LOFAR Data School, 2026

Solar data analysis and imaging

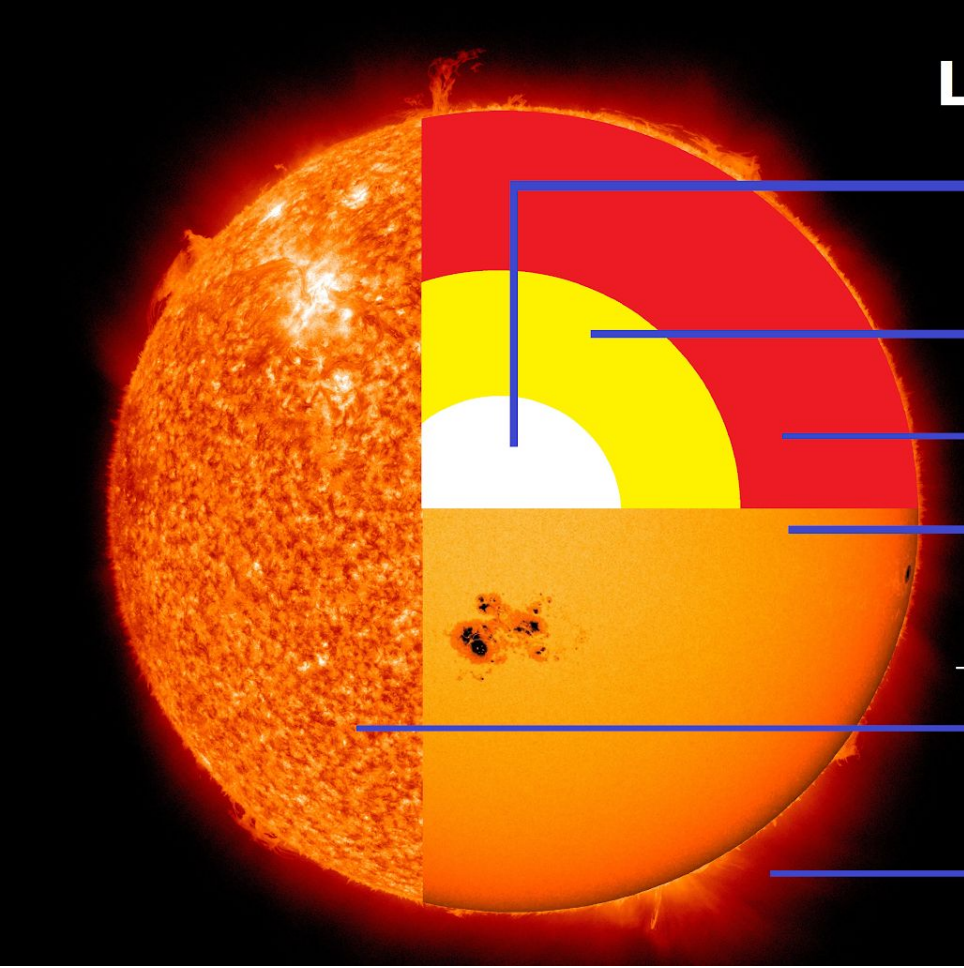
Soham Dey, Maaijke Mevius, Aleksandar Shulevski

17th September 2026

About this session

- Lecture (~40 minutes)
  - Brief introduction to solar radio emissions
  - Challenges of calibration and imaging for solar radio observations at low frequencies
  - Solar IMaging pipeline for LOFAR (SIMPL)
- Tutorial

Layers of the Sun



Core 15,000,000K
Where fusion occurs

Radiative zone 7,000,000K

Convective zone 2,000,000K

Gets hotter going in

Photosphere 6,500K to 4,000K
The visible surface of the Sun
Sunspots

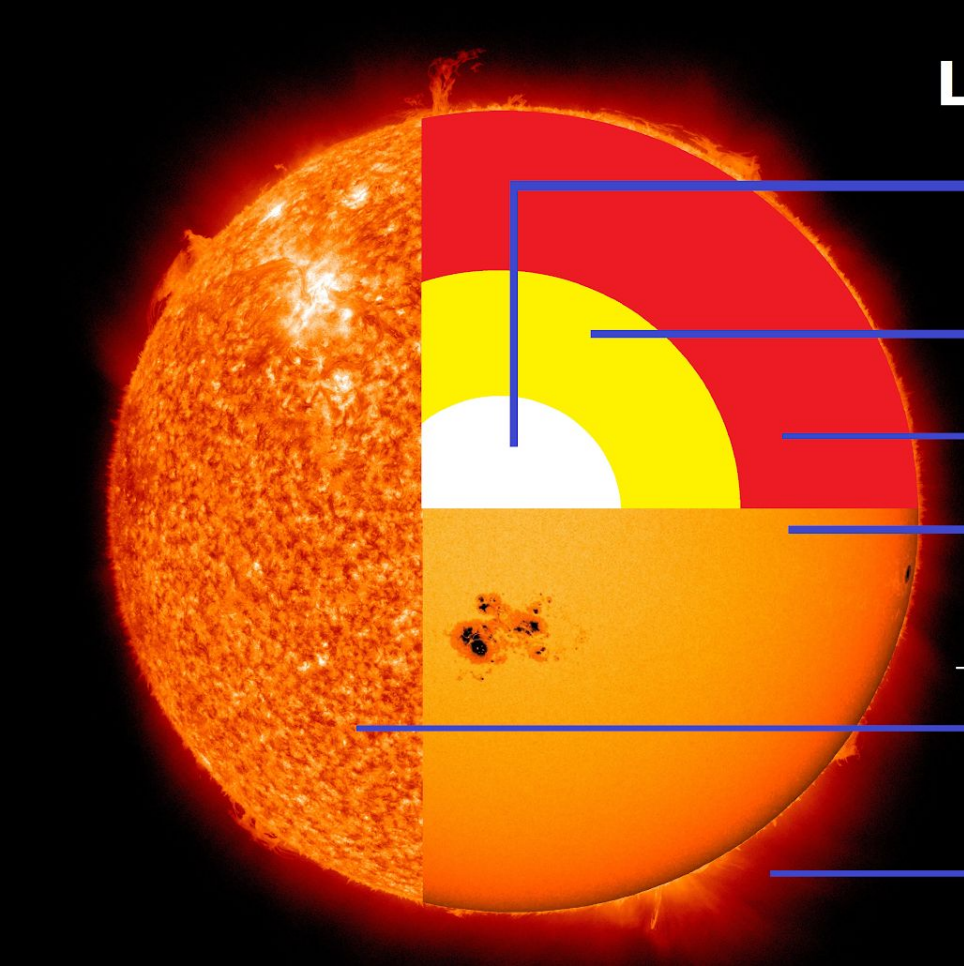
Chromosphere 4,000K to 8,000K
Flares and prominences

Corona 500,000K to 1,000,000K

Gets hotter going out

Source: Wikipedia

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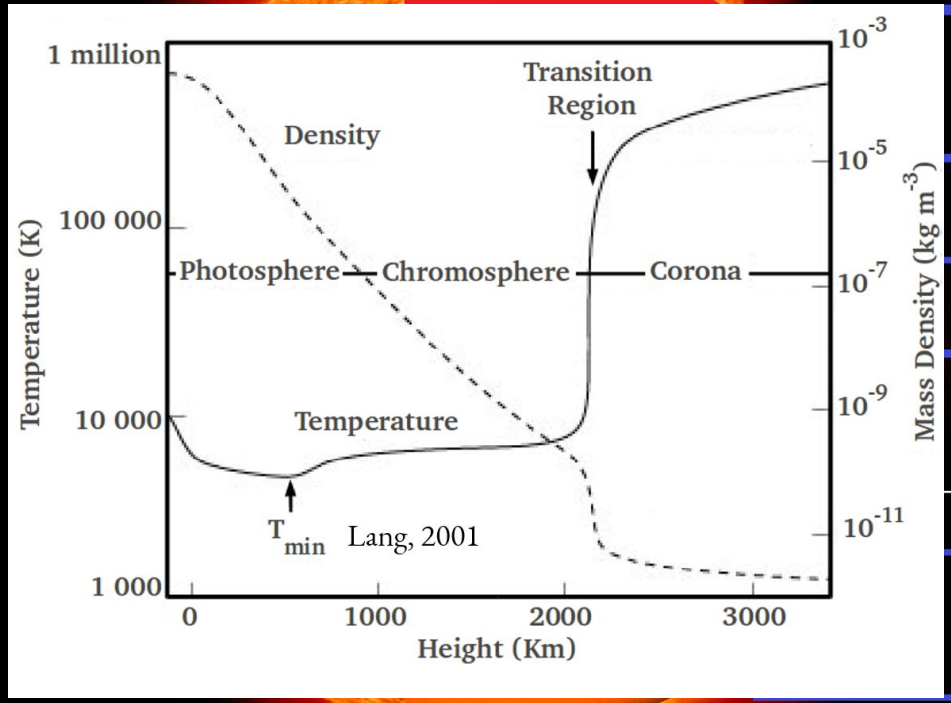
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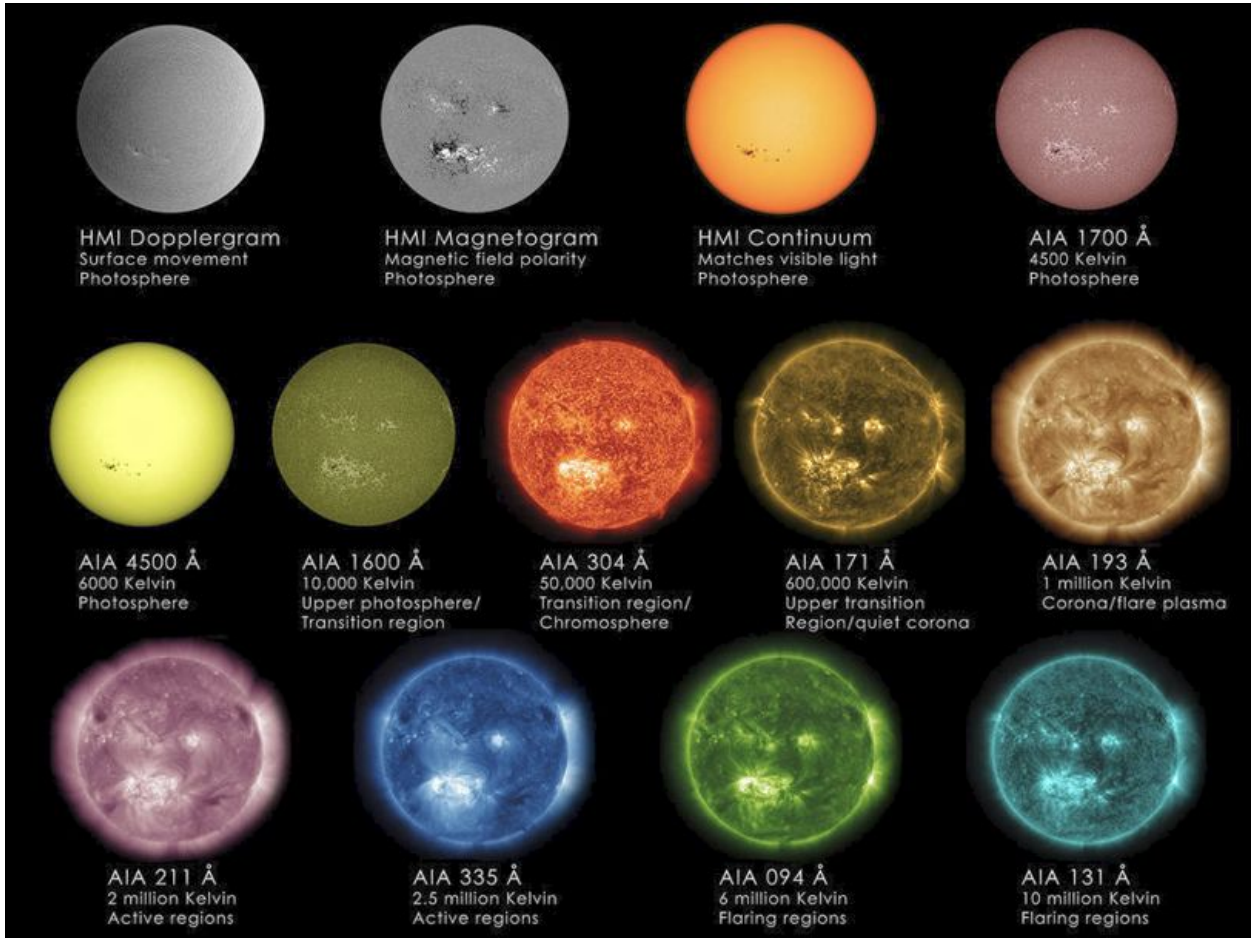
Transition region

Corona 500,000K to 1,000,000K

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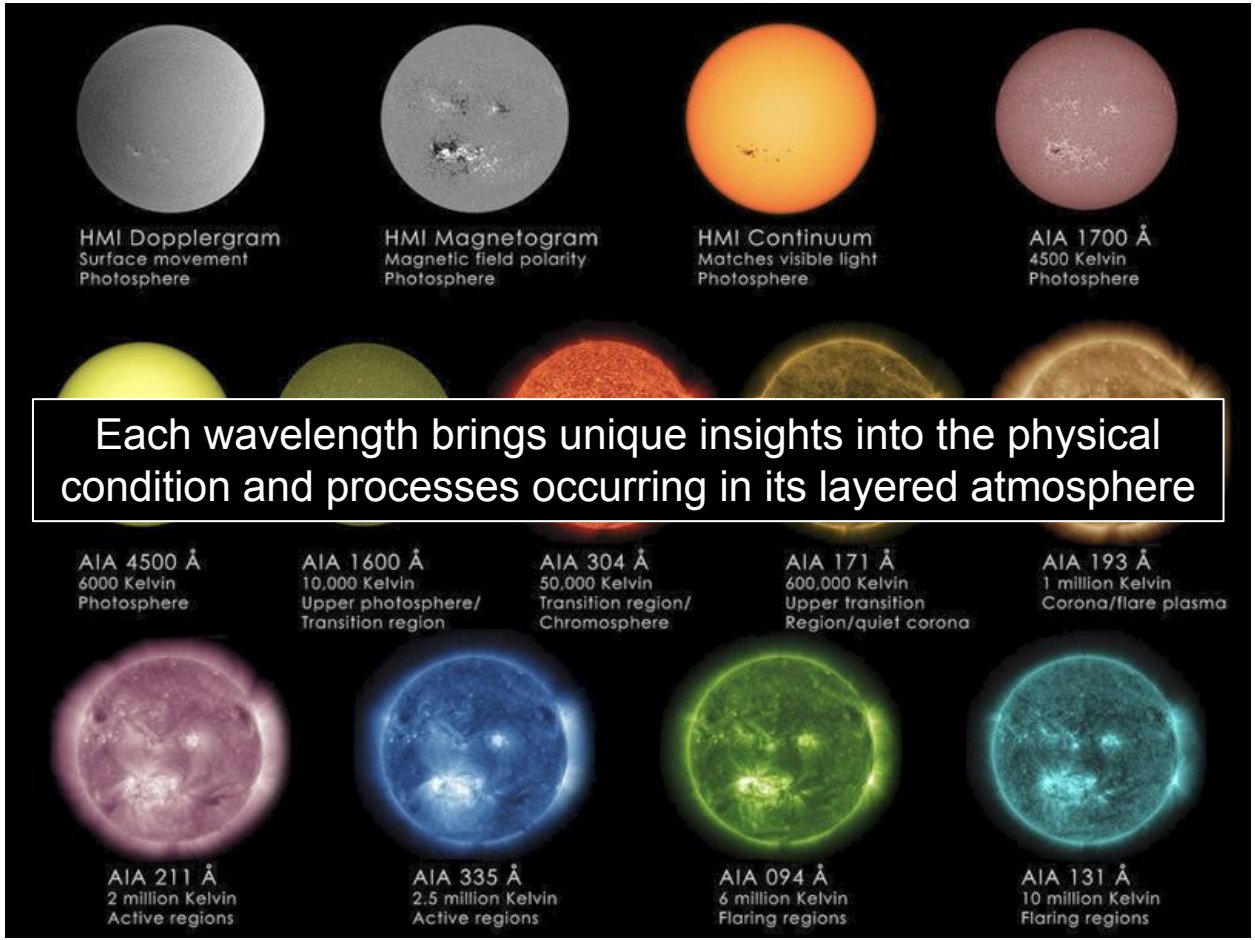
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Remarkably rich and dynamic when studied across the EM spectrum



