NJIT New Jersey Institute of Technology

Radio emission from the Sun:
Recent advances at high frequencies

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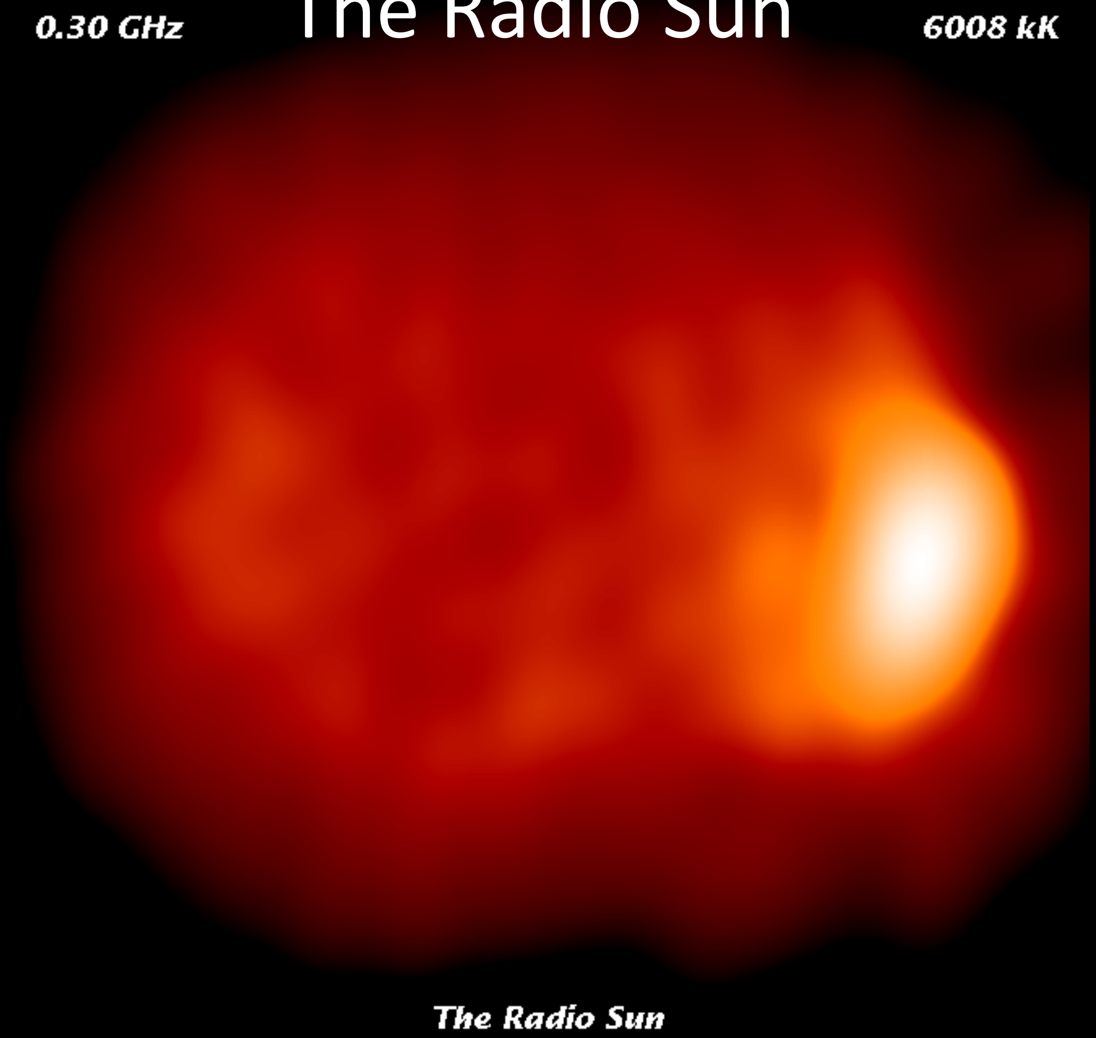
New Jersey Institute of Technology

The Radio Sun

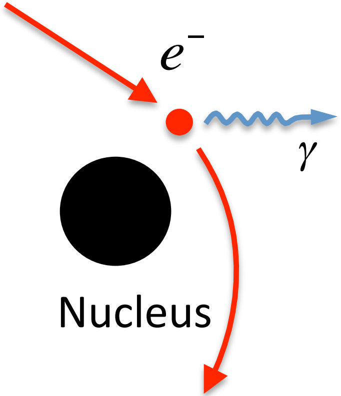


Credit: S. White

Solar Radio Emission

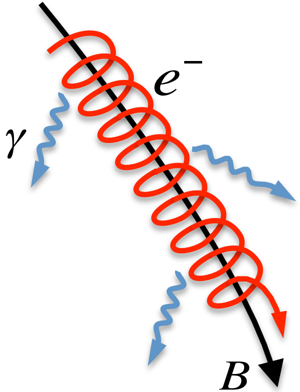
- Produced by different sources via a variety of emission processes
- Provides **rich diagnostics** for both thermal plasma and nonthermal electrons

Bremsstrahlung



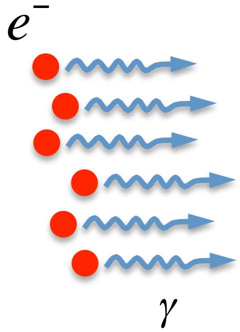
✧ Thermal plasma

Gyromagnetic Radiation

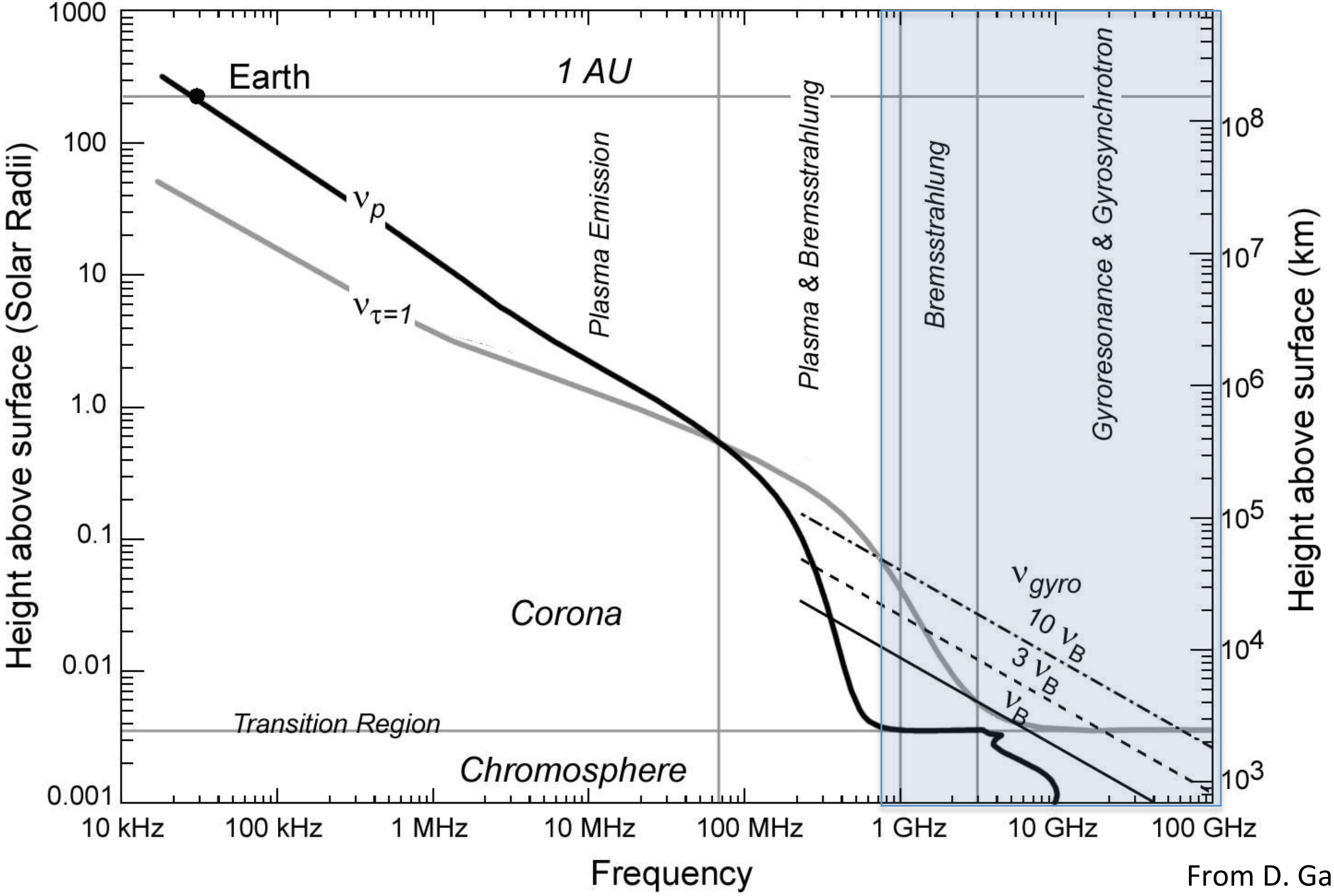


✧ Energetic electrons
✧ Magnetic field
✧ Thermal plasma

Coherent Radiation



✧ Energetic electrons
✧ Background plasma



Height above surface (Solar Radii)
1000
100
10
1.0
0.1
0.01
0.001
Earth
1 AU
ν_p
$\nu_{\tau=1}$
Plasma Emission
Plasma & Bremsstrahlung
Bremsstrahlung
Gyroresonance & Gyrosynchrotron
ν_{gyro}
$10\ \nu_B$
$3\ \nu_B$
ν_B
Corona
Transition Region
Chromosphere
10^8
10^7
10^6
10^5
10^4
10^3
Height above surface (km)
10 kHz
100 kHz
1 MHz
10 MHz
100 MHz
1 GHz
10 GHz
100 GHz
Frequency

