OIMODELER

A modular modelling software for optical interferometry

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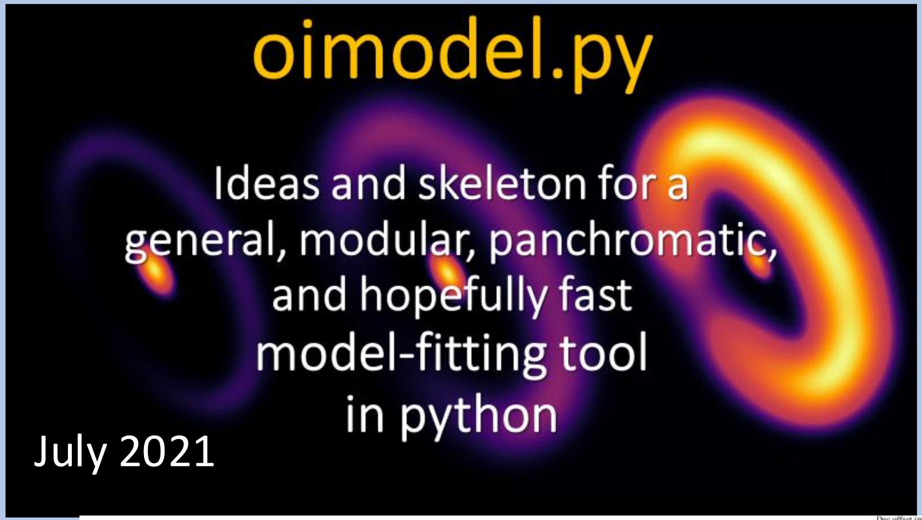
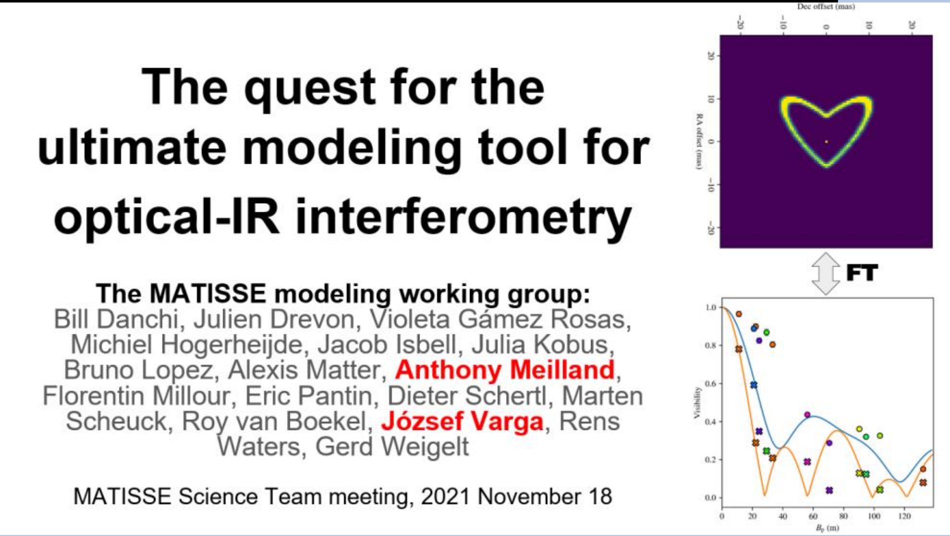
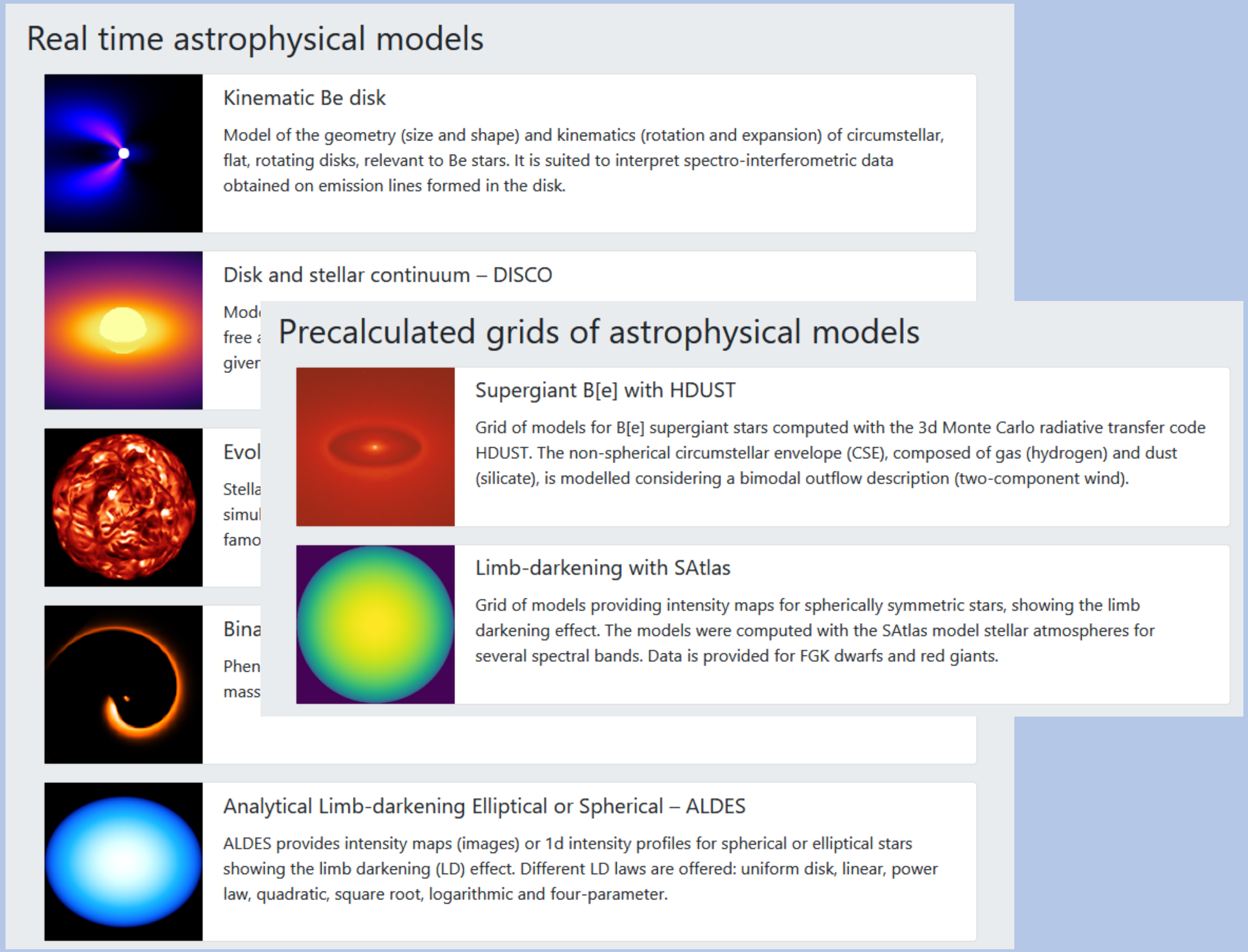
Context of the project (2021)





MATISSE group



JMMC/AMHRA

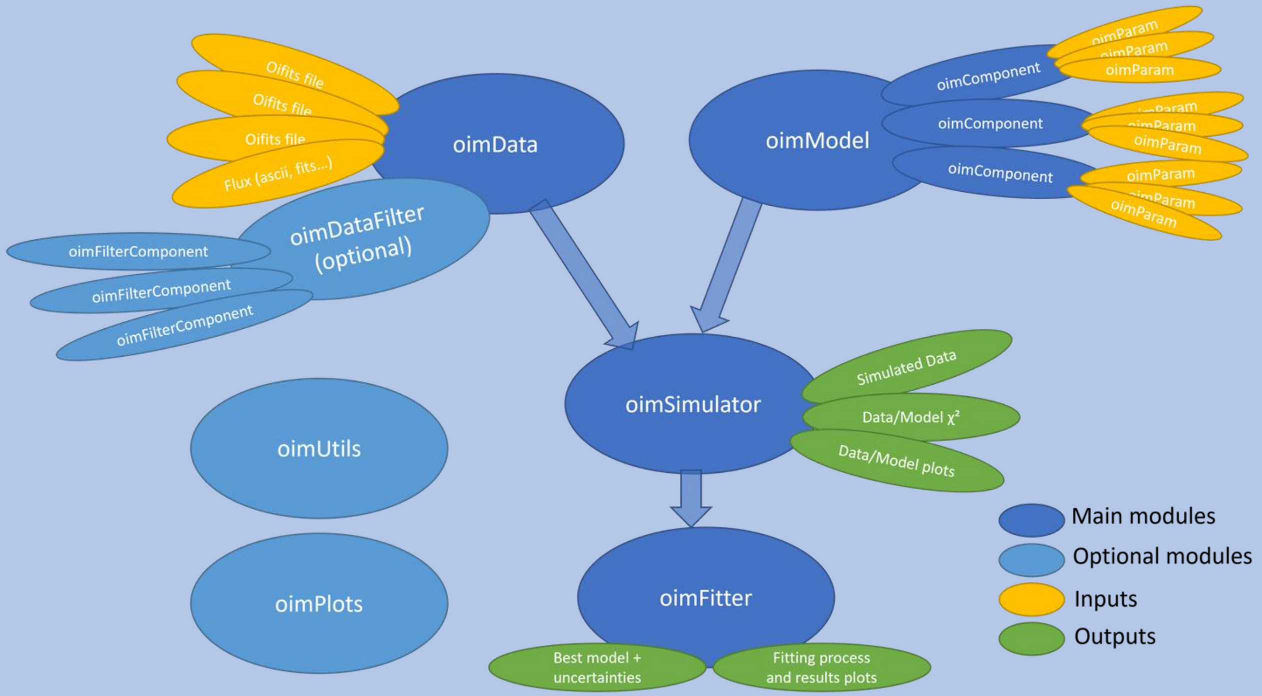
1 - The oimodeler project

Why?

- **Visibility data → Images**

Aims: developing an

- **open source,**
- **modular (object-oriented),**
- **and easily expandable**
- **python library**
- **to model optical interferometric data**



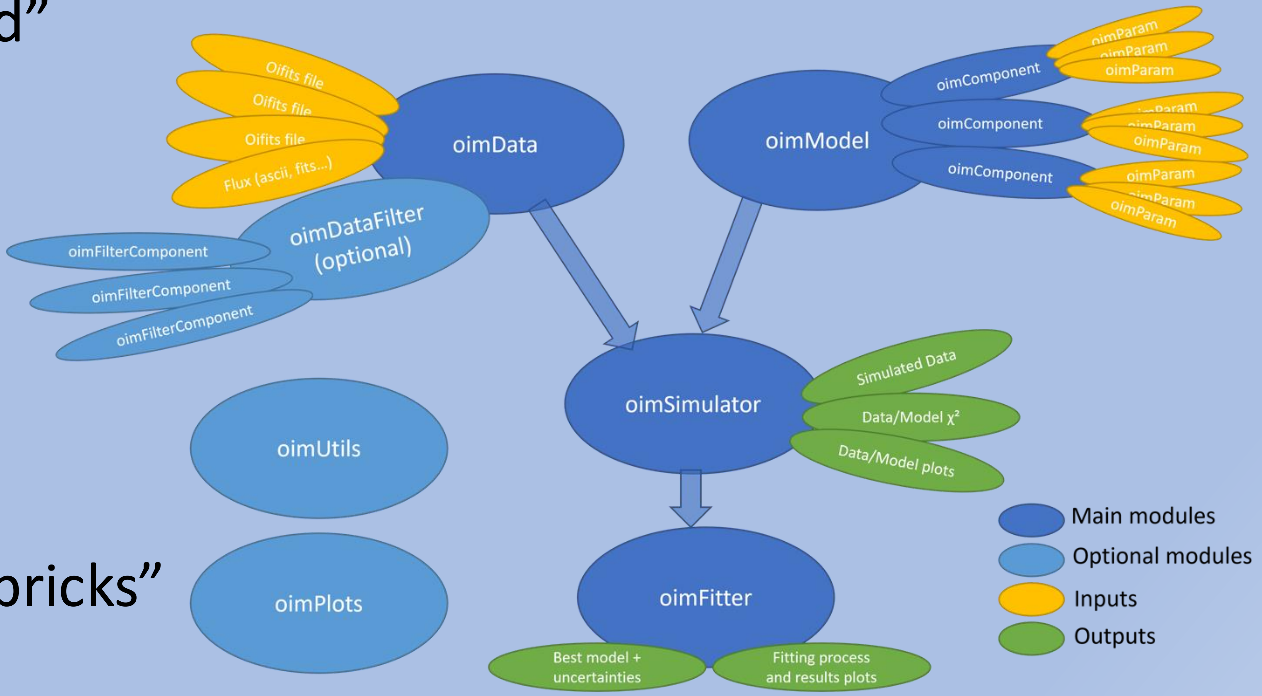
1 - The oimodeler project

Main Functionalities :

- Build **complex models from components** defined **in Fourier or image plane**
- Add **chromaticity** and **time-dependence** to any model-parameters
- Import **images**, **image-cubes**, and **radial profiles** from **RT-models**
- Simulate **all possible data compatible to the OIFITS2 format**
- Manipulate data in the **OIFITS2 format**: cut, smooth, bin, normalize, recompute errors, calibrate …
- Add non-OIFITS2 format **flux and spectra measurements** to your fit
- Easy **data/models comparison** and **χ^2 computation**
- Perform **model-fitting** and **error estimation** with various methods
- easily **plot results** and produce high **quality figures for publication**

