Introduction to PMOIRED: Fitting a uniform disk diameter and limb-darkening

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CHARA Array

Thanks to Antoine Mérand for all the Jupiter notebooks

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Existing modeling tools

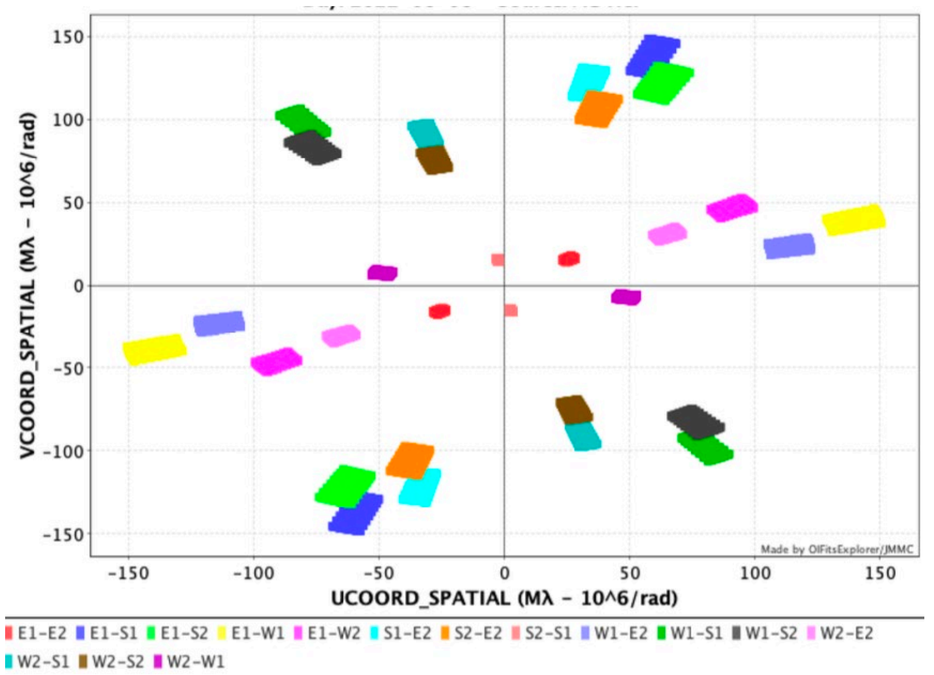
- PMOIRED (Antoine Mérand): Model fitting
- OITOOLS (Fabien Baron): Model fitting + imaging
- Oimodeler (Anthony Meilland): Model fitting
- LITpro (JMMC): Model fitting
- RADPy (Ashley Elliott): Model fitting angular diameter
- CANDID (Antoine Mérand + Alex Gallenne) : Binary search
- Binary Grid Search Procedure in IDL (Gail Schaefer) : Binary search
- ++ others

PMOIRED

- Ref: “Flexible Spectro Interferometric modelling of OIFITS data with PMOIRED” by Antoine Mérand
  https://arxiv.org/abs/2207.11047
- Install:
  pip3 install git+https://github.com/amerand/PMOIRED
- We are using google colab for tutorial

Why modeling when image reconstruction available

- Sparse (u,v)
- Ill-posed problem
- Under estimated uncertainties

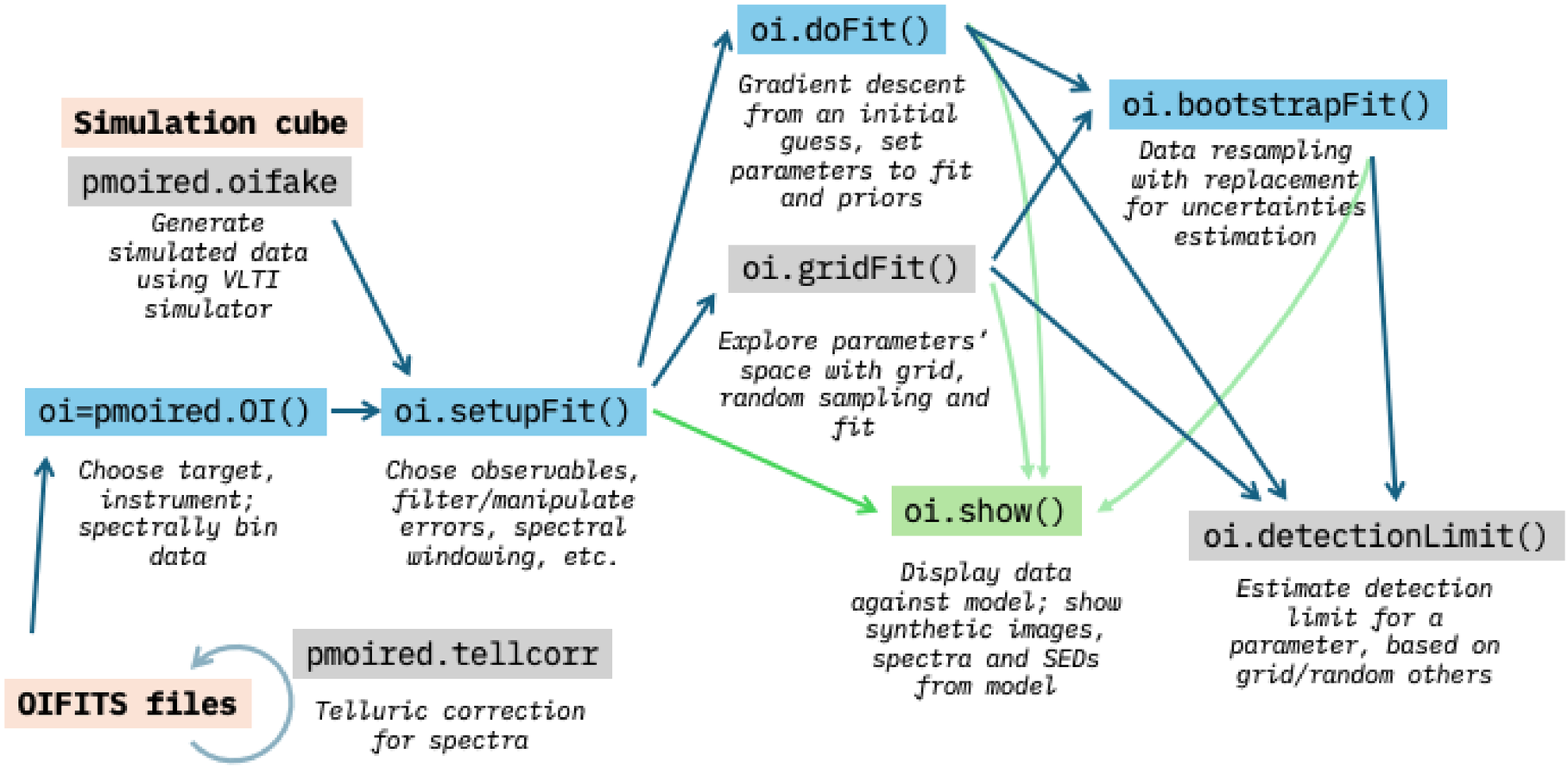


In most cases, when we do both imaging, we also confirm with modeling

Your model, start with simple

- Diameter
- Limb darkening
- Binary detection and separation
- YSO disk modeling
- Star spot modeling
- Spectral data fitting

PMOIRED fitting Philosophy



Credit: Mérand

PMOIRED fitting Philosophy

- OIFITS → Load → Setup → Model → Fit → Evaluate → Uncertainty
- Linear combination of model components

```
oi = pmoired.OI(files)
oi.setupFit(...)
oi.doFit(model)
oi.show()
```

Fit setup

```
oi = pmoired.OI(['MIRCX_L2.2025Jul20.ups_Per.MIRCX_IDL.2025Jul22.AVG15m.oifits',
'MYSTIC_L2.2025Jul20.ups_Per.MIRCX_IDL.2025Jul25.AVG15m.oifits'],
                medFilt=3,
                binning=2)
```

