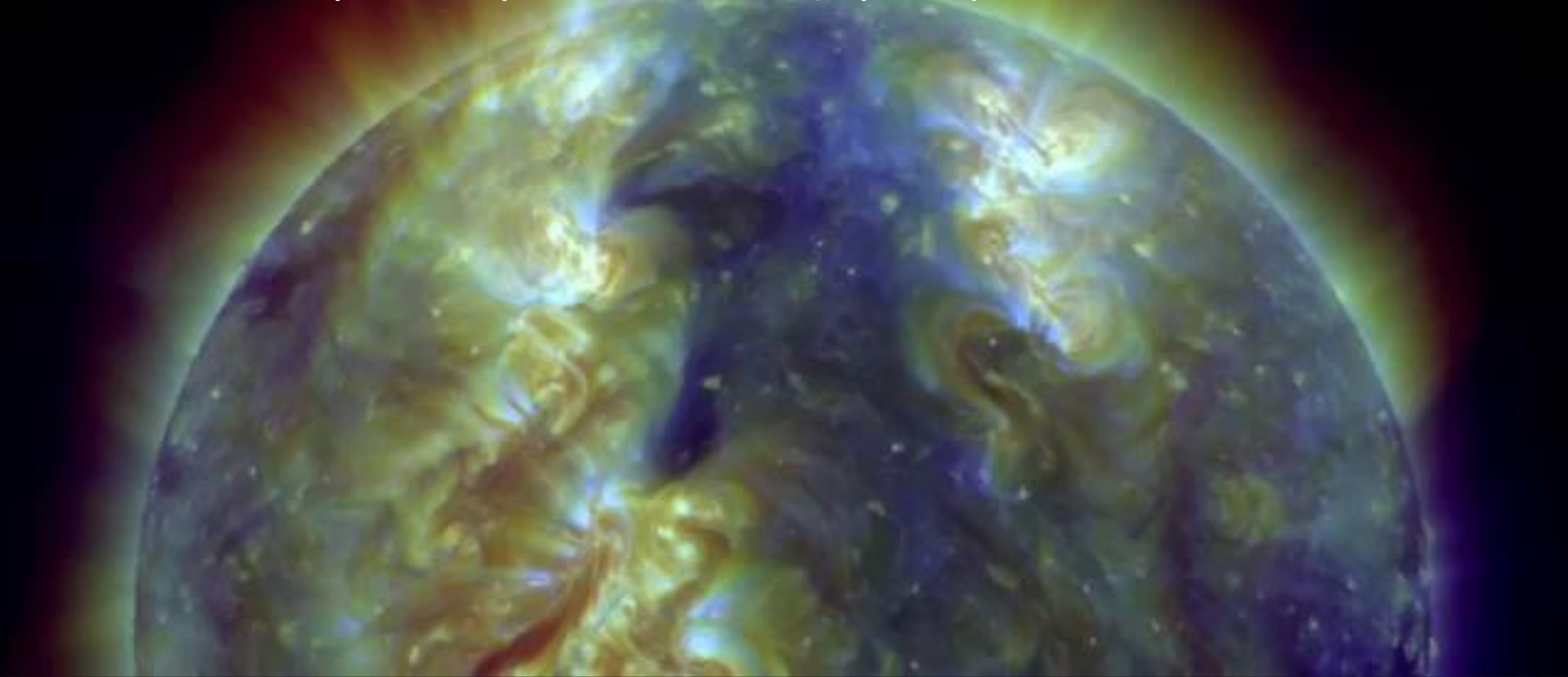
Towards a Next Generation Radiohliograph

T. S Bastian (NRAO) & D. E. Gary (NJIT)



Release of the Midterm Assessment of the *Solar & Space Physics Decadal Survey!* Today

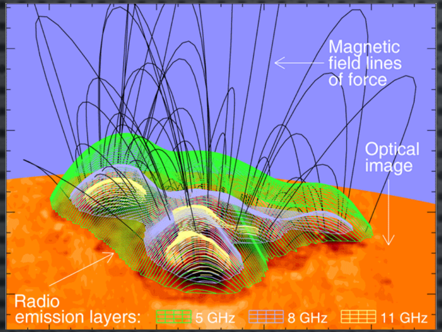
WHAT IS FASR?

A solar dedicated radio array designed to perform time-resolved, ultra-broadband, imaging spectropolarimetry.

Angular resolution	$20/\nu_{GHz}$ arcsec
Frequency range	50 MHz – 21 GHz
Number data channels	2 (dual polarization)
Frequency bandwidth	500 MHz per channel
Frequency resolution	Instrumental: 4000 channels Scientific: min(1%, 5 MHz)
Time resolution	~1 s (full spectrum sweep) 20 ms (dwell)
Polarization	Full Stokes (IQUV)
Number antennas deployed	**A** (2-21 GHz): ~100 **B** (0.3-2.5 GHz): ~70 **C** (50-350 MHz): ~50
Size antennas	**A** (2-21 GHz): 2 m **B** (0.3-2.5 GHz): 6 m **C** (50-350 MHz): LPDA
Array size	4.25 km EW x 3.75 km NS
Absolute positions	1 arcsec
Absolute flux calibration	<10%

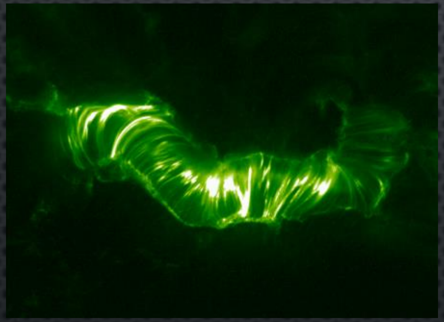
Angular resolution	$30/\nu_{GHz}$ arcsec
Frequency range	200 MHz – 20 GHz
Number data channels	2 (dual polarization)
Frequency bandwidth	1 GHz per channel
Frequency resolution	Instrumental: 125 kHz Scientific: min(1%, 5 MHz)
Time resolution	~0.4 s (full spectrum sweep) 20 ms (dwell)
Polarization	Full Stokes (IQUV)
Number antennas deployed	**A** (2-20 GHz): ~64 **B** (0.2-2 GHz): ~32
Size antennas	**A** (2-20 GHz): 2 m **B** (0.2-2 GHz): 6 m
Array size	3 km linear size
Absolute positions	1 arcsec
Absolute flux calibration	<10%

KEY SCIENCE OBJECTIVES



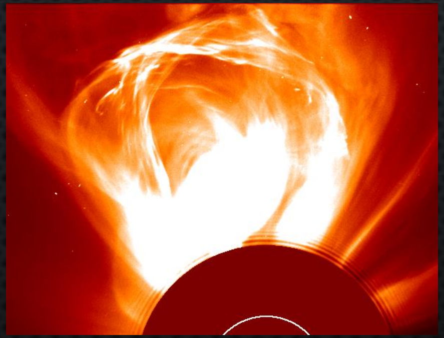
✓ **Nature & Evolution of Coronal Magnetic Fields**

- Quantitative measurements of fields
- Spatial and temporal evolution of fields
- Synergies with O/IR techniques



✓ **Physics of flares**

- Magnetic energy release
- Electron acceleration and transport
- Plasma heating and dynamics



✓ **Drivers of space weather**

- CME precursor & eruption
- CME-driven shocks and SEPs
- Extreme Radio bursts

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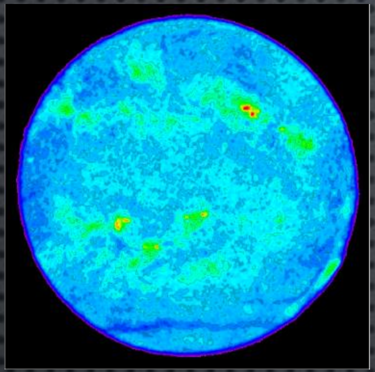
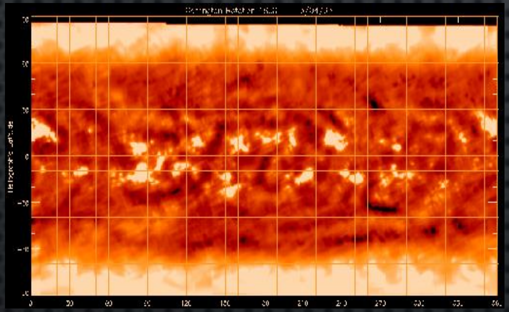


✓ **The "thermal" solar atmosphere**

- Coronal & chromospheric heating
- 3D thermal structure and dynamics
- Solar wind sources

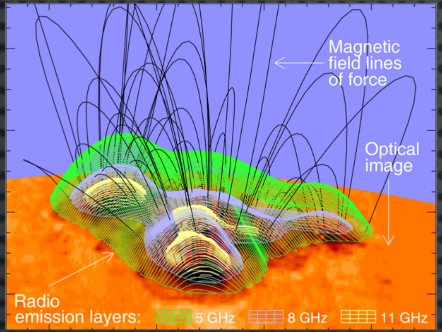


✓ **Synoptic studies**

- Radiative inputs to the upper atmosphere
- Global magnetic field and dynamo
- Flare/burst statistics

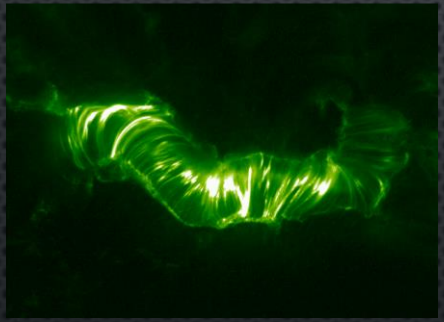
Many of these objectives inform stellar studies, exo-space-weather, & exoplanet habitability!

