Irfu - CEA Saclay
Institut de recherche
sur les lois fondamentales
de l'Univers

l'Observatoire de Paris | LESIA

LOFAR Observations of Jupiter and Saturn

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on the behalf of the TKP PeWG

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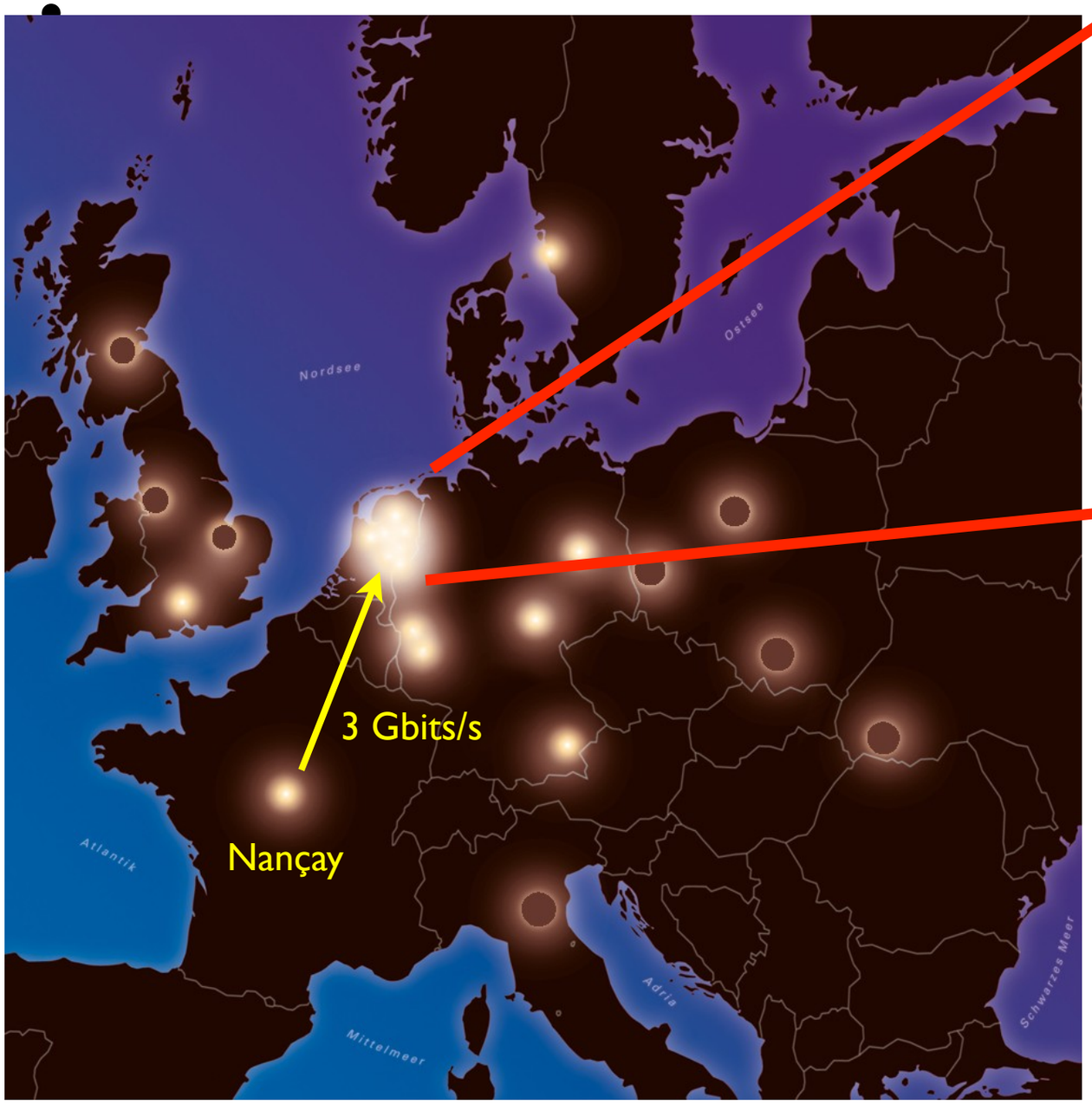
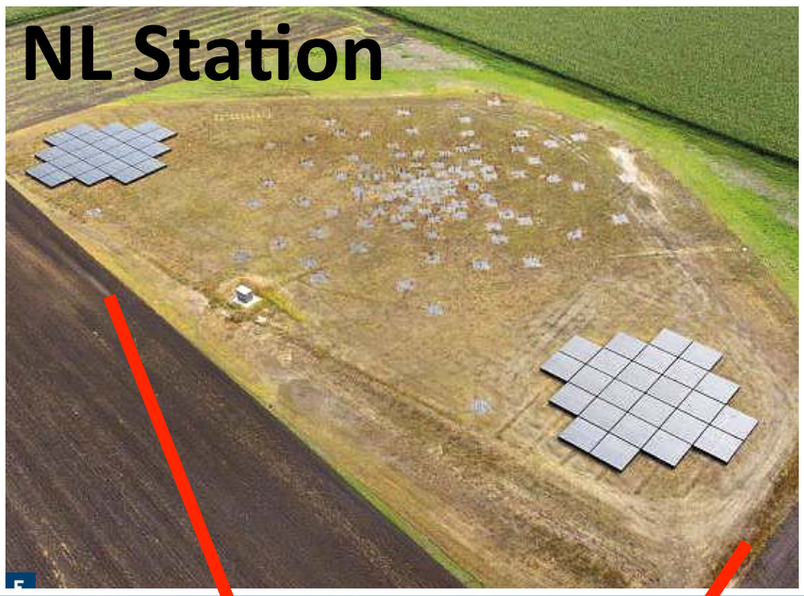
LabEx UnivEarthS

université PARIS DIDEROT PARIS 7

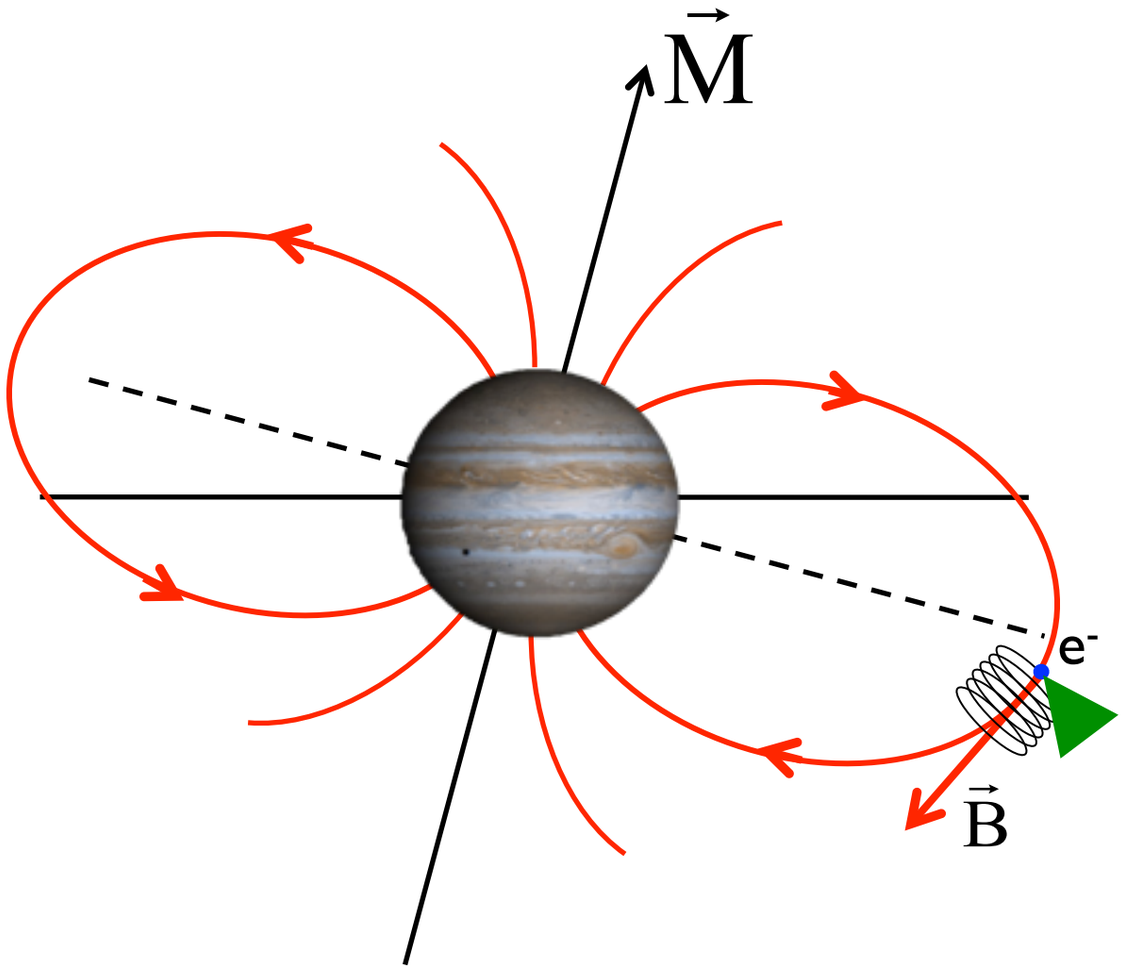
The LOw Frequency ARray

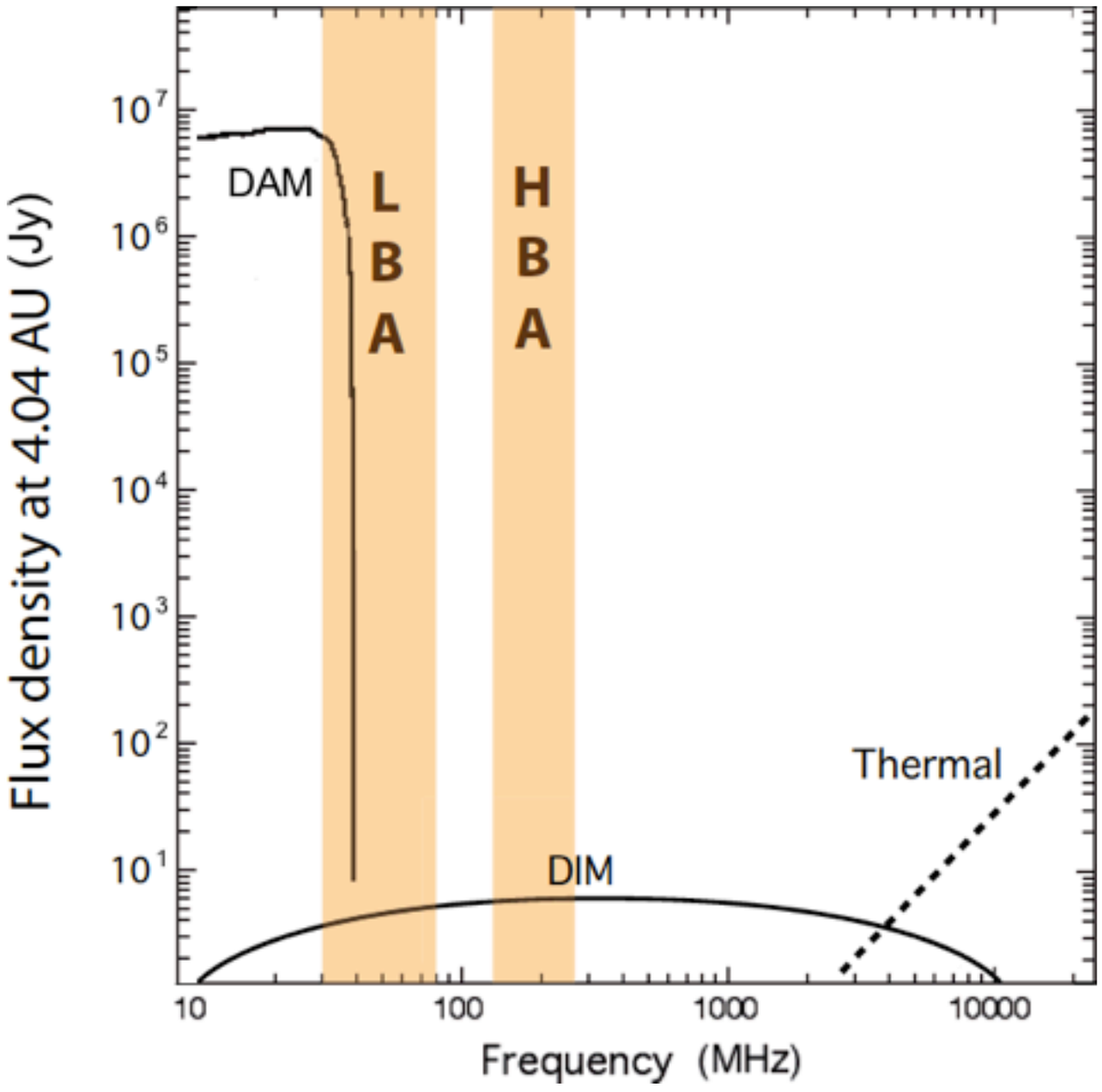
- **Giant digital radio telescope distributed across Europe**
- **Radio interferometer composed of ~48 phased arrays (stations)**
- **Working bands: LBA** 30-80 MHz **& HBA** 120-240 MHz.
-



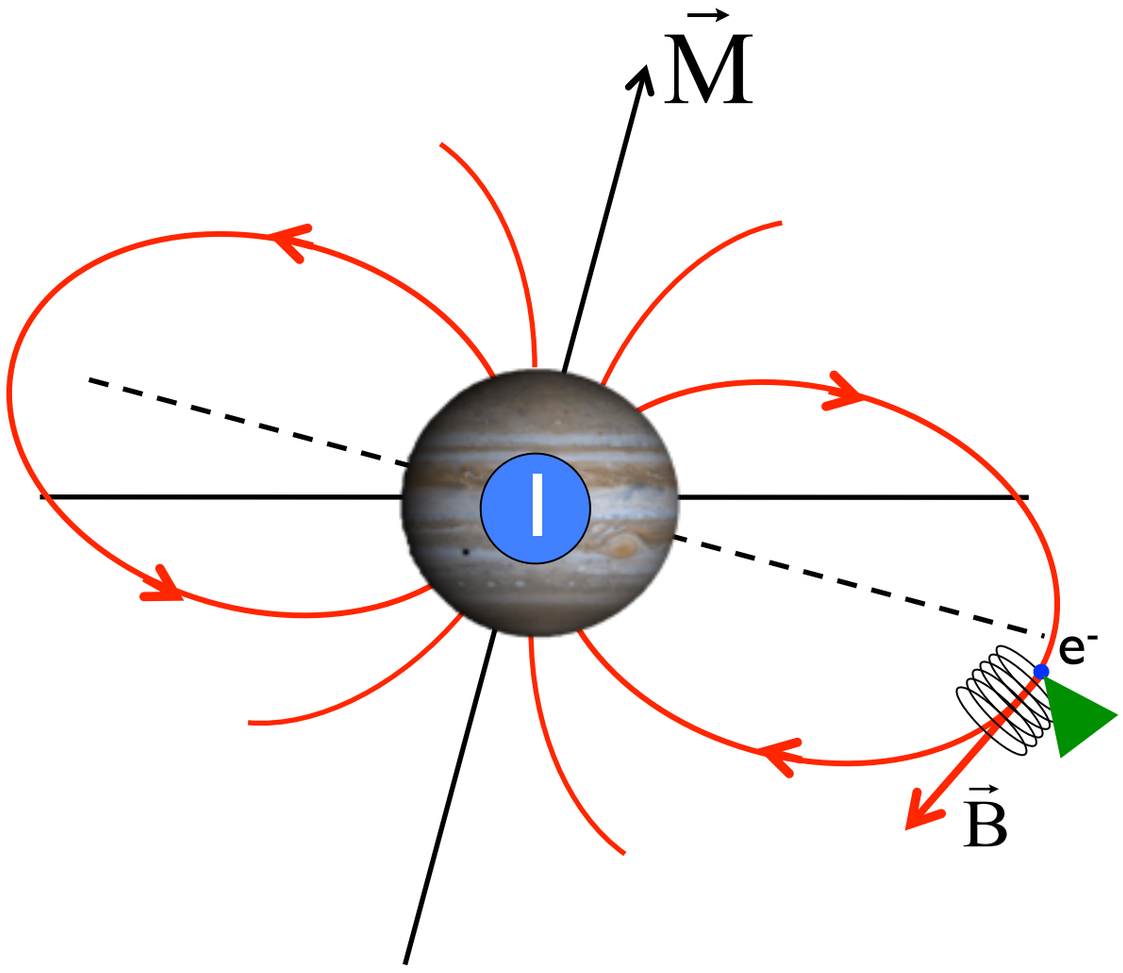


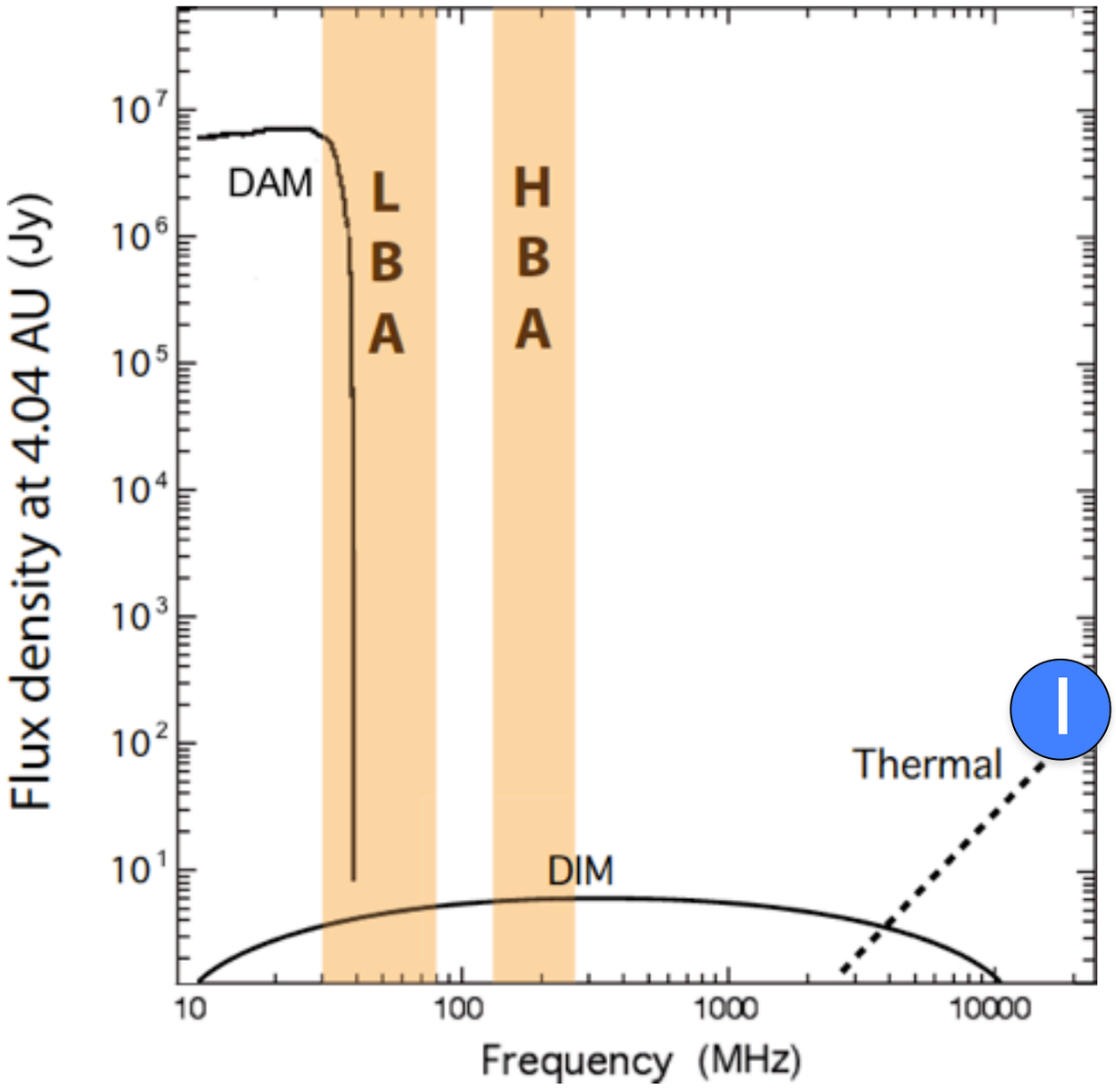
Jupiter radio emissions





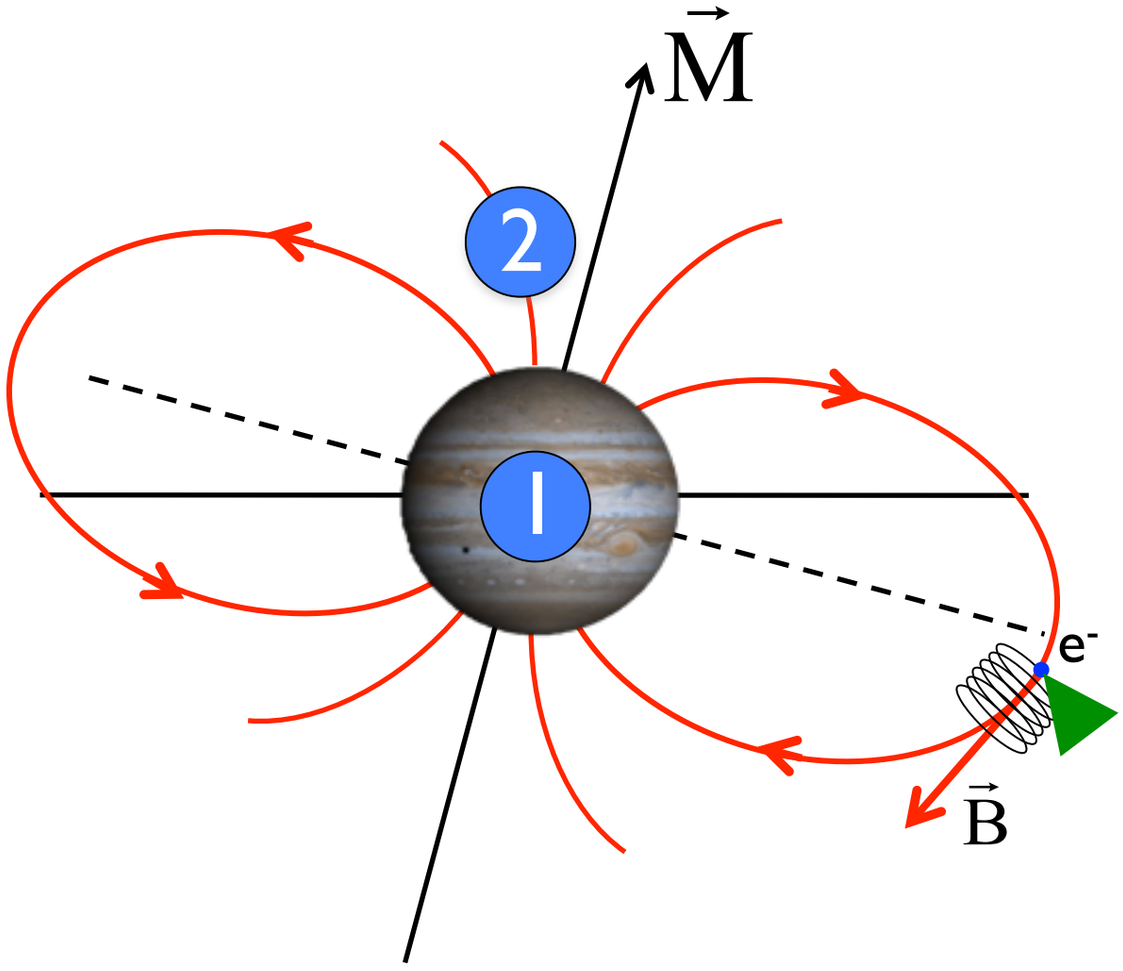
Jupiter radio emissions

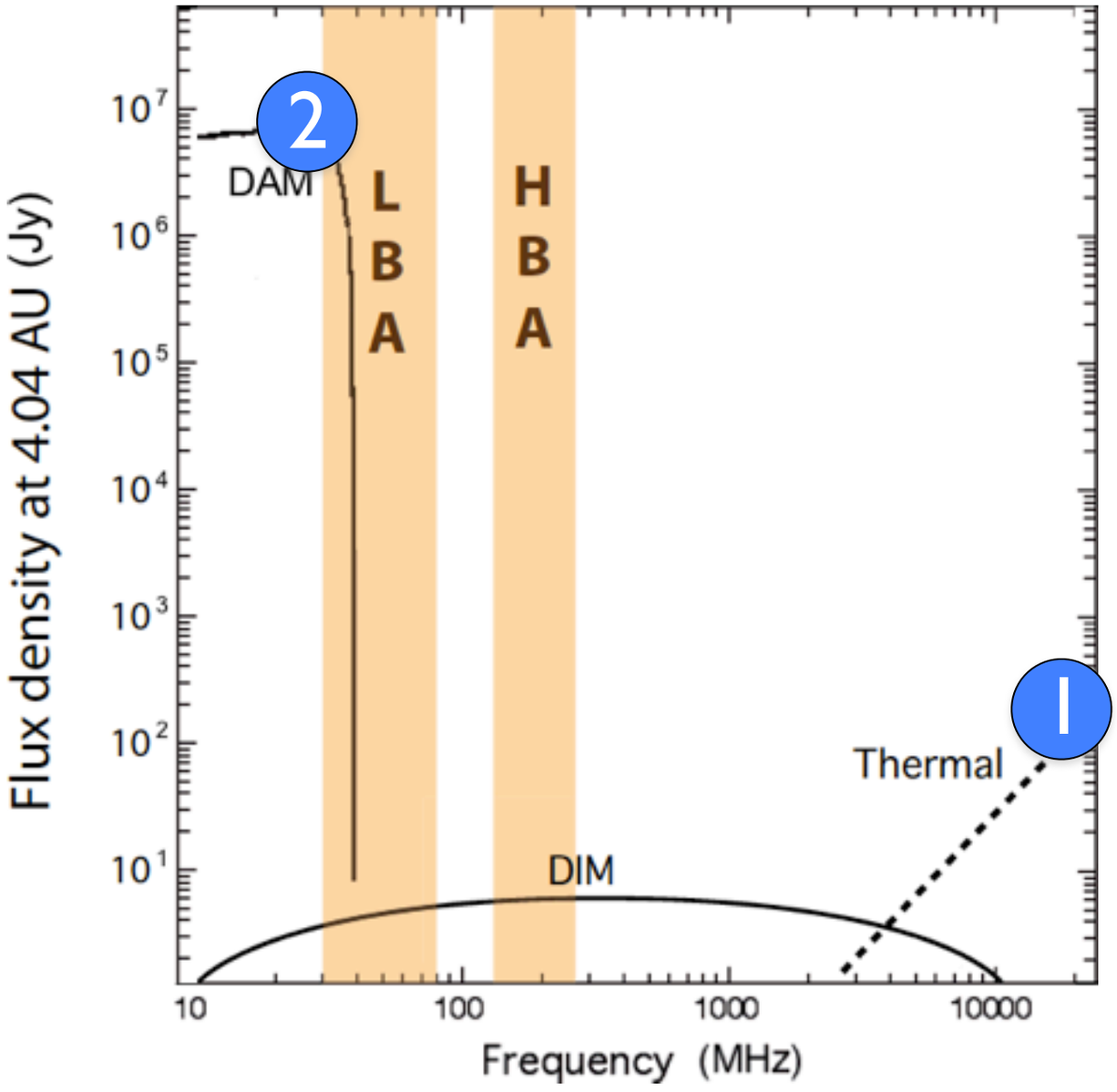




I Thermal (λ ~ cm)

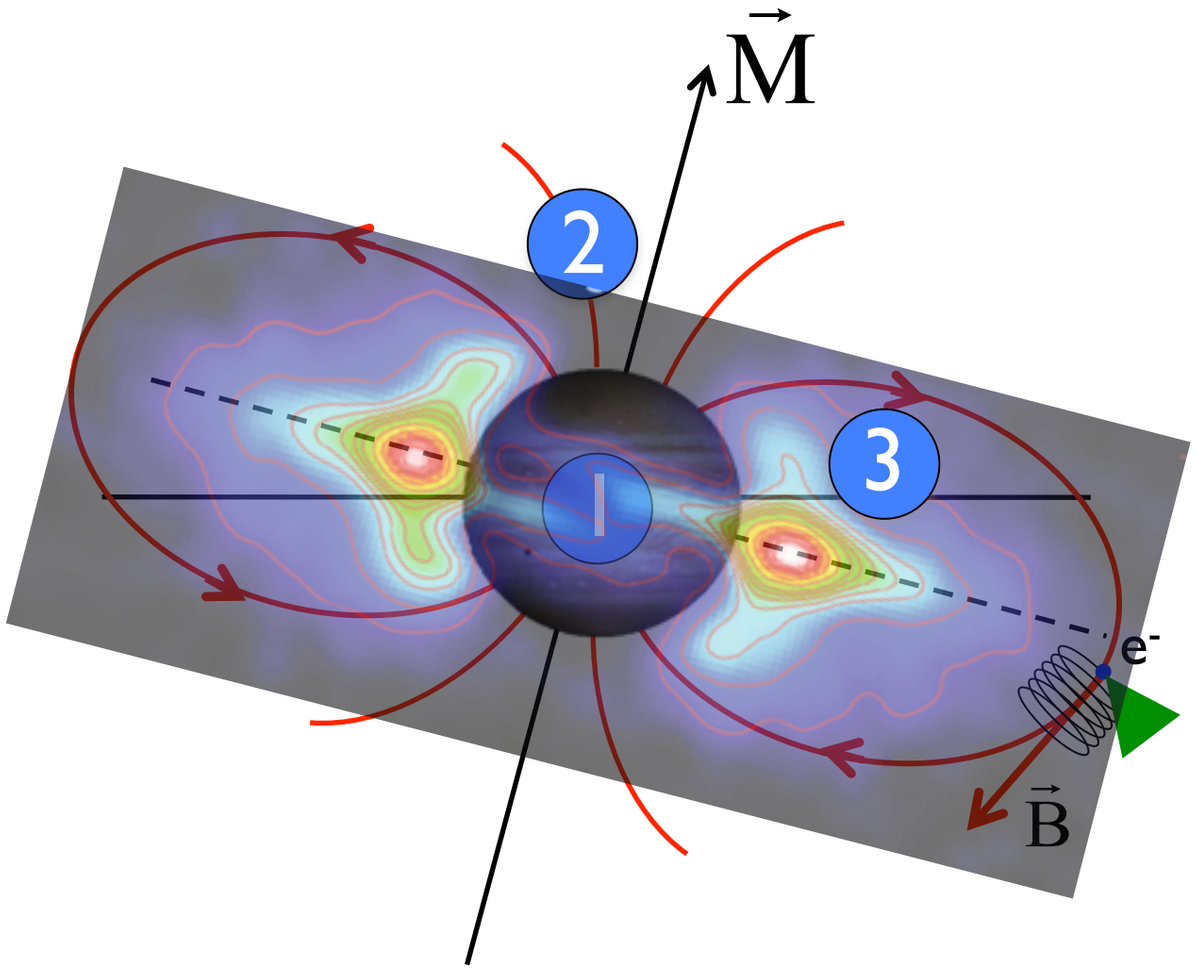
Jupiter radio emissions

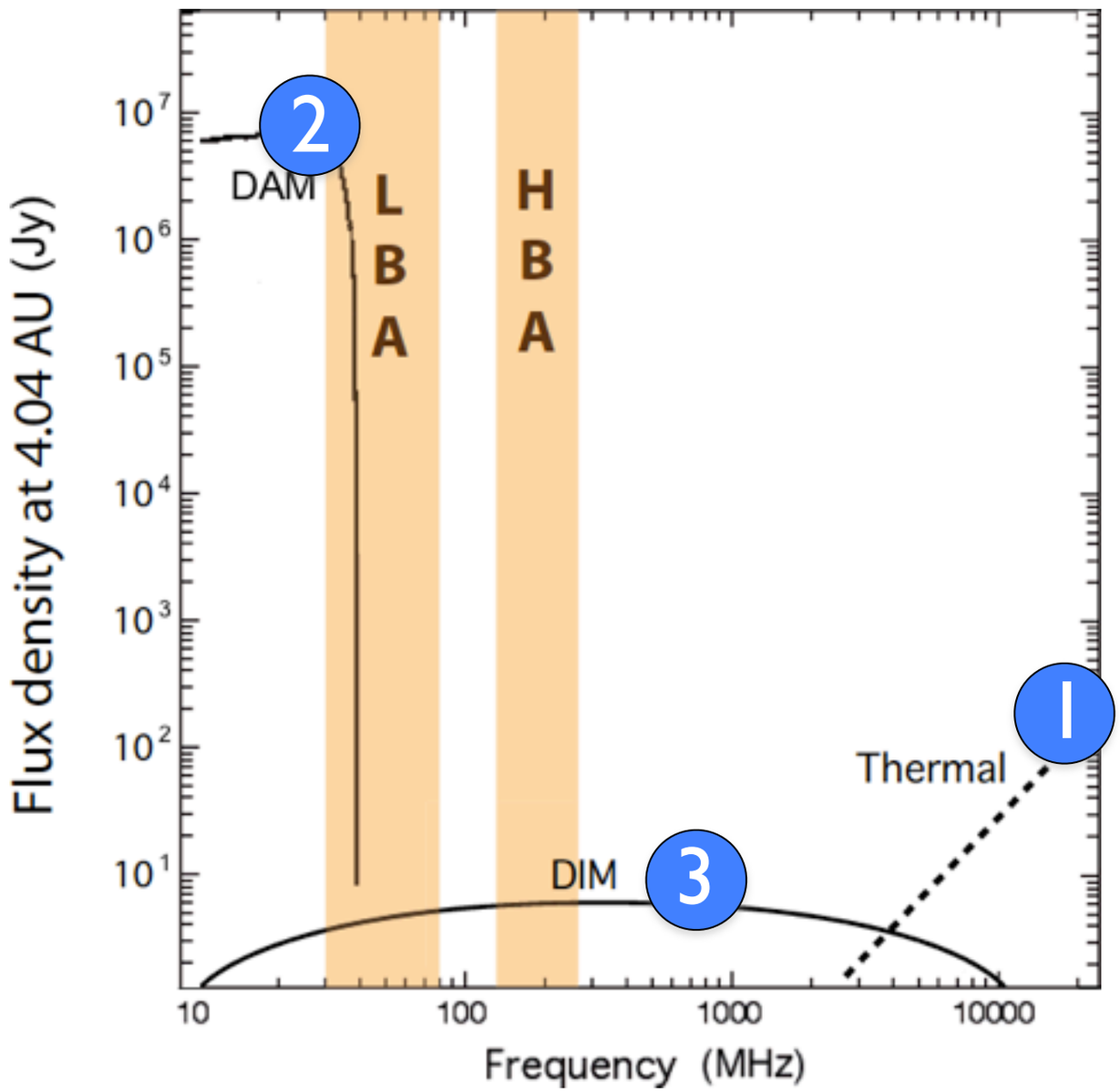




1. Thermal (λ ~ cm)
2. Auroral / Io cyclotron emission (λ ≥ Dm)

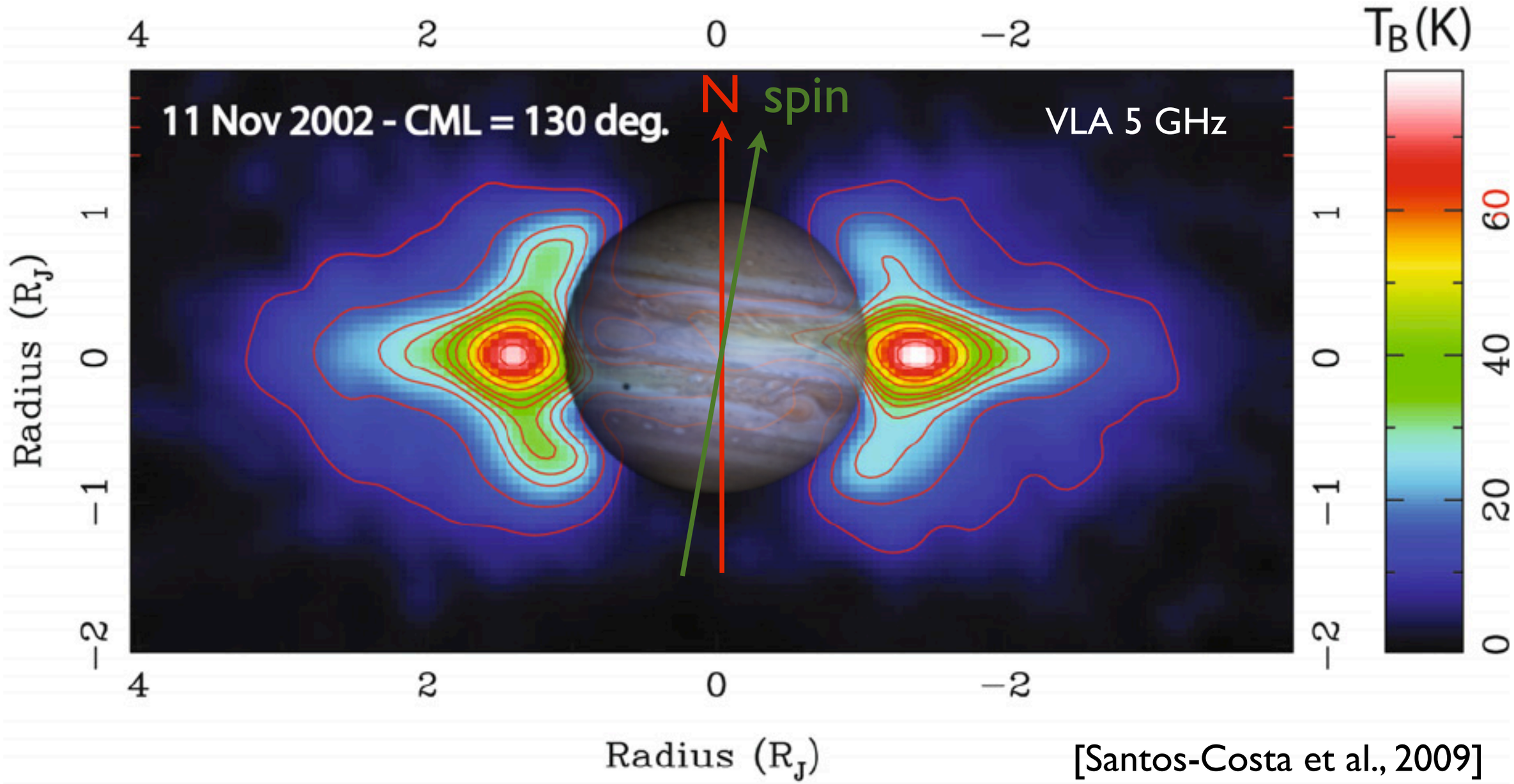
Jupiter radio emissions





1. Thermal (λ ~ cm)
2. Auroral / Io cyclotron emission (λ ≥ Dm)
3. Radiation belts synchrotron emission (λ = cm-dm-m)

Jupiter decimetric emission



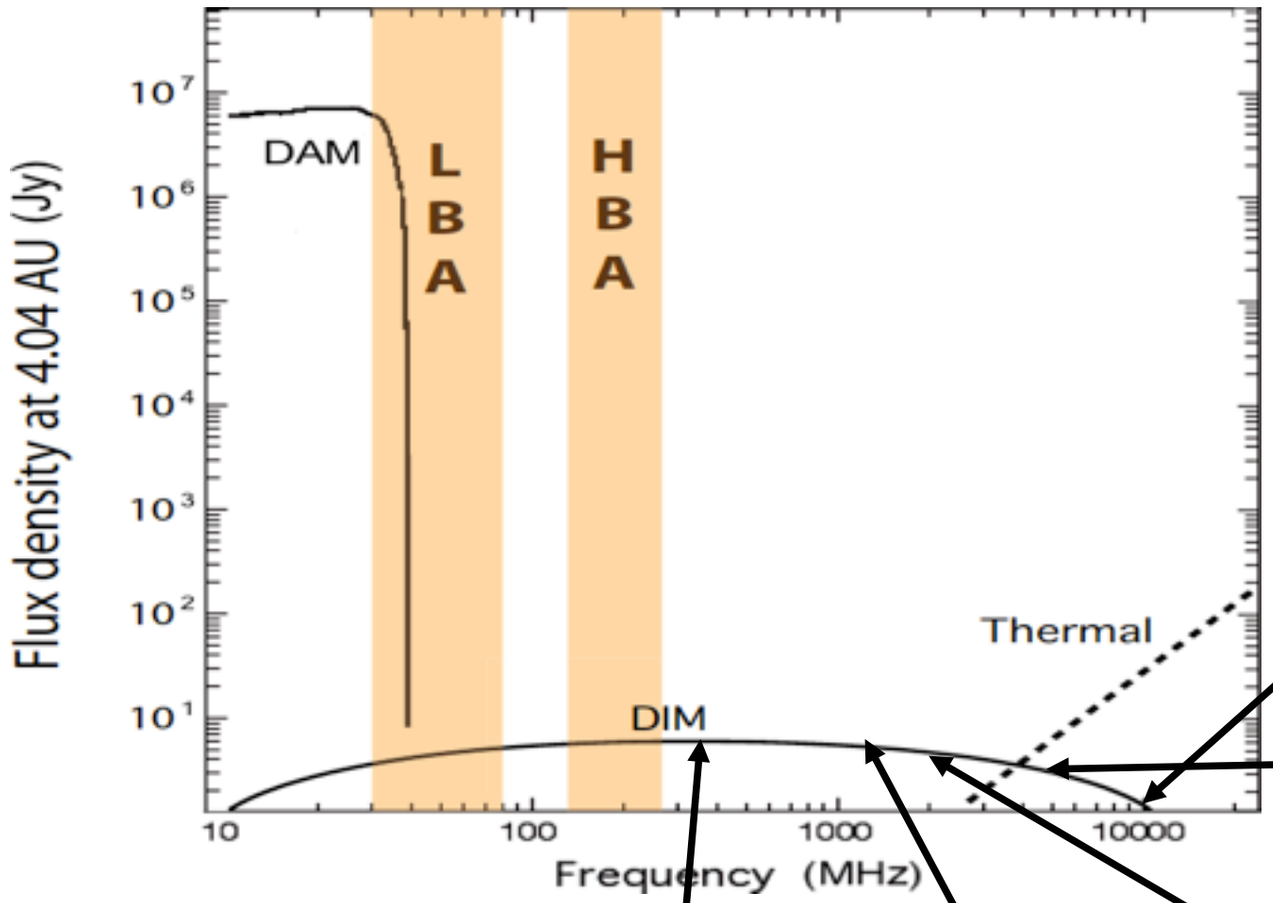
[Santos-Costa et al., 2009]

