Unveiling Elusive Radio Flares in Hot Magnetic OBA Stars with the VLITE Commensal Sky Survey

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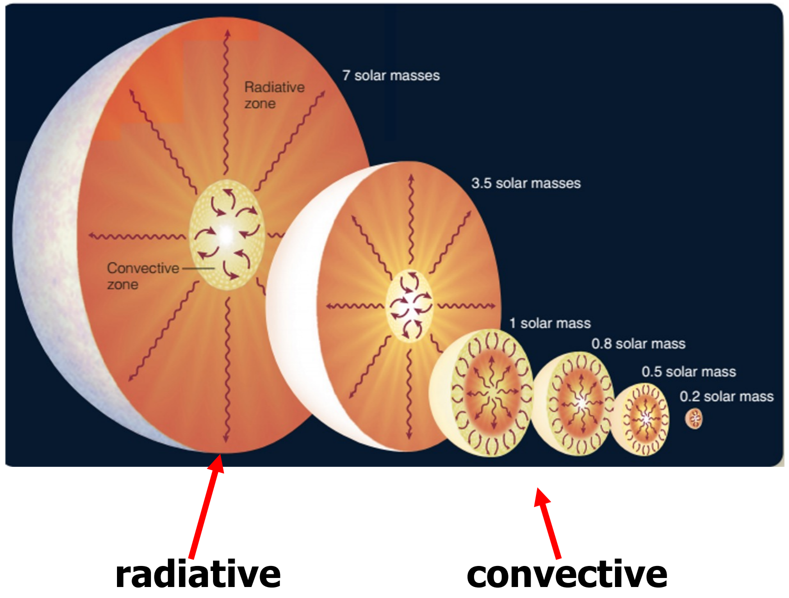
Hot magnetic stars

Early-type stars (O B A)

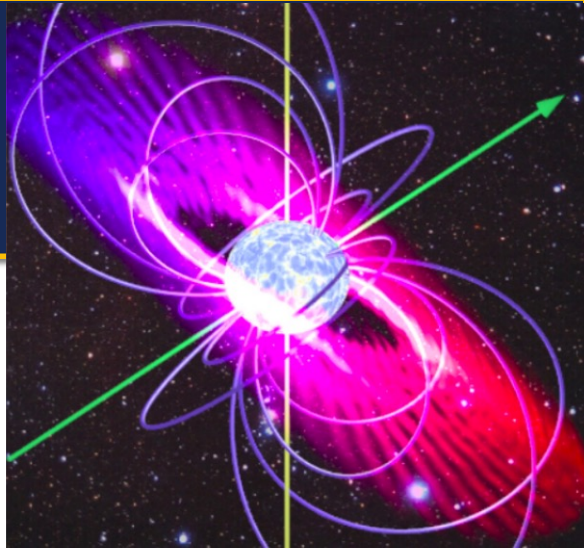
- M > ~ 2 Solar
- **Hot**: T > 10^4 K
- ~10% **magnetic**: B > ~ 0.1 kG
- Radiative heat transport = simple (dipole), stable magnetic fields compared to convective late-types (F G K M)

Do they flare?

- Optical, X-ray, radio flares reported from magnetic & non-magnetic. Attributed to late-type companions



Hot magnetic star flares?



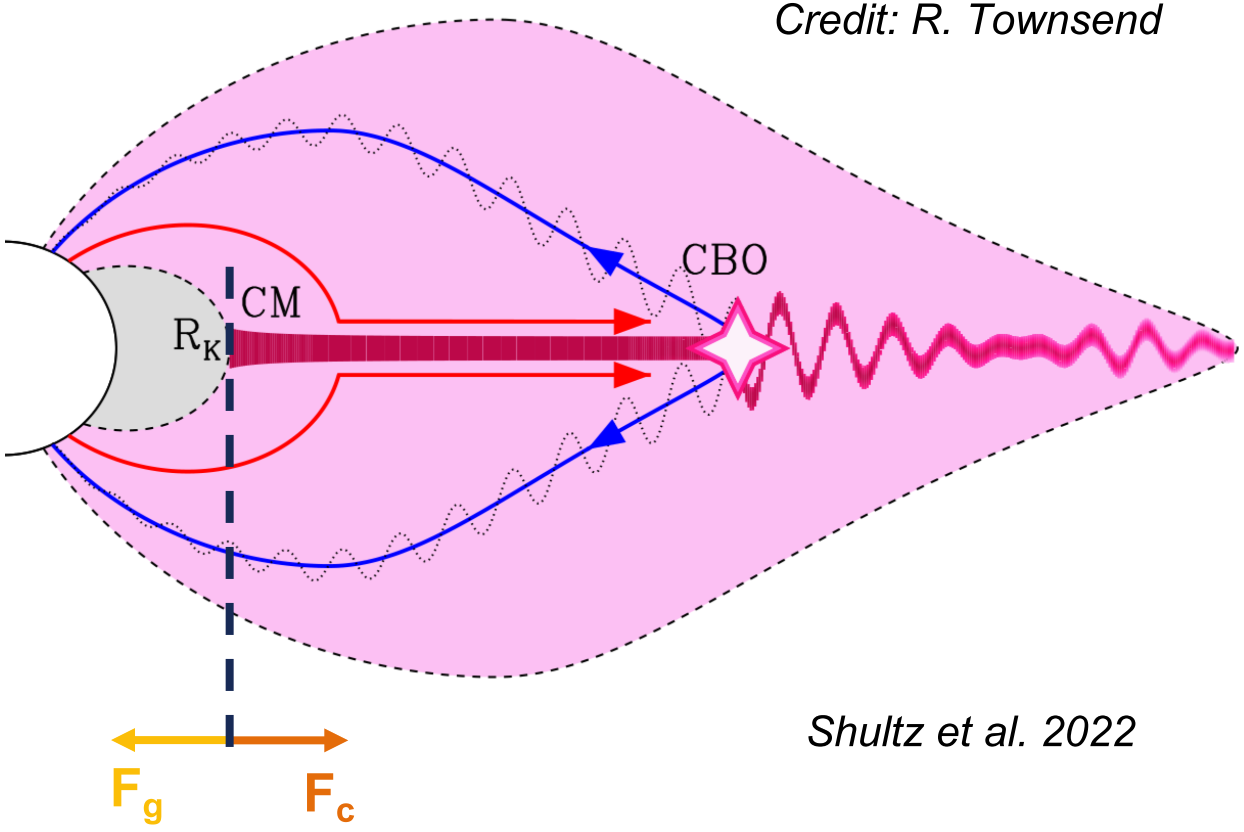
Credit: R. Townsend

Centrifugal Breakout (CBO; Townsend & Owocki 2005)

If sufficiently magnetic & rotating: Kepler radius < Alfvén radius

Centrifugal Magnetosphere (CM)

- Stellar wind forced corotation in magnetosphere
    - forms disk
    - moves outward
- Reconnection, flares when plasma breaks out

