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# Radio emission as stellar activity indicator

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Netherlands Institute for Radio Astronomy
EOSC Future

16th June 2023

# Why study stars in radio?

- Plasma oscillation & charges in magnetic fields all emit in radio wave

  ⟹Excellent probe of plasma dynamics and magnetic field!

- Allow us to study coronae of stars & magnetospheres of exoplanets

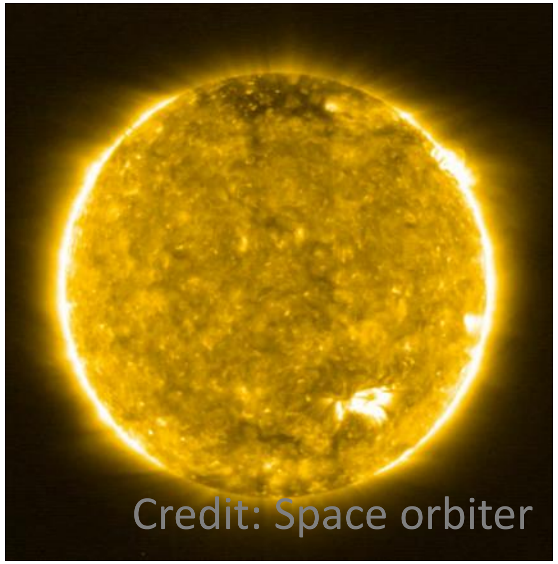

Credit: ESO

1. *Impact of stellar plasma on exoplanets*
2. *Magnetic field strength of exoplanets*
3. *Coronal heating mechanism*

# Engine

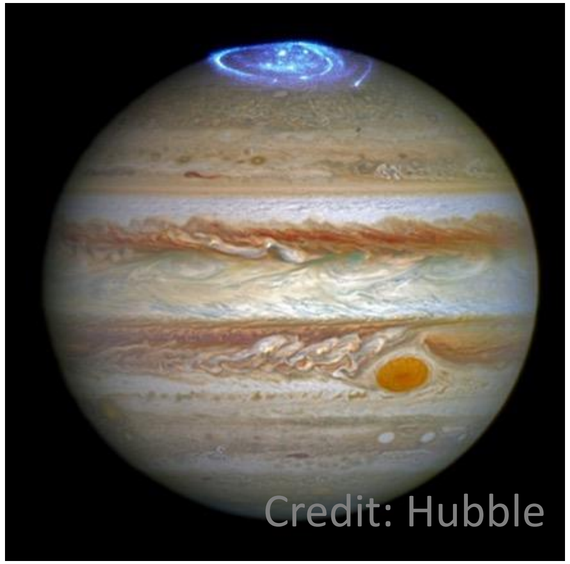
What is powering the radio emission of these objects?

## Sun-like vs Jupiter-like

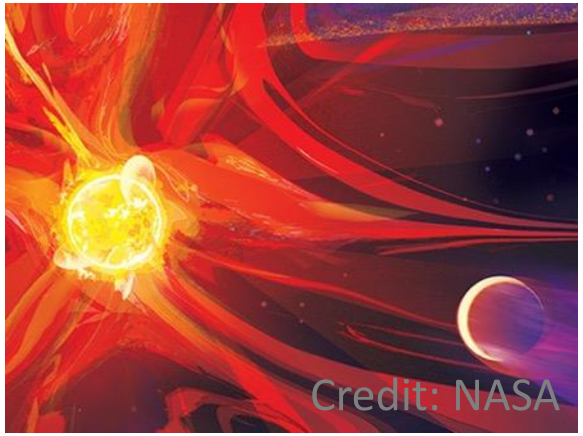



- *Flares*
- *Nanoflares*

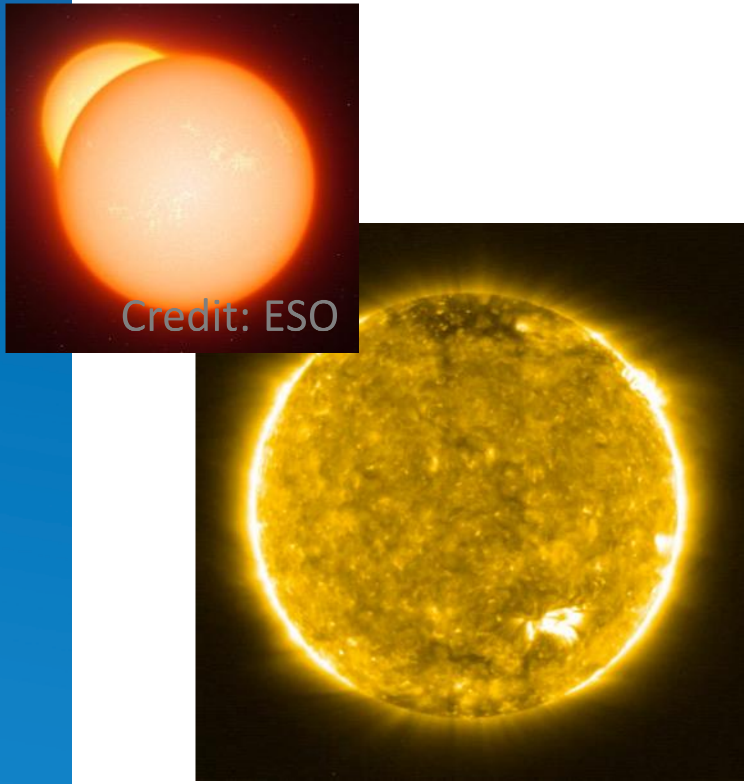
- *Magnetosphere*
- *Dynamo*



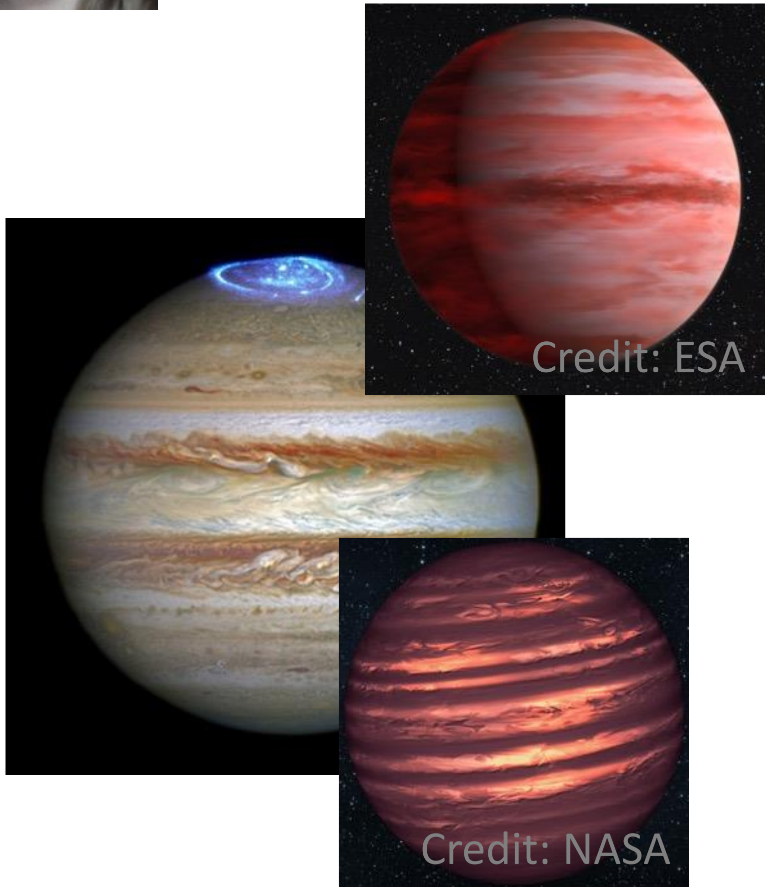
# A bridge




My talk after coffee break!

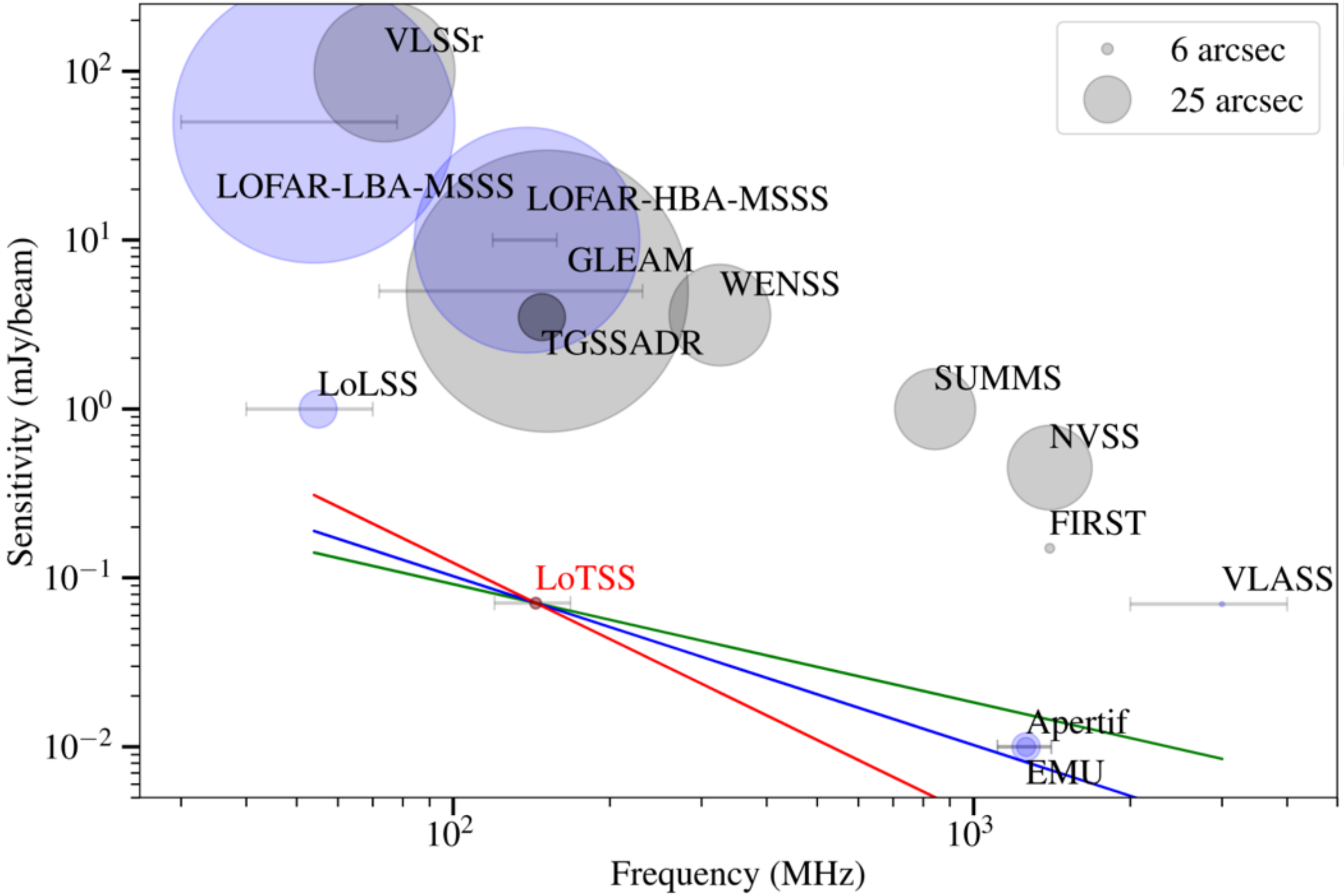



M dwarfs!



# LoTSS & VLASS

- *Two largest radio sky surveys ever conducted (by source counts)*


**LoTSS**

- 120-168 MHz
- Likely coherent
- Has Stokes V info

**VLASS**

- 2-4 GHz
- Likely incoherent
- No Stokes V info

LoTSS: Shimwell et al. 2019 & 2022



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# Gaia Catalogue of Nearby Stars (GCNS)

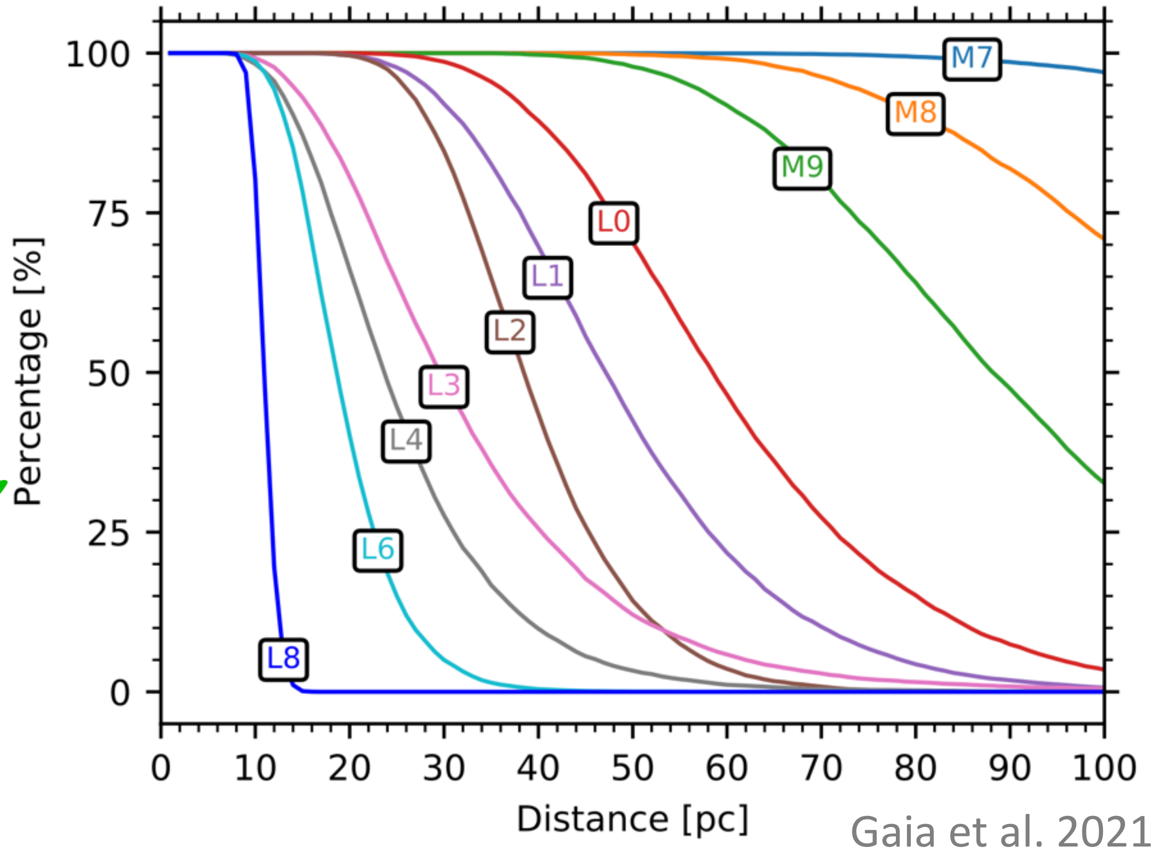
- 331k sources, ~40k within 50pc
- Precise proper motions

