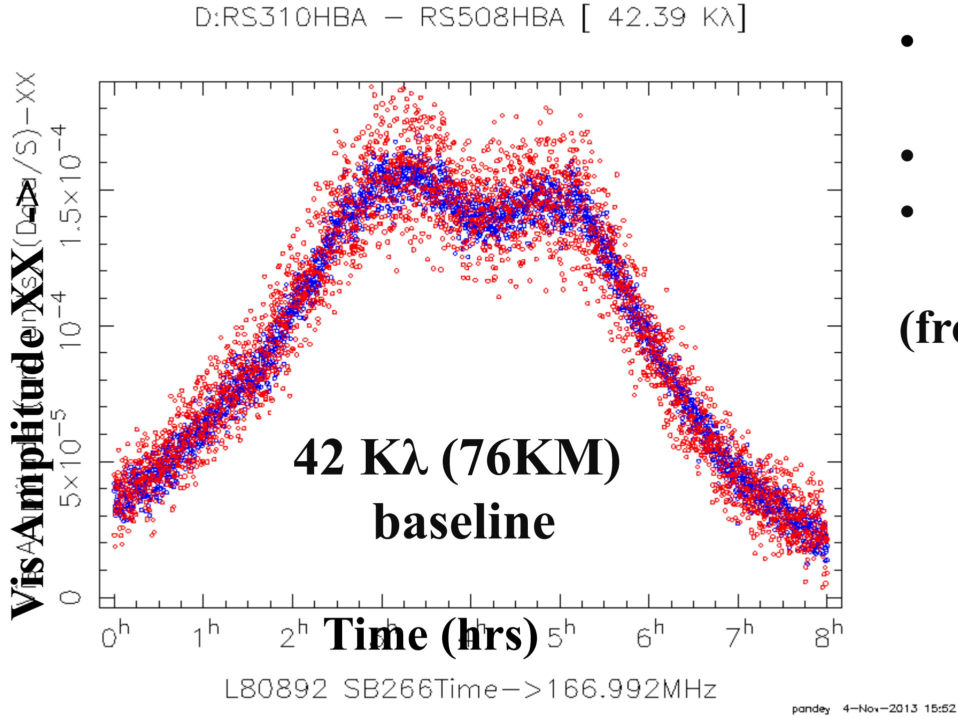


COBALT Data


Raw Visibility Data
Simulated Visibilities (3C196)
All baselines > 76KM
L211589; 165MHz (12Mar2014)
D:RS208HBA – RS509HBA [45.47 KA 82.79 KM]
D:RS210HBA – RS406HBA [42.26 KA 76.94 KM]
7h
3C196 Transit
Vis Amplitude XX ->
Time ->
L211589 SB254Time->164.648MHz
D:RS210HBA – RS407HBA [46.63 KA 84.90 KM]
D:RS210HBA – RS409HBA [44.09 KA 80.27 KM]
D:RS210HBA – RS508HBA [55.68 KA 101.37 KM]
D:RS210HBA – RS509HBA [65.99 KA 120.16 KM]
D:RS310HBA – RS508HBA [41.80 KA 76.10 KM]
D:RS310HBA – RS509HBA [45.99 KA 83.74 KM]
Vis Amp (arb) Blue–DATA Red–PredictedDATA–XX
0h
4h
11h

Improving calibration including more sources

- **In God we Trust, all others bring data.**

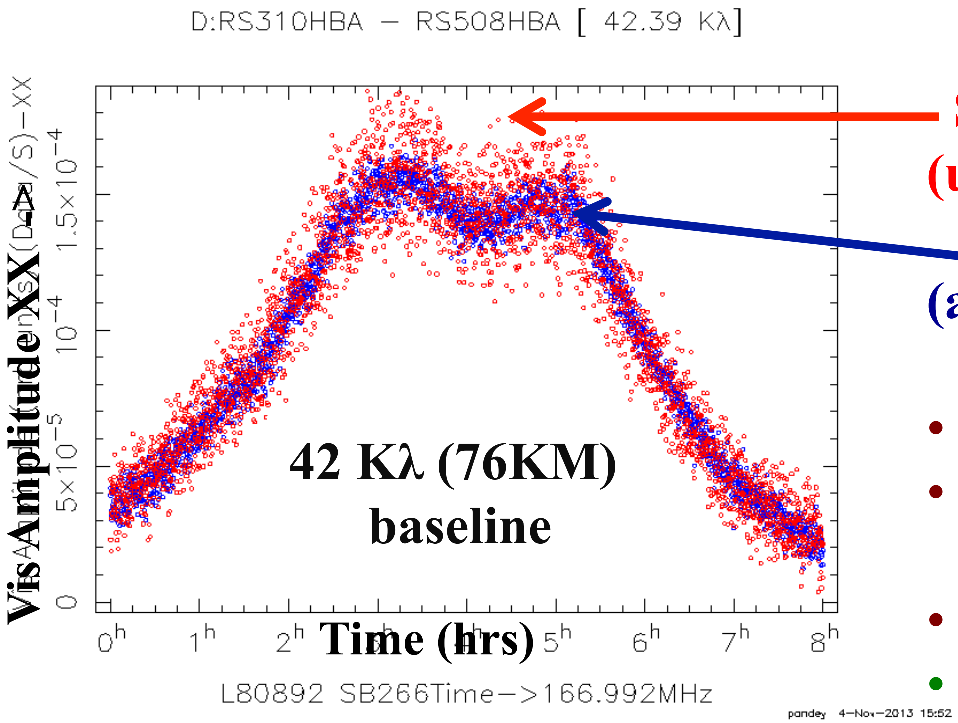


- **Include sources from the WSRT – refit the parametric model for 3C196**
- **Raw Visibility Data**
- **Simulations with 3C196 plus 40 bright sources**

(from WSRT)

Improving calibration including more sources

- Include sources from the WSRT – refit the parametric model for 3C196
  - The refitted model is worse !!

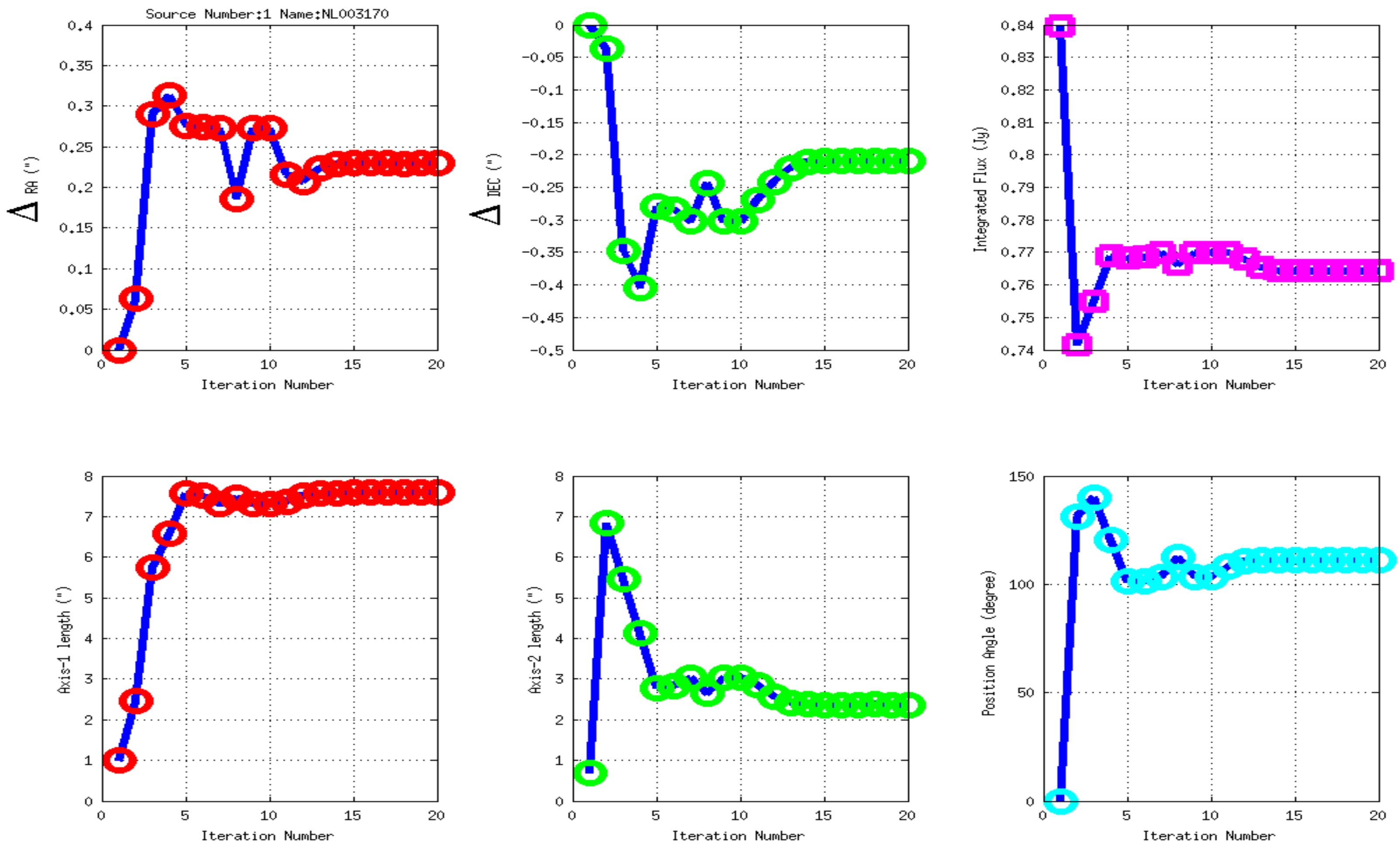


Simulated Visibilities 3C196+40 sources (using WSRT source model)

Raw visibility data (all plots only for XX correlation)

