Magnetic fields of T Tauri stars from near-infrared spectroscopy

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STARRY conference
Leeds, June 2019

UPPSALA
UNIVERSITET

1. What kind of observations & techniques do we use to directly measure stellar magnetic fields?

- **near-IR spectroscopy: Zeeman broadening**
- **optical spectropolarimetry: Zeeman Doppler imaging**

2. What information do these techniques provide?

3. Our high-res spectroscopic observations of T Tauri stars and magnetic field measurements.

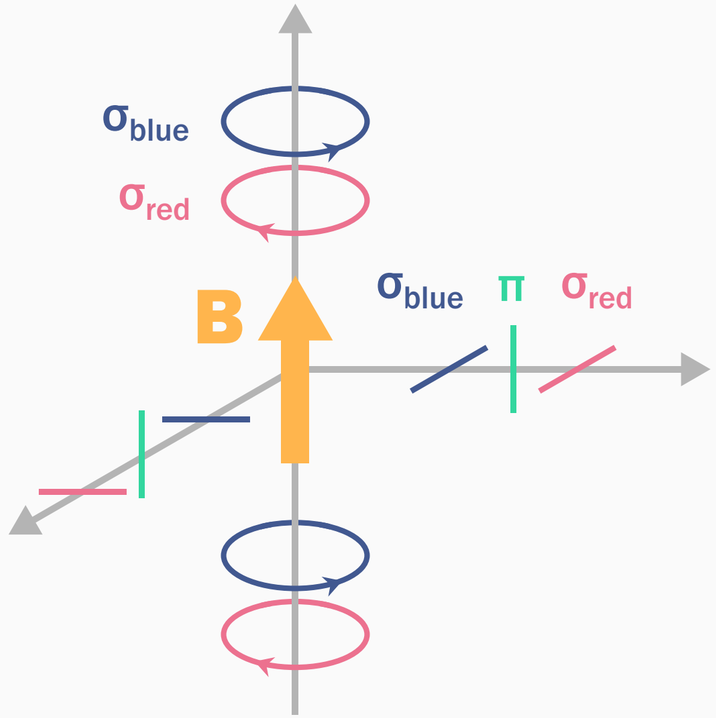
4. How does the future look like?

Zeeman effect

> **Splitting of a spectral line in several components**

The wavelength shift $\Delta\lambda_B$ scales with
> the wavelength λ^2
> the magnetic field strength B
> the effective Landé factor g_{eff}

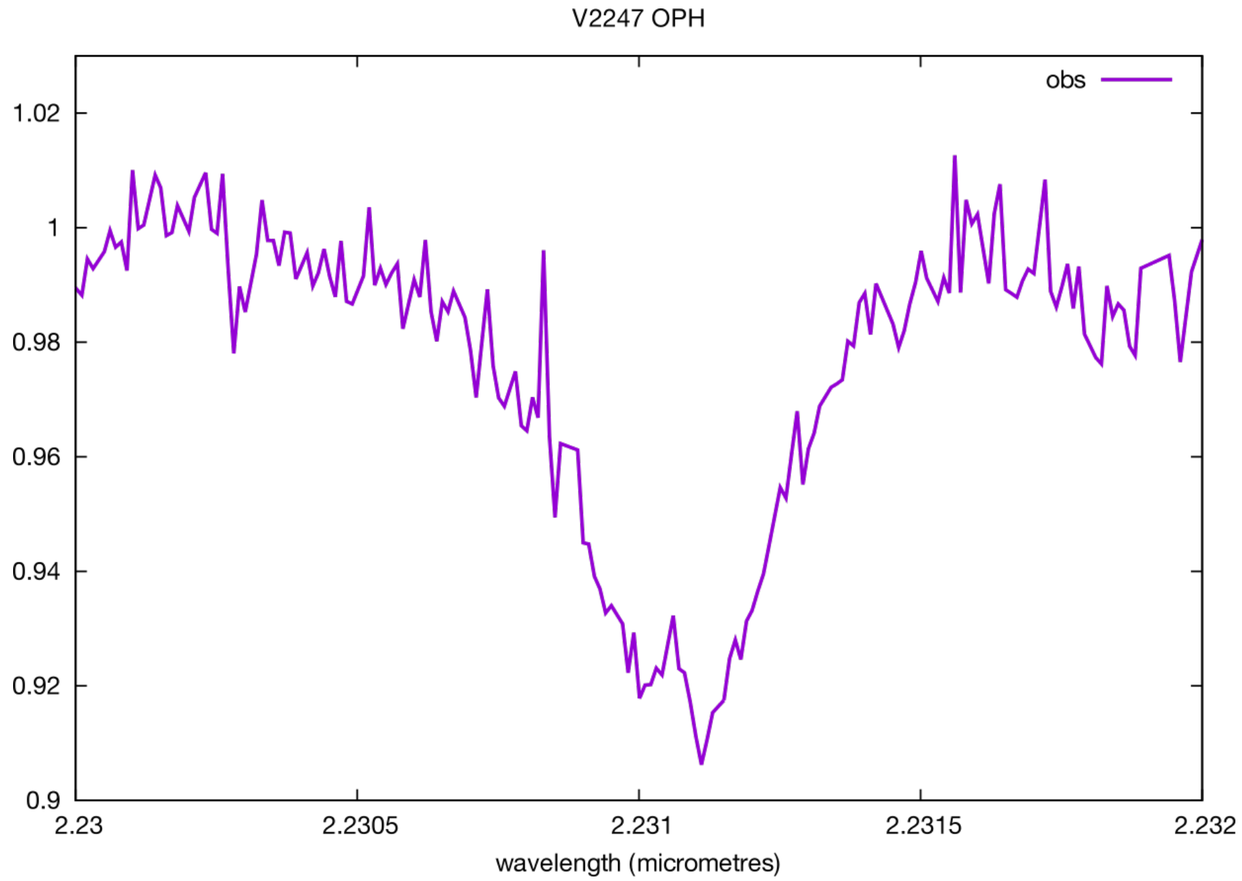
> **Polarization of each component**



Zeeman broadening of spectral lines

Ti I @ 22310.6 Å

$g_{\text{eff}} = 2.5$



You need to know the non-magnetic case.

Zeeman broadening of spectral lines

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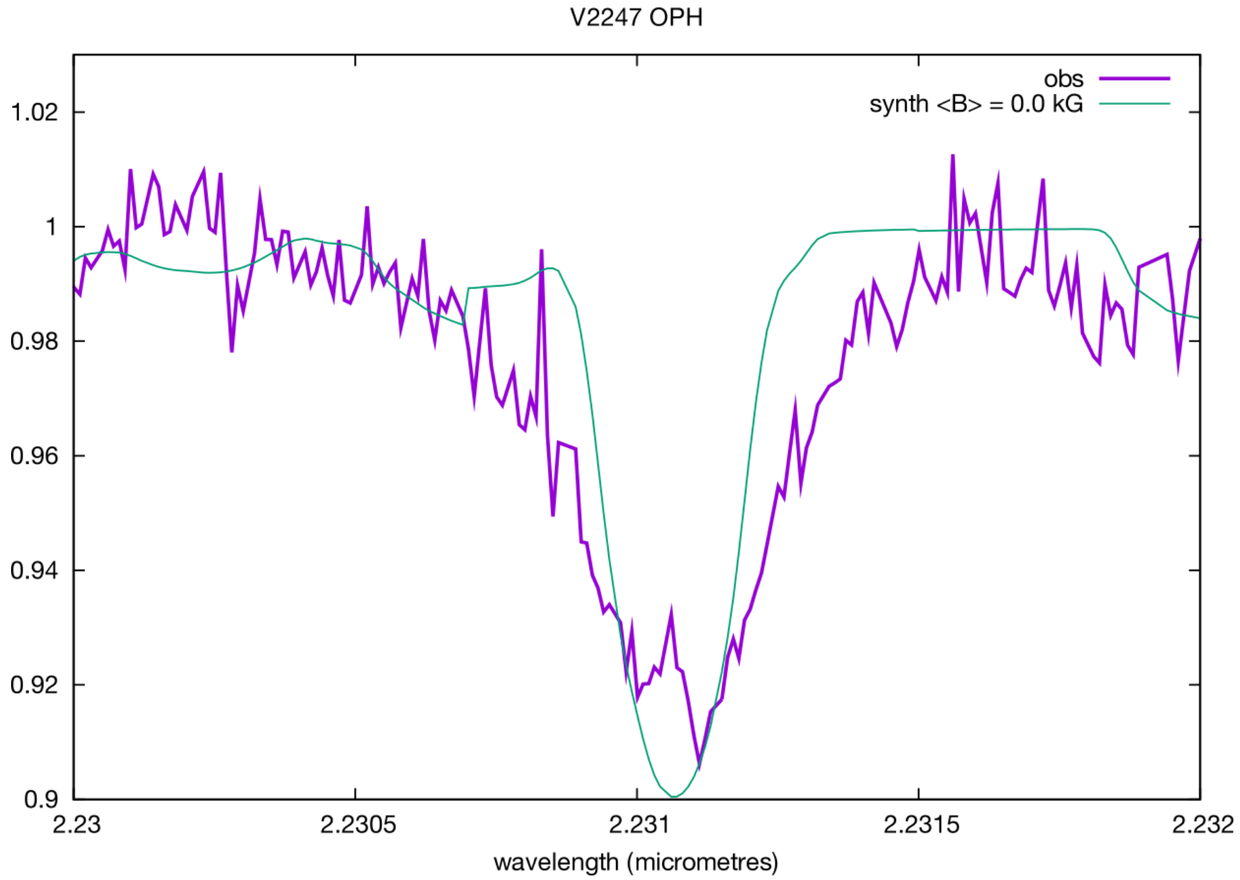

B = 0.0 kG

You need to know the non-magnetic case.

