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Remote Measurement of Plasma Parameters of Coronal Mass Ejections using Spectropolarimetric Radio Imaging

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Coronal Mass Ejections (CMEs)

- Large scale eruptions of magnetized plasma.
- Average velocity - few hundreds to few thousands km/s.
- CME needs few hours to days to reach the Earth.

Routinely CMEs are observed using Thomson scattered white-light observations using coronagraphs and heliospheric imagers

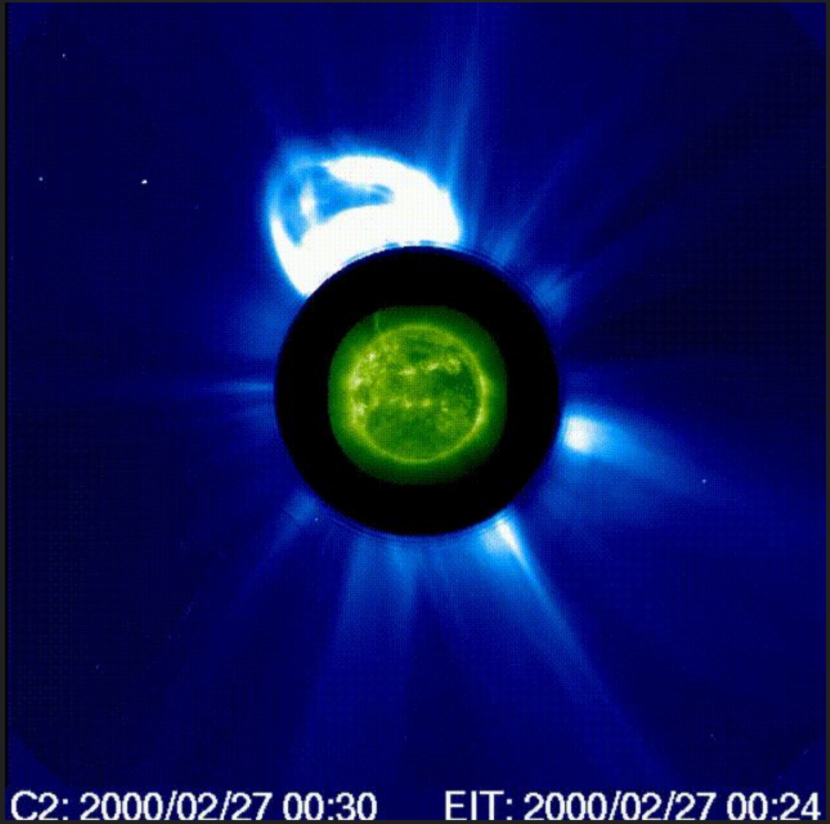
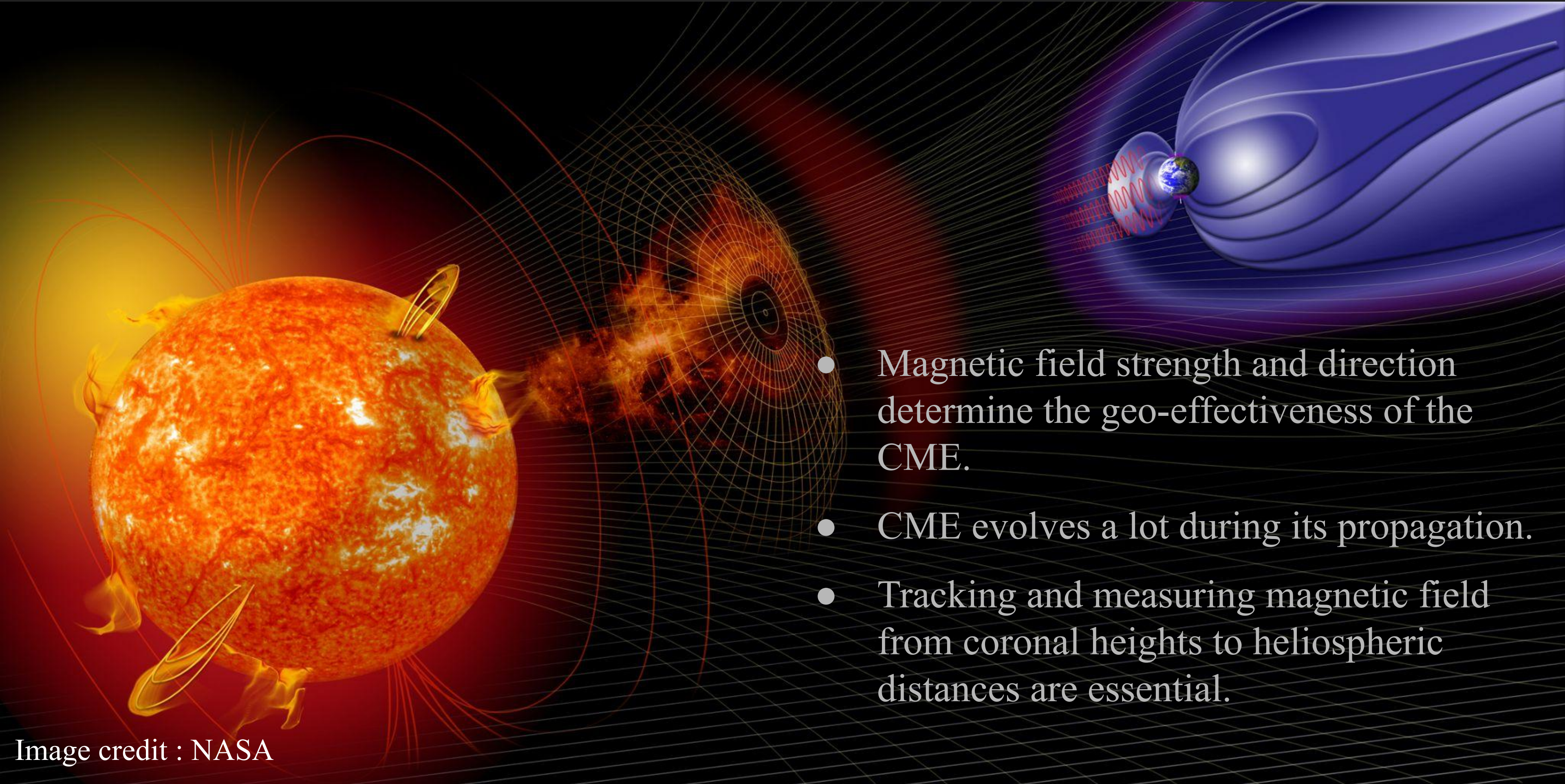


Image credit : SOHO EIT and LASCO C2

How do CMEs affect Earth?



