Deep Meridional Flow Inversions with Spherical Born Kernels and Time-Distance Helioseismology

Vincent Böning, Shukur Kholikov, Jason Jackiewicz, and Markus Roth

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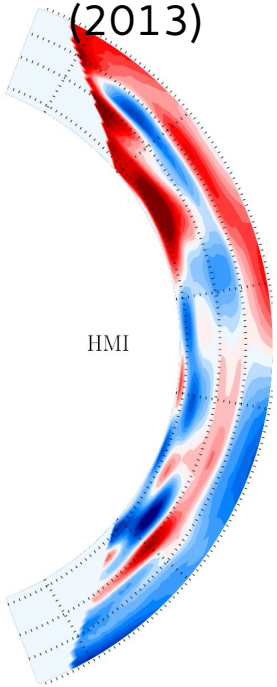
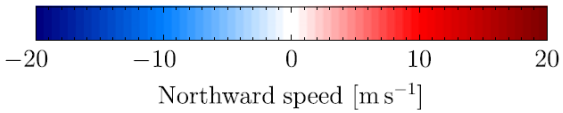
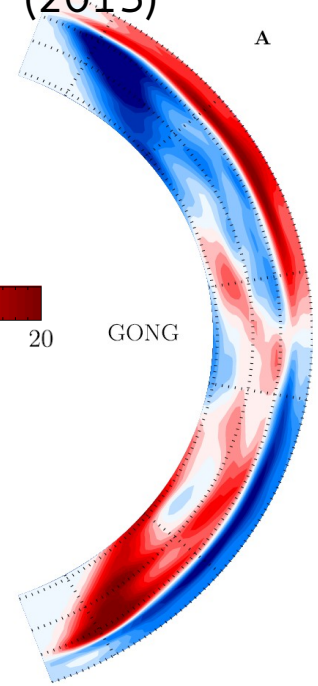
Solar Meridional Flow Inversions from Time-Distance (TD)

Zhao et al. (2013)

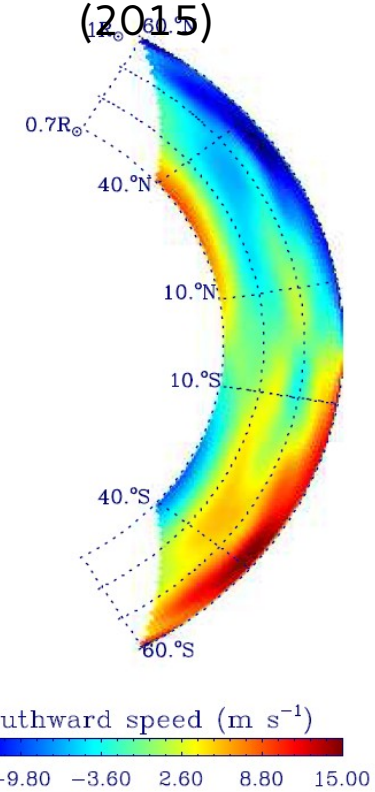




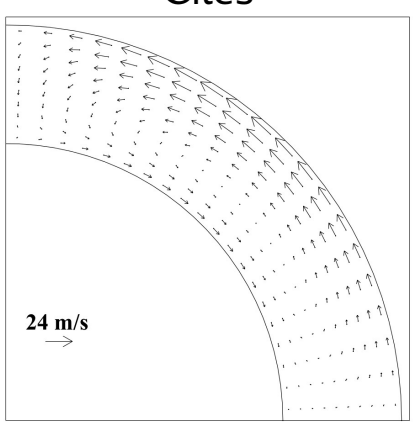
Jackiewicz et al. (2015)

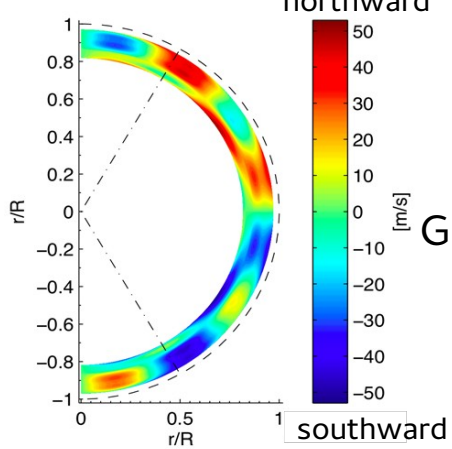


Rajaguru & Antia (2015)



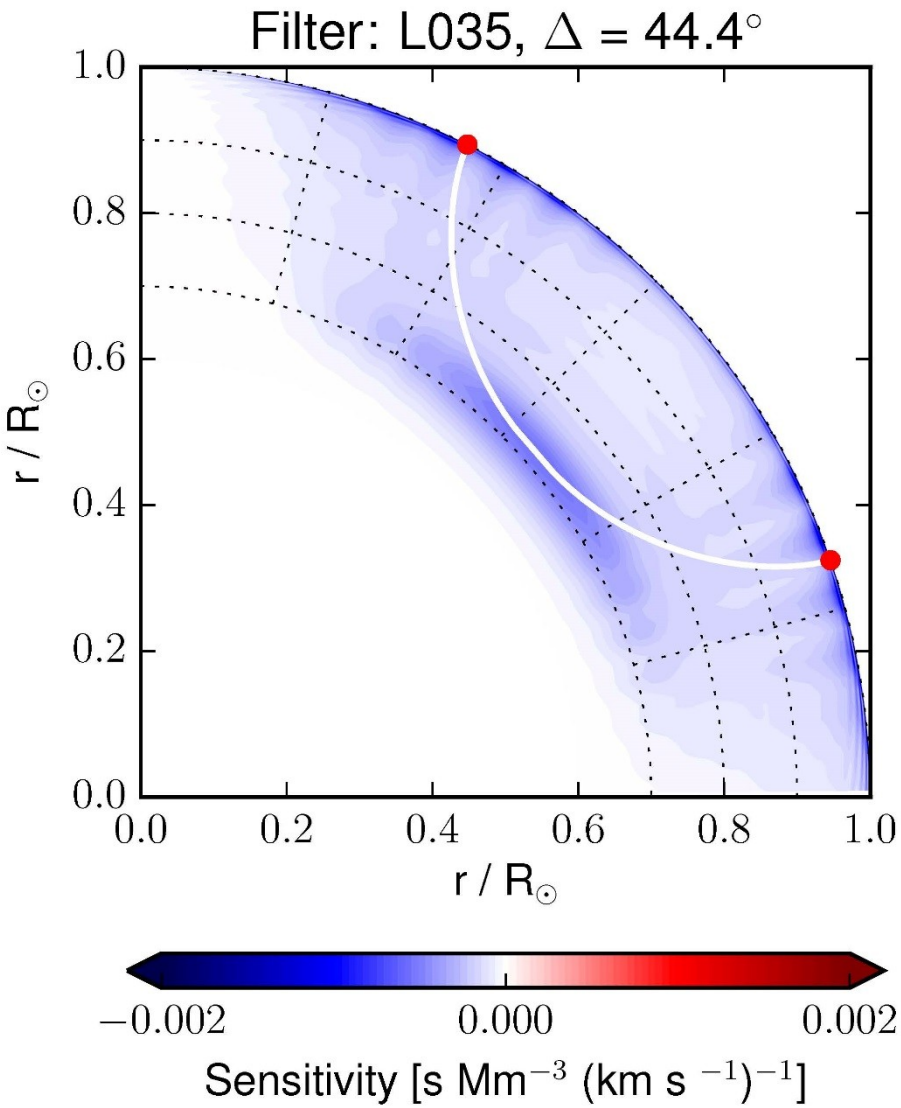
Giles





Schad et al. (2013), Global Helioseism. (not TD)