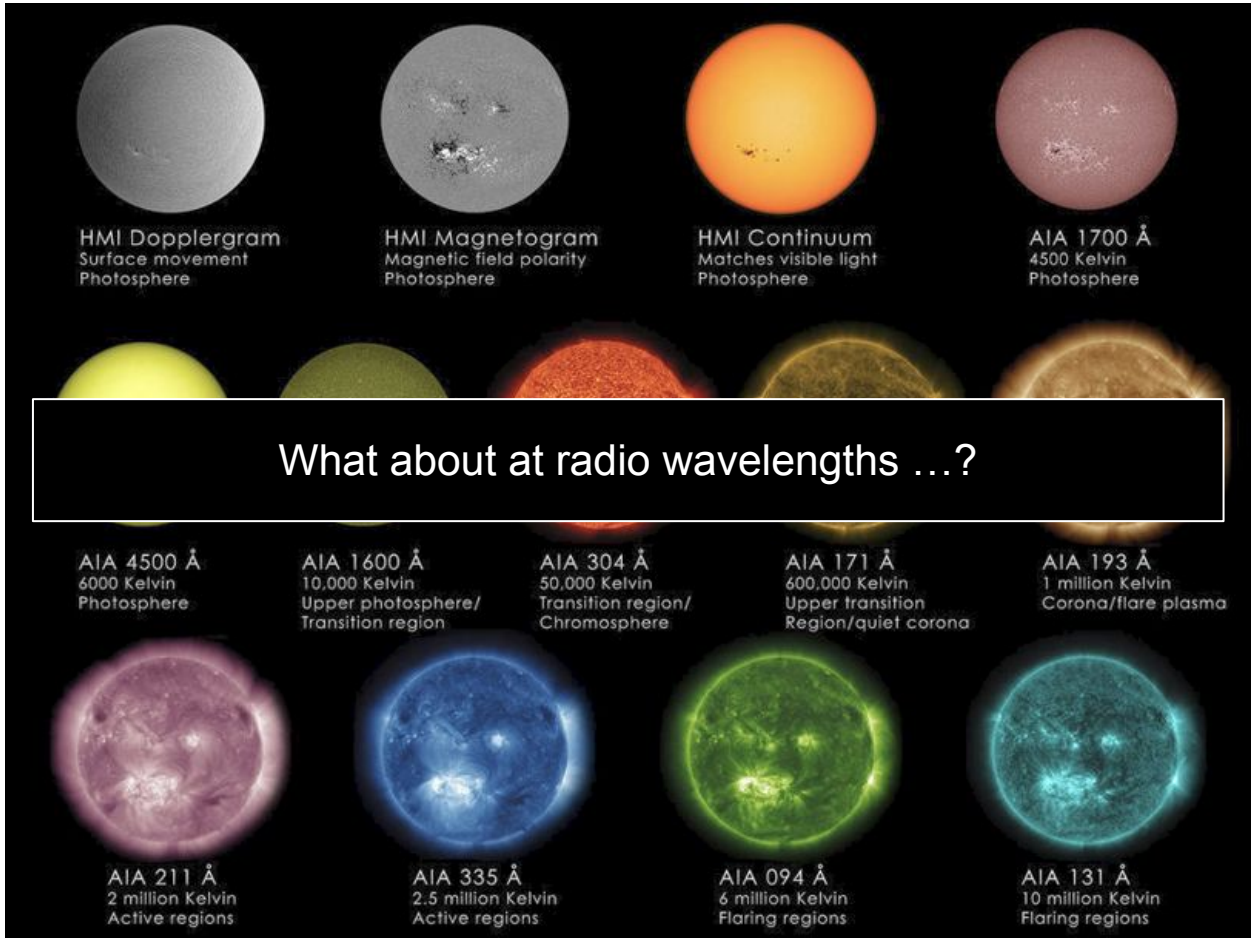
Credit: SDO/NASA

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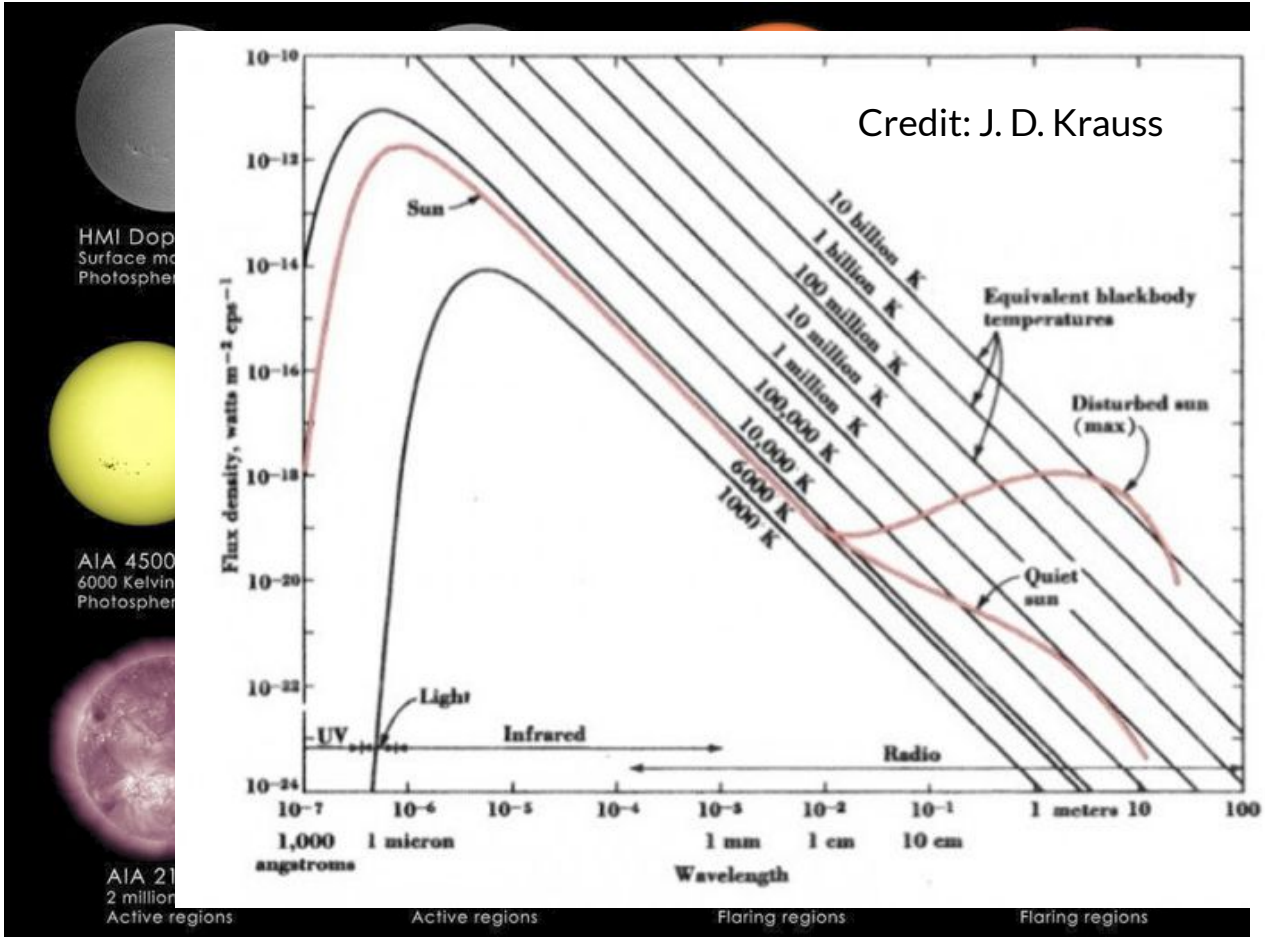
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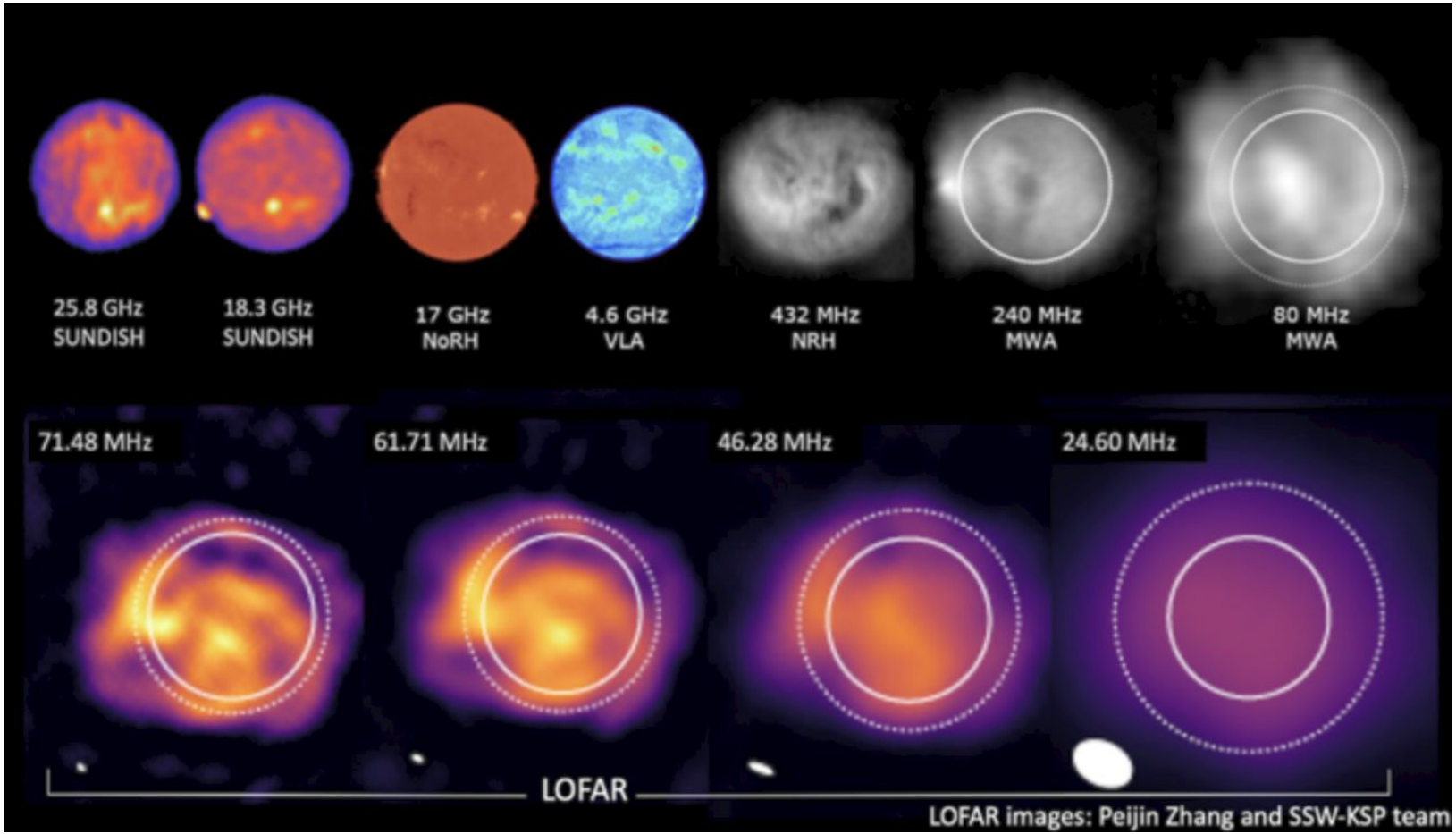


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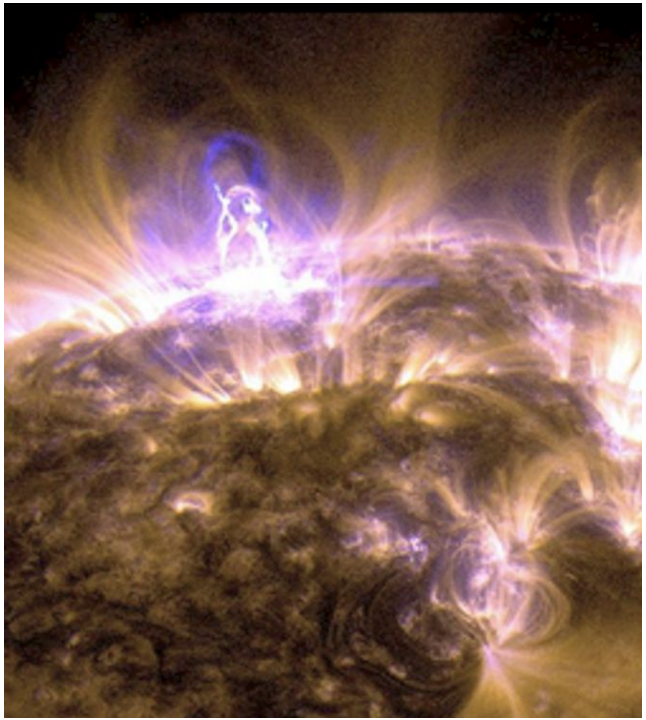
Radio emission from the Sun

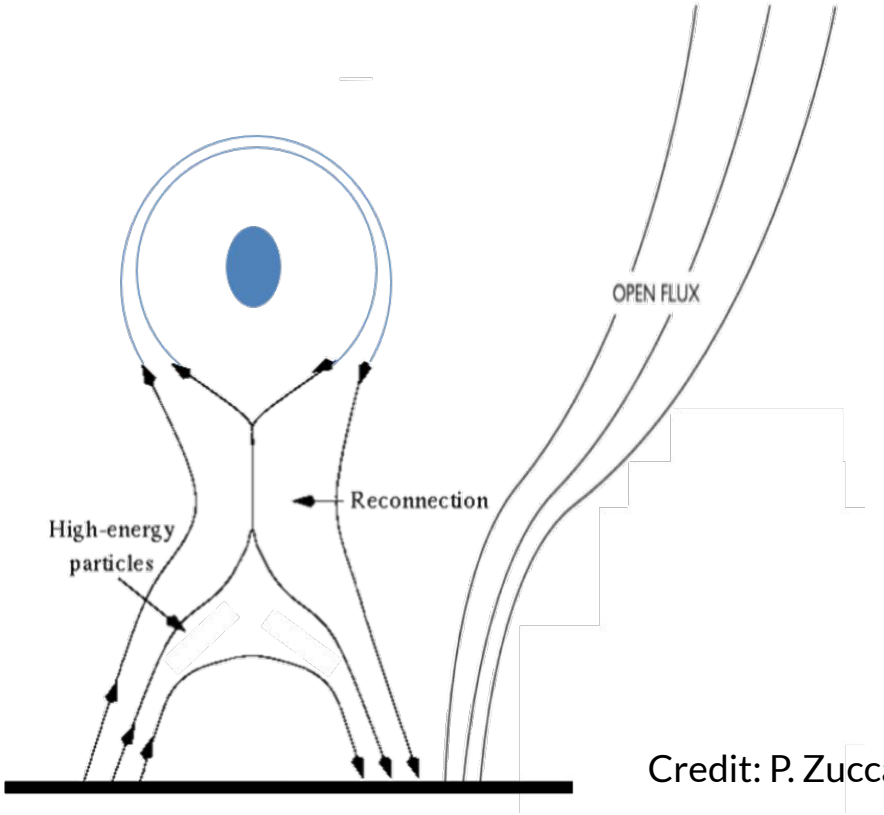


Radio emission from the Sun



Radio emission from the Sun

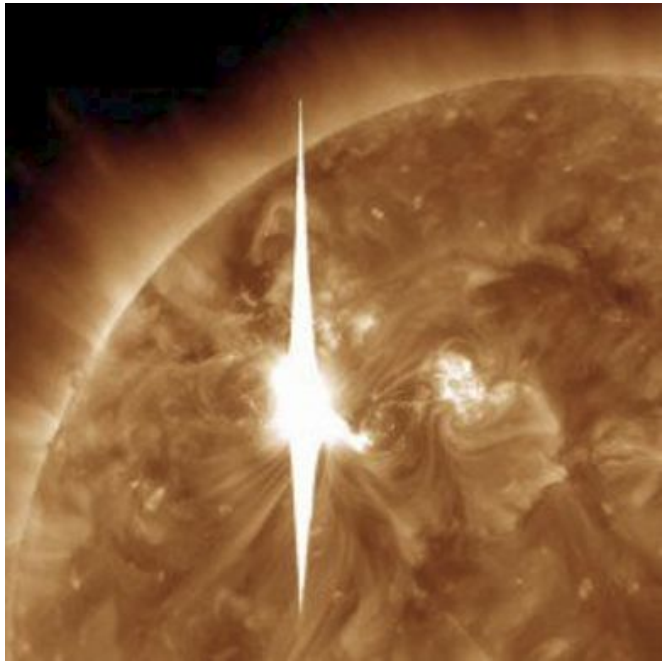


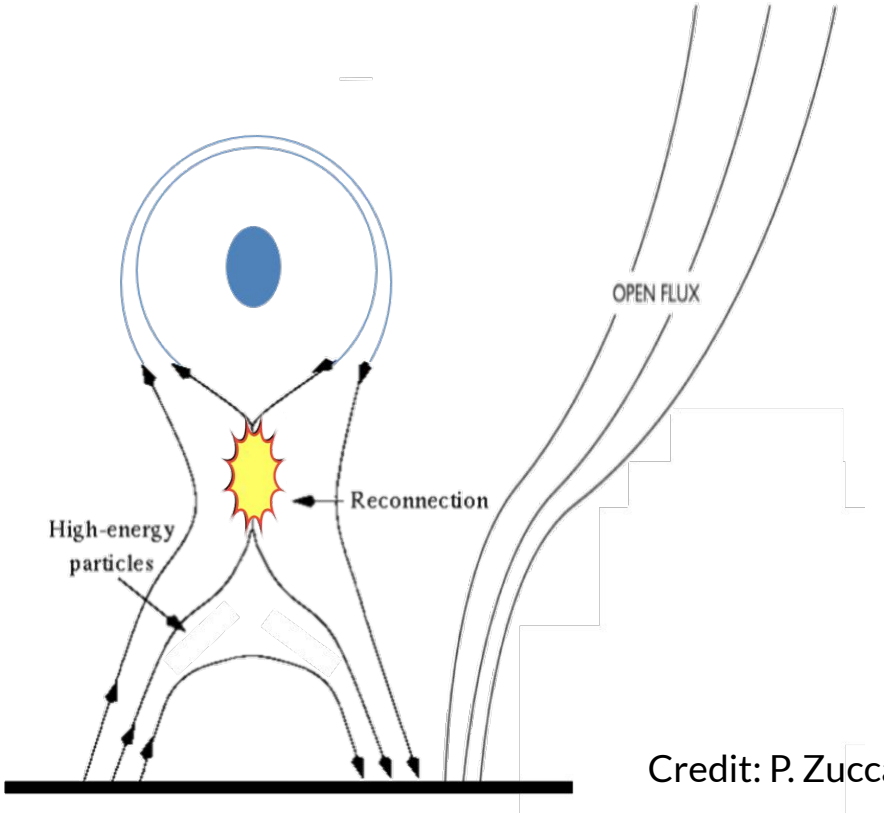


Credit: P. Zucca

Radio emission from the Sun

Solar flares

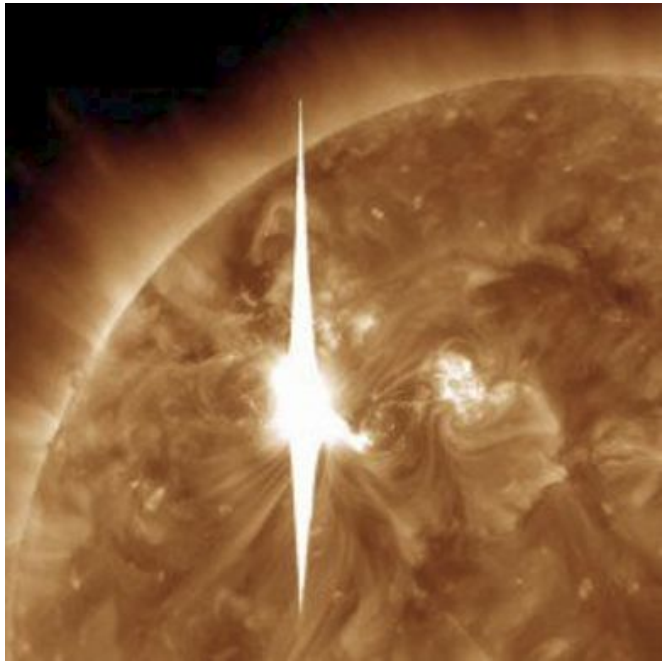


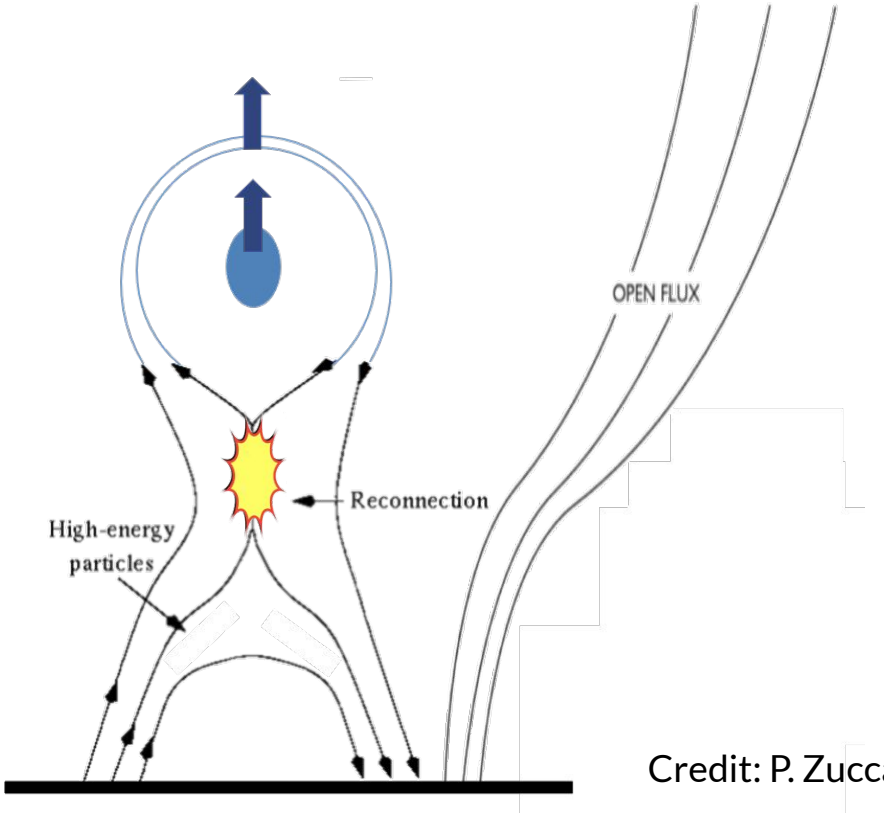


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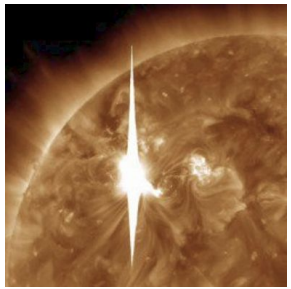




