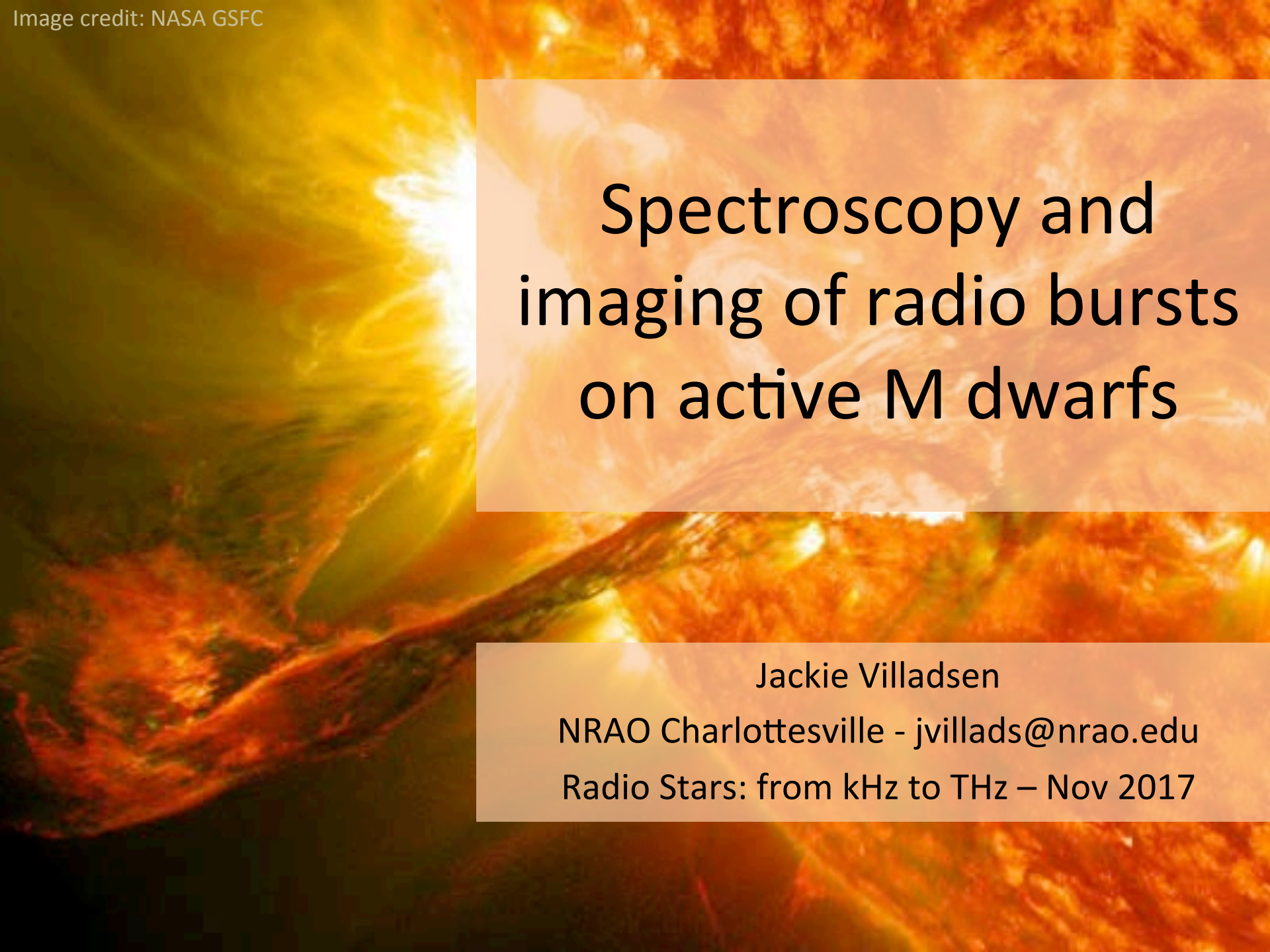


Spectroscopy and imaging of radio bursts on active M dwarfs

Jackie Villadsen
NRAO Charlottesville - jvillads@nrao.edu

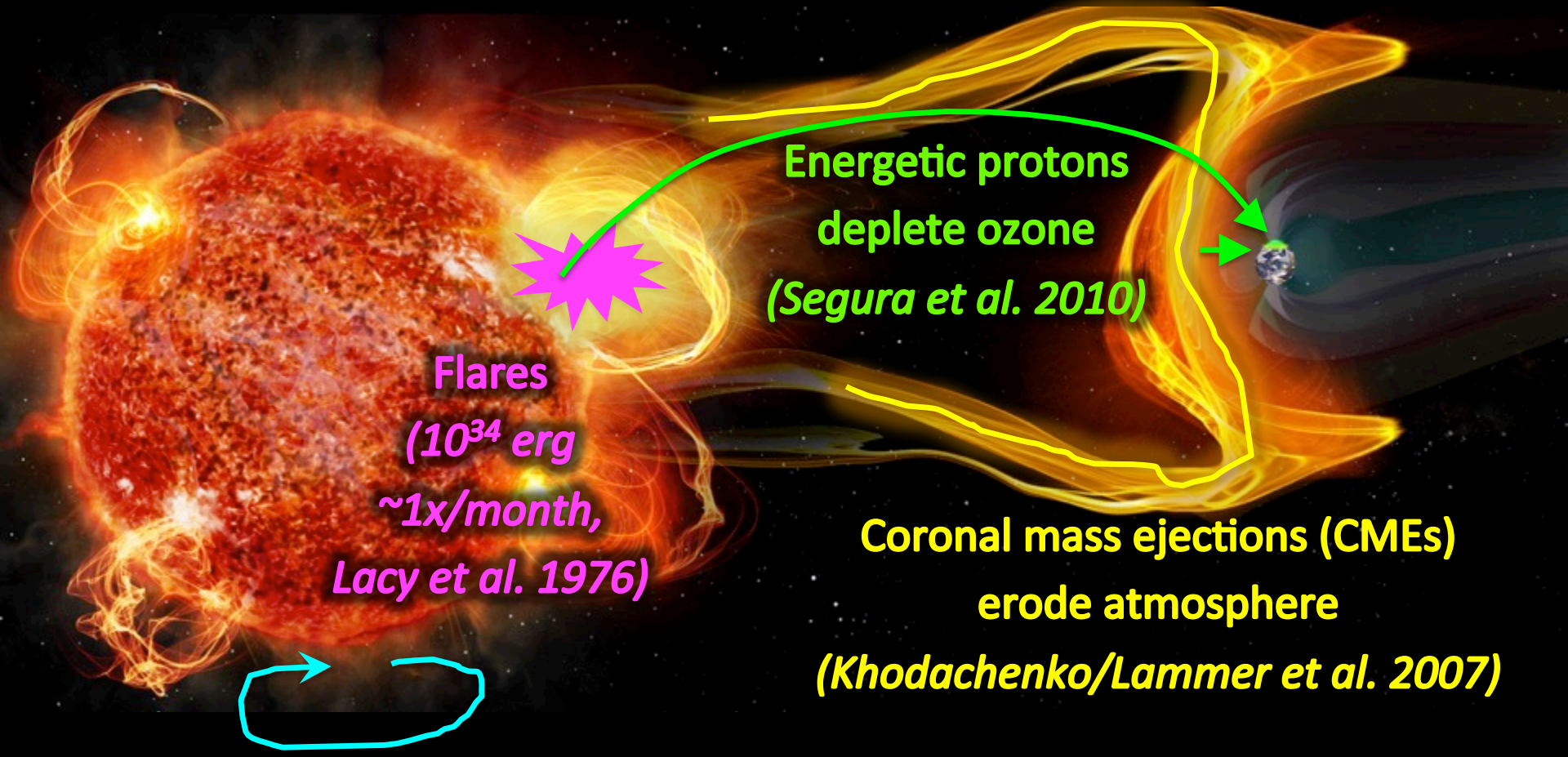
Radio Stars: from kHz to THz – Nov 2017

M dwarf magnetic activity shapes evolution of planetary atmospheres

M dwarf planets have likely evolved under conditions of strong stellar magnetic activity (e.g., West et al. 2008: M dwarf activity lifetime ~ Gyr)

Image credit: Chuck Carter, Gregg Hallinan, and the Keck Institute for Space Studies

M dwarf magnetic activity shapes evolution of planetary atmospheres



CMEs may dominate stellar mass loss *(Osten & Wolk 2015)* and control pre-MS angular momentum evolution *(Aarnio et al. 2013)*

Image credit: Chuck Carter, Gregg Hallinan, and the Keck Institute for Space Studies

M dwarf magnetic activity shapes evolution of planetary atmospheres

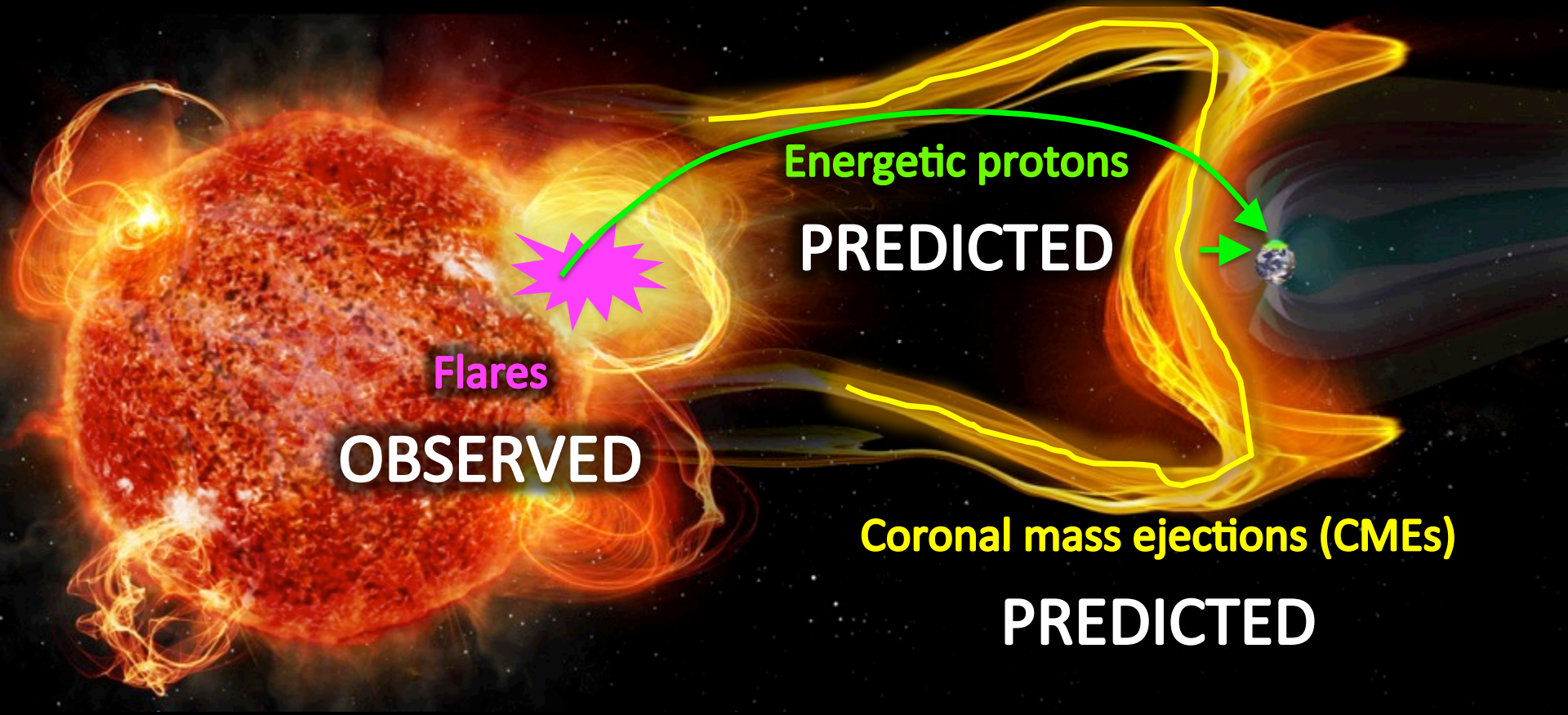
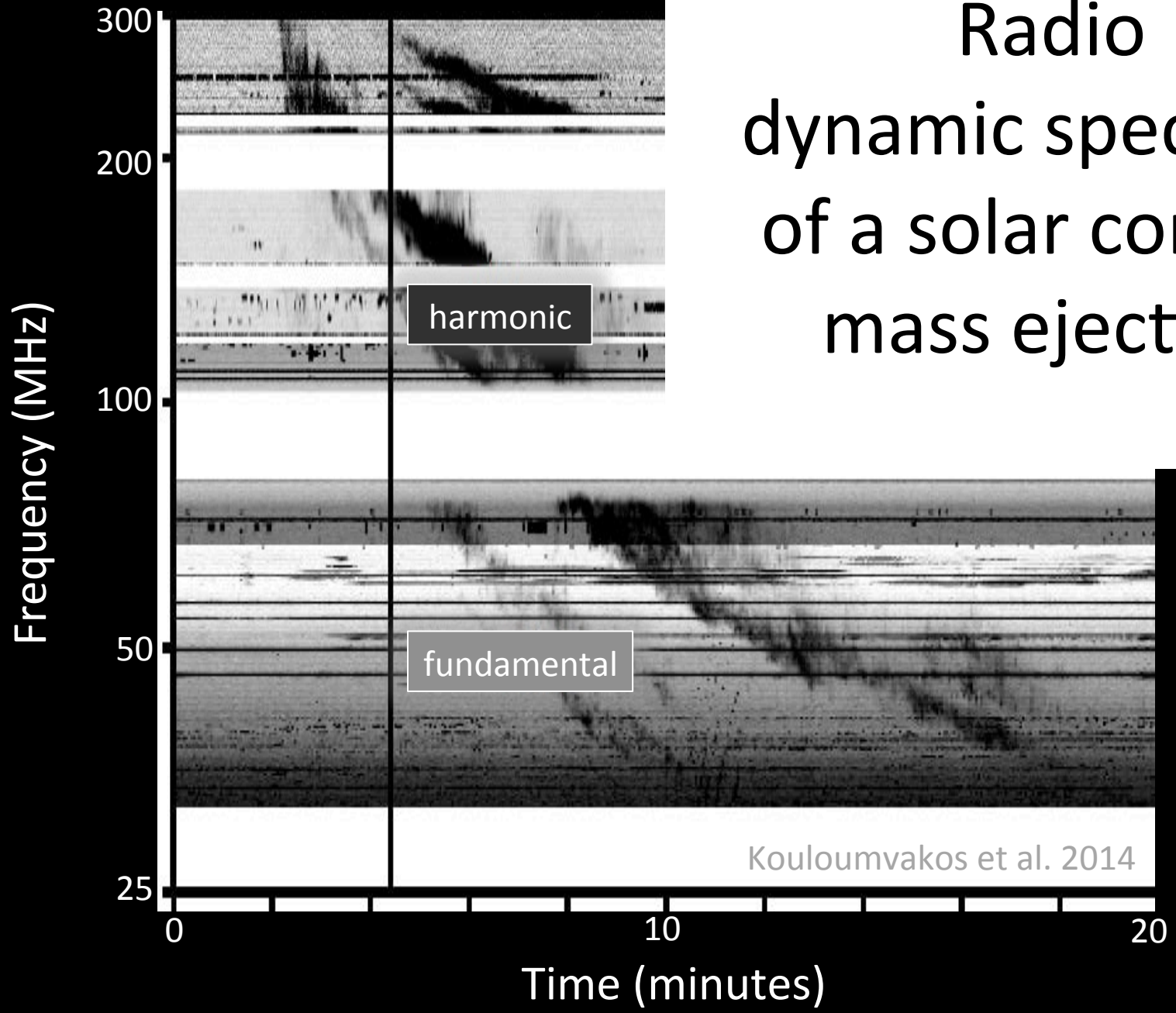
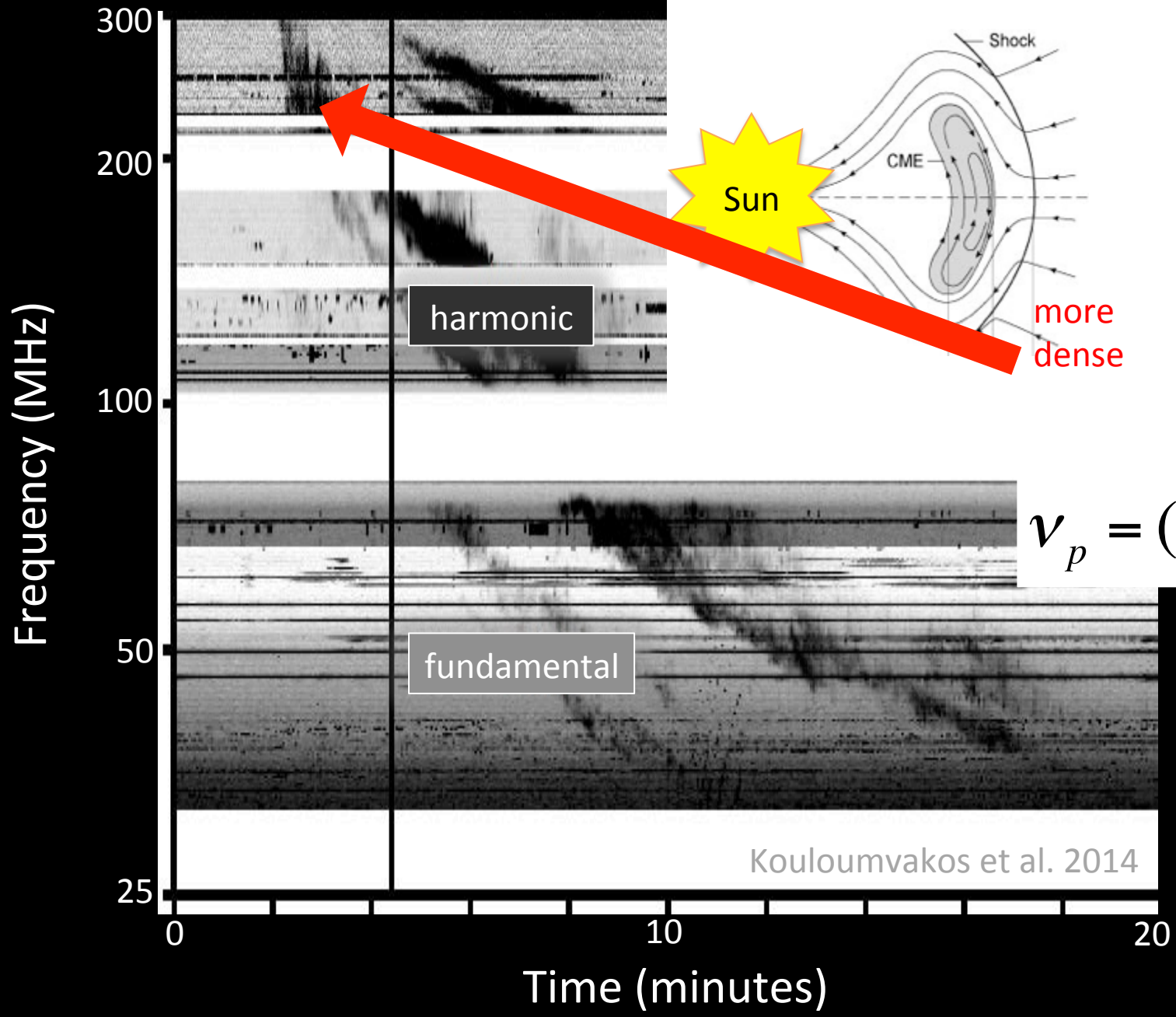
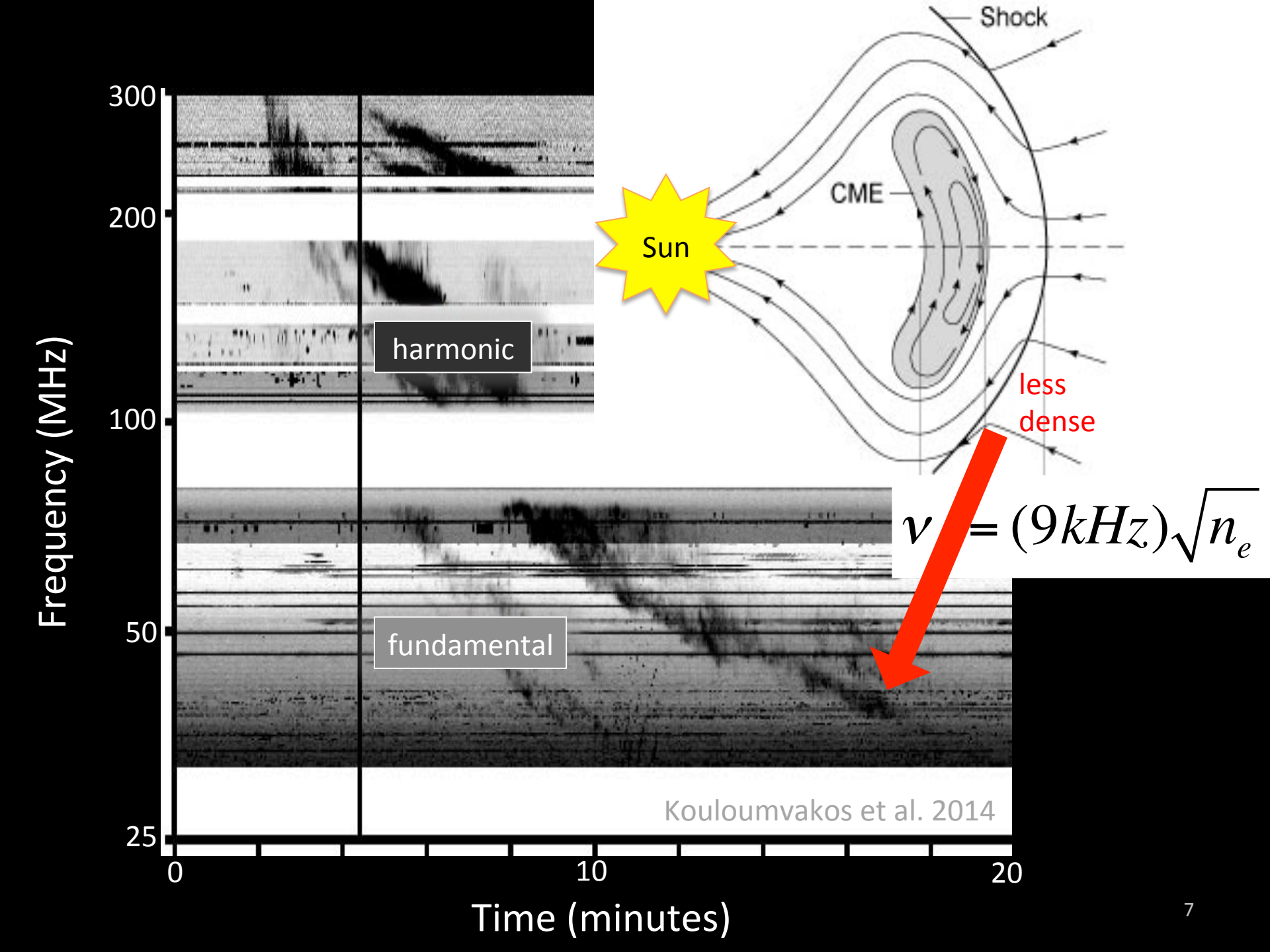


