[C]ompanion [A]nalysis and [N]on-[D]etection in [I]nterferometric [D]ata

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- CANDID is a suite of Python tools to search for high contrast companions around stars from interferometric observations
- OIFITS files as input so any interferometric data should work (OLBI, SAM)

- First presented in Gallenne et al. 2015 (A&A, 579, A68) but it has evolved since then

A&A 579, A68 (2015)
DOI: 10.1051/0004-6361/201525917

Astronomy & Astrophysics

Robust high-contrast companion detection from interferometric observations

The CANDID algorithm and an application to six binary Cepheids⋆

A. Gallenne[1], A. Mérand[2], P. Kervella[3,4], J. D. Monnier[5], G. H. Schaefer[6], F. Baron[6,7], J. Breitfelder[3], J. B. Le Bouquin[8], R. M. Roettenbacher[5], W. Gieren[1,10], G. Pietrzyński[1,9], H. McAlister[6], T. ten Brummelaar[6], J. Sturmann[6], L. Sturmann[6], N. Turner[6], S. Ridgway[11], and S. Kraus[12]

- Freely available on Github:
  - https://github.com/amerand/CANDID
  - https://github.com/agallenne/GUIcandid (additional features + GUI)

CANDID: [C]ompanion [A]nalysis and [N]on-[D]etection in [I]nterferometric [D]ata

Setup

Load Oifits | Close Plots | Quit

Color map: cubehelix Titles N Cores: 15

Exec. Time(s): 300 Region: 0,0

Instrument: All WL range: Full

Fitted Parameters

CP V2 T3amp iCP |V|

diam1: 1.0 alpha: 0 diam2: 0

fratio: 2.0 fres: 0

Fit Map

Step: 5 Fig: Fig 1

rmin: Remove Comp.

rmax N detect: 1

Map

Bootstrap

N: 1000 MC B Fig: Fig 1

x: y:

diam1: diam2:

fratio: fres:

Bootstrap

Detection Map

Step: 5 rmin: rmax Remove Comp. Fig: Fig 1

Nsigma: 3 Maps Method: Both Full map Save Fits

Map

Gallenne et al. (2015)

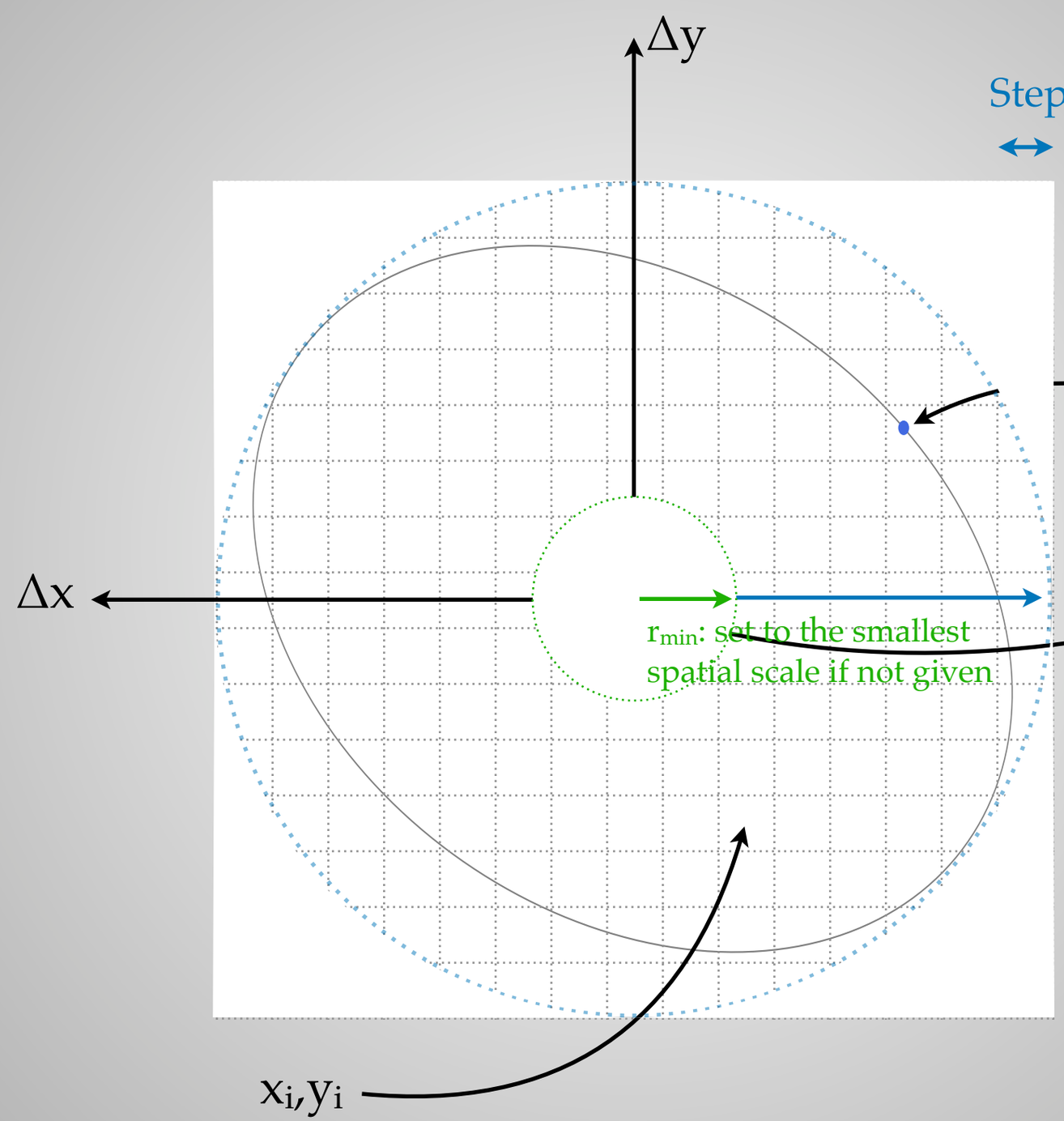
- Two main functionalities:
  1- Search Map
  2- Detection limit maps

- Additional features in my version:
  - Graphical user interface + tool tip (more user friendly)
  - More info when loading the oifits files (baseline length, MJD, ...)
  - Can display several minima
  - Can select a wavelength range
  - Can search in any region (centered on 0 or not)
  - Can select the nσ level for the detection limit map
  - Can save the detection map in fits format

- Uses multiprocessing
- Observables: V^2, $|V|$, CP and $T3_{amp}$
- Fitted parameters: Δx (mas), Δy (mas), f (%), θ_1 (mas), θ_2 (mas), f_{res} (%)
- Possibility to fit a limb-darkened primary diameter with a fixed power law coefficient
- Bandwidth smearing numerically computed

