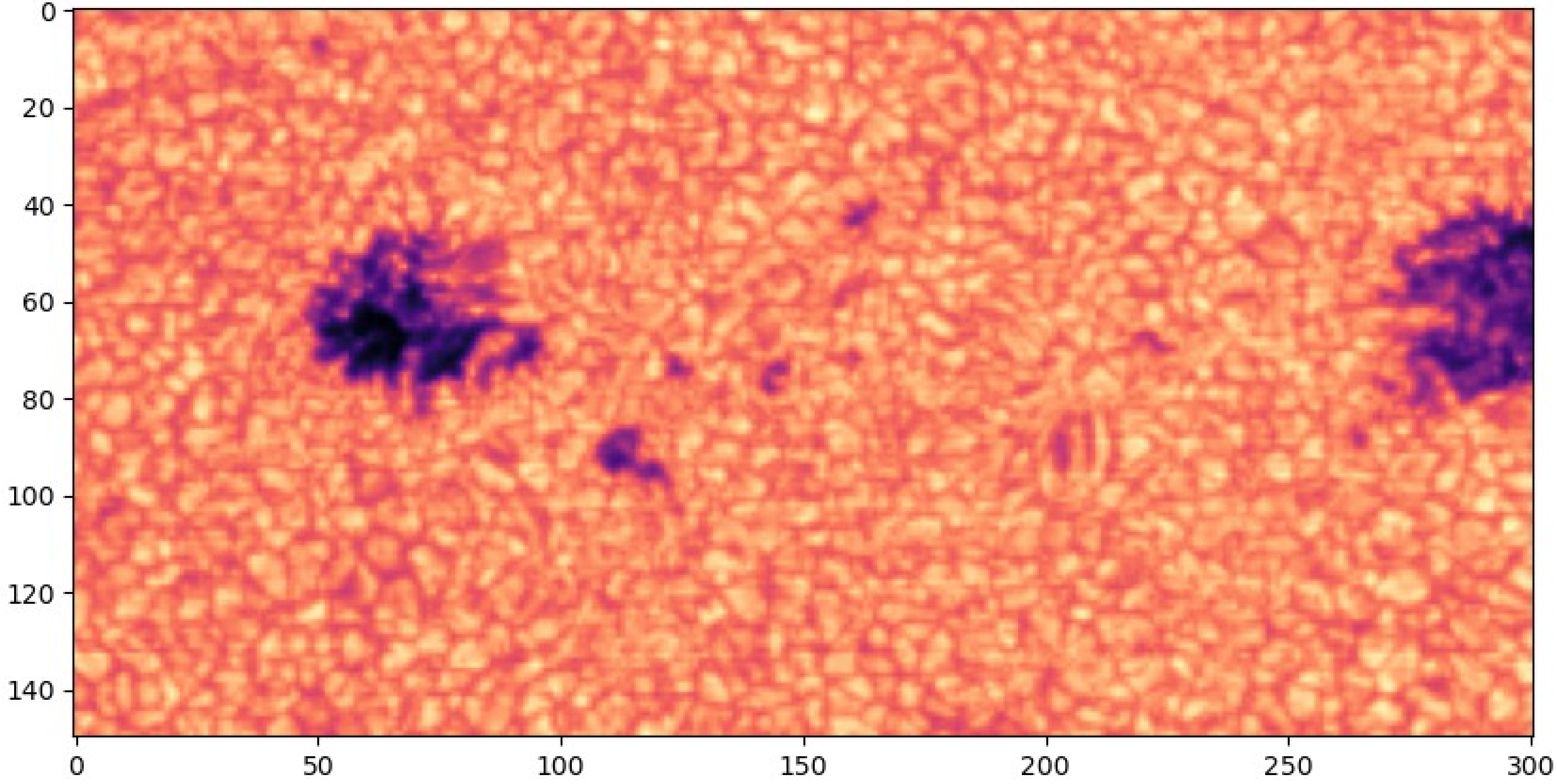
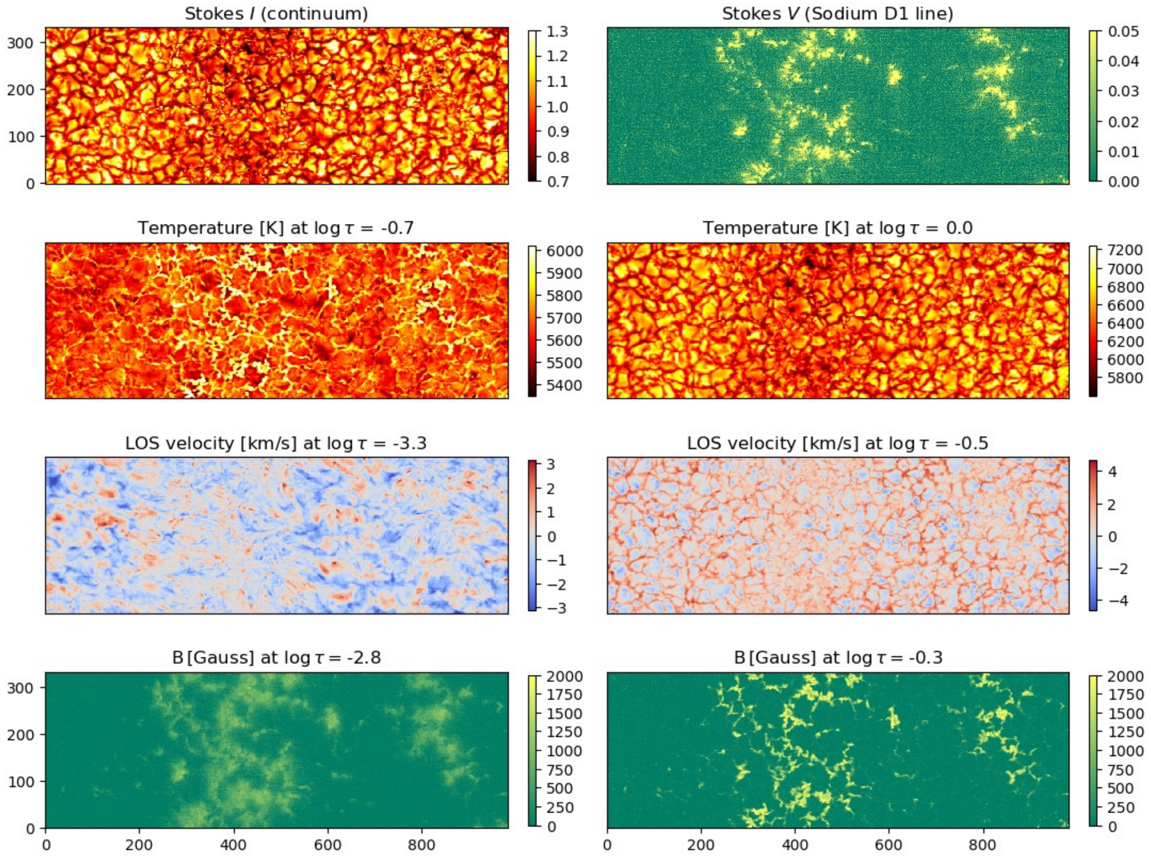


Comparing inversion strategies for active region photospheres

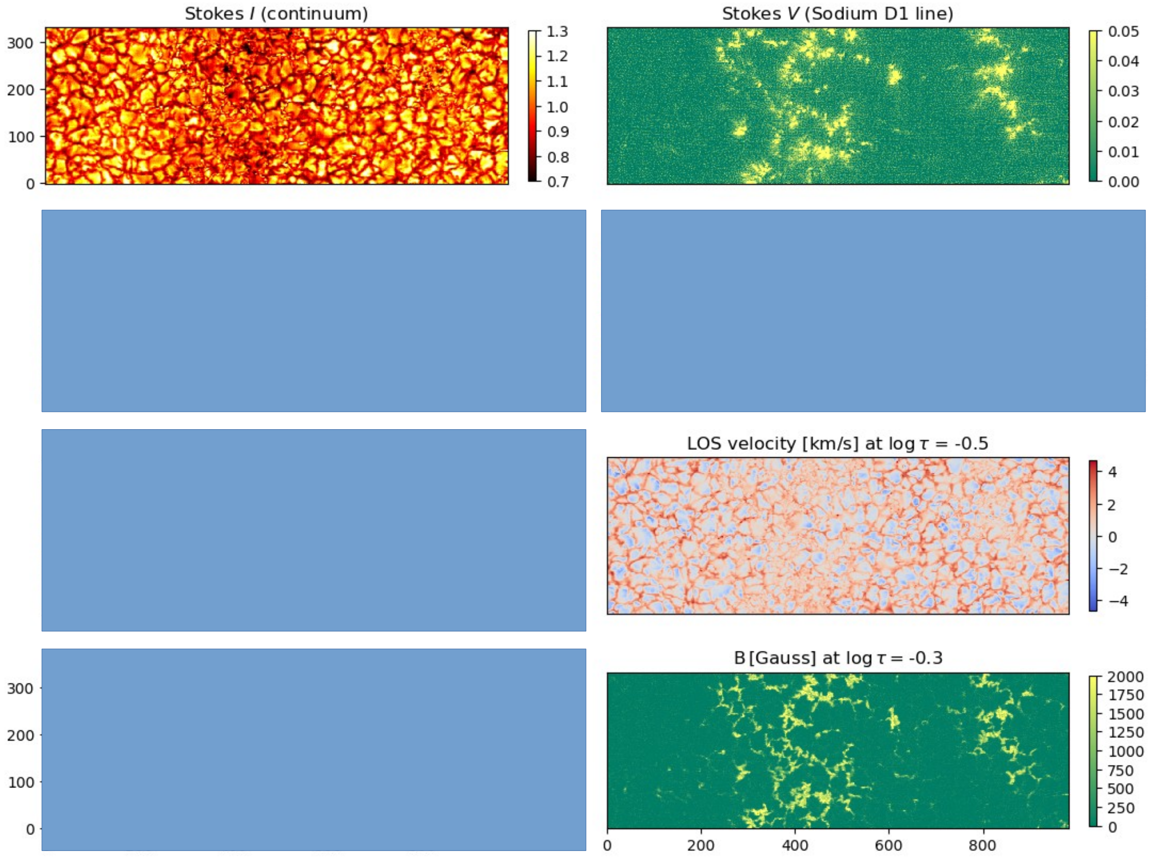
Brief reminder on the inversions

- Methods that fit a depth-dependent atmospheric model to the observed Stokes spectrum.
- Applying them pixel by pixel we get a 2D map or a pseudo-3D model of the observed region
- Several degrees of physical assumptions → we have to choose according to the complexity and according to our data.
- Let's describe them quickly



