2DBAT

2D Bayesian Automated Tilted-ring fitter (2DBAT)

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International Centre for Radio Astronomy Research

CAASTRO ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

Curtin University

The University of Western Australia

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- Performance test (artificial + observed galaxies)
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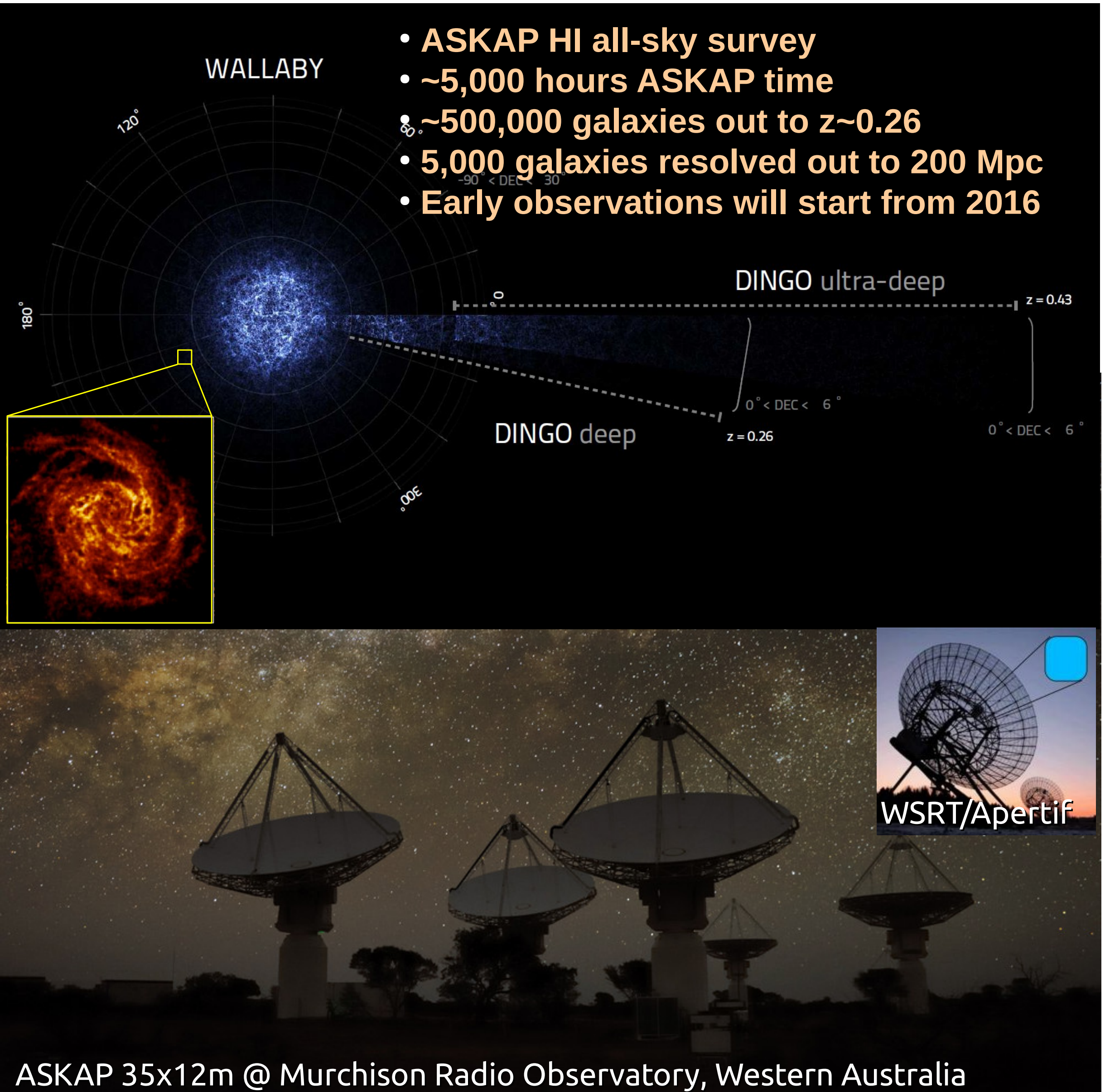
Precision Measurements of Disc Galaxy Dynamics
: SKA pathfinders' HI galaxy surveys



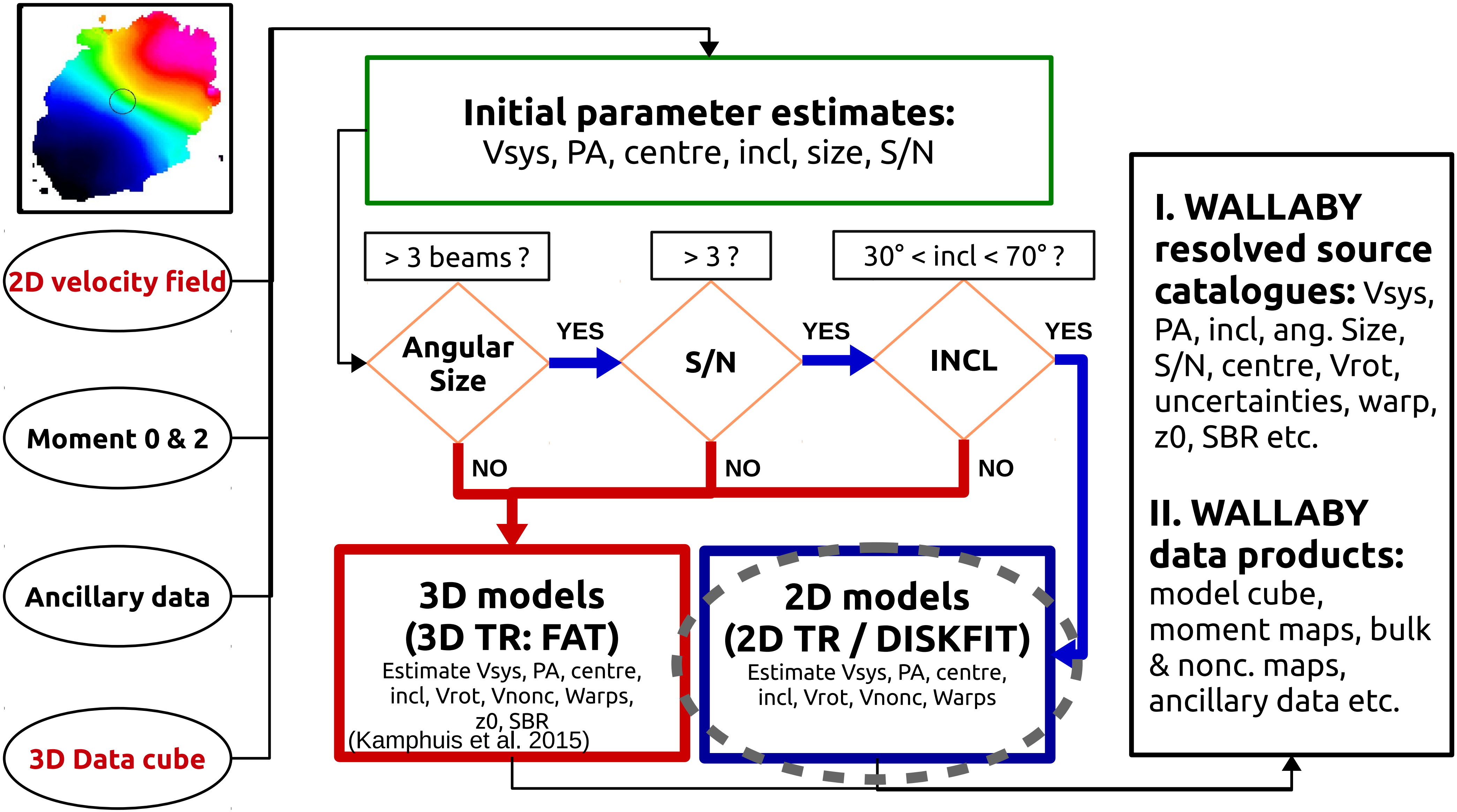
- **WALLABY** : Australian SKA Pathfinder (ASKAP) HI All-Sky Survey (Koribalski & Staveley-Smith et al.) : ~1200 ASKAP pointings (8 hours each) are required