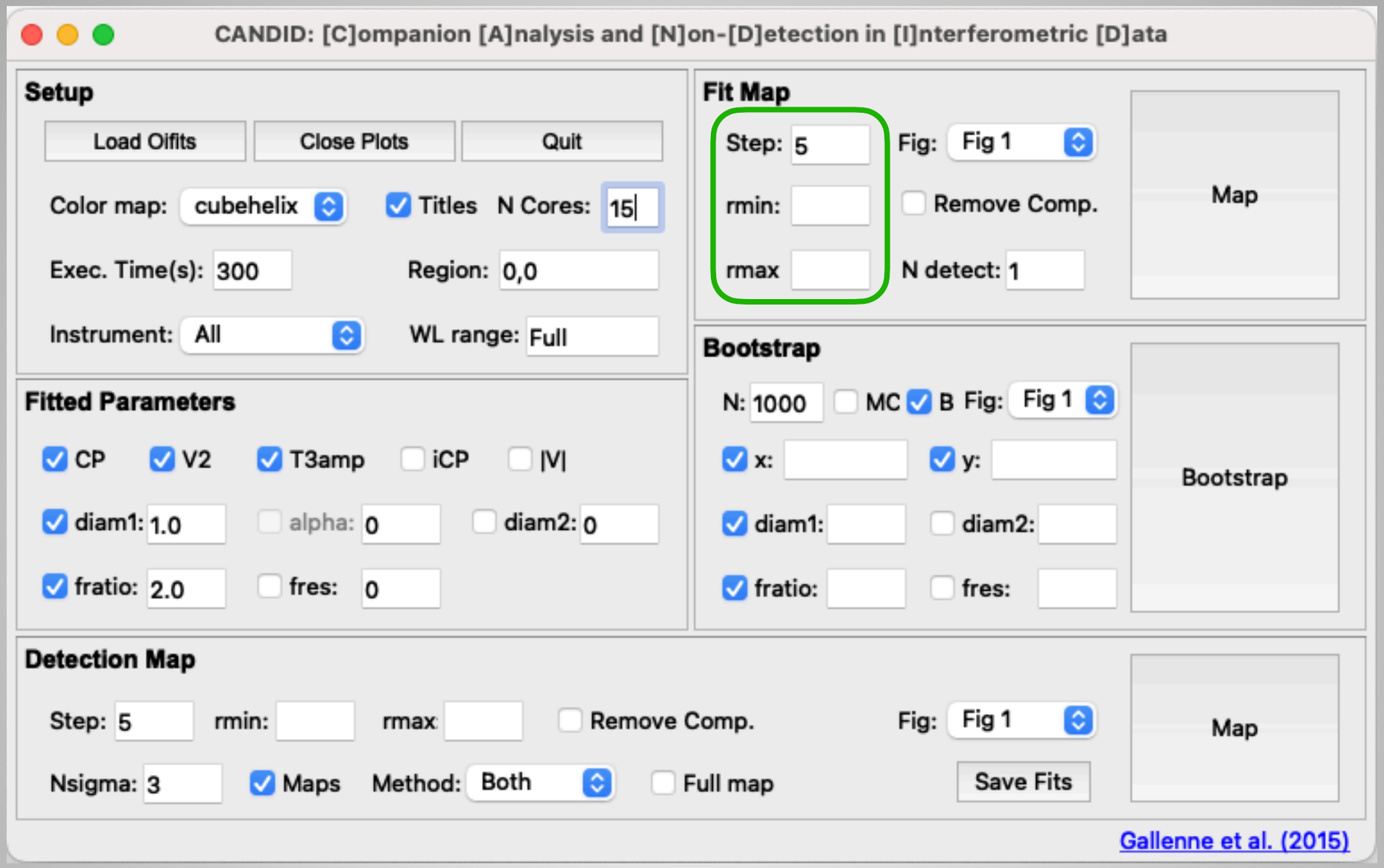
Search Map

- Parameters are fitted at each point (x_i,y_i) of a NxN grid



- All positions are explored by estimating a-posteriori if the grid was dense enough, and provide an estimate of the optimum grid density

Search Map

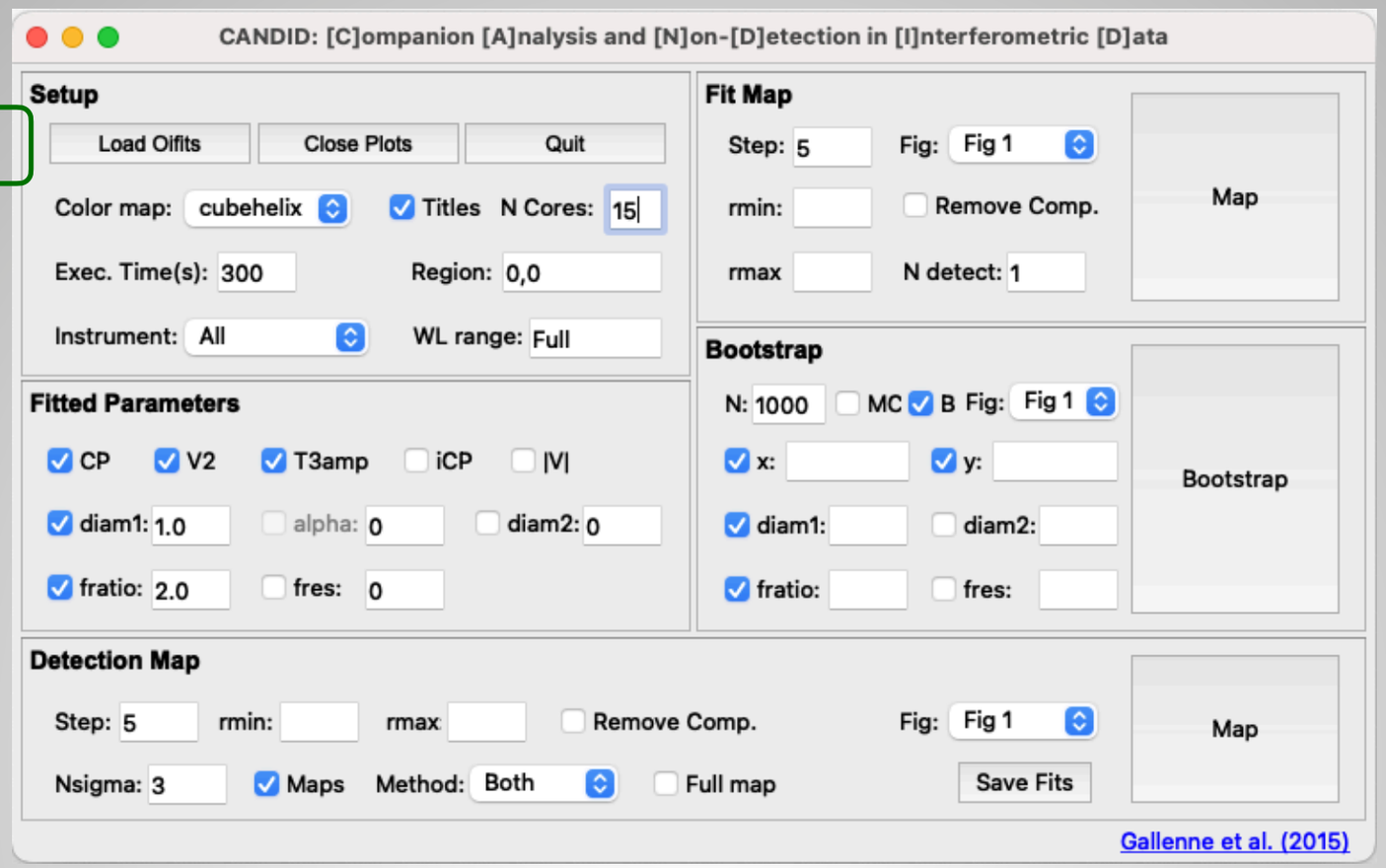



```
In [1]: import candid
In [2]: oi = candid.Open('my oifits files')
```

Search Map

First step is to load an oifits file

1




```
       ========================== This is CANDID ==============================
       [C]ompanion [A]nalysis and [N]on-[D]etection in [I]nterferometric [D]ata
                        https://github.com/amerand/CANDID
       ========================================================================

version: 1.0.7.1 | 2022/12/01
| global parameters (can be updated):
 CONFIG['color map'] cubehelix_r
 CONFIG['chi2 scale'] auto
 CONFIG['long exec warning'] 300
 CONFIG['suptitle'] False
 CONFIG['progress bar'] True
 CONFIG['Ncores'] None
 CONFIG['Nsmear'] 4

| loading file /Users/alex/Data/MIRC/v1334_Cyg_2012Jul27.oifits
| Smallest spatial scale:       0.93 mas
| Diffraction Field of view:  307.44 mas
| WL Smearing Field of view:   40.78 mas
| baselines: S1-S2-E1-W1-W2-E2  (min/max = 32.5/330.4 m)
| H_PRISM: 128 V2 and 112 CP measurements / 8 spectral channels (1.49-1.73um)
| MJD: 56135.454
| compute aux data for companion injection
| observables available: [ 't3', 'cp', 'v2']
| instruments: [ 'H_PRISM']
| rmin= not given, set to smallest spatial scale: rmin= 0.93 mas
| rmax= not given, set to 1.2*Field of View: rmax=48.94 mas
```

```
       ========================== This is CANDID ==============================
       [C]ompanion [A]nalysis and [N]on-[D]etection in [I]nterferometric [D]ata
                        https://github.com/amerand/CANDID
       ========================================================================

version: 1.0.7.1 | 2022/12/01
| global parameters (can be updated):
 CONFIG['color map'] cubehelix_r
 CONFIG['chi2 scale'] auto
 CONFIG['long exec warning'] 300
 CONFIG['suptitle'] False
 CONFIG['progress bar'] True
 CONFIG['Ncores'] None
 CONFIG['Nsmear'] 4

| loading file /Users/alex/Data/GRAVITY/2023-01-26-calibrated.fits
| Smallest spatial scale:       3.07 mas
| Diffraction Field of view:  225.75 mas
| WL Smearing Field of view: FT:      73 mas, SC:   11440 mas
| baselines: A0-G1-J2-J3  (min/max = 58.0/132.4 m)
| GRAVITY_SC: 8186 V2 and 6465 CP measurements / 1628 spectral channels (1.97-2.40um)
| GRAVITY_FT: 32 V2 and 24 CP measurements / 6 spectral channels (1.99-2.38um)
| MJD: 58815.175
| compute aux data for companion injection
| observables available: [ 'cp', 't3', '|v|', 'v2']
| instruments: [ 'GRAVITY_FT', 'GRAVITY_SC']
| rmin= not given, set to smallest spatial scale: rmin= 3.07 mas
| rmax= not given, set to 1.2*Field of View: rmax=87.47 mas
```