1 - The oimodeler project

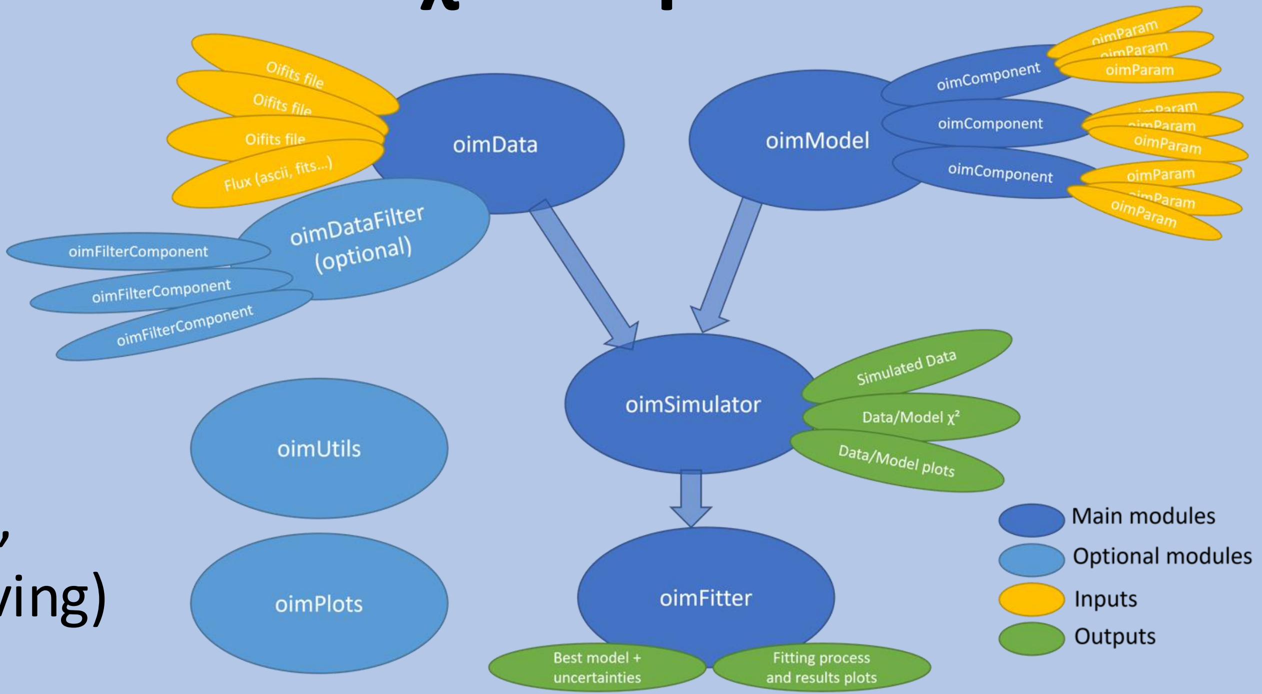
- **oimData: Wrapper for oifits data is astropy.io.fits format**
  - Contains both the oifits data and "optimized" vectors of data and coordinates (u,v,wl,t)
  - Import flux data (from ascii) : **oimFluxData**
    ⬄ conversion to OI_FLUX table
  - Possibility of filtering/modifying data (cut, smooth, bin, reflag…): **oimDataFilter**



- **oimModel: "lego" Model class**
  - **oimComponents**: model components or "bricks"
    - Fourier-based analytical formulas
    - 2D-image-based: computed using FFT
    - 1D-image-based: using Hankel transform (experimental)
  - **oimParam**: components parameters
    - Can be chromatic and/or time-dependent using parameter interpolators
    - Can be linked together by mathematical formula

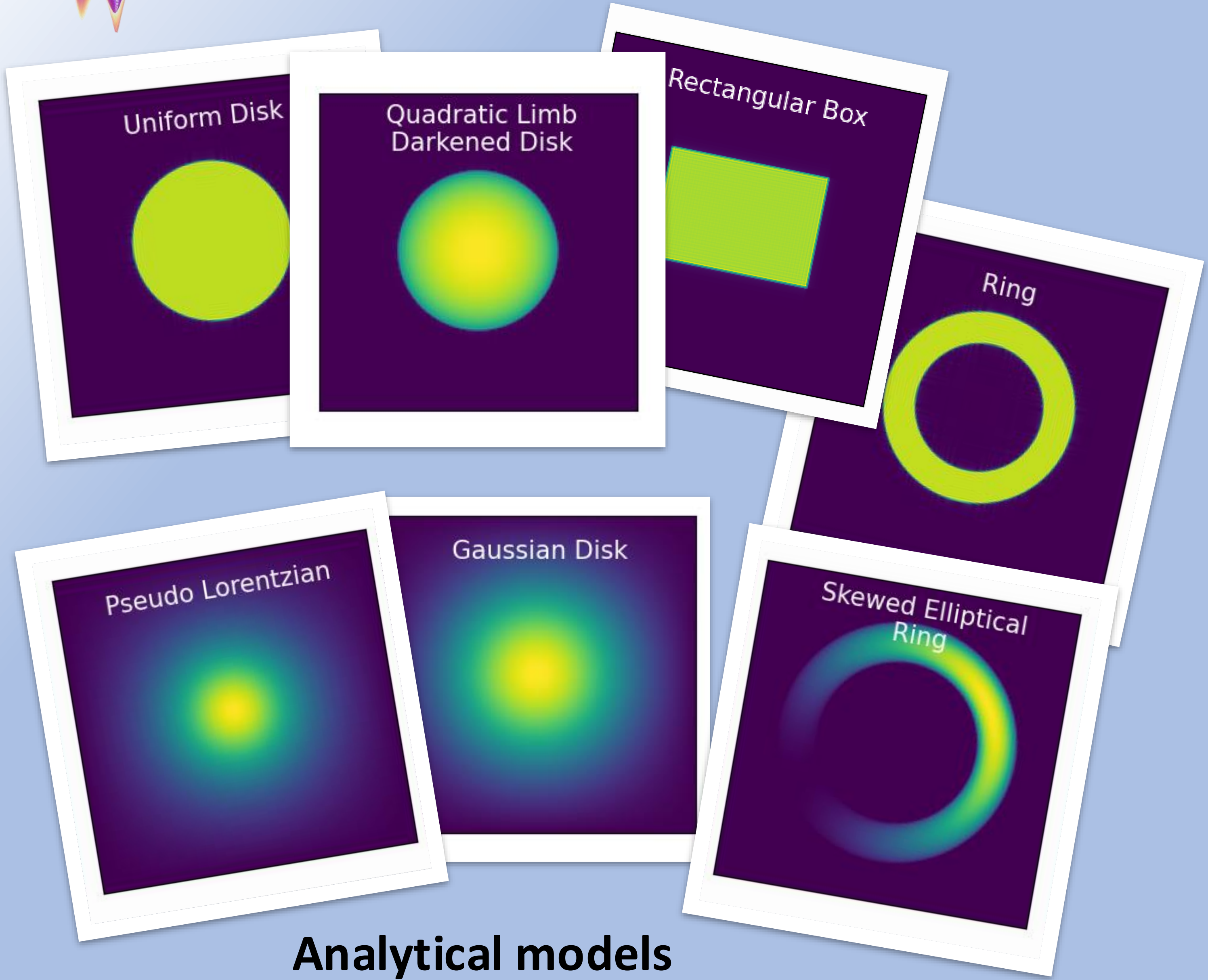
1 - The oimodeler project

- **oimSimulator: simulate data from model and χ^2 computation**
  - Can simulate any kind of oifits2 data for all instruments:
    VIS2DATA, VISAMP
    (absolute, differential, correlated flux)
    VISPHI (absolute and differential),
    T3AMP & T3PHI, FLUXDATA
  - Two modes: fast (only χ^2 for model-fitting),
    slow (simulated data for plotting and saving)

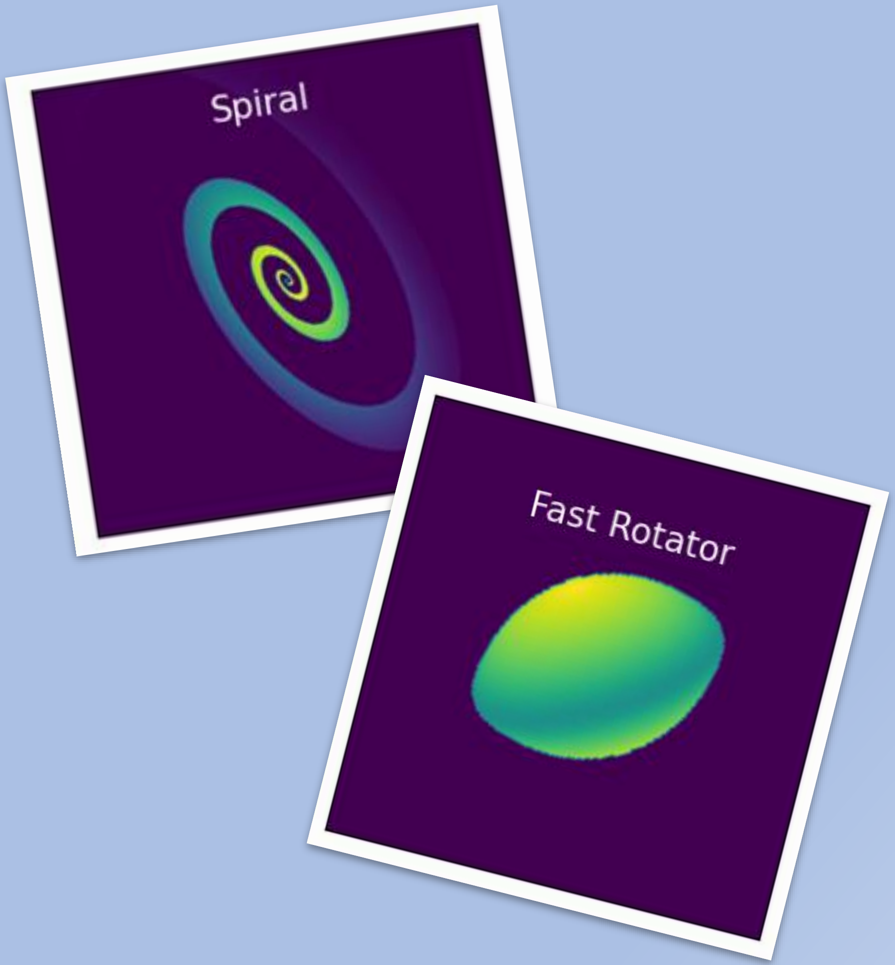


- **oimFitter: Model fitting class(es)**
  - Currently: only an emcee-based implemented: oimFitterEmcee (MCMC)
  - Use the oimSimulator for χ^2 computation
  - Minimized χ^2 and give best (or median) parameters and uncertainties (emcee "style")
- **oimUtils & oimPlots : Helper classes**

