Hands-on Session on Data Analysis
SIR code

Salvo Guglielmino - INAF Catania

International School of Space Science
"The different spatio-temporal scales of the solar magnetism"
12 April 2022

I'm deeply indebted to …

- Luis Bellot Rubio
  - **THE ART OF STOKES INVERSIONS**
  - Lesson at the "Solar Magnetic Fields: Modeling and Measuring Techniques School", 25-28 May 2015, Granada
  - Lesson at the "Spectropolarimetry and Diagnostic Techniques School", 24-Sep / 05-Oct 2018, Estes Park
- Basilio Ruiz Cobo / José Carlos del Toro Iniesta
  - **INVERSION OF THE RADIATIVE TRANSFER EQUATION FOR POLARIZED LIGHT**
    (2016), Living Rev. Sol. Phys. 13, 4

Inversion codes: M-E vs full radiative transfer

Milne-Eddington

- ☺ Results
  - robust
  - easy to interpret
- ☺ Analytical Stokes profiles
- ☺ Fast inversion

- ☹ Asymmetric profiles
- ☹ Poor thermal information
- ☹ No multi-component atmospheres in the resolution element

Full radiative transfer

- ☺ Numerical solution of the RTE
- ☺ Reliable thermal information
- ☺ Stratification of the physical parameter with depth (τ)
- ☺ Deal with asymmetries
- ☺ Allow multi-component atmospheres

- ☹ Computationally demanding: slow inversion
- ☹ Difficult to interpret

Asymmetric Stokes profiles

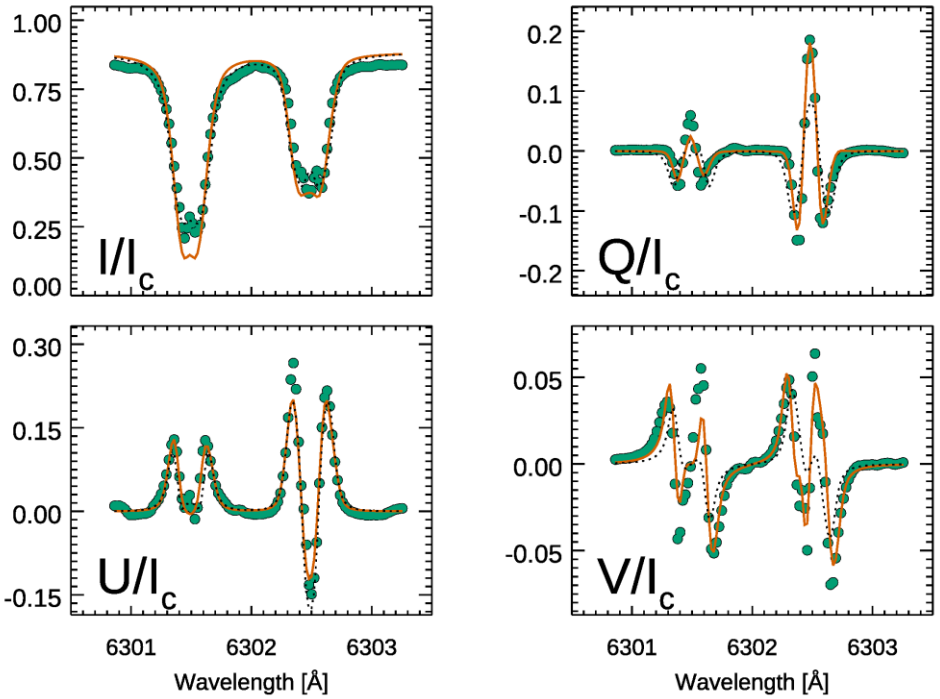
Amplitude asymmetry/
Multi-lobed Stokes profiles

Different magnetic atmospheres coexisting in resolution element

Area asymmetry

Gradients/discontinuities of B **and** v_{LOS} along LOS

Auer & Heasley (1978)



The area asymmetry gives information on the **height variation** of atmospheric parameters

SIR

Stokes Inversion based on Response functions

Ruiz Cobo & del Toro Iniesta (1992), ApJ 398, 375

The *SIR* code

- Provides a numerical solution of the **full radiative transfer** equation in presence of magnetic field

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

(Unno 1956; Rachkovsky 1962)

- Local Thermodynamic Equilibrium (**LTE**) assumption
- Handles Stokes parameters and works in two modes:
  - synthesis mode / inversion mode
- Allows considering either one or two magnetic atmospheres
- Retrieves the thermal, dynamical and magnetic structure of the atmosphere as a function of τ_{500}

The *SIR* code: a few caveats

- Here, we will discuss the **"classical"** approach to SIR, devoted to a single-pixel inversion
- Other *ad hoc* versions of the SIR code exist
- Note that, very recently, major updates have been made, including a Python wrapper for the SIR
  - this allows the user to upload a .fits file containing the observed data and to split the field-of-view among the different CPUs, working in parallel
- Furthermore, SIR is now combined with the RH code to treat non-LTE problems: **DeSIRe code**
  - see Ruiz Cobo et al. (2022), A&A in press
- You can benefit from the free online courses by Carlos Quintero Noda (IAC)
  - youtube.com/channel/UCTR42H92ZJMjv_snYK9Xfmw

Response functions

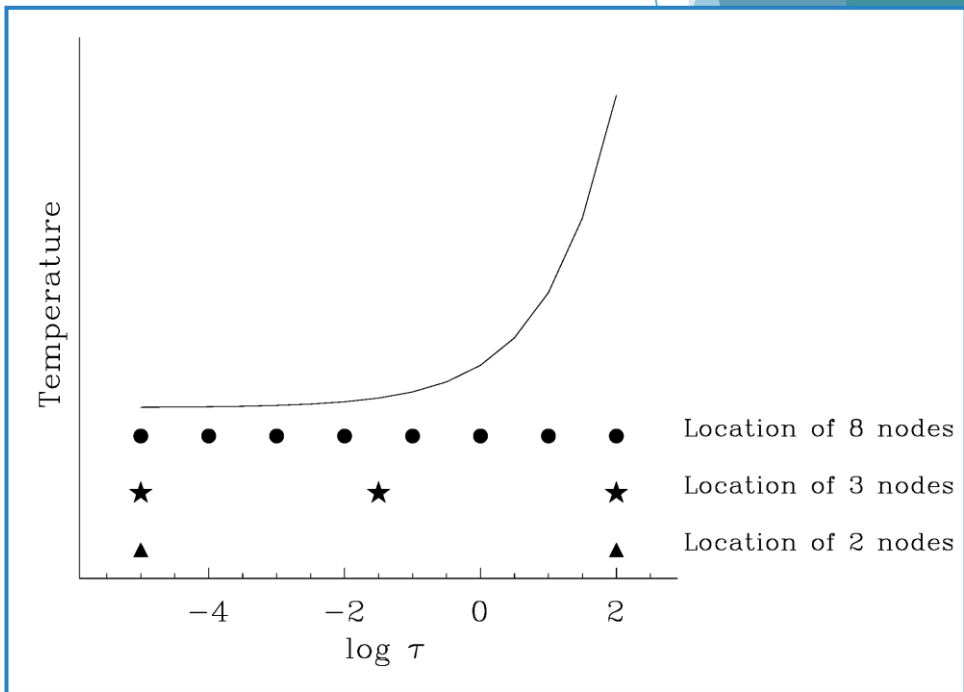
- Can be considered the response of the observed spectrum to the modifications of an atmosphere model
- When changing physical conditions along the optical depth τ, this perturbation results in a modification of the emergent Stokes spectrum

$$\delta \boldsymbol{I}(\lambda) = \int_0^\infty \boldsymbol{R}(\lambda, \tau)\delta x(\tau) d\tau$$

- At first-order perturbative analysis of the RTE:
  - $\delta x(\tau)$ is a perturbation of a single physical parameter $x(\tau)$
  - it propagates resulting in a modification $\delta \boldsymbol{I}(\lambda)$ of the emergent spectrum $\boldsymbol{I}(\lambda)$
  - the quantity $\boldsymbol{R}(\lambda,\tau)$ is a vector containing the response function for each Stokes parameter

The nodes

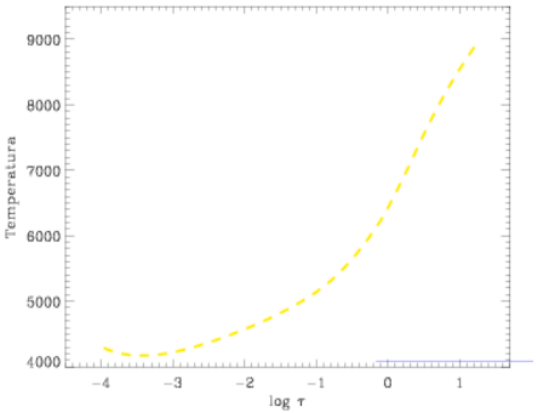
- From an operational point of view, equivalent perturbations (RFs) of a **single physical quantity** are calculated at certain locations (grid points) - the **nodes** – with a cubic-splines interpolation between them
- The optical depth τ is equi-spaced on a logarithmic scale
- Nodes are also equi-spaced
- The number of nodes can be set by the user or automatically optimized by the code
  - no. = 0 -> not inverted
  - no. = 1 -> constant quantity
  - no. = 2 -> linear interpolation



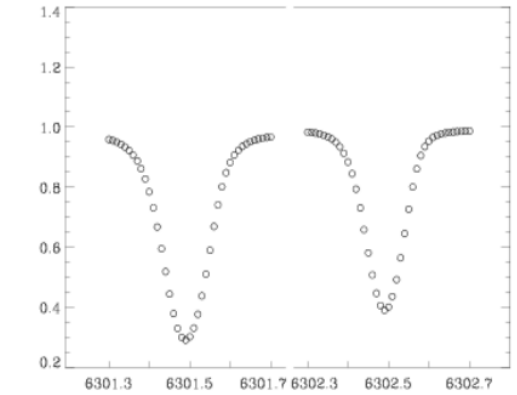
Procedure

- The code iteratively changes each physical quantity, assuming initial constant values for $B(\tau)$, $\gamma(\tau)$ and $\varphi(\tau)$ set by the user
  or deduced from the weak field approximation
- Iteration is repeated to reach convergence, by minimizing the χ^2 merit function containing the differences between the observed and synthetic spectral data

$$\chi^2 \equiv \frac{1}{\nu} \sum_{k=1}^{4} \sum_{i=1}^{M} [I_k^{\mathrm{obs}}(\lambda_i) - I_k^{\mathrm{syn}}(\lambda_i)]^2$$

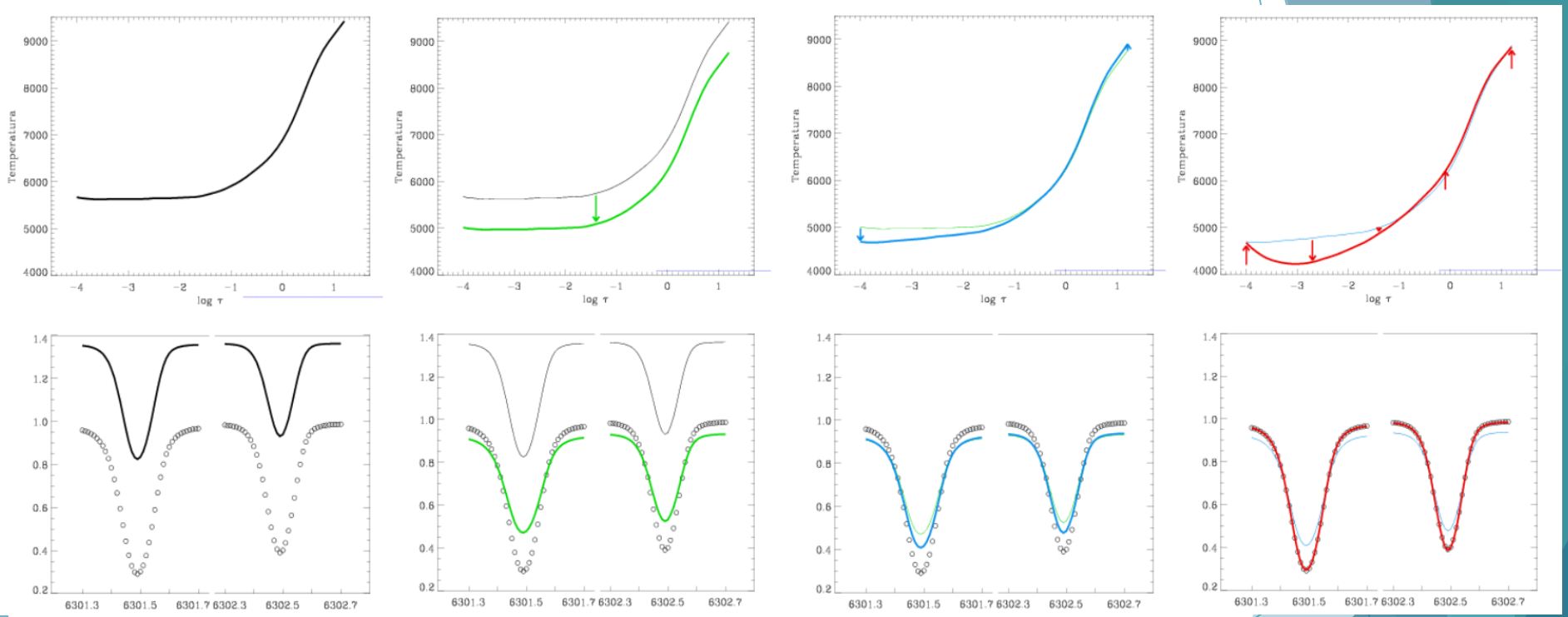


The "real" SUN



Synthetic "observations"