Time-Distance Helioseismology: Born vs. Ray Kernels

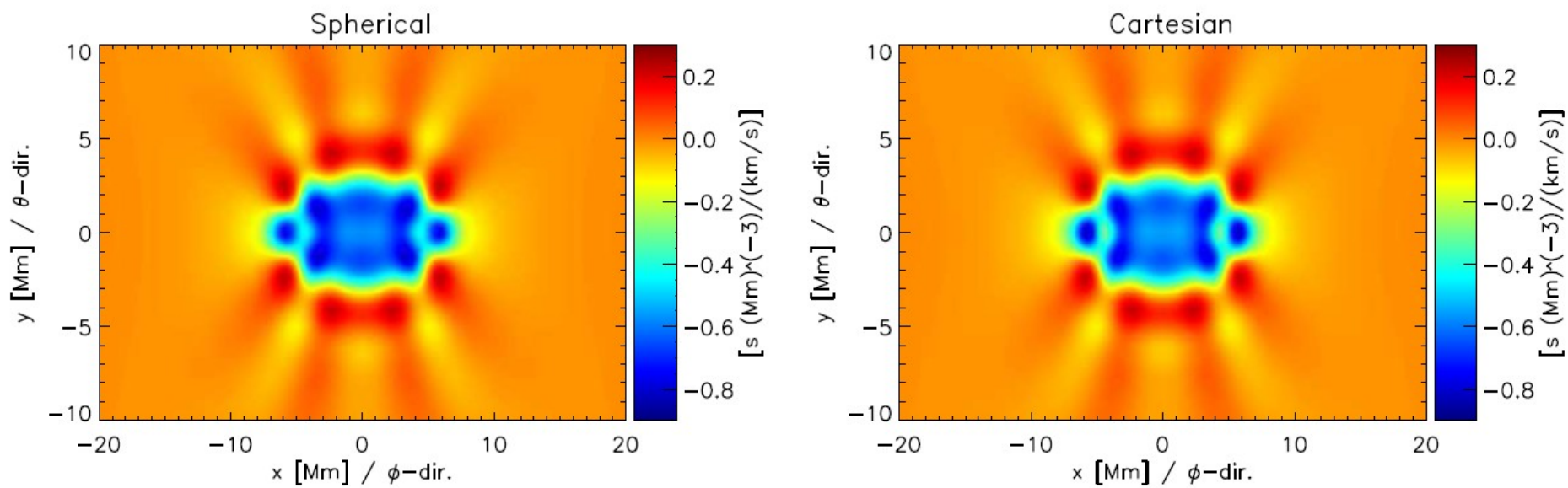


$$\underbrace{\delta\tau_{\mathrm{diff}}^{(i)}}_{\text{observations}} = \int \underbrace{\mathbf{K}^{(i)}(\mathbf{r})}_{\text{model}} \cdot \underbrace{\mathbf{v}(\mathbf{r})}_{\text{flow}} \, \mathrm{d}^3\mathbf{r} + \underbrace{\epsilon^{(i)}}_{\text{errors}}$$

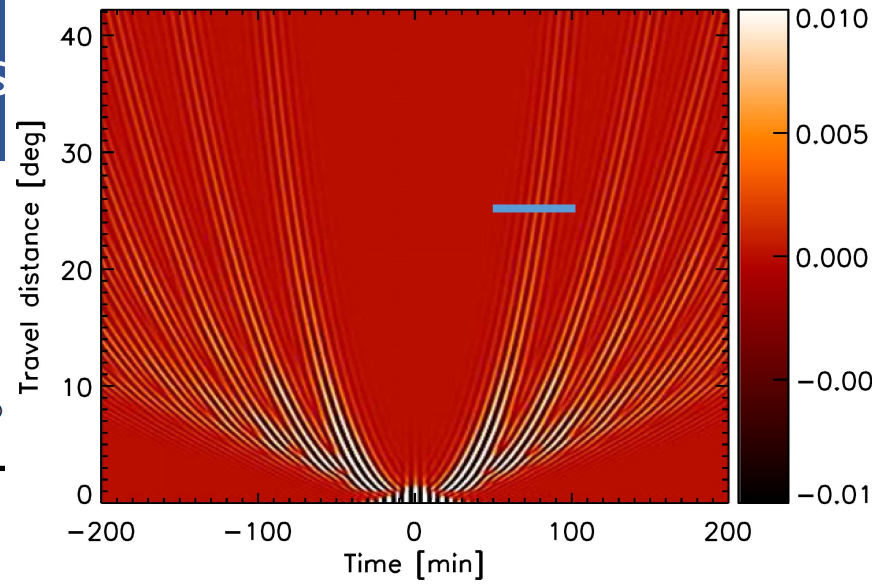
- „Kernel = model"
- Ray kernel:
  - sensitive only along ray path
- Born kernel
  - models complete wave-field in the solar interior
  - via expansion into eigenmodes
  - first-order effect on travel-times

