Overview of The 180° Ambiguity in Solar Vector Magnetic Field Measurements (especially for HMI) and Present Methods for Solving It (especially for HMI)

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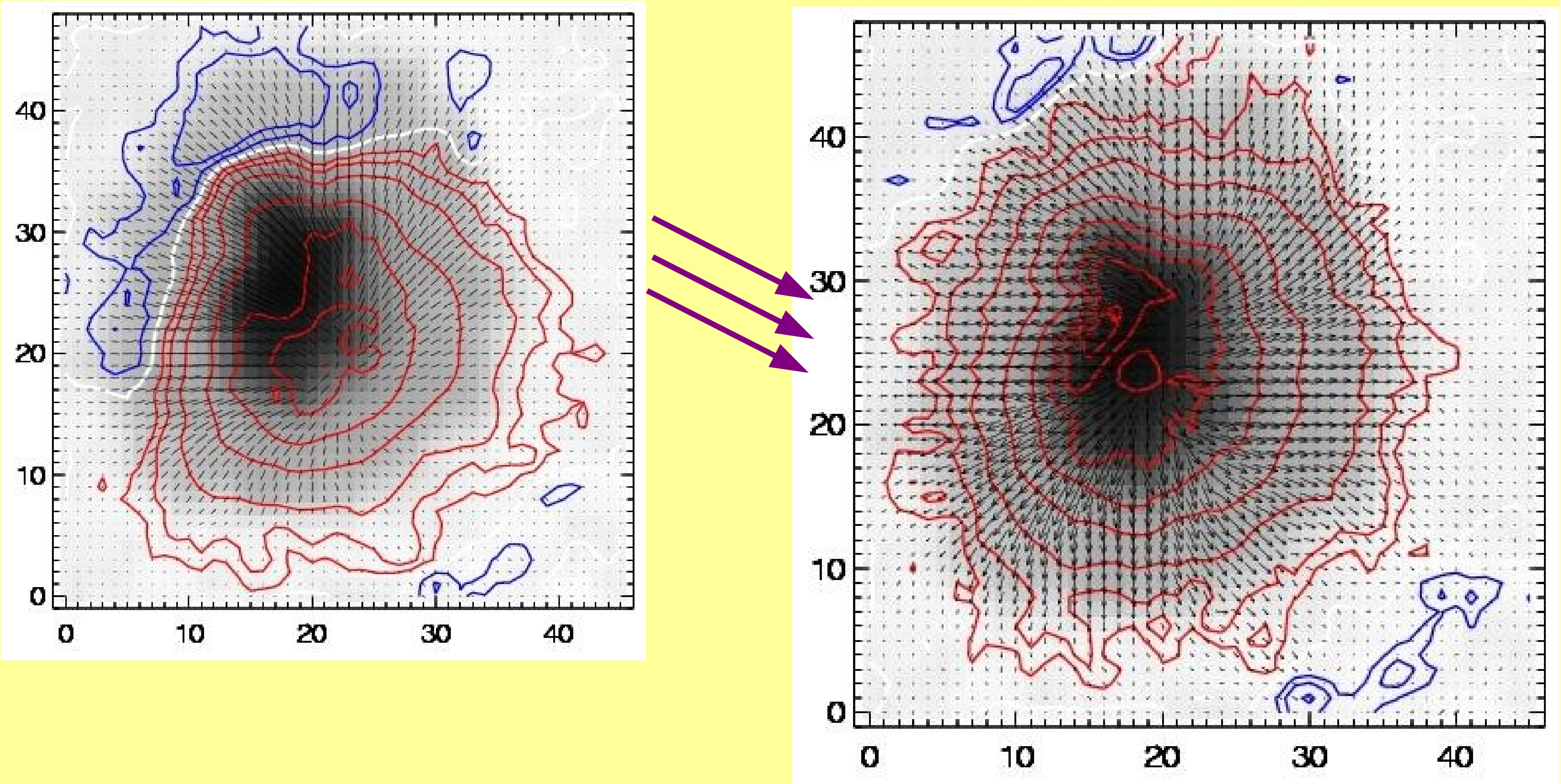
- *Observations are only physical* after ambiguity resolution and expressed as heliographic ***B***

Red/Blue: line-of-sight flux B‖
White: apparent polarity inversion line, Line-segments: B⊥ magnitude & direction. Sunspot is NE at μ≃0.8.

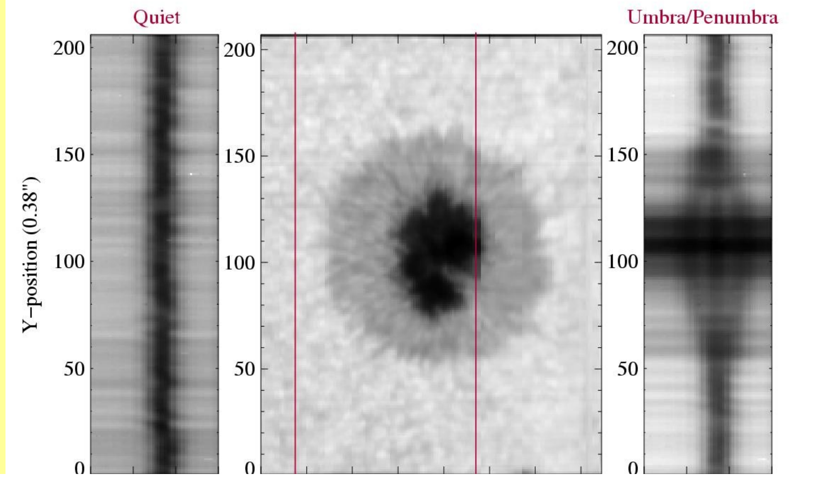
Heliographic *B*, azimuth resolved (note shift in neutral line)

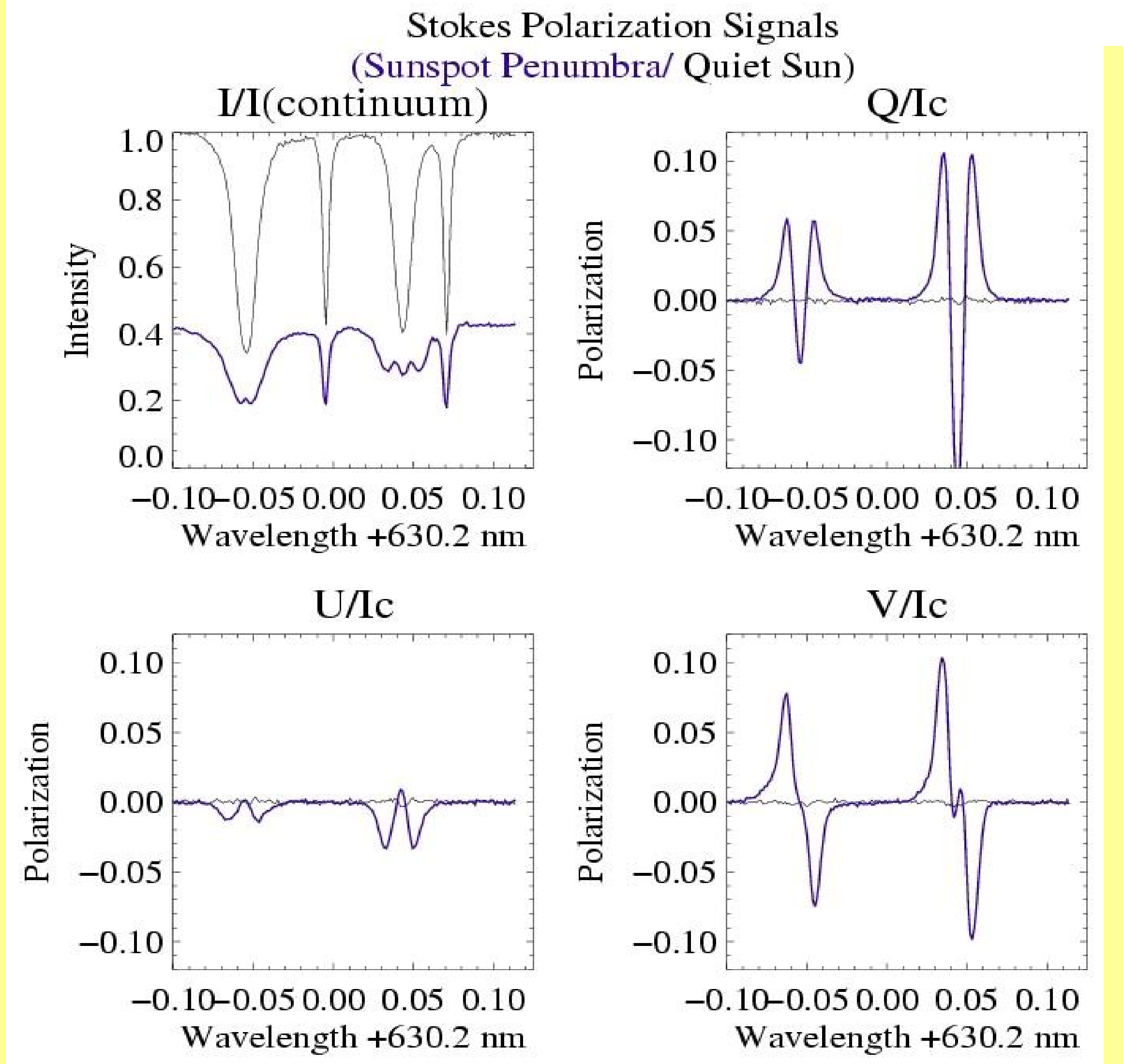


Intro to measuring photospheric magnetic field:

Stokes spectropolarimetry:

- Zeeman effect: magnetic field induces both energy-level splitting and polarization to emergent light of magnetically sensitive lines.
- Splitting proportional to $|\boldsymbol{B}|$:
- Split components are polarized:
  - For $B\perp$: π components are polarized parallel to $B\perp$, σ components are polarized perpendicular to $B\perp$
  - For $B_{\|}$: π components are not visible, and σ components are circularly polarized.
- Final shape of polarization spectra and degree of polarization due to: strength, direction of magnetic field, thermodynamics of plasma, spatial and spectral resolution.
  - Quick reference:
    - $B_{\|} \propto V$
    - $B\perp \propto (Q^2 + U^2)^{1/2}$
    - $\Phi \approx \tan^{-1}(U/Q) \rightarrow -90° < \Phi < 90°$

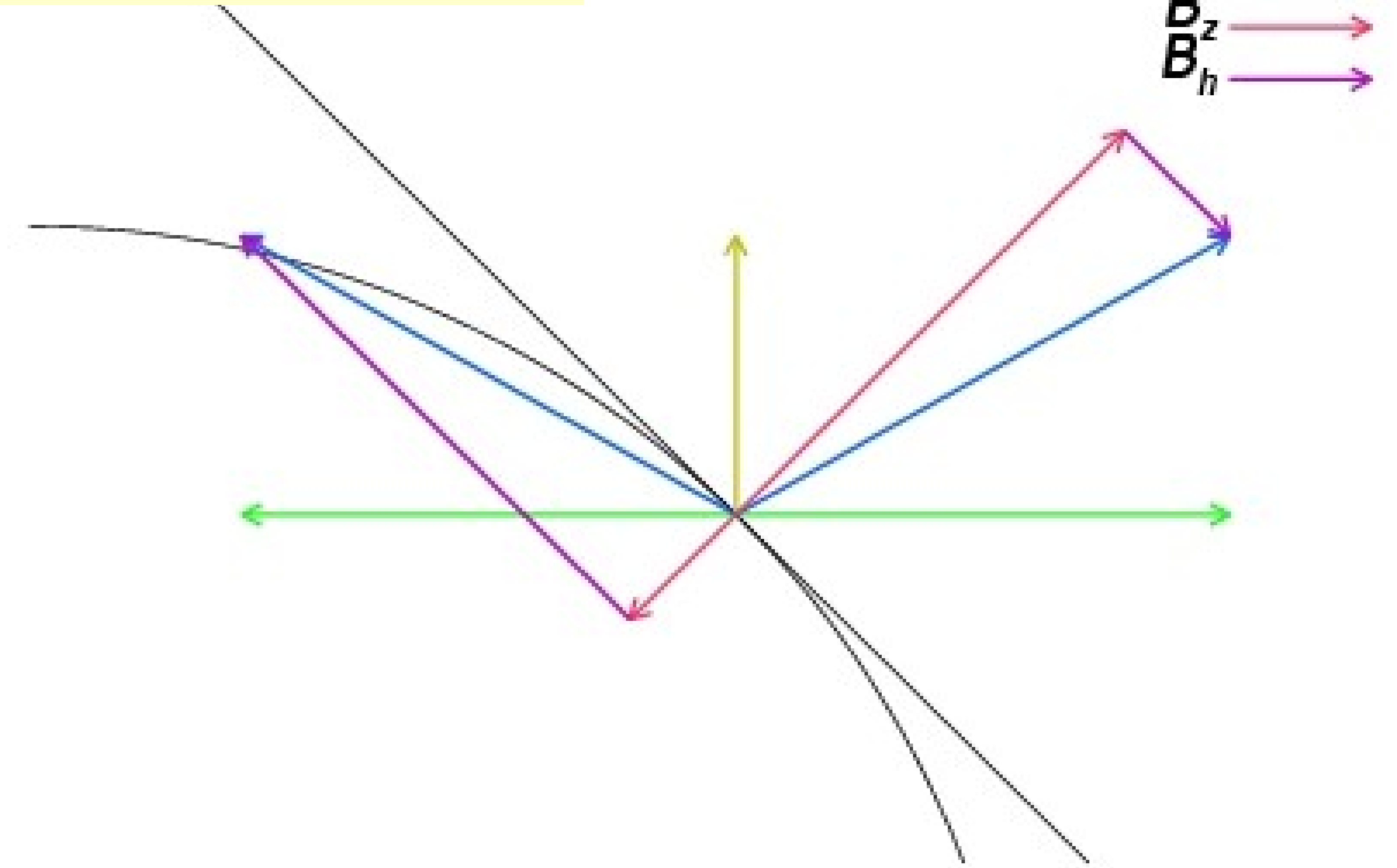


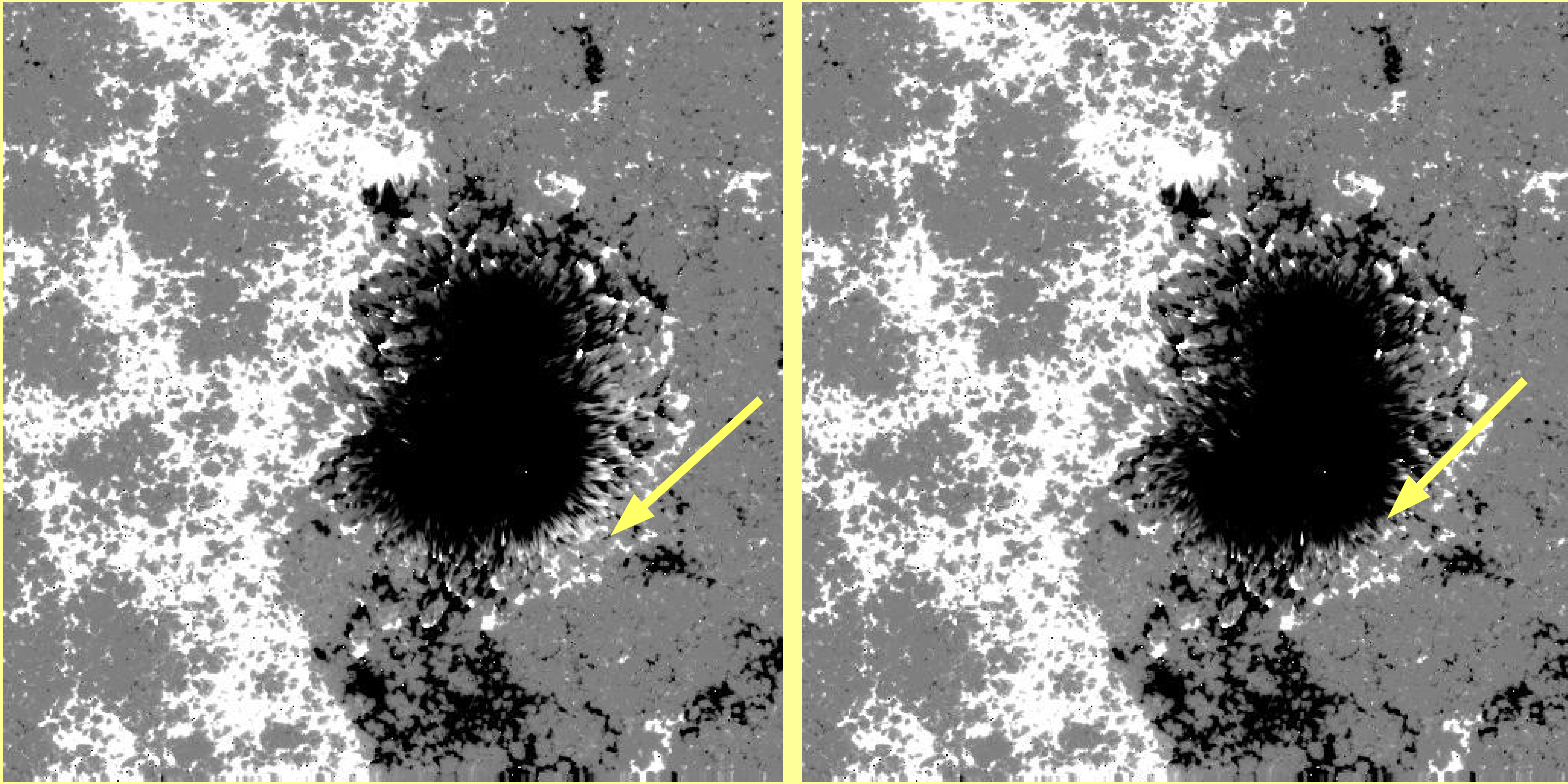


B_{trans} direction is chosen

↓↓↓↓↓↓↓

Bt is ambiguous; direction choice influences **B**, and radial component **Bz**, true magnetic neutral ("inversion") line, *etc*.





