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Bairisch Kölldorf, Austria

## **Science challenges for EST**

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# 1. Preliminary notes

## EST on the German National Roadmap

Table 1: Results of the dimension-based comparative evaluation

Proposal	Scientific Potential	Utilisation	Feasibility	Relevance to Germany as a location of science and research
ACTRIS-D	****	****	*****	****
AtmoSat	*****	****	****	*****
DCOLL	***	*****	****	***
ER-C 2.0	****	****	****	*****
EST	***	*****	****	****
GerBI-RI	***	****	*****	****
LPI	****	****	****	*****
NIF	*****	*****	****	*****
NISC	**	***	***	***
NPL	***	***	***	*****
Tandem-L	***	****	****	*****

From the evaluation report on large-scale research facilities for inclusion in the German National Roadmap.

## 1. Preliminary notes (cont.)

### EST vs. DKIST

At present times, it is hard to think of science challenges that are not going to be tackled with DKIST already before EST is in operation.

But many *new scientific questions will arise, once DKIST is in operation*. Not all of these may be addressable with DKIST but instead may become an interesting target for EST.

## 1. Preliminary notes (cont.)

### EST vs. DKIST (citations from the German roadmap evaluation)

“Through its *specialisation in high-precision polarimetry at many simultaneous wavelengths*, EST is furthermore described as being able to catch up or even outperform the US American Daniel K. Inouye Solar Telescope (DKIST), which is focused on observing the solar corona ... By contrast, *EST's focus are small-scale magnetic fields in the photosphere and chromosphere, ...*”

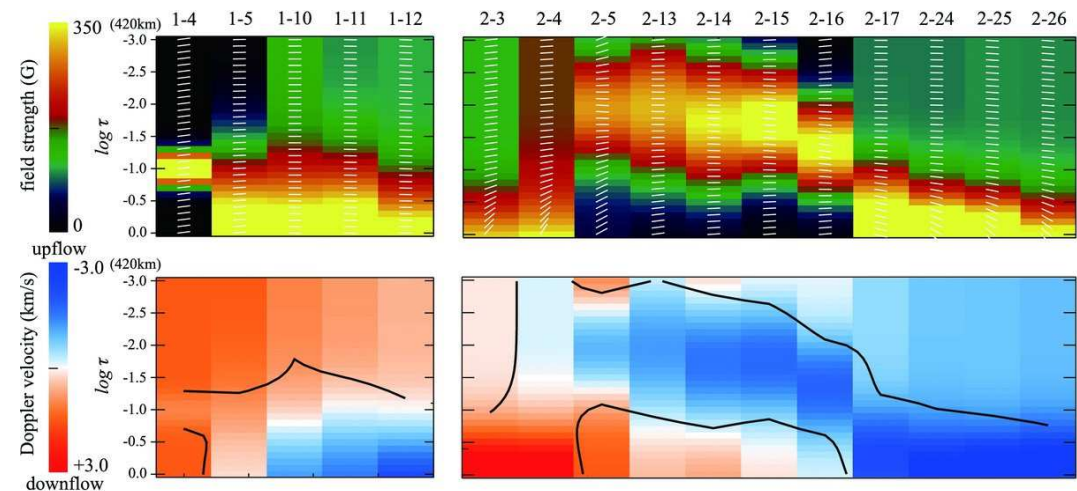
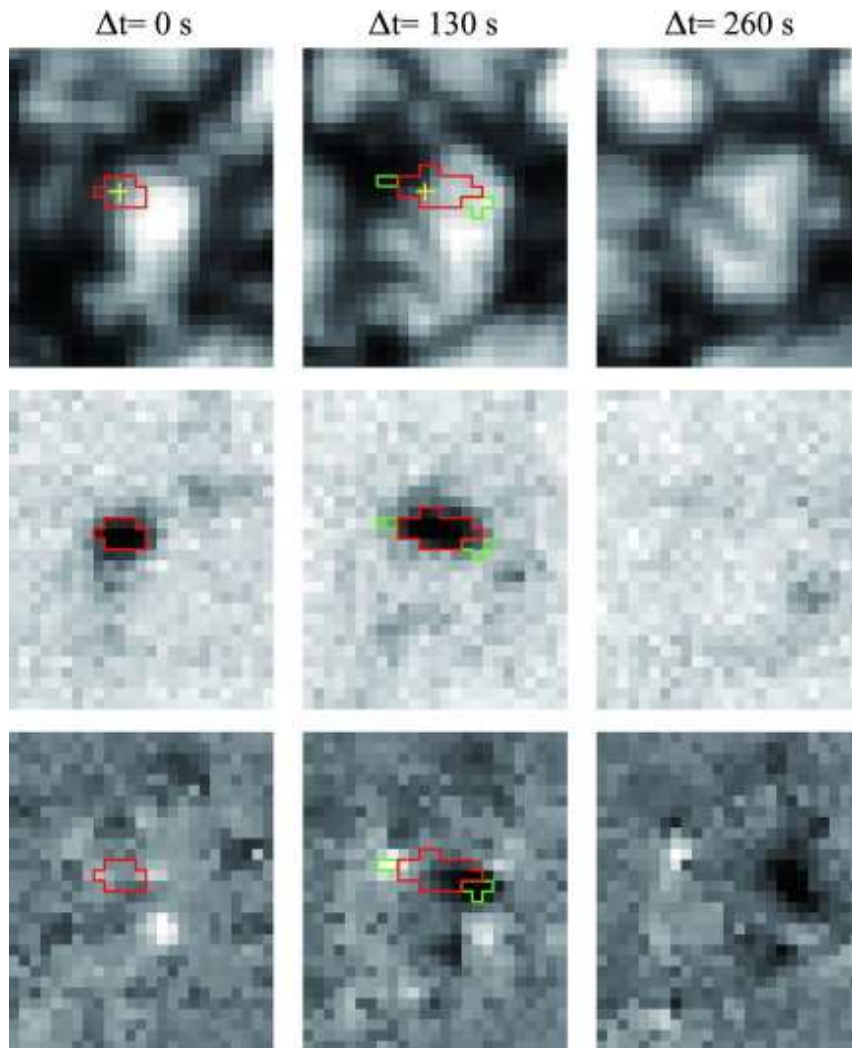
“The high spatial resolution (around 10 km on the solar surface) and *extraordinary polarisation sensitivity (< 0.01 %)* of EST will resolve many fundamental questions in astrophysics.”

## 2. Vector polarimetry at small scales

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Ever since Hinode, the quiet Sun internetwork magnetic field is no more this featureless “turbulent”, “hidden” magnetic field, it was supposed to be. It was revealed that this field possesses structure in the form of tiny loops, transient patches of predominantly horizontally directed magnetic field, and hectogauss flux concentrations.

## 2. Vector polarimetry at small scales (cont.): micro loop

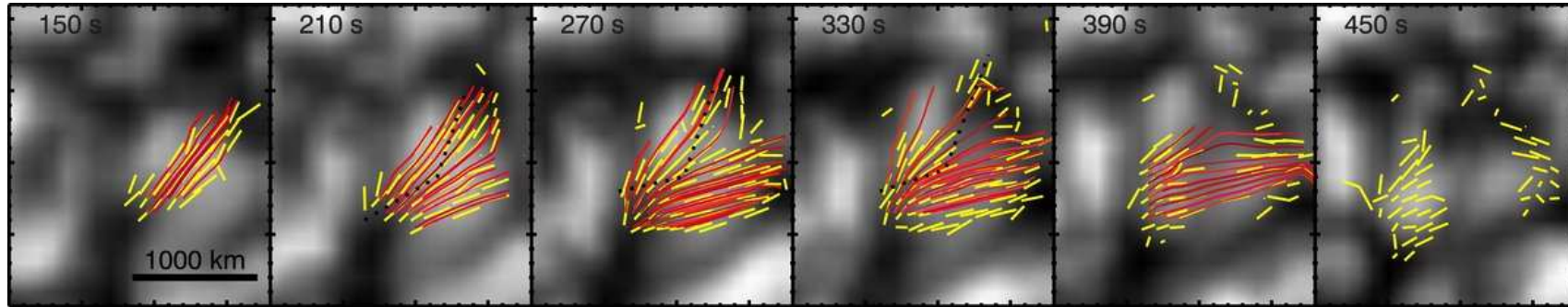


*Left:* Continuum intensity (*top*) linear polarization (*middle*) circular polarization (*bottom*).

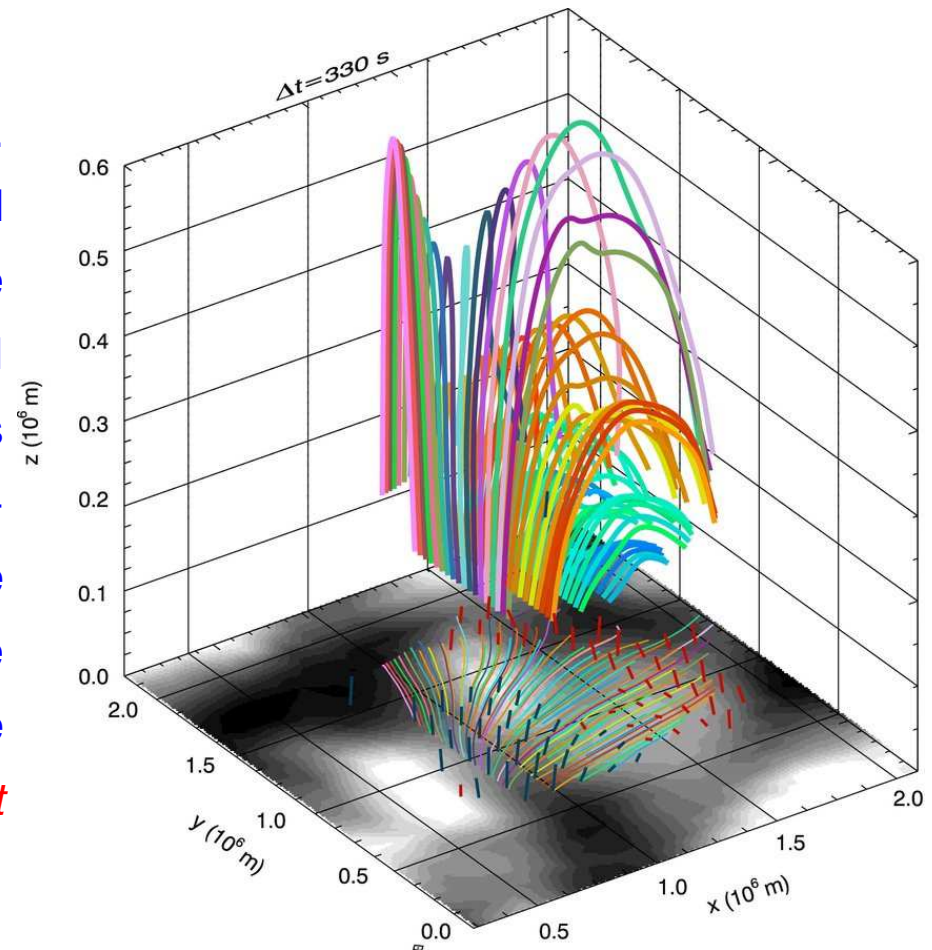
*Right: top:* cross-sectional view of the magnetic field strength of the microloop at the beginning (left) and 130 seconds later (right). *bottom:* cross-sectional view of the Doppler velocity.