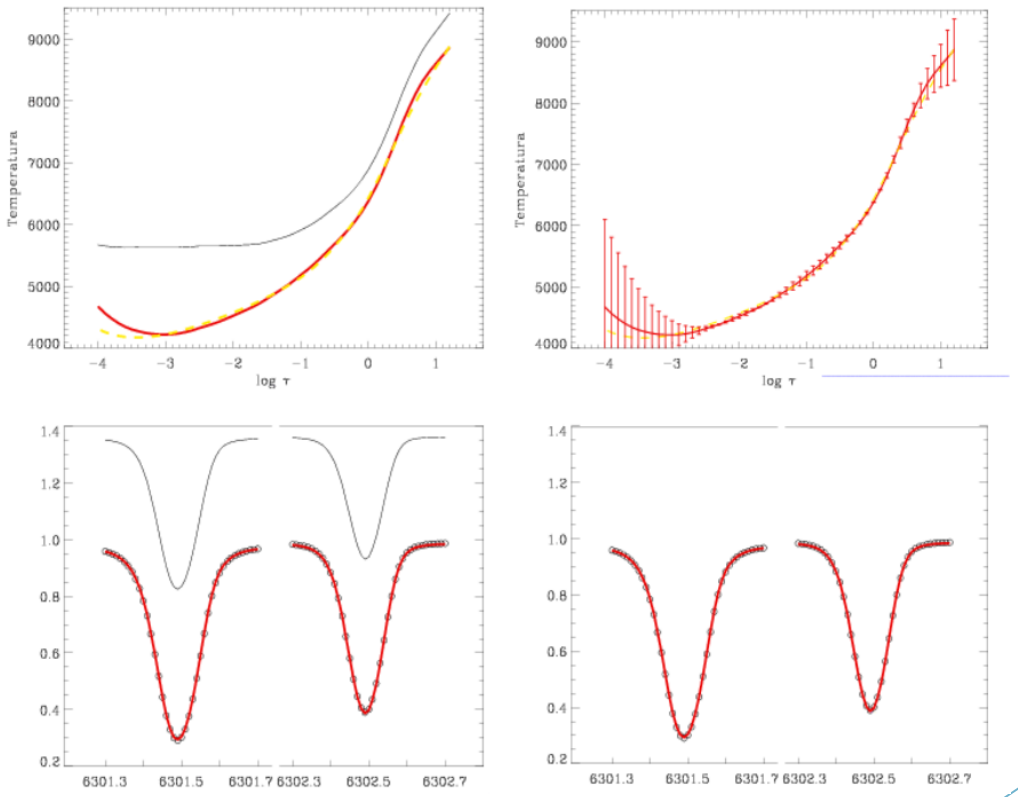
Iterations



initial “guess” model | 1 node | 2 nodes | 5 nodes

Output

initial model vs solution	error bars



https://github.com/BasilioRuiz/SIR-code

REPOSITORY FOR THE SIR CODE

originally developed in FORTRAN

Running SIR

- A file **[].trol** controls the code

sir_eph.trol (~/Desktop/SIR_Hinode/inversion) - gedit

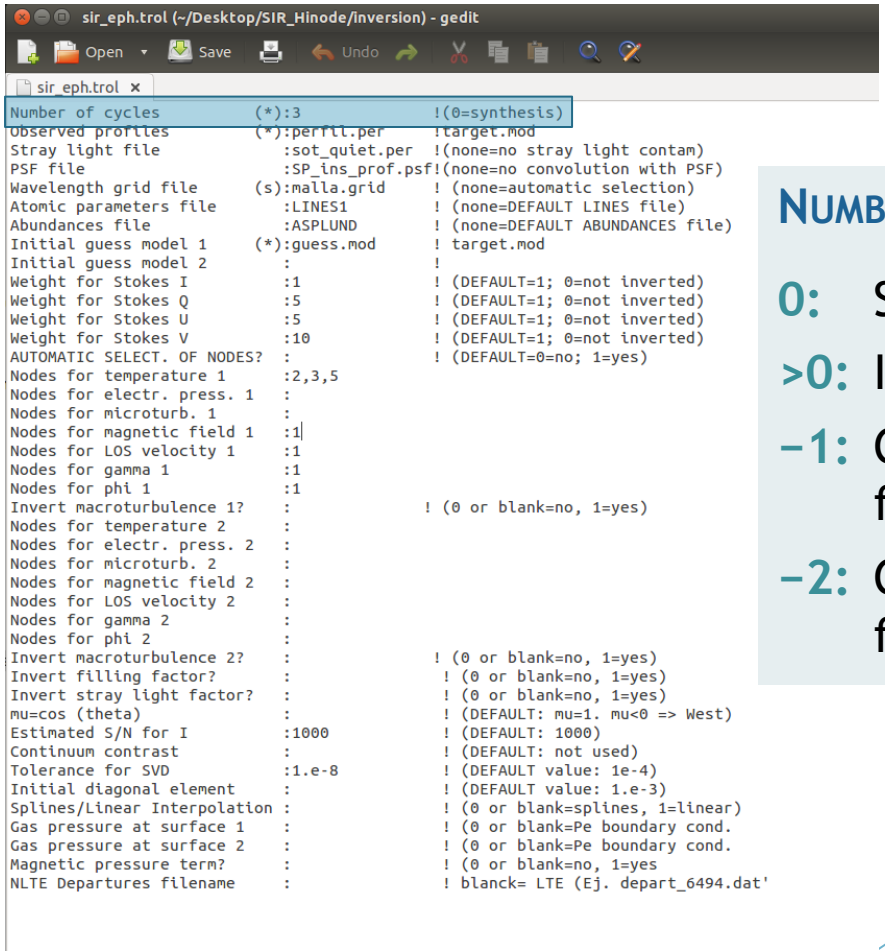
Open ▾ Save Undo

sir_eph.trol ×

```
Number of cycles          (*):3              !(0=synthesis)
Observed profiles         (*):perfil.per     !target.mod
Stray light file             :sot_quiet.per  !(none=no stray light contam)
PSF file                     :SP_ins_prof.psf!(none=no convolution with PSF)
Wavelength grid file      (s):malla.grid     ! (none=automatic selection)
Atomic parameters file       :LINES1         ! (none=DEFAULT LINES file)
Abundances file              :ASPLUND        ! (none=DEFAULT ABUNDANCES file)
Initial guess model 1     (*):guess.mod      ! target.mod
Initial guess model 2        :               !
Weight for Stokes I          :1              ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q          :5              ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U          :5              ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V          :10             ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?  :               ! (DEFAULT=0=no; 1=yes)
Nodes for temperature 1      :2,3,5
Nodes for electr. press. 1   :
Nodes for microturb. 1       :
Nodes for magnetic field 1   :1
Nodes for LOS velocity 1     :1
Nodes for gamma 1            :1
Nodes for phi 1              :1
Invert macroturbulence 1?    :              ! (0 or blank=no, 1=yes)
Nodes for temperature 2      :
Nodes for electr. press. 2   :
Nodes for microturb. 2       :
Nodes for magnetic field 2   :
Nodes for LOS velocity 2     :
Nodes for gamma 2            :
Nodes for phi 2              :
Invert macroturbulence 2?    :               ! (0 or blank=no, 1=yes)
Invert filling factor?       :               ! (0 or blank=no, 1=yes)
Invert stray light factor?   :               ! (0 or blank=no, 1=yes)
mu=cos (theta)               :               ! (DEFAULT: mu=1. mu<0 => West)
Estimated S/N for I          :1000           ! (DEFAULT: 1000)
Continuum contrast           :               ! (DEFAULT: not used)
Tolerance for SVD            :1.e-8          ! (DEFAULT value: 1e-4)
Initial diagonal element     :               ! (DEFAULT value: 1.e-3)
Splines/Linear Interpolation :               ! (0 or blank=splines, 1=linear)
Gas pressure at surface 1    :               ! (0 or blank=Pe boundary cond.
Gas pressure at surface 2    :               ! (0 or blank=Pe boundary cond.
Magnetic pressure term?      :               ! (0 or blank=no, 1=yes
NLTE Departures filename     :               ! blanck= LTE (Ej. depart_6494.dat'
```

Running SIR: cycles

- A file **[].trol** controls the code



NUMBER OF CYCLES

- **0:** Synthesis mode
- **>0:** Inversion mode
- **−1:** Compute response functions at every depth
- **−2:** Compute response functions at the nodes

Running SIR: observed data

- A file **[].trol** controls the code

sir_eph.trol (~/Desktop/SIR_Hinode/inversion) - gedit

Open Save Undo

sir_eph.trol ×

```
Number of cycles          (*):3              !(0=synthesis)
Observed profiles         (*):perfil.per     !target.mod
Stray light file             :sot_quiet.per  !(none=no stray light contam)
PSF file                     :SP_ins_prof.psf!(none=no convolution with PSF)
Wavelength grid file      (s):malla.grid     ! (none=automatic selection)
Atomic parameters file       :LINES1         ! (none=DEFAULT LINES file)
Abundances file              :ASPLUND        ! (none=DEFAULT ABUNDANCES file)
Initial guess model 1     (*):guess.mod      ! target.mod
Initial guess model 2        :               !
Weight for Stokes I          :1              ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q          :5              ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U          :5              ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V          :10             ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?  :               ! (DEFAULT=0=no; 1=yes)
Nodes for temperature 1      :2,3,5
Nodes for electr. press. 1   :
Nodes for microturb. 1       :
Nodes for magnetic field 1   :1
Nodes for LOS velocity 1     :1
Nodes for gamma 1            :1
Nodes for phi 1              :1
Invert macroturbulence 1?    :              ! (0 or blank=no, 1=yes)
Nodes for temperature 2      :
Nodes for electr. press. 2   :
Nodes for microturb. 2       :
Nodes for magnetic field 2   :
Nodes for LOS velocity 2     :
Nodes for gamma 2            :
Nodes for phi 2              :
Invert macroturbulence 2?    :               ! (0 or blank=no, 1=yes)
Invert filling factor?       :               ! (0 or blank=no, 1=yes)
Invert stray light factor?   :               ! (0 or blank=no, 1=yes)
mu=cos (theta)               :               ! (DEFAULT: mu=1. mu<0 => West)
Estimated S/N for I          :1000           ! (DEFAULT: 1000)
Continuum contrast           :               ! (DEFAULT: not used)
Tolerance for SVD            :1.e-8          ! (DEFAULT value: 1e-4)
Initial diagonal element     :               ! (DEFAULT value: 1.e-3)
Splines/Linear Interpolation :               ! (0 or blank=splines, 1=linear)
Gas pressure at surface 1    :               ! (0 or blank=Pe boundary cond.
Gas pressure at surface 2    :               ! (0 or blank=Pe boundary cond.
Magnetic pressure term?      :               ! (0 or blank=no, 1=yes
NLTE Departures filename     :               ! blanck= LTE (Ej. depart_6494.dat'
```

