The art of Stokes inversions

Basilio Ruiz Cobo
Instituto de Astrofísica de Canarias, Spain

Boulder (CO) 15-26 May 2017

Outline

PART 1: Theory

1. The RTE: formal solution & approximations
2. The Response Functions (RF)
3. What is an inversion technique? How does it work?
4. The SIR code.
6. How to choose an inversion technique?
7. Running SIR
   - Input files
   - Visualization of observations, fits, and model atmospheres
   - Tips and tricks

PART 2: SIR exercises

Files

You can download the SIR code, and all the files to run it from:

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

And the slides and exercises from

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

1) The RTE

RTE: $$\frac{dI_\nu}{ds} = -\chi_\nu I_\nu + \eta_\nu$$

Absorption coefficient: $$\chi_\nu = \underbrace{(\chi_{ff} + \chi_{bf})}_{\chi_c} + \chi_{bb}\,\phi(\nu)$$

Emission: $$\eta_\nu$$

Optical depth: $d\tau_\nu = -\chi_\nu\, ds$ (number of mean free path at ν)

Continuum optical depth: $d\tau_c = -\chi_c\, ds$ (number of mean free path at continuum)

Suppose no emission : $$\frac{dI_\nu}{ds} = -\chi_\nu I_\nu \longrightarrow I_\nu = I_\nu(\tau_0)e^{-\int_{\tau_0}\chi_\nu ds} = I_\nu(\tau_0)e^{-\Delta s/\bar{l}}$$

1) The RTE

RTE:

$$\frac{dI_\nu}{ds} = -\chi_\nu I_\nu + \eta_\nu$$

Continuum optical depth: $d\tau_c = -\chi_c\, ds$

$$\frac{dI_\nu}{d\tau_c} = \frac{\chi_\nu}{\chi_c} I_\nu - \frac{\eta_\nu}{\chi_c}$$

1) The RTE

RTE: $$\frac{dI_\nu}{ds} = -\chi_\nu I_\nu + \eta_\nu$$

Continuum optical depth: $d\tau_c = -\chi_c\, ds$

$$\frac{dI_\nu}{d\tau_c} = \frac{\chi_\nu}{\chi_c} I_\nu - \frac{\eta_\nu}{\chi_c} = \frac{\chi_\nu}{\chi_c}\left(I_\nu - \frac{\eta_\nu}{\chi_\nu}\right)$$

1) The RTE

RTE:

$$\frac{dI_\nu}{ds} = -\chi_\nu I_\nu + \eta_\nu$$

Continuum optical depth: $d\tau_c = -\chi_c \, ds$

$$\frac{dI_\nu}{d\tau_c} = \frac{\chi_\nu}{\chi_c} I_\nu - \frac{\eta_\nu}{\chi_c} = \frac{\chi_\nu}{\chi_c}\left(I_\nu - \frac{\eta_\nu}{\chi_\nu}\right) = \kappa\left(I_\nu - S_\nu\right)$$

S_ν

per cm per gram

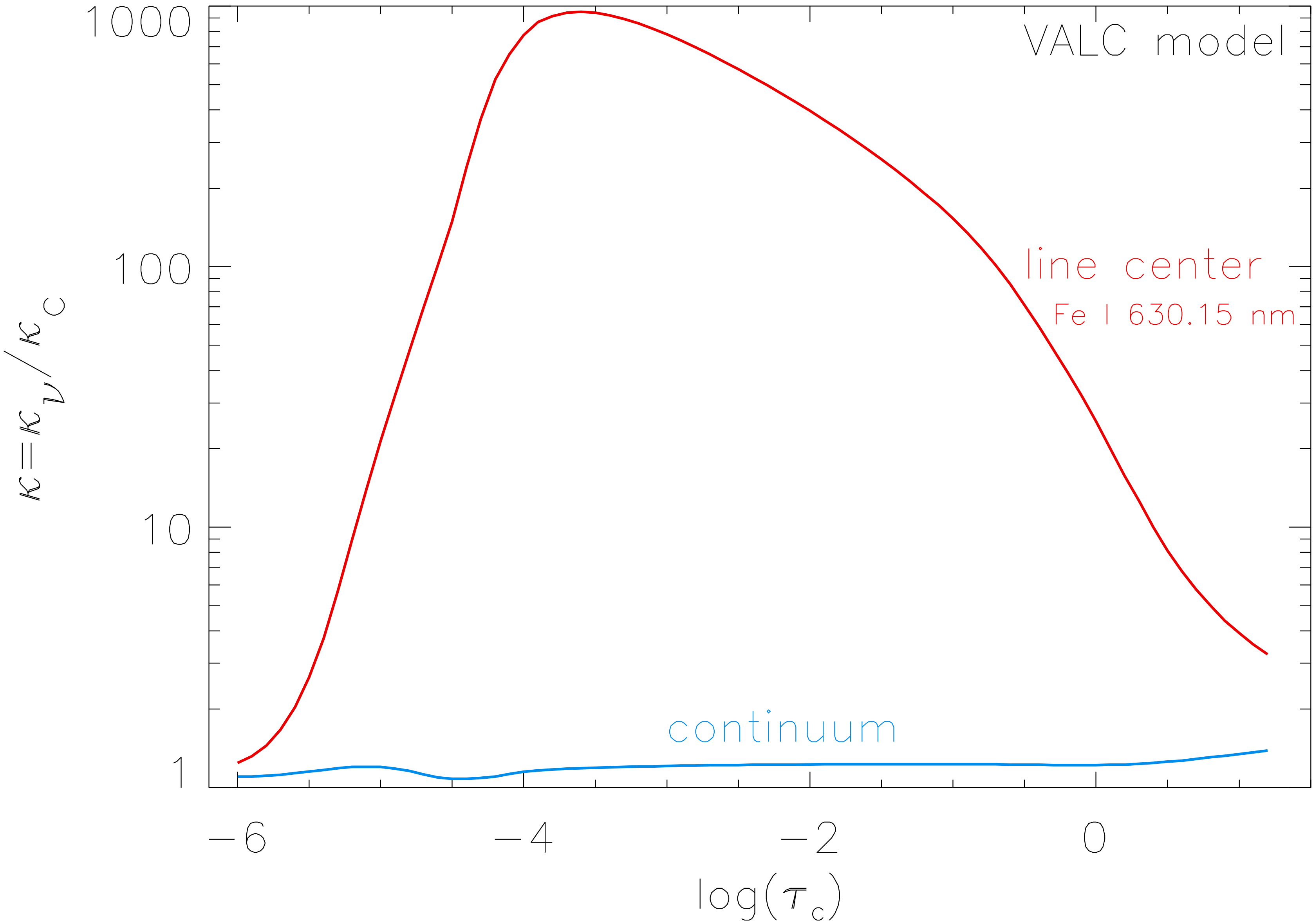
$$\chi_\nu = \kappa_\nu \rho$$

$$\chi_c = \kappa_c \rho$$

$$\frac{\chi_\nu}{\chi_c} = \frac{\kappa_\nu}{\kappa_c} = \kappa$$

1) The RTE

$$\frac{dI_\nu}{d\tau_c} = \kappa\left(I_\nu - S_\nu\right)$$



1) The RTE

$$\boxed{\frac{dI_\nu}{d\tau_c} = \kappa\left(I_\nu - S_\nu\right)}$$

Formal solution: integration factor O

$$\frac{d(OI_\nu)}{d\tau_c} = \frac{dO}{d\tau_c} I_\nu + O\frac{dI_\nu}{d\tau_c} = \frac{dO}{d\tau_c} I_\nu + O\kappa\left(I_\nu - S_\nu\right)$$

$$\frac{dO}{d\tau_c} \equiv -O\kappa$$

$$\frac{d(OI_\nu)}{d\tau_c} = -O\kappa S_\nu$$

$$I_\nu(\tau_1) = O^{-1}(\tau_1)O(\tau_0)I_\nu(\tau_0) - \int_{\tau_0}^{\tau_1} O^{-1}(\tau_1)O(\tau_c)\kappa S d\tau_c$$

1) The RTE

$$\boxed{\frac{dI_\nu}{d\tau_c} = \kappa\left(I_\nu - S_\nu\right)}$$

Formal solution: integration factor O

$$\frac{d(OI_\nu)}{d\tau_c} = \frac{dO}{d\tau_c} I_\nu + O\frac{dI_\nu}{d\tau_c} = \frac{dO}{d\tau_c} I_\nu + O\kappa\left(I_\nu - S_\nu\right)$$

$$\frac{dO}{d\tau_c} \equiv -O\kappa$$

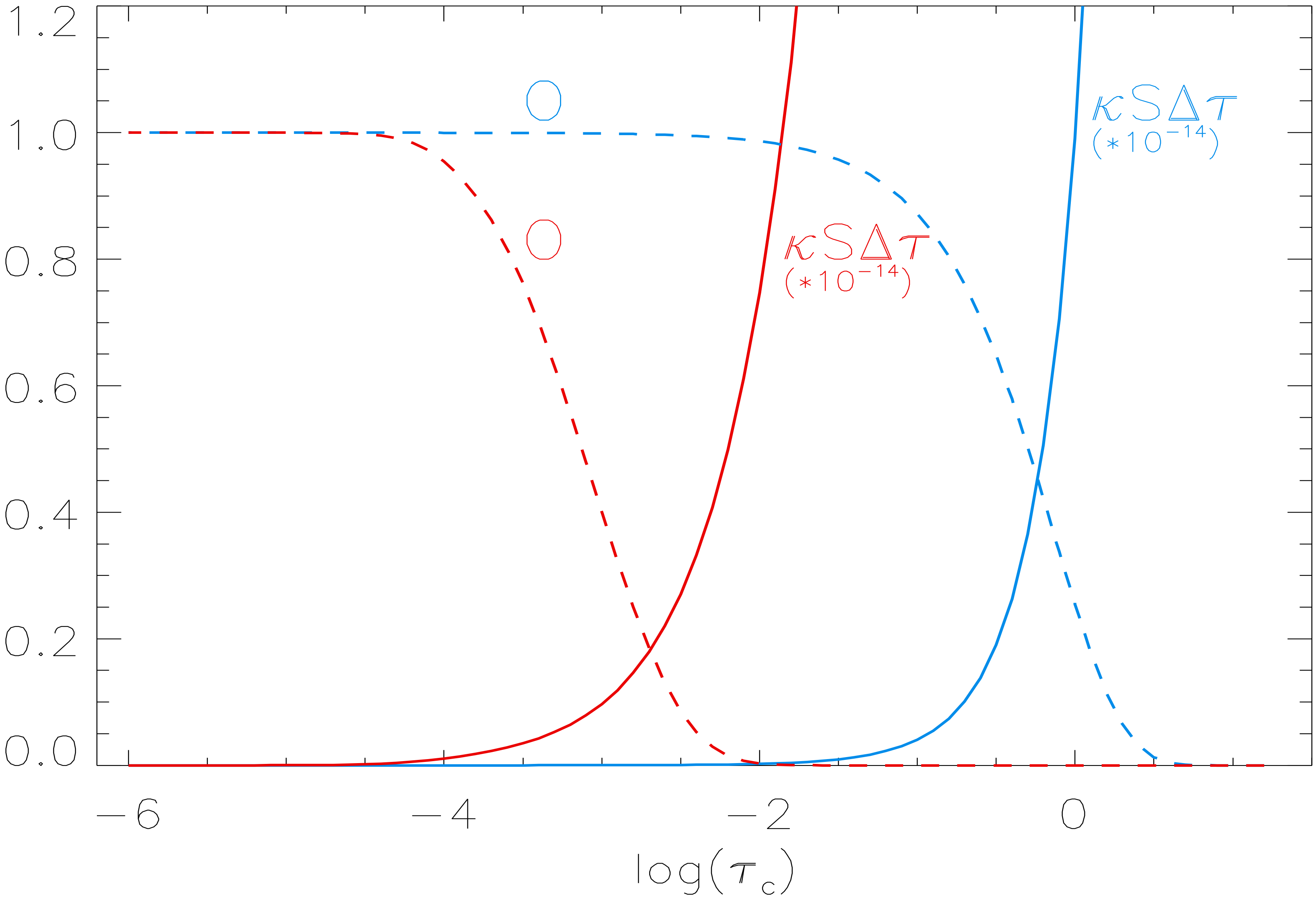
$$\boxed{O\left(\tau\right) = e^{-\int_0^\tau \kappa d\tau}}$$

$$\frac{d(OI_\nu)}{d\tau_c} = -O\kappa S_\nu$$

$$\boxed{I_\nu = O(\tau_0) I_\nu(\tau_0) + \int_0^{\tau_0} O(\tau_c)\kappa S_\nu d\tau_c}$$

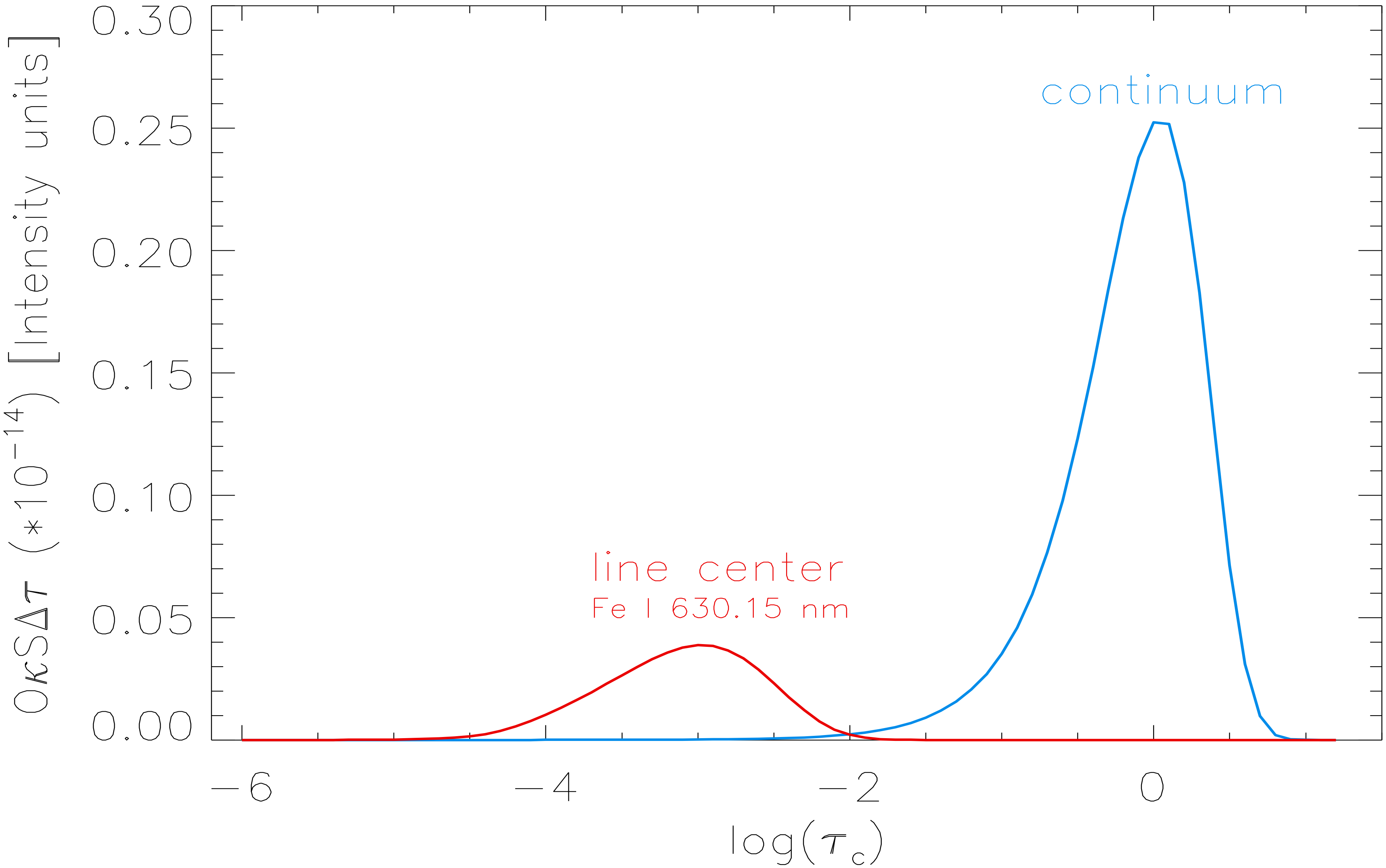
1) The RTE

$$I_\nu = O(\tau_0) I_\nu(\tau_0) + \int_0^{\tau_0} O(\tau_c) \kappa S d\tau_c$$



1) The RTE

$$I_\nu = O(\tau_0) I_\nu(\tau_0) + \int_0^{\tau_0} O(\tau_c)\kappa S d\tau_c$$



1) The RTE

$$I_\nu = O(\tau_0) I_\nu(\tau_0) + \int_0^{\tau_0} O(\tau_c) \kappa S d\tau_c$$

$\kappa(\tau), S_\nu(\tau)$ depend on the atomic populations n=n[T, P, $I_\nu(\tau)$)] $\longrightarrow$ SE equations

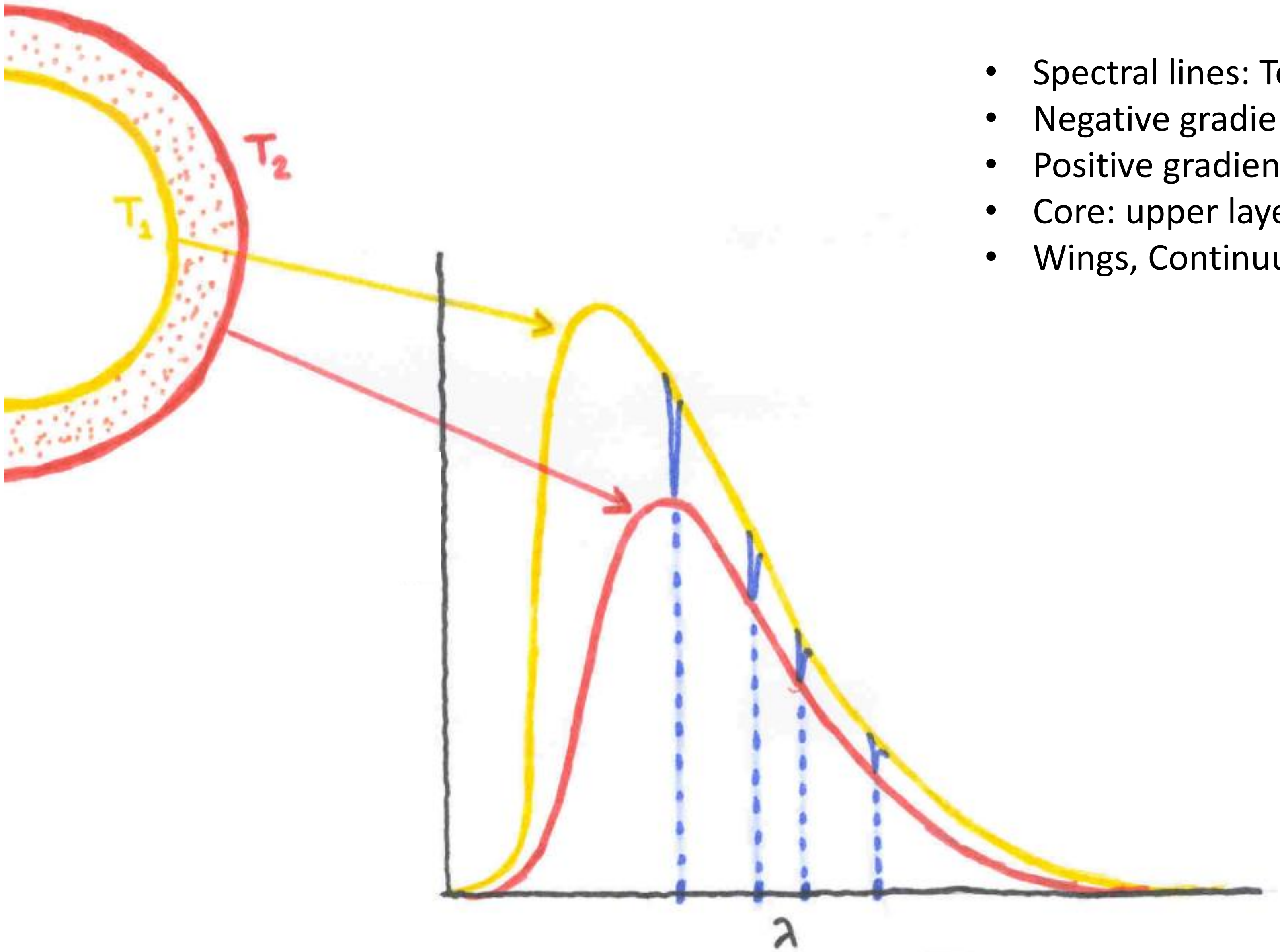
Some possible approximations:

- LTE: n=n[T, P] $\longrightarrow$ $\kappa[T(\tau), P(\tau)]$ & $S_\nu = B_\nu[T(\tau)]$
- Milne- Eddington (ME) approximation: $\kappa(\tau)$ =cte, $S_\nu(\tau) = S_0 + S_1\tau$

$$I_\nu(\tau_\nu = 0) = S_\nu(\tau_\nu = 1)$$

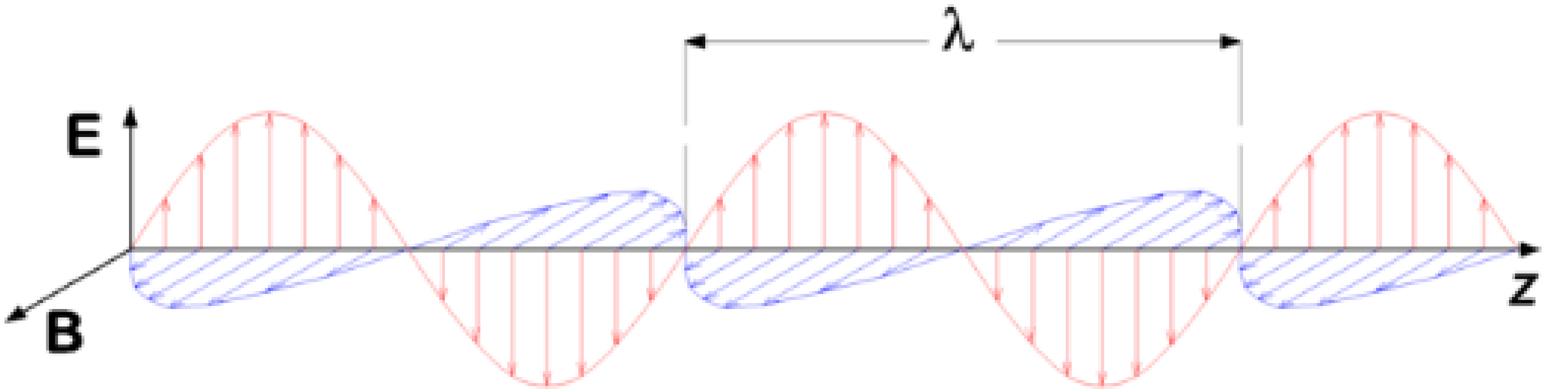
1) The RTE

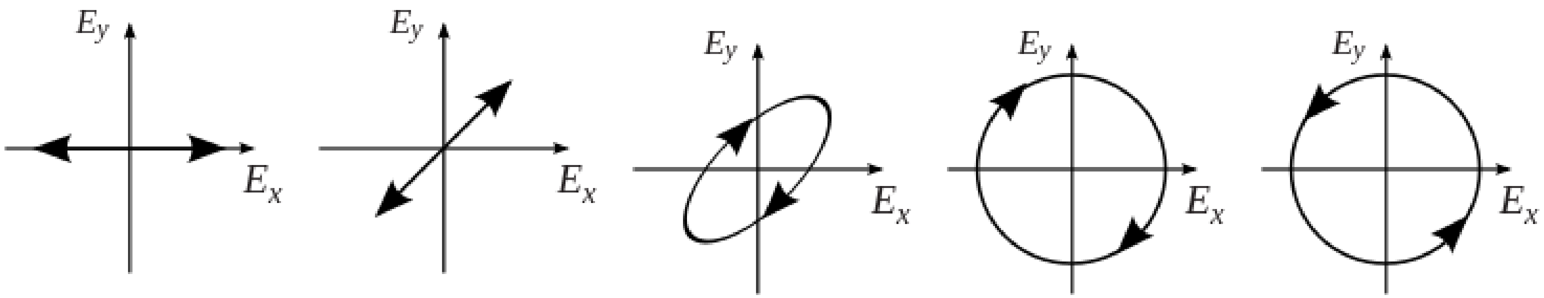
$$I_\nu(\tau_\nu = 0) = S_\nu(\tau_\nu = 1) \cong B_\nu[T(\tau_\nu = 1)]$$



- Spectral lines: Temperature gradient
- Negative gradient: absorption lines
- Positive gradient: emission lines
- Core: upper layers
- Wings, Continuum: deeper layers