Image credit: Chuck Carter, Gregg Hallinan, and the Keck Institute for Space Studies

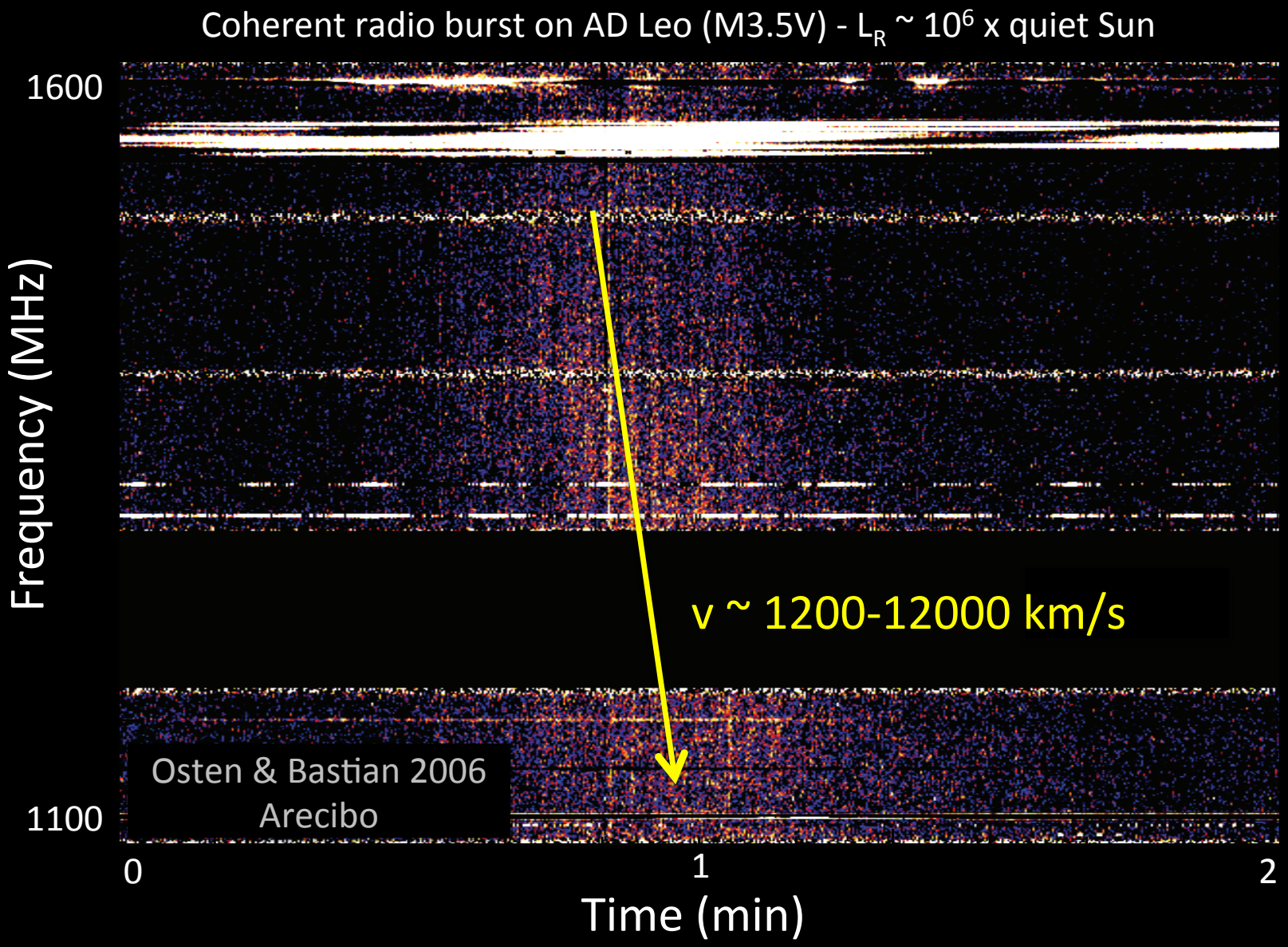
Radio dynamic spectrum of a solar coronal mass ejection




300
200
100
50
25
Frequency (MHz)
0
10
20
Time (minutes)
harmonic
fundamental
Sun
Shock
CME
more
dense
$\nu_p = (9kHz)\sqrt{n_e}$
Kouloumvakos et al. 2014

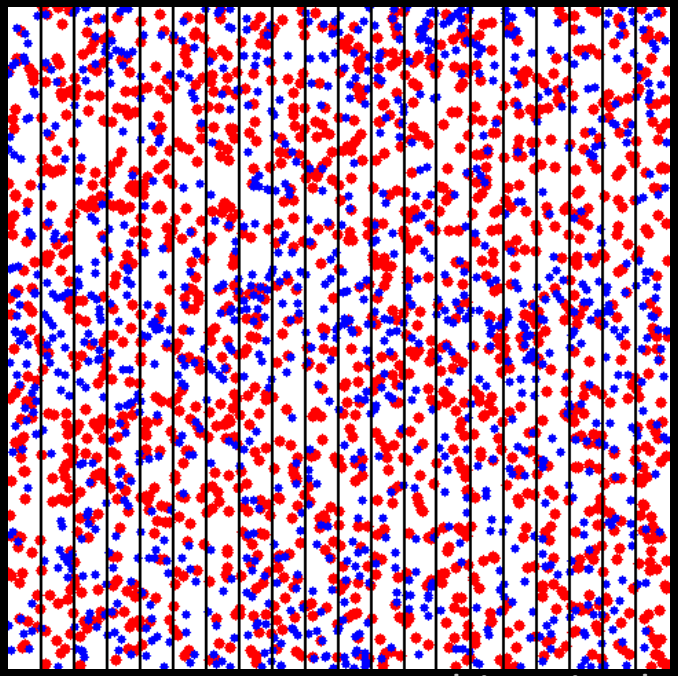

Shock
CME
Sun
less
dense
$\nu = (9kHz)\sqrt{n_e}$
harmonic
fundamental
Kouloumvakos et al. 2014
300
200
100
50
25
Frequency (MHz)
0
10
20
Time (minutes)

Active M dwarfs often produce coherent bursts at 1-5 GHz, many with frequency drift – **are these space weather events?**