perfil.per (~/Desktop/SIR_Hinode/inversion) - gedit

Open Save Undo

perfil.per ×

Line index	Δλ [mA]	I/I_{qs}	Q/I_{qs}	U/I_{qs}	V/I_{qs}
1.00000	-646.796	1.12849	0.000188559	-2.67883e-05	0.000106774
1.00000	-625.247	1.12867	0.000200412	-3.18499e-05	0.000102642
1.00000	-603.698	1.12879	0.000198448	-3.49178e-05	0.000105734
1.00000	-582.149	1.12891	0.000211168	-3.75974e-05	0.000103513
1.00000	-560.600	1.12878	0.000202261	-3.80838e-05	0.000113545
1.00000	-539.051	1.12809	0.000202073	-4.38965e-05	0.000112842
1.00000	-517.503	1.12814	0.000161003	-1.28987e-05	0.000142416
					-06 0.000161545
					-07 0.000160990
					-06 0.000165370
					-06 0.000219871
					-05 0.000221790
					-05 0.000289745
					-06 0.000349858
					-06 0.000515697
					-06 0.000716520
					-06 0.00103652
					-05 0.00144077
					-06 0.00197793
					-06 0.00264956
					-06 0.00349738
					-05 0.00454084
					432 0.00581346
1.00000	-151.169	0.959597	0.00182815	-0.000421819	0.00758691
1.00000	-129.620	0.880233	0.00366770	-0.000888209	0.0104427
1.00000	-108.071	0.771716	0.00579565	-0.00129786	0.0146407
1.00000	-86.5218	0.641247	0.00555384	-0.00124390	0.0185893
1.00000	-64.9728	0.520345	0.00259442	-0.000824384	0.0176900
1.00000	-43.4238	0.441852	-0.000473594	-0.000584818	0.0113755
1.00000	-21.8748	0.414215	-0.00168177	-0.000458559	0.00247350
1.00000	-0.325844	0.435772	-0.000319704	-0.000484066	-0.00740019
1.00000	21.2232	0.516061	0.00229239	-0.000867606	-0.0159185
1.00000	42.7722	0.644968	0.00436436	-0.00135007	-0.0194994
1.00000	64.3212	0.773966	0.00446703	-0.00136629	-0.0179692
1.00000	85.8702	0.873403	0.00317828	-0.000915433	-0.0147687
1.00000	107.419	0.946622	0.00189952	-0.000446100	-0.0114649
1.00000	128.968	0.997238	0.00109185	-0.000204487	-0.00842209
1.00000	150.517	1.03189	0.000624825	-8.89180e-05	-0.00608648
1.00000	172.066	1.05645	0.000334157	2.80152e-06	-0.00440421
1.00000	193.615	1.07362	0.000166469	4.37982e-05	-0.00327001
1.00000	215.164	1.08409	5.46180e-05	8.07207e-05	-0.00247667
1.00000	236.713	1.09281	-2.97400e-05	0.000123527	-0.00188086
1.00000	258.262	1.09898	-4.66386e-05	0.000112189	-0.00147523
1.00000	279.811	1.10250	-3.03289e-05	0.000110473	-0.00109906
1.00000	301.360	1.10486	-3.50169e-06	0.000131458	-0.000796216
1.00000	322.909	1.10365	-6.00132e-05	0.000146945	-0.000604604
1.00000	344.458	1.10510	-8.81505e-05	0.000174671	-0.000523672
1.00000	366.007	1.10926	-1.33310e-05	0.000152337	-0.000436809
1.00000	387.556	1.11377	7.47509e-05	0.000165274	-0.000355264
1.00000	409.105	1.11840	9.82799e-05	0.000153464	-0.000265645
1.00000	430.654	1.12115	8.25851e-05	0.000154243	-0.000134457
1.00000	452.203	1.12238	5.74260e-05	0.000133858	-1.96084e-05

N.B.

In «synthesis mode», this is the output file

Running SIR: stray light

- A file **[].trol** controls the code

sir_eph.trol (~/Desktop/SIR_Hinode/inversion) - gedit

Open ▾ Save Undo

sir_eph.trol ×

```
Number of cycles          (*):3              !(0=synthesis)
Observed profiles         (*):perfil.per     !target.mod
Stray light file             :sot_quiet.per  !(none=no stray light contam)
PSF file                     :SP_ins_prof.psf!(none=no convolution with PSF)
Wavelength grid file      (s):malla.grid     ! (none=automatic selection)
Atomic parameters file       :LINES1         ! (none=DEFAULT LINES file)
Abundances file              :ASPLUND        ! (none=DEFAULT ABUNDANCES file)
Initial guess model 1     (*):guess.mod      ! target.mod
Initial guess model 2        :               !
Weight for Stokes I          :1              ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q          :5              ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U          :5              ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V          :10             ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?  :               ! (DEFAULT=0=no; 1=yes)
Nodes for temperature 1      :2,3,5
Nodes for electr. press. 1   :
Nodes for microturb. 1       :
Nodes for magnetic field 1   :1
Nodes for LOS velocity 1     :1
Nodes for gamma 1            :1
Nodes for phi 1              :1
Invert macroturbulence 1?    :              ! (0 or blank=no, 1=yes)
Nodes for temperature 2      :
Nodes for electr. press. 2   :
Nodes for microturb. 2       :
Nodes for magnetic field 2   :
Nodes for LOS velocity 2     :
Nodes for gamma 2            :
Nodes for phi 2              :
Invert macroturbulence 2?    :               ! (0 or blank=no, 1=yes)
Invert filling factor?       :               ! (0 or blank=no, 1=yes)
Invert stray light factor?   :               ! (0 or blank=no, 1=yes)
mu=cos (theta)               :               ! (DEFAULT: mu=1. mu<0 => West)
Estimated S/N for I          :1000           ! (DEFAULT: 1000)
Continuum contrast           :               ! (DEFAULT: not used)
Tolerance for SVD            :1.e-8          ! (DEFAULT value: 1e-4)
Initial diagonal element     :               ! (DEFAULT value: 1.e-3)
Splines/Linear Interpolation :               ! (0 or blank=splines, 1=linear)
Gas pressure at surface 1    :               ! (0 or blank=Pe boundary cond.
Gas pressure at surface 2    :               ! (0 or blank=Pe boundary cond.
Magnetic pressure term?      :               ! (0 or blank=no, 1=yes
NLTE Departures filename     :               ! blanck= LTE (Ej. depart_6494.dat'
```

STRAY LIGHT CONTAMINATION

Same format as observed Stokes profile file

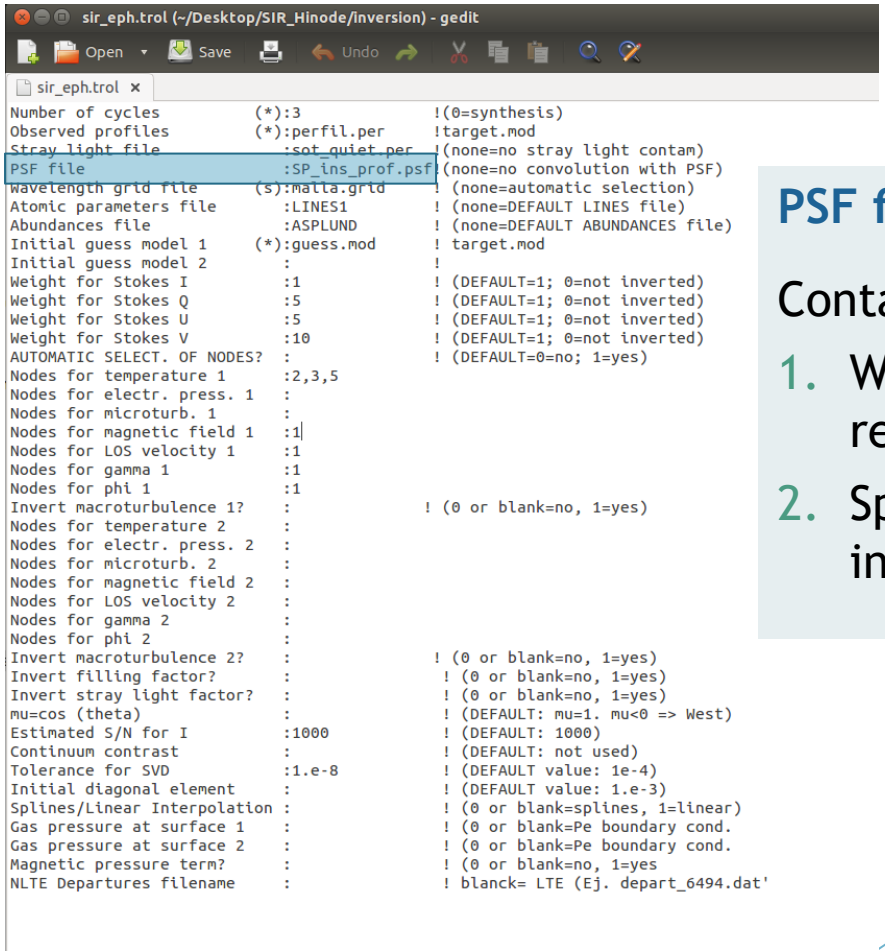
Contains the stray light contamination, assumed to be unpolarized (so that Q=U=V=0)

Stray-light treatment

- Stray-light in 1C inversions:
  - $I_{obs} = (1-\alpha)\, I_1 + \alpha\, I_{stray}$
  - Accounts for both stray light and/or magnetic filling factor
- Stray-light in 2C inversions:
  - It is NOT equivalent to a magnetic filling factor
  - SIR has two free parameters: α and f
  - $I_{obs} = (1-\alpha)\, [f\, I_1 + (1-f)\, I_2\,] + \alpha\, I_{stray}$
- Global vs local stray-light profile
  - Classical treatment: global stray-light profile (average over FOV)
  - local stray-light profile to account for telescope diffraction (e.g. Orozco Suárez et al., 2007)

Running SIR: PSF deconvolution

- A file **[].trol** controls the code



PSF file: [].psf

Contains two columns:

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

Running SIR: wavelength grid

- A file **[].trol** controls the code

sir_eph.trol (~/Desktop/SIR_Hinode/inversion) - gedit

Open ▾ Save Undo

sir_eph.trol ×

```
Number of cycles          (*):3              !(0=synthesis)
Observed profiles         (*):perfil.per     !target.mod
Stray light file             :sot_quiet.per  !(none=no stray light contam)
PSF file                     :SP_ins_prof.psf!(none=no convolution with PSF)
Wavelength grid file      (s):malla.grid     ! (none=automatic selection)
Atomic parameters file       :LINES1         ! (none=DEFAULT LINES file)
Abundances file              :ASPLUND        ! (none=DEFAULT ABUNDANCES file)
Initial guess model 1     (*):guess.mod      ! target.mod
Initial guess model 2        :               !
Weight for Stokes I          :1              ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q          :5              ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U          :5              ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V          :10             ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?  :               ! (DEFAULT=0=no; 1=yes)
Nodes for temperature 1      :2,3,5
Nodes for electr. press. 1   :
Nodes for microturb. 1       :
Nodes for magnetic field 1   :1
Nodes for LOS velocity 1     :1
Nodes for gamma 1            :1
Nodes for phi 1              :1
Invert macroturbulence 1?    :              ! (0 or blank=no, 1=yes)
Nodes for temperature 2      :
Nodes for electr. press. 2   :
Nodes for microturb. 2       :
Nodes for magnetic field 2   :
Nodes for LOS velocity 2     :
Nodes for gamma 2            :
Nodes for phi 2              :
Invert macroturbulence 2?    :               ! (0 or blank=no, 1=yes)
Invert filling factor?       :               ! (0 or blank=no, 1=yes)
Invert stray light factor?   :               ! (0 or blank=no, 1=yes)
mu=cos (theta)               :               ! (DEFAULT: mu=1. mu<0 => West)
Estimated S/N for I          :1000           ! (DEFAULT: 1000)
Continuum contrast           :               ! (DEFAULT: not used)
Tolerance for SVD            :1.e-8          ! (DEFAULT value: 1e-4)
Initial diagonal element     :               ! (DEFAULT value: 1.e-3)
Splines/Linear Interpolation :               ! (0 or blank=splines, 1=linear)
Gas pressure at surface 1    :               ! (0 or blank=Pe boundary cond.
Gas pressure at surface 2    :               ! (0 or blank=Pe boundary cond.
Magnetic pressure term?      :               ! (0 or blank=no, 1=yes
NLTE Departures filename     :               ! blanck= LTE (Ej. depart_6494.dat'
```

wavelength grid file: [].grid

N.B. SIR can invert multiple lines at once

malla.grid (~/Desktop/SIR_Hinode/inversion) - gedit

Open ▾ Save Undo

malla.grid ×

```
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
```

Running SIR: wavelength grid

- A file **[].trol** controls the code

sir_eph.trol (~/Desktop/SIR_Hinode/inversion) - gedit

Open ▾ Save Undo

sir_eph.trol ×

```
Number of cycles          (*):3              !(0=synthesis)
Observed profiles         (*):perfil.per     !target.mod
Stray light file             :sot_quiet.per  !(none=no stray light contam)
PSF file                     :SP_ins_prof.psf!(none=no convolution with PSF)
Wavelength grid file      (s):malla.grid     ! (none=automatic selection)
Atomic parameters file       :LINES1         ! (none=DEFAULT LINES file)
Abundances file              :ASPLUND        ! (none=DEFAULT ABUNDANCES file)
Initial guess model 1     (*):guess.mod      ! target.mod
Initial guess model 2        :               !
Weight for Stokes I          :1              ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q          :5              ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U          :5              ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V          :10             ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?  :               ! (DEFAULT=0=no; 1=yes)
Nodes for temperature 1      :2,3,5
Nodes for electr. press. 1   :
Nodes for microturb. 1       :
Nodes for magnetic field 1   :1
Nodes for LOS velocity 1     :1
Nodes for gamma 1            :1
Nodes for phi 1              :1
Invert macroturbulence 1?    :              ! (0 or blank=no, 1=yes)
Nodes for temperature 2      :
Nodes for electr. press. 2   :
Nodes for microturb. 2       :
Nodes for magnetic field 2   :
Nodes for LOS velocity 2     :
Nodes for gamma 2            :
Nodes for phi 2              :
Invert macroturbulence 2?    :               ! (0 or blank=no, 1=yes)
Invert filling factor?       :               ! (0 or blank=no, 1=yes)
Invert stray light factor?   :               ! (0 or blank=no, 1=yes)
mu=cos (theta)               :               ! (DEFAULT: mu=1. mu<0 => West)
Estimated S/N for I          :1000           ! (DEFAULT: 1000)
Continuum contrast           :               ! (DEFAULT: not used)
Tolerance for SVD            :1.e-8          ! (DEFAULT value: 1e-4)
Initial diagonal element     :               ! (DEFAULT value: 1.e-3)
Splines/Linear Interpolation :               ! (0 or blank=splines, 1=linear)
Gas pressure at surface 1    :               ! (0 or blank=Pe boundary cond.
Gas pressure at surface 2    :               ! (0 or blank=Pe boundary cond.
Magnetic pressure term?      :               ! (0 or blank=no, 1=yes
NLTE Departures filename     :               ! blanck= LTE (Ej. depart_6494.dat'
```