1) The RTE





$$I = \updownarrow + \leftrightarrow$$

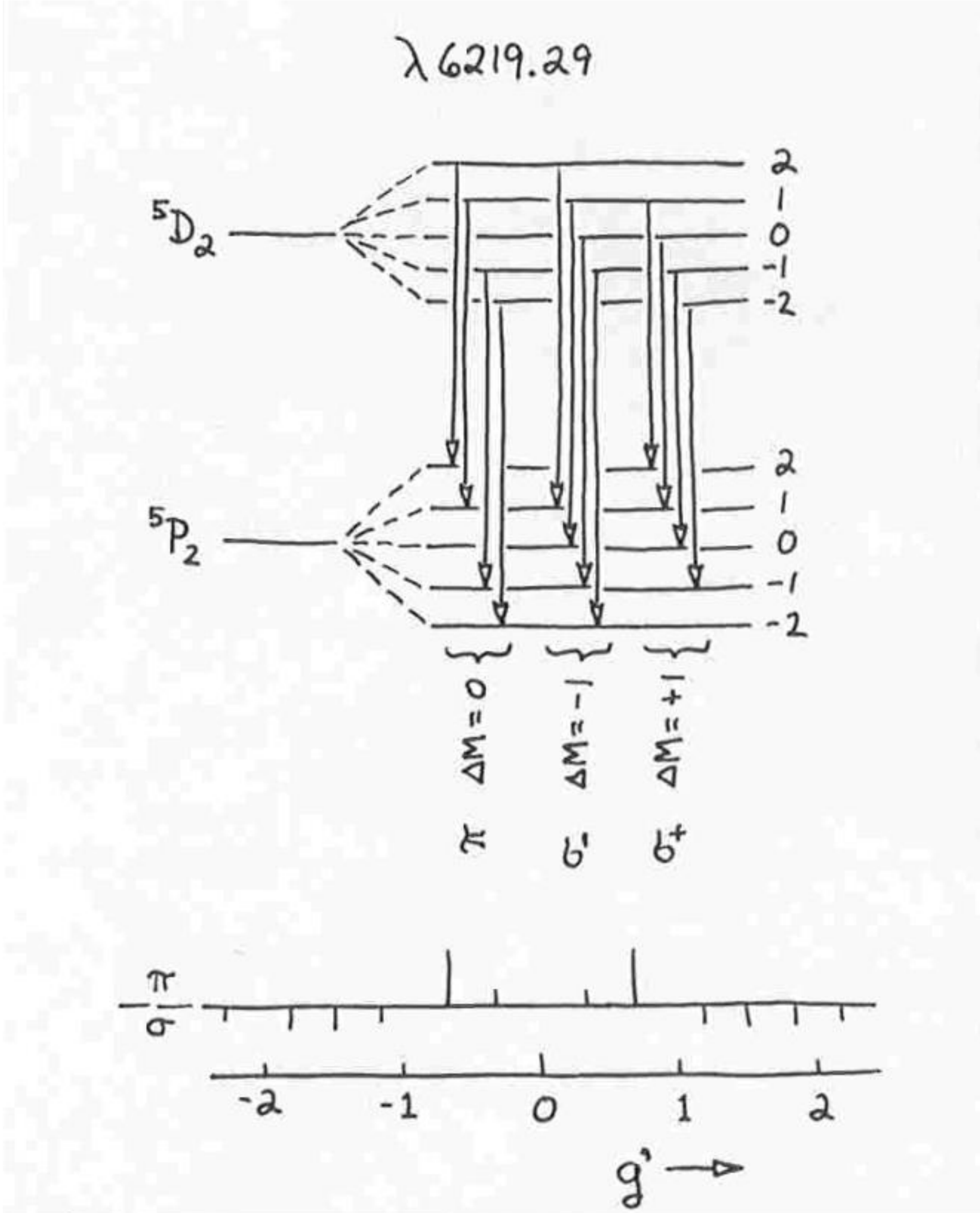
$$Q = \updownarrow - \leftrightarrow$$

$$U = \swarrow\!\!\!\nearrow - \nwarrow\!\!\!\searrow$$

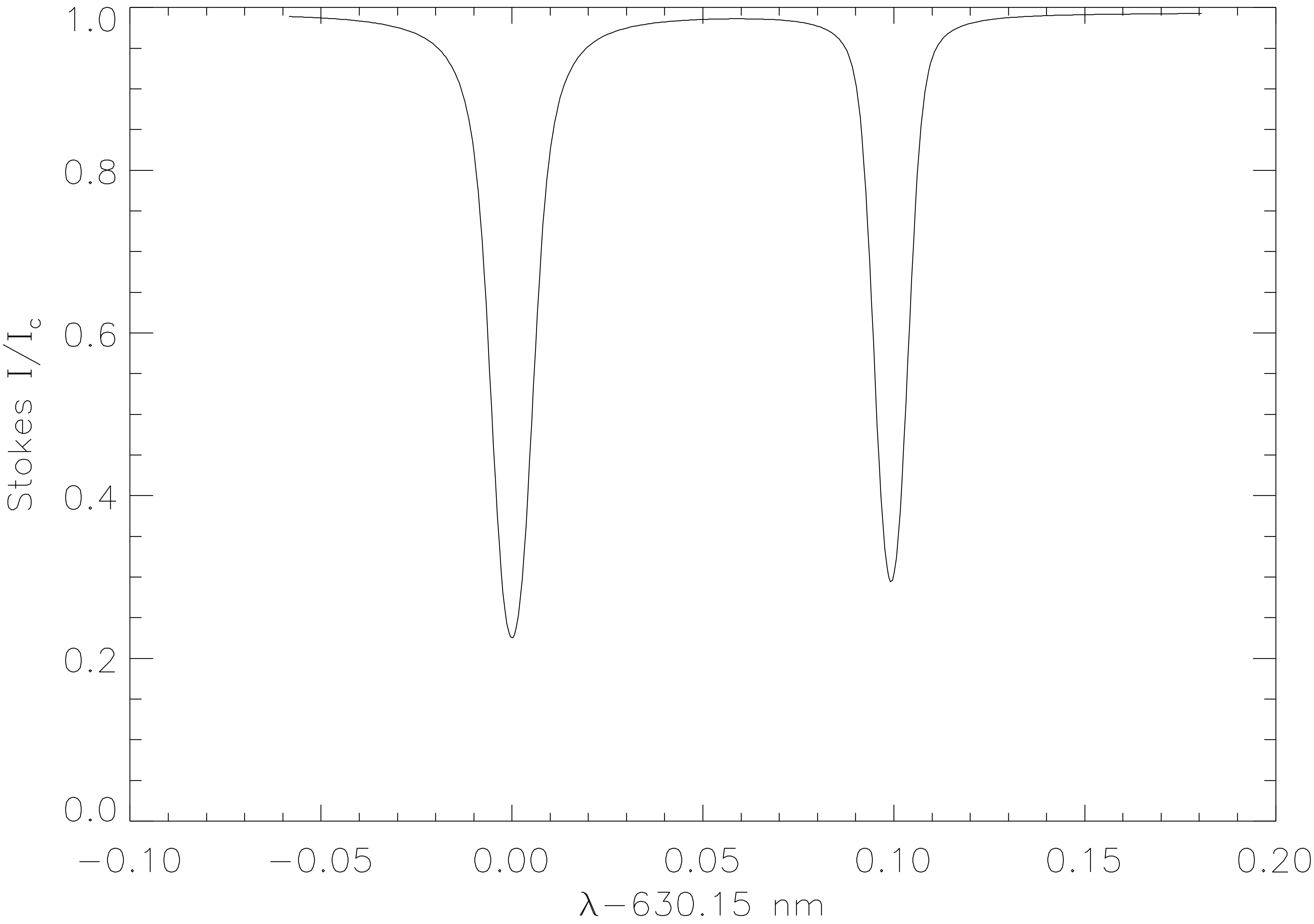
$$V = \circlearrowleft - \circlearrowright$$

1) The RTE

Pieter Zeeman (1865-1943)

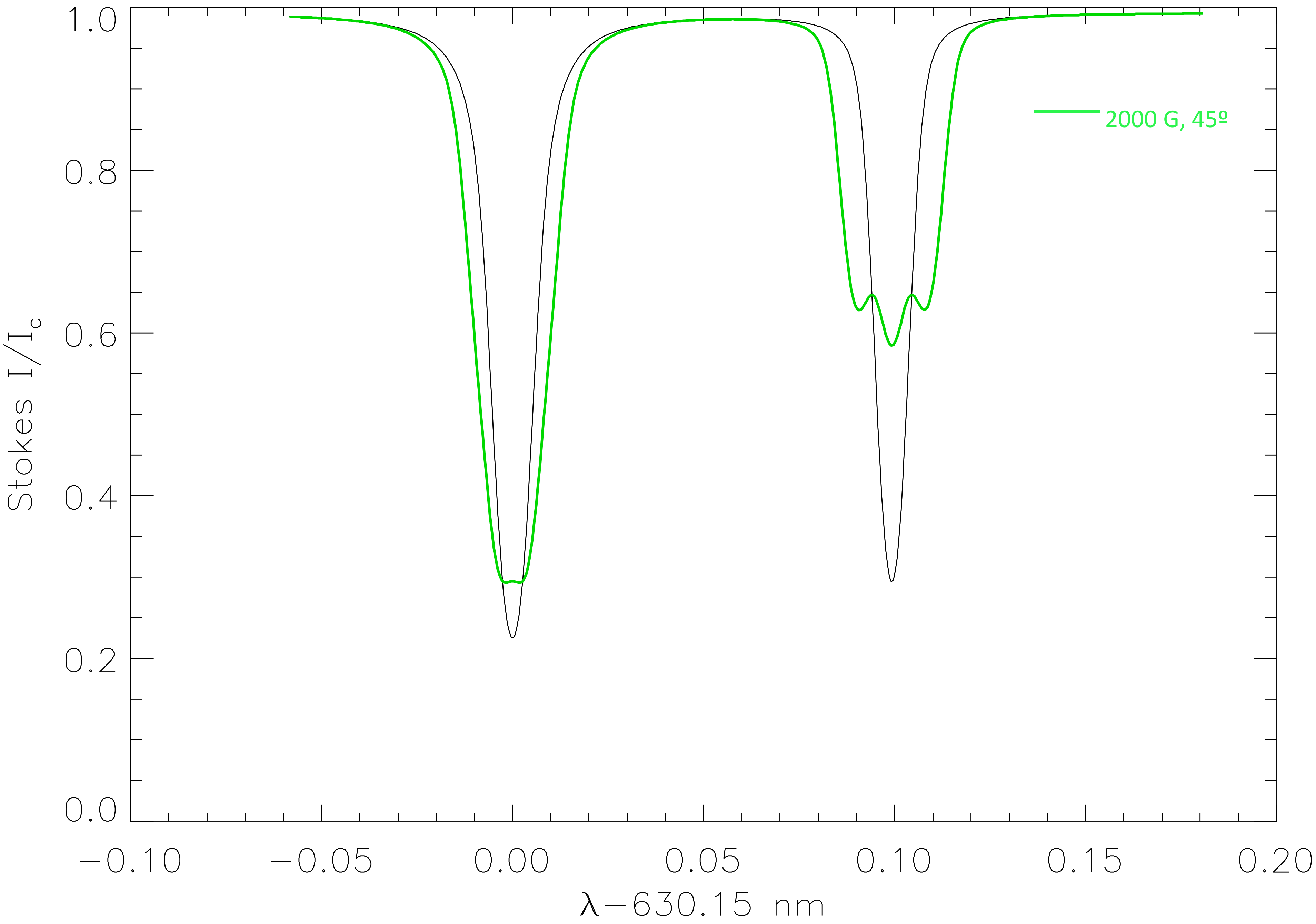


1) The RTE



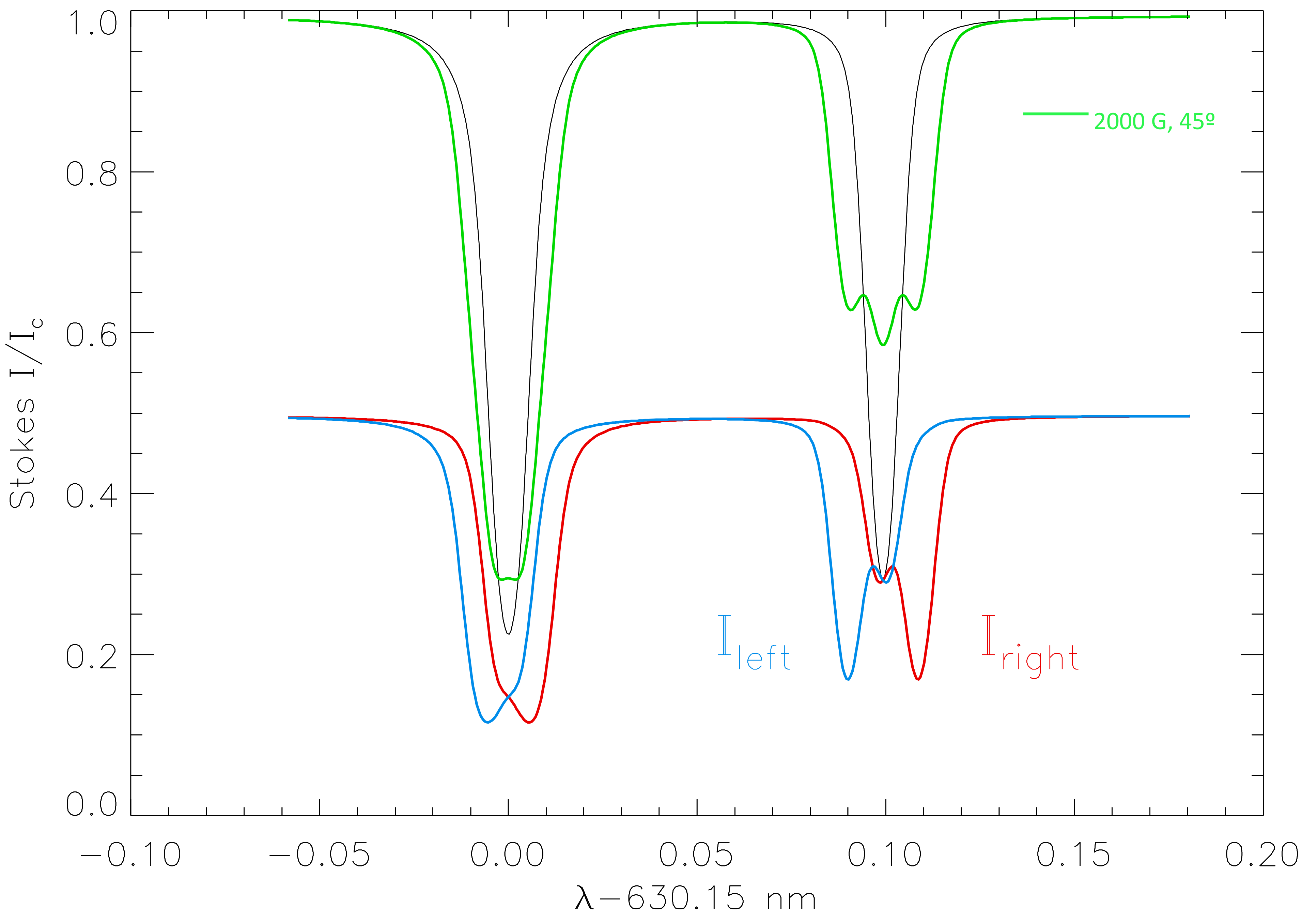
Stokes I/I_c
1.0
0.8
0.6
0.4
0.2
0.0
−0.10
−0.05
0.00
0.05
0.10
0.15
0.20
$\lambda-630.15$ nm

1) The RTE



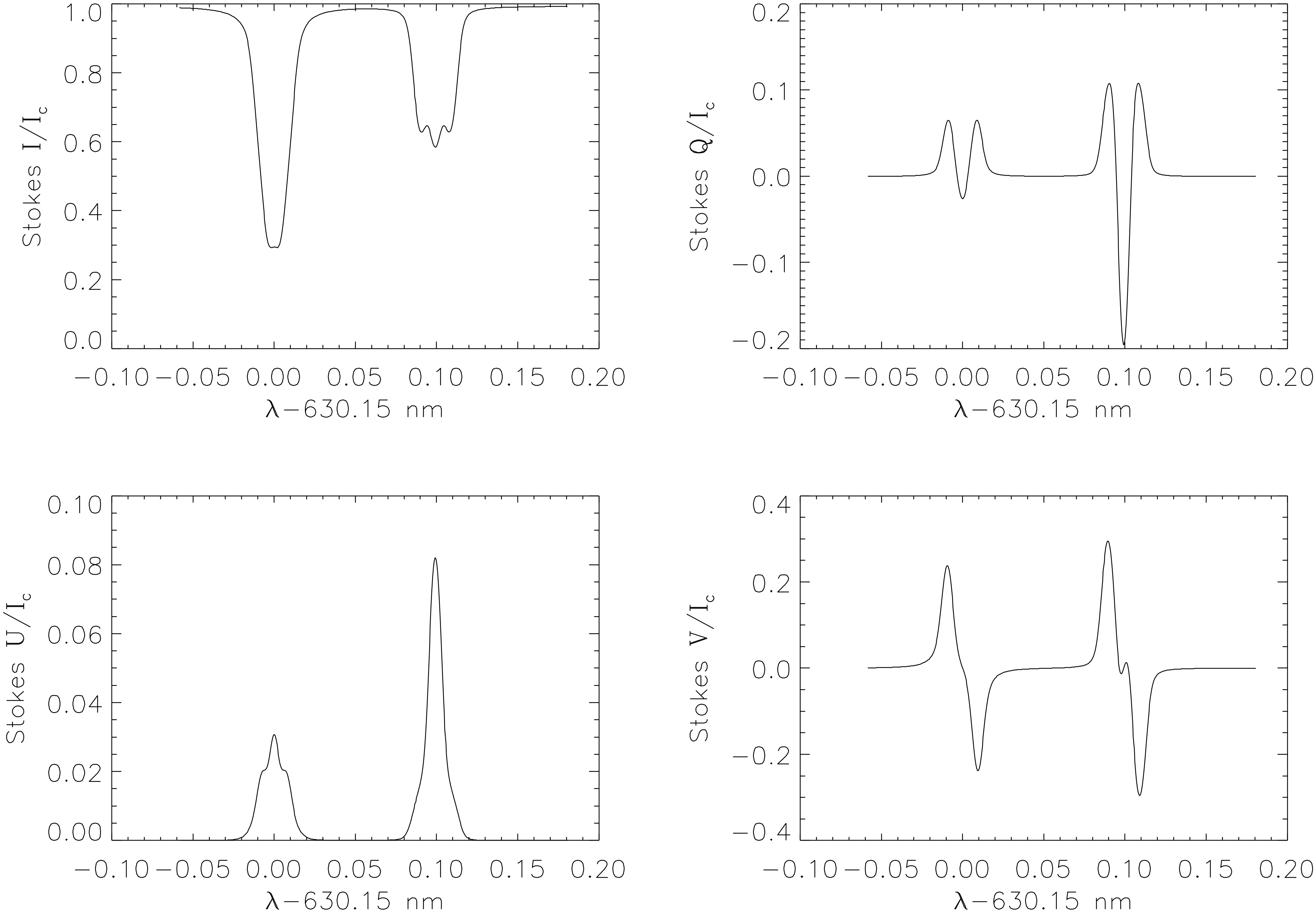
1.0
0.8
0.6
0.4
0.2
0.0
Stokes I/I$_c$
−0.10
−0.05
0.00
0.05
0.10
0.15
0.20
λ−630.15 nm
2000 G, 45º

1) The RTE



1.0
0.8
0.6
0.4
0.2
0.0
Stokes I/I_c
−0.10
−0.05
0.00
0.05
0.10
0.15
0.20
λ−630.15 nm
2000 G, 45º
I_left
I_right

1) The RTE


Stokes I/I_c
1.0
0.8
0.6
0.4
0.2
0.0
Stokes Q/I_c
0.2
0.1
0.0
−0.1
−0.2
Stokes U/I_c
0.10
0.08
0.06
0.04
0.02
0.00
Stokes V/I_c
0.4
0.2
0.0
−0.2
−0.4
−0.10 −0.05 0.00 0.05 0.10 0.15 0.20
λ−630.15 nm

1) The RTE

$$\frac{dI_\nu}{d\tau_c} = \kappa\left(I_\nu - S_\nu\right)$$

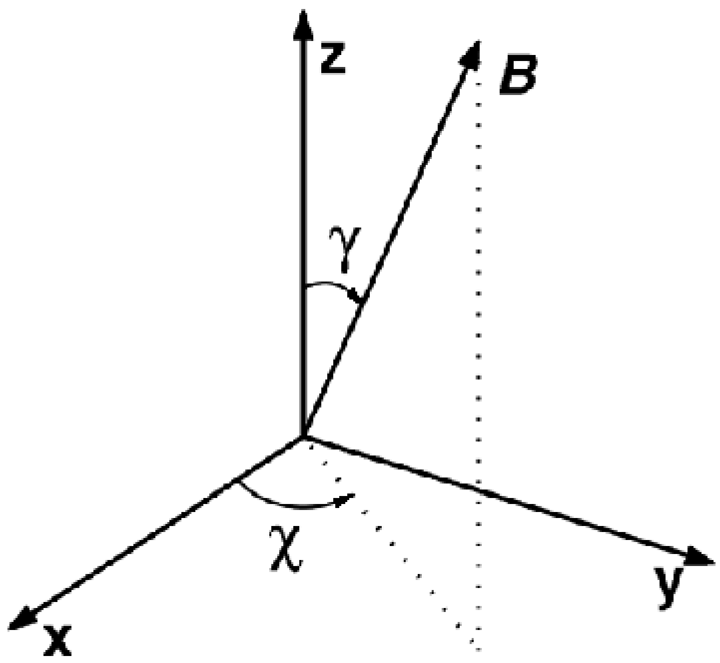
$$I_\nu \rightarrow \vec{I}_\nu = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}$$

$$S_\nu \rightarrow \vec{S}_\nu = \begin{bmatrix} S_I \\ S_Q \\ S_U \\ S_V \end{bmatrix} \overset{LTE}{=} \begin{bmatrix} B_\nu \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\kappa \rightarrow \overline{\overline{K}} = \begin{bmatrix} \eta_I & \eta_Q & \eta_U & \eta_V \\ \eta_Q & \eta_I & \rho_V & -\rho_U \\ \eta_U & -\rho_V & \eta_I & \rho_Q \\ \eta_V & \rho_U & -\rho_Q & \eta_I \end{bmatrix}$$

Landi Degl'Innocenti & Landi Degl'Innocenti (1981)

1) The RTE



$$\eta_I = k_c + \frac{1}{2} k_\ell \left[\eta_p \sin^2 \gamma + \frac{\eta_b + \eta_r}{2} (1 + \cos^2 \gamma) \right],$$

$$\eta_Q = \frac{1}{2} k_\ell \left(\eta_p - \frac{\eta_b + \eta_r}{2} \right) \sin^2 \gamma \cos 2\chi \,,$$

$$\eta_U = \frac{1}{2} k_\ell \left(\eta_p - \frac{\eta_b + \eta_r}{2} \right) \sin^2 \gamma \sin 2\chi \,,$$

$$\eta_V = \frac{1}{2} k_\ell (\eta_r - \eta_b) \cos \gamma \,,$$

$$\rho_Q = \frac{1}{2} k_\ell \left(\rho_p - \frac{\rho_b + \rho_r}{2} \right) \sin^2 \gamma \cos 2\chi \,,$$

$$\rho_U = \frac{1}{2} k_\ell \left(\rho_p - \frac{\rho_b + \rho_r}{2} \right) \sin^2 \gamma \sin 2\chi \,,$$

$$\rho_V = \frac{1}{2} k_\ell (\rho_r - \rho_b) \cos \gamma \,.$$

$$\kappa \rightarrow \overline{\overline{K}} = \begin{bmatrix} \eta_I & \eta_Q & \eta_U & \eta_V \\ \eta_Q & \eta_I & \rho_V & -\rho_U \\ \eta_U & -\rho_V & \eta_I & \rho_Q \\ \eta_V & \rho_U & -\rho_Q & \eta_I \end{bmatrix}$$

Landi Degl'Innocenti & Landi Degl'Innocenti (1981)

1) The RTE

$$\frac{d\vec{I}_\nu}{d\tau_c} = \overline{\overline{K}}\left(\vec{I}_\nu - \vec{S}_\nu\right)$$

$$\frac{dI_\nu}{d\tau_c} = \kappa\left(I_\nu - S_\nu\right)$$

$$\frac{d\overline{\overline{O}}}{d\tau_c} \equiv -\overline{\overline{O}}\,\overline{\overline{K}}$$

$$\frac{dO}{d\tau_c} \equiv -O\kappa$$

$$O(\tau) = e^{-\int_0^\tau \kappa d\tau}$$

$$\overline{\overline{O}}(\tau) = e^{-\int_0^\tau \overline{\overline{K}} d\tau}$$

$$I_\nu = O(\tau_0)I_\nu(\tau_0) + \int_0^{\tau_0} O(\tau_c)\kappa S_\nu d\tau_c$$

$$\vec{I}_\nu = \overline{\overline{O}}(\tau_0)\vec{I}_\nu(\tau_0) + \int_0^{\tau_0} \overline{\overline{O}}(\tau_c)\overline{\overline{K}}\vec{S}_\nu d\tau_c$$

2) Response Functions

$$\frac{d\vec{I}_\nu}{d\tau_c} = \overline{\overline{K}}\left(\vec{I}_\nu - \vec{S}_\nu\right)$$

$\overline{\overline{K}}$ & $\vec{S}_\nu$ depend on atmosphere $\vec{a} = (T(\tau), P(\tau), \vec{B}(\tau), v_{LoS}(\tau))$

Can we evaluate, in first order, how much change $\vec{I}_\nu$ when we perturb $x = a_i(\tau_j)$?

$$\frac{d(\vec{I}_\nu + \delta\vec{I}_\nu)}{d\tau_c} = \overline{\overline{(K + \delta K)}}\left[(\vec{I}_\nu + \delta\vec{I}_\nu) - (\vec{S}_\nu + \delta\vec{S}_\nu)\right]$$

$$\overline{\overline{\delta K}} \approx \frac{\partial \overline{\overline{K}}}{\partial x}\delta x \qquad \delta\vec{S} \approx \frac{\partial \vec{S}}{\partial x}\delta x$$

