Time-Distance Inversions of Two Realistic Sunspot Simulations

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Motivation

- TD used often in the past to recover flows QS and around sunspots
  - (Duvall et al. 1993, Zhao et al 2001, Gizon et al. 2003, Zhao & Kosovichev 2003, Couvidat et al. 2006, Jackiewicz et al. 2008, Kosovichev & Duvall 2011, Svanda 2012 …)

- QS TD results promising in upper ~3-5 Mm
  - Lots of uncertainty around active regions possessing strong B-fields
  - Not really any general consensus about subsurface structure of sunspots (shallow, deep? flow structure?)

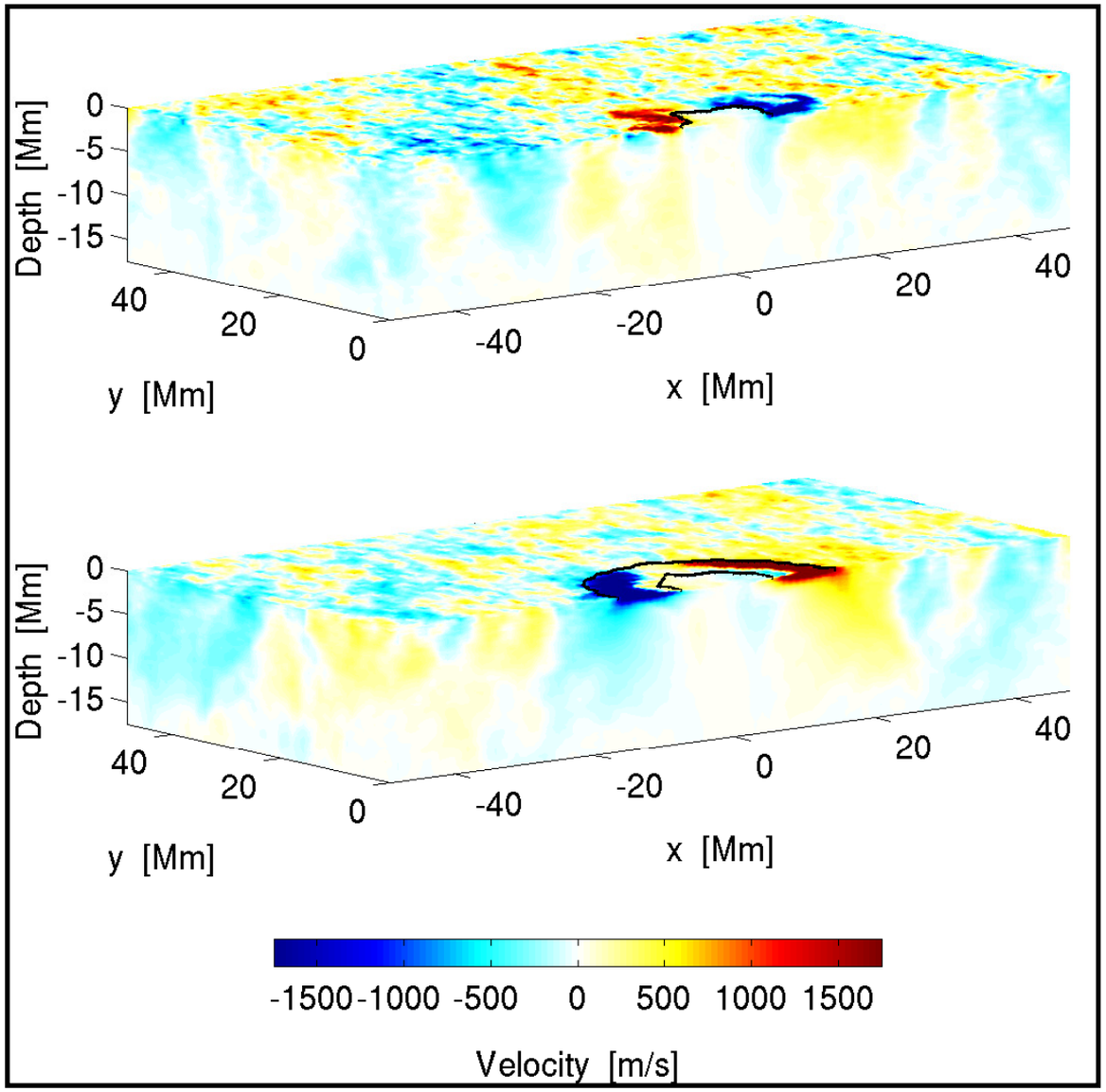
- Goal to shed light on the validity of current TD methods around active regions
  - Ultimately have confidence in real Sun - tough without validation
  - Comparisons between methods can be useful, but if both are wrong (active regions), it doesn't help
  - Use realistic MHD simulations for which we know the real flow structure

- Disclaimer: We don't expect to accurately recover flows near spots - show for completeness

- Filtering, tt's, kerns, etc. (recent pub, QS analysis is same)

Sunspot Data

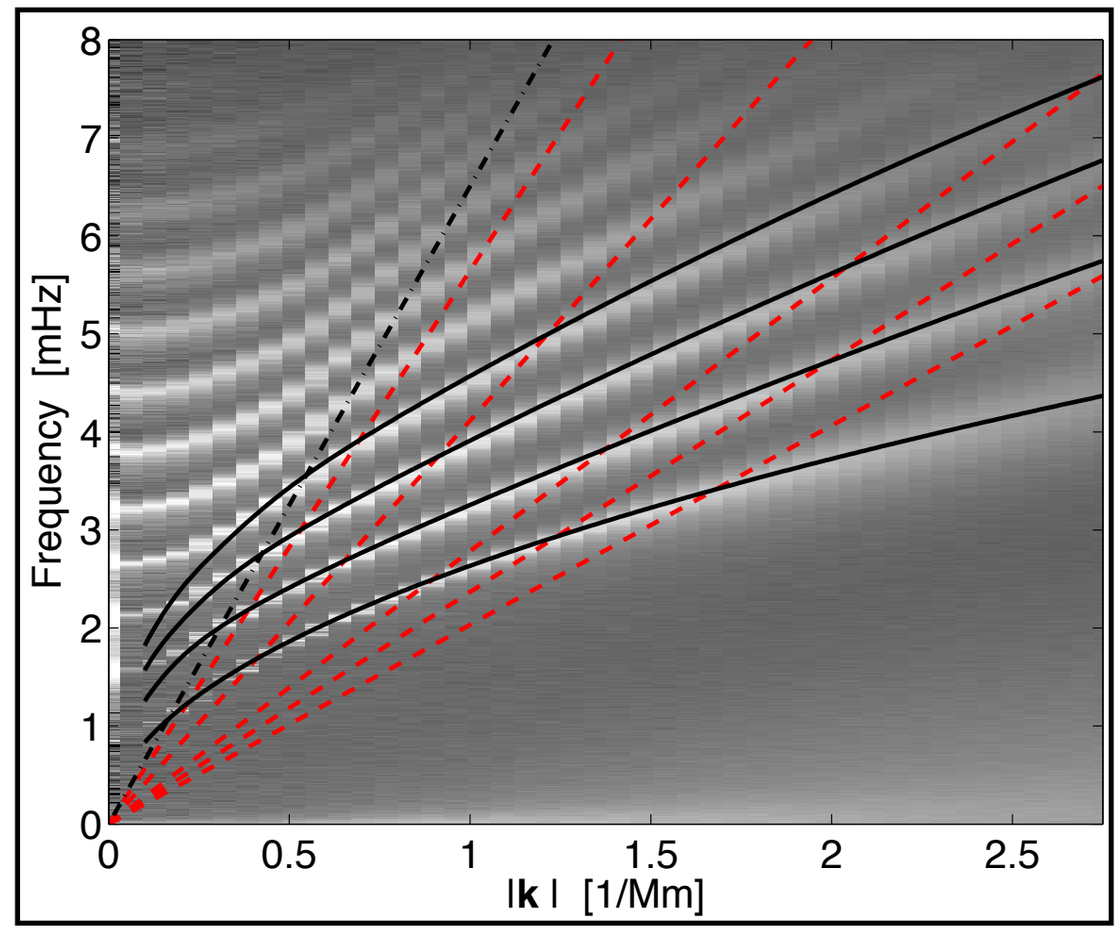
- Use two sims (LRes, HRes)
- Provided by M. Rempel (Rempel 2009 a,b)
- Each is ~98x98x18 Mm
- HRes. of 48x48x24 km
- LRes. of 128x128x48 km
- HRes formed and maintained a penumbra, LRes had no penumbra ("pore")
- Both contain large-scale flow structures away from spot (Fig, time avg'd vx) - vel's high
- Surface gravity and acoustic waves



Data Filtering

- Doppler time series at tau = 0.01 layer (45 sec) spanning 25 hr.
- Filter out waves whose travel times we would like to measure
- Tested two filter types: phase-speed (common phase-speed and ~depth) and ridge (common radial order) (Fig)
- Ridge filters f-p3 centered on solid black
- First five ps filters from Couvidat et al. (2006) (td1-td5) dashed red
- Power turns up (bound. effect reflections) - Above 12 Mm (40 km/s) dash-dot line
- Filters applied by a multiplication in the Fourier domain