Far left: $B_{\|}$ of “Japan sunspot” at S10 W11 (μ=0.98) from the Hinode SP; some false positive penumbral areas due to projection.

Right: Bz, radial field. Even at μ=0.98, $\sum B_{\|} \neq \sum B_z$

Ambiguity resolution:

- ***All methods follow same two steps:***
  - Assume a model field
  - Choose azimuth which best matches the model field: $\boldsymbol{B_t^{model} \cdot B_t^{obs} > 0}$
- ***Differences come in model chosen,....***
  - Potential field, non-potential field,zebra-stripes...
    - There are different ways to compute a potential field....
  - Same at all scales? Or a different model for large- and small-scale structures?
  - Most consistent with ___ ($\nabla \bullet B=0$? Jz=0? Multi-fractal? Smoothness?)
- ***... and how to implement "best match".***
  - Manually evaluate ("by my eye")
  - Iteratively pixel-by-pixel with (or without) neighboring pixel results?
  - Optimize a global function
  - Down-hill gradient, Multi-dimensional conjugate gradient,
  - Genetic, Amoeba, others....

NWRA's Automated Ambiguity Resolution for HMI: General approach

- **Loosely based on the "Minimum-Energy Approach":**
  - Minimize the functional $E = \sum \left(\lambda \left| J_z \right| + \nabla \cdot \vec{B} \right)$
- **J_z requires derivatives in the horizontal, heliographic plane**
  - J_z employed rather than some approximation to J, to increase speed and reduce need for additional derivatives.
- **$\nabla \cdot$B requires derivatives in the *vertical* as well as horizontal direction.**
  - The derivatives for $\partial B_z / \partial z$ are computed from a potential field using the observed unambiguous line-of-sight field as the boundary.
  - Tests showed derivatives from the potential field were adequate if combined with a robust optimization

NWRA's Automated Ambiguity Resolution, cont'd.

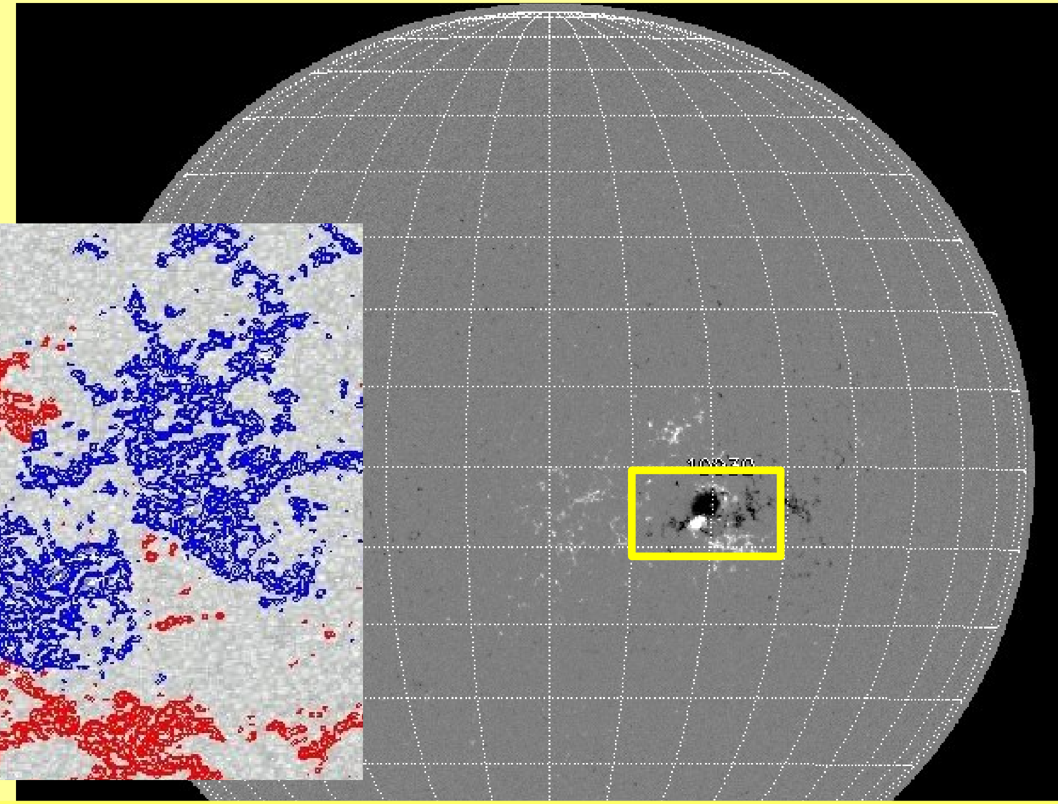
- **Global Optimization: Simulated Annealing is used to minimize the functional in strong-field areas.**
  - **Cooling schedule can be modified to best suit pipeline or targeted science.**
- **Weak-field areas solved by acute-angle to nearest-neighbor.**
  - **Propagate "correct" solution to areas dominated by noise.**

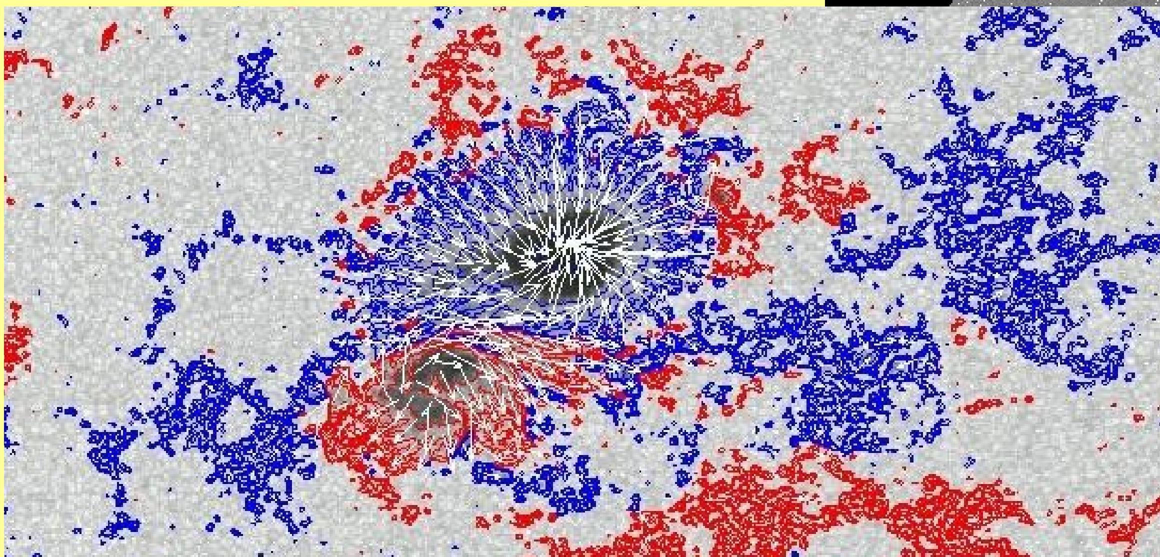
Why "Minimum Energy" approach?

- **Best-Performing automated algorithm when tested against a variety of modeled observational challenges:**
  - **highly-mixed potential/non-potential,**
  - **off-disk-center constant twist**
  - **off-disk-center constant twist with added photon noise**
  - **limited spatial resolution**

See Metcalf et al 2006;
Leka et al 2009 (in press)