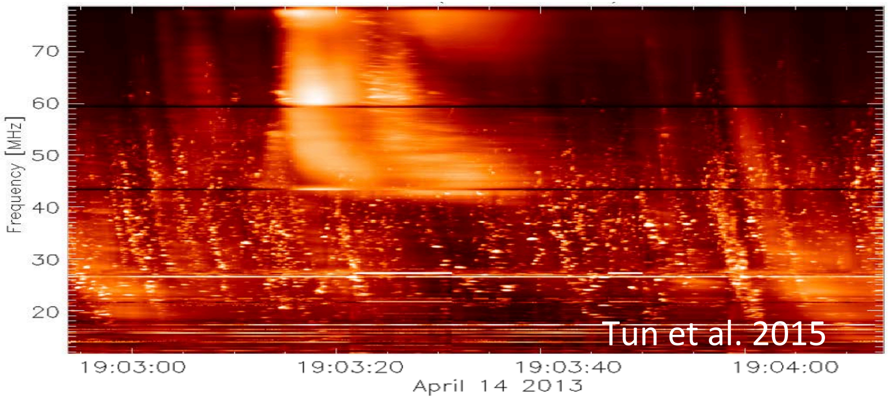
From D. Gary

Solar Radio Observing Techniques: Dynamic Spectroscopy

Antenna

+

FFT Machine



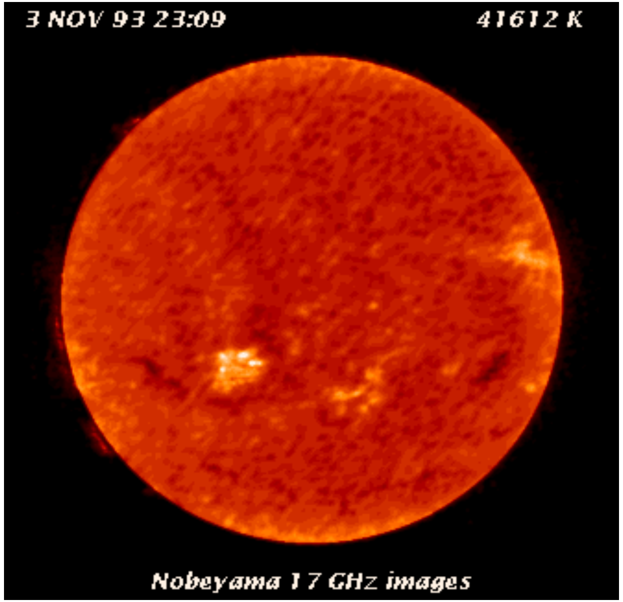
Dynamic Spectrum:

In most cases, our spectral resolution and cadence are not limited by sensitivity, but by the instrumentation capability

Solar Radio Observing Techniques:

Radio Synthesis Imaging

Radio Interferometer



Credit: S. White

When Imaging Meets Dynamic Spectroscopy

2012 Mar 10 M8.4 flare

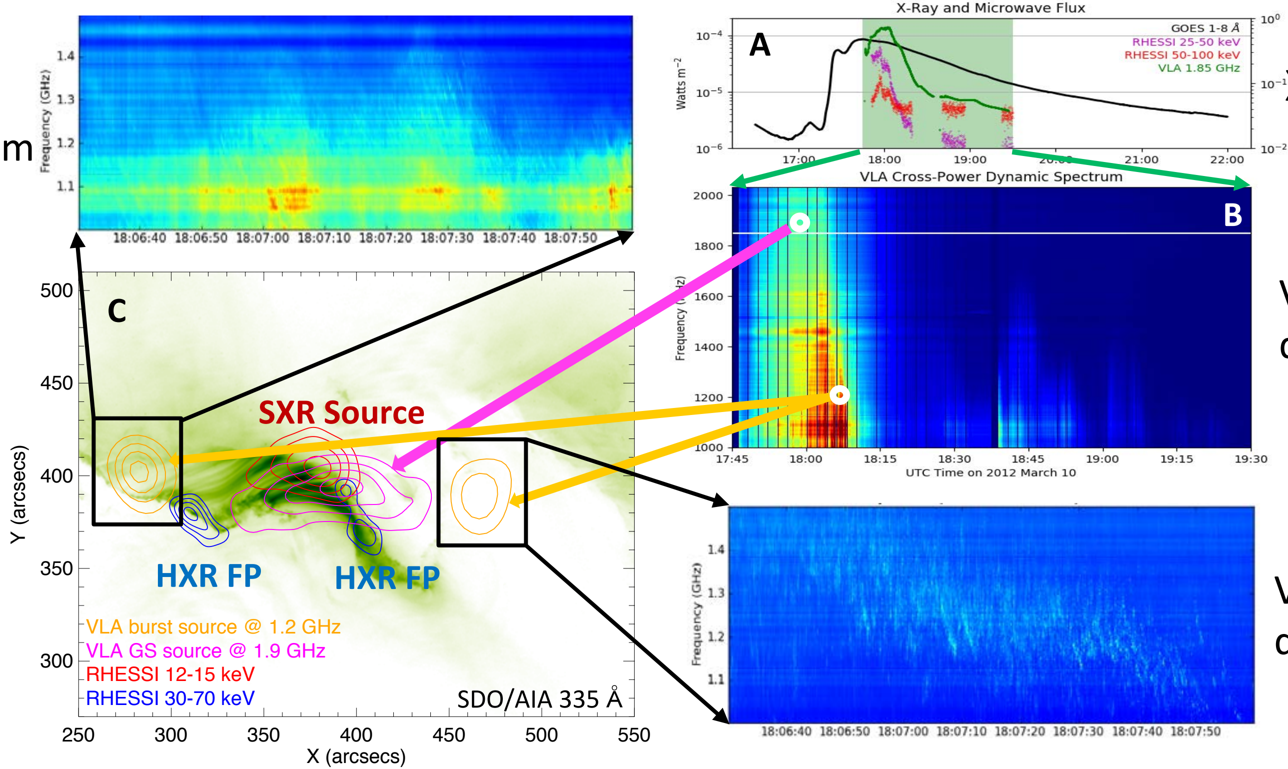
VLA “vector” dynamic spectrum

X-ray light curve

VLA cross-power dynamic spectrum

EUV, X-ray, and radio images

VLA “vector” dynamic spectrum



New generation radio facilities: Jansky VLA

Karl G. Jansky Very Large Array

Solar observing started in late 2011

- General purpose radio observatory
- Microwave range: 1–8 GHz (currently available for solar observing)
- Probes low solar corona (<~1.15 R_{sun}). Great for solar flare and active region science.

❖ 27 25-meter antennas
❖ ~20”/GHz for C configuration
❖ Instantaneous bandwidth up to 2 GHz
❖ Full Stokes polarization
❖ ***Up to 50 ms and 1 MHz resolution***

New generation radio facilities: EOVSA

Expanded Owens Valley Solar Array

- **Located at OVRO/Caltech, operated by NJIT**
- **Fully commissioned in 2017**

- ***Solar-dedicated*** radio observatory
- Microwave range 1–18 GHz (now 2.5–18 GHz due to RFI)
- Probes low corona (<~1.15 R_{sun}). Great for solar flare and active region science

❖ 13 2.1-m antennas + 1 27-m antenna for calibration
❖ Max baseline 1.56 km (typically ~60"/GHz)
❖ Full Stokes correlation
❖ Sweeps ***1–18 GHz in 1 second***

New generation radio facilities: ALMA

Atacama Large Millimeter Array

Solar observing started in 2016 (Cycle 4)

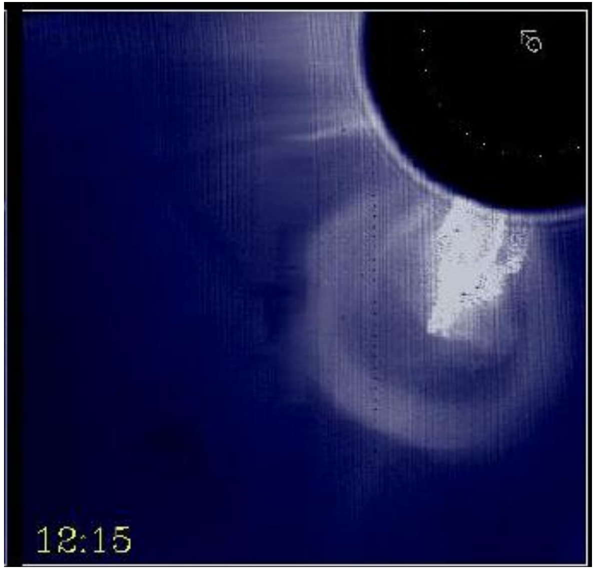
- General purpose radio observatory
- Bands 3 and 6 currently available for solar observing (~100 GHz & 230 GHz, Bands 7 & 9 being commissioned)
- Probes solar chromosphere (~1–1.003 R_{sun}). Great for observing detailed thermal structures in chromosphere

❖ ~50 antennas for INT and 3 antennas for total-power fast scan

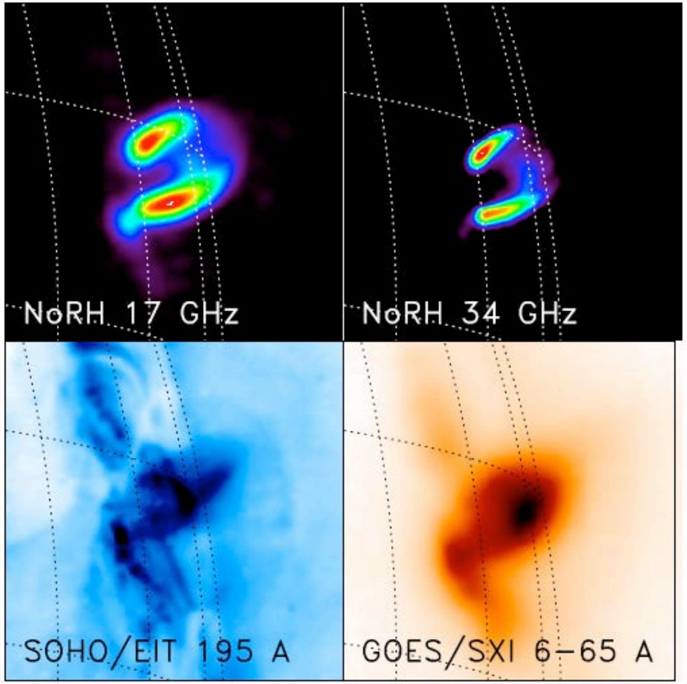
❖ ***Sub-arcsecond spatial resolution***!

