Future Directions of Magnetic Field Measurements

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Outline

- Key Science Questions
- Key Observations
- Key Measurements
- Key Problems and Possible Solutions

Key Science Questions

- How is magnetic flux generated?
- How is magnetic flux removed?
- How is energy transported and transformed?

Key Observations

- magnetic field and its connectivity
- velocity field
- temperature, density, composition

all from below the photosphere to the corona and beyond as a function of time at spatial and temporal resolutions compatible with the underlying physical processes

Key Measurements

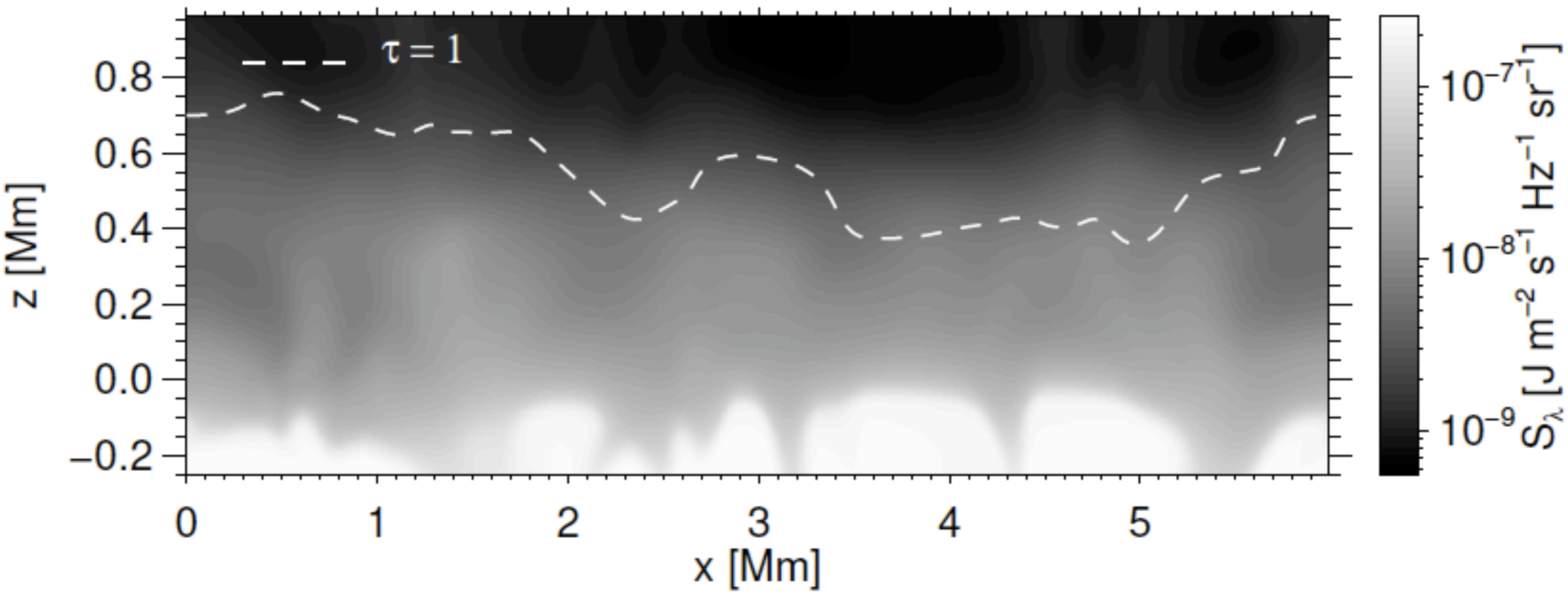
- Sound speed and velocity vector fields in the solar interior → helioseismology
- Sensitive, precise photospheric magnetic and velocity vector field measurements → spectropolarimetry
- Sensitive and precise chromospheric magnetic and velocity vector field measurements → spectropolarimetry
- Coronal magnetic and velocity vector fields → spectroscopy, spectropolarimetry, radio, extrapolations
- Temperature, density, composition from photosphere to corona → spectroscopy

Key Problem 1: Where

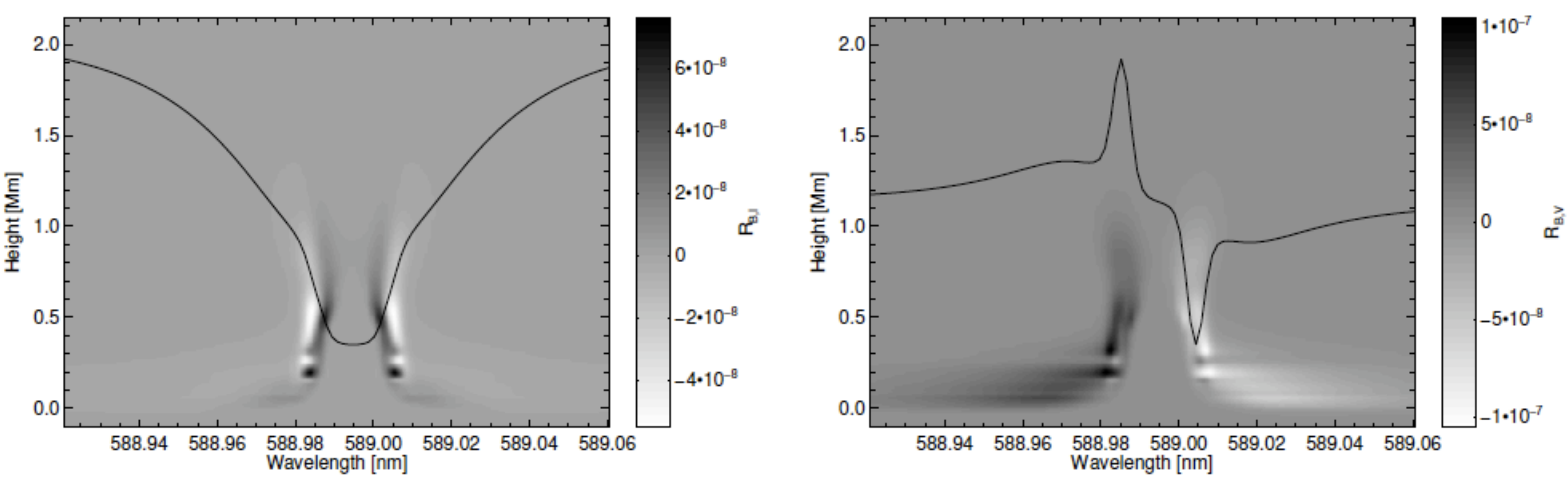
Want to measure magnetic fields in a volume, but not easy to know where we measure