Details: Magnetic Concentrations (“the Patches”): IN PIPELINE





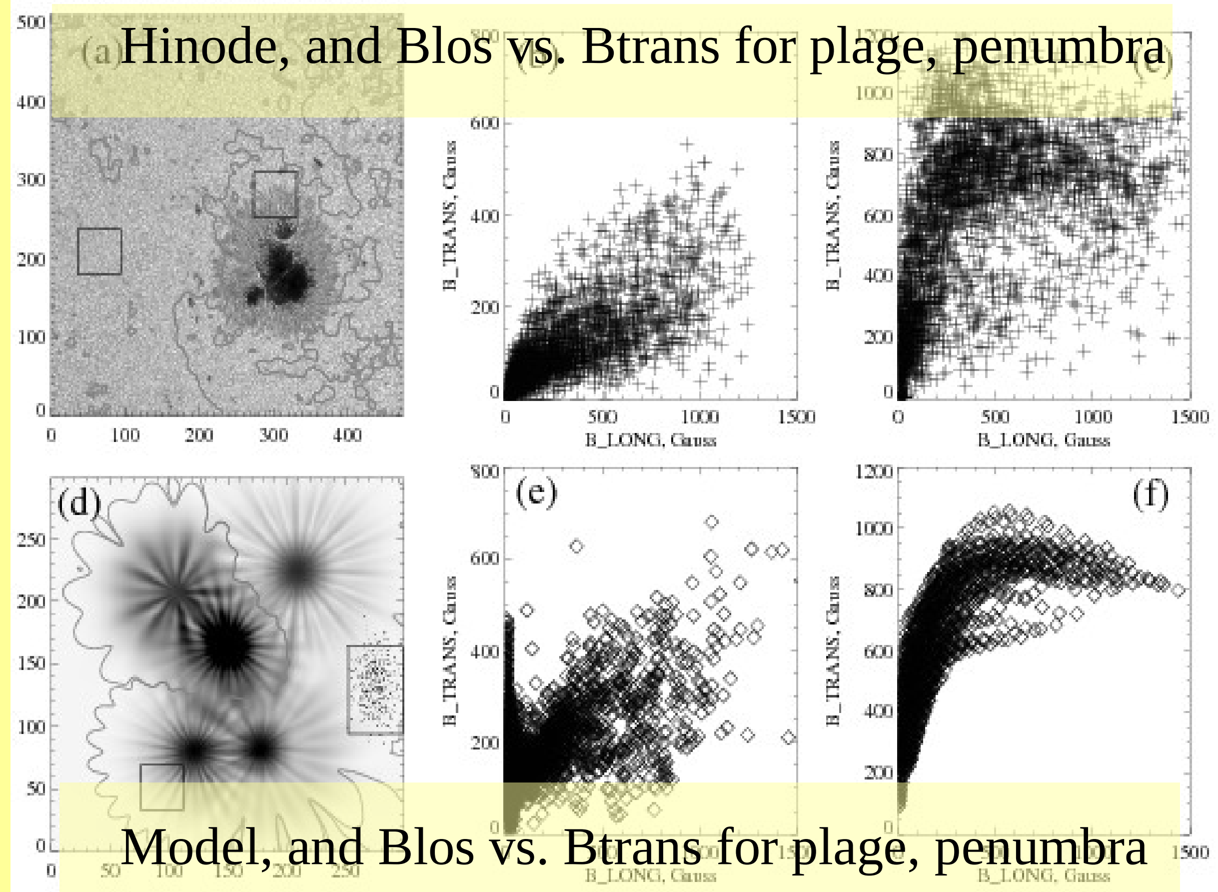
- Planar approximation: patch is approximated as a plane with a tangent point at the center.
  - can use FFTs for speed.
- Quick-Look:
  - Fast annealing schedule, higher threshold for annealing
  - Options are built-in for potential-field acute-angle and nearest-neighbor smoothing, as needed for speed.
- Science-Grade:
  - slower schedule, lower thresholds (anneal every pixel if possible)

Test data:

Synthetic: test algorithm against noise, spatial resolution

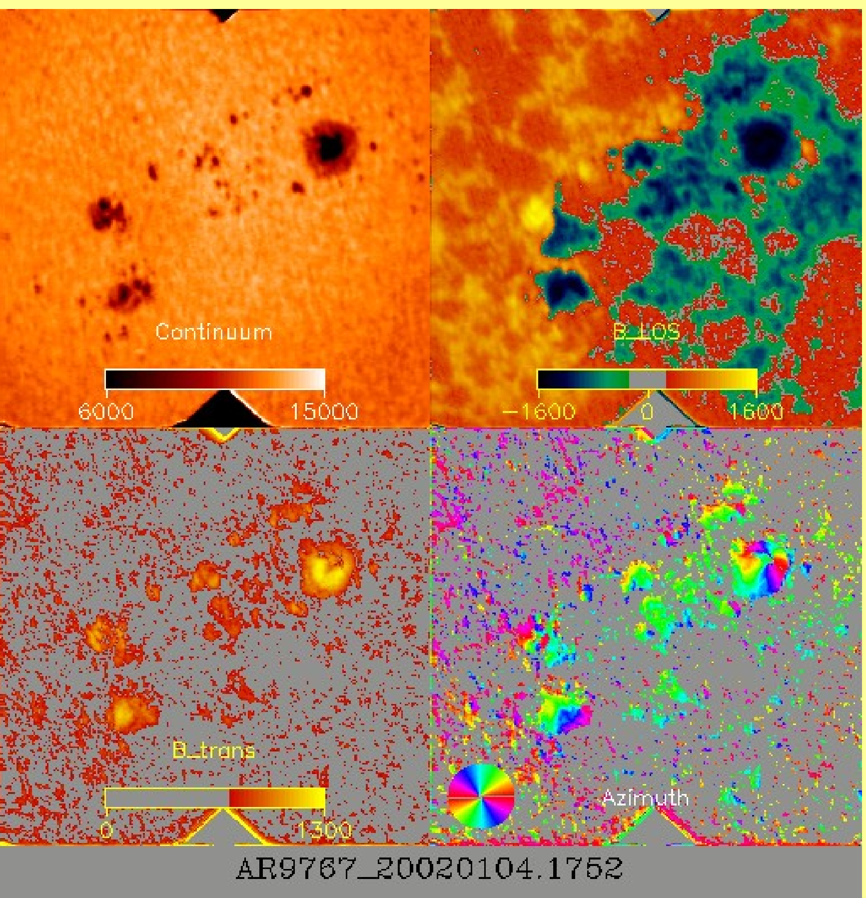
Hinode: high-resolution, various noise effects

Imaging Vector Magnetograph: instrument design very similar to HMI



Hinode, and Blos vs. Btrans for plage, penumbra

Model, and Blos vs. Btrans for plage, penumbra

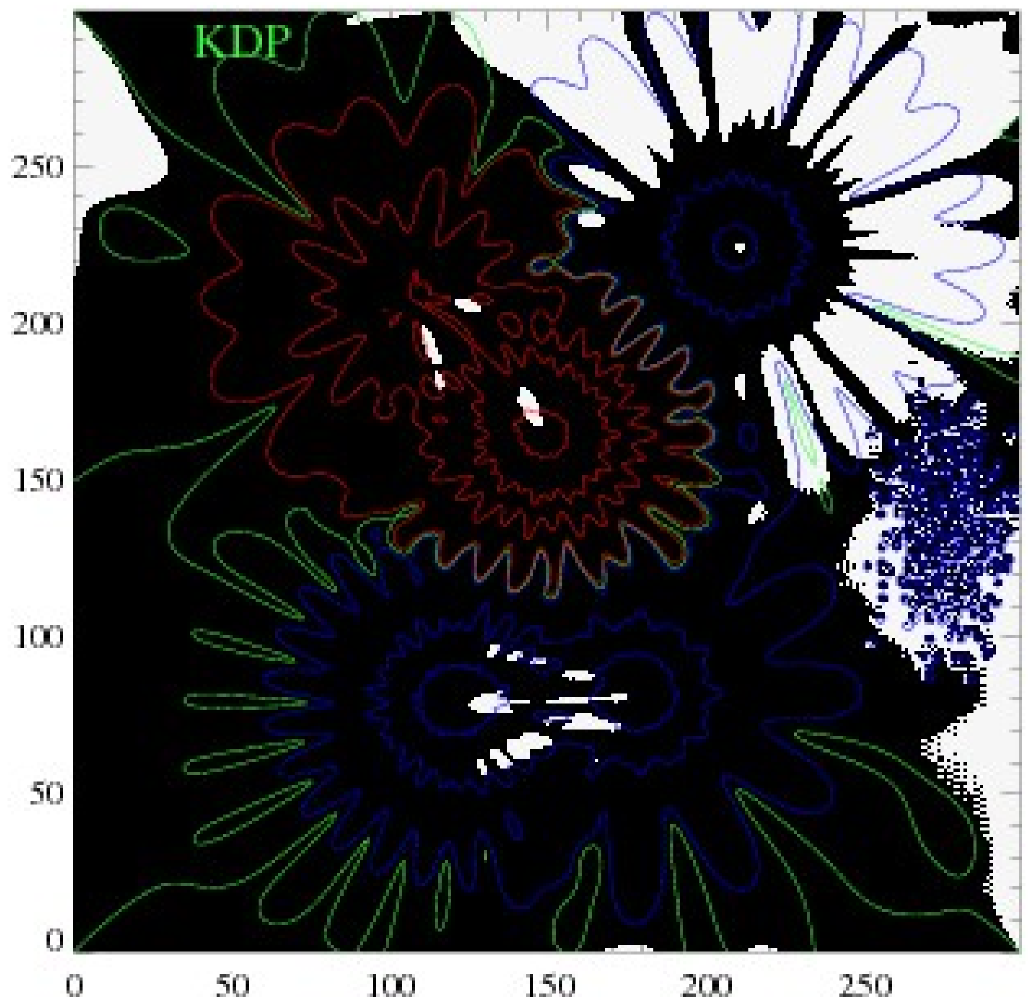


IVM data, 2002:

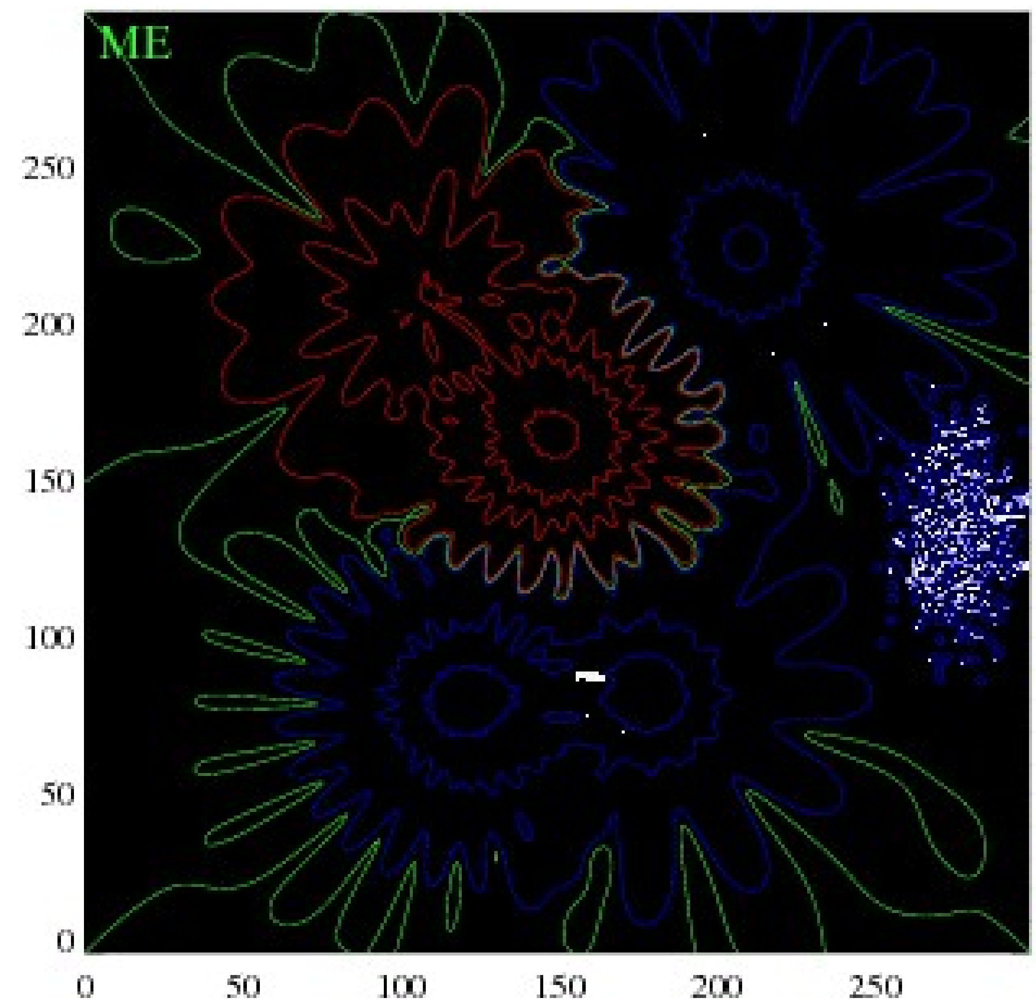
Continuum, Blos, Btrans, Bazimuth

Model Data: **bin10, or 0.3'' resolution, black=correct, white=incorrect:**

Potential-Field Solution



NWRA Minimum-Energy Solution



M_{area}	M_{Bt}	M_{Jz}	$M_{delta\text{-}B}$
0.83	0.98	-1.11	74.0G
1.00	1.00	0.80	0.8G

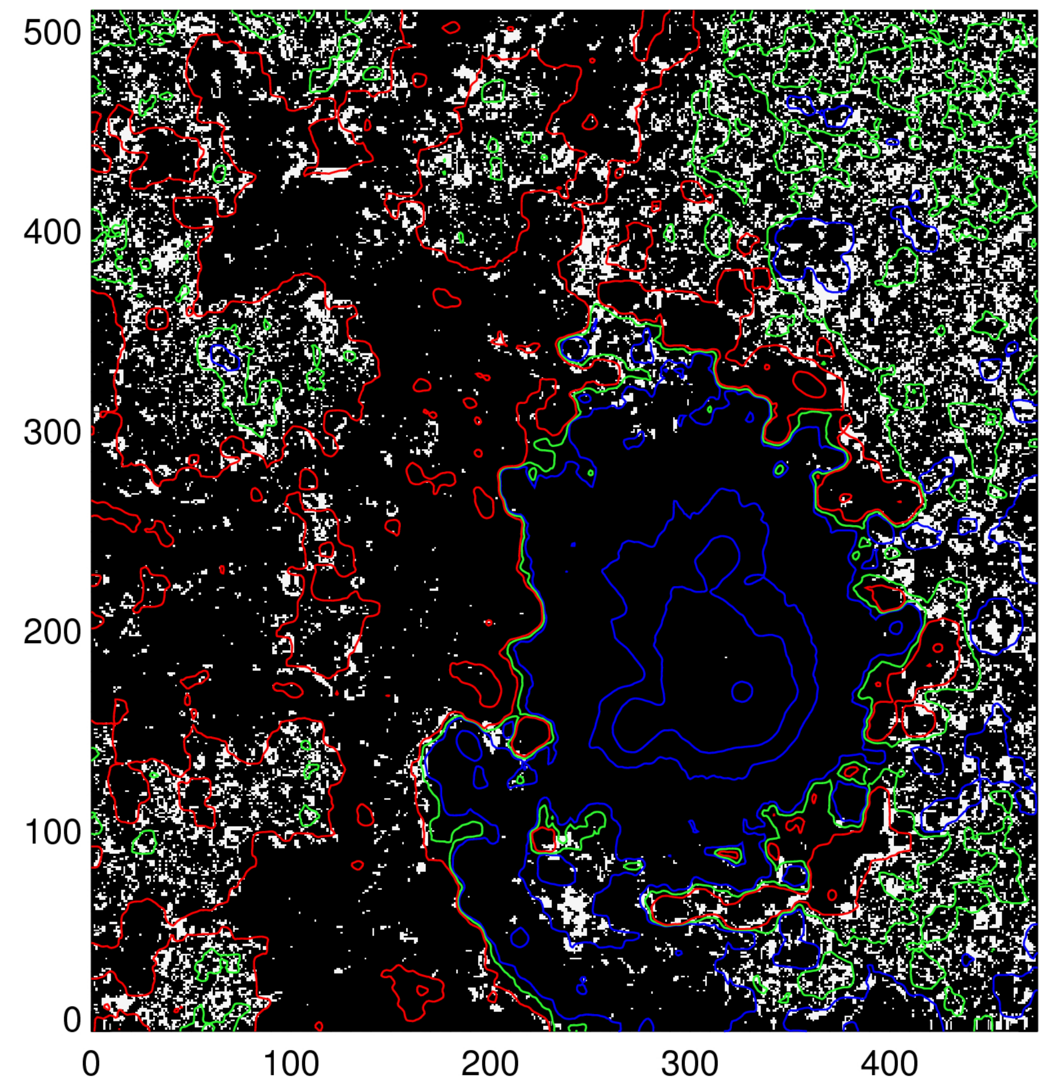
Hinode/SP example:

AR 10953 30 April 2007 during filament formation (same as earlier slide) .

White/Black: where ME0, AZAM dis/agree.

Result: Good agreement in spot, filament-formation area, and most of the plage regions.

Very weak-signal areas, well, garbage in, garbage out....



