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Space-Weather Ground-Based Radio Observations in the Context of the Heliosphere-Earth System

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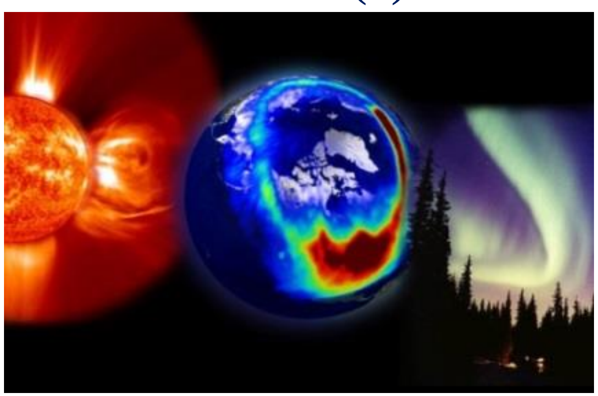

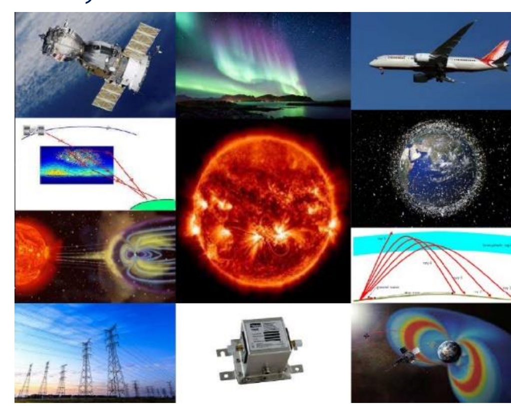

Outline

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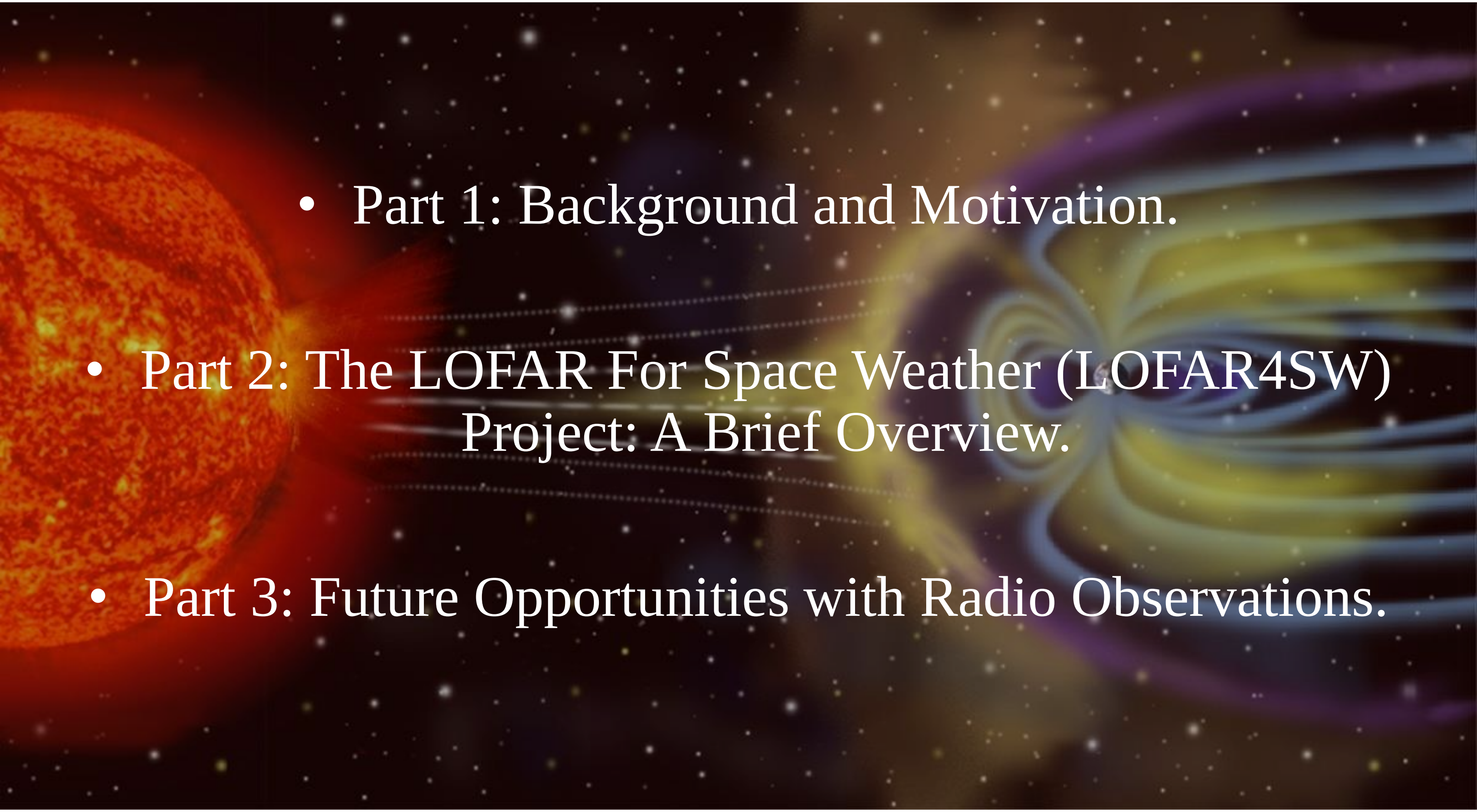


