Radio stars and exoplanets

Discovering the space weather of other worlds

Funded by the European Union

European Research Council
Established by the European Commission

Joseph Callingham

Head of the SKA Science Group, ASTRON

Assistant Professor, Leiden University

SKA Sweden Day, Gothenburg, Sweden – 11th of September 2024

Olena Shmahalo/Quanta Magazine

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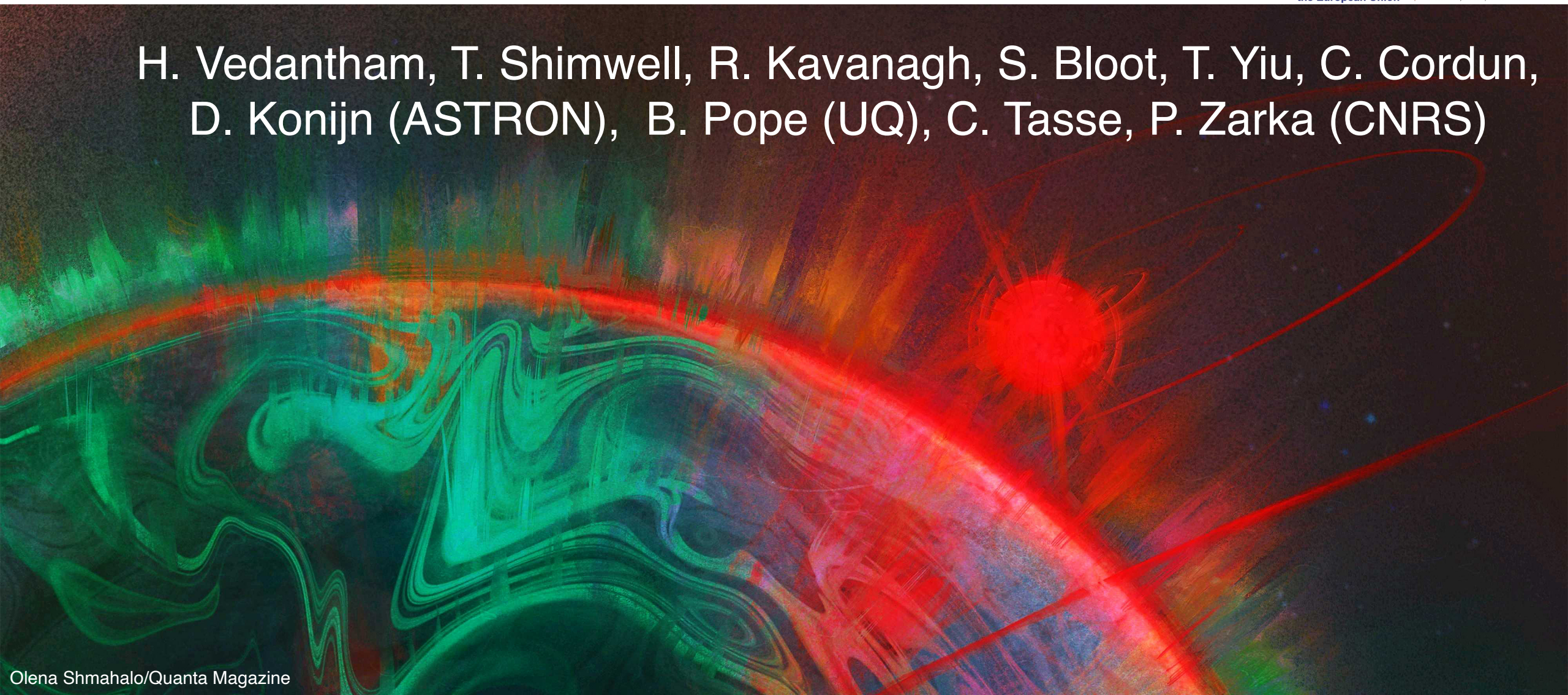
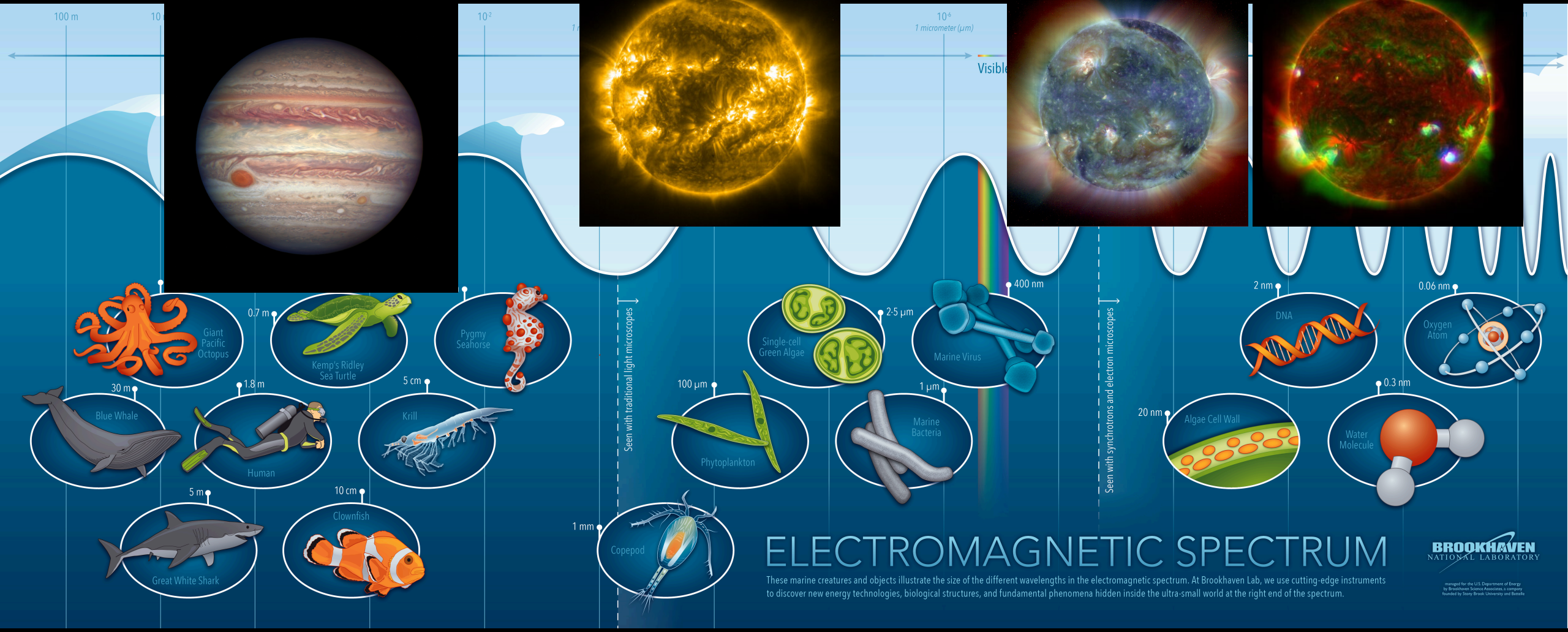
H. Vedantham, T. Shimwell, R. Kavanagh, S. Bloot, T. Yiu, C. Cordun,
D. Konijn (ASTRON), B. Pope (UQ), C. Tasse, P. Zarka (CNRS)



Olena Shmahalo/Quanta Magazine


100 m
10
10⁻²
1 micrometer (µm)
10⁻⁶
Visible
Giant Pacific Octopus
0.7 m
Kemp's Ridley Sea Turtle
Pygmy Seahorse
30 m
Blue Whale
1.8 m
Human
5 cm
Krill
5 m
Great White Shark
10 cm
Clownfish
Seen with traditional light microscopes
1 mm
Copepod
100 µm
Phytoplankton
Single-cell Green Algae
2-5 µm
1 µm
Marine Bacteria
400 nm
Marine Virus
Seen with synchrotrons and electron microscopes
2 nm
DNA
0.06 nm
Oxygen Atom
20 nm
Algae Cell Wall
0.3 nm
Water Molecule
ELECTROMAGNETIC SPECTRUM
These marine creatures and objects illustrate the size of the different wavelengths in the electromagnetic spectrum. At Brookhaven Lab, we use cutting-edge instruments to discover new energy technologies, biological structures, and fundamental phenomena hidden inside the ultra-small world at the right end of the spectrum.
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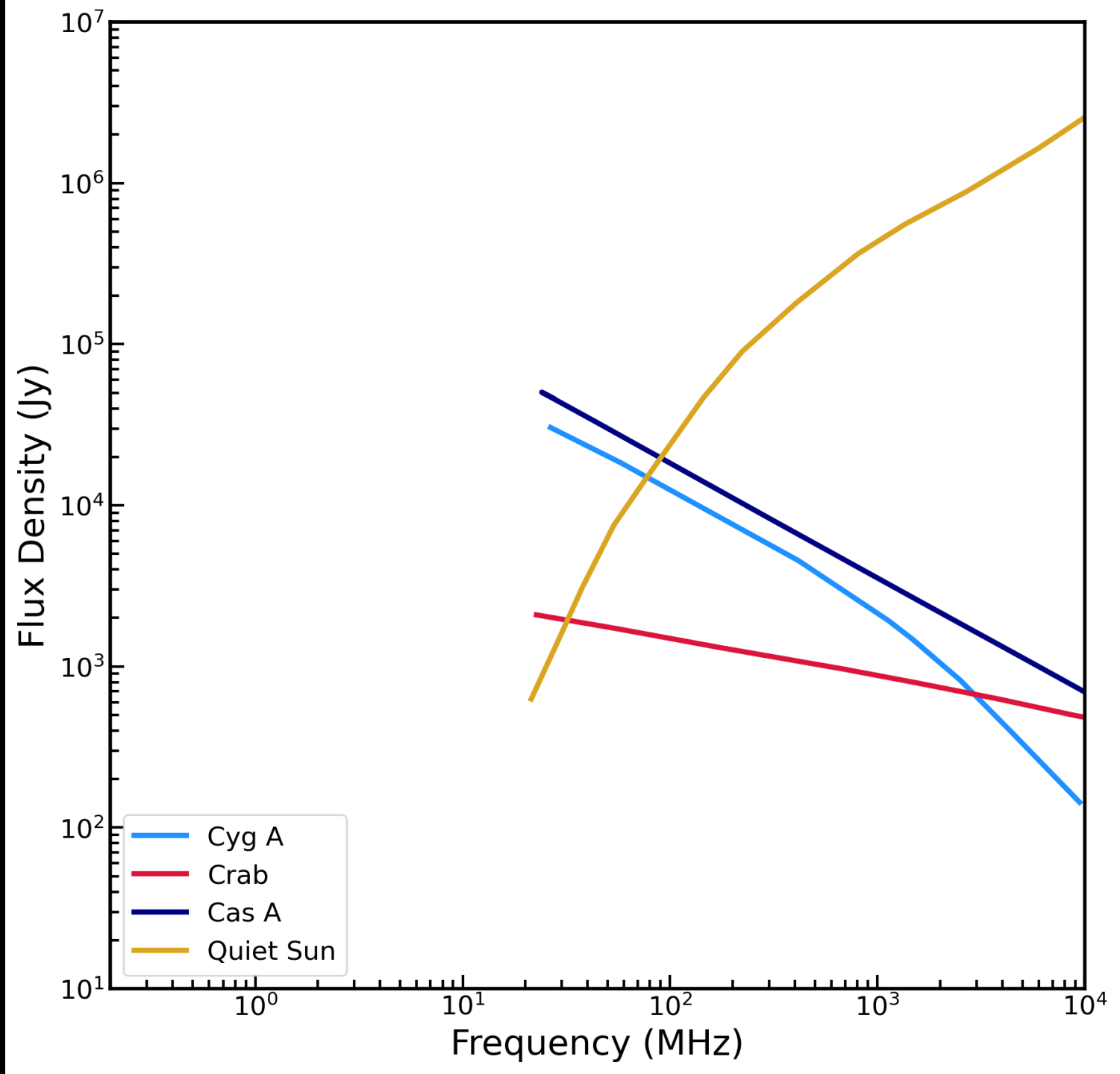
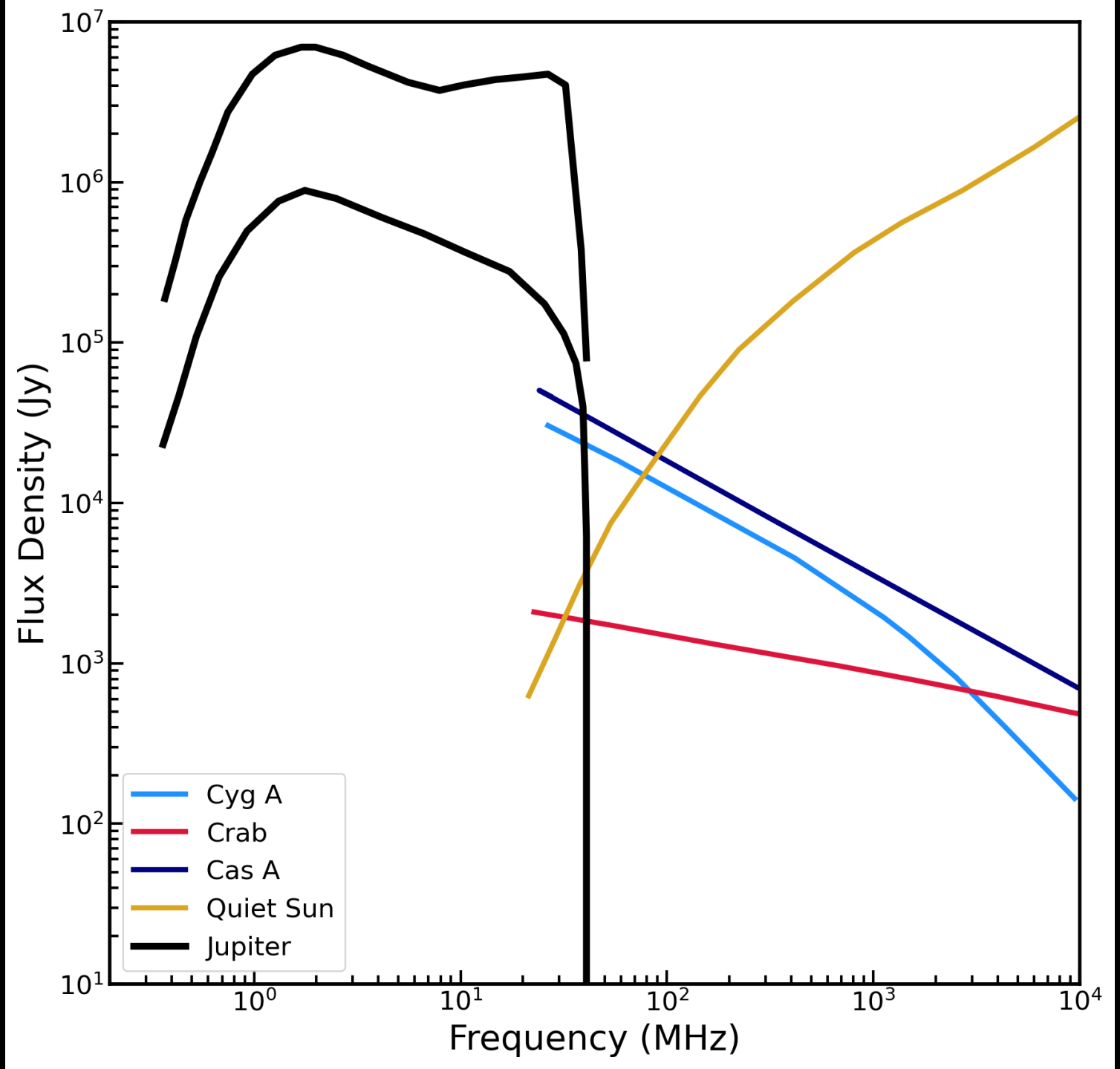
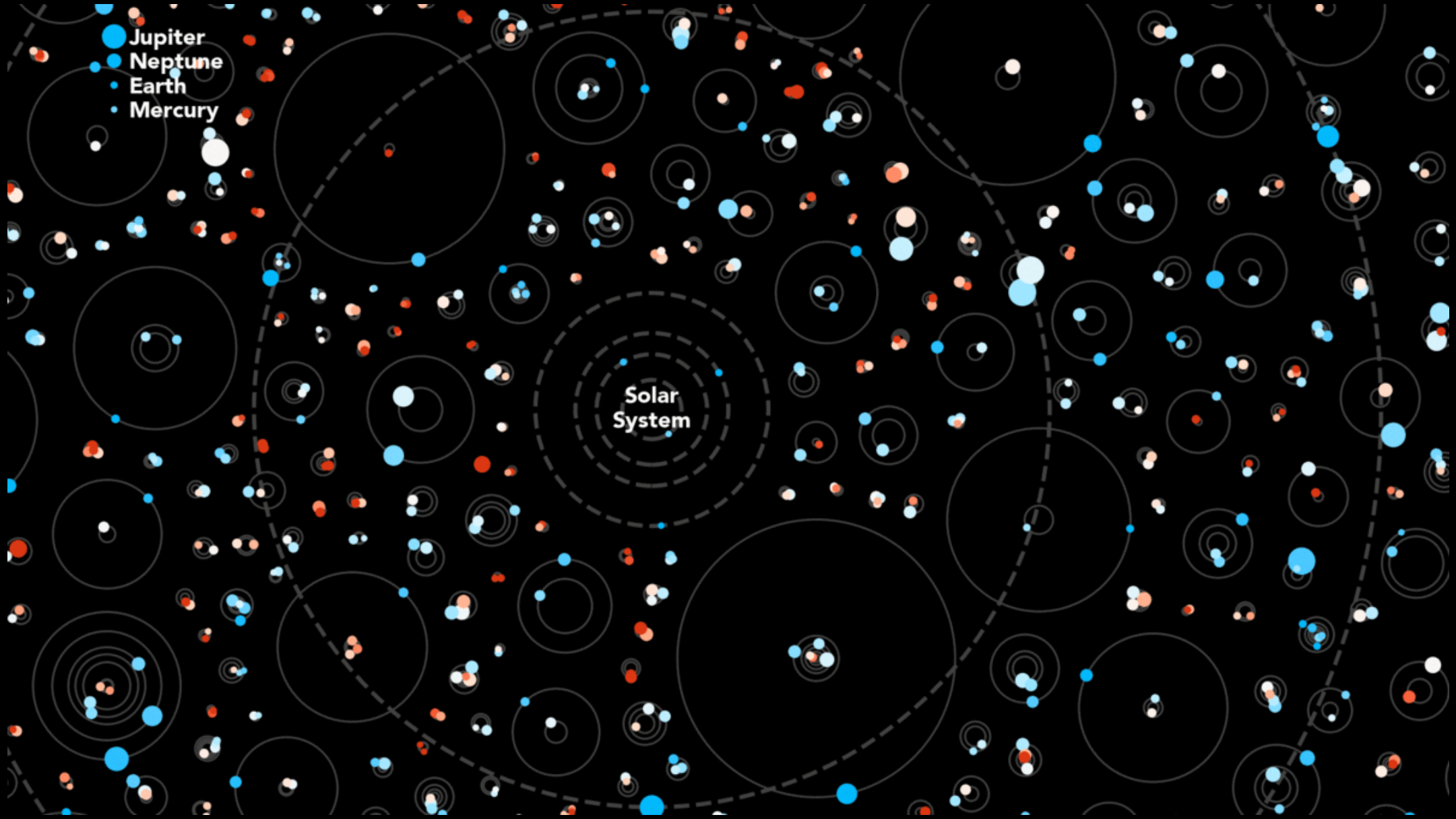


Modelled off Zarka (2007)

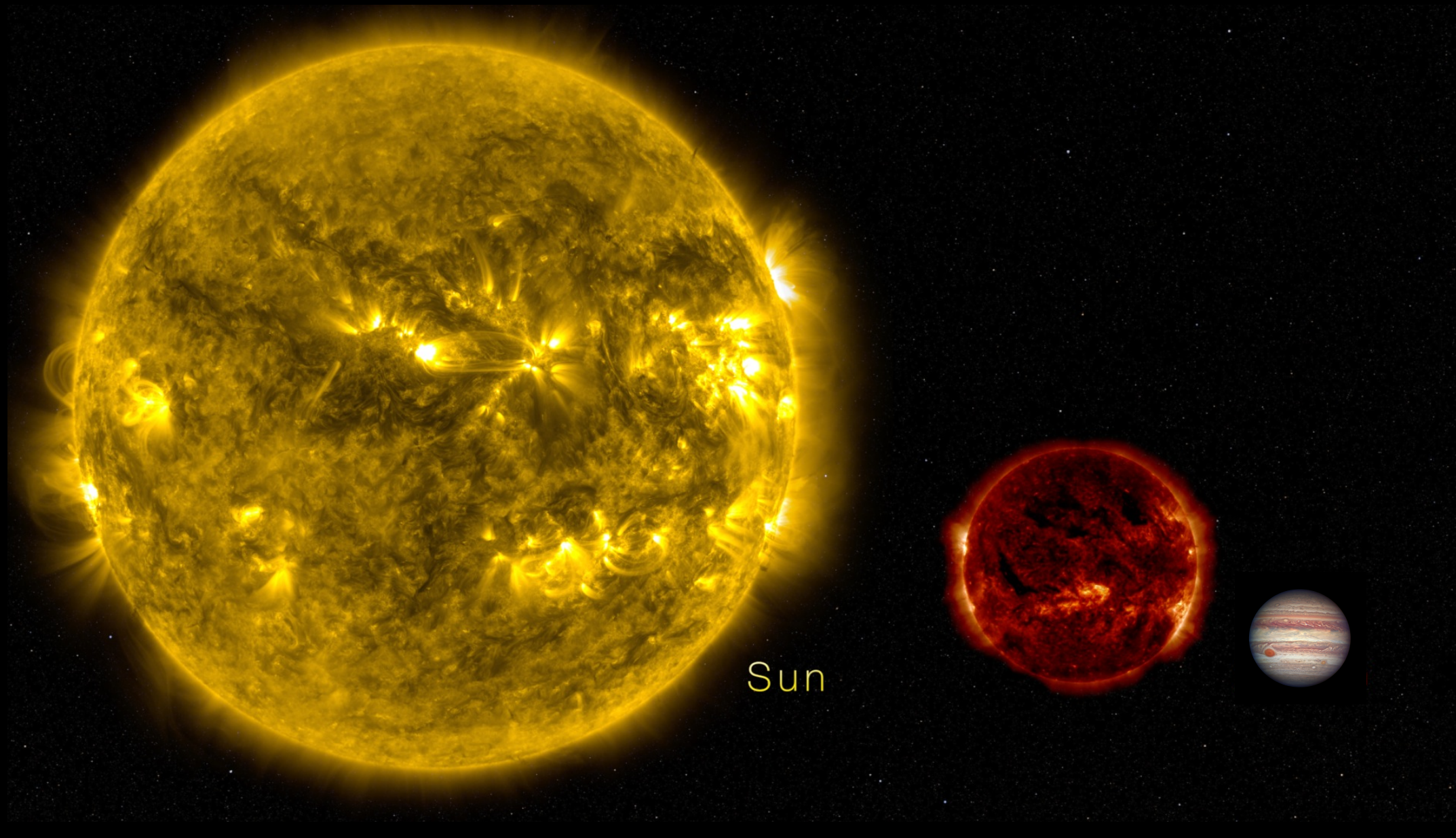


Modelled off Zarka (2007)