⟹ Radio x GCNS within 50pc ✓

- Complete to late M within 50pc

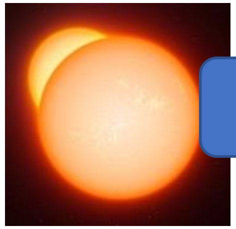
⟹ Look for trends in spectral type ✓

GCNS Completeness per spectral type

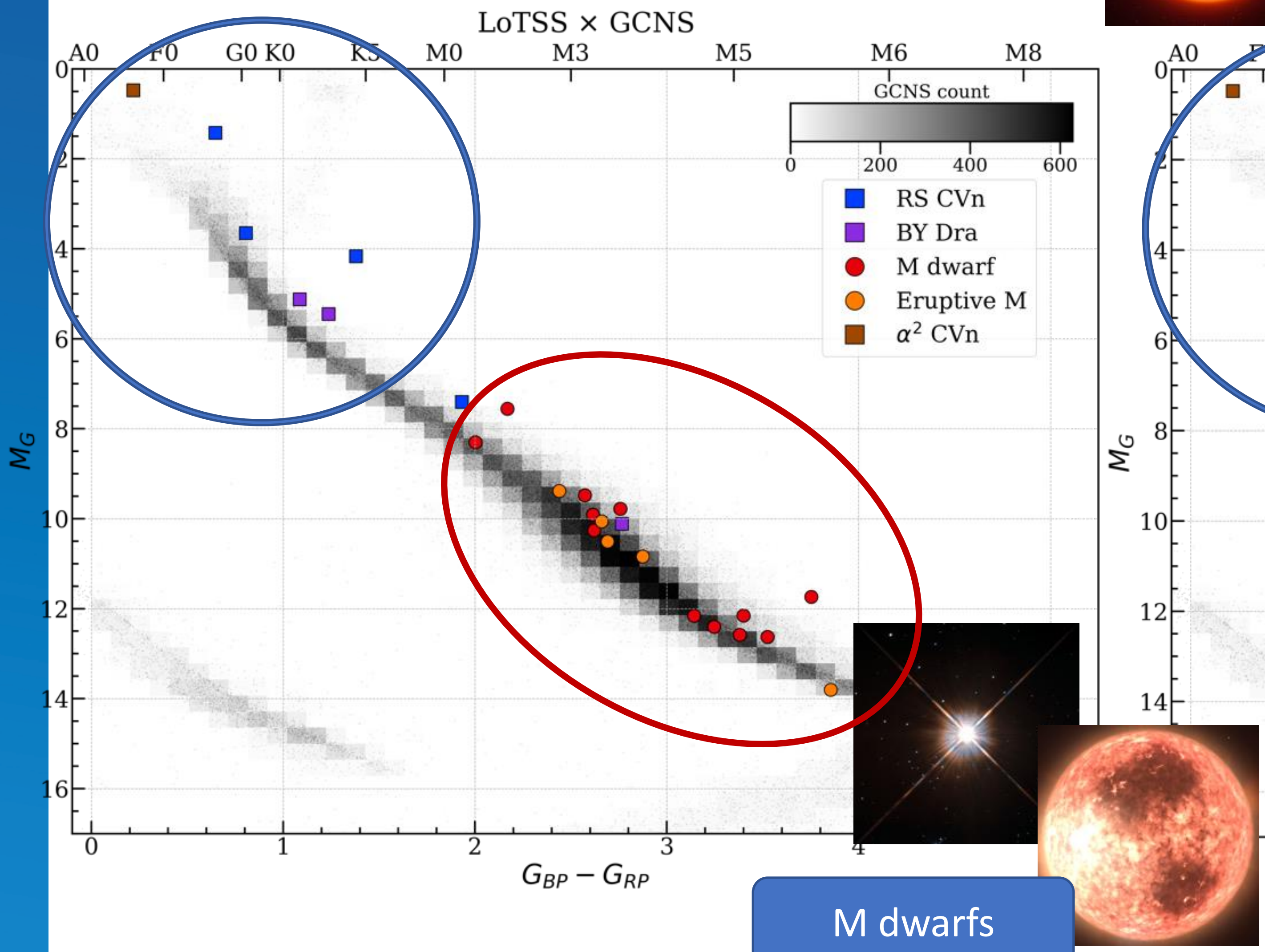



Gaia et al. 2021

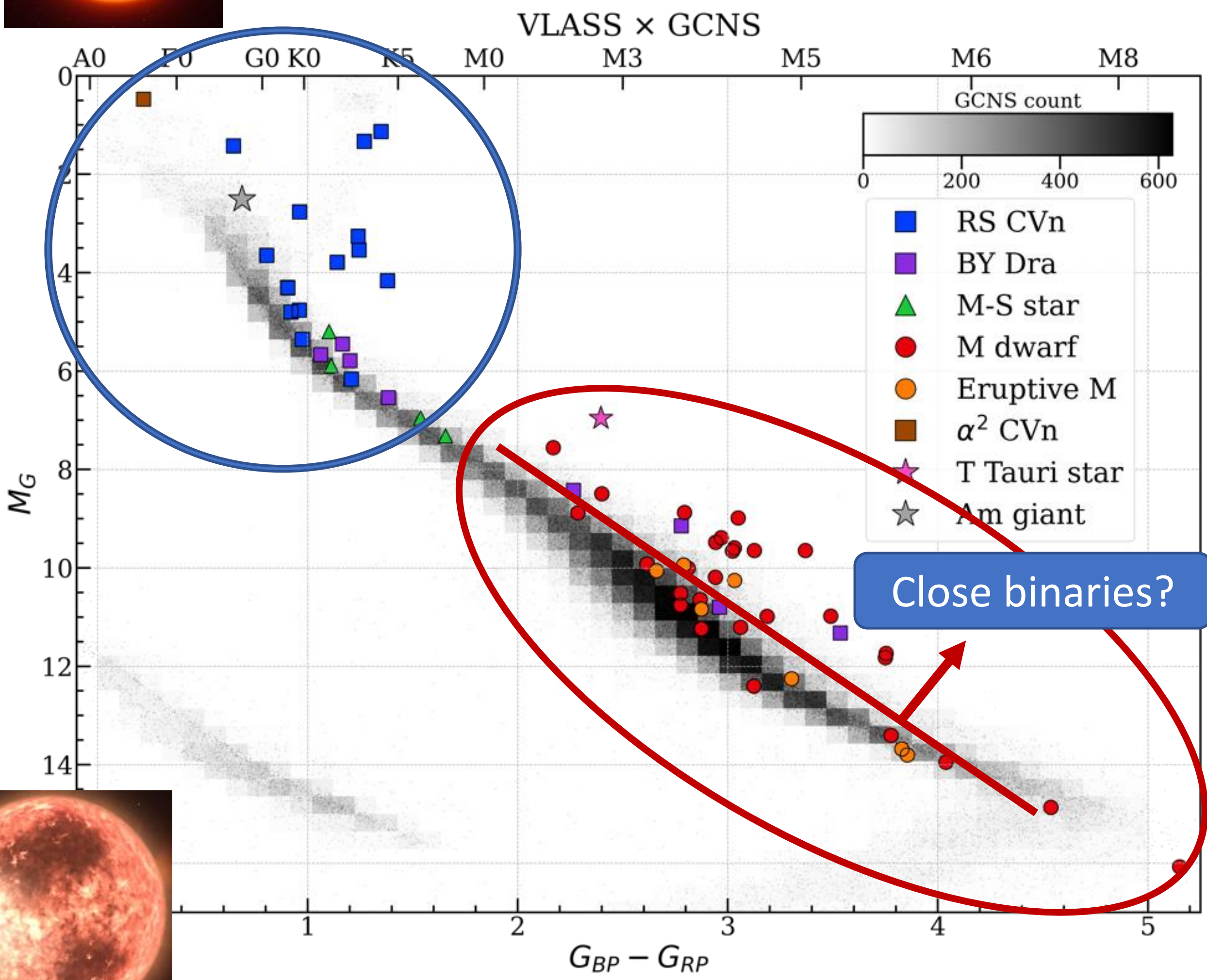
# Results



Chromospherically active stars (CAS)




M dwarfs




Close binaries?

Yiu et al. in prep.

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# Results

Bowler et al. 2019

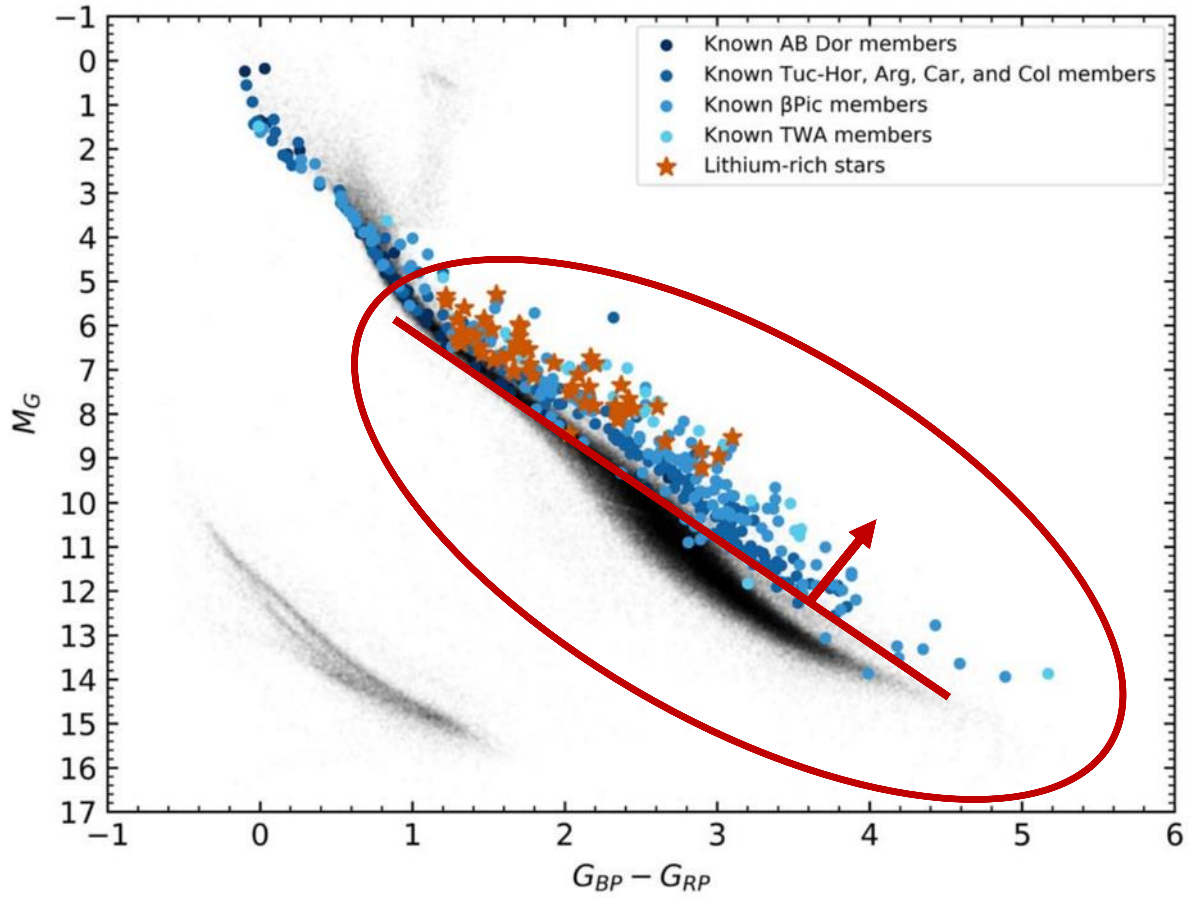
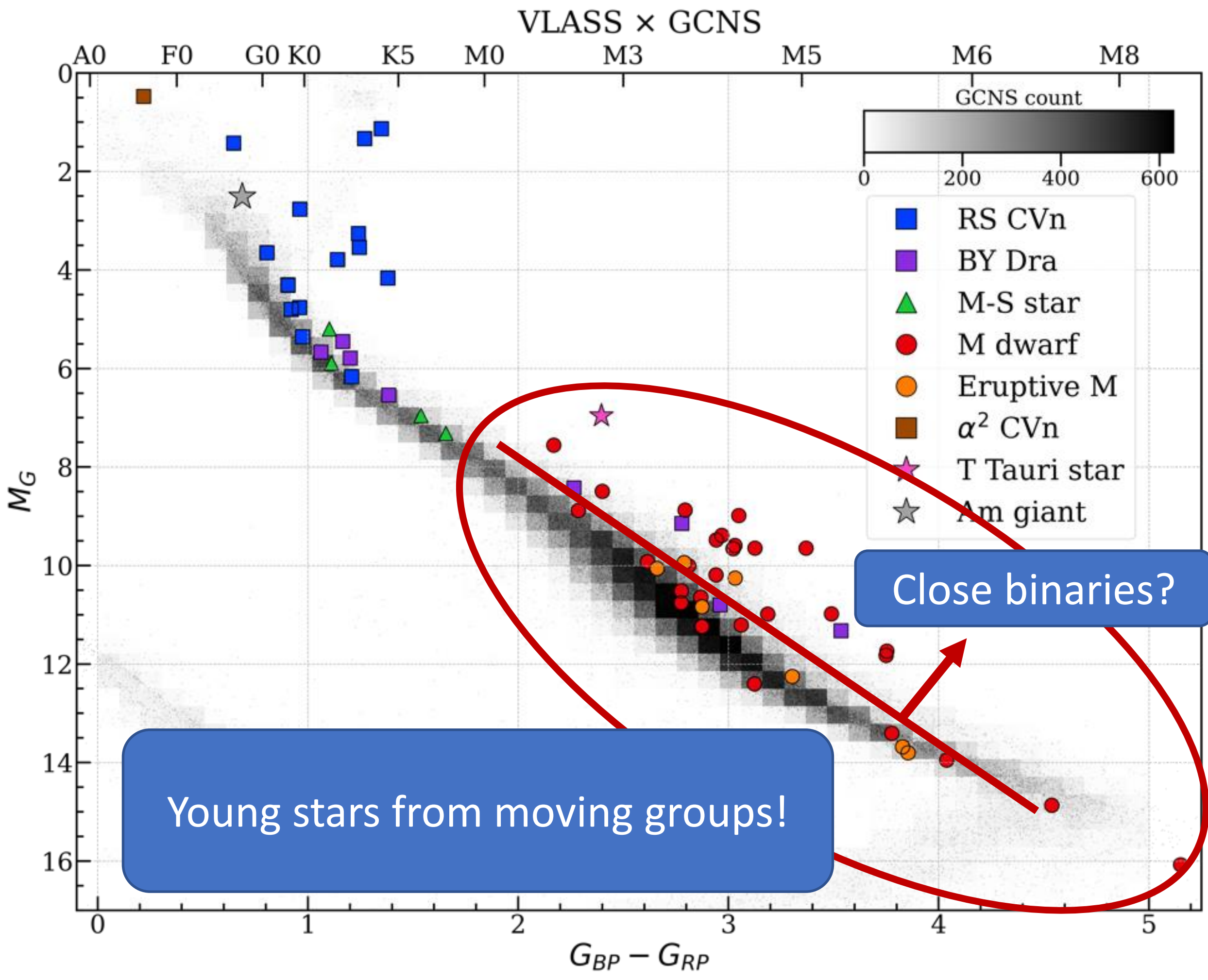



**Figure 6.** Positions of lithium-rich stars (red stars) in the *Gaia* color–magnitude diagram relative to known moving group members from Malo et al. (2013). The *Gaia* color–magnitude diagram shows stars within 100 pc with spurious entries removed following Lindegren et al. (2018).



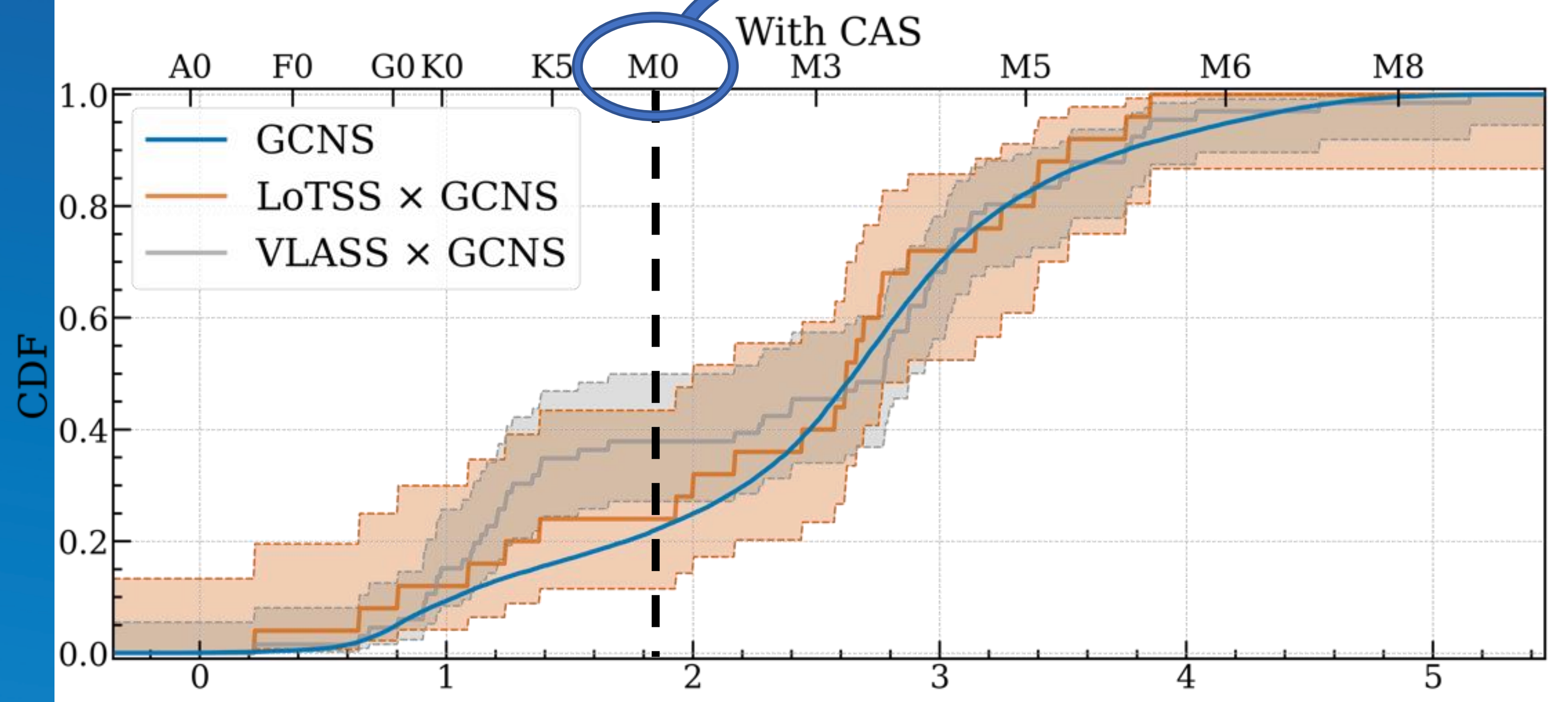

Yiu et al. in prep.

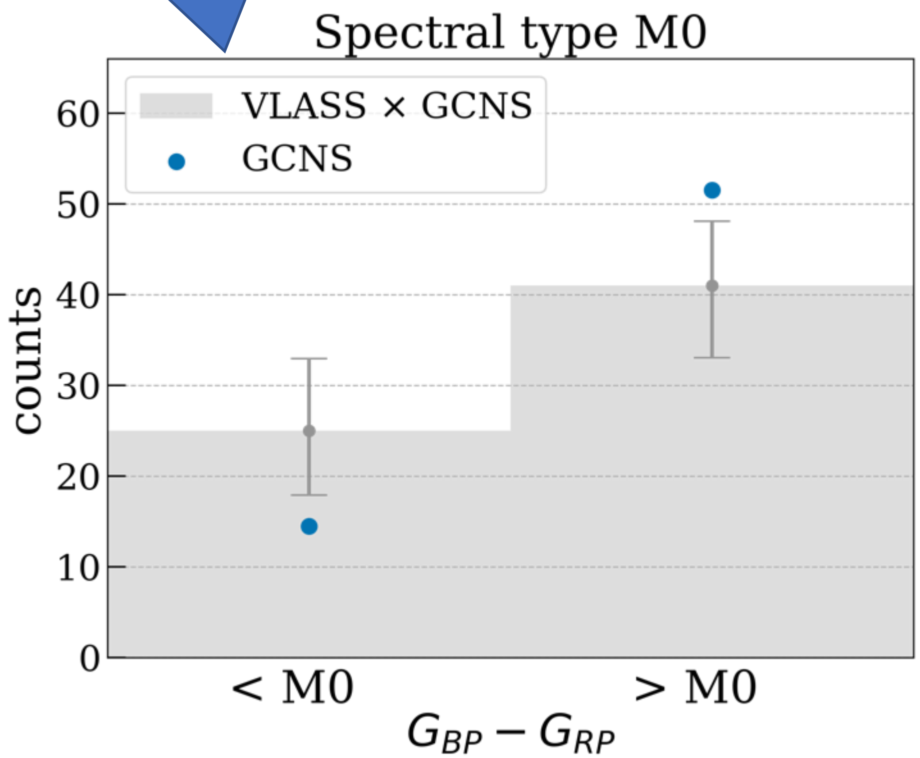
# Looking for transition

LoTSS: 120-168 MHz

VLASS: 2-4 GHz

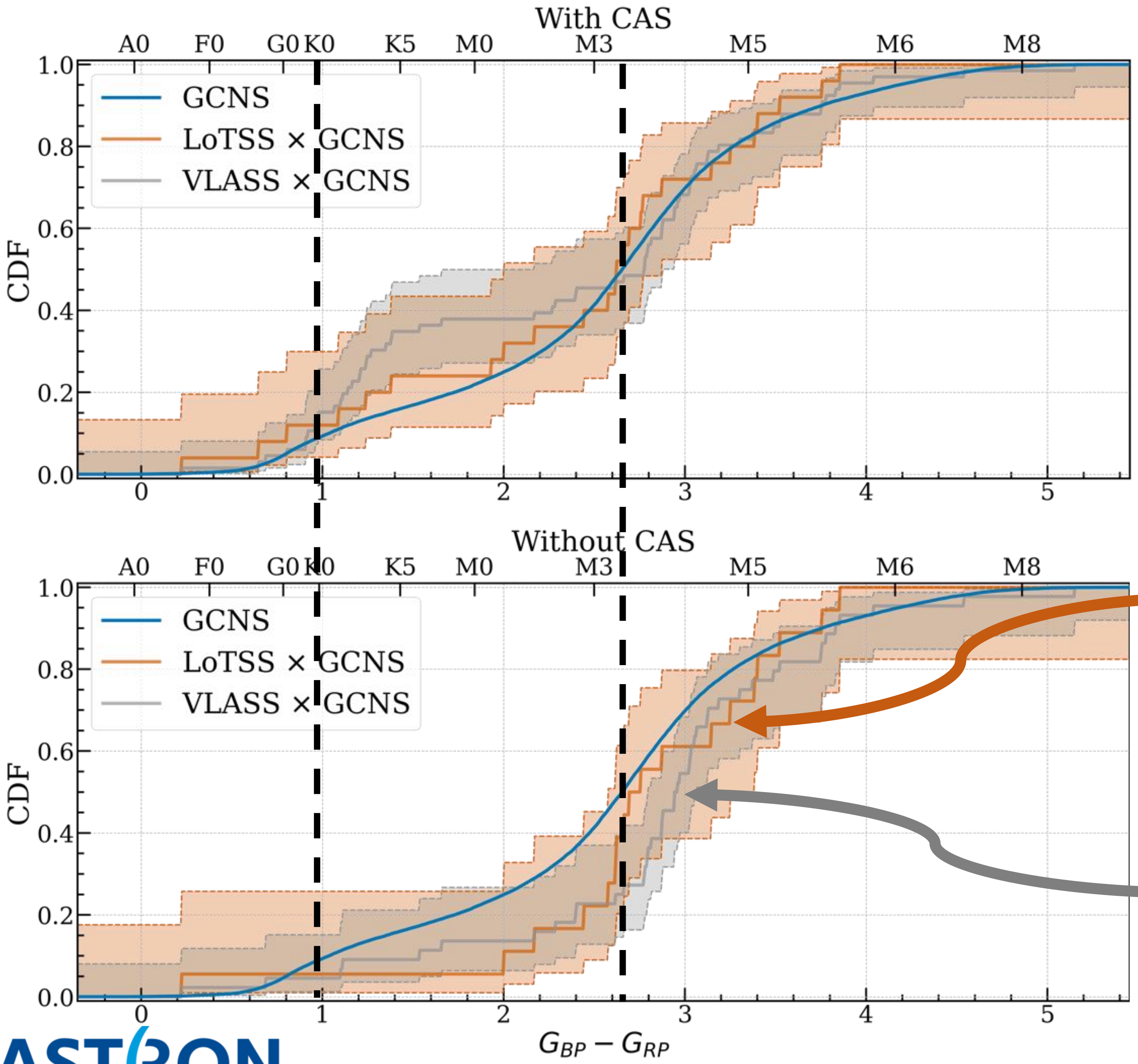
Cumulative distribution function




95% CL

Yiu et al. in prep.




