# LITpro model fitting software for optical interferometry

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# What is LITpro ?

- Parametric model fitting software for interferometry
  - LITpro: Lyon Interferometric Tool prototype
  - Conceived and developed up-to-now at CRAL in Lyon
  - Graphical User Interface developed at JMMC (Jean-Marie Mariotti Center)
  - Maintained and improved by the "model-fitting" group at JMMC (several labs in France)

- Aim: "exploit the scientific potential of existing interferometers", e.g. VLTI

- Complementary to image reconstruction
  - Sparse (u,v) coverage
  - Reconstructed images identify models
  - Model fitting extracts measured quantities

# Leading requirements of LITpro

- Accessible to "general users" + flexible for "advanced users"
  - Opposite needs:
    - General users want simplicity (stepping stone)
    - Advanced users want a powerful tool (pioneering work)
  - Exchanges:
    - general users —(needs)—› advanced users
    - general users ‹—(training)— advanced users
  - Progress must benefit to everybody (share experiences)

- Concentrate on the model of the object
  - Easy implementation of new models.
  - Only need to compute the Fourier transform of the object specific intensity on given coordinates (***u***, ***v***, ***λ***, ***t***)

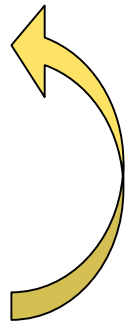
# Leading requirements ⇒ implementation

- Accessible to astronomers + flexible for advanced users
  - flexible ⇒ high level language (*Yorick*)
    - easy modifications and adds in the software
    - "expert layer"
  - accessible ⇒ GUI
    - new abilities exposed once they are validated in the "expert" layer
- Concentrate on the model of the object
  - From Fourier transform of the object:
    - Modeled data (interferometric, spectroscopic, photometry, …)
    - Images
  - LITpro also provides
    - Modeling builder (with GUI or filling a form)
    - Fitter "engine"
    - Tools for analysis

