Low-frequency radioastronomy and stellar physics

[KISS, 2016]

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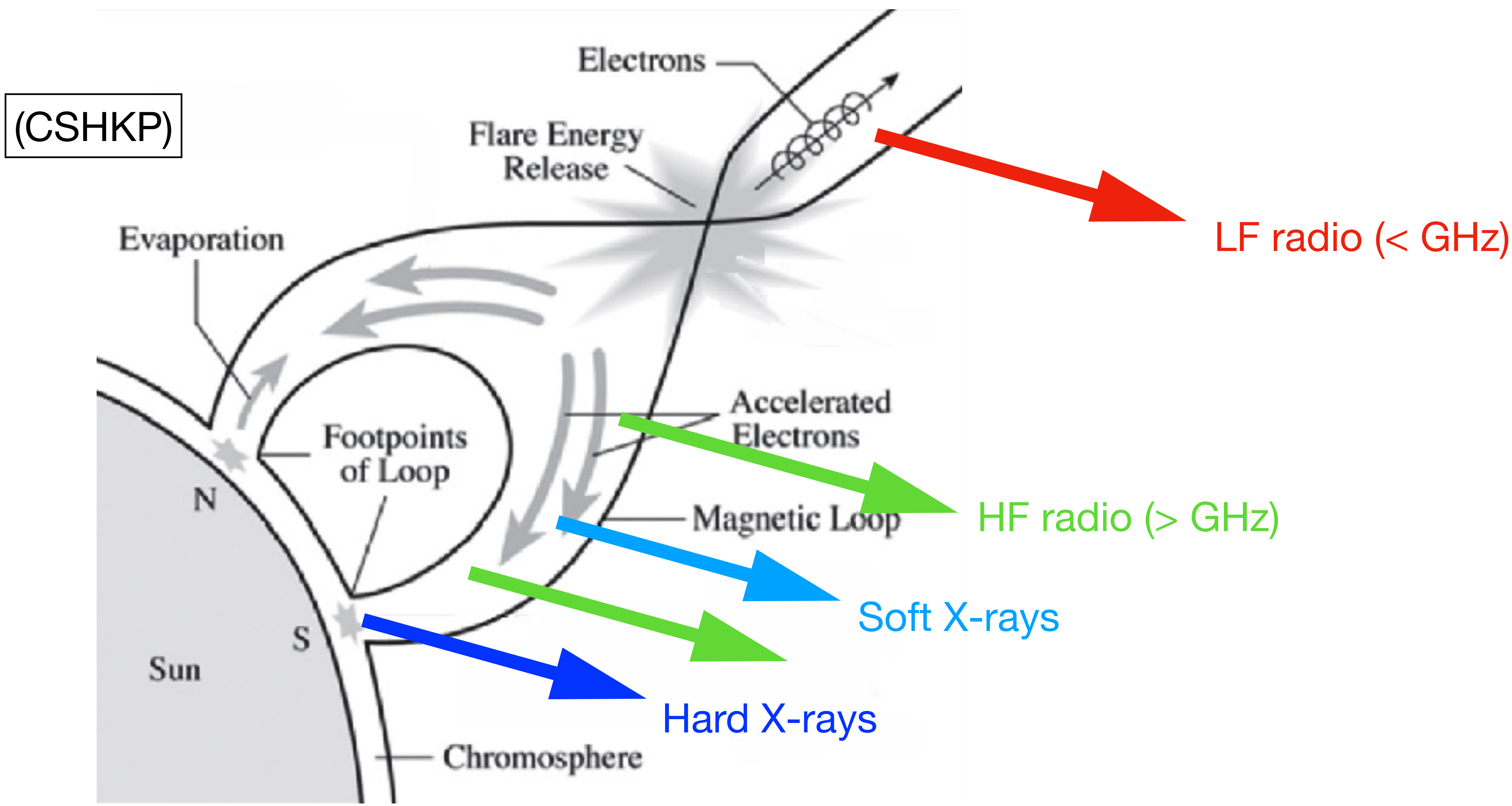
Standard Solar/stellar flare model

- Magnetic reconnection ⇒ e- acceleration ⇒ collisional heating of chromosphere/low corona
- Accelerated e- produce quasi-steady incoherent gyrosynchrotron emission (thermal/non-thermal, mostly HF (≥GHz) + hard X-rays at flux tube footprints
- Heated plasma produces soft X-rays (0.2-2 keV) via Bremsstrahlung (+ chromospheric lines e.g. Hα)



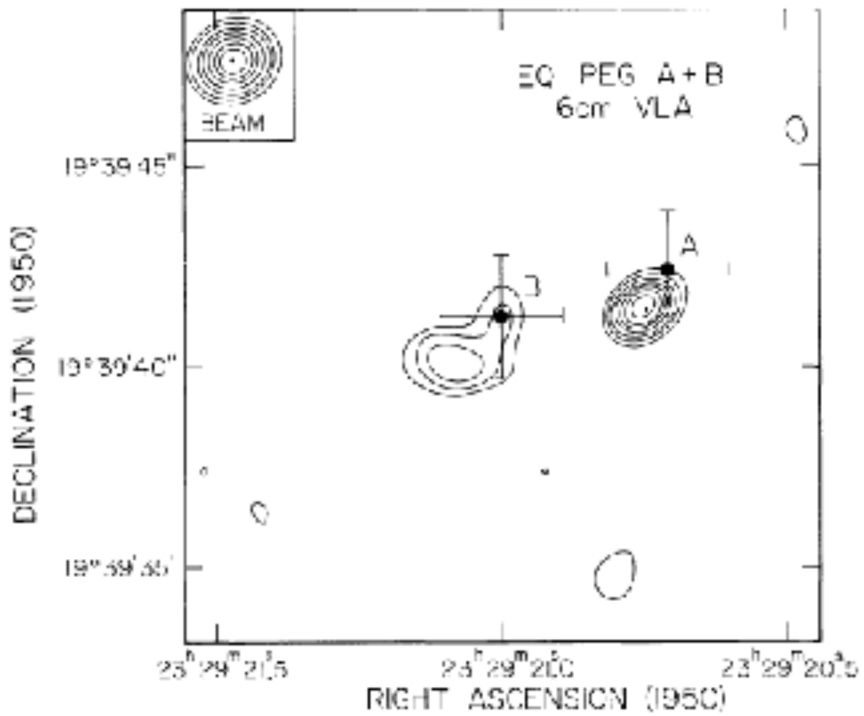
[Lang, 2006]

Standard Solar/stellar flare model

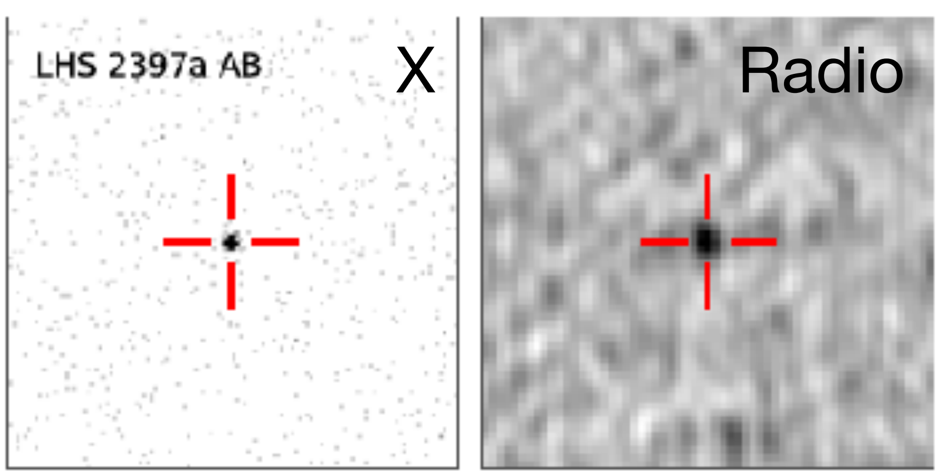
- Stellar radio & X-rays commonly detected
- Radio & X-rays are correlated (Neupert effect, Güdel-Benz relation)
  ⇒ interpreted in the frame of the standard flare model

[Neupert, 1968;
Güdel & Benz, 1993;
Benz & Güdel, 1994]

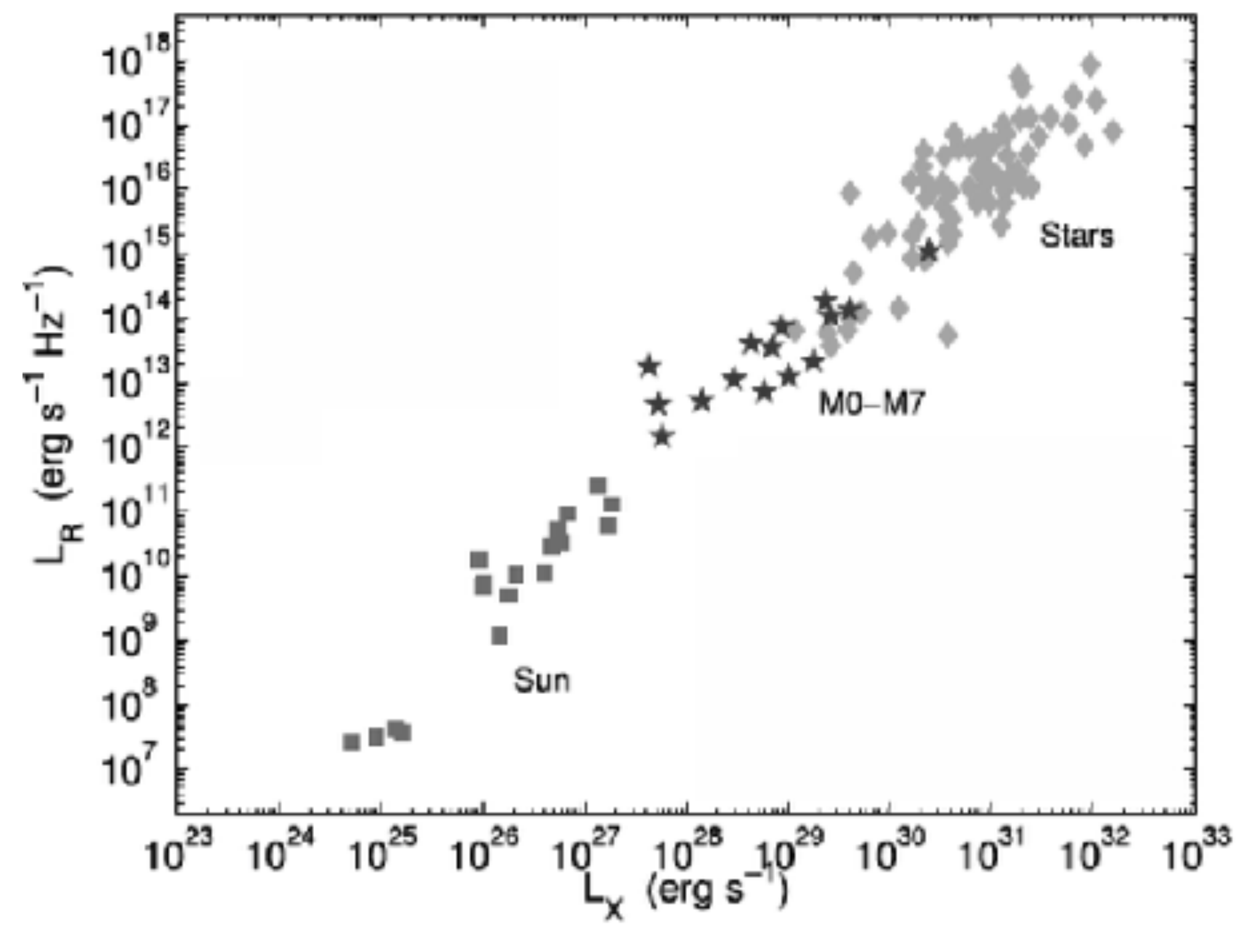
EQ Peg at 4.9 GHz (0.6 & 0.4 mJy), M4 & M6, 6.26 pc



[Dulk, 1985, from Topka & Marsch, 1982]



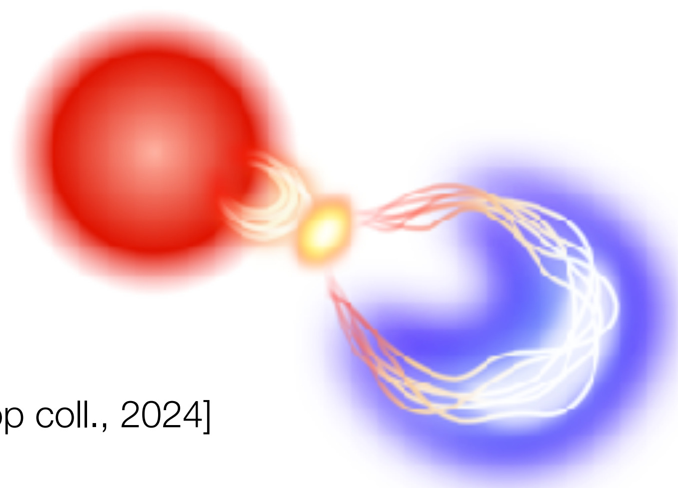
[Williams et al., 2014]



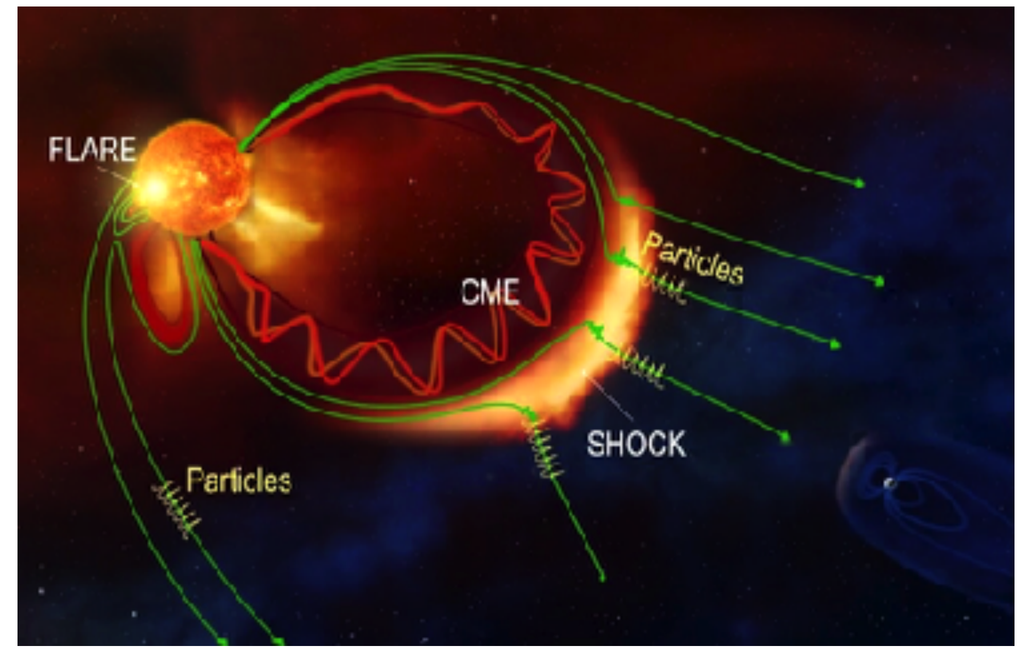
[Berger, 2006]