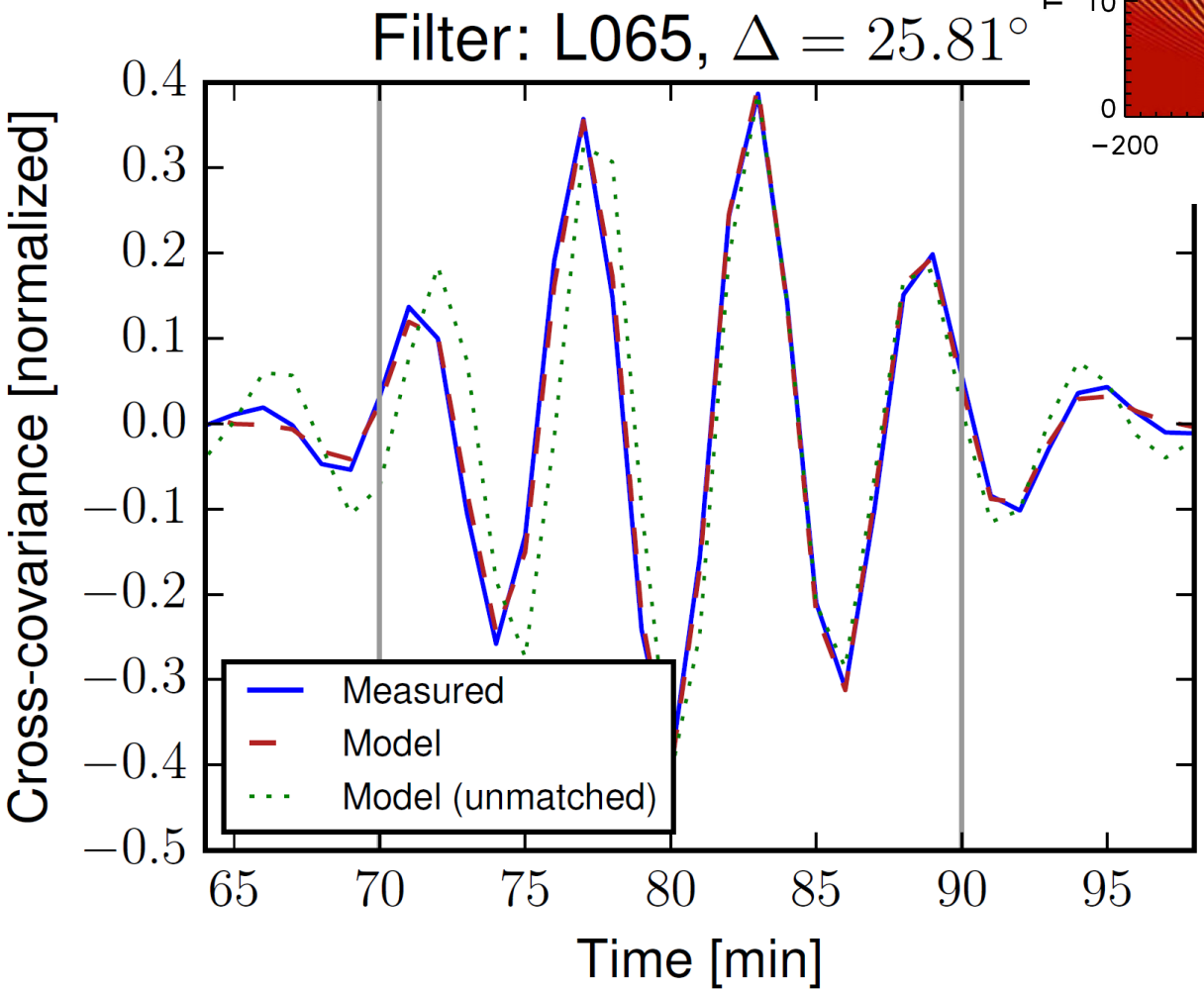
Born Kernels: Spherical vs. Cartesian

- General framework: Gizon & Birch (2002)
- **Cartesian kernels for flows**: Birch & Gizon (2007)
- **Spherical kernels for flows:** Böning et al. (2016)
- Sanity check: Successful.



