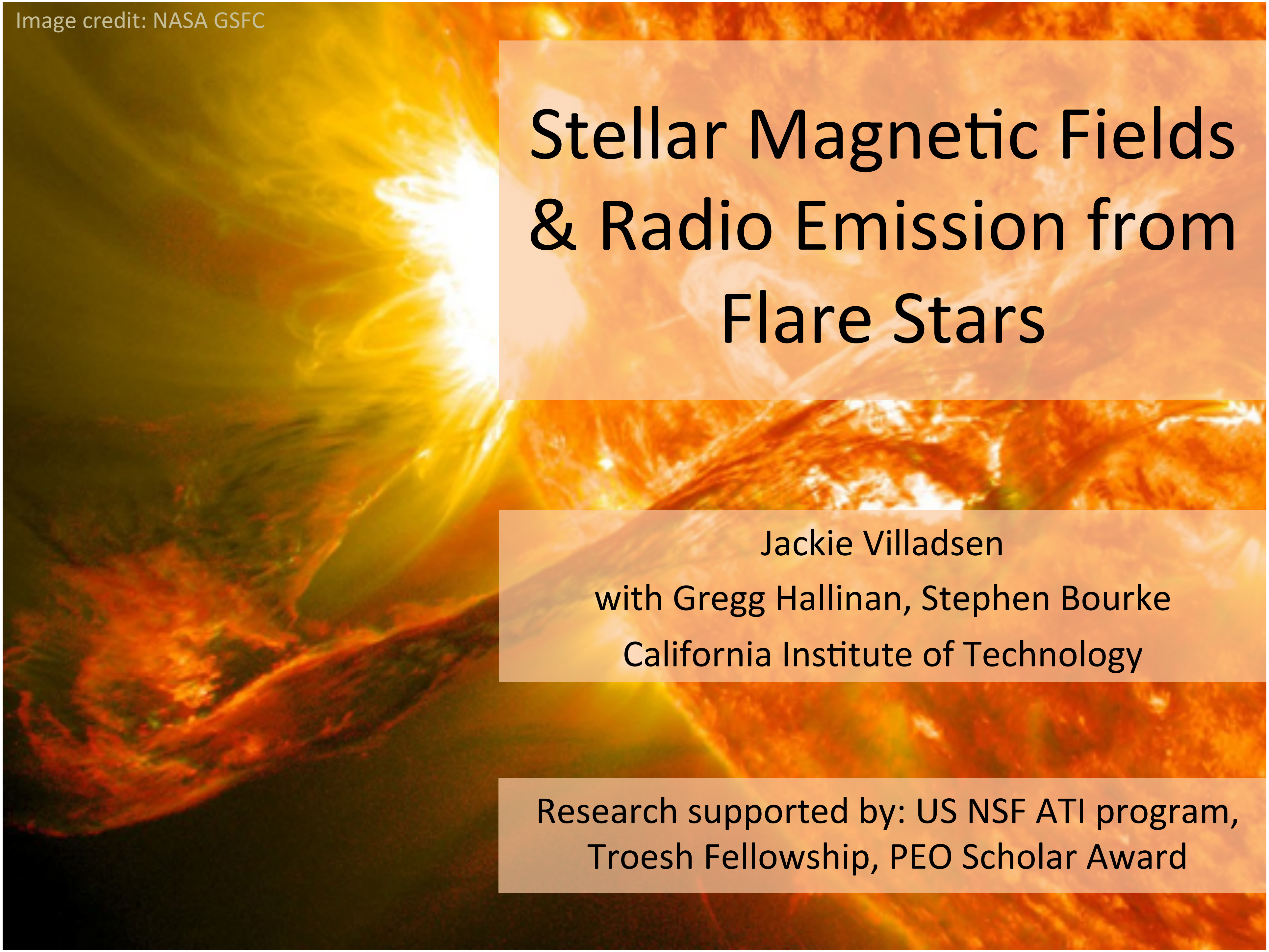
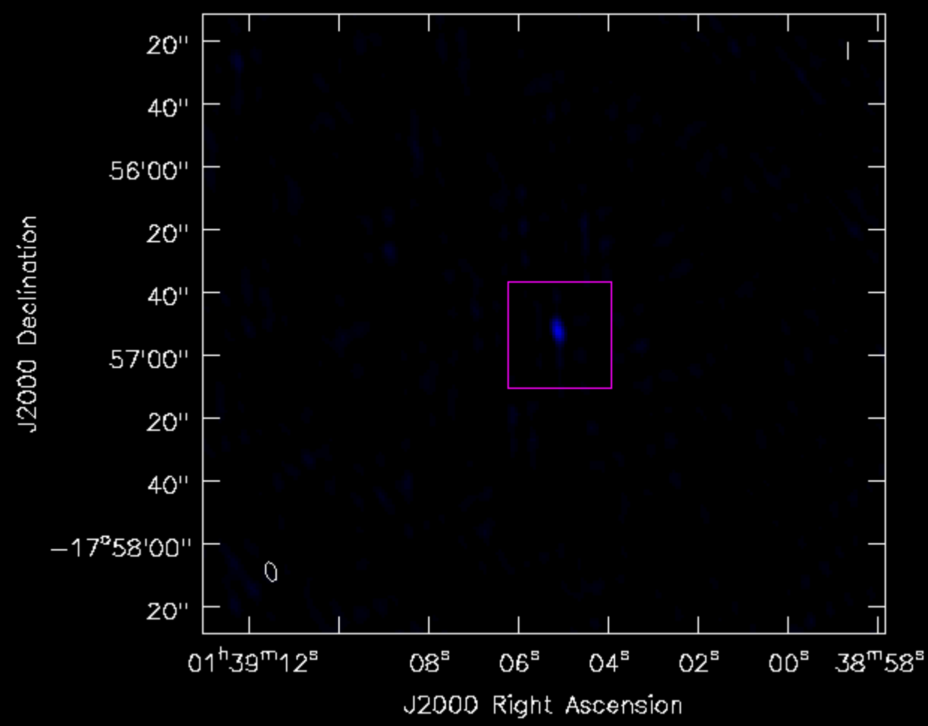


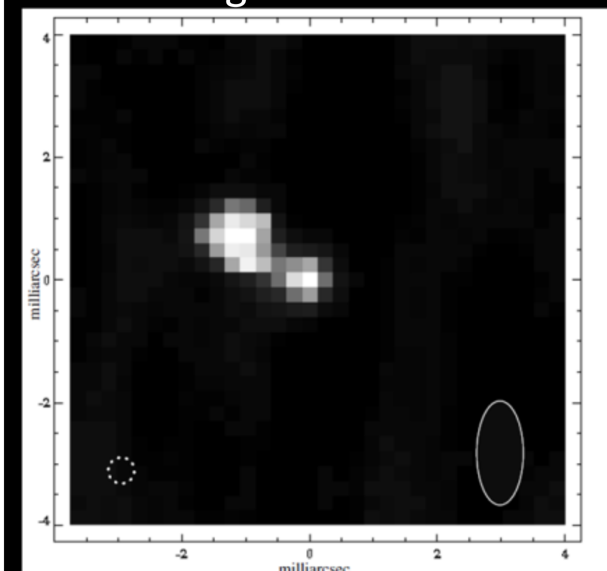
Image credit: NASA GSFC
Stellar Magnetic Fields & Radio Emission from Flare Stars
Jackie Villadsen
with Gregg Hallinan, Stephen Bourke
California Institute of Technology
Research supported by: US NSF ATI program, Troesh Fellowship, PEO Scholar Award

UV Ceti – Radio Emission of a Prototypical Flare Star

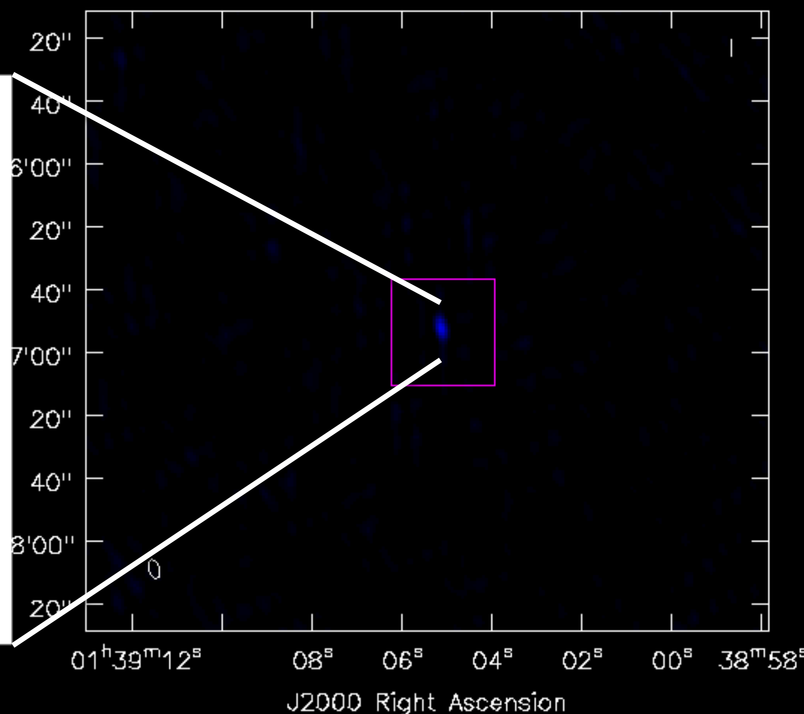


UV Ceti – Radio Emission of a Prototypical Flare Star

VLBA image of radio corona



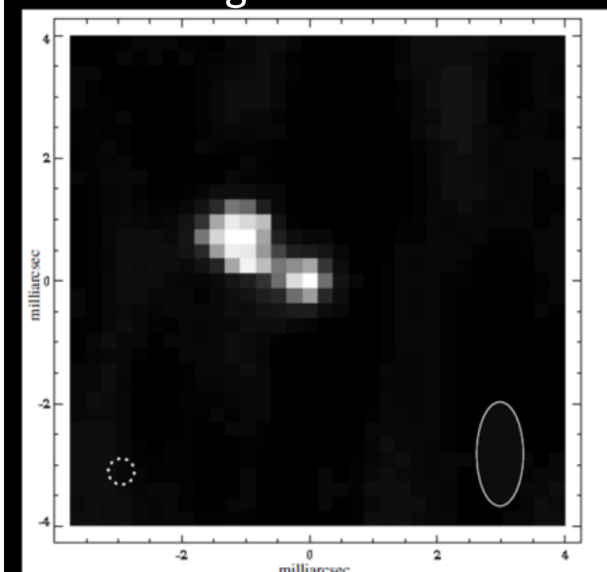
Benz et al. 1998



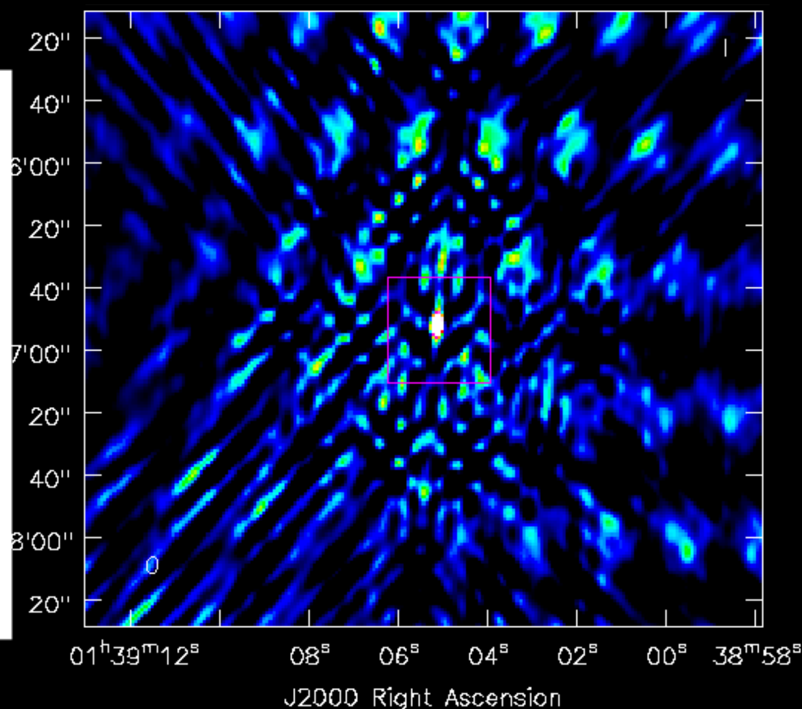
Gyrosynchrotron from energetic electrons in closed magnetic field

UV Ceti – Radio Emission of a Prototypical Flare Star

VLBA image of radio corona



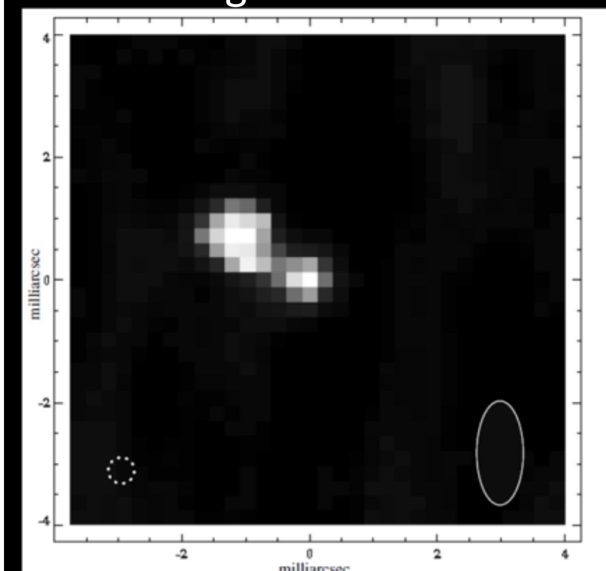
Benz et al. 1998



Gyrosynchrotron from energetic electrons in closed magnetic field

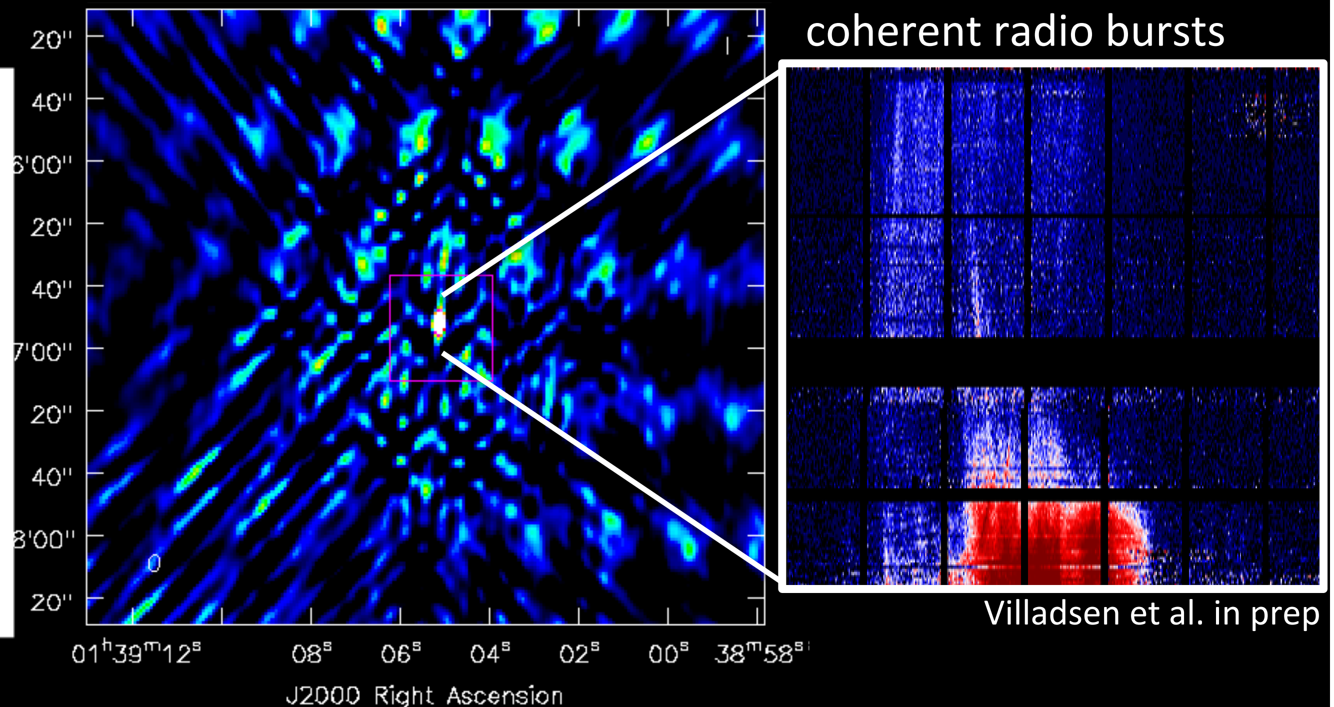
UV Ceti – Radio Emission of a Prototypical Flare Star

