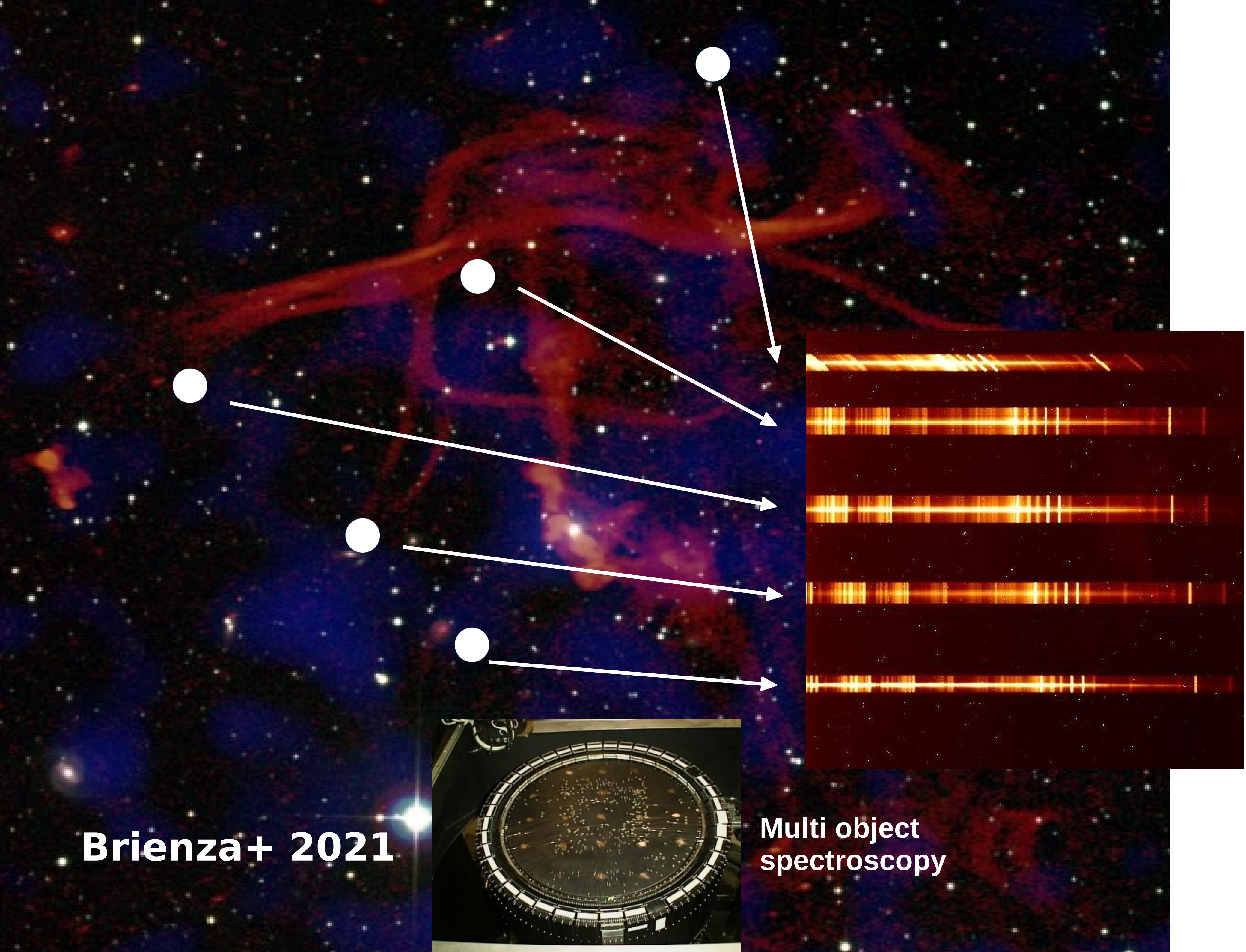
Automated Detection of Polarized Bursts in Low-Frequency Radio Emissions from Stars and Exoplanets

Cyril Tasse

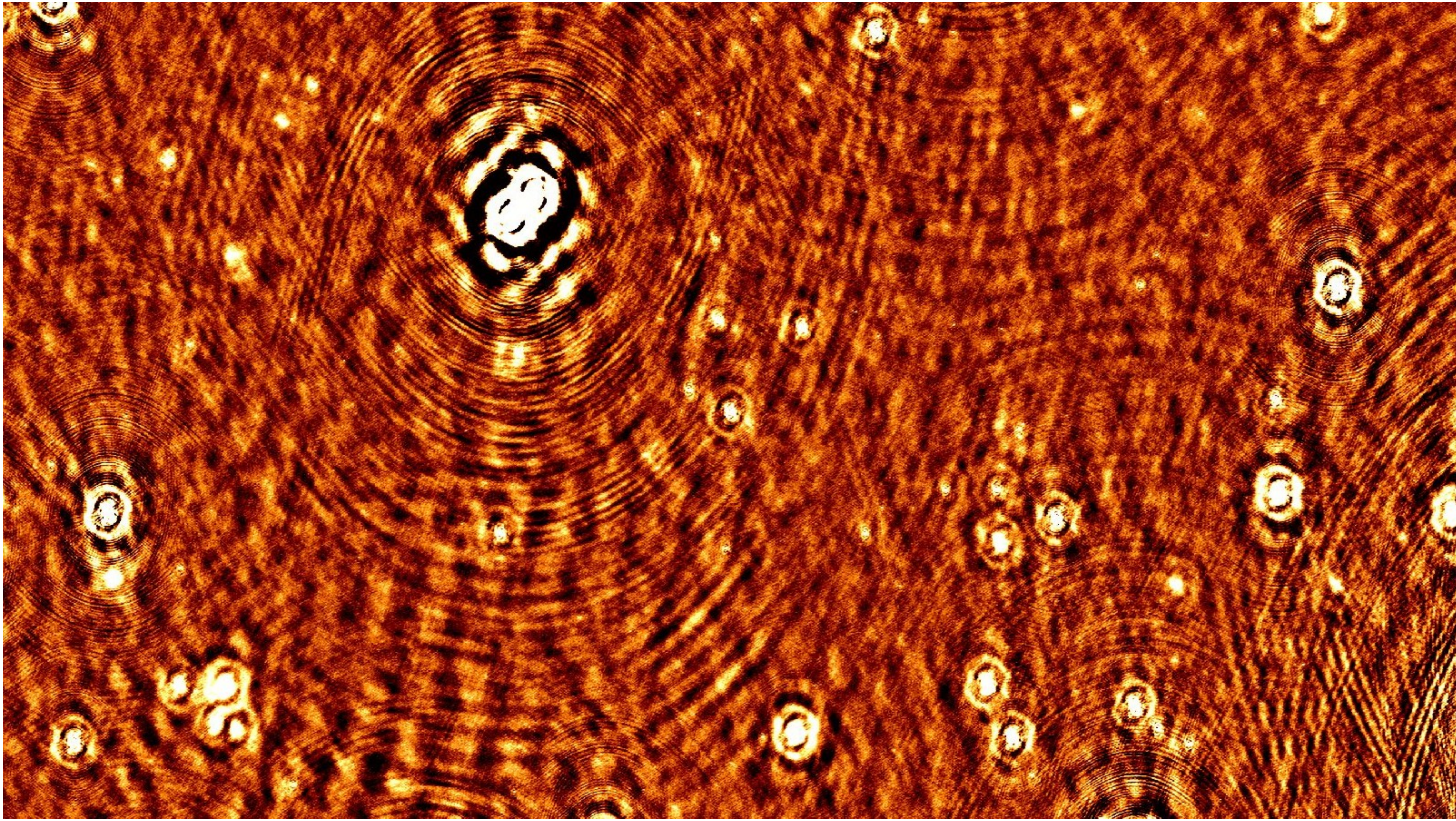
Philippe Zarka, Martin Hardcastle, Tim Shimwell, Alan Loh,
Joe Callingham, Harish Vedantham, Laurent Lamy,
And the SKSP

LoTSS/DynSpecMS story

- 2017: we were discussing with Philippe Zarka, and Alan Loh exoplanets observations with LOFAR
- DDF-pipeline: DD-selfcal calls DDF (imaging) / kMS (calibration)
- Why not phase up residual visibilities towards sets of selected targets?

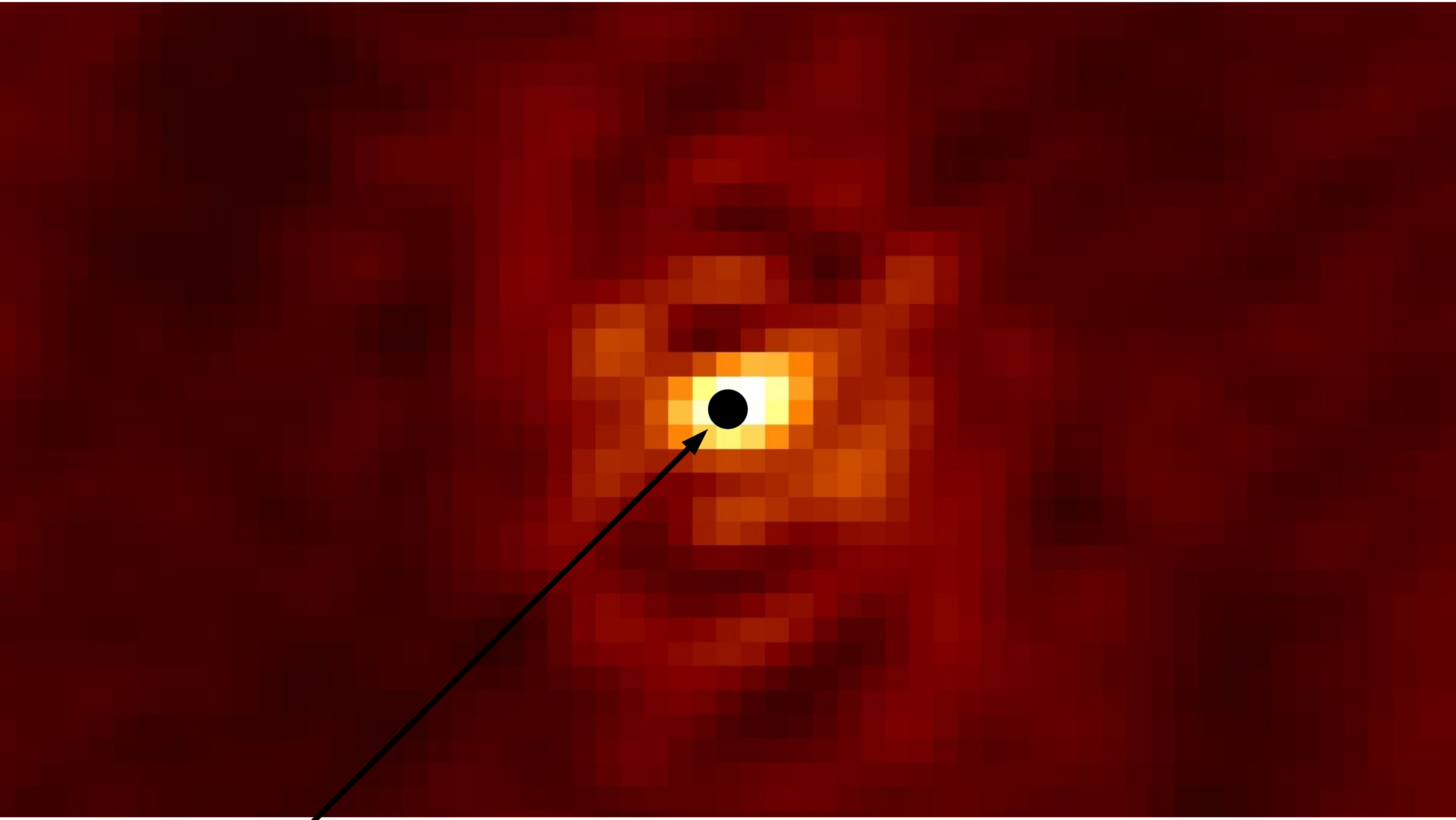

Brienza+ 2021
Multi object
spectroscopy

Interferometry and imaging



$$\left\langle \widehat{\mathbf{X}_s} \right\rangle = \sum_{(pq),t\nu} \mathbf{V}_{(pq),t\nu} \exp\left(2i\pi \frac{\nu}{c}\left(u_{pq,t} l_s + v_{pq,t} m_s + w_{pq,t}(n_s - 1)\right)\right)$$

Interferometry and imaging



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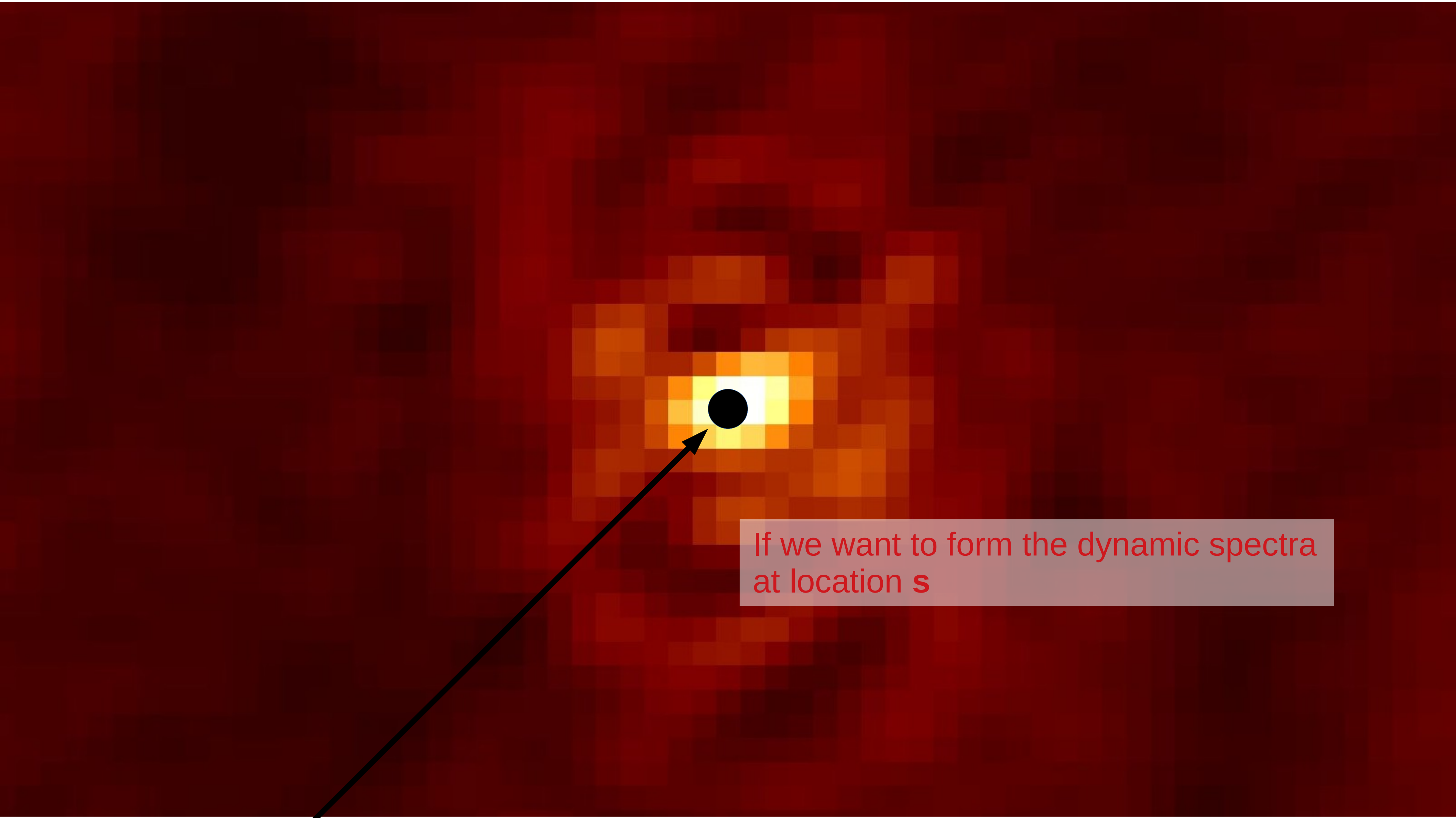