- Magnetic field strength and direction determine the geo-effectiveness of the CME.
- CME evolves a lot during its propagation.
- Tracking and measuring magnetic field from coronal heights to heliospheric distances are essential.

Image credit : NASA

Measuring CME Entrained Magnetic Field

- Routine coronagraphs observations at visible wavelengths can not provide direct measurements of magnetic fields of CMEs.
- "Flux Rope from Eruption Data" or FRED of the reconnected flux-rope (Gopalswamy et al. 2022) and geometrical modeling of white-light observations can provide in-direct estimation.
- Observations at radio wavelengths are well-suited for remote measurement of CME magnetic fields.

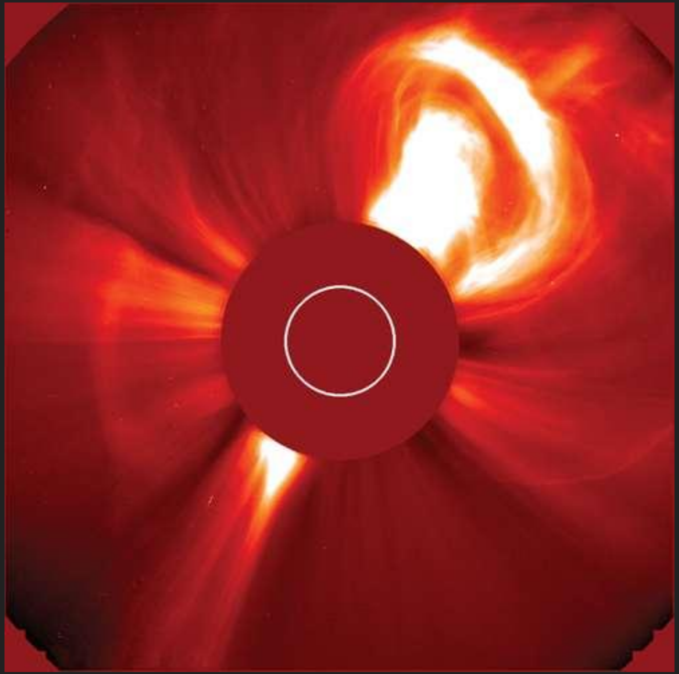


Image credit : LASCO C2

Space Weather Observable at Radio Wavelengths

- Direct methods –
  - Radio bursts (upto 1.5 $R_\odot$ using ground-based instruments)
    - From CME shocks and core
  - Radio emission from CME plasma (upto ~10 $R_\odot$)
    - Circular polarization of thermal emission (e.g., Ramesh et al. 2020)
    - Gyrosynchrotron emission (e.g., Bastian et al. 2001, Carley et al. 2017)
- In-direct methods –
  - Interplanetary Scintillation (IPS)
  - Faraday rotation (FR) measurements (Kooi et al. 2022, for a review)
    - Background linearly polarized galactic/extra-galactic radio sources
    - Linearly polarized galactic diffuse emission

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Gyrosynchrotron Emission from CME Plasma

Gyrosynchrotron (GS) Emission from CMEs

- Gyrosynchrotron emission is produced by gyrating electrons in magnetic fields.
- Produced by mildly relativistic ($\gamma \sim$ 1-5) non-thermal or thermal electrons (Ramaty 1969)
- Mildly relativistic electrons inside CME plasma are originated either from source region, due to shock acceleration or due to local magnetic reconncection (Mondal et al. 2020).
- Produce gyrosynchrotron emission in the presence of CME magnetic fields.