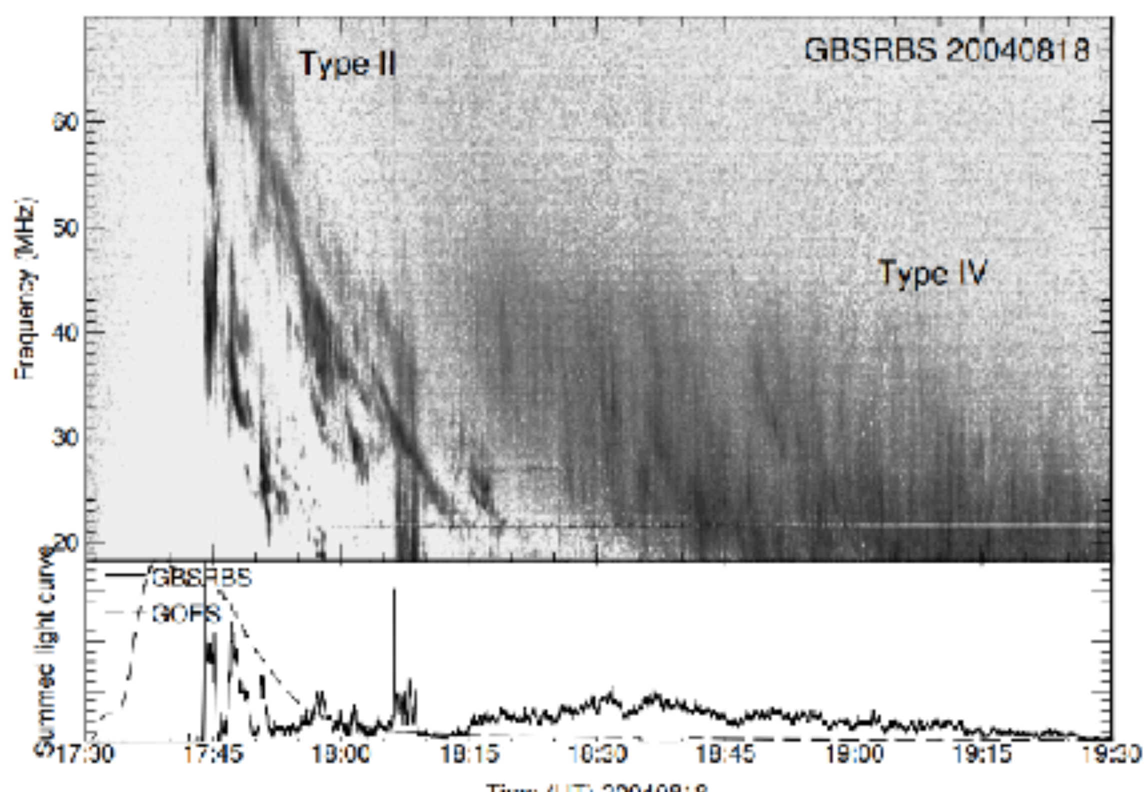
Low-Frequency radio emissions

- LF radio emissions come from higher in the corona: e- beams and CMEs (vectors of space weather)
- e- beams can be accelerated directly by magnetic reconnections, or by CME-associated shocks
- Accelerated e- produce bursts of coherent LF emission (tracers of space weather): plasma emission (f_{pe} or 2 f_{pe} = F, H), or Electron Cyclotron Maser (ECM)

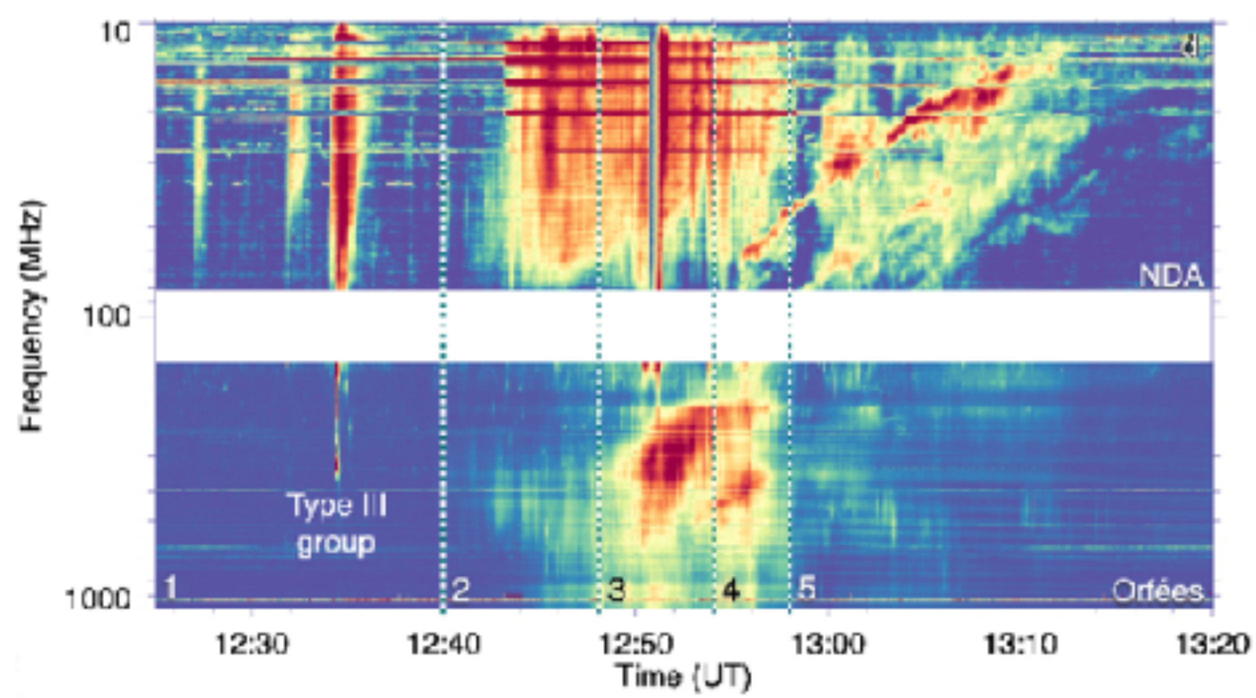


[Lorentz workshop coll., 2024]





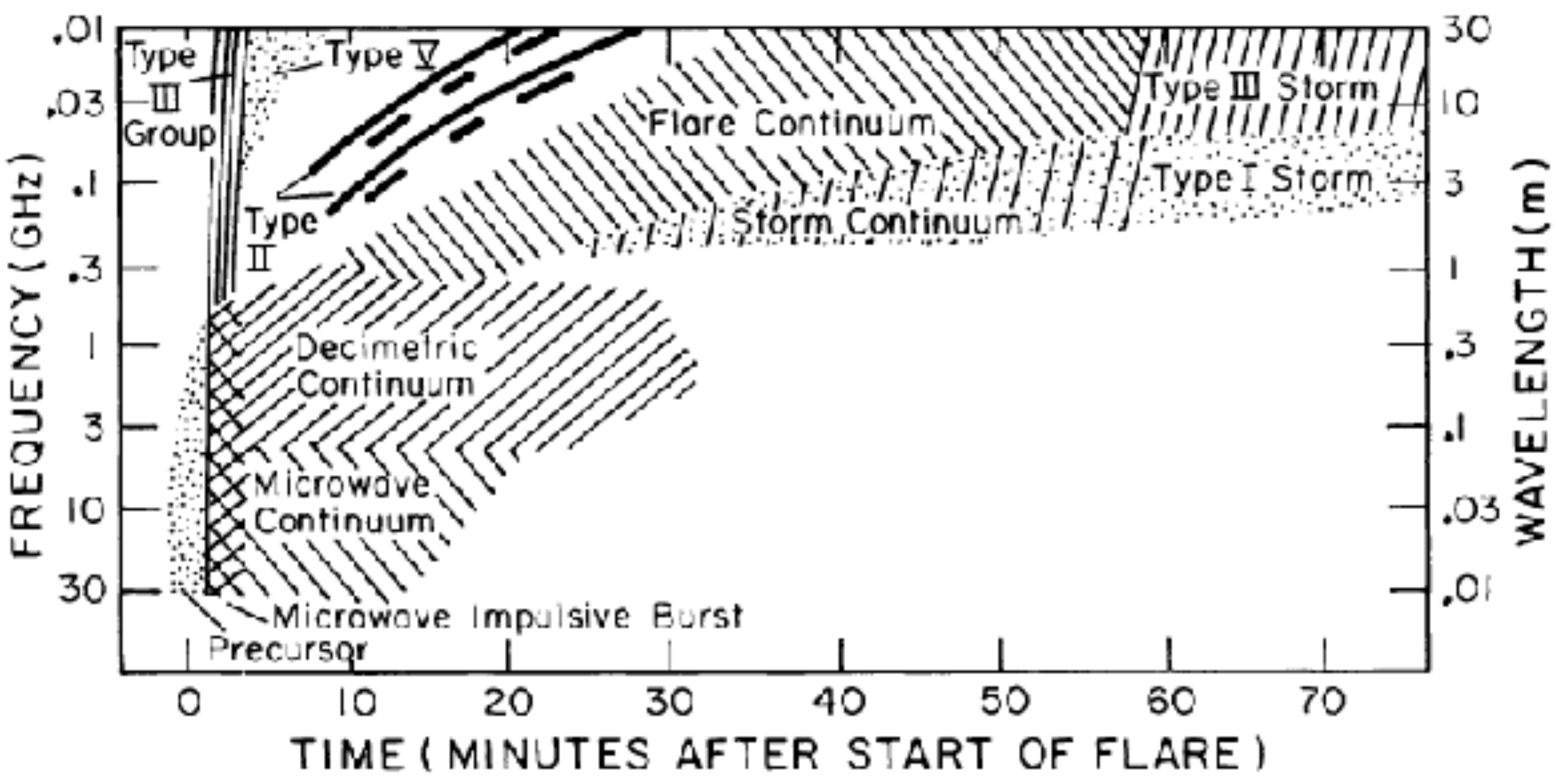
[White, 2007]



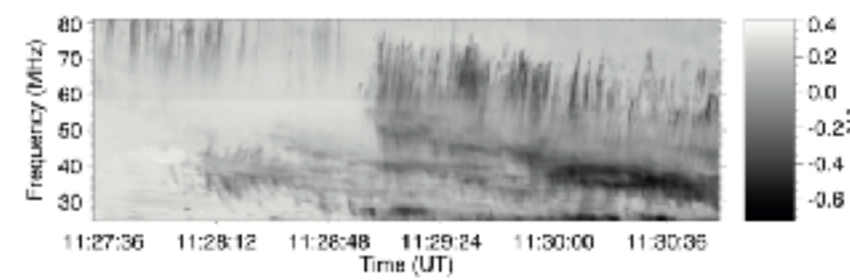
[SKA French White Book, 2017]

Low-Frequency radio emissions

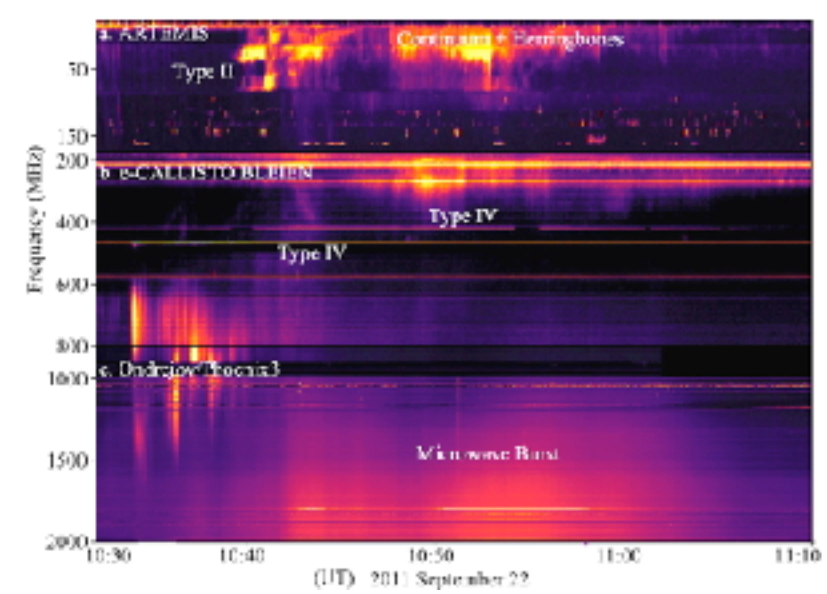
- 5 Solar burst types identified historically/morphologically:
  - Type I ("noise storm") : hours, continuum + bursts (related to non-eruptive active regions) → *F plasma emission from low altitudes*
  - Type II : minutes-hours, long + small-scale bursts (herringbones…), e- accelerated from shocks at CME edges → *F & H plasma emission* [only proof of escaping coronal material]
  - Type III : seconds, e- beams on open field lines → *F (& H?) plasma emissions*
  - Type IV : continuum from loops or flux ropes (several varieties), during/after decay phase of large flares, driven by continuous injection of energetic e- into post-flare magnetic structures, following CMEs (Type II) → *F plasma emission (or gyrosynchrotron)*
  - Type V : continuum, following type III → *H plasma emission ?*



[Dulk, 1985]



[Briand et al., 2022]