These files contain:

1. For a given line, identified with the **«line index»**
   ion λ E χ
   log *gf* transition
   collisional parameters
2. Abundances of the different atomic species

Running SIR: model (I)

- A file **[].trol** co

sir_eph.trol (~/Desktop/SIR_Hinode/

Open Save

sir_eph.trol ×

```
Number of cycles              (*):3
Observed profiles             (*):perfil.
Stray light file                 :sot_qui
PSF file                         :SP_ins_
Wavelength grid file          (s):malla.g
Atomic parameters file           :LINES1
Abundances file                  :ASPLUND
Initial guess model 1         (*):guess.m
Initial guess model 2            :
Weight for Stokes I              :1
Weight for Stokes Q              :5
Weight for Stokes U              :5
Weight for Stokes V              :10
AUTOMATIC SELECT. OF NODES?      :
Nodes for temperature 1          :2,3,5
Nodes for electr. press. 1       :
Nodes for microturb. 1           :
Nodes for magnetic field 1       :1
Nodes for LOS velocity 1         :1
Nodes for gamma 1                :1
Nodes for phi 1                  :1
Invert macroturbulence 1?        :
Nodes for temperature 2          :
Nodes for electr. press. 2       :
Nodes for microturb. 2           :
Nodes for magnetic field 2       :
Nodes for LOS velocity 2         :
Nodes for gamma 2                :
Nodes for phi 2                  :
Invert macroturbulence 2?        :
Invert filling factor?           :
Invert stray light factor?       :
mu=cos (theta)                   :
Estimated S/N for I              :1000
Continuum contrast               :
Tolerance for SVD                :1.e-8
Initial diagonal element         :
Splines/Linear Interpolation     :
Gas pressure at surface 1        :
Gas pressure at surface 2        :
Magnetic pressure term?          :
NLTE Departures filename         :
```

atmospheric model file: [].mod

guess.mod (~/Desktop/SIR_Hinode/inversion) - gedit

Open Save Undo

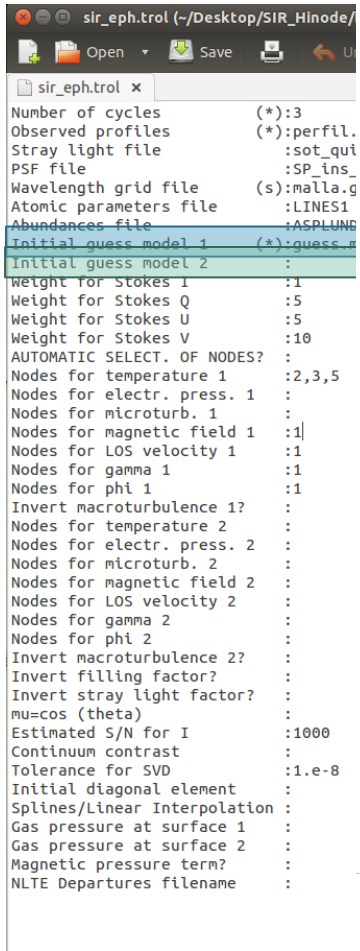
guess.mod ×

```
 1.  1.  0.
 1.4000   9560.0  6.04679E+03  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00 -8.1793E+01  2.0906E+05  3.4256E-07
 1.3000   9390.0  5.05430E+03  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00 -7.6217E+01  2.0384E+05  3.4006E-07
 1.2000   9220.0  4.19934E+03  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00 -7.0886E+01  1.9888E+05  3.3791E-07
 1.1000   9050.0  3.46707E+03  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00 -6.5787E+01  1.9417E+05  3.3610E-07
 1.0000   8880.0  2.84362E+03  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00 -6.0906E+01  1.8969E+05  3.3462E-07
 0.9000   8710.0  2.31616E+03  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00 -5.6231E+01  1.8541E+05  3.3345E-07
 0.8000   8520.0  1.82792E+03  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00 -5.1710E+01  1.8127E+05  3.3329E-07
 0.7000   8290.0  1.35724E+03  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00 -4.7202E+01  1.7715E+05  3.3474E-07
 0.6000   8030.0  9.52178E+02  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00 -4.2533E+01  1.7284E+05  3.3719E-07
 0.5000   7750.0  6.34620E+02  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00 -3.7536E+01  1.6821E+05  3.3999E-07
 0.4000   7440.0  3.92523E+02  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00 -3.1973E+01  1.6299E+05  3.4319E-07
 0.3000   7140.9  2.38248E+02  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00 -2.5597E+01  1.5698E+05  3.4438E-07
 0.2000   6860.0  1.44058E+02  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00 -1.8222E+01  1.5004E+05  3.4263E-07
 0.1000   6610.0  8.93928E+01  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00 -9.7098E+00  1.4212E+05  3.3681E-07
 0.0000   6390.0  5.74393E+01  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  0.0000E+00  1.3330E+05  3.2677E-07
-0.1000   6200.0  3.85914E+01  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  1.0887E+01  1.2376E+05  3.1270E-07
-0.2000   6035.0  2.70588E+01  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  2.2855E+01  1.1380E+05  2.9539E-07
-0.3000   5890.0  1.97078E+01  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  3.5769E+01  1.0370E+05  2.7580E-07
-0.4000   5765.0  1.49363E+01  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  4.9445E+01  9.3764E+04  2.5478E-07
-0.5000   5650.0  1.15850E+01  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  6.3705E+01  8.4227E+04  2.3353E-07
-0.6000   5540.0  9.12943E+00  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  7.8423E+01  7.5230E+04  2.1272E-07
-0.7000   5430.0  7.26618E+00  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  9.3485E+01  6.6860E+04  1.9289E-07
-0.8000   5330.0  5.90801E+00  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  1.0875E+02  5.9188E+04  1.7396E-07
-0.9000   5240.0  4.88788E+00  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  1.2405E+02  5.2260E+04  1.5623E-07
-1.0000   5160.0  4.09997E+00  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  1.3930E+02  4.6069E+04  1.3986E-07
-1.1000   5080.0  3.44883E+00  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  1.5443E+02  4.0573E+04  1.2511E-07
-1.2000   5010.0  2.92983E+00  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  1.6940E+02  3.5713E+04  1.1167E-07
-1.3000   4950.0  2.51030E+00  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  1.8421E+02  3.1427E+04  9.9456E-08
-1.4000   4895.0  2.15948E+00  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  1.9886E+02  2.7652E+04  8.8491E-08
-1.5000   4840.0  1.85733E+00  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  2.1335E+02  2.4328E+04  7.8740E-08
-1.6000   4790.0  1.60330E+00  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  2.2769E+02  2.1404E+04  6.9999E-08
-1.7000   4750.0  1.39482E+00  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  2.4190E+02  1.8831E+04  6.2103E-08
-1.8000   4720.0  1.22314E+00  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  2.5601E+02  1.6566E+04  5.4980E-08
-1.9000   4690.0  1.07228E+00  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  2.7005E+02  1.4571E+04  4.8670E-08
-2.0000   4660.0  9.39734E-01  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  2.8401E+02  1.2815E+04  4.3079E-08
-2.1000   4630.0  8.23307E-01  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  2.9790E+02  1.1269E+04  3.8127E-08
-2.2000   4600.0  7.21053E-01  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  3.1172E+02  9.9076E+03  3.3740E-08
-2.3000   4575.0  6.33958E-01  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  3.2547E+02  8.7089E+03  2.9820E-08
-2.4000   4550.0  5.57158E-01  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  3.3918E+02  7.6532E+03  2.6349E-08
-2.5000   4525.0  4.89446E-01  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  3.5285E+02  6.7233E+03  2.3275E-08
-2.6000   4490.0  4.26053E-01  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  3.6646E+02  5.9047E+03  2.0601E-08
-2.7000   4460.0  3.72282E-01  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  3.8001E+02  5.1841E+03  1.8208E-08
-2.8000   4430.0  3.25100E-01  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  3.9350E+02  4.5498E+03  1.6089E-08
-2.9000   4405.0  2.84999E-01  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  4.0695E+02  3.9913E+03  1.4194E-08
-3.0000   4380.0  2.49670E-01  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  4.2039E+02  3.4992E+03  1.2515E-08
-3.1000   4355.0  2.18546E-01  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  4.3383E+02  3.0657E+03  1.1027E-08
-3.2000   4330.0  1.91128E-01  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  4.4727E+02  2.6836E+03  9.7088E-09
-3.3000   4305.0  1.66973E-01  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  4.6073E+02  2.3468E+03  8.5397E-09
-3.4000   4280.0  1.45691E-01  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  4.7424E+02  2.0499E+03  7.5026E-09
-3.5000   4250.0  1.26332E-01  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  4.8781E+02  1.7879E+03  6.5900E-09
-3.6000   4225.0  1.09879E-01  6.000E+04  5.0000E+02  0.0000E+00  9.0000E+01  0.0000E+00  5.0146E+02  1.5567E+03  5.7717E-09
```

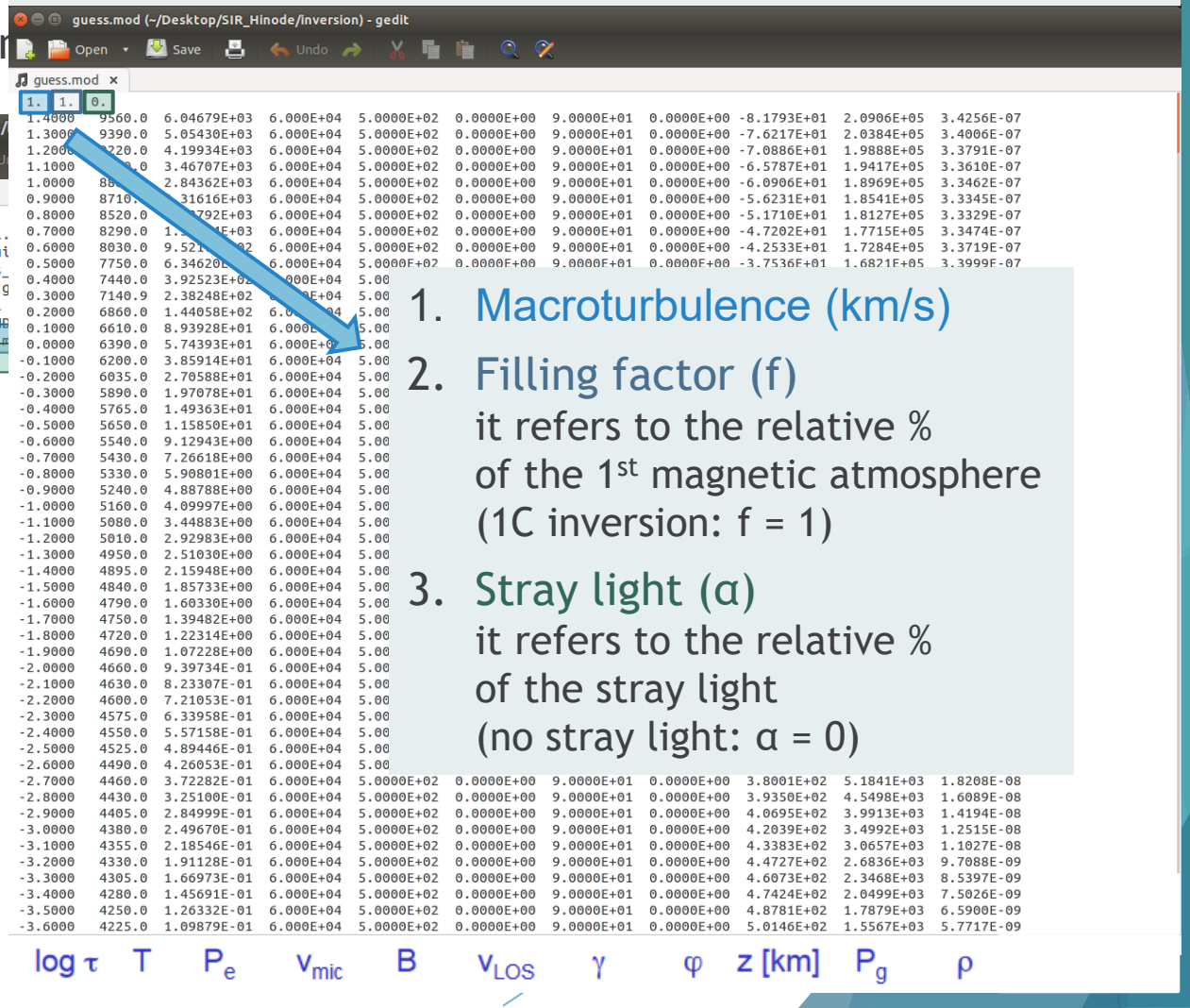
$\log \tau$ T P_e v_{mic} B v_{LOS} γ φ z [km] P_g ρ