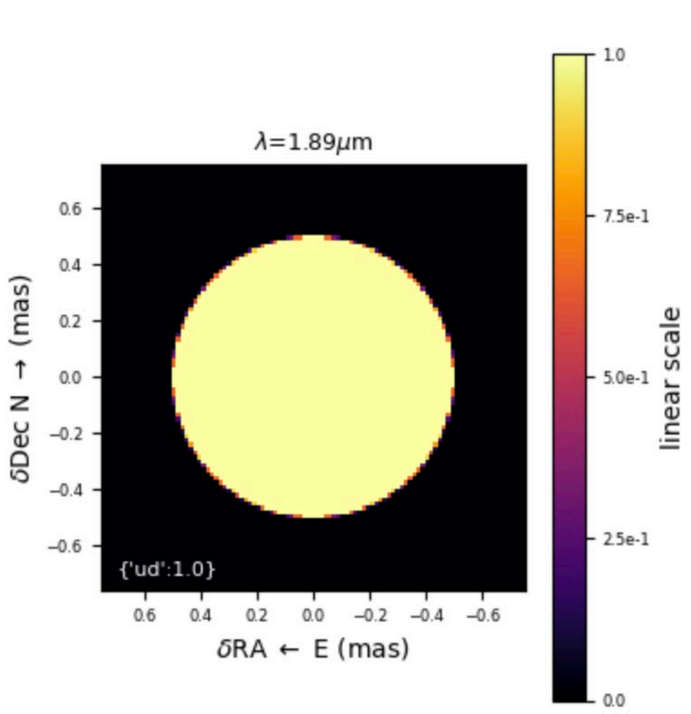
```
oi.setupFit({'obs':['V2'],
             'max error':{'V2':0.2},
             'min relative error':{'V2':0.04},
              'wl ranges':[(1.45, 1.75)], #H-band
              'baseline ranges': [(10,350)]
            })
```

How we can prepare a model?

- Every component is a dictionary
- The keys describe morphology, position, flux, and orientation
- More complex scenes are built by combining simple pieces