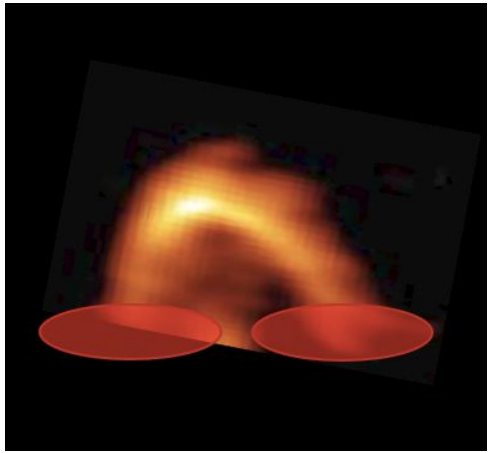
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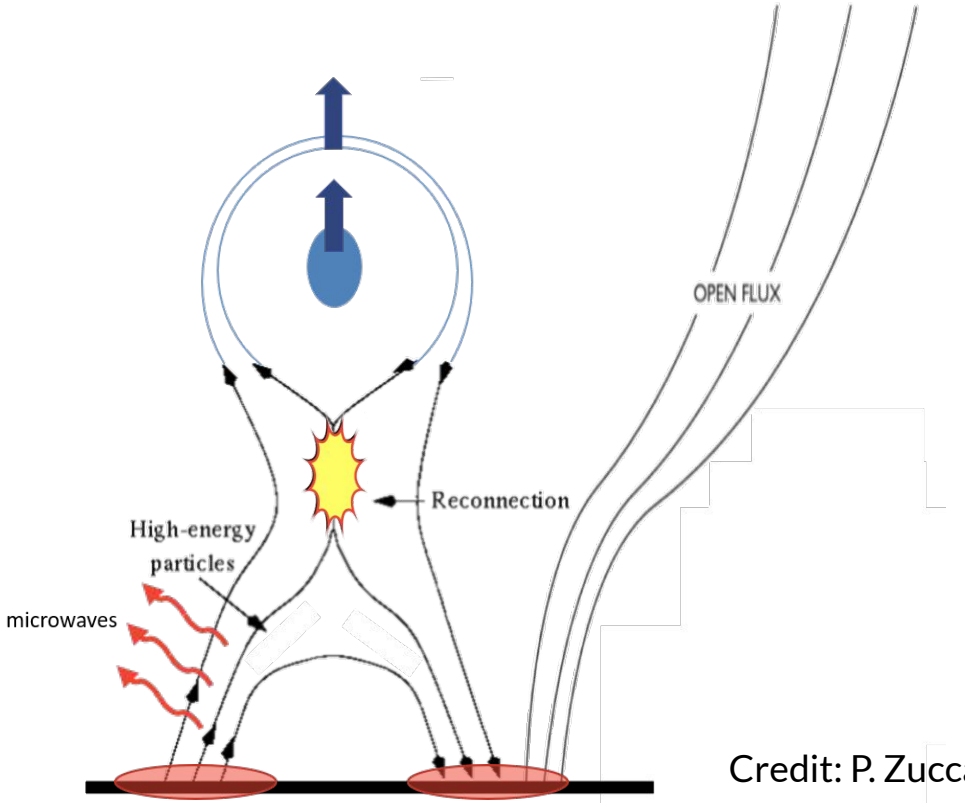
Radio emission from the Sun

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Nobeyama 17 GHz

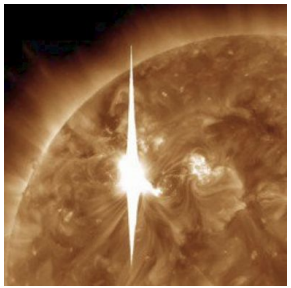




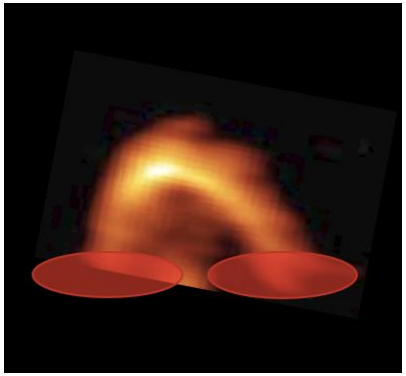
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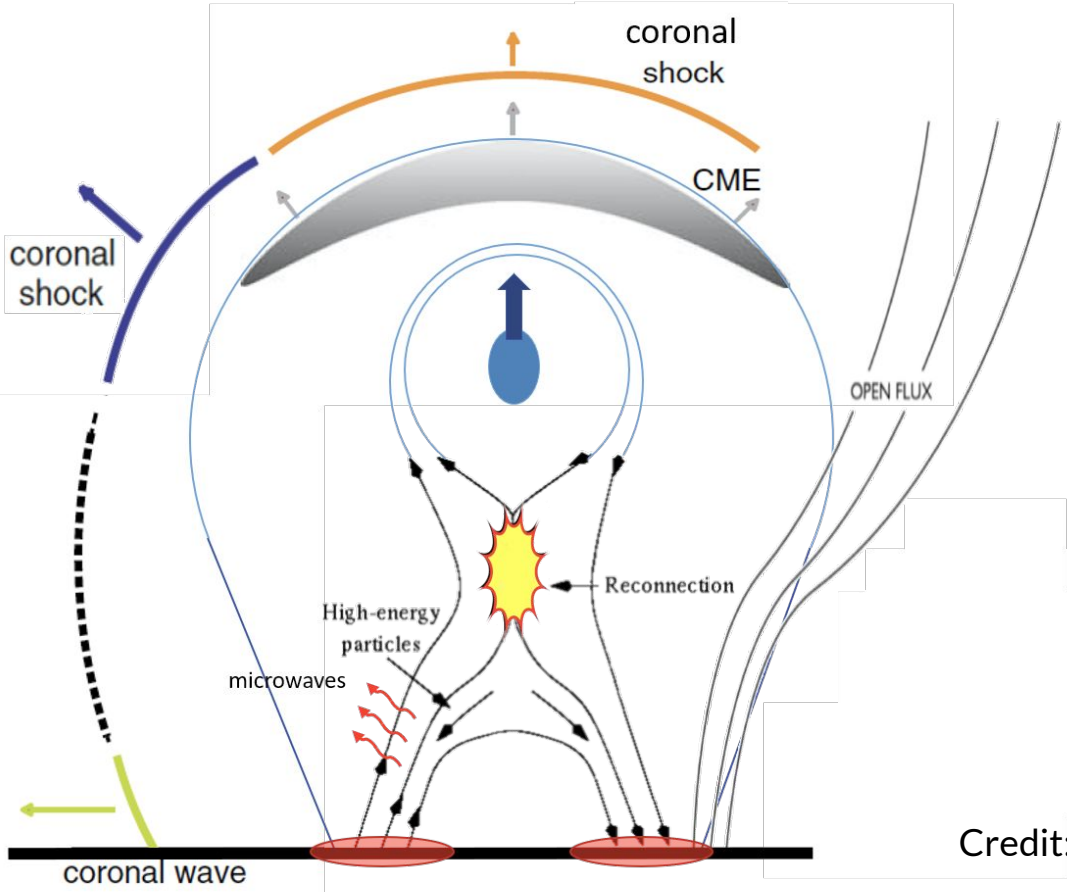
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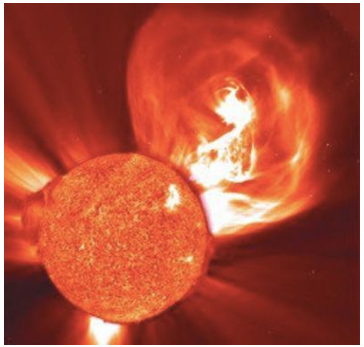


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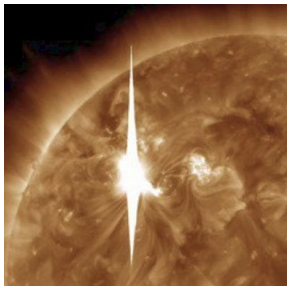
Coronal Mass Ejections
SOHO white light



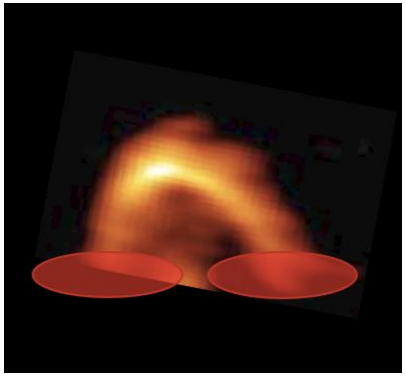
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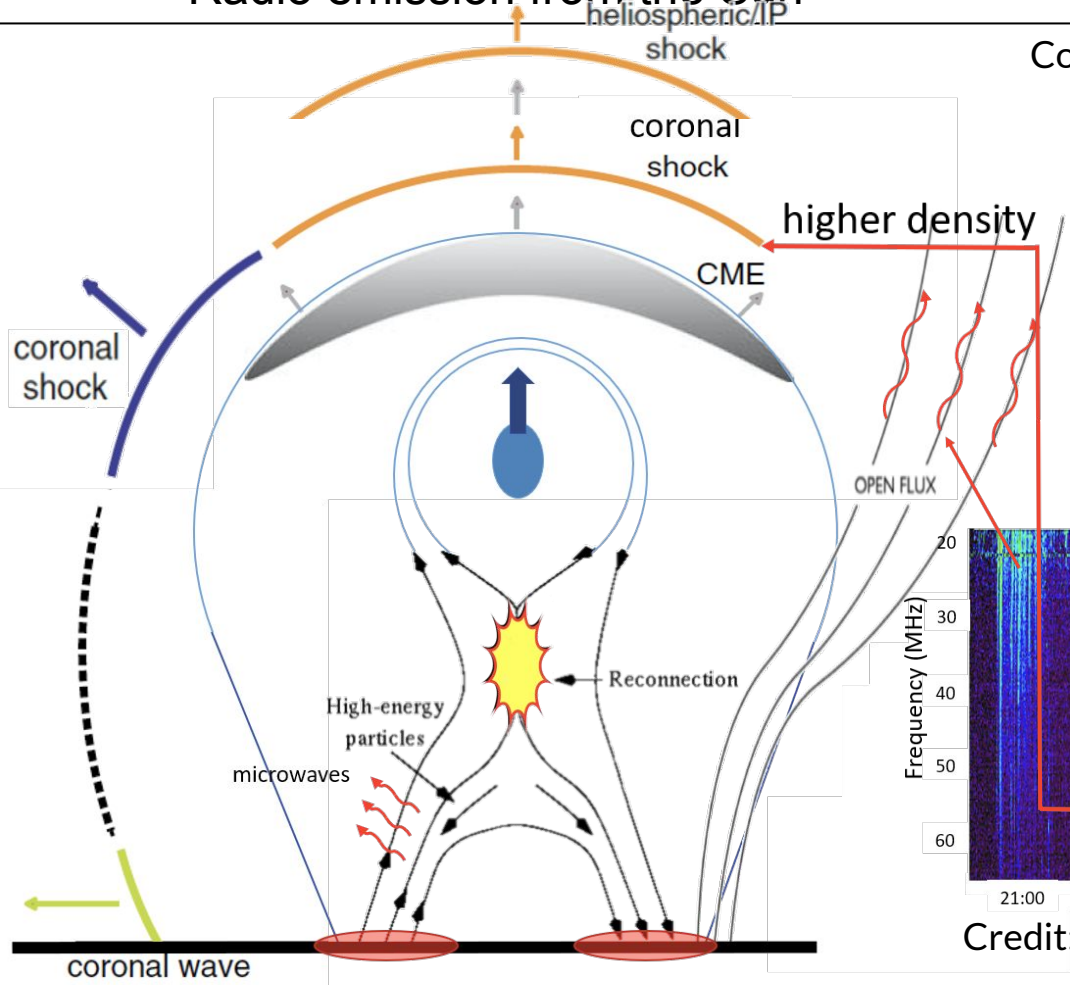
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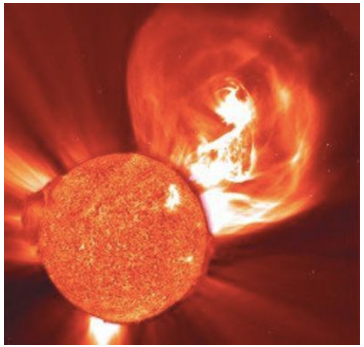


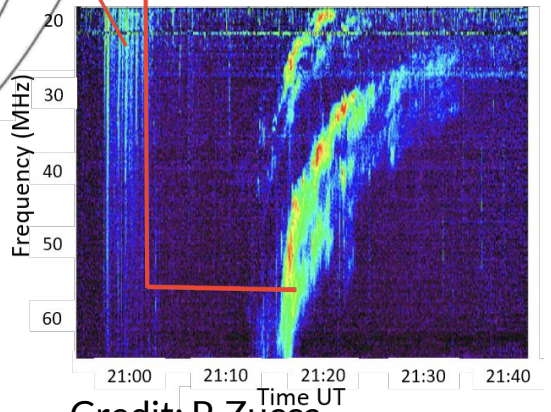
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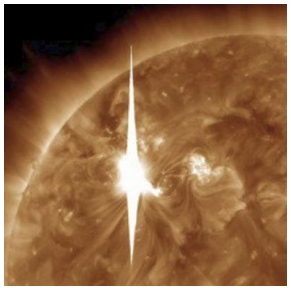




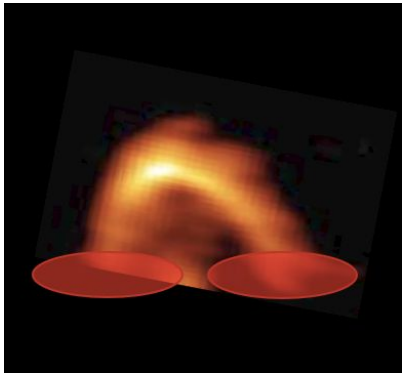
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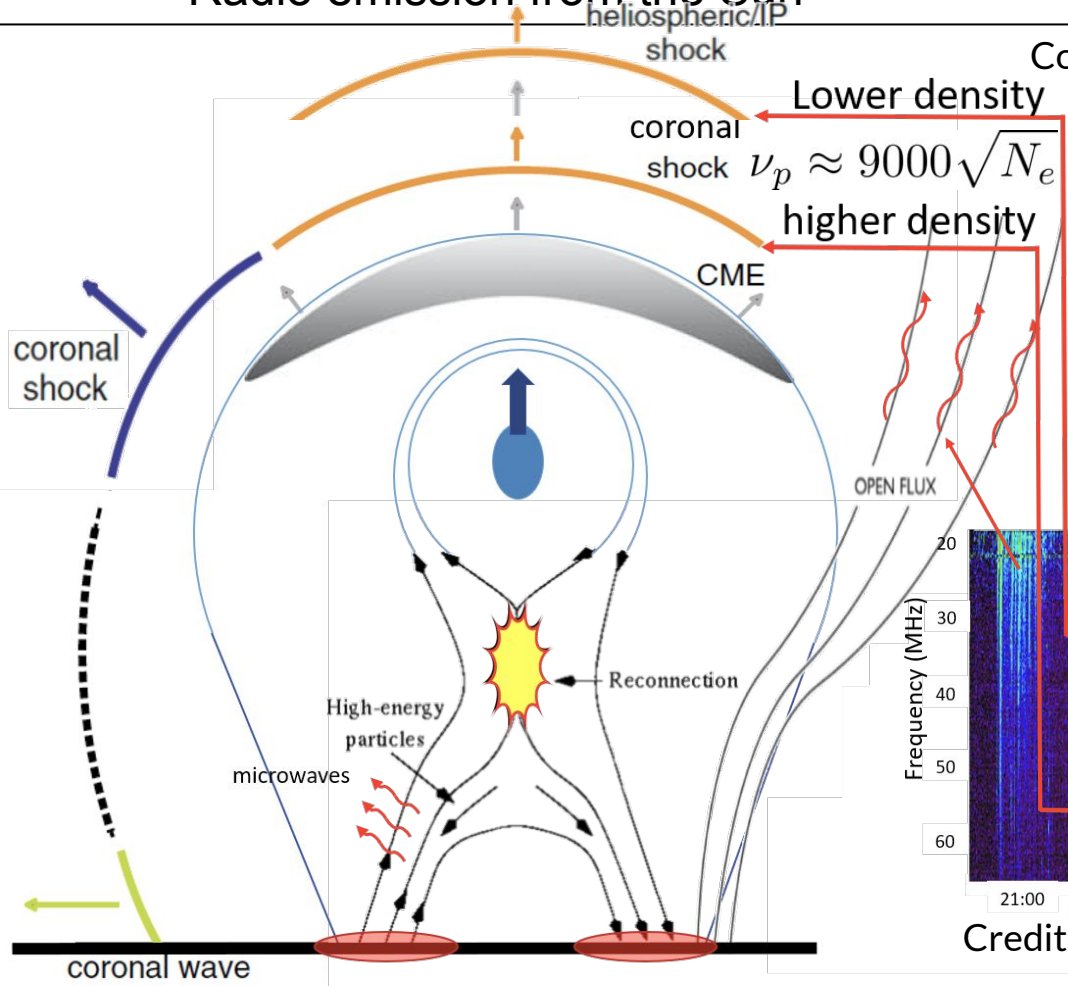
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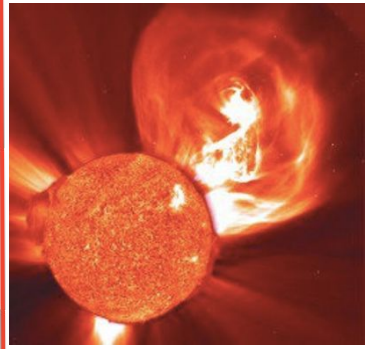