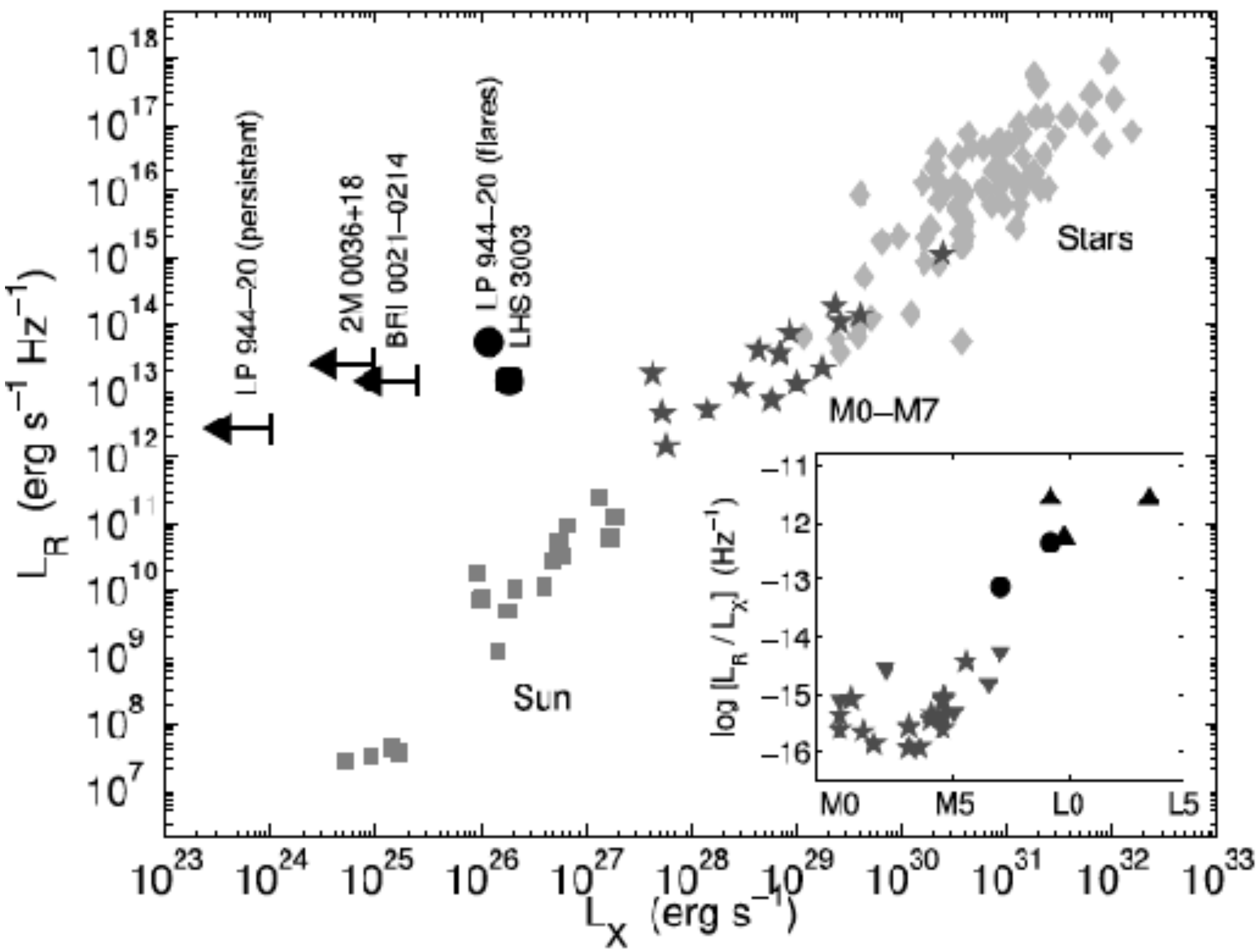
[Morosan et al., 2019]

- Emission process is identified via T_B, circular polarization, t-f structure/sporadicity, δf/f [see e.g. Vedantham, 2020]
- Bursts & flares are identified via correlation with optical/X activity.

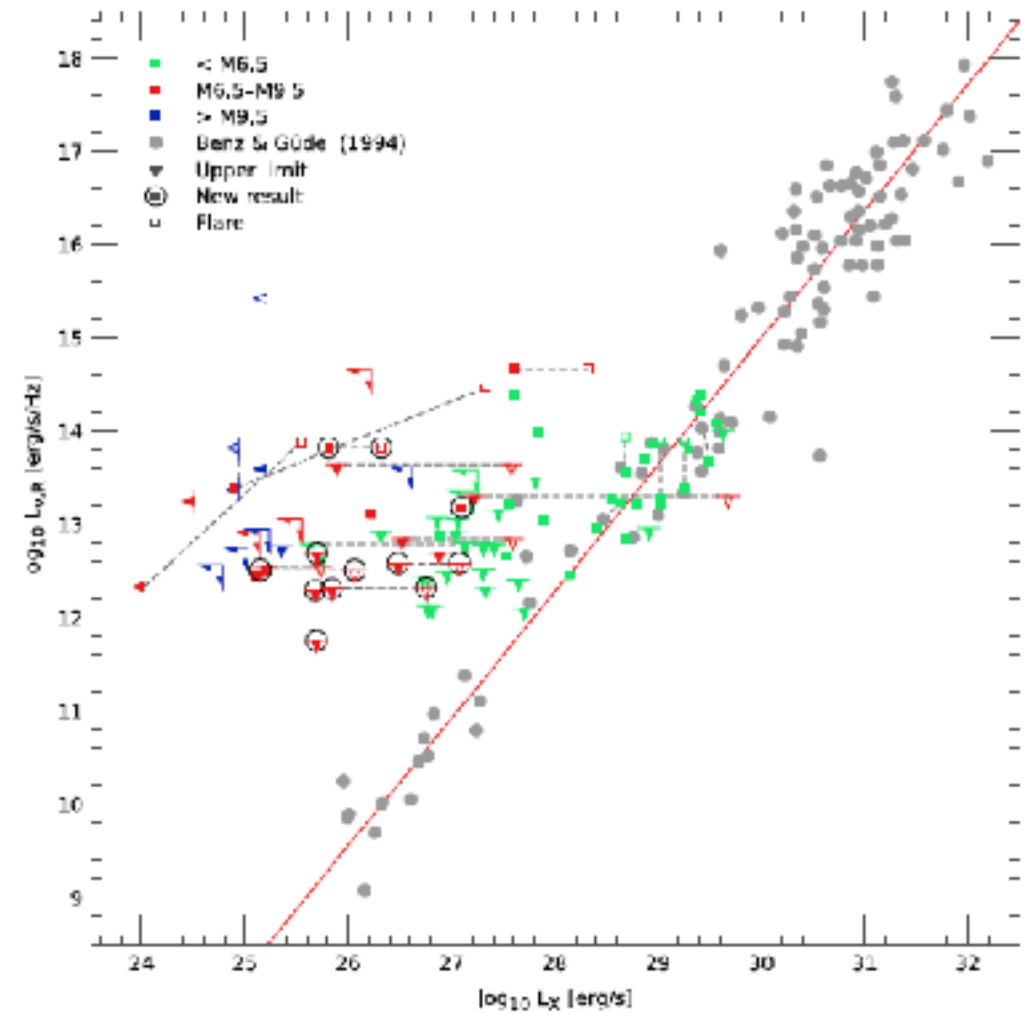
Stellar flares and radio emissions

- HF radio observations of stellar flares can be interpretation via standard flare model (flares at all scales), but low mass stars (late M, L, T, Y) are over-luminous in radio

VLA 8.46 GHz [Berger, 2006]



VLA 5.-8.46 GHz [Williams et al., 2014]

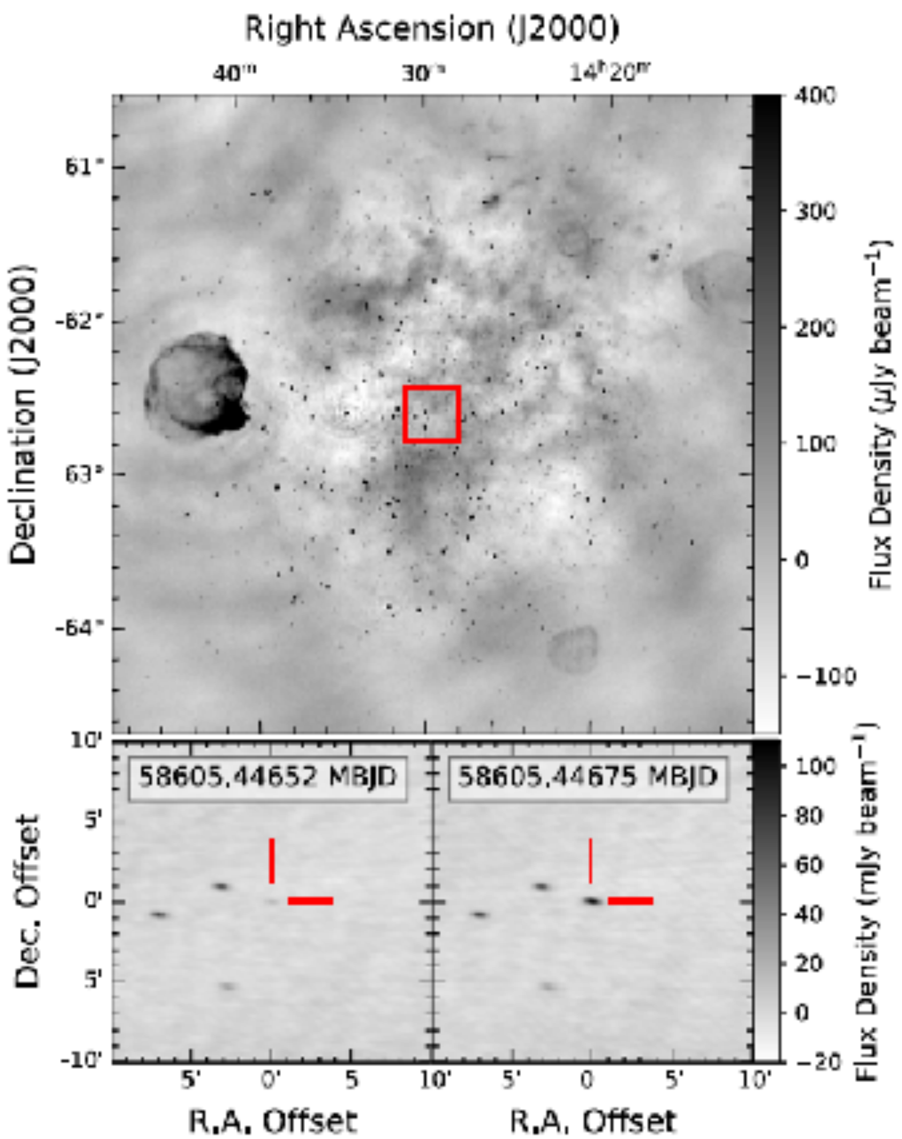


⇒ intensive observations of low-mass stars, more numerous & more active than solar-type stars

⇒ search for LF radio bursts

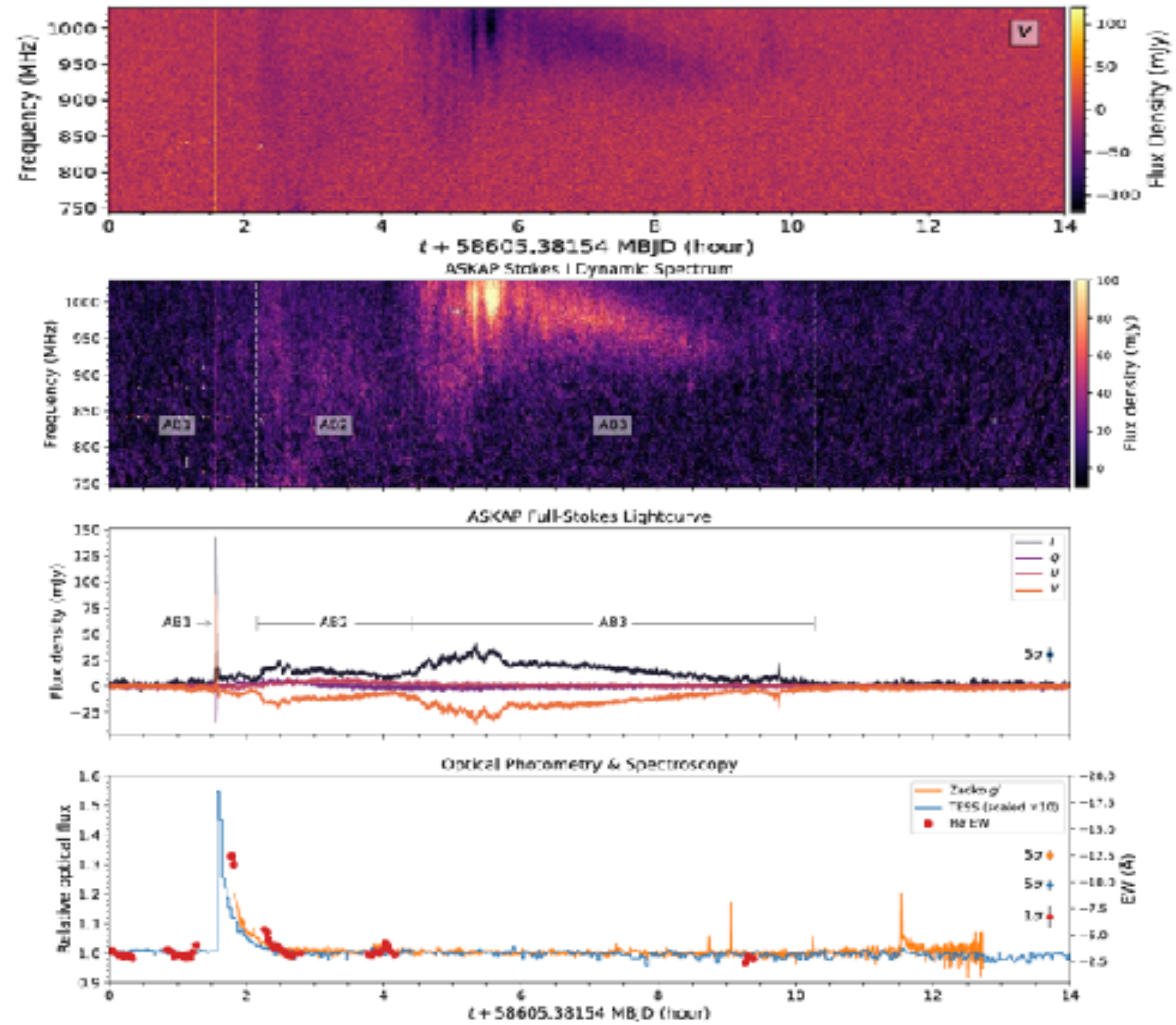
Stellar radio bursts

- Only one type IV detected up to now: Proxima Centauri (M5.5, 1.3 pc, P_{rot}=83.5d) with ASKAP



[Zic et al., 2020]

Dynamic spectrum obtained by sum of visibilities at phase center



(+ possible strong radio burst from dM4.0e star YZ Canis Minoris in time-series data with the Jodrell Bank interferometer at 408 MHz, beginning ~17 minutes after flaring activity in optical and X-ray wave bands ⇒ putatively identified as type IV)

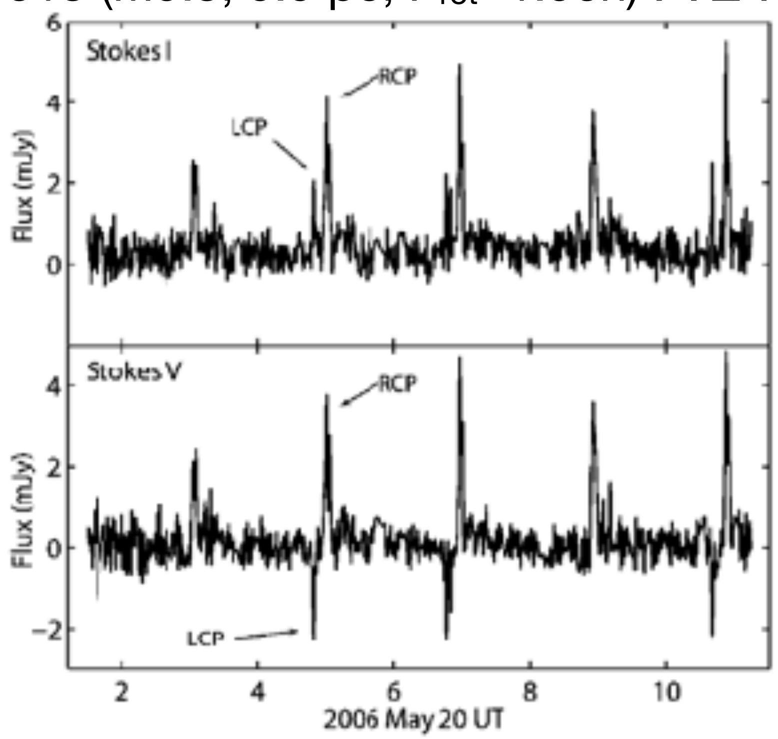
[Kahler et al., 1982]

- Why no type II: sensitivity ? trapping of plasma in strong magnetic field of M dwarfs ? CMEs sub-Alfvénic ?