Zeeman broadening of spectral lines

Ti I @ 22310.6 Å

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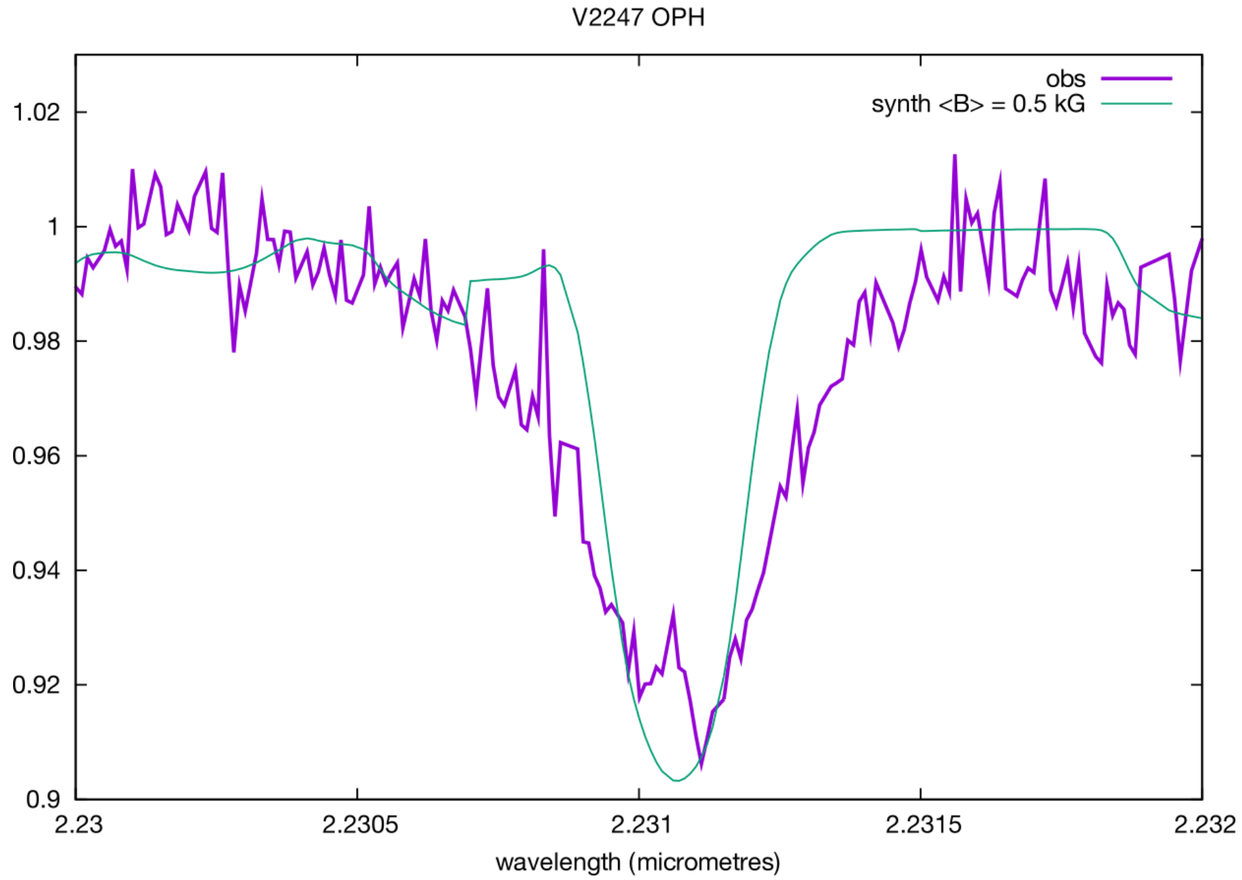
B = 0.5 kG

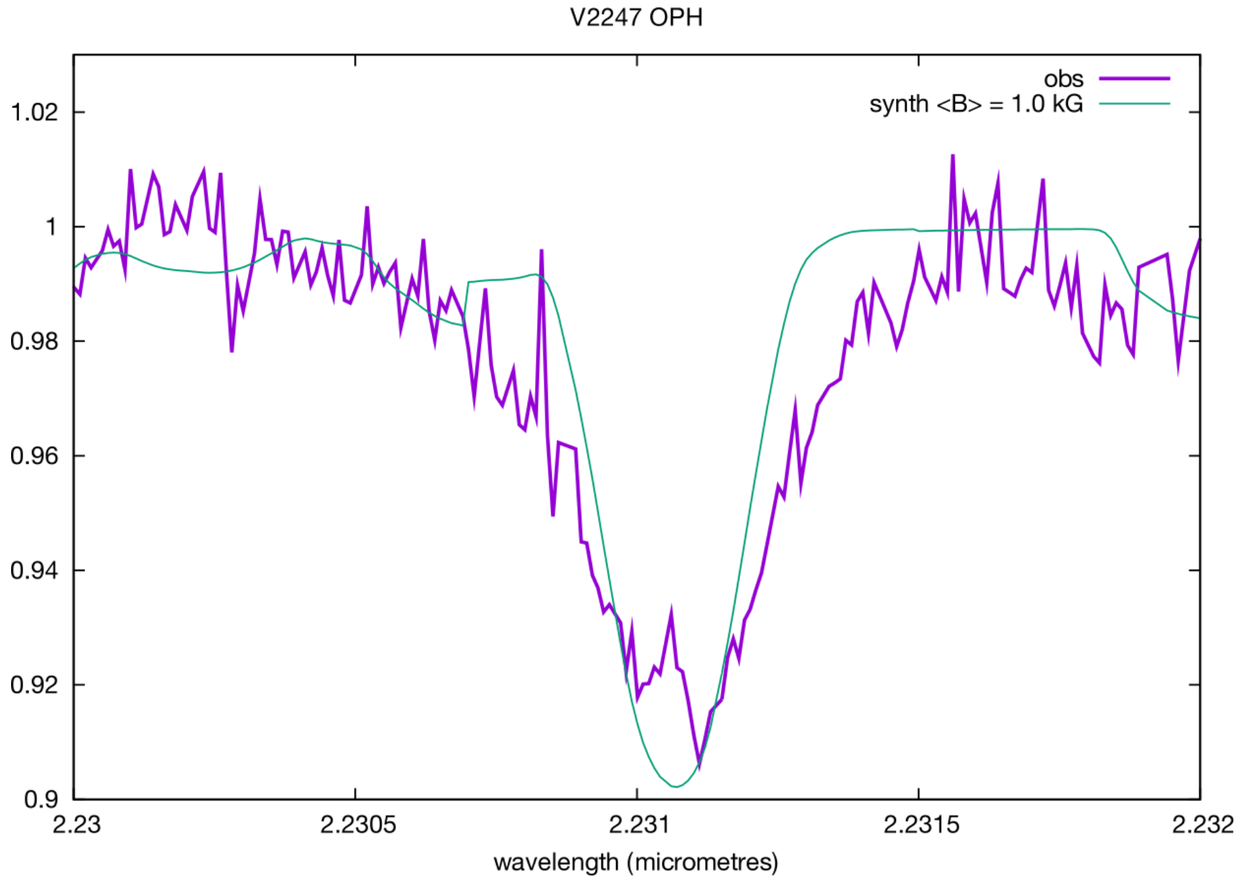


Zeeman broadening of spectral lines

Ti I @ 22310.6 Å

g_{eff} = 2.5

B = 1.0 kG



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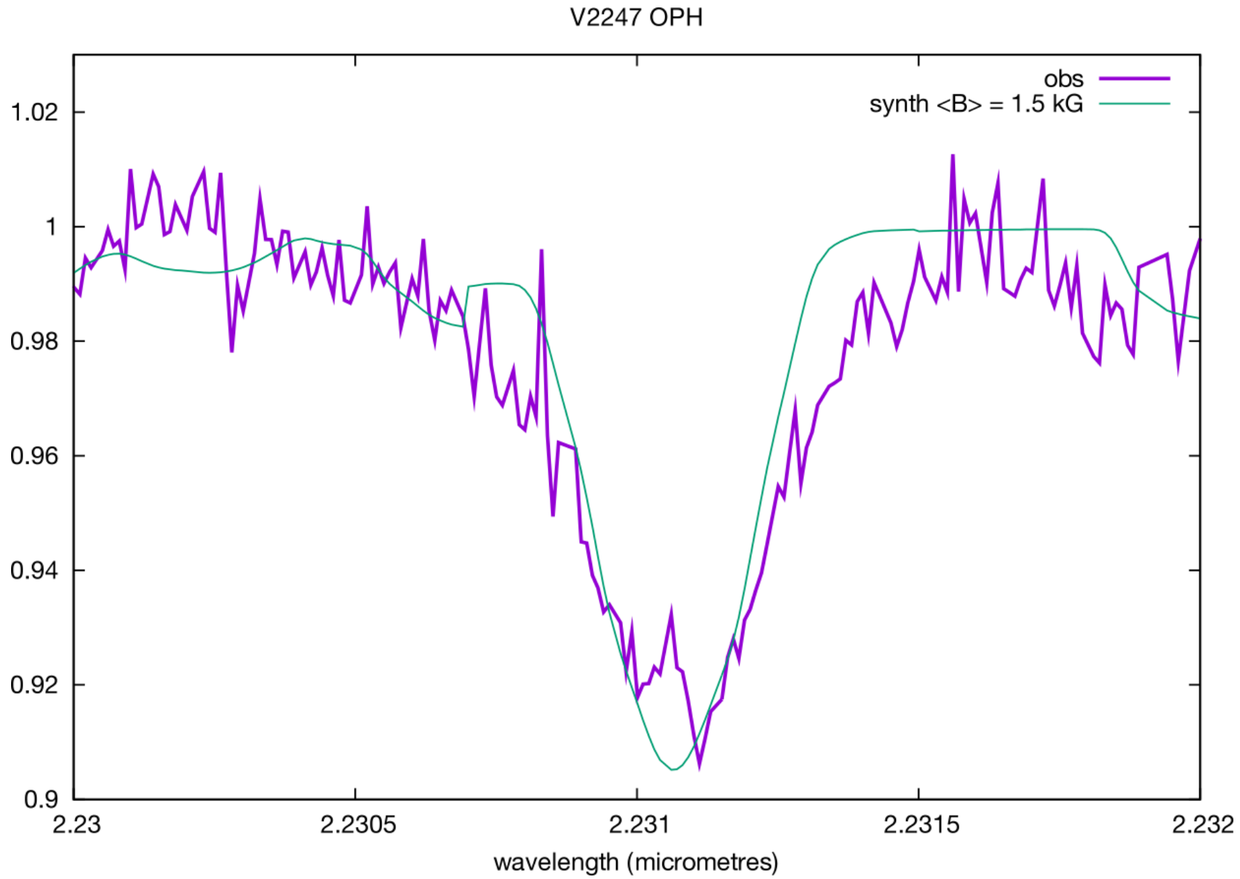

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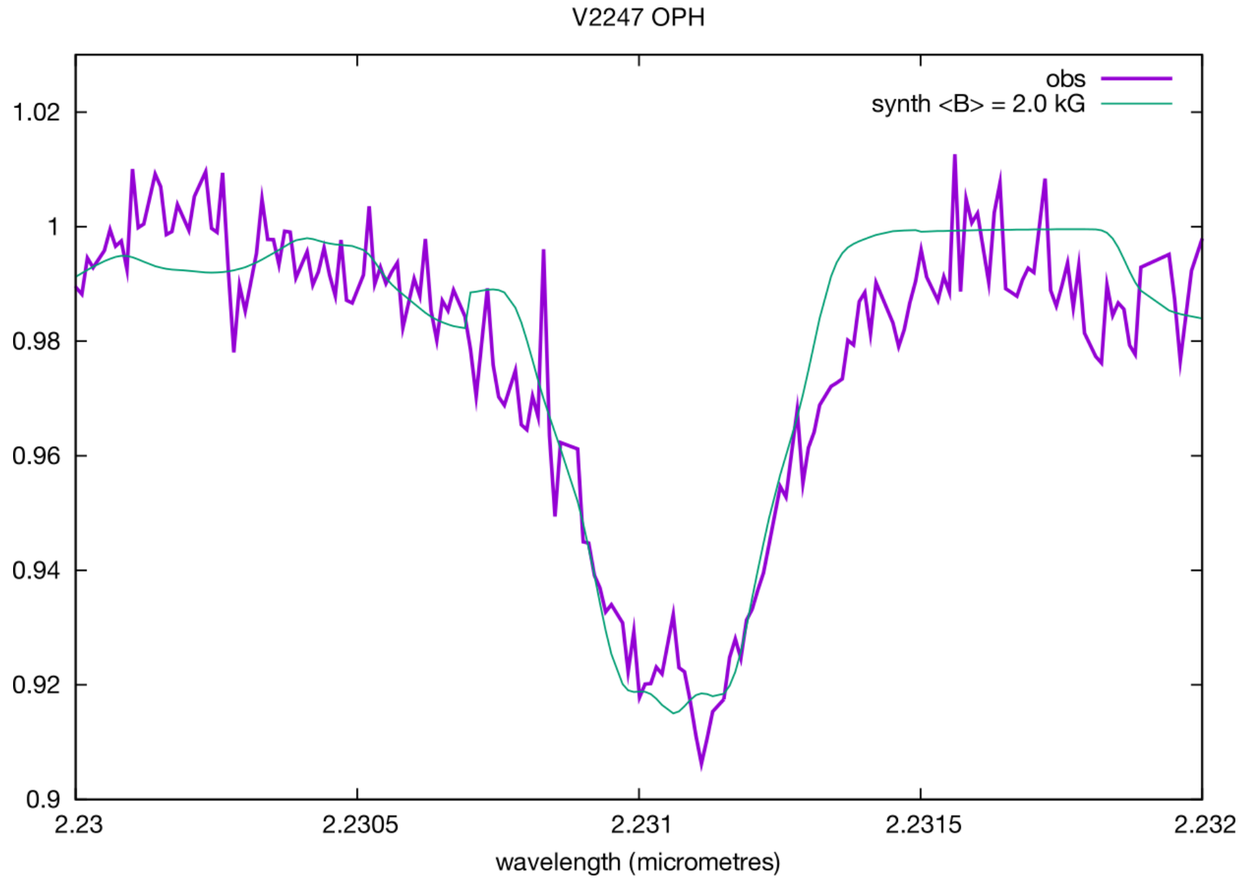