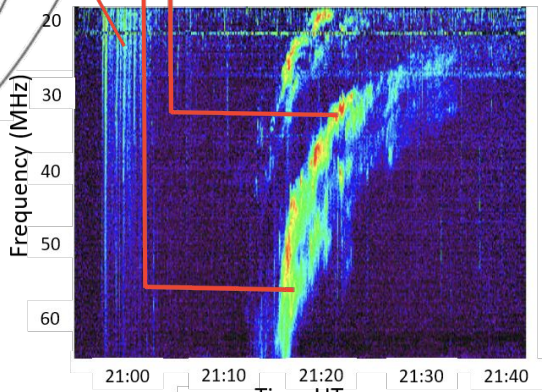
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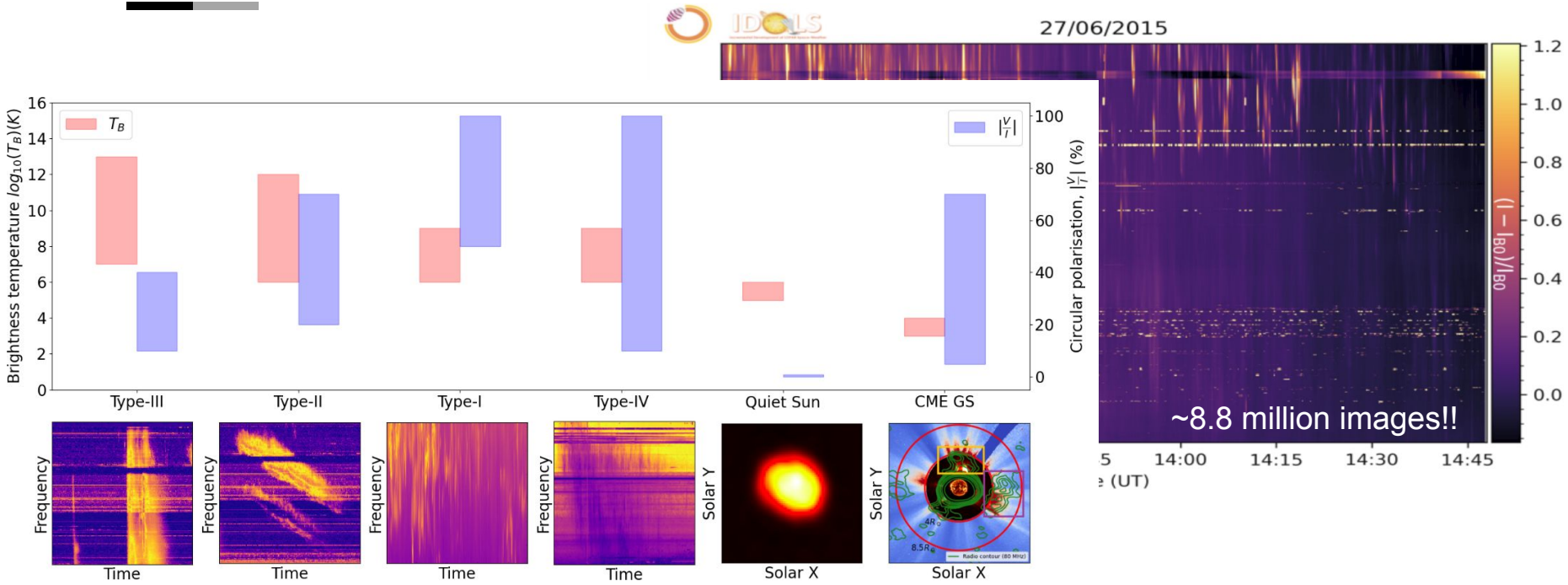
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Nature of solar radio emission

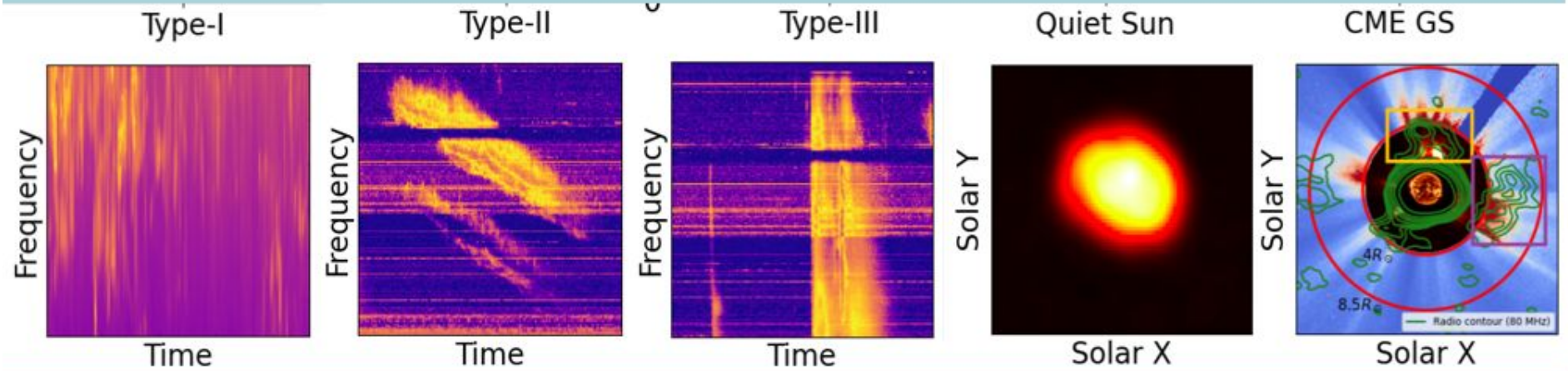


Structured over small temporal and spectral scales; Rapid changes in morphology
Spans 9+ orders of magnitude in intensity and 2+ orders in fractional polarisation

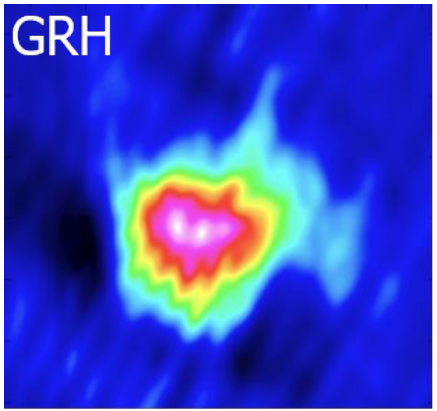
Kansabanik, 2022

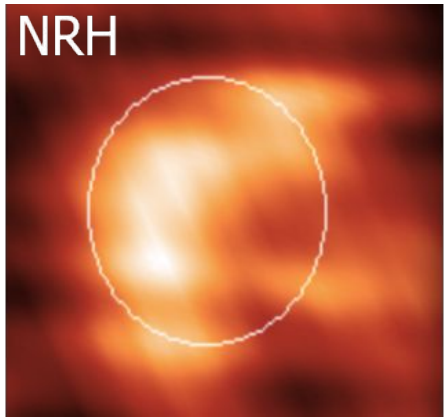
Why spectroscopic snapshot imaging?

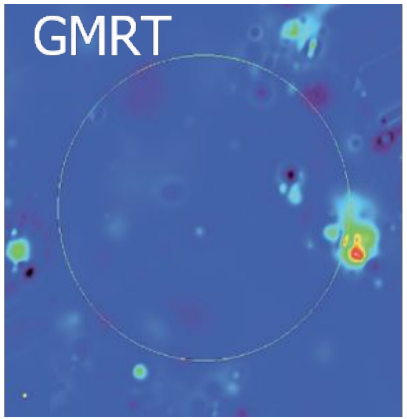
- Solar radio emissions: quiet, noise storms, bursts, CMEs
- Many orders of magnitude variations within small time & frequency spans
- A lot of information is lost with dynamic spectra only studies – imaging required

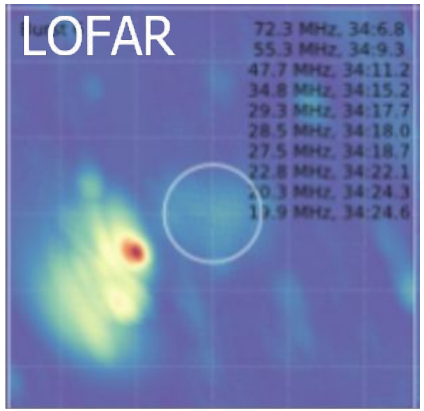


Observation Challenges in Radio Wavelengths



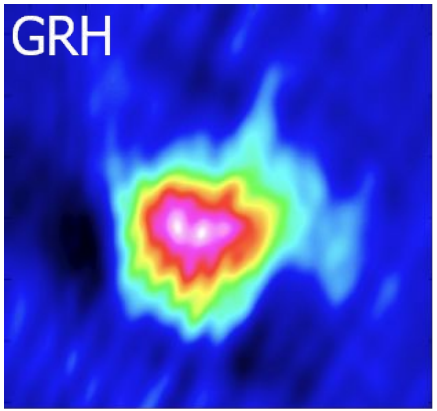


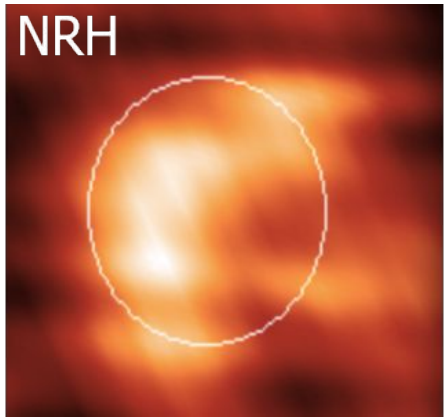


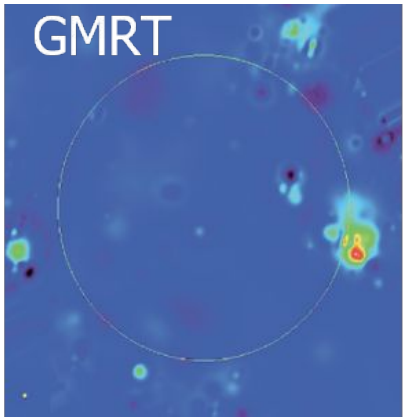


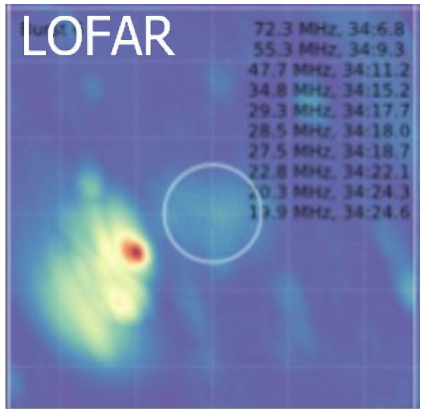
Radio images do not look as beautiful as images at other wavelengths

Observation Challenges in Radio Wavelengths







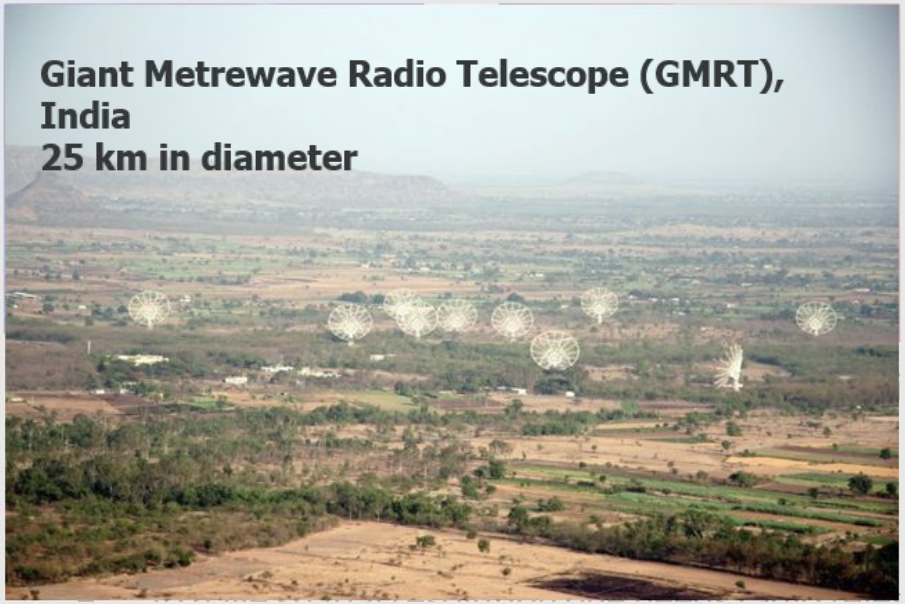


Radio images do not look as beautiful as images at other wavelengths

- To have spatial resolution one needs radio telescope of size few tens to thousands in diameter
- Radio imaging is done through a technique called ‘Radio Interferometry’ to make a synthetic radio telescope with diameter of few tens to thousand km.

Observation Challenges in Radio Wavelengths

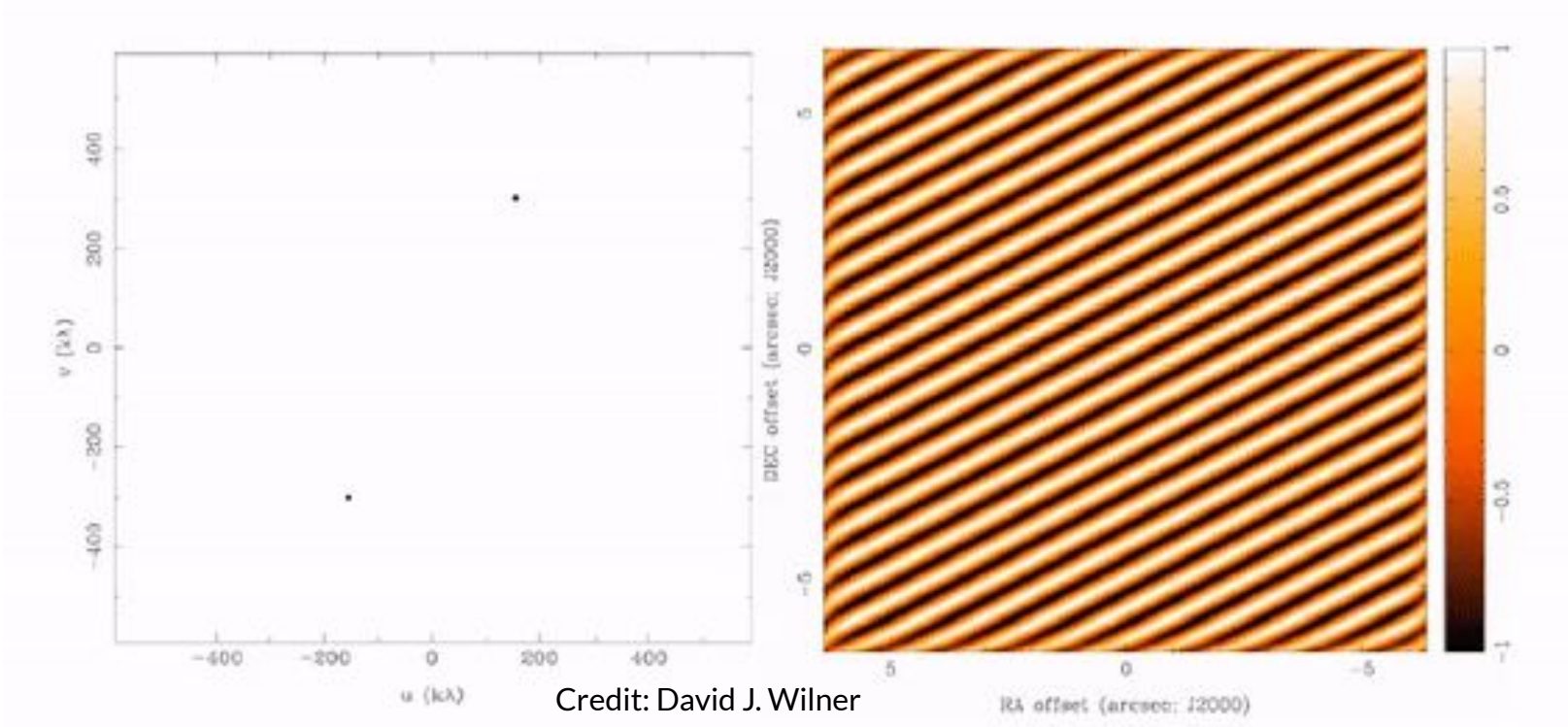
GRH NRH GMRT LOFAR





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A Very Basic Working Principle of Radio Interferometry