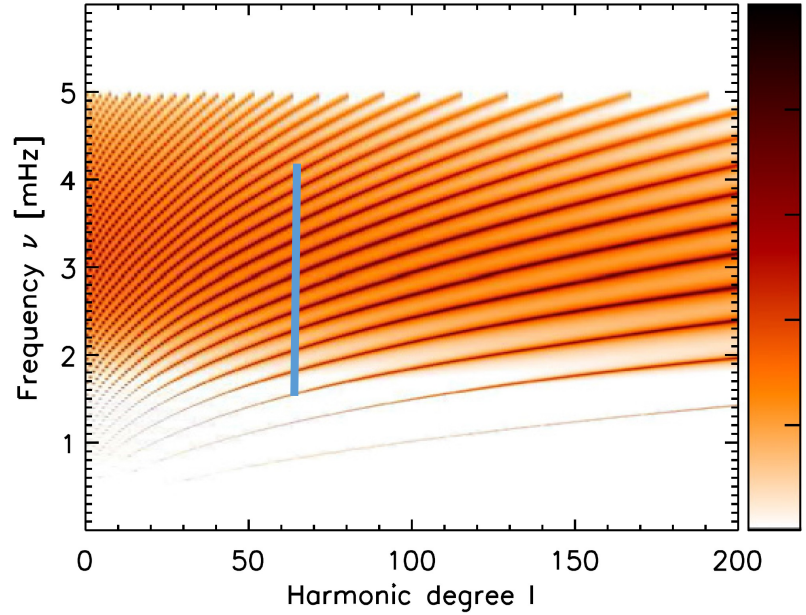
Validation: Cross-Covariances

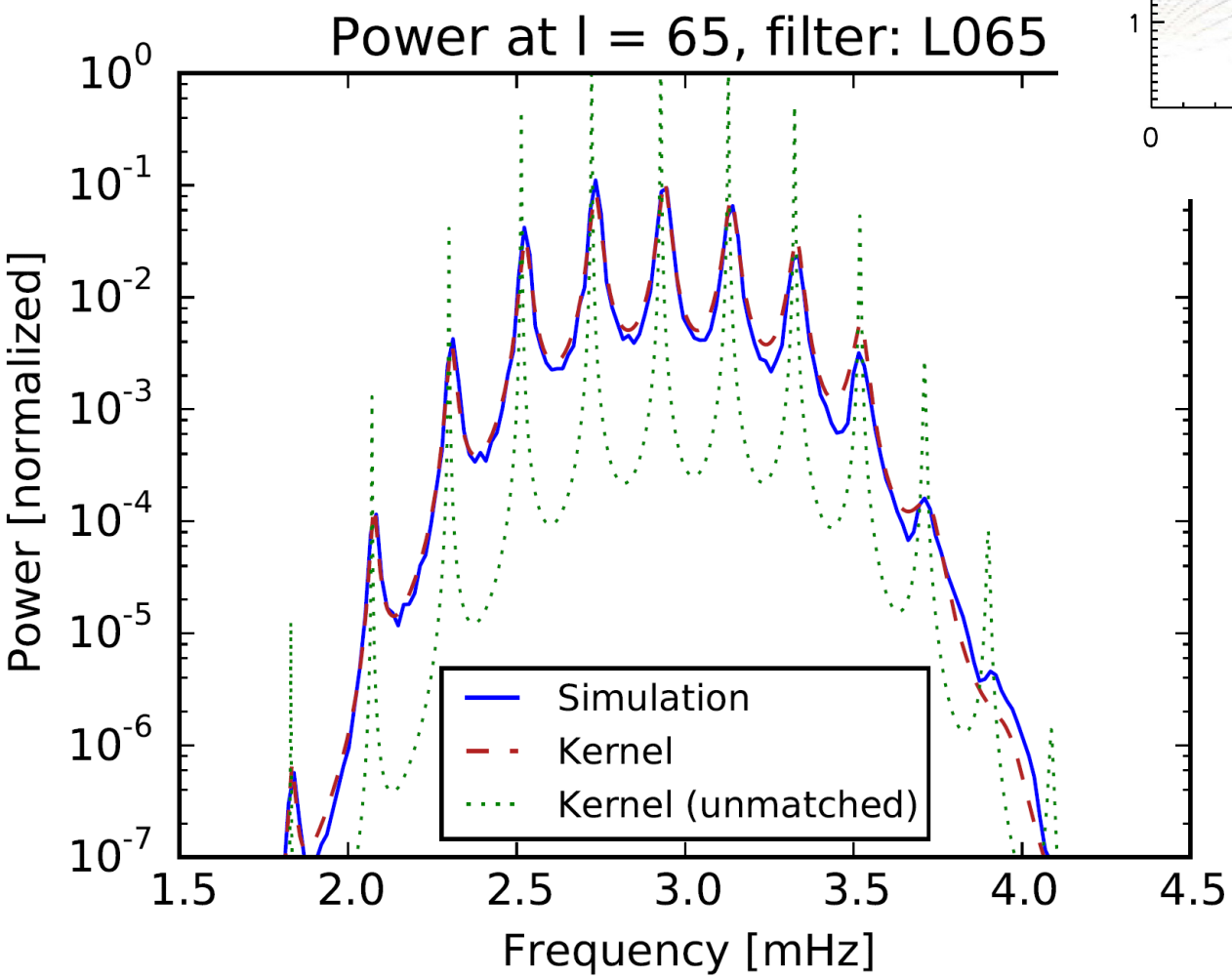




- Validation performed using artificial data from the simulation of Hartlep et al. (2013)
- Compared to model, which corresponds to kernel computation

Validation: Power Spectrum





- Validation performed using artificial data from the simulation of Hartlep et al. (2013)
- Compared to model, which corresponds to kernel computation

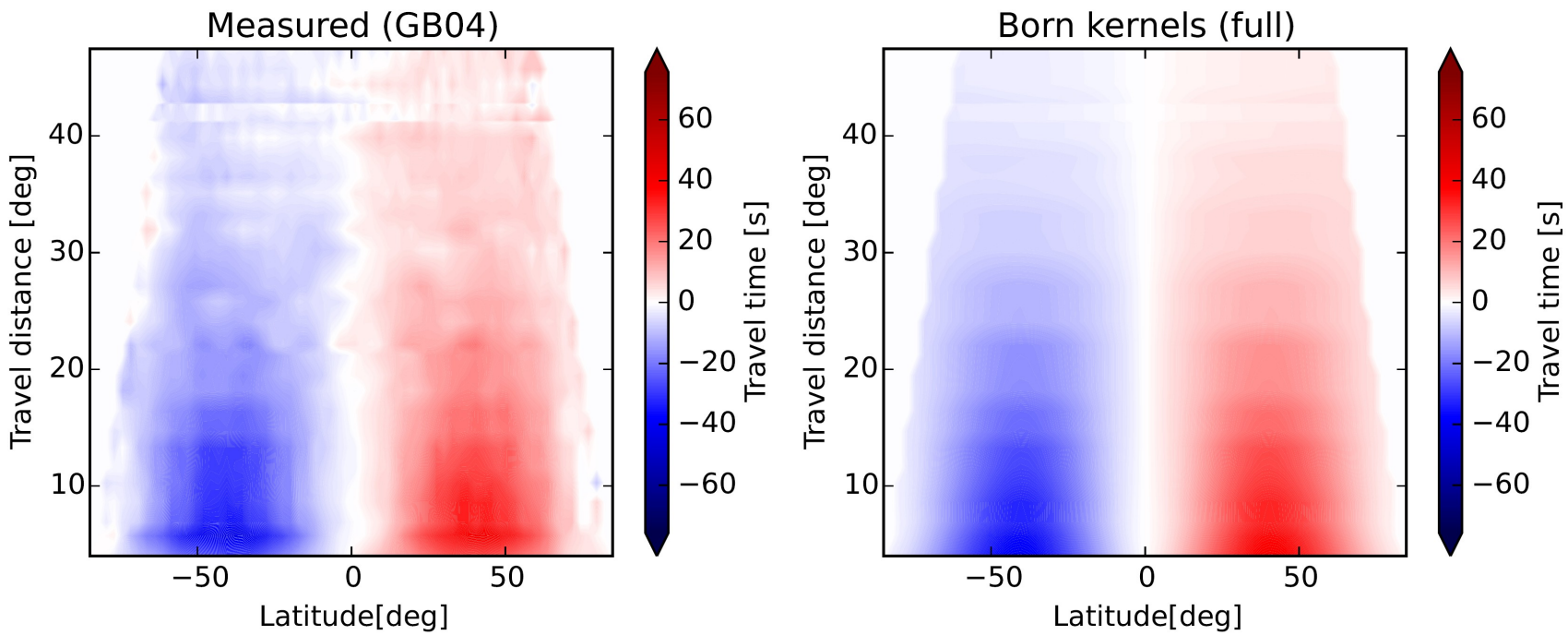
Validation: Forward Travel Times

Born Kernels

Flow Model from Simulation

Measurements from Simulation

$$\underbrace{\delta\tau_{\text{diff}}^{(i)}}_{\text{GB04 fit}} = \underbrace{\int \mathbf{K}^{(i)}(\mathbf{r}) \cdot \mathbf{v}(\mathbf{r})\, \mathrm{d}^3\mathbf{r}}_{\text{forward model}} + \underbrace{\epsilon^{(i)}}_{\text{errors}}$$