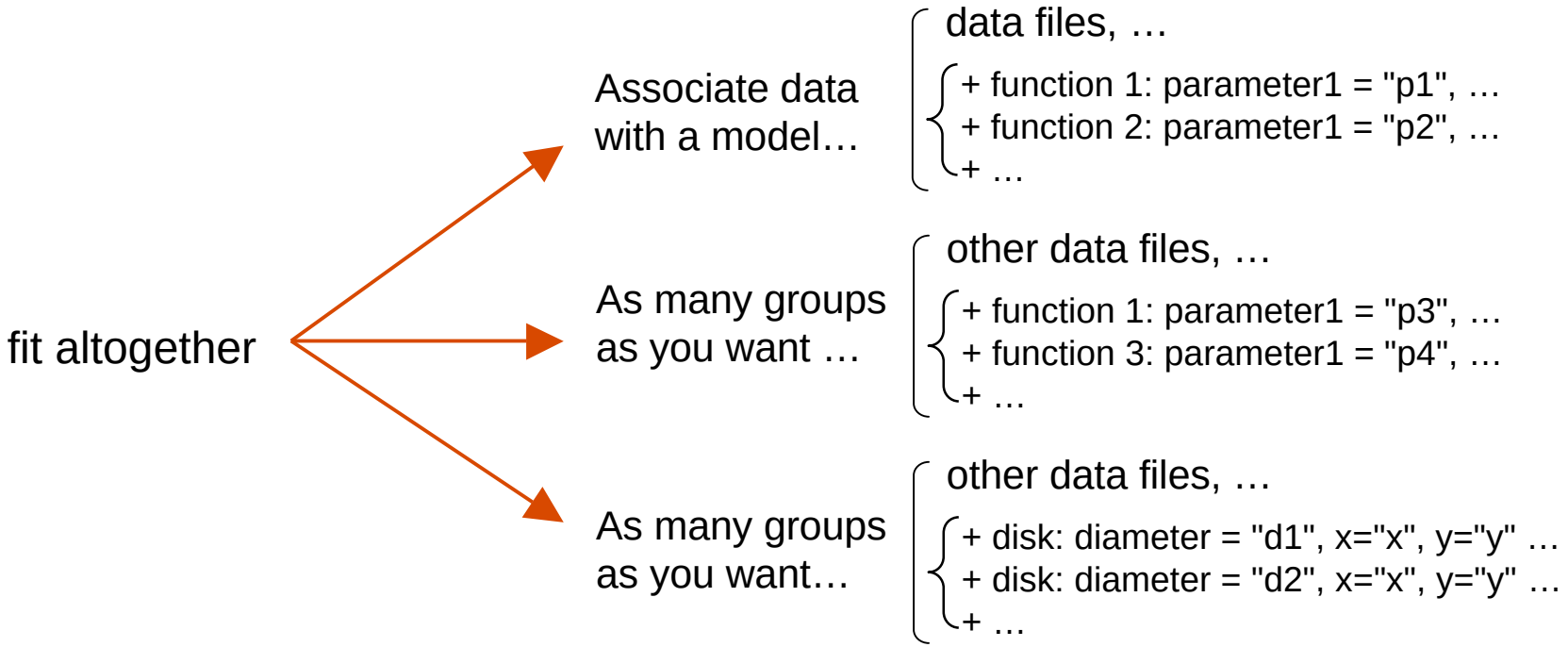
# Types of data

- OIFITS
  - Squared visibilities (VIS2)
  - Complex visibilities (VISAMP, VISPHI)
  - Bispectrum (T3AMP, T3PHI)

- Others
  - Spectral Energy Distribution (dispersed fringes mode)
  - Photometry (see example)
  - …



# Setting up the fitting process / principle



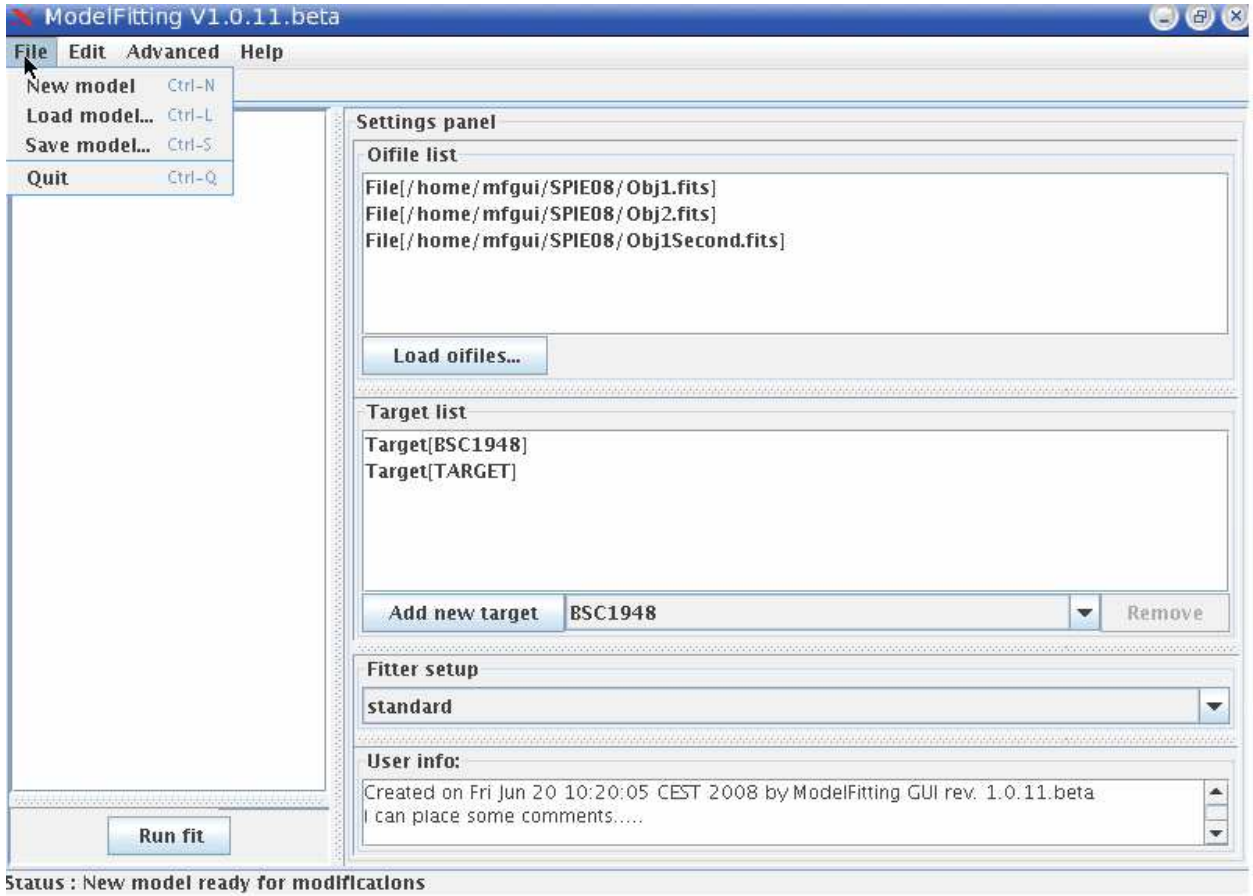

- Through the GUI
  or through a form (file editor)

