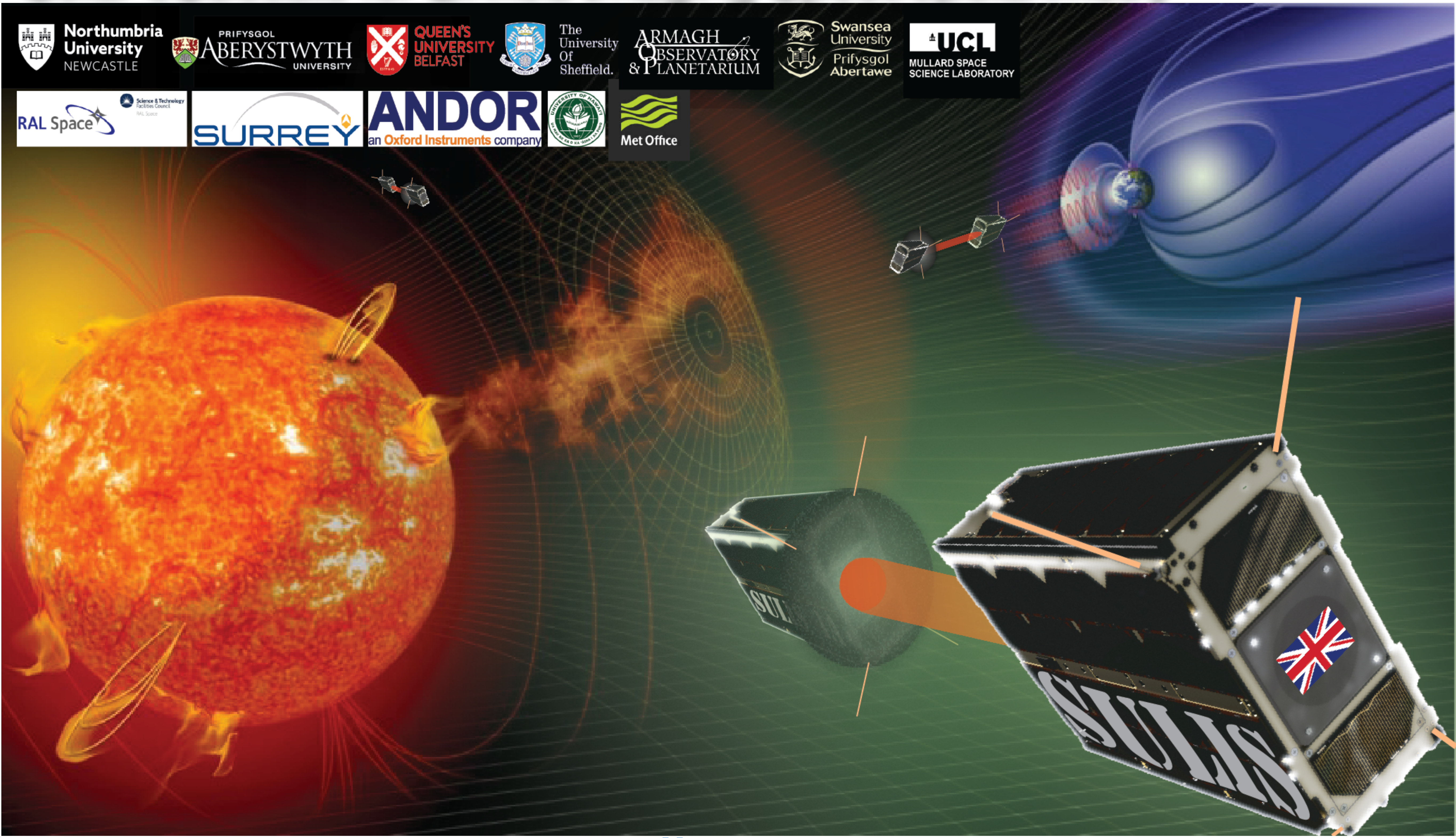
Dr Eamon Scullion
Northumbria University
eamon.scullion@northumbria.ac.uk

SULIS

10 Jan 2019
UK Missions Forum

Northumbria University
NEWCASTLE

Solar cUbesats for Linked Imaging Spectropolarimetry



http://sulis.space

#TakeOnTomorrow

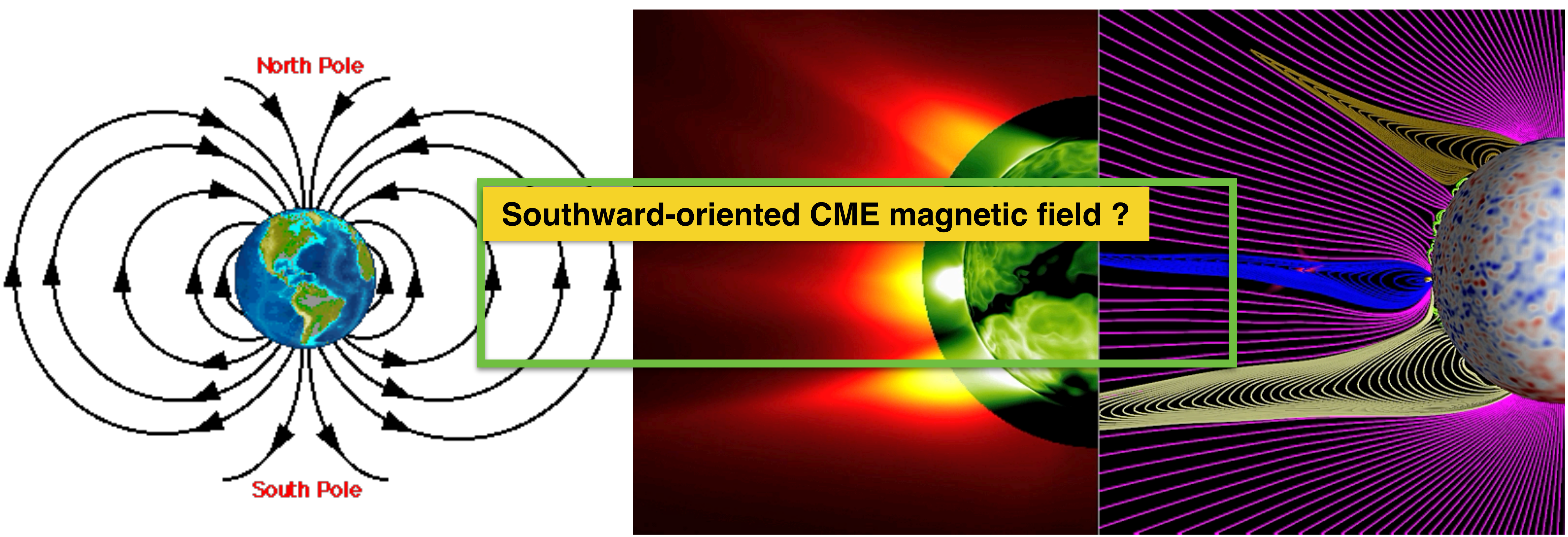
Science Mission: 3D Coronal Magnetometry

$\mathbf{B}(\mathbf{r};t)$, $T(\mathbf{r};t)$, and $n(\mathbf{r};t)$ with $\Delta t = 1$ min

Northumbria University NEWCASTLE

Coronal Magnetic Fields: One of the most important observables, yet, one of the least known about. It is challenging but it is doable:

- ***Flares*** – *Energy released is stored in the coronal magnetic field*
- ***CMEs*** *– Magnetic field orientation / energy, driving instabilities (torus), EIT waves -> Science behind Space Weather.*
- ***Coronal heating & Solar Wind Acceleration****– Alfven(ic) waves / dissipation mechanisms, Magnetic Reconnection.*
- ***We <u>need</u> 3D magnetic field vectors to properly & accurately quantify it - multiple simultaneous spectropolarimetric view points ? - go to space!***
- ***Future:*** *DKIST / EST cannot do 3D coronal magnetic fields or full disk or far corona (rely on ageing satellites*
- ***<u>Can</u> it be done?:*** *Yes, see later slides …*



SULIS compliments **operational space weather missions** (e.g ESAs potential **L5 mission, NASA's L1** follow-on to **DISCOVR** and the **ASPIICS/ PROBA-3)** paving the way for future space weather instruments.