VLBA image of radio corona



Benz et al. 1998

VLA, LWA, Starburst: "spectropolarimetry" of coherent radio bursts



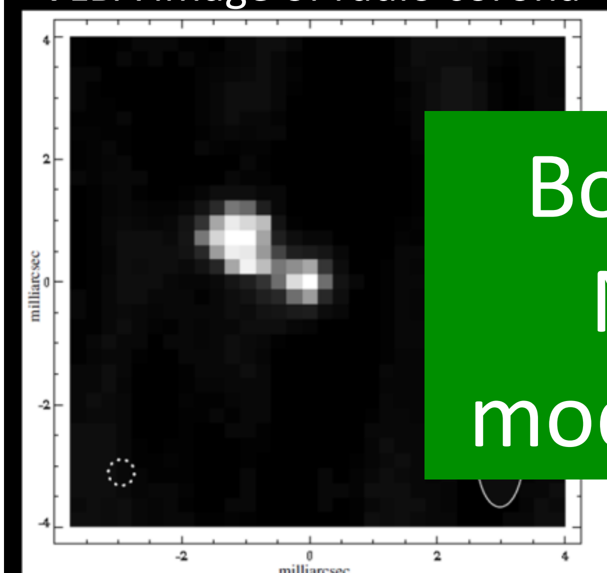
Villadsen et al. in prep

Gyrosynchrotron from energetic electrons in closed magnetic field

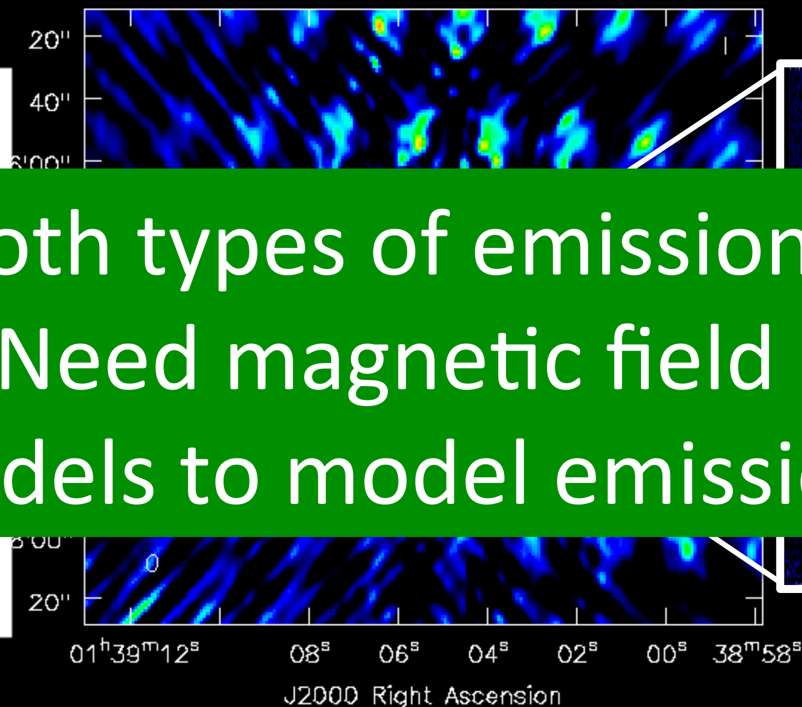
Plasma or cyclotron maser from coronal shock fronts, magnetic reconnection sites, aurorae

UV Ceti – Radio Emission of a Prototypical Flare Star

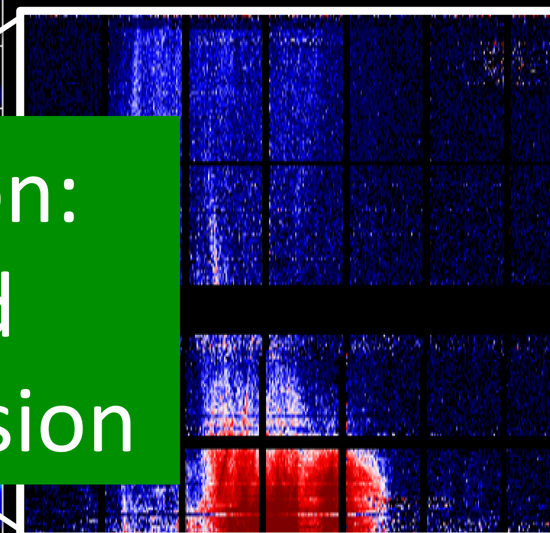
VLBA image of radio corona



Benz et al. 1998



VLA, LWA, Starburst: "spectropolarimetry" of coherent radio bursts



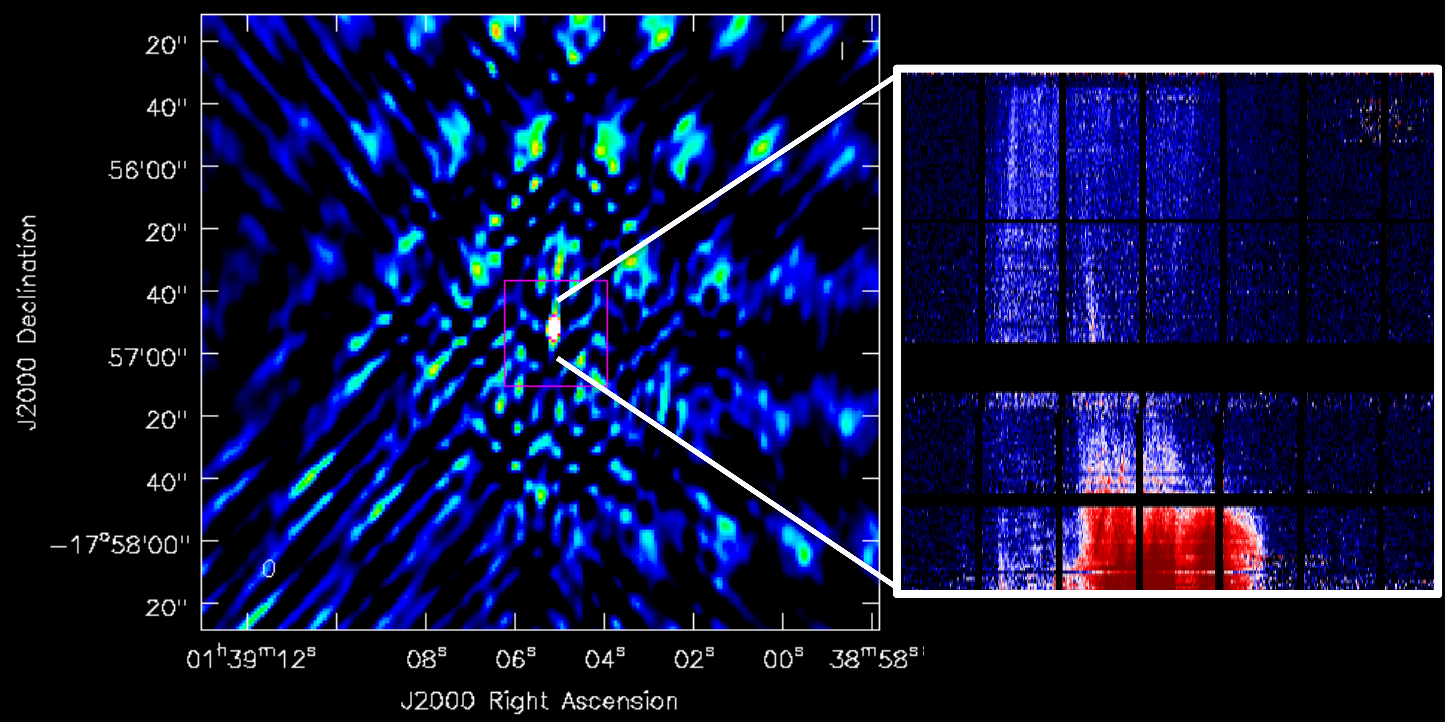
Villadsen et al. in prep

Both types of emission: Need magnetic field models to model emission

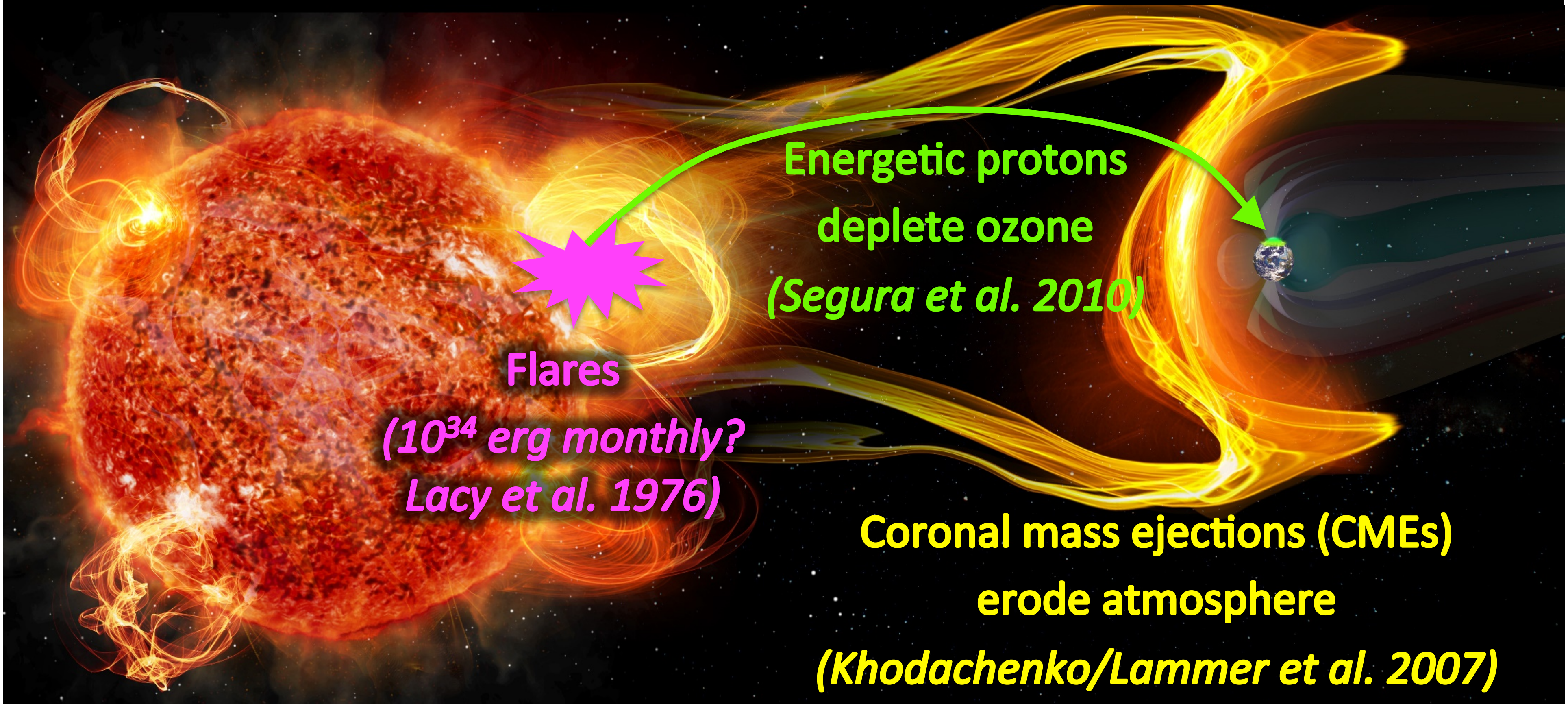
Gyrosynchrotron from energetic electrons in closed magnetic field

Plasma or cyclotron maser from coronal shock fronts, magnetic reconnection sites, aurorae

Dynamic spectroscopy of radio bursts – why and how



Dressing & Charbonneau 2013: nearest transiting habitable-zone Earth-size planet around M dwarf is within 10 pc



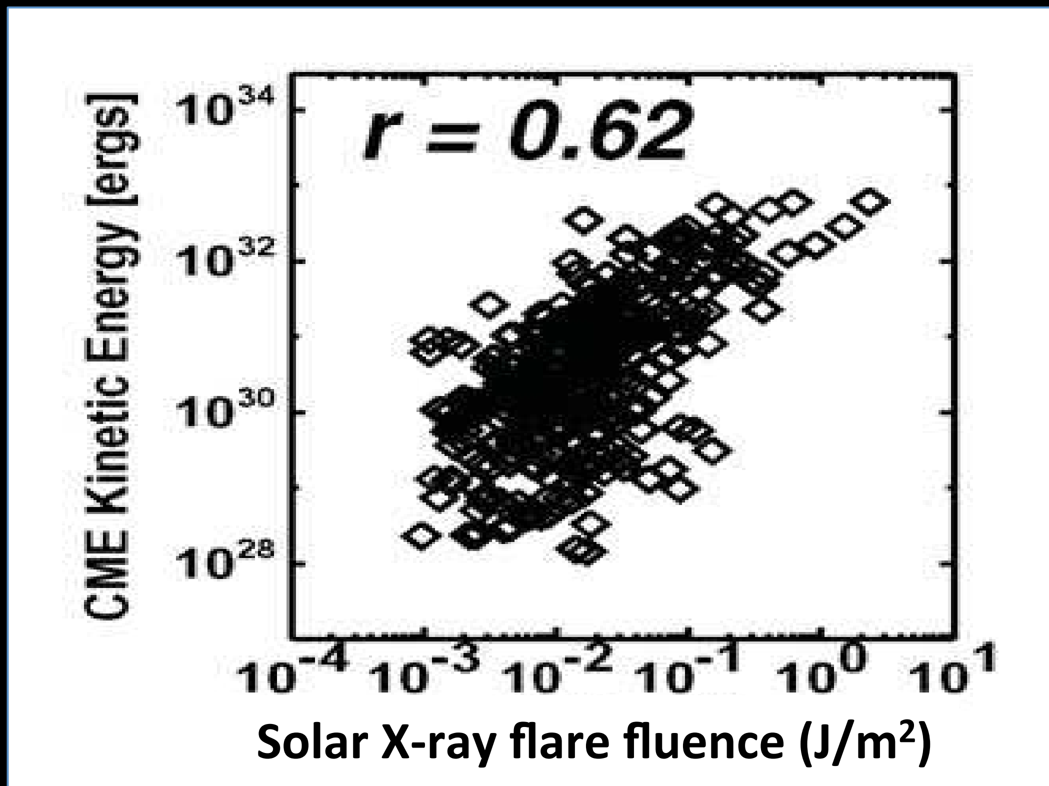
These planets have likely evolved under conditions of strong stellar magnetic activity (e.g., West et al. 2008: M dwarf activity lifetime ~ Gyr)

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

CMEs and proton events have not been observed on other stars.

Drake et al. 2014, Osten & Wolk 2015 – predict stellar CME mass loss rate
Segura et al. 2010 – predict proton flux from large AD Leo flare

Lack of observational data → must extrapolate properties of solar flares



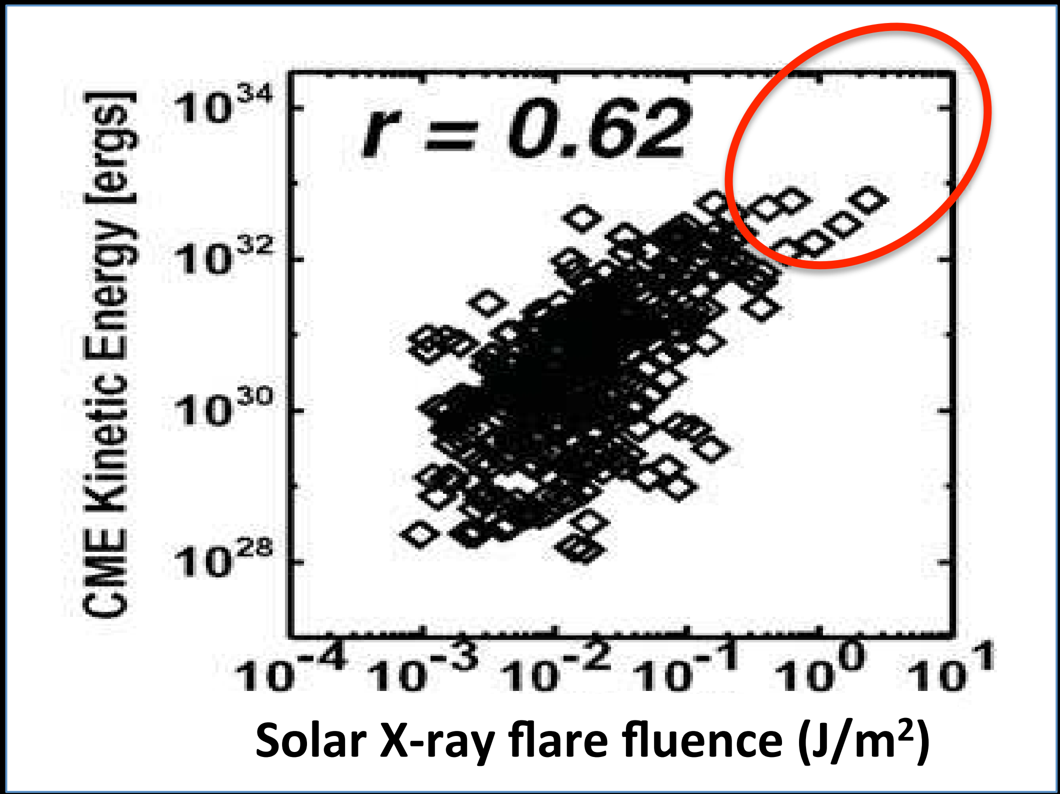
Yashiro & Gopalswamy 2009

Can we extrapolate flare properties from Sun to active stars?