➔ If combined with Apertif northern sky shallow survey at comparable sensitivity but at a higher angular resolution, > 1 million galaxies detected in HI out to z~0.26,

➔ Of these, **>10,000 galaxies within 200 Mpc are expected to be resolved by more than 3 beams across semi-major axes (Duffy et al. 2012)**

Kinematic parameter extraction for WALLABY/DINGO

: **ASKAP WALLABY/DINGO** (>5,000) + **Apertif survey** (~7,000) galaxies



Key requirements for the automated 2D tilted-ring fit

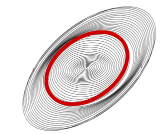
- **Robustness**
  - insensitive to initial estimates
  - less affected by localised outlying pixels or blobs
  - representative but enough degrees of freedom to optimally regularise any radial variations in PA/INCL/VROT/VEXP

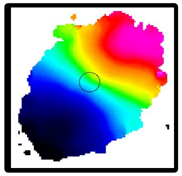
- **Efficiency**
  - Fast enough with good accuracy for the massive data stream from WALLABY

- **Automation**
  - Estimation of initial priors
  - Convergence check

→ **Fit a 2D model to all the available pixels** of the velocity field at one time rather than doing fits on a ring-by-ring basis
→ **Find best fits via MCMC sampling** given optimal priors of the ring parameters
→ **Parallel processing**

2D tilted-ring model





- 2D tilted-ring model

$$\begin{aligned} v_{\mathrm{LOS}}(x,y) = v_{\mathrm{SYS}}(x,y) \\ + \sin i \times \{v_{\mathrm{ROT}}(x,y)\cos\theta + v_{\mathrm{EXP}}(x,y)\sin\theta\} \end{aligned}$$

where

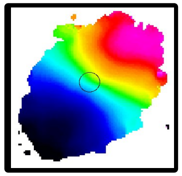
$$\cos\,\theta = \frac{-(x - x_C) \times \sin\phi + (y - y_C) \times \cos\phi}{r},$$

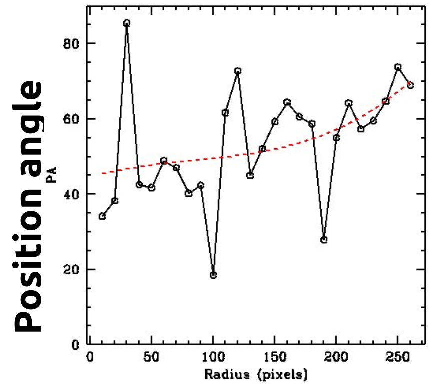
$$\sin\theta = \frac{-(x - x_C) \times \cos\phi - (y - y_C) \times \sin\phi}{r\cos i},$$

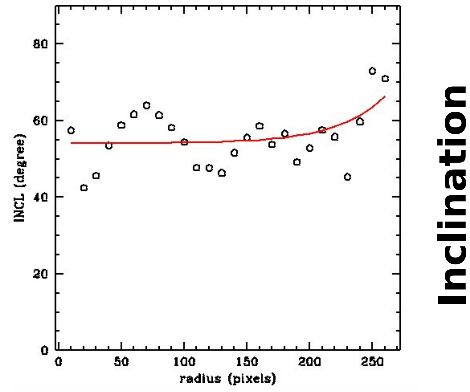
- Each ring is defined by seven ring parametres which can be regularised by either **single values** or **functional forms**:

  - kinematic centre (**XPOS, YPOS**) & systemic velocity (**VSYS**)
  - position angle (**PA**), inclination (**INCL**), expansion velocity (**VEXP**) and rotation velocity (**VROT**)

Kinematic position angle, inclination & VEXP







- To remove any unphysical discontinuities of PA & INCL and regularise their radial variations, we use B-splines:

$$\phi(r) = \sum_{m=1}^{n} c_m^{\phi} B_{m,k}^{\phi}(r) \qquad i(r) = \sum_{m=1}^{n} c_m^{i} B_{m,k}^{i}(r) \qquad v_{\mathrm{EXP}}(r) = \sum_{m=1}^{n} c_m^{v_{\mathrm{EXP}}} B_{m,k}^{v_{\mathrm{EXP}}}(r)$$

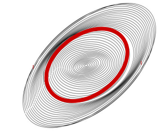
where

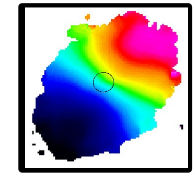
$$B_{m,1}(r) = \begin{cases} 1 & t_m \le r < t_{m+1} \\ 0 & \text{else} \end{cases}$$

$$B_{m,k}(r) = \frac{r - t_m}{t_{m+k-1} - t_m} B_{m,k-1}(r) + \frac{t_{m+k} - r}{t_{m+k} - t_{m+1}} B_{m+1,k-1}(r)$$

$$t = \{t_0, t_1, ..., t_{n+k-1}\}$$

- By increasing either **the number of knot vectors** (t) or **the order of splines** (e.g., constant, linear, quadratic, and cubic) (**or both**), we can increase the degrees of freedom of the models





Rotation velocity (VROT)

- We use Einasto halo model (Einasto 1965; 1968) for a representative rotation velocity (VROT)

  - widely adopted for taking the density profiles (+ rotation velocities) of dark matter halos of galaxies not only in simulations but also in observations

  - compared to both the classical pseudo-isothermal and NFW halo models with two free parameters, it provides better descriptions (e.g., bulge-dominant or -less rotation curves) by tuning a third parameter, the so-called Einasto index 'n' which quantifies the degree of curvature of the profile

$$M_{\mathrm{E}}(r) = 4\pi n r_{-2}^{3} \rho_{-2} e^{2n} 2n^{-3n} \gamma(3n, \frac{r}{r_{-2}}) \quad \text{where} \quad \gamma(3n, x) = \int_{0}^{x} dt\, e^{-t} t^{3n-1}$$

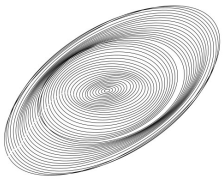
$$\rightarrow \quad v_{\mathrm{E}}(r) = \sqrt{\frac{G M_{\mathrm{E}}(r)}{r}}$$

$$= \sqrt{4\pi G n \frac{r_{-2}^{3}}{r} \rho_{-2} e^{2n} 2n^{-3n} \gamma(3n, \frac{r}{r_{-2}})}$$

r-2
Rho-2
n

2D Bayesian Automated Tilted-ring fitter

- A functional form of 2D tilted-ring model based on B-splines + Einasto profile



$$v_{\mathrm{MODEL}} = v_{\mathrm{MODEL}}(x_{\mathrm{C}}, y_{\mathrm{C}}, v_{\mathrm{SYS}}, c_i^{v_{\mathrm{EXP}}}, c_m^{\phi}, c_n^{i}, n, r_{-2}, \rho_{-2})$$

where

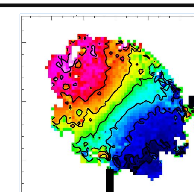
PA $$\phi(r) = \sum_{m=1}^{n} c_m^{\phi} B_{m,k}^{\phi}(r)$$

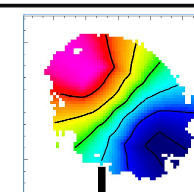
INCL $$i(r) = \sum_{m=1}^{n} c_m^{i} B_{m,k}^{i}(r)$$

VEXP $$v_{\mathrm{EXP}}(r) = \sum_{m=1}^{n} c_m^{v_{\mathrm{EXP}}} B_{m,k}^{v_{\mathrm{EXP}}}(r)$$