Objectives

1) Provide the ***first direct measurements*** of the **3D coronal magnetic field** (*unique science*).

2) Provide eclipse-quality imaging **out to 5 solar radii** for deeper understanding of **physics underpinning space weather.**

3) Demonstrate UK-led future technologies (*proximity flying* CubeSat's; laser optical communications; Li-Fi; TFSC PV systems).

Coronal Emission Lines (CEL)

Saturated Hanle Effect: Visible / IR Coronal Magnetic fields

Northumbria University NEWCASTLE

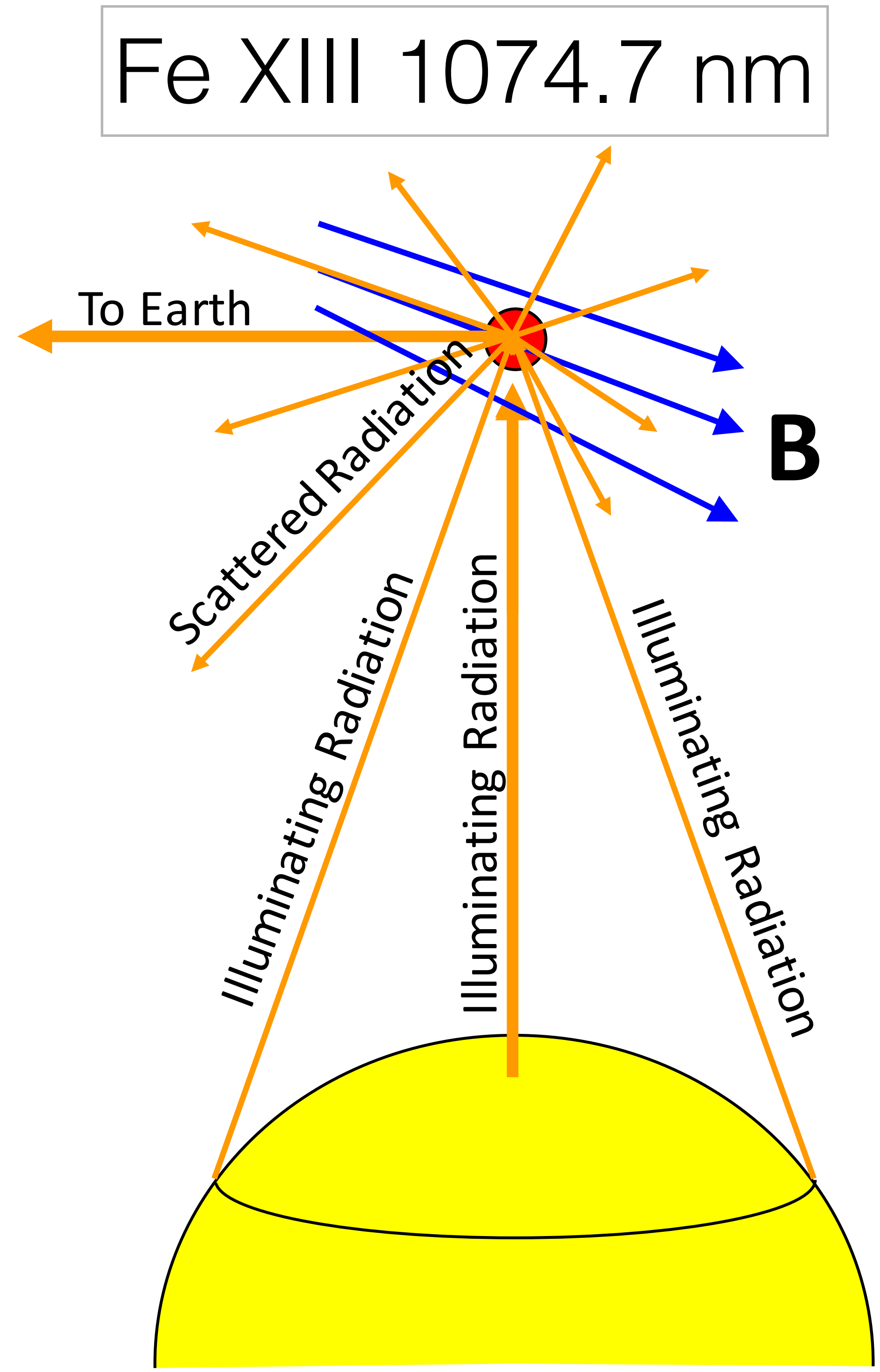
- **Saturated Hanle effect is due to resonant scattering of photospheric radiation by highly ionised atoms in the solar corona**
  - M1 (magnetic dipole transition)
  - Optically thin atmosphere
  - Anisotropic illumination
  - Low collisional rate

- **CEL circular polarisation yields information about the strength of longitudinal coronal magnetic field**
  - *First demonstrated in 1998 (**Lin, Penn, Tomczyk 2000**)*
  - ***Only two measurements exist to date:***

    Lin, Penn, Tomczyk, 2000; Lin, Kuhn, Coulte 2004
  - *CEL polarisation has no sensitivity to the strength of transverse component of coronal magnetic field vector*

- **CEL linear polarisation yields information about the orientation of coronal magnetic field vector projected in the plane-of-the-sky**
  - *Subject to van Vleck effect – **90 degree ambiguity:***

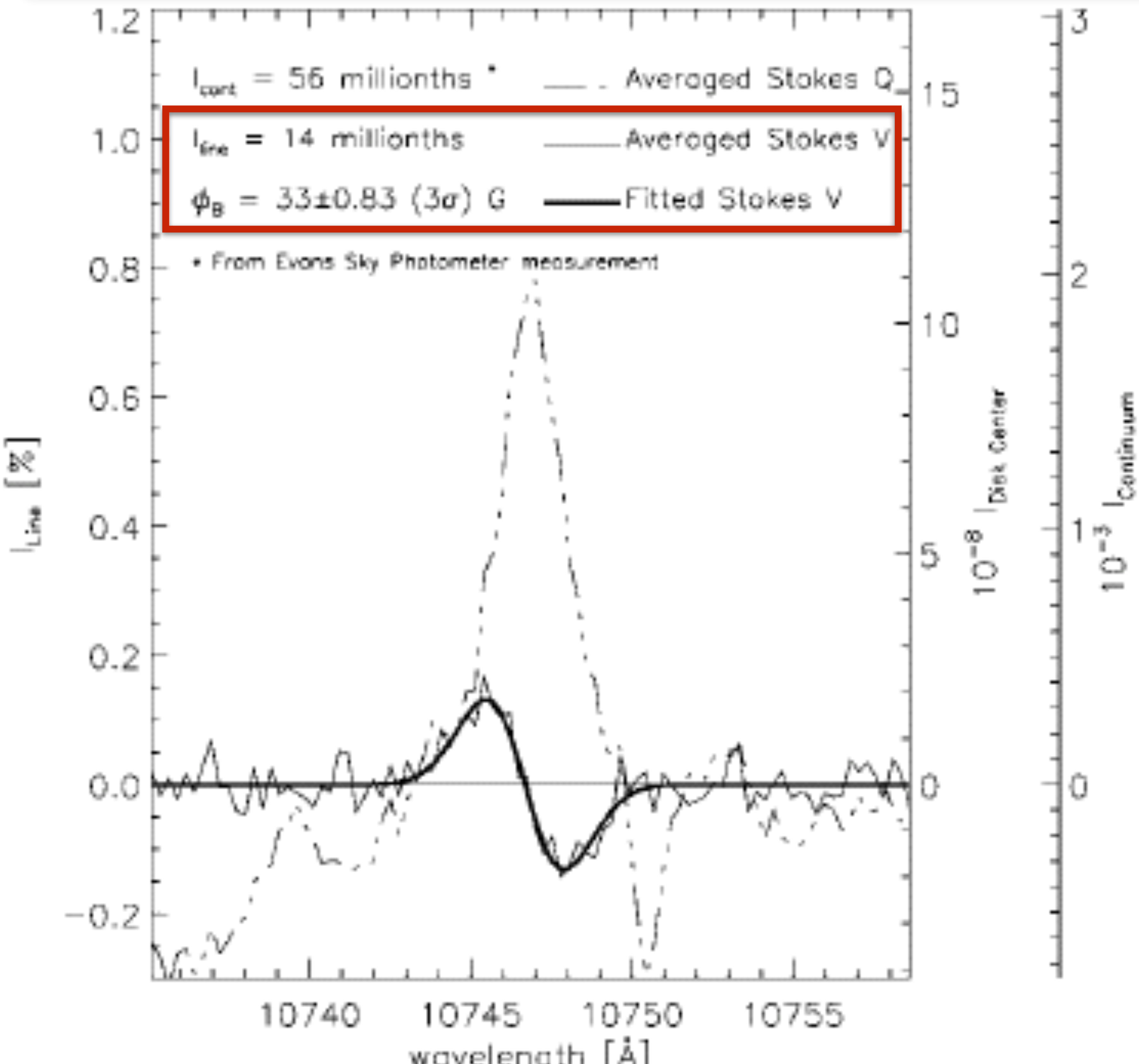
    to disambiguate 3D vector requires multiple viewing angles
  - *Substantial linear polarization signals: 1% – 10 %*
  - *First measured in 1960s and 1970s…*
  - *Routine full-corona (< 1.4 R_sun) observations are been performed now by HAO CoMP instrument*