HRes Power

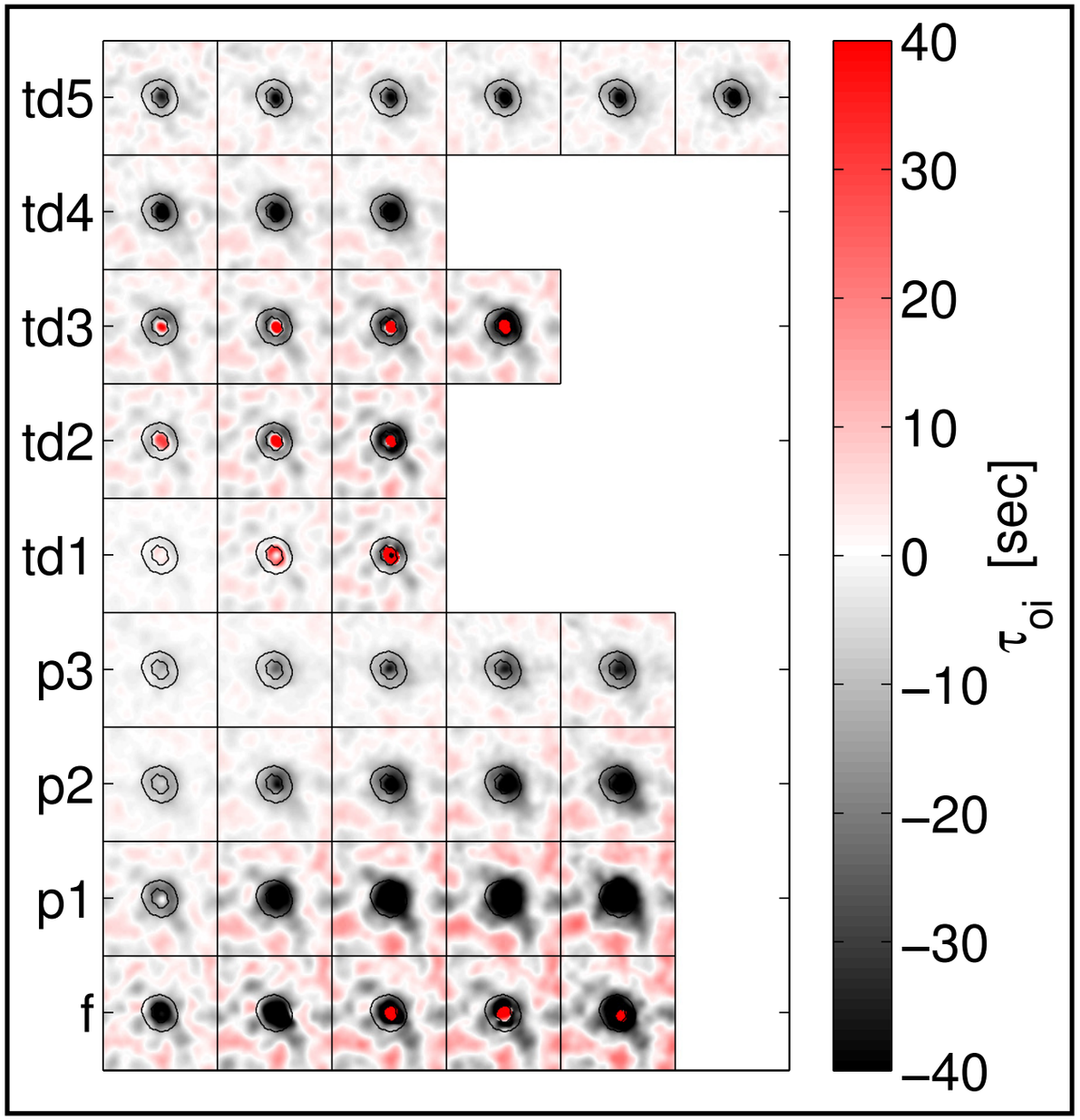


Travel Times

- Two definitions: Gizon & Birch (2002, 2004)
  - GB02 and GB04
  - GB04 linearized version of GB02 (xcorr phase and amp)
  - Trivial to compute

- Travel times measured in the center-to-annulus and quadrant configurations
  - out-in (oi), west-east (we), north-south (ns) (Fig, Δ inc. left to right)

- GB02: ttoi ± changes with filter type and measurement Δ
  - Δ change also seen by Braun & Birch (2008), Couvidat (2012)
  - GB04 almost uniformly positive for both sims (inflow)

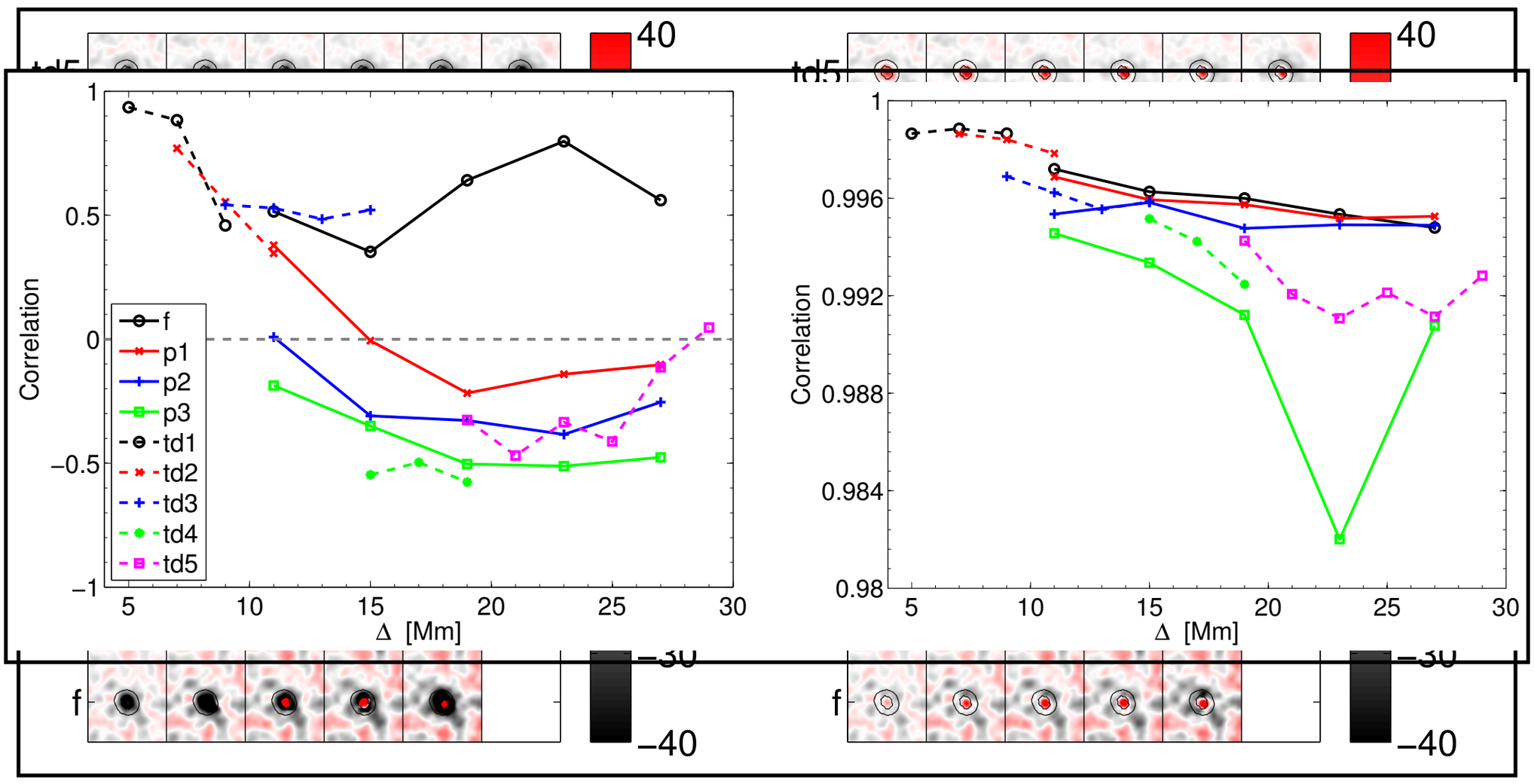


HRes GB02 ttoi, filters

Travel Times

- The two definitions agree pretty well away from spots (Fig 1)
- Correlate GB02 & GB04 tt's for all filters and distances (Fig 2)
- Then apply circular mask of radius 25 Mm and correlate again (Fig)
  - Past 25 Mm, GB02 and GB04 show good correlation (>0.98)

HRes GB02 (L), GB04 (R) ttoi



Forward-Modeled tt's

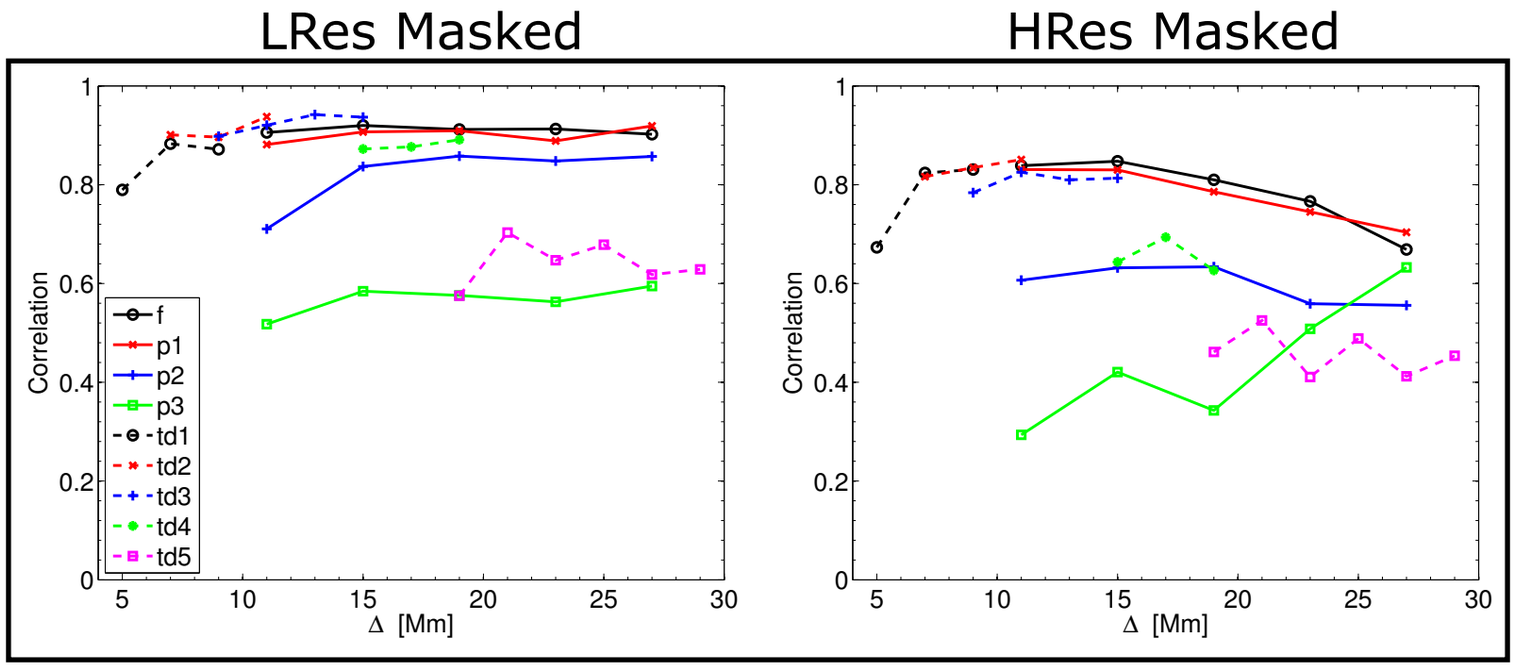
- Kernels in Born: computation of kernels depends on accurate modeling of simulation power spectra
  - Find QS and spot simulation power spectra identical in the sense that they matched the model power equally well
  - And we don't account for B-field in kernel computation