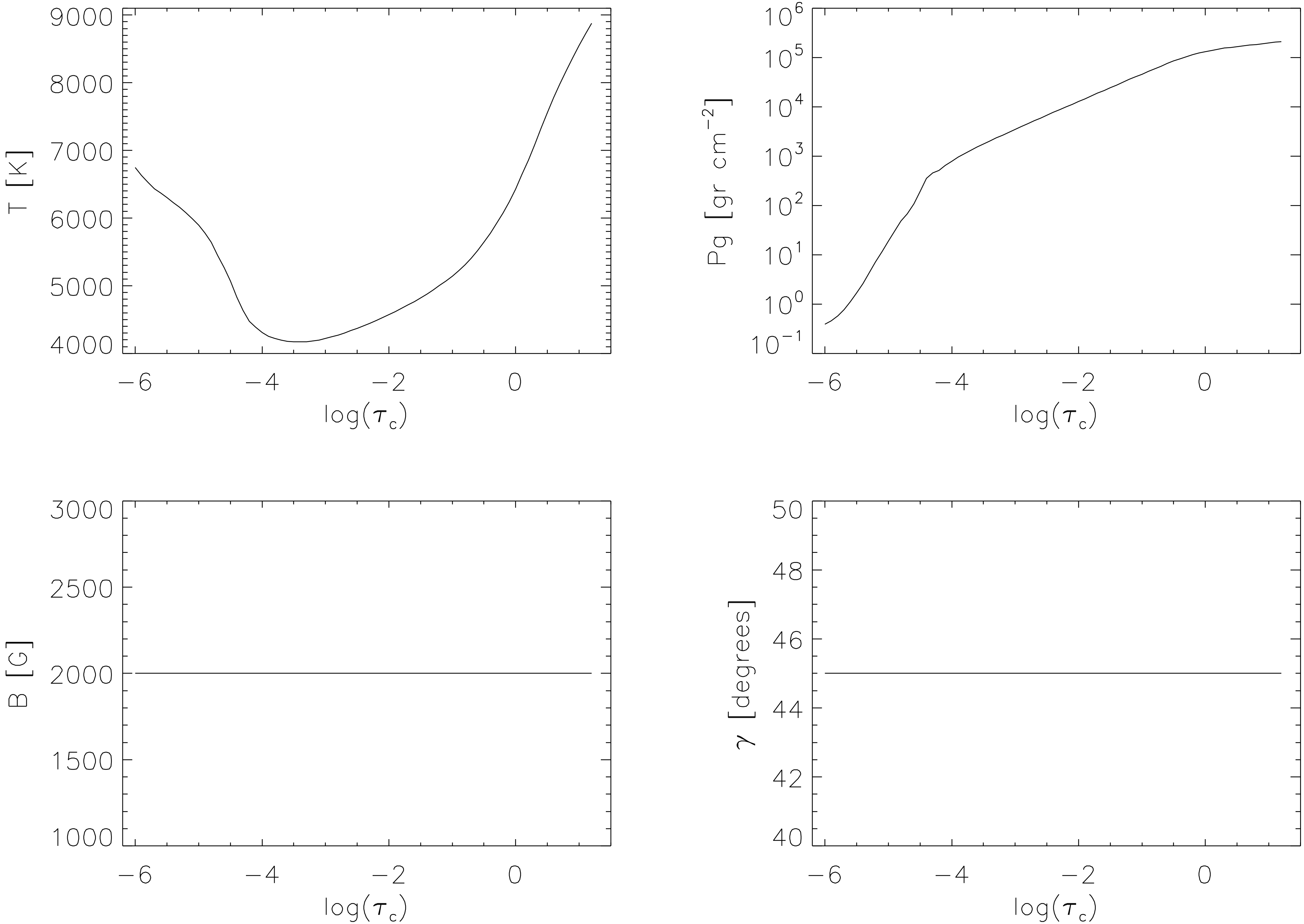
$$\frac{d(\delta\vec{I}_\nu)}{d\tau_c} = \overline{\overline{K}}\left[\delta\vec{I}_\nu - \vec{\tilde{S}}_\nu\right]$$

$$\vec{\tilde{S}}_\nu = \overline{\overline{K}}^{-1}\left[\overline{\overline{\delta K}}(\vec{I}_\nu - \vec{S}_\nu) - \delta\vec{S}_\nu\right]$$

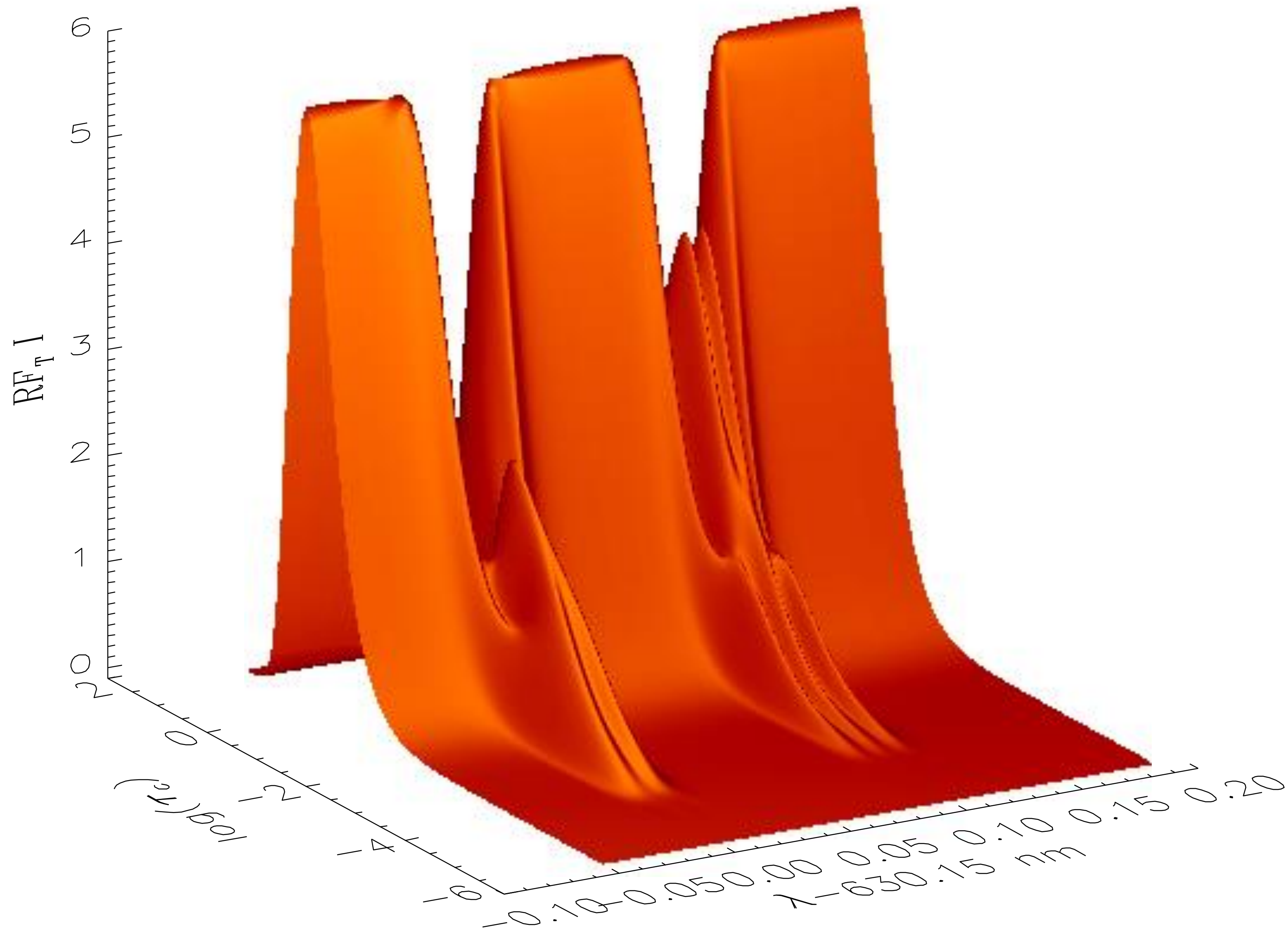
$$\delta\vec{I}_\nu = \int_0^{\tau_c} \overline{\overline{O}}(\tau_c)\overline{\overline{K}}\vec{\tilde{S}}\,d\tau_c \equiv \int_0^{\tau_c} R_x \delta x\, d\tau_c$$

$$\boxed{R_x = \overline{\overline{O}}\left[\frac{\partial \overline{\overline{K}}}{\partial x}(\vec{I}_\nu - \vec{S}_\nu) - \overline{\overline{K}}\frac{\partial \vec{S}_\nu}{\partial x}\right]}$$

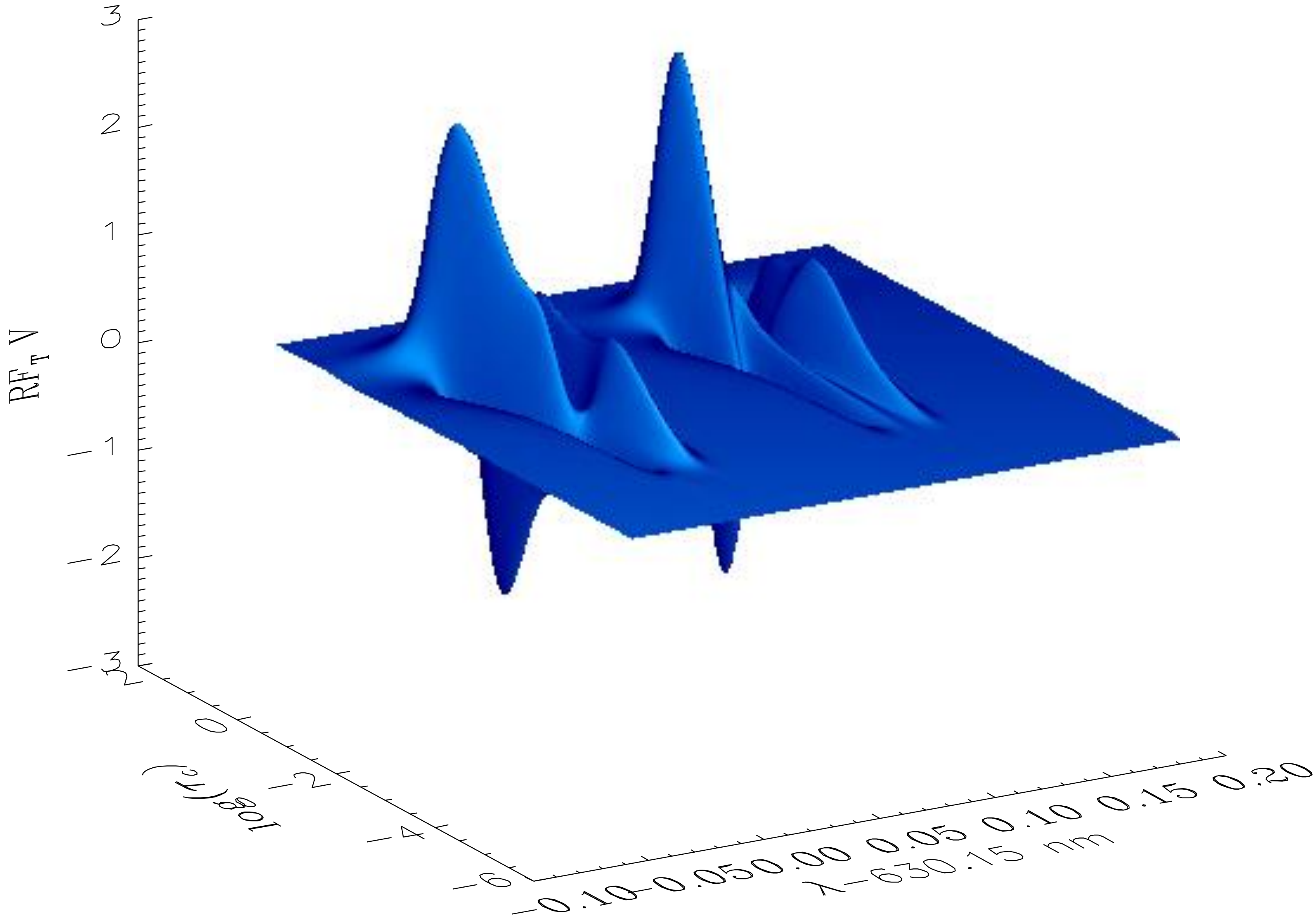
2) Response Functions



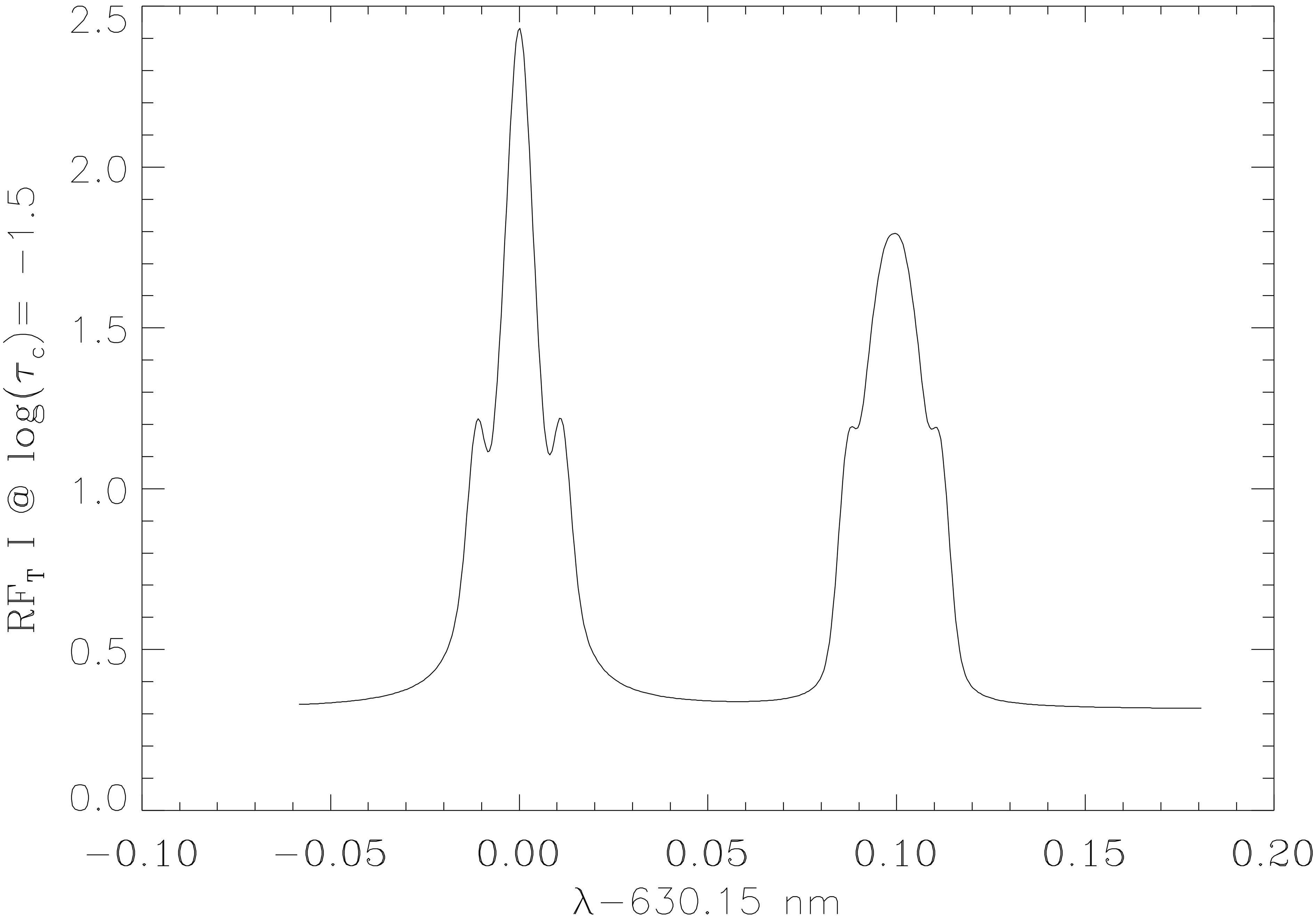
2) Response Functions



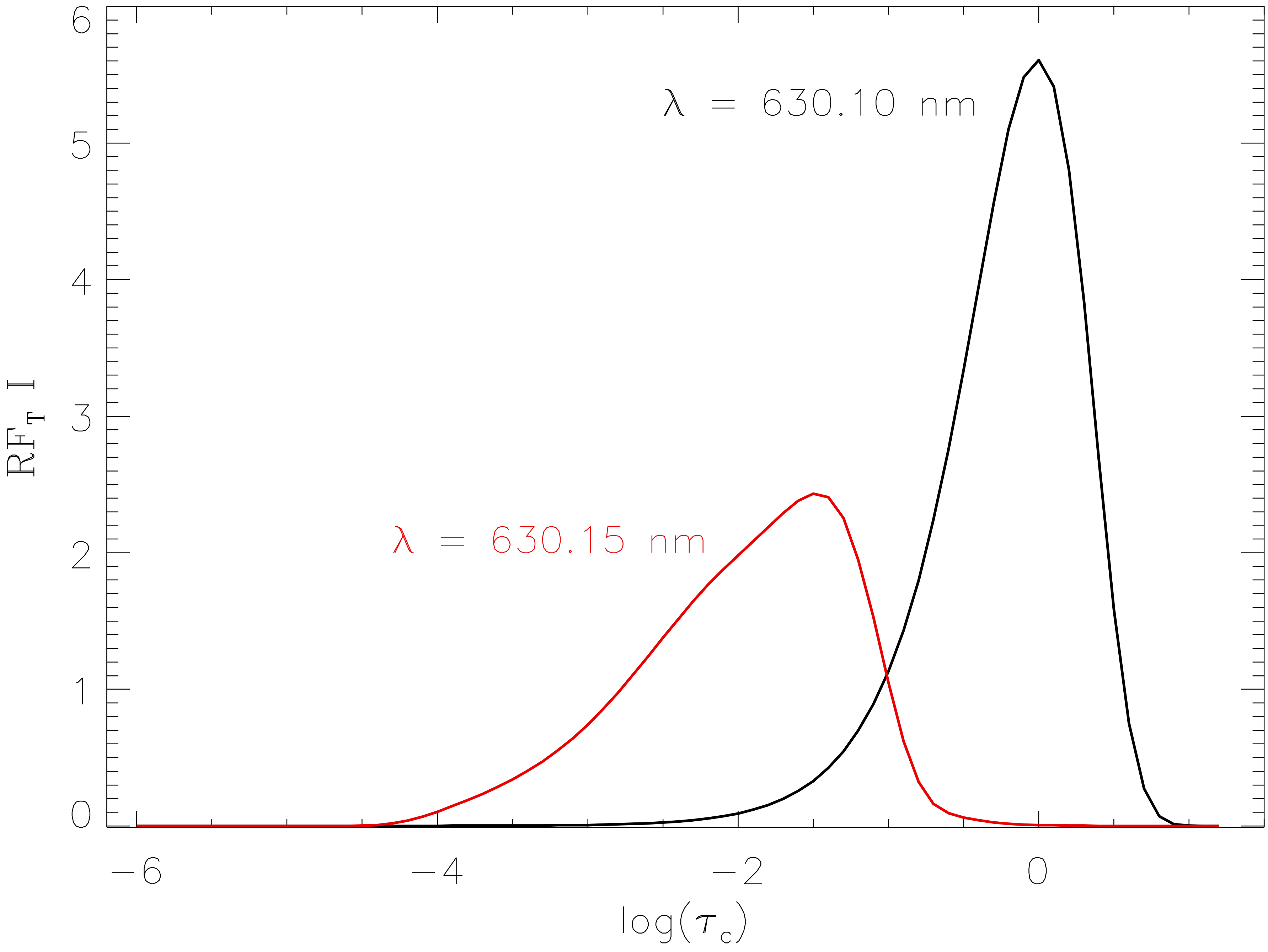
2) Response Functions



2) Response Functions



2) Response Functions



2) Response Functions

$$\left.\begin{array}{l}\text{Table of physical magnitudes} \\ \vec{a} = (T(\tau), P(\tau), \vec{B}(\tau), v_{LoS}(\tau)) \\ \text{+ atomic parameters} \\ \text{+ scenario} \\ \text{+ approximations} \\ \text{+ physical laws}\end{array}\right\} \xrightarrow[\text{(solving RTE)}]{\text{Synthesis}} \vec{I}_\nu \ \& \ \vec{R}_x$$

$$\delta I_{\lambda_i} = \int R_{\lambda_i, x} \, \delta x \, \mathrm{d}\,\tau$$

$$\begin{pmatrix} \delta I_{\lambda_1} \\ \vdots \\ \delta I_{\lambda_n} \end{pmatrix} = \begin{pmatrix} R_{\lambda_1, x_1} & \cdots & R_{\lambda_1, x_m} \\ \cdot & \cdots & \cdot \\ R_{\lambda_n, x_1} & \cdots & R_{\lambda_n, x_m} \end{pmatrix} \begin{pmatrix} \delta x_1 \\ \vdots \\ \delta x_m \end{pmatrix}$$

What is an inversion technique?

- Any method used to infer the physical conditions of the atmosphere from the interpretation of 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 temperature, gas velocity

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

What is an inversion technique?

-What's an IT?

Fredholm's inhomogeneous ec. first kind:

$$g(t) = \int_a^b K(t,s) f(s) ds$$

$g(t)$ data

$K(t,s)$ kernel

$f(s)$ unknown

This equation, through a quadrature, becomes:

$$K \cdot f = g$$

as g is no null if we could evaluate K^{-1}

the solution: $f = K^{-1} \cdot g$ but… this is not the general case

What is an inversion technique?

$$g(t) = \int_a^b K(t,s) f(s) ds$$

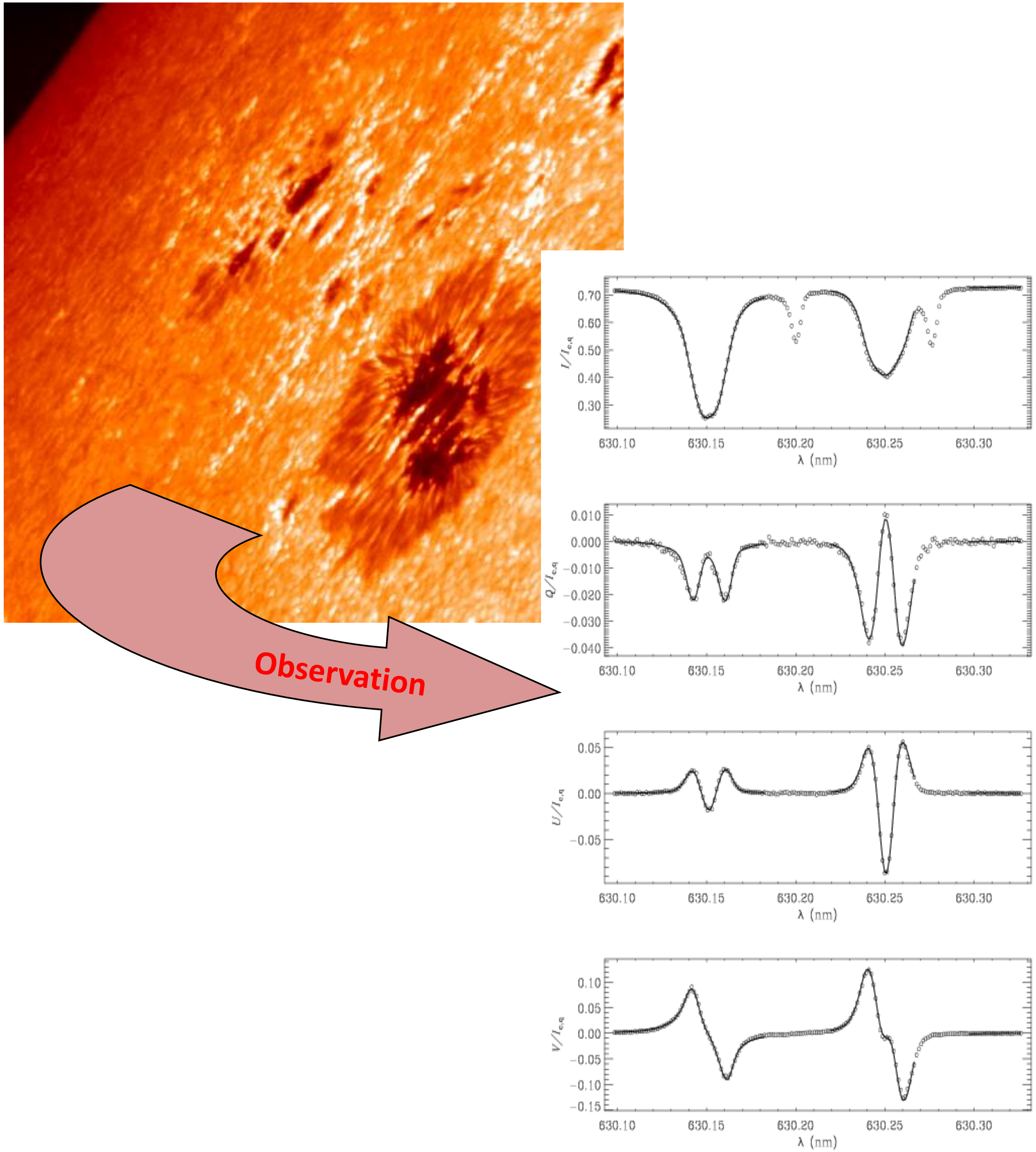
$f(s)$ become smoothed by the kernel $K(t,s)$