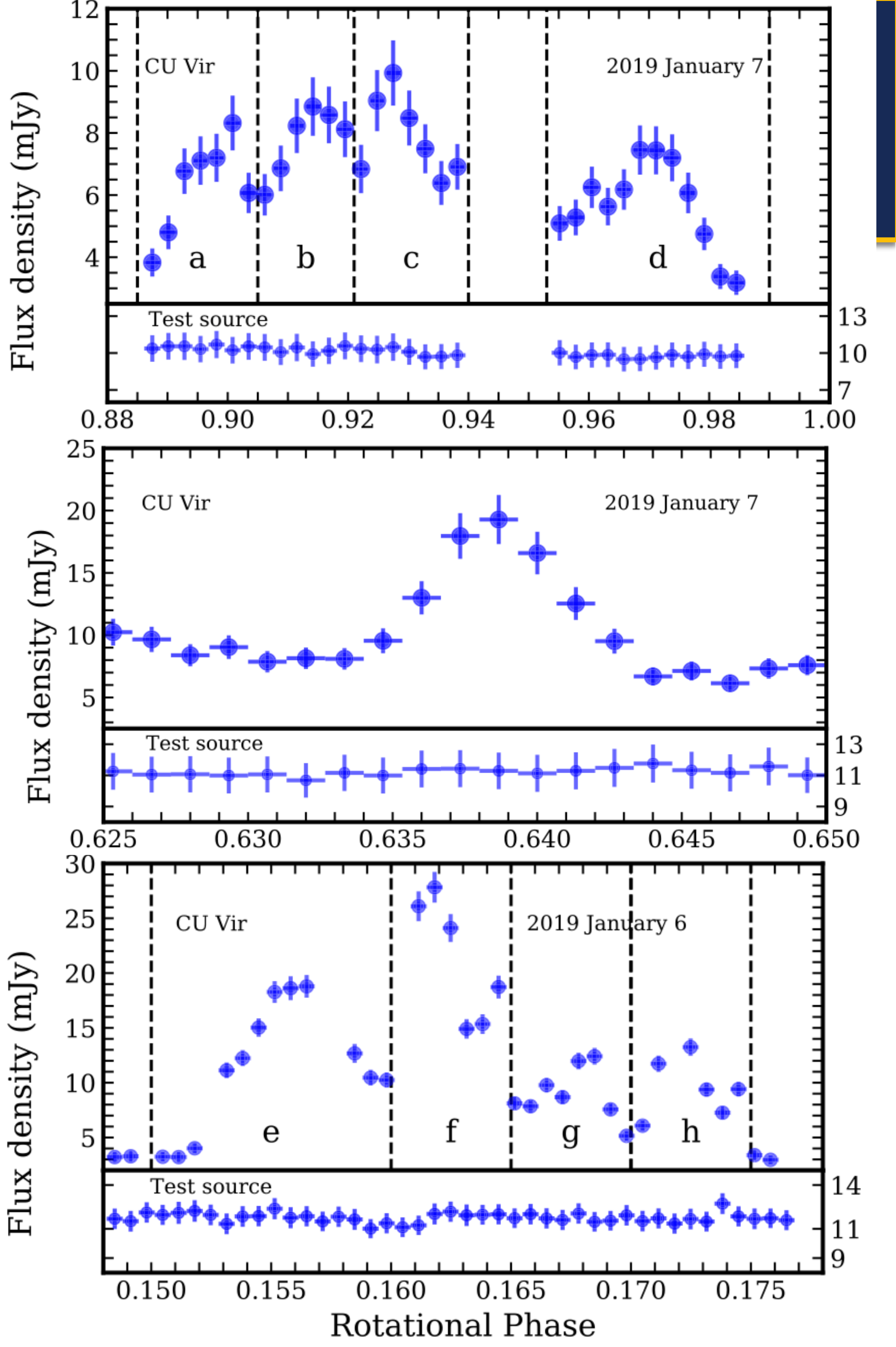


Shultz et al. 2022

CBO detection in CU Vir?

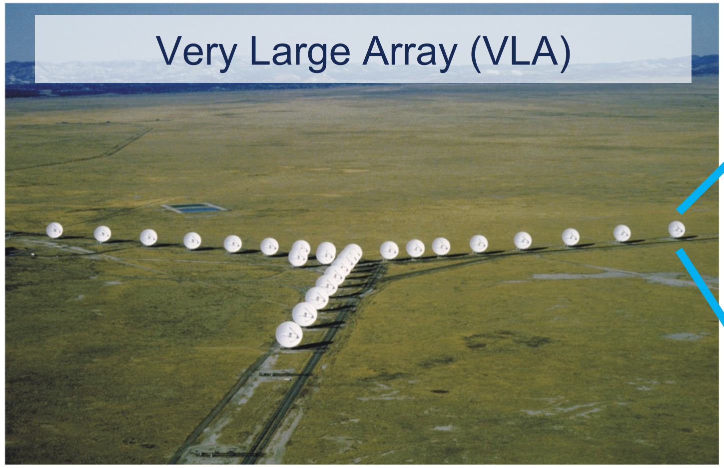
Das & Chandra (2021): 1st observational evidence of CBO?

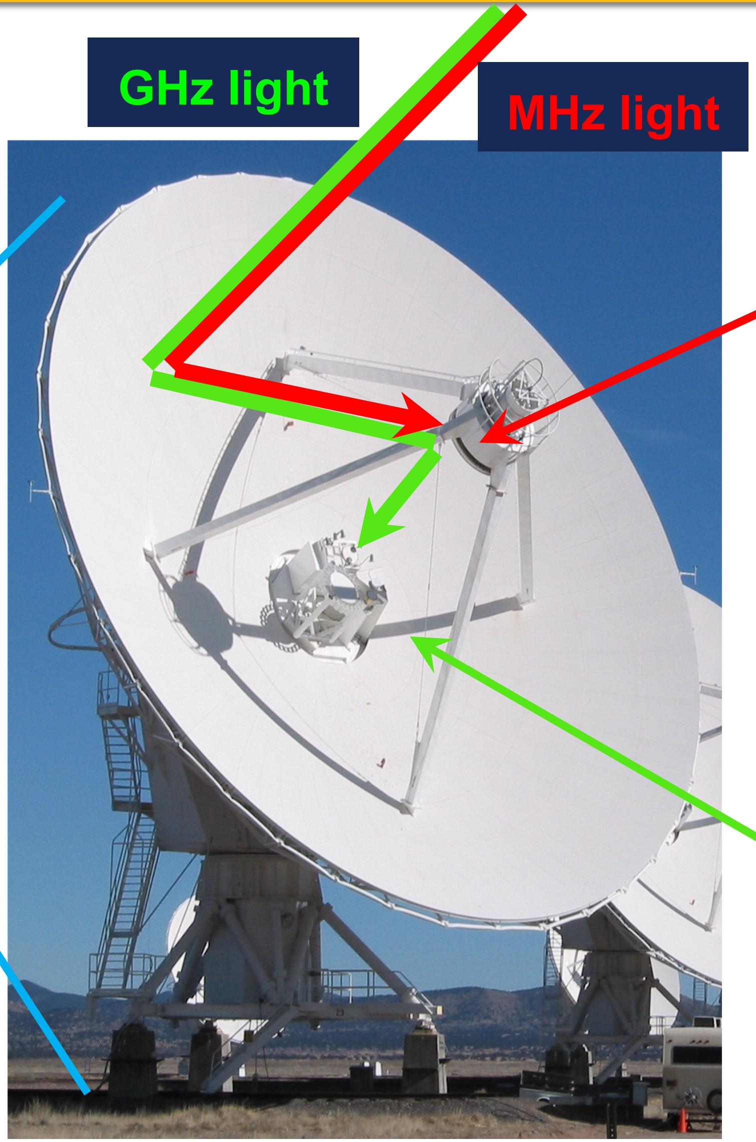
- Observed transient radio emission from CU Virgins
  - GMRT 500-800 MHz
  - Δt ~ 4 - 8 min
  - Circularly polarized
  - Coherent (T > 10^{14} K)
  - L ~ 10^{17} erg/s/Hz



VLA Low-band Ionosphere & Transient Experiment (VLITE)

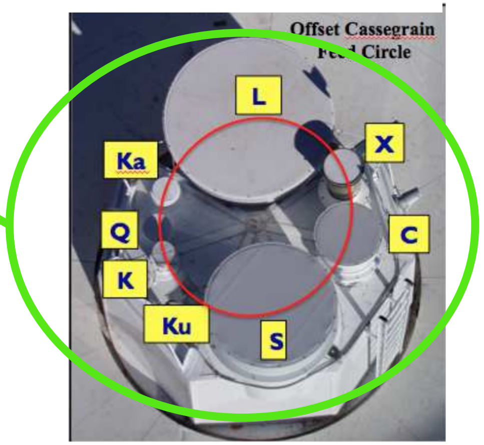
Commensal P band observing at VLA prime focus





Low frequency receivers (primary focus)

High frequency receivers (secondary focus)