Zeeman broadening of spectral lines

Ti I @ 22310.6 Å

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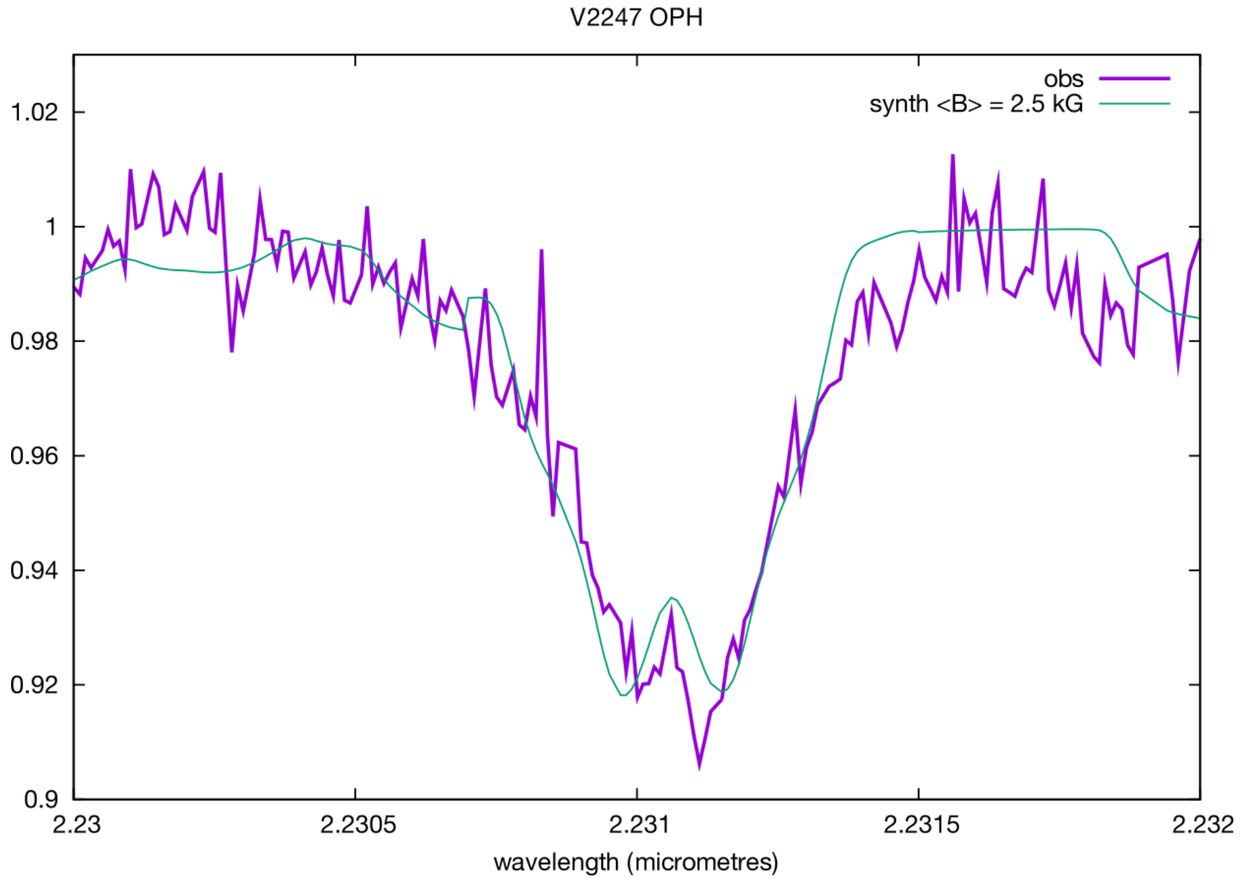
B = 2.5 kG

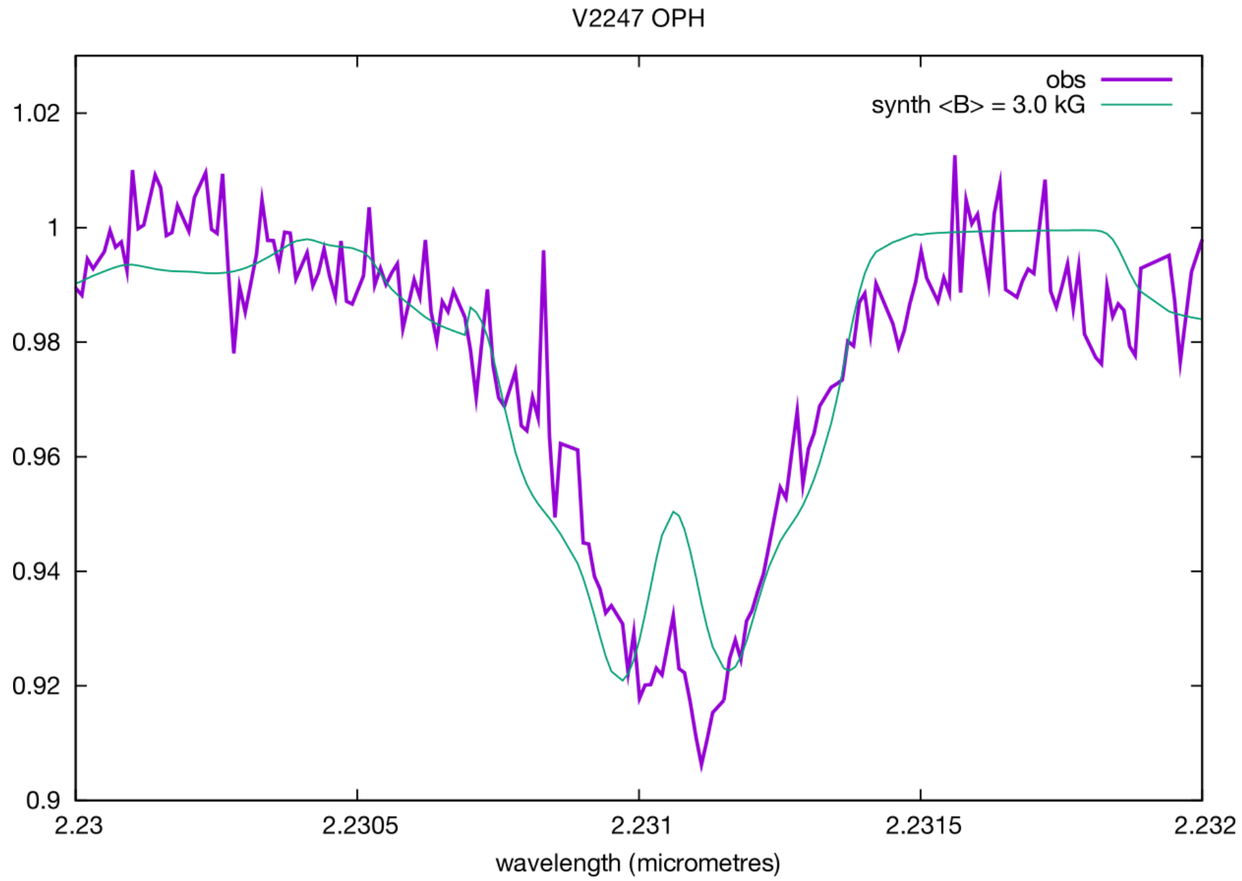


Zeeman broadening of spectral lines

Ti I @ 22310.6 Å

g_{eff} = 2.5

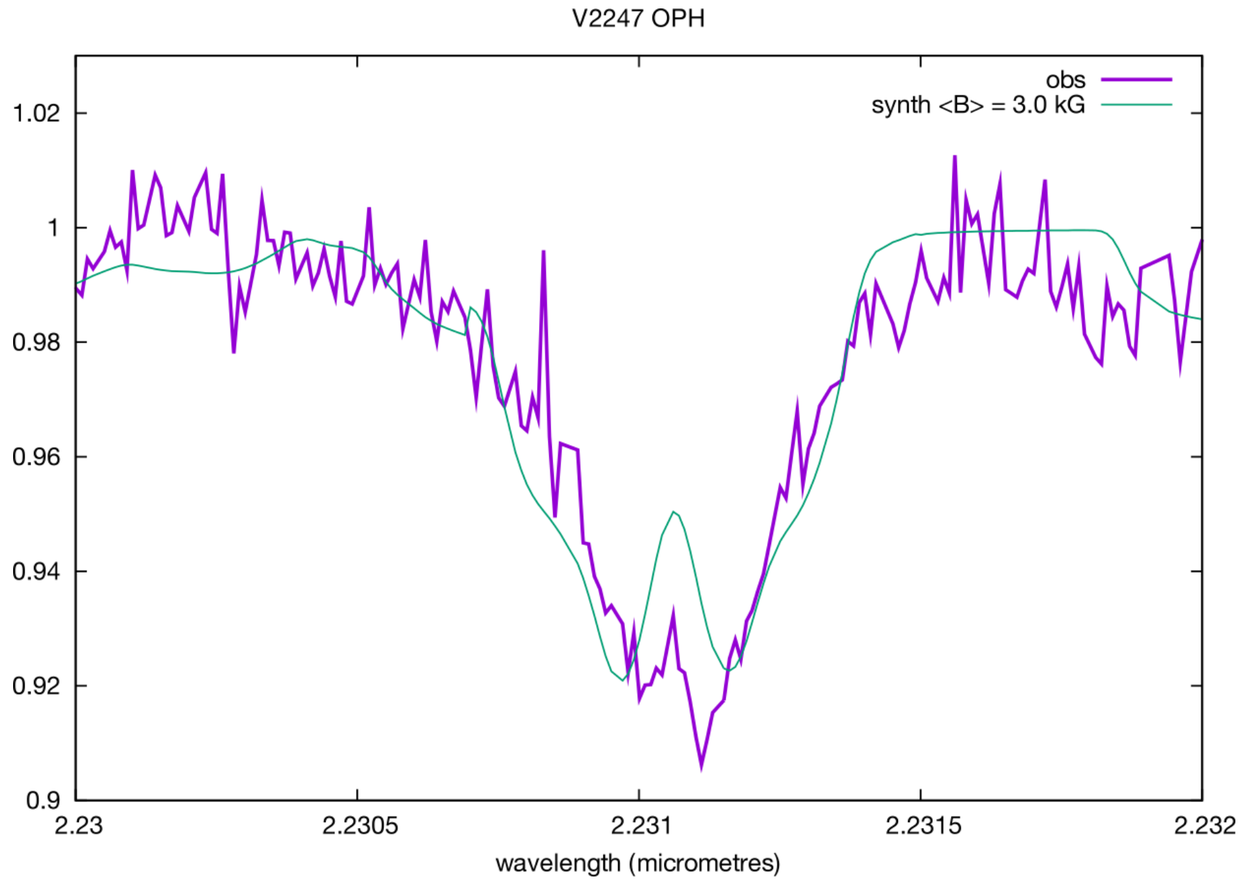
B = 3.0 kG



Zeeman broadening of spectral lines

Ti I @ 22310.6 Å

g_{eff} = 2.5



What do you get?