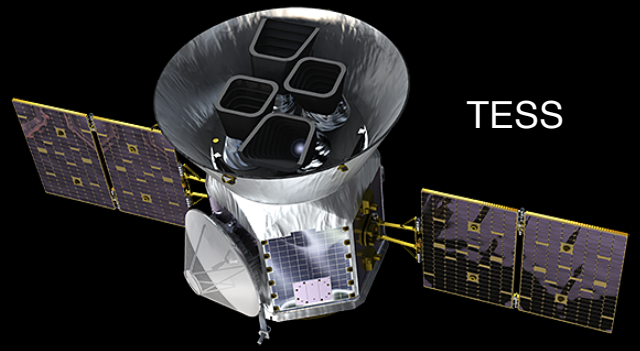
Exoplanet population explosion…



… around the most common stars in the Galaxy…



Population explosion around M dwarfs



M dwarf System

b c d e f g h

Enlarged 25x

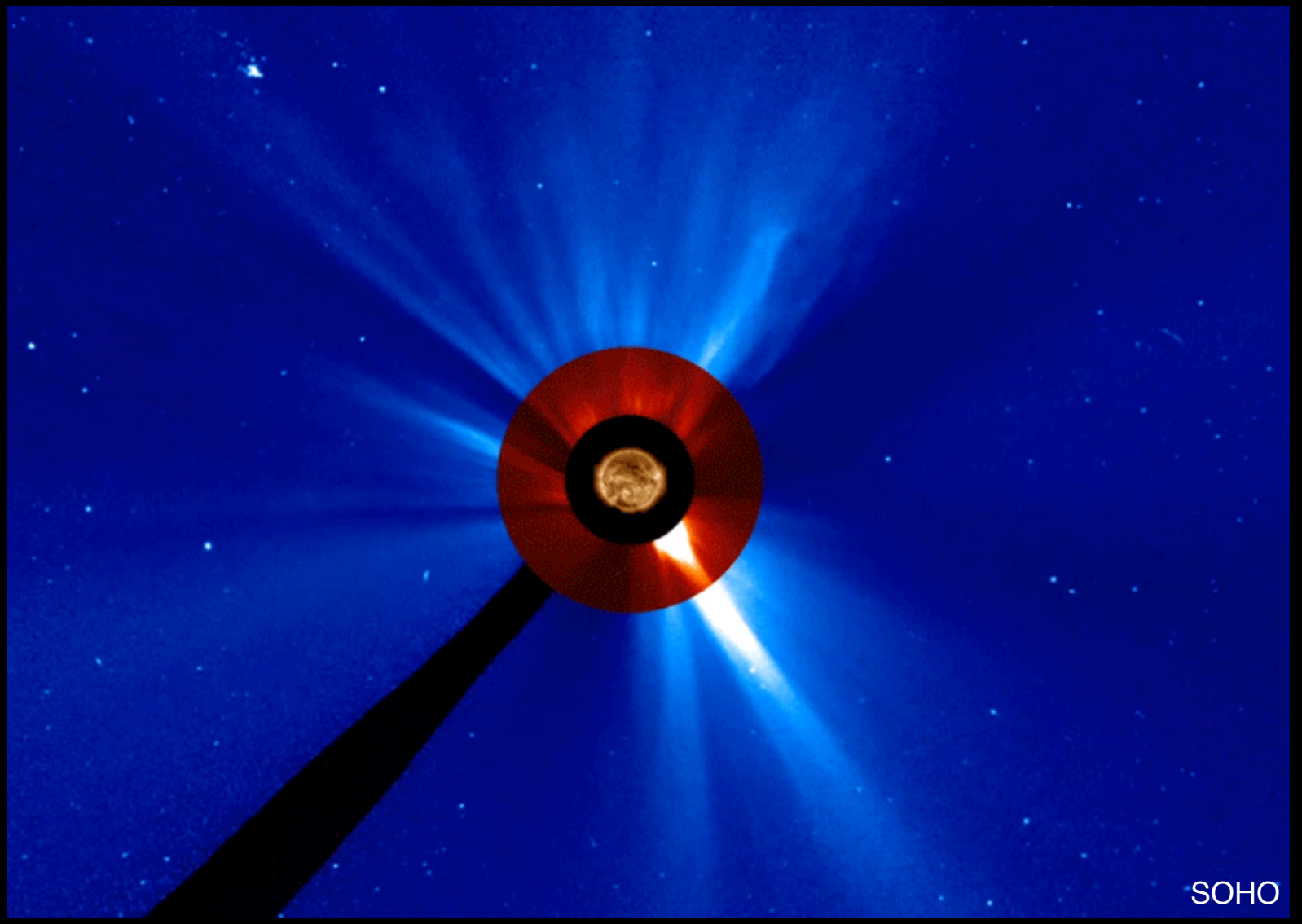
Inner Solar System

Mercury Venus Earth Mars

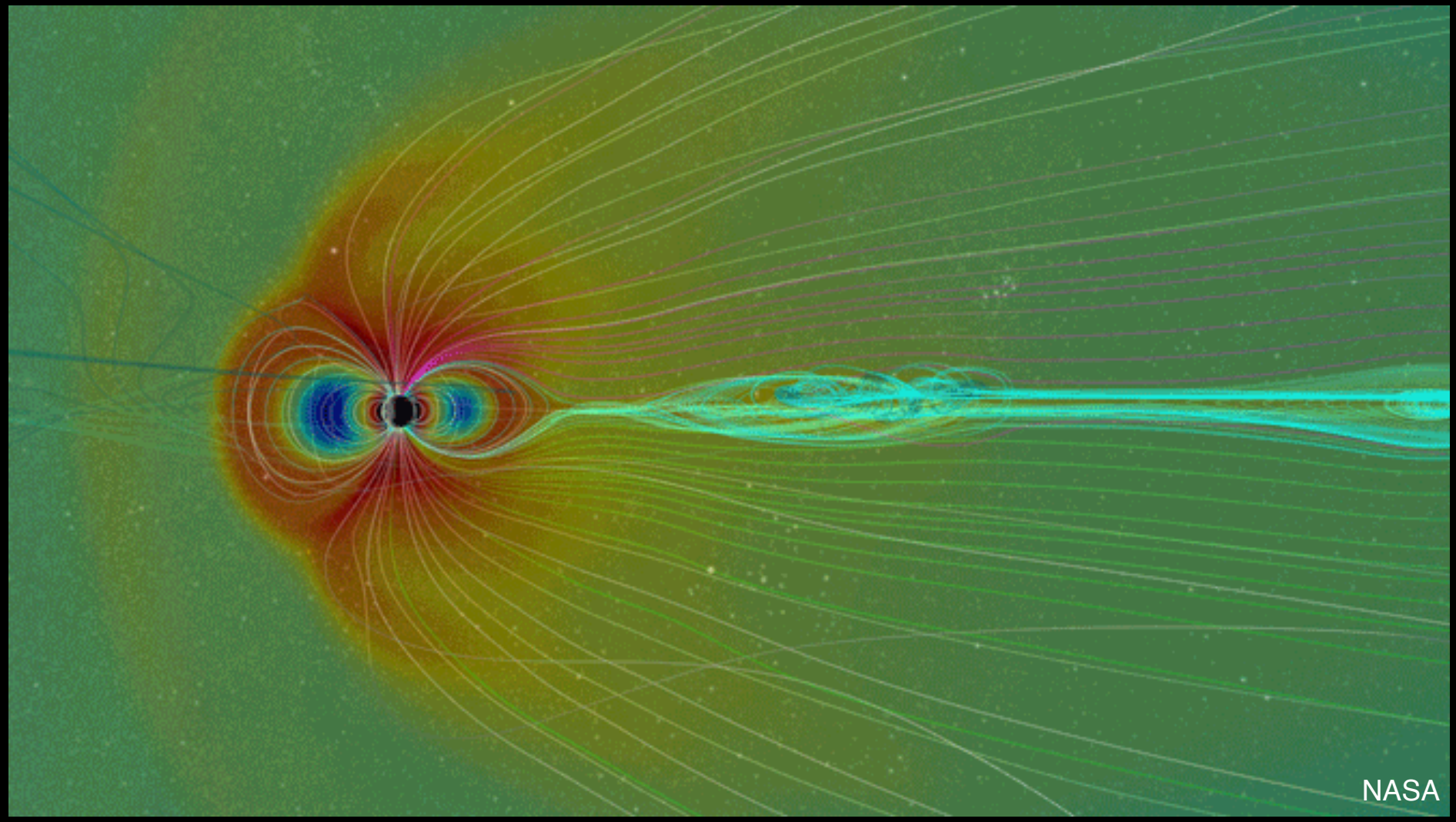
NASA

Illustration

Sometimes a star is not a great host…



… and our magnetic field protects us

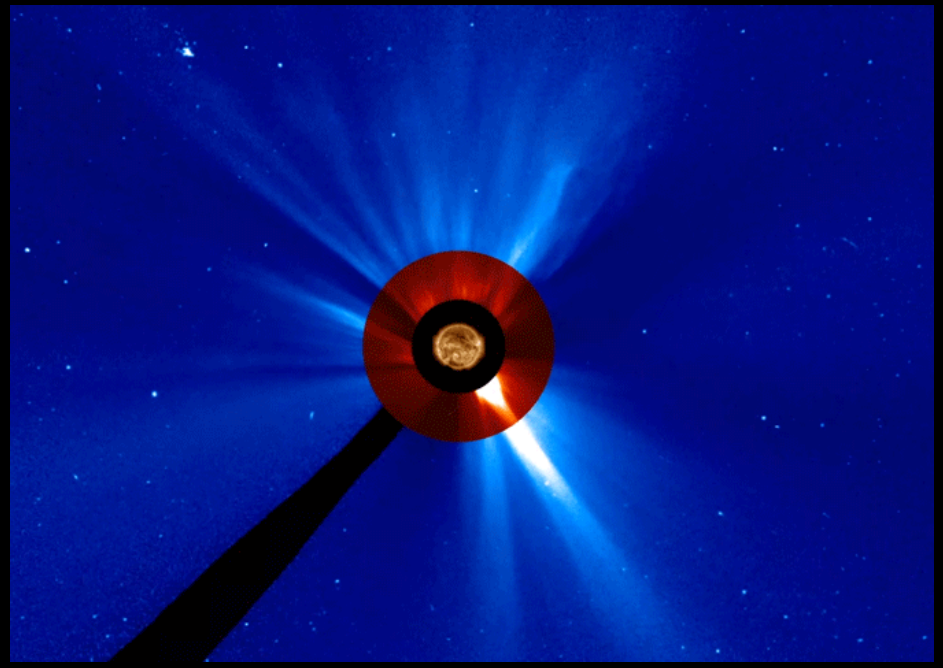


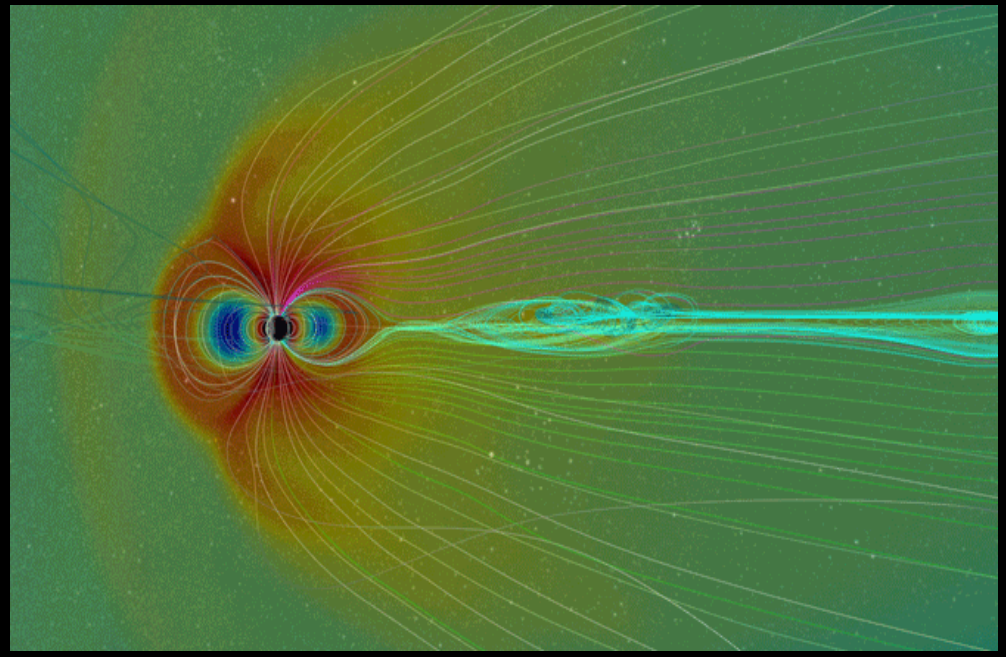
e.g. Khodachenko et al. (2007), Tsurutani et al. (2014)
etc

Unknown extrasolar space weather conditions

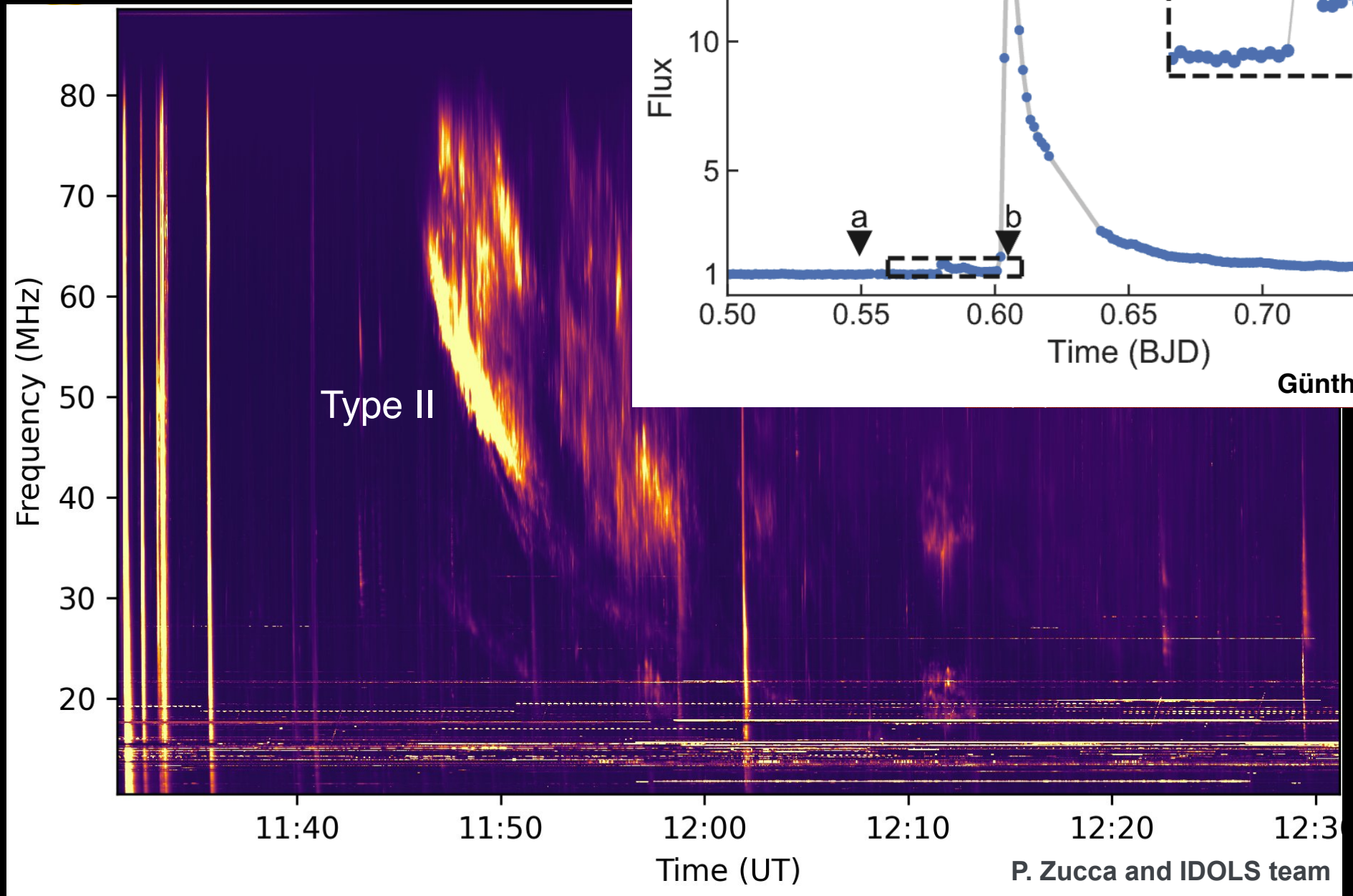
A CME has not been unambiguously detected outside our Solar System

We have not directly measured the magnetic field of an exoplanet





How can radio help?

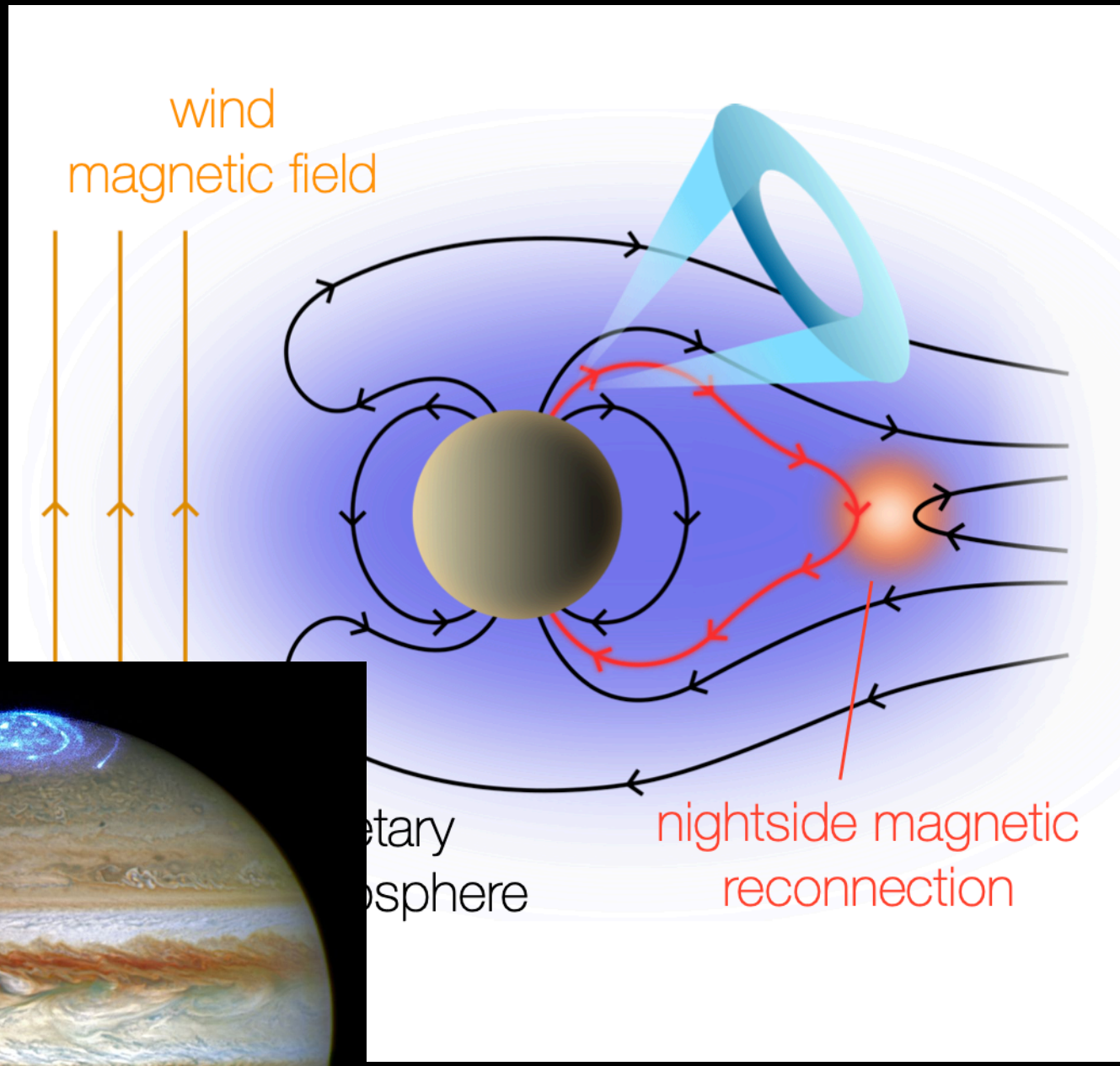


P. Zucca and IDOLS team

Günther et al. (2020)

Radio aurora via two mechanisms

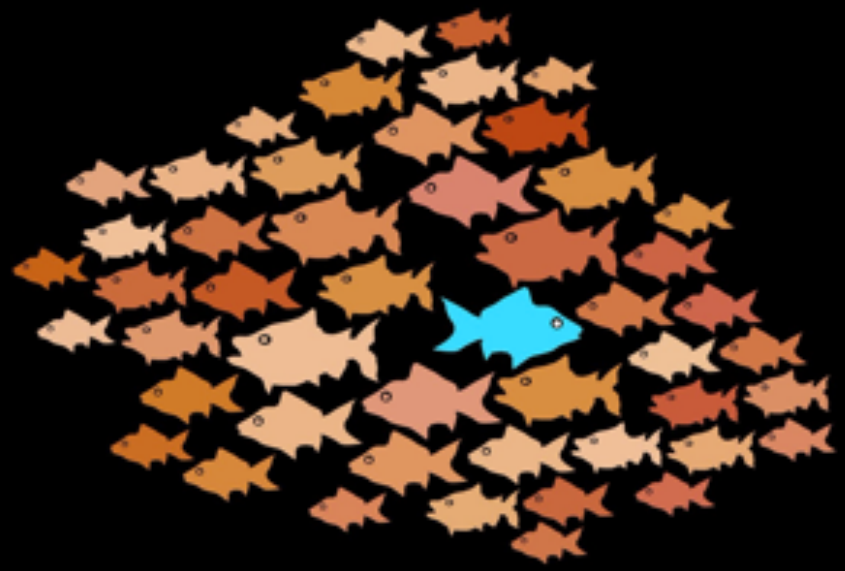
Callingham et al. (2021a,b)



Callingham et al. (2024)

Detection technique

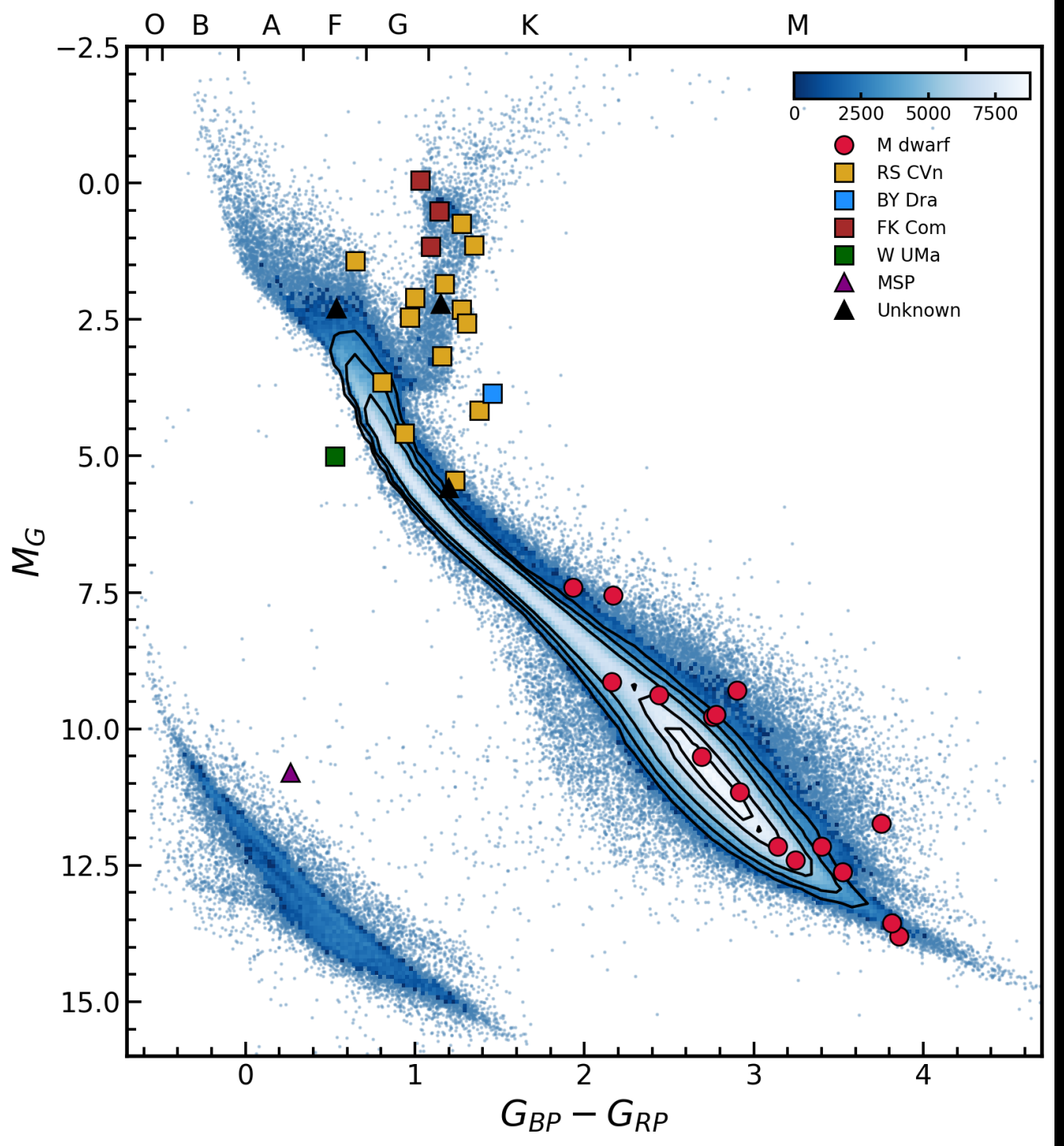
1. Blind Stokes V source finding in low resolution (20”) images (excluding near >125 mJy sources) of 4 sigma sources
2. Association with Stokes I source (within 5” of Stokes V) to minimise statistical fluctuations
3. Association with a Gaia source that has a parallax / parallax_error >= 3
4. Bonus: time variability – AGN variability at low-frequencies quite low (Bell et al. 2018)