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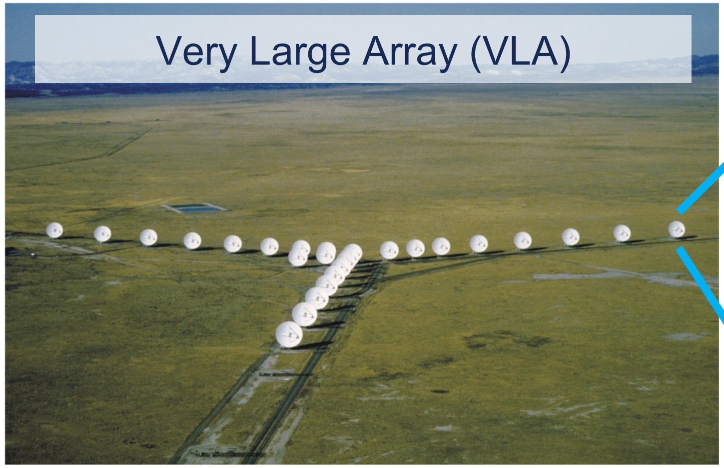
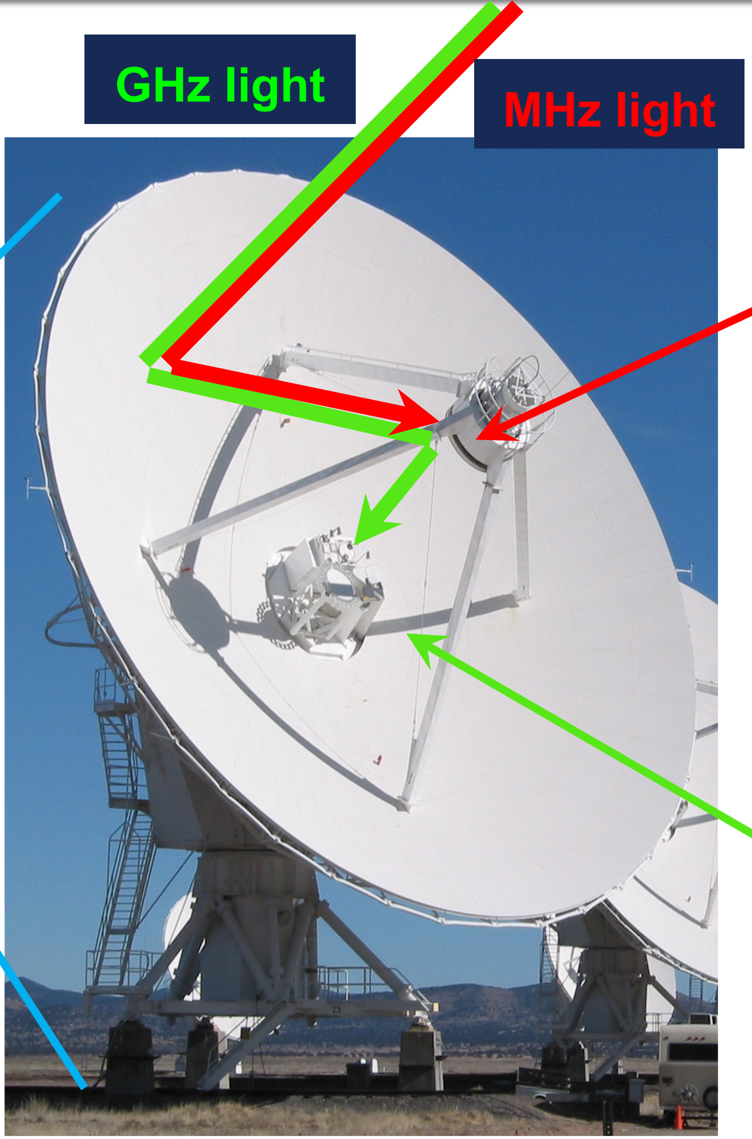


- **340 MHz**
- **BW = 40 MHz**
- **N = 18 antennas**
- **$1 million investment on $440 million infrastructure** (inflation adjusted)



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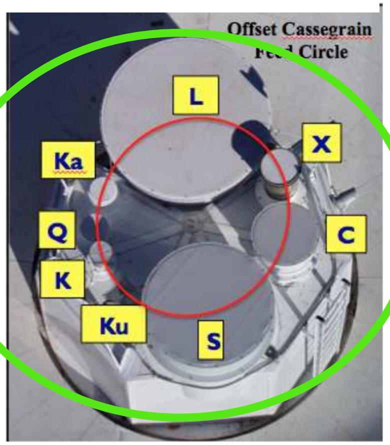
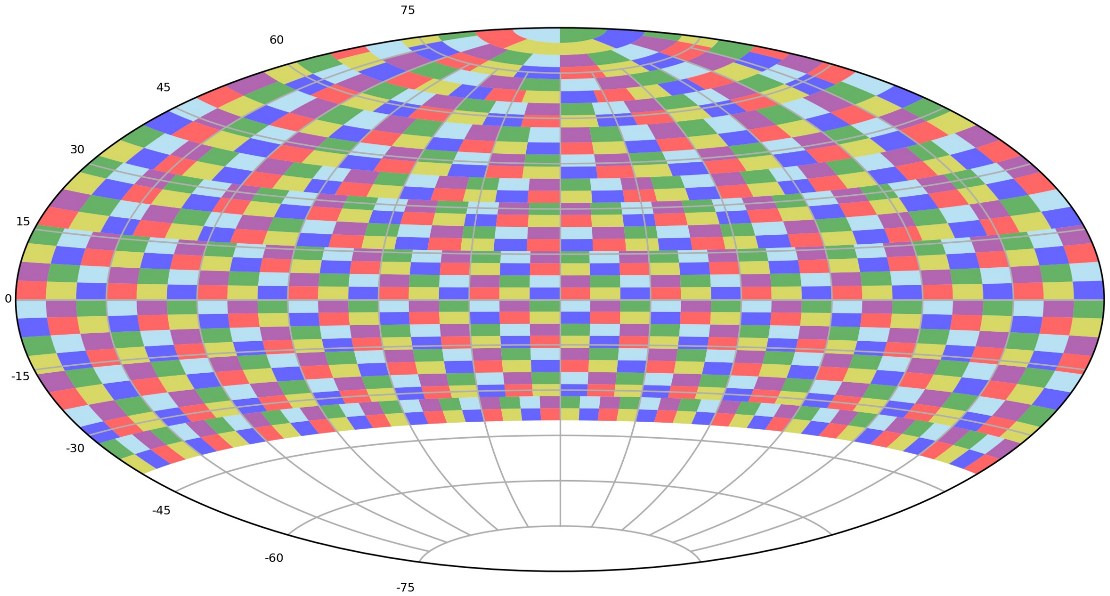


VLA Sky Survey

VLA Sky Survey (VLASS) Lacy et al. 2020

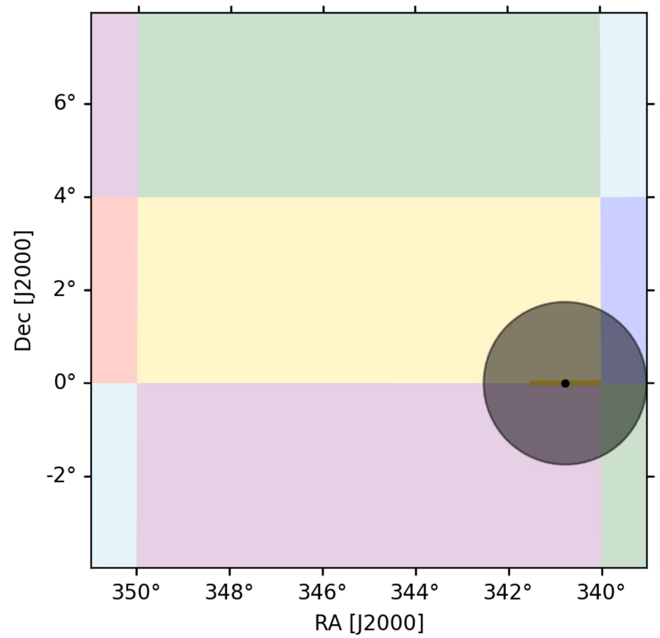
- 3 GHz, 34,000 deg^2 (Dec > -40 deg)
- 3 epochs. 1600 hrs/epoch. Δt ~ 32 months
- On The Fly observing mode
- 10 x 4 deg tiles, ΔDec ~ 7 arcmin