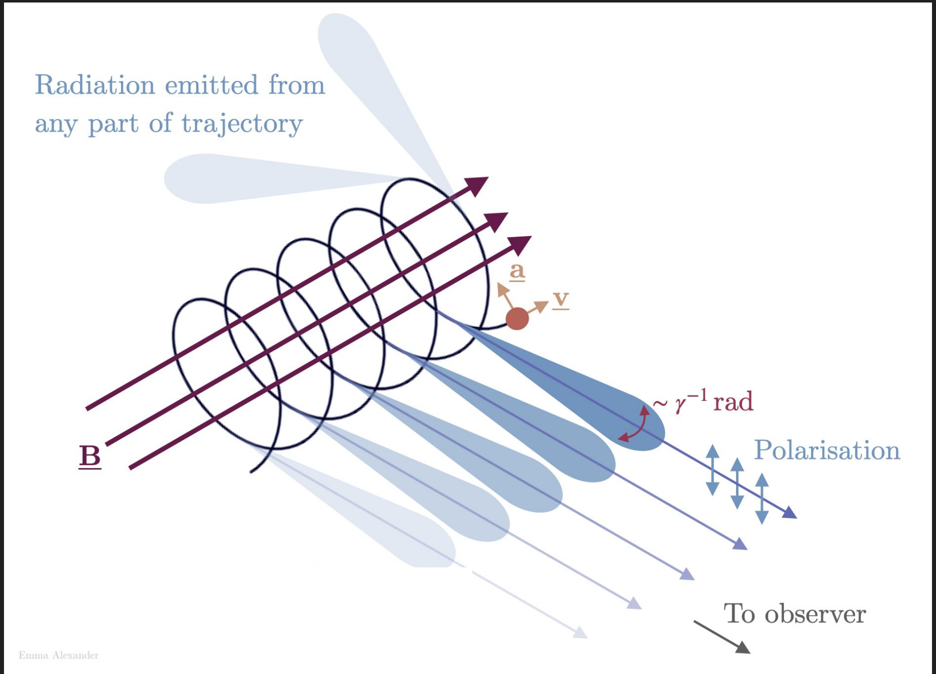
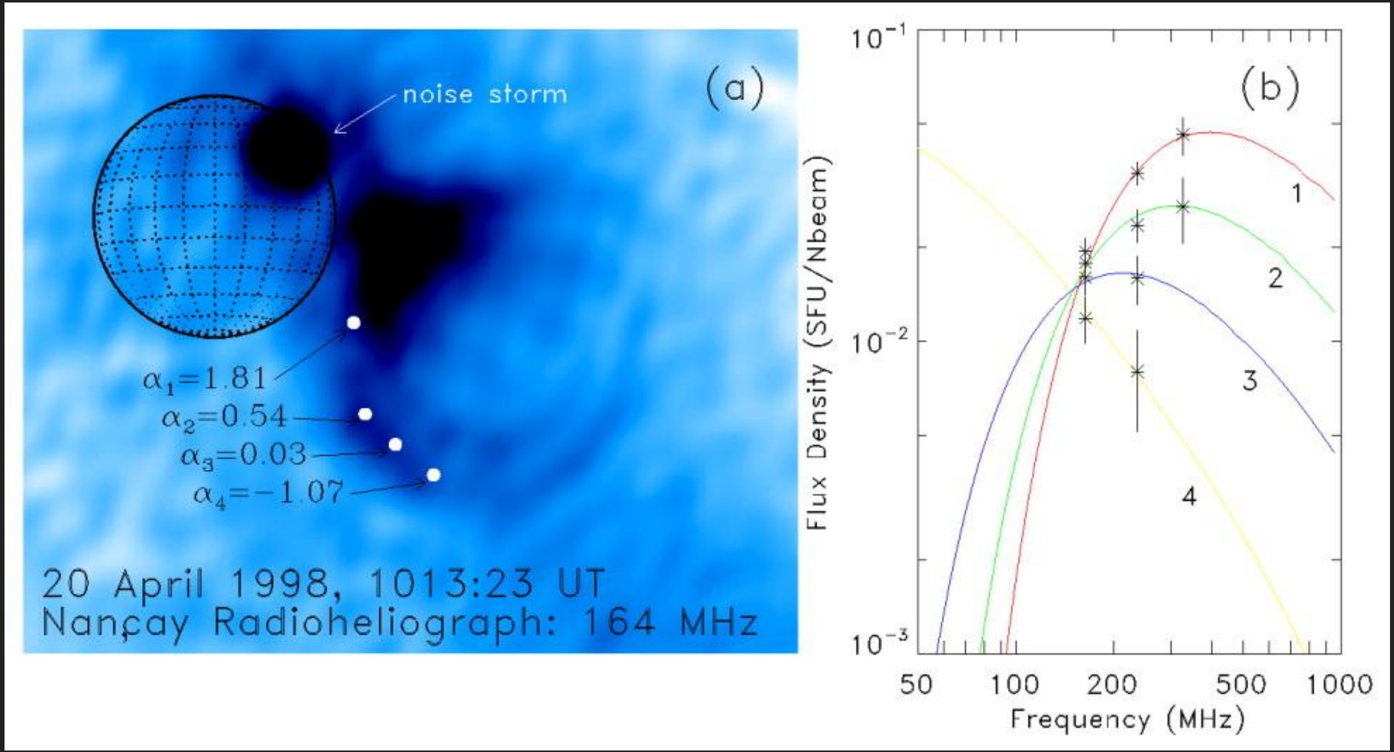