- Simulated data allows us to test kernel performance through forward modeling
  - Convolution between kernels and actual simulation flow fields

- If kerns perfect and no tt noise, FM should match measured tt's perfectly
  - Always some level of noise, don't account for B-field (might expect significant mismatch)

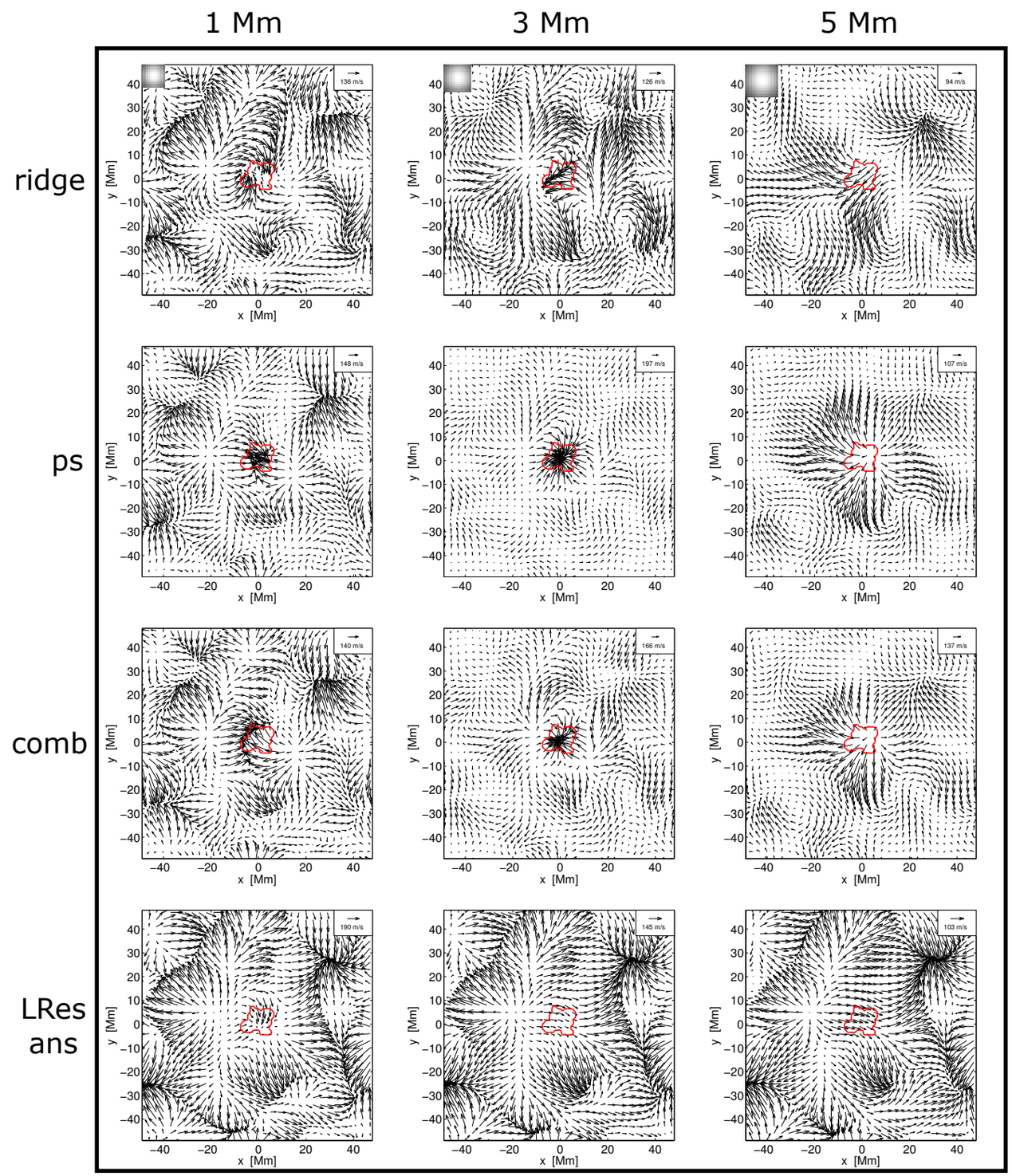
- FM oi tt's computed and correlated with measured ones (Fig, masked)

- High corr., but bad corr. for p3 and td5 (same as QS)



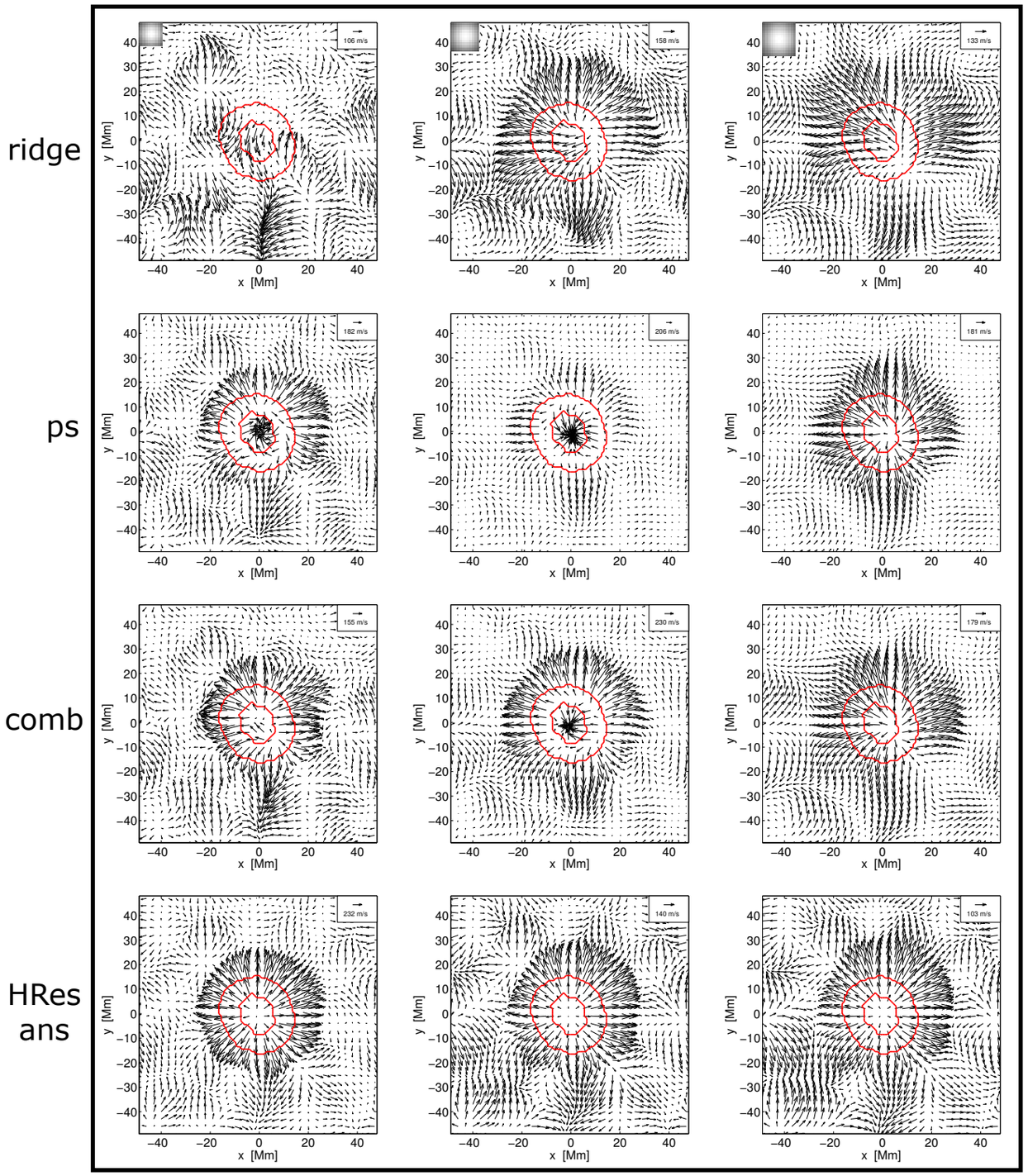
SOLA LRes vh Inversions

- Quick - can use the already-computed QS weights (same kernels and travel-time noise)
- (Fig) Each row shows flow maps recovered by inverting diff. set of GB02 tt's
- Each column is a diff. depth
  - Bottom row are sim. flow maps
- 1 Mm - Capture much of the overall flow structure away from spot (flows only effected in umbra)
- 3 Mm - Some struct. still visible, but surrounding flows washed out by large flows in umbra
- 5 Mm - Sign change around spot (outflow now)
- None of this flow structure is visible in the actual simulation



