Data analysis
Milne-Eddington inversion codes

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Outline

- What are inversions?
- How do they work?
- Milne-Eddington inversions
- Available codes
- Tips and tricks

- P-MILOS
  - General description
  - Input/output files
- Example

What is an inversion?

- In a broad sense, any inference of the physical conditions of the solar atmosphere based on the interpretation of observed Stokes profiles
  - Weak-field approximation, center-of-gravity method...
  - Forward modeling
  - PCA, artificial neural networks
  - Least-squares fitting

- What we want: vector magnetic field, gas velocity, temperature

- What to expect: a model atmosphere capable of reproducing the observations…. nothing else!

Radiative transfer equation

- The Stokes parameters obey the RTE

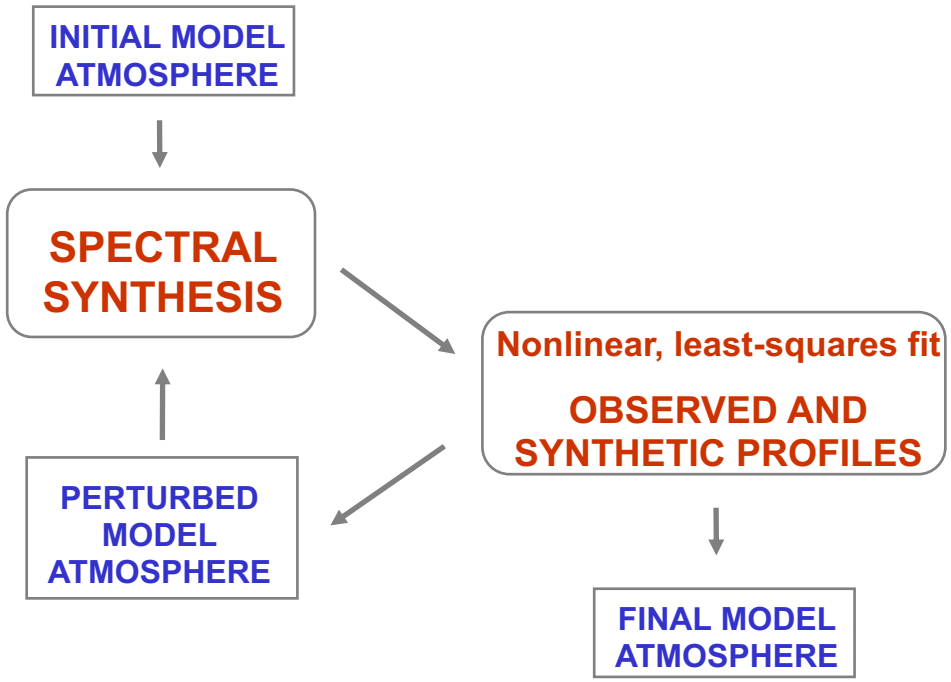
$$\frac{d}{d\tau}\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} \eta_I & \eta_Q & \eta_U & \eta_V \\ \eta_Q & \eta_I & \rho_V & -\rho_U \\ \eta_U & -\rho_V & \eta_I & \rho_Q \\ \eta_V & \rho_U & -\rho_Q & \eta_I \end{pmatrix} \begin{pmatrix} I-S \\ Q \\ U \\ V \end{pmatrix}$$

(Unno 1956; Rachkovsky 1962)

- $\eta_{I,Q,U,V}$ and $\rho_{Q,U,V}$ depend on $\mathbf{a} \equiv (B, \gamma, \chi, v_{LOS}, T, P_e, v_{mic})$
- This means that
  - Four Stokes parameters needed to understand just one of them
  - Proper interpretations of the Stokes vector require a good knowledge of the atmosphere (**a**)

Least-square inversions

- The complete line transfer problem has to be solved
- Self-consistent inferences → least-square inversions



Advantages

- No simplifying assumptions
- Full Stokes vector fitted
- Complex model atmospheres
- All atmospheric parameters inferred at the same time

How do they work?

- Inversion driven by χ^2-minimization

$$\chi^2(\mathbf{a}) = \frac{1}{N_{\text{free}}} \sum_{j=1}^{4} \sum_{i=1}^{N_\lambda} \frac{w_{ij}^2}{\sigma_j^2} \left[I_j^{\text{obs}}(\lambda_i) - I_j^{\text{syn}}(\lambda_i, \mathbf{a}) \right]^2$$

- 2nd order Levenberg-Marquardt algorithm

$$\nabla \chi^2(\mathbf{a}) + \mathbf{A}(\chi^2) \cdot \delta \mathbf{a} = 0$$

- Matrix **A** needs to be inverted to find δa. Two problems:
  - A has large dimension
  - A is quasi-singular
- Two solutions:
  - Use fewer free parameters or fewer nodes
  - Modified SVD method (Ruiz Cobo & del Toro Iniesta 1992)

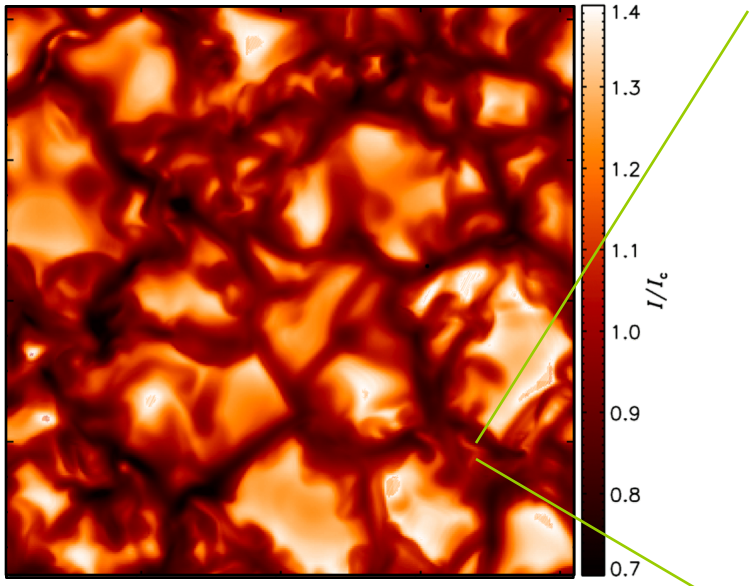
Inversions based on ME atmospheres

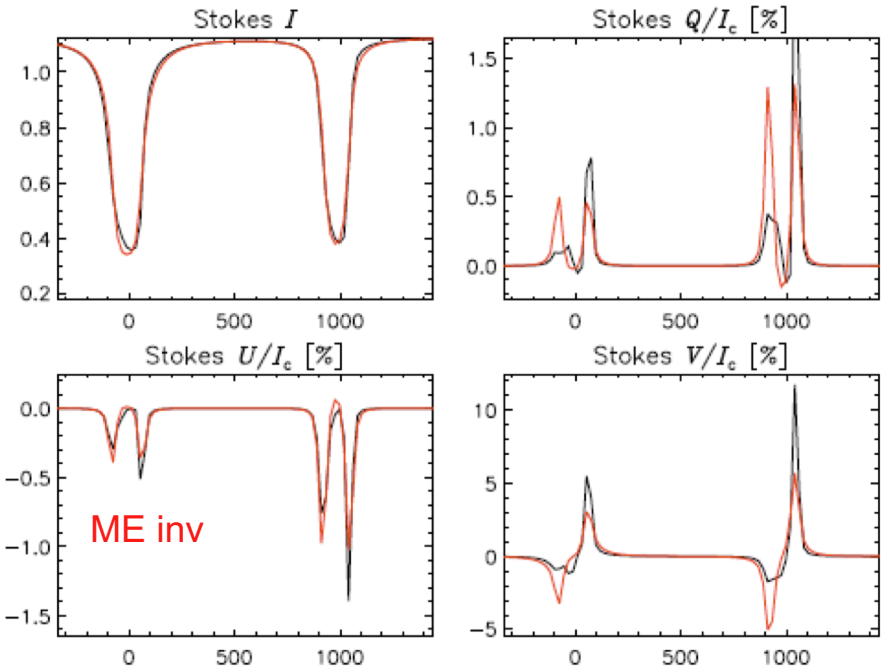
- ME atmosphere
  - Source function is linear with optical depth
  - Absorption matrix does not vary with optical depth
- Nine free parameters (plus v_{mac} and stray light)
- Analytical Stokes profiles

- Very fast inversion
- Smooth maps of physical quantities
- Results are reasonably accurate and easy to interpret