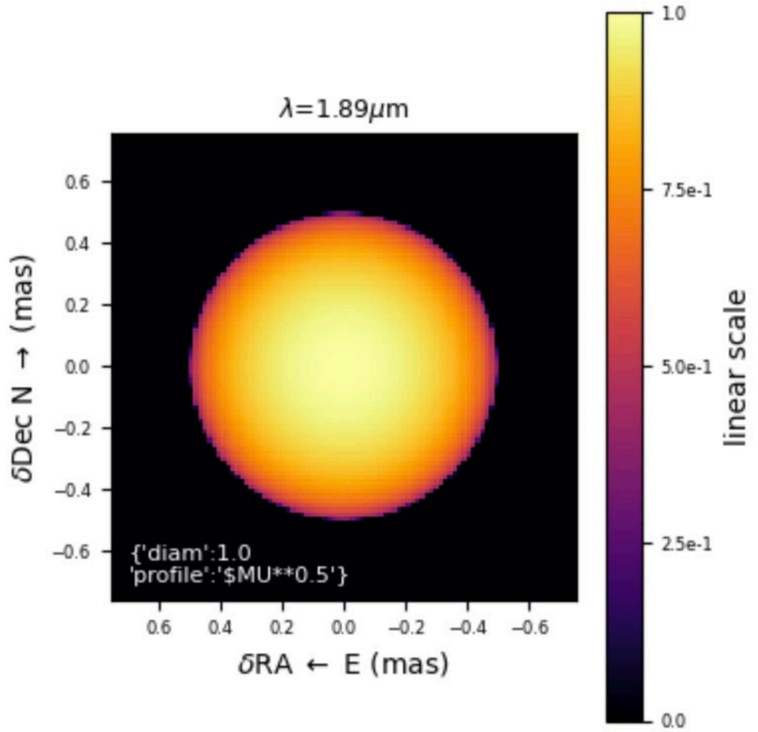
Model preparation: Basic components

Uniform Disk



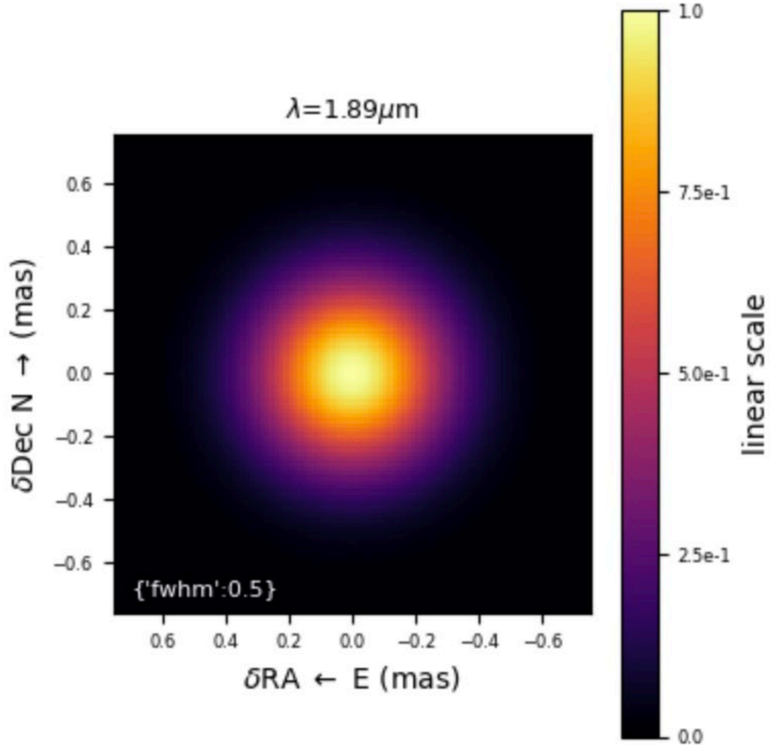
{'ud':1}

Limb darkened disk



{'diam':1, 'profile':'$MU**0.5'}

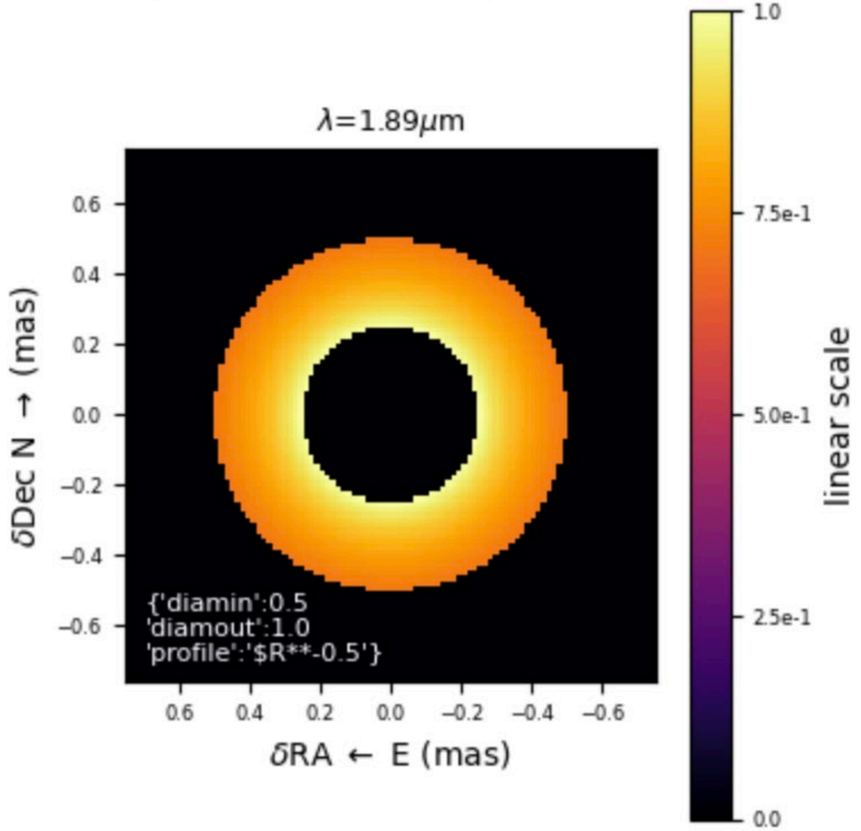
Gaussian



{'fwhm':0.5}

Disk rings

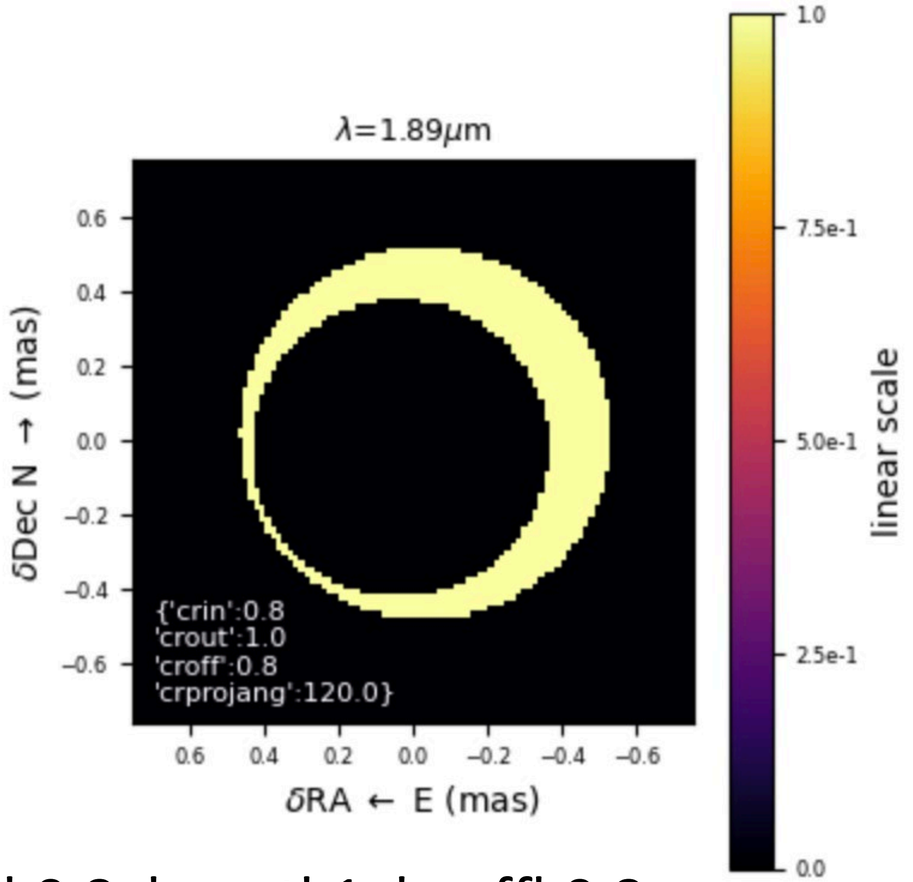
Ring with radial profile



{'diamin':0.5, 'diamout':1,

‘profile':'$R**-0.5'},

Ring with radial profile

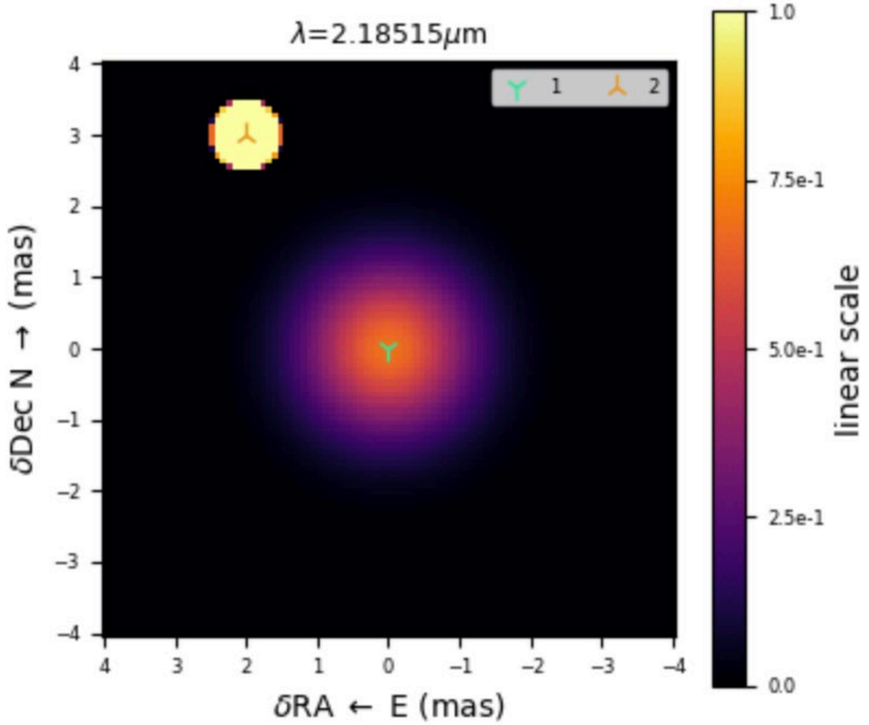


{'crin':0.8, 'crout':1, 'croff':0.8,

'crprojang':120},

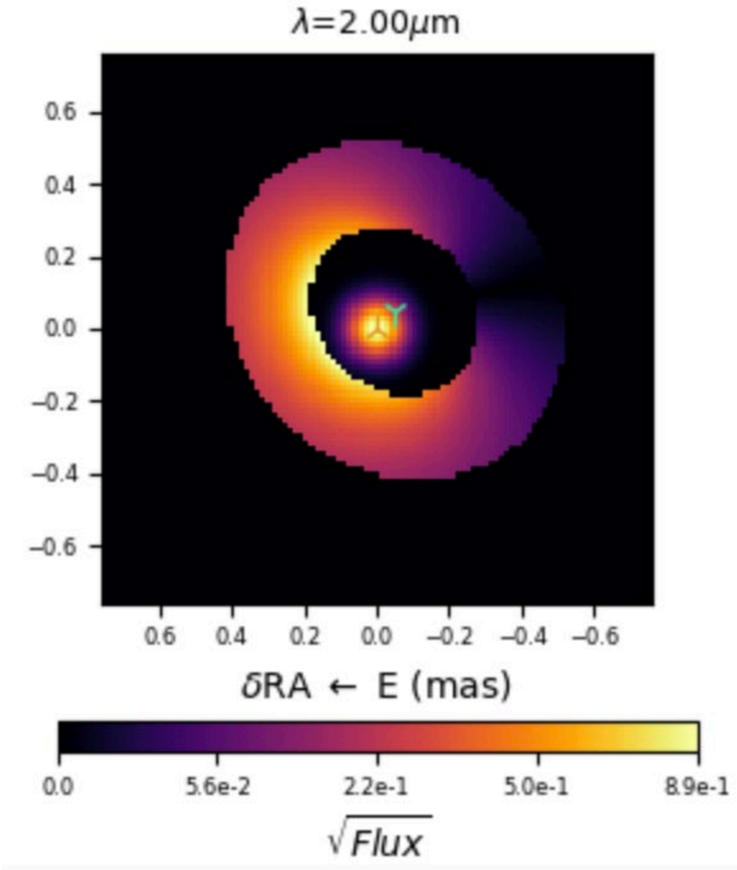
Multi-component scenes

Binary




```
model =
{'star,fwhm':2,
  'companion,ud':1,
   ‘companion,f':1,
‘companion,x:2,
'companion,x:3,
 }
```