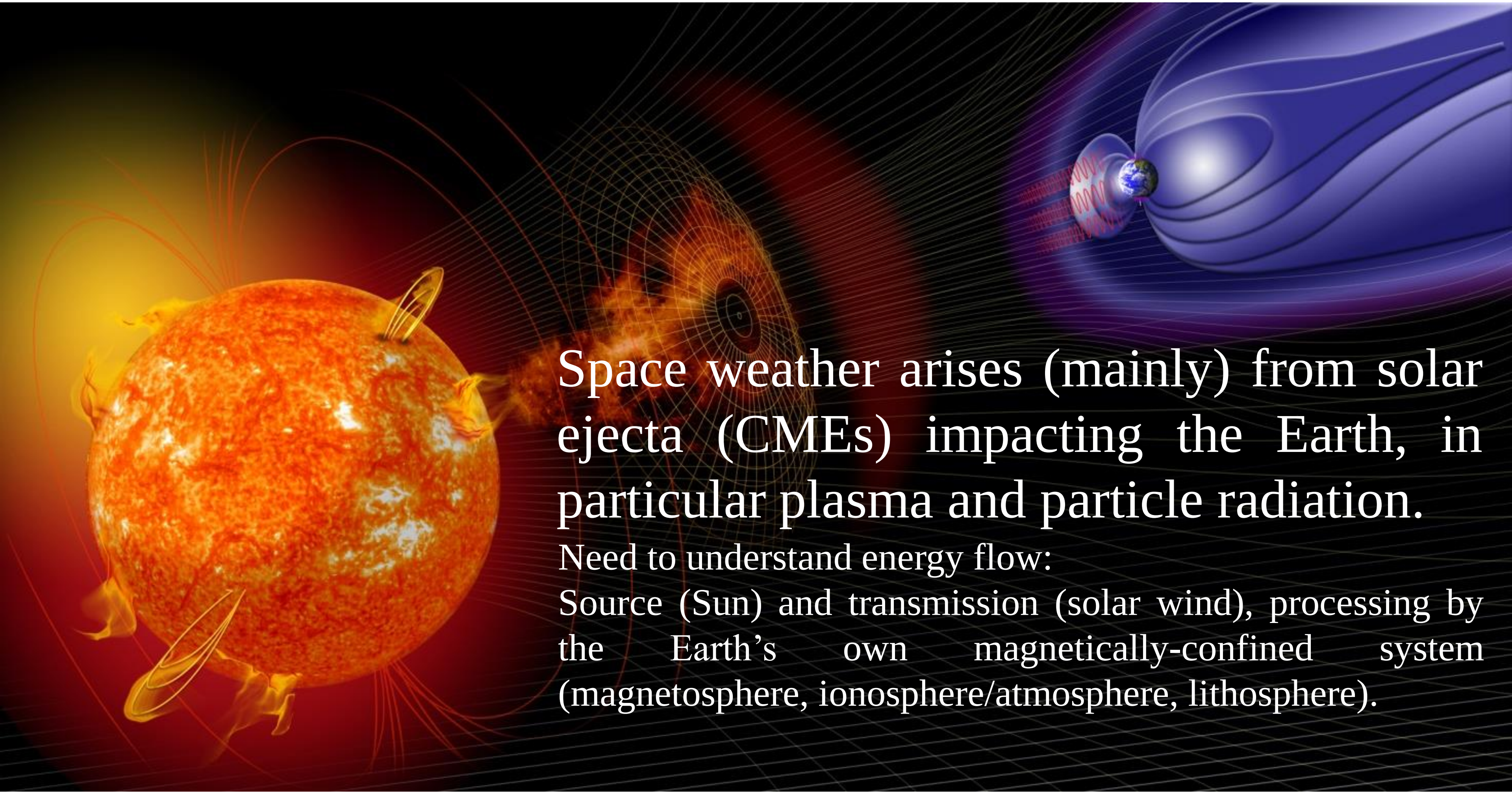
- Part 1: Background and Motivation.
- Part 2: The LOFAR For Space Weather (LOFAR4SW) Project: A Brief Overview.
- Part 3: Future Opportunities with Radio Observations.

Part 1

Background and Motivation.

What and Why?

Because space weather is the entire
Sun-Heliosphere-Earth system!