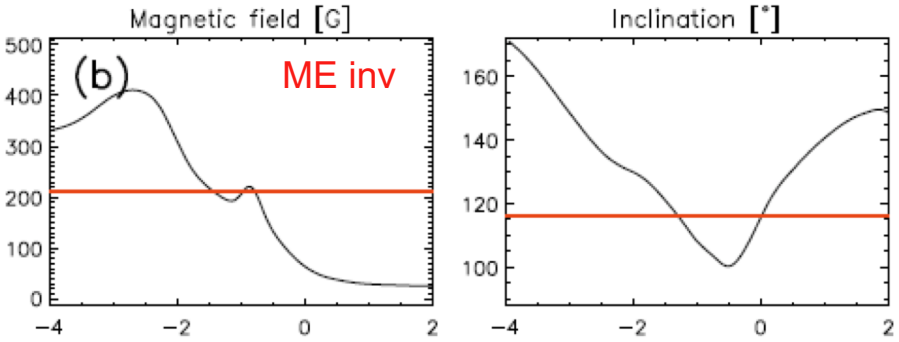
ME inversions of high-spatial resolution profiles

MHD simulations (Vögler et al. 2005)

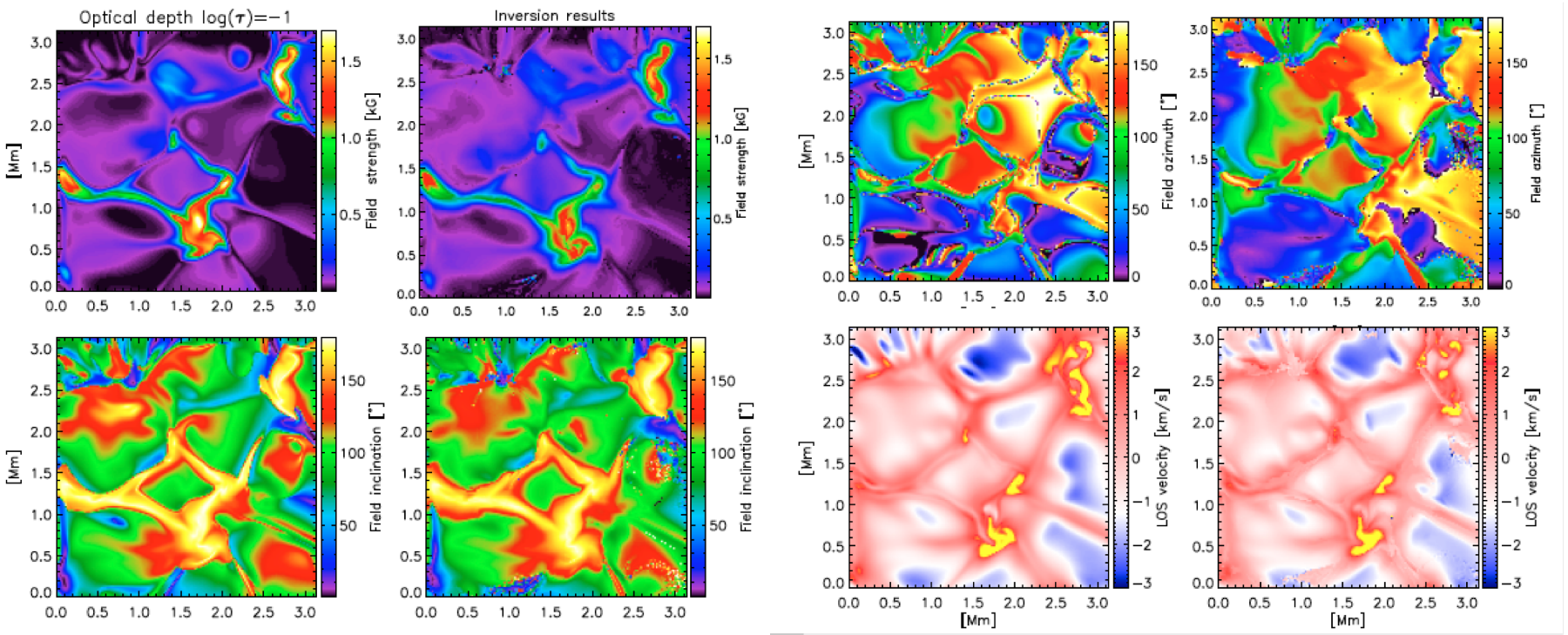




- Profiles reasonably well fitted
- ME results are some kind of "average" of physical parameters along the LOS



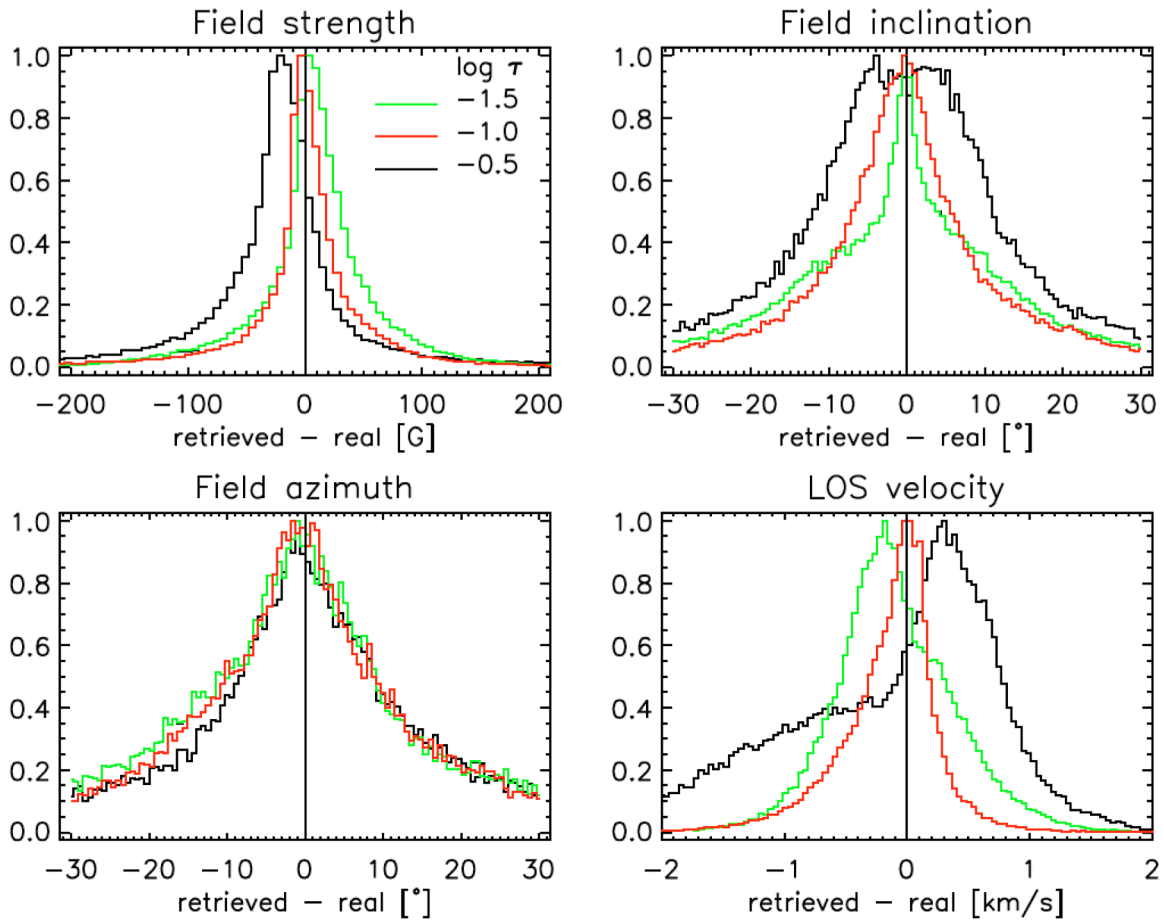
ME inversions of high-spatial resolution profiles



- Atmospheric parameters from MHD simulation at log τ = -1
- Maps of inferred B, γ and v_{LOS} very similar to real ones!