Search Map

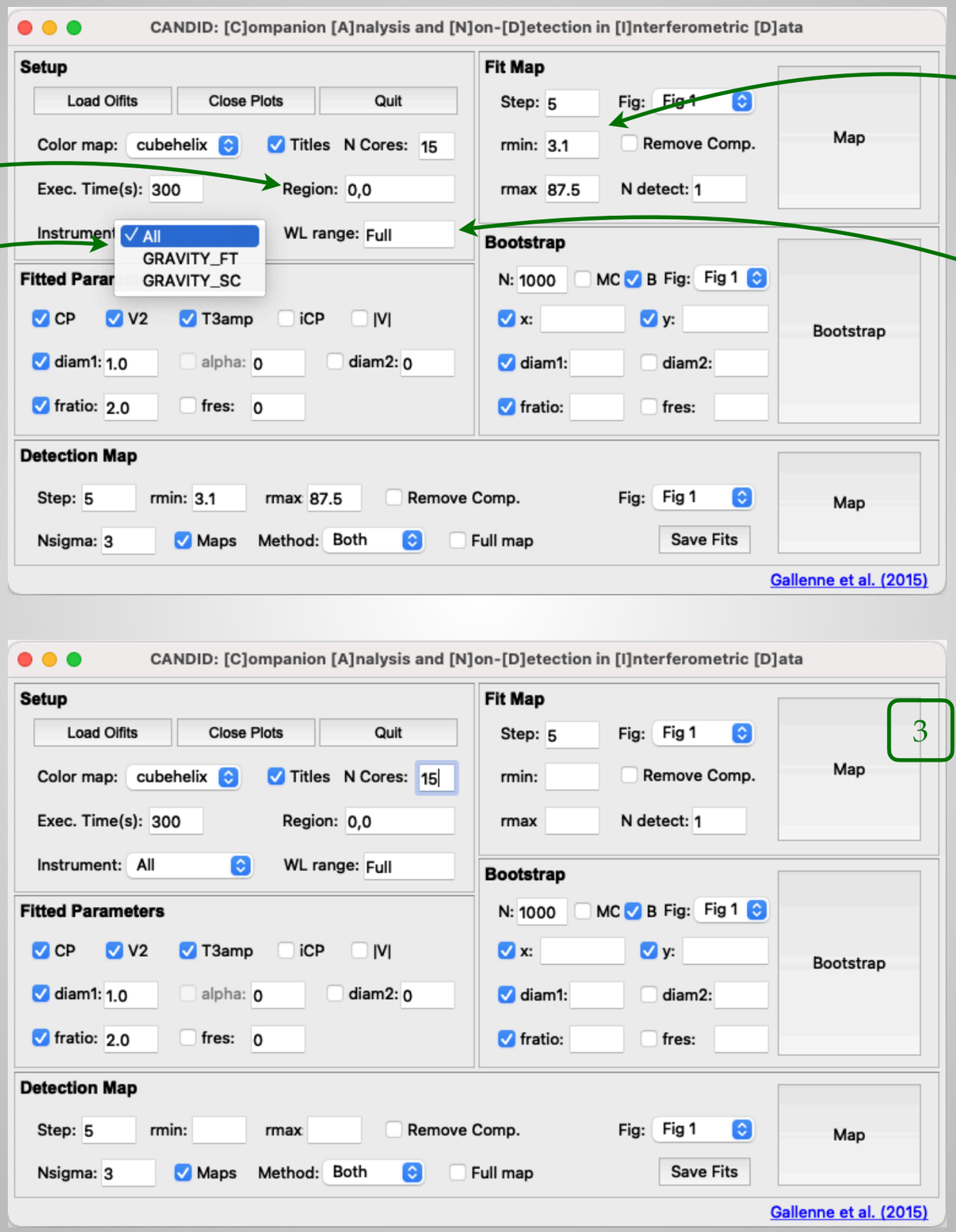
2 Initial setup

Select region

Select instrument(s)

Parameters updated.
Modify if necessary

Select wavelength range



3 Start searching

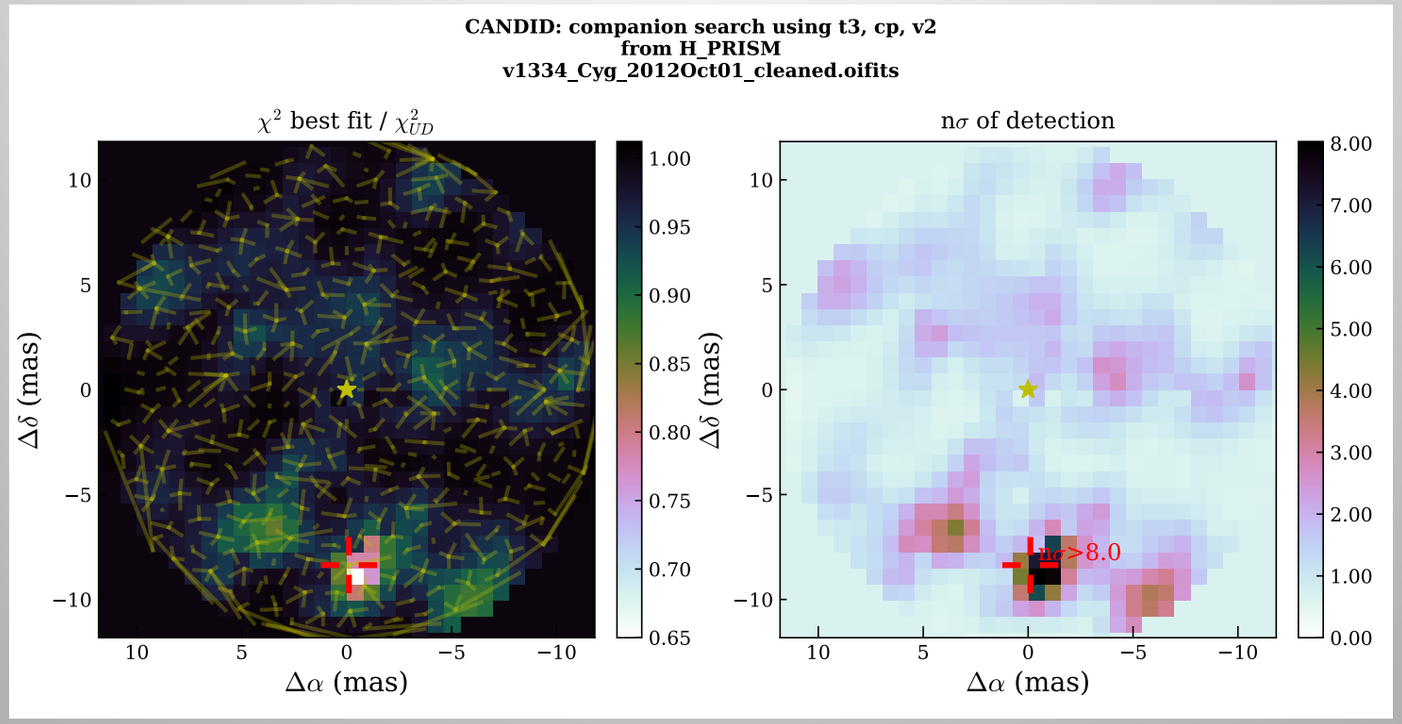
Search Map

```
| setting up Nsmear = 3
 | observables: ['t3', 'cp', 'v2'] from ['t3', 'cp', 'v2']
 | instruments: ['H_PRISM'] from ['H_PRISM']
 | baselines:  ['S1-S2-E1-W1-W2-E2']
 | mean JD: 2456201.711200
 | UD diam Fit
 | best fit diameter: 0.487 +- 0.004 mas
 | chi2 = 1.951
 |=============================================    | 92%   1 s remaininggd take about 32 seconds
 | grid of fit took 9.4 seconds
 | Computing map of interpolated Chi2 minima
 | 101 individual minima for 104 fits
 | 10, 50, 90 percentiles for fit displacement: 0.2, 0.5, 0.9 mas
 | grid step was 2.0 mas
 | 1.0 fit per minima with step 2.00
 | minima density: 2.1 mas
 > WARNING, grid may be too wide! --> try step=0.73mas
 | Rbf interpolating: 101 points -> 169 pixels map
 | BEST FIT 0: chi2=1.1631
 | alpha*=   0.0000 [none]
 |  diam*=   0.4359 +- 0.0041 [mas]
 |      f=   3.0961 +- 0.0973 [% primary]
 |      x=  -0.1070 +- 0.0151 [mas]
 |      y=  -8.3626 +- 0.0097 [mas]
 | for information:
 |    sep=   8.3633mas
 |     PA= -179.2668deg
 | chi2r_UD=1.95, chi2r_BIN=1.16, NDOF=1531 -> n sigma:     8 (assumes uncorr data)
 | Correlations:  >=.9 >=.8 >=.7 >=.5 >=.2 <.2
 |           0    1    2    3
 | 0:diam* #### -.44  .01 -.04
 | 1:    f -.44 #### -.02  .03
 | 2:    x  .01 -.02 #### -.29
 | 3:    y -.04  .03 -.29 ####
```