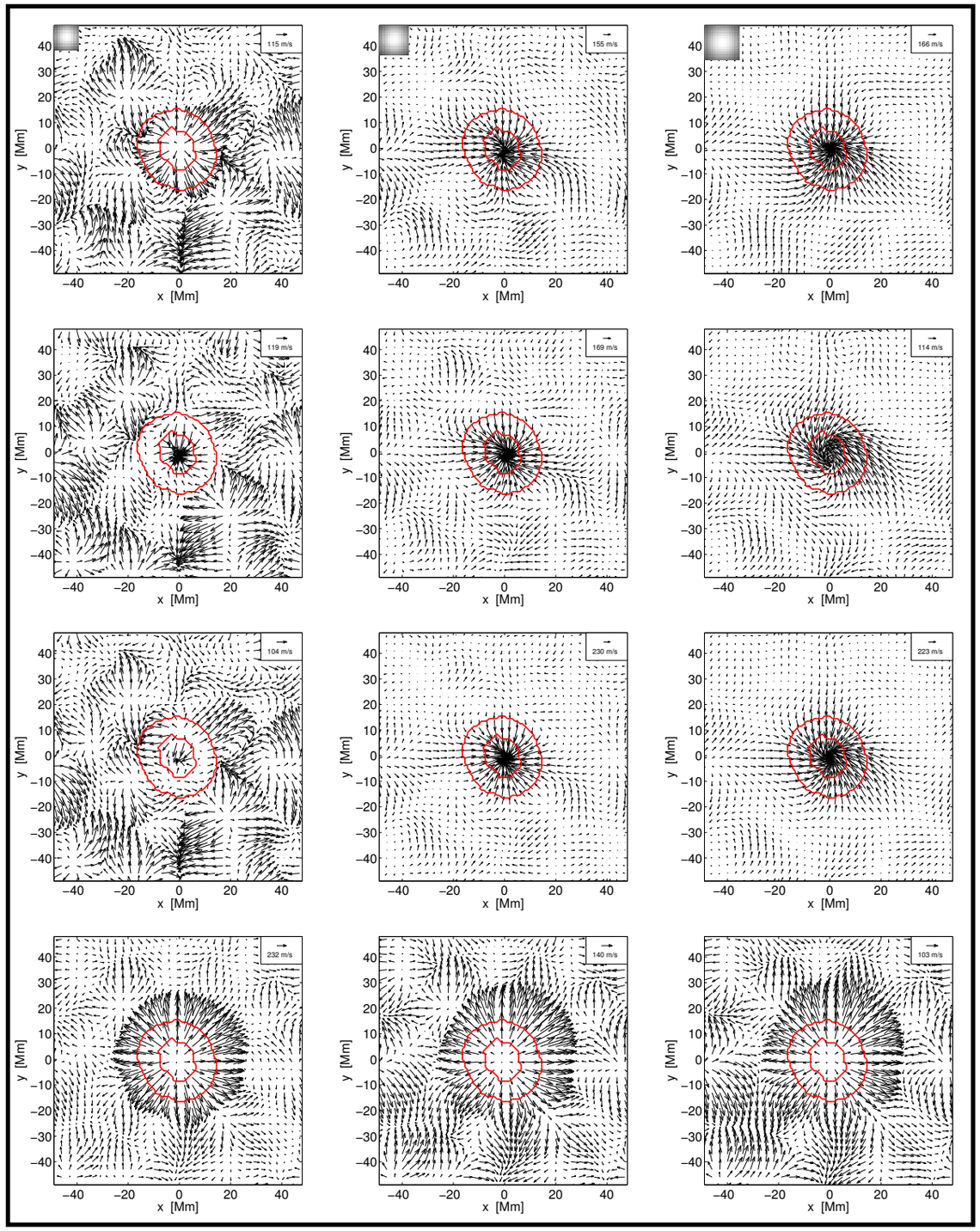
HRes vh Inversion Results

Both GB02 and GB04 shown here



HRes see moat flow - Hard to tell both do okay away from spot

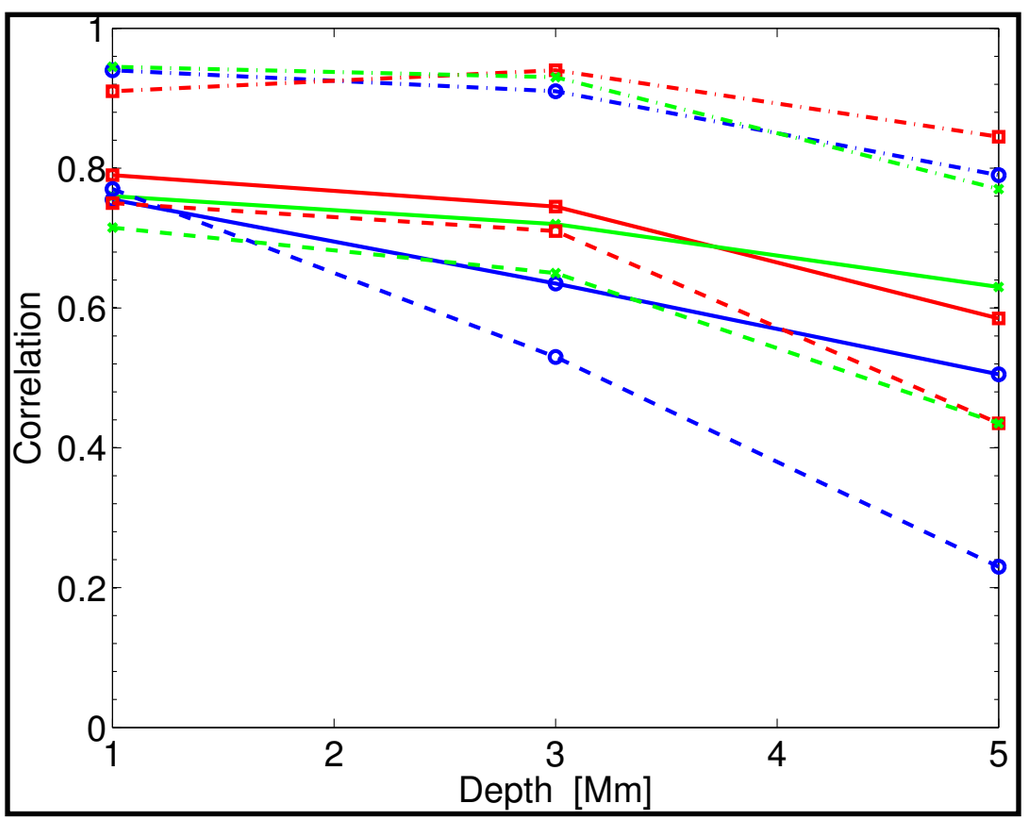
1 Mm 3 Mm 5 Mm



GB02 gets moat flow (not GB04), inflow seen in umbra

HRes Correlations

- I said they agree well outside of the spots - mask and correlate inv's and answer (Fig)
  - Filter type is given by line color, but don't worry about that now
  - Solid lines are GB02 and dashed are GB04 (agree well in upper 3 Mm)
  - Inverted forward-modeled correlations are very high (kind of weird?)



Spot Conclusions

- Able to recover flow structure in upper 3 Mm, but only at sufficiently large distances from these magnetic features (~30 Mm)

- Consistently underestimate flow amplitudes (like quiet Sun sims)
  - Could be non-linearities due to strong flows? (many >500 m/s)

- No single “best” filtering scheme
  - Ridge, ps, comb filtering
  - ps and comb give comparable results, ridge worst

- Inversions of GB02 tt’s are more robust (suggested before)

- Inversions of forward-modeled tt’s outperform those of measured tt’s in terms of horizontal flow correlations
  - Probably highlights our inability to accurately measure travel times around strong magnetic features

Sensitivity Kernels

- Need to relate surface tt measurements to subsurface conditions present in simulations

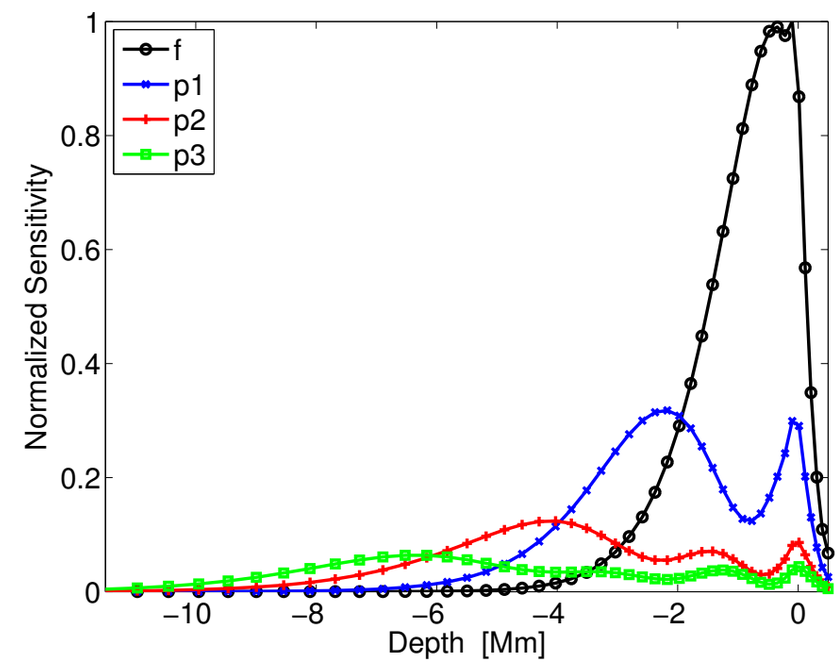
$$\delta\tau^a(\boldsymbol{r}) = h_r h_z \sum_{ij} \boldsymbol{K}^a(\boldsymbol{r}_i - \boldsymbol{r}, z_j) \cdot \boldsymbol{v}(\boldsymbol{r}_i, z_j) + N^a(\boldsymbol{r})$$