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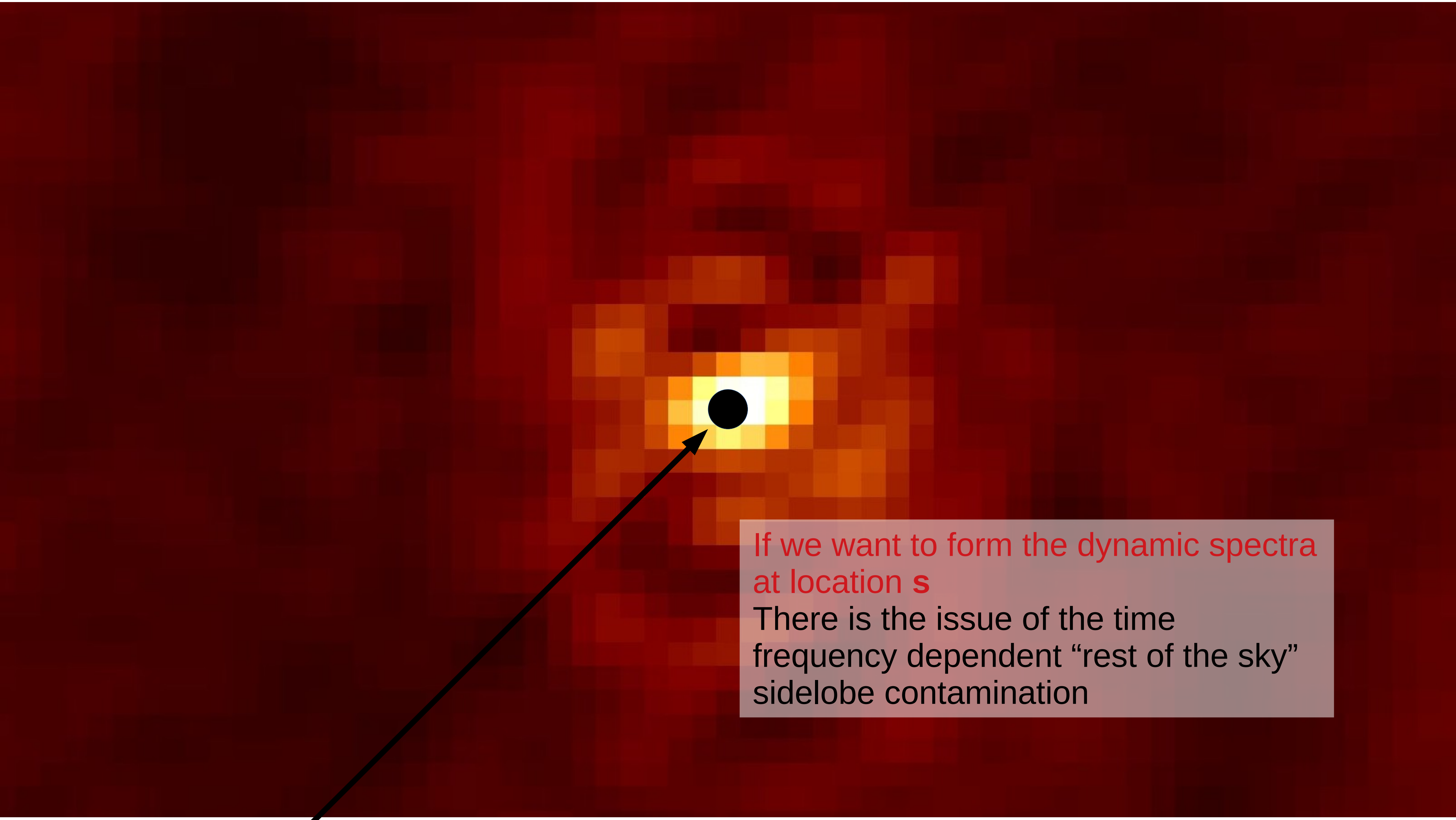
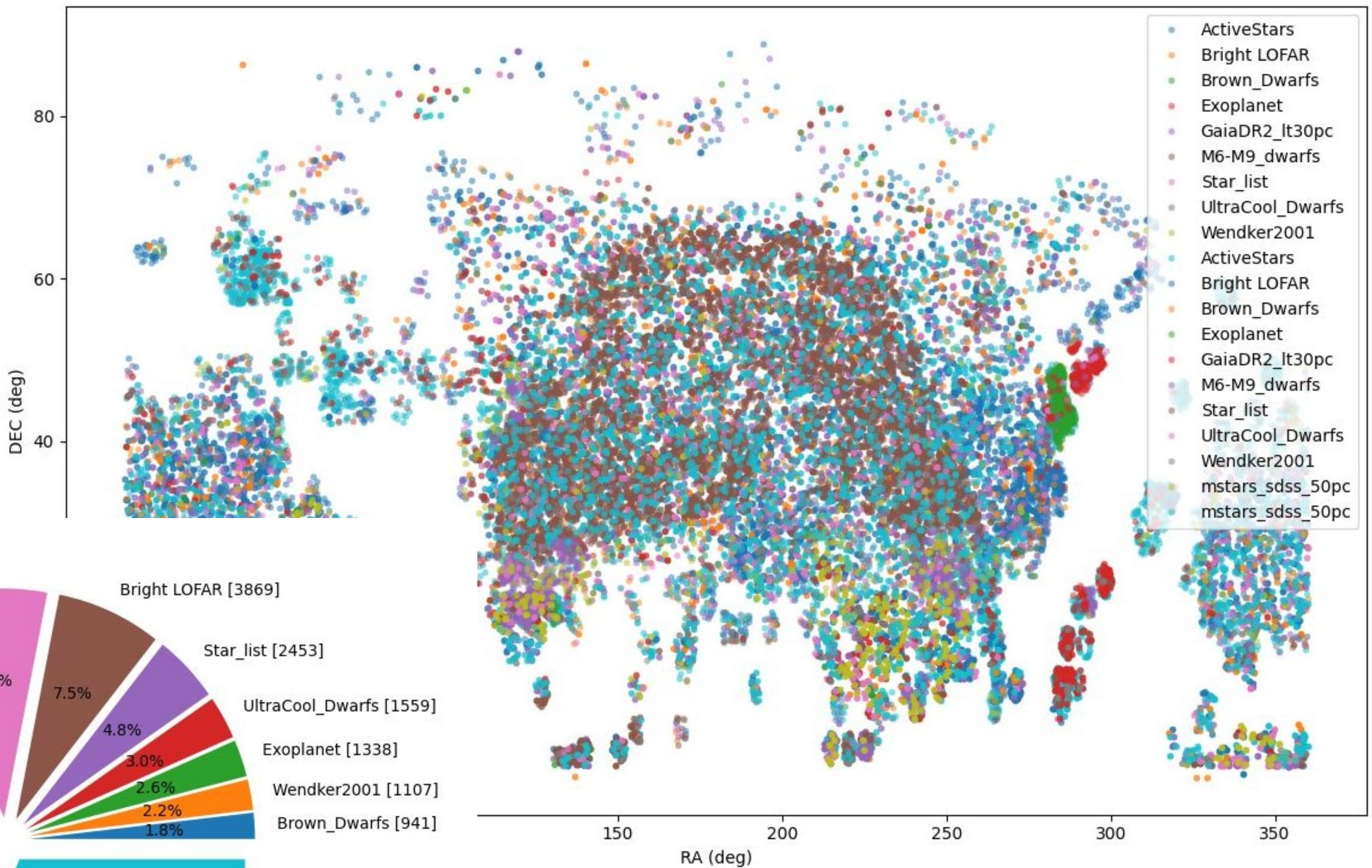
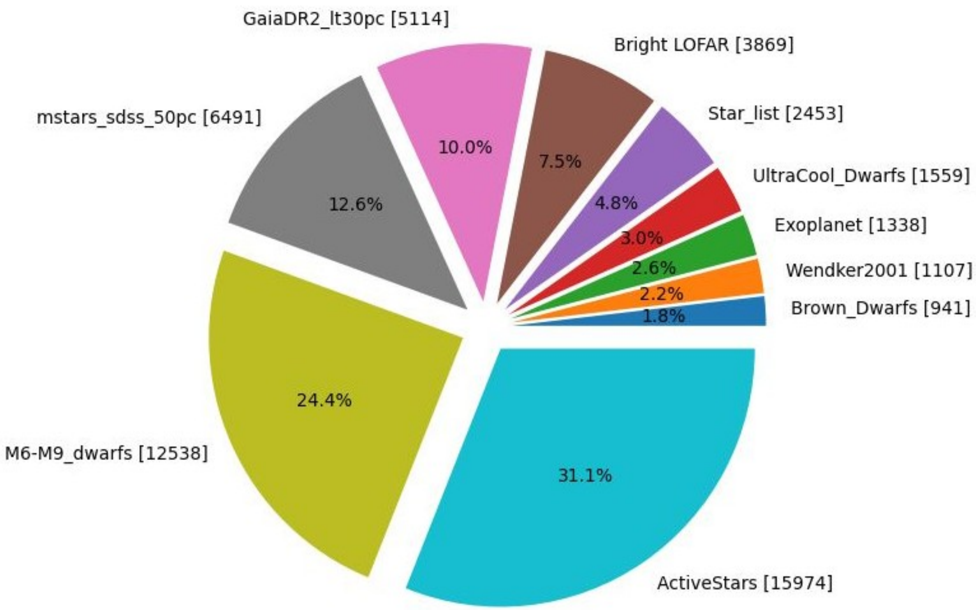


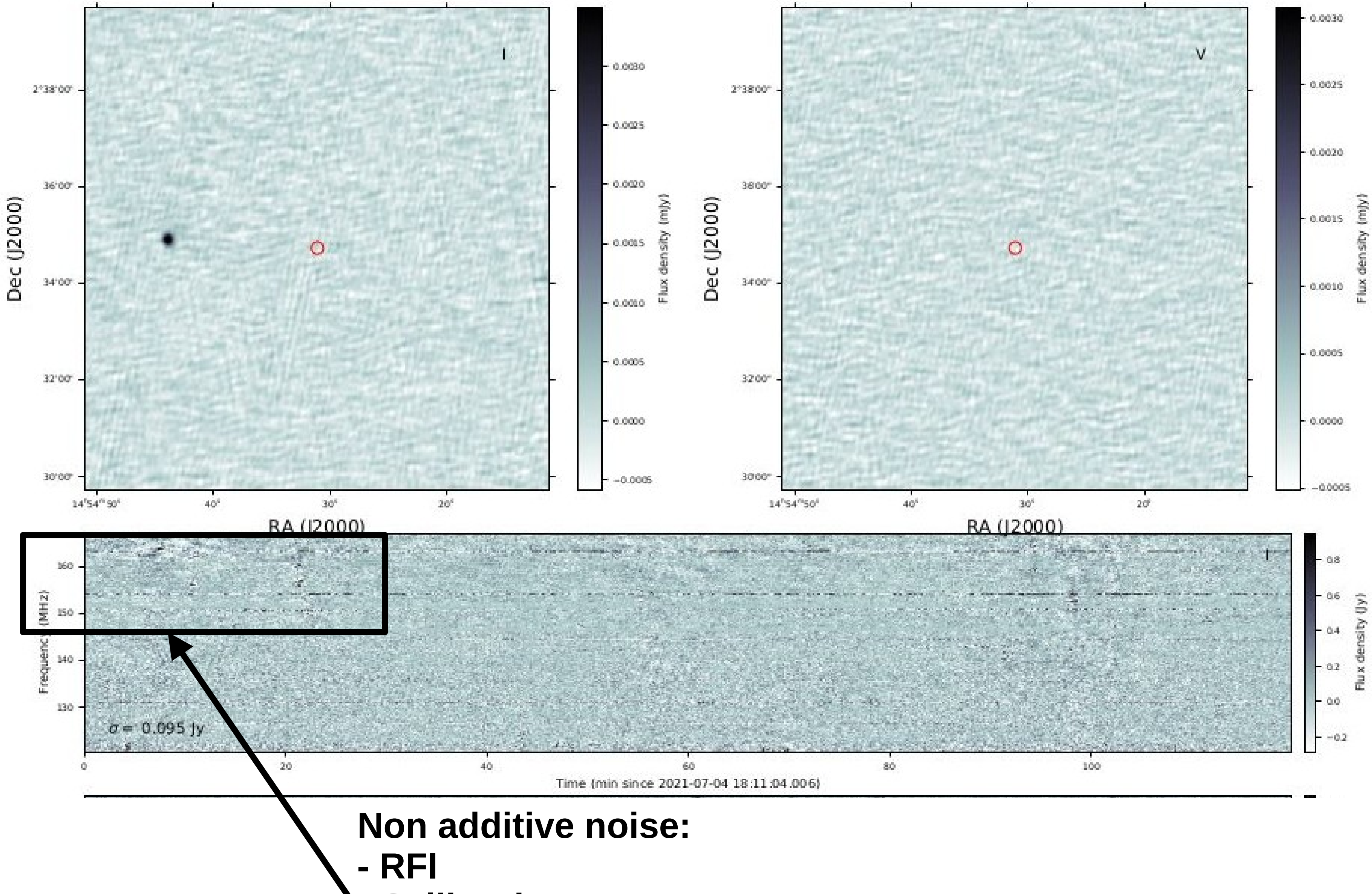
$$\left\langle \widehat{\mathbf{X}_{s,t\nu}} \right\rangle = \sum_{(pq)} \mathbf{V}_{(pq),t\nu} \exp\left(2i\pi\frac{\nu}{c}\left(u_{pq,t}l_{\mathbf{s}} + v_{pq,t}m_{\mathbf{s}} + w_{pq,t}(n_{\mathbf{s}} - 1)\right)\right)$$

LoTSS/DynSpec sample



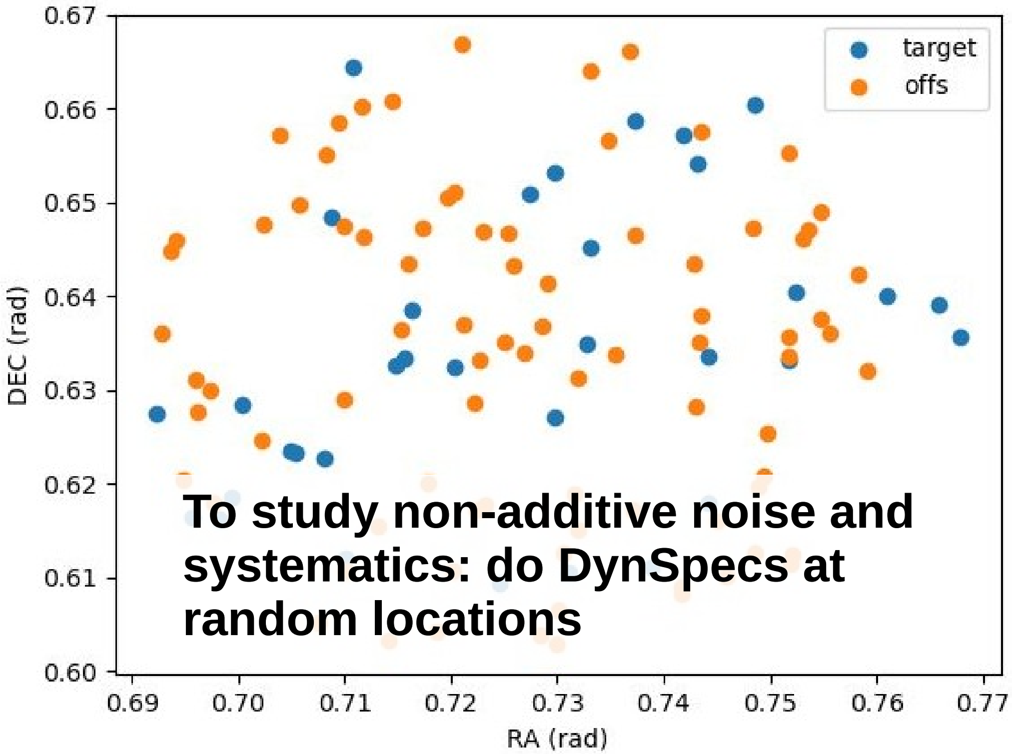


Noise properties

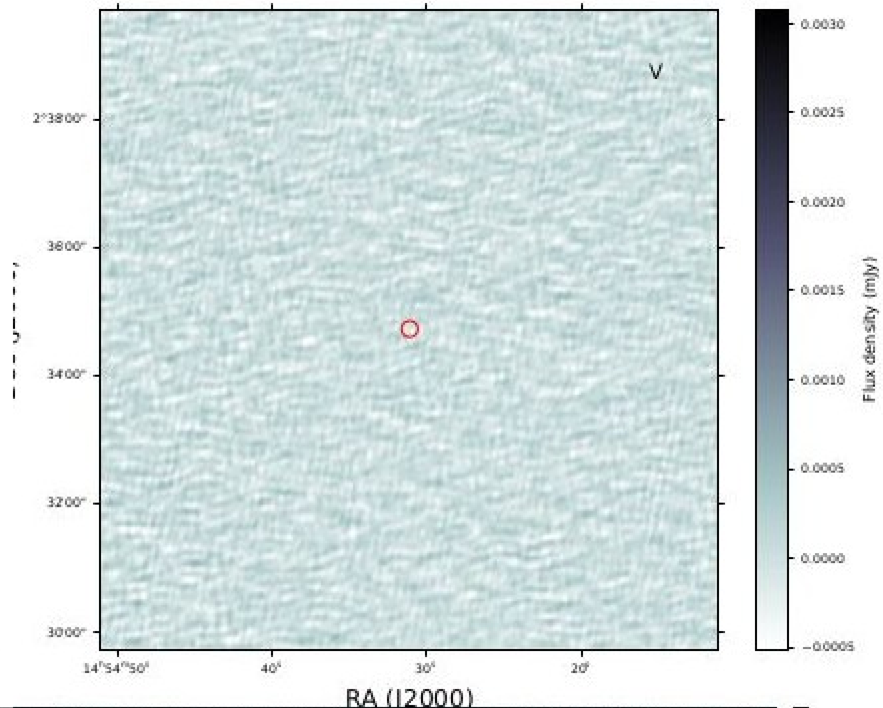


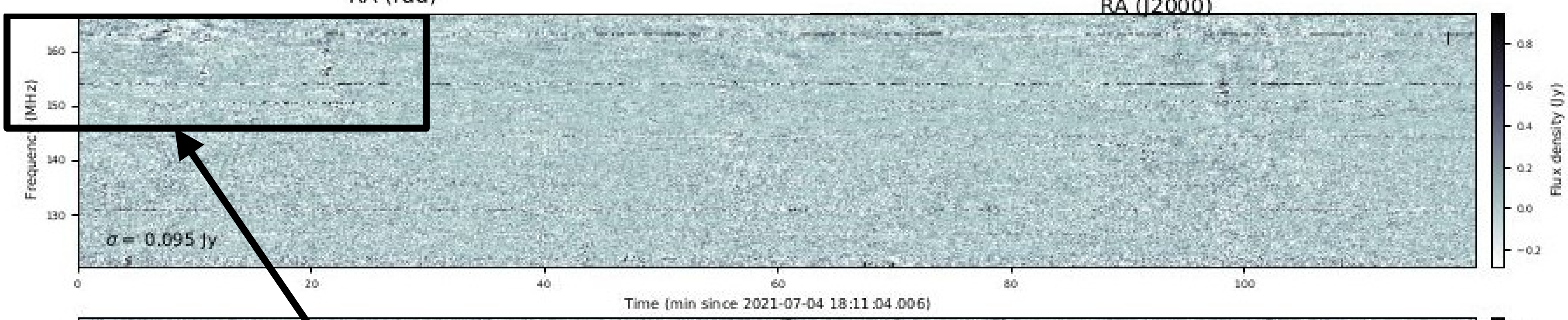
Non additive noise:
- **RFI**
- **Calibration errors**
- **Leaking source**

Noise properties



To study non-additive noise and systematics: do DynSpecs at random locations





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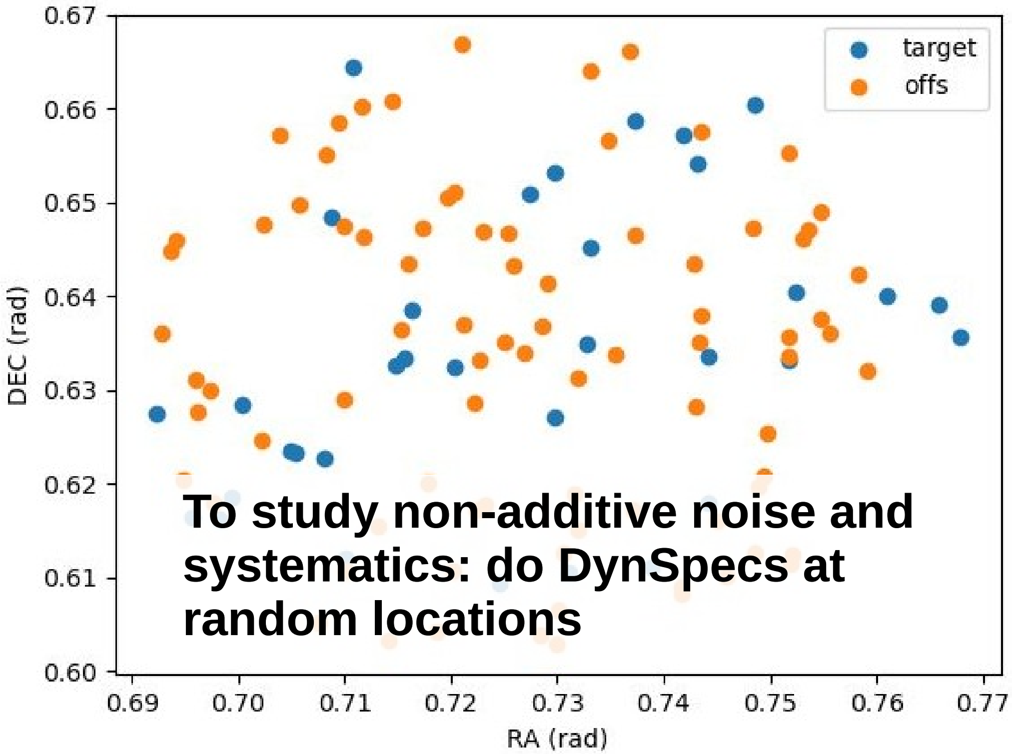

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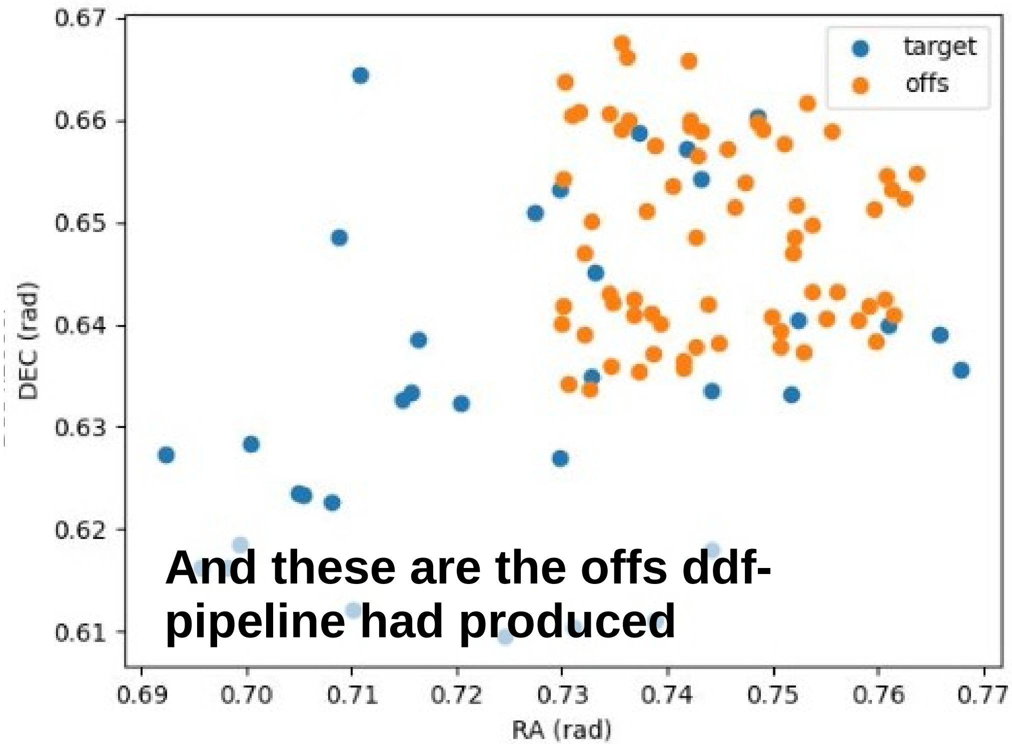
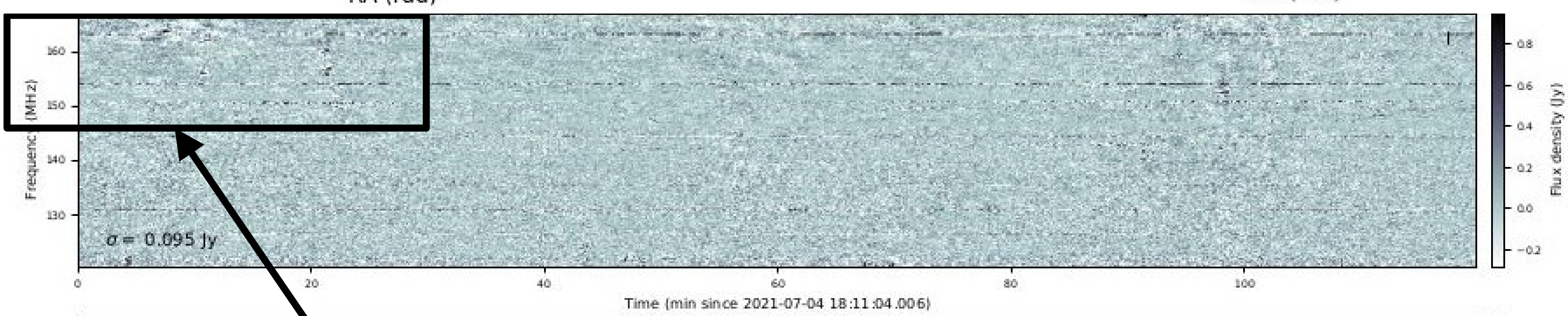