Solar flare and Coronal Mass Ejections

CME (white light)

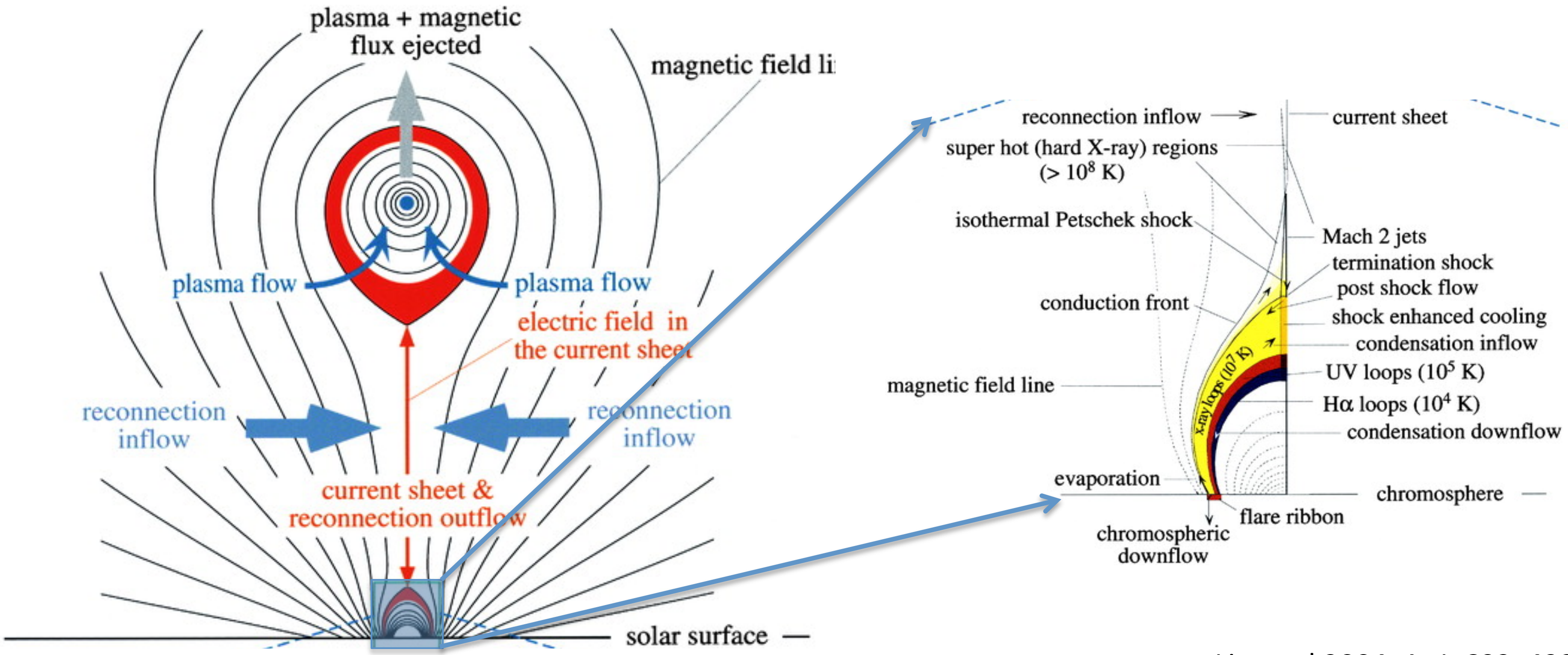


Flare signatures near the surface



From T. Bastian

Unified flare-CME model



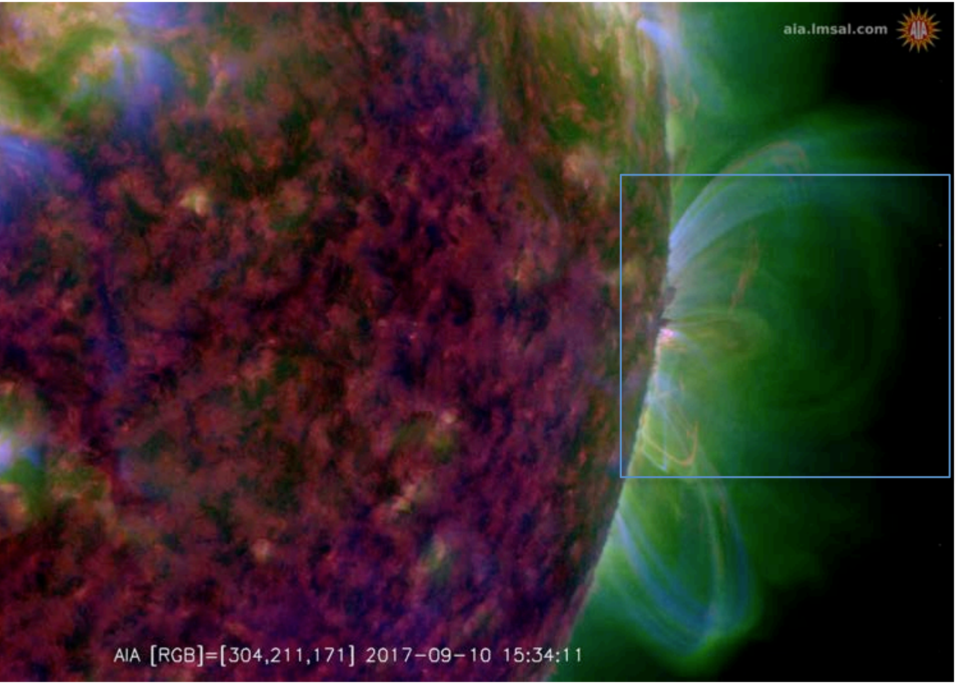
Lin et al 2004, ApJ, 602, 422

Outstanding Questions

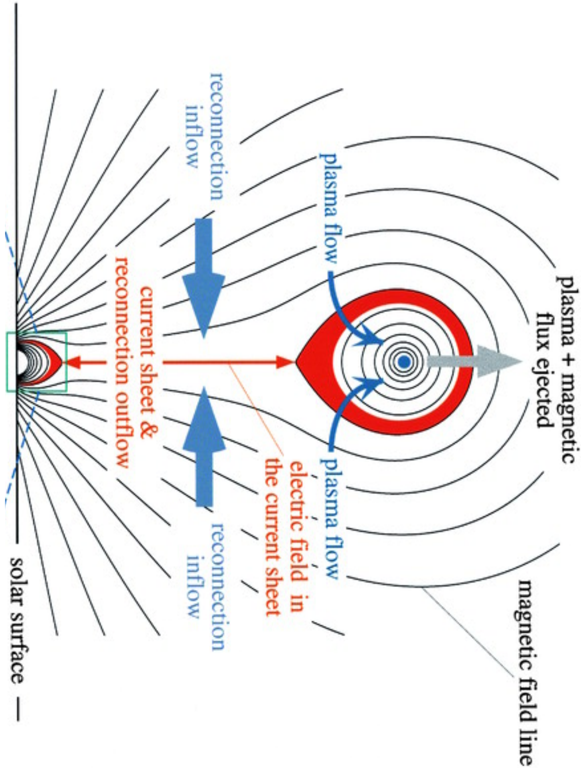
- When, where, and how do major ***space weather*** drivers such as solar flares and coronal mass ejections occur?
- Solar flares and CMEs are excellent laboratories to study ***catastrophic magnetic energy release*** processes that also occur on other stars
  - Where and how does magnetic energy store and release?
  - How are charged particles accelerated to relativistic speeds?
  - How is plasma heated to multiple millions of degrees?
  - How does energy transport in the highly-coupled solar atmosphere?