Running SIR: model (II)

- A file **[].trol** co



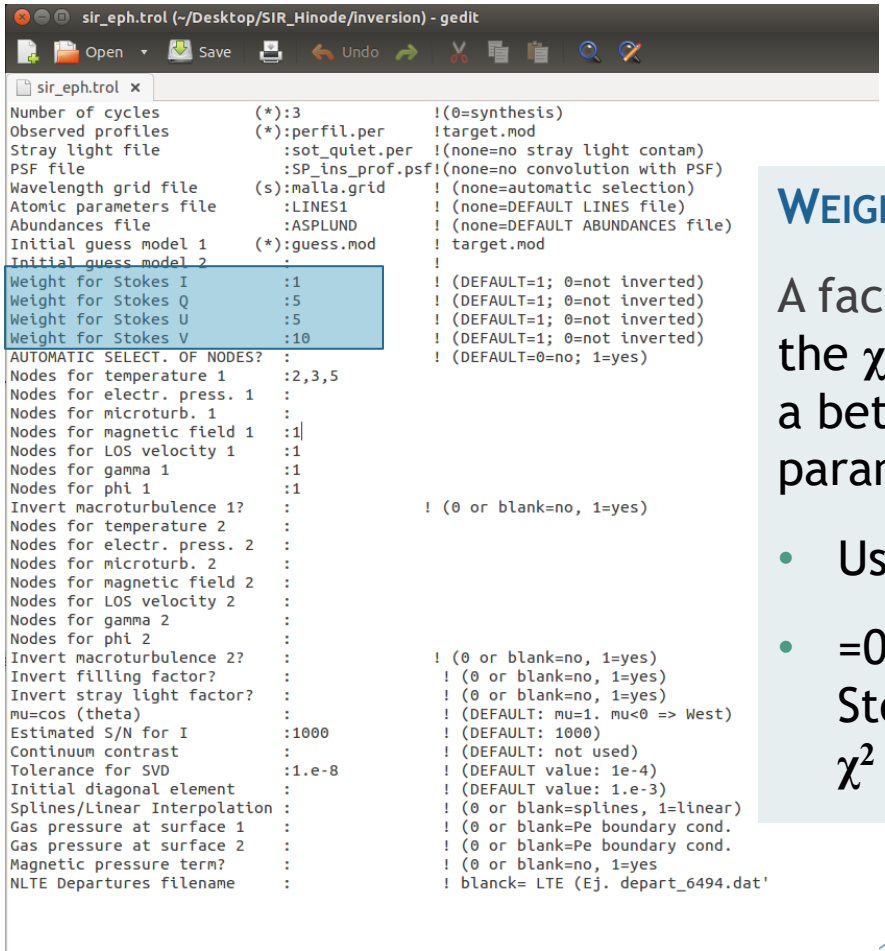
atmospheric model file: [].mod



1. Macroturbulence (km/s)
2. Filling factor (f)
   it refers to the relative %
   of the 1st magnetic atmosphere
   (1C inversion: f = 1)
3. Stray light (α)
   it refers to the relative %
   of the stray light
   (no stray light: α = 0)

Running SIR: weights for Stokes

- A file **[].trol** controls the code



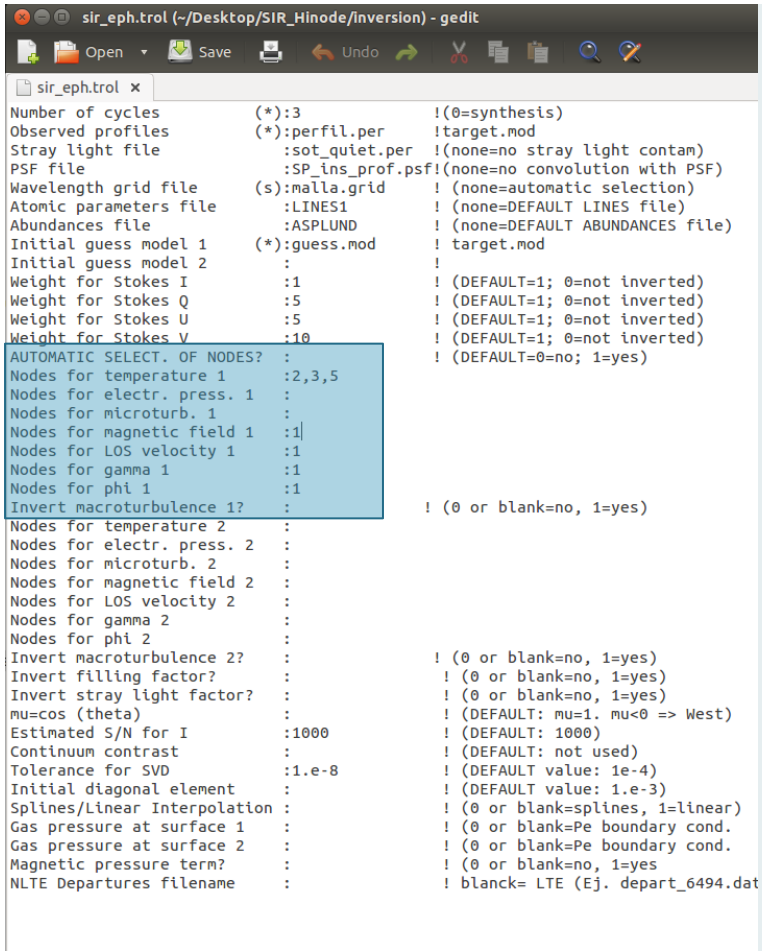
WEIGHTS

A factor that can be added into the χ^2 merit function to force a better fit for a given Stokes parameter (Q, U, V)

- Used for peculiar profiles
- =0 excludes the fit to the Stokes parameter from the χ^2 merit computation

Running SIR: choice of nodes

- A file **[].trol** controls the code



NUMBER OF NODES

Each column corresponds to a cycle

E.g. assume we have 3 cycles with

- nodes for **T: 2,3,5**
- nodes for **B/v_{LOS}: 1,2**

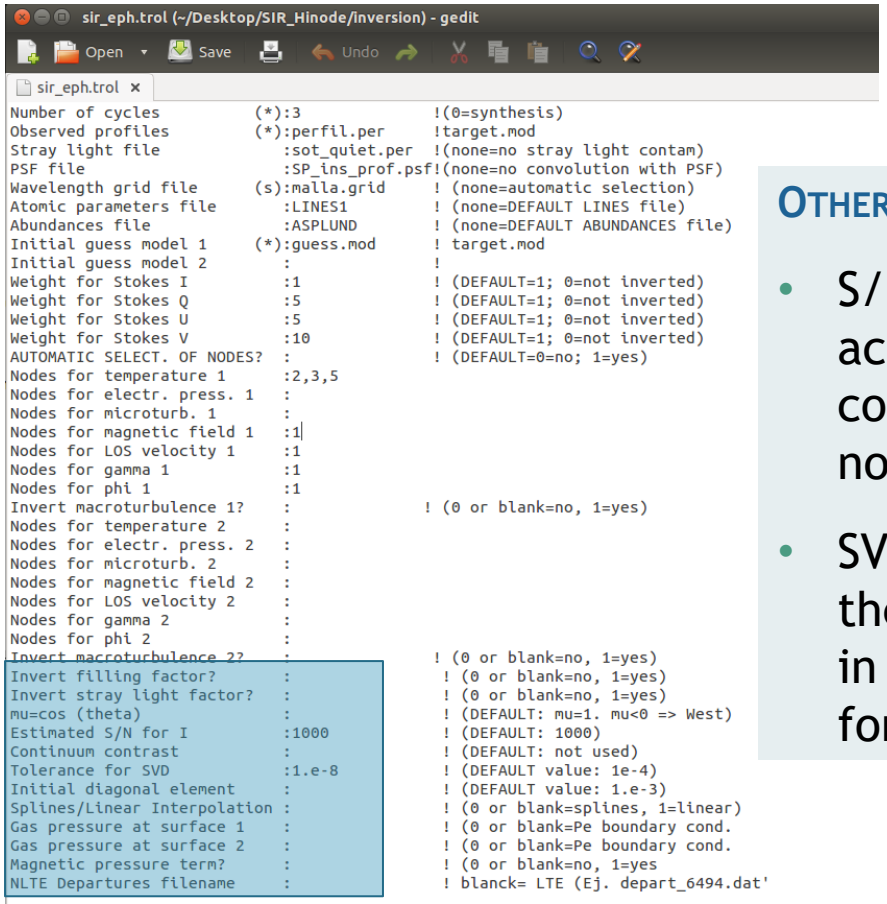
1. In the first cycle, 2 nodes for T and 1 for B/v_{LOS} will be used
2. In the second cycle, 3 for T and 2 for B/v_{LOS} will be used
3. In the third cycle, 5 for T and again 2 for B/v_{LOS} will be used

0 nodes in electron pressure -> HE

no. of nodes * means any value (only for automatic selection)