Orozco Suárez et al. 2010, AA, 518, A2

ME inversions of high-spatial resolution profiles



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Inversions based on ME atmospheres

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- Nine free parameters
- Analytical Stokes profiles
- Very fast inversion
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- Results are easy to interpret

- Simplistic treatment of line formation
- No thermal information. No height variations
- Cannot account for asymmetric Stokes profiles

Available Stokes inversion codes

Array of ME, LTE and NLTE inversion codes

- Serve different purposes: fast analyses vs accurate NLTE calculations
- Most of them capable of multi-line inversions

ME codes

HELIX
(Lagg et al. 2004)

MILOS
(Orozco Suárez et al. 2007)

VFISV
(Borrero et al. 2011)

P-MILOS
(Cabrera & Bellot Rubio 2020)

LTE codes

SIR
(Ruiz Cobo & del Toro Iniesta 1992)

SPINOR
(Frutiger et al. 2000)

2D SPINOR
(van Noort 2012)

SIR-parallel
(Thonhofer, Bellot Rubio, et al 2014)

NLTE codes

NICOLE
(Socas-Navarro et al. 2015)

STIC
(de la Cruz Rodríguez et al 2018)

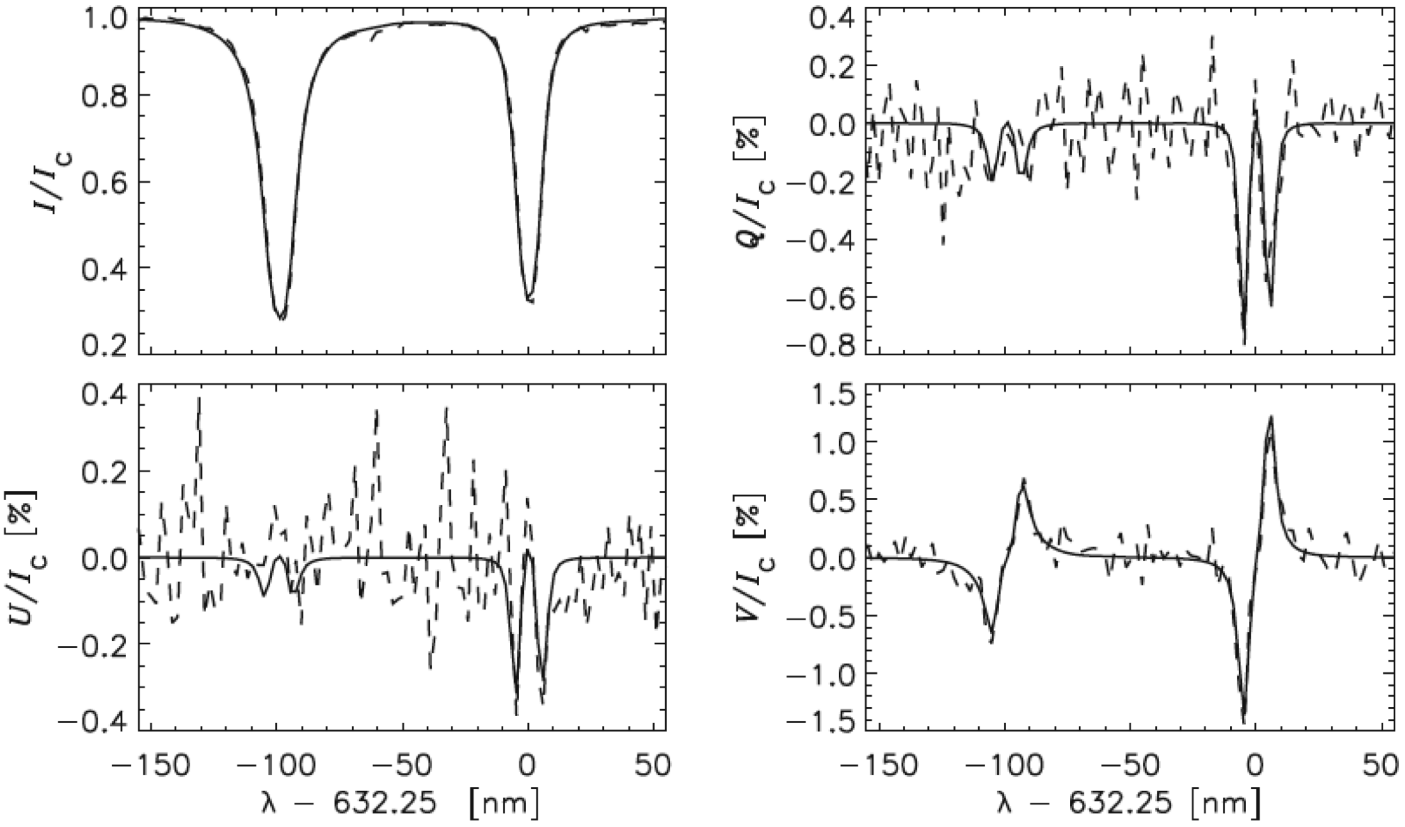
DESIRE
(Ruiz Cobo et al., 2022)

Tips and tricks

- First of all, look at the profiles
- Try a ME-like inversion, it usually works
  - If the V profiles are very asymmetric, fit only I, Q, and U
- Examine the fits: are they reasonably good?

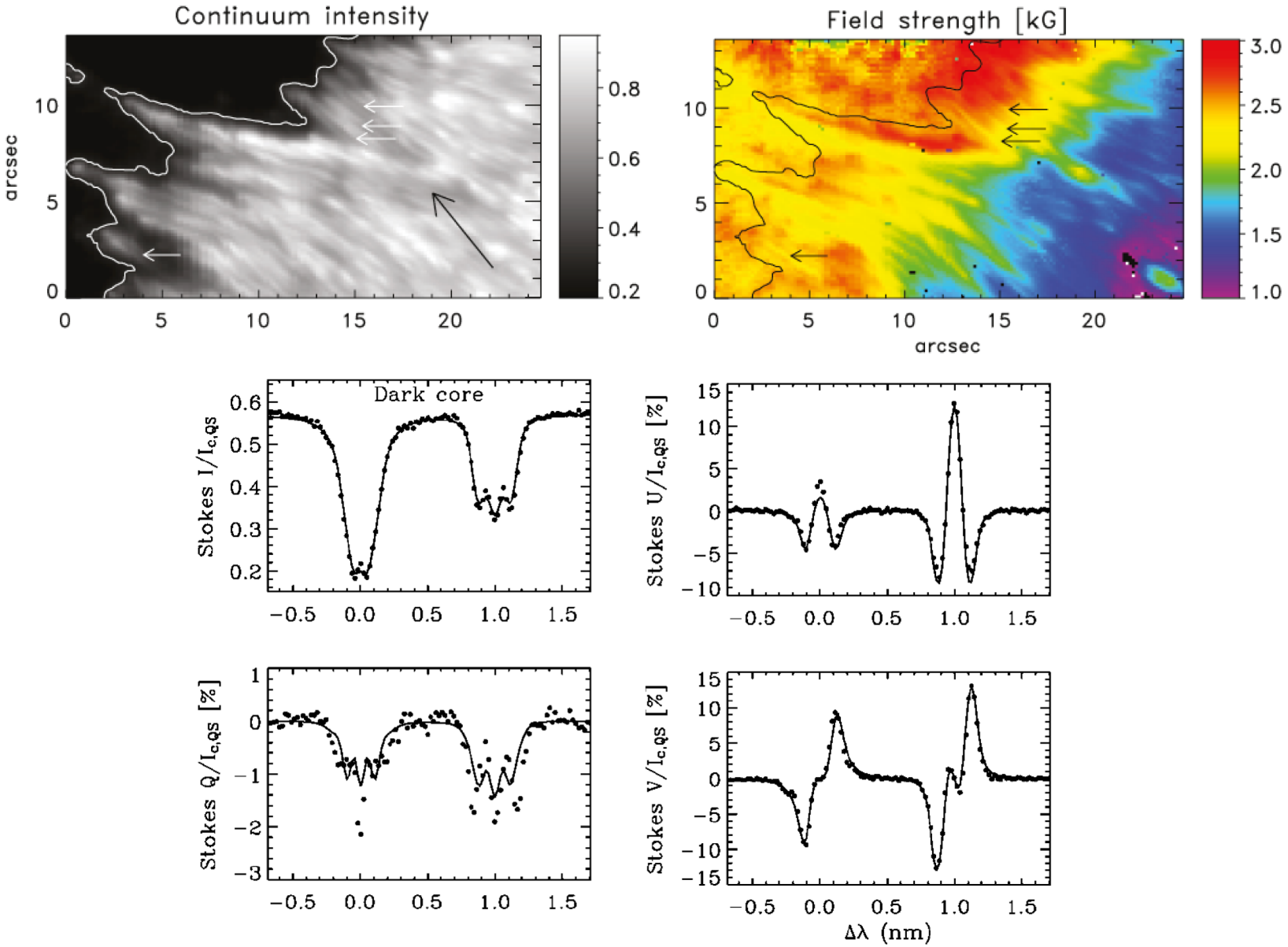
ME inversion of QS Hinode/SP data

B=177 G, γ=107º, f=0.42



Orozco Suárez et al. 2007, ApJ, 670, L61

ME inversion of sunspot Hinode/SP data



Tips and tricks

- First of all, look at the profiles
- Try a ME-like inversion, it usually works
  - If the V profiles are very asymmetric, fit only I, Q, and U
- Examine the fits: are they reasonably good?
- Identify
  - Pixels with bad fits and/or large asymmetries
  - Regions where interesting physical processes occur!
- Run more complex inversions on these pixels
  - Which model are you going to use?
    1C model, 2C model, flux tube model, uncombed model?

Tips and tricks

- First of all, look at the profiles
- Try a ME-like inversion, it usually works
  - If the V profiles are very asymmetric, fit only I, Q, and U
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- Run more complex inversions on these pixels
  - Which model are you going to use?
    1C model, 2C model, flux tube model, uncombed model?
  - Use results from ME-like inversion as initialization

- Ask yourself if the retrieved model atmosphere makes sense!!
- Experts are always around: ask them for advice!