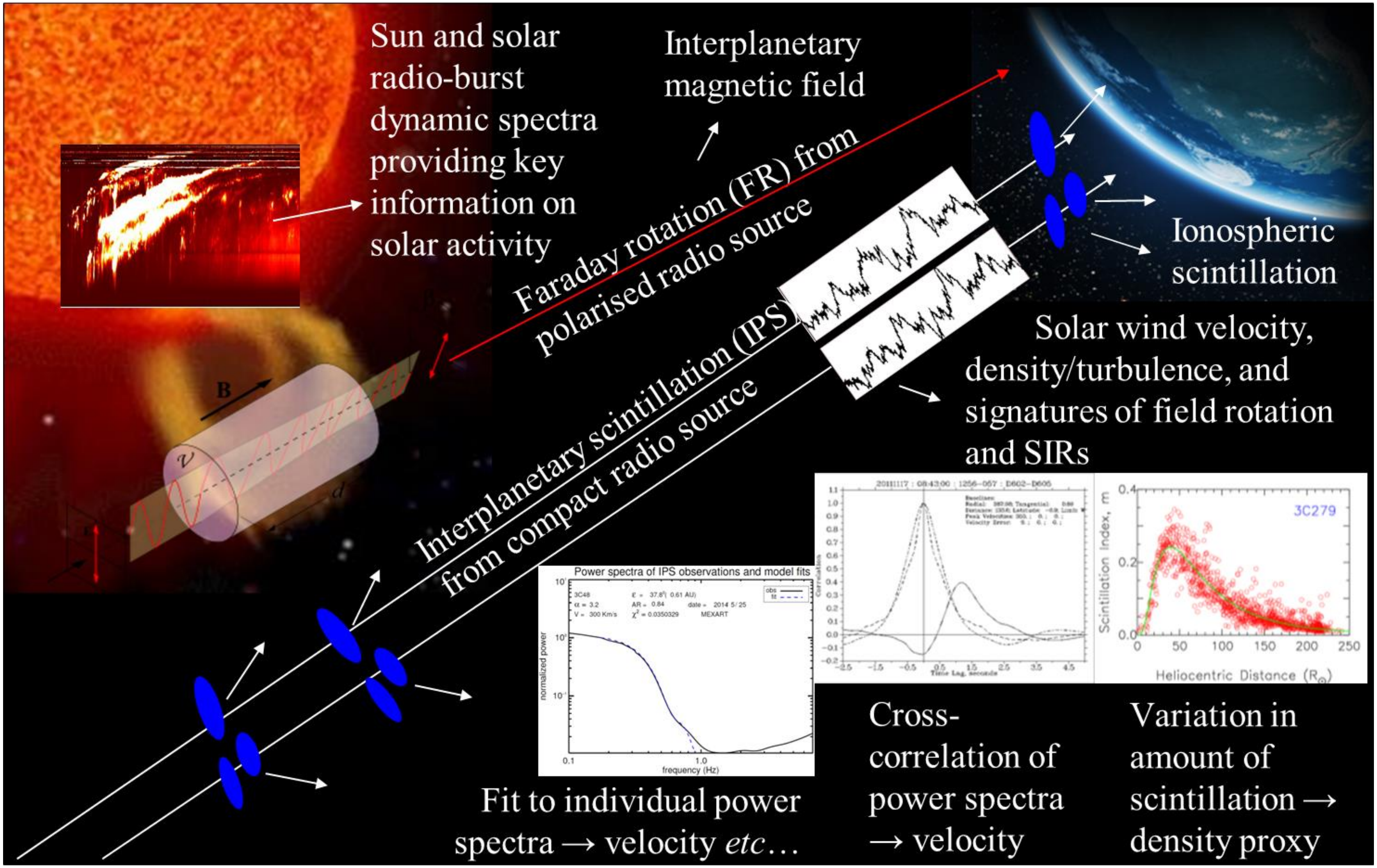


Space weather arises (mainly) from solar ejecta (CMEs) impacting the Earth, in particular plasma and particle radiation.

Need to understand energy flow:
Source (Sun) and transmission (solar wind), processing by the Earth's own magnetically-confined system (magnetosphere, ionosphere/atmosphere, lithosphere).

Space Weather Example Impacts…

Radio Techniques (Plus Imaging)



Current Radio Capabilities

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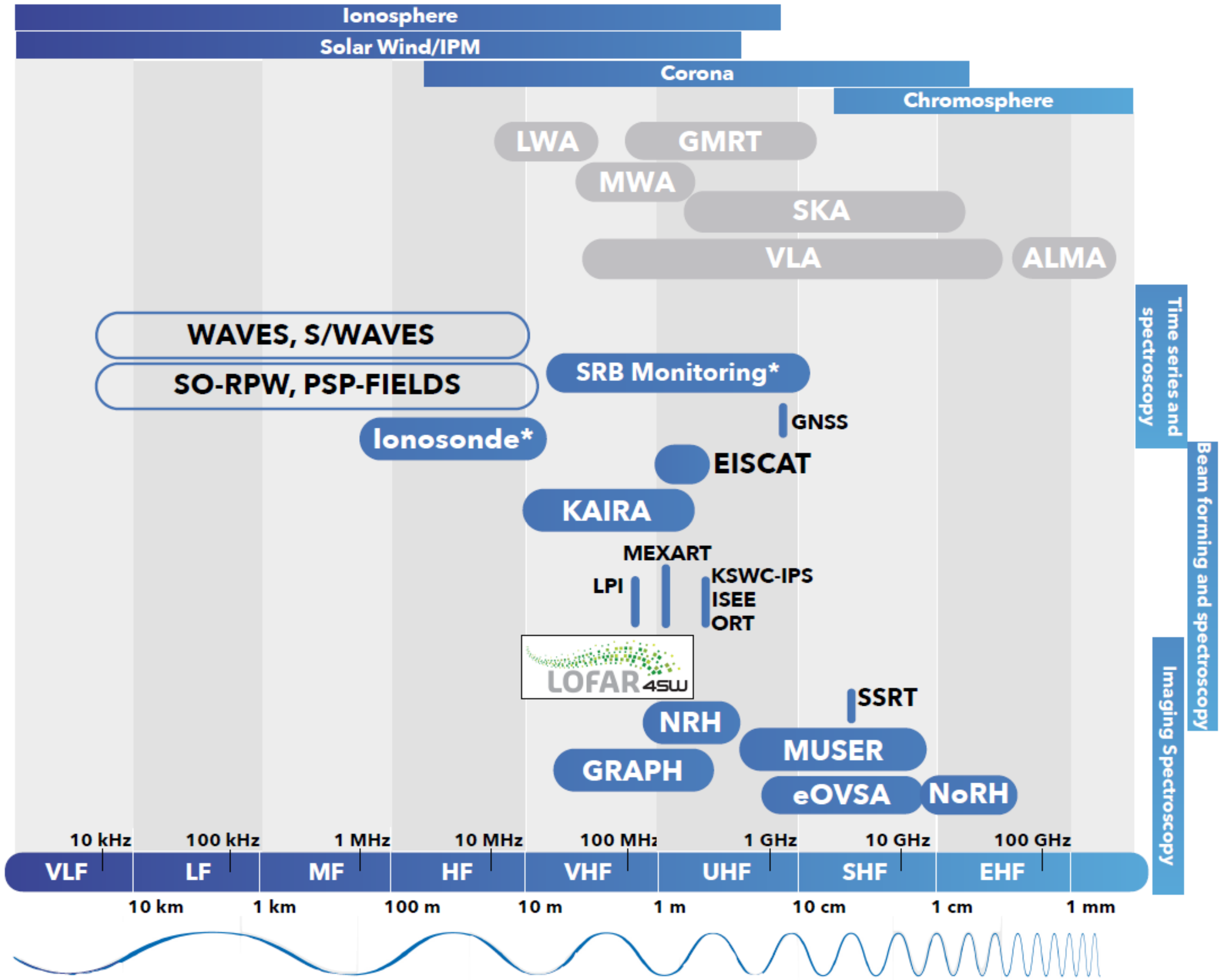

- Carley *et al.*, JSWSC, 2020; and LOFAR4SW Project…

Part 2

The LOFAR For Space Weather (LOFAR4SW) Project: A Brief Overview.

(Funded under the Horizon 2020 Programme H2020 INFRADEV-2017-1 under grant agreement 777442.)