Much more likely to find CAS in both LoTSS and VLASS

LoTSS P-value from KS test ≈ 10% ⟹ Need more detections to be significant

VLASS P-value from KS test ≈ 0.05% ⟹ Not consistent with background rate!

Yiu et al. in prep.

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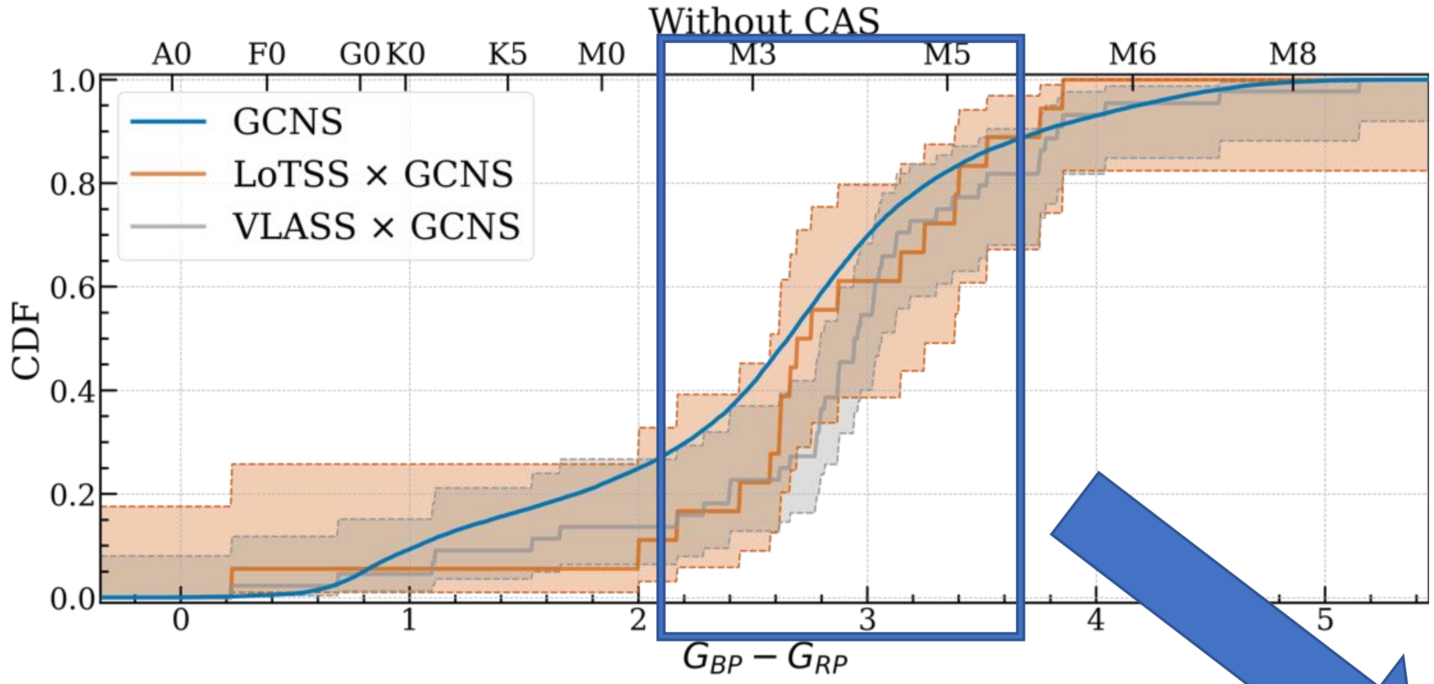
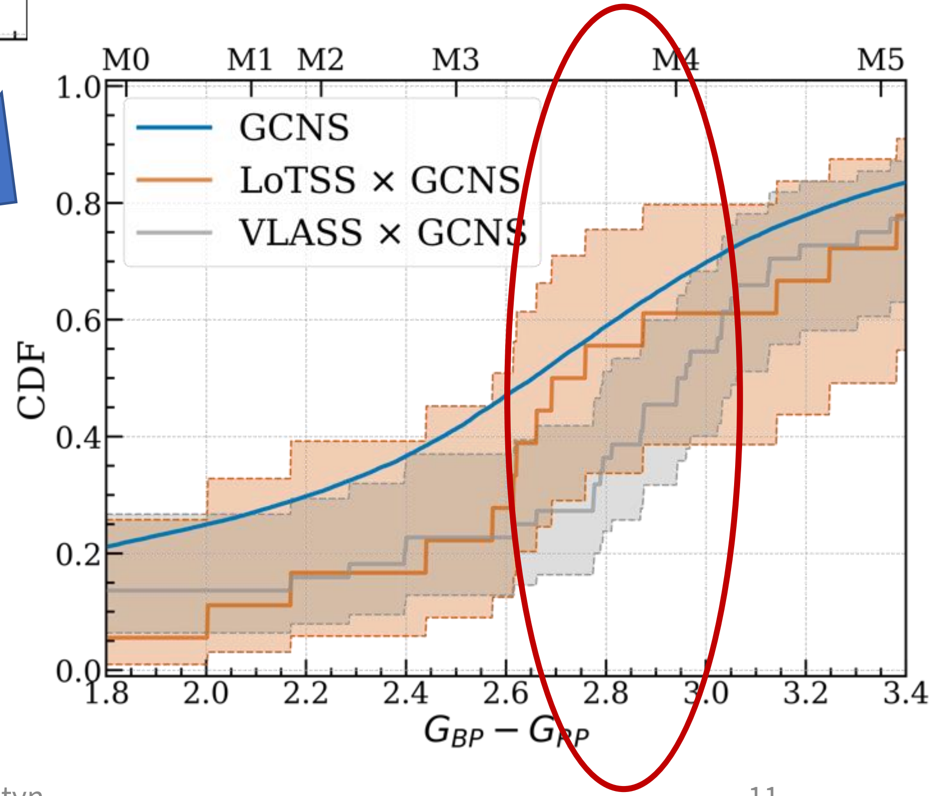
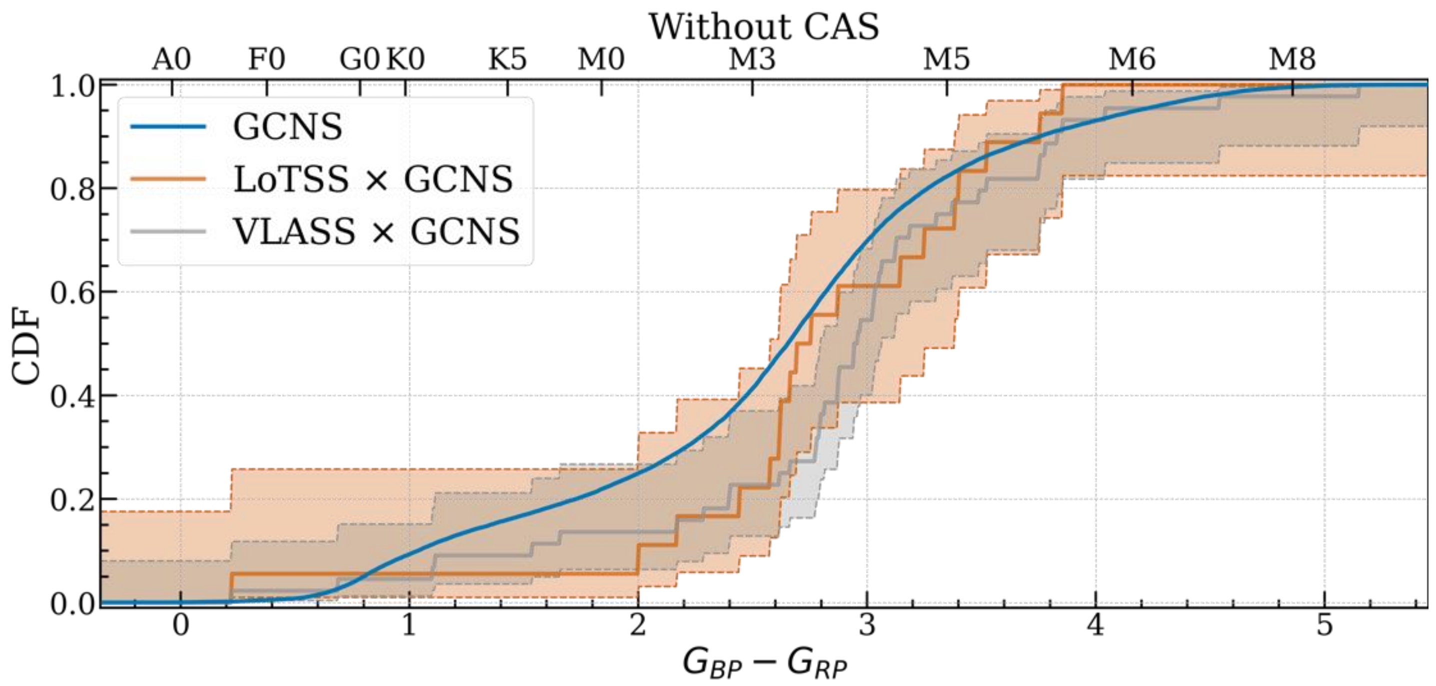



Evolution in radio detection with spectral type!



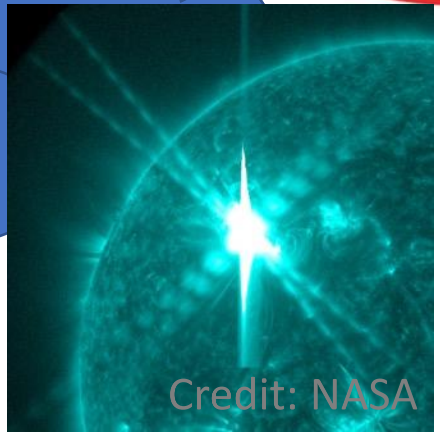

**M4 Transition:** fully convective regime?




⟹ Evolution in radio detection with spectral type!

**Does radio follow other known stellar activity indicators?**

Flares!





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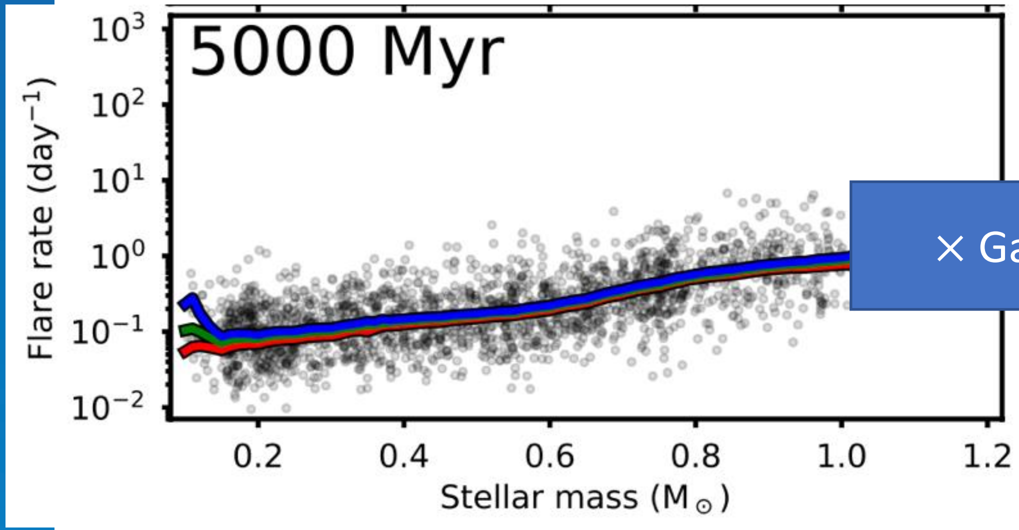
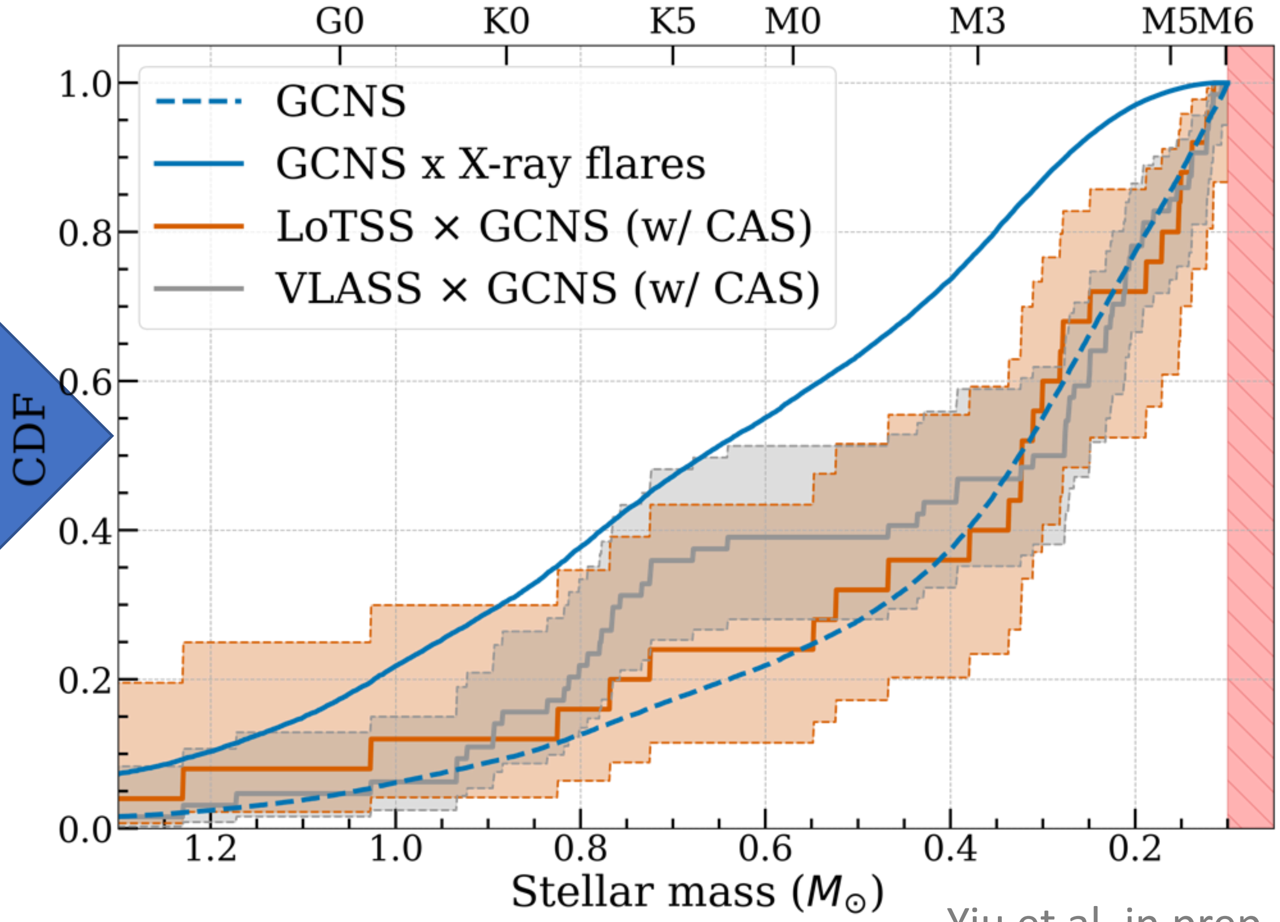
# CDF with X-ray flares




Johnstone et al. 2020

× Gaia CDF

Cumulative distribution function




Yiu et al. in prep.

⟹ Both surveys inconsistent with X-ray flares!

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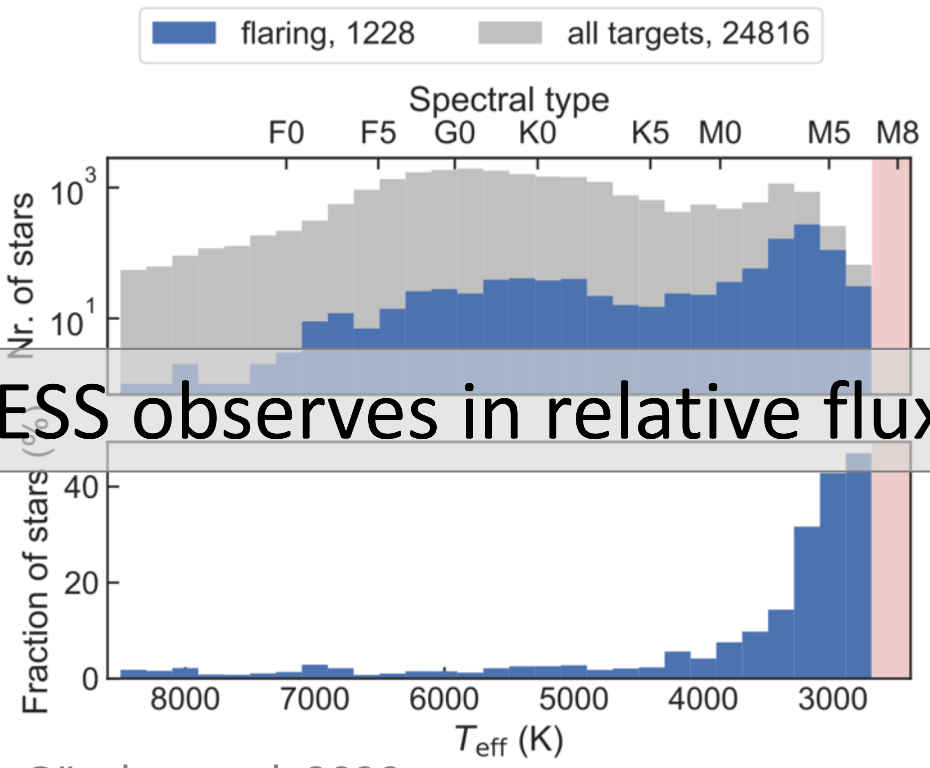
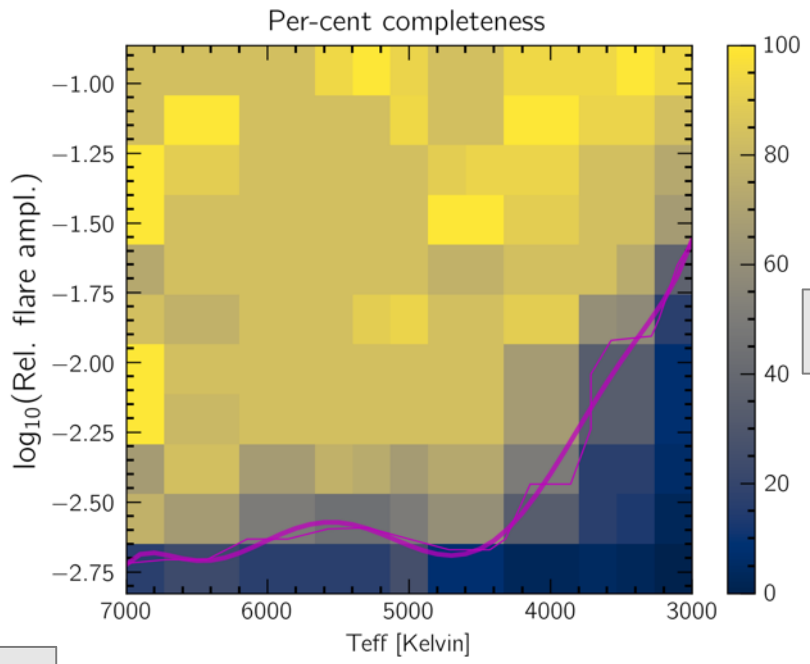
# CDF with TESS flares

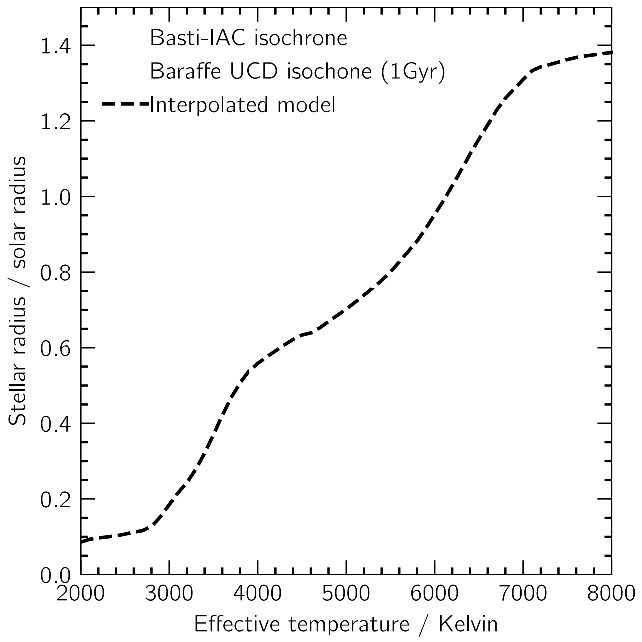



TESS observes in relative flux!

