ES02 : Exoplanets & Stars

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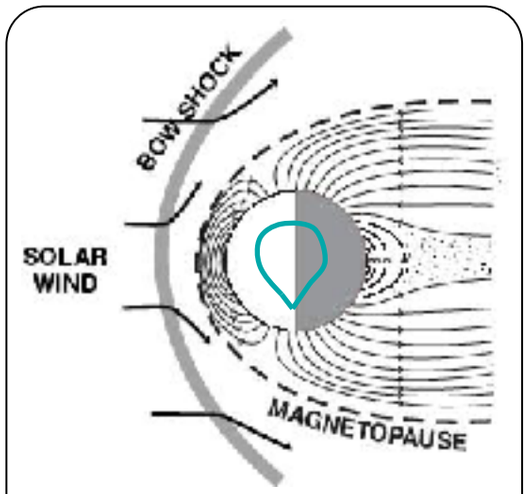
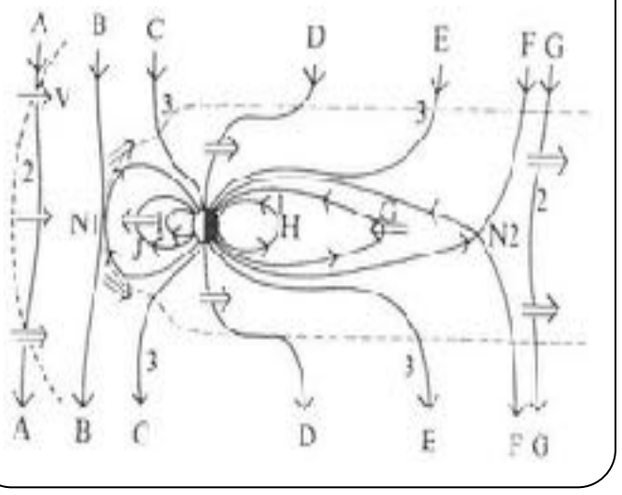
+ the ES02 team (see below)

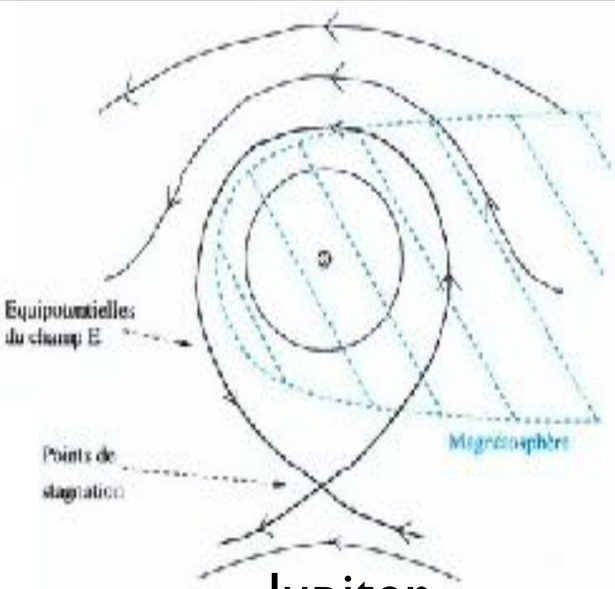
All Solar system magnetospheres are different !



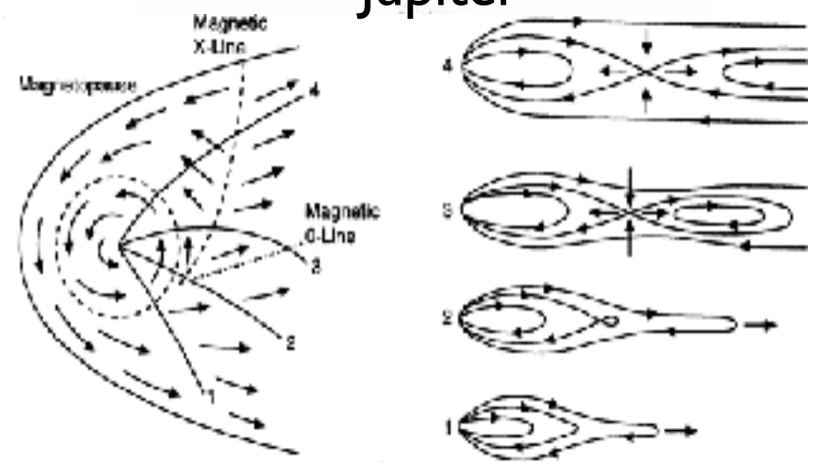
Mercury

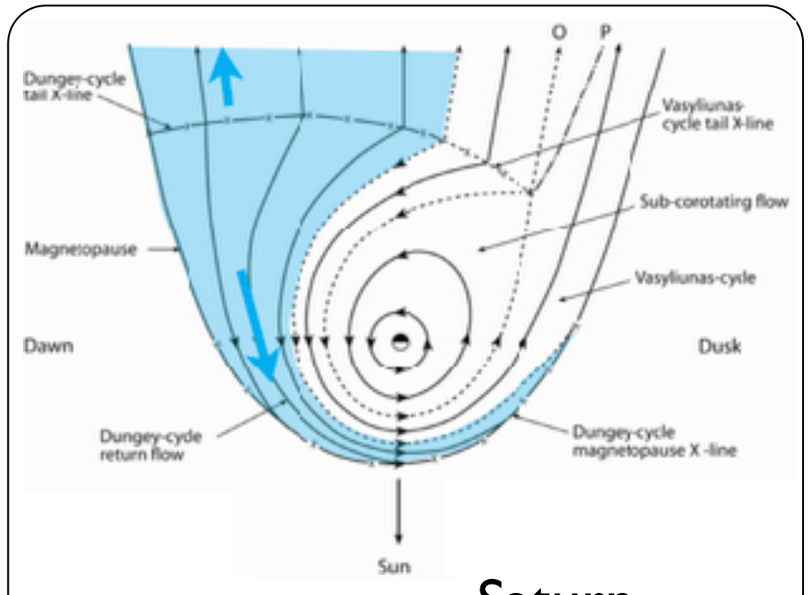
Earth



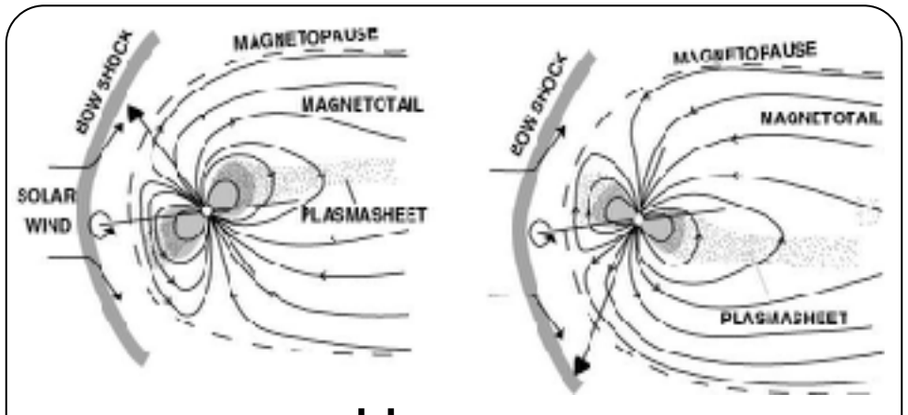


Jupiter

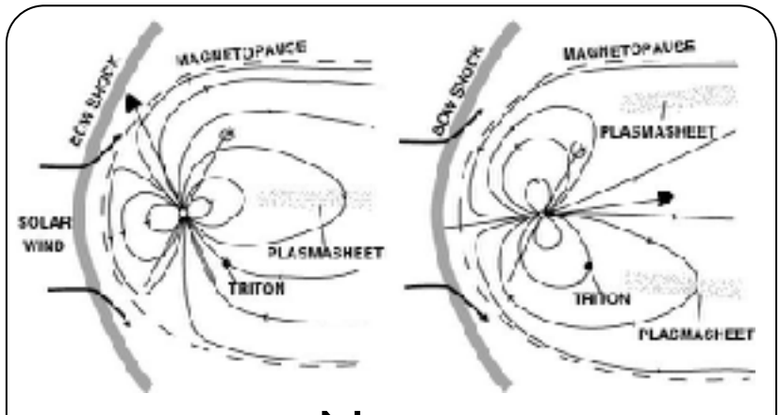




Saturn



Uranus

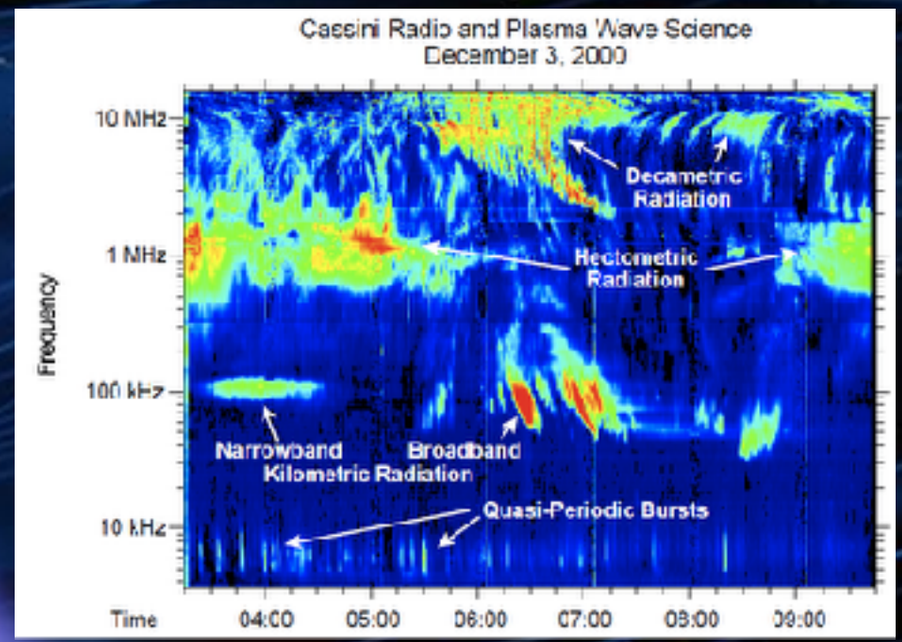


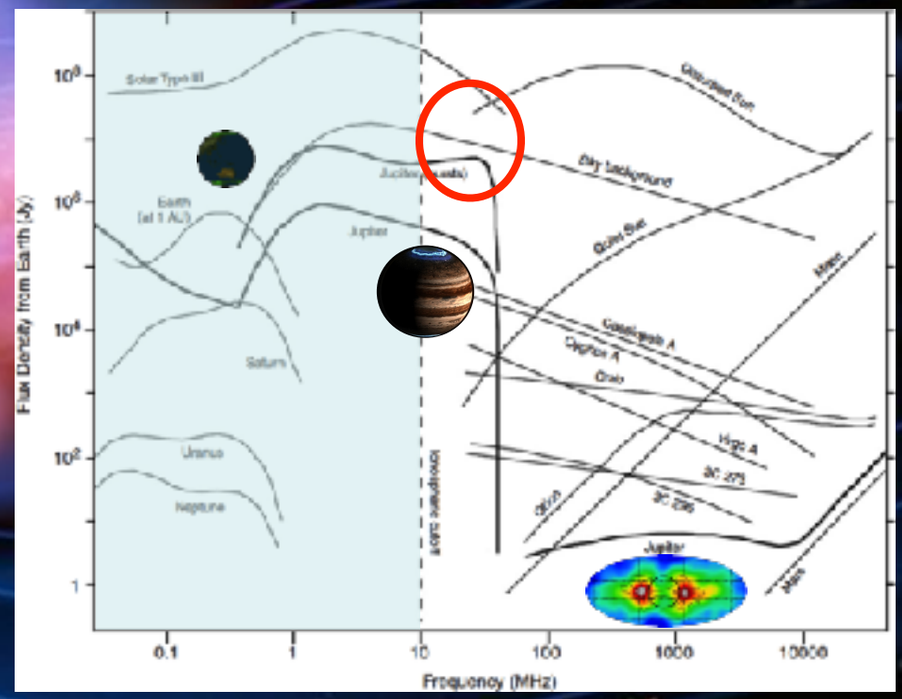
Neptune

→ need for comparative exo-magnetospheric physics

Long-term effort to detect radio emission from exoplanets

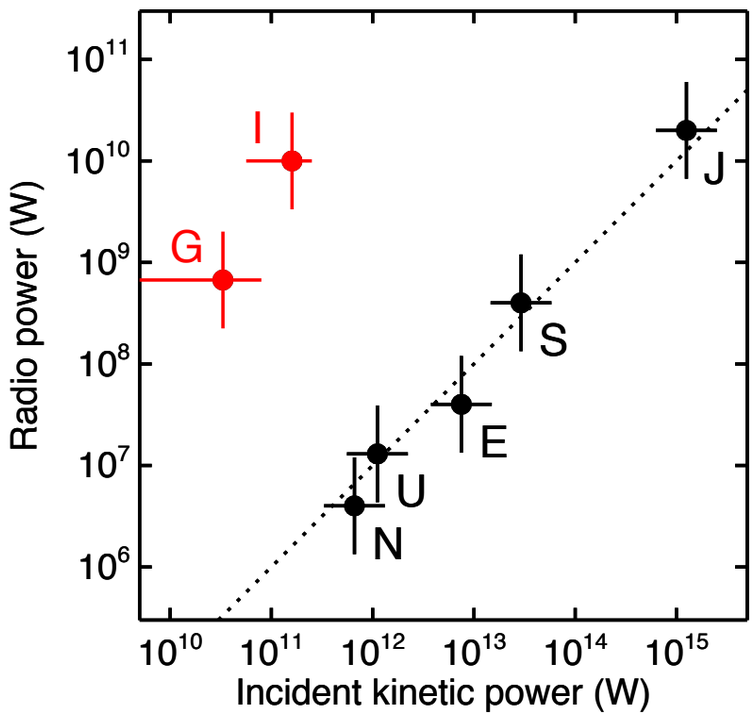
Inspiration : Jupiter is an intense radio emitter (~Sun)

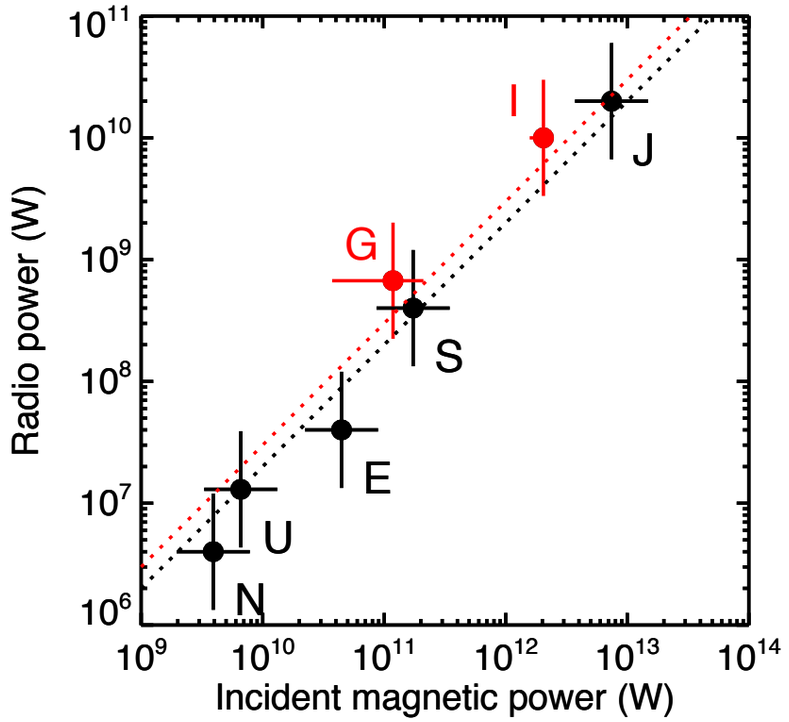




But : Not detectable at stellar distances

Scaling law predictions



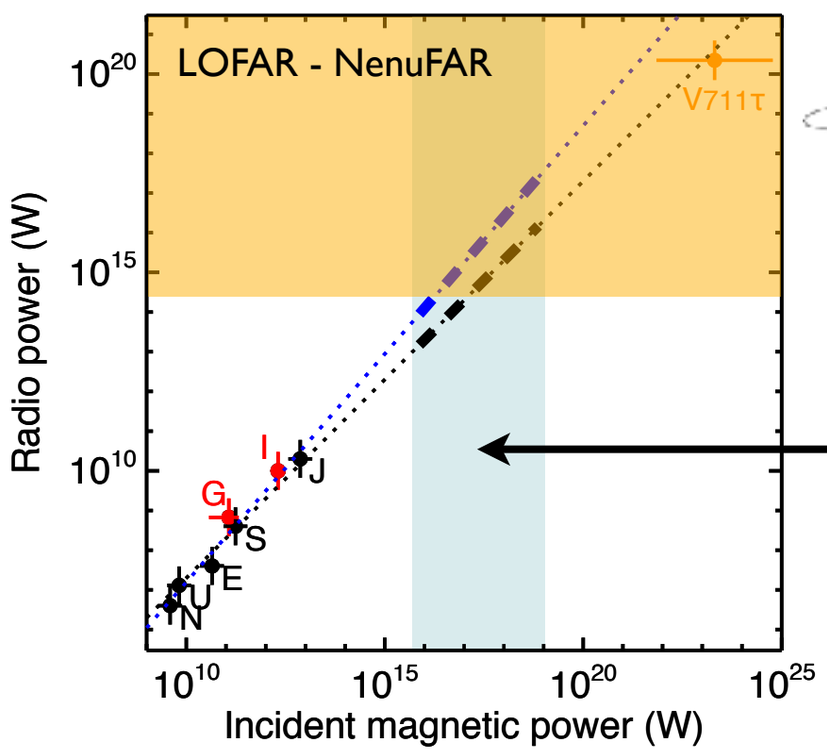


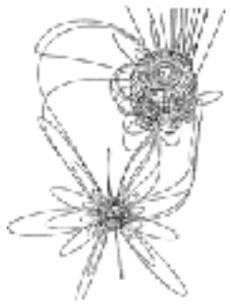
$$P_d = \varepsilon \, (V_{flow} B_{\perp}^{\,2} / \mu_o) \, \pi R_{obs}^{\,2}$$

$$P_r = \beta \, (V_{flow} B_{\perp}^{\,2} / \mu_o) \, \pi R_{obs}^{\,2} = \beta \, P_d / \varepsilon$$