Key Science Objectives



✓ **Nature & Evolution of Coronal Magnetic Fields**

- **Coronal magnetography (Quiescent & Dynamic)**
- **Temporal & spatial evolution of fields**
- Synergies with O/IR techniques



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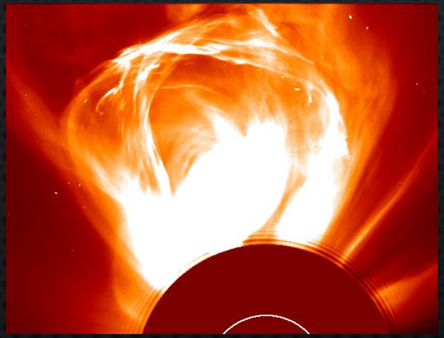


✓ **Drivers of space weather**

- CME precursor & eruption
- CME-driven shocks and SEPs
- **Extreme radio bursts**

Coronal Magnetography

DEG

Thermal gyroresonance	Active regions ($|\mathbf{B}| \rightarrow \mathbf{B?}$)	Imaging spectroscopy & polarimetry (cm-λ)	White & Kundu 1997
Nonthermal gyrosynchrotron	Flares & CMEs ($|\mathbf{B}| \rightarrow \mathbf{B}$)	Imaging spectroscopy & polarimetry (cm-λ, flares; m-λ CMEs)	Bastian+ 1998, 2001 Fleishman+ 2009
Thermal free-free	Quiet sun, active regions ($B_\parallel$)	Imaging spectroscopy & polarimetry (m-λ to cm–λ)	Gelfriekh 2004
Loop oscillations	Flares (discrete loops)	Imaging spectroscopy & polarimetry (m-λ to cm-λ)	Benz+ 1984 Aschwanden+
Mode coupling	Active region corona (topological)	Imaging spectroscopy & polarimetry (cm-λ)	Ryabov 2004
Radio bursts	Corona (statistical, cases)	Imaging spectroscopy & polarimetry (dm-λ, Dm–λ)	Dulk & McLean 1978
Propagation techniques	Corona & heliosphere ($B_\parallel$ and fluctuations)	Long baseline interferometry (cm-λ to m–λ)	Spangler+ Bastian 2001

THE IDEA

LEVERAGE RADIO OBSERVATIONS OF THERMAL EMISSION TO MEASURE MAGNETIC FIELDS IN VARIOUS REGIONS OF THE NON-FLARING SOLAR ATMOSPHERE:

- THERMAL FREE-FREE OPACITY → B_{LOS}

$$\kappa^{ff}_{R,L} = \left(\frac{\pi}{2}\right)^{1/2} \frac{1}{3c} \frac{\nu_p^2}{(\nu + \sigma \nu_B \cos\theta)^2} \frac{4\pi e^4}{m^{1/2}} \frac{\Sigma Z_i^2 n_i}{(kT)^{3/2}} \Lambda \sim n^2 T^{-3/2} \nu^{-2}$$

- THERMAL GYRORESONANCE OPACITY → $|B|$

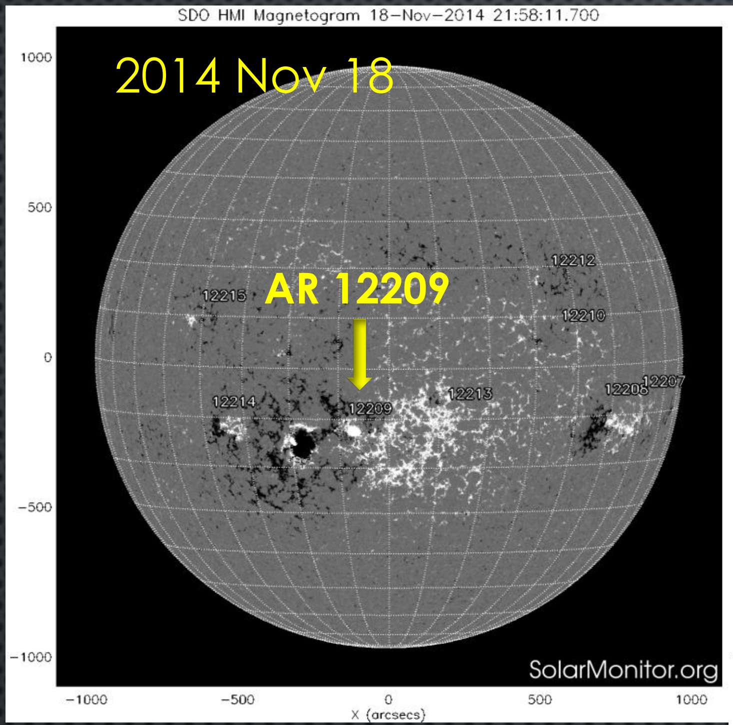
$$\kappa^{gr}_{R,L} = \left(\frac{\pi}{2}\right)^{5/2} \frac{\nu_p^2}{\nu} \frac{s^2}{s!} \left(\frac{s^2 \beta_o^2 \sin^2\theta}{2}\right)^{s-1} (1 - \sigma \cos\theta)^2 \sim n \nu^{-1} T^{s-1}$$

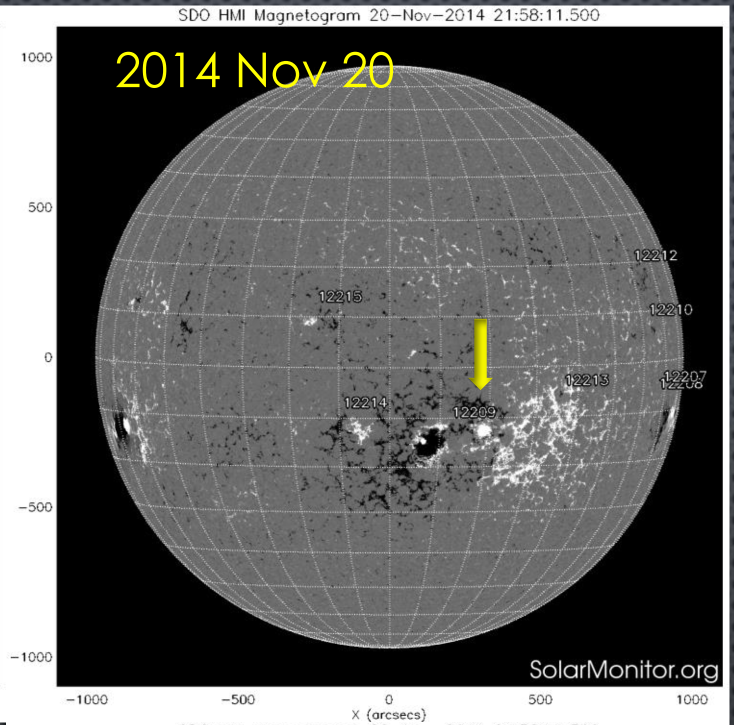
$\nu_{Be} = 2.8\ B$ MHz

$\nu_{pe} = 0.9\ n_e^{1/2}$ MHz

$s = \nu/\nu_{Be}$

WHERE S = +1 FOR O-MODE AND -1 FOR X-MODE AND S=2,3 UNDER TYPICAL CORONAL CONDITIONS.


SDO HMI Magnetogram 18-Nov-2014 21:58:11.700
2014 Nov 18
AR 12209
12212
12215
12210
12213
12214
12209
12208
12207
SolarMonitor.org
X (arcsecs)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2014 Nov 20
12212
12215
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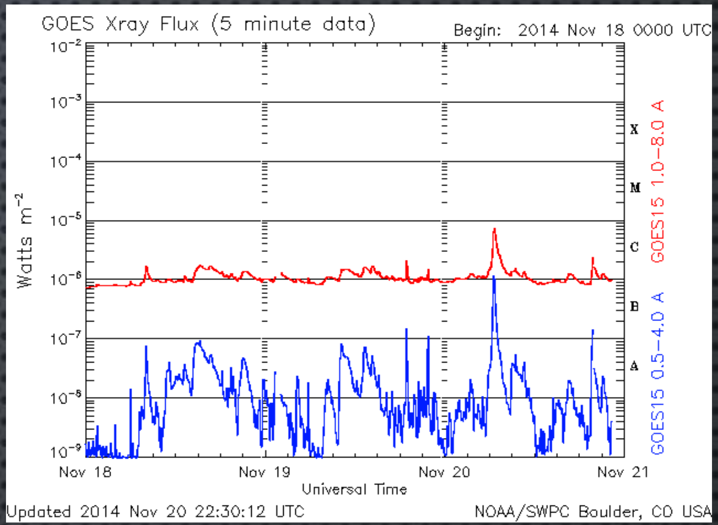
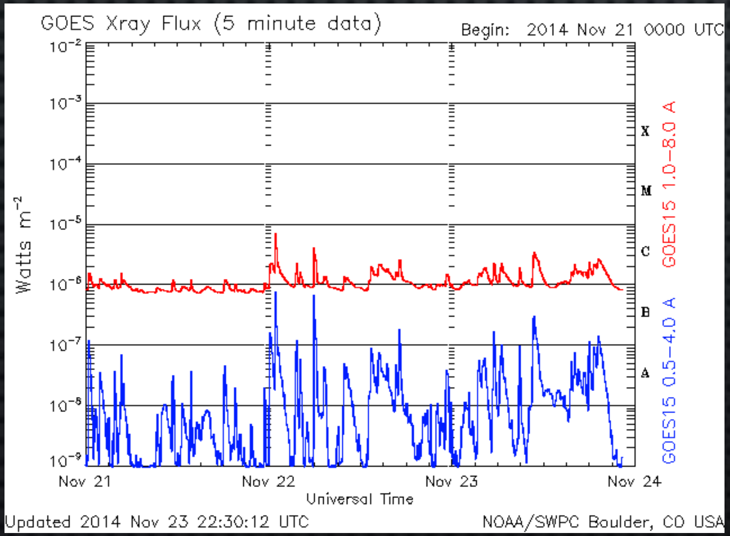
12208
SolarMonitor.org
X (arcsecs)


GOES Xray Flux (5 minute data)
Begin: 2014 Nov 18 0000 UTC
Watts m^{-2}
X
M
C
B
A
GOES15 1.0–8.0 A
GOES15 0.5–4.0 A
Nov 18
Nov 19
Nov 20
Nov 21
Universal Time
Updated 2014 Nov 20 22:30:12 UTC
NOAA/SWPC Boulder, CO USA