#TakeOnTomorrow

First Definitive Coronal Stokes *V* Measurement December 1998 (Lin, Penn, Tomczyk 2000)

Northumbria University NEWCASTLE



Fe XIII 1074.7 nm

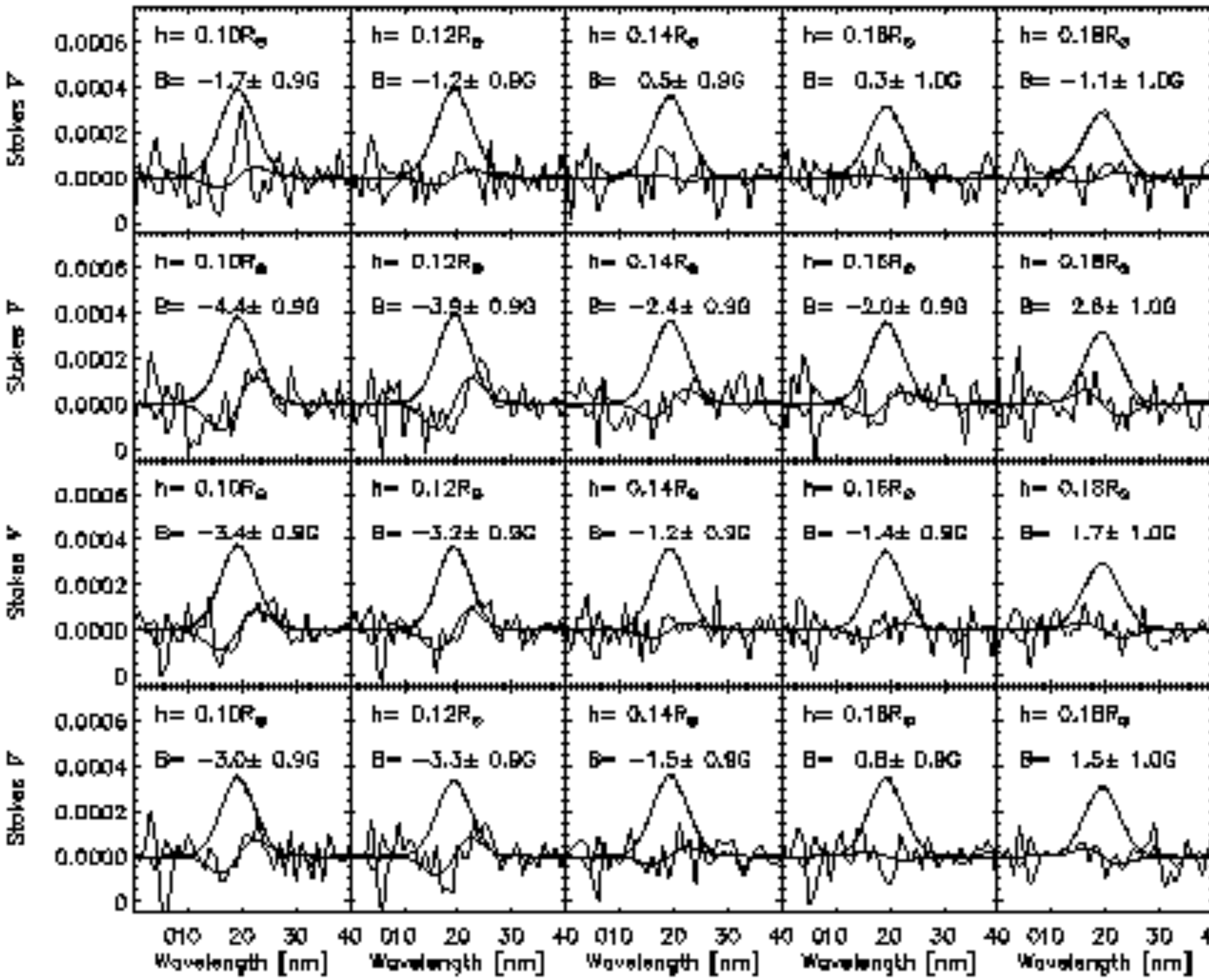
- NSO/SP Evans Solar Facilities **40 cm coronagraph**
- 240 arcsec^2 FOV (summed over the entire length of slit).
- *2560 seconds (**44 minutes**) integration time (Q & V).*
- *Coronal magnetic field can be measured with Zeeman effect diagnostics!*