→ General flow - obstacle interaction

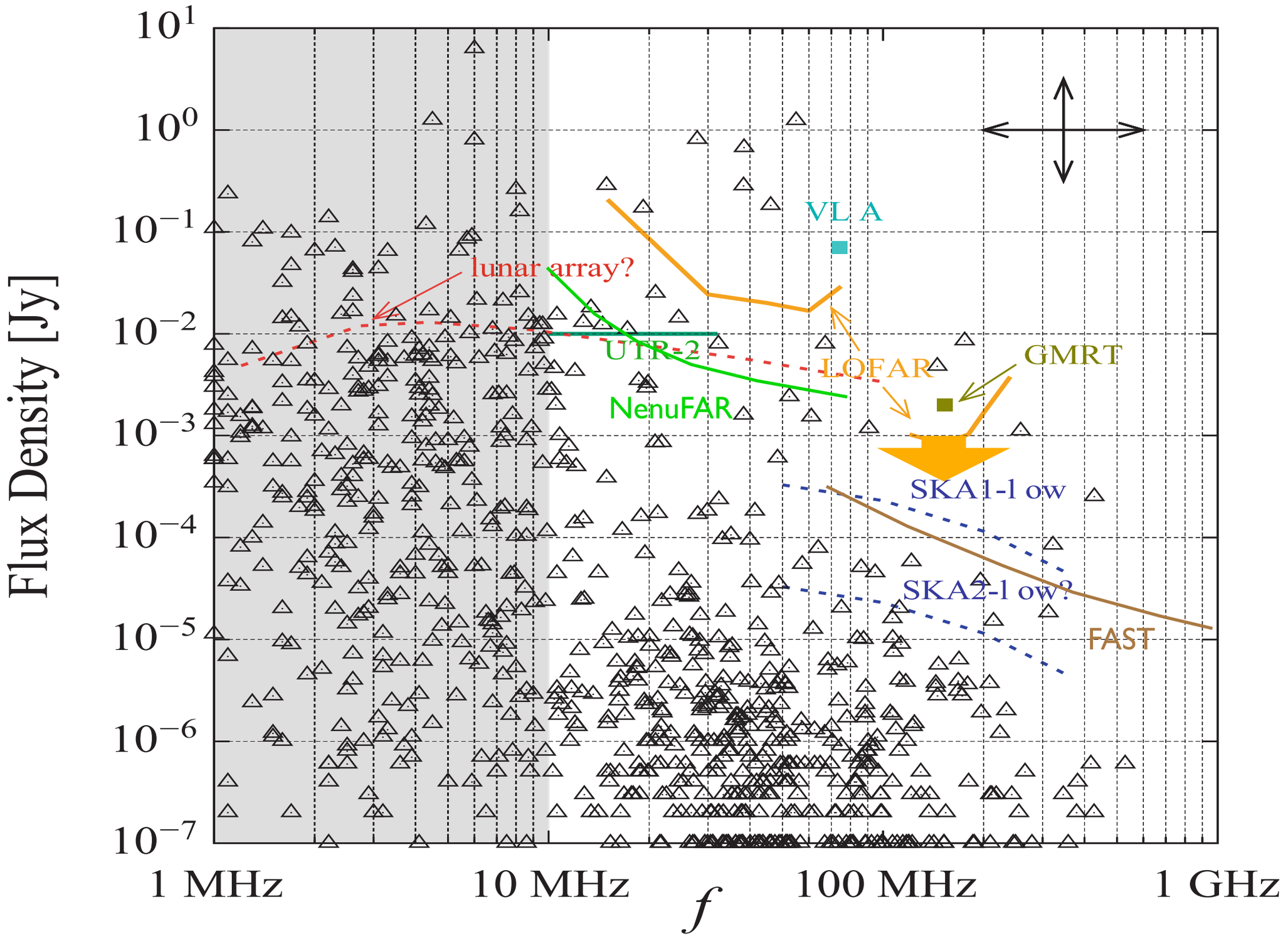
[Zarka et al., 2018]





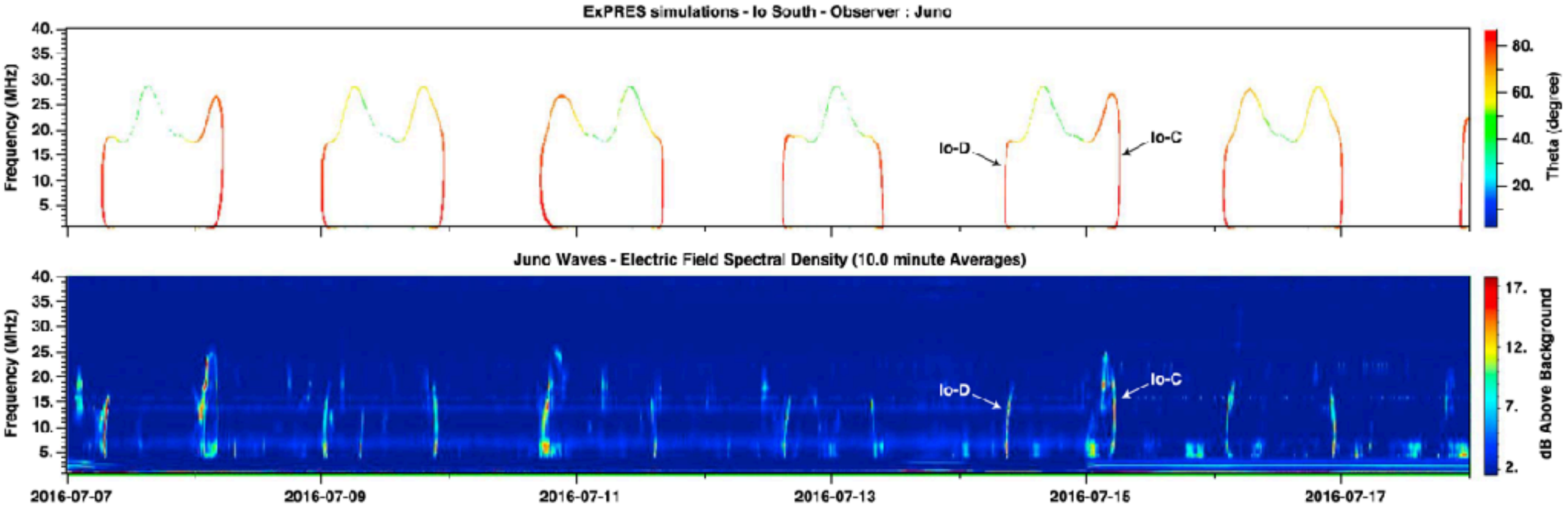
hot Jupiters : magnetospheric emission and Io-induced emission x $10^{3\text{-}6}$

Signals potentially detectable with LOFAR, UTR-2, NenuFAR



[Grießmeier et al., 2011; Grießmeier, 2018]

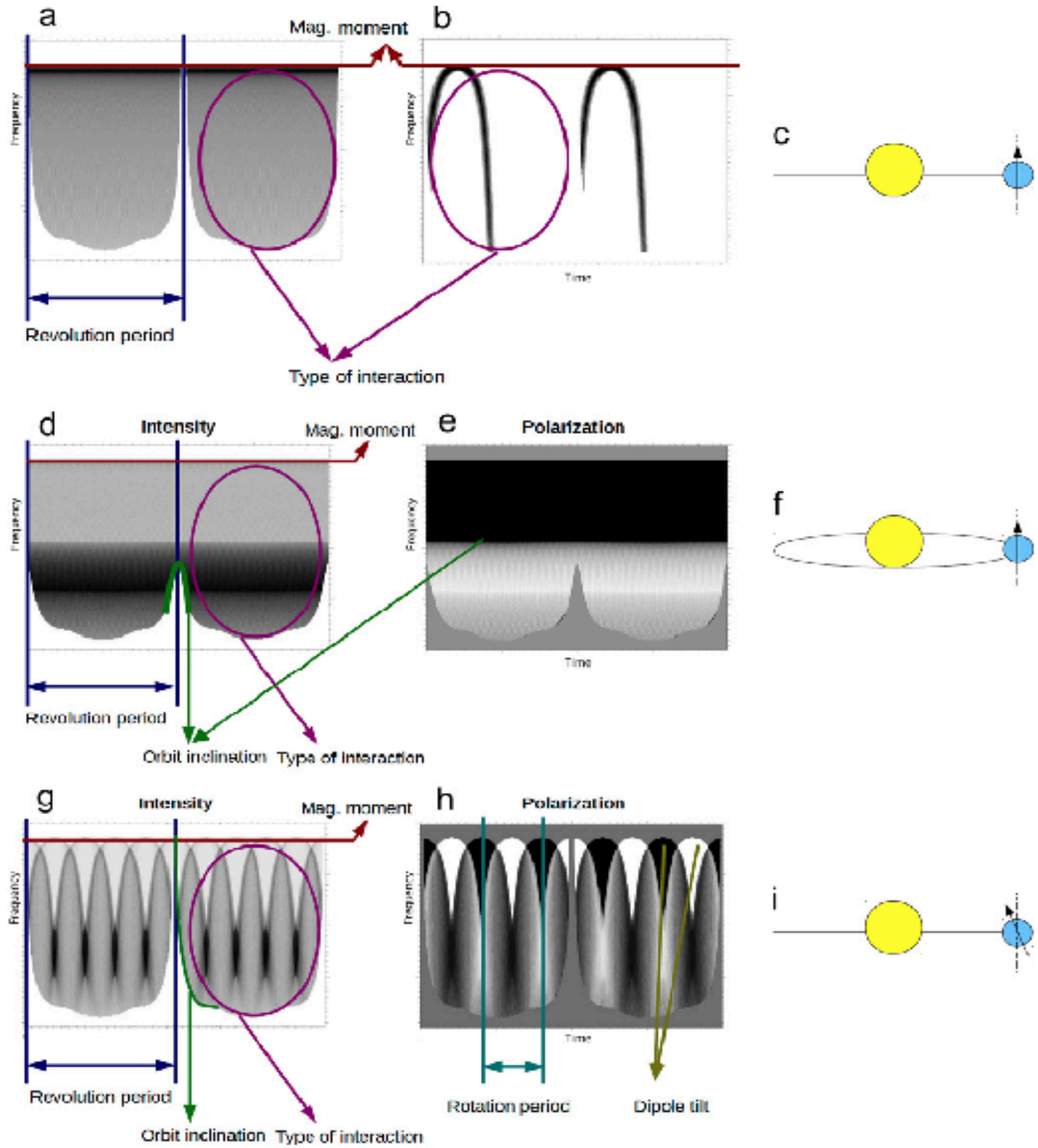
Modelisation



[Louis et al., 2017]

Motivations

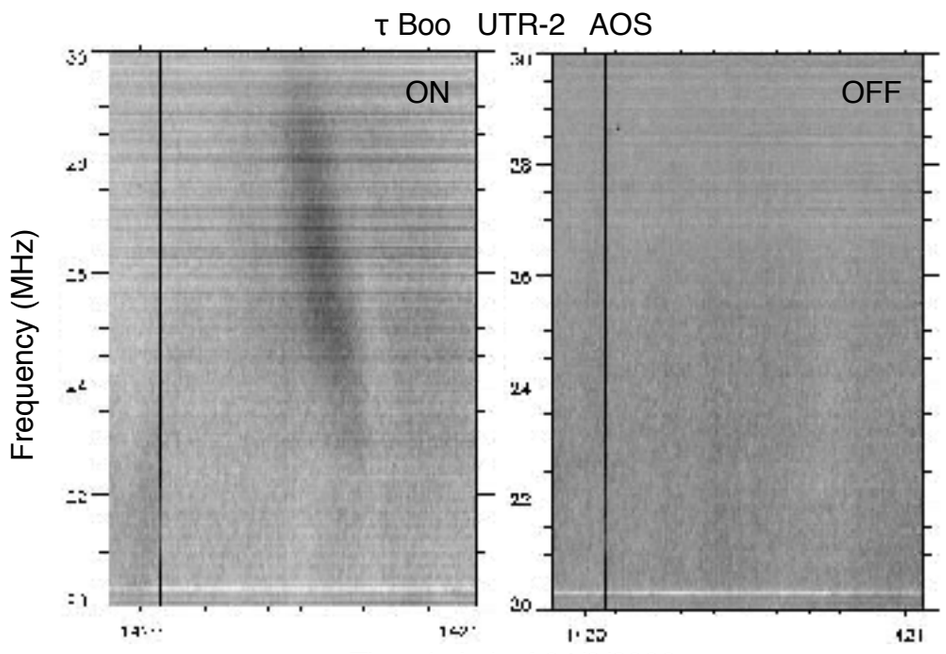
B, internal structure, exo-magnetospheric physics, SPI, habitability ...



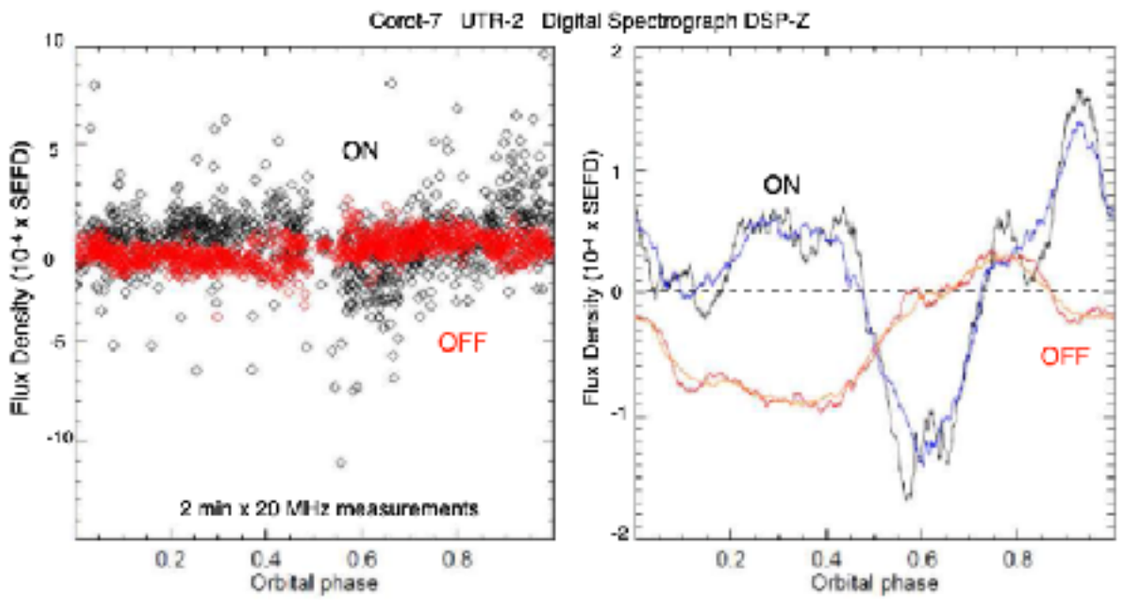
[Hess & Zarka, 2011]

Past observations

Exoplanets, SPI (UTR-2)