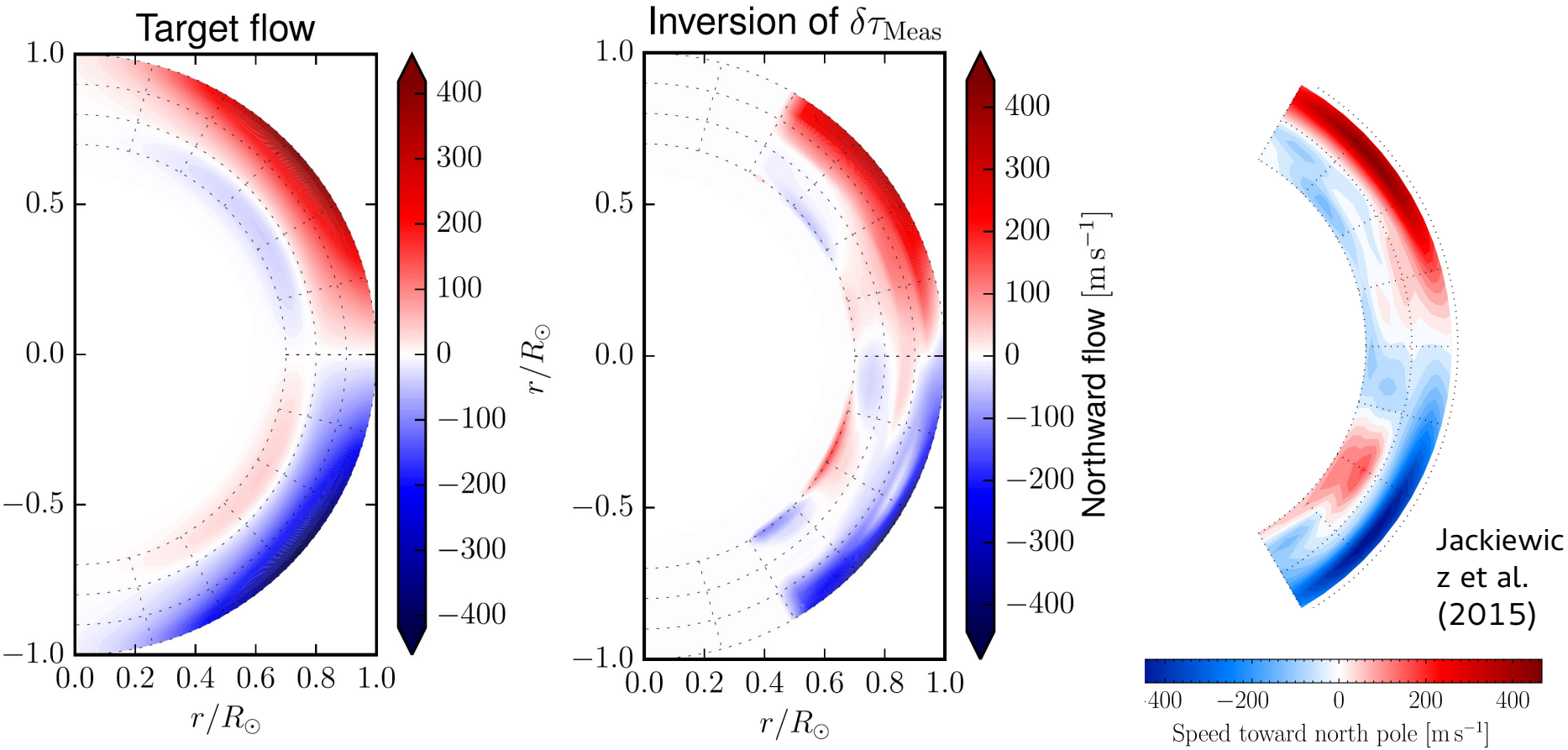
- Travel time measurements: Jackiewicz et al. (2015)

SOLA Inversion Results: Born vs. Ray Kernels

Input to simulation

Born Kernels

Ray Kernels

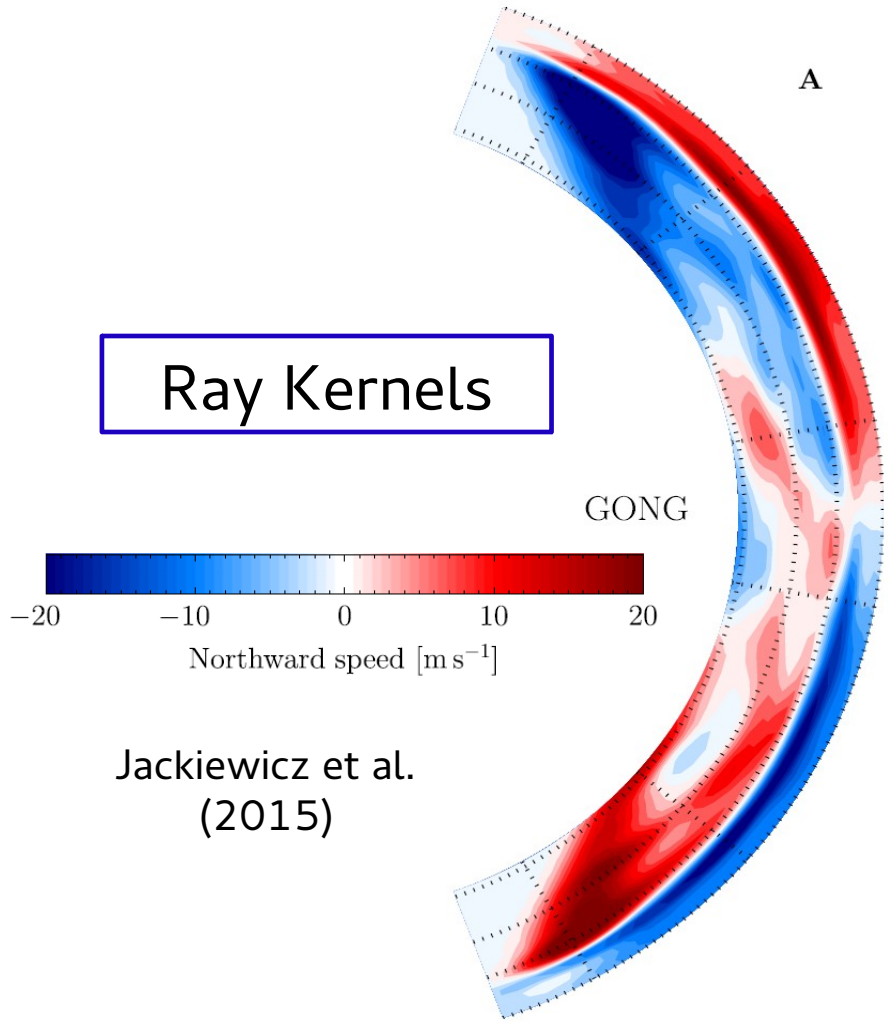


- Born and ray: similar results, including „wrong sign spots“
- Checked parameter space: Impossible to achieve opposite sign there.
- Inversion errors probably underestimated.

Next Step: GONG Data !?!?