Do solar flare-CME relationships hold for high-energy stellar flares?

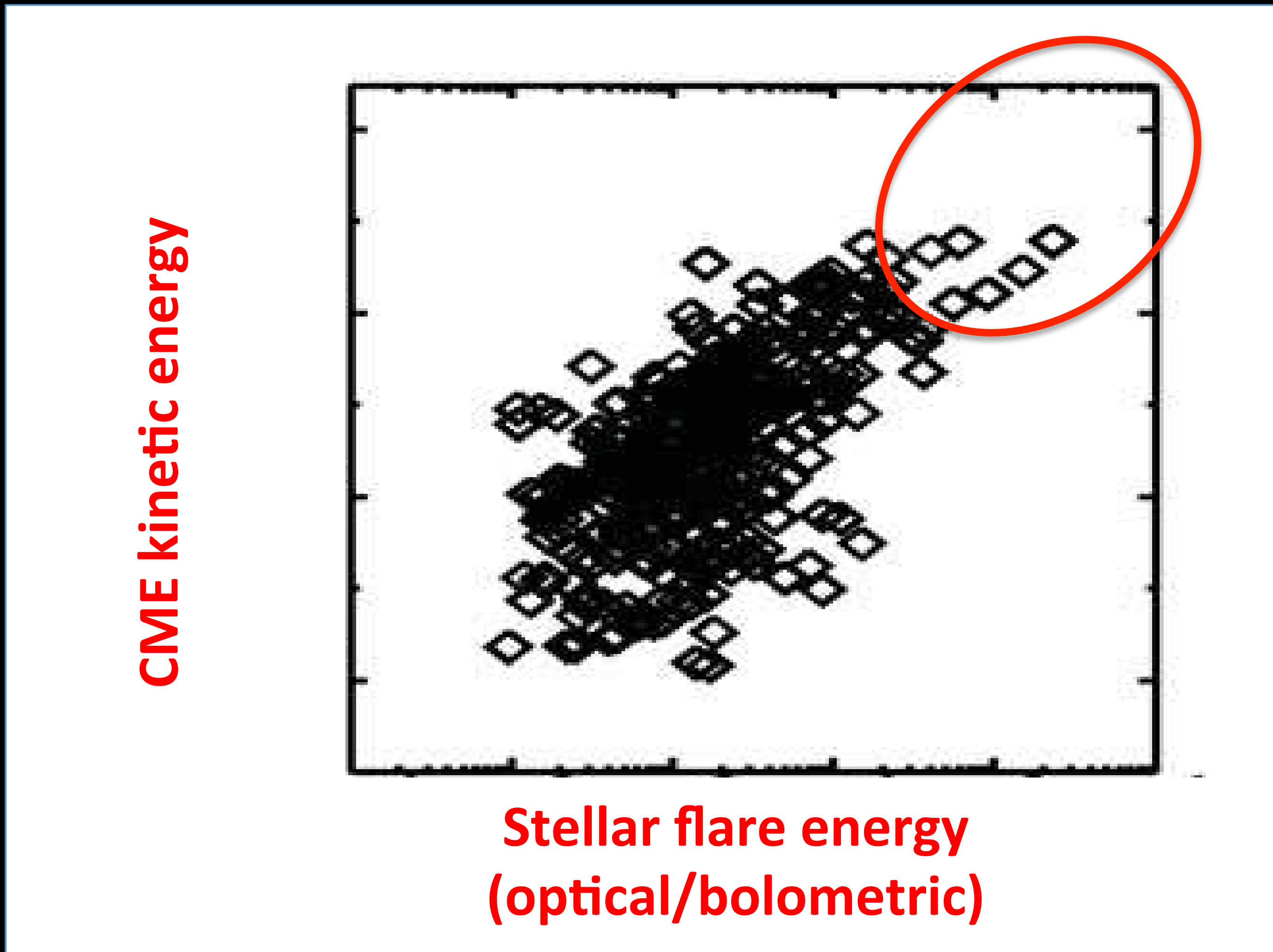
Do the strong large-scale magnetic fields of active stars prevent CMEs and escape of energetic particles?

Does the lack of differential rotation imply few/no eruptions? (Jardine talk)



Yashiro & Gopalswamy 2009

Goal: Test Relationship of CMEs and High-Energy Stellar Flares



Visible light: CMEs and protons much fainter than star and planet

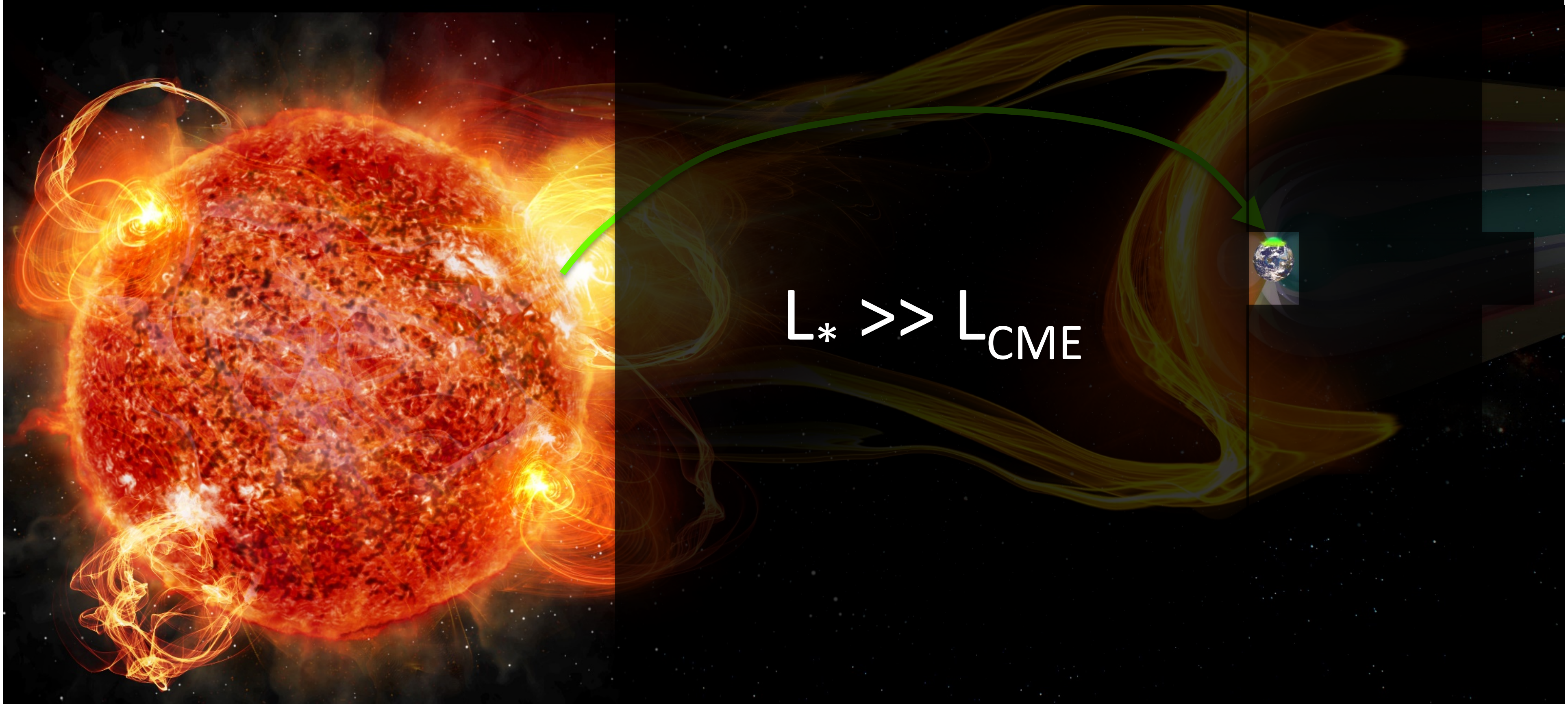


Image credit: Chuck Carter, Gregg Hallinan, and the Keck Institute for Space Studies

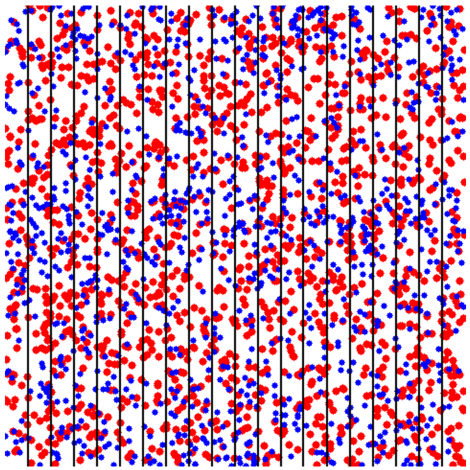
Radio: CMEs and protons linked to radio bursts much brighter than star

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

Diagnostic tool:
Dynamic spectroscopy of
stellar coherent radio bursts

Coherent: instability causes wave growth
allowing $T_b >> T_{eff}$ of exciting electrons

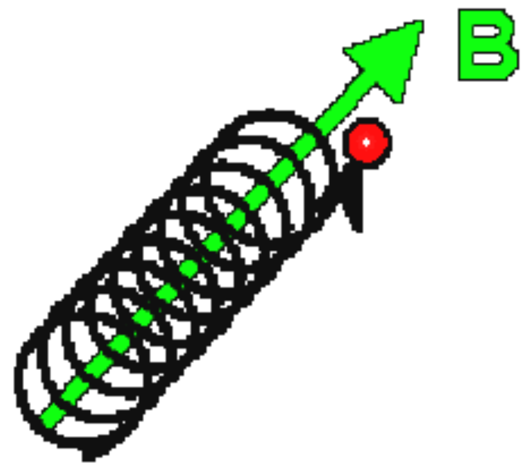
Plasma emission



Andris Vaivads

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

Electron cyclotron maser (ECM) emission

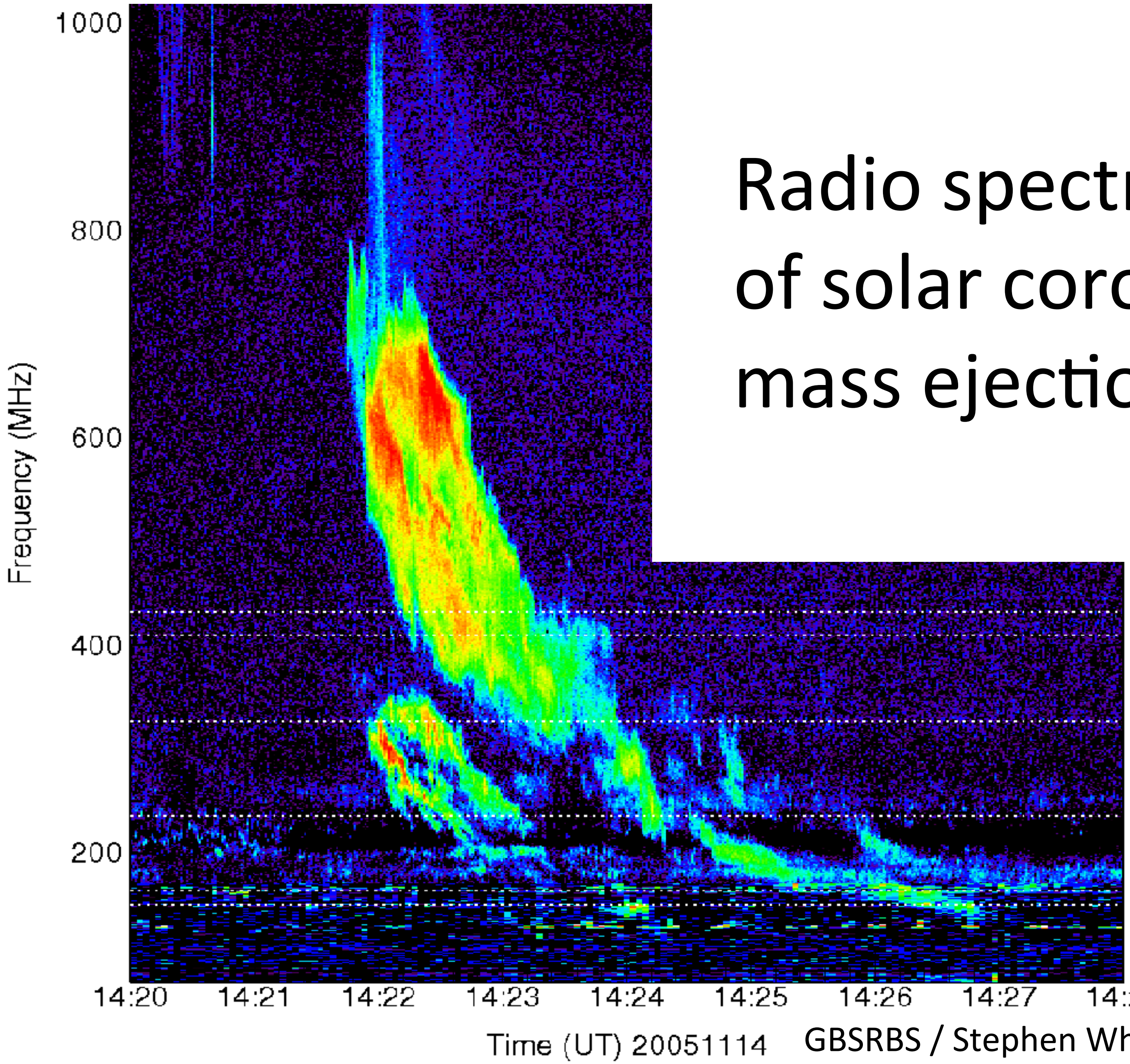


http://tempest.das.ucdavis.edu/pdg/ECE/

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

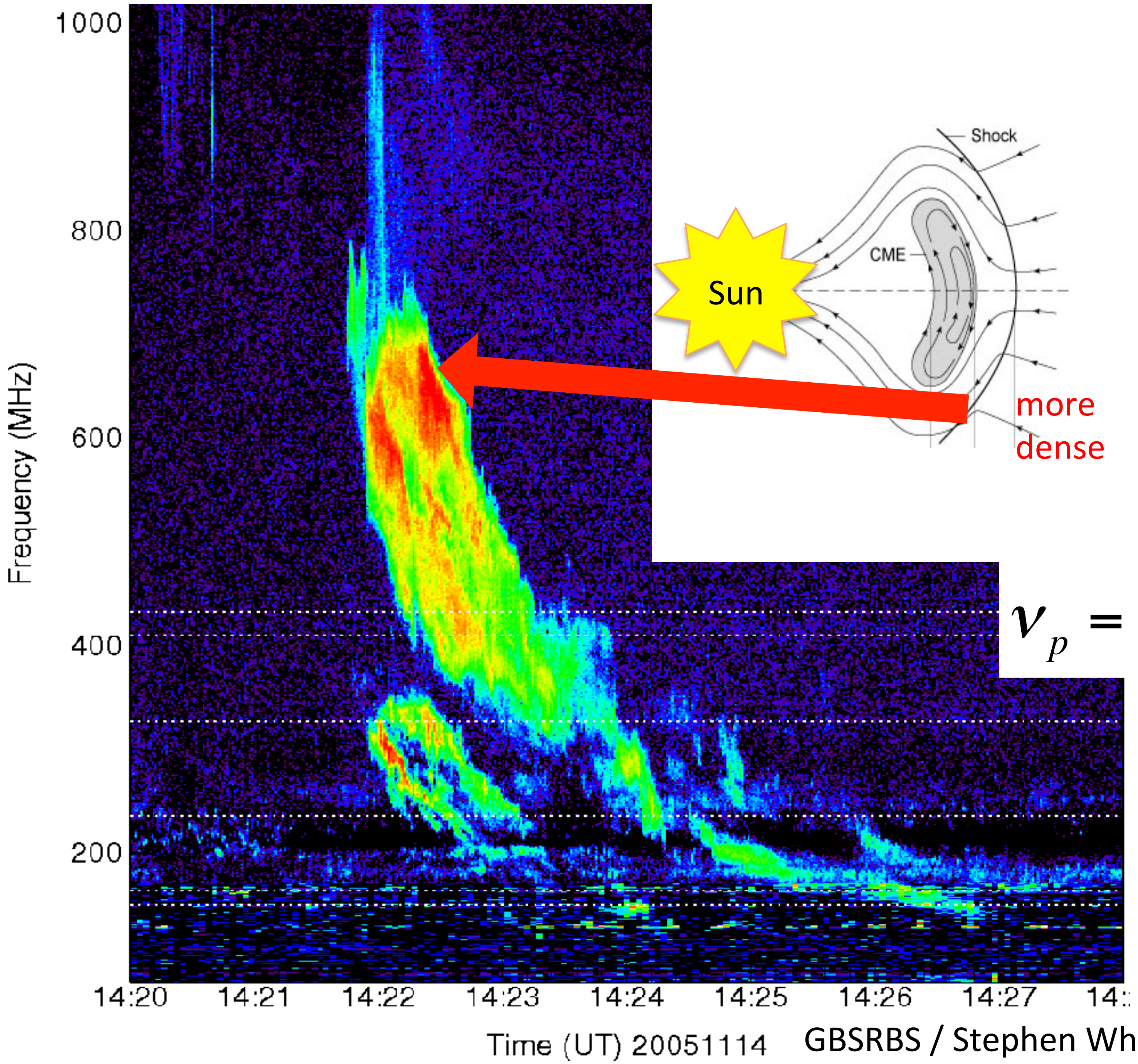
Sources of high-energy electrons: magnetic reconnection, CME shock fronts, electron beams following open field lines (associated with proton events)