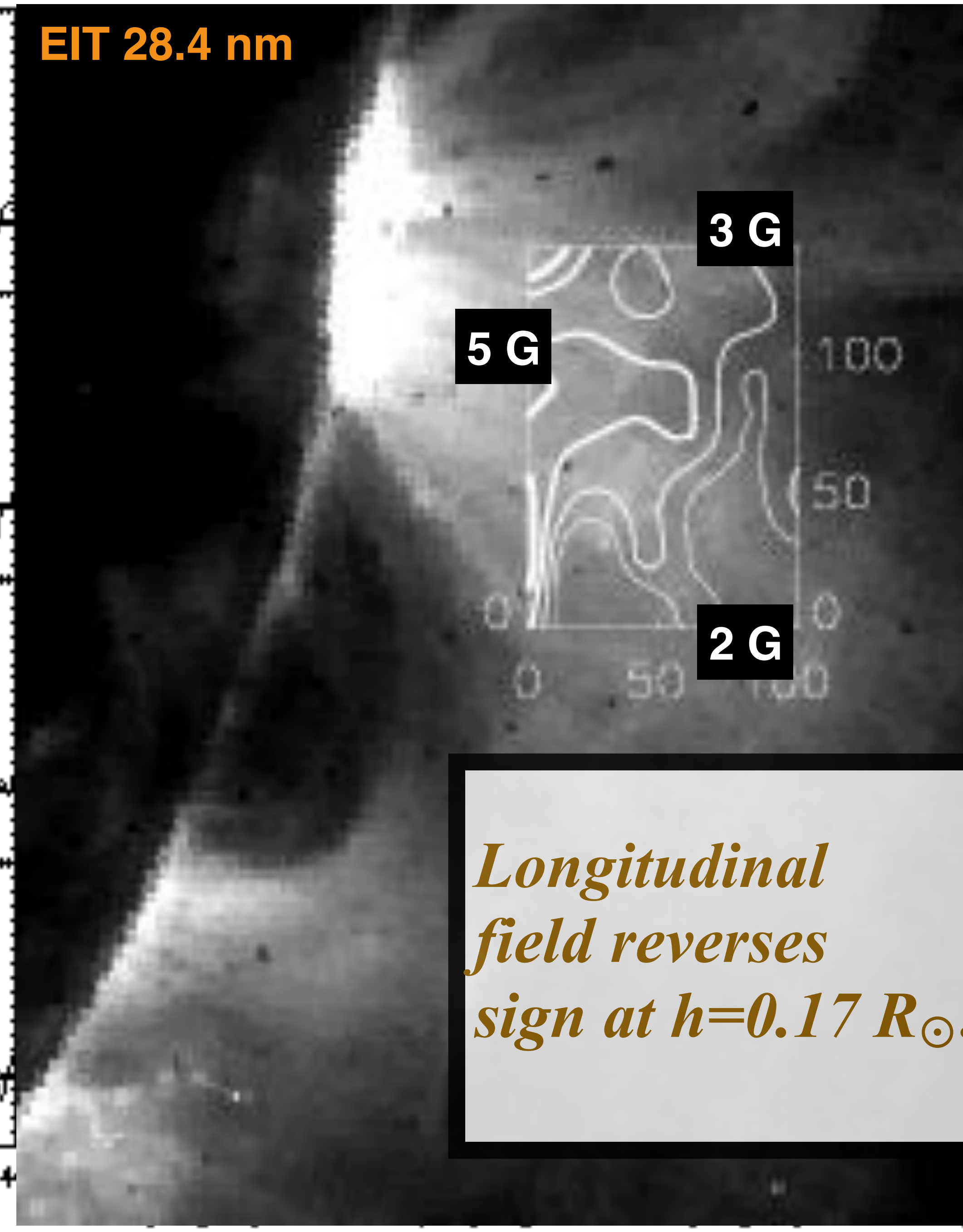
#TakeOnTomorrow

‘Vector’ Coronal Magnetogram 6 April 2004

(Lin, Kuhn, Coulte 2004)

Northumbria University NEWCASTLE





Stokes *I, Q, U, & V* Observation:

- 20 arcsec/pixel resolution, Telescope pointing @ 0.25 $R_\odot$
- **70 min. integration on Stokes *V*, 15 min. integration Stokes *Q* & *U***

#TakeOnTomorrow

Recent Technological Breakthroughs

Northumbria University NEWCASTLE

- **Fabrication of Ultra-Low Scattered Light Optics**
  - High-grade fiber-optic glass with low internal scattering
  - Superpolishing technology for fabrication of new coronagraph objective lens (preferred to mirrors!) with **0.01 ppm scattered light** is now feasible.

- **Large-scale multiplexing instrument design**
  - Multi-slit, multi-spectral spectrographs increase system throughput of individual telescope by a factor of > 500x

- **Missions with circumsolar, out-of-ecliptic, and near-Sun orbits are feasible now**
  - e.g., STEREO, Parker Solar Probe, Solar Orbiter
  - Cluster of small telescopes can achieve the magnetic field sensitivity of a single large telescope with reduced mission cost - employing tomographic inversions to reconstruct 3D magnetic field vectors

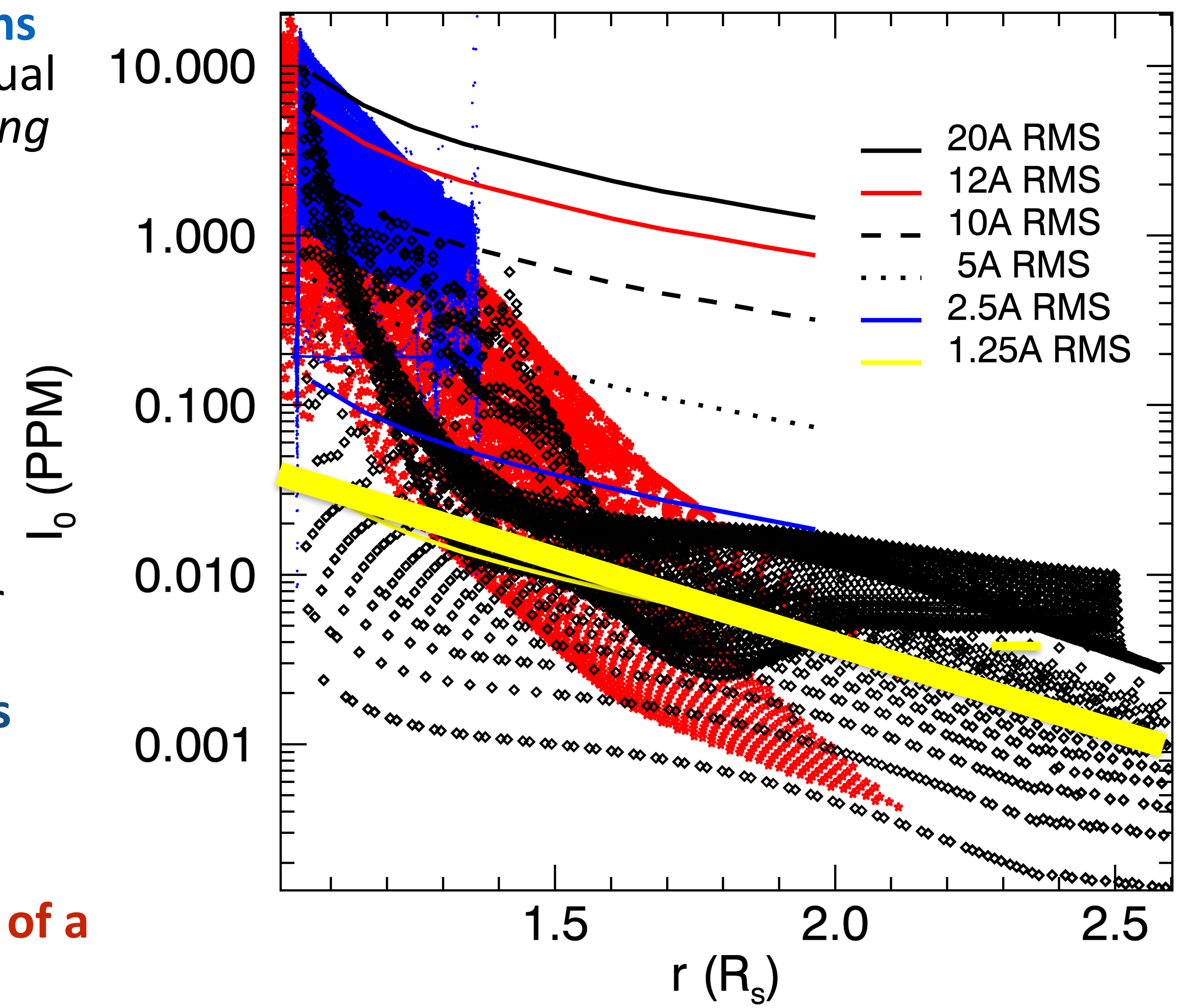
Recent Technological Breakthroughs

Northumbria University NEWCASTLE

- **Fabrication of Ultra-Low Scattered Light Optics**
  - High-grade fiber-optic glass with low internal scattering
  - **0.1 nm RMS Superpolishing technology** for fabrication of new coronagraph objective lens (preferred to mirrors: scattering / dust!) with **0.01 ppm scattered light** is now feasible.