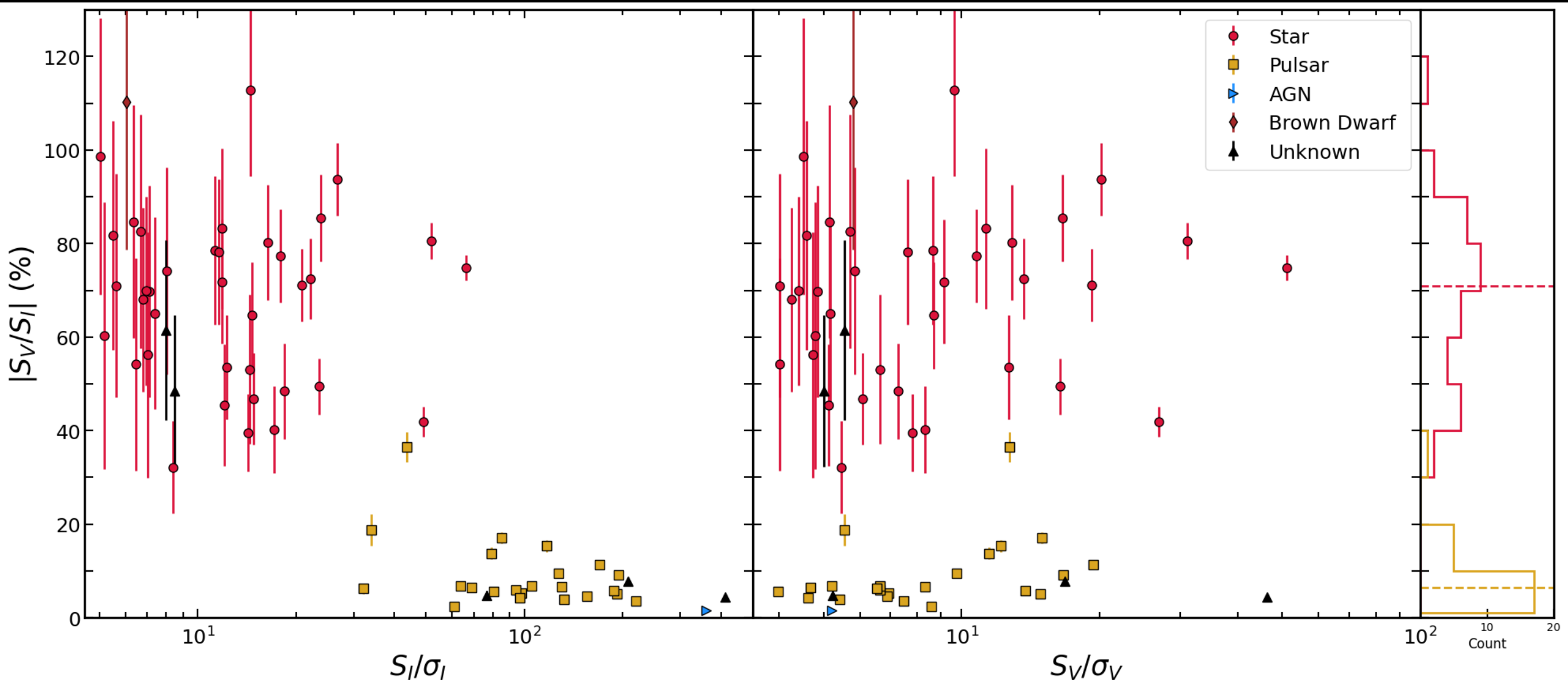
V-LoTSS

- Most sensivity widefield circularly-polarised survey ever conducted
- 68 sources detected in ~25% of the sky. Largely split in stars (M dwarfs, active stars, brown dwarfs), pulsars, and AGN.
- Expect 300+/-100 detections by end of survey
- Most interesting is an “isolated” F5 dwarf. Astrometric signal?
- Complimentary to Pritchard et al. (2022, 2023) and others

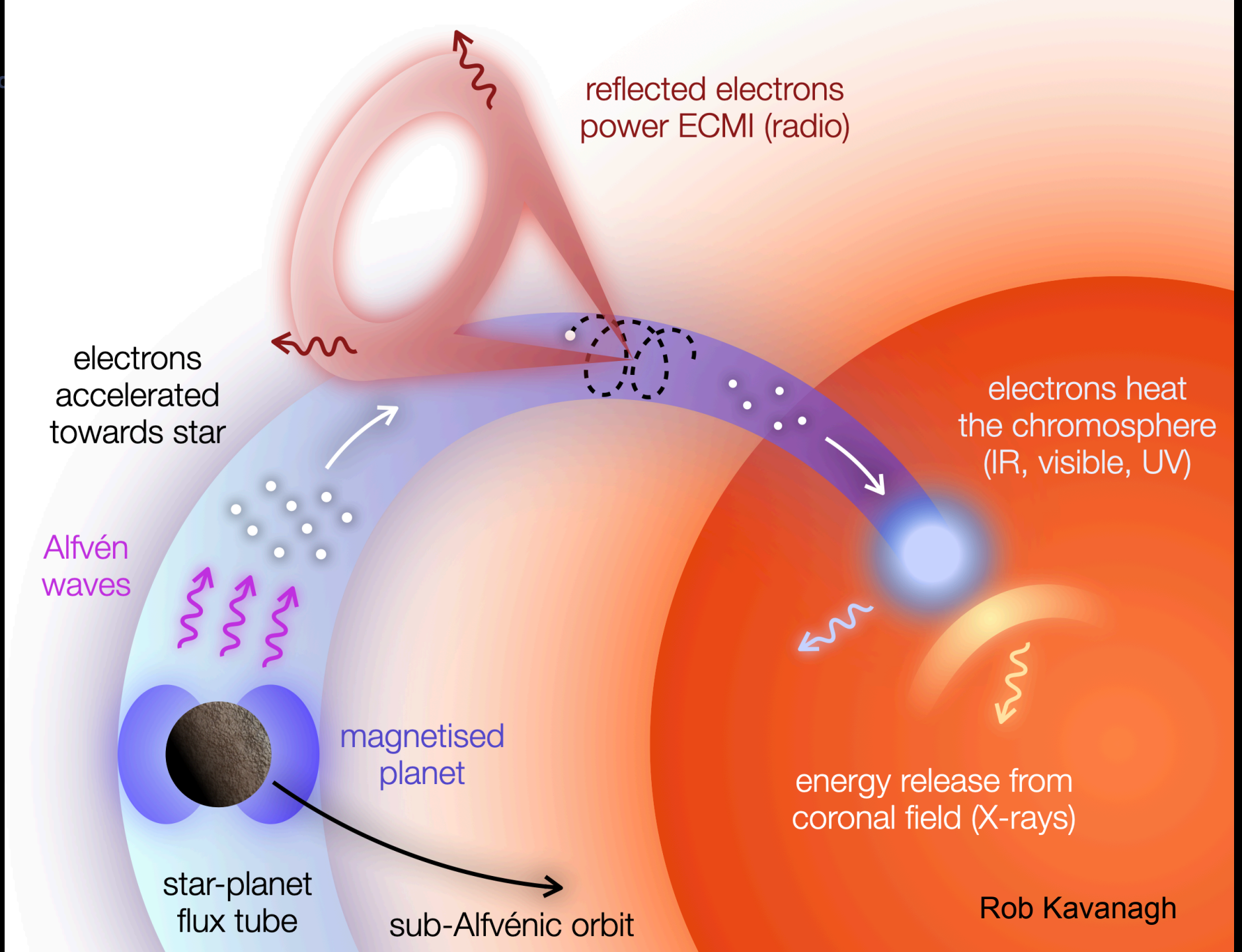
Callingham et al. (2023)



V-LoTSS

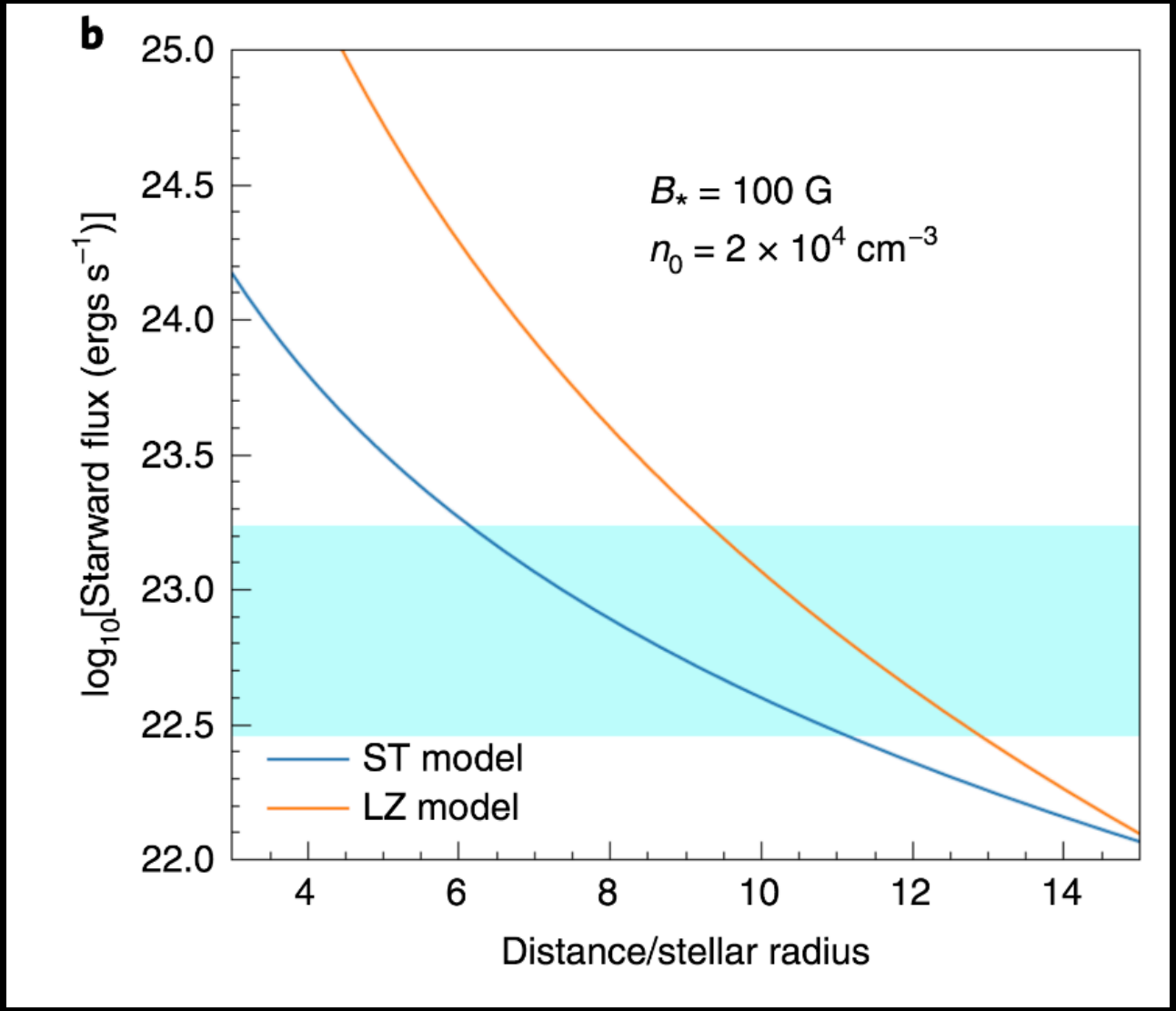

Star
Pulsar
AGN
Brown Dwarf
Unknown
$|S_V/S_I|$ (%)
S_I/σ_I
S_V/σ_V
Count

What is causing the radio emission in aurorae?



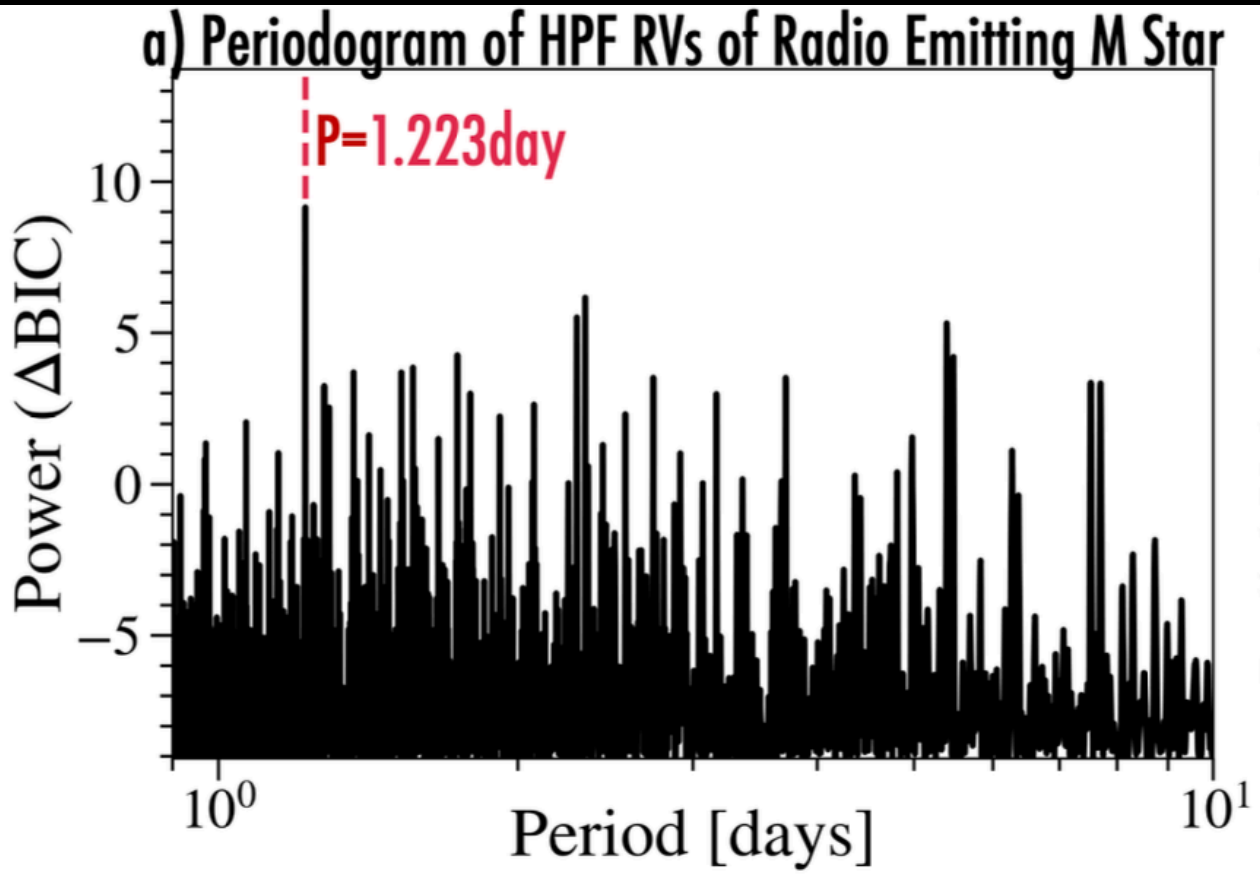
ECMI Fits the bill

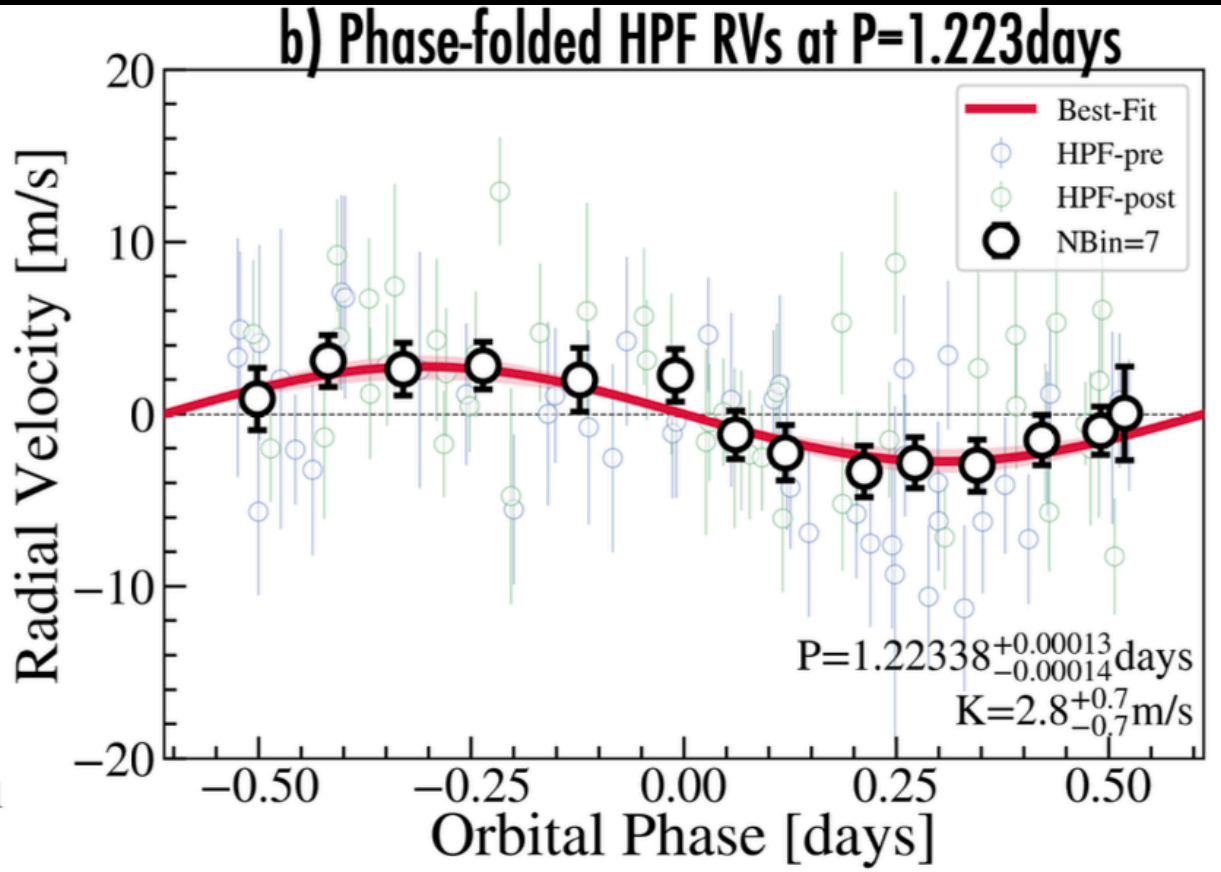
- Sub-alfvenic interaction with a planet – Earth-size planet in short period (up to ~1-5 day orbit) works



Turnpenney et al. (2018), Saur et al. 2013, Vedantham et al. (2020)

RV Detection?

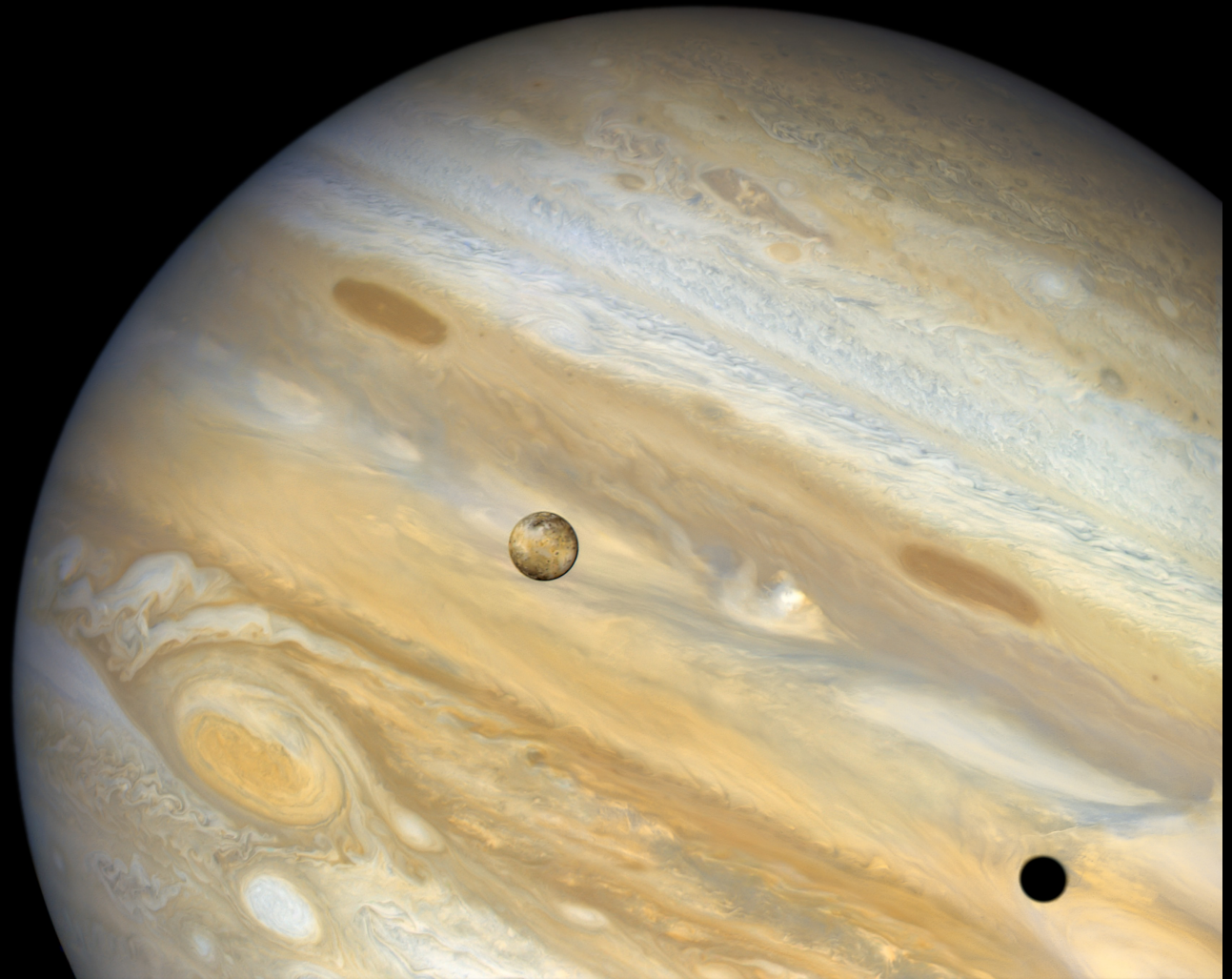




Stefansson et al.