Radio bursts from low-mass stars

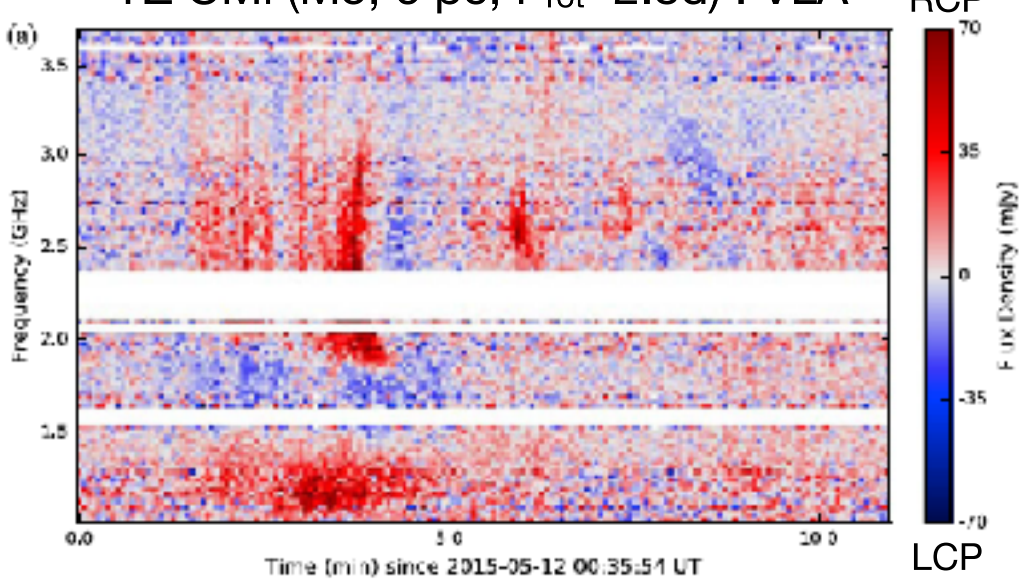
- Bursts from low-mass stars dominated by ECM emission
  periodic, beamed, circularly polarized, intense, unrelated to flares ⇒ ~ no solar analogue
- ⇒ due to large scale B (kG) ? fast-rotation ?

TVLM 513 (M9.3, 9.9 pc, P_{rot}=1.96h) : VLA 8.44 GHz

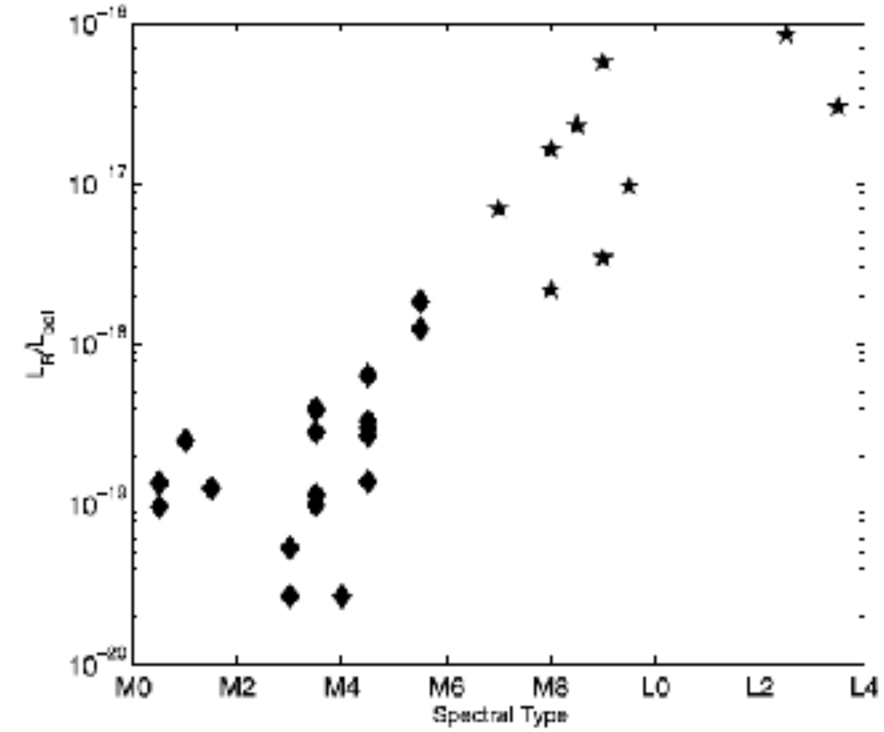


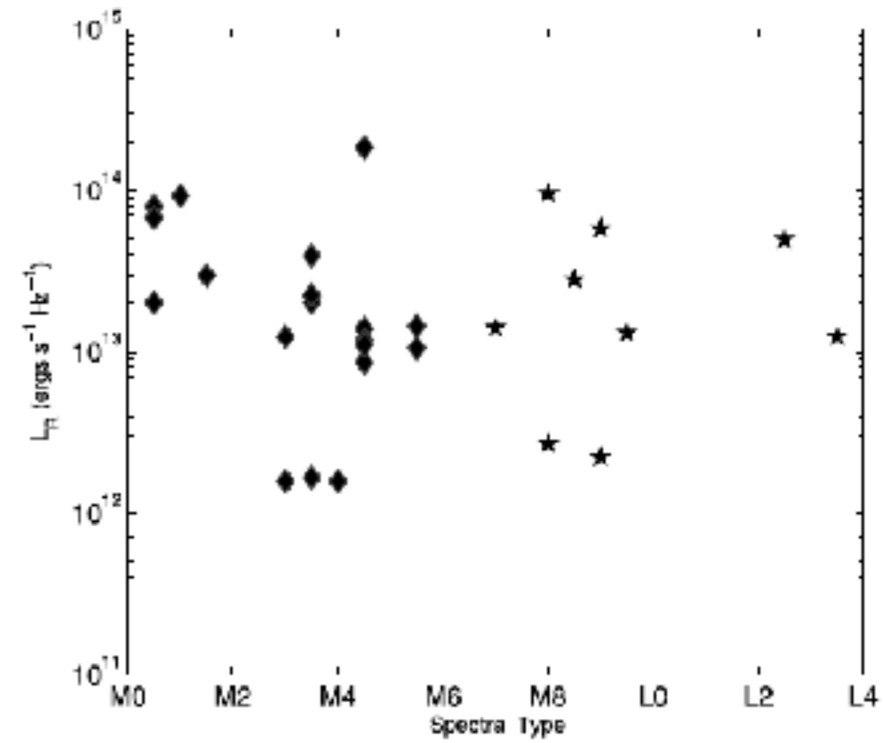
[Hallinan et al., 2007]

YZ CMi (M5, 6 pc, P_{rot}=2.8d) : VLA



[Villadsen & Hallinan, 2019]



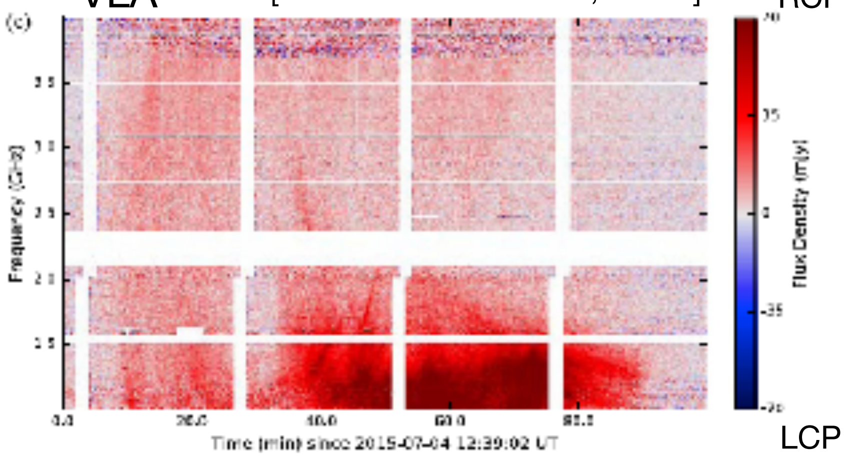


[Hallinan et al., 2008]

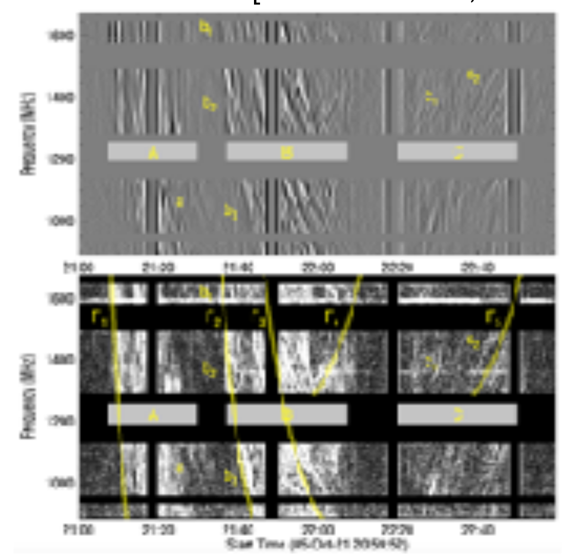
Radio bursts from low-mass stars

- UV Ceti (M5.5, 2.7 pc, P_{rot}=5.45h)

VLA [Villadsen & Hallinan, 2019]

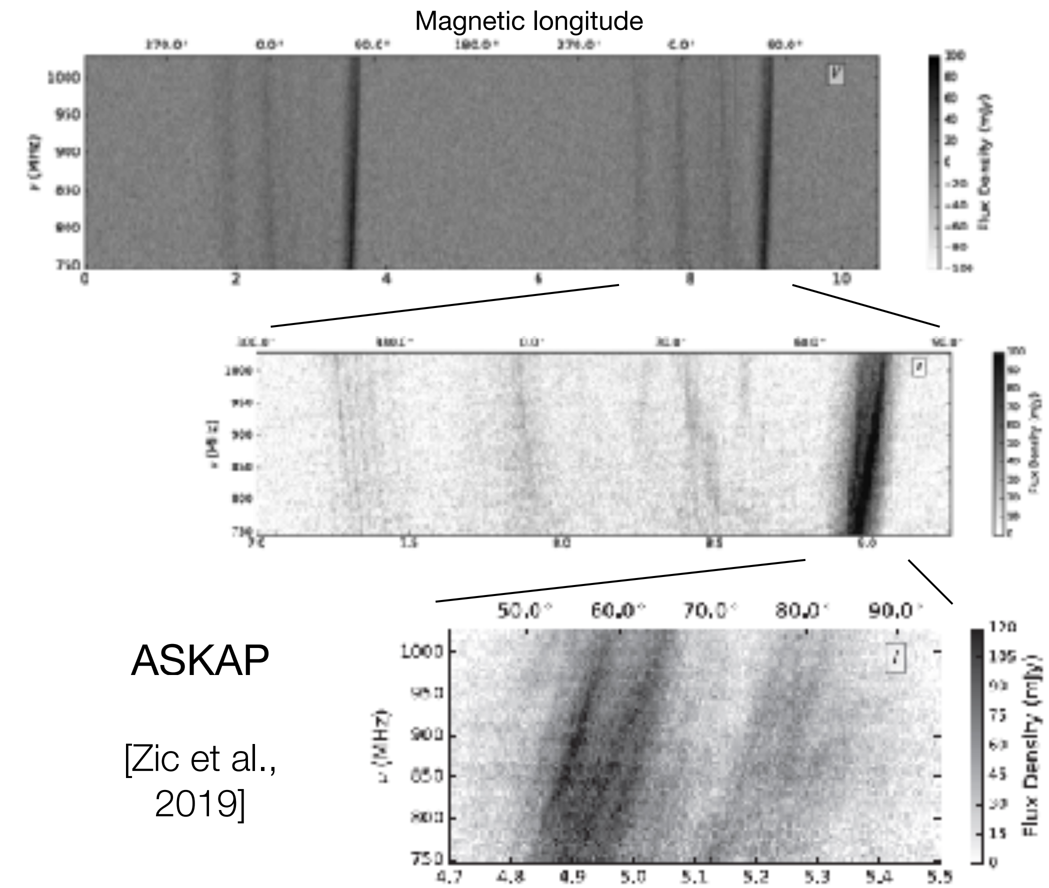


MeerKAT [Bastian et al., 2022]



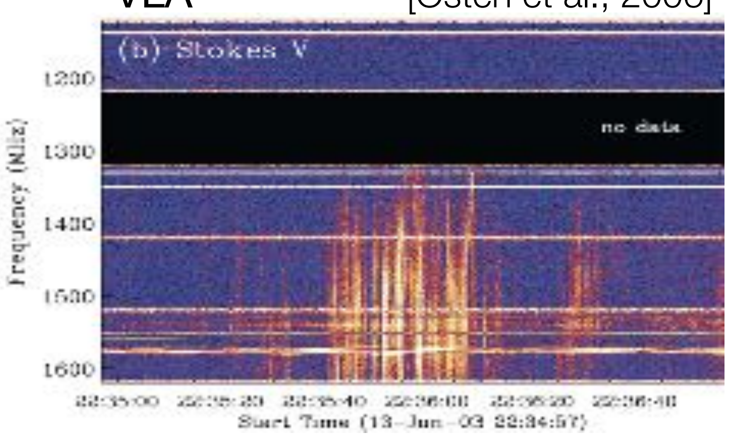
ASKAP

[Zic et al., 2019]