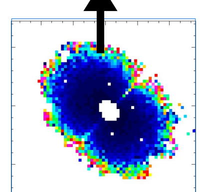
VROT $$v_{\mathrm{E}}(r) = \sqrt{4\pi G n \frac{r_{-2}^3}{r} \rho_{-2} e^{2n} 2n^{-3n} \gamma(3n, \frac{r}{r_{-2}})}, \quad \gamma(3n, x) = \int_0^x dt\, e^{-t} t^{3n-1}$$

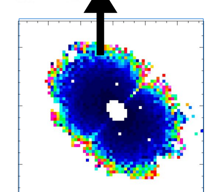
- Log-likelihood function with Gaussian errors





$$\log L = -\frac{N}{2} \log 2\pi - \sum_{m=0}^{\mathrm{nax1}} \sum_{n=0}^{\mathrm{nax2}} \log v_{\mathrm{w-error}}^{\mathrm{LOS}}(m,n) - \frac{1}{2} \sum_{m=0}^{\mathrm{nax1}} \sum_{n=0}^{\mathrm{nax2}} \left[\frac{v_{\mathrm{LOS}}(m,n) - v_{\mathrm{MODEL}}(m,n)}{v_{\mathrm{w-error}}^{\mathrm{LOS}}(m,n)} \right]^2$$





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$$v^{\mathrm{LOS}}_{\mathrm{w-error}}(m,n) = \alpha \frac{v^{\mathrm{LOS}}_{\mathrm{error}}(m,n)/w(m,n)}{S_{\mathrm{peak}}(m,n)/S_{\mathrm{rms}}(m,n)}$$

Weighted error

Scale factor

Error of velocity profiles

Geometrical weight

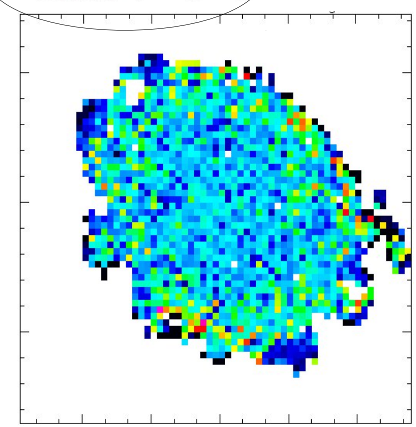
$$w(m,n) = \frac{l_{\mathrm{outermost}}}{l(m,n)} \times |\cos(\theta)|^{\mathrm{t}}$$

(l: the perimeter of a ring)

Peak flux of velocity profiles

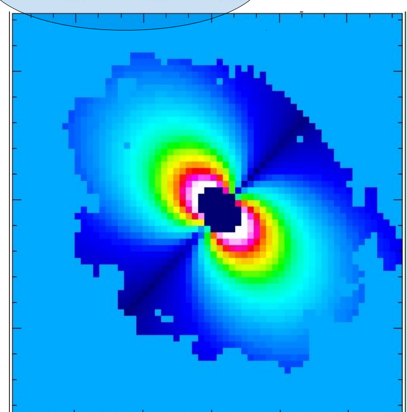
rms of velocity profiles

$v^{\mathrm{LOS}}_{\mathrm{error}}(m,n)$



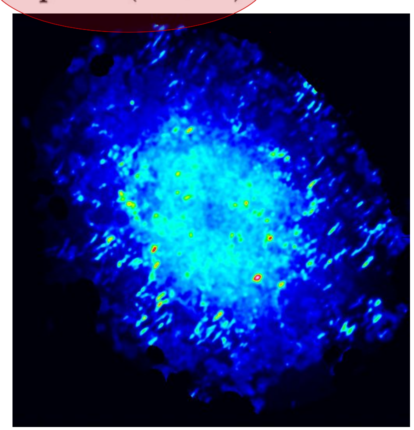
x

$w(m,n)$



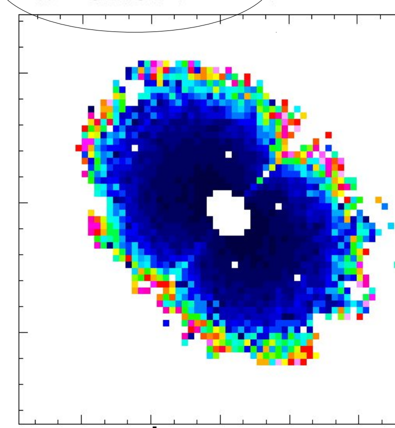
/

$S_{\mathrm{peak}}(m,n)$



=

$v^{\mathrm{LOS}}_{\mathrm{w-error}}(m,n)$



$$\log L = -\frac{N}{2}\log 2\pi - \sum_{m=0}^{\mathrm{nax1}}\sum_{n=0}^{\mathrm{nax2}} \log v^{\mathrm{LOS}}_{\mathrm{w-error}}(m,n) - \frac{1}{2}\sum_{m=0}^{\mathrm{nax1}}\sum_{n=0}^{\mathrm{nax2}} \left[\frac{v_{\mathrm{LOS}}(m,n) - v_{\mathrm{MODEL}}(m,n)}{v^{\mathrm{LOS}}_{\mathrm{w-error}}(m,n)}\right]^2$$

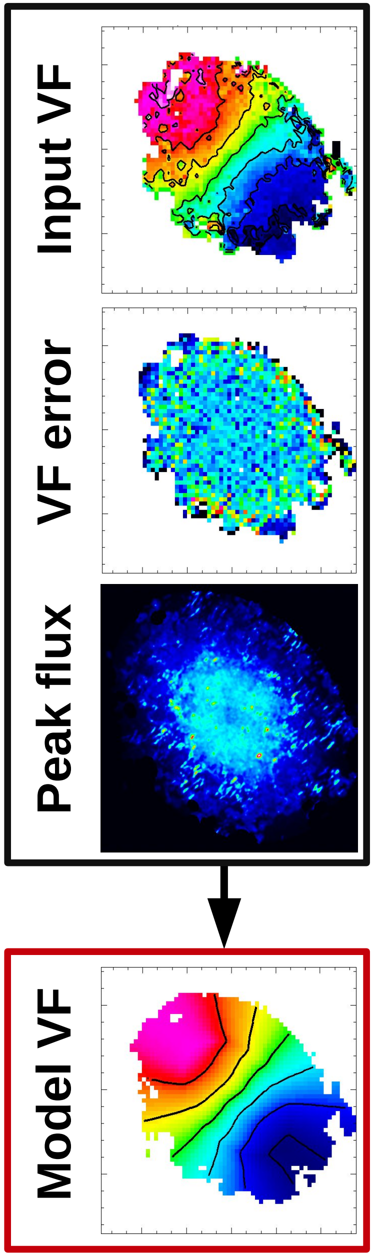
2D Bayesian Automated Tilted-ring fitter

2DBAT

A. Mask outlying pixels & find the largest connected area
: velocity field + velocity field error + peak flux map (mom 4)

B. Provide initial priors
: perform ellipse fits, and derive initial values
: perform TR fits and regularise the parameters (B-splines)
→ provide (rough) initial priors of the ring parameters

C. Perform 2D Bayesian fits via MCMC sampling
: find optimal priors via **quick & dirty fits** with a smaller sampling number
: perform a **full Bayesian fit** with the found priors + the regularisation setup
→ derive the final rotation velocity given the derived rings



2D Bayesian Automated Tilted-ring fitter

2DBAT

- Standalone software for 2D tilted-ring analysis based on Bayesian MCMC technique

  - **robust & coherent 2D kinematic analysis:** (1) masks outlying pixels; (2) estimates priors; (3) regularise ring parameters with B-splines + Einasto profile; (4) carries out Bayesian fits & derives rotation curves

  - **fully automated:** only broadly defined ranges of ring parameters are required