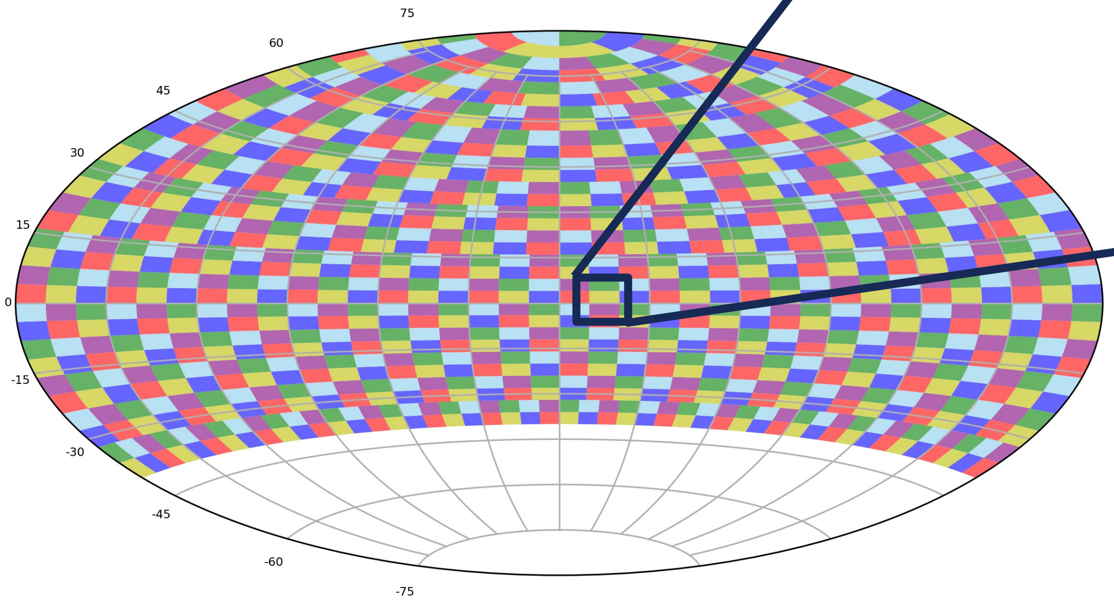


VCSS: VLITE During VLASS

VLITE Commensal Sky Survey (VCSS)

- VLITE OTF observing:
  - step delay center 1.5 deg in RA
  - integrate while antennas slew (~ 28 s)
  - 3.5 deg wide, highly overlapping snapshot images
  - Sources sampled by ~ 45 snapshots over ~ 90 min, but irregular sampling (days - year) along tile borders





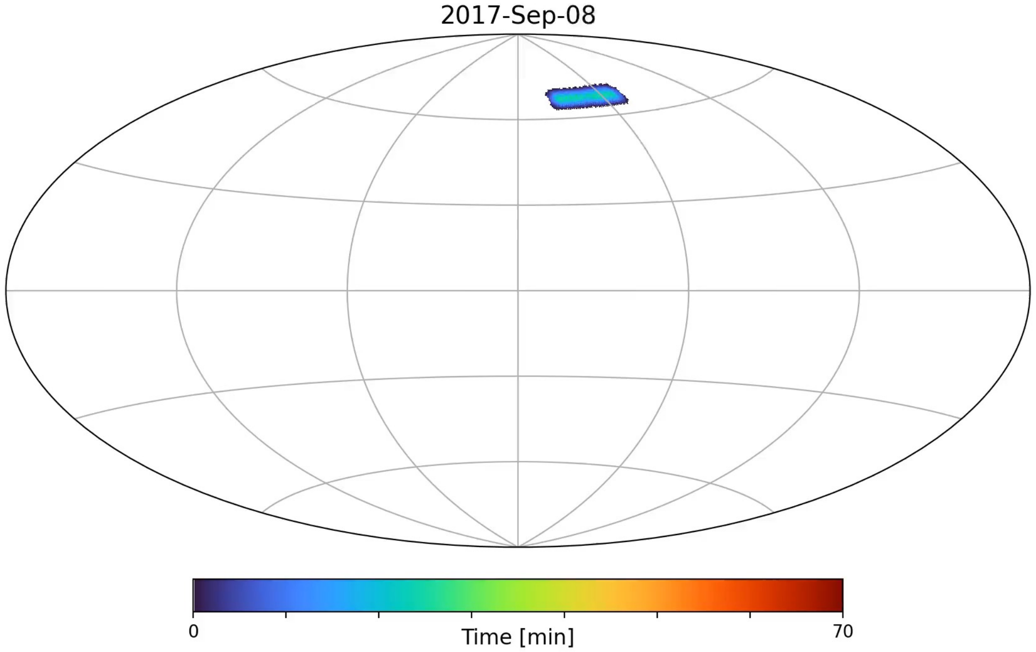
VCSS Snapshots

Snapshot image catalog (per epoch)

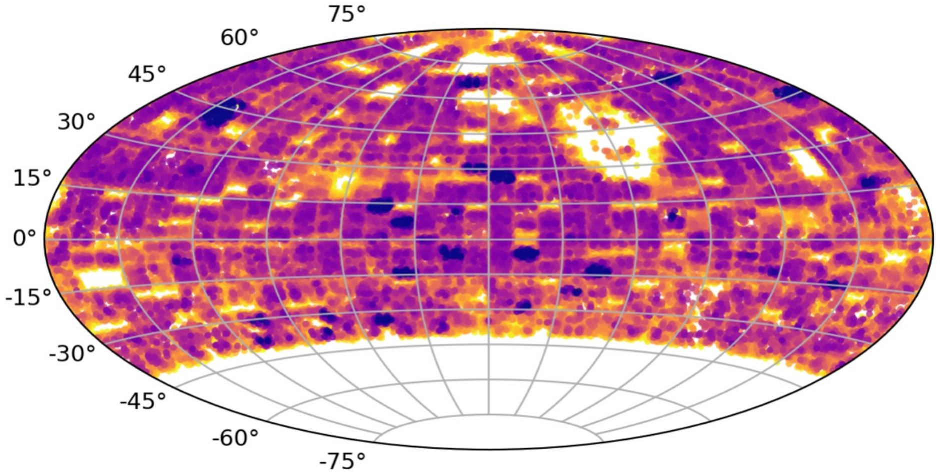
- ★ ~ 160,000 images (Stokes I)
- ★ ~ 10 deg^2 FoV
- ★ ~ 15" resolution
- ★ ~ 32,000 deg^2 coverage after quality checks
- ★ ~ 7-10 mJy/bm noise

Snapshot source catalog (per epoch)

- ★ ~ 1.4 million sources (SNR > 5)
- ★ ~ 300,000 w/ catalog matches (TGSS & RACS-low)
- ★ Best VLITE data for bright (S > 50 mJy), ~ min timescale transient searching



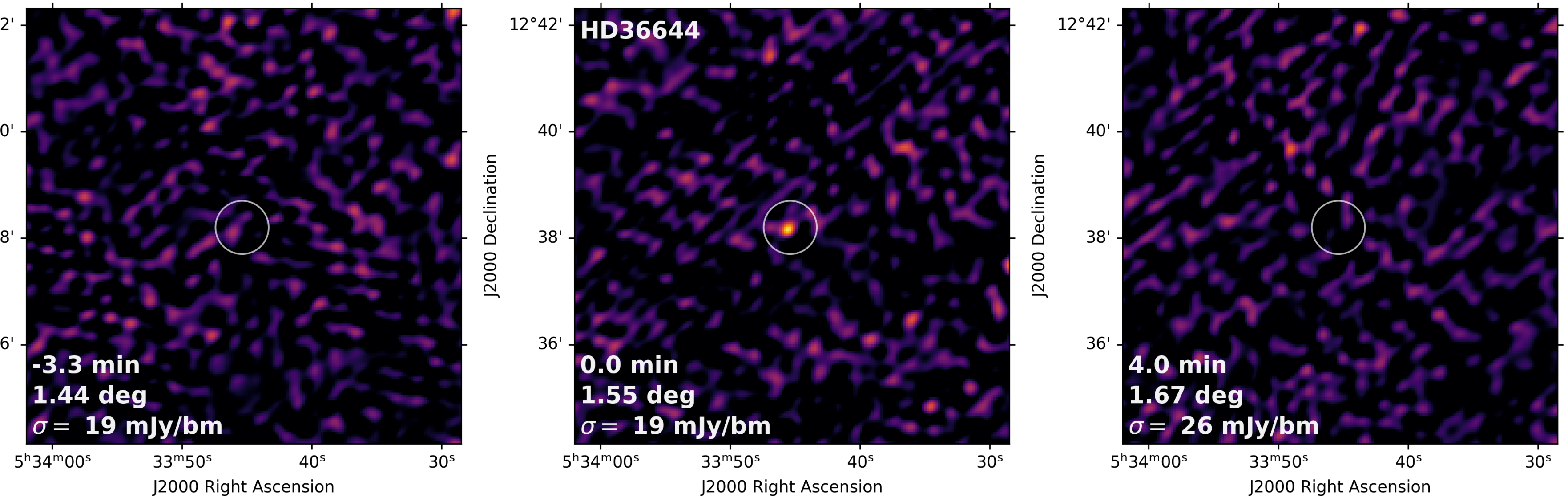
VCSS epoch 1 + 2 sky coverage
Sept 2017 – Feb 2022