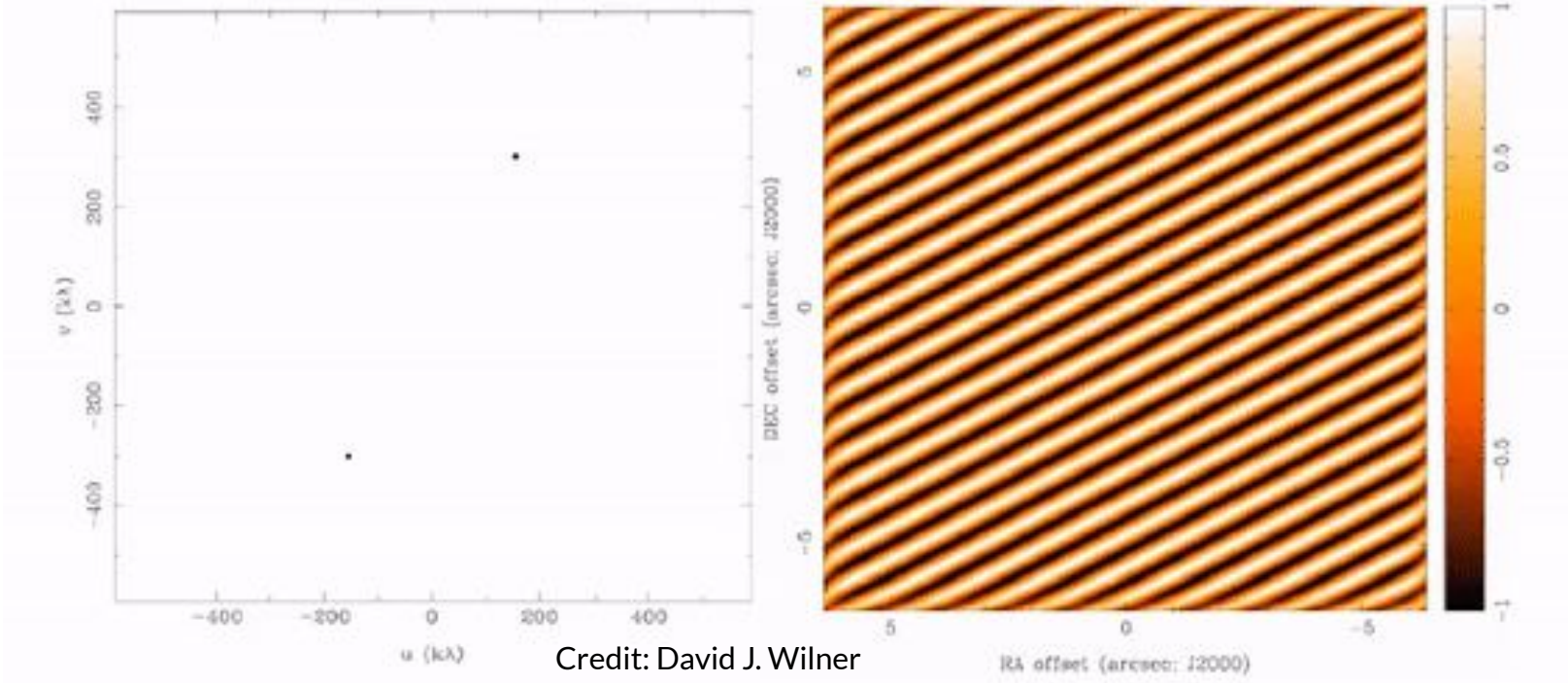


Credit: David J. Wilner

- Each antenna pair measure a single Fourier component of the sky brightness
- Adding such multiple fringes in different orientations give image of a point source in the sky

A Very Basic Working Principle of Radio Interferometry

Ideally, one needs dense sampling of these Fourier components to best reconstruction of the sky



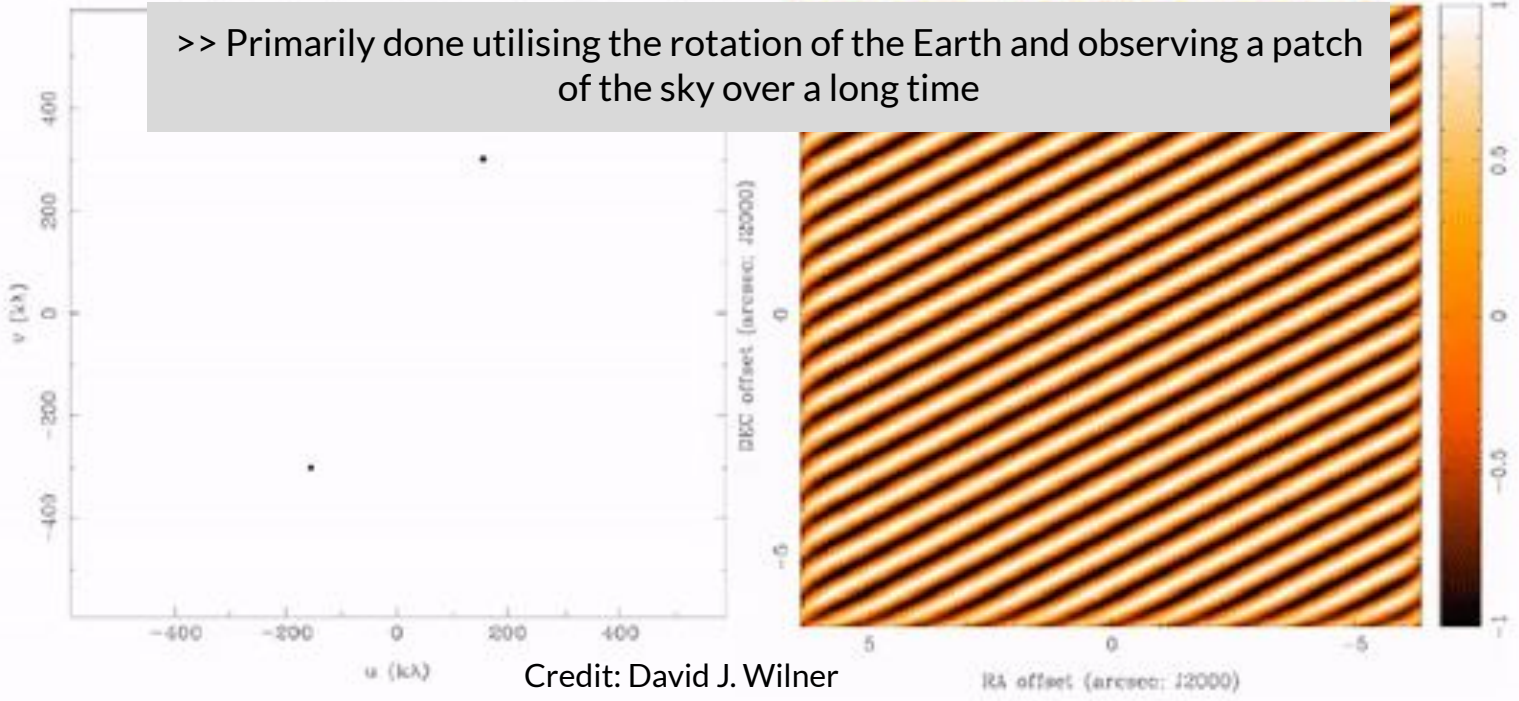
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>> Primarily done utilising the rotation of the Earth and observing a patch of the sky over a long time



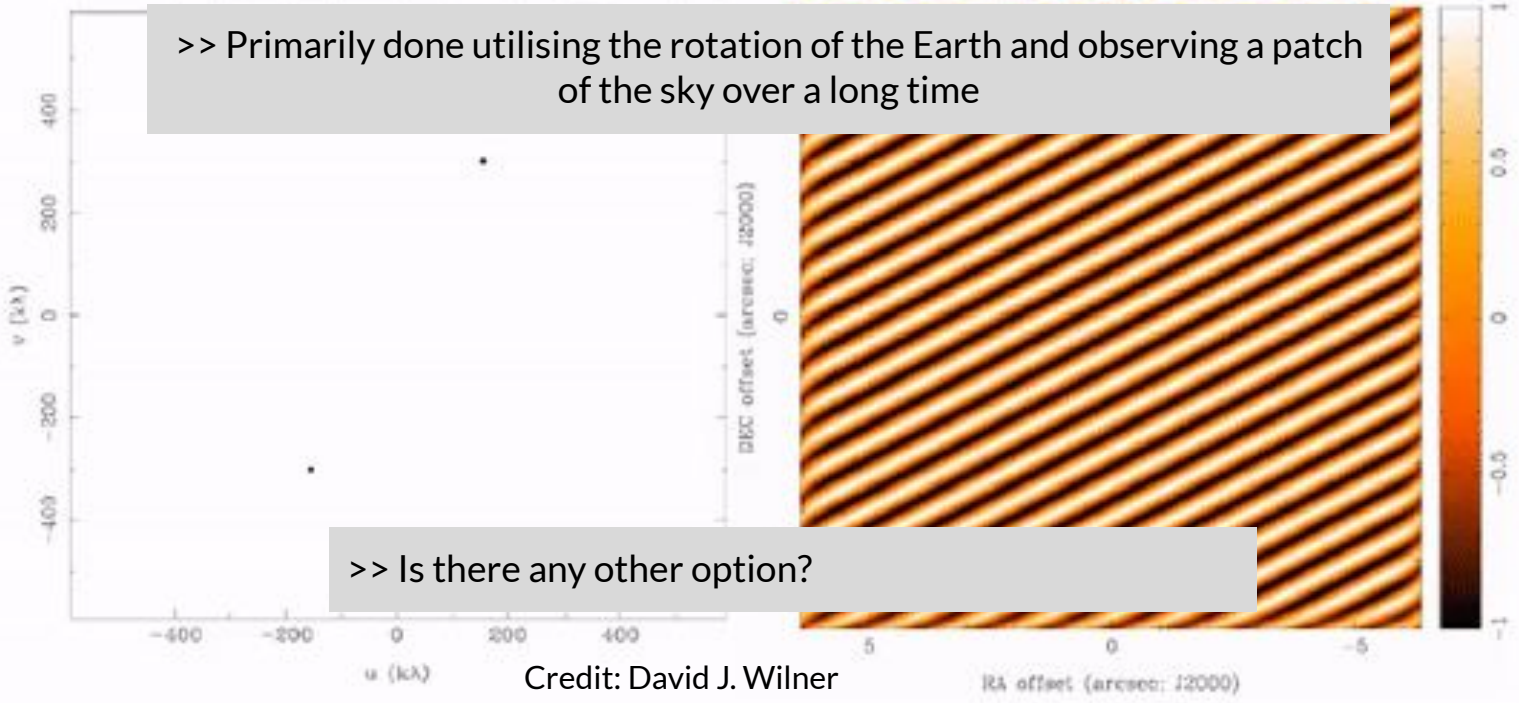
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>> Is there any other option?

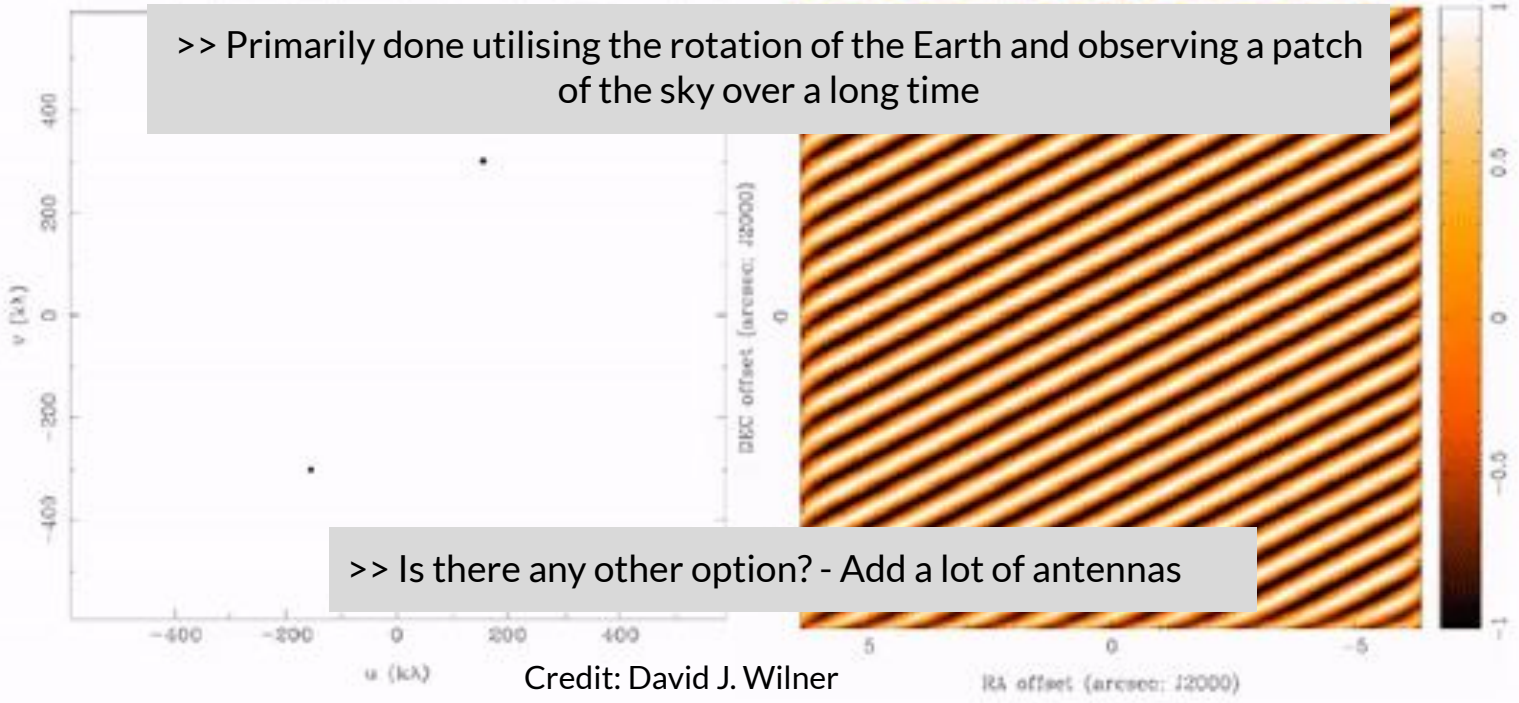
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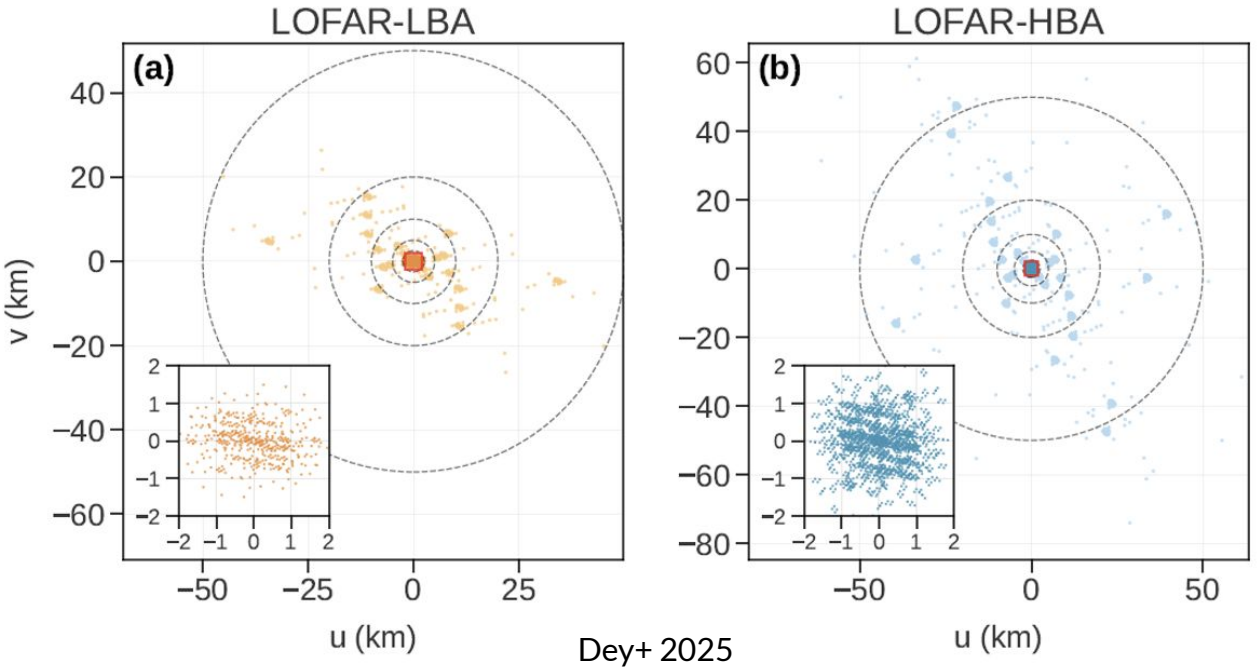


>> Is there any other option? - Add a lot of antennas

Credit: David J. Wilner

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- Adding such multiple fringes in different orientations give image of a point source in the sky

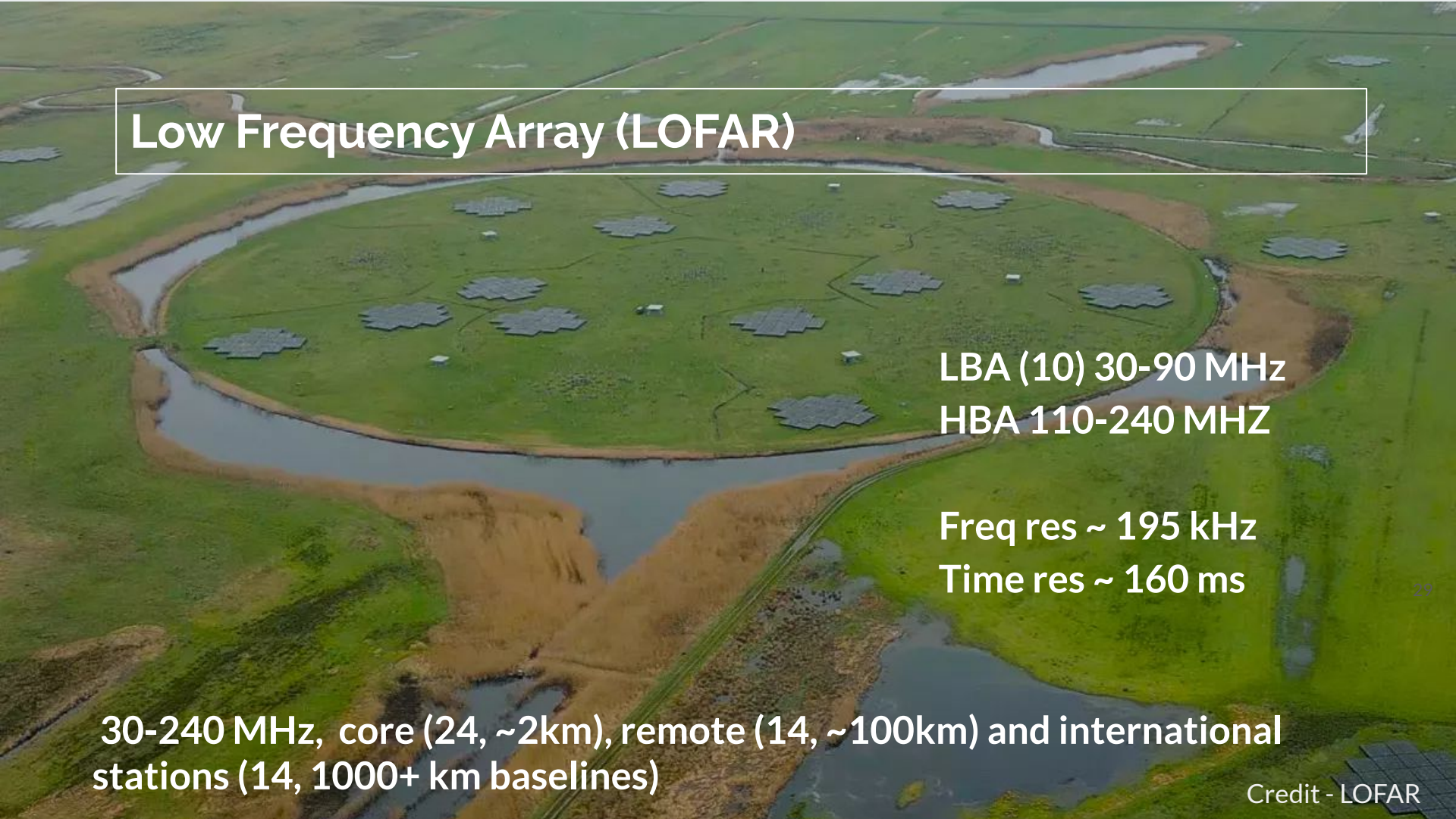
Dense uv-sampling: Critical for spectroscopic-snapshot imaging!