Star with disk

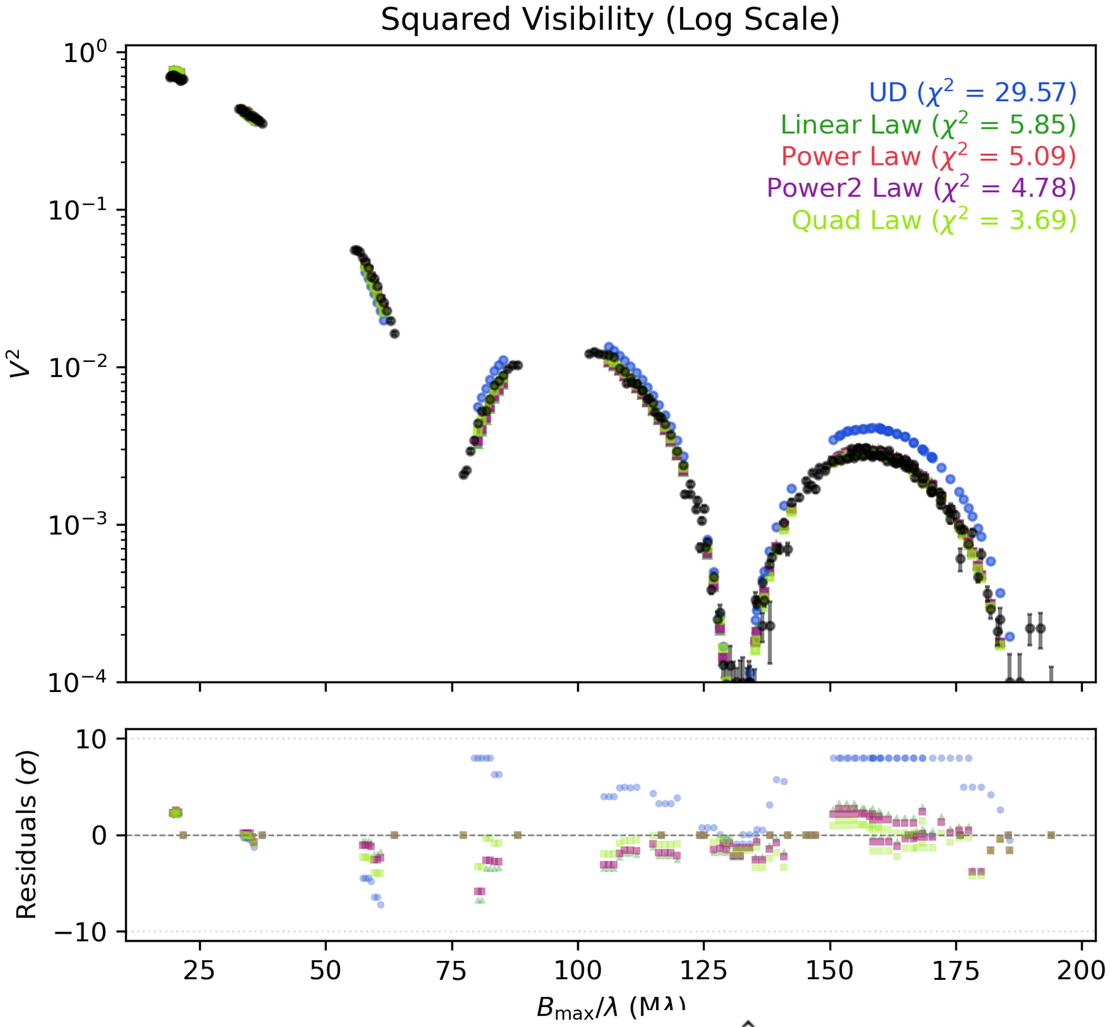


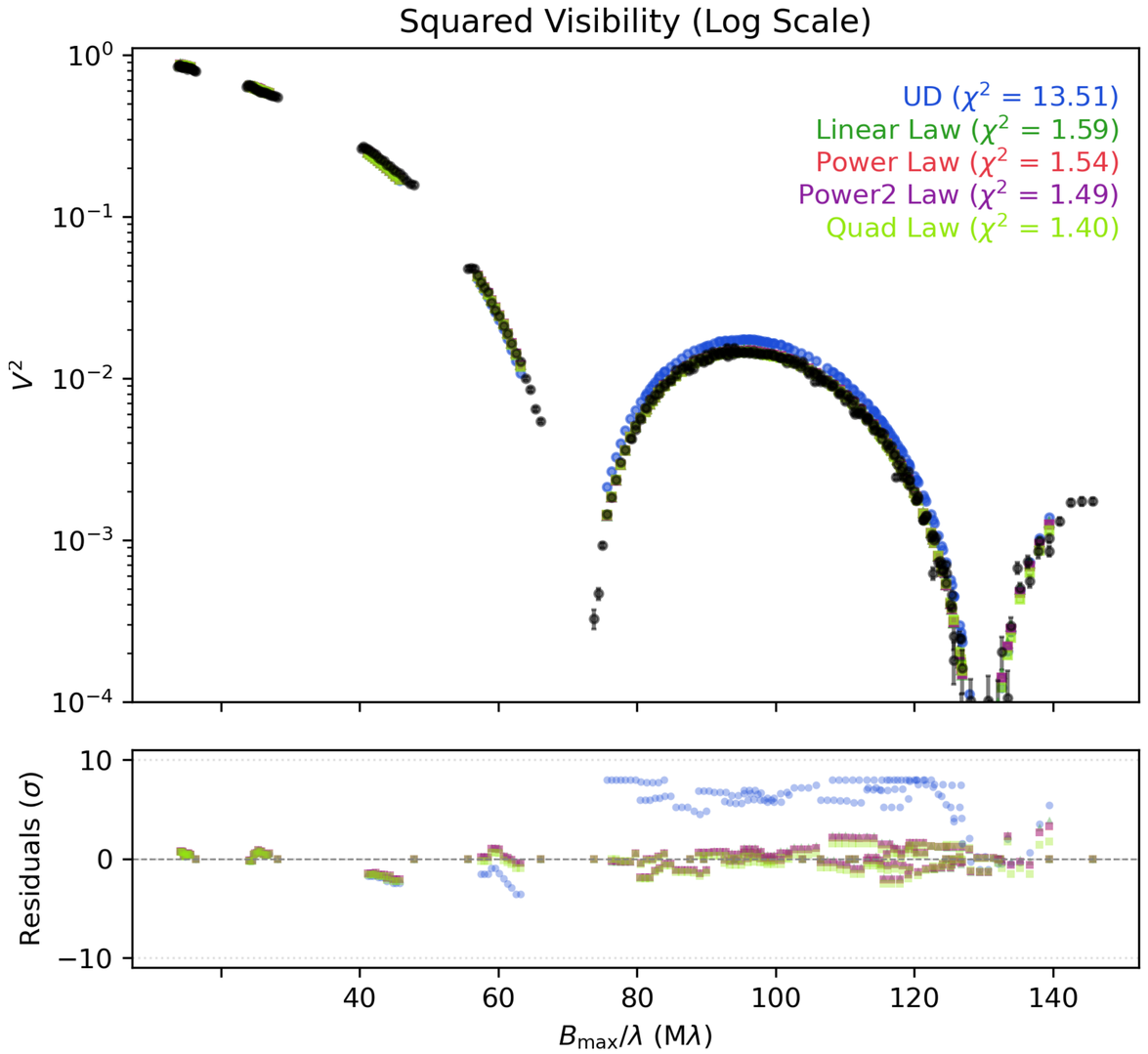

```
model = {'disk,diamin':0.5,
        'disk,diamout':1,
        'disk,profile':'$R**-2',
        'disk,az amp1':1,
        'disk,az projang1':60,
        'disk,projang':45,
        'disk,incl':-30,
        'disk,x':-0.05,
        'disk,y':0.05,
        'disk,spectrum':'5*($WL)**-2',
        'star,fwhm':0.1,
        'star,spectrum':'$WL**-3',
        }
```