2 - Some of the components available in oimodeler

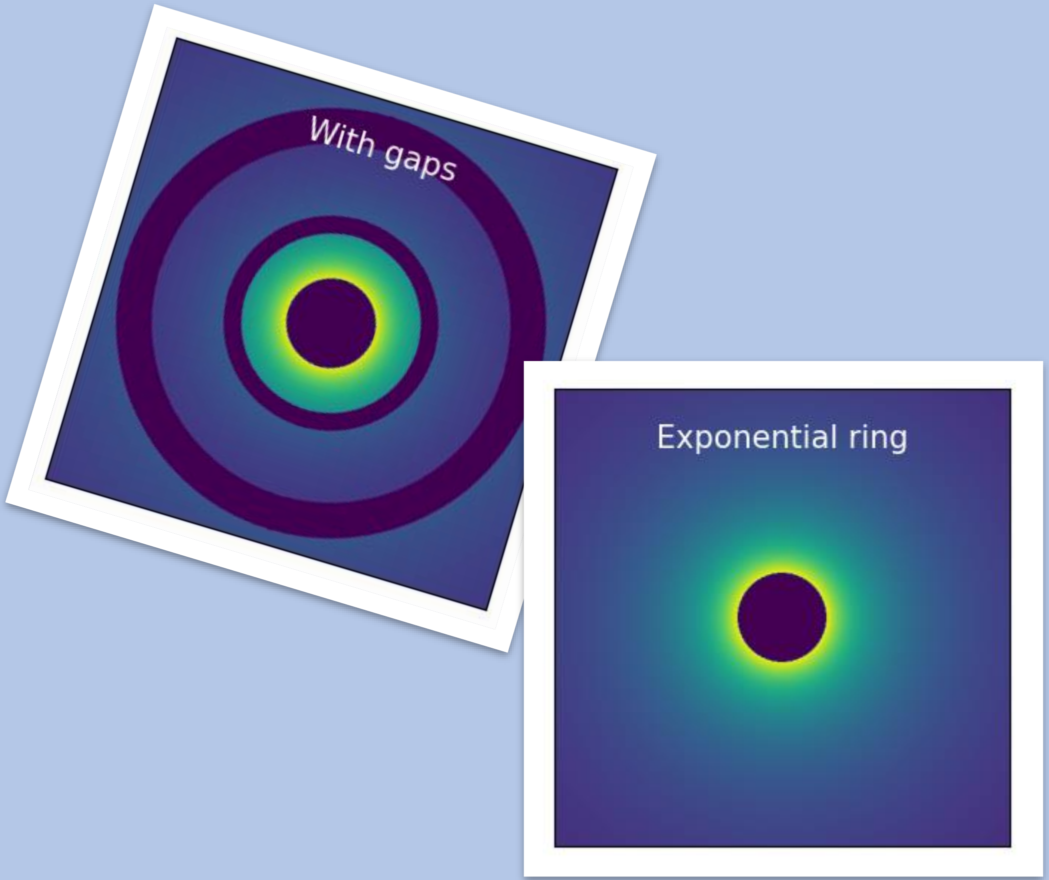


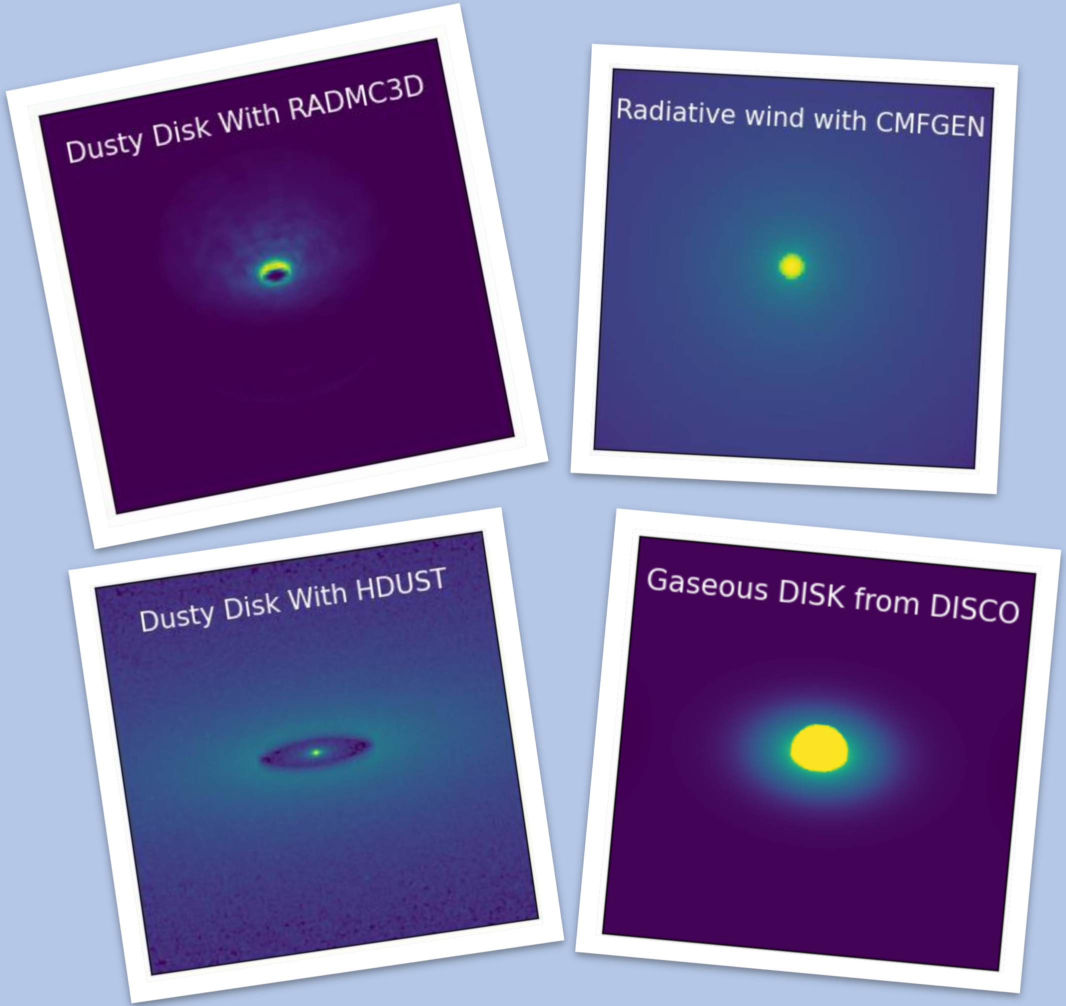
Analytical models
directly defined in Fourier plane



Analytical and numerical toy or
Semi-physical models in Image plane
FFT is used to compute visibilities

2 - Some of the components available in oimodeler





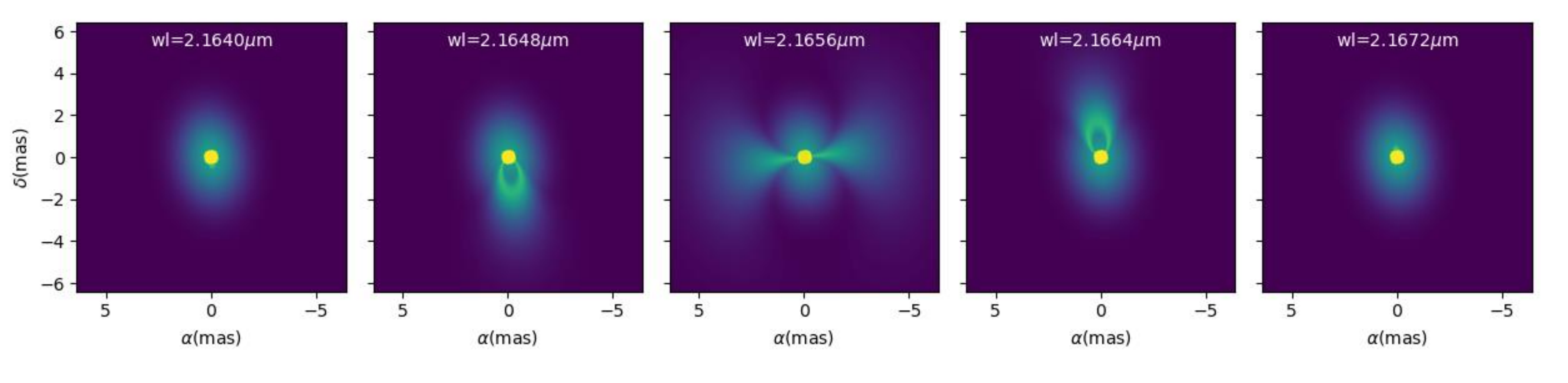
Radial profiles

Toy-models or output from stellar atmosphere models
Hankel-Transform is used to compute visibilities

Images or images cubes in fits format

for instance, outputs from radiative transfer codes

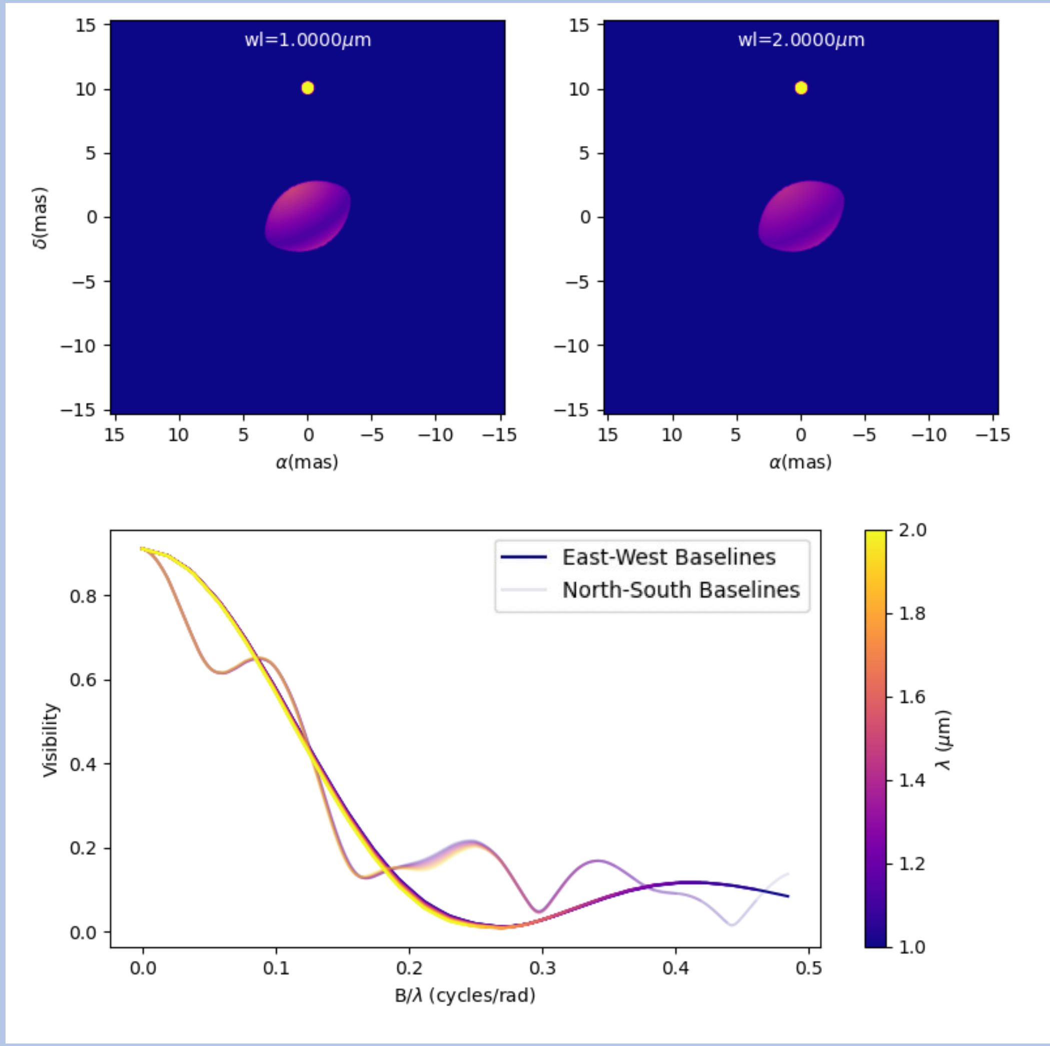
2 - Some of the components available in oimodeler

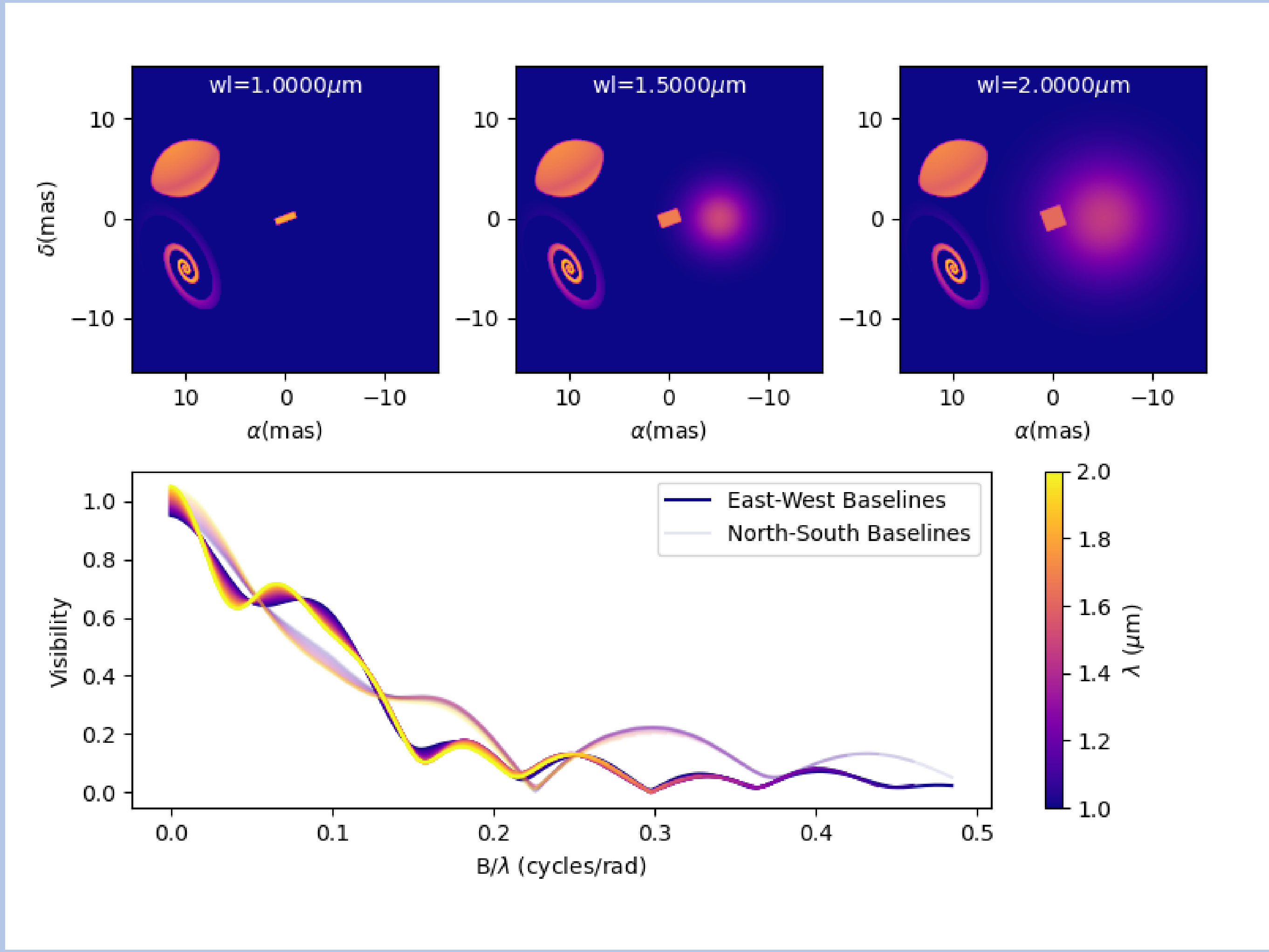


Kinematic models in absorption or emission lines

(such as Rotating/expanding disk from Meilland et al. 2012)