Running SIR: other settings

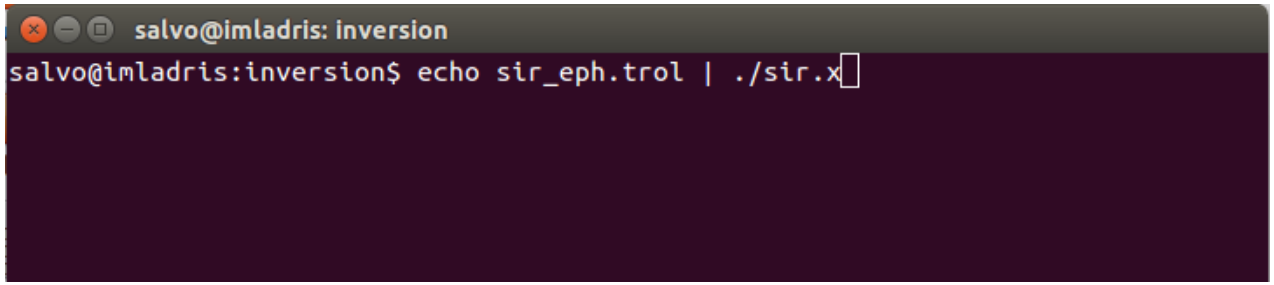
- A file **[].trol** controls the code



OTHER INVERSION SETTINGS

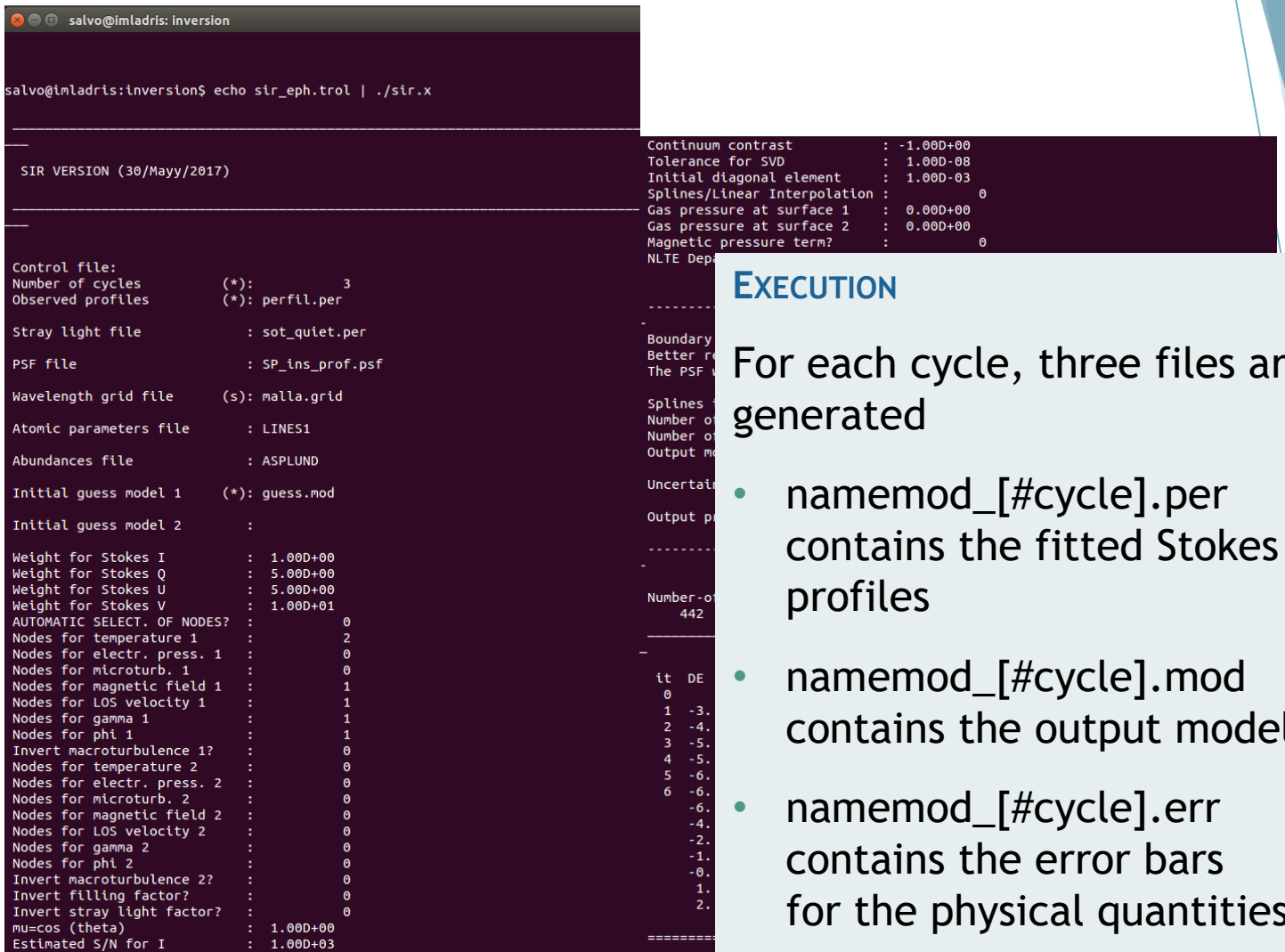
- S/N ratio are related to the acceptable quality of the fit, compared to the instrumental noise
- SVD tolerance indicates the convergence threshold in the χ^2 merit function for the iterations

Executing SIR



echo **sir.trol | ./sir.x**

Executing SIR



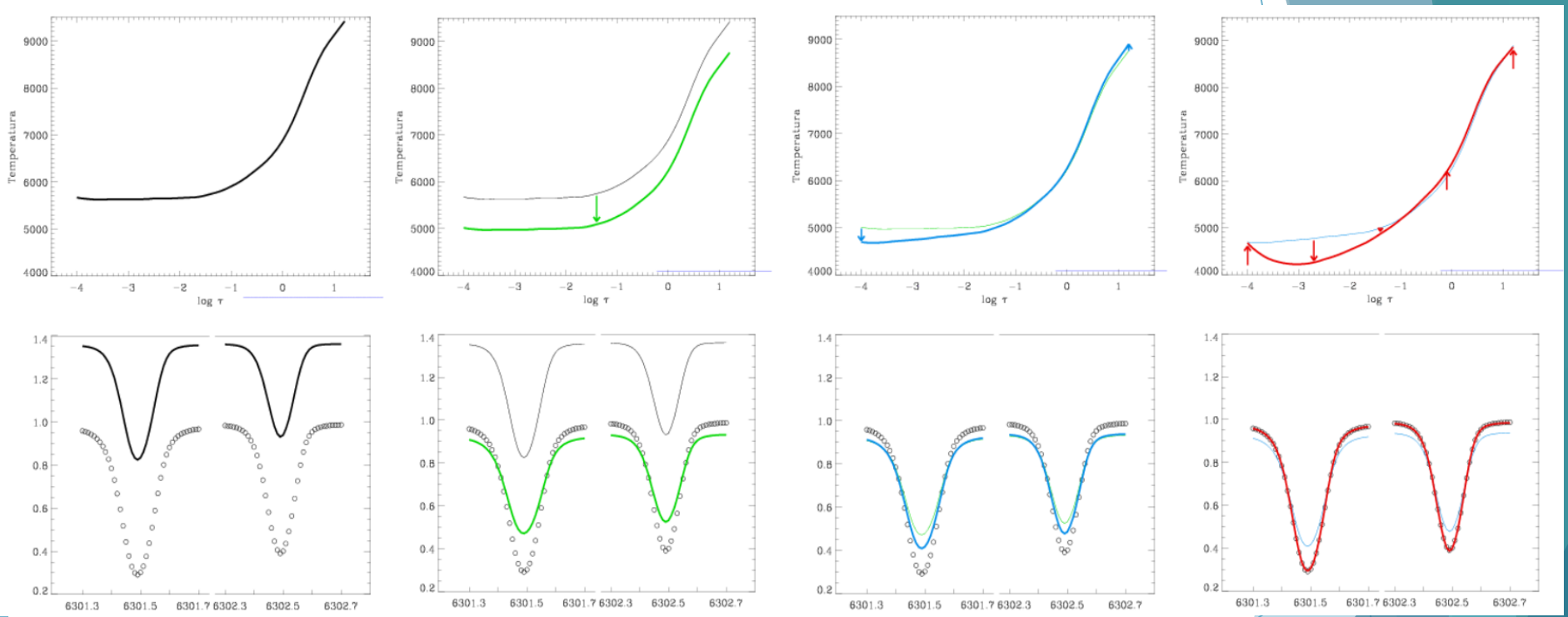
EXECUTION

For each cycle, three files are generated

- namemod_[#cycle].per contains the fitted Stokes profiles
- namemod_[#cycle].mod contains the output model
- namemod_[#cycle].err contains the error bars for the physical quantities

Executing SIR

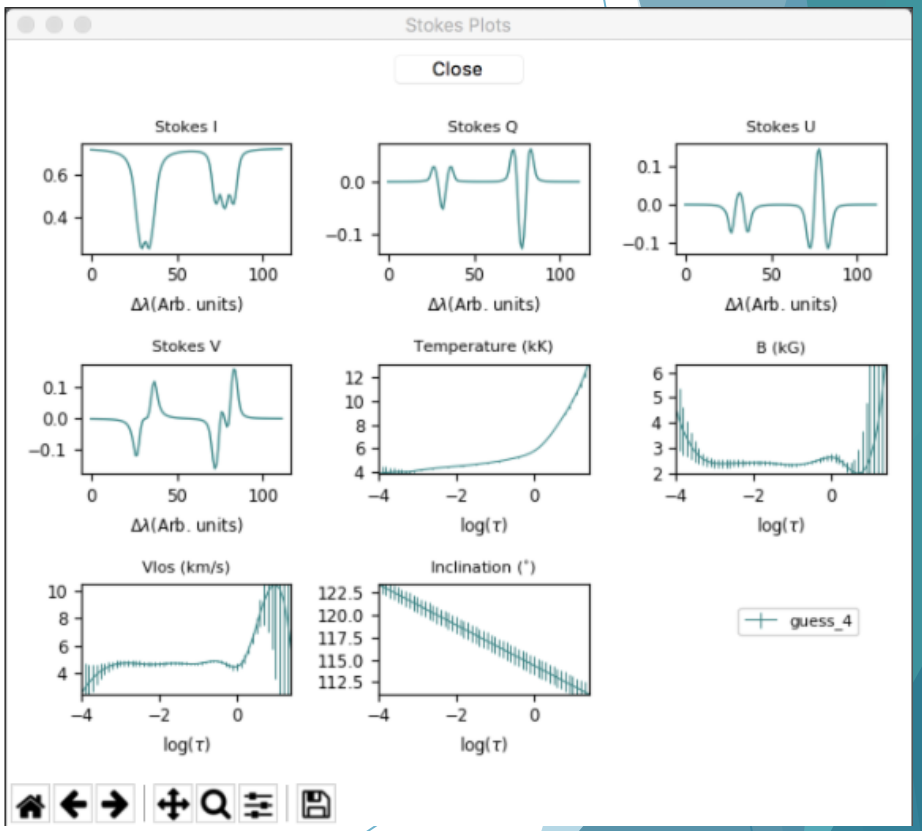
3 cycles



guess.mod	guess_1.mod	guess_2.mod	guess_3.mod
profile.per	guess_1.per	guess_2.per	guess_3.per

Visualizing SIR results

- IDL **GRAPHICS.PRO**
  - included in the SIR standard distribution
  - [path]/idl/graphics.pro
- Python **SIRGUI.PY**
  - https://github.com/rcenteno/SIR_GUI



Milne-Eddington-like inversion

- An **inversion scheme**, i.e., a set of cycles and nodes that has only 1 node for all the physical parameters except for T, which has 2+ nodes for all the cycles, can be treated as a **Milne-Eddington-like inversion**
- Main advantages:
  - "fast" inversion (with respect to other full RTE schemes)
  - realistic thermal stratification
  - comparable with ME results
  - easy to interpret
- Contra:
  - asymmetries cannot be treated
  - much slower than ME approach

Milne-Eddington-like inversion

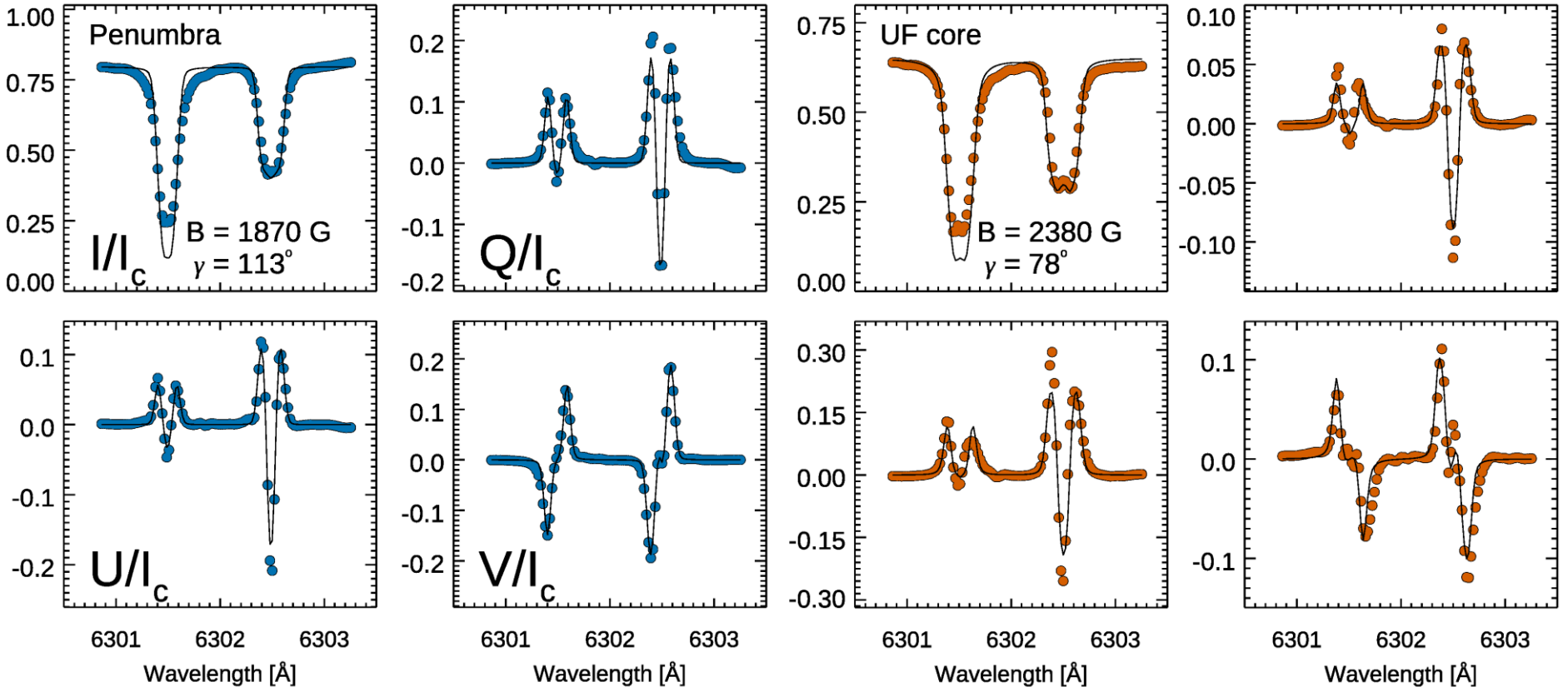
sir_eph.trol (~/Desktop/SIR_Hinode/inversion) - gedit