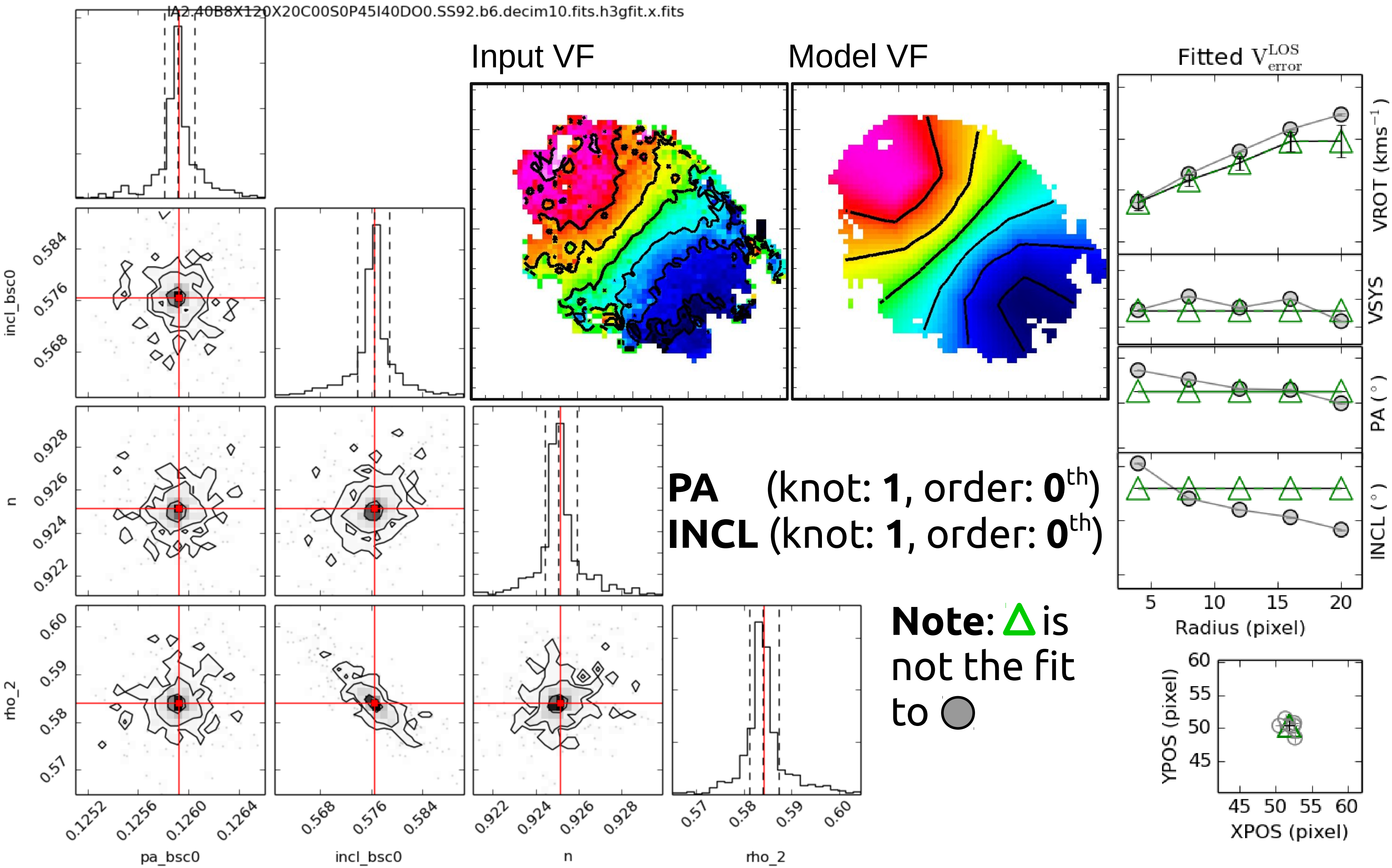
  - **parallelised:** Massage Passing Interface (MPI) supported

  - **written in C with publicly available libraries:** MultiNest v3.7 (Feroz & Bridges 2008; 2009), CFITSIO, GSL, standard ANSI C & MPI libraries; compiled by mpicc

  - **will comprise the WALLABY kinematics pipeline** together with FAT (3D TR models; Kamphuis et al. 2015) + DISKFIT (2D flat disc models; Spekkens et al. 2010)

  - **publicly available soon via github**

Performance test (artificial VF)



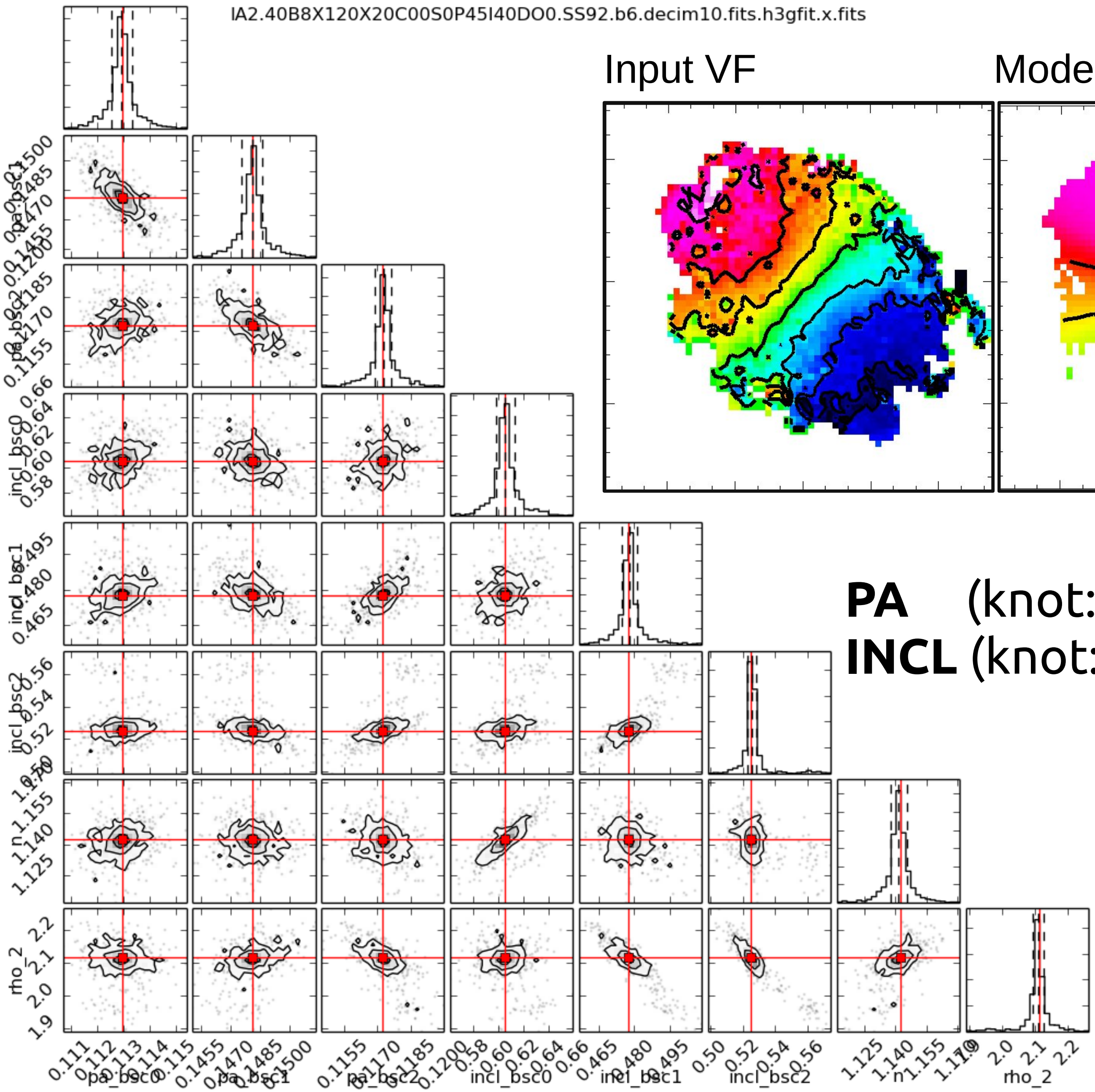
PA (knot: **1**, order: **0**th)
INCL (knot: **1**, order: **0**th)