Recent Examples from EOVSA:

Imaging flare loops filled with energetic electrons



X8.1 flare on 2017 Sep 10



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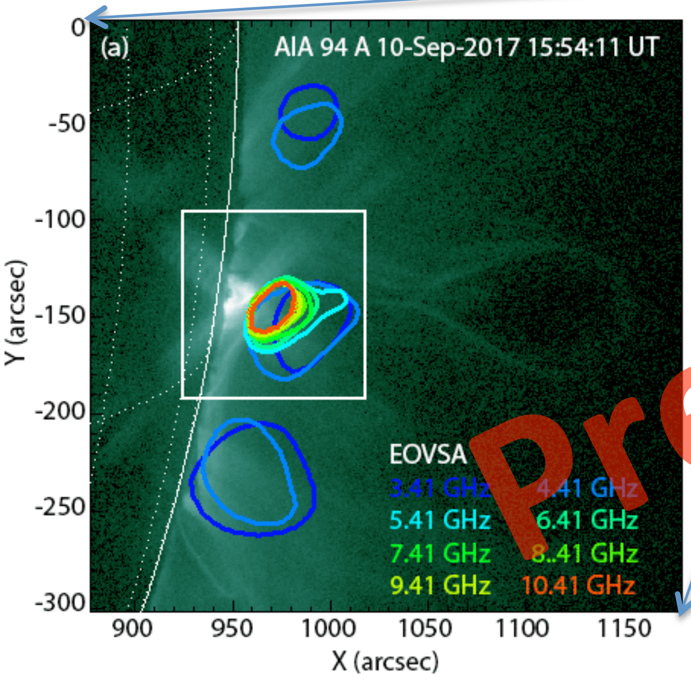
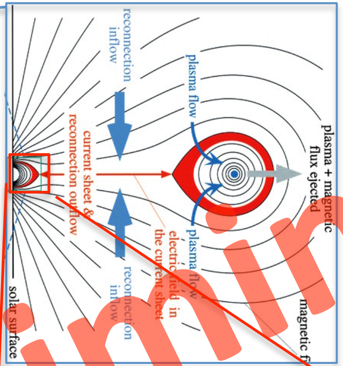
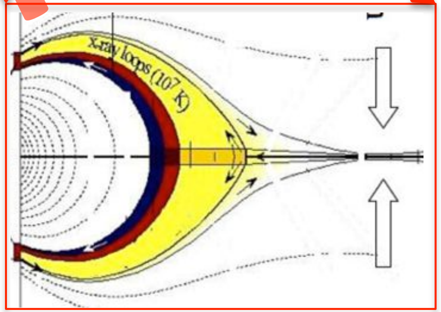
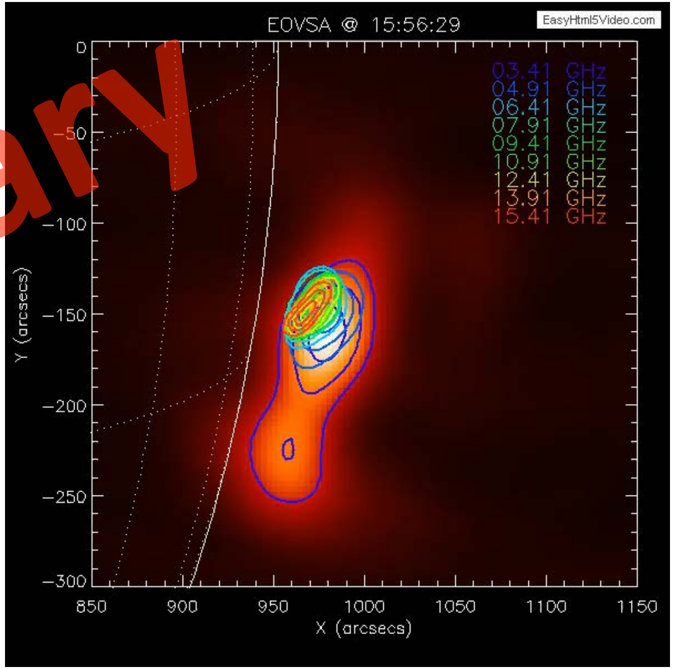
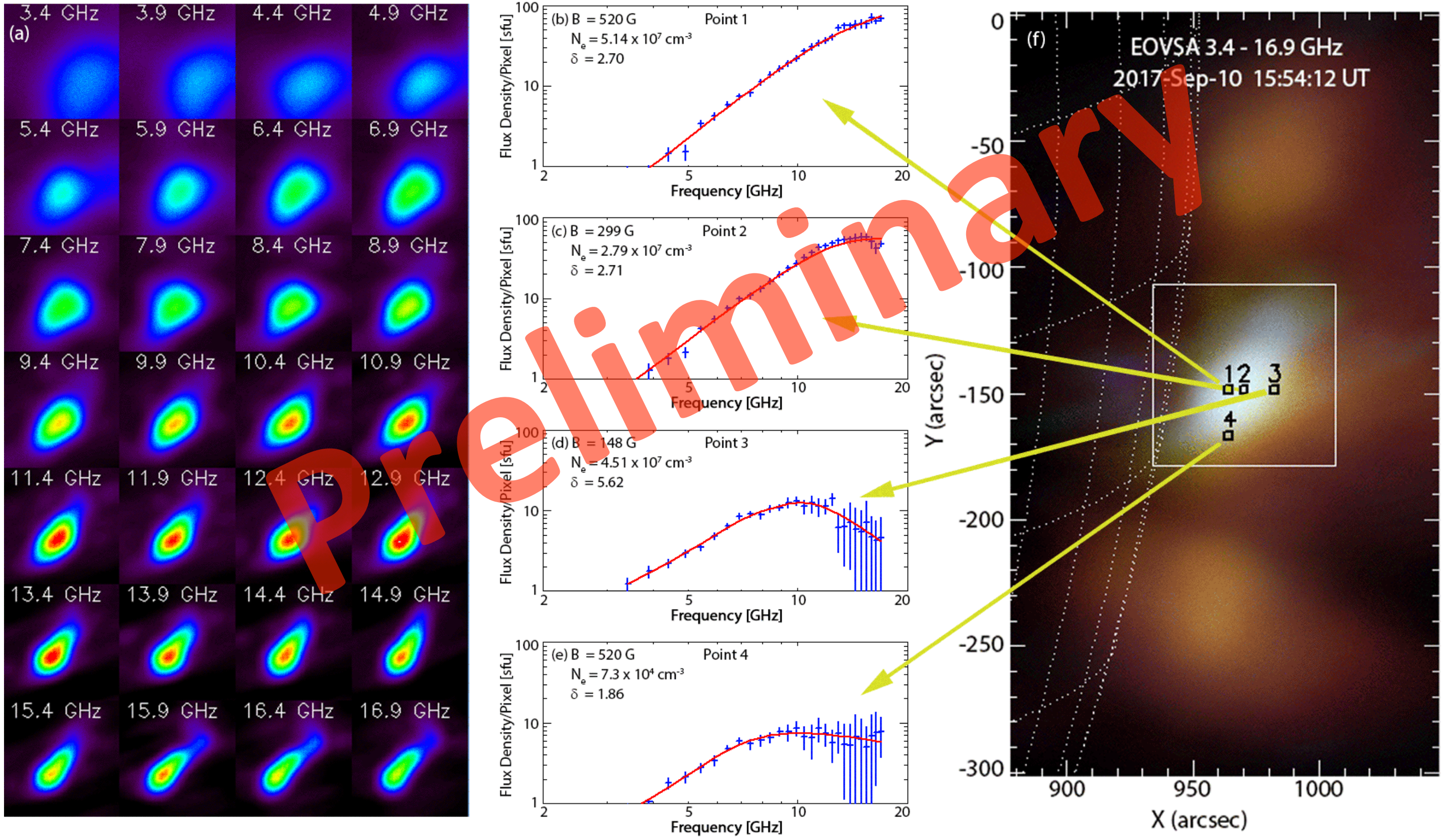








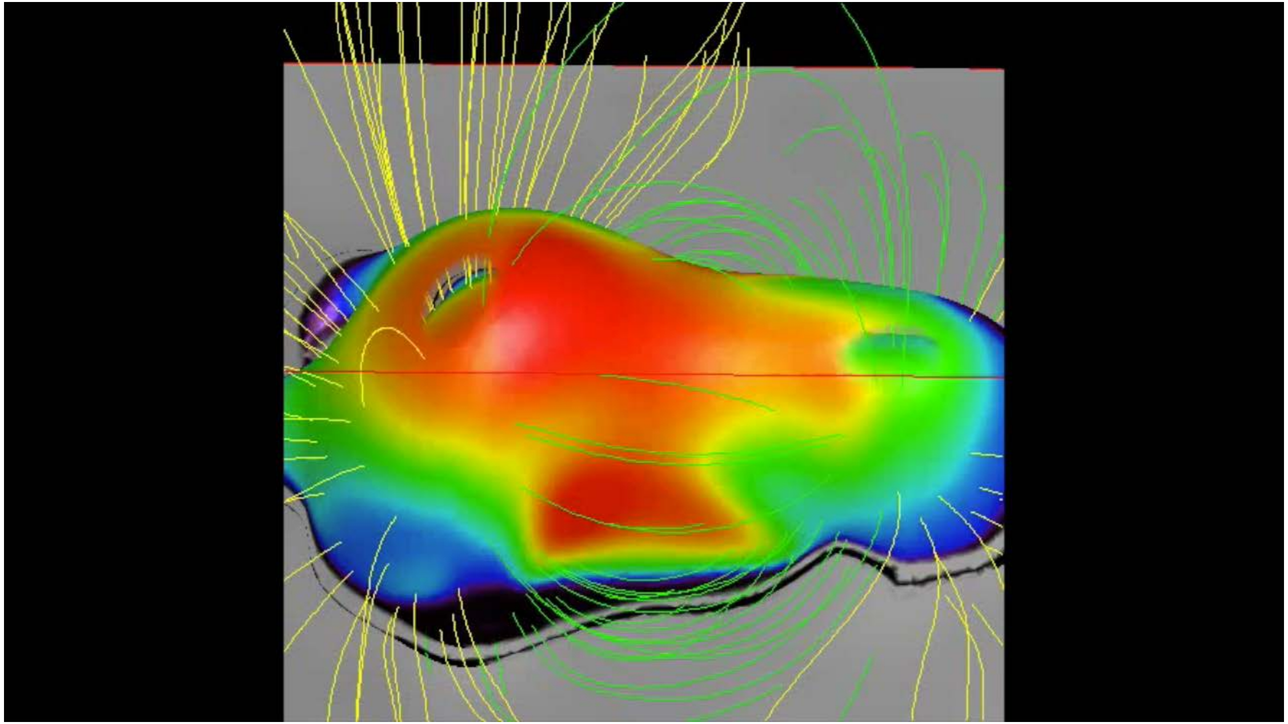
Spatially Resolved Gyrosynchrotron Spectra