1) Small $g(t)$ perturbations are compatible with huge changes in $f(s)$

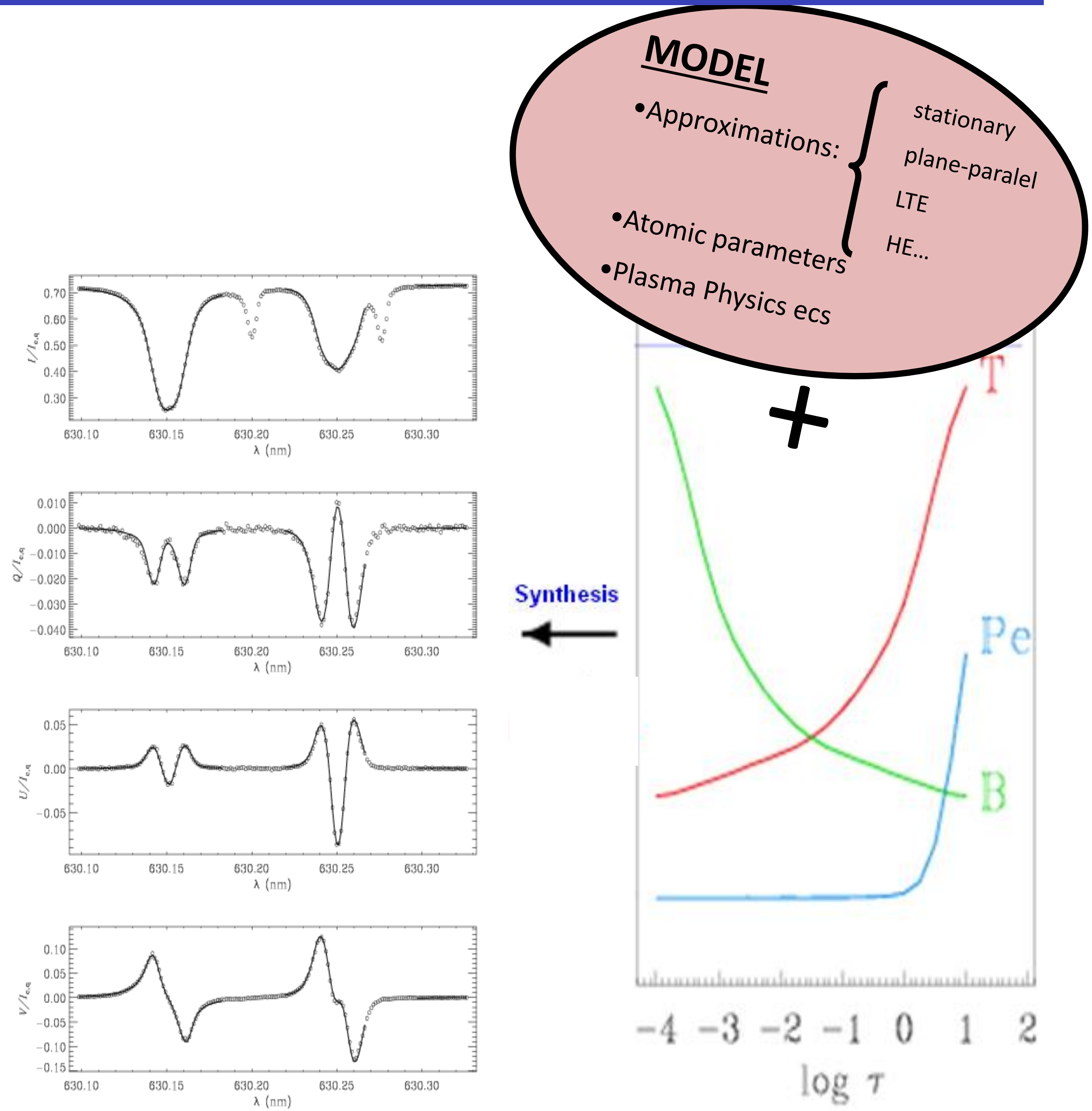
2) Smoothing means lost information, then "recover" $f(s)$ is imposible

3) We have a discrete set of $g(t)$ values and we'd wish a function $f(s)$

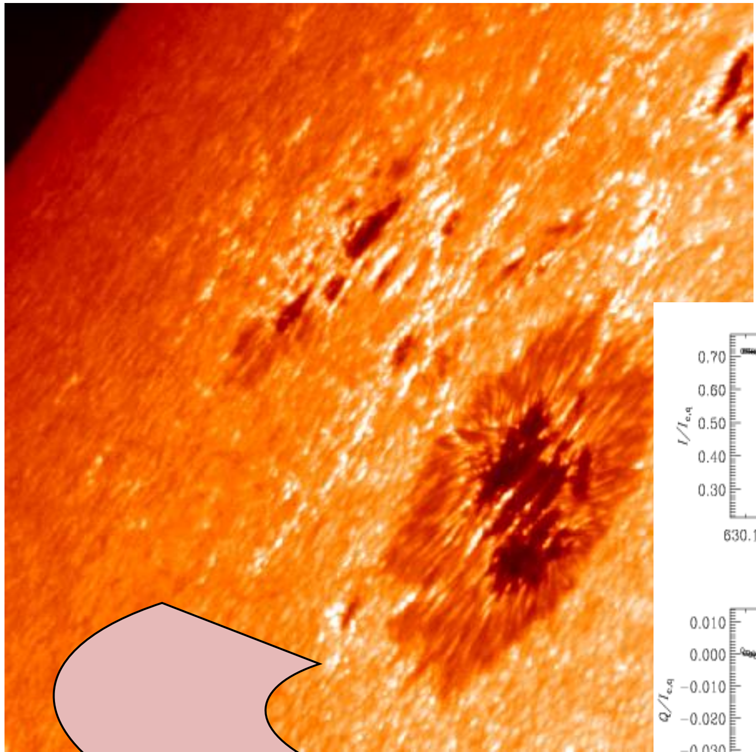
What is an inversion technique?



What is an inversion technique?

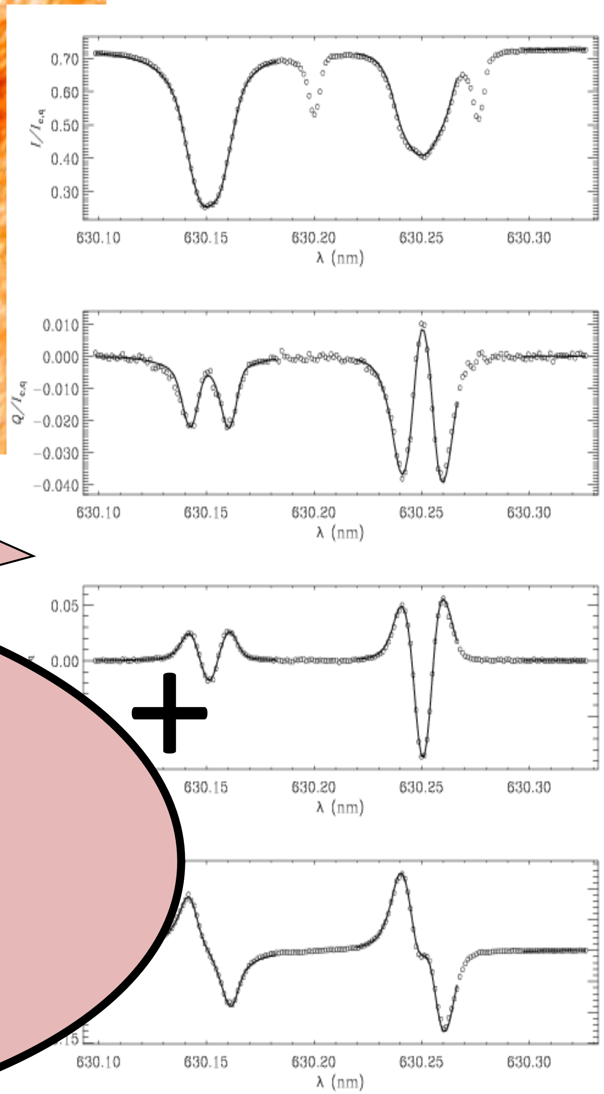


What is an inversion technique?

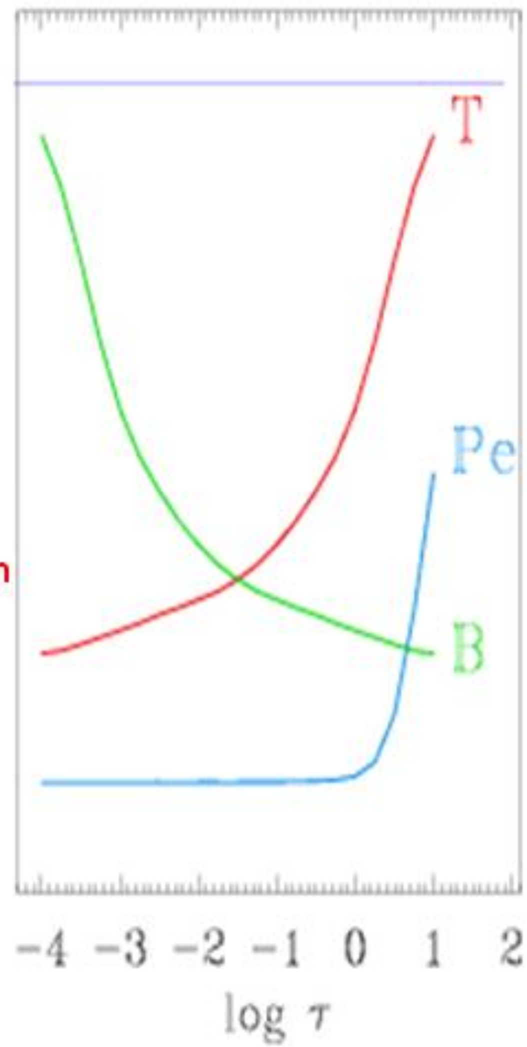


- The model (except free parameters values) must be known a priori
- We only fit the free parameters

Observation



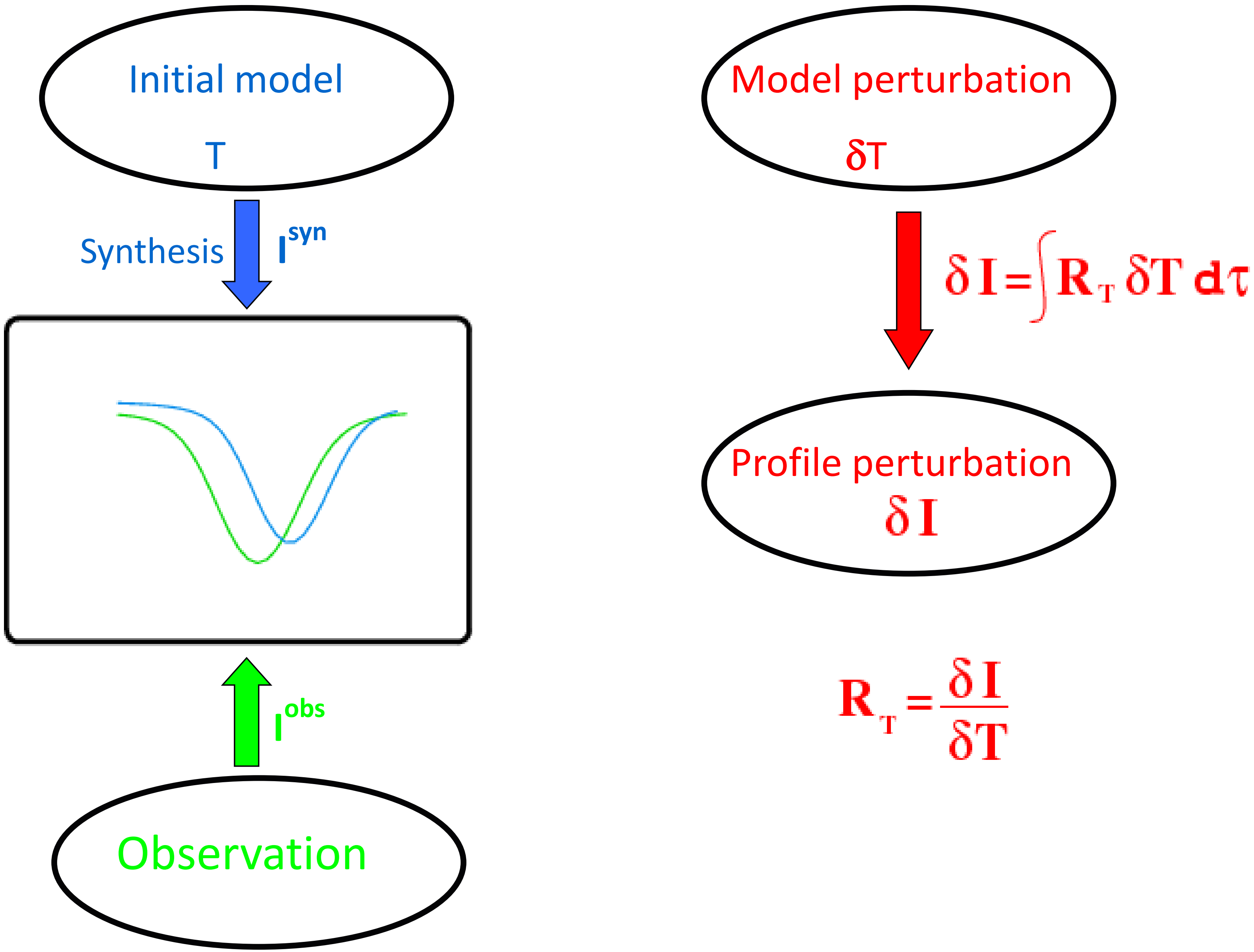
Inversion



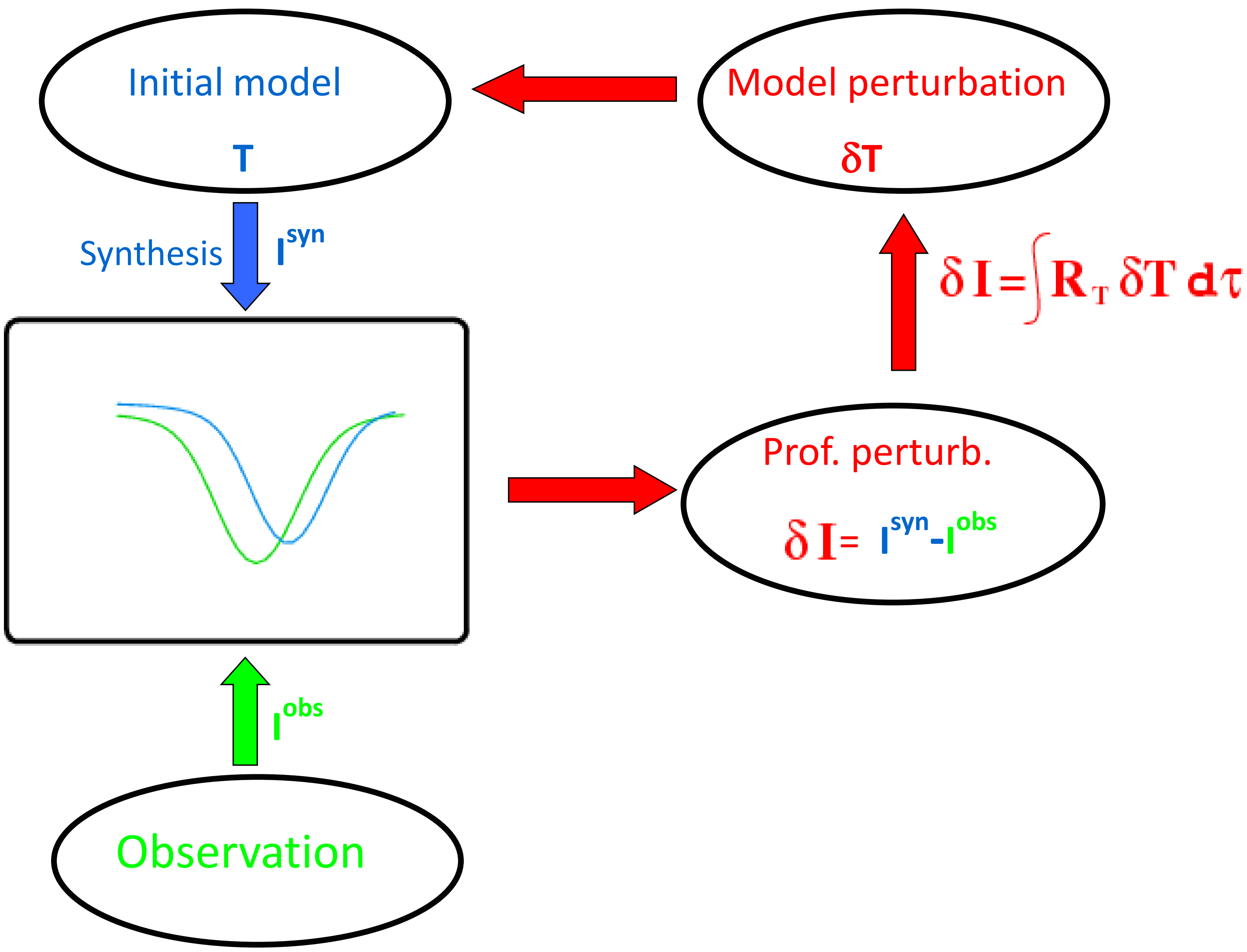
MODEL

- Approximations: stationary, plane-paralel, LTE, HE…
- Atomic parameters
- Plasma Physics ecs

SIR inversion technique



SIR inversion technique



SIR inversion technique

- Inversion driven by χ^2-minimization

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

- Minimization: 2nd order Levenberg-Marquardt algorithm

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

SIR inversion technique

$$\chi^2 \equiv \frac{1}{\nu} \sum_{i=1}^{M} \left[I^{\mathrm{obs}}(\lambda_i) - I^{\mathrm{sin}}(\lambda_i, \vec{a}) \right]^2$$

Least squares

$$\vec{a} = (T_1, T_2, ...T_n, B_1, B_2, ...B_n, ...)$$

$$\nabla \chi^2(\vec{a}) = - [A] \, \delta\vec{a}$$

$$\delta\vec{a} = [A]^{-1} \cdot \nabla \chi^2(\vec{a})$$

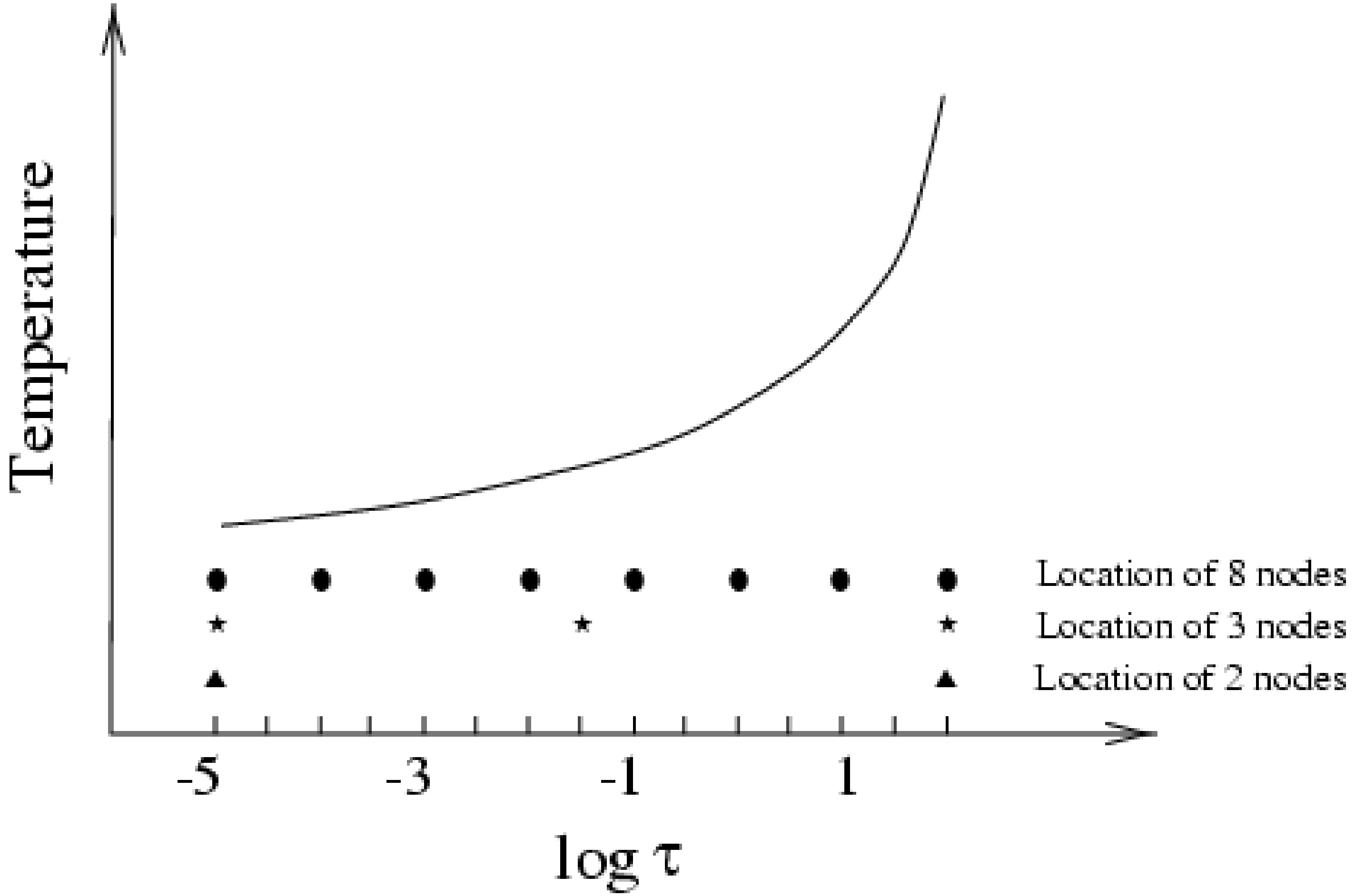
SIR inversion technique

$$\delta\vec{a} = [A]^{-1} \cdot \nabla\chi^2(\vec{a})$$

inverting A

- Very large (1)
- Singular (2)

1) Sequential increase of unknown number



SIR inversion technique

$$\delta\vec{a} = [A]^{-1} \cdot \nabla\chi^2(\vec{a})$$

inverting A

- Very large (1)
- Singular (2)

1) Sequential increase of unknown number

2) Singularities elimination through SVD (Singular Value Decomposition)

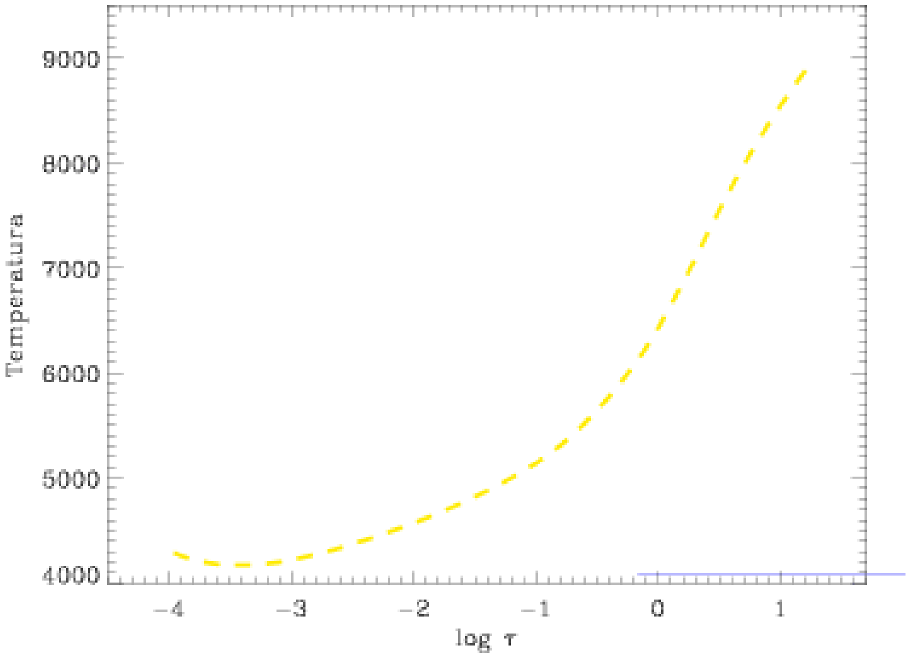
$A = U\, W\, V^T$ with U & V ortonormal matrix

y W =diagonal(w_{jj})