# Fitting process

- Levenberg-Marquardt algorithm (modified)
  - Combined with a Trust Region method
  - Bounds on the parameters
  - Partial derivatives of the model by finite differences

- More latter…
  - Search of global minimum

# Implementation of the GUI




- Implemented in JAVA
  - Web service
  - Links with other services (JMMC)
    - Virtual Observatory
    - Data explorer
    - User feedback
    - …
- GUI only tell "expert layer" (*Yorick*) what to do
- First public release: October 2009

# Work in progress

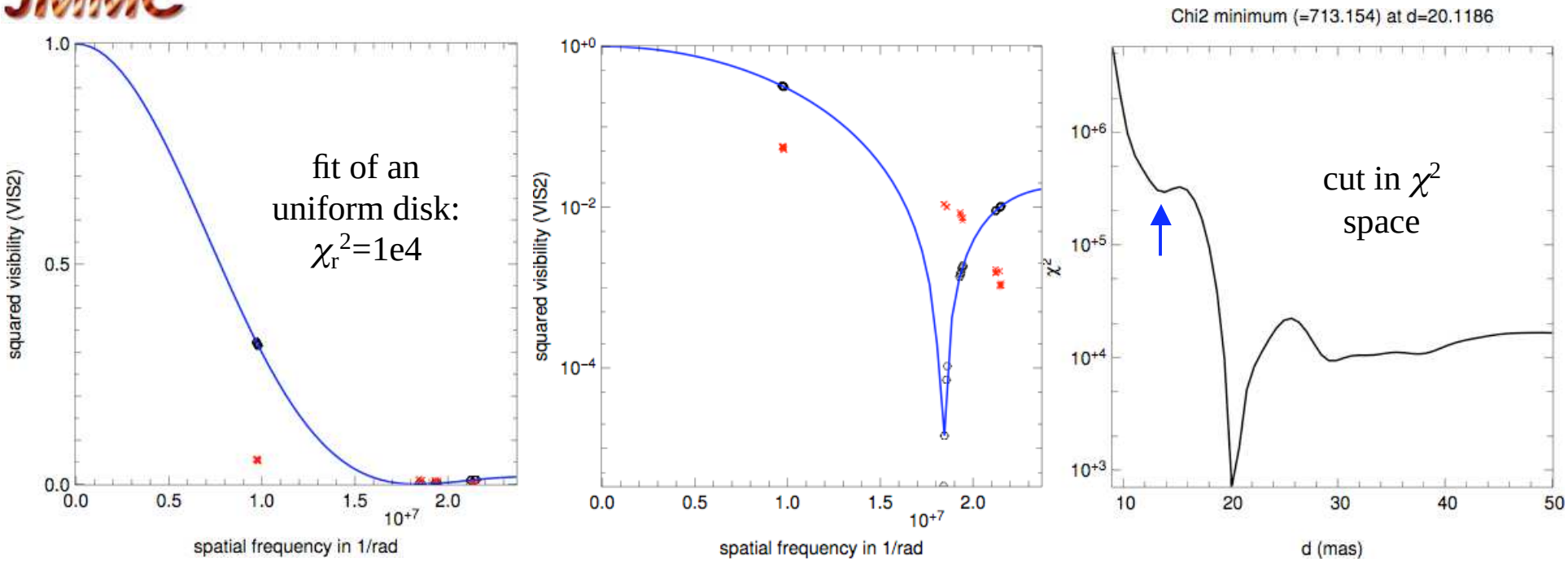
- LITpro
  - First public release Octobre 2009

- High in the list for near future
  - Search for global minimum of $\chi^2$
  - Tools for multichromatic modeling (e.g. dynamics)
  - Cooperation between Image reconstruction and Model fitting