Two coherent emission mechanisms produce solar radio bursts

Plasma emission

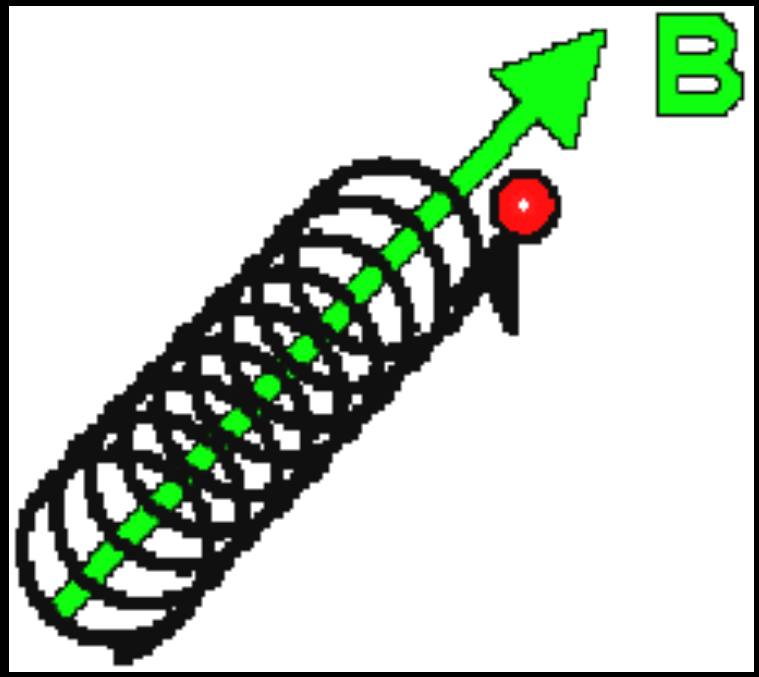


Andris Vaivads

$$\omega_{pe} = (4\pi n_e e^2/m_e)^{1/2}$$

Solar and stellar flares,
CME shock fronts, proton events

Electron cyclotron maser (ECM) emission



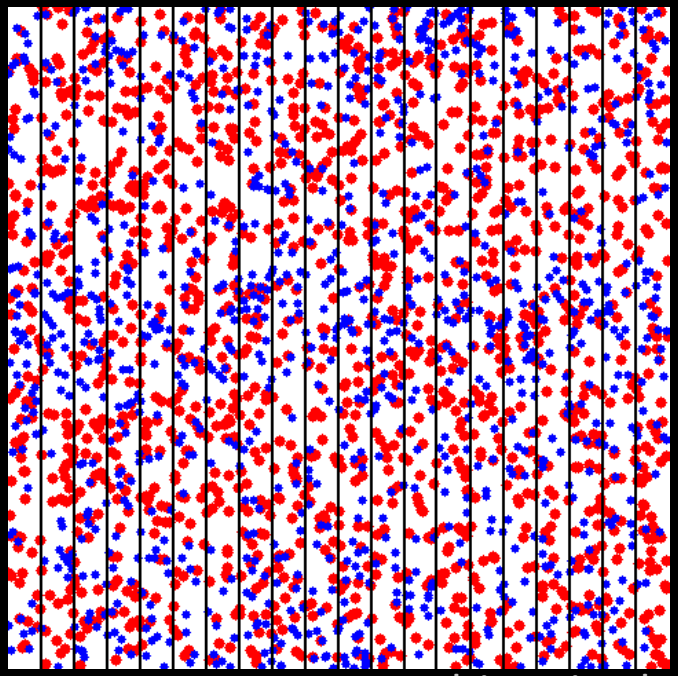
http://tempest.das.ucdavis.edu/pdg/ECE/

$$\omega_{ce} = eB/m_e c$$

Solar and stellar flares,
aurorae of brown dwarfs & planets

Coronal density and magnetic field strength correspond to low radio frequencies

Plasma emission

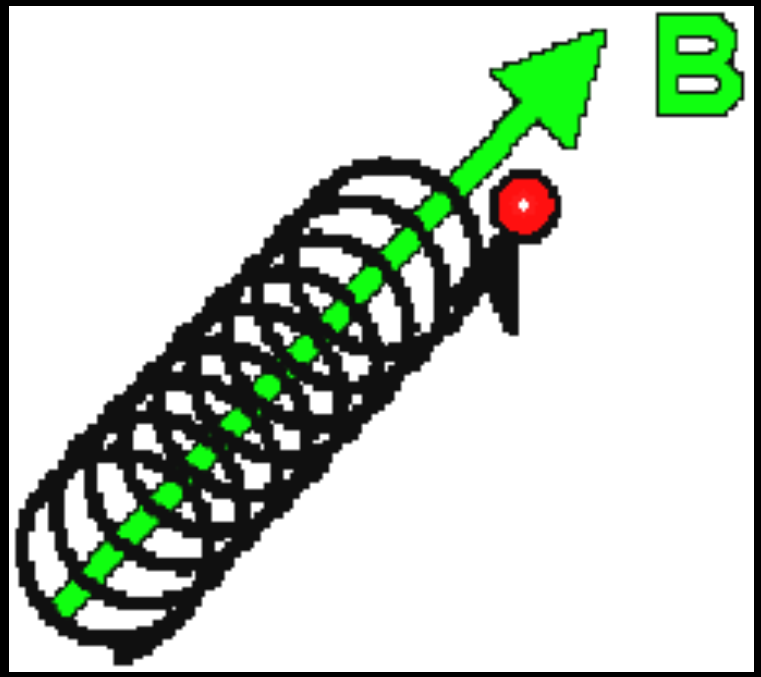


Andris Vaivads

$\omega_{pe} = (0.9\ \text{GHz})\ (n_e/10^{10}\ \text{cm}^{-3})^{1/2}$

Observed up to ~1-2 GHz on Sun and stars

Electron cyclotron maser (ECM) emission

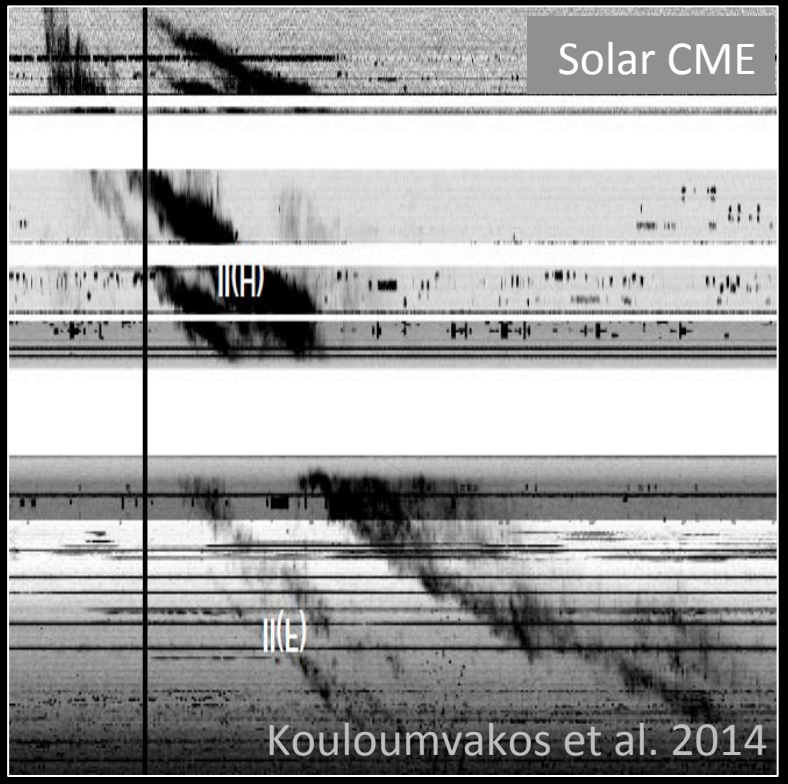


http://tempest.das.ucdavis.edu/pdg/ECE/

$\omega_{ce} = (2.8\ \text{GHz})\ B_{kG}$

Observed up to ~10 GHz on magnetic brown dwarfs

VLA+VLBA survey of active M dwarfs: detect coronal motion and image structure

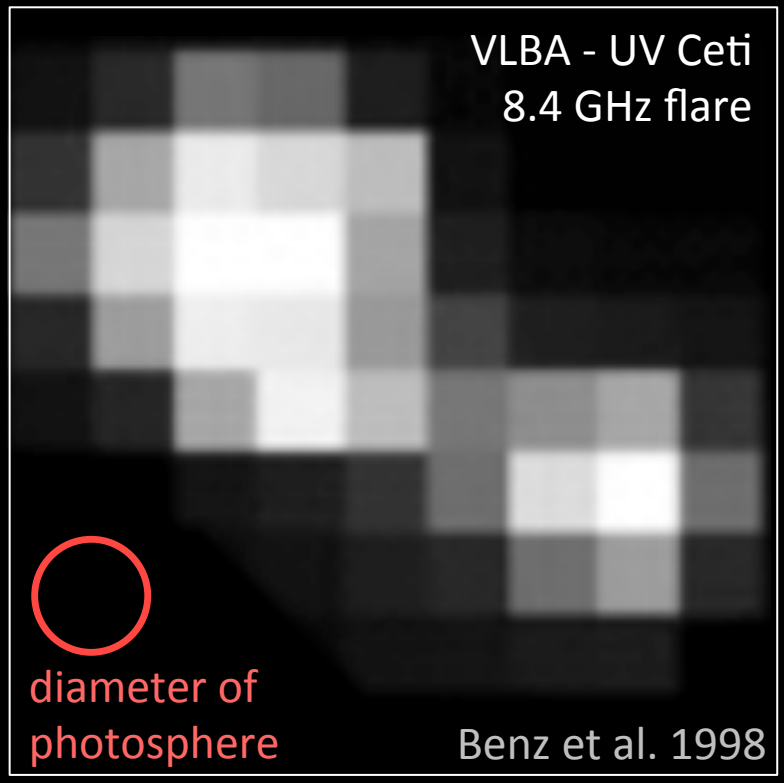


VLA: Dynamic spectrum

58 hours, 22 epochs, 5 stars

0.22-0.48, 1-4 GHz

or 1-6 GHz



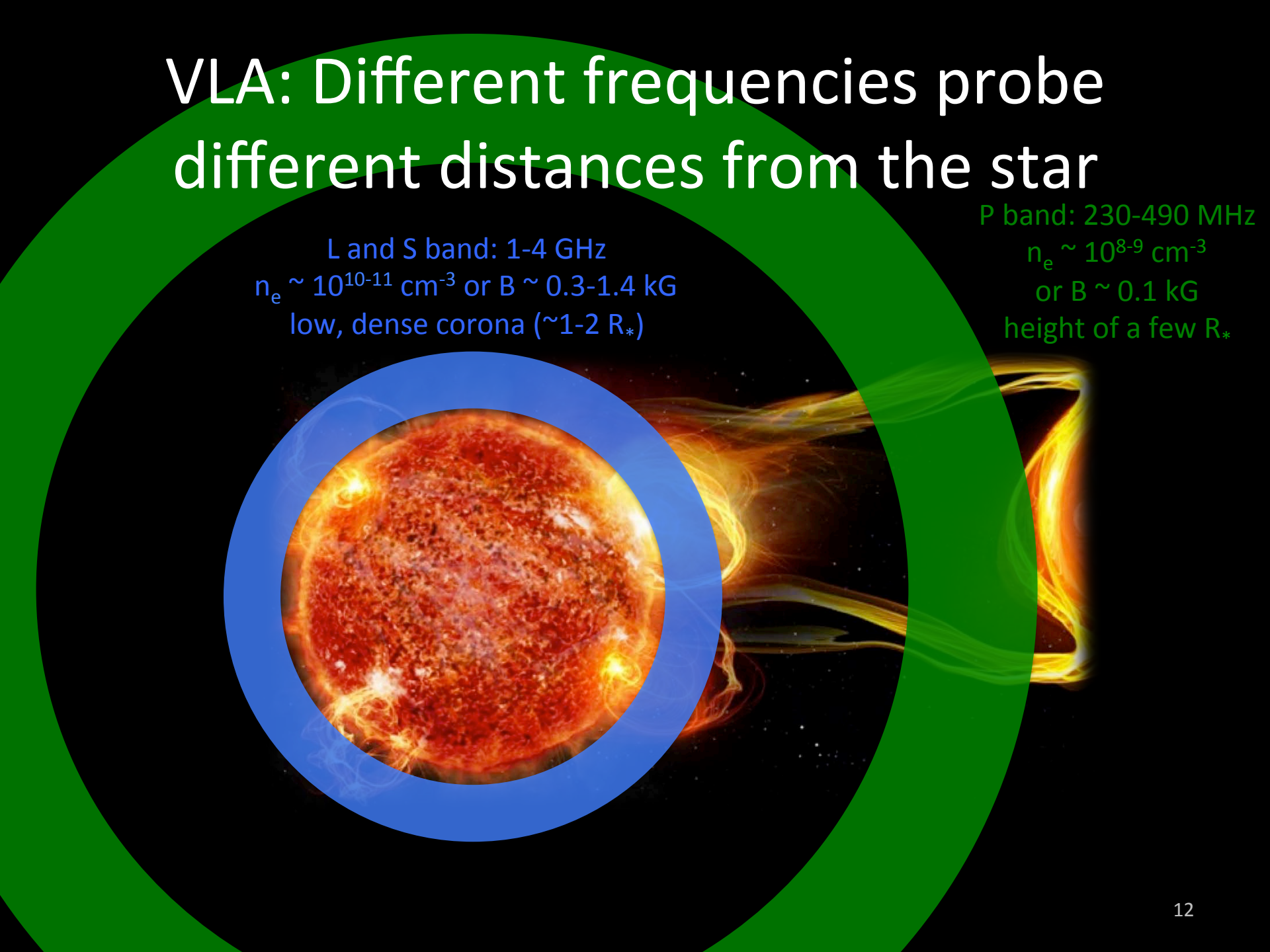
VLBA: Imaging

24 hours (AD Leo, UV Cet)

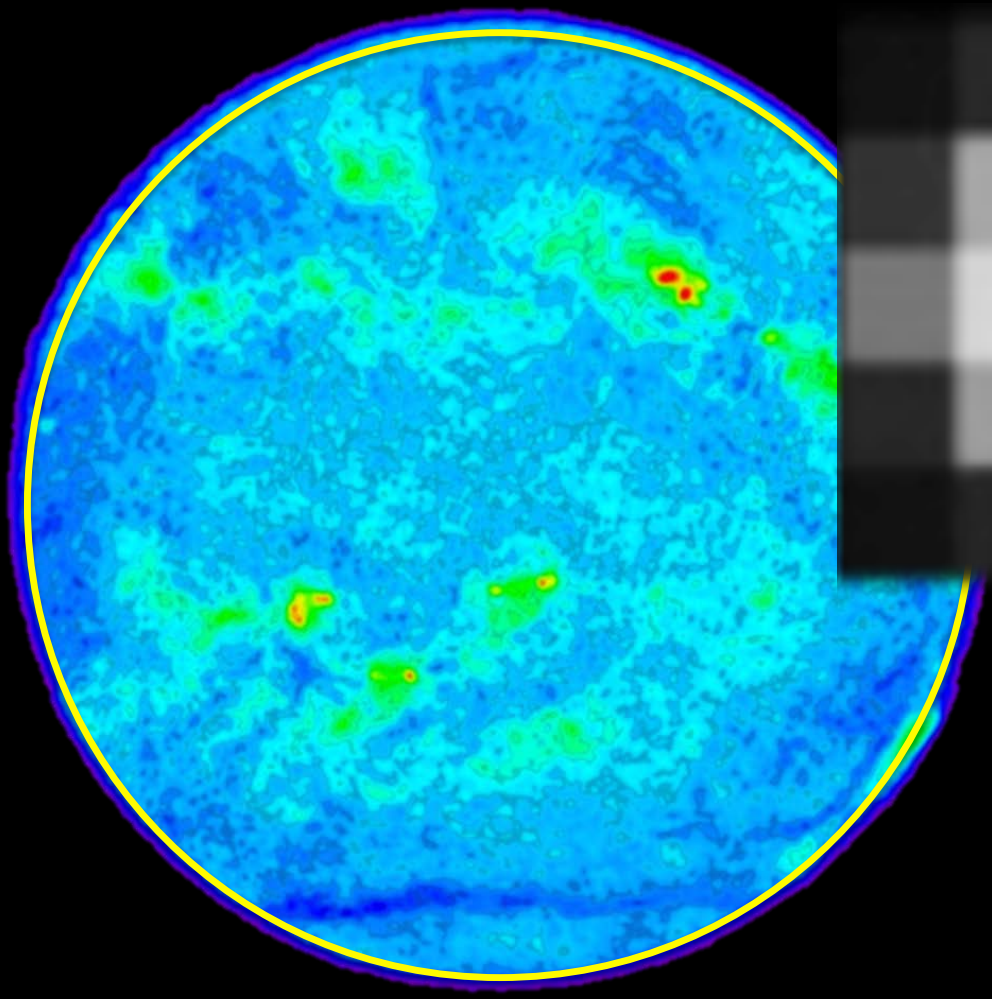
8.3-8.5 GHz

Resolution ~ stellar diameter

VLA: Different frequencies probe different distances from the star



VLBA: Image large-scale structure in non-thermal radio corona



1000x brighter than Sun

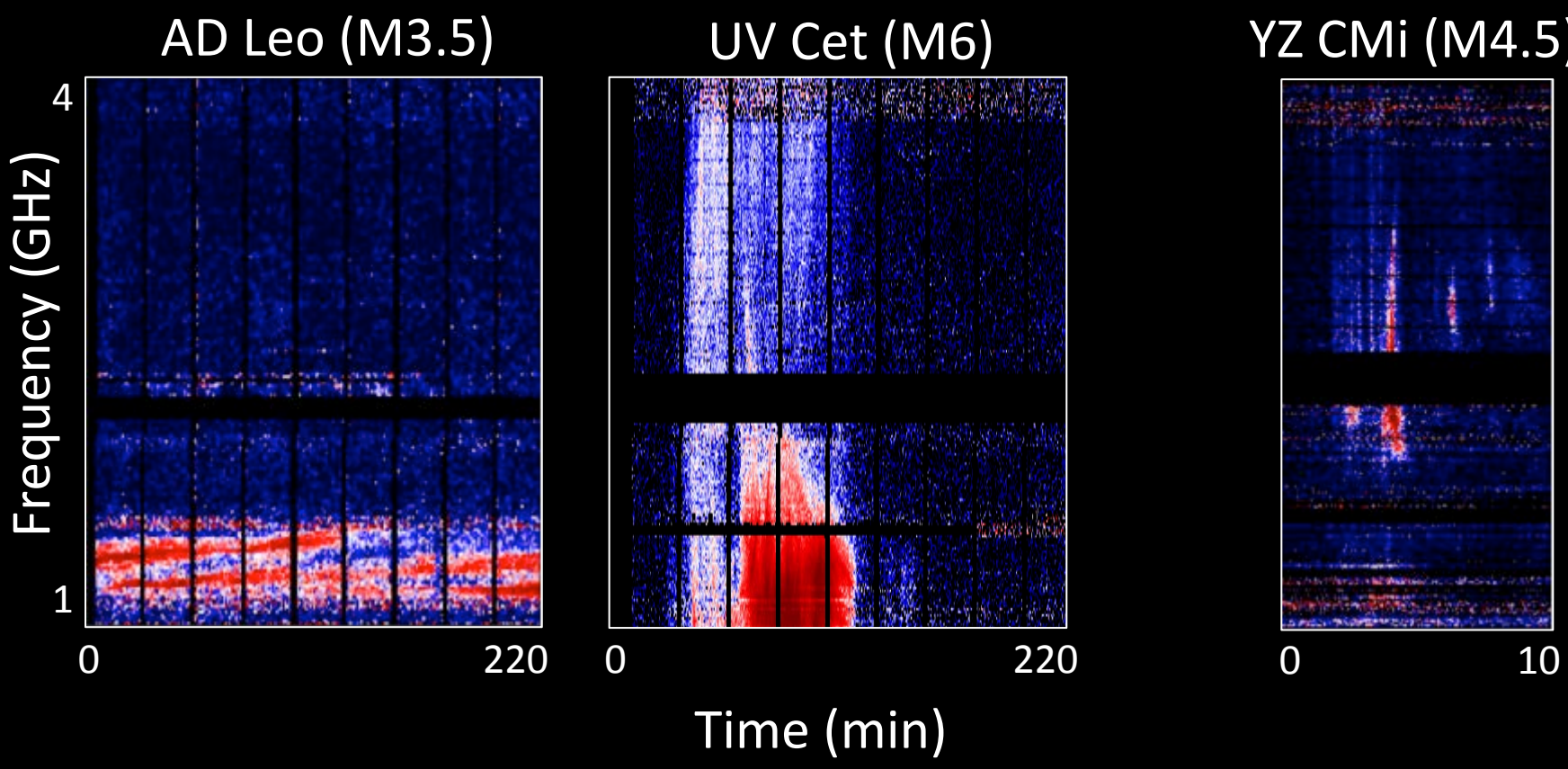
4.6 GHz Sun. Stephen White/NRAO/AUI.

8.4 GHz VLBA UV Ceti flare. Benz et al. 1998.

VLA survey: Coherent radio bursts in 13 of 23 epochs, occur on variety of timescales

Long bursts (>~1 hour)
Requires ongoing electron acceleration

Short bursts (sec - min)
Powered by individual flares?



Red: Intense emission

Blue: No emission

VLA survey: Coherent radio bursts in 13 of 23 epochs, occur on variety of timescales

Long bursts (>~1 hour)
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Short bursts (sec - min)
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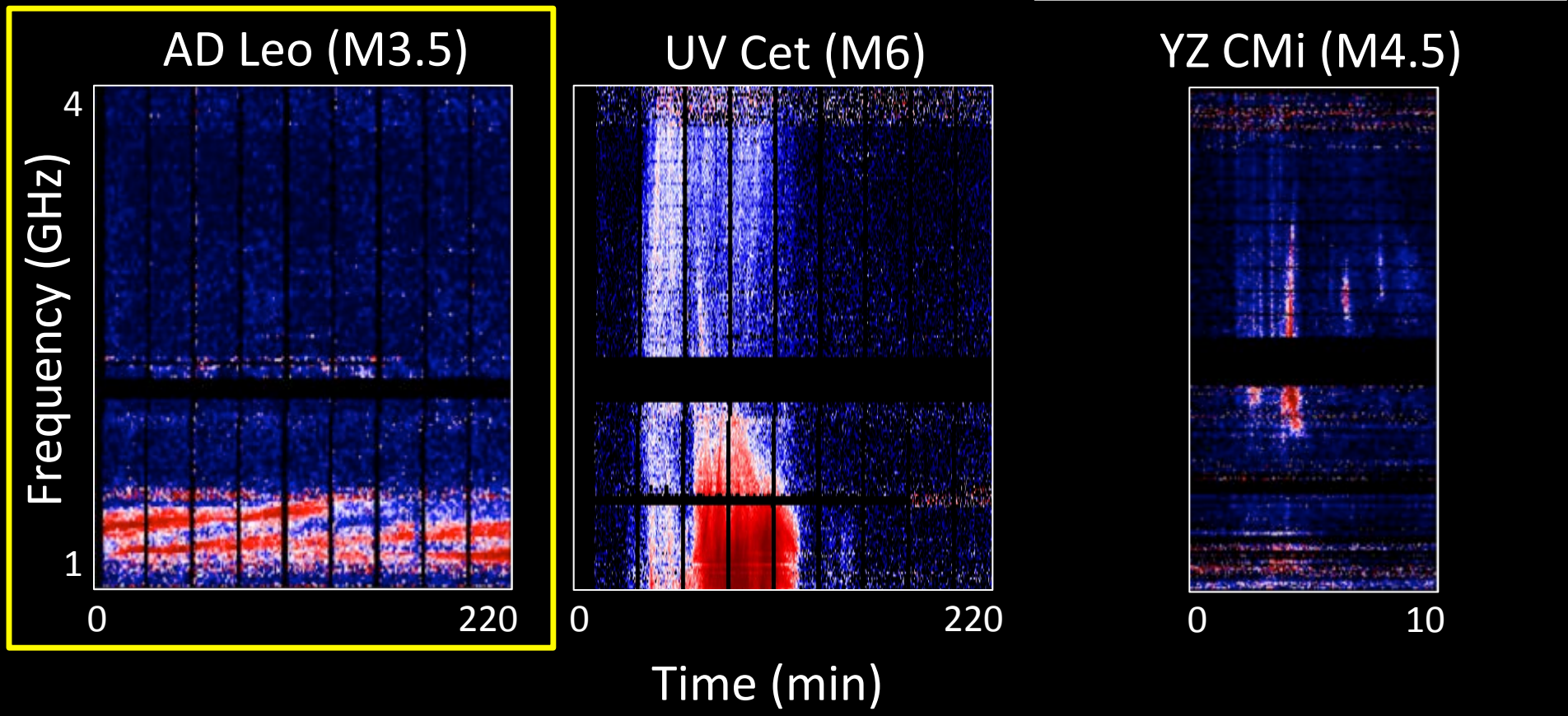
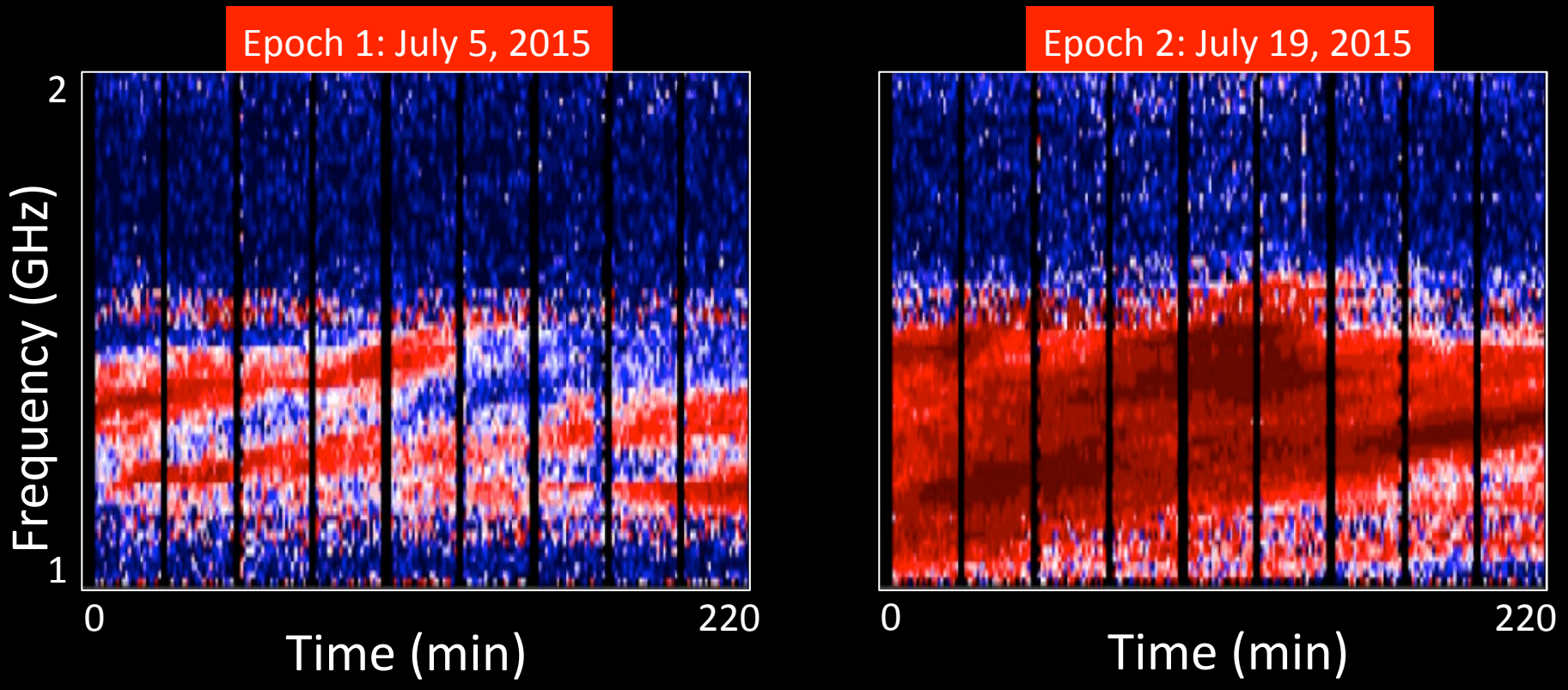