And these are the offs ddf-pipeline had produced



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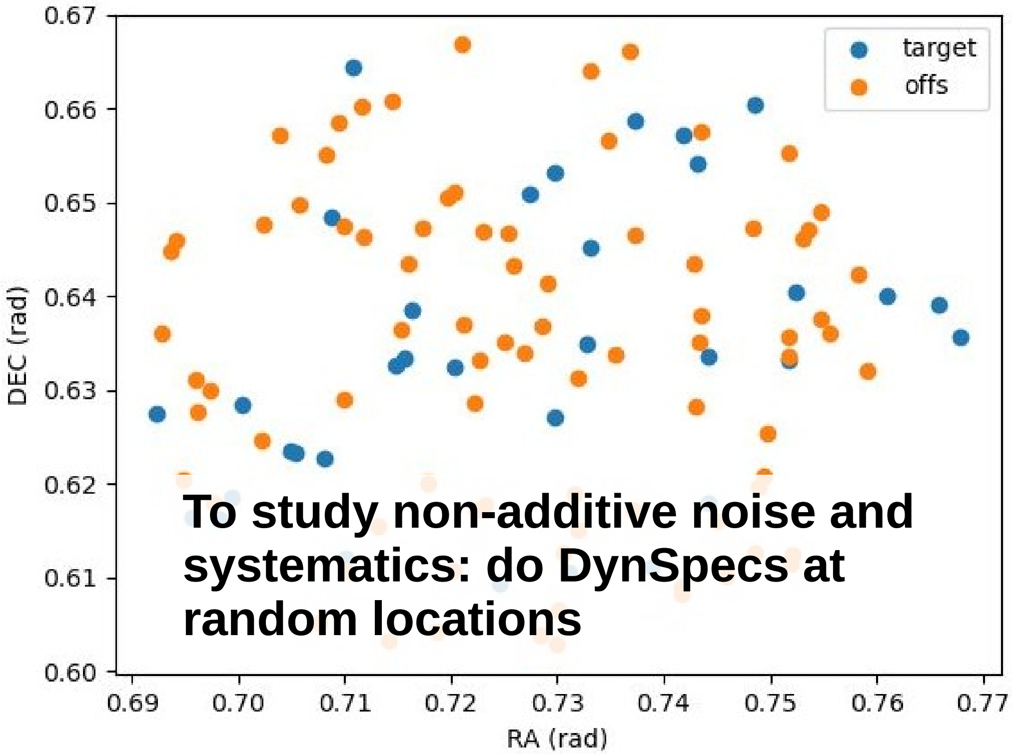

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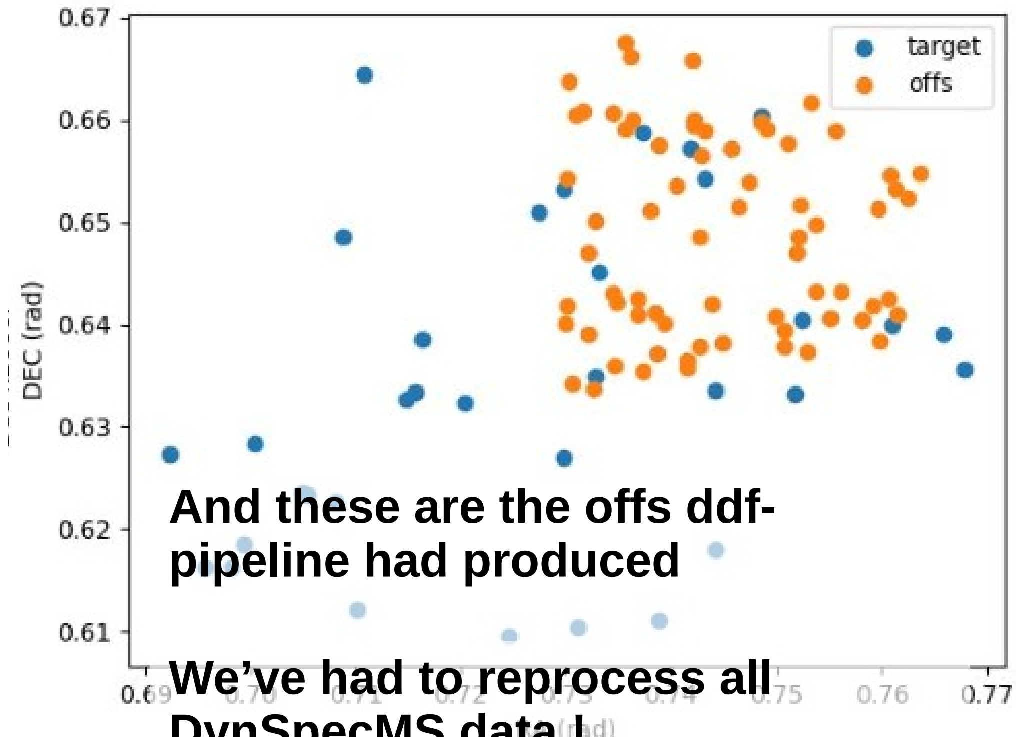

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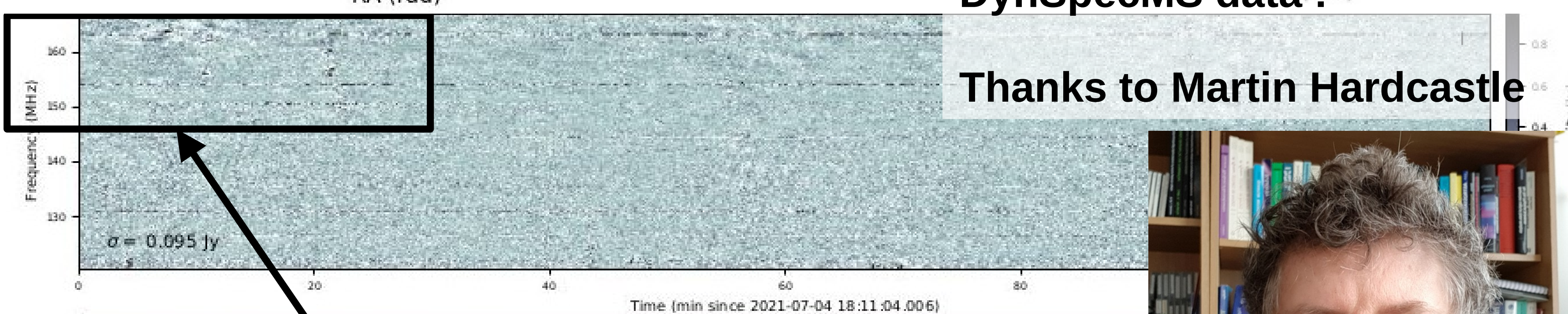
We've had to reprocess all DynSpecMS data !

Thanks to Martin Hardcastle



Non additive noise:

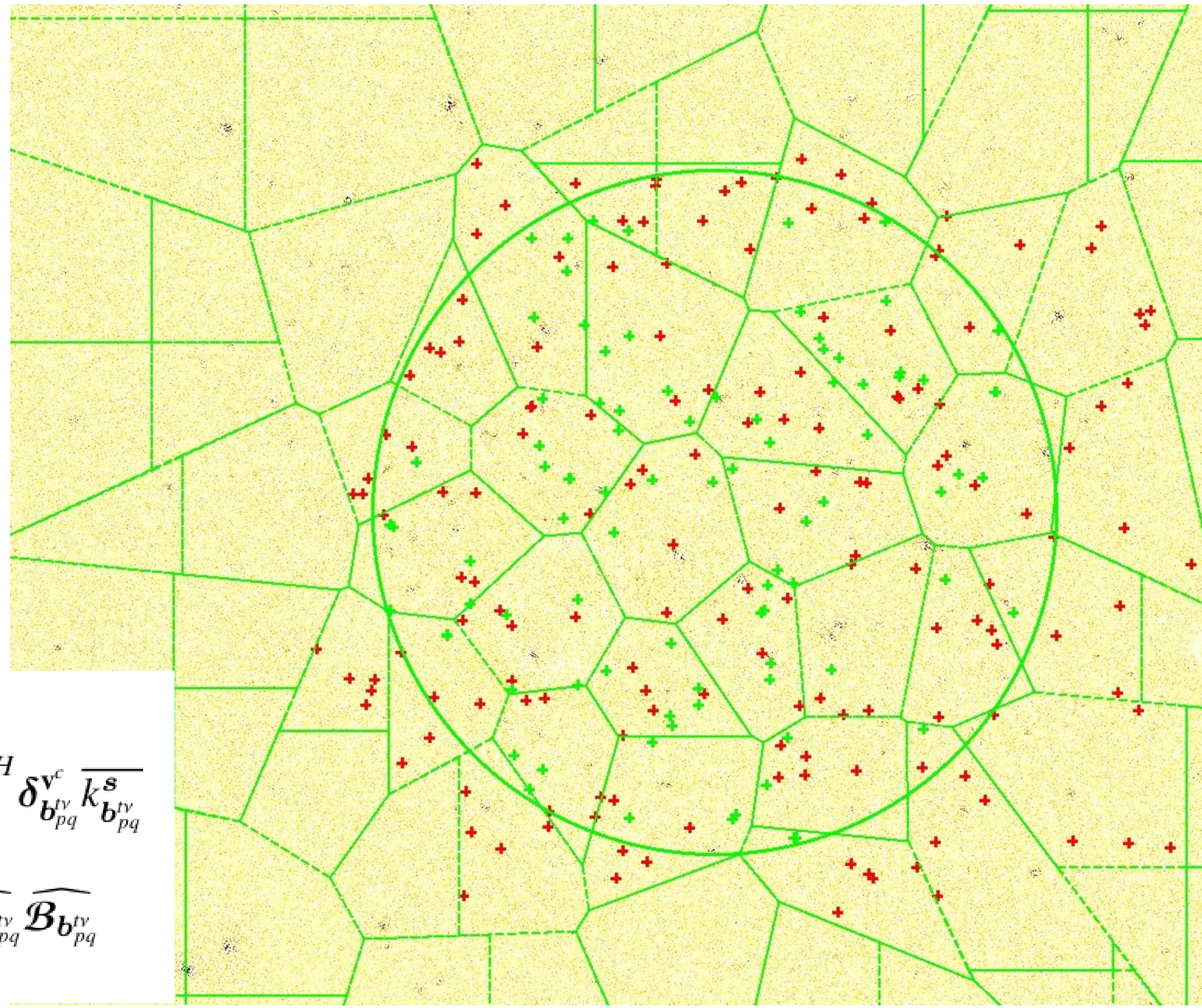
- RFI
- Calibration errors
- Leaking source

New processing

- Off positions are taken at smarter places

- Some clipping is applied to Jones matrices

- Jones matrices are applied properly (not inverting them!)

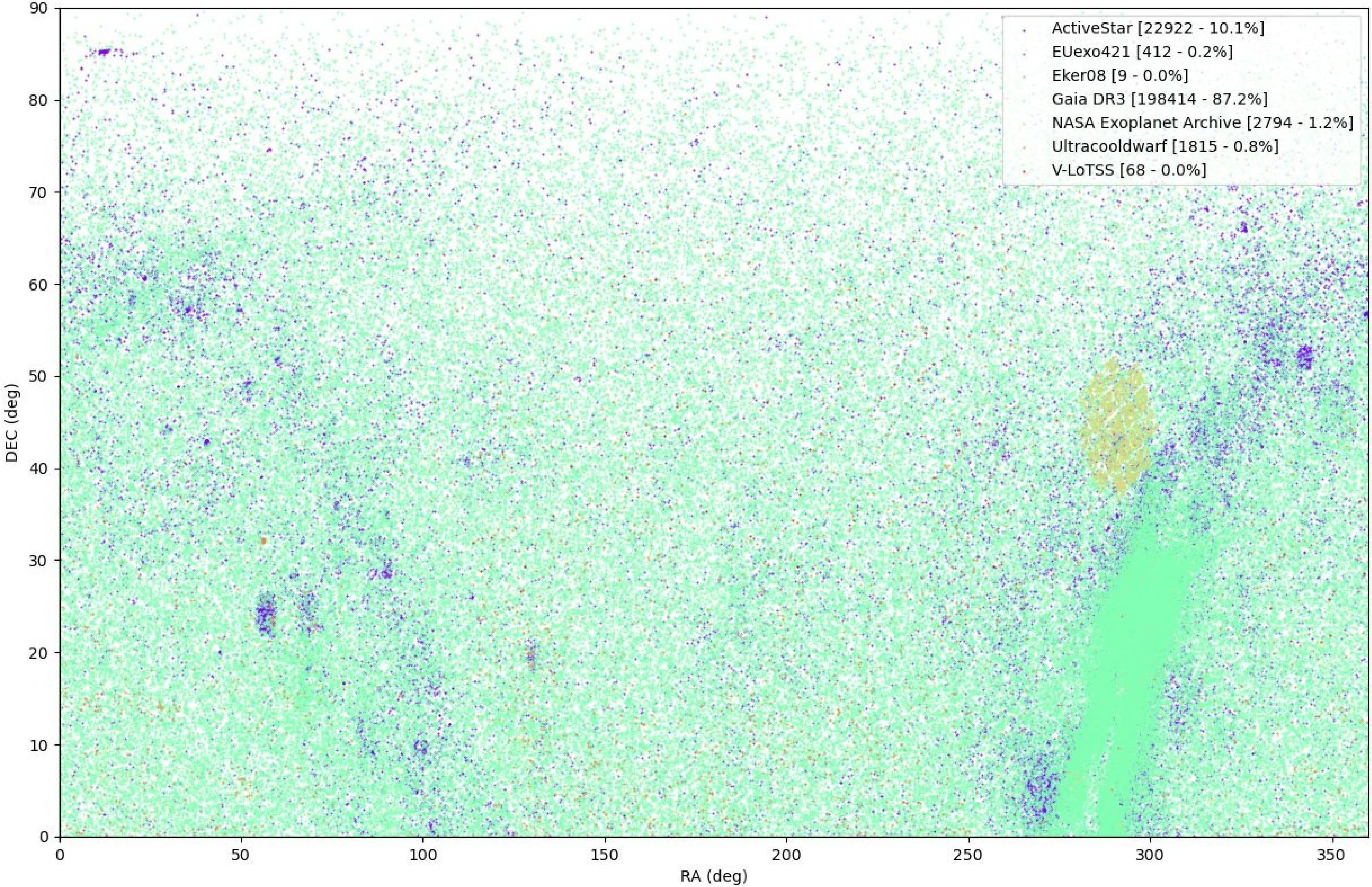


$$\widehat{\mathbf{x}_{\boldsymbol{s},tv}} = \widehat{\mathbf{x}_{\boldsymbol{s},v}} + \boldsymbol{\delta}^{\mathbf{x}}_{\boldsymbol{s},tv}$$

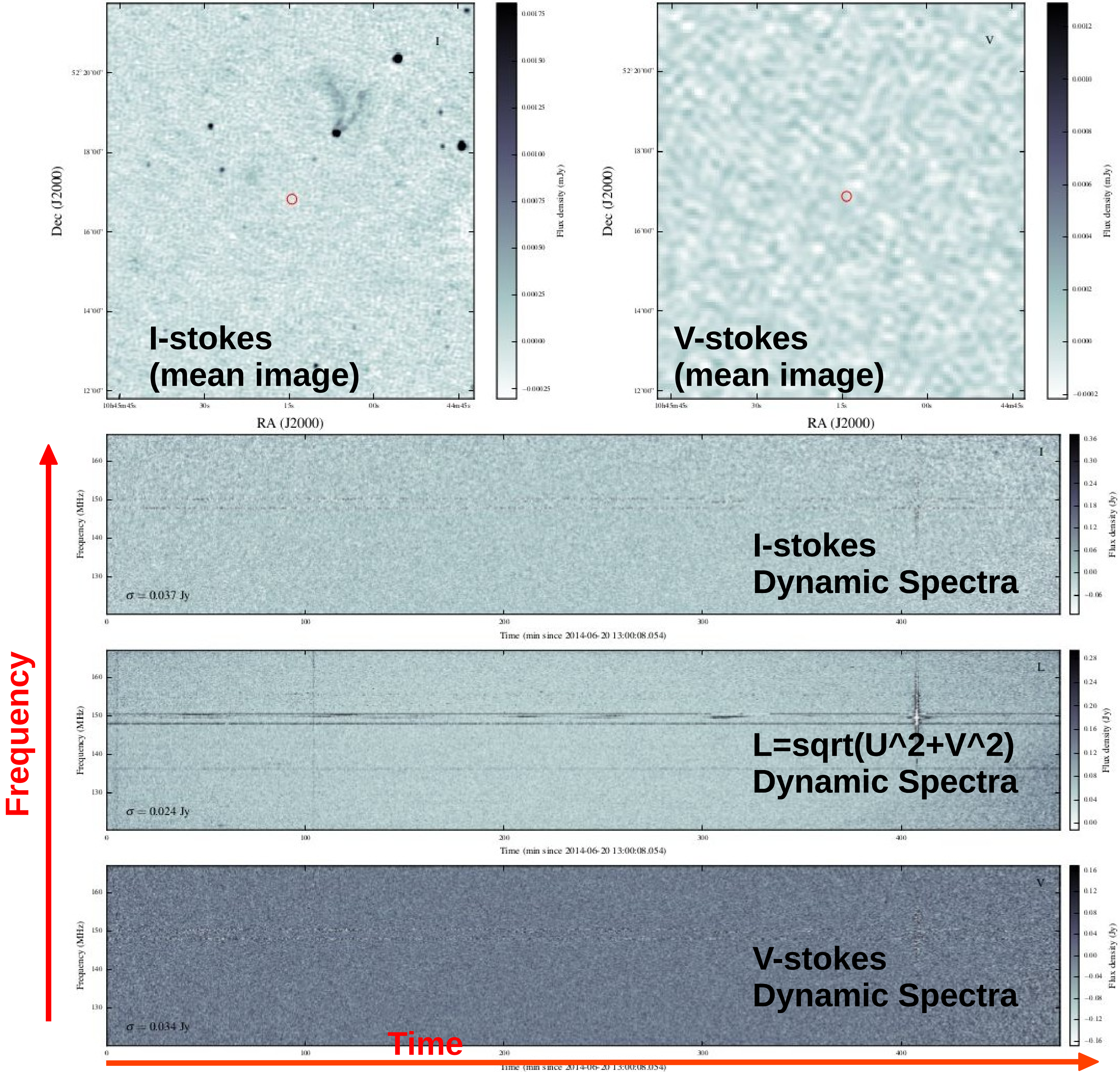
$$\text{with } \boldsymbol{\delta}^{\mathbf{x}}_{\boldsymbol{s},tv} = C^{-1}_{\boldsymbol{s},tv} \sum_{(pq)} \widehat{\mathcal{B}_{\mathbf{b}^{tv}_{pq}}}^{H} \widehat{\mathcal{J}_{\mathbf{b}^{tv}_{pq}}}^{H} \boldsymbol{\delta}^{\mathbf{v}^c}_{\mathbf{b}^{tv}_{pq}} \overline{k^{\boldsymbol{s}}_{\mathbf{b}^{tv}_{pq}}}$$

$$\text{and } C_{\boldsymbol{s},tv} = \sum_{(pq)} \widehat{\mathcal{B}_{\mathbf{b}^{tv}_{pq}}}^{H} \widehat{\mathcal{J}_{\mathbf{b}^{tv}_{pq}}}^{H} \widehat{\mathcal{J}_{\mathbf{b}^{tv}_{pq}}} \widehat{\mathcal{B}_{\mathbf{b}^{tv}_{pq}}}$$