So what? You have a few detections

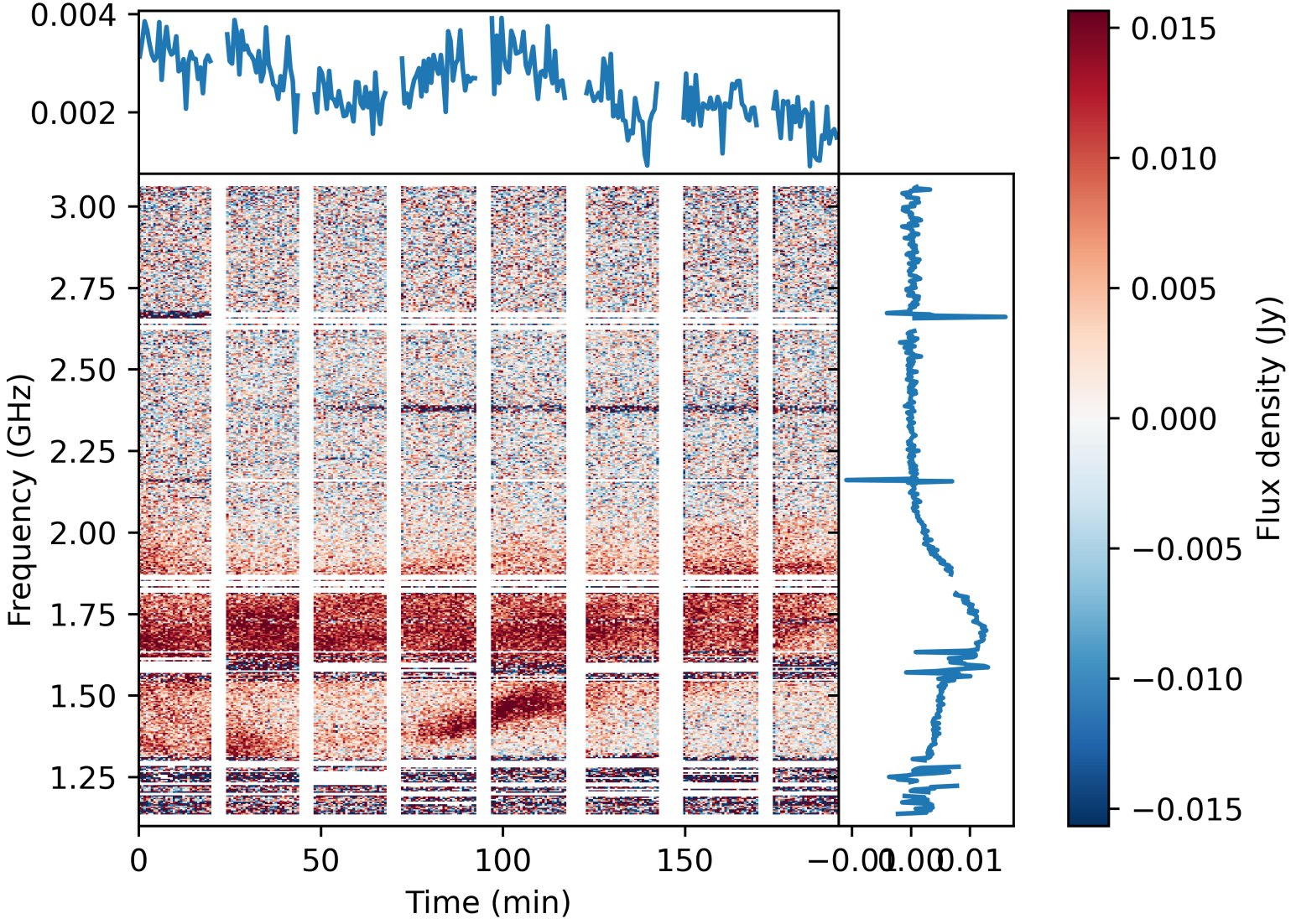
- High time-frequency resolution of the bursts
- Search for periodicity
- Exploiting the lowest frequencies



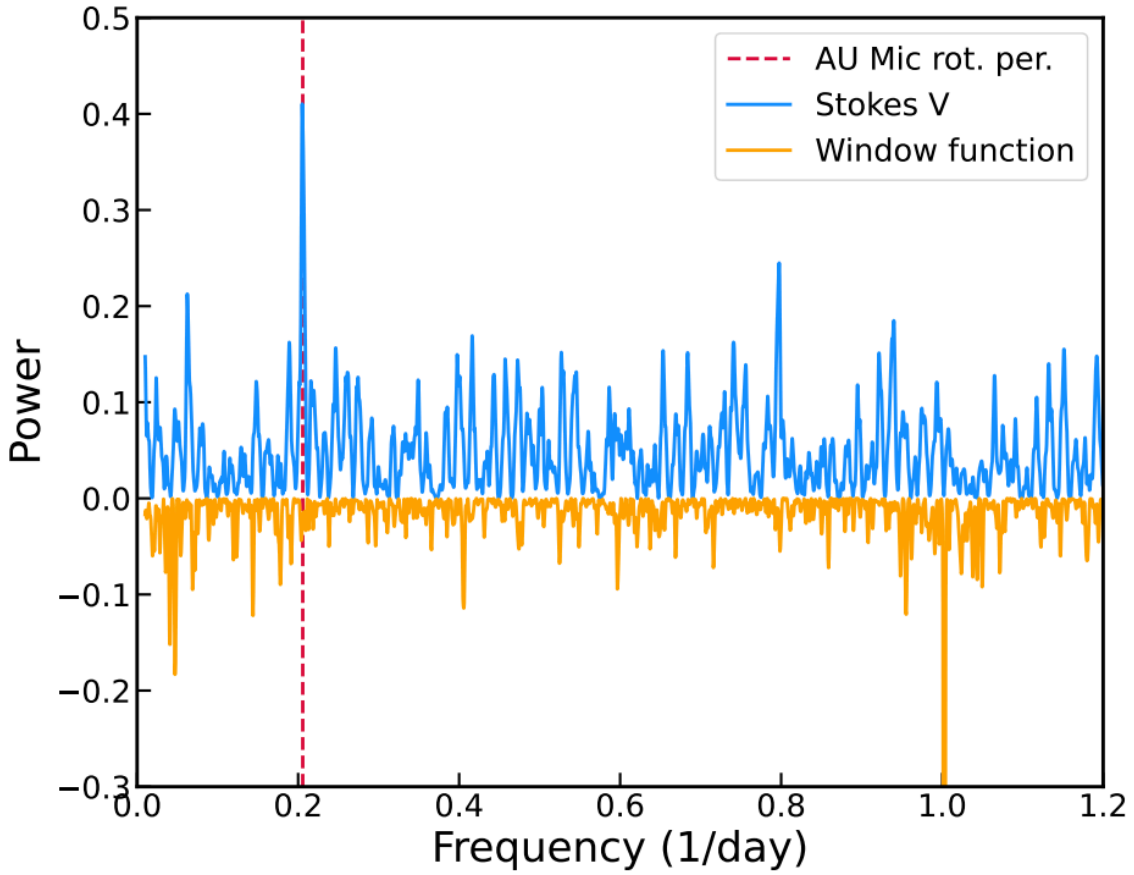
Periodicity Search and cut off in AU Mic (Bloot et al. 2024)

- Over 250 hours
- Complimentary to Villadesen et al. (2019)

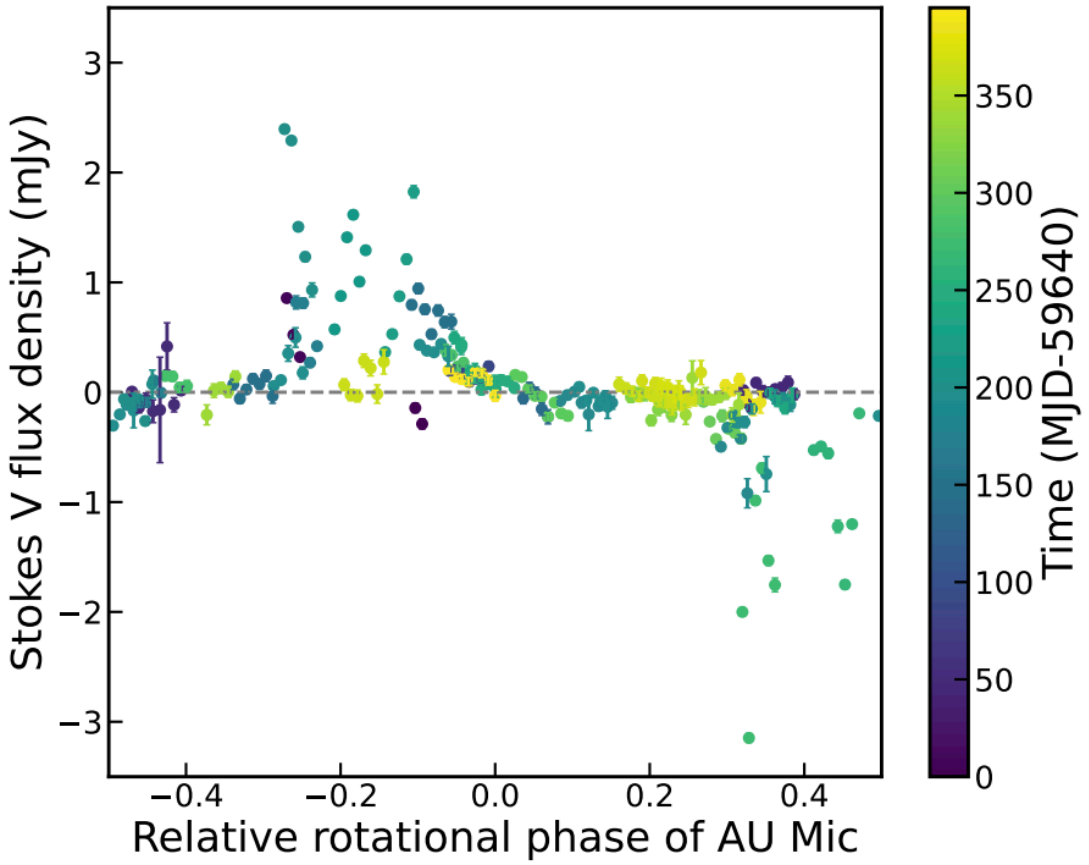
Sanne Bloot



Periodicity Search on AU Mic

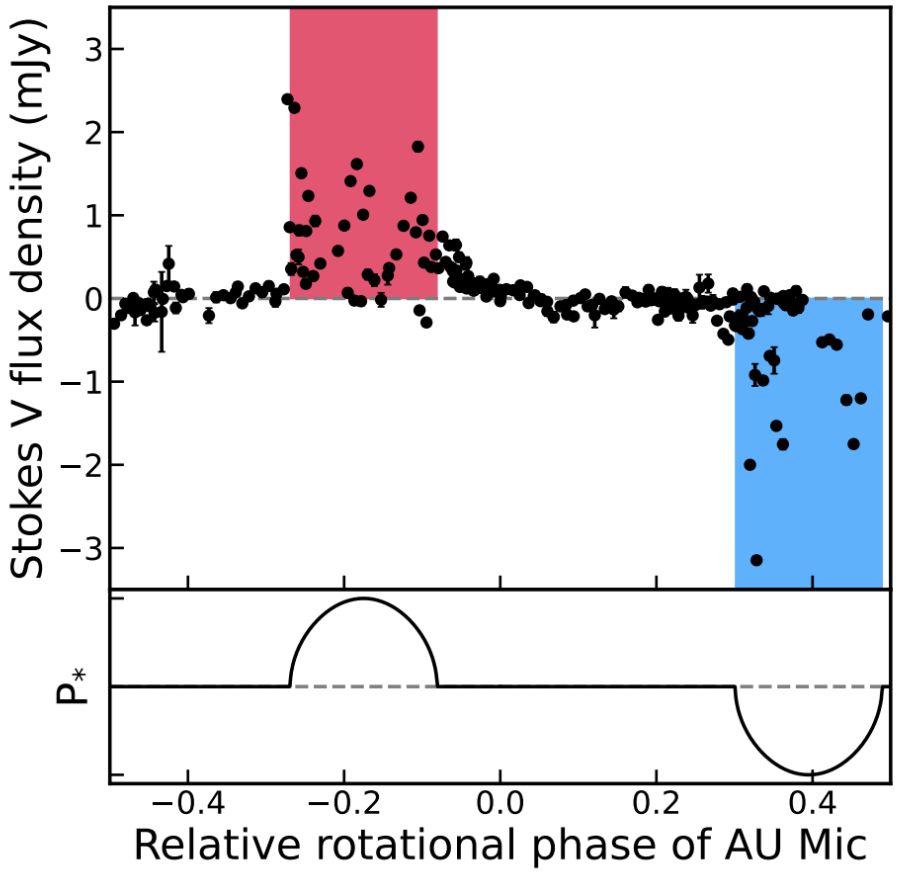


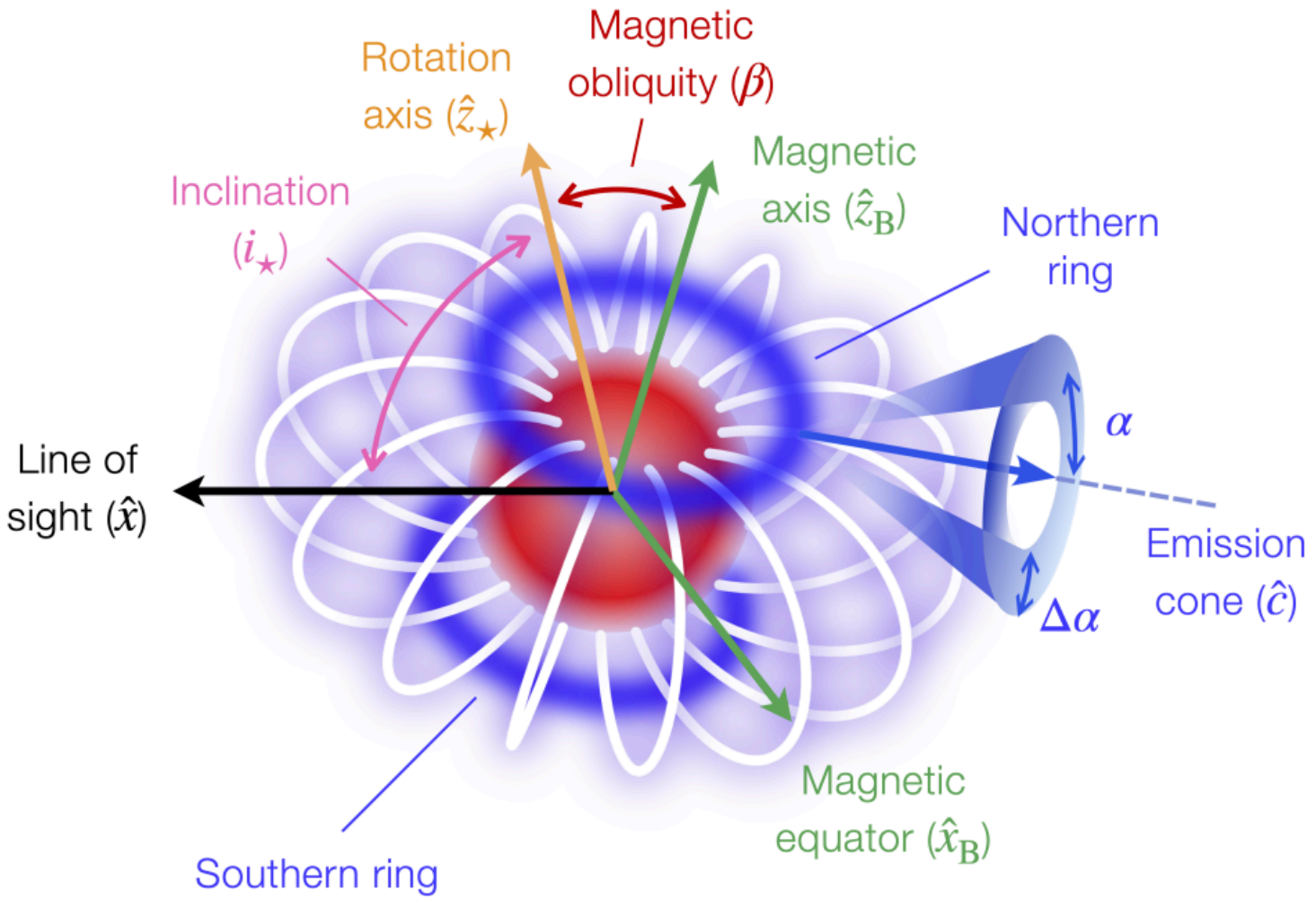
(a)



(b)

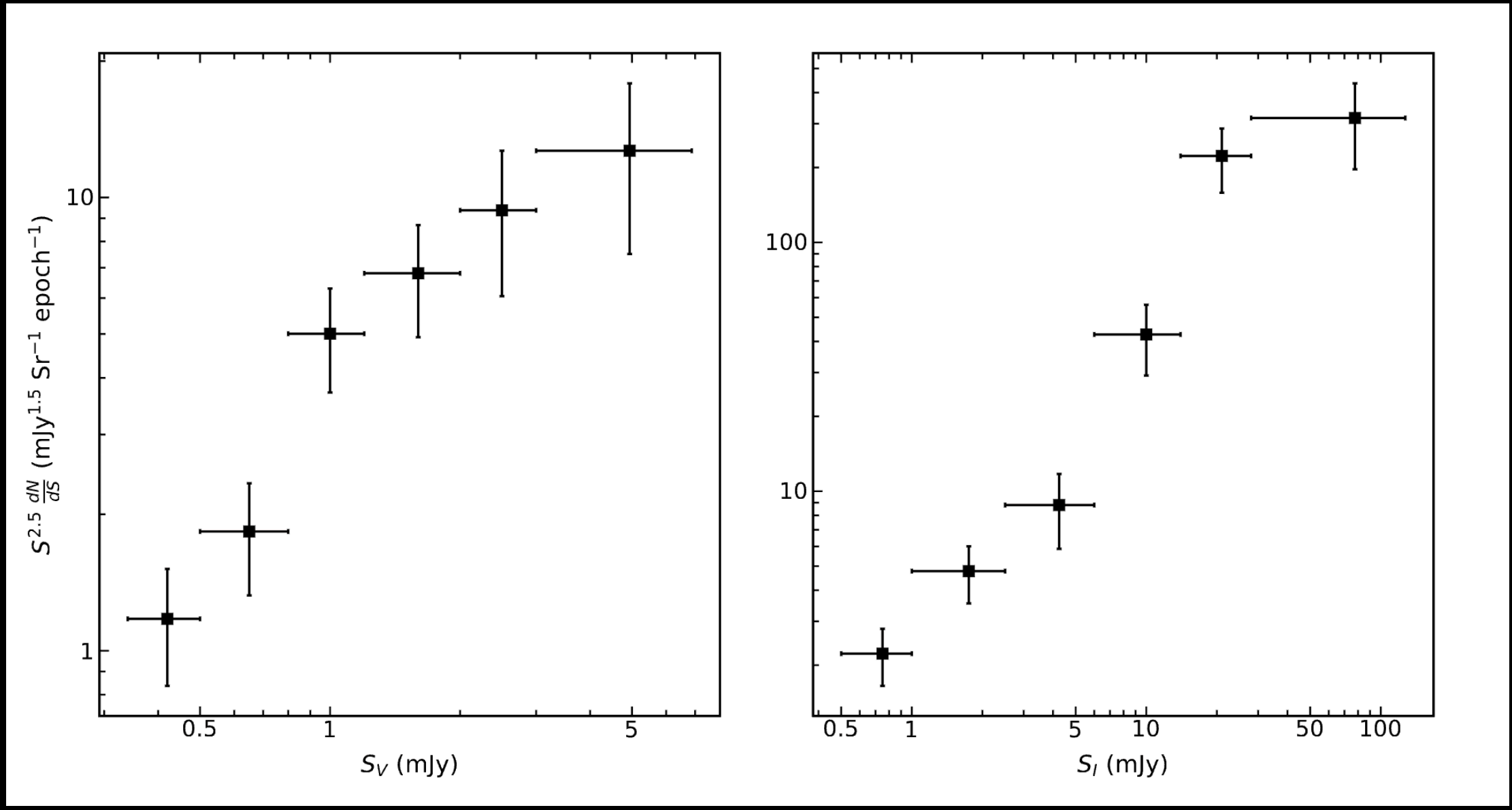
Auroral Ring Model





What about the SKA?

~10^3 M dwarfs!

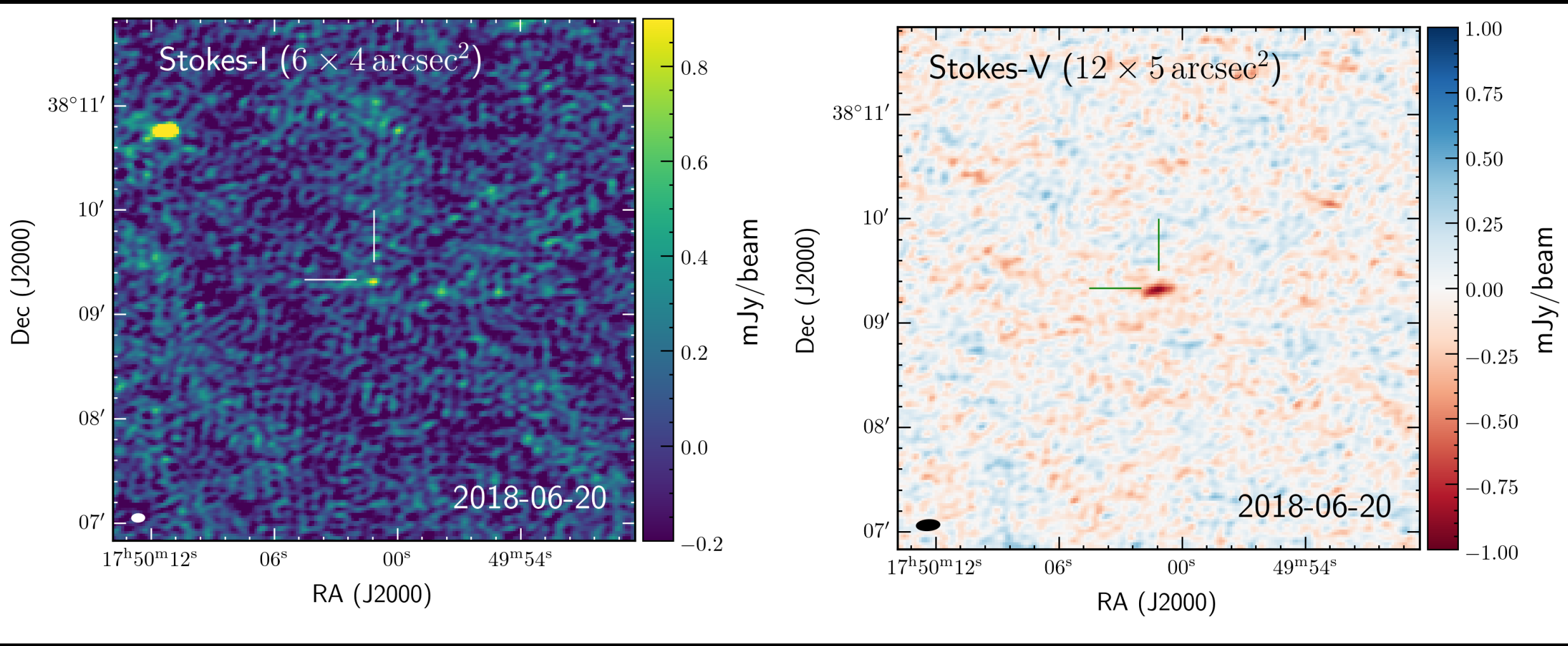


Conclusions

- First detections of stellar systems at low radio frequencies
- New parameter space
- So far inference based arguments – now hunting for the smoking gun signature (periodicity) and direct emission

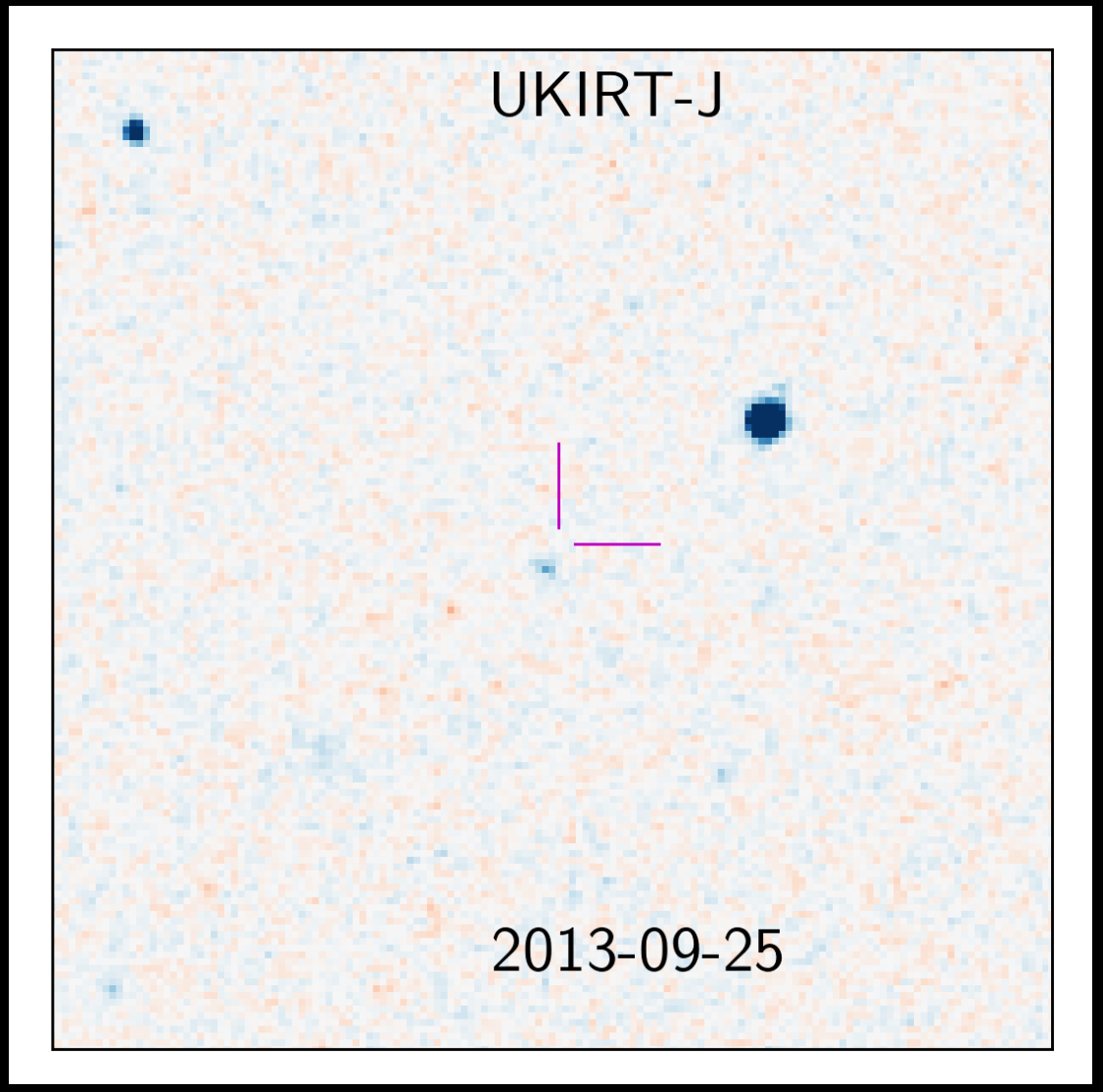
First discovery - Elegast

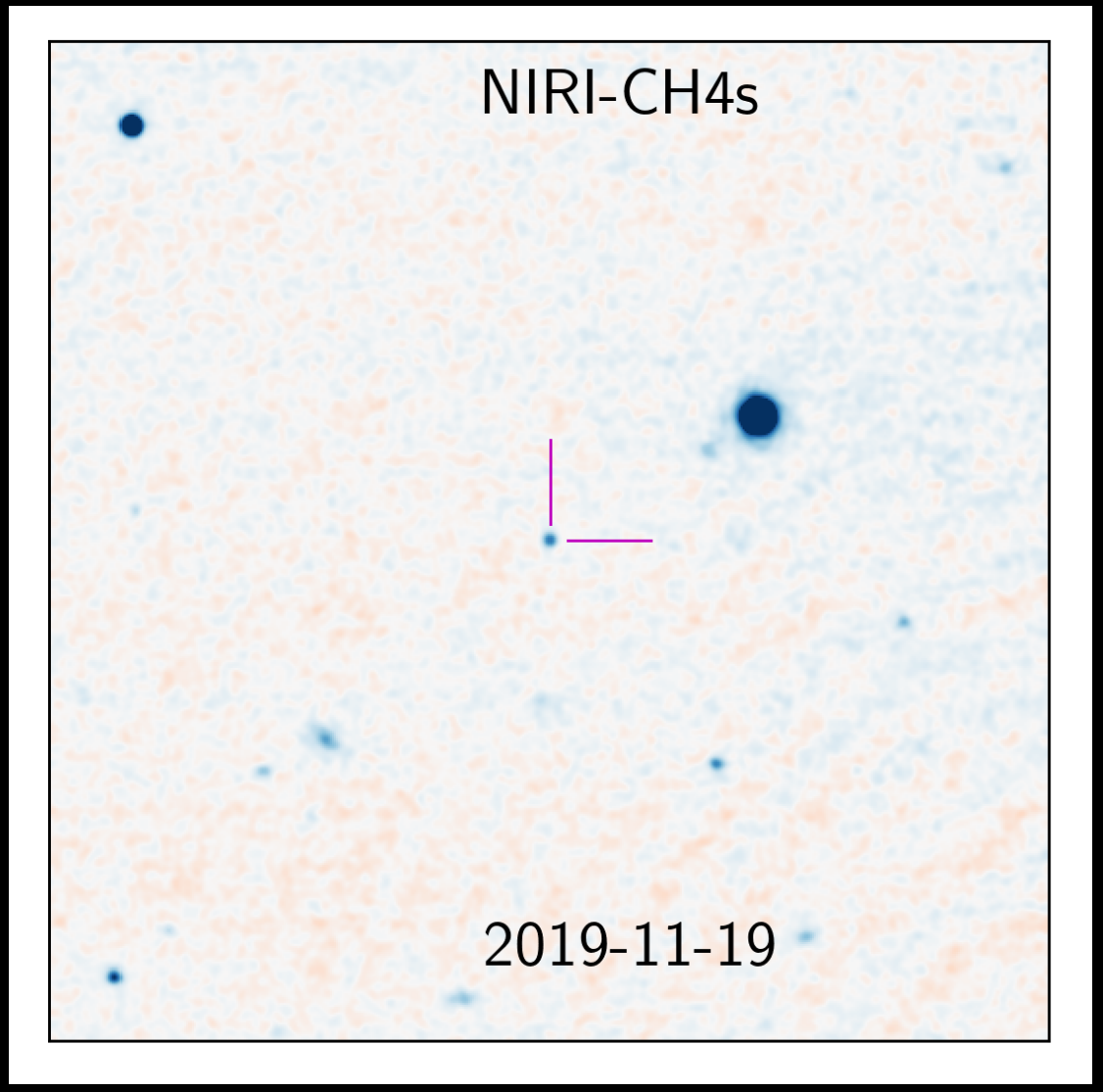
- No counterpart in Gaia, PanSTARRS (has to be >23rd mag!), 2MASS, or standard WISE
- ~1 mJy at 144 MHz, 100% circularly polarised, detected twice in three epochs