Günther et al. 2020

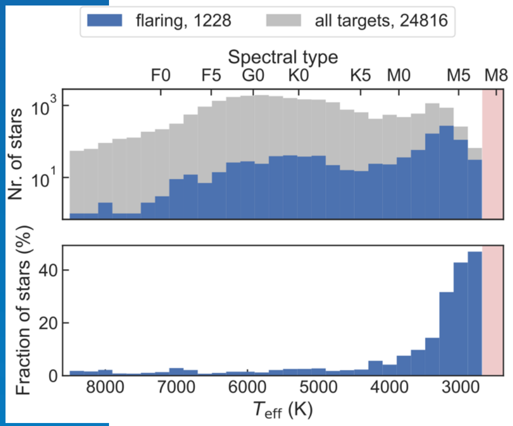



Relative flux completeness

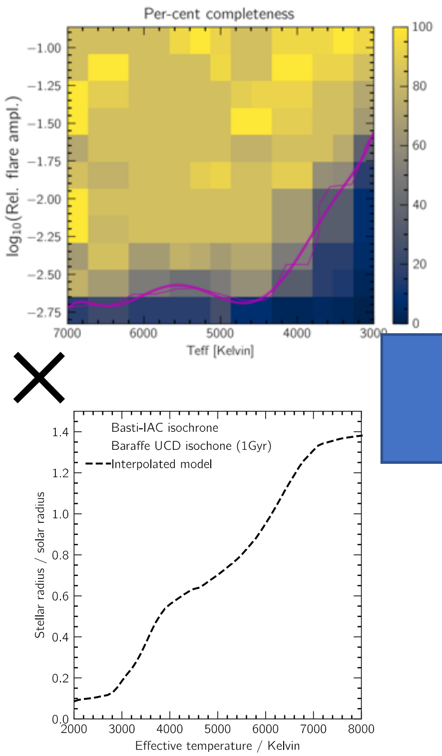



Flare energy threshold

# CDF with TESS flares

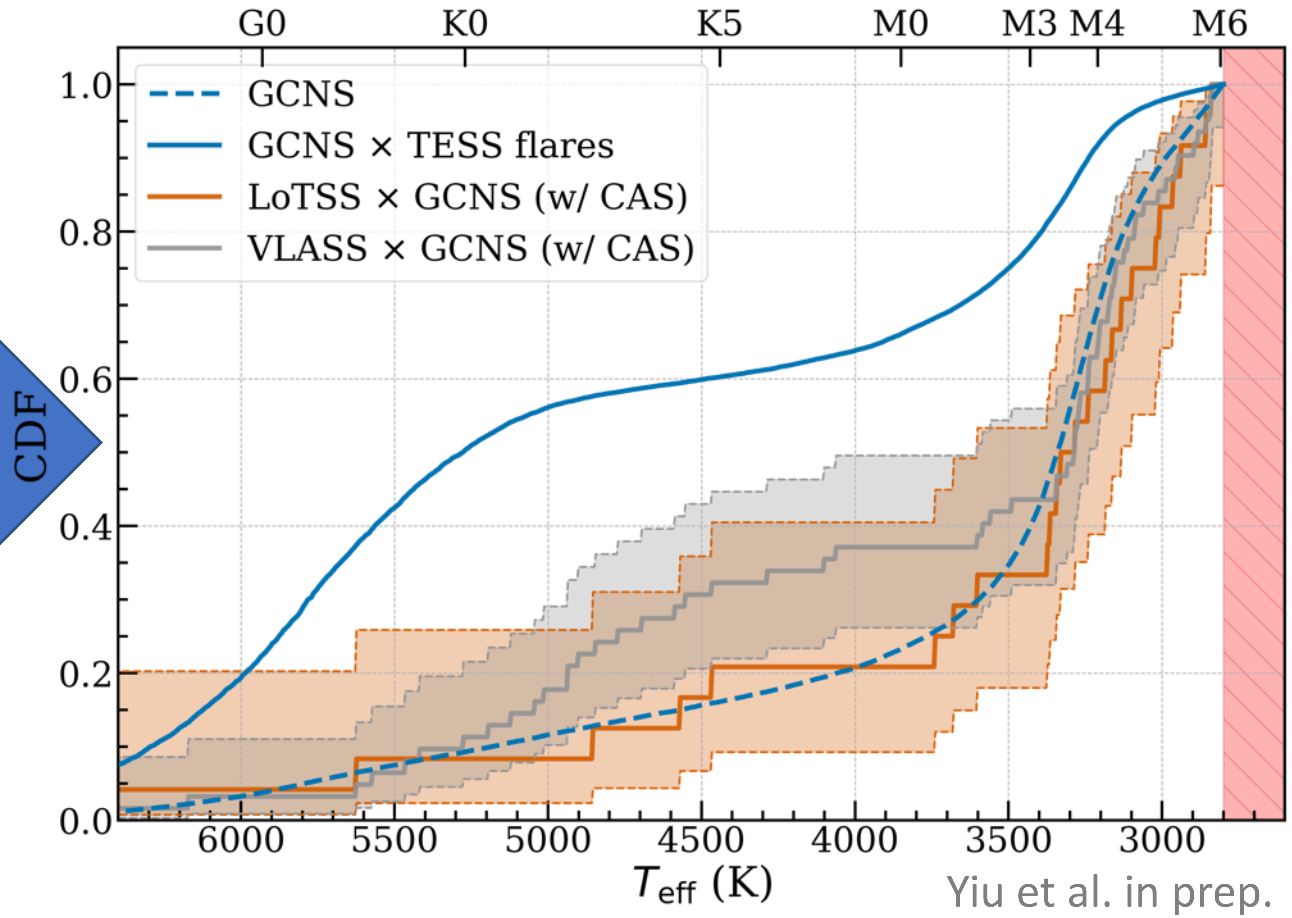



Günther et al. 2020




× Gaia CDF

Cumulative distribution function

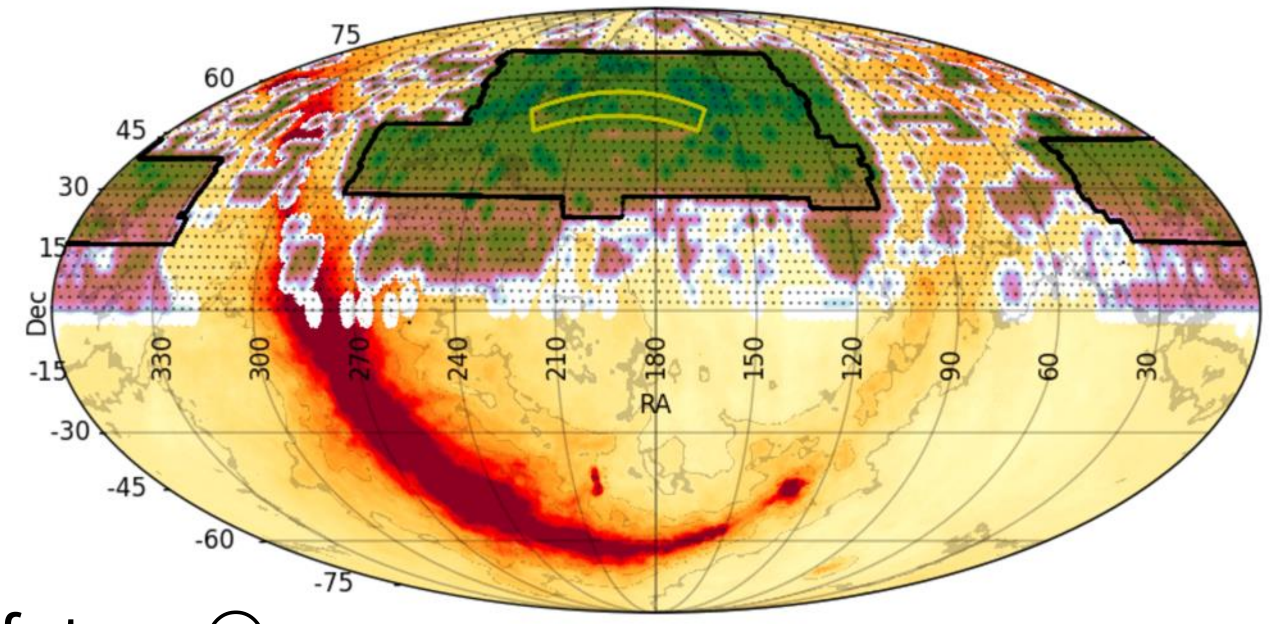



Yiu et al. in prep.

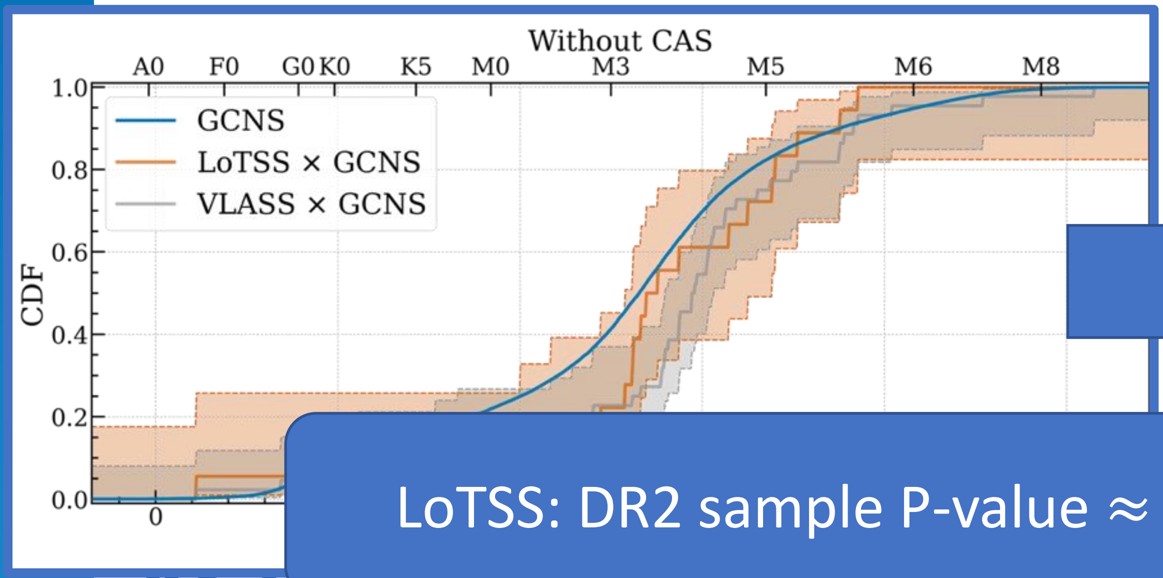
⟹ Both surveys inconsistent with optical flares!

# Future

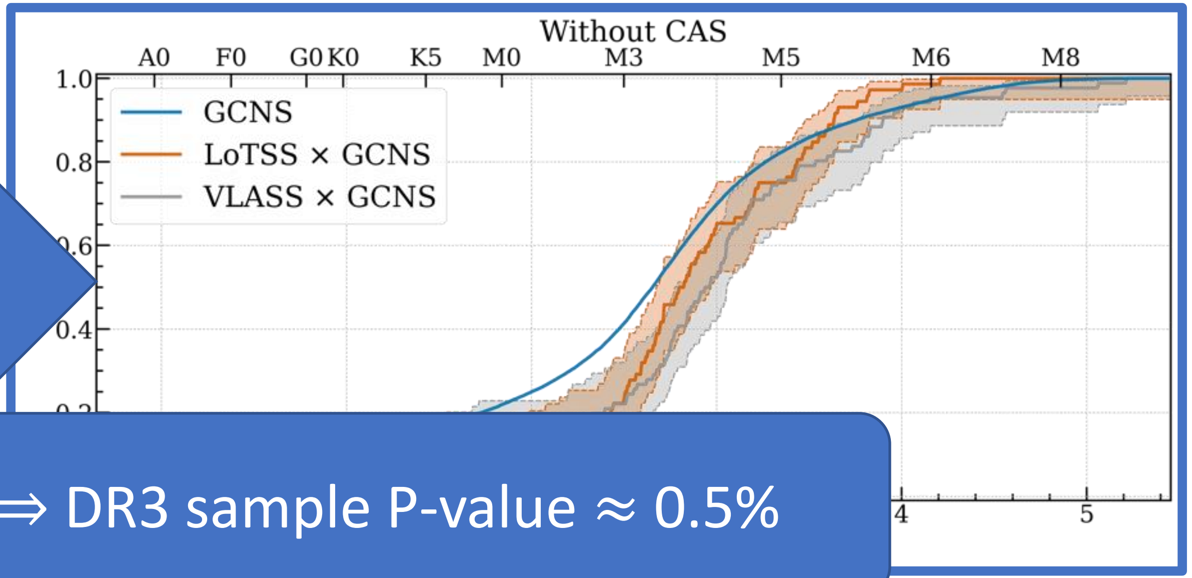
- LoTSS: the rest of the sky
- VLA: 1 more epoch to go




- Larger sample (~100 stars) in the future ☺



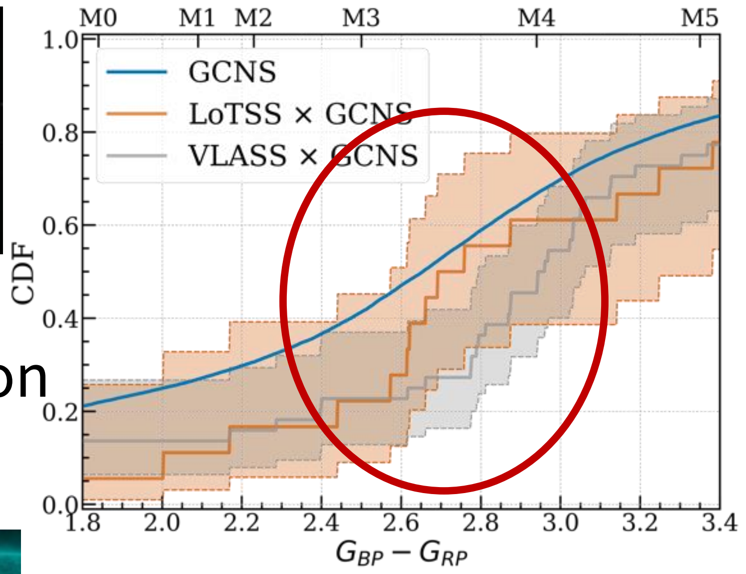

DR3




LoTSS: DR2 sample P-value ≈ 10% ⟹ DR3 sample P-value ≈ 0.5%

# Conclusion

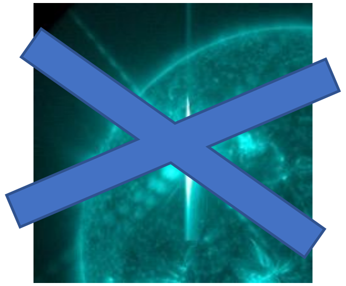
- Bulk of radio detections: CAS & (young) M dwarfs



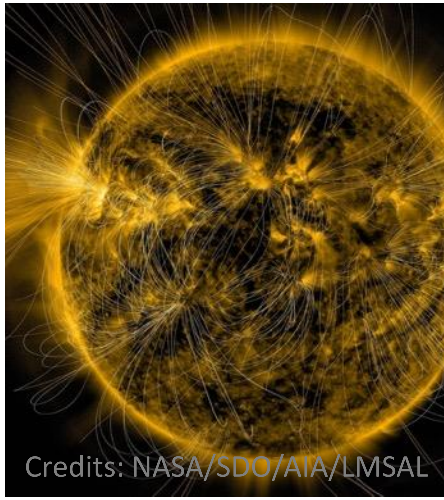

- Radio activity evolves with spectral type in VLASS population

$\Longrightarrow$ Transition ~M4 dwarf: Convective regime?

- Radio evolution ≠ Optical or X-ray flare activity



- Hypothesis: **Radio traces large-scale stellar magnetic field strength**




- Full sky of LoTSS will confidently tell us the story

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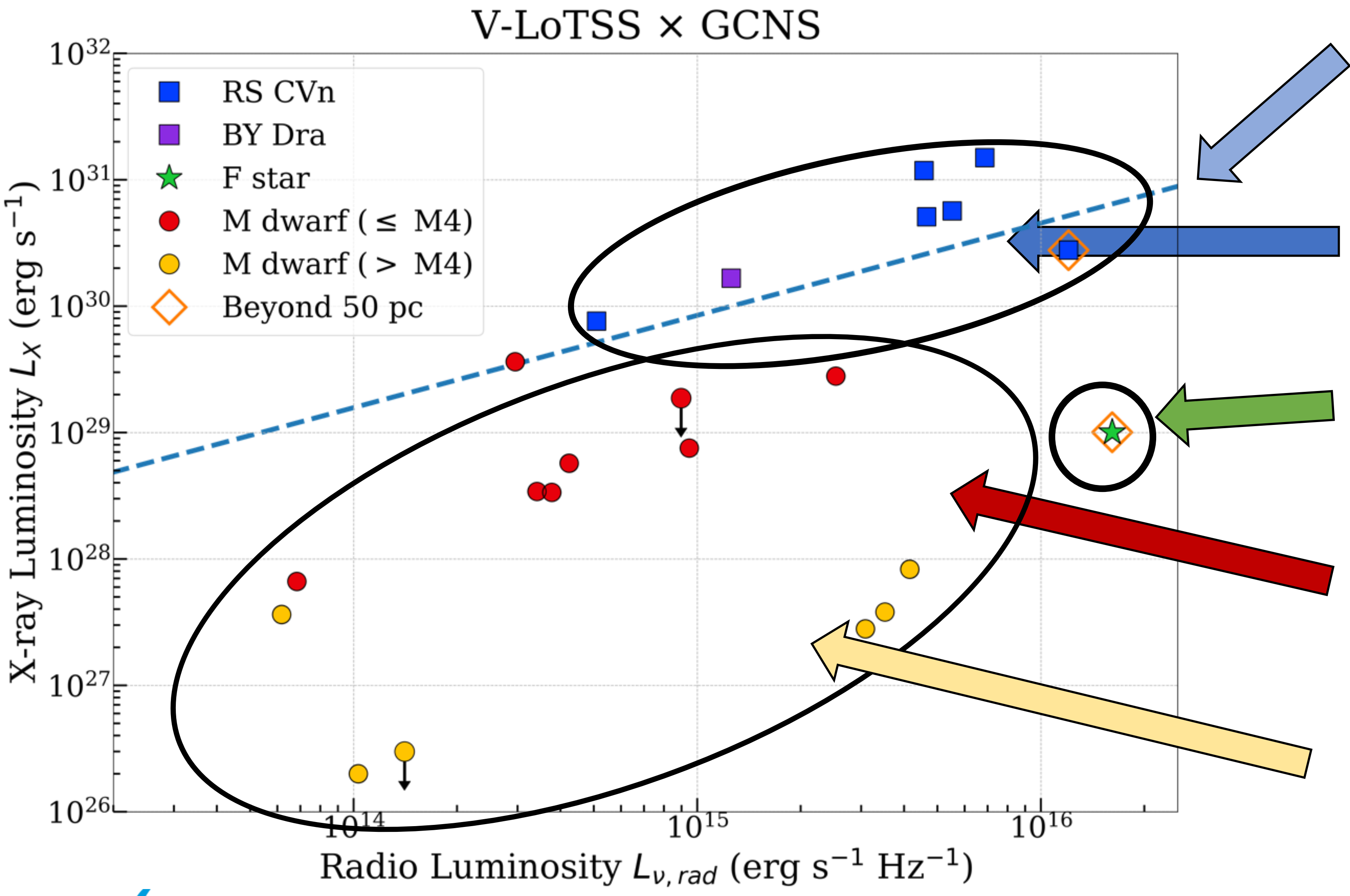
# Extra: M4 transition in GB