Red: Intense emission

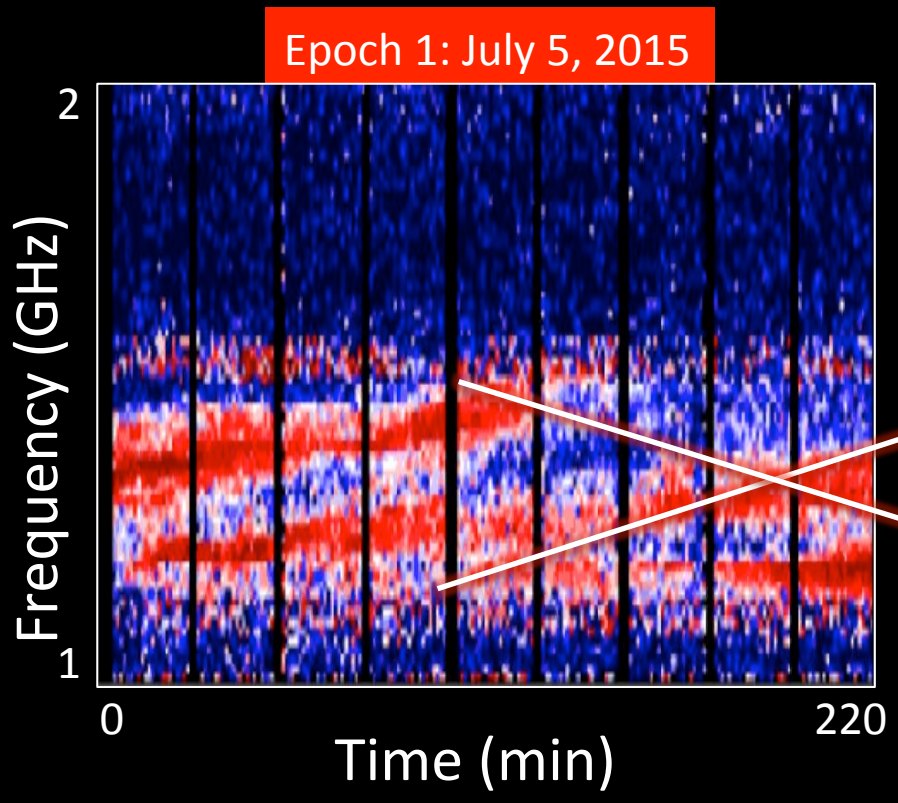
Blue: No emission

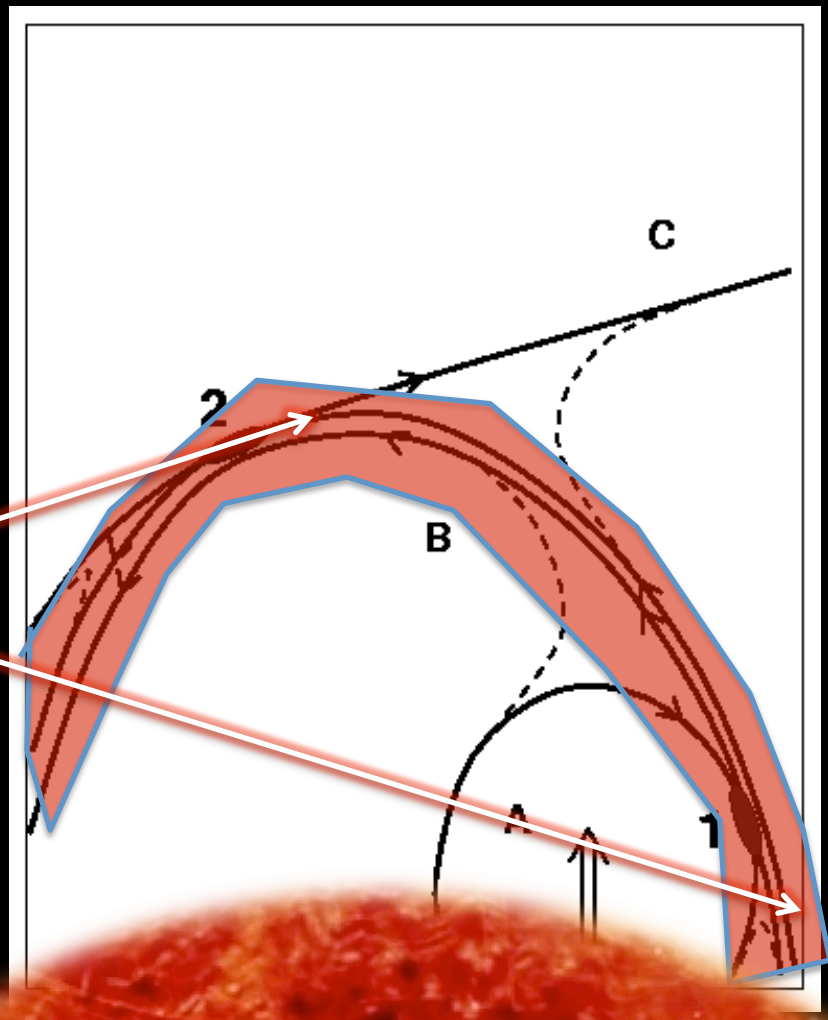
AD Leo (M3.5): A two week long coherent radio storm? 100% circular polarization



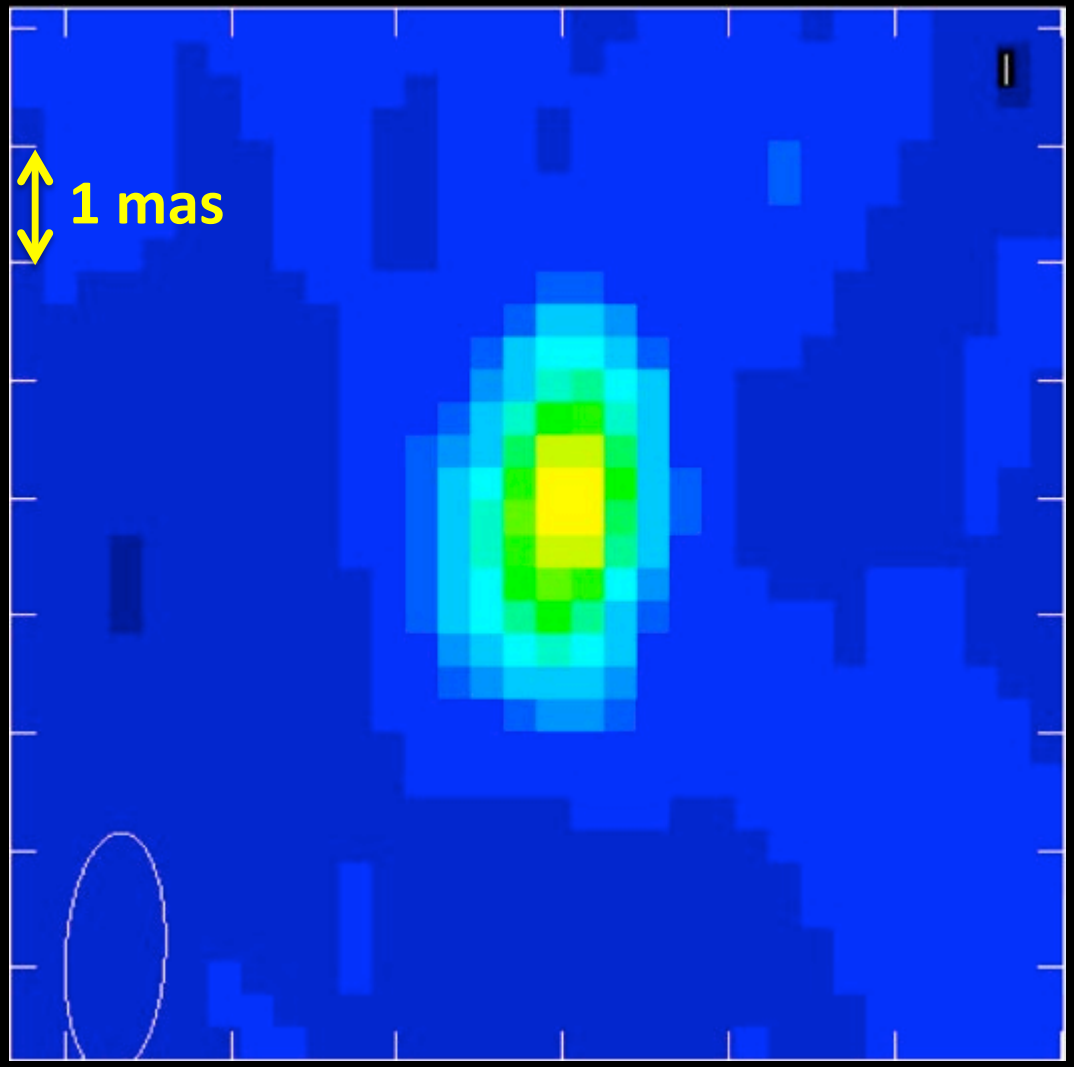
AD Leo: Long-duration narrowband emission can be produced by emerging magnetic flux

Benz 2004





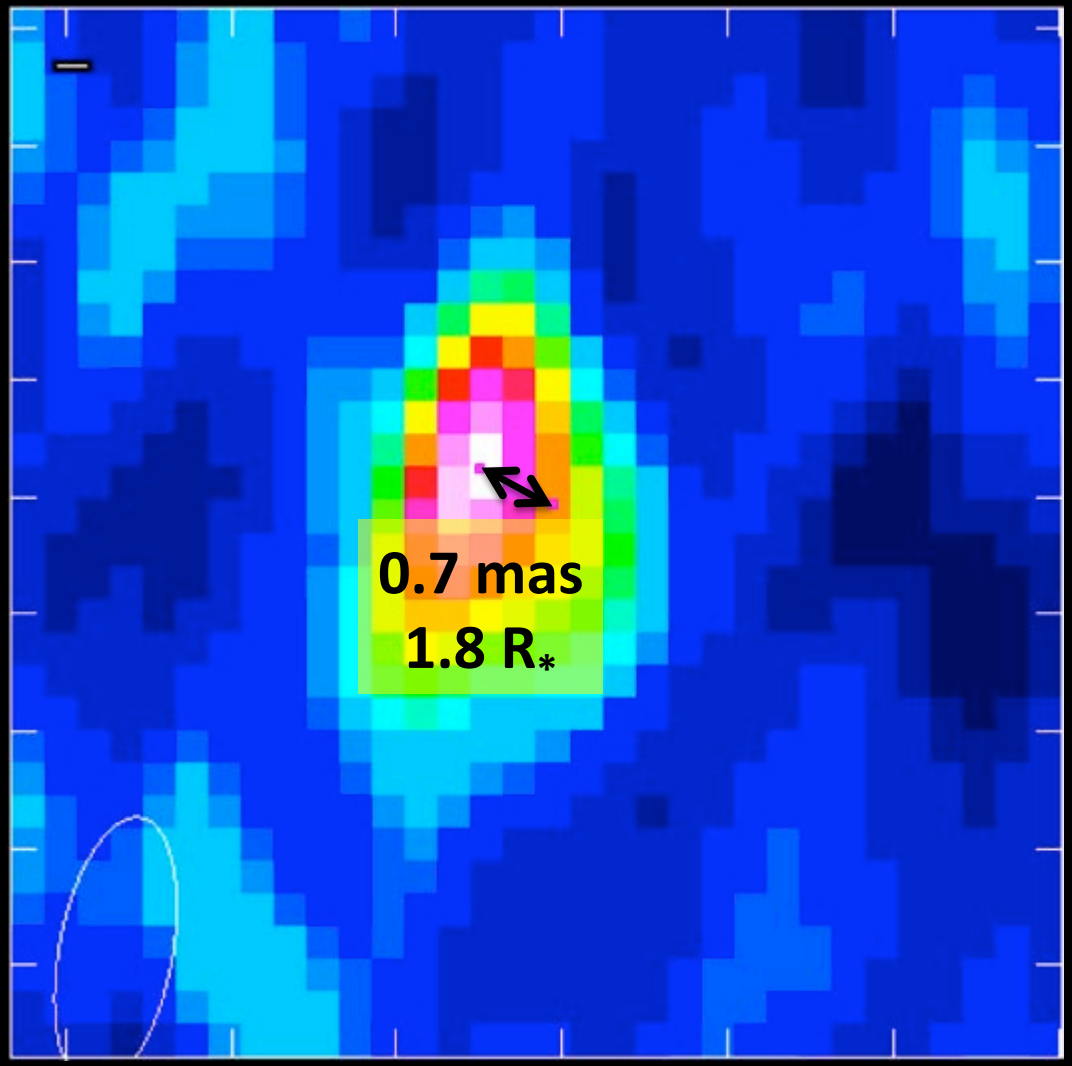
VLBA imaging of AD Leo: Flare offset from quiescent emission



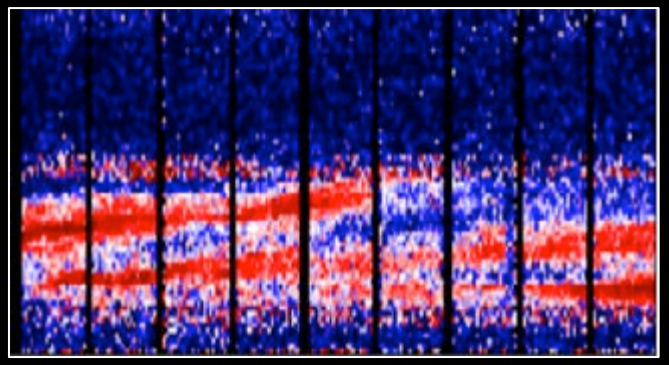
8.4 GHz emission is gyrosynchrotron from non-thermal electrons

First epoch of long-duration 1.1-1.6 GHz coherent storm: Quiescent 8.4-GHz emission at high levels

VLBA imaging of AD Leo: Flare offset from quiescent emission



Flare is separated from quiescent peak by 0.9 stellar diameters

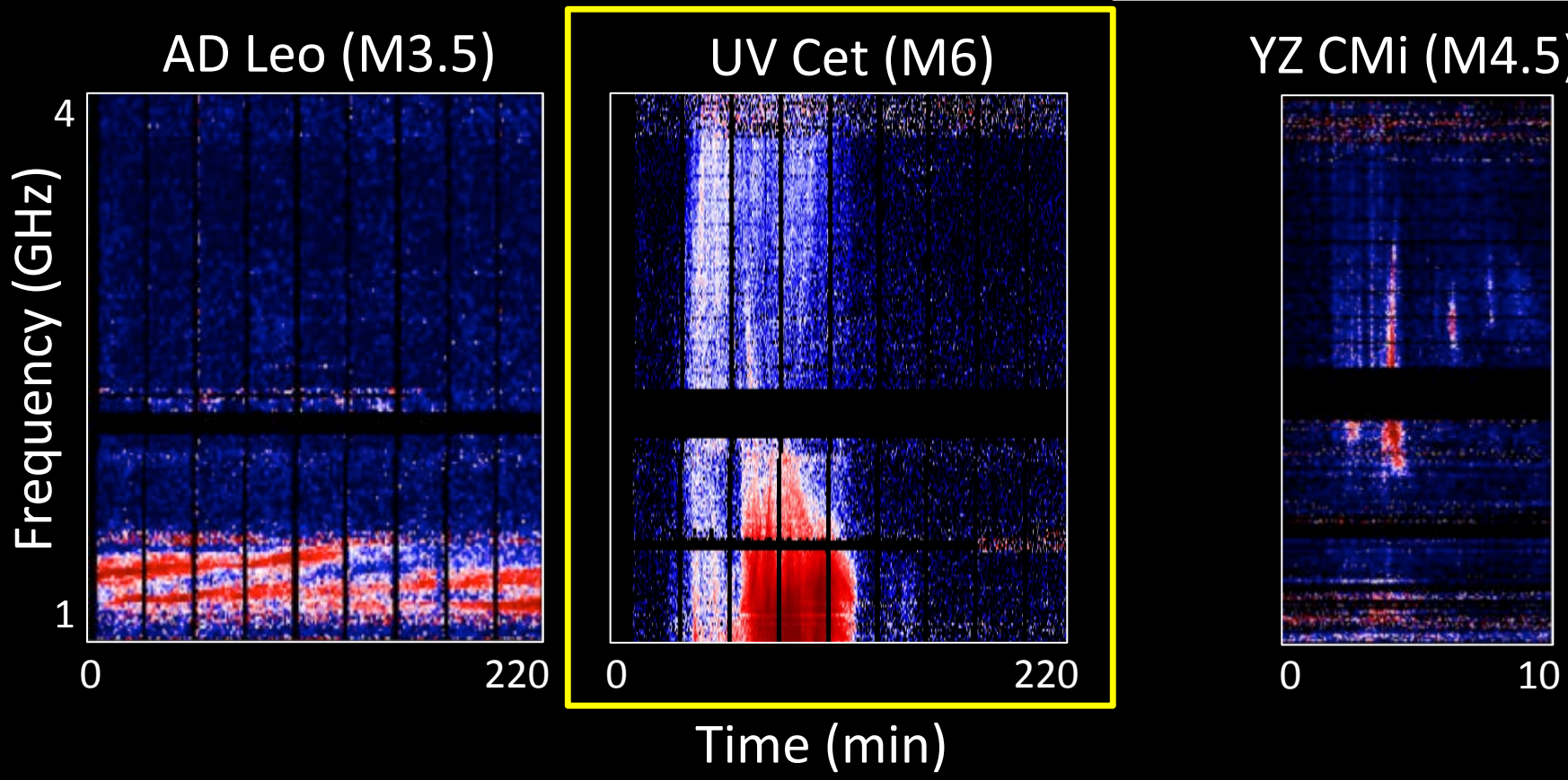


Dynamic spectrum does not show evidence of outwards source motion :(

VLA survey: Coherent radio bursts in 13 of 23 epochs, occur on variety of timescales

Long bursts (>~1 hour)
Requires ongoing electron acceleration

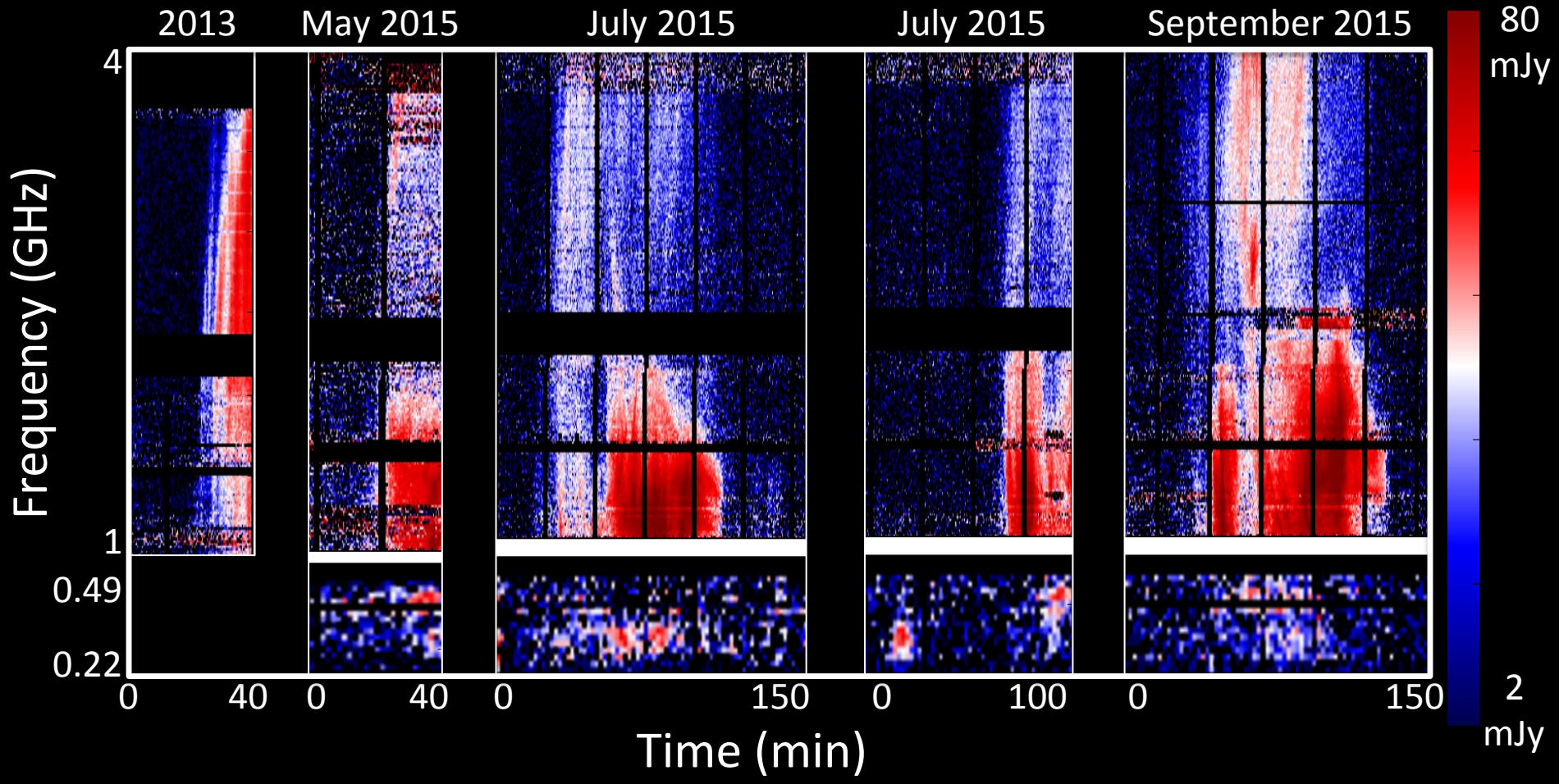
Short bursts (sec - min)
Powered by individual flares?