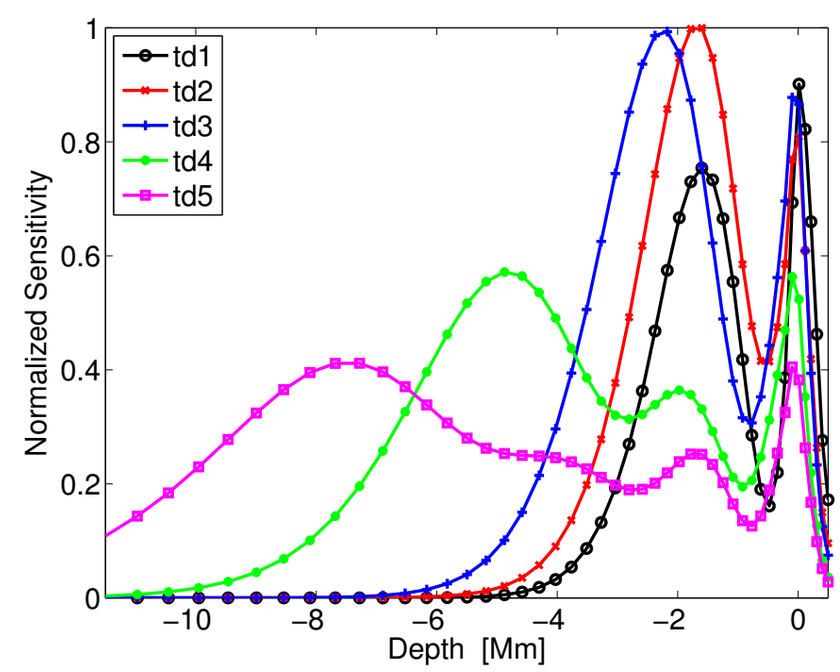
- Represent the sensitivity of wave travel times to flows

- This is a linear relationship between tt's and flows
  - Assumes tt's vary linearly with the subsurface perturbation

- Set of kernels in Born approximation (Birch 2007)
  - One set per filter, per Δ (Fig, hor. avg.)

- Note: B-field perturbations not accounted for in kernel computation
  - Significant consequences



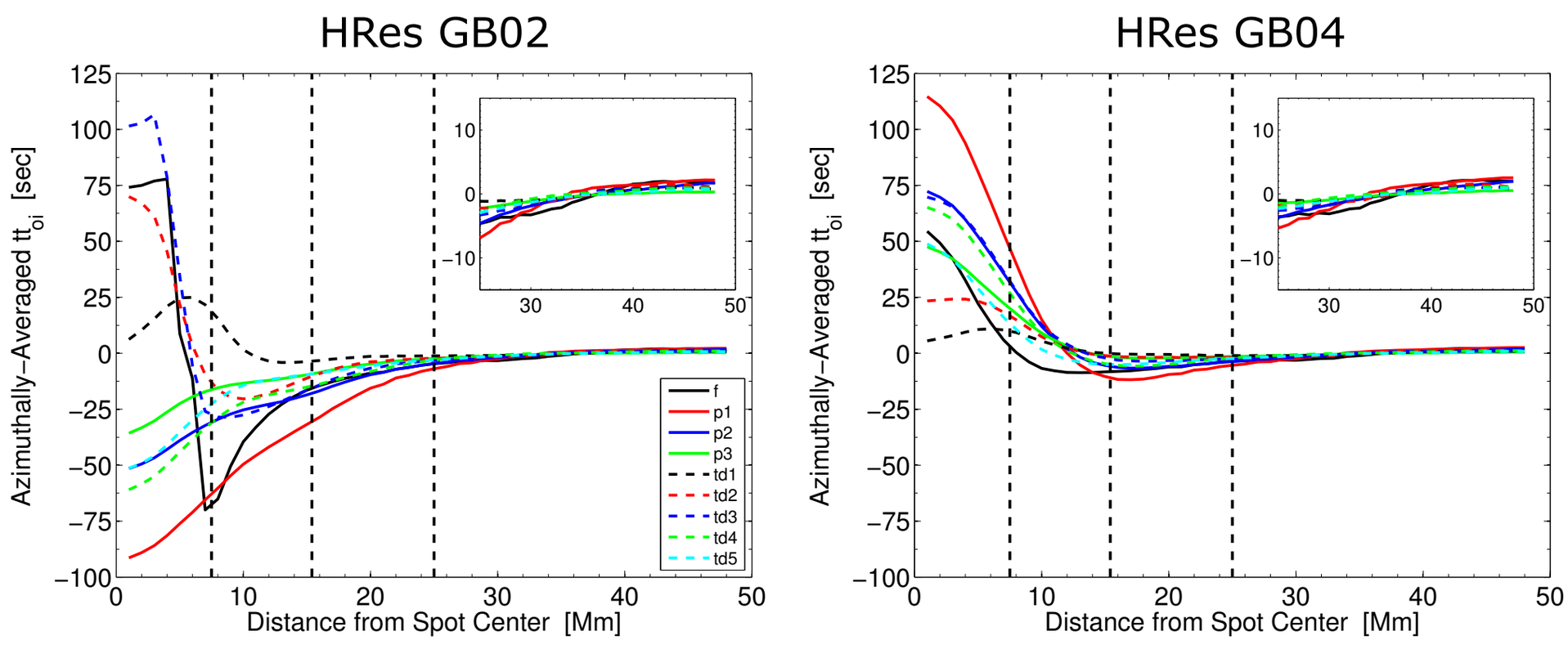


Spot Intro

- A major goal in solar physics is to understand the subsurface structure of sunspots, as they are a dominant feature at the solar surface
- Despite abundant surface observations, there is no general consensus about their subsurface properties
- Helioseismic results regarding spot structure are often mixed regarding depth (shallow, deep?) and flow structure
- Goal: use two of the most realistic spot simulations we have available to us to test performance of TD helioseismic methods (flows)
- Disclaimer: We don’t expect to accurately recover flows near spot (see what happens)
- Identical to QS in terms of filtering, kernels, tt’s, inversions (weights)

Travel Times

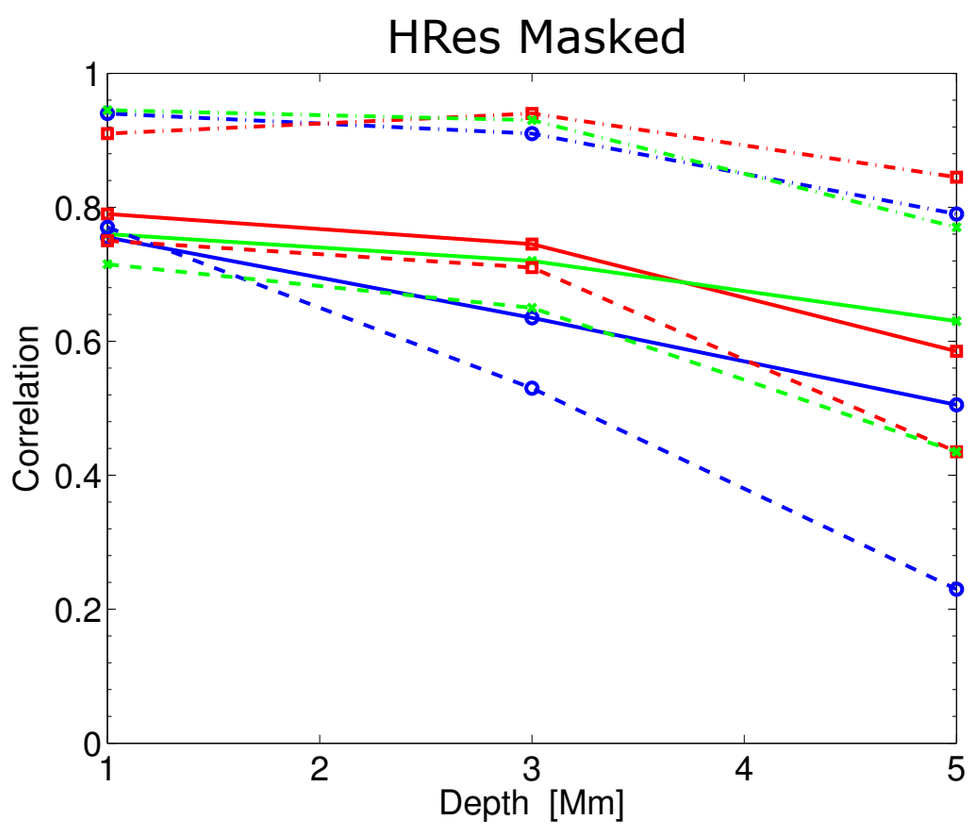
- Illustrate comparison another way: Azim-avg oi tt's around spot center rad profile (Fig)
- Dashed lines are boundaries of umb., pen., 25 Mm mask
- Inset plots >25 Mm
- Effect of B-field evident near spot (sign diff. between GB02 and GB04)
- Agreement at 25-30Mm, then small values

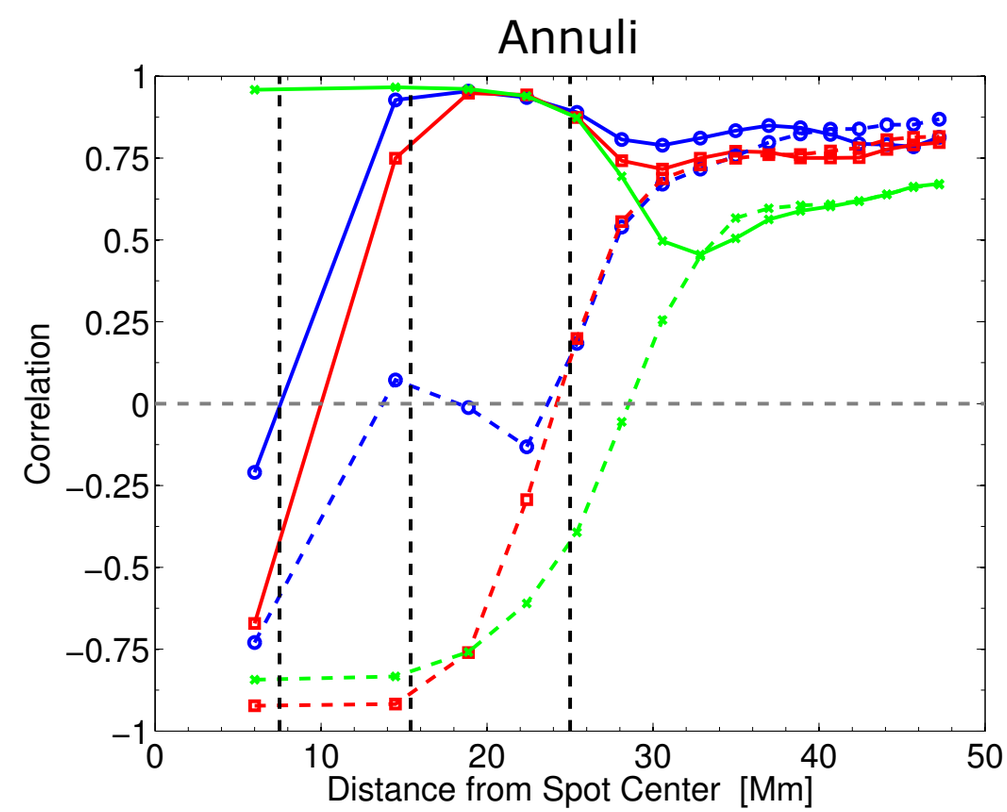


HRes Correlations

- I said they agree well outside of the spots - mask and correlate inv's and answer (Fig 1)
  - Filter type is given by line color, but don't worry about that now
  - Solid lines are GB02 and Dashed are GB04 (agree well in upper 3 Mm)
  - Inverted forward-modeled correlations are very high (kind of weird?)