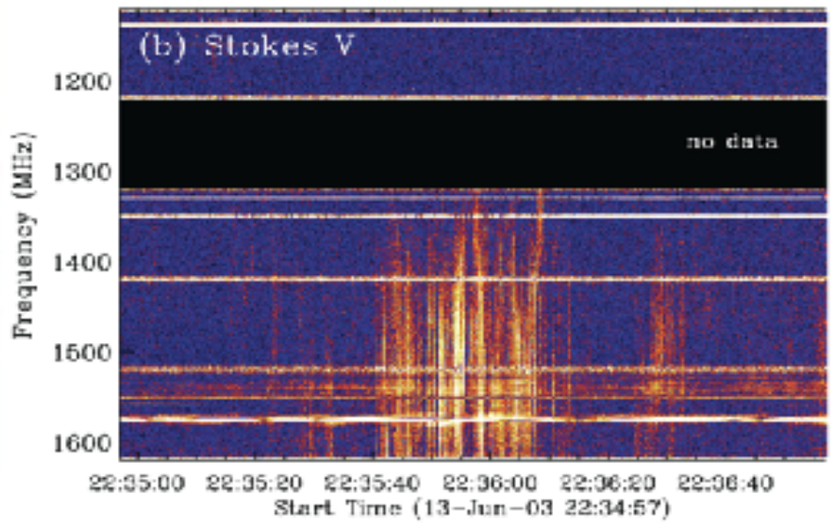


[UTR-2, unpublished]

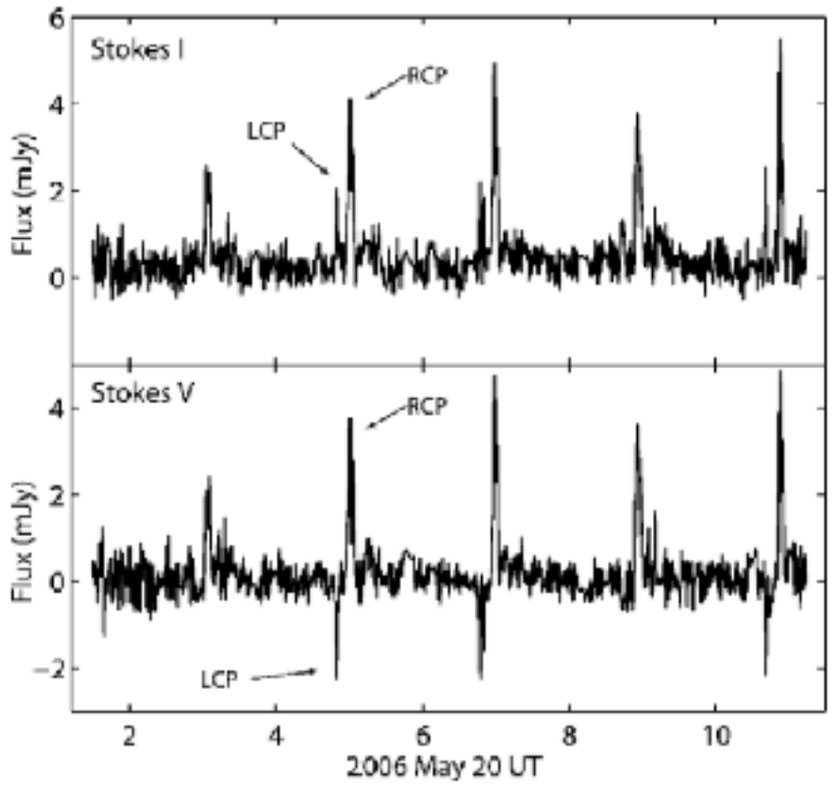


[Vasylieva & Zarka, 2015]

Cool dwarfs (VLA)



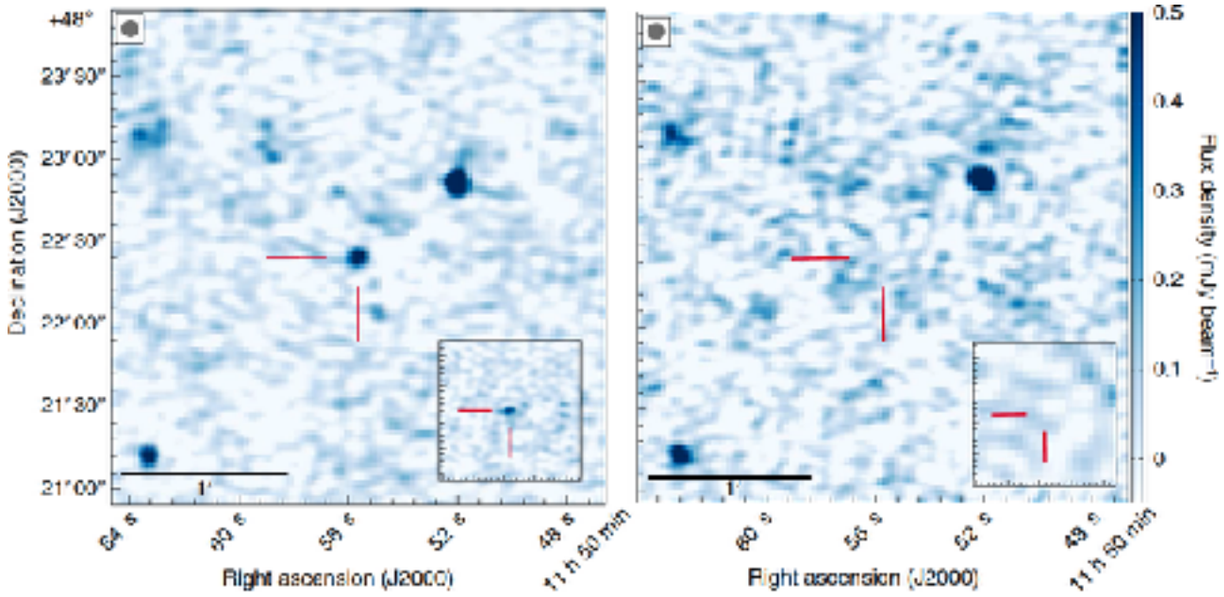
[Osten & Bastian, 2006]



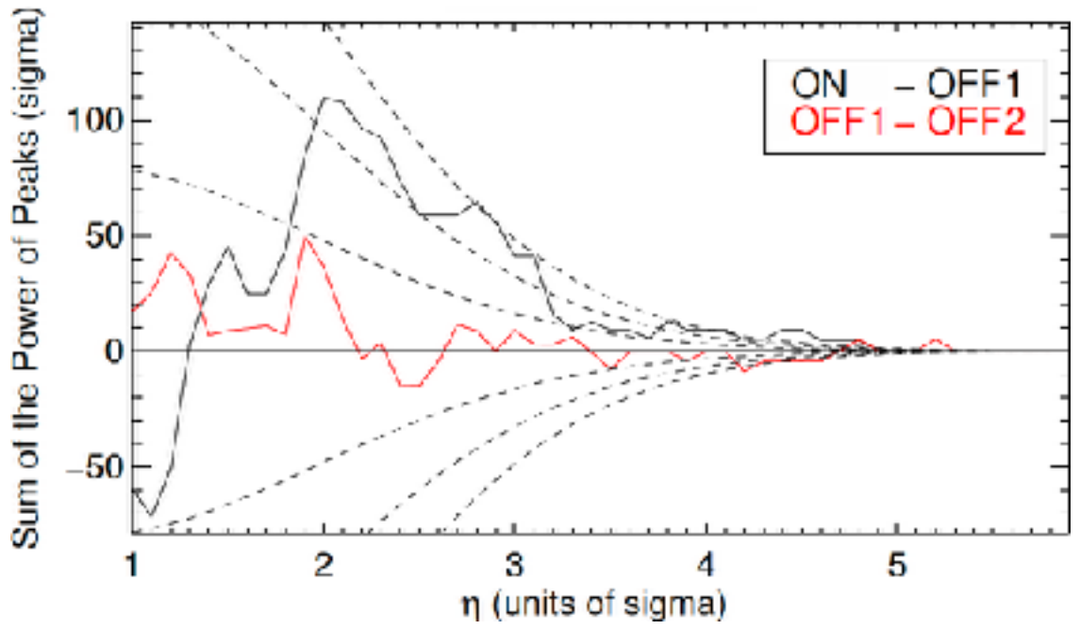
[Hallinan et al., 2007]

Recent observations

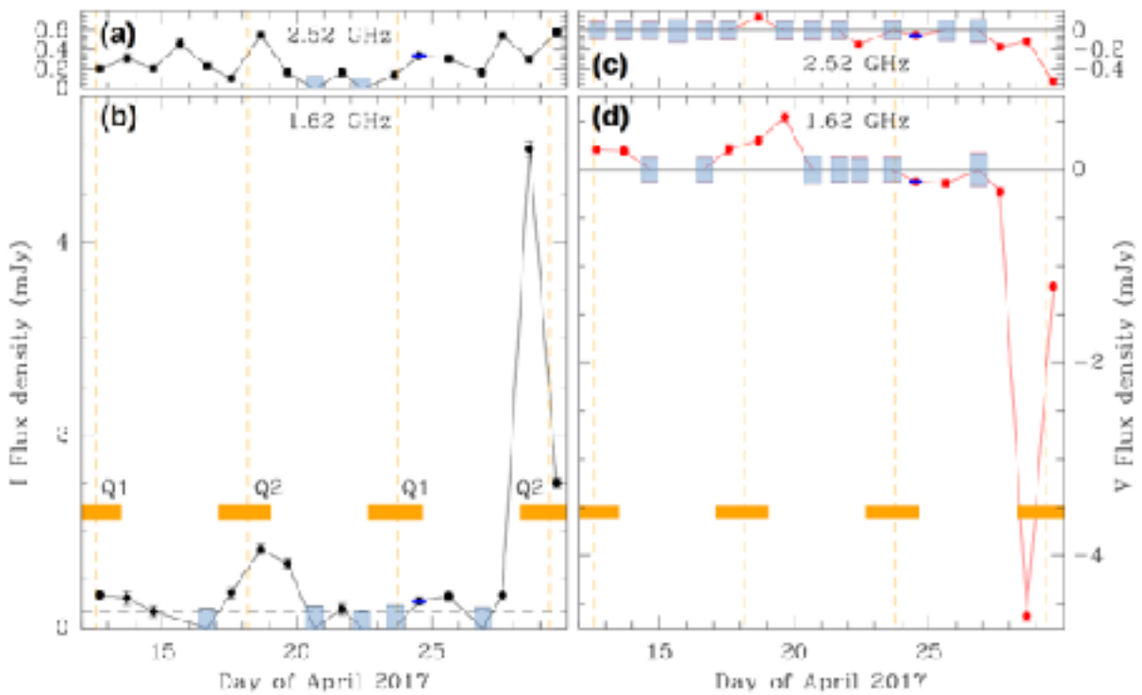
Exoplanets, SPI (LOFAR, ATCA)



[Vedantham et al., 2020]

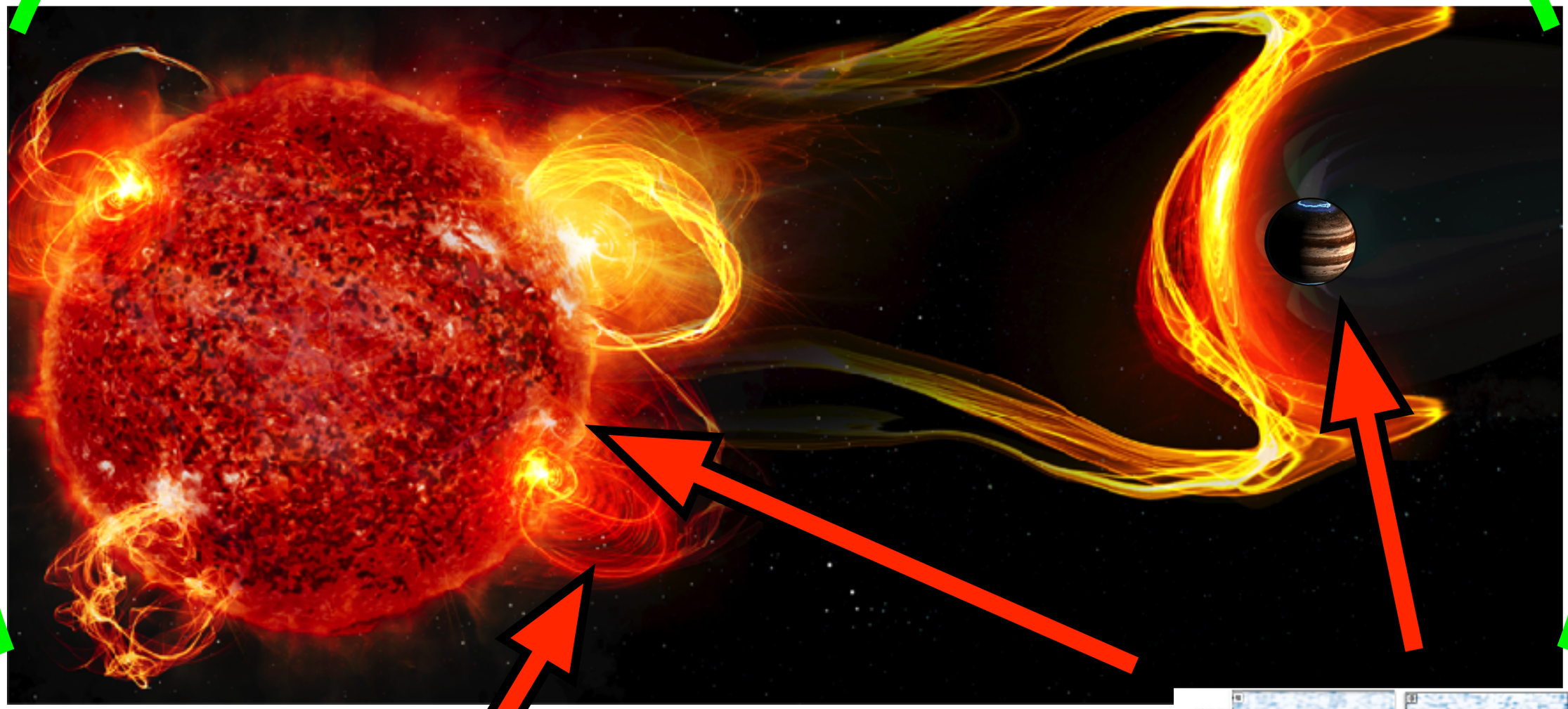


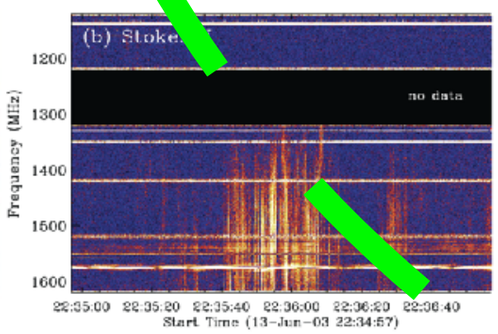
[Turner, Zarka et al., 2021]

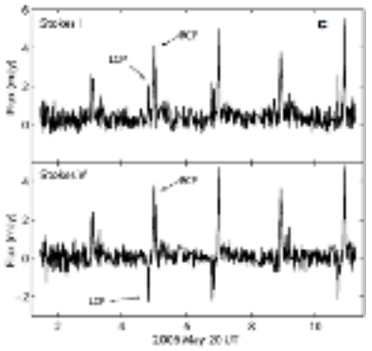


[Perez-Torres et al., 2021]

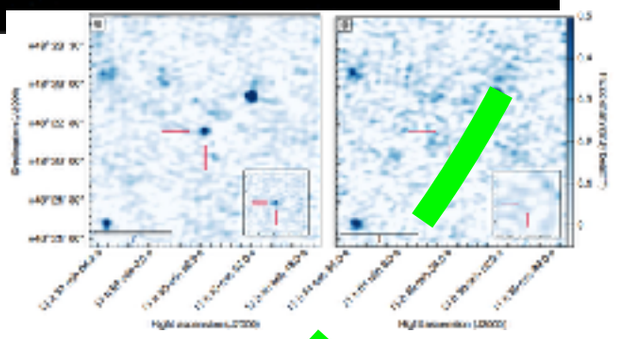
Comparative exo-magnetospheric physics & stellar activity

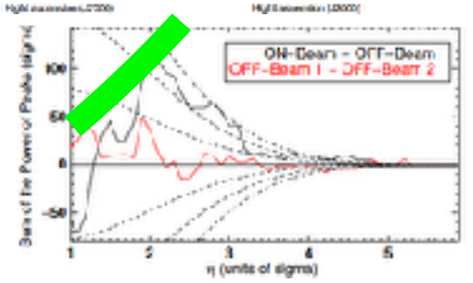






[Osten & Bastian, 2006 ; Hallinan et al., 2007]





[Vedantham et al., 2020 ; Turner et al., 2021]