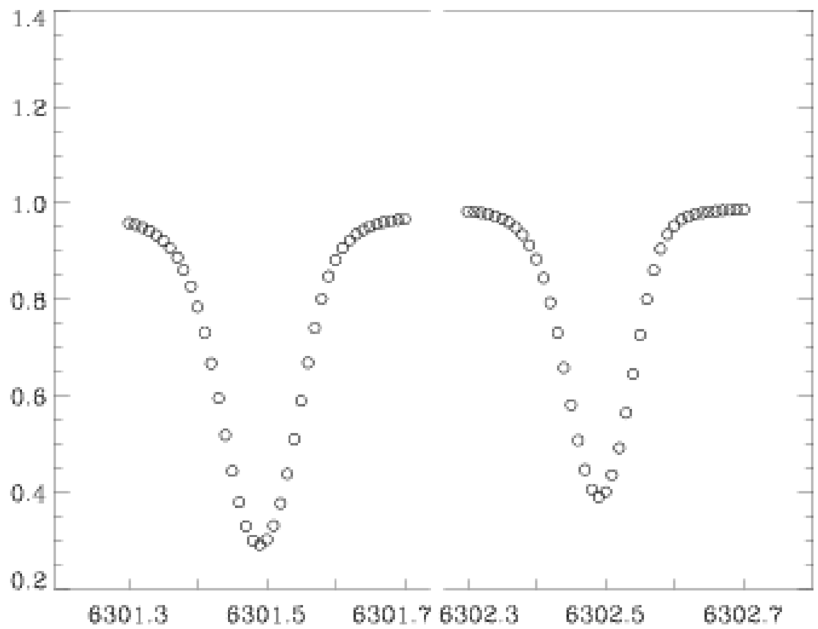
$A^{-1} = V\, W^{-1}\, U^T$ with W^{-1} =diagonal($1/w_{jj}$)

but doing $(W^{-1})_{jj}=0$ si $w_{jj} \cong 0$

SIR inversion technique

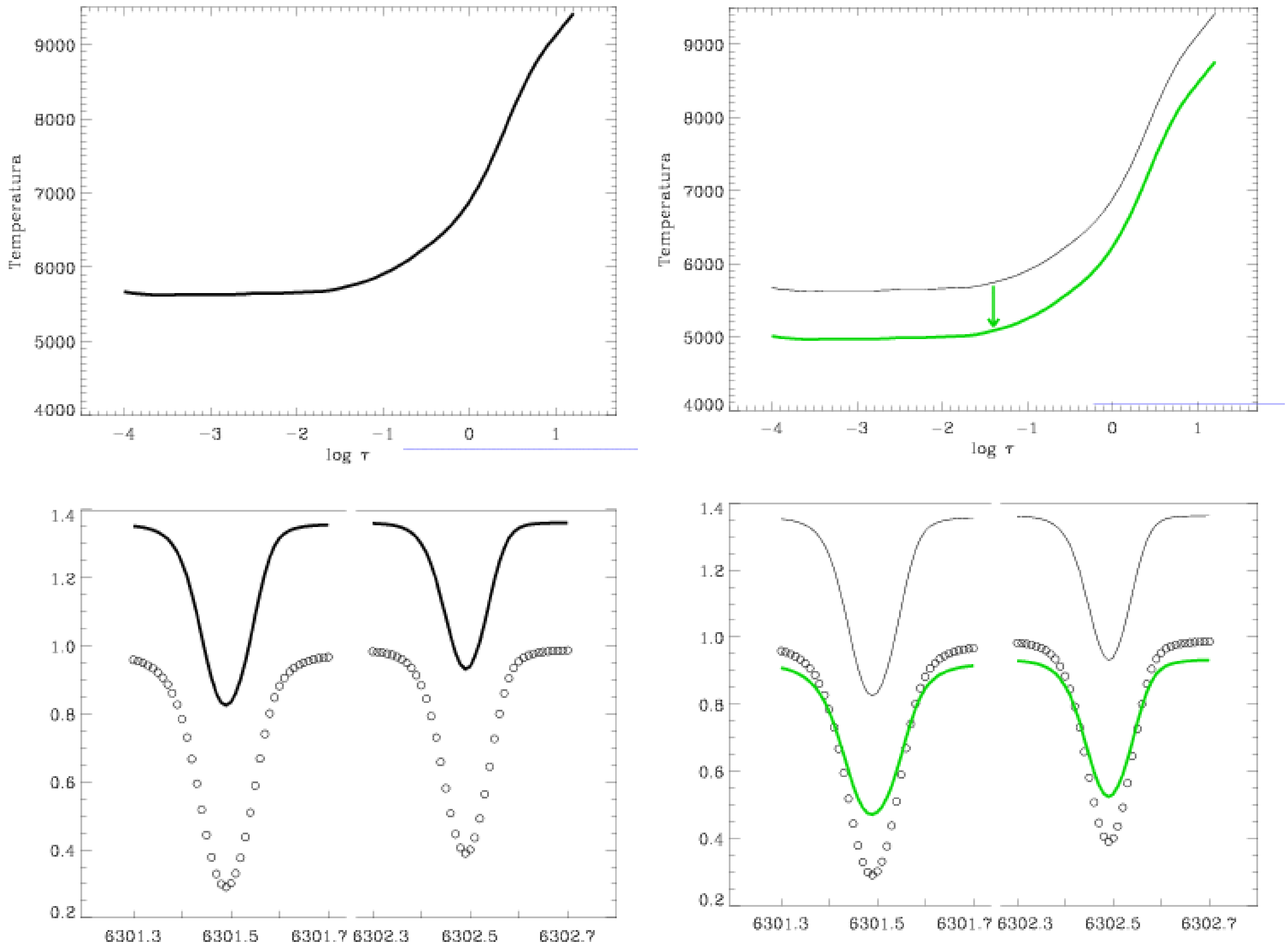


The “real” SUN

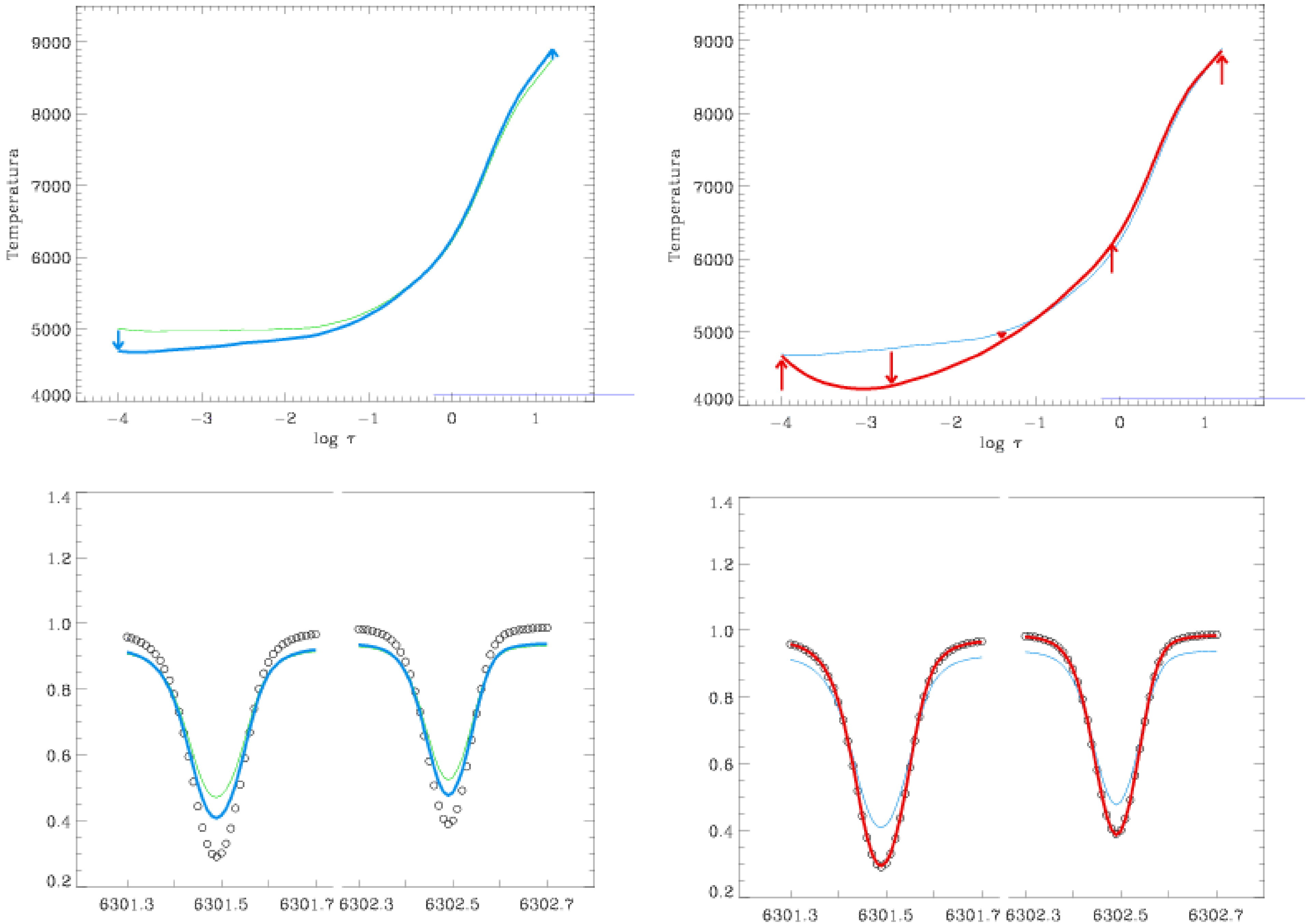


Synthetic “observations”

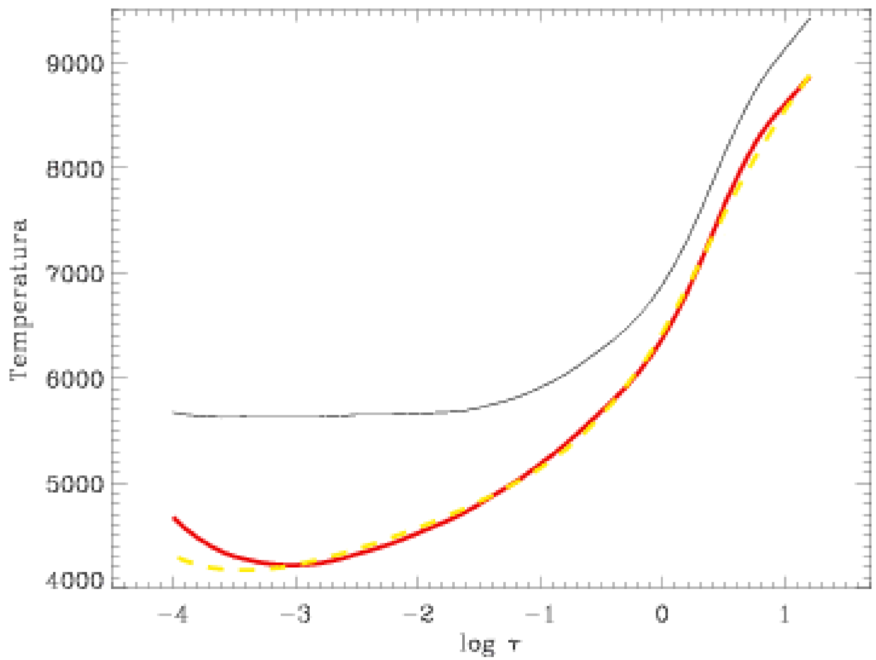
SIR inversion technique

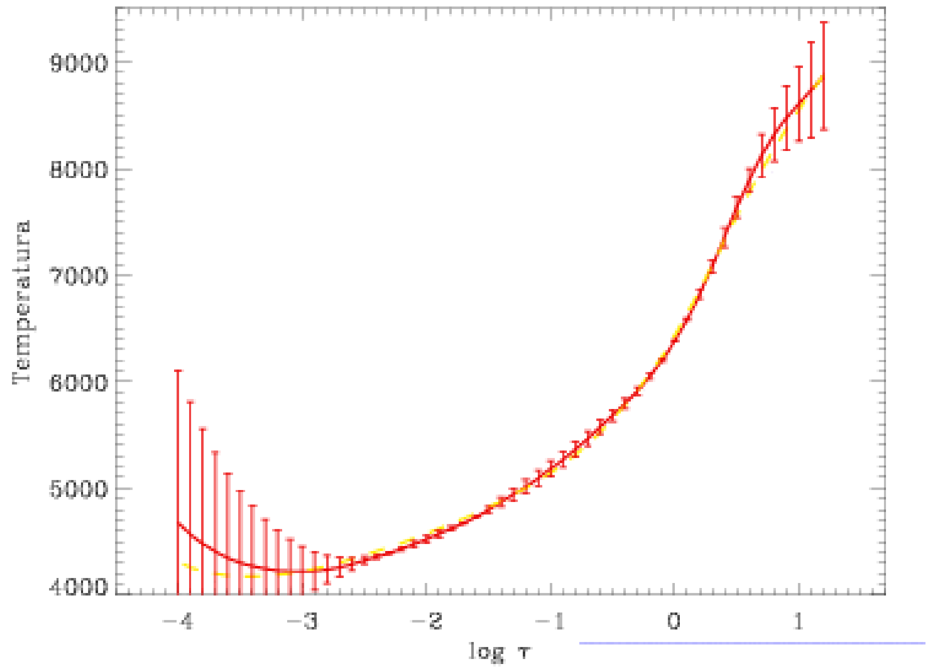


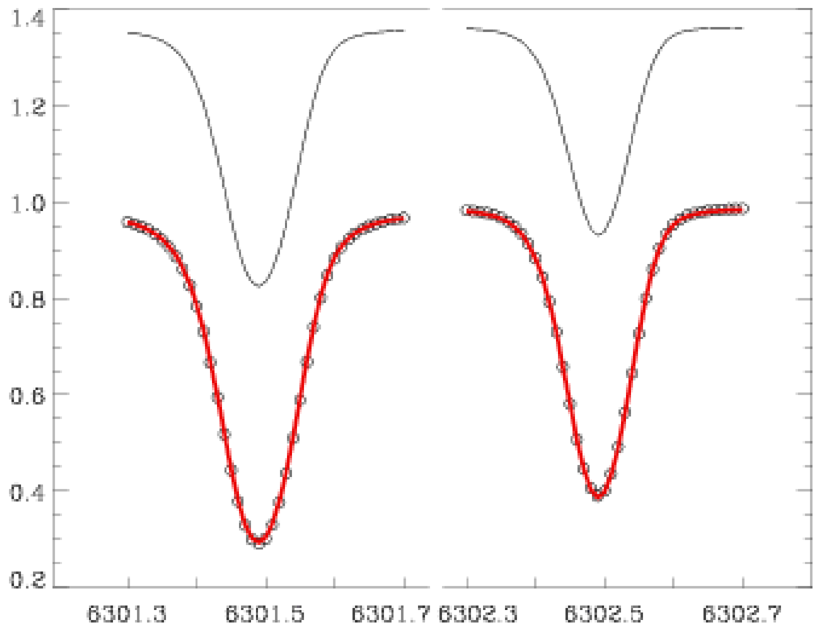
SIR inversion technique

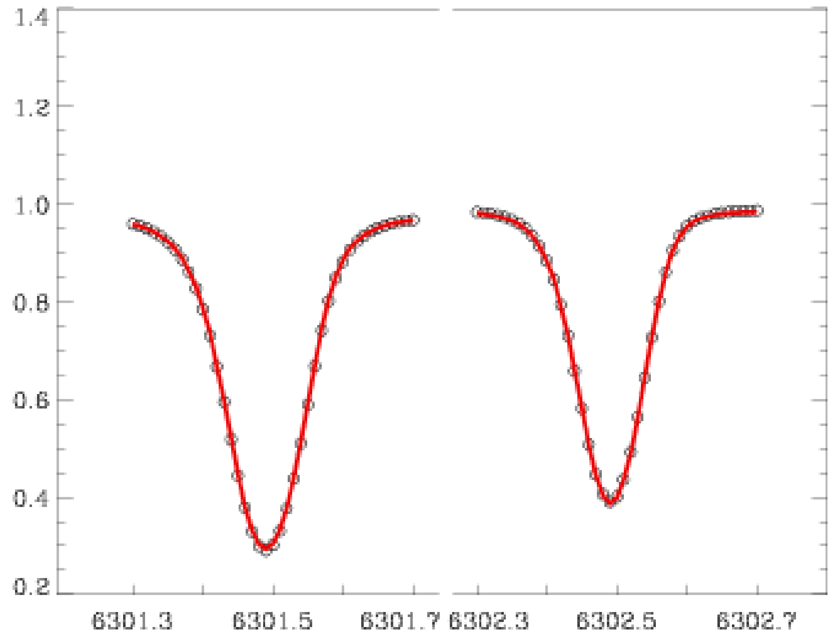


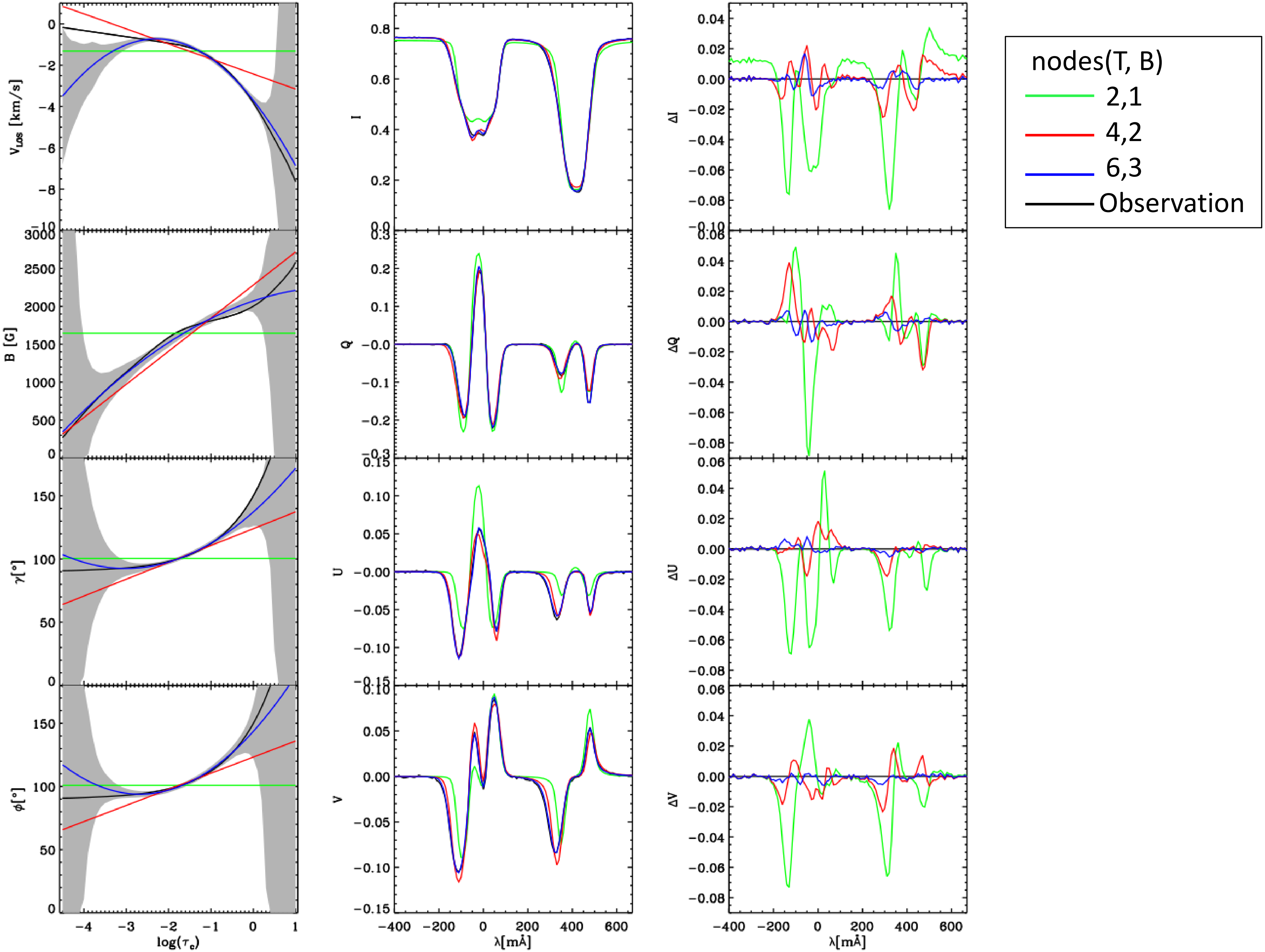
SIR inversion technique



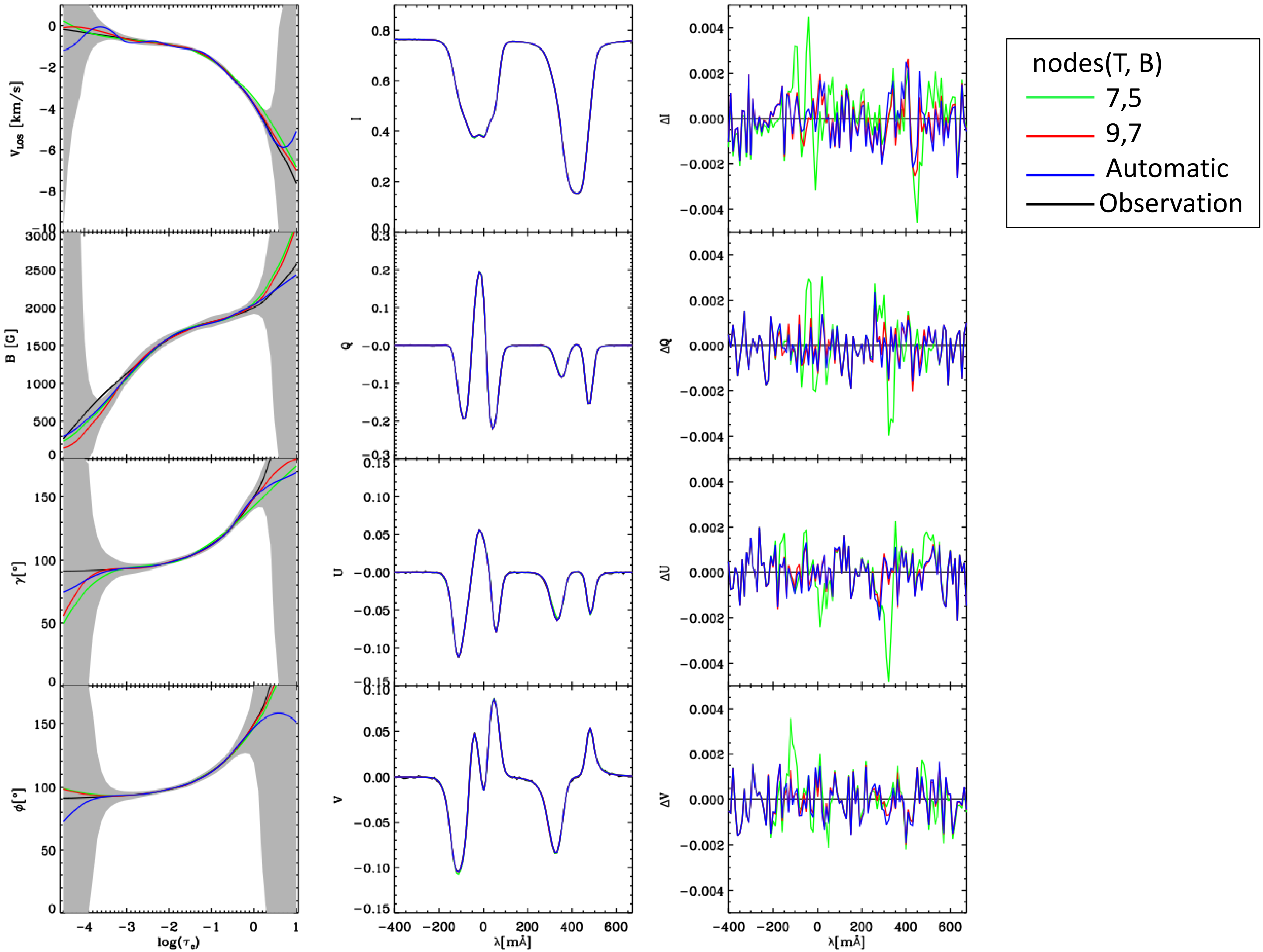








nodes(T, B)
2,1
4,2
6,3
Observation
v_{LOS} [km/s]
B [G]
γ[°]
ϕ[°]
log(τ_c)
I
Q
U
V
λ[mÅ]
ΔI
ΔQ
ΔU
ΔV



nodes(T, B)
7,5
9,7
Automatic
Observation
v_{LOS} [km/s]
B [G]
γ[°]
ϕ[°]
log(τ_c)
I
Q
U
V
λ[mÅ]
ΔI
ΔQ
ΔU
ΔV

How to choose an inversion technique

Some Reviews:

- Socas Navarro (2001) ASP Conf Series 236, 487
- del Toro Iniesta (2003) Astronomische Nachrichten 324, 383
- Bellot Rubio (2006) ASP Conf Series, 358, 107
- Ruiz Cobo (2007) ‘Modern Solar Facilities’, Göttingen
- Asensio Ramos et al (2012) ApJ 748, 83
- del Toro Iniesta & Ruiz Cobo (2016) Livings Reviews in Solar Physics, 13,4

How to choose an inversion technique

Constant quantities			
KPNO	Harvey et al. (1972)	LM	
HAO-KPNO	Auer et al. (1977)	LM	
Florence	Landolfi et al. (1984)	LM	✓
HAO-ASP	Skumanich et al. (1985)	LM	✓
IAC MISMA	Sánchez Almeida (1997)	LM	✓
CSIRO-Meudon	Rees et al. (2000)	PCA	✓
HAO MELANIE	Socas-Navarro et al. (2001)	LM	✓
HAO FATIMA	Socas-Navarro et al. (2001)	PCA	✓
AIP ANN	Carroll and Staude (2001)	ANN	
HAO He I D_3	López Ariste and Casini (2003)	PCA	✓
HAO ANN	Socas-Navarro (2003)	ANN	
MPS HELIX	Lagg et al. (2004)	GA	✓
IAC Molecular	Asensio Ramos (2004)	LM	
IAA MILOS	Orozco Suárez and del Toro Iniesta (2007)	LM	✓
IAC HAZEL	Asensio Ramos et al. (2008)	LM	✓
HAO VFISV	Borrero et al. (2011)	LM	✓
IAC Sparse	Asensio Ramos and de la Cruz Rodríguez (2015)	GD	✓

LM Levenberg–Marquardt, *ANN* artificial neural networks, *GA* genetic algorithm, *B* Bayesian, *GD* gradient descent

How to choose an inversion technique

Variable quantities			
ETH Flux tube	Keller et al. (1990)	LM	
IAC SIR	Ruiz Cobo and del Toro Iniesta (1992)	LM	✓
ETH IT	Solanki et al. (1992b)	LM	
IAC Flux tube	Bellot Rubio et al. (1997)	LM	✓
ETH SPINOR	Frutiger and Solanki (1998)	LM	✓
IAC NLTE	Socas-Navarro et al. (2000)	LM	
HAO LILIA	Socas-Navarro (2001)	LM	✓
HAO-IAC NICOLE	Socas-Navarro (2001)	LM	✓
KIS SIRGAUS	Bellot Rubio (2003)	LM	✓
IAA SIRJUMP	Louis et al. (2009)	LM	✓
IAC Bayes	Asensio Ramos et al. (2009)	B	✓
MPS Spatially coupled	van Noort (2012)	LM	✓
IAC Regularization	Ruiz Cobo and Asensio Ramos (2013)	LM	✓

LM Levenberg–Marquardt, *ANN* artificial neural networks, *GA* genetic algorithm, *B* Bayesian, *GD* gradient descent

How to choose an inversion technique

People usually select an inversion method for strange reasons: if the code is available, if it is easier or faster than others, (or was written for my boss), etc., instead of selecting the most convenient for each specific problem.

I classify available IT in 3 families:

1. ME must be used in case in which you do not know the physics controlling the line formation, or you have few wavelength points for each pixel.
2. PCA when you need fast results.
3. SIR (or similar) when you believe that your knowledge of the formation of the lines used is appropriate (and/or you be plenty of time or you be… a little crazy.)

How to choose an inversion technique

1. ME family

- Skumanich & Lites (1984, 1987) ; Landolfi (1984); Lagg et al (2004)
- Extensively used in HAO (ASP data).

Juanma Borrero told me that his ME code inverts a 1000x1000 Hinode data in just 3 min.

- Advantages: - fast (a typical map takes ~ hr).
  - simple use & easy interpretation of results.
  - robust & reliable.
  - HE, LTE etc approximations are not needed.

- Shortcoming: - unable to fit asymmetric Stokes profiles. (but: robust against noise)
  - no gradients. (but: even theoreticians understand the results)
  - no temperature, pressure & density information. (but: no physics knowledge is required)
  - the number of free parameter grows with the number of spectral lines (but: no excuses!)

How to choose an inversion technique

2. SIR family (a lot of children): an incomplete list

- Ruiz Cobo & del Toro Iniesta (1992): SIR code
- Frutiger, Solanki et al (2000): SPINOR code [see also Bernasconi & Solanki (1996)]
- Bellot Rubio, Ruiz Cobo & Collados (1997): FT geometry [see also Frutiger & Solanki (1998)]
- Bellot Rubio (2003) [see also Borrero, Lagg, Solanki & Collados (2005)]: Uncombed penumbral model
- Socas Navarro, Trujillo Bueno & Ruiz Cobo (2000): SIR-NLTE code
- Sánchez Almeida et al (1996): MISMA code
- Allende Prieto, Ruiz Cobo & García López (1998): MISS code [see also Frutiger et al (2000), Rüedi et al (1997)]

How to choose an inversion technique

2. SIR family

- Advantages: - Arbitrarily complex along line of sight (gradients, multicomponents, etc)

  - Thermodynamic information.