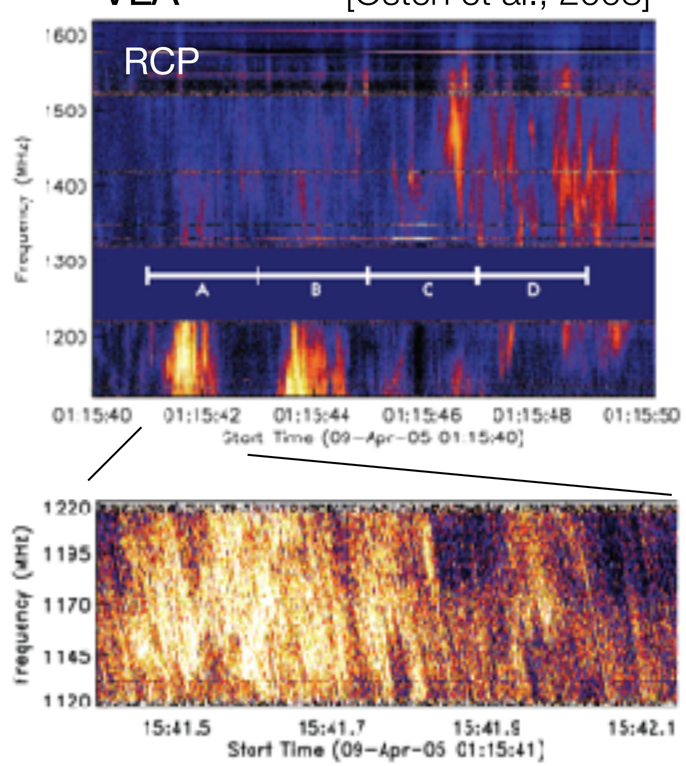


- AD Leo (M3.5, 4.97 pc, P_{rot}=2.23d)

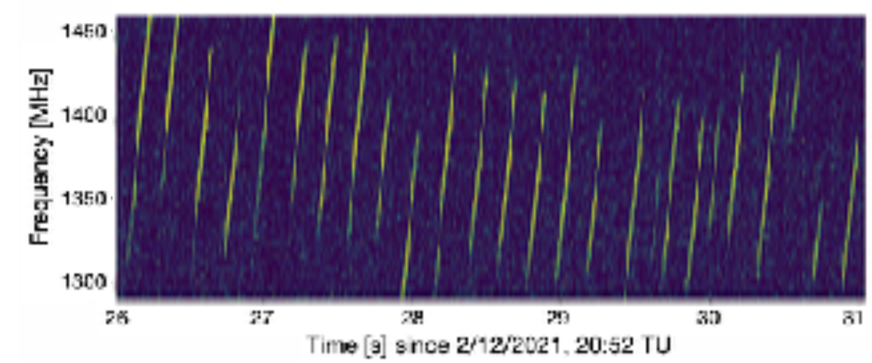
VLA [Osten et al., 2006]



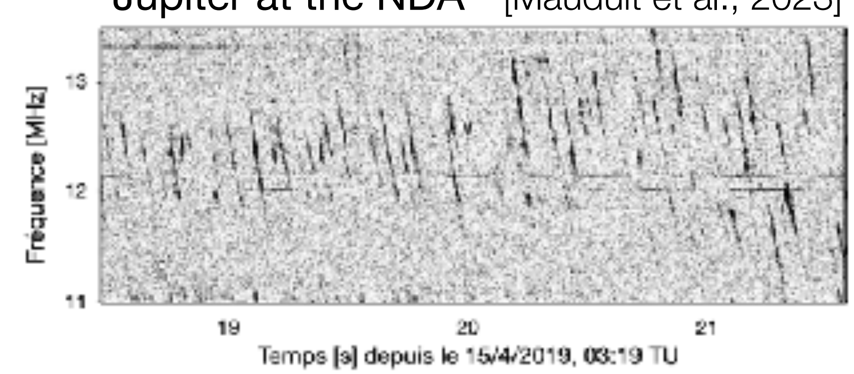
VLA [Osten et al., 2008]



FAST [Zhang et al., 2023 ; Zarka, Louis et al., in prep.]



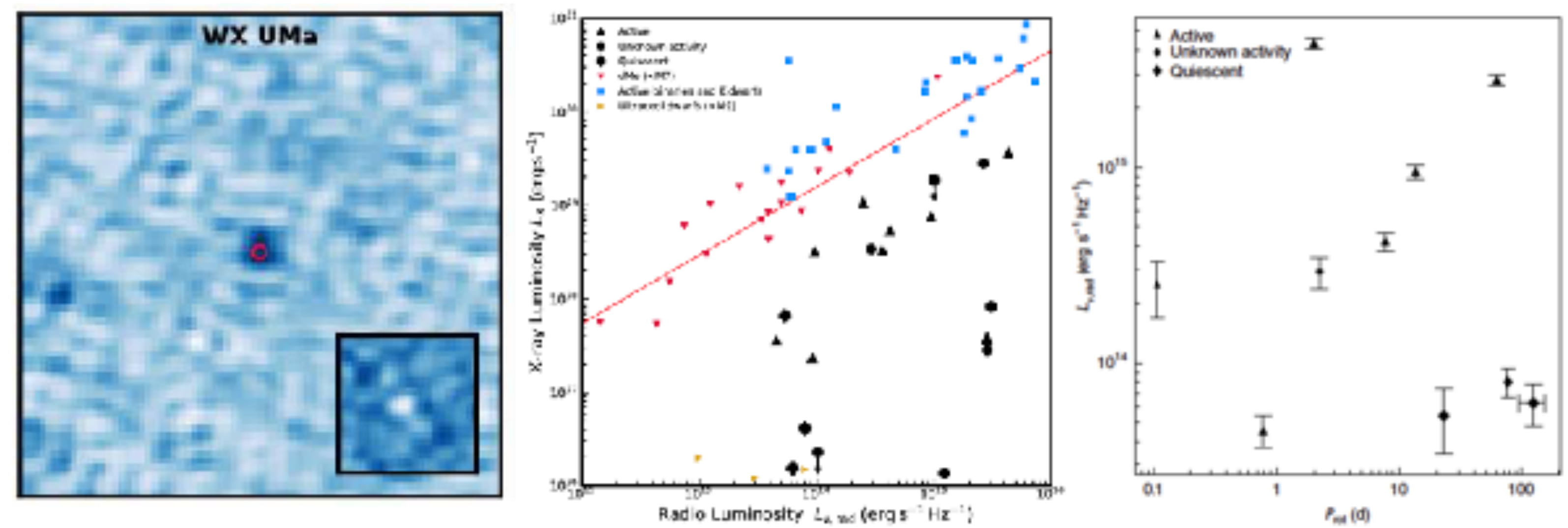
Jupiter at the NDA [Mauduit et al., 2023]



- drifting bursts, reminiscent of Jupiter S-bursts ⇒ supports ECM

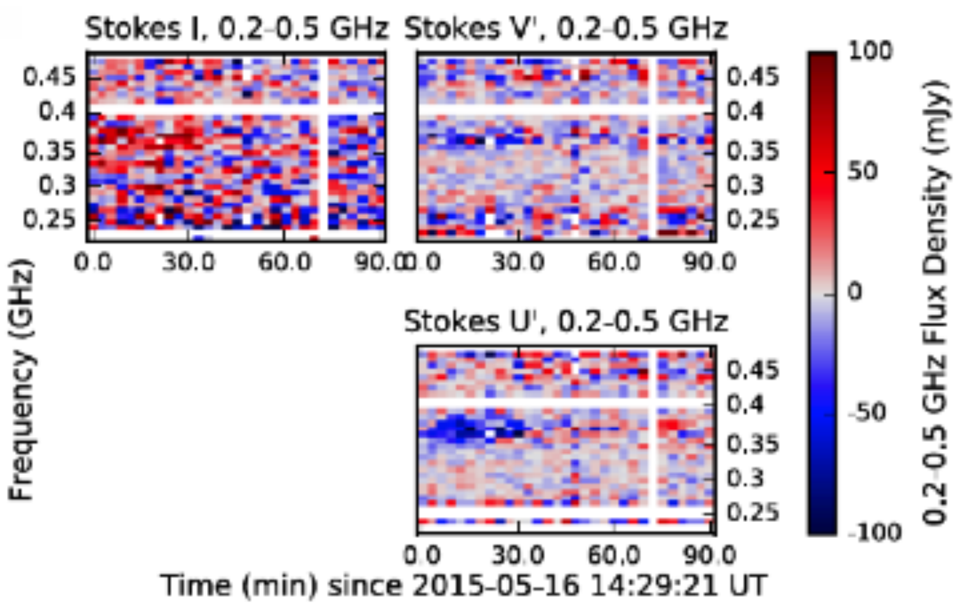
LF radio bursts from low-mass stars

LOFAR: 19 M dwarfs, M1.5 to M6, at 144±24 MHz



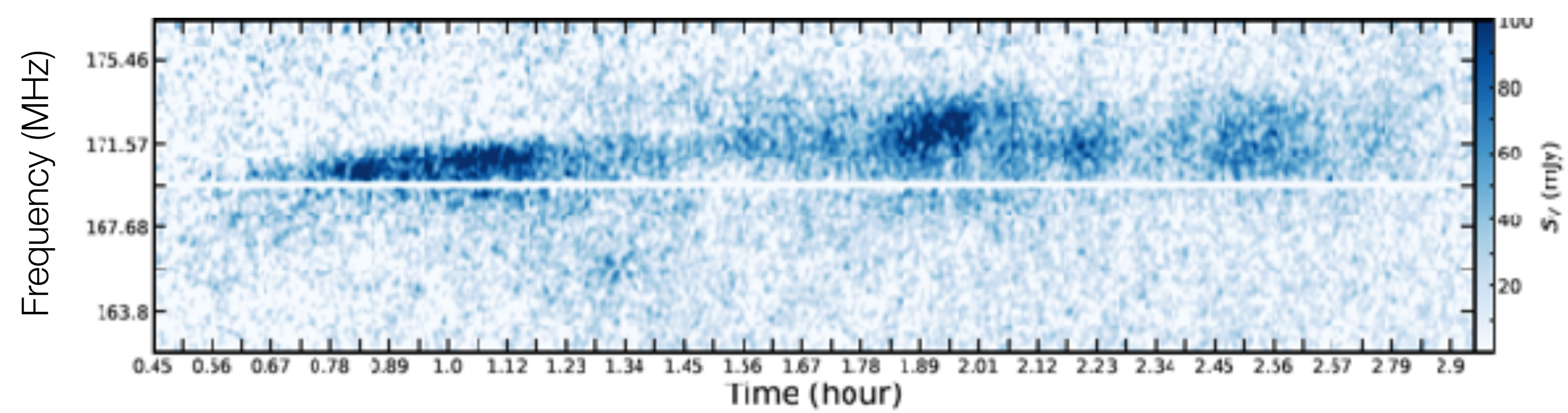
[Callingham et al., 2021a]

EQ Peg (M4 & M6, 6.26 pc) : VLA



[Villadsen & Hallinan, 2019]

LOFAR: CR Dra, M1.5, 20.4 pc, P_{rot}=1.984d

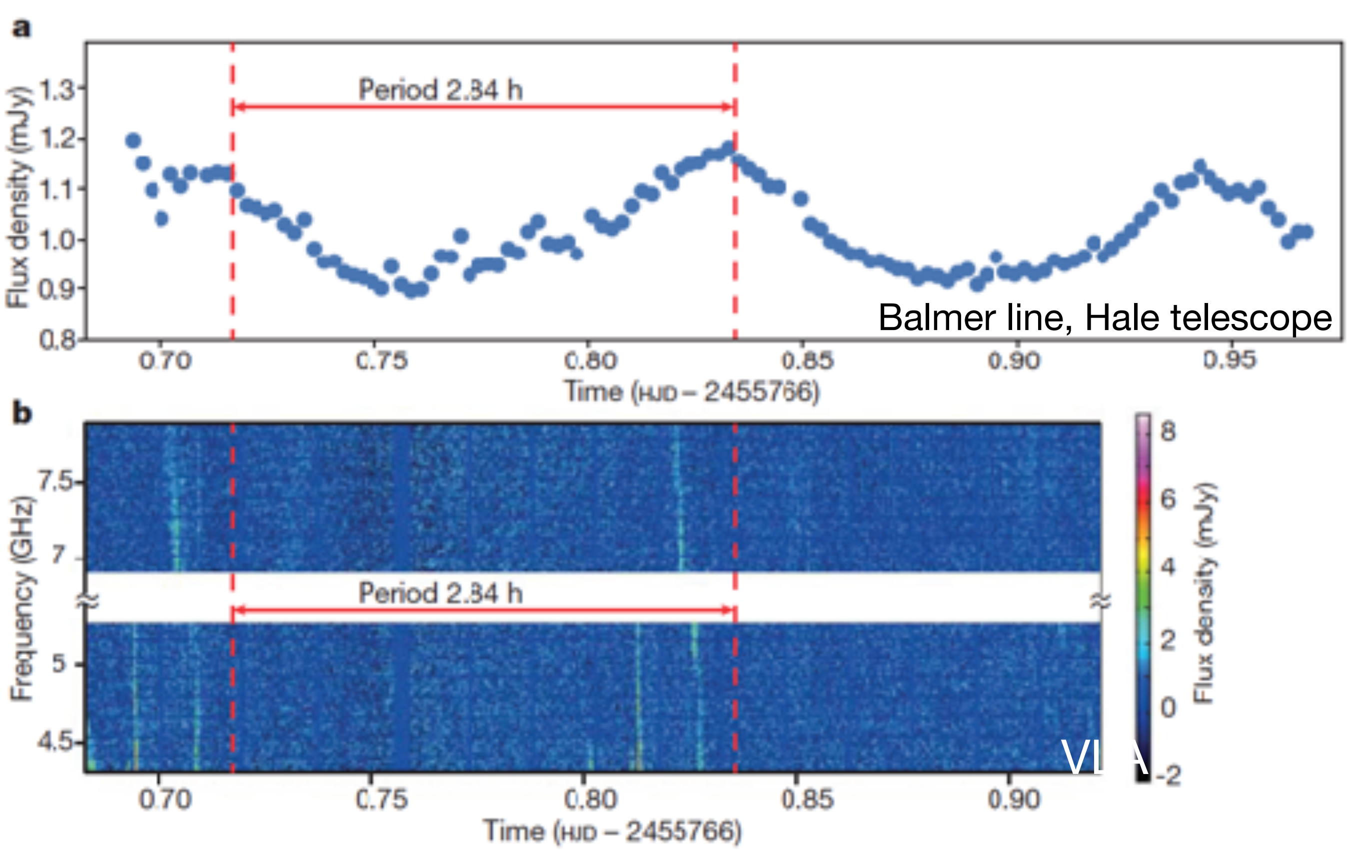


[Callingham et al., 2021b]