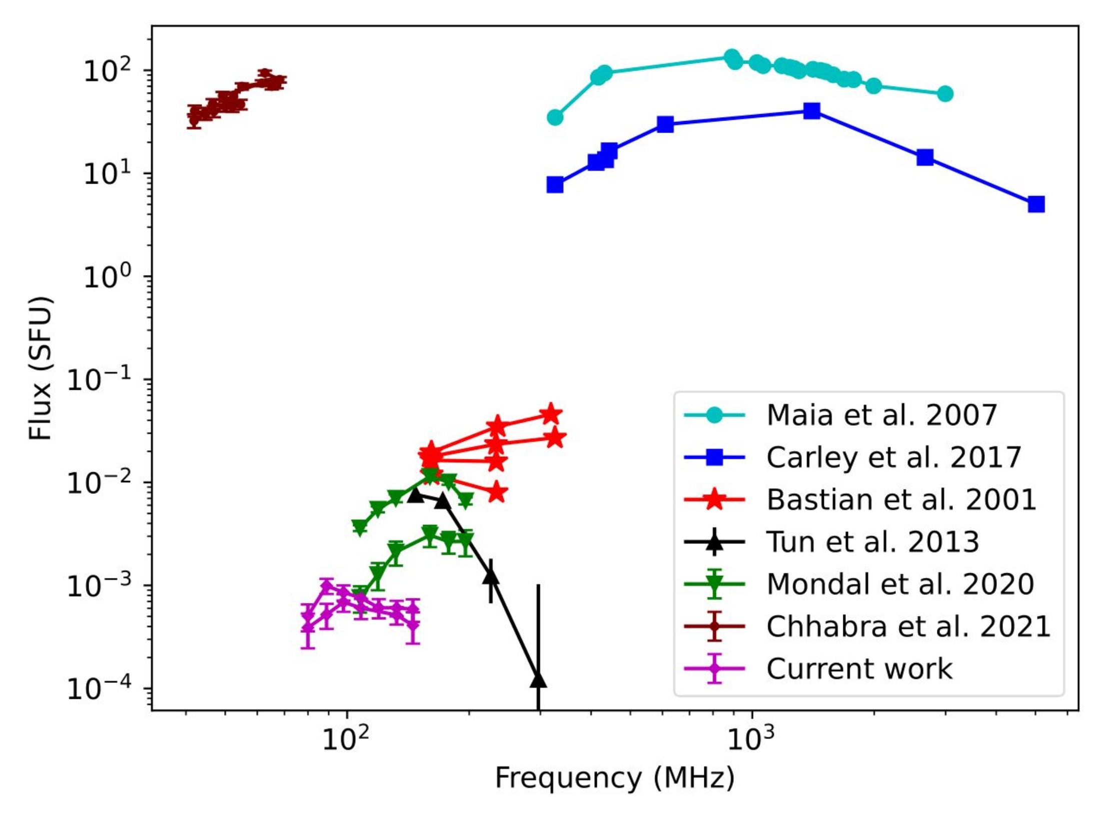
Image credit: Wikipedia

First Detection of GS Emission from CME



Detected radio emission upto 2.8 $R_\odot$ (Bastian et al. 2001)

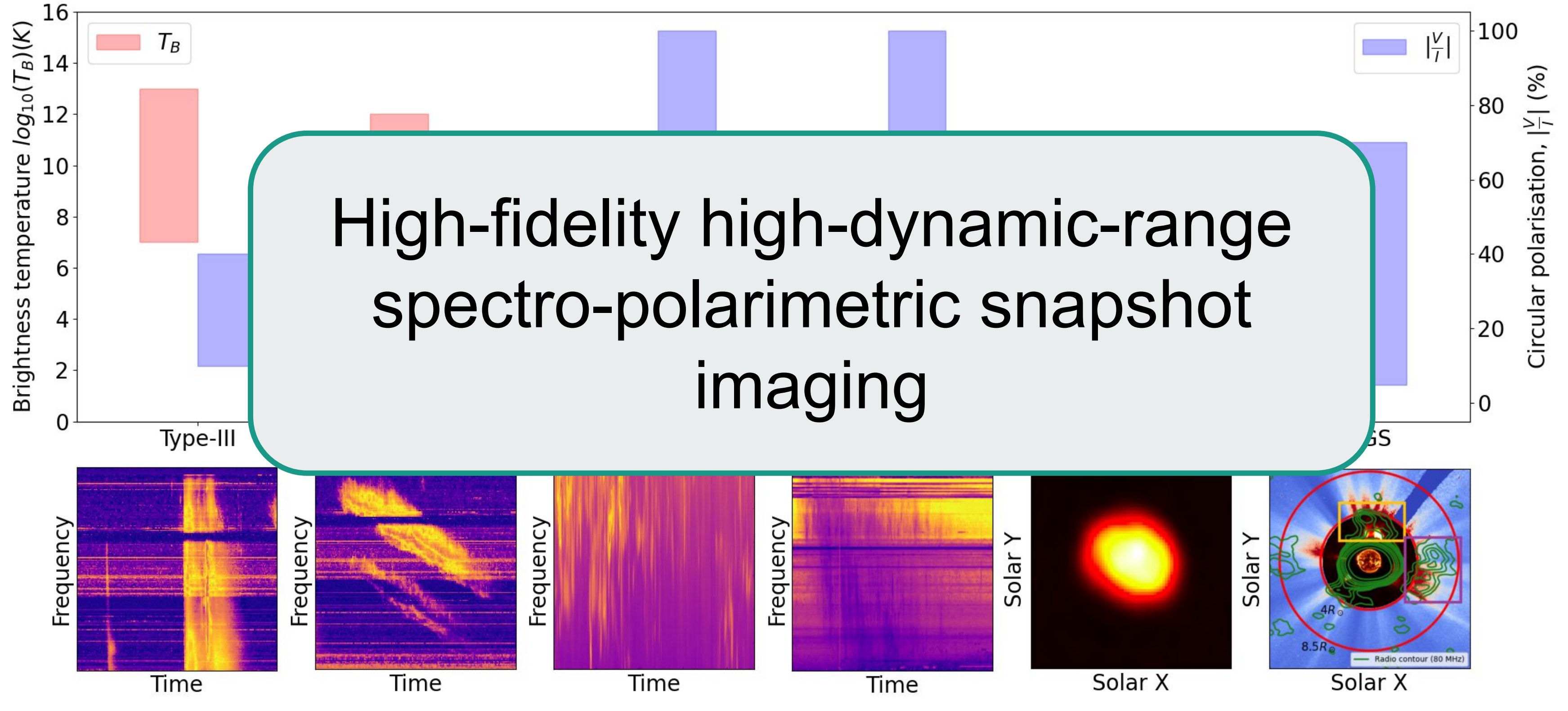
Other Earlier Studies



Kansabanik et al. 2023, Submitted to ApJ, arXiv:2301.06522

- Most of them are associated with the fast CMEs.
- Spectral-coverage are not always good.
- Numbers of them are non-imaging studies, hence do not have any spatial information.
- Limited detection due to observational challenge.

Observational Challenges



High-fidelity high-dynamic-range spectro-polarimetric snapshot imaging

Kansabanik 2022, Solar Physics, 297, 122

Tackling these Challenges

- Radio interferometric imaging is a Fourier synthesis imaging.
- Dense array coverage is required to improve the fidelity of the images.
- Robust characterization and modeling of instrument.
- Robust calibration of the instrumental and ionospheric effects.