From *Ishikawa, Tsuneta & Jurčák (2010) ApJ 713, 1310.*

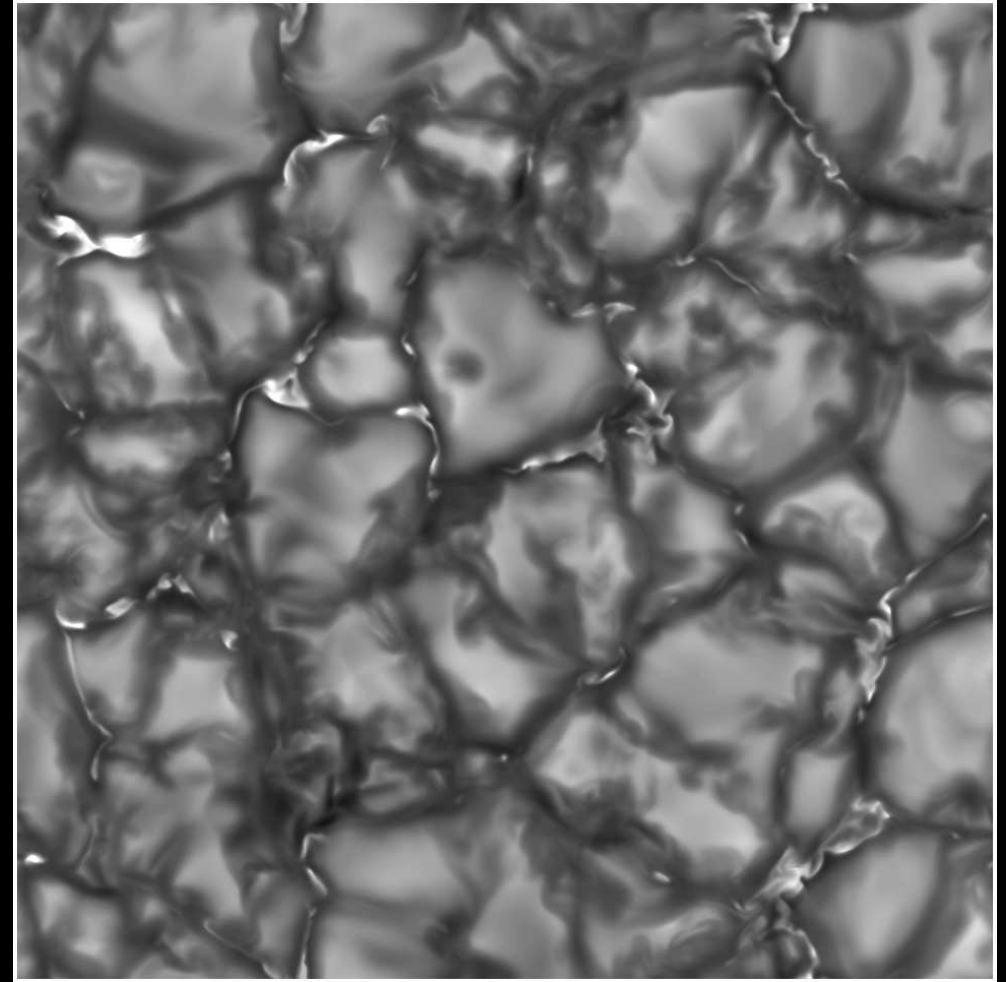
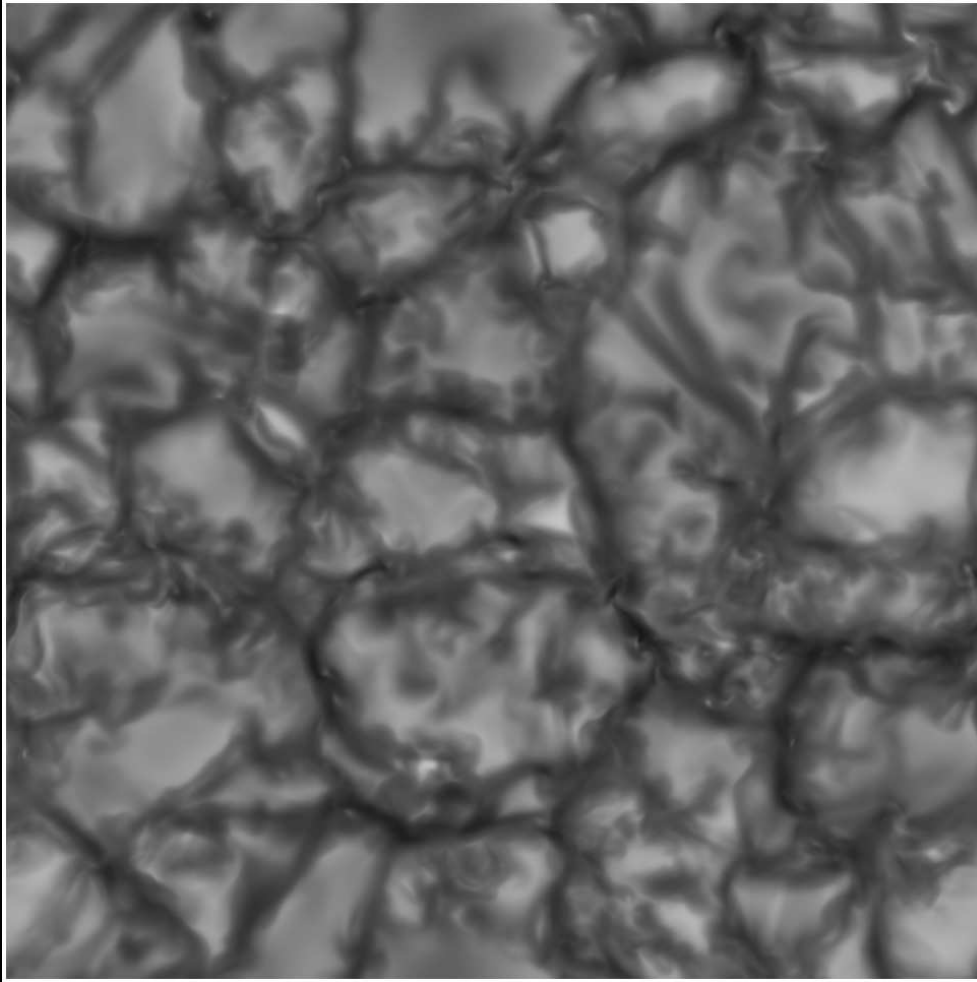
## 2. Vector polarimetry at small scales (cont.): micro loop



*Top:* Magnetic emergence at granular scales. Yellow segments indicate the azimuth retrieved from inversions. Red lines show representative magnetic field lines. *Right:* Three-dimensional reconstruction of the magnetic field. Short lines indicate magnetic field orientation. Representative field lines are calculated starting at the height of formation of the Fe I 630 nm lines at one footpoint and followed until they reach the same height at the other end. *Martínez Gonzalez et al. (2010) ApJL 714, L94.*



## 2. Vector polarimetry at small scales (cont.)



Note the difference in granular substructure between the simulation instants without magnetic field (left) and with magnetic field (right). The magnetic field seems the granular flows to shape more laminar like.

Courtesy, *F. Calvo, IRSOL*

Computations: *Centro Svizzero di Calcolo Scientifico*



## 2. Vector polarimetry at small scales (cont.)

### Challenge:

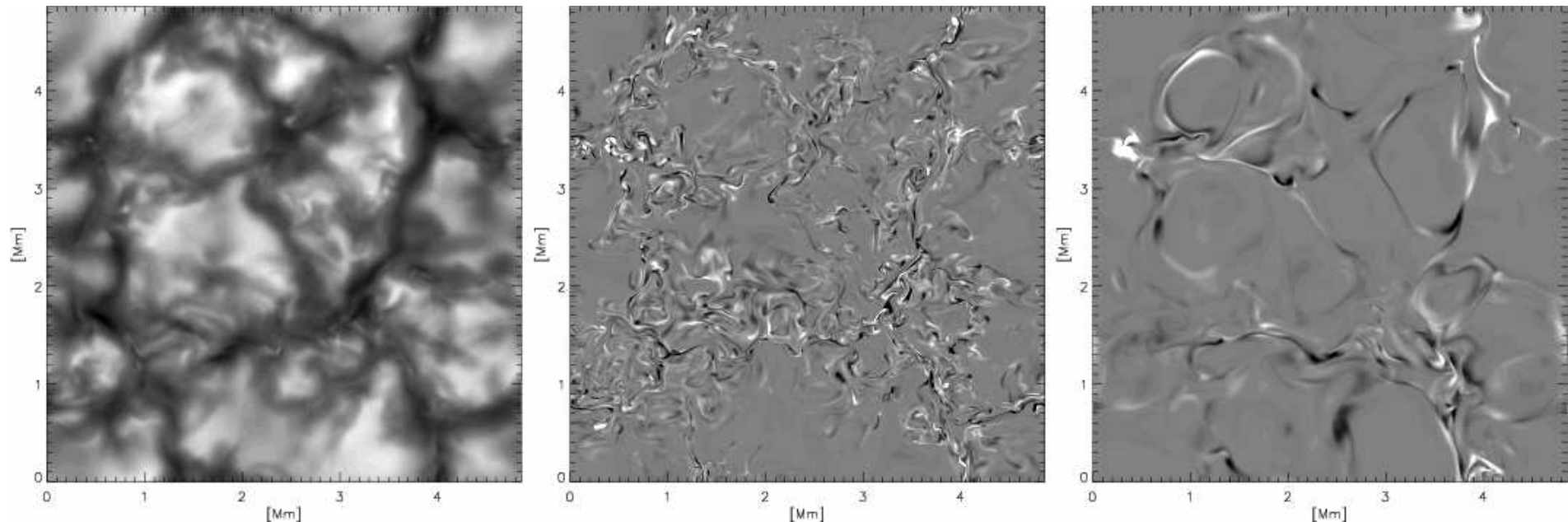
*Make that “hidden” magnetic field visible!*

How does the quiet Sun “turbulent” magnetic field exactly look like? Determine the topography and evolution of the small-scale weak magnetic field of the Sun in three-dimensional space (vector polarimetry).

Why? Not just “because it’s there”. But we want to know it in search for the *turbulent surface dynamo*, for the *dissipation of magnetic fields* on smallest scales, for the *photospheric origin of waves and flows* in the chromosphere and above, etc.