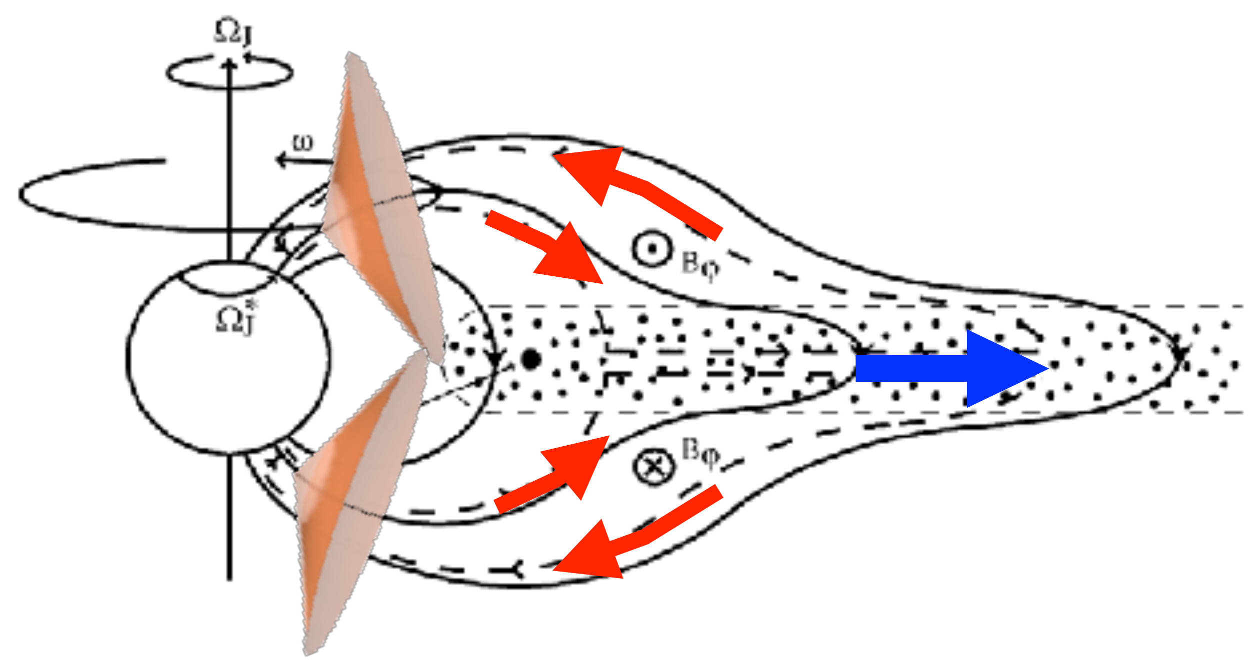
Auroral-like stellar radio emissions ?

- ECM ⇒ magnetosphere-like emissions (large scale B for low mass stars similar to Jupiter's) ?
- require few keV e- beams ⇒ engine ?
  - Plasma corotation breakdown: origin of plasma = dense wind, CMEs, or planet (~Io at Jupiter), invoked e.g. for CR Dra [Callingham et al., 2021b]

LSR J1835+3259 (M8.5, 5.67 pc, P_{rot}=2.84h, low activity)



[Hallinan et al., 2015]

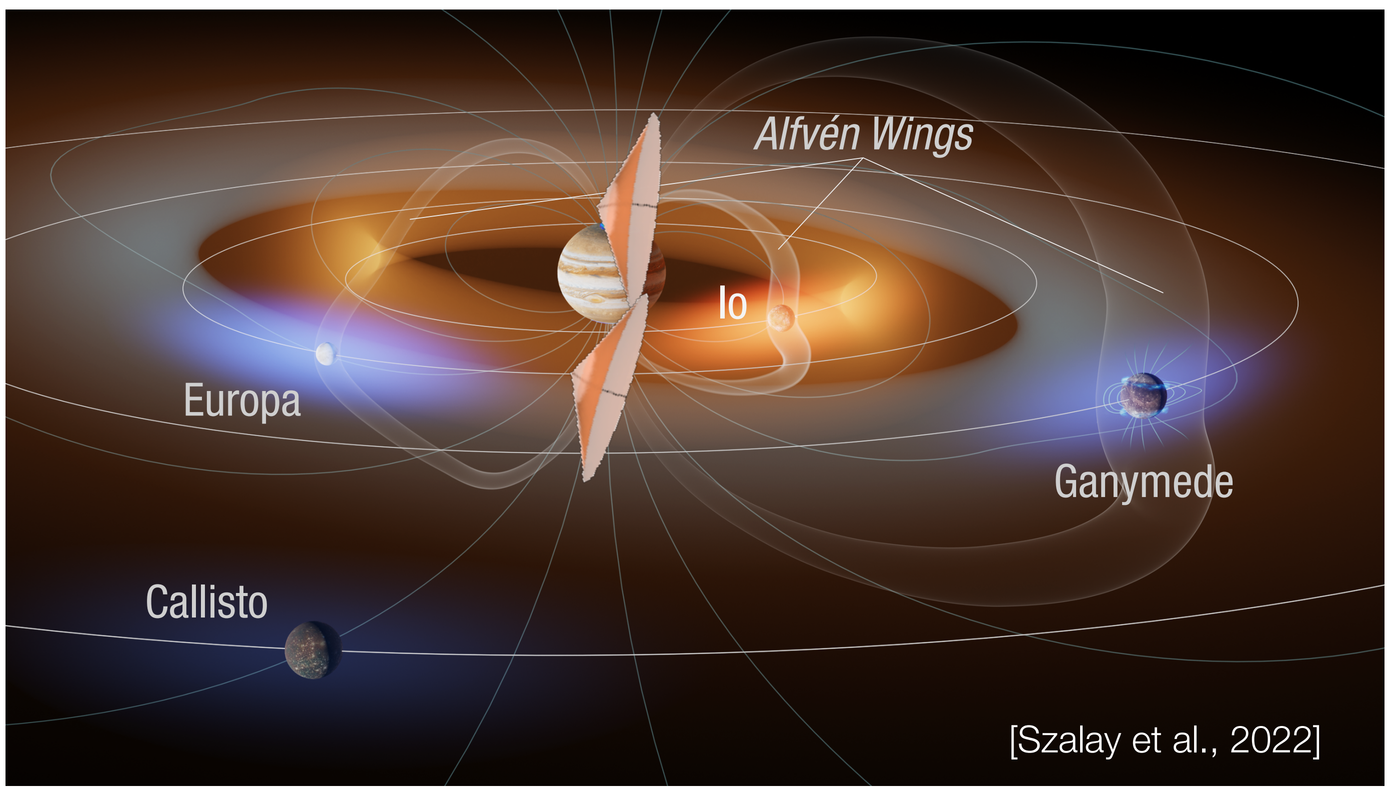


[Cowley & Bunce, 2001]

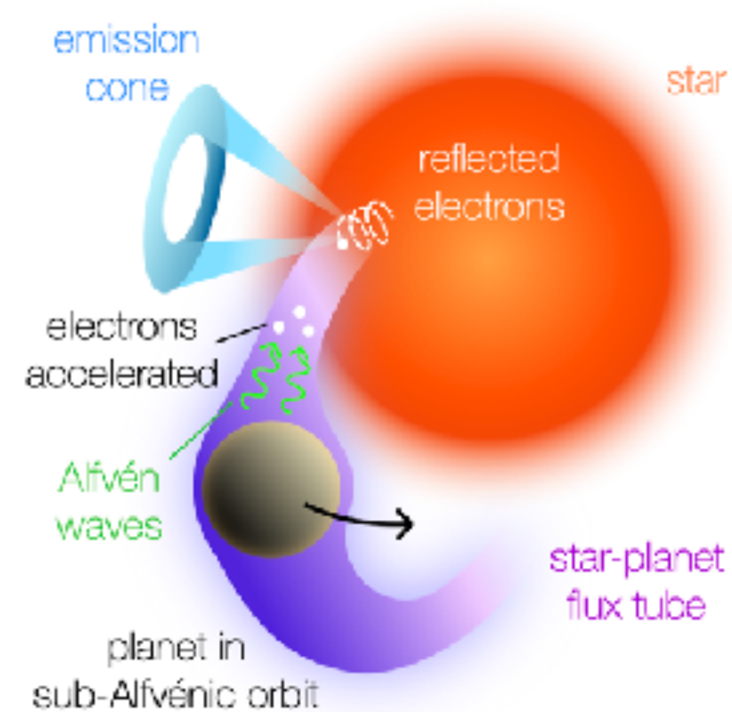
centrifugal motion ⇒ J// ⇒ accelerated e-

Auroral-like stellar radio emissions ?

- ECM ⇒ magnetosphere-like emissions (large scale B for low mass stars similar to Jupiter's) ?
- require few keV e- beams ⇒ engine ?
  - Plasma corotation breakdown: origin of plasma = dense wind, CMEs, or planet (~Io at Jupiter), invoked e.g. for CR Dra [Callingham et al., 2021b]
  - Star-Planet (plasma) Interaction inducing radio emission in stellar B field (~Io-Jupiter) [Vedantham et al., 2020a ; Perez-Torres et al., 2021 ; Pineda & Villadsen, 2023]



[Szalay et al., 2022]

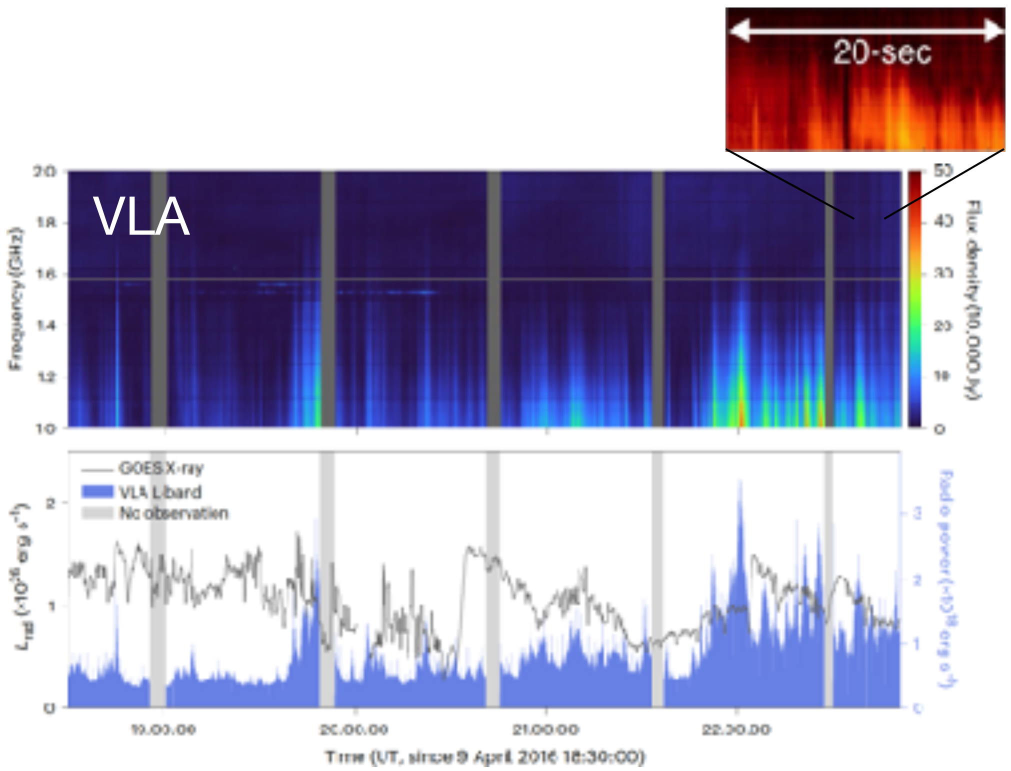


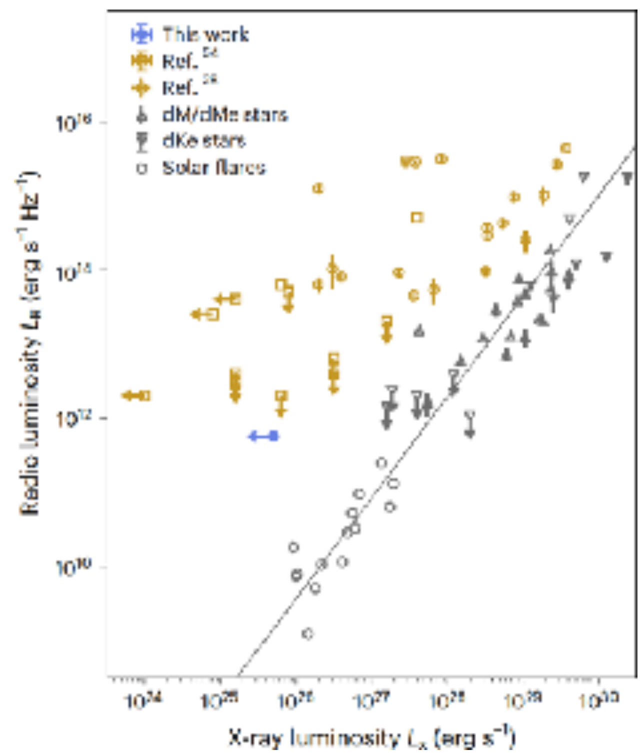
[Lorentz workshop coll., 2024]

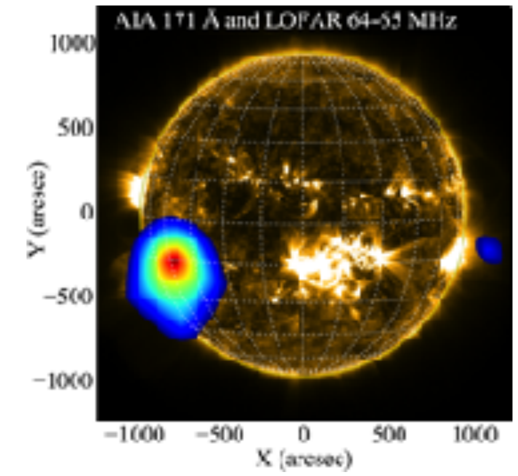
<u>NB</u>: Need of a plasma cavity when elliptical polarization is present: UV Ceti [Zic et al., 2019; Bastian et al., 2022], CR Dra [Callingham et al., 2021b] ; may be necessary in all cases to prevent CMI radiation a f_{ce} not to be absorbed at the second gyroresonant harmonic layer)

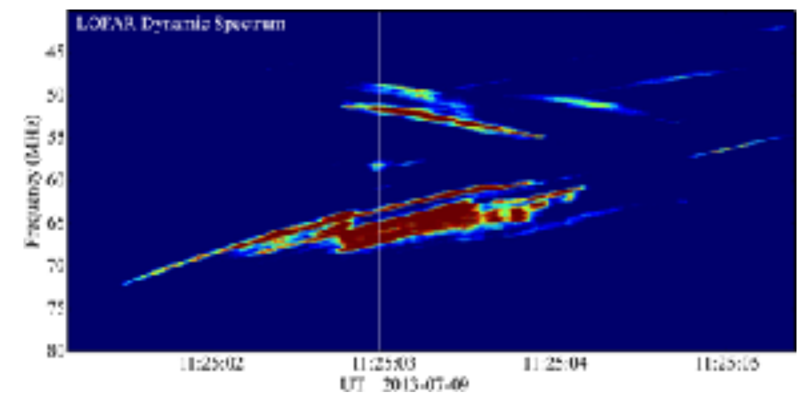
Auroral-like solar radio emissions ?