Sources of high-energy electrons: magnetic reconnection, Jupiter's plasma torus, magnetic interactions w/ satellite – responsible for aurora



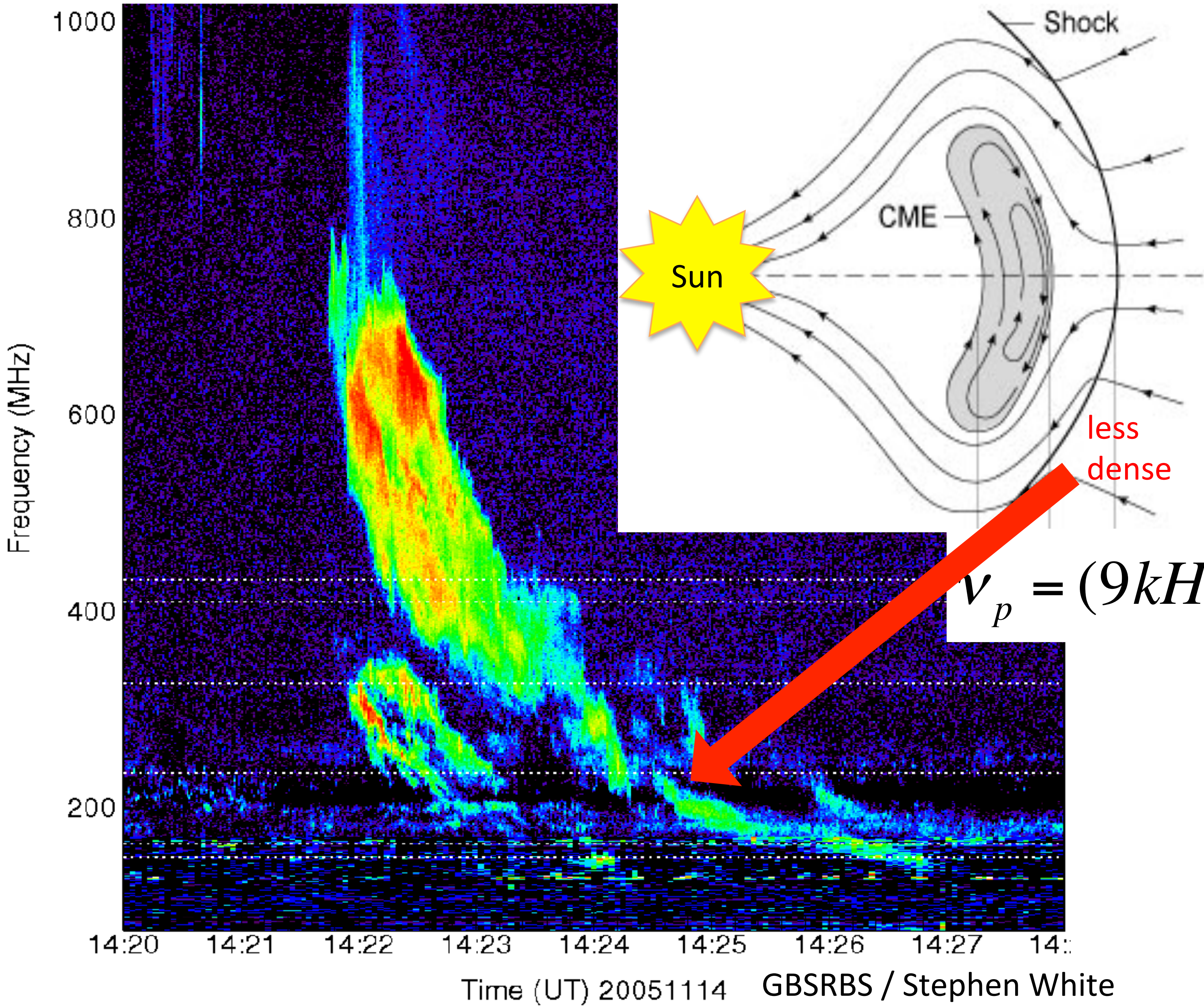
Radio spectrum of solar coronal mass ejection

GBSRBS / Stephen White



$$\nu_p = (9kHz)\sqrt{n_e}$$

GBSRBS / Stephen White



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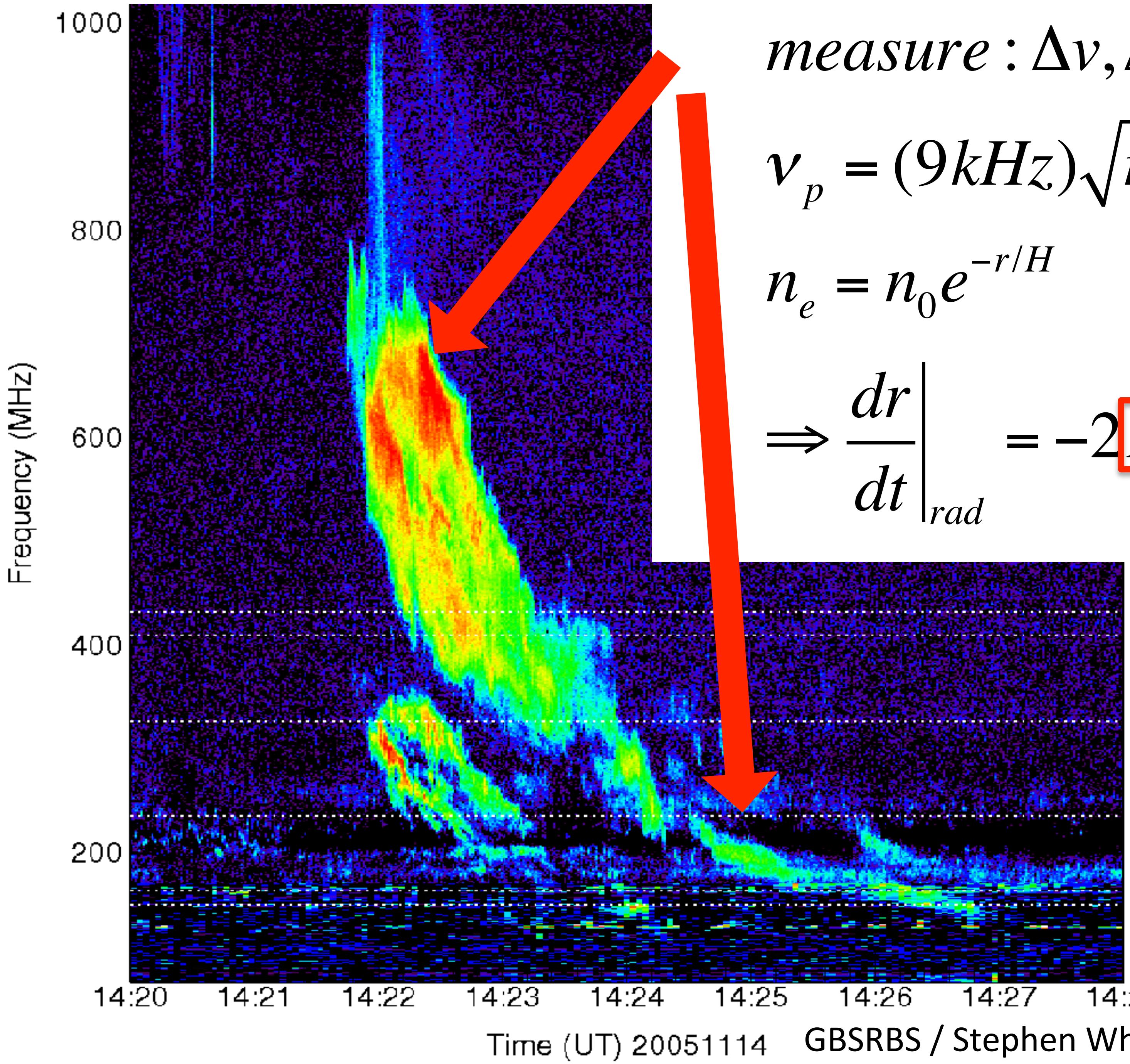
GBSRBS / Stephen White



GBSRBS / Stephen White

$$measure: \Delta\nu, \Delta t, \nu_c$$

$$\nu_p = (9kHz)\sqrt{n_e}$$

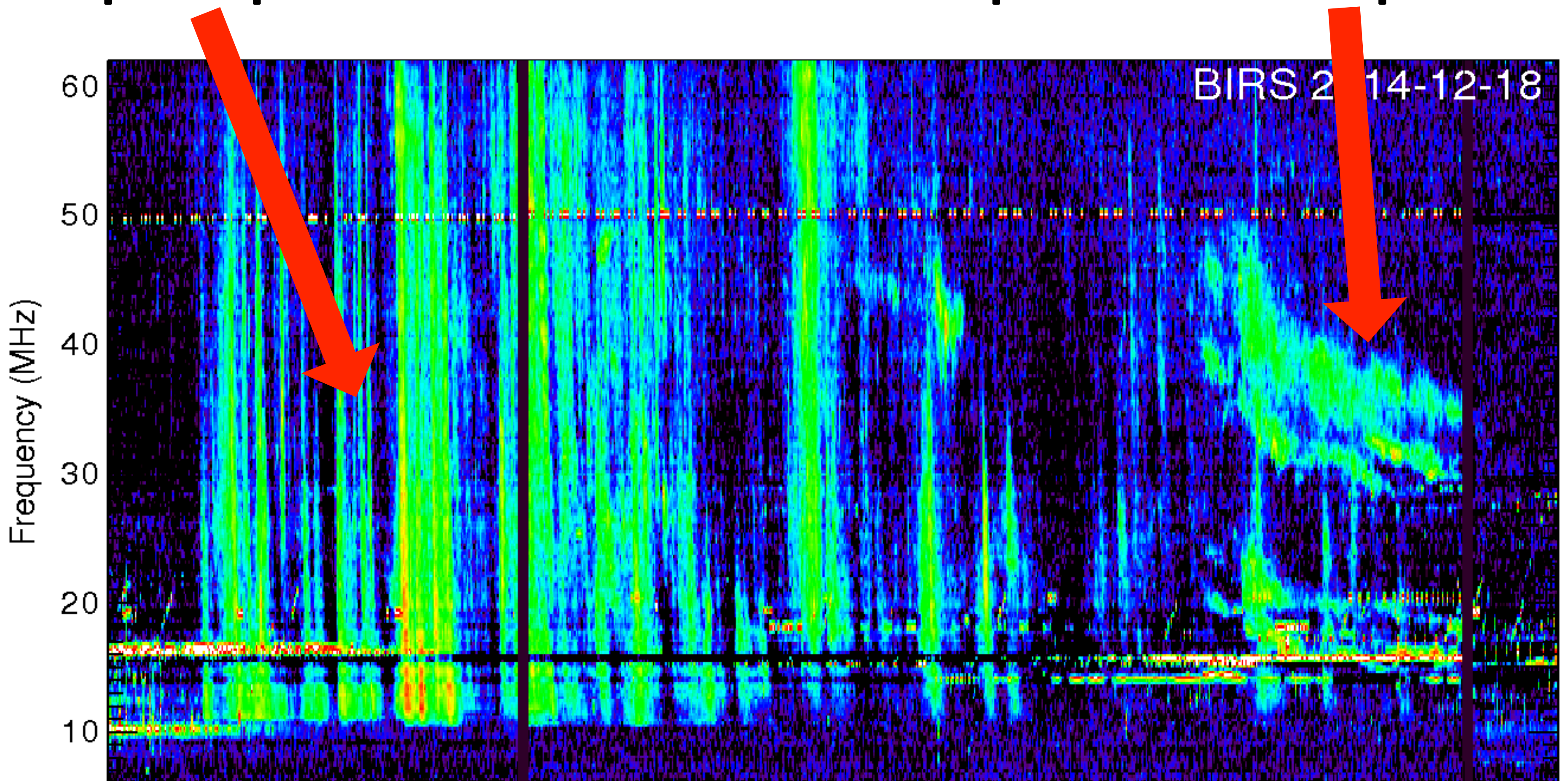
$$n_e = n_0 e^{-r/H}$$

$$\Rightarrow \left.\frac{dr}{dt}\right|_{rad} = -2H\left(\frac{\Delta\nu / \Delta t}{\nu_c}\right)$$

Need to know plasma density scale height to measure speed

v ~ 100,000 km/s
→ predicts proton event
deplete planet's ozone

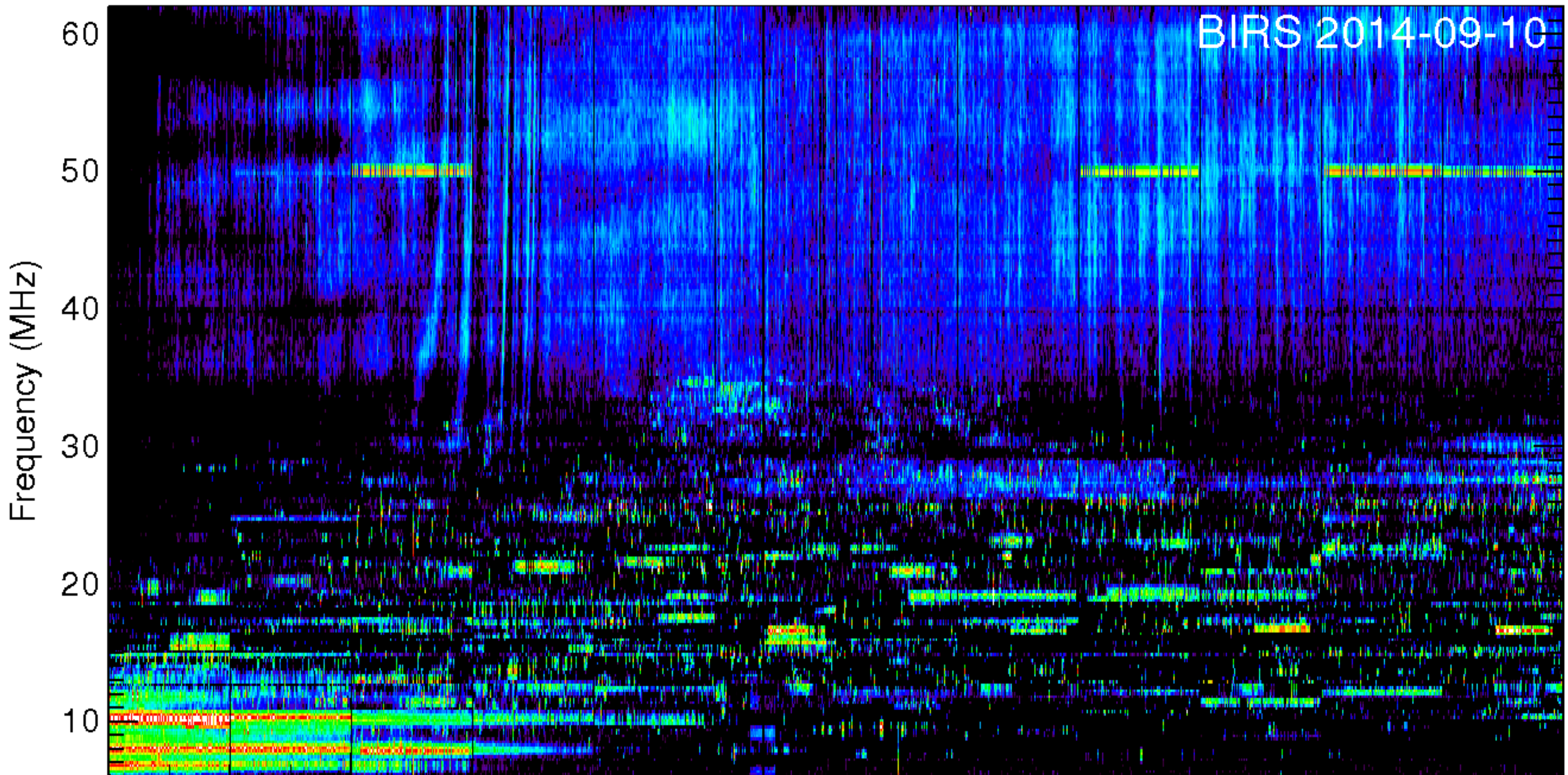
v ~ 1,000 km/s (>Alfven speed)
→ CME shock front
erode planet's atmosphere