3 - Combining components to build complex models





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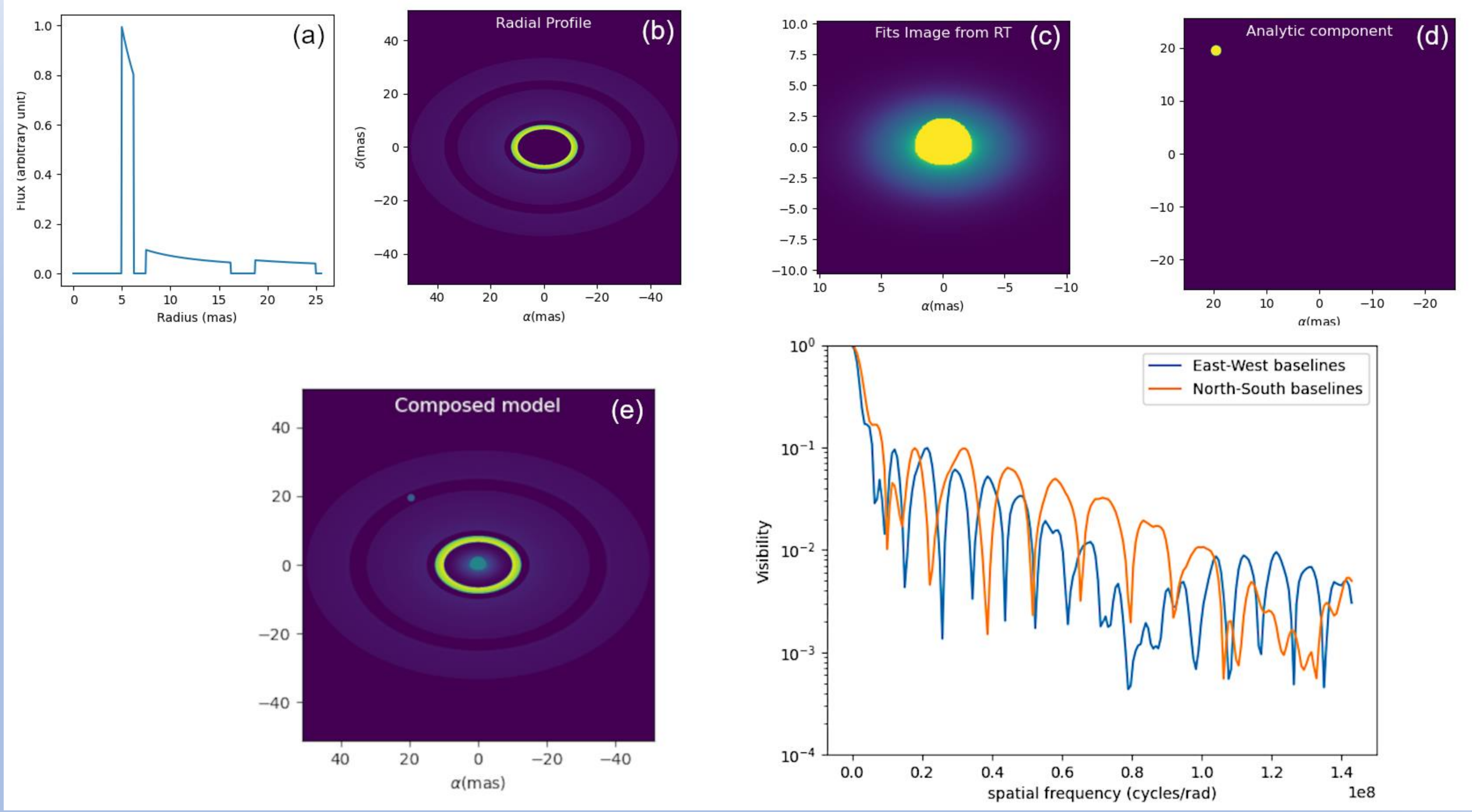


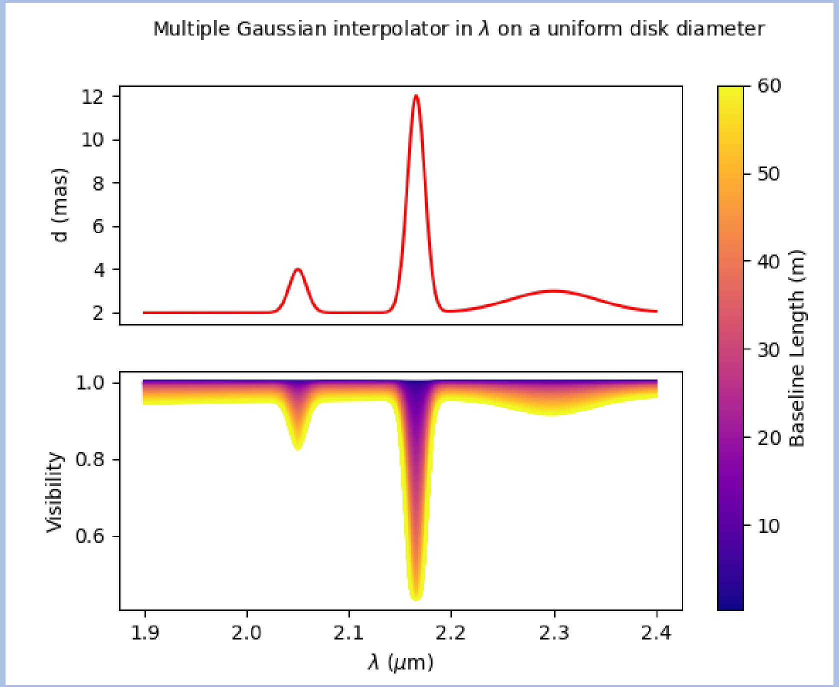
4 - Adding time-dependence or chromaticity to any parameter

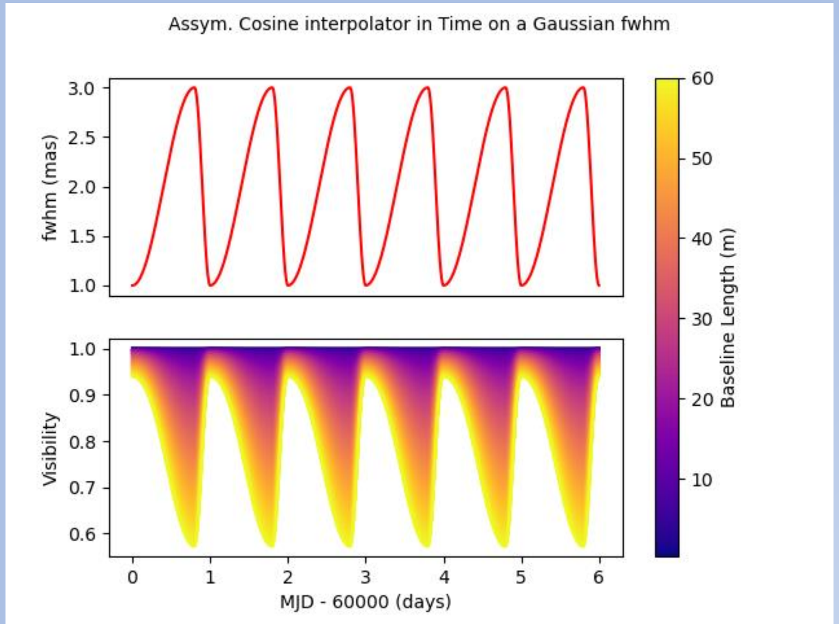
Parameter interpolators can be used to :

- simulate **chromatic changes to the intensity distribution**
- Simulate **time dependence** : pulsation, binarity …

Many interpolators are available in oimodeler:

Class name	oimInterp macro	Description	Parameters
oimParamInterpolatorWl	"wl"	Interp between key wl	wl, values
oimParamInterpolatorTime	"time"	Interp between key time	mjd, values
oimParamGaussianWl	"GaussWl"	Gaussian in wl	val0, value, x0, fwhm
oimParamGaussianTime	"GaussTime"	Gaussian in time	val0, value, x0, fwhm
oimParamMultipleGaussianWl	"mGaussWl"	Multiple Gauss. in wl	val0 and value, x0, fwhm
oimParamMultipleGaussianTime	"mGaussTime"	Multiple Gauss. in time	val0 and value, x0, fwhm
oimParamCosineTime	"cosTime"	Asym. Cosine in Time	T0, P, values (optional x0)
oimParamPolynomialWl	"polyWl"	Polynomial in wl	coeffs
oimParamPolynomialTime	"polyTime"	Polynomial in time	coeffs

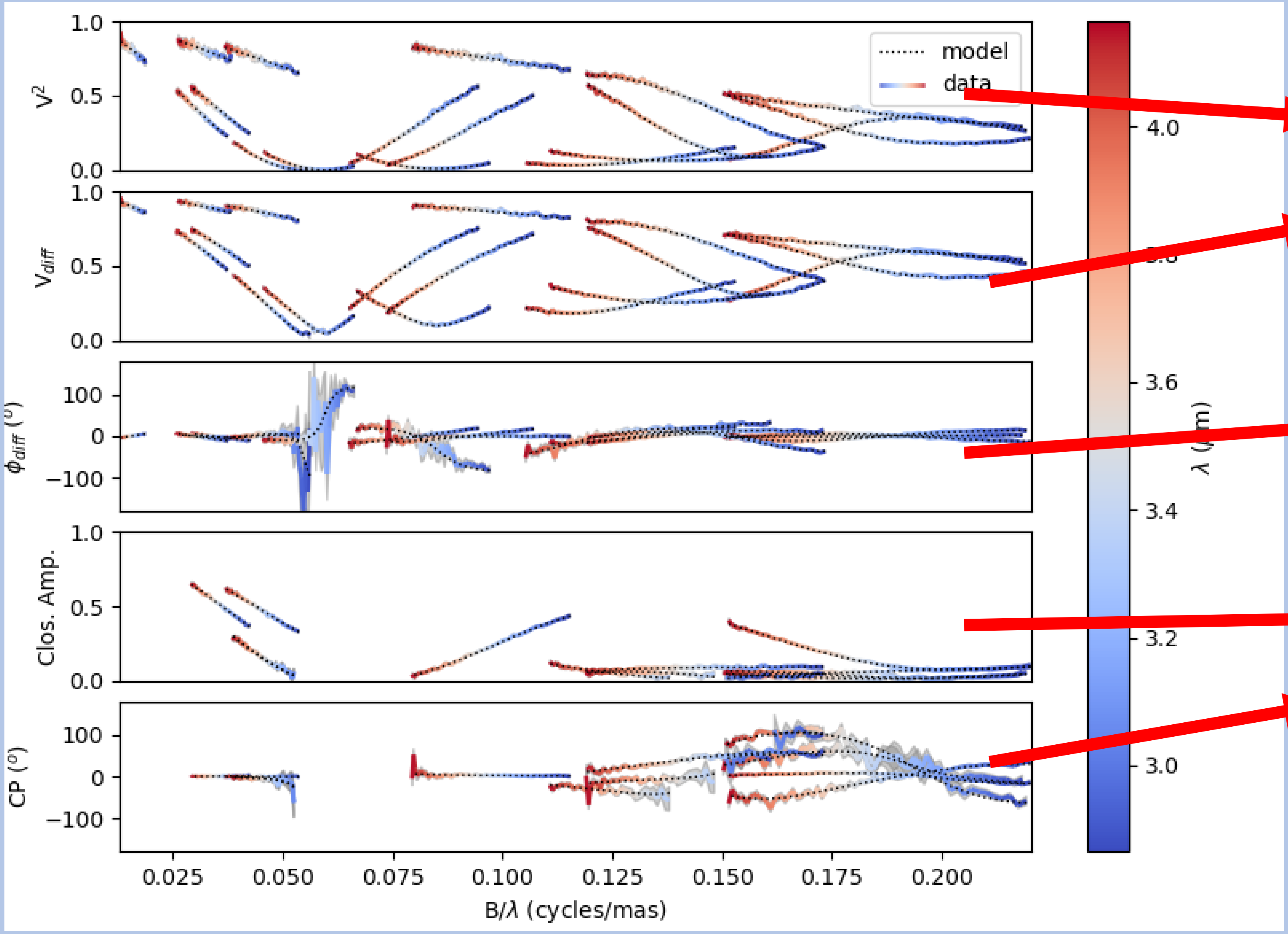




New interpolators can easily be **implemented by users**

5 - Compute synthetic OIFITS2 quantities

Taking data from any instrument and a model oimodeler can simulate any OIFITS2 quantities



VIS2DATA: square visibility

VISAMP:
- absolute visibility,
- differential visibility
- correlated flux

VISPHI:
- absolute phase
- differential phase

T3AMP: amplitude of the triple product

T3PHI: Closure phase

+ FLUXDATA:
- absolute flux
- normalized flux

6 - Performing model-fitting using various methods

In the current version oimodeler includes 4 model-fitting algorithms:

- **MCMC sampler** based on the **emcee** package
- **Dynamic Nested (DN) sampler** based on the **dynesty** package
- **Levenberg-Marquardt (LM)** χ^2 minimizer
- **Regular grid** χ^2 explorer

Uncertainties can be estimated using the posterior probability function (MCMC or DN sampler) or the covariant matrix (LM)

