DKIST 4m-telescope as a Solar microscope and a photon bucket

Two new observational results

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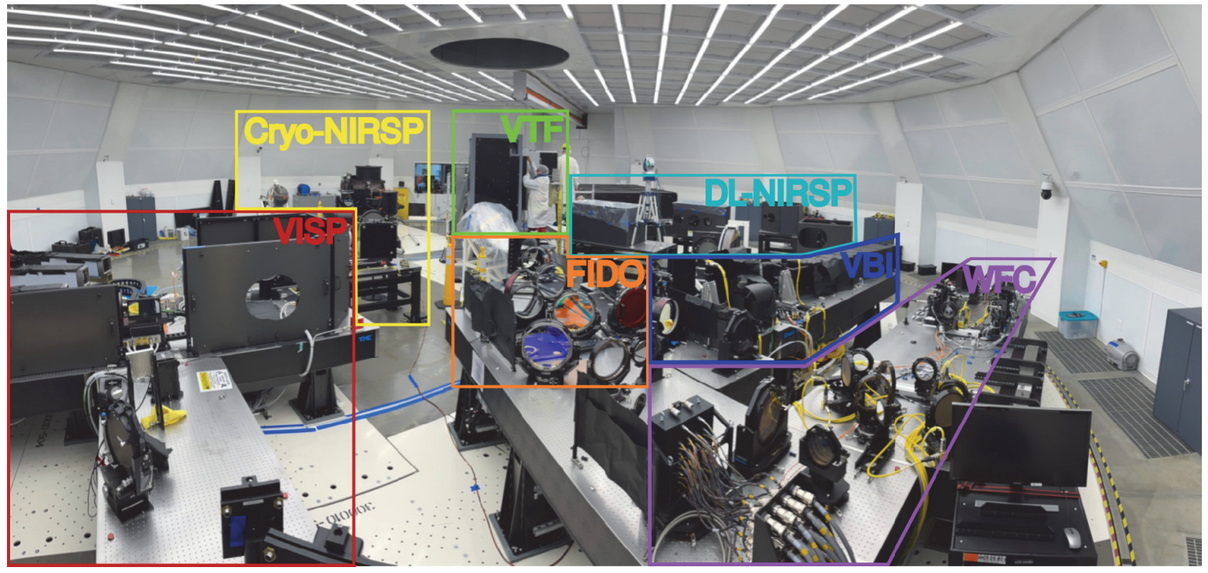
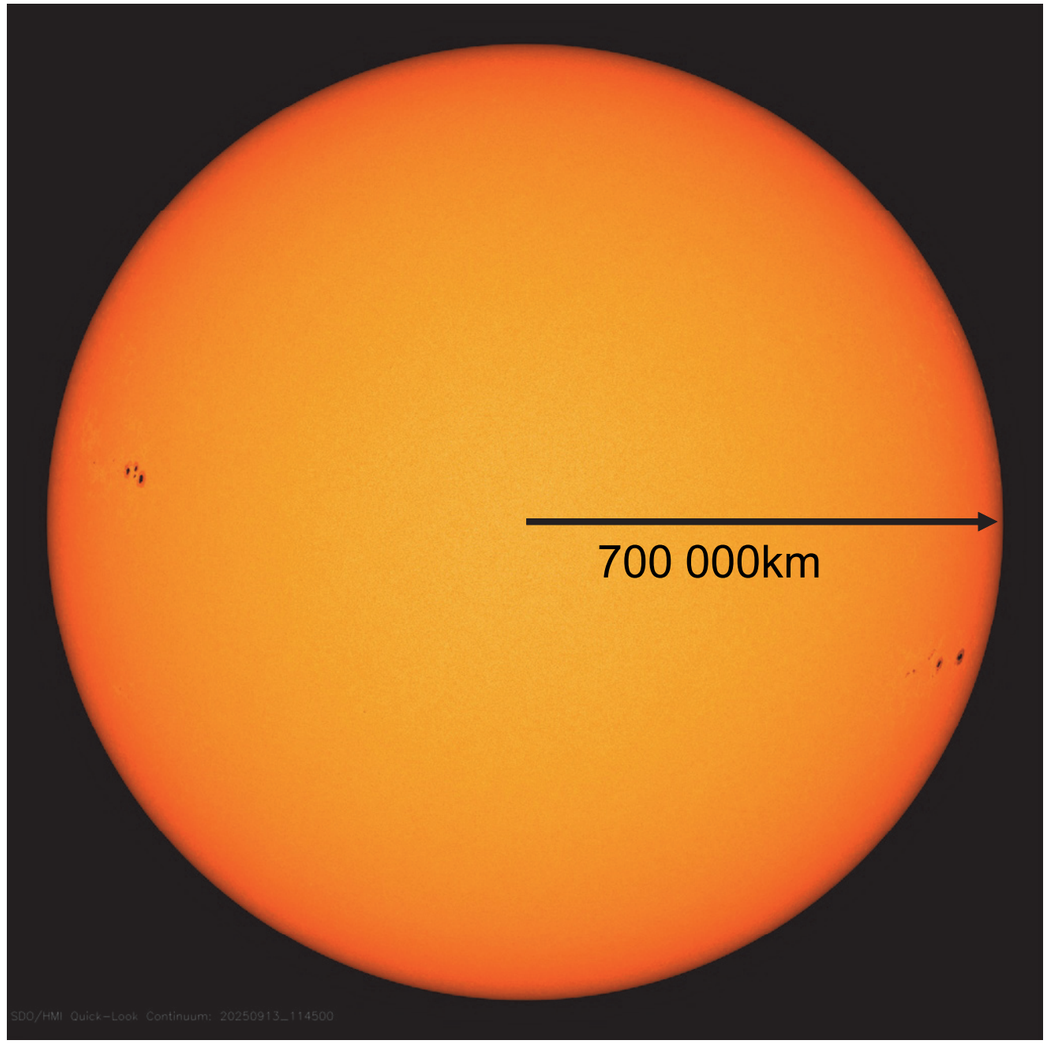
DKIST: Daniel K. Inouye Solar Telescope

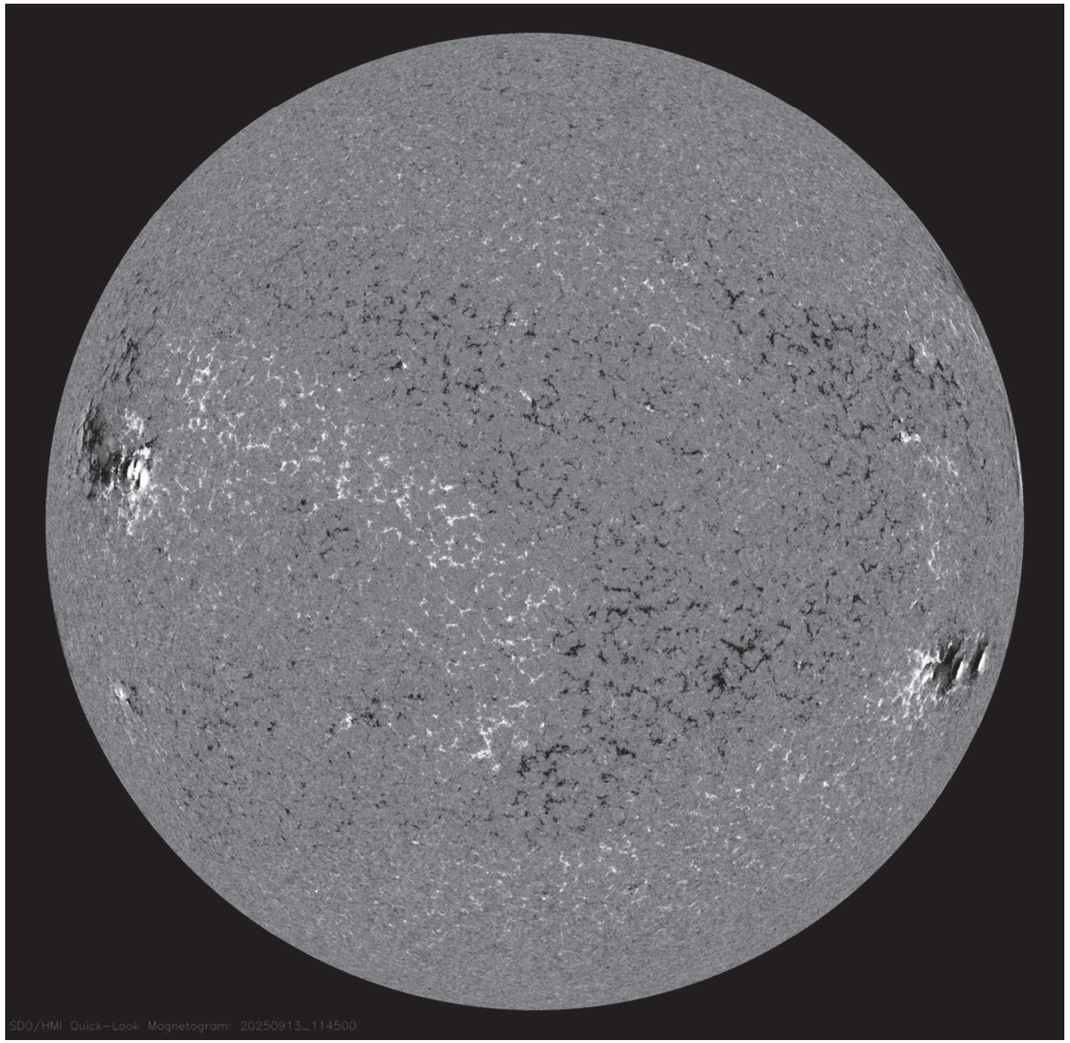
Credit: NSO / NSF / AURA



- 4 m, off-axis, Haleakalā (Maui)
- Science operations since ~ 2019
- 5 instruments (4 working, VTF installed)
- Also designed as a “coronograph”
- Available, in principle, to anyone

We usually care about the Sun’s magnetic field





The Sun today*. Left: broadband image in visible domain (less structure);
Right: magnetic field map (more structure)

Why?

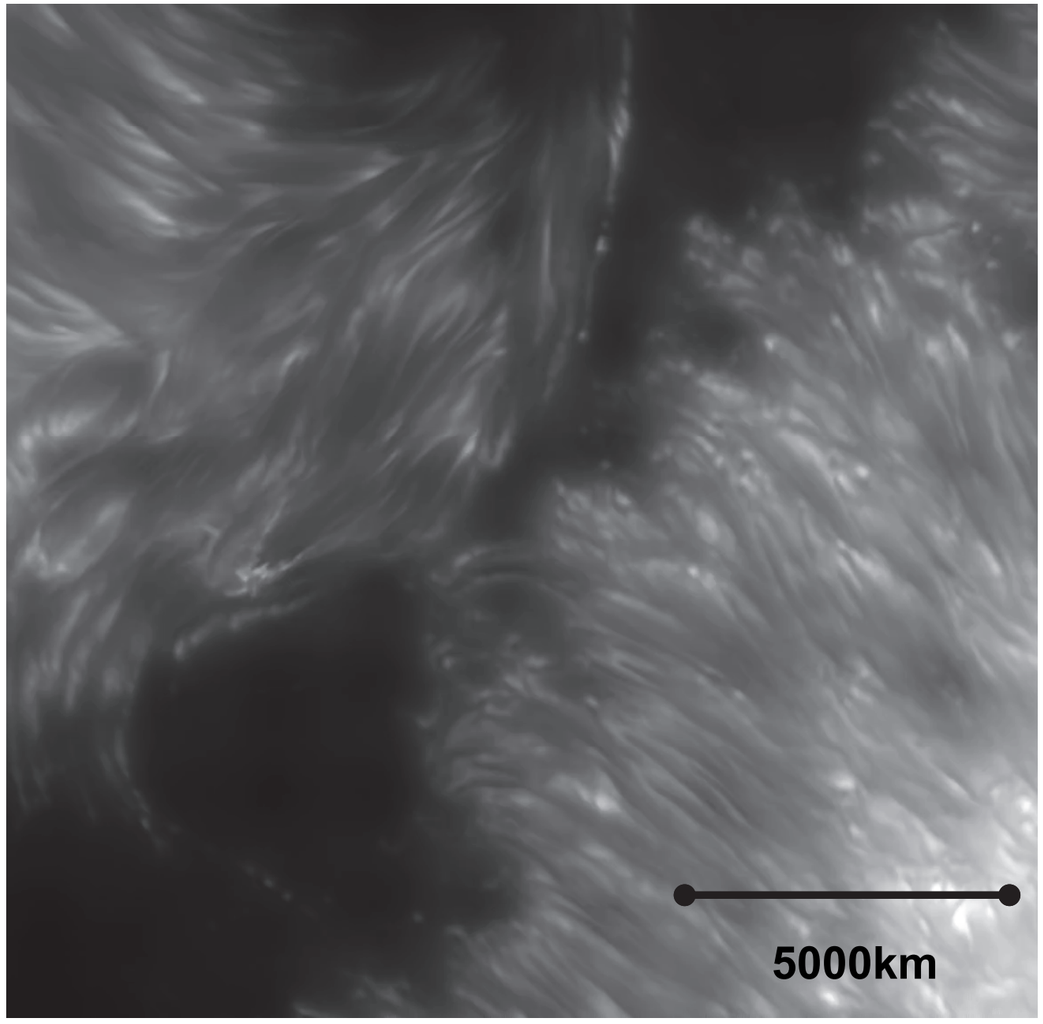
Depending on the density of the medium and the strength of the magnetic field, it's contribution to energy and force balance can be substantial, even dominant!

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\rho \frac{d\mathbf{u}}{dt} = -\rho \nabla \Phi - \nabla p + \boxed{\frac{1}{\mu_0} (\nabla \times \mathbf{B}) \times \mathbf{B}}$$

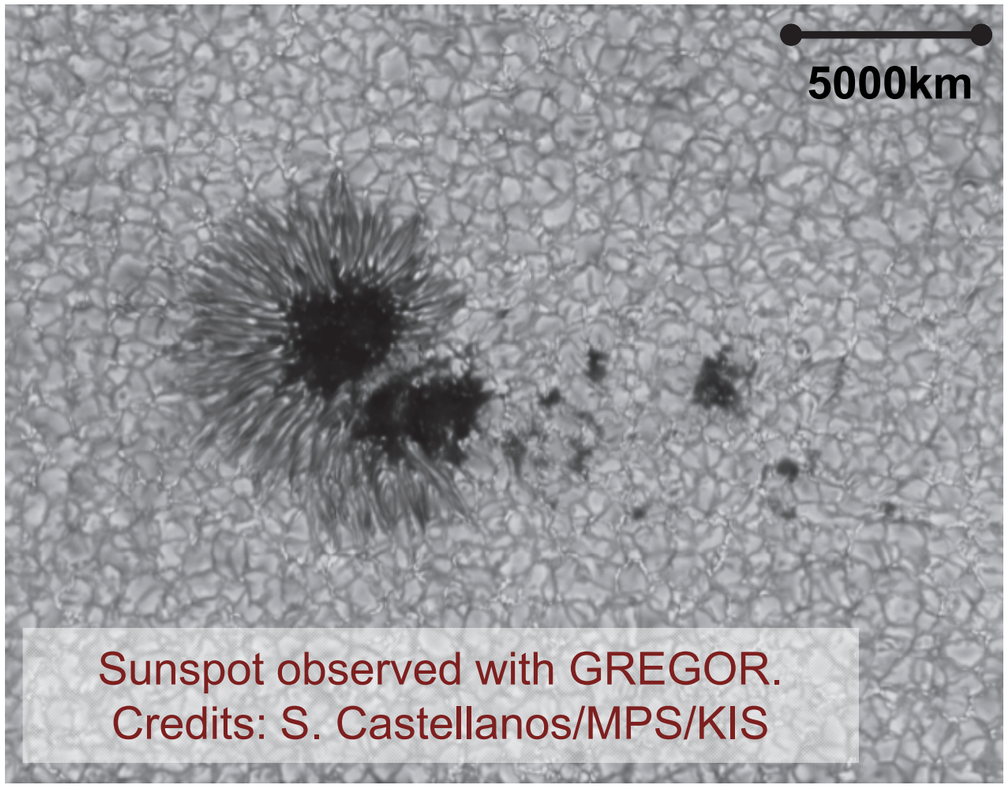
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B})$$

$$\nabla \cdot \mathbf{B} = 0$$



A small solar flare, observed with GREGOR solar telescope. Note different wavelength. Credits: S Castellanos/MPS/KIS

Why is the Sun so special?



Sunspot observed with GREGOR.
Credits: S. Castellanos/MPS/KIS

Diffraction limit of optical telescopes

$$\theta = 1.22\,\frac{\lambda}{D} = 0.012'',$$

The angular size of the Sun seen from Proxima Centauri

$$\rho = \frac{R_\odot}{d} = 0.004''.$$

$$\theta = 1.22\,\frac{\lambda}{D} \approx 0.08'',$$

$$\Delta x = \theta \times 1\,\mathrm{AU} \approx 60\,\mathrm{km}.$$

Why do we build the big telescopes?