- optically thick → 2-D (corrugated) ‘surface’
- optically thin → integral along line of sight
- response functions with respect to magnetic field may not be what one wants
- → spatial derivatives of magnetic field incorrect

Na I D_1 optical depth unity (Uitenbroek 2006)



Na I D_2 response function to B (Uitenbroek 2006)

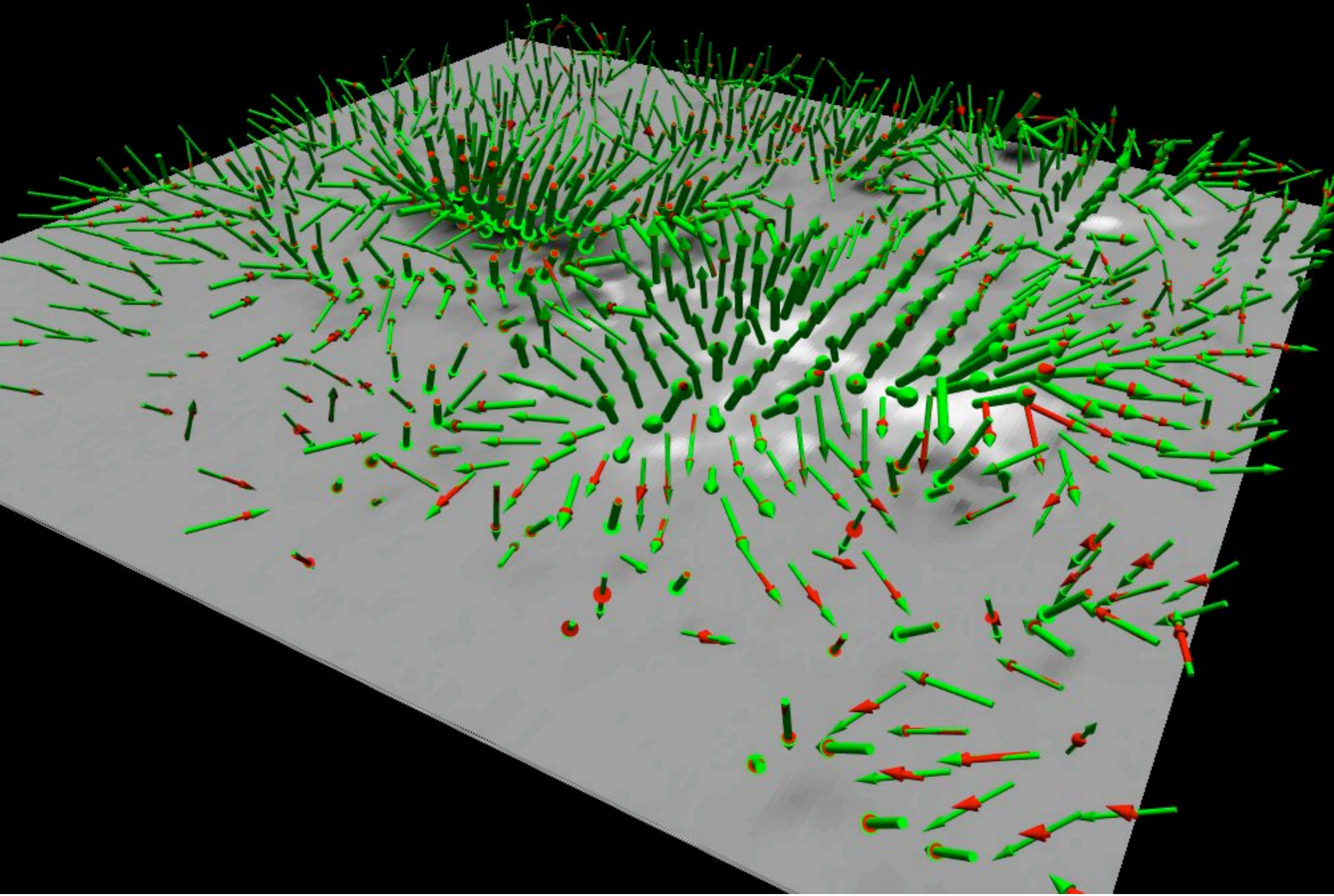


Possible Solutions I

- translate between optical depth at different wavelengths and geometrical height
- empirical 3-D models with physical constraints (semi-empirical) that reproduce all measurements
- observe with different lines of sight (stereoscopy)

Key Problem 2: Filling Factor

- filling factor α, field strength B, inclination γ:
  - Stokes V ~ α B cos γ (line of sight flux)
  - Stokes Q, U ~ α B^2 $\sin^2 \gamma$
- '3 unknowns, 2 equations'
  - difficult to distinguish between α and B
  - influences inclination determination
  - proportionality influenced by temperature