Güdel-Benz Law

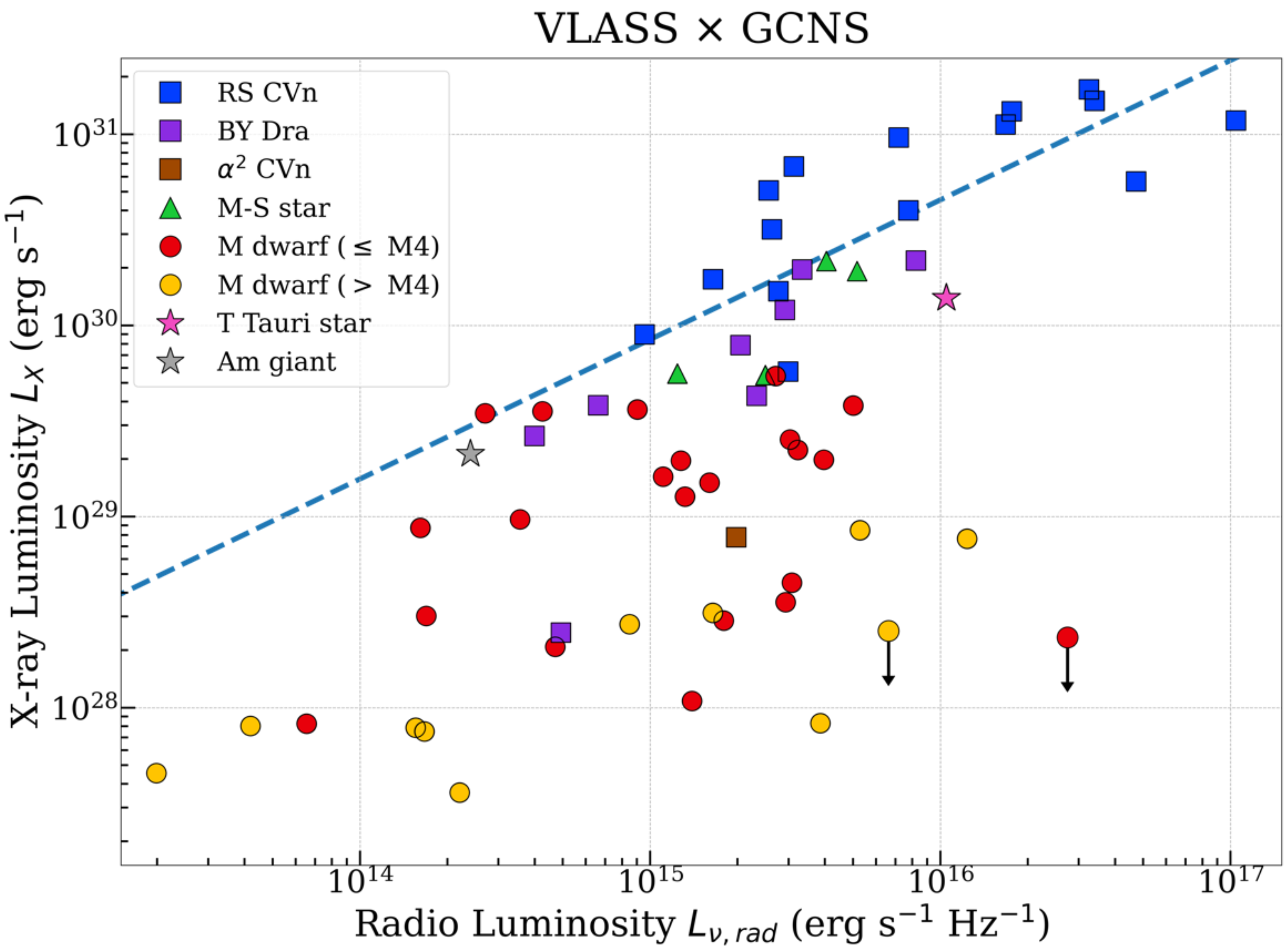
A,F,G,K stars are all RSCVn

Away from RSCVn!

M dwarfs consistently radio bright

Later than M4: quite a gap!

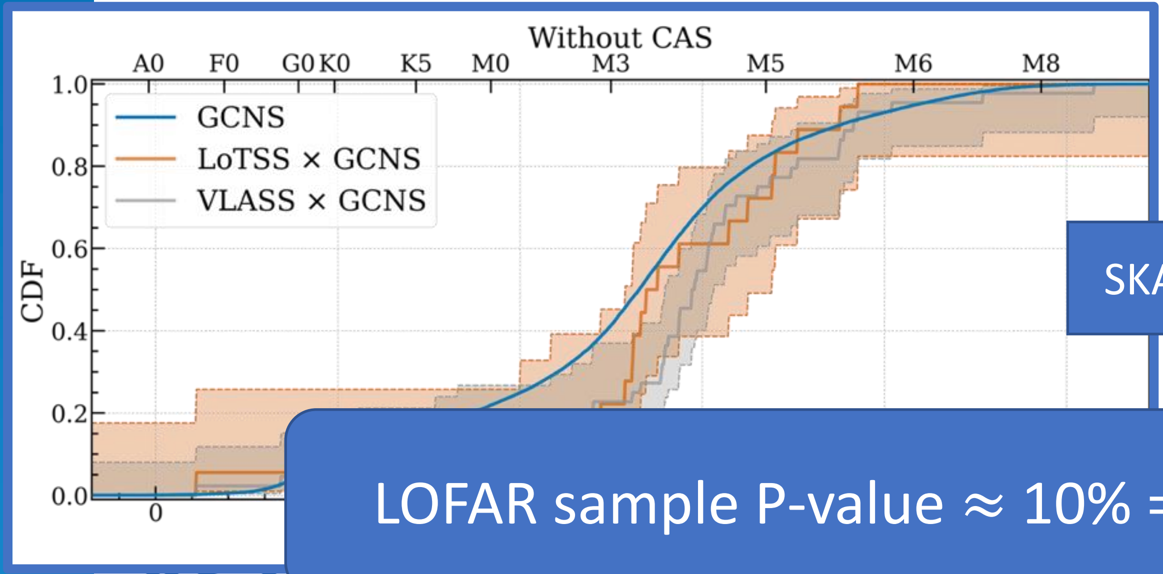
# Extra: M4 transition in GB



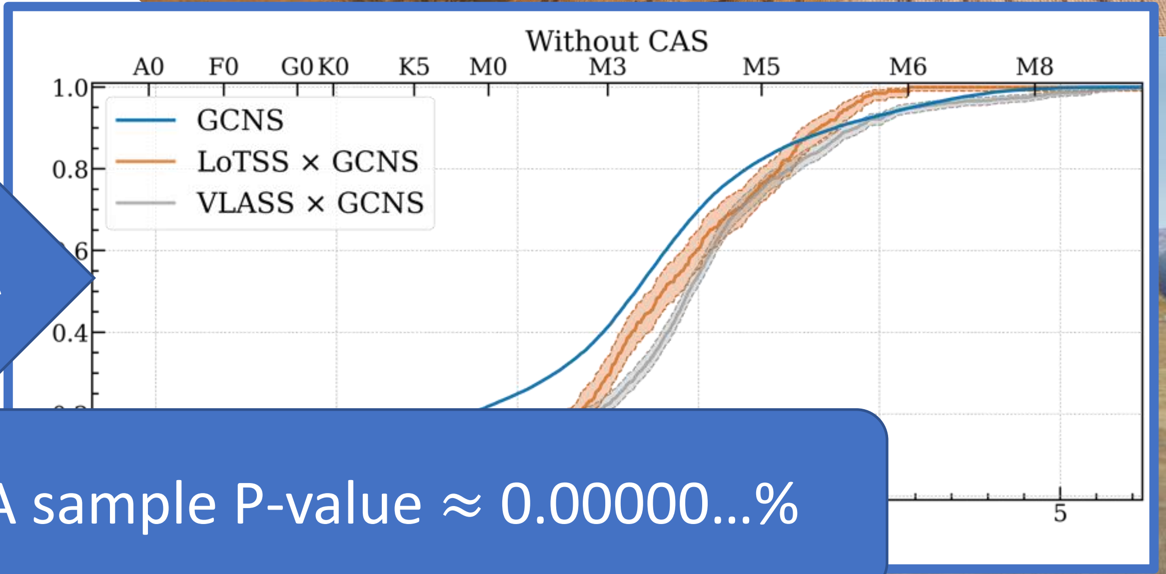
# Advent of SKA & ngVLA

- SKA-Low: 8 × sensitivity of LOFAR
- ngVLA: 10 × sensitivity of VLA

- In an all-sky survey: $N \propto S^{-3/2}$




SKA/ngVLA




LOFAR sample P-value ≈ 10% ⟹ SKA sample P-value ≈ 0.00000…%

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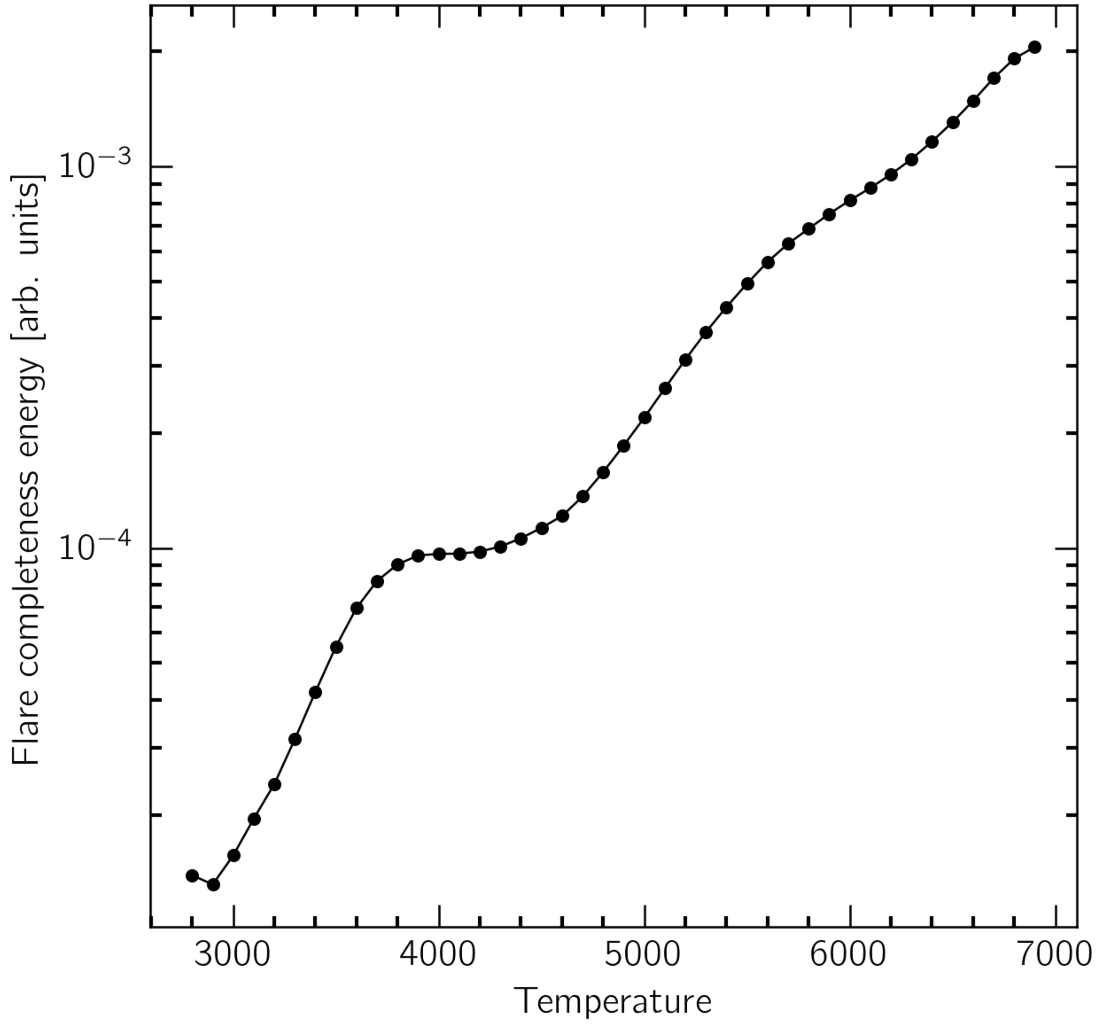
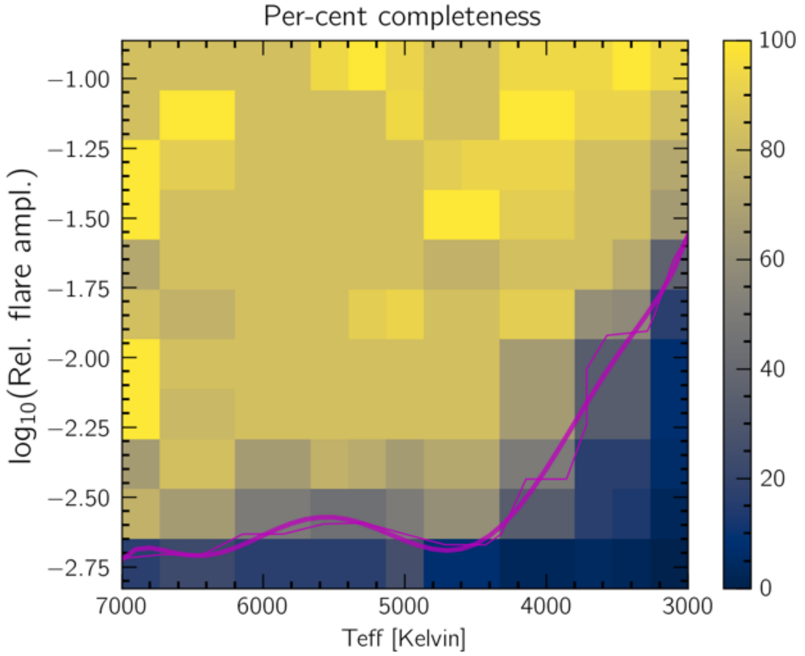
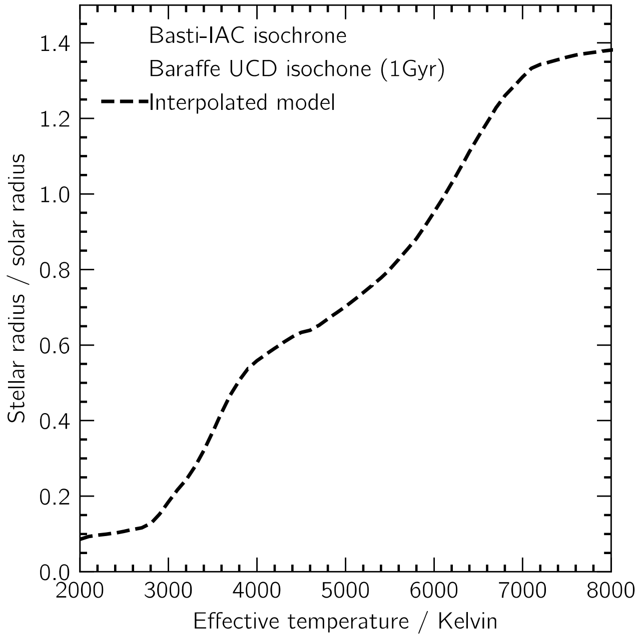
# Debiasing TESS flares