P-MILOS inversion code

P-MILOS is a parallel ME inversion code

(Cabrera & Bellot Rubio 2021)

- Highly optimized for speed
- Written in C
- Parallelized using MPI
- I/O based on FITS data cubes
- Control and auxiliary files have SIR-like format

- Accepts any photospheric spectral line (but only one!)
- 1-component ME atmospheres + stray light factor
- Convolution with instrumental PSF and macroturbulence

Installing P-MILOS

Download code and manual from

https://github.com/IAA-InvCodes/P-MILOS

Compile with

```
cd [path]/code
make
```

Copy binaries pmilos.x and milos.x to /usr/local/bin or make soft links

```
cd /usr/local/bin
sudo ln –s [path]/code/pmilos.x
sudo ln –s [path]/code/milos.x
```

Running P-MILOS: input files

P-MILOS is controlled by a control file: [ ].mtrol

pmilos.mtrol

```
Number of cycles          (*):50              ! 0=synth,n=max iter,-1=classic
Observed profiles         (*):data/2014.09.28_09:18:00_xtalk_t    !
Stray light file             :                ! (none=no stray light)
PSF file                     :CRISP_6173_1mA.psf   !file or Gaussian FWHM in mA
Wavelength grid file      (*):wavelength.grid   !
Atomic parameters file    (*):LINES             !
Abundance file               :                ! not used with ME models
Initial guess model 1     (*):guess.mod         !
Initial guess model 2        :                ! not implemented
Weight for Stokes I          :1               ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q          :1               ! (DEFAULT=1; 0=not inverted)
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AUTOMATIC SELECT. OF NODES?  :                ! not implemented
Nodes for S_0 1              :1               ! (0 or blank=no, 1=yes)
Nodes for S_1 1              :1               ! (0 or blank=no, 1=yes)
Nodes for eta0 1             :1               ! (0 or blank=no, 1=yes)
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Nodes for LOS velocity 1     :1               ! (0 or blank=no, 1=yes)
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Nodes for lambda_doppler 1   :1               ! (0 or blank=no, 1=yes)
Nodes for damping 1          :1               ! (0 or blank=no, 1=yes)
Invert macroturbulence 1     :0               ! (0 or blank=no, 1=yes)
Nodes for S_0 2              :                ! not used
Nodes for S_1 2              :                ! not used
Nodes for eta0 2             :                ! not used
Nodes for magnetic field 2   :                ! not used
Nodes for LOS velocity 2     :                ! not used
Nodes for gamma 2            :                ! not used
Nodes for phi 2              :                ! not used
Nodes for lambda_doppler 2   :                ! not used
Nodes for damping 2          :                ! not used
Invert macroturbulence 2?    :                ! not used
Invert filling factor?       :                ! not used
Invert stray light factor?   :0               ! (0 or blank=no, 1=yes)
mu=cos (theta)               :                ! (DEFAULT mu=1, mu<0 => West)
Estimated S/N for I          :1000            !
Continuum contrast           :                ! Not used
Initial diagonal element     :0.1             ! (DEFAULT value: 1.e-1)
Use FFT for convolutions     :                ! (0, blank=direct conv;1=FFT)
Diagonal element acceleration:1               ! (0 or blank=no, 1=yes)
```

-:--- **pmilos.mtrol** All L1 Git-master (Fundamental)

Number of cycles:

0: Synthesis mode

>0: Maximum number of iterations

-1: Use classical estimates (center of gravity method, LOS velocity by FFT method)

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pmilos.mtrol

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Nodes for damping 1          :1                 ! (0 or blank=no, 1=yes)
Invert macroturbulence 1     :0                 ! (0 or blank=no, 1=yes)
Nodes for S_0 2              :                  ! not used
Nodes for S_1 2              :                  ! not used
Nodes for eta0 2             :                  ! not used
Nodes for magnetic field 2   :                  ! not used
Nodes for LOS velocity 2     :                  ! not used
Nodes for gamma 2            :                  ! not used
Nodes for phi 2              :                  ! not used
Nodes for lambda_doppler 2   :                  ! not used
Nodes for damping 2          :                  ! not used
Invert macroturbulence 2?    :                  ! not used
Invert filling factor?       :                  ! not used
Invert stray light factor?   :0                 ! (0 or blank=no, 1=yes)
mu=cos (theta)               :                  ! (DEFAULT mu=1, mu<0 => West)
Estimated S/N for I          :1000              !
Continuum contrast           :                  ! Not used
Initial diagonal element     :0.1               ! (DEFAULT value: 1.e-1)
Use FFT for convolutions     :                  ! (0, blank=direct conv;1=FFT)
Diagonal element acceleration:1                 ! (0 or blank=no, 1=yes)
```

-:--- **pmilos.mtrol** All L1 Git-master (Fundamental)

Stokes data cube: [ ].fits

Stokes profile file: [ ].per

emacs@orion.iaa.es

File Edit Options Buffers Tools Help

```
 1.00000     -583.463     0.744716  0.000127651  -0.00144671  -0.00170201
 1.00000     -561.933     0.745056  0.000340403  -0.00153181  -0.00165946
 1.00000     -540.403     0.744716  0.000127651  -0.00157436  -0.00174456
 1.00000     -518.873     0.748843   0.00246792  -0.00076596  -0.00178711
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 1.00000     -475.813     0.747226 -0.000723356   0.00063825  -0.00187221
 1.00000     -454.283     0.733653   0.00102121   0.00170201  -0.00272322
 1.00000     -432.753     0.740121   0.00212752  -0.00195732  -0.00276577
 1.00000     -411.223     0.735525  0.000170201  0.000936107  -0.00221262
 1.00000     -389.693     0.742163 -0.000765906   0.00140416  -0.00199987
 1.00000     -368.163     0.734802  0.000680805   0.00102121  -0.00399973
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 1.00000     -325.103     0.729611  0.000723356   0.00276577  -0.00531879
 1.00000     -303.573     0.737951  0.000638255 -8.51007e-05  -0.00714846
 1.00000     -282.043     0.723824 -8.51007e-05 -0.000340403   -0.0123821
 1.00000     -260.513     0.727994  -0.00127651 -0.000510604  -0.00804201
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 1.00000      234.677     0.519199   -0.0100419  -0.00578685     0.132885
 1.00000      256.207     0.576302  -0.00536134  -0.00191477    0.0843773
 1.00000      277.737     0.616980 -0.000808456  -0.00136161    0.0598258
 1.00000      299.267     0.656424  -0.00736121 -0.000255302    0.0405930
--:--  perfil.per       (Text Fill)--L1--C0--Top----------
```

Line index | $\Delta\lambda$ [mA] | I/I_{qs} | Q/I_{qs} | U/I_{qs} | V/I_{qs}

read_profile.pro

write_profile.pro

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```
Number of cycles          (*):50               ! 0=synth,n=max iter,-1=classic
Observed profiles         (*):data/2014.09.28_09:18:00_xtalk_t    !
Stray light file            :                  ! (none=no stray light)
PSF file                    :CRISP_6173_1mA.psf   !file or Gaussian FWHM in mA
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Nodes for damping 1         :1                 ! (0 or blank=no, 1=yes)
Invert macroturbulence 1    :0                 ! (0 or blank=no, 1=yes)
Nodes for S_0 2             :                  ! not used
Nodes for S_1 2             :                  ! not used
Nodes for eta0 2            :                  ! not used
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Nodes for LOS velocity 2    :                  ! not used
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Nodes for damping 2         :                  ! not used
Invert macroturbulence 2?   :                  ! not used
Invert filling factor?      :                  ! not used
Invert stray light factor?  :0                 ! (0 or blank=no, 1=yes)
mu=cos (theta)              :                  ! (DEFAULT mu=1, mu<0 => West)
Estimated S/N for I         :1000              !
Continuum contrast          :                  ! Not used
Initial diagonal element    :0.1               ! (DEFAULT value: 1.e-1)
Use FFT for convolutions    :                  ! (0, blank=direct conv;1=FFT)
Diagonal element acceleration:1                ! (0 or blank=no, 1=yes)
```

-:--- **pmilos.mtrol** All L1 Git-master (Fundamental)

Stray light file

Same format as Stokes profile file. Contains the stray light contamination, assumed to be unpolarized (so that Q=U=V=0)

Stray-light considerations

- Stray-light in 1C inversions:
  - $I_{obs} = (1-\alpha)\, I_1 + \alpha\, I_{stray}$
  - Accounts for both stray light and/or magnetic filling factor
- Global vs local stray-light profile
  - Classical treatment: global stray-light profile (average over FOV)
  - Orozco Suárez et al. (2007): local stray-light profile accounts for telescope diffraction
- Deconvolution of instrumental PSF (only space-based obs!)