GOES Xray Flux (5 minute data)
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Watts m^{-2}
X
M
C
B
A
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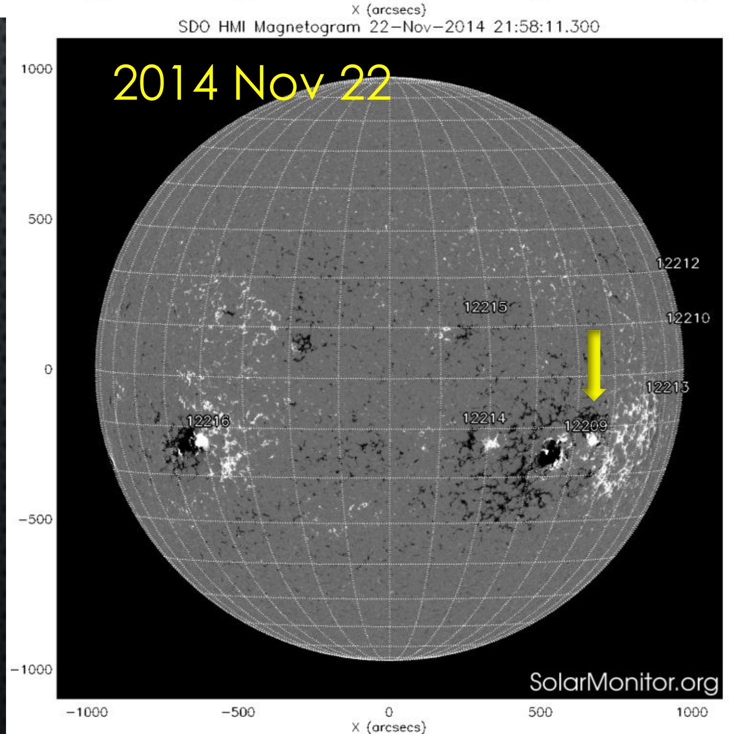
SDO HMI Magnetogram 22-Nov-2014 21:58:11.300
2014 Nov 22
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12210
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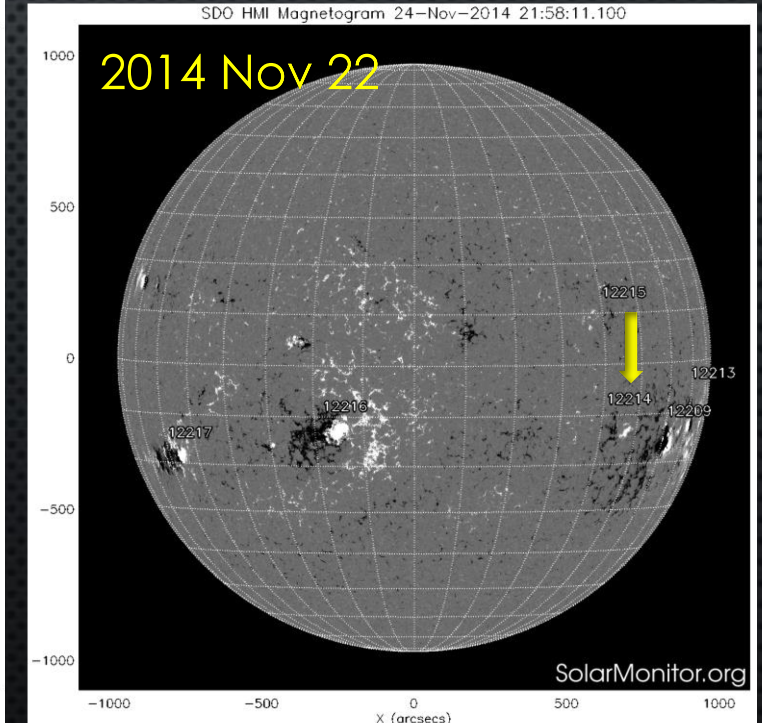
12216
12214
12209
SolarMonitor.org
X (arcsecs)

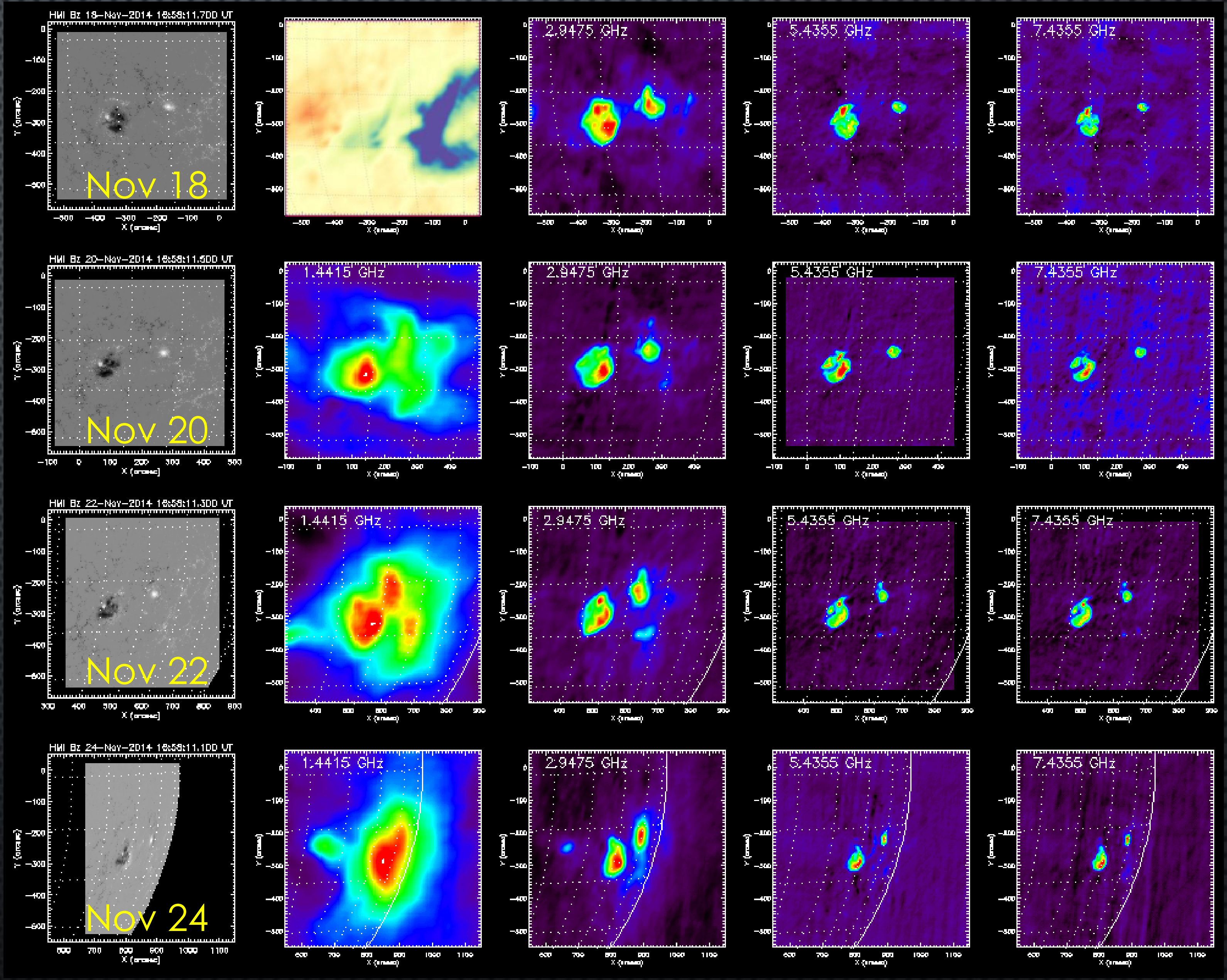

SDO HMI Magnetogram 24-Nov-2014 21:58:11.100
2014 Nov 22
12215
12213
12214
12209
12216
12217
SolarMonitor.org
X (arcsecs)

2014 Nov 18-24

Observations in VLA C

- 1-8 GHz (time sharing)
- Dual-pol'n (RCP/LCP)
- 1000 channels/GHz (RFI)
- ~4 hrs per day

- At **low frequencies** (<1.5 GHz) the emission is optically thick to free-free absorption
- The free-free opacity rapidly diminishes with **increasing frequency,** revealing gyro-resonance emission associate with strong magnetic fields over the dominant sunspots.



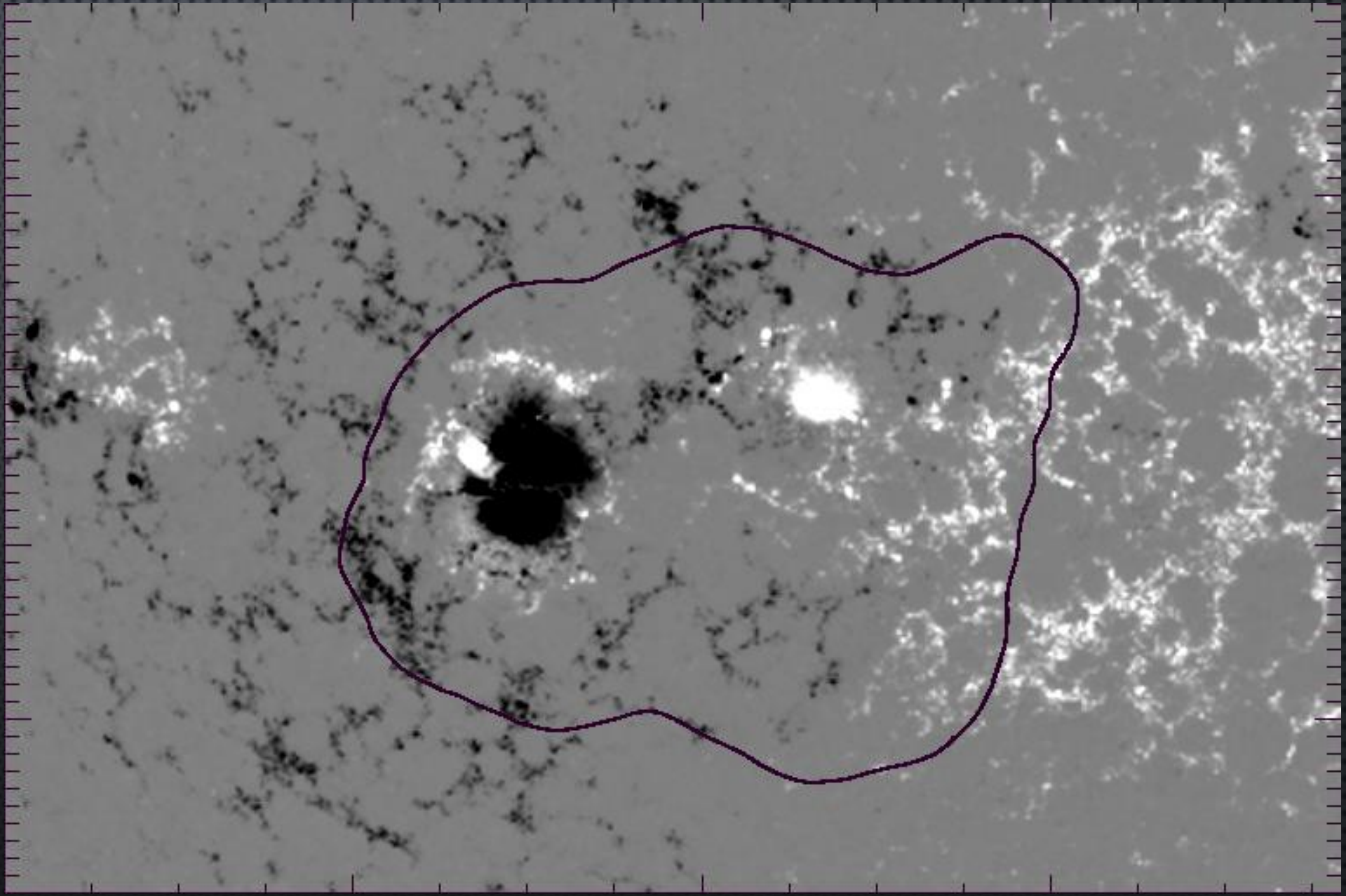
THE IDEA

For a given line of sight, measure the brightness temperature spectrum in RCP and LCP.