  - adaptation to many geometries & scenarios.

  - LTE/NLTE, HE, mass conservation etc.

  - uncertainties estimation.

- Shortcoming:- Slow (20-30 times slower than ME)
  (but: new SIR version –upcoming soon!!- will nearly reach ME rates)

  - Difficult use
  (but: for simplified problems –like only linear stratifications-- is straightforward)

  - Unicity (but: only if you are ambitious)

How to choose an inversion technique

3. PCA family

- Look-up-table inversion method, based in PCA
- Rees et al (2000); Socas Navarro et al (2001); López Ariste & Casini (2002)
- Since 2004 used in THEMIS for real-time inversions

- Advantages: - extremely fast (one order of magnitude faster than ME)
  - simple use, robust & reliable

- Shortcoming: - few free parameter determination (ME)
  - slightly more inaccurate that ME inversions

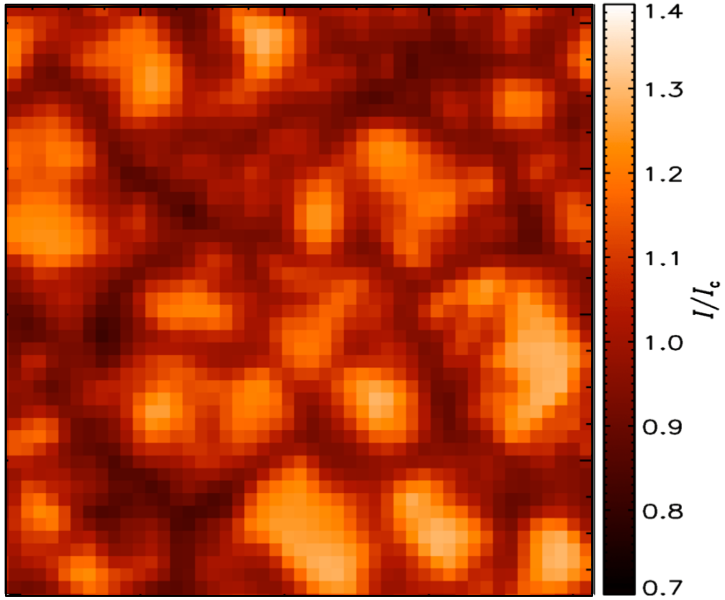
How to choose an inversion technique

Conclusions

1. ME must be used in case in which you do not know the physics controlling the line formation or few spectral points.
2. PCA when you need fast results.
3. SIR (or similar) when you believe that your knowledge of the formation of the lines used is appropriate.

ME inversions of high-spatial resolution profiles

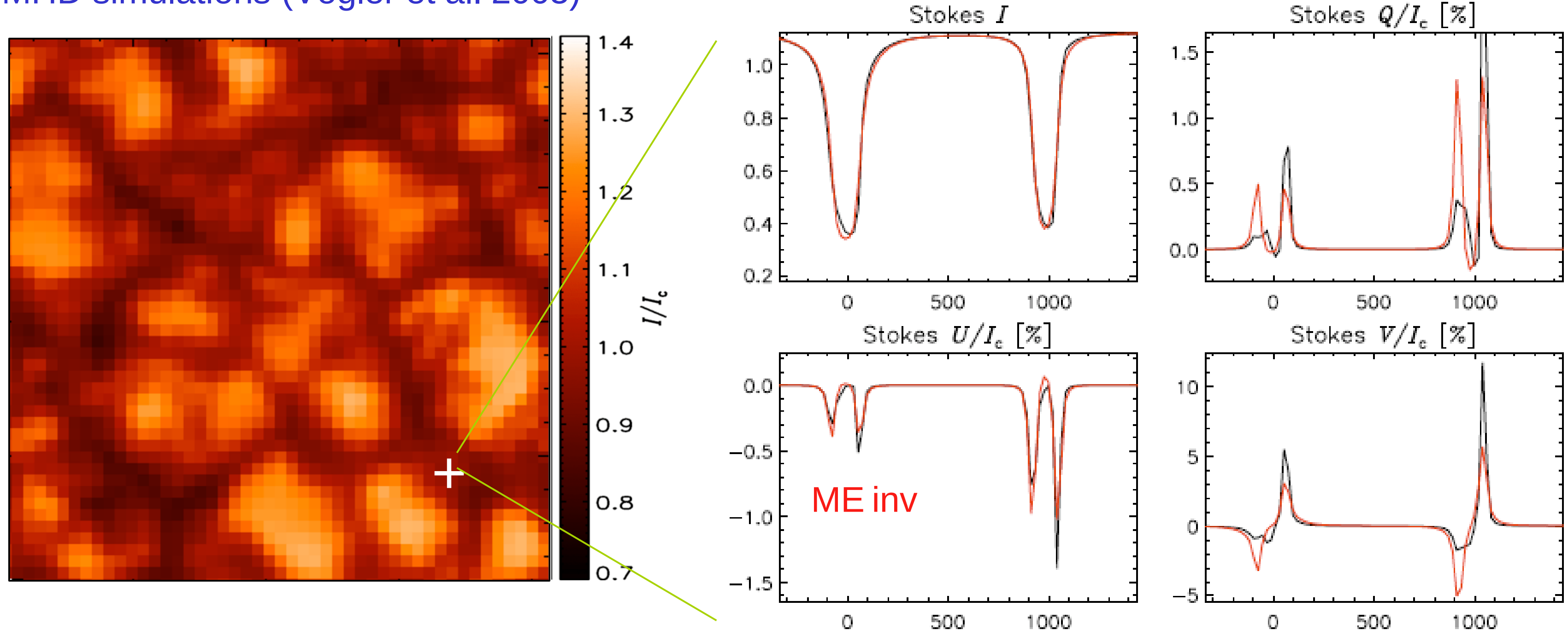
MHD simulations (Vögler et al. 2005)

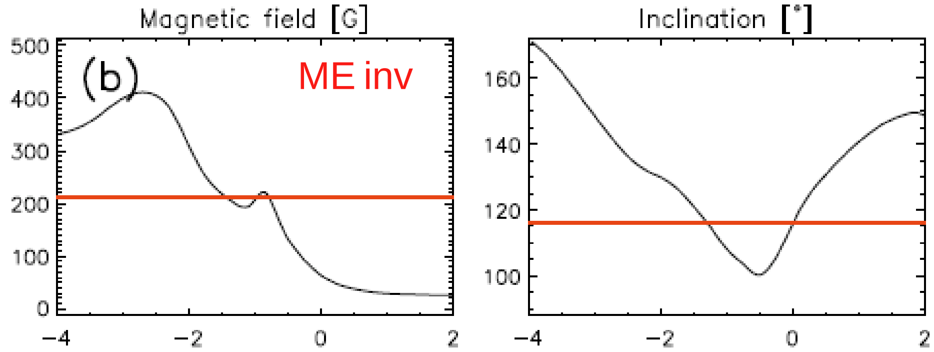


- Fe I 630.1 and 630.2 nm profiles degraded to Hinode/SP resolution and pixel size

ME inversions of high-spatial resolution profiles

MHD simulations (Vögler et al. 2005)

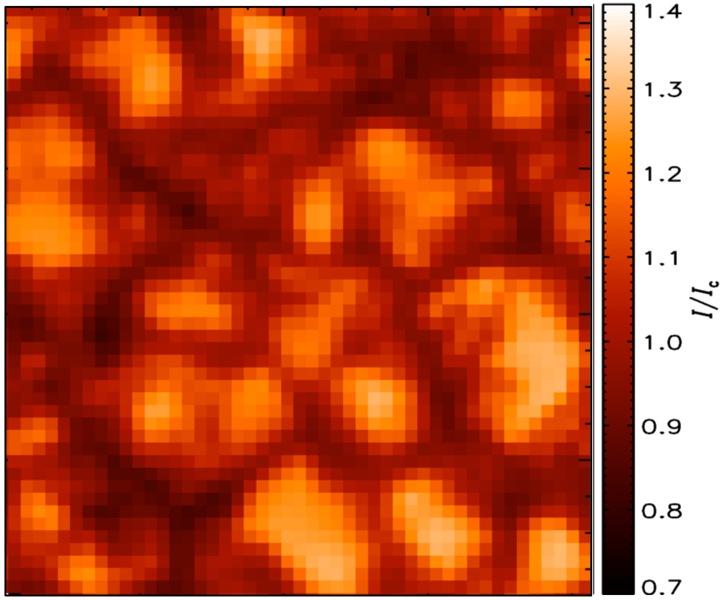


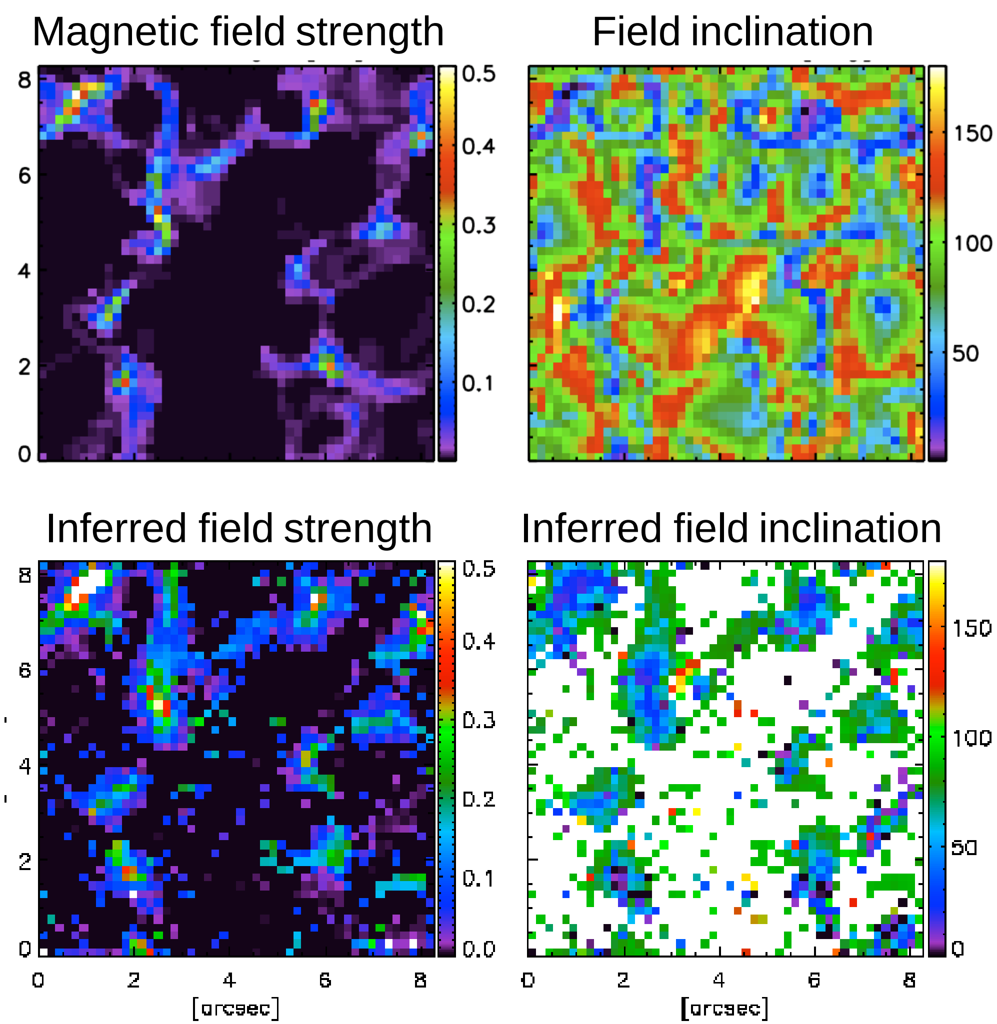


- Profiles reasonably well fitted
- ME results are some kind of "average" of physical parameters along the LOS

ME inversions of high-spatial resolution profiles

MHD simulations (Vögler et al. 2005)

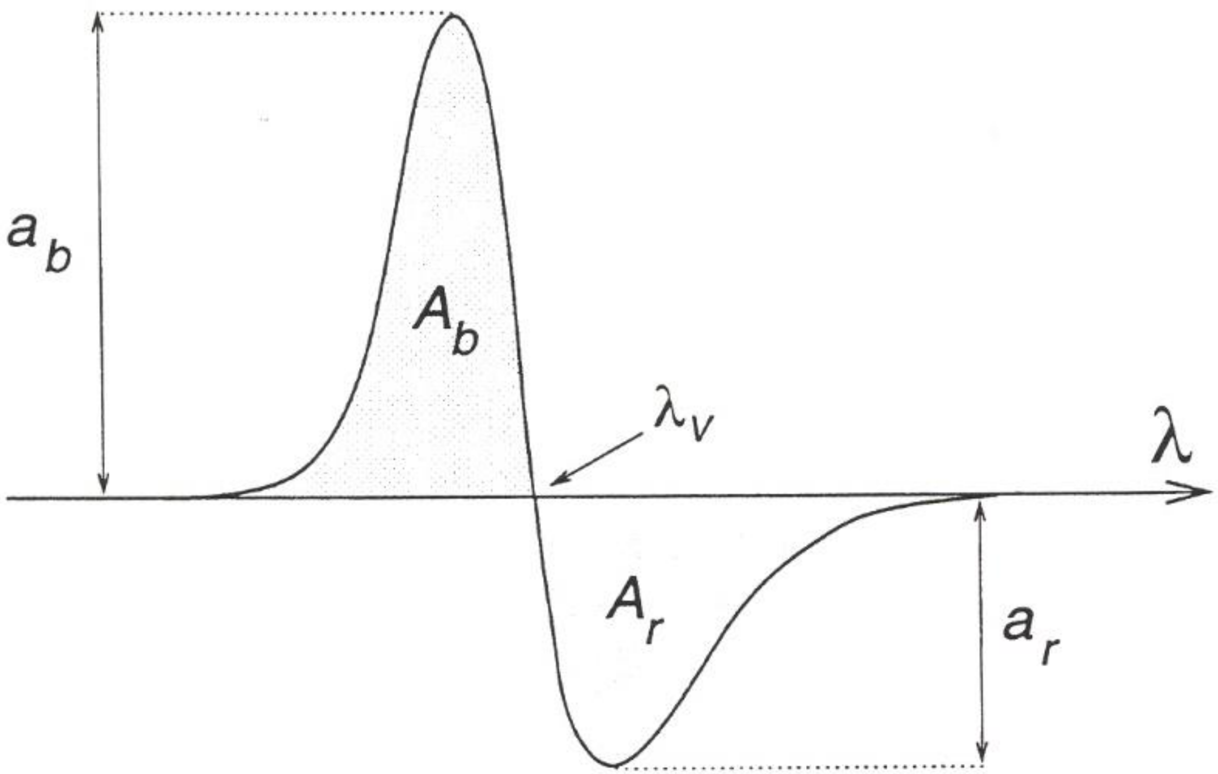




- Atmospheric parameters from MHD simulation at log τ = -2
- Maps of inferred B and γ similar to real ones!

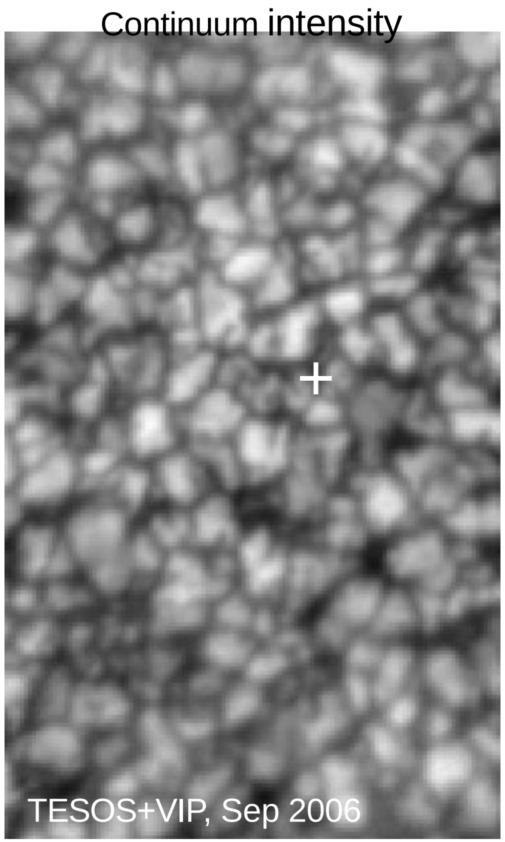
Orozco Suárez et al. 2007, ApJ, 662, L31

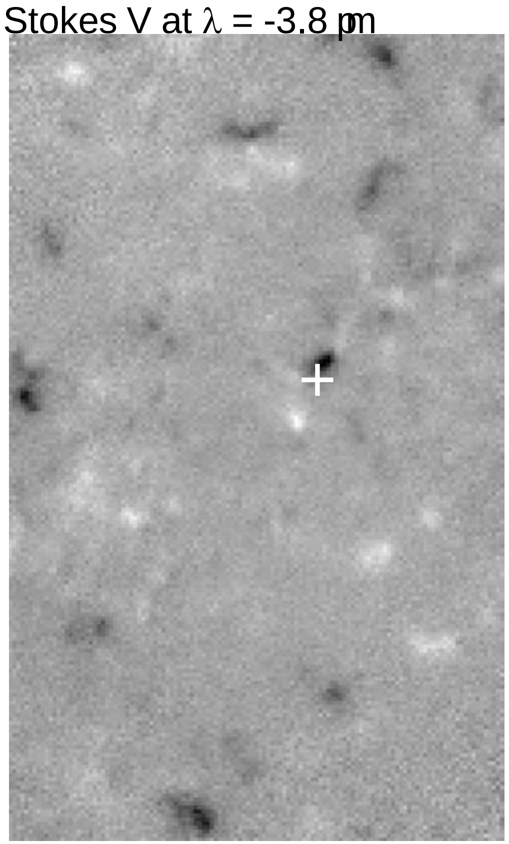
Accounting for asymmetries

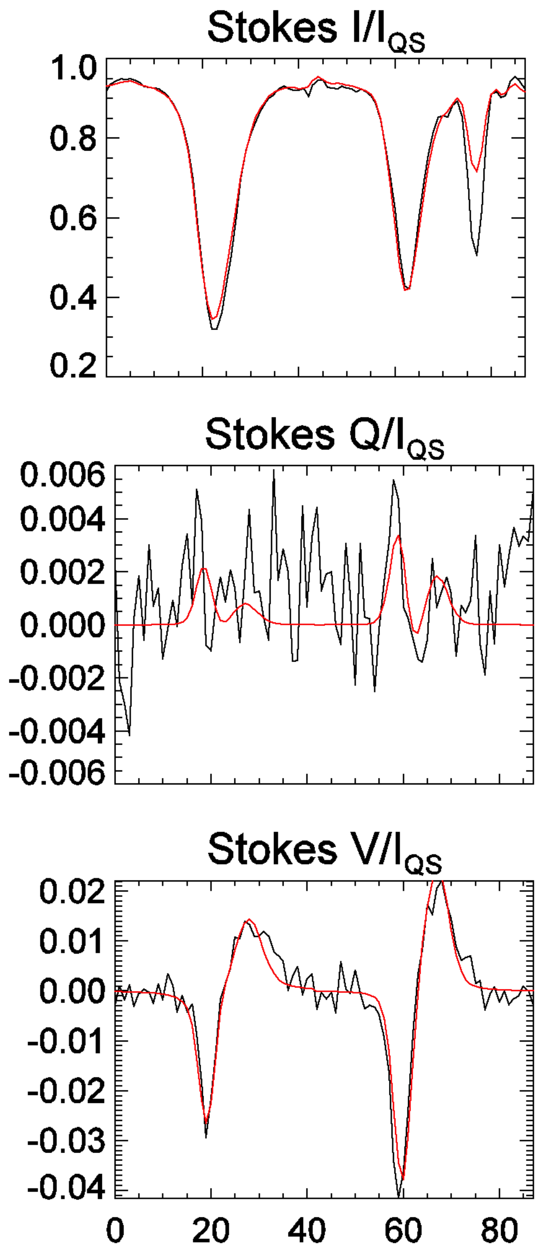


$$\delta a \equiv \frac{a_\mathrm{b} - a_\mathrm{r}}{a_\mathrm{b} + a_\mathrm{r}}, \quad \delta A \equiv \frac{A_\mathrm{b} - A_\mathrm{r}}{A_\mathrm{b} + A_\mathrm{r}},$$

Asymmetric Stokes profiles







- KIS/IAA Visible Imaging Polarimeter + TESOS + KAOS
- VTT, Observatorio del Teide
- Spatial resolution: ~0.4"
- Quiet Sun at center, Fe I 630.15 and 630.25 nm

The origin of asymmetries

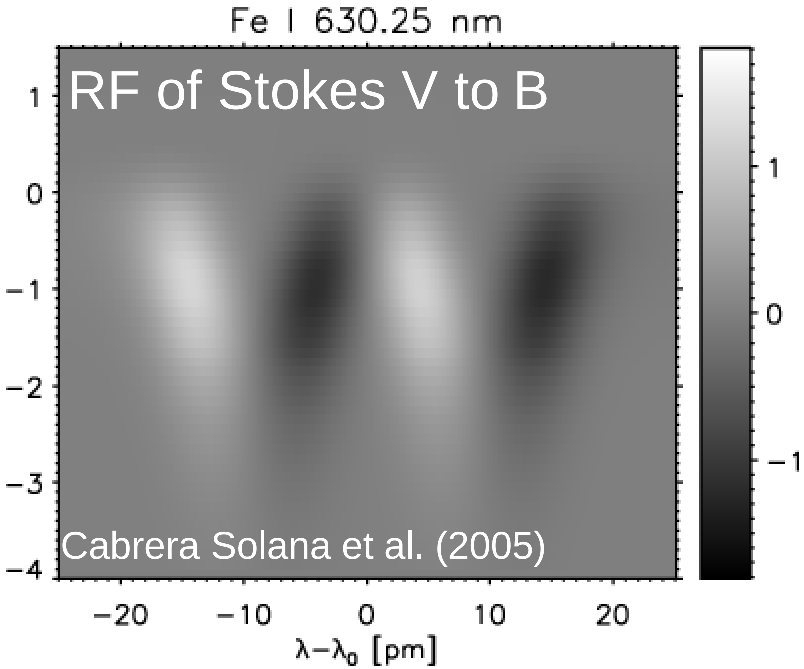
Amplitude asymmetry/
Multi-lobed Stokes profiles

Different magnetic atmospheres coexisting in resolution element

Area asymmetry

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

Auer & Heasley (1978)

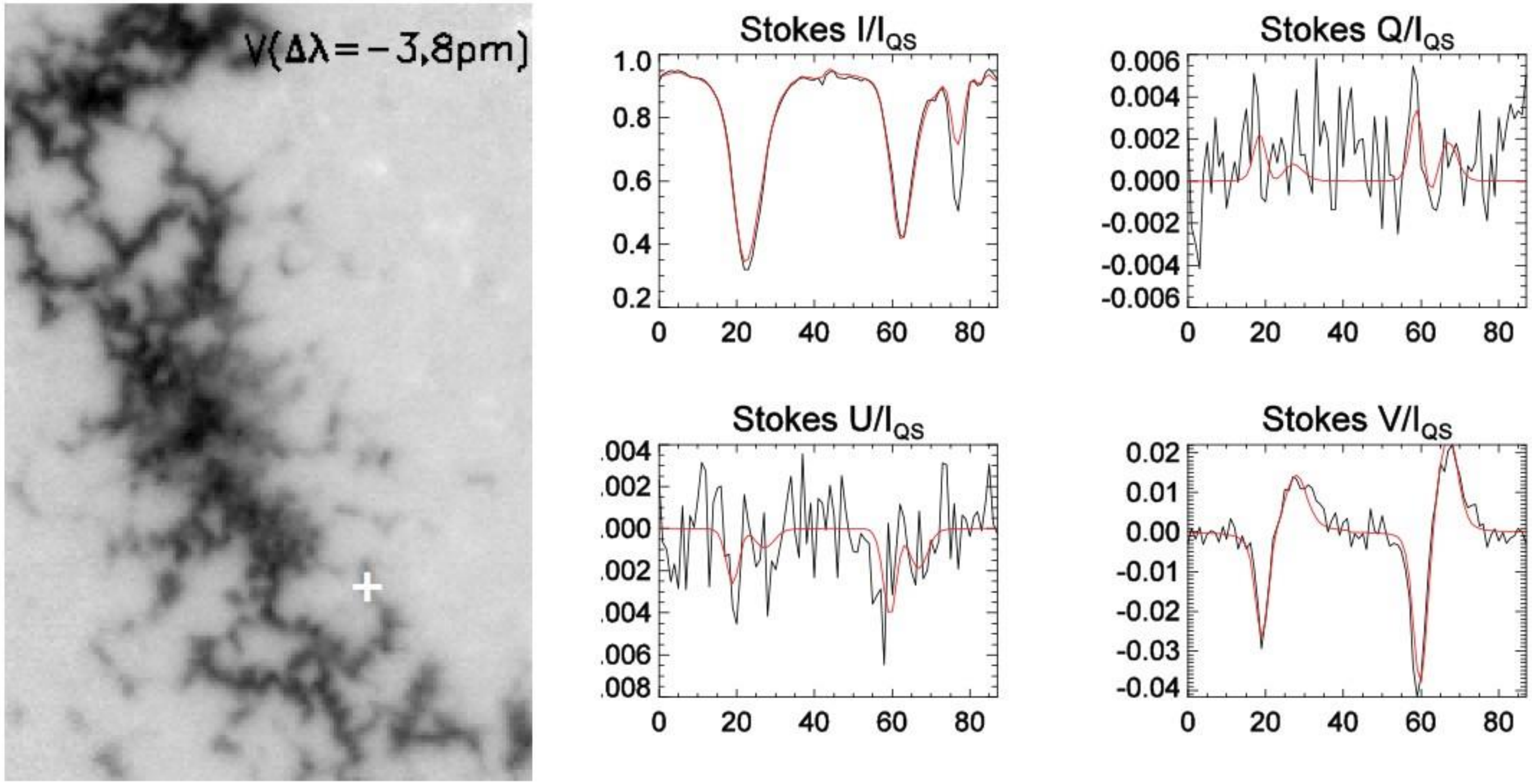


The area asymmetry gives information on the height variation of atmospheric parameters