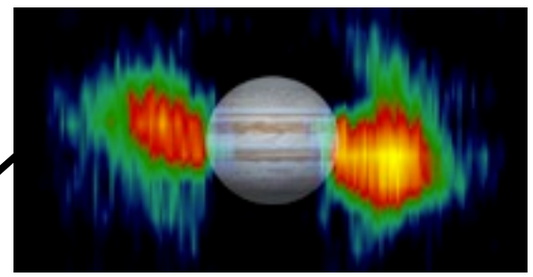
3 Radiation belts' synchrotron emission (λ = cm-dm-m)

- Belts radiating from ~1 to ~3 R_J
- Energetic particles (ions, e- of 100s keV → 10s MeV) trapped near the magnetic equator
- Anisotropic (beamed) and polarized emission (~20-25% linear, <1% circular)

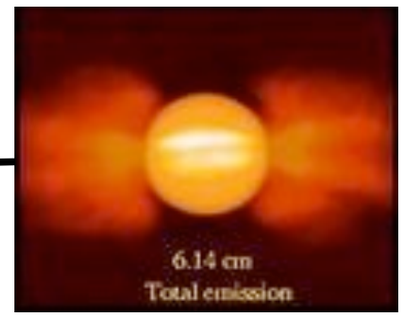
Jupiter decimetric emission

LF → low e- energies (100s keV) , HF → (10s MeV)





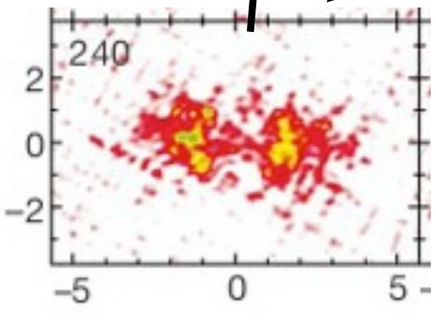
14 GHz / 2 cm
Cassini



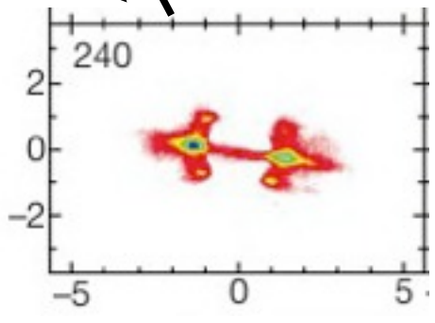
5 GHz / 6 cm

VLA

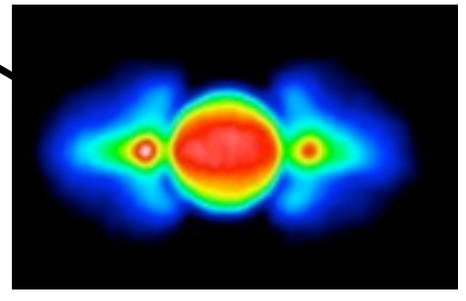
ATCA



333 MHz / 90 cm



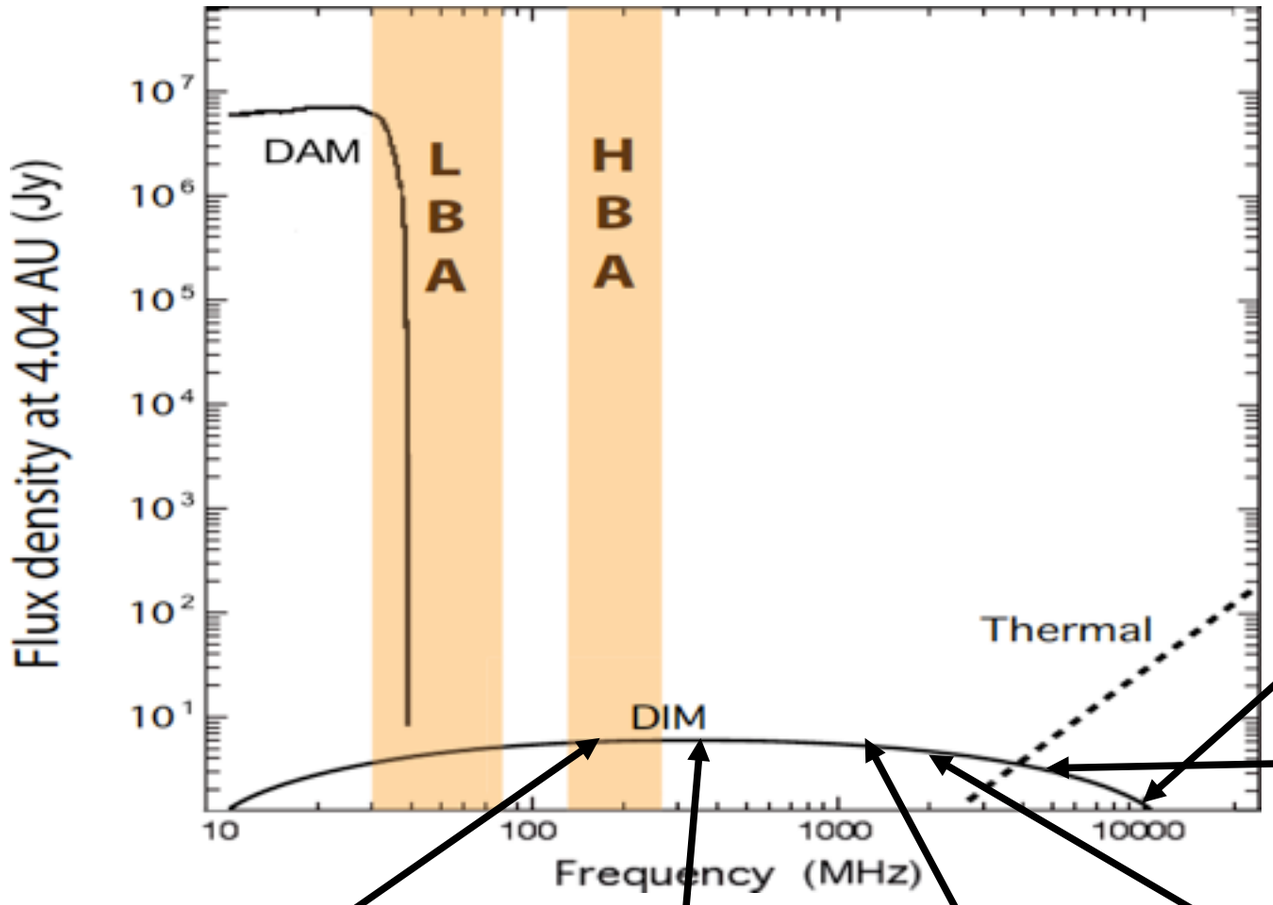
1.4 GHz / 20 cm

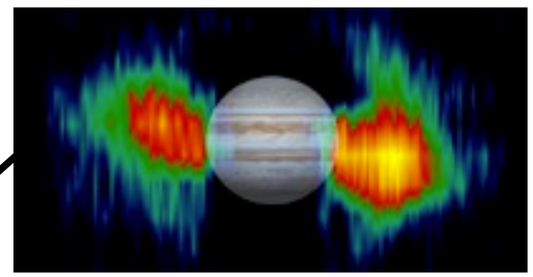


2.3 GHz / 13 cm

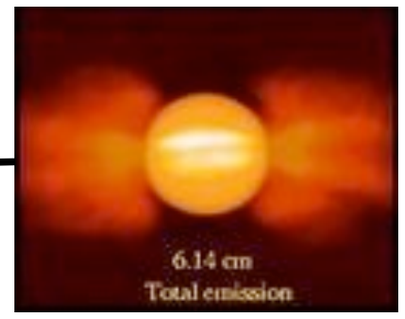
Jupiter decimetric emission

LF → low e- energies (100s keV) , HF → (10s MeV)

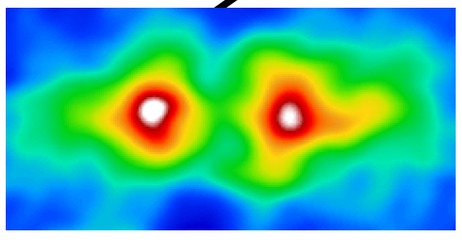




14 GHz / 2 cm
Cassini

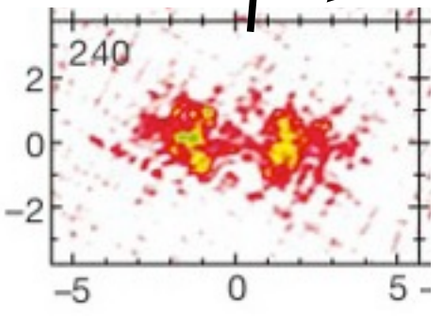


5 GHz / 6 cm

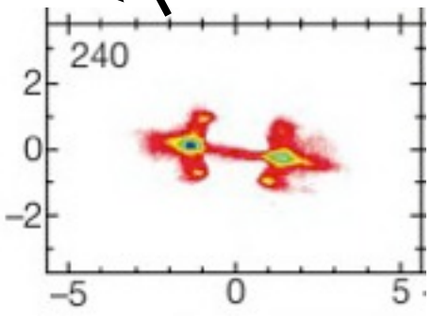


LOFAR HBA / ~2 m
(127-172 MHz)

VLA

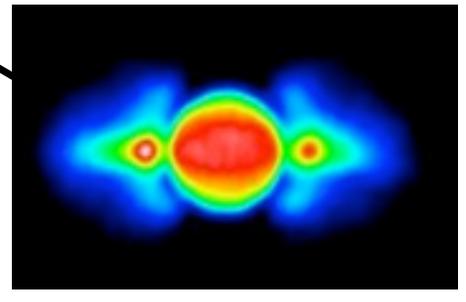


333 MHz / 90 cm



1.4 GHz / 20 cm

ATCA



2.3 GHz / 13 cm

Motivations for low frequency observations

Characteristics of the emission

- Resolved LF brightness distribution
- Polarization, extent to LF ? spectral variations ?

Dynamics

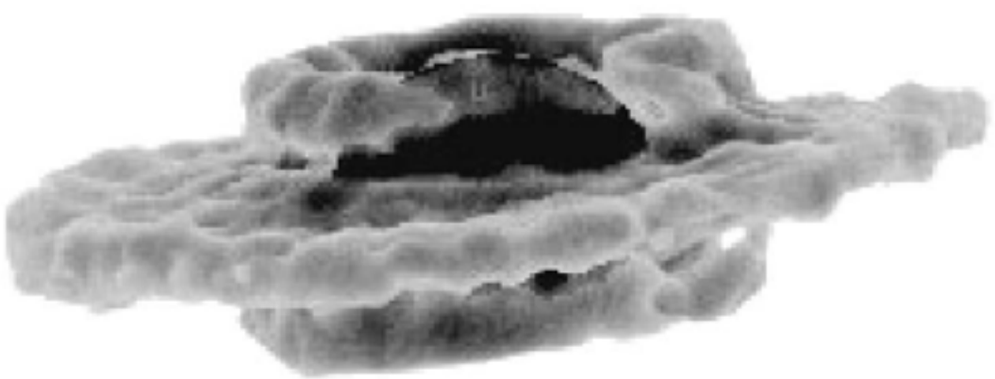
- Magnetospheric dynamics, time variability.
- Electron acceleration & transport processes:

  pitch angle scattering, inward diffusion, effect of satellites, interaction with dust, losses ...

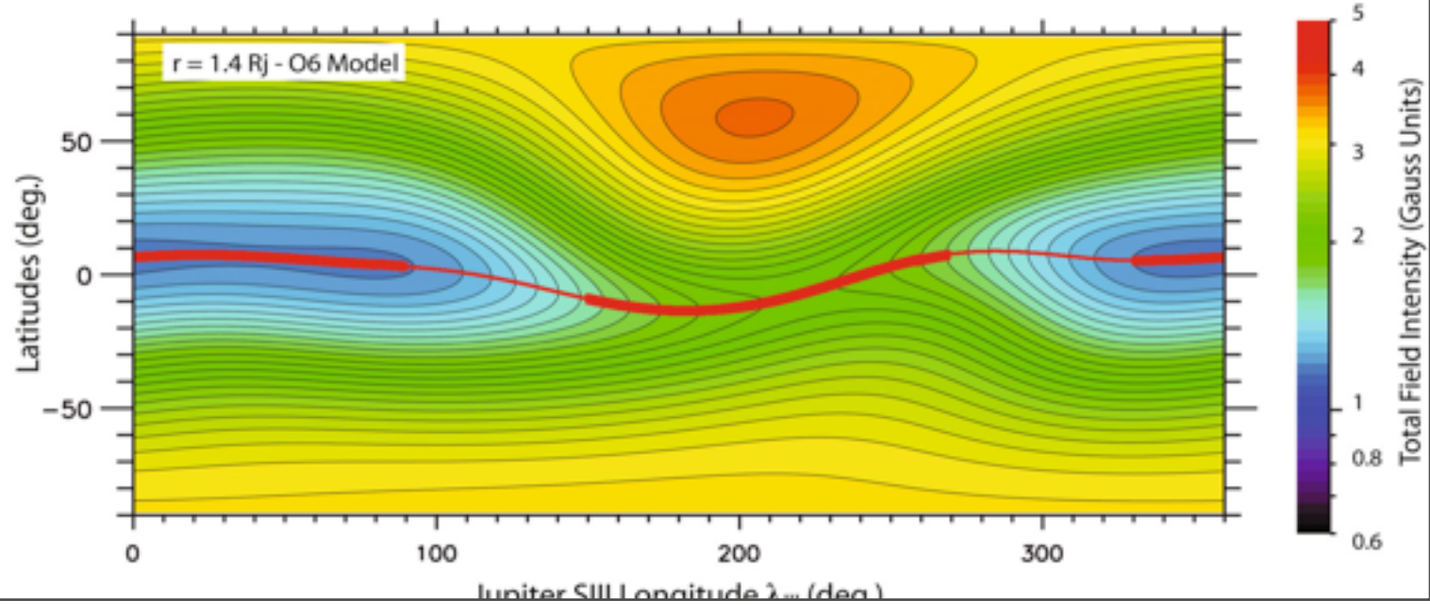
Modeling

- Comparison with models (Salammbô 3D)
- 3D reconstruction of B field by tomography
- Topology of multipolar B_{Jup} at low latitudes close to the planet

[de Pater & Sault, 1998]



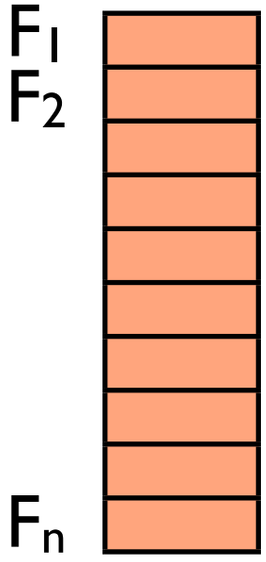
[Connerney et al., 1993 ; Santos-Costa, 2009]



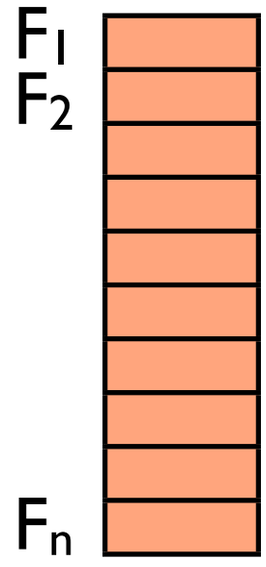
Planetary data processing

1 « standard » LOFAR observation = 2 datasets: Calibrator + Target sub-bands (SB)

Phase calibrator SBs



Target SBs



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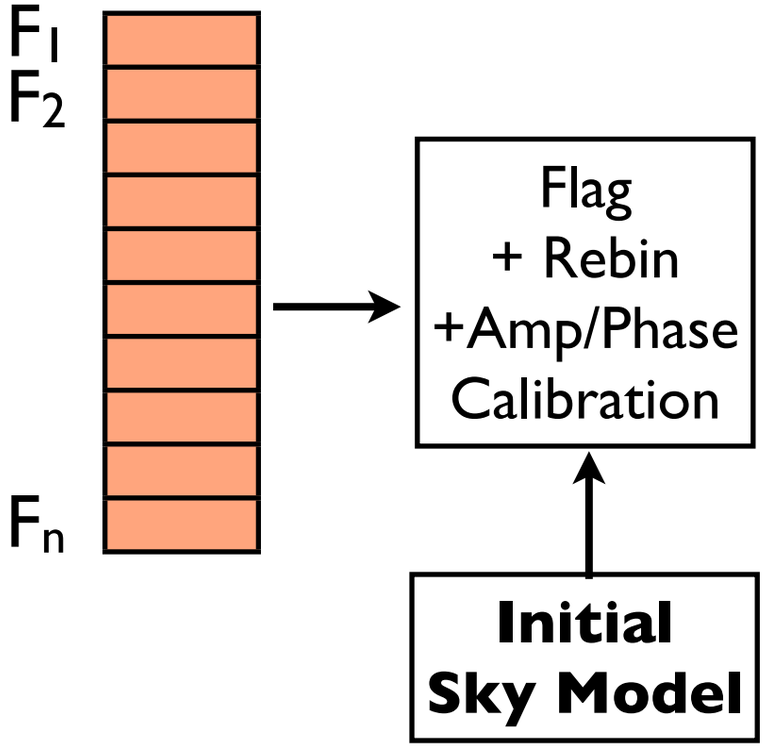
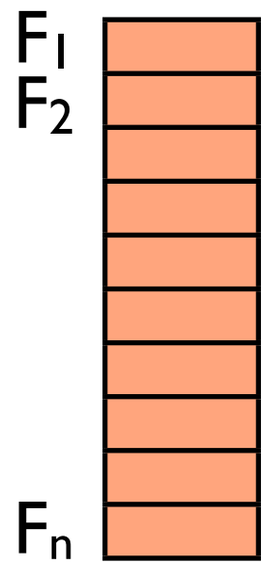


Target SBs

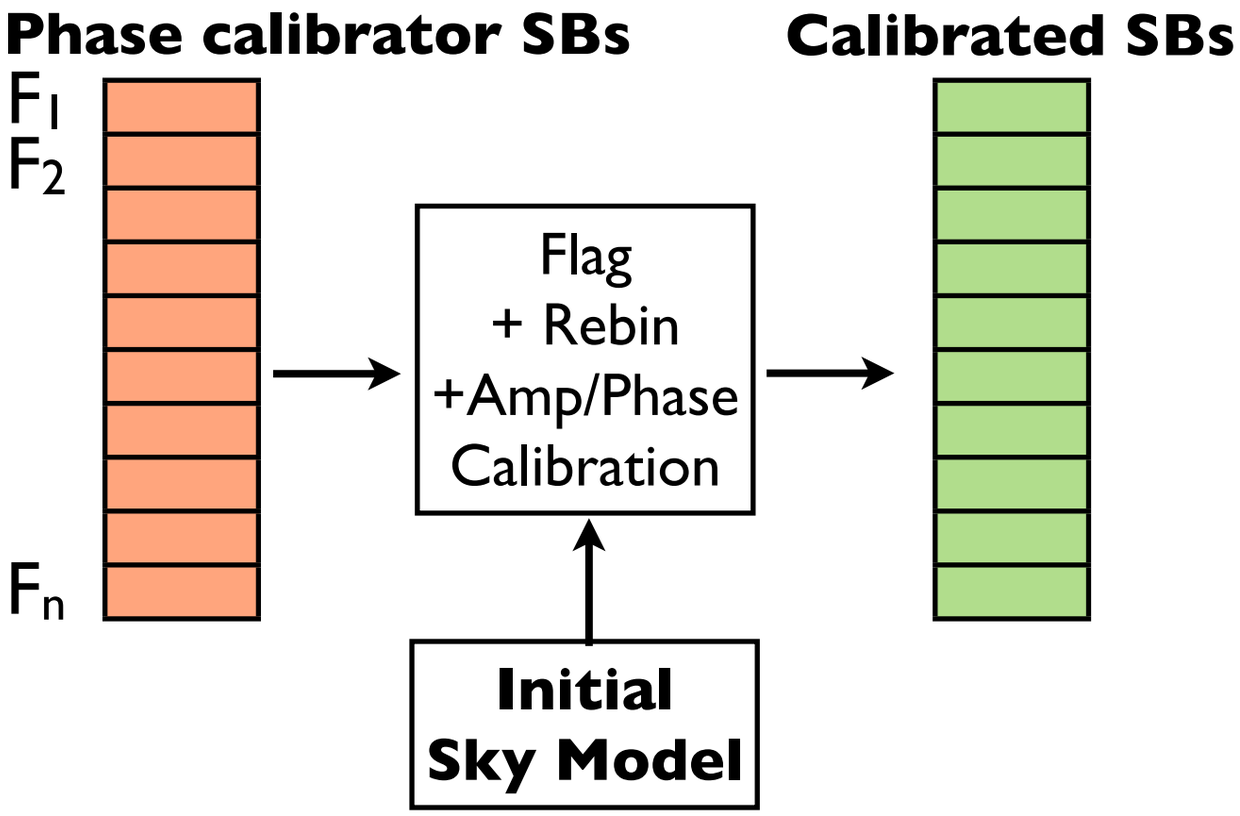


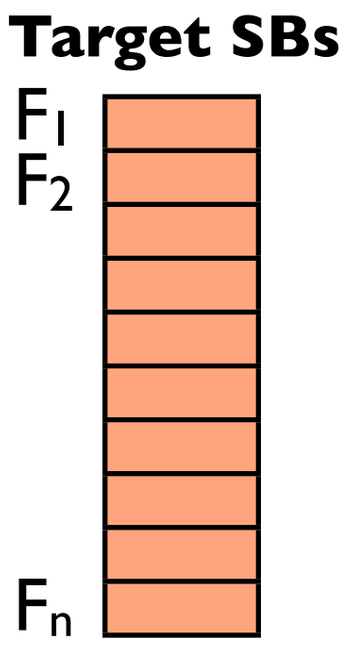
Planetary data processing

Cal

Target

1 « standard » LOFAR observation = 2 datasets: Calibrator + Target sub-bands (SB)





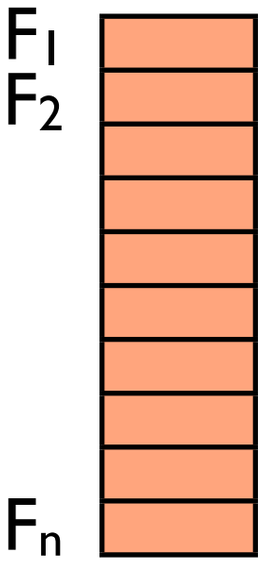
Planetary data processing

1 « standard » LOFAR observation = 2 datasets: Calibrator + Target sub-bands (SB)

Cal

Target

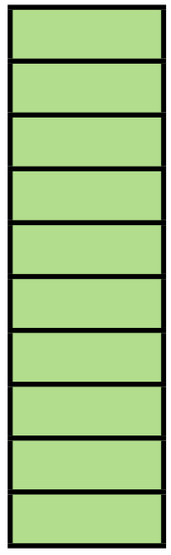
Phase calibrator SBs



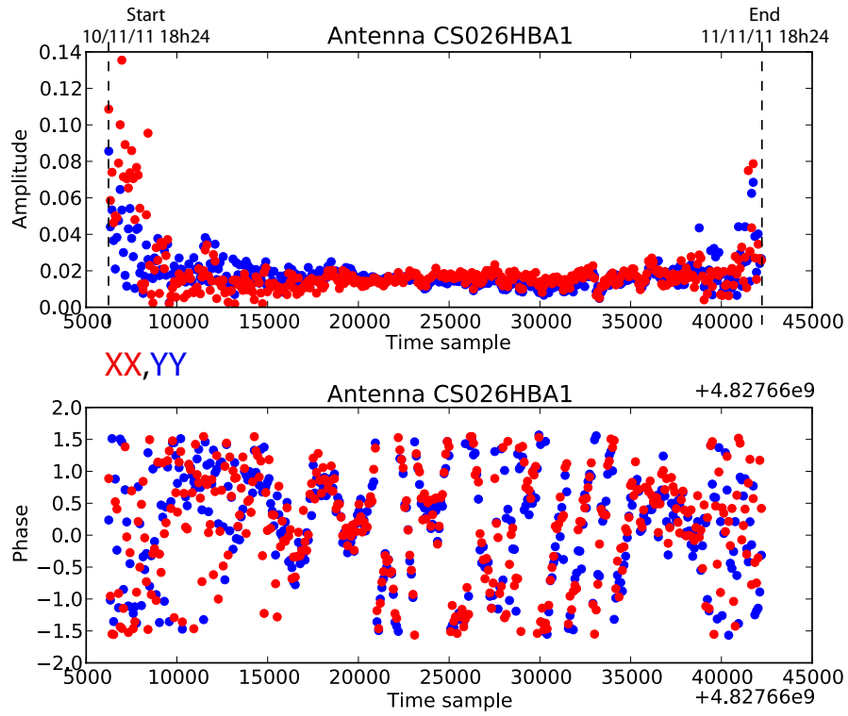
Flag
+ Rebin
+Amp/Phase
Calibration

Initial Sky Model

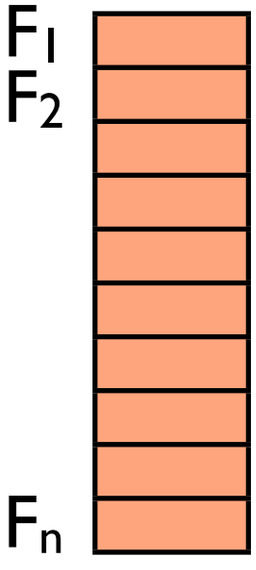
Calibrated SBs



Inspecting calibration solutions



Target SBs



Planetary data processing

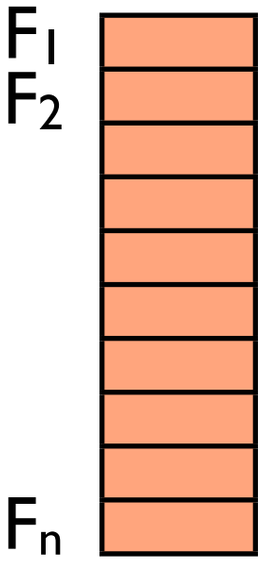
1 « standard » LOFAR observation = 2 datasets: Calibrator + Target sub-bands (SB)

Cal

Target

Inspecting calibration solutions

Phase calibrator SBs



Flag
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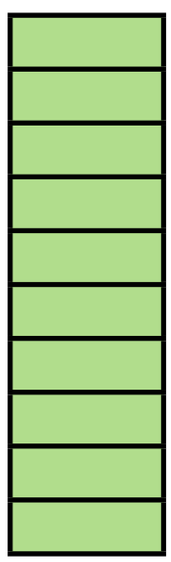
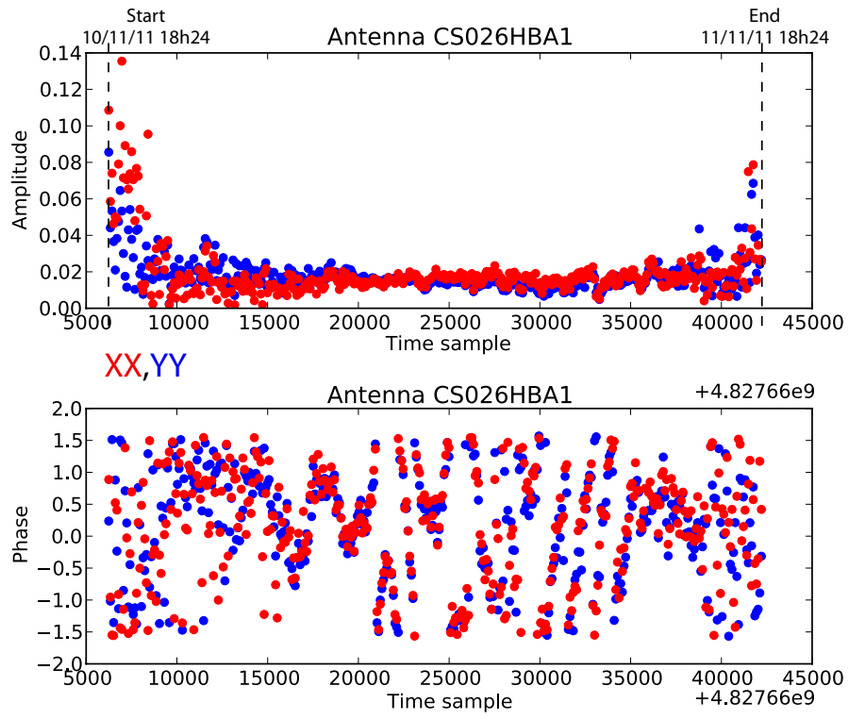
Calibration

Calibrated SBs





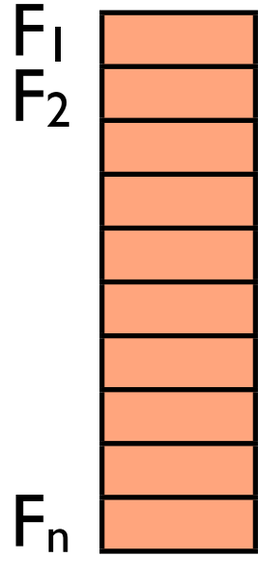
Imaging

New Sky Model

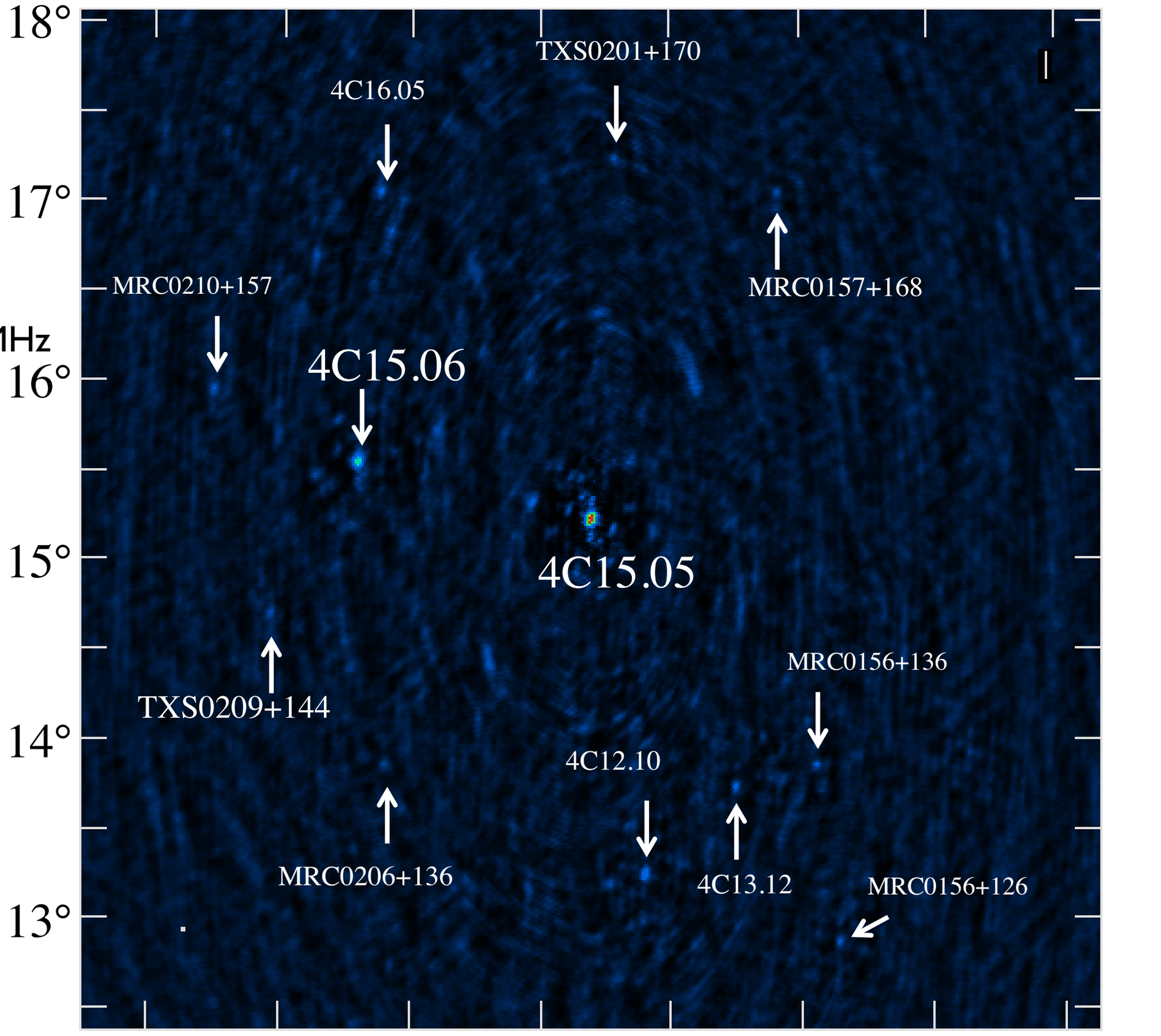
Initial Sky Model

Online catalogs

Target SBs



- 4C15.05
  6.5 Jy @ 160 MHz
- Other sources
  ~1-5 Jy



Planetary data processing

1 « standard » LOFAR observation = 2 datasets: Calibrator + Target sub-bands (SB)

Cal

Target

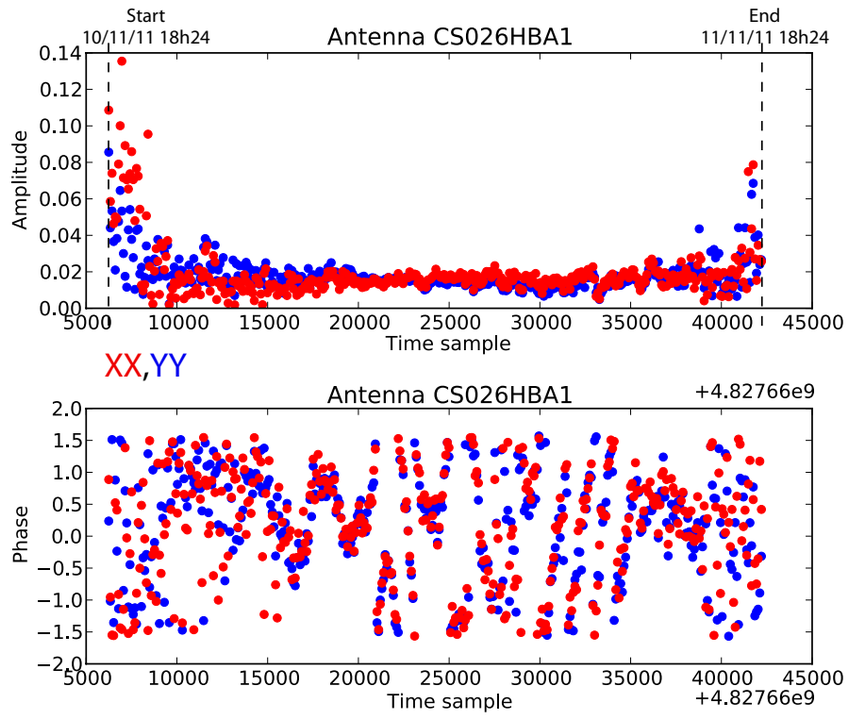
Phase calibrator SBs

F_1
F_2
F_n

Flag
+ Rebin
+Amp/Phase
Calibration

Calibrated SBs

Inspecting calibration solutions



Imaging

New Sky Model

Initial Sky Model

Online catalogs

Target SBs

F_1
F_2
F_n

Planetary data processing

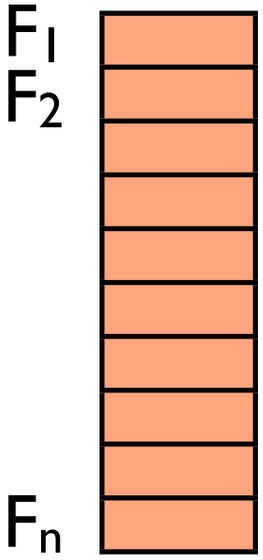
1 « standard » LOFAR observation = 2 datasets: Calibrator + Target sub-bands (SB)

Cal

Target

Inspecting calibration solutions

Phase calibrator SBs



Flag
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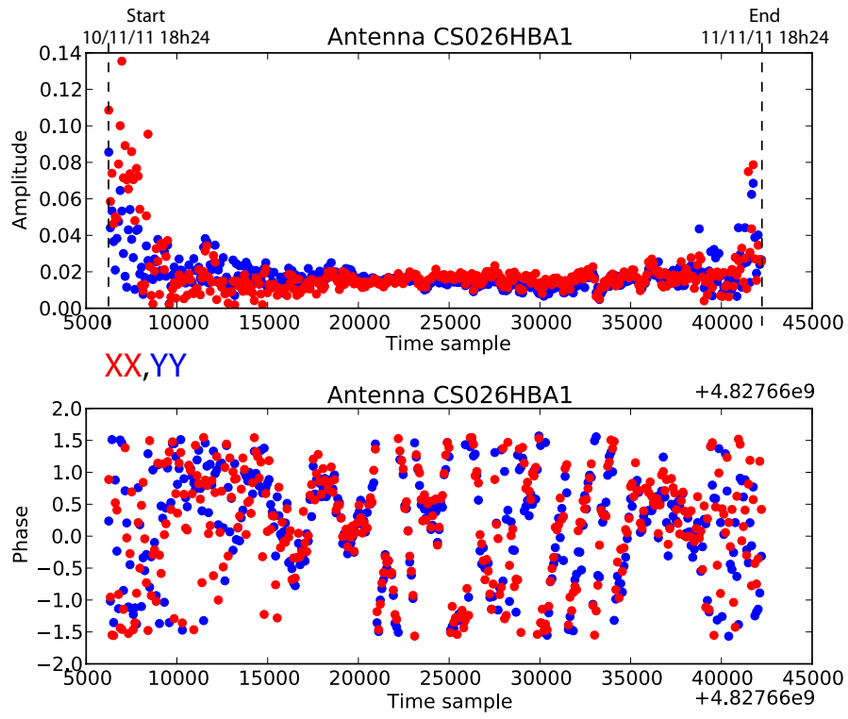
+Amp/Phase
Calibration

Calibrated SBs



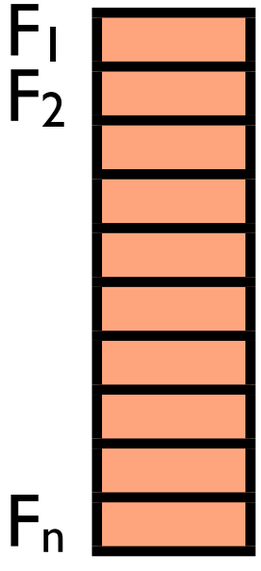
Imaging

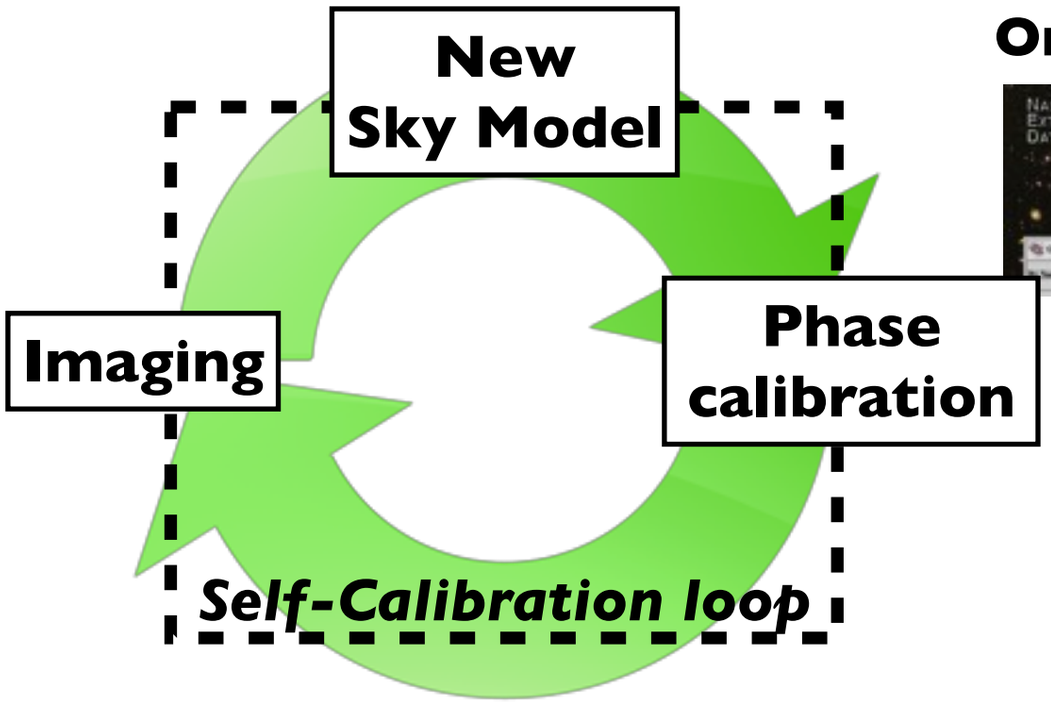
New Sky Model

Initial Sky Model

Online catalogs

Target SBs





Planetary data processing

1 « standard » LOFAR observation = 2 datasets: Calibrator + Target sub-bands (SB)