Harmonic breaks determine whether s=2 or 3 and the field is thereby determined.

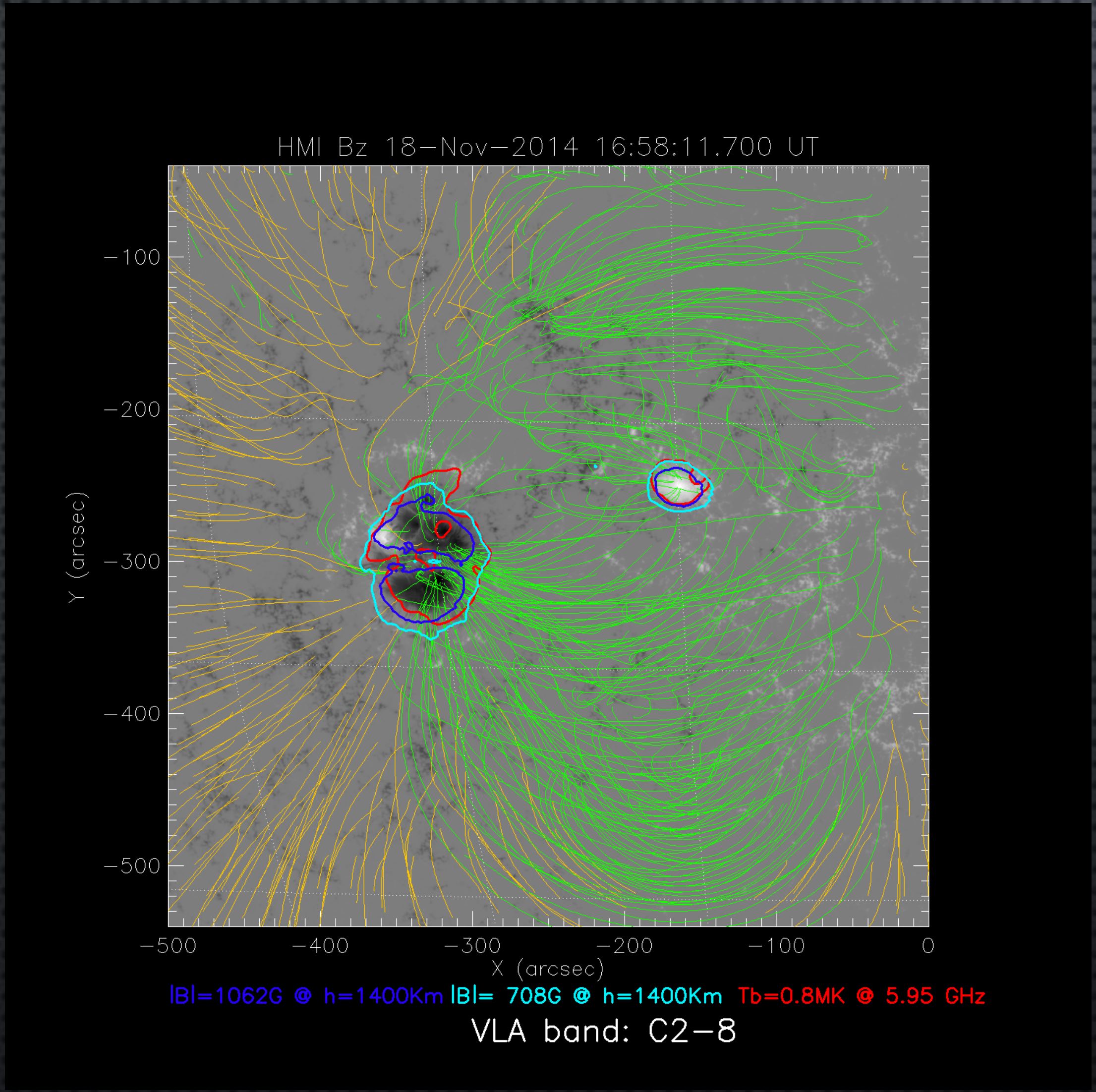
3D information is embodied in the spectrum. Forward modeling is required to jointly determine T, n, and **B**. Note that vector info is also contained in the ensemble of T_B spectra!

2014 Nov 18: “coronal magnetogram”

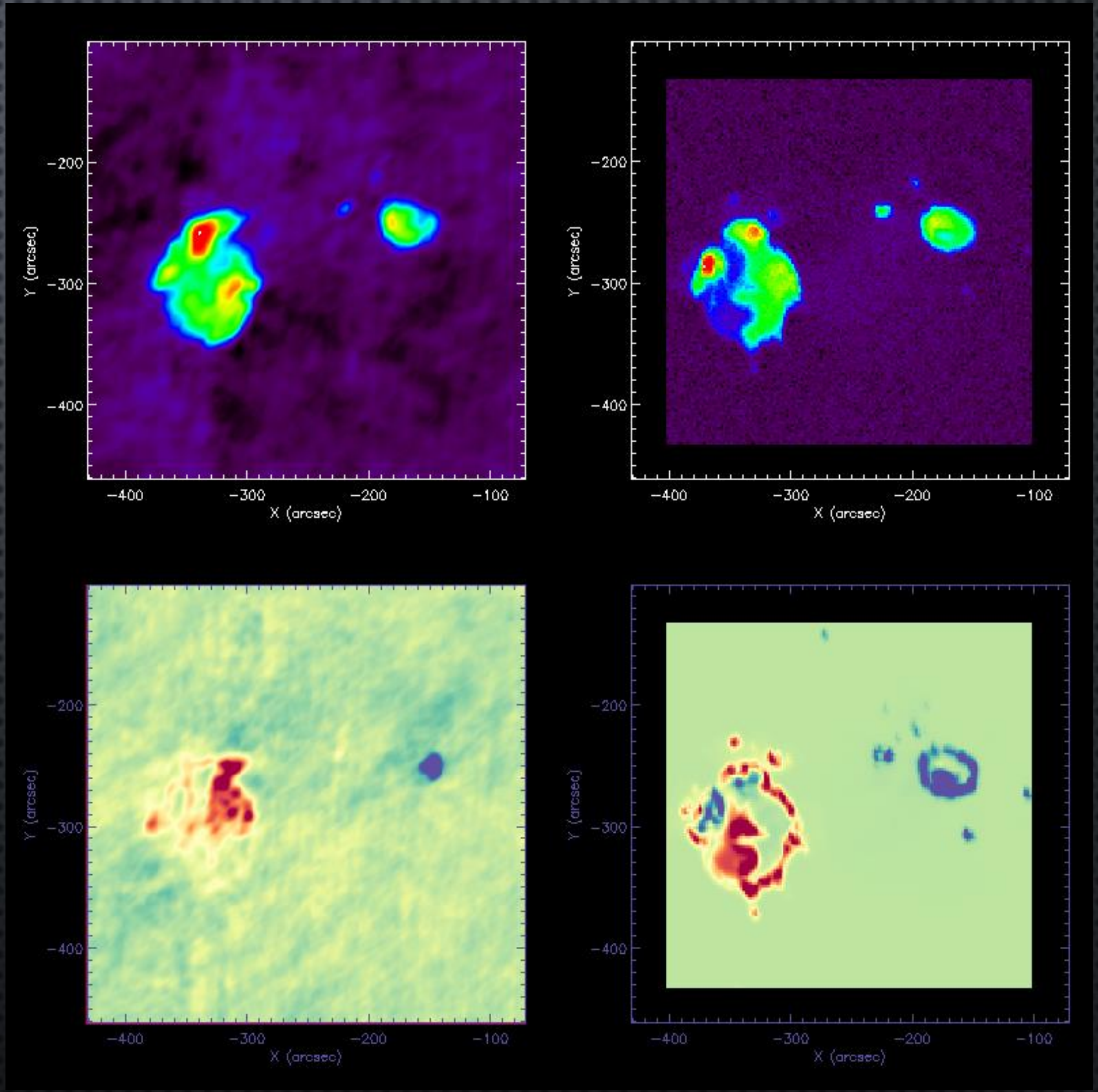


Mok et al 2003

MODELING



HMI Bz 18-Nov-2014 16:58:11.700 UT
Y (arcsec)
X (arcsec)
|B|=1062G @ h=1400Km |B|= 708G @ h=1400Km Tb=0.8MK @ 5.95 GHz
VLA band: C2-8



Y (arcsec)
X (arcsec)

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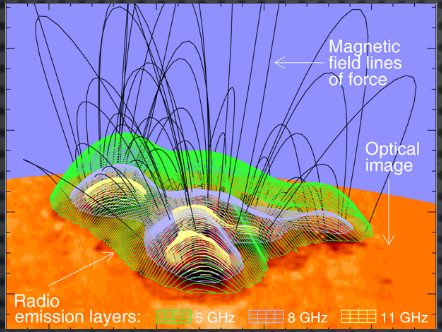

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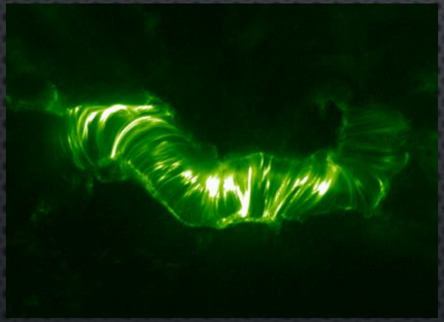