Better resolution

$$\begin{aligned} \theta &= 1.22\frac{\lambda}{D} \\ \Delta x &= \frac{1}{2}\,\theta \times 1\ \mathrm{AU} \end{aligned}$$

Better collecting power

$$N \propto D^2$$

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Better collecting power

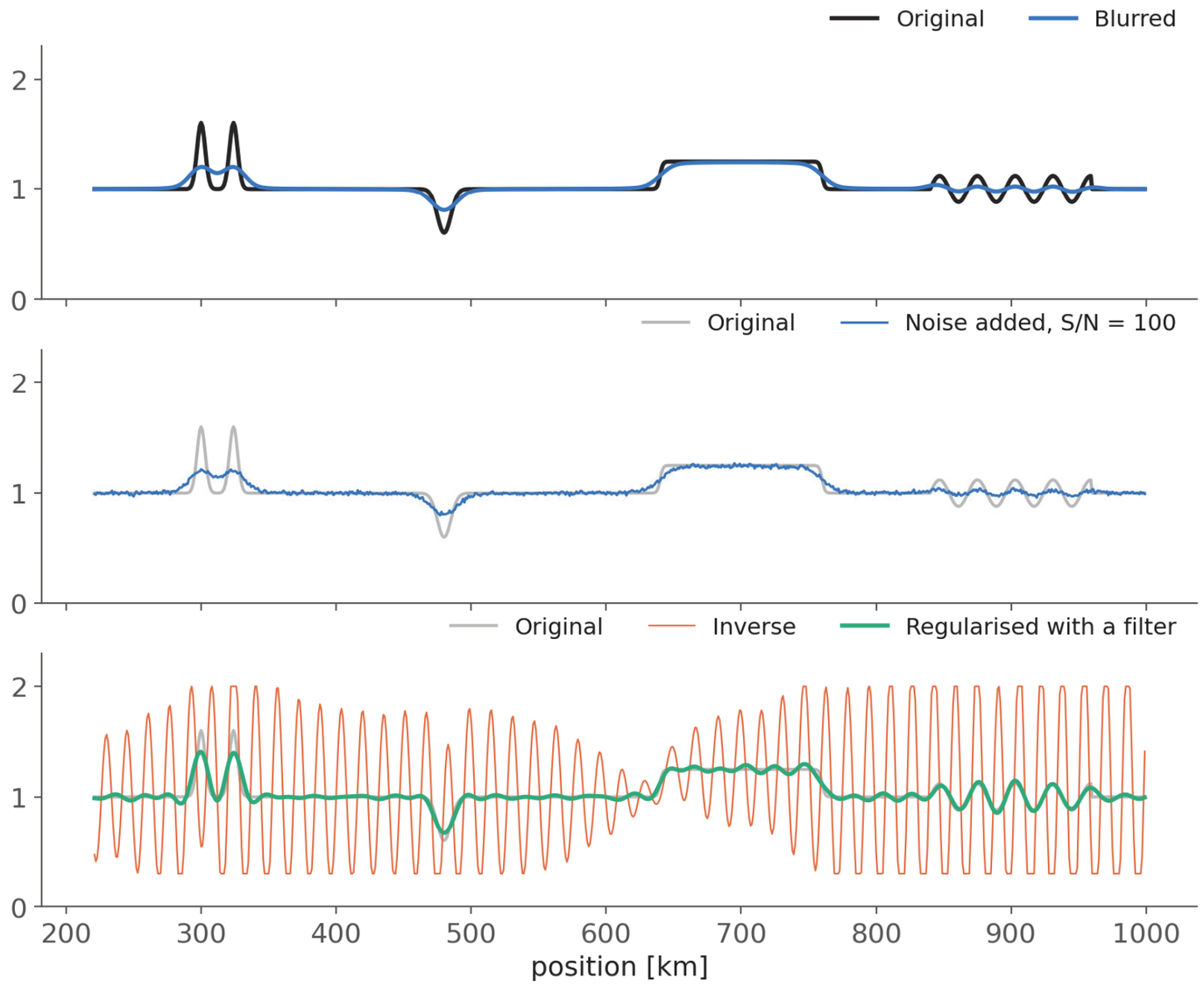
$$N \propto D^2$$

$$N = D^2 \times \Delta x^2 \times \frac{1}{d^2} \times \Delta t \times \Delta\lambda \times \frac{I_\lambda}{h\nu}$$

PLUS the effects of Earth's atmosphere
(**and I don't mean the absorption**)

Paradoxical outcome: The bigger the telescope we have, the MORE noisy the observations at the diffraction limit are

The atmosphere blurs (convolves) the image

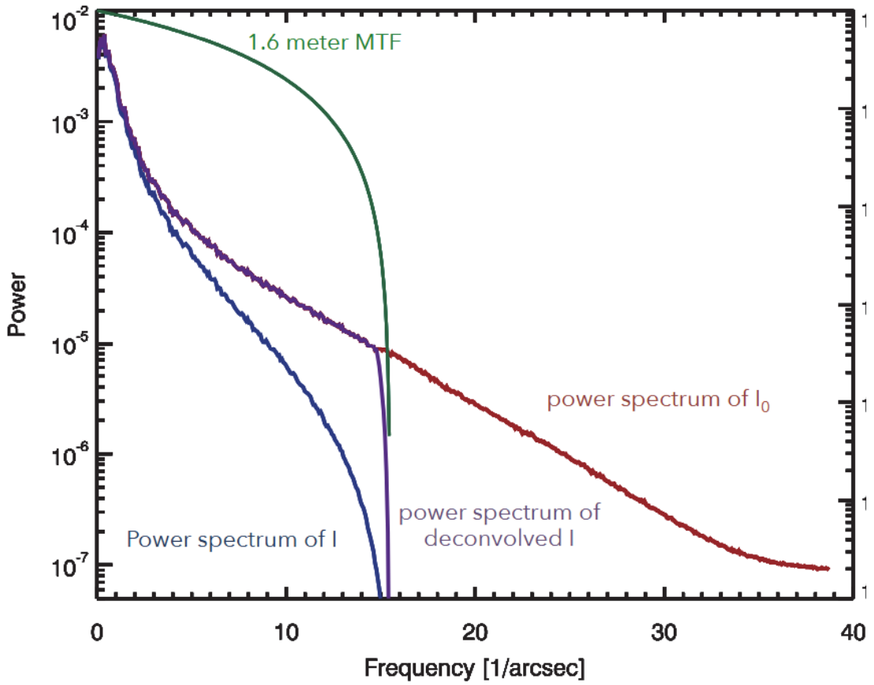


$$I(x,y)^{\text{obs}} = I(x,y) * PSF(x,y) + \epsilon$$

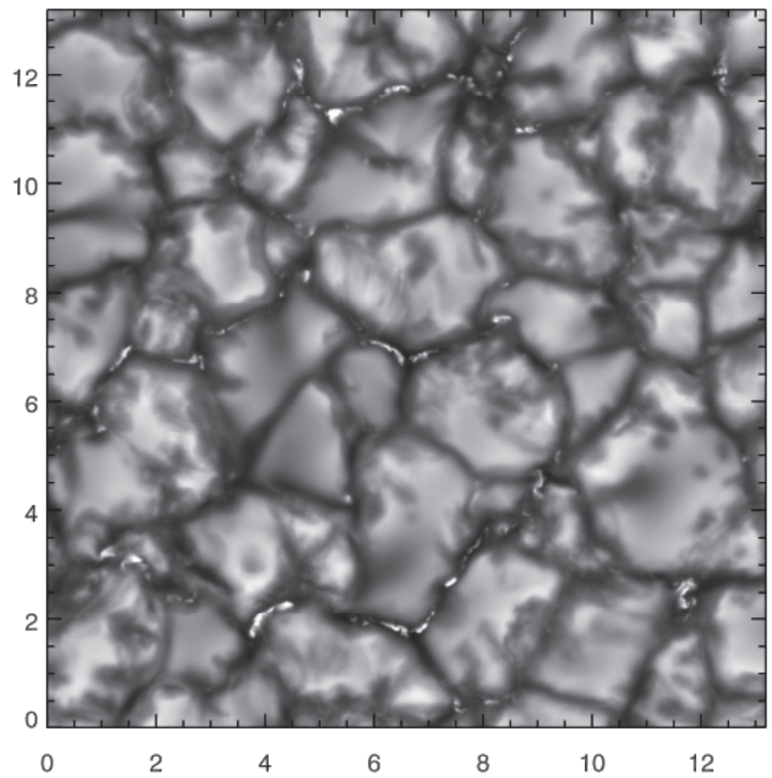
- In practice, PSF is **NOT** the theoretical PSF of the 4m telescope
- It is also unknown, so that is why we use MOMFBD
  (we leave this for the bar later)
- And every observation is noisy
- This immediately makes the deconvolution **catastrophic**

So in practice it looks like this

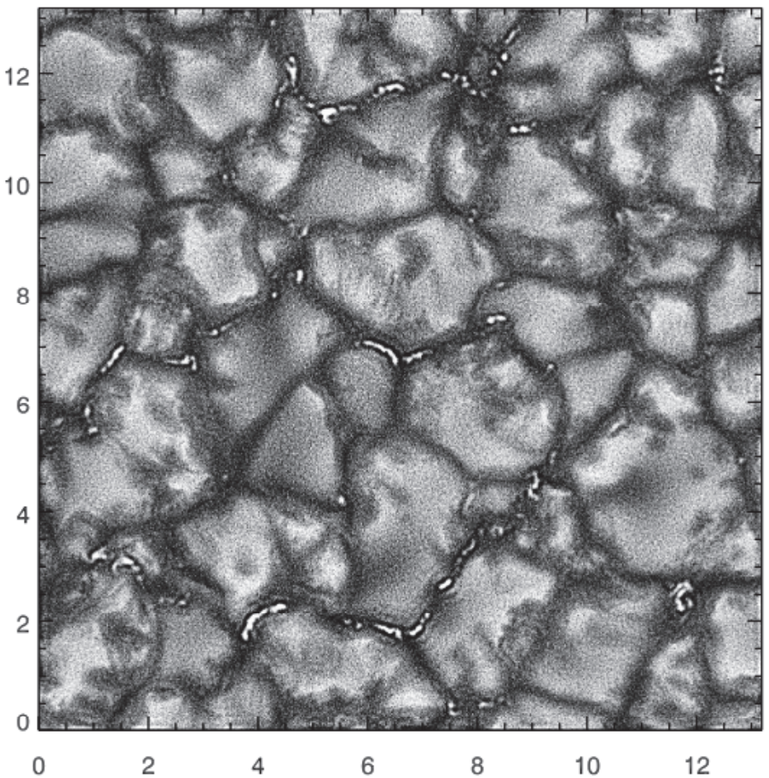
$$I(x,y)^{\mathrm{obs}} = I(x,y) * PSF(x,y) + \epsilon$$



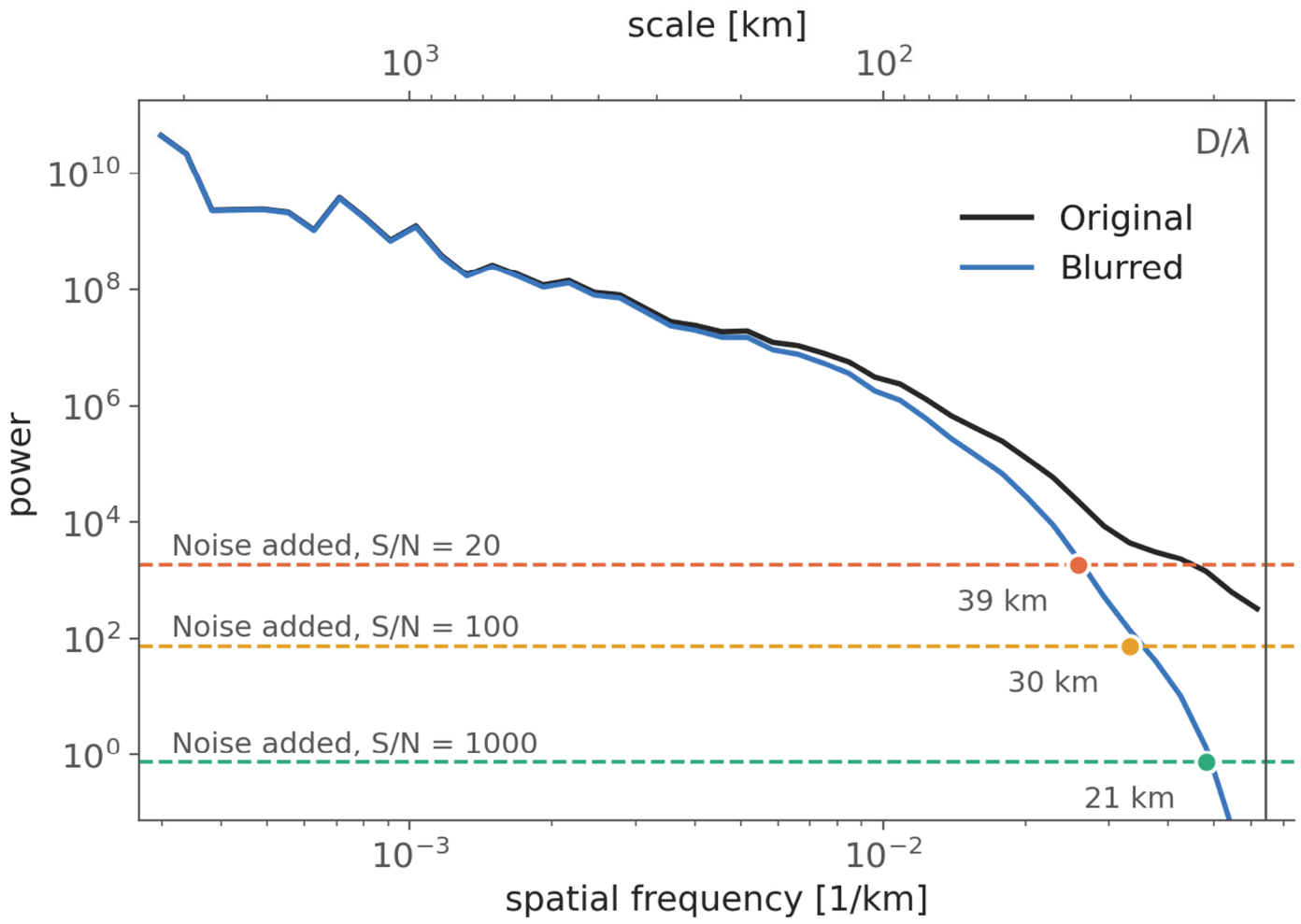
4-meter Diffraction Limited



1.6-meter Diffraction Limited
Deconvolved, 2% noise



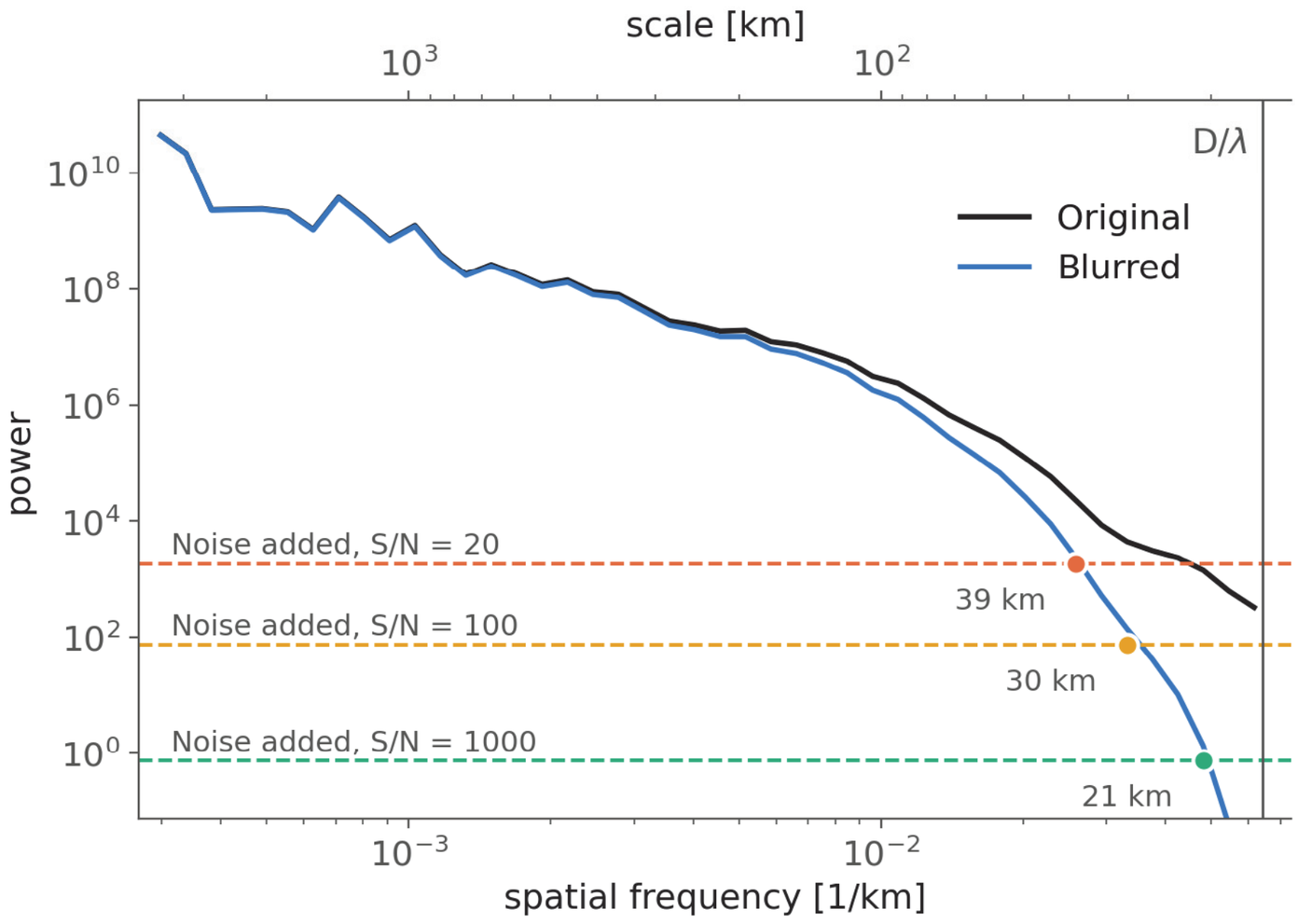
Noise determines how fine details we can see



- Power decreases with k
- PSF multiplies the power
- Noise is flat (white?)
- We can't recover details below the noise cutoff
- S/N 1000 → ~20 km
- S/N 20 → ~40 km
- Diffraction limit requires photons
- How to get them?

$$N = D^2 \times \Delta x^2 \times \frac{1}{d^2} \times \Delta t \times \Delta\lambda \times \frac{I_\lambda}{h\nu}$$

Can you see what was wrong with the original instrument?



$$N = D^2 \times \Delta x^2 \times \frac{1}{d^2} \times \Delta t \times \Delta\lambda \times \frac{I_\lambda}{h\nu}$$