- **Large-scale multiplexing instrument design**
  - **Multi-slit, multi-spectral spectrographs** increase system throughput of individual telescope by a factor of *>500x: Enabling multi-termperature /density structre, large FOV (far off-limb), High Cadence (fast CMEs ~1 hour start to end)*

- **Missions with circumsolar, out-of-ecliptic, and near-Sun orbits are feasible now**
  - e.g., STEREO, Parker Solar Probe, Solar Orbiter
  - **External occulter significantly reduces scattered light** than internal.occulter systems.
  - **Cluster of small 15 cm telescopes can achieve the magnetic field sensitivity of a single large 1-m telescope with significant cost saving**

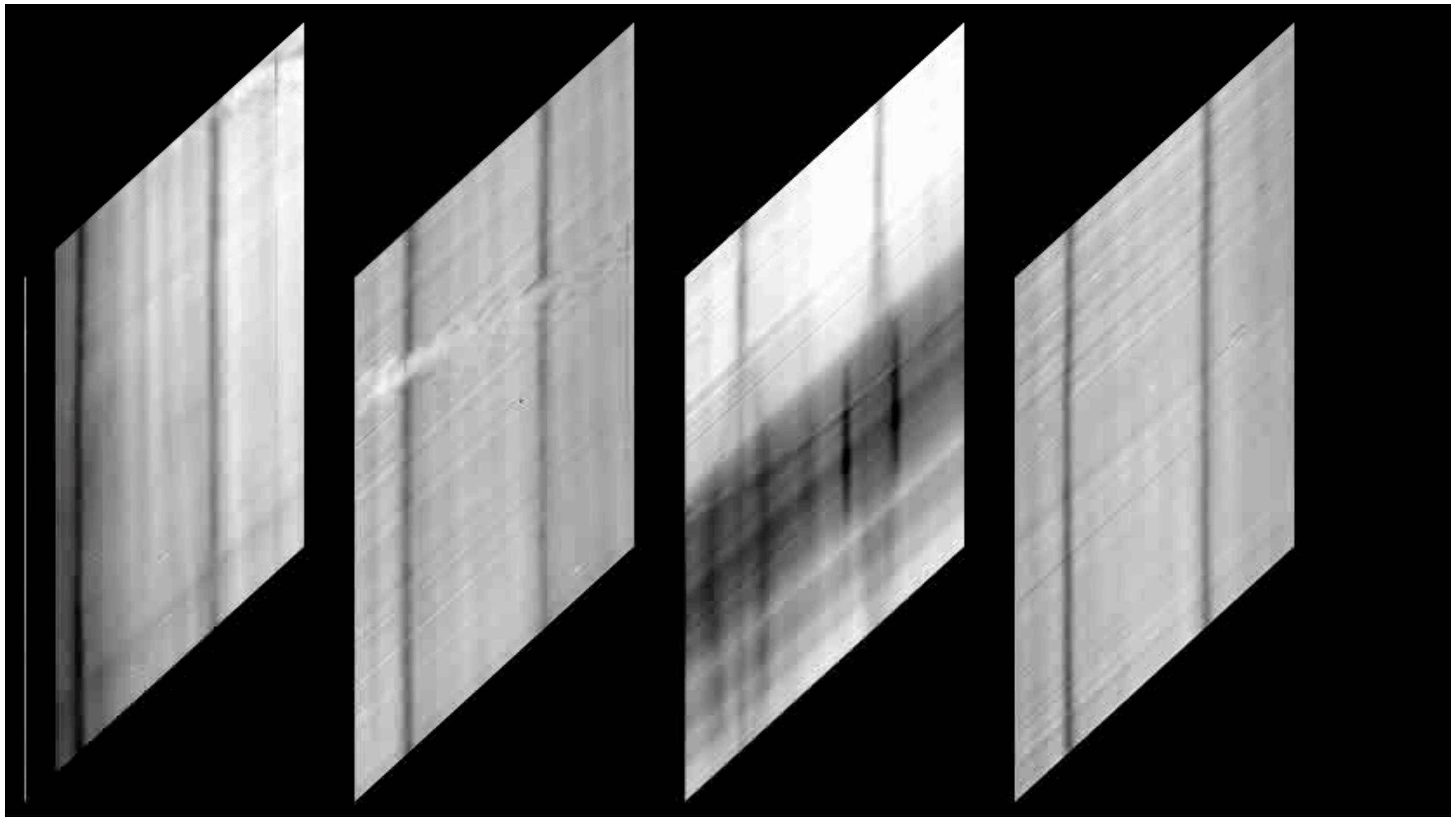


Spatial Multiplexing by Multiple-Slit Spectroscopy

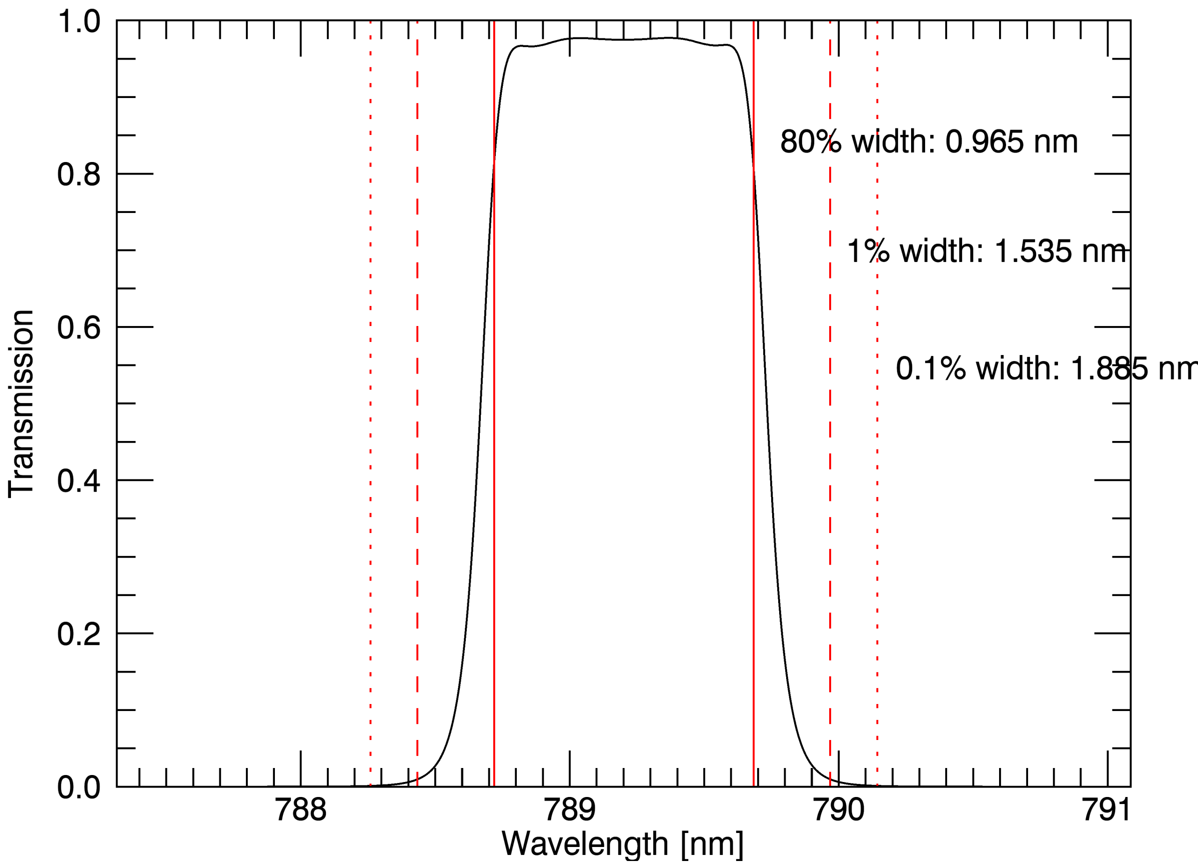
(Prof. Lin, IfA University of Hawaii, PI of DL-NIRSP DKIST)

- *mxSPEC demonstration*: **Full Disk Scan with 60 Scan Steps in 6 sec**
  2K x 2K IR camera operating at 10 Hz frame rate.