- Another test: correlate annuli of increasing radii (but same area) (Fig 2)
  - See how corr. changes with distance from spot center
  - Solid lines are GB02 and dashed are GB04
  - Find agreement after ~30 Mm





Quiet Sun Helioseismology

- Before jumping in to the active regions, first validate using quiet-Sun simulations - if promising, then go on to more complicated

- Couple of previous QS validation studies: Zhao et al. (2007) inversions in ray approximation of convective sims by Benson et al.
  - Good horizontal flow correlation, but bad vertical

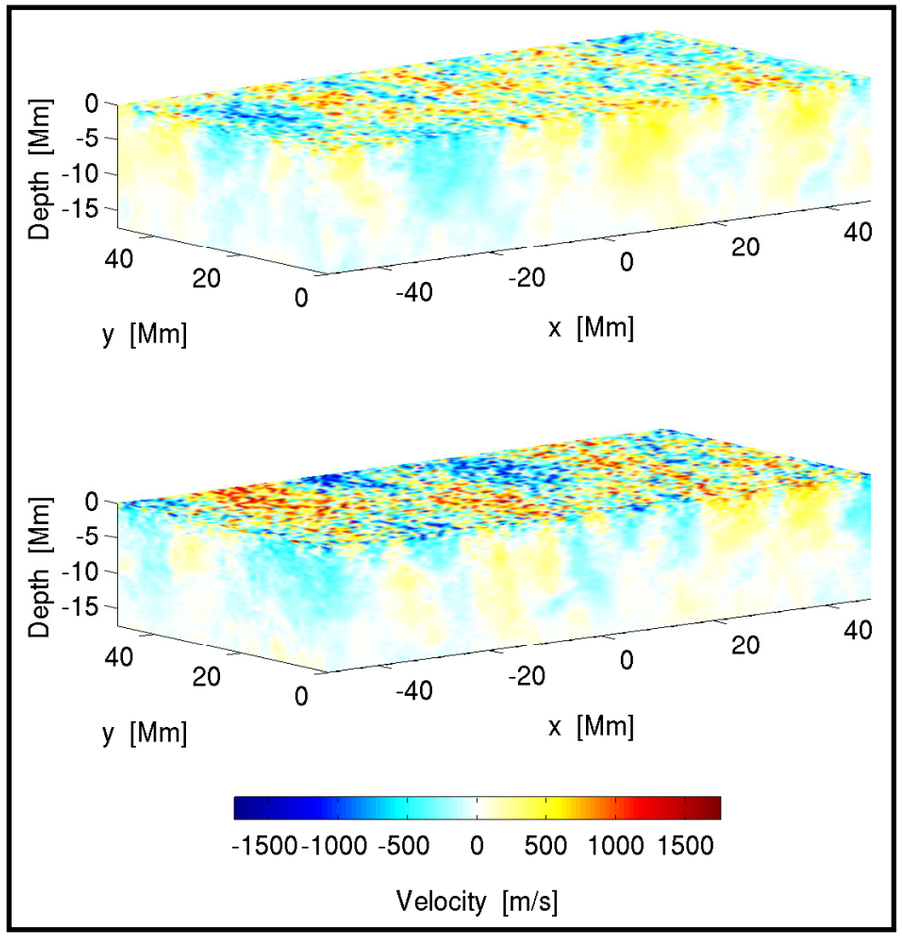
- Svanda et al. (2011) invert FM travel times
  - Good horizontal and improved vertical flow correlations
  - Implemented regularization parameters to minimize x-talk

- How do our inversions compare?

- Some detail about data filtering, tt's, kerns, etc. (sunspot analysis is same)

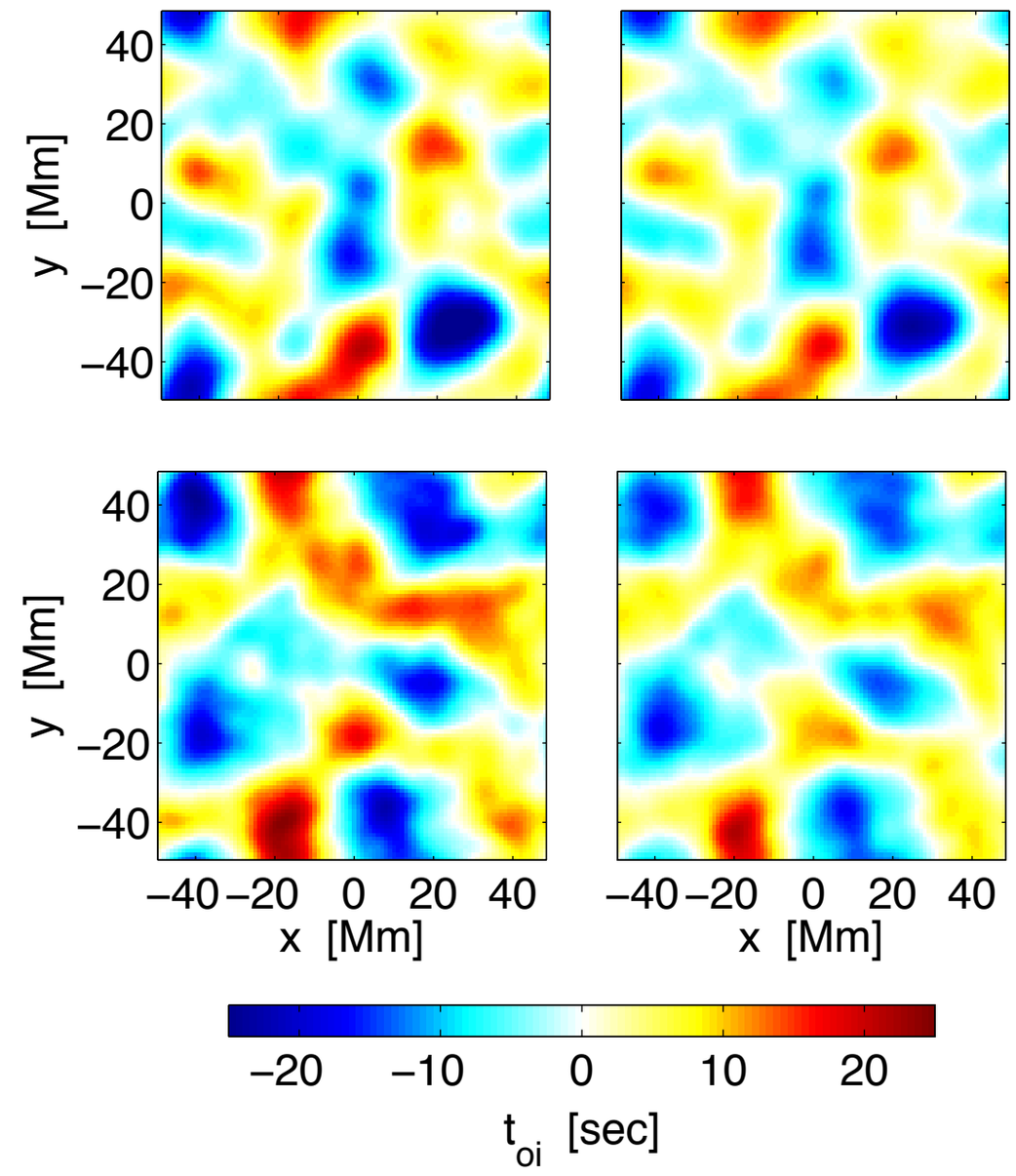
QS-Simulations

- Use two QS-sims (QS1, QS2) - 20 hrs
- Provided by M. Rempel (Rempel 2009 a,b)
- Each is ~98x98x18 Mm
  - QS1 64x64x32 km
  - QS2 128x128x48 km (Fig, vx)
- Periodic boundary conditions, and both are magnetic
- Both contain large-scale supergranule-sized flows (fast) which extend deeply through domains
- Surface gravity and acoustic waves



Travel Times

- Wave travel times meas. by finding difference between measured cross-covariances between pairs of points and a reference cross-covariance function
- Two definitions: Gizon & Birch (2002, 2004) - GB02 and GB04
- Travel times measured in the center-to-annulus and quadrant configurations
- Measured over 11-29 Mm inc. of 4 Mm
- One tt-map per distance, per filter (117 measurements) (Fig, large flows)
- Corr > 0.99, GB04 10% larger