Red: Intense emission

Blue: No emission

UV Ceti (M6): 90-minute bursts, similar over months

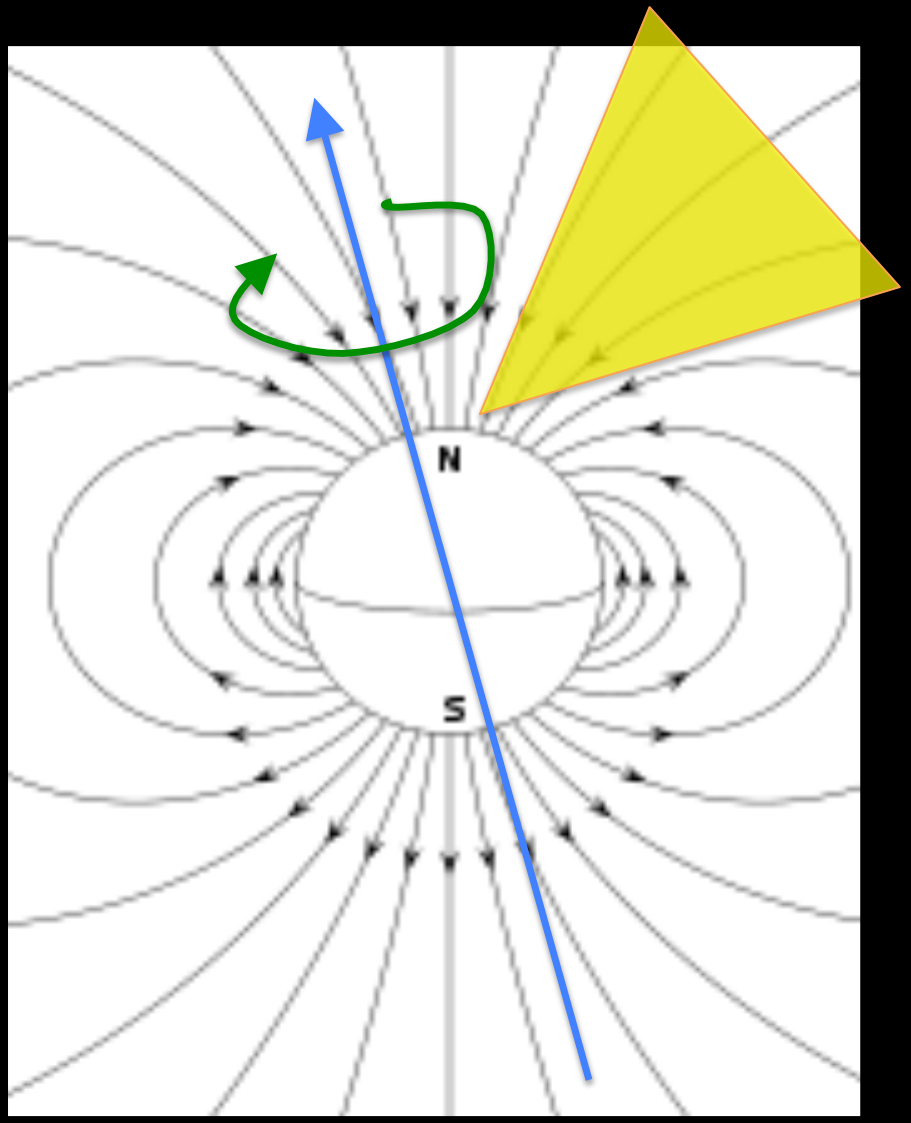


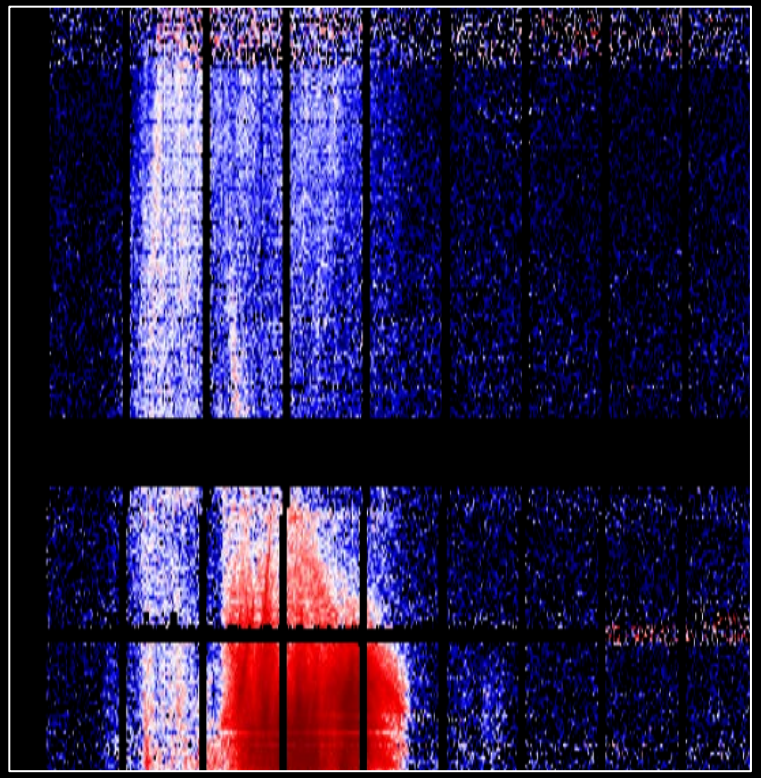
All bursts have strong right circular polarization

→long-lasting stable magnetic field dominates in source region

Resolved imaging identifies bursts with UV Cet, not BL Cet

Interpretation: UV Ceti has a periodic radio aurora, like brown dwarfs and planets

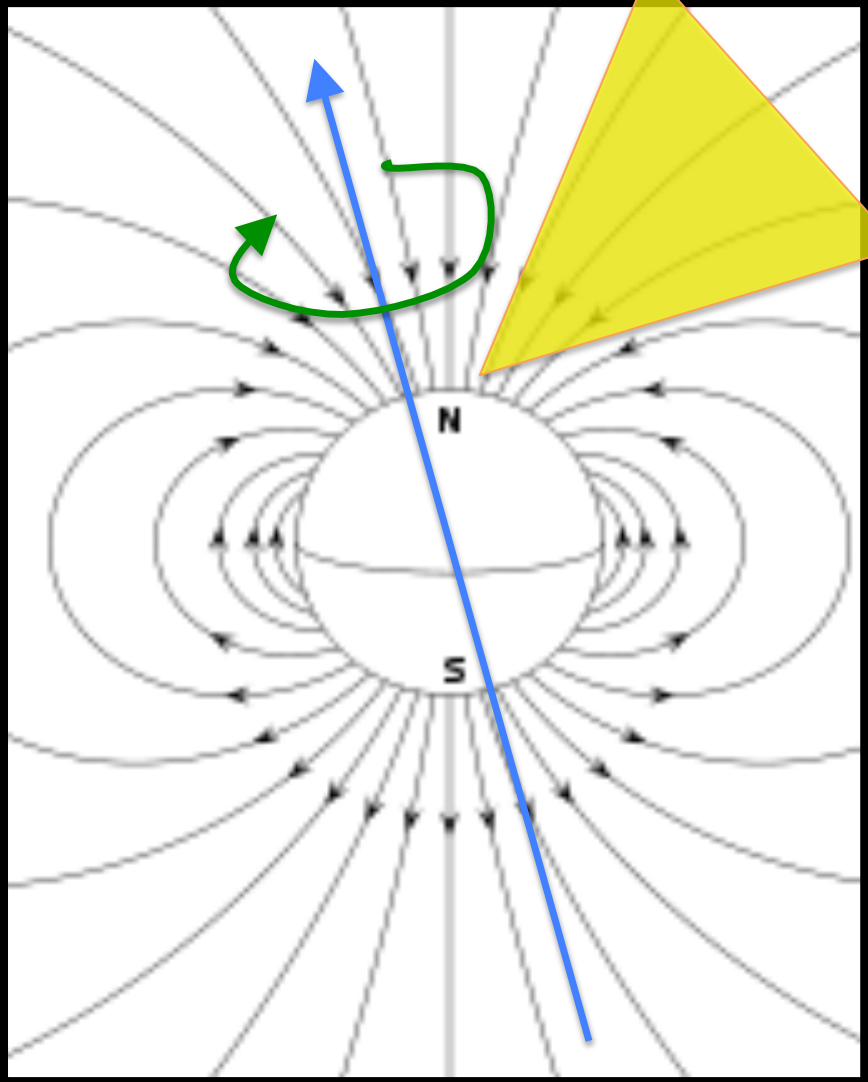


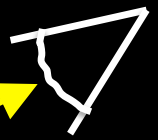


Frequency drift due to geometric modulation!

Dipole image: Wikipedia

Interpretation: UV Ceti has a periodic radio aurora, like brown dwarfs and planets





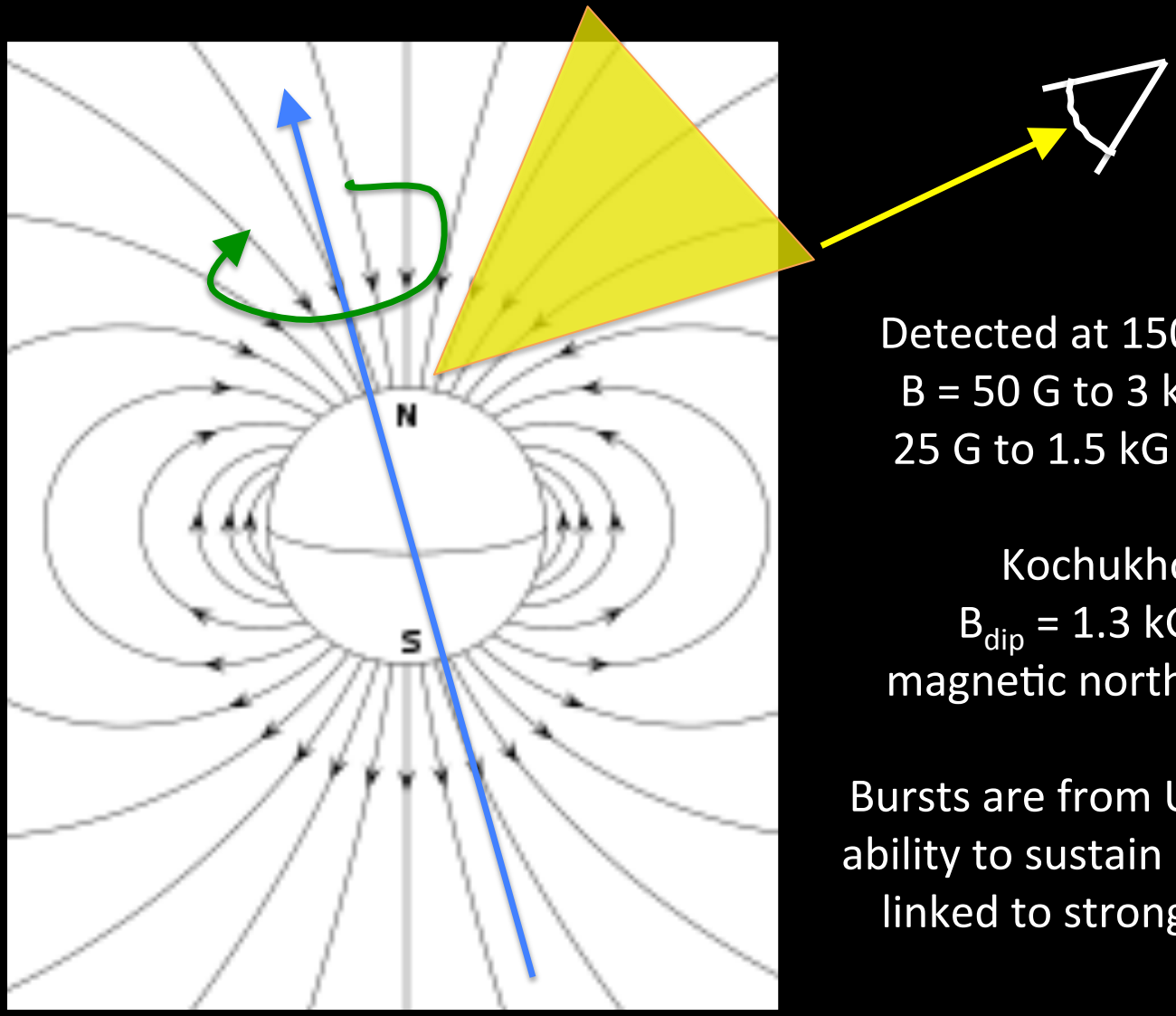
Barnes et al. 2016:
inclination = 60 deg
P_{rot} = 5.45 hours

UV Ceti bursts also detected at 150 MHz in left and right polarization (Lynch et al. 2017)

- South magnetic pole obscured at high frequencies?
- Beaming angle effect?

Dipole image: Wikipedia

Interpretation: UV Ceti has a periodic radio aurora, like brown dwarfs and planets



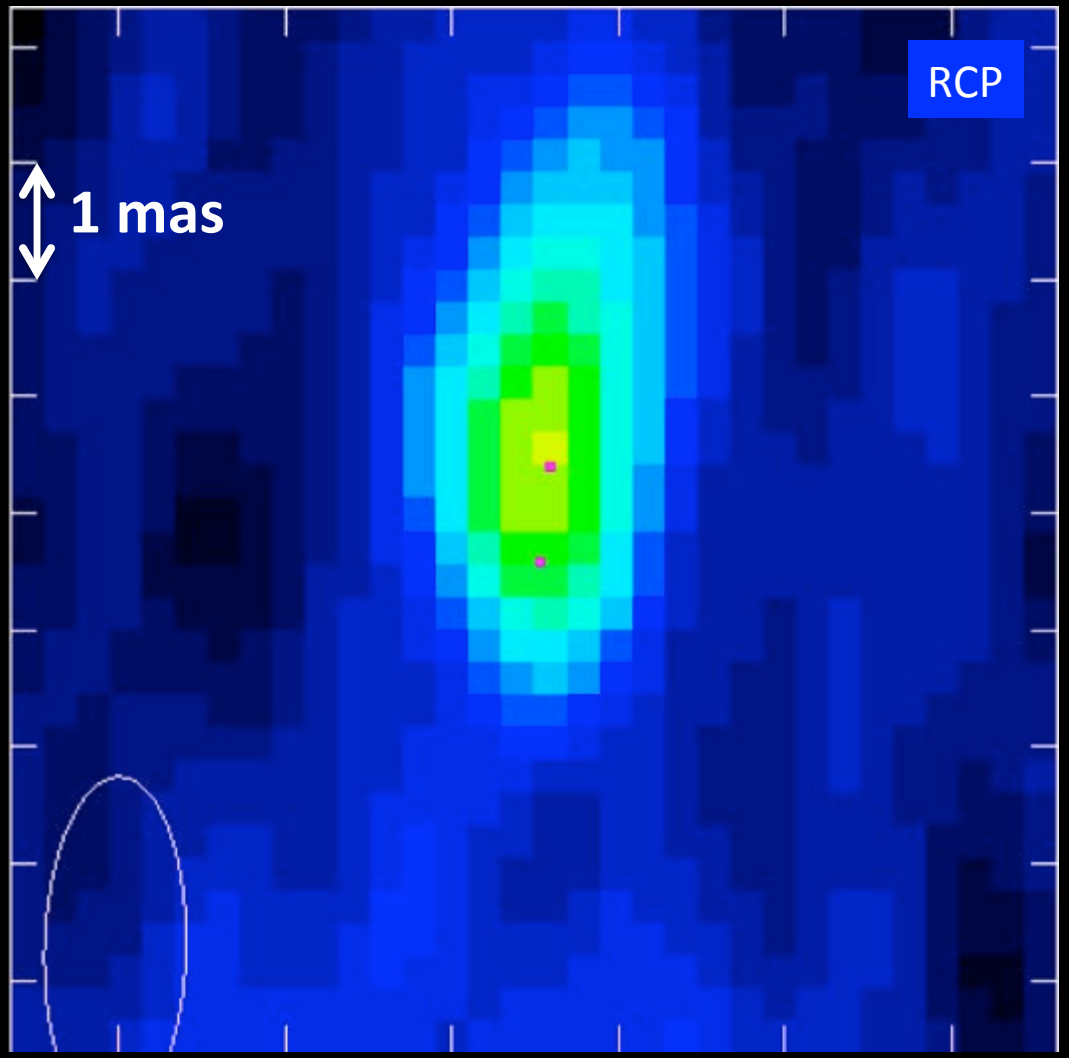
Detected at 150 MHz to 8.5 GHz →
B = 50 G to 3 kG if first harmonic,
25 G to 1.5 kG if second harmonic

Kochukhov et al. 2017:
B_{dip} = 1.3 kG, <Bf> = 6.7 kG,
magnetic north pole always visible

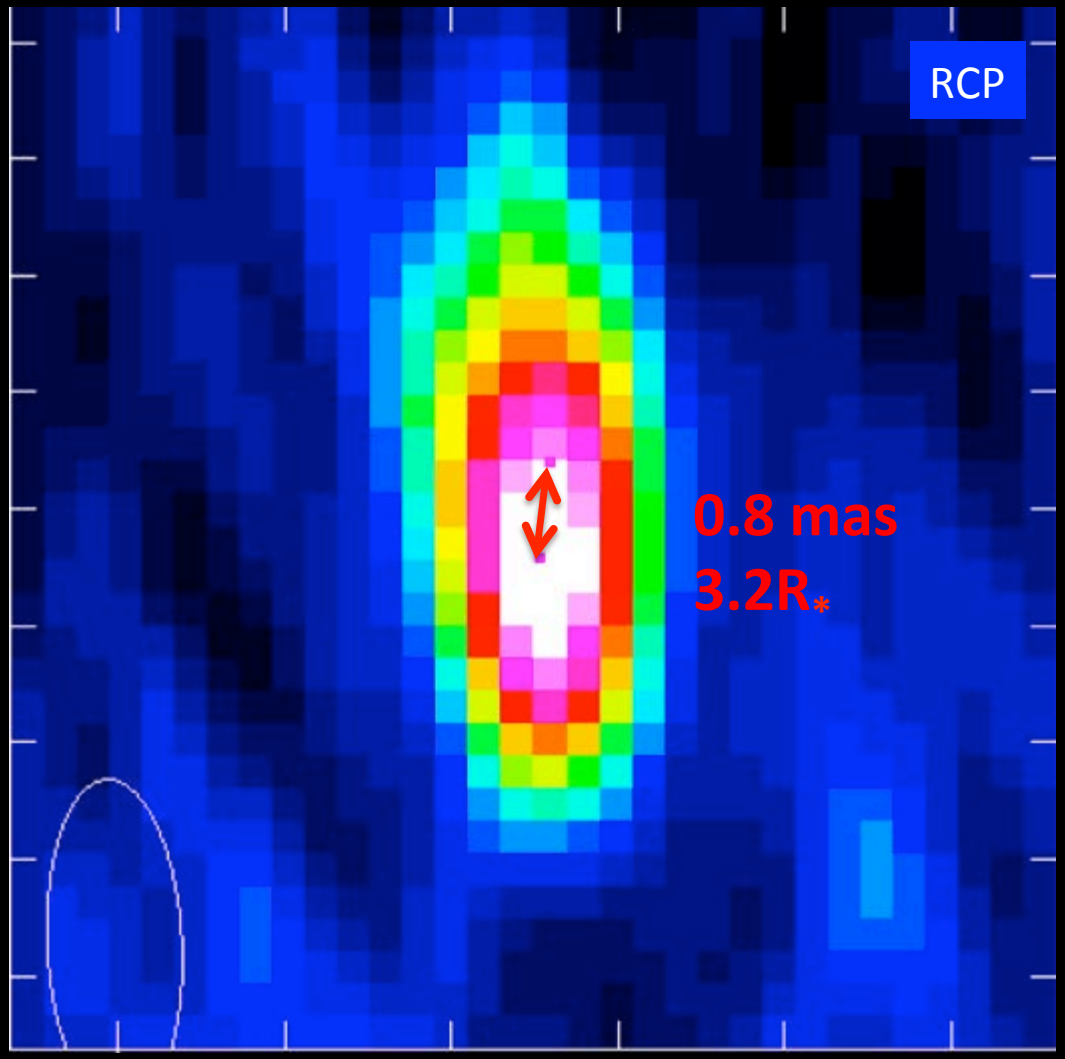
Bursts are from UV Cet, not BL Cet – is ability to sustain powerful radio aurora linked to strong large-scale B field?