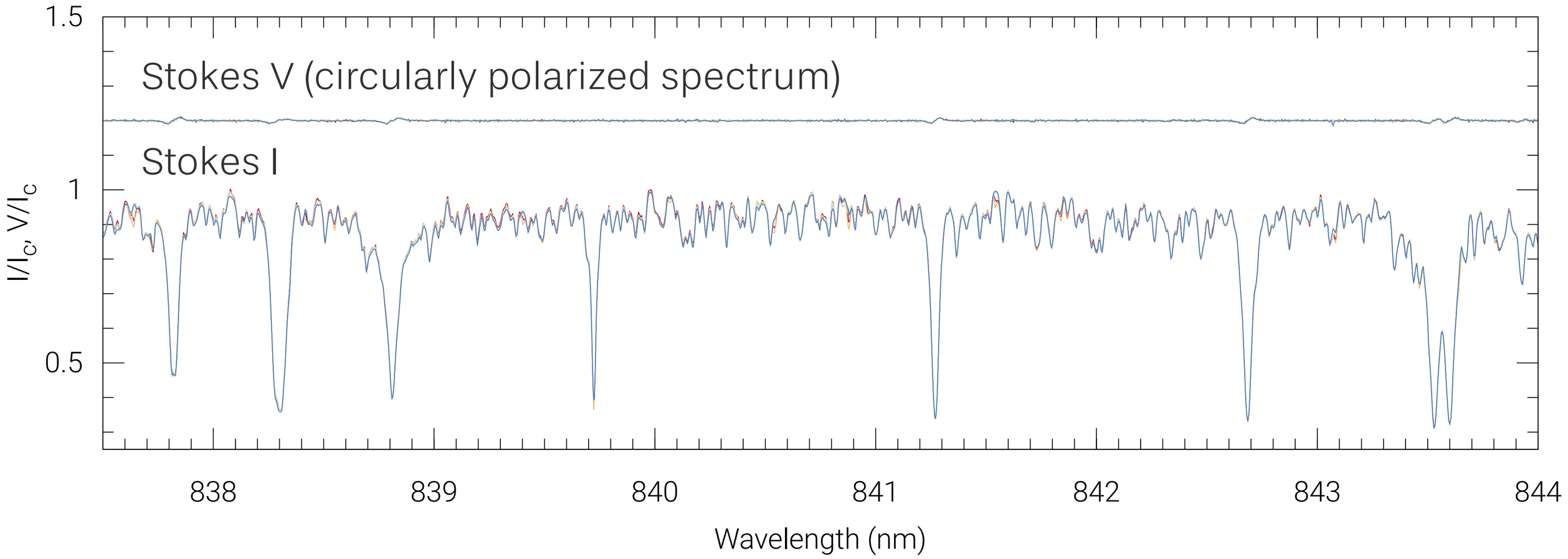
- Good estimation of the mean unsigned magnetic field <B>
- Small-scale fields

What you don't get?

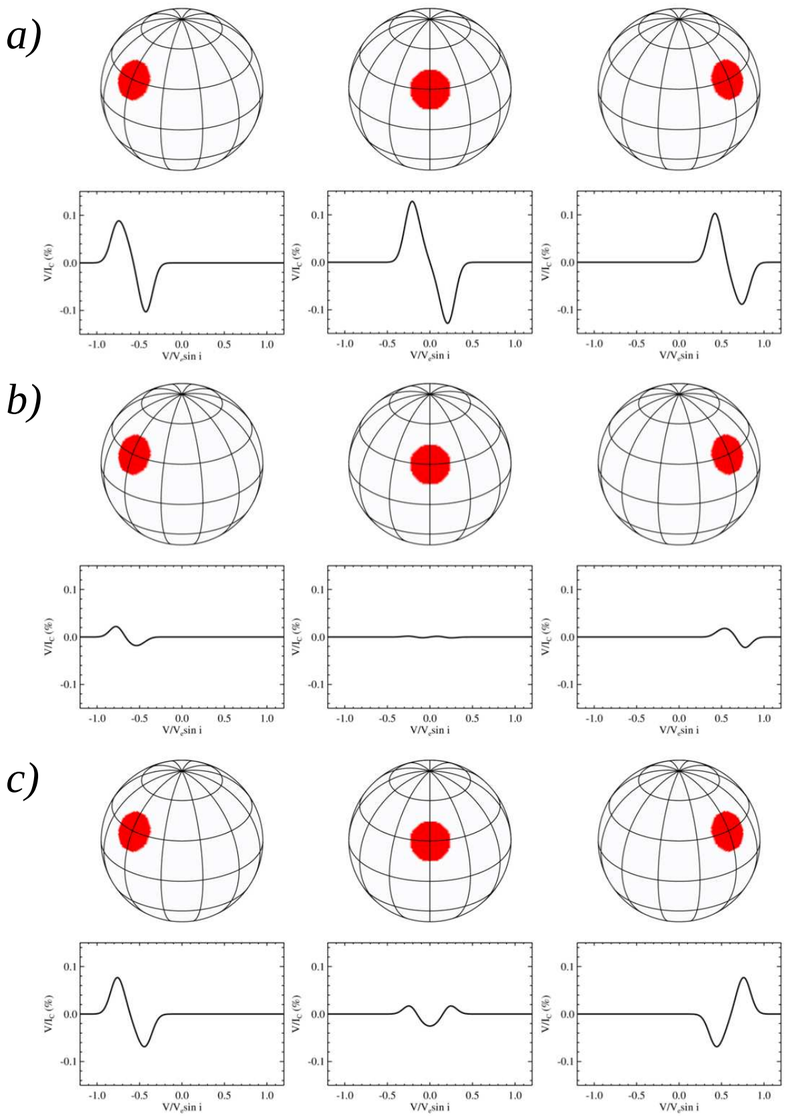
- Topology of the magnetic field (i.e complex/simple, axisymmetry, poloidal/toroidal)

Polarized spectra

For Stokes QUV we know the non-magnetic case: it's zero.



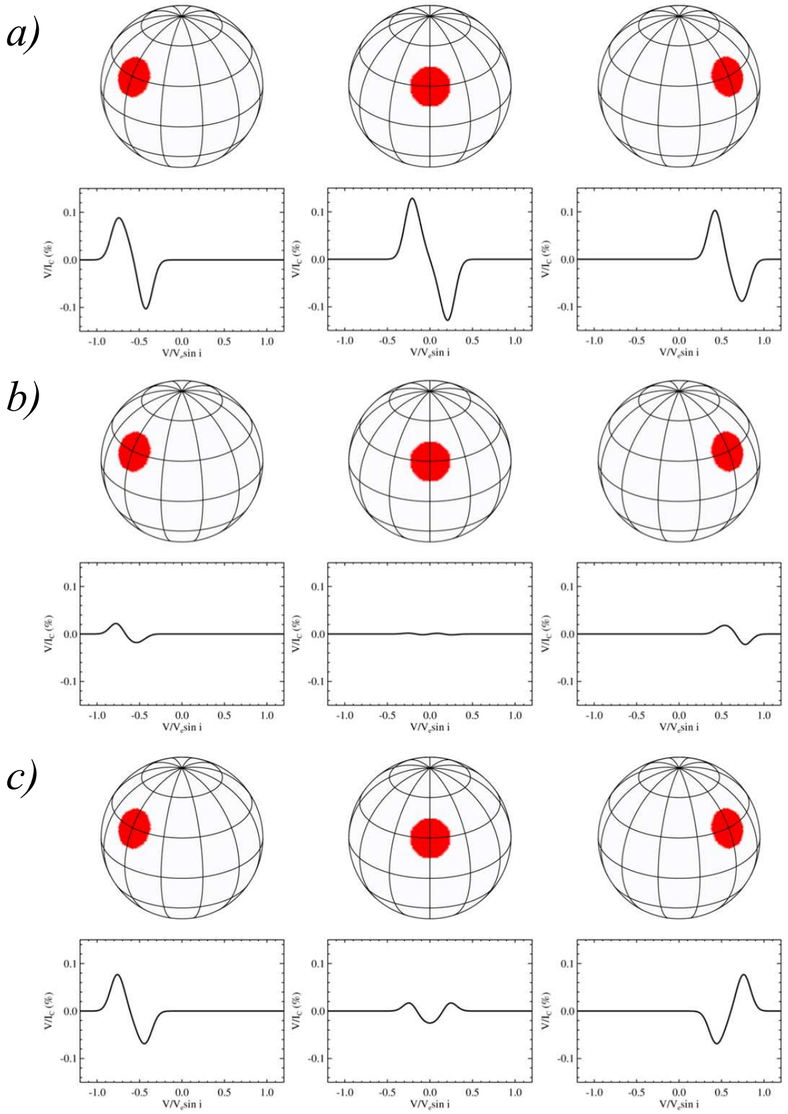
Zeeman Doppler Imaging (ZDI)



- **Radial** field
- **Meridional** field
- **Azimuthal** field

Only one cool star (II Peg, Rosén et al. 2015) has been mapped through ZDI with Stokes IQUV.

Zeeman Doppler Imaging (ZDI)



- **Radial** field
- **Meridional** field
- **Azimuthal** field

What do you get?