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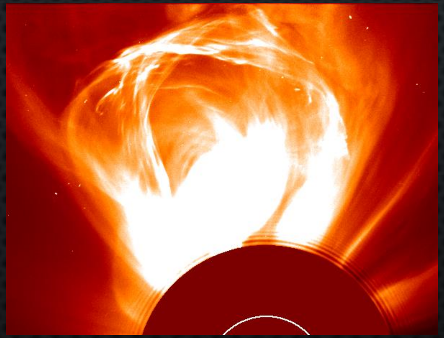

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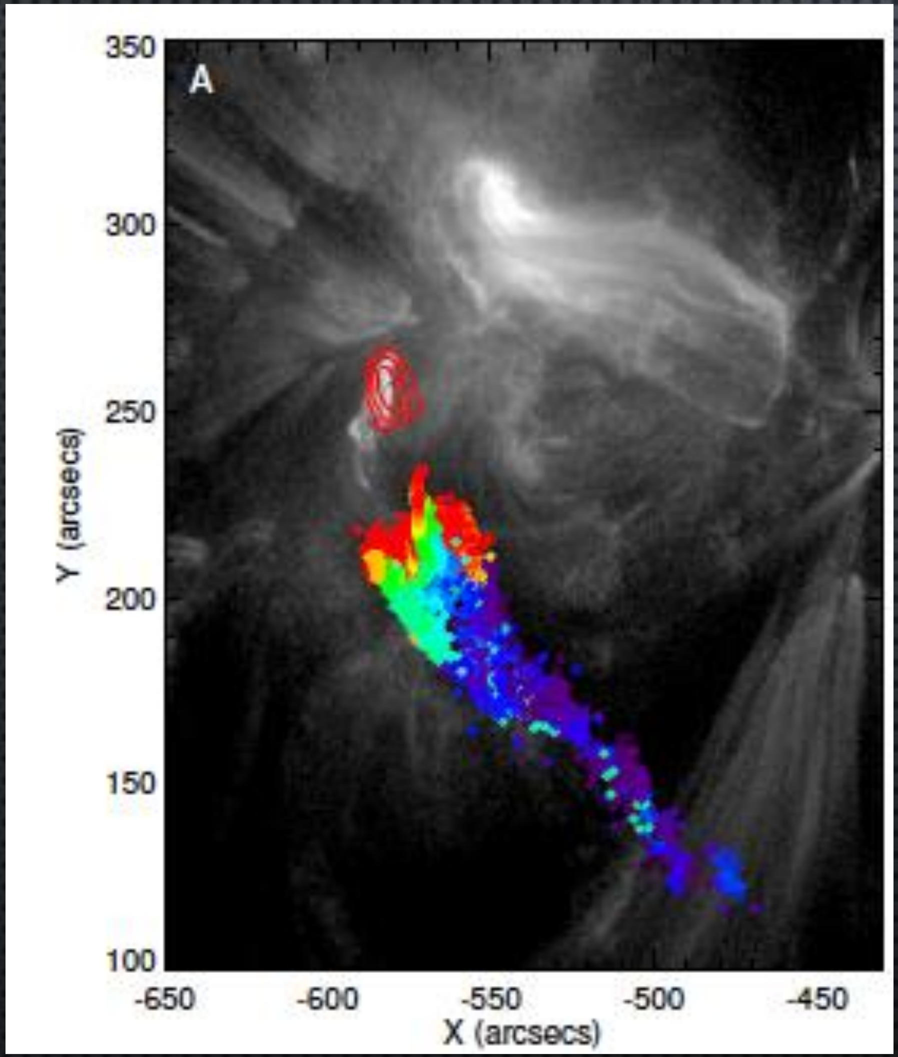
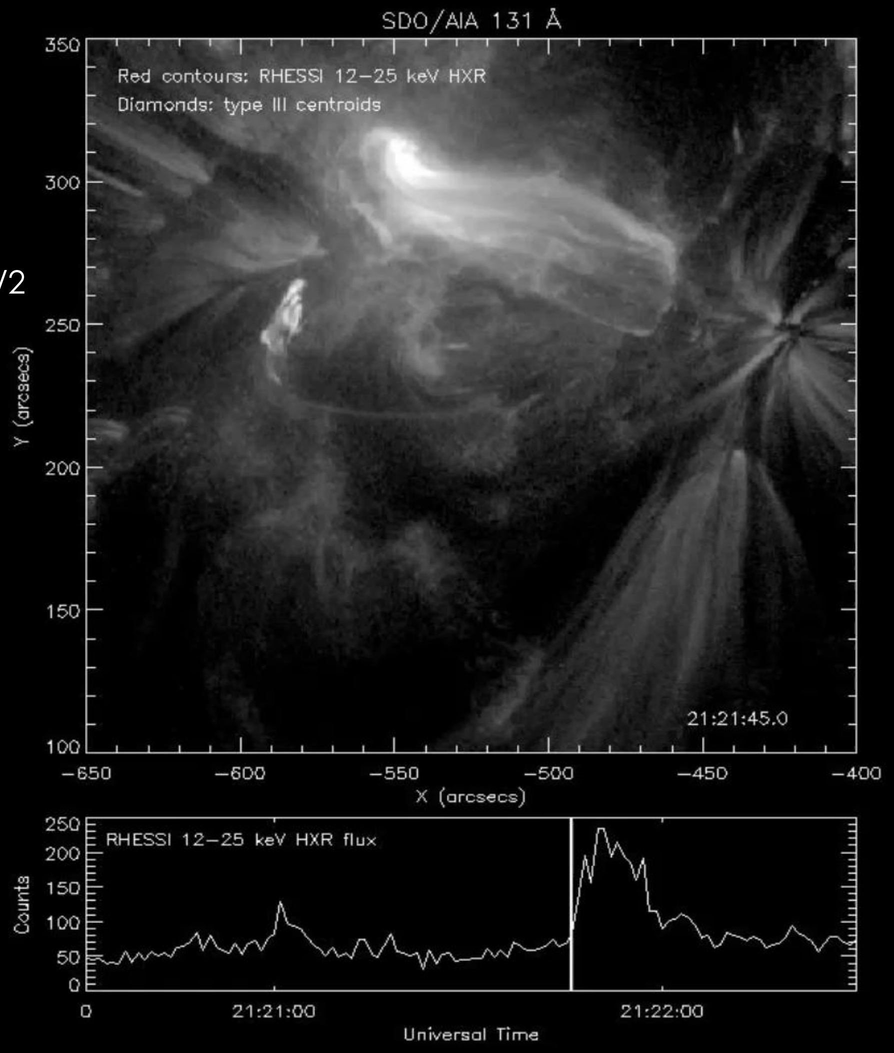
ELECTRON BEAM TRAJECTORIES