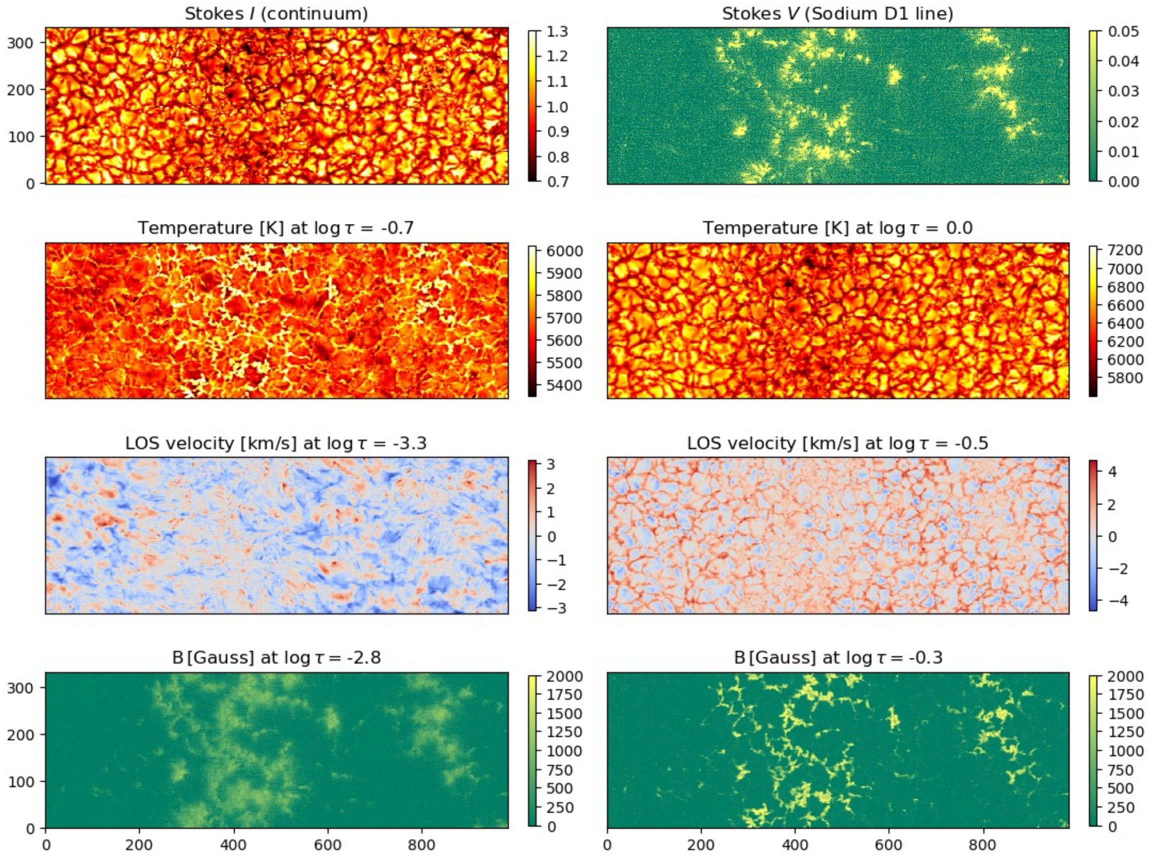
Milne-Eddington inversions

- All physical parameters are considered constants, except for the source function that has a slope in order to reproduce line depth
- Only meaningful information is the magnetic field vector and the line-of-sight velocity
- Can’t be applied to multi-line observations (unless the lines are very similar).
- Incredibly fast: ms per pixel, easy to implement spatial coupling (will be important later).



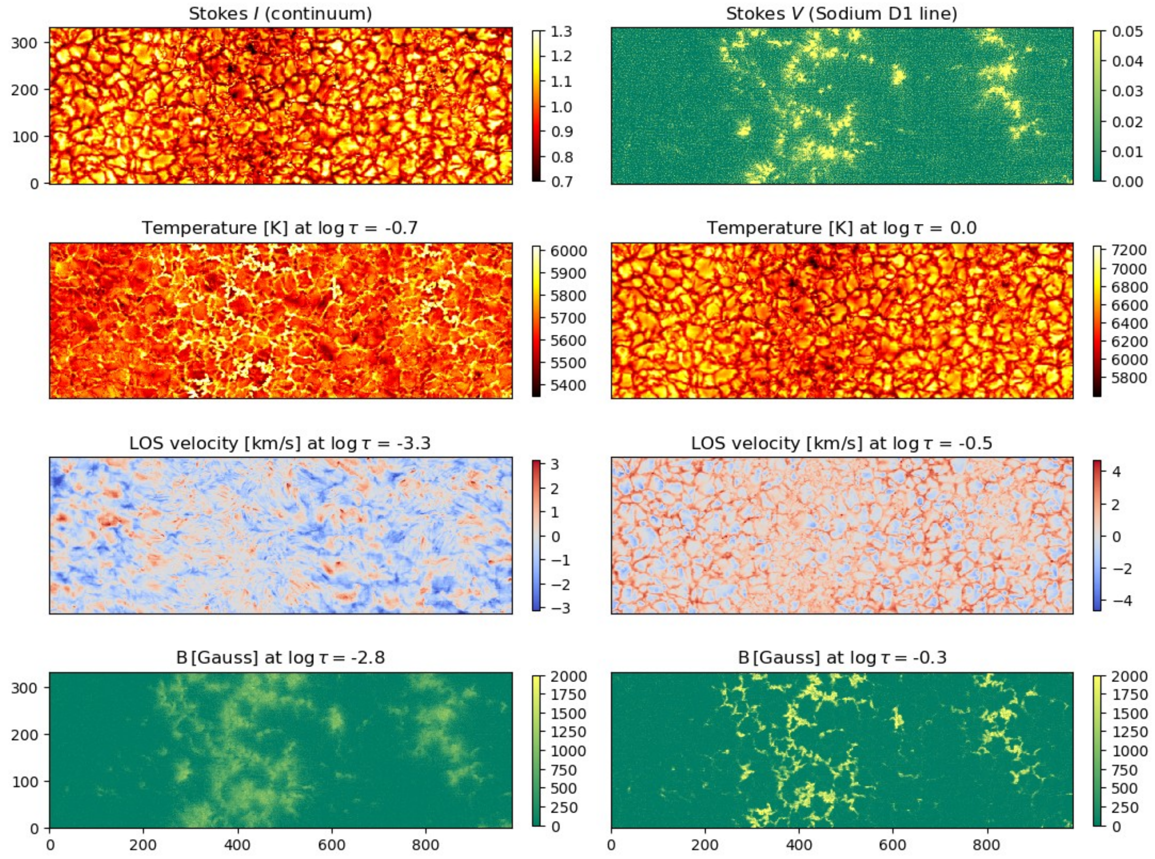
LTE (SIR) inversions

- Consider a depth dependent atmosphere where the RTE solution is numerical and opacity and emissivity follow from the Saha and Boltzman equations
- It’s possible to capture depth dependence of temperature, velocity magnetic field…
- Can be applied to photospheric lines (even chromospheric with some ad-hoc corrections)
- Fast: seconds per pixel. (To get runtime @ a 256 node server, for a 1000 x 1000 map, replace seconds with hours).



NLTE (StIC) inversions

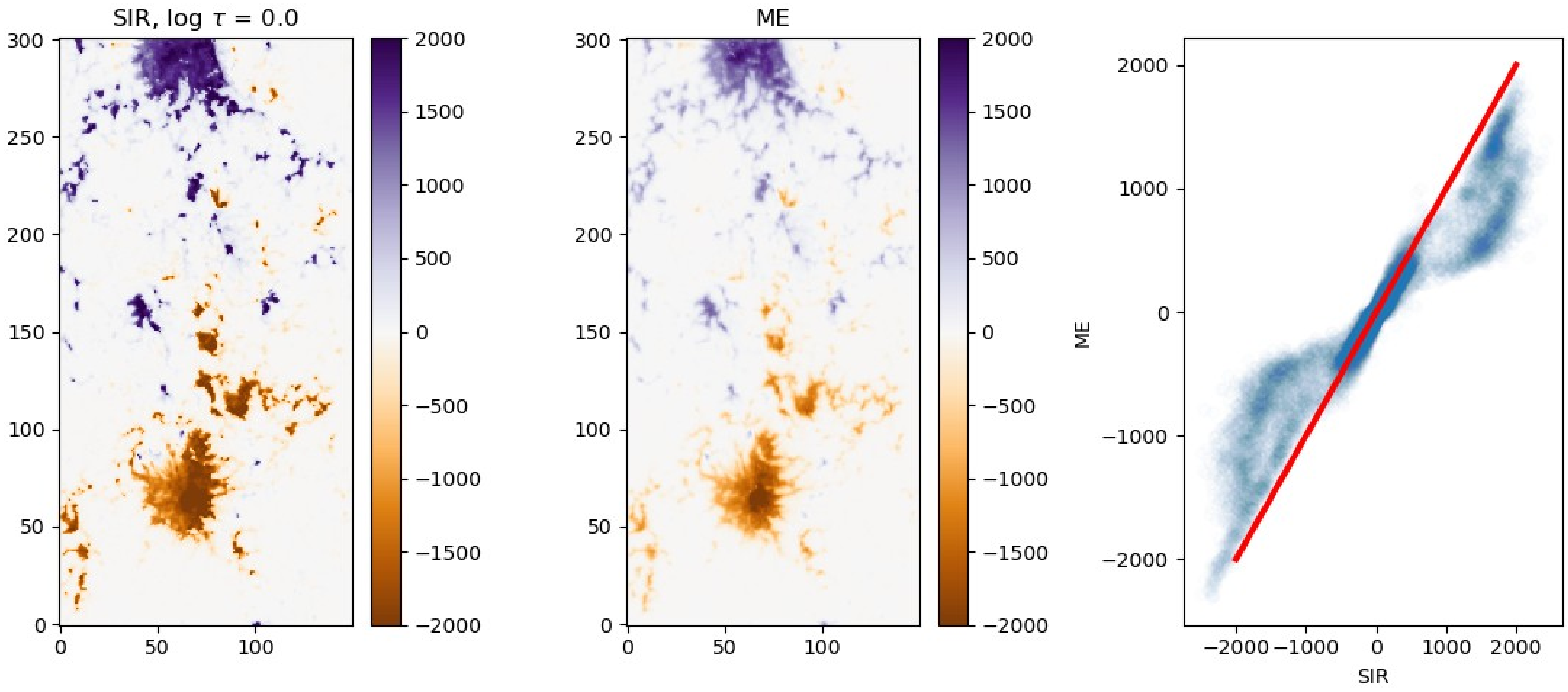
- Consider a depth dependent atmosphere where the RTE solution is numerical and opacity and emissivity **don't** follow from the Saha and Boltzman equations
- Can be self-consistently applied to chromospheric lines
- Not so fast: minutes per pixel (can be major hassle to execute them).
- The only way to self-consistently interpret Sodium D lines, Ca II 8542, Mg I b2… etc.