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Nodes for damping 1         :1                 ! (0 or blank=no, 1=yes)
Invert macroturbulence 1    :0                 ! (0 or blank=no, 1=yes)
Nodes for S_0 2             :                  ! not used
Nodes for S_1 2             :                  ! not used
Nodes for eta0 2            :                  ! not used
Nodes for magnetic field 2  :                  ! not used
Nodes for LOS velocity 2    :                  ! not used
Nodes for gamma 2           :                  ! not used
Nodes for phi 2             :                  ! not used
Nodes for lambda_doppler 2  :                  ! not used
Nodes for damping 2         :                  ! not used
Invert macroturbulence 2?   :                  ! not used
Invert filling factor?      :                  ! not used
Invert stray light factor?  :0                 ! (0 or blank=no, 1=yes)
mu=cos (theta)              :                  ! (DEFAULT mu=1, mu<0 => West)
Estimated S/N for I         :1000              !
Continuum contrast          :                  ! Not used
Initial diagonal element    :0.1               ! (DEFAULT value: 1.e-1)
Use FFT for convolutions    :                  ! (0, blank=direct conv;1=FFT)
Diagonal element acceleration:1                ! (0 or blank=no, 1=yes)
```

-:--- **pmilos.mtrol** All L1 Git-master (Fundamental)

PSF file: [ ].psf

Contains two columns

1. Wavelength in mA with respect to center of the line
2. Spectral PSF of the instrument

Can also specify FWHM of Gaussian PSF (in mA)

Running P-MILOS: input files

P-MILOS is controlled by a control file: [ ].mtrol

pmilos.mtrol

```
Number of cycles          (*):50               ! 0=synth,n=max iter,-1=classic
Observed profiles         (*):data/2014.09.28_09:18:00_xtalk_t    !
Stray light file             :                 ! (none=no stray light)
PSF file                     :CRISP_6173_1mA.psf   !file or Gaussian FWHM in mA
Wavelength grid file      (*):wavelength.grid  !
Atomic parameters file    (*):LINES            !
Abundance file               :                 ! not used with ME models
Initial guess model 1     (*):guess.mod        !
Initial guess model 2        :                 ! not implemented
Weight for Stokes I          :1                ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q          :1                ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U          :1                ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V          :1                ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?  :                 ! not implemented
Nodes for S_0 1              :1                ! (0 or blank=no, 1=yes)
Nodes for S_1 1              :1                ! (0 or blank=no, 1=yes)
Nodes for eta0 1             :1                ! (0 or blank=no, 1=yes)
Nodes for magnetic field 1   :1                ! (0 or blank=no, 1=yes)
Nodes for LOS velocity 1     :1                ! (0 or blank=no, 1=yes)
Nodes for gamma 1            :1                ! (0 or blank=no, 1=yes)
Nodes for phi 1              :1                ! (0 or blank=no, 1=yes)
Nodes for lambda_doppler 1   :1                ! (0 or blank=no, 1=yes)
Nodes for damping 1          :1                ! (0 or blank=no, 1=yes)
Invert macroturbulence 1     :0                ! (0 or blank=no, 1=yes)
Nodes for S_0 2              :                 ! not used
Nodes for S_1 2              :                 ! not used
Nodes for eta0 2             :                 ! not used
Nodes for magnetic field 2   :                 ! not used
Nodes for LOS velocity 2     :                 ! not used
Nodes for gamma 2            :                 ! not used
Nodes for phi 2              :                 ! not used
Nodes for lambda_doppler 2   :                 ! not used
Nodes for damping 2          :                 ! not used
Invert macroturbulence 2?    :                 ! not used
Invert filling factor?       :                 ! not used
Invert stray light factor?   :0                ! (0 or blank=no, 1=yes)
mu=cos (theta)               :                 ! (DEFAULT mu=1, mu<0 => West)
Estimated S/N for I          :1000             !
Continuum contrast           :                 ! Not used
Initial diagonal element     :0.1              ! (DEFAULT value: 1.e-1)
Use FFT for convolutions     :                 ! (0, blank=direct conv;1=FFT)
Diagonal element acceleration:1                ! (0 or blank=no, 1=yes)
```

-:--- **pmilos.mtrol** All L1 Git-master (Fundamental)

Wavelength grid file: [ ].grid

emacs@dhcp-200-191.mtk.nao.ac.jp

File Edit Options Buffers Tools Help

```
IMPORTANT: a) All items must be separated by commas.
           b) The first six characters of the last line
              in the header (if any) must contain the symbol ---

Line and blends indices   :   Initial lambda     Step      Final lambda
(in this order)                     (mA)          (mA)          (mA)
--------------------------------------------------------------------------
1.2                       :       -645.9,         21.53,     1743.93
```

--:-- malla.grid (Text Fill)--L7--C17--All

Necessary in synthesis and inversion mode

Can also be given as a FITS file

Running P-MILOS: input files

P-MILOS is controlled by a control file: [ ].mtrol

pmilos.mtrol

```
Number of cycles          (*):50               ! 0=synth,n=max iter,-1=classic
Observed profiles         (*):data/2014.09.28_09:18:00_xtalk_t    !
Stray light file             :                 ! (none=no stray light)
PSF file                     :CRISP_6173_1mA.psf   !file or Gaussian FWHM in mA
Wavelength grid file      (*):wavelength.grid  !
Atomic parameters file    (*):LINES            !
Abundance file               :                 ! not used with ME models
Initial guess model 1     (*):guess.mod        !
Initial guess model 2        :                 ! not implemented
Weight for Stokes I          :1                ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q          :1                ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U          :1                ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V          :1                ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?  :                 ! not implemented
Nodes for S_0 1              :1                ! (0 or blank=no, 1=yes)
Nodes for S_1 1              :1                ! (0 or blank=no, 1=yes)
Nodes for eta0 1             :1                ! (0 or blank=no, 1=yes)
Nodes for magnetic field 1   :1                ! (0 or blank=no, 1=yes)
Nodes for LOS velocity 1     :1                ! (0 or blank=no, 1=yes)
Nodes for gamma 1            :1                ! (0 or blank=no, 1=yes)
Nodes for phi 1              :1                ! (0 or blank=no, 1=yes)
Nodes for lambda_doppler 1   :1                ! (0 or blank=no, 1=yes)
Nodes for damping 1          :1                ! (0 or blank=no, 1=yes)
Invert macroturbulence 1     :0                ! (0 or blank=no, 1=yes)
Nodes for S_0 2              :                 ! not used
Nodes for S_1 2              :                 ! not used
Nodes for eta0 2             :                 ! not used
Nodes for magnetic field 2   :                 ! not used
Nodes for LOS velocity 2     :                 ! not used
Nodes for gamma 2            :                 ! not used
Nodes for phi 2              :                 ! not used
Nodes for lambda_doppler 2   :                 ! not used
Nodes for damping 2          :                 ! not used
Invert macroturbulence 2?    :                 ! not used
Invert filling factor?       :                 ! not used
Invert stray light factor?   :0                ! (0 or blank=no, 1=yes)
mu=cos (theta)               :                 ! (DEFAULT mu=1, mu<0 => West)
Estimated S/N for I          :1000             !
Continuum contrast           :                 ! Not used
Initial diagonal element     :0.1              ! (DEFAULT value: 1.e-1)
Use FFT for convolutions     :                 ! (0, blank=direct conv;1=FFT)
Diagonal element acceleration:1                ! (0 or blank=no, 1=yes)
-:---  pmilos.mtrol   All L1    Git-master  (Fundamental)
```

Atomic parameter file

emacs@orion.iaa.es

File Edit Options Buffers Tools Help

```
  1=FE 1 6301.5012    1.0  3.654  -0.75   5P 2.0- 5D 2.0  0.243  2.3520e-14
  2=FE 1 6302.4936    1.0  3.686  -1.236  5P 1.0- 5D 0.0  0.240  2.3976e-14
--:--  LINES          (Text Fill)--L3--C0--All
```

Line index | Ion | λ | E | χ | log gf | transition | collisional parameters

Same format as SIR atomic file, but only central wavelength and transition are used for calculating the Zeeman pattern

Running P-MILOS: input files

P-MILOS is controlled by a control file: [ ].mtrol

pmilos.mtrol