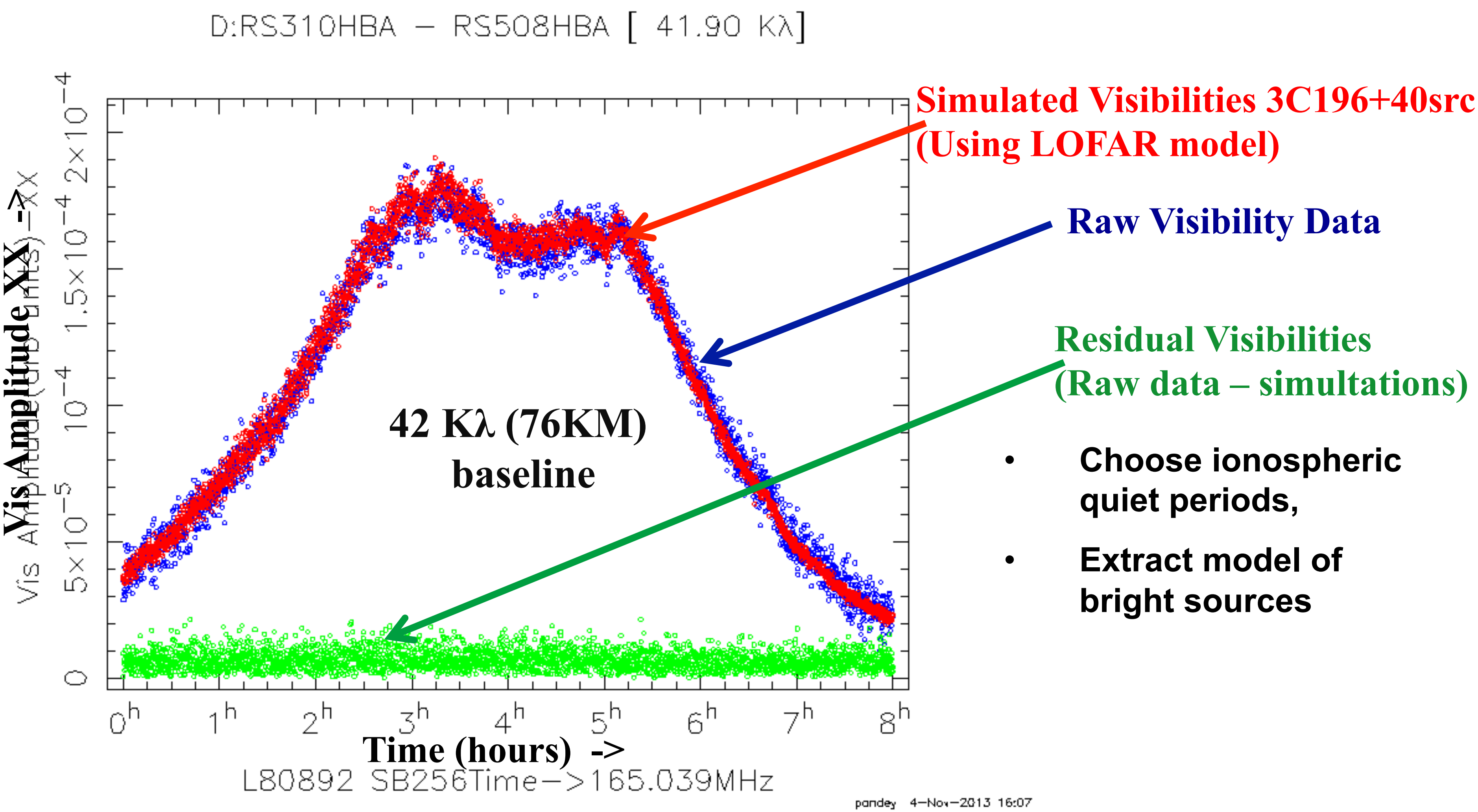
- Most of these sources are resolved!
- LOFAR Long baselines are like mini-VLBI for WSRT like array!
- LBL need high resolution model !
- So we need to model these sources using the LOFAR data!
- Limit uv, quiet ionospheric conditions
- Go for parametric fitting!

Flux and Position Fitting – uv plane



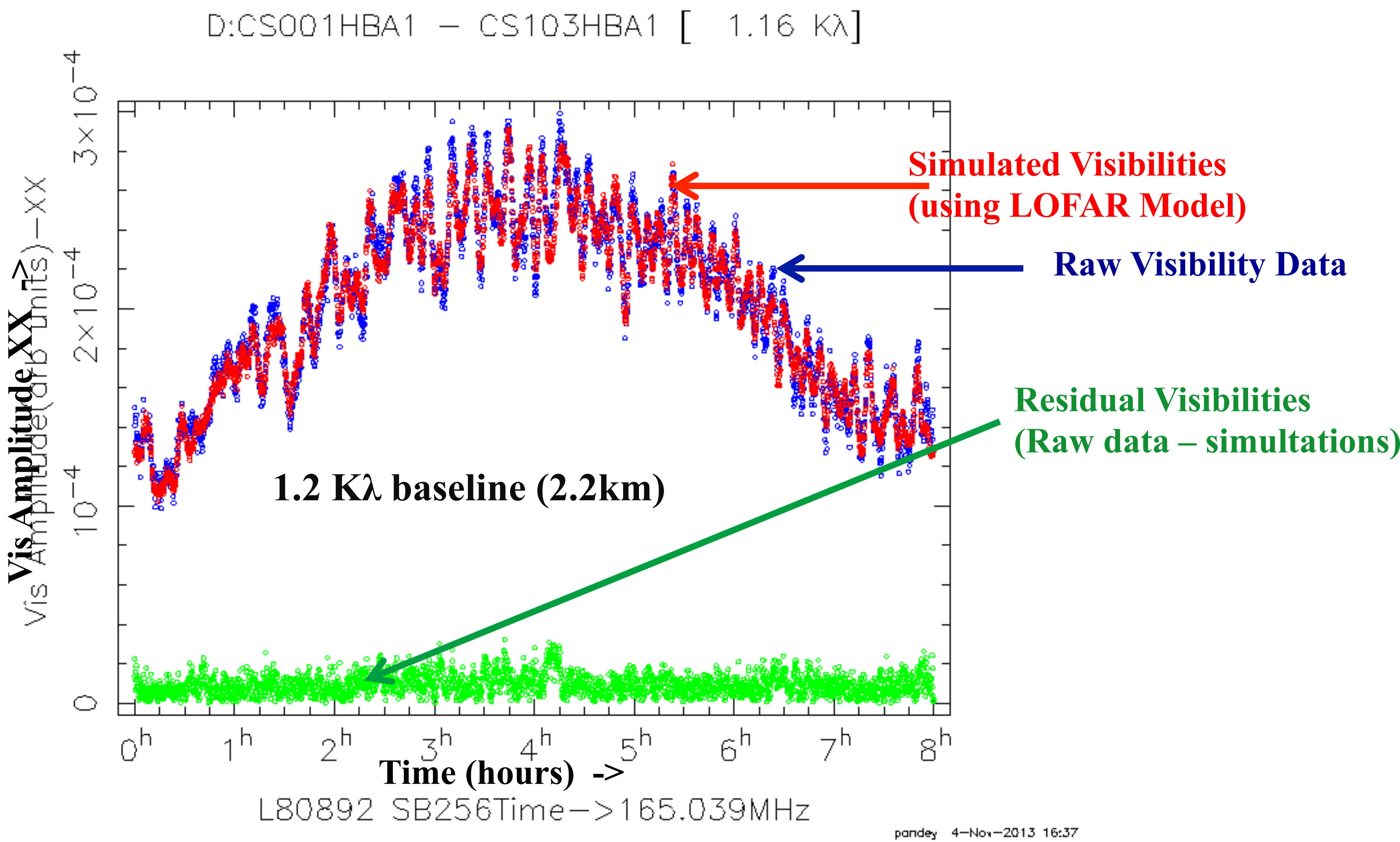
Bright sources parametric model fitting-RESULTS

- Gets back the good model of 3C196 or even better !

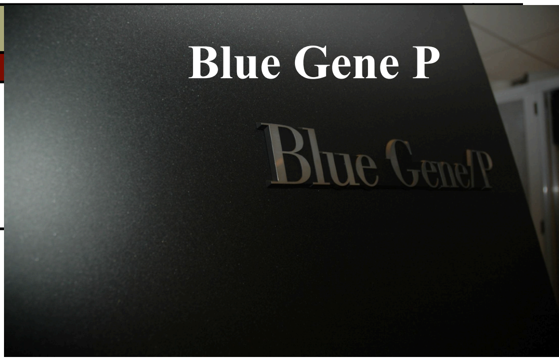


- Choose ionospheric quiet periods,
- Extract model of bright sources

Bright sources parametric model fitting-RESULTS

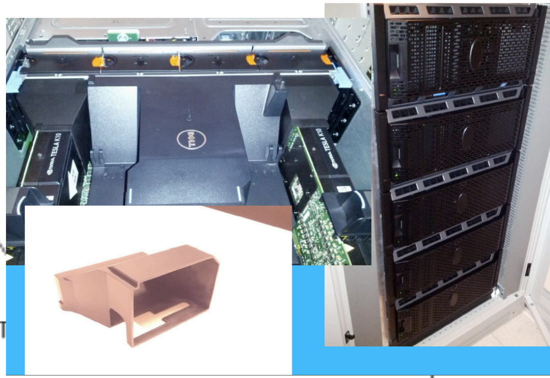


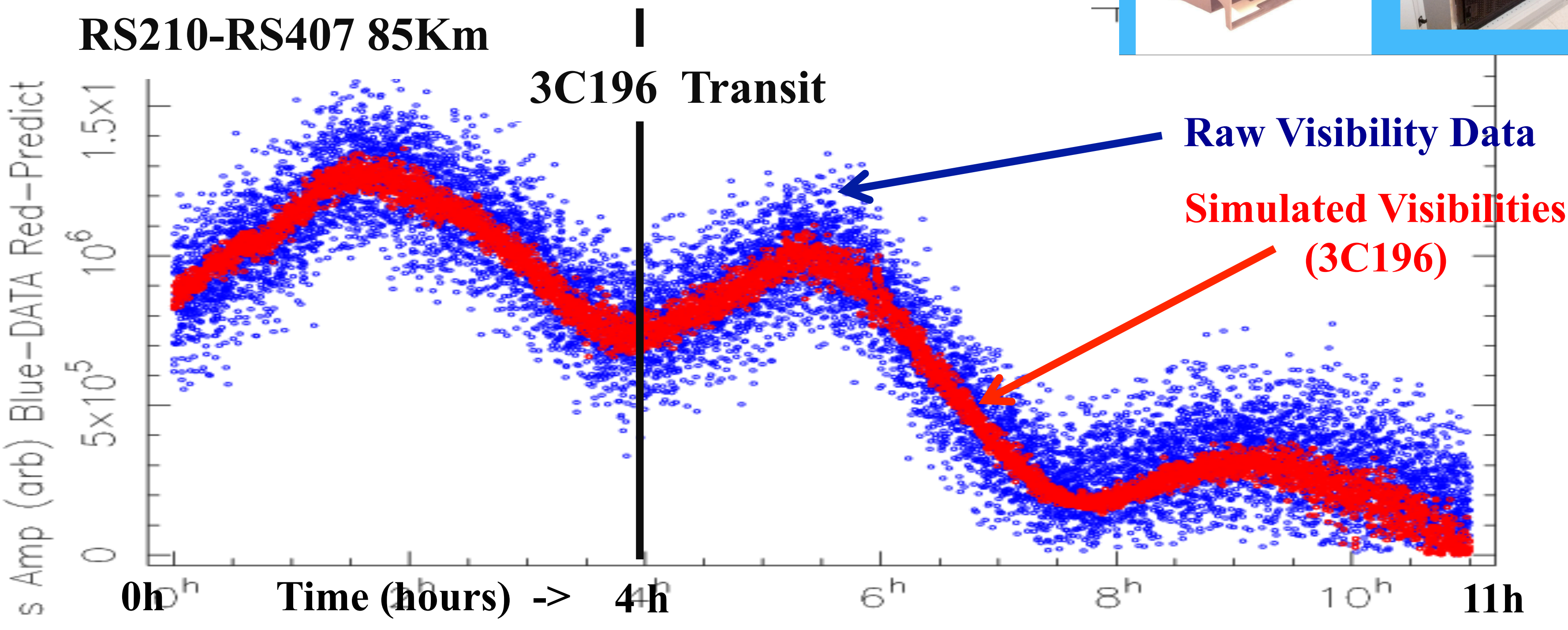
Conclusions & Road ahead - II



- LOFAR Correlator changed from
- IBM Blue-Gene P – GPGPU COBALT
- COBALT– 8 nodes with 2K10 each
- (can correlate ~70 stns)!
- Default correlator since a few weeks