From the original webpage of VBI at DKIST:

3.4 seconds for images with the same physical FOV (single or multiple λ); 2.667 seconds are for data acquisition: 80 frames acquired at a rate of 30 Hz

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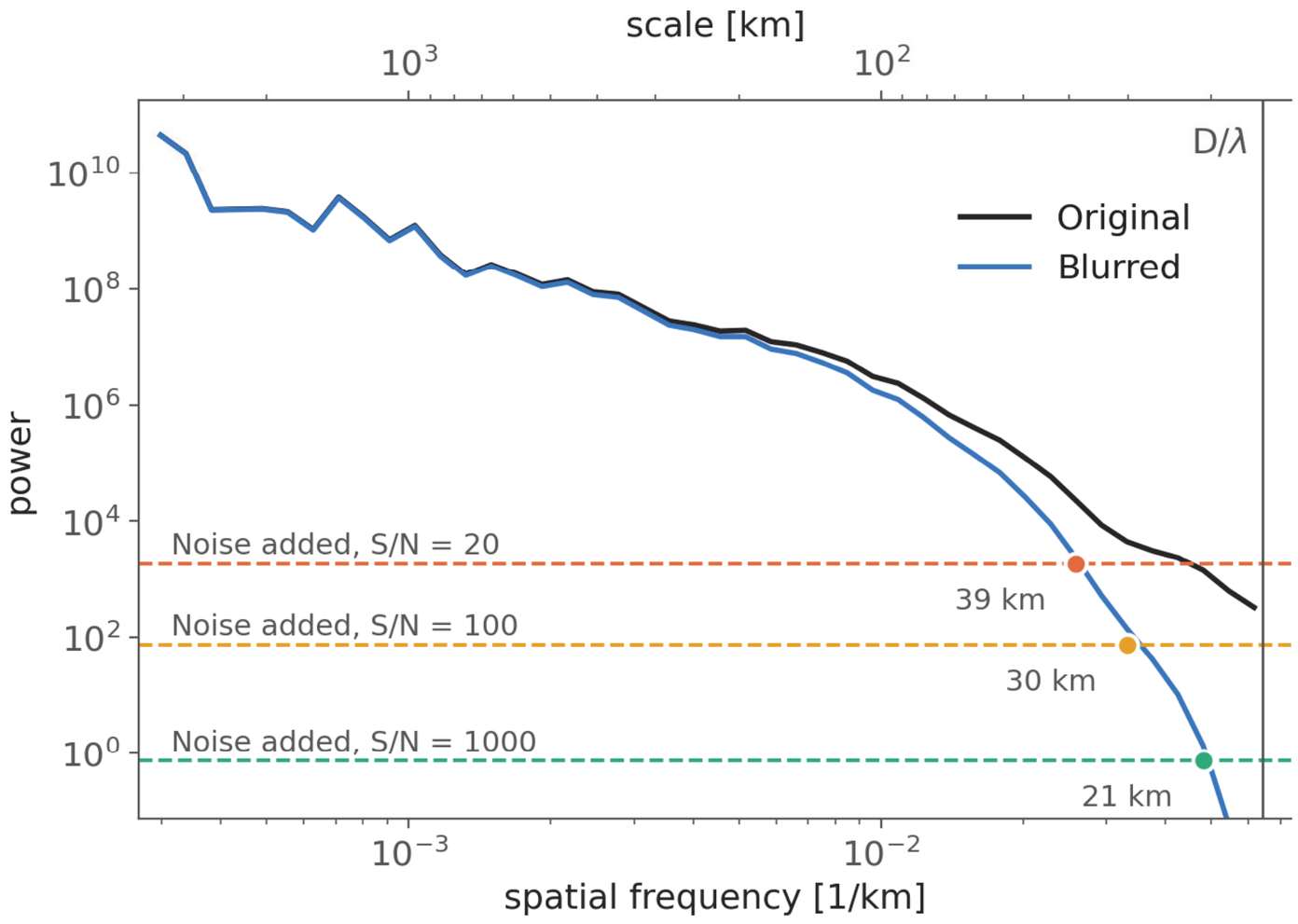

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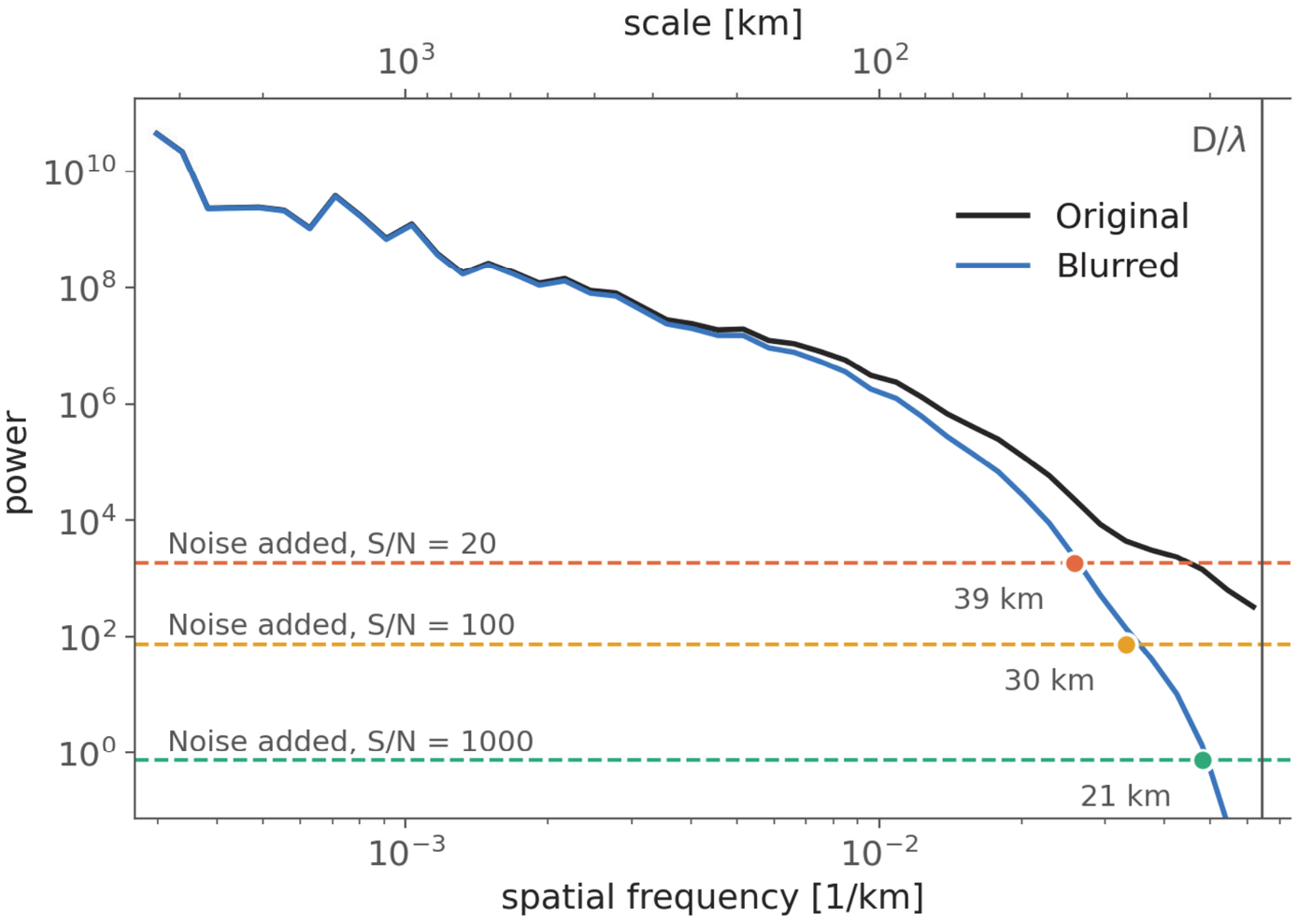

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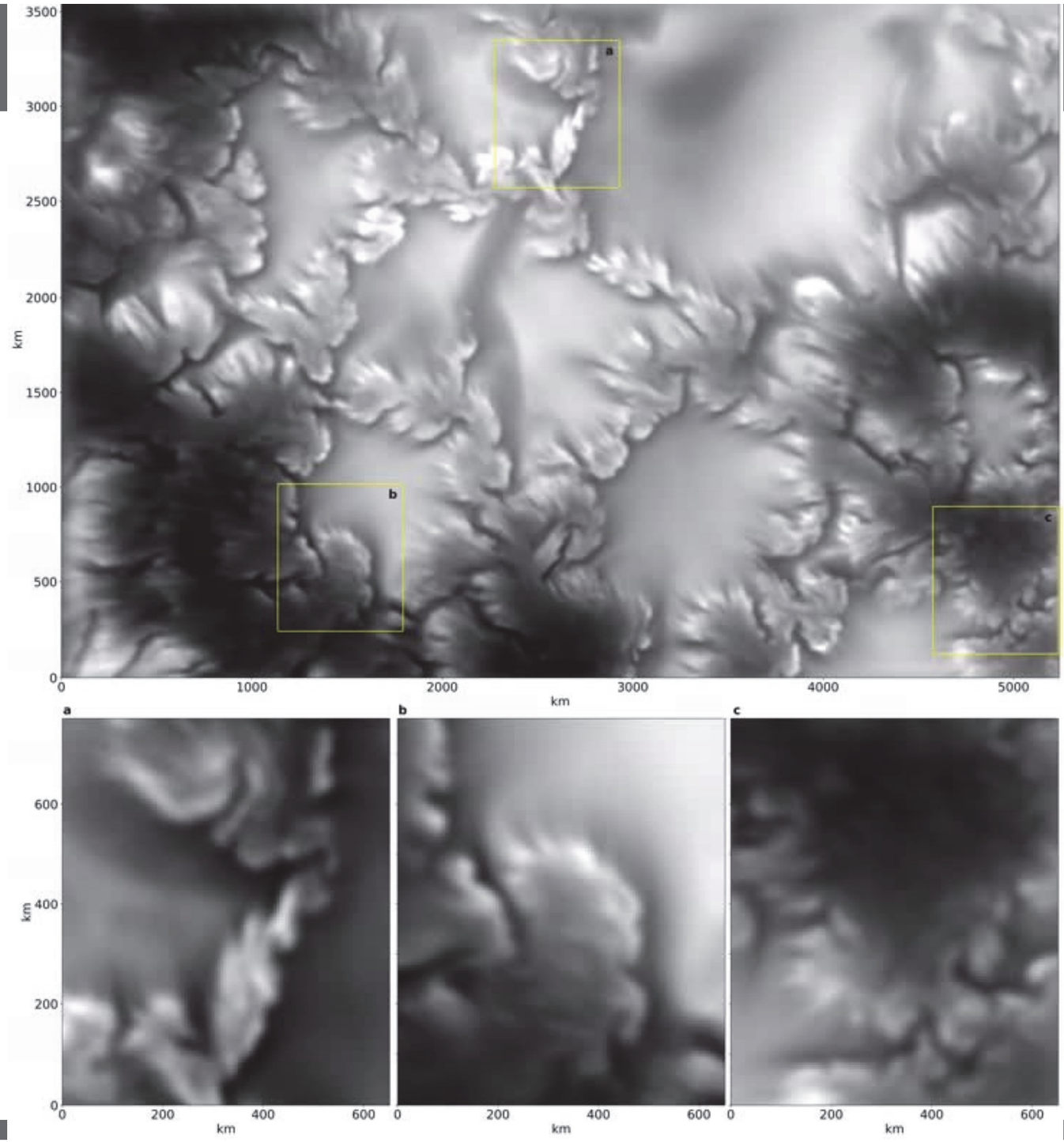
The original duty cycle of the VBI was 3%!

They took ~ 25 times faster camera to improve the image.

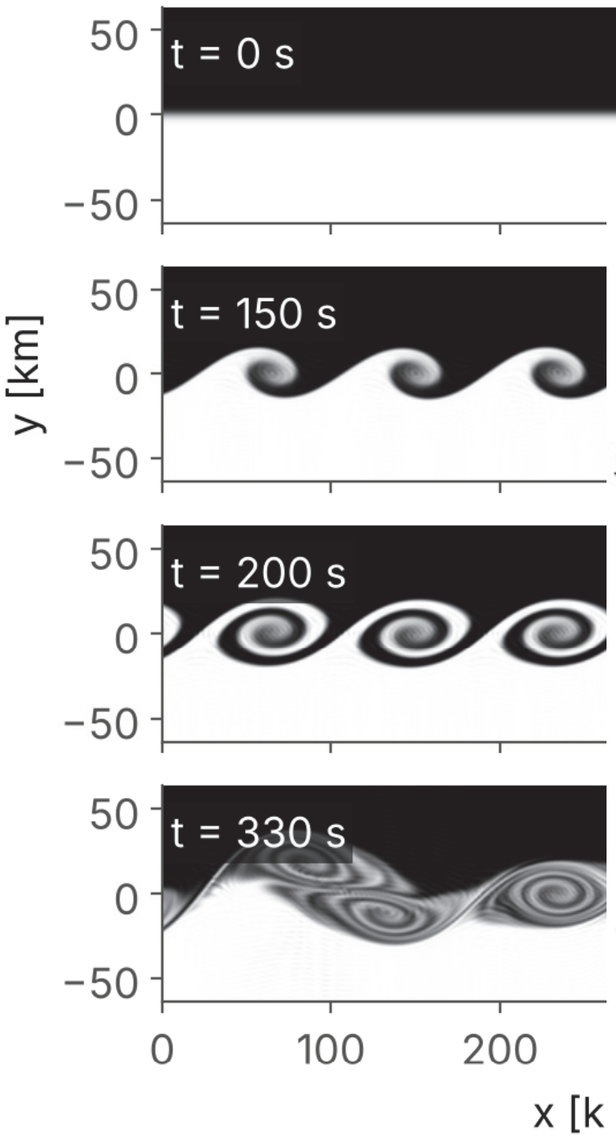
Then you get this

- 416 nm, 0.5 nm filter, 2.7s effective cadence
- “Filigree” close to an active region
- Striations and instabilities at the edge of magnetic elements