LOFAR Locations

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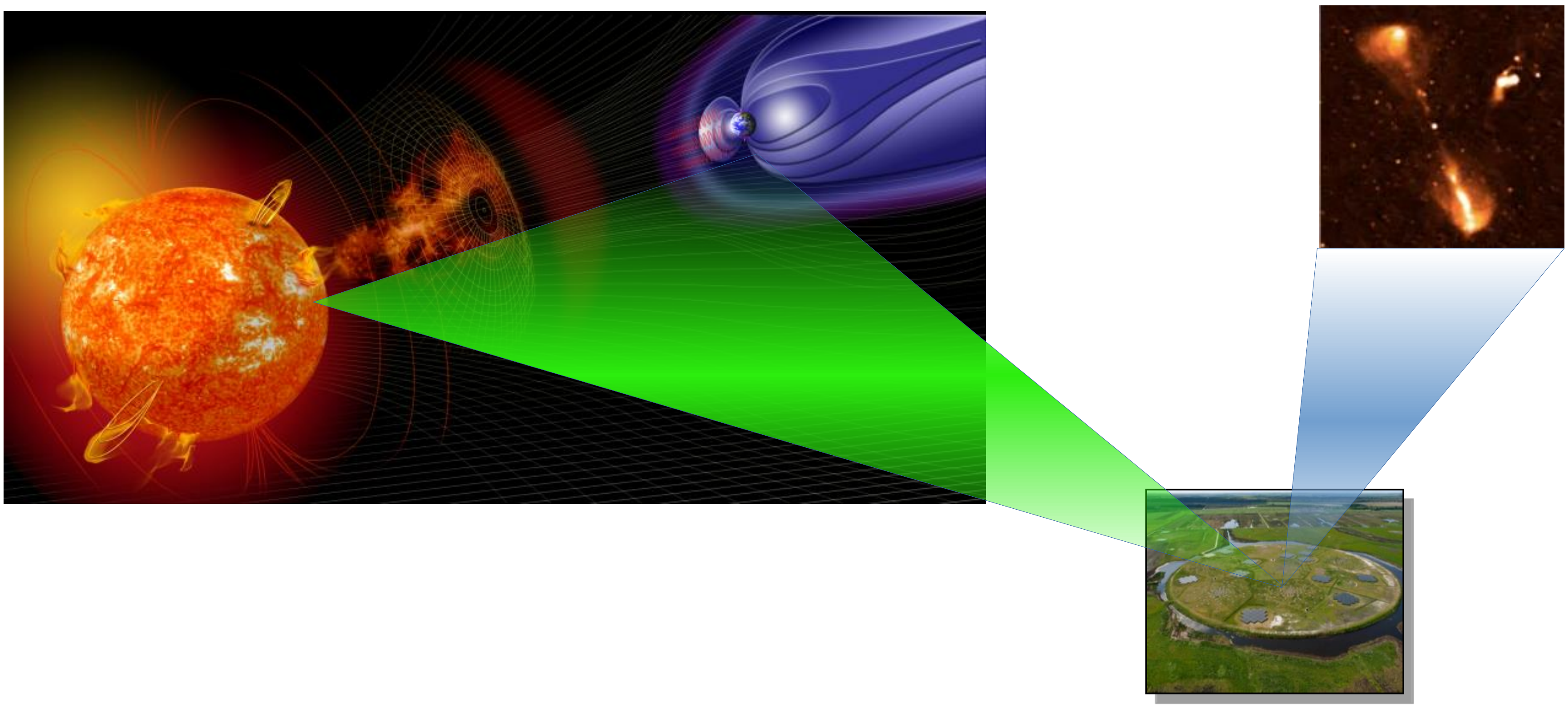
- 38 NL stations and 14 international stations.
- 1 new station to come in Italy (2023?).
- 1 new station to come in Bulgaria (2024?).

- Frequency range: 10-250 MHz.
- High time and frequency resolution.
- Multi-beam capabilities.

LOFAR4SW Ultimate Challenge

- Make one telescope into two:
  - With NO effect on normal astronomy operations!



Space-Weather Advancements

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Final Combined LOFAR4SW Use Case Prioritisations					
Use Case	Subject	Final Priority (across all domains)	Final Priority (across all domains)	Science or Monitoring/ Operations	Use Case for Both Science and Monitoring/
H8	Faraday rotation from pulsars (R2O)	Top	1	Sc	Yes
S2	CME imaging (R2O)	Top	1	Sc	Yes
H2	G-levels from IPS	Top	1	MO	Yes
H4	Space weather IPS	Top	1	MO	No
H5	All-sky snapshot IPS	Top	1	MO	No
I1	Imaging riometer	Top	1	MO	Yes
I11	Passive radar (<10 MHz) [Extend <10MHz to ~40MHz]	Top	1	MO	No
S1	SW monitoring	Top	1	MO	No
H6	Solar wind turbulence (R2O)	High	2	Sc	No
I3	Scintillation pattern flow	High	2	Sc	No
I5	Wide-bandwidth scintillation (R2O)	High	2	Sc	No
I6	High-resolution all-sky scintillation (core)	High	2	Sc	No
P1	Jupiter Space Weather	Medium	2	Sc	No
S5	Quiet Sun/C-holes (R2O)	High	2	Sc	Yes
S7	Fine structure	High	2	Sc	No
S5	Quiet Sun/C-holes	High	2	MO	Yes
H1	Multi-station IPS (R2O)	High	3	Sc	Yes
H2	G-levels from IPS (R2O)	High	3	Sc	Yes
I1	Imaging riometer (R2O)	High	3	Sc	Yes
S3	Type II/shocks (R2O)	High	3	Sc	No
S4	Type III/particles (R2O)	High	3	Sc	No
I2	Monitoring S4	High	3	MO	No
H7	Solar wind density from pulsar DM (R2O)	High	4	Sc	Yes
I10	TID (LOFAR+GNSS)	High	4	Sc	No
I7	TID (R2O)	High	4	Sc	Yes
I8	MLT wind fields	High	4	Sc	No
S6	Long term sources (R2O)	High	4	Sc	No
I7	TID	High	4	MO	Yes
H1	Multi-station IPS	High	5	MO	Yes
S2	CME imaging	Medium	6	MO	Yes
H8	Faraday rotation from pulsars	Medium	7	MO	Yes
I4	All-sky scintillation (single station)	Medium	8	MO	No
H7	Solar wind density from pulsar DM	Medium	9	MO	Yes
H3	IPS Imaging	Not Classified/ Blue Skies	-	-	NO
H9	FR Galactic Background	Not Classified/ Blue Skies	-	-	NO
I9	Passive radar (>40MHz)	Not Classified/ Blue Skies	-	-	NO