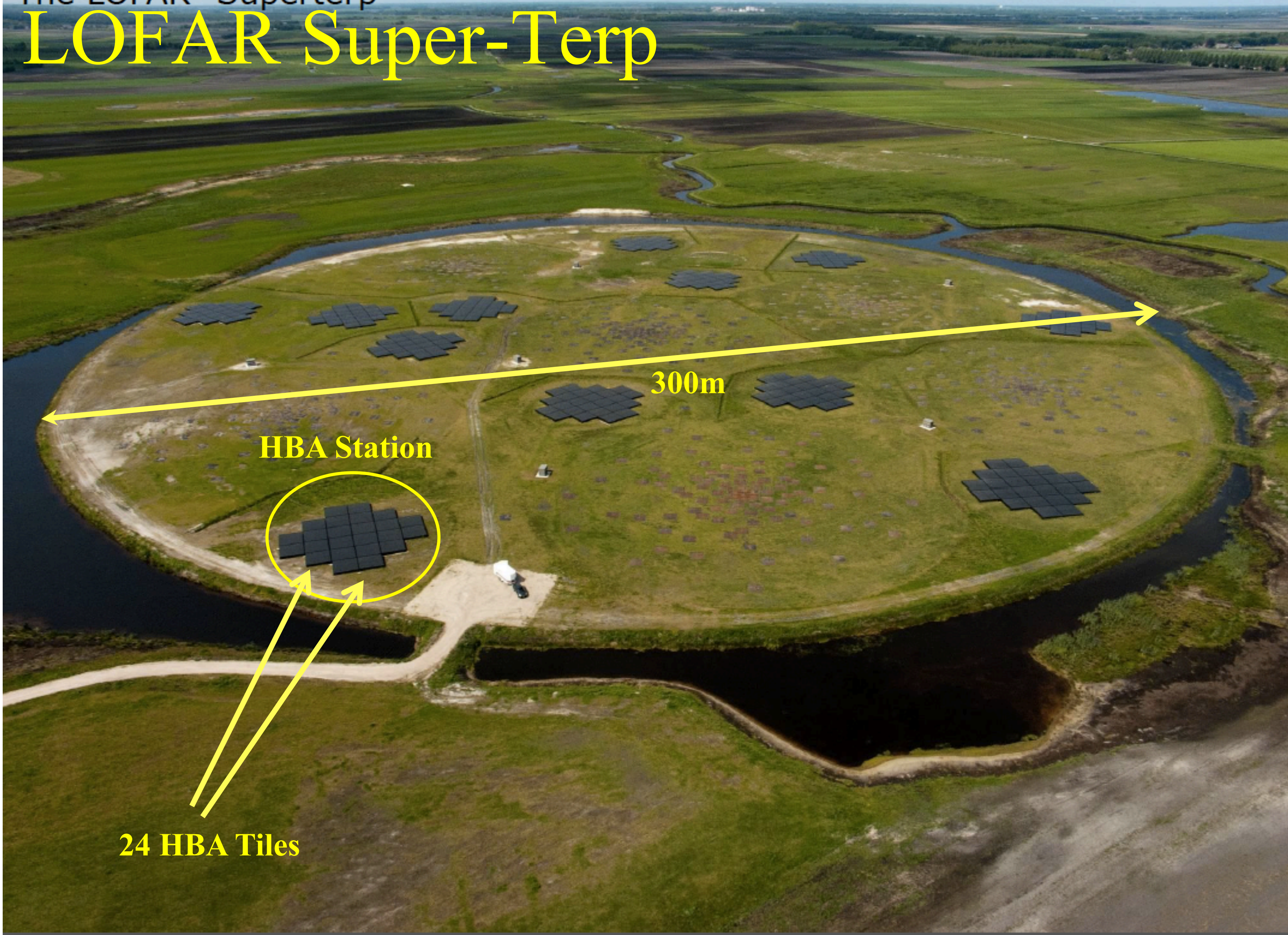
Final COBALT system





The LOFAR "Superterp"

LOFAR Super-Terp



Conclusions & Road ahead - III

EoR Cluster also as LOFAR Super-Terp Correlator!

Processing and correlate (when required)!

- **EoR Group – can we correlate 288 tiles within superterp?!!**

  (at some point of time in future)

(Lots of challenges regarding data rates, connections)

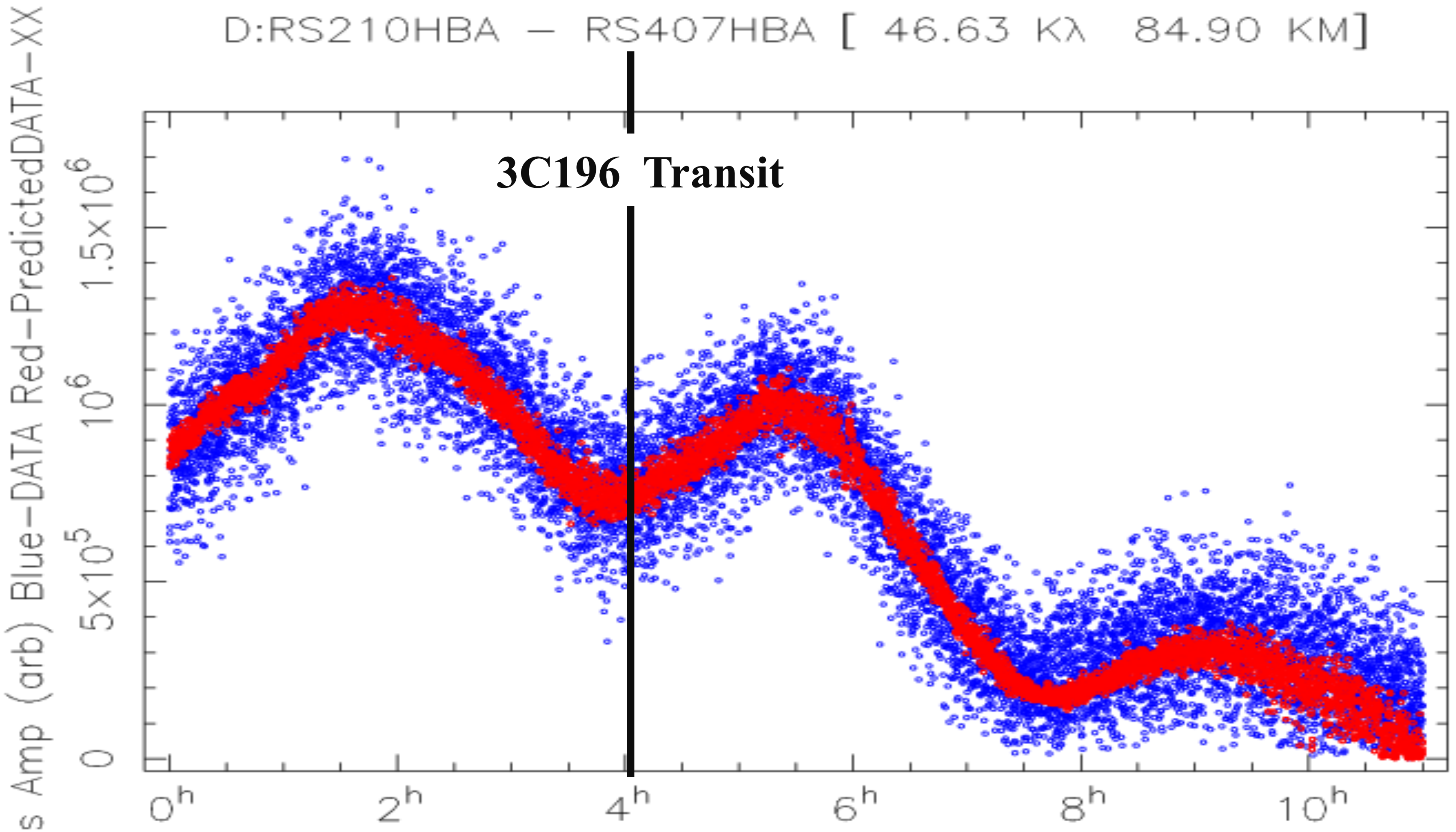
- **Input bandwidth ~ four times more (~60GB/s)**

  Correlator requirements – 16 times more (crossing PetaFlop)!