- Multi-slit spectroscopy **enabling technology:**
  - –DWDM (Dense Wavelength Division & Multiplexing) Band Pass Isolation Filter
  - –High efficiency, narrow-band, sharp edges interference filters **developed for fiber-optics communication.**



Scanning by Multi-Slit Spectrograph of active region taken by mxSPEC (DST demonstration)

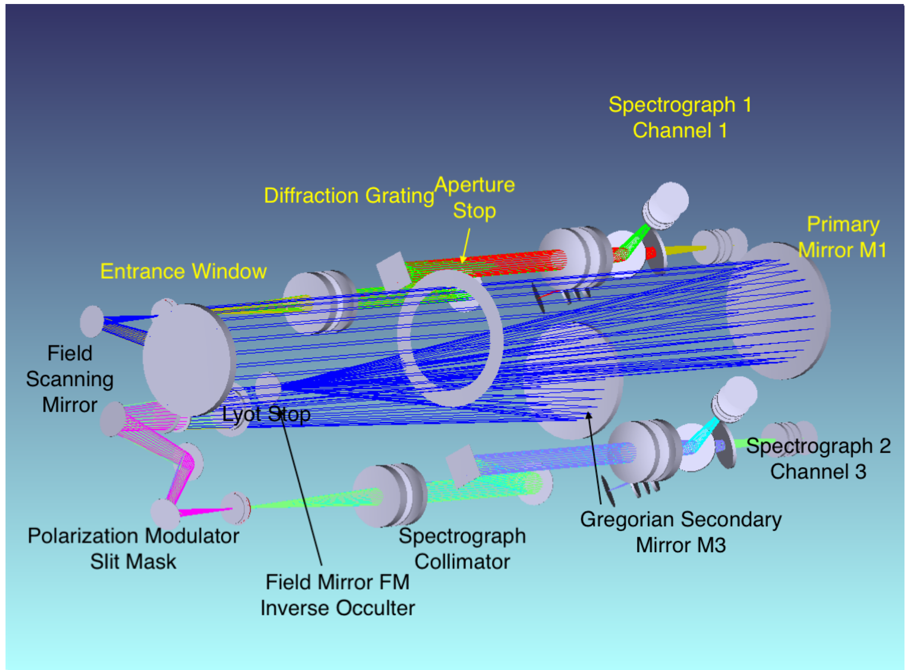


DWDM (Dense Wavelength Division & Multiplexing) Band Pass Isolation Filter

Leading CubeSat Instrumentation:
Massively-multiplexed Coronal Spectropolarimeter and Magnetometer (mxCSM)

$2M NSF funding TRL-4/5: 2019-2023

- **15-cm aperture singlet objective coronagraph**,
- 2'' spatial res., Enhanced Schupmann Optical System
  - **2.5A RMS surface microroughness, 1 x 10^{-7} scattered light** @ 1.1 R_{sun}, **FOV >2 R_{sun},**
  - Super achromatic design with double Mangin correctors (**400 - 1100 nm wavelength range**)
- **99 slits, 2 spectrographs, 6 spectral channels**
  - **Can fit inside a 4U CubeSat**



Schematic of mxCSM optical path

Table 3. Estimates of mxCSM Signal-to-Noise ratio and detectability of the Fe XIII 1075nm line.

Observing Mode	$\Delta x \times \Delta y$	Δt	T_{map}	I_{sc}	SN_I	SN_L	SN_V	$B_{3\sigma}$
1. Full-field Scan	1″ × 1″	1.5s	1m	5	256	13	0.26	117G
1a. 20″ average of Mode 1	20″ × 20″	1.5s	1m	5	5120	256	5	6G
1b. 10 min average of 1a	20″ × 20″	15s	10m	5	16250	810	16	2G
2. Sit-and-Stare mode	1″ × 1″	5m	5m	5	3600	180	4	8G
3. Full-field Scan	1″ × 1″	1.5s	1m	**0.5**	810	40	0.8	37G
3a. 10" average of Mode 3	10″ × 10″	1.5s	1m	**0.5**	8100	400	8	4G

Circular Polarization Amplitude ~ **5 x 10^{-5} I_{line} /Gauss: Requires a cluster of small space coronagraphs**

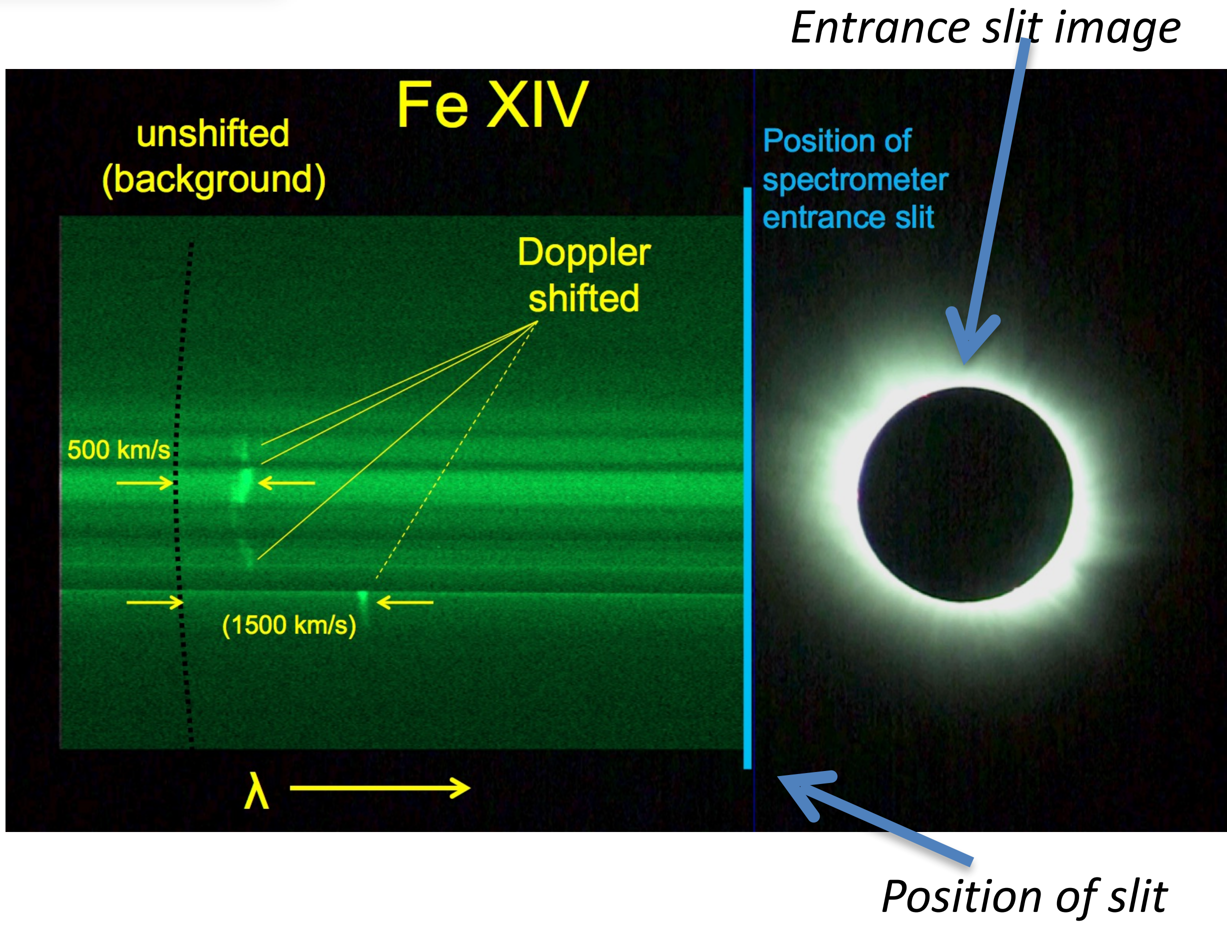
Trailing CubeSat Instrumentation:
Hyperspectral imager for the coronal spectrometer