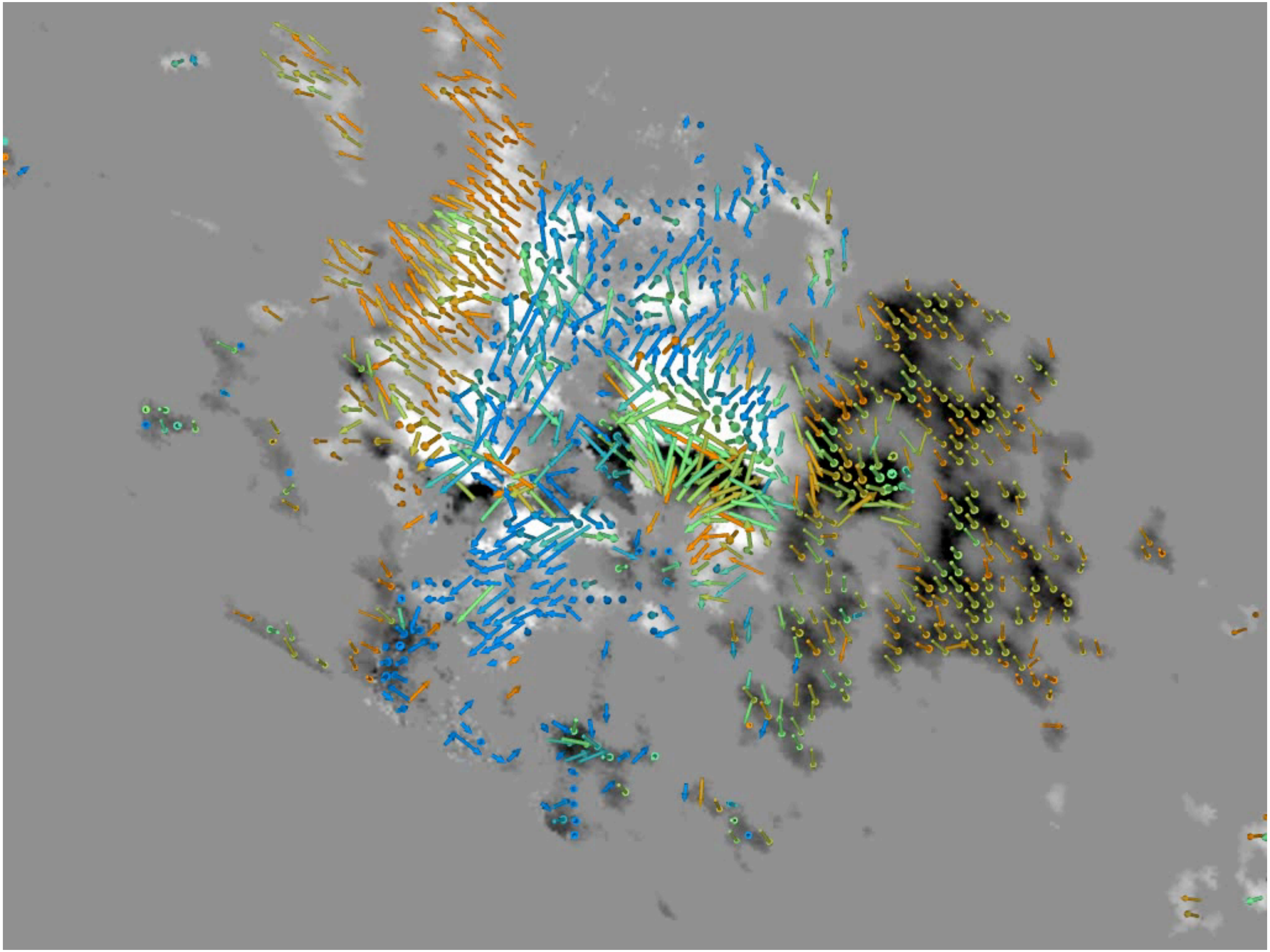
Input **ME-Inversion**

Possible Solutions 2

- be aware of limitations in derived magnetic field vector maps
- go to infrared where Zeeman effect is larger → precise vectors at smaller field strengths
- use several (>2) spectral lines
- use different mechanism of spectral line polarization: Zeeman, Hanle, hyperfine structure

Key Problem 3: 180° Ambiguity

- linear polarization cannot distinguish between transverse component with opposite directions
- cannot solve it in ‘interesting’ regions



SOLIS/VSM, inversion courtesy Catherine Fischer

Possible Solutions 3

- observe at several heights to see geometrical changes
- observe with different lines of sight (stereoscopy)
- make use of temporal information