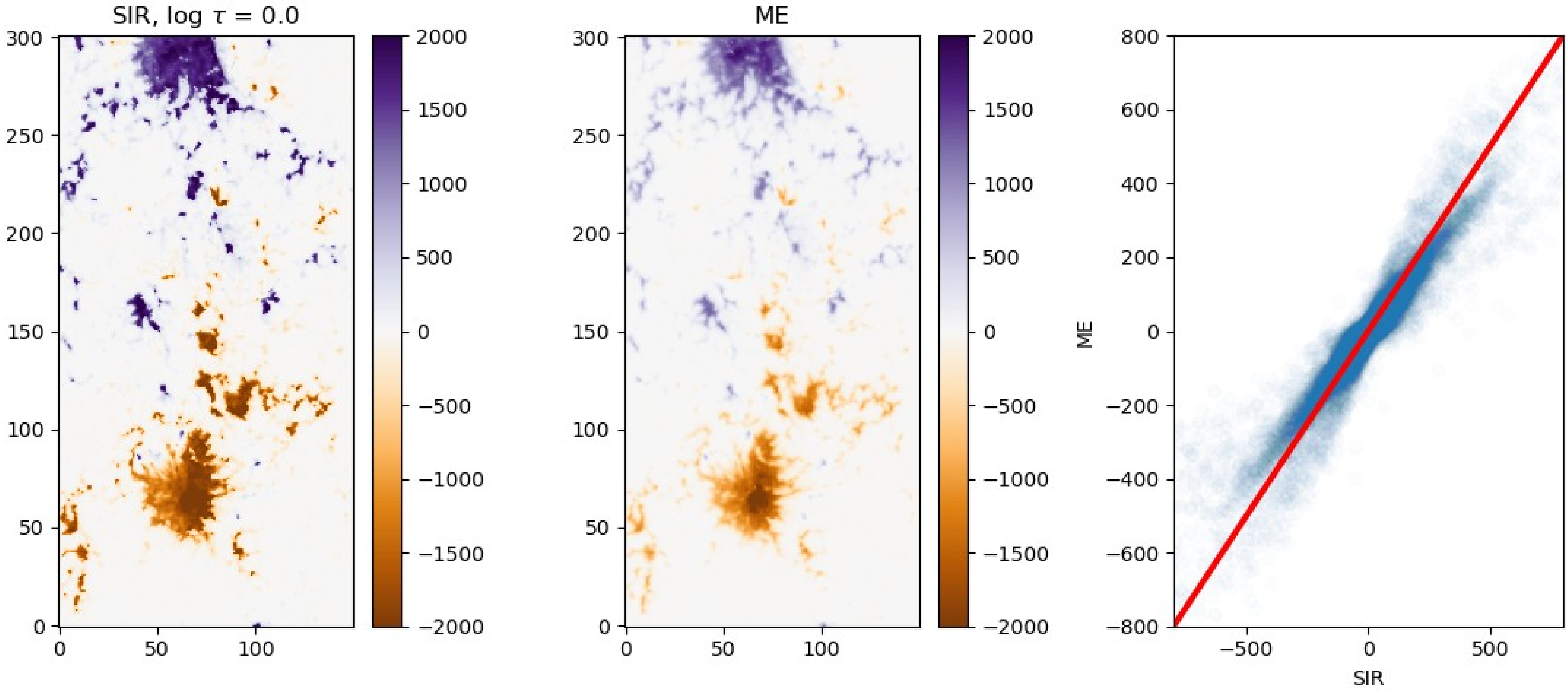
Here we are comparing ME inversion and SIR

- The motivation came from an “S” shape that we saw in some comparisons between Na D inversions and extrapolations from the photosphere at the last ISSI meeting (in spring)
- A usual suspect is the inversion method: because of the noise, poor sensitivity or too complext model, weird variations in the physical parameters can appear.
- The test: compare Milne-Eddington inversion (everything constant), and a SIR inversion (in this case, linear gradient of the magnetic field) with each other.
- Data: Hinode active region observed at 30/09/2018 – two photospheric neutral Iron lines
- Keep mind that ME gives 1 value, while SIR gives a **depth dependent magnetic field**
- Range of sensitivites of the Fe I lines is from log tau =0 to log tau = -2, on average.
- This translates to a ~ 300 km height span.

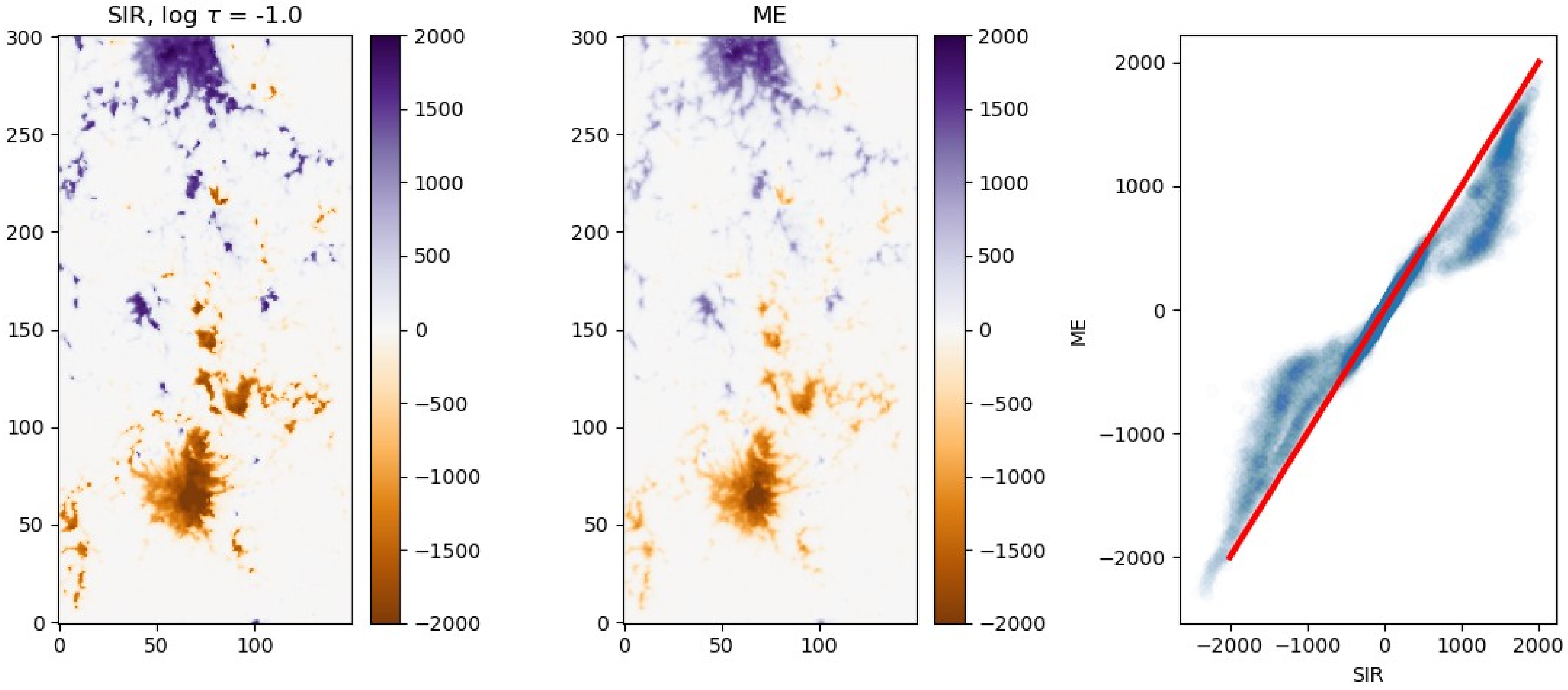
ME vs SIR at deep photosphere



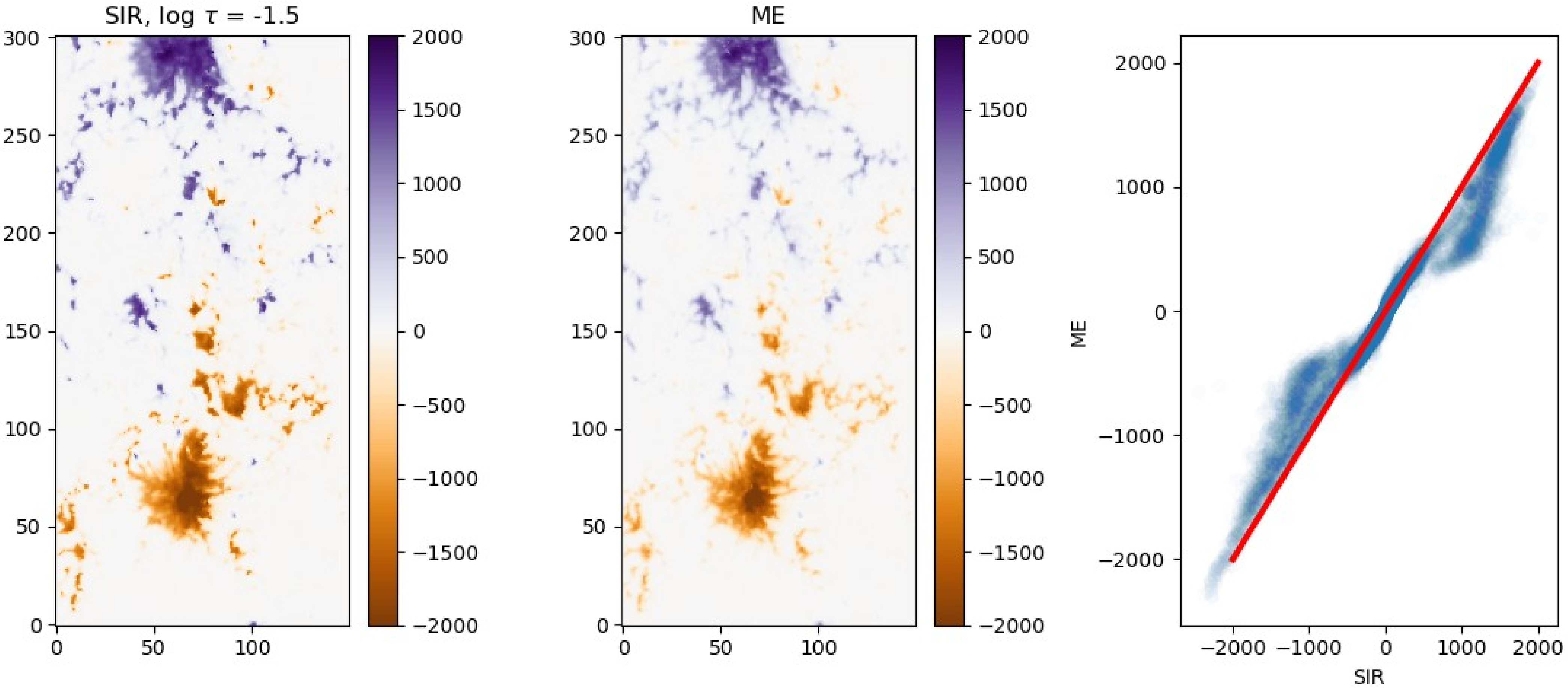
ME vs SIR at deep photosphere – weak fields