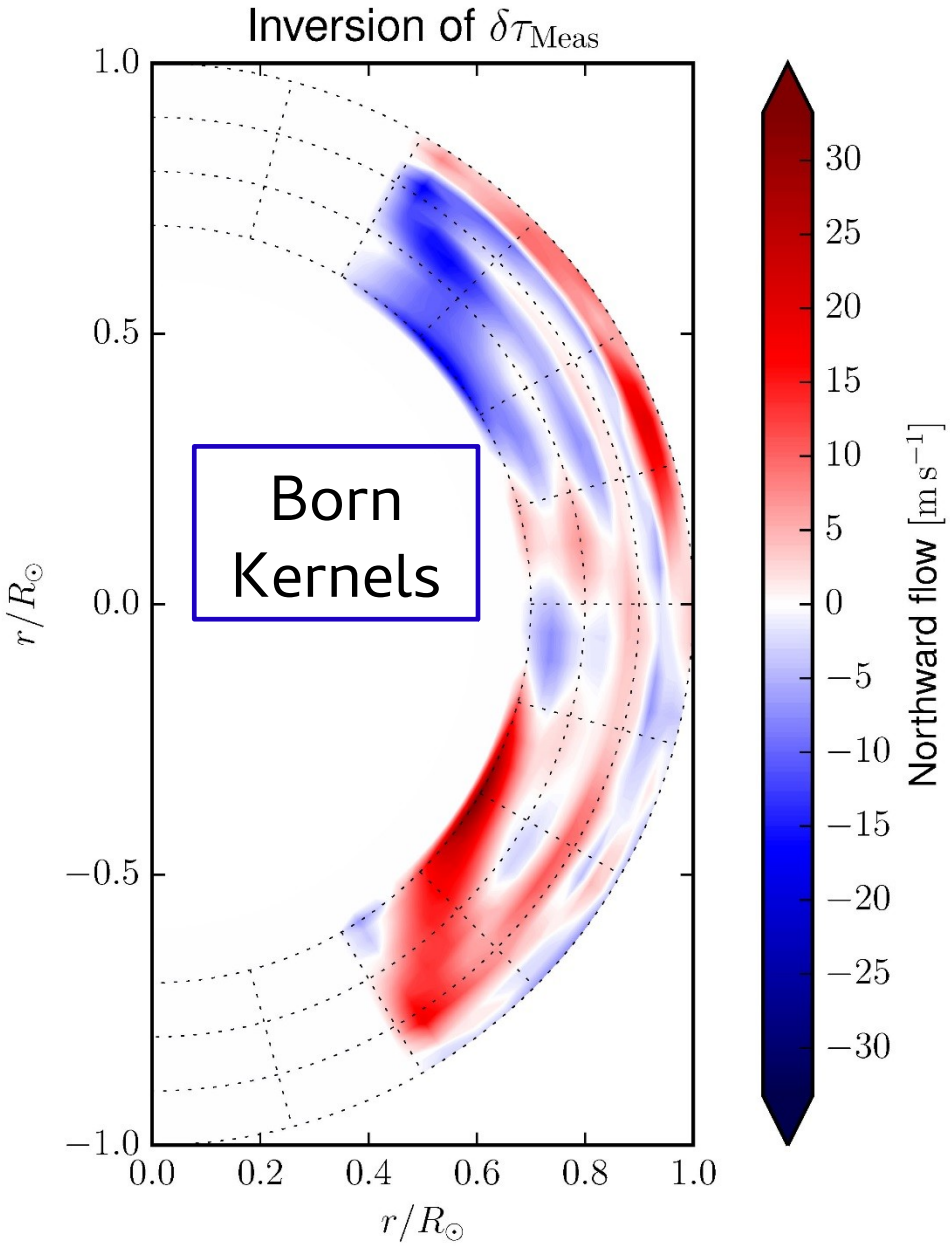
Born Kernels

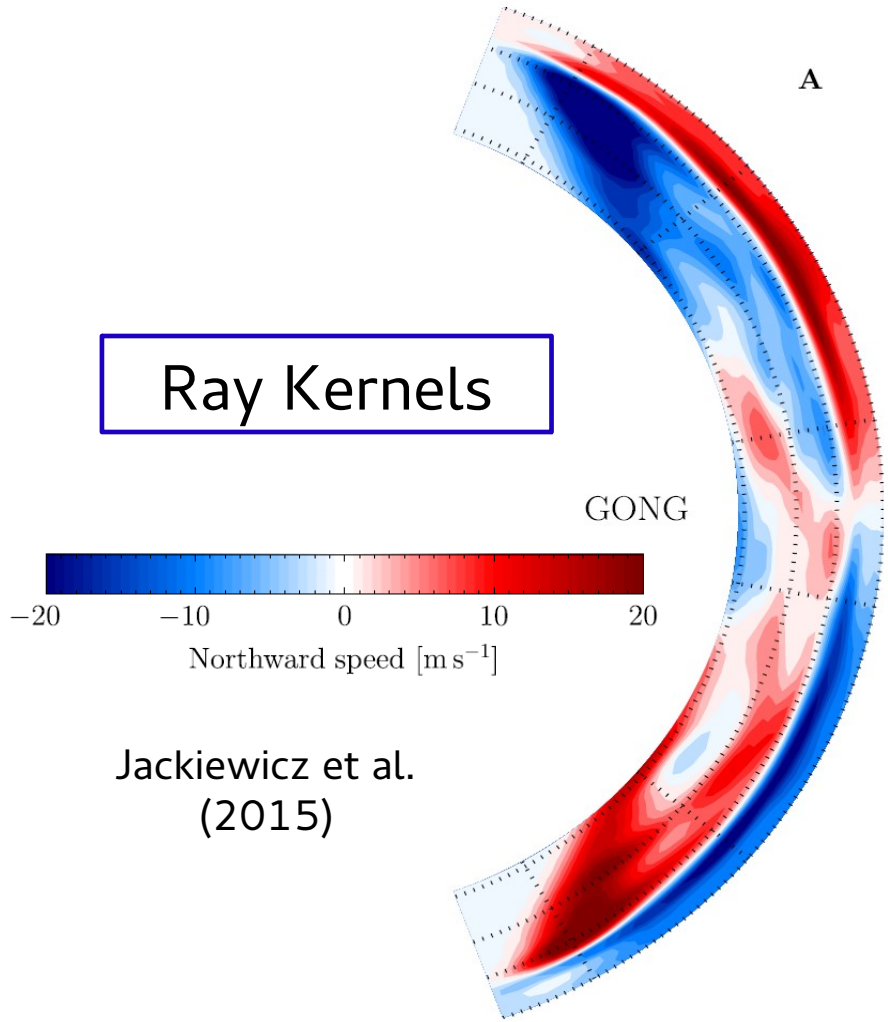
Ray Kernels



Jackiewicz et al. (2015)