	M_{area}	M_{flux}	M_{Bt}
Minimum-Energy Solution vs AZAM	0.86	0.98	1.00

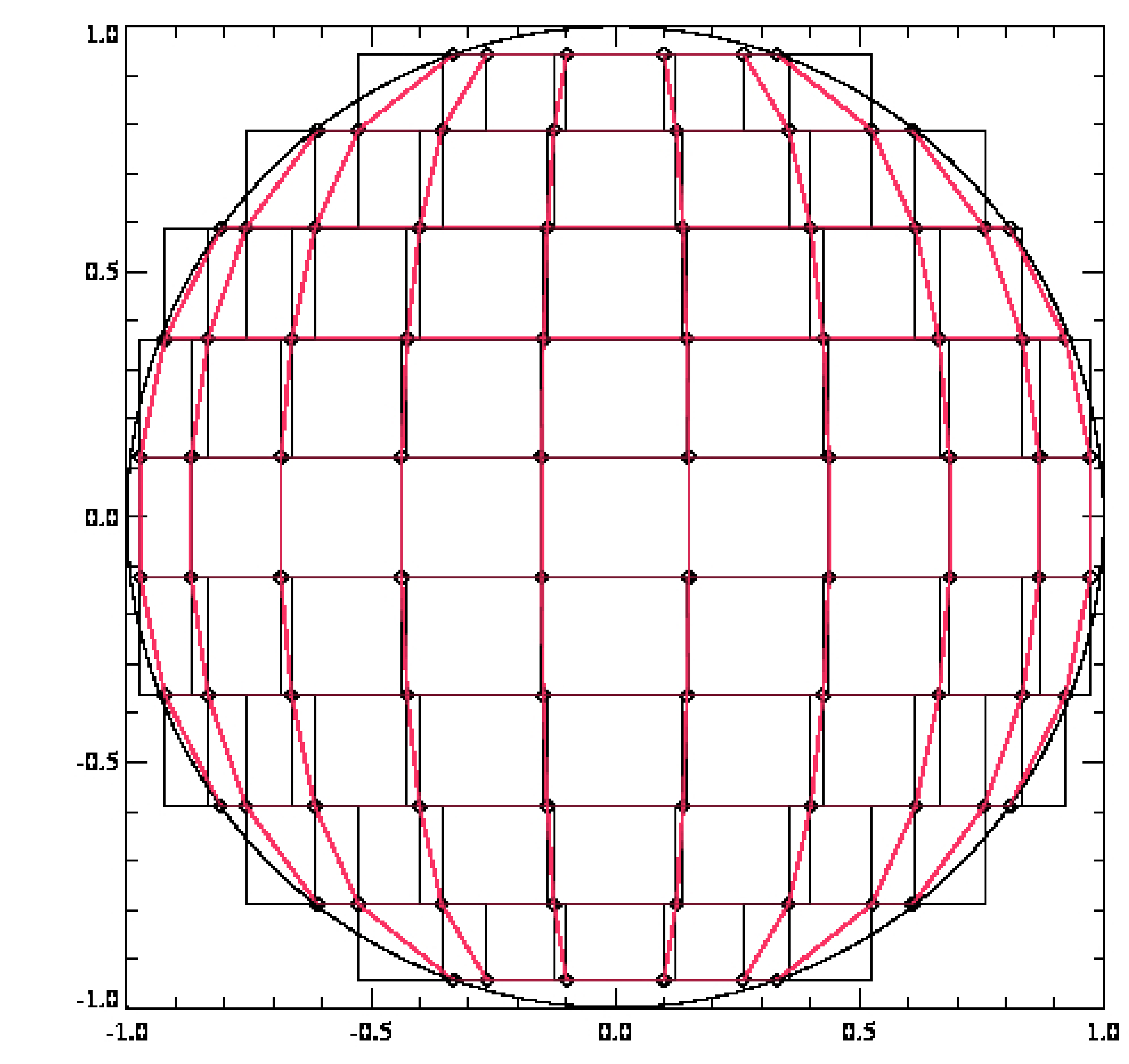
- *No time-series continuity algorithm* (that is research, not pipeline code.)

Details: Full-Disk Vector Magnetograms

Status: In progress.

Facts of Life:

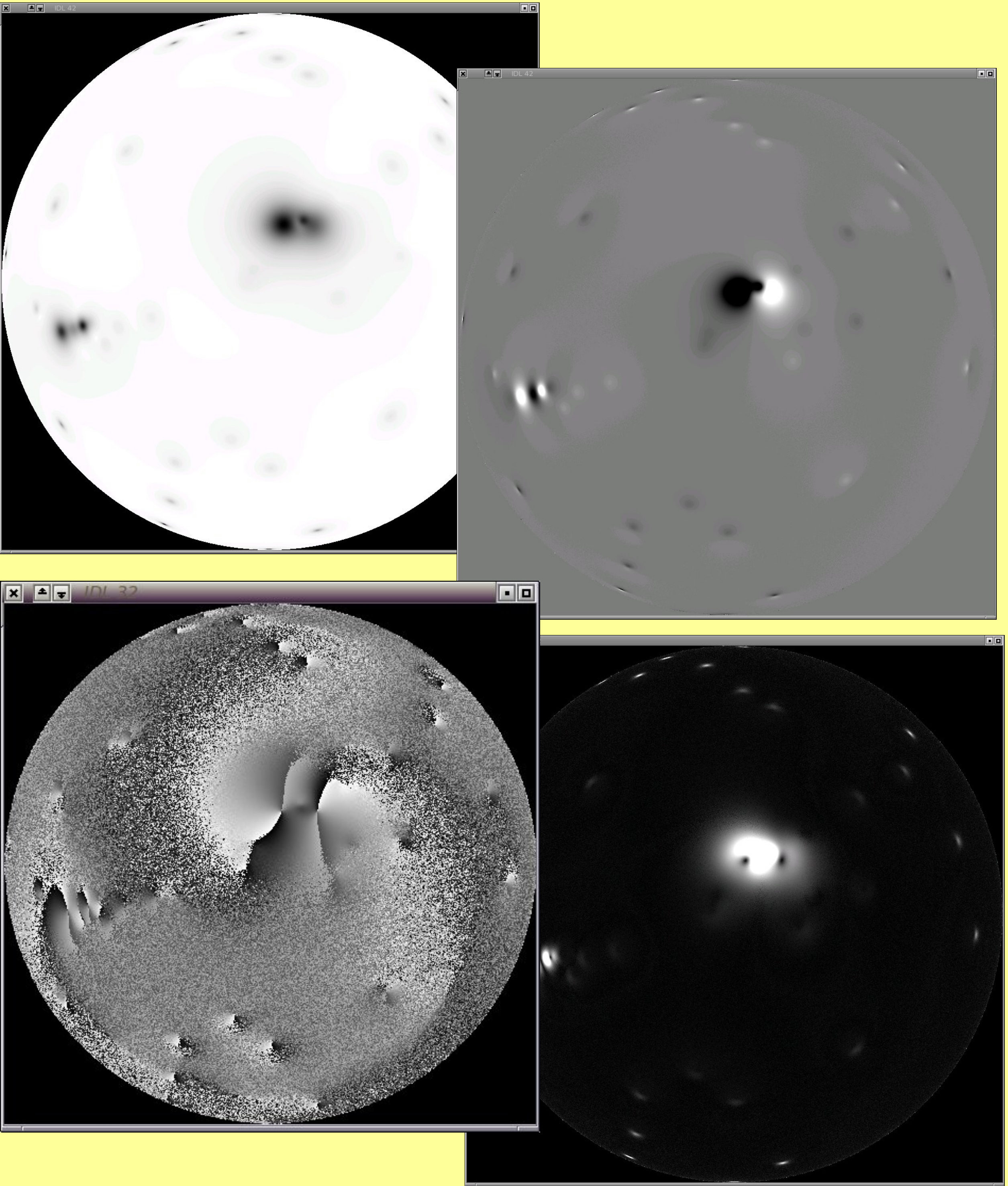
- **Curvature now important:**
  - FFTs can no longer be used,
  - Algorithms get very slow
- **Lots of pixels:**
  - Speed is crucial, however
  - any approach which employs tiling *must not result in discontinuities* in final product



Approach

- **The required derivatives** are calculated using Mollweide-projection tiles and planar approximation (speed)
- **Annealing** occurs over full disk
  - utilize strong-field masking if available.

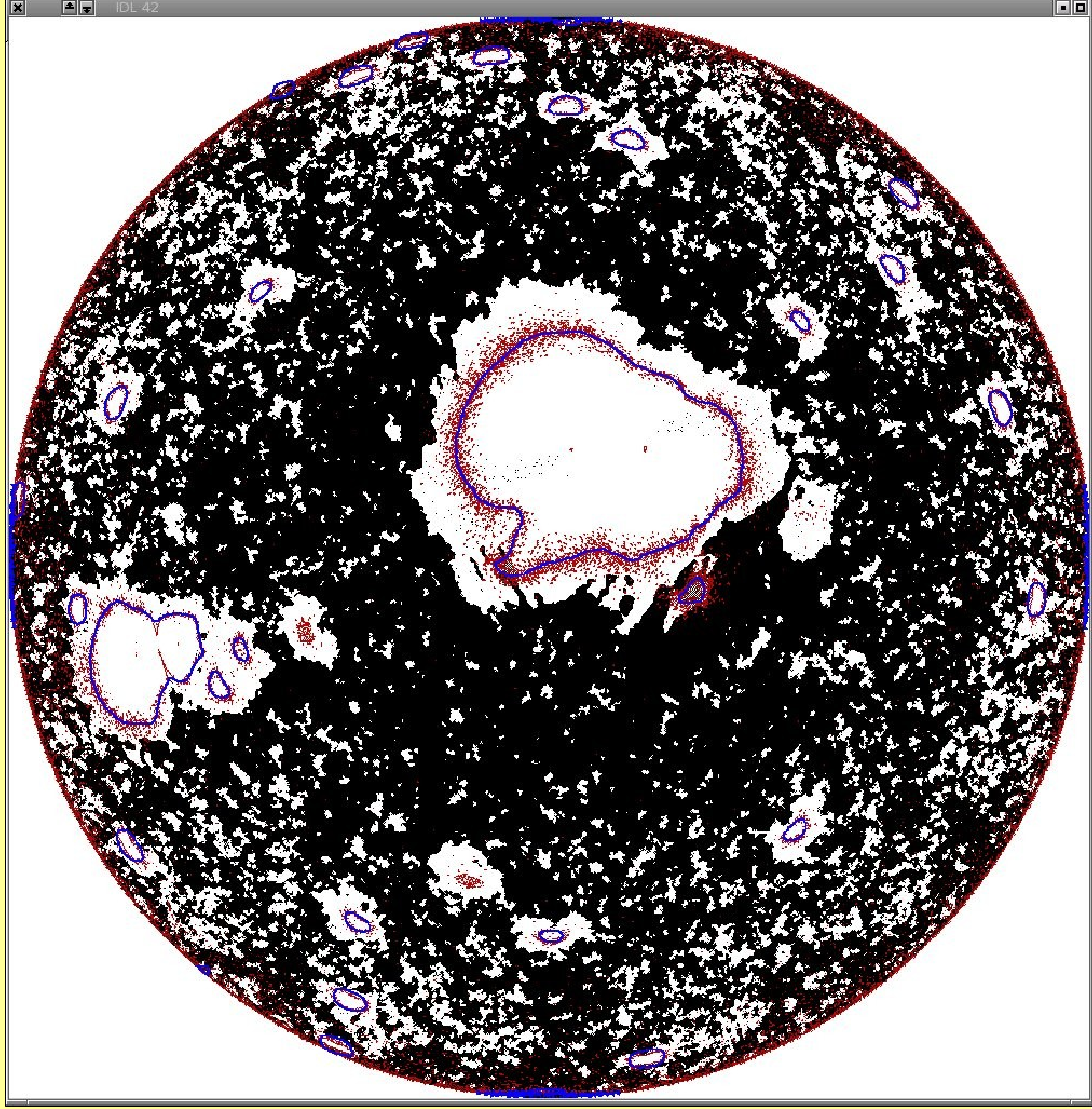
Details: Full-Disk Vector Magnetograms, cont'd: Full-Disk test data.