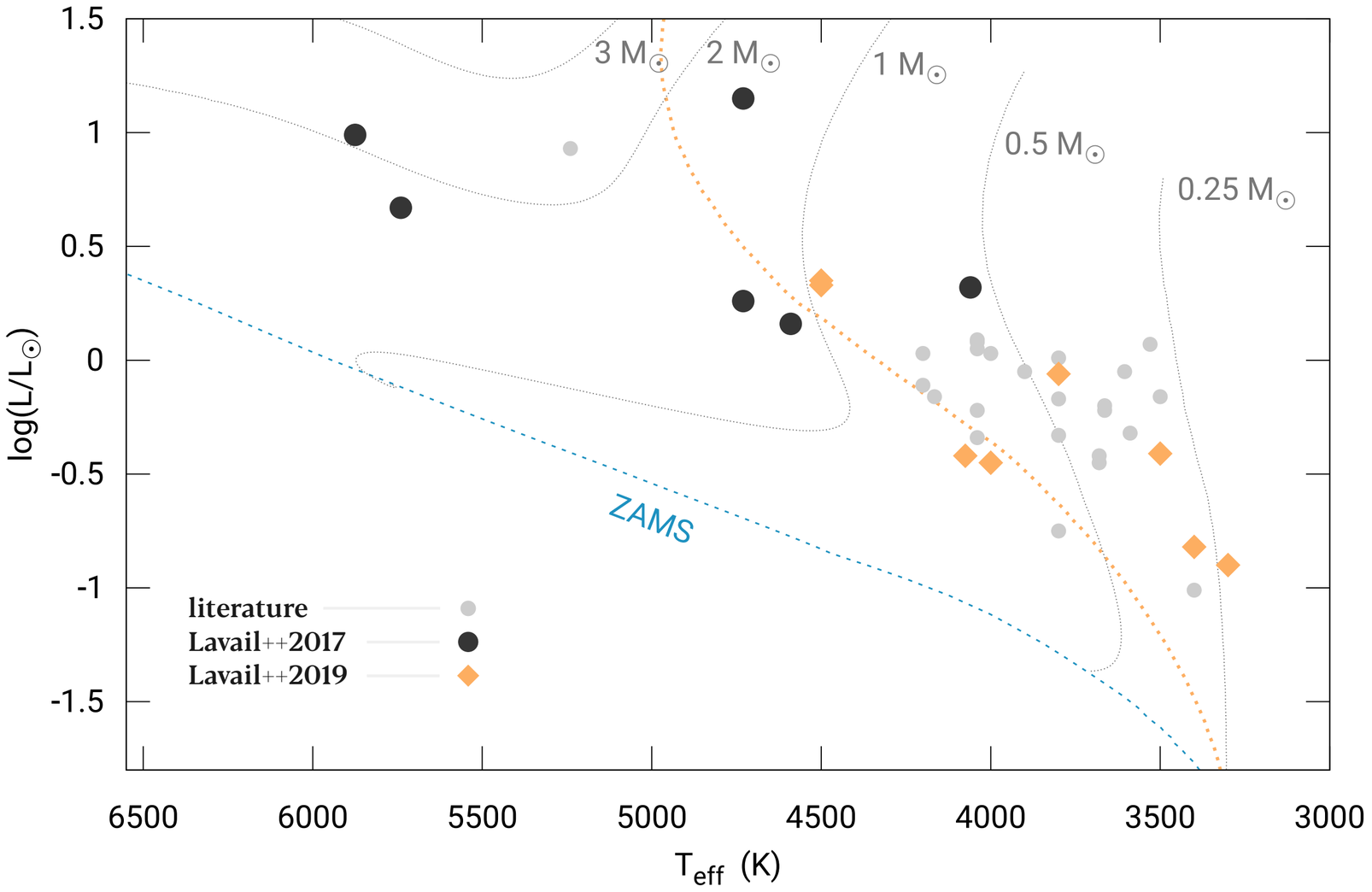
- Topology of the ⋆**large scale**⋆ surface magnetic field

What you don't get?

- The small-scale stuff (most of the magnetic field)

Time for some results

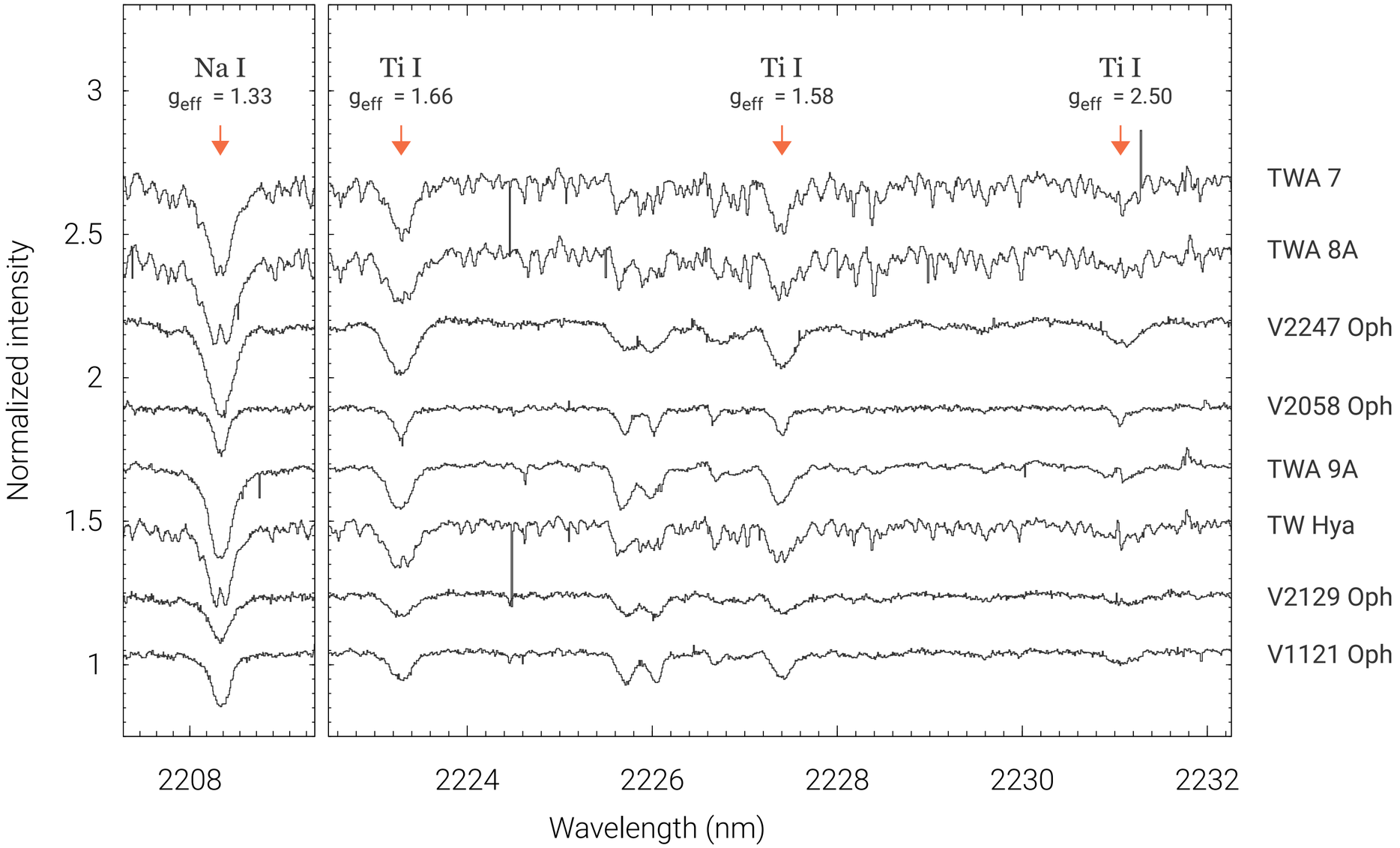
Zeeman broadening of T Tauri stars



- Lavail++2019
(in prep)
- Sokal++2018
(2018ApJ...853..120S)
- Lavail++2017
(2017A&A...608A..77L)
- Yang & Johns-Krull 2011
(2011ApJ...729...83Y)
- Yang, Johns-Krull & Valenti 2005, 2008
(2005ApJ...635..466Y,2008AJ....136.2286Y)