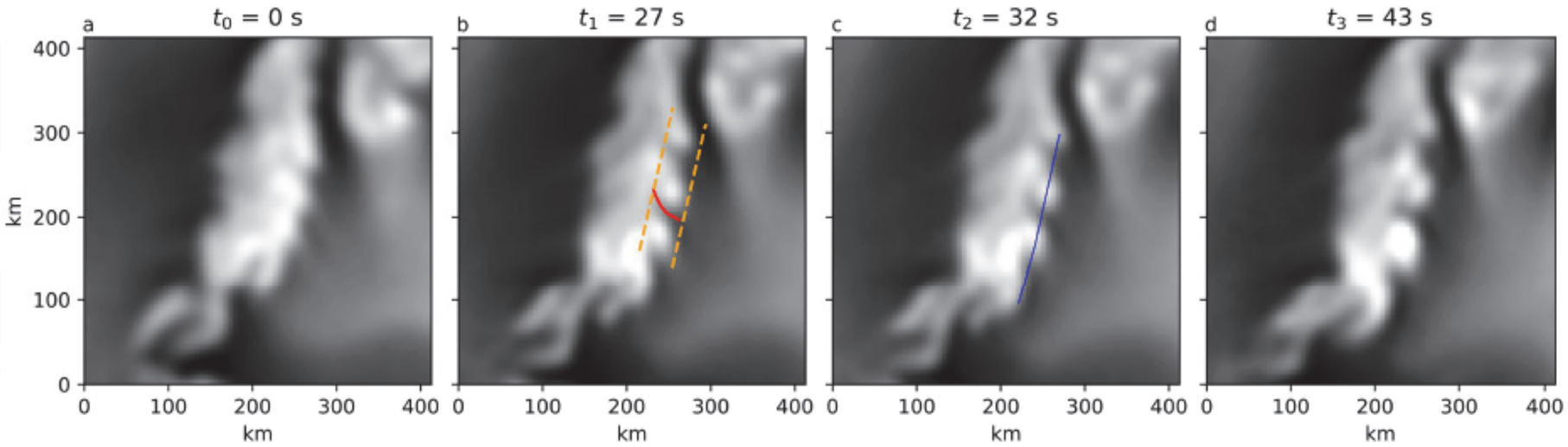
Kuridze, et al. 2026, Nature 656, 595

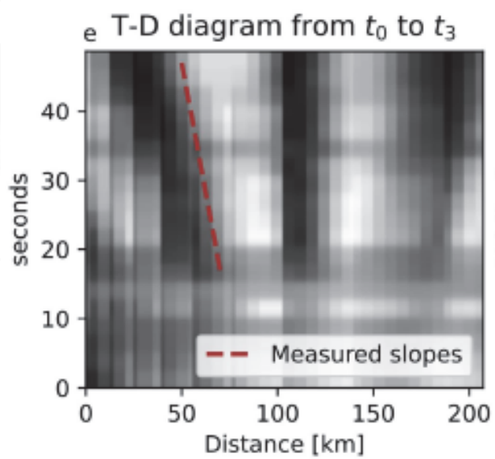


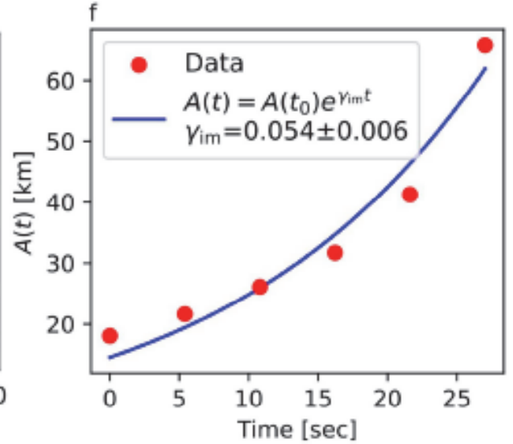
Kelvin–Helmholtz instability

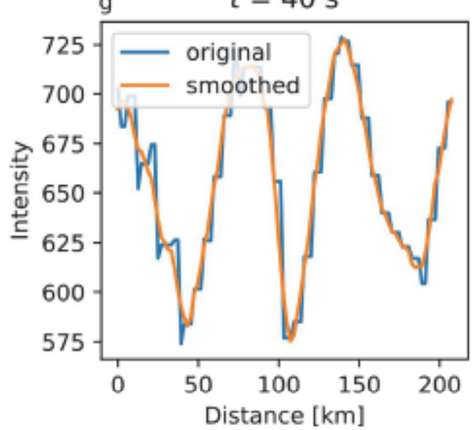


- Shear between two flows
- Instability grows, rolls up, mixes





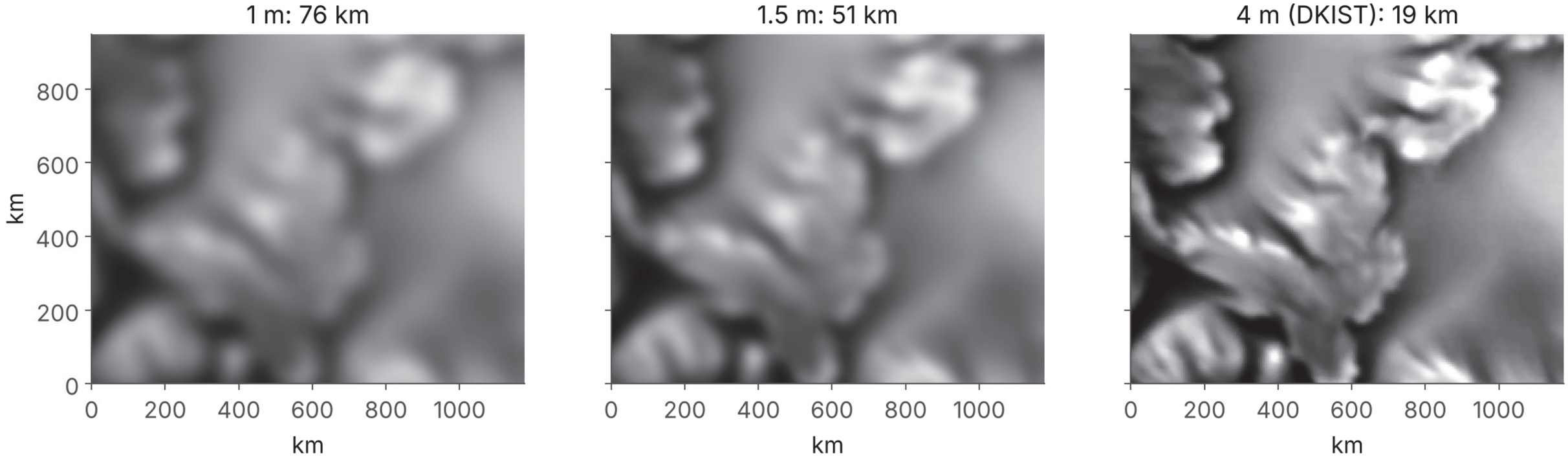




h

Parameter	Value
λ [km]	64.06
d [km]	--
v_{app} [km/s]	0.67
v_{ph} [km/s]	--
ΔU [km/s]	--
ρ_1/ρ_2	--
γ [s^{-1}]	0.054

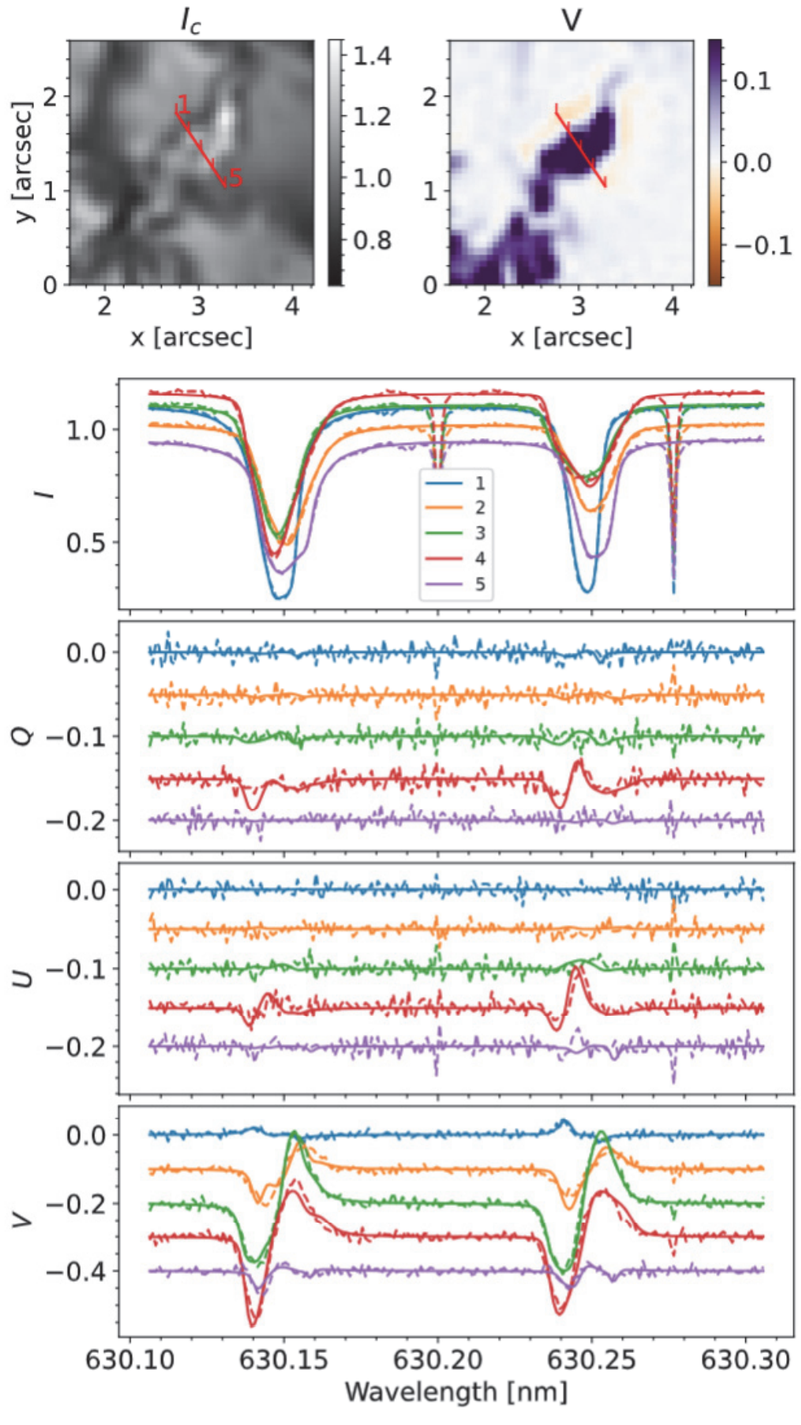
Why was this not seen before?



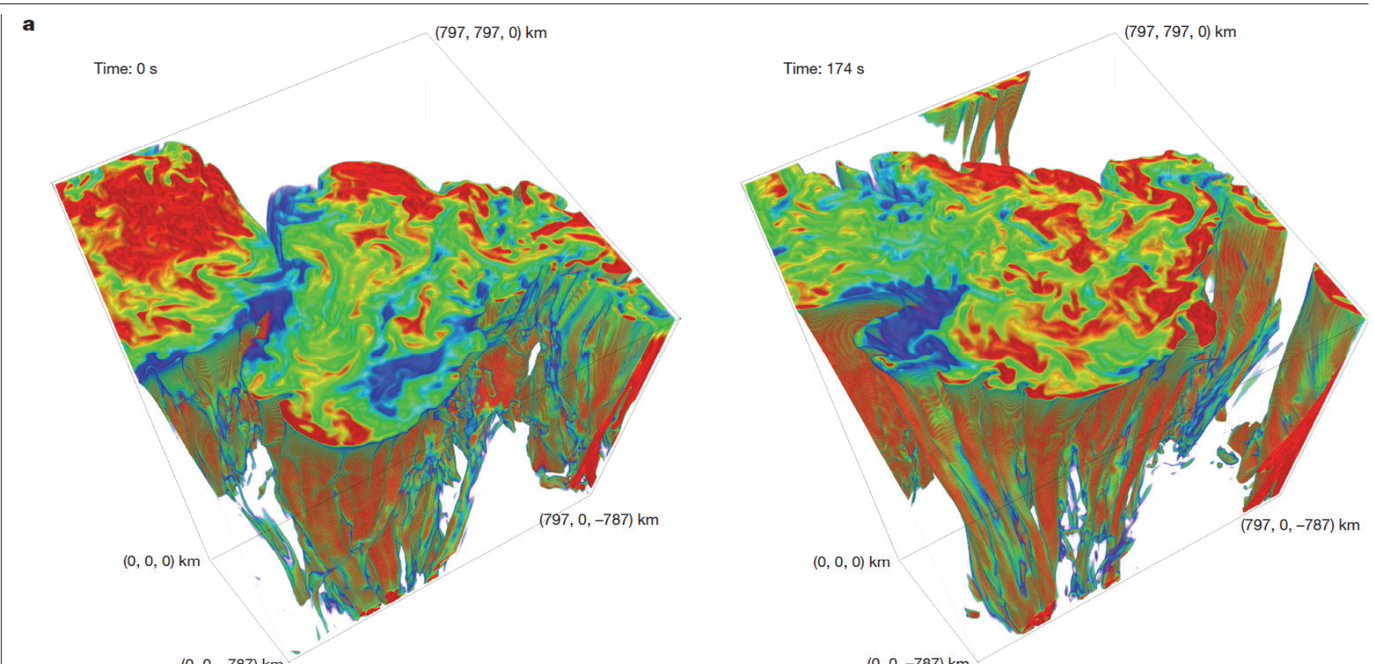
- A 1 m or 1.5 m telescope could not resolve it (example on the next page)
- To achieve the 4-m diffraction limit, we needed **PHOTONS**

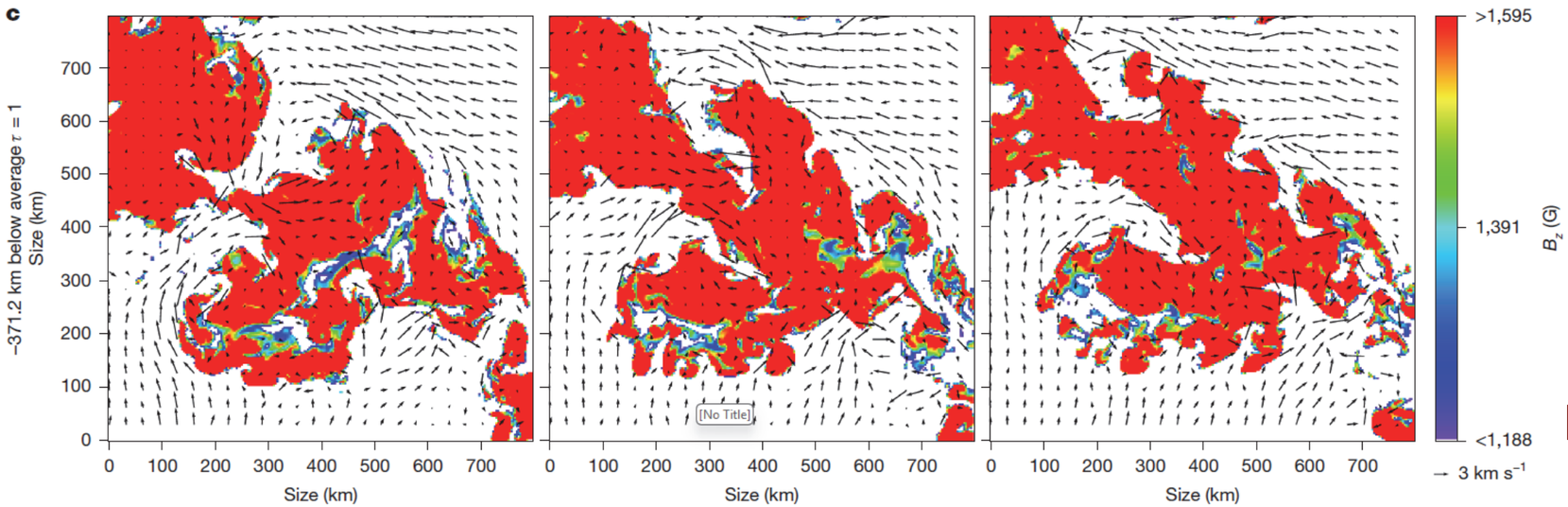
Example from a 1-m telescope

- This is a spectropolarimetric inversion using the FIRTEZ code (Borrero et al, 2019+), applied to:
- MiHI IFU (van Noort et al 2023+): simultaneous spatial and spectral information over a small patch of the solar atmosphere
- Inversion then yields variation of physical parameters in (x,y,z,t)
- This was the master's thesis of Gaojian Liu at the University of Freiburg (see also Liu et al, 202



Consequences



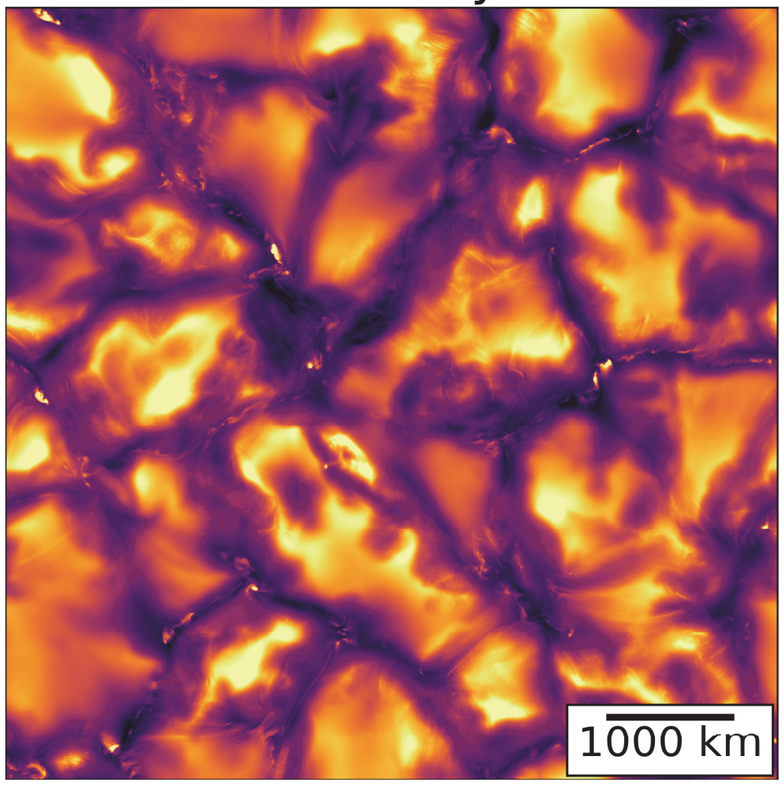


- Vertical rolls, ~100 to −400 km
- Stronger deeper → flux tubes split
- Mixing of magnetized and field-free plasma braids field lines → energy for the corona
- Reveals “striations", also near the disk center

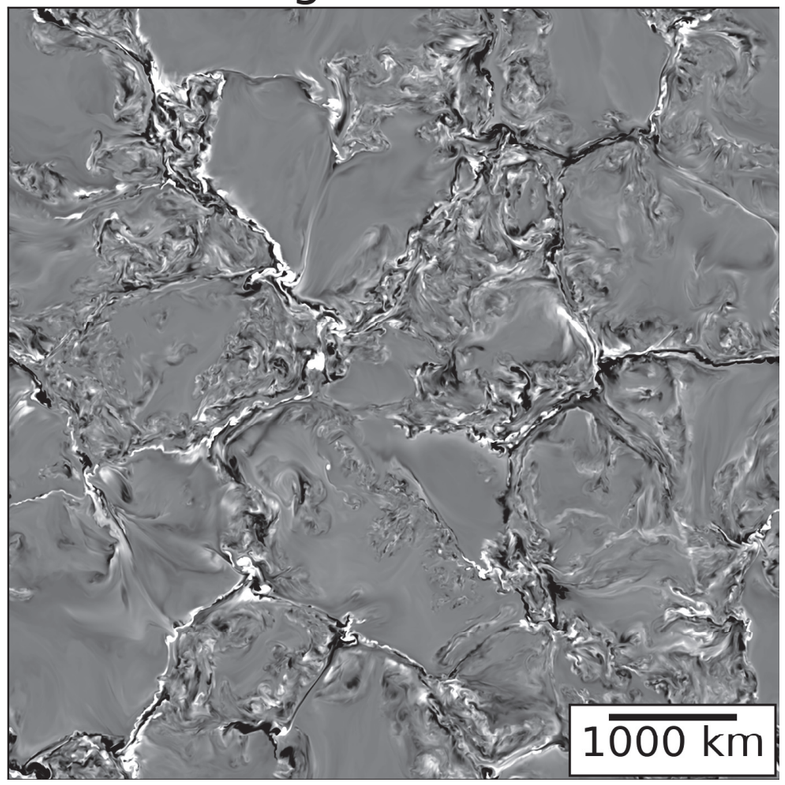
Kuridze, et al. 2026, Nature 656, 595

Now, what about even smaller-scale fields?