```
Number of cycles          (*):50               ! 0=synth,n=max iter,-1=classic
Observed profiles         (*):data/2014.09.28_09:18:00_xtalk_t    !
Stray light file             :                 ! (none=no stray light)
PSF file                     :CRISP_6173_1mA.psf   !file or Gaussian FWHM in mA
Wavelength grid file      (*):wavelength.grid   !
Atomic parameters file    (*):LINES             !
Abundance file               :                 ! not used with ME models
Initial guess model 1     (*):guess.mod         !
Initial guess model 2        :                 ! not implemented
Weight for Stokes I          :1                ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q          :1                ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U          :1                ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V          :1                ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?  :                 ! not implemented
Nodes for S_0 1              :1                ! (0 or blank=no, 1=yes)
Nodes for S_1 1              :1                ! (0 or blank=no, 1=yes)
Nodes for eta0 1             :1                ! (0 or blank=no, 1=yes)
Nodes for magnetic field 1   :1                ! (0 or blank=no, 1=yes)
Nodes for LOS velocity 1     :1                ! (0 or blank=no, 1=yes)
Nodes for gamma 1            :1                ! (0 or blank=no, 1=yes)
Nodes for phi 1              :1                ! (0 or blank=no, 1=yes)
Nodes for lambda_doppler 1   :1                ! (0 or blank=no, 1=yes)
Nodes for damping 1          :1                ! (0 or blank=no, 1=yes)
Invert macroturbulence 1     :0                ! (0 or blank=no, 1=yes)
Nodes for S_0 2              :                 ! not used
Nodes for S_1 2              :                 ! not used
Nodes for eta0 2             :                 ! not used
Nodes for magnetic field 2   :                 ! not used
Nodes for LOS velocity 2     :                 ! not used
Nodes for gamma 2            :                 ! not used
Nodes for phi 2              :                 ! not used
Nodes for lambda_doppler 2   :                 ! not used
Nodes for damping 2          :                 ! not used
Invert macroturbulence 2?    :                 ! not used
Invert filling factor?       :                 ! not used
Invert stray light factor?   :0                ! (0 or blank=no, 1=yes)
mu=cos (theta)               :                 ! (DEFAULT mu=1, mu<0 => West)
Estimated S/N for I          :1000             !
Continuum contrast           :                 ! Not used
Initial diagonal element     :0.1              ! (DEFAULT value: 1.e-1)
Use FFT for convolutions     :                 ! (0, blank=direct conv;1=FFT)
Diagonal element acceleration:1                ! (0 or blank=no, 1=yes)
```

-:--- **pmilos.mtrol** All L1 Git-master (Fundamental)

Model file: [].mod

guess.mod

```
eta_0                :20
magnetic field [G]   :1100
LOS velocity [km/s]  :0.2
Doppler width [A]    :0.03
damping              :0.05
gamma [deg]          :120
phi   [deg]          :150
S_0                  :0.35
S_1                  :0.5
v_mac [km/s]         :0
filling factor       :1
```

-:--- **guess.mod** All L1 Git-master (Modula-2)
Beginning of buffer

Only a 1C model atmosphere can be used at the moment

Running P-MILOS: input files

P-MILOS is controlled by a control file: [ ].mtrol

pmilos.mtrol

```
Number of cycles          (*):50               ! 0=synth,n=max iter,-1=classic
Observed profiles         (*):data/2014.09.28_09:18:00_xtalk_t    !
Stray light file             :                 ! (none=no stray light)
PSF file                     :CRISP_6173_1mA.psf   !file or Gaussian FWHM in mA
Wavelength grid file      (*):wavelength.grid   !
Atomic parameters file    (*):LINES             !
Abundance file               :                 ! not used with ME models
Initial guess model 1     (*):guess.mod         !
Initial guess model 2        :                 ! not implemented
Weight for Stokes I          :1                ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q          :1                ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U          :1                ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V          :1                ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?  :                 ! not implemented
Nodes for S_0 1              :1                ! (0 or blank=no, 1=yes)
Nodes for S_1 1              :1                ! (0 or blank=no, 1=yes)
Nodes for eta0 1             :1                ! (0 or blank=no, 1=yes)
Nodes for magnetic field 1   :1                ! (0 or blank=no, 1=yes)
Nodes for LOS velocity 1     :1                ! (0 or blank=no, 1=yes)
Nodes for gamma 1            :1                ! (0 or blank=no, 1=yes)
Nodes for phi 1              :1                ! (0 or blank=no, 1=yes)
Nodes for lambda_doppler 1   :1                ! (0 or blank=no, 1=yes)
Nodes for damping 1          :1                ! (0 or blank=no, 1=yes)
Invert macroturbulence 1     :0                ! (0 or blank=no, 1=yes)
Nodes for S_0 2              :                 ! not used
Nodes for S_1 2              :                 ! not used
Nodes for eta0 2             :                 ! not used
Nodes for magnetic field 2   :                 ! not used
Nodes for LOS velocity 2     :                 ! not used
Nodes for gamma 2            :                 ! not used
Nodes for phi 2              :                 ! not used
Nodes for lambda_doppler 2   :                 ! not used
Nodes for damping 2          :                 ! not used
Invert macroturbulence 2?    :                 ! not used
Invert filling factor?       :                 ! not used
Invert stray light factor?   :0                ! (0 or blank=no, 1=yes)
mu=cos (theta)               :                 ! (DEFAULT mu=1, mu<0 => West)
Estimated S/N for I          :1000             !
Continuum contrast           :                 ! Not used
Initial diagonal element     :0.1              ! (DEFAULT value: 1.e-1)
Use FFT for convolutions     :                 ! (0, blank=direct conv;1=FFT)
Diagonal element acceleration:1                ! (0 or blank=no, 1=yes)
```

```
-:---  pmilos.mtrol   All L1    Git-master  (Fundamental)
```

Running P-MILOS: input files

P-MILOS is controlled by a control file: [ ].mtrol

pmilos.mtrol

```
Number of cycles          (*):50               ! 0=synth,n=max iter,-1=classic
Observed profiles         (*):data/2014.09.28_09:18:00_xtalk_t    !
Stray light file             :                 ! (none=no stray light)
PSF file                     :CRISP_6173_1mA.psf   !file or Gaussian FWHM in mA
Wavelength grid file      (*):wavelength.grid   !
Atomic parameters file    (*):LINES             !
Abundance file               :                 ! not used with ME models
Initial guess model 1     (*):guess.mod         !
Initial guess model 2        :                 ! not implemented
Weight for Stokes I          :1                ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q          :1                ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U          :1                ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V          :1                ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?  :                 ! not implemented
Nodes for S_0 1              :1                ! (0 or blank=no, 1=yes)
Nodes for S_1 1              :1                ! (0 or blank=no, 1=yes)
Nodes for eta0 1             :1                ! (0 or blank=no, 1=yes)
Nodes for magnetic field 1   :1                ! (0 or blank=no, 1=yes)
Nodes for LOS velocity 1     :1                ! (0 or blank=no, 1=yes)
Nodes for gamma 1            :1                ! (0 or blank=no, 1=yes)
Nodes for phi 1              :1                ! (0 or blank=no, 1=yes)
Nodes for lambda_doppler 1   :1                ! (0 or blank=no, 1=yes)
Nodes for damping 1          :1                ! (0 or blank=no, 1=yes)
Invert macroturbulence 1     :0                ! (0 or blank=no, 1=yes)
Nodes for S_0 2              :                 ! not used
Nodes for S_1 2              :                 ! not used
Nodes for eta0 2             :                 ! not used
Nodes for magnetic field 2   :                 ! not used
Nodes for LOS velocity 2     :                 ! not used
Nodes for gamma 2            :                 ! not used
Nodes for phi 2              :                 ! not used
Nodes for lambda_doppler 2   :                 ! not used
Nodes for damping 2          :                 ! not used
Invert macroturbulence 2?    :                 ! not used
Invert filling factor?       :                 ! not used
Invert stray light factor?   :0                ! (0 or blank=no, 1=yes)
mu=cos (theta)               :                 ! (DEFAULT mu=1, mu<0 => West)
Estimated S/N for I          :1000             !
Continuum contrast           :                 ! Not used
Initial diagonal element     :0.1              ! (DEFAULT value: 1.e-1)
Use FFT for convolutions     :                 ! (0, blank=direct conv;1=FFT)
Diagonal element acceleration:1                ! (0 or blank=no, 1=yes)
-:---  pmilos.mtrol   All L1    Git-master  (Fundamental)
```

Number of nodes

- Indicates which model parameters are kept fixed or inverted
- 0 means parameter is kept fixed
- 1 means parameter is inverted

- Only 1C model atmospheres can be handled for the moment

Running P-MILOS: input files

P-MILOS is controlled by a control file: [ ].mtrol

pmilos.mtrol

