Ground-based perspective of PRE radioastronomy, from historical observations to modern giant facilities

Philippe Zarka

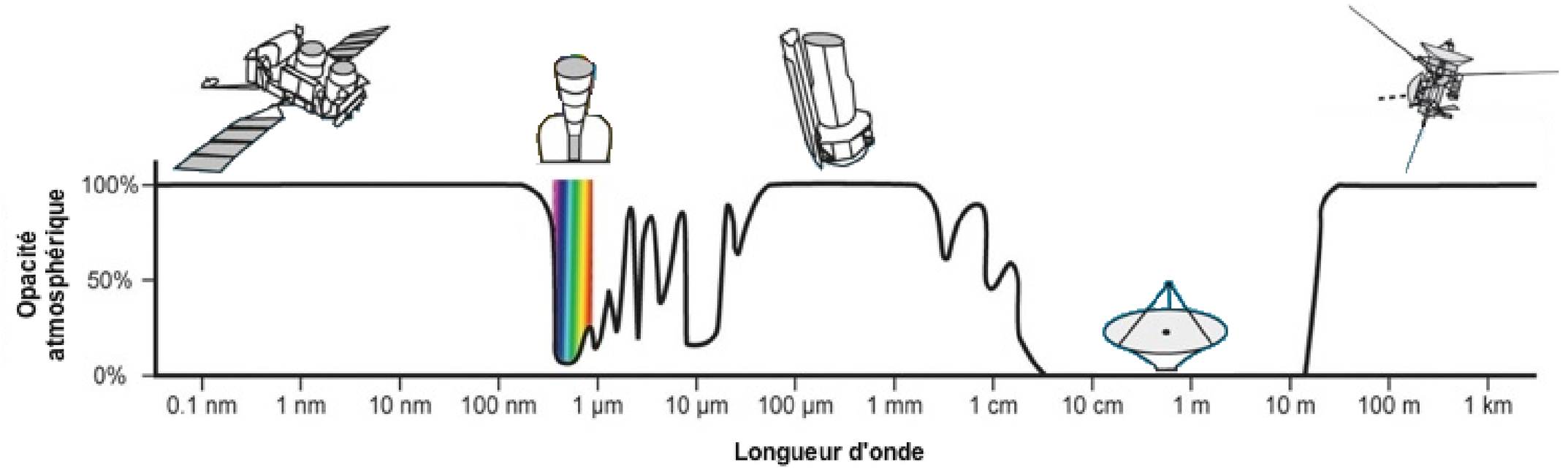
LIRA & ORN, CNRS - Observatoire de Paris - PSL

- Heroic times
  - Jupiter, Sun
- Single dishes and phased arrays: t-f studies
  - Jupiter (<1990, 1990-2000, 2000-2010, 2010-2020, 2020+)
  - Sun, Stars, Exoplanets
- Interferometers: imaging studies
  - Jupiter, Sun, Stars, Exoplanets
- Dynamic spectra (t-f) from imaging data
  - Stars, Exoplanets
- Prospects

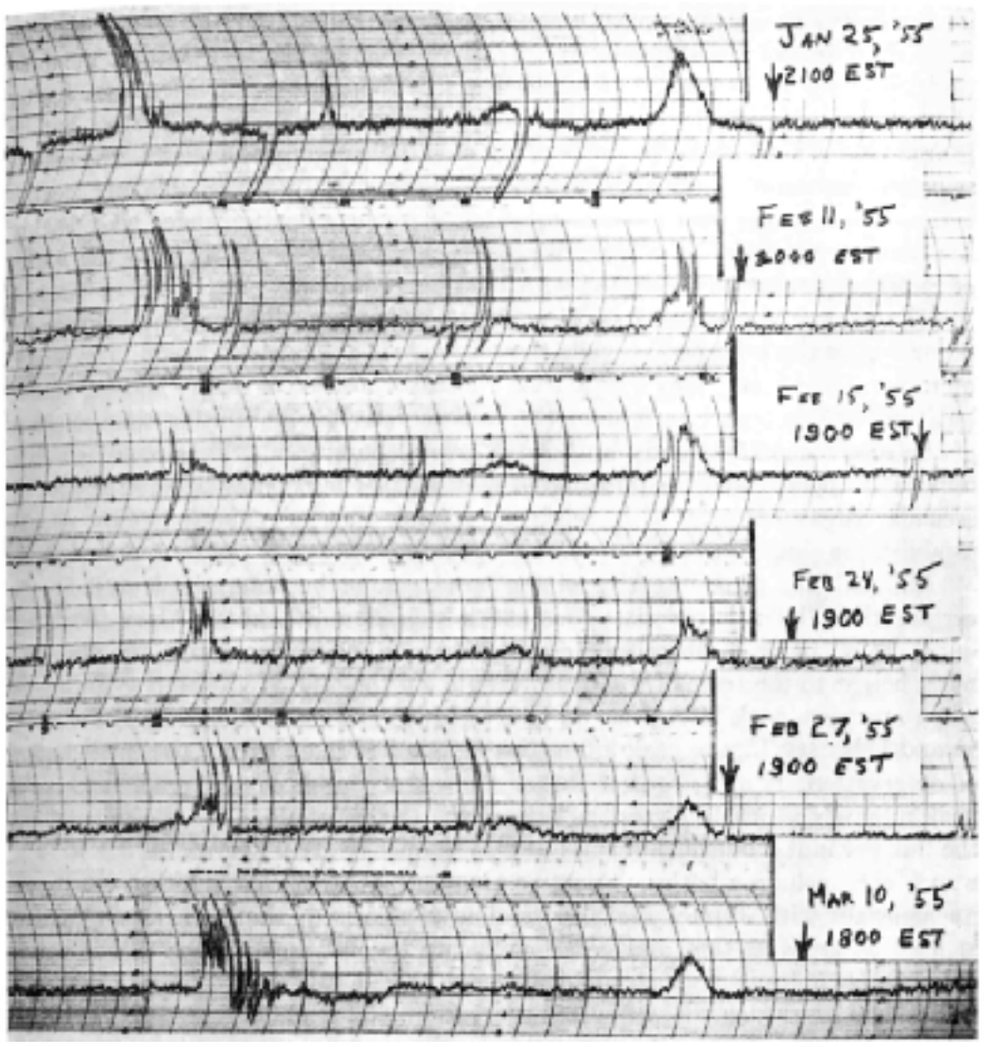
A sketchy, biased review ...

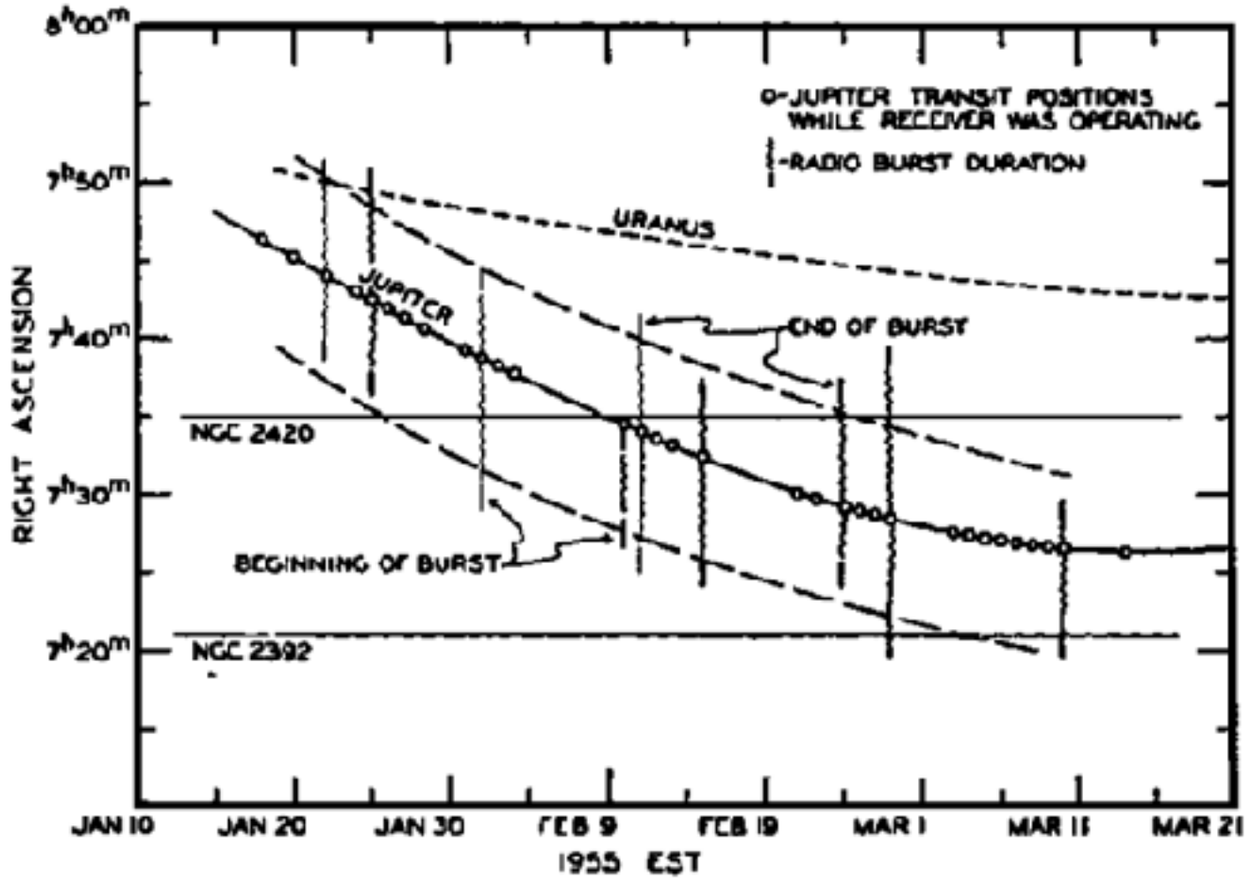
- Heroic times
  - Jupiter, Sun
- Single dishes and phased arrays: t-f studies
  - Jupiter (<1990, 1990-2000, 2000-2010, 2010-2020, 2020+)
  - Sun, Stars, Exoplanets
- Interferometers: imaging studies
  - Jupiter, Sun, Stars, Exoplanets
- Dynamic spectra (t-f) from imaging data
  - Stars, Exoplanets
- Prospects

Heroic times



Jupiter



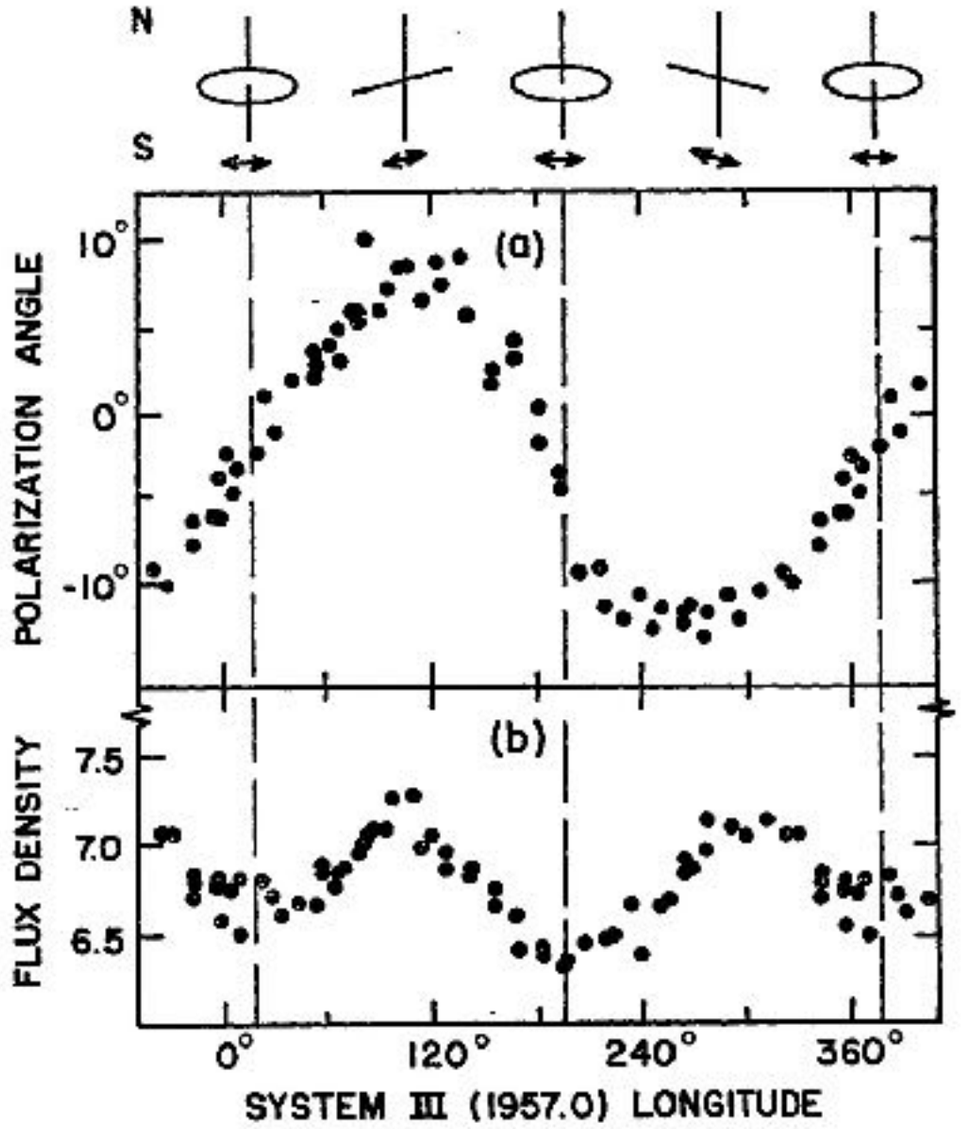


Mills Cross of Carnegie Institution, Washington, 22.2 MHz

[Burke & Franklin, 1955; Franklin & Burke, 1956]

→ electron cyclotron in 10 G B-field

Jupiter

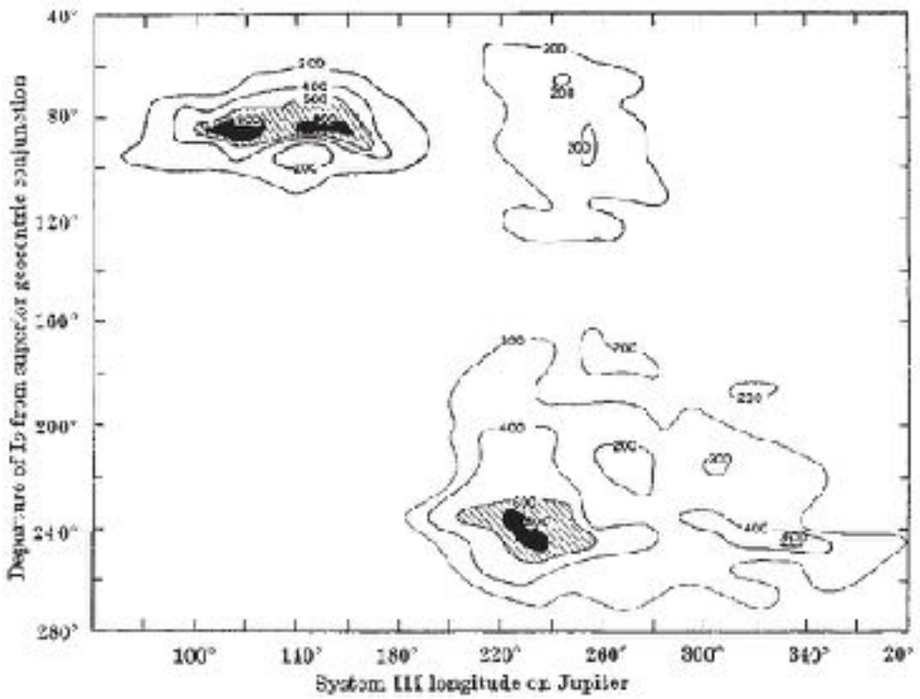


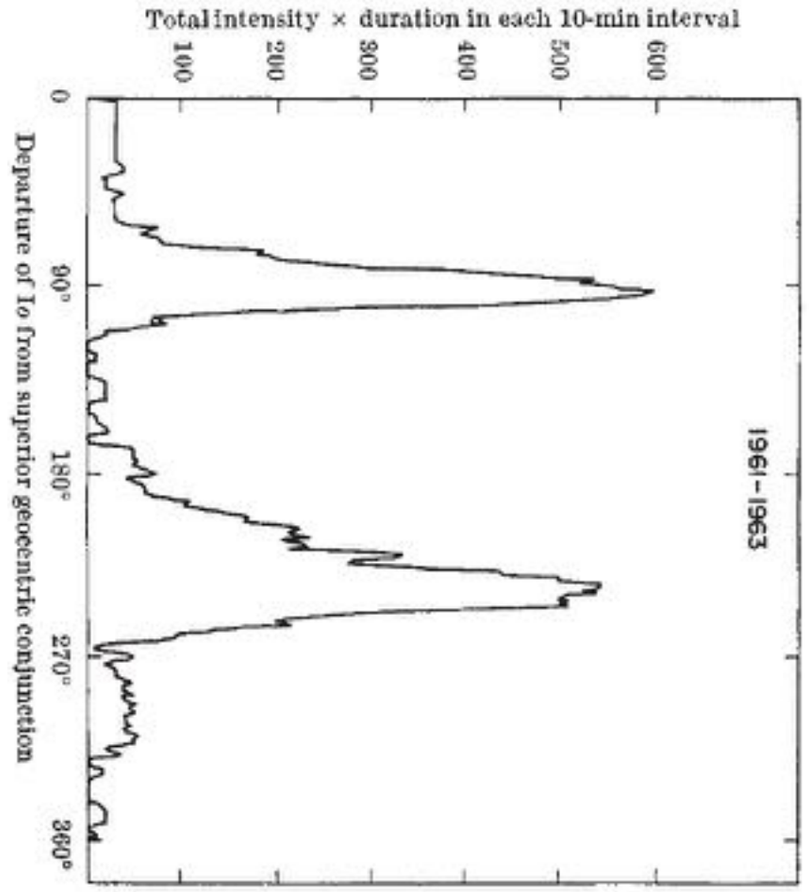
1-3 GHz

[Sloanaker, 1959; Roberts & Stanley, 1959; Roberts & Komesaroff, 1964]

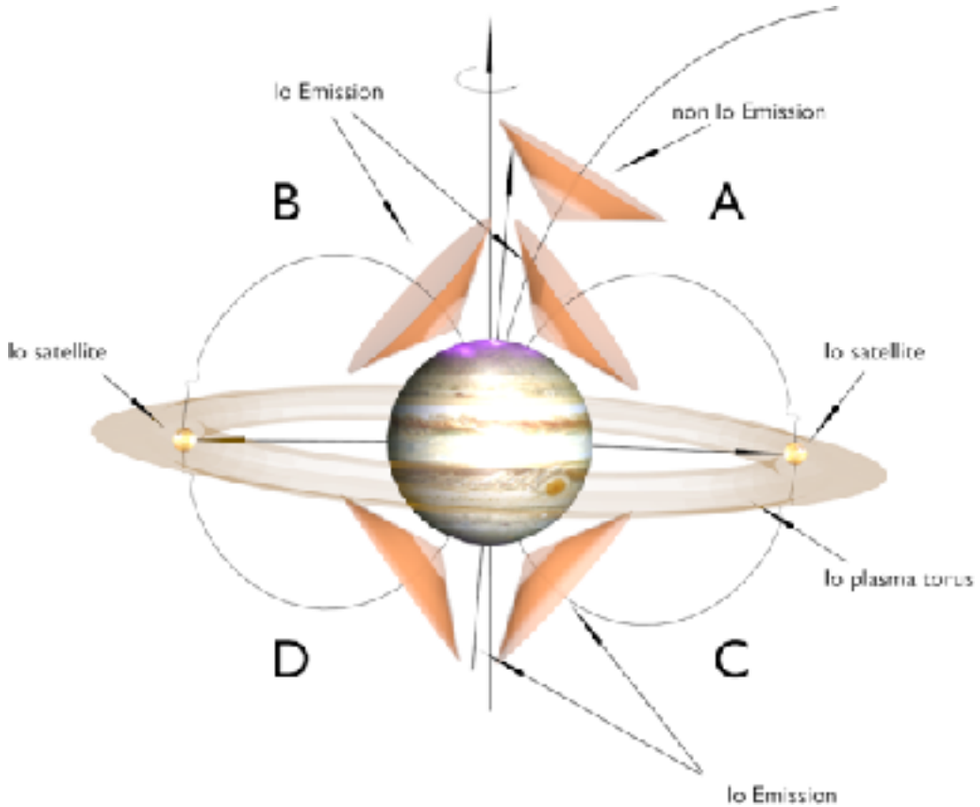
→ Jovian B dipole tilted by 10°

Jupiter



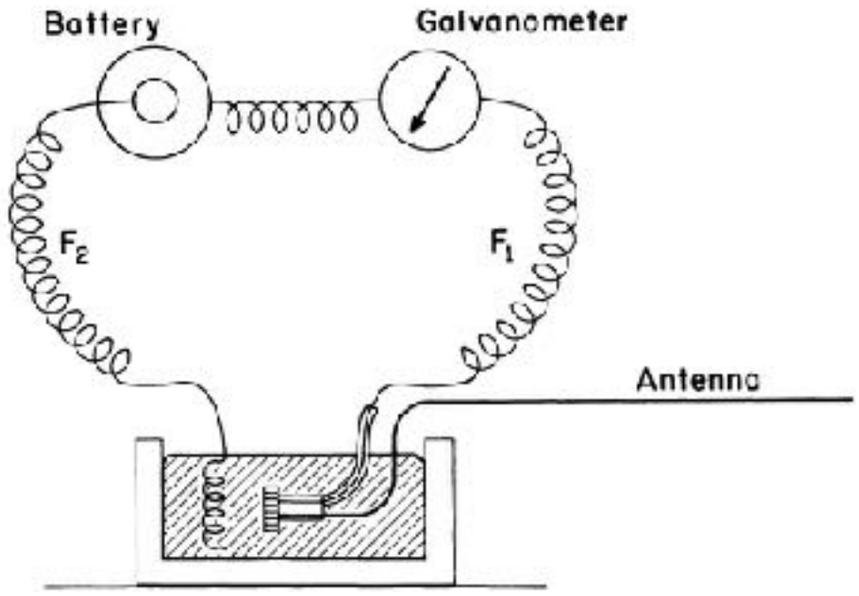


[Bigg, 1964]