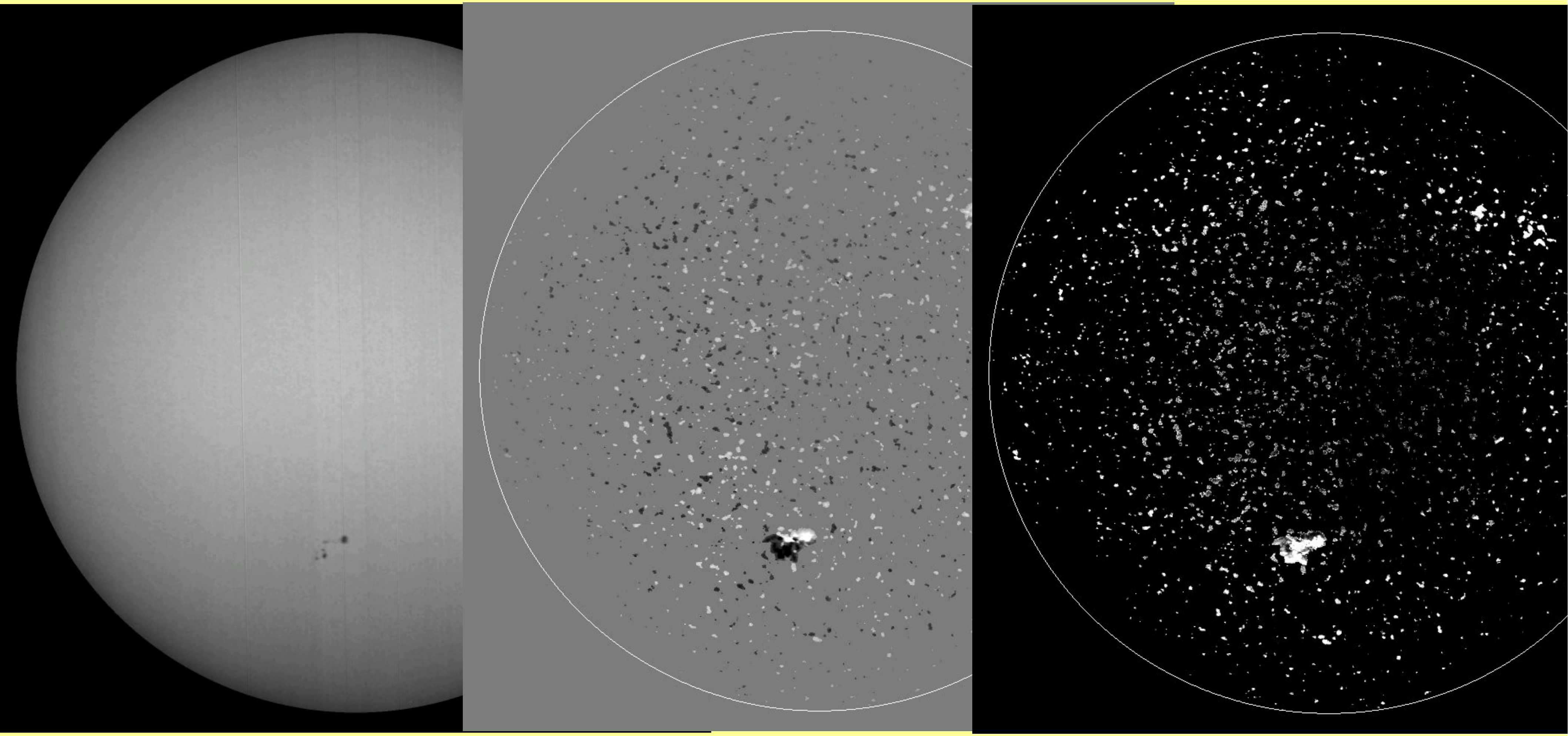
- Multiple point-source collections on a sphere.
- Each "active region" has a different force-free twist parameter α; resulting entire configuration is thus not force-free.
- There is effectively a preferential polarity in the two hemispheres (results in a net dipole moment).
- Magnetogram "sampled" at ≈2".
- Stokes polarization spectra were calculated at each pixel based on Milne-Eddington stationary atmosphere
- Photon-noise added at $\sigma I/Ic \approx 10^{-3}$
- Re-inverted assuming same restrictions.

RESULTS:

White: where correct for all of 10 different random-number seeds.
Red: contour of the threshold used for smoothing: Btrans=100G.
Blue: smoothed 100G contour.
Interpretation: correctly-resolved areas generally extend beyond threshold boundaries. No tiling boundaries visible.



A recent attempt to apply method to SOLIS data:

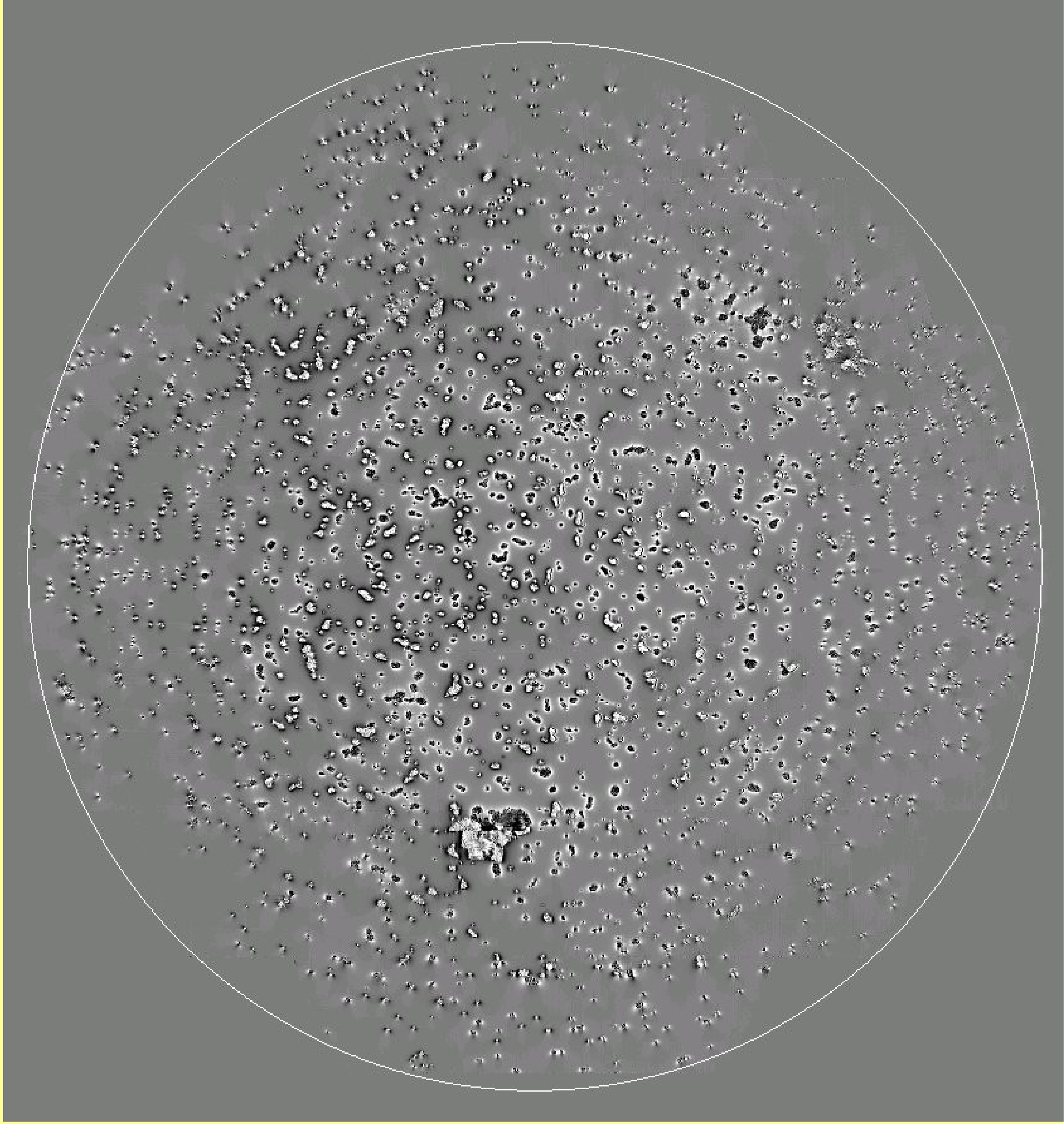


Full-disk scan 2009 July 04 15:12 UT. Fully-inverted w/ Milne-Eddington. SOLIS ME data are inverted only above a set polarization threshold.

Problem:

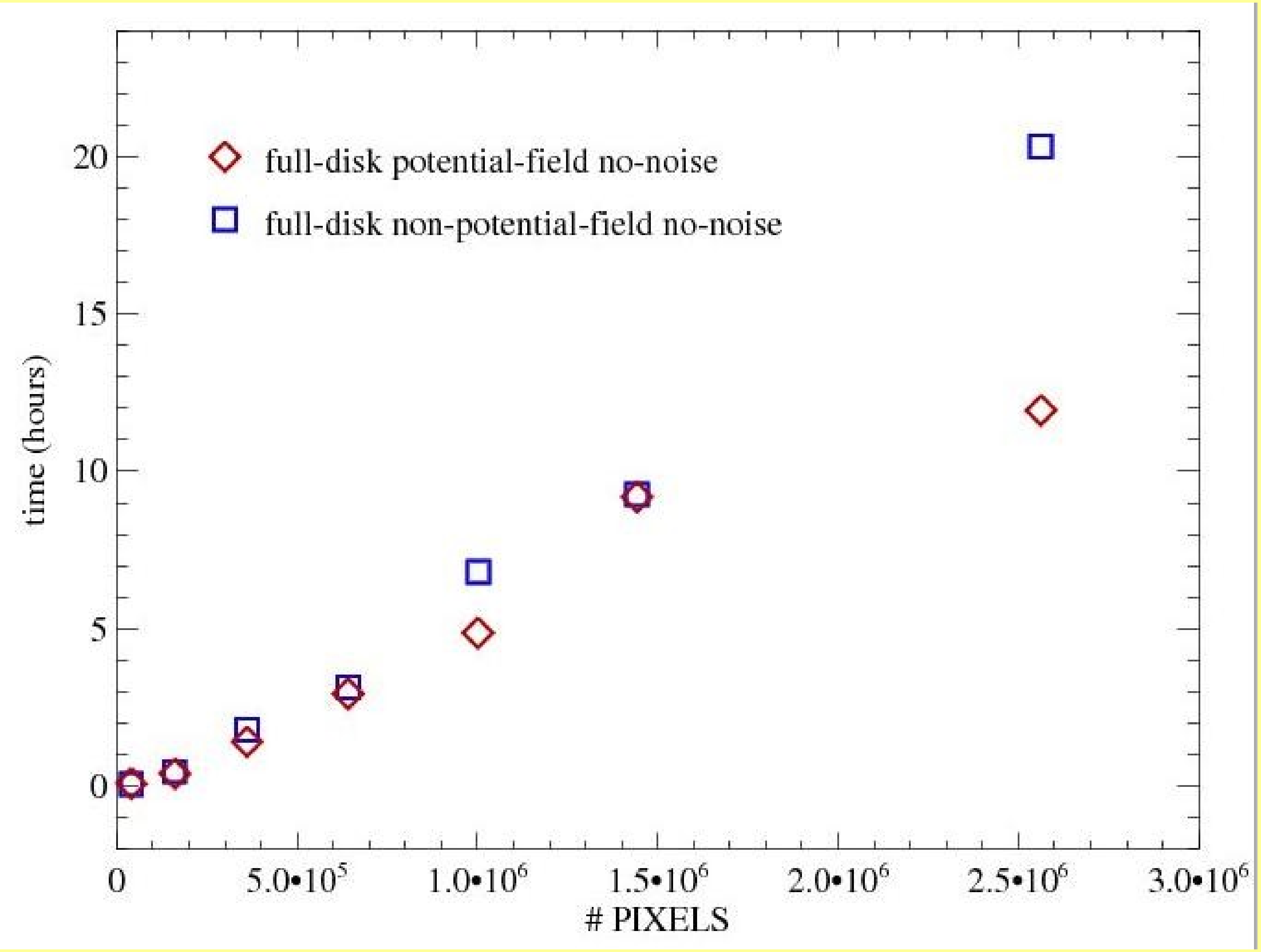
Computed derivatives (required for $\nabla \bullet B=0$) suffer serious ringing due to abrupt transition between inverted and non-inverted data (“cliffs”). Ambiguity resolution with the minimum-energy method using these derivatives...wasn't good.

HMI will invert every pixel and this should not be a problem.



Speed:

Test different resolutions of model full-disk data using one core of a quad-core 2.6GHz linux machine (similar to n02 here).



(This is why we (1) need more processors and (2) are working on implementing strong-field masking for annealing, so that we're not spending time annealing data which is just noise.)

Summary

- Ambiguity resolution a *necessary evil* for vector magnetic field data
- Method and code based on a well-tested algorithm will be in the HMI pipeline, with options built-in to suit both quick-look and science-grade data.

- Things to consider:
  - Surface potential field is being calculated during this step. For efficiency, should these products be saved?
  - There is presently no explicit handling of time-series data. This may be incorporated later after research projects are finished.
  - Uncertainties in magnetic-field data products may be a mix of propagation of errors from photometry, $\chi 2$ from fitting/inversion, and probabalistic uncertainties from ambiguity resolution. How can we quote a single uncertainty? *Should* we quote a single uncertainty?

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Just a few different approaches:

- **Potential-field acute-angle**
  - Using *FFTs* (K. Leka, J. Jing) with/without flux balance, boundary padding
  - Based on *Green's Function solution* (J. Li, V. Yurchyshyn)
- **Large-Scale Potential method** (A. Pevtsov)
  - assumes large-scale fields are potential, deviations increase with spatial resolution
- **Linear Force-Free Acute-Angle method** (H.N. Wang)
  - Best-fit to LFFF field consistent with coronal-loop observations
- **Uniform Shear Method** (Y.J. Moon)
  - assumes shear angle follows a normal distribution
- **Magnetic Pressure Gradient** (J. Li)
  - assumes magnetic pressure decreases with height
- **Minimum Structure** (M. Georgoulis)
  - Minimize a component of current analytically, then numerical smoothing
- **NonPotential Magnetic Field Calculation** (M. Georgoulis)
  - Finds the distribution of Bz whose potential extrapolation plus a calculated non-potential component best matches the observed heliographic field.
- **Pseudo-Current Method** (A. Gary)
  - Minimizes J_z^2 by locating sources of non-potentiality
- **U. Hawai`i Iterative Method (Metcalf, Fan & Leka)**
  - Iterates locally to minimizes Jz and div(***B***), then acute-angle neighbor smooths
- **Minimum-Energy solution (Metcalf)**
  - Global optimization of *J* and div(***B***), numerous weighting options

- **Early synoptic vector magnetic field instruments made it v*ery* clear *very* early on that *automated* data-reduction algorithms were required, *including ambiguity resolution.***
  - U.Hawai`i's Haleakala Stokes Polarimeter,
  - Imaging Vector Magnetograph;
  - NAOJ/Mitaka's Flare Telescope,
  - MSFC's vector magnetograph, BBSO's video magnetograph.
  - Observer-driven instruments: less data and less automation needed. Human-based interactive approaches were possible.

- **With high-resolution and high-cadence data (Hinode, ATST, SDO/HMI, SOLIS), algorithm(s) are required with high *performance value*** (courtesy C. Henney):
  - *Accurate enough for science goals*
  - Stable for conditions of interest (e.g. Full-disk)
  - Fast relative to inversion time,
    (define Time= InversionTime / AmbigTime)
  - Is the algorithm automatic?
    If yes, (set Auto= 1, otherwise Auto= ∞)
  - **Merit = (% accuracy * Stability + Time) / Auto**

Continuing Challenges:

- Visualization