Dey+ 2025

- Fourier imaging technique - each baseline measures one Fourier component of the radio sky
- Must gather all of the information needed over short time duration and spectral span
- Has become possible only recently with the new technology instrumentation.

Low Frequency Array (LOFAR)



LBA (10) 30-90 MHz
HBA 110-240 MHZ

Freq res ~ 195 kHz
Time res ~ 160 ms

30-240 MHz, core (24, ~2km), remote (14, ~100km) and international stations (14, 1000+ km baselines)

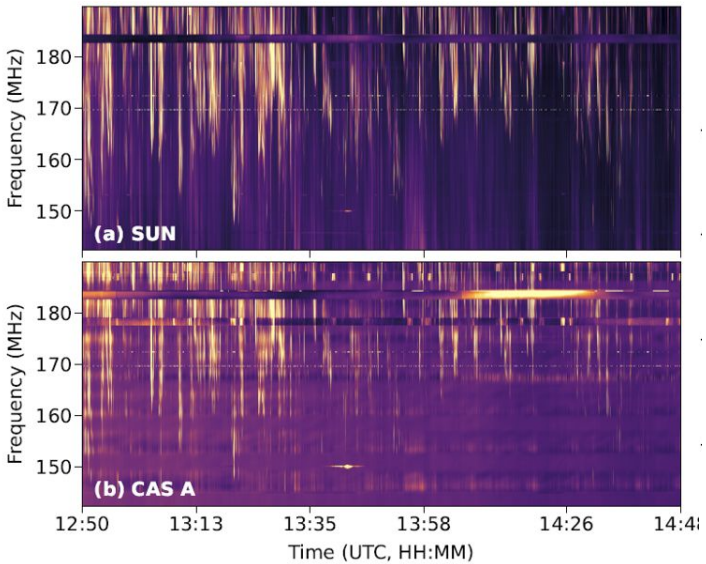
Credit - LOFAR

Other challenges

- Dynamic nature and extremely high flux densities, with complex structures

Other challenges

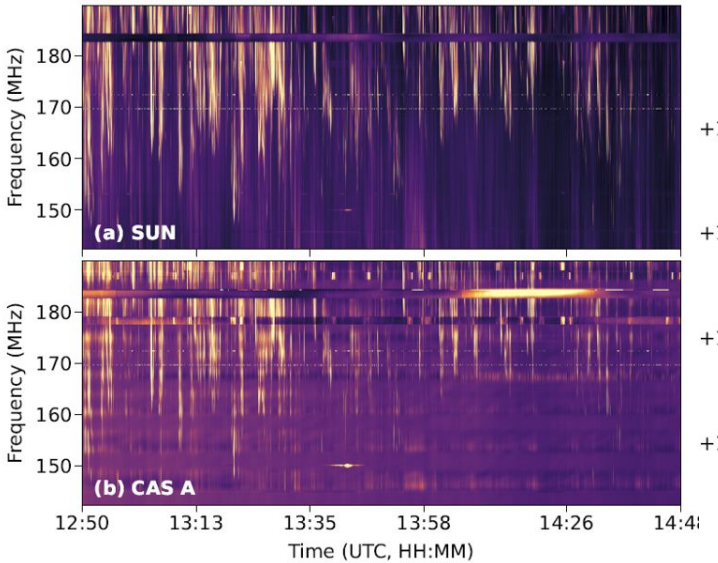
- Dynamic nature and extremely high flux densities, with complex structures
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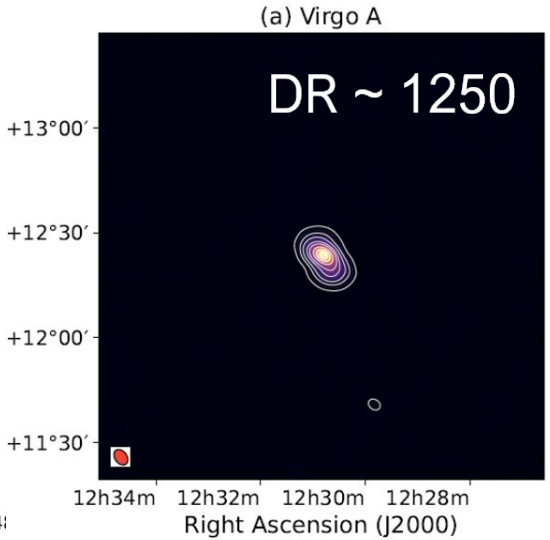


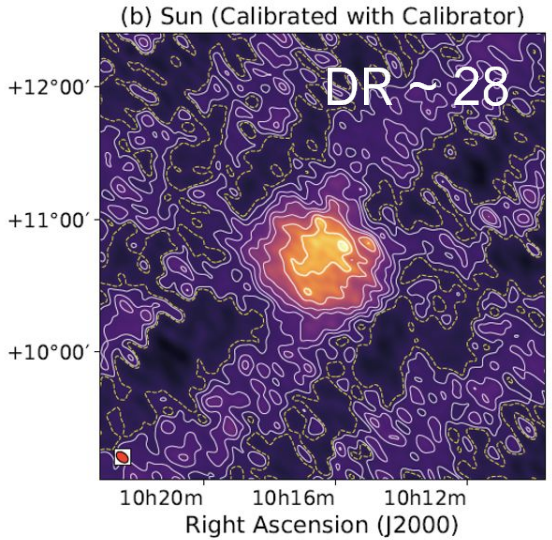
Dey+ 2025

Other challenges

- Dynamic nature and extremely high flux densities, with complex structures
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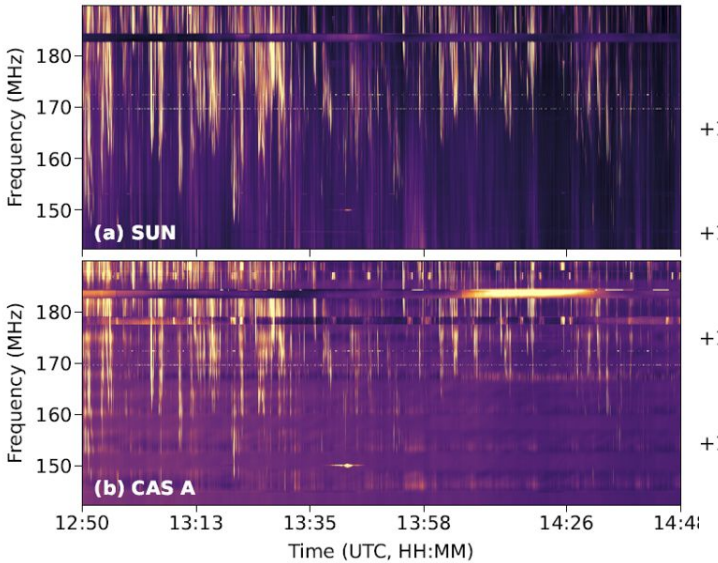


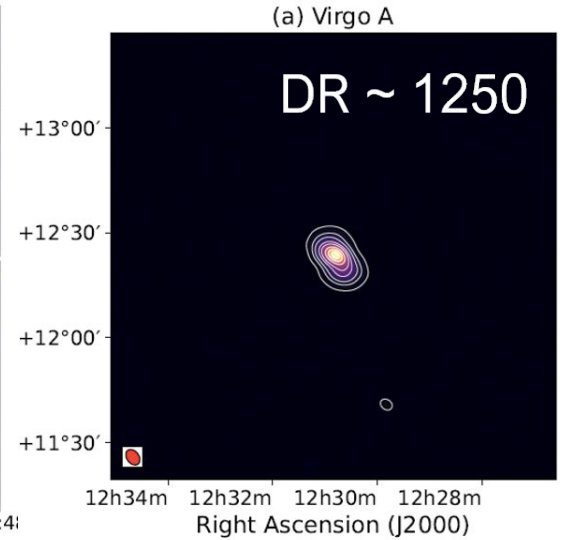


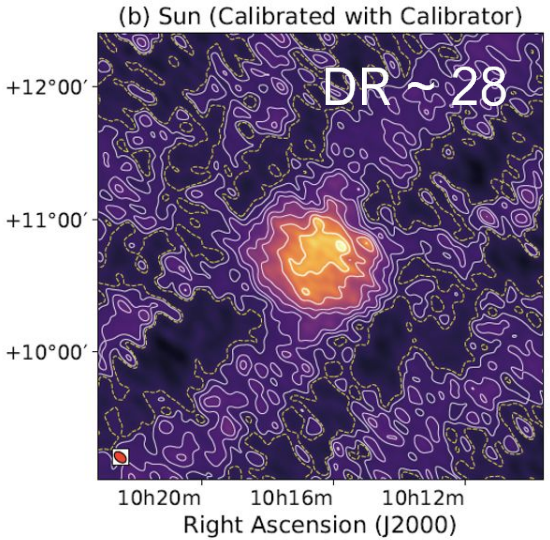
Dey+ 2025

Other challenges

- Dynamic nature and extremely high flux densities, with complex structures
- Strong solar signals (even during ‘quiet times’ contaminate calibrator observations
- If the calibrator is far away - ionospheric phases introduce significant errors
- How can we identify RFIs and flag them in solar datasets?





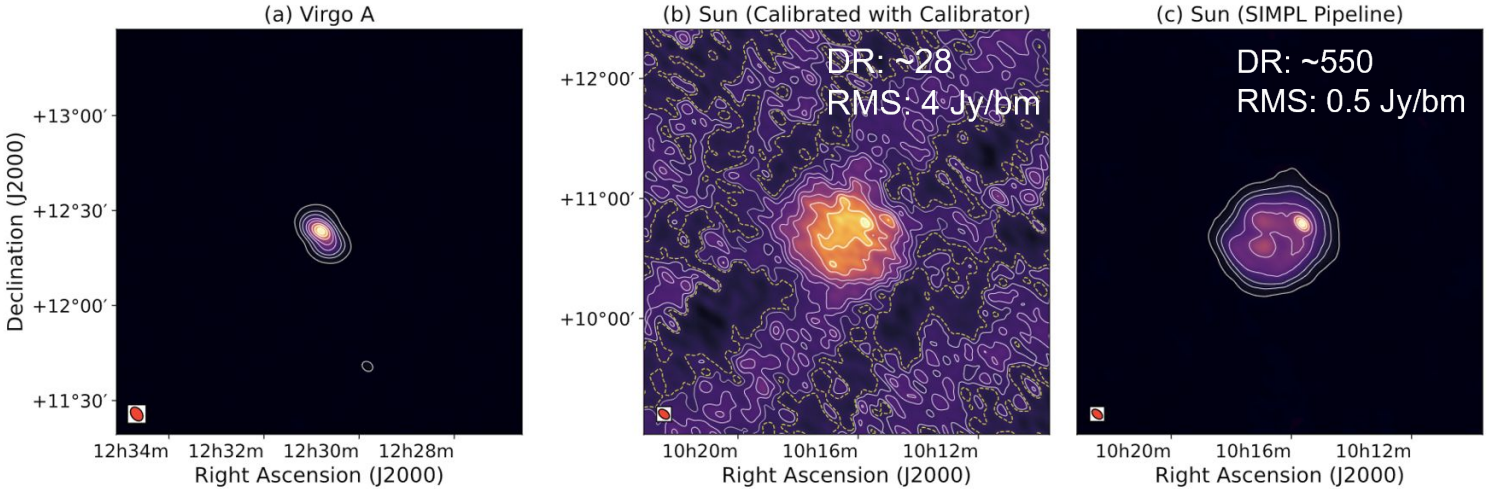


Dey+ 2025

Solar IMaging Pipeline for LOFAR (SIMPL)

Dey, Oberoi, Zucca+ 2025

- Fully automated end to end
- Careful calibration solution estimation
- Self-calibration based
- Flagger for solar data
- Significant improvement in Dynamic Range and image fidelity



Solar IMaging Pipeline for LOFAR (SIMPL): core strategy

Dey, Oberoi, Zucca+ 2025

- Choose a suitable time range for calibrating using calibrator
- Apply only the amplitude part of the solutions
- Solve phases entirely via self-calibration

Solar IMaging Pipeline for LOFAR (SIMPL): core strategy

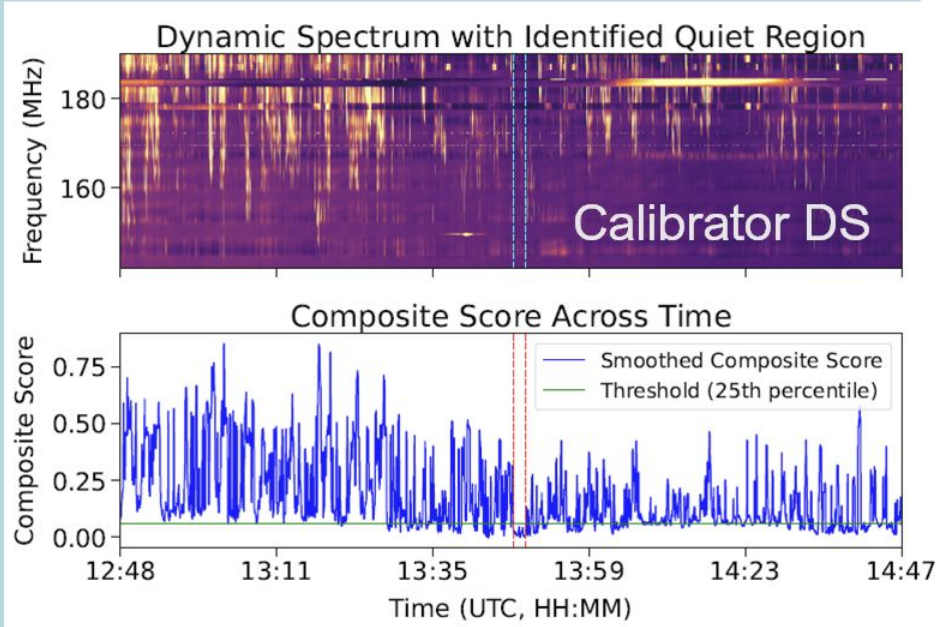
Dey, Oberoi, Zucca+ 2025

- Choose a suitable time range for calibrating using calibrator
- Apply only the amplitude part of the solutions
- Solve phases entirely via self-calibration

Therefore to get a nice image of the Sun using this pipeline, you don't need a calibrator source!
Calibrator is required for absolute flux calibration

Choosing a suitable timerange for calibration

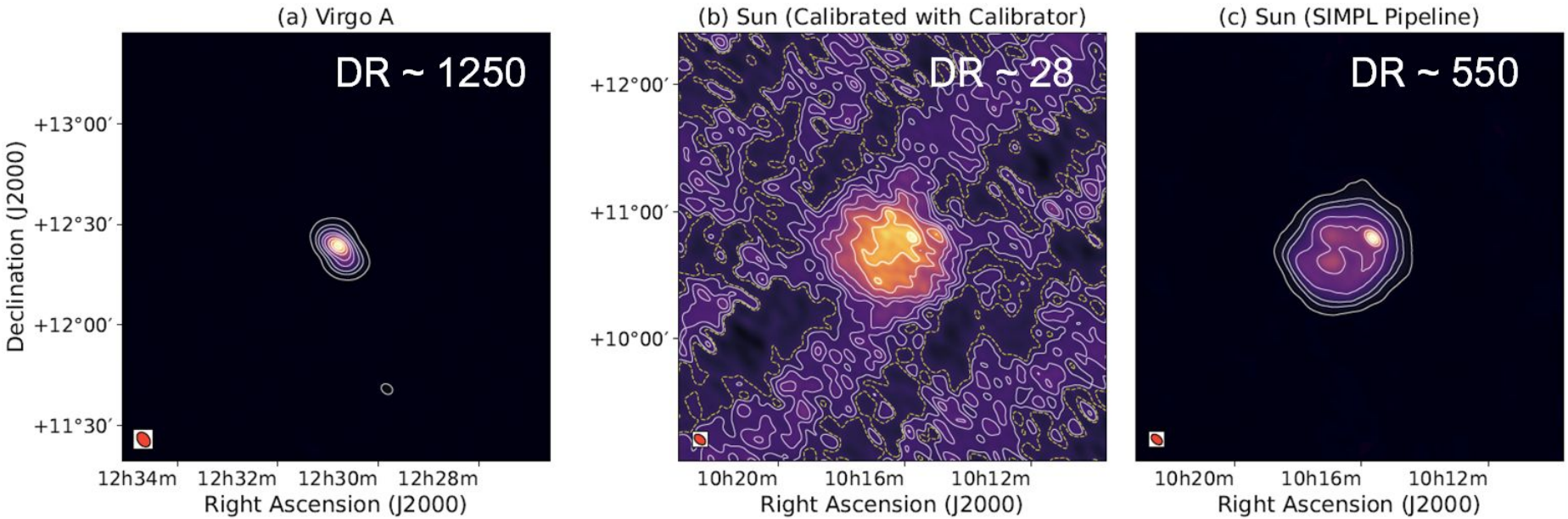
- Calibration solutions are obtained when the source is least affected by solar contamination
- Composite score-based approach
- Lowest 25th percentile chosen
- Atleast continuous 30s
- Apply only the amplitude part of the solutions



$$z = w_1 * \sigma + w_2 * \mathrm{MAD} + w_3 * \mathrm{Skew} + w_4 * \mathrm{Kurt} + w_5 * (1 - \mathrm{Entropy})$$