Single beam or pixel

Observations

- Targets : 21+2 exoplanets, ~14 stars

2MASS_J10475385+2124234	30.67 h
AD_LEO	98.15 h
EQ_PEG	16.93 h
EV_LAC	28.00 h
LP212-62	80.07 h
LSR_J1835+3259	51.30 h
SIMP_J013656_5+093347_3	6.00 h
TVLM_513-46546	62.77 h
UV_CETI	27.00 h
V830_TAU	106.15 h
WISEPA_J101905	132.75 h
WISEP_J112254_73+255021_5	24.18 h
WX_UMA	95.45 h
YZ_CMI	20.98 h
Total	**780 h**
CR_DRA	323.87 h
GJ_1151	244.00 h
Total	**568 h**

47_UMA	12.00 h
51_PEG	17.00 h
55_CNC	74.75 h
COROT-7	190.17 h
EPS_ERI	43.83 h
GJ_1214	39.33 h
GJ_65	18.00 h
HAT-P-11	107.50 h
HD_179949	28.00 h
HD_189733	129.97 h
HD_209458	25.00 h
HD_80606	37.00 h
TAU_BOOTIS	98.38 h
TAU_BOOTIS_JOINT_CAMPAIGN_TAU_BOOTIS	64.22 h
TRAPPIST-1	51.00 h
UPS_AND	128.08 h
VAN_MAANEN_STAR	16.00 h
WASP-12	22.50 h
WASP-33	42.00 h
WASP-76	3.00 h
WOLF_28	13.95 h
Total	**1160 h**

Observations

- Joint campaigns with LOFAR on CR Dra
- Joint campaigns with LWA & UTR-2 on Tau Bootes
- Intensive campaigns on LoTSS targets : GJ 1151, WISEPA_J101905…

- Present parameters for Exoplanets:

  Day: Freq. range = 30.1-67.4 MHz

  Night: Freq. range = 21.1-58.4 MHz

  df=3.05 kHz dt=21.0 msec

  4 beams (1 On, 3 Off)

- Present parameters for Stars:

  Freq. range = 12-86.9 MHz

  df=3.05 kHz dt=42.0 msec

  2 beams (1 On, 1 Off),

Beamformed-TF pipeline

- Suite of IDL procedures based on **read_nu_spec.pro** *(see talk tomorrow)*
  - *proc_es02.pro*
  - *batch_proc_es02.pro*
  - *check_es02_fits.pro*

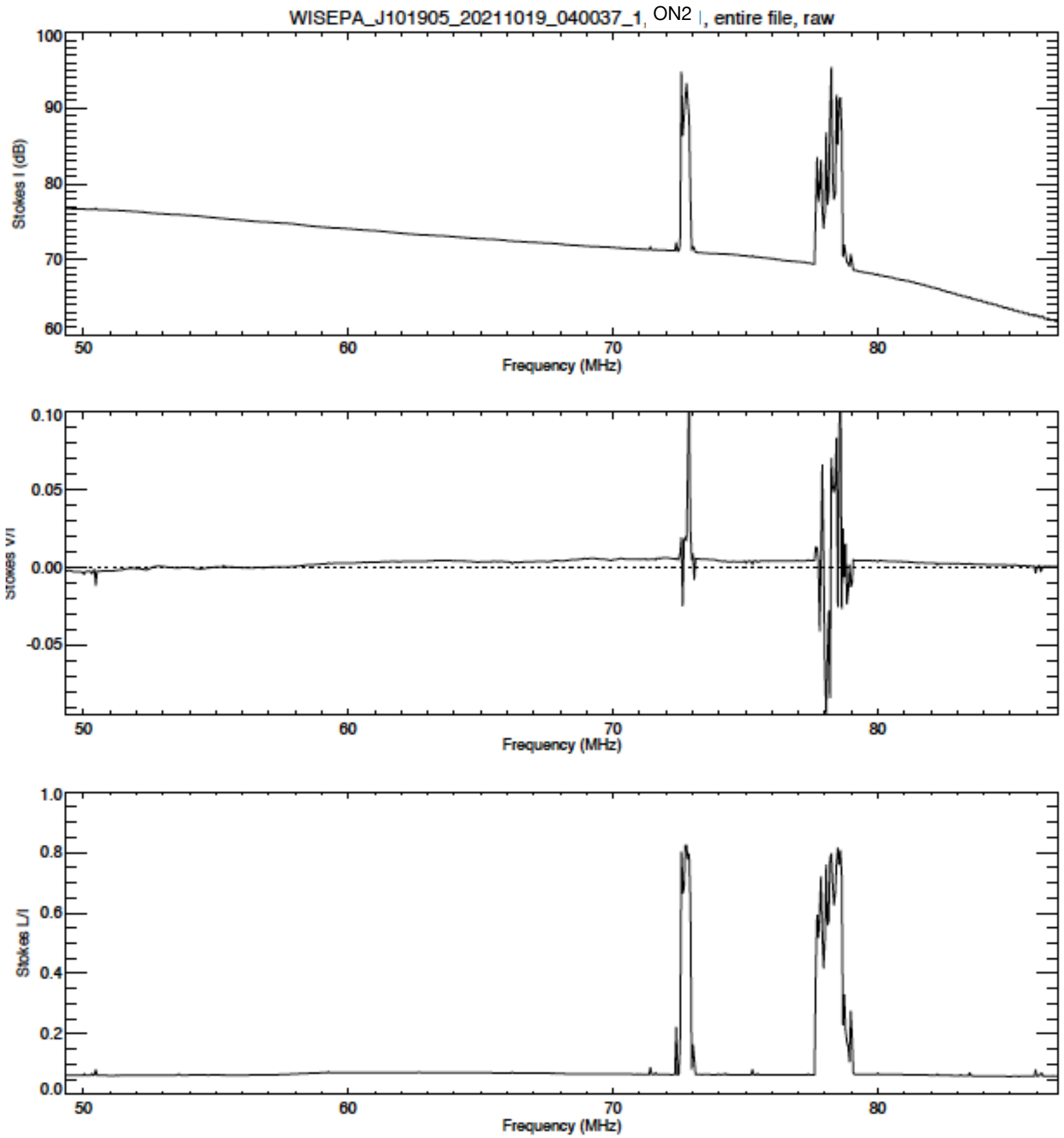
- RFI mitigation, correction of gain jumps, Stokes IVL or IQUV, temporal and spectral integrations

READ_NU_SPEC, path+file, data,time,freq,beam,ndata, nt,dt,nf,df,ns, jd0,h0,
corrf,corrt, nchannels=4, ntimes=12, nstokes=3 *[or 4]*, ex_chan=[0],
ex_beamlets=*[list…]*, fclean=[4.,101], /bclean, /tclean, tflat=[7,36.5,70.],
/fill, writefits=2, writetxt=2, block_inc=1000

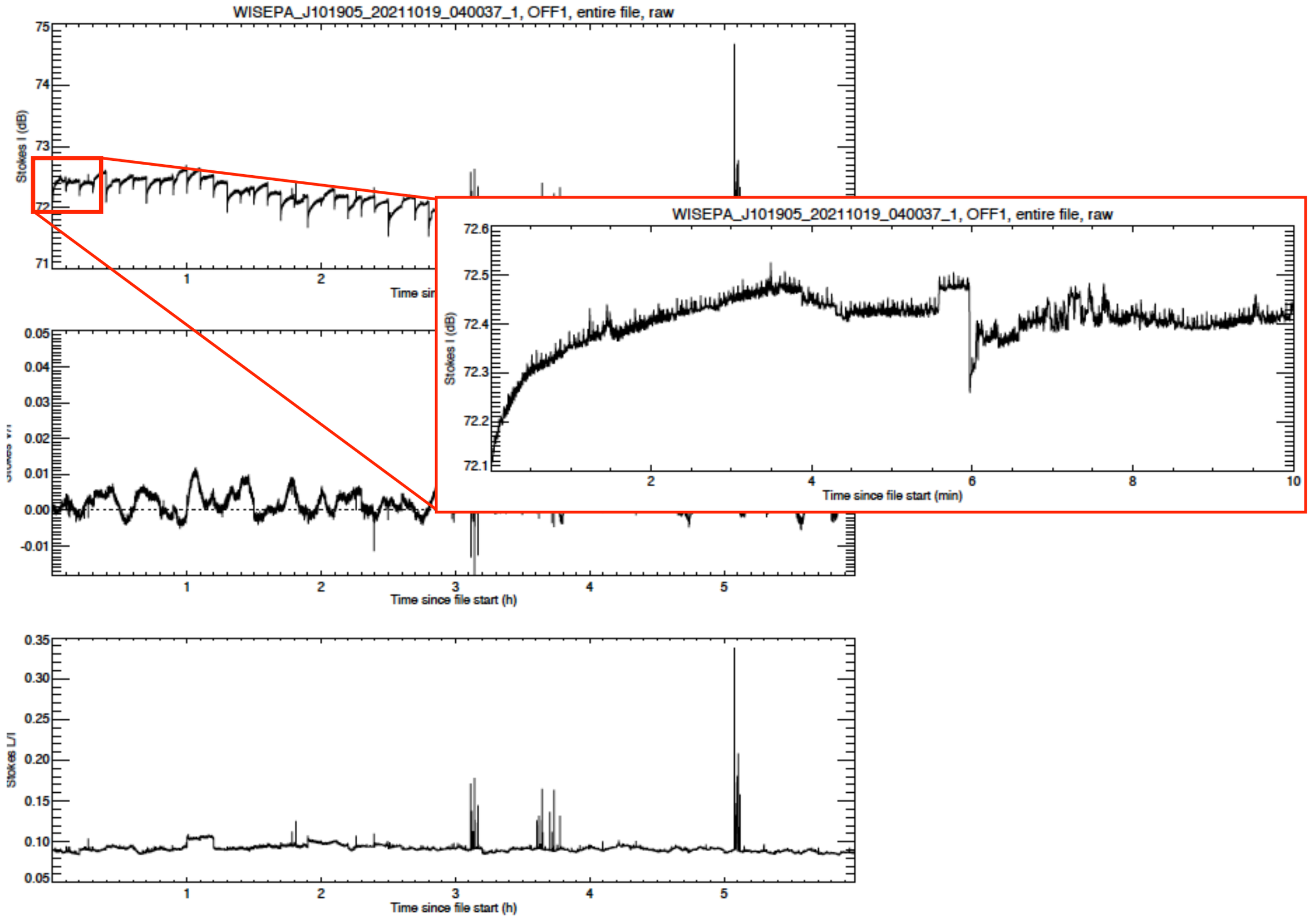
→ *list of excluded beamlets is determined from the integrated spectrum of raw data.*

- Produces L1 **fits** data, **txt** raw header, **pdf quick-looks** on L0 data directory
- Runs at ~2±1 x observing time speed per thread

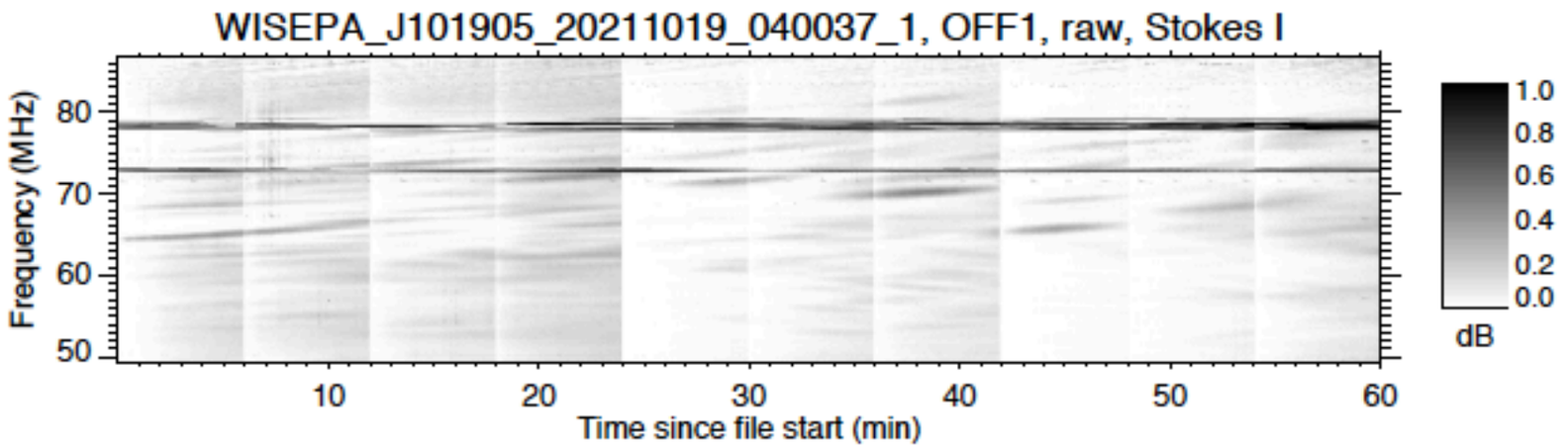
Quick-look example (WISEPA_J101905 observation)

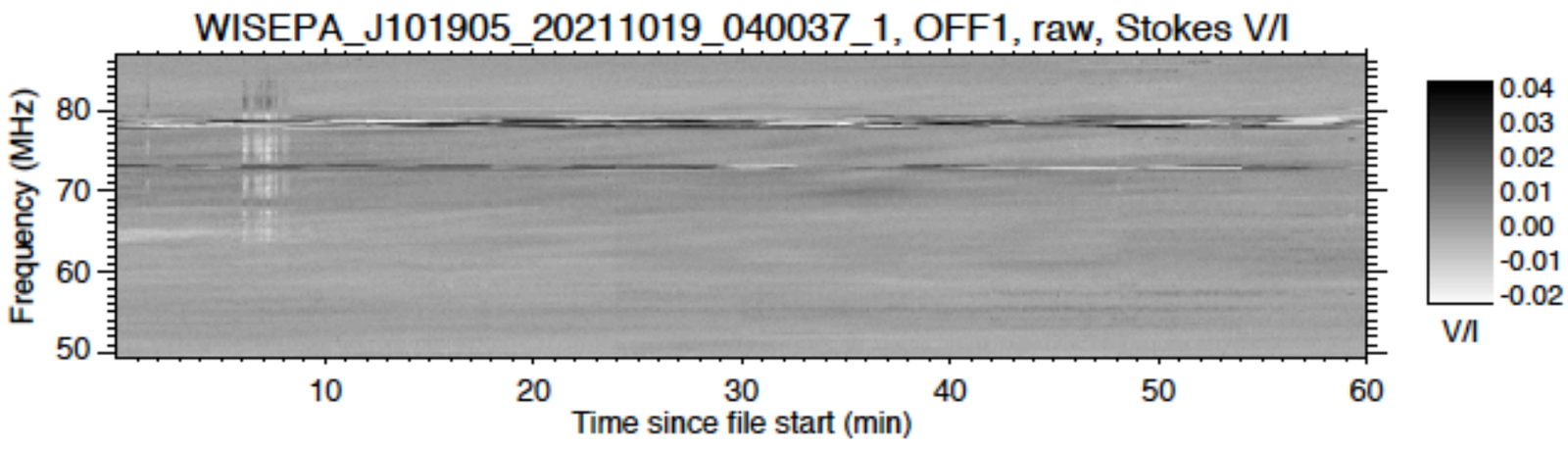


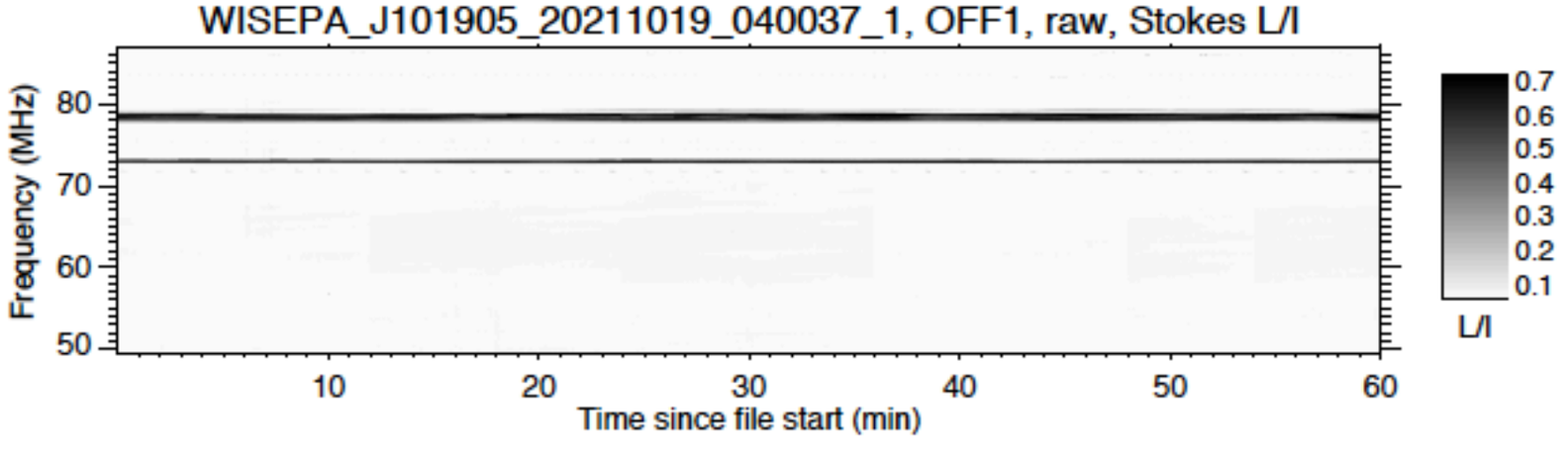
Quick-look example (WISEPA_J101905 observation)