Accounting for asymmetries

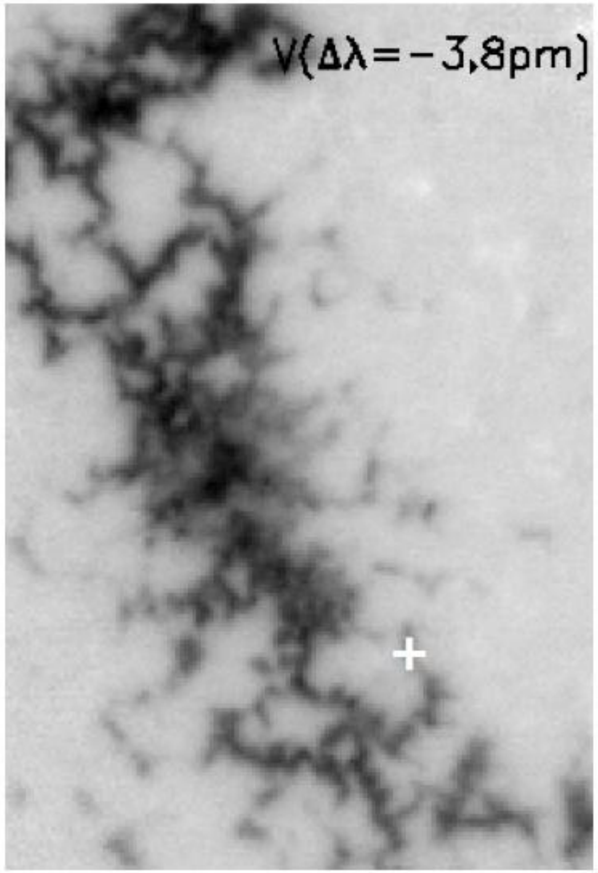
- Inversion codes capable of dealing with asymmetries
  - Are based on numerical solution of RTE
  - Provide reliable thermal information
  - Use *less free parameters than ME* codes
  - Infer stratifications of physical parameters with depth

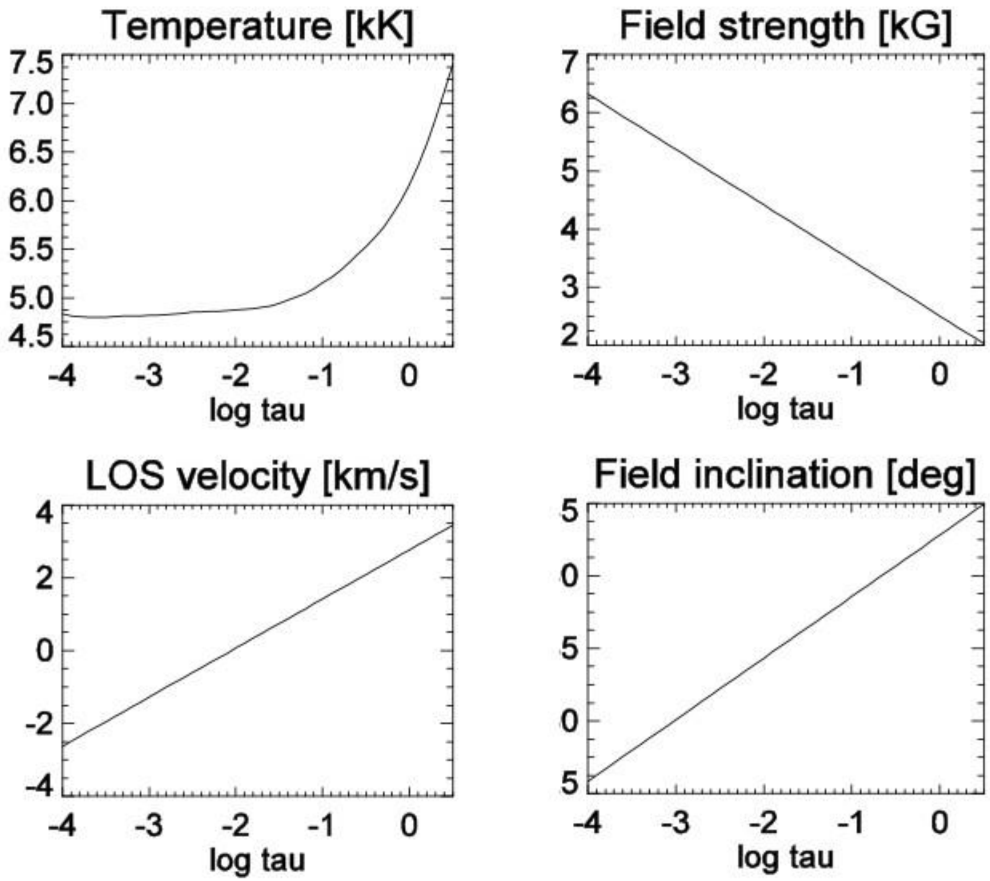
Accounting for asymmetries



- VIP + TESOS + KAOS
- SIR with 10 free parameters
- Bellot Rubio et al. (2007)

Accounting for asymmetries

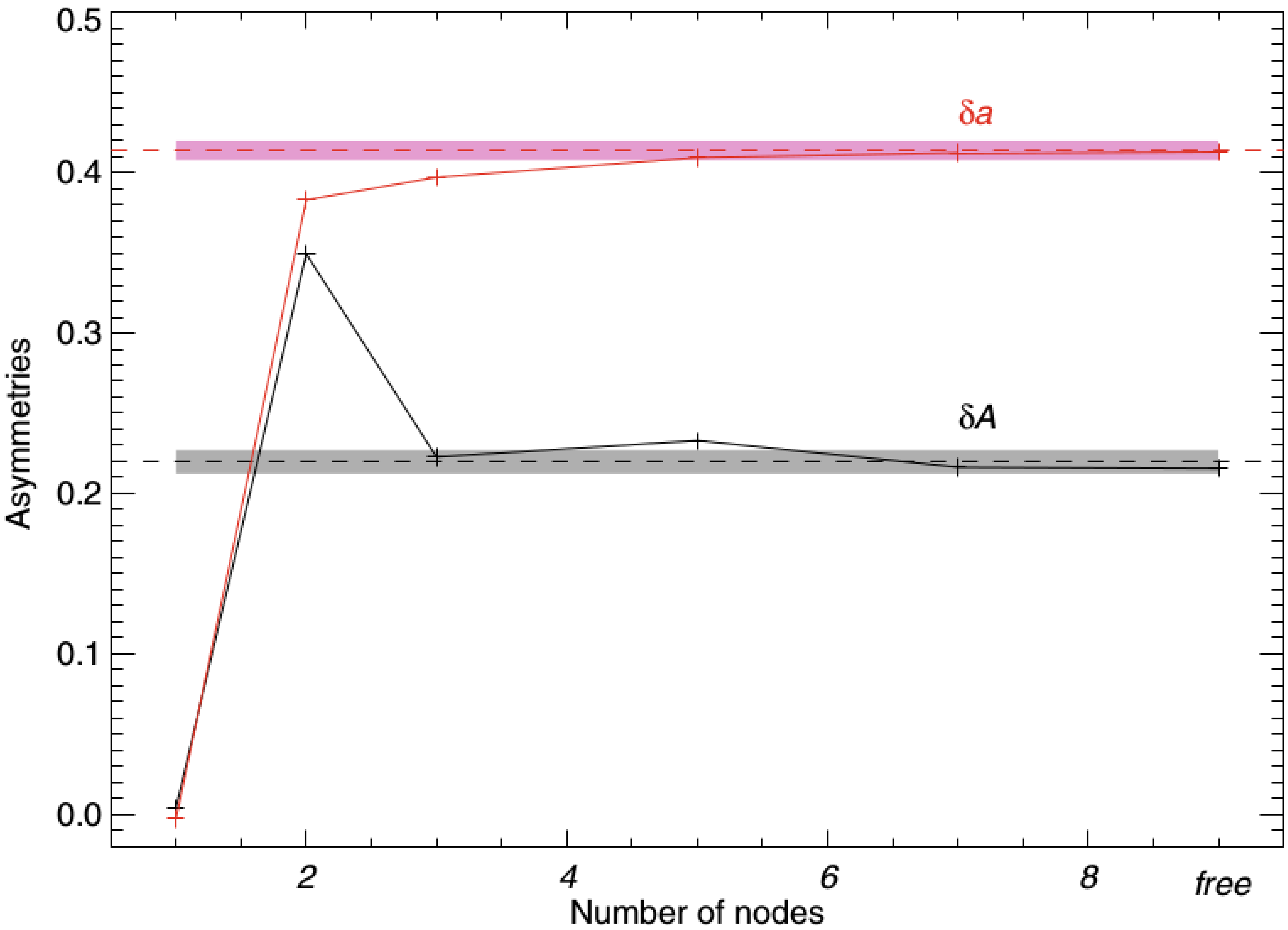




- VIP + TESOS + KAOS
- SIR with 10 free parameters
- Bellot Rubio et al. (2007)

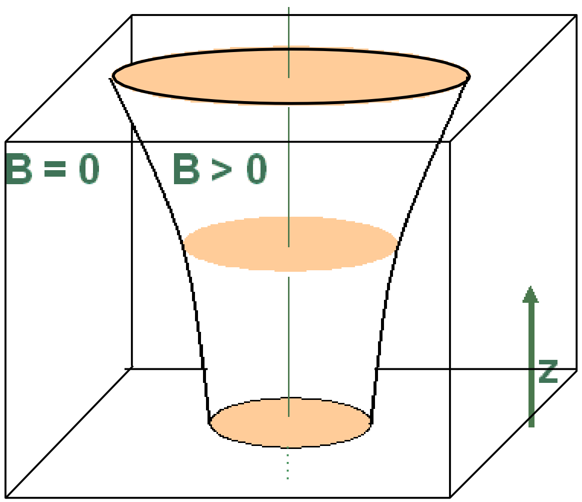
Accounting for asymmetries

$$\delta a \equiv \frac{a_{\mathrm{b}} - a_{\mathrm{r}}}{a_{\mathrm{b}} + a_{\mathrm{r}}}, \quad \delta A \equiv \frac{A_{\mathrm{b}} - A_{\mathrm{r}}}{A_{\mathrm{b}} + A_{\mathrm{r}}},$$

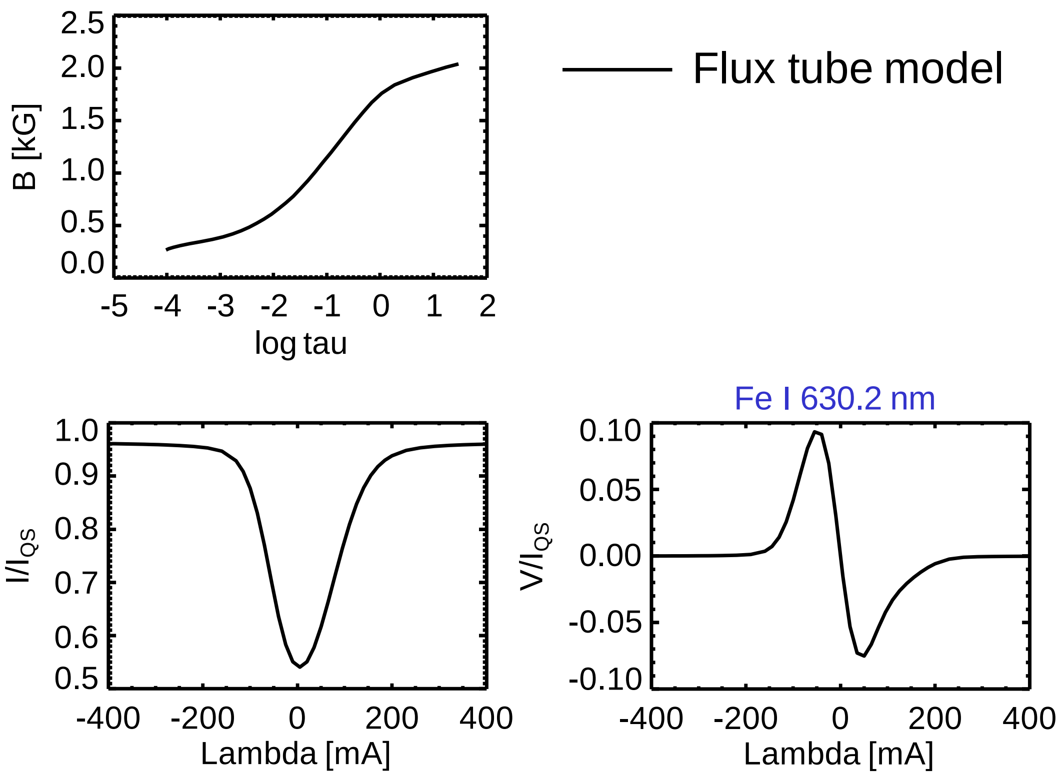


Be careful with the choice of atmospheric model!

- The results change if the physical model is changed
  - Too simplistic models; often they cannot describe the real atmosphere
  - BUT: we get information about the magnetic structure of the atmosphere!

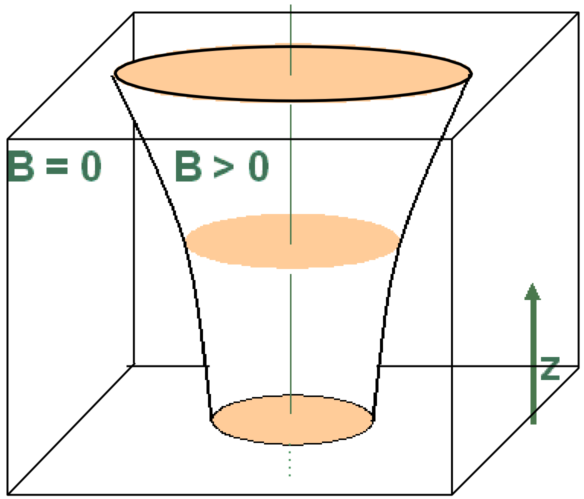


Magnetic flux tubes in facular regions

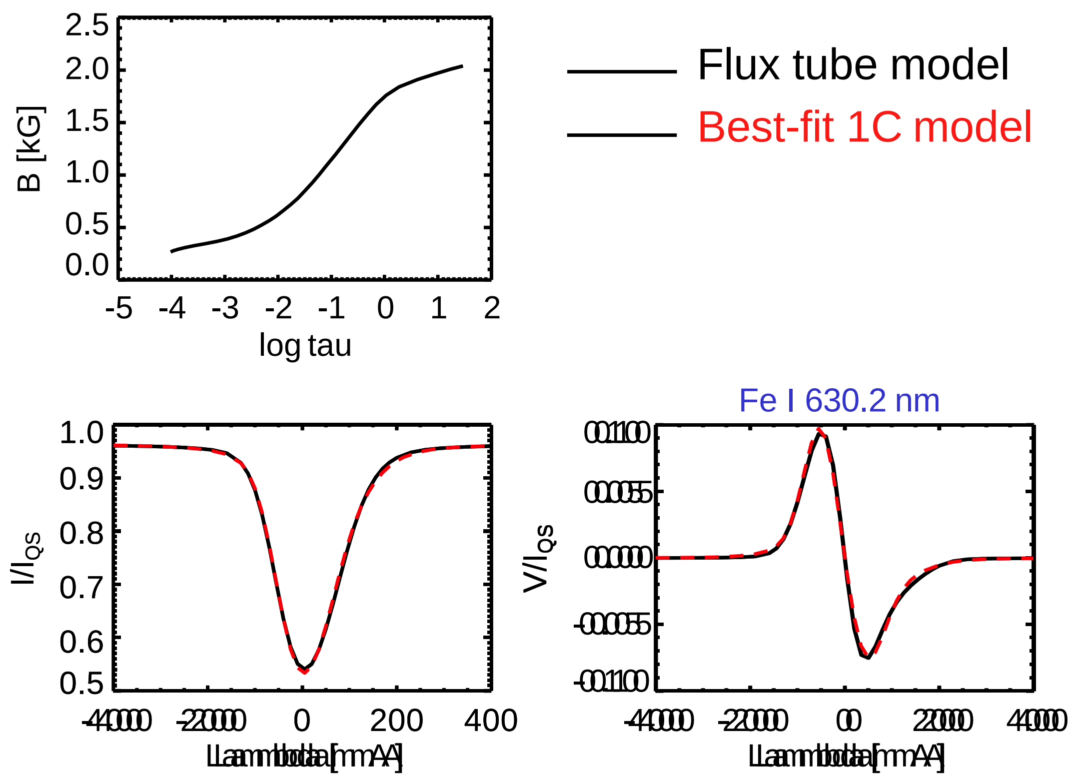


Be careful with the choice of atmospheric model!

- The results change if the physical model is changed
  - Too simplistic models; often they cannot describe the real atmosphere
  - BUT: we get information about the magnetic structure of the atmosphere!

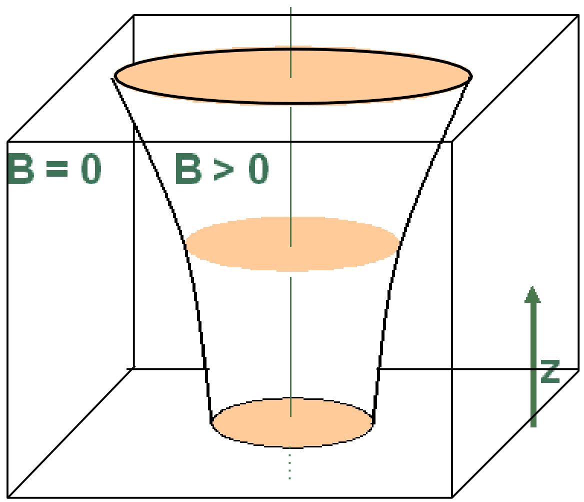


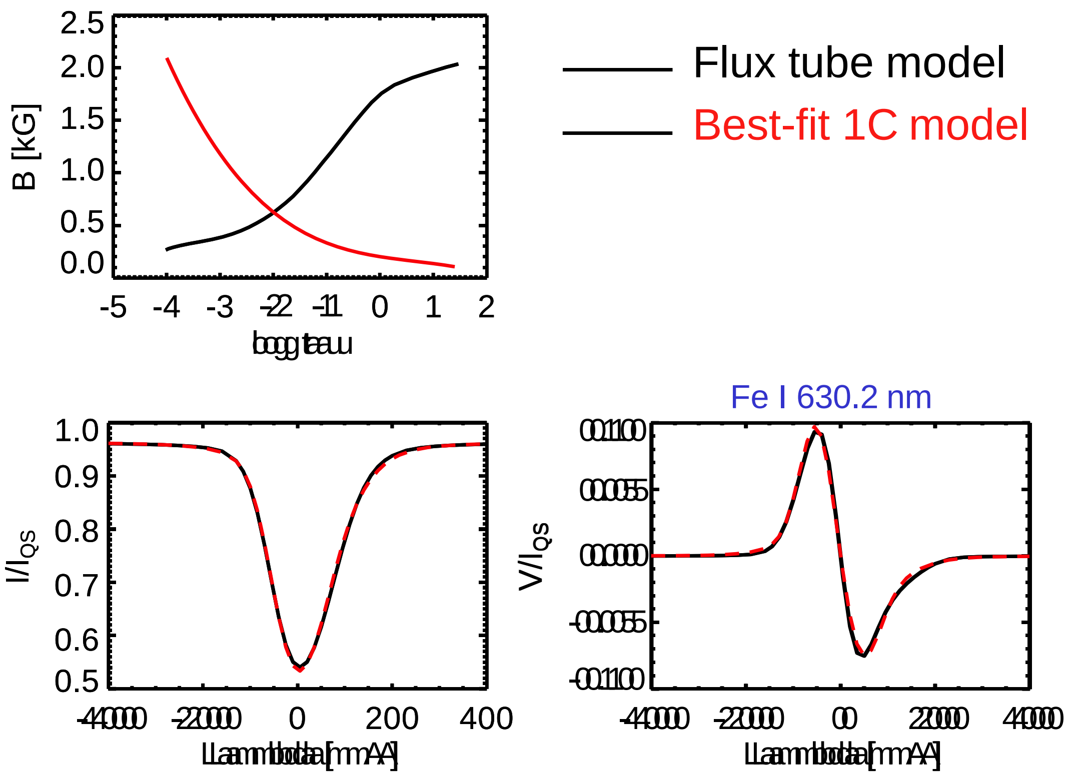
Magnetic flux tubes in facular regions



Be careful with the choice of atmospheric model!

- The results change if the physical model is changed
  - Too simplistic models; often they cannot describe the real atmosphere
  - BUT: we get information about the magnetic structure of the atmosphere!





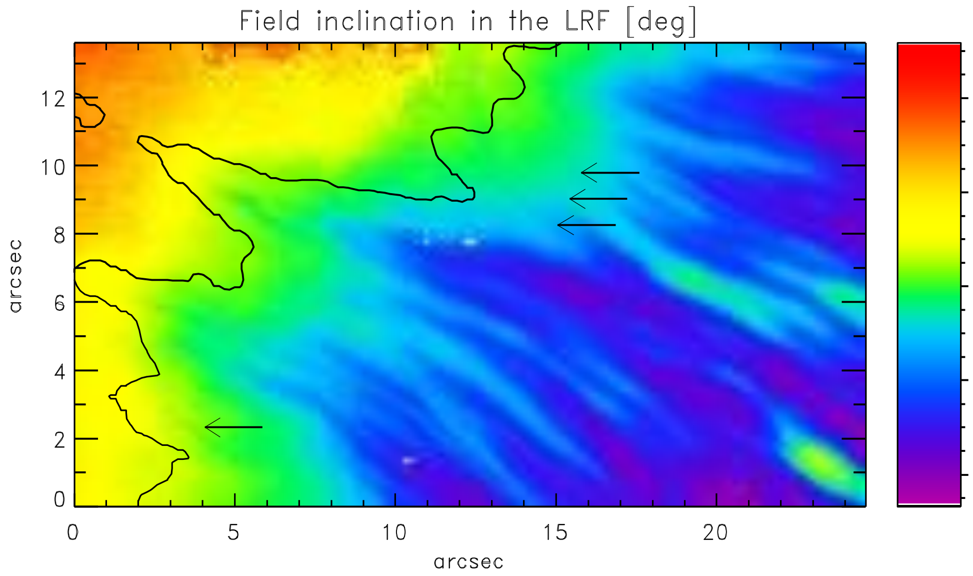
EXERCISE 3

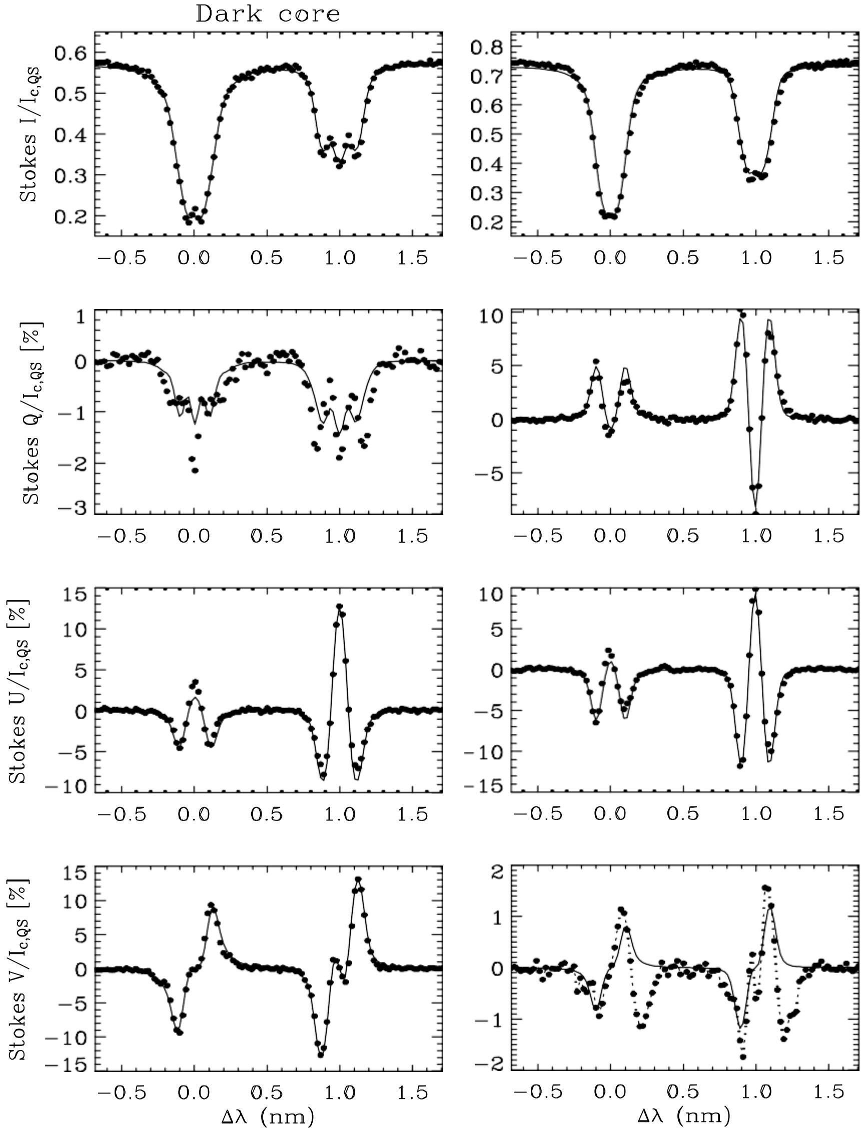
Facular profiles from ASP

Tips and tricks

- First of all, look at the profiles
- Try a ME-like inversion, it usually works
  - For example, use 1C SIR inversion with height-independent atmospheric parameters
  - If the V profiles are very asymmetric, fit only I, Q, and U
- Examine the fits: are they reasonably good?