### 3. The quest of the small-scale dynamo

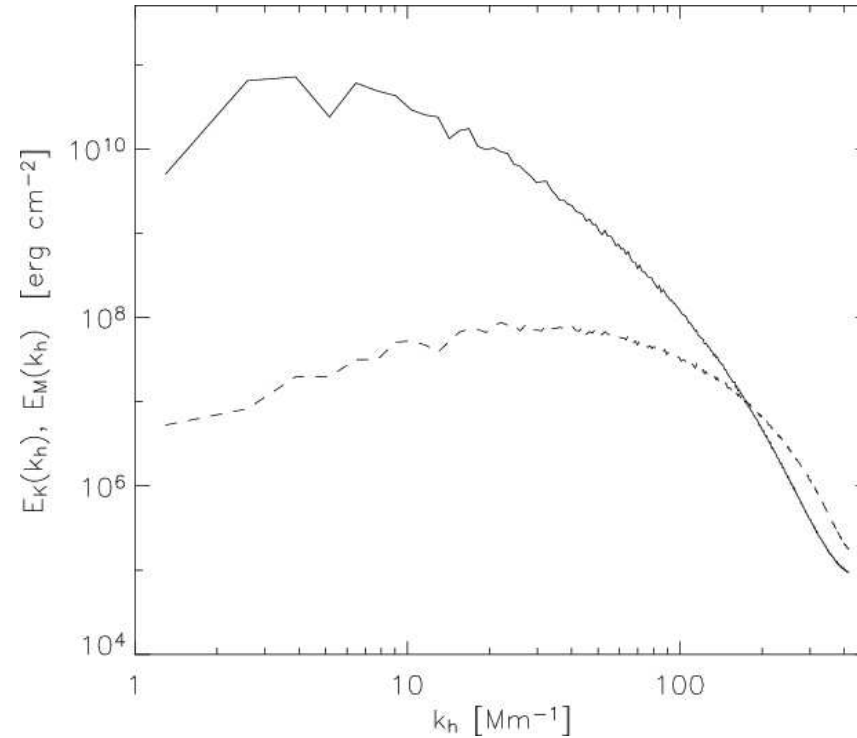
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*Left:* Bolometric intensity. *Middle:* Vertical magnetic field at  $\langle \tau_c \rangle = 1$  saturating at  $\pm 250$  G.  $\langle B_z \rangle = 25.1$  G. *Right:* Vertical magnetic field at  $\langle \tau_c \rangle = 0.01$  saturating at  $\pm 50$  G.  $\langle B_z \rangle = 3.2$  G. From *Vögler & Schüssler (2007) A&A 465, L43*.

*Observing proposal:* Compare magnetic field from polarimetry of a deeply forming line (e.g., Fe I 1564.85,  $g=3$ ) with that from a line forming in the middle/upper photosphere (e.g., Fe I 617.33,  $g=3$ ).

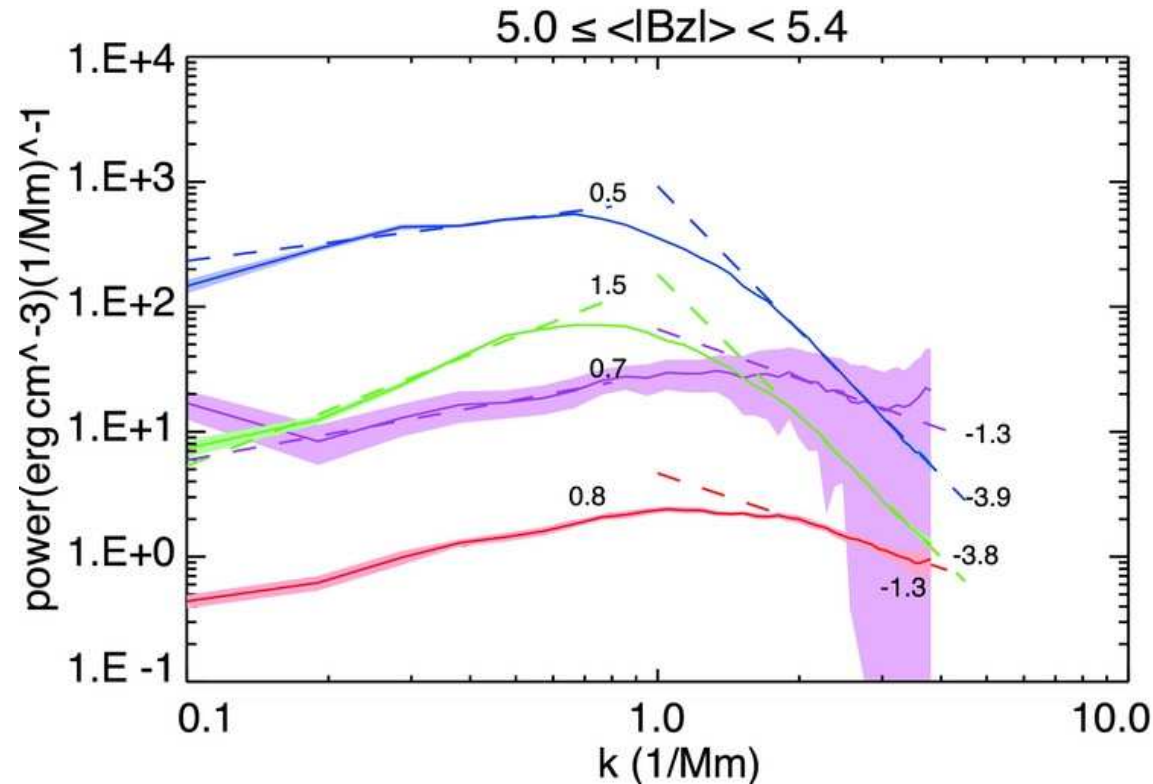
### 3. The quest of the small-scale dynamo (cont.)



*Energy spectra* of the vertical components of *velocity* (solid curve) and *magnetic field* (dashed curve) as functions of horizontal wave number at  $z = 0$ . The kinetic energy spectrum peaks at  $k_h \approx 3 \dots 4 \text{ Mm}^{-1}$  corresponding to granular scales. The magnetic energy spectrum peaks at an order of magnitude smaller scales, at  $k_h \approx 30 \dots 50 \text{ Mm}^{-1}$ .

From *Vögler & Schüssler (2007) A&A 465, L43*.

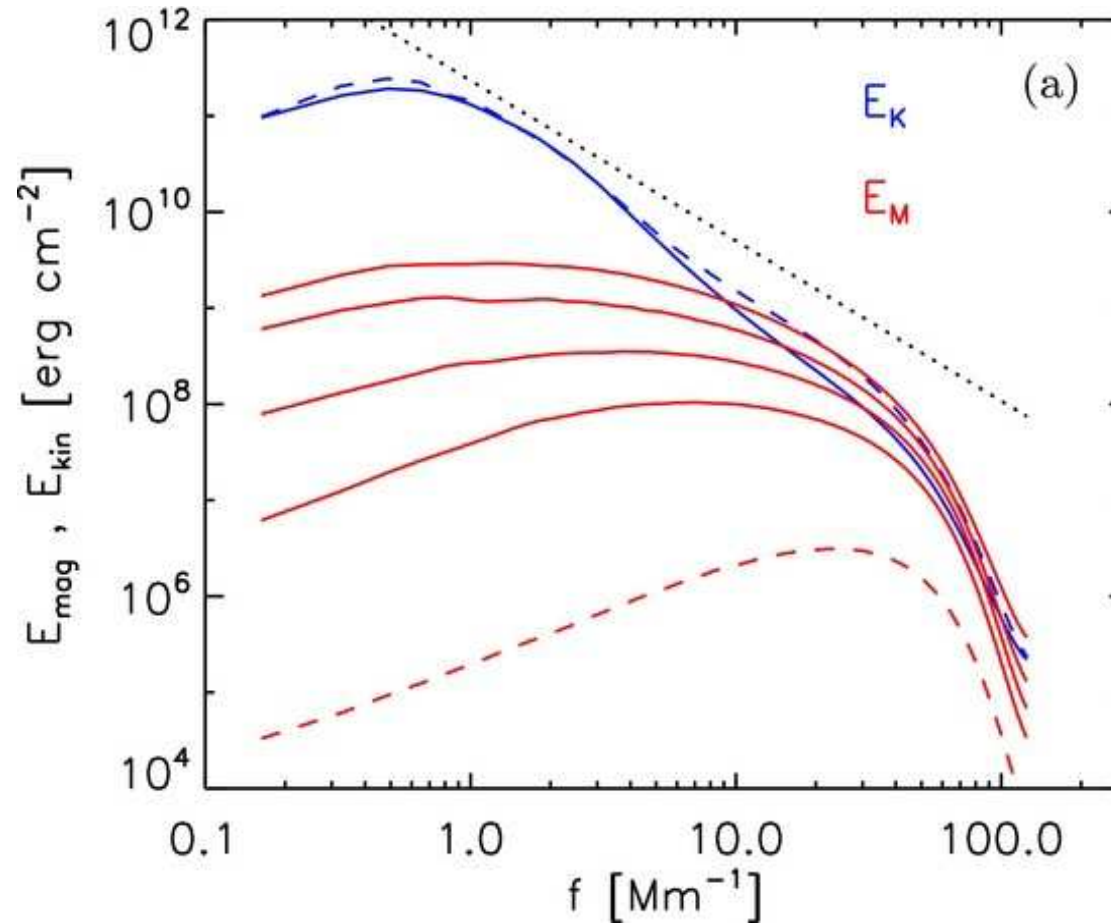
### 3. The quest of the small-scale dynamo (cont.)



Power spectra  $D_{\text{th}}(k)$  (green),  $D_{v_z}(k)$  (blue),  $D_{B_z}(k)$  (red), and  $D_{B_h}(k)$  (purple) in the weak internetwork region (from Hinode/SP data). The shaded area of each power spectrum represents the  $\pm 1\sigma$  range. The numbers indicate the power-law indices obtained between  $k = 0.15$  and  $0.6 \text{ Mm}^{-1}$  and between  $k = 1.8$  and  $3.2 \text{ Mm}^{-1}$ .

From *Katsukawa & Orozco Suarez (2012) ApJ 758, 139*.

### 3. The quest of the small-scale dynamo (cont.)



*Kinetic (blue) and magnetic (red) energy spectra on the surface of  $\tau = 1$ . Dashed curves refer to the kinematic growth phase when Lorentz-force feedback is negligible. As time evolves the peak of magnetic power moves toward larger scales (solid red curves from bottom to top).*

From *Rempel (2014) ApJ 789, 132.*

### 3. The quest of the small-scale dynamo (cont.)

Other evidences of fast dynamo action in the surface layer are:

- good balance of magnetic polarities in quiet regions (low netto magnetic flux);
- random azimuthal orientation of the horizontal field component;
- independence of the strength of the turbulent weak-field component on the phase of the solar cycle;
- small latitudinal dependency.