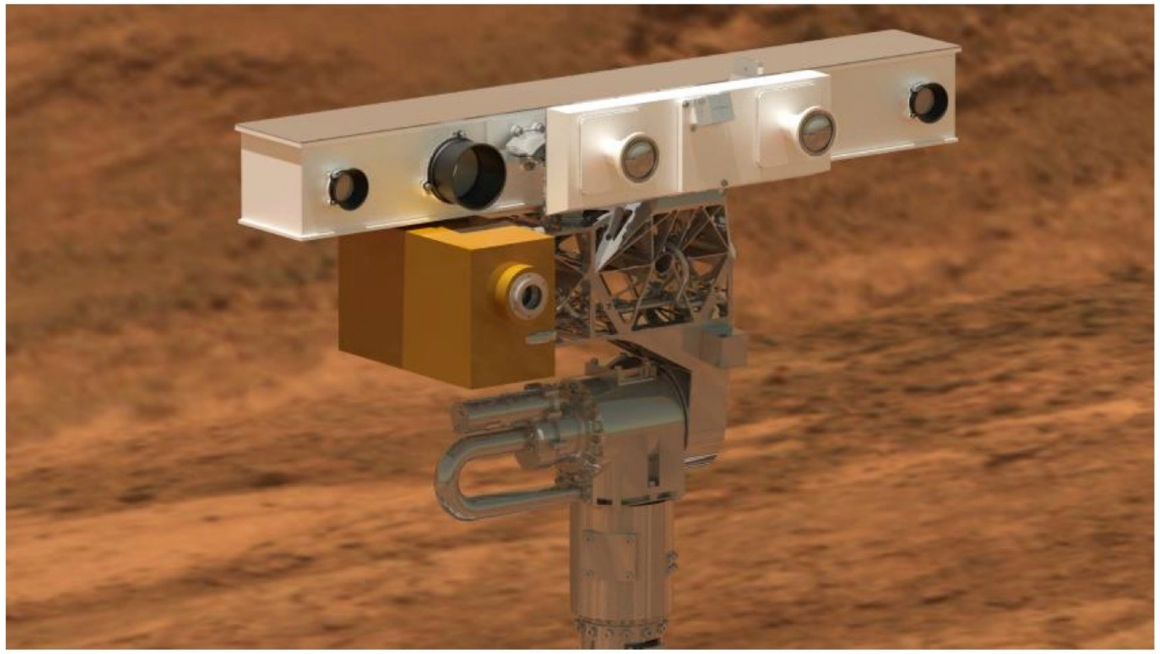
PRIFYSGOL ABERYSTWYTH UNIVERSITY

Eclipse-quality imaging out to 5 solar radii

Current eclipse system:

- Spectrometer entrance slit etched on an angled mirror (i.e. slit jaw images)
- Mirror provides focused images of corona (with slit)
- Images provide important context for the spectrometer observations, as slit scans across corona





Rendered image of ExoMars PanCam.
Image Credit H. Miles

Proposed hyperspectral imager

- Replace slit camera with hyperspectral system
- Provides broadband spectra of corona in visible/NIR
- Based on Aberystwyth expertise with hyperspectral imagers for Earth/planetary observations

STFC PRD grant (ST/N002962/1)

#TakeOnTomorrow

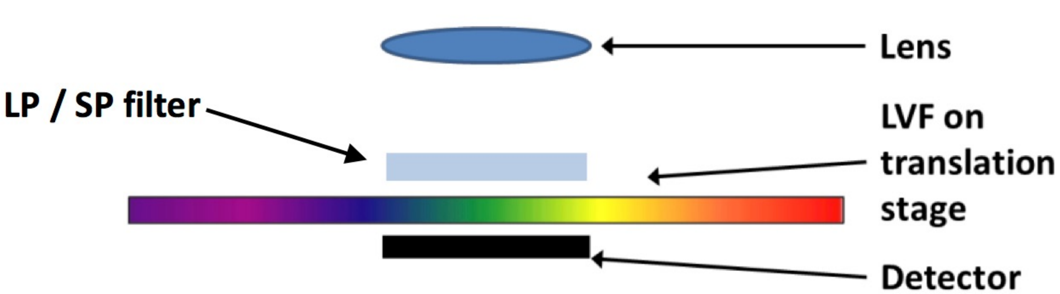
Trailing CubeSat Instrumentation:
Hyperspectral imager for the coronal spectrometer

PRIFYSGOL ABERYSTWYTH UNIVERSITY

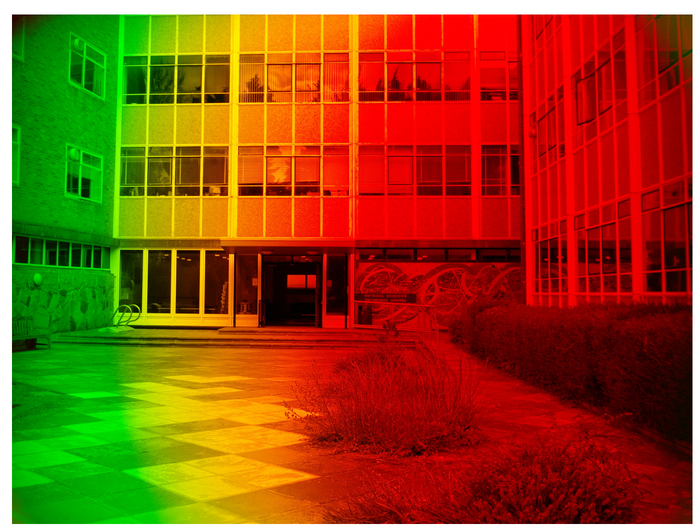
Entrance slit image

The hyperspectral concept

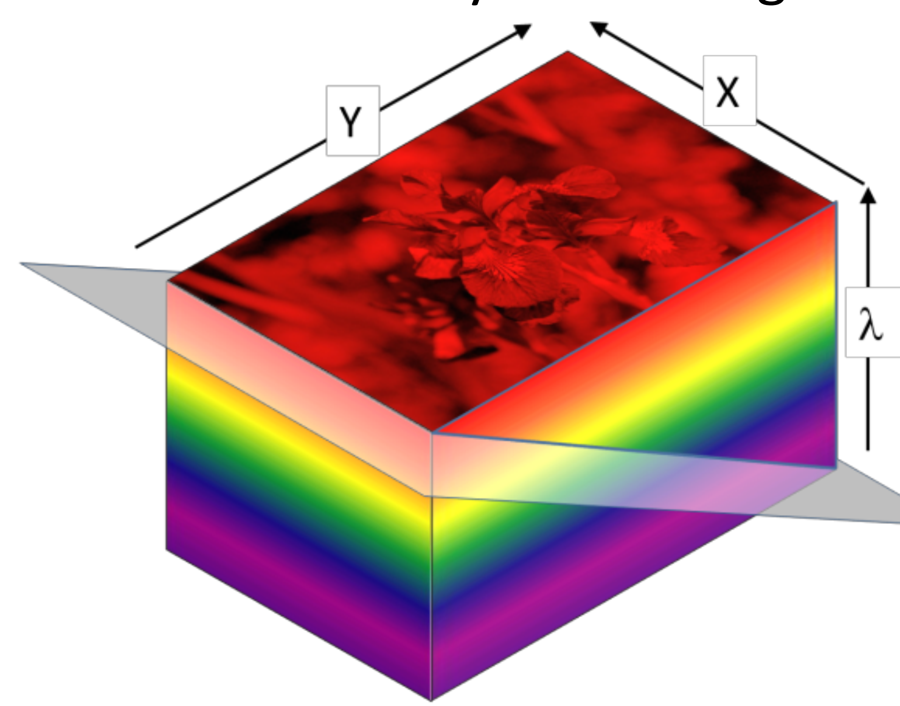
- **Linear variable filter in front of detector** provides 2D image which varies in wavelength along one axis
- **Scanning camera** across target builds up **hyperspectral data cube [x, y, λ].**
- **Camera simpler and more compact** than conventional pushbroom hyperspectral imagers.
- 2D image always available to determine location of spectrograph slit
- **No other space- or ground-based mission will** routinely collect data of this clarity in the range of 1.5–5 solar radii from the Sun.



LVF hyperspectral camera layout



Variable filter in front of a commercial colour camera – showing dispersion across the 2D image.