Combine these two types to forecast proton events (Winter & Ledbetter 2015)

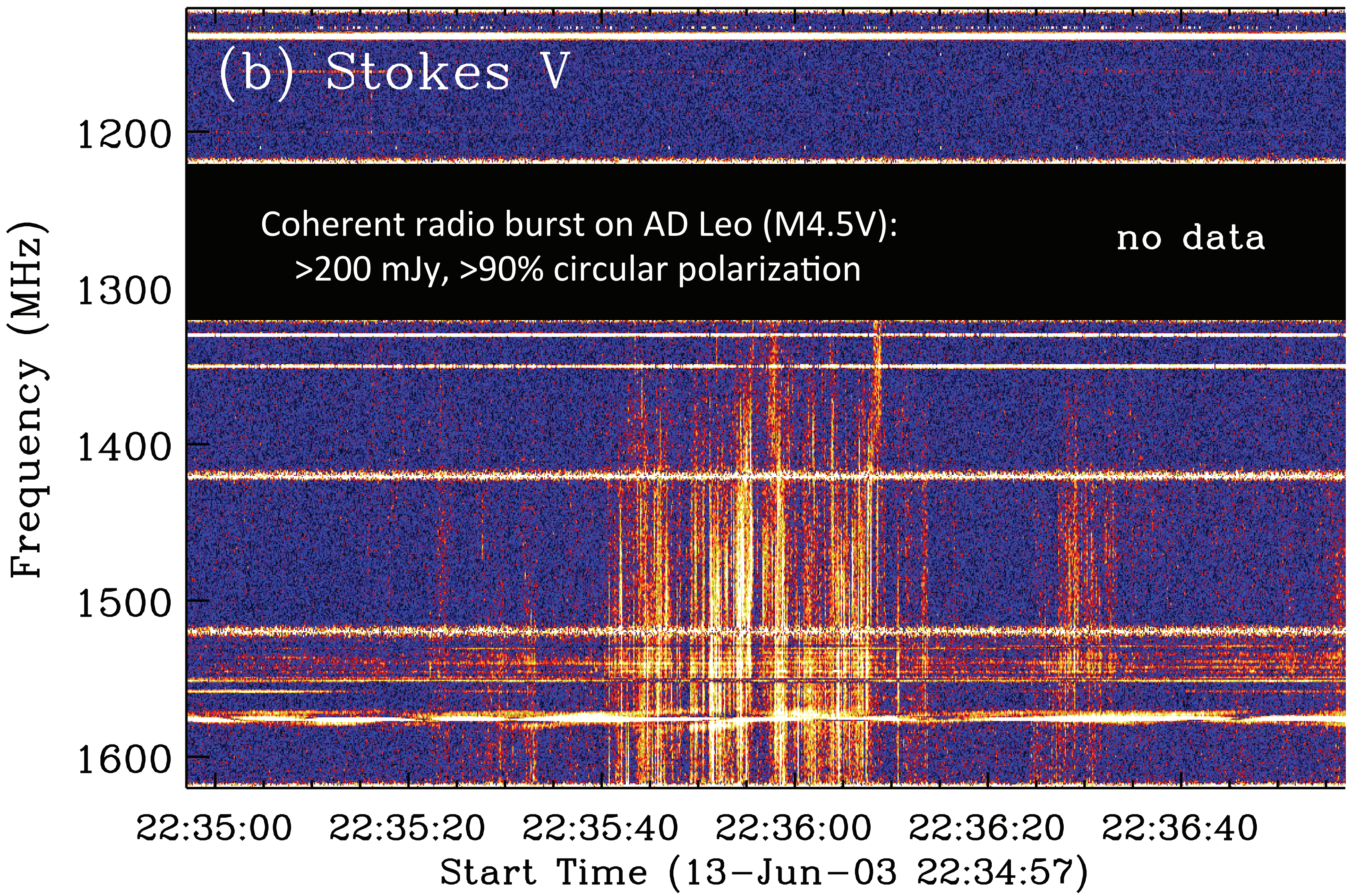
GBSRBS / Stephen White

Caution: there are many complex types of solar radio bursts – identify source type based on frequency sweep rate, overall spectral morphology, polarization, imaging, multiwavelength data



GBSRBS / Stephen White

Active M dwarfs make good targets:
They are known sources of bright coherent radio bursts



Osten & Bastian 2006

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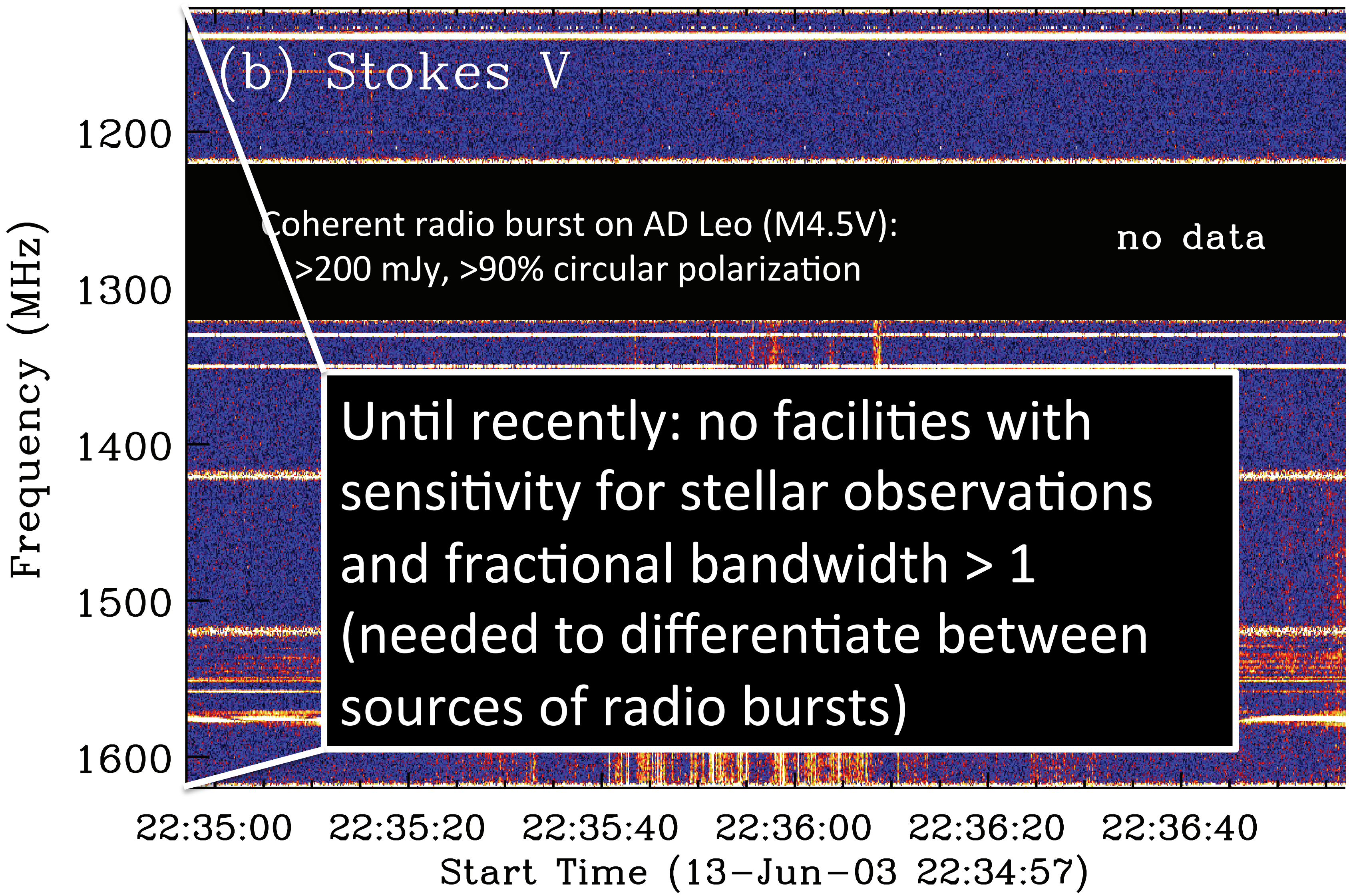
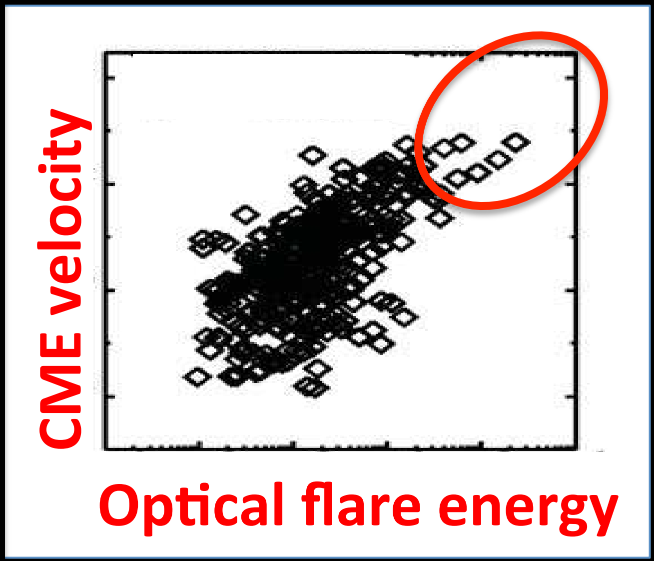


Osten & Bastian 2006

What are the requirements for detecting stellar CMEs?

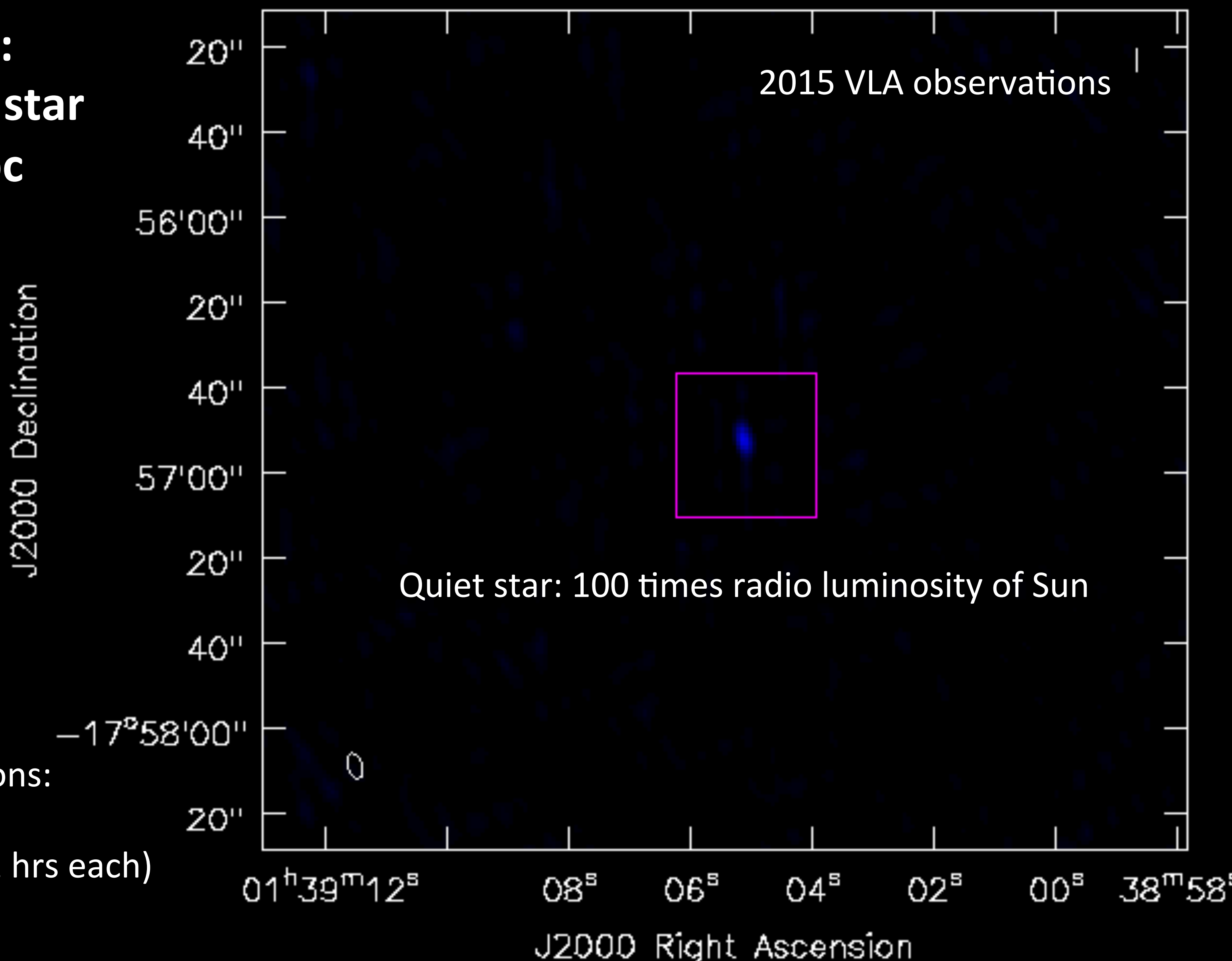


Wide fractional bandwidth
($f_{max}/f_{min} > 1$)

Sensitive
(Cooled receivers,
large telescopes)

Lots of observing time
(Dedicated facility – AD Leo
10^{34} erg flare ~ 1/month?)
e.g. Lacy et al. 1976

UV Cet: M6V flare star at 2.6 pc

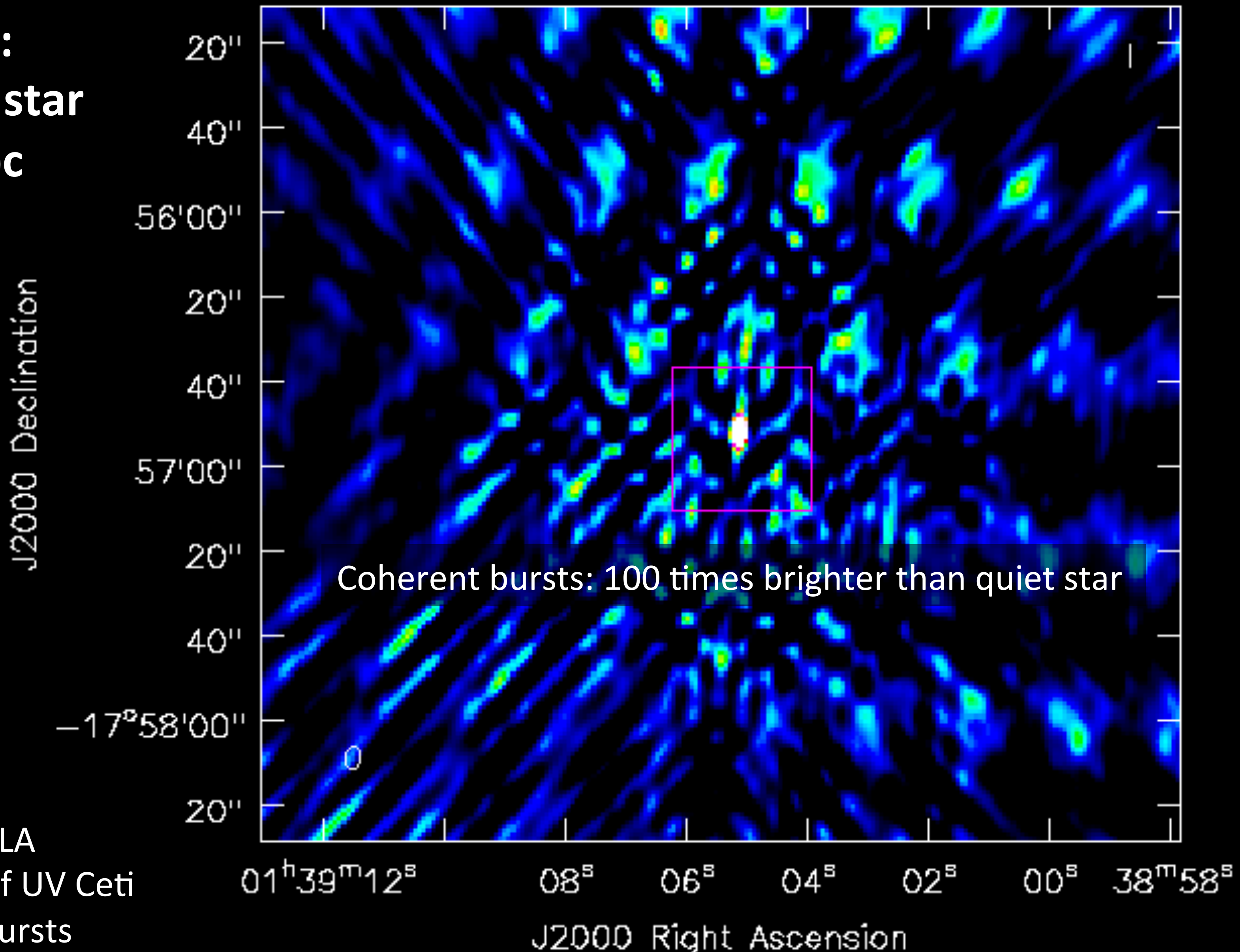


2015 observations:

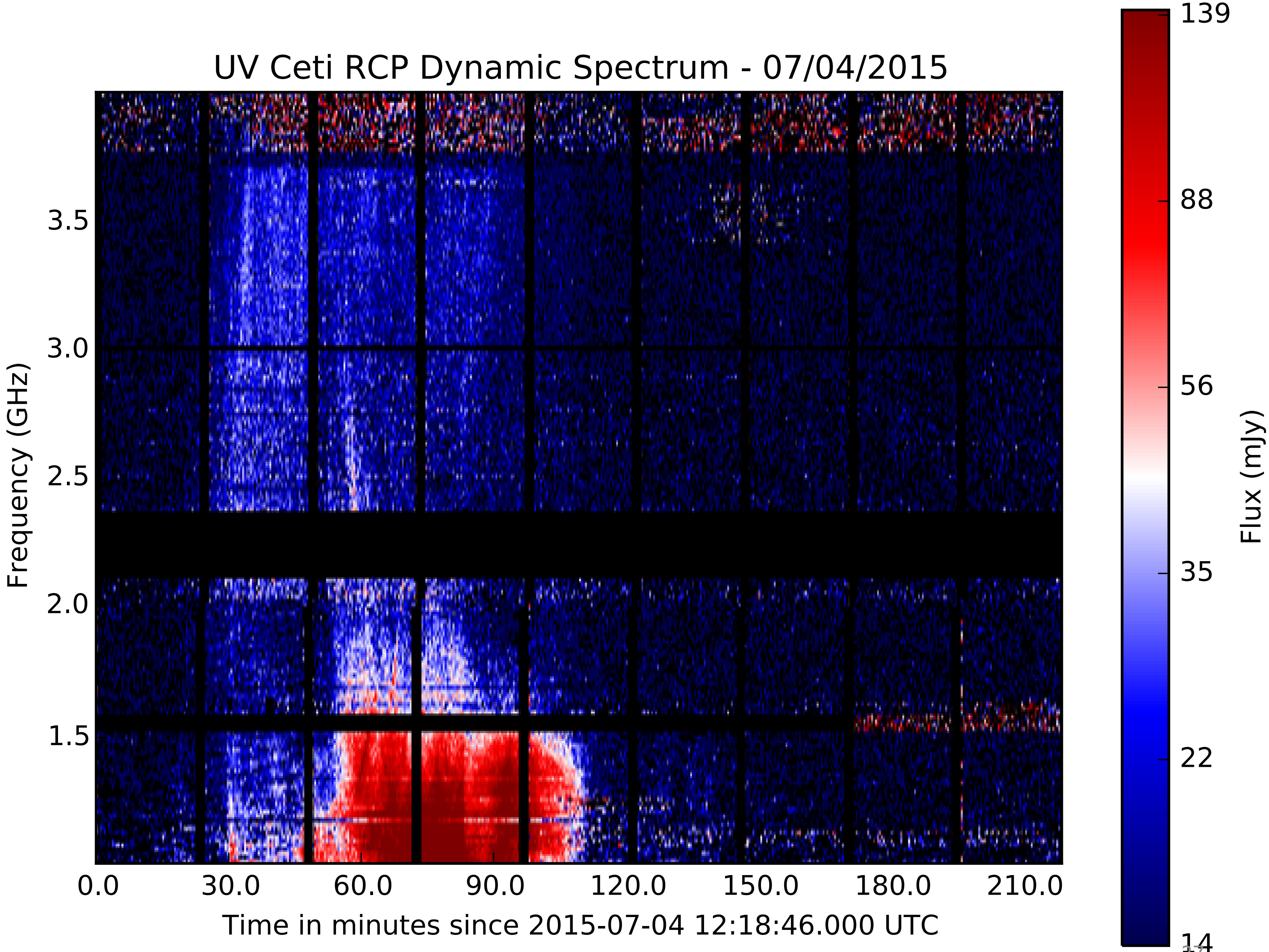
VLA + VLBA: (12 hrs each)
UV Cet, AD Leo

VLA only: (4 hrs each)
YZ CMi, EQ Peg, EV Lac

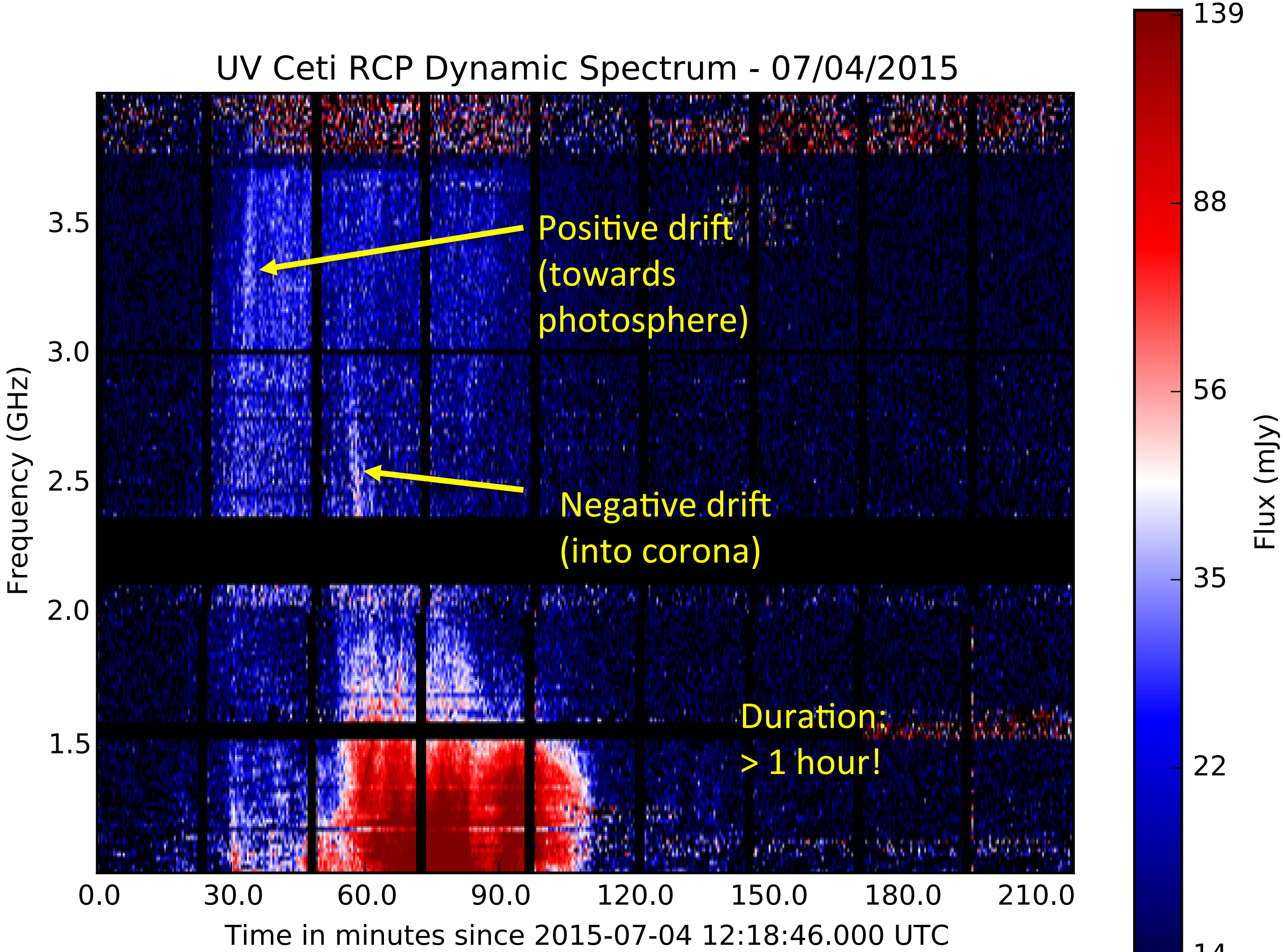
UV Cet: M6V flare star at 2.6 pc



~24 hours of VLA observations of UV Ceti – 7 coherent bursts (Villadsen et al. in prep, includes simultaneous VLBI)



Coherent radio burst also detected at 300 MHz and 8.5 GHz



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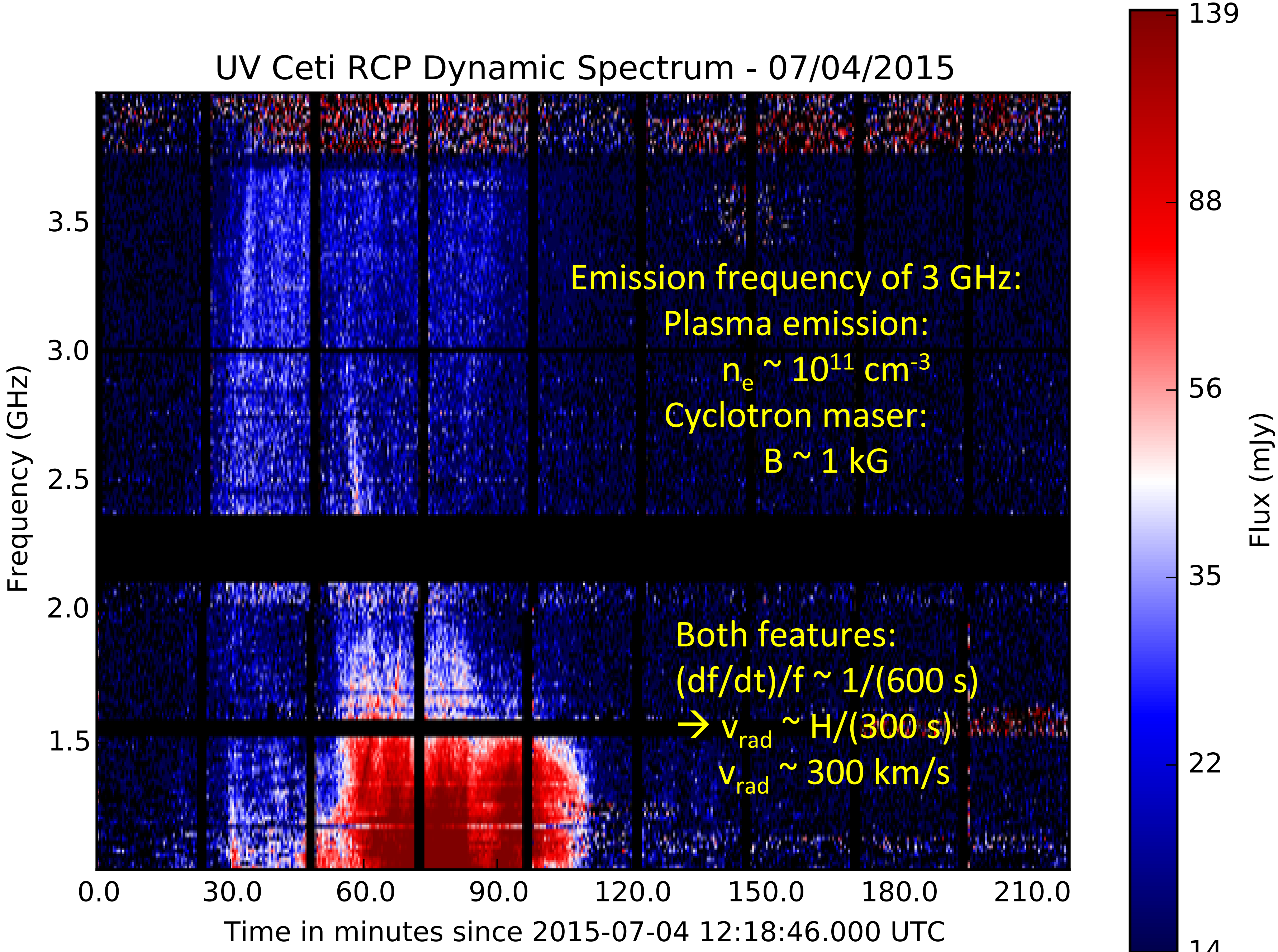