Note: △ is not the fit to ●

Performance test (artificial VF)

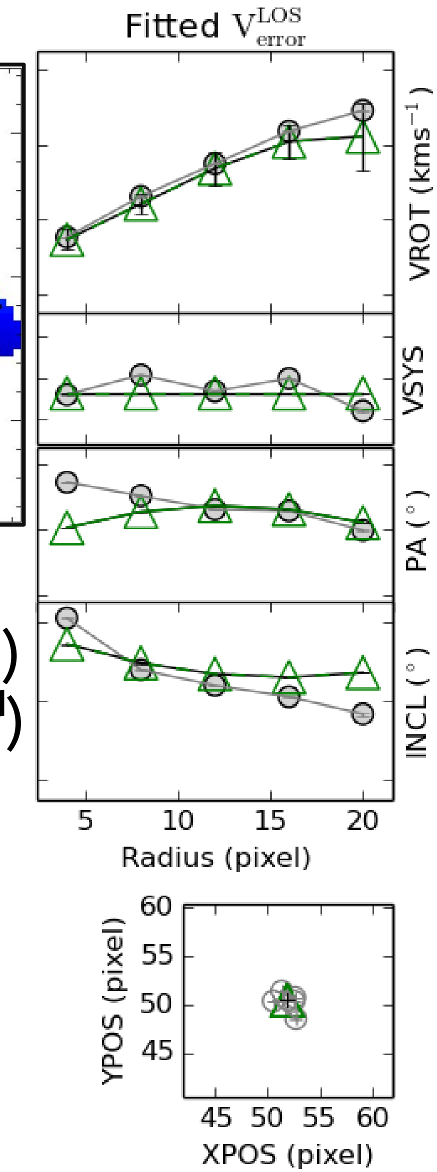
2DBAT

IA2.40B8X120X20C00S0P45I40DO0.SS92.b6.decim10.fits.h3gfit.x.fits



Input VF

Model VF



PA (knot: **1**, order: **2nd**)

INCL (knot: **1**, order: **2nd**)

Note: △ is not the fit to ●

Performance test (artificial VF)

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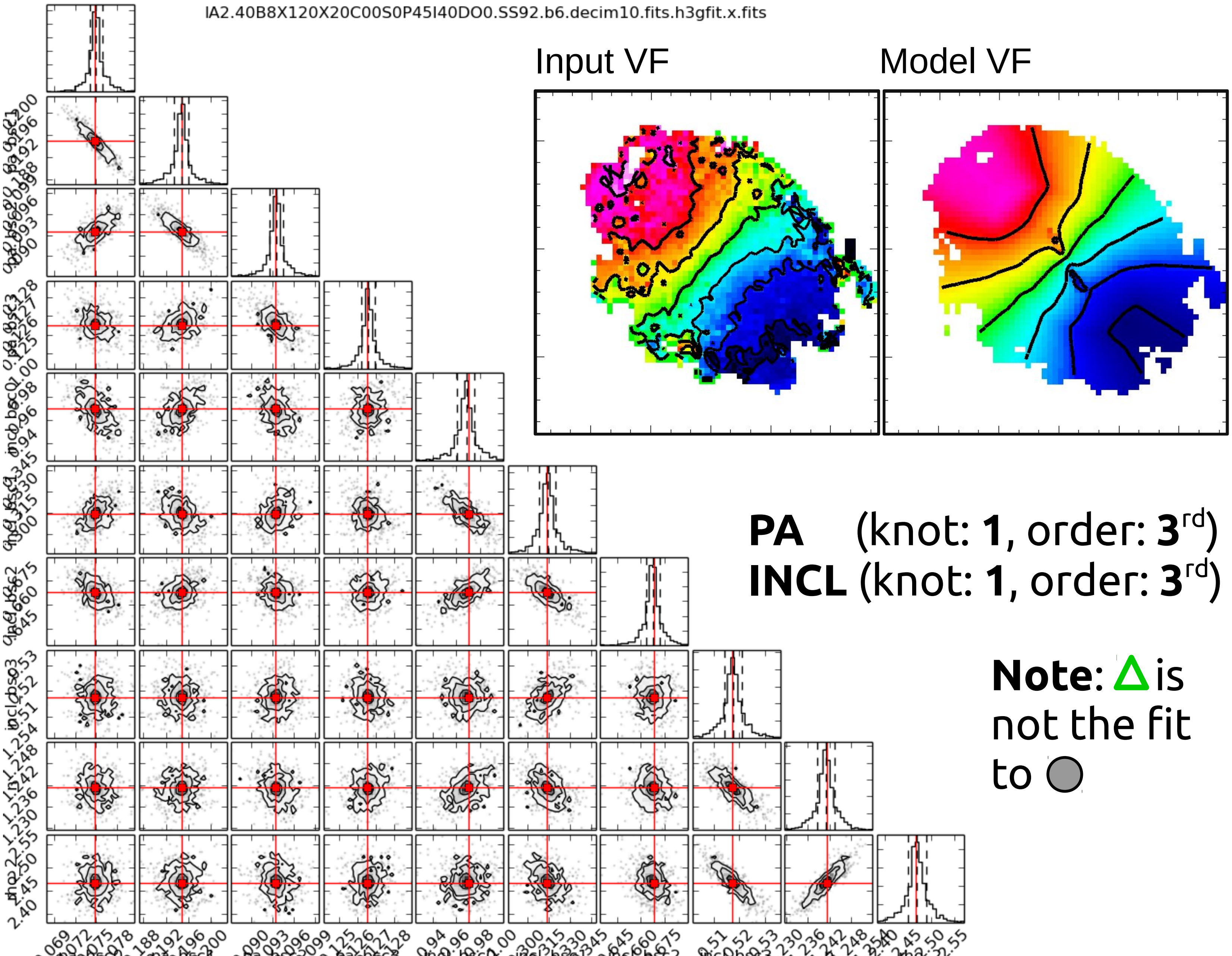
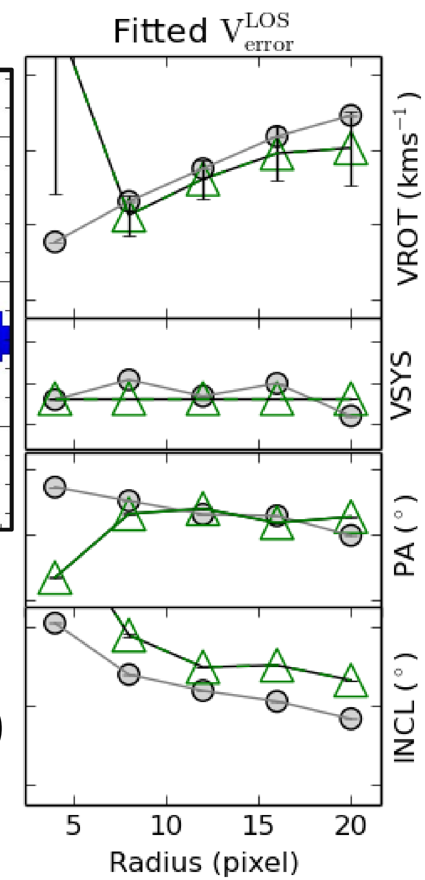
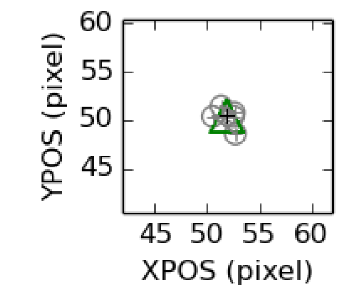