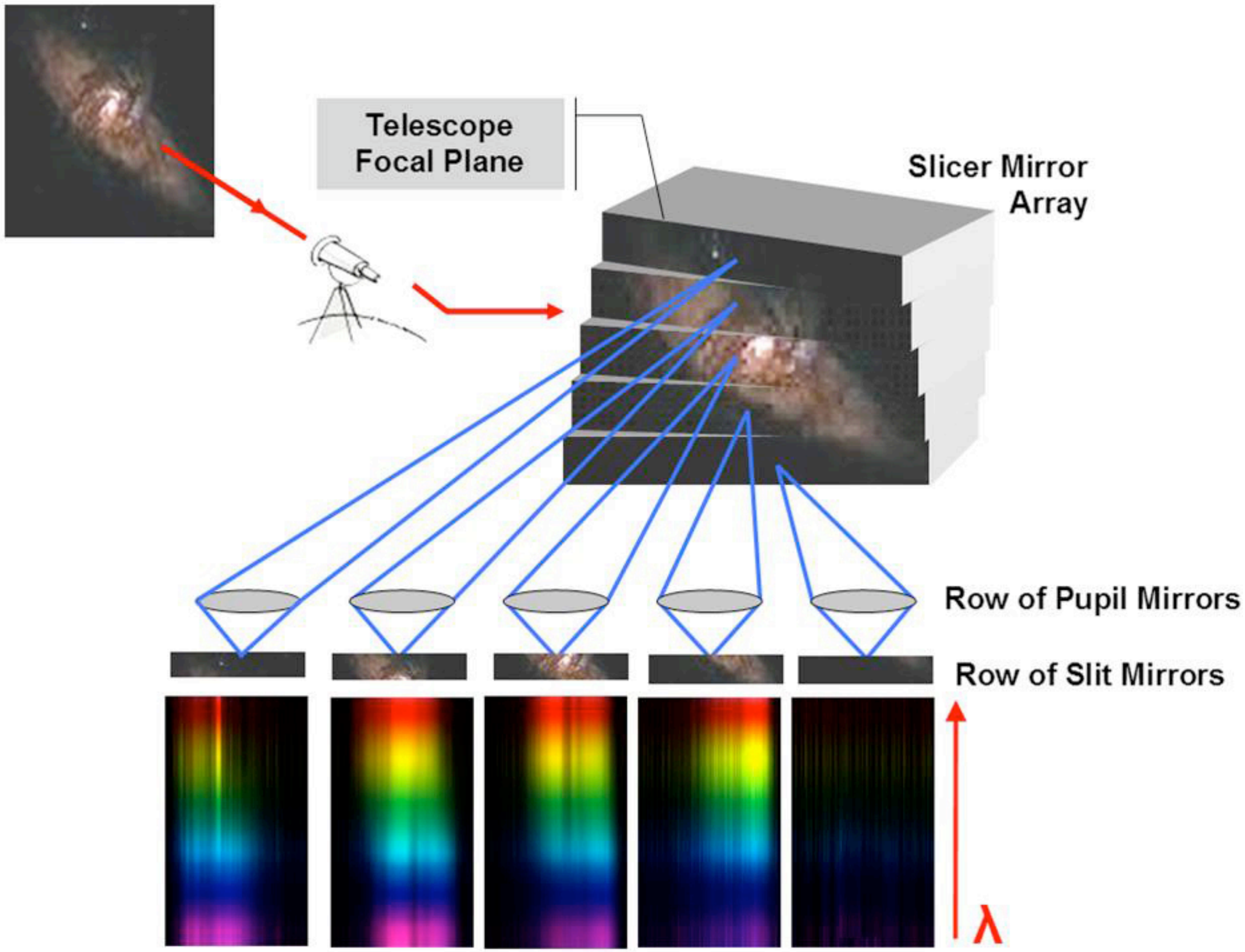
Key Problem 4: Photons

- polarimetry is photon-starved because of rapid solar evolution at small spatial scales
- slit-spectrographs and tunable filters discard most photons of interest
- time scales of scans need to be faster than typical dynamic time scales of solar evolution

Possible Solutions 4

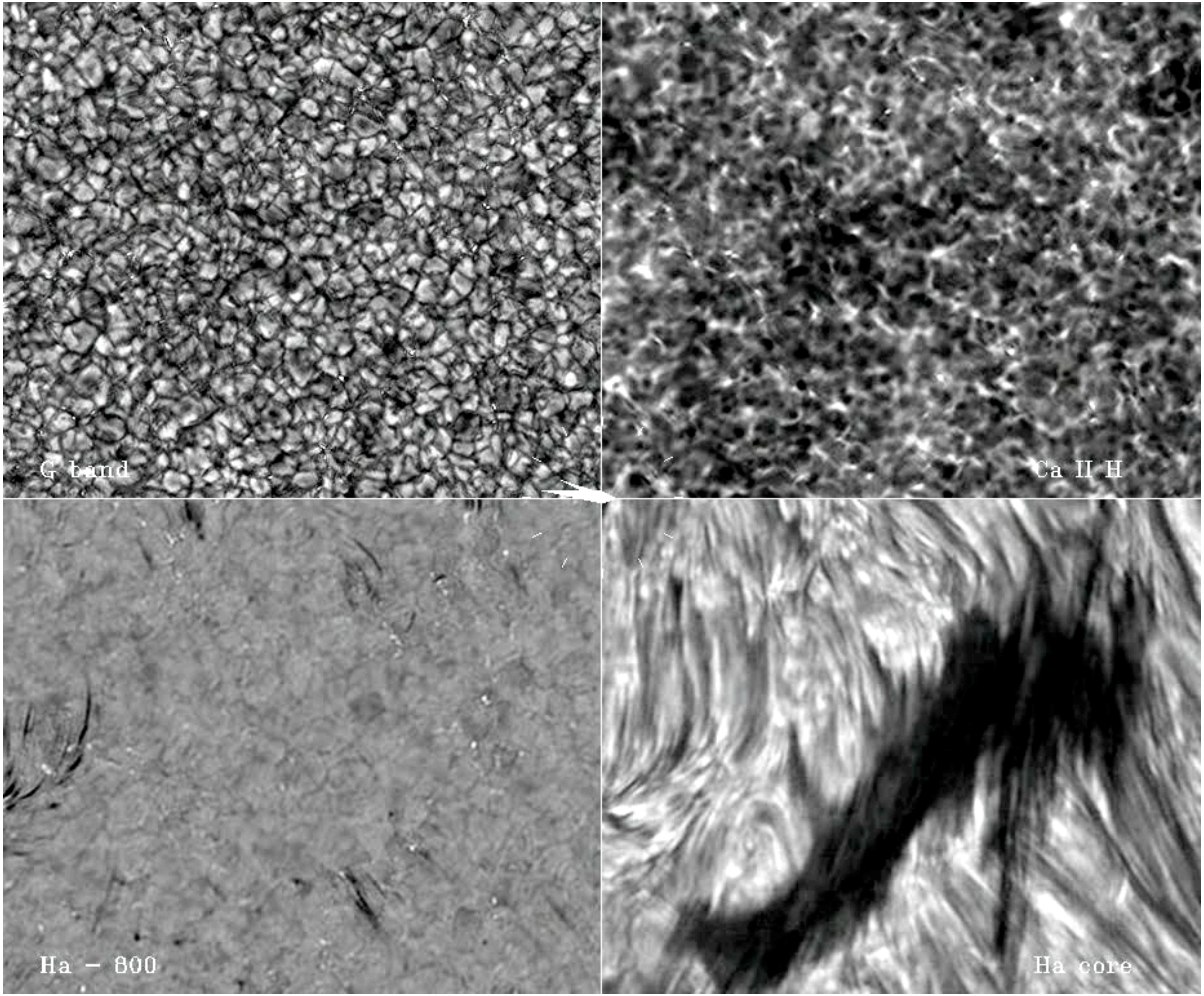
- need to measure many spectral and spatial pixels simultaneously
- Integral Field Units (IFU)
  - all-reflective image slicer
  - multi-slit
  - microlens arrays
  - fiber bundles
- multi-wavelength filters
- combine information from many spectral lines

Image Slicer IFU



The Chromosphere

- magnetic fields gain dominance over gas dynamics
- flares/CMEs defined and triggered by topological complexity of magnetic field that permeates through chromosphere
- fine-scale structuring, highly dynamic nature of chromosphere due to continuously evolving magnetic fields make this regime the hardest to diagnose, model and understand
- harbors key processes that convey energy, mass, and momentum fluxes to corona and beyond