Intensity



Magnetic field

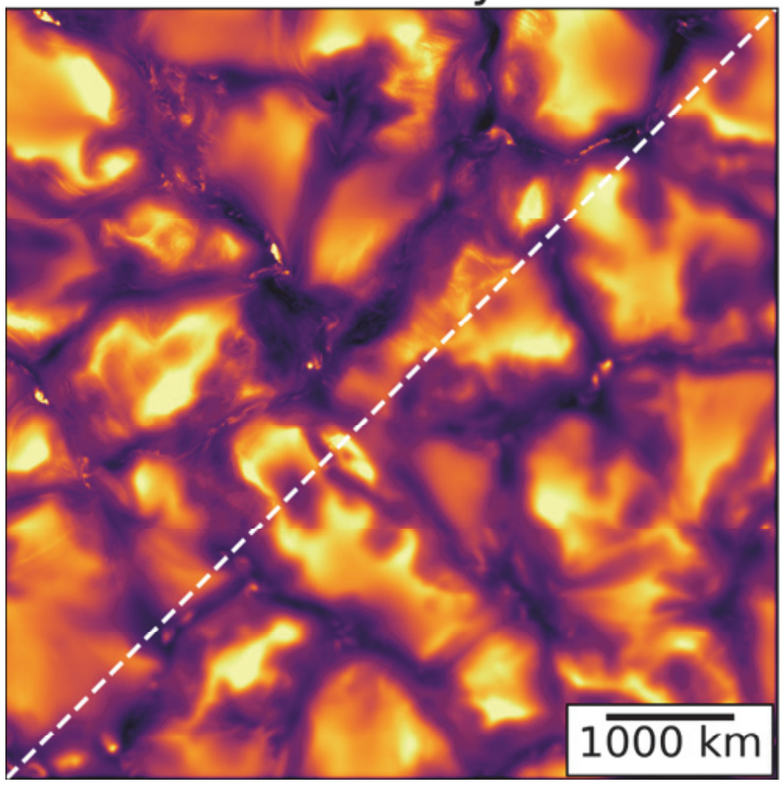


Quiet Sun simulation with MURaM code. 2km resolution

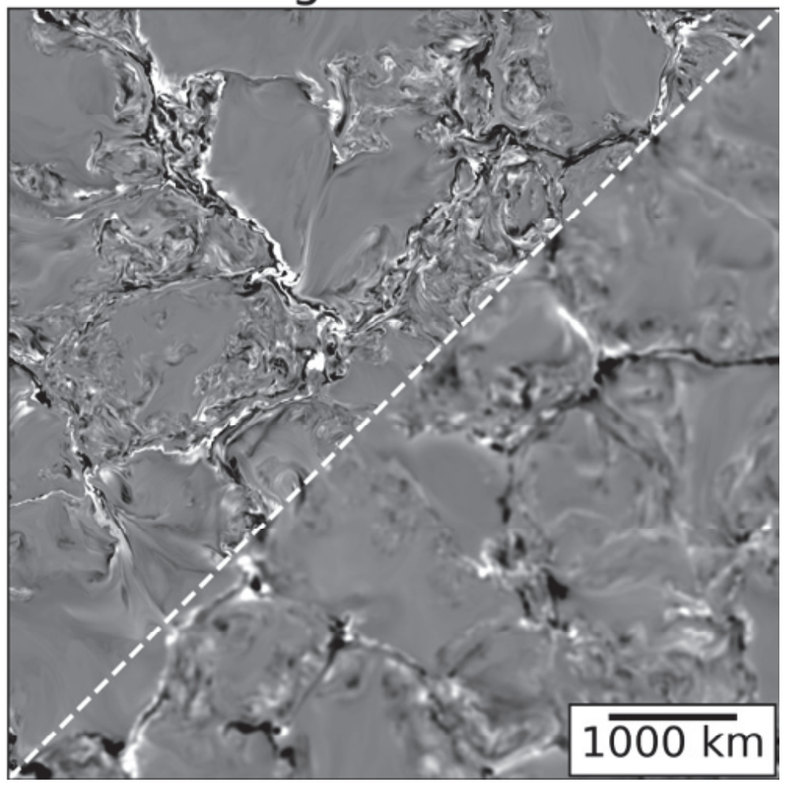
- Interaction between the magnetic field and plasma (small-scale dynamo) generates this tangled field.
- If you look carefully, you will see that this field affects the plasma, too. Measuring it is **paramount.**

They are notoriously hard to measure

Intensity



Magnetic field



As observed with 50 km resolution

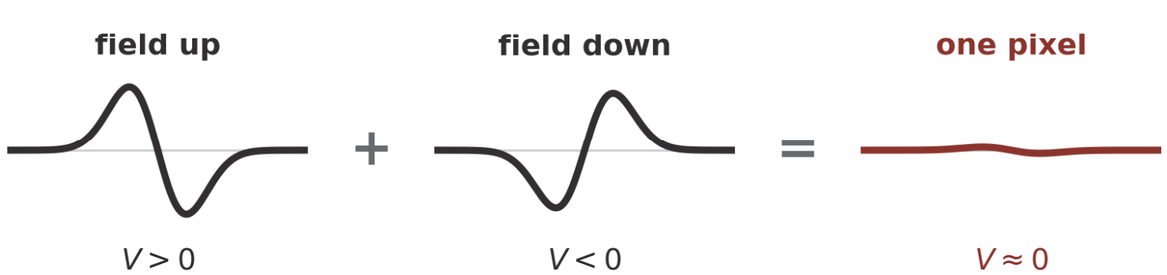
- Even with the very optimistic resolution, **half of the magnetic energy cannot be detected.**
- It is very hard to achieve even this resolution (remember the noise?)

Alternative diagnostics is needed!

Zeeman diagnostics for the weak fields:

$$V \approx k \times \frac{dI_\lambda}{d\lambda} B_z$$

Circular polarization flips sign with the field direction



Problem:
The magnetic energy is “invisible”

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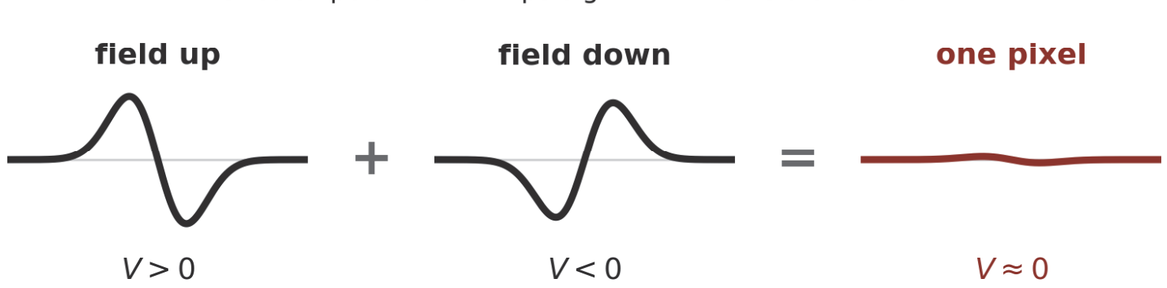
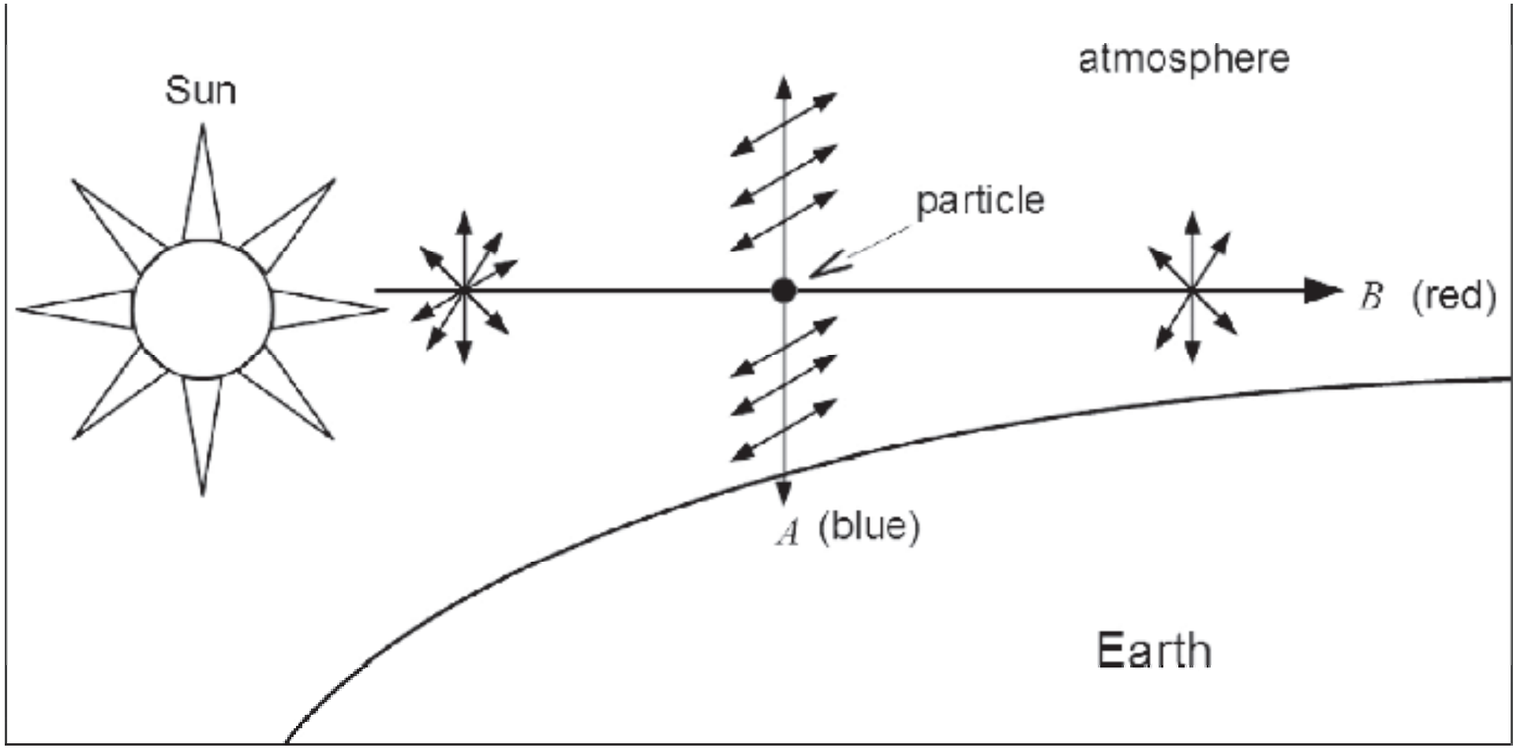


Problem:
The magnetic energy is “invisible”

Since 1993, we have been thinking of the Hanle effect. Change in linear **scattering polarization** due to the Magnetic field.

Solution: Hanle depolarization is sensitive to the sub-pixel fields.

Scattering polarization: the blue sky



$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \frac{r_c^2}{2R^2} \begin{pmatrix} 1+\cos^2\Theta & \sin^2\Theta & 0 & 0 \\ \sin^2\Theta & 1+\cos^2\Theta & 0 & 0 \\ 0 & 0 & 2\cos\Theta & 0 \\ 0 & 0 & 0 & 2\cos\Theta \end{pmatrix} \begin{pmatrix} I' \\ Q' \\ U' \\ V' \end{pmatrix}$$

Rayleigh scattering matrix, Θ = scattering angle

- Sunlight comes from one direction
- Scattered at 90° → fully linearly polarized
- $Q/I = \sin^2\Theta / (1 + \cos^2\Theta)$
- Forward / backward: no polarization
- Check it with sunglasses or a polarizing filter for a camera

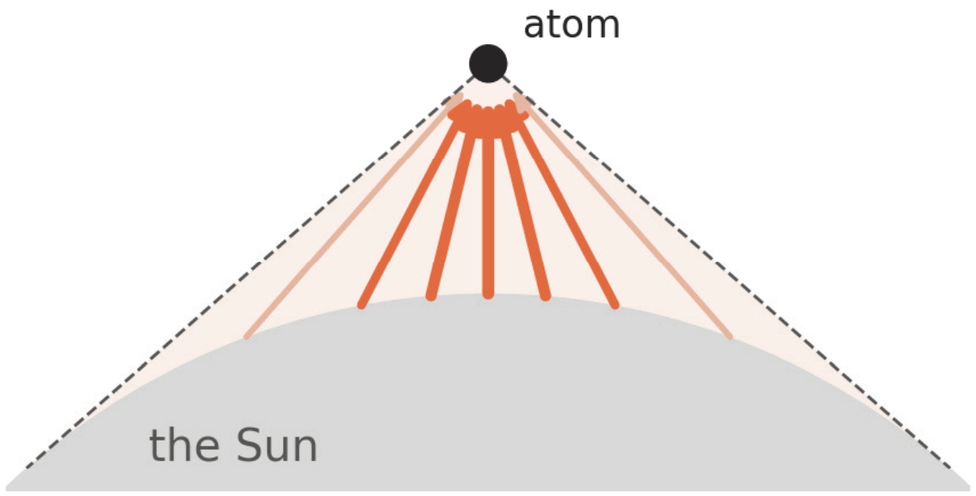
What happens if we put the slab close to the solar surface?

The Sun is not a point source anymore, and the light will come from the whole hemisphere

What happens if we put the point close to the solar surface?

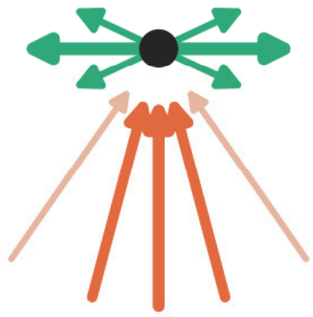
Incoming light is a cone

to observer
(out of the screen)