Hyperspectral data cube captured by scanning camera along y axis

Technology Demonstration

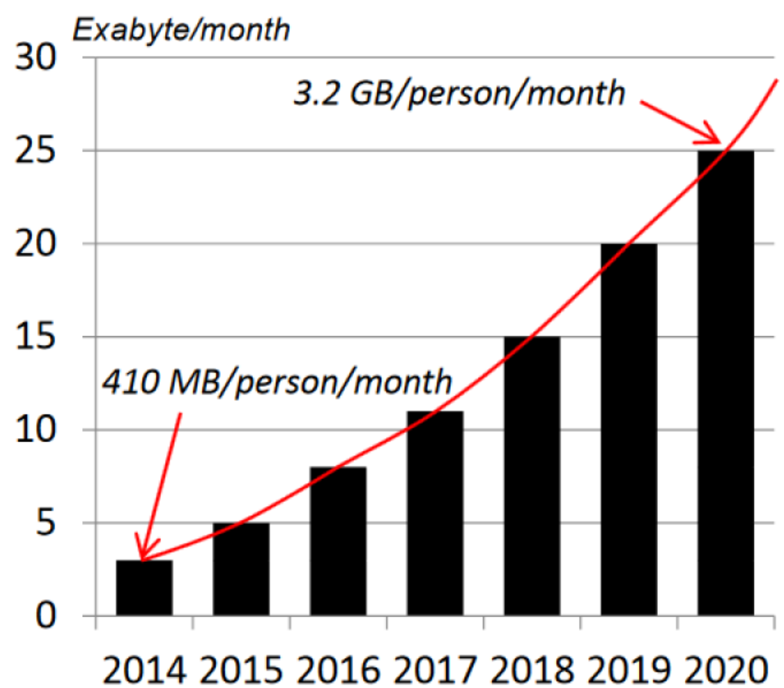
Laser Optical Communications: *Li-Fi*

(**Prof. Fary Ghassemlooy, OCRG, former chair of IEEE**)

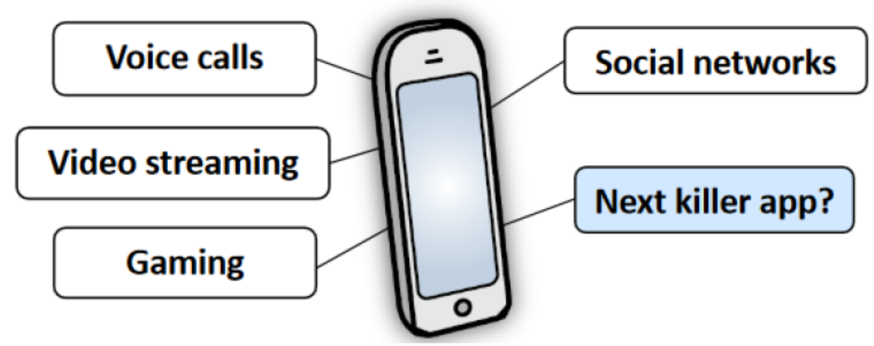
Success of Wireless Communications

Martin Cooper's law

The number of simultaneous voice/data connections has doubled every 2.5 years (+32% per year) since the beginning of wireless



Martin Cooper
Inventor of handheld cellular phones



Network Throughput:

Throughput = Cell density · Available spectrum · Spectrum efficiency

(bit/s in area) (Cell/area) (Hz) (bits/s/Hz/Cell)

rrow

Technology Demonstration

Laser Optical Communications: *Li-Fi*

(**Prof. Fary Ghassemlooy, OCRG, former vice-chair of IEEE**)

1 - 10 Gb/s Data Rates

(**NASA's lunar laser communication demonstration achieved downlink rate of 622 Mbps, 2013**)

- The **spectropolarimeter** will have a maximum data rate of ~**100Mbps per detector.** The **coronagraph (no polarimetry)** require **~25Mbps per detector**. Redistribute the data between each CubeSat pair.

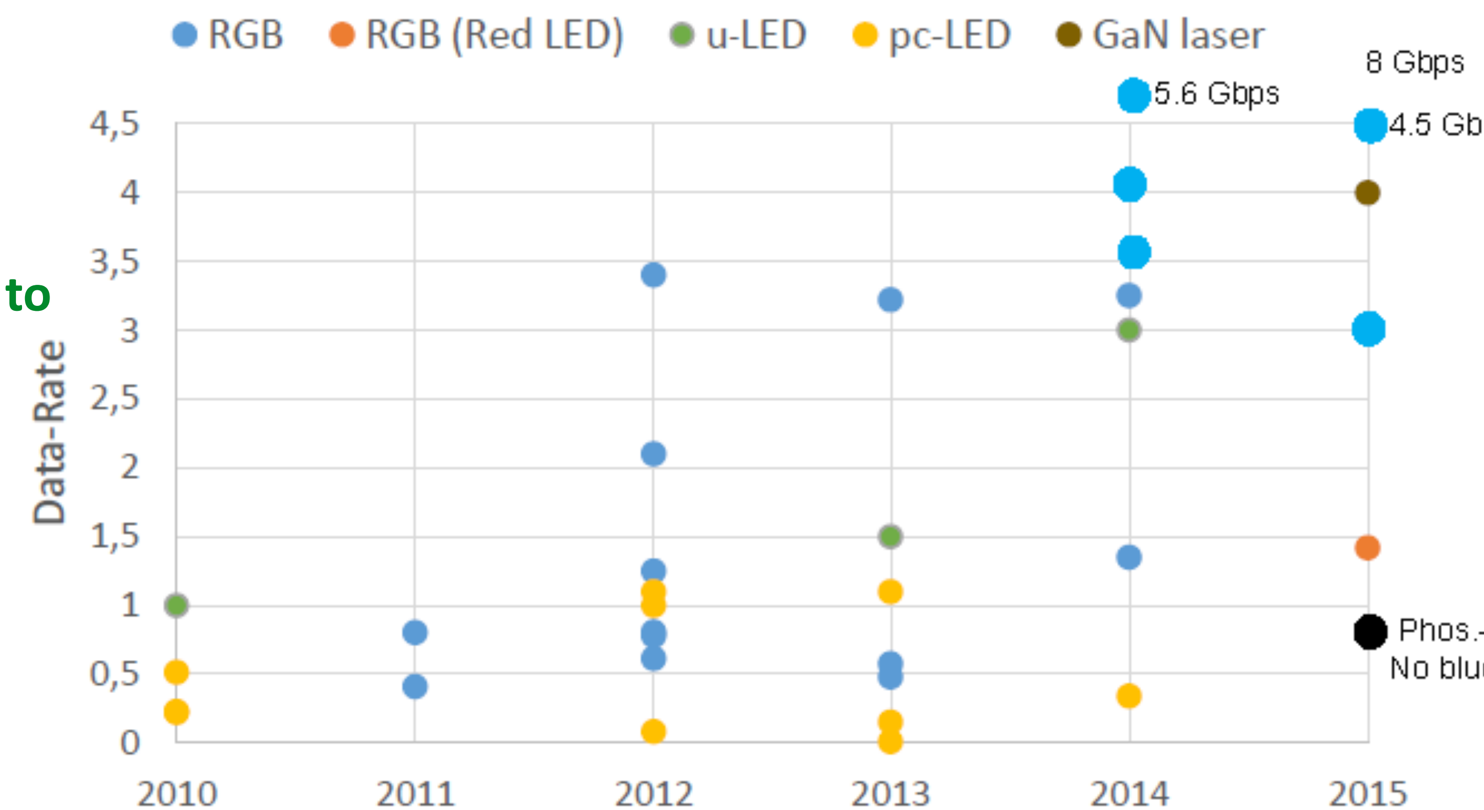
Power - by - light

- **Powering PV solar cells across large distances**, using laser light. Large-format PV cells capable of power increases from 10 kW to 100 kW in CubeSats. **CESR University Swansea, worlds first TFSC for space application.**

Proximity Formation Flying

(**AAREST mission highlights need for new approaches to assembly of future large space telescopes**)

- Critically important for **maintaining a functioning coronagraph**. CubeSat clusters which self-consistently control **precision and close proximity manoeuvres.**



Technology Demonstration

Laser Optical Communications: *Li-Fi*

(**Prof. Fary Ghassemlooy, OCRG, former chair of IEEE**)

Li-Fi technology is a novel solution for:

- limited satellite bandwidth (VLC offers **expansive bandwidth**)
- connectivity (Li-Fi is **highly energy efficient** in monochromatic laser light)
- range (**ethernet internet speeds**).

***Li-Fi* offers a wide range of applications including:**

short range optical wireless body networks for healthcare applications,
medium range inter-vehicular and vehicle-to-infrastructure communications
ultra-long range for inter-satellite links.

Similarly, proposed in the ESA-DOCS and INSTANT mission concepts

What Next?

#TakeOnTomorrow