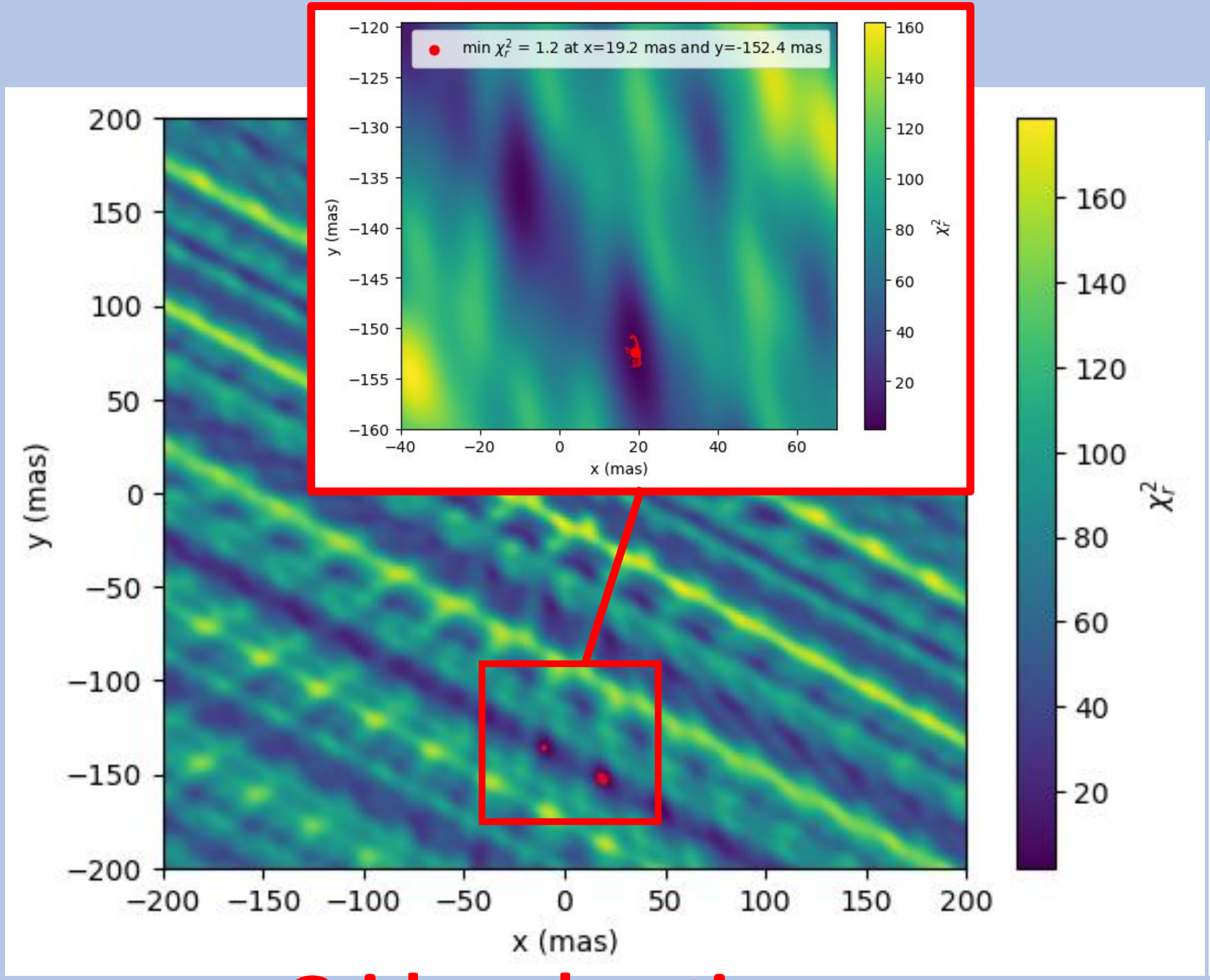
6 - Performing model-fitting using various methods

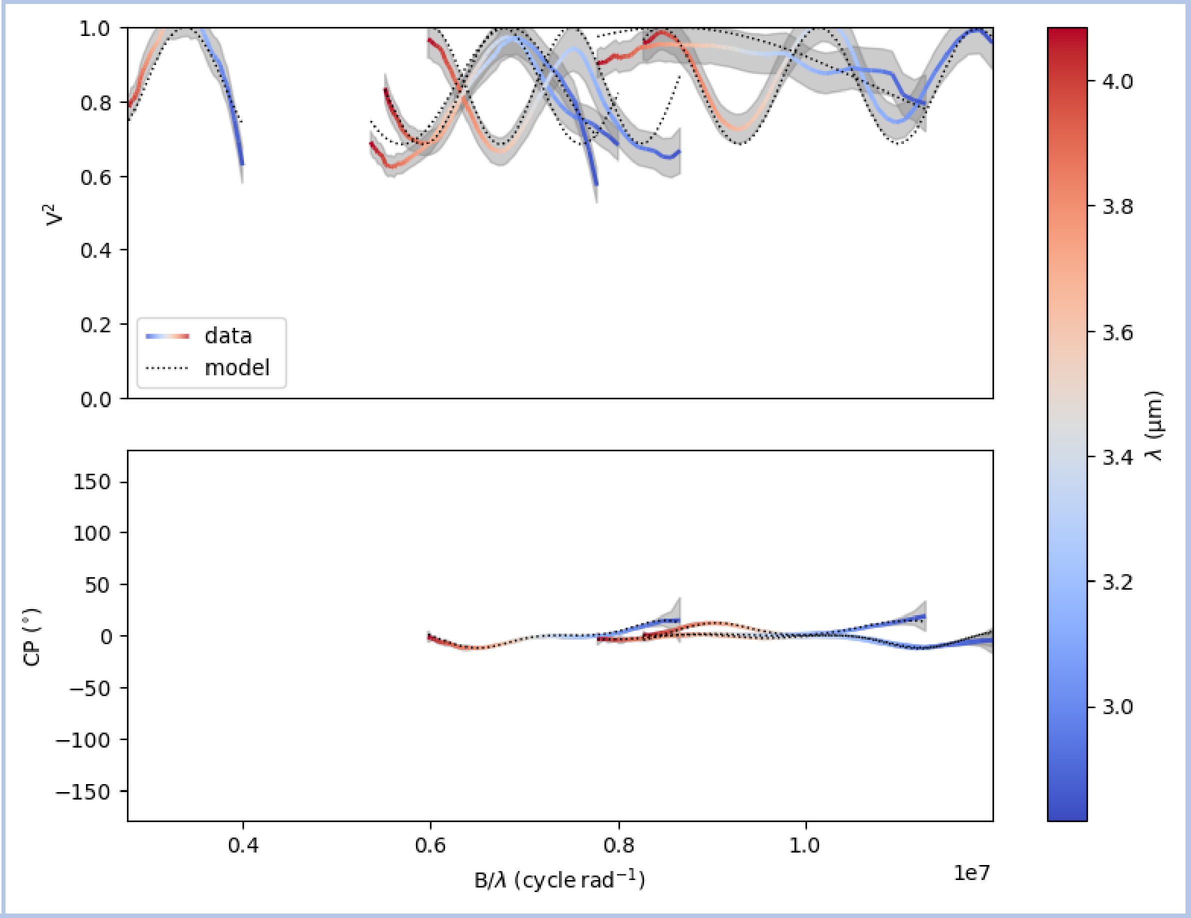
Some examples from the 2024 VLTI School

- **the stellar surface of Canopus (PIONIER)**
- **the Binary star 94 Aqr (MATISSE-LOW)**
- **The T Tauri star HD 179278 (MATISSE-LOW)**
- **The Herbig star MWC 297 (MATISSE-HIGH)**
- **The Herbig star HD58647 (GRAVITY-HIGH)**
- **The B[e] star FS CMa (MATISSE-LOW)**

6 - Performing model-fitting using various methods

Binary star 94 Aqr observed with the VLTI/MATISSE

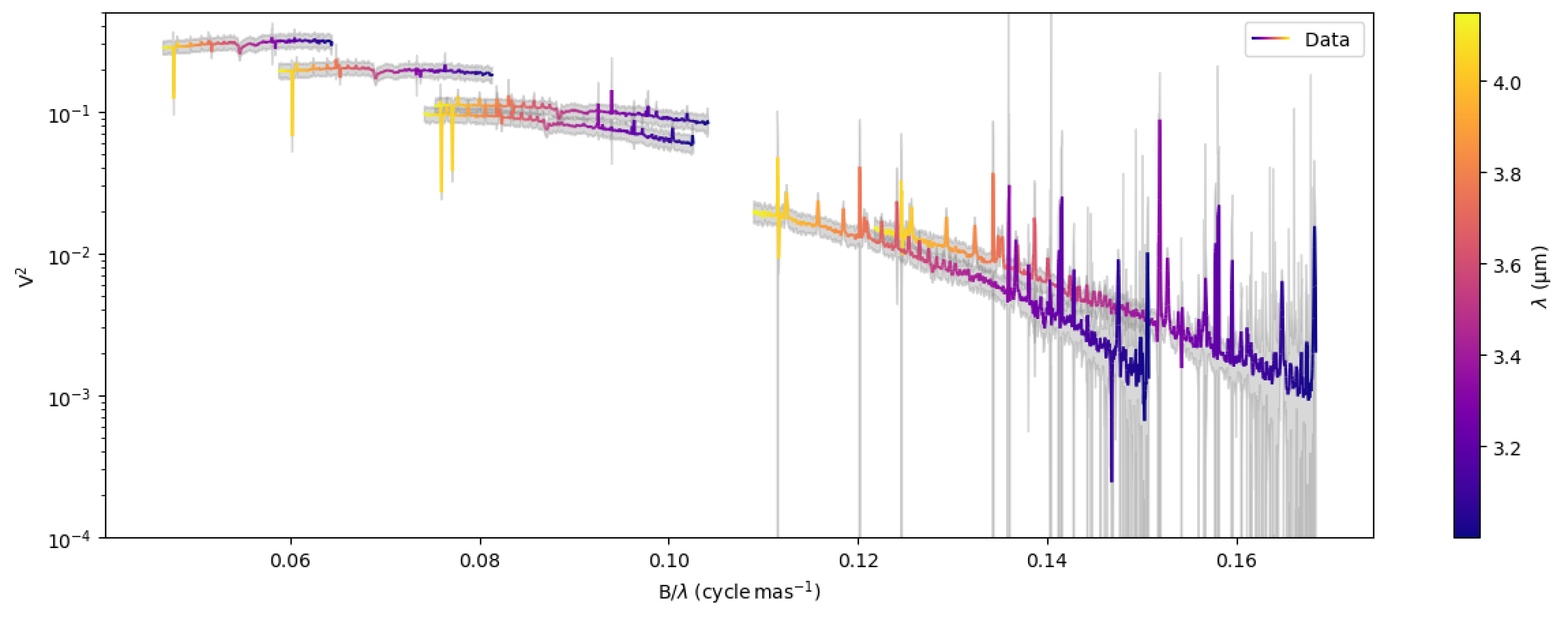




Grid exploration

6 - Performing model-fitting using various methods

Herbig Be star MWC297 observed with MATISSE



Modelling the Continuum + line emission

6 - Performing model-fitting using various methods

Herbig Be star MWC297 observed with MATISSE

Building a chromatic model with 3 components

```
wl0 = 4.0518e-6 # meter

star = oim.oimPt()
continuum = oim.oimEGauss()
line = oim.oimEGauss(f=oim.oimInterp('GaussWl',val0=0, value=100, x0=wl0, fwhm=5e-9))
line.params['pa']=oim.oimParamLinker(continuum.params['pa'])
line.params['elong']=oim.oimParamLinker(continuum.params['elong'])
model = oim.oimModel(star,continuum,line)
```