Practical Tips

- Large calibrators
- Underestimated errors
- Parameter degeneracy
  UD vs limb darkening
  flux ratio ↔ size (binary/disk)
  inclination ↔ elongation

Target: ups Per





Limb darkening laws:

$$\hat{I}_{\rm lin}(\mu) = 1 - a(1-\mu),$$
$$\hat{I}_{\rm pow}(\mu) = \mu^{\alpha},$$
$$\hat{I}_{\rm quad}(\mu) = 1 - u_1(1-\mu) - u_2(1-\mu)^2,$$
$$\hat{I}_{\rm p2}(\mu) = 1 - p_1\ \left(1-\mu^{\alpha_1}\right).$$

Practical Tips

- Local minima problem, use gridsearch or random search
- Needs good initial guess
- PMOIRED flexibility is powerful, but it also makes it easy to build over-parameterized models. Do not overfit.
- Always look at residuals (not just χ^2)
- Residuals: systematic trends, i.e., wrong model
- Residuals: random scatter, i.e., good model
- High correlation, model is not constrained
- Bootstrap for real uncertainties

Grid search / random search

```
expl = {'grid':{'c,x':(-R/2*step, R/2*step, step), 'c,y':(-R/2*step, R/2*step, step)}}
```

```
expl = {'rand':{'c,x':(-R*step/2, R*step/2), ‘c,y':(-R*step/2, R*step/2)}}
```

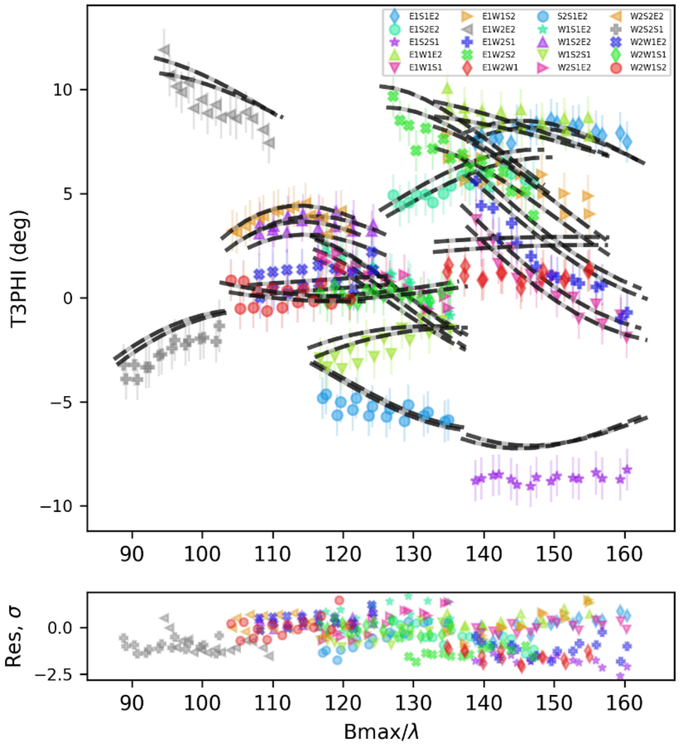
```
oi.gridFit(expl, model=param,
doNotFit=['*,f', 'c,ud'],
prior=[('c,f', '<', 1)],
constrain=[('np.sqrt(c,x**2+c,y**2)', '<=', R*step/2), ('np.sqrt(c,x**2+c,y**2)', '>', step/2) ])
```

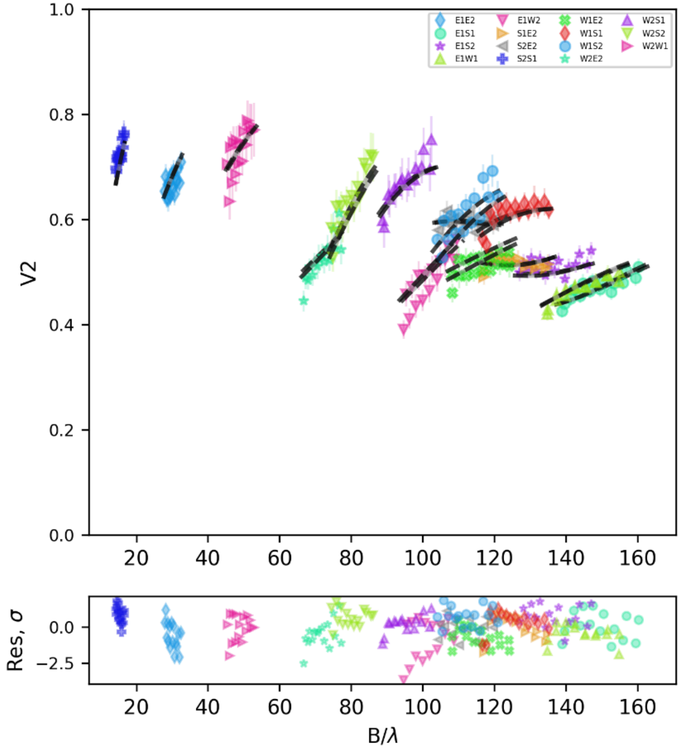
(See Robert Klement tutorial)