LOFAR4SW Use Case Prioritisations - Science		
Use Case	Subject	Science Priority (Final within each domain)
H8	Faraday rotation from pulsars (R2O)	Top
S2	CME imaging (R2O)	Top
H6	Solar wind turbulence (R2O)	High
I3	Scintillation pattern flow	High
I5	Wide-bandwidth scintillation (R2O)	High
I6	High-resolution all-sky scintillation (core)	High
P1	Jupiter Space Weather	Medium
S5	Quiet Sun/C-holes (R2O)	High
S7	Fine structure	High
H1	Multi-station IPS (R2O)	High
H2	G-levels from IPS (R2O)	High
I1	Imaging riometer (R2O)	High
S3	Type II/shocks (R2O)	High
S4	Type III/particles (R2O)	High
H7	Solar wind density from pulsar DM (R2O)	High
I10	TID (LOFAR+GNSS)	High
I7	TID (R2O)	High
I8	MLT wind fields	High
S6	Long term sources (R2O)	High

LOFAR4SW Use Case Prioritisations - Monitoring/Operations		
Use Case	Subject	Monitoring/Operations Priority (Final within each domain)
H2	G-levels from IPS	Top
H4	Space weather IPS	Top
H5	All-sky snapshot IPS	Top
I1	Imaging riometer	Top
I11	Passive radar (<10 MHz) [Extend <10MHz to ~40MHz]	Top
S1	SW monitoring	Top
S5	Quiet Sun/C-holes	High
I2	Monitoring S4	High
I7	TID	High
H1	Multi-station IPS	High
S2	CME imaging	Medium
H8	Faraday rotation from pulsars	Medium
I4	All-sky scintillation (single station)	Medium
H7	Solar wind density from pulsar DM	Medium

Overall (left), Science (Above-left), and Monitoring/ Operations (Above-right).

Final Combined LOFAR4SW Use Case Prioritisations					
Use Case	Subject	Final Priority (across all domains)	Final Priority (across all domains)	Science or Monitoring/ Operations	Use Case for Both Science and Monitoring/
H8	Faraday rotation from pulsars (R2O)	Top	1	Sc	Yes
S2	CME imaging (R2O)	Top	1	Sc	Yes
H2	G-levels from IPS	Top	1	MO	Yes
H4	Space weather IPS	Top	1	MO	No
H5	All-sky snapshot IPS	Top	1	MO	No
I1	Imaging riometer	Top	1	MO	Yes
I11	Passive radar (<10 MHz) [Extend <10MHz to ~40MHz]	Top	1	MO	No
S1	SW monitoring	Top	1	MO	No

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Why LOFAR4SW…

- The LOFAR4SW Design Study was the first step towards a fully-capable LOFAR Space-Weather instrument!

Astronomers propose project of observations to be run during a 6-month observation “cycle”.

Projects are reviewed by a panel of international scientists who then allocate time awards.

Observations scheduled based on awarded time.

Station signal processing → Central correlation and data processing → Data Archive → Astronomers

We don’t know what the Sun may do next, or when, so need to monitor to be able to observe and study all possible events.

The current LOFAR system is unsuited to the type of monitoring needed to accomplish this:

For example, during the highly active period of September 2017:
- Missed observing the largest solar flare of the last cycle by ~30 minutes!
- Stopped observing the second largest just at its peak.
- Did not observe Earth-bound CMEs.
- Did not observe strong ionospheric response.

Hence LOFAR4SW! An EC-funded Design Study to **design an upgrade to LOFAR to allow full-time monitoring of space weather in parallel with radio astronomy.**

LOFAR4SW Upgrade Progress…

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LOFAR4SpaceWeather: Towards Space Weather Monitoring with Europe's Largest Radio Telescope

A fully-implemented LOFAR4SW will be one of Europe's most comprehensive space weather observatories, shedding new light on several aspects of the space weather system, from the Sun to the solar wind to the ionosphere.

Part 3

Future Opportunities with Radio Observations.

The Heliosphere – 12/09/17 CME (1)