The claim that the existence of the turbulent surface dynamo was proven is *always a good bet* because the turbulent surface convection is a chaotic flow, which for sure produces dynamo action.

The question rather is: *To which degree is the observed small-scale surface magnetic field generated by the turbulent surface dynamo?* To what fraction does it result from to the global magnetic field of the Sun as it is manifest in sunspots and the solar cycle?

### 3. The quest of the small-scale dynamo (cont.)

further processes to be reconsidered:

- Turbulent magnetic pumping acts in removing magnetic flux from the surface to deeper layers of the convection zone.
- Remnants of decaying sunspots and ephemeral active regions.
- Remnants of large scale magnetic flux ropes which failed to form sunspots.
- Magnetic field that is generated by flows throughout the convection zone on increasingly larger scales with depth. The small-scale field as an integral part of the globally acting dynamo (*Stein et al. 2003, ASP Conf. Ser., 286, 121*).

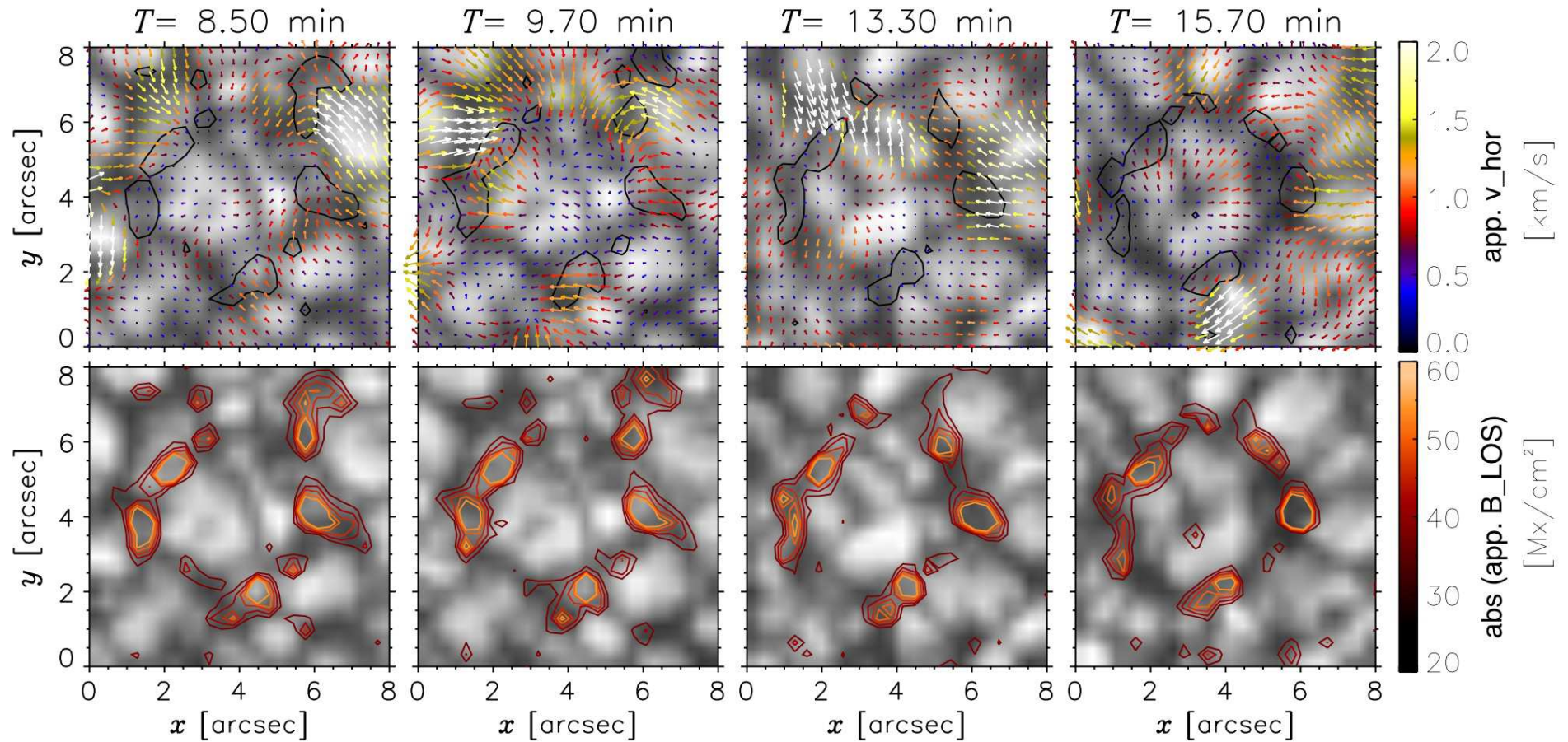
### 3. The quest of the small-scale dynamo (cont.)

#### Challenge:

High precision polarimetry at high spatial resolution for  
*determining the spatial spectrum of the small-scale magnetic field.*  
Interlocking of observations with realistic numerical simulation.  
Simulations with varying magnetic Reynolds and Prandtl number.



## 4. The photospheric origin of waves and flows

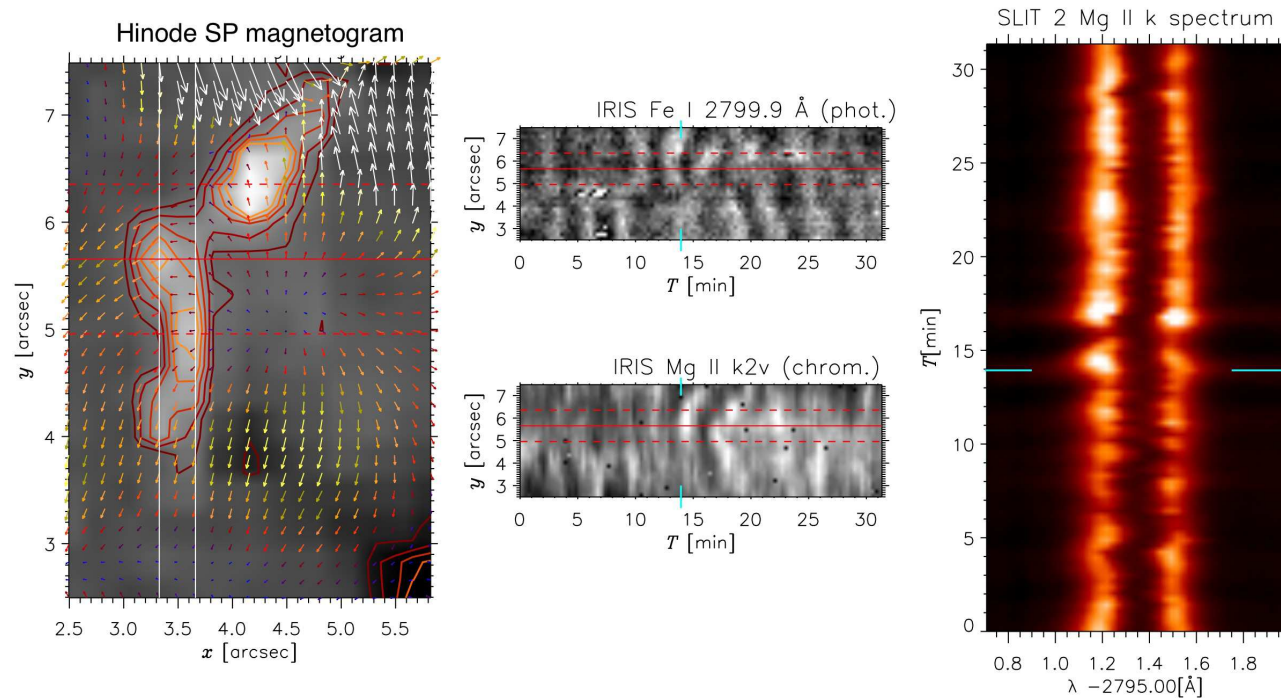


Time series of an *exploding granule* with horizontal velocity field (top panels) and line-of-sight magnetic field strength (bottom panels).

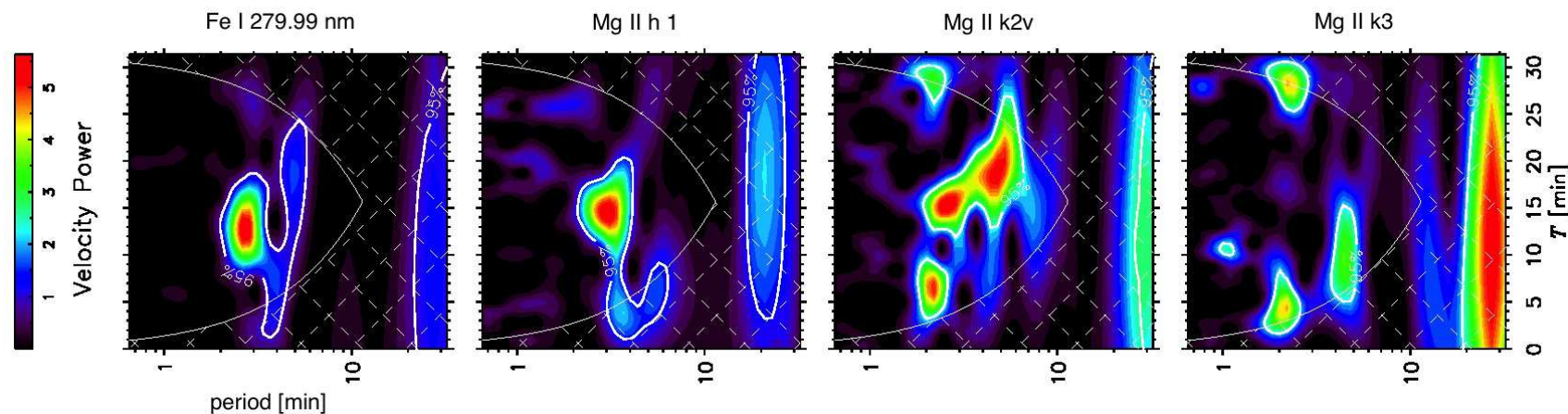
*Fischer et al. (2017) A&A 602, L12.*

## 4. The photospheric origin of waves and flows (cont.)

Fischer et al. (2017)