X-Ray jet

Type IIIdm

$\nu = 2\nu_{pe} \propto n_e^{1/2}$

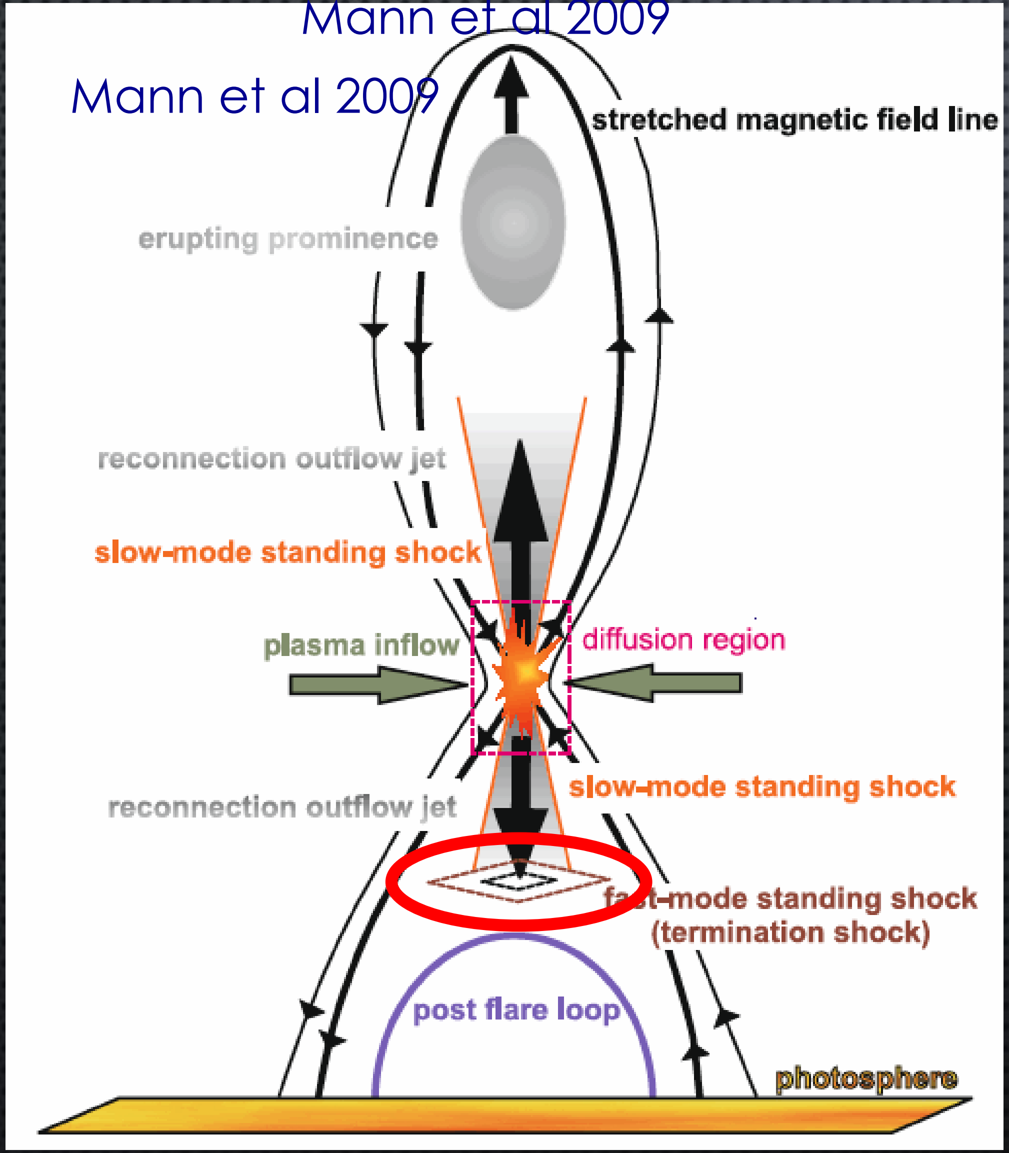


Chen + 2013

SHOCK ACCELERATION IN FLARES

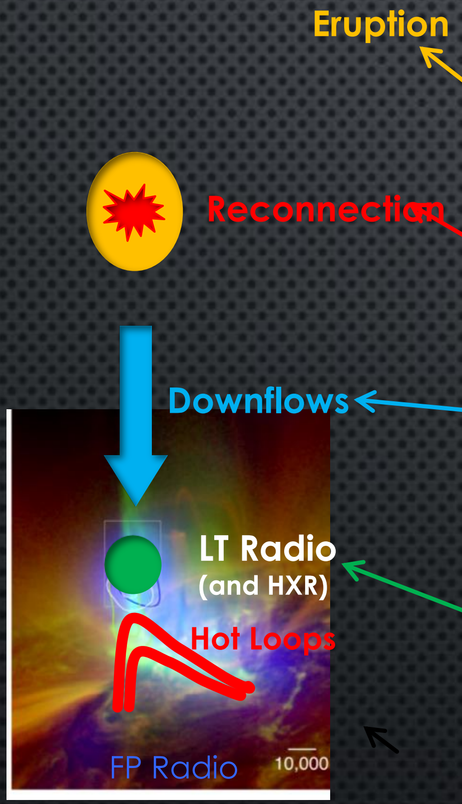
Mann et al 2009

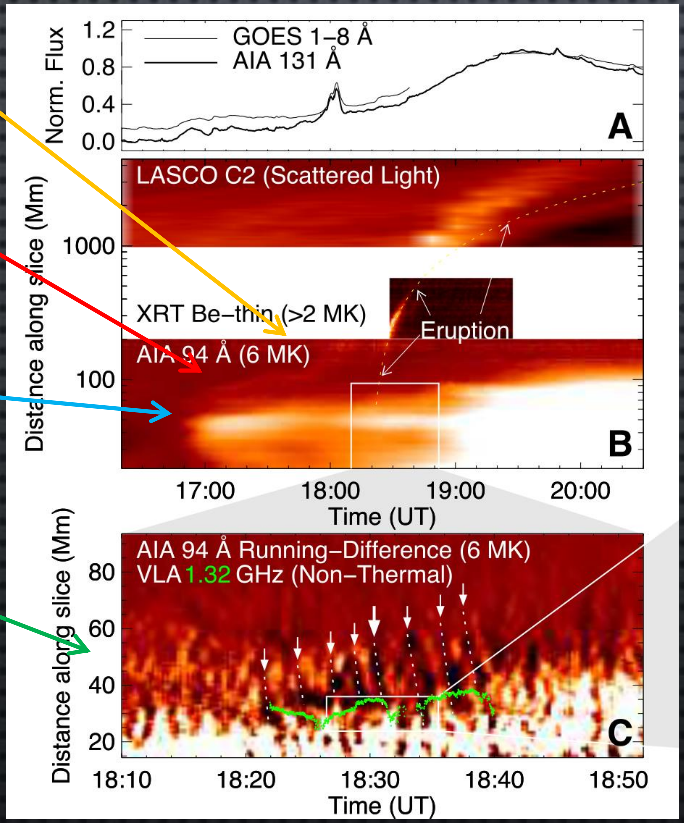
Mann et al 2009

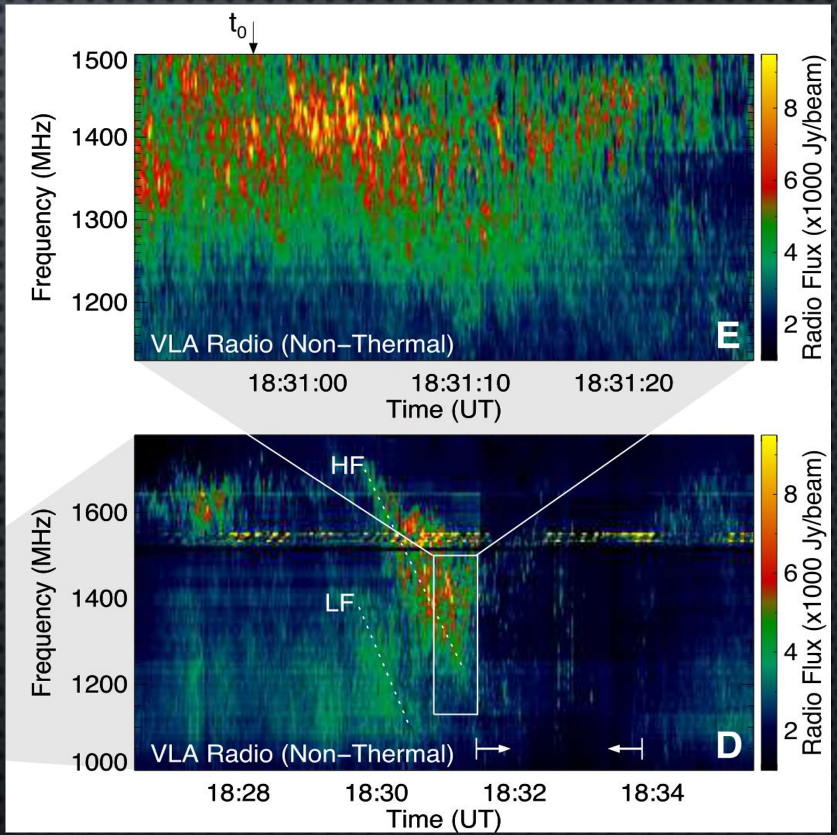


Chen + 2014 2015

RADIO & HXR SOURCE AT THE TERMINATION OF RECONNECTION DOWNFLOWS



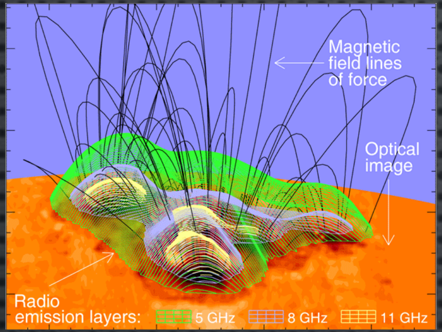




Drifting structure consisting of numerous short-lived, narrowband radio bursts

Chen + 2015

Key Science Objectives



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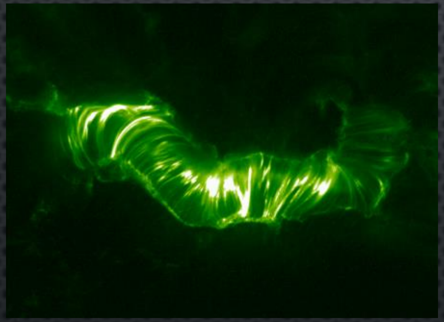

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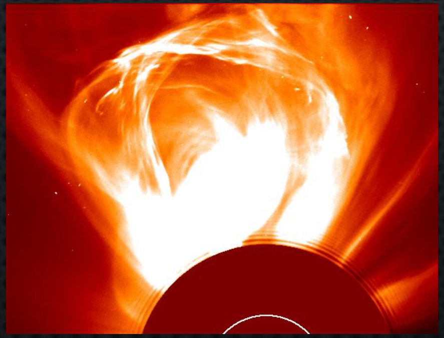

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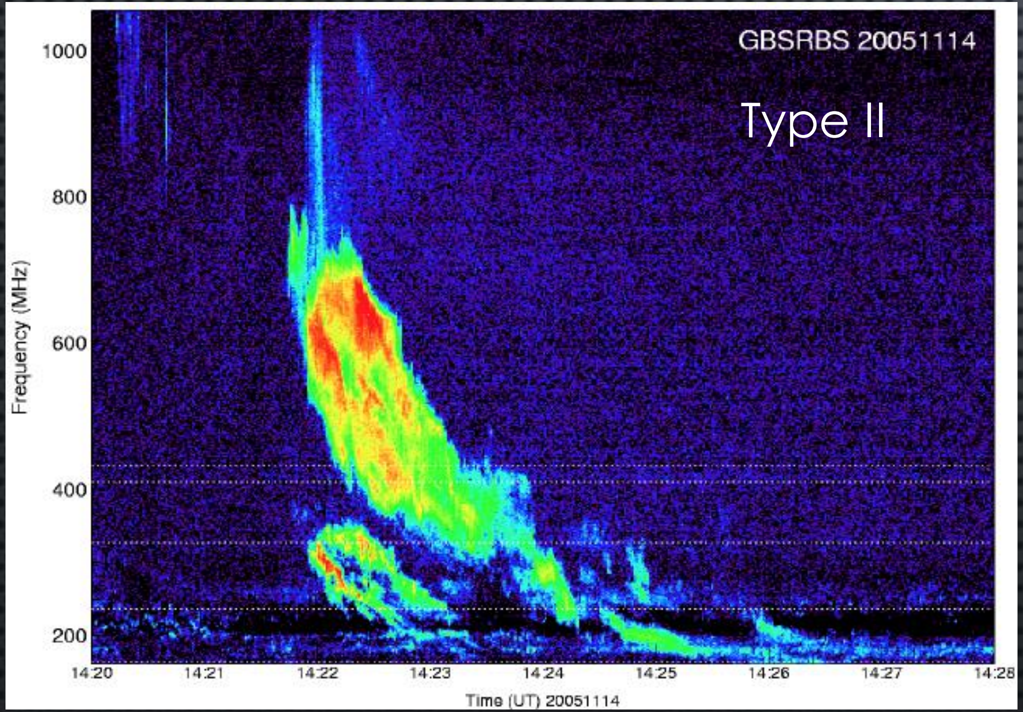
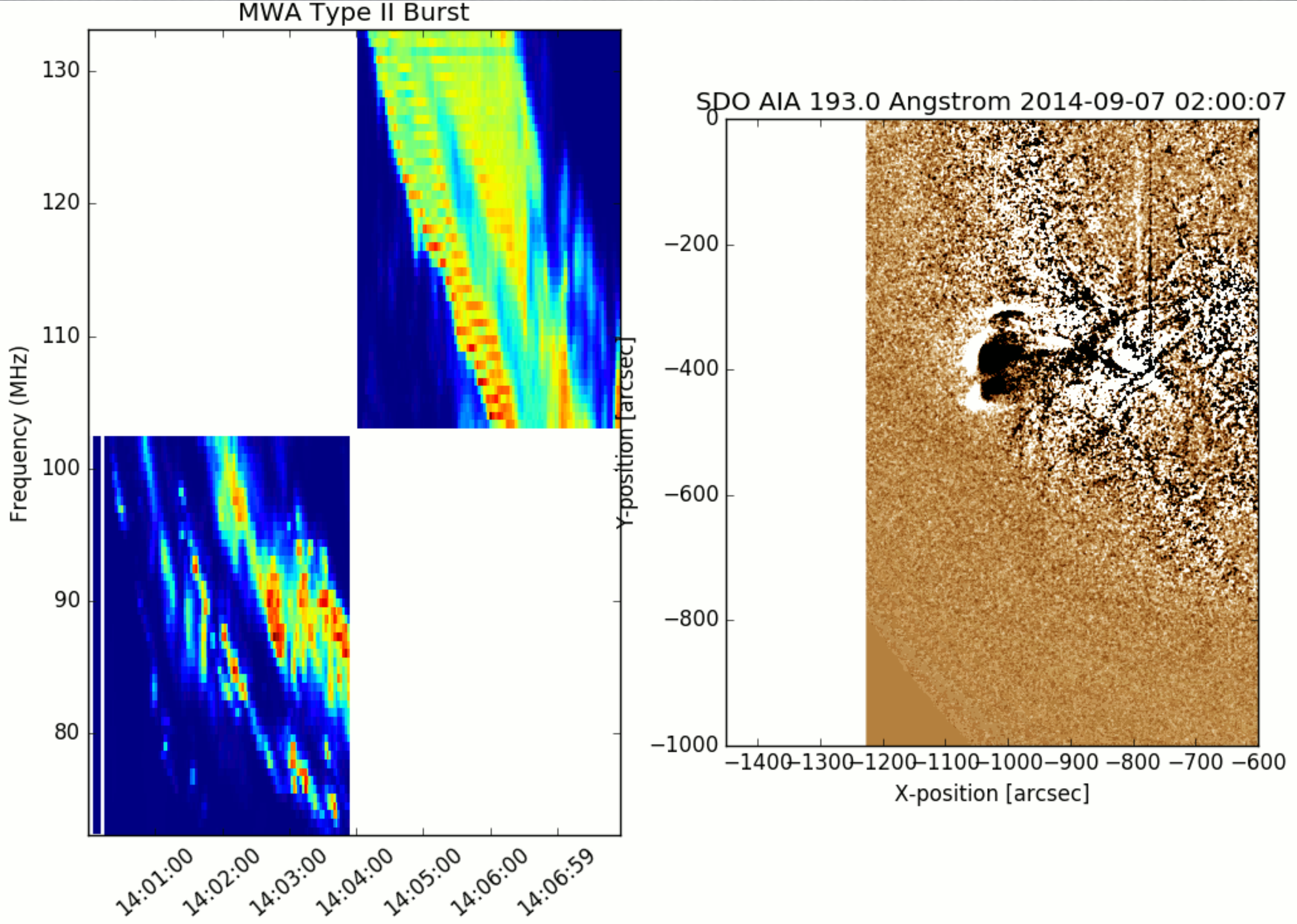
SHOCKS AND CMES