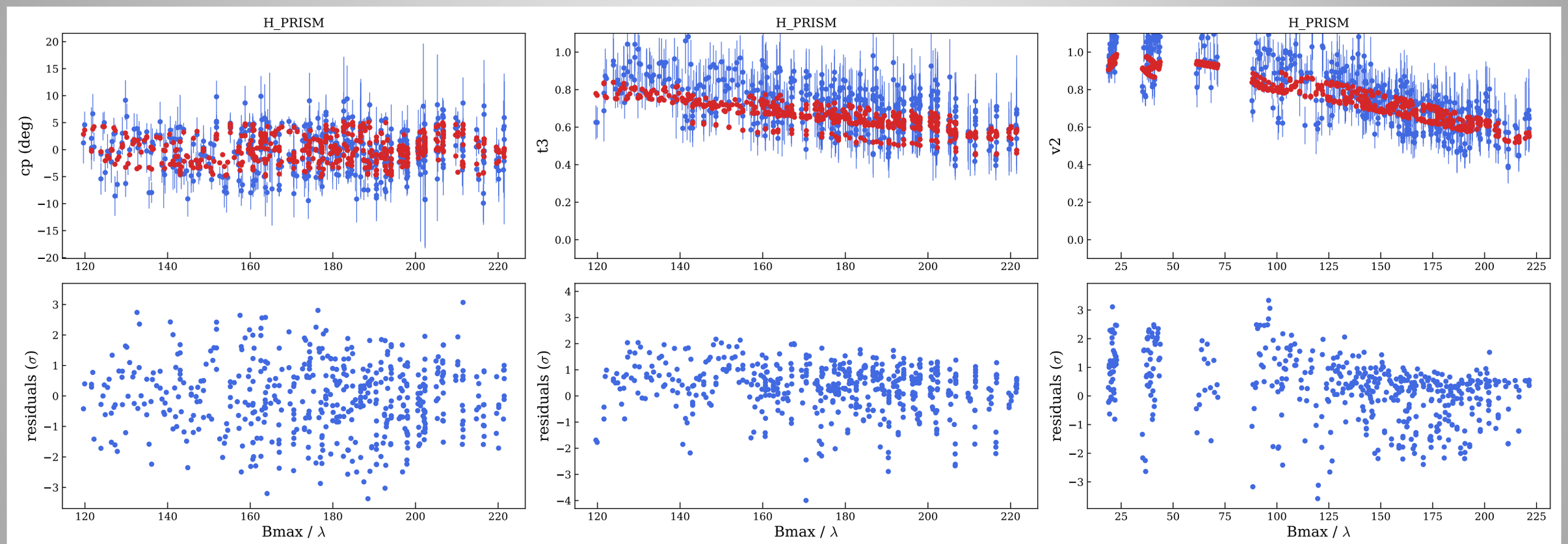
Fitted parameters {

Fit "Travel distance"