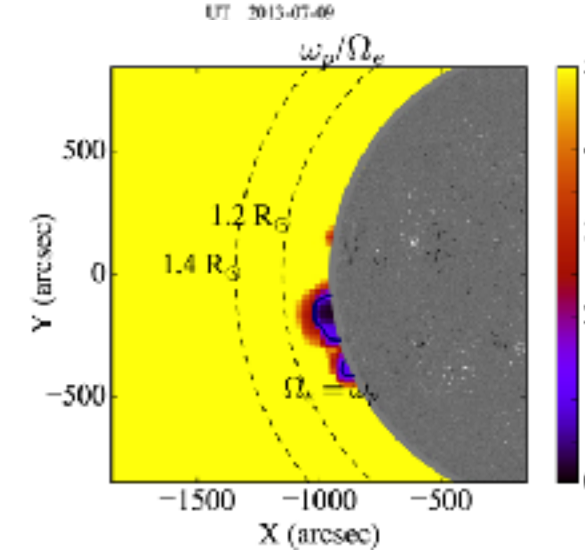
- Possible ECM in strongly Solar magnetic loops ⇒ « auroral-like » ? [Yu et al., 2023]
- Already seen by [Morosan et al., 2015, 2016]

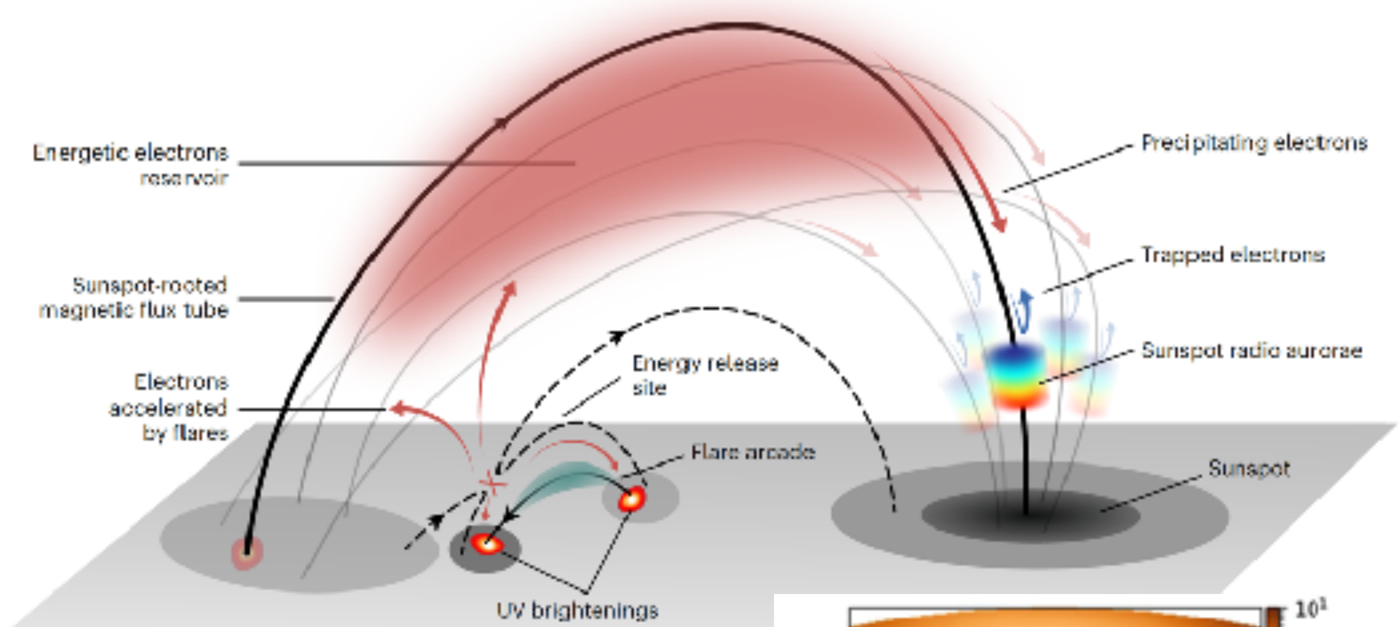


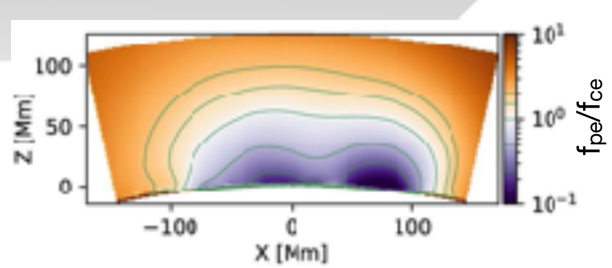










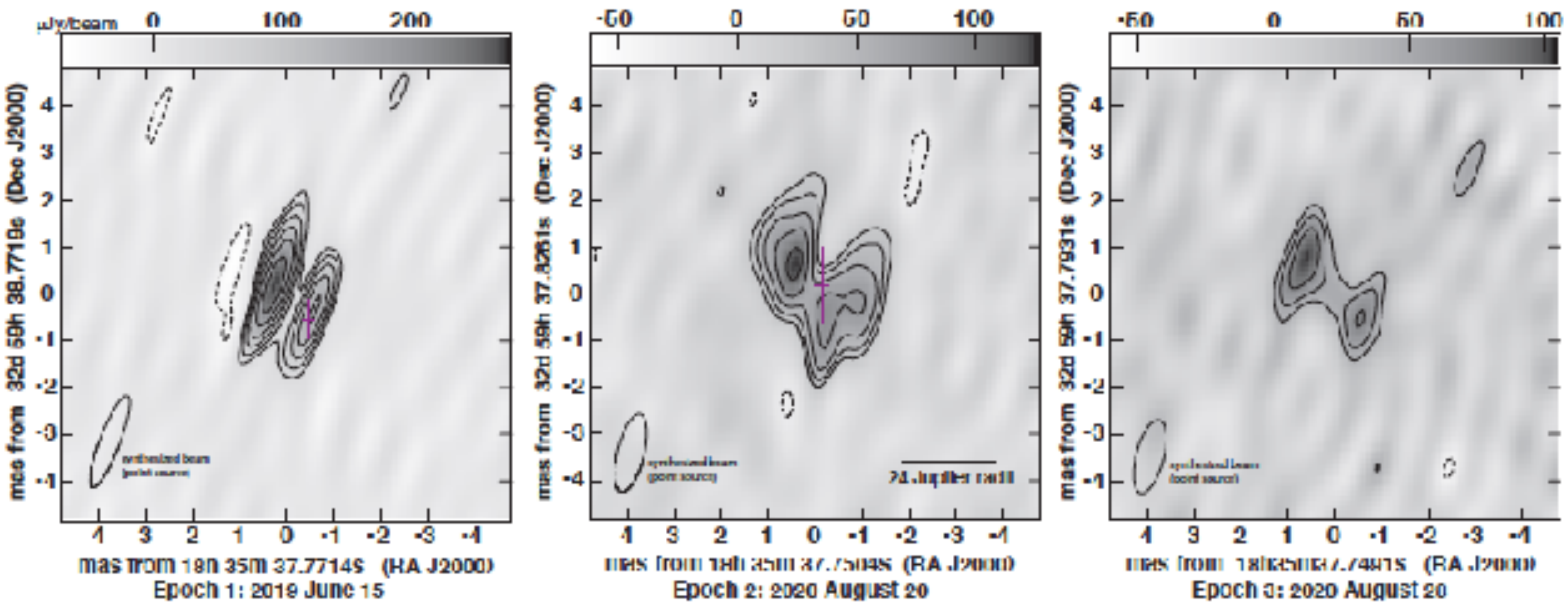


[Yu et al., 2023]

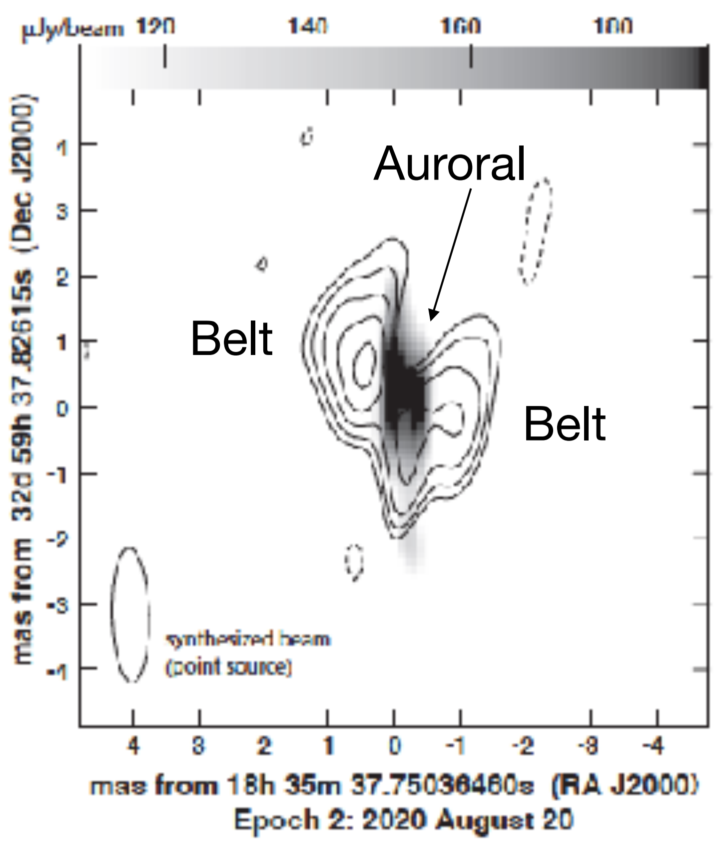
[Morosan et al., 2015, 2016]

Stellar radiation belts

LSR J1835+3259 (M8.5, 5.67 pc, P_{rot}=2.84h) : VLBA (VLA, GBT, Effelsberg)

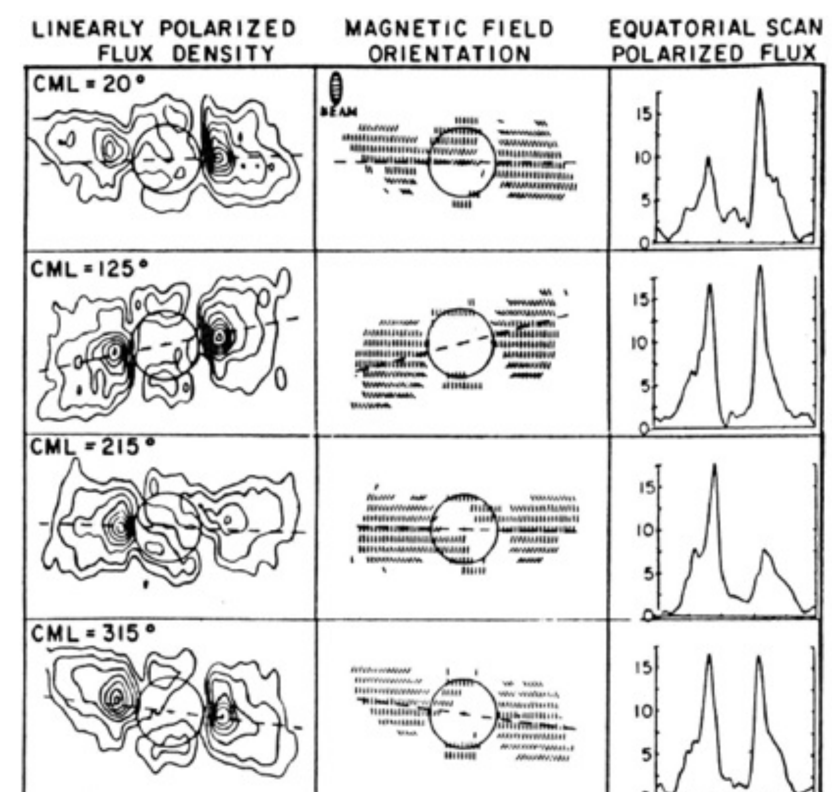


Auroral emission suppressed in time series
< 1 mJy
~15 MeV e-



[Kao et al., 2023 ; Climent et al., 2023]

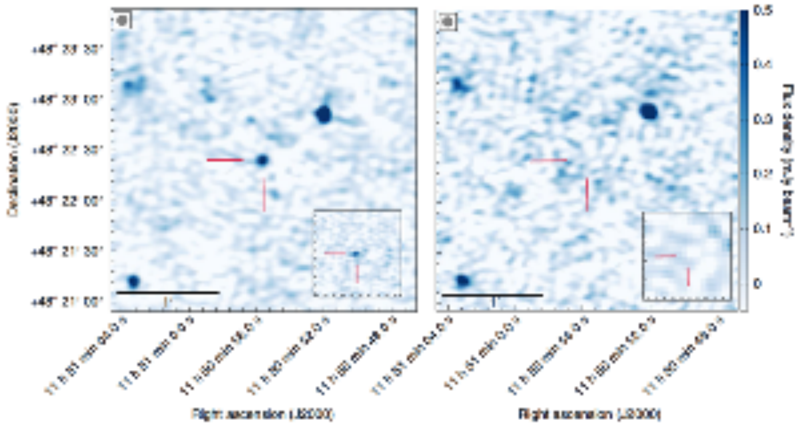
Jupiter : WSRT, 5 GHz

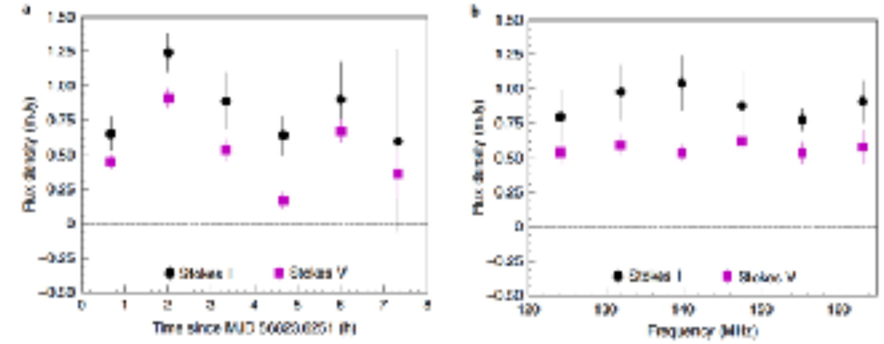


[Radhakrishnan & Roberts, 1960 ; de Pater, 1981]

Star-Planet Interactions ?