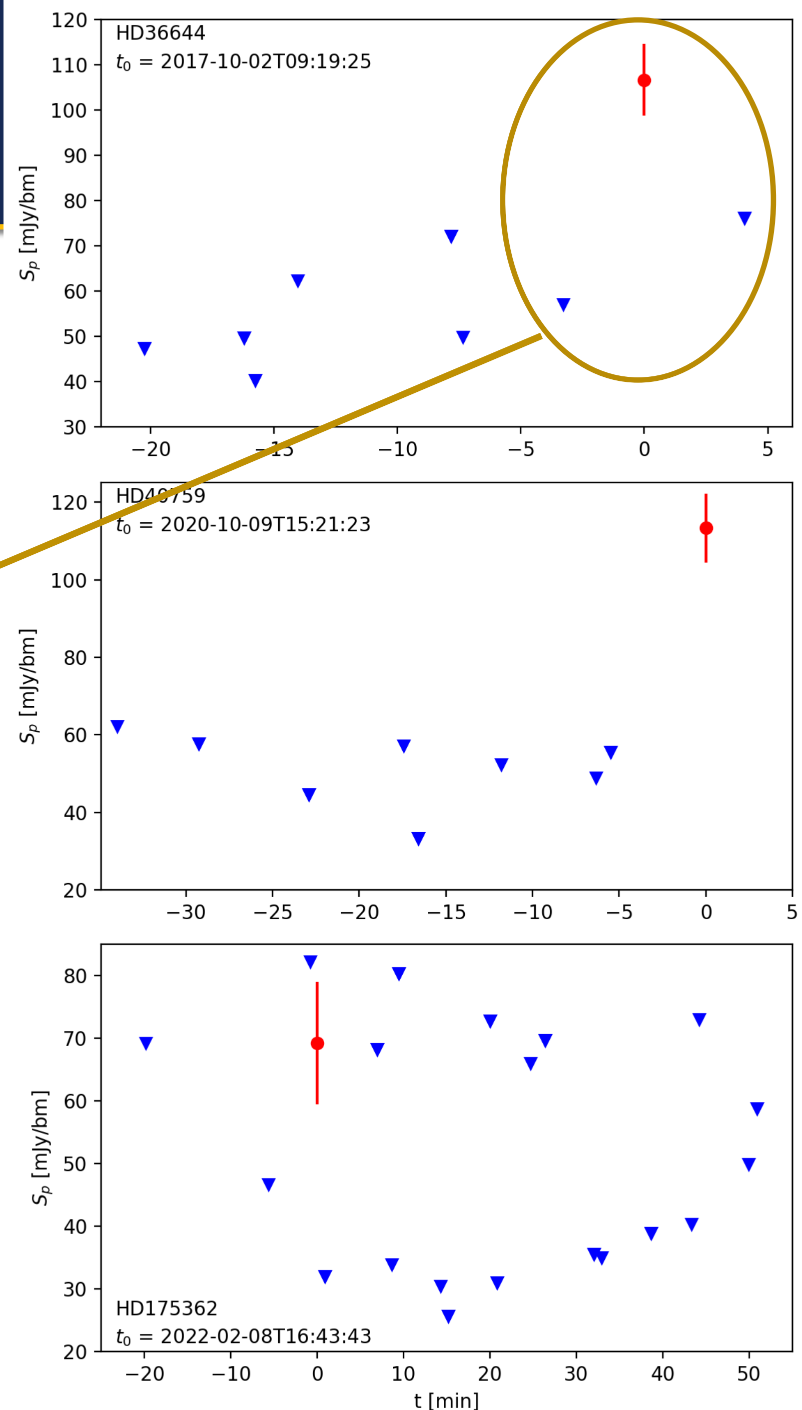


Distribution of catalog-matched epoch 1 sources

VCSS hot magnetic star detections

- Catalog of 761 magnetic OBA stars (Shultz et al. in prep)
- 3 matches: HD 36644, HD 40759, HD 175362
- 1 detection each: S ~ 100 mJy; t ~ min; $T_b > 10^{12}$ K
- No VLASS counterparts but observations not coincident

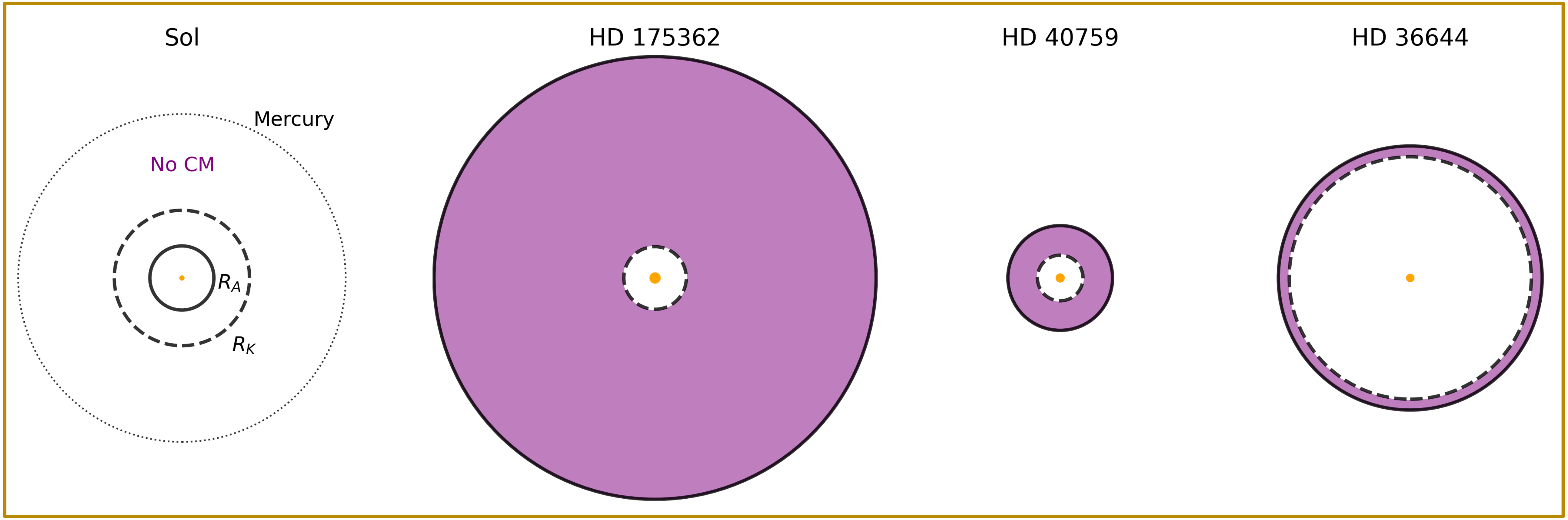




Do they have CMs?

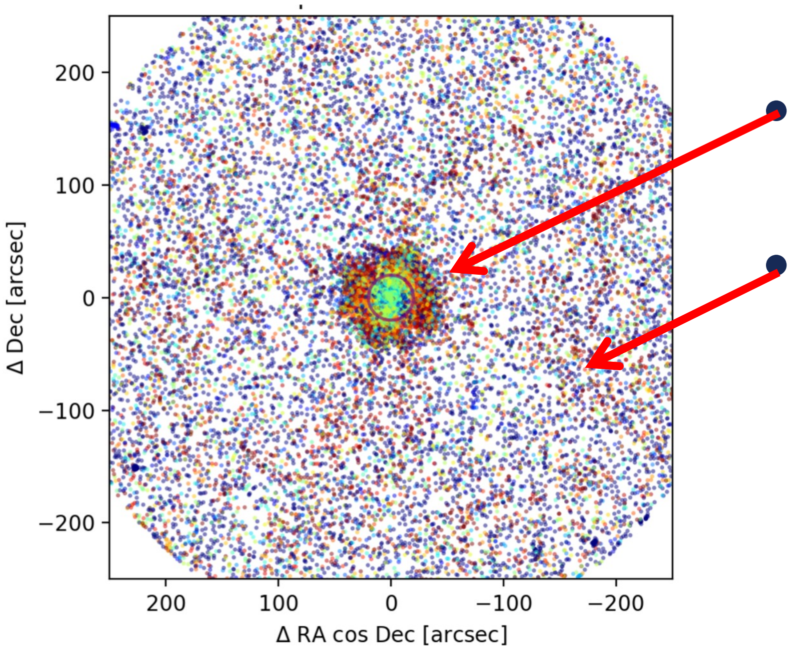
Stellar parameters consistent w/ hosting centrifugal magnetospheres

$$R_K = \left(\frac{GM_*}{\Omega^2}\right)^{\frac{1}{3}} \qquad \frac{R_A}{R_*} = 0.3 + (0.25 + \eta_*)^{\frac{1}{4}} \qquad \eta_* = \frac{B_{eq}^2 R_*^2}{\dot{M} v_\infty}$$



Are the detections real?