Recent Examples from EOVSA:
Mapping Solar Active Regions

- Solar active regions are the ***source for all major solar activities***
- Measuring B field in the **corona** remains a ***major challenge*** at all other wavelengths, but ***readily accessible from radio gyroresonance radiation***
- Requires ***wide frequency coverage*** to sample B field in active regions (100s to 1000s G)

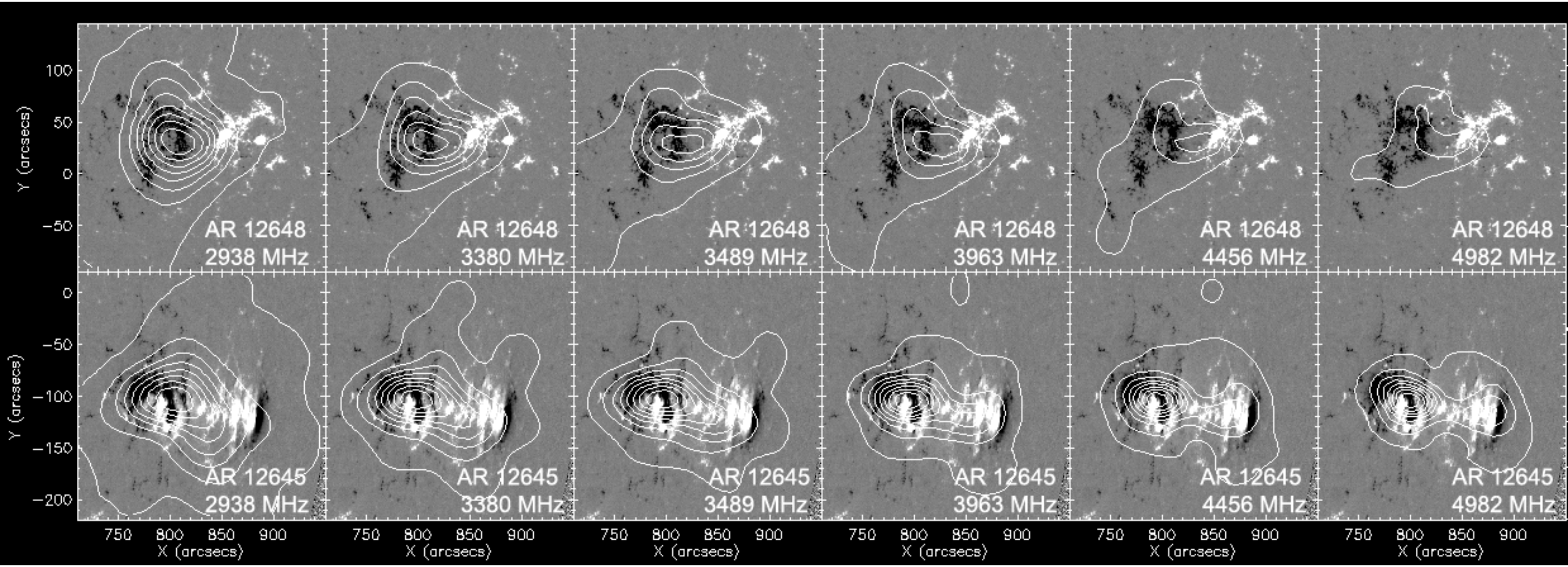
Recent Examples from EOVSA:
Mapping Solar Active Regions



From D. Gary

"Isogauss" gyroresonance layers: $f = sf_{ce} = 2.8\times10^6\, sB$

Recent Examples from EOVSA:
Mapping Solar Active Regions



B ~ 350 G | 402 G | 415 G | 472 G | 530 G | 594 G

Assuming s=3

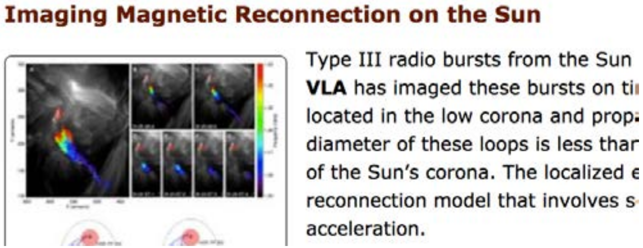
From D. Gary

Examples of Solar Studies with JVLA

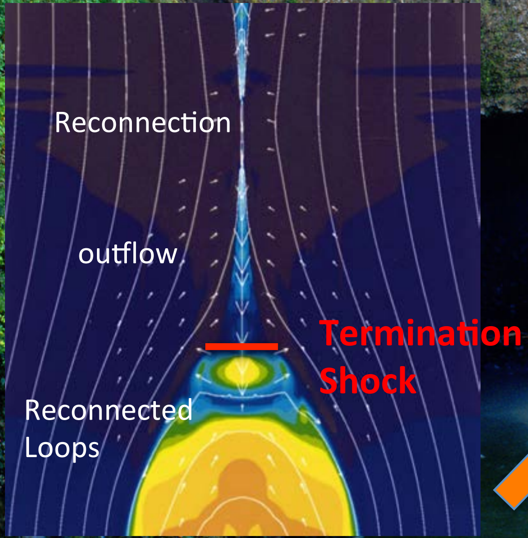
- Mapping solar flare termination shock
  - Chen et al. 2015, *Science*, 350, 1238
- Tracing fast electron beams
  - Chen et al. 2017, in prep
  - Chen et al. 2013, *ApJL*, 763, 21