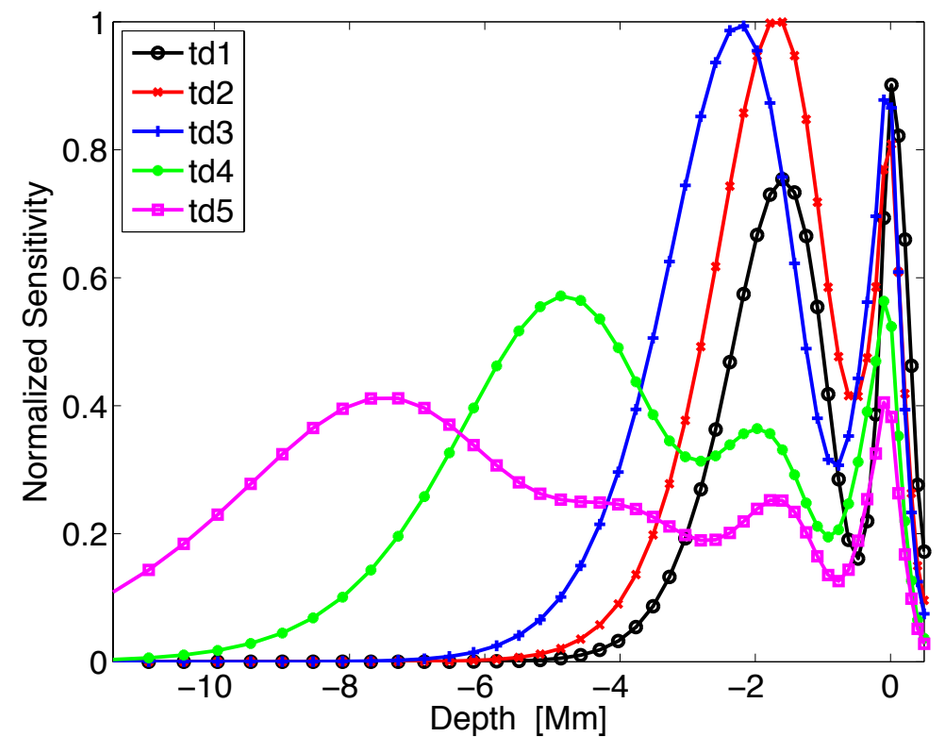
GB04 ttoi QS1, QS2, p2 (L), td3 (R)

Sensitivity Kernels

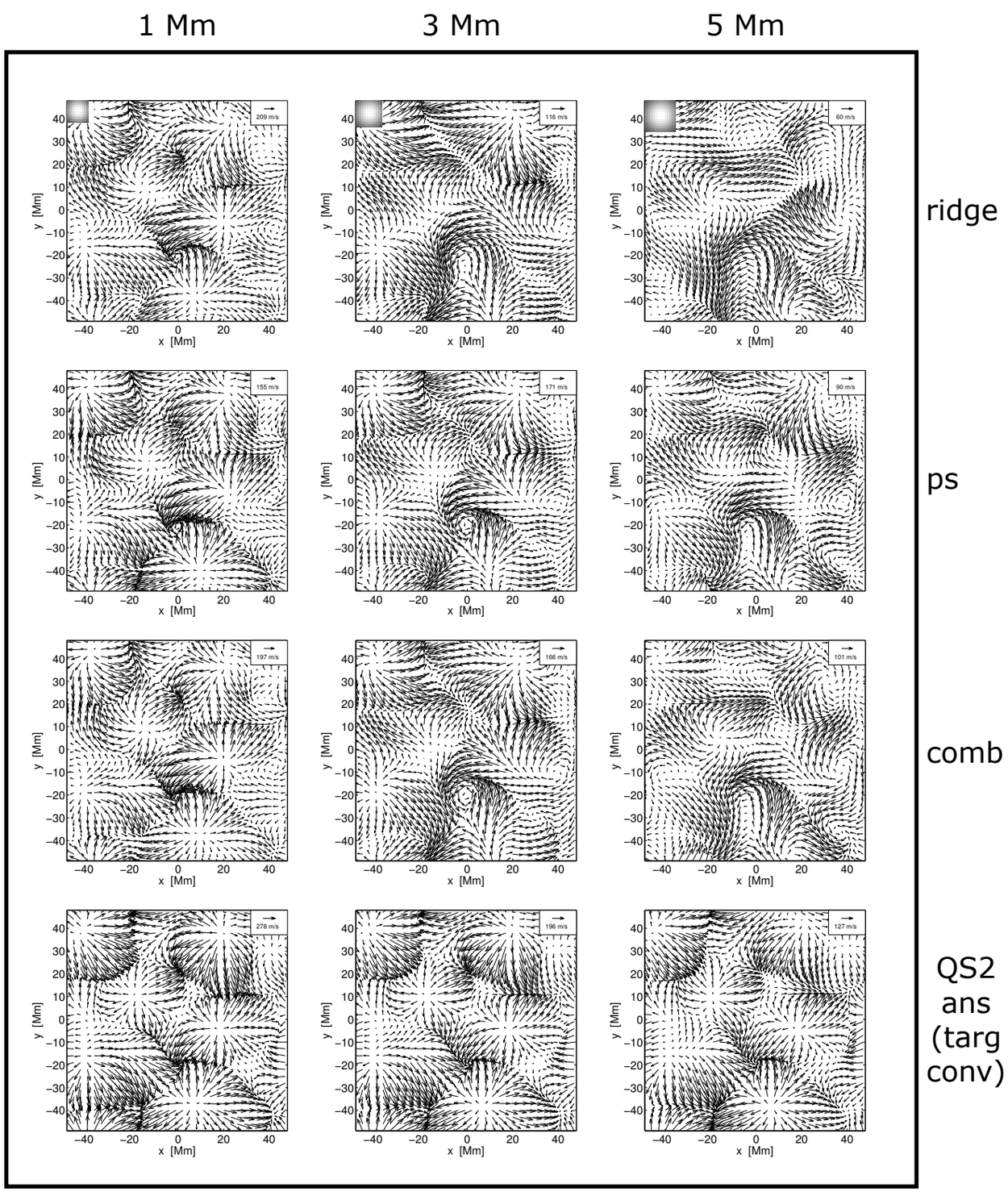
- Need to relate surface tt measurements to subsurface conditions present in simulations
- Represent the sensitivity of wave travel times to flows

$$\delta\tau^a(\boldsymbol{r}) = h_r h_z \sum_{ij} \boldsymbol{K}^a(\boldsymbol{r}_i - \boldsymbol{r}, z_j) \cdot \boldsymbol{v}(\boldsymbol{r}_i, z_j) + N^a(\boldsymbol{r})$$

- This is a linear relationship between tt perturbation and flows
- Set of kernels in Born approximation (Fig, hor. avg.)
- Can compute FM tt's by convolving kernels and sim flows - compare to measured ones
- High corr. between meas. and modeled tt's, except p3 and td5 (modeling issue?) (Fig)