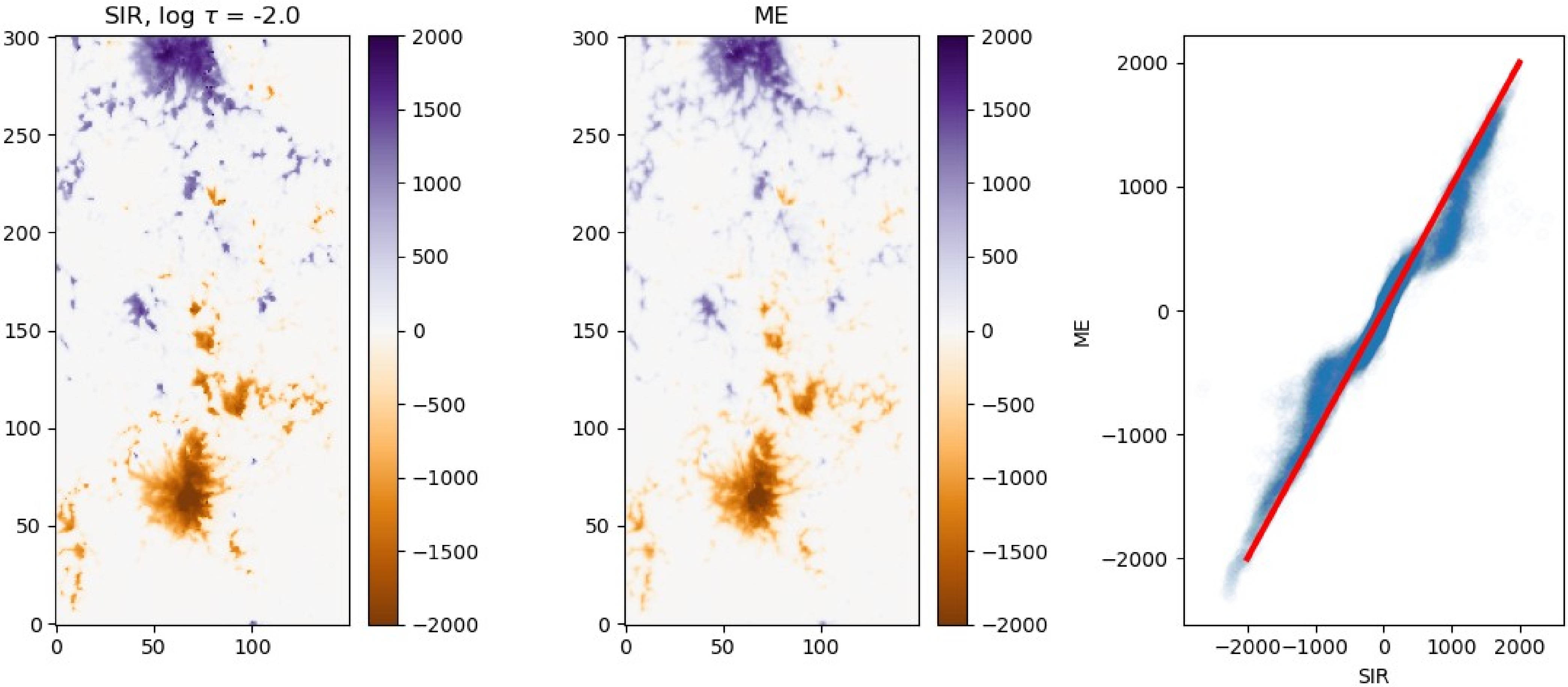
ME vs SIR comparison at logtau = -1.0



ME vs SIR at peak sensitivity of Fe I (log tau = -1.5)



ME vs SIR at upper photosphere (log tau = -2)

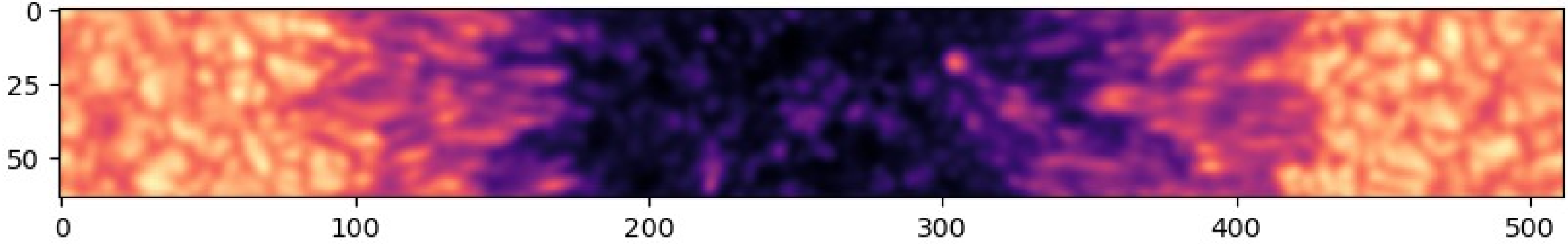


Why is this so?

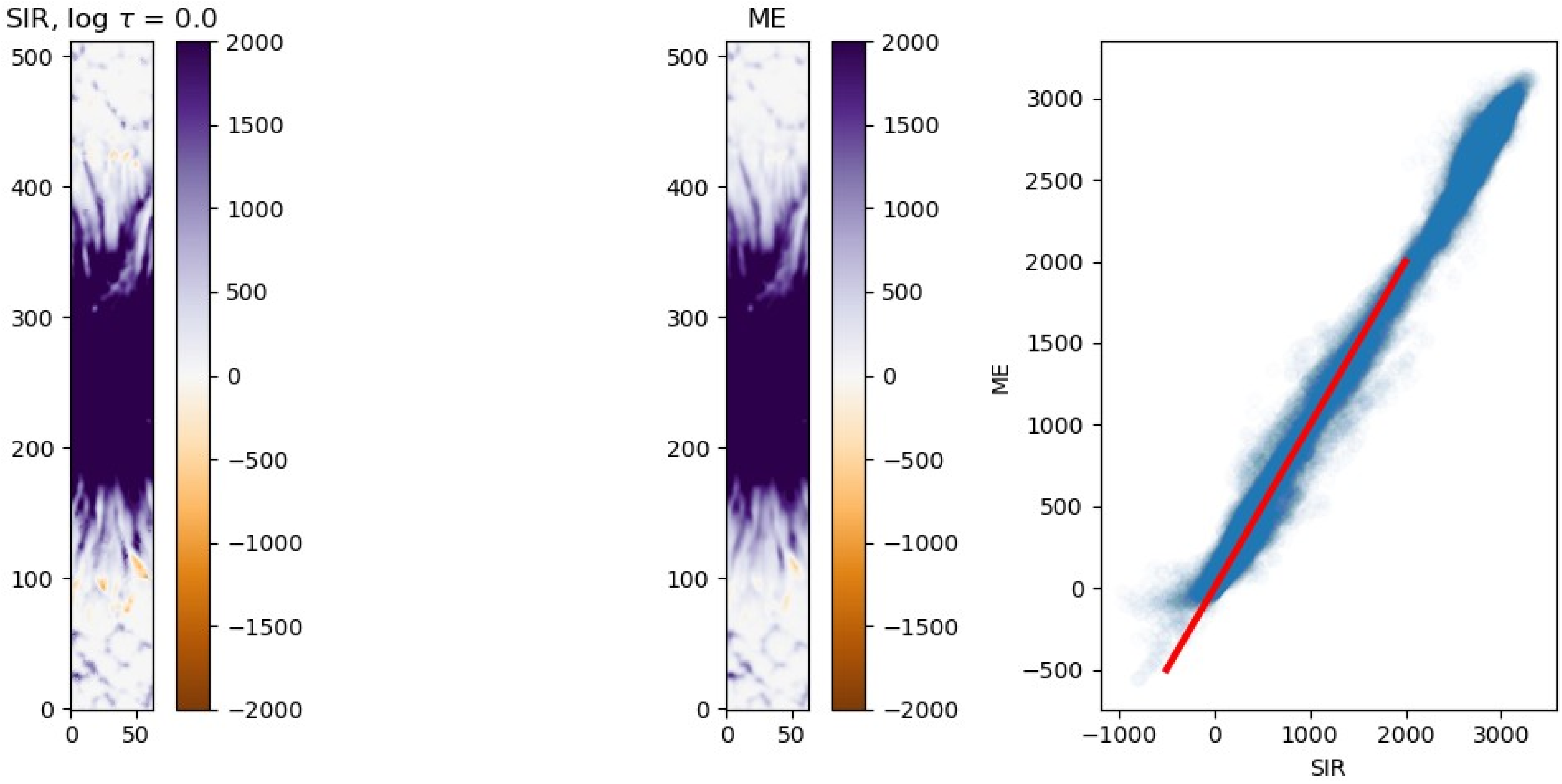
- My initial suspicion was that this is due to intricacies in the line formation
- Different atmospheres have different structures and different **response functions**
- ME atmosphere infers some mean magnetic field over the line formation region and it will be equal to the actual B at different depths in different features (umbra, penumbra, QS…)
- How to check that?
- Come in with the known solution, i.e. simulation

Double-checking on simulated data

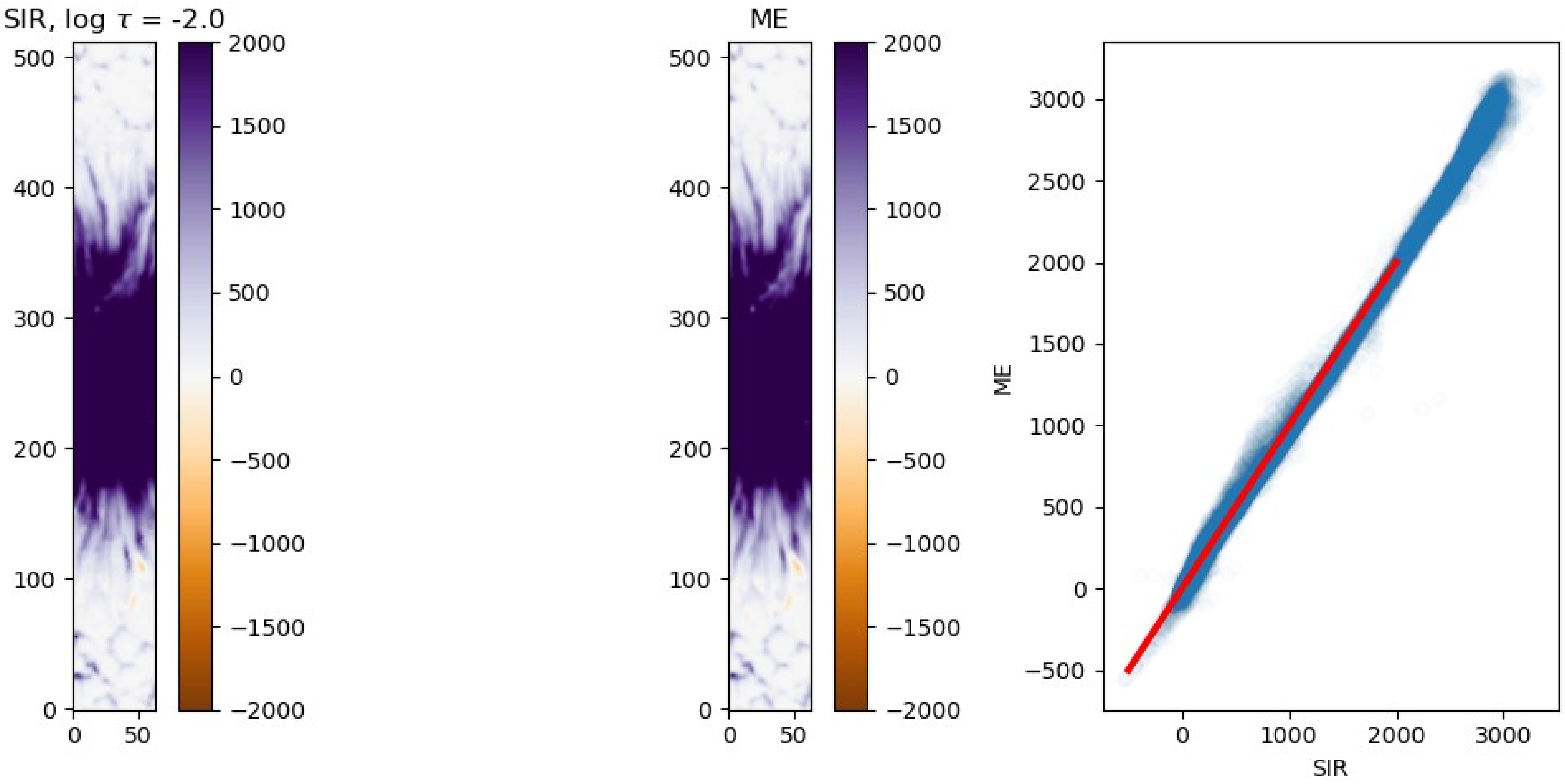
- Slice of the Sunspot simulation, used in Borrero et al. (2019), provided by M. Rempel, 16 km horizontal 12 km vertical resolution.
- Synthesize the Hinode lines using SIR
- Apply spectral and spatial degradadation, to make it look like Hinode SOT/SP data
- Invert using M-E and SIR, and compare
- Below: Continuum intensity from the simulated dataset. Note much much smaller FoV.