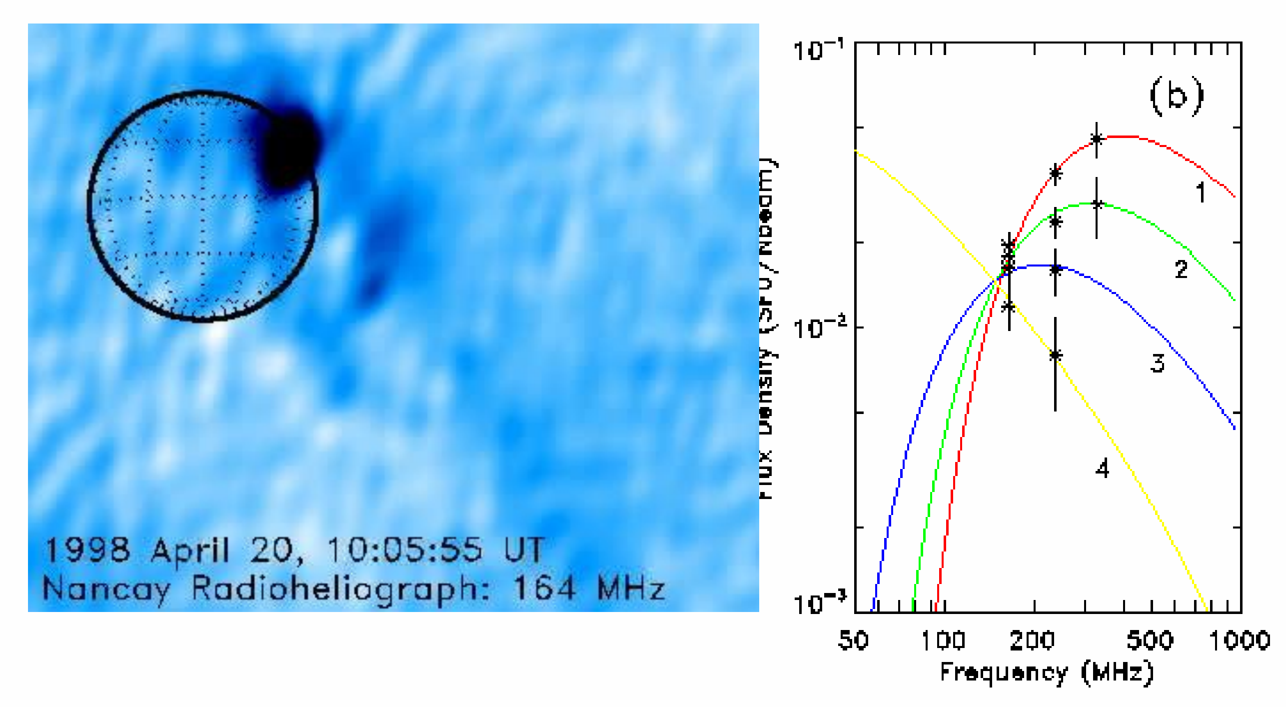
Green Bank Solar Radio Burst Spectrometer

Murchison Widefield Array (MWA)



Oberoi + 2016

SHOCKS AND CMES

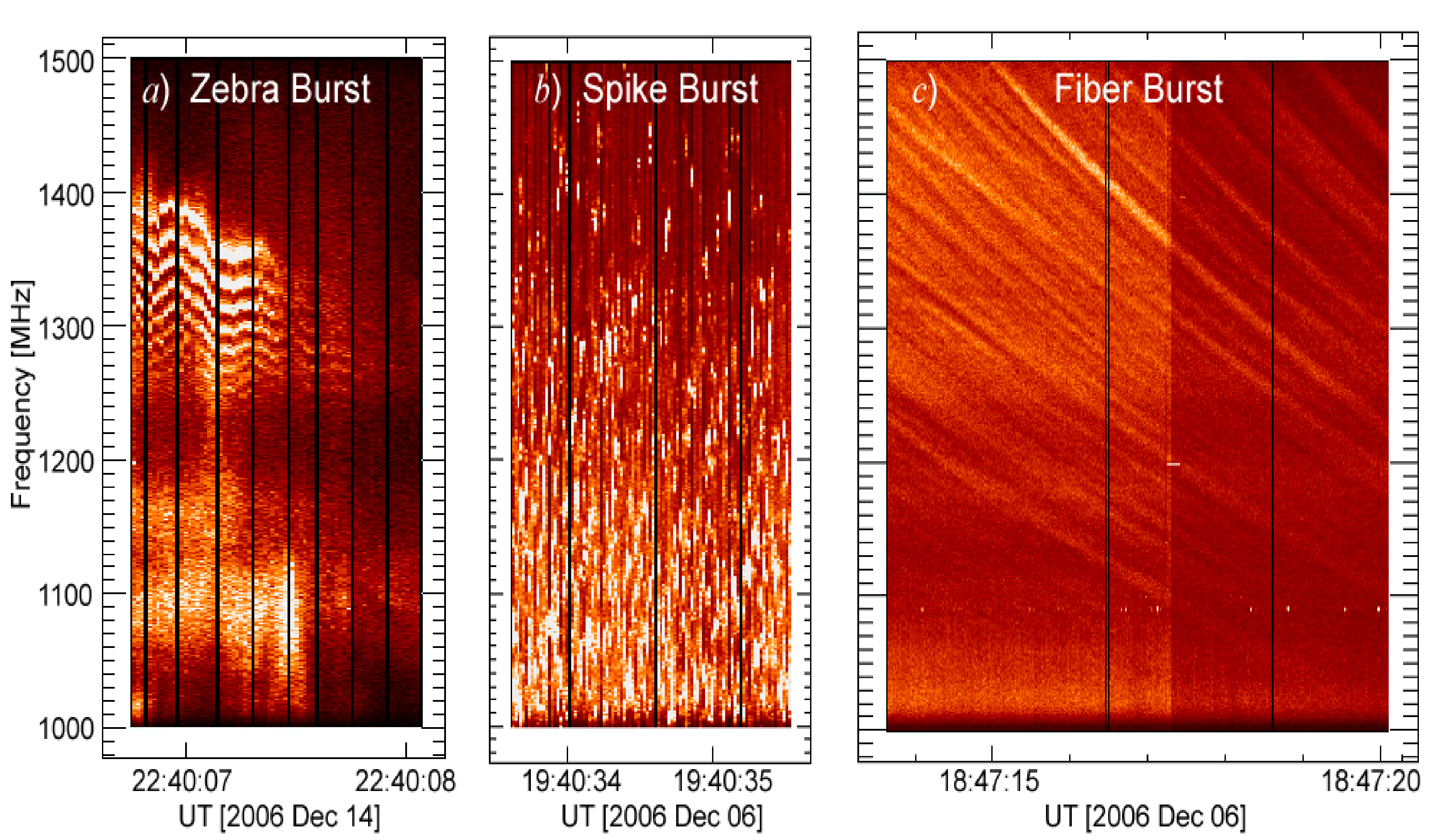


Nancay Radioheliograph (150-450 MHz)

- Synchrotron emission from MeV electrons associated with fast CME
- Razin suppression allows estimate of CME magnetic field!

LoS	α	R_{sun}	ϕ (deg)	n_e (cm^{-3})	B(G)	ν_{RT} (MHz)
1	1.81	1.45	234	2.5×10^7	1.47	330
2	0.54	2.05	218.5	1.35×10^7	1.03	265
3	0.03	2.4	219.5	6.5×10^6	0.69	190
4	-1.07	2.8	221	5×10^5	0.33	30

NEW DOMAIN: COHERENT RADIO BURSTS



FASR Subsystems Testbed

The natural frequencies of the solar corona – ν_{pe} and ν_{Be} – occur at dm-λ to m-λ.