SOLA Inversions (vh) QS2



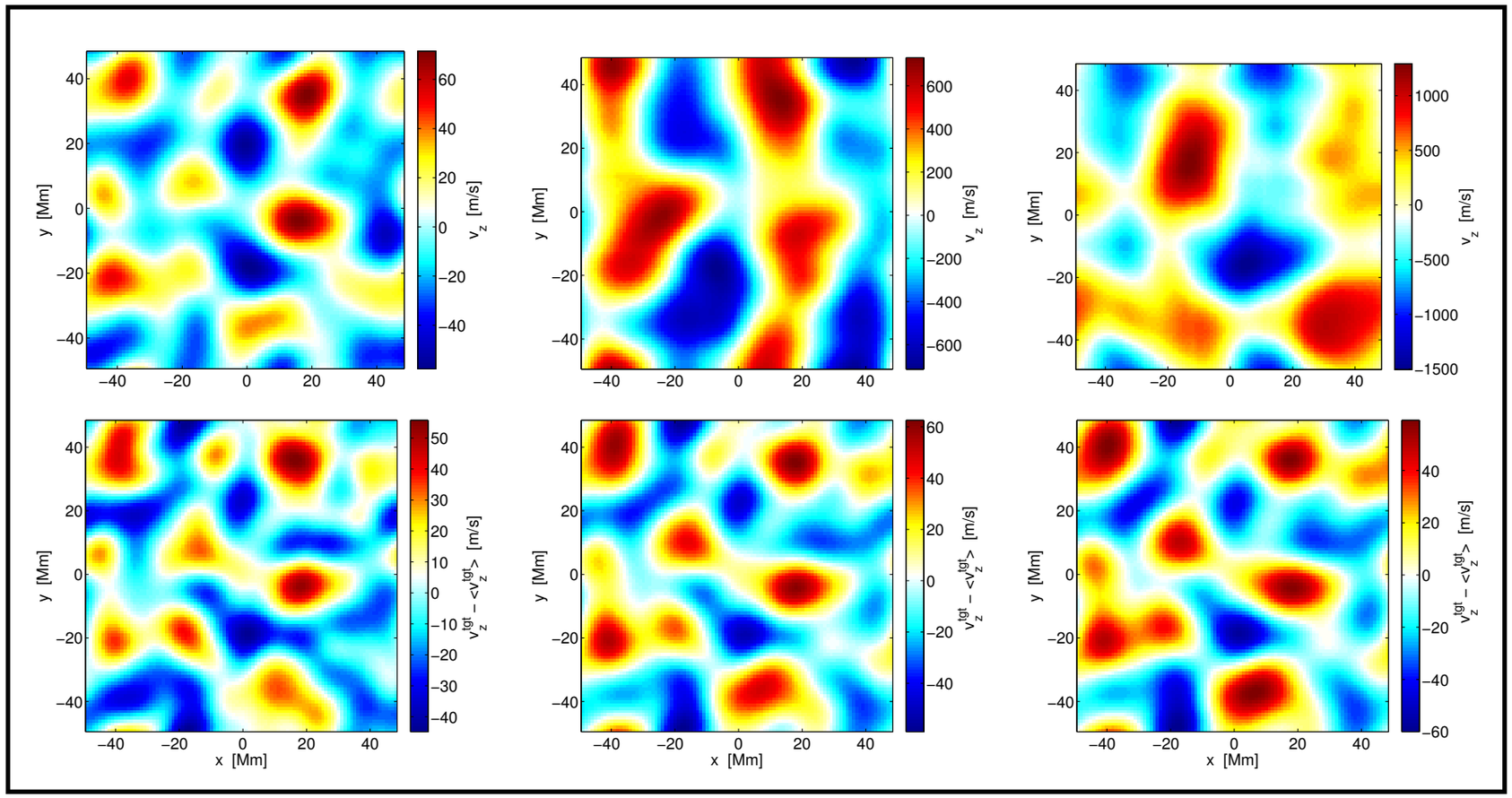
noise = 35 m/s

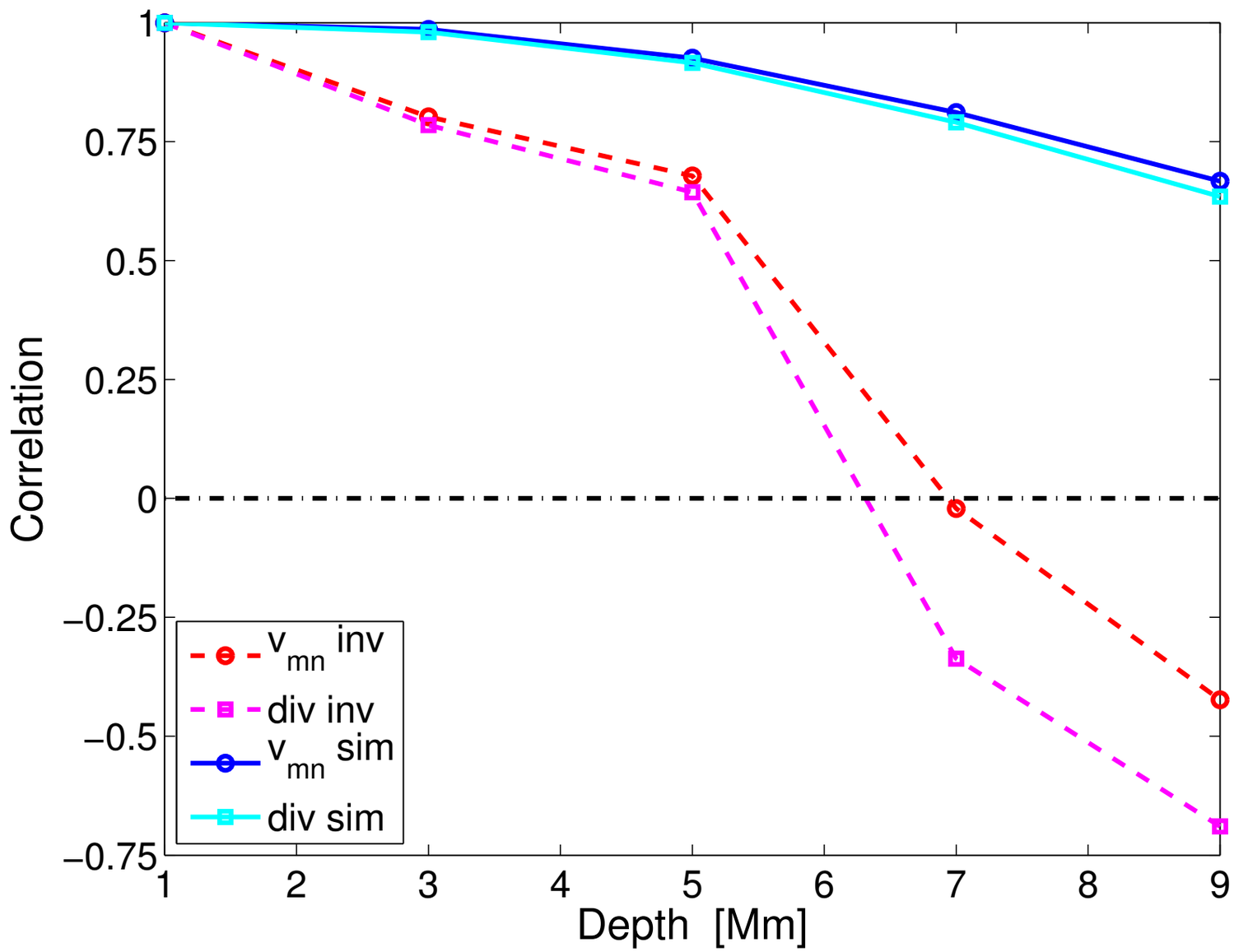
- Each row inv's by inverting diff. set of tt's
- Each column is a diff. depth
- Results reliable in upper 3 Mm
  - Corrs. 0.9, 0.8, 0.6
- Underestimate flow vel's by 50%
- ps slightly better, ridge is the worst

QS2 vz Inversions

- Implemented weight and x-talk constraints Svanda et al. (2011) (Fig)
- Phase-speed: QS2 okay at 1 Mm, all others very bad
- QS1 bad at all depths

ps inversions best
cols: 1, 3, 5 Mm




1
0.75
0.5
0.25
0
−0.25
−0.5
−0.75
Correlation
1
2
3
4
5
6
7
8
9
Depth [Mm]
v mn inv
div inv
v mn sim
div sim

Spot Intro

- A major goal in solar physics is to understand the subsurface structure of sunspots, as they are a dominant feature at the solar surface

- Despite abundant surface observations, there is no general consensus about their subsurface properties
  - Mechanism of formation
  - How they are assembled and transported through the convections zone
  - What their 3D subsurface structure is

- They are of particular importance as they are a product of the solar dynamo, and are associated with energetic solar events like flares and coronal mass ejections

- Helioseismic results regarding spot structure are often mixed regarding depth (shallow, deep?) and flow structure

- Goal: use two of the most realistic spot simulations we have available to us to test performance of TD helioseismic methods (flows)

- Disclaimer: We don’t expect to accurately recover flows near spot (see what happens)

- Identical to QS in terms of filtering, kernels, tt’s, inversions (weights)

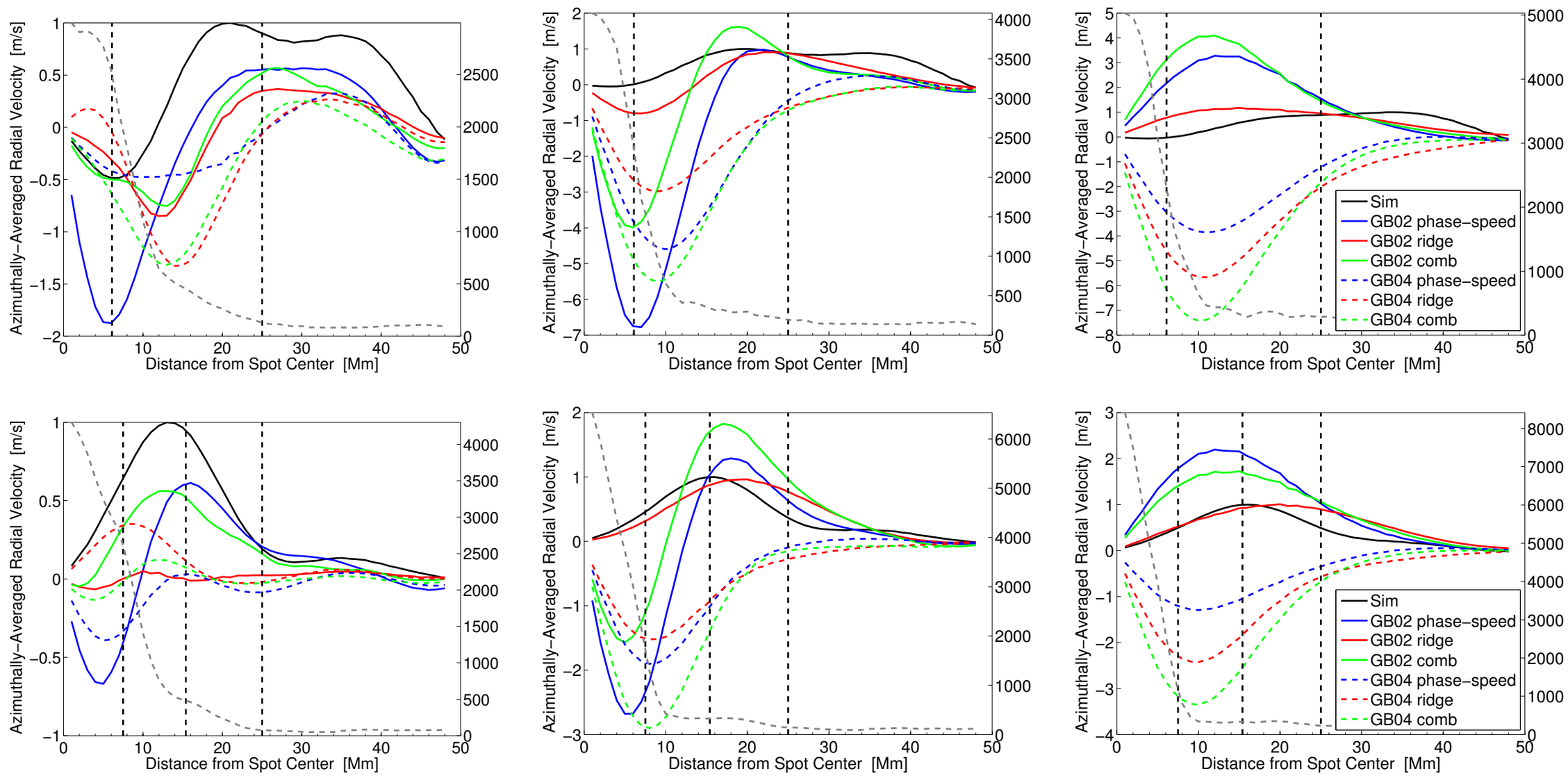
10) Quick QS Conclusions

- Horizontal inversion results correlate well with simulation flow maps in upper 3 Mm of domains (0.8-0.9), but worse deeper

- We consistently underestimate flow amplitudes
  - Possibly suggests some non-linearity of the forward problem due to strong flows in the sims (>500 m/s)

- Phase-speed filtering scheme slightly outperformed the others in terms of flow correlations in the upper 5 Mm

- Vertical inversions show very poor correlation with simulation flow maps at nearly every depth


Azimuthally−Averaged Radial Velocity [m/s]
Distance from Spot Center [Mm]
Sim
GB02 phase−speed
GB02 ridge
GB02 comb
GB04 phase−speed
GB04 ridge
GB04 comb