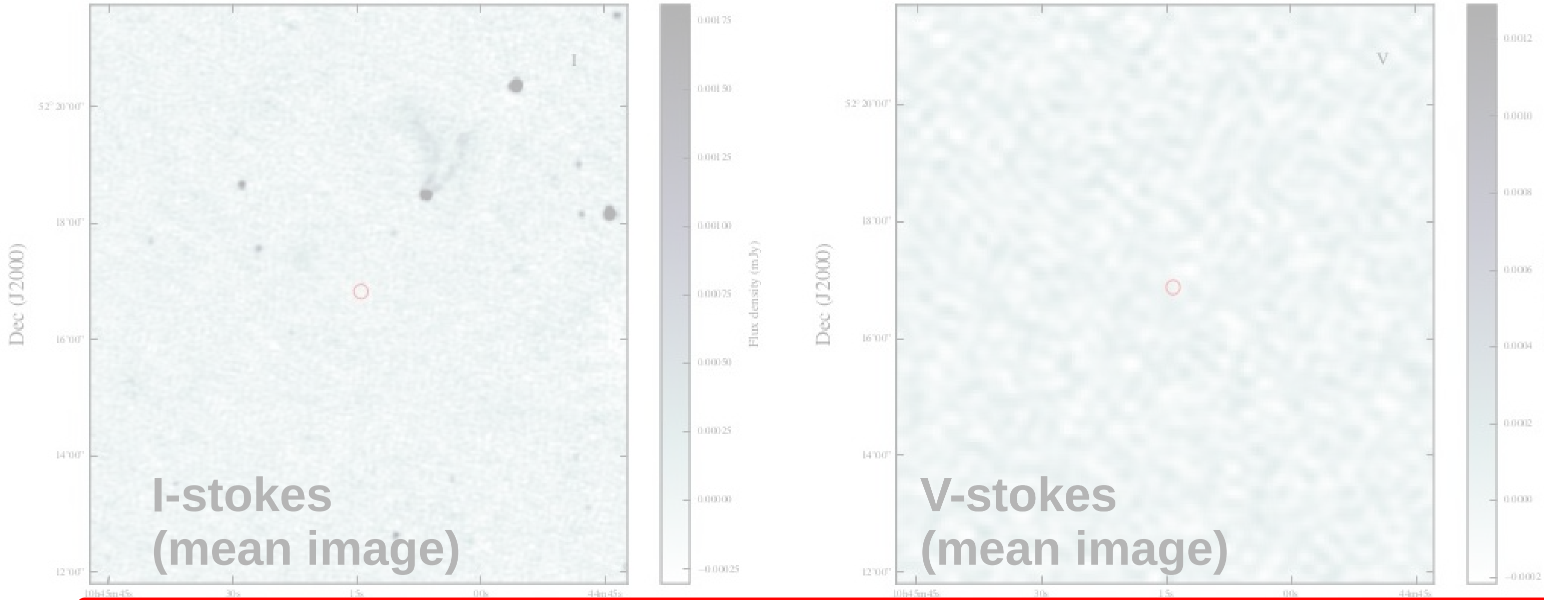
New catalog 227665 targets



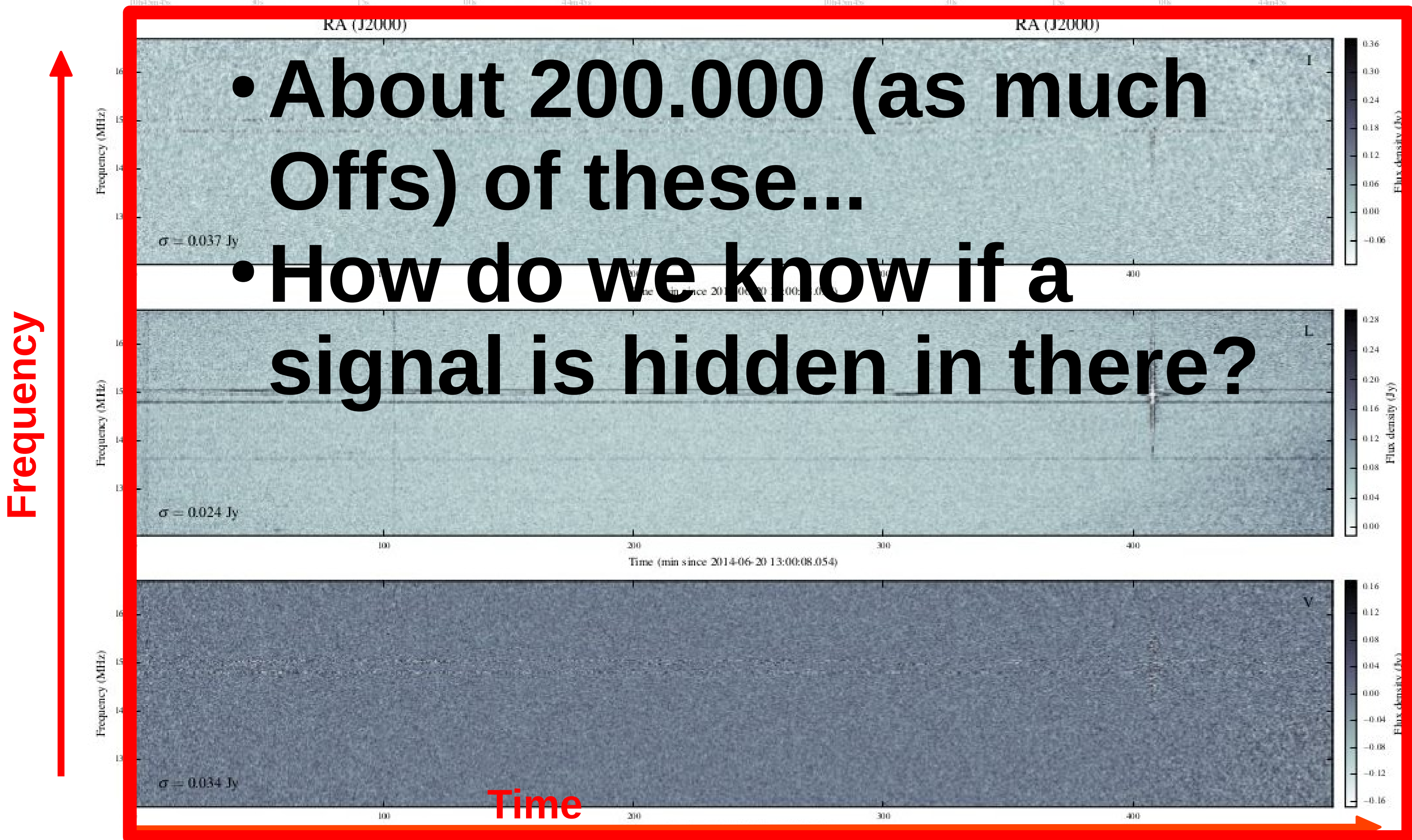
Typical output

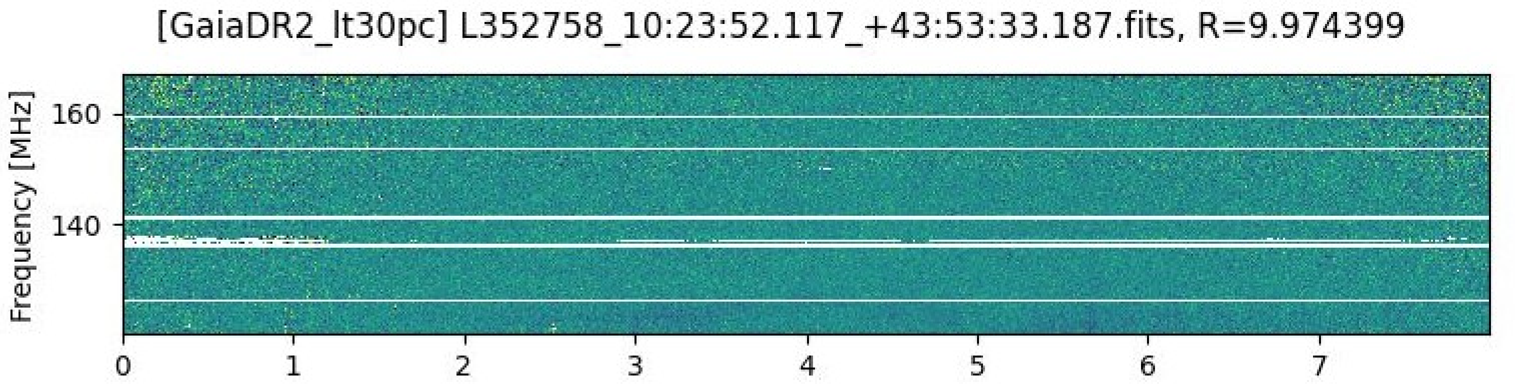


Typical output

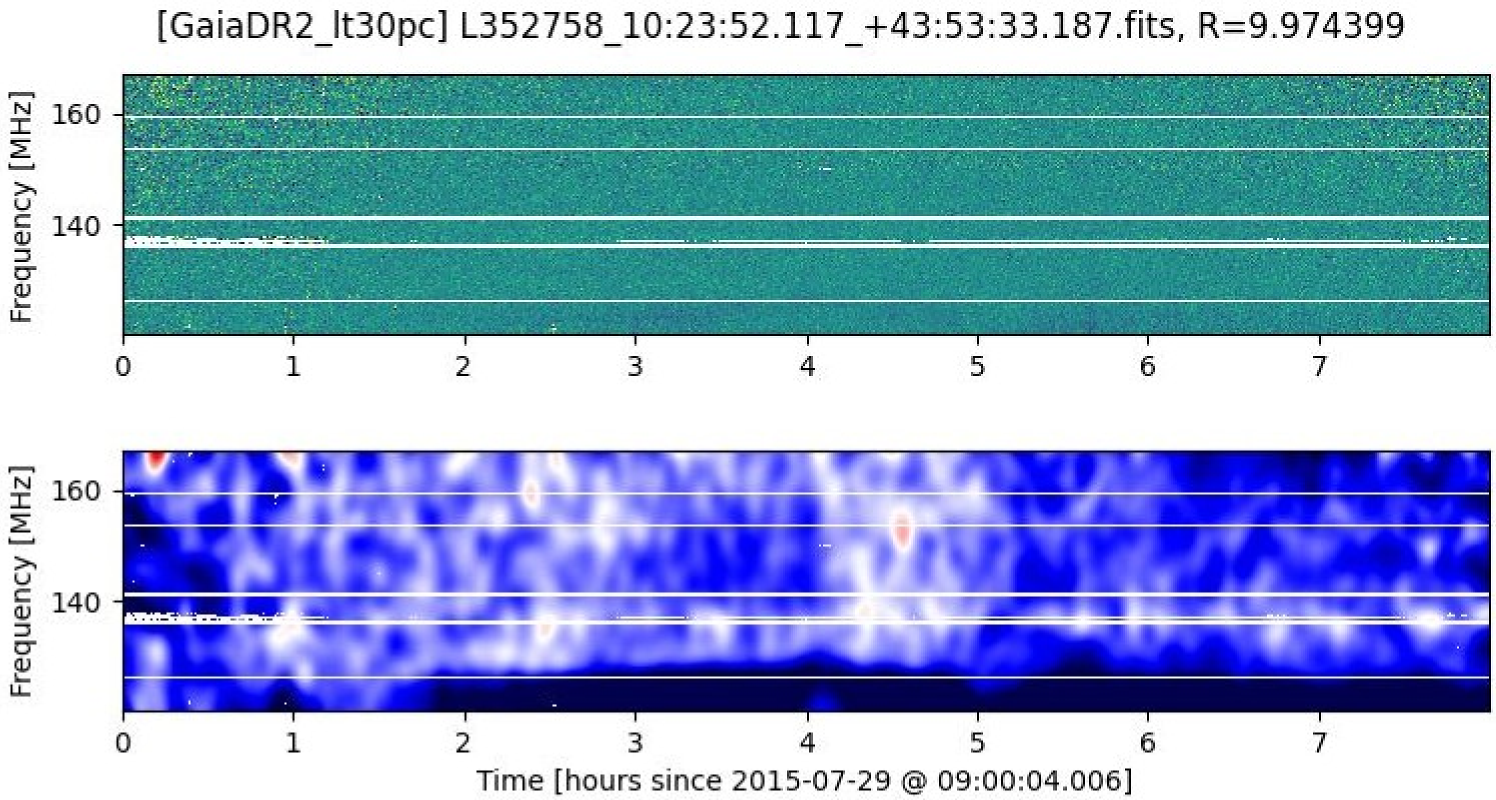


- About 200.000 (as much Offs) of these...
- How do we know if a signal is hidden in there?

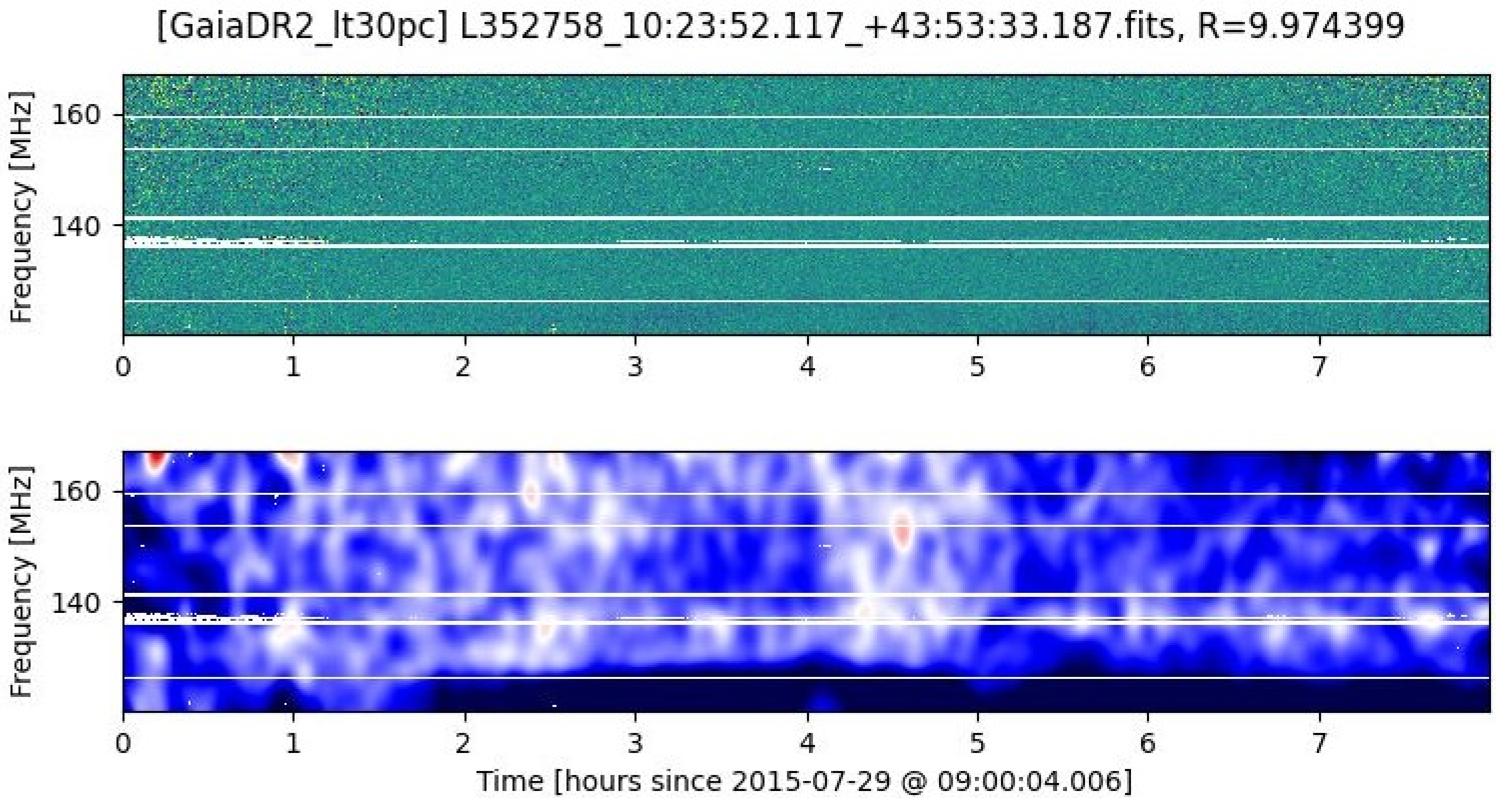


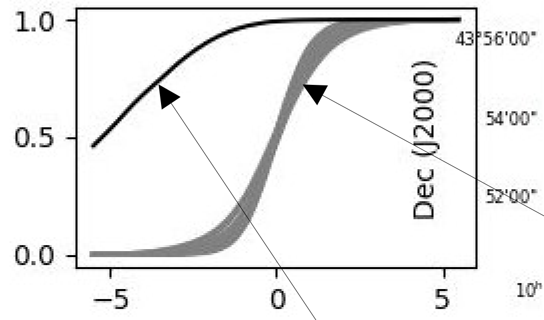

[GaiaDR2_lt30pc] L352758_10:23:52.117_+43:53:33.187.fits, R=9.974399
Frequency [MHz]
160
140
0
1
2
3
4
5
6
7

“Flag”



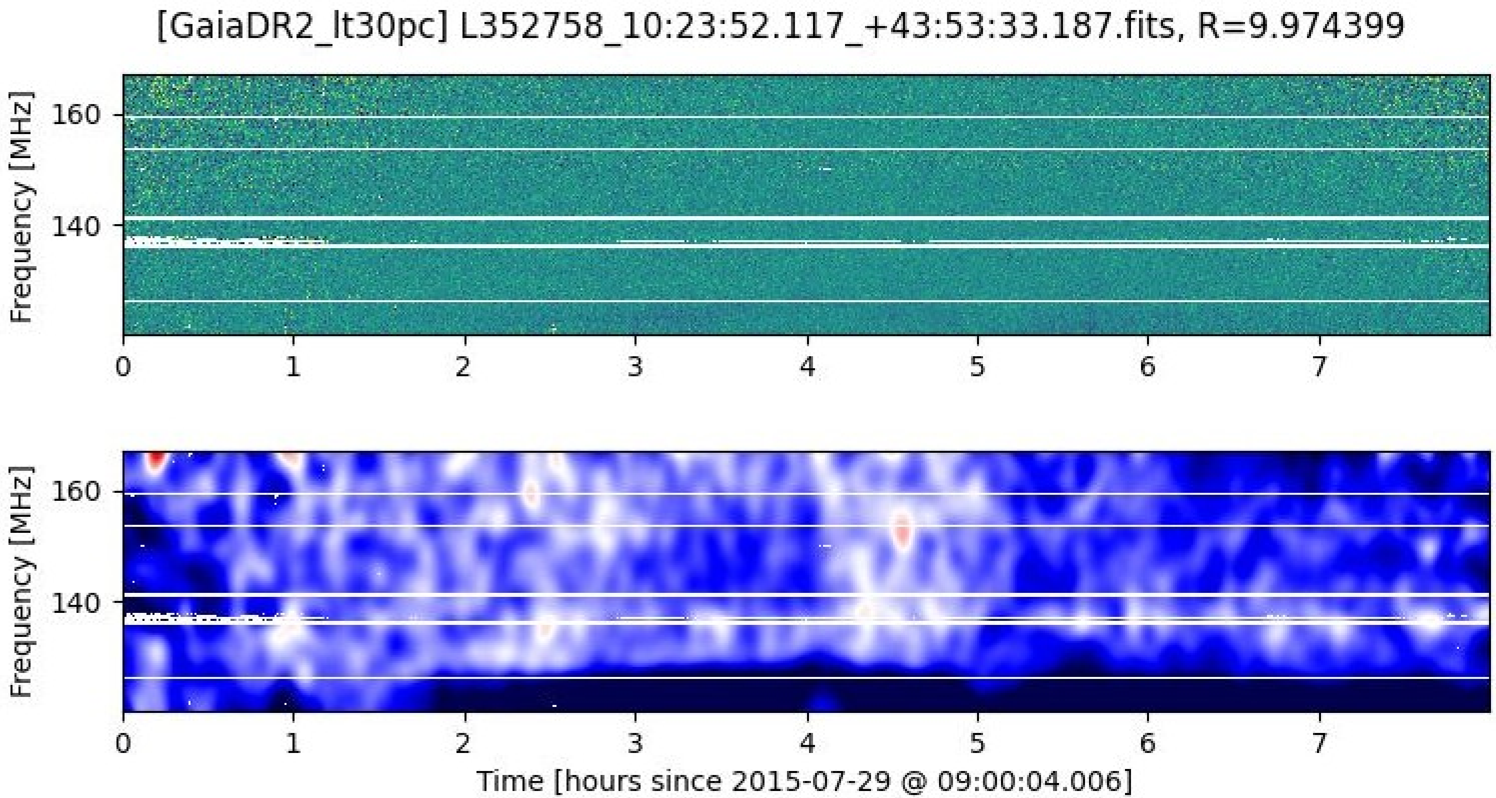
Denoising (Convolve with some function)