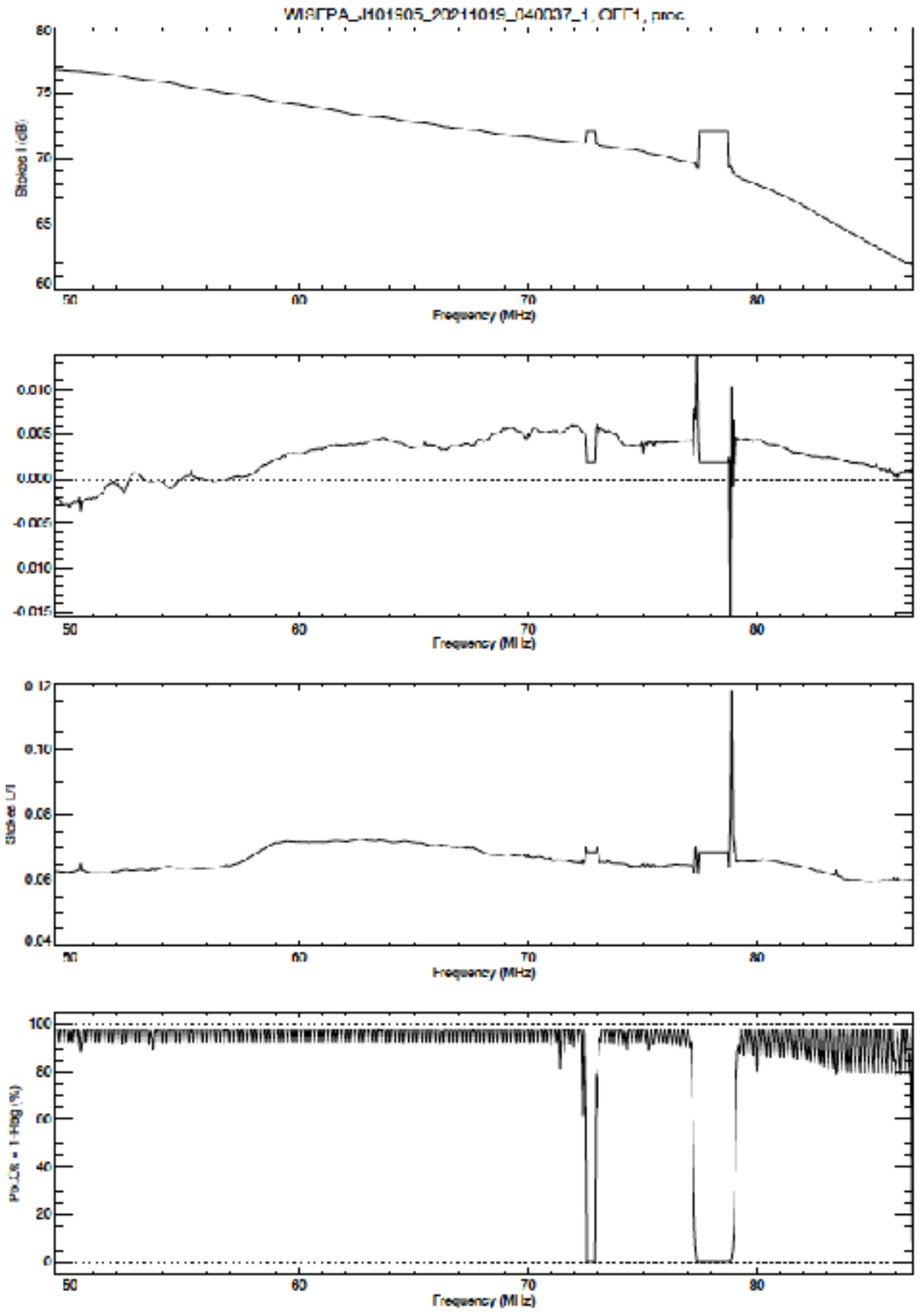
Quick-look example (WISEPA_J101905 observation)



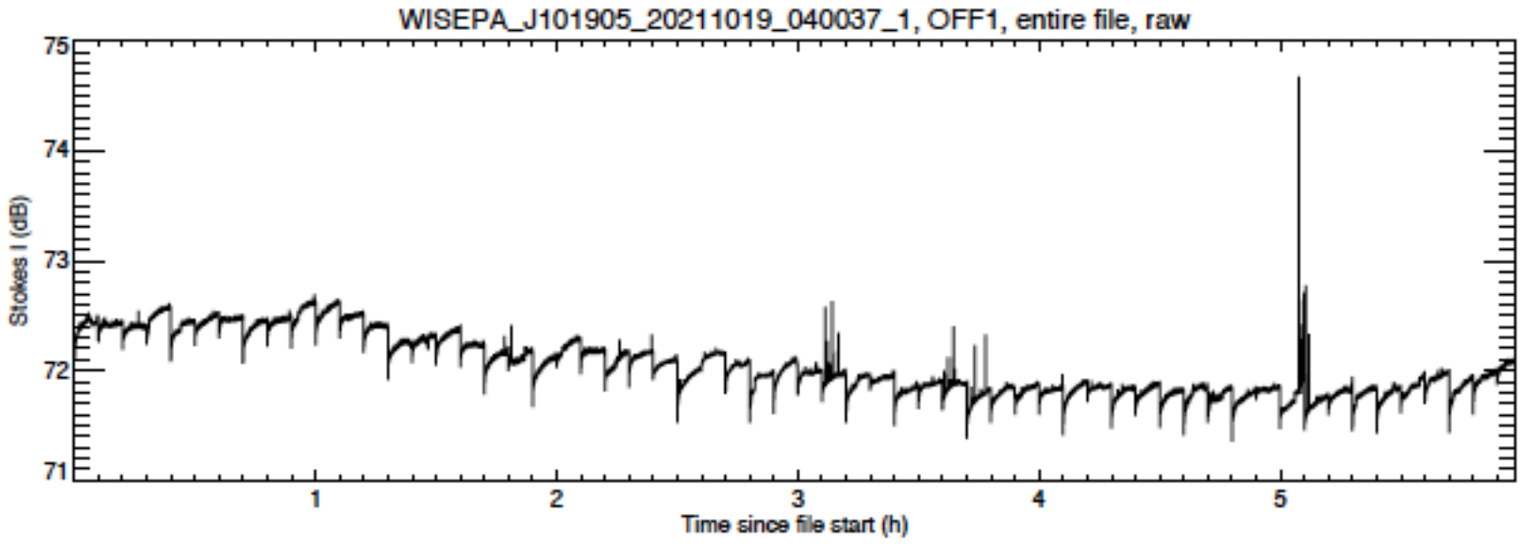




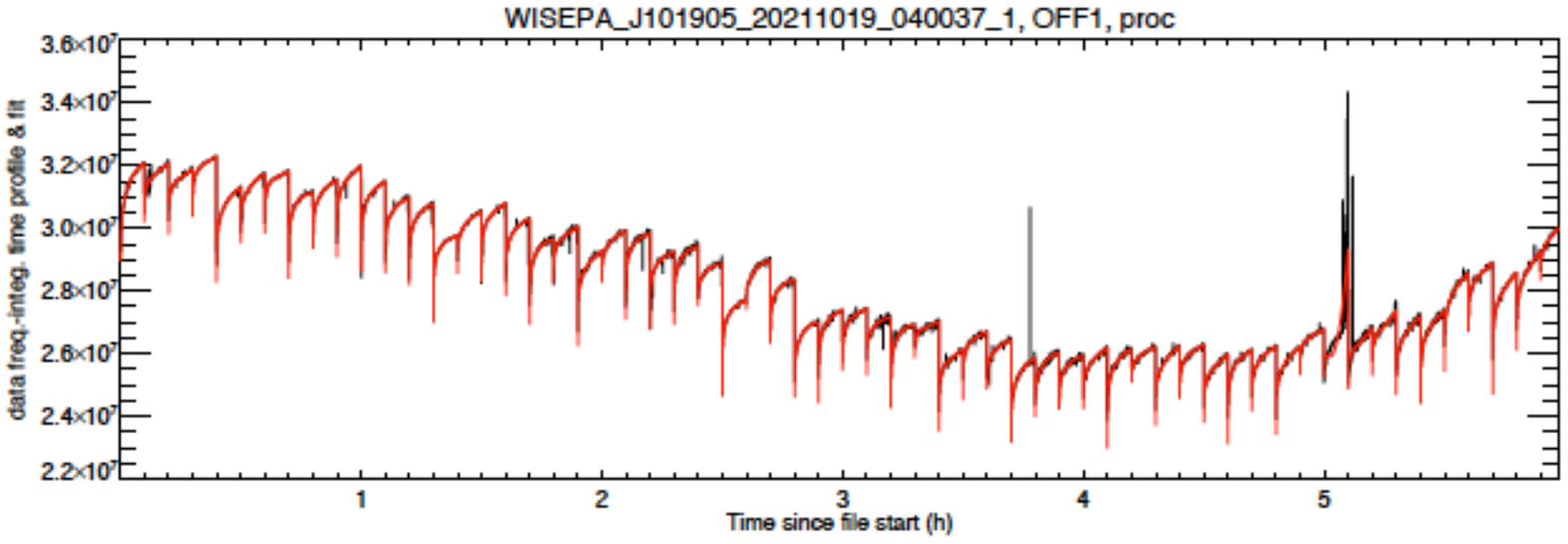
Quick-look example (WISEPA_J101905 observation)



Quick-look example (WISEPA_J101905 observation)



$$I = (a \log t + b)(ct^2+dt+e)$$



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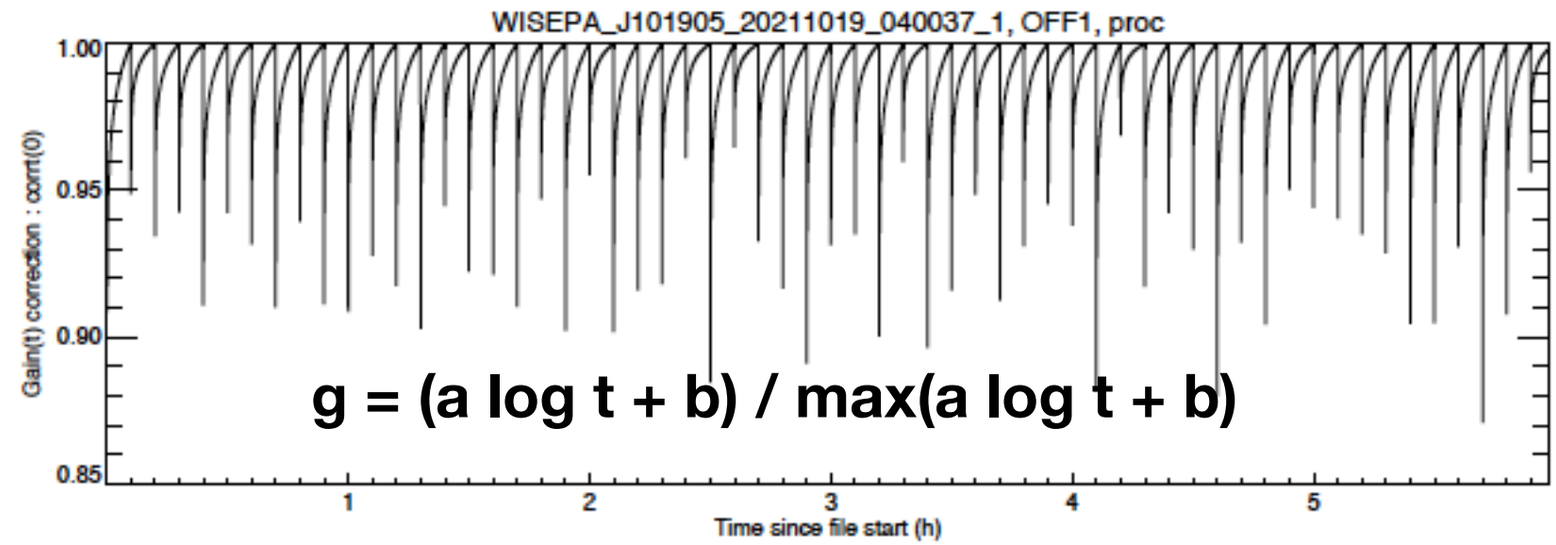
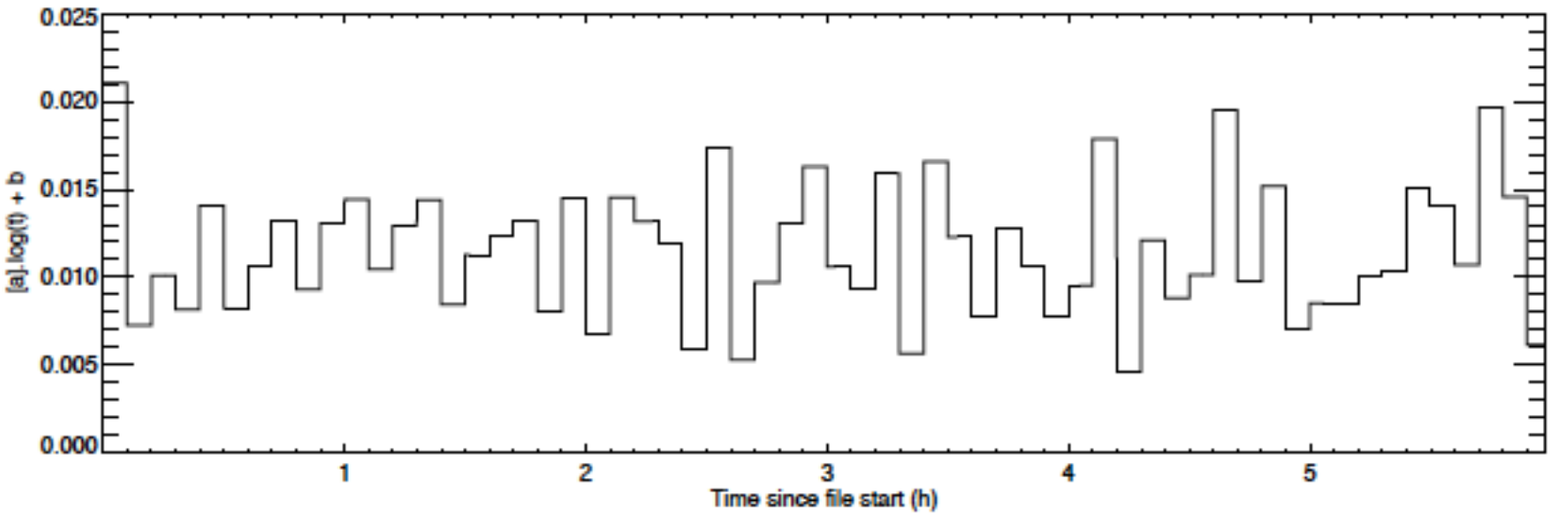
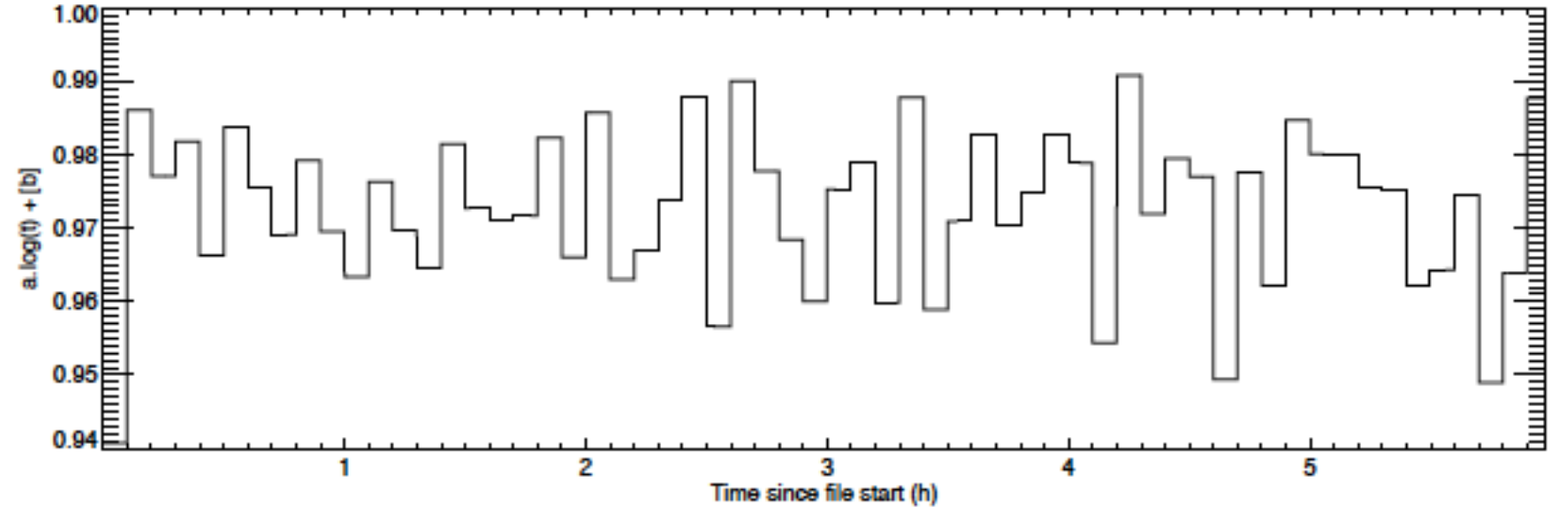