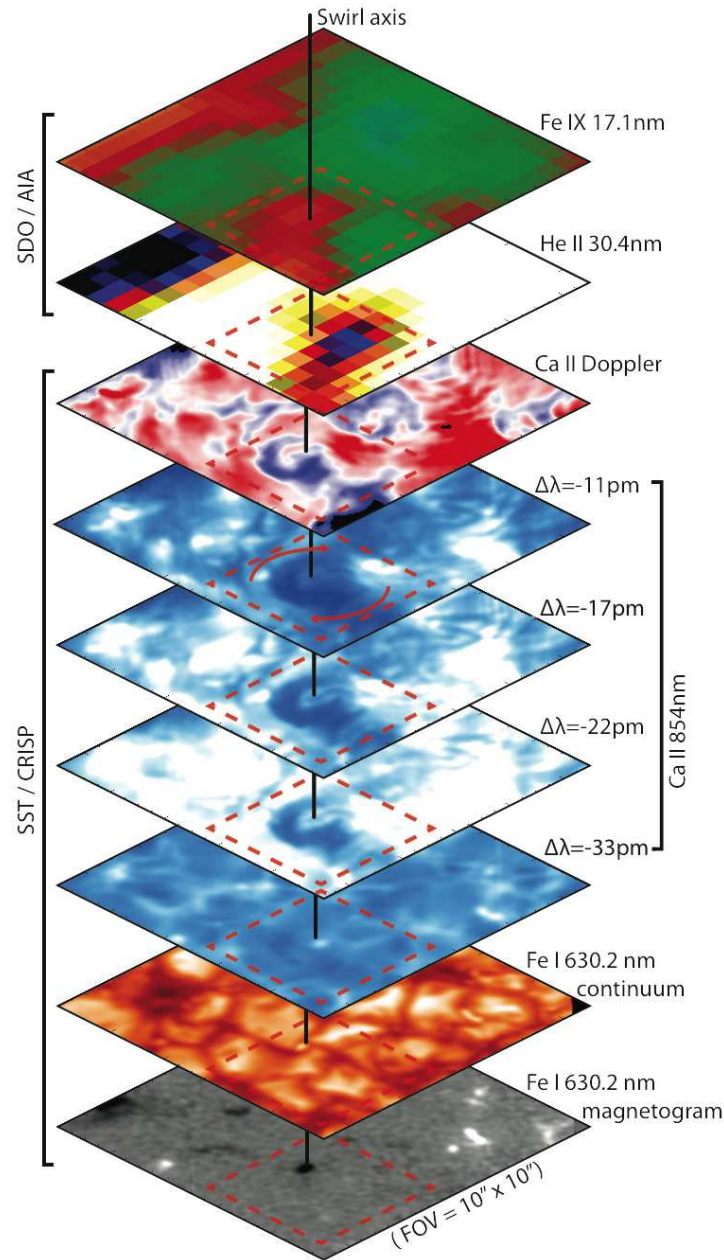


*Left:* Hinode SP magnetogram of one of the squeezed magnetic elements. *Middle:* Time-slice diagram of the intensity in a photospheric and a chromospheric spectral line. *Right:* Spectrum of Mg II k as a function of time.



Wavelet analysis of the Doppler velocity from the photosphere (Fe I 279.99 nm) to the upper chromosphere (Mg II k3). The wave power disappears in between Mg II k2v to Mg II k3.

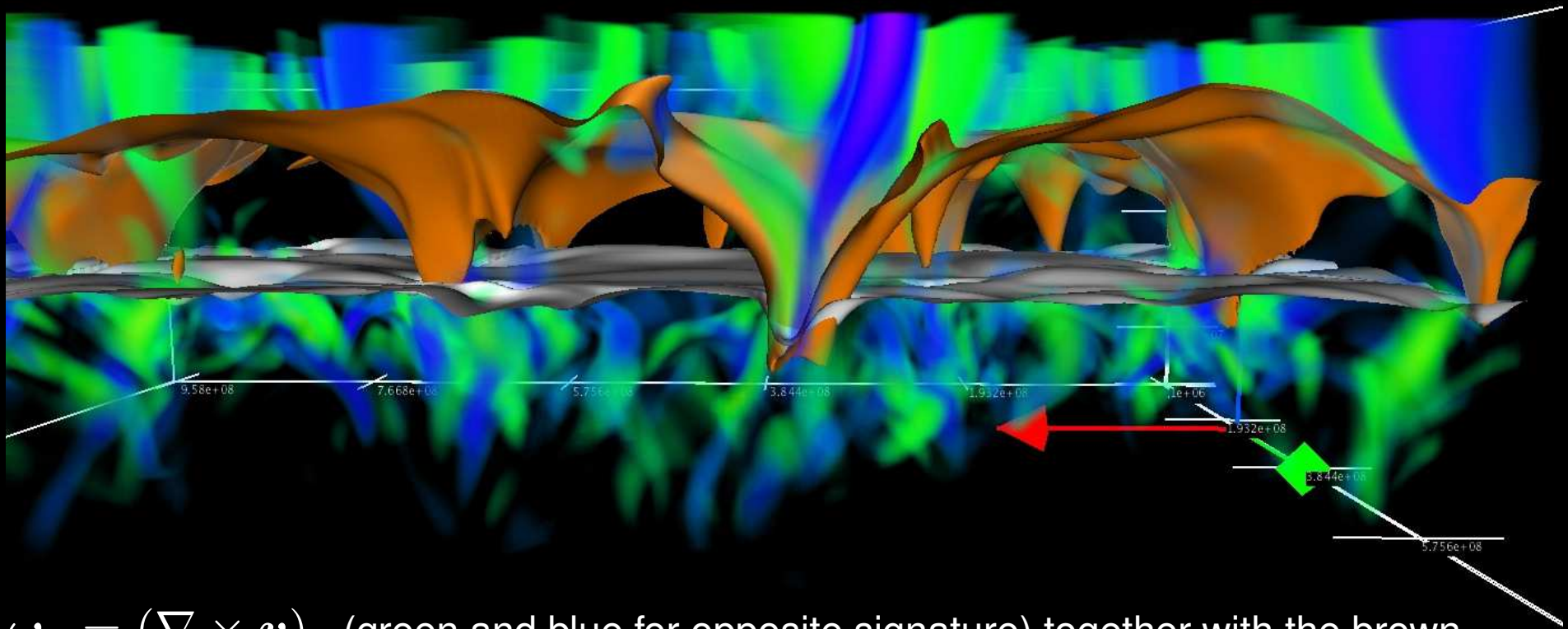
## 4. The photospheric origin of waves and flows (cont.)



### *Multi-Waveband Observation:*

Layered atmosphere from the *photosphere* (bottom panel: magnetogram, Fe I 630.2 nm continuum), through the *chromosphere* (Dopplergram, Ca II 854.2 nm) and the *transition region* (He II 30.4 nm) to the *low corona* (top: Fe IX 17.1 nm). Co-temporal observations with SDO/AIA (cadence, 12 s; image scale, 0.699'' per pixel) and SST/CRISP (cadence, 14 s; Ca II 854.2 nm; image scale, 0.0699'' per pixel). From *Wedemeyer-Böhm et al. (2012) Nature 486, 505.*

## 4. The photospheric origin of waves and flows (cont.)



$\omega_z = (\nabla \times \mathbf{v})_z$  (green and blue for opposite signature) together with the brown surface of plasma  $\beta = 1$ . Grey: surface of  $\tau_c = 1$ . Simulation carried out with CO5BOLD, visualization with VAPOR 3D (Clyne et al. 2007). Courtesy, *Ch. Nutto*.

See *Steiner & Rezaei (2012)* for more details.

#### 4. The photospheric origin of waves and flows (cont.)

##### Challenge:

Observing the *magnetic coupling from the convection zone to the corona* by simultaneous observations in multiple spectral lines including polarimetry with ground based and space borne instruments.

Identify *cause and effect* of plasma motions with *high cadence* observations at highest possible spatial resolution.

## **5. Polarimetric accuracy**

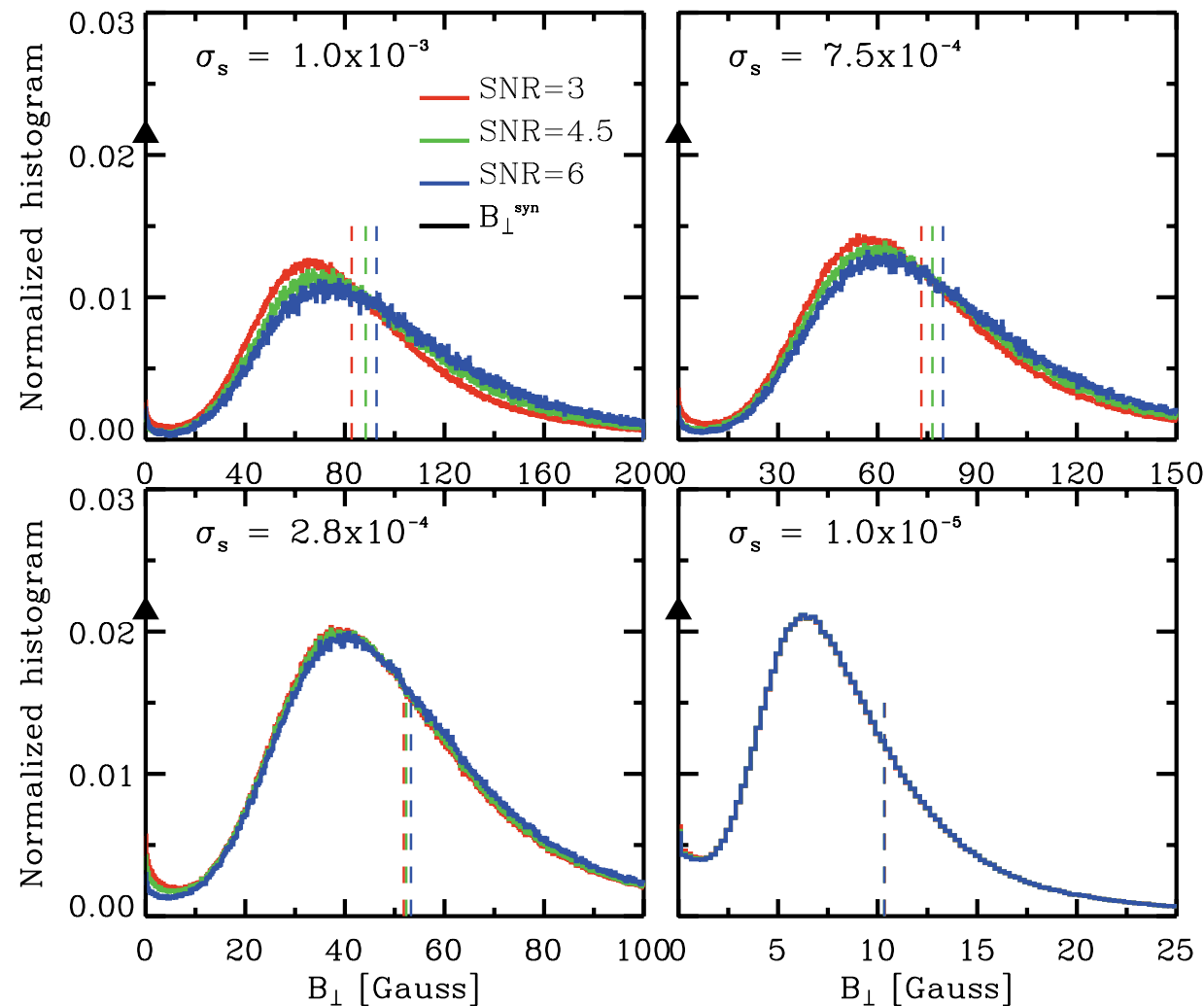
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Highly precise measurement of the linear polarization components is needed to determine the true topography of small-scale magnetic field.