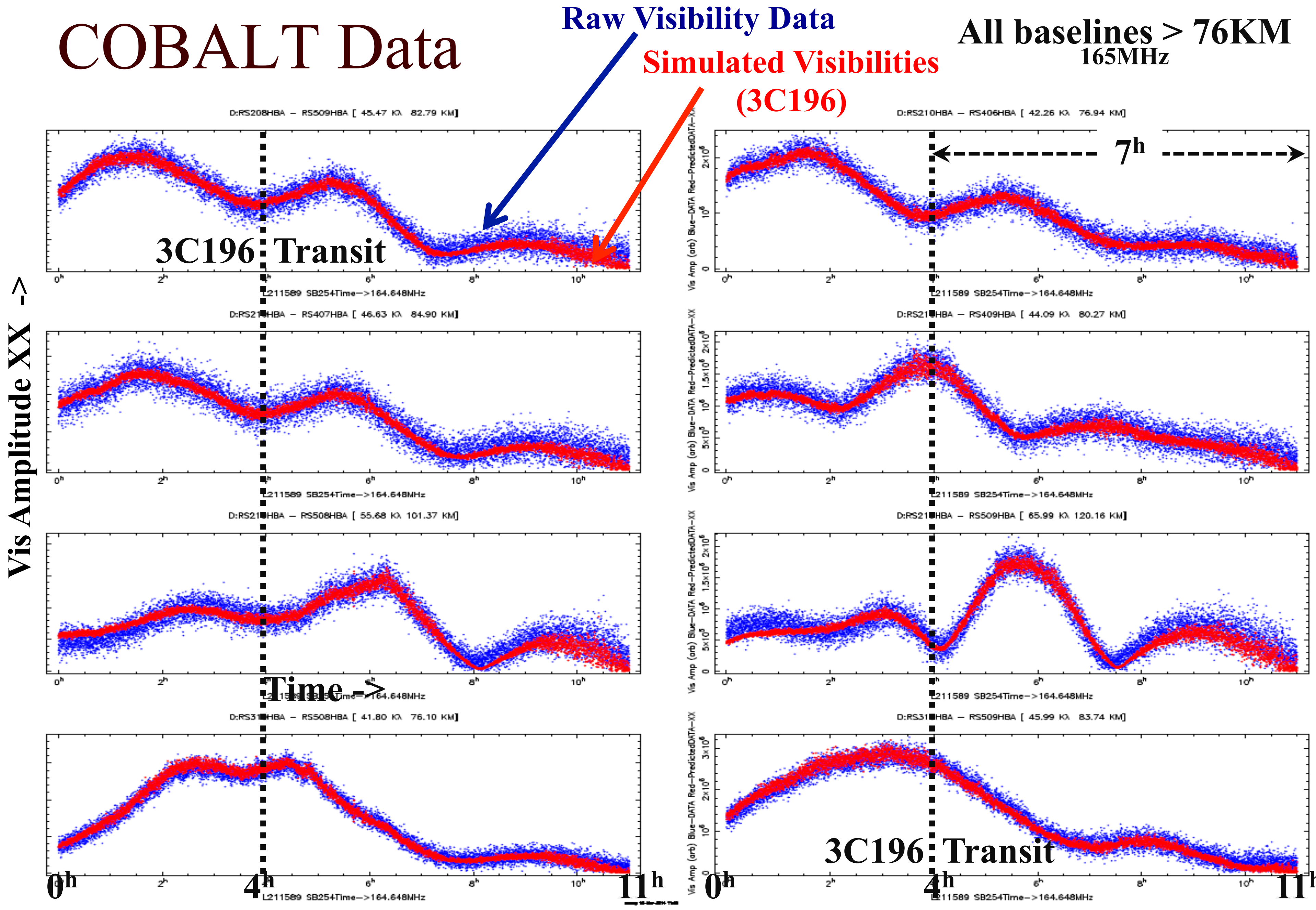
Very Exciting phase of HPC & Science

ASTRON

COBALT Data

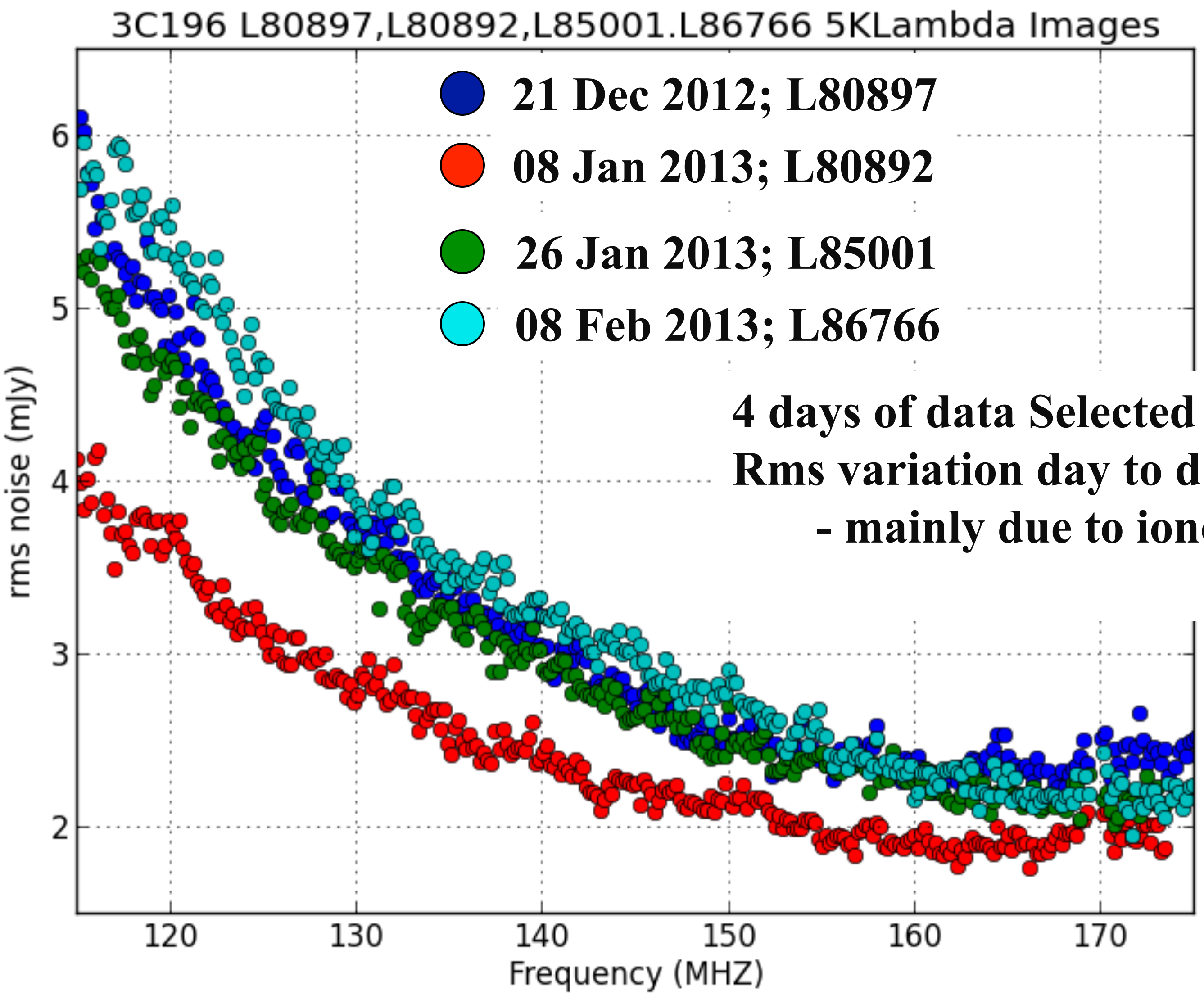

D:RS210HBA – RS407HBA [46.63 Kλ 84.90 KM]
3C196 Transit
s Amp (arb) Blue–DATA Red–PredictedDATA–XX
0
5x10^5
10^6
1.5x10^6
0^h
2^h
4^h
6^h
8^h
10^h

COBALT Data



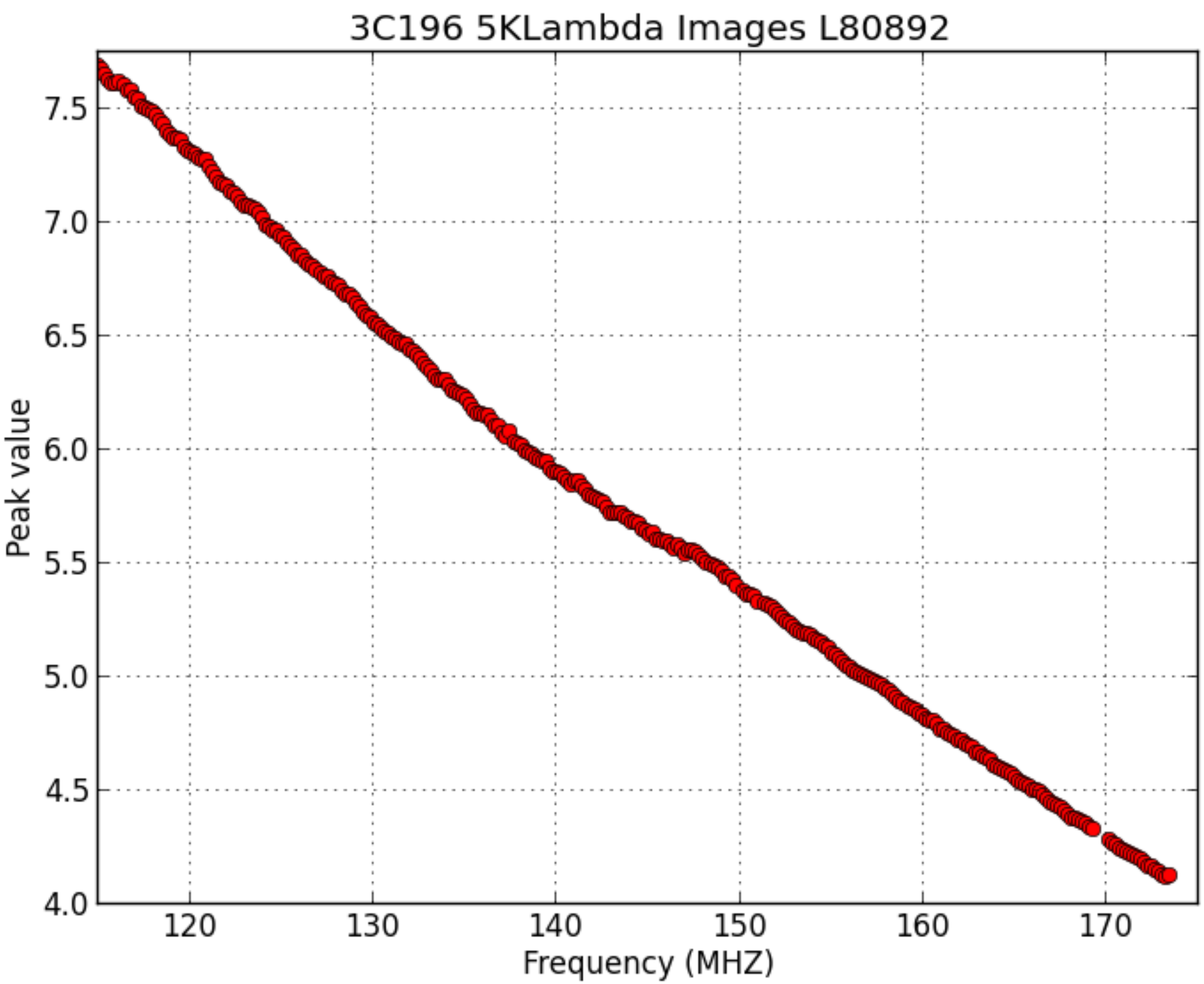
Raw Visibility Data
Simulated Visibilities
(3C196)
All baselines > 76KM
165MHz
D:RS208HBA – RS509HBA [45.47 Kλ 82.79 KM]
D:RS210HBA – RS406HBA [42.26 Kλ 76.94 KM]
7h
3C196 Transit
L211589 SB254Time->164.648MHz
Vis Amplitude XX ->
Vis Amp (arb) Blue-DATA Red-PredictedDATA-XX
Time ->
0h
4h
11h

Noise on different days



4 days of data Selected for various checks
Rms variation day to day
- mainly due to ionospheric activity

Measured peak value (non fitted) of a bright source in each subband (180KHz) image (0821+4702)



Flux calibration along freq smooth.