# On the adventure of model fitting

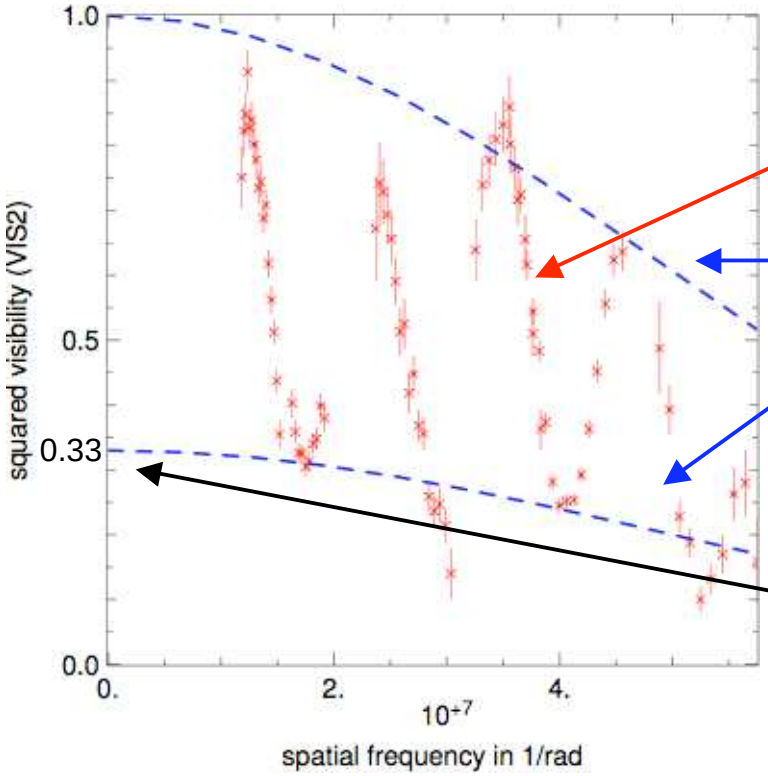
- Local minimum
  - example of an uniform disk
- Observe your data… the Guru way 
  - useful for the initial guess (local minimum)
- Degeneracies
  - on the total energy
- Example of a "heterogeneous" model-fitting

# Beware of local minima !




- local minima exists even for a uniform disk, depending on data
- what to do ?
  - change first guess
  - cuts in $\chi^2$ sub-spaces
  - use bounds
  - do not forget the low frequencies (or just confirm what we already know…)

# Observe your data !




$$V^2_{\min} = 0.33 \Rightarrow r = 0.27$$

Modulation = binary (or >2 components)

Attenuation = components resolved

binary convolved by an extended function

⇩

Fourier transform multiplied by a window

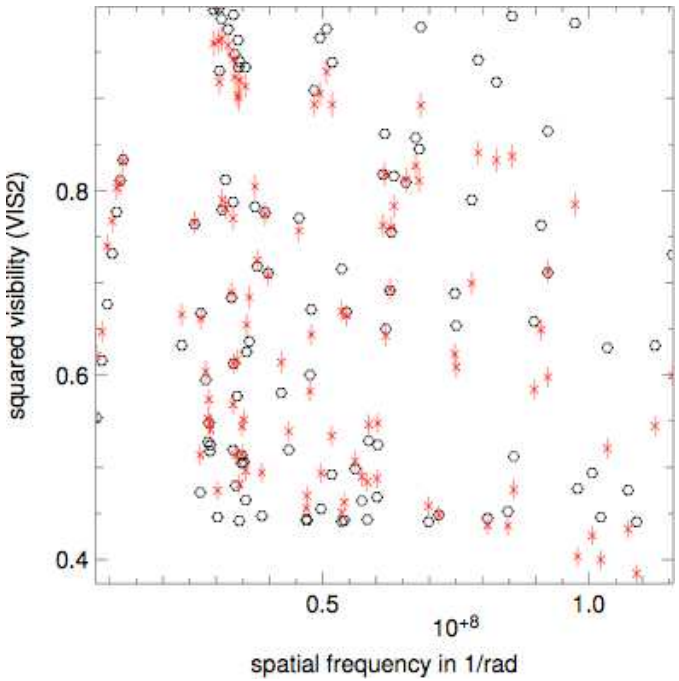
Minimum of modulation gives intensity ratio of the components:

$$r = \frac{1 - \sqrt{V^2_{\min}}}{1 + \sqrt{V^2_{\min}}}$$

*— Starting from a good first guess may be decisive —*

# Degeneracy on total energy

fit of a binary




Model of the binary

- main component at (0,0) with intensity i1
- secondary at (x,y) with intensity i2

```
Final values for fitted parameters and standard deviation:
      i1 =     0.20152 +/- 9.95e+04
      i2 =      0.9982 +/- 4.93e+05
       x =     -6.6657 +/-  0.00441  mas
       y =       20.08 +/-  0.00631  mas
.
       Chi2: initial= 7.376e+04 - final=  1983 - sigma= 14.2127
reduced Chi2: initial=     730.3 - final= 19.63 - sigma= 0.14072
Number of degrees of freedom = 101
.
--- Correlation matrix ---
           i1       i2        x        y
  i1        1        1   0.0011  -0.0015
  i2        1        1   0.0011  -0.0015
   x   0.0011   0.0011        1    -0.44
   y  -0.0015  -0.0015    -0.44        1
```

- this degeneracy does not change $\chi^2$
- huge errors because of no curvature of $\chi^2(\boldsymbol{x}_{best})$ for i1+i2
- this prevents reading the values of i1 and i2

# Degeneracy on total energy: solution

- FAQ:
  - We could construct a normalized model !
  - Yes, but we want to combine all sorts of functions…
  - We could combine normalized functions !
  - Not always possible ! Ex: disk with constant amplitude (spot on a star)

- *When total energy is not fixed by the data*, we add this constraint:

$$\chi^2_\star(\boldsymbol{x}) = \chi^2(\boldsymbol{x}) + N_d \left( \frac{\sum_i \Delta\lambda_i \, m_i(\boldsymbol{x}, \boldsymbol{u} = 0)}{\sum_i \Delta\lambda_i} - 1 \right)^2$$

This drives total energy to unity

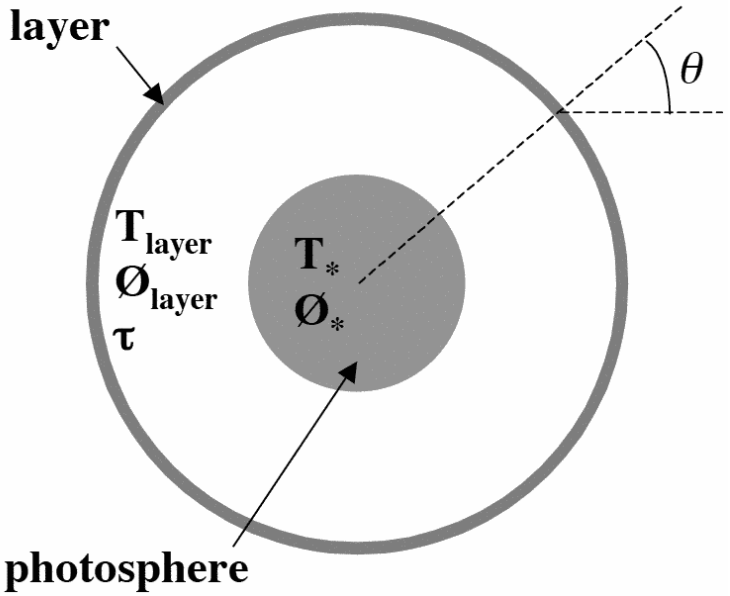
- But the added term MUST BE ZERO at the end of the fit !
  - If not: $\chi^2$ is changed and quantities are wrong !

- Other degeneracies in practice
  - translation of the map (unless phase reference)
  - symmetries if no phase
  - …

# Degeneracy on total energy: solved

```
Final values for fitted parameters and standard deviation:
      i1 =     0.83203 +/-   0.0812
      i2 =     0.16797 +/-   0.0164
       x =     -6.6657 +/-  0.00441  mas
       y =       20.08 +/-  0.00631  mas
.
        Chi2: initial= 7.376e+04 - final=  1983 - sigma= 14.2127
reduced Chi2: initial=     730.3 - final= 19.63 - sigma= 0.14072
Number of degrees of freedom = 101
.
--- Correlation matrix ---
           i1       i2        x        y
  i1        1        1  0.00021  0.00058
  i2        1        1  -0.0011  -0.0029
   x  0.00021  -0.0011        1    -0.44
   y  0.00058  -0.0029    -0.44        1
```