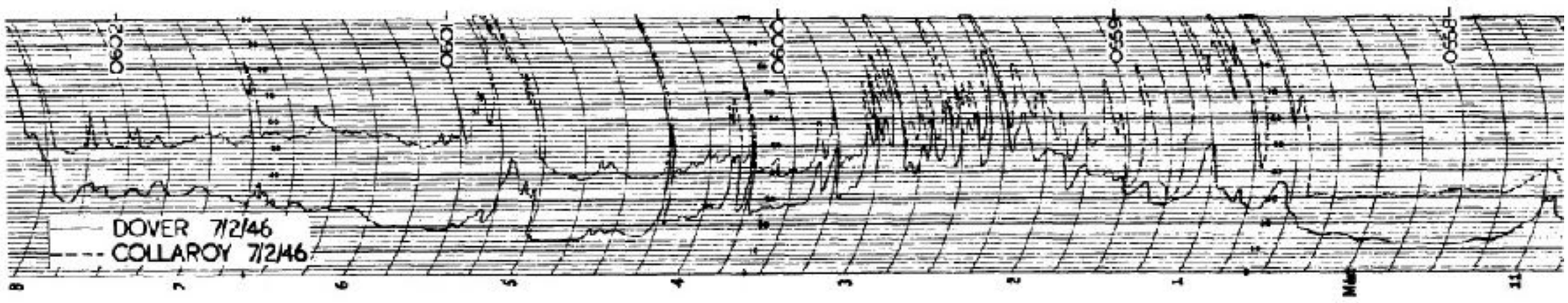


[Marques et al., 2017]

Sun



[Nordmann, 1902 ; Deslandres & Décombe, 1902]



[McCready et al., 1947]

→ Solar emission at 50-75 MHz [Hey, 1946]

& 200 MHz

- Heroic times
  - Jupiter, Sun
- Single dishes and phased arrays: t-f studies
  - Jupiter (<1990, 1990-2000, 2000-2010, 2010-2020, 2020+)
  - Sun, Stars, Exoplanets
- Interferometers: imaging studies
  - Jupiter, Sun, Stars, Exoplanets
- Dynamic spectra (t-f) from imaging data
  - Stars, Exoplanets
- Prospects

Single dishes & phased arrays: t-f studies

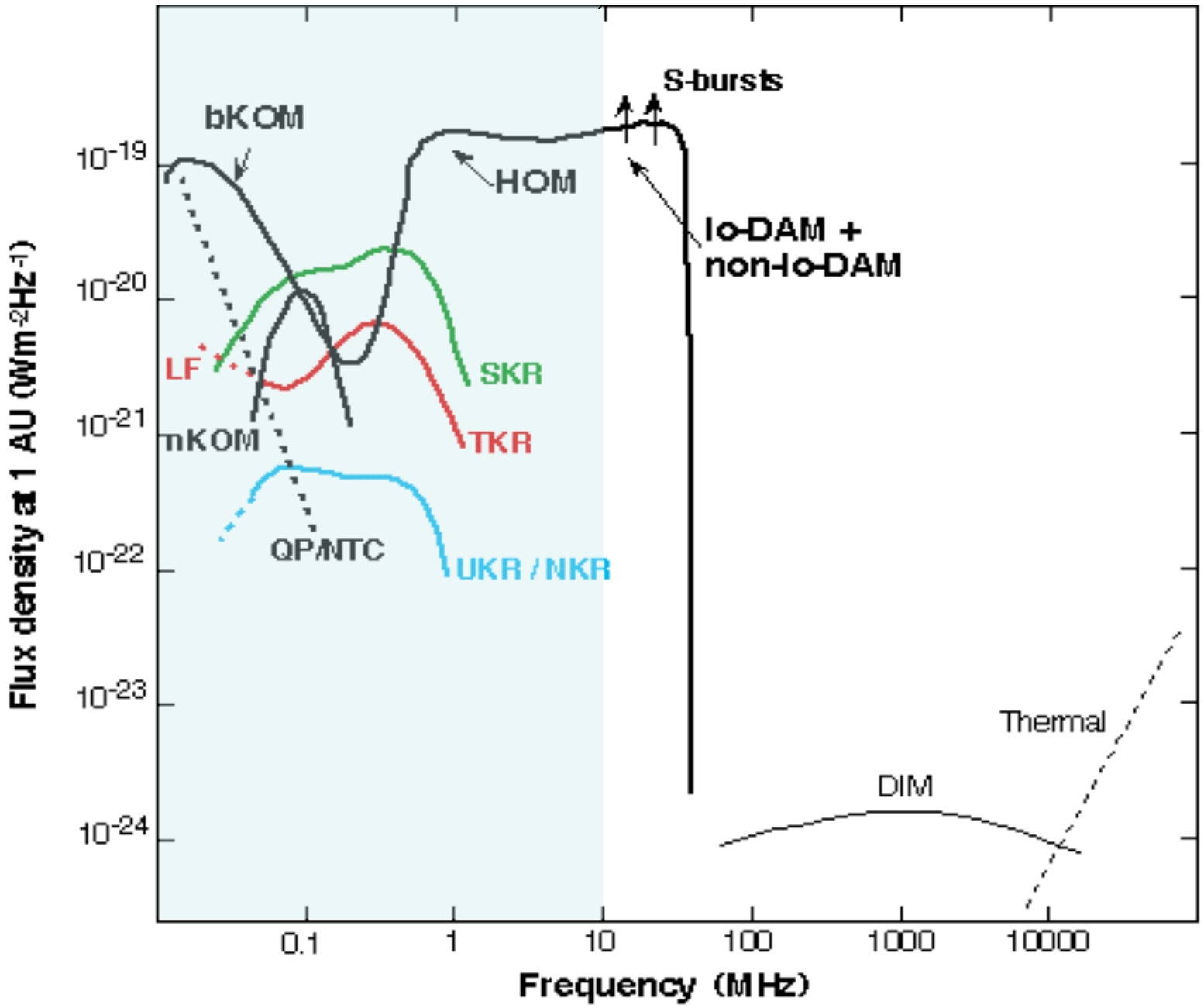
NDA

UTR-2

LWA

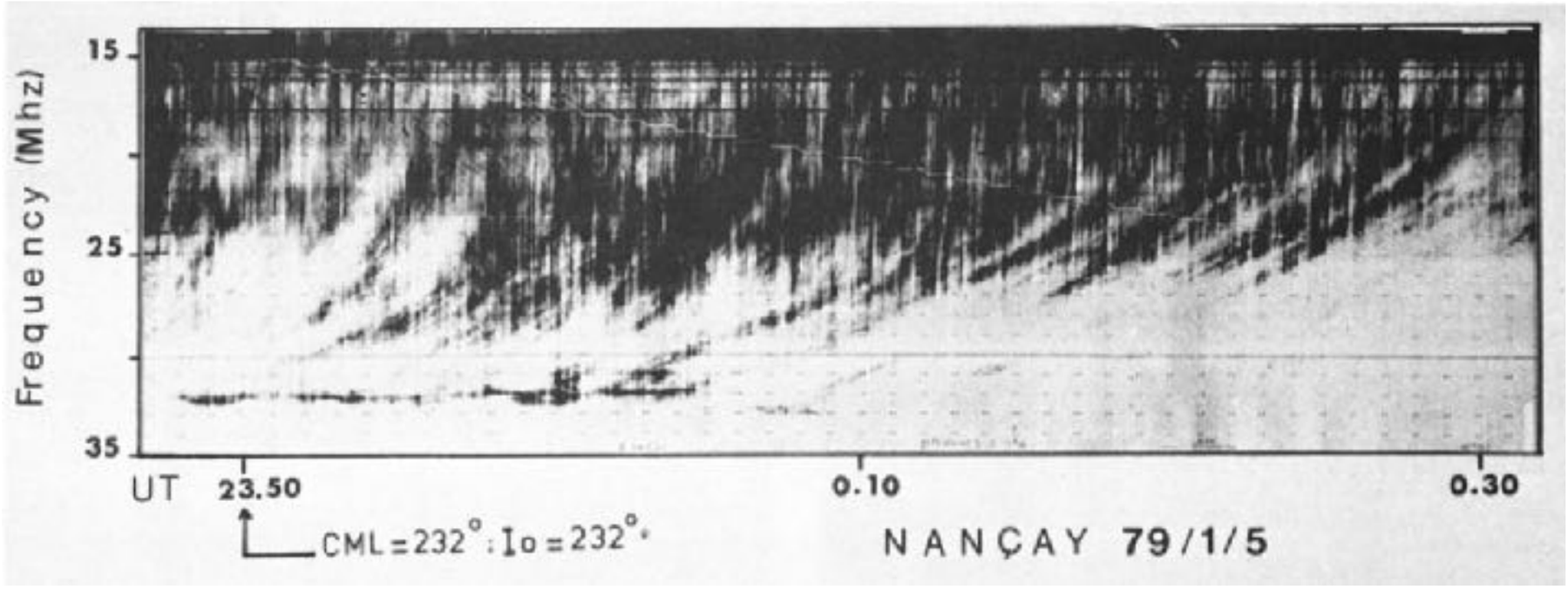
Arecibo

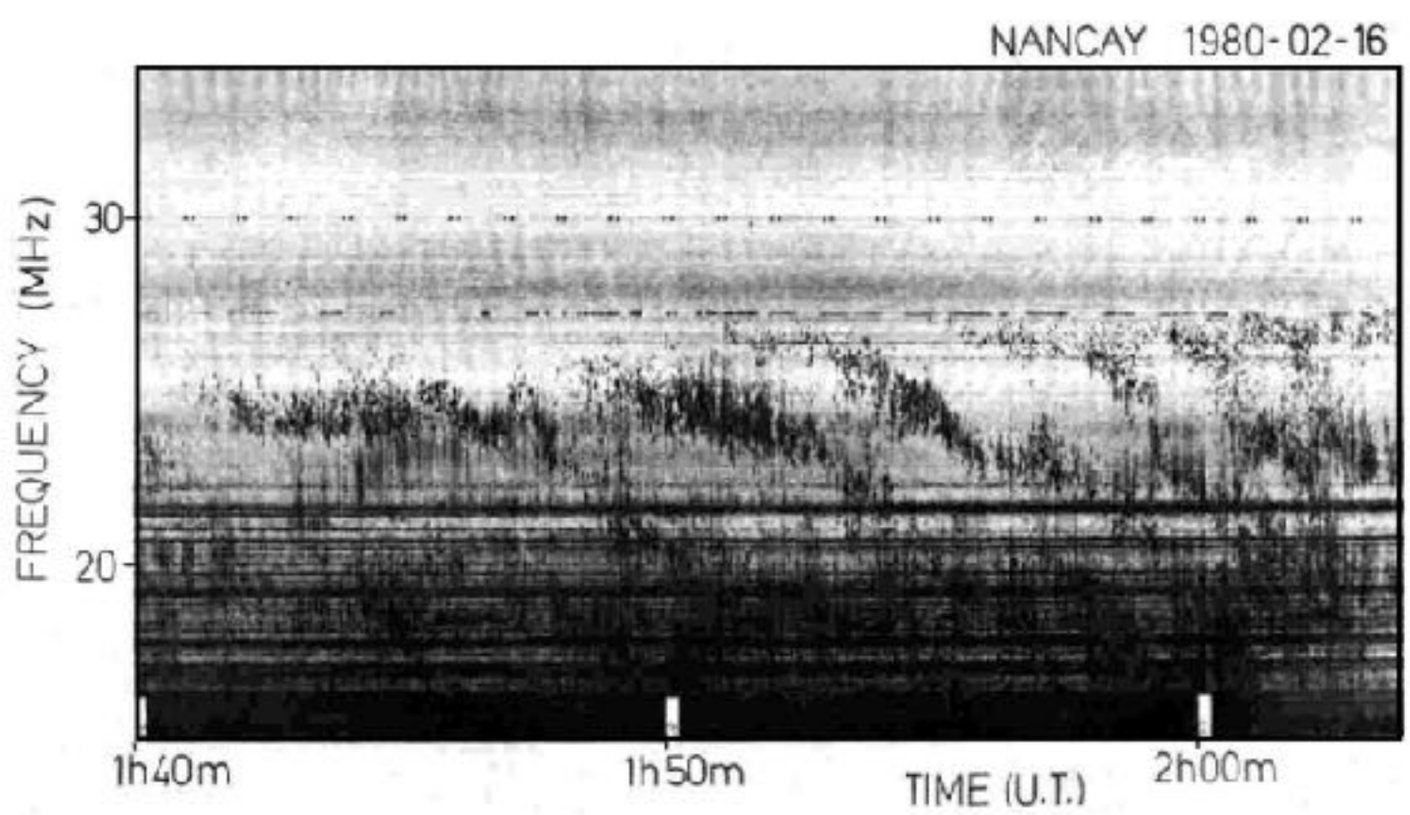
Jupiter



[Zarka, 1998, 2000]

Jupiter: <1990

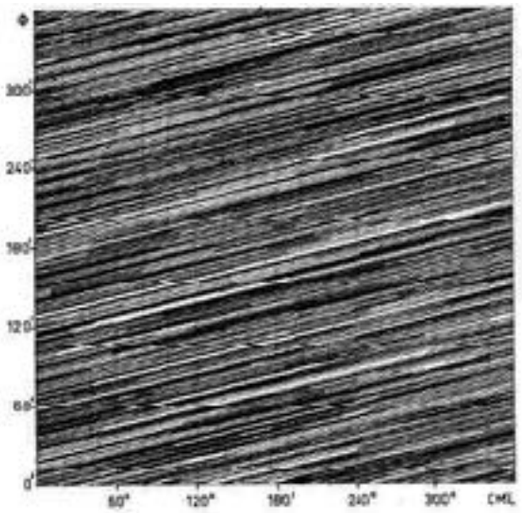


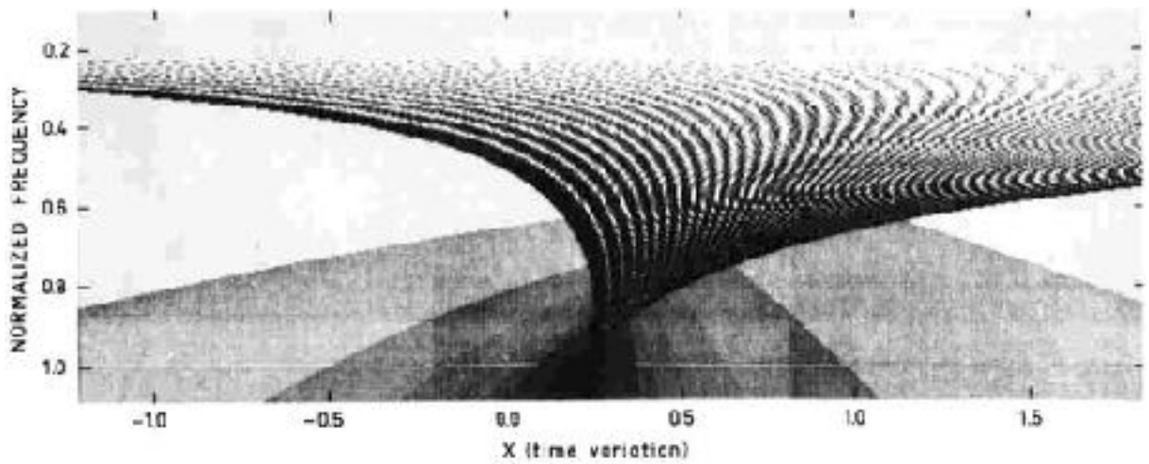


→ analog records

Jupiter: <1990

- Catalogs & occurrence statistics [Leblanc et al., A&Asupp 1981, 1983, 1989, 1990, 1993]
- Arcs morphology ? [Lecacheux et al. 1981, Gurnett & Goertz, 1982]
- Scintillation (ionosphere, IPS) → source location [Genova et al., 1981]
- S-bursts occurrence & interpretation as upgoing e- beams [Ellis, 1980; Leblanc & Genova, 1981]