```
Number of cycles          (*):50               ! 0=synth,n=max iter,-1=classic
Observed profiles         (*):data/2014.09.28_09:18:00_xtalk_t    !
Stray light file             :                 ! (none=no stray light)
PSF file                     :CRISP_6173_1mA.psf   !file or Gaussian FWHM in mA
Wavelength grid file      (*):wavelength.grid   !
Atomic parameters file    (*):LINES             !
Abundance file               :                 ! not used with ME models
Initial guess model 1     (*):guess.mod         !
Initial guess model 2        :                 ! not implemented
Weight for Stokes I          :1                ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q          :1                ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U          :1                ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V          :1                ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?  :                 ! not implemented
Nodes for S_0 1              :1                ! (0 or blank=no, 1=yes)
Nodes for S_1 1              :1                ! (0 or blank=no, 1=yes)
Nodes for eta0 1             :1                ! (0 or blank=no, 1=yes)
Nodes for magnetic field 1   :1                ! (0 or blank=no, 1=yes)
Nodes for LOS velocity 1     :1                ! (0 or blank=no, 1=yes)
Nodes for gamma 1            :1                ! (0 or blank=no, 1=yes)
Nodes for phi 1              :1                ! (0 or blank=no, 1=yes)
Nodes for lambda_doppler 1   :1                ! (0 or blank=no, 1=yes)
Nodes for damping 1          :1                ! (0 or blank=no, 1=yes)
Invert macroturbulence 1     :0                ! (0 or blank=no, 1=yes)
Nodes for S_0 2              :                 ! not used
Nodes for S_1 2              :                 ! not used
Nodes for eta0 2             :                 ! not used
Nodes for magnetic field 2   :                 ! not used
Nodes for LOS velocity 2     :                 ! not used
Nodes for gamma 2            :                 ! not used
Nodes for phi 2              :                 ! not used
Nodes for lambda_doppler 2   :                 ! not used
Nodes for damping 2          :                 ! not used
Invert macroturbulence 2?    :                 ! not used
Invert filling factor?       :                 ! not used
Invert stray light factor?   :0                ! (0 or blank=no, 1=yes)
mu=cos (theta)               :                 ! (DEFAULT mu=1, mu<0 => West)
Estimated S/N for I          :1000             !
Continuum contrast           :                 ! Not used
Initial diagonal element     :0.1              ! (DEFAULT value: 1.e-1)
Use FFT for convolutions     :                 ! (0, blank=direct conv;1=FFT)
Diagonal element acceleration:1                ! (0 or blank=no, 1=yes)
```

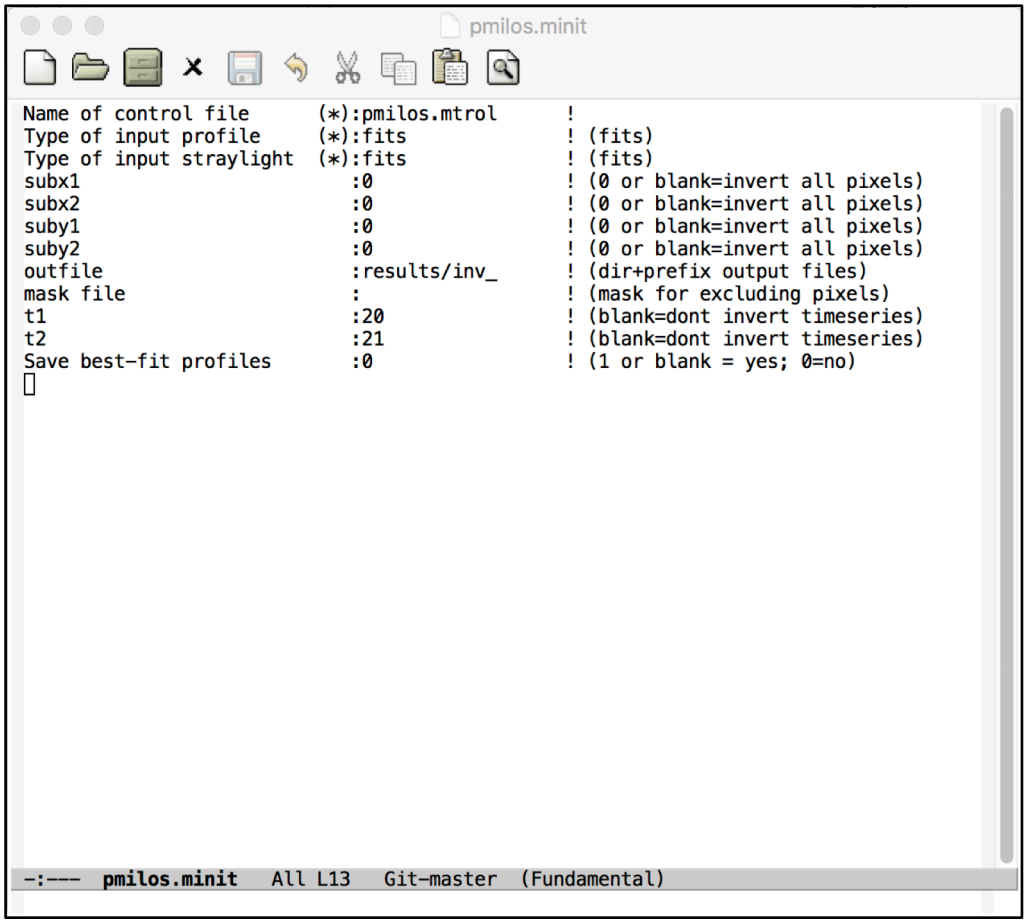
-:--- **pmilos.mtrol** All L1 Git-master (Fundamental)

Other inversion settings

- Signal-to-noise ratio
- Initial diagonal element for SVD algorithm
- Use direct convolution of FFT convolution
- Acceleration of convergence scheme

Running P-MILOS: input files

The inversion of data cubes is controlled by an init file: [ ].minit



File used to

- Specifies control file name
- Allows cropping of FOV
- Allows masking pixels
- Define first and last datacubes

- Similar to init file in SIR-parallel

Example

- Inversion of **data cube** taken by CRISP instrument at Swedish 1-m Solar Telescope
  - Fe I 6173 spectral scan with 30 wavelengths
  - Field of view 894 x 883 pixels (789 000 pixels)
  - Convolution with CRISP PSF
  - 9 free parameters to be determined (no stray light, no macro)
  - Maximum number of iterations: 50
- Code run on 128-core AMD EPYC 7742 2.25 GHz server

Executing the inversion

Run the inversion on 128 cores

```
mpiexec -n 128 ../P-MILOS/pmilos.x ./pmilos.minit
```

Executing the inversion

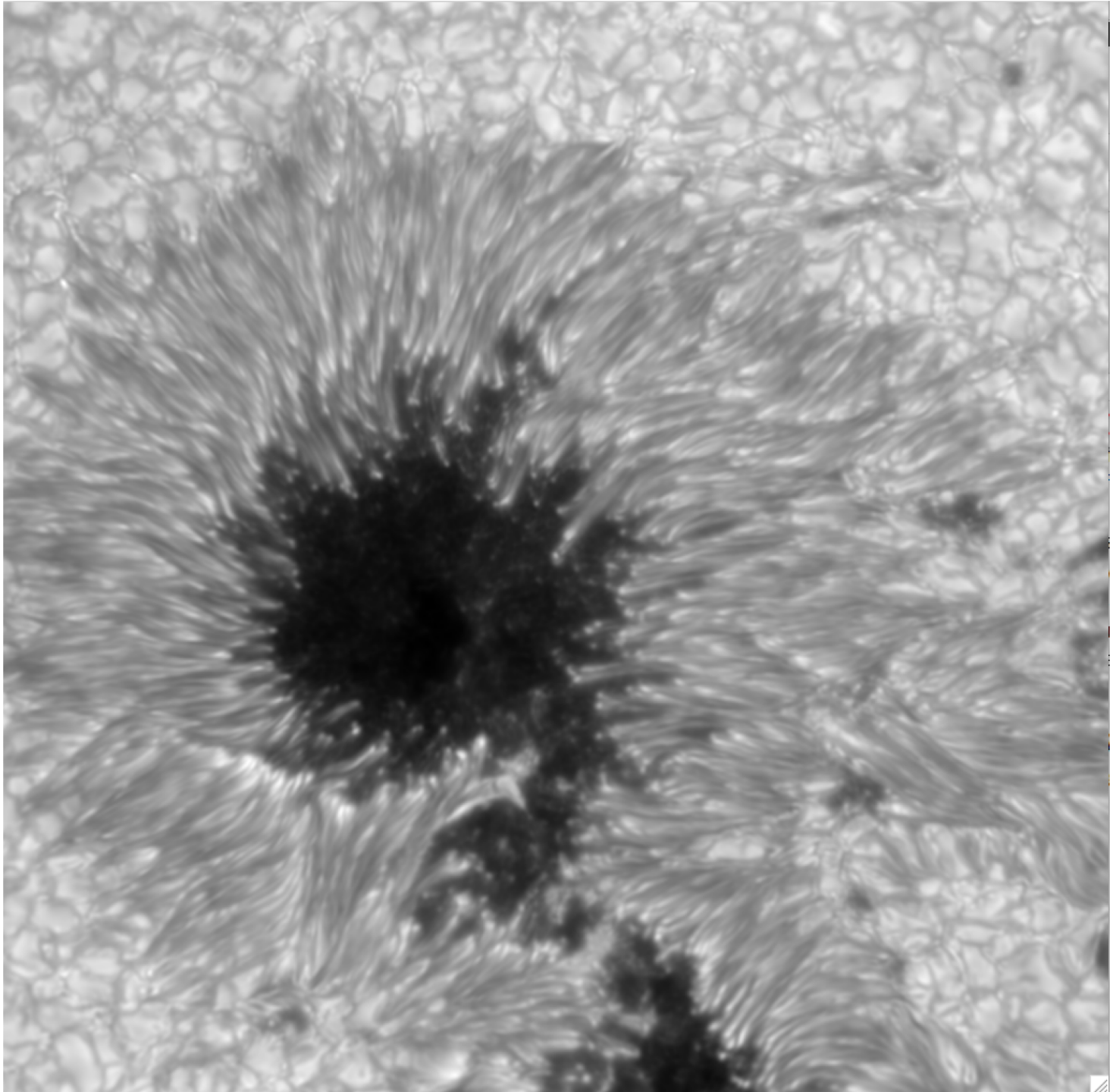
Run the inversion on 128 cores