## 5. Polarimetric accuracy (cont.)

Stochastic study of noise affected synthetic Stokes profiles derived from atmospheric models with a strictly vertical magnetic field by *Borrero & Kobel (2011) A&A 527, A29*



Histograms of the retrieved  $B_{\perp}$  from Stokes profiles with signal to noise ratio  $\text{SN} \geq 3$  (red),  $\text{SN} \geq 4.5$  (green), and  $\text{SN} \geq 6$  (blue). Levels of noise are  $\sigma_s = 10^{-3}$  (top left),  $\sigma_s = 7.5 \times 10^{-4}$  (top right),  $\sigma_s = 2.8 \times 10^{-4}$  (bottom left), and  $\sigma_s = 1.0 \times 10^{-5}$  (bottom right).

## 5. Polarimetric accuracy (cont.)

### Challenge:

We need a polarimetric accuracy of  $I_{\text{pol}}/I_{\text{cont}} \leq 10^{-4}$   
for resolving the quest of the horizontal magnetic field.



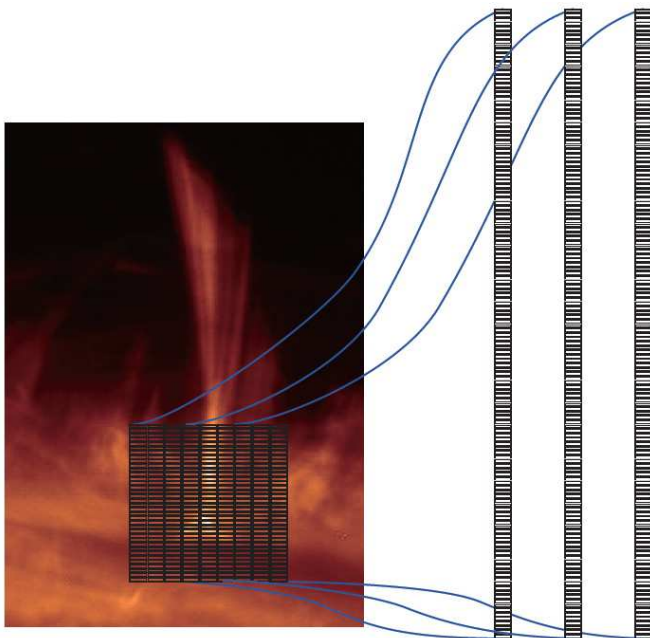
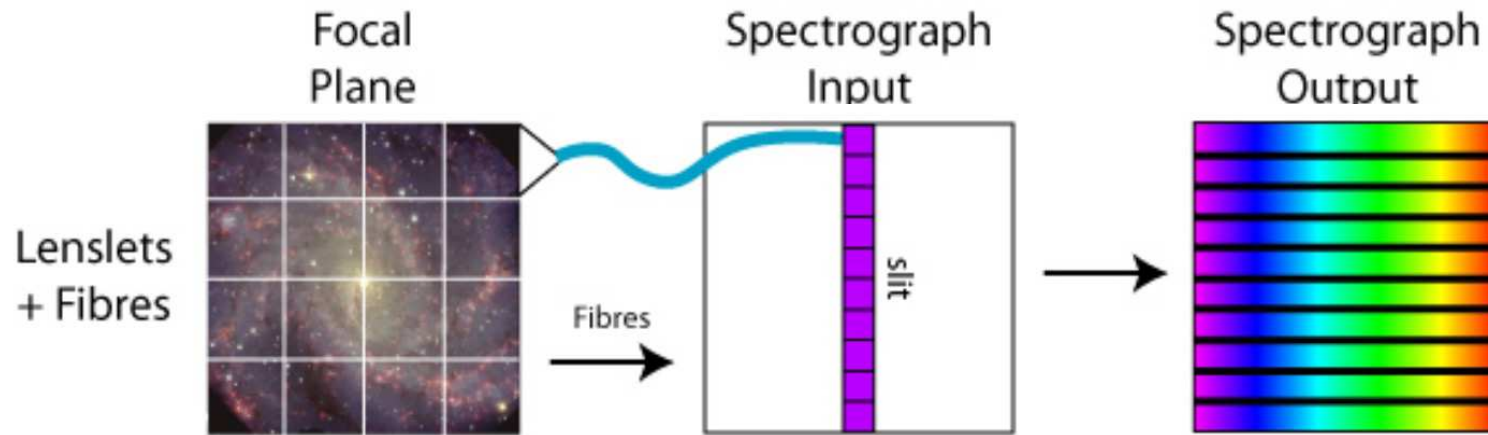
## 6. Integral Field Units

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A spectrograph equipped with an *integral field unit (IFU)* is an optical instrument combining spectrographic and imaging capabilities. It delivers a spectrum to each spatial resolution element.

Integral field units are likely to become the *standard equipment and way of observing the Sun.*

## 6. Integral Field Units (cont.)

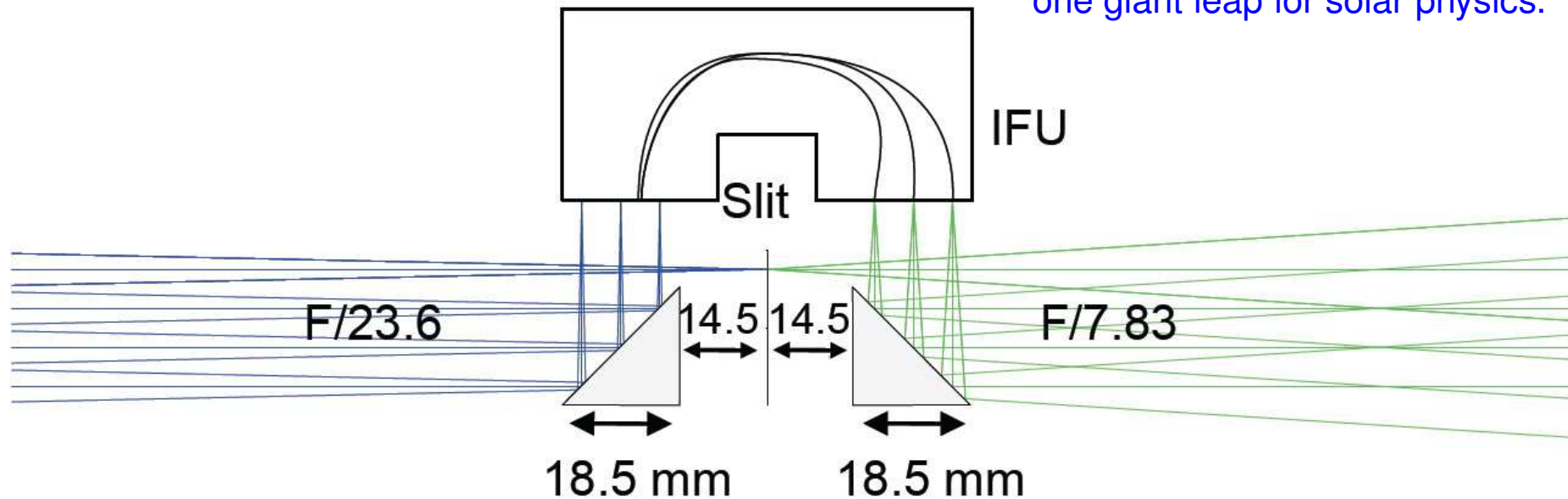


Concept of an *optical fiber IFU*. The 2-D array of the optical fibers at the entrance of the IFU (left) is converted into 3 arrays (slits) at the exit of IFU (right), which feeds the light into the spectrograph.

From Solar-C: The Next Space Solar Mission (2012).

## 6. Integral Field Units (cont.)

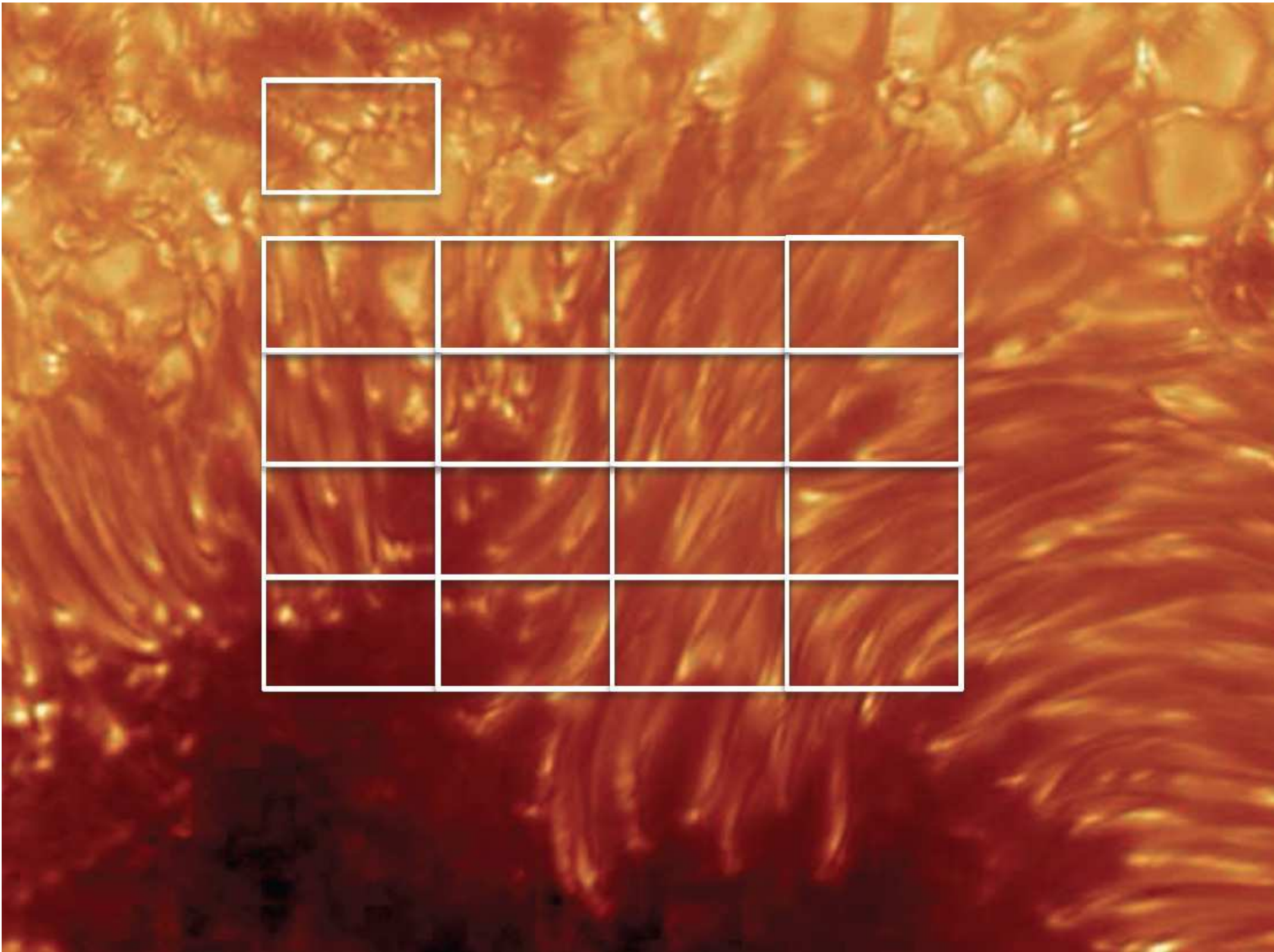
That's one small step for the light,  
one giant leap for solar physics.