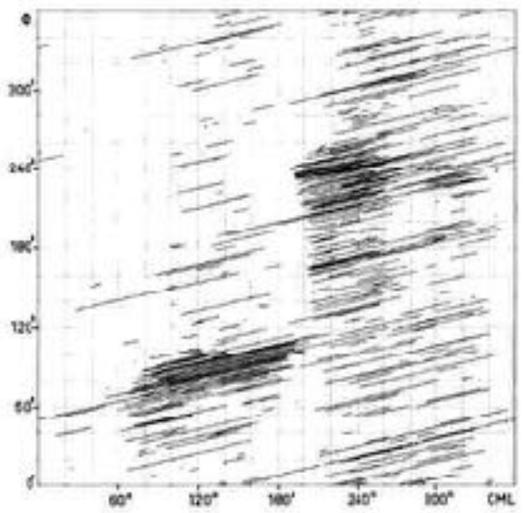
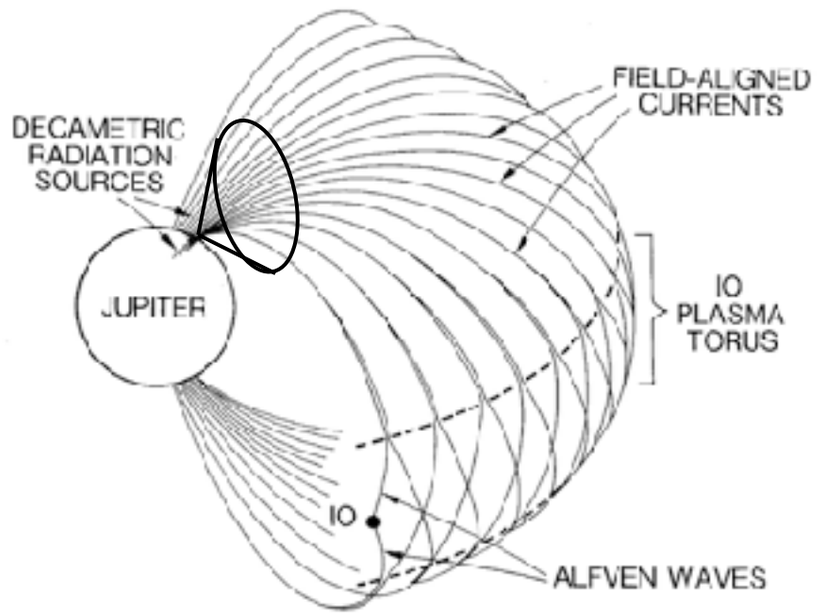
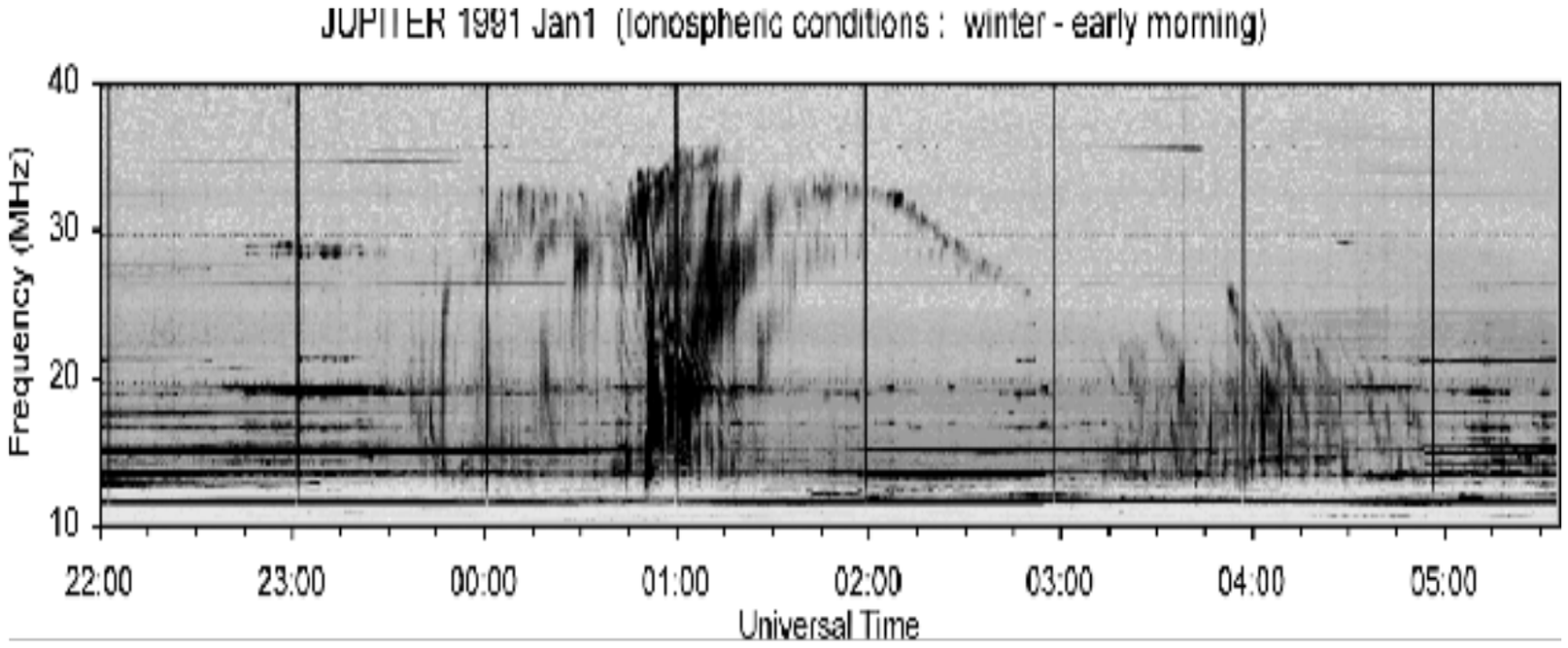
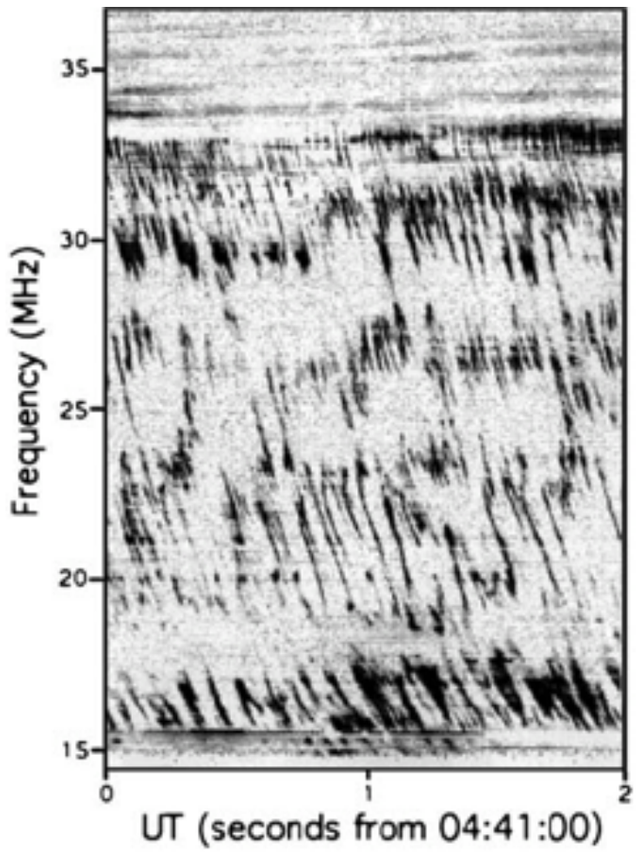


FIGURE 6. — The CML and Io-phase diagram for the period of January 1978 to December 1979. a) the observation tracks ; b) the emission tracks.



Jupiter: 1990-2000

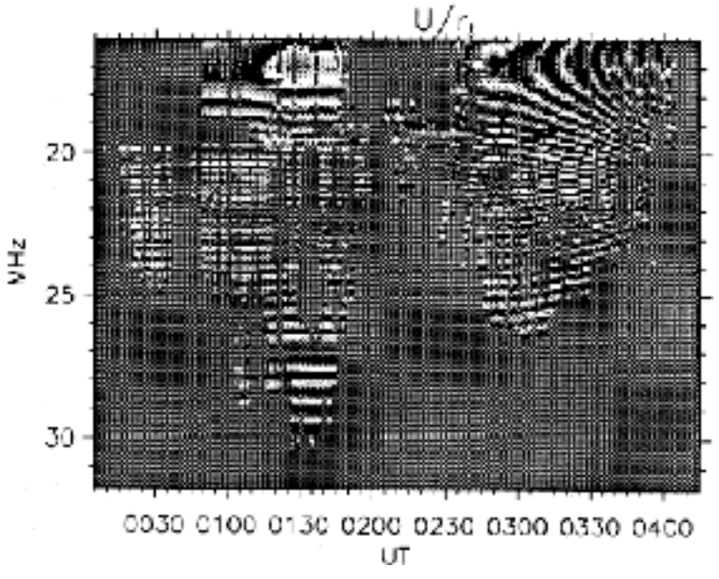


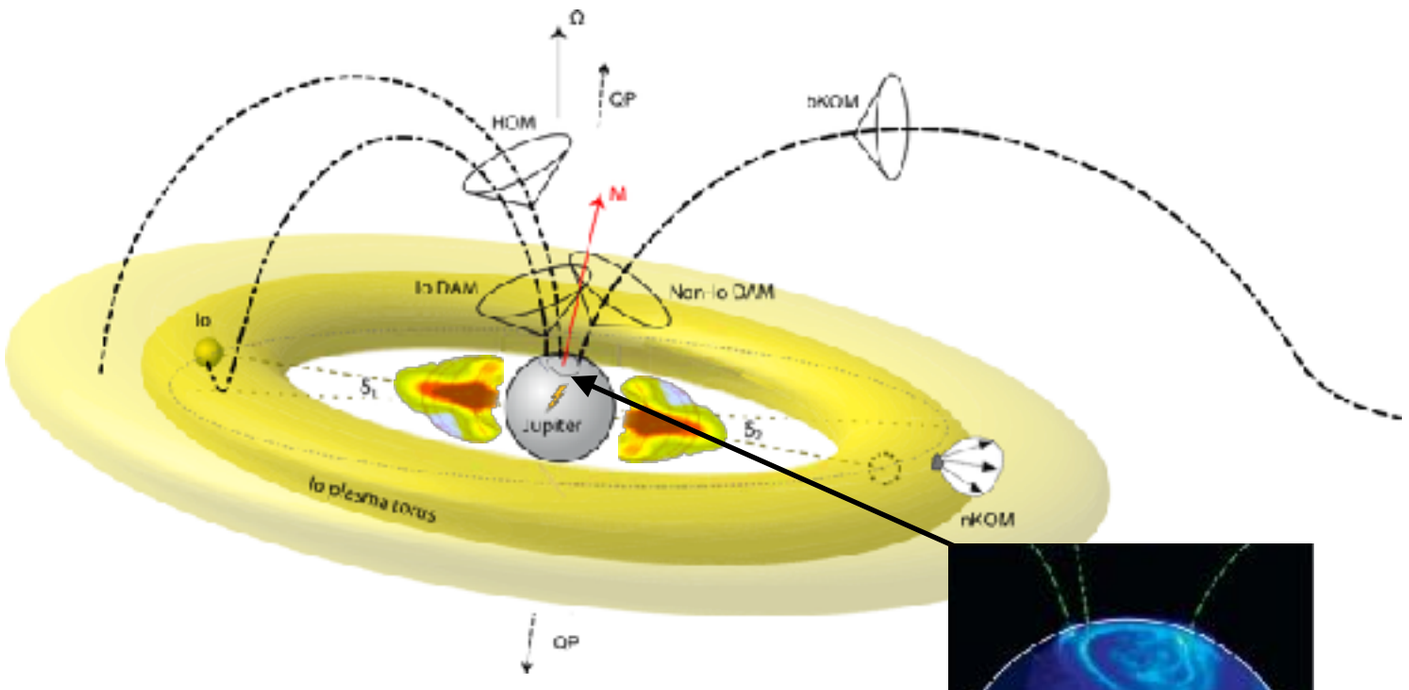


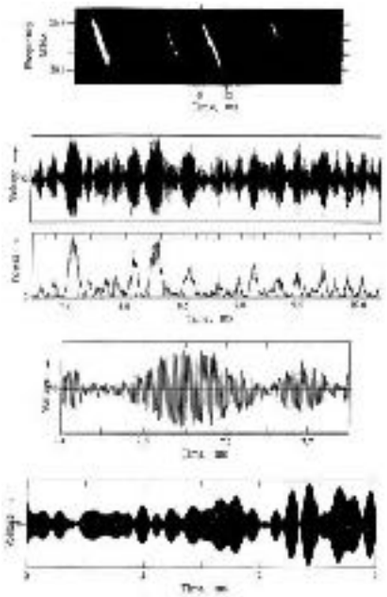
→ digital SFA
→ spectropolarimeter (4 Stokes)
→ AOS

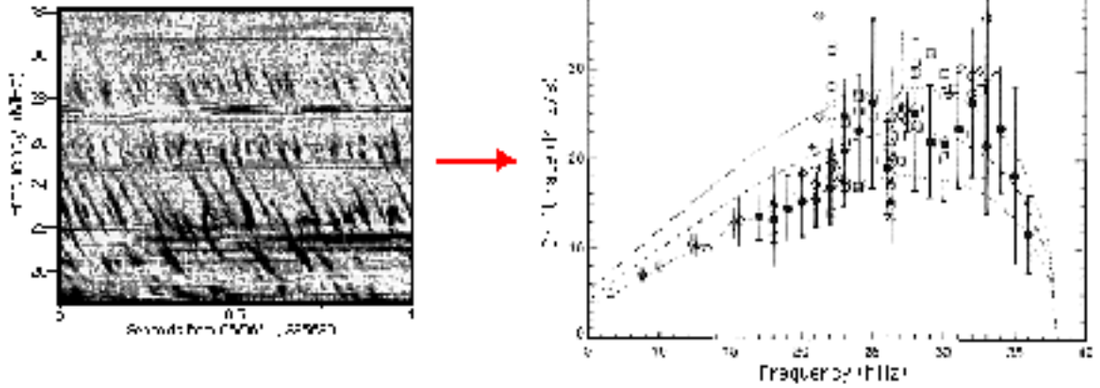
Jupiter: 1990-2000

- DAM polarization → N_e in sources [Dulk et al., 1992, 1994]
- Arcs morphology ? [Queinnec & Zarka, 1998]
- Correlations Radio/UV [Prangé et al., 1993]
- S-bursts fast measurements & scenario [Zarka et al., 1996]
- DAM microstructure [Carr et al., 1999]

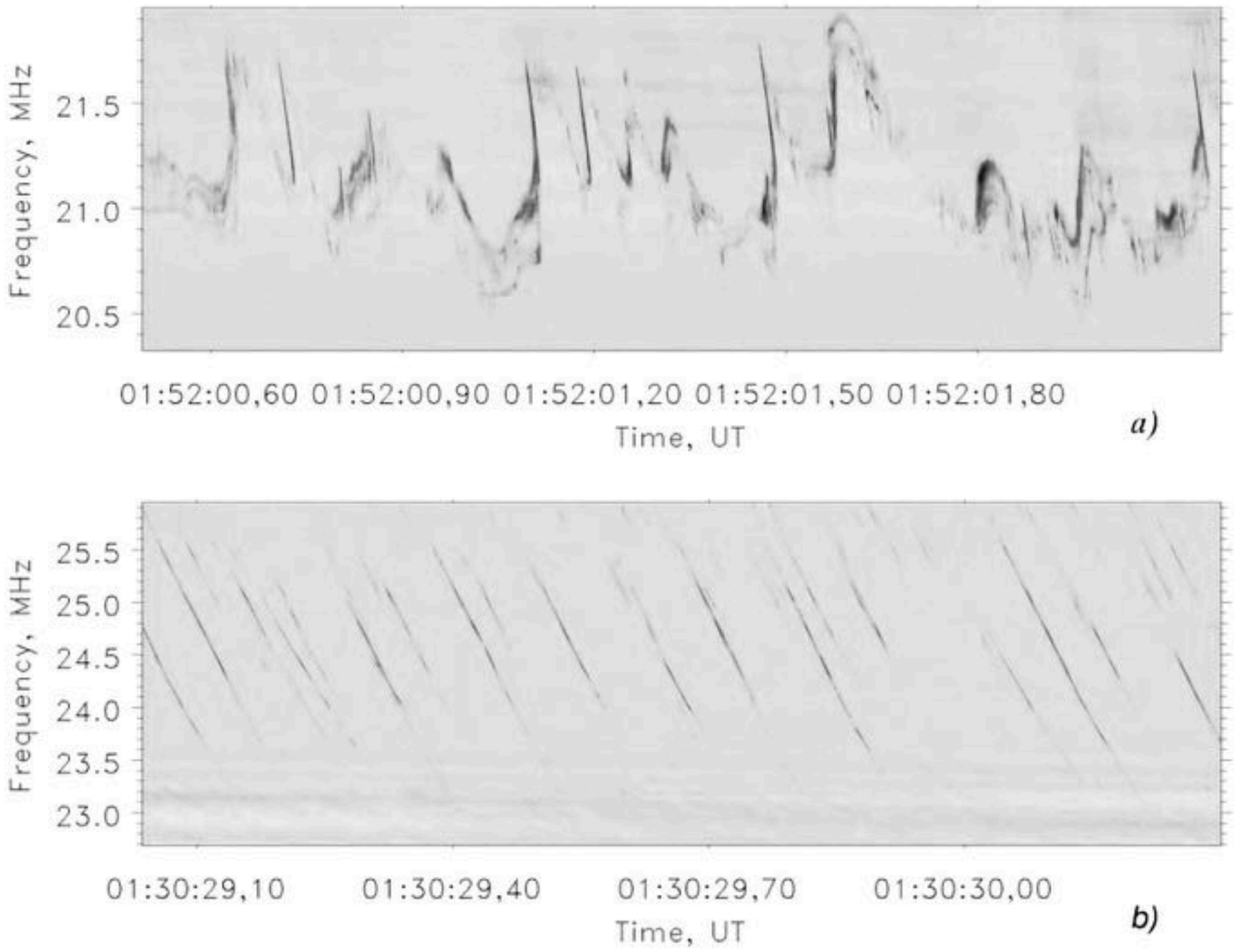








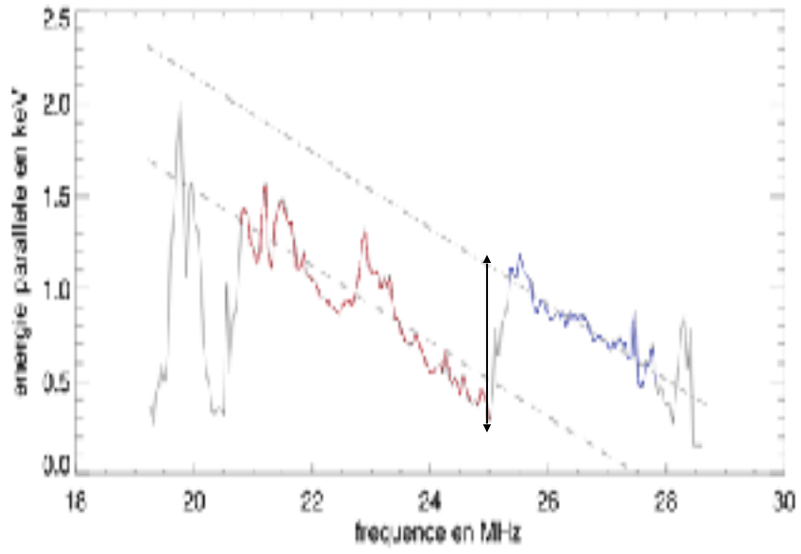
Jupiter: 2000-2010



→ digital (FFT) spectrographs at NDA & UTR-2
→ waveform capture

Jupiter: 2000-2010

- Potential drops, e- & ion holes along Jupiter's B lines [Hess et al., 2007a, 2009]
  → e- acceleration by Alfvén waves, S-bursts & arcs modelling [Hess et al., 2007b, 2008a]
- DAM microstructure [Ryabov et al., 2007]
- First version of ExPRES code [Hess et al., 2008b]
- First correlations NDA-LOFAR [Nigl et al., 2007]



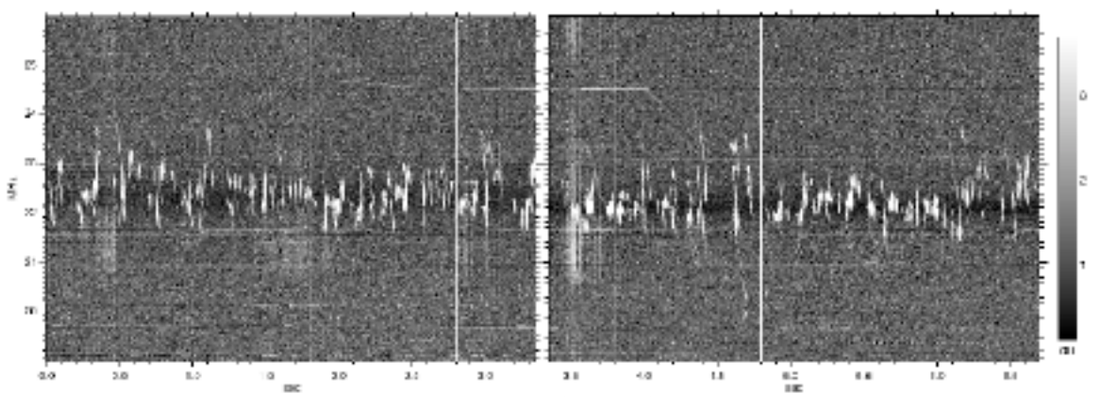
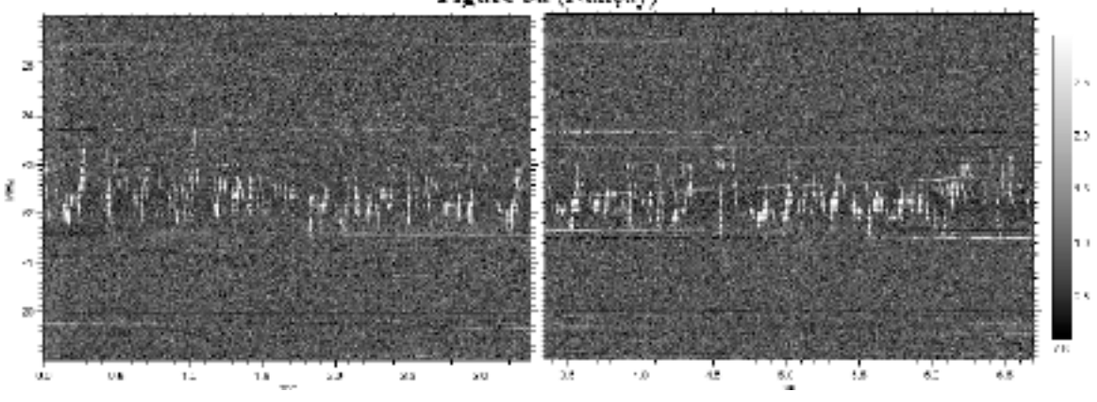
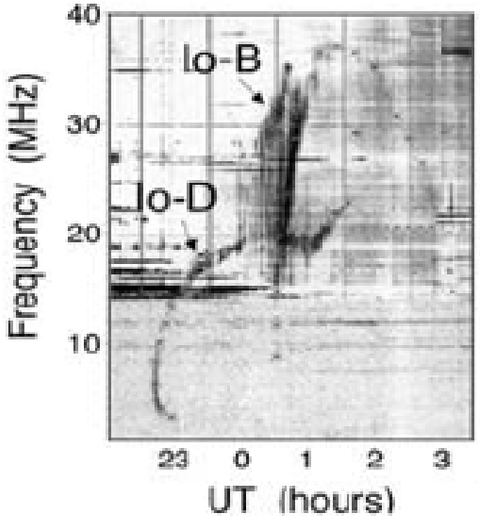
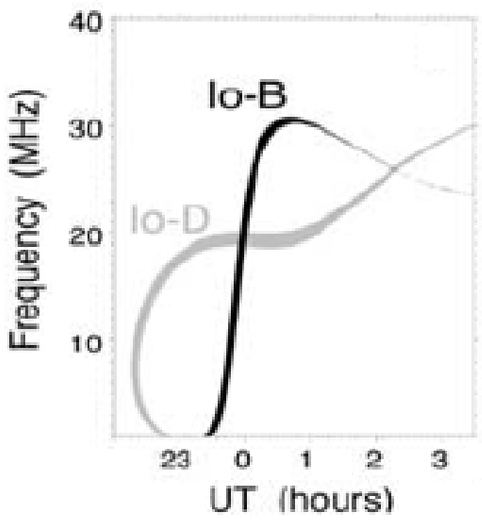