```
mpiexec -n 128 ../P-MILOS/pmilos.x ./pmilos.minit
```

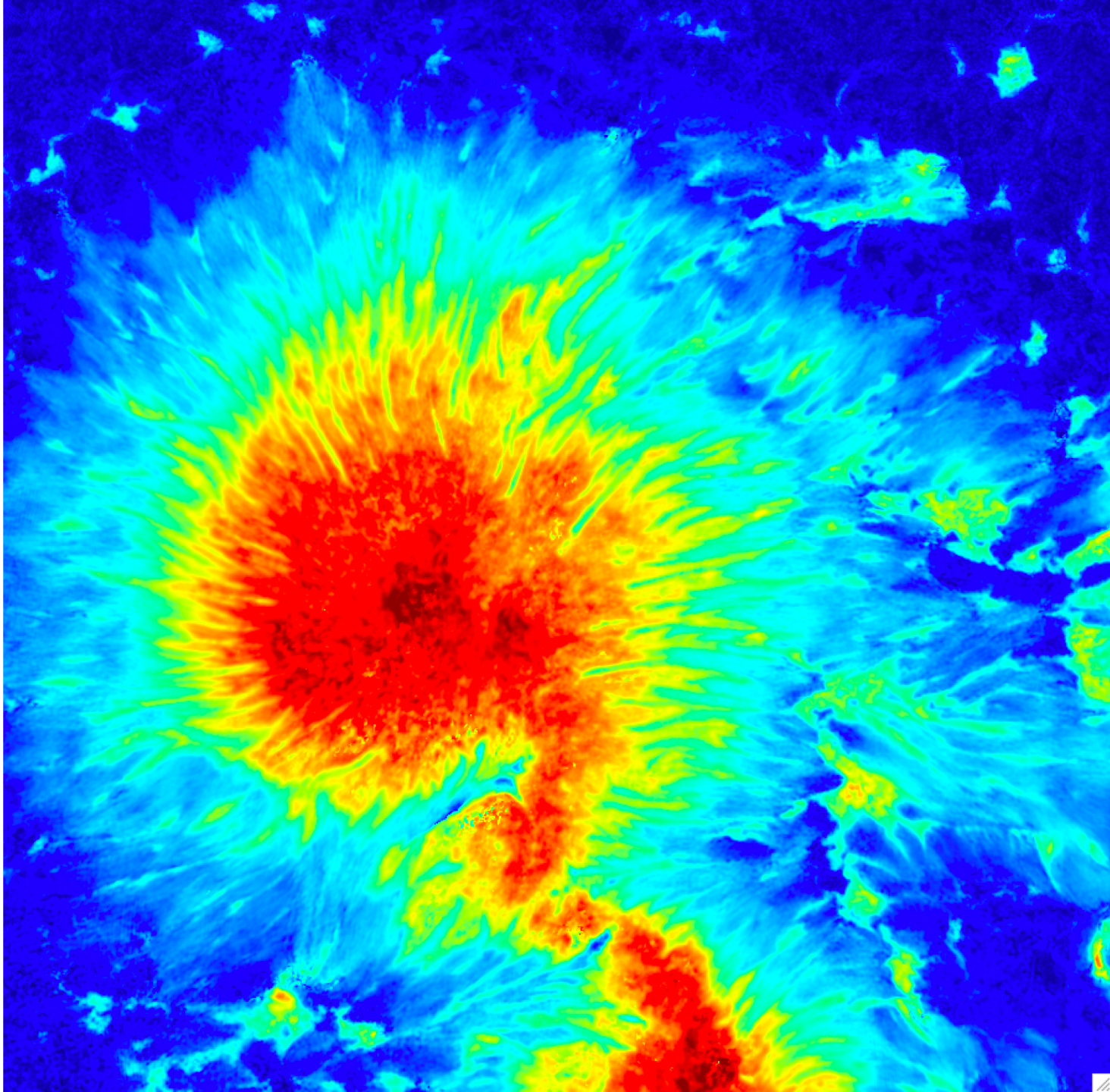
Total inversion time: 4.31 s

183 155 px/s = 1430 px/s/core

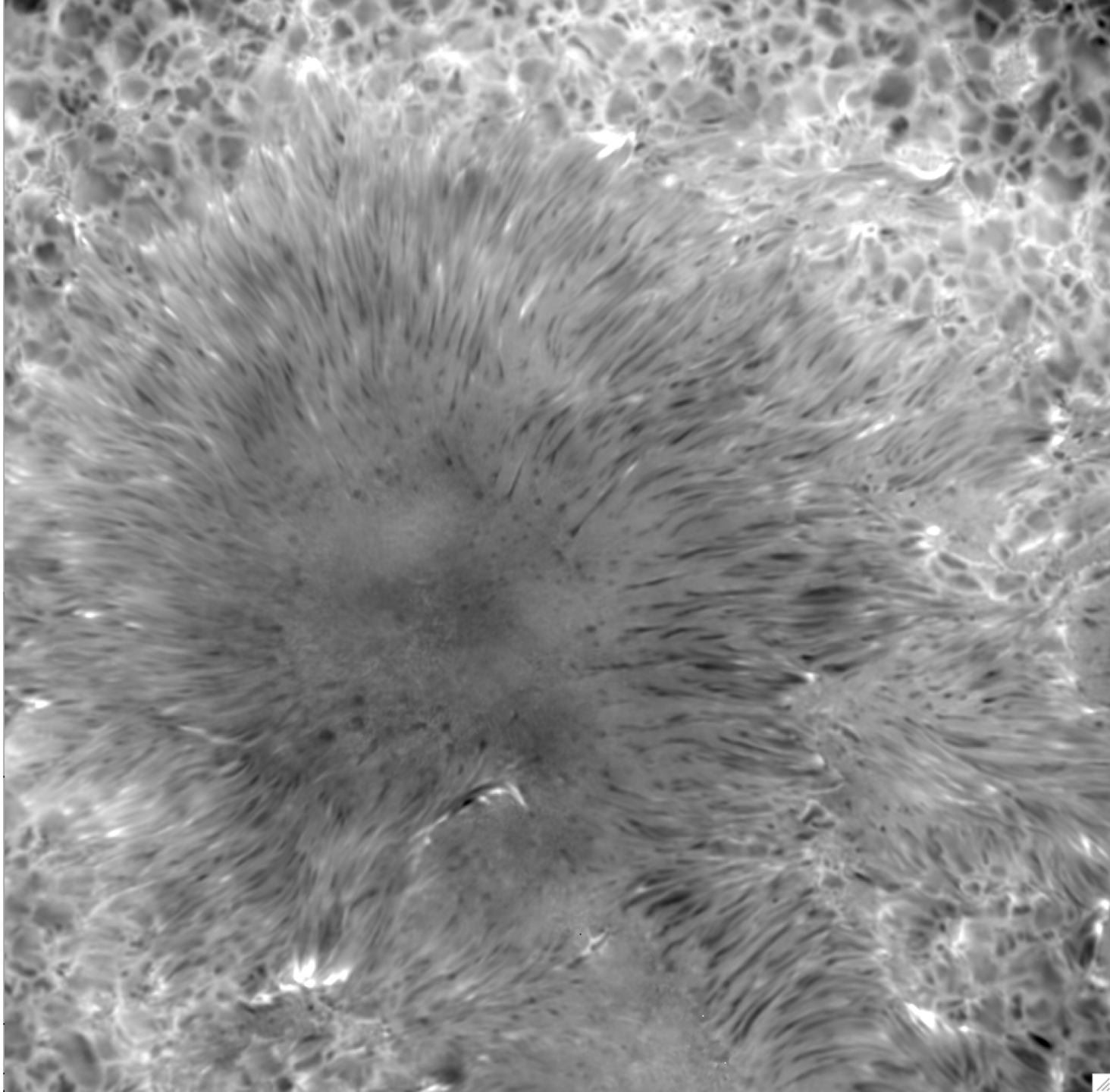
S_0+S_1



Magnetic field strength (Gauss)



Line of sight velocity (km/s)



P-MILOS inversions

- Useful to analyze large amounts of data
  - High-cadence time series of 2D spectropolarimetric measurements
  - E.g. CRISP data at SST

- Give average vector magnetic field and LOS velocity. Can be used for statistical purposes
- Rather insensitive to noise
- Very fast and robust, can be applied without supervision
- Allows to study temporal evolution!

- Pixels with bad fits easily identified through large χ^2 values
- More detailed analyses can be performed on these pixels
- Useful as initialization for more complex inversions