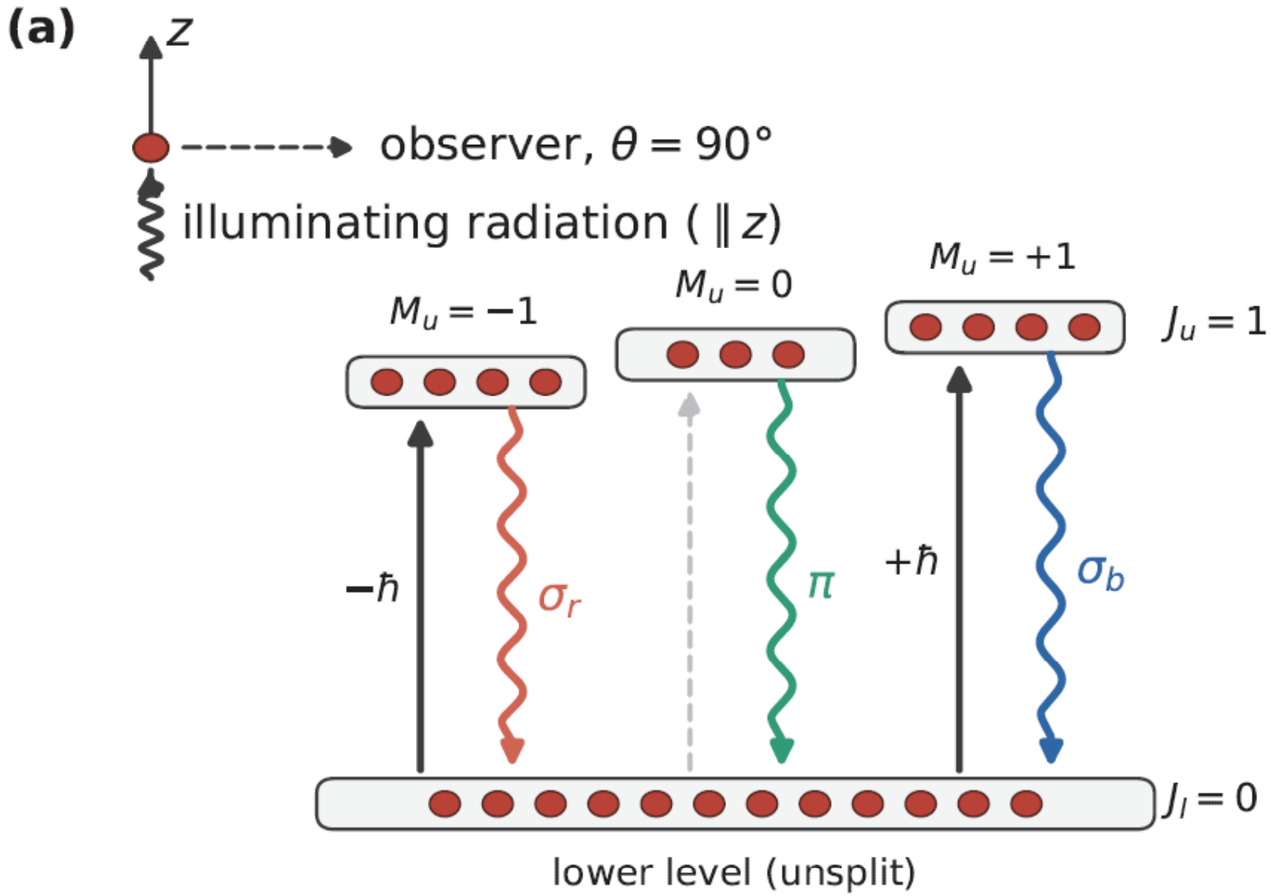
what the atom sees

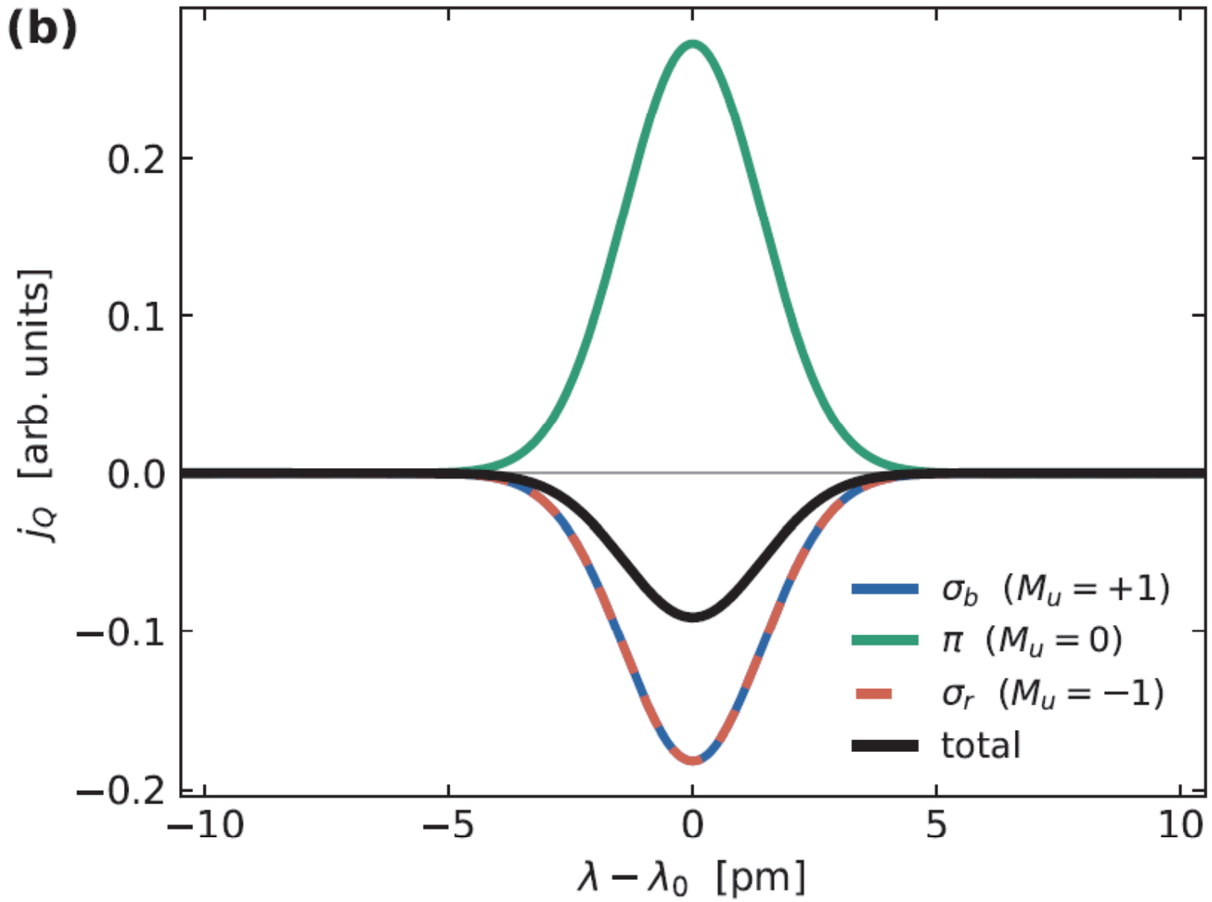
polarized ∥ limb
|Q| < I



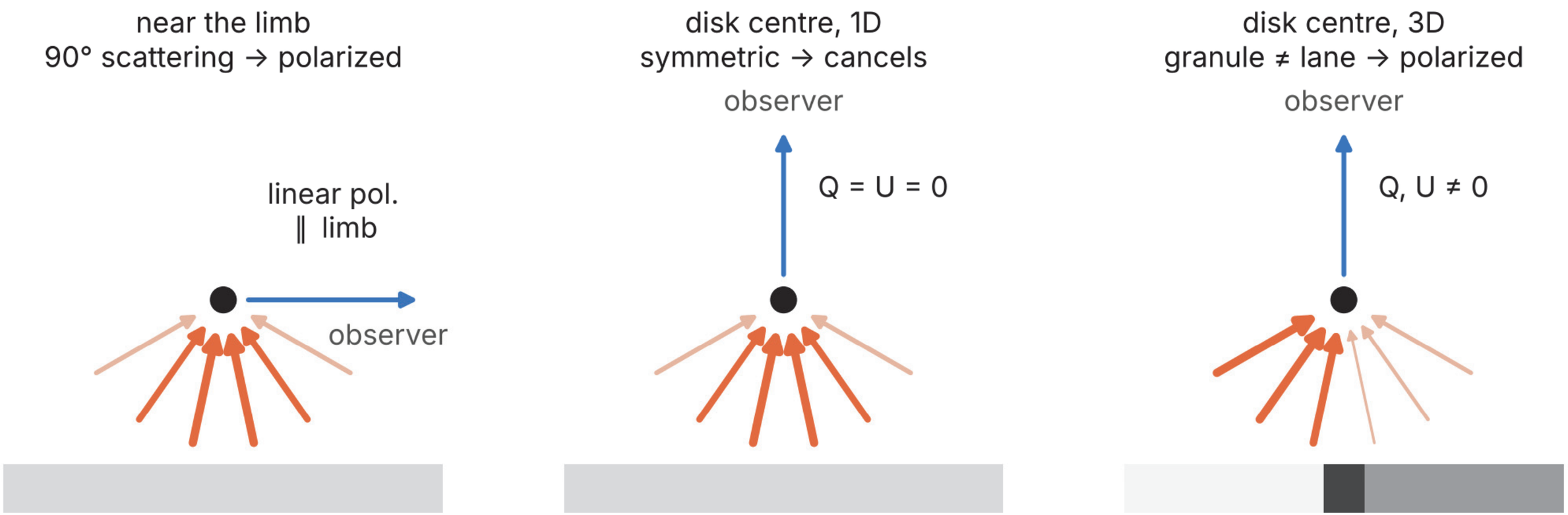
- Anisotropic light from below (limb darkening)
- Seen from the observer: polarized ∥ limb

Scattering polarization on atomic level



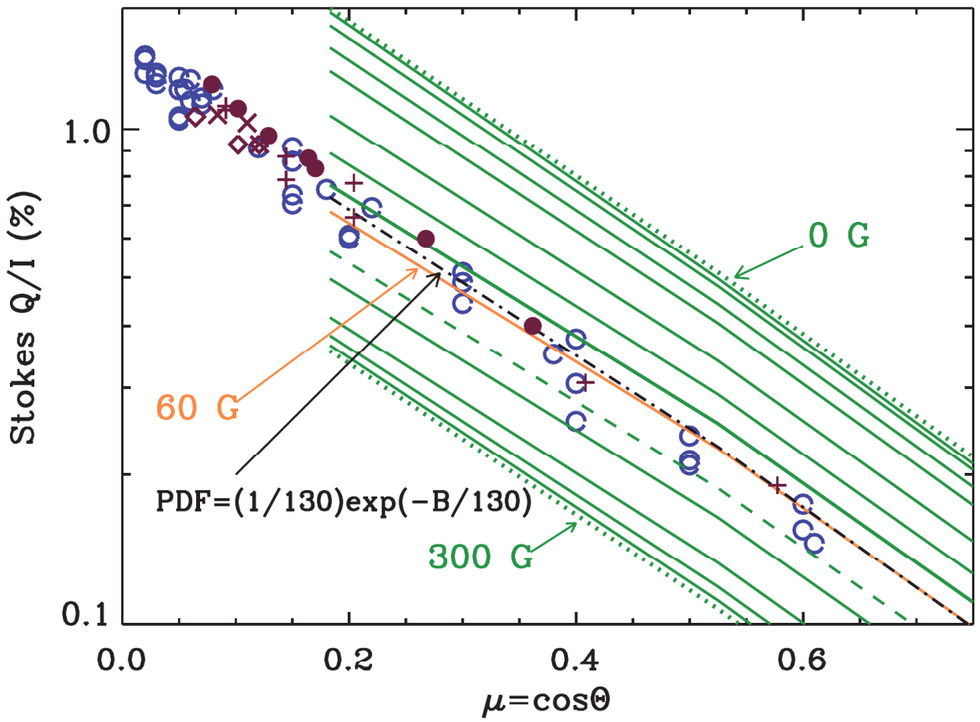


Scattering polarization: vertical vs horizontal anisotropy



- Anisotropic light creates polarized scattered light
- This means that we need to observe a spectral line that is formed by scattering
- An example of this is 460.7 nm line of neutral strontium

Hanle effect so far: spatially averaged signals



Sr I 4607 Å; lines: 3D model, 0–300 G (Trujillo Bueno et al. 2004)

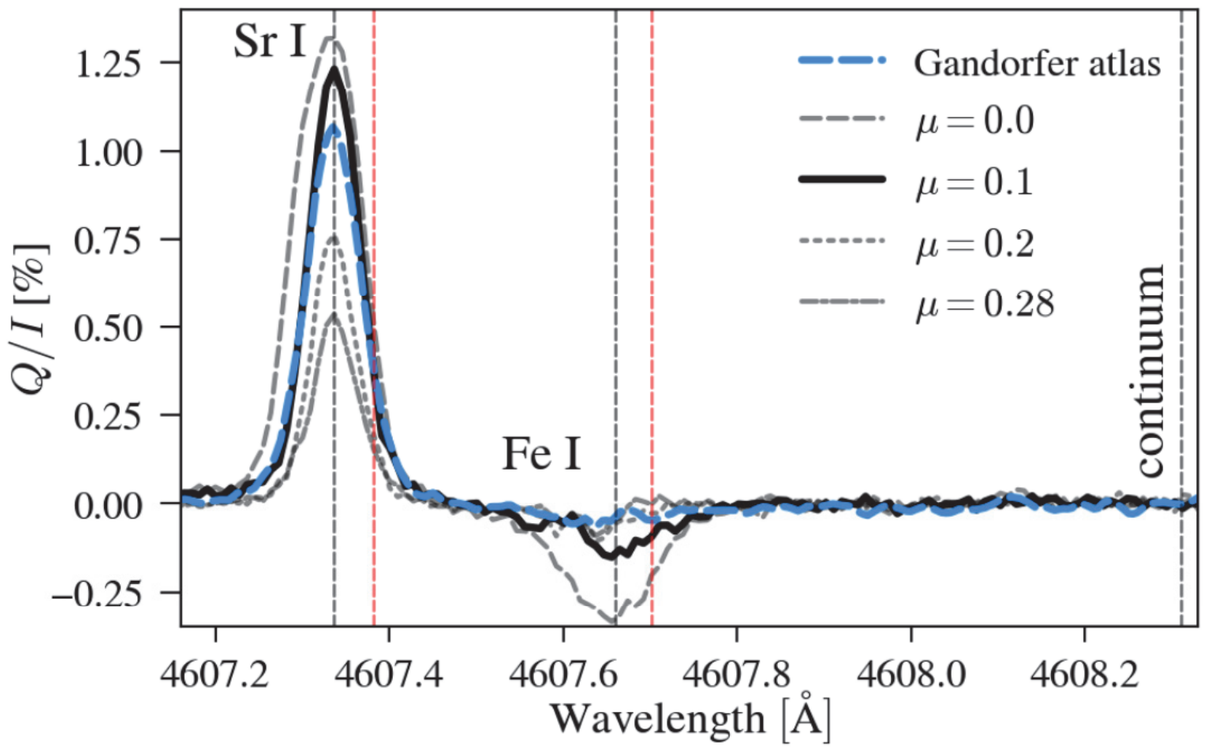
1D models (Faurobert-Scholl 1993, 1995)

- Observed centre-to-limb variation of Q/I
- vs. zero-field Q/I in a 1D atmosphere
- ⟨B⟩ ~ 10-50 G

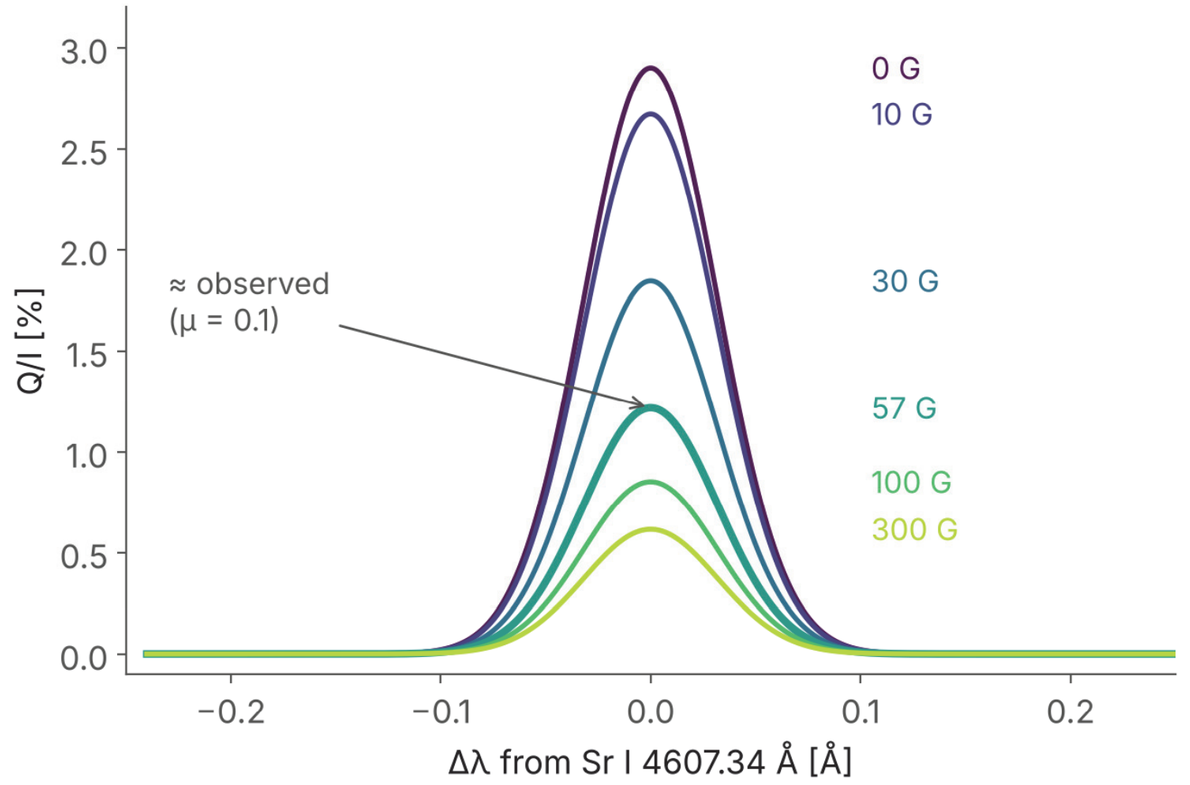
3D model (Trujillo Bueno et al. 2004)

- Zero-field Q/I from a 3D simulation
- Observed ≈ 0.4 × zero field
- ⟨B⟩ ≈ 130 G: a large energy reservoir
- This assumes exponential PDF of the field

How does Hanle diagnostics work?

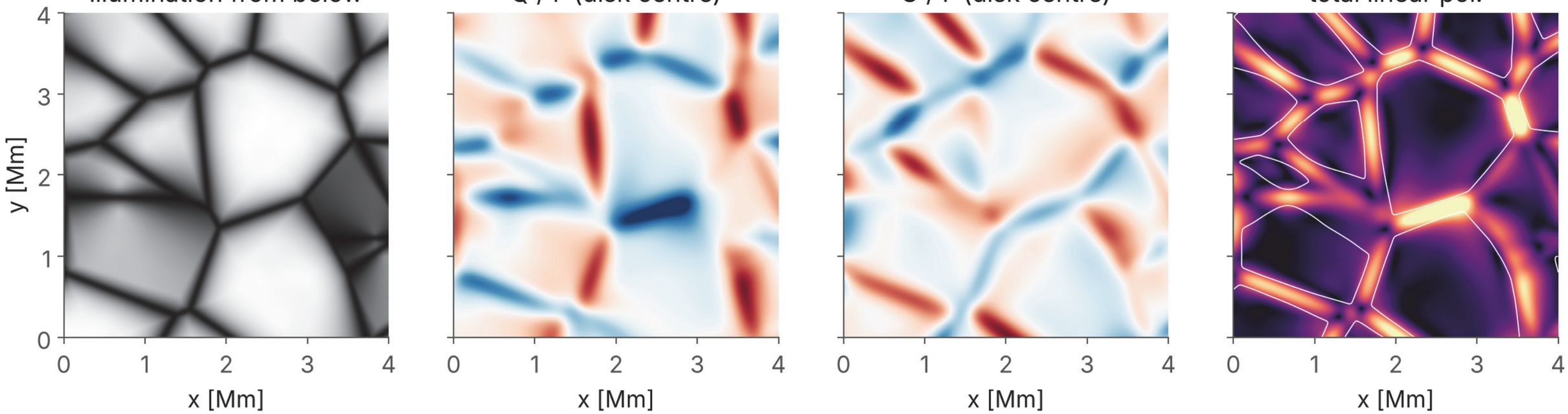


Sr I 4607 Å, observed Q/I near the limb, DKIST/ViSP (Zeuner et al. 2026, Fig. 3)



Same line for different tangled fields (single scattering, B_H ≈ 47 G; schematic)

Disk center: anisotropy in granules will create polarization

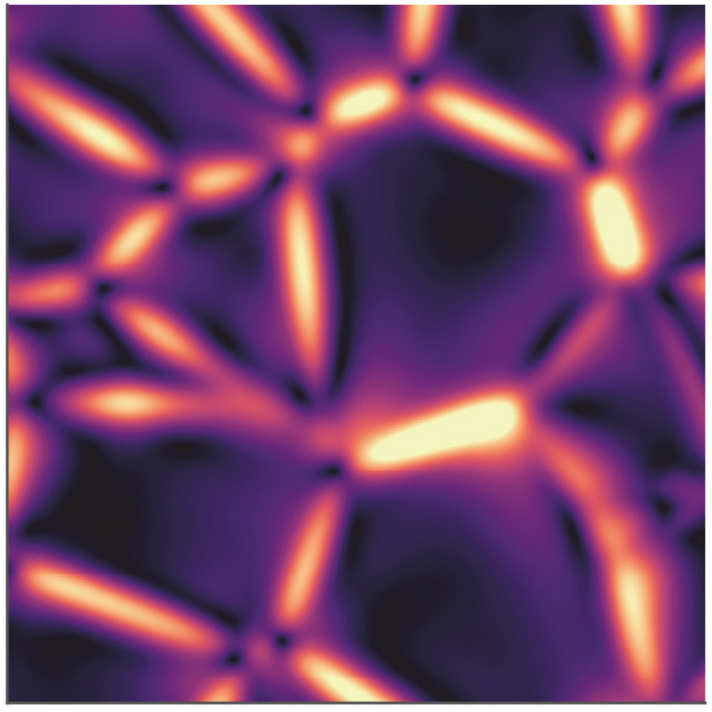


- Q, U: both signs, mean ≈ 0
- Strongest at granule edges
- Also: horizontal velocity gradients
- Interpretation needs 3D transfer