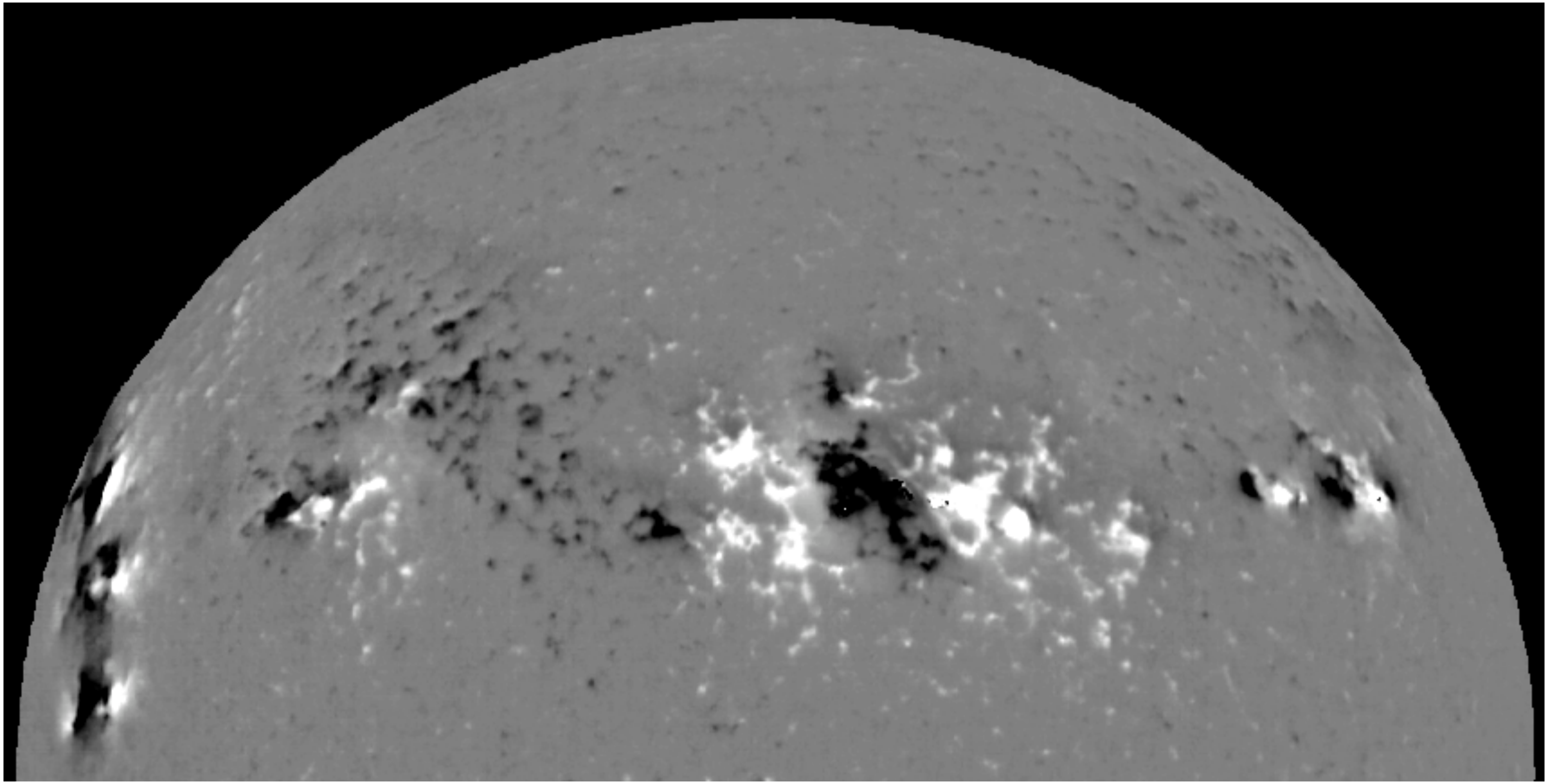


DOT G-band, Ca II H, Hα-0.8A, Hα core

Key Problem 5: Chromospheric Magnetic Field Measurements

- strong spectral lines (e.g. Ca IR triplet)
  - only a few spectral lines
  - requires NLTE radiative transfer
- He I 1083.0 nm, weak in quiet sun
- UV lines
  - Zeeman effect/Doppler width ~ λ
  - require full NLTE radiative transfer
- field-strength, filling factor difficult to determine

Large-scale Chromospheric Magnetic Fields



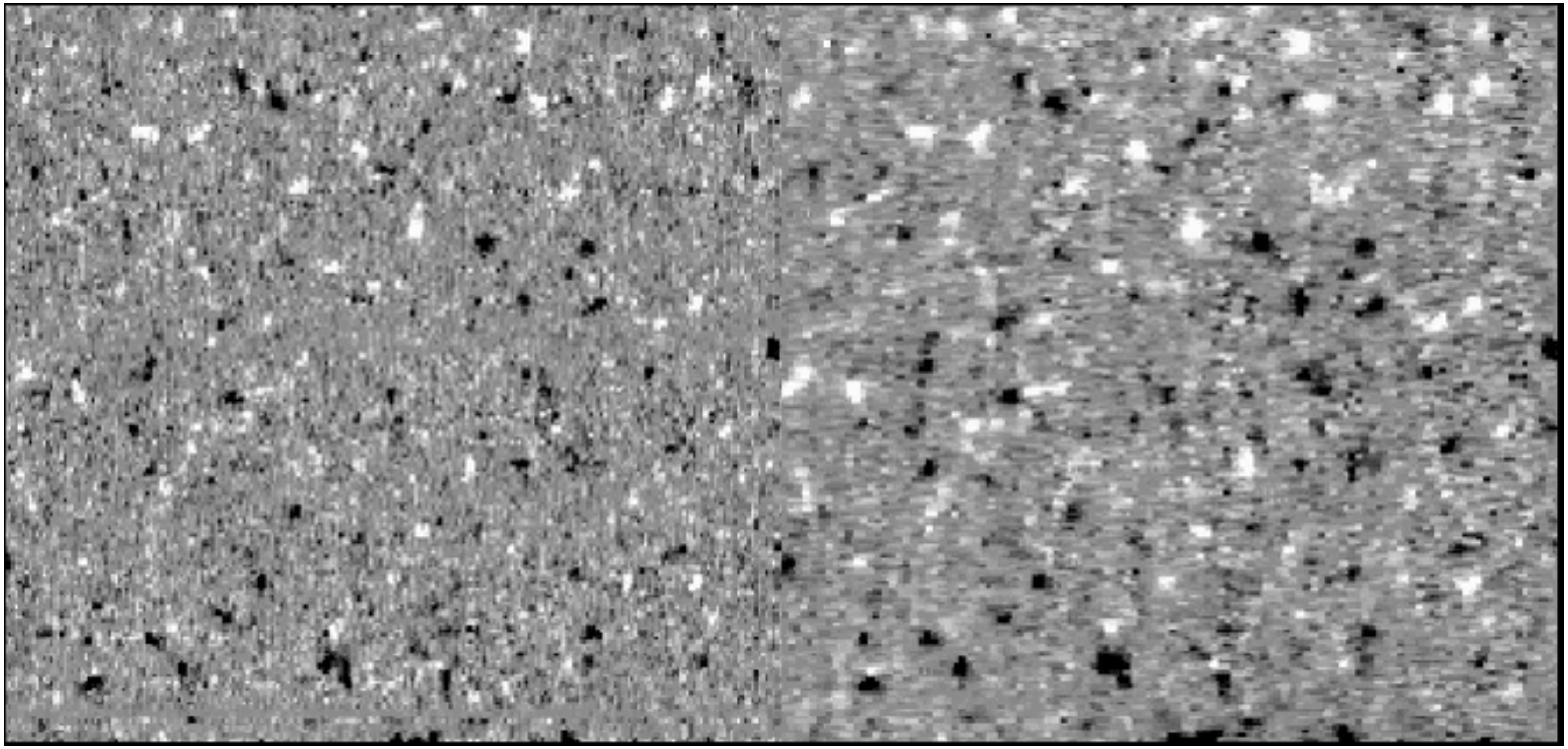
chromospheric minus photospheric magnetogram