Dipole image: Wikipedia

VLBA 8.4 GHz: Quiescent emission



VLBA 8.4 GHz: Coherent burst



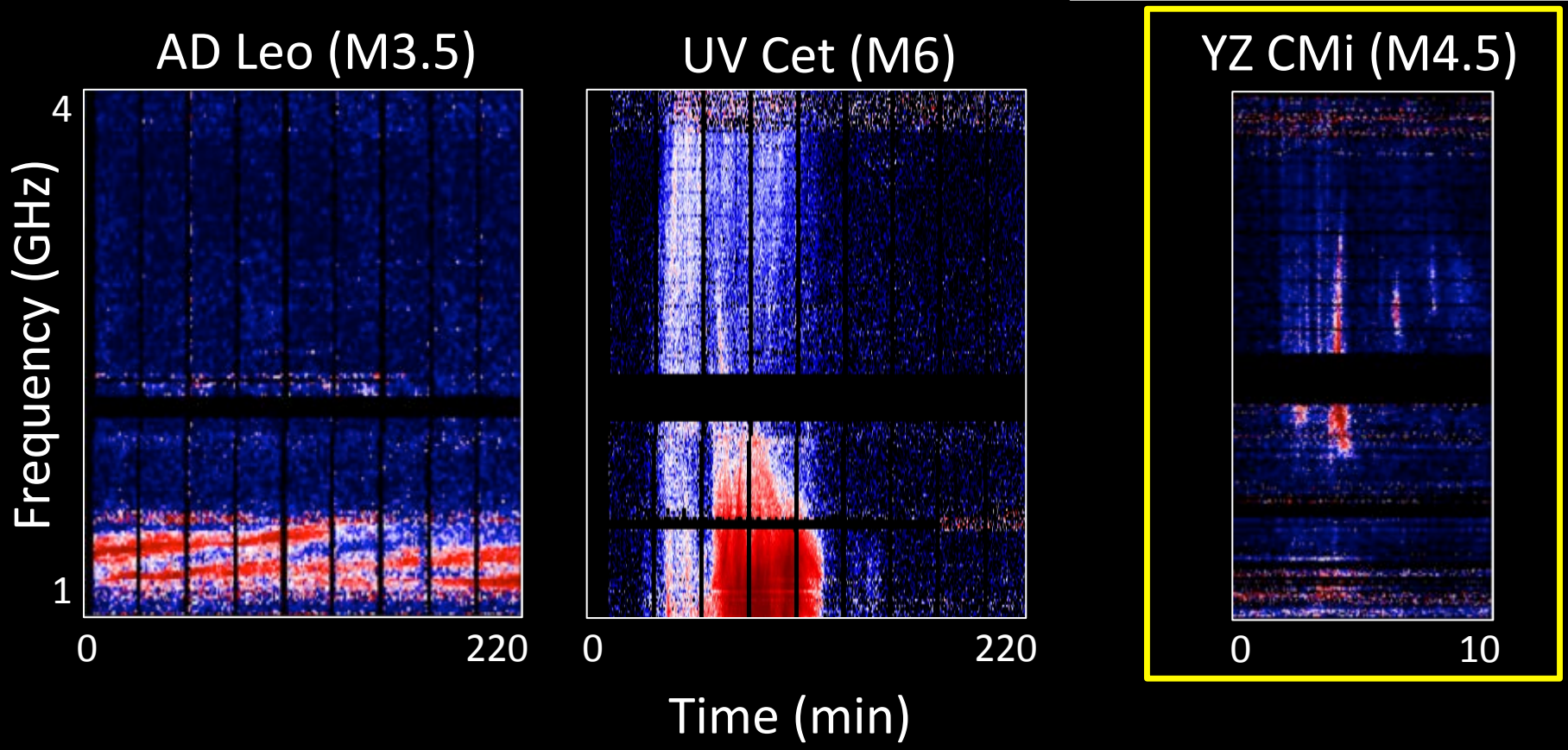
If this offset is real:

Coherent emission comes from 3 kG field, near photosphere → quiescent (incoherent) emission originates off stellar limb

VLA survey: Coherent radio bursts in 13 of 23 epochs, occur on variety of timescales

Long bursts (>~1 hour)
Requires ongoing electron acceleration

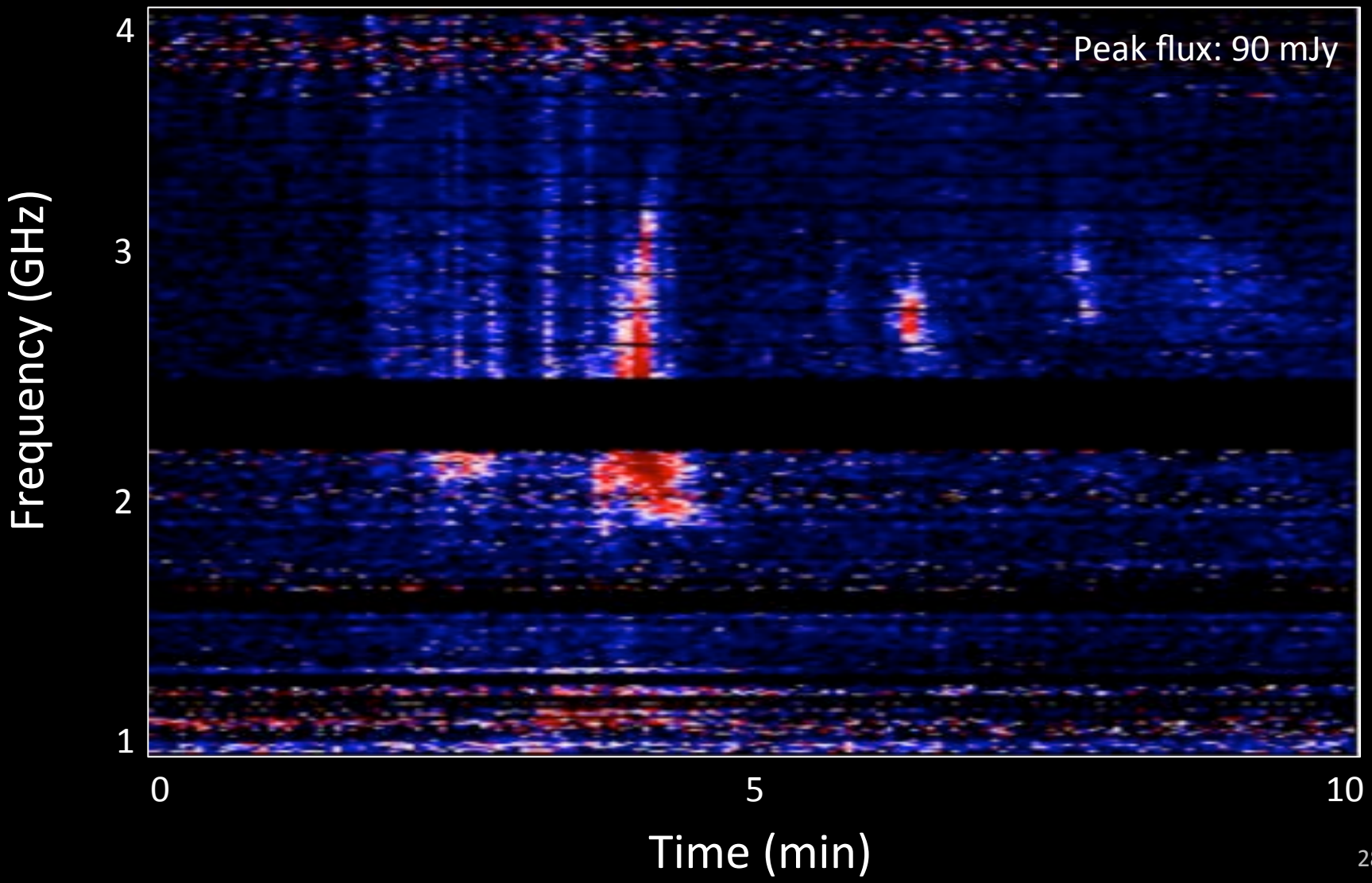
Short bursts (sec - min)
Powered by individual flares?



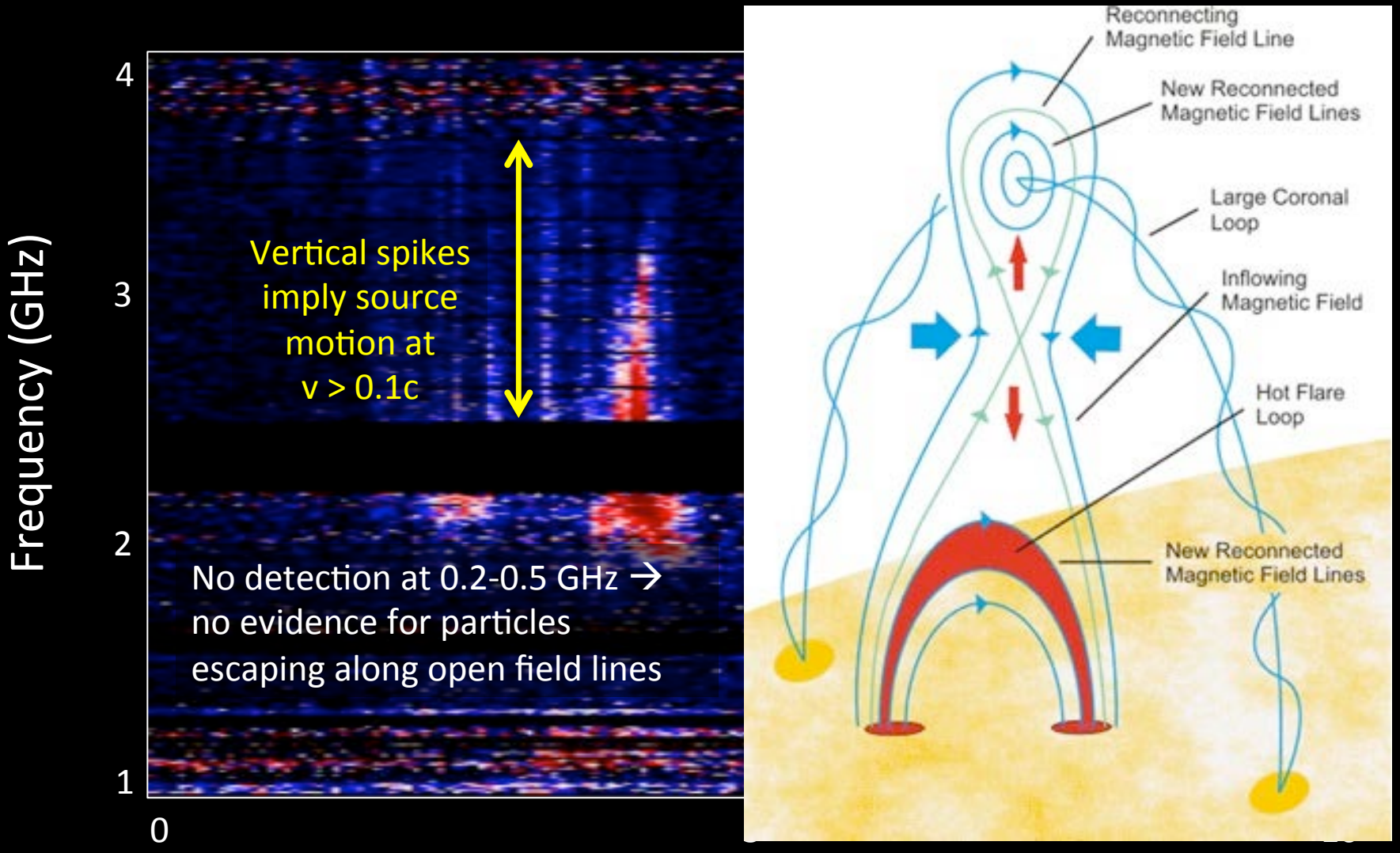
Red: Intense emission

Blue: No emission

YZ CMi (M4.5): Short duration burst with vertical spikes, implying rapid frequency drift



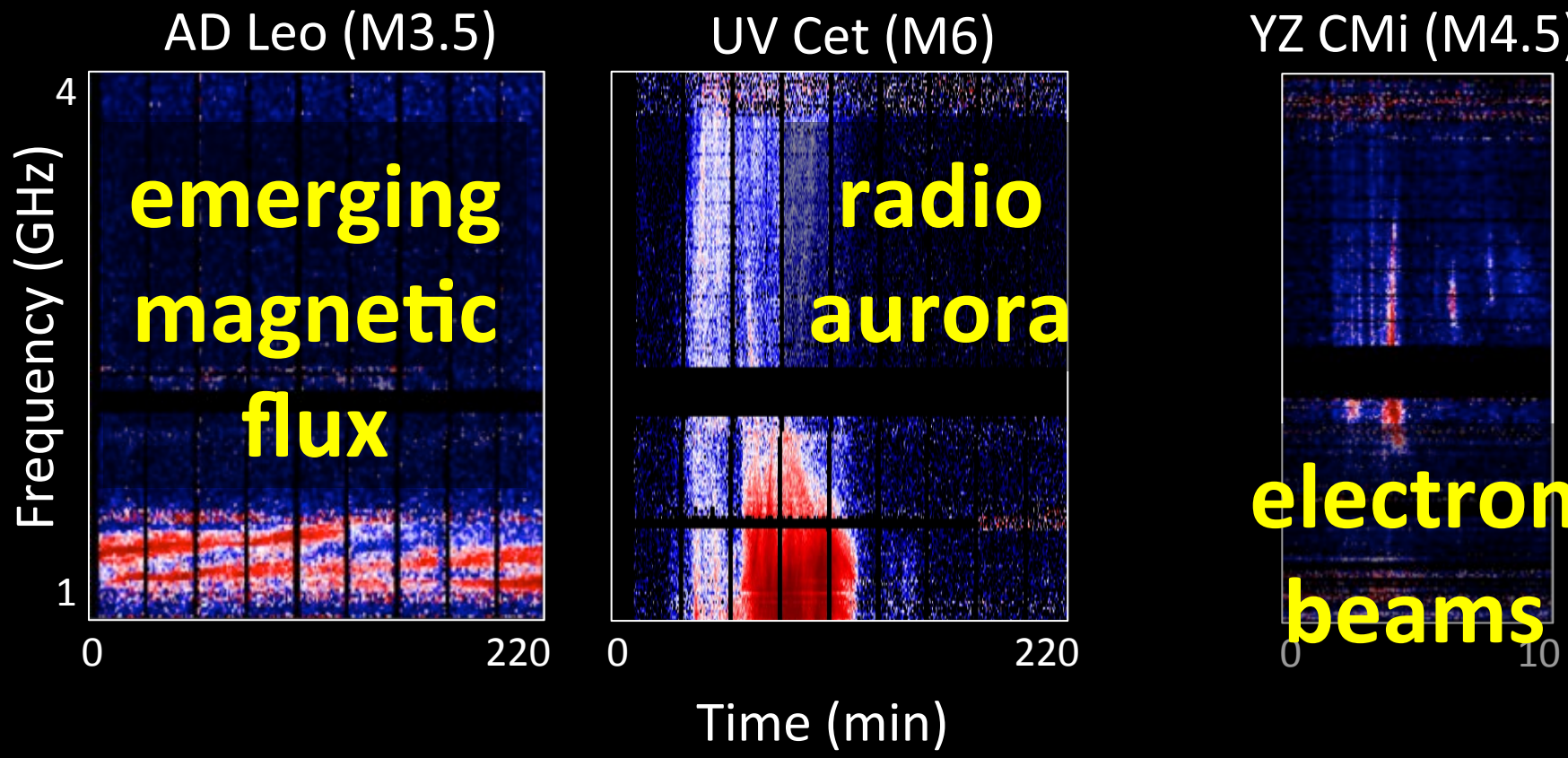
YZ CMi: Vertical spikes may be due to electron beams from magnetic reconnection site



Coherent radio bursts trace electron acceleration in corona

Long bursts (>~1 hour)
Requires ongoing electron acceleration

Short bursts (sec - min)
Powered by individual flares?



Red: Intense emission

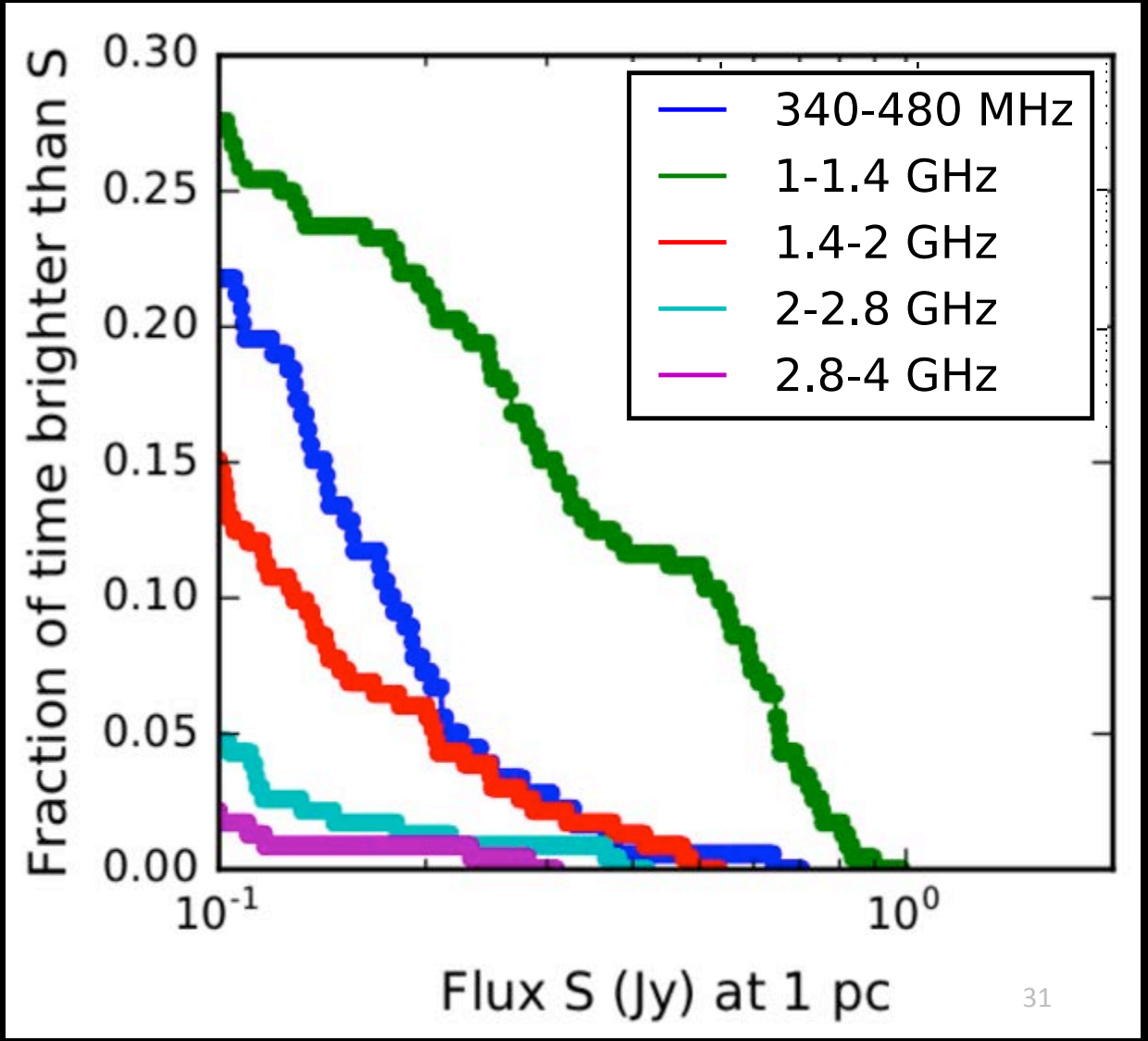
Blue: No emission

Active M dwarfs are effective particle accelerators

At 1-1.4 GHz, active M dwarfs spend 25% of time bursting at >~10x quiescent flux

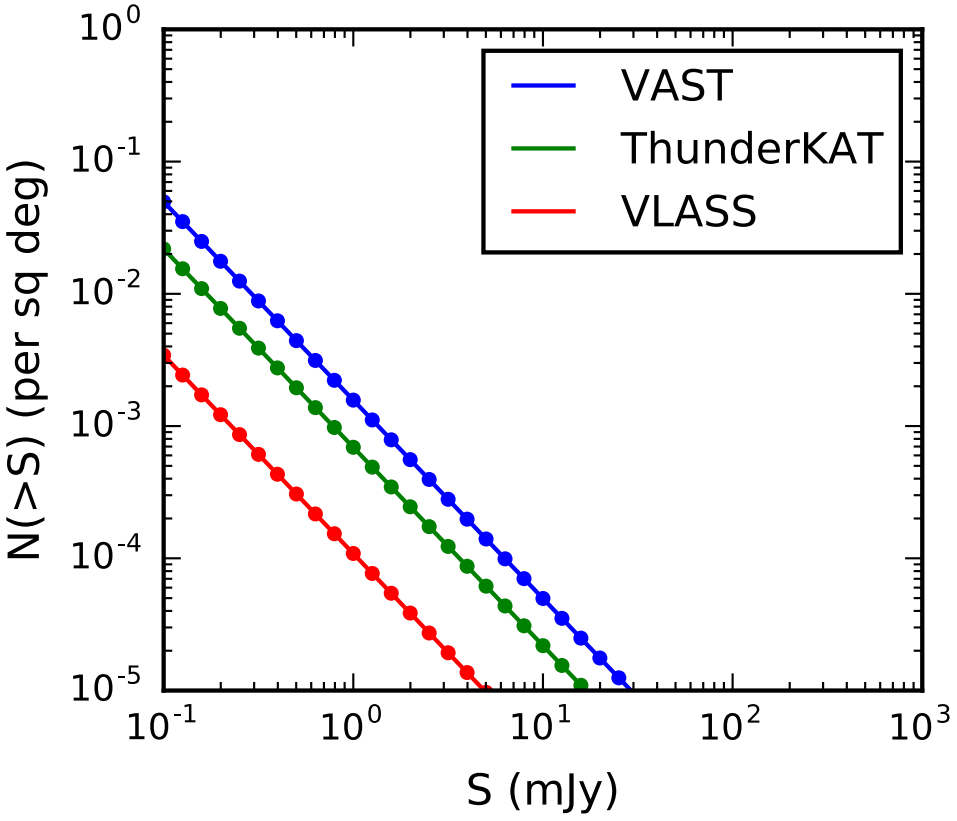
Significant source of galactic radio transients