$> \sqrt{2}/2 *$ size of the square grid

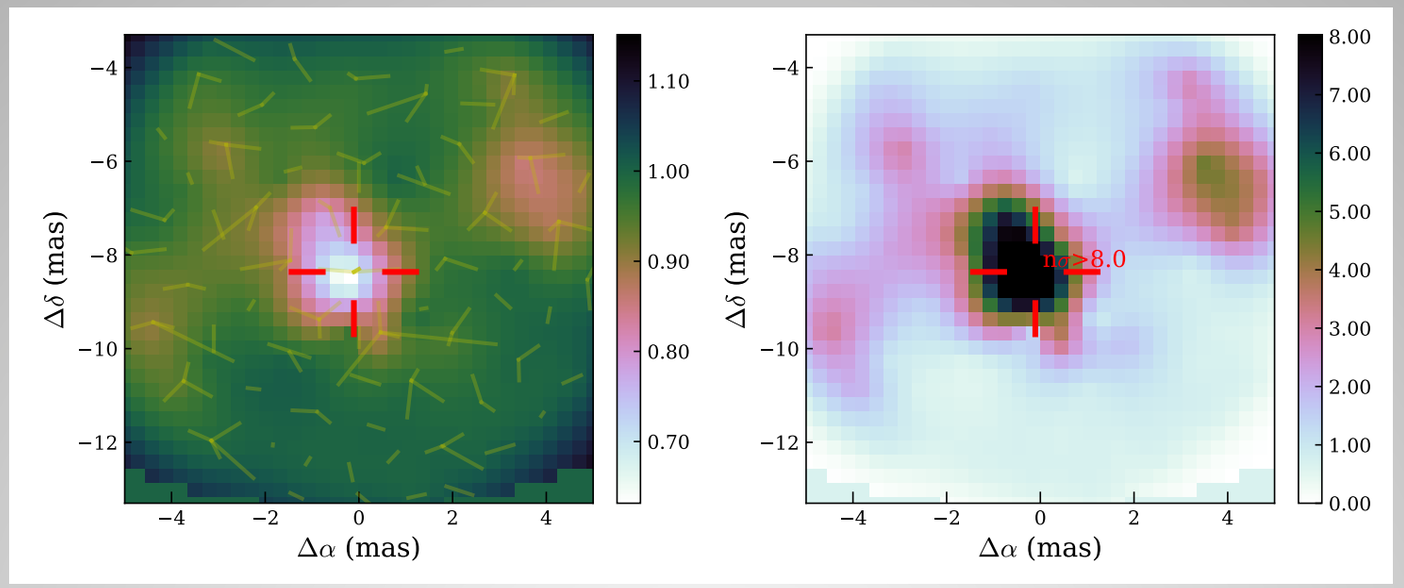


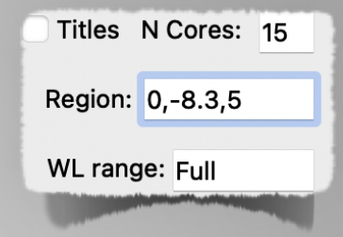
Search Map



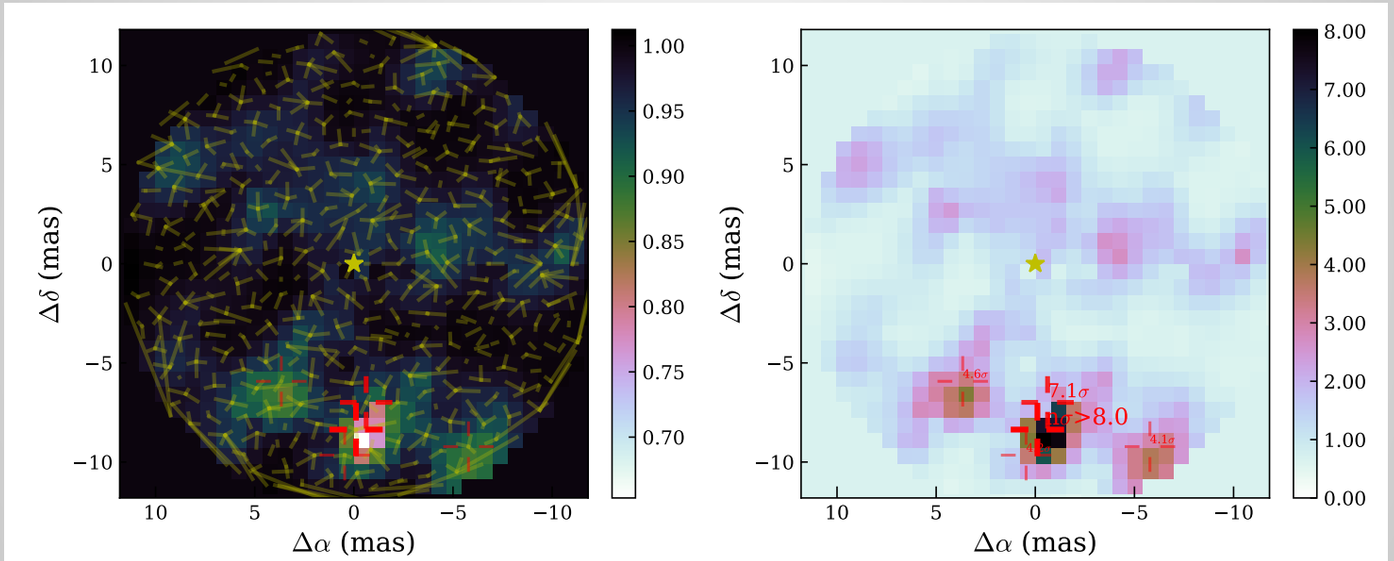
Search Map

- Region:

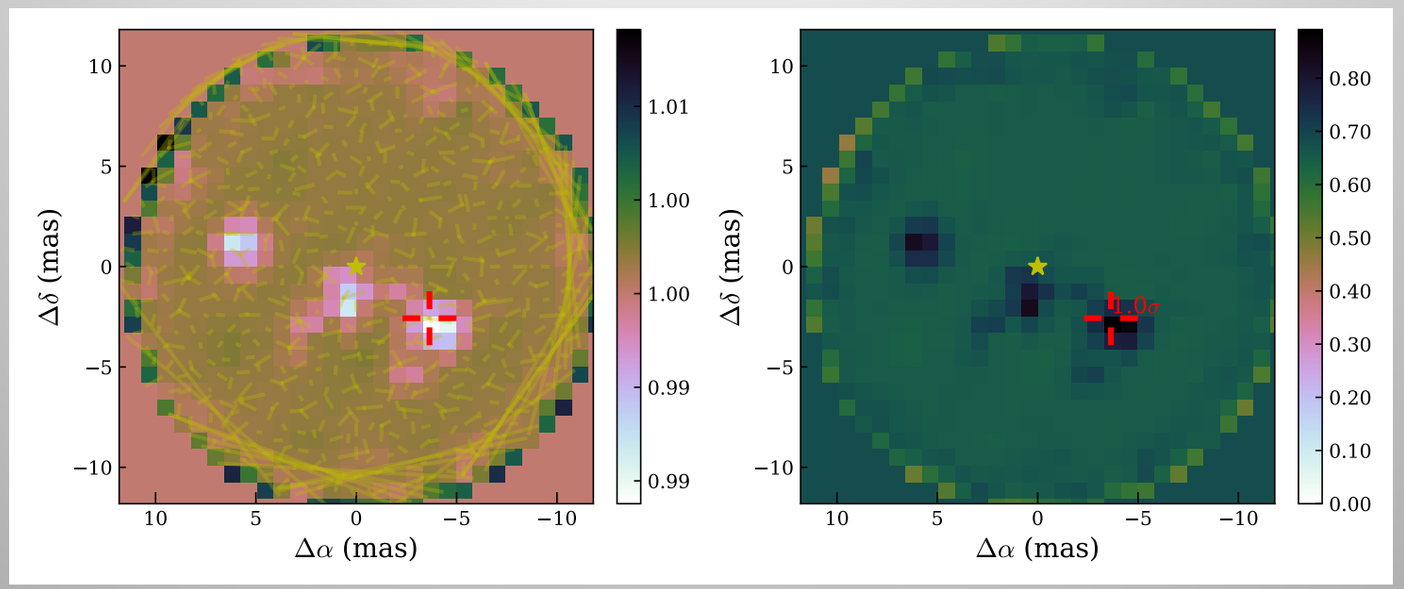


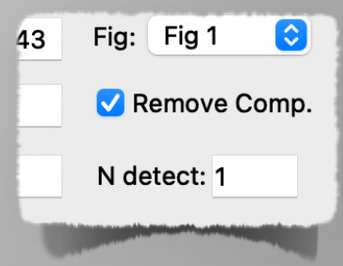


- N Detect:



- Companion removed:





Search Map

CANDID: [C]ompanion [A]nalysis and [N]on-[D]etection in [I]nterferometric [D]ata

Setup

Load Oifits | Close Plots | Quit

Color map: cubehelix | Titles | N Cores: 15

Exec. Time(s): 300 | Region: 0,0

Instrument: H_PRISM | WL range: Full

Fitted Parameters

CP | V2 | T3amp | iCP | |V|

diam1: 1.0 | alpha: 0 | diam2: 0

fratio: 2.0 | fres: 0

Fit Map

Step: 0.727 | Fig: Fig 1

rmin: 0. | Remove Comp. | Map

rmax 12 | N detect: 1

Bootstrap

N: 1000 | MC | B | Fig: Fig 1

x: -0.107 | y: -8.363

diam1: 0.436 | diam2: 0

fratio: 3.1 | fres: 0 | Bootstrap

Detection Map

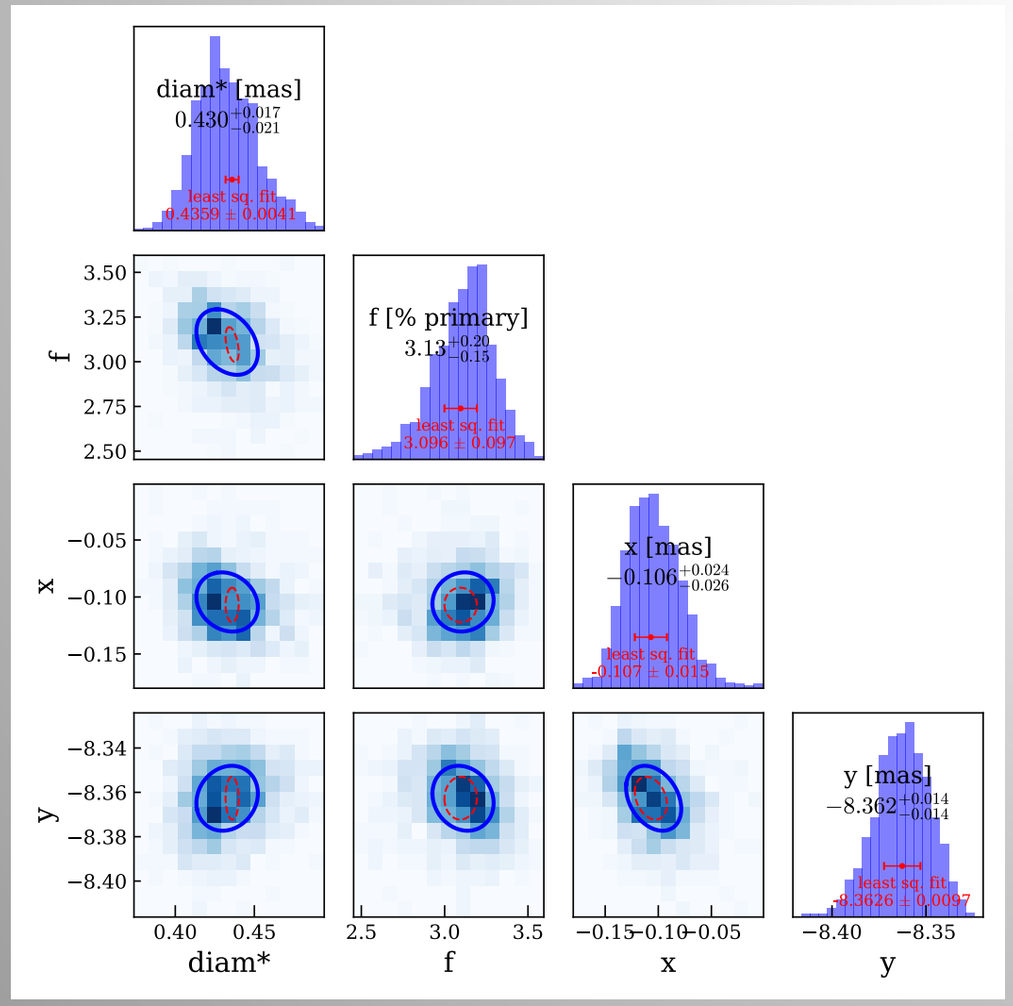
Step: 0.727 | rmin: 0.9 | rmax: 49.0 | Remove Comp. | Fig: Fig 1