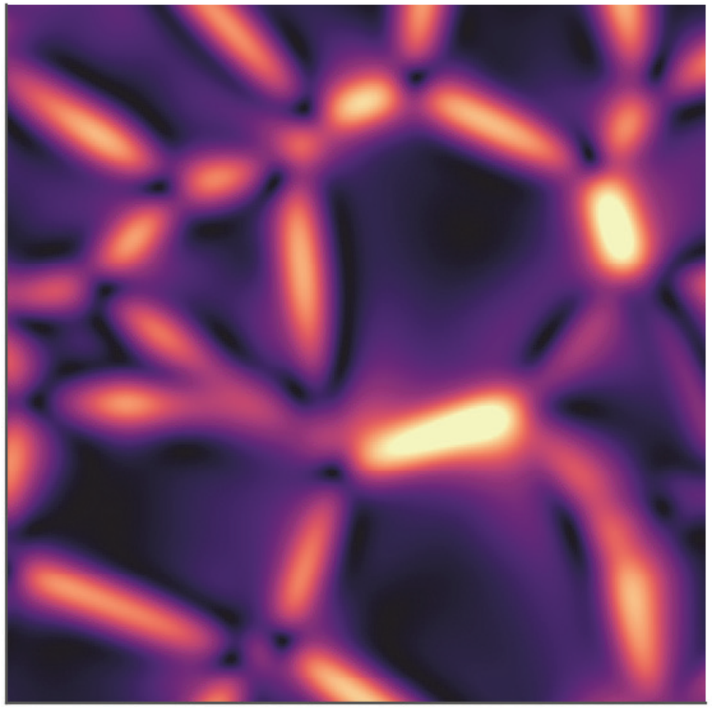
Toy model: atom 150 km above a granular surface, illuminated from below and from the sides

Magnitude is very sensitive to the resolution

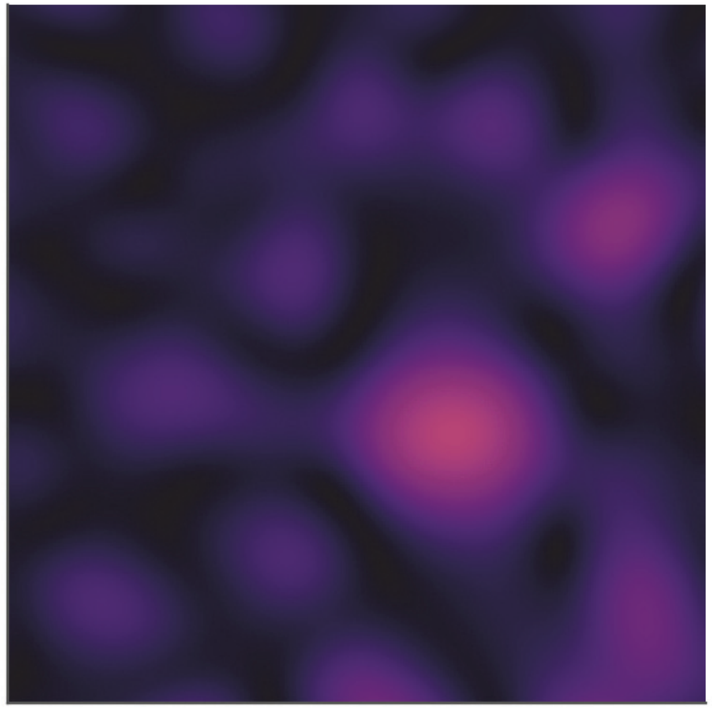
total lin. pol., resolved



total lin. pol., 0.2"

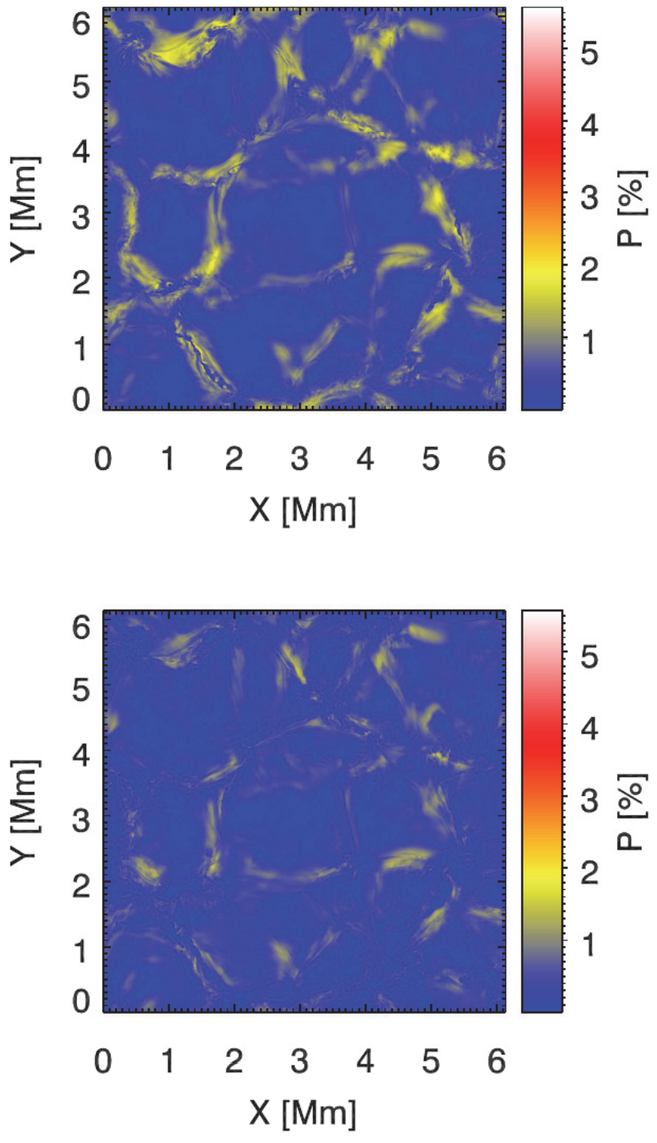


total lin. pol., 1"



> Spatial fluctuations need to be ≪ 0.5" (del Pino Alemán et al. 2018)

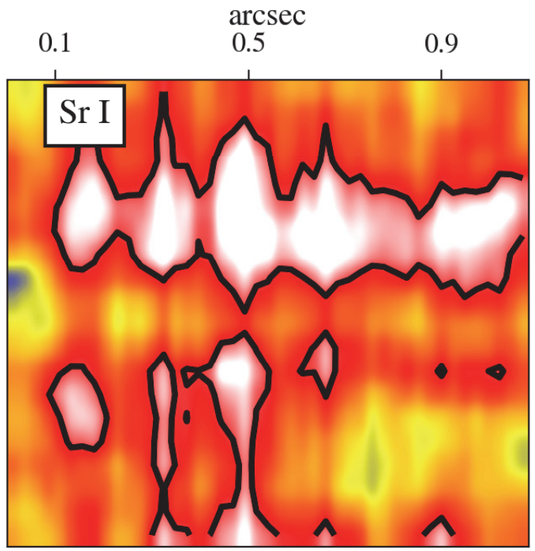
Prediction: full 3D radiative transfer

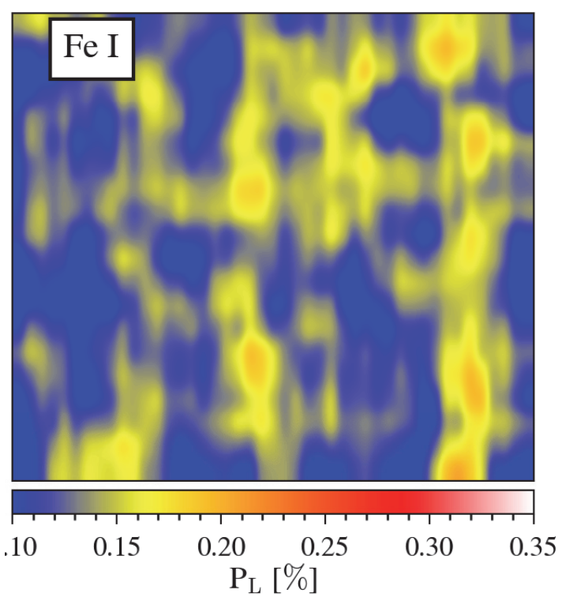


- Sr I 460.7 nm in a MURaM model, 8 km resolution
- Zero field: up to ~2% at granule edges
- Hanle: depolarization ~×2
- Spatial average → 0 at disk centre
- Fluctuations: magnetically sensitive
- Decrease in spatial resolution quickly destroys this

del Pino Alemán et al. 2018, ApJ 863, 164

First resolved maps: DKIST/ViSP



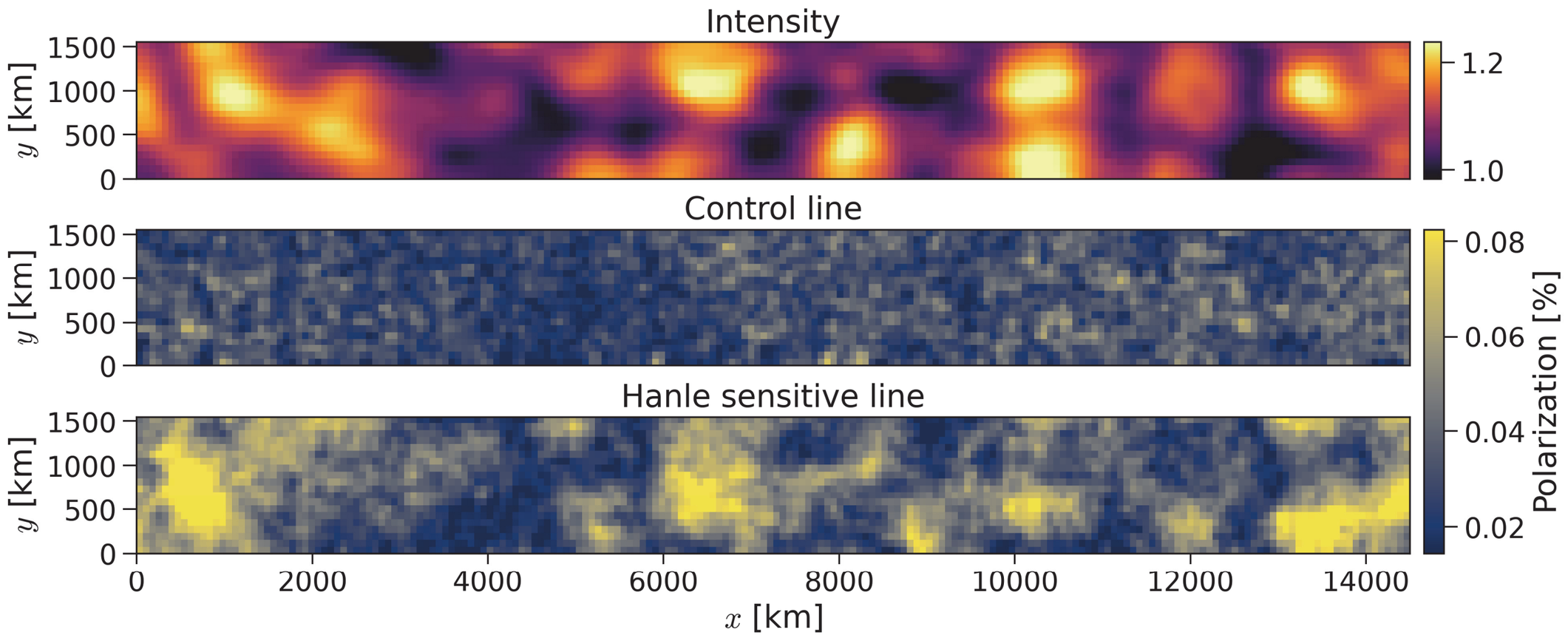


- μ = 0.74, ~0.2", 30 s per slit step
- Sr I polarized, Fe I not → scattering
- Noise ~0.1%, peaks ~0.4%
- Disk centre: still noise-dominated

Photon-starved
< 1% of the field of view at S/N > 4 in the polarization

Zeuner et al. 2025, A&A 703, L10; Zeuner et al. 2026, A&A 708, A97

New: resolved signals at disk centre



- DKIST/ViSP, July 2026, Sr I 460.7 nm at disk centre
- Structure above the noise; control line flat(ter?)

Preliminary

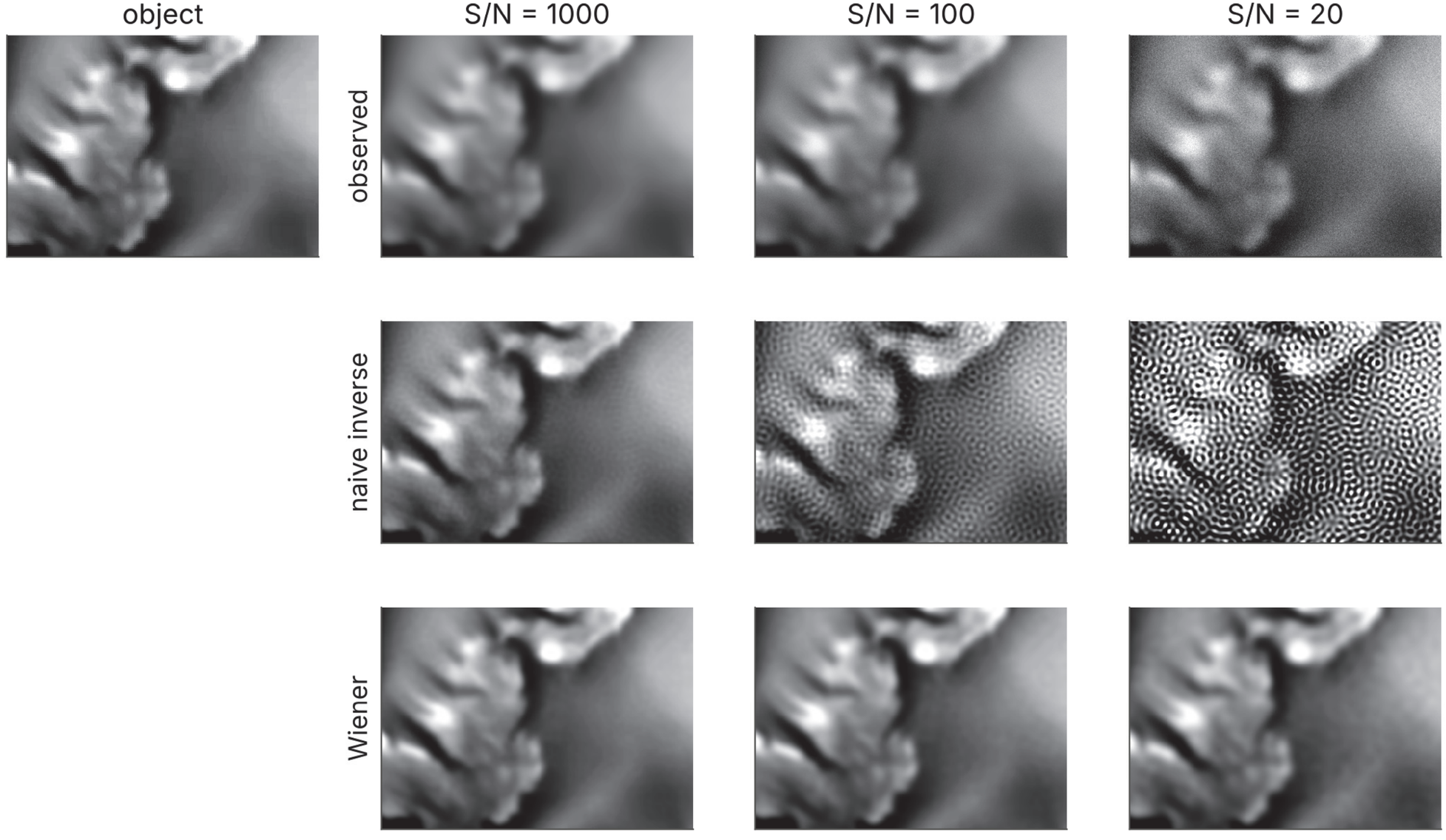
Comparison between the two observations:

	Microscope (KHI)	Photon bucket (Sr I)
Signal	contrast ~10–20%	polarization ~0.1%
Band	0.5 nm	~0.01 Å
Exposure	100 μs × 2000	seconds per slit step
Resolution	19 km	~150 km (0.2")
Limited by	optics, seeing	photons, solar evolution

Common idea:
The Sun is a plasma laboratory where we can see the physical processes at scales that we will not reach in other stars for decades to come.

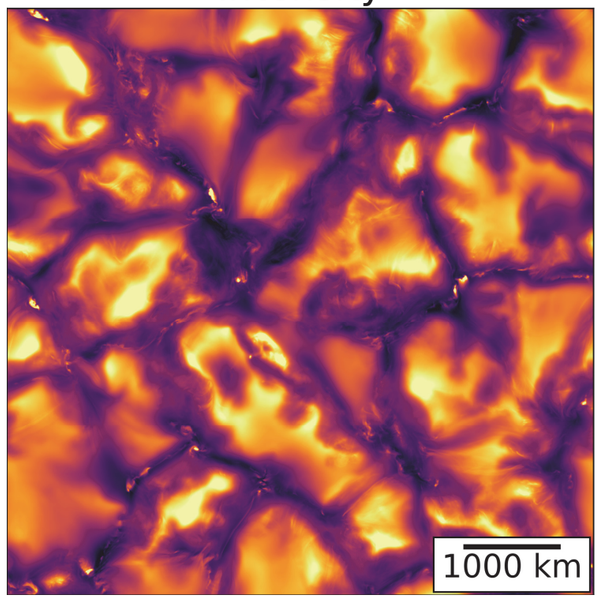
Questions? Critique? comments?