Bright bursts most frequent at 1-1.4 GHz; solar bright bursts most common at <1 GHz (Nita et al. 2002)

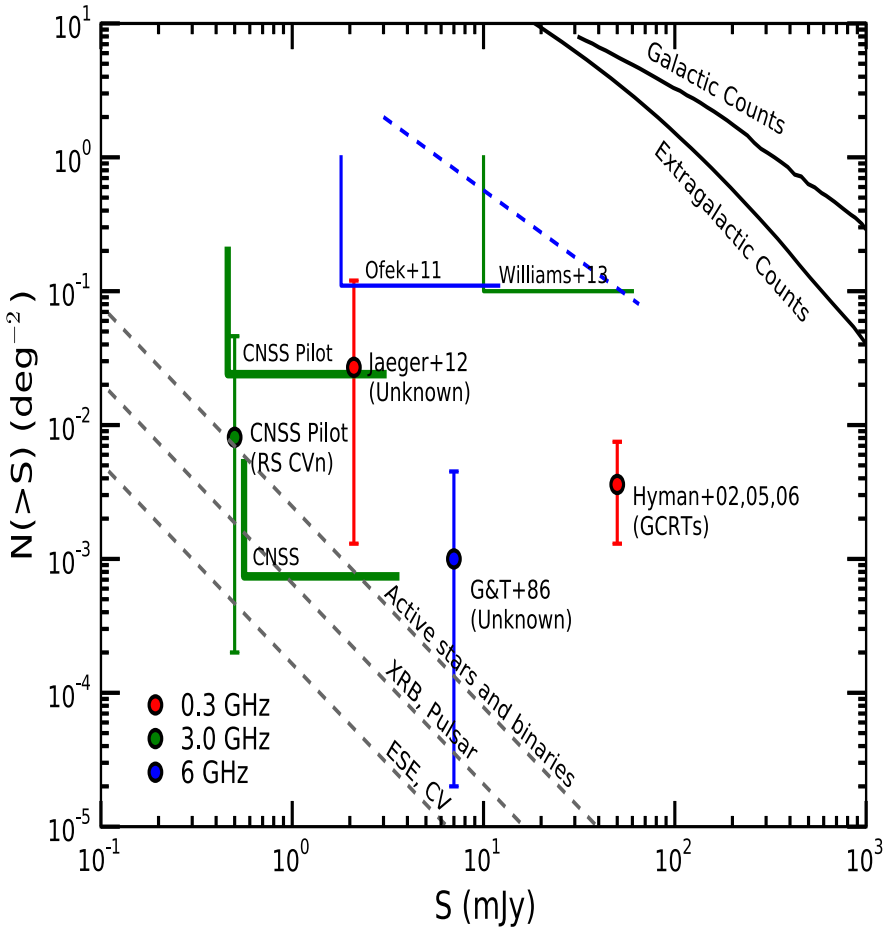


Transient density due to coherent radio bursts on active M dwarfs

VLA survey of active M dwarfs
(Villadsen et al. in prep)



Mooley et al. 2016 CNSS galactic transients

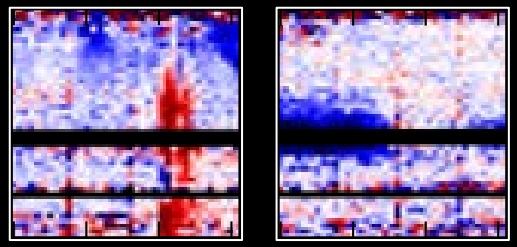


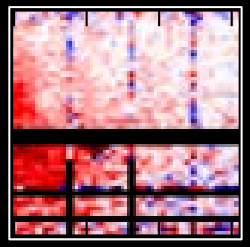
YZ CMi

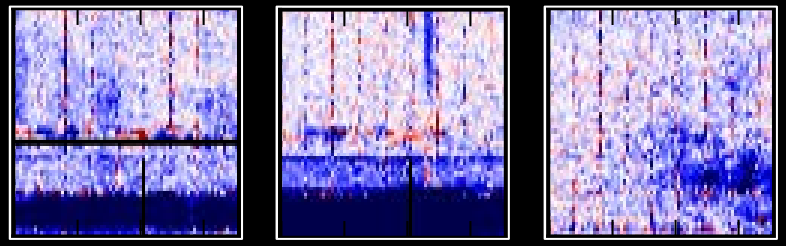
EQ Peg

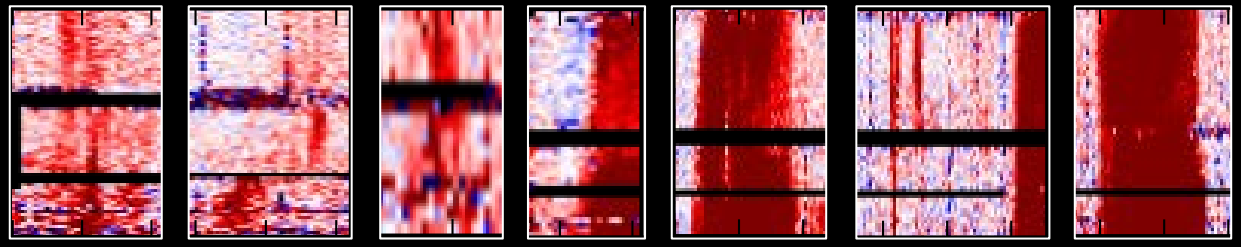
AD Leo

UV Cet





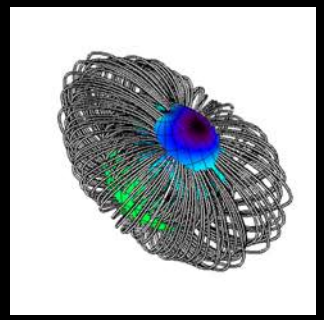




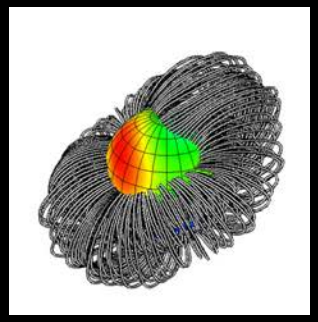
Stokes V polarization of long-duration >1 GHz bursts consistent across epochs

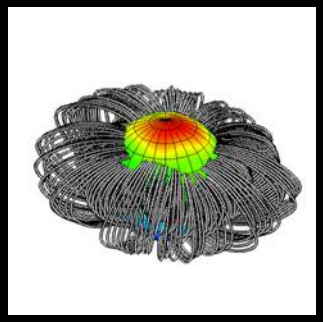
Red: RCP
Blue: LCP

YZ CMi

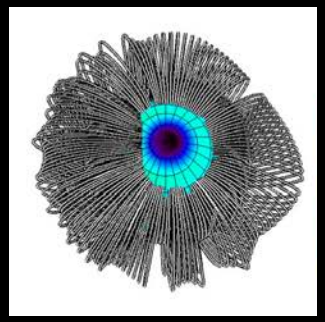


EQ Peg

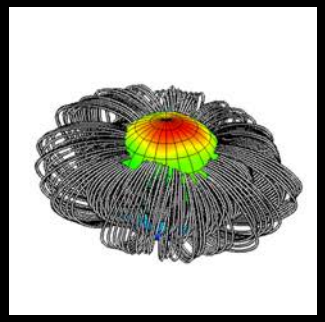




AD Leo



UV Cet
(EQPeg B as proxy)

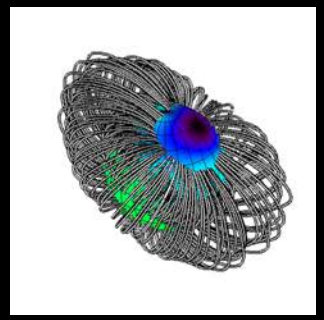


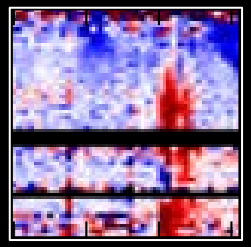
Compare burst polarization to large-scale B field (Zeeman Doppler Imaging)

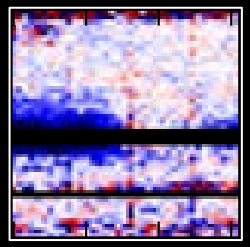
Red: North
Blue: South

Zeeman Doppler Imaging: Morin+2008, Lang+2014; Kochukov & Lavail 2017

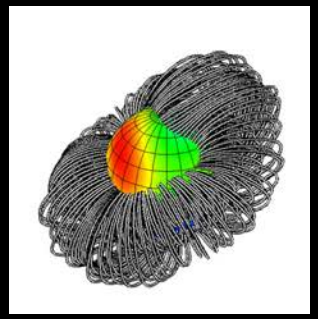
YZ CMi

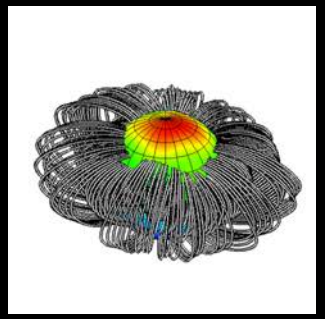


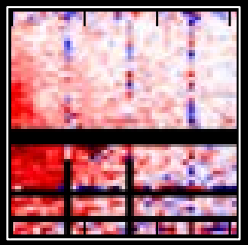




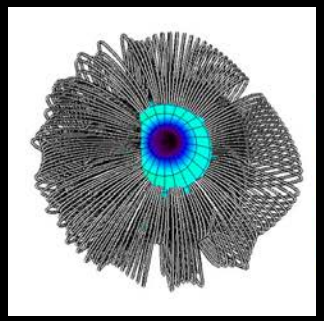
EQ Peg

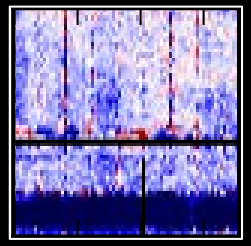


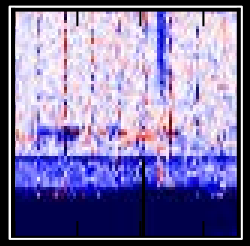


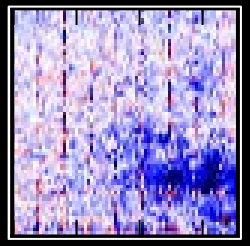


AD Leo

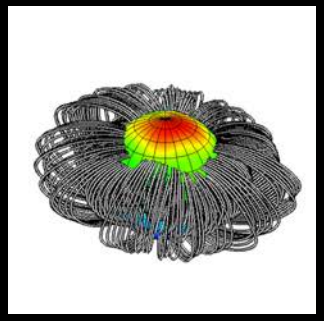


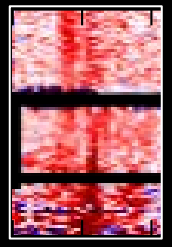


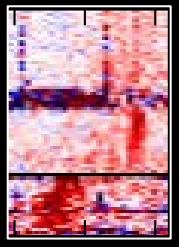


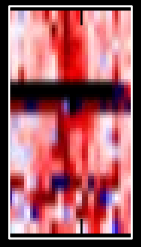


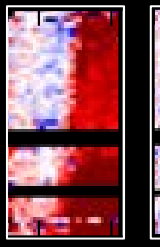
UV Cet
(EQPeg B as proxy)

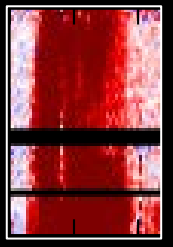


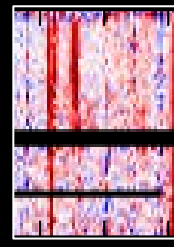


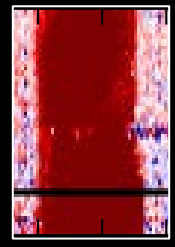












Polarization of long-duration >1 GHz bursts is determined by large-scale B field

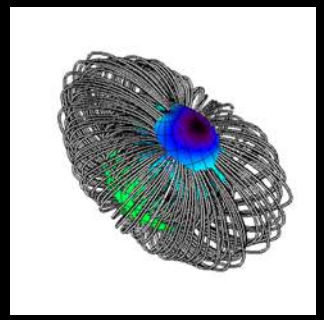
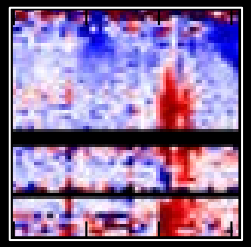
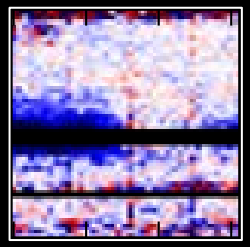
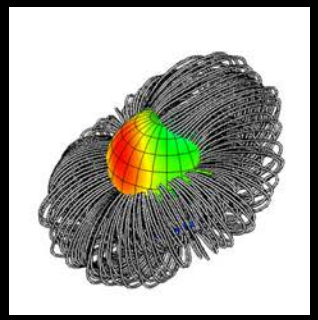
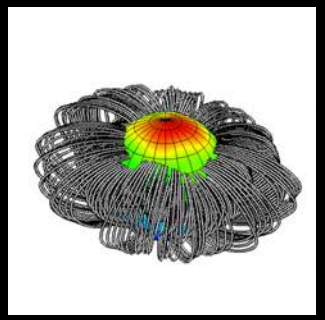
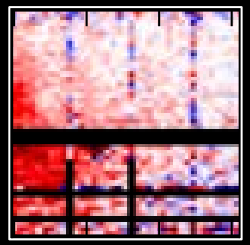
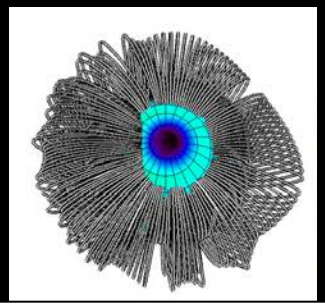
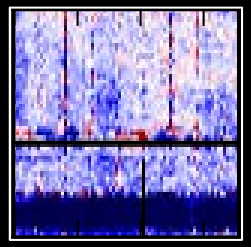
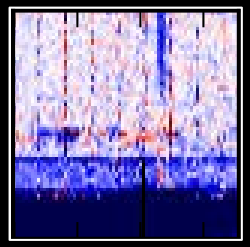
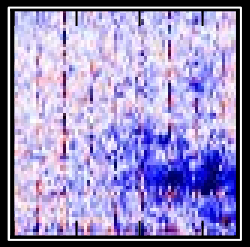
Red: RCP/North
Blue: LCP/South

Zeeman Doppler Imaging: Morin+2008, Lang+2014; Kochukov & Lavail 2017

YZ CMi

EQ Peg

AD Leo

Polarization of long-duration >1 GHz bursts is determined by large-scale B field

Red: RCP/North

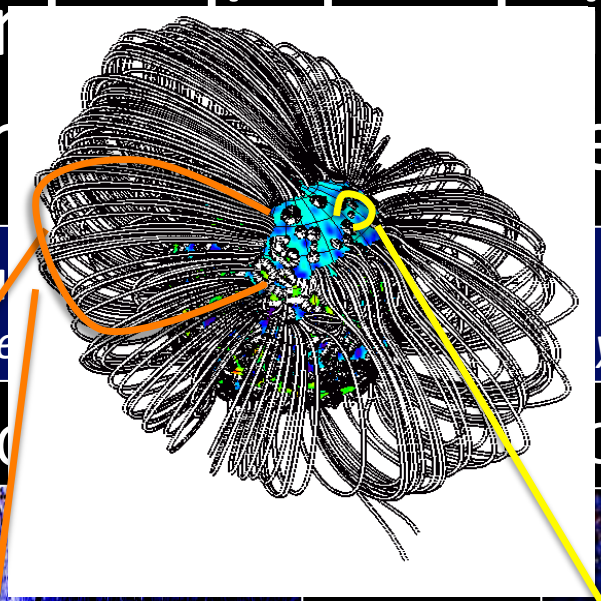
Blue: LCP/South

Long duration coherent bursts from active M dwarfs are x-mode emission from electrons in the large-scale magnetic field – same characteristics as radio aurora, even if not periodic

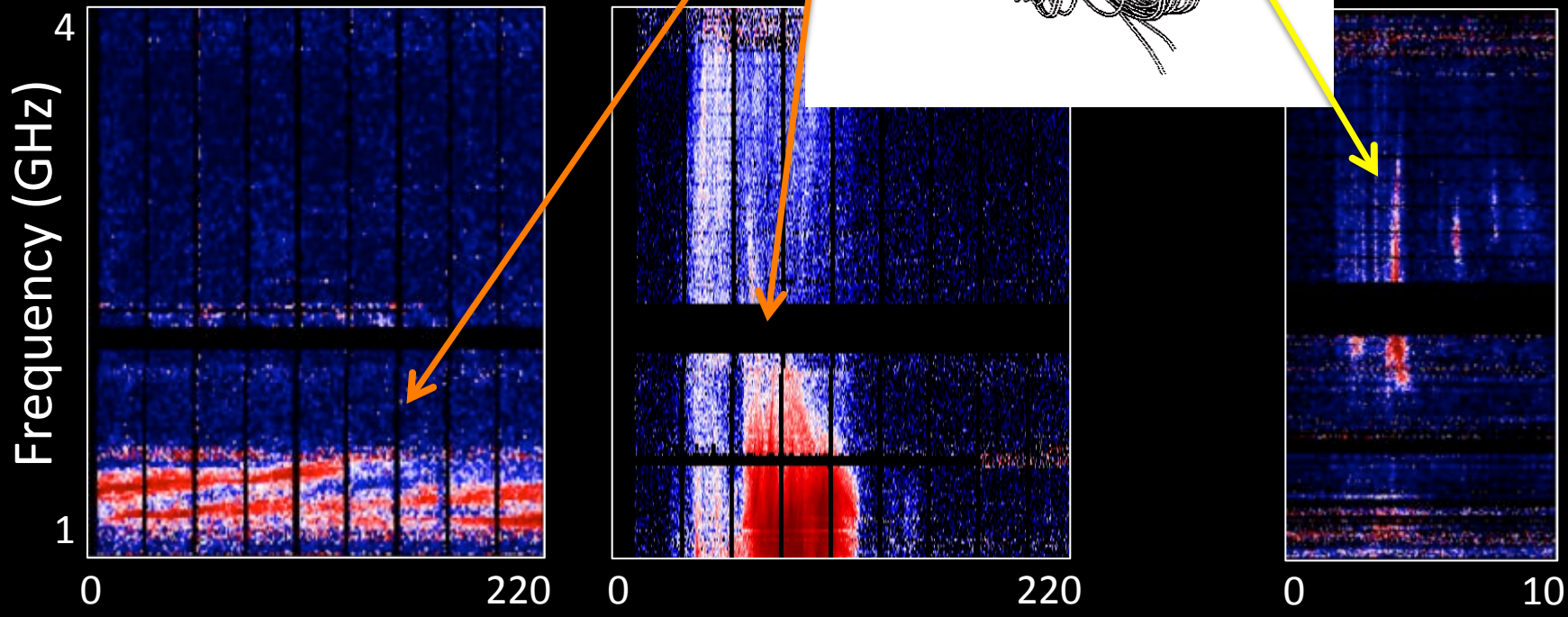
VLA survey: Coherer… in 13 of 23 epochs, occur or… escales

Long bursts (>~1 hou… rsts (sec - min)

Requires ongoing electron accele… y individual flares?