- Problem: ~ 1,000,000 unmatched sources only detected once, per epoch



- Inner artifacts
  - Dominant < 60” from catalog-matched sources
- Outer artifacts:
  - Isotropic
  - SNR dependent
  - Large snapshot-to-snapshot variations

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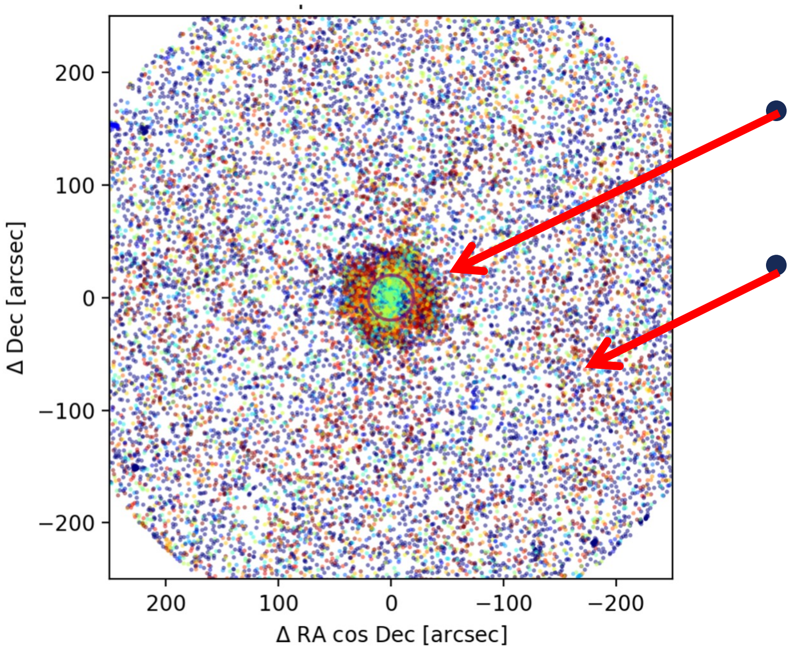

- Inner artifacts
  - Dominant $< 60''$ from catalog-matched sources
- Outer artifacts:
  - Isotropic
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- Solution: Statistics

$$\lambda = \sum_{j}^{stars} \sum_{i}^{snaps} \Omega_* \frac{n_i}{\Omega_{FoV}} \qquad P(N;\lambda) = \frac{\lambda^N e^{-\lambda}}{N!}$$

$\lambda = 0.44$; $P(3; 0.44) = 0.009$

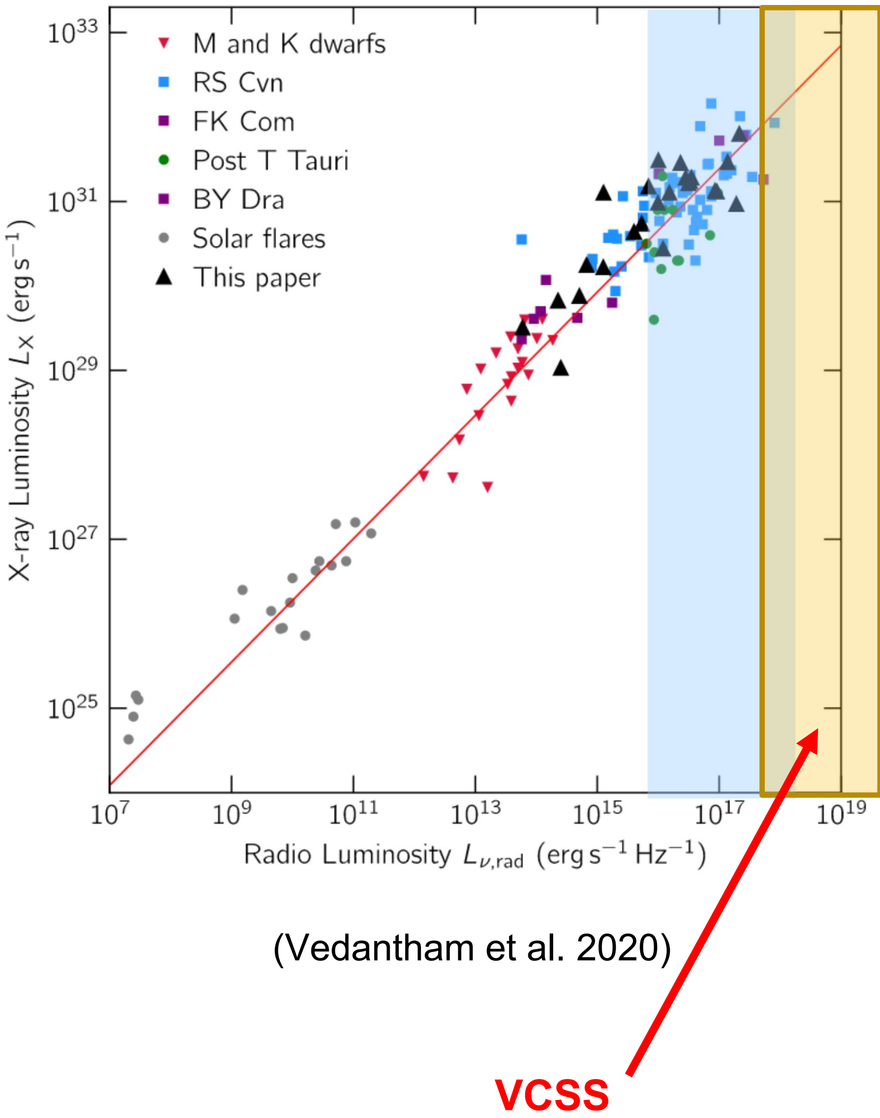
< 1% chance false associations

Hot magnetic star flares

- VCSS: L ~ 10^{18} – 10^{19} erg/s/Hz
- M dwarf flares: L < 10^{15} erg/s/Hz
  → late type companion origin unlikely
- RS CVn, FK Com flares > 10^{17} erg/s/Hz
  → no evidence for these companions

VCSS sees high energy tail of CBO flare distribution?

- Solar flare energy power-law distributed (Aschwanden et al. 2000)
- Earlier type stars have more high energy flares (Yang & Liu 2019)



(Vedantham et al. 2020)

Take Home Messages

Do hot magnetic stars flare by CBO?

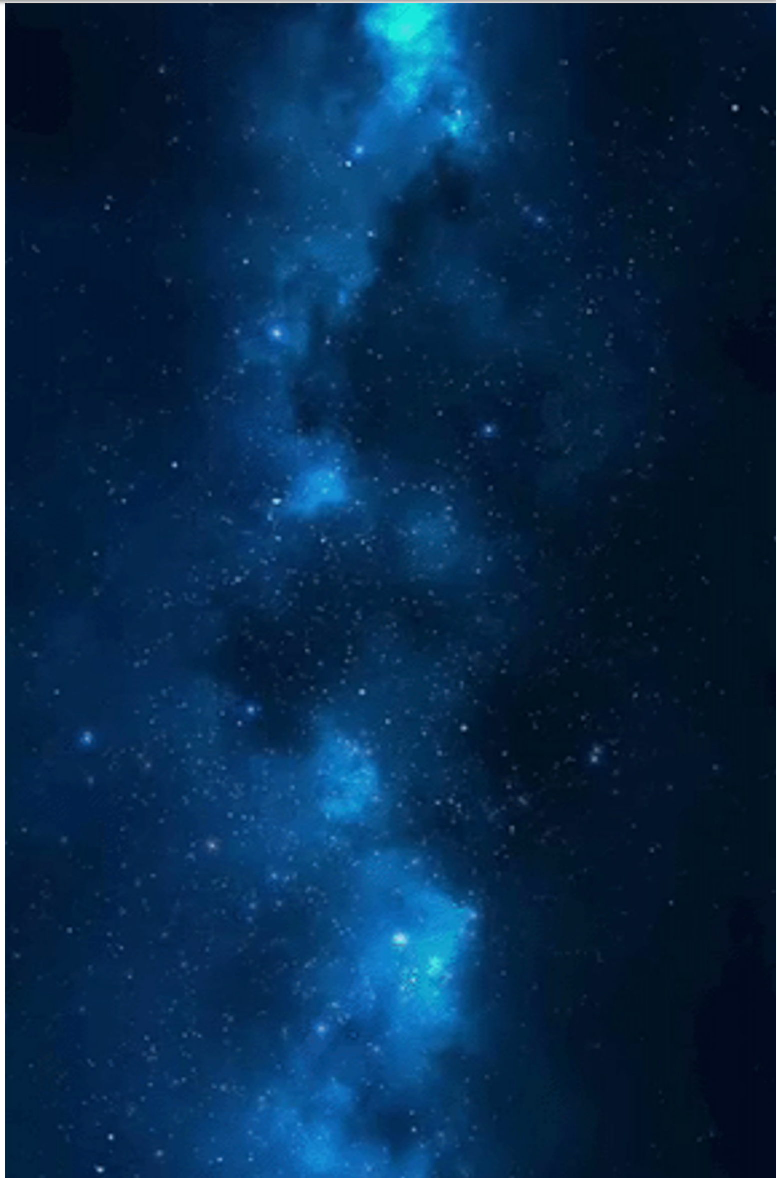
VCSS statistical detections not definitive but provide promising candidates for follow-up monitoring