NSO/KPVT photospheric magnetogram

courtesy Jack Harvey

Small-scale Chromospheric Magnetic Fields

FeI 853.8 nm **CaII 854.2 nm**



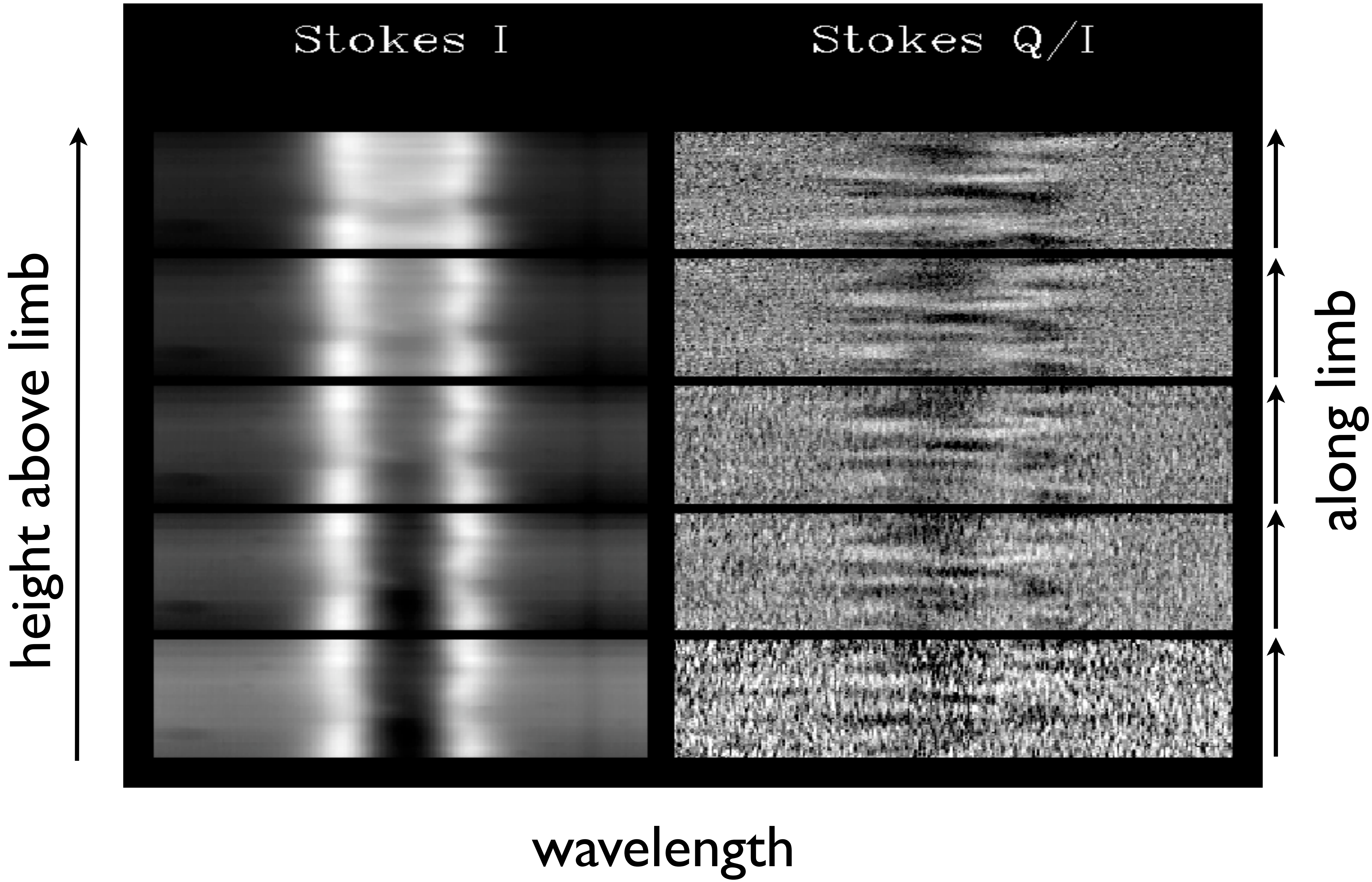
photosphere **chromosphere**

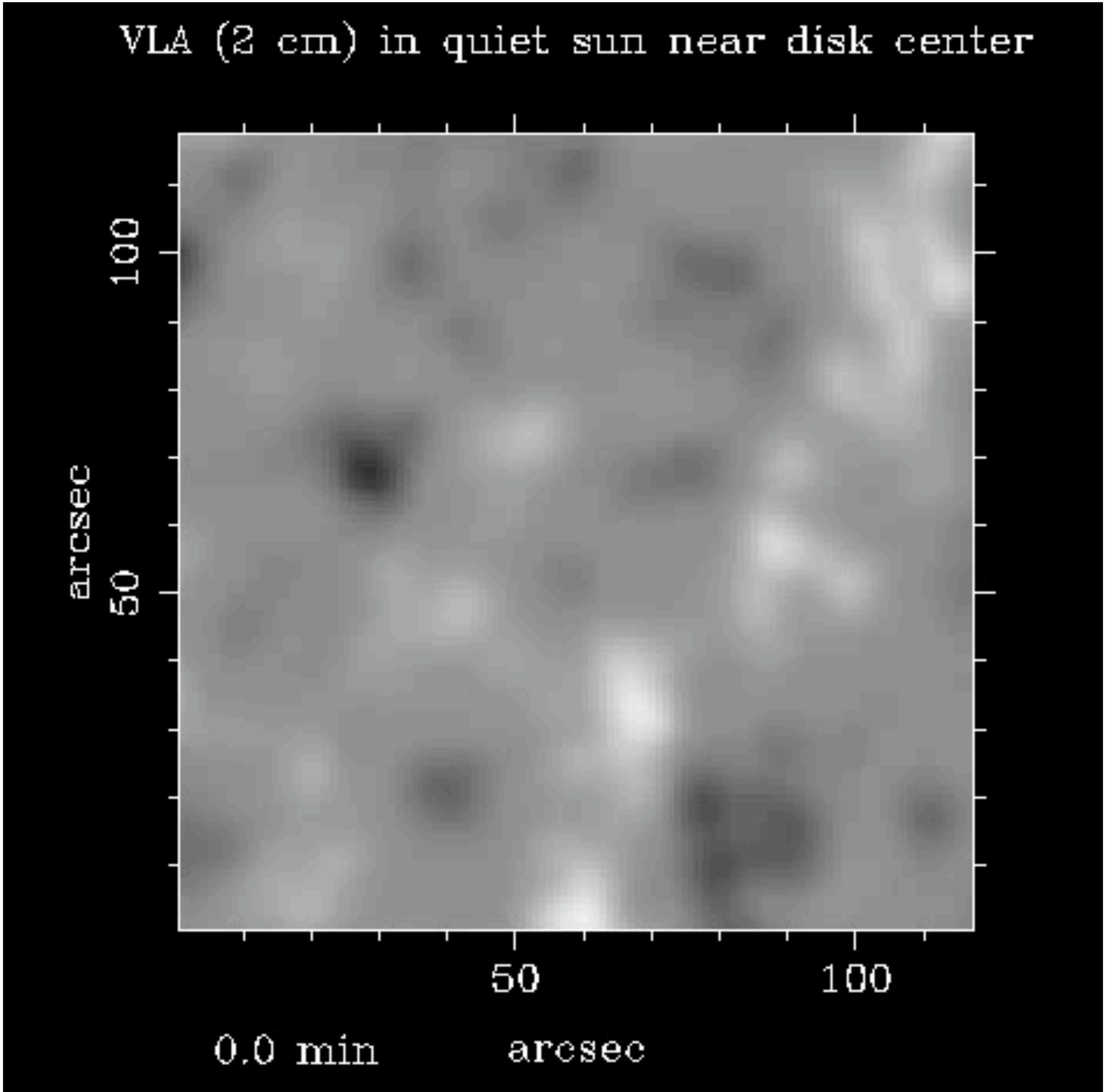
NSO/KPVT, original data courtesy Karen Harvey

Possible Solutions 5

- chromospheric field might be less dynamic than what intensity images indicate
- be aware of limitation of chromospheric vector field measurements (line-of-sight flux and azimuth ‘good’)
- extrapolations from photosphere as additional constraint
- Hanle effect as additional constraint (limb only?)
- radio observations provide excellent temperature measurements from chromosphere to corona