Tracks from the YaPSI grid
http://www.astro.yale.edu/yapsi/

Observed spectra with CRIRES@VLT

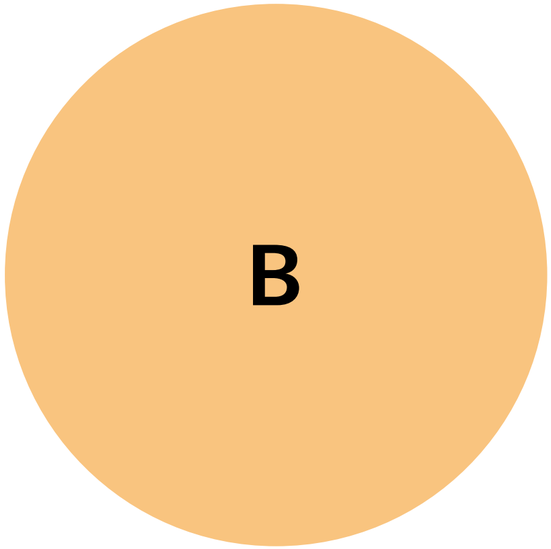


$R = 10^5$

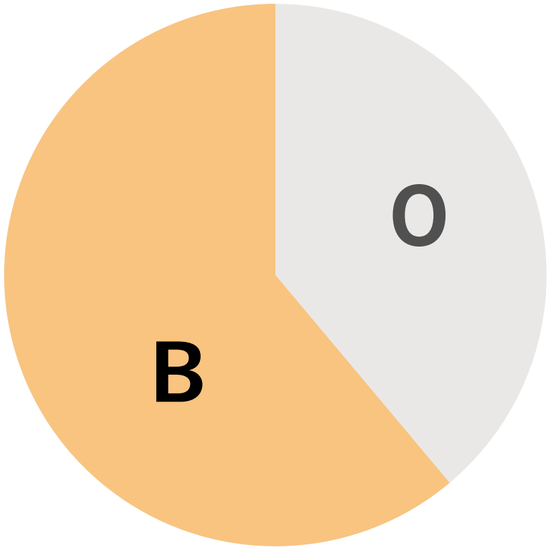
K-band

Magnetic field distribution

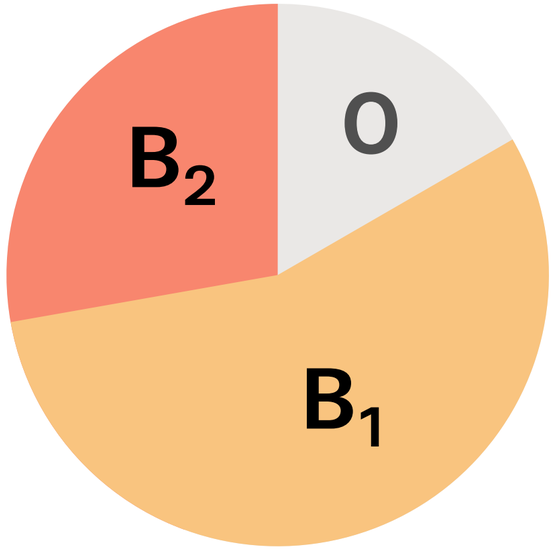
Model 0



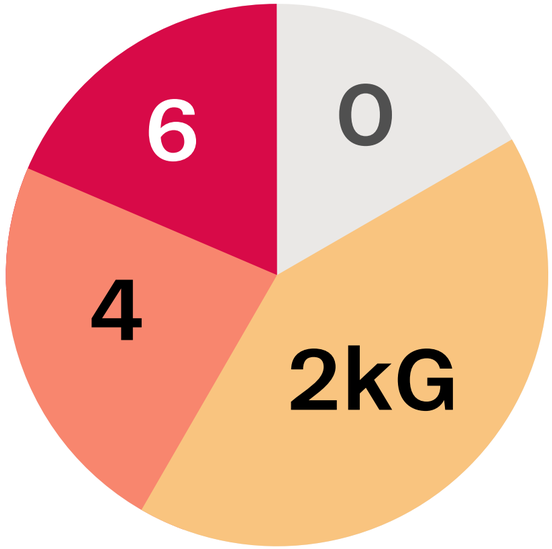
Model 1



Model 2



Model 3



Flores++2019
Sokal++2018
Lavail++2017

Lavail++2019
Lavail++2017
Yang++2011
Yang++2008

Lavail++2019
Lavail++2017
Yang++2011
Yang++2008

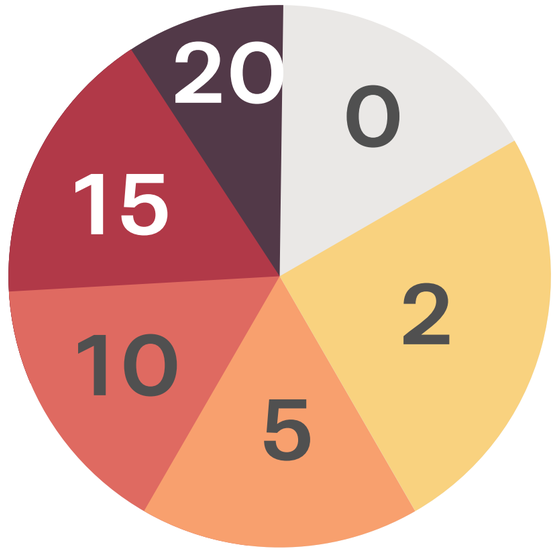
Lavail++2019
Lavail++2017
Yang++2011
Yang++2008

Magnetic field distribution (cont'd)

M1

M2

M??

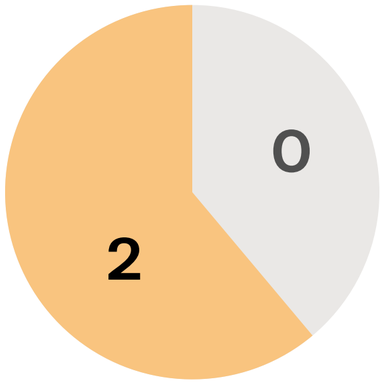


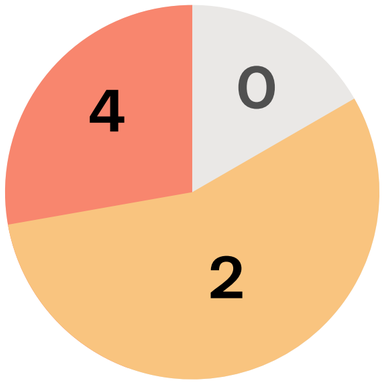
what's next ????

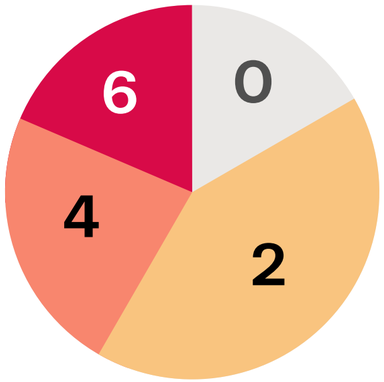
My attempt: "data-driven" approach

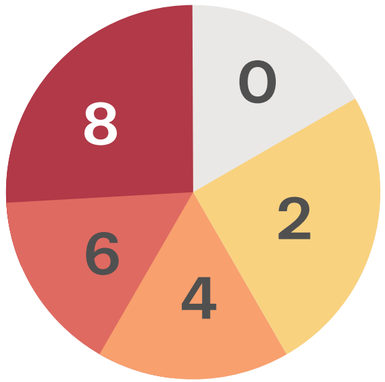
- Generalize Model 3 (0,2,4,6 kG) to higher field strength (0,2,4,6,8,10 … kG)
- Introduce some sort of regularization to avoid overfitting the data

We select the model that yields the lowest information criterion.





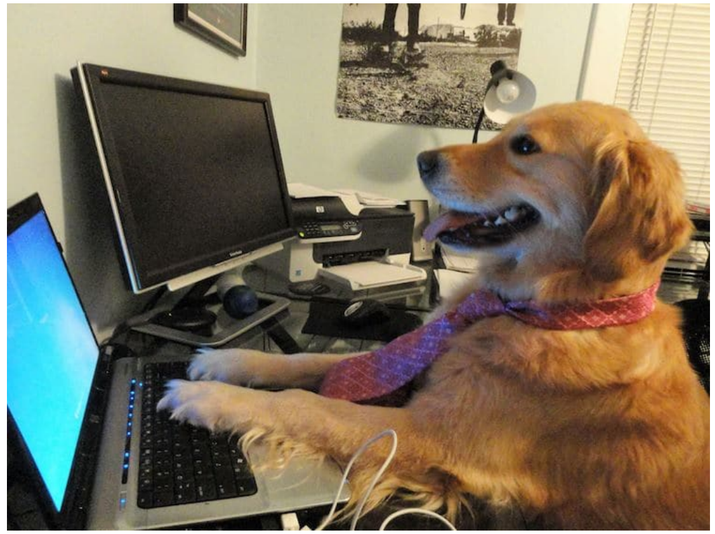




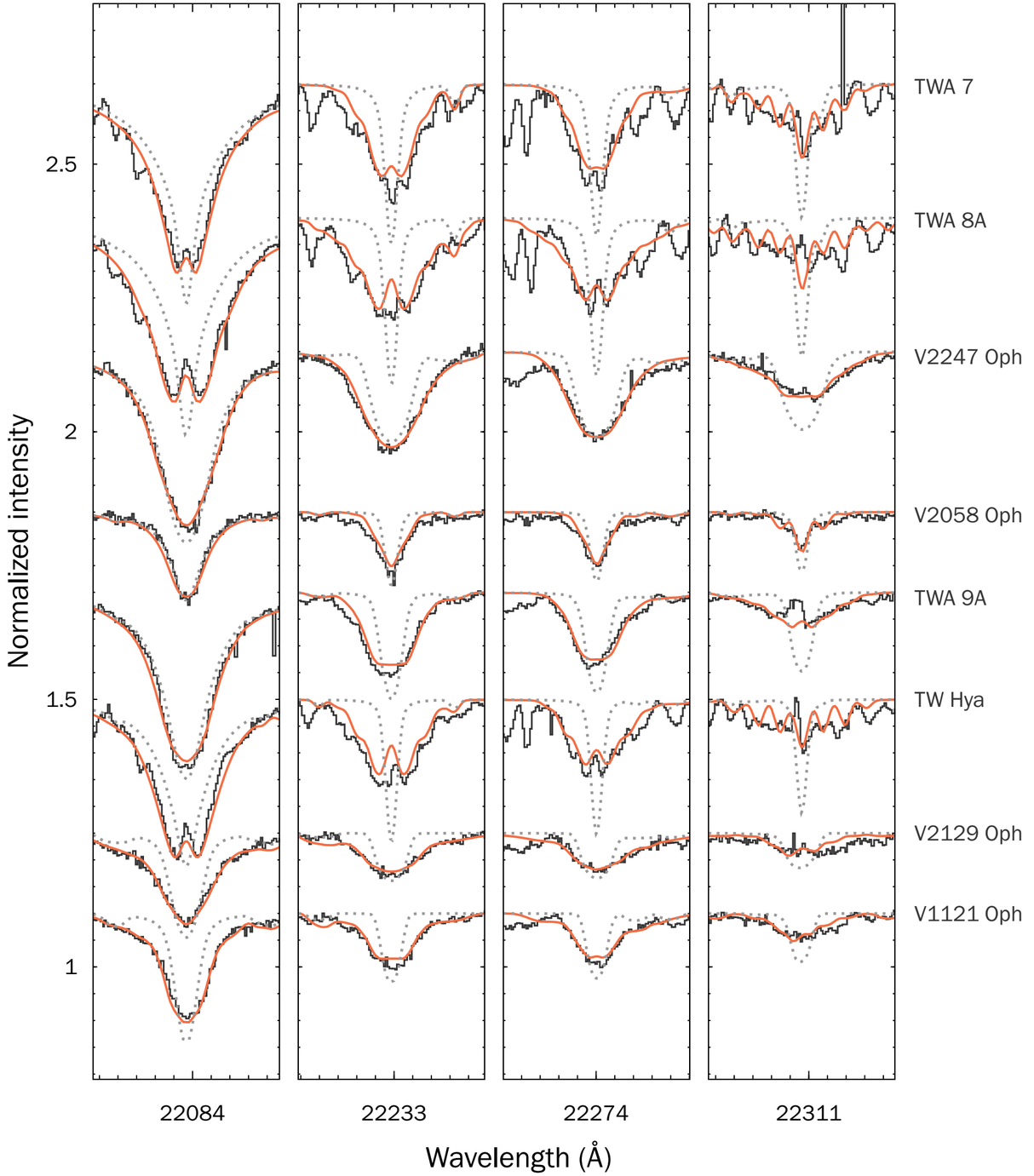
etc ....

Fitting magnetically sensitive spectral lines

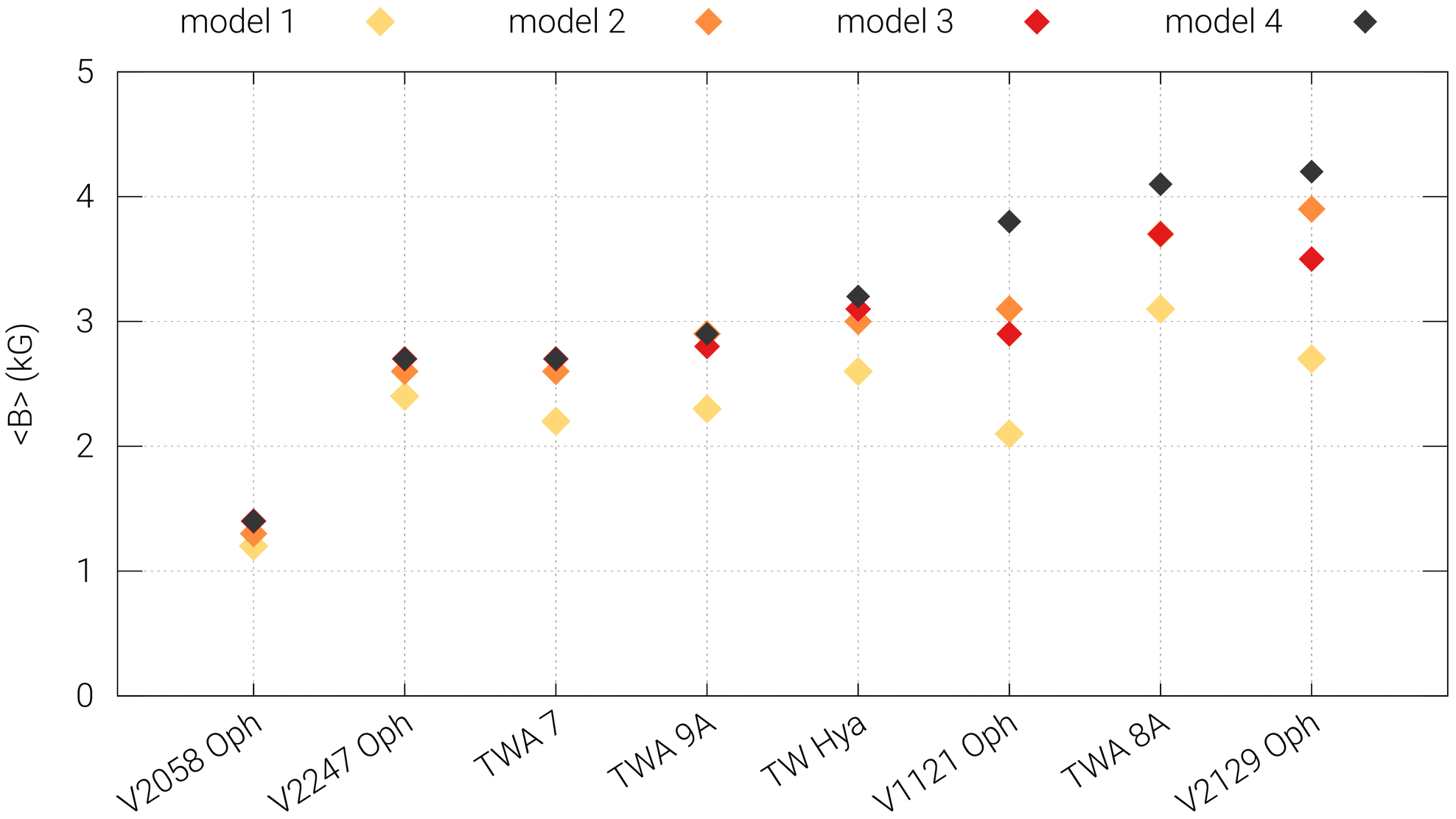
observed spectrum
best non-magnetic fit
best magnetic fit