More VCSS data to search:

- Epoch 3.1 – 83,000 snapshots, no detections ☹
- Epoch 3.2 – starting soon!
- Epoch 4 – ?

1100 hrs VLITE data (non-VCSS) to search

Polisensky et al., 2023, ApJ, 958, 152



False association probability

For a stellar catalog, calculate expected # false associations:

Expected number:

$$\lambda = \sum_{j}^{stars} \sum_{i}^{snaps} \Omega_* \frac{n_i}{\Omega_{FoV}}$$

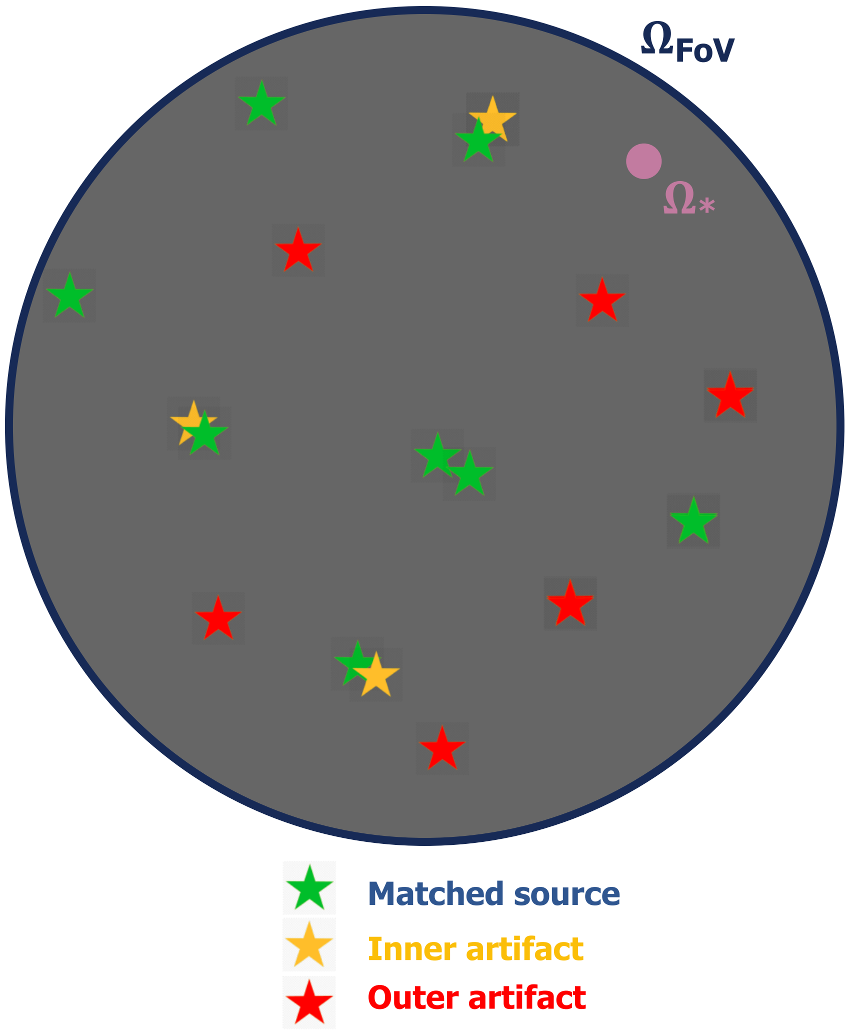
n_i = # artifacts in i^{th} snapshot
= # outer artifacts SNR > Cut

Probability observe *N* when λ expected:

$$P(N;\lambda) = \frac{\lambda^N e^{-\lambda}}{N!}$$

$\lambda = 0.44$; $P(3; 0.44) = 0.009$

< 1% chance false associations



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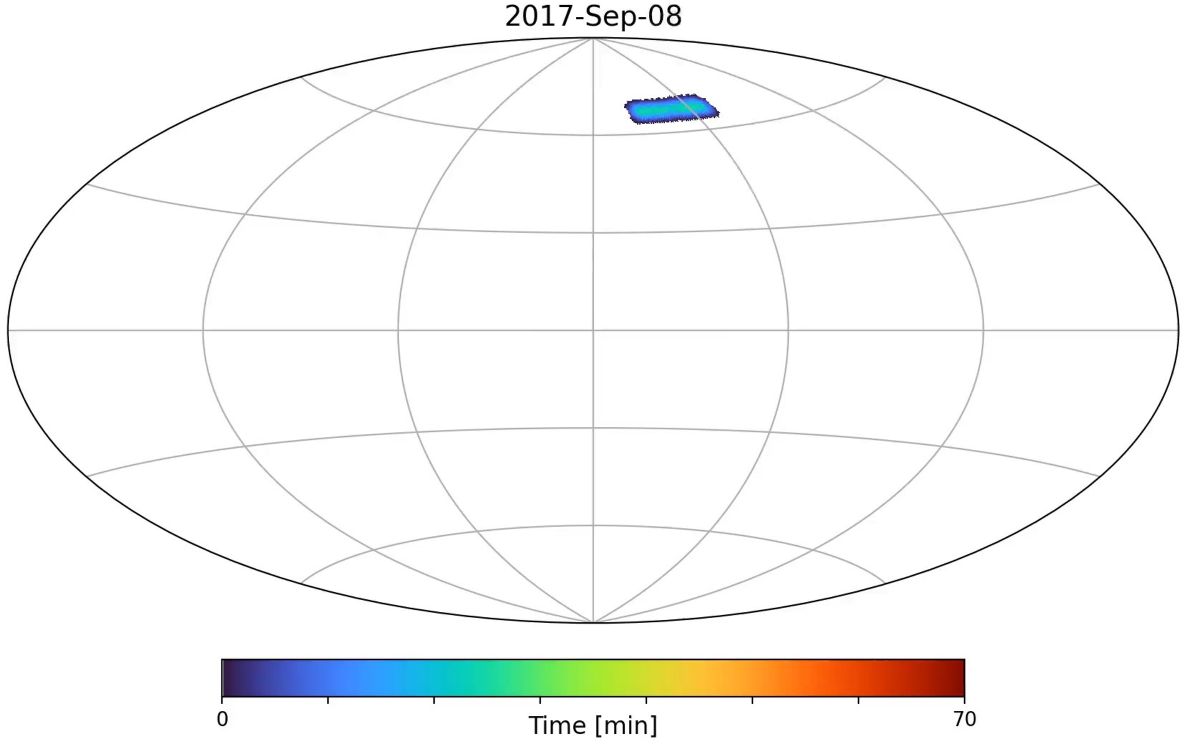
- ★ ~ 7-10 mJy/bm noise (~ 50 sources/image)