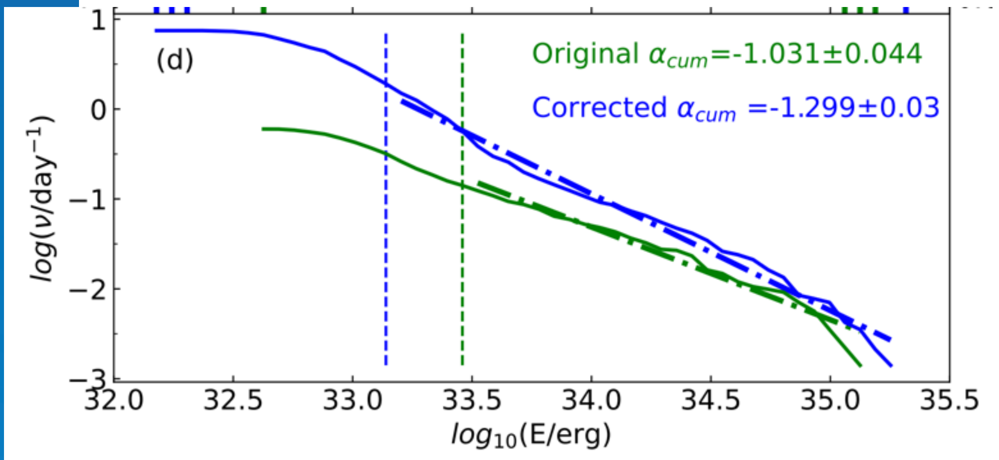



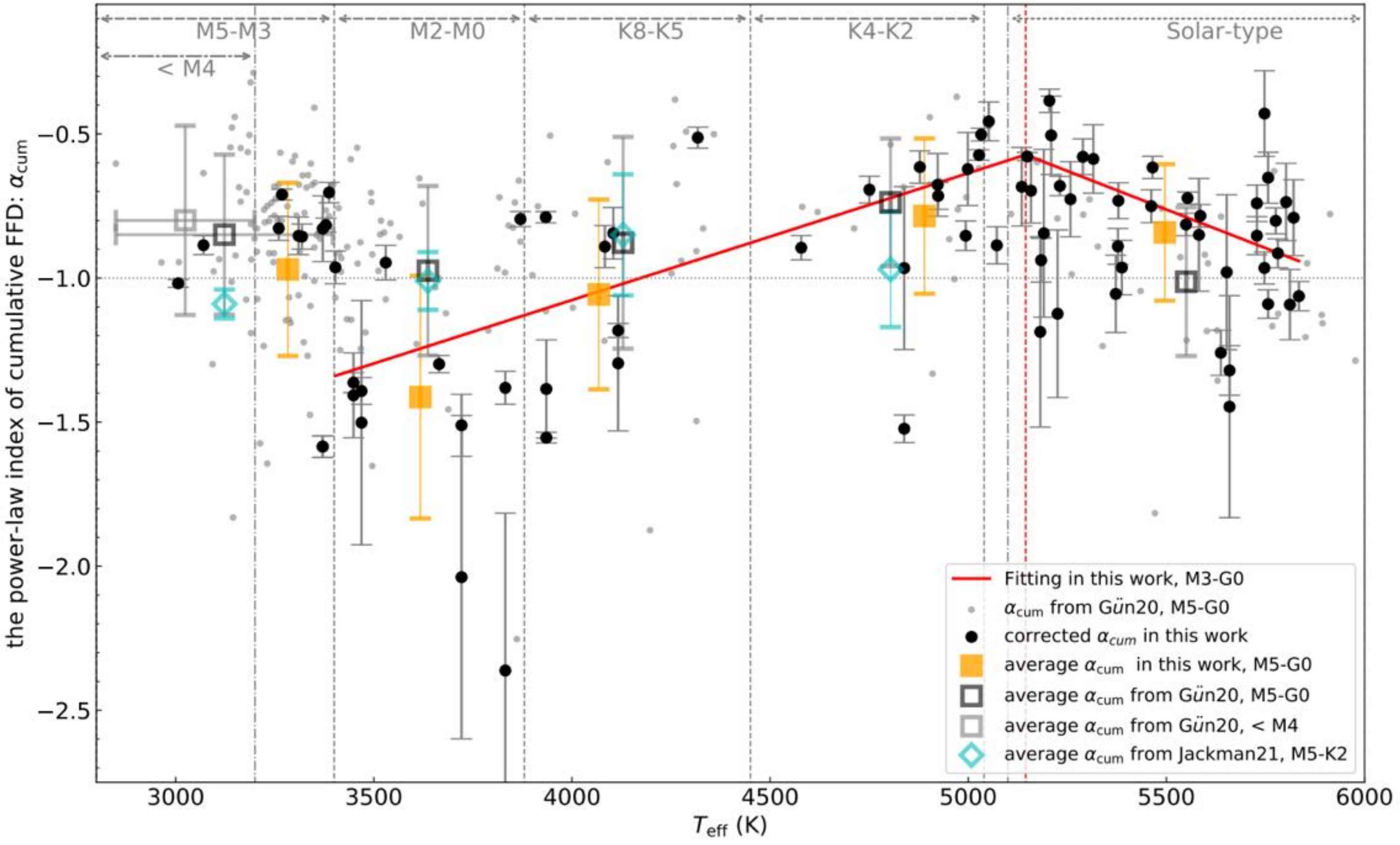




Stellar quiescent flux:
Planck function

# Debiasing TESS flares

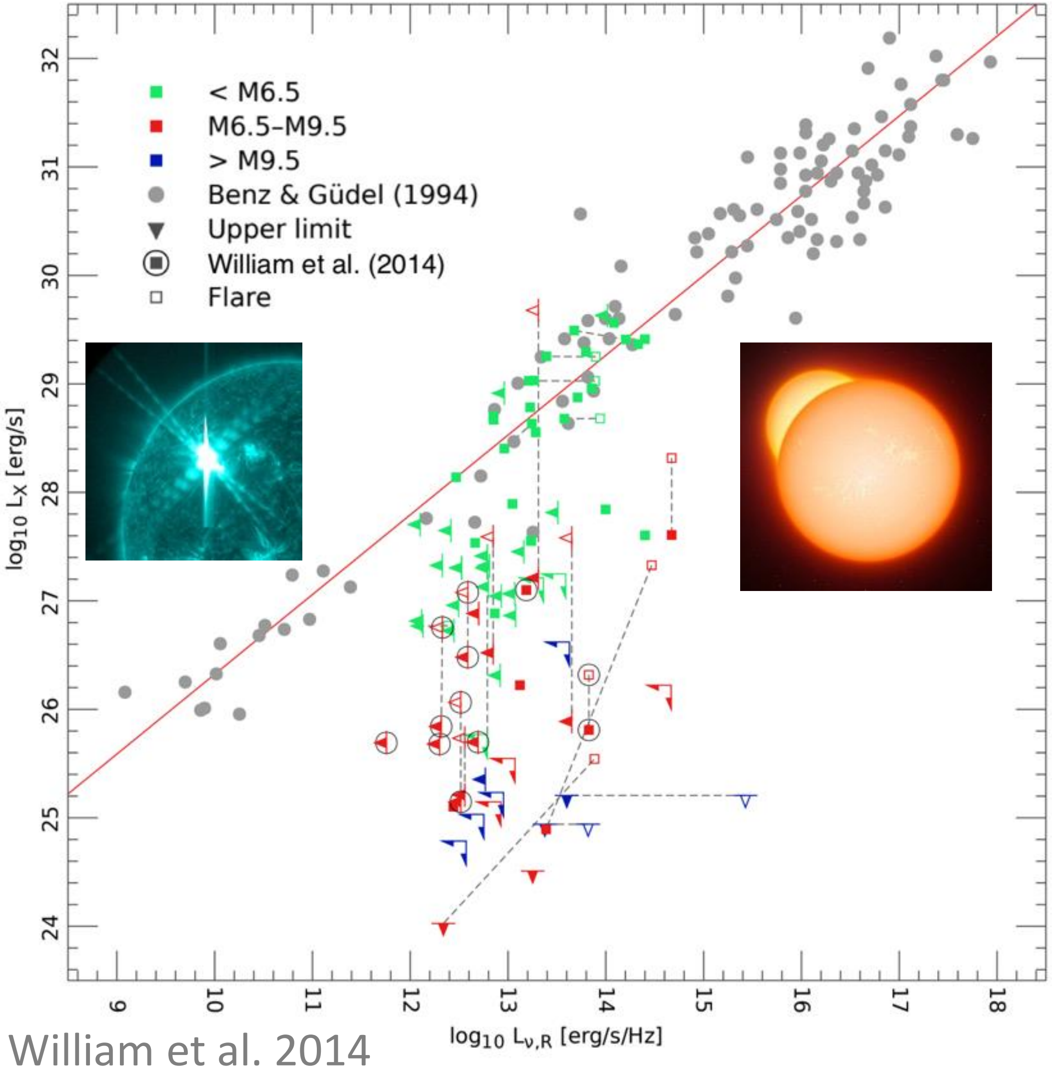
$$log_{10}(\nu) = \beta + \alpha_{\rm cum} log_{10}(E),$$




Gao et al. 2023

# Güdel-Benz relation




William et al. 2014

Güdel-Benz Law

- Empirical law: $L_X \propto L_{\nu,rad}$
- Valid across ~10 orders of magnitude! (from active binary to solar flare)
- Thought to be gyrosynchrotron ***(incoherent emission)***

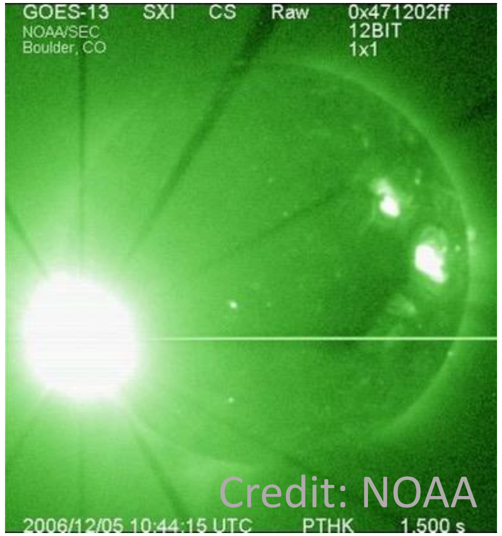
Sun-like vs ~~Jupiter-like~~

# Emission mechanism

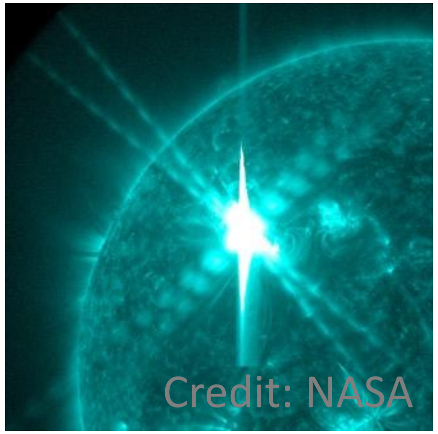
**Incoherent** vs **Coherent**

- *Free-free*
- *Gyrosynchrotron*

- *Plasma oscillation*
- *Cyclotron maser*

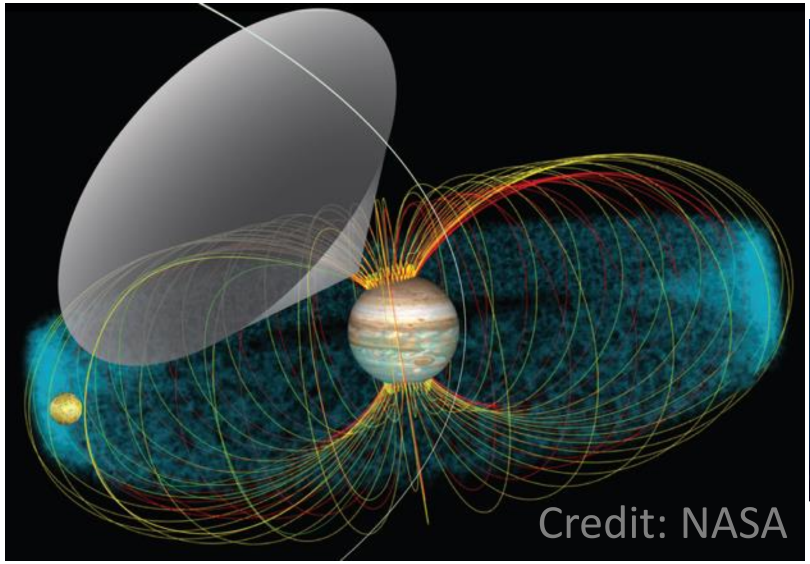



$\sim$ 100 MHz





$\sim$ GHz





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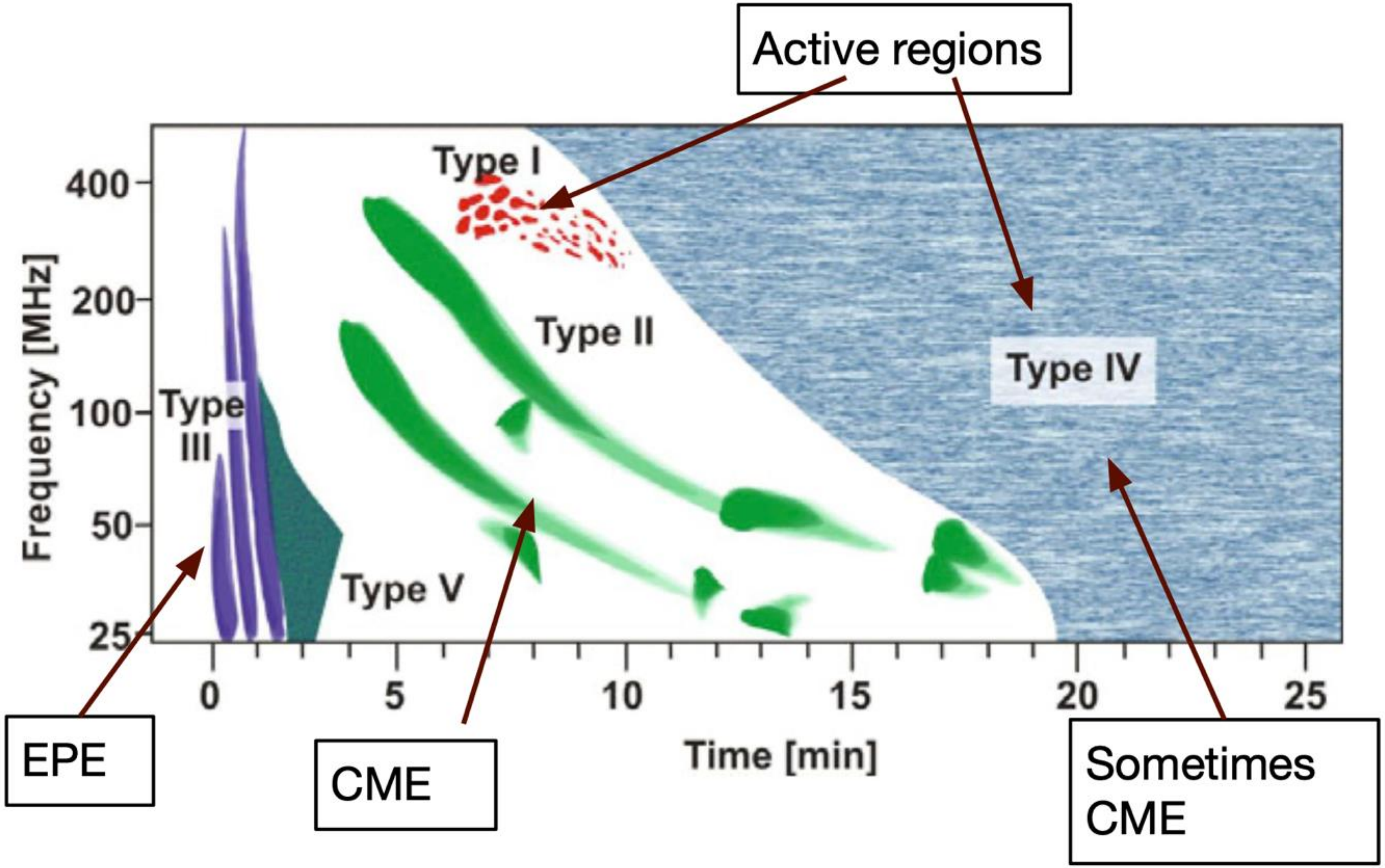
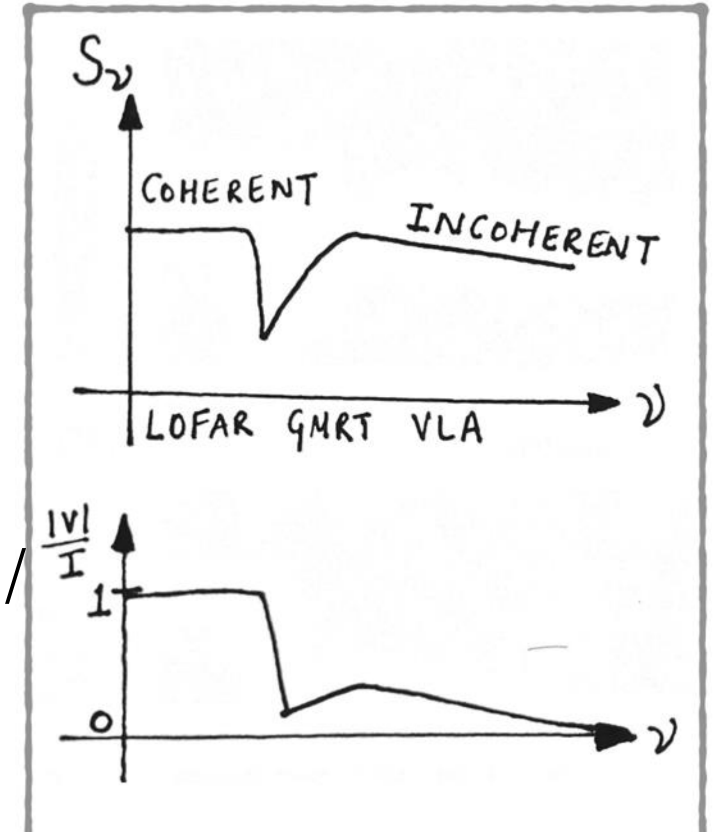
# Plasma emission dominates solar bursts

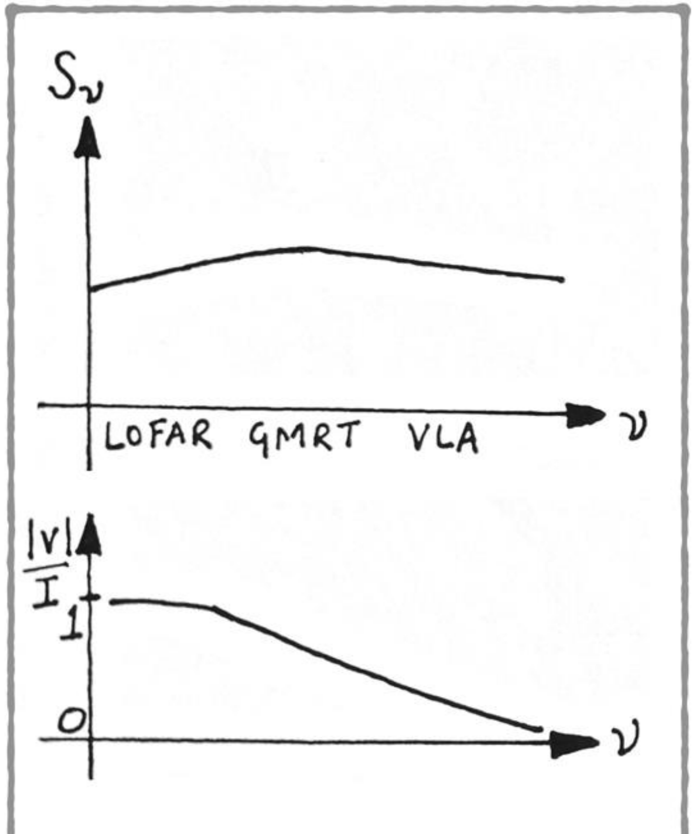


# 144MHz Güdel-Benz hypotheses

- 5 GHz: gyrosyhcrotron
- 144 MHz: plasma emission/ cyclotron maser




Model-1




Model-2

- 5 GHz: gyrosyhcrotron
- 144 MHz: gyro-resonance

**Strongly constrain coronal heating model!**

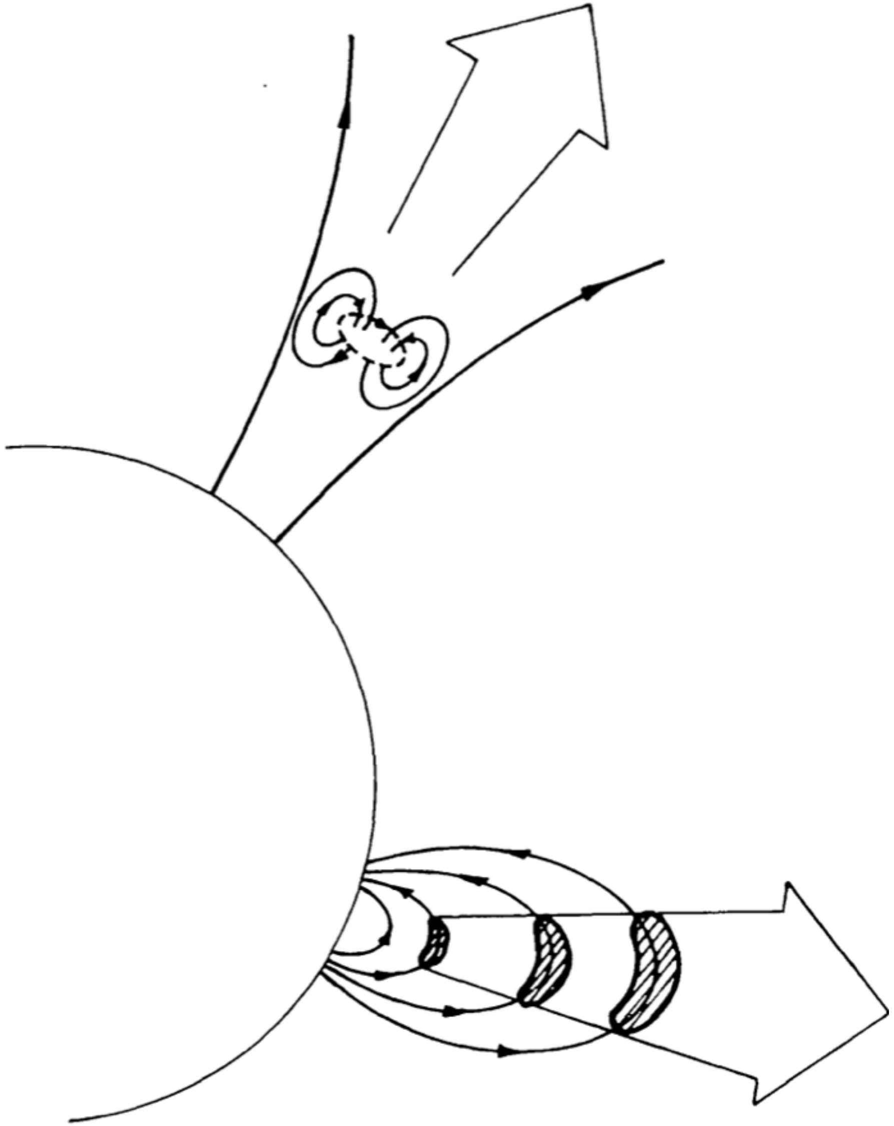
**Source size at 144MHz around 30–50 stellar radii!**

# Model 2: *moving* Type IV solar radio burst

- Expanding blob of plasma

- High polarisation fraction (~ 100 %) can only be generated emission occurs at very low harmonics of the cyclotron frequency