Nsigma: 3 | Maps | Method: Both | Full map | Save Fits | Map

Gallenne et al. (2015)

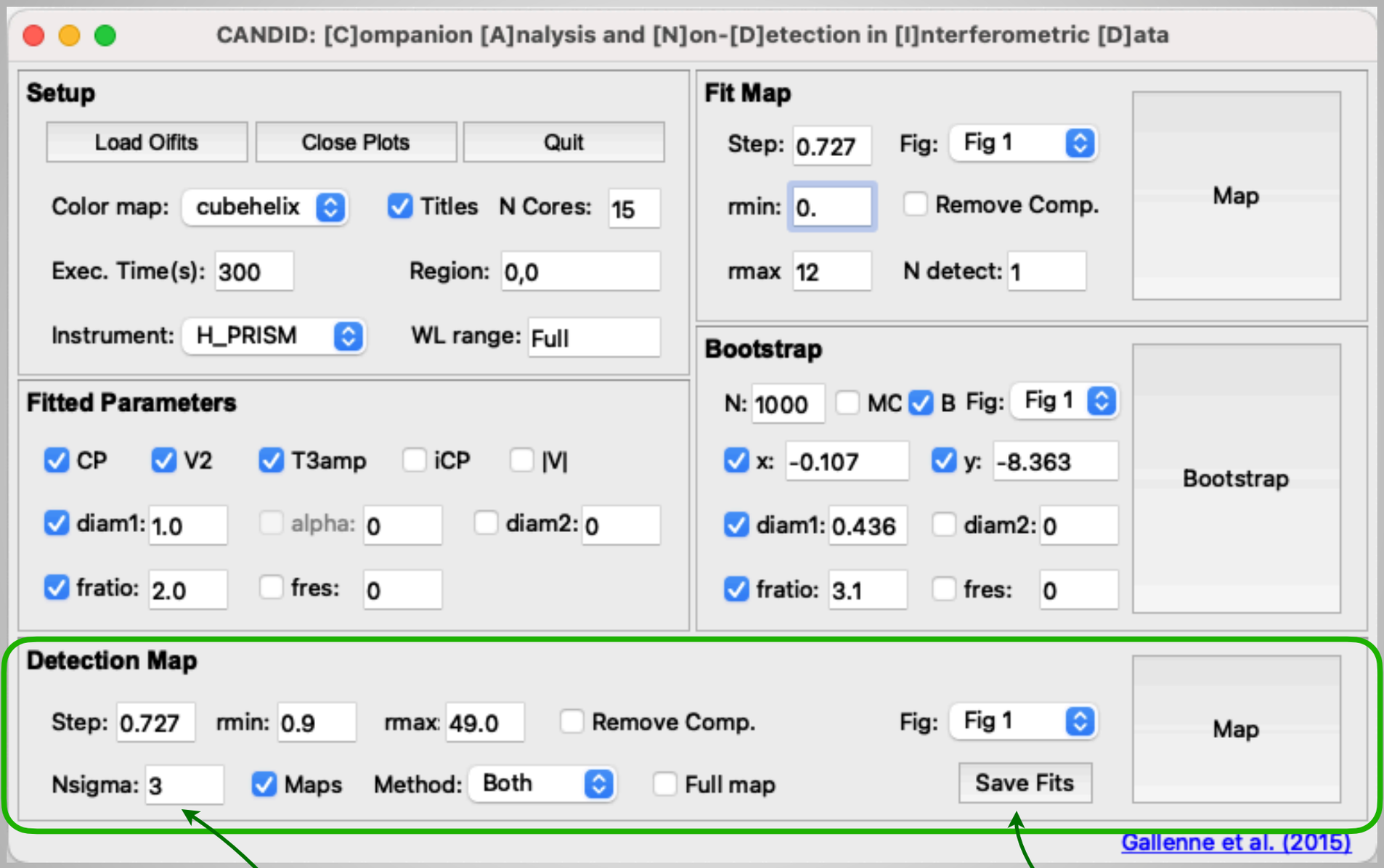
4 Start bootstrapping

Last search already filled




```
| using best solution from last search (fitMap or chi2Map)
| running N=1000 fit  [Pooling 15 processors]... it should take about 207 seconds
| ------------------------------------------
| Reference Least Square Fit (all data):
| chi2 = 1.163
|   alpha* =   0.0000 +- 0.0000 none
|    diam* =   0.4359 +- 0.0041 mas
|       f =   3.0960 +- 0.0973 % primary
|       x =  -0.1070 +- 0.0151 mas
|       y =  -8.3626 +- 0.0097 mas
| Correlations:  >=.9 >=.8 >=.7 >=.5 >=.2 <.2
|          0    1    2    3
| 0:diam* #### -.44  .01 -.03
| 1:    f -.44 #### -.02  .02
| 2:    x  .01 -.02 #### -.29
| 3:    y -.03  .02 -.29 ####
| ------------------------------------------
| Boostrapping on 61 MJDs: 56201.14836 => 56201.30280
|================================================== |  99%   0 s remainingg
| grid of fit took 11.7 seconds
| sigma clipping in position and flux ratio for nSigmaClip= 4.5
| All fits [N=1000] 16, 50 and 84% percentiles:
| x:  -0.1297  -0.1058  -0.0794
| y:  -8.3767  -8.3622  -8.3478
| f:   2.9333   3.1303   3.2848
| d:   0.4134   0.4305   0.4517
| 1 fits ignored
|    diam* =   0.4304 + 0.0170 - 0.0212 mas
|       f =   3.1303 + 0.1960 - 0.1545 % primary
|       x =  -0.1058 + 0.0238 - 0.0265 mas
|       y =  -8.3622 + 0.0145 - 0.0145 mas
| Astrometric error ellipse:
|       x =  -0.1044 mas
|       y =  -8.3627 mas
|      PA = 165.8945 deg
|       a =   0.0266 mas
|       b =   0.0135 mas
| Correlations:  >=.9 >=.8 >=.7 >=.5 >=.2 <.2
|          0    1    2    3
| 0:diam* #### -.33 -.18  .15
| 1:    f -.33 ####  .06 -.15
| 2:    x -.18  .06 #### -.32
| 3:    y  .15 -.15 -.32 ####
```