# Example: chromatic model + heterogeneous data / 1




*Perrin et al, A&A 426, 279, 2004*

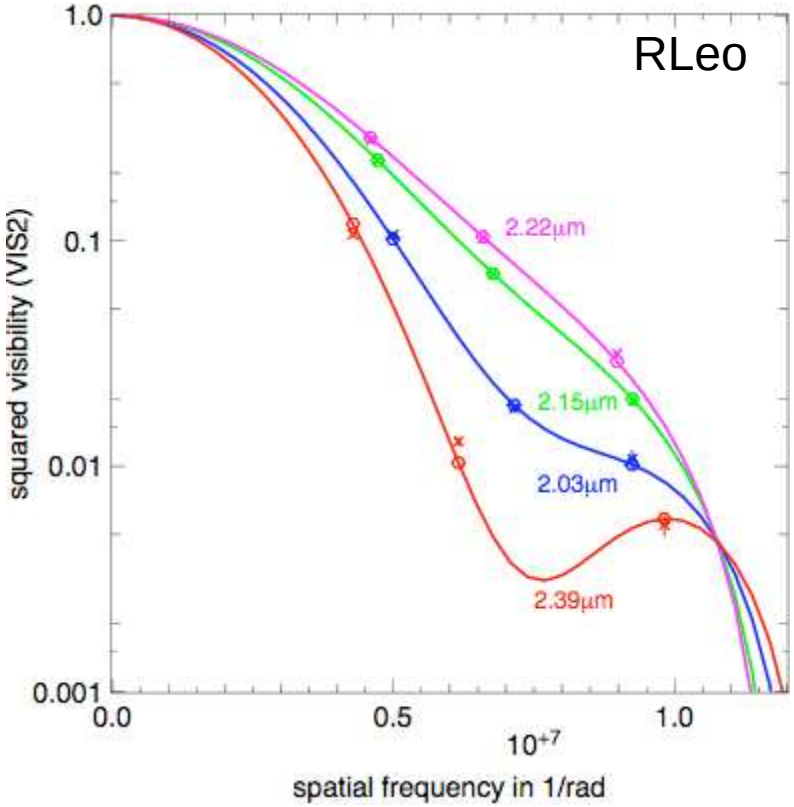
$$I(\lambda,\theta) = B(\lambda,T_\star)\exp(-\tau(\lambda)/\cos(\theta)) + B(\lambda,T_{\rm layer})\left[1-\exp(-\tau(\lambda)/\cos(\theta))\right]$$

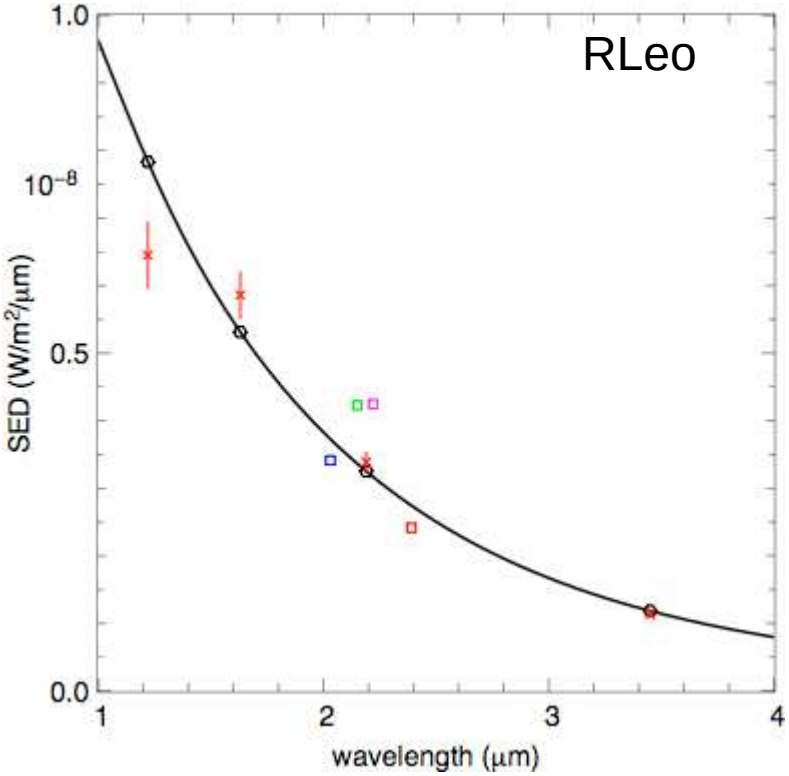
for $\sin(\theta) \le \text{Ø}_\star/\text{Ø}_{\rm layer}$ and:

$$I(\lambda,\theta) = B(\lambda,T_{\rm layer})\left[1-\exp(-2\tau(\lambda)/\cos(\theta))\right]$$