Murchison Widefield Array (MWA) (Square Kilometre Array precursor)

128 (currently 144) antenna tiles, 80 - 300 MHz, 30.72 MHz bandwidth, 10 kHz, 0.25 s

(Tingay et al. 2013, Wayth et al. 2018)

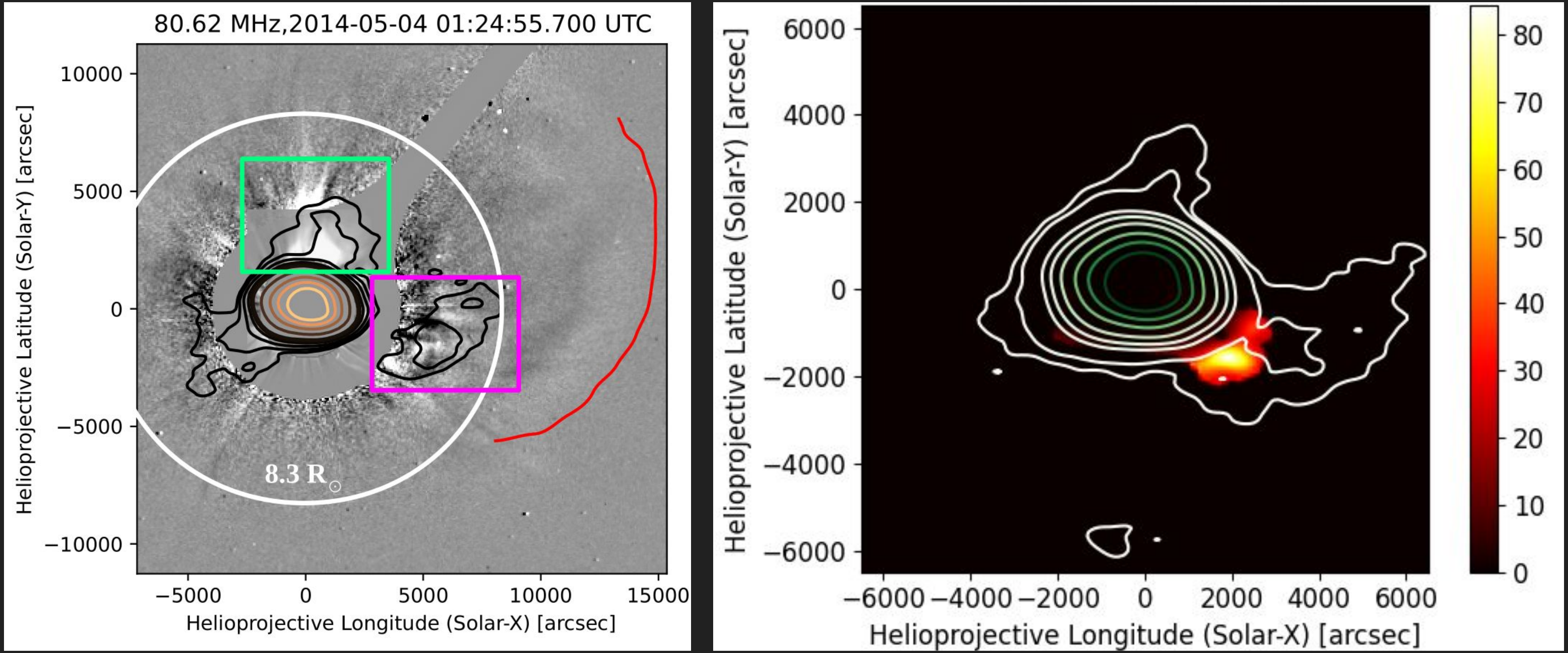
Tackling these Challenges

- High fidelity spectro-polarimetric snapshot imaging (10 kHz and 0.5 s).
- Dynamic range varies between 300 to 10^5.
- Polarization calibration is on per high quality astronomical observations
    - Residual leakage from Stokes I to Stokes Q is about 1%.
    - Residual leakage from Stokes I to Stokes U, V is less than 0.1%.
- Leakages are measured using background radio sources.

Polarimetry using Automated Imaging Routine for the Compact Arrays for the Radio Sun (P-AIRCARS)

(Kansabanik et al 2022a, ApJ 932 110, Kansabanik et al. 2022b, Accepted at ApJS, arXiv:2209.06666)