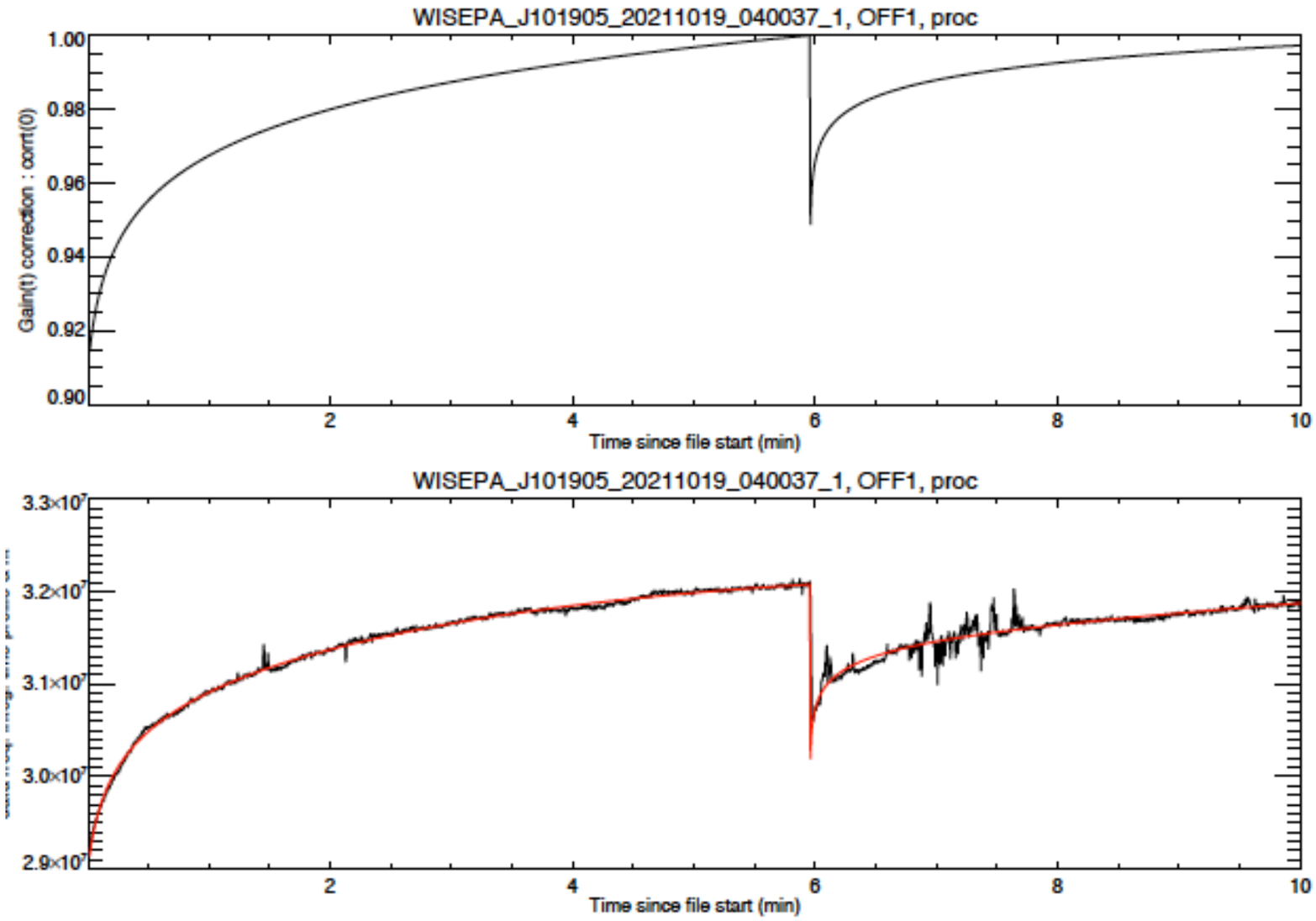


a

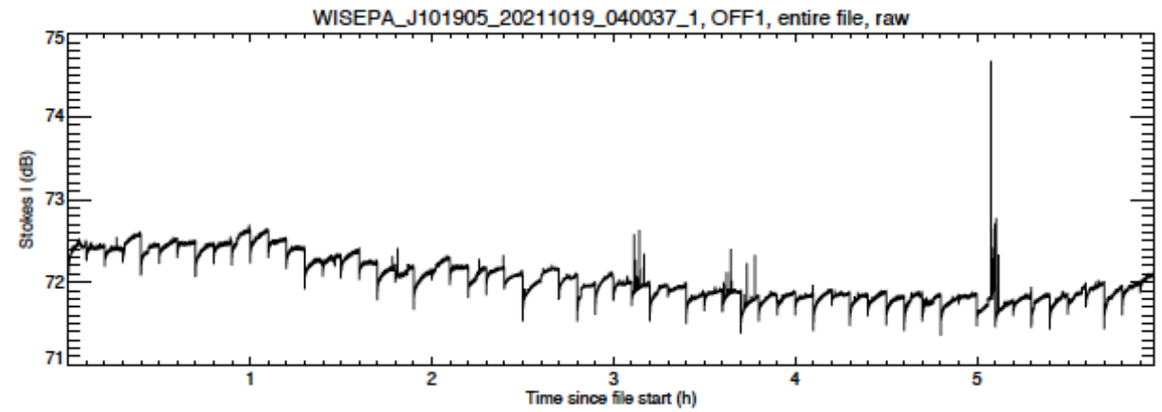


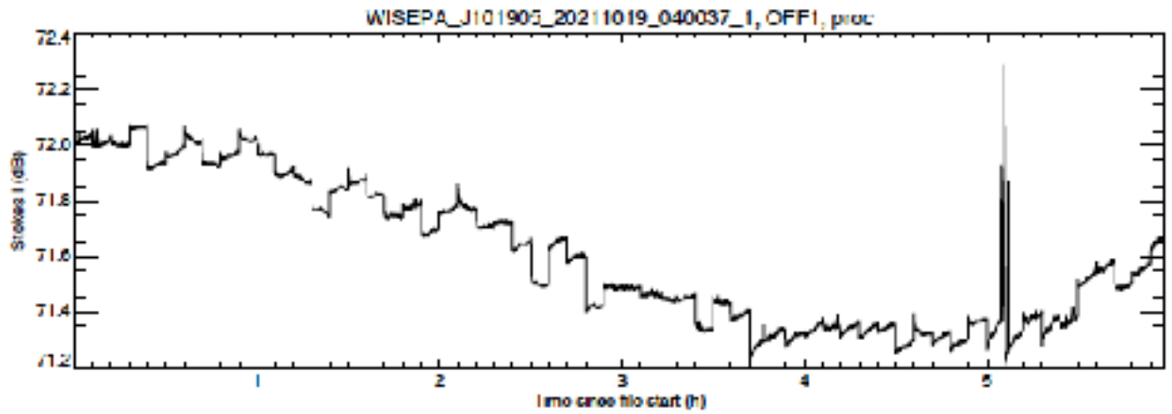
b

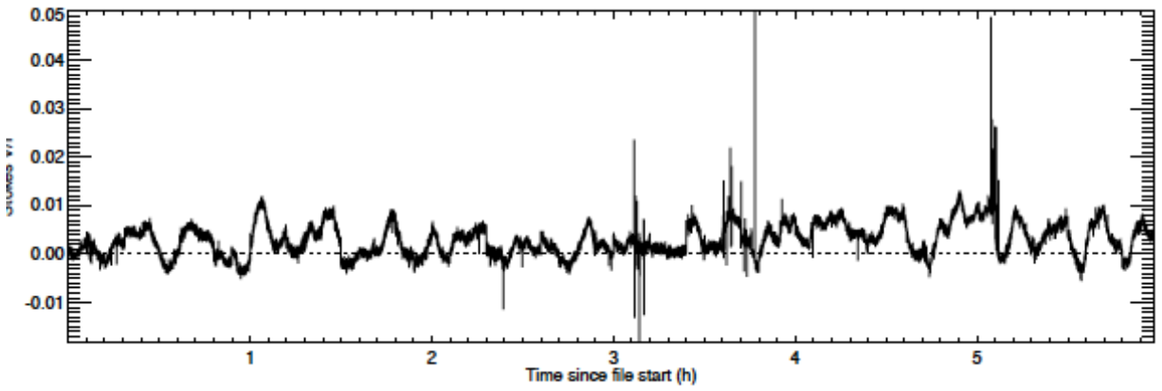
Quick-look example (WISEPA_J101905 observation)

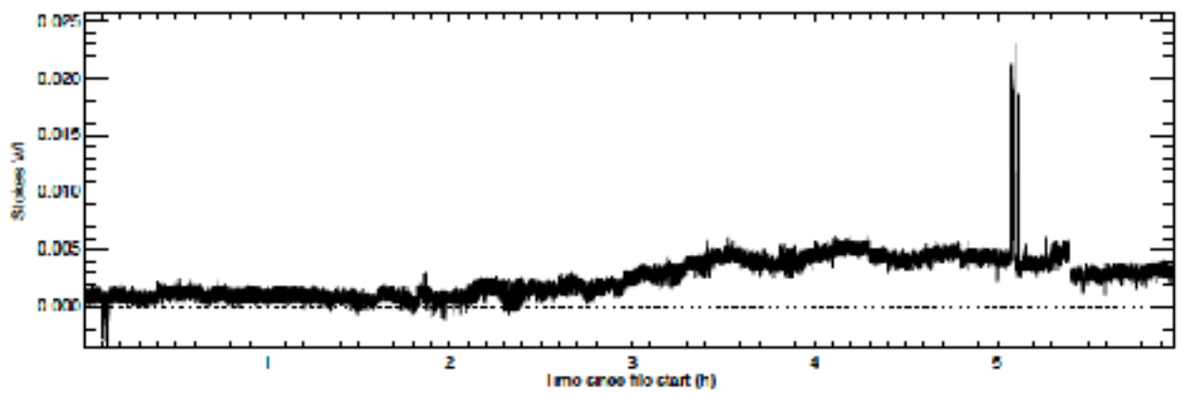


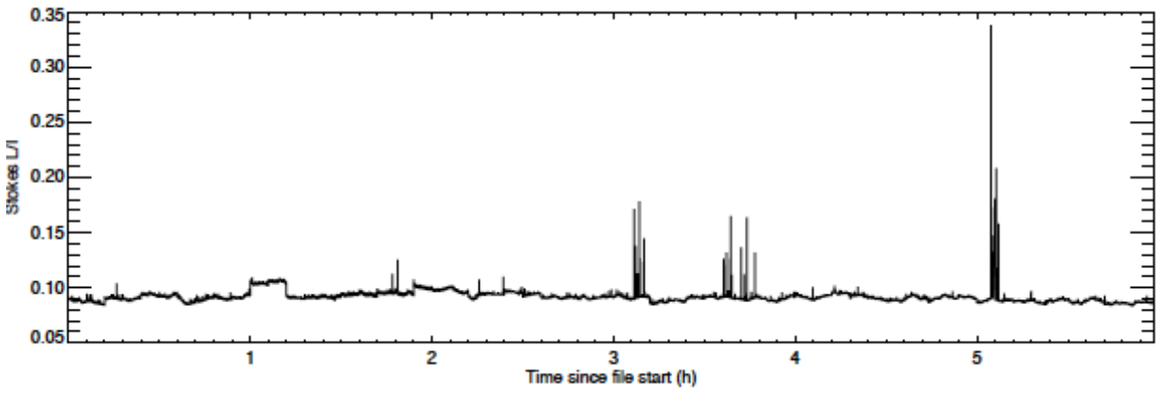
Quick-look example (WISEPA_J101905 observation)