Inversions of GONG Data: Born vs. Ray Kernels





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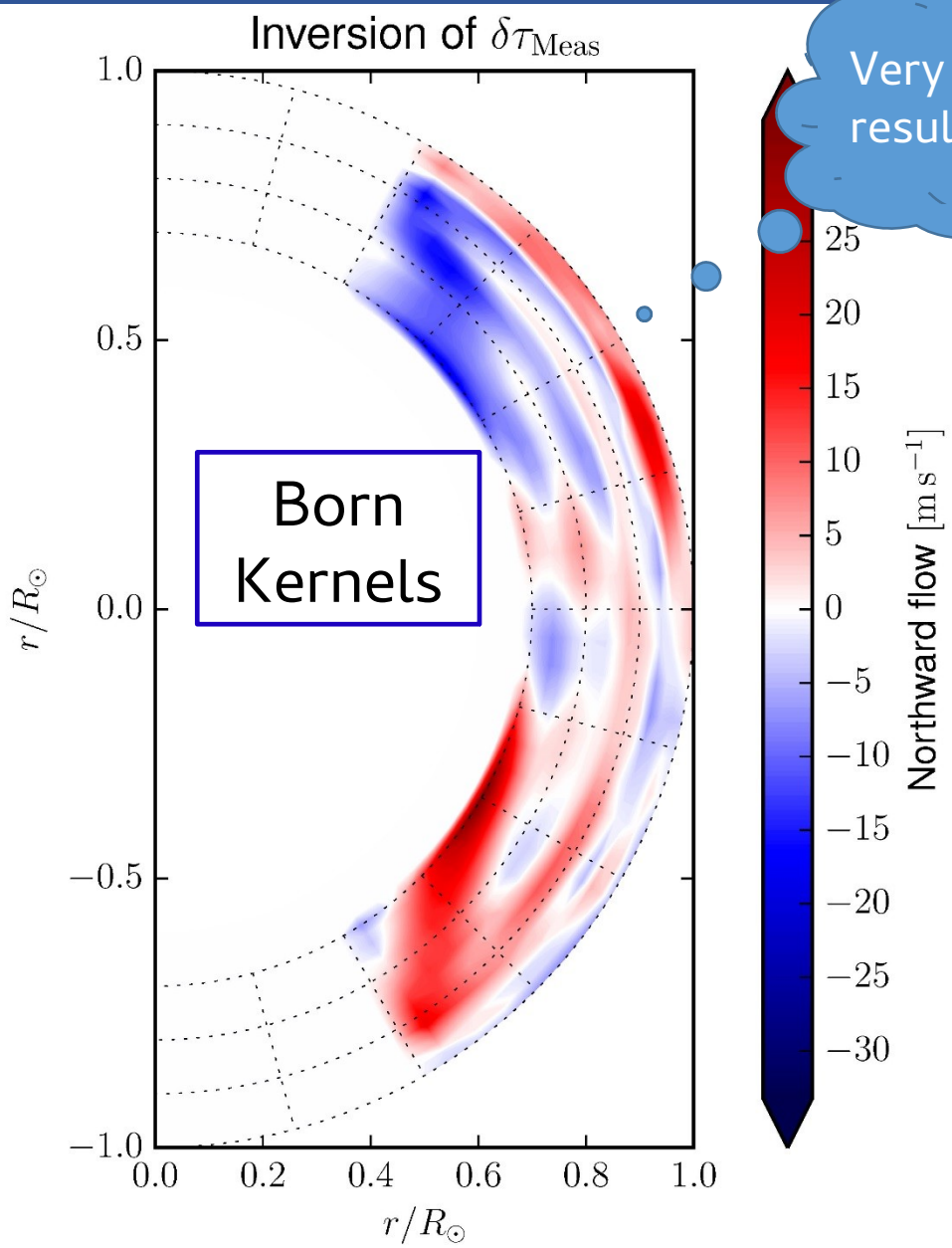
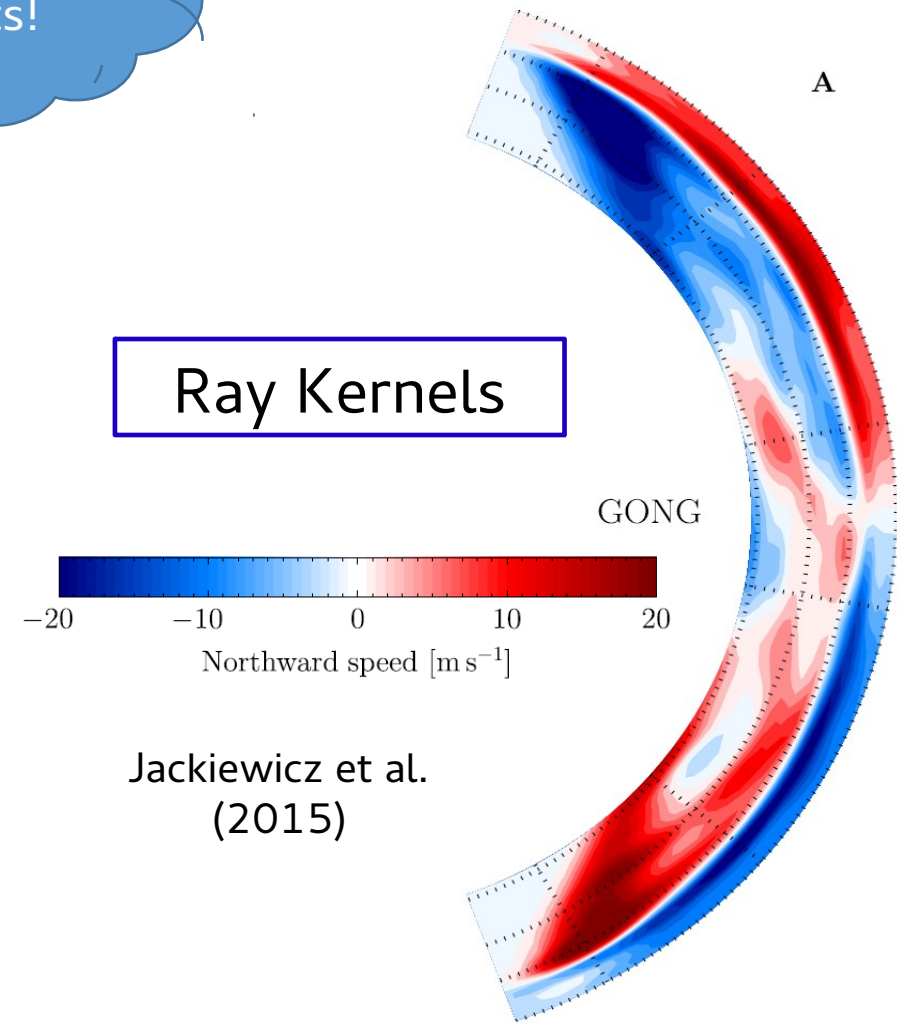
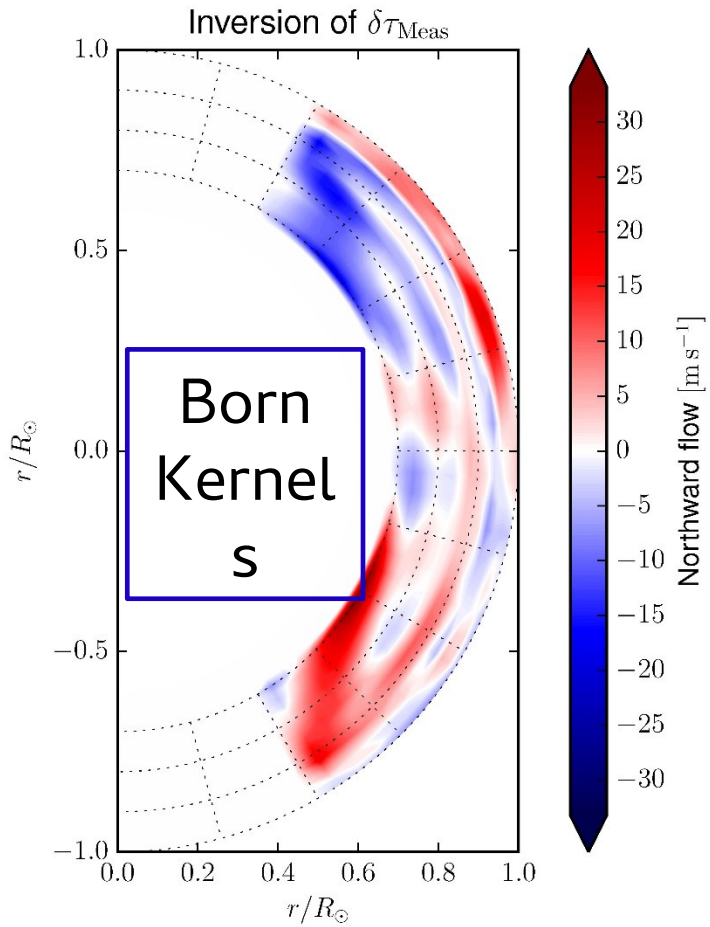