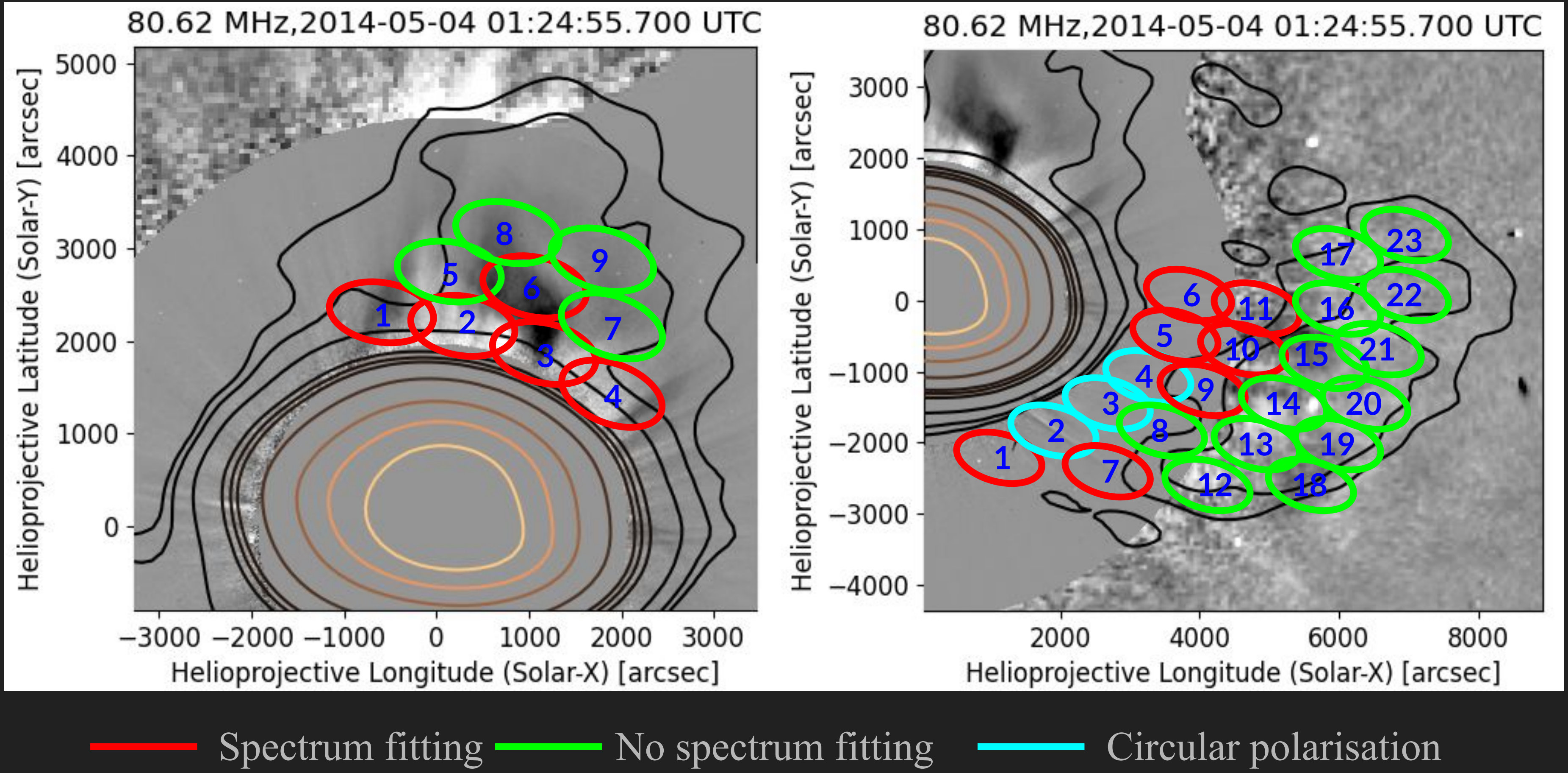
GS Radio Emission from CMEs



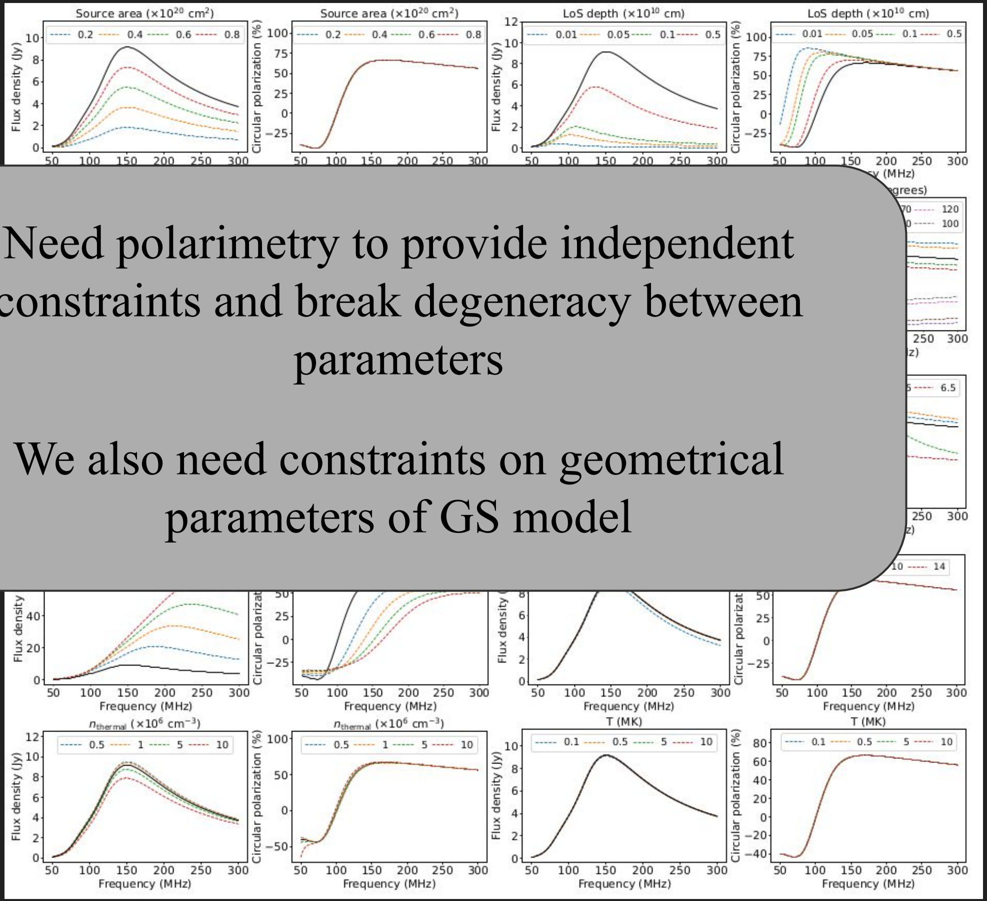
Detection of the faintest GS emission at the highest heliocentric distance (8.3 $R_\odot$)