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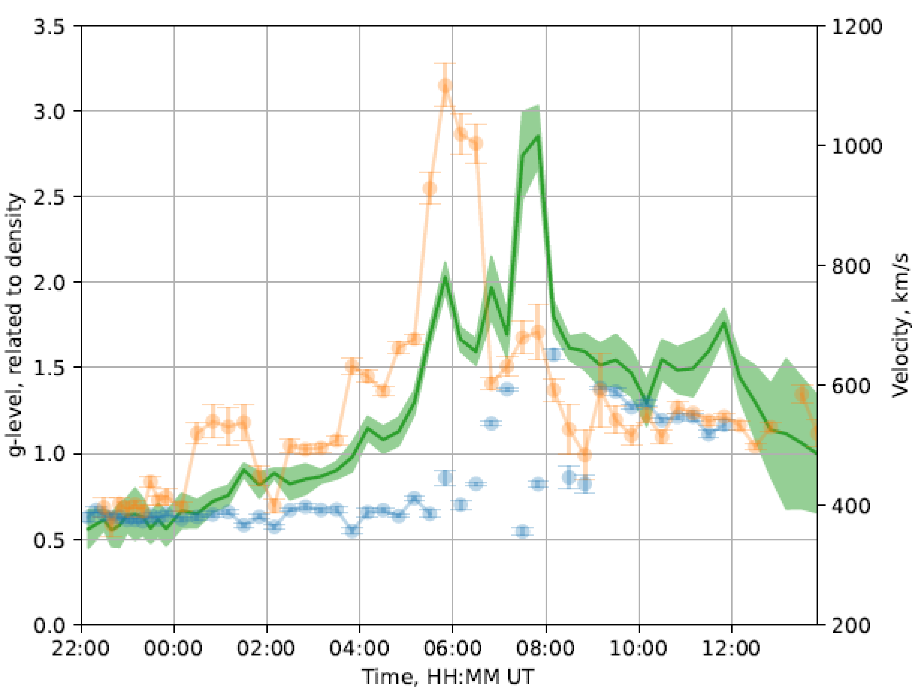
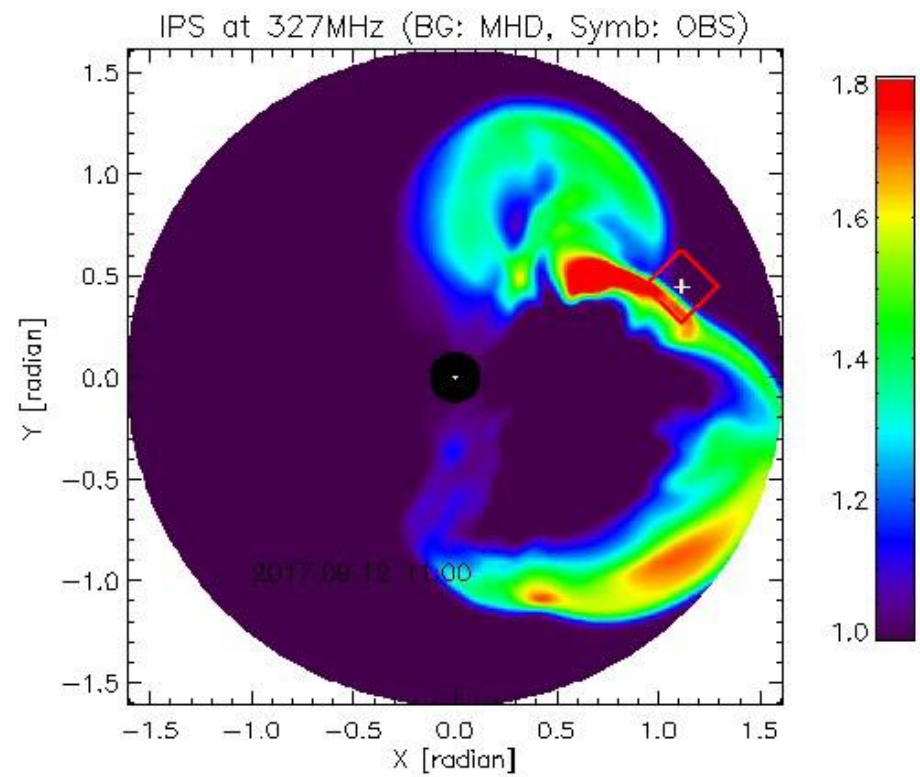
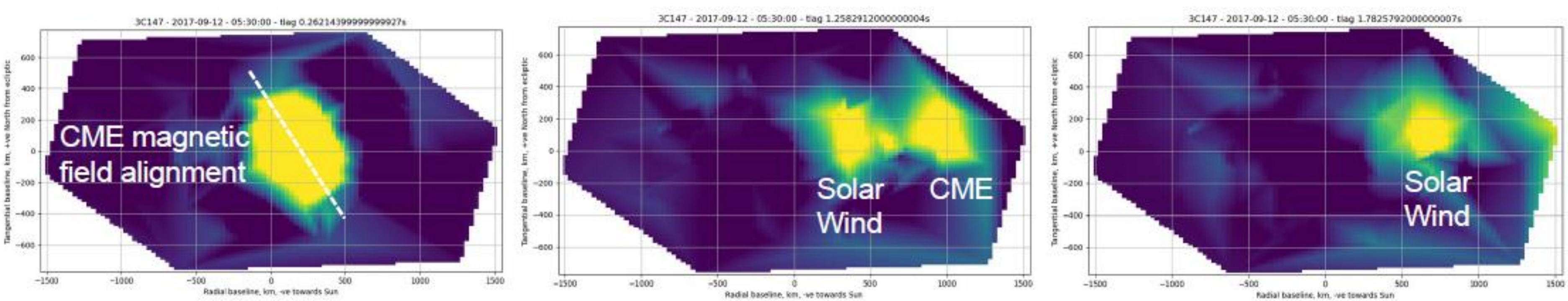
- LOFAR can obtain detailed information on the solar wind and CME velocity, density, and turbulence, from long-duration observations as well as building up a dataset of short-duration observations suitable for driving tomographic/kinematic and MHD models.