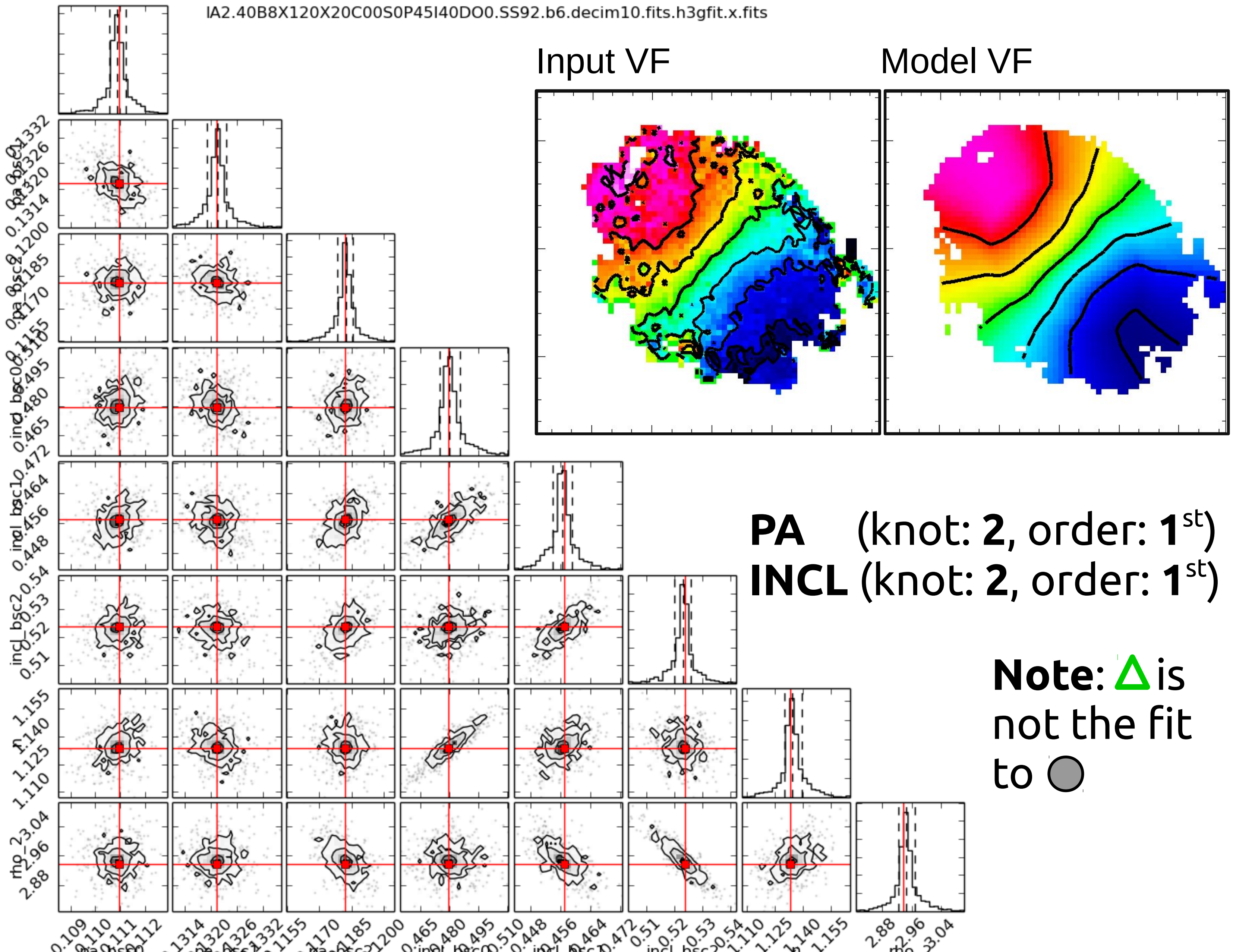


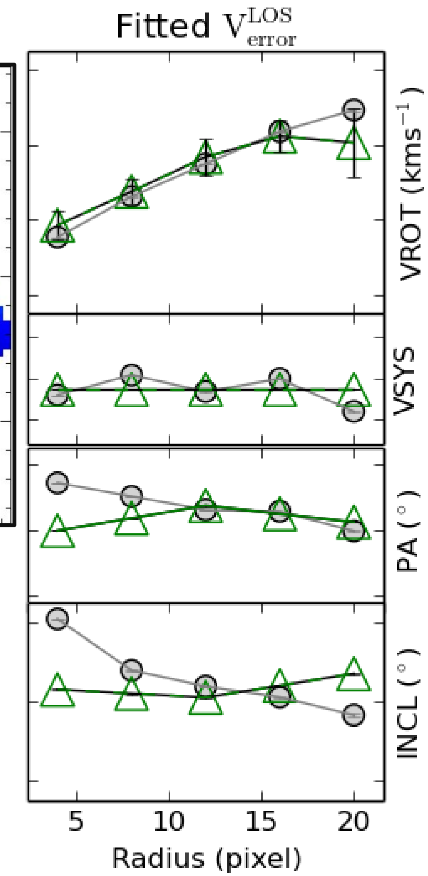
PA (knot: **1**, order: **3**rd)

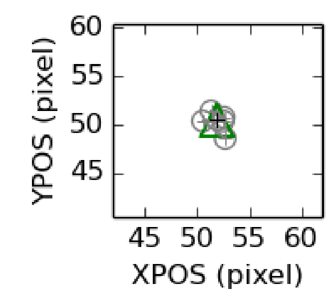
INCL (knot: **1**, order: **3**rd)

Note: △ is not the fit to ●

Performance test (artificial VF)







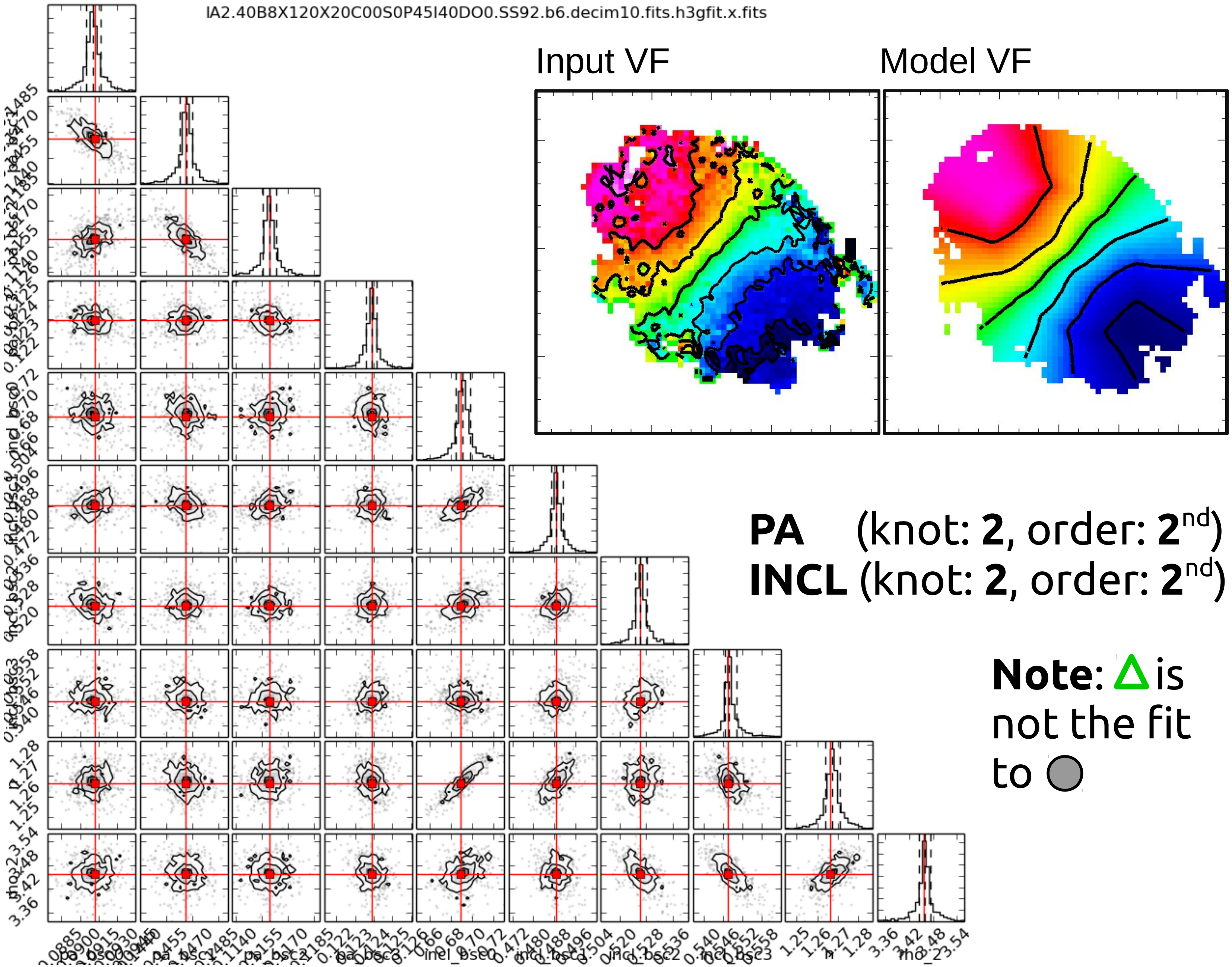
PA (knot: **2**, order: **1**st)
INCL (knot: **2**, order: **1**st)