Kansabanik et al. 2023, Submitted to ApJ, arXiv:2301.06522

Spatially Resolved Spectroscopy



Sensitivity of GS Model Parameters

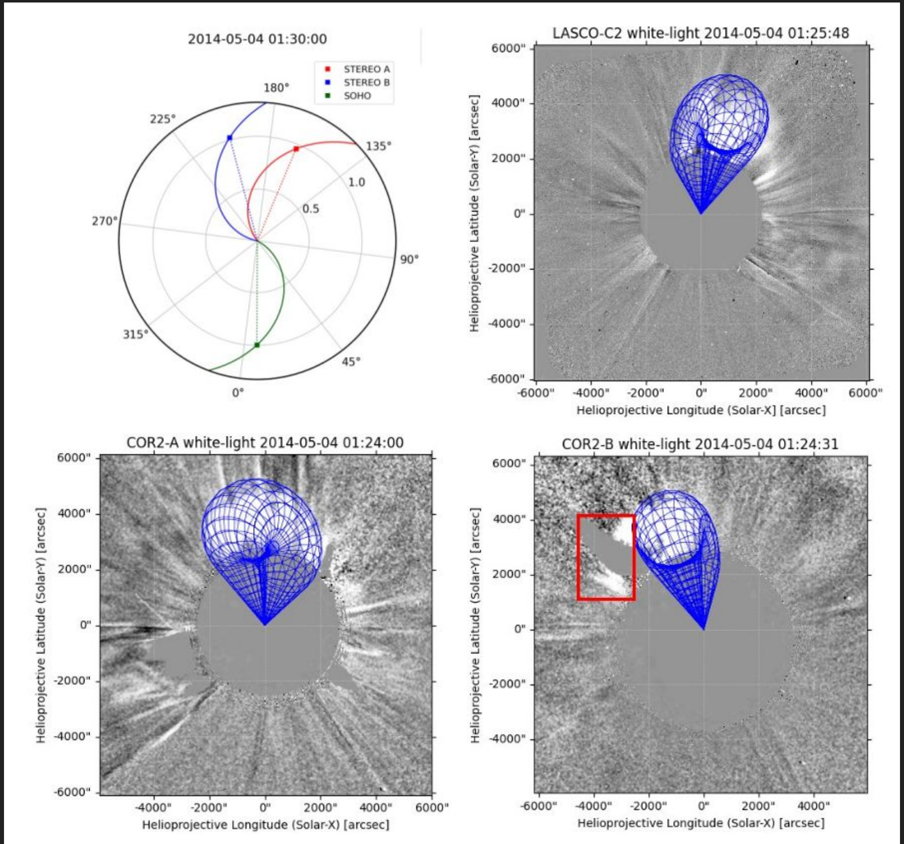


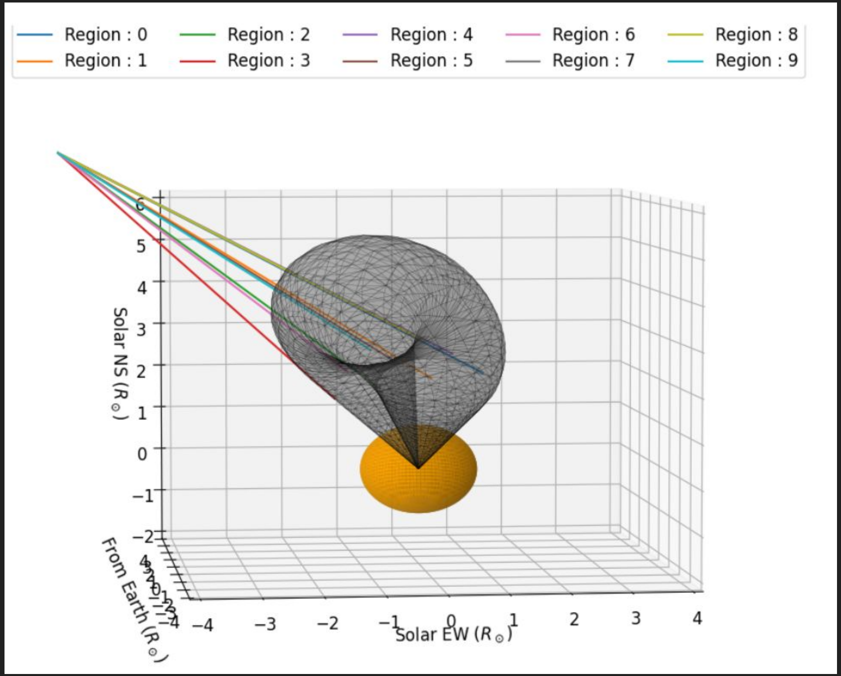
- Need polarimetry to provide independent constraints and break degeneracy between parameters
- We also need constraints on geometrical parameters of GS model

- Exact expression of GS emission (Ramaty 1969) is compute intensive.
- We use numerical GS code developed by Fleishman & Kuznetsov 2010 and Kuznetsov & Fleishman 2021a.
- We consider single power-law distribution for non-thermal electrons