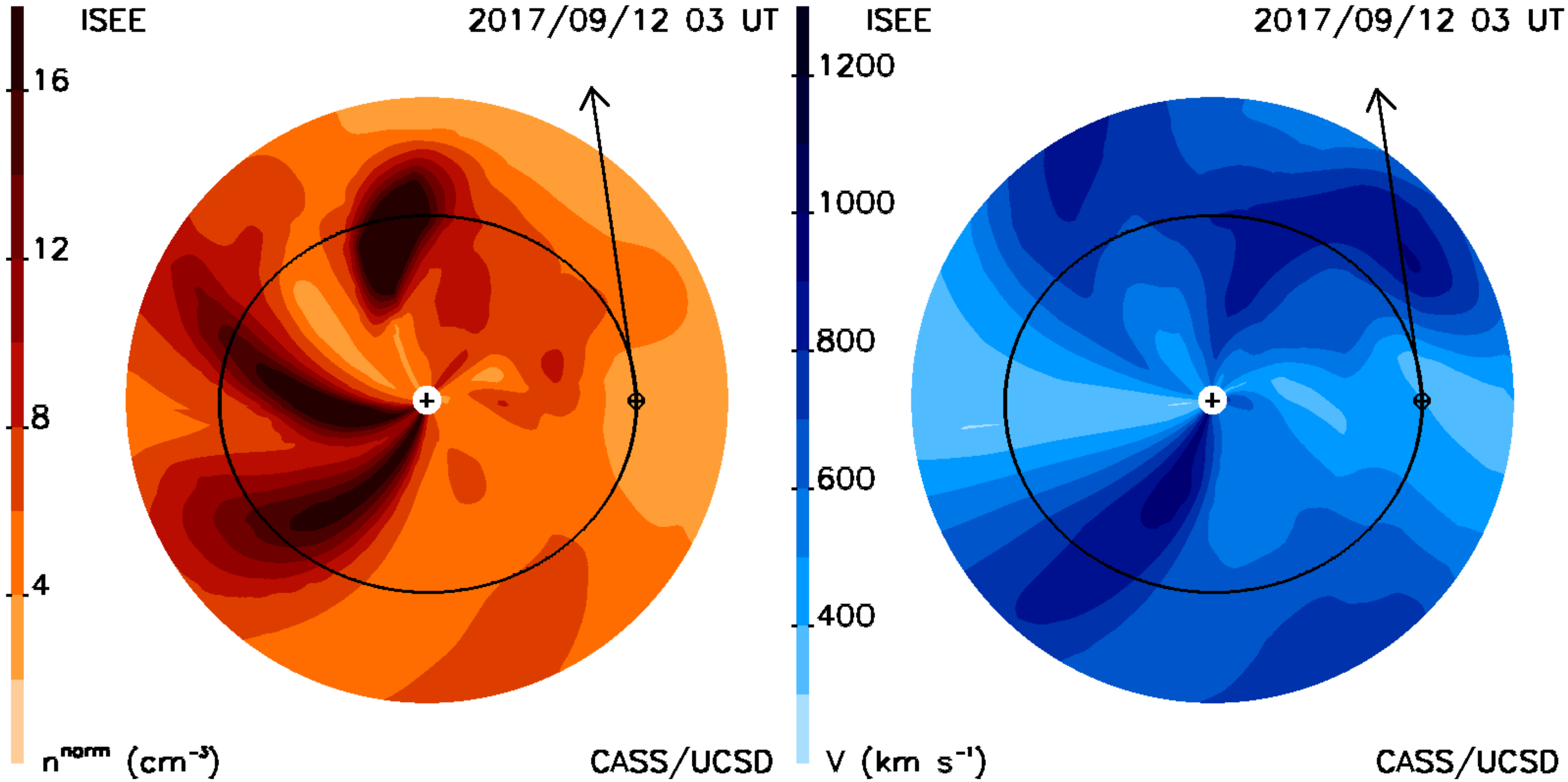
The Heliosphere – 12/09/17 CME (2)

- LOFAR “imaging” of the turbulent scintillation structure gives fundamental information on the small-scale structure within the solar wind and CMEs as well as of the fundamental structure of the radio sources on the sky.
- Images below (see Fallows *et al*., ASR, 2022 for details) show the 2-D spatial correlation of many baseline combinations of the LOFAR IPS observations of radio source 3C147 on 12 September 2017 during the passage of a CME…
- Also, Iwai *et al*., ASR, 2022 (same issue – COSPAR roadmap).



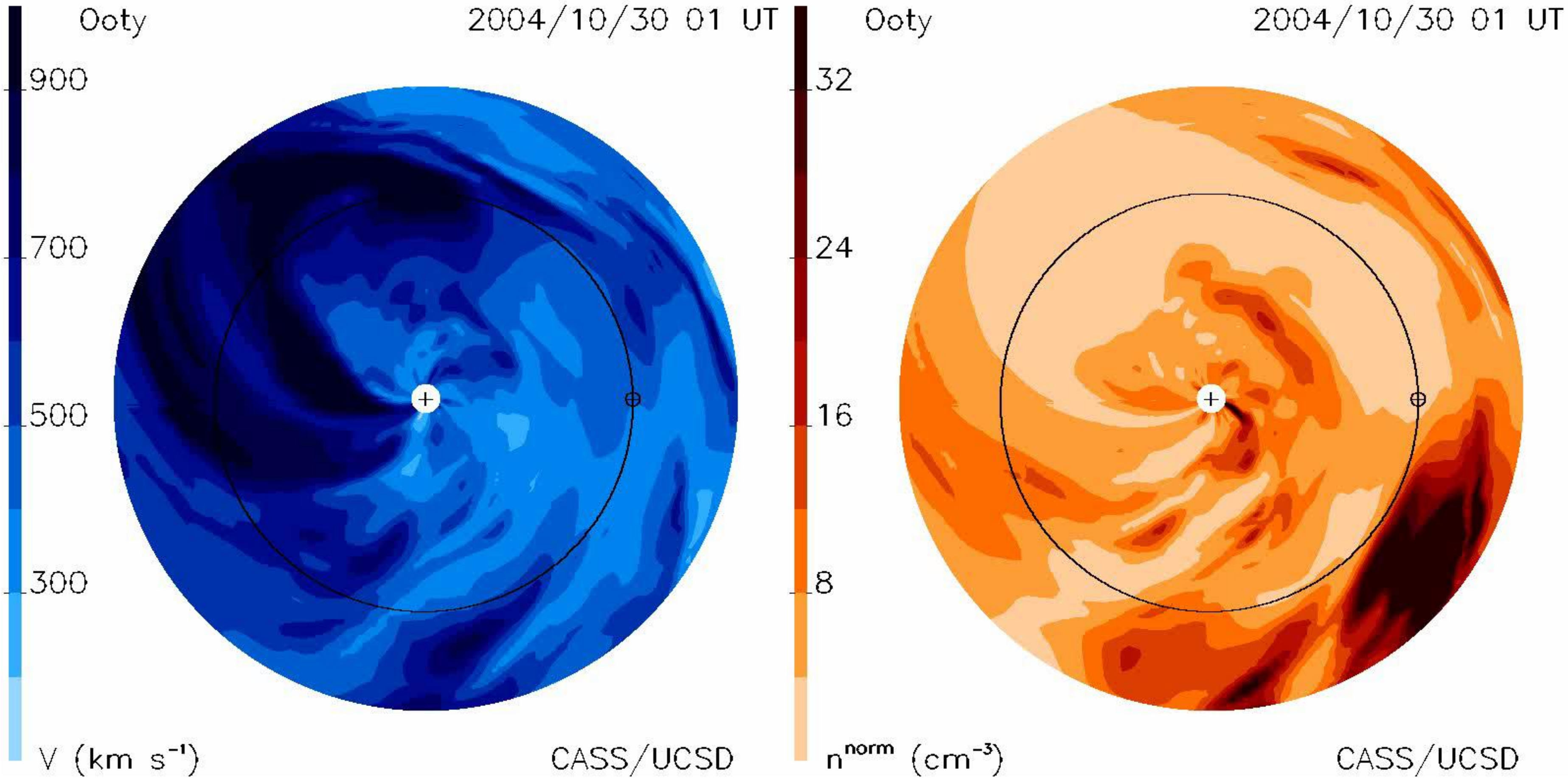
The Heliosphere – 12/09/17 CME (3)