1C SIR inversion of Hinode/SP data





EXERCISE 2

Dark-cored penumbral filament

Basilio Ruiz Cobo

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
- 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?
  - Use ME results as initialization
  - Give more weight to the strangest Stokes parameter
  - Keep it simple! See if linear stratifications (2 nodes) are sufficient
- Ask yourself if the retrieved model atmosphere makes sense!!
- Experts are always around: ask them for advice!

Running SIR: input files

CONTROL FILE

```
Number of cycles           (*):1          ! (0=synthesis)
Observed profiles          (*):perfil.per !
Stray light file              :           ! (none=no stray light contam)
PSF file                      :           ! (none=no convolution with PSF)
Wavelength grid file       (s):malla.grid ! (none=automatic selection)
Atomic parameters file        :LINES      ! (none=DEFAULT LINES file)
Abundances file               :THEVENIN   ! (none=DEFAULT ABUNDANCES file)
Initial guess model 1      (*):guess.mod  !
Initial guess model 2         :
Weight for Stokes I           :1          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q           :4          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U           :4          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V           :4          ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?   :0          ! (DEFAULT=0=no; 1=yes)
Nodes for temperature 1       :2
Nodes for electr. press. 1    :
Nodes for microturb. 1        :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?     :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)                :0.64       ! (DEFAULT: mu=1. mu<0 => West)
Estimated S/N for I           :200        ! (DEFAULT: 1000)
Continuum contrast            :           ! (DEFAULT: not used)
Tolerance for SVD             :           ! (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          ! (0 or blank=no, 1=yes)
NLTE Departures filename      :           ! blanck= LTE (Ej. depart_6494.dat'
--:**  sir.trol        (Text Fill)--L1--C0--Top----------------------------
```

PROFILE FILE

Line index	Δλ [mA]	I/I_{qs}	Q/I_{qs}	U/I_{qs}	V/I_{qs}
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	-0.000765906	-0.00178711
1.00000	-497.343	0.745269	0.000127651	-0.000170201	-0.00251047
1.00000	-475.813	0.747226	-0.000723356	0.000638255	-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
1.00000	-346.633	0.739014	0.00204242	0.00221262	-0.00659530
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
1.00000	-238.983	0.706846	-0.000468054	0.000765906	-0.0117439
1.00000	-217.453	0.700123	-0.000510604	-0.00314873	-0.0152756
1.00000	-195.923	0.702464	-0.00408483	-0.00297852	-0.0265514
1.00000	-174.393	0.678252	0.000638255	-0.000765906	-0.0284236
1.00000	-152.863	0.660679	-0.00276577	-0.00497839	-0.0282534
1.00000	-131.333	0.637872	-0.00527624	-0.00259557	-0.0340403
1.00000	-109.803	0.624213	-0.00399973	-0.00195732	-0.0439545
1.00000	-88.2730	0.576983	-0.00472309	-0.000468054	-0.0545495
1.00000	-66.7430	0.542261	-0.00421248	-0.00408483	-0.0738248
1.00000	-45.2130	0.488776	-0.00182966	-0.00425503	-0.100972
1.00000	-23.6830	0.404739	-0.00672295	-0.0135310	-0.146373
1.00000	-2.15300	0.351679	-0.00923342	-0.0158713	-0.161393
1.00000	19.3770	0.303214	-0.0100419	-0.0198710	-0.136459
1.00000	40.9070	0.259472	-0.0120843	-0.00851007	-0.0844624
1.00000	62.4370	0.237303	-0.0113184	0.00527624	-0.0372741
1.00000	83.9670	0.256664	-0.0192328	0.0169776	-0.0101695
1.00000	105.497	0.264961	-0.0185094	0.0184668	0.00974403
1.00000	127.027	0.240495	-0.0143395	0.00719101	0.0344232
1.00000	148.557	0.258706	-0.0125523	-0.00859517	0.0799521
1.00000	170.087	0.307894	-0.0135736	-0.0171478	0.145863
1.00000	191.617	0.375719	-0.00799946	-0.0212326	0.175392
1.00000	213.147	0.432439	-0.00608470	-0.0139140	0.173350
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--------

read_profiles.pro

write_profiles.pro

Running SIR: input files

emacs@orion.iaa.es

File Edit Options Buffers Tools Help

```
Number of cycles          (*):1         ! (0=synthesis)
Observed profiles         (*):perfil.per  !
Stray light file             :          ! (none=no stray light contam)
PSF file                     :          ! (none=no convolution with PSF)
Wavelength grid file      (s):malla.grid  ! (none=automatic selection)
Atomic parameters file       :LINES     ! (none=DEFAULT LINES file)
Abundances file              :THEVENIN  ! (none=DEFAULT ABUNDANCES file)
Initial guess model 1     (*):guess.mod  !
Initial guess model 2        :
Weight for Stokes I          :1         ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q          :4         ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U          :4         ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V          :4         ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?  :0         ! (DEFAULT=0=no; 1=yes)
Nodes for temperature 1      :2
Nodes for electr. press. 1   :
Nodes for microturb. 1       :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?    :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)               :0.64      ! (DEFAULT: mu=1. mu<0 => West)
Estimated S/N for I          :200       ! (DEFAULT: 1000)
Continuum contrast           :          ! (DEFAULT: not used)
Tolerance for SVD            :          ! (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         ! (0 or blank=no, 1=yes)
NLTE Departures filename     :          ! blanck= LTE (Ej. depart_6494.dat'

--:**  sir.trol         (Text Fill)--L1--C0--Top----------------------------
```

WAVELENGTH GRID FILE

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---------------------------
```

Running SIR: input files

emacs@orion.iaa.es

File Edit Options Buffers Tools Help

```
Number of cycles          (*):1          ! (0=synthesis)
Observed profiles         (*):perfil.per !
Stray light file             :           ! (none=no stray light contam)
PSF file                     :           ! (none=no convolution with PSF)
Wavelength grid file      (s):malla.grid ! (none=automatic selection)
Atomic parameters file       :LINES      ! (none=DEFAULT LINES file)
Abundances file              :THEVENIN   ! (none=DEFAULT ABUNDANCES file)
Initial guess model 1     (*):guess.mod  !
Initial guess model 2        :
Weight for Stokes I          :1          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q          :4          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U          :4          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V          :4          ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?  :0          ! (DEFAULT=0=no; 1=yes)
Nodes for temperature 1      :2
Nodes for electr. press. 1   :
Nodes for microturb. 1       :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?    :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)               :0.64       ! (DEFAULT: mu=1. mu<0 => West)
Estimated S/N for I          :200        ! (DEFAULT: 1000)
Continuum contrast           :           ! (DEFAULT: not used)
Tolerance for SVD            :           ! (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          ! (0 or blank=no, 1=yes)
NLTE Departures filename     :           ! blanck= LTE (Ej. depart_6494.dat'
```

--:** sir.trol (Text Fill)--L1--C0--Top----

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 | Atom | λ | E χ | log gf | transition

Running SIR: input files

```
emacs@orion.iaa.es
File  Edit  Options  Buffers  Tools  Help

Number of cycles          (*):1           ! (0=synthesis)
Observed profiles         (*):perfil.per  !
Stray light file             :            ! (none=no stray light contam)
PSF file                     :            ! (none=no convolution with PSF)
Wavelength grid file      (s):malla.grid  ! (none=automatic selection)
Atomic parameters file       :LINES       ! (none=DEFAULT LINES file)
Abundances file              :THEVENIN    ! (none=DEFAULT ABUNDANCES file)
Initial guess model 1     (*):guess.mod   !
Initial guess model 2        :
Weight for Stokes I          :1
Weight for Stokes Q          :4
Weight for Stokes U          :4
Weight for Stokes V          :4
AUTOMATIC SELECT. OF NODES?  :0
Nodes for temperature 1      :2
Nodes for electr. press. 1   :
Nodes for microturb. 1       :1
Nodes for magnetic field 1   :1
--:**  sir.trol        (Text Fill)--
```

MODEL FILE

```
emacs@orion.iaa.es
File  Edit  Options  Buffers  Tools  Help

 1.191199      1.000000      0.0000000E+00
```

log τ	T	P_e	v_{mic}	B	v_{LOS}	γ	φ	z [km]	P_g	ρ
1.4000	8886.7	3.07074E+03	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	-1.1482E+02	2.1731E+05	3.7768E-07
1.3000	8728.1	2.52511E+03	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	-1.0502E+02	2.1085E+05	3.7393E-07
1.2000	8569.4	2.06383E+03	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	-9.5670E+01	2.0474E+05	3.7053E-07
1.1000	8410.7	1.67605E+03	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	-8.6739E+01	1.9896E+05	3.6747E-07
1.0000	8252.1	1.35199E+03	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	-7.8201E+01	1.9347E+05	3.6474E-07
0.9000	8093.4	1.08291E+03	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	-7.0025E+01	1.8826E+05	3.6231E-07
0.8000	7914.7	8.37268E+02	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	-6.2107E+01	1.8324E+05	3.6103E-07
0.7000	7696.1	6.04266E+02	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	-5.4178E+01	1.7821E+05	3.6153E-07
0.6000	7447.4	4.09270E+02	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	-4.5889E+01	1.7294E+05	3.6293E-07
0.5000	7178.8	2.61987E+02	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	-3.6876E+01	1.6719E+05	3.6429E-07
0.4000	6880.1	1.54640E+02	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	-2.6596E+01	1.6061E+05	3.6536E-07
0.3000	6592.3	9.00154E+01	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	-1.4459E+01	1.5286E+05	3.6304E-07
0.2000	6322.8	5.28586E+01	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	0.0000E+00	1.4374E+05	3.5603E-07
0.1000	6084.1	3.25596E+01	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	1.7050E+01	1.3330E+05	3.4316E-07
0.0000	5875.4	2.13316E+01	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	3.6610E+01	1.2186E+05	3.2486E-07
-0.1000	5696.8	1.49885E+01	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	5.8242E+01	1.0997E+05	3.0238E-07
-0.2000	5543.1	1.11864E+01	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	8.1274E+01	9.8263E+04	2.7768E-07
-0.3000	5409.4	8.73575E+00	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	1.0504E+02	8.7213E+04	2.5255E-07
-0.4000	5295.8	7.06379E+00	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	1.2903E+02	7.7100E+04	2.2806E-07
-0.5000	5192.1	5.80998E+00	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	1.5291E+02	6.8018E+04	2.0521E-07
-0.6000	5093.5	4.81886E+00	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	1.7653E+02	5.9945E+04	1.8436E-07
-0.7000	4994.8	4.00224E+00	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	1.9975E+02	5.2811E+04	1.6563E-07
-0.8000	4906.1	3.34879E+00	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	2.2255E+02	4.6524E+04	1.4855E-07
-0.9000	4827.5	2.82042E+00	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	2.4496E+02	4.0987E+04	1.3300E-07
-1.0000	4758.8	2.39137E+00	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	2.6702E+02	3.6110E+04	1.1887E-07
-1.1000	4690.1	2.02242E+00	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	2.8878E+02	3.1812E+04	1.0625E-07
-1.2000	4631.5	1.72307E+00	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	3.1028E+02	2.8020E+04	9.4772E-08
-1.3000	4582.8	1.48063E+00	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	3.3157E+02	2.4673E+04	8.4341E-08
-1.4000	4539.1	1.27741E+00	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	3.5269E+02	2.1721E+04	7.4964E-08
-1.5000	4495.5	1.10053E+00	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	3.7366E+02	1.9116E+04	6.6613E-08
-1.6000	4456.8	9.52386E-01	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	3.9451E+02	1.6816E+04	5.9107E-08
-1.7000	4428.2	8.33382E-01	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	4.1526E+02	1.4788E+04	5.2313E-08
-1.8000	4409.5	7.37876E-01	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	4.3592E+02	1.3002E+04	4.6192E-08
-1.9000	4390.8	6.53162E-01	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	4.5649E+02	1.1432E+04	4.0787E-08
-2.0000	4372.2	5.78038E-01	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	4.7698E+02	1.0052E+04	3.6016E-08
-2.1000	4353.5	5.11436E-01	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	4.9737E+02	8.8384E+03	3.1803E-08

```
--:--  guess_1.mod      (Text Fill)--L1--C0--Top----
Loading mwheel...done
```

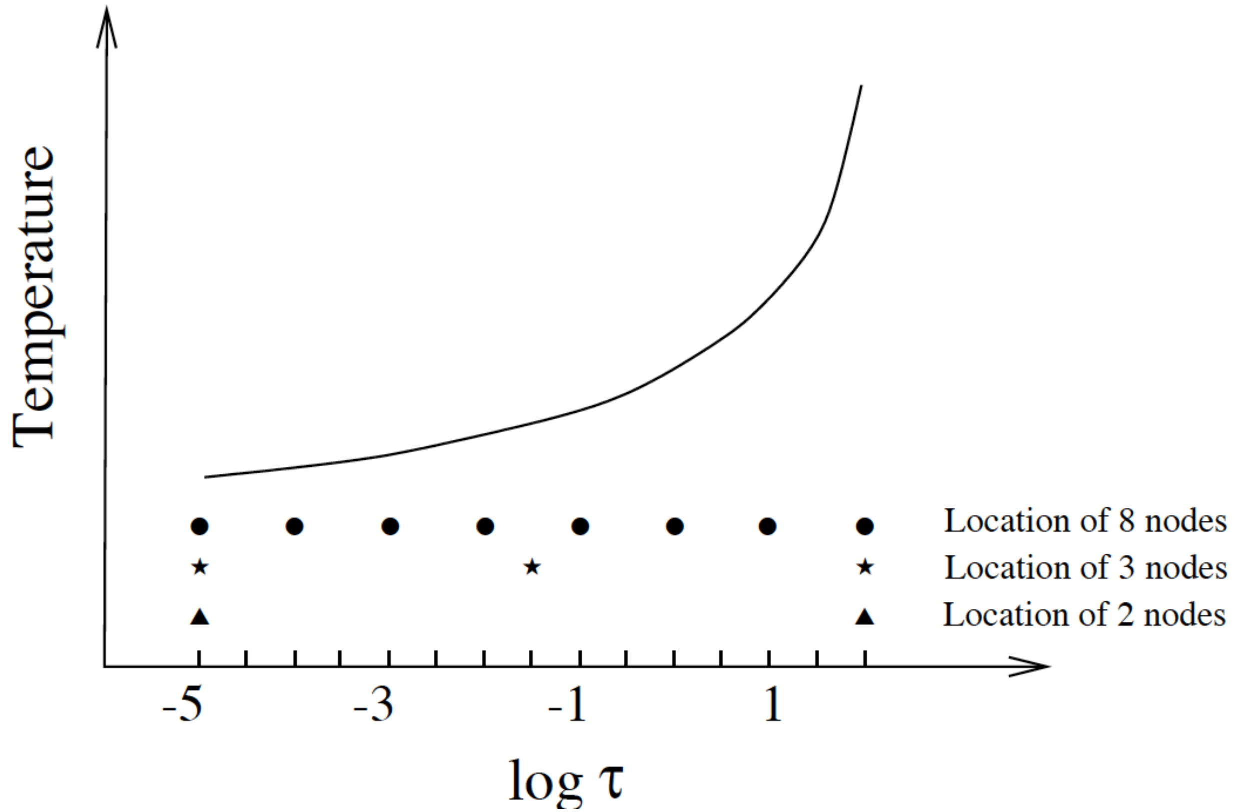
read_model.pro

write_model.pro

modelador3.x

Concept of nodes

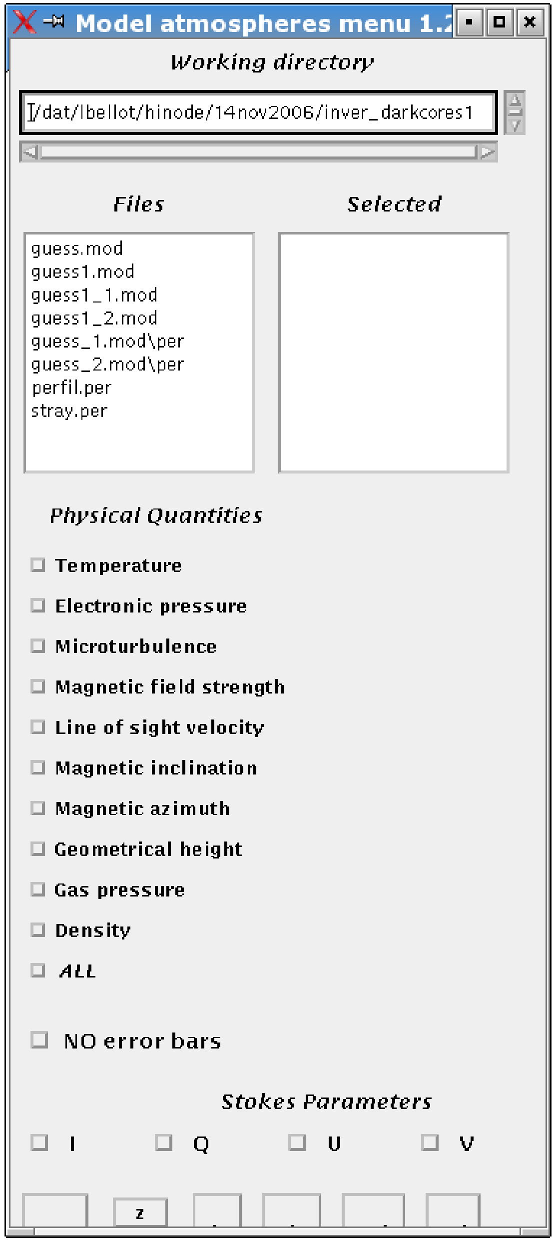
- Keeping the number of free parameters small:
  - Atmospheric parameters perturbed in coarse grid (nodes)
  - Full stratifications in finer grid by cubic spline interpolation

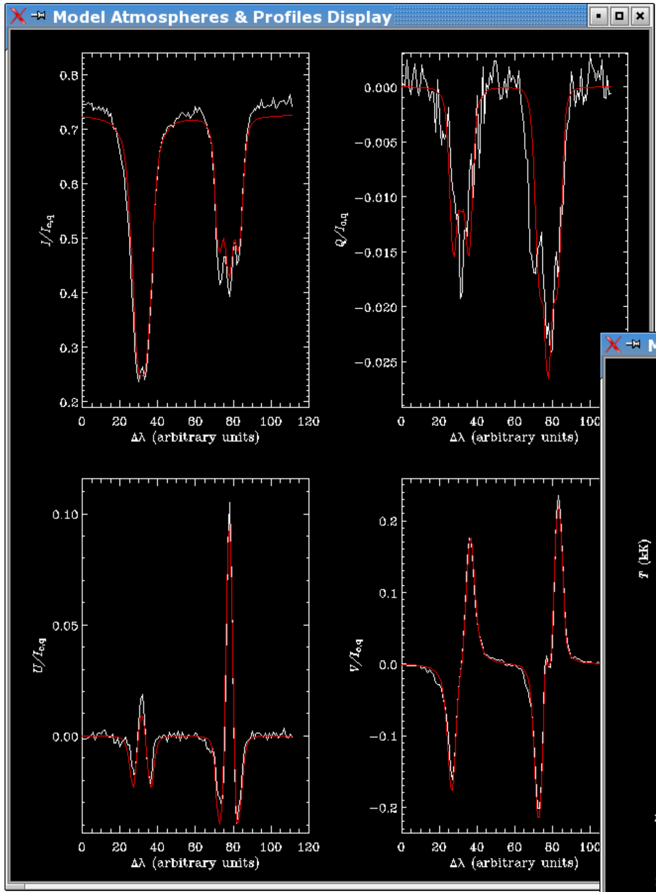


Executing the inversion

```
echo sir.trol | sir.x
```

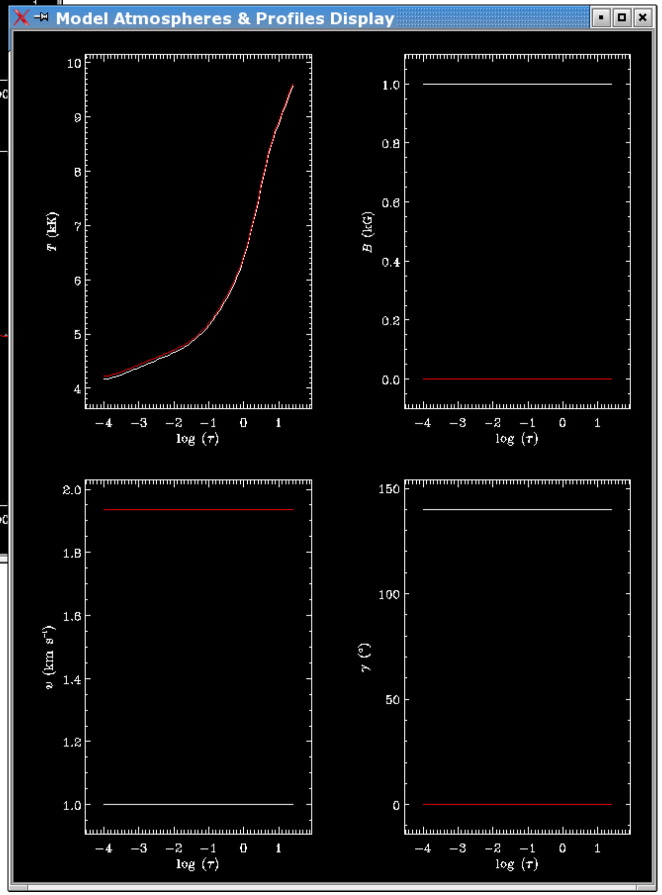
Visualizing SIR results: graphics2.pro





Stokes profiles

Model atmospheres



SIR exercises

Download exercises from

http:/SIR/SIR_exercises.tar

Exercise 1

Spectral synthesis and inversion of synthetic profiles

Use HSRA model to synthesize Stokes profiles with

1. constant B, inclination and v_{LOS} (e.g., 1 kG, 60°, 2 km/s)
2. constant v_{LOS}, gradients of B and inclination
3. gradients of B, inclination and v_{LOS}

Invert profiles from (3), starting from initial guess model with flat stratifications of B, v_{LOS}, and inclination (modify hsra.mod)

- 1 node in B, vlos, inclination
- 2 nodes in B, v_{LOS} and inclination

```
read_model,filename,tau,t,pe,mic,b,vel, gamma,phi,mac,filling,sl
b=1000.+200* tau
write_model,filename,tau,t,pe,mic,b,vel,gamma,phi,mac,filling,sl
```

Exercise 2

Inversion of profiles from dark-cored penumbral filament

Hinode/SP observations with SNR~1000, no telluric lines,
two lines Fe I 630.1 and 630.2 nm

Strong, symmetric signals

1. What kind of model would you use to invert them?
2. Can the fit be improved with more nodes in T? (use 2 cycles!)
3. What happens with 2 nodes in B and v_{LOS}?
4. What happens with 10 nodes in B and v_{LOS}?

If no instrumental PSF is available, use macroturbulence to mimick its effect (i.e, invert v_{mac})
Use more weight for Q, U and V to force better fits to those parameters
A worse equivalent SNR does not necessarily mean a worse fit (i.e., a lower chi^2)
Beware of models with too much freedom!

Exercise 3

Inversion of facular profiles in quiet Sun

Advanced Stokes Polarimeter observations, averaged over facular region, SNR~10000, but poor spatial resolution

Two lines Fe I 630.1 and 630.2 nm (plus telluric lines!)

Strong signals, large Stokes V area and amplitude asymmetries

1. What kind of model would you try to invert them?
2. Use two cycles, increasing number of nodes in 2nd cycle
3. Invert stray-light fraction, micro- and macro-turbulence

We invert Stokes I and V only, so vertical fields should be assumed
Use large negative number (e.g., -2) in profiles to ignore blends in Stokes I during inversion
Use instrumental PSF and macroturbulence at the same time
Use stray light profile
Use weights of 10 and 100 for Stokes V

Exercise 4

Inversion of quiet-Sun internetwork profiles

Hinode/SP observations at disk center, integrated for 6 min, SNR~10^5, still high spatial resolution

Two lines Fe I 630.1 and 630.2 nm

Extremely weak signals, but linear polarization clearly seen. Large asymmetries.

1. What kind of model would you try to invert them?
2. Use three cycles with increasing number of nodes
3. Invert stray-light fraction and microturbulence (flat stratification)
4. Interpret resulting model

No need for macroturbulence when high-resolution data are inverted using telescope PSF
Use following weights: 1,4,4,4

Exercise 5

Inversion of sunspot penumbral profiles near PIL

Hinode/SP observations with SNR~1000, no telluric lines, two lines Fe I 630.1 and 630.2 nm

Strong signals, but Stokes V profile with three lobes......

1. What kind of model would you use to invert them?
2. One-component model with opposite magnetic polarities along LOS? Two-component model?
3. Try both!

Inversion of these profiles will not be easy. Do your best!
Give more weight to Stokes V to force better fits. Increase weight with cycle
If everything fails, use superpowers...

Exercise 6

Internetwork profiles with very weak Q, U signals

Simulated Hinode obs, SNR~800, Fe I 630.1 and 630.2 nm

Synthesize Stokes profiles from 2 component model:

1. magnetic atmosphere with B=200 G, γ = 10º, filling factor=5%
2. non-magnetic atmosphere (hsra.mod), filling factor=95%
3. Save profiles. Then add noise at the level of 10^{-3} using *add_noise,filename,1.25e-3*. Save the noisy profiles.

Invert noise-free, then noisy profiles. Use simple 2C model, freezing 2nd component to hsra.mod.

Interpret resulting field inclinations.
If you are curious (*you should!*), repeat exercise with only one line

Use 2C models for synthesis and inversion
Beware of noisy linear polarization profiles, especially when only one line is available!

Exercise 7

Inversion of CRISP profiles from sunspot penumbrae

SST/CRISP observations with SNR~500, sequential spectral sampling of Fe I 617.3 nm (30 wavelengths in ~30 s)

Strongly Doppler-shifted polarization profiles

1. What kind of model would you use to invert them?
2. Try stray-light contamination, 1C or 2C model
3. You are on your own! I have not inverted these profiles yet...

Example of Stokes profiles observed with a Fabry-Pérot interferometer
Extremely high spatial resolution, but modest spectral resolution (~50 mA at 617 nm)
Sequential sampling of line means first and last wavelengths are observed ~30 s apart

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

- 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)
  - Orozco Suárez et al. (2007): local stray-light profile accounts for telescope diffraction