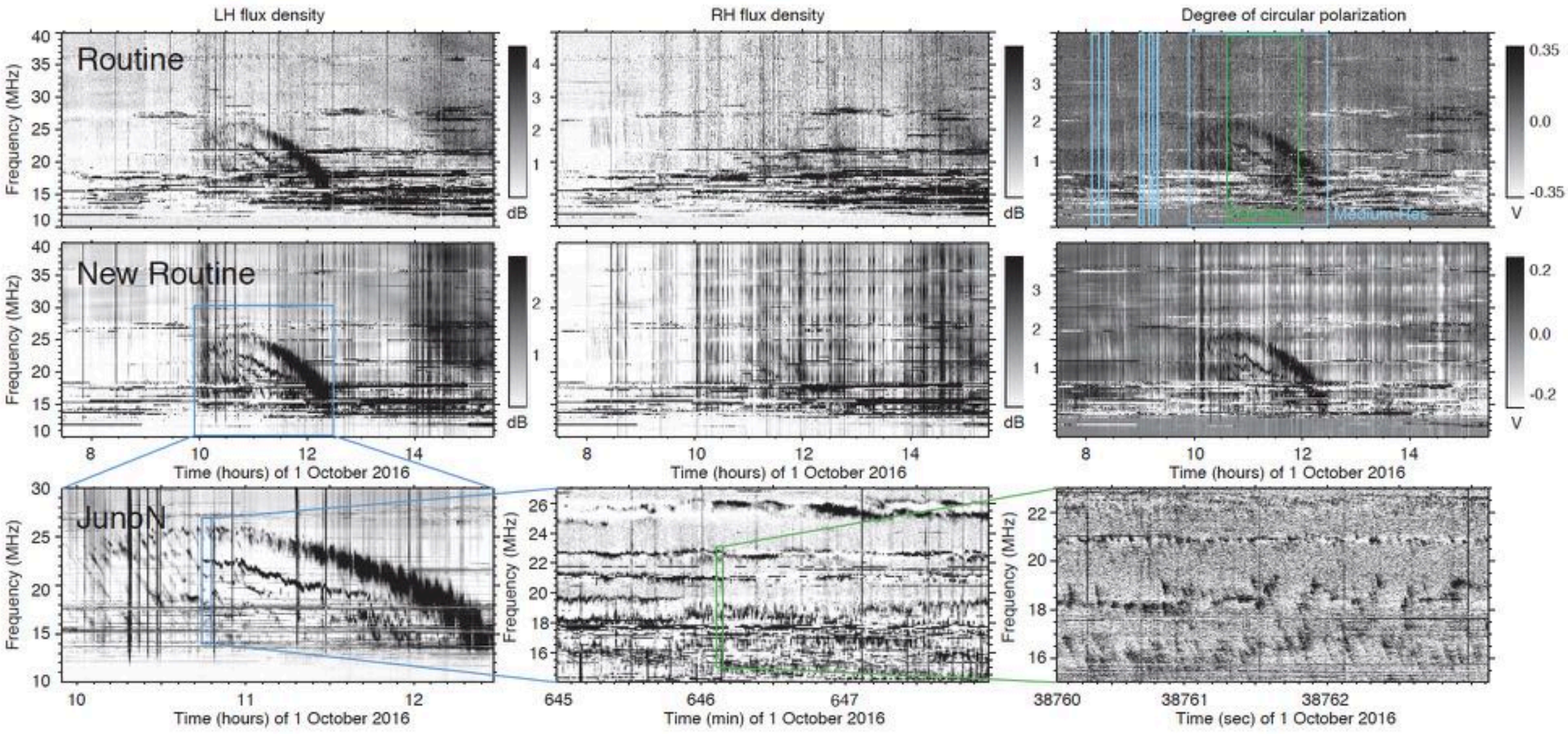
Figure 3a (Nançay)







Jupiter: 2010-2020

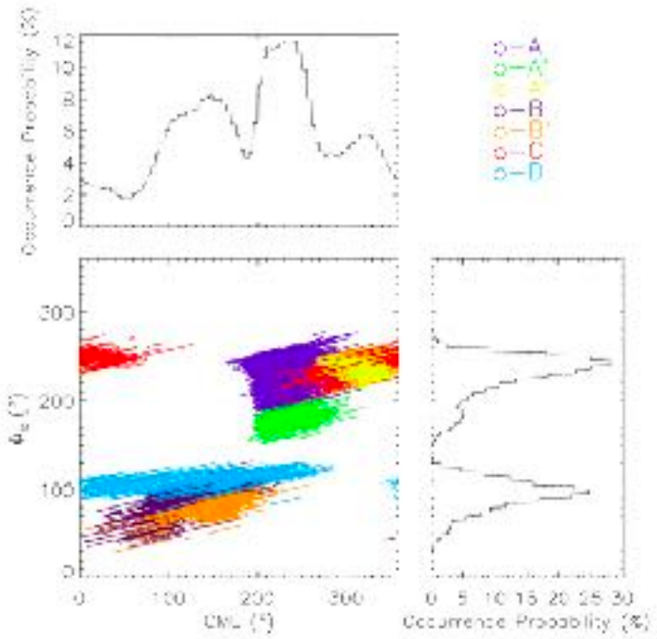


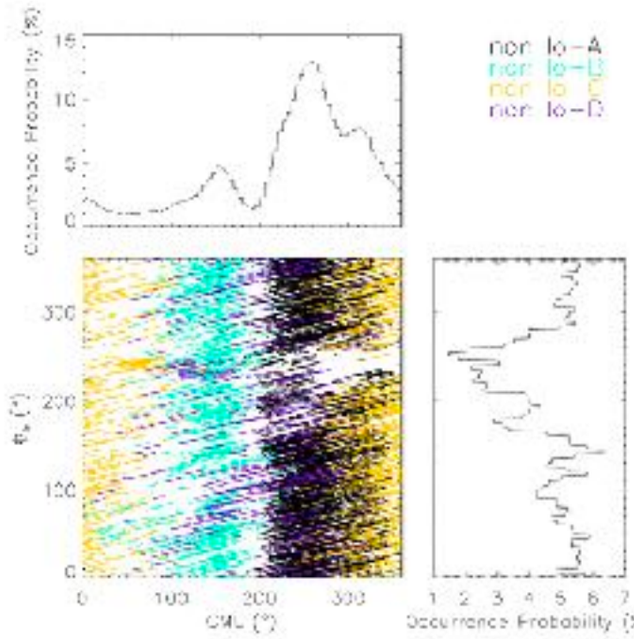
[Lamy et al., 2017]

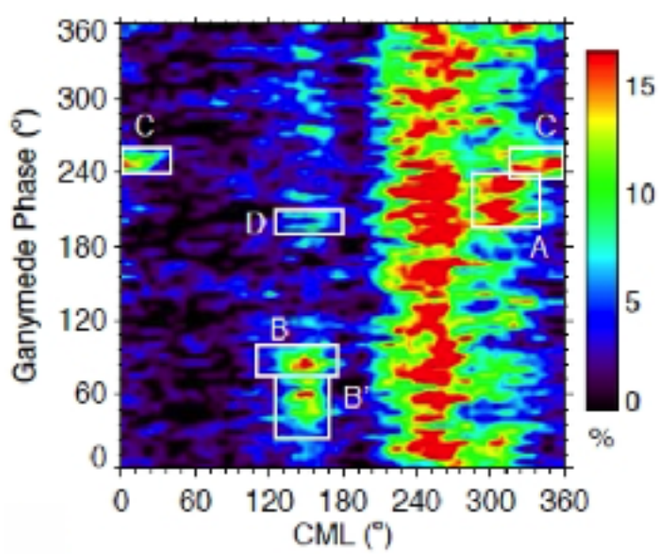
→ NewRoutine, Mefisto & Juno-N receivers

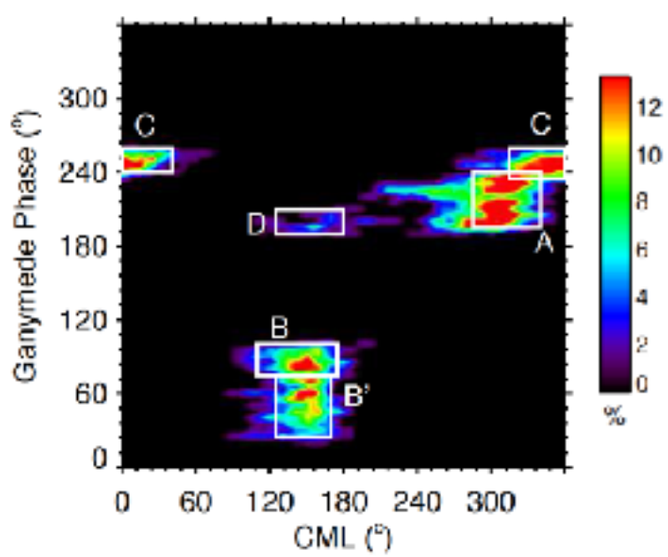
Jupiter: 2010-2020

- NDA catalog 1990-2016(2020) [Marques et al., 2017]
  → DAM control by Ganymede [Zarka et al., 2018]
- Final version of ExPRES code [Louis et al., 2019]
  → First predictions for Exoplanets [Hess & Zarka, 2011]



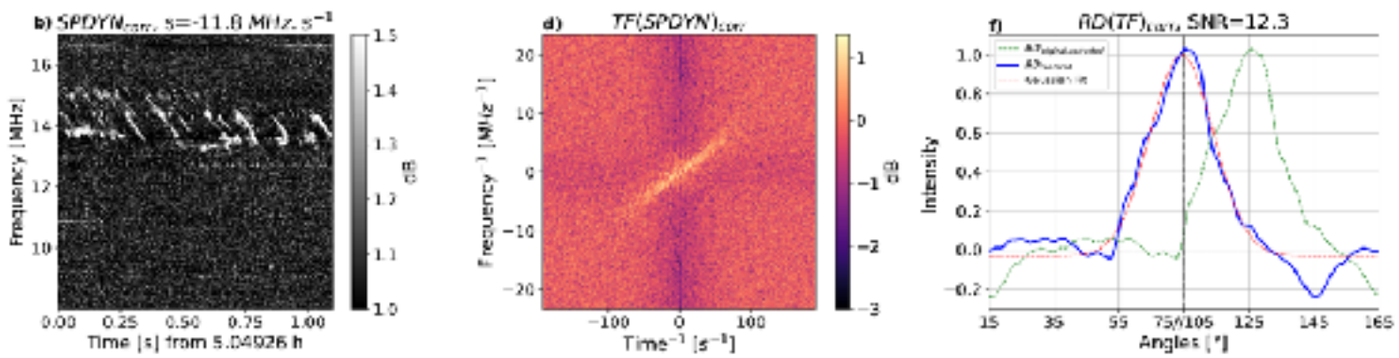


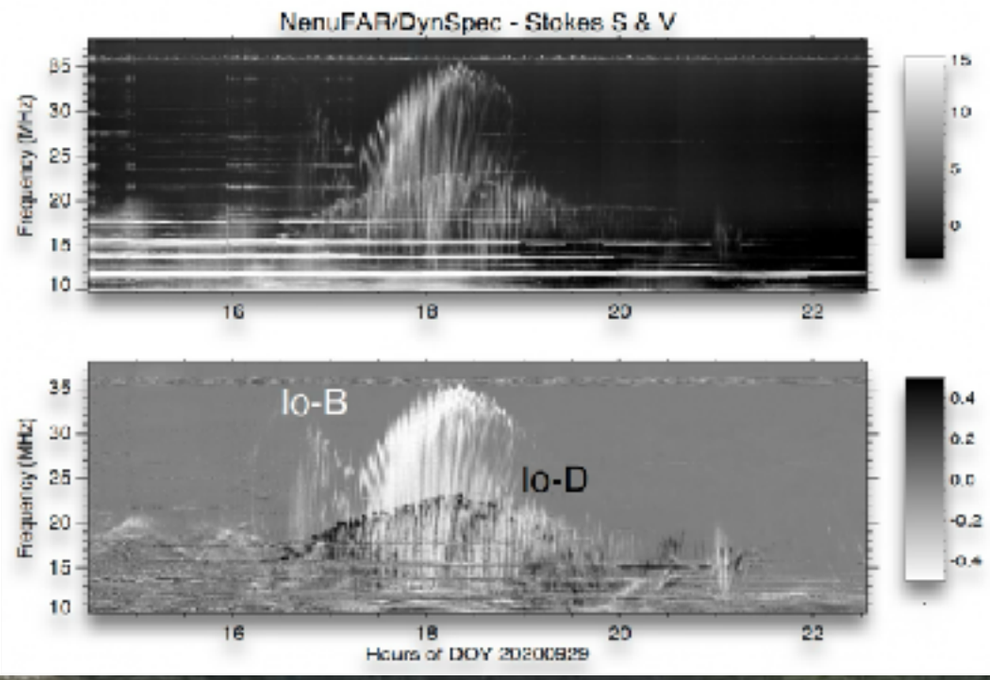




Jupiter: 2020+

- Digitization of NDA analog archives [Lamy et al., 2023]
- DAM control by Europa [Jacome et al., 2022]
- Automatic recognition of S-bursts [Mauduit et al., 2023]
- NenuFAR beamformed studies of Jupiter emissions [Lamy et al., 2022]

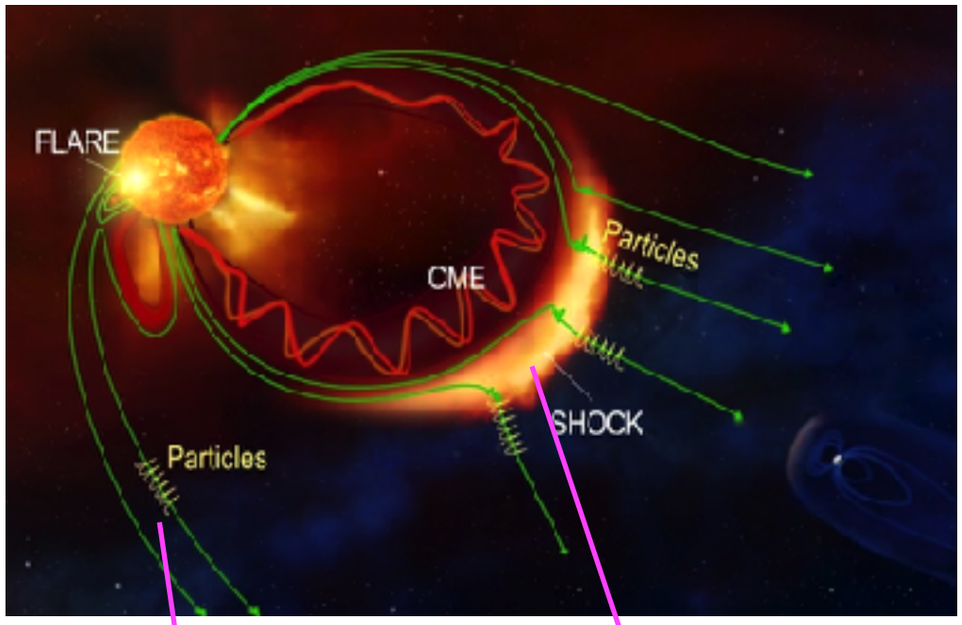


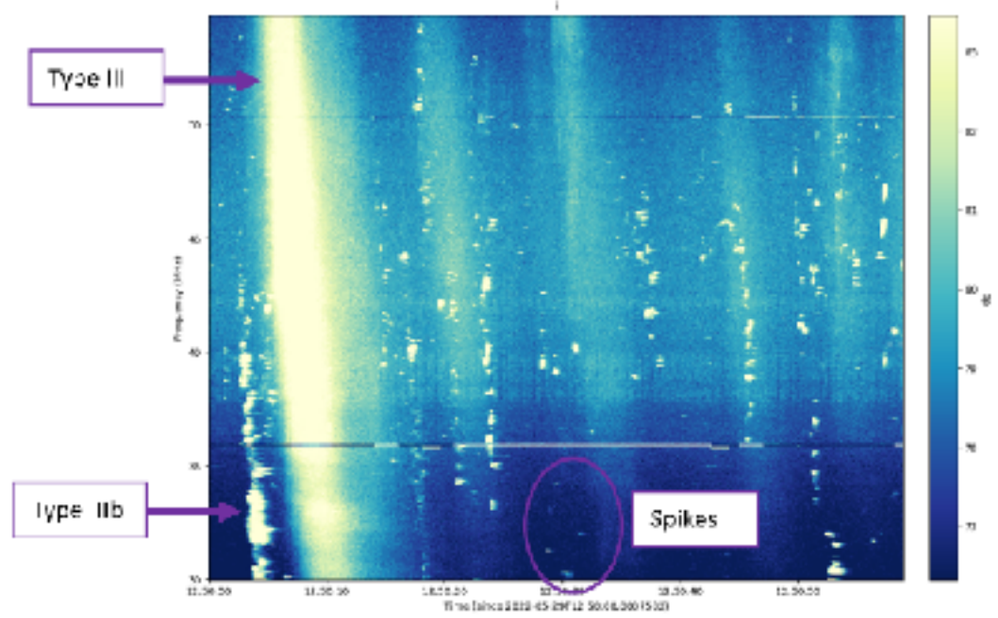


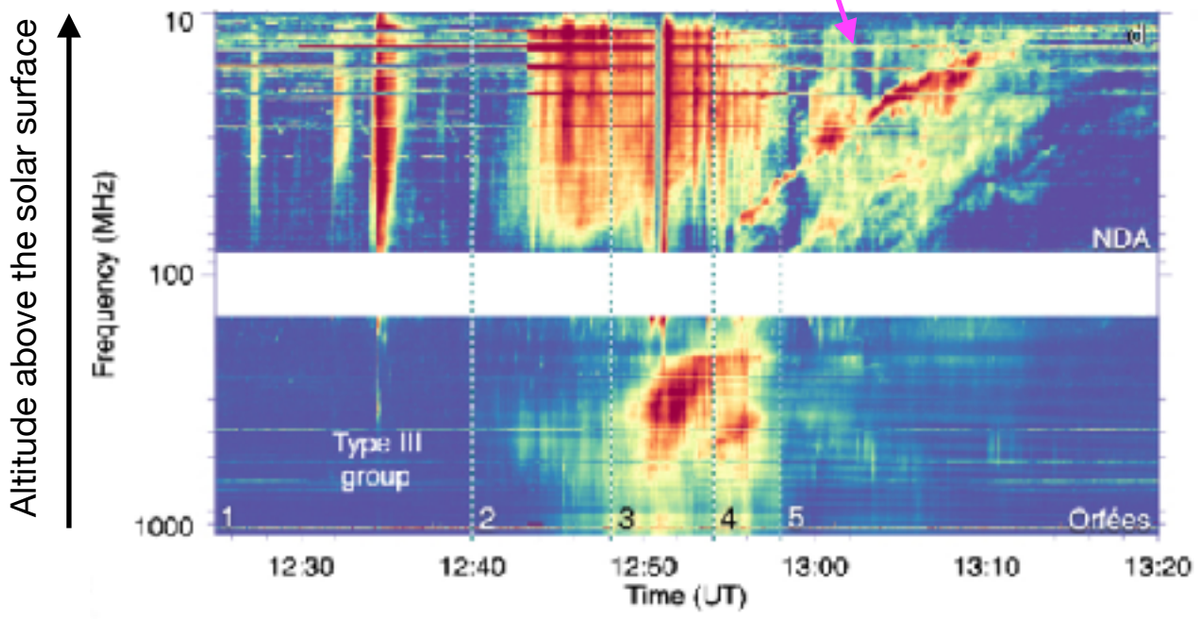
- Heroic times
  - Jupiter, Sun
- Single dishes and phased arrays: t-f studies
  - Jupiter (<1990, 1990-2000, 2000-2010, 2010-2020, 2020+)
  - Sun, Stars, Exoplanets
- Interferometers: imaging studies
  - Jupiter, Sun, Stars, Exoplanets
- Dynamic spectra (t-f) from imaging data
  - Stars, Exoplanets
- Prospects