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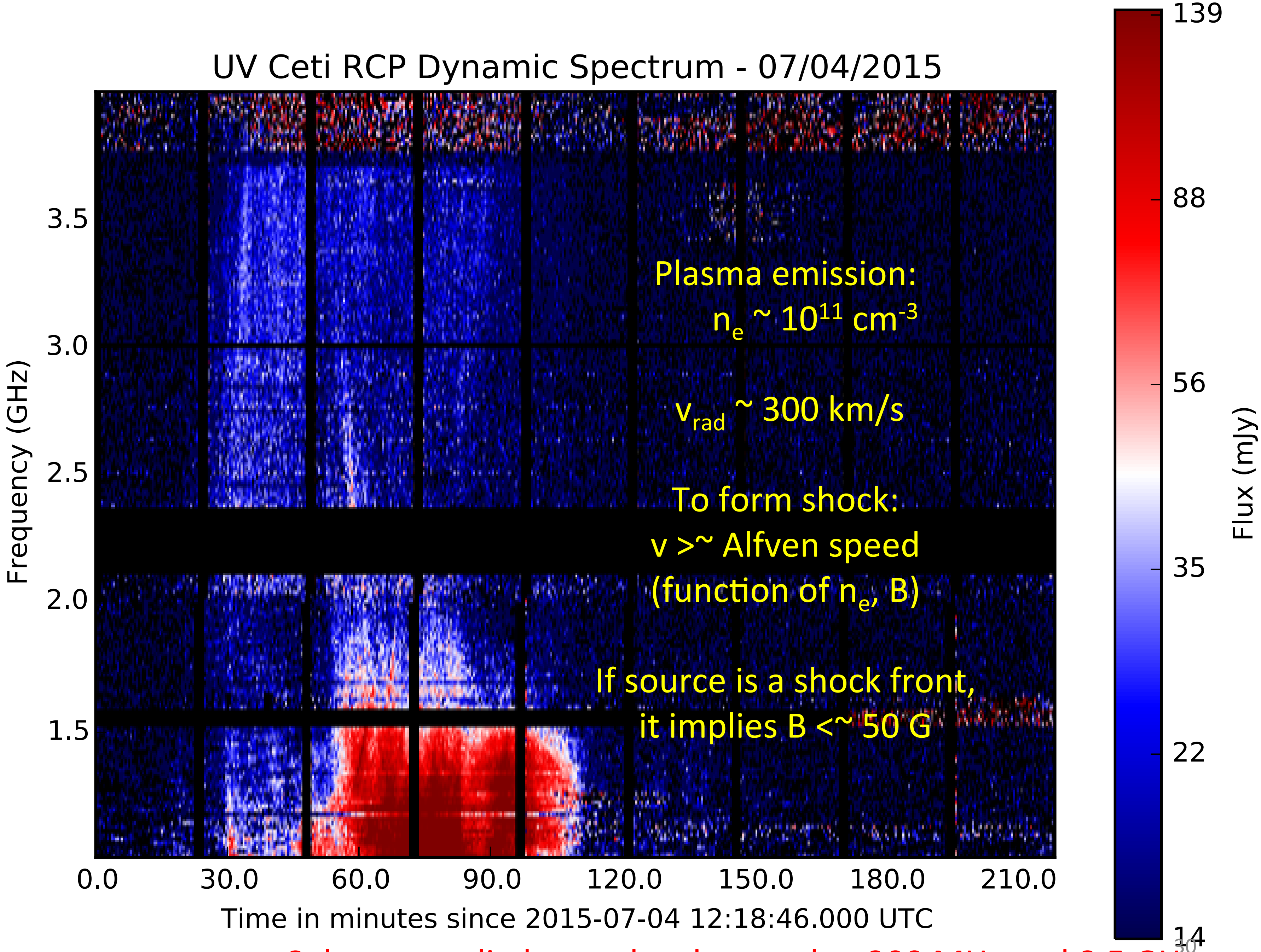
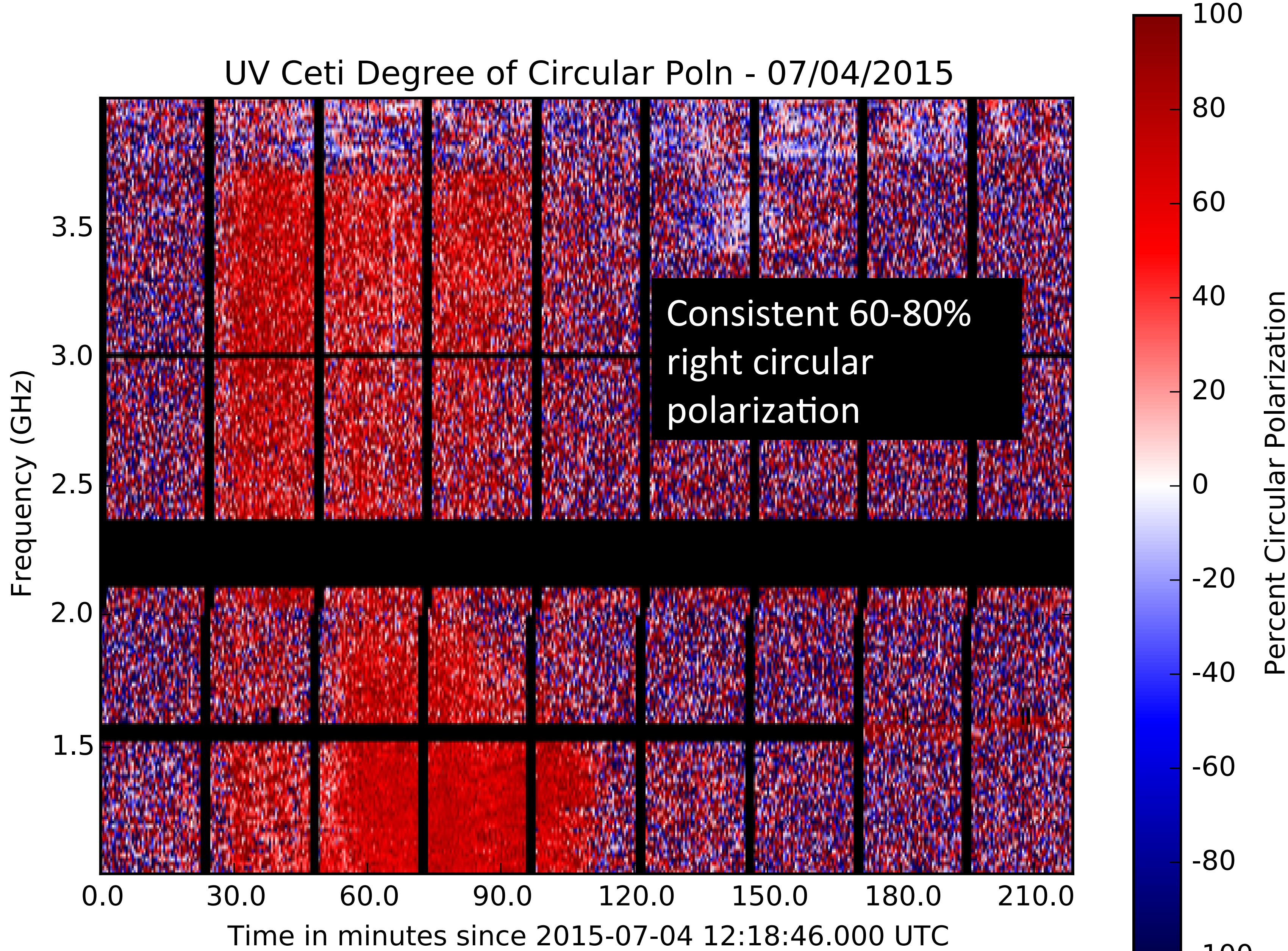


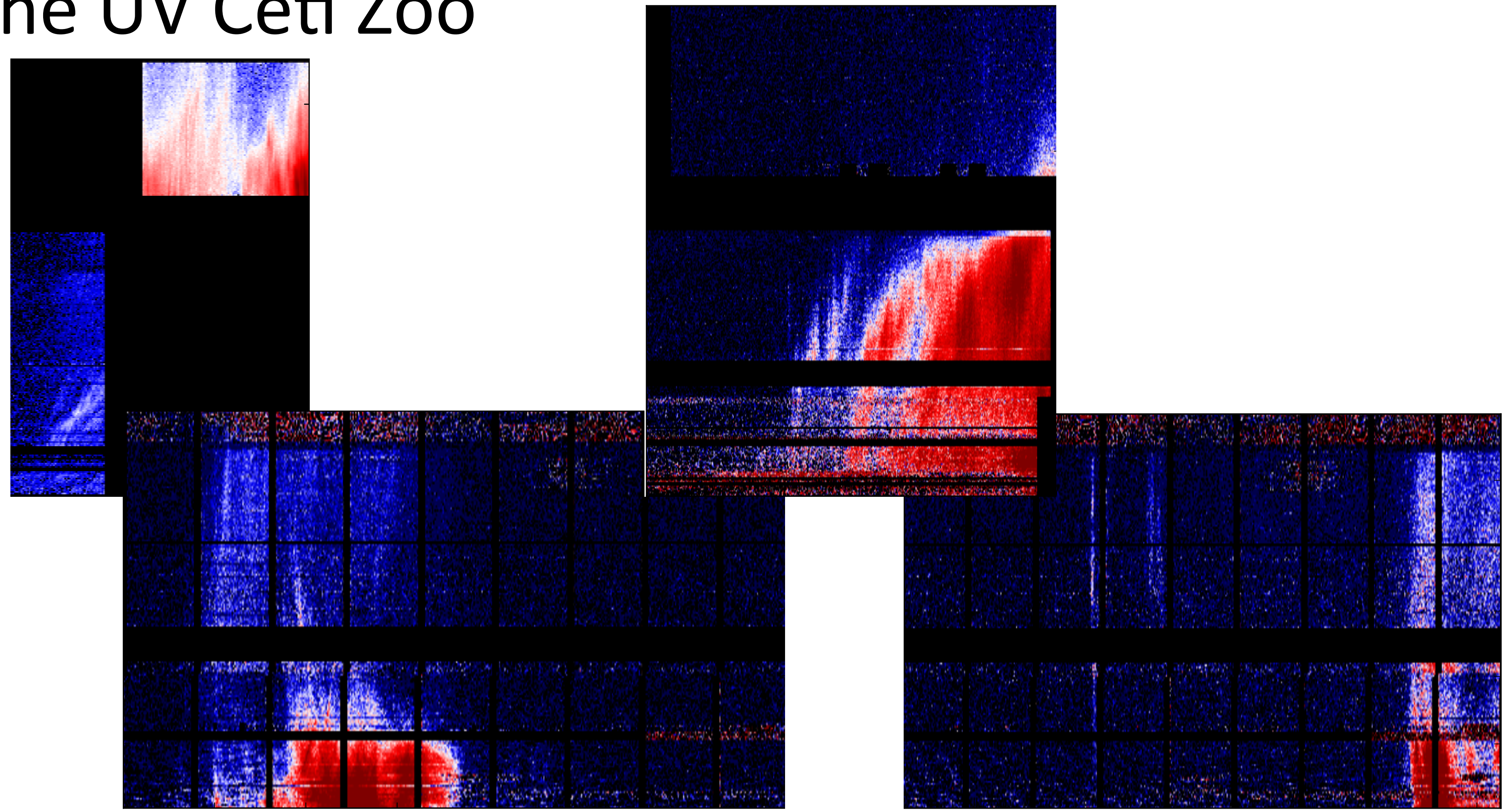
Coherent radio burst also detected at 300 MHz and 8.5 GHz

UV Ceti Radio Burst 3 – July 4, 2015



Villadsen et al., in prep

The UV Ceti Zoo

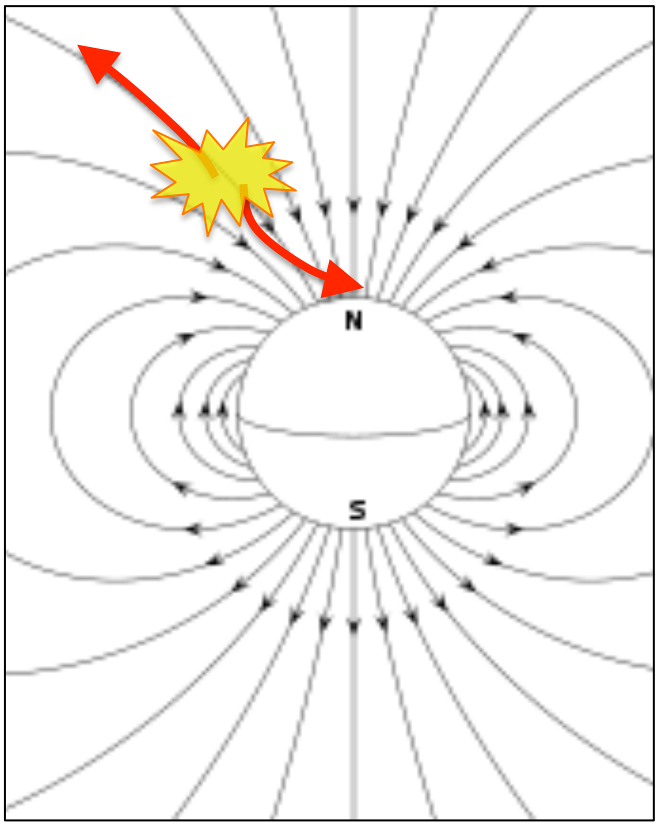


- Short & long-duration coherent bursts – timescales of 2 min to >1 hr
- Observed coherent bursts have varying morphology but all share strong righthand circular polarization (~60-80%), consistent across 4.5 years

  → long-lasting stable magnetic field dominates in source region
- Detected apparent source motion away from star

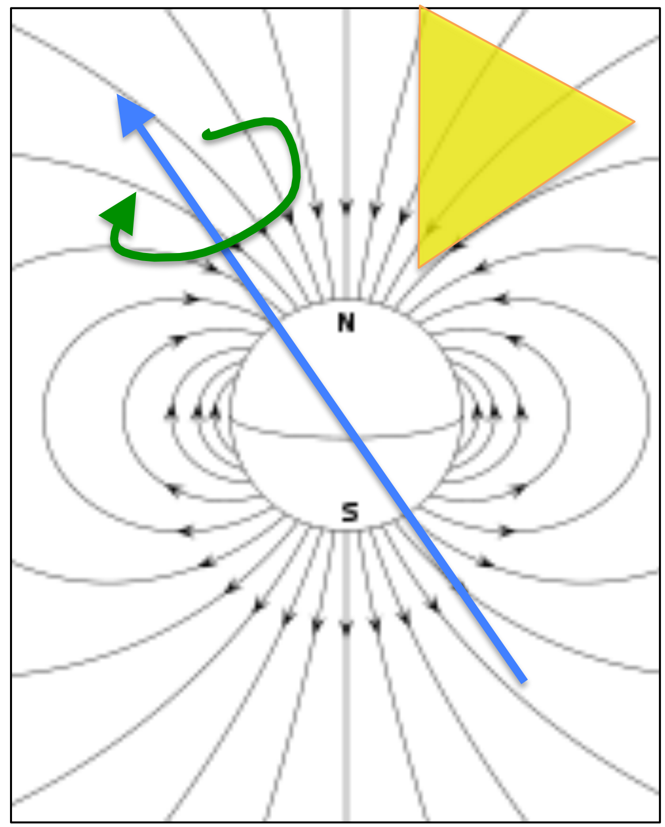
Scenario 1:

Bi-directional source motion



Scenario 2:

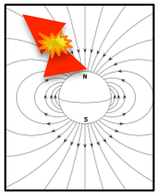
Rotationally-modulated auroral emission (like Jupiter)



Is velocity fast enough to form shock?

Useful to have models for coronal plasma density & B field

Dipole image: Wikipedia



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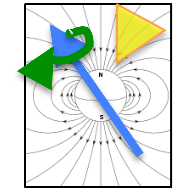


Scenario 2:

Rotationally-modulated auroral emission (like Jupiter)

Learned from radio burst:

Emission frequency → plasma density

$$f\ (\mathrm{GHz}) = (n_e/10^{10})^{1/2}$$

Condition to form shock: $v > v_{Alfven}$
Implies max value for B at shock front

Detected burst:
$n_e \sim 10^{11}\ \mathrm{cm}^{-3}$, B < 50 G at source
(depends on density scale height!)

Emission frequency → magnetic field strength

$$f = (3\ \mathrm{GHz}) * B\ (\mathrm{kG})$$

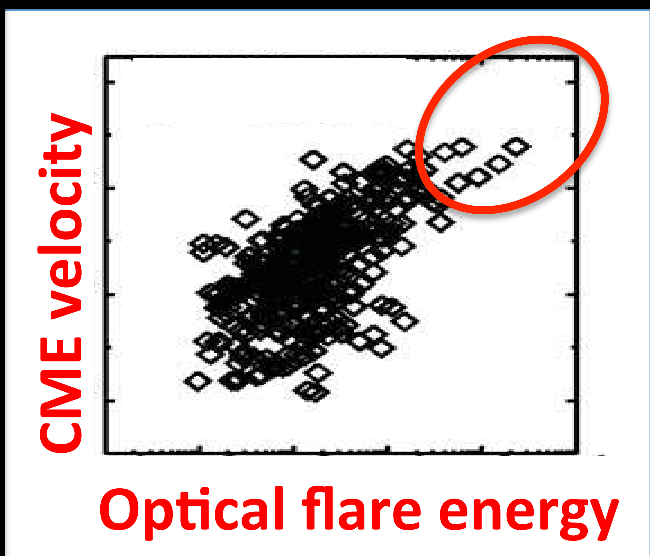
Detected burst: f ~ 300 MHz – 8.5 GHz →
B ~ 100 G – 3 kG at source

Would like to know:

Ideal world: 3D models of coronal B field, density for emission frequencies from 20 MHz to 10 GHz (B ~ 7 G – 3 kG, $n_e \sim 3\times10^6 - 3\times10^{11}$)

Most urgent: constraints on plausible B(r) (B vs. height), coronal density scale height and base density (use L_X?)

What are the requirements for detecting stellar CMEs?