Ignoring phase part of the calibration solutions

- Unreliable and produces different results depending on ionospheric conditions, angular separation from Sun, etc
- More reliable to start with simple quiet Sun model for self-calibration



Recap of self-calibration

- In standard radio interferometric calibration using calibrator sources, the sky model is well known
- The complex direction-independent antenna gains, g_p, are determined by minimising:

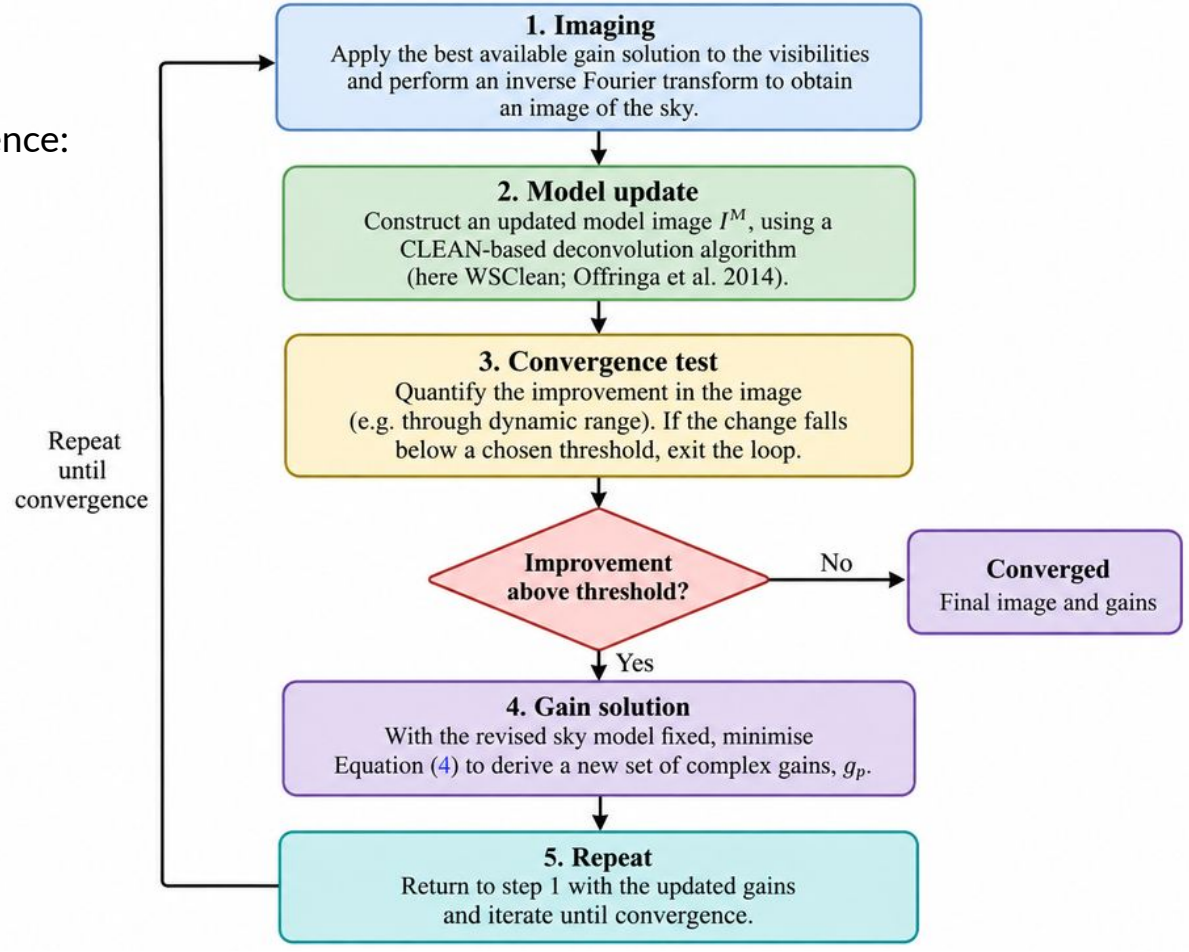
$$\Phi = \sum_{p,q} \left| V_{pq} - g_p g_q^* V_{pq}^{\mathrm{M}} \right|^2$$

- When the sky brightness distribution is not known, both the gains and the sky model may be treated as free parameters
- This equation can be written as: $\Phi = \sum_{p,q} \left| V_{pq} - g_p g_q^* \mathcal{F}\left[I^{\mathrm{M}}\right]_{pq} \right|^2$

The system can be solved as long as the number of free parameters describing the sky and the complex antenna gains remains smaller than the number of measured visibilites

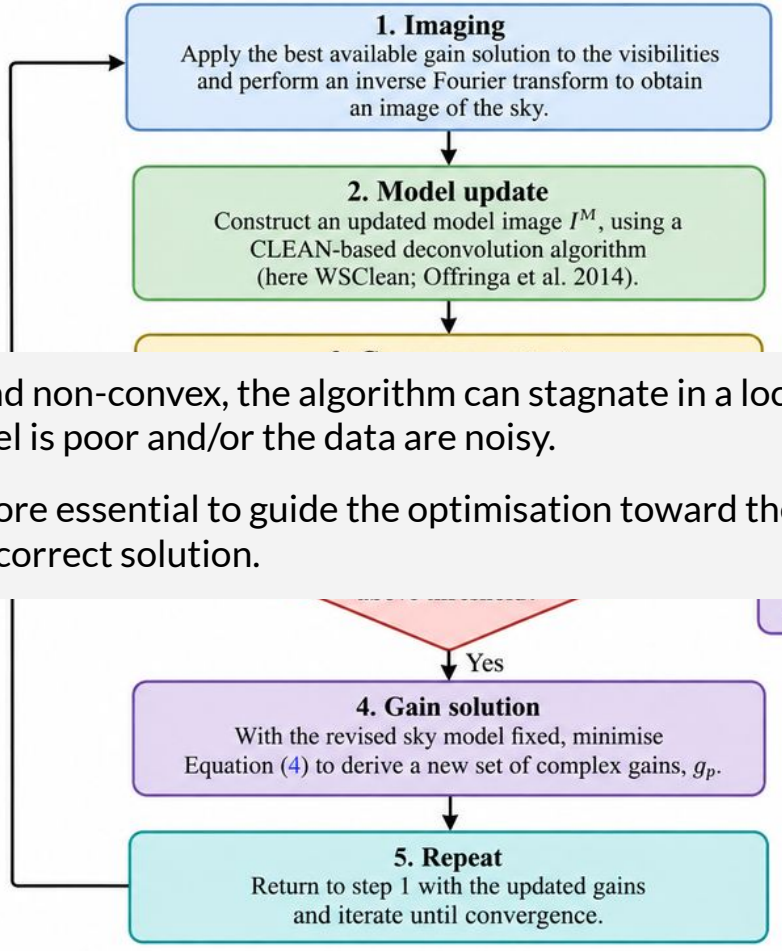
Recap of self-calibration

Therefore to minimise Φ, we run the following iterative loop until convergence:



Recap of self-calibration

Therefore to minimise Φ, we run the following iterative loop until convergence:

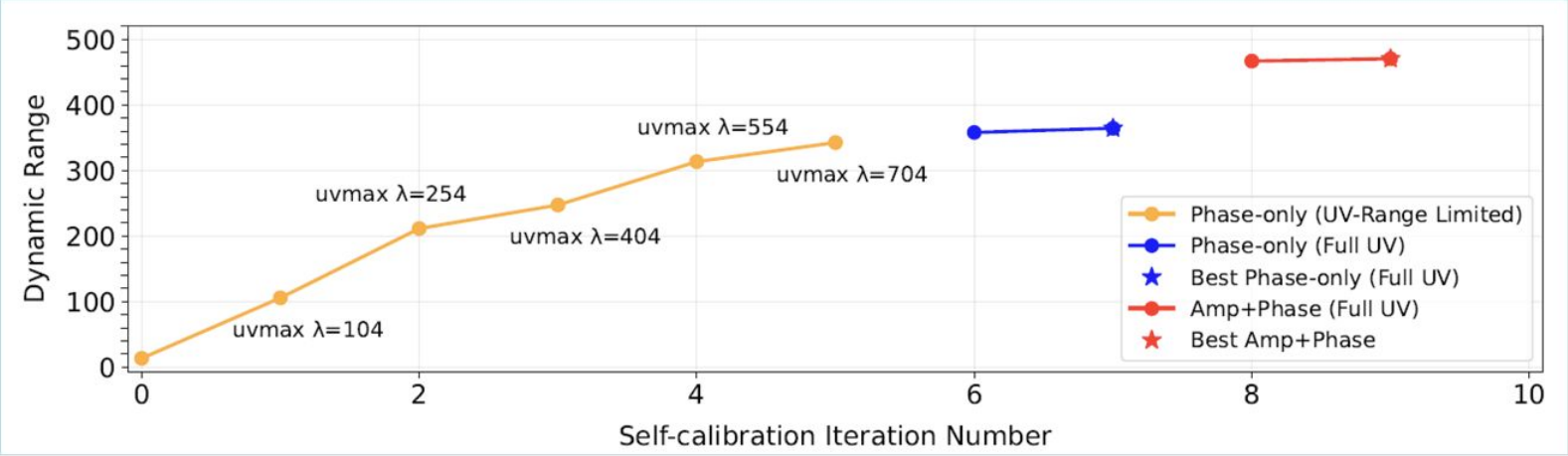


Because the objective function is non-linear and non-convex, the algorithm can stagnate in a local minimum if the initial sky model is poor and/or the data are noisy.

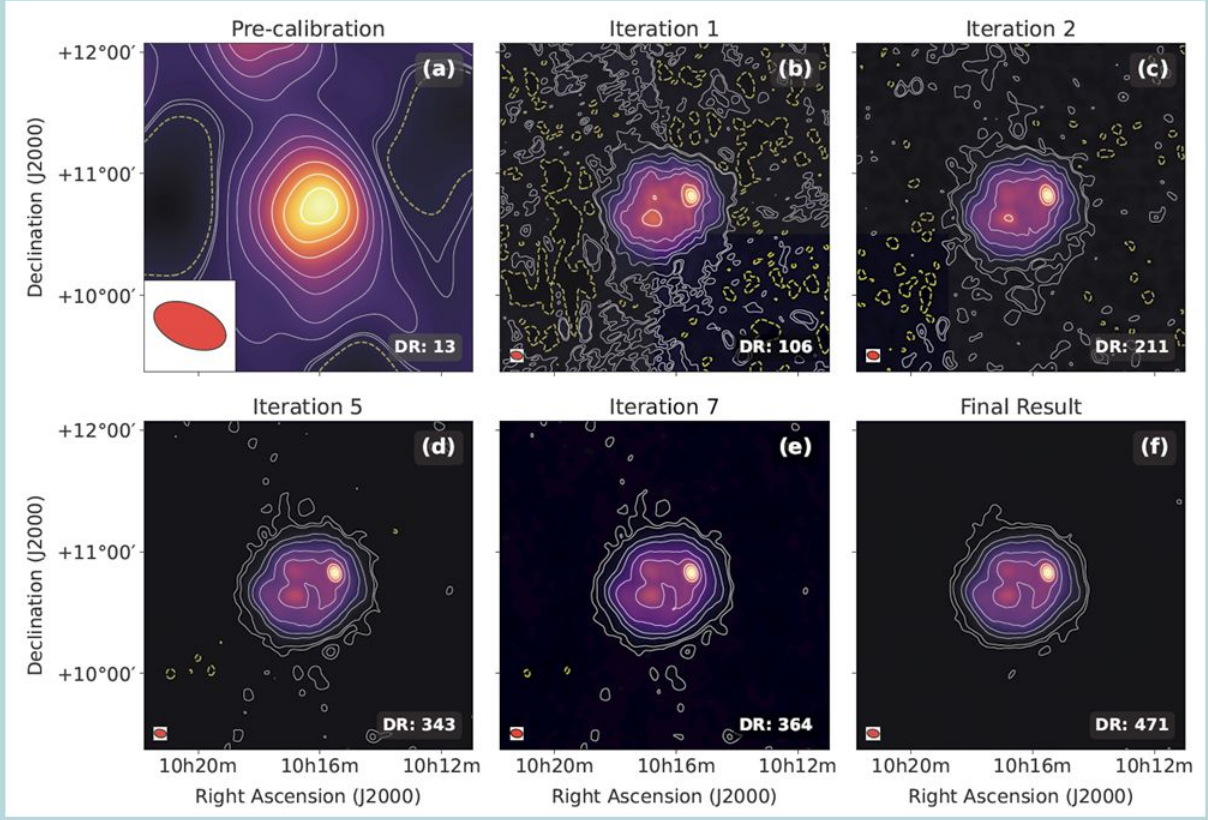
Providing a realistic starting model is therefore essential to guide the optimisation toward the physically correct solution.

Self-calibration

- No phase solution applied from calibrator observation
- Iterative addition of longer baselines
- First uvrange to ensure Sun is unresolved
- Use a simple gaussian model
- Make the model more accurate with iterations



Self-calibration



Track DR, rms, negatives for each iteration

Contours at -1%, 0.5%, 1%, 5%, 10%, 20%, 30%, 50%, 70% & 90% of the peak intensity

Why does this work?