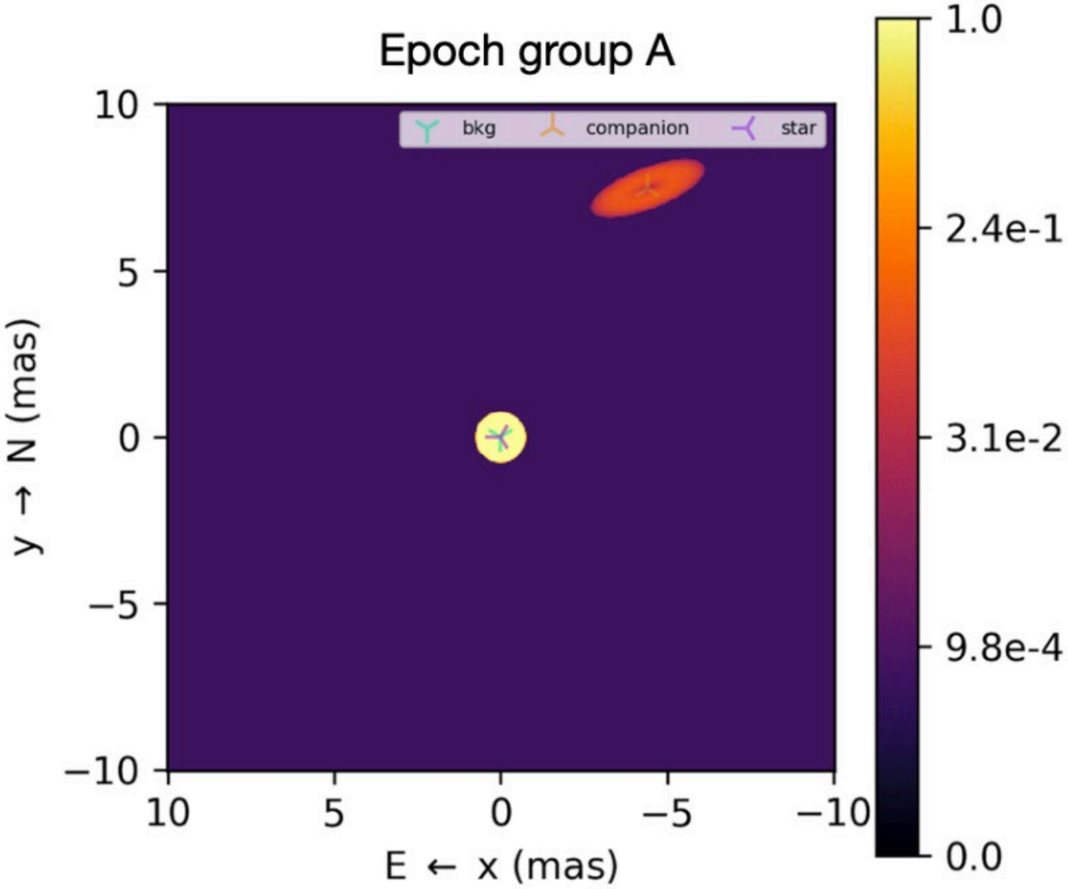
Model interpretation ≠ truth

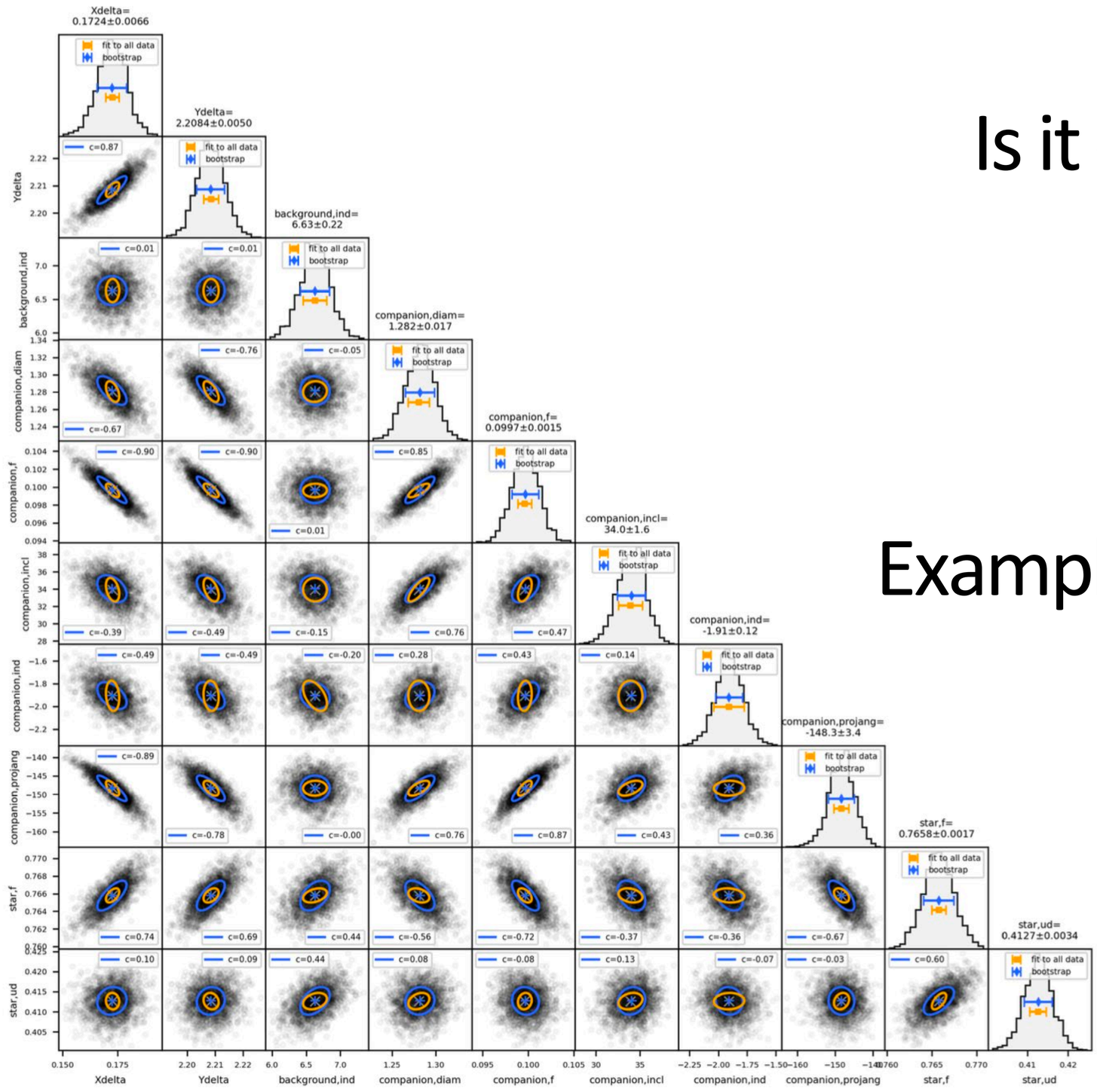
If your model becomes complicated, it should be because the data demand it — not because the software allows it.

Is it overfitting?





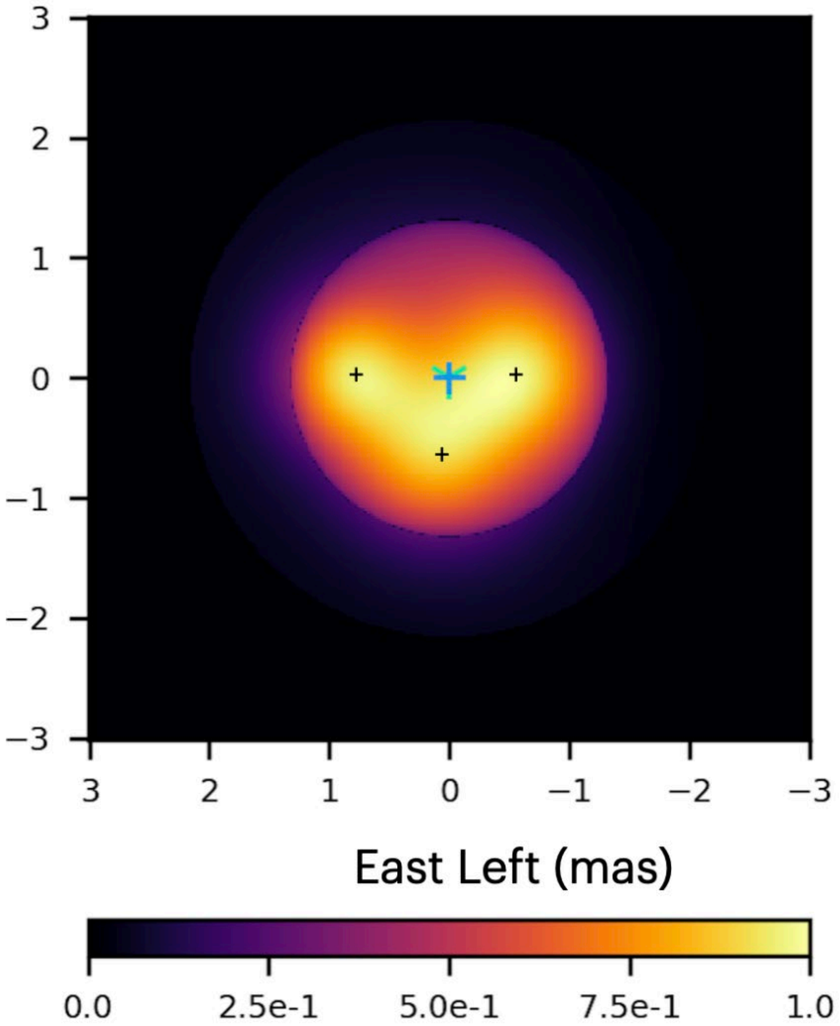




Is it overfitting?