NRAO Press Release 2015 Dec 3

NRAO 2013 Science Highlights

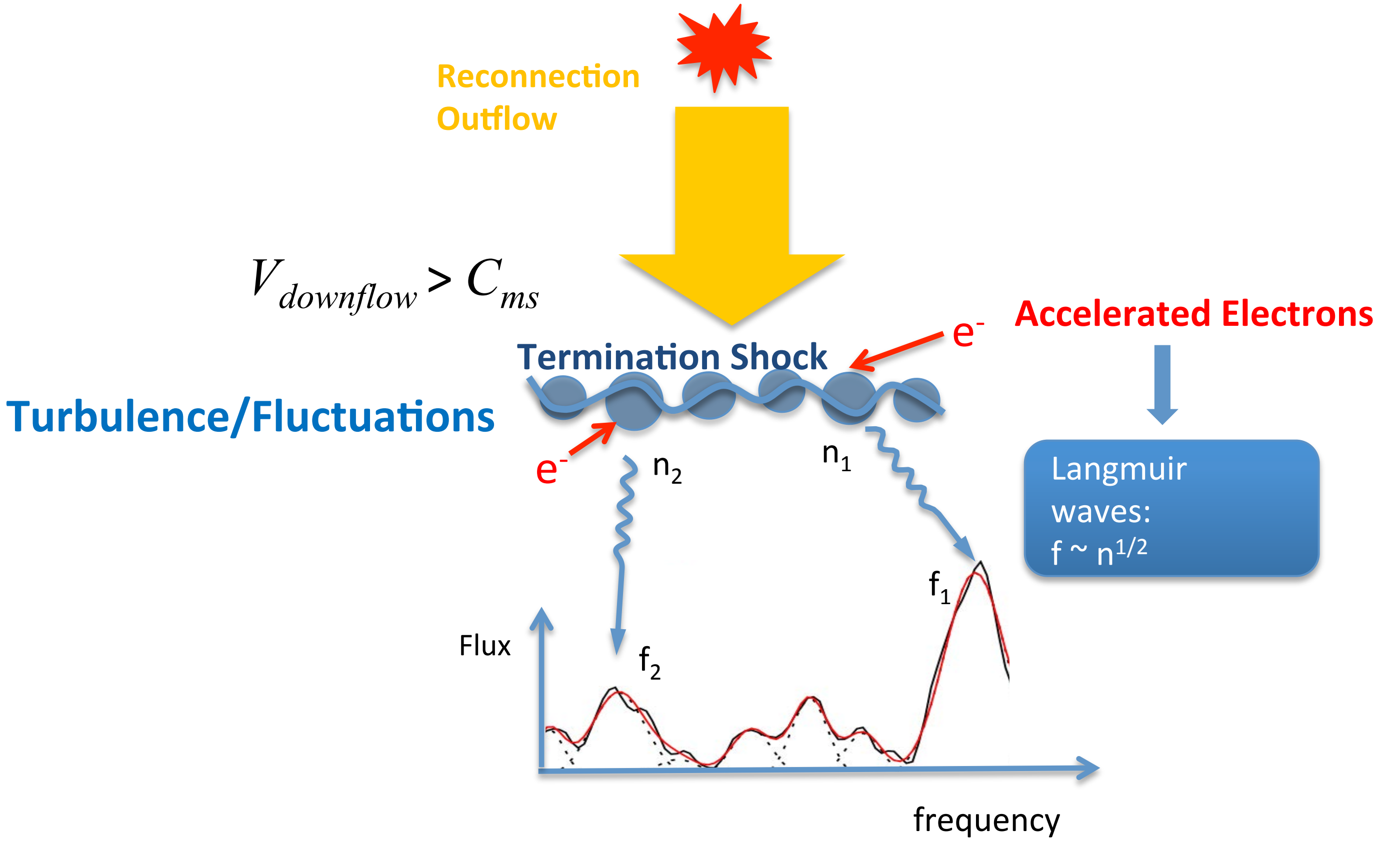


Solar Flare Termination Shock

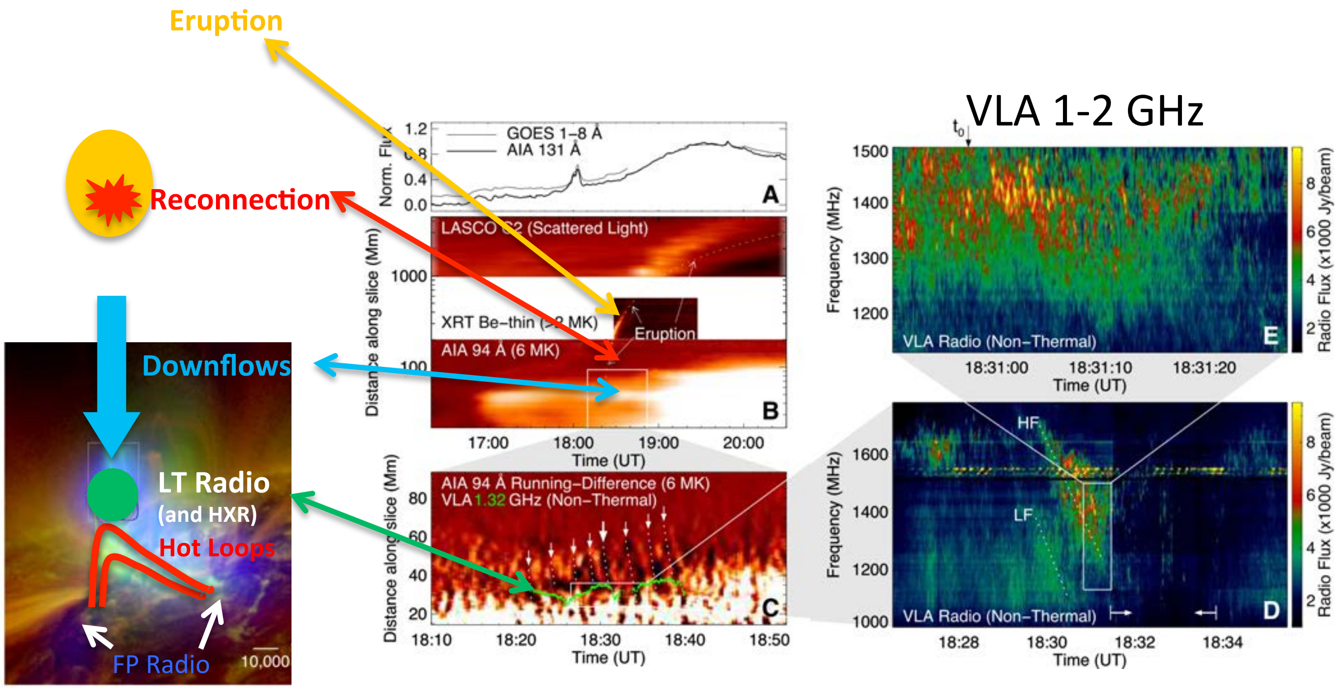


- ❑ TSs suggested as one mechanism for accelerating electrons in flares
- ❑ However, solid observational evidence remains elusive

Radio Emission at a Termination Shock

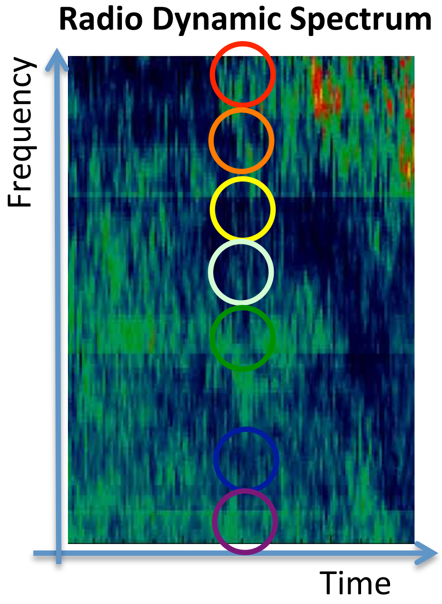


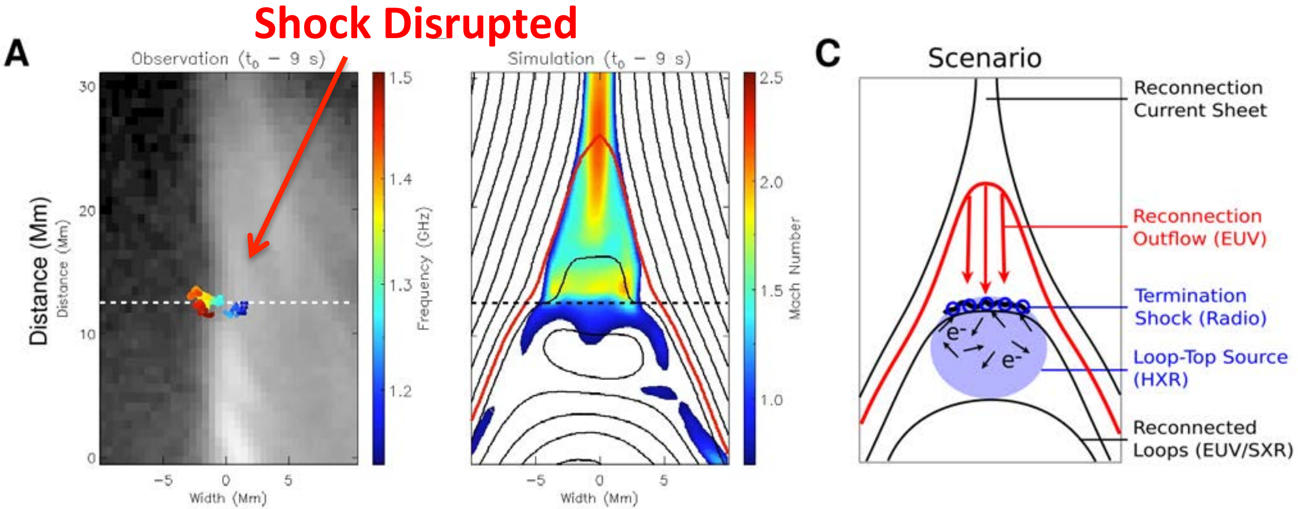
Radio and HXR source at the front of reconnection downflows



Drifting structure consisting of numerous short-lived, narrowband coherent radio bursts

Dynamic shock surface outlined





Shock evolution in 1-s cadence

MHD simulation (by C. Shen @ CfA)

Main results:

- First convincing observational identification of a solar flare termination shock
- Demonstrated its role in accelerating electrons

Chen et al. 2015, *Science,* 350, 1238

Examples of Solar Studies with JVLA

- Mapping solar flare termination shock
  - Chen et al. 2015, *Science*, 350, 1238
- Tracing fast electron beams
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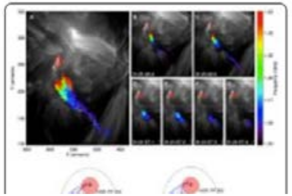
NRAO Press Release 2015 Dec 3

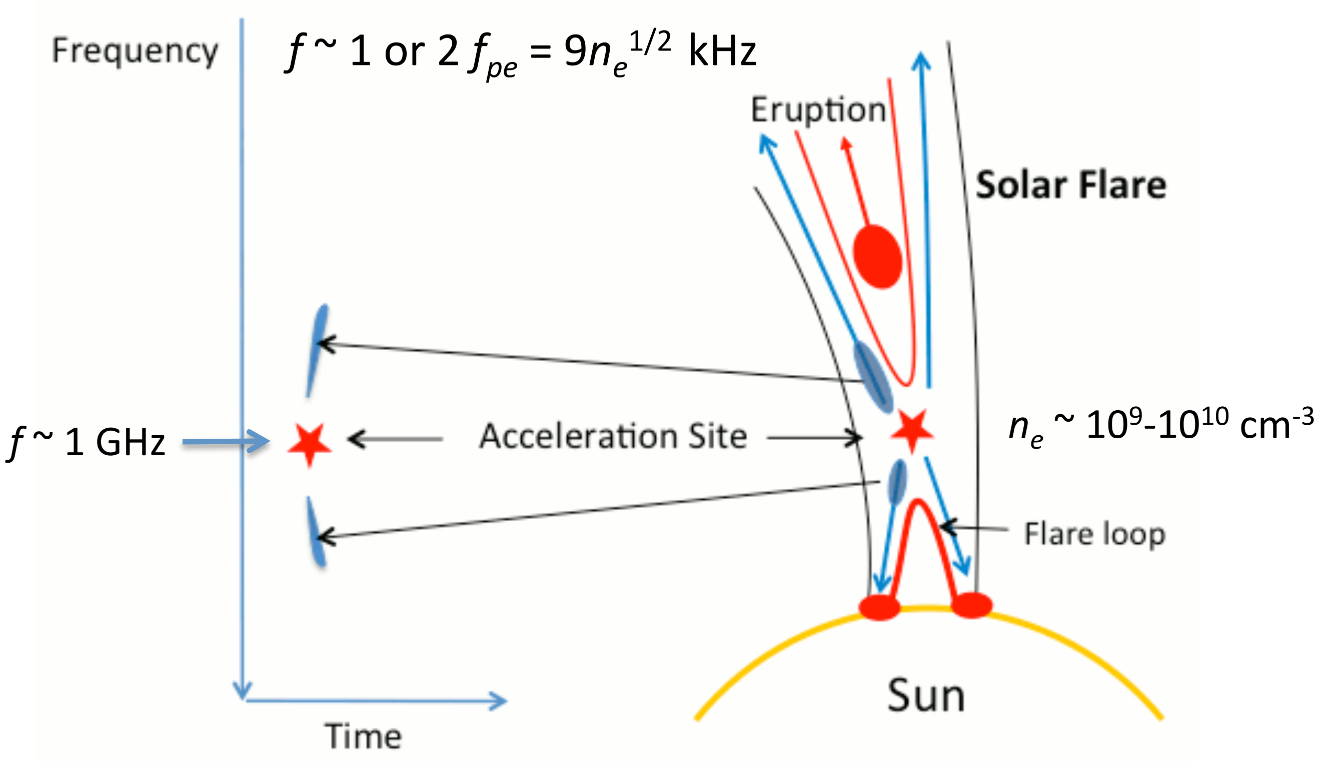
NRAO 2013 Science Highlights

Imaging Magnetic Reconnection on the Sun



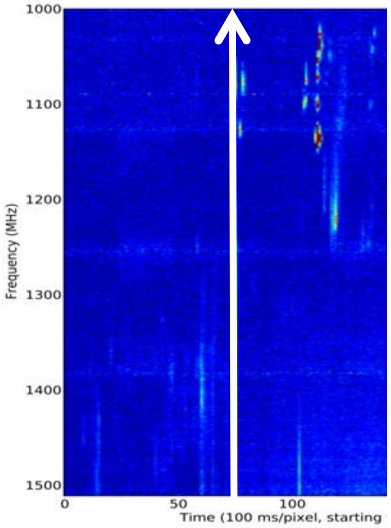
Type III radio bursts from the Sun
VLA has imaged these bursts on ti
located in the low corona and prop
diameter of these loops is less thar
of the Sun's corona. The localized e
reconnection model that involves s
acceleration.