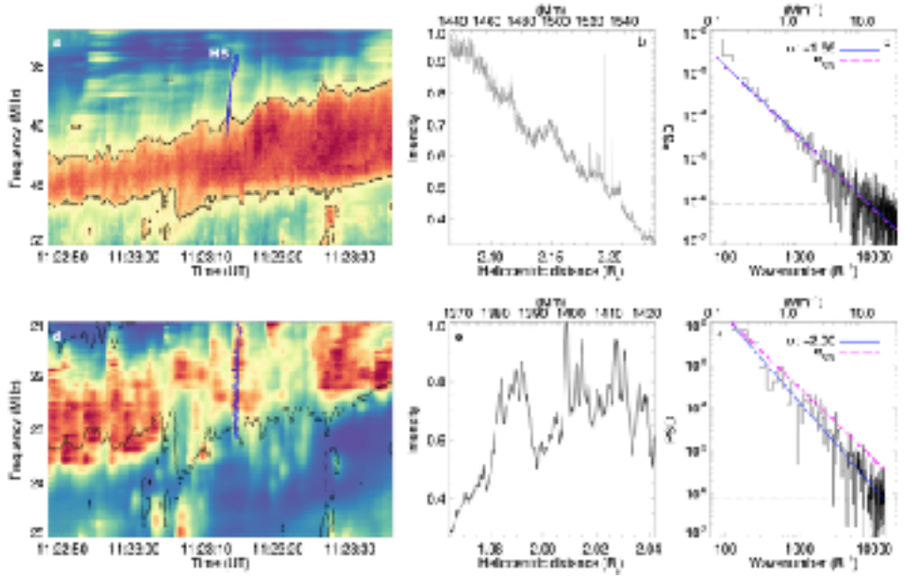
Sun

- Solar burst studies (type II & III & spikes) [Briand et al., 2008; Melnik et al., 2015; Pick et al., 2016, Shevchuk et al., 2016]
- NenuFAR beamformed studies of Solar bursts [Carley et al., 2021; Briand et al., 2022]



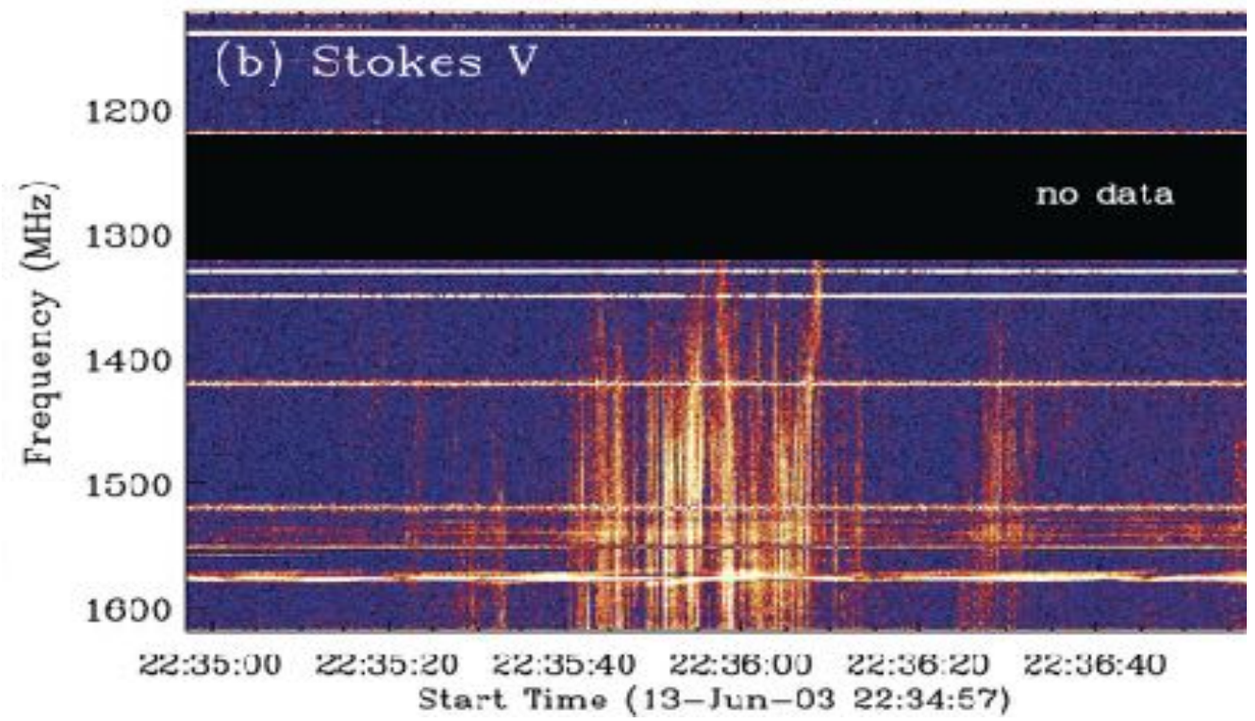


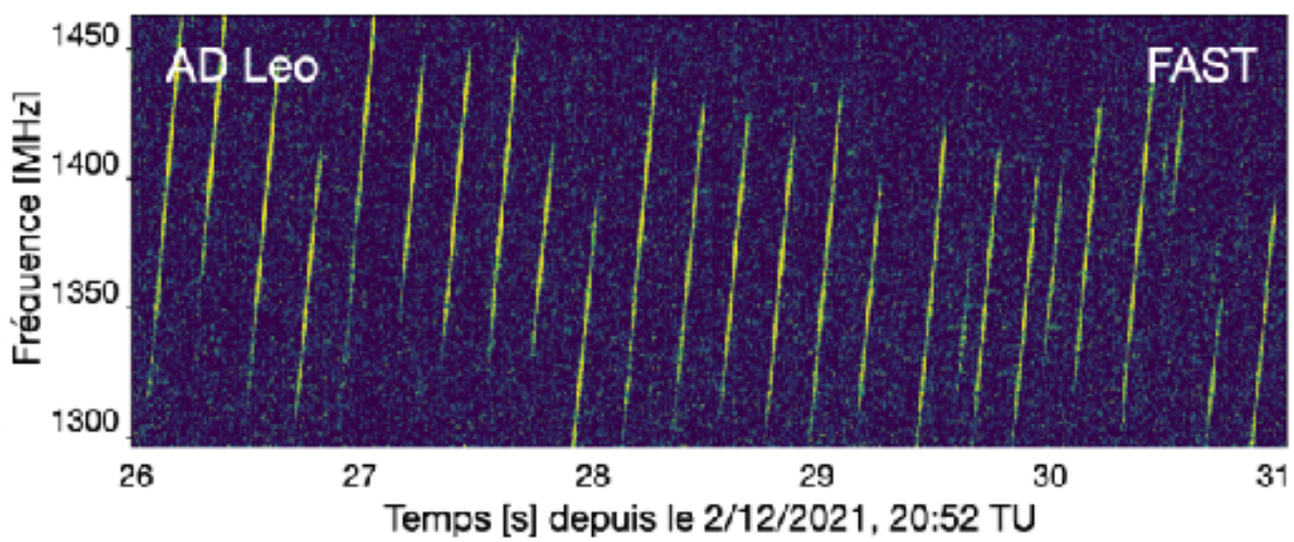




Stars

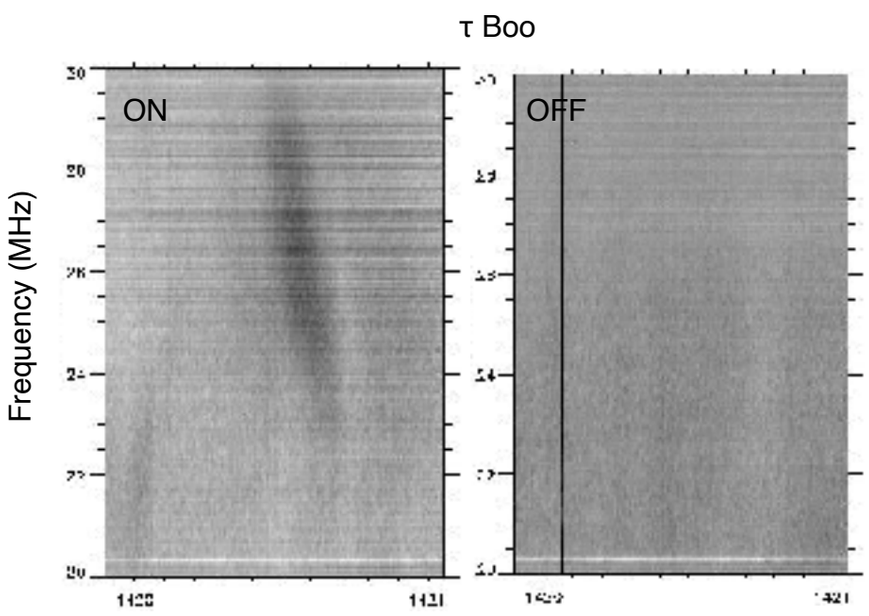
- Bursts, fine structures, light curves [Osten et al., 2006, 2008; Zhang et al., 2023; Zarka et al., 2025]

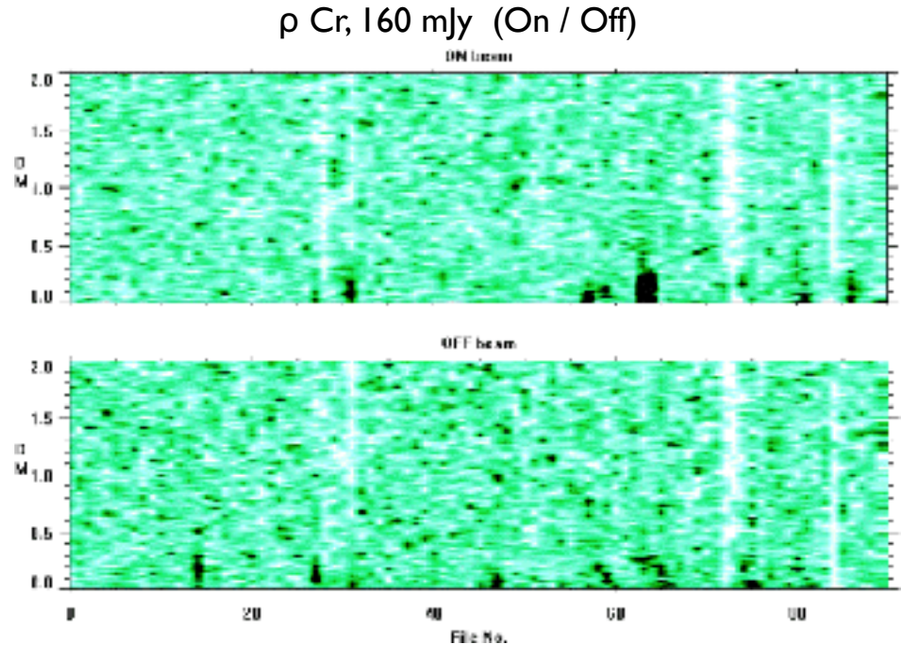


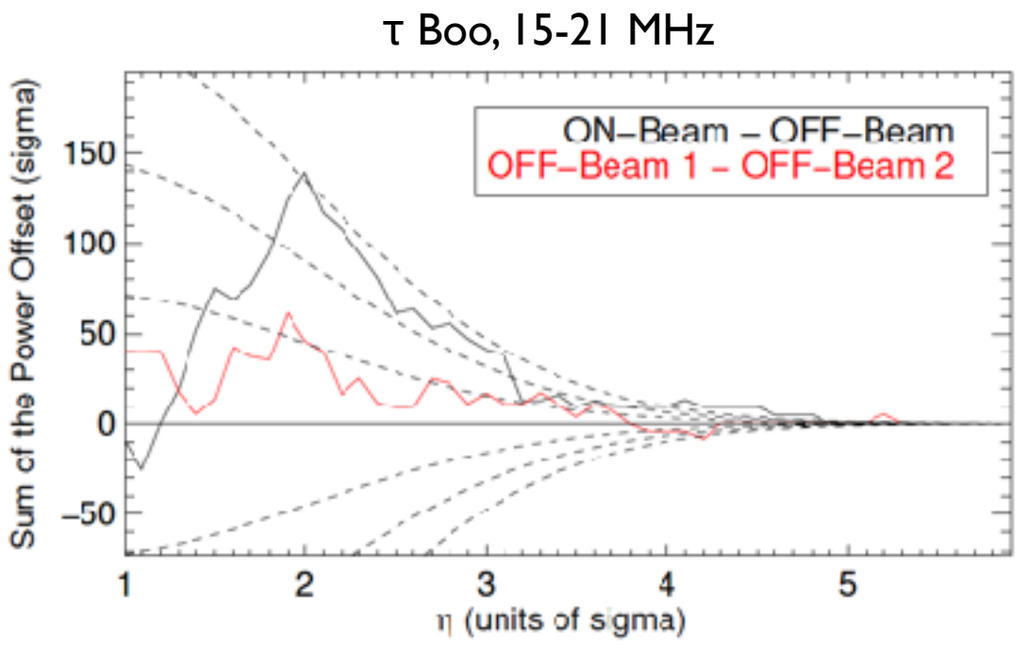


Exoplanets

- Inconclusive tentative detections [Ryabov et al., 2004; Vasylieva, 2015; Turner et al., 2021, 2024]







- Heroic times
  - Jupiter, Sun
- Single dishes and phased arrays: t-f studies
  - Jupiter (<1990, 1990-2000, 2000-2010, 2010-2020, 2020+)
  - Sun, Stars, Exoplanets
- Interferometers: imaging studies
  - Jupiter, Sun, Stars, Exoplanets
- Dynamic spectra (t-f) from imaging data
  - Stars, Exoplanets
- Prospects

Interferometers: imaging studies

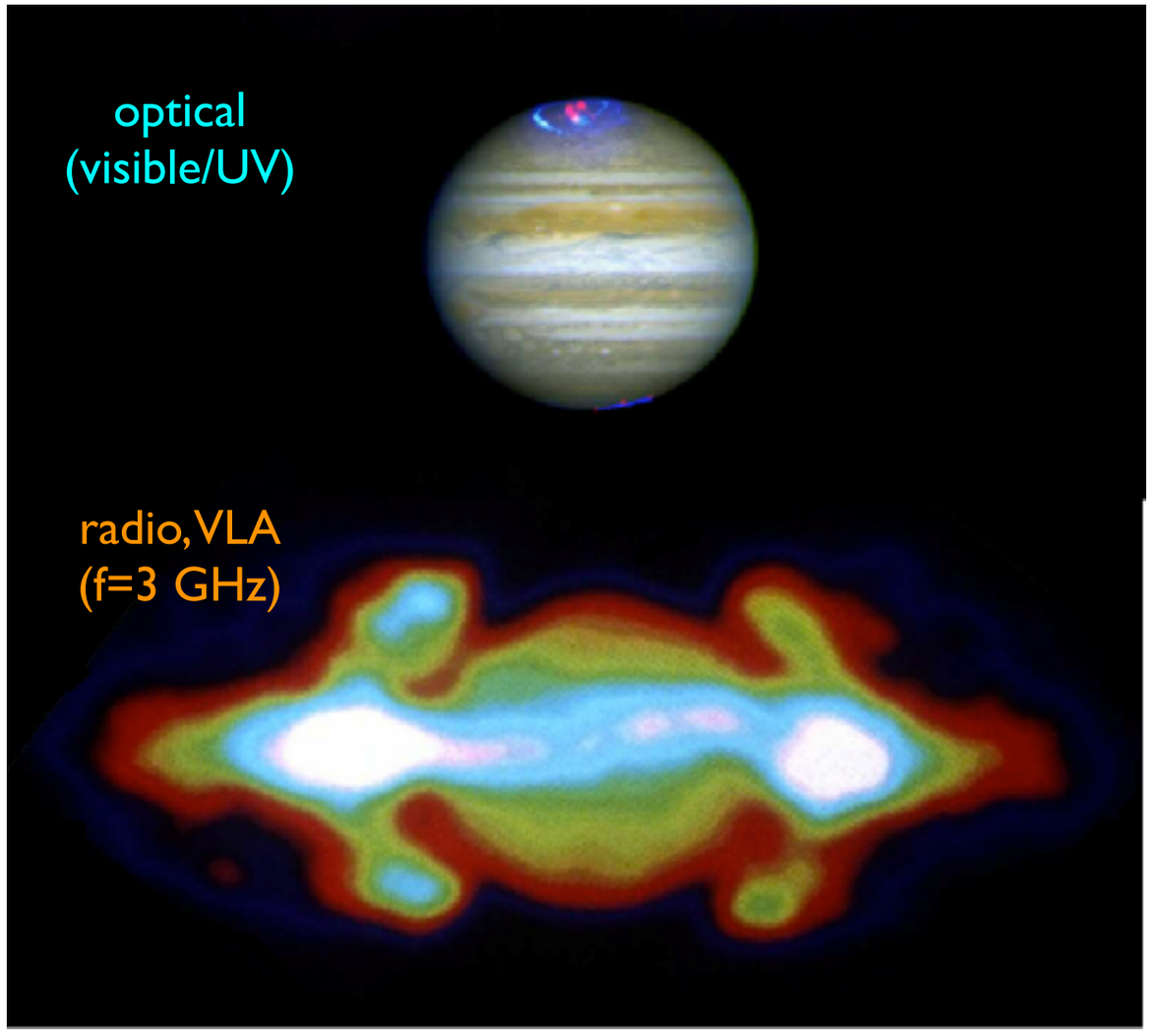
VLA

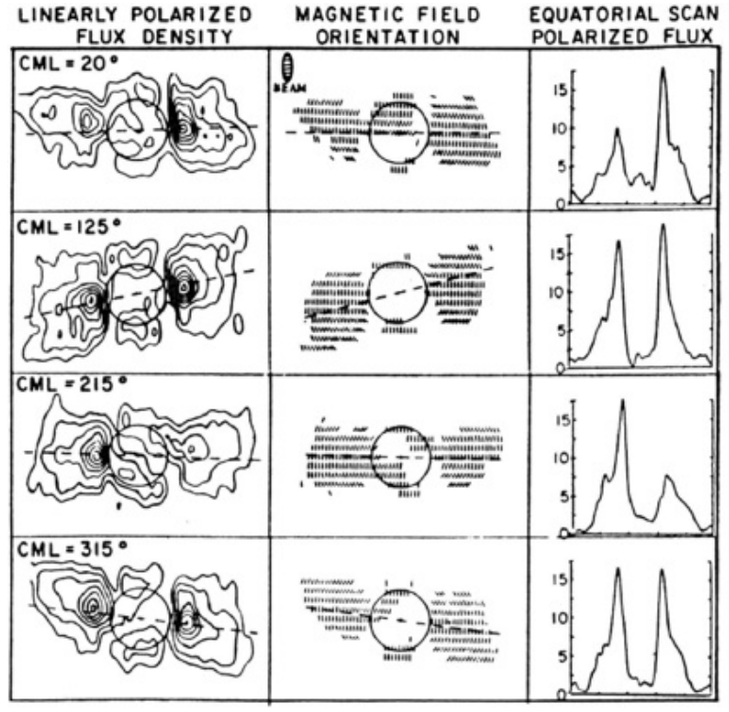
LOFAR

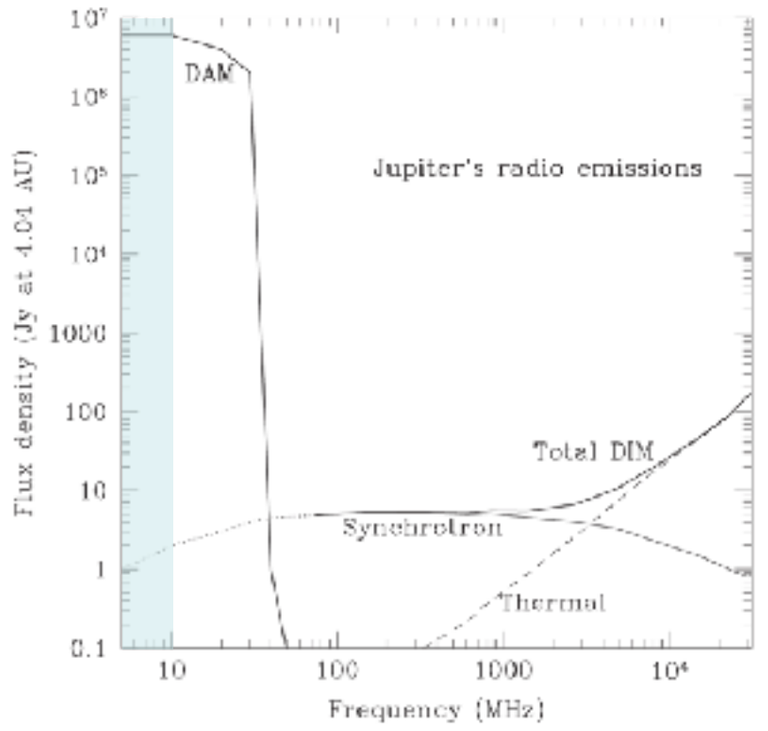
Jupiter: imaging

- Imaging, polarization, variability of radiation belts (incl. SL9 impact)