- Emitting electrons at kinetic temperatures of $\approx 10^{9.5}$ K that are barely relativistic



Dulk 1973

# Model 2: *moving* Type IV solar radio burst

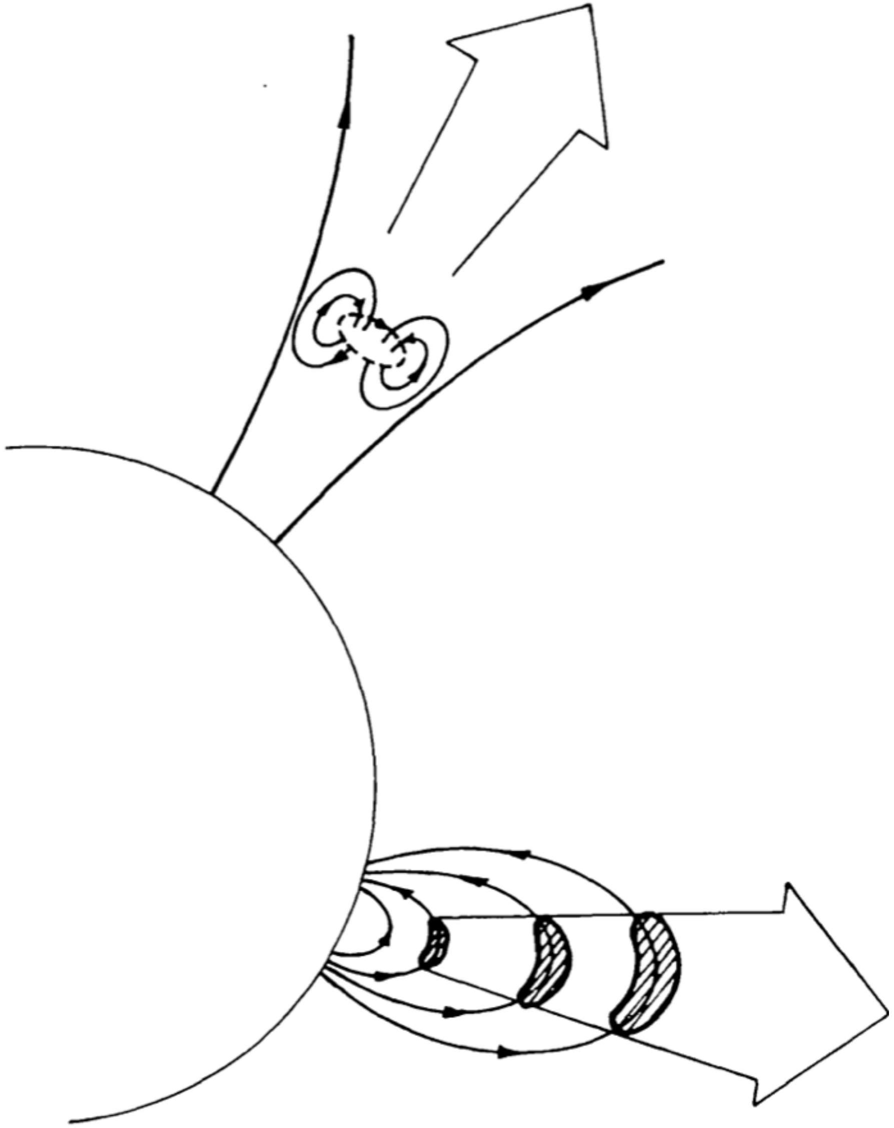
- Centimetre-wave emission:

Generated when the blob is small and its particles relativistic
$\Longrightarrow$ Gyrosynchrotron emission at 5 GHz

- Metre-wave emission:

As the blob expands to tens of stellar radii, its particles lose energy

$\Longrightarrow$ Gyro-resonance emission at low harmonics at 144 MHz



Dulk 1973

# What coherent emissions tell us

- Plasma emission:

$$\nu_p = \sqrt{\frac{e^2 n_e}{\pi m_e}} \approx 0.009\sqrt{n_e}\ \mathrm{MHz} \qquad T_b(\nu = 150\ \mathrm{MHz}) \lesssim \begin{cases} 10^{11}\ \mathrm{K} & \text{(continuous)} \\ 10^{18}\ \mathrm{K} & \text{(burst)} \end{cases}$$

- Cyclotron maser emission:

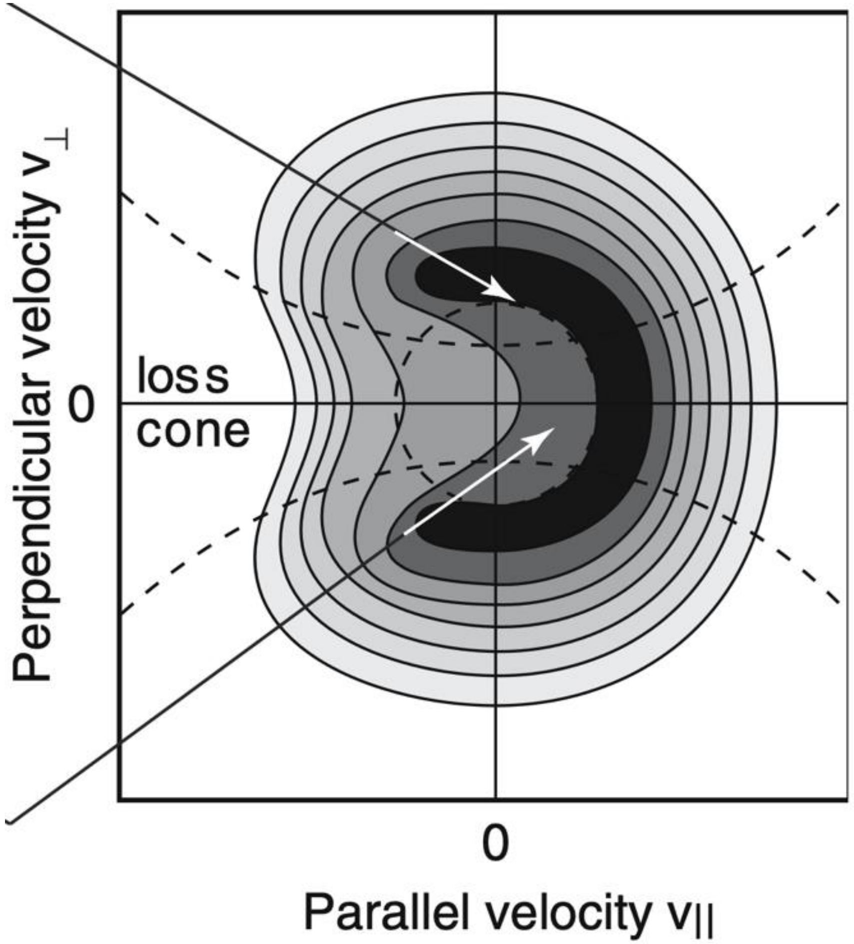
$$\nu_B = \frac{eB}{2\pi m_e c} \approx 2.8B\ \mathrm{MHz} \qquad T_b \lesssim 10^{20}\ \mathrm{K} \qquad \nu_p \ll \nu_B$$

# Electron cyclotron maser mechanism

- Source of free energy: an inverted (or unstable) population of electrons

- In the two-dimensional momentum space, the inversion usually takes the form of a loss-cone distribution of mildly relativistic electrons

- Loss cone refers to an absence of gyrating electrons at low pitch angles, creating a population inversion in $v_\perp$




Treumann et al. 2006

# Advantages of LOFAR

- Low frequency (10 to 240 MHz)

$\implies$ > 1 mJy source cannot be due to synchrotron radiation

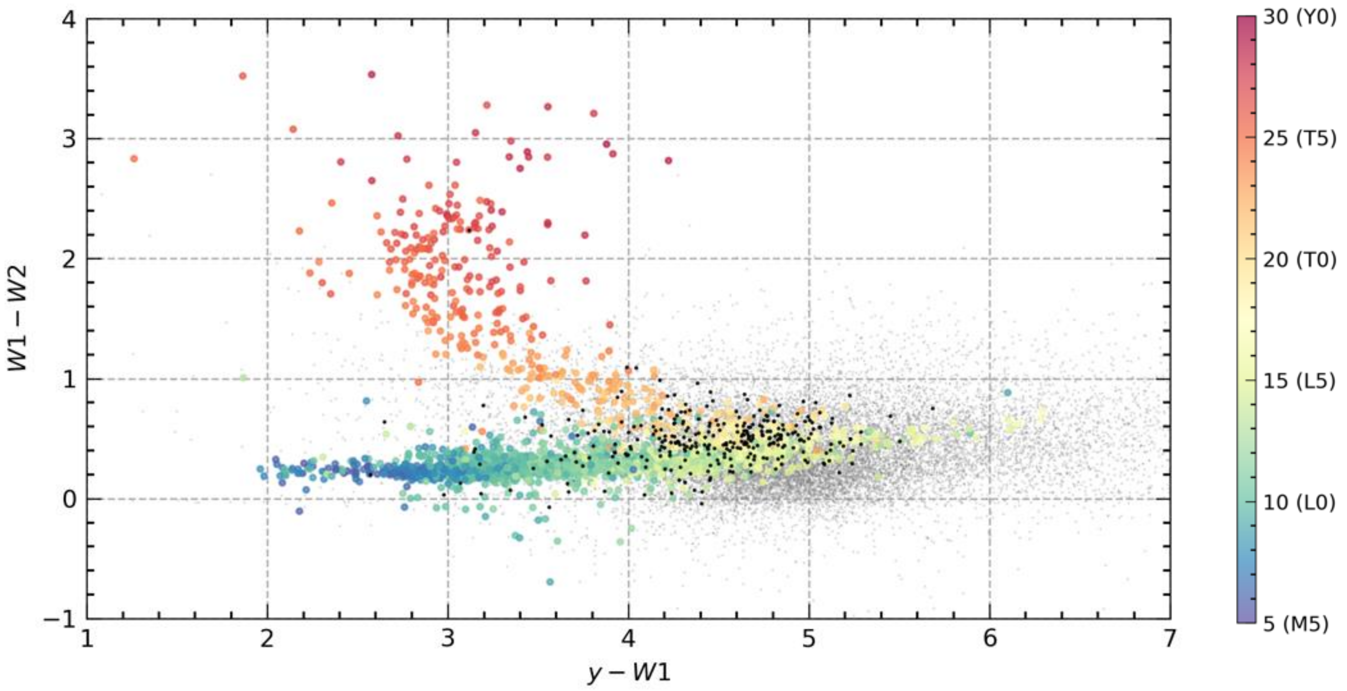
$$S_\nu \propto \nu^2 T_b \Omega$$

- Stokes-V $\implies$ highly circularly polarised sources

Therefore, incoherent emission!

# Challenges

Colour-colour diagram




- Most sources are extragalactic ☹

Source density

Max. separation

$$N_{\mathrm{false}} \propto N_s N_{s'} \theta^2$$

- Chance-coincidence associations!

# Solution: LoTSS Stokes-V + Gaia!

- LoTSS Stokes-V: ~6k sources (Callingham et al., in prep.)

- Circularly polarised sources $\Longrightarrow$ coherent emission

- $\mathcal{O}(\gtrsim 4)$ less dense than LoTSS Stokes-I

$\Longrightarrow$ No more false matches ☺

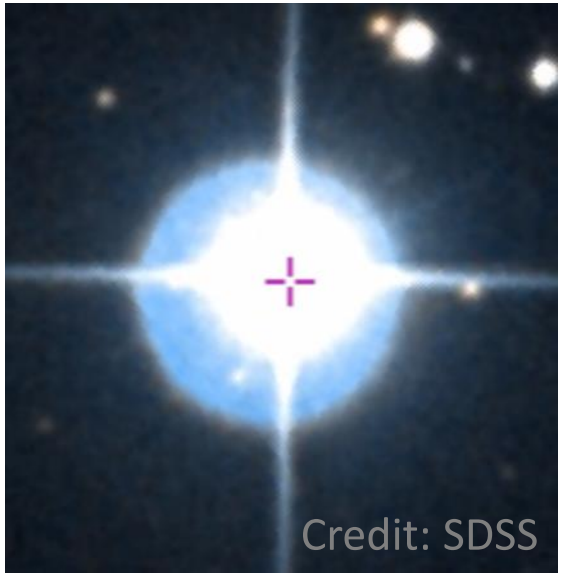
Source density

Max. separation

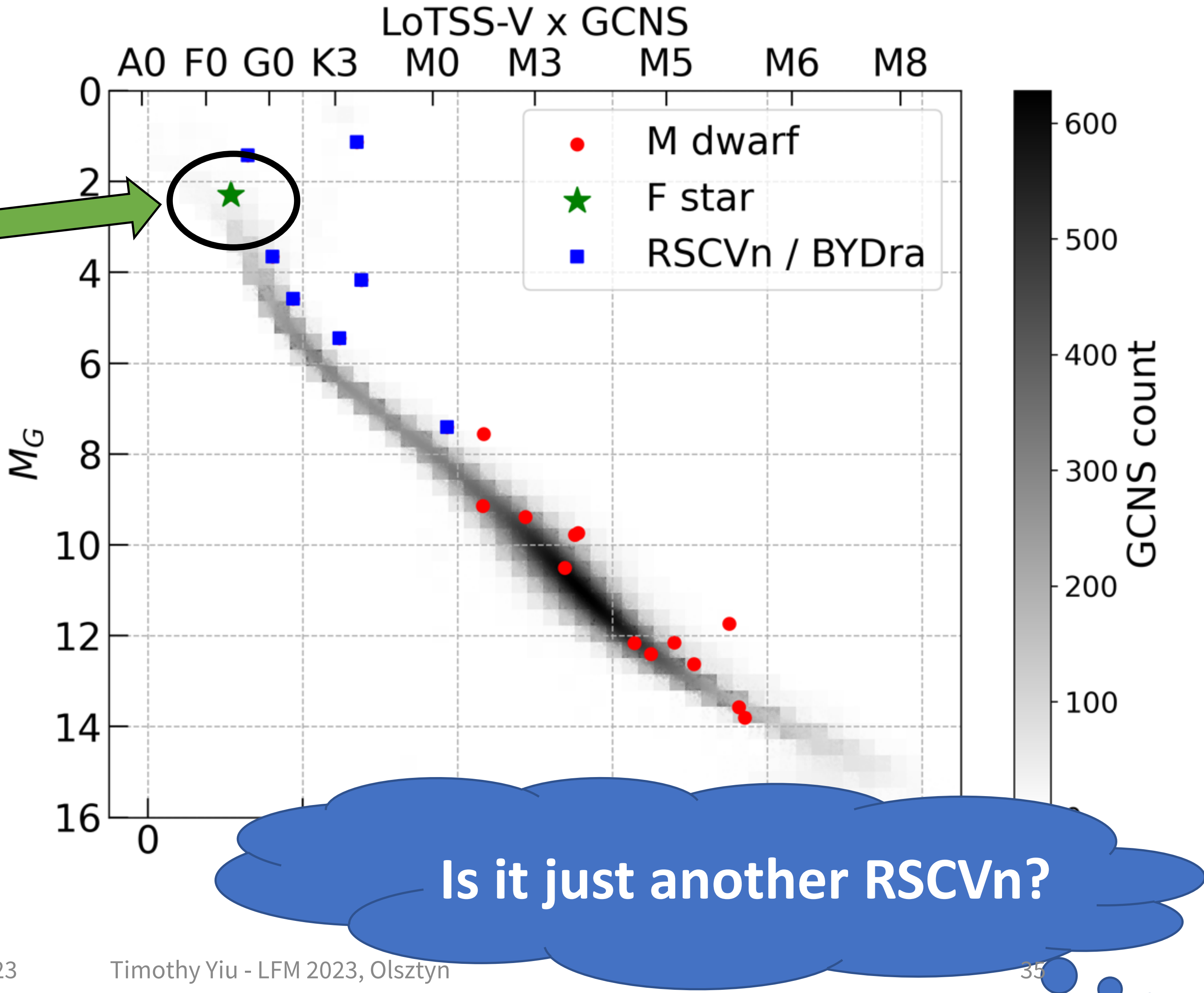
$$N_{false} \propto N_s N_{s'} \theta^2$$

# Remember?

- F stars are not known to be radio bright




HD 220242: an F5 star

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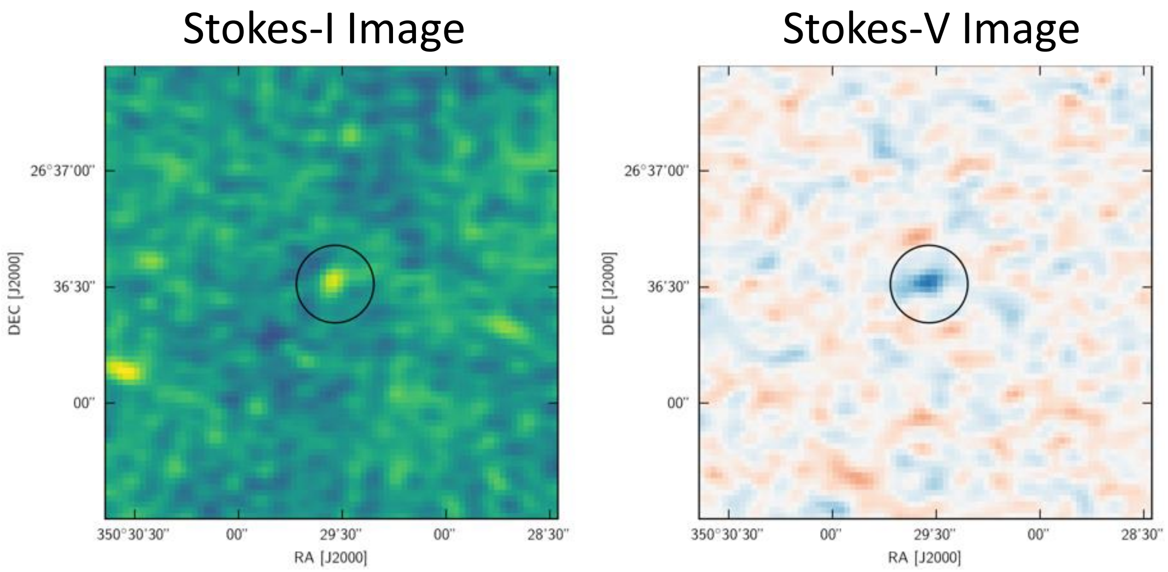
# Oddity: HD 220242



Yiu et al. in prep.