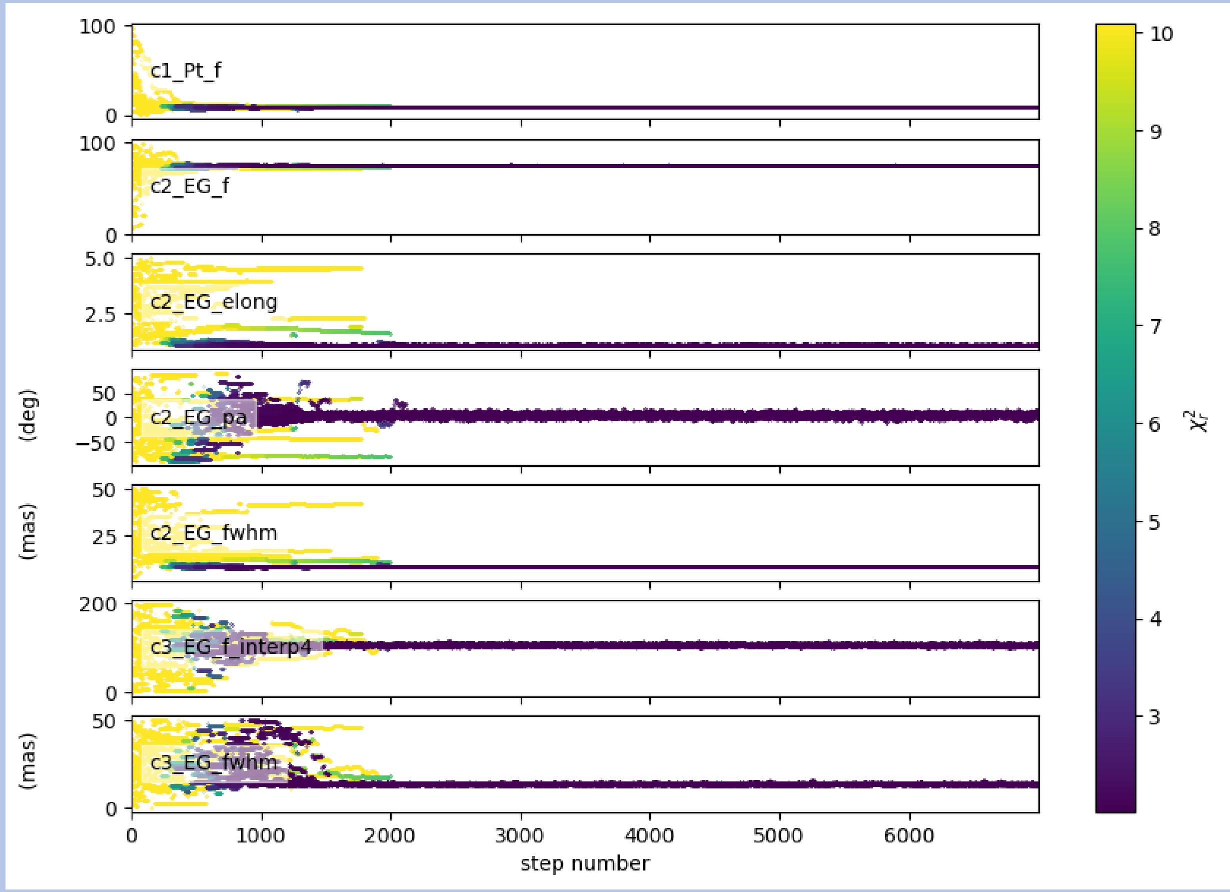
7 Free parameters

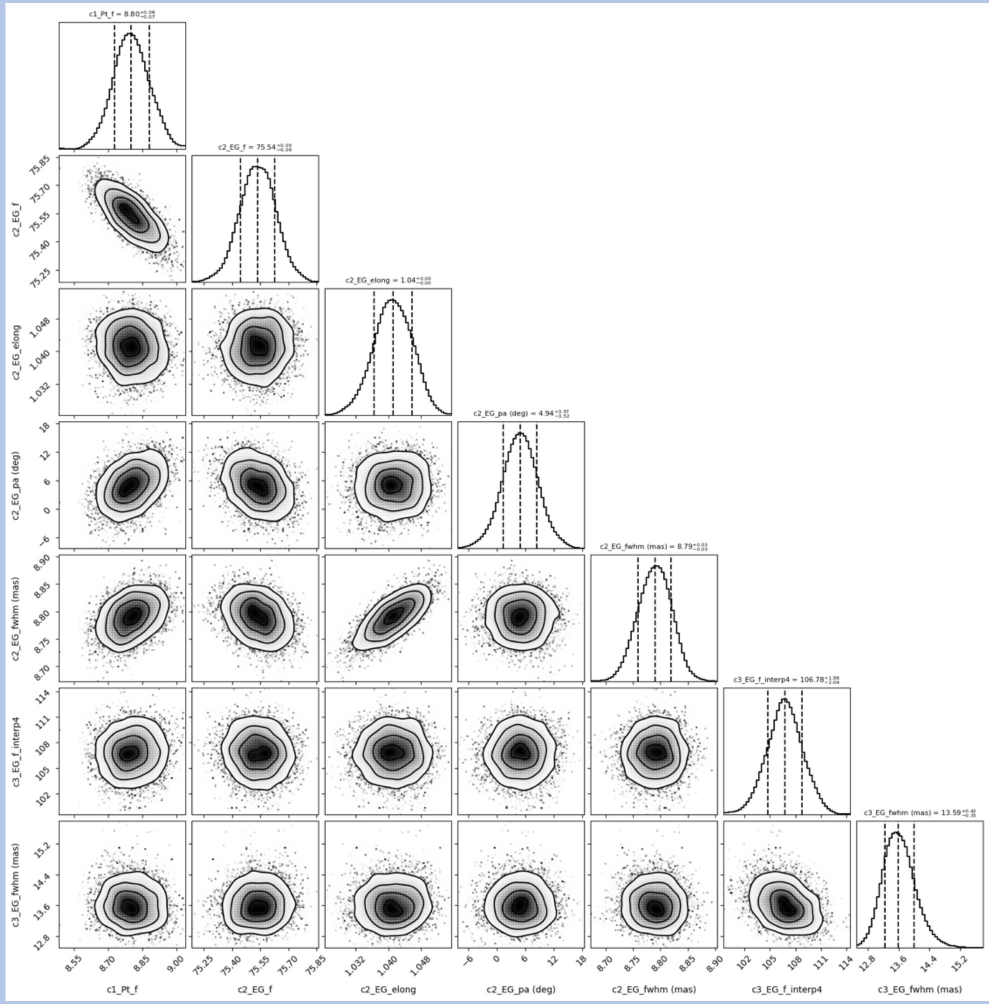
```
model.getFreeParameters()
```

```
{'c1_Pt_f': oimParam at 0x1d5e8c56fd0 : f=1 ± 0  range=[0,100] free=True ,
 'c2_EG_f': oimParam at 0x1d5e8c58990 : f=1 ± 0  range=[0,100] free=True ,
 'c2_EG_elong': oimParam at 0x1d5e8c363d0 : elong=1 ± 0  range=[1,5] free=True ,
 'c2_EG_pa': oimParam at 0x1d5e8c5ac50 : pa=0 ± 0 deg range=[-90,90] free=True ,
 'c2_EG_fwhm': oimParam at 0x1d5e8c5a090 : fwhm=0 ± 0 mas range=[0,50] free=True ,
 'c3_EG_f_interp4': oimParam at 0x1d5e782c5d0 : f=115 ± 0  range=[0,200] free=True ,
 'c3_EG_fwhm': oimParam at 0x1d5e8c53290 : fwhm=0 ± 0 mas range=[0,50] free=True }
```