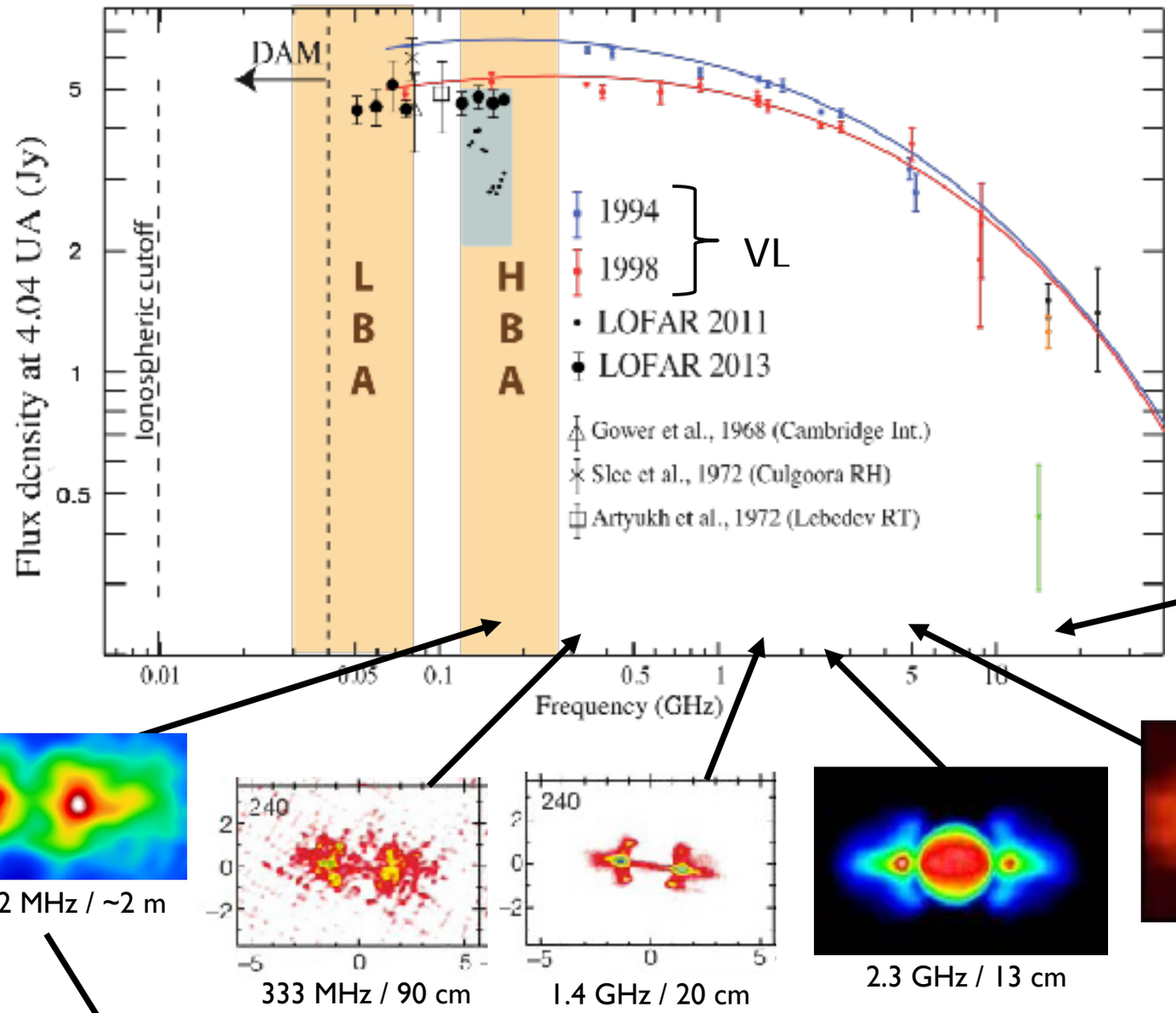
[de Pater et al., 1981...2004; Santos-Costa et al., 2001...2014]



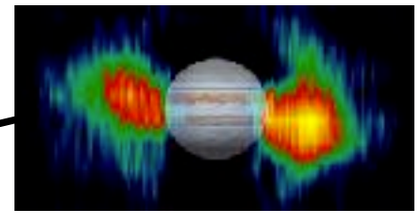




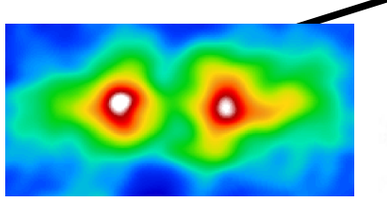
Jupiter: imaging



[de Pater & Dunn, 2003]



14 GHz / 2 cm

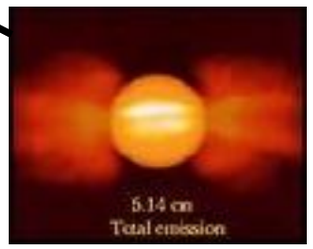


127-172 MHz / ~2 m

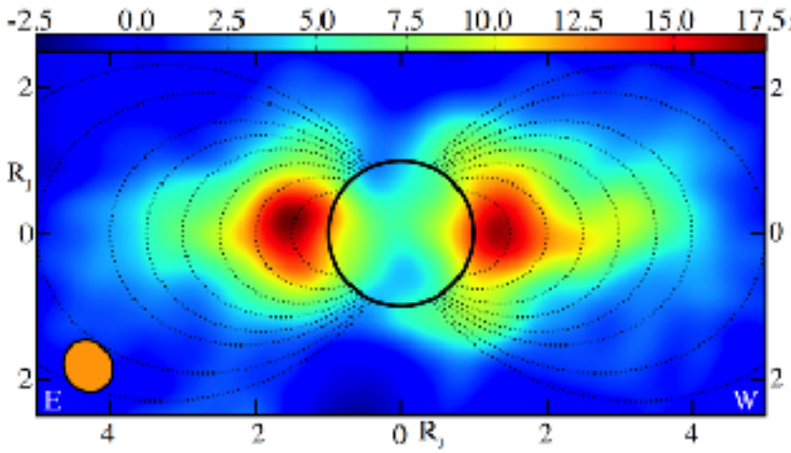
333 MHz / 90 cm

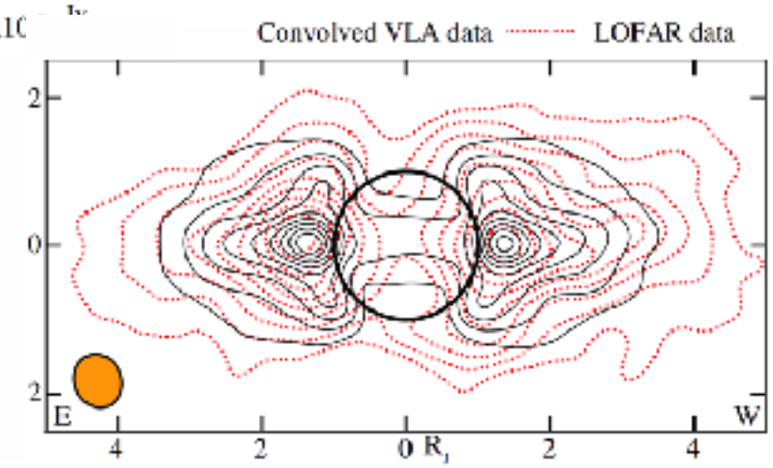
1.4 GHz / 20 cm

2.3 GHz / 13 cm



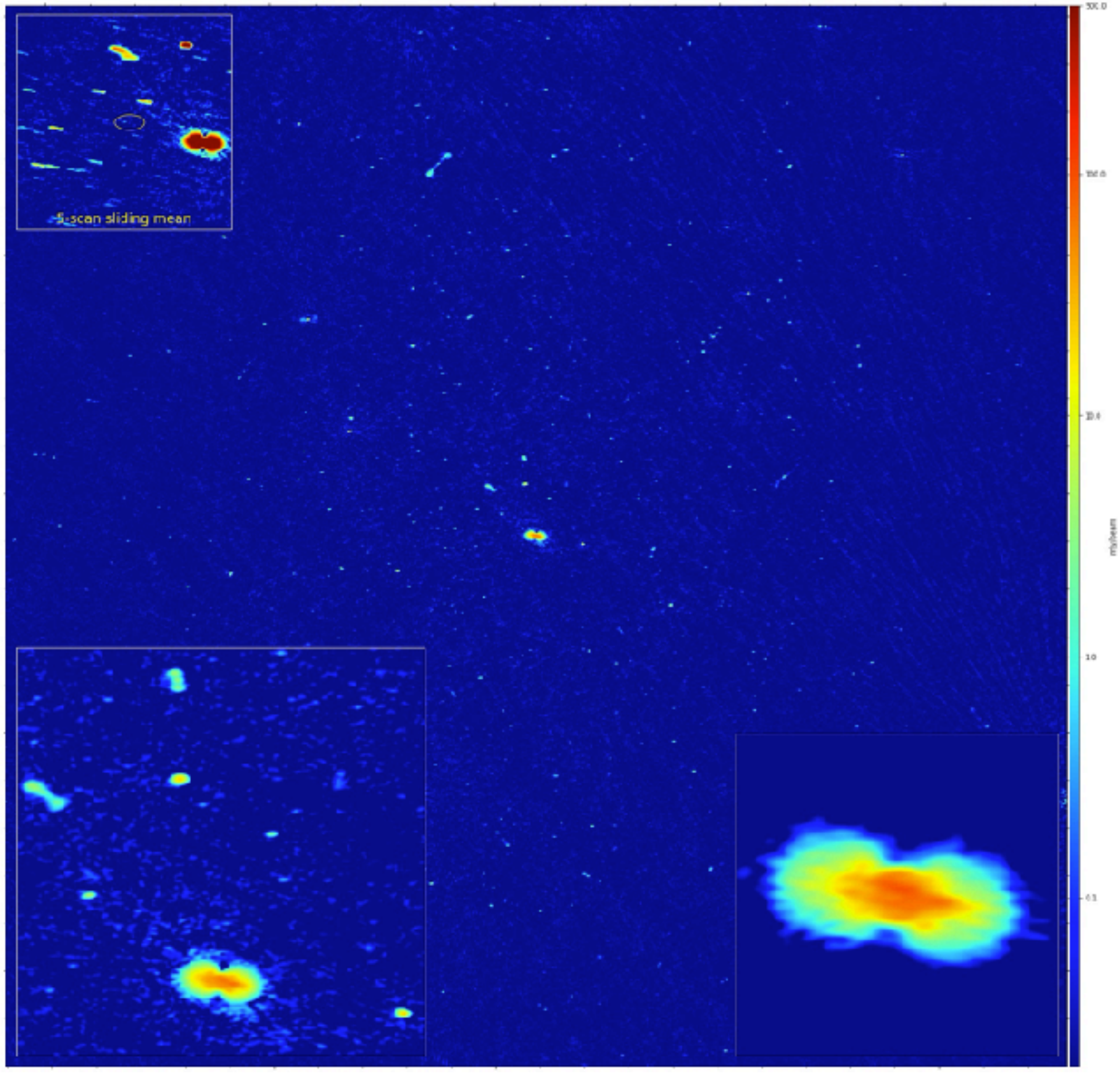
5 GHz / 6 cm





[Girard et al., 2016]]

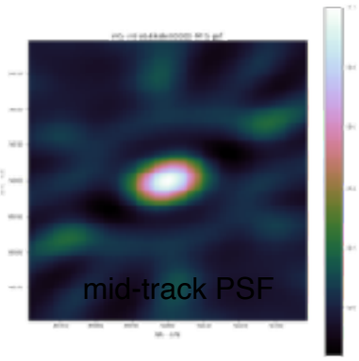
Jupiter: imaging

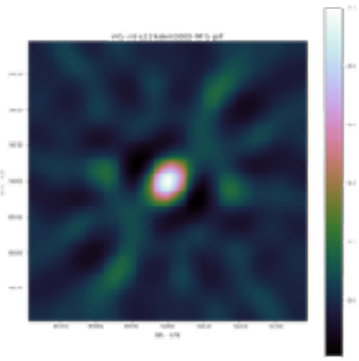


MeerKAT movie

Great Conjunction of
21/12/2020
880 - 1650 MHz
~17 min. / image + gaps
27 images : total ~8h30

Credits : Oleg Smirnov &
RATT (ratt.center) &
SARAO (sarao.ac.za)





end-track PSF

Jupiter : VLBI

- Limits on DAM source size [Dulk, 1967]
- VLBI on DAM [Wucknitz et al., 2024]

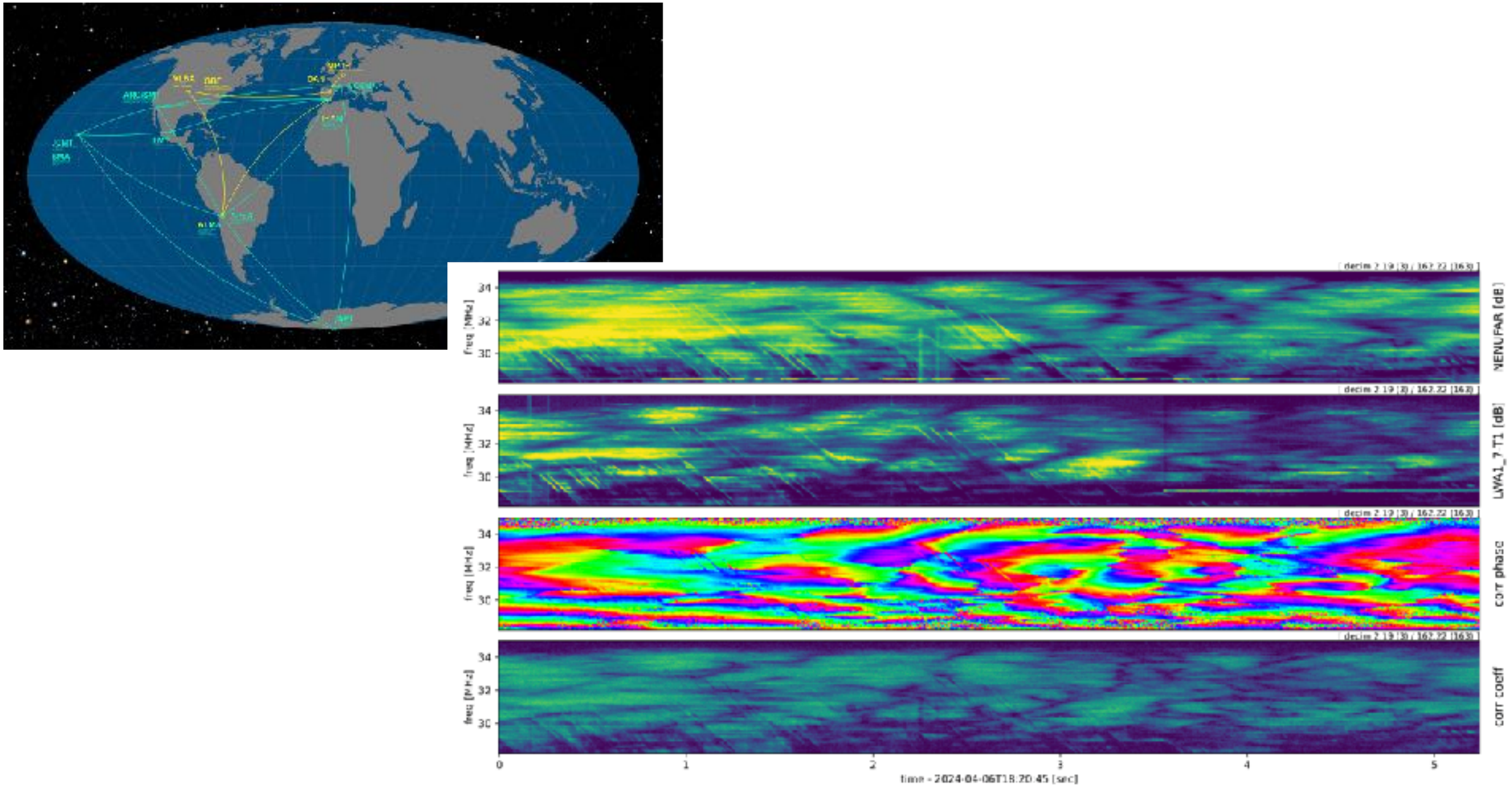


Fig. 7. Fringes on the transatlantic NenuFAR–LWA1 baseline, panels as in Fig. 5. To our knowledge, these are the first transatlantic fringes at 30 MHz.