Example of bootstrap

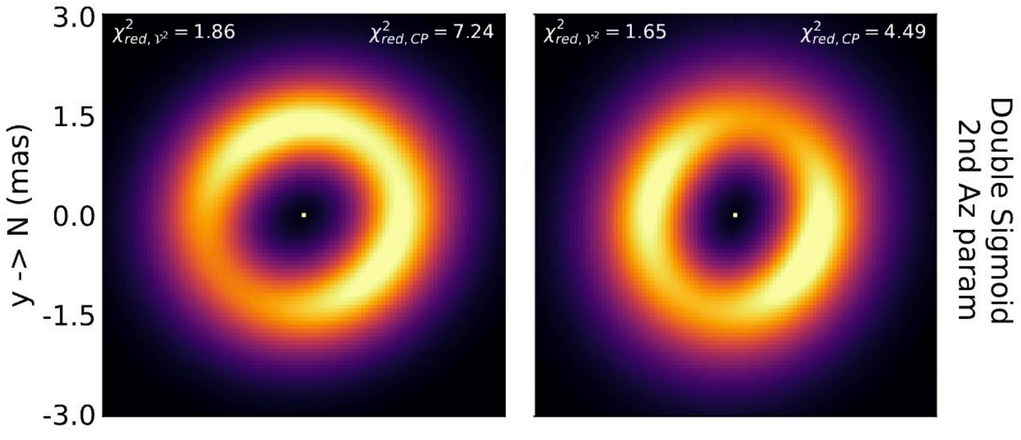
Example: Convection cells on the star surface



- Fit three convection cells on the surface
- Complex model: star with limb darkening model, with convection gaussian spots

Anugu et al. 2024

Example: Young stellar disk



Modeled disk from pmoired

Ibrahim et al. 2023

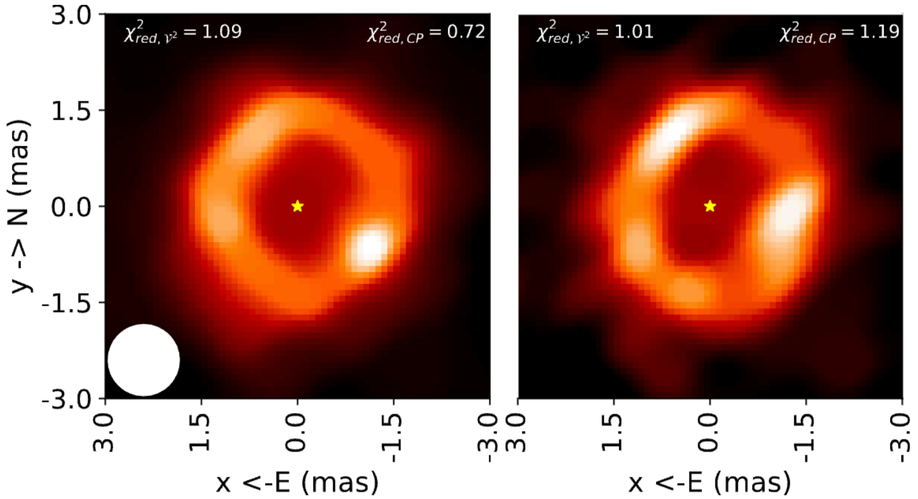
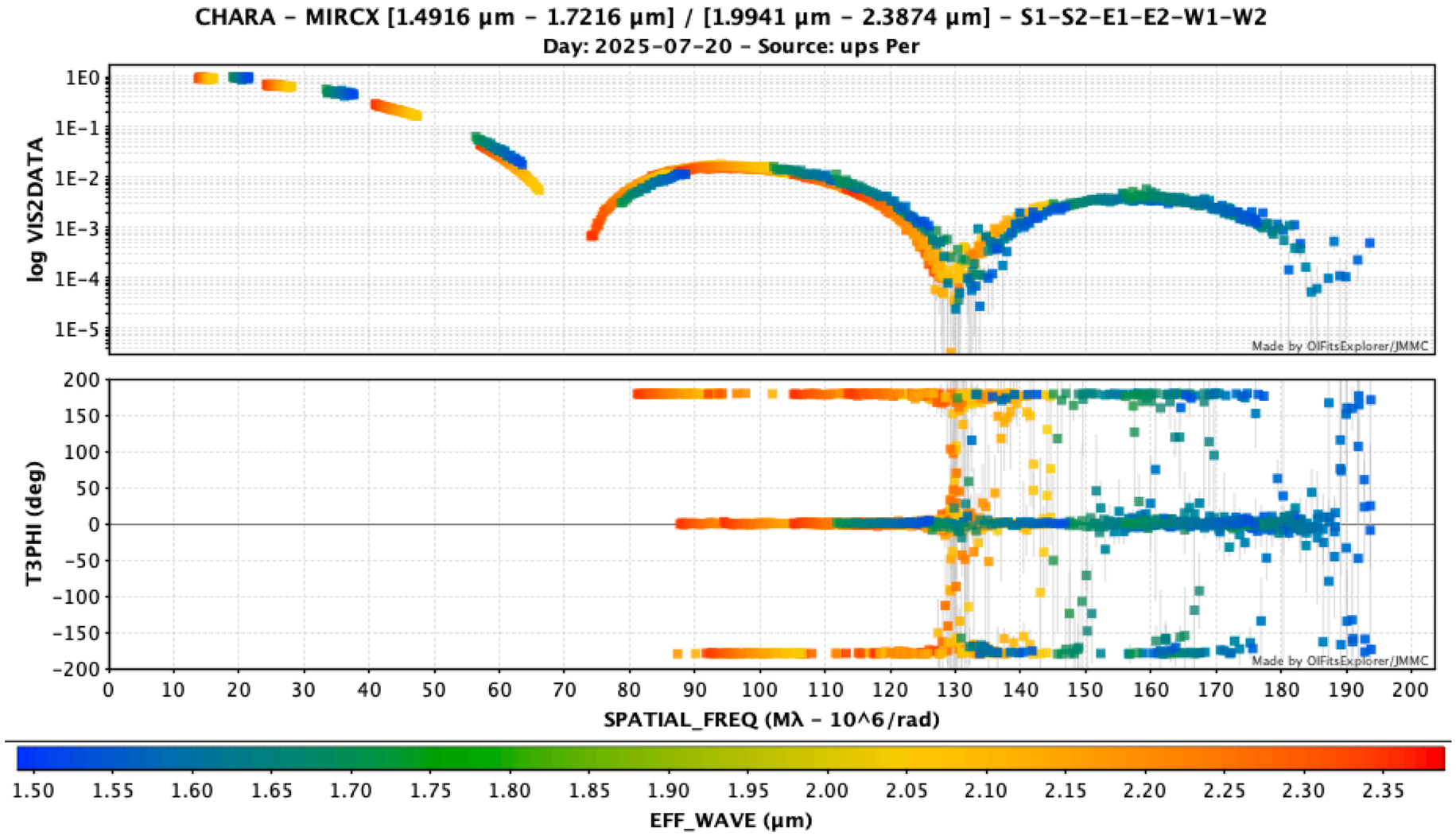