6 - Performing model-fitting using various methods

Herbig Be star MWC297 observed with MATISSE

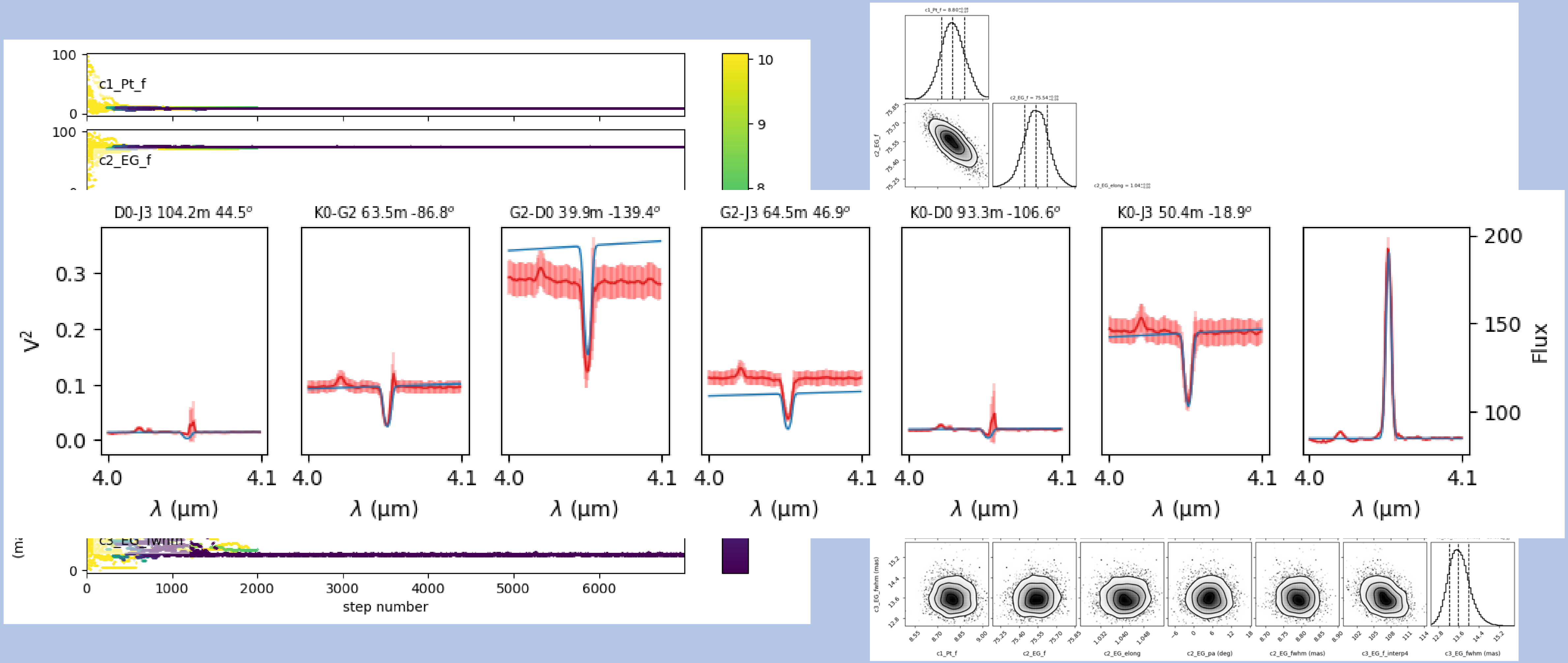




MCMC sampling

6 - Performing model-fitting using various methods

Herbig Be star MWC297 observed with MATISSE

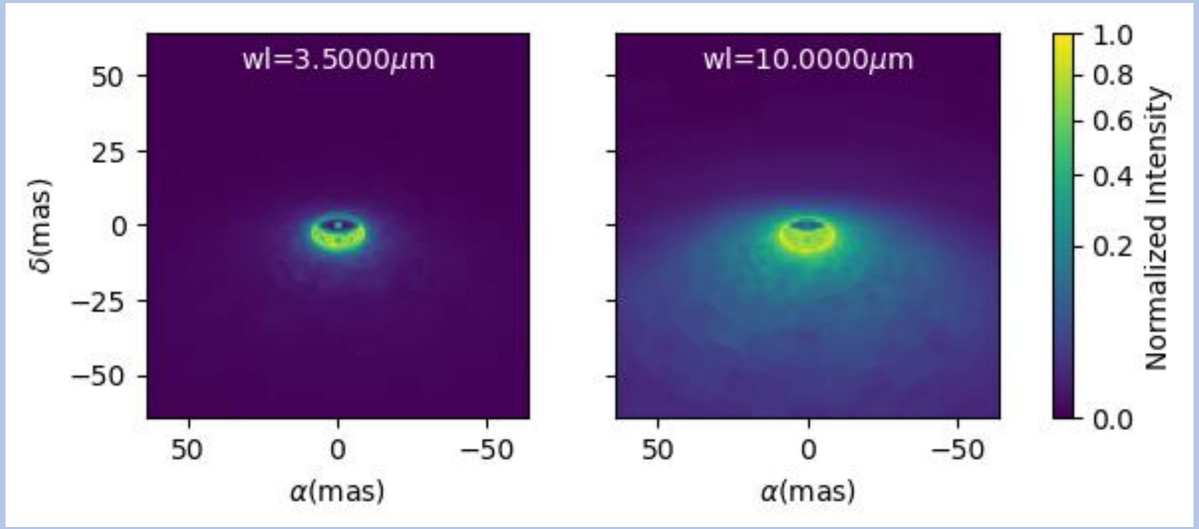


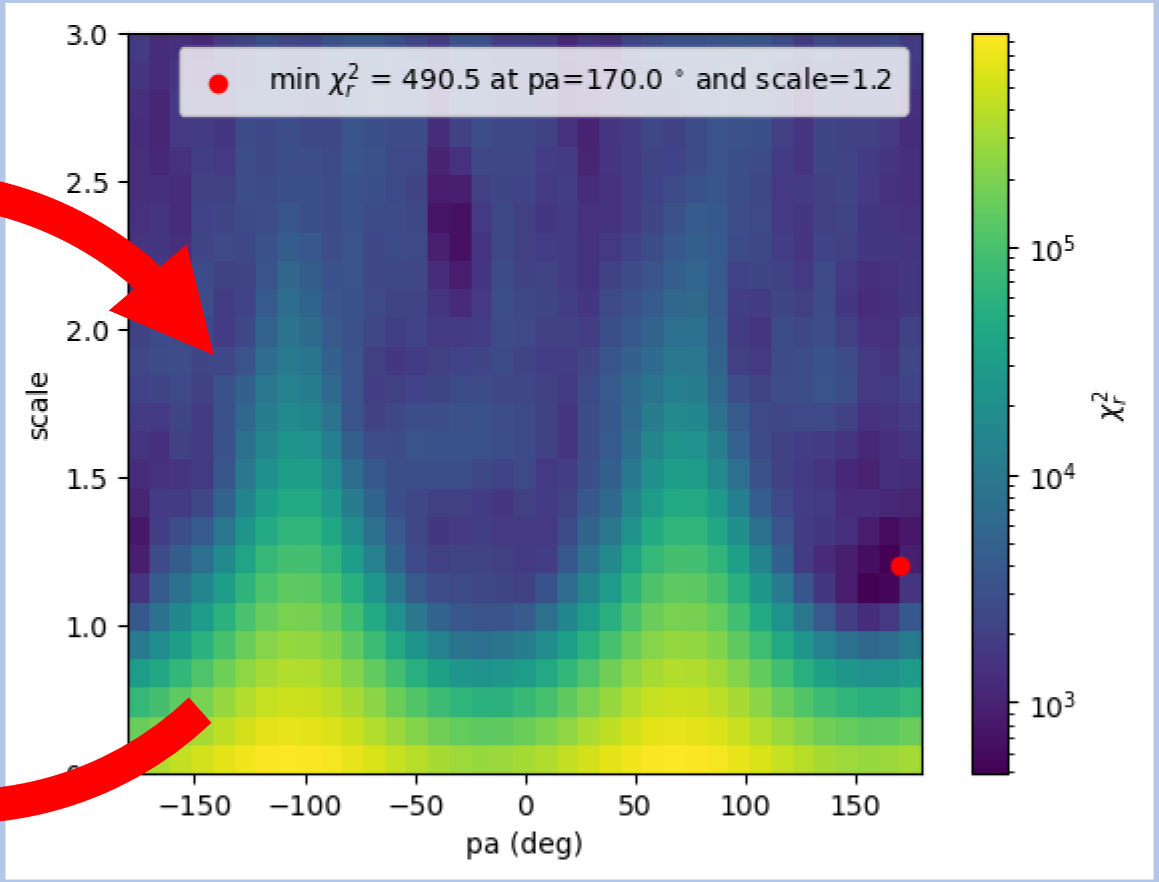
MCMC sampling

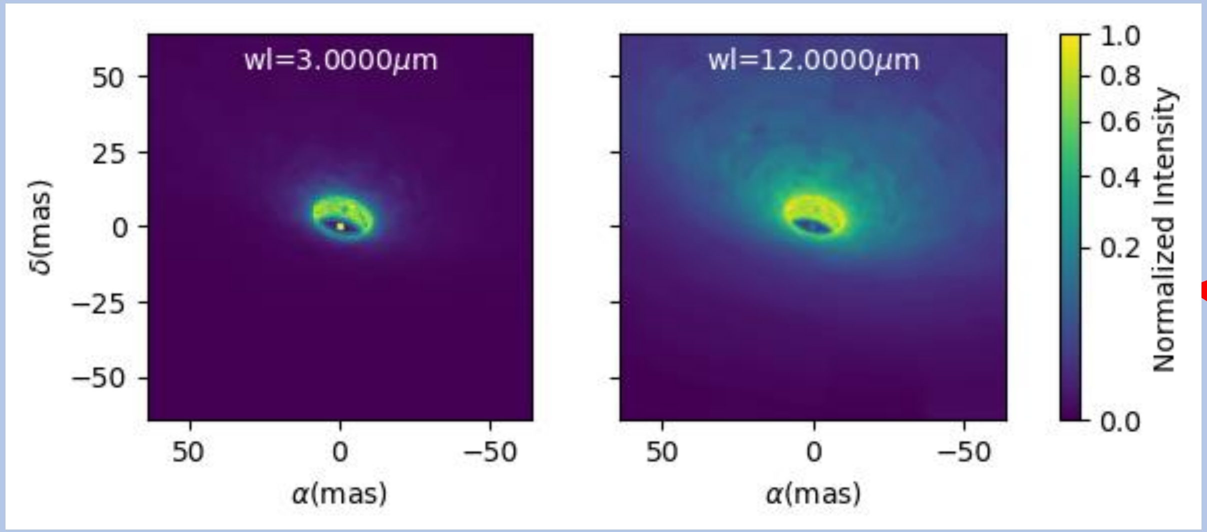
6 - Performing model-fitting using various methods

B[e] star FS CMa

RADMC3D RT model (from 2021 VLTI School)



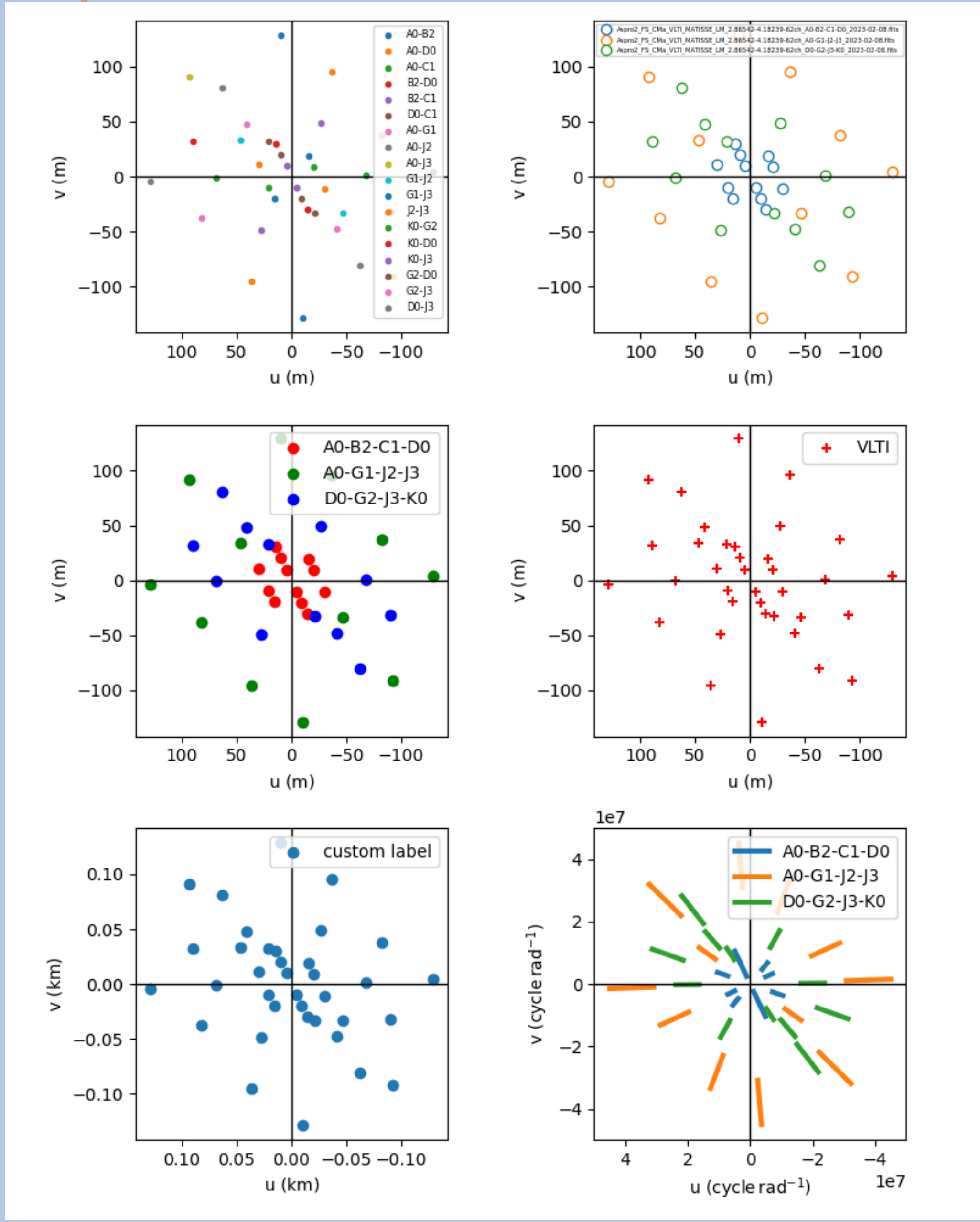


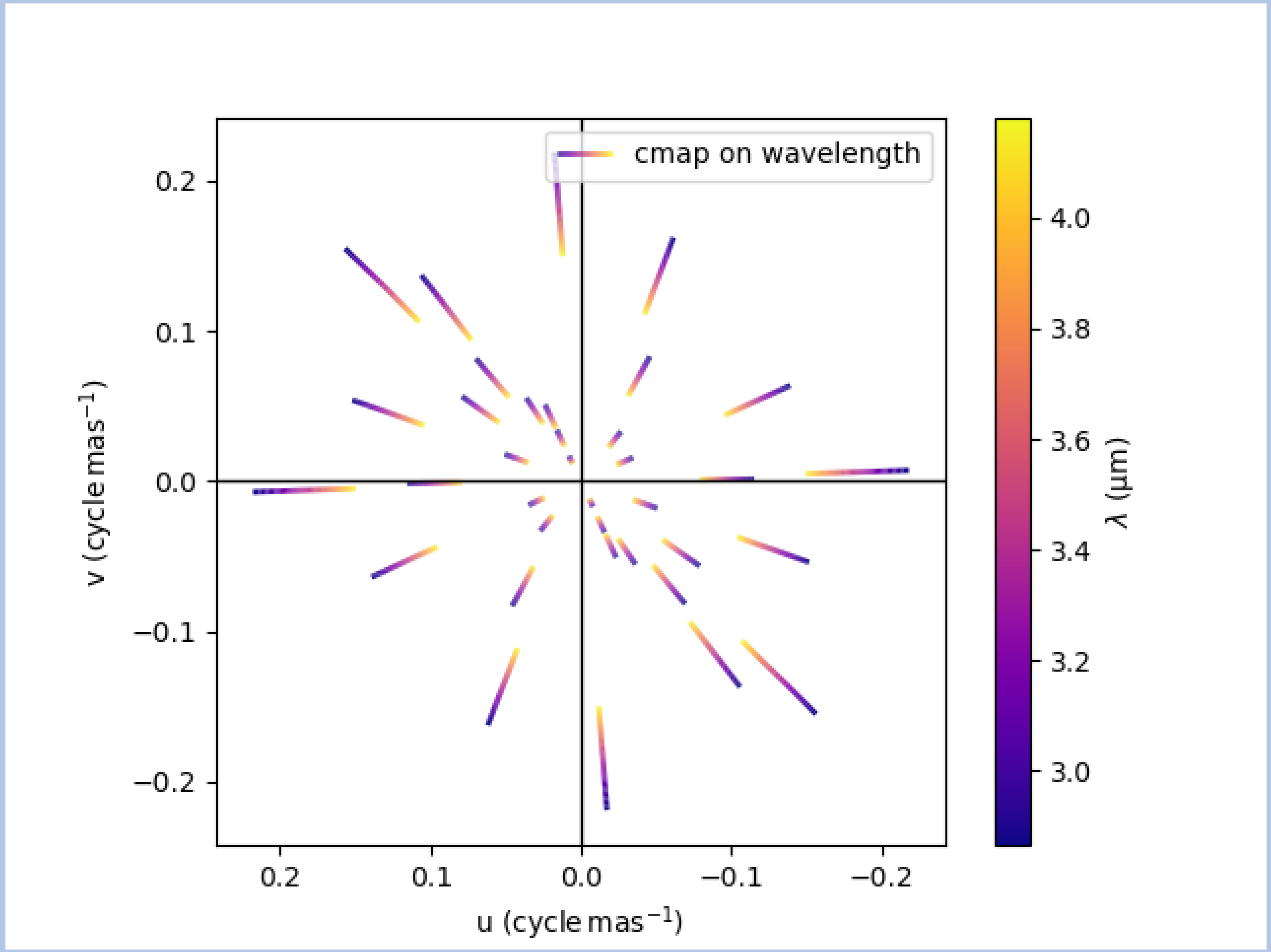


Best-fit (i.e., scaled and rotated) model

Grid exploration on major-axis PA and scaling factor

7 – Easily plot results and produce high quality figures





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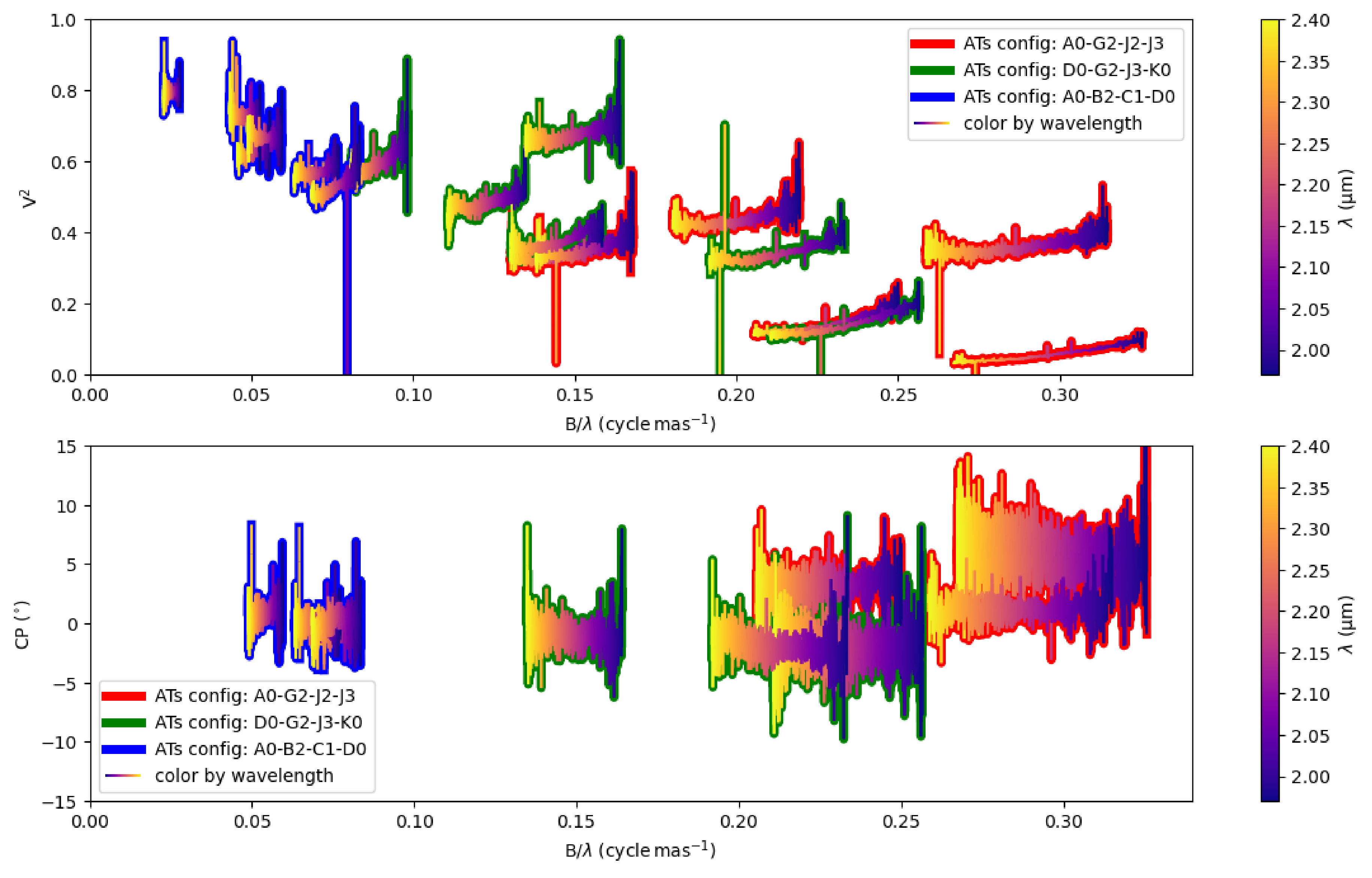