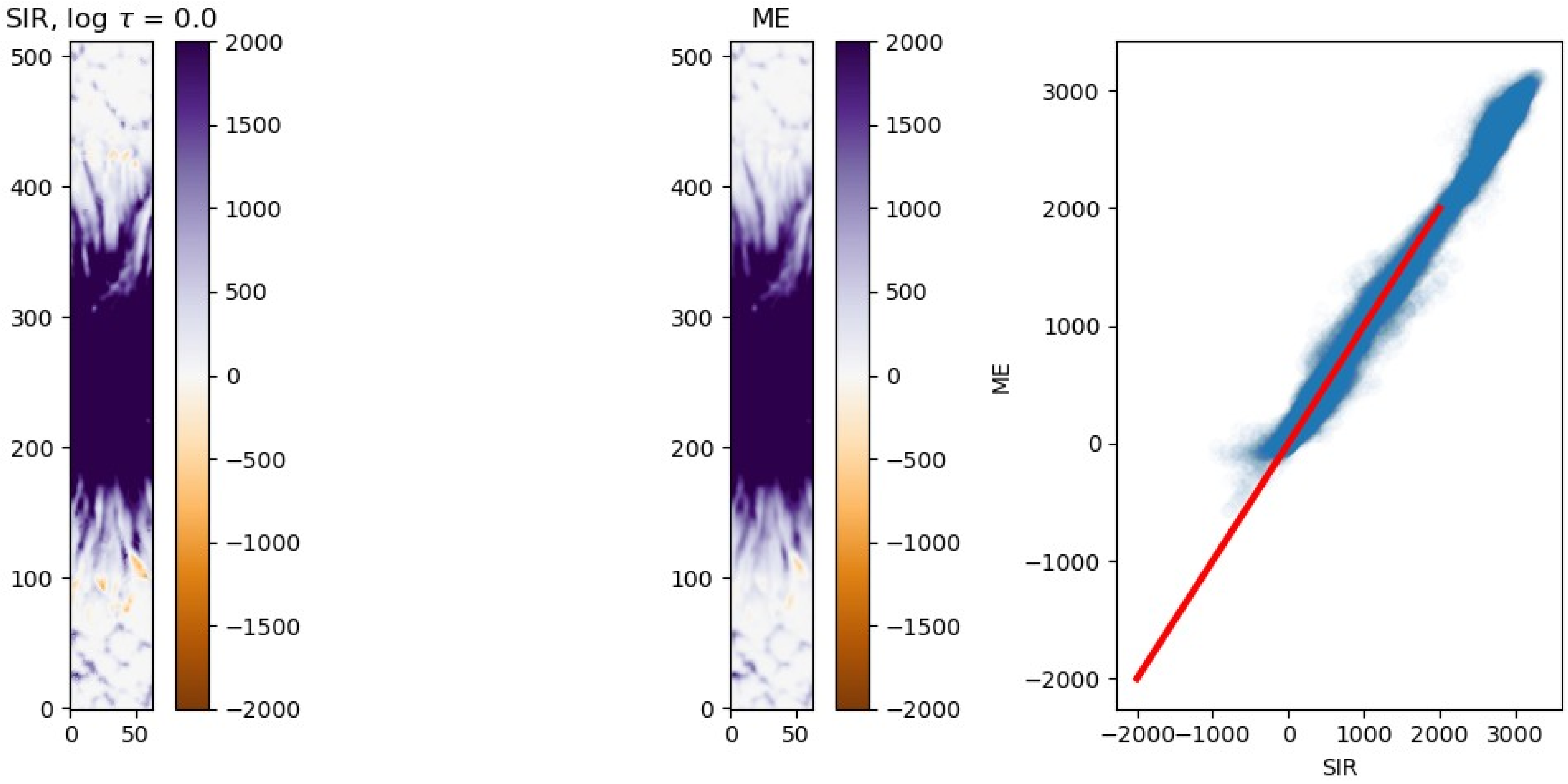
ME vs SIR at deep photosphere



ME vs SIR at deep photosphere



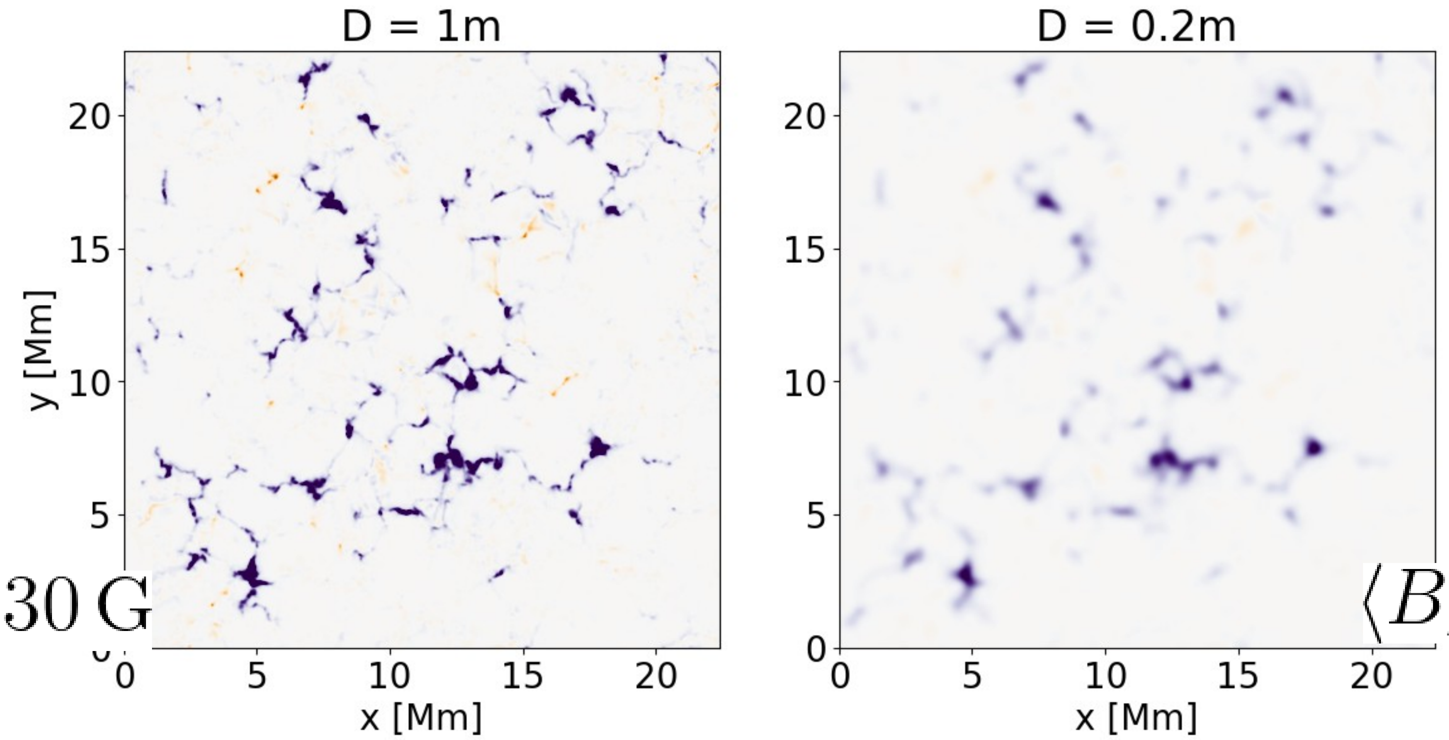
ME vs SIR at deep photosphere



What can be done next?

- Use larger simulation, maybe with flux balance
- Apply more instrumental effects
- Apply spatially coupled inversions / apply deconvolution?
- Or just ignore and conclude that SIR is better?
- Let's have some follow up....

$\langle B_z \rangle = 30\,\mathrm{G}$



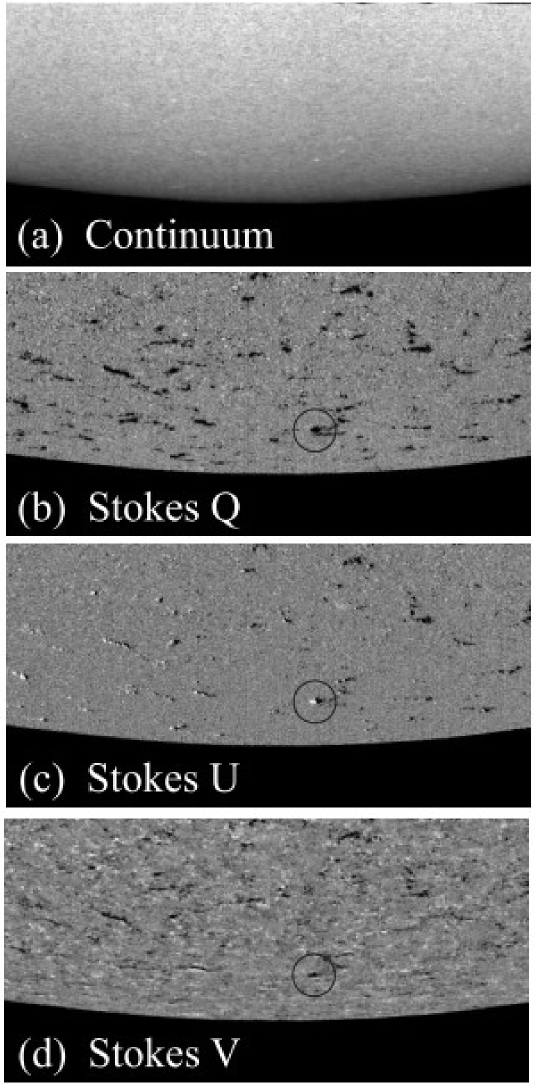
$\langle B_z \rangle = ?$

Difficulties in estimating photospheric magnetic fields

Motivation

- Open flux especially important at the poles as it drives the solar wind – missing flux problem (Linker et al, 2017)
- Inferring polar fields is difficult
- See Tsuneta et al. (2008), Prabhu et al (2020), as well as (Ito et al 2009, Pastor Yabar et al 2018)
- To explore the limitations of inversion, we:

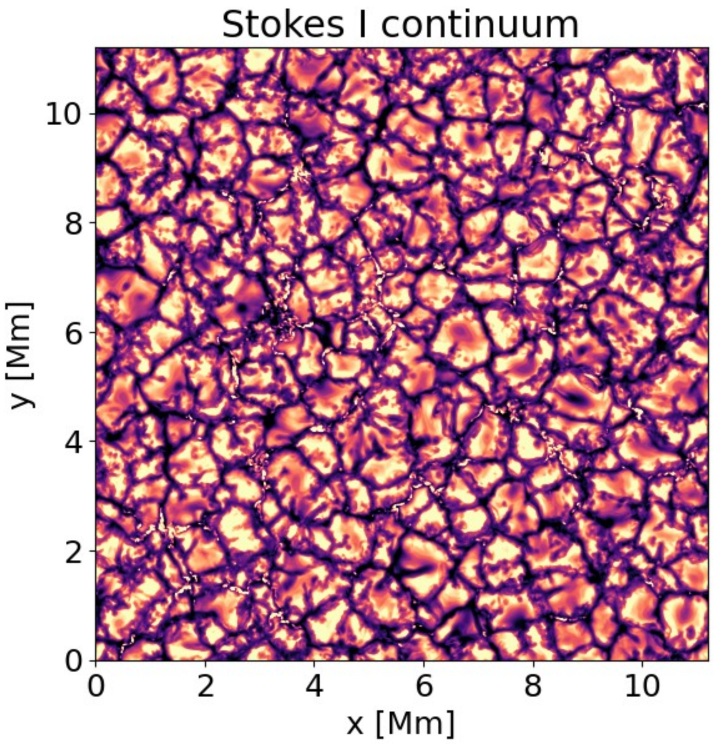
  Model the polar observations using a MuRAM MHD cube & SIR → Invert the synthetic data using various approaches
- We analyze the influence of: Spatial resolution, Viewing geometry, Inversion approach: (ME, ME + filling factor, depth stratified)

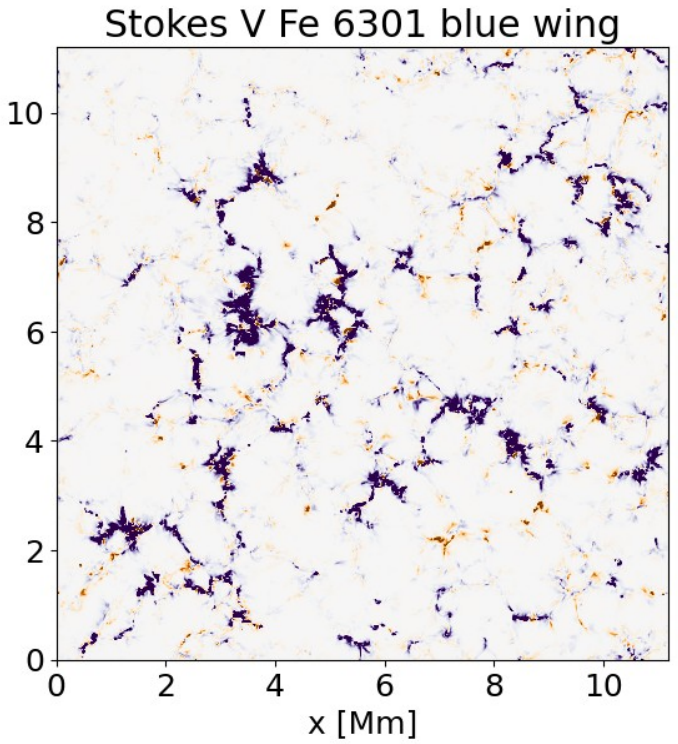


Right: Hinode SOT/SP observations from Tsuneta et al. 2008

Setup

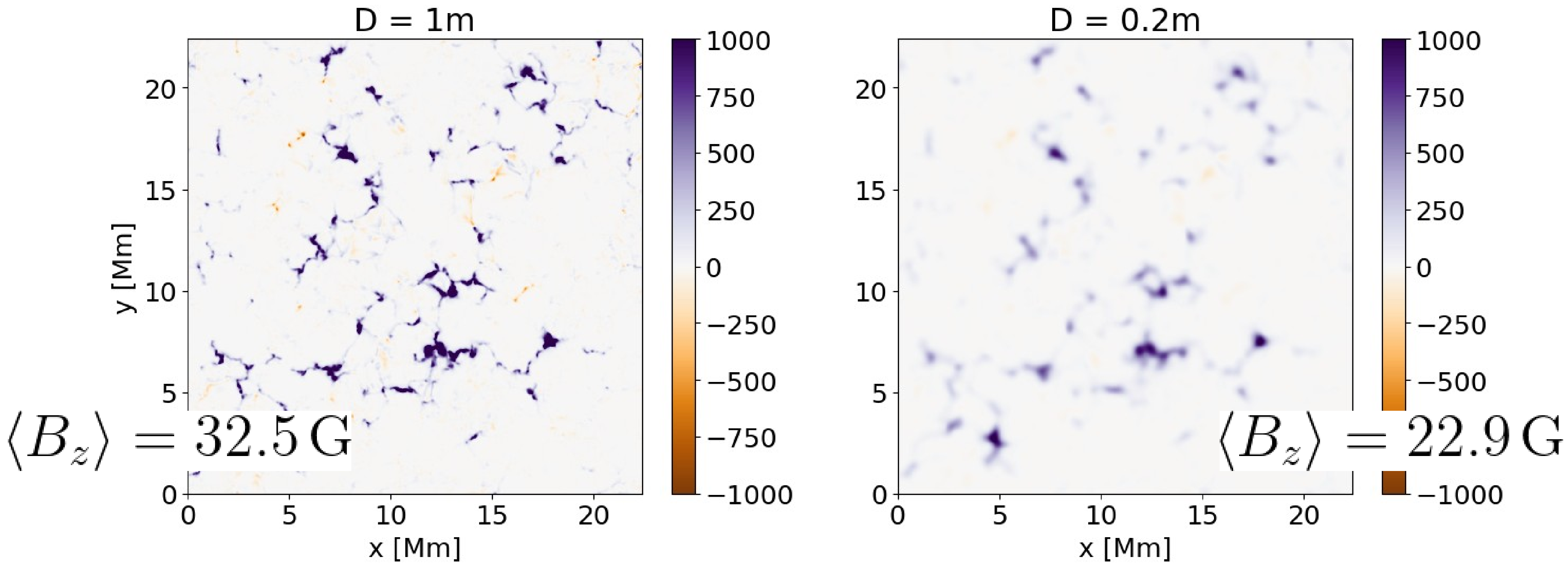
- The mean vertical field in the simulation is 30 Gauss – Ideally, we want to recover this with a given instrument and viewing geometry
- We synthesize widely used 6301/6302 lines of Fe I in LTE, at the disk center and at mu = 0.4. At the "pole" cube is tilted, spectra synthesized and spatially binned





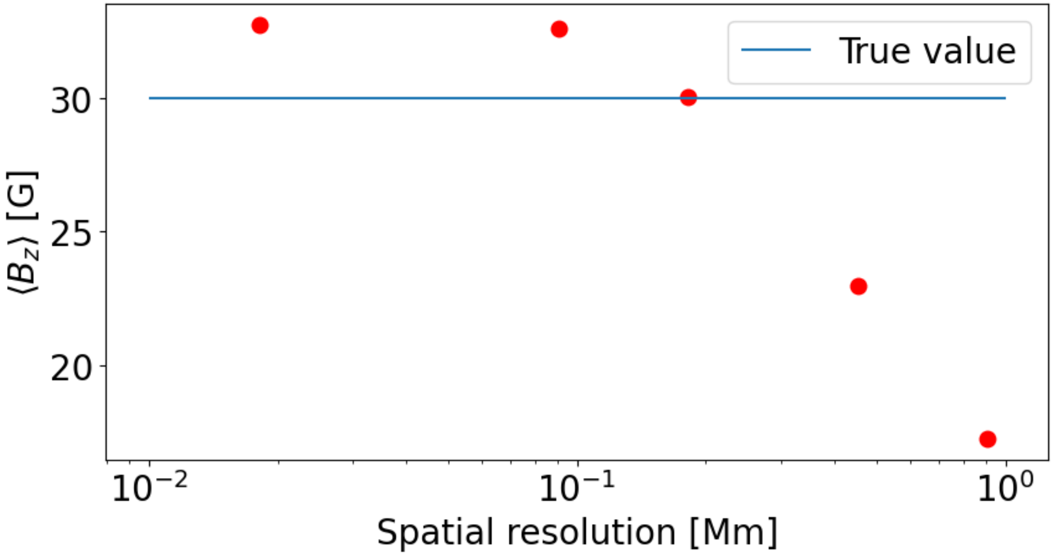
Disk center

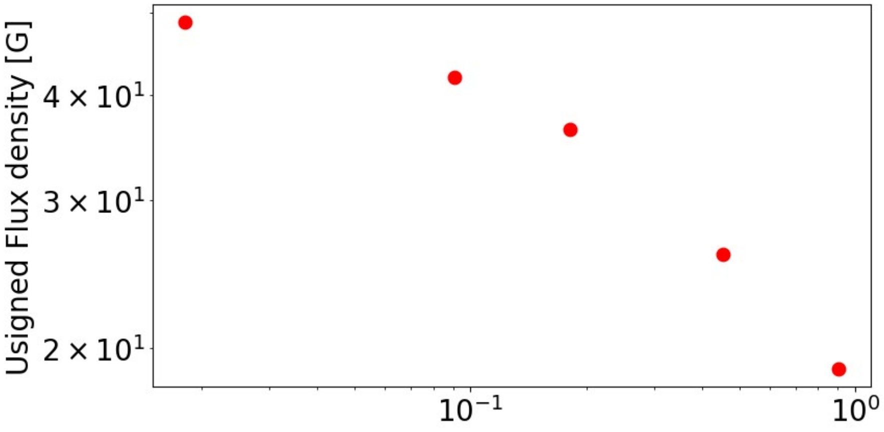
- The mean vertical field in the simulation is 30 Gauss – Ideally, we want to recover this with a given instrument and viewing geometry
- Sanity check: Disk center. However… (Standard Milne-Eddington inversion)