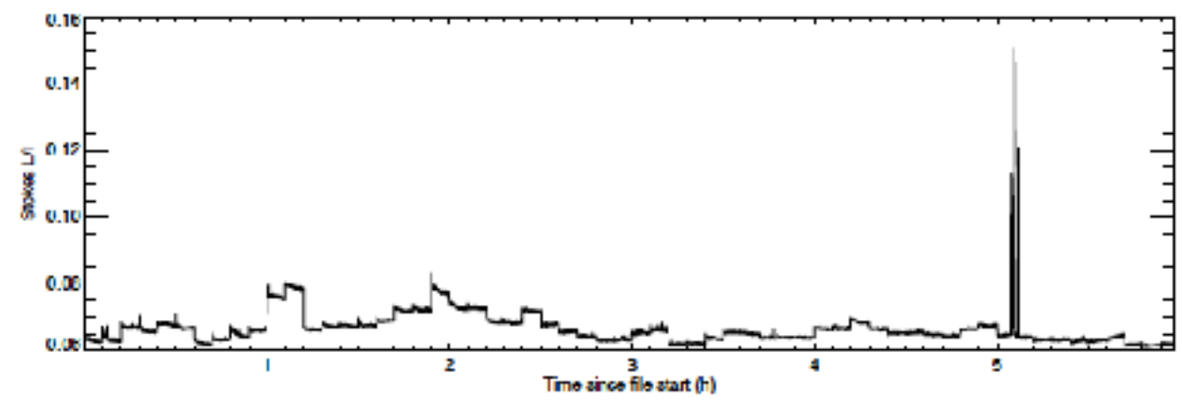


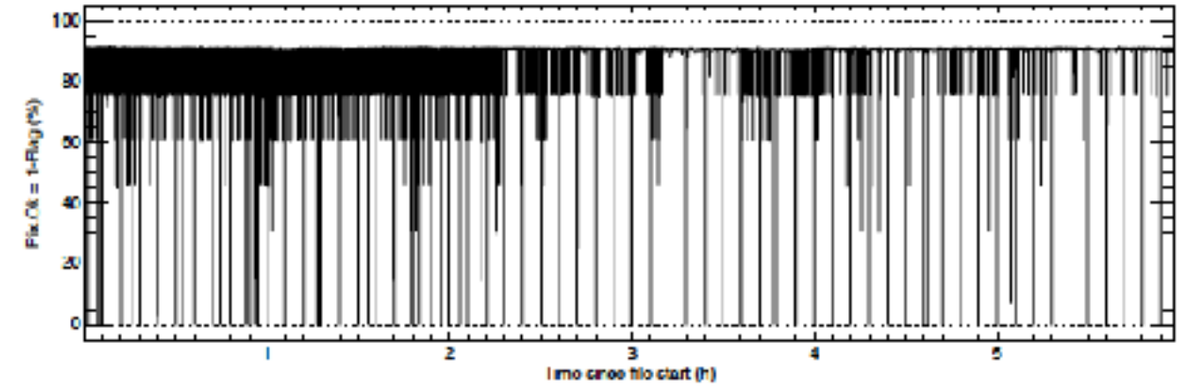












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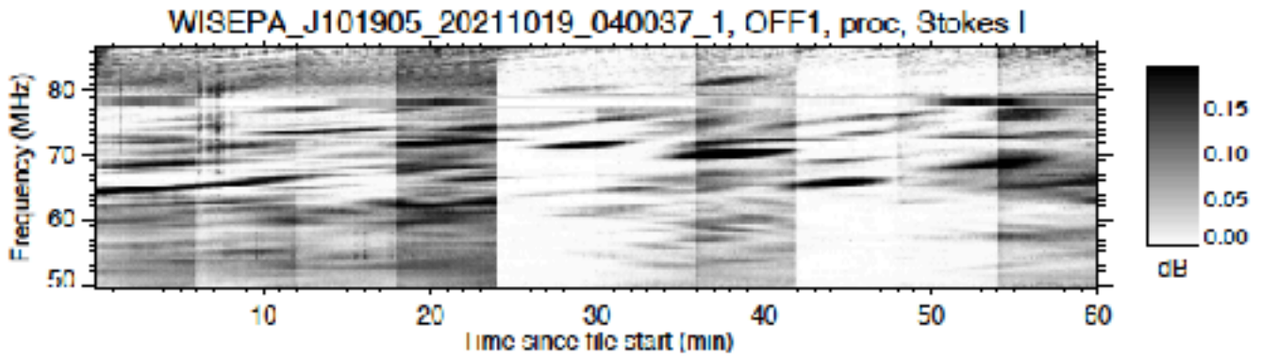
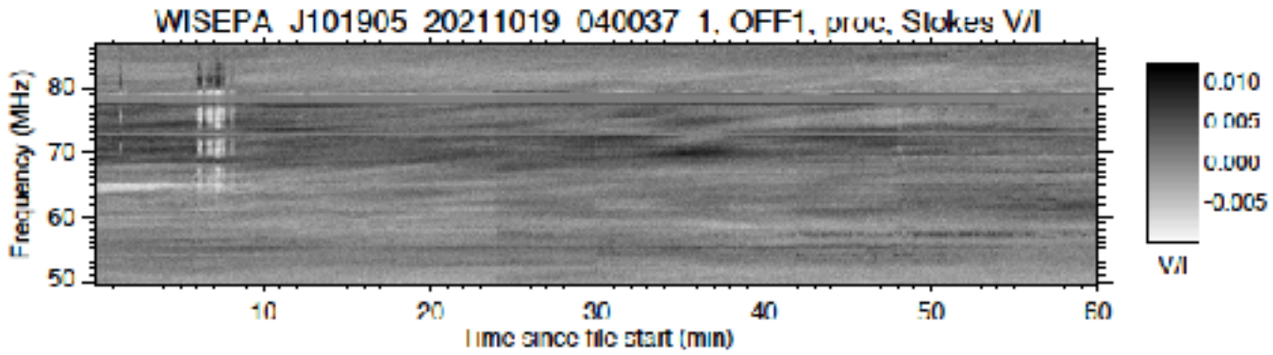
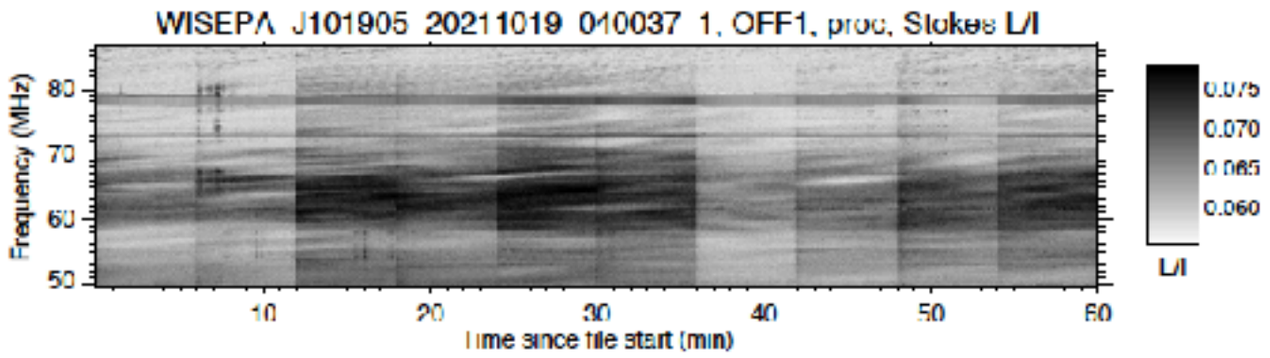
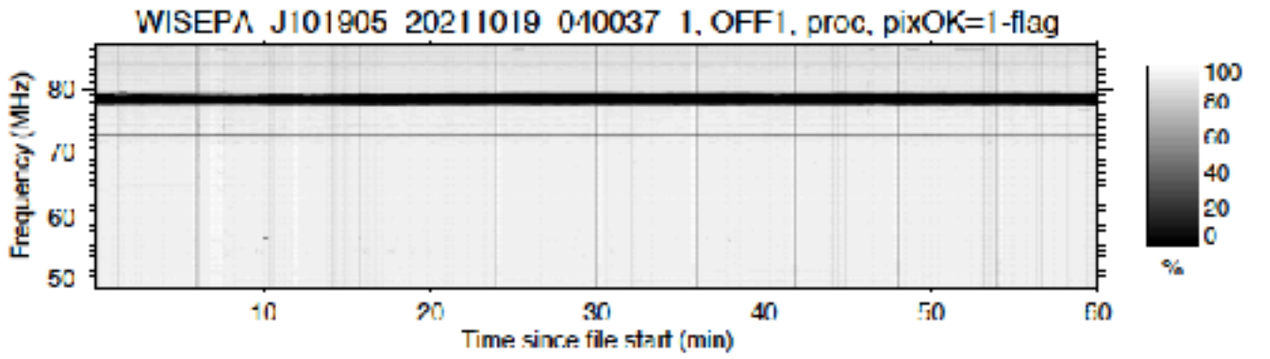








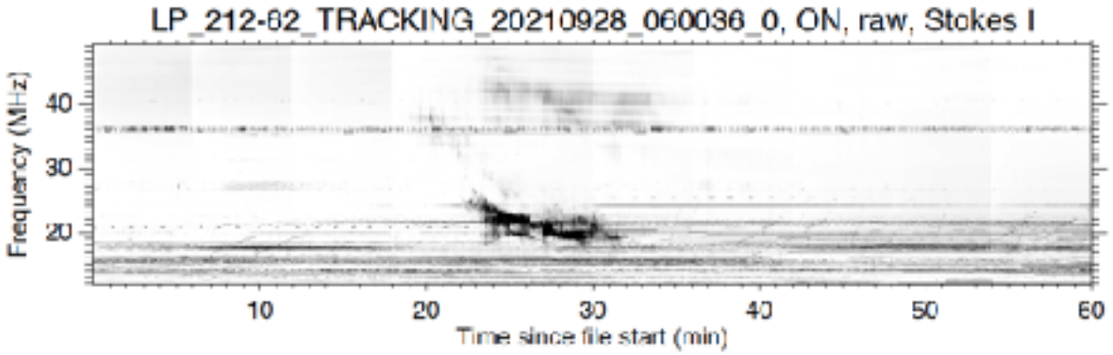
Data products

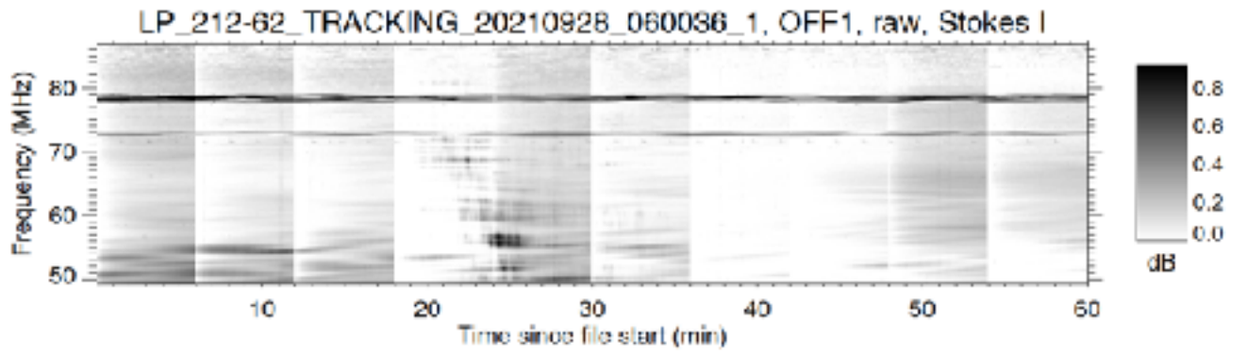
- L0 :
  - Exoplanets : df=3.05 kHz dt=21.0 msec, 4 beams (1 On, 3 Off), 20-30 MHz to 60-70 MHz
  - Stars : df=3.05 kHz dt=42.0 msec, 2 beams (1 On, 1 Off), 12-87 MHz
- L1 :
  - 48 kHz x 250 msec, Stokes IVL, RFI mitigation, gain correction (6-min.)
  - One L1 file per L0 file
  - Volume reduced by ~x192

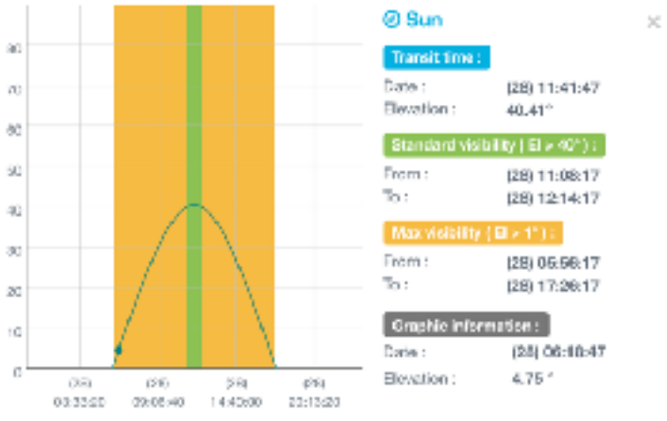
```
/databf2/nenufar-tf/ES02/2021/03/20210317_213000_20210318_060000_CR_DRA_TRACKING

          2876 Mar 17 21:30 CR_DRA_TRACKING_20210317_213035.parset              => L0

     243658055 Mar 18 05:59 CR_DRA_TRACKING_20210317_213035_0.spectra.log       => L0
      11784211 Mar 18 05:59 CR_DRA_TRACKING_20210317_213035_0.spectra.info      => L0
          2752 Mar 17 21:30 CR_DRA_TRACKING_20210317_213035_0.apodisation       => L0

  286306465968 Mar 18 05:59 CR_DRA_TRACKING_20210317_213035_0.spectra           => erased

    1492767360 Mar 23 22:44 CR_DRA_TRACKING_20210317_213035_0.spectra.fits      => L1
      81064816 Mar 23 22:45 CR_DRA_TRACKING_20210317_213035_0.pdf               => L1
          1321 Mar 23 22:03 CR_DRA_TRACKING_20210317_213035_0.spectra.txt       => L1

x4   1, 2, 3.spectra
```

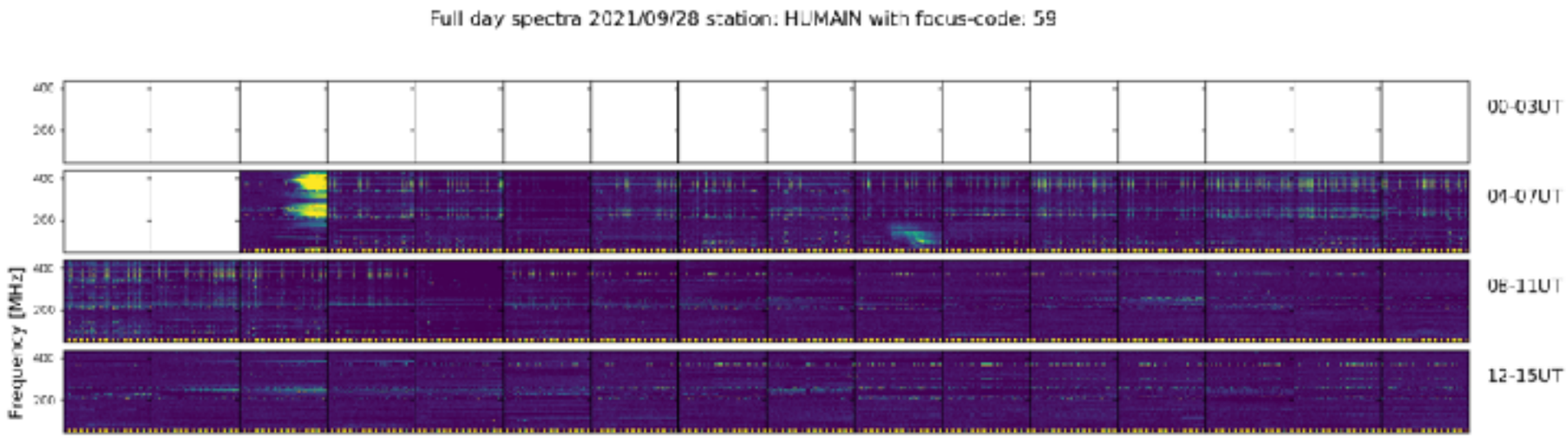
- Erasing of L0 .spectra files, epitaph file, reorganization of data in L0 & L1 folders (manual procedure for the moment)

Quick-looks inspection









- False alert ⇒ observe when Sun (& Jupiter) beyond the horizon !

Post-processing

- Further RFI mitigation (explore Kurtosis of flag RFI - G. Hellbourg)
- Filtering of sources in side lobes (HF blobs) : nenupy, 2D-filtering …
- Combine ON & OFF files (Exo: 3 OFFs, Stars: 1 OFF) : ON-OFF, ON / OFF⇒ ⇒

  Borealis pipeline (JT / JMaG / PZ) [Turner et al., A&A, 2021]

  ⇒ ongoing adaptation to NenuFAR (6 min. interval, background variation…)

- Search for Stokes V signal
- Stack / t-t_meridian (per target)
- Stack / orbital or rotation period (per target)
- Fourier, Lomb-Scargle periodograms
- …

Coordinated analyses in ES02 team

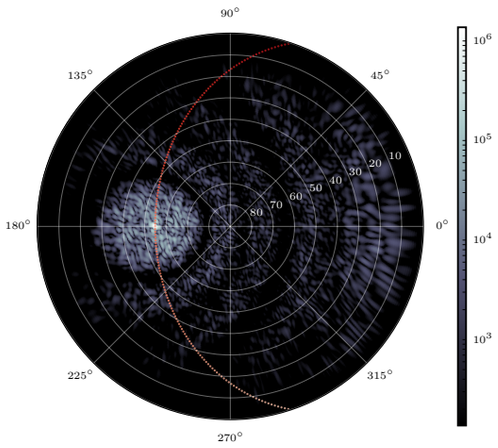
- P. Zarka (VCR, pre- & post-processing)
- L. Lamy (inspection, analysis of candidate strong bursts)
- J.-M. Grießmeier, J. Turner, J. Girard, B. Cecconi (post-processing)
- A. Loh (nenupy)
- O. Ulyanov, S. Yerin, V. Zakharenko, M. Sidorchuk, H. Krishnan (tbd)

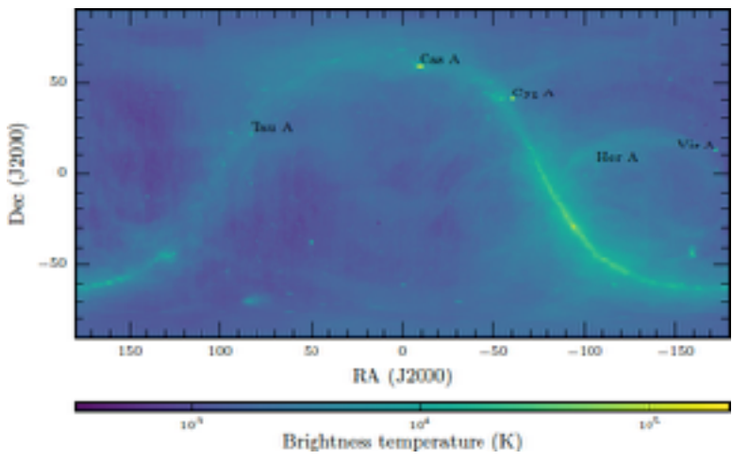
  +
- C. Gédor (ex-Master 2 intern 2020: smart subband selection)
- R. Jolly (ex-Master 2 intern 2021: first post-processing tests)
- E. Mauduit (present PhD ≥2021: target selection, t-f-beam optimization)

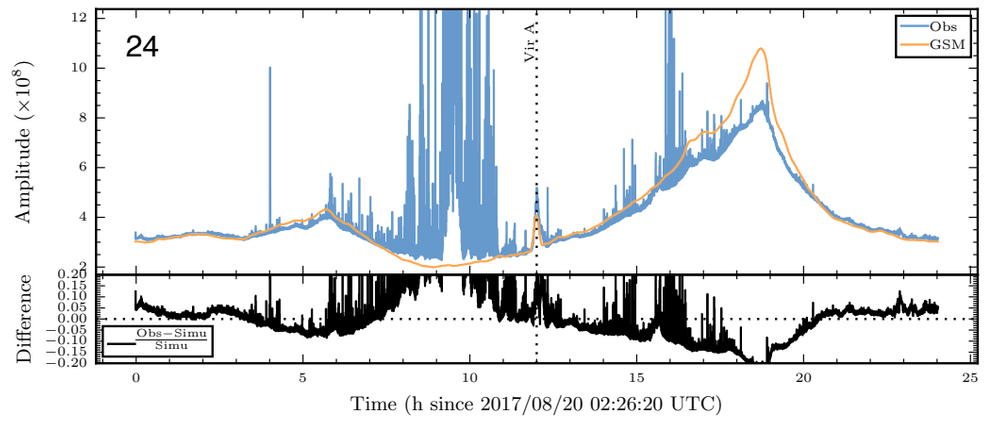
  +
- new members invited: V. Ryabov, H. Kita, T. Kimura
- Exoradio fellows to come

Ongoing/future work

- Redefinition of target selection criteria (bibliography)
- Weighted target selection tool
- nenupy simulations: avoid A-team, Sun, Jupiter in secondary ring



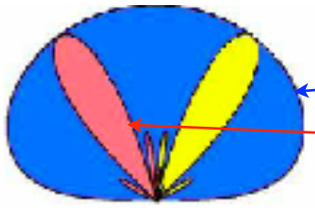




- Orbital phases coverage
- Grouping targets in NenuFAR analog beams
- Implement and use DynSpecMS (tests on LOFAR LoTSS data)
- Spectral coverage optimization: smart subband selection based on SST & LOFAR LBA statistics

  ⇒ the NenuFAR RFI environment (with ES12 & ES13)

Receivers and signal path



antenna beam

MA beam (analog-phased)

Compact core (400 m) : 96 MA x 2 polar.