Dm-λ type III radio bursts from fast electron beams

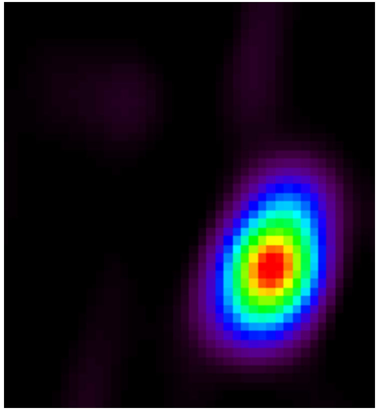


Snapshot of a Beam Trajectory

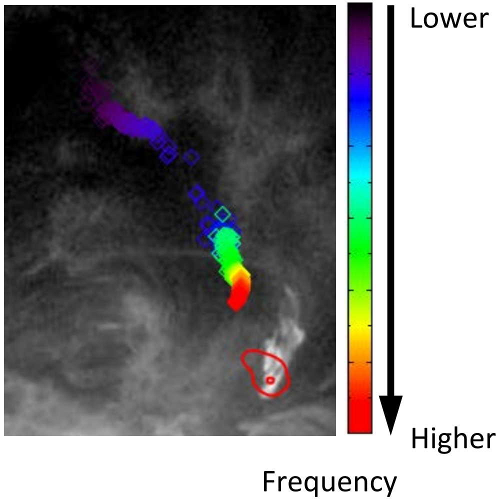
High-resolution
Dynamic spectrum



Channel-by-channel
spectral imaging

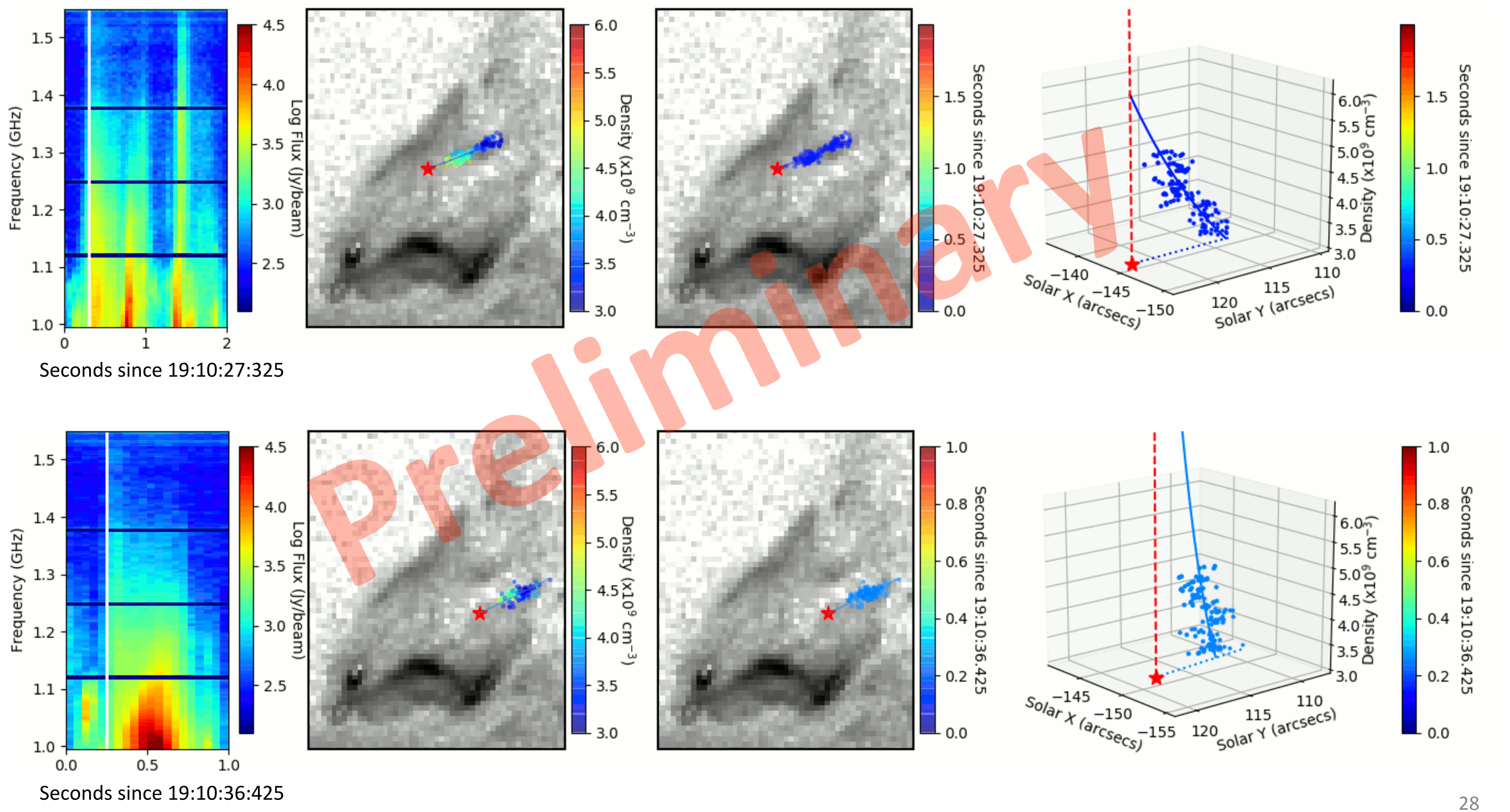


Electron beam trajectory



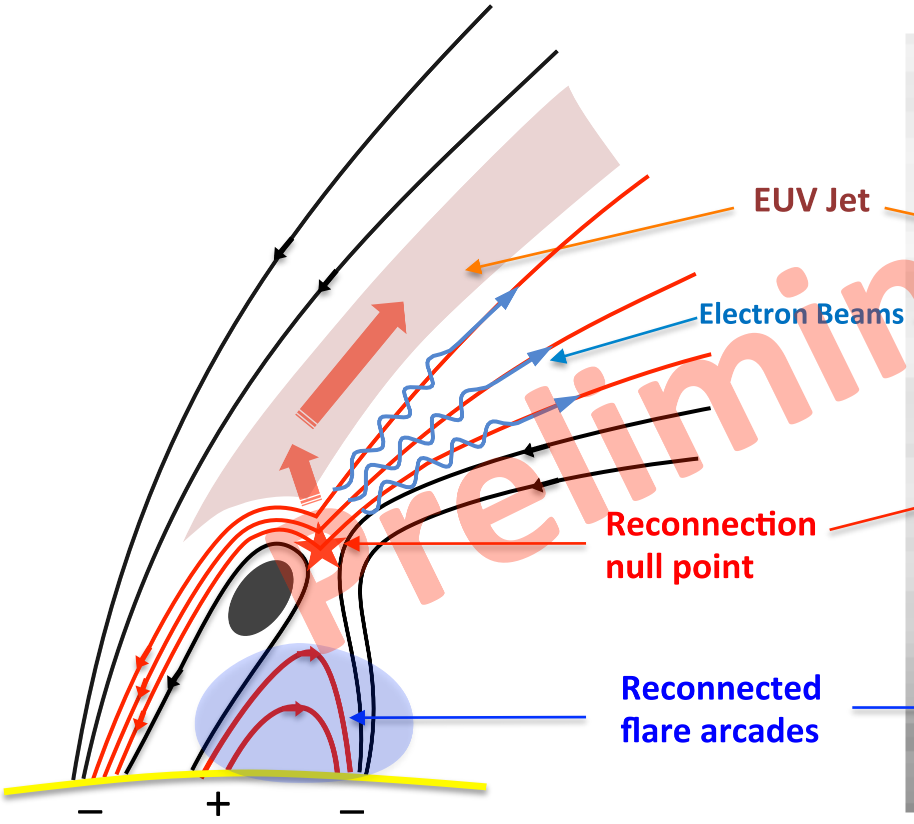
Chen et al. 2013, *ApJL*, 763, 21

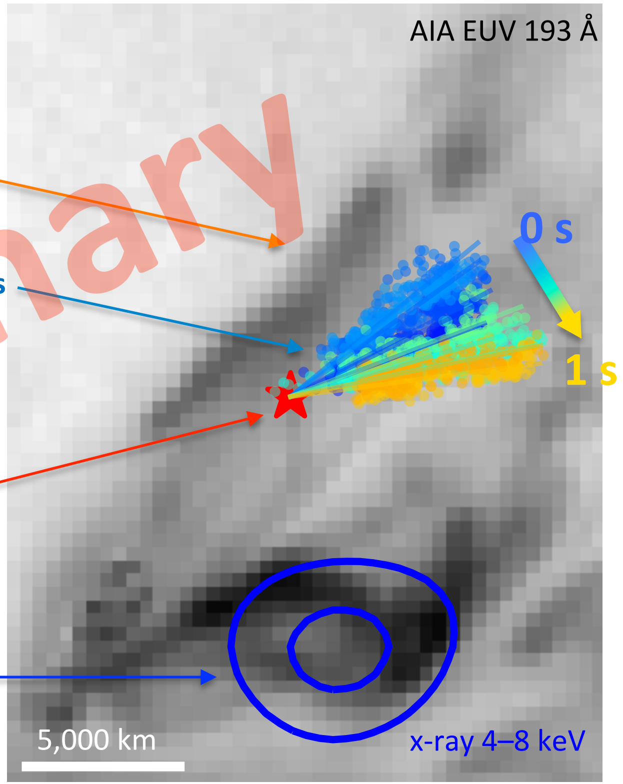
Dynamic spectrum | Colored in **Freq** | Colored in **Time** | Colored in **Time**