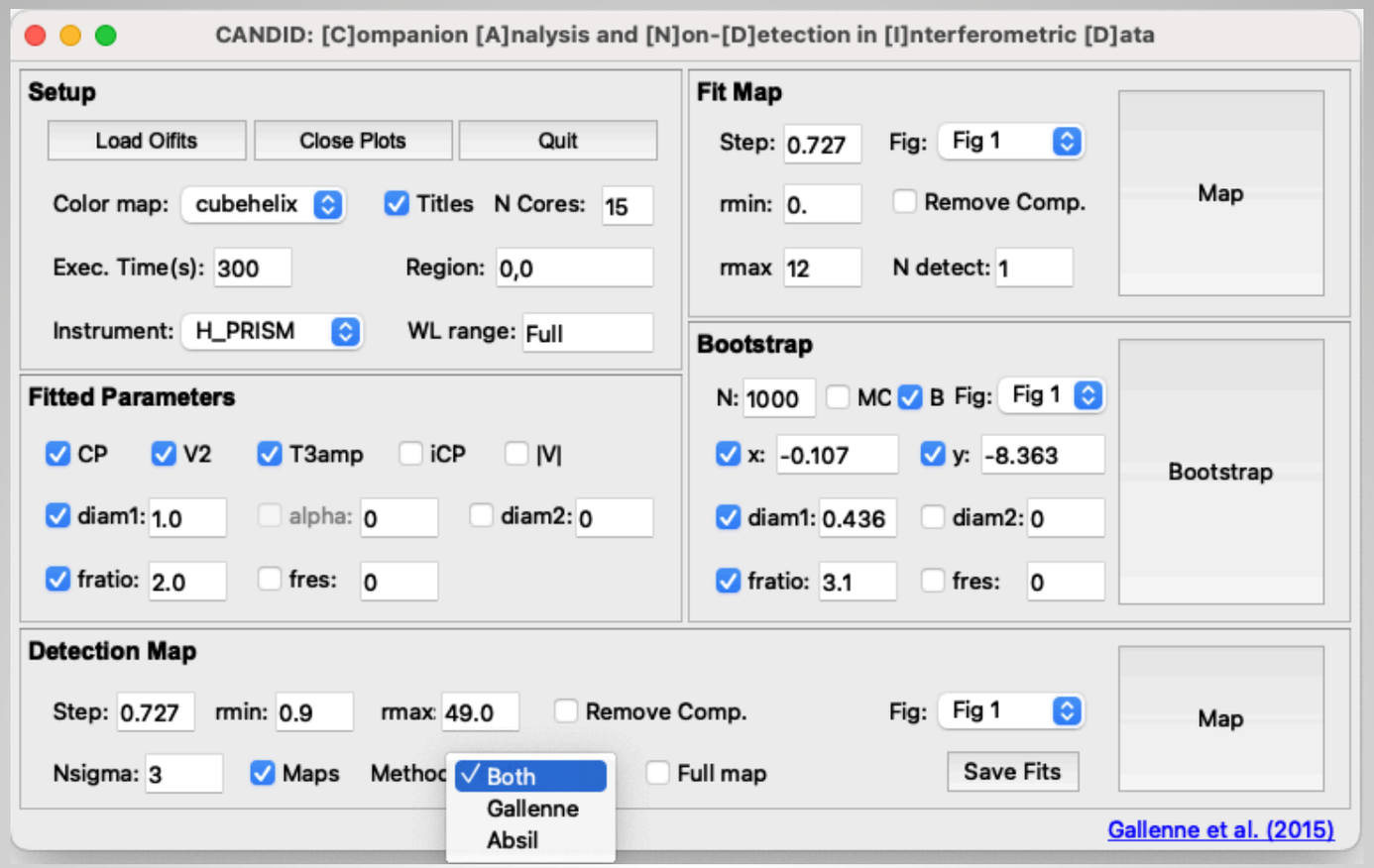
Detection Limits



Can change the requested detection level

Can save the final map in fits format

Detection Limits



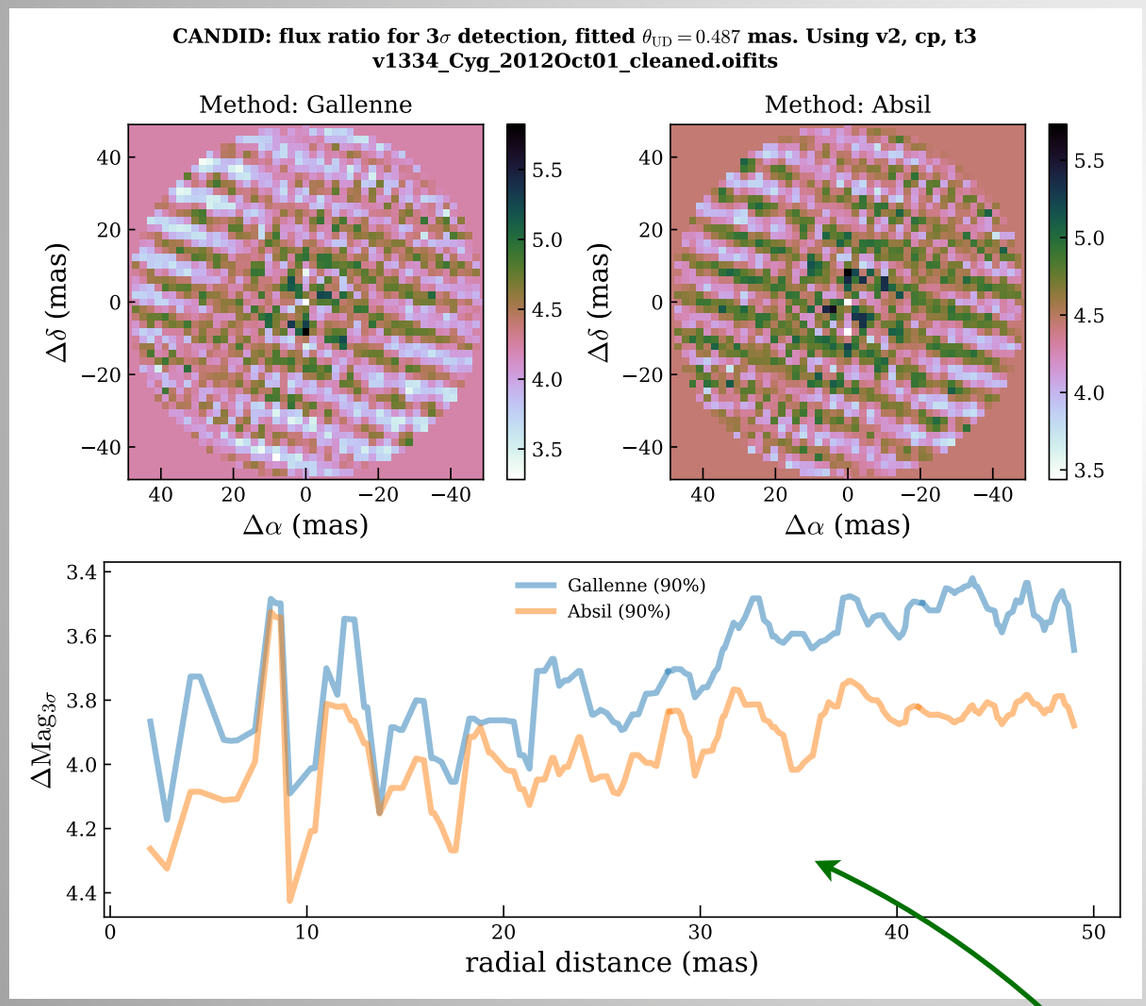
- Two methods for each astrometric position:
  - **Absil**: compare a uniform disk model (true model) with a binary model (hypothesis) --> Absil et al. 2011, A&A, 535, A68
  - **Gallenne**: inject a companion with various flux ratio and compare the binary model (true model) with a uniform disk (hypothesis)