Cal

Target

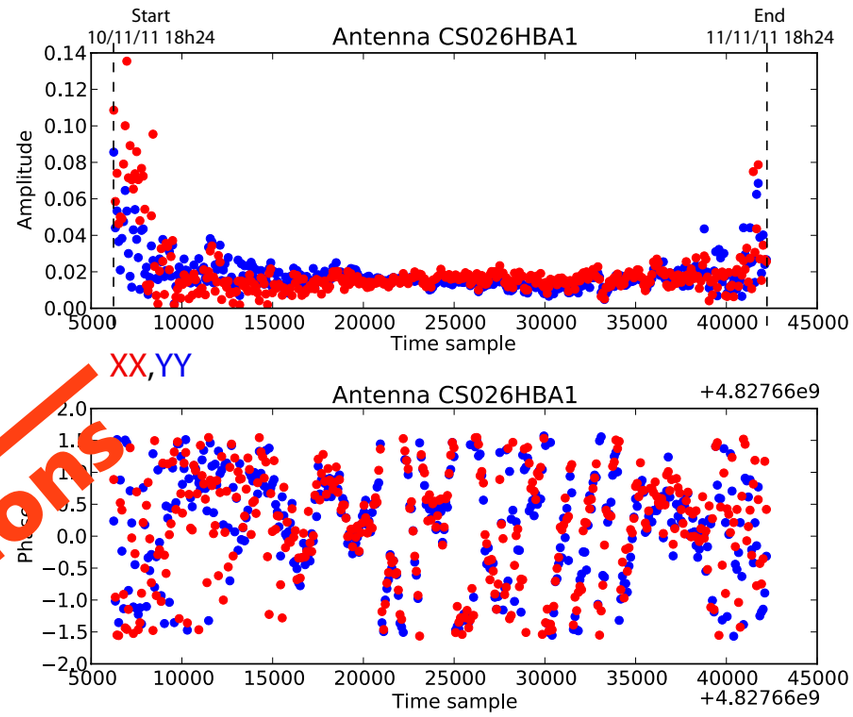
Inspecting calibration solutions

Phase calibrator SBs

F_1
F_2
F_n

Flag
+ Rebin
+Amp/Phase
Calibration

Calibrated SBs



Imaging

New Sky Model

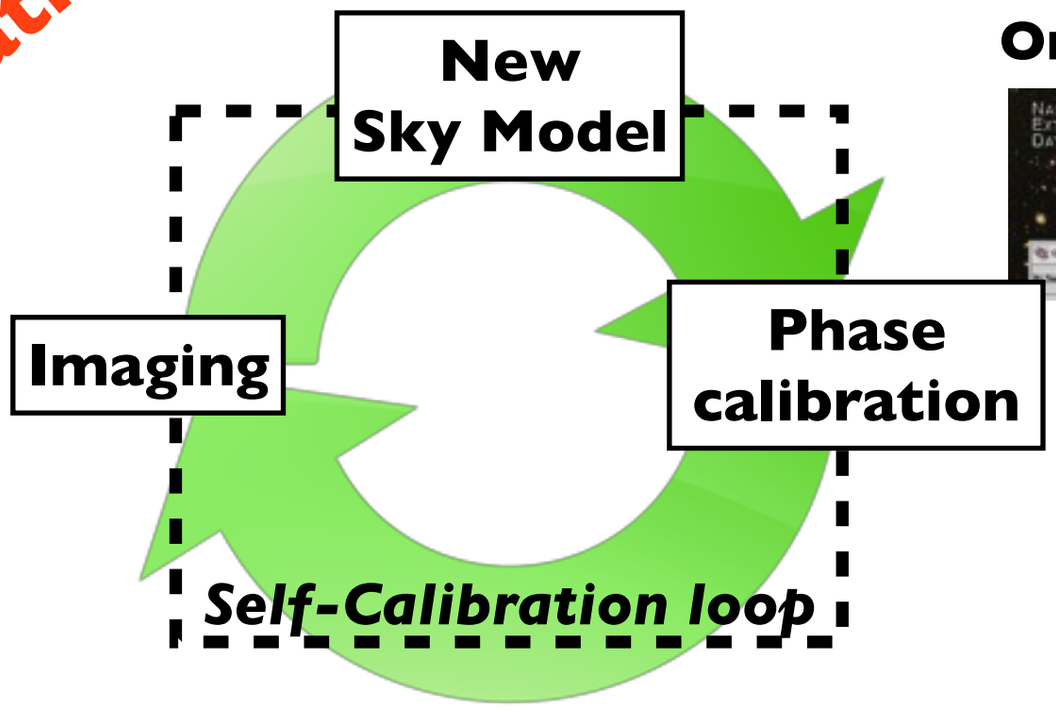
Initial Sky Model

Transfer calibration solutions

Online catalogs

Target SBs

F_1
F_2
F_n



Planetary data processing (cont'd)

Target SBs

Planetary data processing (cont'd)

18h-20h

30’

25’

20’

NVSS source

Jupiter

11°14’00’’

10’

05’

PSF

Declination

45s 30s 15s 07m00s 2h06m45s 30s 15s 00s 05m45s

Right ascension

20h-22h

Declination

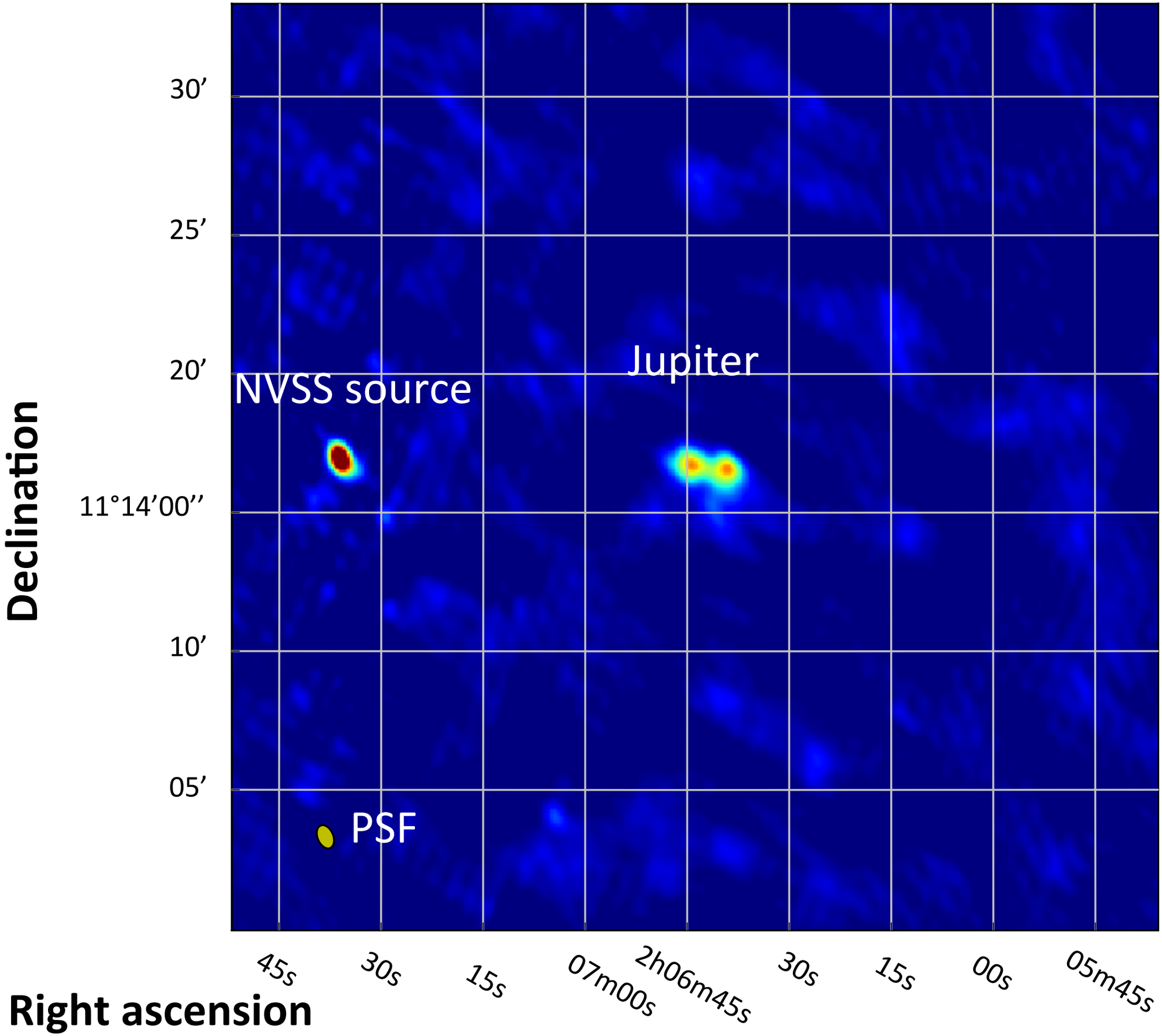
30’
25’
20’
11°14’00’’
10’
05’

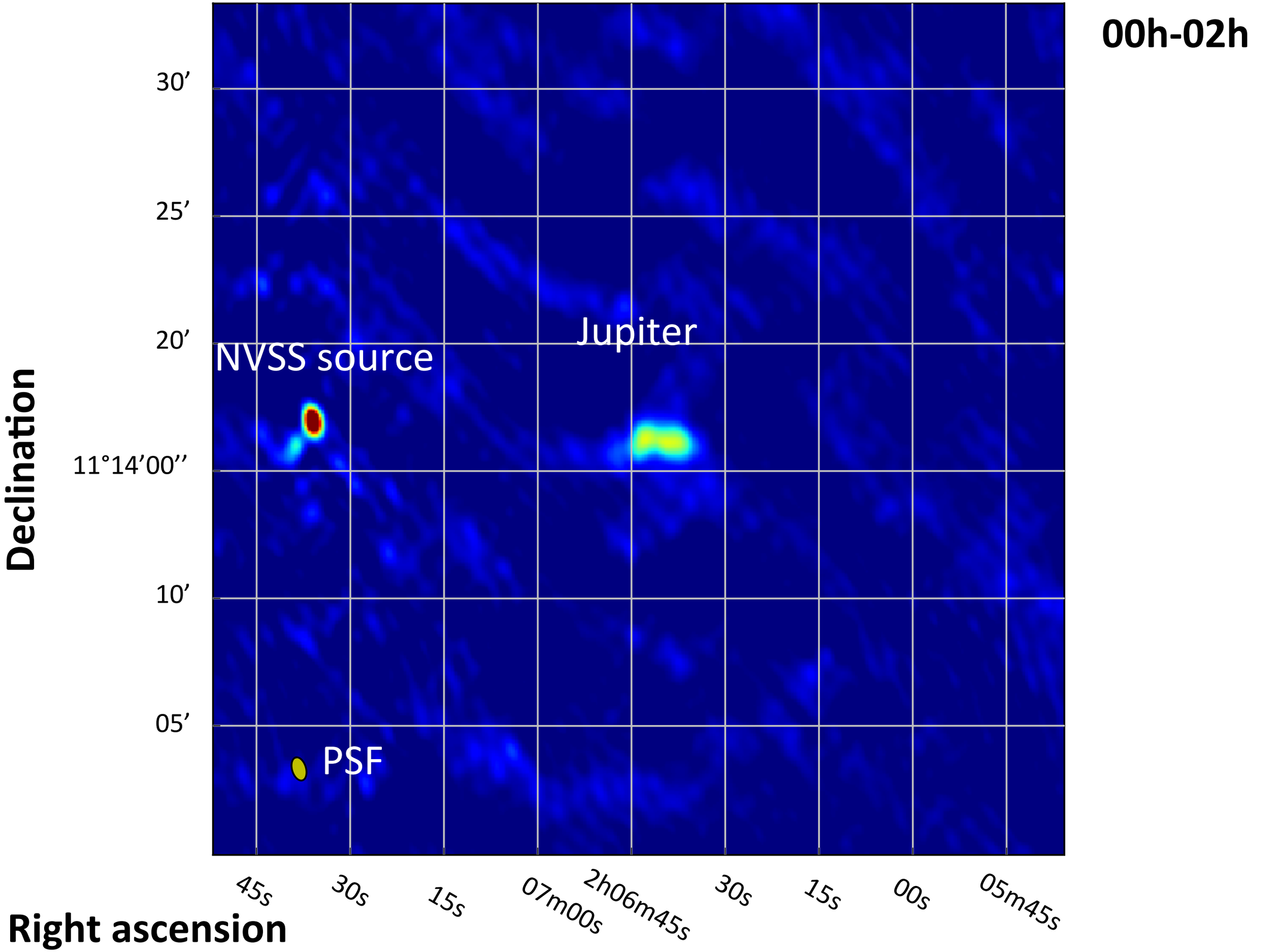
NVSS source
Jupiter
PSF

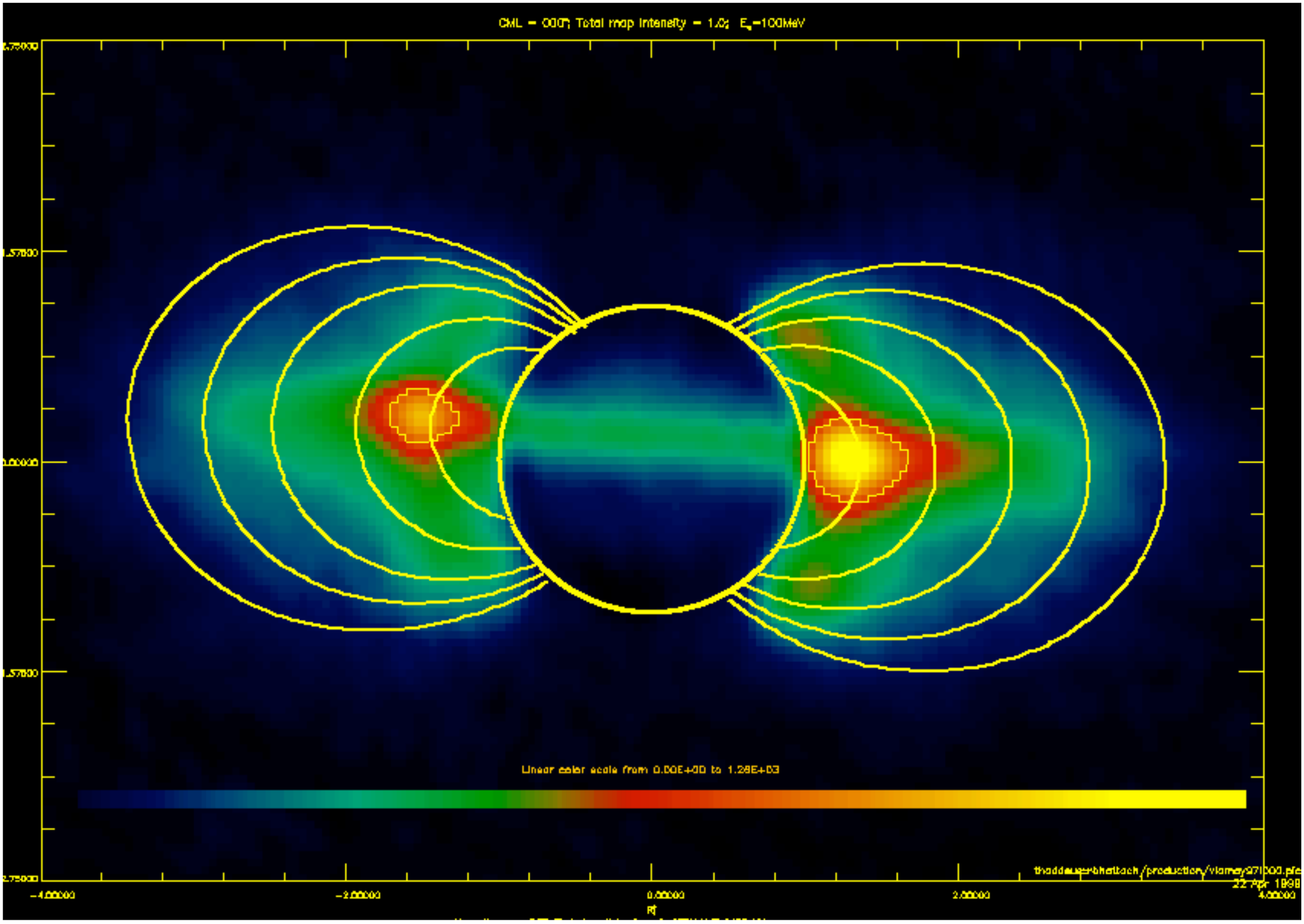
45s 30s 15s 07m00s 2h06m45s 30s 15s 00s 05m45s

Right ascension

22h-00h


30’
25’
20’
11°14’00’’
10’
05’
NVSS source
Jupiter
PSF
45s
30s
15s
07m00s
2h06m45s
30s
15s
00s
05m45s
Declination
Right ascension


00h-02h
30’
25’
20’
11°14’00’’
10’
05’
Declination
NVSS source
Jupiter
PSF
45s
30s
15s
07m00s
2h06m45s
30s
15s
00s
05m45s
Right ascension

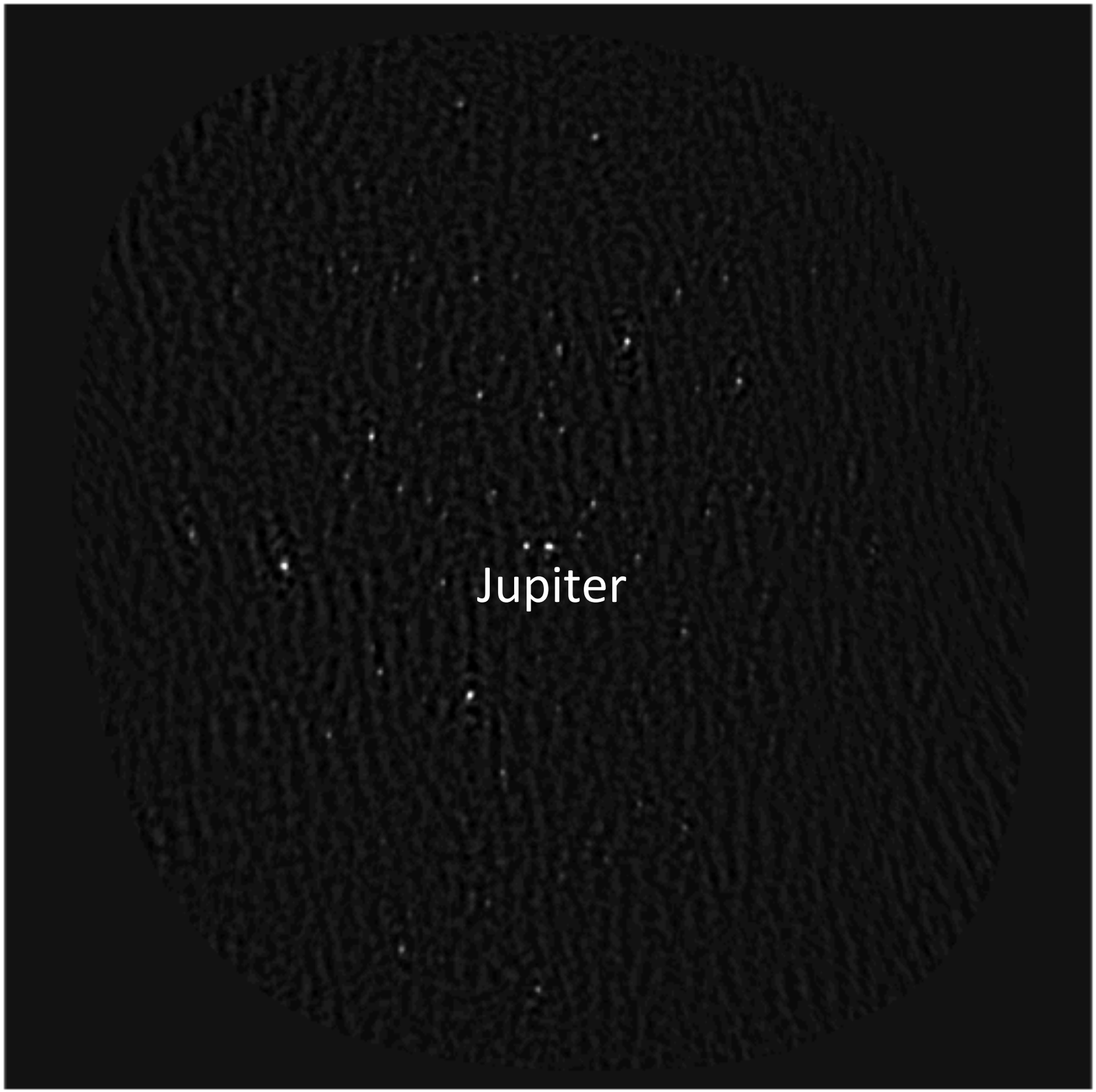


[Levin et al., 2001] http://juno.wisc.edu/science_magnetosphere.html

other sources

SB30-39

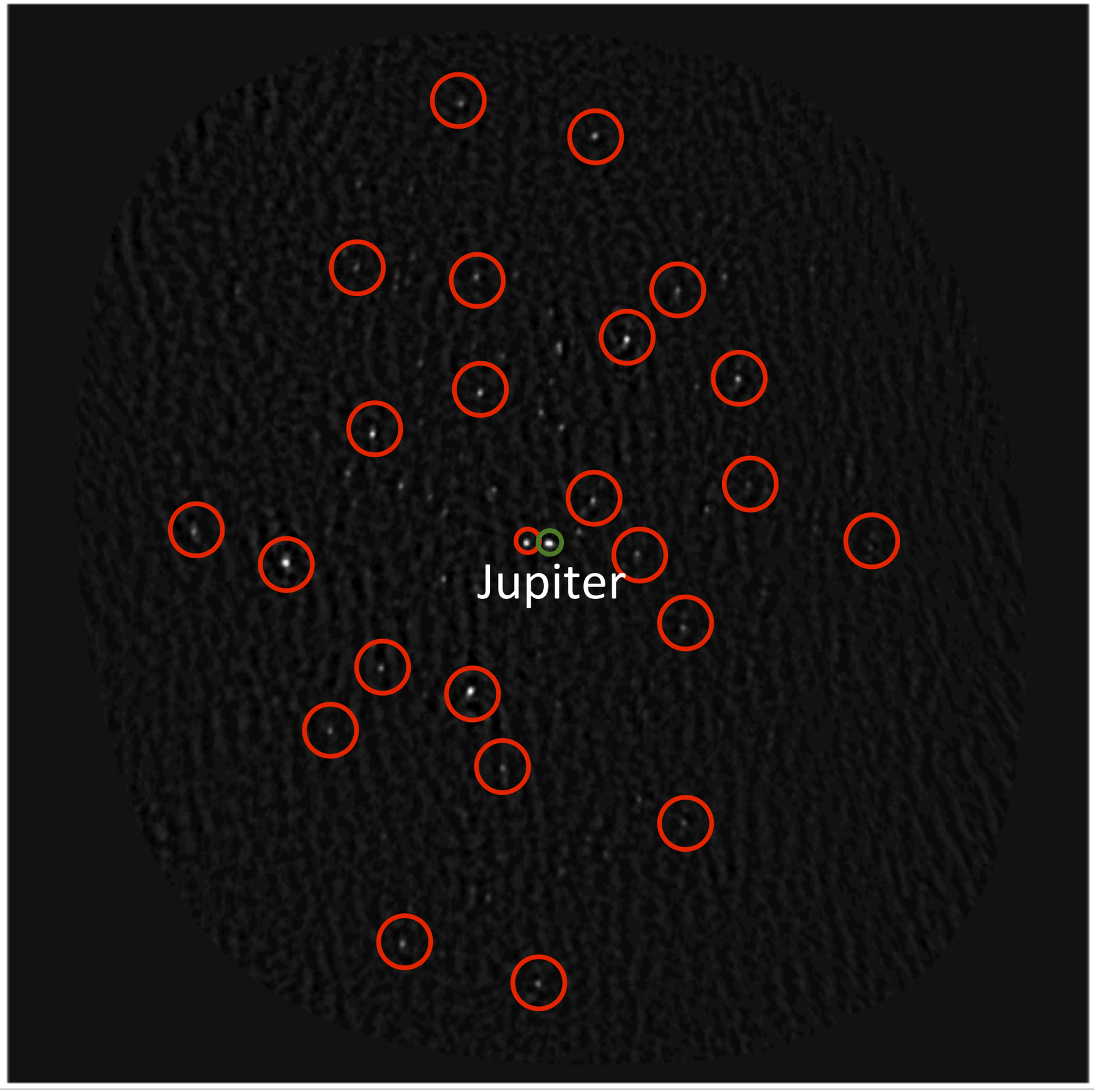
10°x10°

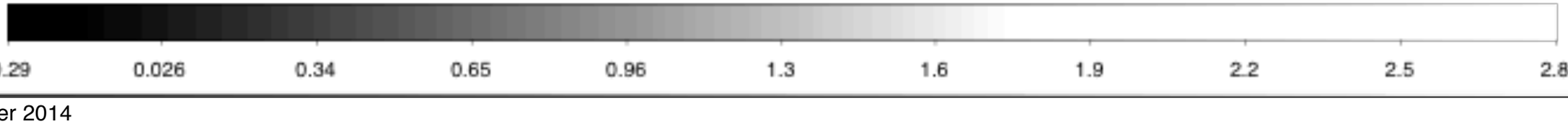


other sources

SB30-39

10°x10°

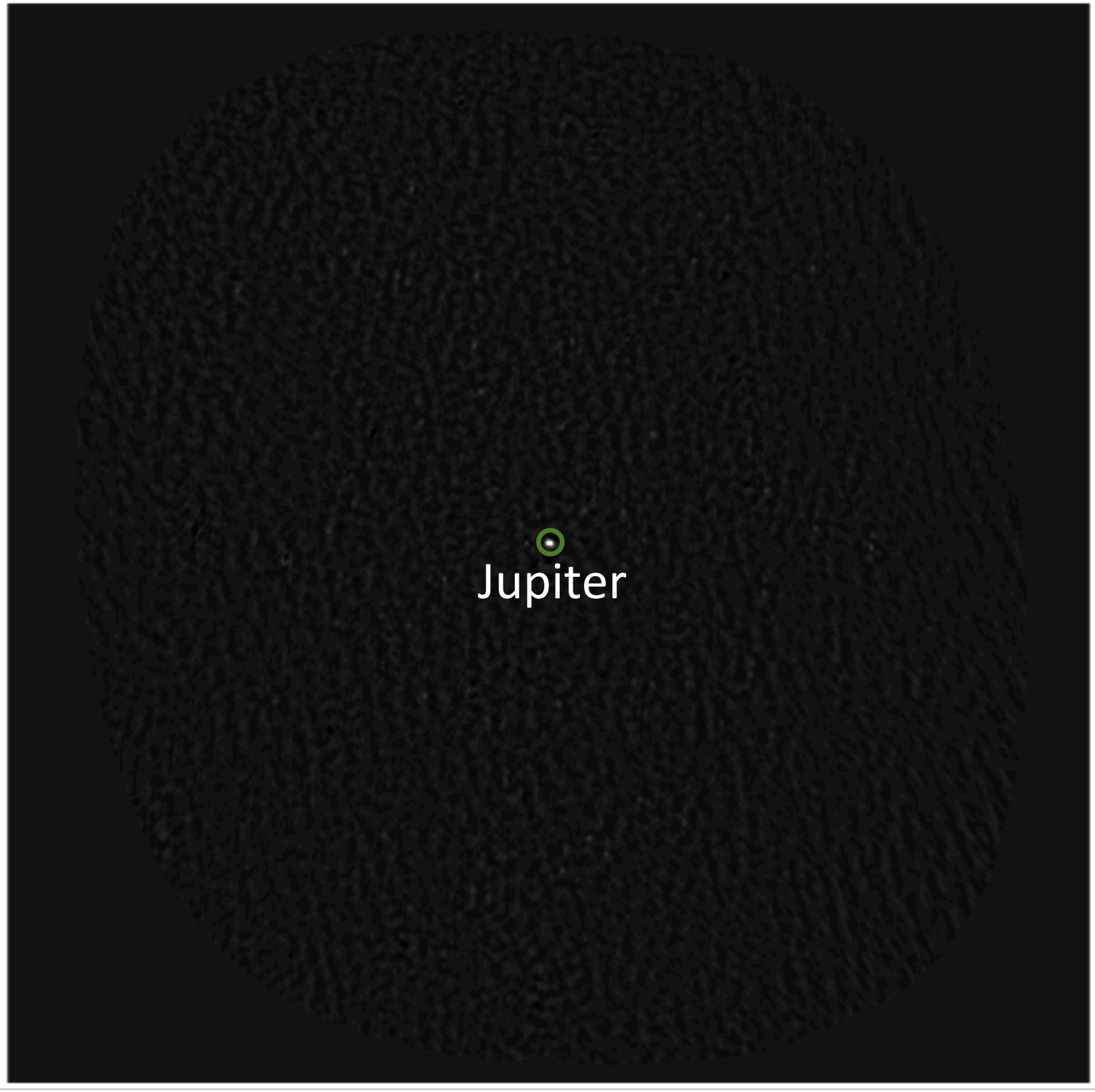




other sources

SB30-39

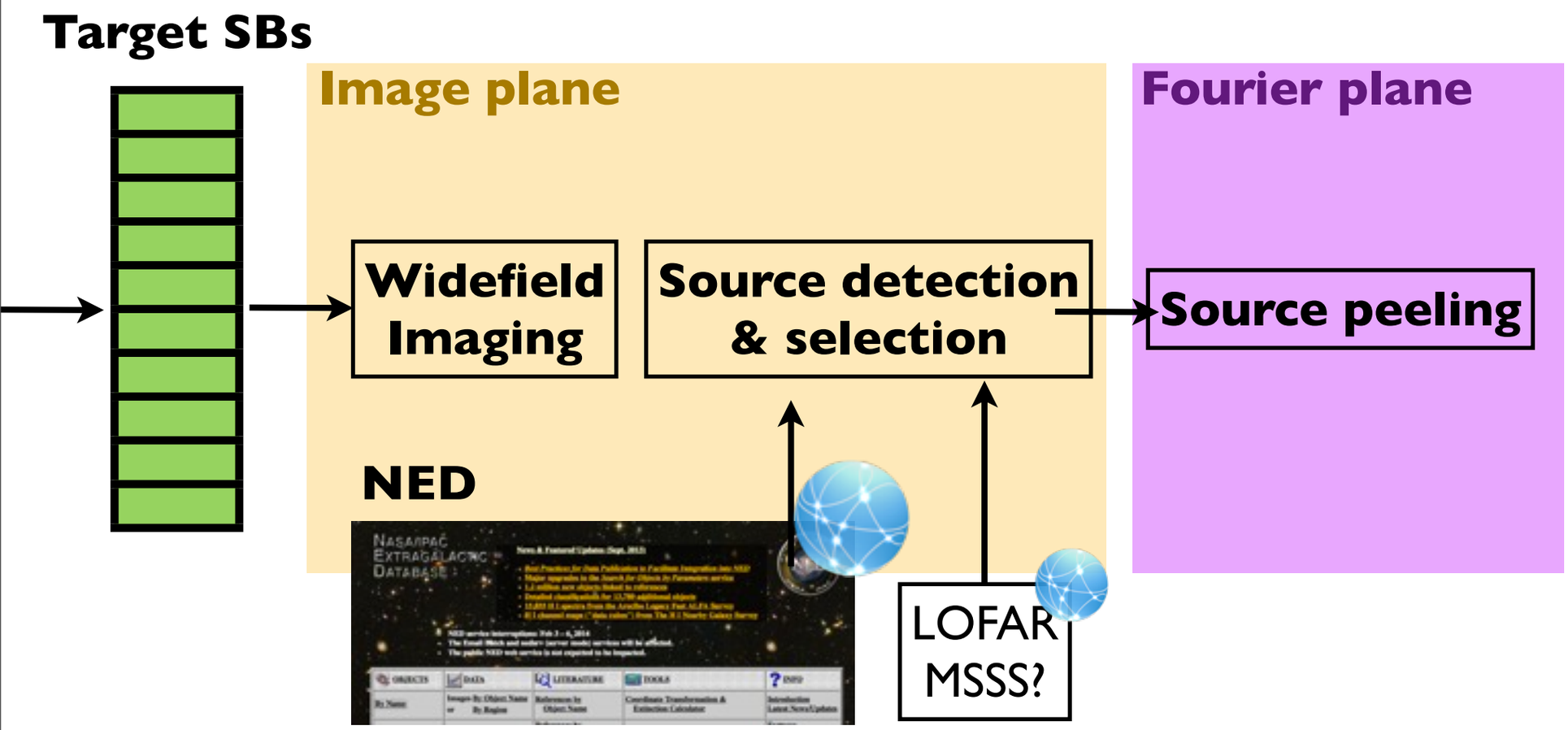
10°x10°



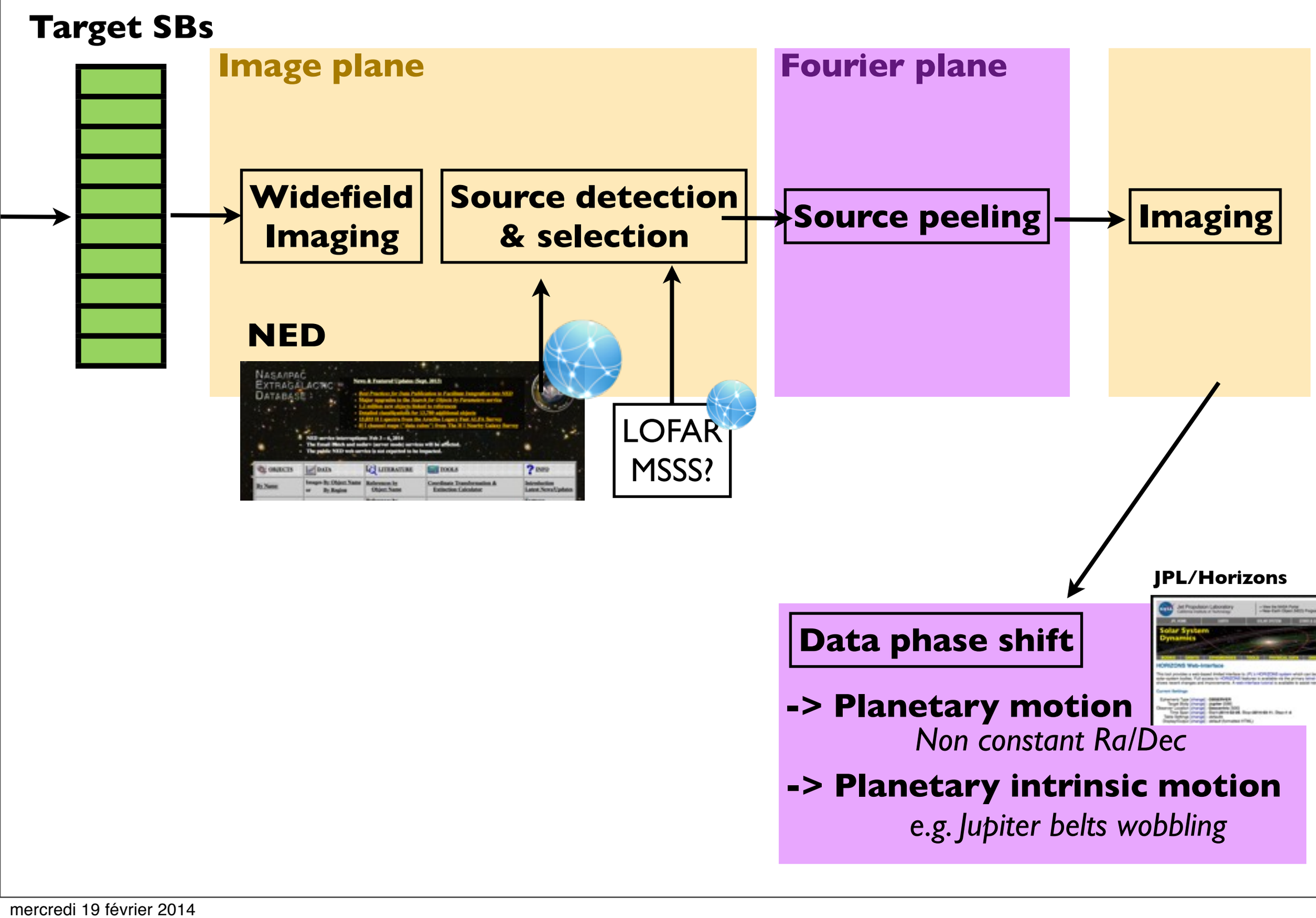
Planetary data processing (cont'd)

Target SBs

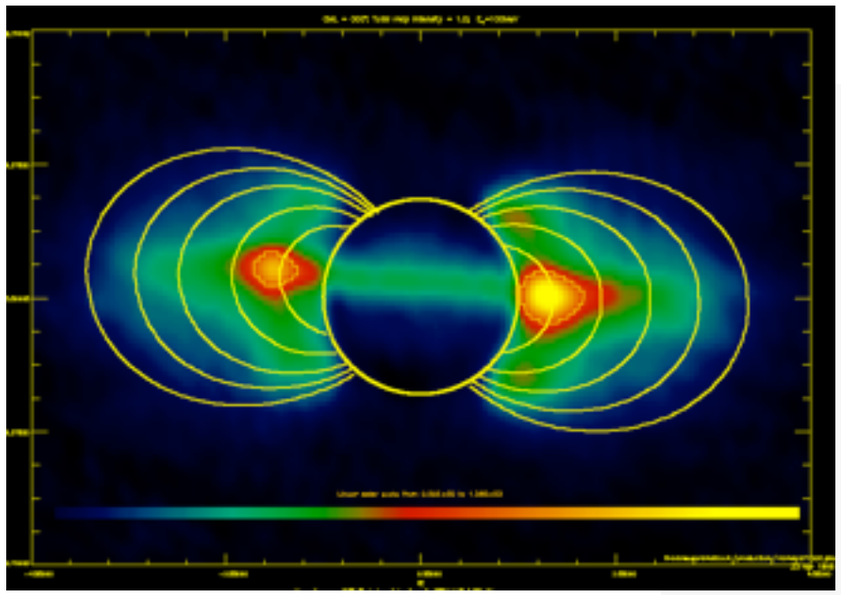
Planetary data processing (cont'd)



Planetary data processing (cont'd)