The IFU injects lights from the 3 slits into the spectrograph while the true single slit also injects light simultaneously. In total *4 spectra are created* at the spectrum mask.

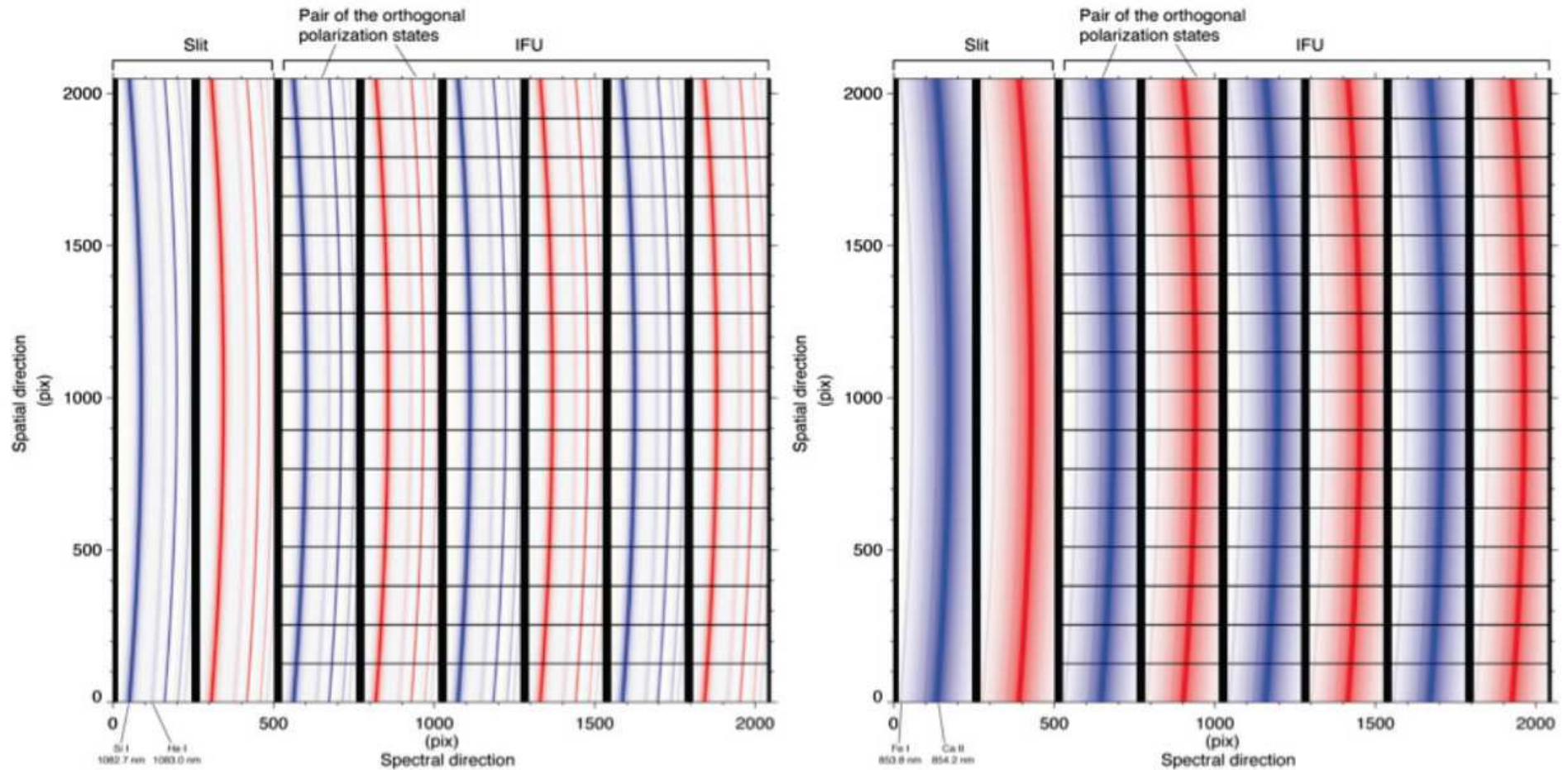
Because two orthogonal polarization states are created by the PBS, there are *8 spectra imaged on the  $2k \times 2k$  detector*. From Solar-C: The Next Space Solar Mission (2012).

# 6. Integral Field Units (cont.)



Courtesy, Haosheng Lin

## 6. Integral Field Units (cont.)



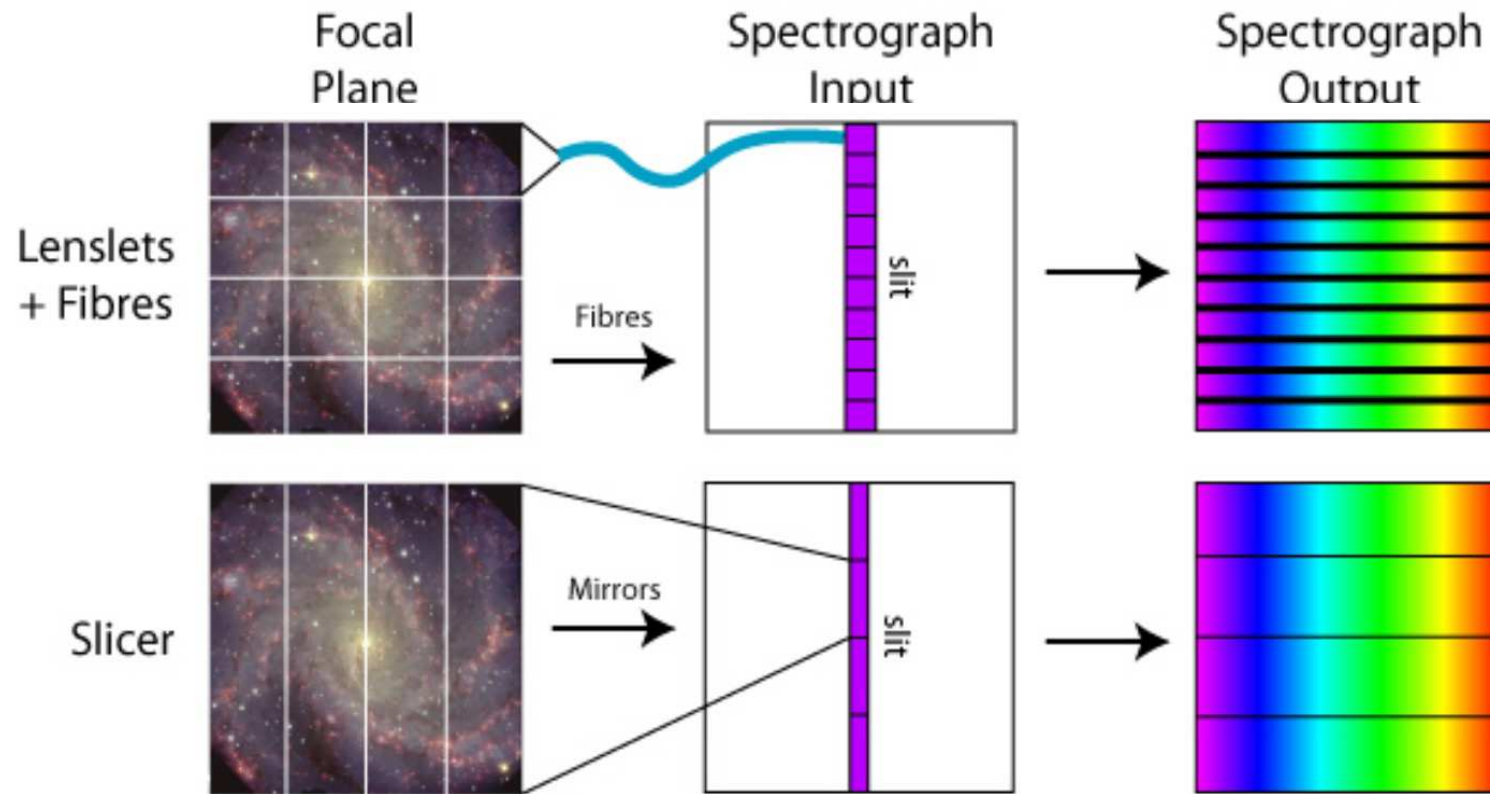
Simulated *spectra on the detector* for *He I 1083 nm* (left) and for *Ca II 854 nm* (right).

The left most spectrum is from the true slit, and the other three spectra are from IFU.

The two orthogonal polarization states are indicated by the red and blue colors.