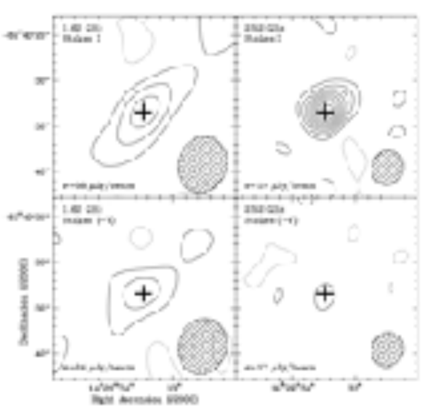
- GJ 1151 (M4.5, 8.04 pc, P_{rot} = 130d) : LOFAR, 144 MHz ⇒ Planet at P_{orb}~2 d ?

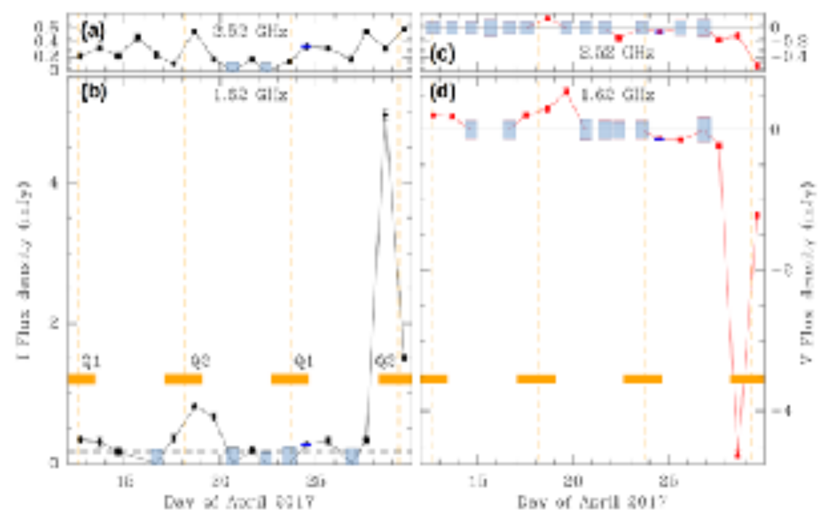




[Vedantham et al., 2020]

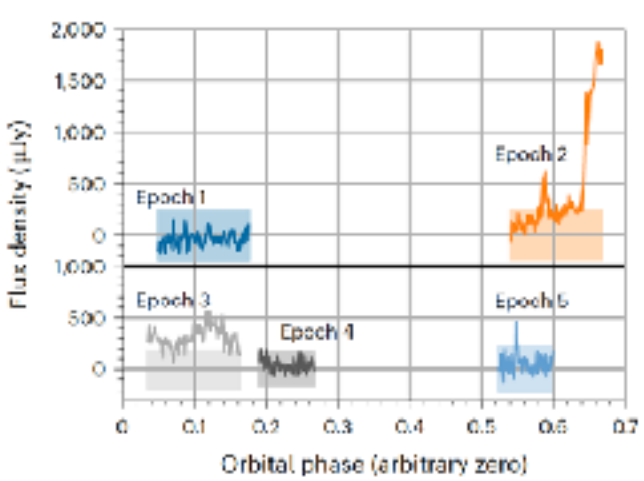
- Proxima Cen (M5.5, 1.3 pc, P_{rot} = 89d) : ATCA, 1.6-2.5 GHz ⇒ Proxima b, P_{orb} = 11.186 d ?

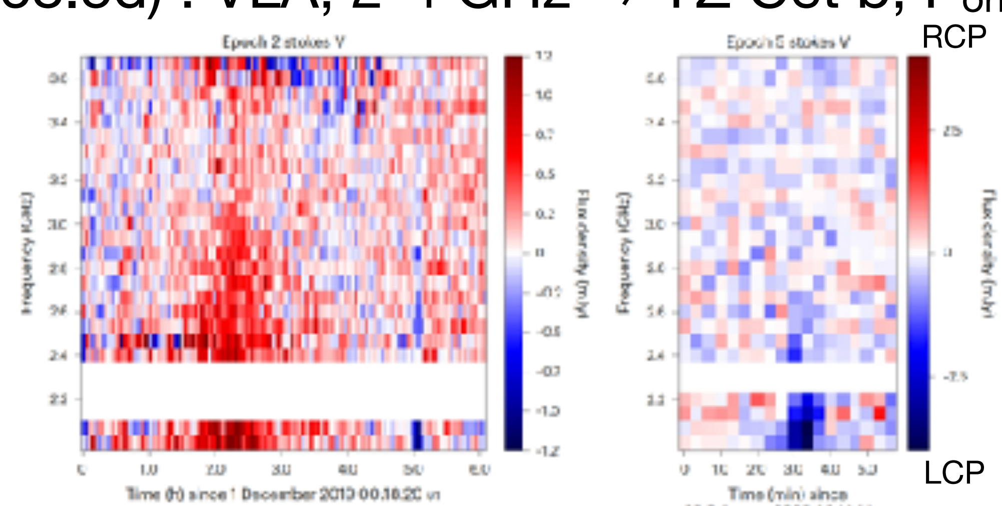




[Perez-Torres et al., 2021]

- YZ Ceti (M4.5, 3.71 pc, P_{rot} = 68.5d) : VLA, 2-4 GHz ⇒ YZ Cet b, P_{orb} = 2.02 d ?





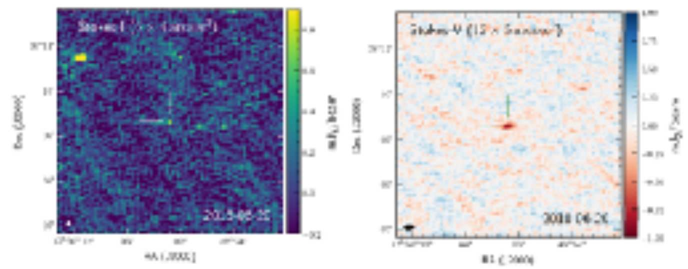
[Pineda & Villadsen, 2023]

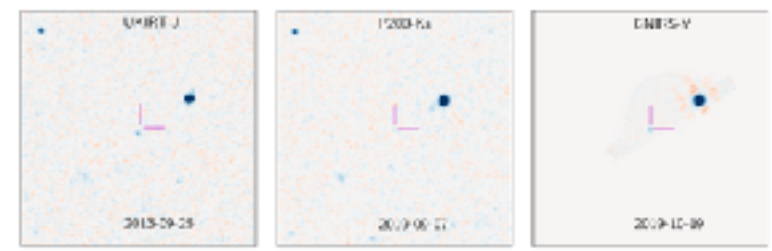
⇒ None confirmed

Radio discoveries of brown dwarfs

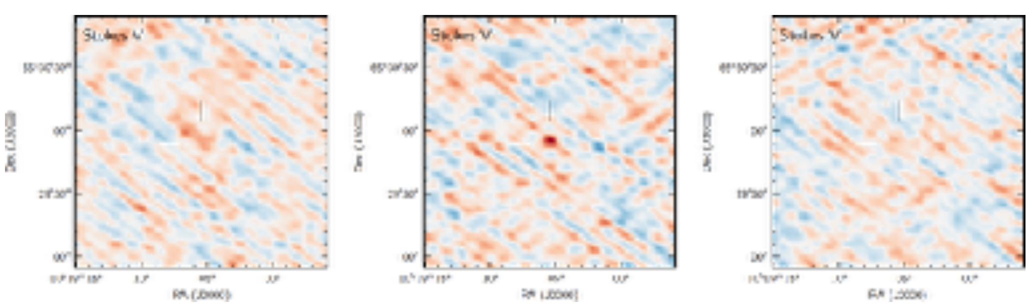
- 2 brown dwarfs discovered by LOFAR = scaled-up planetary magnetospheres ? ⇒ B ~planetary (follow-up identification in IR)

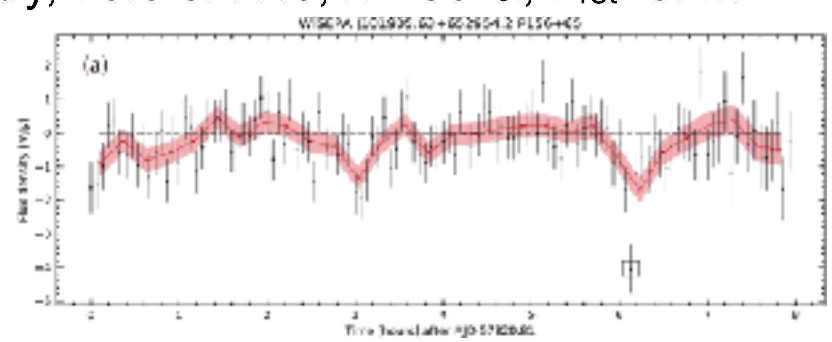
BDR J1750+3809 (cold methane dwarf, T6.5, 65 pc, B ≥25 G, P_{rot}~2h ? [Vedantham et al., 2020b]

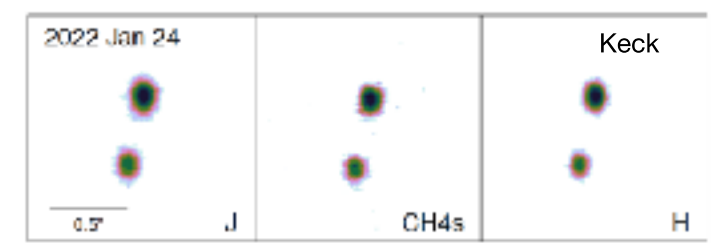




WISEP J101905.63+652954.2 (binary, T5.5 & T7.0, B ~50 G, P_{rot}~3.1h [Vedantham et al., 2023]

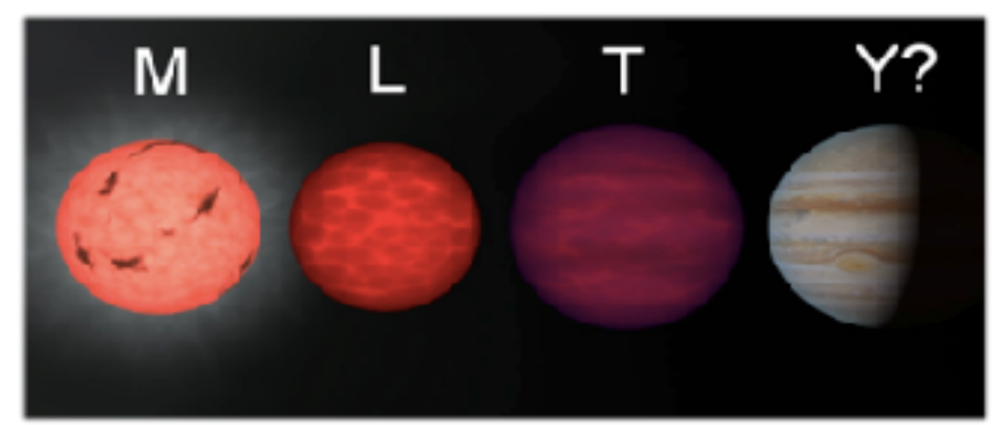






- from brown dwarfs to exoplanets (decreasing P_{rot}, cooler & more neutral atmosphere, larger-scale stable B topologies, weaker |B|)

  ⇒ radio measurements bring unique constraints for dynamo theories & radio emission scaling laws



- Possible ECM from 14 RSCVn systems with LOFAR [Toet et al., 2021]
- Possible ECM from 2 T-Tauri stars with LOFAR [Feeney-Johansson et al., 2021]

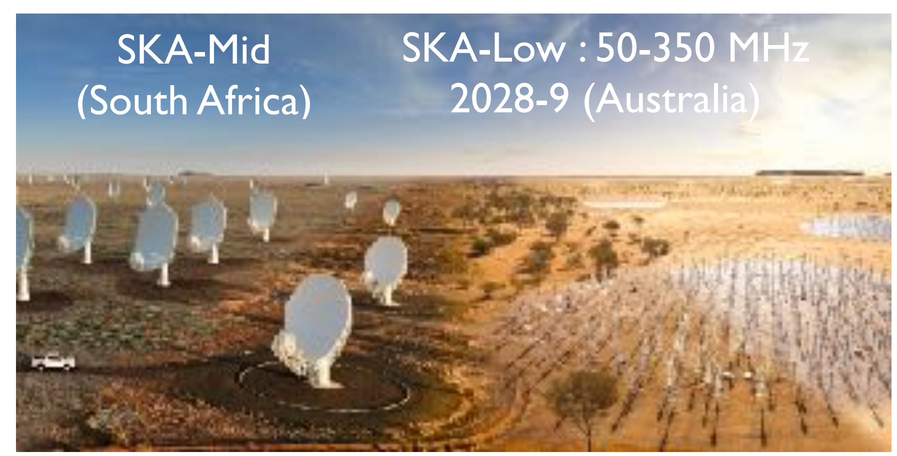
Conclusions - Perspectives

- Emerging field ⇒ **field has emerged** ⇒ physics to follow + follow-up observations needed
- High prospects for exo-space weather, planetary B field, exo-m'spheric physics, habitability ?

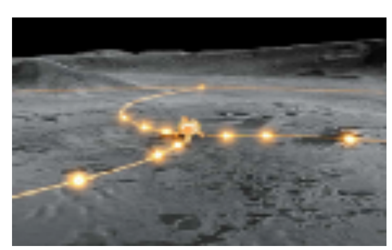
  - NenuFAR : 10-85 MHz

  - LOFAR 2.0 : 30-250 MHz

  - SKA : 50 MHz - >15 GHz



  - LOFAR-on-the-Moon ?



- Importance of multi-λ: TESS, Kepler ⇒ massive/continuous optical tracing of stellar activity/flaring
  ⇒ distinguish between coronal & MS processes

Merci.

General references

- Lorentz workshop (Callingham et al.), *Radio Stars and Exoplanets*, Nature Astr., submitted.
- Zic thesis, 2020, *https://www.atnf.csiro.au/research/student/theses/2020/AndrewZic-thesis.pdf*