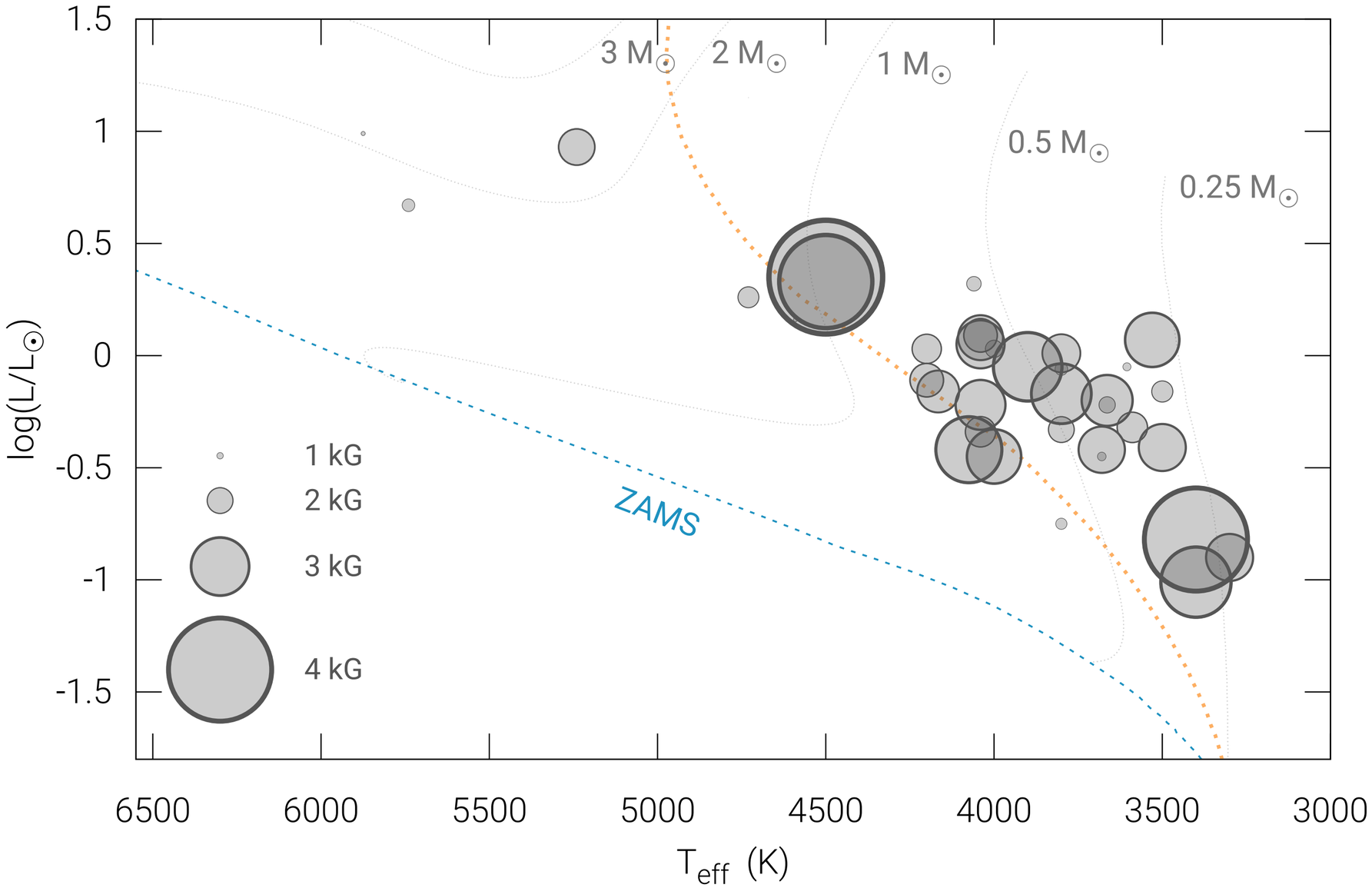
Code and some reduced data available at:
github.com/astro-alexis/magnotron-tts