Open Save Undo

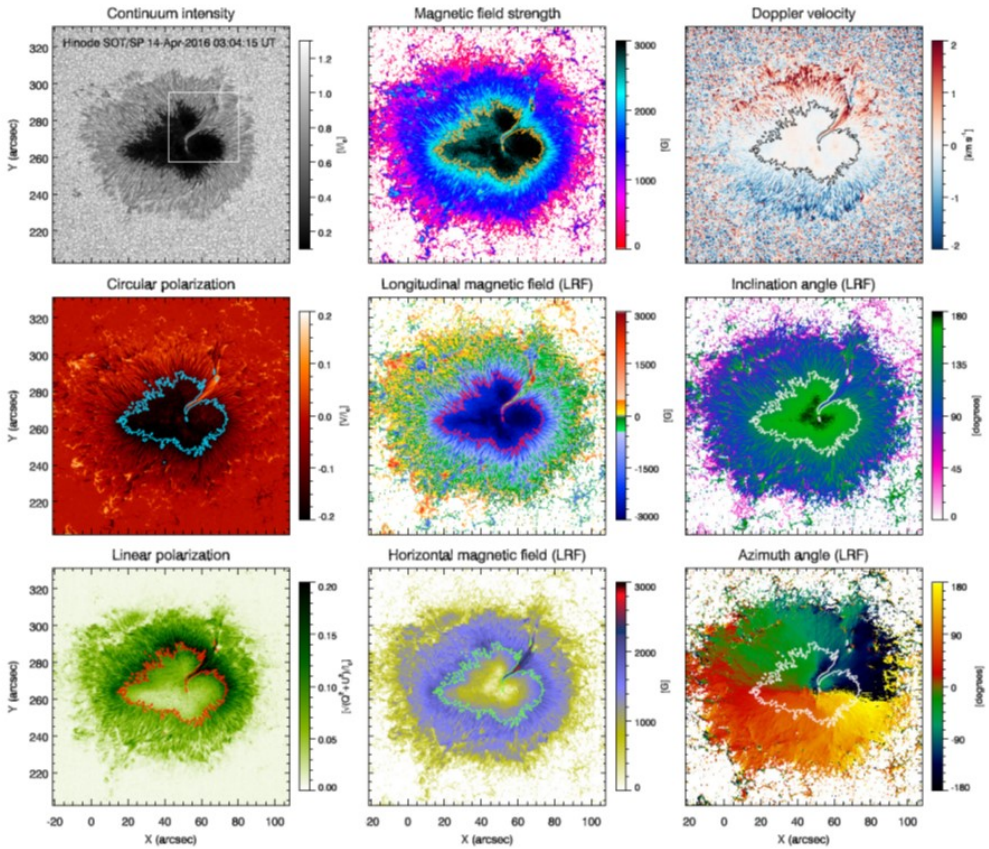
sir_eph.trol

```
Number of cycles          (*):3              !(0=synthesis)
Observed profiles         (*):perfil.per     !target.mod
Stray light file             :sot_quiet.per  !(none=no stray light contam)
PSF file                     :SP_ins_prof.psf!(none=no convolution with PSF)
Wavelength grid file      (s):malla.grid     ! (none=automatic selection)
Atomic parameters file       :LINES1         ! (none=DEFAULT LINES file)
Abundances file              :ASPLUND        ! (none=DEFAULT ABUNDANCES file)
Initial guess model 1     (*):guess.mod      ! target.mod
Initial guess model 2        :               !
Weight for Stokes I          :1              ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q          :5              ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U          :5              ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V          :10             ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?  :               ! (DEFAULT=0=no; 1=yes)
Nodes for temperature 1      :2,3,5
Nodes for electr. press. 1   :
Nodes for microturb. 1       :
Nodes for magnetic field 1   :1
Nodes for LOS velocity 1     :1
Nodes for gamma 1            :1
Nodes for phi 1              :1
Invert macroturbulence 1?    :              ! (0 or blank=no, 1=yes)
Nodes for temperature 2      :
Nodes for electr. press. 2   :
Nodes for microturb. 2       :
Nodes for magnetic field 2   :
Nodes for LOS velocity 2     :
Nodes for gamma 2            :
Nodes for phi 2              :
Invert macroturbulence 2?    :               ! (0 or blank=no, 1=yes)
Invert filling factor?       :               ! (0 or blank=no, 1=yes)
Invert stray light factor?   :               ! (0 or blank=no, 1=yes)
mu=cos (theta)               :               ! (DEFAULT: mu=1. mu<0 => West)
Estimated S/N for I          :1000           ! (DEFAULT: 1000)
Continuum contrast           :               ! (DEFAULT: not used)
Tolerance for SVD            :1.e-8          ! (DEFAULT value: 1e-4)
Initial diagonal element     :               ! (DEFAULT value: 1.e-3)
Splines/Linear Interpolation :               ! (0 or blank=splines, 1=linear)
Gas pressure at surface 1    :               ! (0 or blank=Pe boundary cond.
Gas pressure at surface 2    :               ! (0 or blank=Pe boundary cond.
Magnetic pressure term?      :               ! (0 or blank=no, 1=yes
NLTE Departures filename     :               ! blanck= LTE (Ej. depart_6494.dat'
```

Milne-Eddington-like inversion: examples

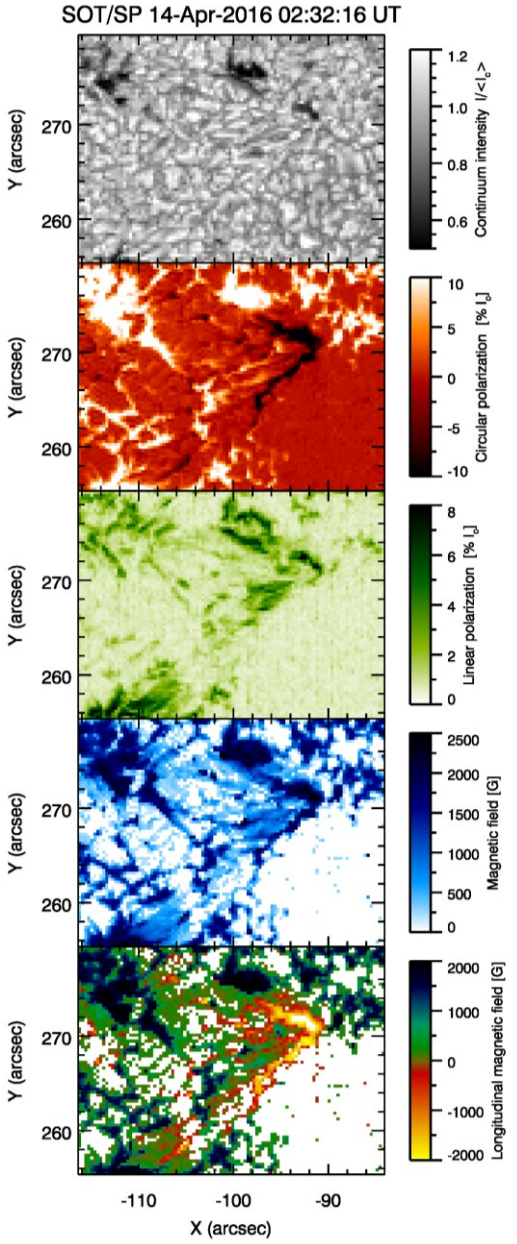


Milne-Eddington-like inversion: contexts



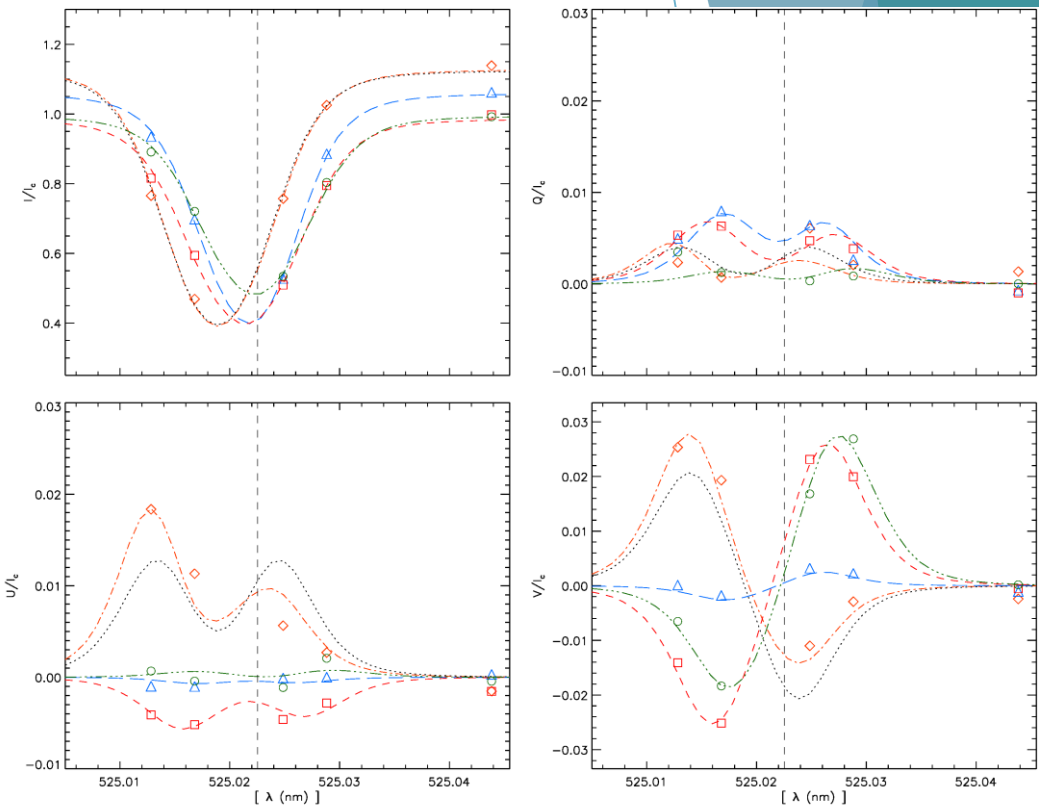
SUNSPOT

EMERGING FLUX REGION

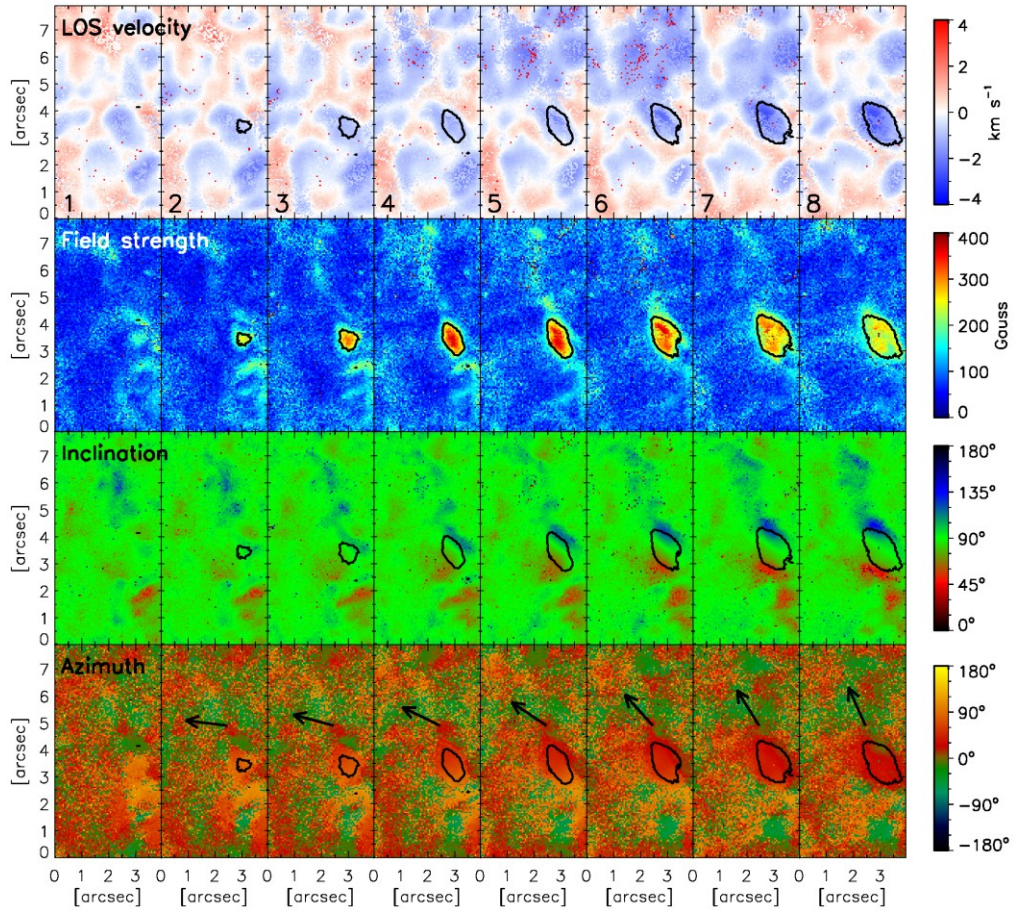


Using linear gradients

- Observed (symbols) **I, Q, U, V** profiles, for a sample of IMaX spectra, with the corresponding fits (lines) obtained with the **SIR code**
  - **blue** (triangles/long dashed): horizontal fields, no gradients
  - **red** (squares/dashed): vertical fields, no gradients
  - **green** (circle/dot-dot-dot dashed): asymmetry in Stokes V with weak L_s signal, with gradients
  - **orange** (diamonds/dot dashed): asymmetry in the blue and red lobes of Stokes U and V, with gradients
- The dotted line represents the fit **without gradients** to the plotted **orange** spectrum
  (for Stokes I the dotted line falls on top of the orange one)
- The dashed vertical line indicates the nominal line center λ