- UCSD 3-D tomography using ISEE, Japan, IPS data along with the LOFAR line-of-sight projection to radio source 3C147 superimposed on the images (density, left; velocity, right).



And if we had even more IPS data…

- Using the UCSD 3-D Tomography for space-weather reconstructions of the inner heliosphere in this detail…?

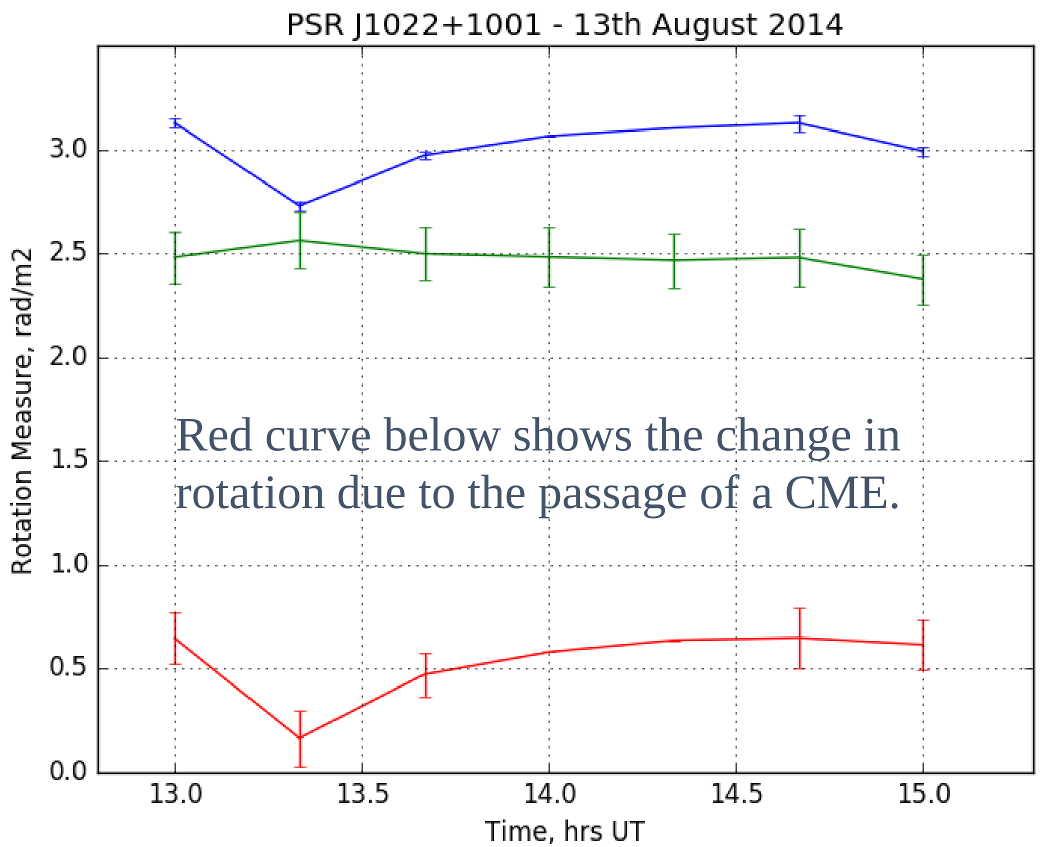


- See Bisi *et al*., Ann. Geophys., 2009 for further details…

Potential for CME Magnetic Fields

- The “Holy Grail” of space-weather prediction is considered to be that of the magnetic field across the inner heliosphere from the Sun to the Sun-Earth L1 where is it measured.

- Measurements of the Faraday rotation (FR) of pulsar signals traversing CMEs show considerable promise in being able to observe the magnetic field of a CME in the inner heliosphere.



And closer to the Earth…

- Studies of magnetospheric dynamics and magnetosphere-ionosphere coupling are crucially dependent on information about the upstream solar wind/CMEs.
  - These which plays a dominant role in determining activity within the Earth's space-environment.
- The ability to track the arrival of such features with long lead-in times, to know their speed, dimensions, and structure, will revolutionise our understanding of factors controlling the detrimental "geoefficiency" of solar storms.
- The use of radio-wave scintillation observations from LOFAR enables us to model in detail the actual spatial and temporal evolution of scintillation-inducing structures in both the heliosphere and ionosphere, gaining unique insight through a combination of single- and multi-station observations.

…With Possible Ways Forward…

- Analysis and interpretation of historical LOFAR scintillation data for both the heliosphere and the ionosphere.
  - Extract basic inner-heliospheric and ionospheric parameters.
- Research on unique LOFAR observations to identify novel additional parameters (*e.g.* magnetic field orientation) to include the characterisation of inner-heliospheric and ionospheric micro-structure.
- Understand the magnetosphere-ionosphere response to inner-heliospheric structures detected and analysed through LOFAR observations of scintillation, utilising ground-based (*e.g.* SuperDARN, EISCAT_3D, SuperMAG), and spacecraft mission (*e.g.* SMILE), measurements.
- Ultimately, an improvement to current space-weather forecast capabilities.

…And A Future Potential Project!