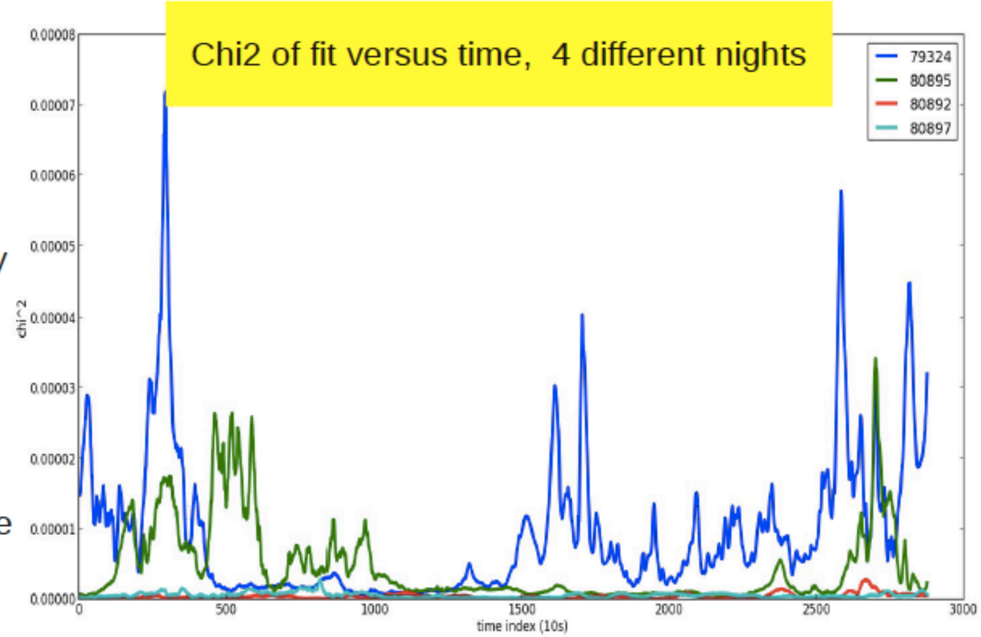
Thanks 3C196 !!

Max difference – 20mJy (not fitted)

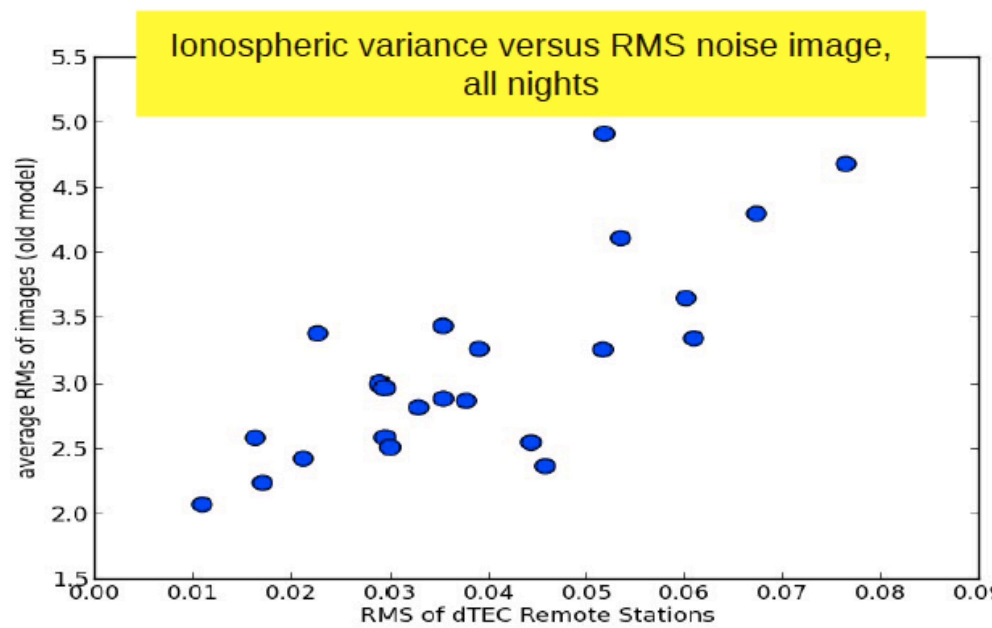
- **Station beam**
- **Spectral index**
- **Resolved at high frequencies?**

Ionosphere

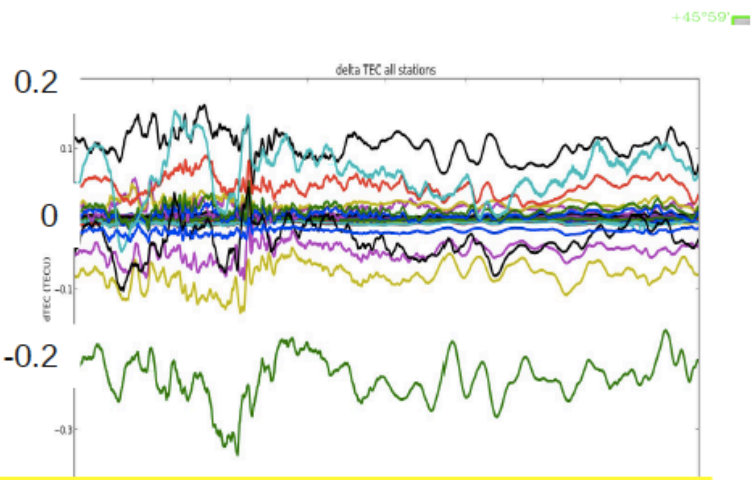
- Start from selfcal phases:
  - Extract differential ionospheric delay per station using frequency dependence (and wide bandwidth)
  - Fit 2D linear screen
    - If the ionosphere could be described by a linear gradient over the fov a single direction independent selfcal would be sufficient for ionospheric calibration
    - 99% of the times a linear gradient will NOT do
    - Investigate “wildness” of the ionosphere by examining the chi2 of the fit
  - Fit higher order (2D/3D) screen for direction dependent corrections (ongoing)



Chi2 of fit versus time, 4 different nights



Ionospheric variance versus RMS noise image, all nights



Fitted dTEC versus time L80897, all stations

Ionosphere

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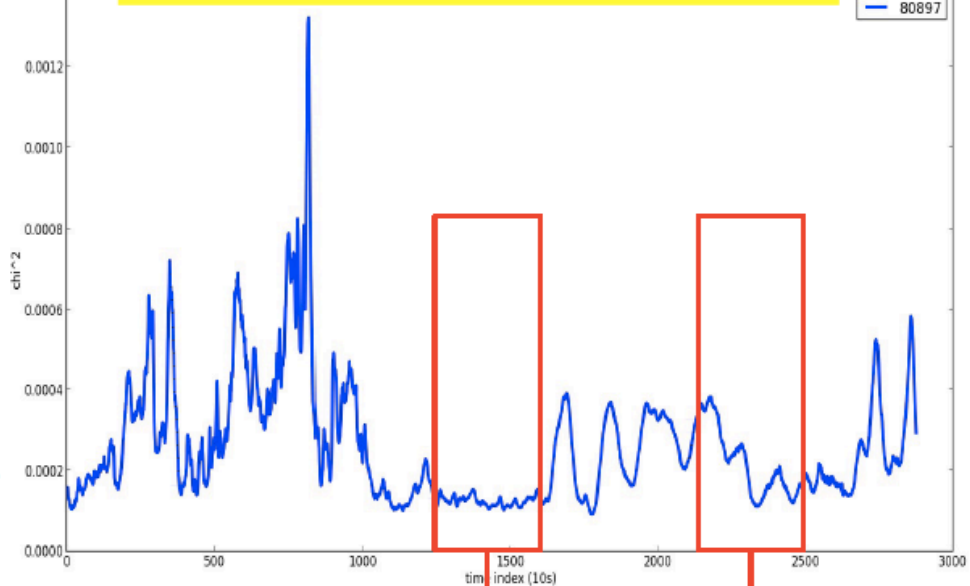
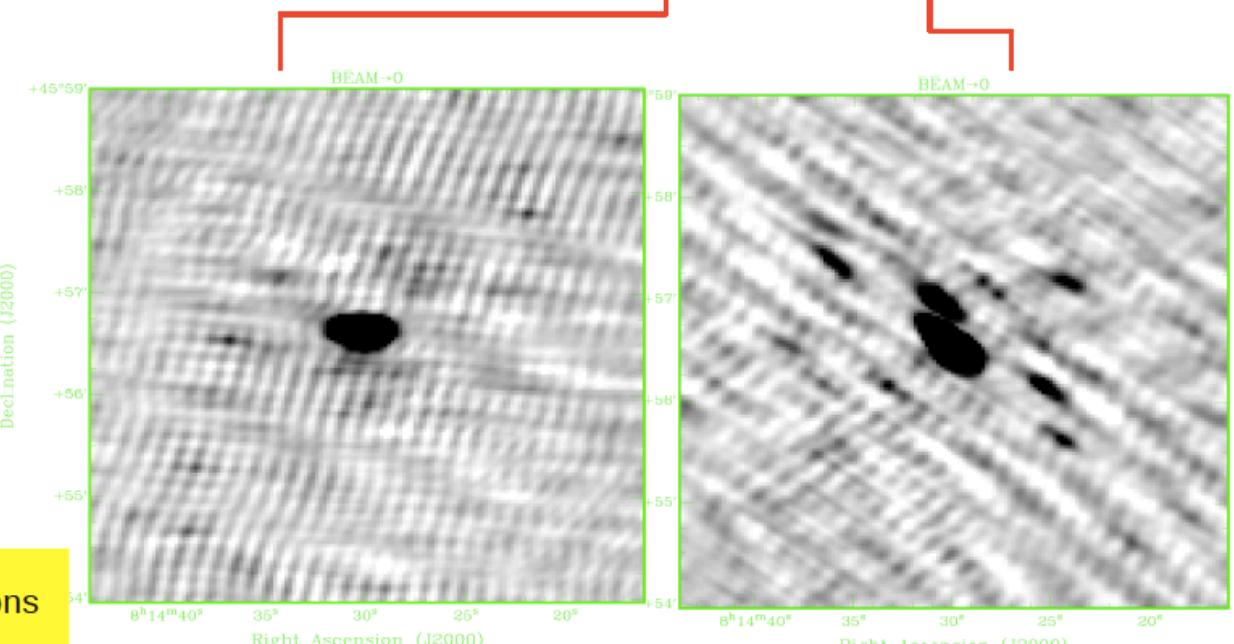
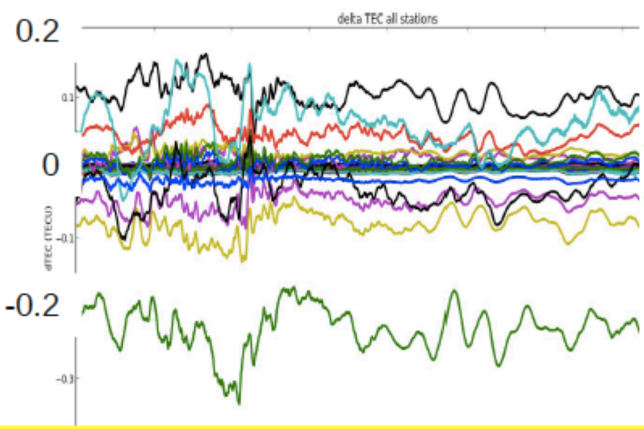
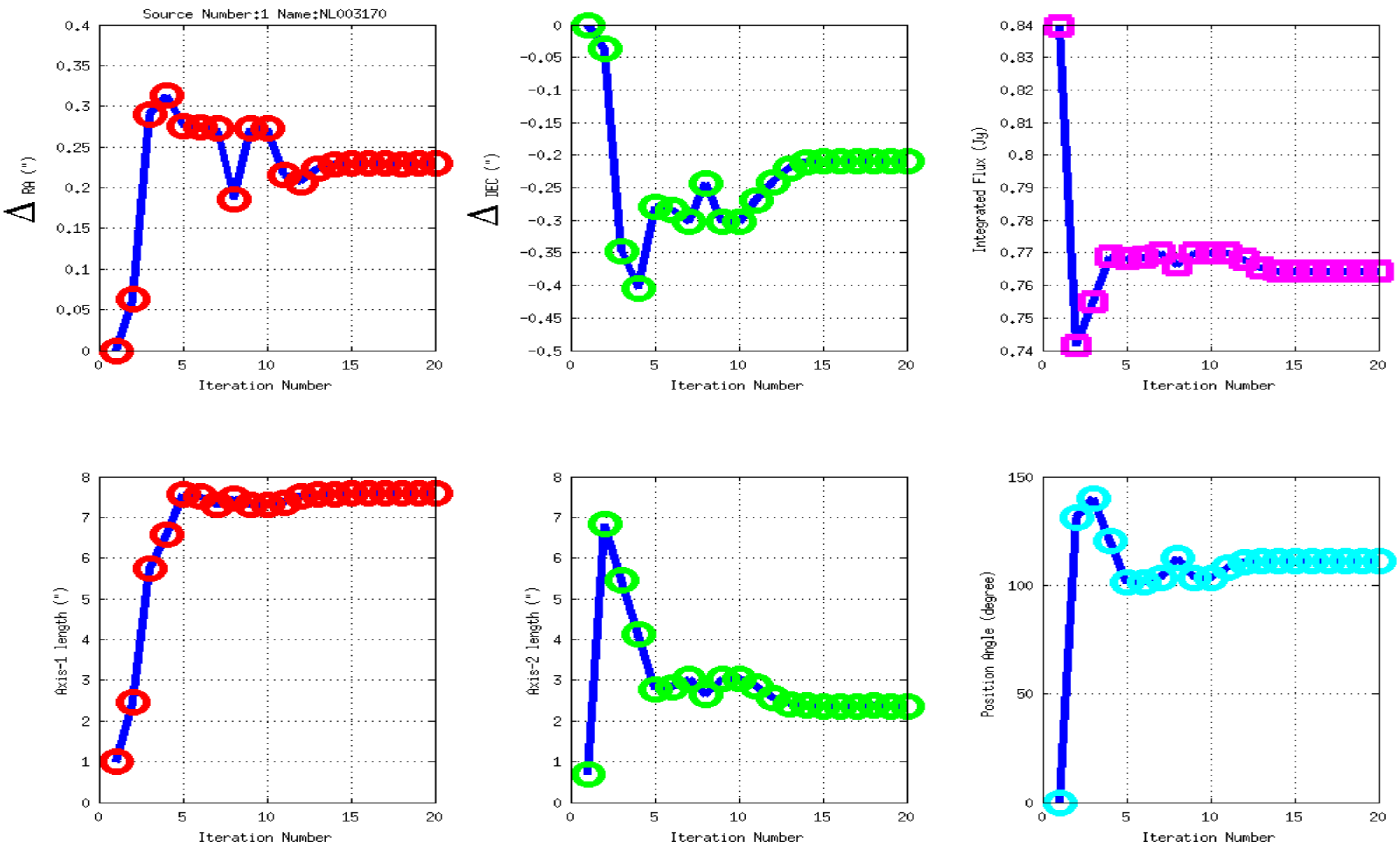
Chi2 of fit versus time L80897