Scattering Polarization in CaII 854.2 nm





VLA (2 cm) in quiet sun near disk center
100
50
arcsec
50
100
0.0 min
arcsec

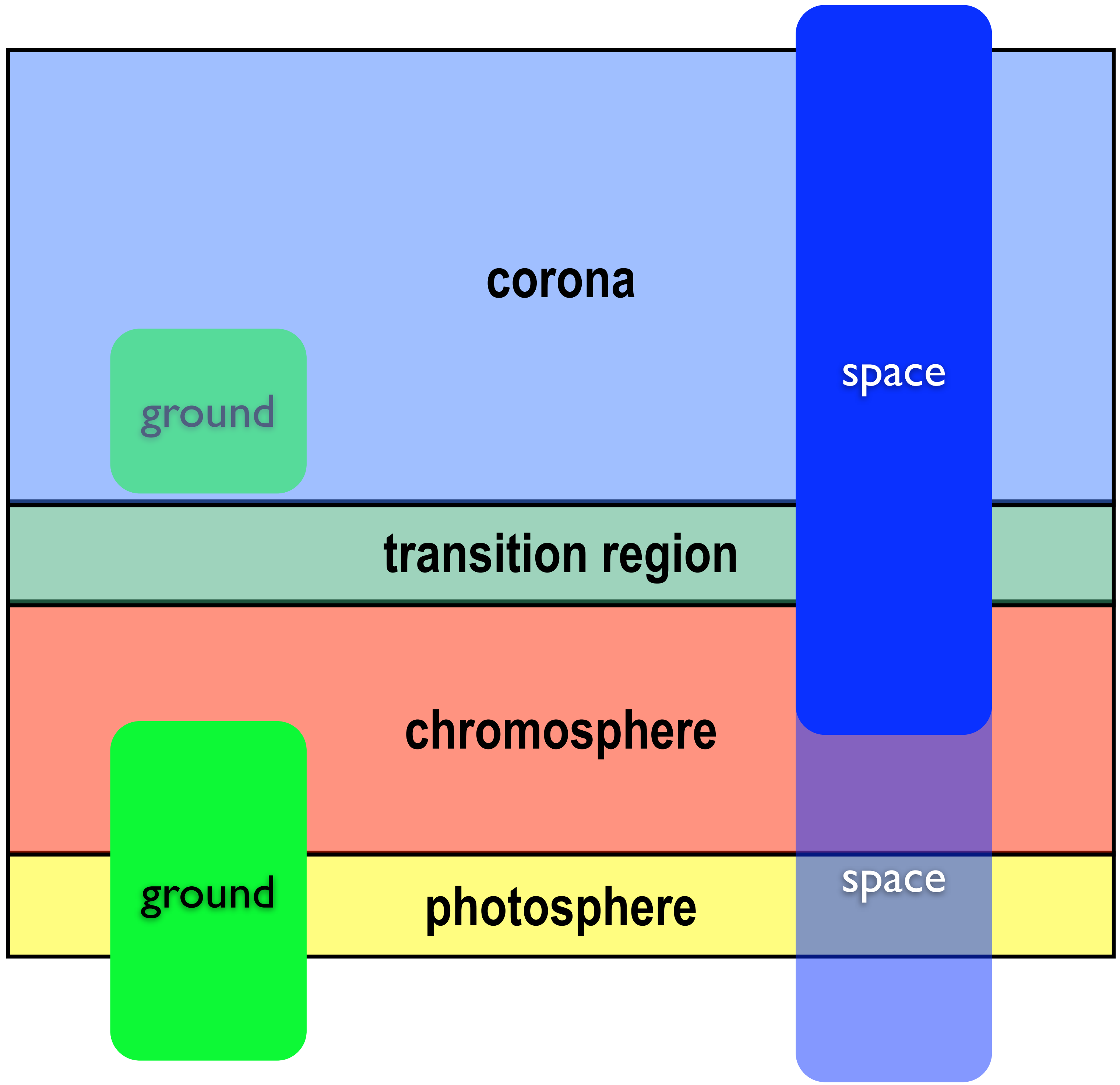
Key Problem 6: Coronal Magnetic Field

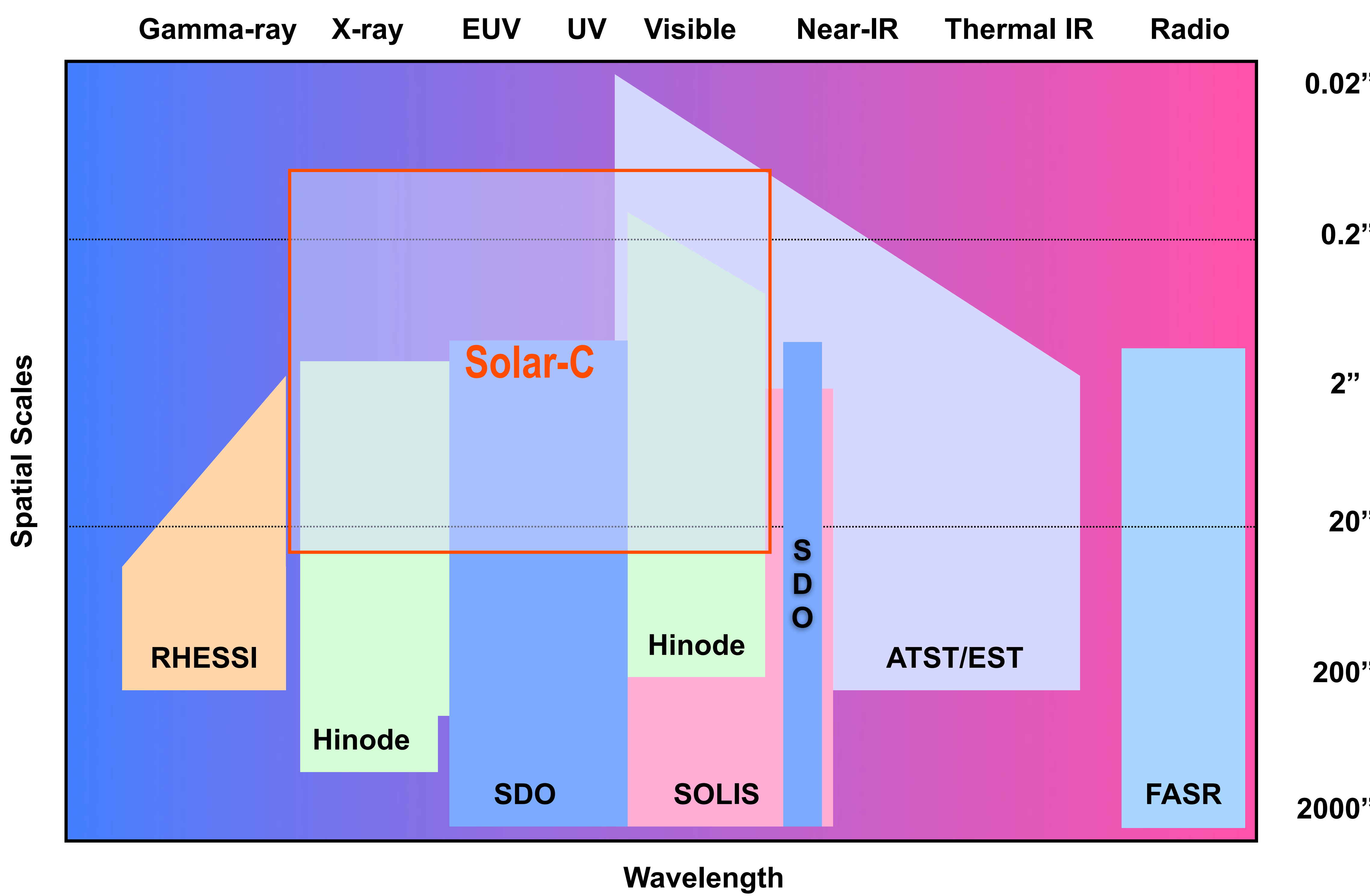
- difficult to measure directly
  - in dark parts of corona
  - when connectivity down to photosphere is important
- extrapolations:
  - photosphere is not force-free
  - photospheric field inclination often not well determined
  - 180° ambiguity not solved in interesting regions

Possible Solutions 6

- coronal polarimetry at limb from different point of view
- extrapolations:
  - line-of-sight flux and azimuth well determined
  - chromosphere more force-free than photosphere
  - use temporal information

Observing System




Gamma-ray
X-ray
EUV
UV
Visible
Near-IR
Thermal IR
Radio
0.02”
0.2”
2”
20”
200”
2000”
Spatial Scales
Wavelength
Solar-C
RHESSI
Hinode
SDO
Hinode
SOLIS
S D O
ATST/EST
FASR

Conclusions

- need to observe magnetic fields in time-dependent 3-D volumes by measuring polarization of many, carefully selected spectral lines
- need 3-D semi-empirical models to translate measurements into 3-D magnetic field observations
- understanding requires numerical simulations
- operate at suitable part of solar cycle