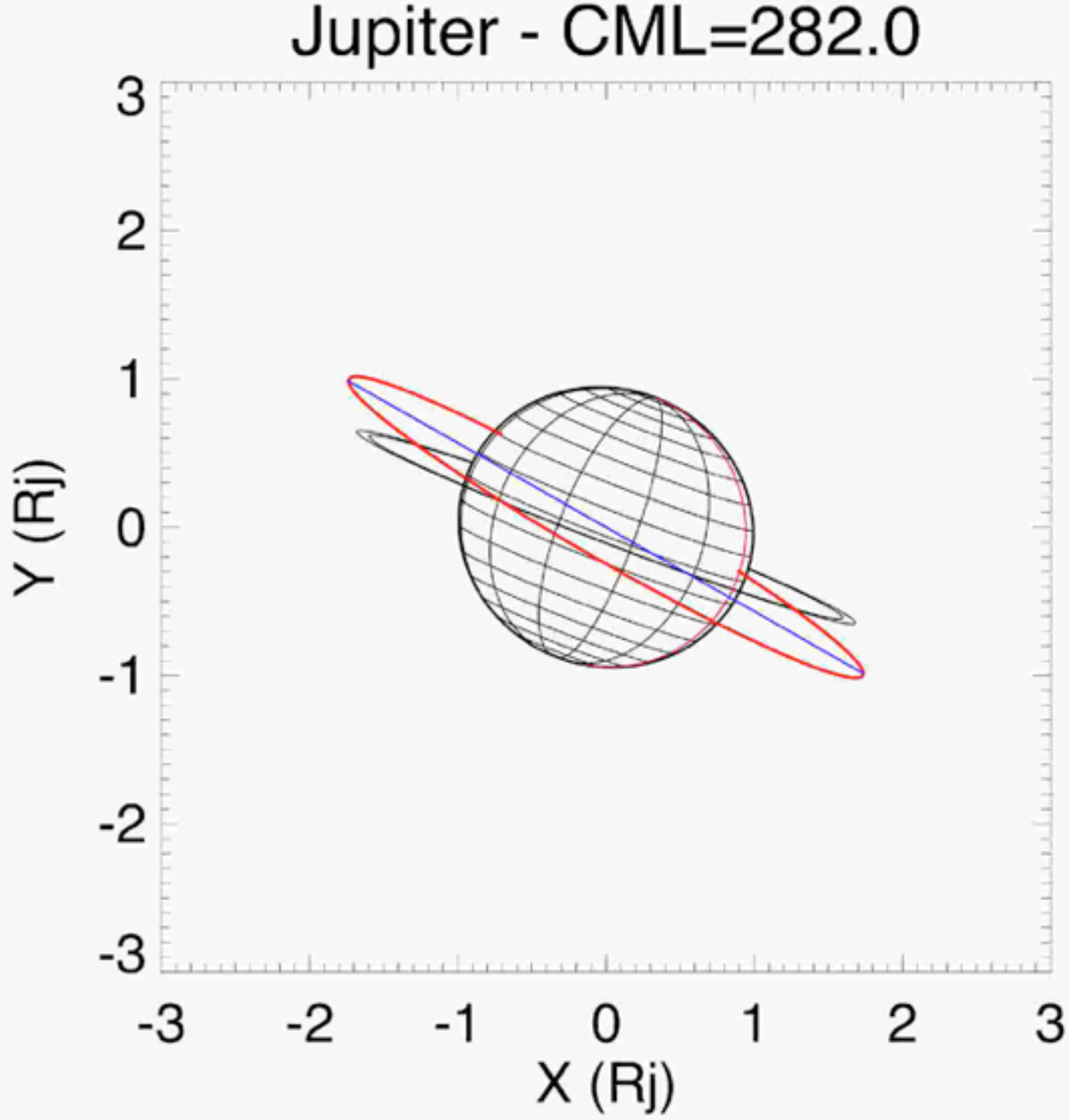
Planetary data processing (cont'd)



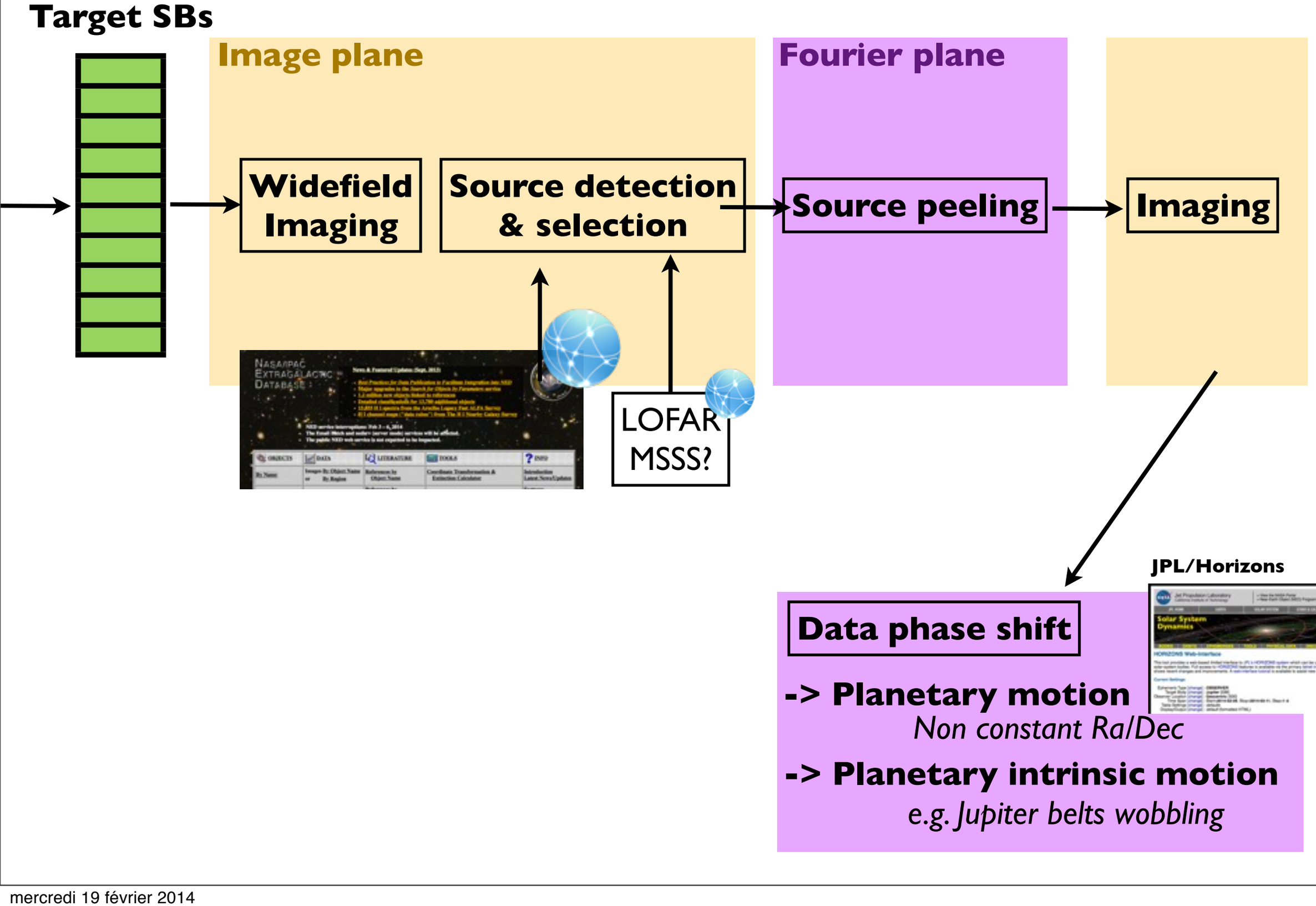
Magnetic equator

Mean direction

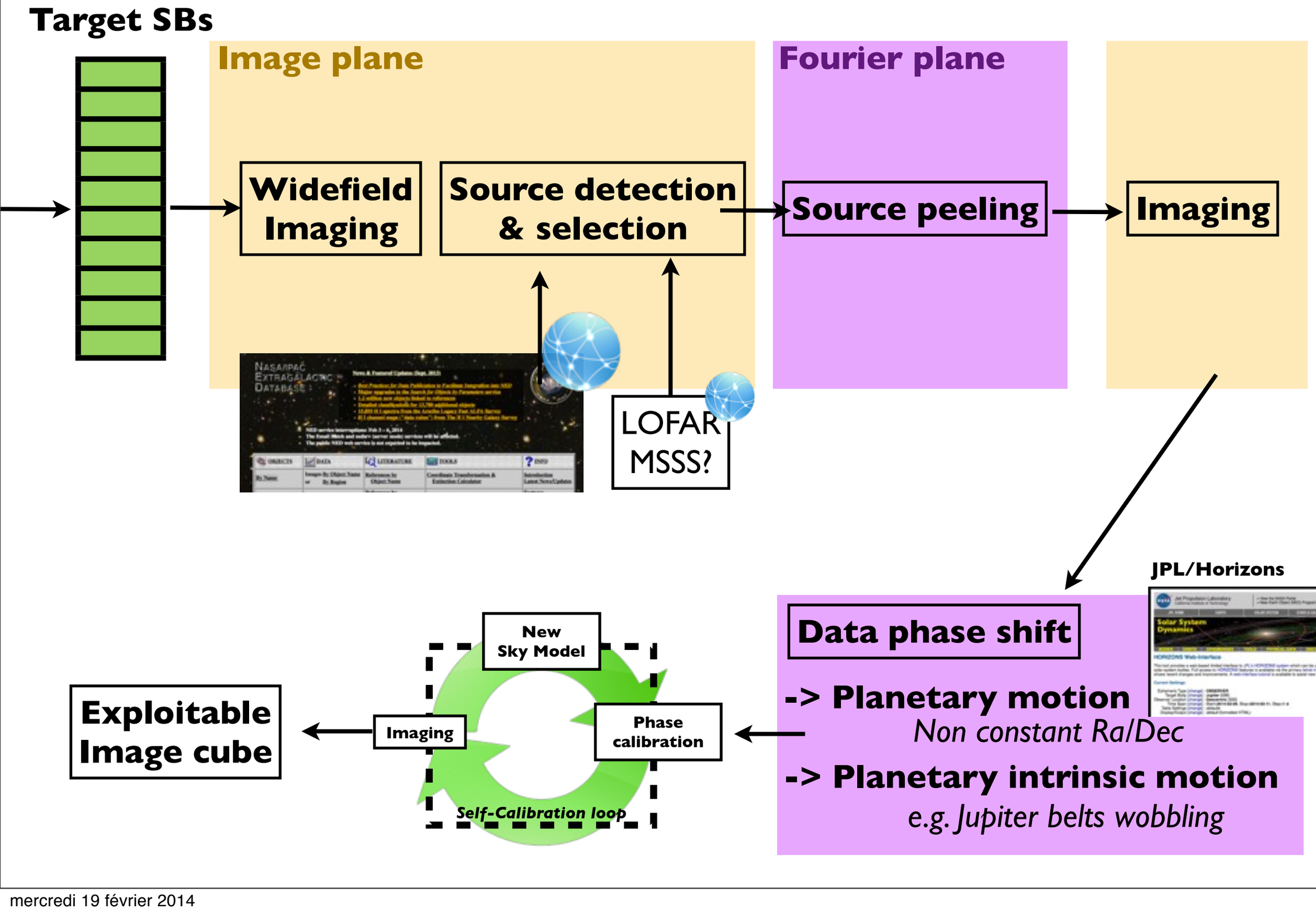
Observer longitude



Planetary data processing (cont'd)



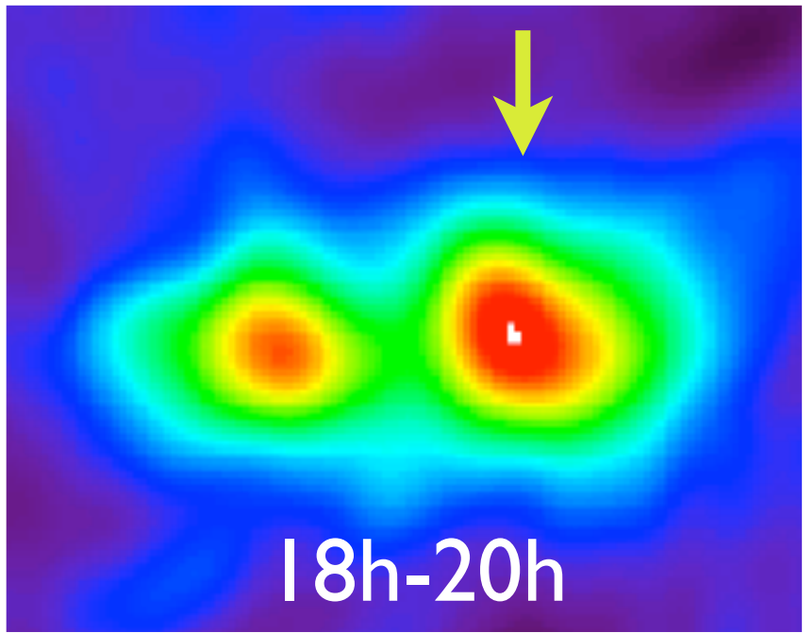
Planetary data processing (cont'd)

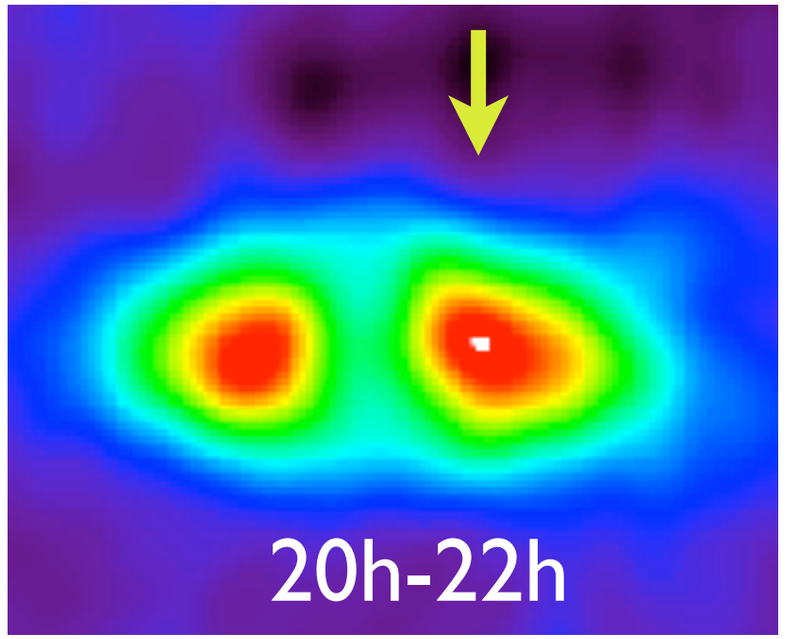


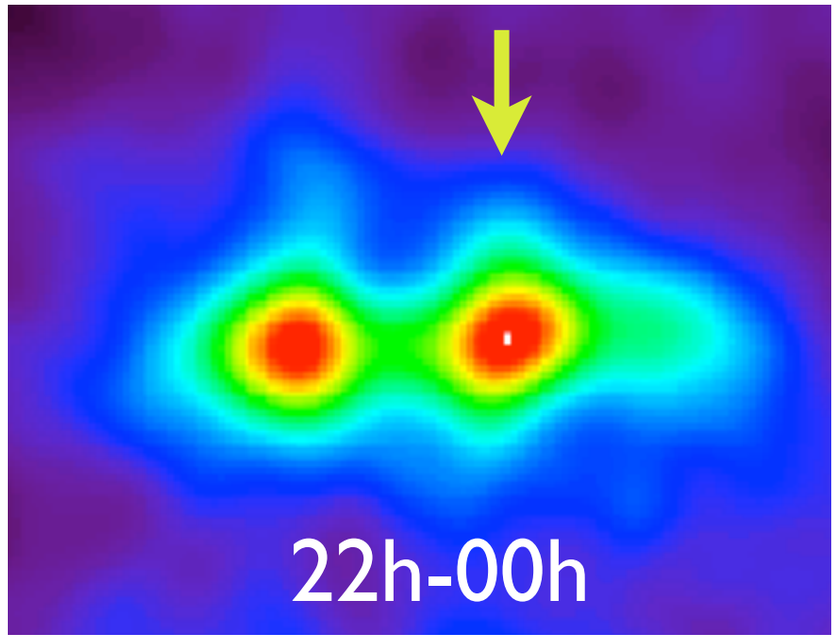
Results

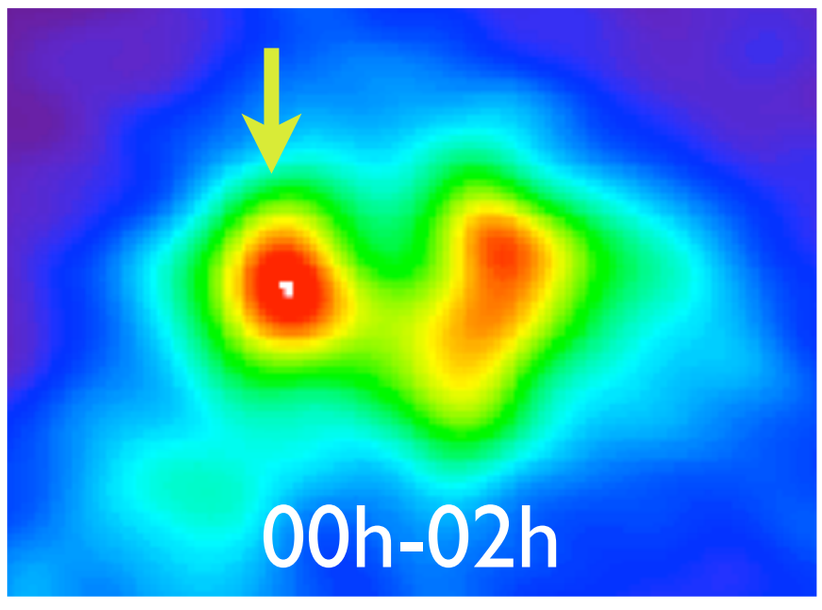
2-hour & Frequency averaged images

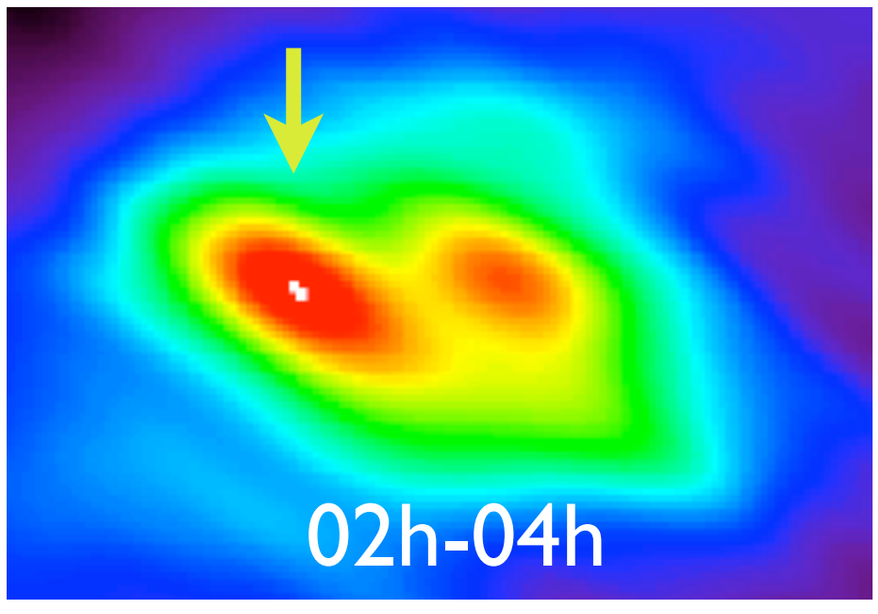
Δf = 127-172 MHz, Δt = 2h, uv= 0-15 kλ corrected from motion & wobble,
Beam = 17.8”x15.5”, Pixel = 2", Jupiter disk = 49”







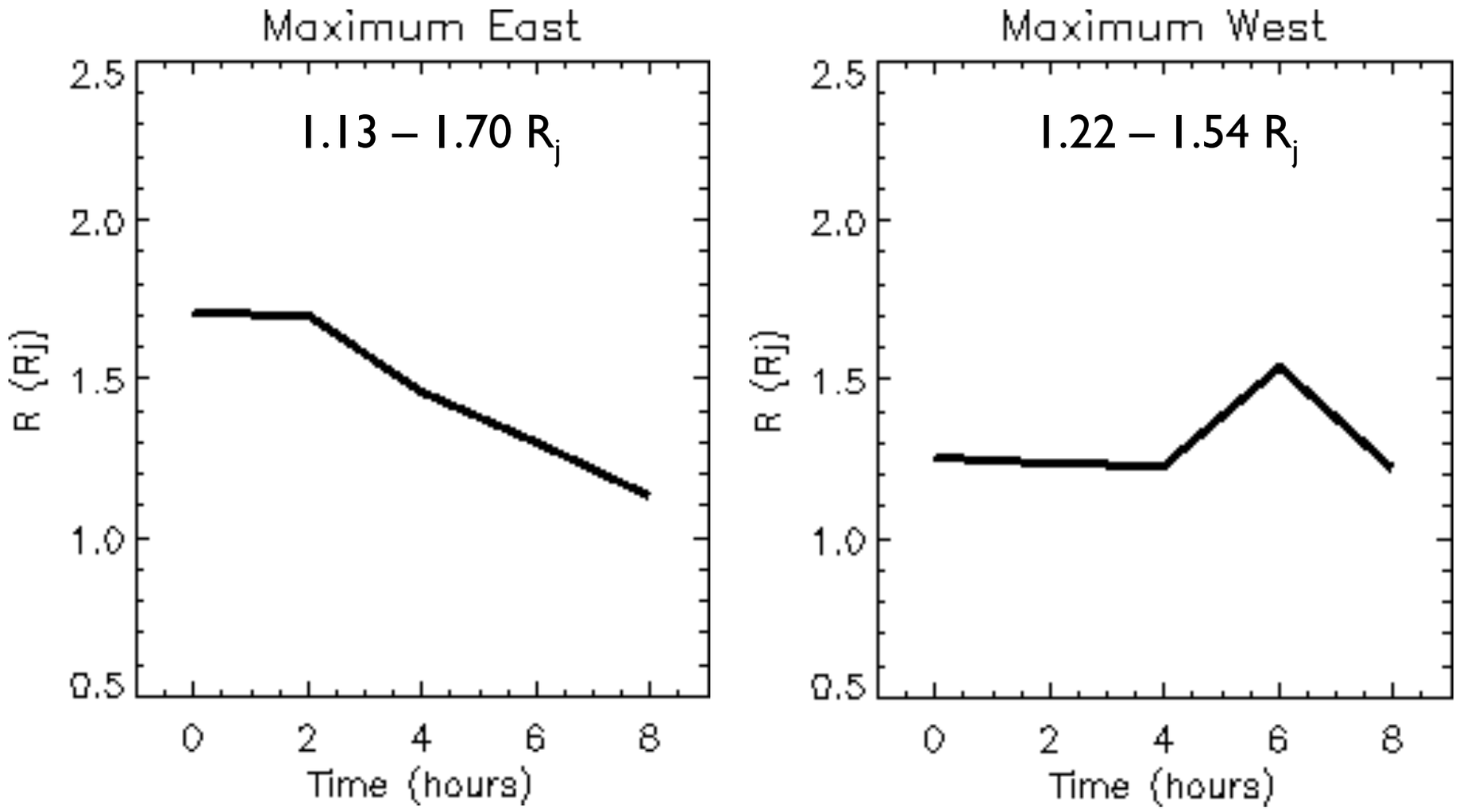




distortion (low elevation)

Results

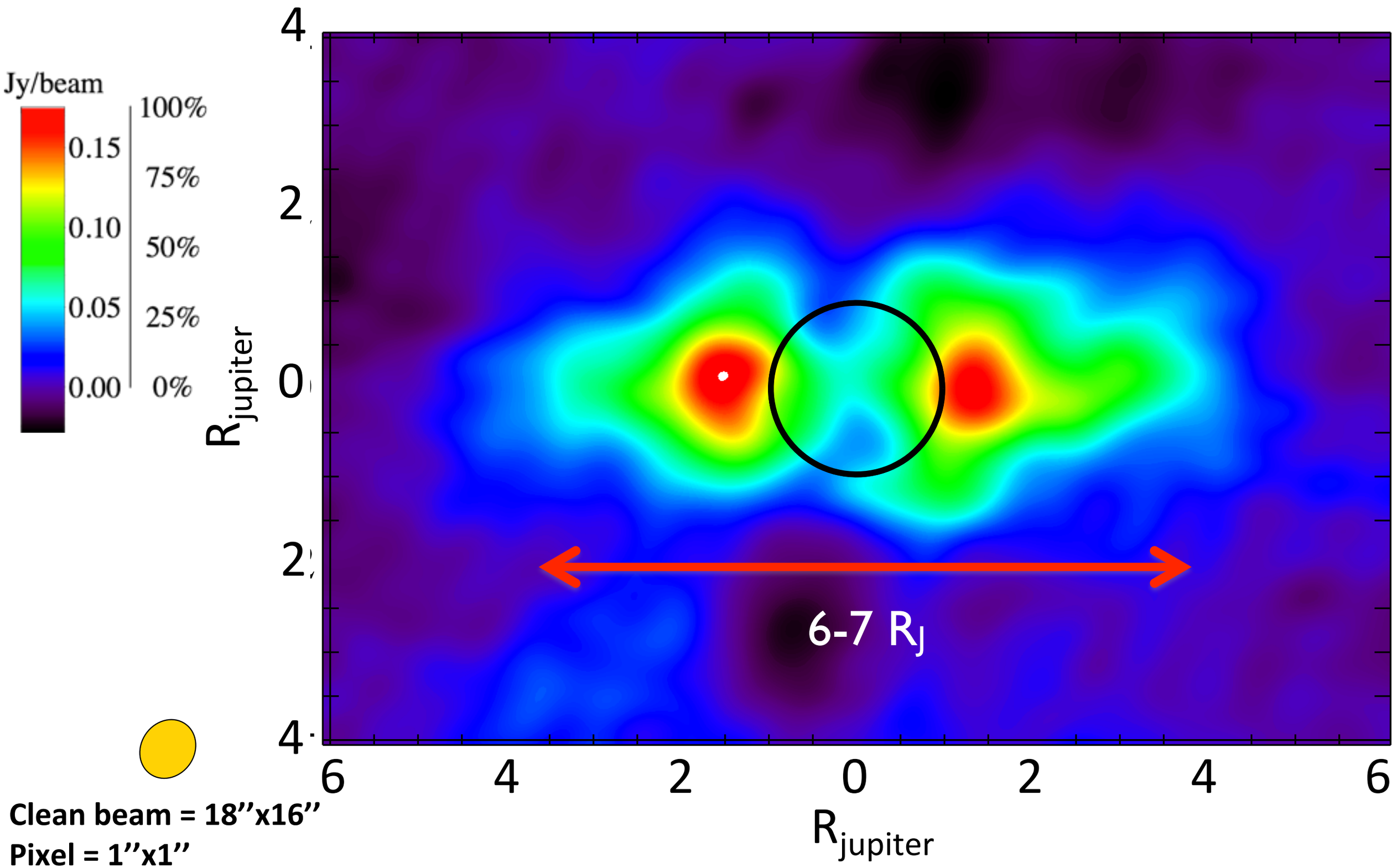
E & W peaks location on 2-hr time integrated images



Consistent with radial excursions measured at HF (e.g. ~ 0.25 R_j from 1.45 to 1.7 R_j)
[Dulk et al., 1997]

Resolved intensity maps

- **Integration over 127-172 MHz, Δt = (best) 7h, (u,v)= 0-15 kλ**

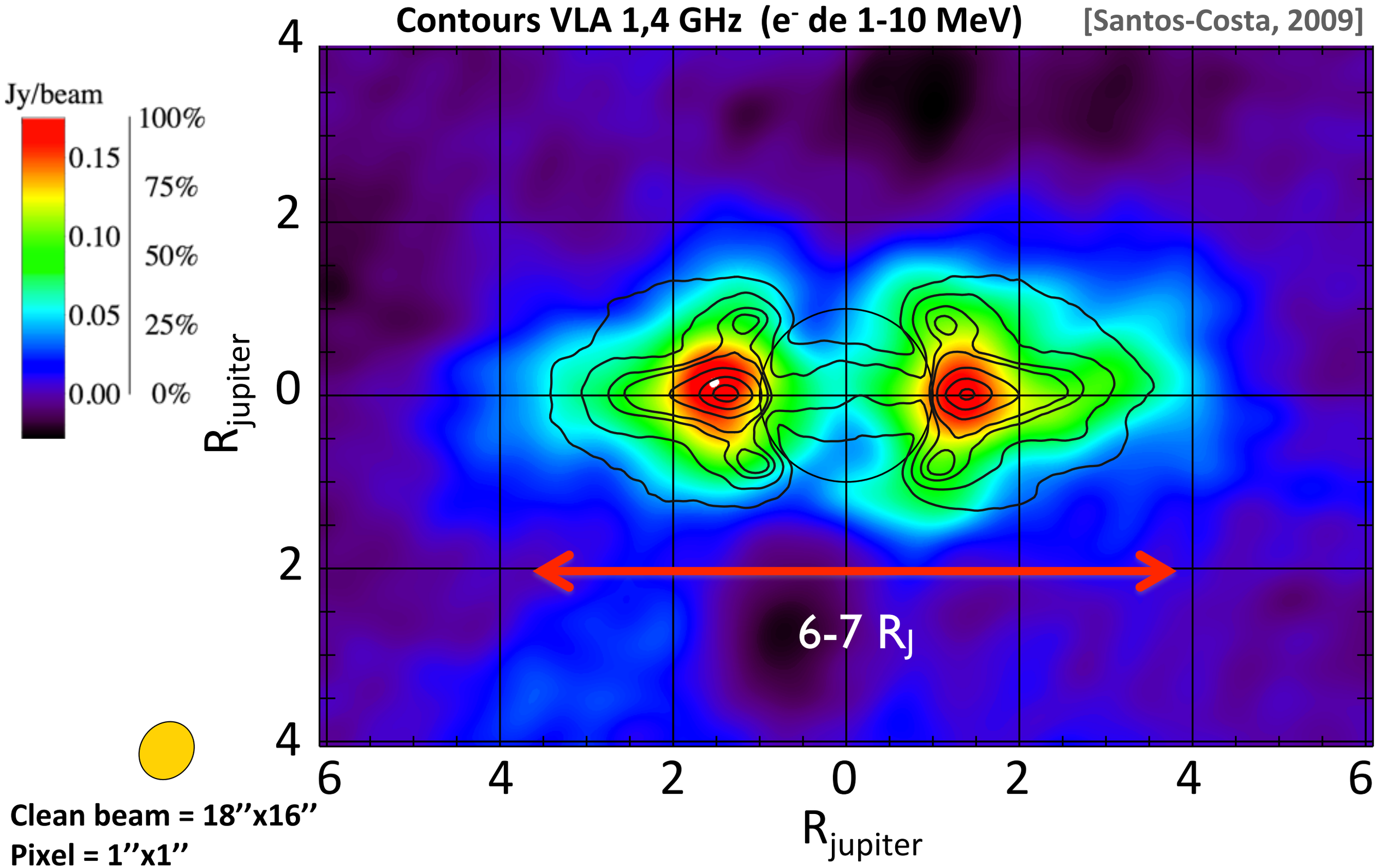


Clean beam = 18''x16''

Pixel = 1''x1''

Resolved intensity maps

- **Integration over 127-172 MHz, Δt = (best) 7h, (u,v)= 0-15 kλ**

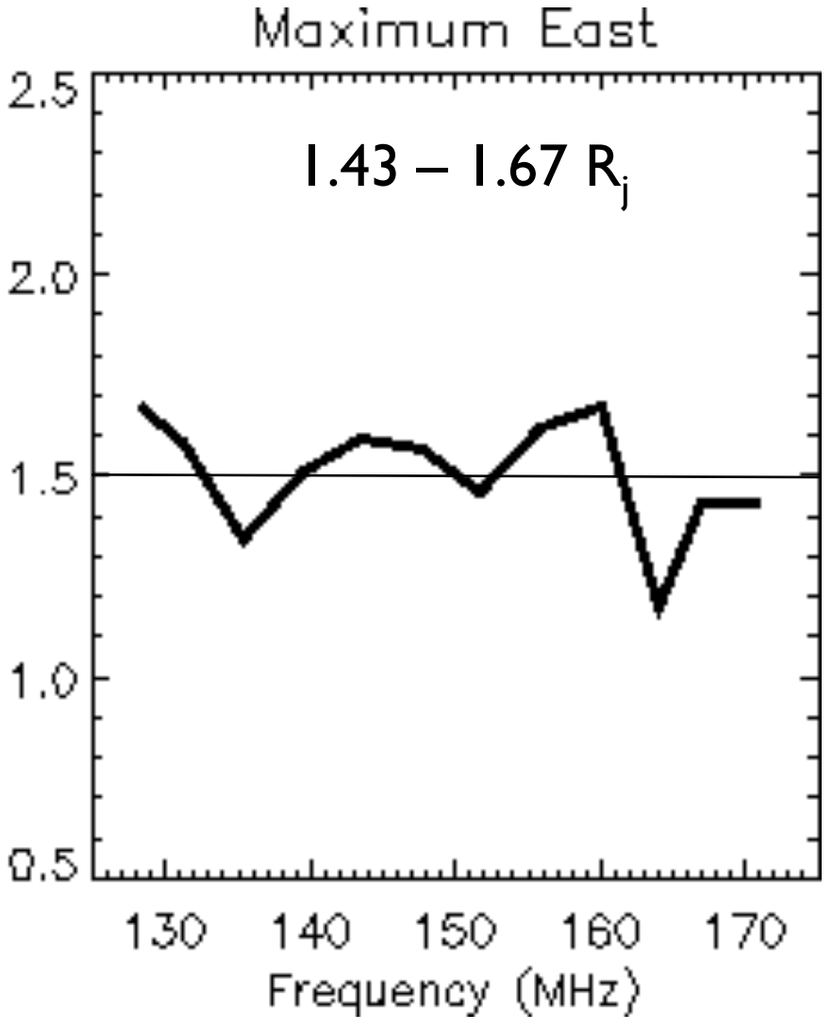


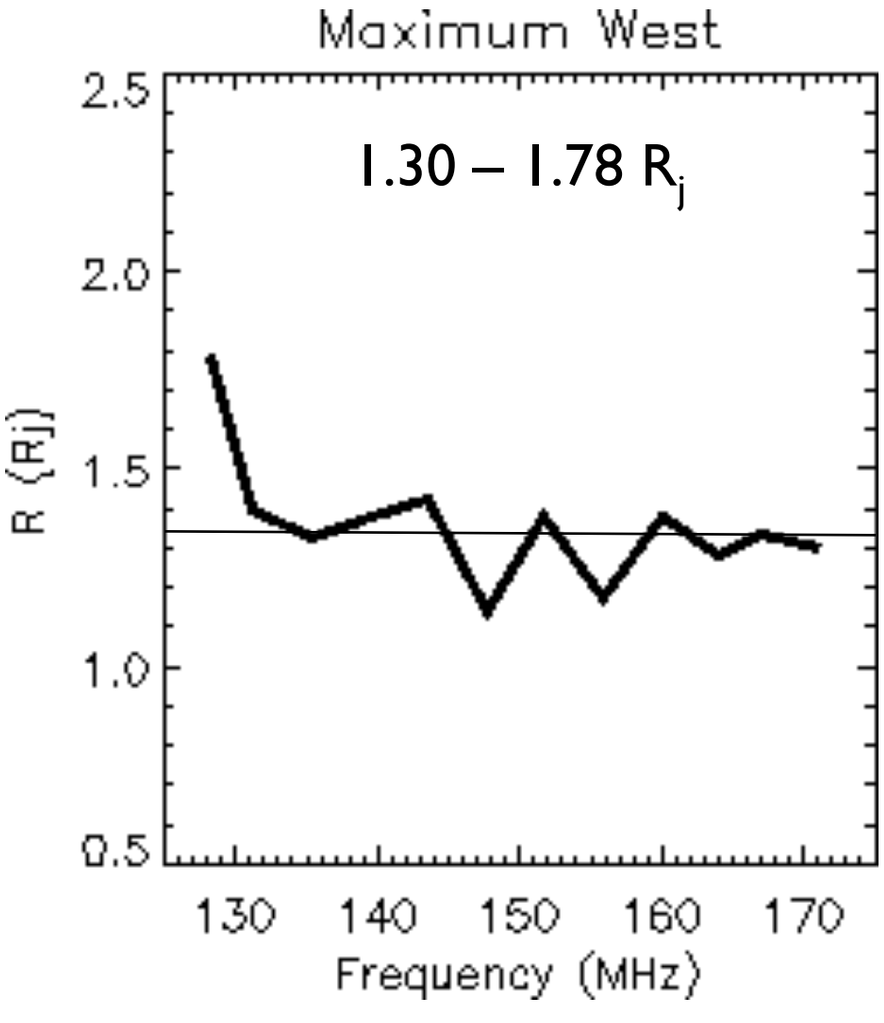
Clean beam = 18''x16''

Pixel = 1''x1''

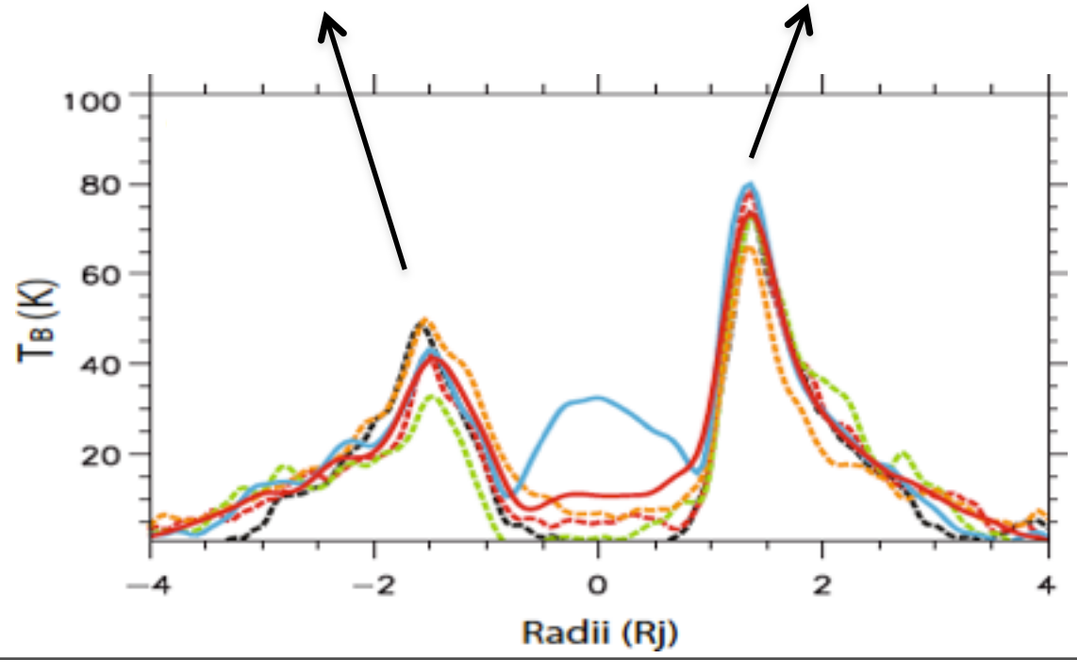
E & W peaks location on 10-hr time integrated images