Wide fractional bandwidth

($f_{max}/f_{min} > 1$) ✓

Sensitive

(Cooled receivers, large telescopes) ✓

Lots of observing time

(Dedicated facility – AD Leo 10^{34} erg flare ~ 1/month?)

e.g. Lacy et al. 1976

Starburst Program

- 1-6 GHz dynamic spectrum of flare stars
- Dedicated facility: observe >20 hrs/day
- Currently commissioning first of two 27-m antennas
- Simultaneous optical monitoring

Receivers refurbished by Owens Valley Solar Array

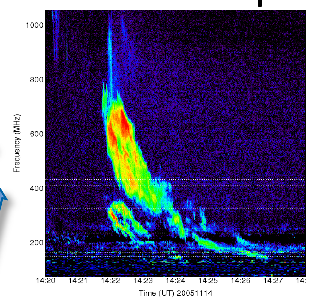
Starburst Collaboration:
Gregg Hallinan (PI), Jackie Villadsen (Project Scientist), Ryan Monroe (Lead Engineer), Stephen Bourke, James Lamb, David Woody, Dale Gary, David Hawkins, Stephen Muchovej, Oliver King, Julien Morin, Mark Hodges

Project funded by the NSF Advanced Technologies and Instrumentation (ATI) program

Starburst: Monitoring Extreme Space Weather Events on Active M Dwarfs

Starburst: 1-6 GHz
(targeted)

Detect stellar CMEs
& measure speed

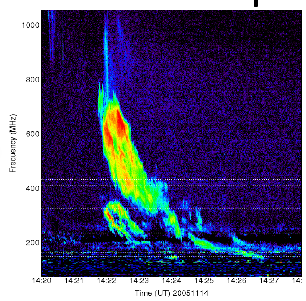


LWA-OVRO: 20-80 MHz
(images whole sky
1x/second)

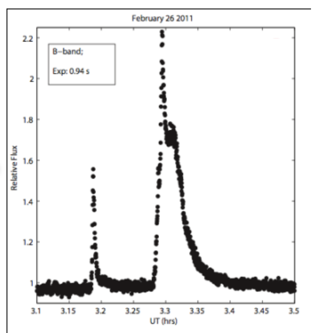
Starburst: Monitoring Extreme Space Weather Events on Active M Dwarfs

Owens Valley Radio Observatory

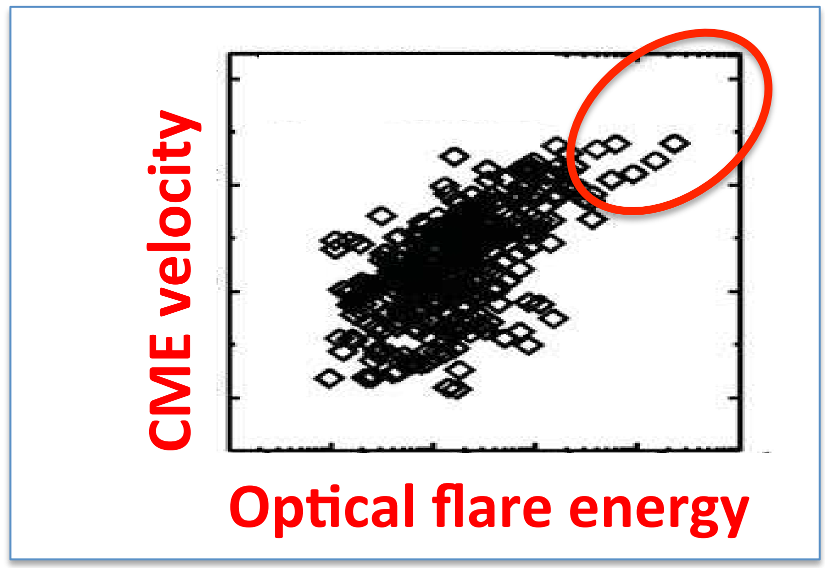
Detect stellar CMEs & measure speed



CSU San Bernardino



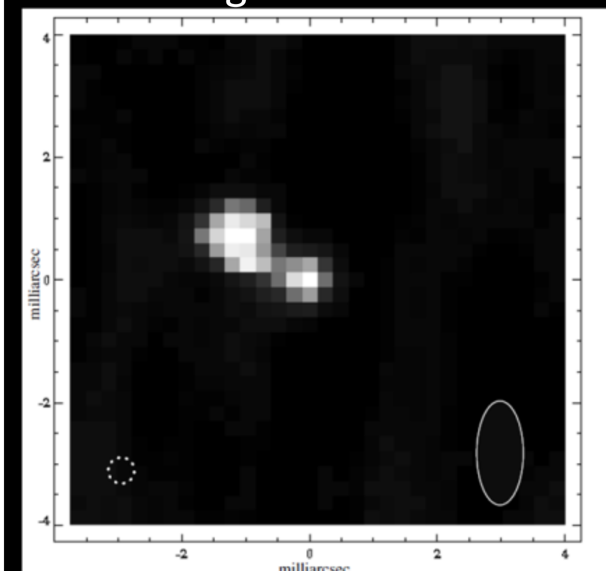
Measure optical flare energy



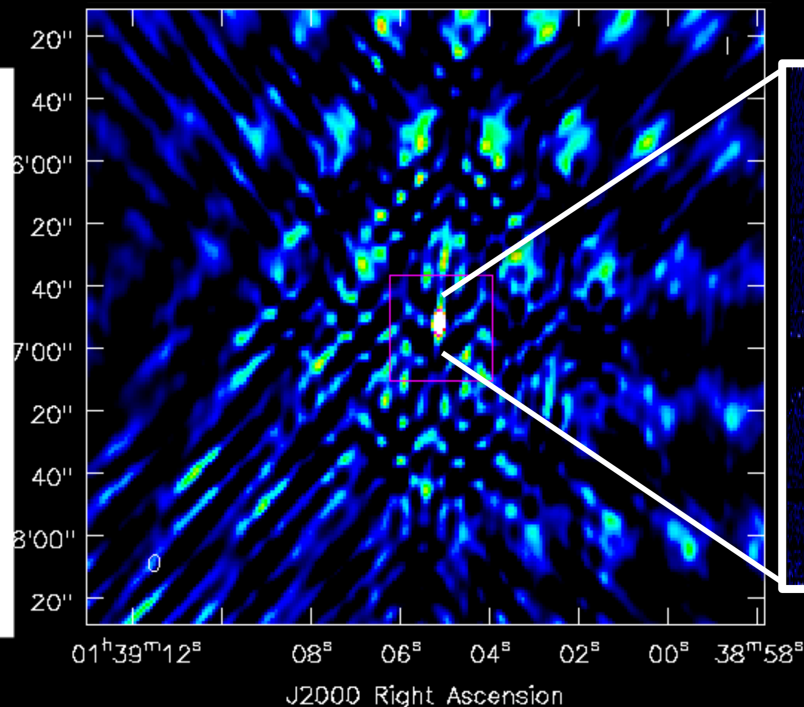
Compare to ZDI models of magnetic field, X-ray measurements of coronal density, & VLBI high-resolution radio imaging of stellar corona

UV Ceti – Radio Emission of a Prototypical Flare Star

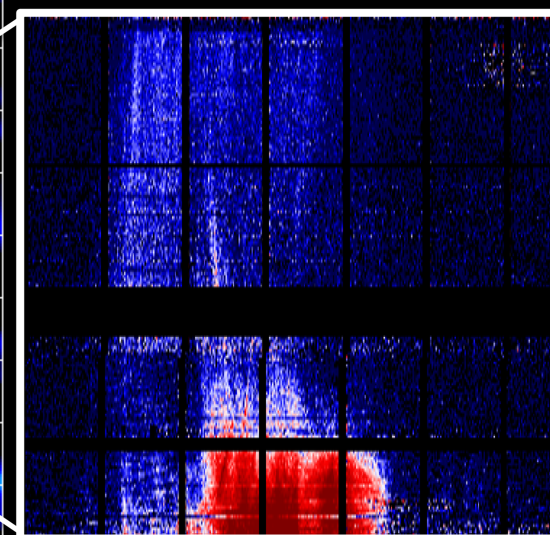
VLBA image of radio corona



Benz et al. 1998



VLA, LWA, Starburst: "spectropolarimetry" of coherent radio bursts



Villadsen et al. in prep

Gyrosynchrotron from energetic electrons in closed magnetic field

Plasma or cyclotron maser from coronal shock fronts, magnetic reconnection sites, aurorae

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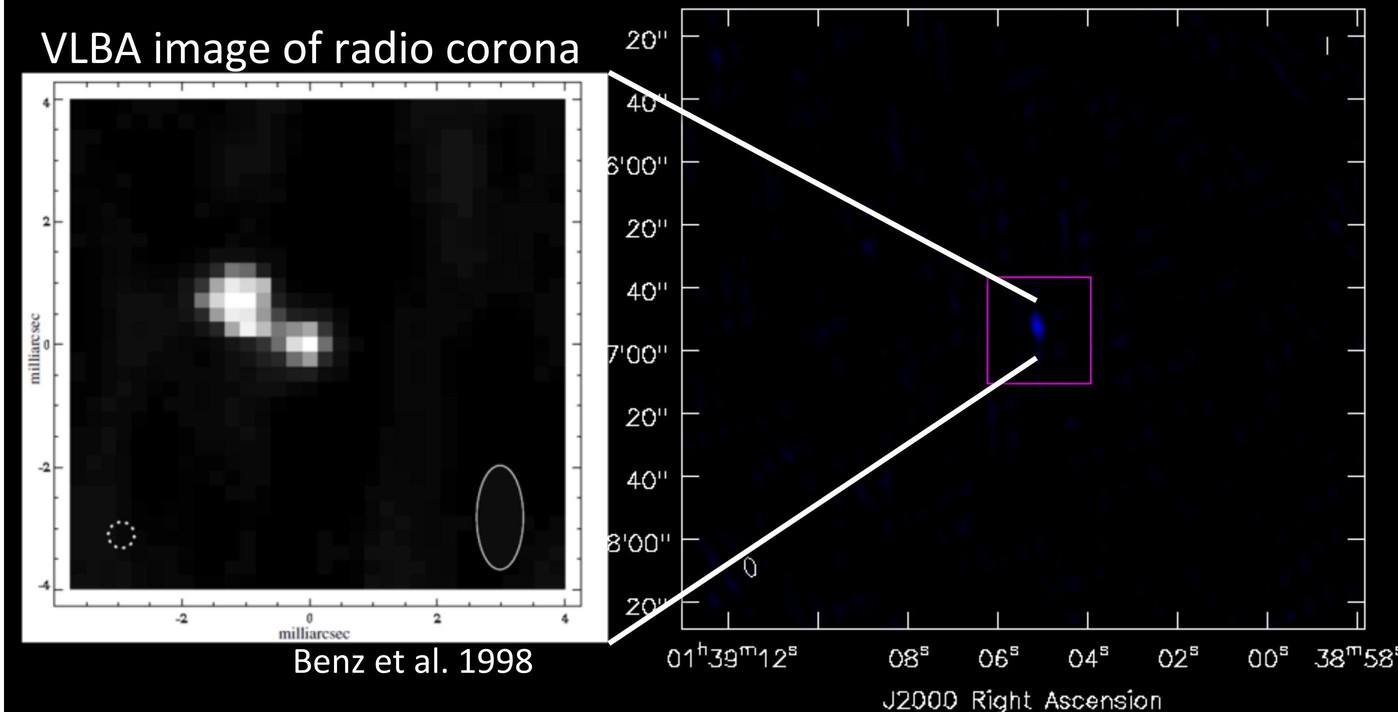
VLBA image of radio corona



Benz et al. 1998

Gyrosynchrotron from energetic electrons in closed magnetic field

Why VLBA?

- Some M dwarf radio coronae have been resolved by VLBI
- Recent VLBA upgrade → big increase in sensitivity
- Triggered VLBA within 15 min demonstrated for GRBs
- Plan: Use Starburst program to trigger VLBA
- So far: simultaneous VLA + VLBA obs, 12 hrs each on UV Cet, AD Leo (reduction underway)

Can radio imaging constrain source surface or stellar wind parameters?

- Some M dwarf radio coronae have been resolved by VLBI → lower limit on closed field size

Single stars

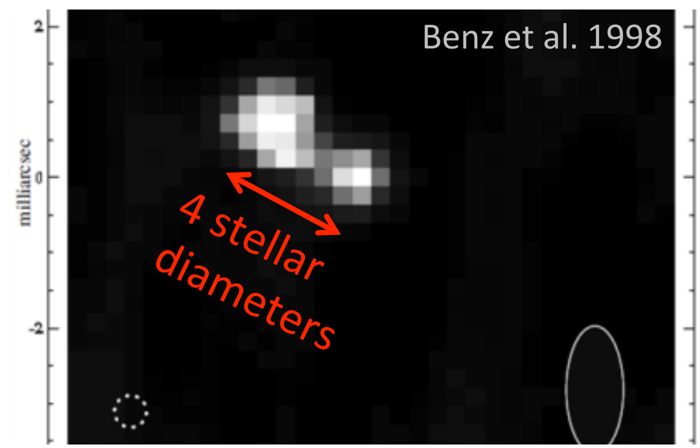
UV Cet (M6V) – (Benz et al. 1998)
two radio lobes separated by 4D$_*$

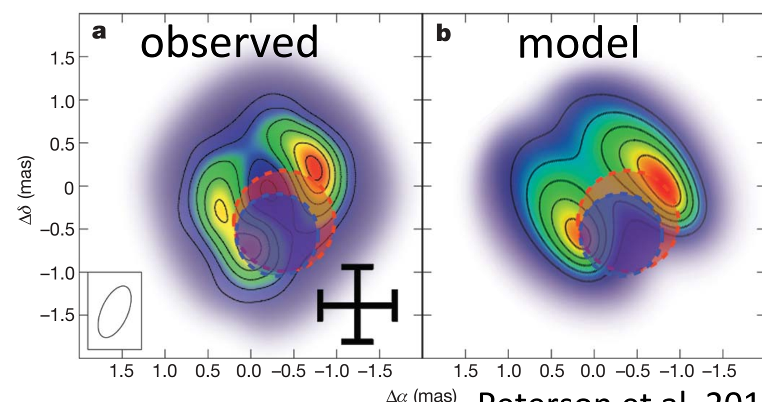
YZ CMi (M4.5V) – (Pestalozzi et al. 2000)
radio corona height ~ 0.7R$_*$ above photosphere

Close binaries

YY Gem (M1V + M1V) – (Alef et al. 1997)
radio source size 2.1D$_*$; no radio eclipse

Algol (B8V + K0IV) – (Peterson et al. 2010)
large radio lobes on K star modeled as closed mag loop on l-shells 2-4 (2-4R$_*$)

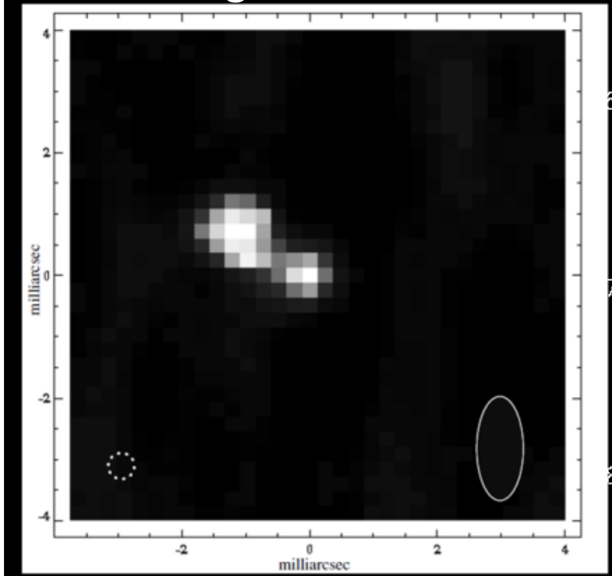




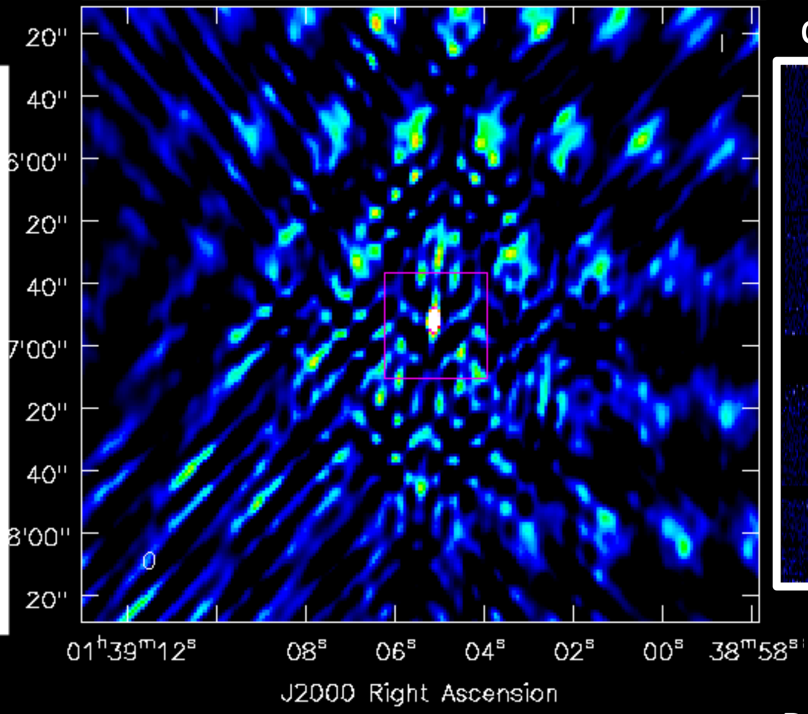
Peterson et al. 2010

UV Ceti – Radio emission determined by stellar magnetic field

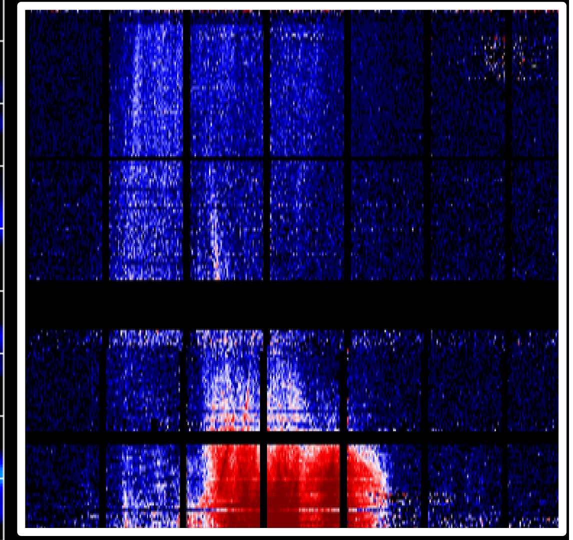
VLBA image of radio corona



Benz et al. 1998



VLA, LWA, Starburst: "spectropolarimetry" of coherent radio bursts



Villadsen et al. in prep

Gyrosynchrotron from energetic electrons in closed magnetic field

Plasma or cyclotron maser from coronal shock fronts, magnetic reconnection sites, aurorae