Vedantham, Callingham et al. (2020)

First IR hint and follow up

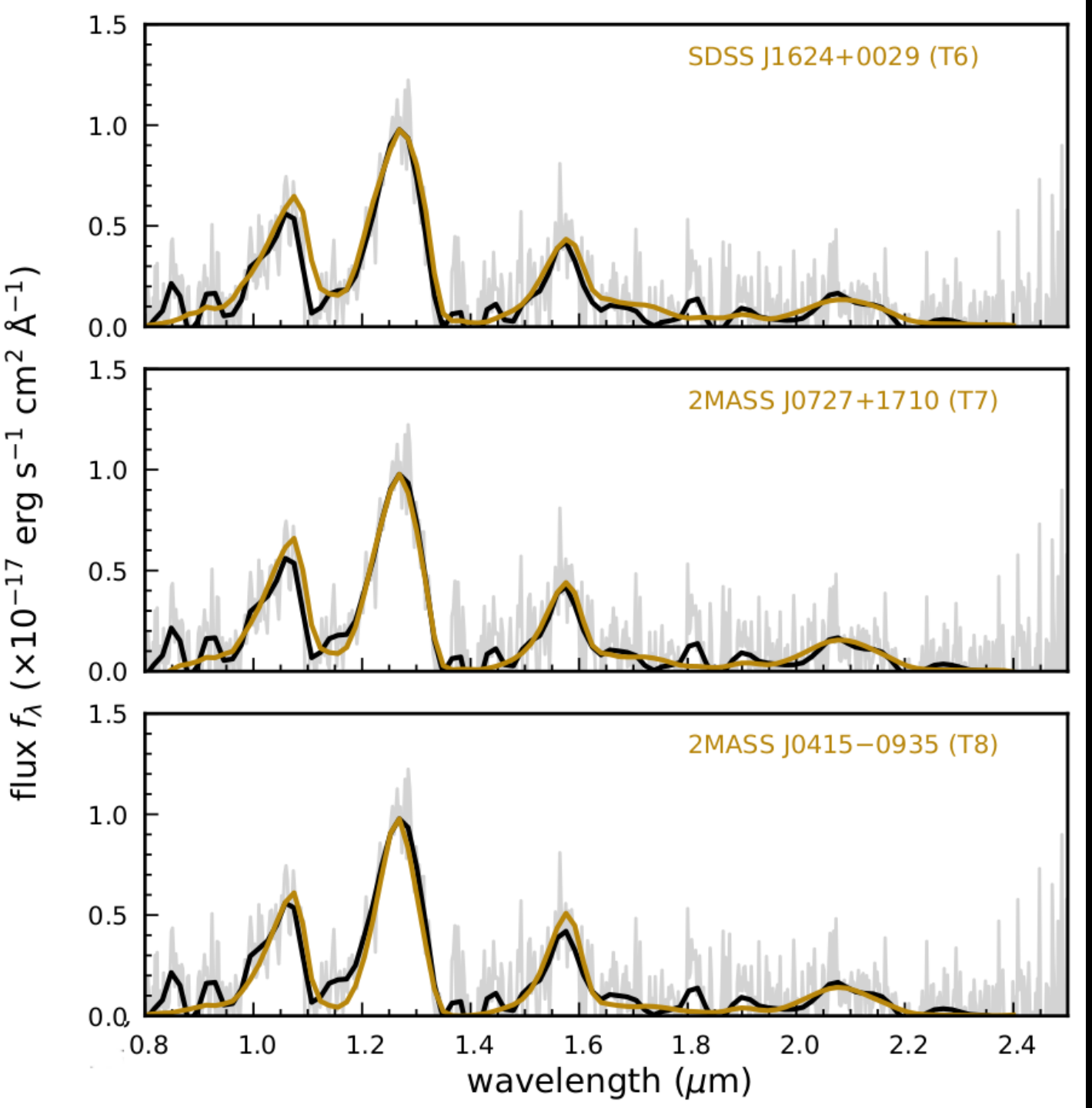




Vedantham, Callingham et al. (2020)

IR Spectra

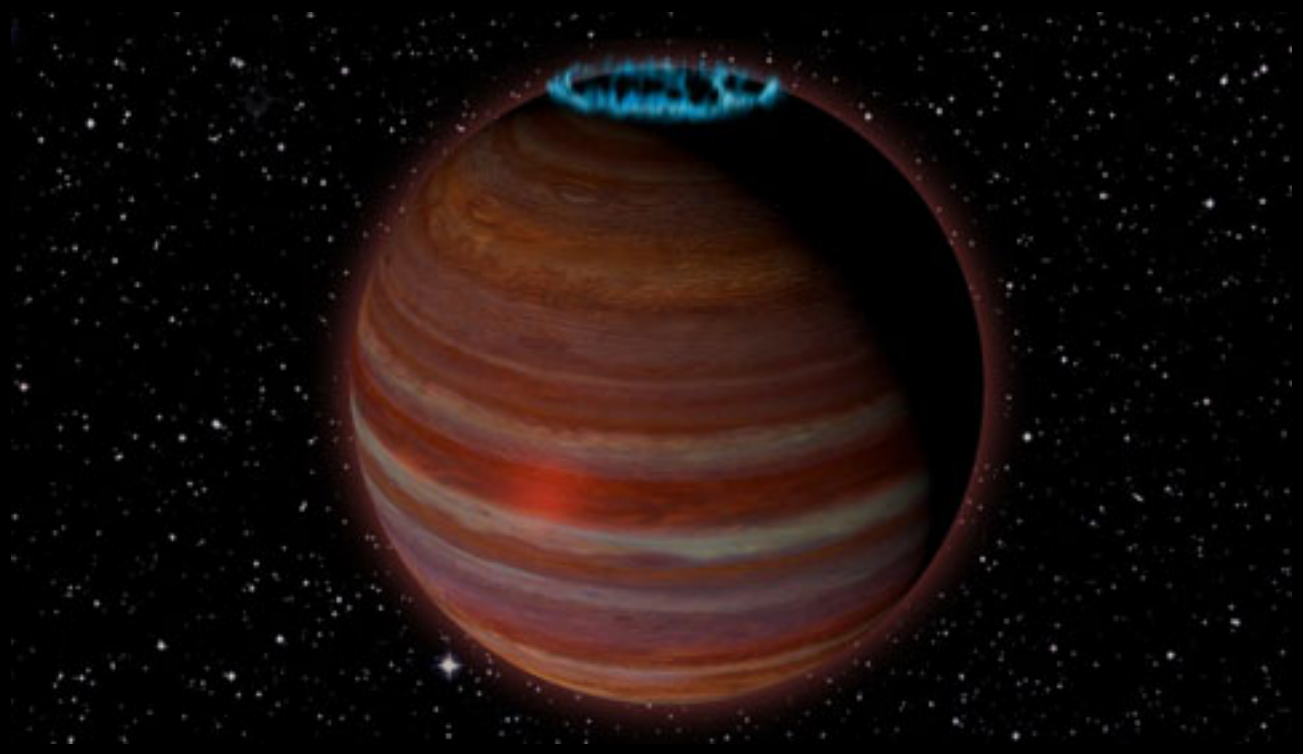
Confirmation of a ~T6.5 +/- 1.0 dwarf



Vedantham, Callingham et al. (2020)

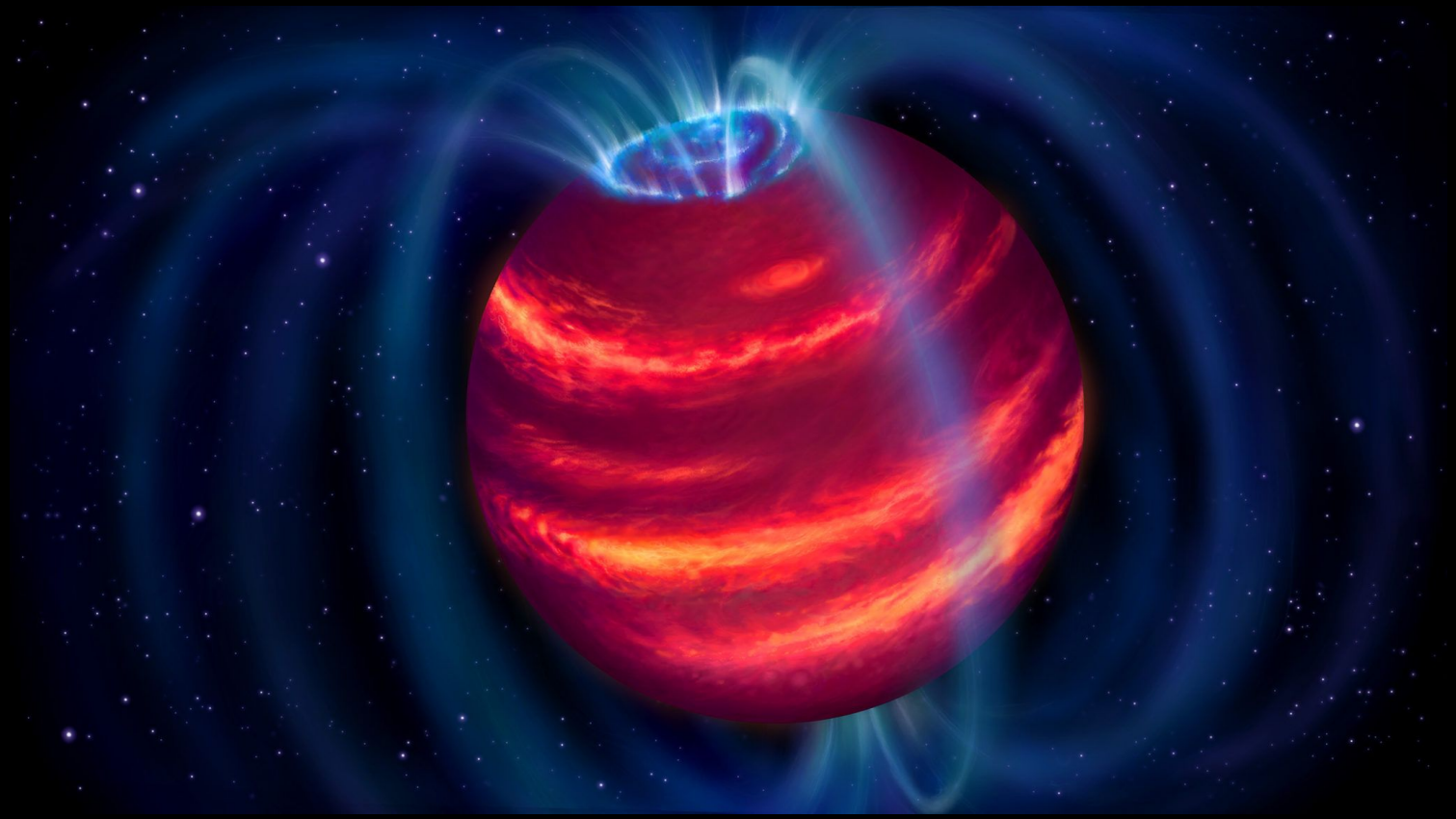
So what?

- Brown dwarfs have been known to be radio bright since mid-2000s (e.g. Berger 2006, Hallinan et al. 2008, Zic et al. 2019)
- However, **all of these studies followed-up known brown dwarfs** from the infrared
- So different biases – what did we find?



Elegast is the most luminous radio brown dwarf discovered

- The spectral class implies a **very large** distance of ~65 pc. All other radio cold brown dwarfs are <~10pc.
- Therefore, the radio luminosity of Elegast is over two orders of magntiude larger than previous population
- Furthermore, low-frequency imply we are detecting B >~ 25 G, comparable to Jupiter

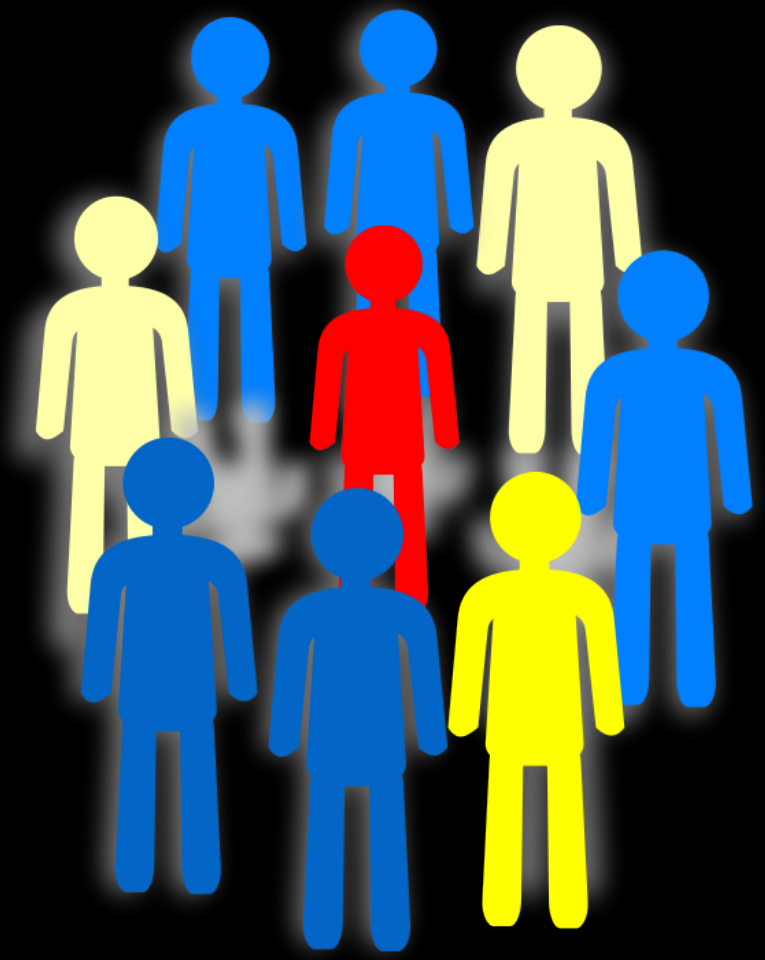


New Low Frequency Population

Type	Number
Flare Stars (dMe)	6
Active? M dwarfs	9
Quiescent M dwarfs	4
Contact binary	1
Millisecond Pulsars	1
RS CVn	15

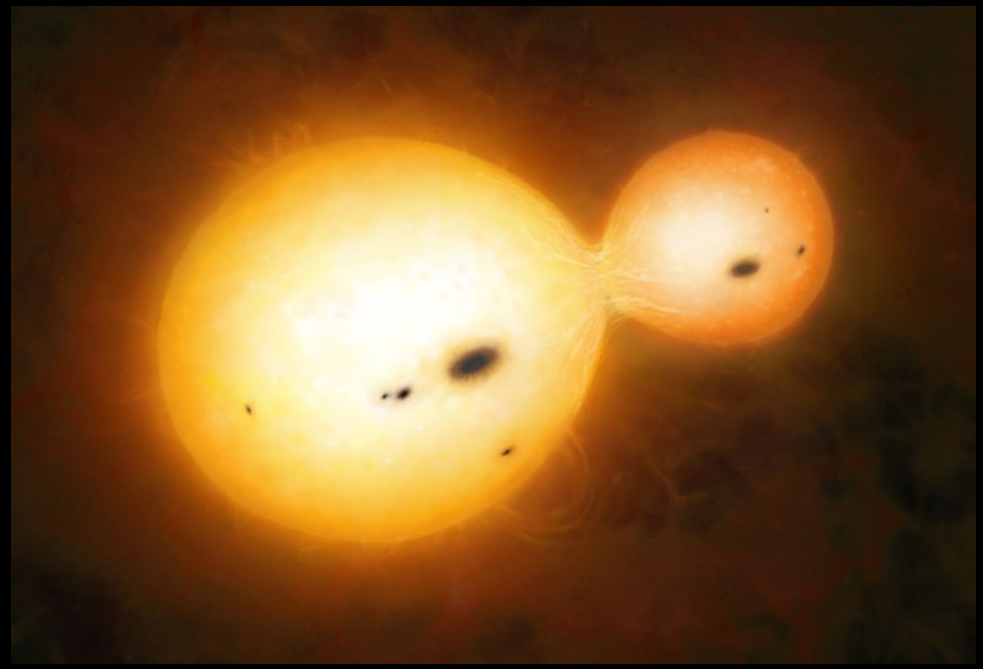
Callingham et al. (2021b), Nature Astronomy

First ever population – what can you do?

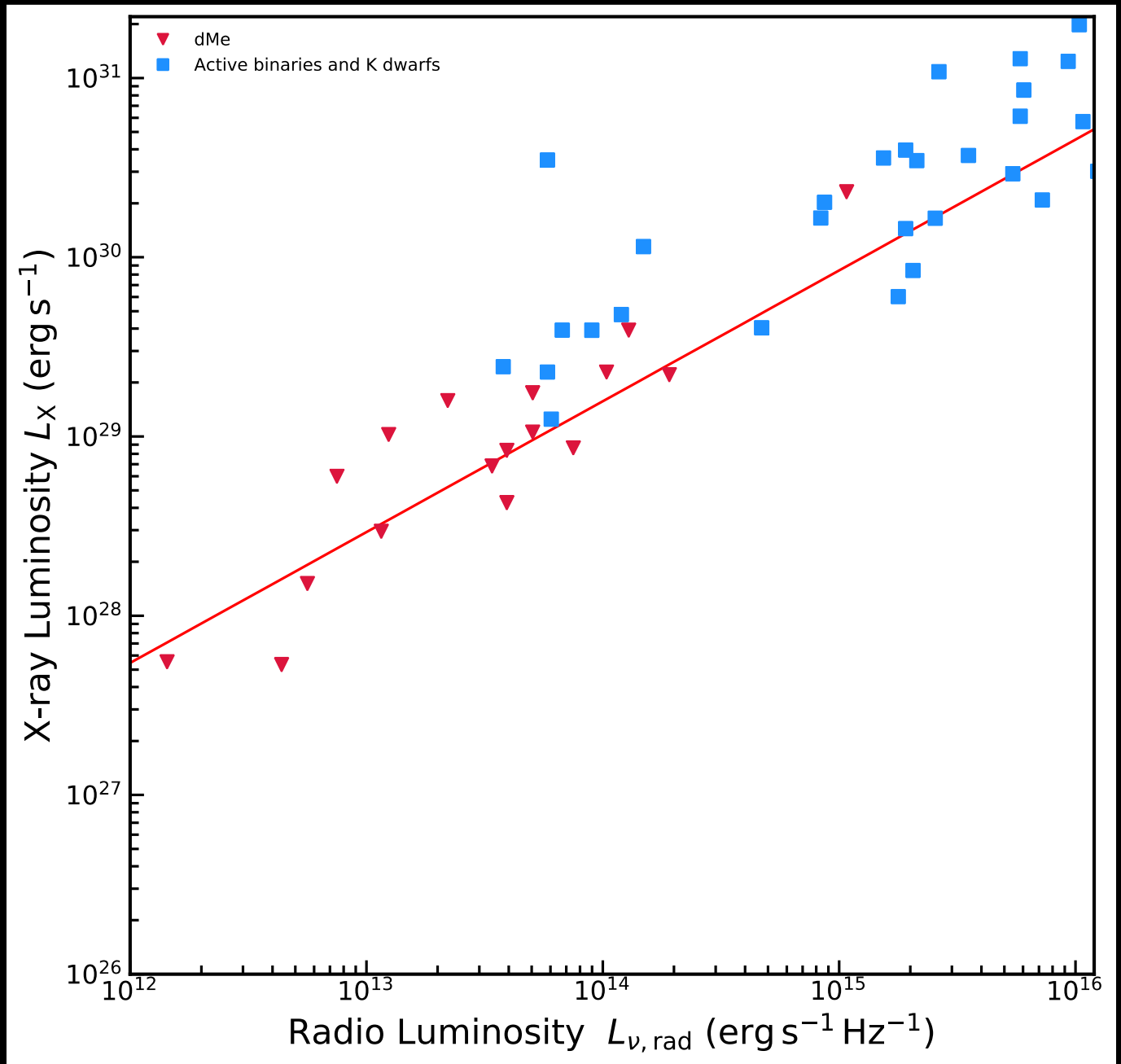


Emission and brightness temp?