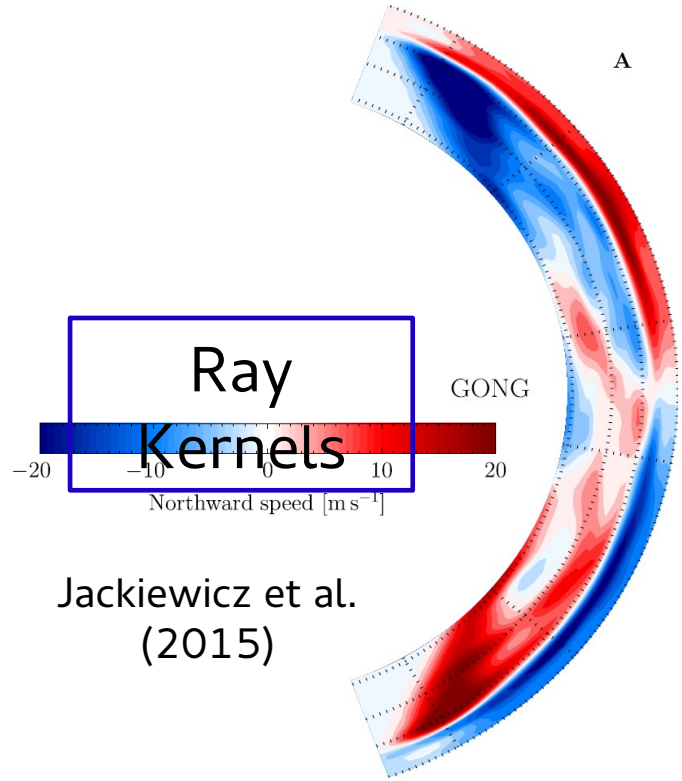
Very first results!



Jackiewicz et al. (2015)

Inversions of GONG Data: Born vs. Ray Kernels





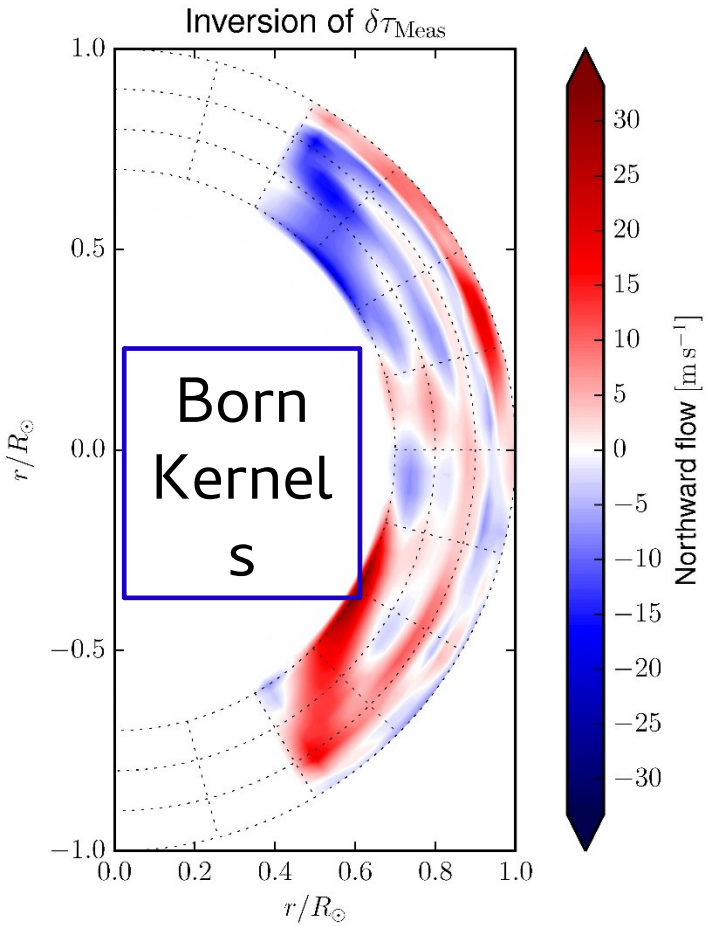
Jackiewicz et al. (2015)

- Quite a few similarities, especially in deep regions
- Born kernels: Still some challanges near the surface
- Return flow even shallower ???

Conclusions

Born Kernels: New model for inferring meridional flow with TD:

- Successfully validated,
- First inversions of GONG data give results which are similar to ray kernels in deep layers,
- Differences to ray kernels: Location of the flows w.r.t. depth (expected from literature).
- More work to be done: Stay tuned in 2017!



Thank you very much!

Acknowledgements

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