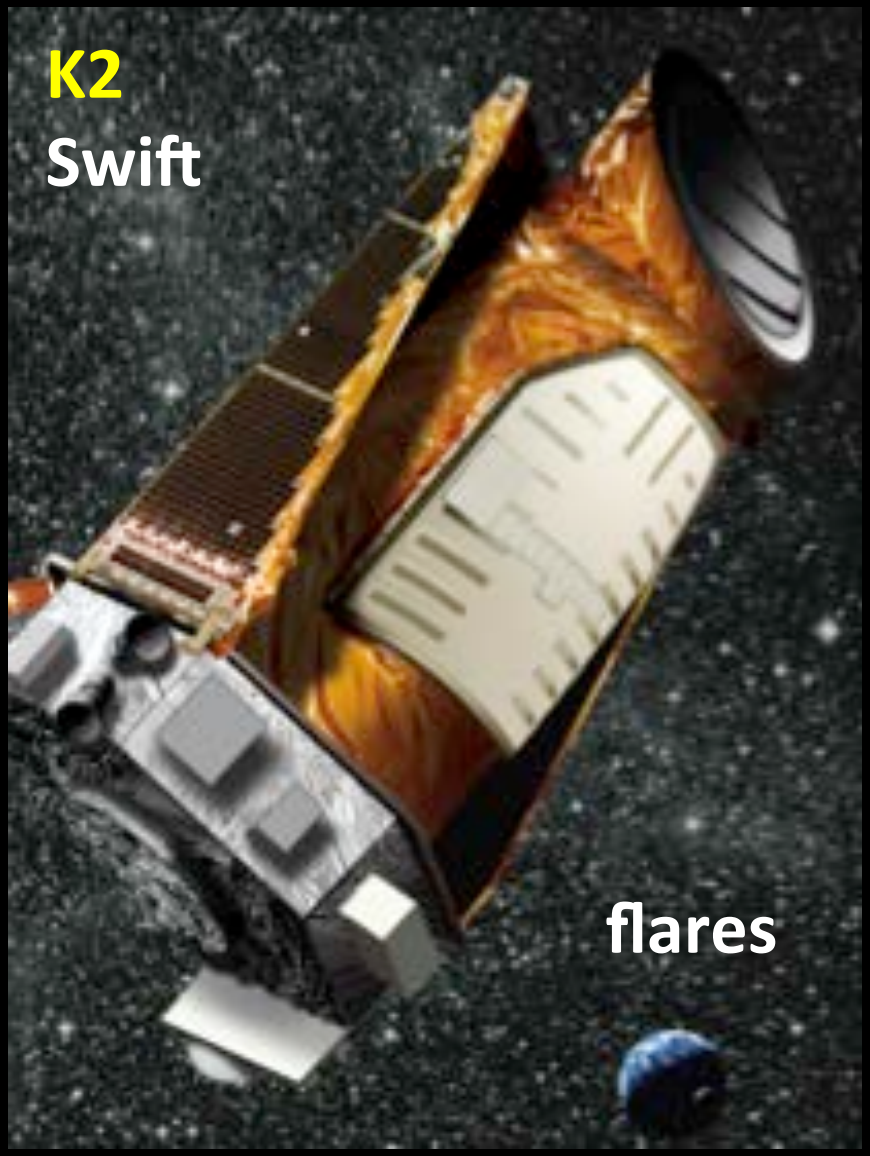
AD Leo (M3.5) UV … CMi (M4.5)

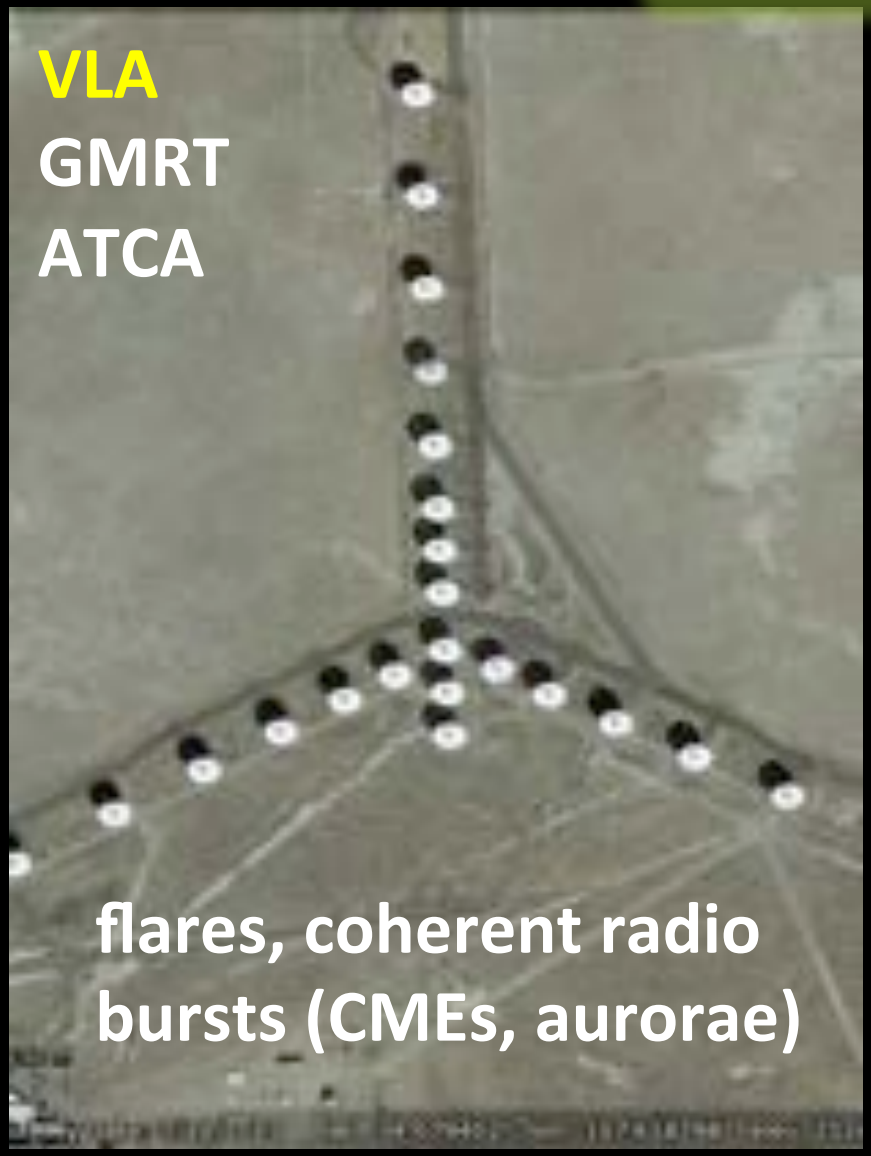


Polarization consistent with star's optical Stokes V polarization→ large-scale magnetic structures

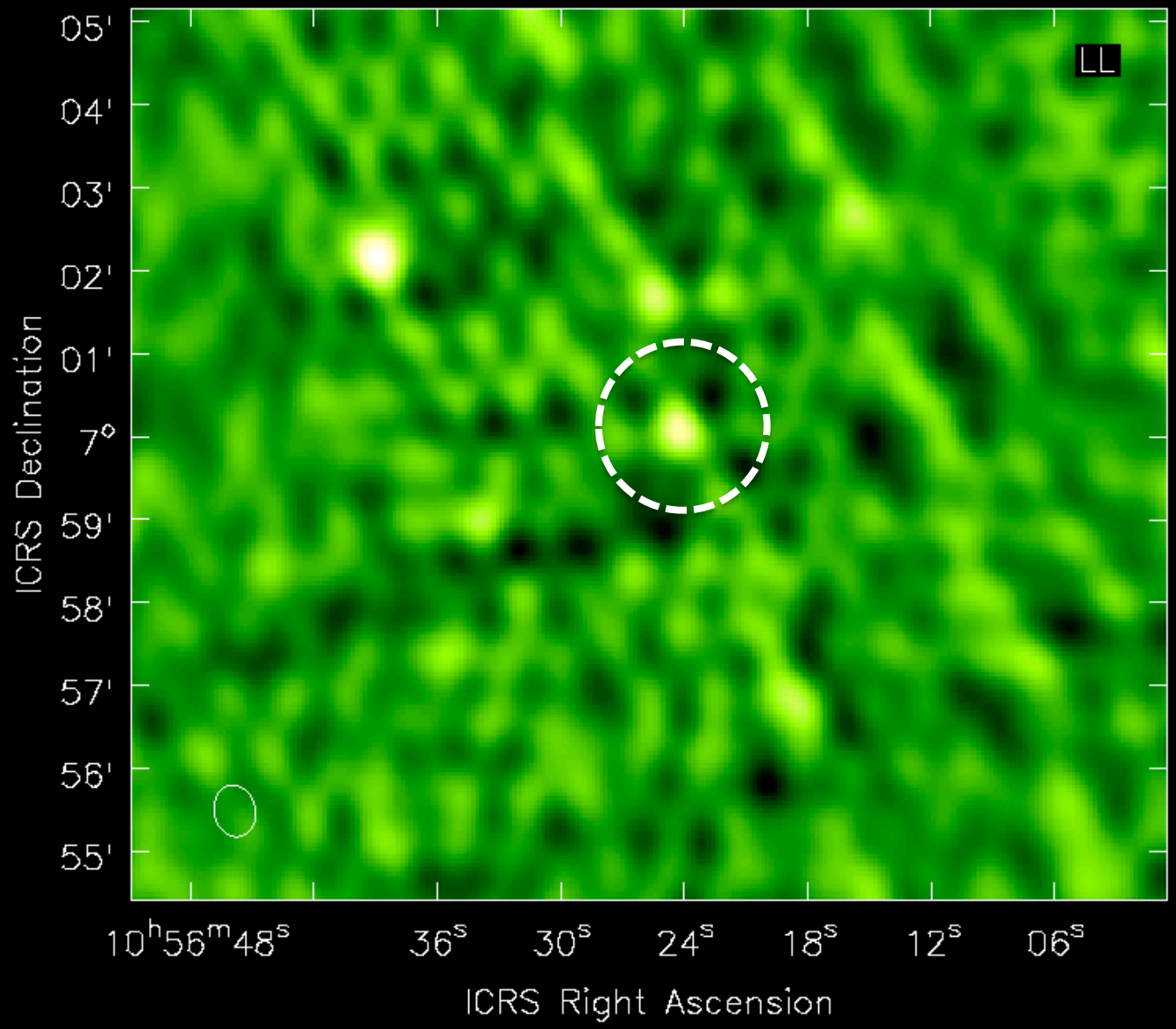
Polarization varies→ small-scale magnetic structures

CN Leo (Wolf 359): Radio & optical monitoring





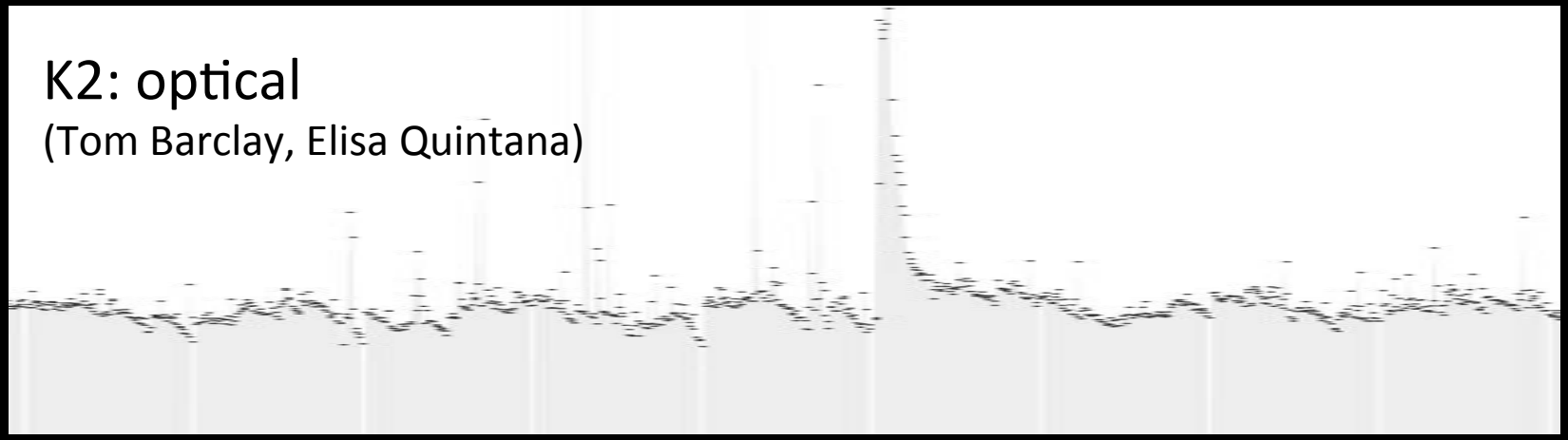
VLA X band image: CN Leo flare

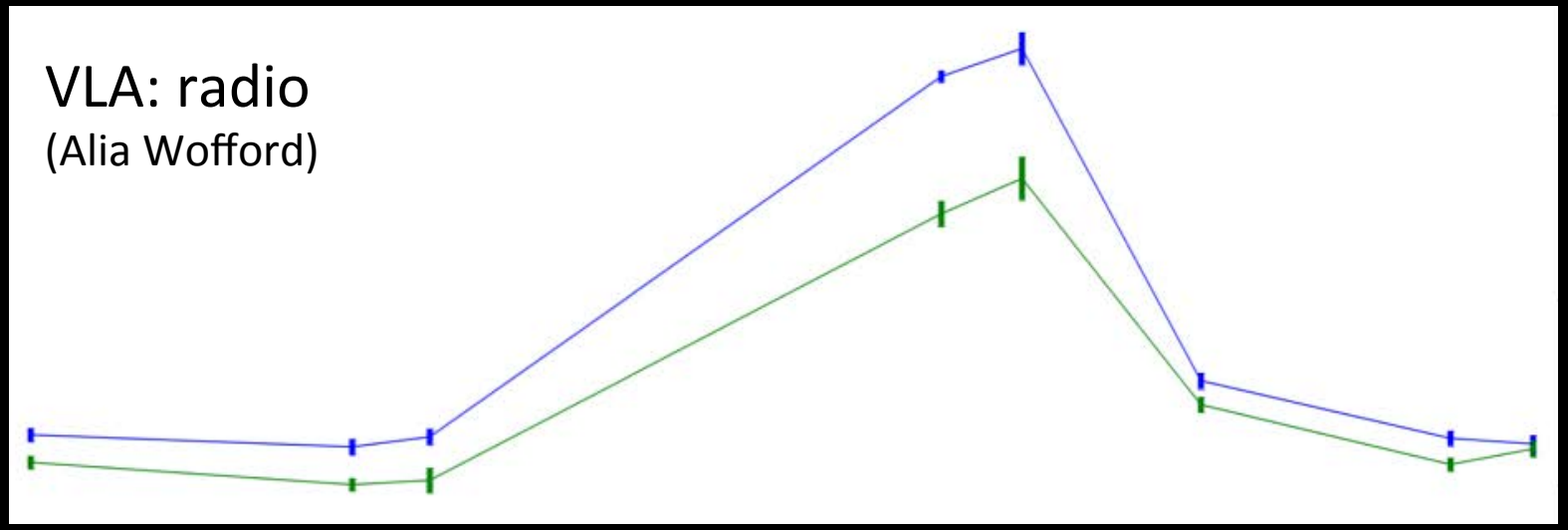


Project lead:
Alia Wofford,
undergraduate at
Elizabeth City
State University

Please talk to me
if you have any
recommendations
for astrobiology
PhD programs/
advisors!

First look: Large radio and optical flare

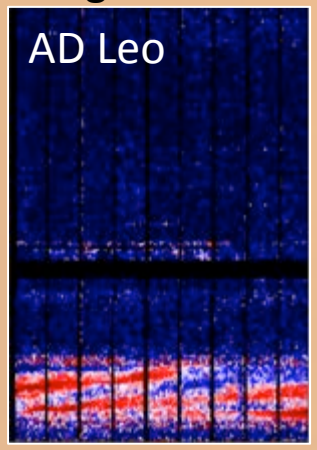




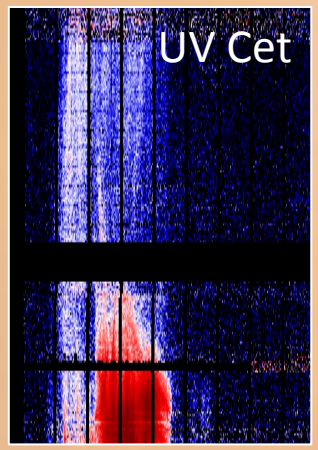
20 days

Wideband radio spectroscopy reveals dynamic processes in coronae of active M dwarfs

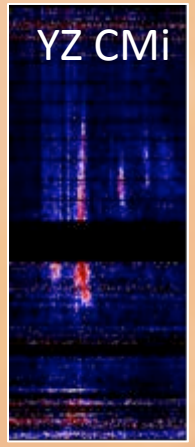
emerging magnetic flux



periodic radio aurora



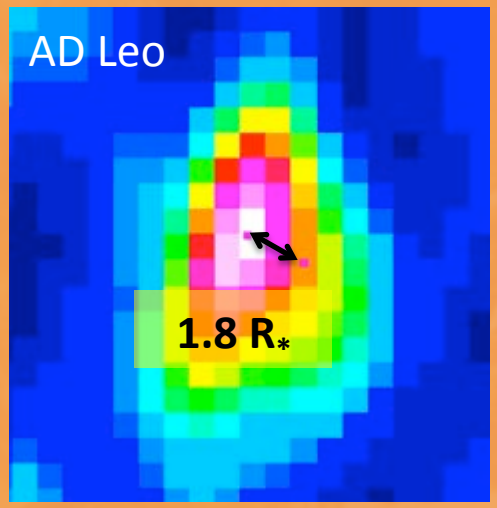
e- beams from flare



What mechanisms accelerate the electrons producing long-duration coherent bursts?

No source motion observed passing beyond minimum observed frequency
→ no CMEs, or CMEs with no emission?

Very long baseline imaging pinpoints radio flares relative to quiescent corona



Search for off-limb flares associated with outwards source motion seen in coherent bursts

Analyzing: optical + radio to determine relationship to flares

Wolf 359: K2, Swift, VLA, GMRT, ATCA

Collaborators and advisors: Gregg Hallinan, Stephen Bourke, Ryan Monroe, Tim Bastian, Alia Wofford, Elisa Quintana, Tom Barclay, Beverly Thackeray, Starburst team, JPL DSN team
Research funding: NSF GRFP, NSF ATI Program (Starburst project), Troesh Fellowship, PEO Scholar Award, Jansky Postdoctoral Fellowship