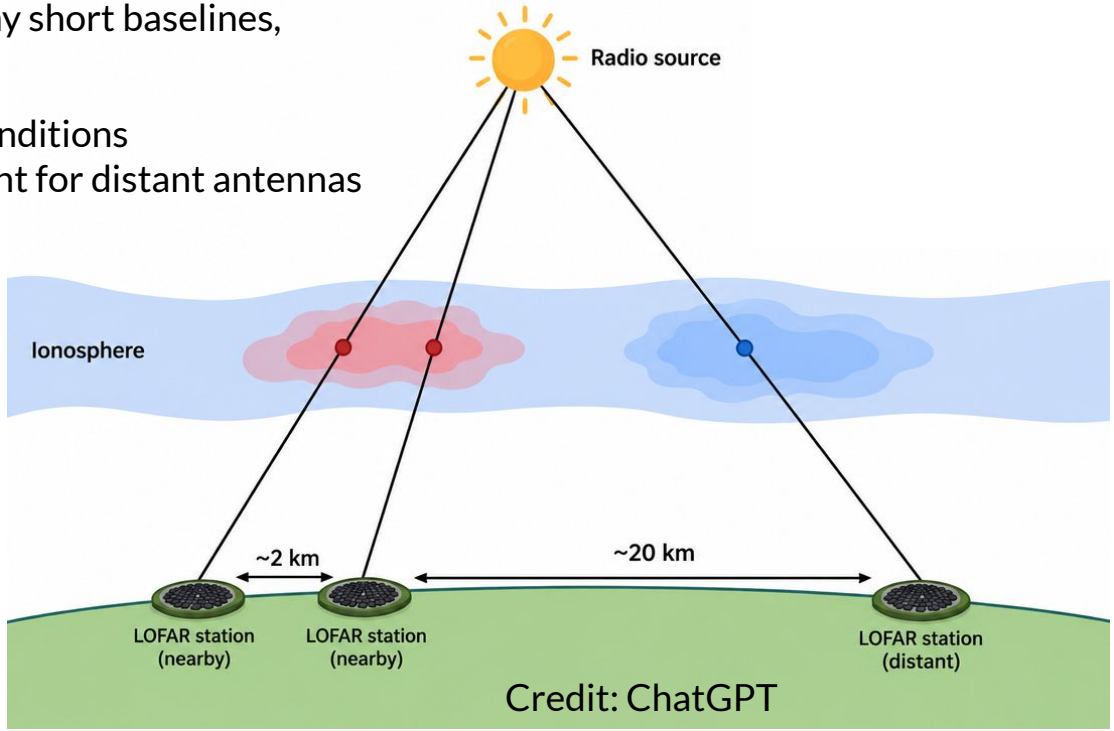
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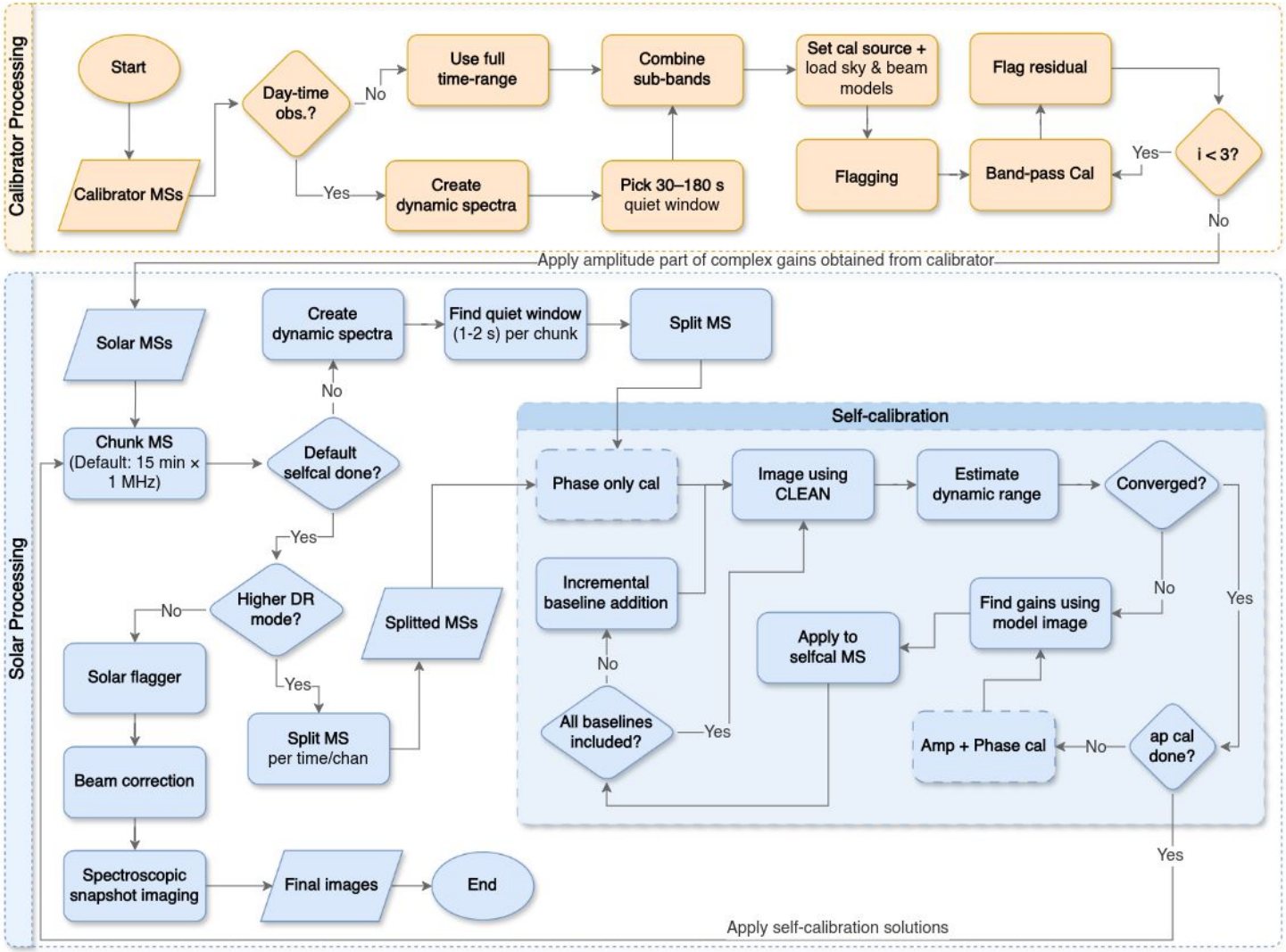
- It works for LOFAR if we are using only the core stations (or some of the nearest remote stations)
- This is because they have dense instantaneous uv-coverage
- For distant stations, there are not many short baselines,
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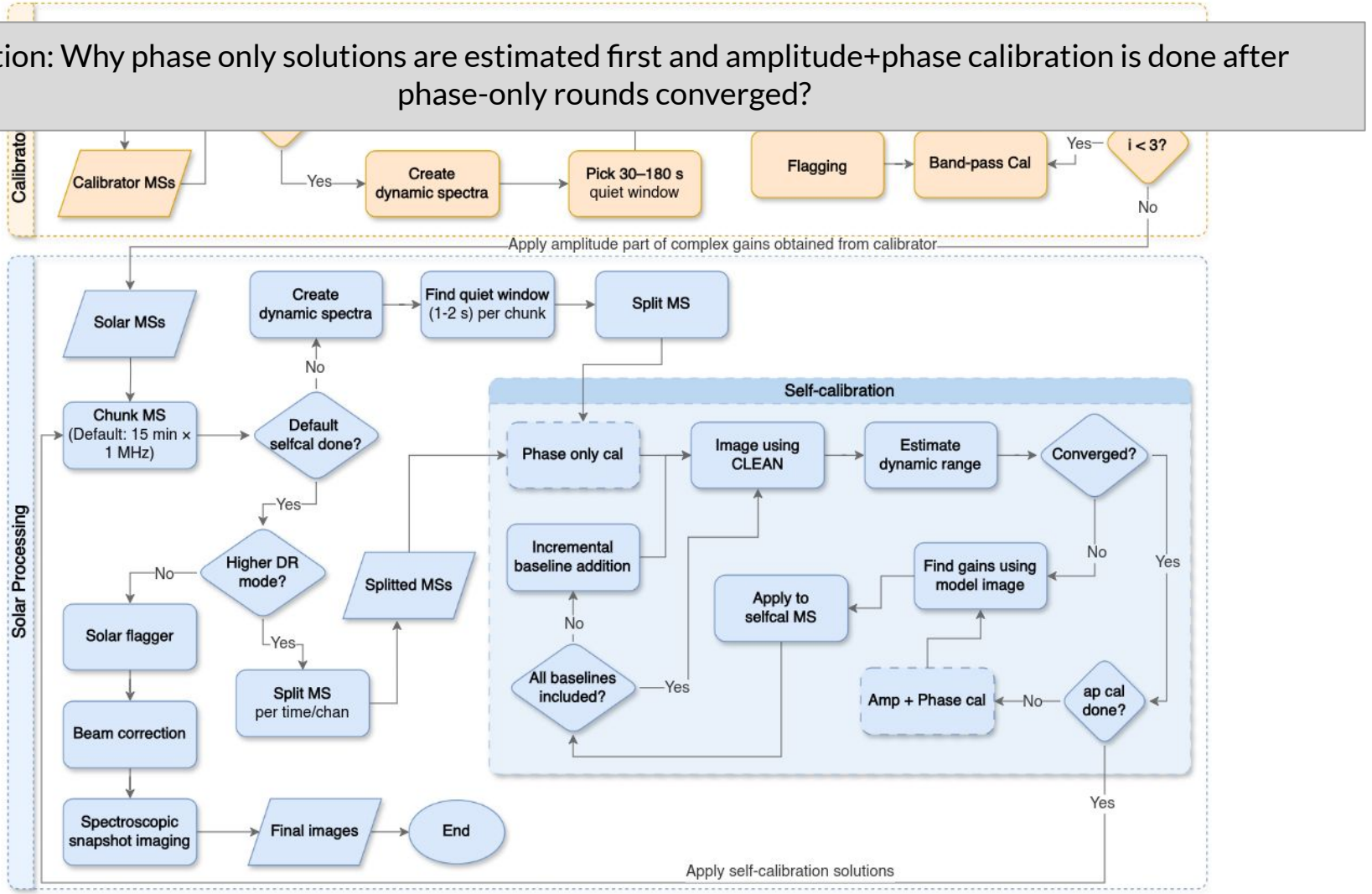
- It works for LOFAR if we are using only the core stations (or some of the nearest remote stations)
- This is because they have dense instantaneous uv-coverage
- For distant stations, there are not many short baselines, to start with an unresolved Sun
- Another challenge: the ionospheric conditions might be different along the line of sight for distant antennas



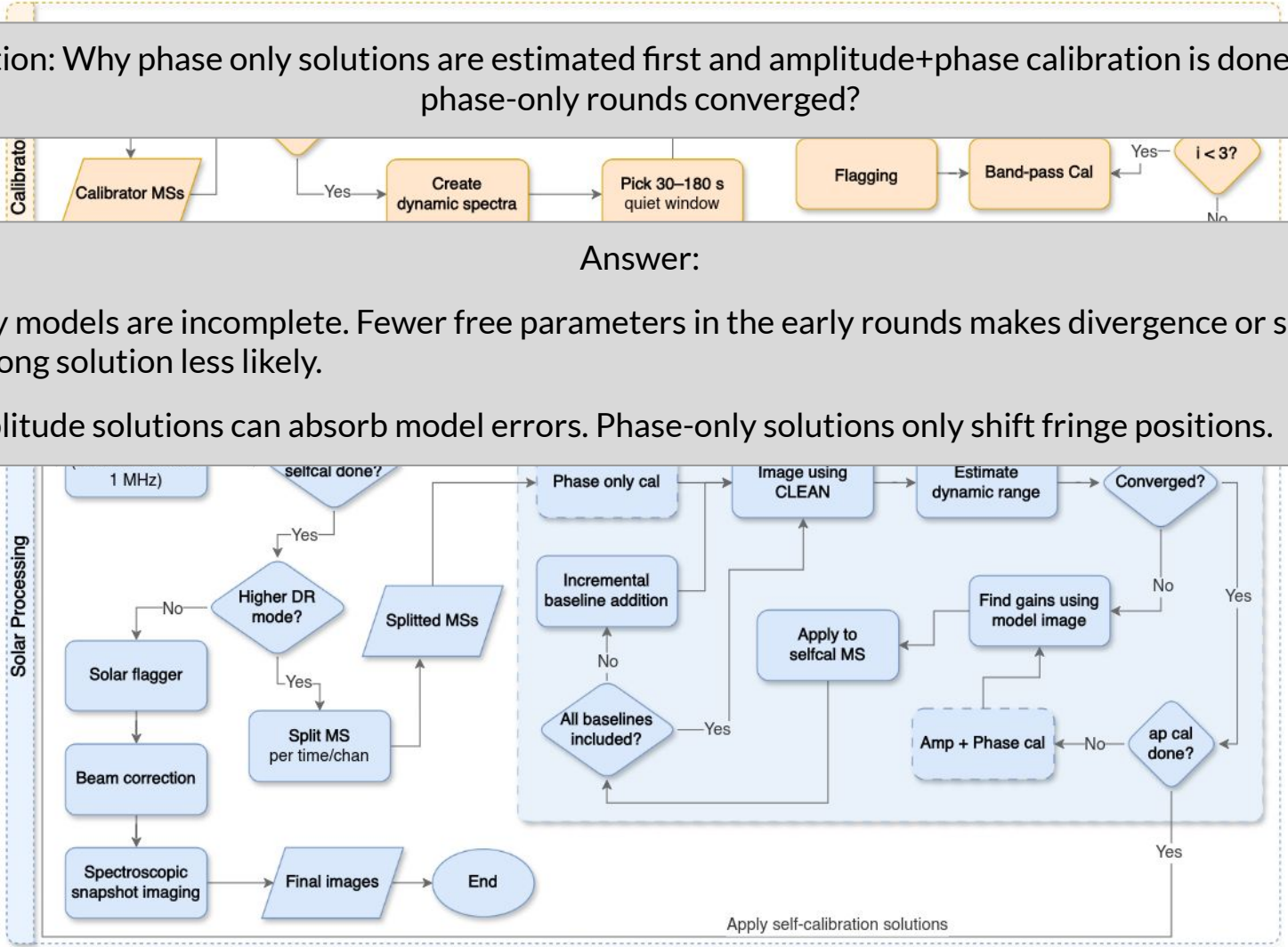
Credit: ChatGPT


Calibrator Processing
Start
Calibrator MSs
Day-time obs.?
No
Yes
Use full time-range
Create dynamic spectra
Combine sub-bands
Pick 30–180 s quiet window
Set cal source + load sky & beam models
Flagging
Flag residual
Band-pass Cal
Yes
i < 3?
No
Apply amplitude part of complex gains obtained from calibrator
Solar Processing
Solar MSs
Chunk MS (Default: 15 min × 1 MHz)
Default selfcal done?
No
Yes
Create dynamic spectra
Find quiet window (1-2 s) per chunk
Split MS
Higher DR mode?
No
Yes
Splitted MSs
Split MS per time/chan
Solar flagger
Beam correction
Spectroscopic snapshot imaging
Final images
End
Self-calibration
Phase only cal
Image using CLEAN
Estimate dynamic range
Converged?
No
Yes
Incremental baseline addition
Find gains using model image
Apply to selfcal MS
No
All baselines included?
Yes
Amp + Phase cal
No
ap cal done?
Yes
Apply self-calibration solutions

Question: Why phase only solutions are estimated first and amplitude+phase calibration is done after phase-only rounds converged?



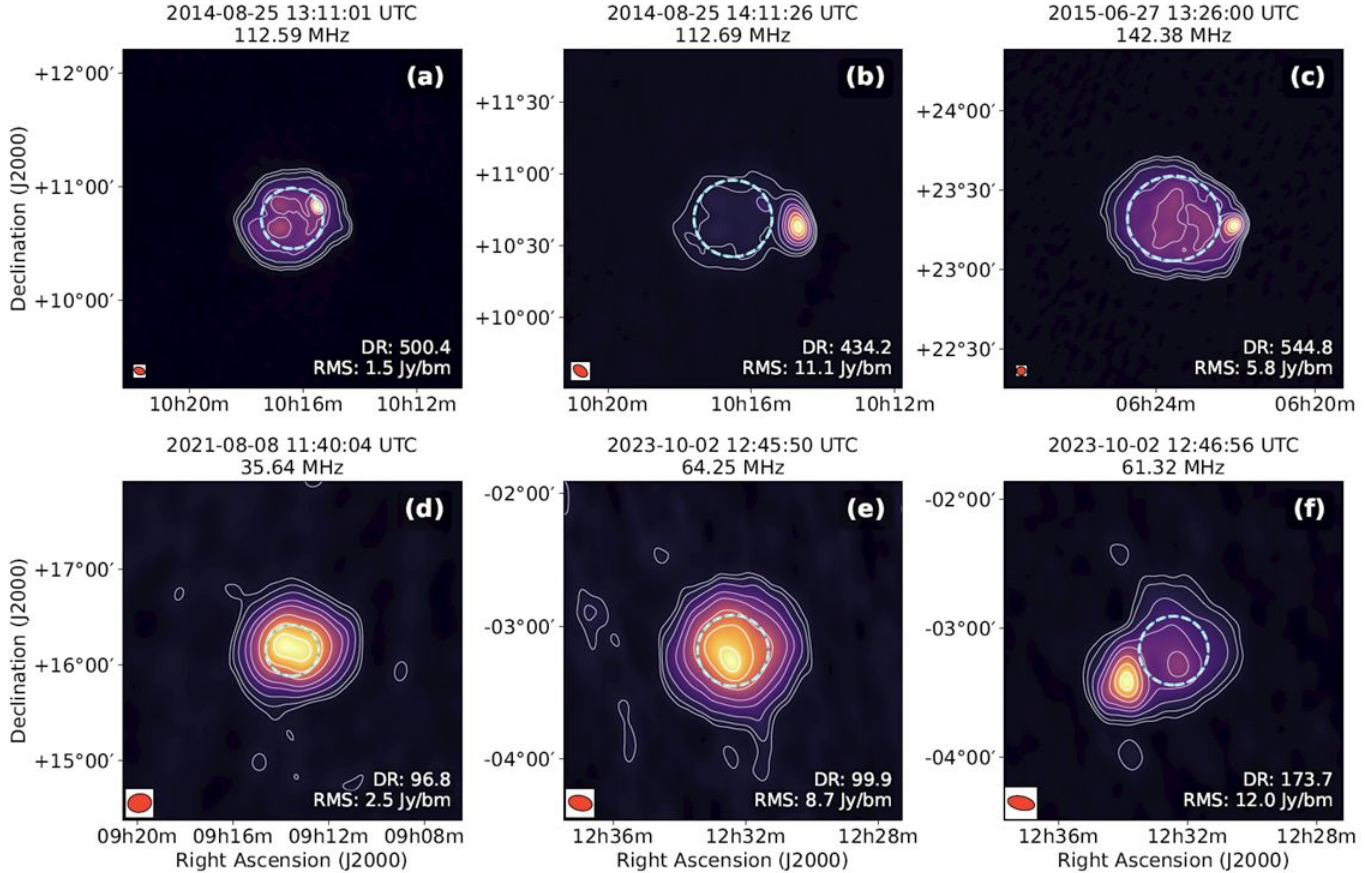
Question: Why phase only solutions are estimated first and amplitude+phase calibration is done after phase-only rounds converged?



Answer:

- Early models are incomplete. Fewer free parameters in the early rounds makes divergence or settling on a wrong solution less likely.
- Amplitude solutions can absorb model errors. Phase-only solutions only shift fringe positions.

Some example outputs …



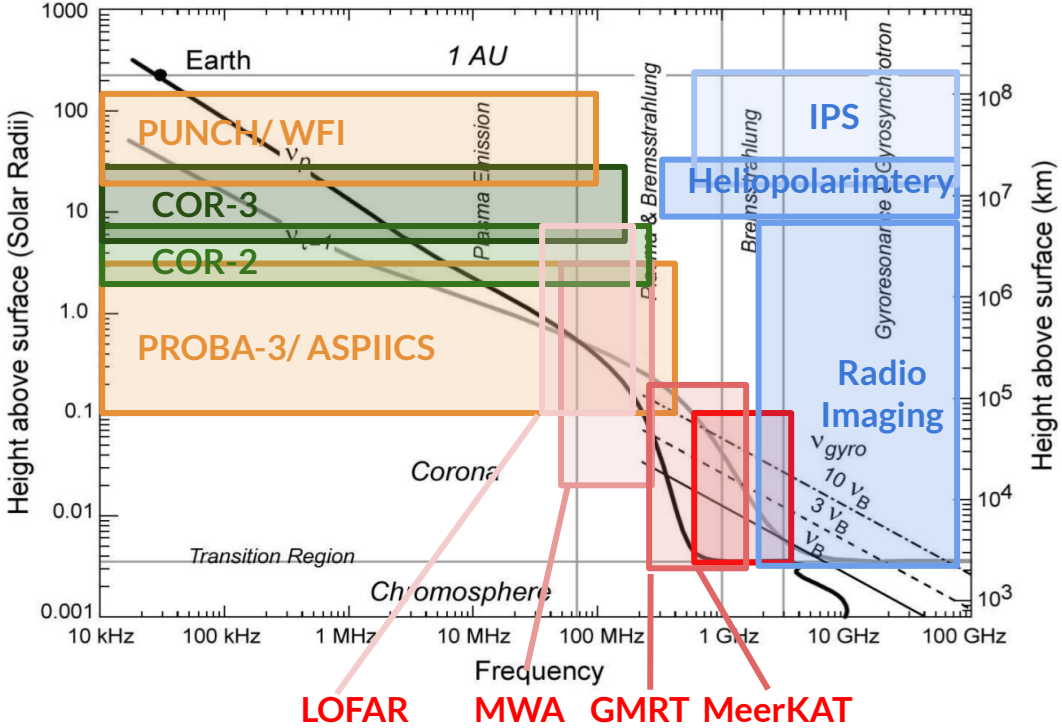
Tutorial

- You are provided with
  - Data : contains a solar MS file
  - Workdir (for MacOS users) : Output of the pipeline
  - selfcal_fits (for MacOS users)
  - solar_lofar_tutorial.ipynb
  - Dynamic_spectra.png
  - Singularity container: simpl_LDS.sif
- For LINUX users: open jupyter notebook using the command:

  PYTHONNOUSERSITE=1 singularity exec --bind /path/to/where/you/have/all/these/files simpl_LDS.sif jupyter notebook --no-browser --notebook-dir=/path/to/notebook/directory
- For MACOS users: The notebook should be run from the flocs Docker container. Make sure that ll data is visible in the container by putting it in ~/lofardataschool which should be visible in /data in the container

Backup slides

Radio probes of Sun and Heliosphere



$$\nu_p \approx 9000\sqrt{N_e}$$

$$\nu(\tau_{ff}=1) \approx \frac{0.5\ N_e\ L^{1/2}}{T_e^{3/4}}$$

$$\nu_B \approx 2.8 \times 10^6 B$$

Gary and Hurford, 2004

Solar noise storms: the most common active metric emission

- Broadband continuum ($\gtrsim$ 100 MHz wide) lasting hours to days, overlaid with short-lived (0.1–10 s), narrowband (~few MHz) type I bursts
- Strongly circularly polarized → fundamental plasma emission
- Powered by nonthermal electrons trapped in closed loops above active regions