Distant MA (≤3 km) : 6 MA x 2 polar.

analog signals

analog signals

analog signals

- Digitization
- Channelization

LOFAR FR606 backend

- Digitization
- Channelization
- Beamforming

LOFAR Super Station

LaNewBa

- Digitization
- Channelization
- Beamforming

NenuFAR Transient Buffer

Broadcast on VLAN

UnDySPuTeD : dynamic spectra

- Channelization
- Integration

UnDySPuTeD : pulsar

- Coherent dedispersion
- Folding / Integration

SETI Machine

NenuFAR Beamformer

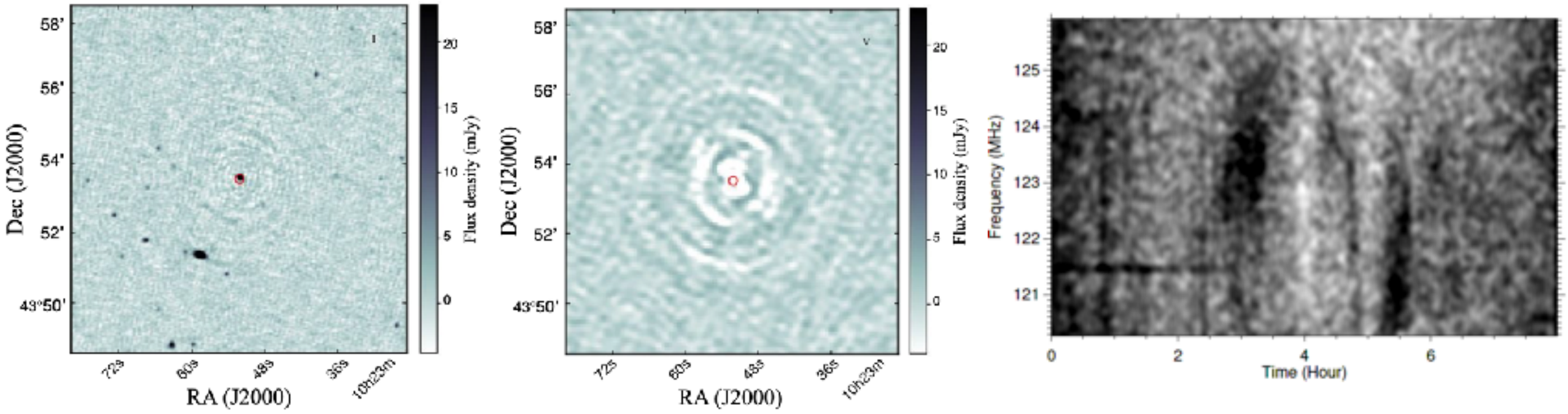
NICKEL Correlator

- Channelization
- Correlation
- Calibration + Imaging

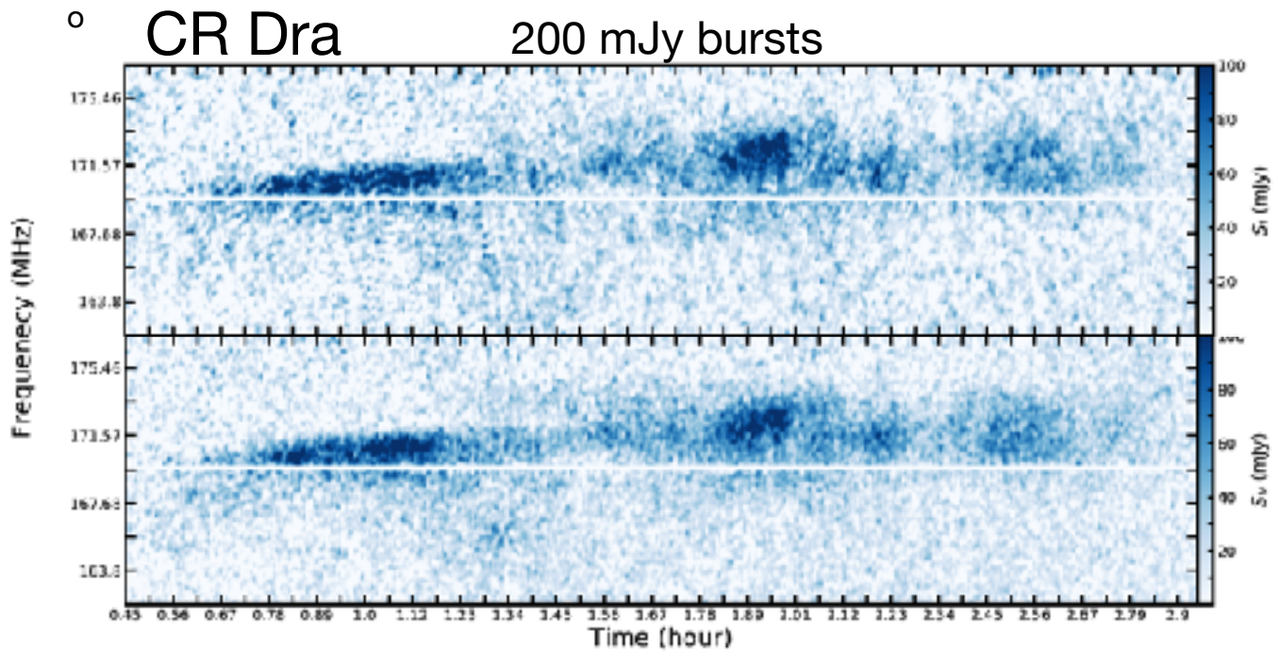
NenuFAR Imager

COPPER nodes : pre-processing

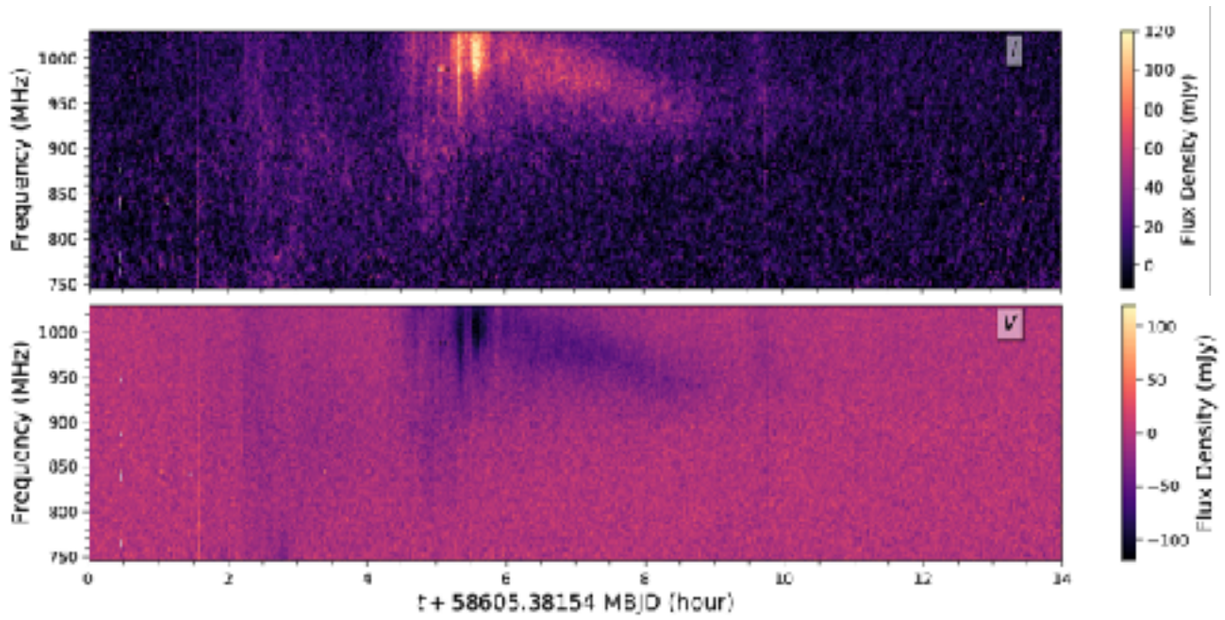
MODS : multi-object dynamic spectroscopy



[Tasse et al., in prep]



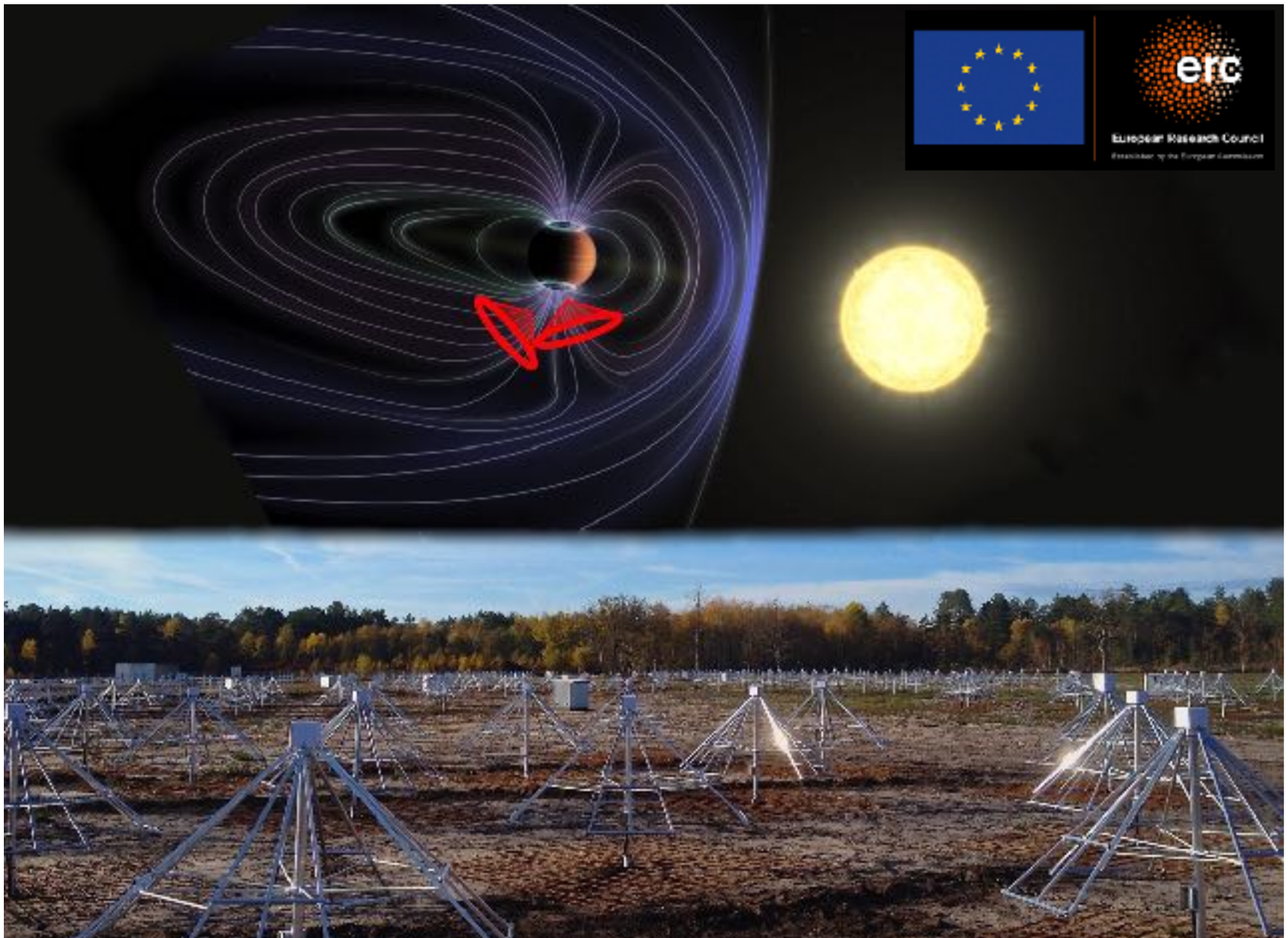
[Callingham et al., 2021]



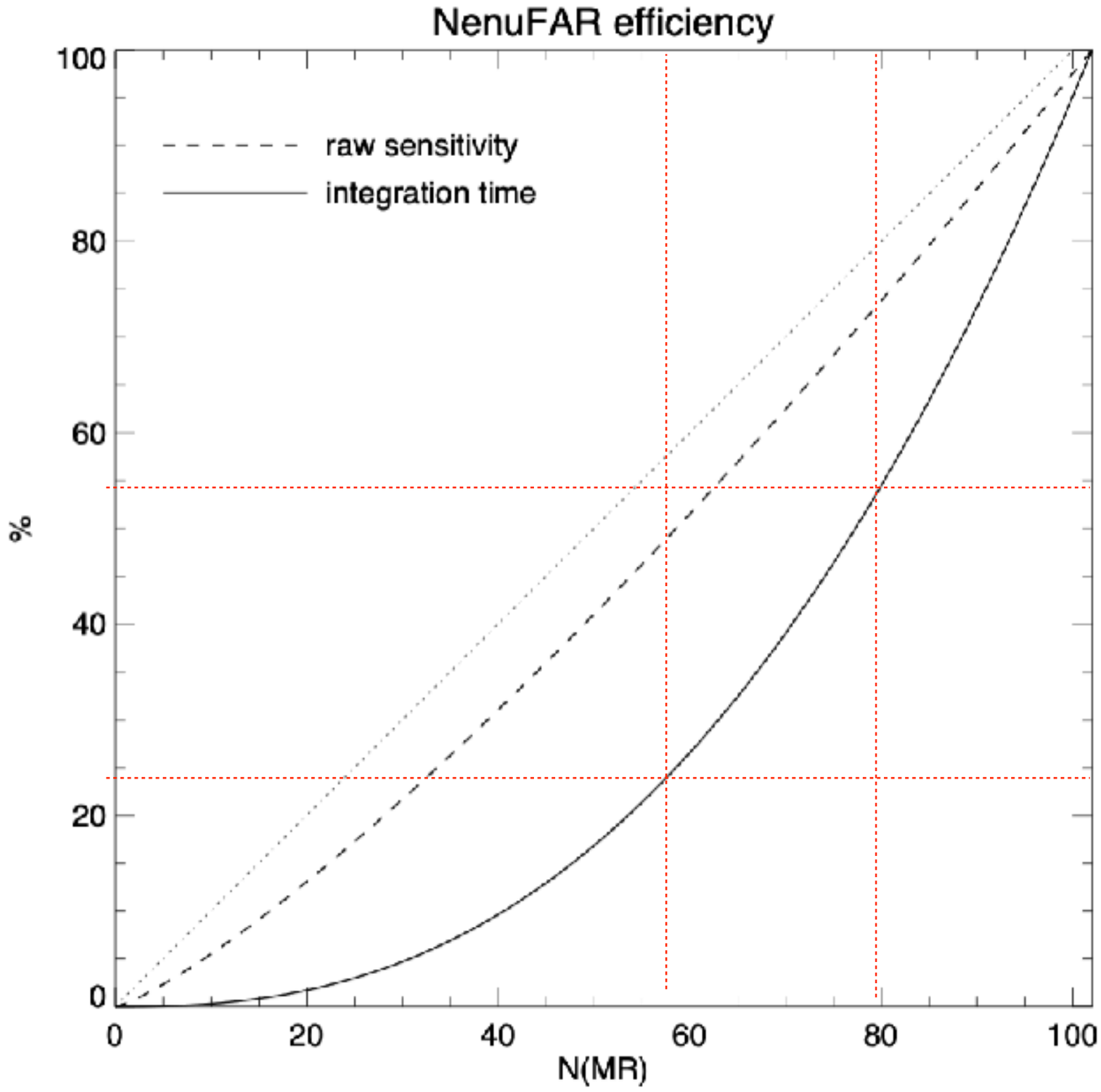
[Zic et al., 2021]

The project EXORADIO

- Large program with NenuFAR : 500-1000 h / semester from S6
- Target selection → Beamformed + MODS observations
- Detection, modelling, follow-up, interpretation → exo-magnetospheric physics, SPI + stellar bursts
- 2 Post-docs + 1 PhD, computing nodes, storage, NenuFAR upgrade & operation



Evolution of the sensitivity and integration time



Thanks.

To be continued …