Erupting Jet-Reconnection Scenario

Radio, EUV, and X-ray Observations

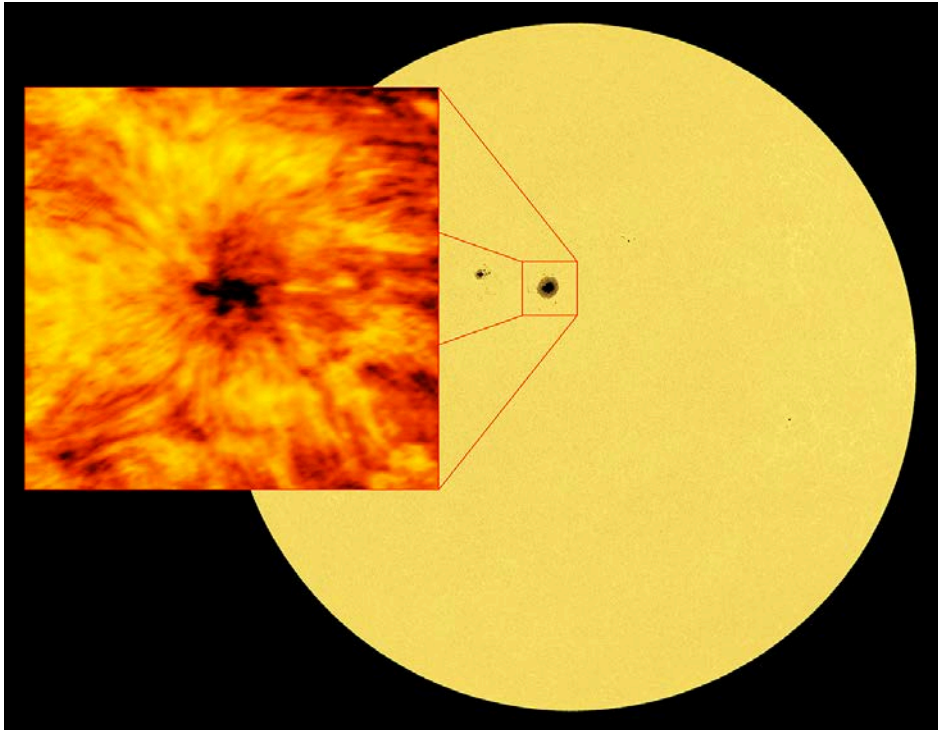




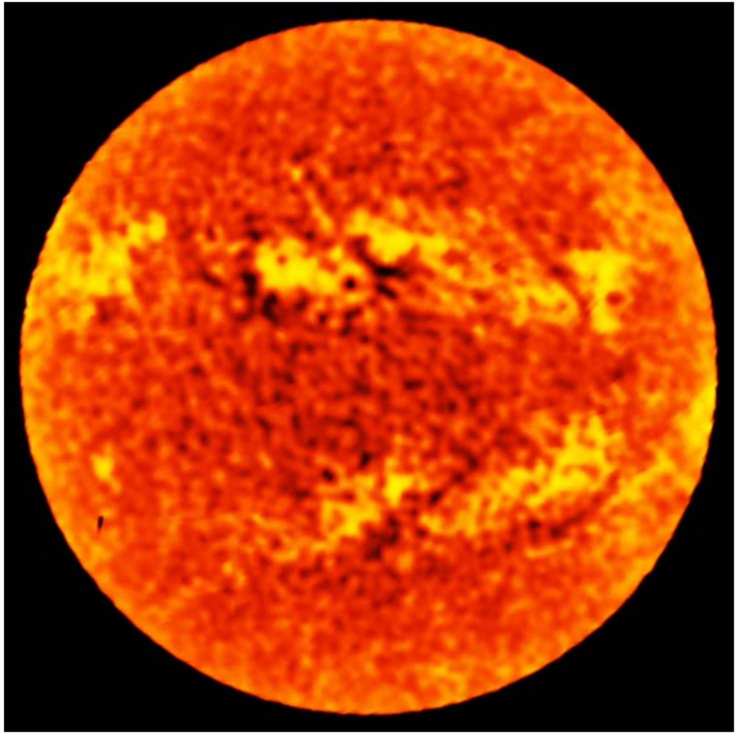
Pinpointing the magnetic reconnection/electron acceleration site

Chen et al., *in prep*

Recent Examples from ALMA:
Imaging detailed structures in chromosphere



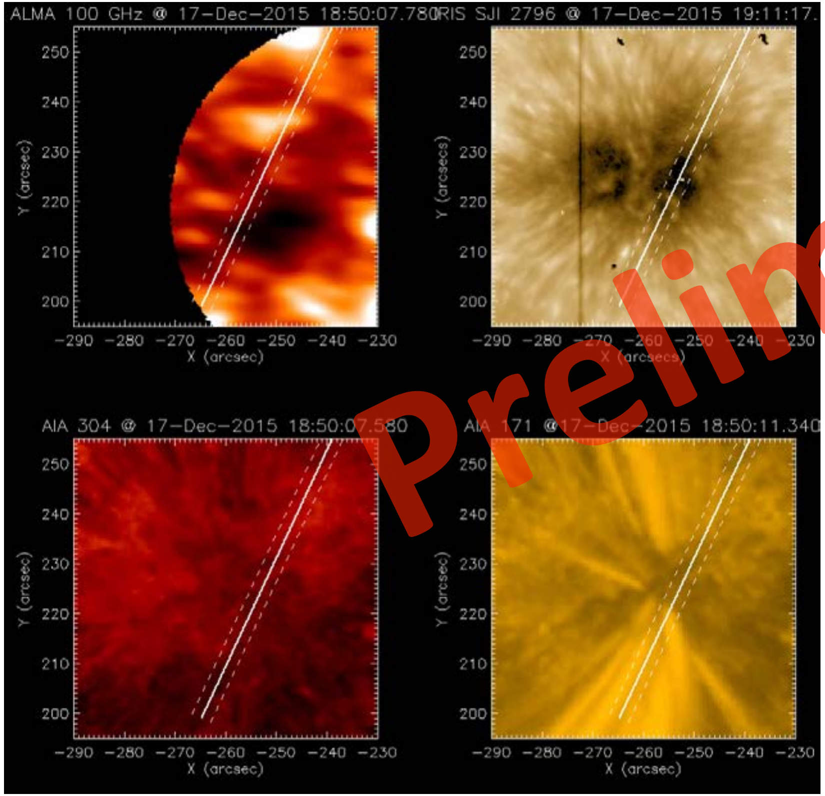
Thermal structure & magnetic field (Stephen's talk)

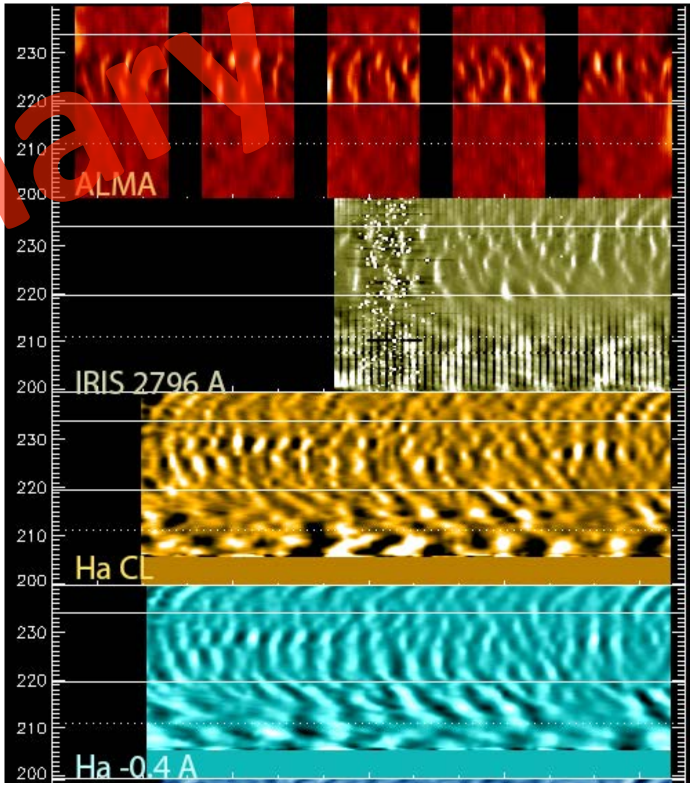


Credit: ALMA (NRAO/ESO/NAOJ)

Recent Examples from ALMA:

Probing dynamics in chromosphere





Concluding Remarks

- Solar radio astronomy has *entered a new era*, thanks to new instrumentation that offers *broadband dynamic spectral imaging,* opening up new opportunities for solar physics and space weather research
- Provides detailed studies of magnetic energy storage and release, particle acceleration, emission processes, as well as structure, dynamics, and magnetic field of the solar atmosphere


Thank you