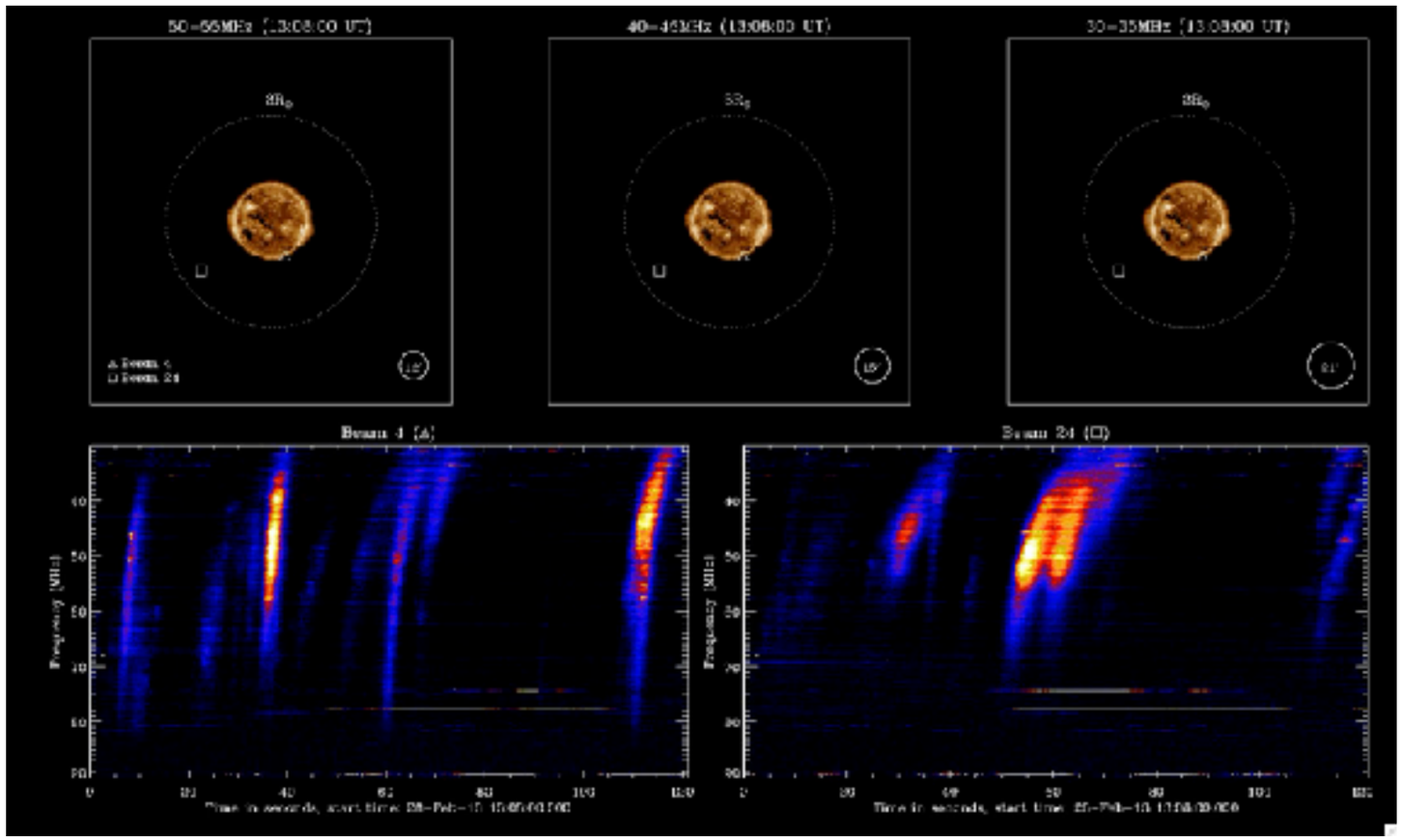
(Wucknitz et al., 2024)

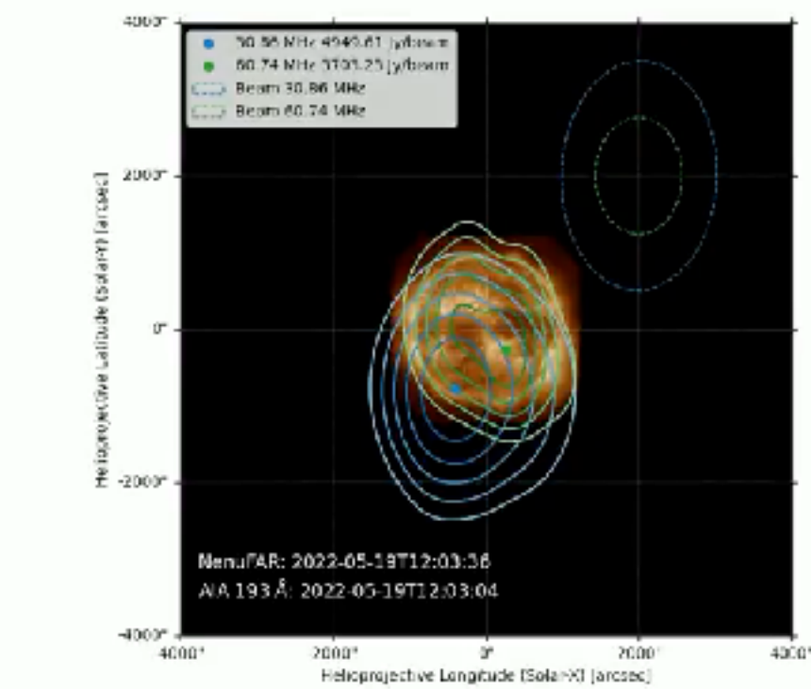
Sun: imaging

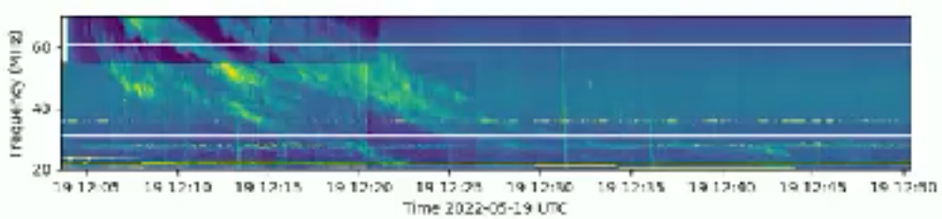
- Solar multi-beam studies with LOFAR
- NenuFAR imaging & t-f analyses

[Morosan et al., 2014, 2015, 2017, 2019, 2022, 2025]

[Briand, Murphy...]





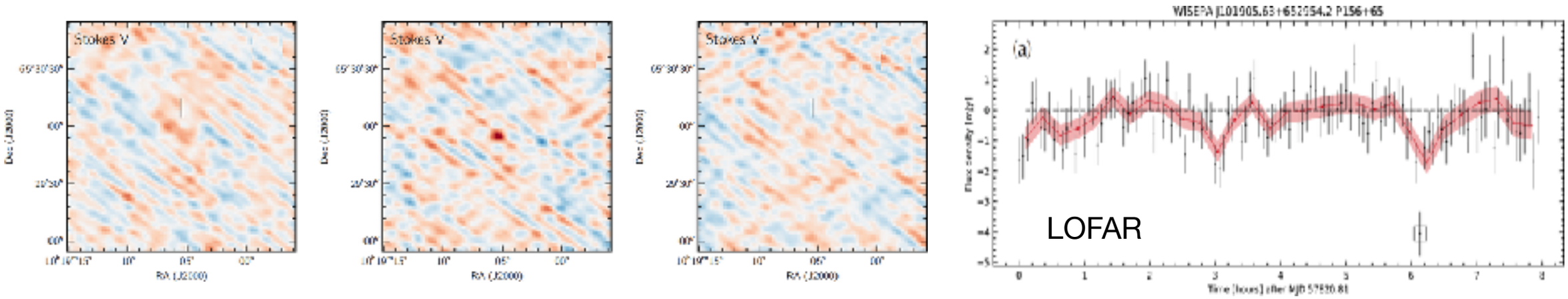


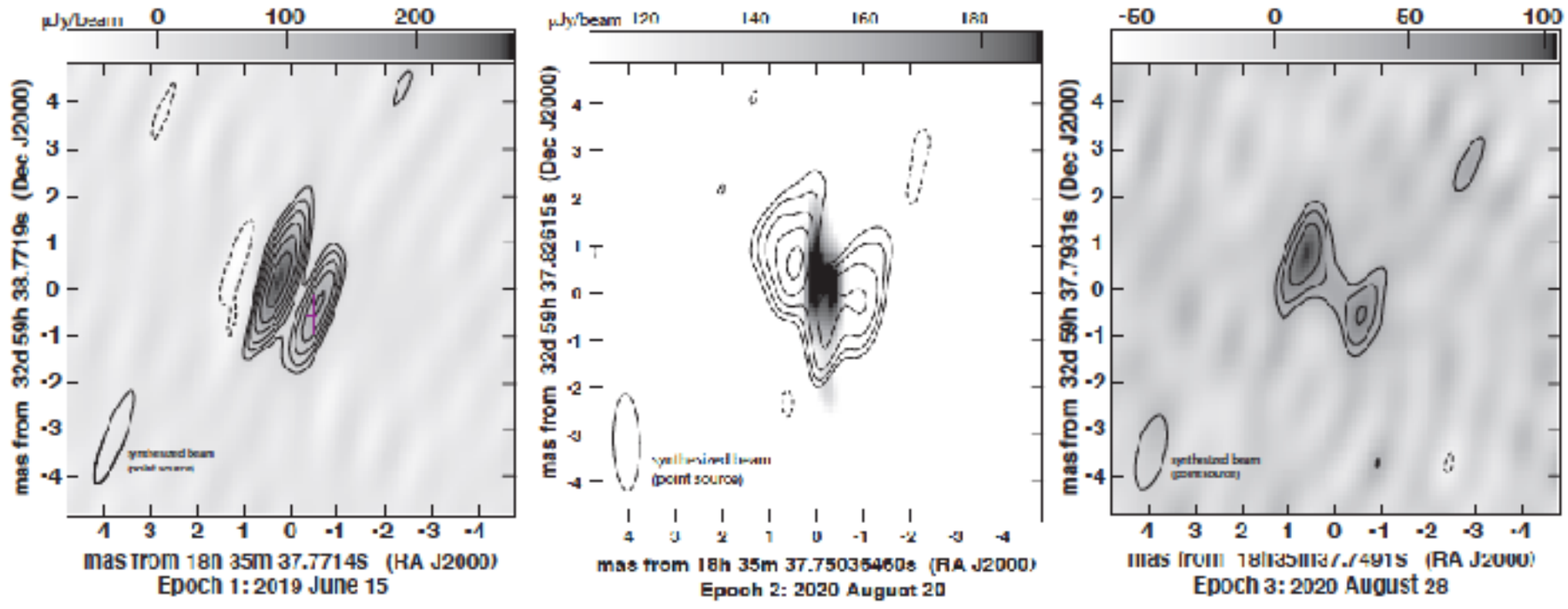
Stars: imaging & VLBI

- Stellar observations & discoveries with LOFAR/LoTSS → BD, T Tau, RSCVn...

  [Coughlan et al., 2017, Vedantham et al. 2020,2022,2023; Callingham et al, 2021a,b; Davis et al., 2021; Tet et al., 2021; Feeney-Johansson et al., 2021; Hajduk et al., 2022]

- Stellar radiation belts (HSA, EVN) → mas, 0.1 mJy [Kao et al., 2023 ; Climent et al., 2023]



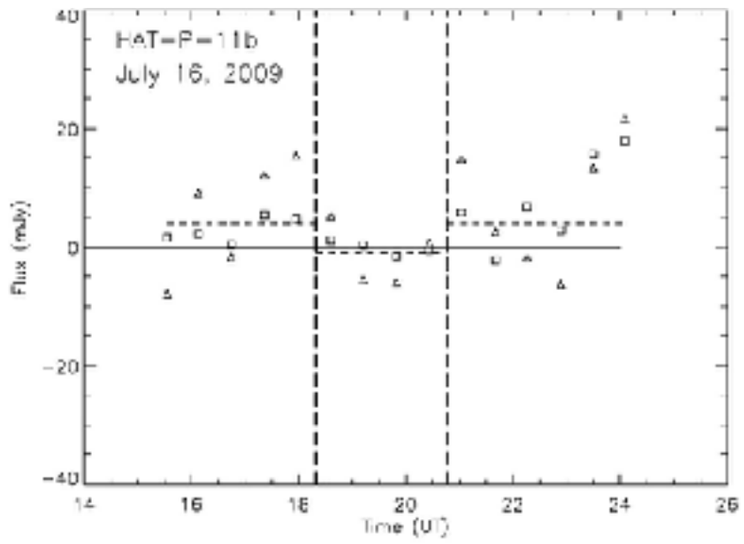


Exoplanets: imaging

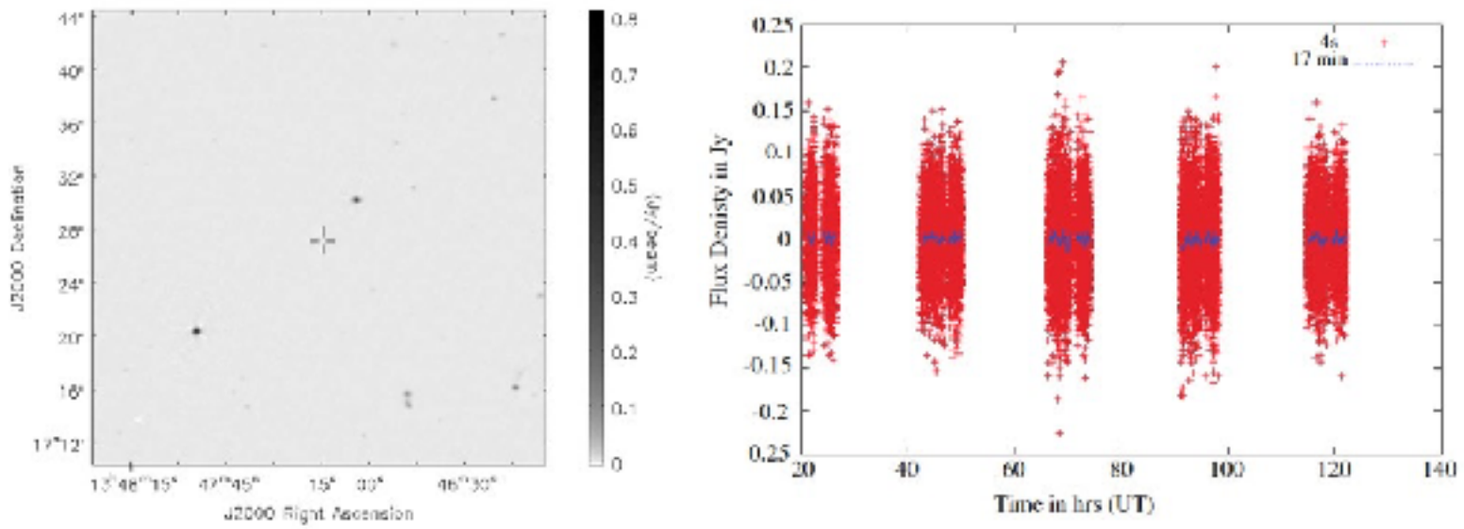
- Clues, candidates, but no confirmed detections (GMRT, VLA, LOFAR)

[Lecavelier et al., 2013; Hallinan et al., 2013; deGasperin et al., 2020, Vedantham et al. 2020]

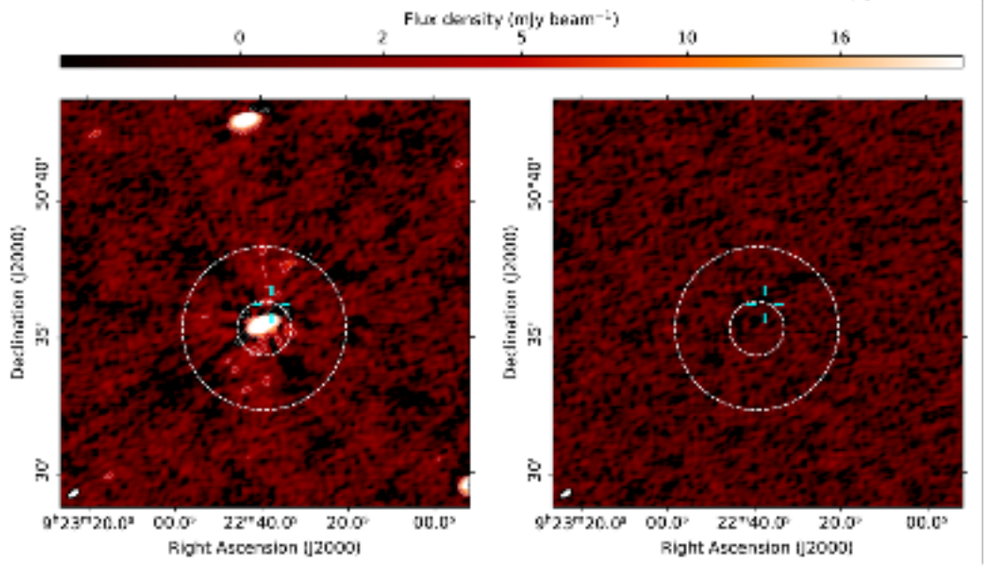
GMRT, Hat-P-11, 150 MHz, ~4 mJy



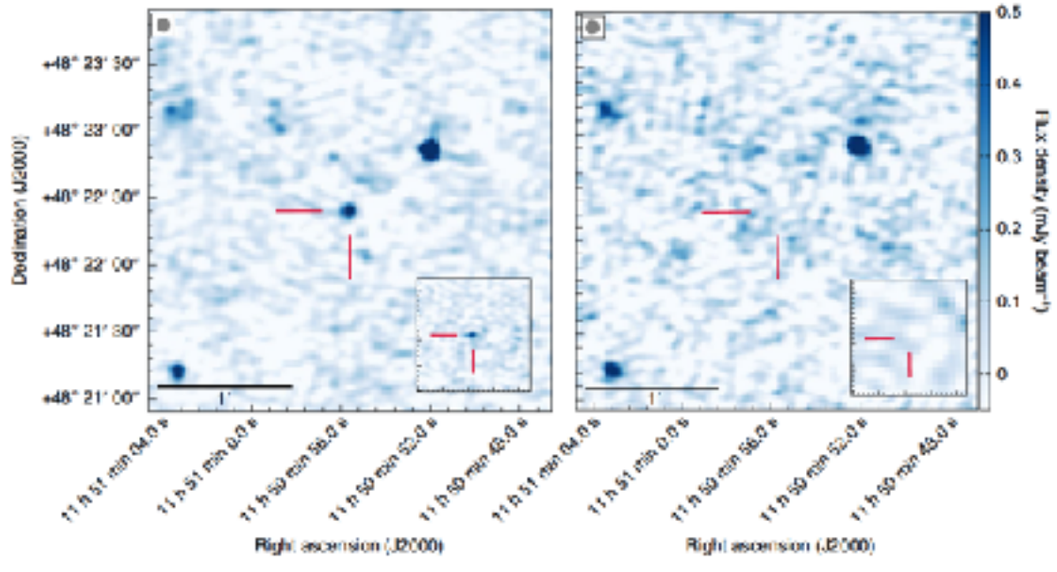
GMRT, τ Boo, 150 MHz, <1 mJy



LOFAR, HD 80606, 30-78 MHz, <10 mJy

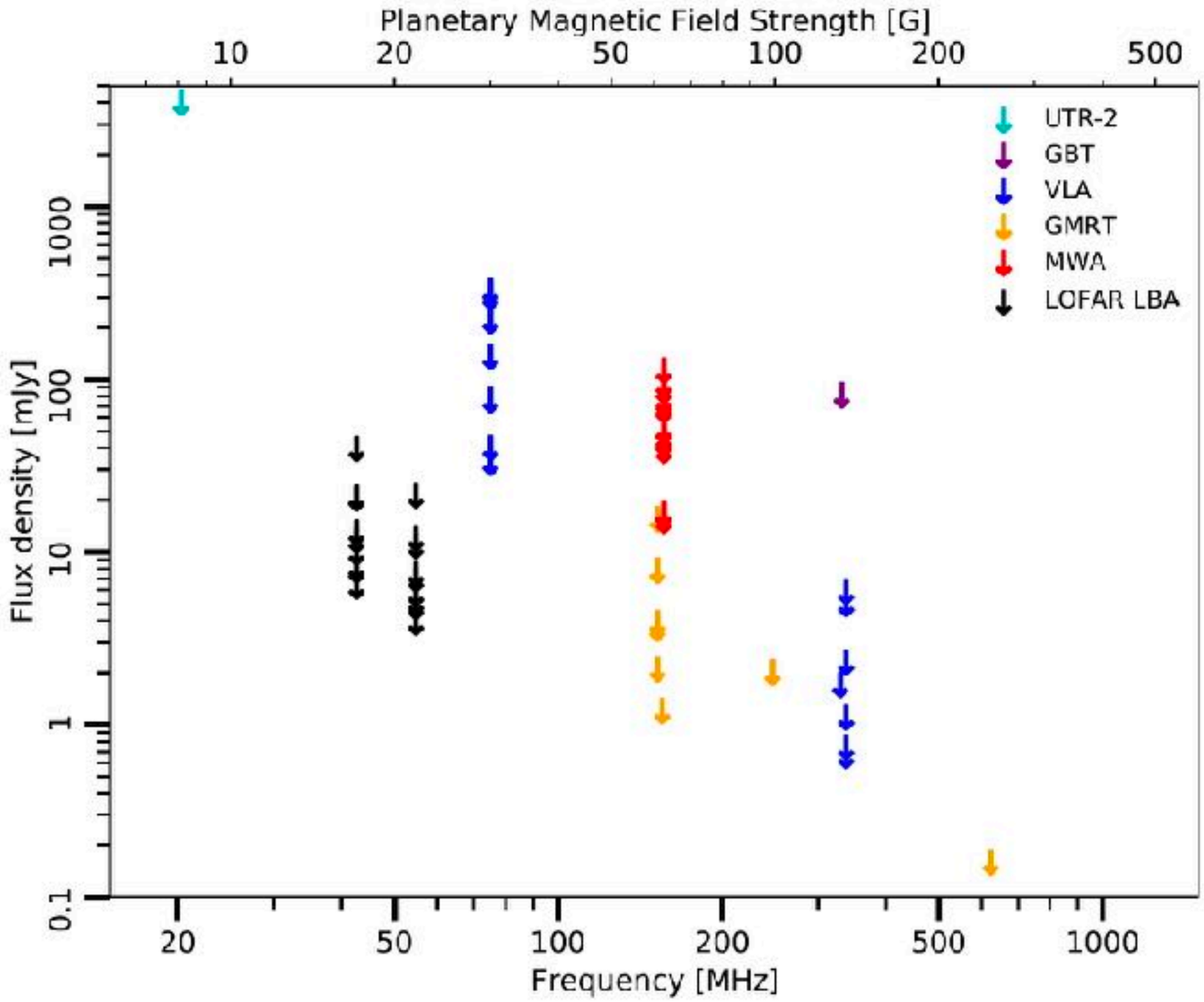


LOFAR, GJ 1151, 120-170 MHz, ~1 mJy (V)



Exoplanets: imaging

→ Where are they ?