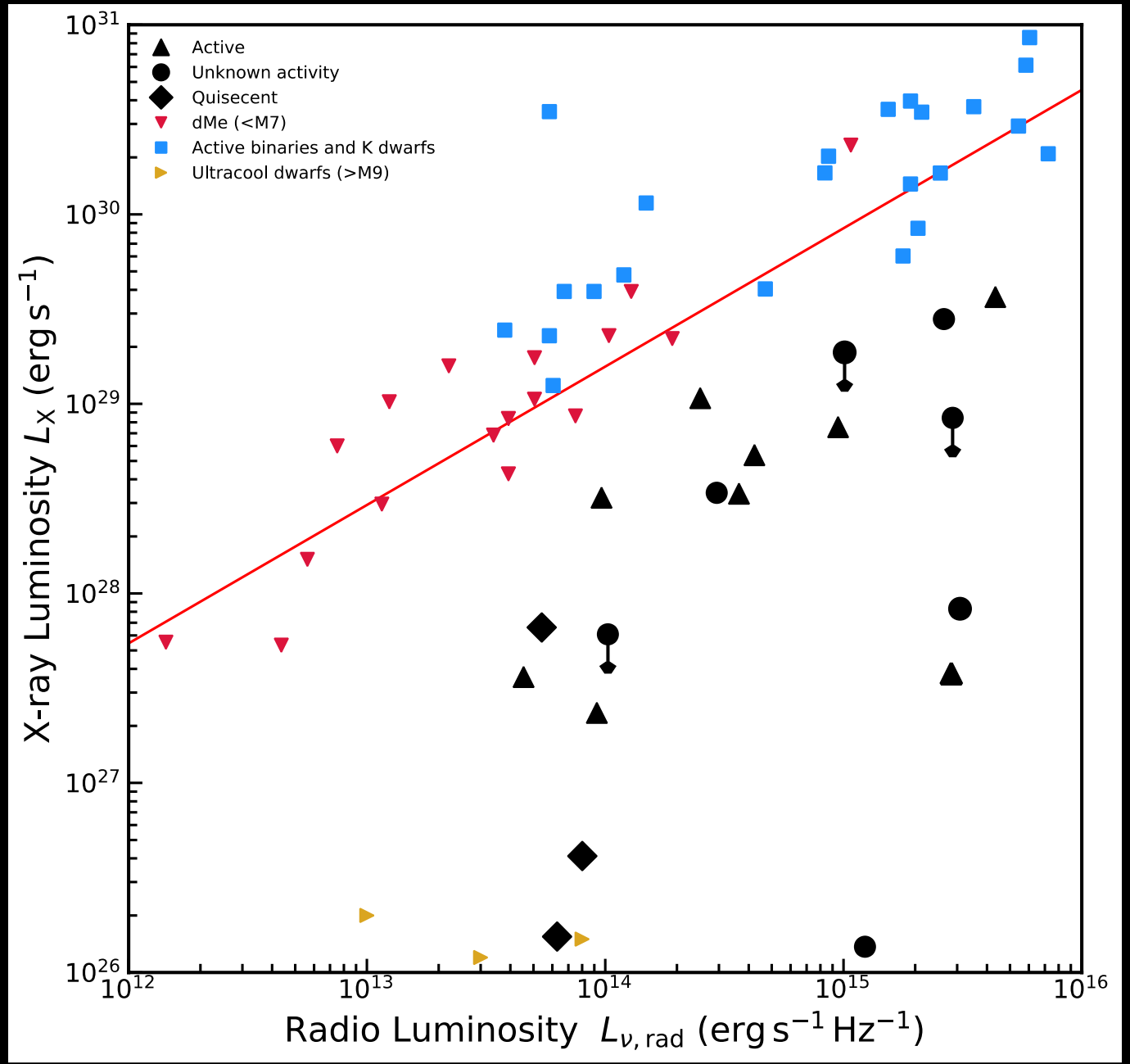
- All stars >60% circularly polarised
- All stars with brightness temperature $>10^{12}$ K (some even up to $>10^{14}$ K)
- Only ECMI works



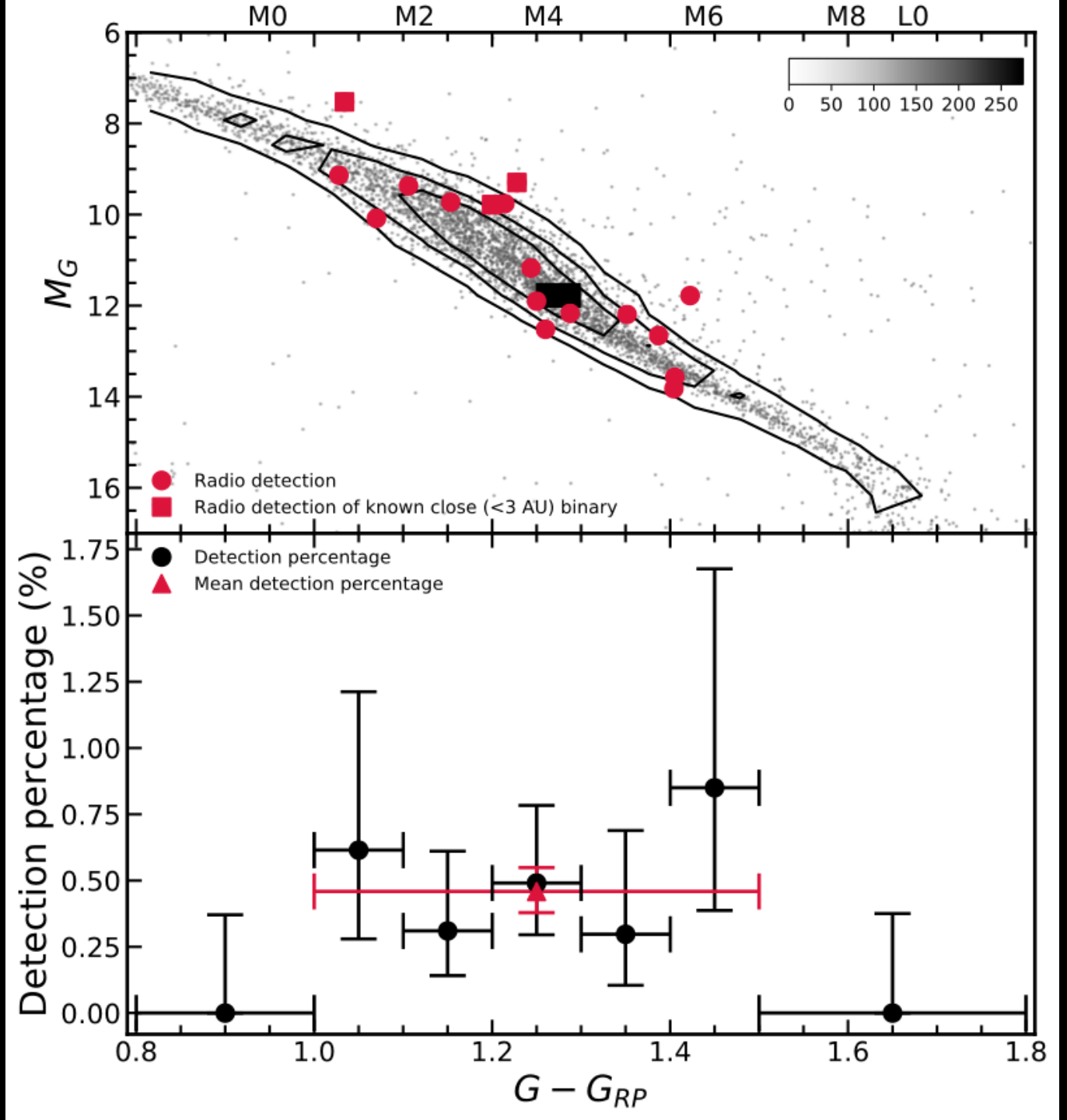
Güdel-Benz relationship



Güdel-Benz relationship

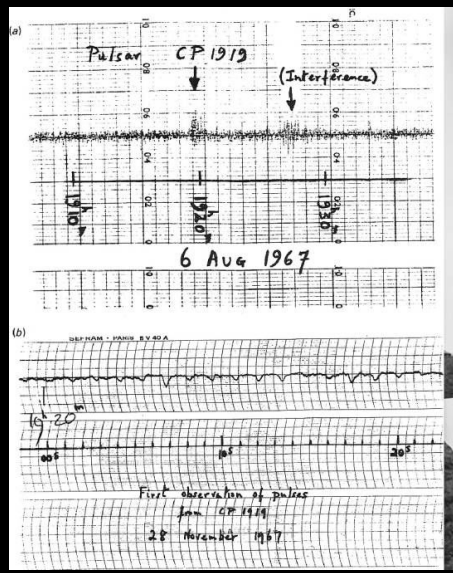


What stars do we see?



Come work at ASTRON!

- Bell Burnell Fellowship 3+1 year independent position (due December 22)

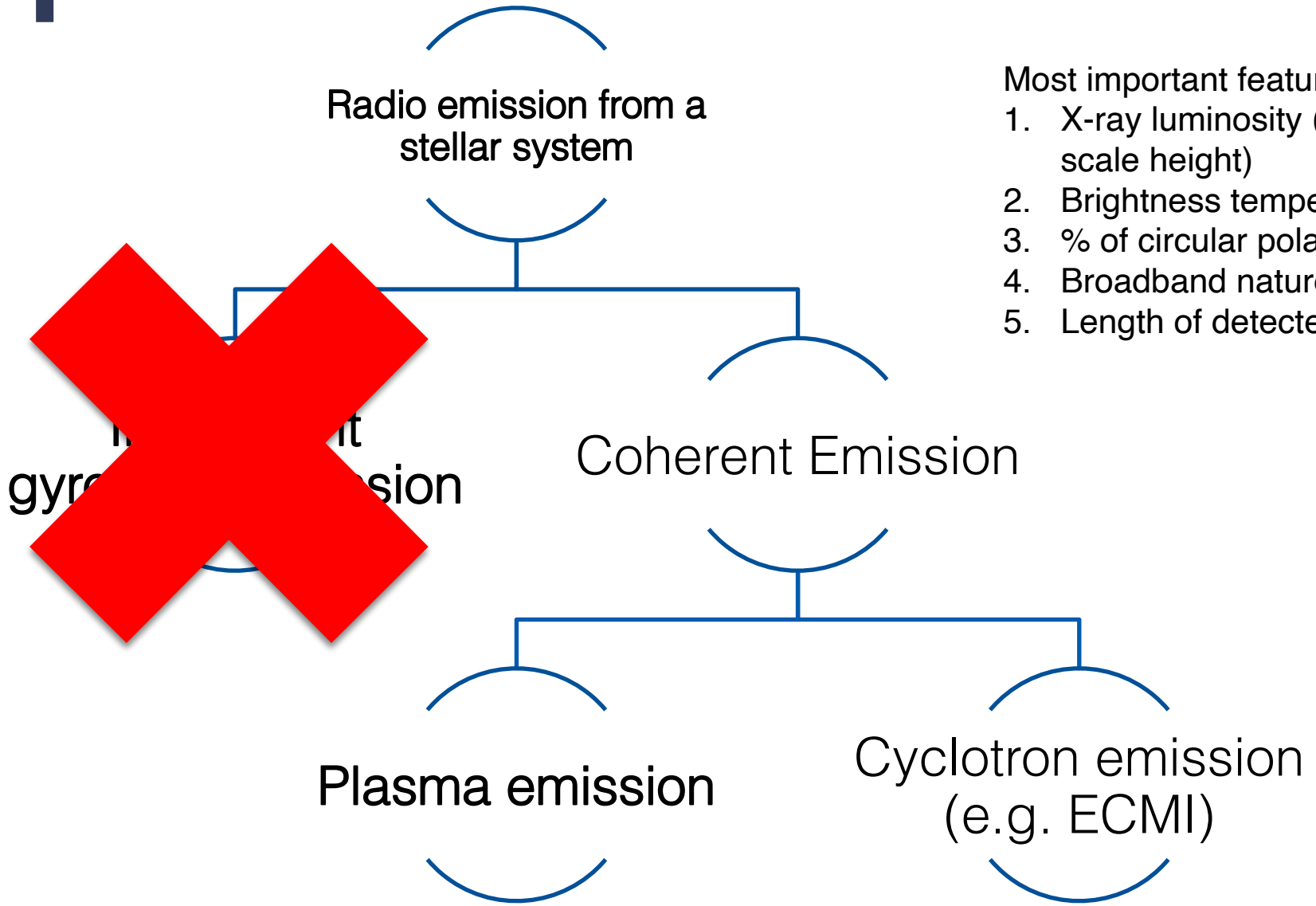


Physical characteristics of the star

- Quiescent, slow-rotating, X-ray faint M dwarf with no known stellar companion, small coronal height. Different to all other metrewave detections (e.g. UV Ceti)

Parameter		AD Leo
Spectral Type	M4.5V	M3V
Distance (pc)	8.04	4.96
Mass ($M_\odot$)	0.17	0.42
Radius ($R_\odot$)	0.19	0.44
Chandra X-ray luminosity ($\times 10^{28}$ erg s^{-1})	$< 1.1 \times 10^{-2}$	2.3
ROSAT X-ray luminosity ($\times 10^{28}$ erg s^{-1})	$< 1.6 \times 10^{-2}$	9.2
Coronal Temperature (MK)	< 2.8	6.4
ROSAT X-ray / Bolometric luminosity ($\times 10^{-5}$)	< 1.07	105.74
Rotation velocity ($v \sin i$, km s^{-1})	< 4.1	2.6
Rotation period (days)	130 ± 30	2.2
Coronal magnetic field strength (kG)	Unknown	0.19

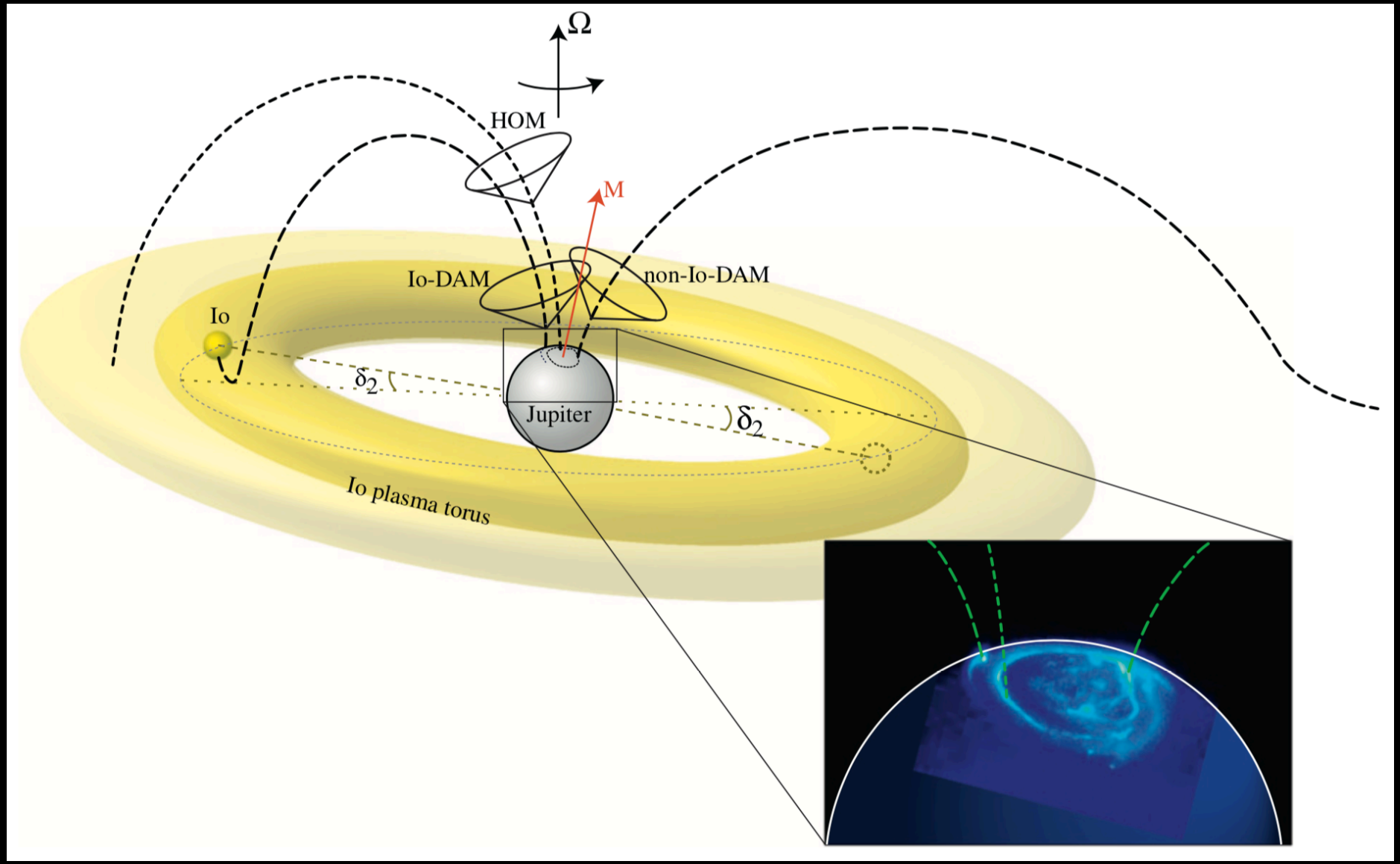
Interpretation of emission



Most important features:

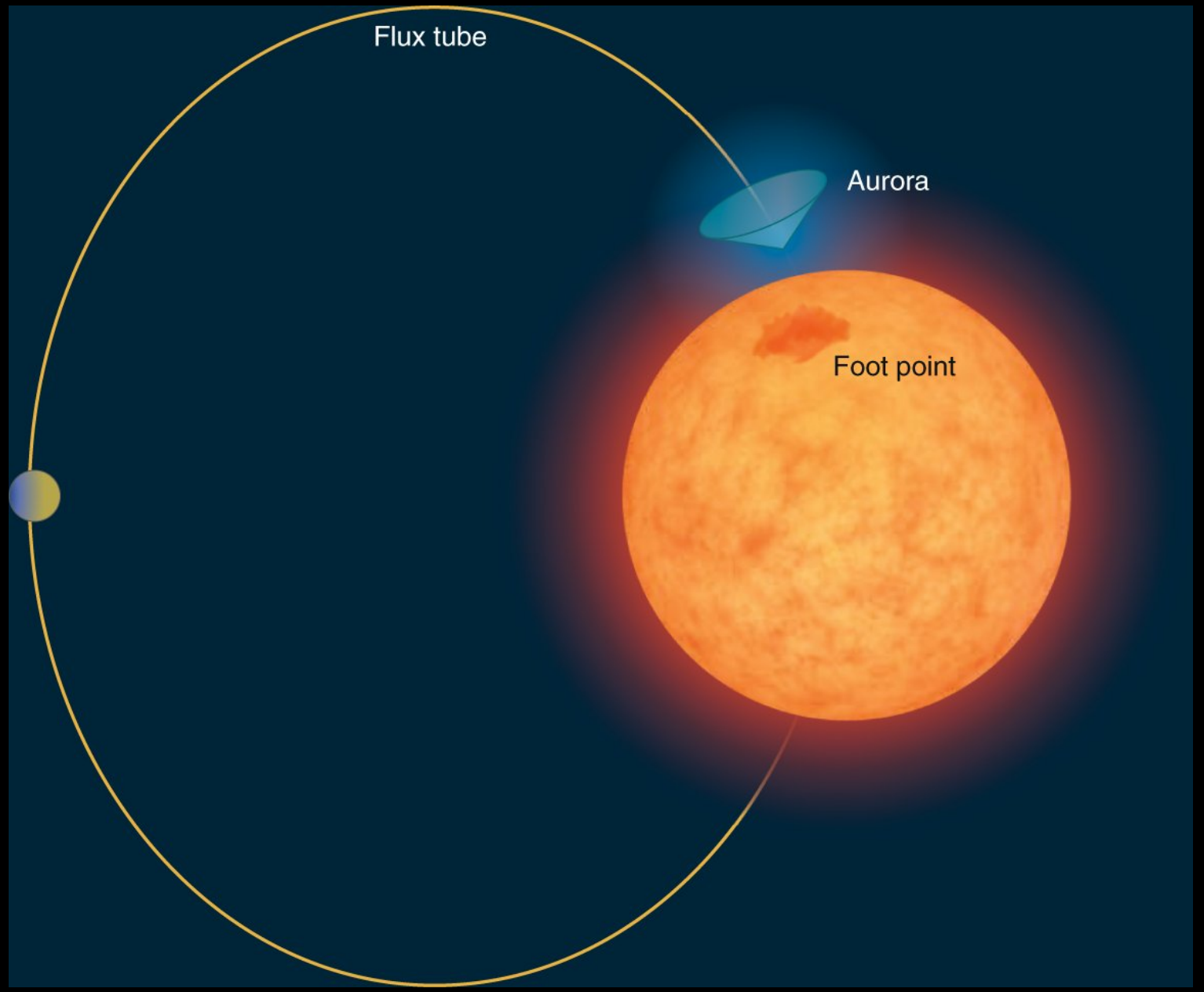
1. X-ray luminosity (which dictates coronal scale height)
2. Brightness temperature
3. % of circular polarisation
4. Broadband nature
5. Length of detected emission

Jupiter-Io Interaction



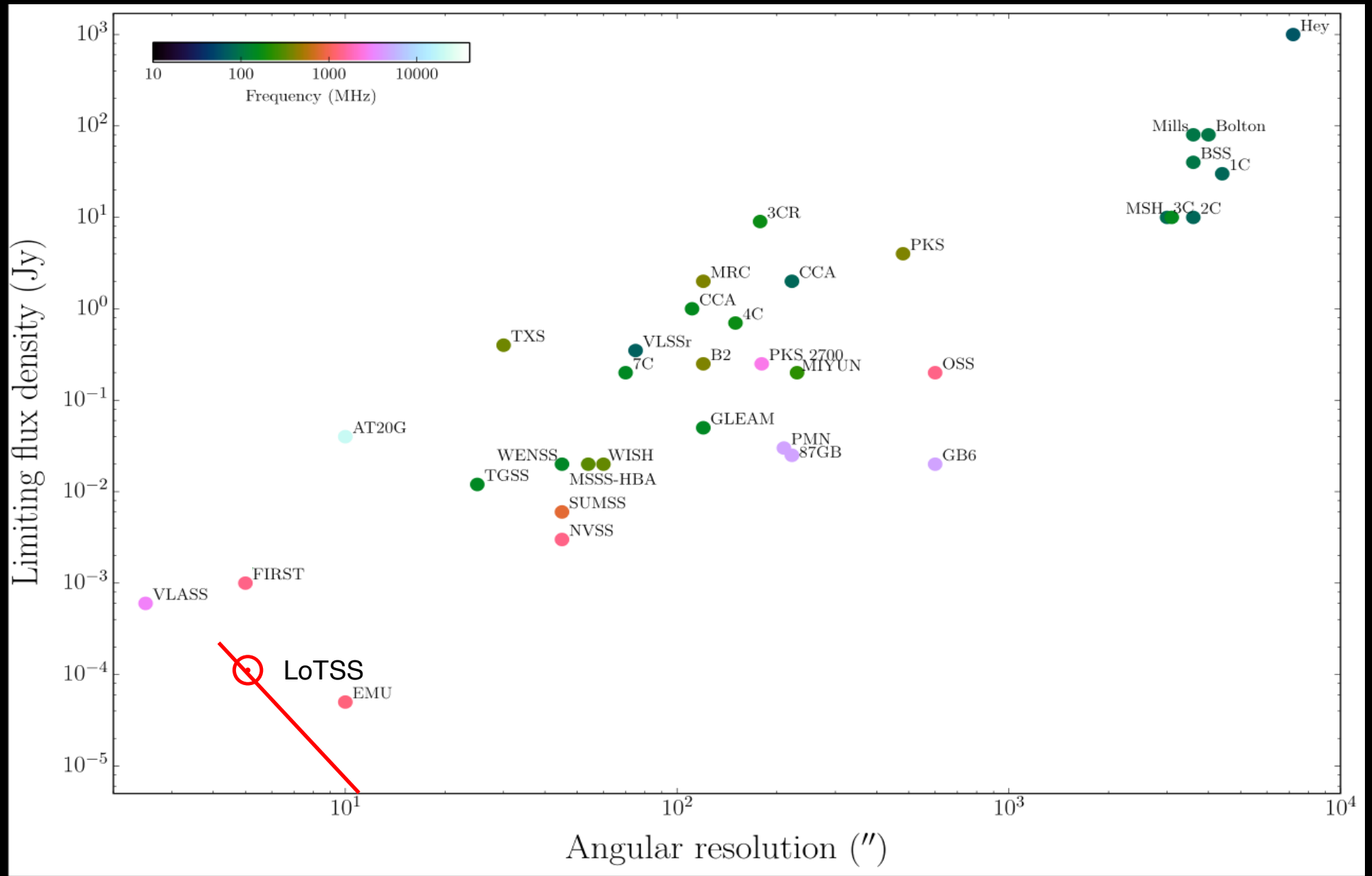
Cecconi and Zarka

Jupiter-Io Interaction Scaled-up

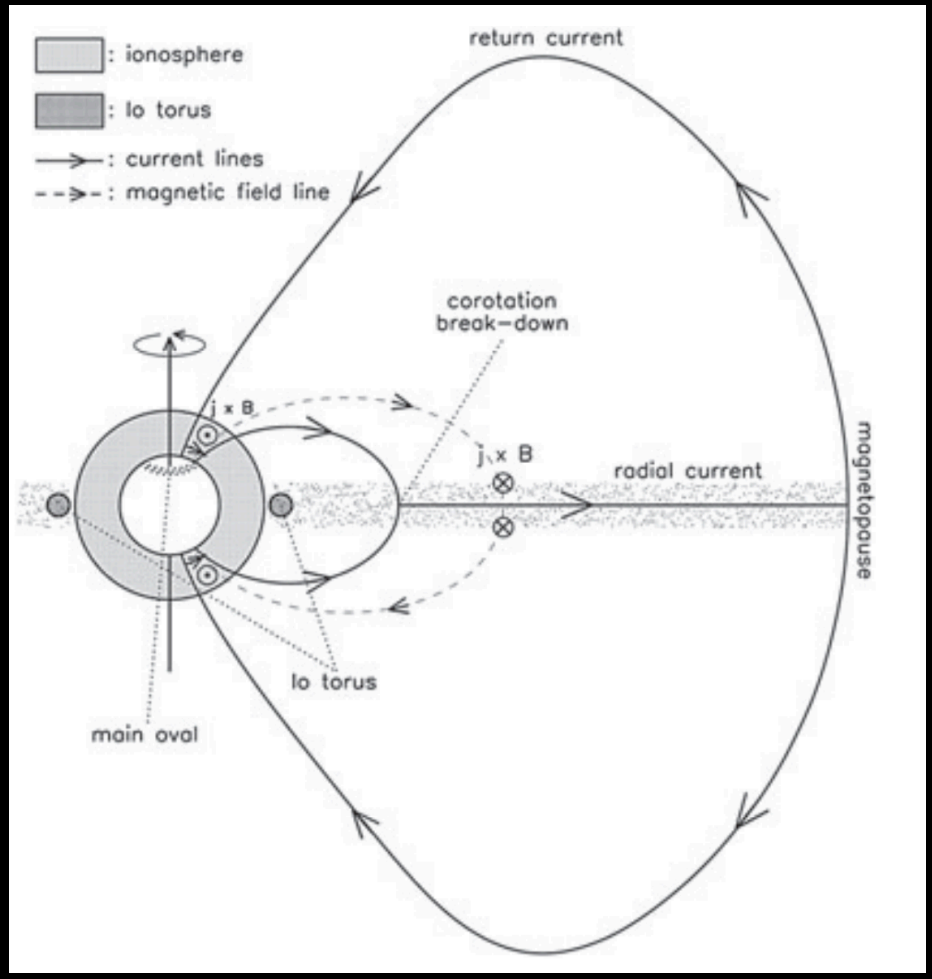


Predictions by Lazio (2006) Zarka (2007), Turnpenney et al. (2018), Saur et al. (2013) and many more