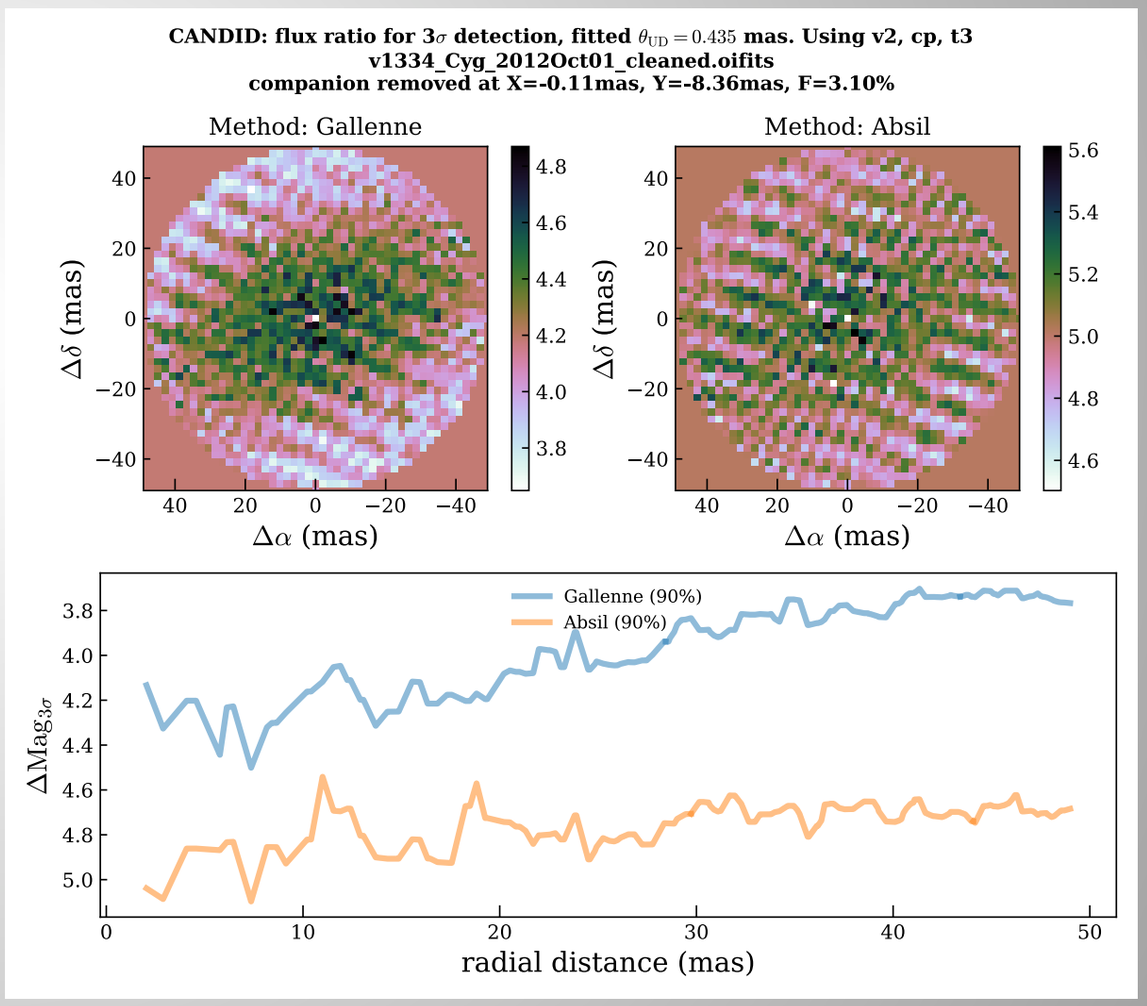
$$P(\Delta\alpha, \Delta\delta) = 1 - CDF_\nu\left(\frac{\nu\chi^2_{\mathrm{UD}}}{\chi^2_{\mathrm{r,bin}}(\Delta\alpha, \Delta\delta)}\right)$$

$$P(\Delta\alpha, \Delta\delta) = 1 - CDF_\nu\left(\frac{\nu\chi^2_{\mathrm{r,bin}}(\Delta\alpha, \Delta\delta)}{\chi^2_{\mathrm{UD}}}\right)$$

Detection Limits

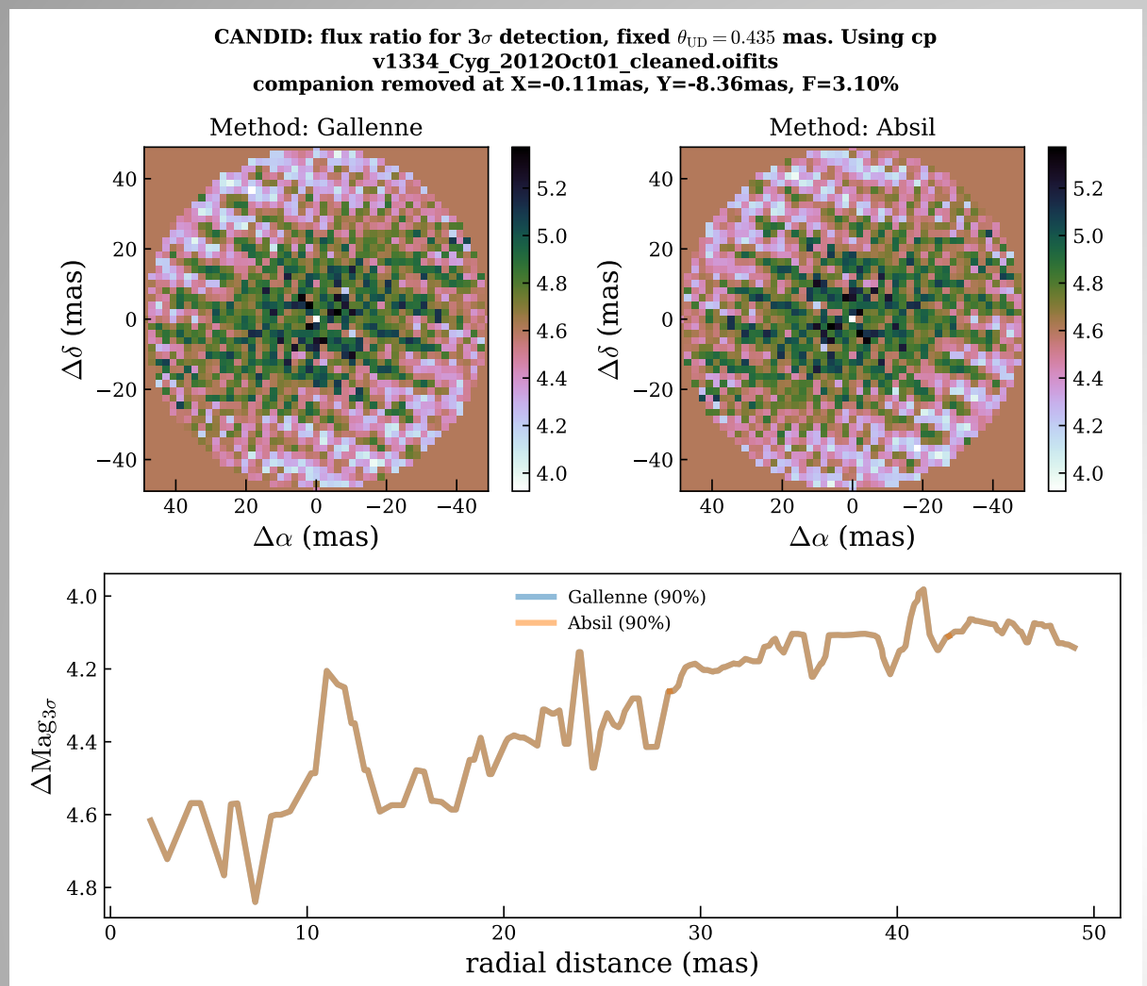
- Injection method is more robust to biased data when estimating detection limits
- Remove (analitically) a previously detected companion





Radial profile f(r) using 90% completeness level from the cumulated histogram in rings for all azimuths

Detection Limits



- Injection and Absil method identical because no UD diameter is fitted

```
| setting up Nsmear = 4
| observables: ['t3', 'v2', 'cp'] from ['t3', 'v2', 'cp']
| instruments: ['H_PRISM'] from ['H_PRISM']
| UD diam Fit
| best fit diameter: 0.435 +- 0.003 mas
| chi2 = 1.161
| Detection Limit Map 20x20  [Pooling 15 processors]... it should take about 137 seconds
| Method: Gallenne
|================================================ | 99%   0 s remainingg
| Method: Absil
|================================================ | 99%   0 s remainingg
|
| Average detection limits:
| r <  24mas: dm = 4.21mag, std = 0.10mag
| r >  24mas: dm = 3.93mag, std = 0.10mag
| r <  49mas: dm = 4.00mag, std = 0.15mag
```

That is all you need to know about CANDID
to fit a simple binary model

Thank you