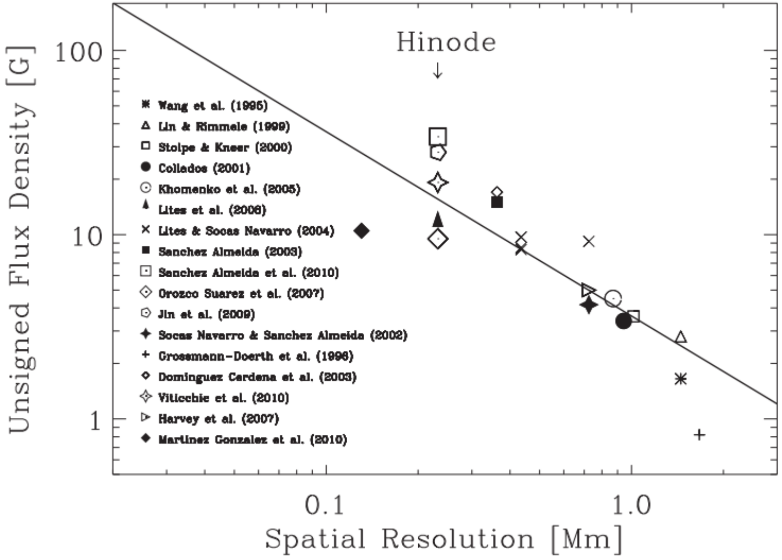


Disk center

- Decrease in the spatial resolution → Decrease of both net and the unsigned flux:



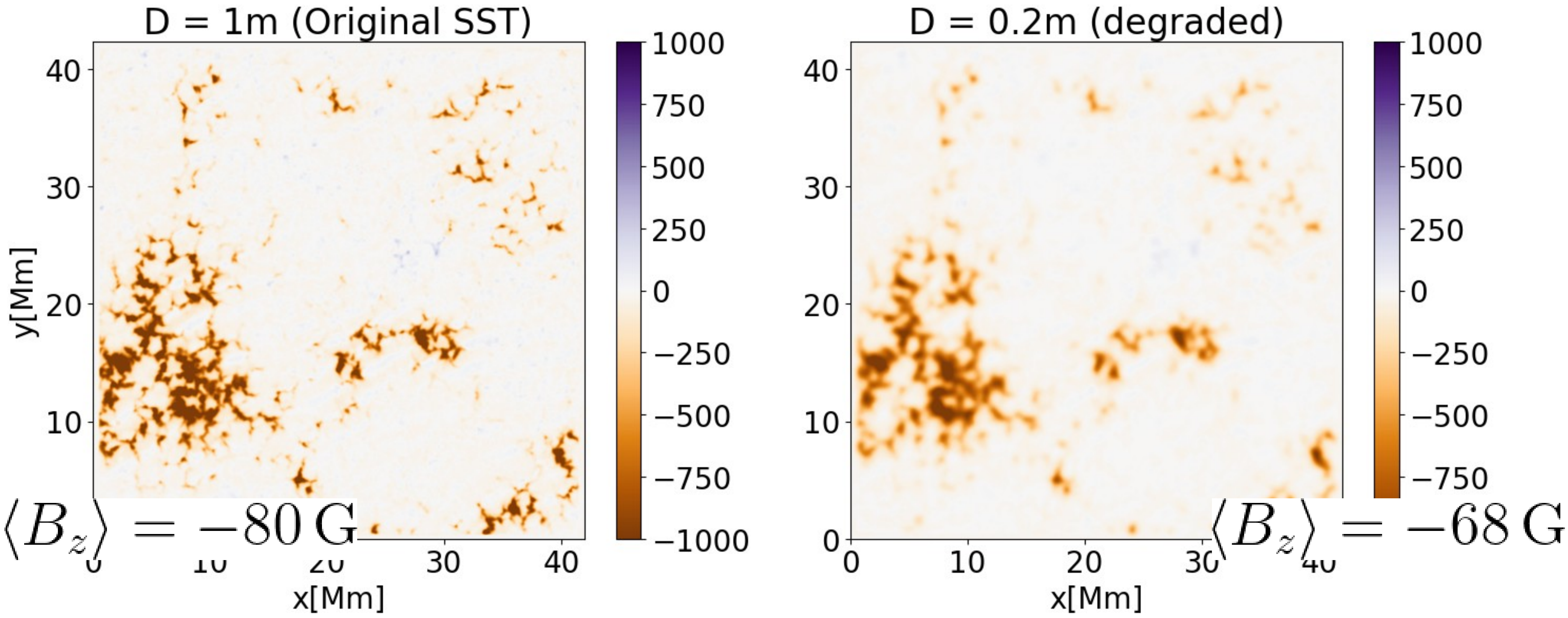




Right: Unsigned Flux density vs. Spatial resolution, from Sanchez Almeida & Martinez Gonzalez (2011)

Replication with the real data

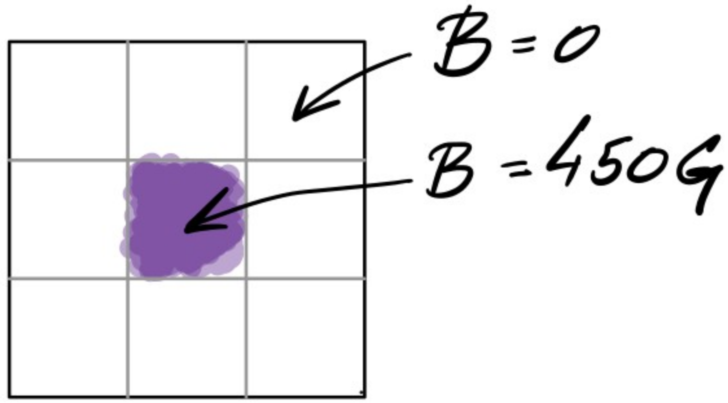
- Fe I 630 nm lines observed @ SST/CRISP (data from Kianfar et al. 2021).

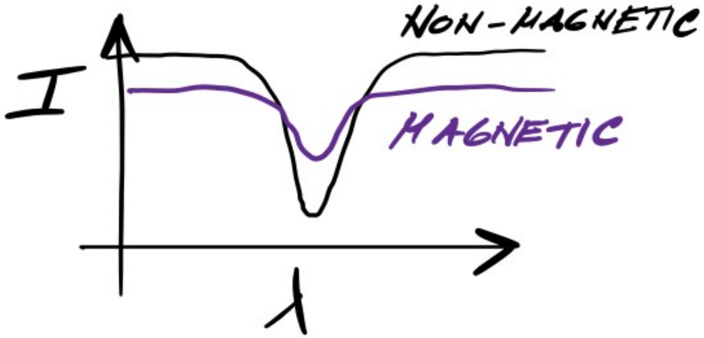


Where does this bias come from?

- Inversion is a non-linear process. PSF application is linear (discussed in Plowman and Berger 2020a,b,c, GONG end-to-end simulation)

- This effect will appear even in the weak field approximation. Consider the following:





$$V = kB\frac{dI}{d\lambda}$$

$$\left(\frac{dI}{d\lambda}\right)_{\text{mag}} = \frac{1}{2}\left(\frac{dI}{d\lambda}\right)_{\text{non-mag}} = x$$

$$\langle B\rangle_{\text{resolved}} = \frac{450\text{G}}{9} = \boxed{50\text{G}}$$

$$\langle B\rangle_{\text{non-resolved}} = \frac{V_{\text{tot}}}{k(dI/d\lambda)_{\text{tot}}} = $$

$$= \frac{kBx}{k \times 17x} = \boxed{26.5\text{G}}$$

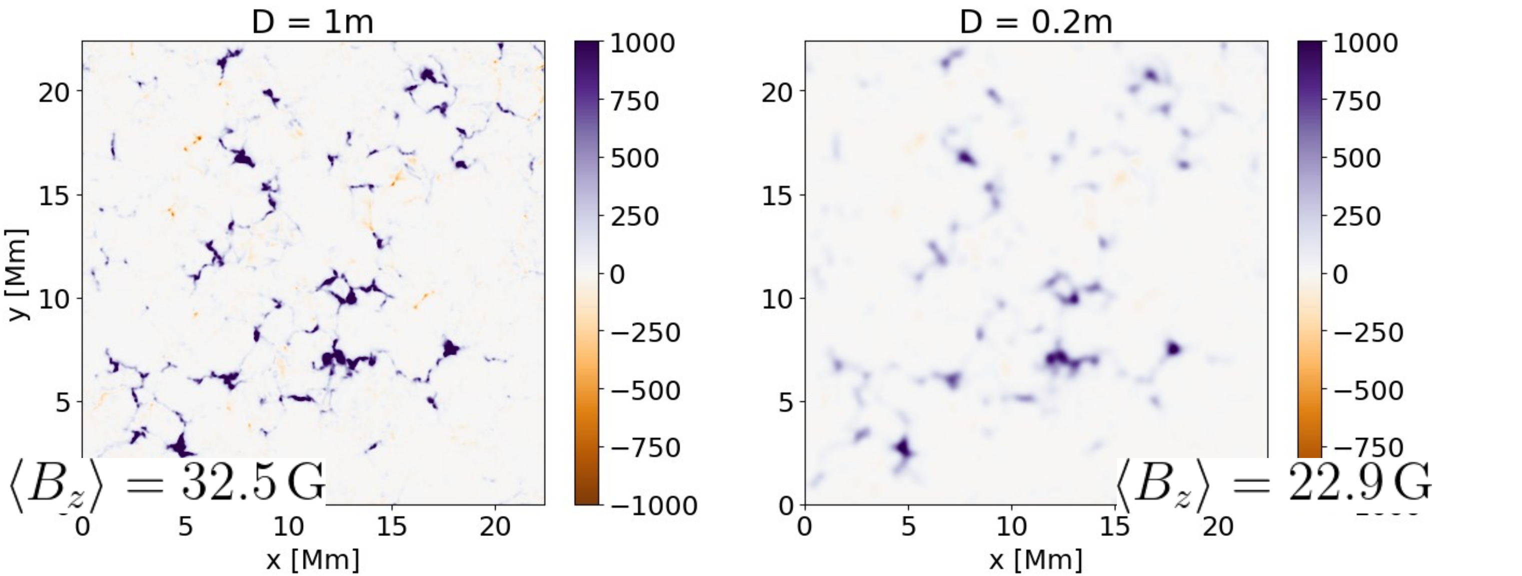
Disk center

- This is reproduced with multiple inversion codes and PSF shapes. Repeating the experiment with simplified atmosphere we found:

  At high resolutions we see more flux because of corrugation of tau = 1 surface

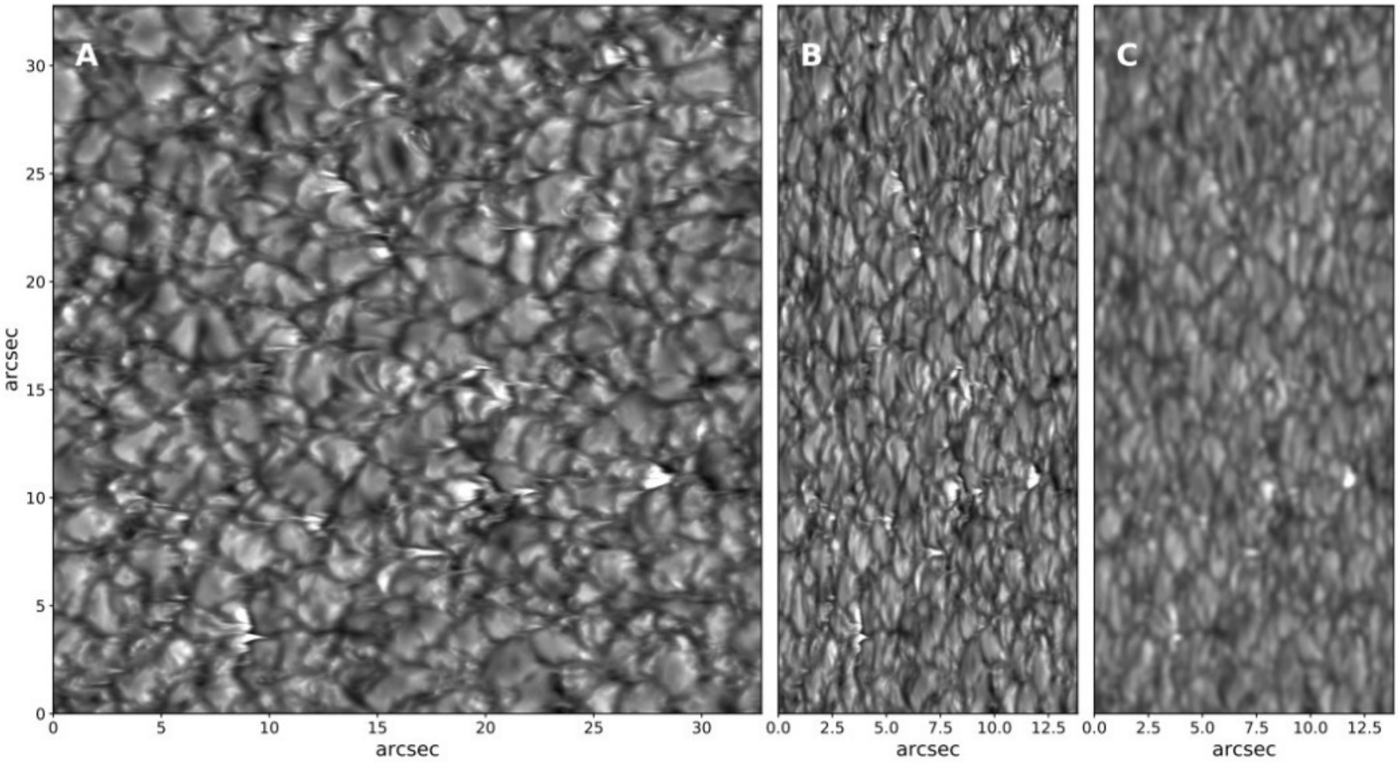
  At low resolutions we see less flux because of RT nonlinearity

- This effect is, of course, dependent on the spatial structure of the field



At the limb (mu = 0.4)

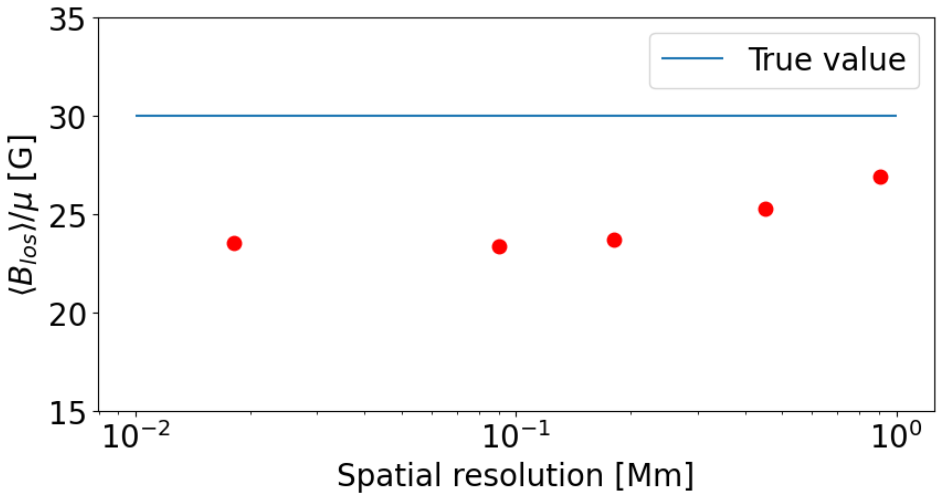
- On top of the PSF, additional effects: obliqueness + projection + noise
- Cube tilted → Spectra are calculated → Projected → Application of the PSF
- Inversions with 4 different approaches: ME with local/global/no stray light, SIR (Centeno et al. 2023)

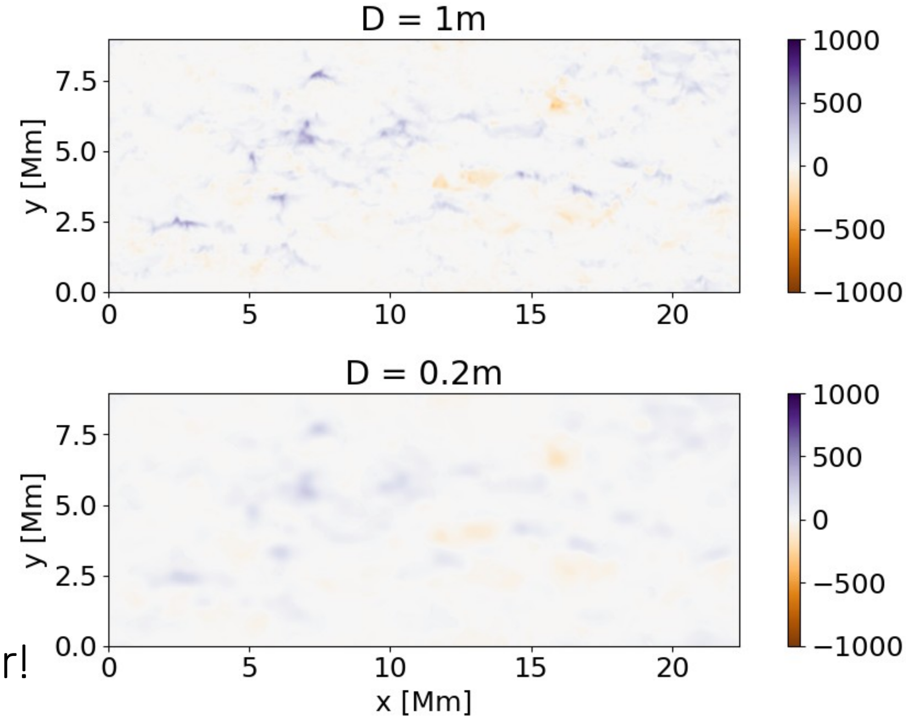


A) Image from a tilted cube
B) Pixels projected to LOS
C) PSF of Hinode applied

At the limb, the PSF effect disappears

- LOS flux almost constant with the PSF – effect of decreased contrast?
- Simply de-projecting the LOS flux does not do the trick (~ 25% loss).
- Disambiguation is necessary (e.g. Ito et al 2010)

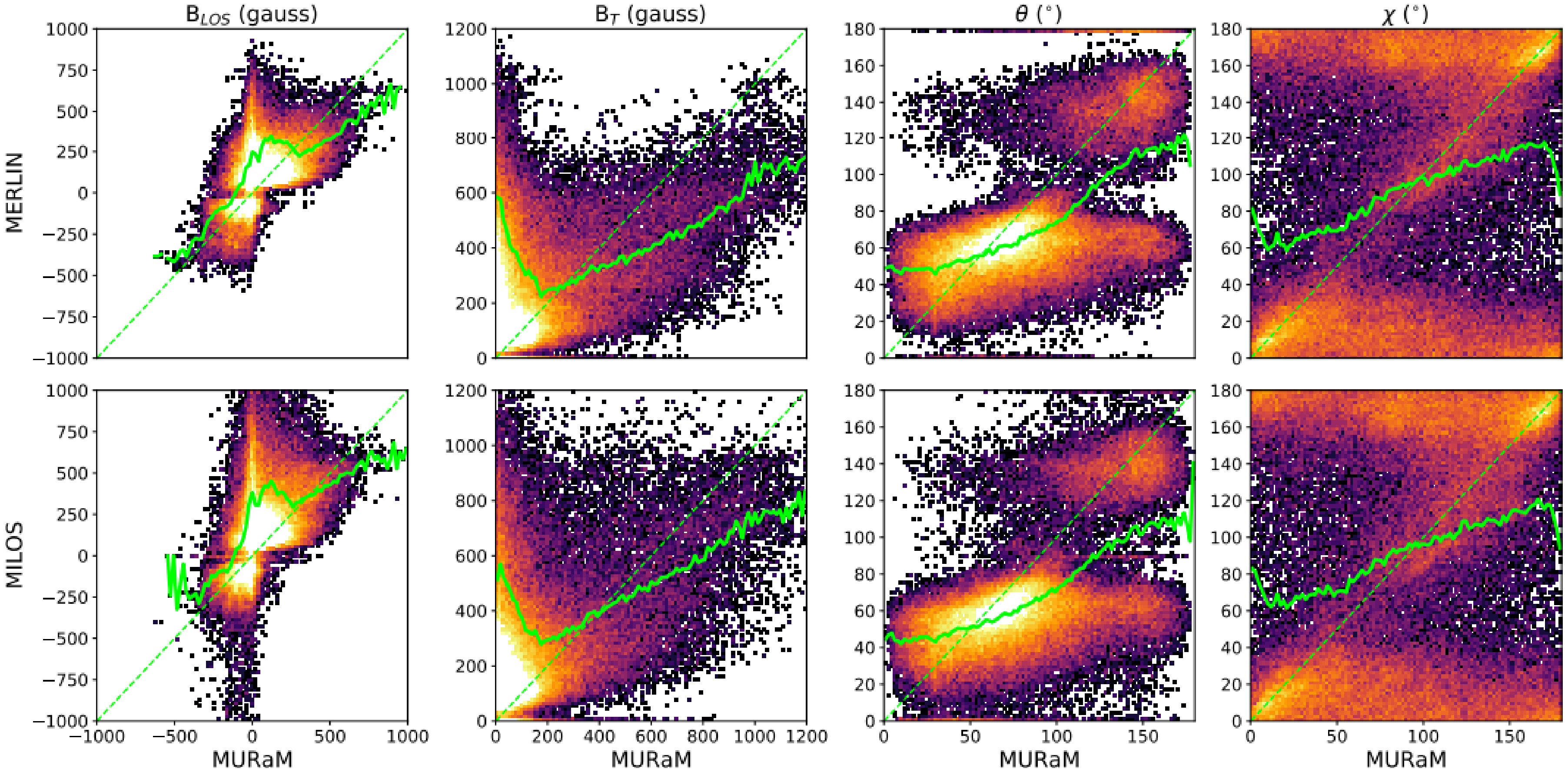




- But for that we need the full magnetic field vector!

At the limb

- (Not surprisingly), the intrinsic magnetic field properties cannot be recovered (Hinode resolution)



Conclusions

To infer the open (net) magnetic flux, we need:

- High-resolution observations (even at the disk center) / Spatially coupled inversions
- Reliable disambiguation – *Stereoscopic methods?*
- (Maybe) multi-line / multi-height capabilities
- (Probably) good SNR
- ToDo: Extend this study with all of the above and propose observing / inversion strategies
- Questions? Comments? Suggestions?

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