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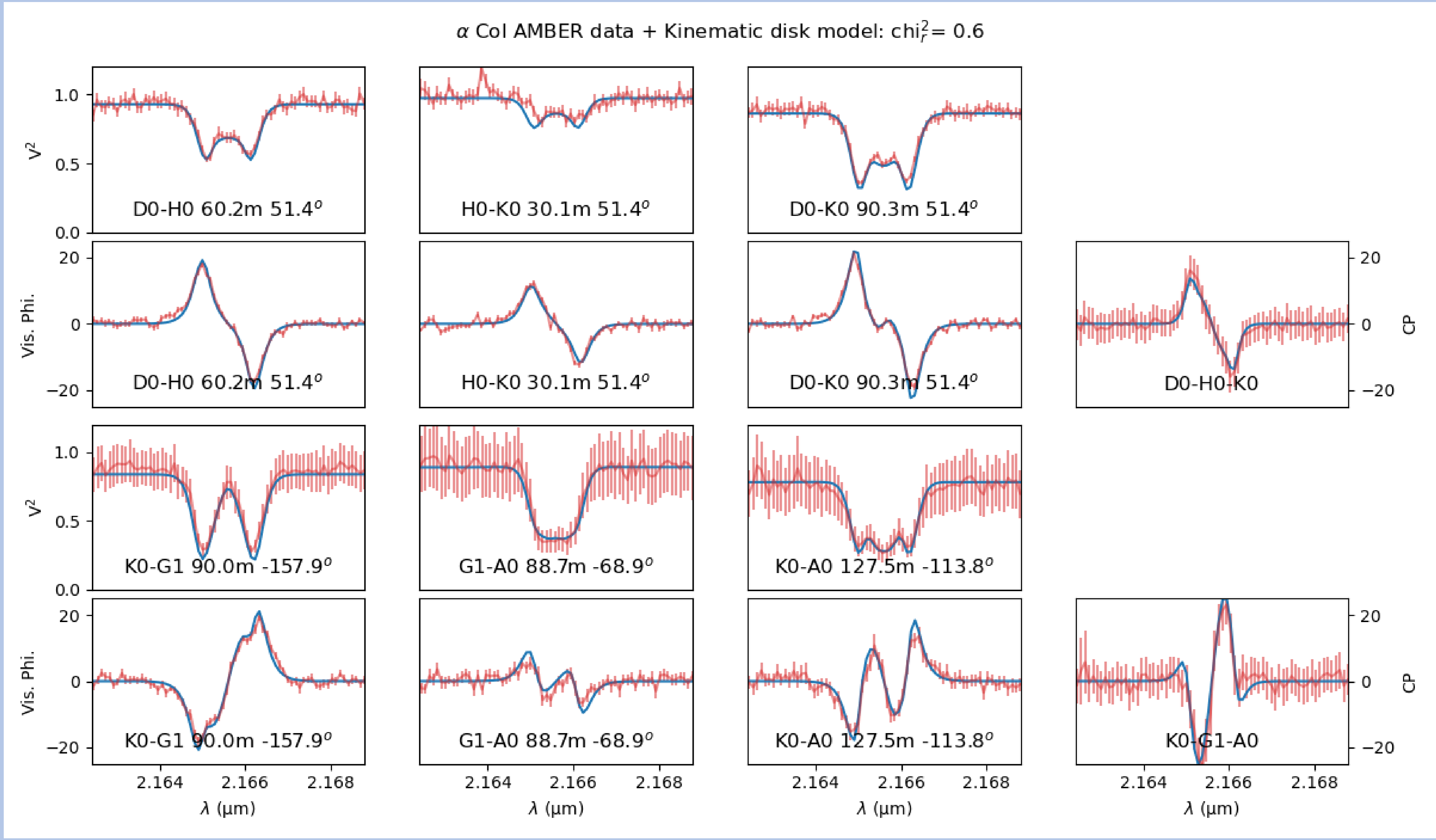
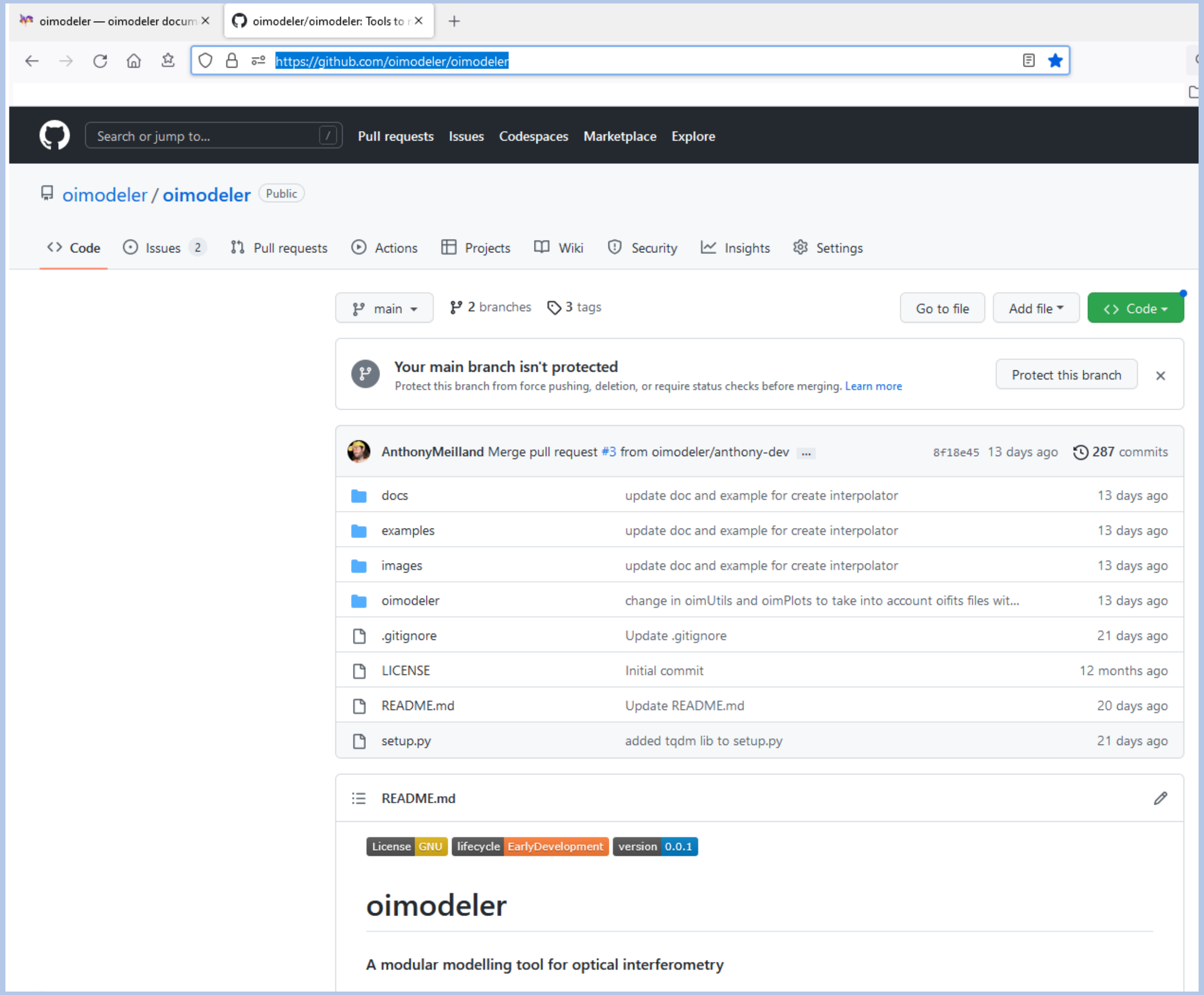
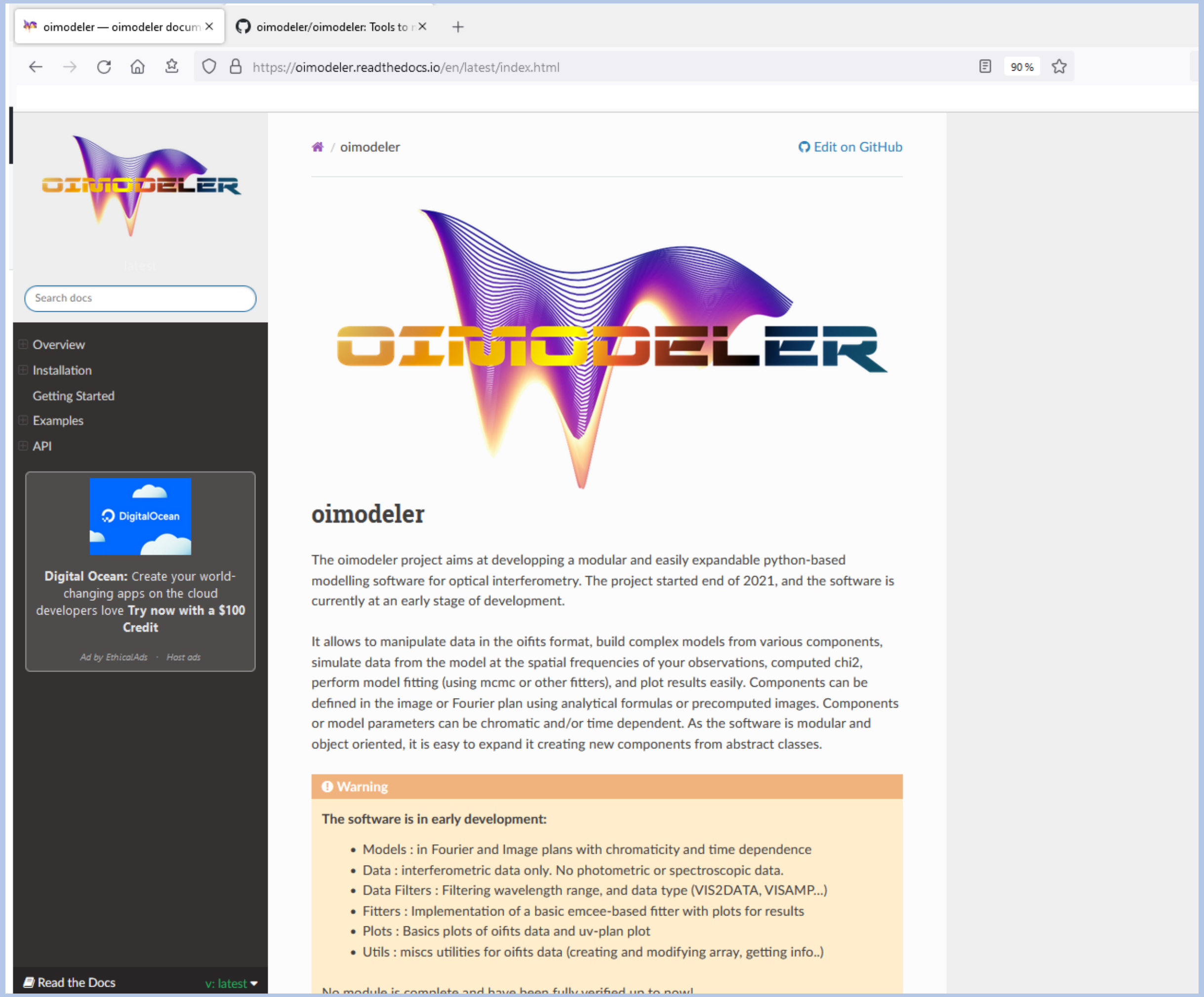


8 - oimodeler on the web



Code available on github
+ automatic installation through pip
https://github.com/oimodeler



Documentation + examples available on readthedocs
https://oimodeler.readthedocs.io

Conclusion & Perspective

Code is fully functional, and core development ended in 2023

New features added in 2024:

- Data: Importing photometric/spectroscopic data
- Components: temperature gradient, pseudo-Lorentzian, LDDs
- Fitters: grid explorer & LM minimization
- Filters: expression-based flagging on many criteria: length, PA, SNR…
- Other: new template plots

Presentation of the code

- at SPIE 2024 (Poster + Paper)
- at the VLTI School 2024 (Tutorials on MATISSE, PIONIER and GRAVITY data)

Multiple papers using oimodeler in preparation:

- MATISSE: B[e] l Pup (Abello et al.), MATISSE B[e] Survey (Abello et al.)
- Binaries with CHARA SPICA + MIRCX: (Jonak et al)
- Binary Be star Del Cen Disk and orbit: AMBER + MATISSE + PIONIER (Houlbreque et al.)
- Disk of the YSO HD 100453 (van Haastere et al.)
- Disk around the young spectroscopic binary DX Cha (Juhász et al.) …