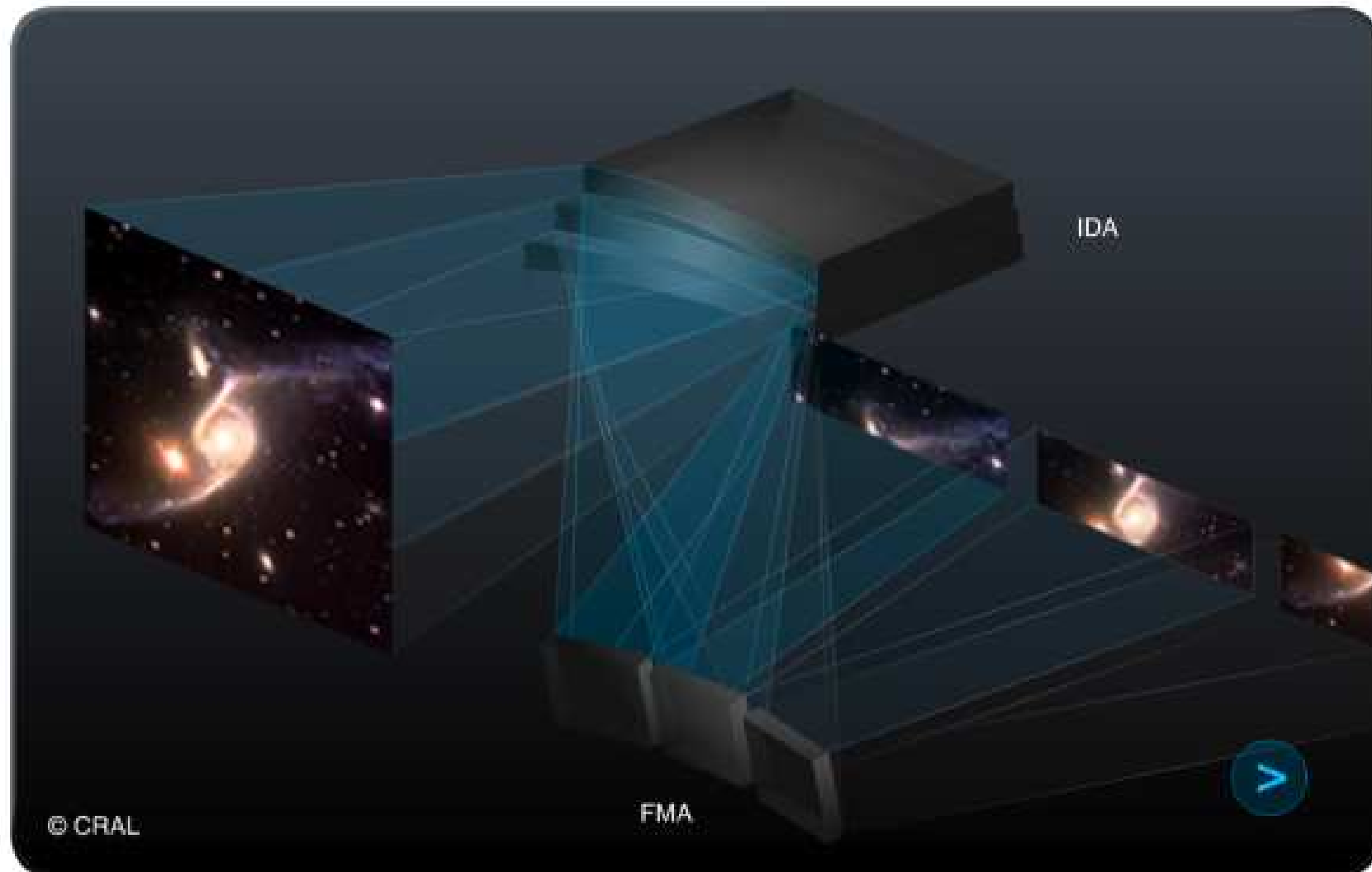
From Solar-C: The Next Space Solar Mission (2012).

## 6. Integral Field Units (cont.)

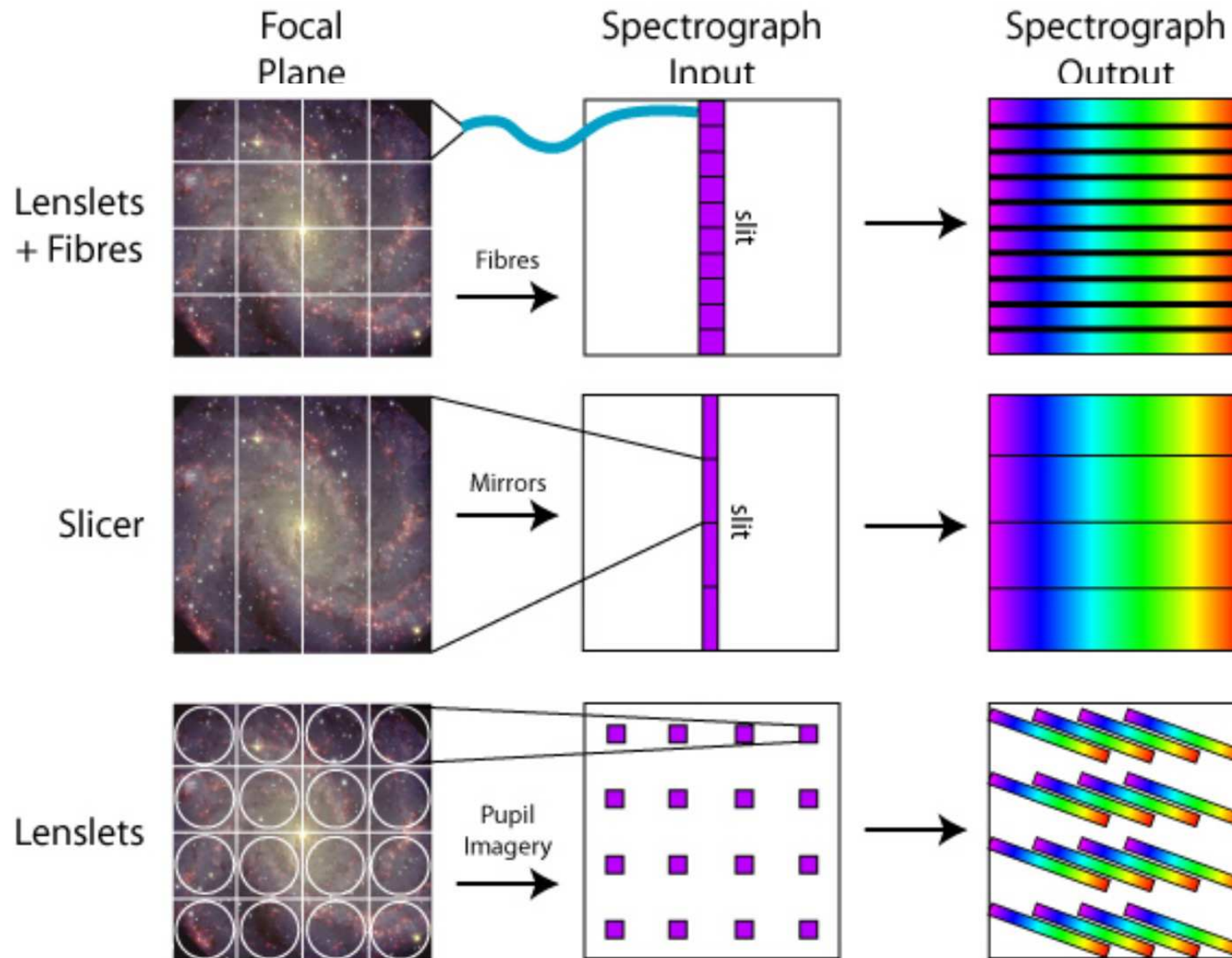


## 6. Integral Field Units (cont.)

### Image slicer technology: MUSE at ESO



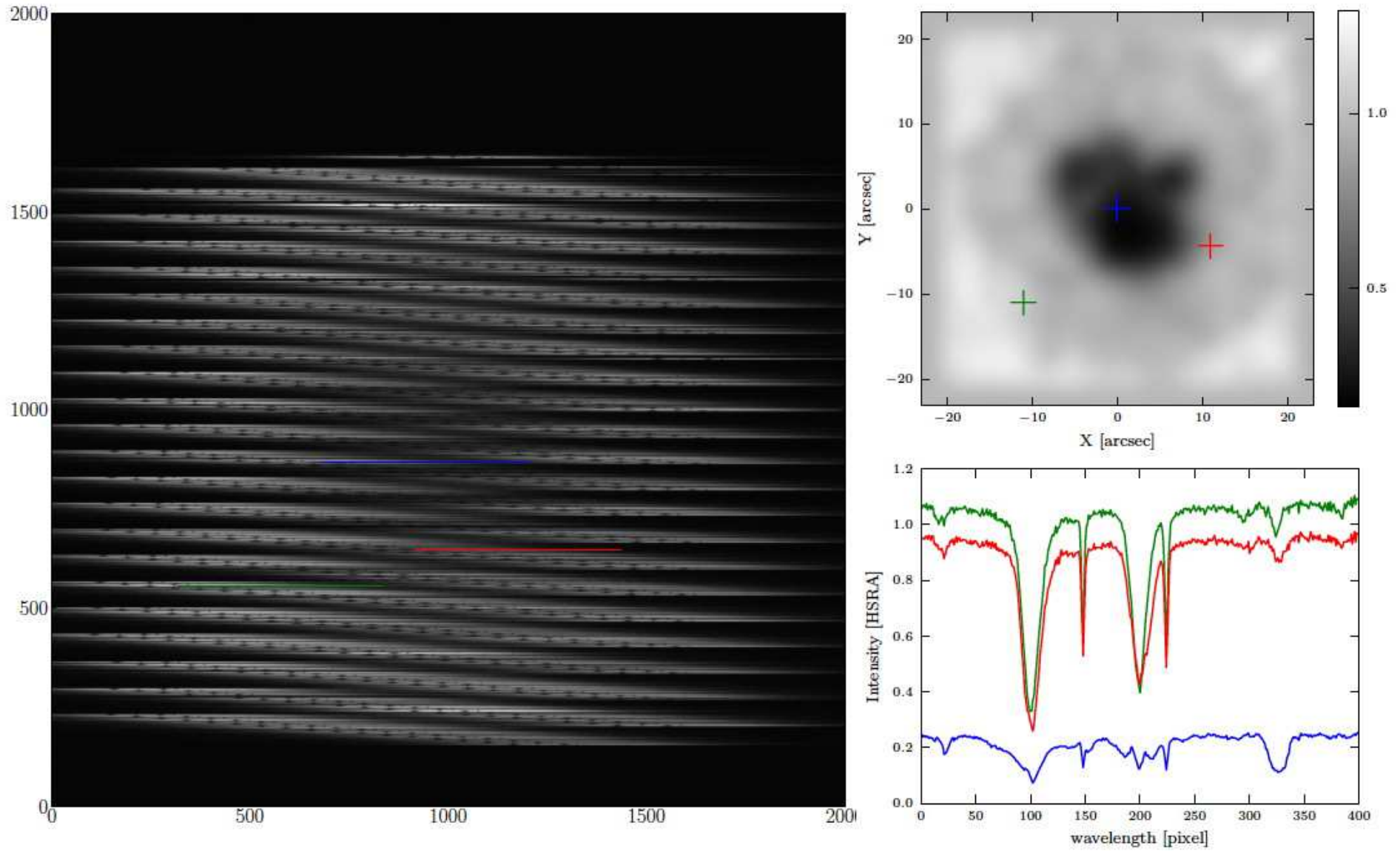
## 6. Integral Field Units (cont.)



<http://ifs.wikidot.com/what-is-ifs>



## 6. Integral Field Units (cont.)



Courtesy, Michiel van Noort

## 8. Conclusions

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- With future large solar telescopes, we should be in a position to map the *three-dimensional topography of the weak quiet Sun magnetic field* and track its origin. For this, however, we need high *polarimetric accuracy* ( $\leq 10^{-4}$ ).
- We need better *interlocking of 'realistic' simulations with observations*. Therefore, the advancement of numerical simulations must be an integral part of the development and construction of large solar telescopes.
- We should be in a position to *track single dynamic small-scale events* on short time scales and differentiate *cause and effect*.
- Observations of *multiple spectral lines and wavelengths with multiple instruments*, combining space borne and ground based instruments are essential to understand the *magnetic coupling between convection zone, photosphere, chromosphere, and the corona*.
- *Integral field units* are likely the future way to observing the Sun.

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