- Why this example in particular ?
  - Fitting procedure is difficult
    - Need to improve procedures for "general users" (accessible ?)
    - How LITpro performs ?
  - Fitting interferometric + photometric data
    - Assess how it can help the fitting process

# Example: chromatic model + heterogeneous data / 2

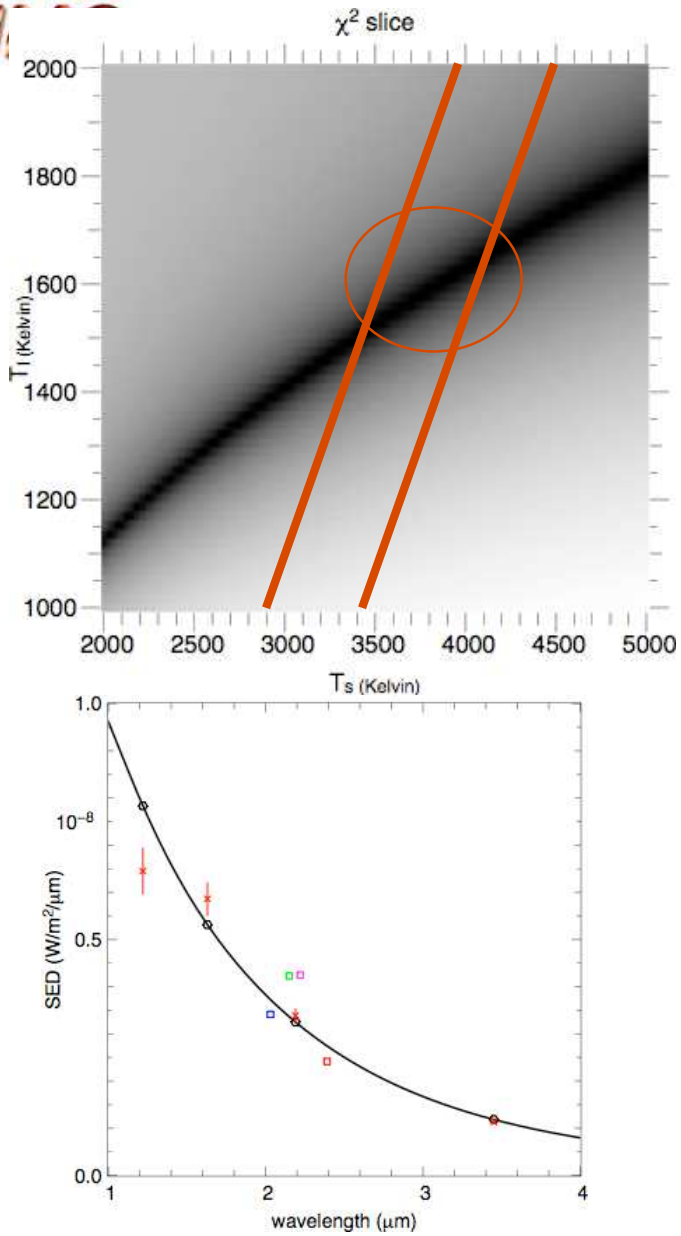



*Perrin et al, A&A 426, 279, 2004*

- squared visibilities : 4 sub-bands in K band (IOTA)
- magnitudes : J, H, K, L bands (Whitelock et al 2000)