1.5 R_j

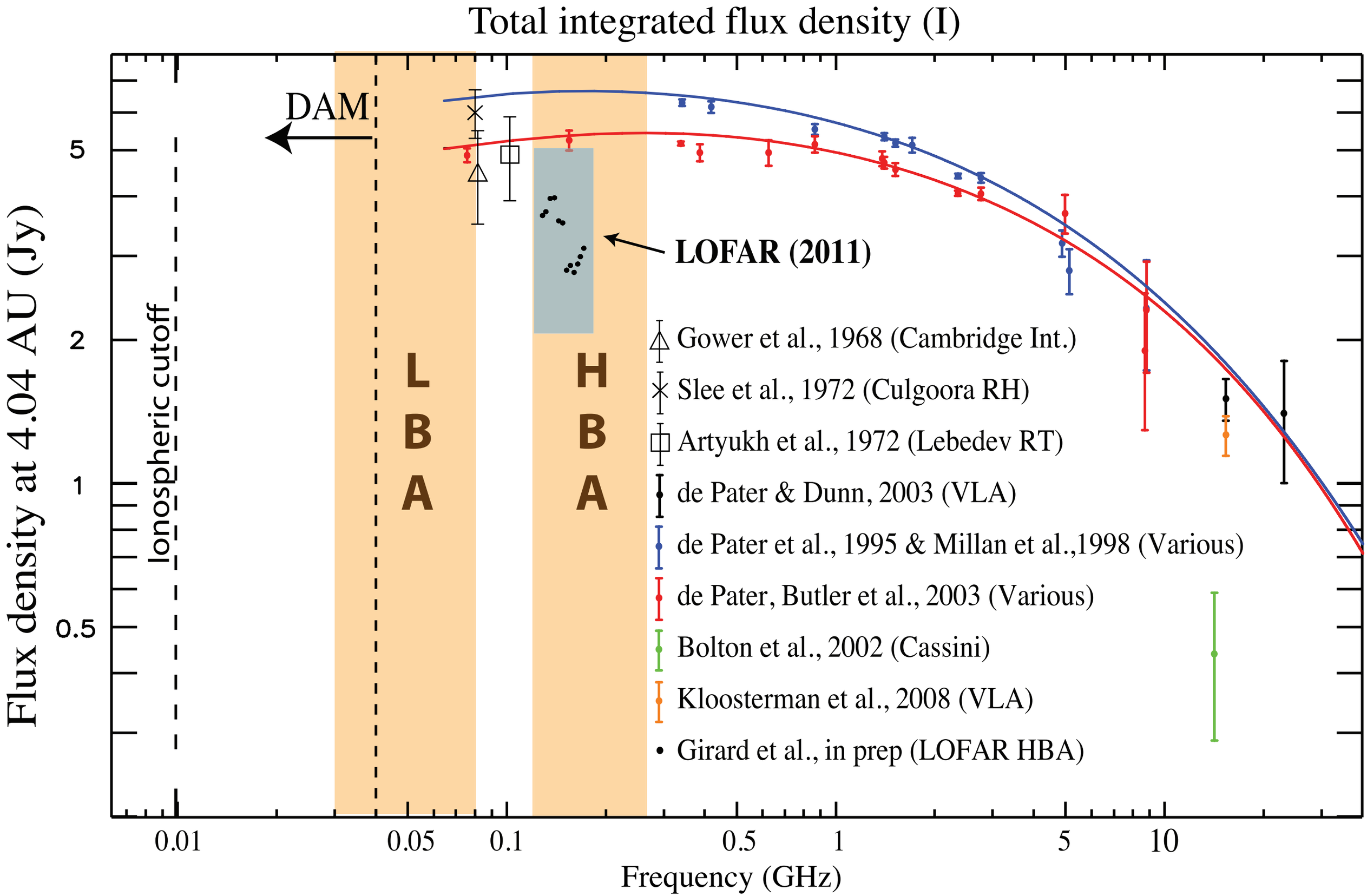




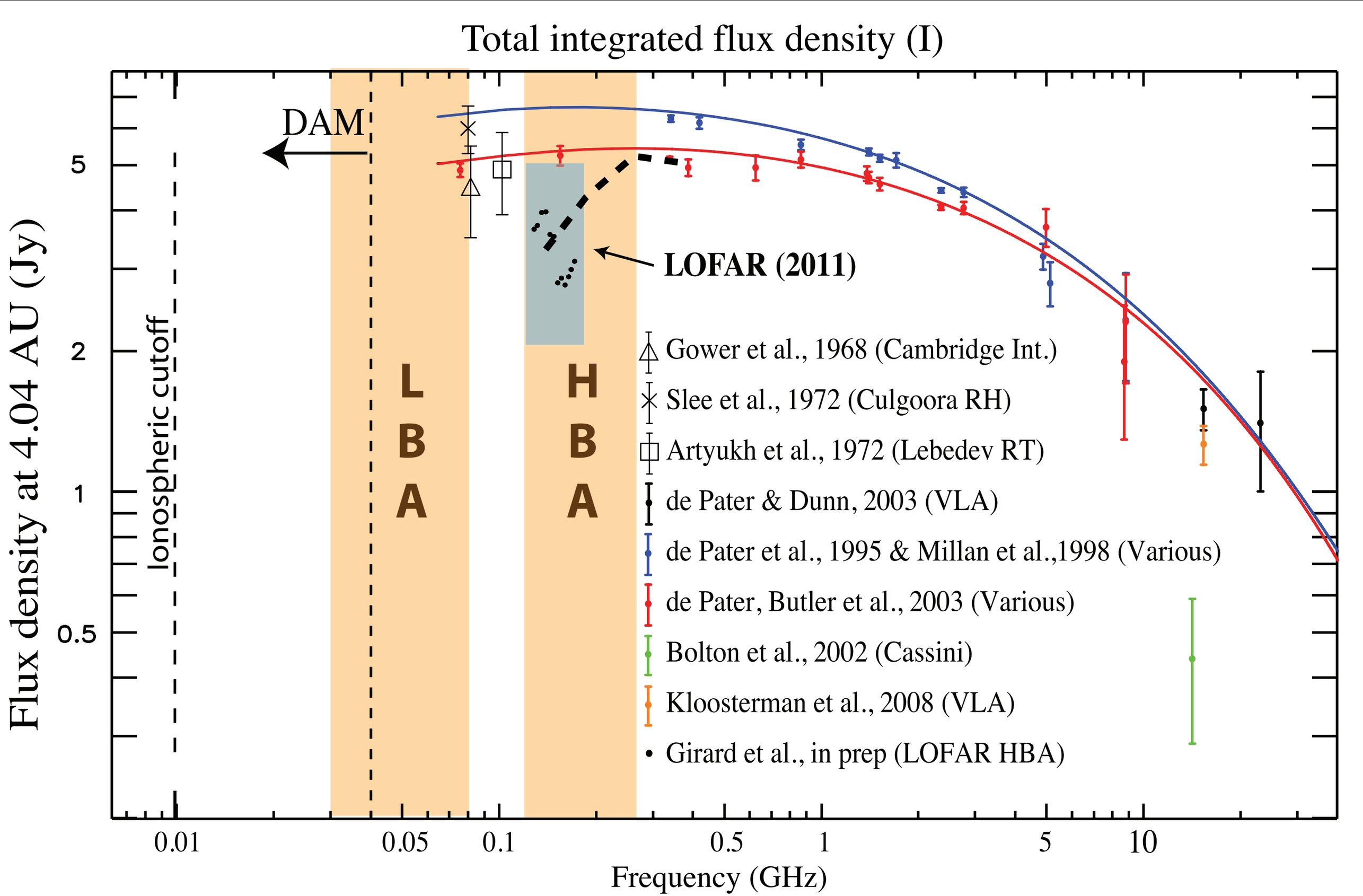
1.35 R_j



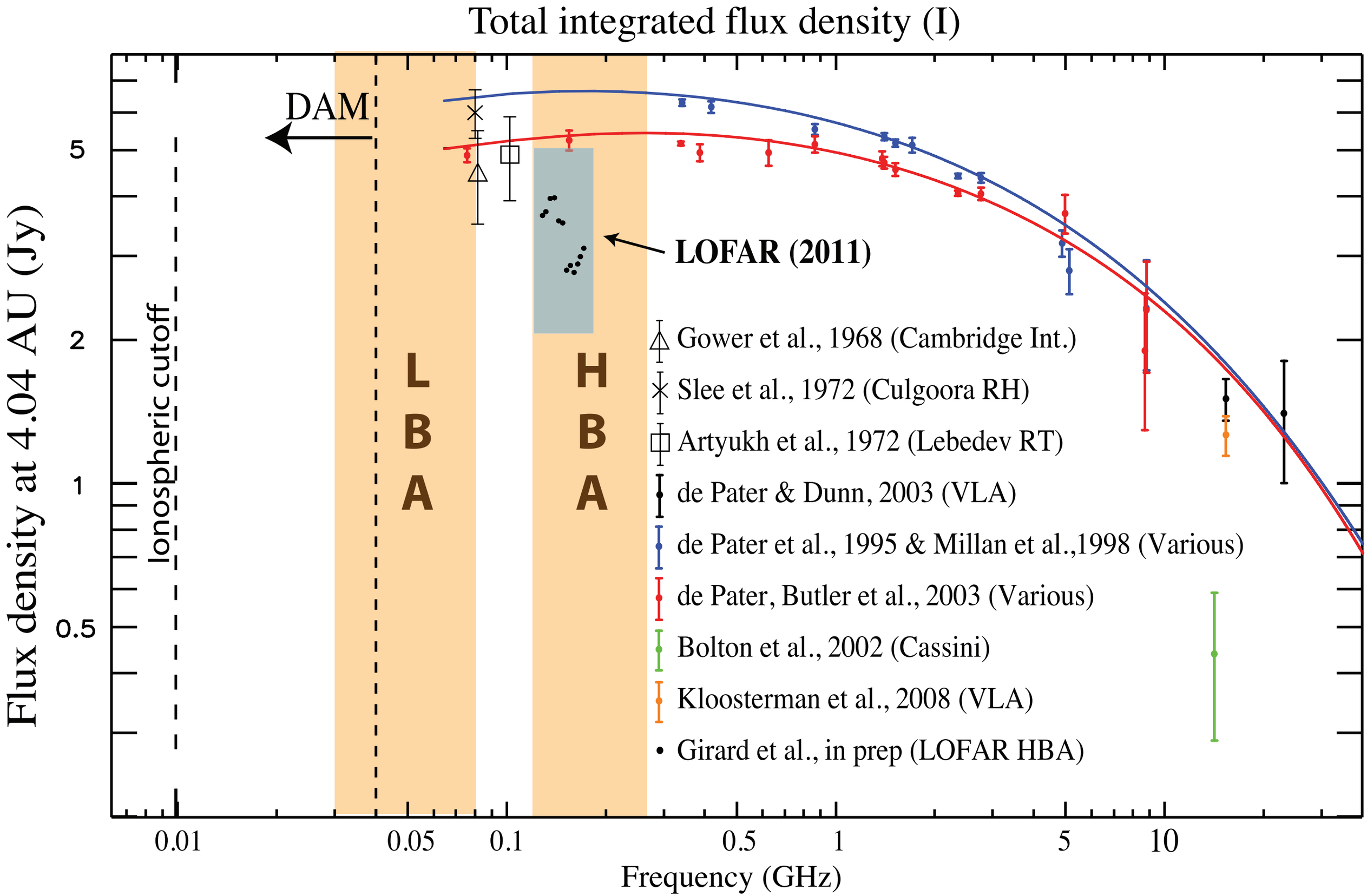
VLA 5 GHz
[Santos-Costa et al., 2009]



(Girard et al., SF2A 2012, adapted from Kloosterman et al., 2008)



(Girard et al., SF2A 2012, adapted from Kloosterman et al., 2008)



(Girard et al., SF2A 2012, adapted from Kloosterman et al., 2008)

Total integrated flux density (I)

DAM

c cutoff

04 AU (Jy)

5

2

X

X

LOFAR 2013

LOFAR (2011)

L

H

B

A

Gower et al., 1968 (Cambridge Int.)

Slee et al., 1972 (Culgoora RH)

Artyukh

de Pater

de Pater

de Pater

Bolton e

Klooster

Girard e

0.5

Frequency (

12, adapted fr

F=55 MHz jup−LBA−cor−3.image

4C21.16

Jupiter

22°
45'
30'
15'
21°
45'
30'
15'

J2000 Declination

04h25m 23m 21m 19m 17m

J2000 Right Ascension

F=149 MHz jup−3.image

4C21.16

Jupiter

45'
30'
15'
21°
45'
30'
15'
20°

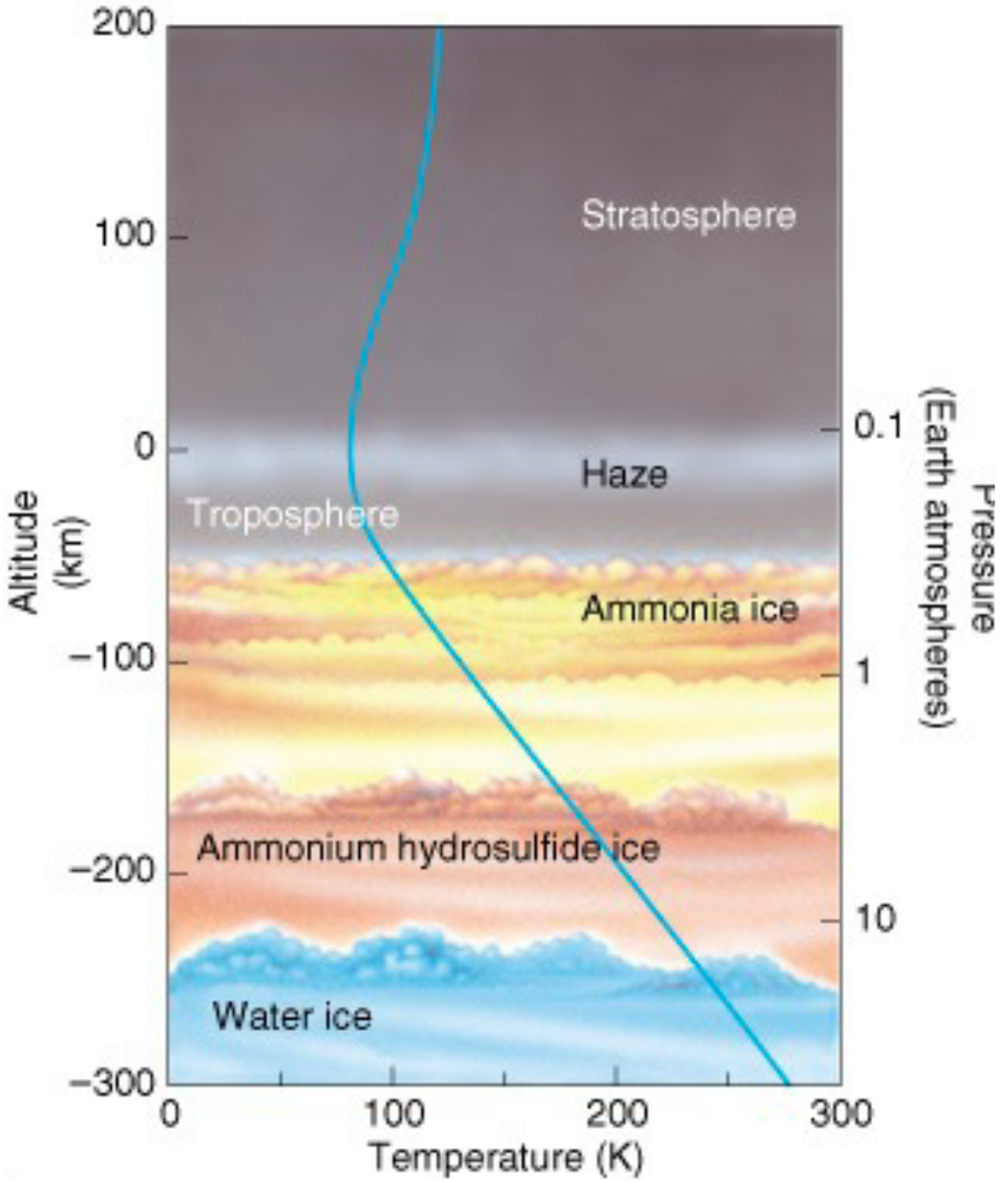
J2000 Declination

04h25m 23m 21m 19m 18m 17m

J2000 Right Ascension

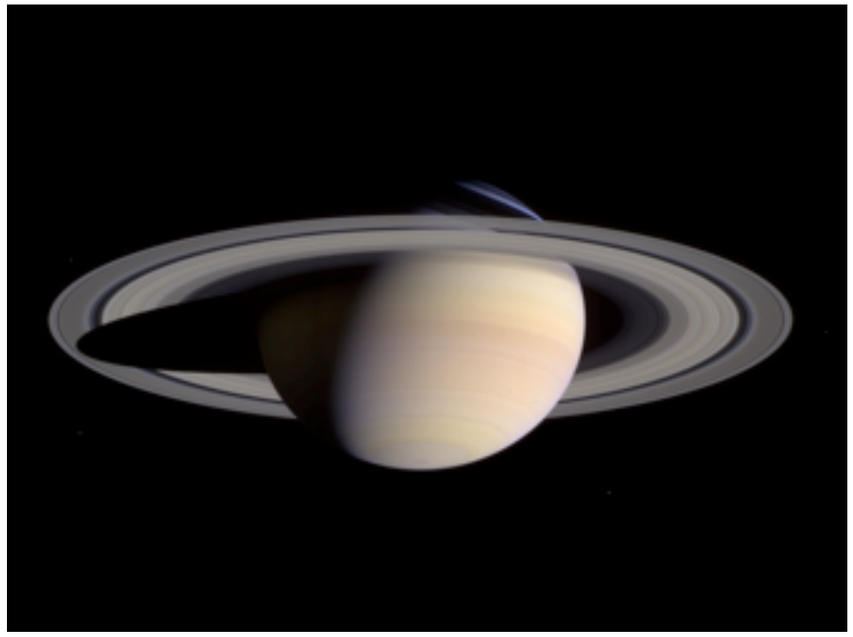
Saturn thermal emission

- LF probe deeply into Saturn atmosphere (~kbar)
- Measurement of the abondance of water

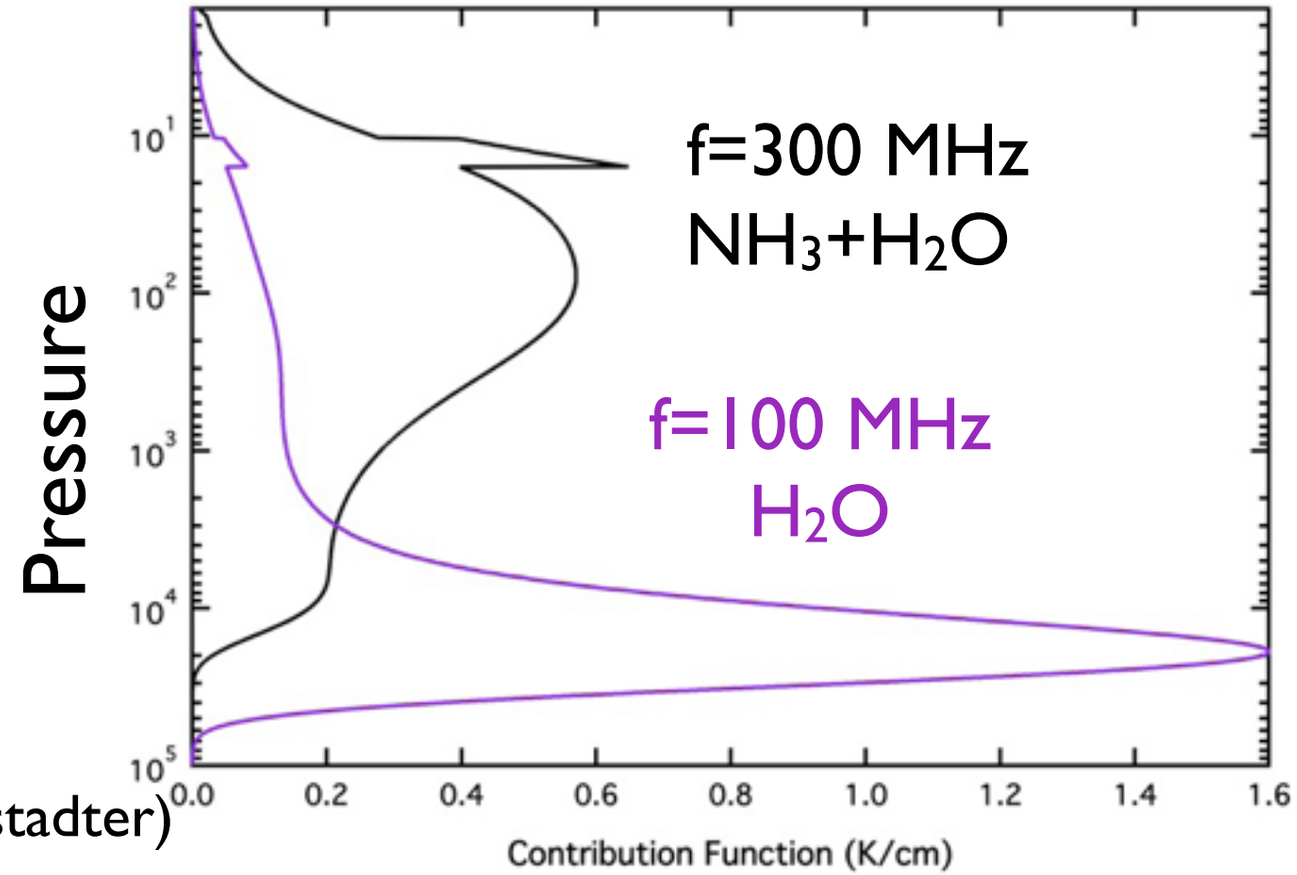


Repartition of materials

See Daniel Gautier's talk tomorrow

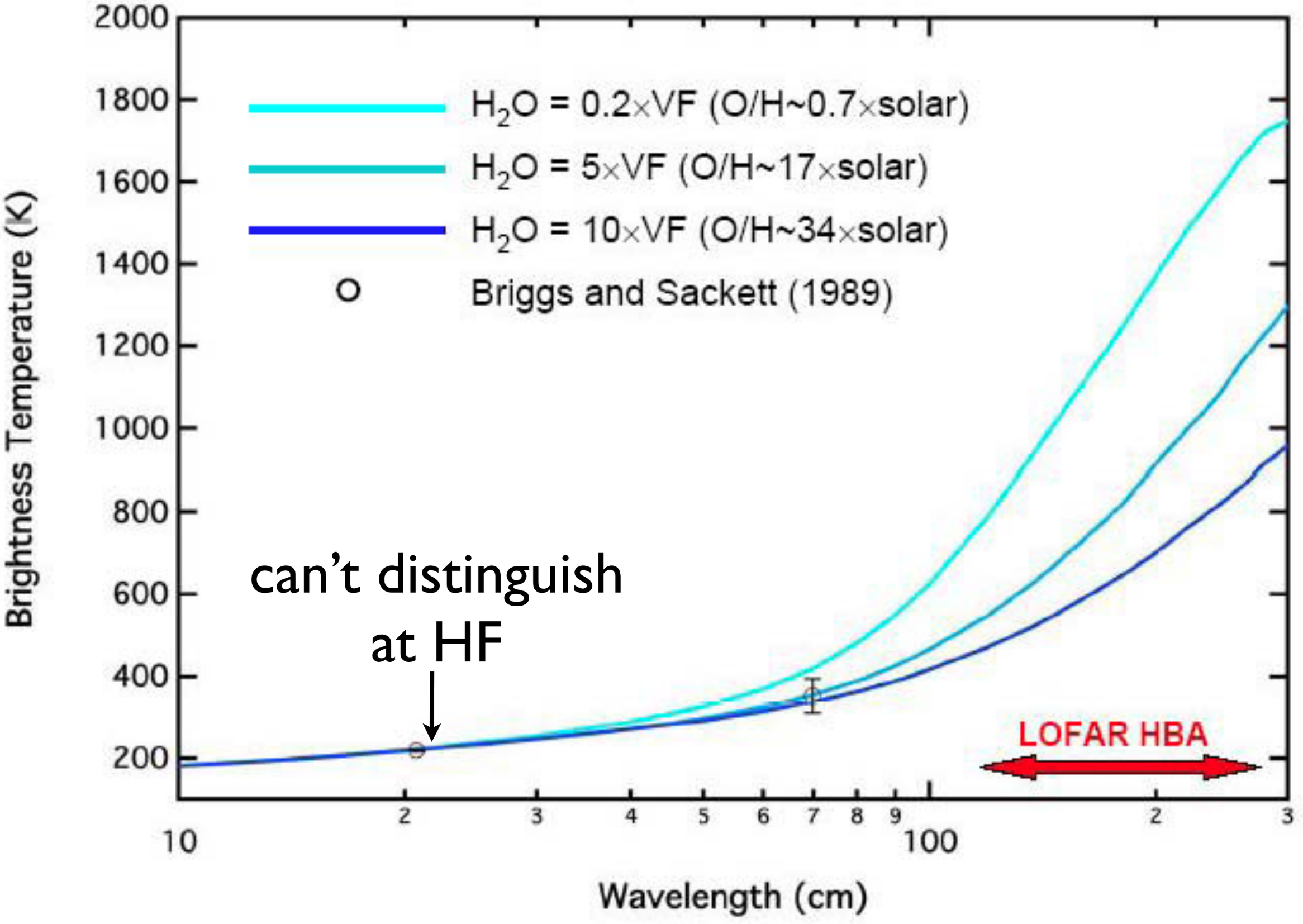


Contribution to the thermal emission

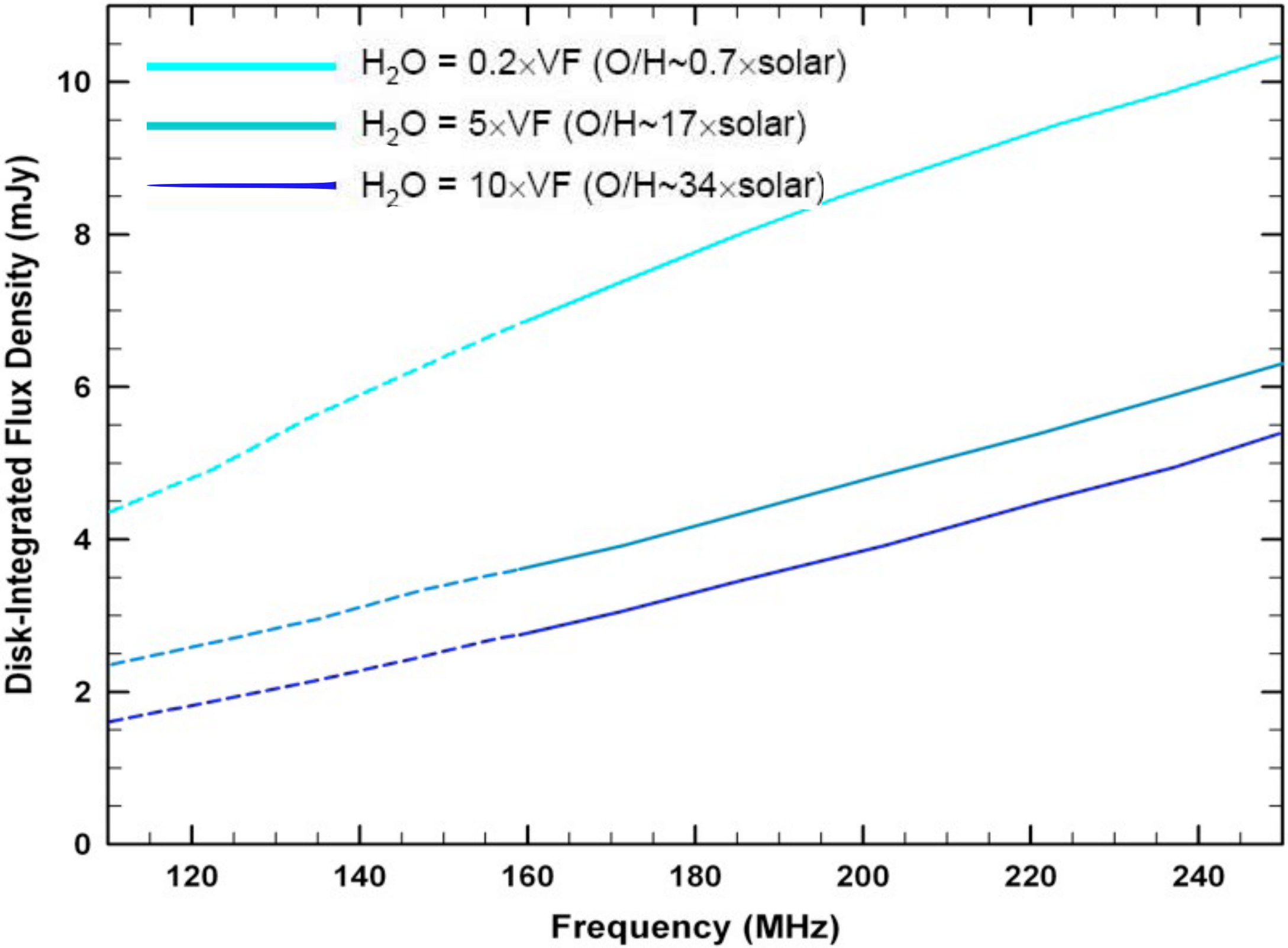


(plot from M. Hofstadter)

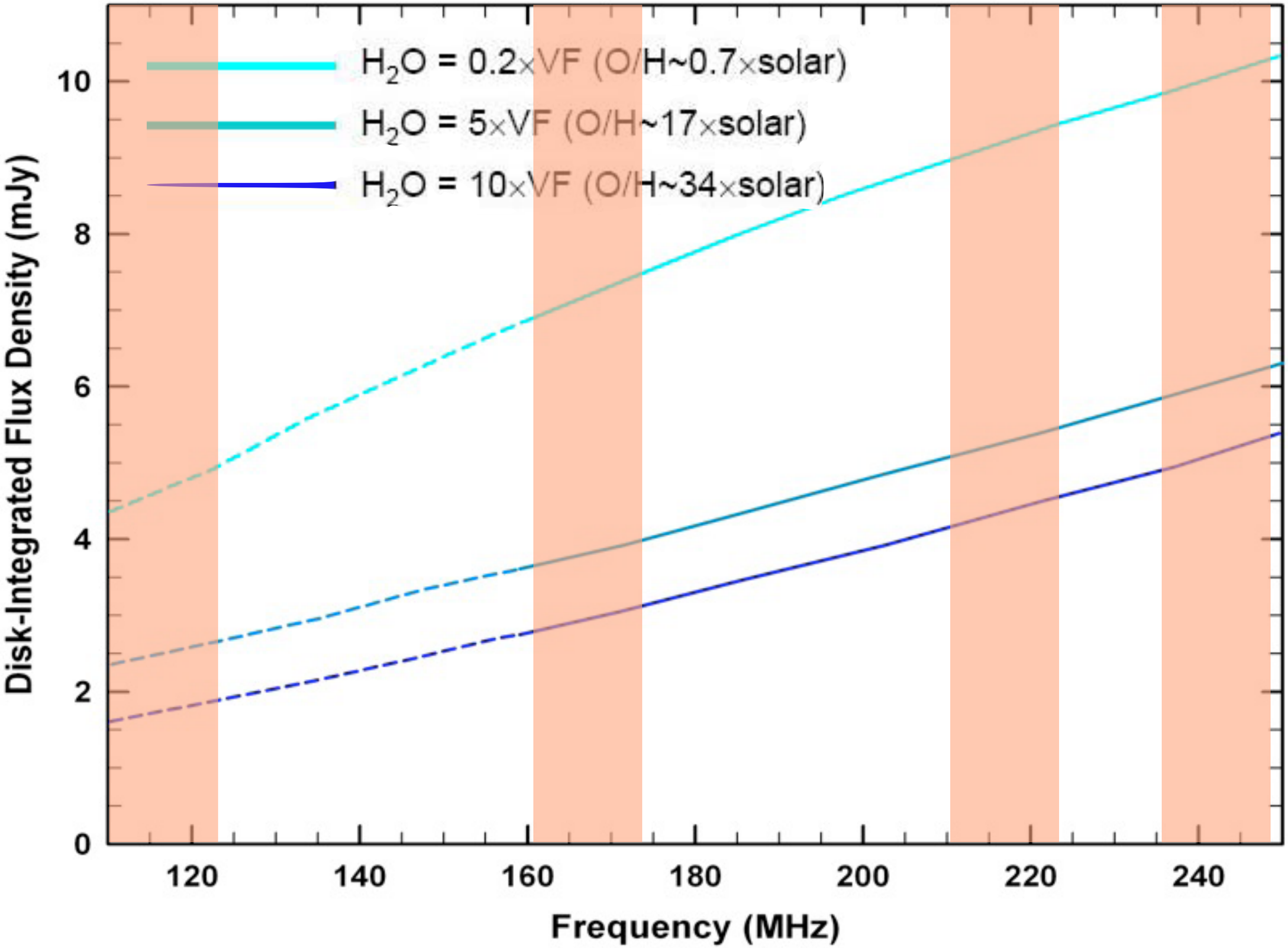
Saturn thermal emission



Saturn thermal emission

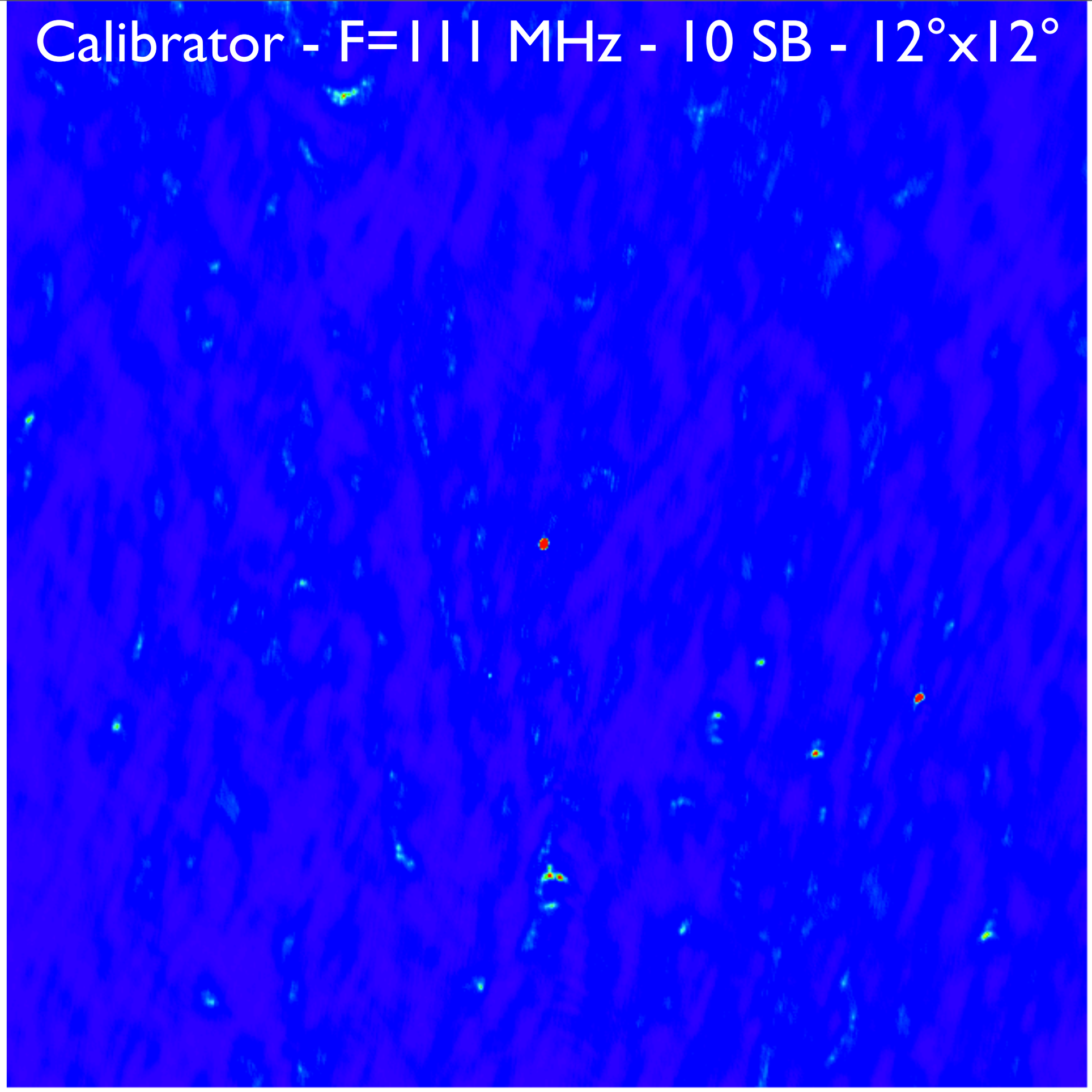


Saturn thermal emission

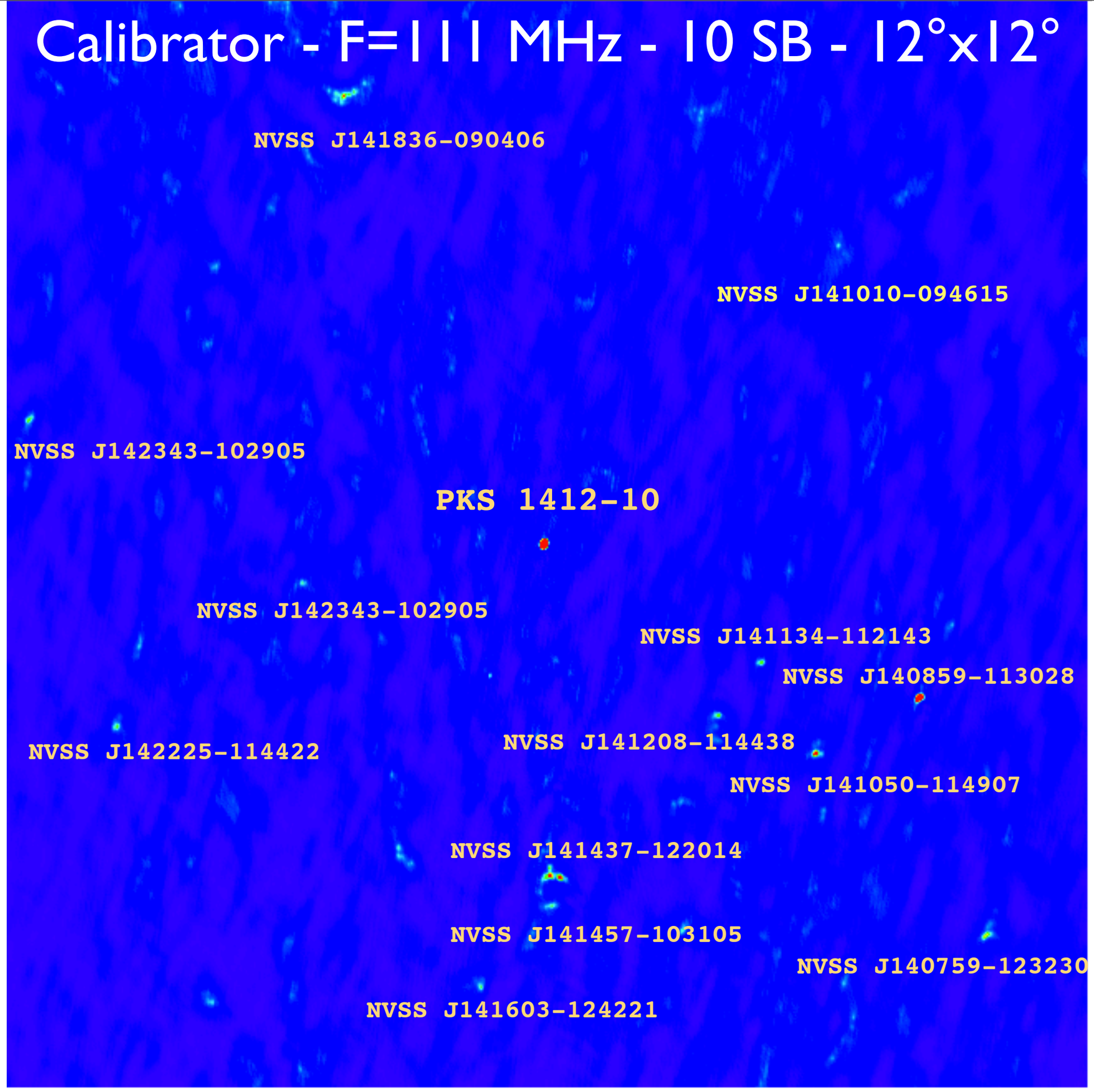


- Observed (20h) and being processed...