Note: △ is not the fit to ●

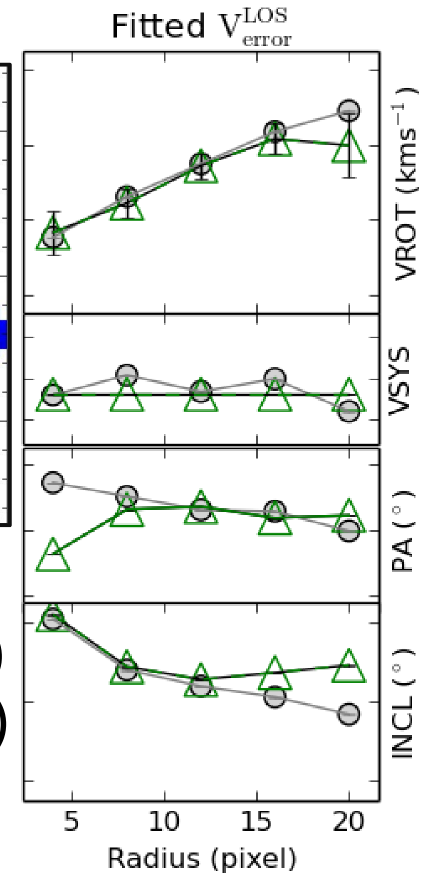
Performance test (artificial VF)

2DBAT

IA2.40B8X120X20C00S0P45I40DO0.SS92.b6.decim10.fits.h3gfit.x.fits

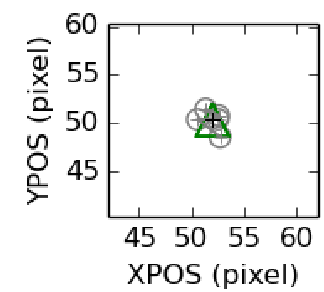


Input VF Model VF

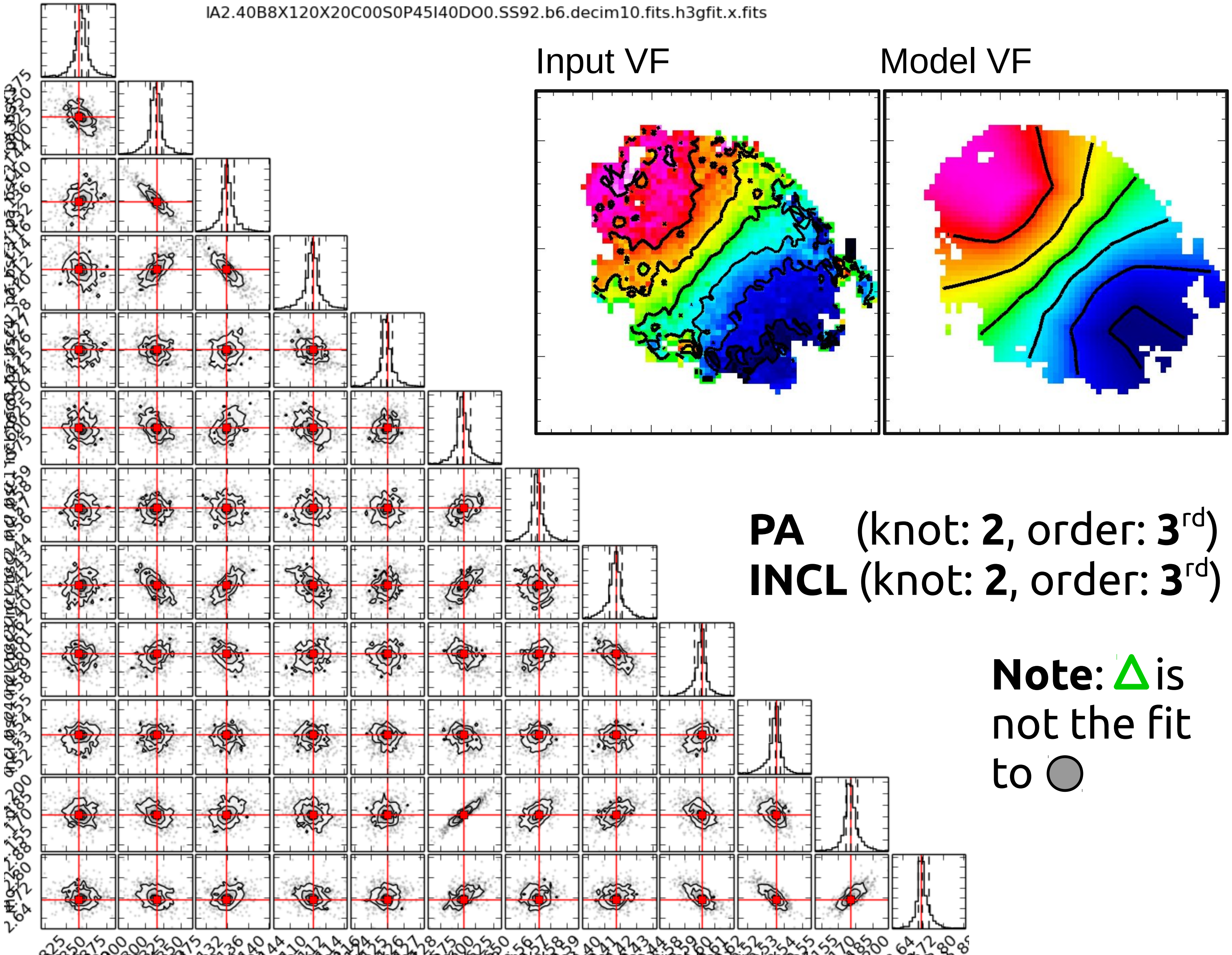


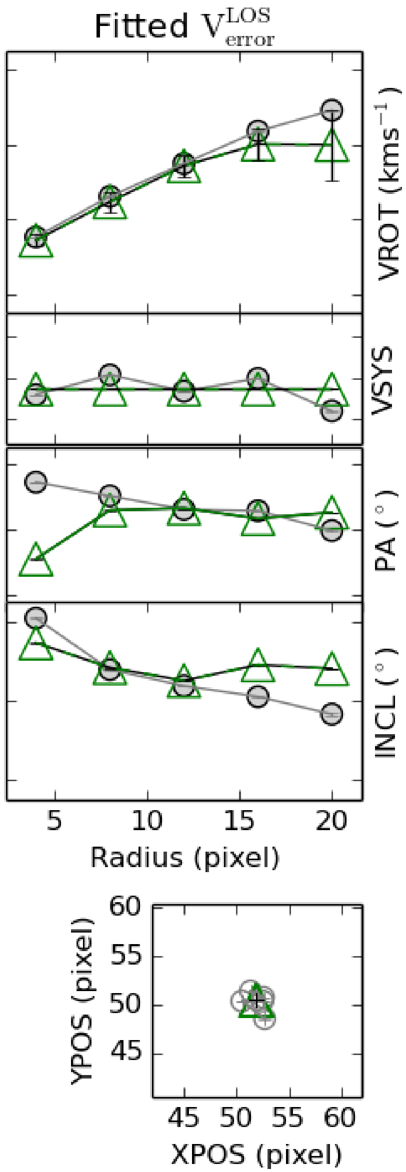
PA (knot: **2**, order: **2**nd)
INCL (knot: **2**, order: **2**nd)