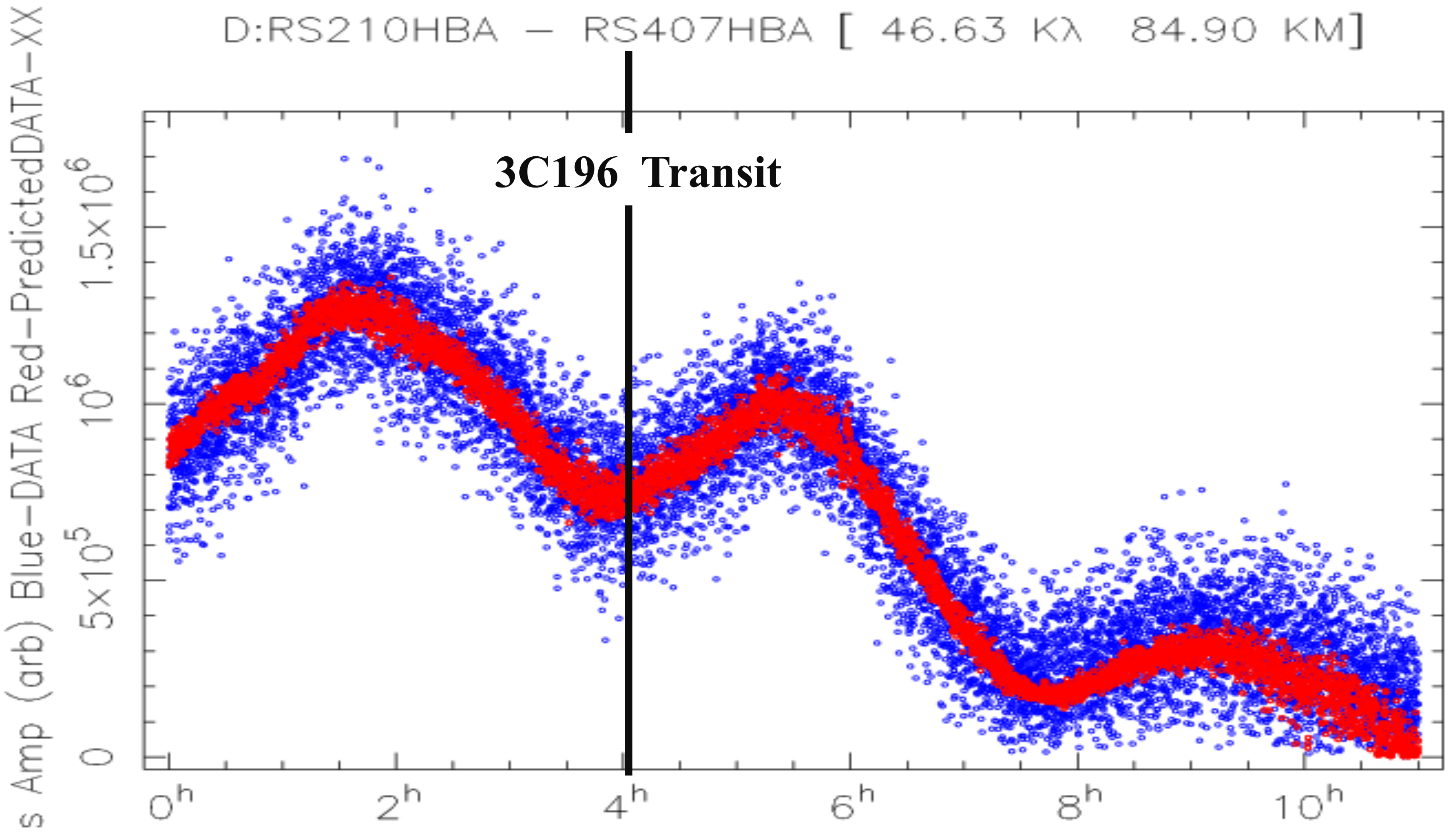




Fitted dTEC versus time L80897, all stations


Source Number:1 Name:NL003170
Δ RA (")
Δ DEC (")
Integrated Flux (Jy)
Axis-1 length (")
Axis-2 length (")
Position Angle (degree)
Iteration Number
Iteration Number
Iteration Number
Iteration Number
Iteration Number
Iteration Number

COBALT Data



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10^h

Challenges

Dynamic ranges in the data motivate an accurate & precise calibration, imaging and signal extraction strategy.

Discrete sources	10^{4-9} μJy/beam
Galactic Foregrounds + Confusion	10^{3} μJy/beam
Thermal/Sky Noise	10 μJy/beam
EoR 21-cm signal	1 μJy/beam

Short Mathematical Data Model

Every visibility (coherency matrix element) can be written as a linear superposition of the entire sky-brightness distribution (in I, Q, U & V), i.e.

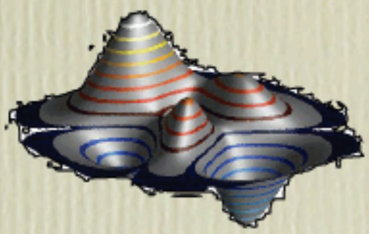
$$\mathbf{v} = \mathbf{A}(\mathbf{p})\mathbf{s} + \mathbf{n} \qquad \mathbf{s} = \begin{pmatrix} \mathbf{s}_{\mathrm{GSM}} \\ \mathbf{s}_{\mathrm{LSM}} \\ \mathbf{s}_{\mathrm{grid}} \end{pmatrix}$$

Classical "Clean-Selfcal" loop iteratively solves **s** (through Cleaning) and **p** (through Self-calibration) until convergence.

This works well if the sky is nearly empty. However for the EoR KSP the entire sky is filled!

Short Mathematical Data Model: Reprocessing = Calibration

Solving for **p** is a highly non-linear process bound to converge to secondary minima if not carried out carefully.



Reprocessing:

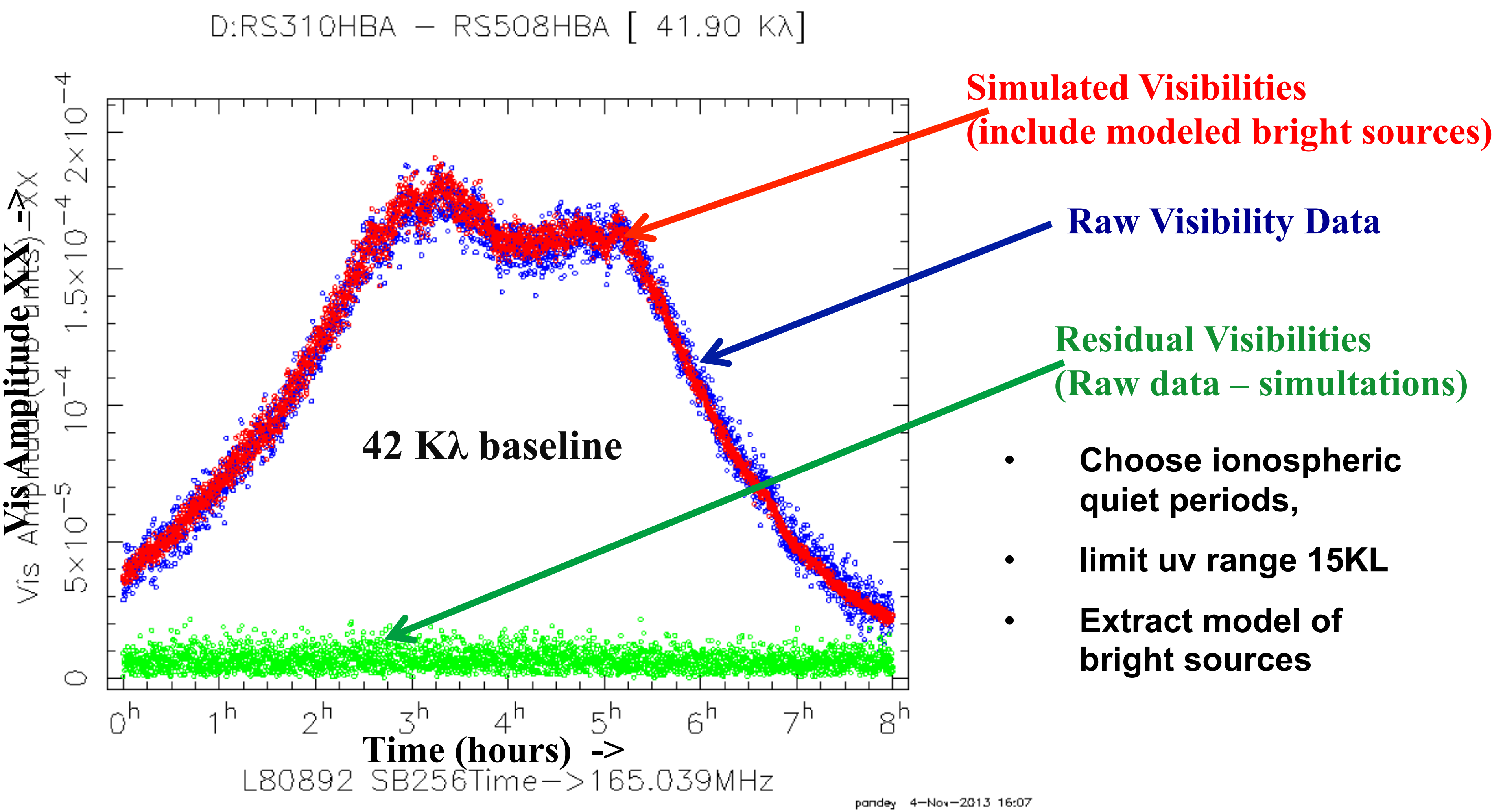
i.e. finding a good initial solution of **p** for all instrument and sky effects using a modified clean-calibration loop and a simple model for **s** (e.g. bright calibrator sources):