- ≈2 mJy in Stokes-V, ≈100% CP

- Lack of double-line emission/excess radial velocity (Nordström et al., 2004)

⟹ ***Not RSCVn!***

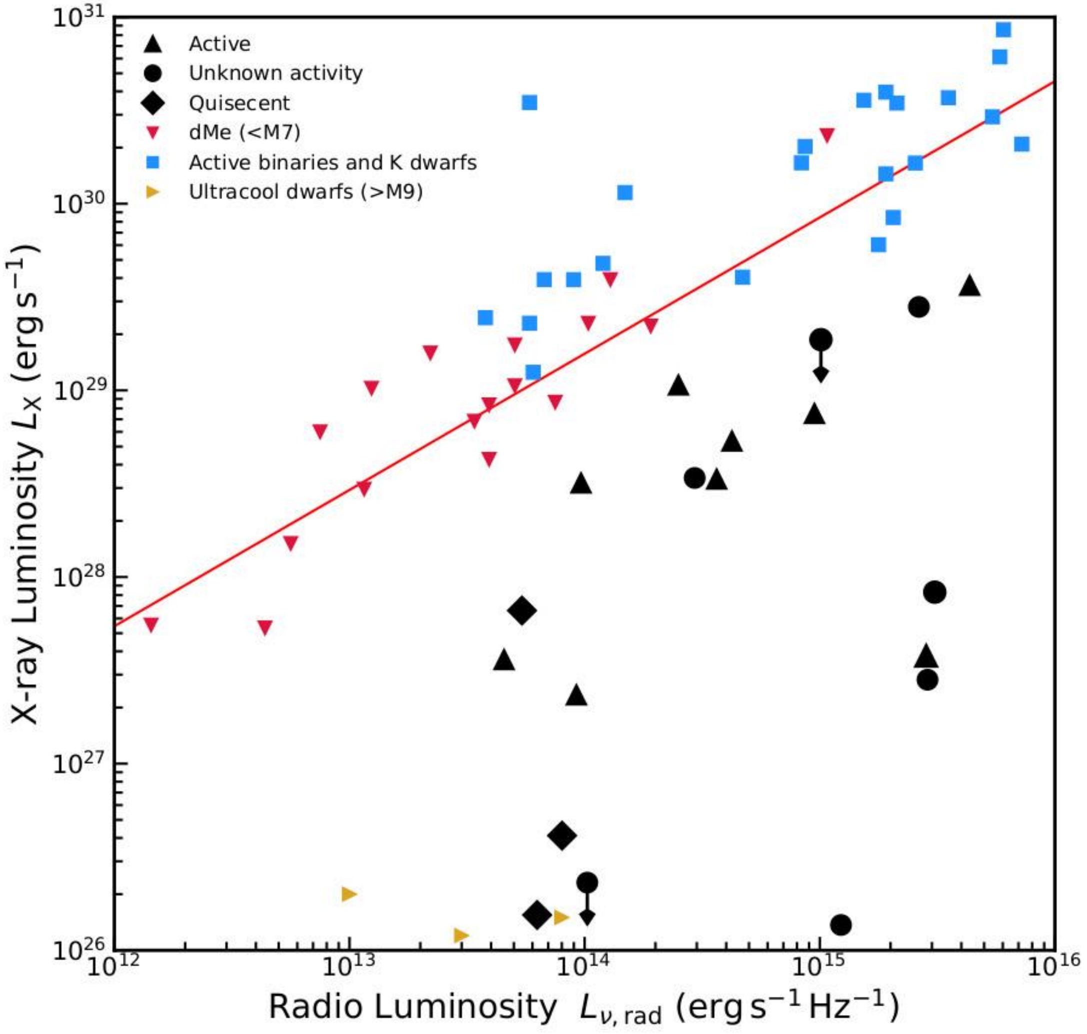
- Hipparcos-Gaia PM anomaly (Kervella et al., 2019)

⟹ Tangential acceleration

**Possible BD companion?!**

(To be continued…)

# Gudel-Benz in LOFAR?




Callingham et al. 2021

- Historically, GB law observed in 5 GHz
- LOFAR observes at ~100 MHz

⟹ ~~Gyrosynchrotron emission~~

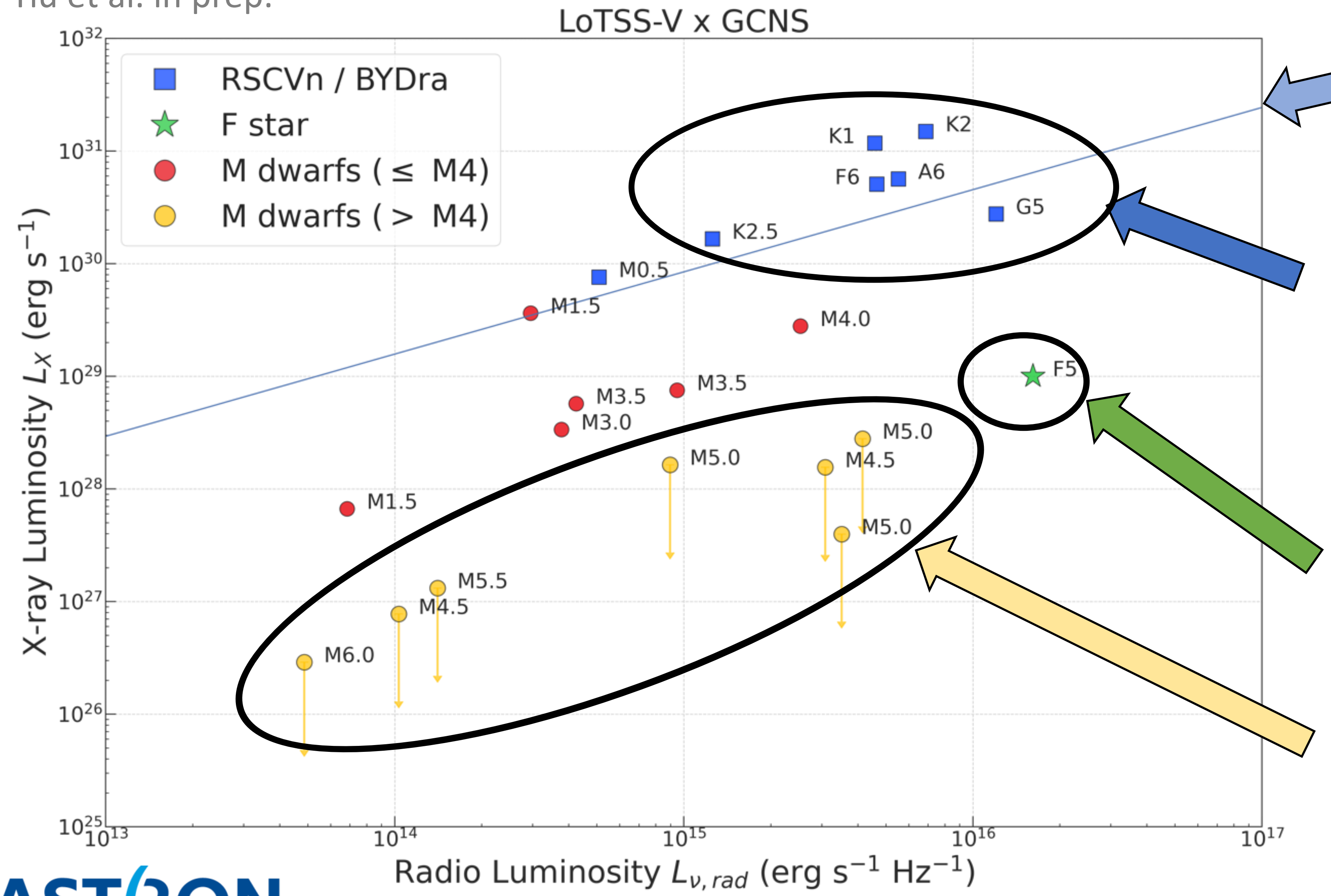
- Coherent radio-emitting M dwarfs

⟹ No longer obeys GB!

- Consistently radio bright/X-ray dim

# X-ray vs Radio Luminosity

Yiu et al. in prep.




Güdel-Benz Law

A,F,G,K stars are all RSCVn

Away from RSCVn!

M dwarfs consistently radio bright

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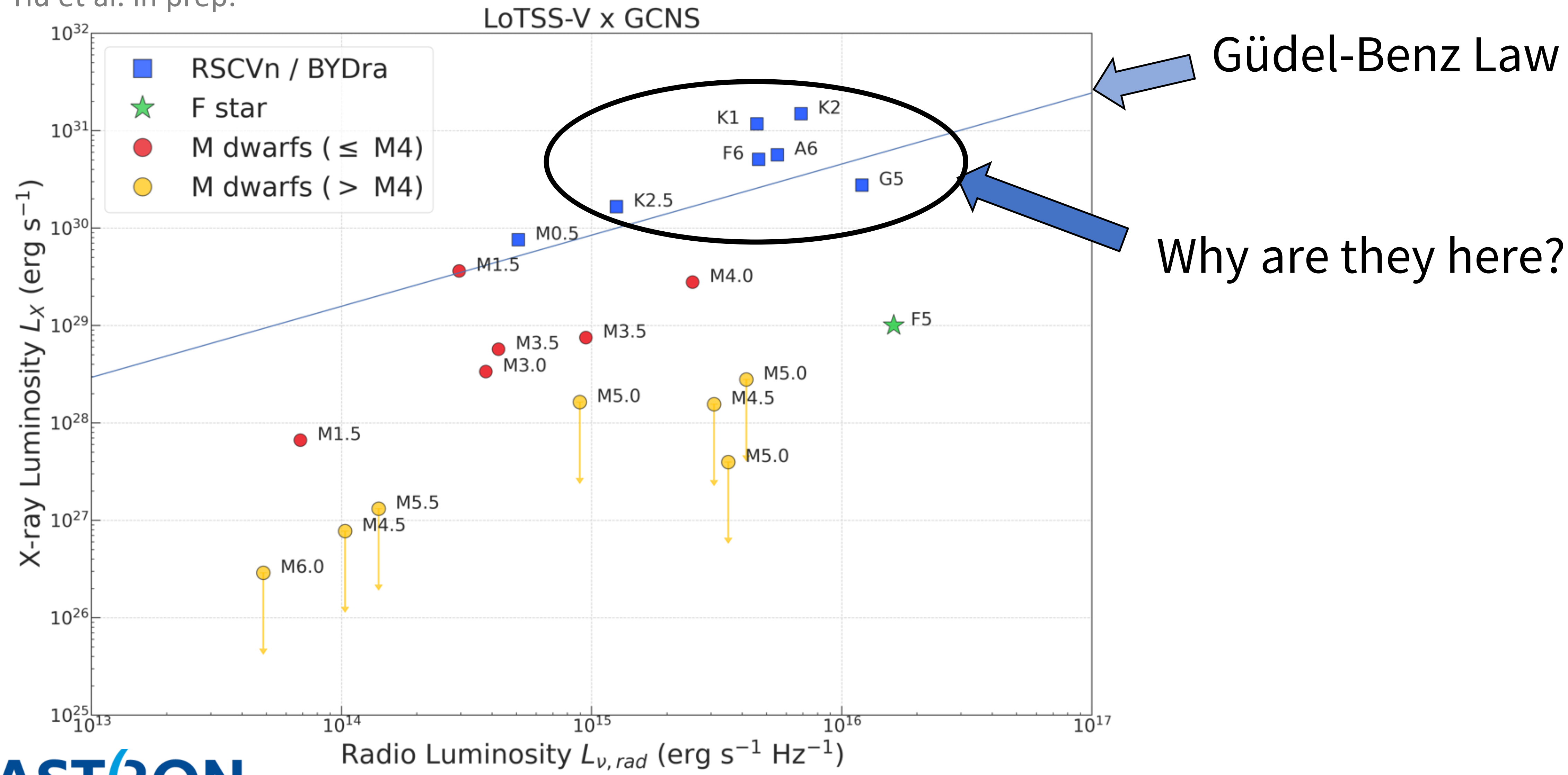
# One last thing…

Yiu et al. in prep.

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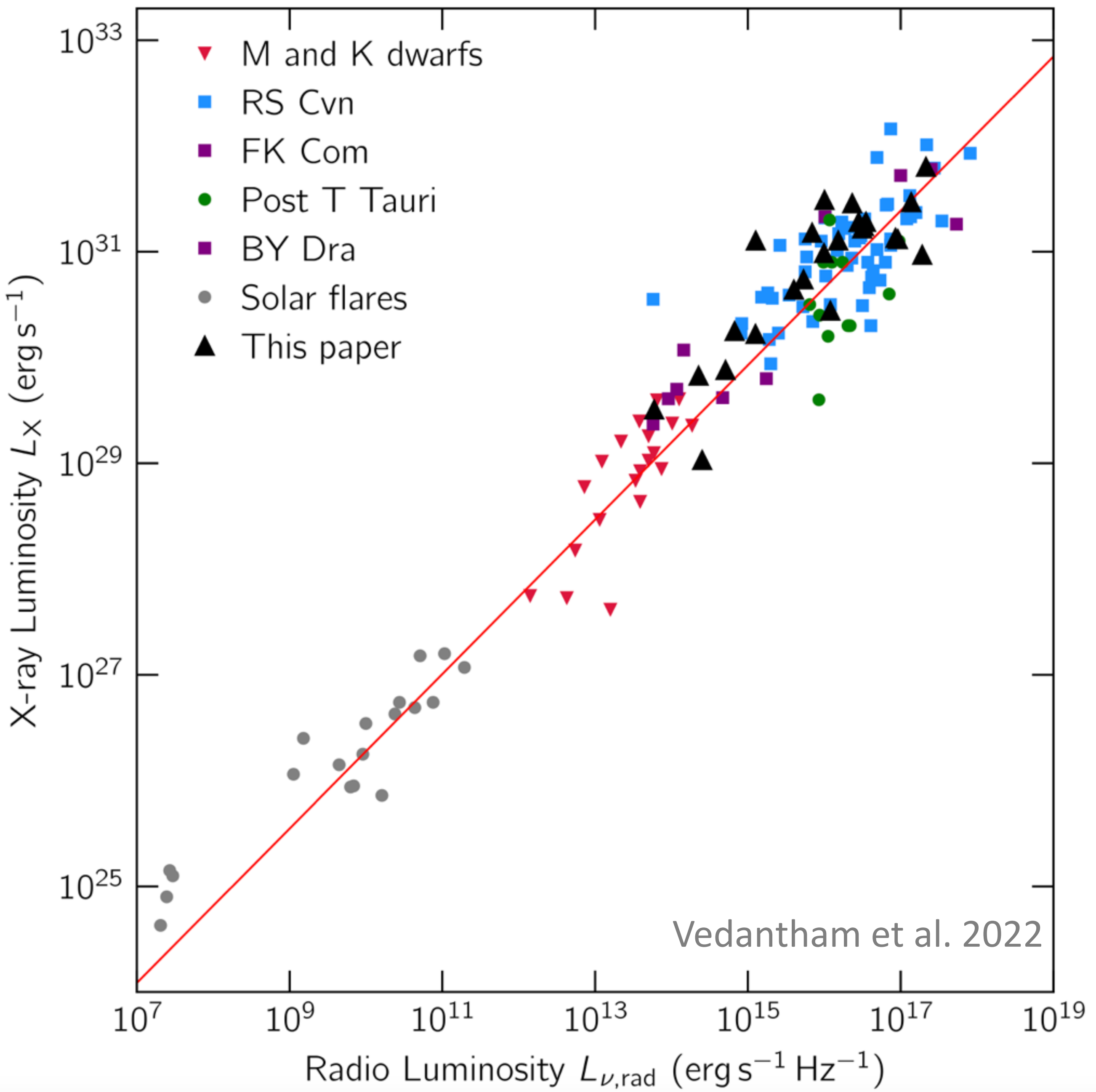
# Gudel-Benz in LOFAR

- These sources have high CP fraction + high $T_b$

$\Longrightarrow$ ***Coherent mechanism!***

- Cannot be gyrosynchrotron & Should not obey GB…

- And yet it does?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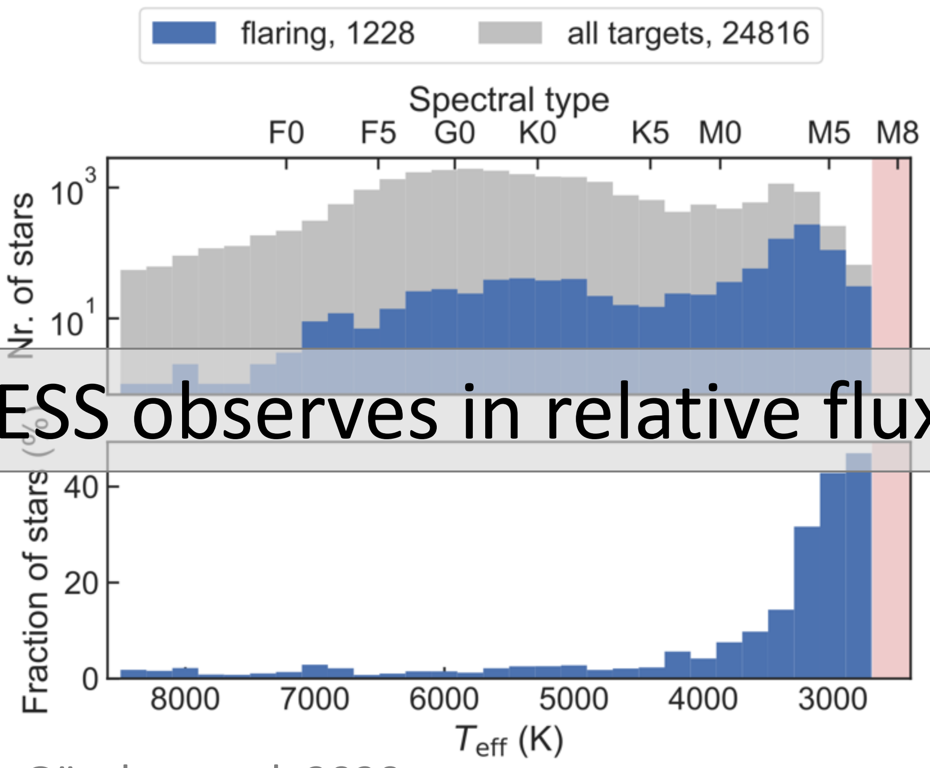
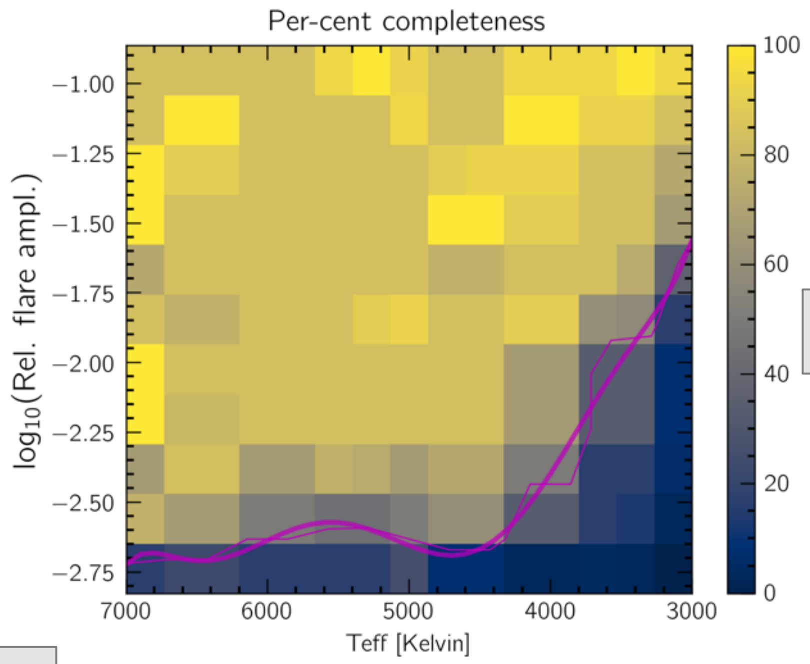
# CDF with TESS flares

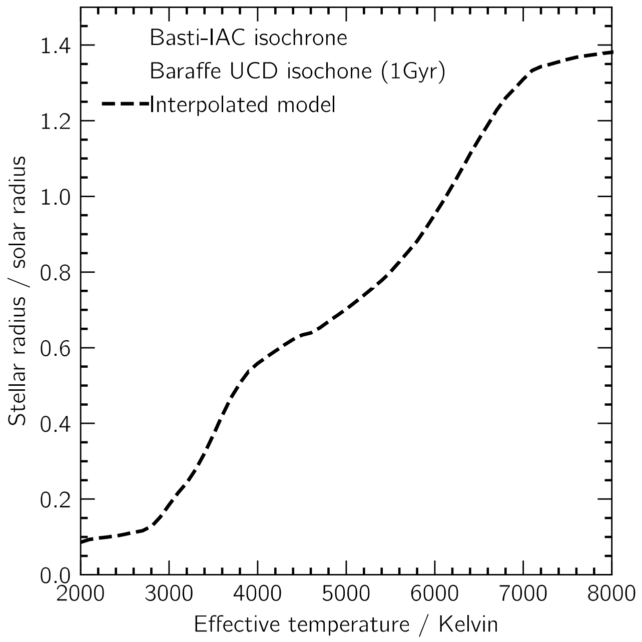



TESS observes in relative flux!

Günther et al. 2020




Relative flux completeness




Flare energy threshold

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*How low can you go?*

# Science at Low Frequencies IX
# December 11-15, 2023

The 9th annual SALF conference will be hybird, with the in-person component hosted near the University of Amsterdam.

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