A rich "zoo" of coherent radio bursts occurs at low harmonics of these frequencies or combinations thereof:

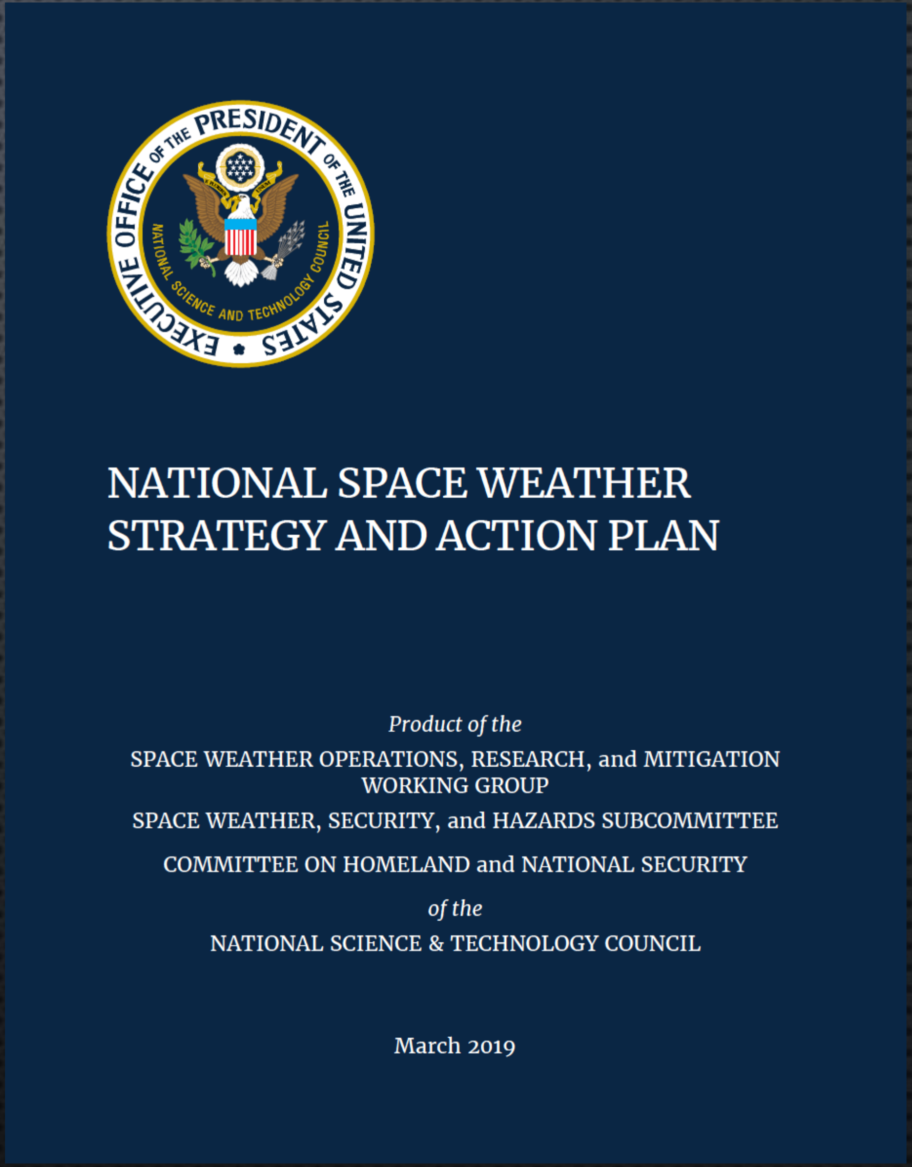
- Plasma radiation (ν_{pe})
- Spike bursts ECM (ν_{Be})
- Zebra pattern DPR (ν_{UH})

- Their diagnostic potential is only just now being realized.

A PRACTICAL MATTER: COHERENT RADIO BURSTS

National Space Weather Strategy & Action Plan (2015, 2019)

- Multi-agency plan in response to potential for significant SWx events
- Five major threats undergoing benchmarking:
  - solar radio bursts
  - induced geoelectric fields
  - ionizing radiation
  - ionospheric disturbances
  - upper atmospheric expansion
- The science of coherent bursts and our ability to predict them as a SWx hazard needs attention!


EXECUTIVE OFFICE OF THE PRESIDENT OF THE UNITED STATES
NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

NATIONAL SPACE WEATHER STRATEGY AND ACTION PLAN

Product of the

SPACE WEATHER OPERATIONS, RESEARCH, and MITIGATION WORKING GROUP

SPACE WEATHER, SECURITY, and HAZARDS SUBCOMMITTEE

COMMITTEE ON HOMELAND and NATIONAL SECURITY

of the

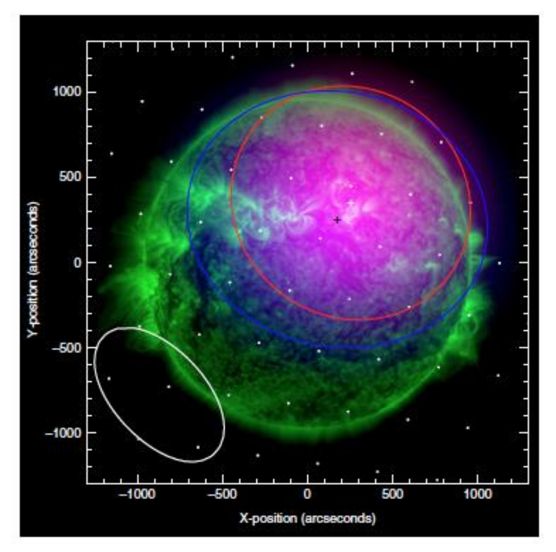
NATIONAL SCIENCE & TECHNOLOGY COUNCIL

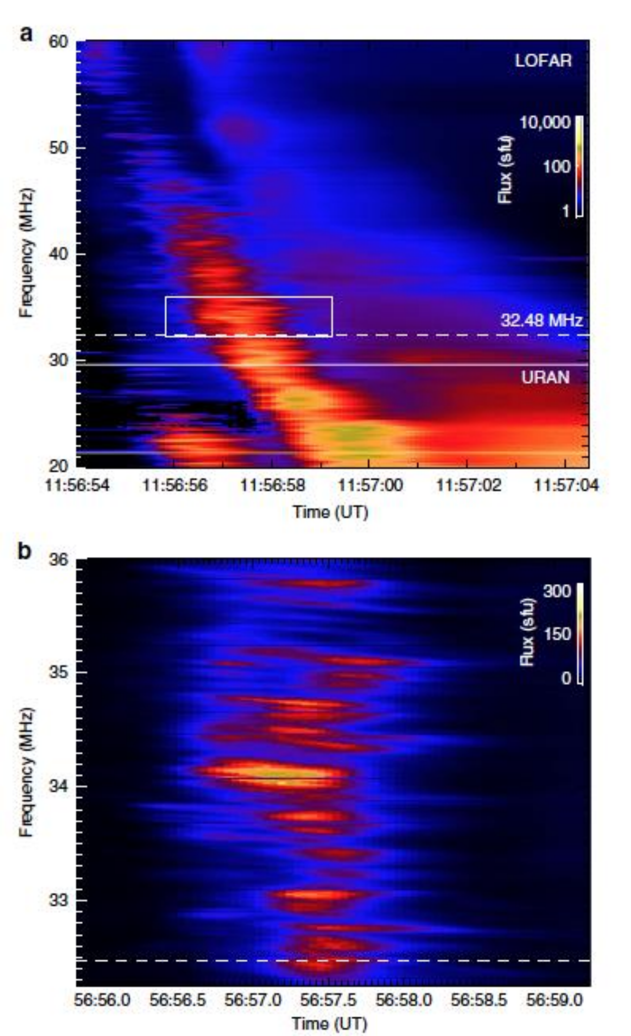
March 2019

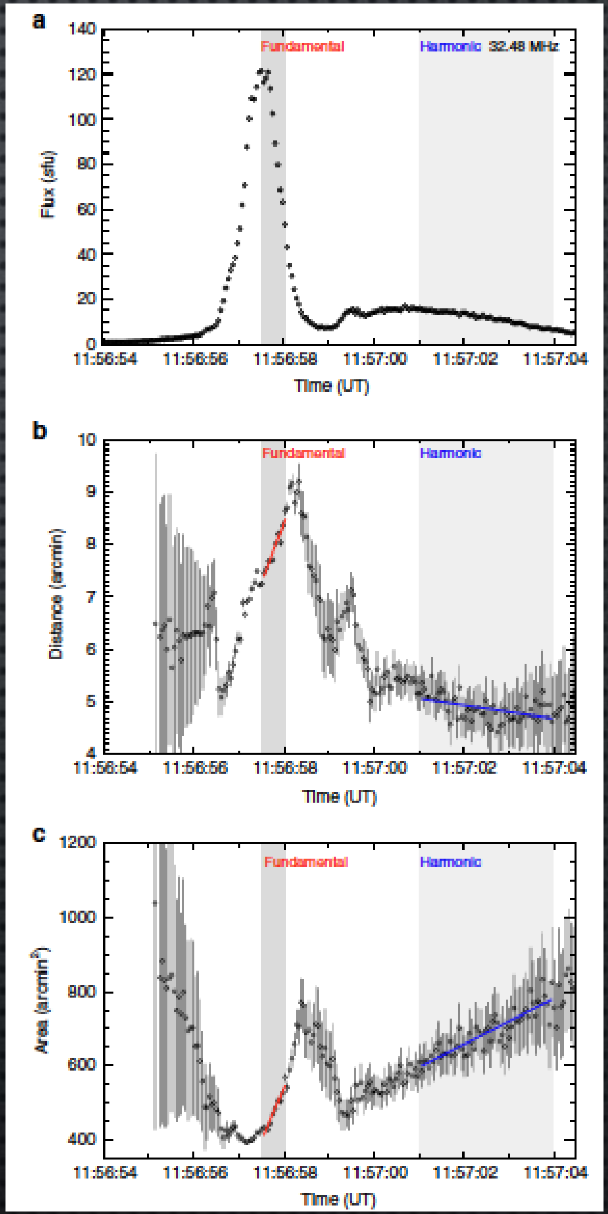
TYPE III RADIO BURSTS

LOFAR

Use type III radio bursts to demonstrate time delay due to multi-path propagation.







Kontar + 2017