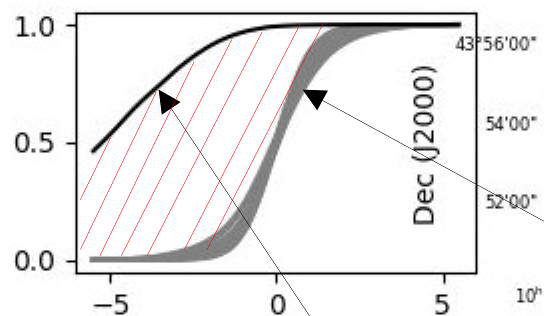




Cumulative distribution of pixels in Target dynamic spectra

Cumulative distribution of pixels in Off dynamic spectra

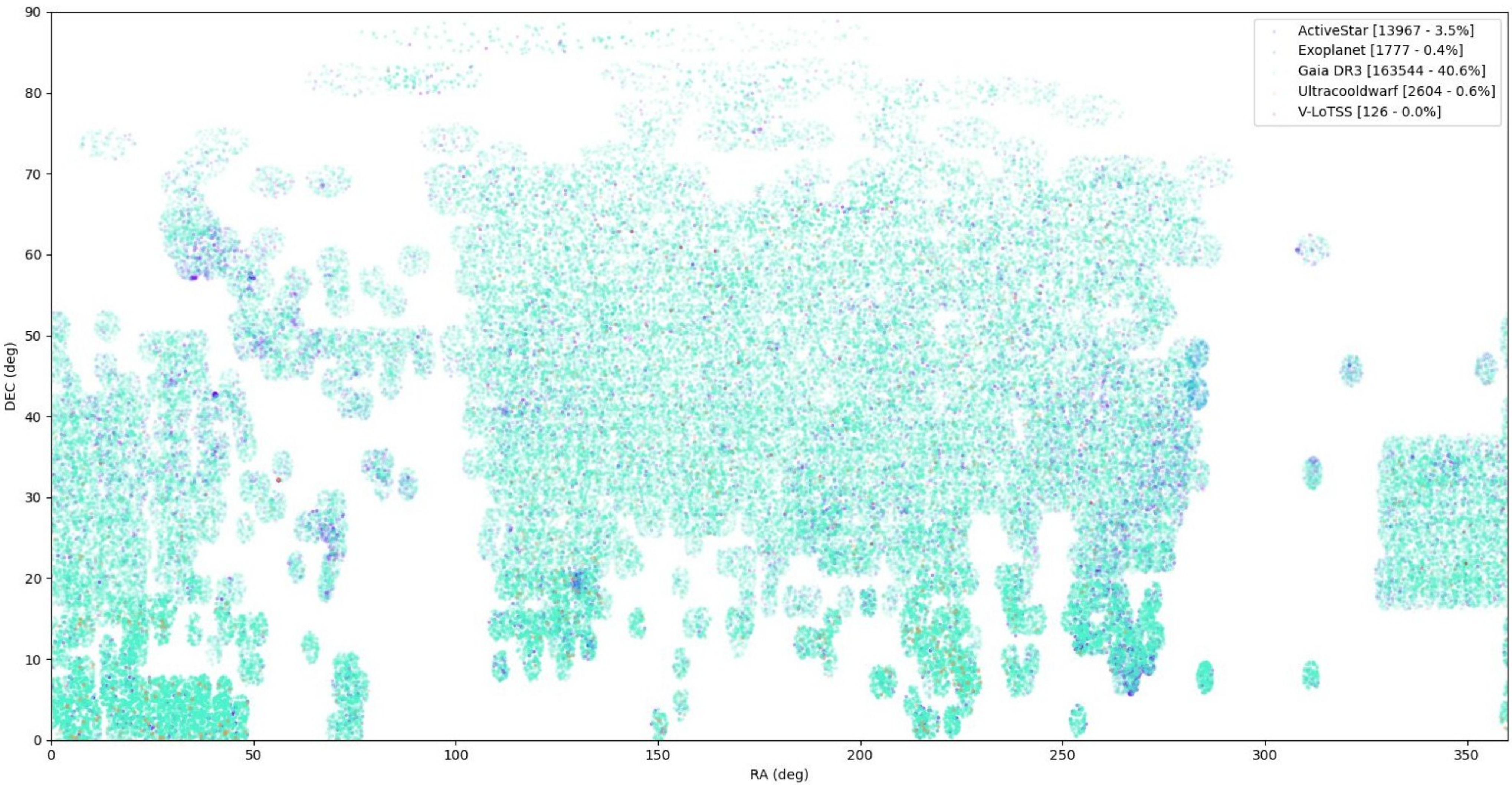




Define a distance between distributions: modified-Wasserstein metric

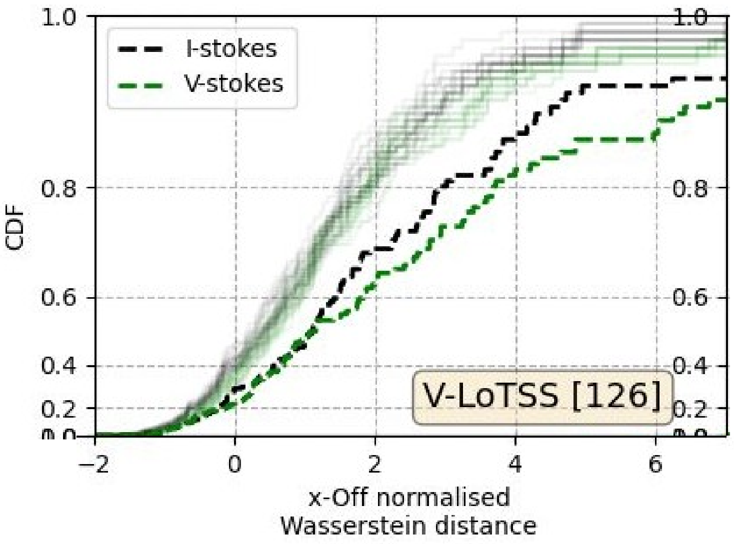
Cumulative distribution of pixels in Target dynamic spectra

Cumulative distribution of pixels in Off dynamic spectra



ActiveStar [13967 - 3.5%]
Exoplanet [1777 - 0.4%]
Gaia DR3 [163544 - 40.6%]
Ultracooldwarf [2604 - 0.6%]
V-LoTSS [126 - 0.0%]
DEC (deg)
RA (deg)
0
10
20
30
40
50
60
70
80
90
0
50
100
150
200
250
300
350

Going Beyond bright detections
Statistical analysis: 182018 Target spectra



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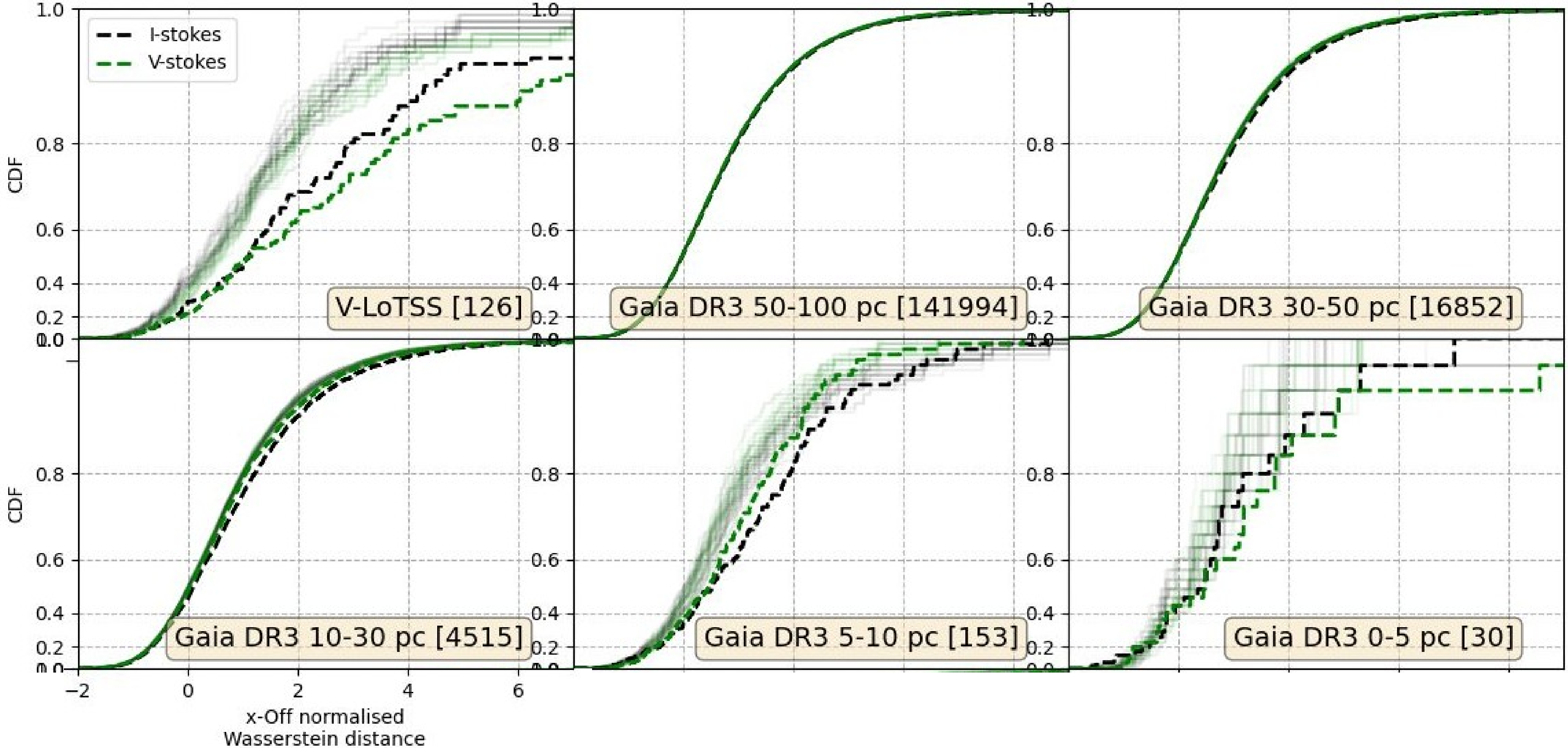

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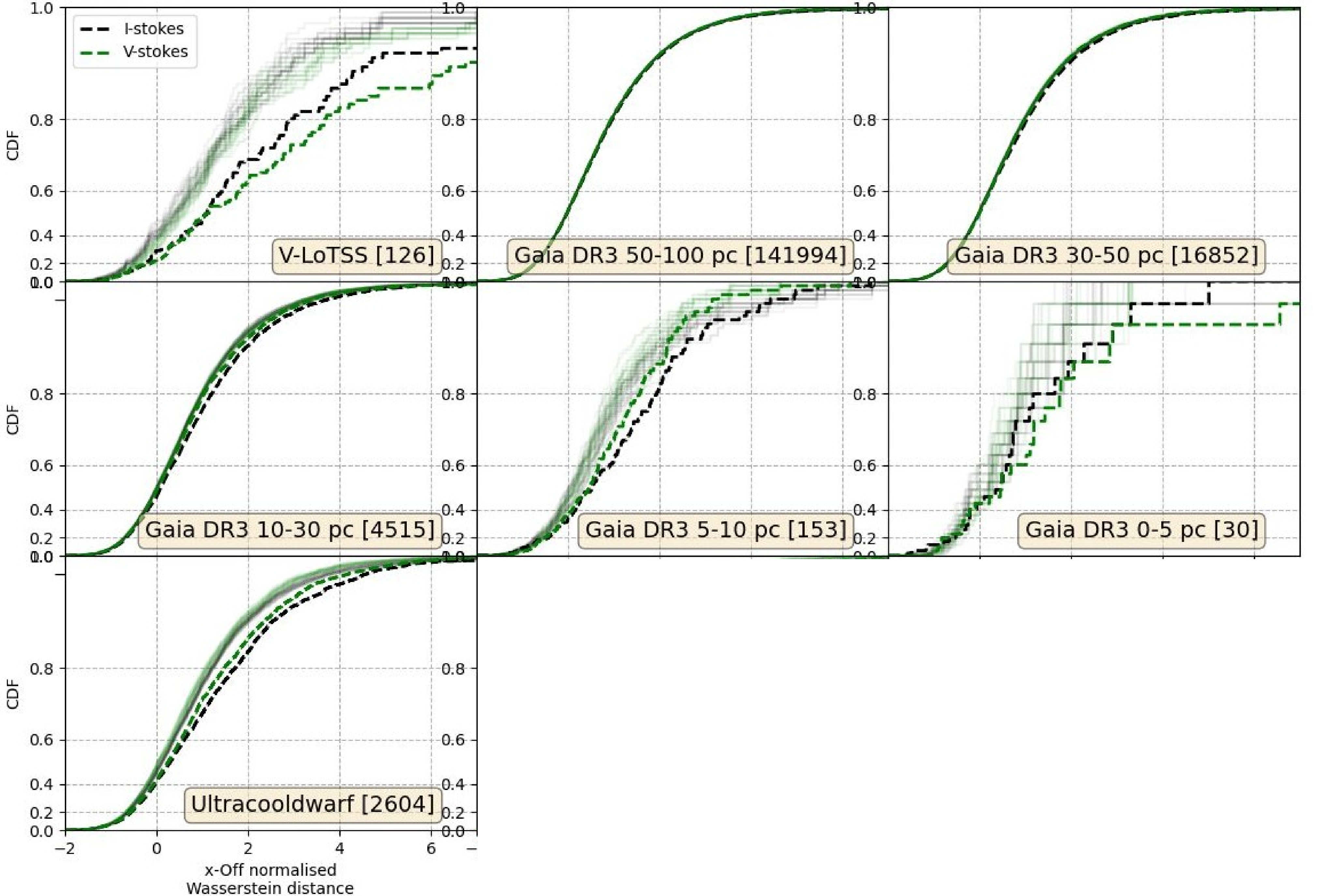

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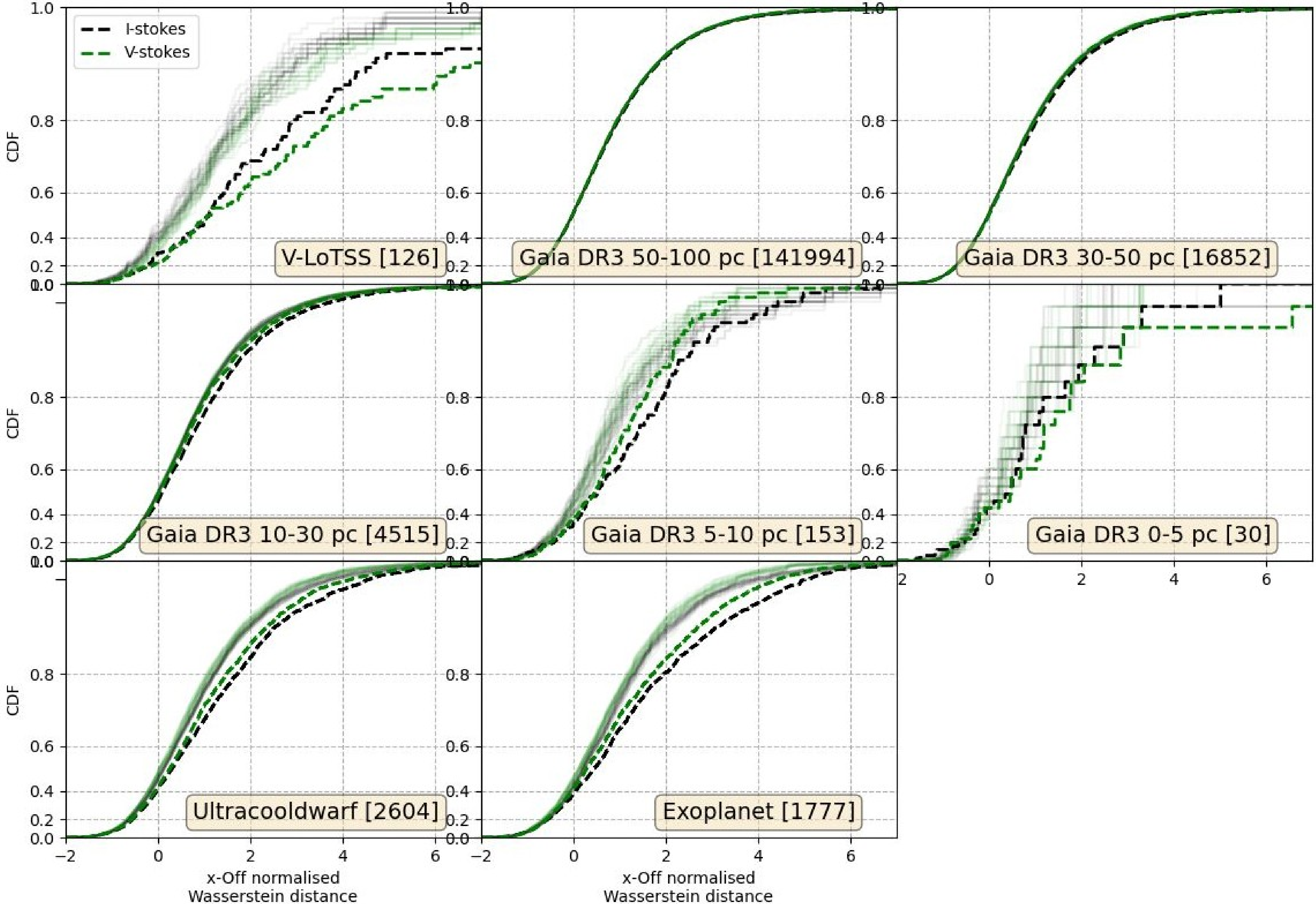
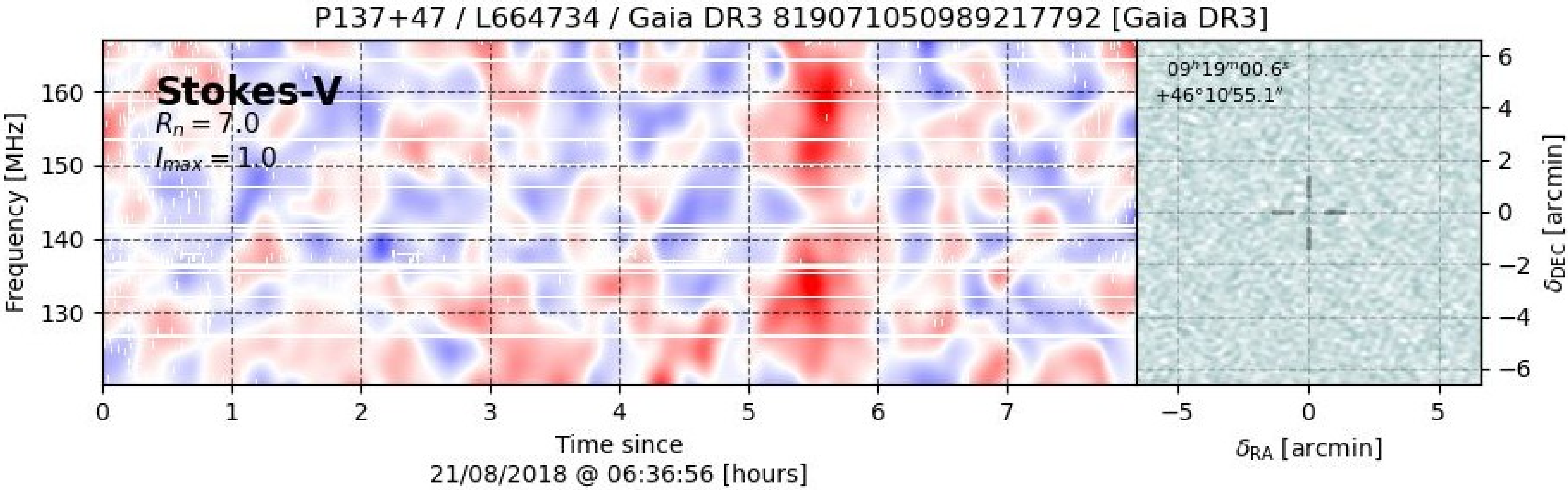
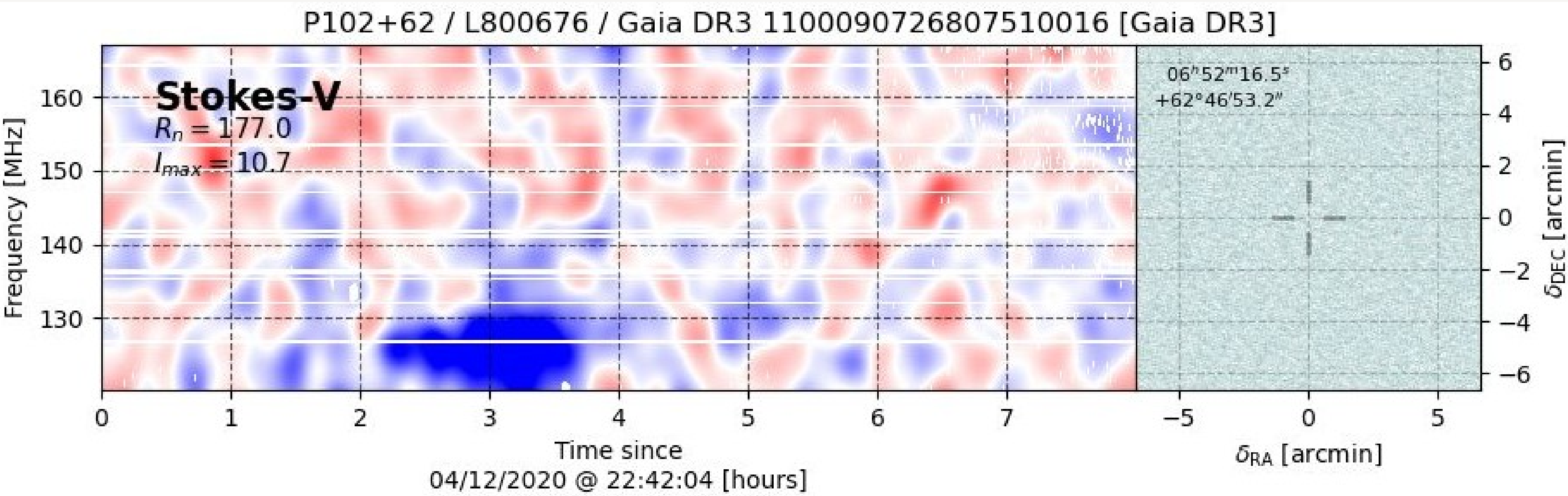