# Perrin et al. fitting procedure



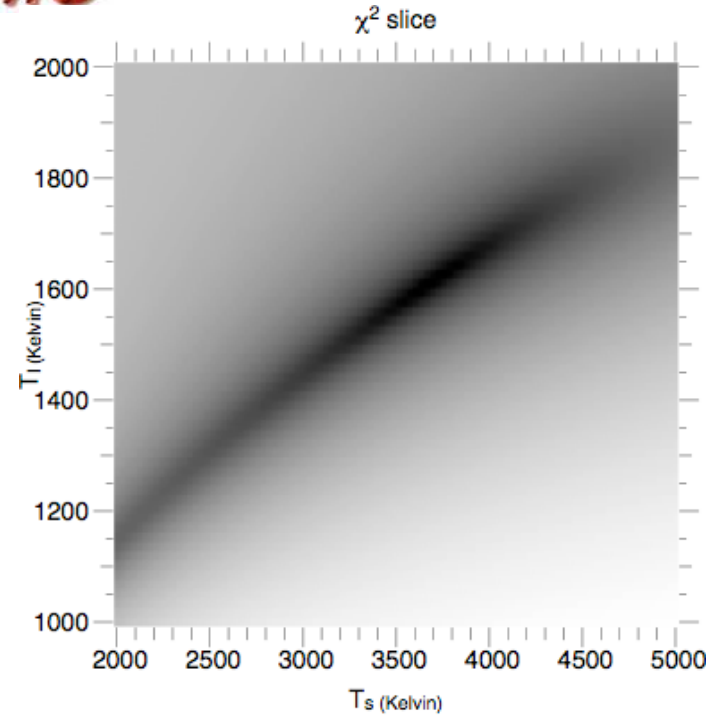

1) $(R_*, R_L)$ from gridding
   - fit all other parameters from fixed sampled values $(R_*, R_L)$
   - arbitrary initial values of other parameters

2) $(T_*, T_L)$ from gridding + intersection with K photometry
   - Difficult to use the other bandwidths

3) Fit 4 optical depths from fixed other parameters

4) Compare photometry with other bandwidths: J, H, L.

# Simultaneous fitting of all the data




1) Overall size of the object ?
   - Radius of uniform disk: 18 mas

2) Overall temperature ?
   - For an uniform disk: 1540K

3) Fit from this initial values
   - Initial values of optical depths set to zero => uniform disk

May be useful (and reassuring) to use physical arguments for the first guess…

# Comparison of results

| Parameter | Perrin et al. | Simultaneous fit | Fit with relative photometry |
|---|---|---|---|
| $R_\star$ (mas) | 10.94 ± 0.85 | 11 ± 0.13 | 11 ± 0.19 |
| $R_L$ (mas) | 25.00 ± 0.17 | 25.4 ± 0.16 | 25.4 ± 0.18 |
| $T_\star$ (K) | 3856 ± 119 | 3694 ± 113 | 3778 ± 163 |
| $T_L$ (K) | 1598 ± 24 | 1613 ± 35 | 1681 ± 174 |
| $\tau_{2.03}$ | 1.19 ± 0.01 | 1 ± 0.14 | 0.9 ± 0.35 |
| $\tau_{2.15}$ | 0.51 ± 0.01 | 0.42 ± 0.08 | 0.36 ± 0.17 |
| $\tau_{2.22}$ | 0.33 ± 0.01 | 0.27 ± 0.05 | 0.23 ± 0.11 |
| $\tau_{2.39}$ | 1.37 ± 0.01 | 1.2 ± 0.13 | 1.08 ± 0.32 |
| $\gamma$ | – | – | 0.9 ± 0.2 |

Fit with only relative photometry, like the SED given by an optical interferometer

Correlation matrix

| | R_l | Rs_ratio | T_l | T_s | tau1 | tau2 | tau3 | tau4 |
|---|---|---|---|---|---|---|---|---|
| R_l | 1 | -0.66 | -0.36 | 0.14 | 0.21 | 0.17 | 0.16 | 0.13 |
| Rs_ratio | -0.66 | 1 | 0.71 | -0.6 | -0.67 | -0.67 | -0.66 | -0.62 |
| T_l | -0.36 | 0.71 | 1 | -0.74 | -0.94 | -0.93 | -0.93 | -0.92 |
| T_s | 0.14 | -0.6 | -0.74 | 1 | 0.91 | 0.91 | 0.92 | 0.92 |
| tau1 | 0.21 | -0.67 | -0.94 | 0.91 | 1 | 0.99 | 0.99 | 0.99 |
| tau2 | 0.17 | -0.67 | -0.93 | 0.91 | 0.99 | 1 | 0.99 | 0.99 |
| tau3 | 0.16 | -0.66 | -0.93 | 0.92 | 0.99 | 0.99 | 1 | 0.99 |
| tau4 | 0.13 | -0.62 | -0.92 | 0.92 | 0.99 | 0.99 | 0.99 | 1 |

# Conclusions on the adventure

- Local minima even with uniform disk
  - cuts in $\chi^2$ space
  - change first guess
  - check $\chi_r^2$ if variations are significant
- Model-fitting algorithm has no brain
  - use yours: look carefully at the data: (u,v) coverage, baselines
- Degeneracies may appear
  - check covariances of parameters
  - check ON/OFF normalization of total energy
- Quality of the fit / model
  - chi2
  - understand errors *and correlations* on parameters
  - various plots