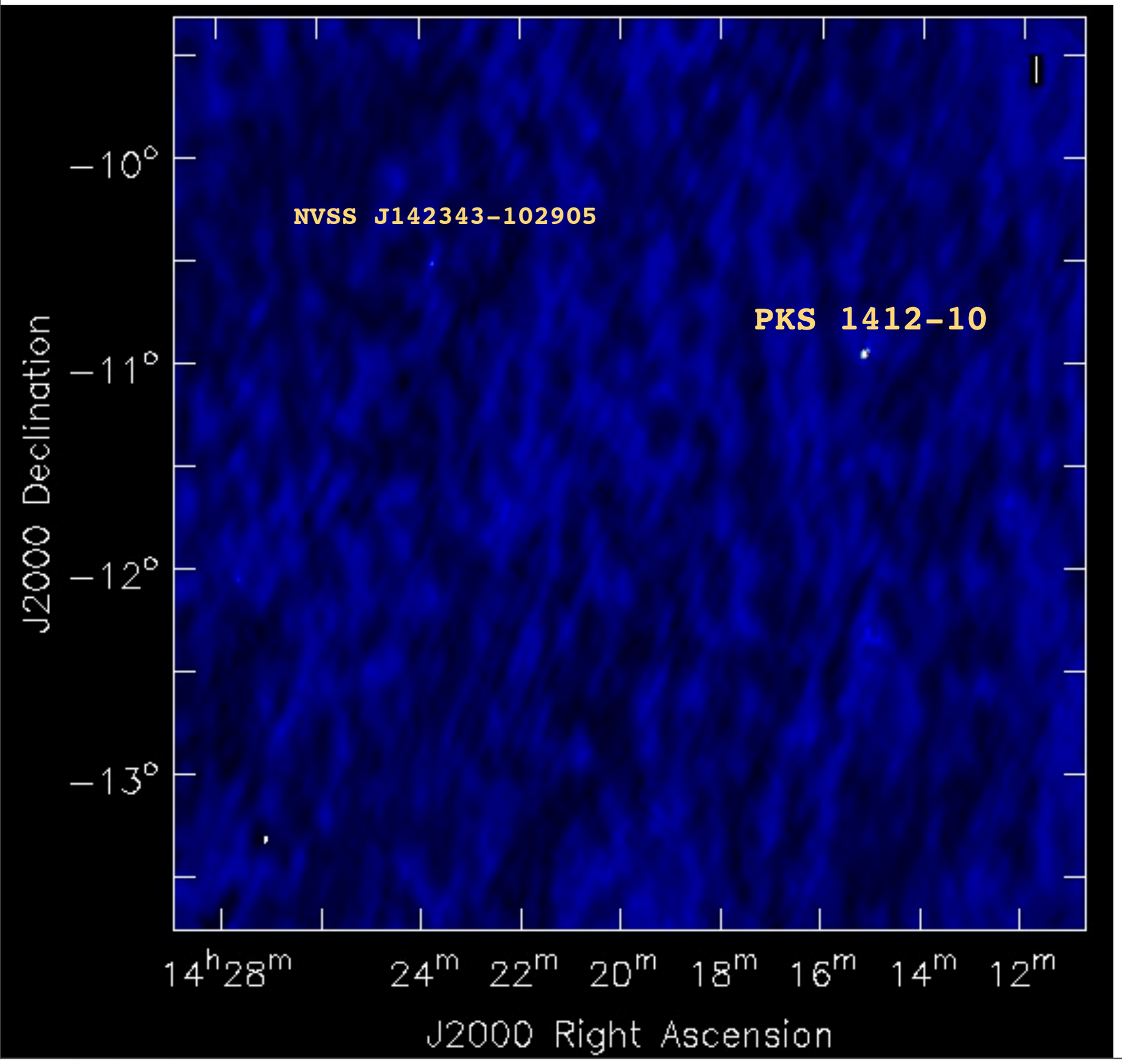
Calibrator - F=111 MHz - 10 SB - 12°x12°

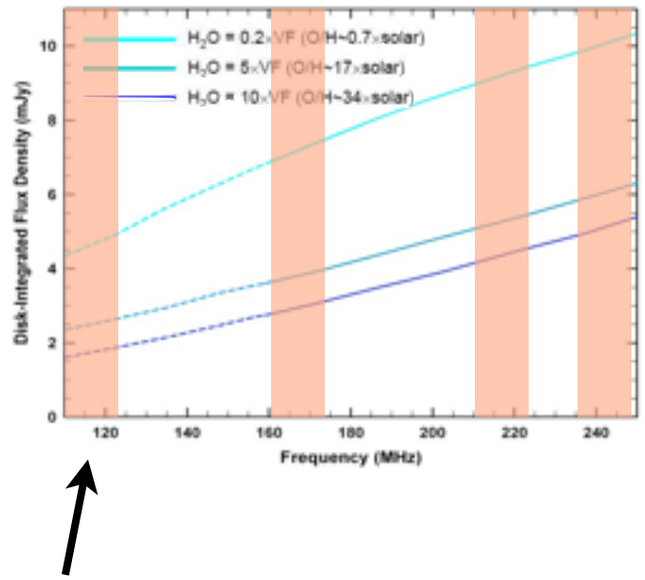


Calibrator - F=111 MHz - 10 SB - 12°x12°



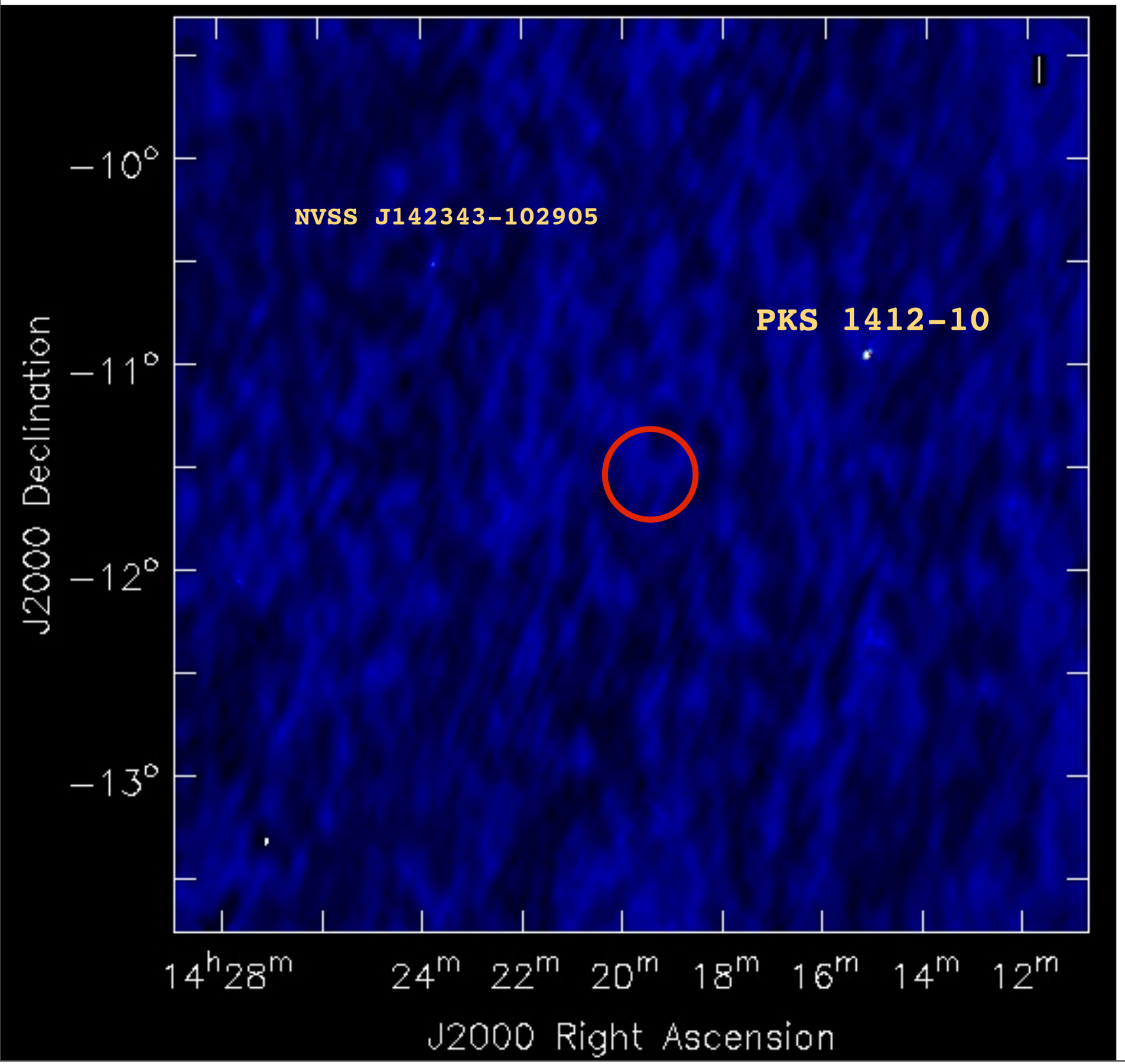
Saturn field - F=111 MHz - 10 SB - 12°x12°

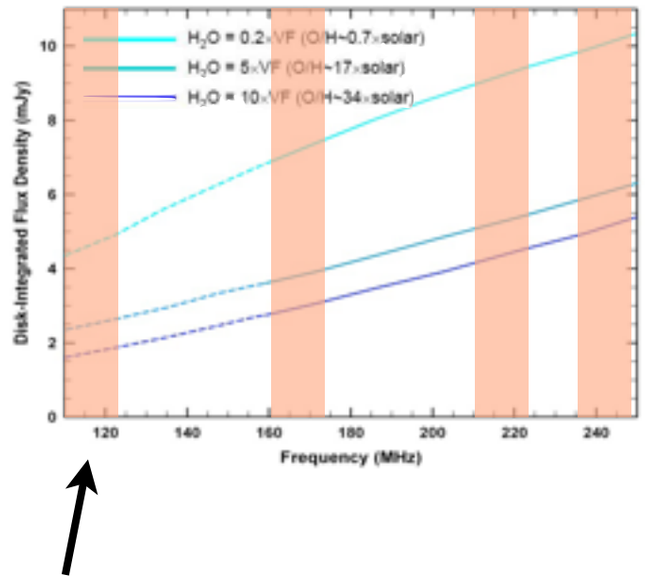




On going...

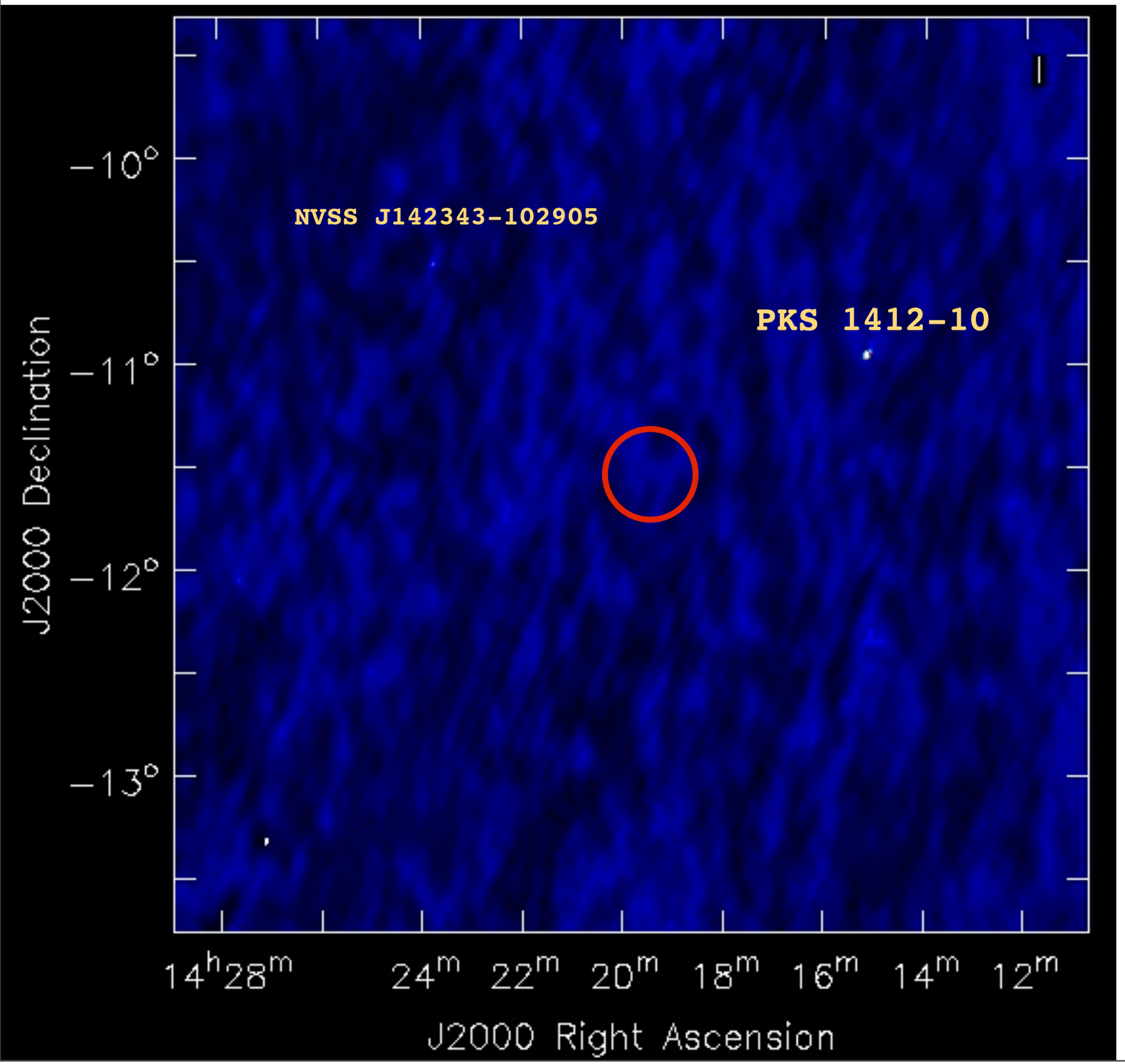
Saturn field - F=111 MHz - 10 SB - 12°x12°

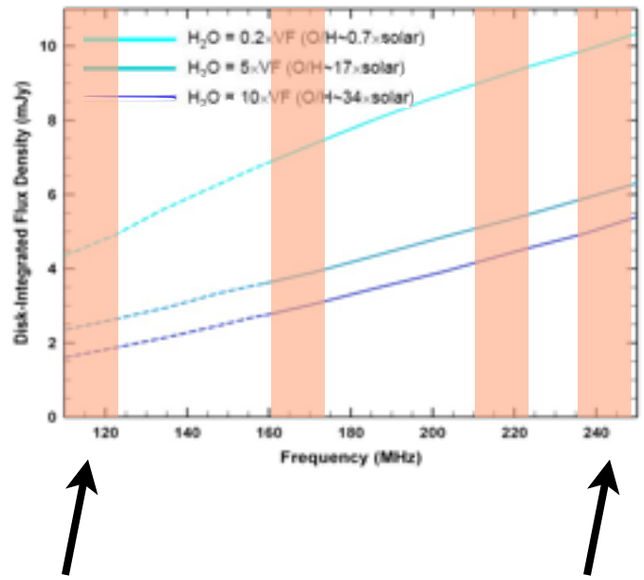




On going...

Saturn field - F=111 MHz - 10 SB - 12°x12°



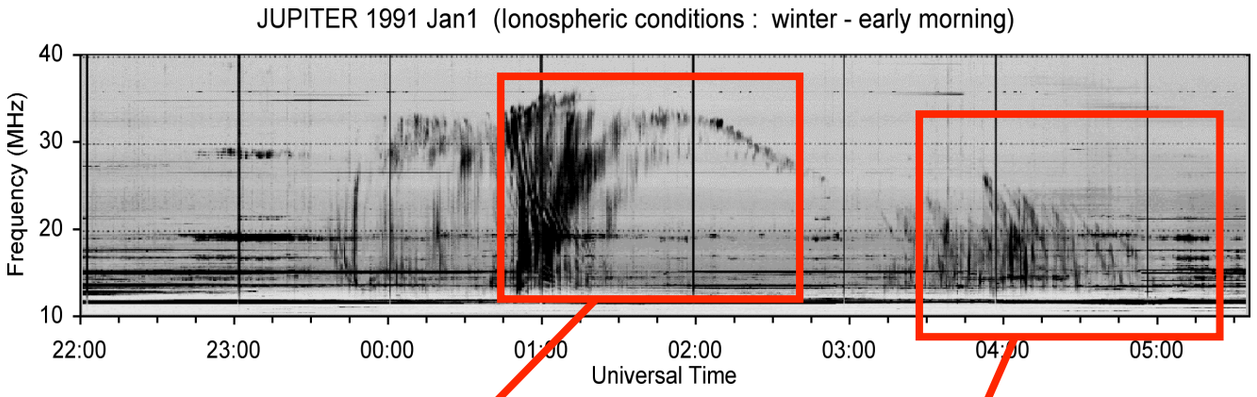


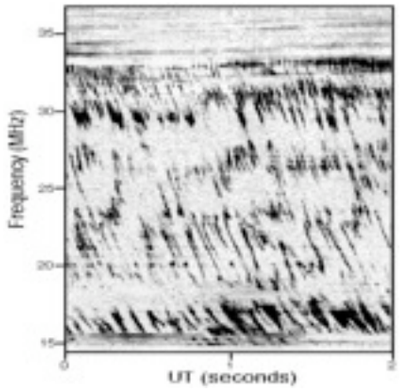
On going...

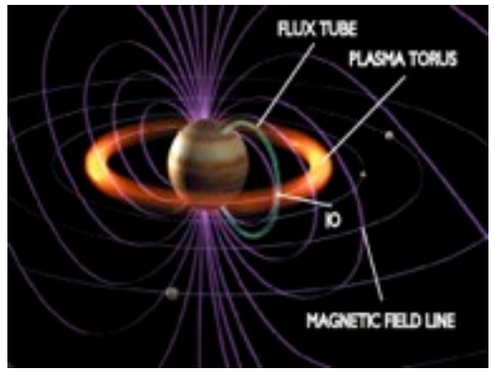
Other observations of Jupiter & Saturn

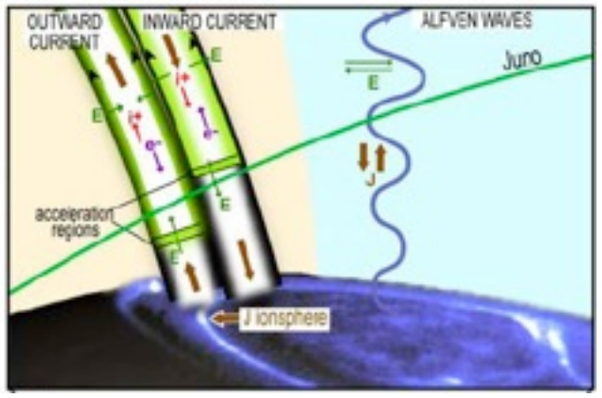
Other observations of Jupiter & Saturn

- **Jupiter Decameter emission (LC0_002, Wucknitz et al.)**



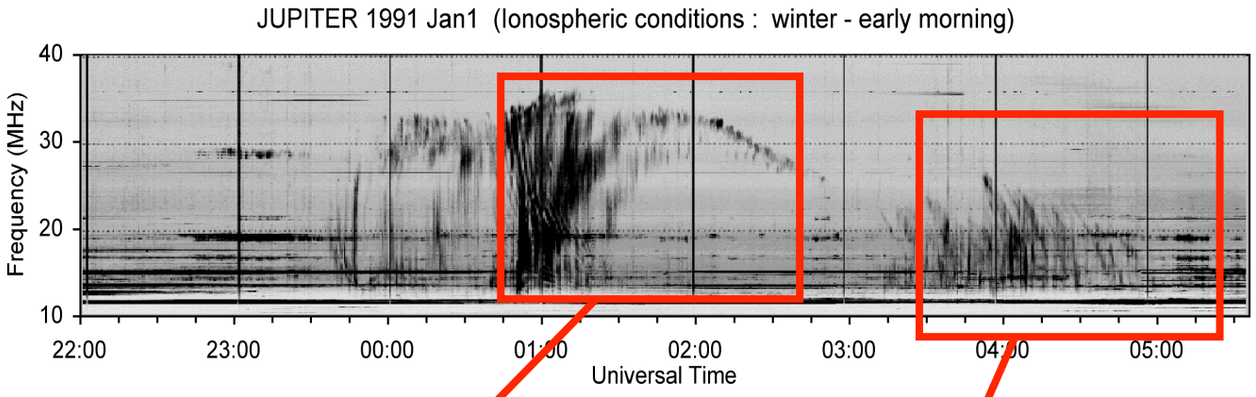


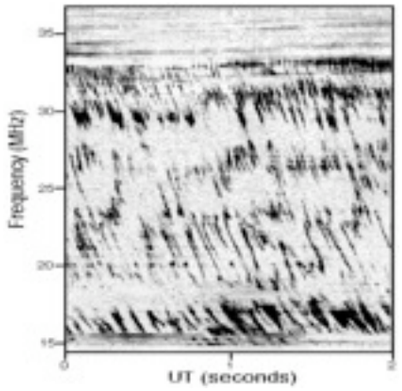


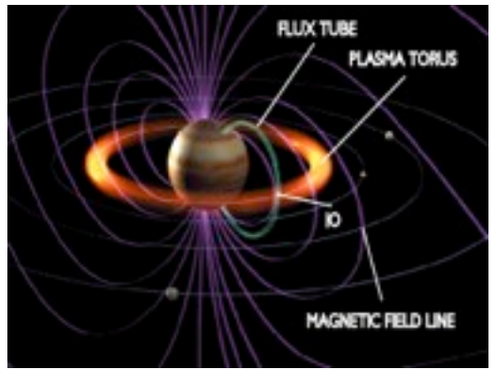


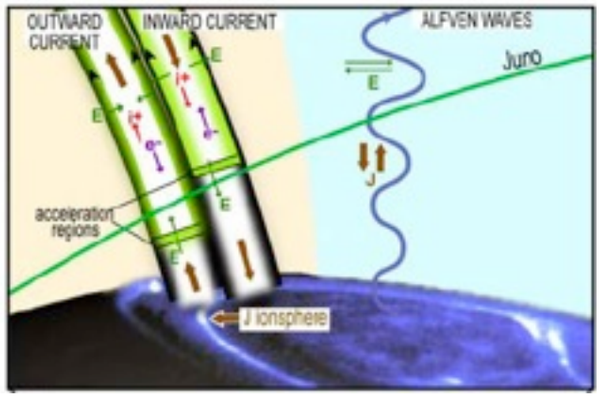
Other observations of Jupiter & Saturn

- **Jupiter Decameter emission (LC0_002, Wucknitz et al.)**

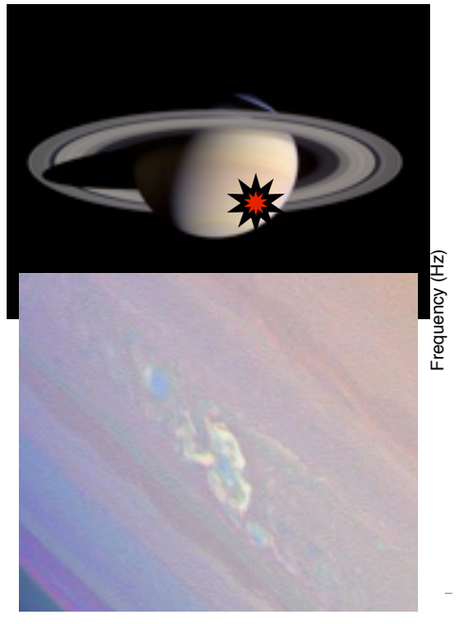


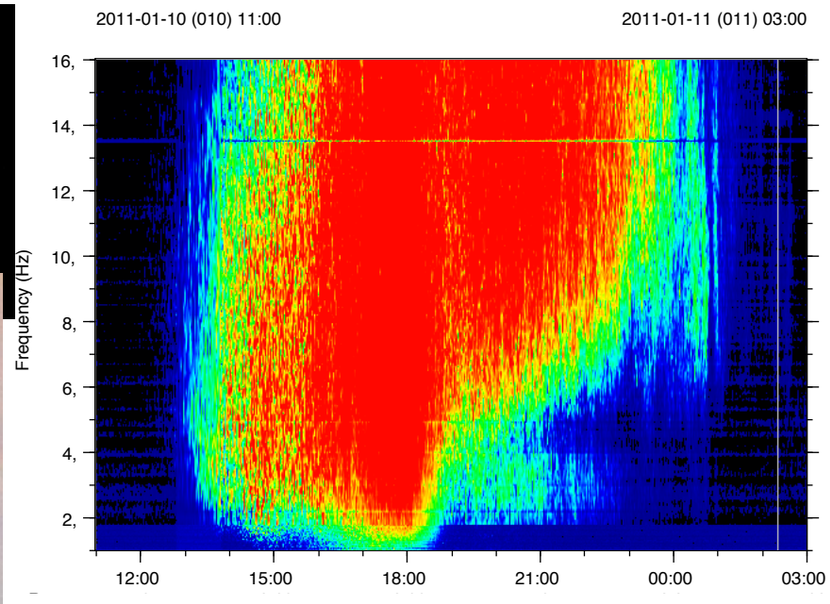


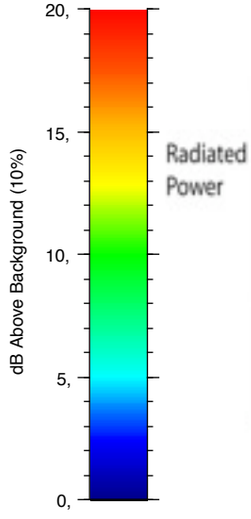


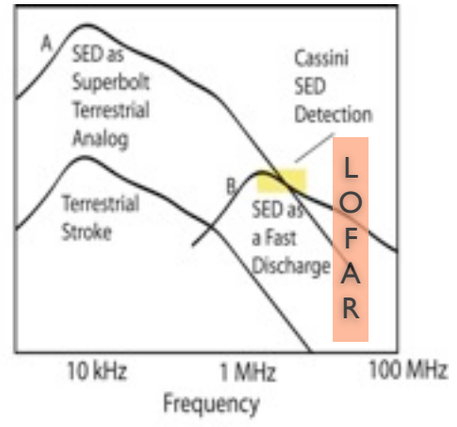


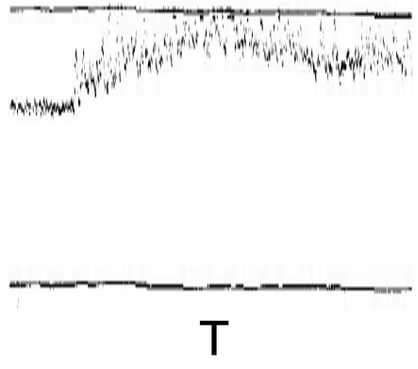
- **Saturn Electrostatic Discharges (LC1_005, J.-M. Grießmeier et al.)**





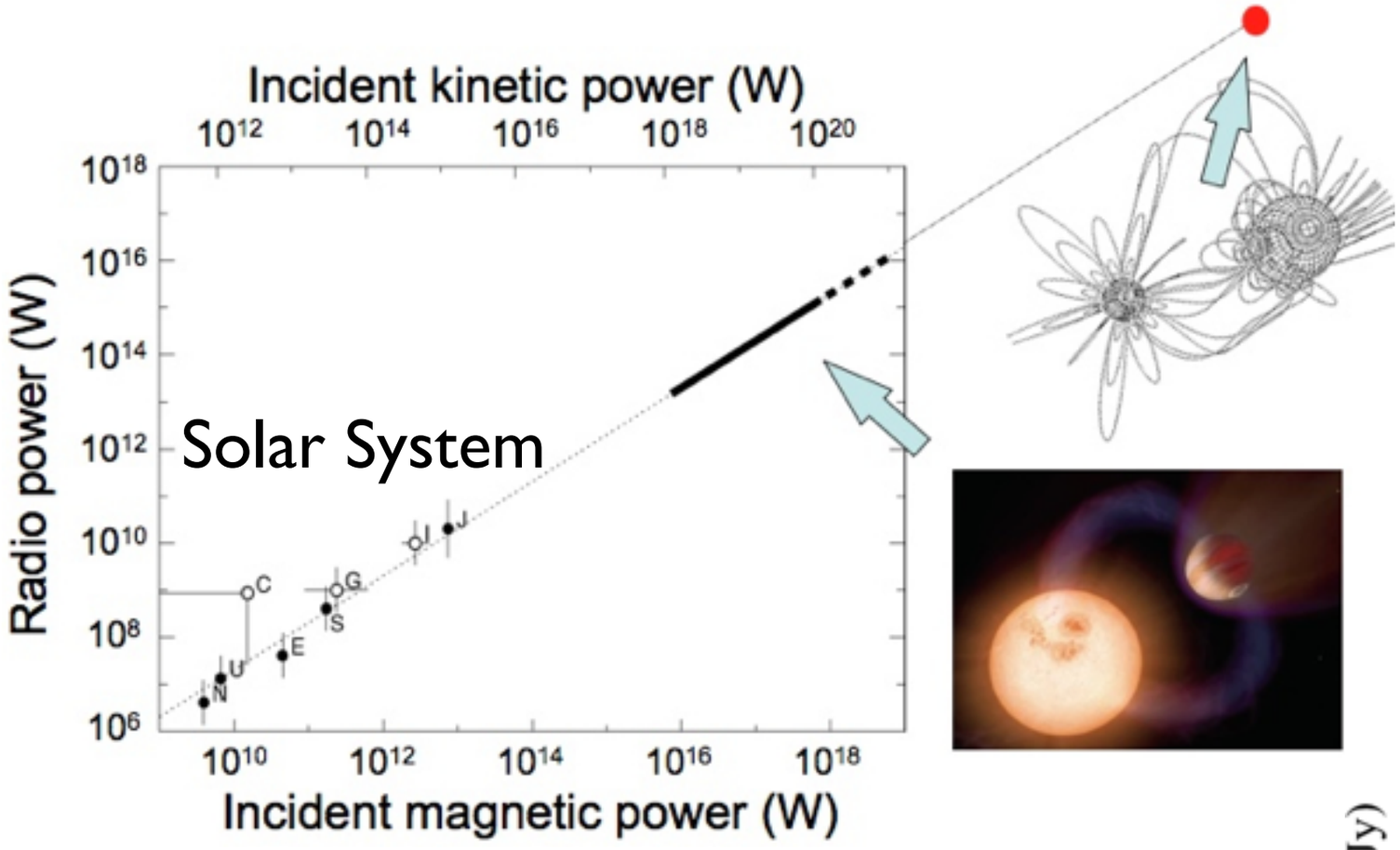




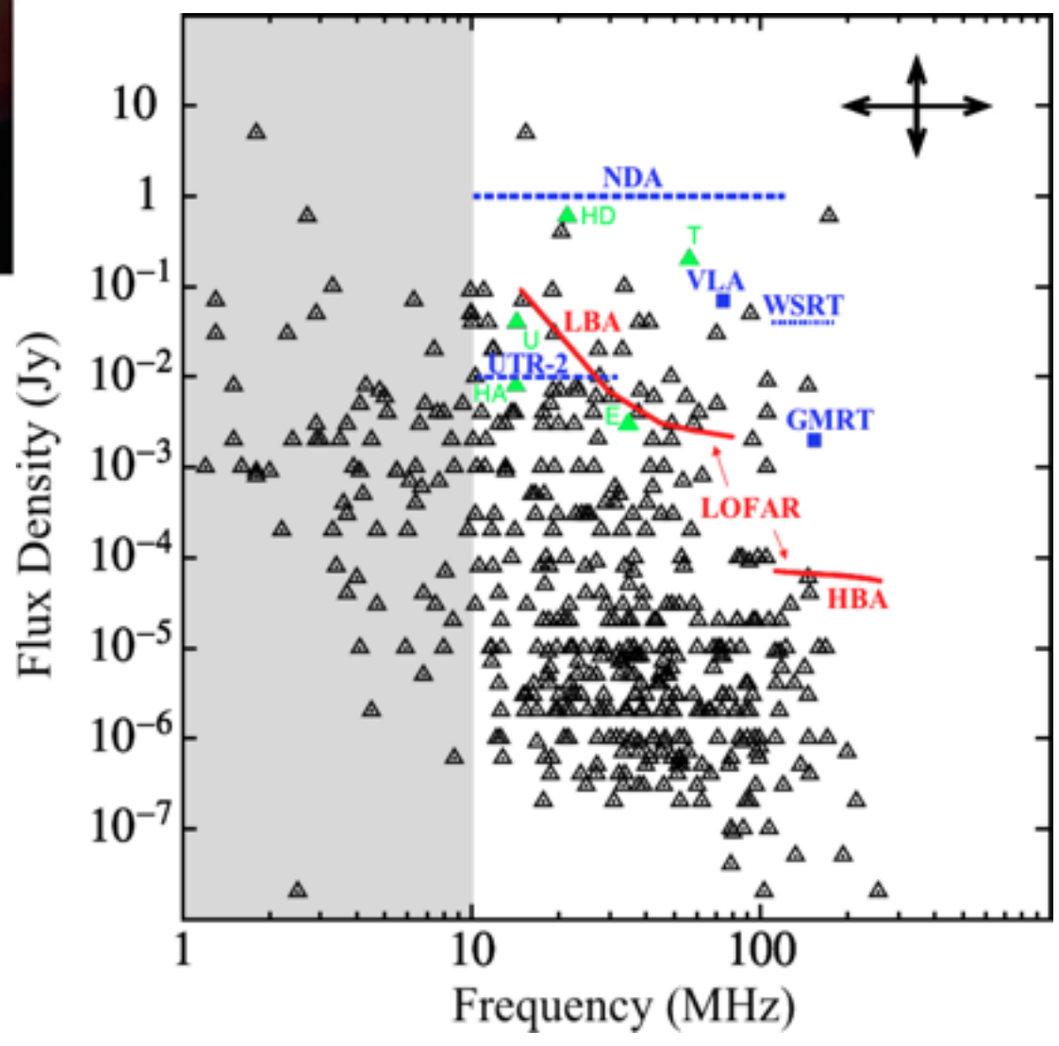


Other observations of exoplanetary systems

- **Radio exoplanetary search and characterization (LC0_007&LC1_032, Zarka et al.)**



[Zarka, 2007]



New facilities for standard data reduction

l'Observatoire de Paris

Meudon

- **Storage**

shared space (LOFAR, NDA, UTR-2...)

- **Processing** (PSL mesocenter)

- **Software** (07/2013)

LOFAR software deployed

Low level Job submission

Proposals to get CPU time

Fully deployed in dec 2013

- **Storage** (~200 Tb)

shared (LOFAR, FR606-SS, NenuFAR...)

- **Processing**

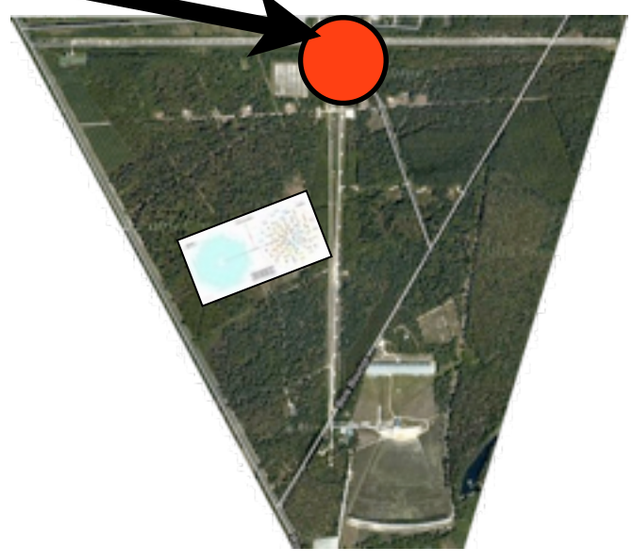
2 Ice-like nodes

- **Software**

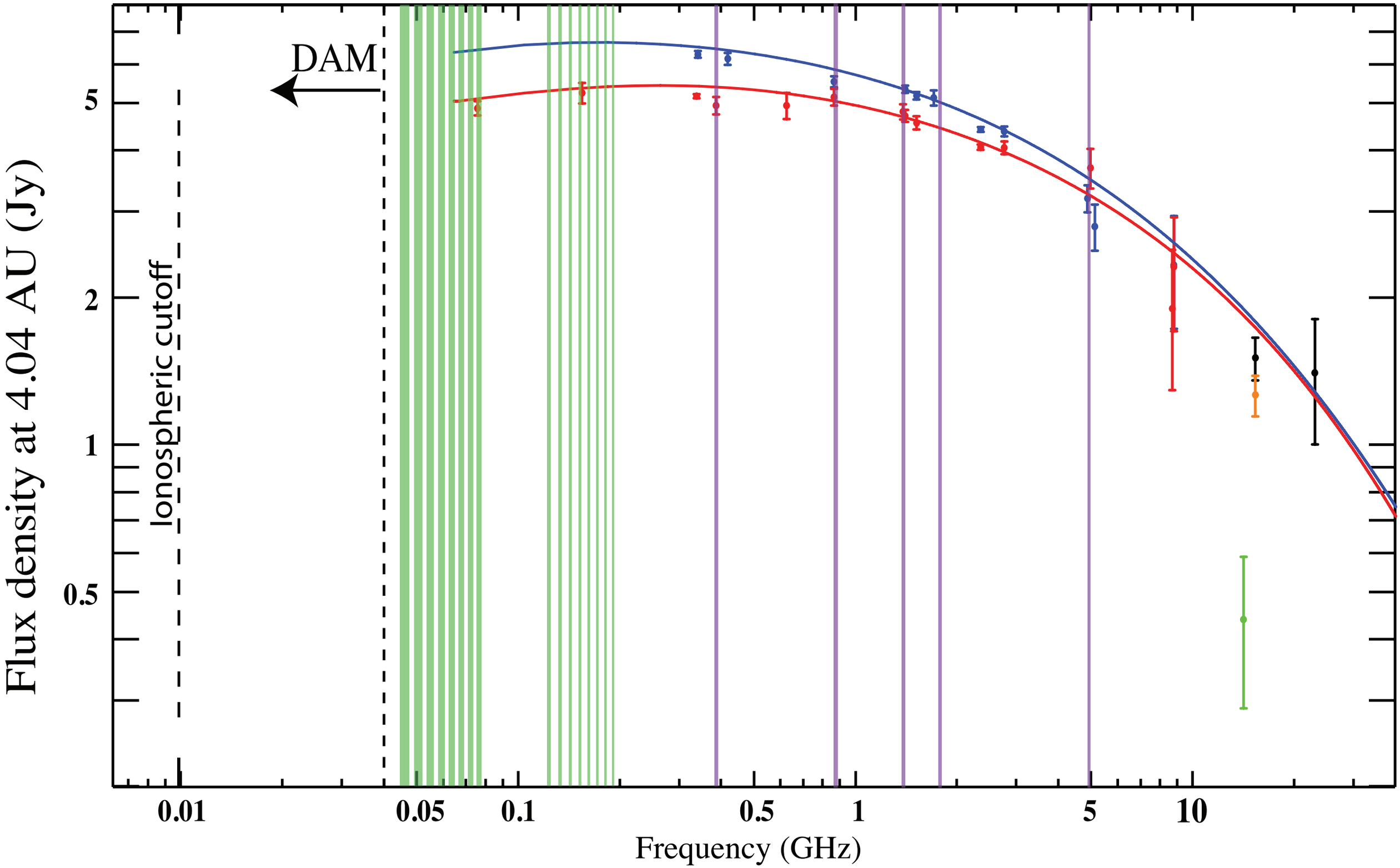
LOFAR software deployed ➢ ***Full use***
calibration, imaging, pipeline(s)...