What does **p** contain:

1. Bandpass calibration
2. Dipole rotations
3. Complex Telescope Gains
4. Complex omni-directional beam
5. Ionospheric phase fluctuations
6. Faraday rotation
7. What ever else might be out there....

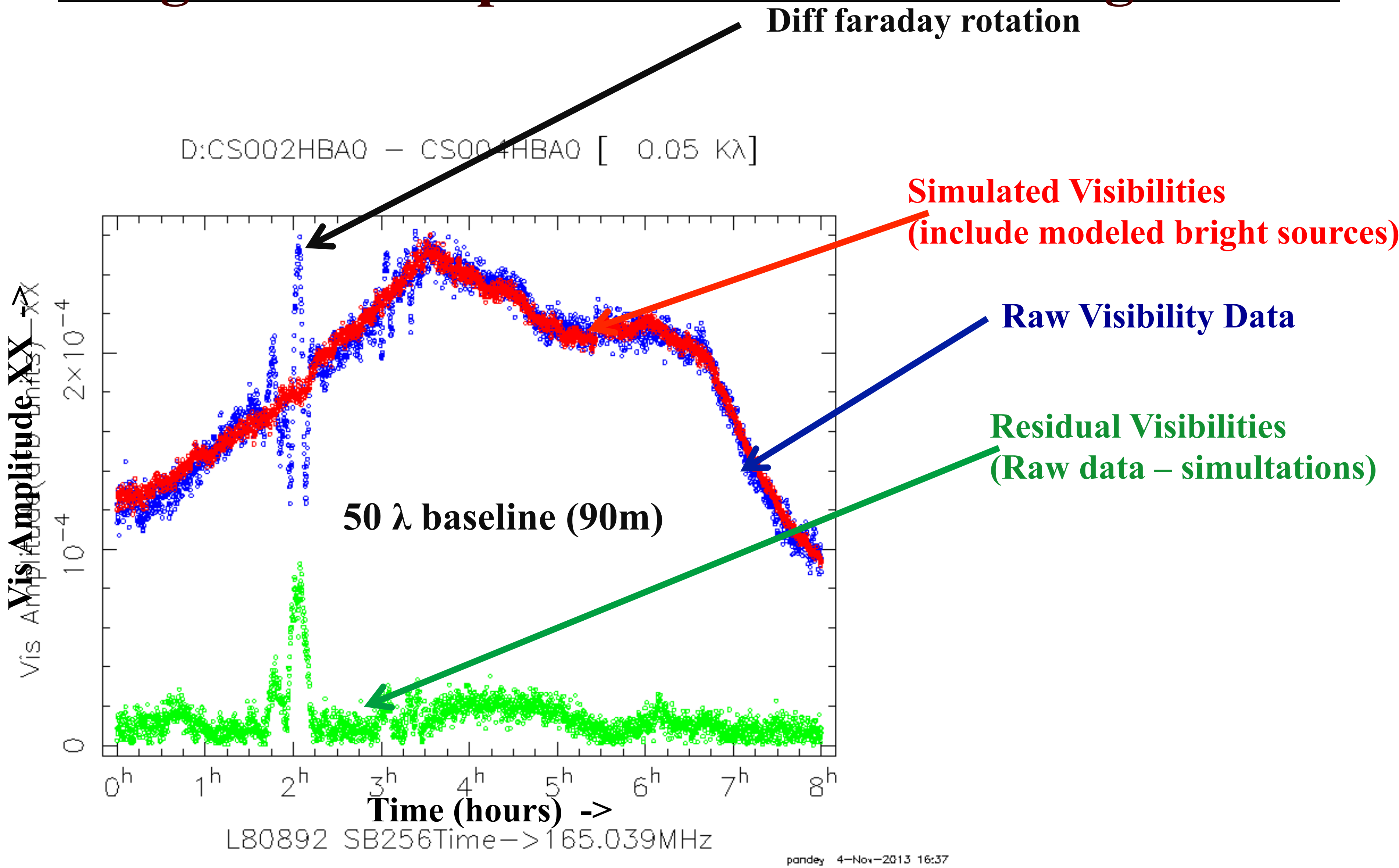
Bright sources parametric model fitting-RESULTS

- **Gets back the good model of 3C196 or even better !**



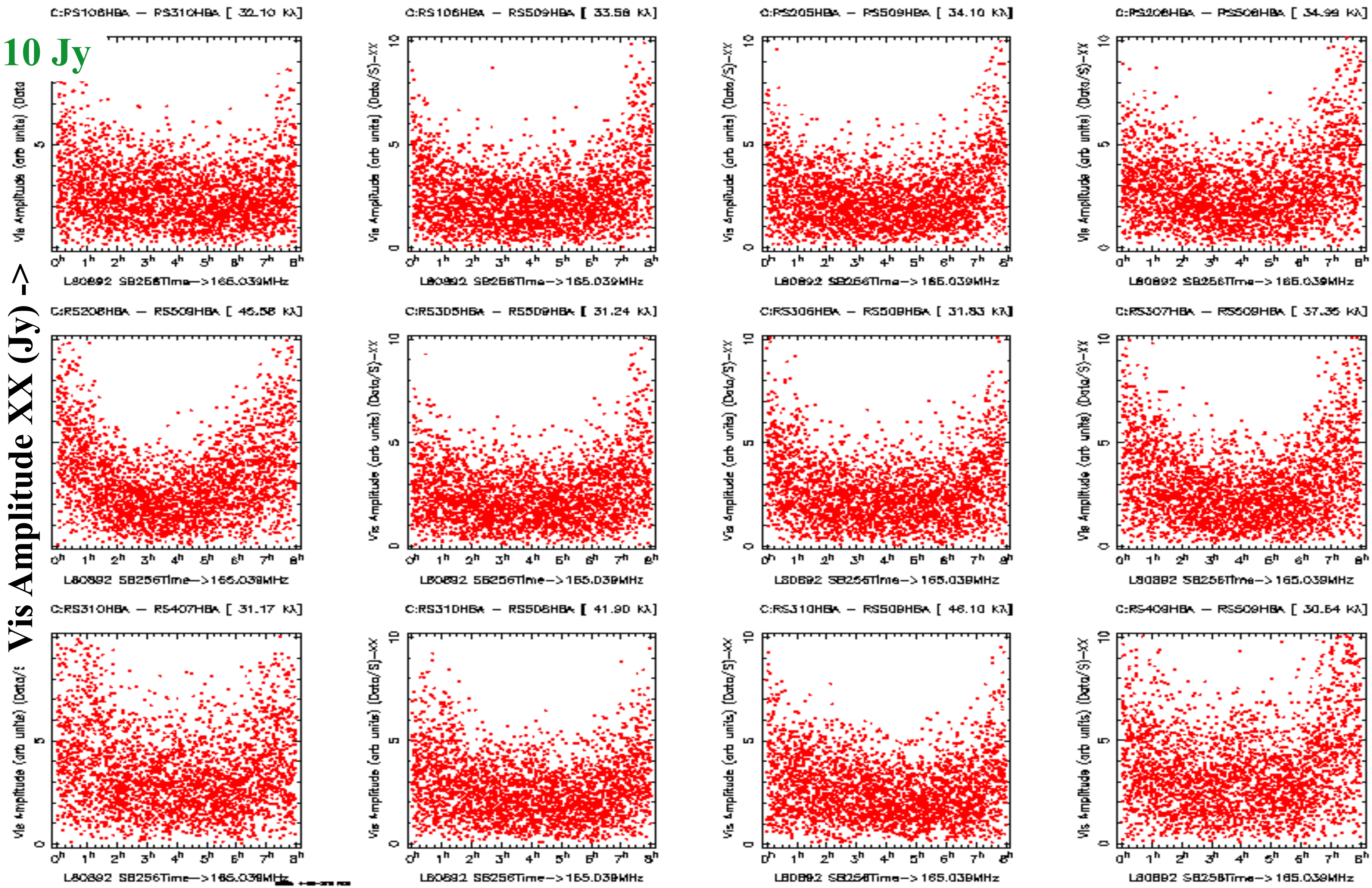
- **Choose ionospheric quiet periods,**
- **limit uv range 15KL**
- **Extract model of bright sources**