$$u(E) = N\,E^{-\delta}\ (E_{min} < E < E_{max})$$

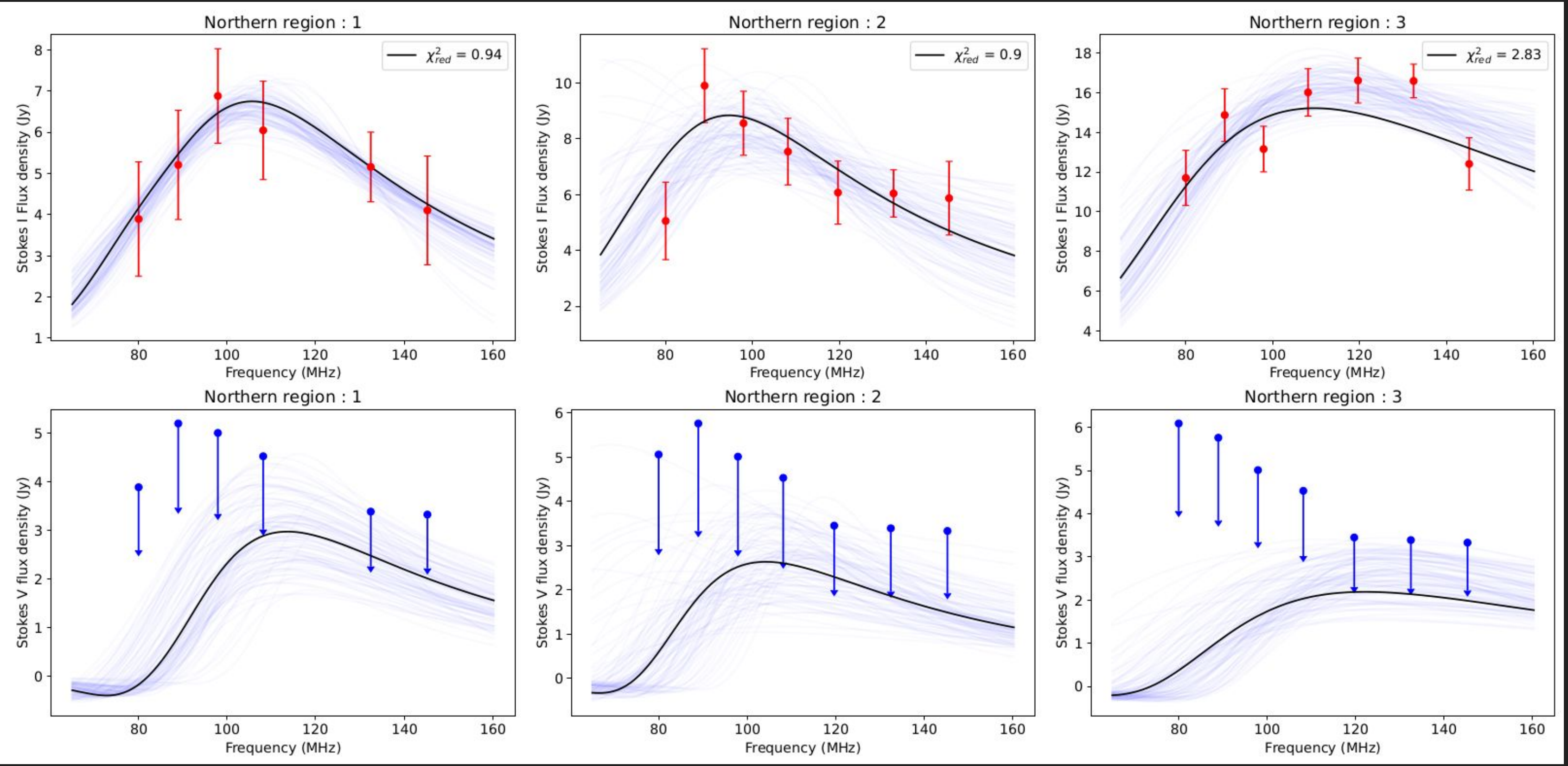
Geometrical Constraints (Multi-vantage Point Observations)



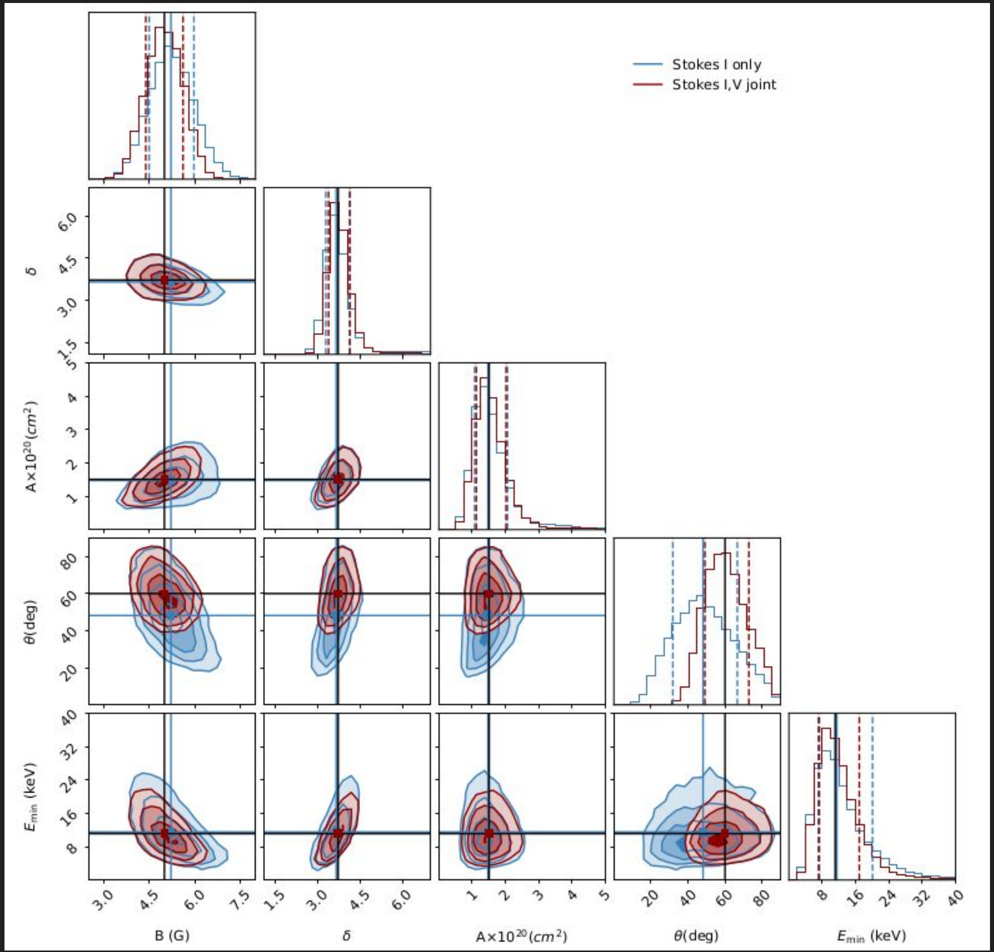


This provides upper bounds on the LoS depth of the GS source

GS Modeling – Stokes I and V Joint Modeling



Importance of Joint Stokes I and V Modeling



- ❖ Even upper limits on absolute Stokes V provides tighter constraints on model parameters (upto 30% improvements).
- ❖ Joint Stokes I and V modeling allows to fit more parameters
- ❖ Estimated GS model parameters
  - Magnetic field strength (B)
  - Area of emission (A)
  - Non-thermal electron power-law index (δ)
  - LoS angle with the magnetic field
  - E_{min}
  - LoS depth