LoTSS sensitivity, resolution, and time on sky

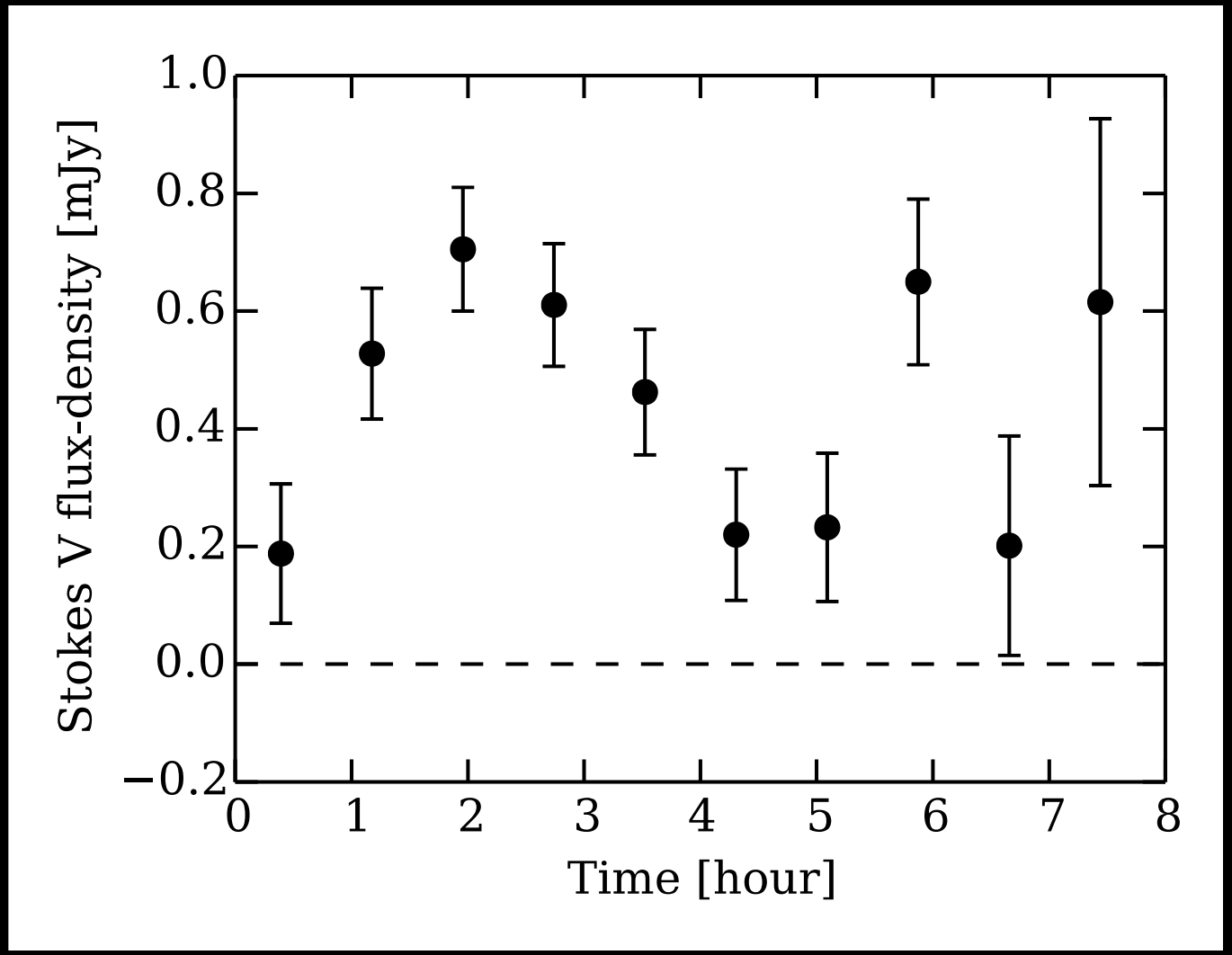


Breakdown of co-rotation



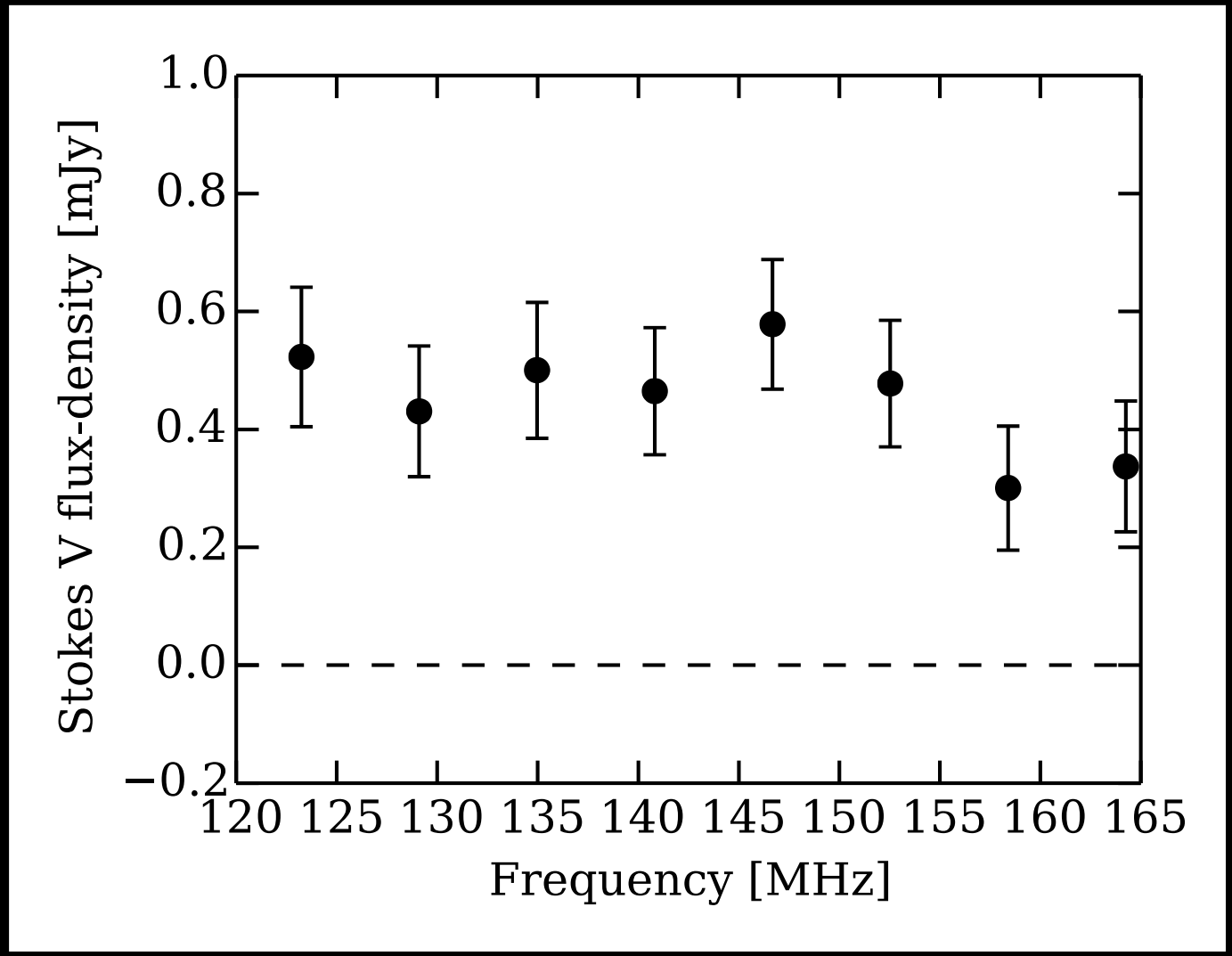
Chané et al. (2013)

Emission characteristics – variable(ish)



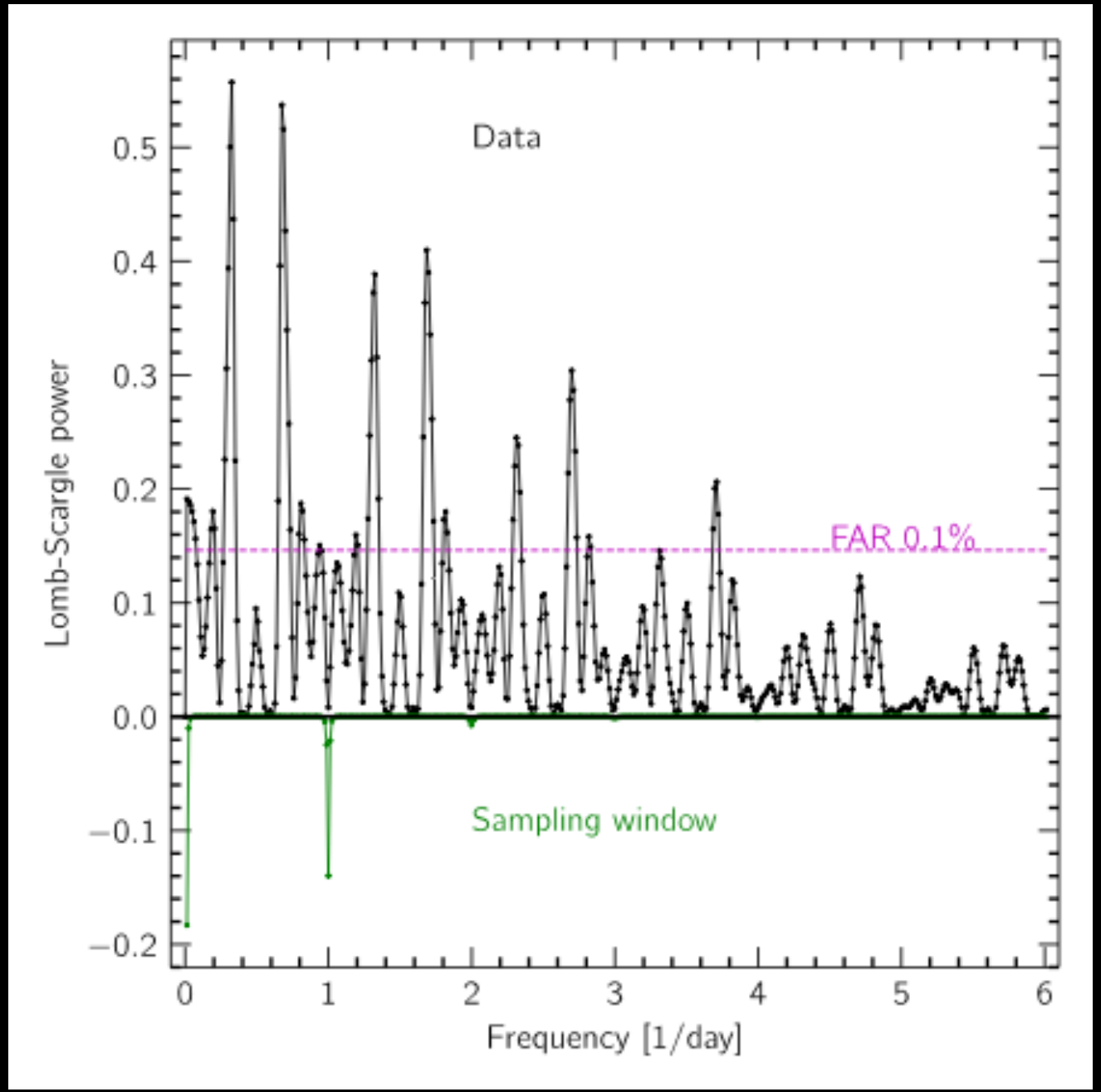
Vedantham, Callingham et al. (Nat. Astro., 2020)

Emission characteristics – flatish

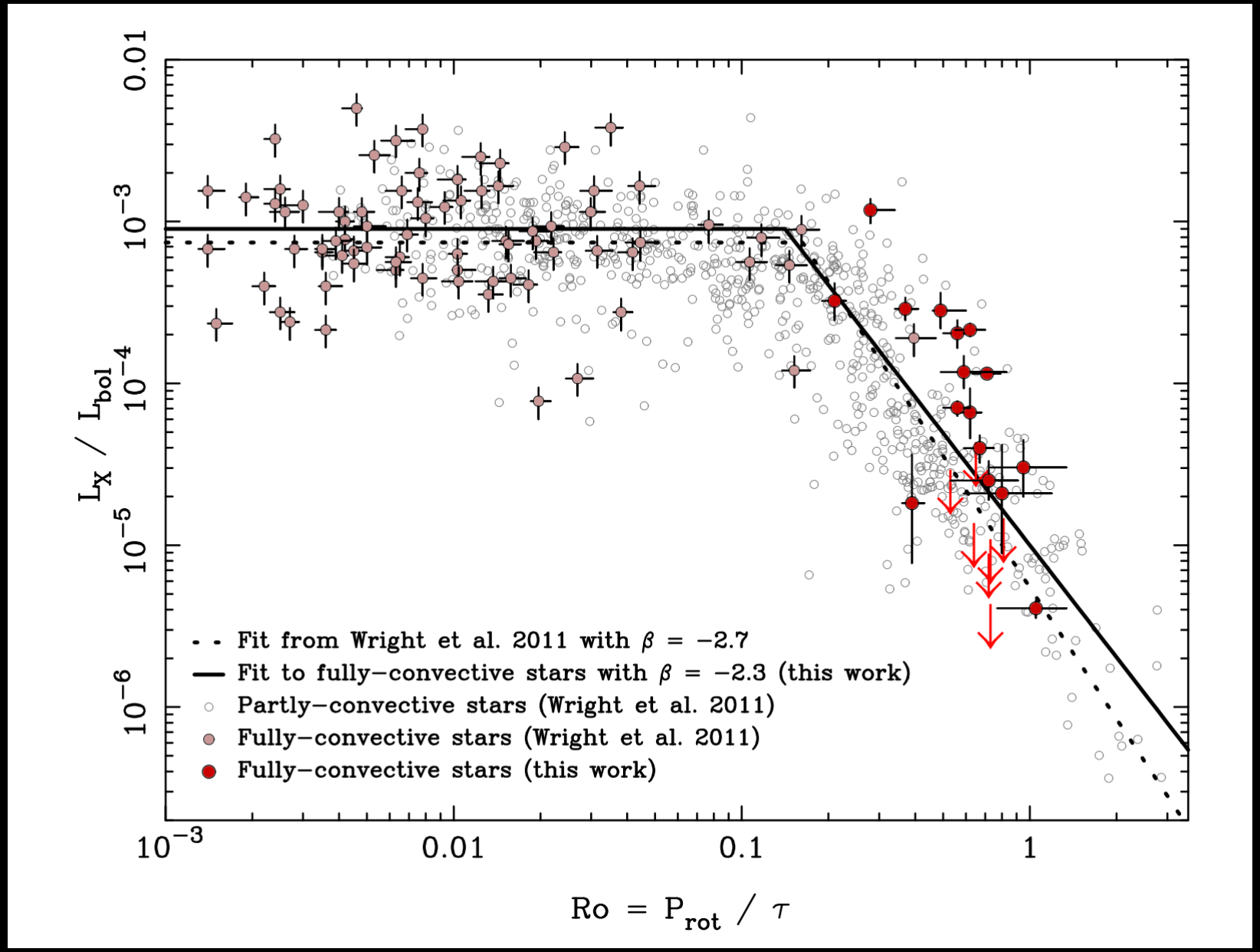


Vedantham, Callingham et al. (Nat. Astro., 2020)

Periodicity Search - PRELIMINARY

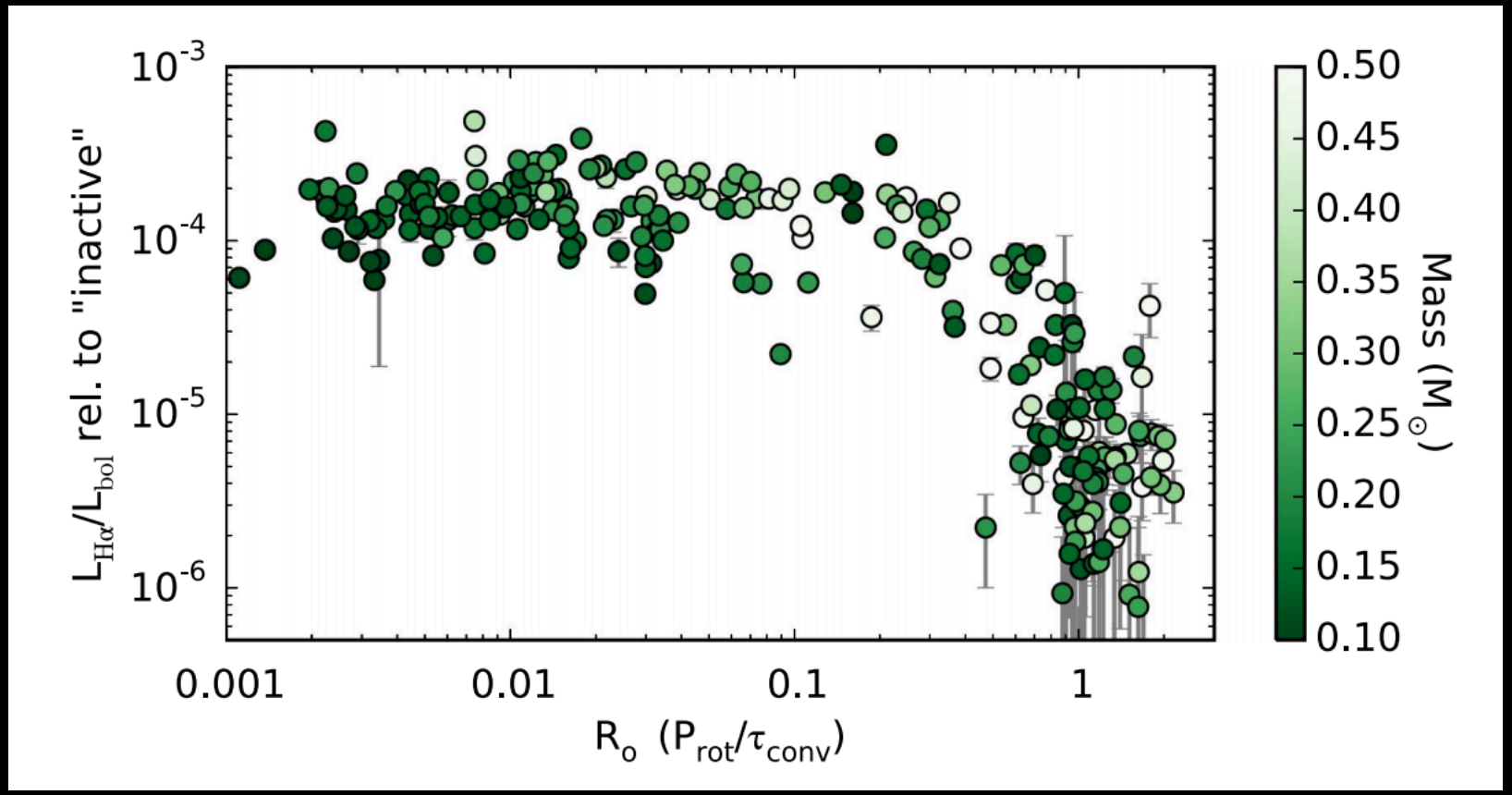


X-ray and rotation



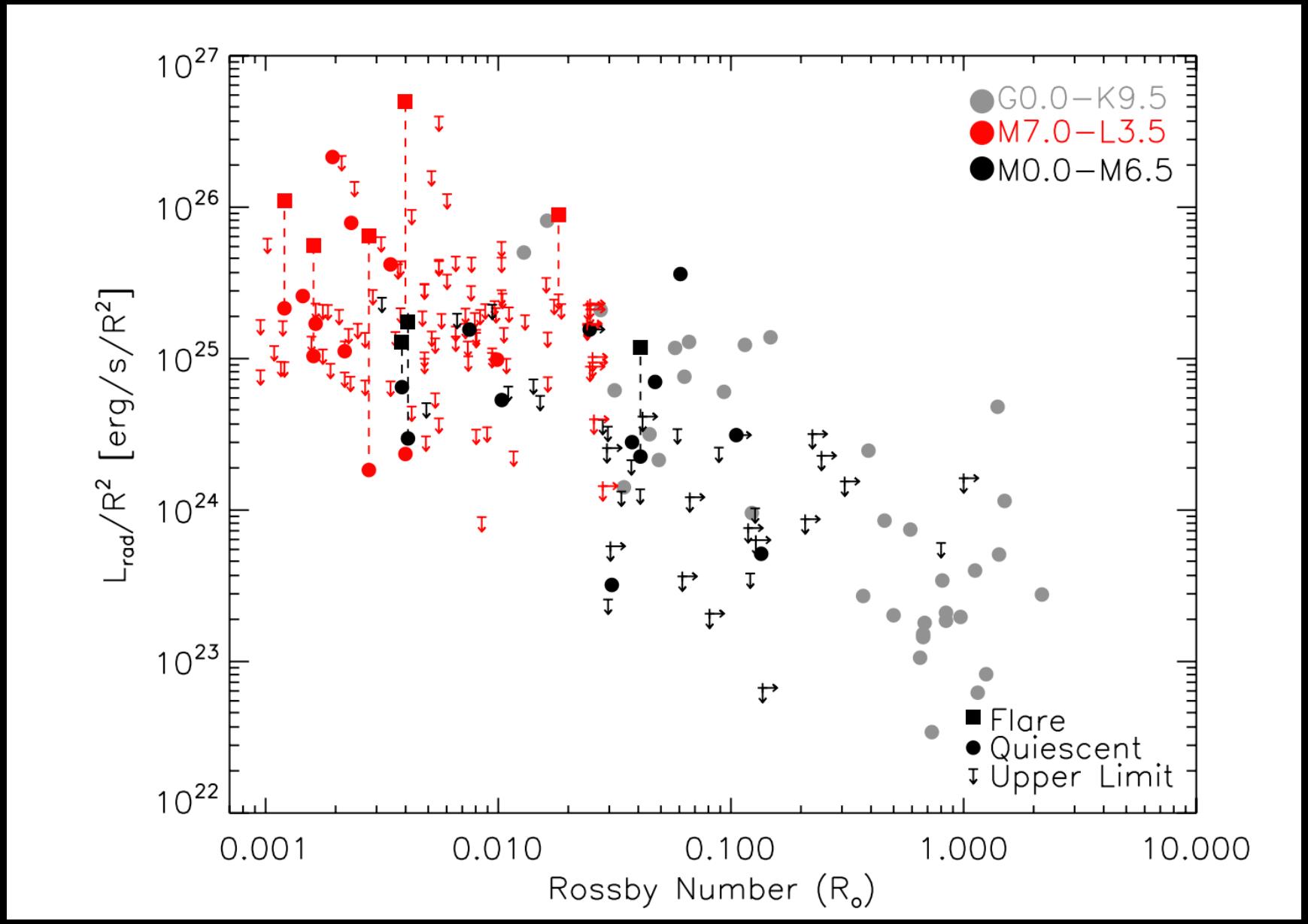
Wright et al. (2018)