Nançay

Station de Radioastronomie de Nançay



Observations from 2013



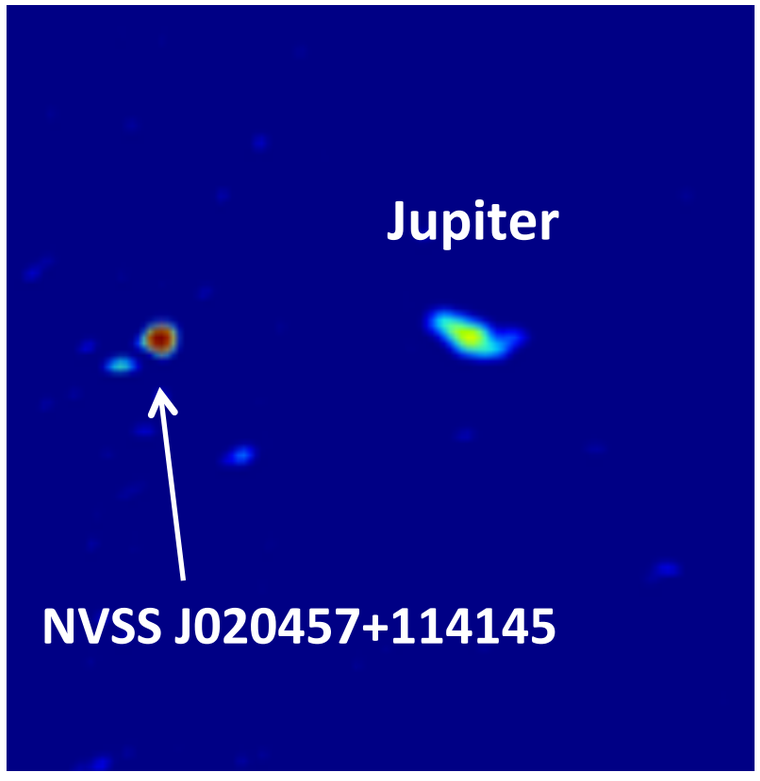
- **LOFAR (LBA & HBA) + WSRT (6 cm → 78 cm)**
- **Observed in 2013:** **LOFAR: 2x5h45** **WSRT: 2x5h45**

LOFAR commissioning observation 10-11/11/2011

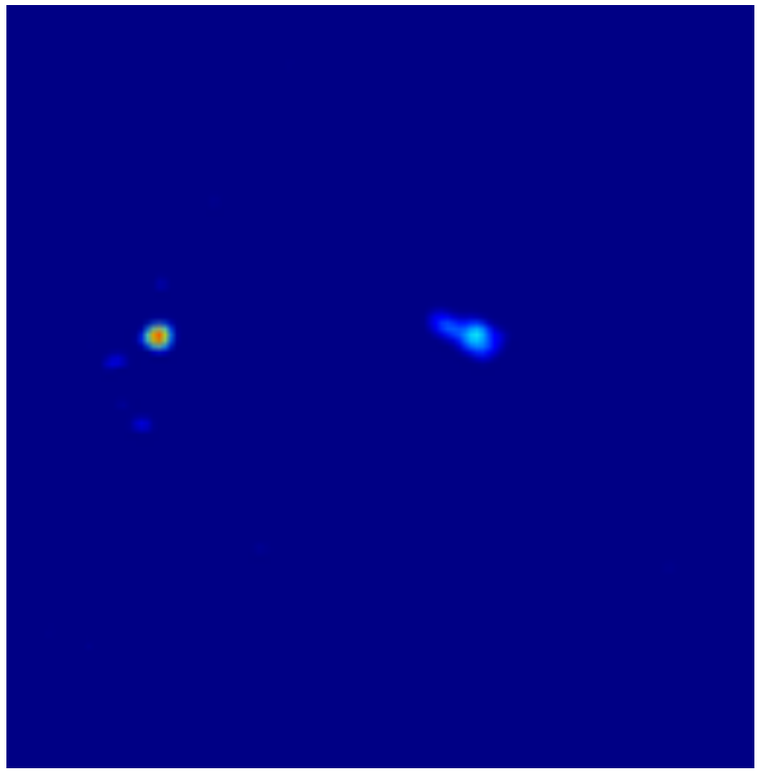
- 10 consecutives hours (~1 planetary rotation)
- HBA 127-172 MHz
- 29 NL stations
- 2 beams : Jupiter & flux calibrator 4° away
- $\delta t = 0.3$ ms , $\delta f = 3$ kHz
- Full Stokes measurement → only I was processed
- data size ~450 GB

Δt =18h-20h uv=0.2~5kλ beam=50”x30” color: 0,1-0,9 Jy/beam

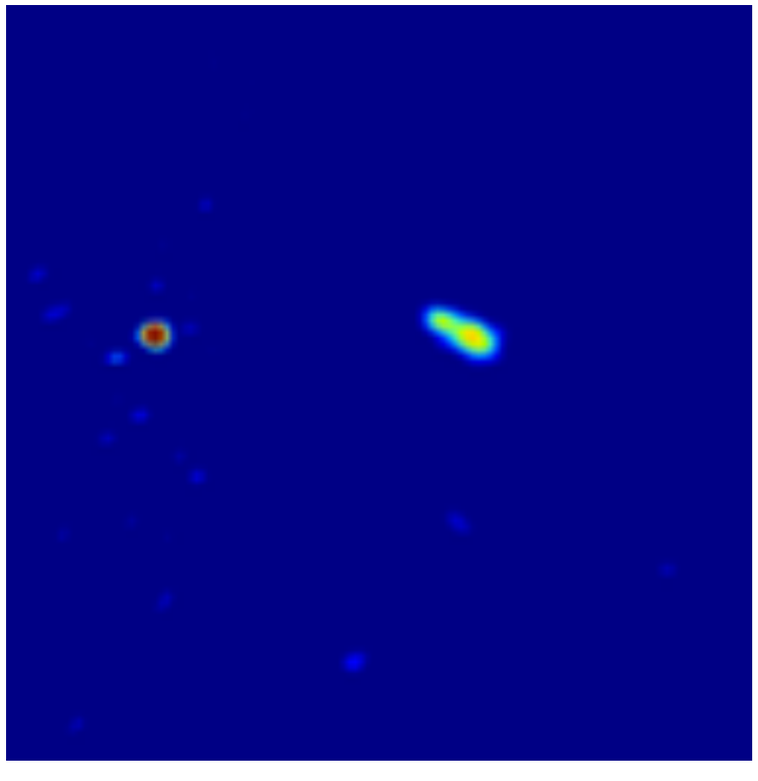
127-133 MHz



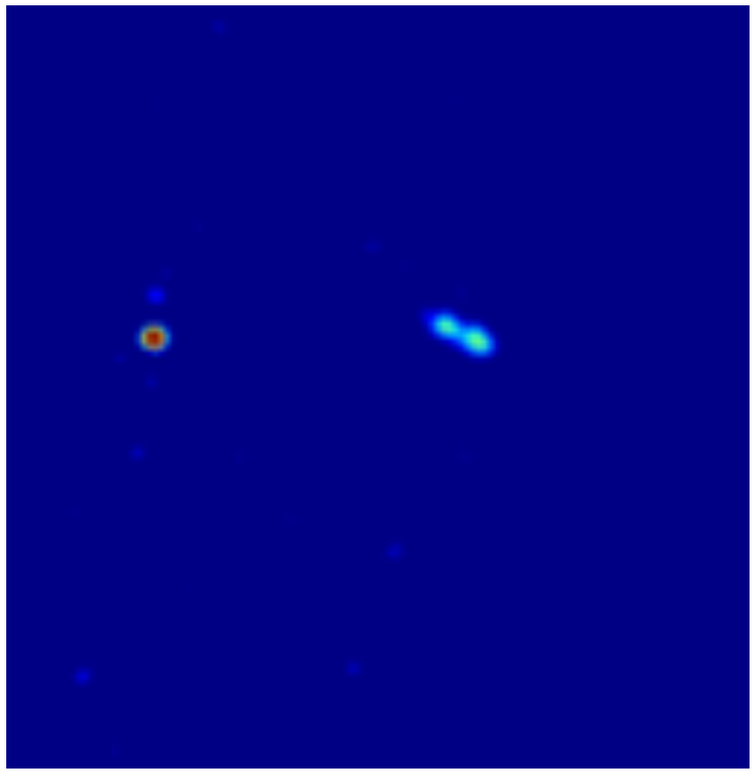
133-141 MHz



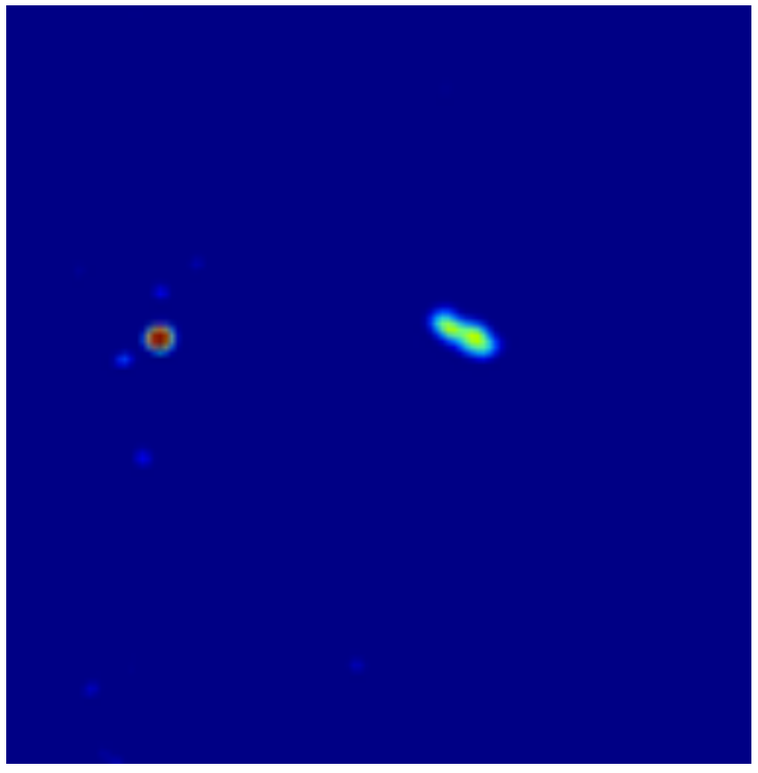
141-149 MHz



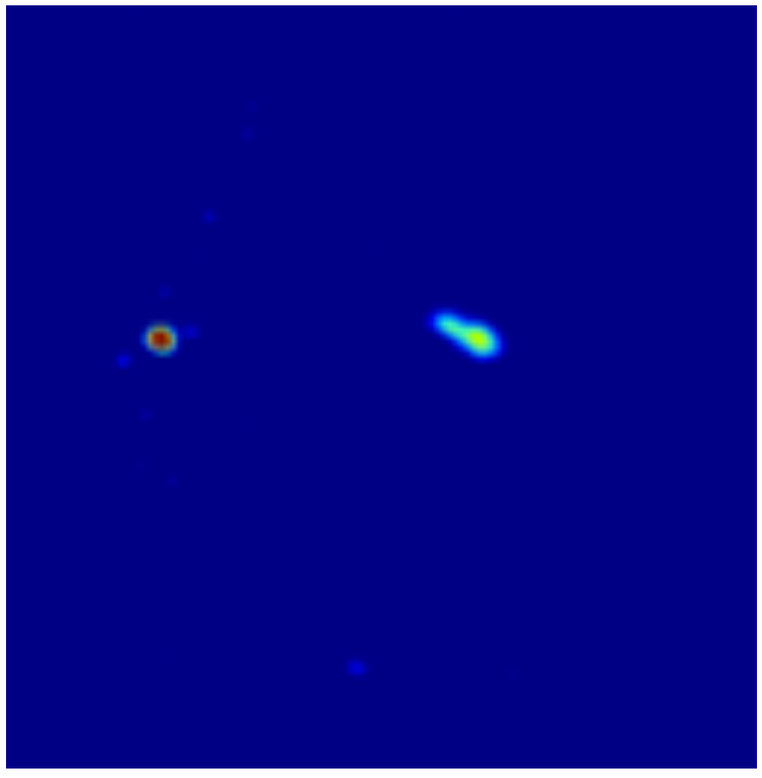
150-157 MHz



158-166 MHz

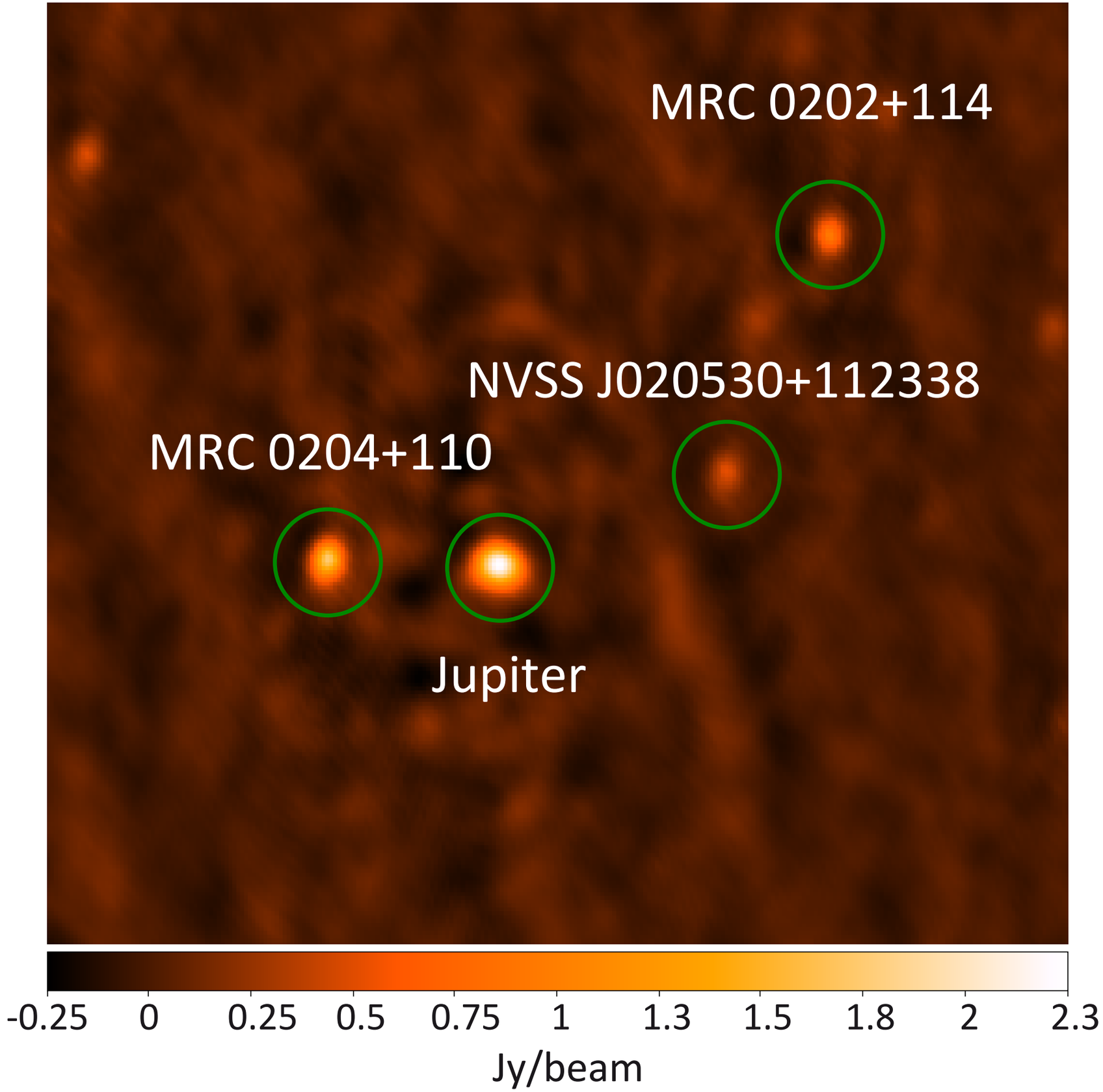


166-172 MHz

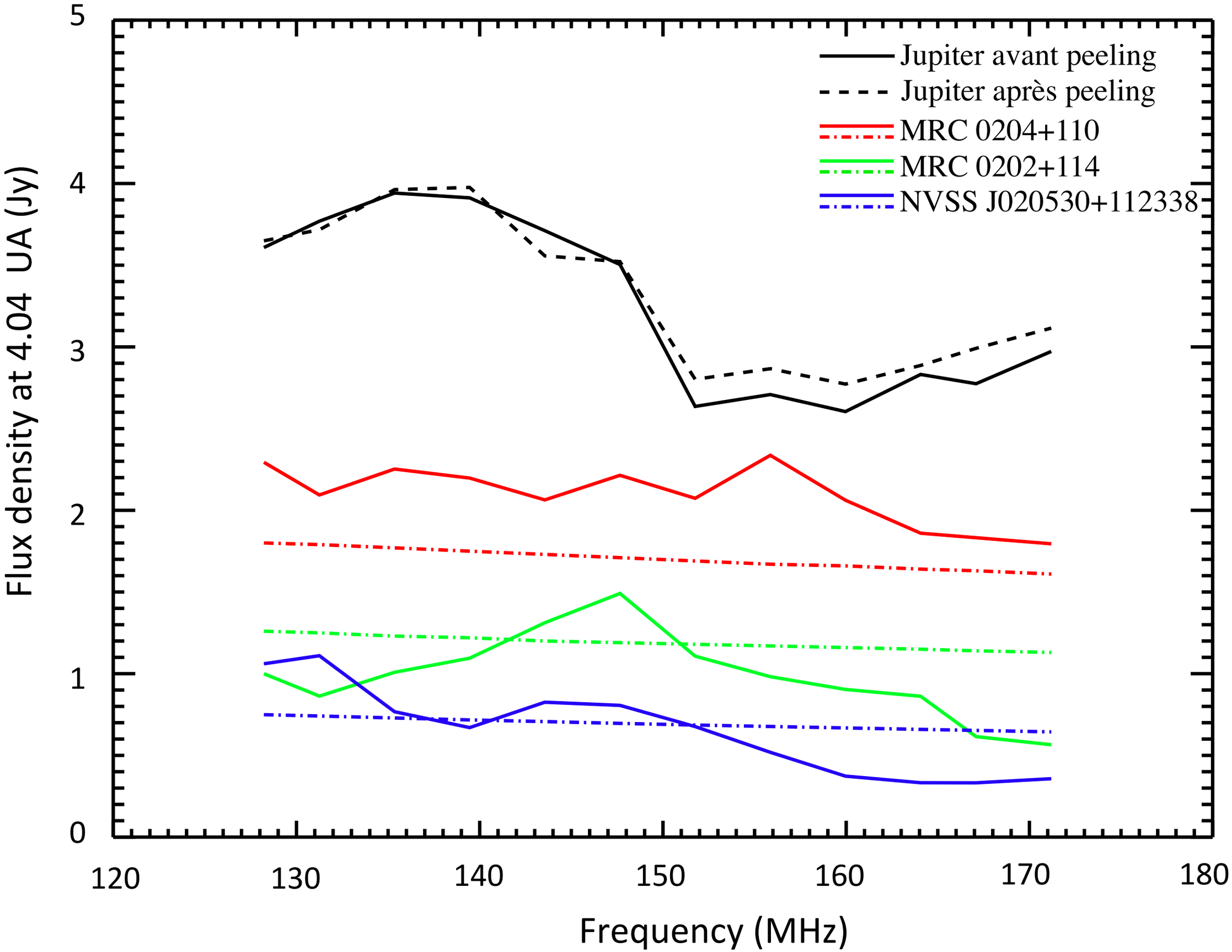


Integrated flux density

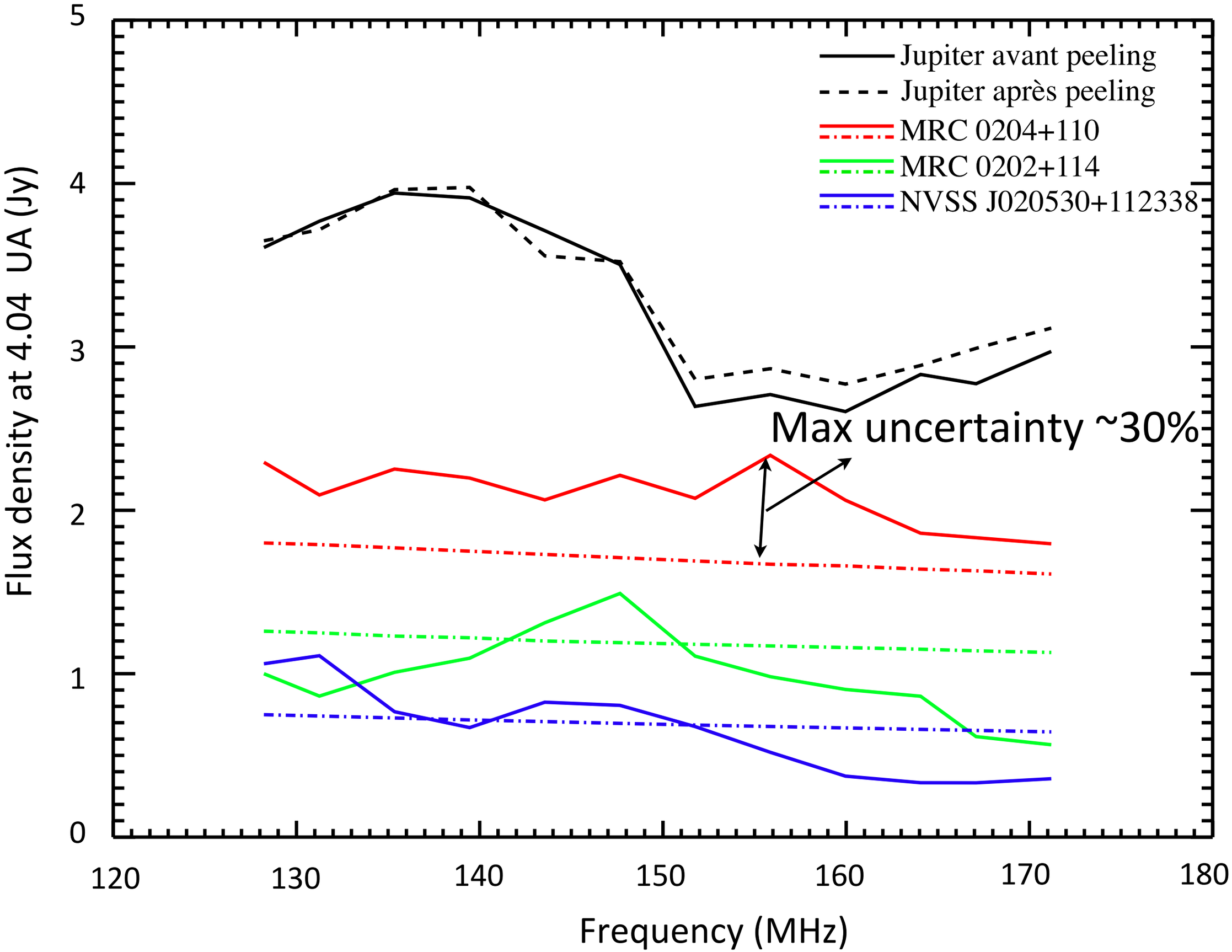
- **Nearby sources around Jupiter in data before source substraction**

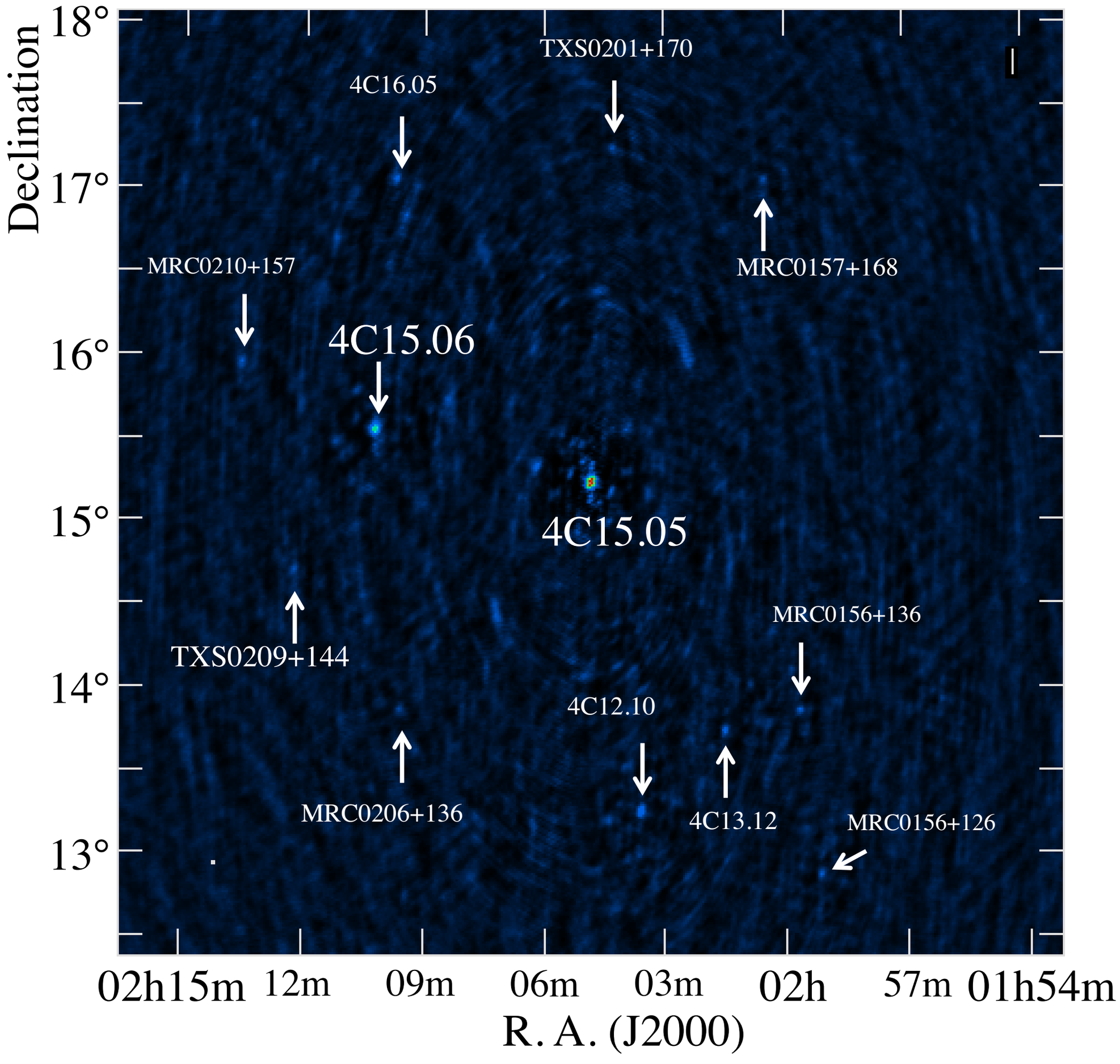


Integrated flux density



Integrated flux density



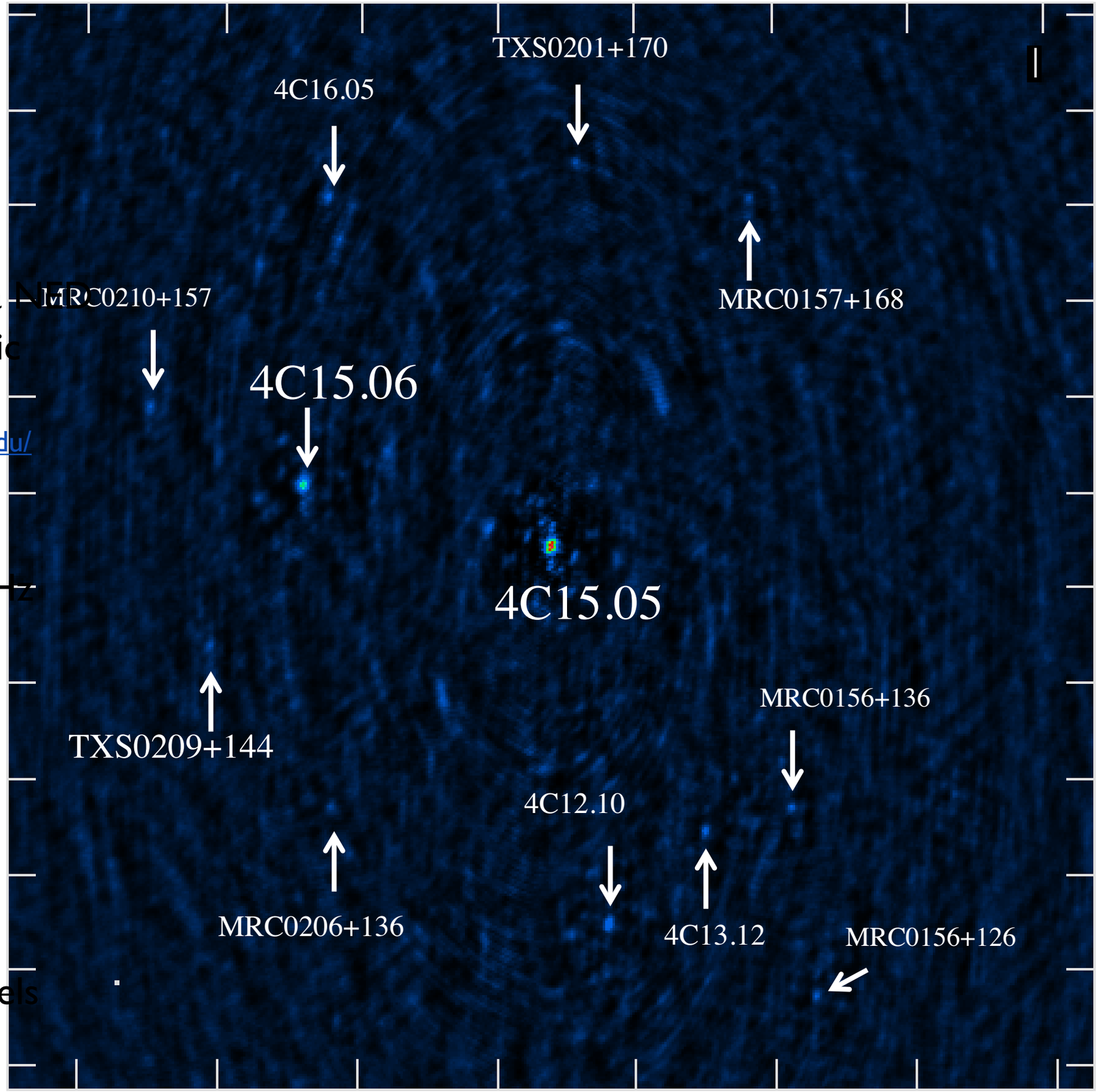

Declination
18°
17°
16°
15°
14°
13°
TXS0201+170
4C16.05
MRC0210+157
MRC0157+168
4C15.06
4C15.05
TXS0209+144
MRC0156+136
4C12.10
MRC0206+136
4C13.12
MRC0156+126
02h15m
12m
09m
06m
03m
02h
57m
01h54m
R. A. (J2000)

- Identification via NED (Nasa Extragalactic Database)
http://ned.ipac.caltech.edu/

- 4C15.05
6.5 Jy @ 160 MHz

- Other sources
~1-5 Jy

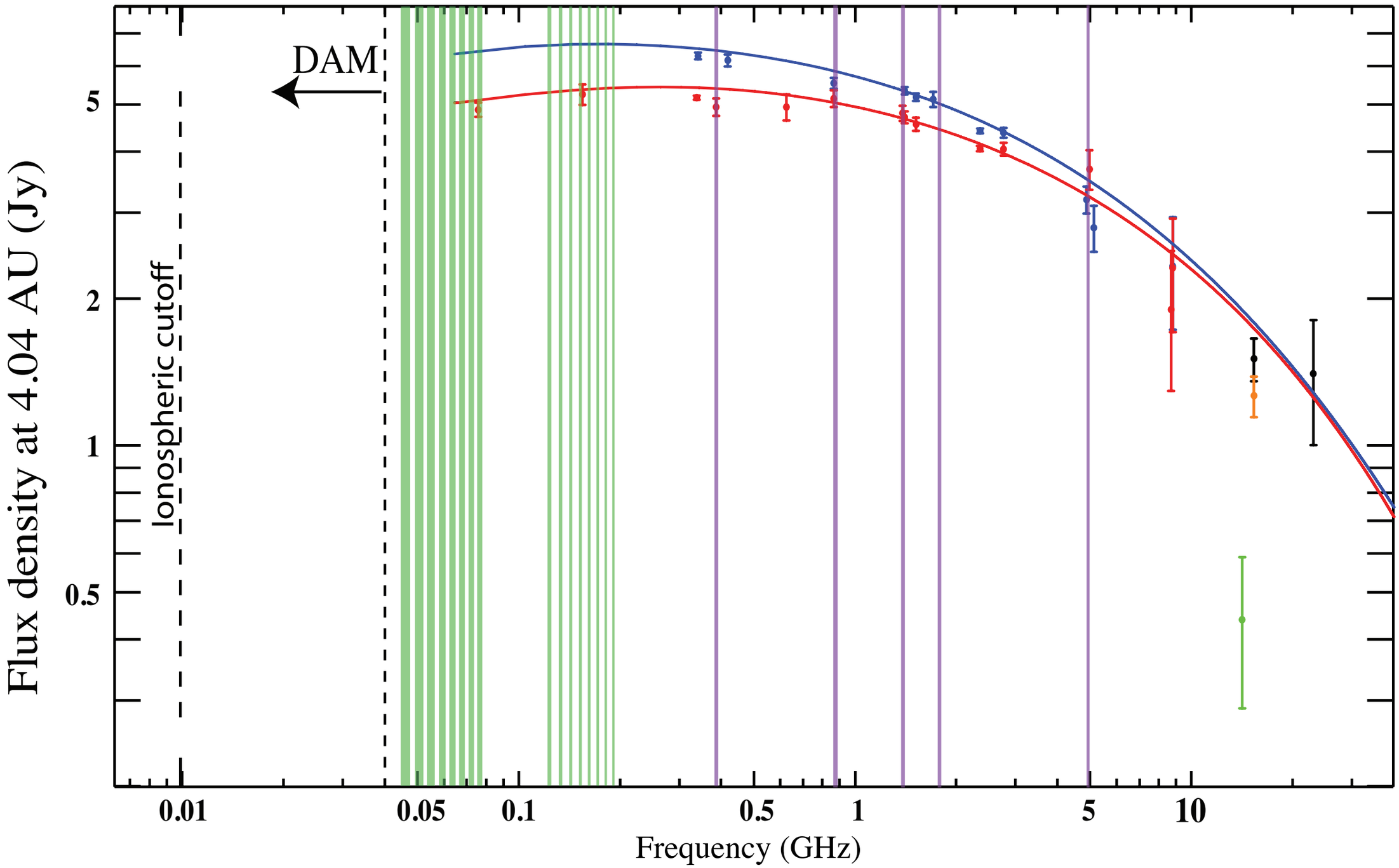
- Image over
10 SB
uv=0.2-4 kλ,
2048 x 2048 pixels
5°x5°



LC0_006 (de Pater et al.)

- **LOFAR (LBA & HBA) + WSRT (6 cm → 78 cm)**
- **Observed in 2013:** **LOFAR: 2x5h45**
- **Allocated time 11h50** **WSRT: 2x5h45**

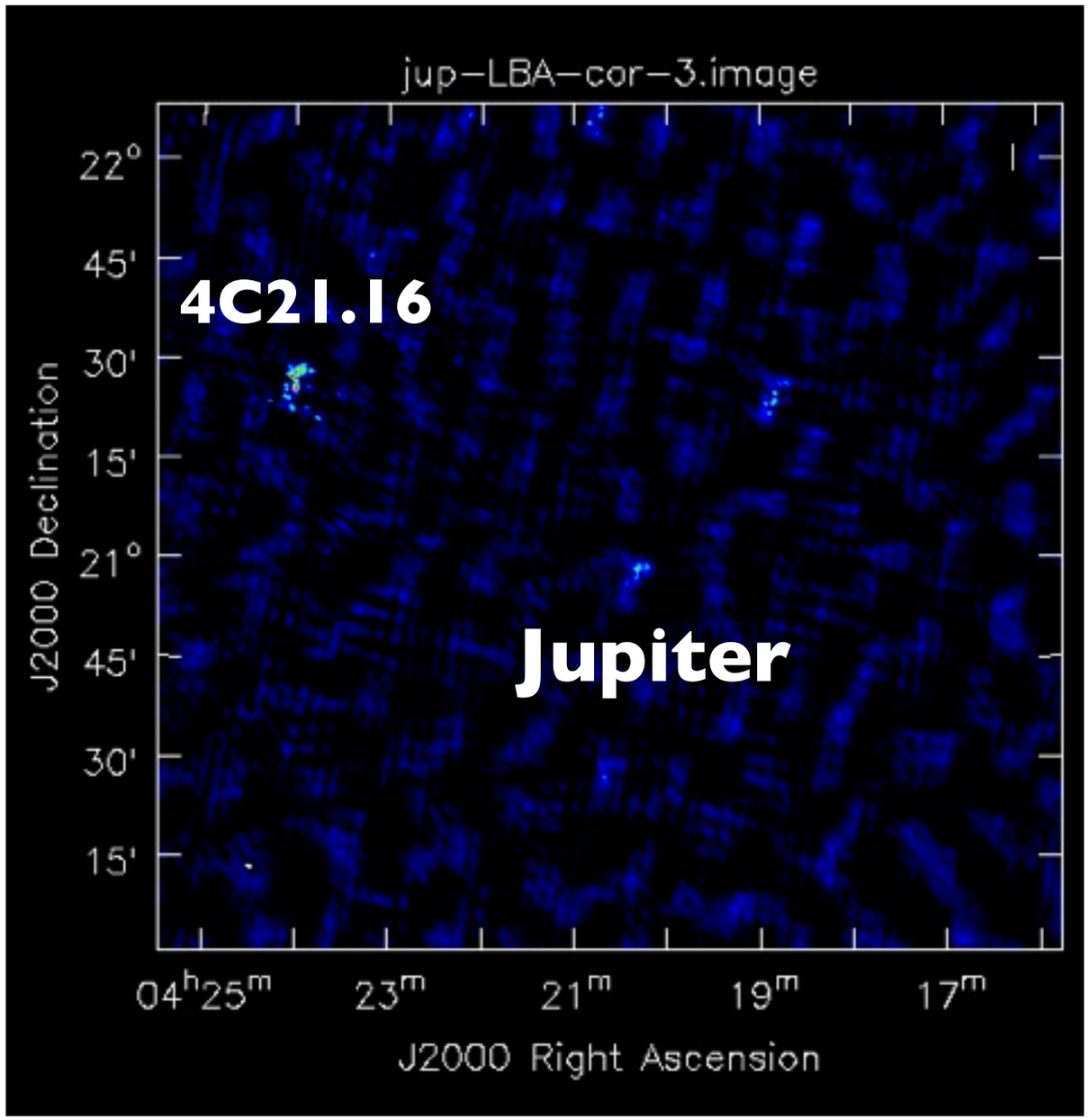
	LOFAR	WSRT
Day 1	HBA	6, 13, 21 cm
Day 2	LBA	21, 24, 78 cm



On going work...

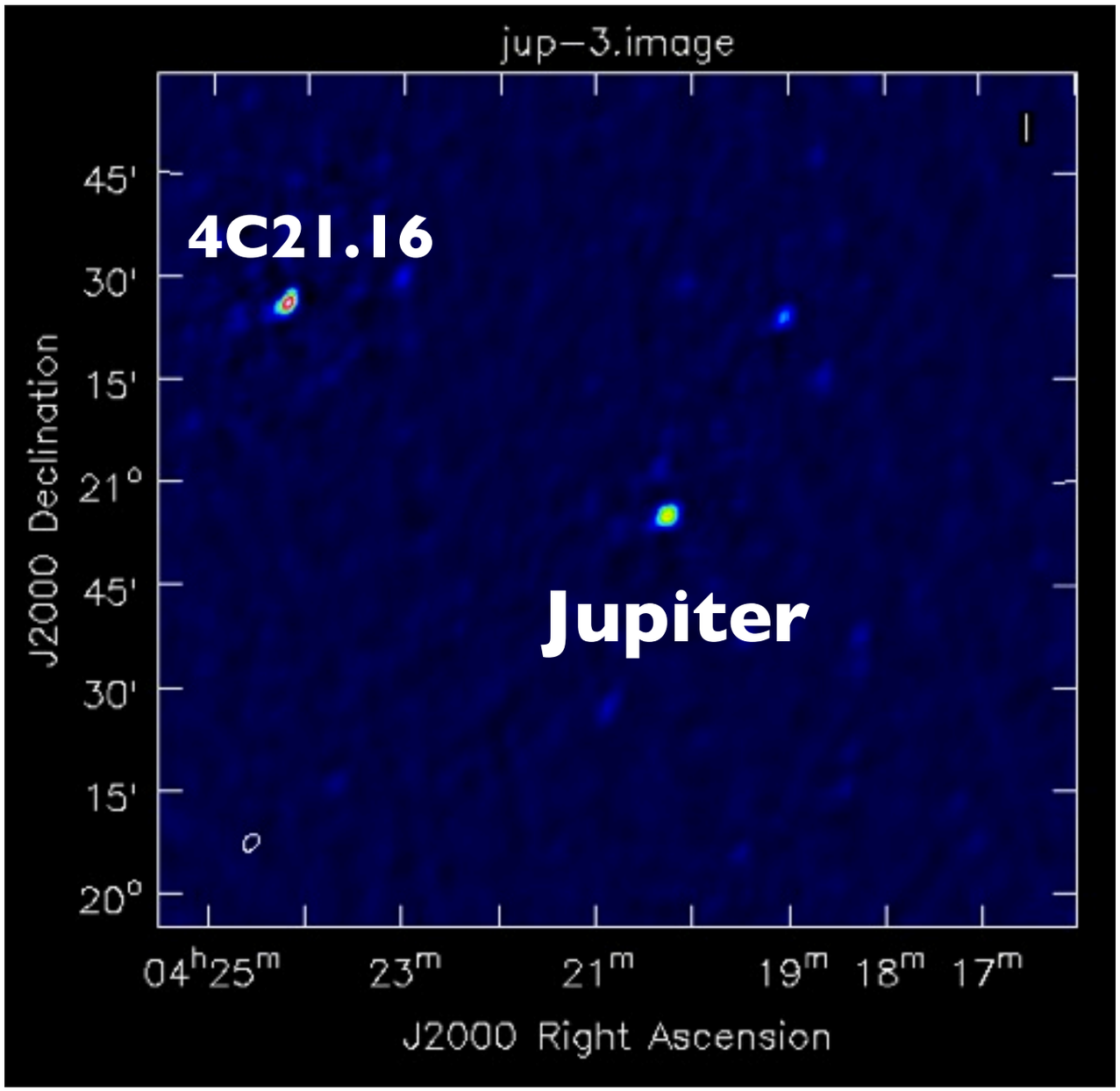
LBA

F=55 MHz - 10 SB - 37 stat - 2h



HBA

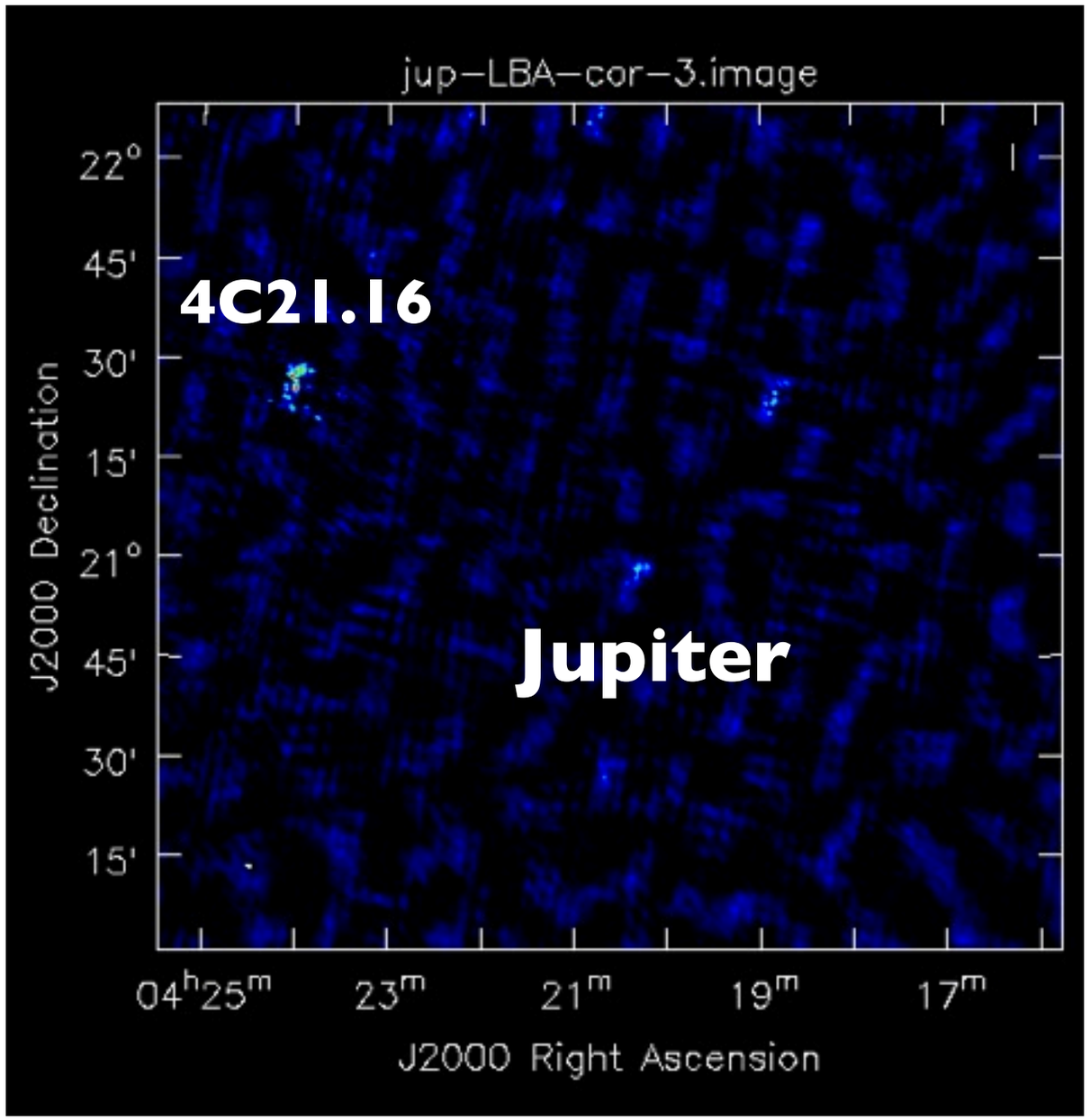
F=149MHz - 15 SB - Nstat=57 (HBA DUAL) - 2h



On going work...