Analysis pipeline selects everything that have Rn>7





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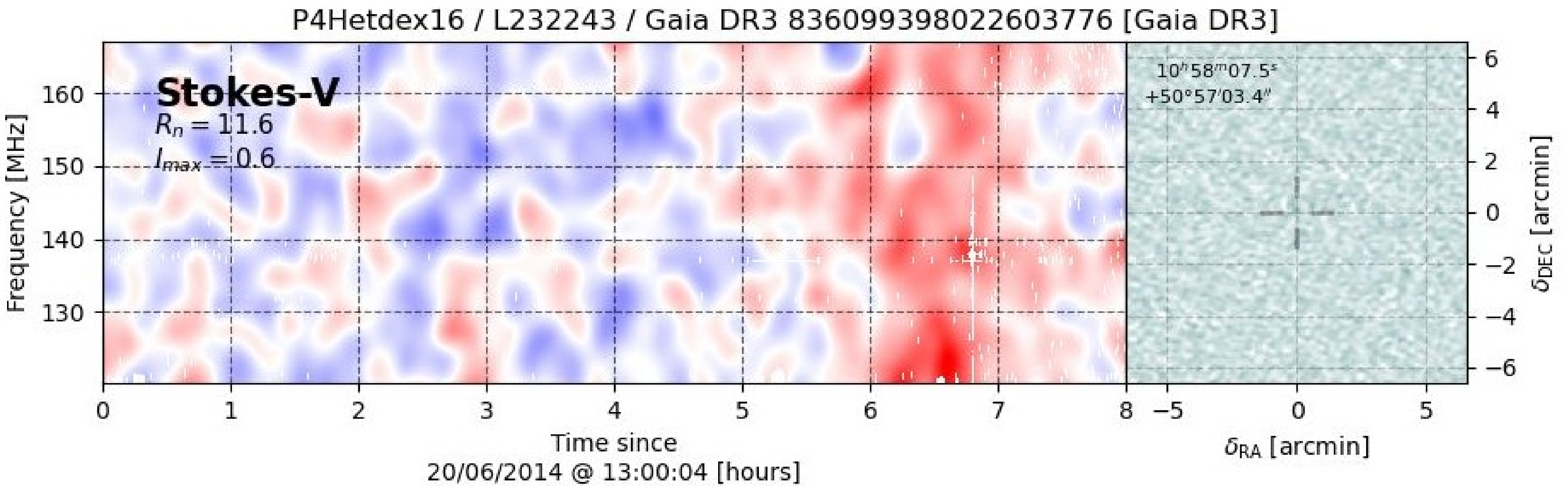

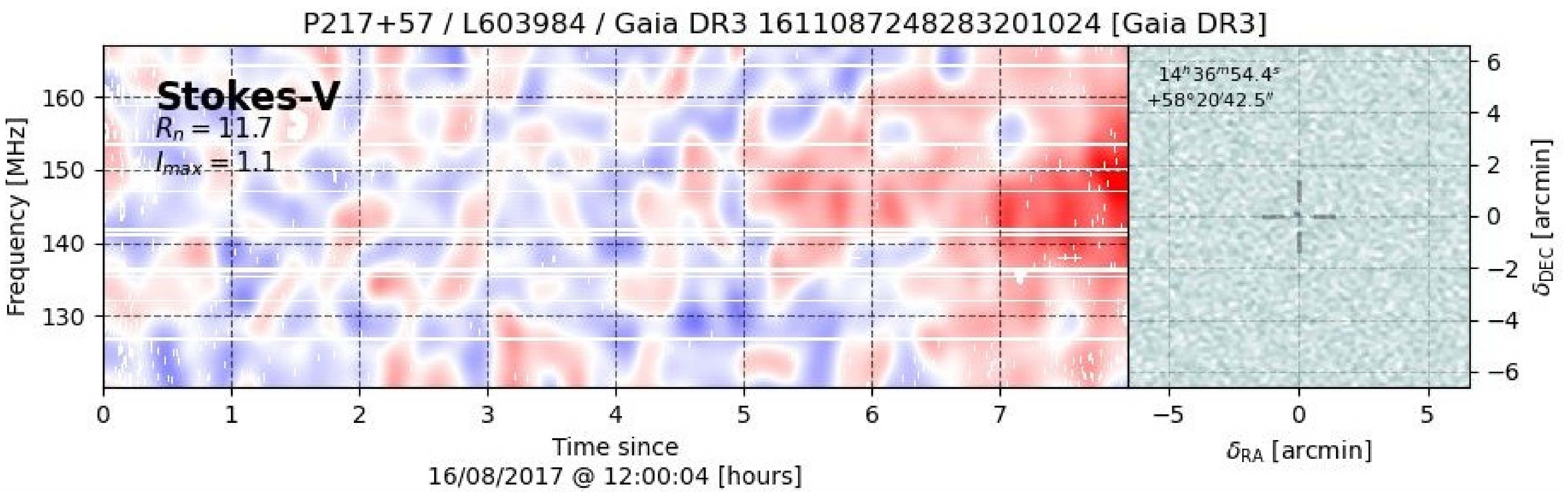

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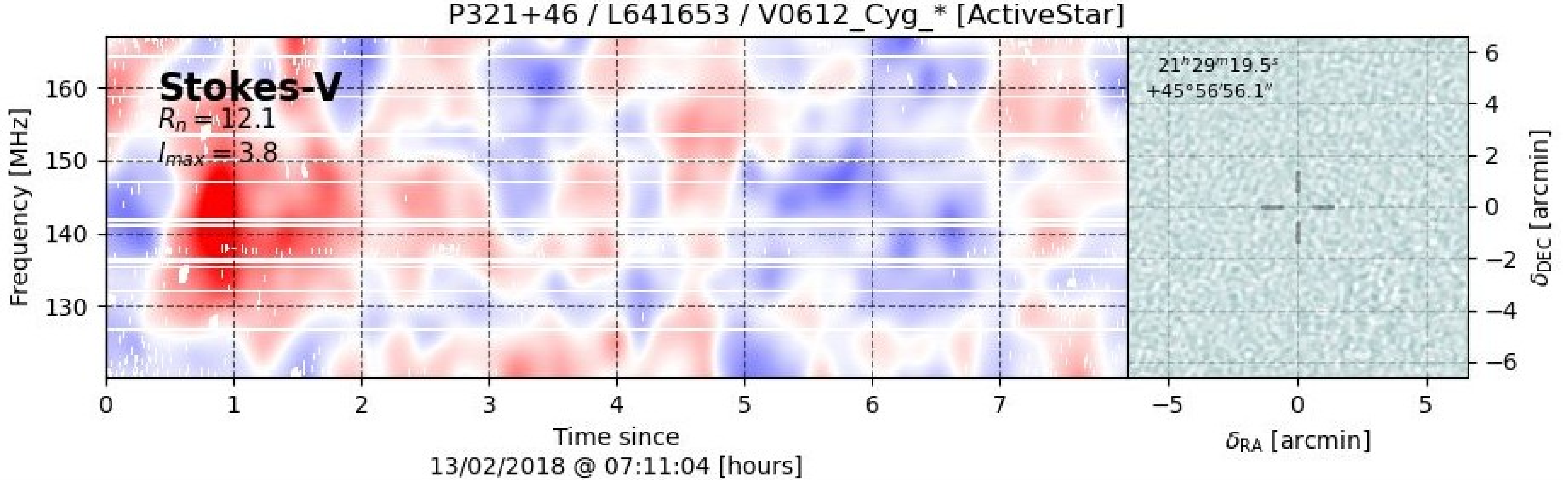

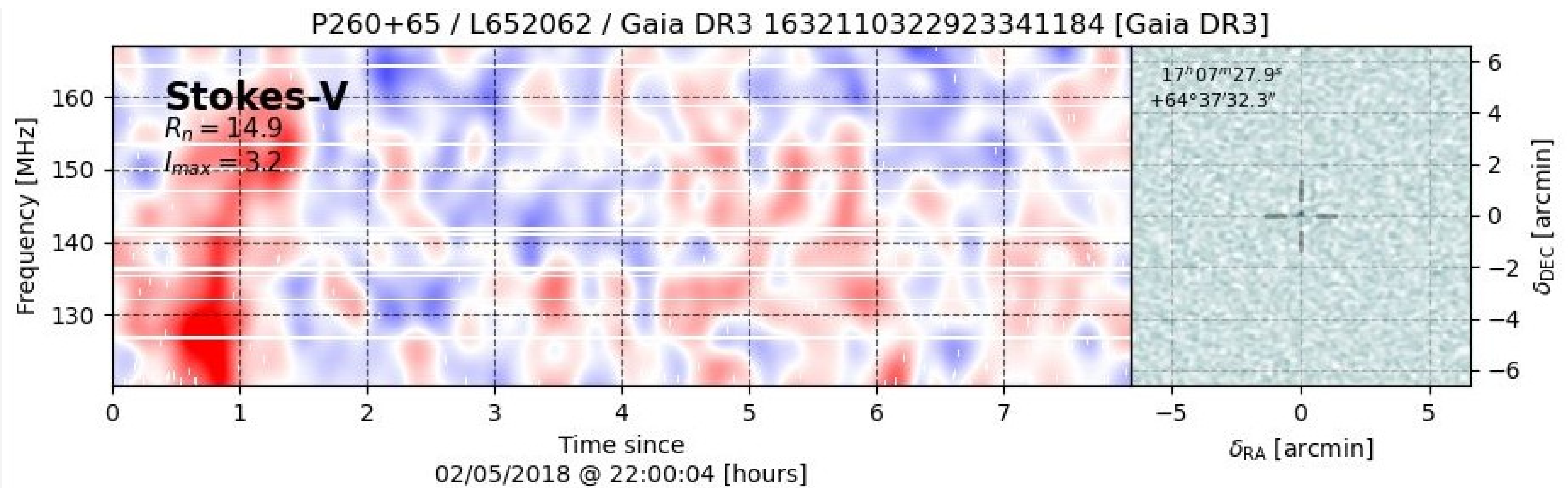

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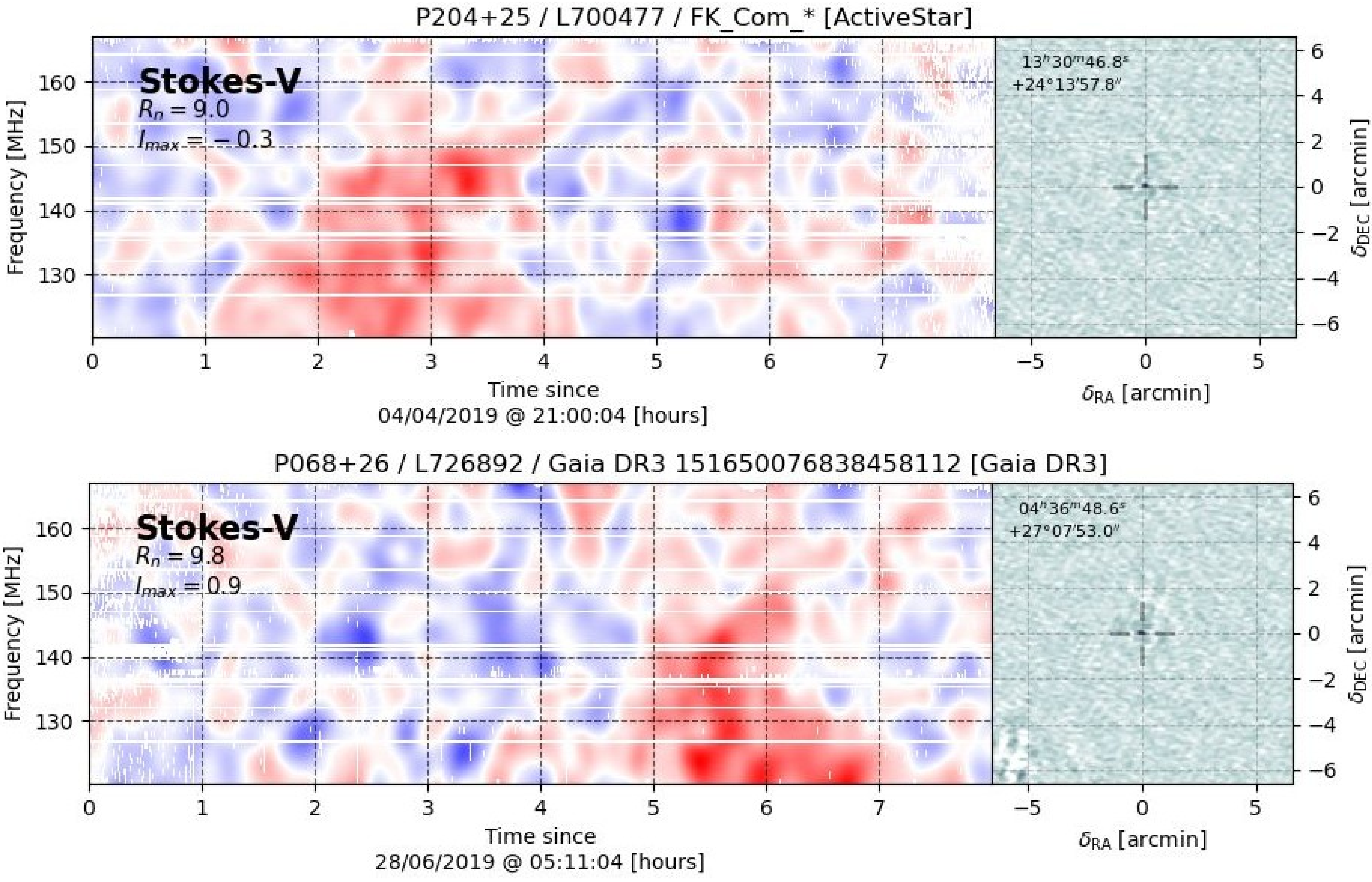