H-alpha properties of stars



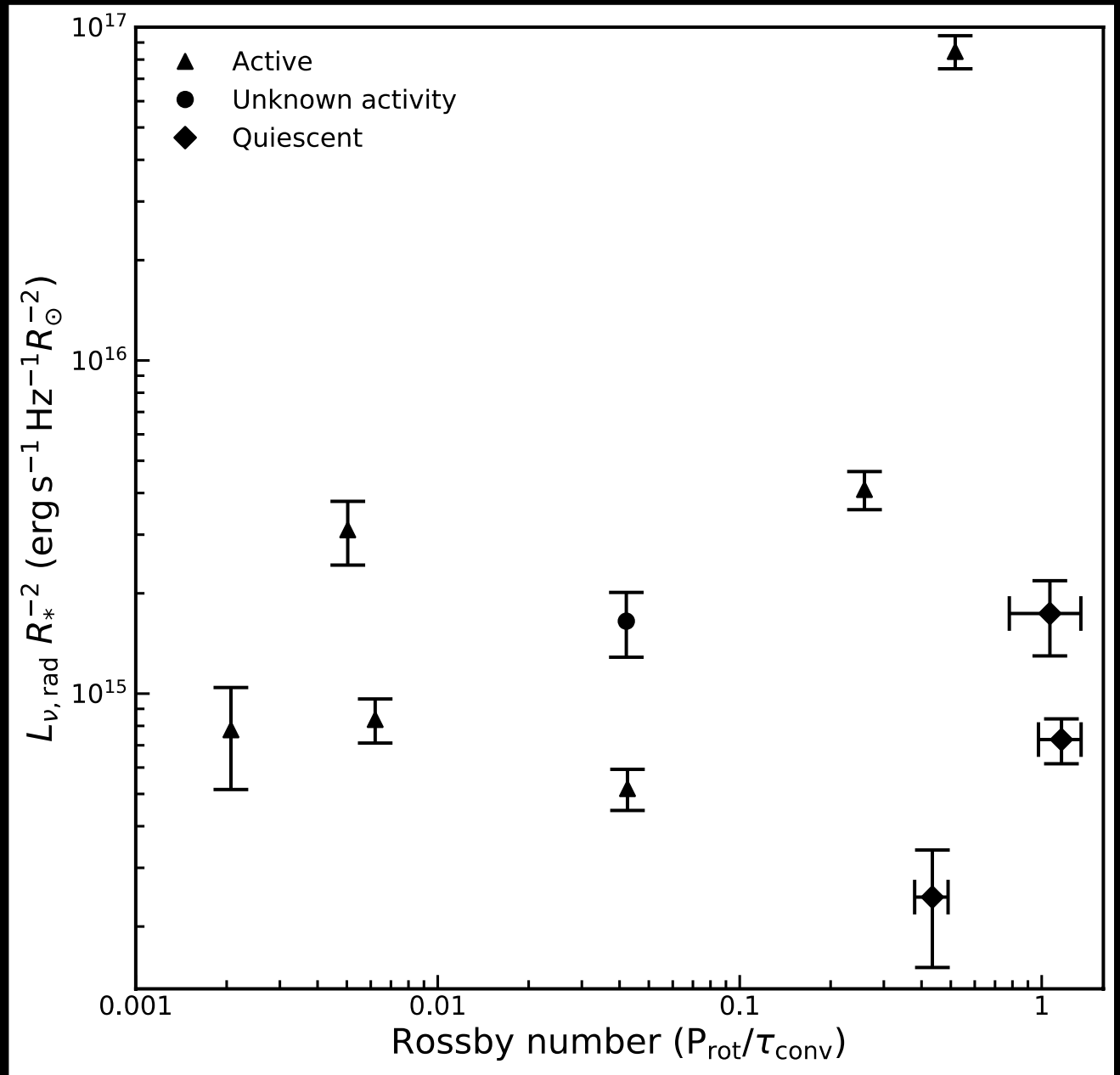
Newton et al. (2018)

Rotation and radio



McLean et al. (2012)

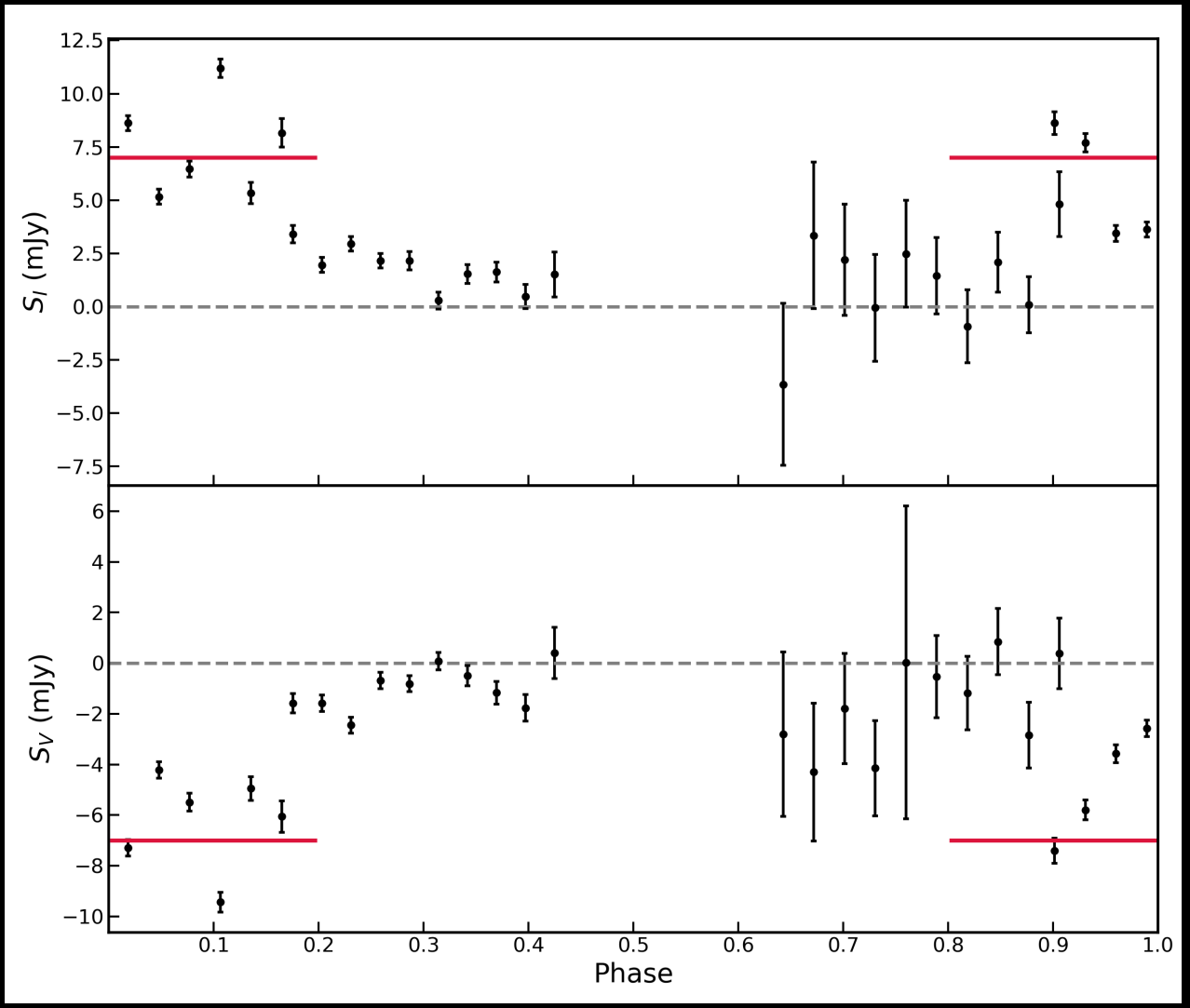
Rotation and radio

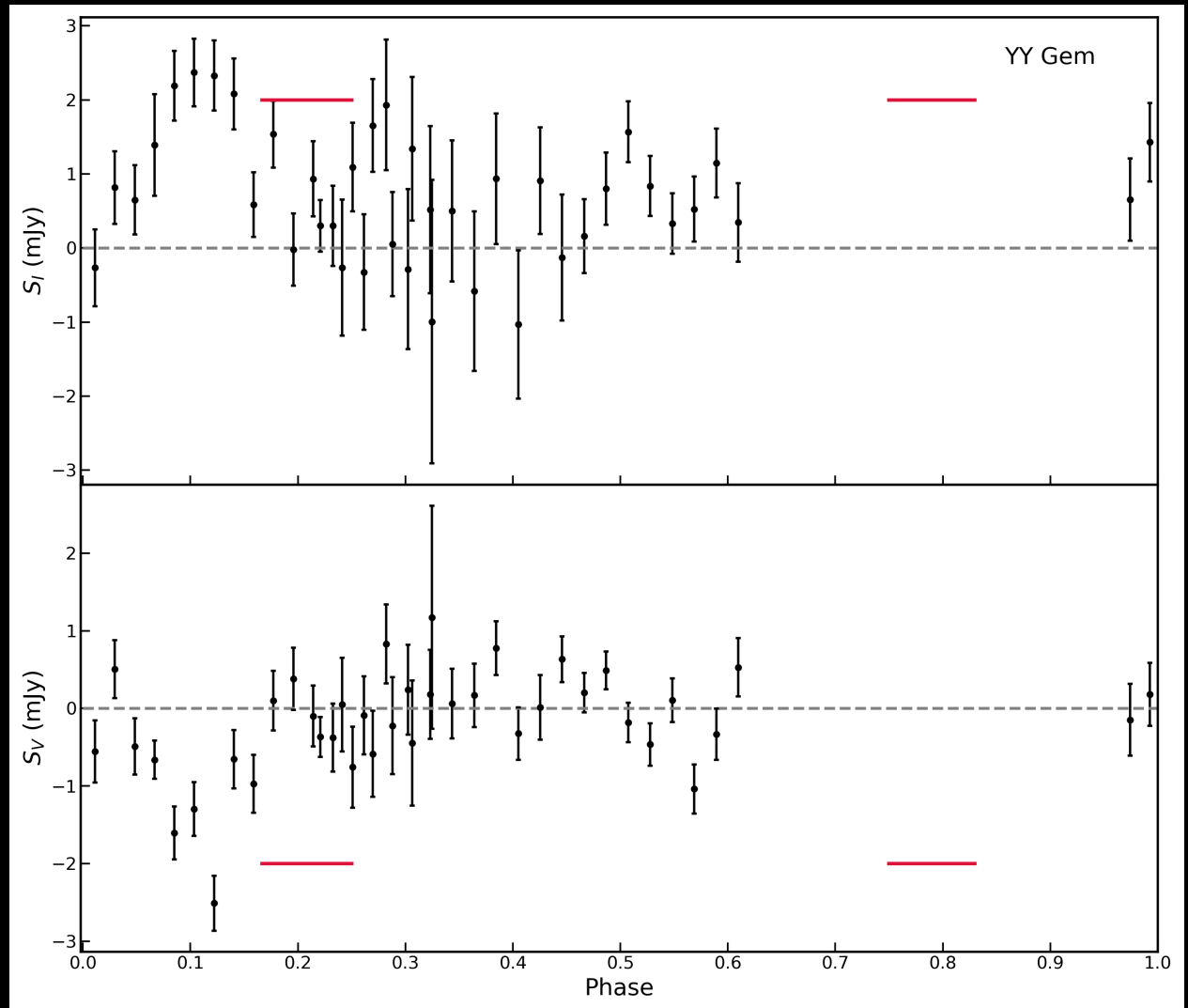


Active binaries

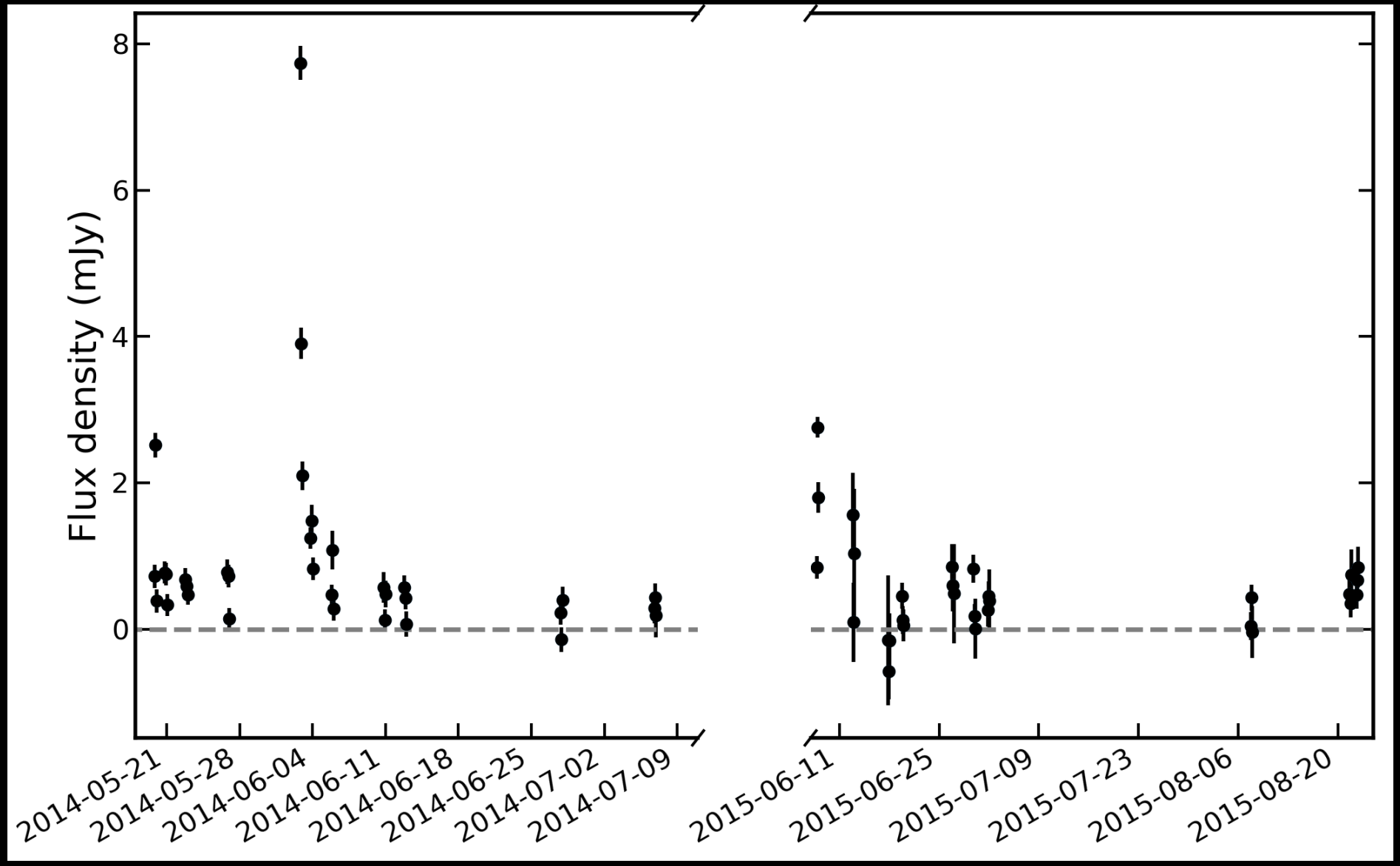
- Detected a whole bunch of active stars. Loss-cone maser does not seem able to work – need something more efficient

Toet et al. (submitted)

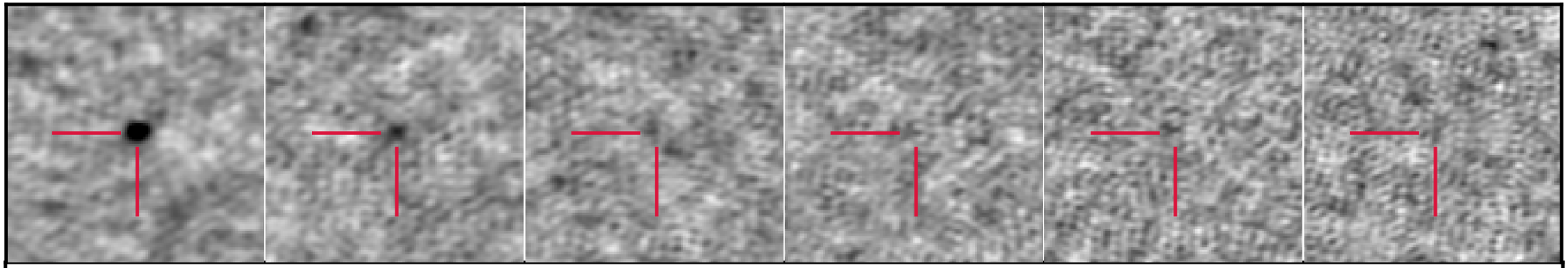


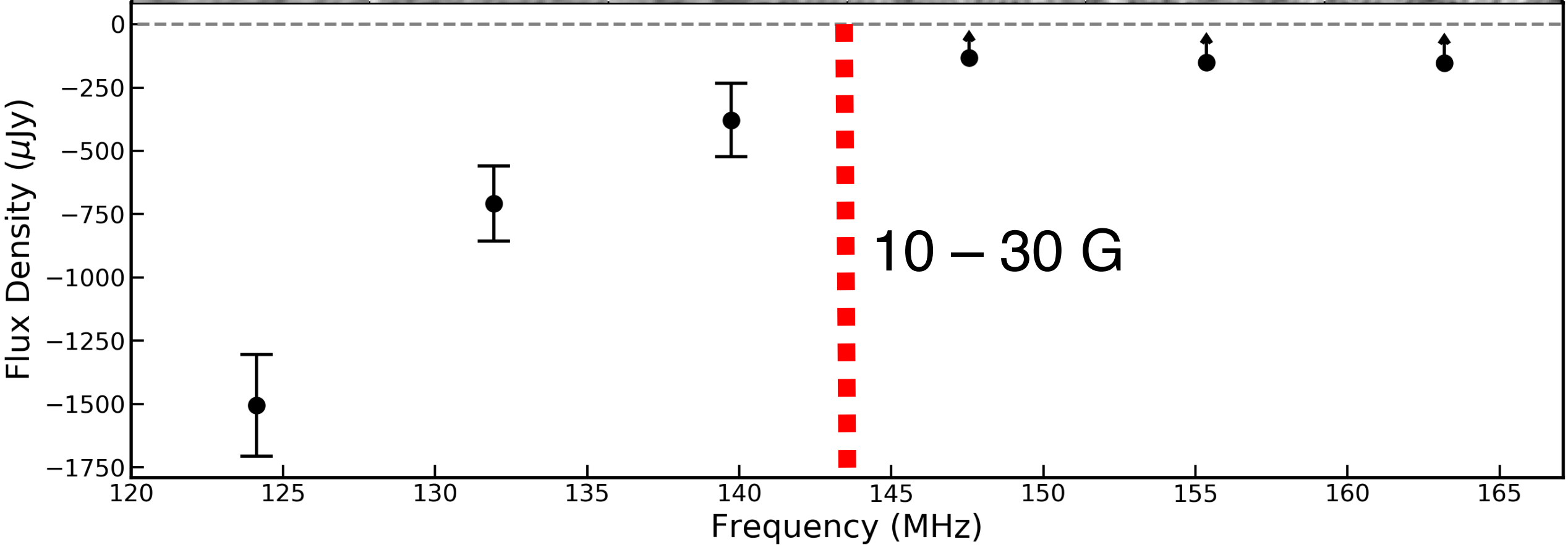


Bursts from CR Dra?

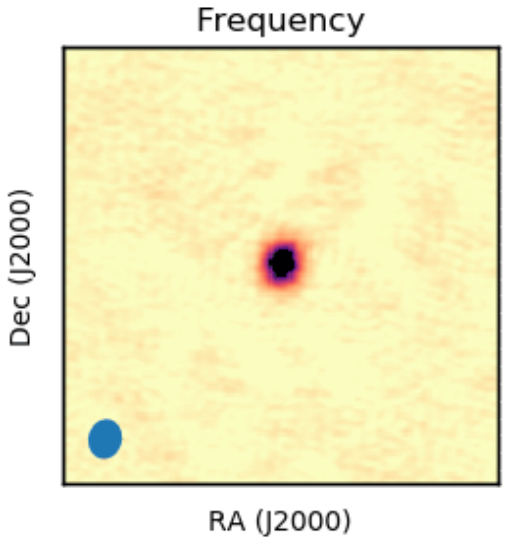


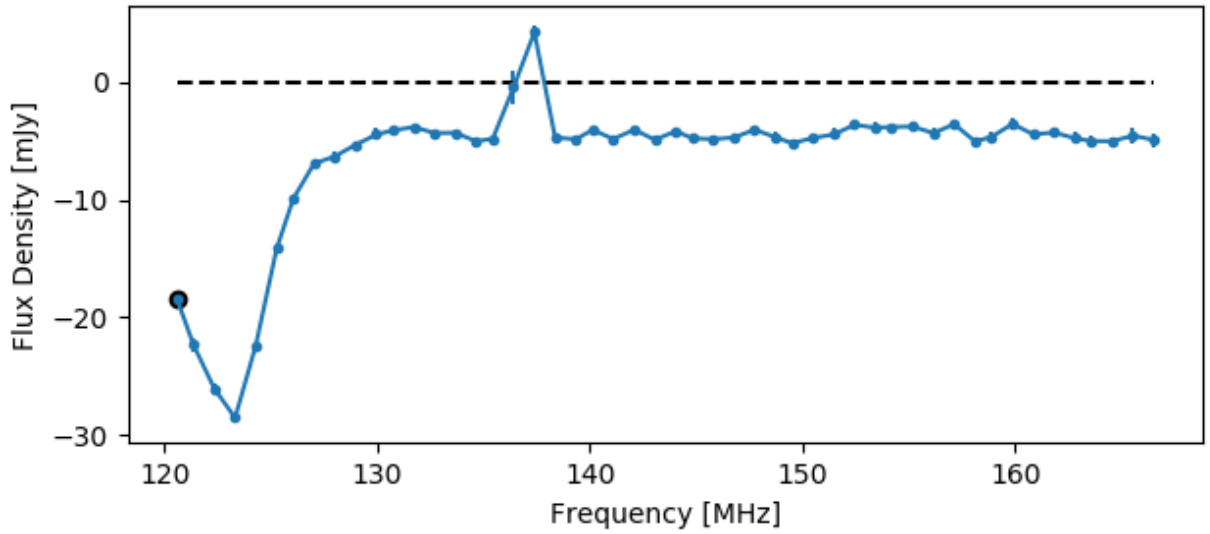
Cut-off in spectrum of candidate

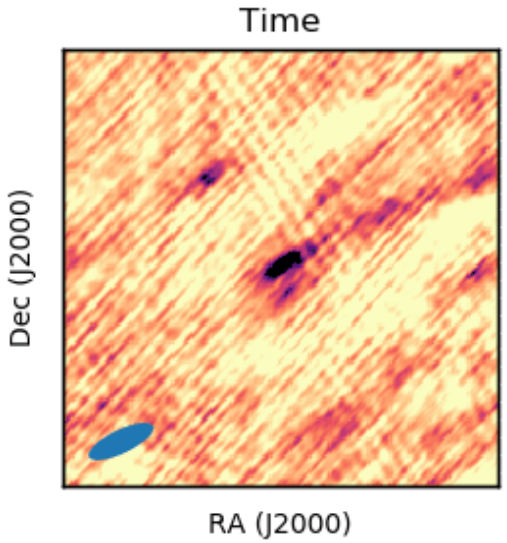


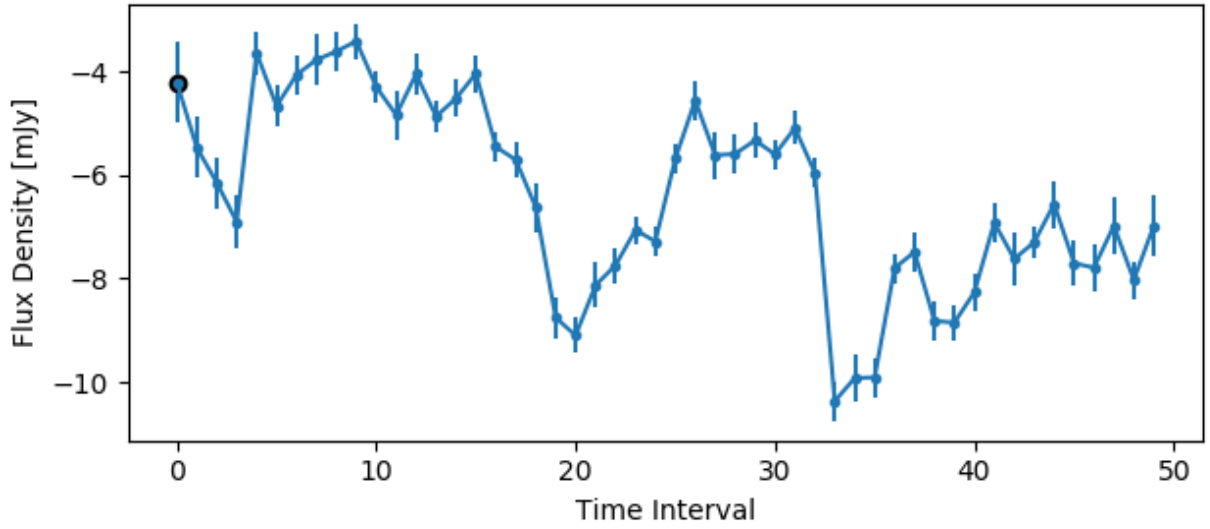


Data rich, theory poor









Lightcurves