Bright sources parametric model fitting-RESULTS

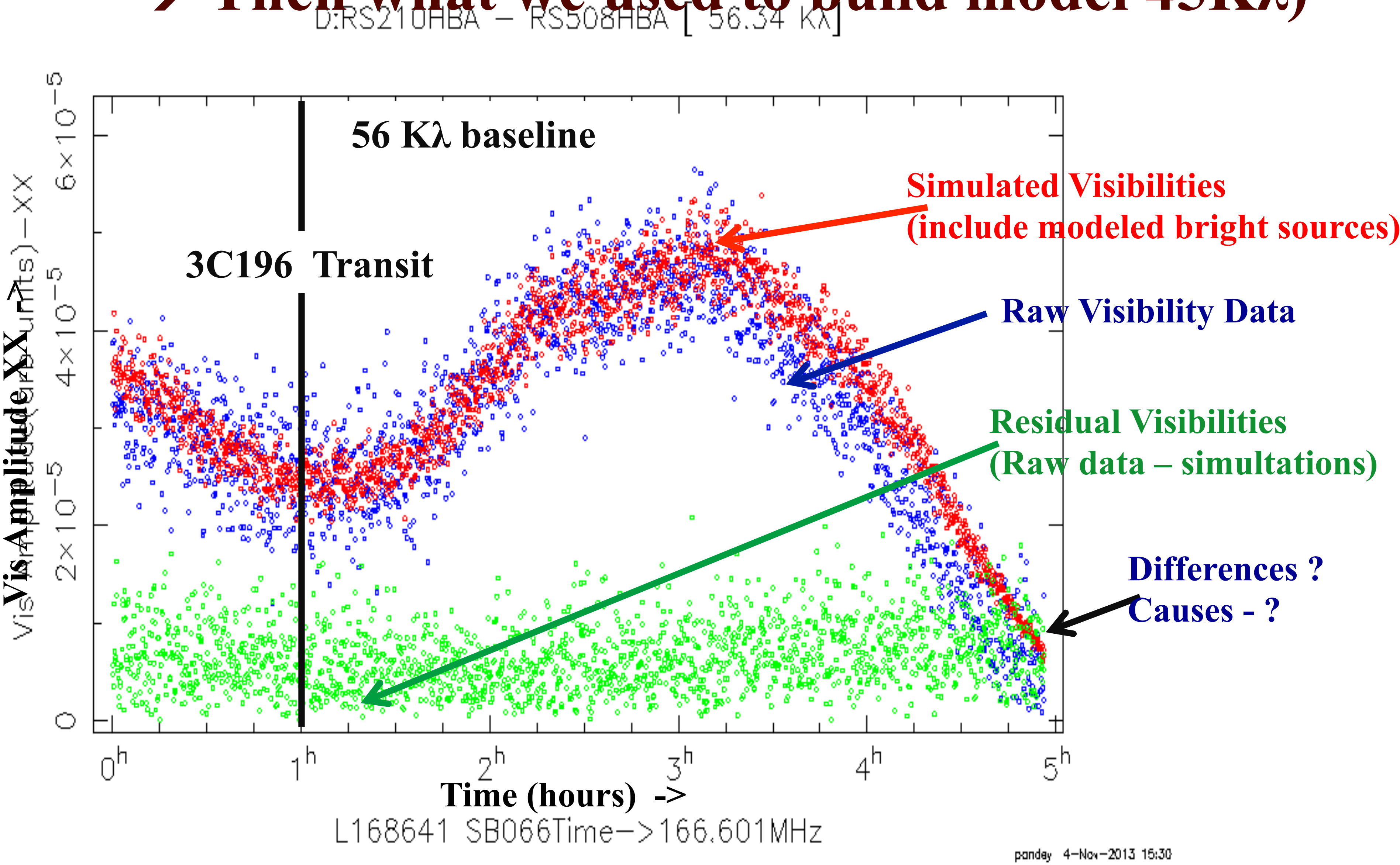


Improving Calibration !

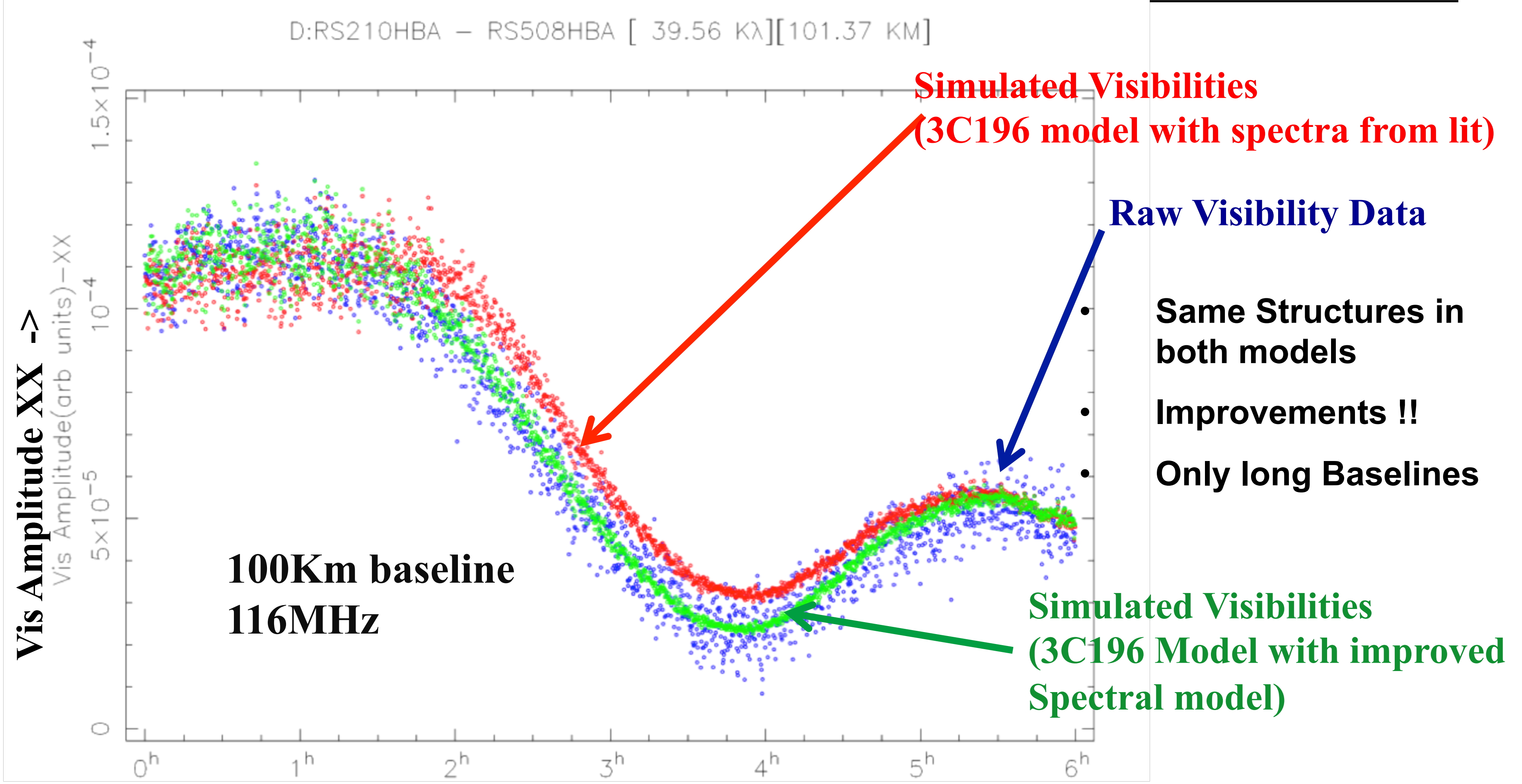
Residual Visibilities in Jy
(After Subtracting 3C196)
Baselines > 30KL



Test the model at even longer baselines
→ Then what we used to build model ~~45Kλ)~~



Accurate 3C196 Spectrum model -RESULTS



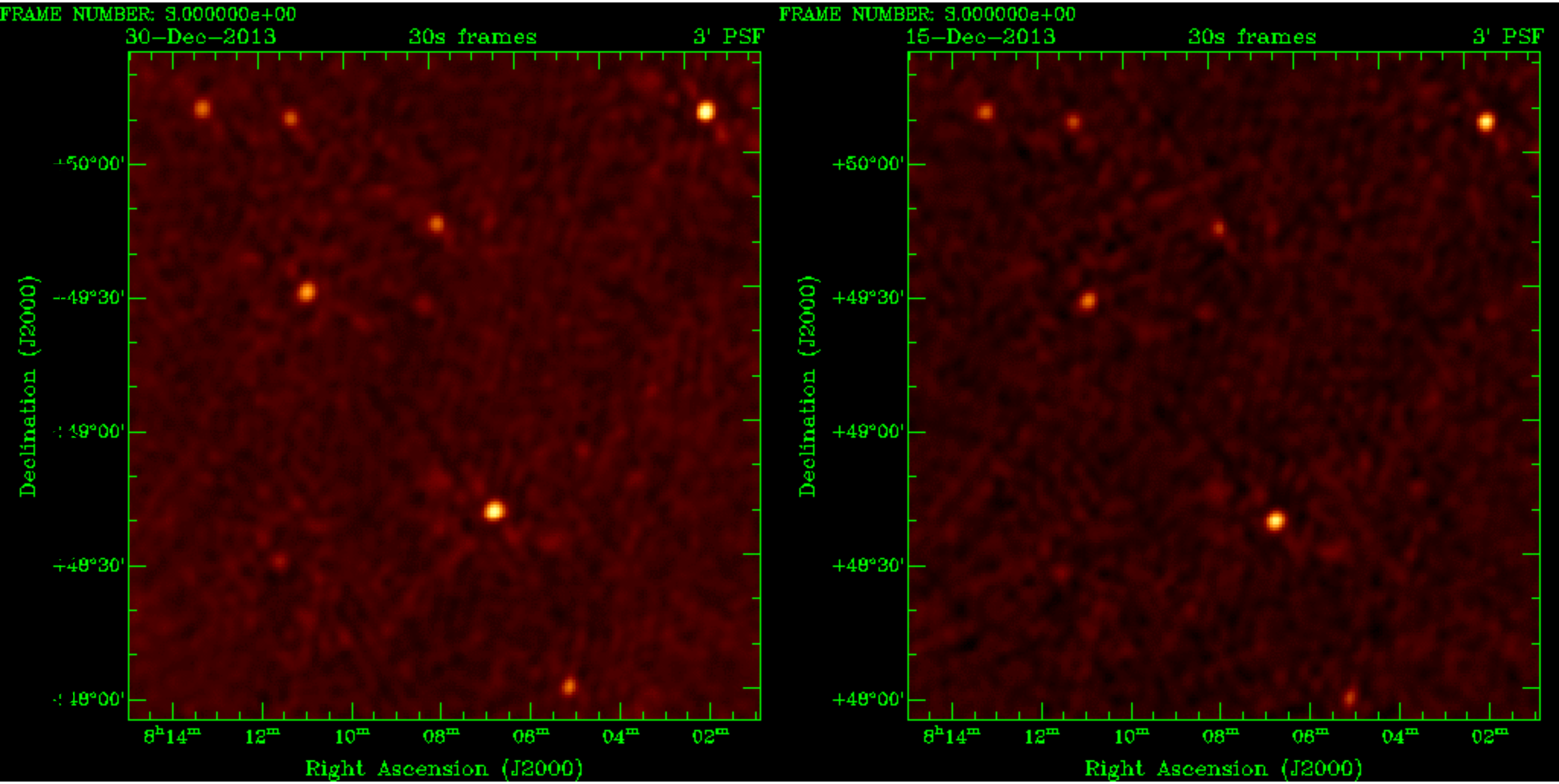
- Same Structures in both models
- Improvements !!
- Only long Baselines

Time (hours) ->

3C196 Model obtained by super-resolution
Good enough for LoFAR-EoR

Bright sources parametric model fitting-Challenges

Ionospheric Effects on 2 days (3C196 subtracted)



Amplitude and Position variation with time (3' PSF; 30s Frames)

Astron daily image 07-03-2014 (Ger)