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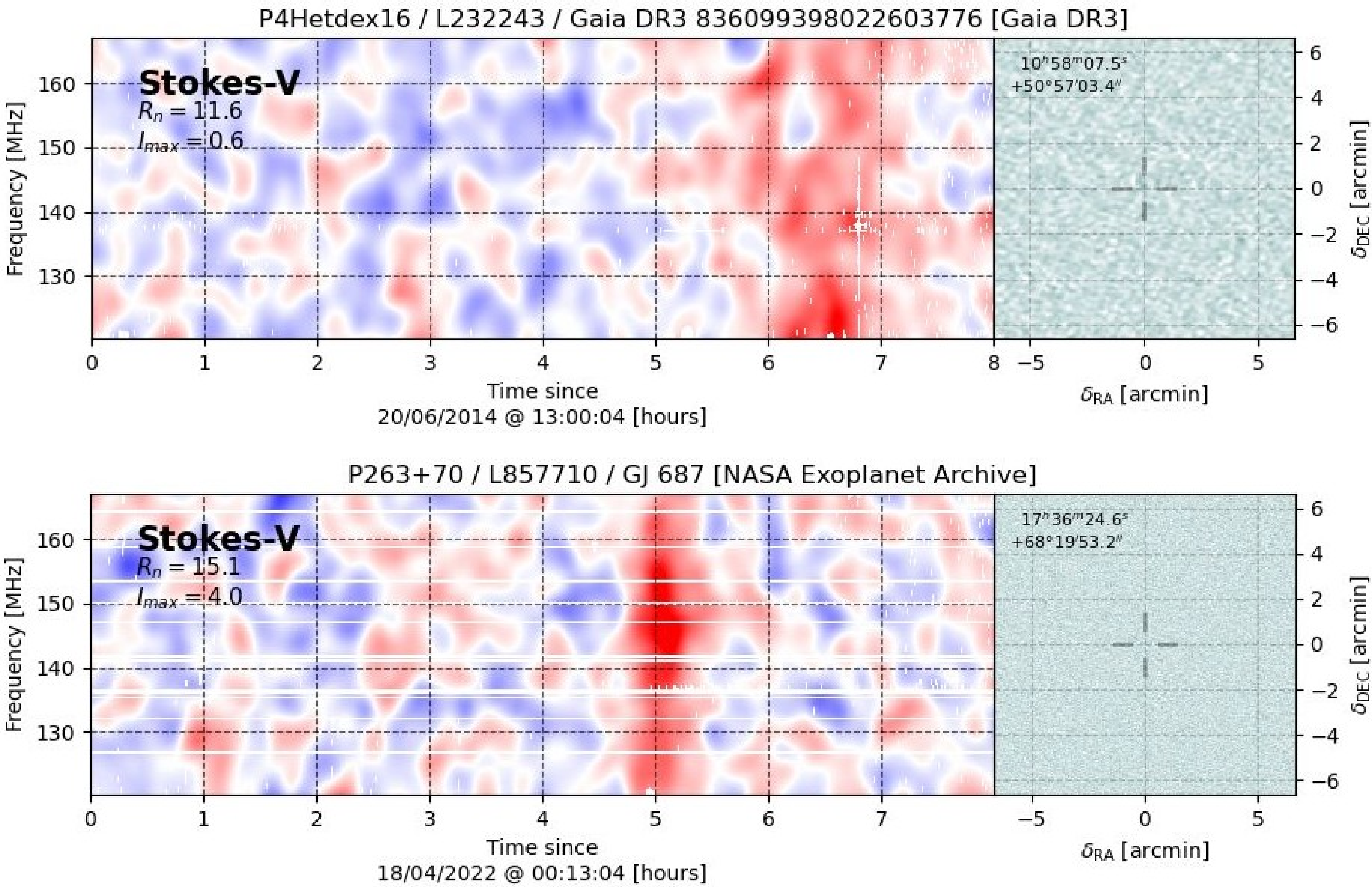
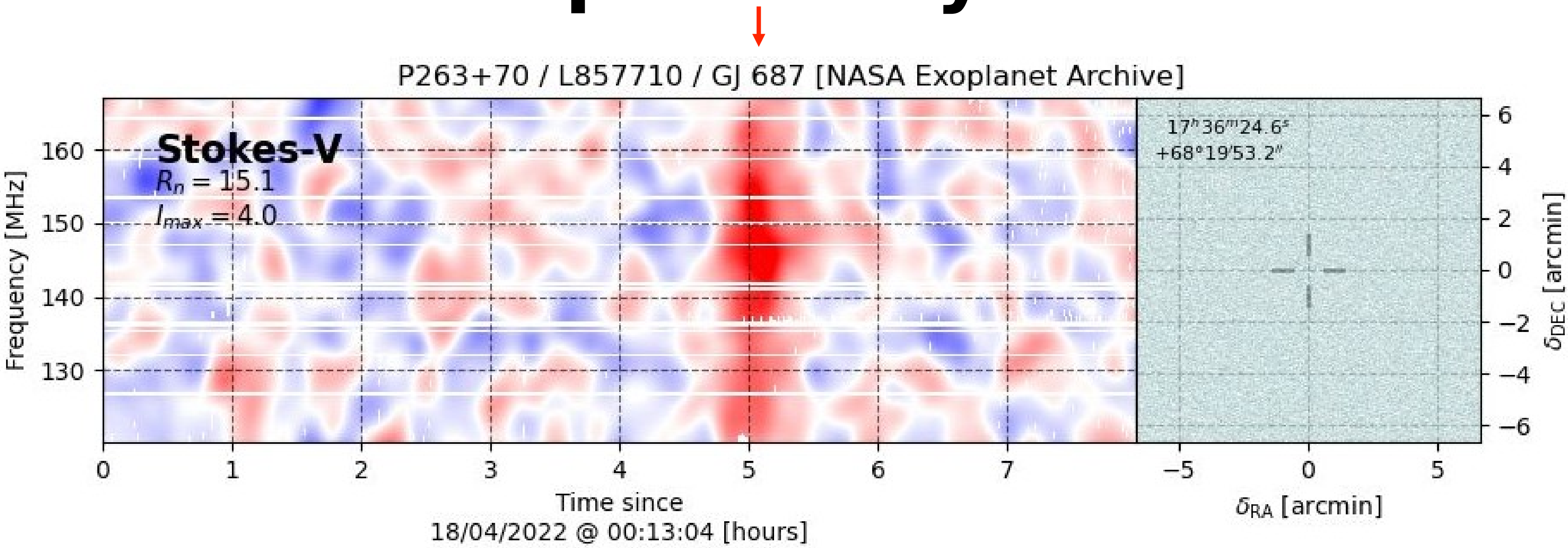
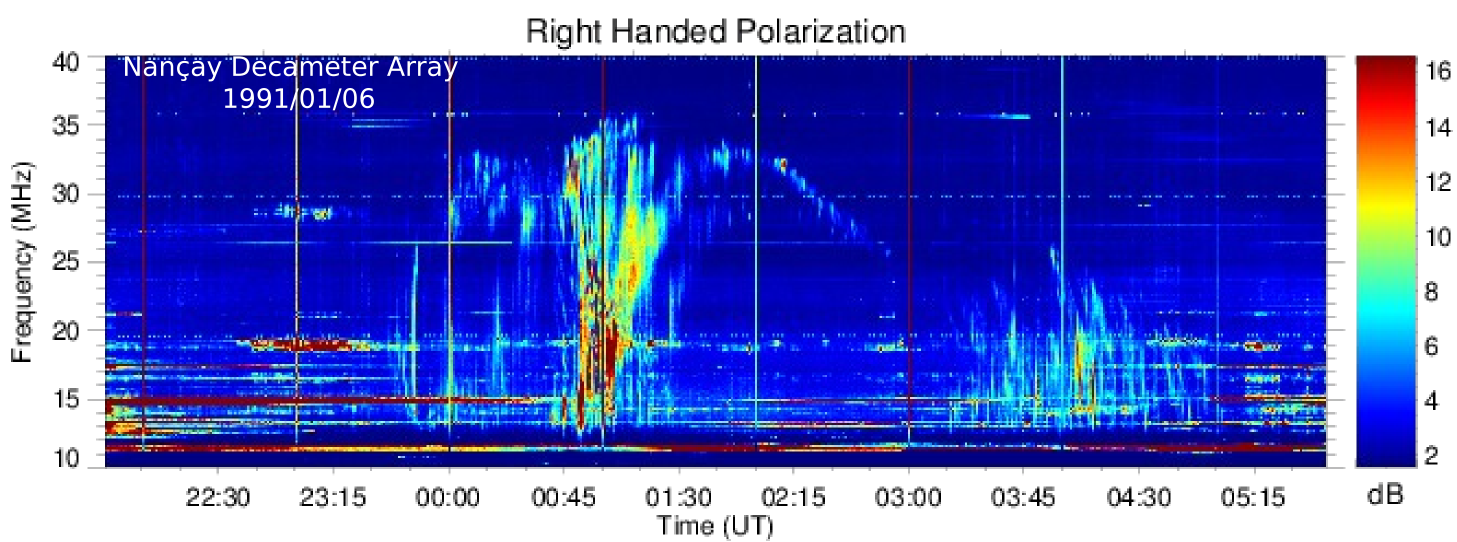


LOFAR’s exoplanetary radio burst ?



Planetary (Jupiter) radio bursts



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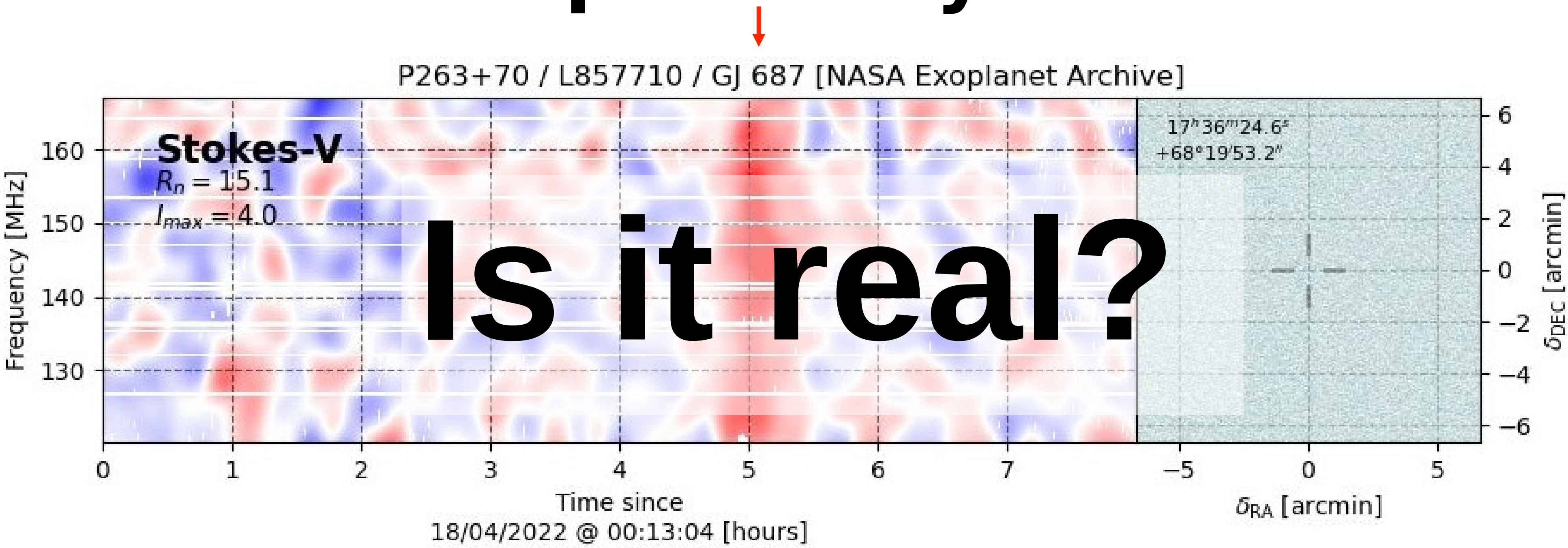

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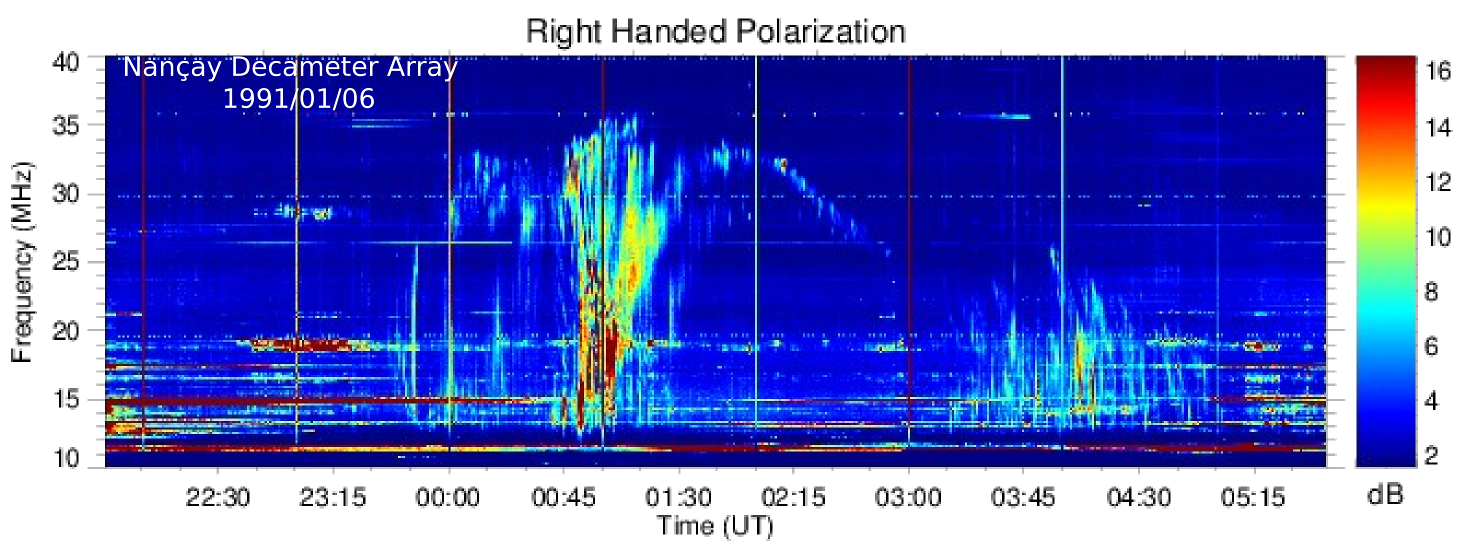
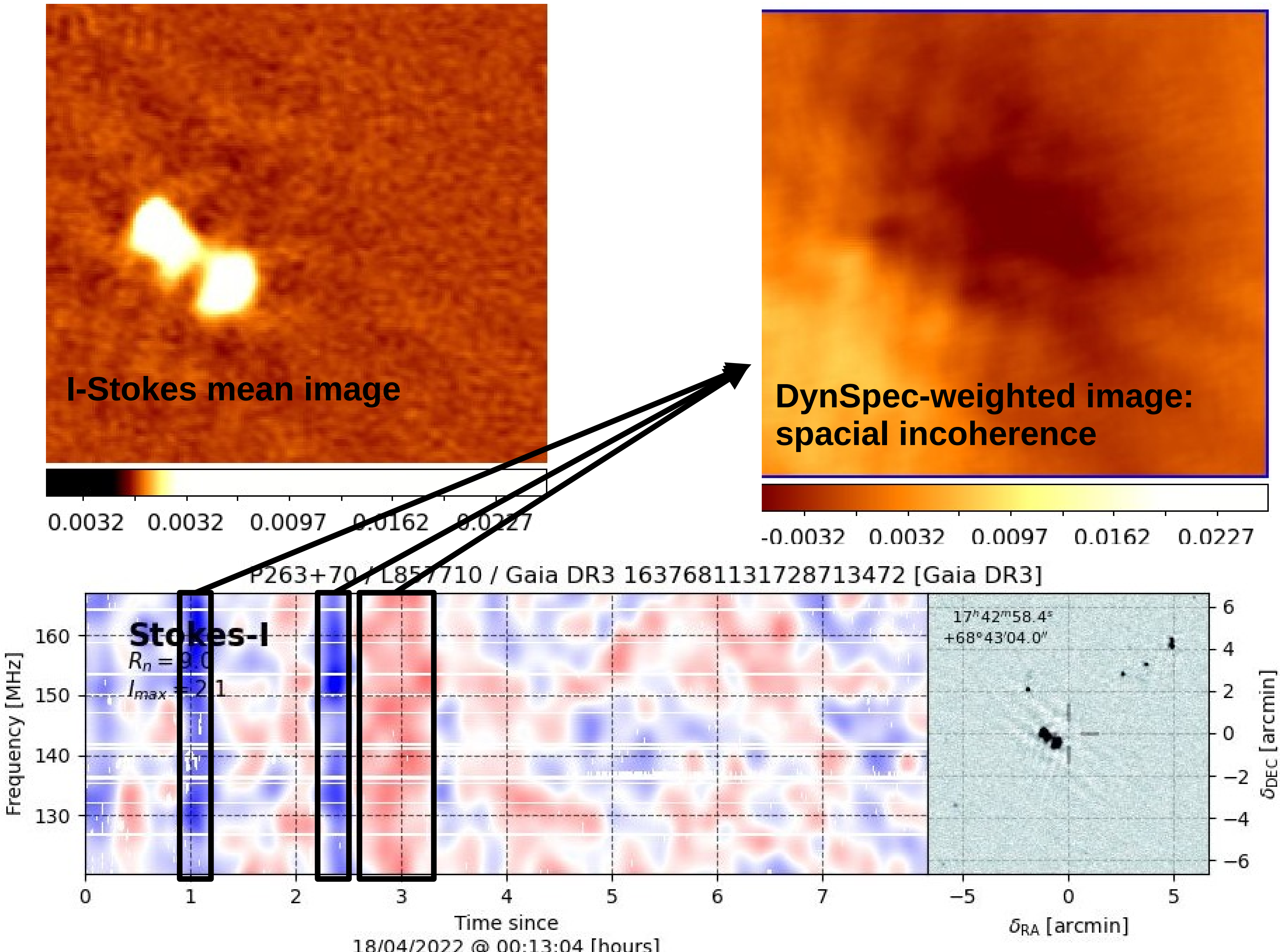


How do we know if an emission is real?
Is it spacially coherent?



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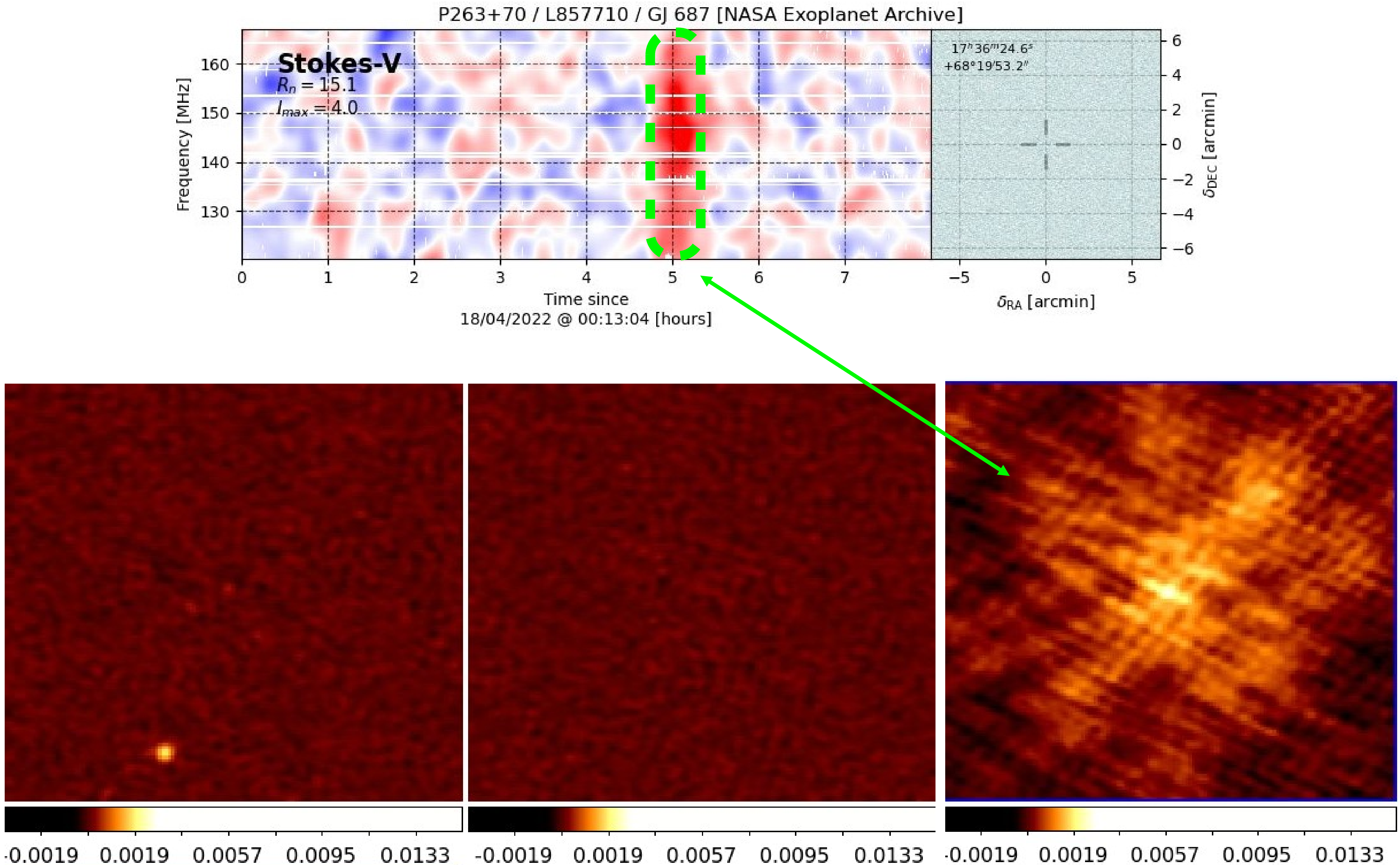


Stokes I (8h x 50 MHz) Stokes V (8h x 50 MHz) Stokes V (SNR > 2)

LOFAR's exoplanetary radio burst

GJ 687 [exoplanet.eu] : M3.5V star (red dwarf), in double system

$d = 4.5$ pc, $T_{corona} = 3413 \pm 28$ K, $M = 0.41\ M_\odot$, $R = 0.42\ R_\odot$

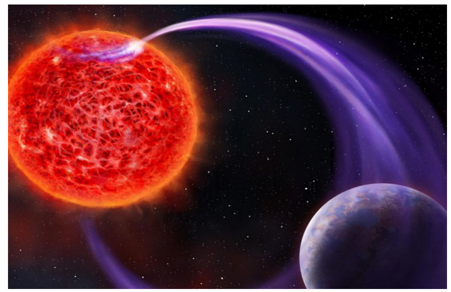
2 planets (radial velocity technique):

- GJ 687b : $a = 0.16$ AU, $e=0.17$ ($P=38.1$ days), $M\sin(i) = 0.054\ M_J$
- GJ 687c : $a = 1.16$ AU, $e=0.4$ ($P=728$ days), $M\sin(i) = 0.05\ M_J$

} ~ Neptune (conservative) ($R_P \sim 25000$ km)

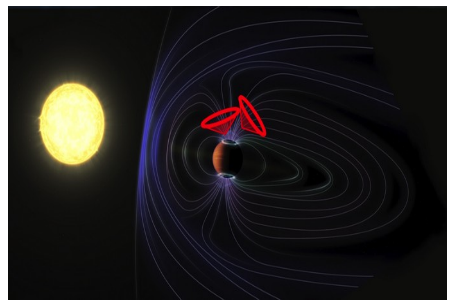
$S = 2$ mJy $\rightarrow$ $T_B = S\, \lambda^2\, d^2 / (k\, \pi\, R^2) = 10^{13\text{-}14}$ K

coherent radiation process : Cyclotron Maser Instability ?