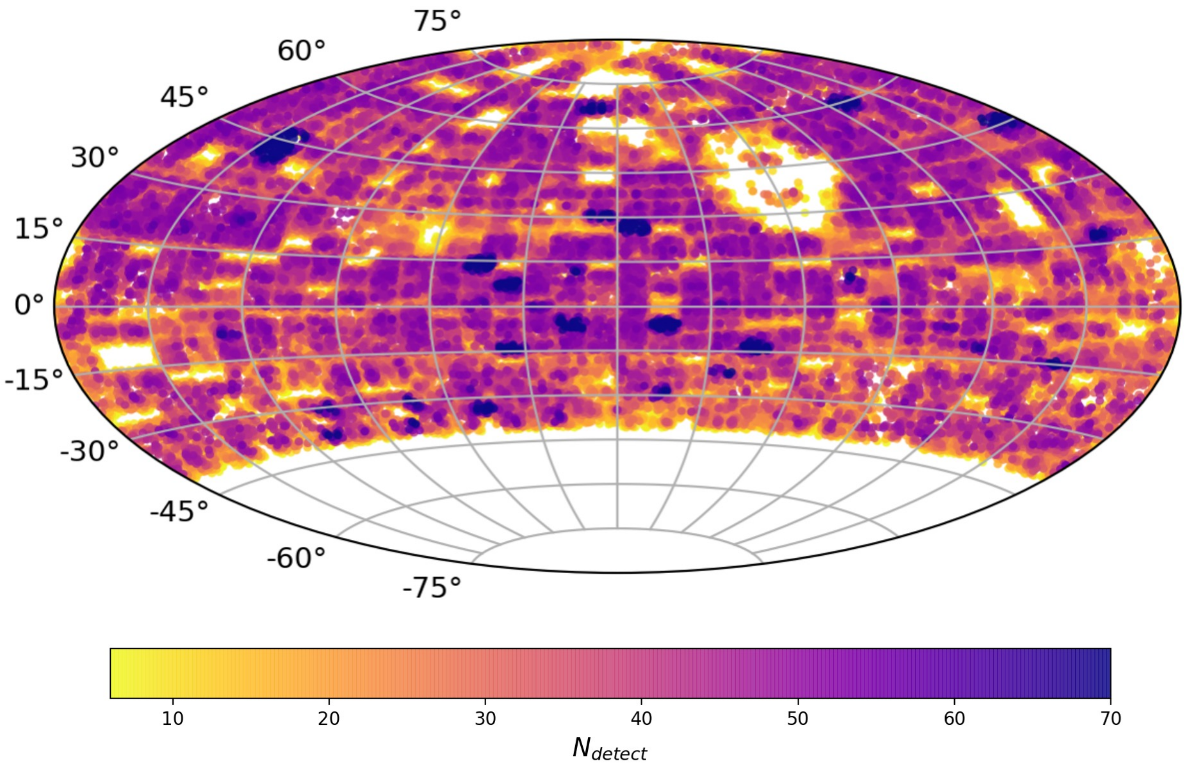
VCSS epoch 1 + 2 sky coverage
Sept 2017 – Feb 2022

VCSS Snapshot Sources

Snapshot source catalog (per epoch)

★ ~ 1.4 million sources SNR > 5

★ ~ 300,000 w/ catalog matches –
TGSS (150 MHz) & RACS-low (888 MHz)
S > 50 mJy



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VLITE Commensal Sky Survey (VCSS)

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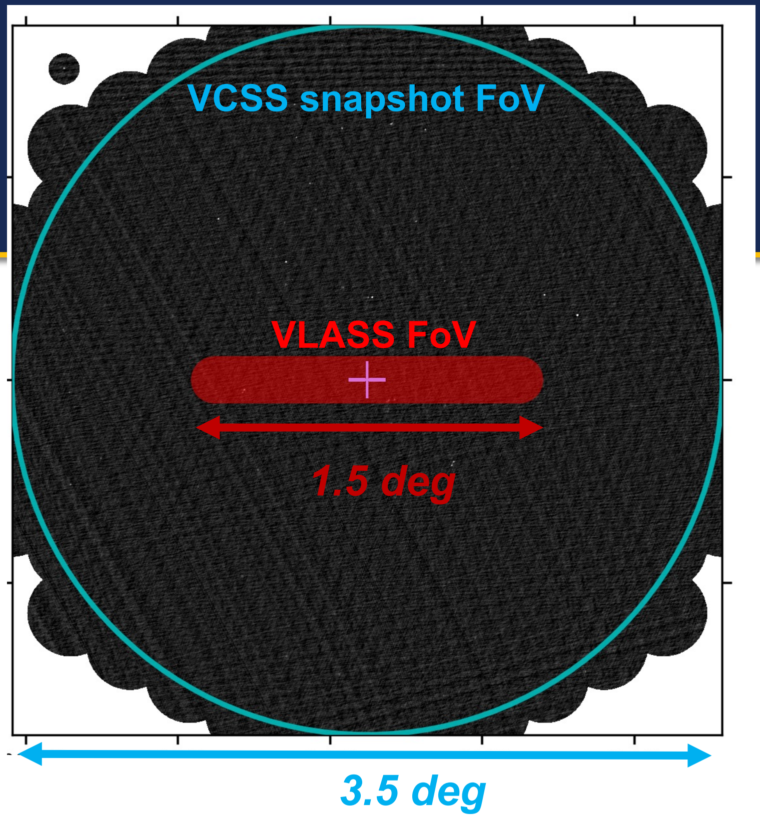
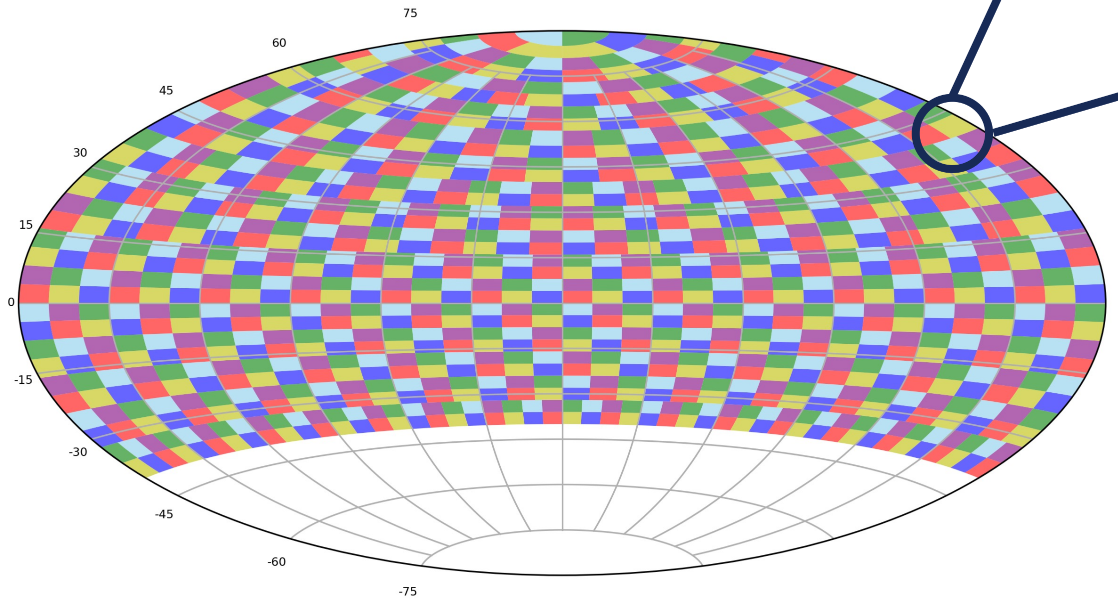
    - integrate while antennas slew (~ 28 s)
    - 3.5 deg snapshot images
    - 820 snapshots/day





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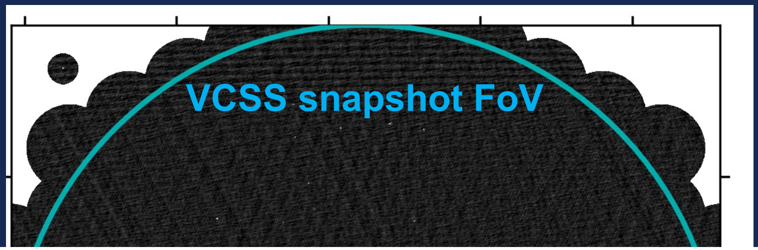

VLITE Commensal Sky Survey (VCSS)

- 3.5º + 7.2’ Dec offsets = snapshots highly overlapping
- Sources sampled by 40-50 snapshots over ~ 90 min, but irregular sampling (days - year) along tile borders