Same test on a real DKIST scene

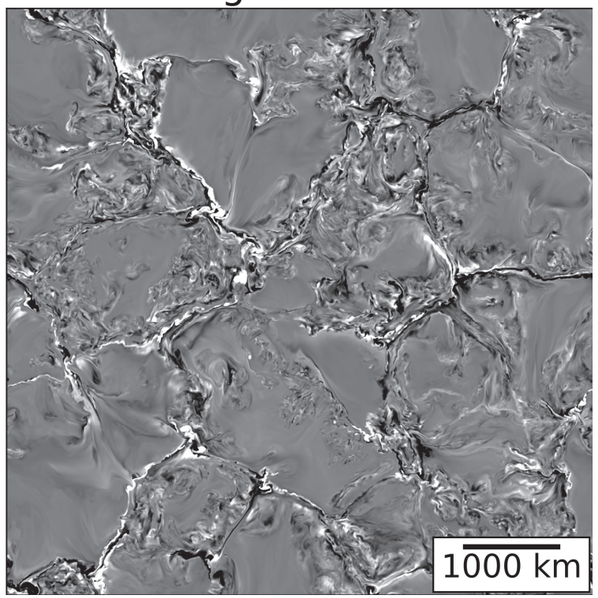


The Sun up close

Intensity

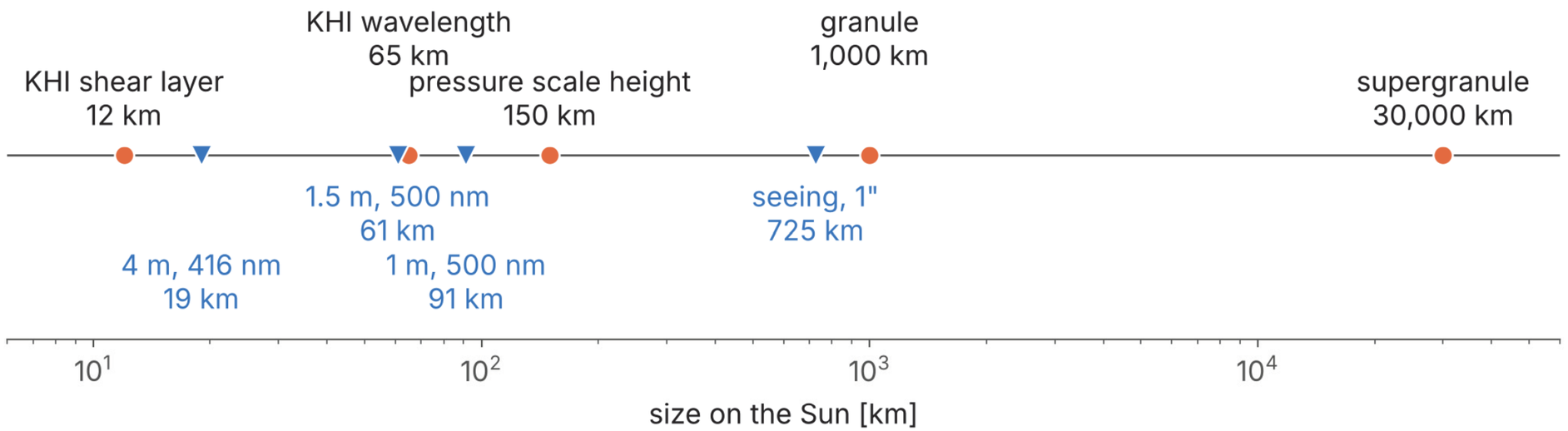


Magnetic field



- 1" ≈ 725 km
- Granules: ~1000 km, ~10 min
- Magnetic structure: ≪ 100 km
- Seeing: ~1"

Quiet Sun, MURaM simulation



Many short frames → one sharp image

1 frame (S/N 20)

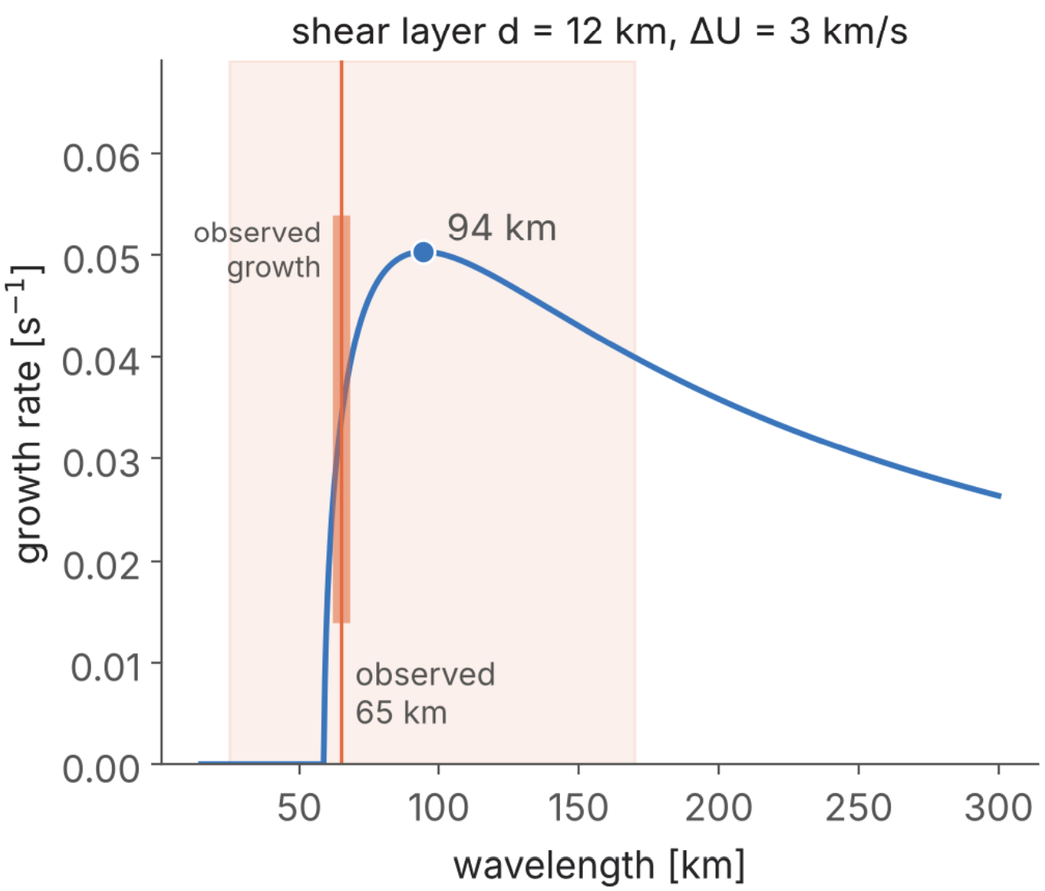
25 frames (S/N 100)

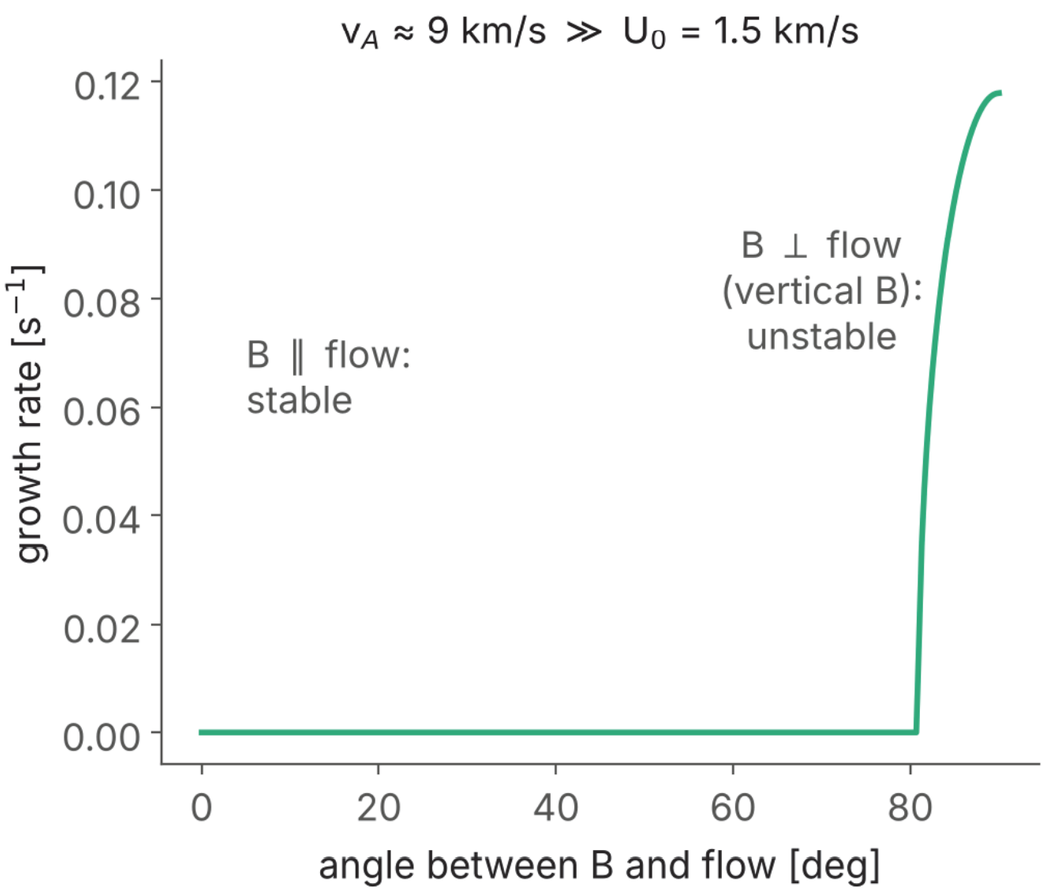
2000 frames (S/N 894)

- 740 frames/s, 100 µs each
- Focused + defocused image
- 2000 frames → 1 image / 2.7 s

- Multi-frame blind deconvolution
- 6 km pixels
- 19 km: diffraction limit at 416 nm

Linear theory with solar numbers

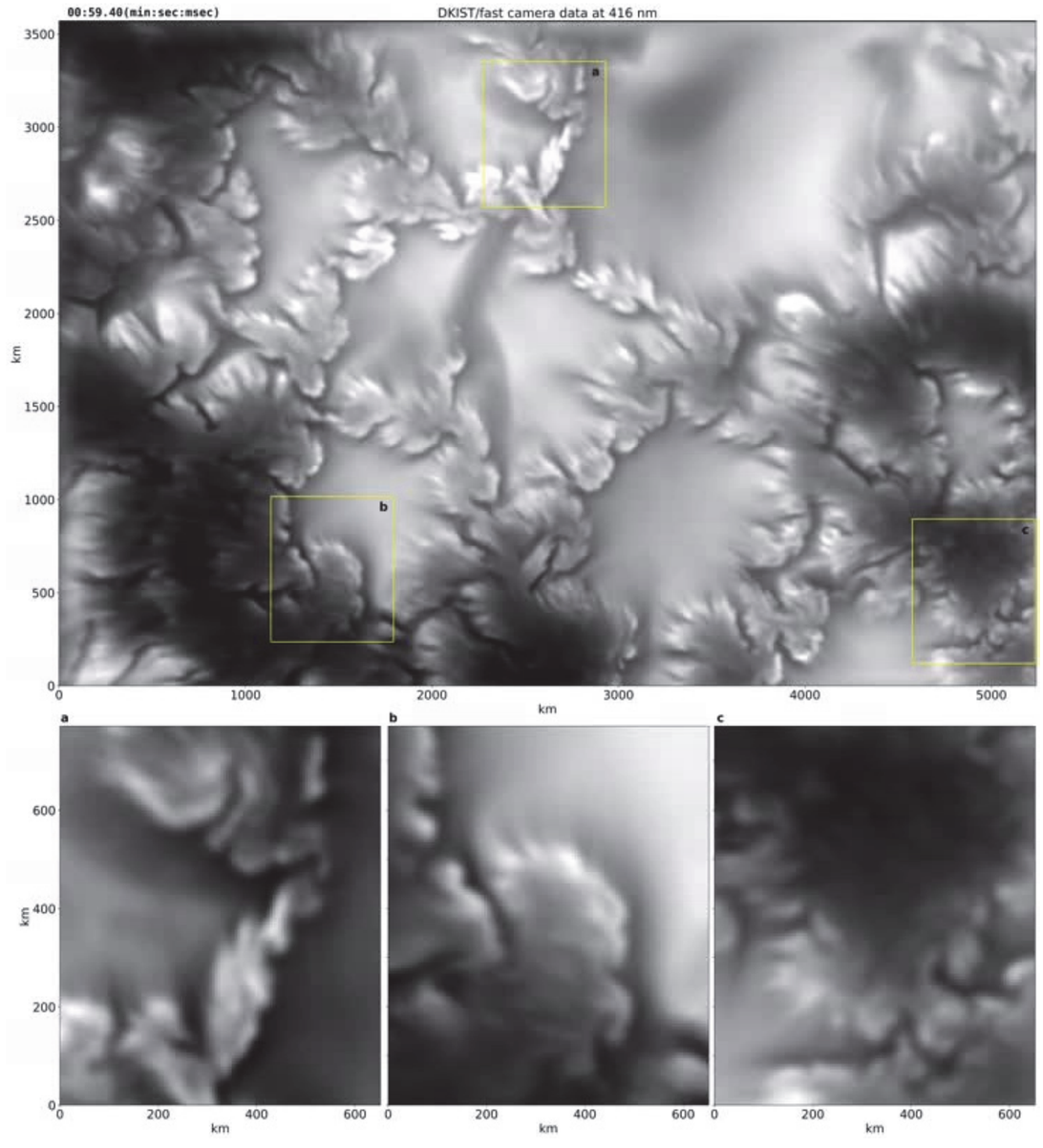




- Fastest λ ≈ 8 × shear-layer thickness; e-folding ≈ 20 s
- Strong field, but vertical: ⊥ to the shear → no stabilization

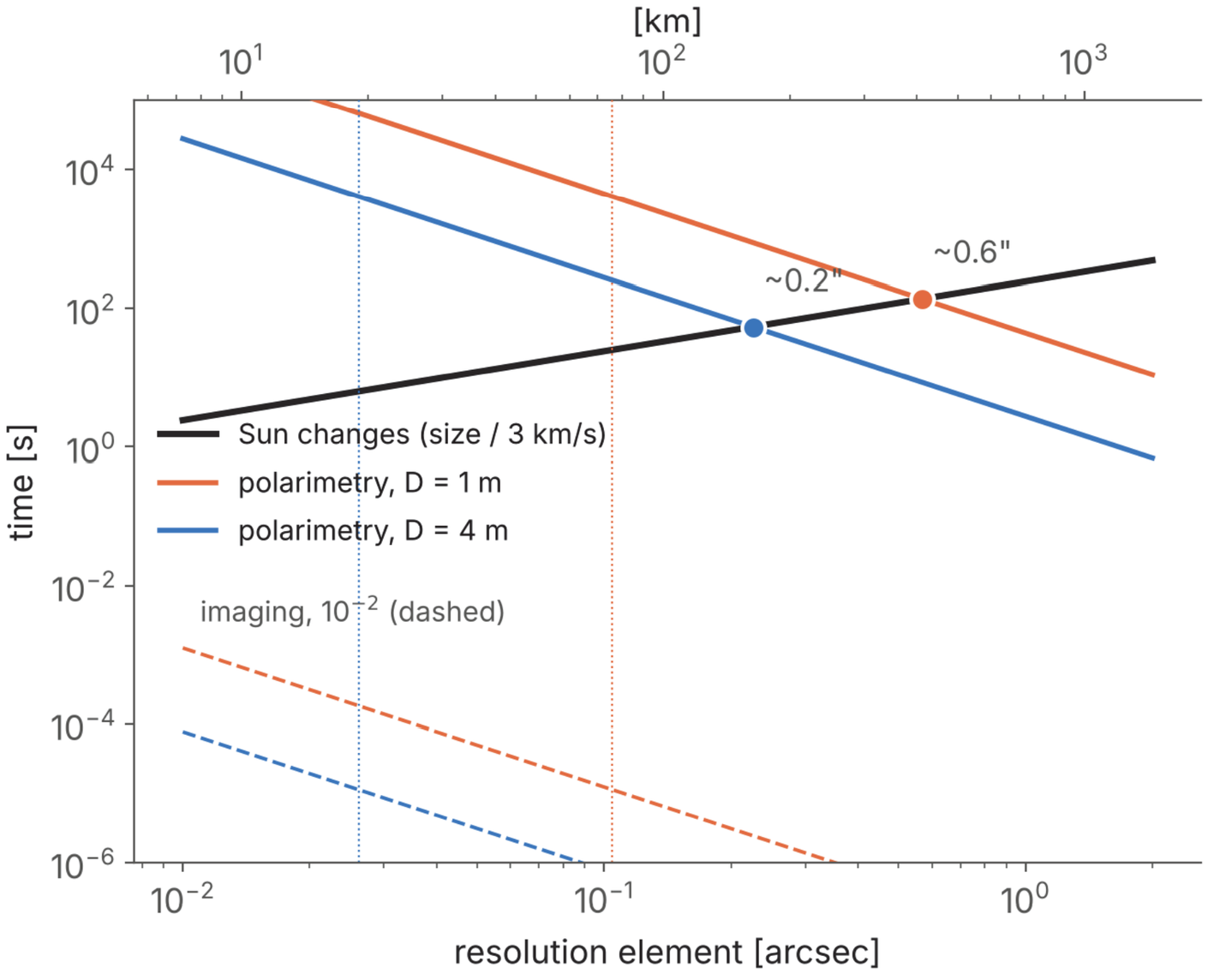
DKIST: vortices at every magnetic boundary

- Pores near an active region
- 416 nm, 0.5 nm filter, 3 min
- Vortices along magnetic edges
- λ ≈ 65 km (25–170 km)
- Growth 0.01–0.05 s^{-1}
- Reproduced by MURaM (3 km grid)



Kuridze, Wöger et al. 2026, Nature 656, 595 (Suppl. Video 1)

Photon budget



- Photons per diffraction element ∝ λ², not D
- Fixed 0.2": 4 m gets 16× more
- Imaging, 19 km: ~10 μs
- Polarimetry 10^{-4}: ~1 min at 0.2"
- Finest scale ∝ D^(−2/3)