$\rightarrow$ $P = S\, \Omega\, d^2\, \Delta f \sim 9\ 10^{12}$ W

with $\Omega = 0.16$ sr for SPI, and $\Delta f \sim 150$ MHz



$P \sim 9\ 10^{13}$ W

$\rightarrow$ with $\Omega = 1.6$ sr for a full auroral oval

(but requires $B_P \geq 58$ G)

LOFAR's exoplanetary radio burst

GJ 687 star: $B_\odot$ = 1-5 kG, V = 50 - 100 km/s, N ~ 100 x Solar Wind

[Afram & Berdyugina, 2019; Wood et al., 2021; Villadsen and Hallinan, 2019]

Innermost planet GJ 687b :

$R_{obstacle} = R_P$ (if ~unmagnetized) to 14 R_P (magnetosphere with $B_P \sim 58$ G)

→ predicted $P_{radio} = \beta\, V\, B^2\, \pi\, R_{obstacle}^2 / \mu_0 = 10^{10\text{-}13}\, (R_{obstacle} / R_P)^2$ W

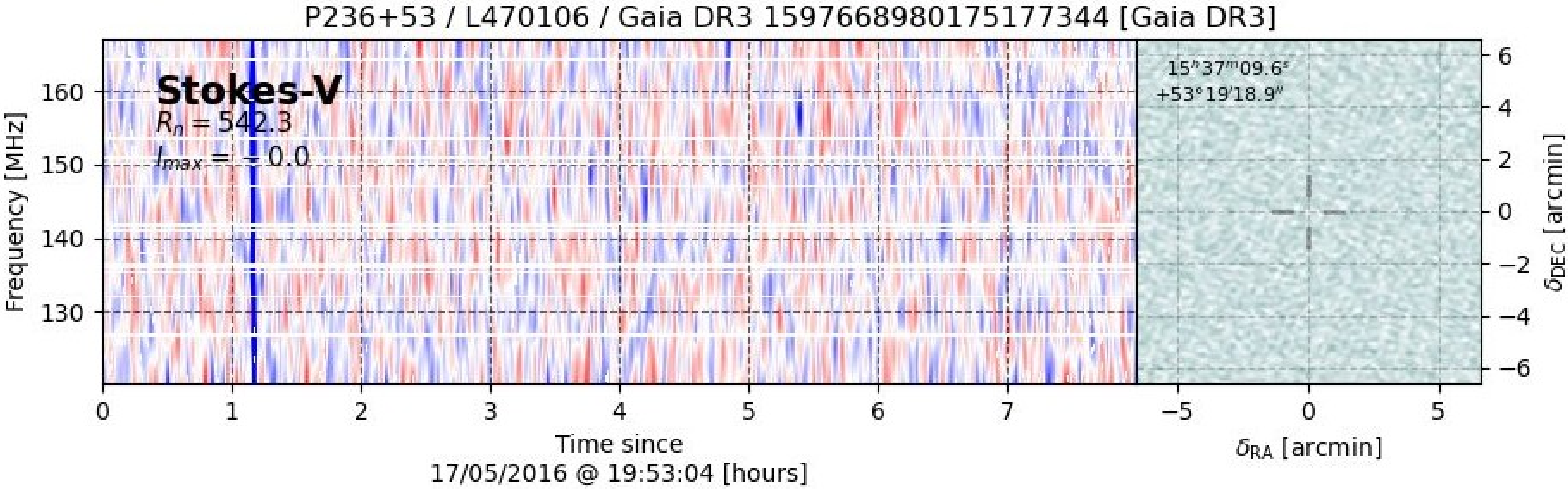
[Zarka, 2007; Zarka et al., 2018]

→ ~ **consistent with detected power even for an unmagnetized Neptune**

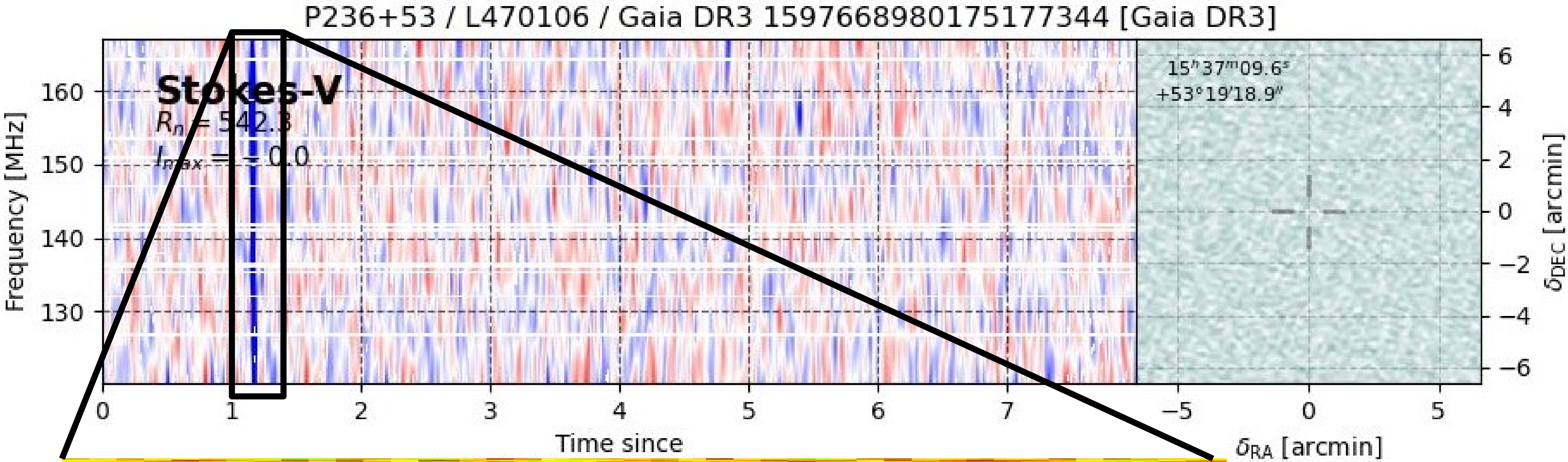
- Stellar or SPI (Star/Planet Interaction) / planetary emission ?

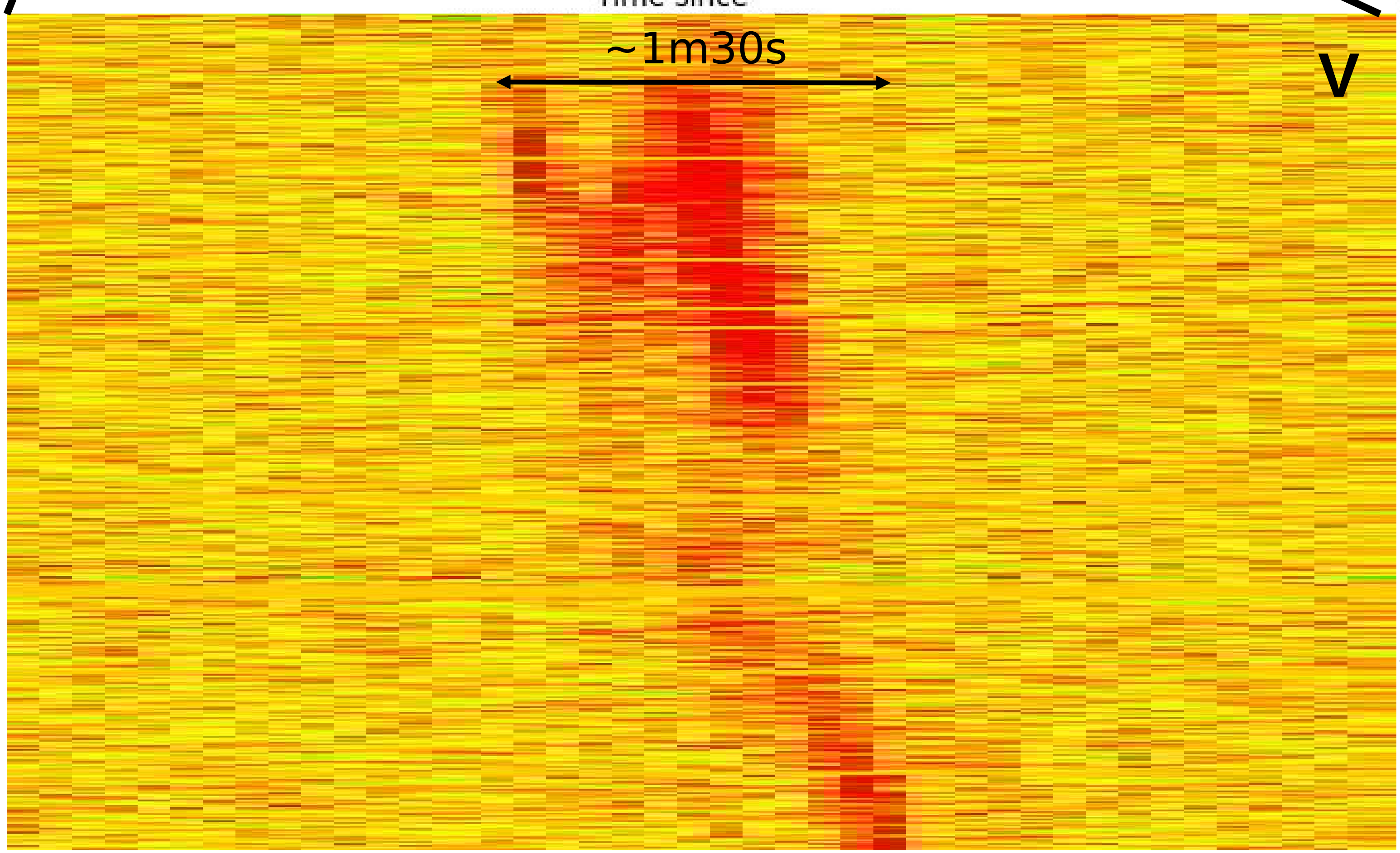
- Definitive proof = (polarized) radio signal modulated by orbital period

→ need for follow-up observations



P236+53 / L470106 / Gaia DR3 1597668980175177344 [Gaia DR3]
Stokes-V
$R_n = 542.3$
$I_{max} = -0.0$
Frequency [MHz]
Time since
17/05/2016 @ 19:53:04 [hours]
15^{h}37^{m}09.6^s
+53°19′18.9″
$\delta_{\rm DEC}$ [arcmin]
$\delta_{\rm RA}$ [arcmin]



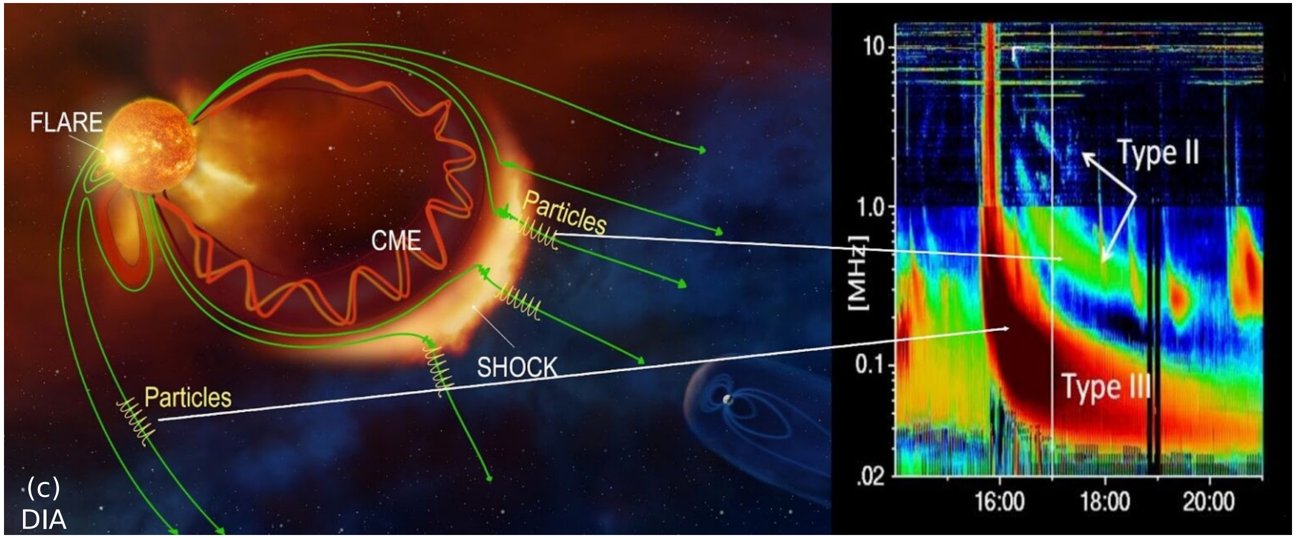


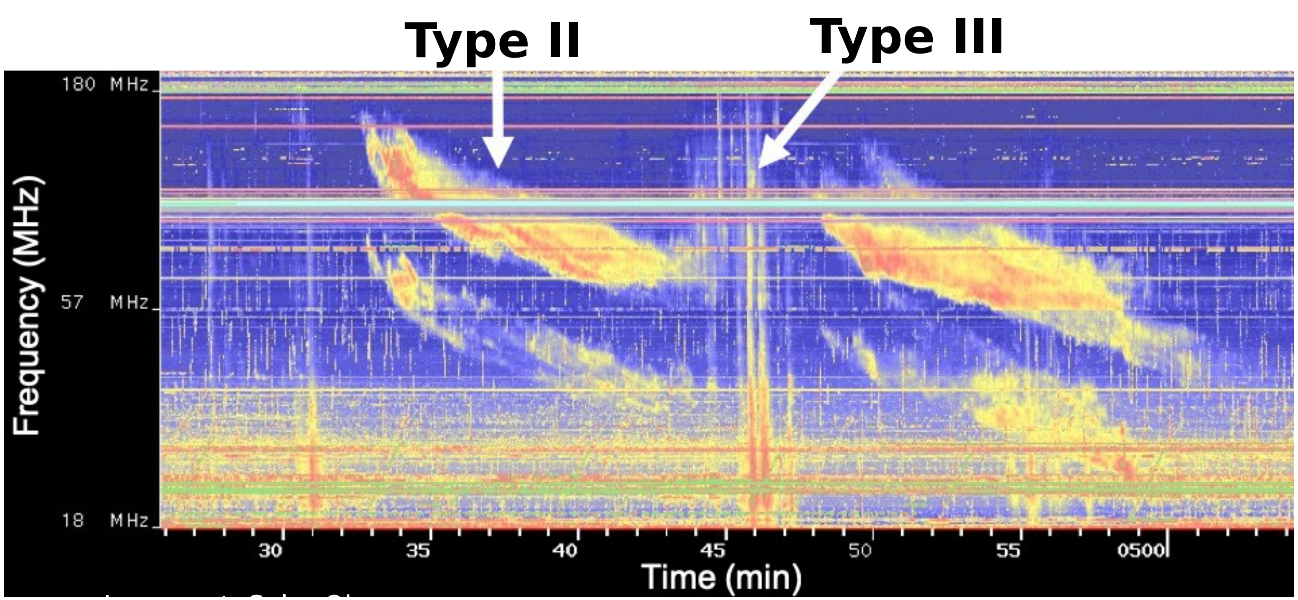
Rosa Keers (with
Joe Callingham)
had spoted this one
by eye too last year

Solar Type II & III bursts

- **Type II** = shock due to super-Alfvénic CME through solar corona (V = 500-3000 km/s) → electron acceleration
- **Type III** = electron beam through solar corona (V ~ 0.1-0.3c = 30000-100000 km/s)

in both cases → Langmuir waves at fpe → conversion to radio waves at f_{pe} or 2 f_{pe} (f_{pe} [kHz] = 9 $N_e^{1/2}$ [cm^{-3}])

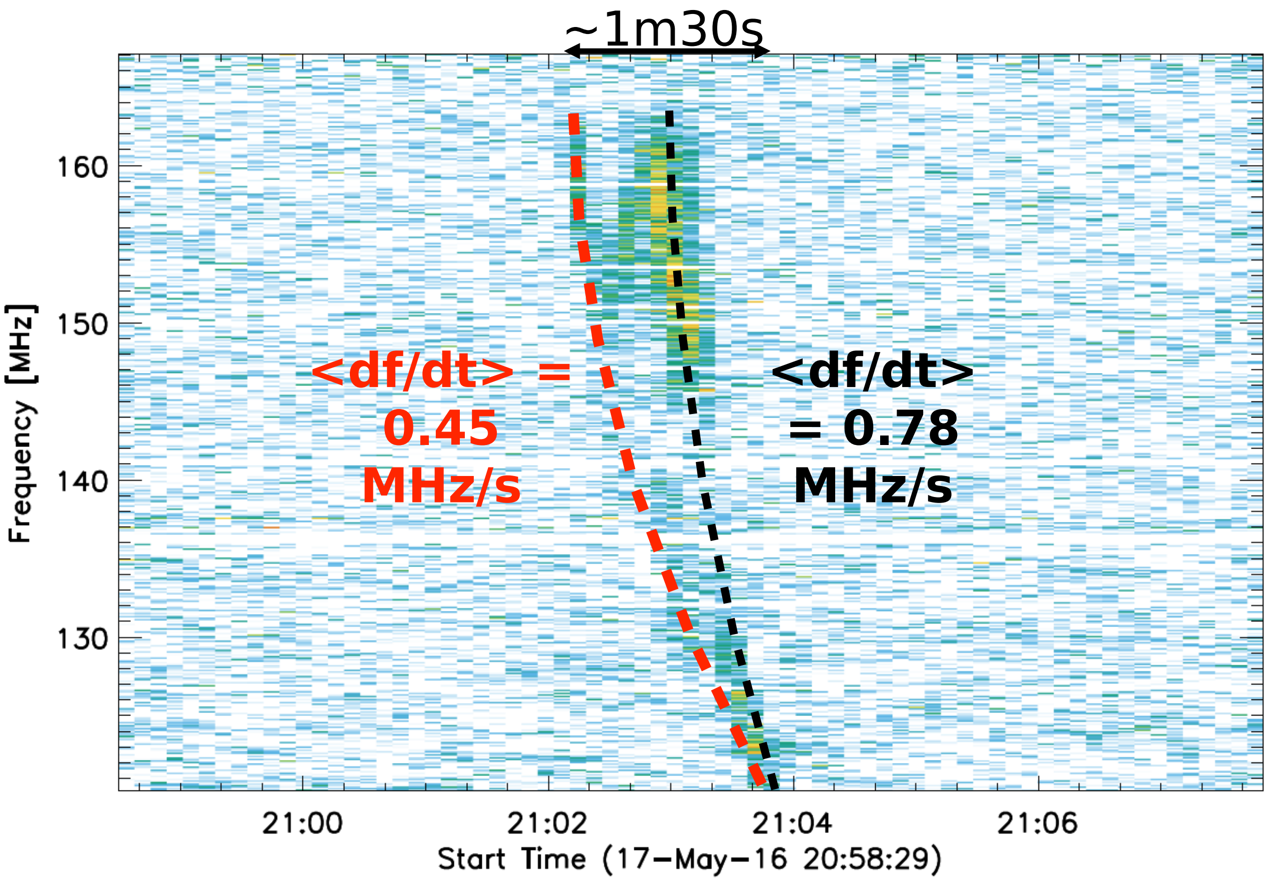


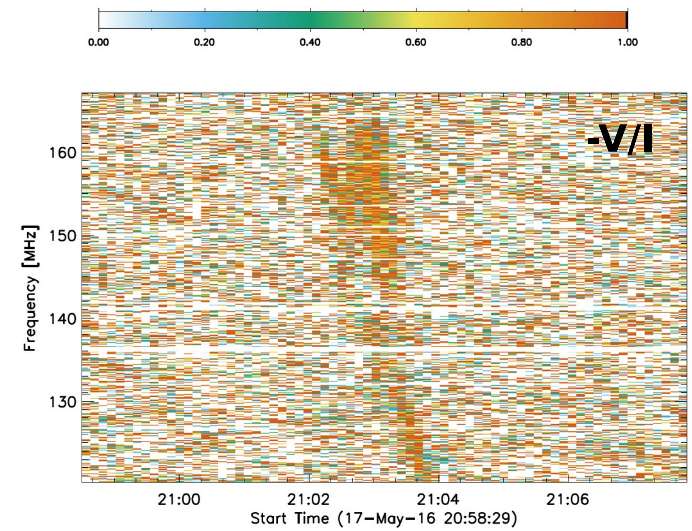


LOFAR's stellar burst

StKM 1-1262 (Gaia DR2) : M0 star (red dwarf)

d = 41 pc, age = 10.5 Gyr, T_{corona} ~ 3800 K, M = 0.6 $M_\odot$, R = 0.7 $R_\odot$





Preliminary analysis by:
Hamish Reid, Philippe Zarka,
and Joe Callingham

Corona in hydrostatic equilibrium (approximation): $N_e = N_o \exp(-z/H)$

Sun: $N_o \sim 3\ 10^8\ cm^{-3}$, $H \sim 10^8$ m

[Villadsen and Hallinan, 2019]

Red dwarf: N_o ~ x100, H ~ 0.5-1.2 10^8 m

$f \sim f_{pe}$ (V/I ~ -1) $\Rightarrow df/dt = -f\ V / 2H \Rightarrow |V| = (2H/f)\ df/dt$ = 400 - 1300 km/s $\Rightarrow$ **Type II** !

Conclusion

- The project is now mature and we have detected tens of strong individual signals

- There is also a strong statistical signal

  -> We might conclude on SPI/magnetospheric emission vs stellar emission

- Each individual detection provide physical information on the source (cf above)

- Need for followup observation for orbital period / rotation period

- Method is powerful and cheap – could be used as a bi-product of SKA surveys