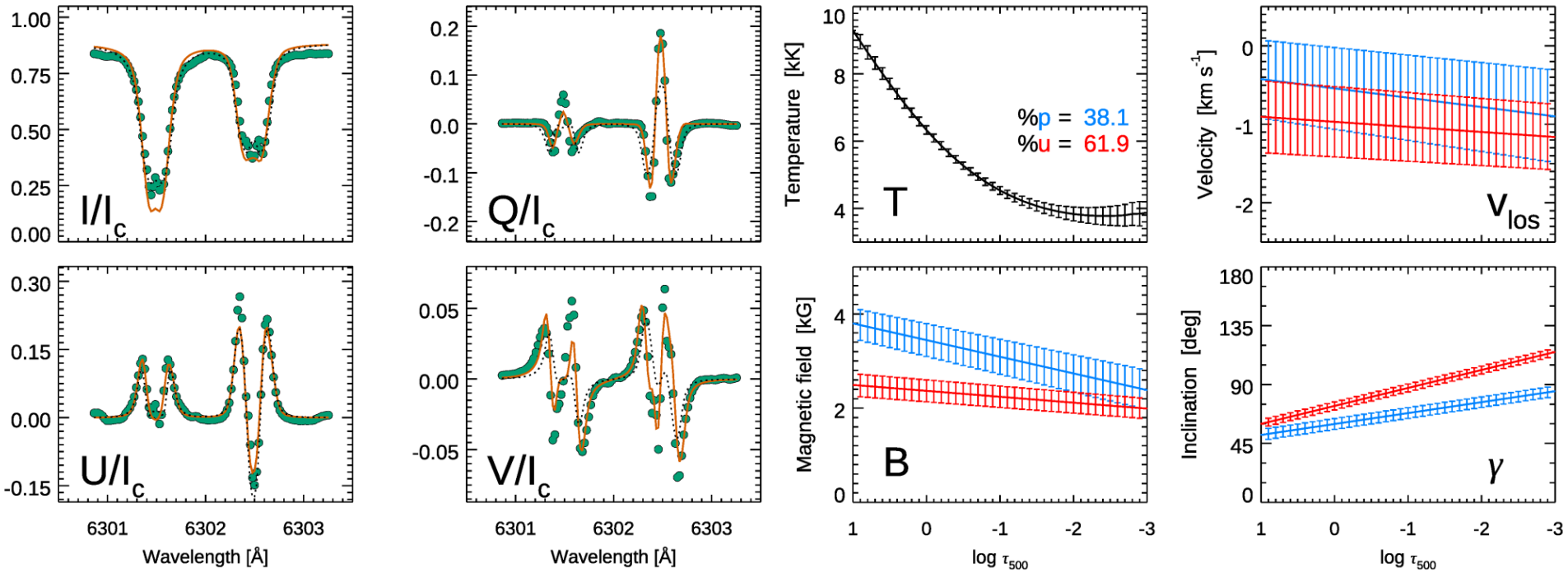


Using linear gradients

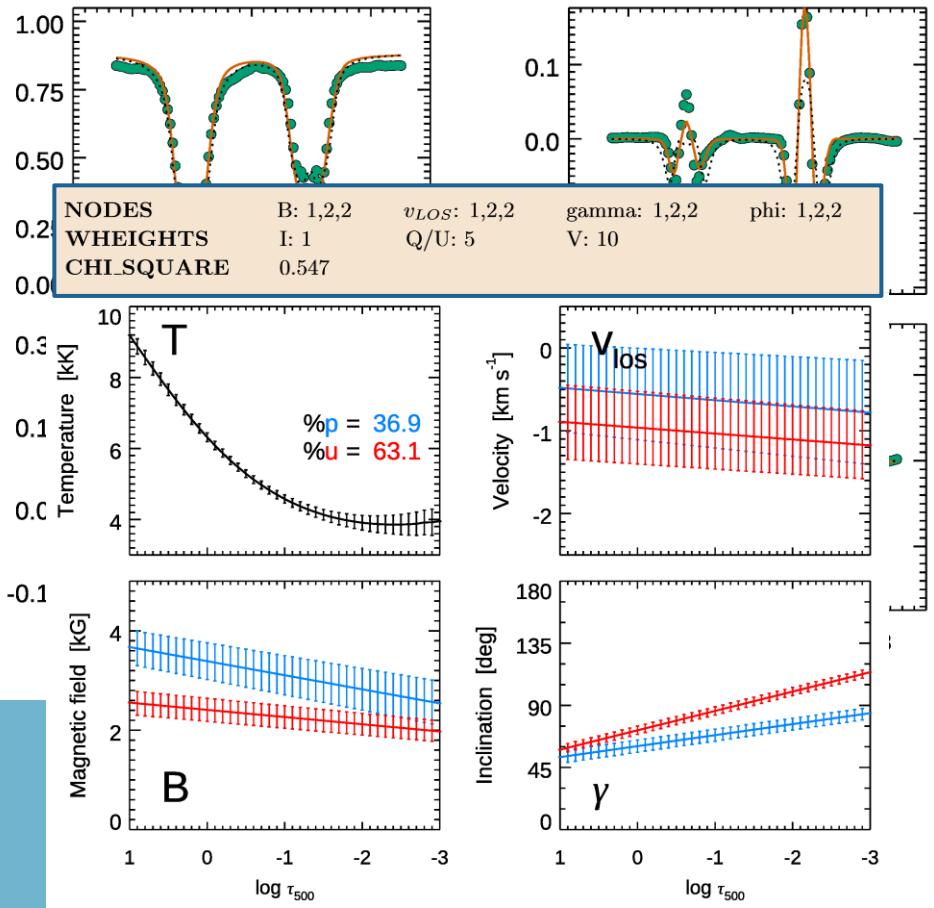


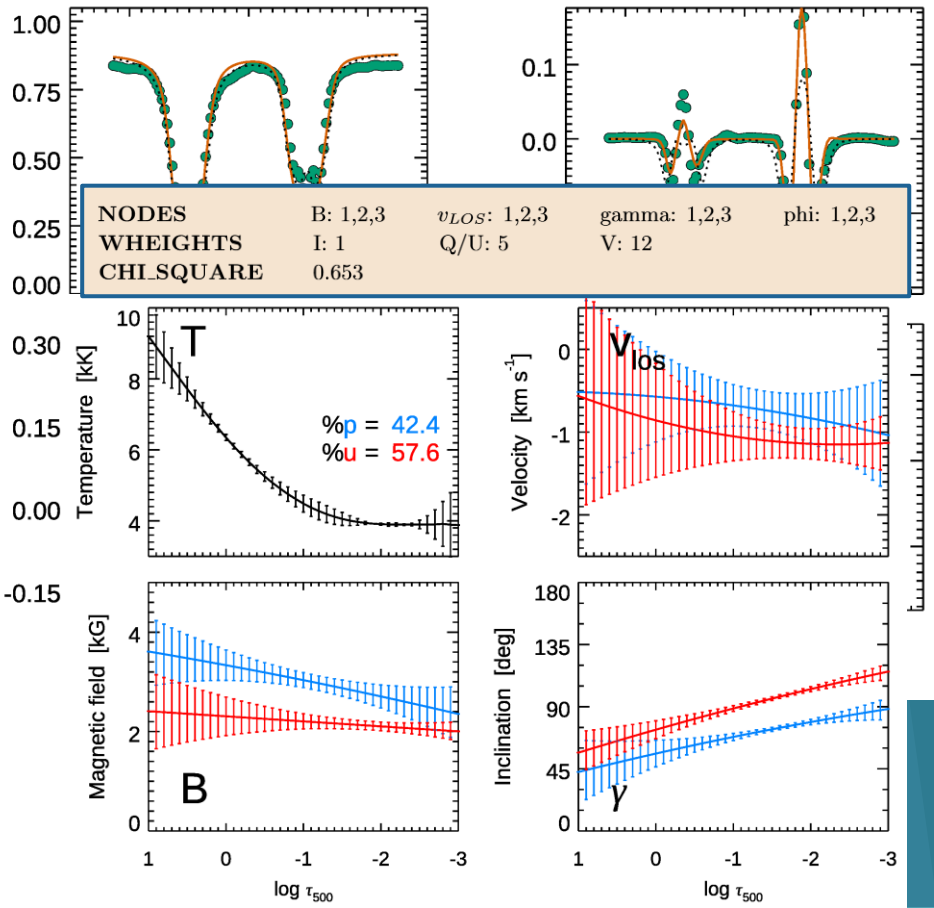
EVALUATION AT LOG τ = -2

Two-component inversions: gradients are enough

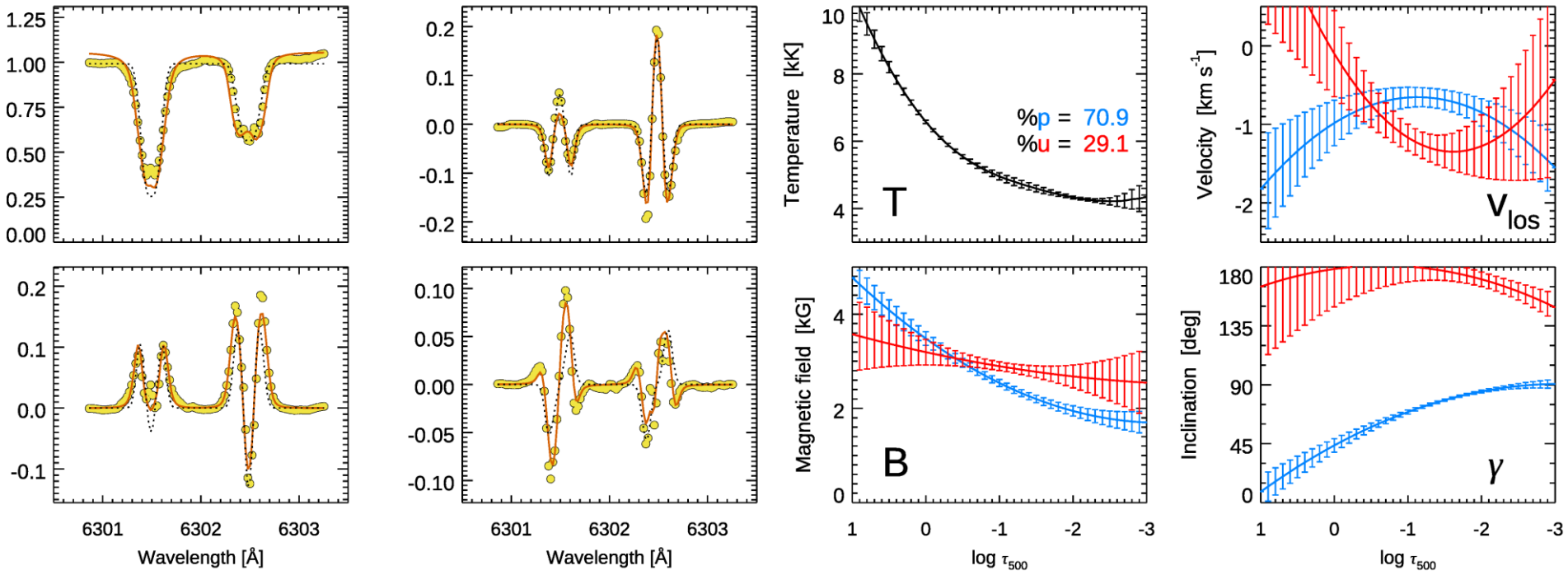


Two-component inversions: comparing results





Two-component inversions: a more complex situation



Conclusions

- Full RTE inversions are able to give significant physical information, although they are computationally costly
- Examine the fits: are they reasonably good with M-E?

- SIR is a flexible and powerful inversion code in LTE
- Be careful with the choice of atmospheric model!
  The interpretation is not straightforward…
  - always start with a M-E-like inversion
  - keep the number of free parameters (nodes) small
  - ask yourself if the retrieved model atmosphere makes sense
- Uniqueness problems
  - results may change if the physical model is changed