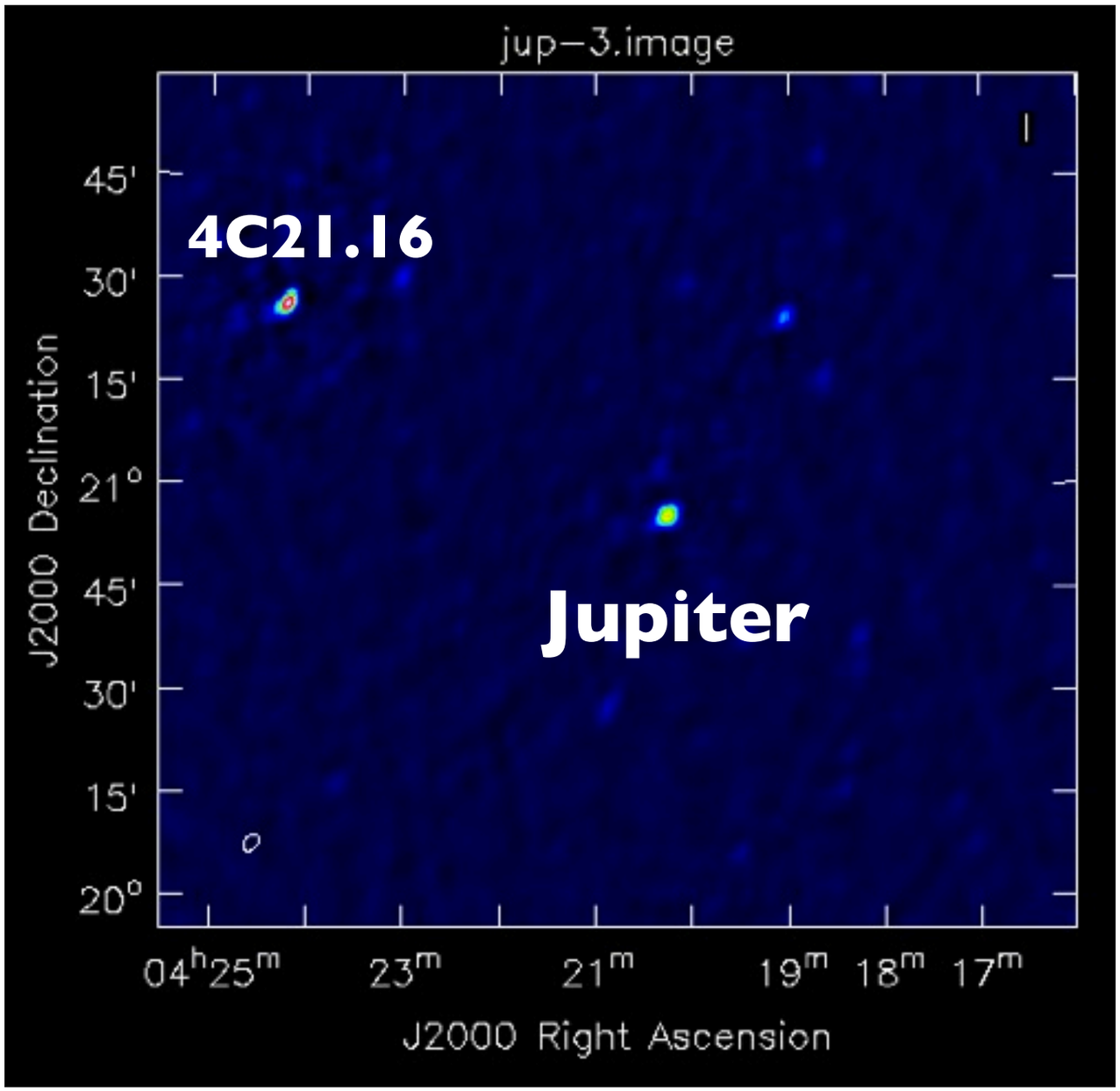
LBA

F=55 MHz - 10 SB - 37 stat - 2h



HBA

F=149MHz - 15 SB - Nstat=57 (HBA DUAL) - 2h

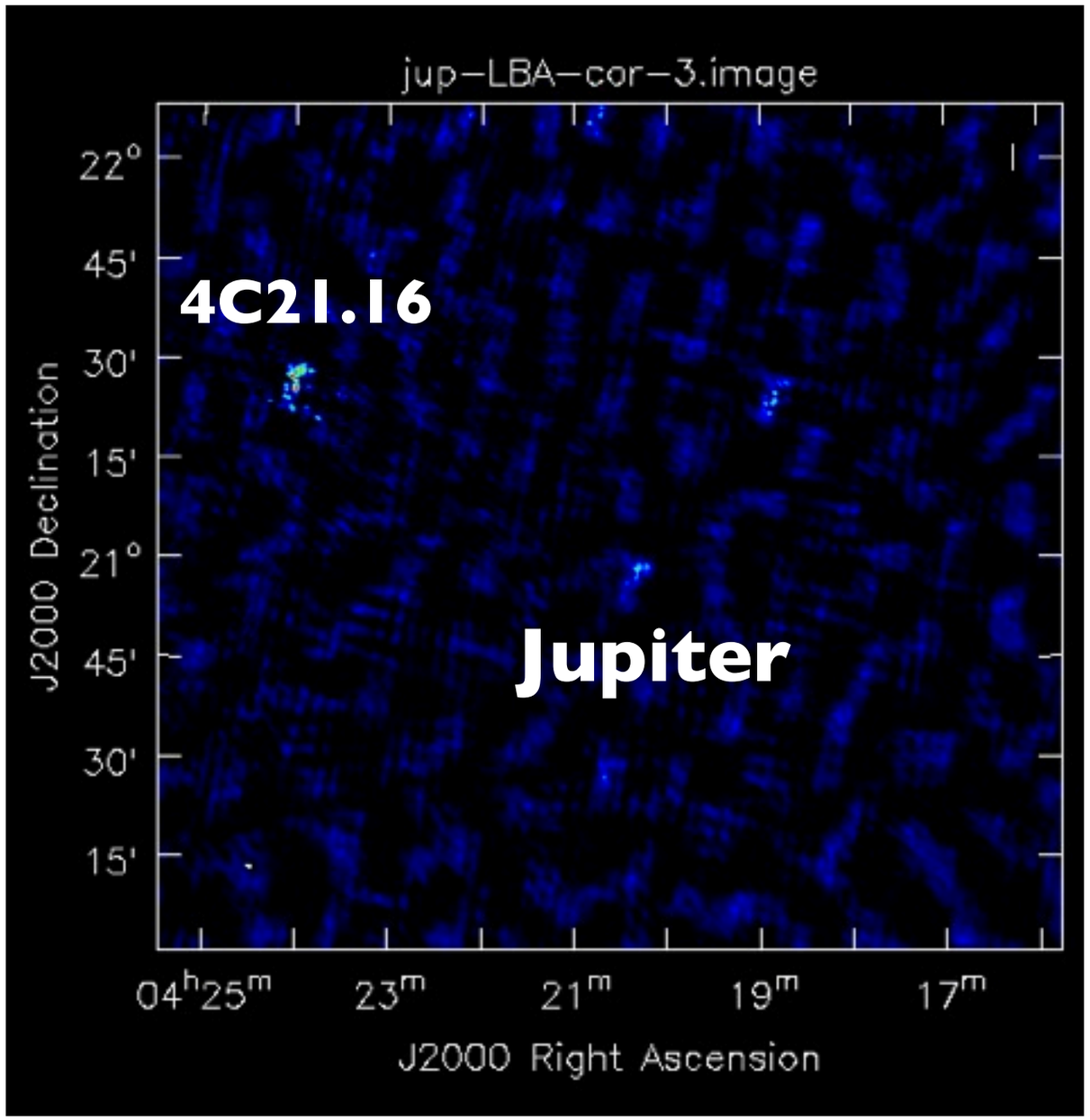


- full study on-going...
  spectrum, resolved emission, comp. with WSRT, temporal variability...

On going work...

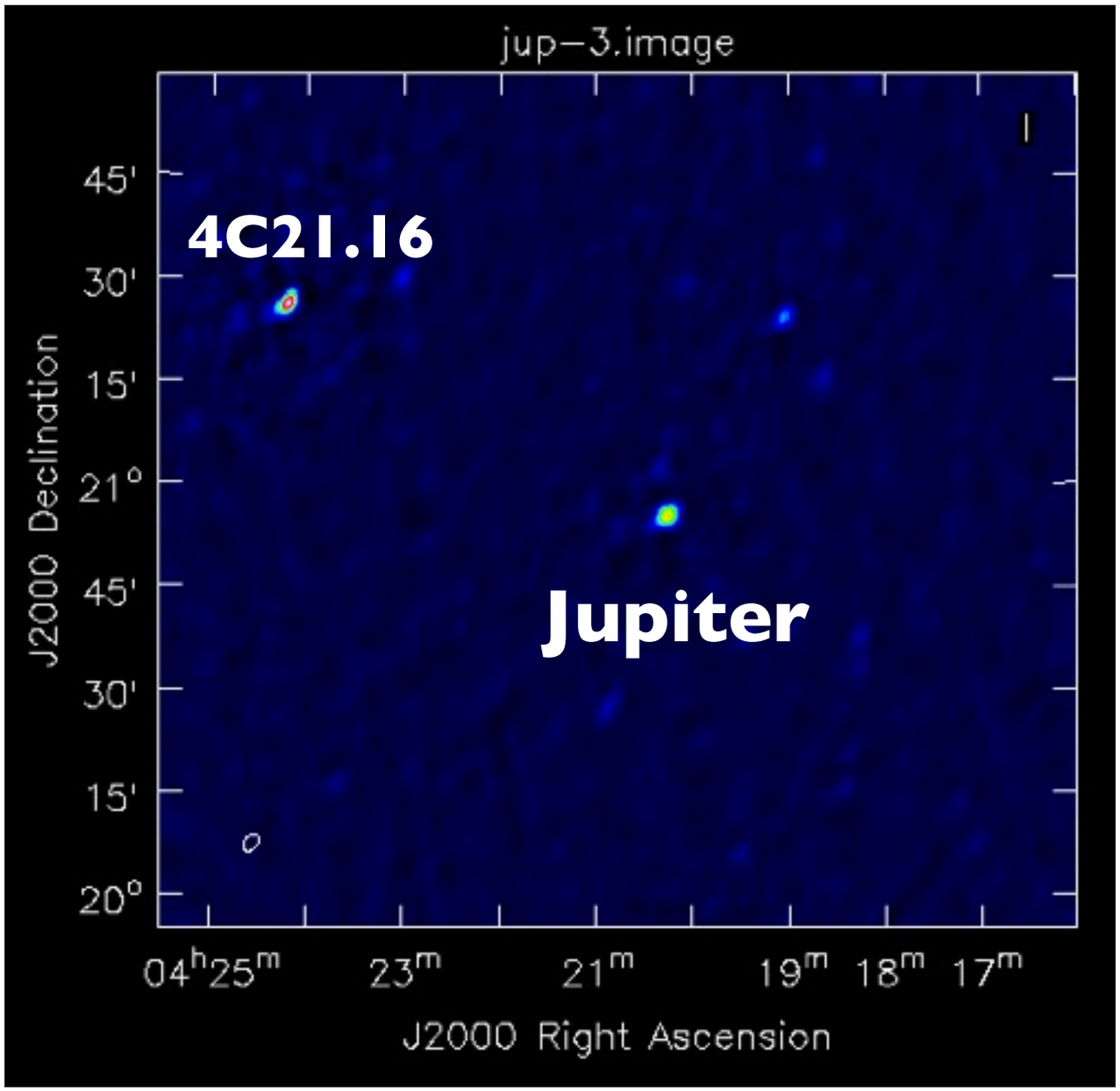
LBA

F=55 MHz - 10 SB - 37 stat - 2h



HBA

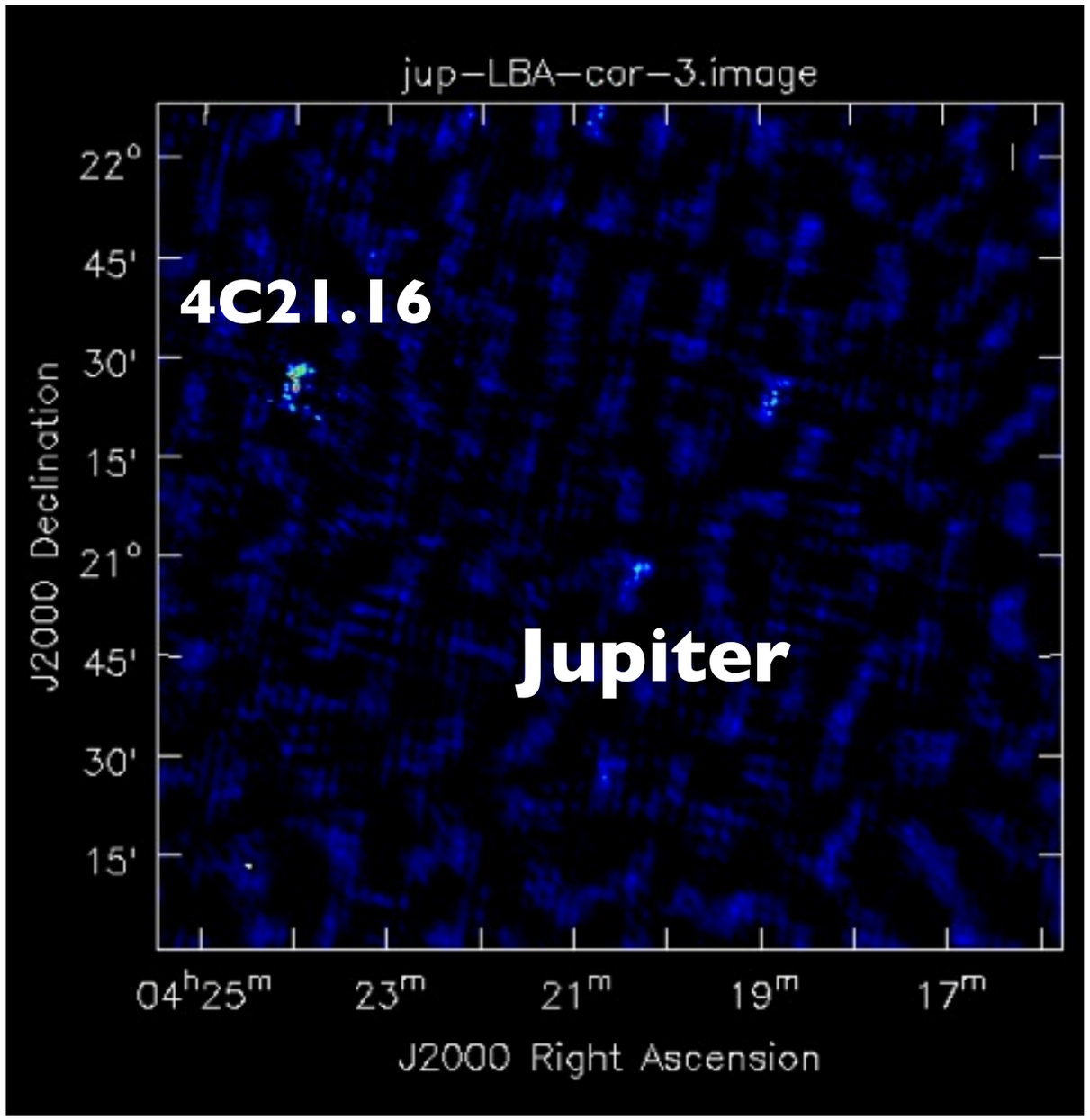
F=149MHz - 15 SB - Nstat=57 (HBA DUAL) - 2h



On going work...

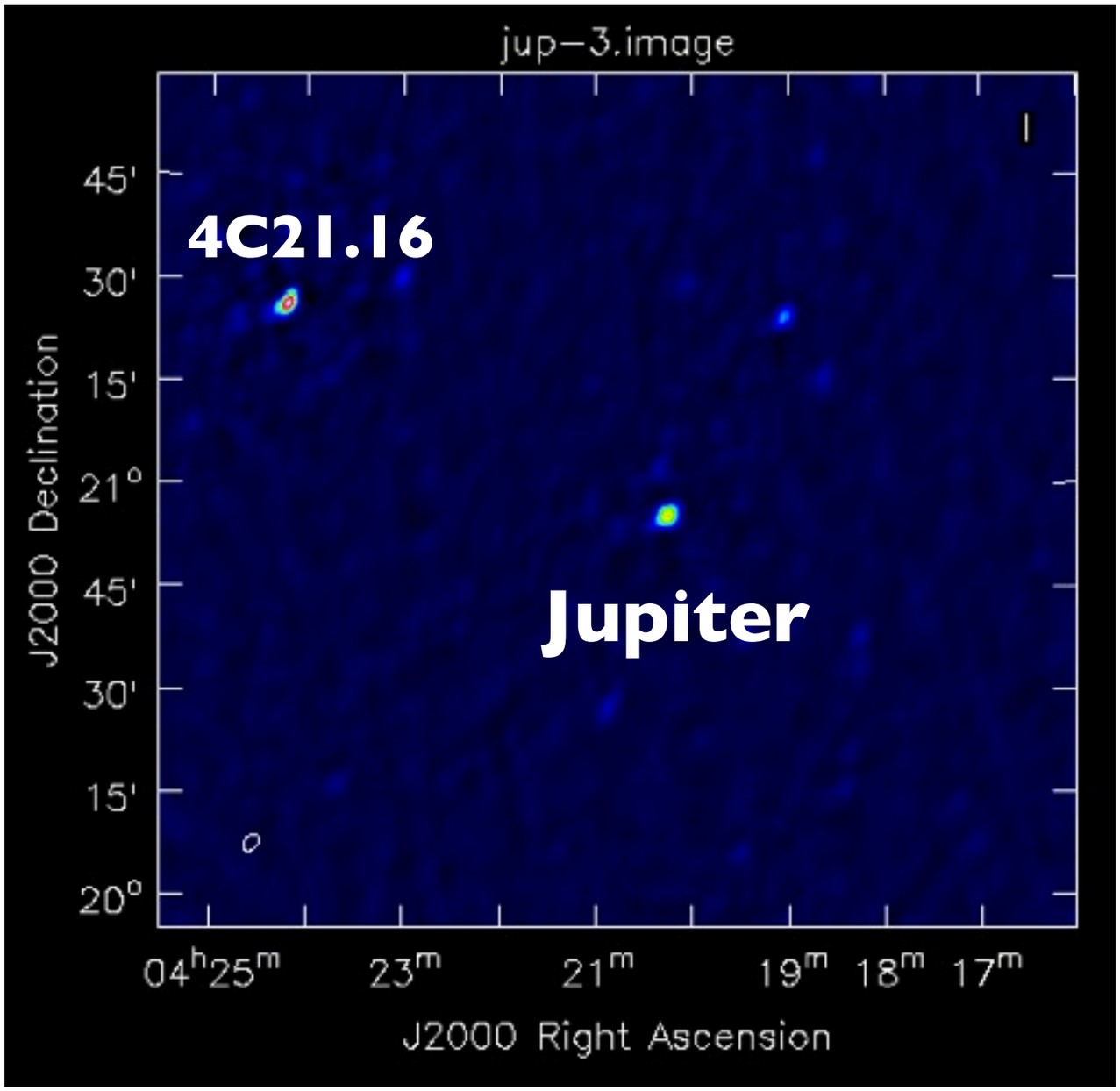
LBA

F=55 MHz - 10 SB - 37 stat - 2h

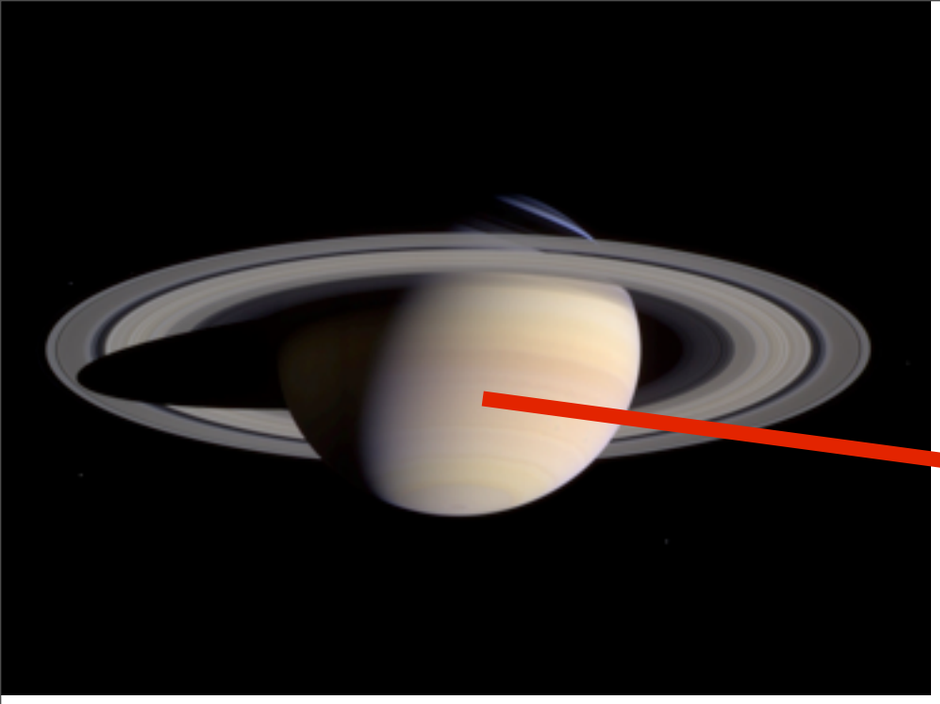


HBA

F=149MHz - 15 SB - Nstat=57 (HBA DUAL) - 2h

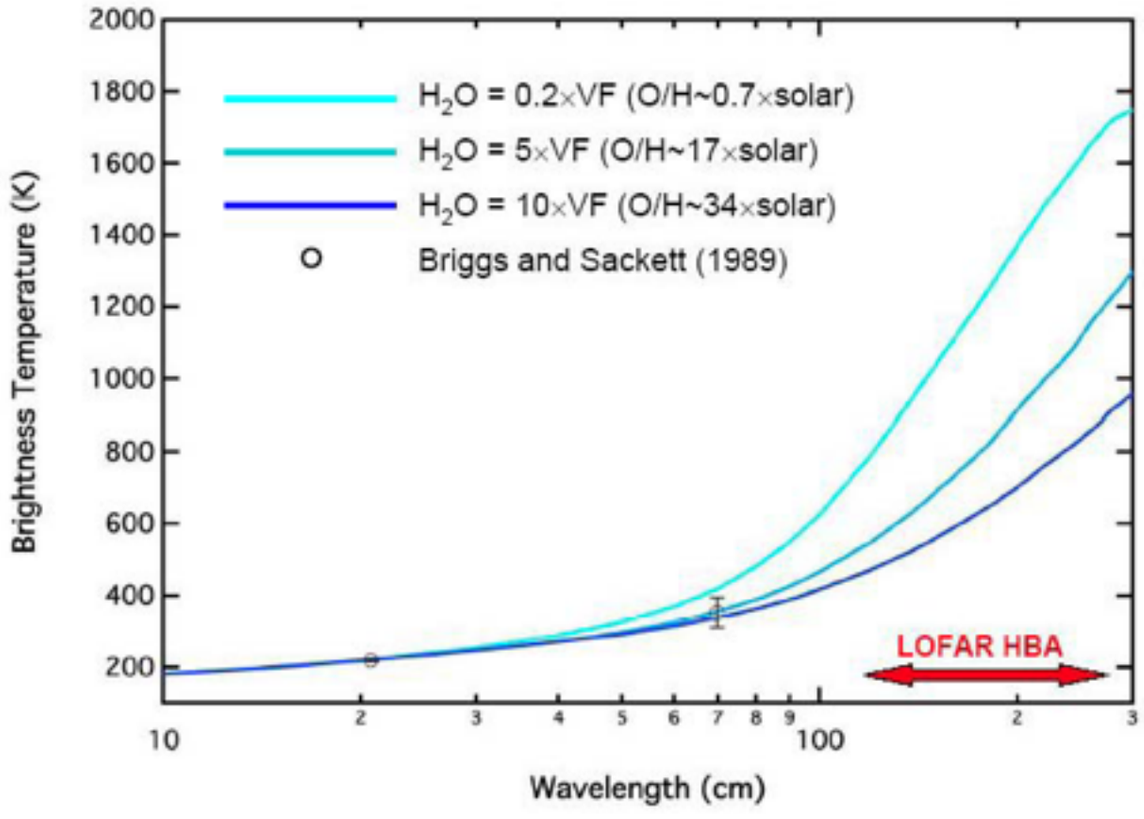


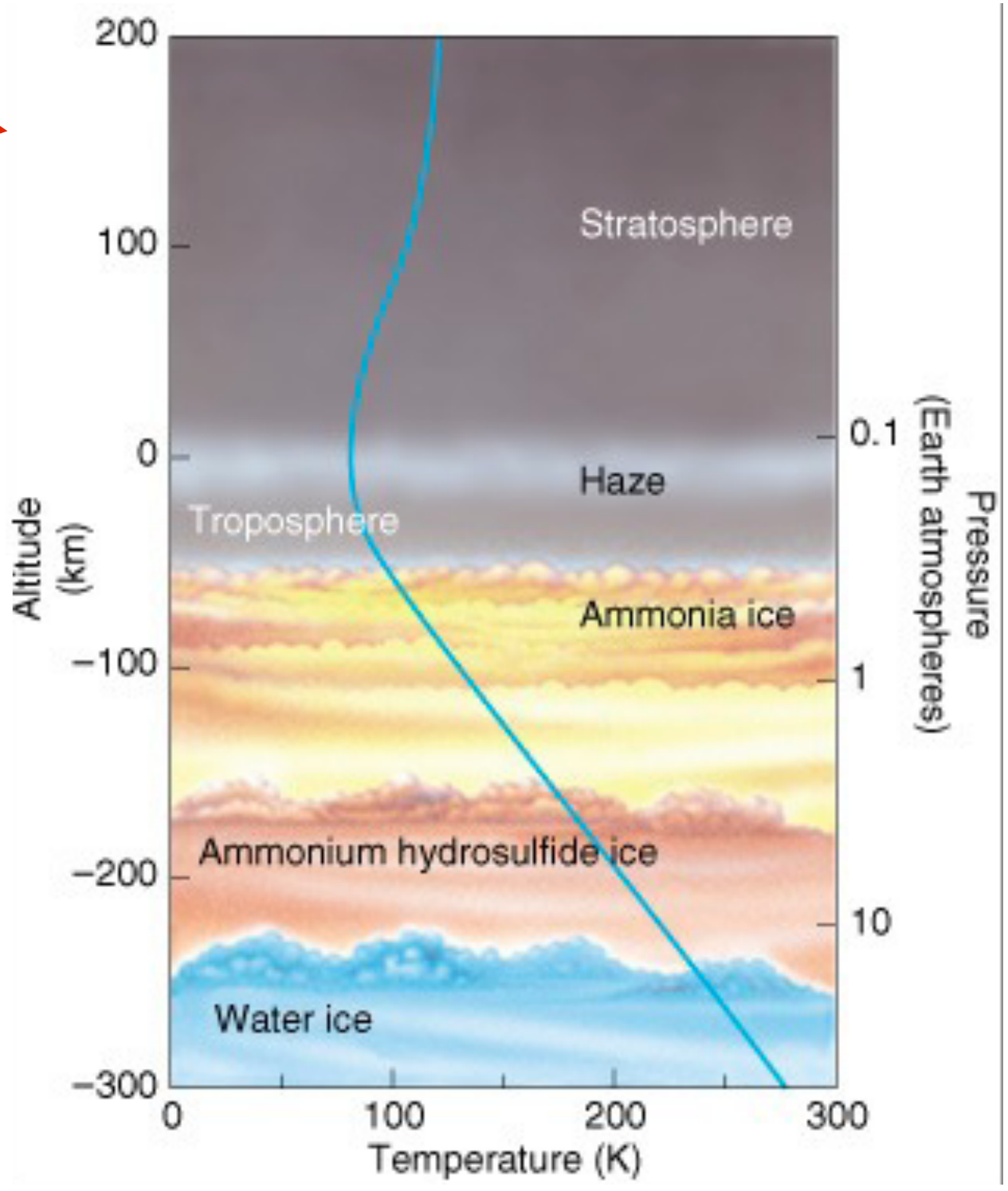
- full study on-going...
  spectrum, resolved emission, comp. with WSRT, temporal variability...



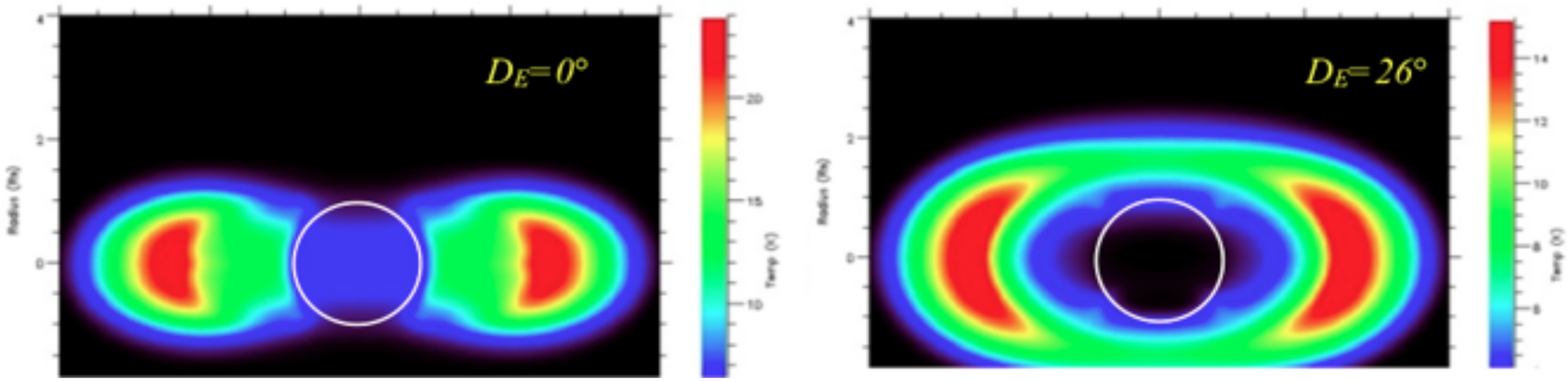
Saturn thermal emission (LC0_005, Courtin et al.)

See Daniel Gautier's talk tomorrow

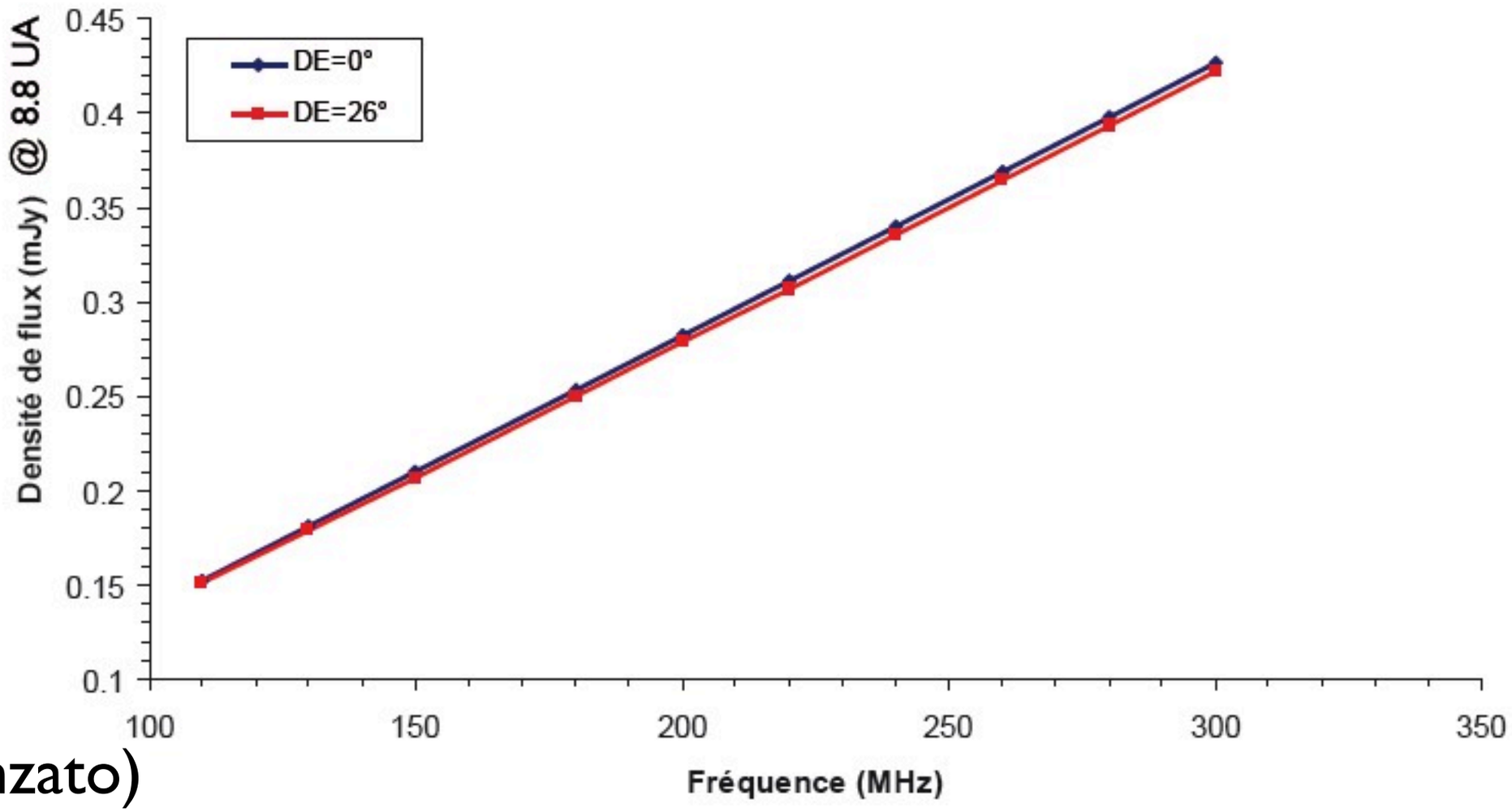




Next step **Residual Synchrotron radiation ?**



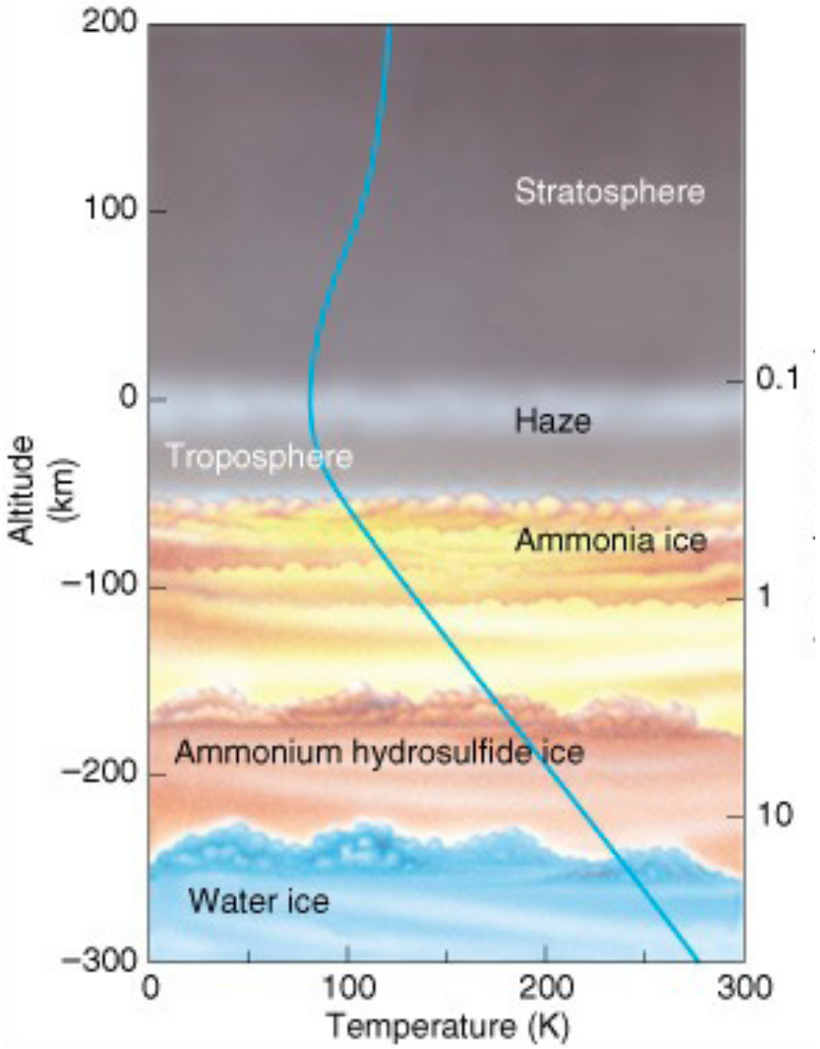
Simulated map of synchrotron emission (110-300 MHz)



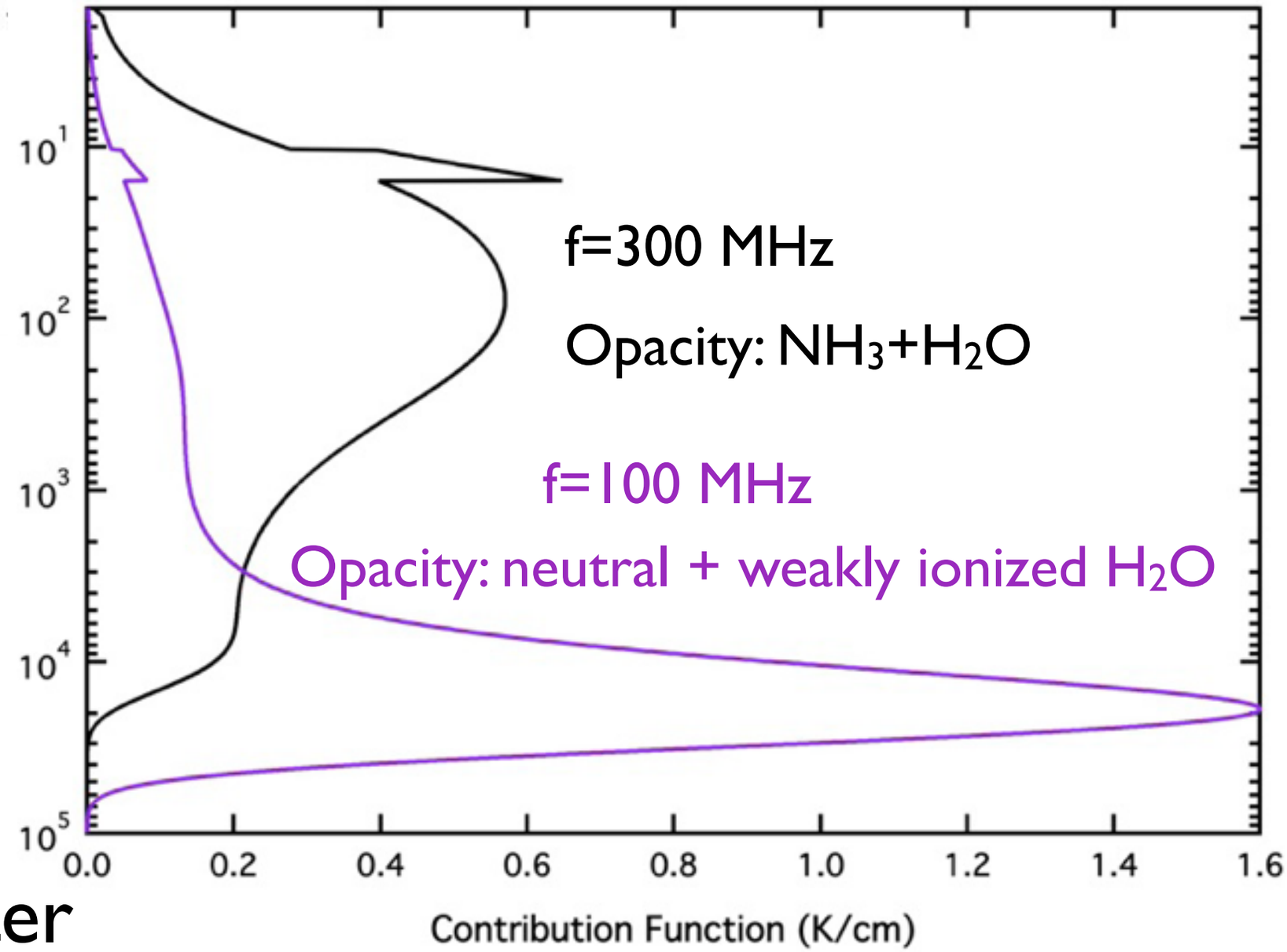
(L. Lorenzato)

Saturn thermal emission (LC0_005, Courtin et al.)

- Probe deeply into Saturn atmosphere
- Measure the abundance of water



Contribution to the thermal emission



Hoffstadter