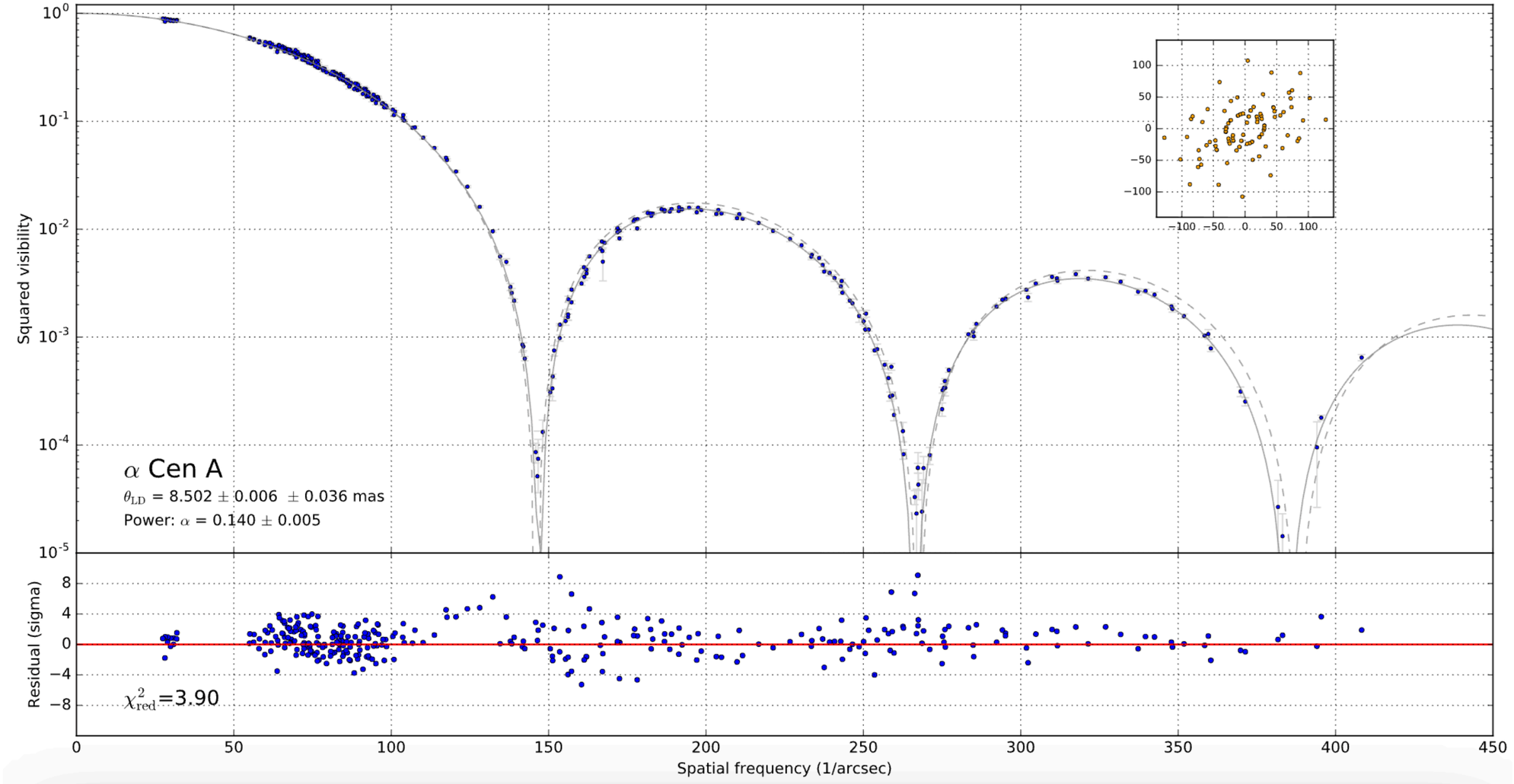
Image from oitools

Tutorial

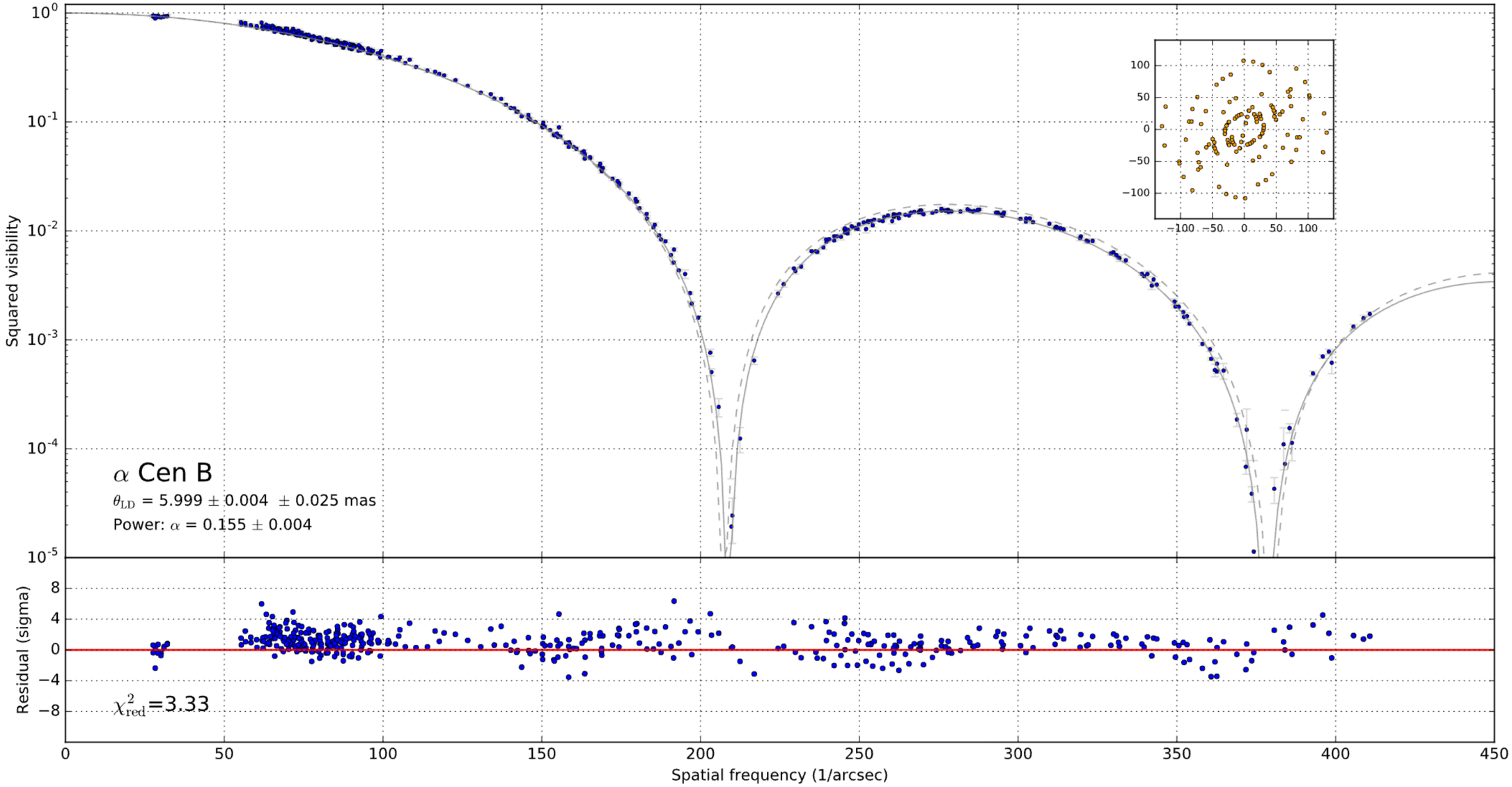
- ups Per
- We fit uniform disk diameter
- limb darkened diameter
- Limb darkening coefficients



alf Can A


Squared visibility
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
α Cen A
θ_{LD} = 8.502 $\pm$ 0.006 $\pm$ 0.036 mas
Power: α = 0.140 $\pm$ 0.005
Residual (sigma)
8
4
0
−4
−8
χ^2_{red}=3.90
0
50
100
150
200
250
300
350
400
450
Spatial frequency (1/arcsec)
100
50
0
−50
−100
−100 −50 0 50 100

alf Can B


Squared visibility
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
α Cen B
$\theta_{\rm LD}$ = 5.999 ± 0.004 ± 0.025 mas
Power: α = 0.155 ± 0.004
100
50
0
−50
−100
−100 −50 0 50 100
Residual (sigma)
8
4
0
−4
−8
$\chi^2_{\rm red}$=3.33
0 50 100 150 200 250 300 350 400 450
Spatial frequency (1/arcsec)