- Heroic times
  - Jupiter, Sun
- Single dishes and phased arrays: t-f studies
  - Jupiter (<1990, 1990-2000, 2000-2010, 2010-2020, 2020+)
  - Sun, Stars, Exoplanets
- Interferometers: imaging studies
  - Jupiter, Sun, Stars, Exoplanets
- Dynamic spectra (t-f) from imaging data
  - Stars, Exoplanets
- Prospects

Dynamic spectra (t-f) from imaging data

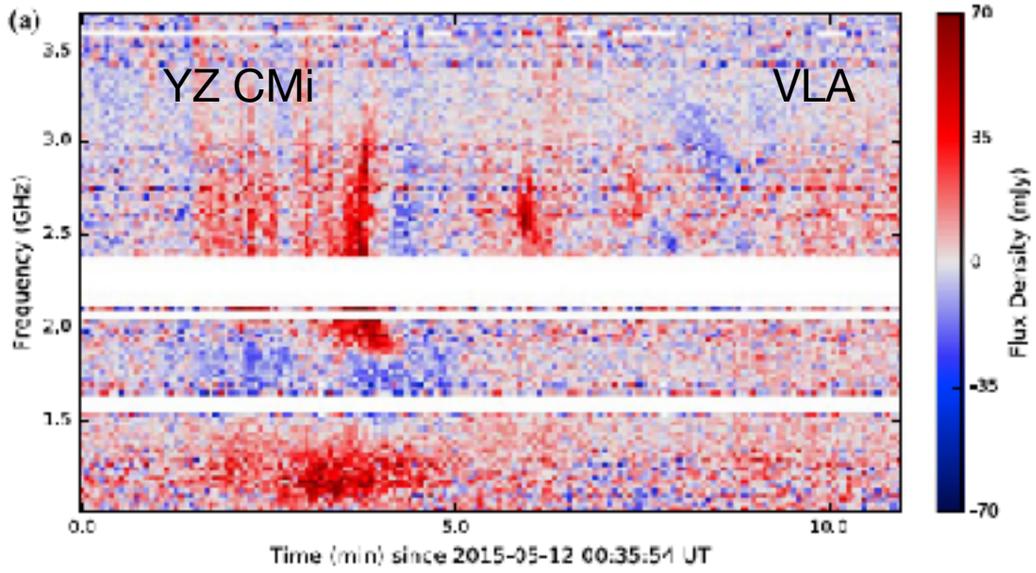
$\Sigma\ V(u,v)$ = dynamic spectrum at phase center

all baselines

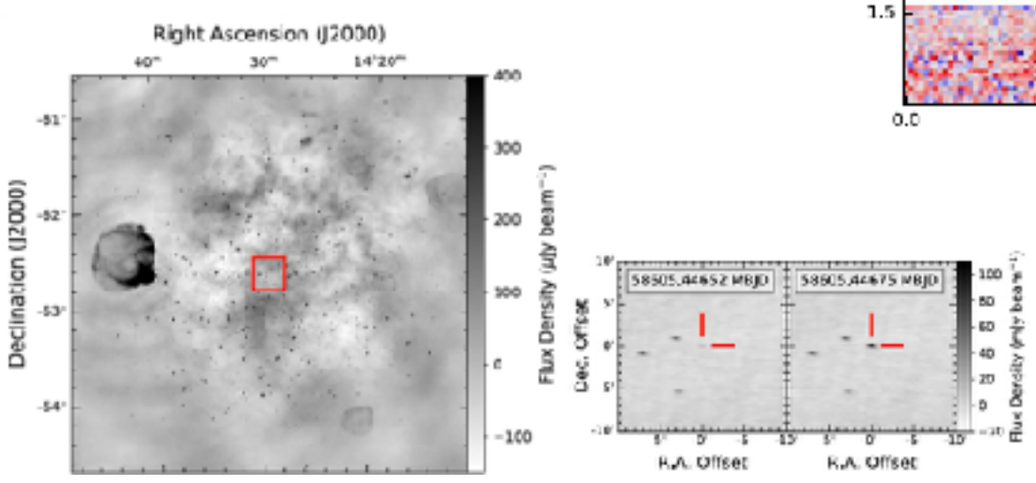
Stars

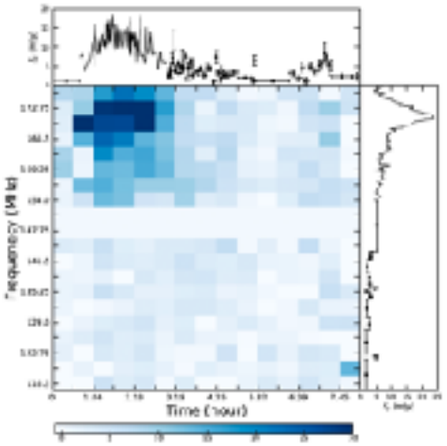
- Stellar dynamic spectra → bursts

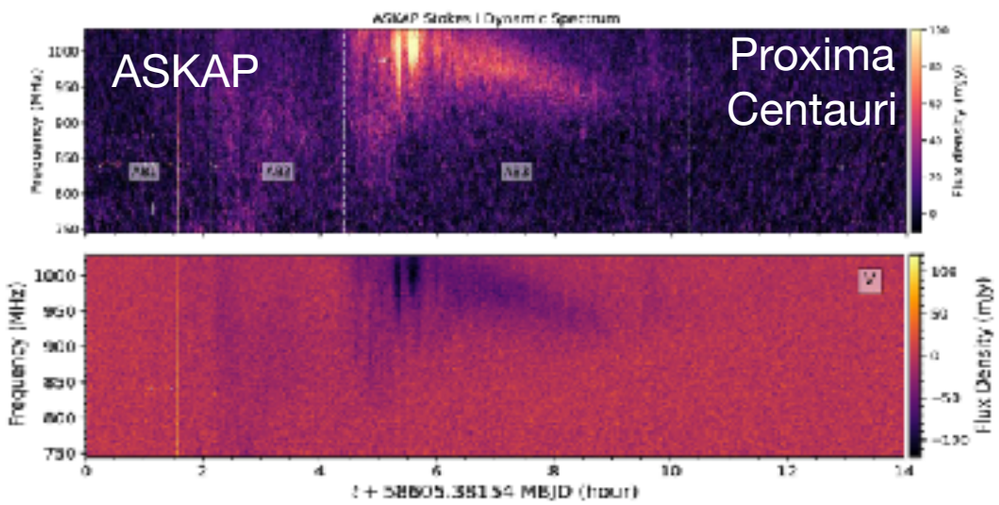
[Villadsen & Hallinan, 2019; Zic et al., 2020; Callingham et al., 2021]

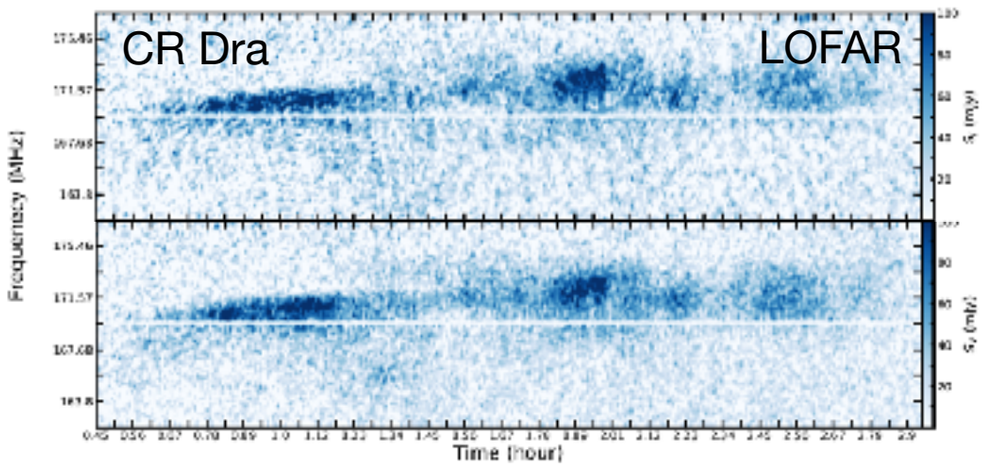


Type IV-like stellar burst









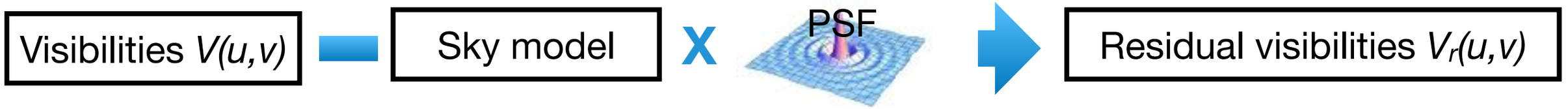
Stars, Exoplanets

$\Sigma\ V(u,v).\vec{e}^{i\vec{k}.\vec{b}}$ = dynamic spectrum in direction $\vec{k}$

→ digital Integral Field Spectroscopy

[Tasse et al., Nat. Ast., in revision]

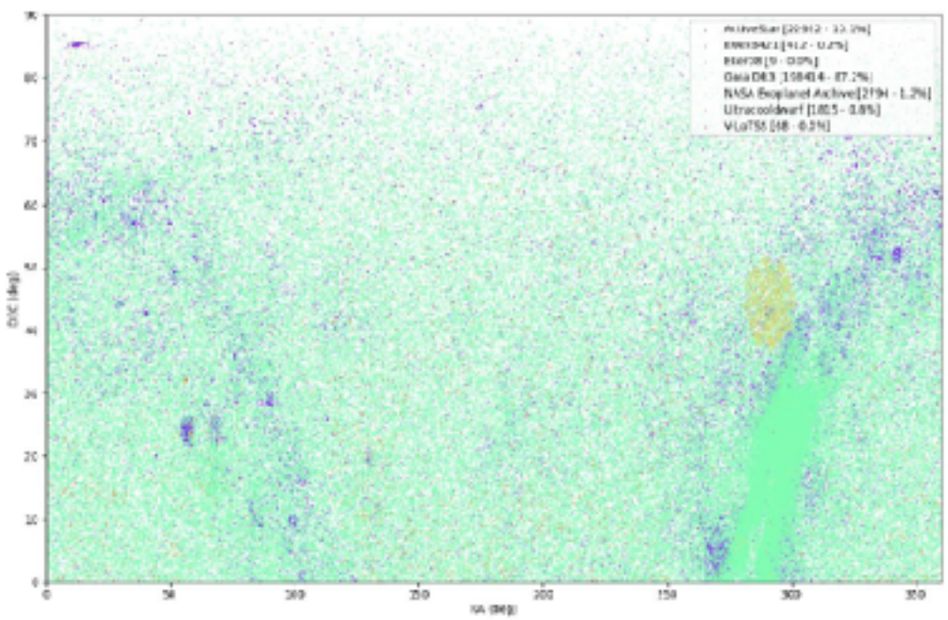
Improvement :



$\Sigma\ V_r(u,v).\vec{e}^{i\vec{k}.\vec{b}}$ = dynamic spectrum of the fluctuations in direction $\vec{k}$

→ DynSpecMS :

hundred directions per field possible
efficiency +++
input catalog (stars & exoplanets)



Stars, Exoplanets

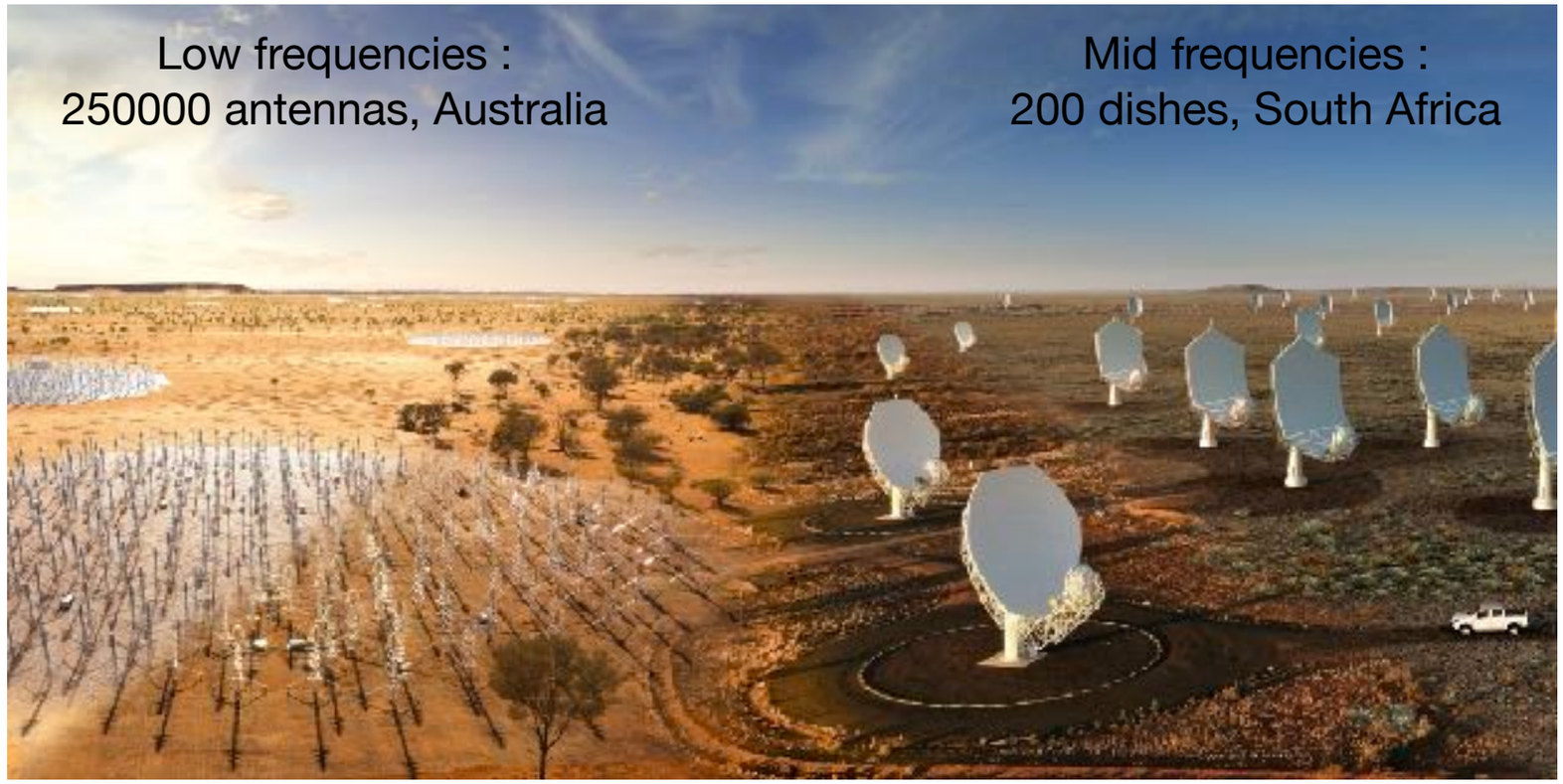
- First detection of bursts in "high-variability" LOFAR dynamic spectra
- Confirmation via re-imaging
- Consistent with Star-Planet Interaction emission
- Application to NenuFAR

[Tasse et al., Nat. Ast., in revision; Zhang et al., A&A, in revision]

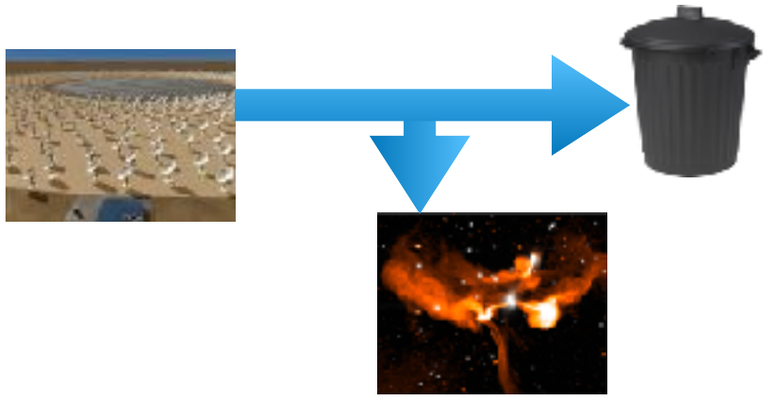
- First stellar type II burst ?

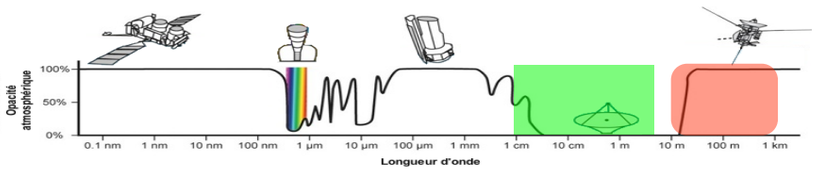
[Tasse et al., Nat. Ast., in revision; **Callingham et al., Nature, in revision**]

- Heroic times
  - Jupiter, Sun
- Single dishes and phased arrays: t-f studies
  - Jupiter (<1990, 1990-2000, 2000-2010, 2010-2020, 2020+)
  - Sun, Stars, Exoplanets
- Interferometers: imaging studies
  - Jupiter, Sun, Stars, Exoplanets
- Dynamic spectra (t-f) from imaging data
  - Stars, Exoplanets
- Prospects

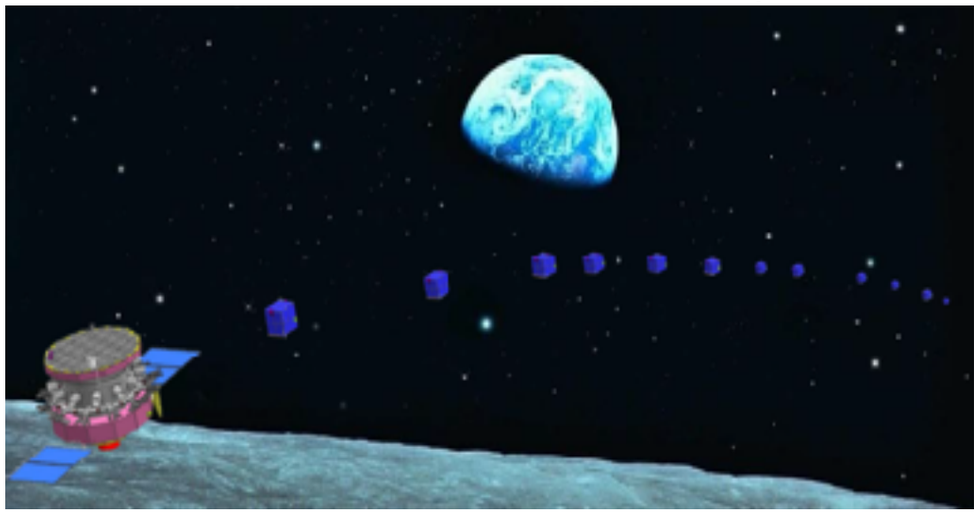


- Problematics:

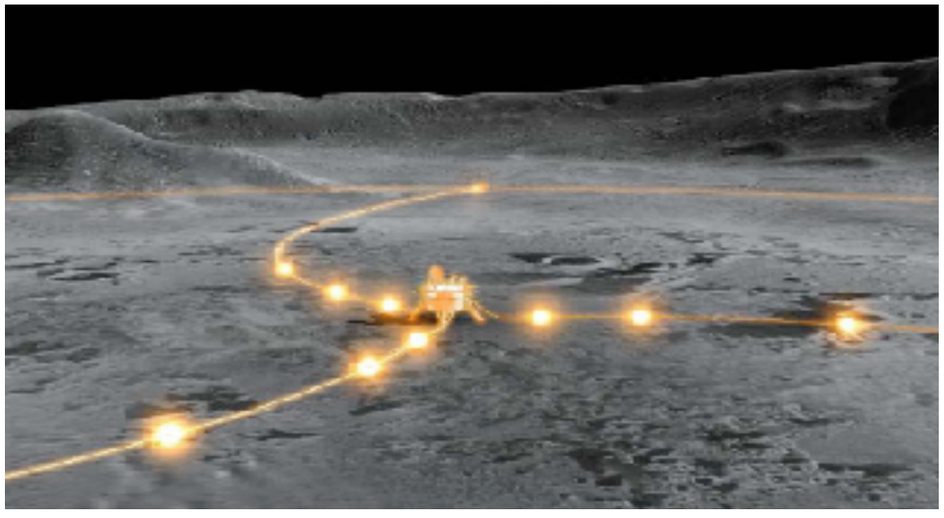




VLF radio interferometry from space



Large antenna array on the Moon



Thank you.

Questions ?