Comparing different models

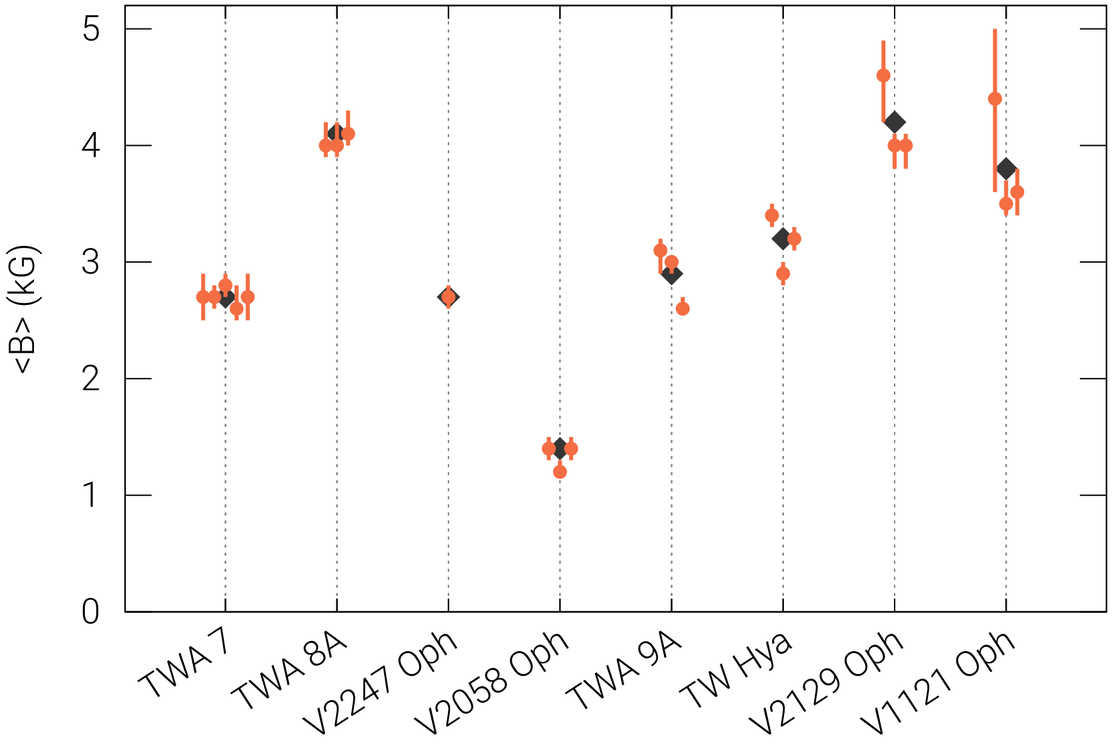


Zeeman broadening of T Tauri stars

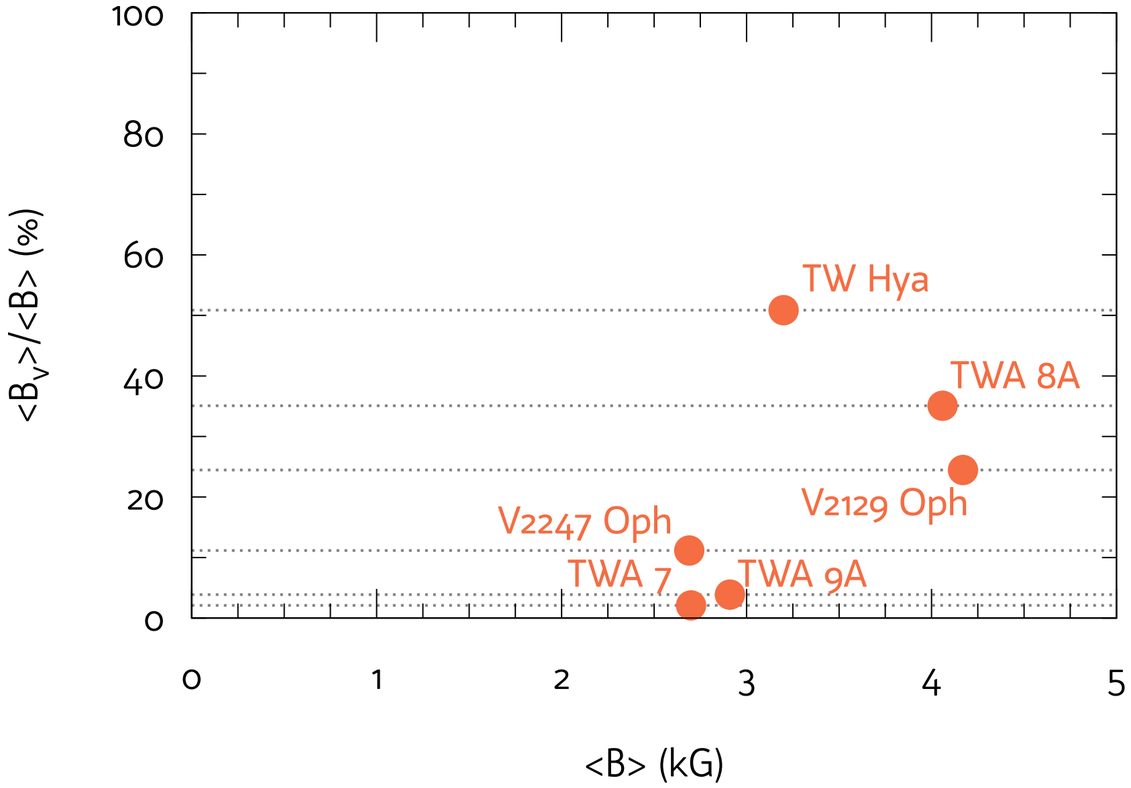


Characterizing the surface magnetic field

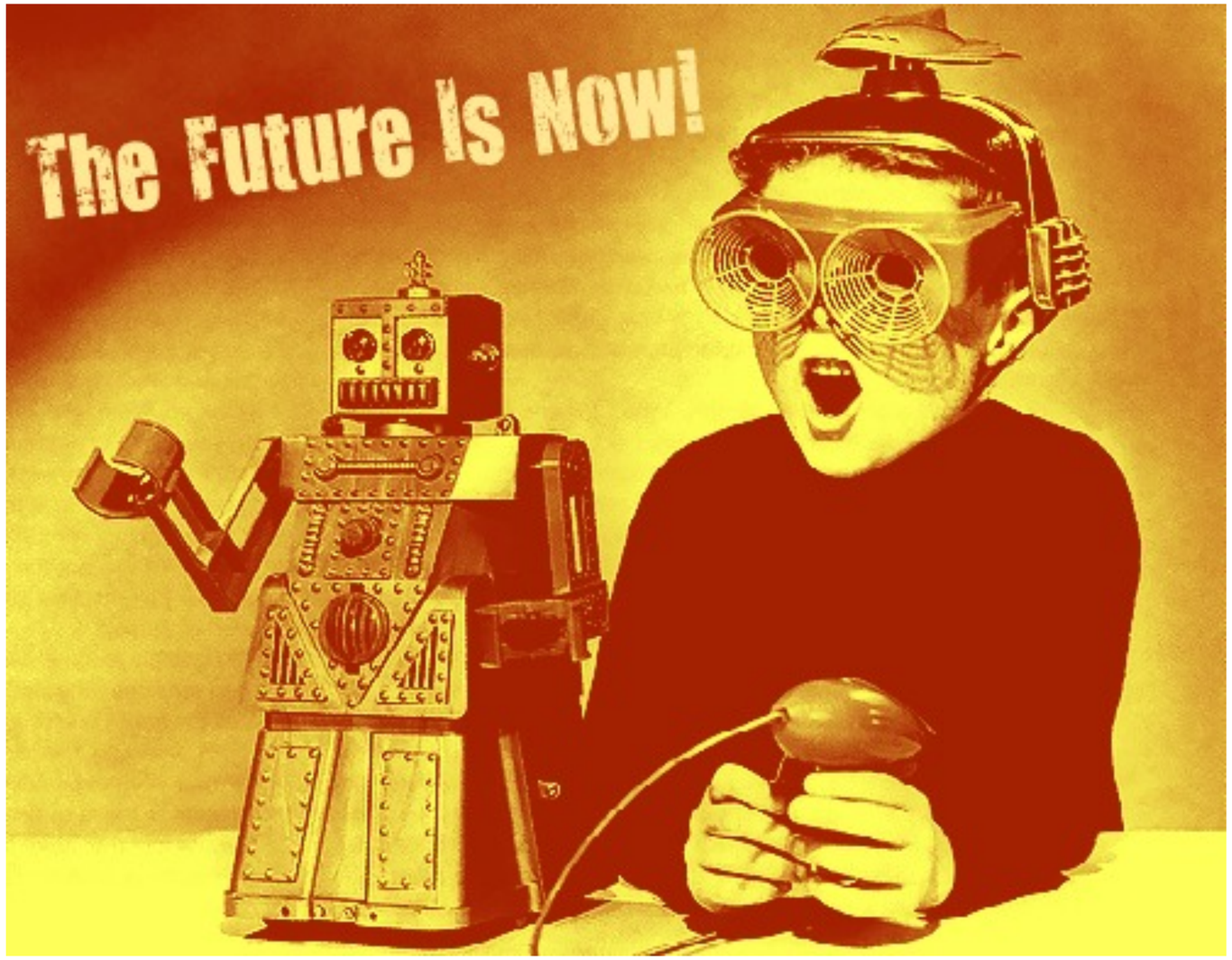
- Very limited temporal variability of <B>



- ZDI recovers 2–50% of the average magnetic field measured from Zeeman broadening

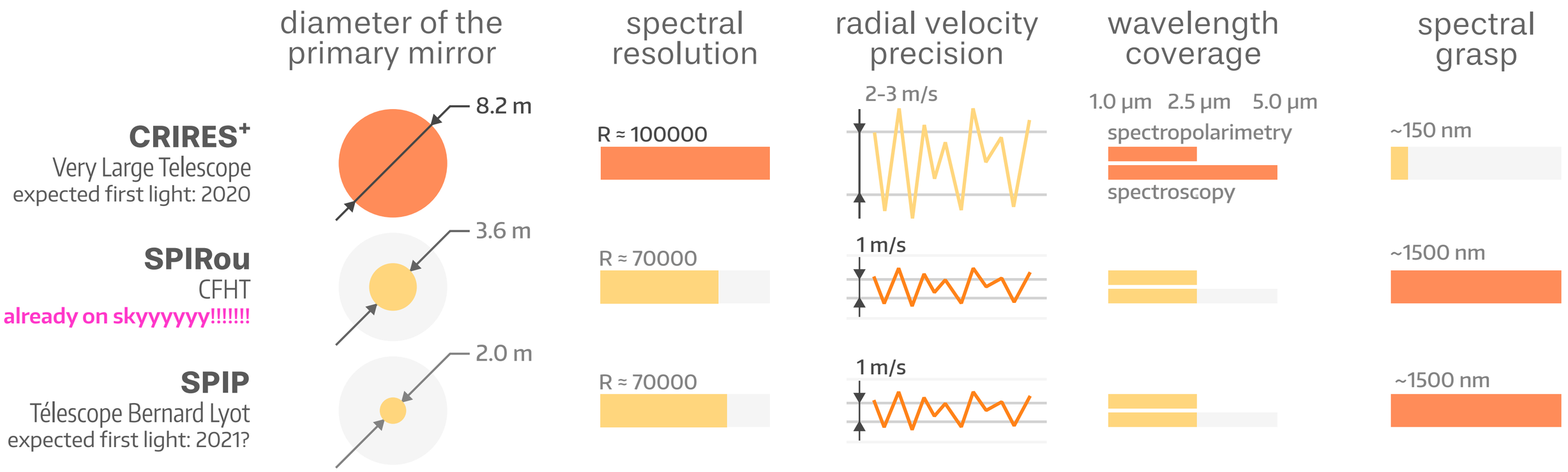


How does the future look like?



Next-gen instrumentation!

high-resolution near-infrared spectropolarimeters!!!

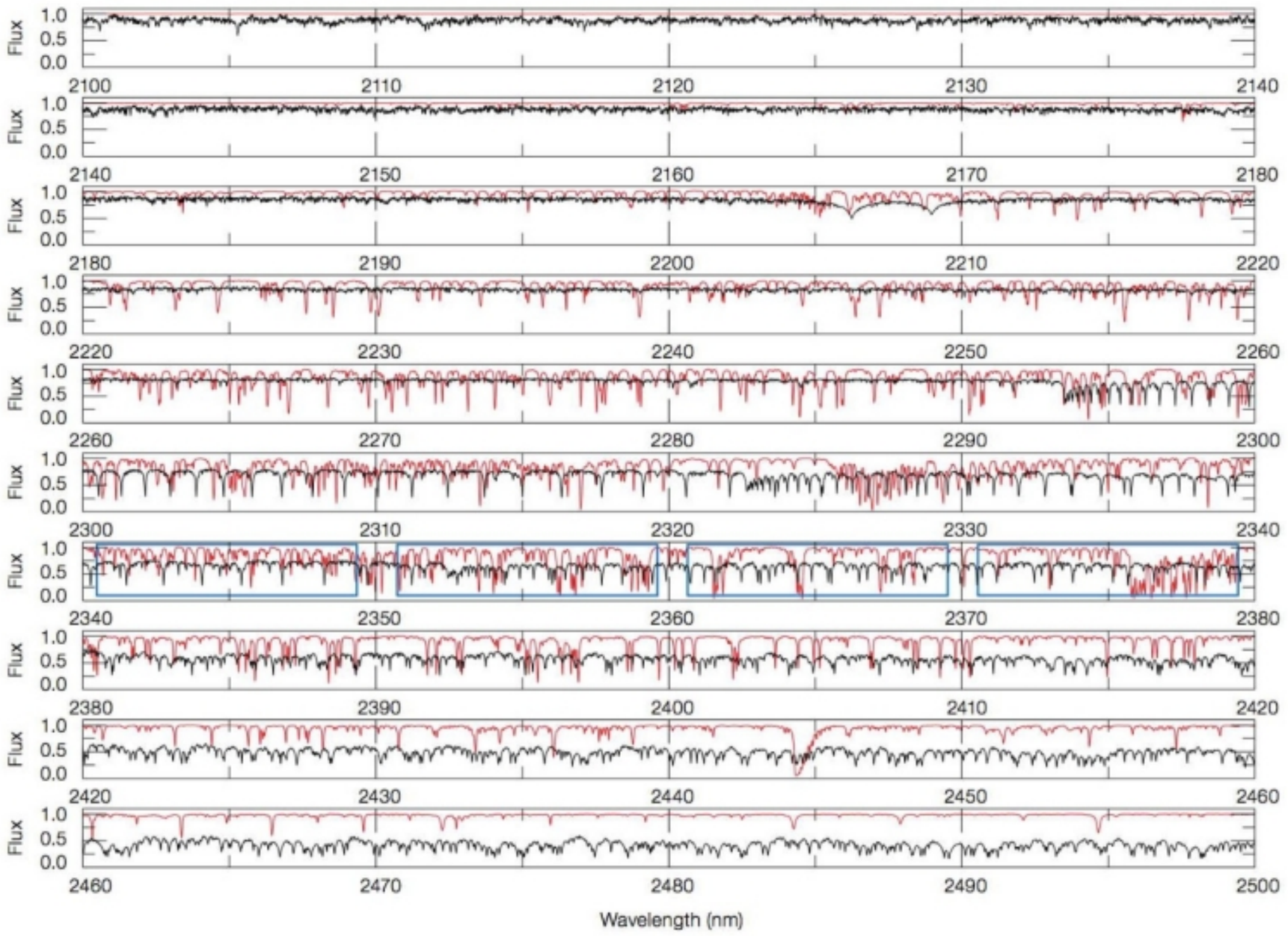


CRIRES+

spectral resolution	50,000 and 100,000
wavelength coverage	0.95 - 5.3 µm | YJHKLM bands
RV precision	2-3 m/s
slit length	10 arcseconds
slit width	0.2 and 0.4 arcseconds
polarimetry	linear + circular (YJHK bands)
adaptive optics	60 actuator curvature sensing
cross-disperser	6 exchangeable gratings

CRIRES+

10x larger spectral grasp!!!



Take-away

- **It's a good time to be alive**

(good instrumentation and data coming!)

- We don't find strong magnetic fields on IMTTS/IMPs yet, but small sample!

(more spectra would be nice :wink :wink SPIRou)

- Magnetic fields of T Tauri stars has wide range strength (does not depend of HRD position), and the field seems to be rather well distributed over the surface.

- Zeeman Doppler Imaging recovers more or less <B> (2–50%), this seems to depend on the field topology