Note: △ is not the fit to ●



Performance test (artificial VF)

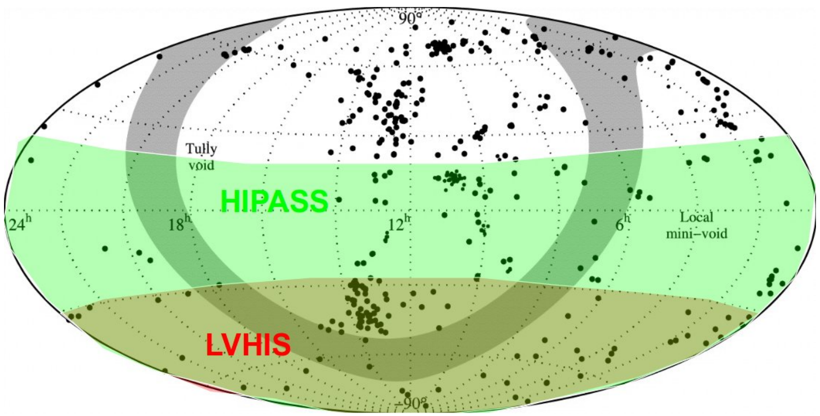




PA (knot: **2**, order: **3**rd)
INCL (knot: **2**, order: **3**rd)

Note: △ is not the fit to ●

Performance test (LVHIS)



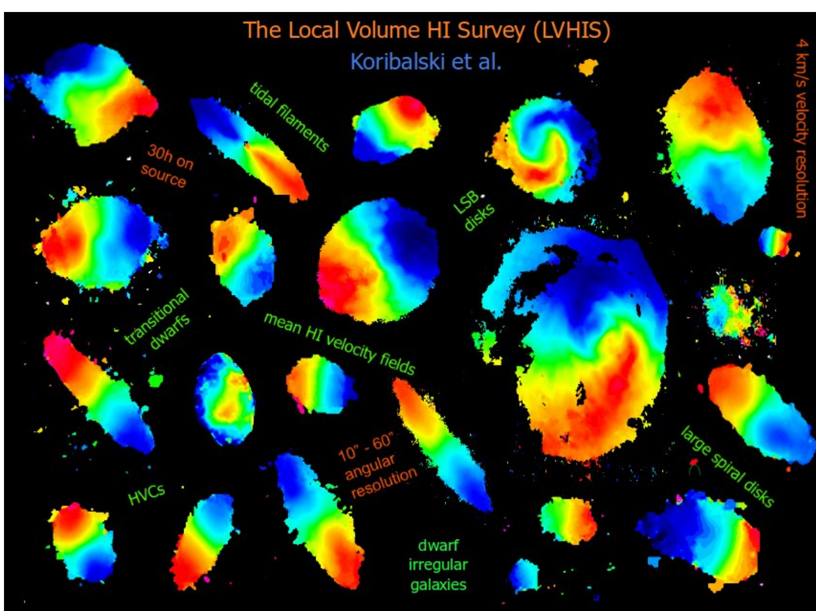
from Karachentsev et al. (2004)
(based on 450 LV galaxies with D<10 Mpc)

- **The Local Volume HI Survey (LVHIS)**

  - ATCA ~2400 hours of 82 nearby, gas-rich galaxies (~30 hours for each galaxy; $M_{HI} = 10^7 \sim 10^{10}\ M_\odot$)

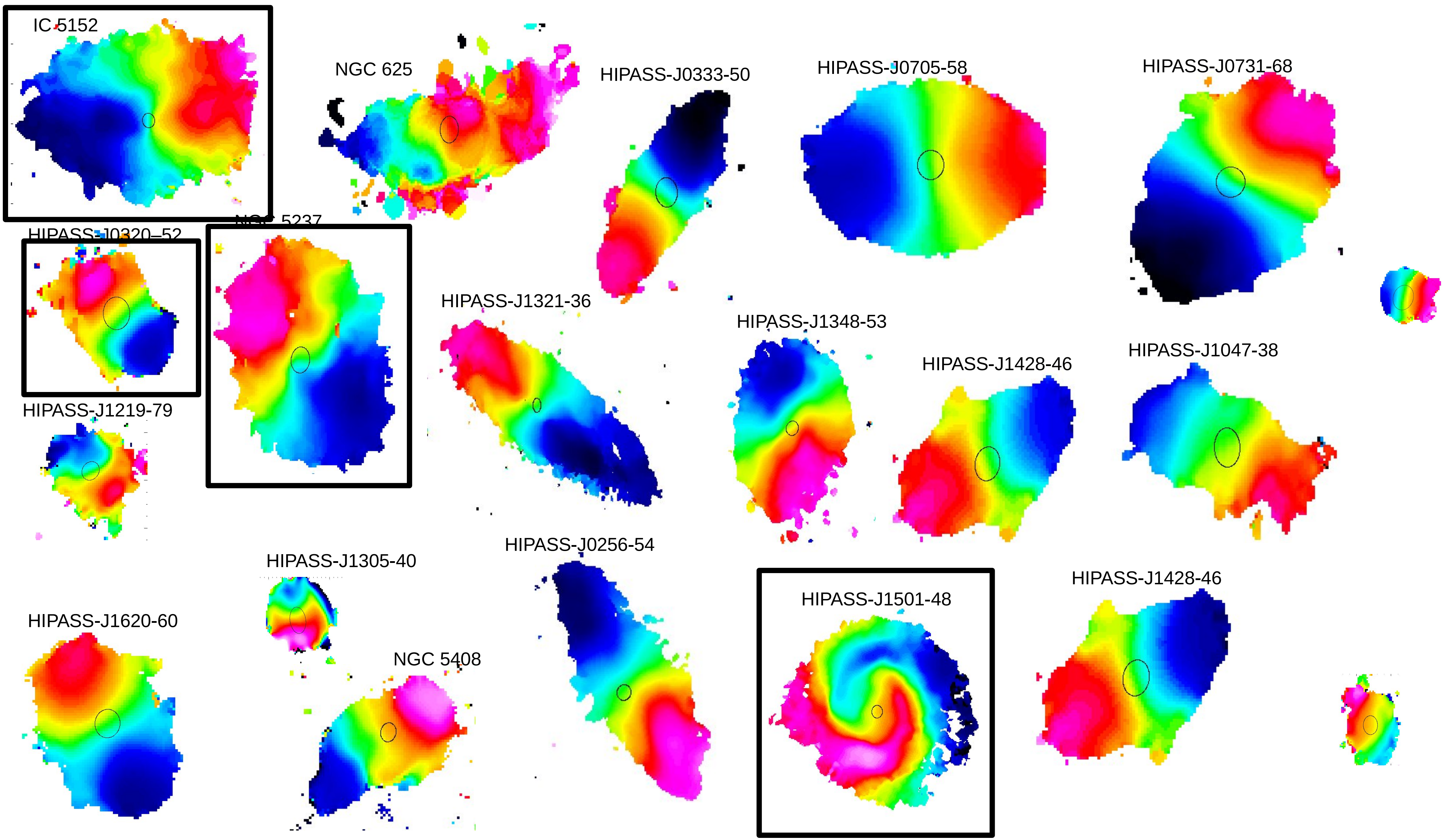
  - Provide a comprehensive HI galaxy atlas

  - Set a benchmark for the upcoming HI SKA pathfinders galaxy surveys

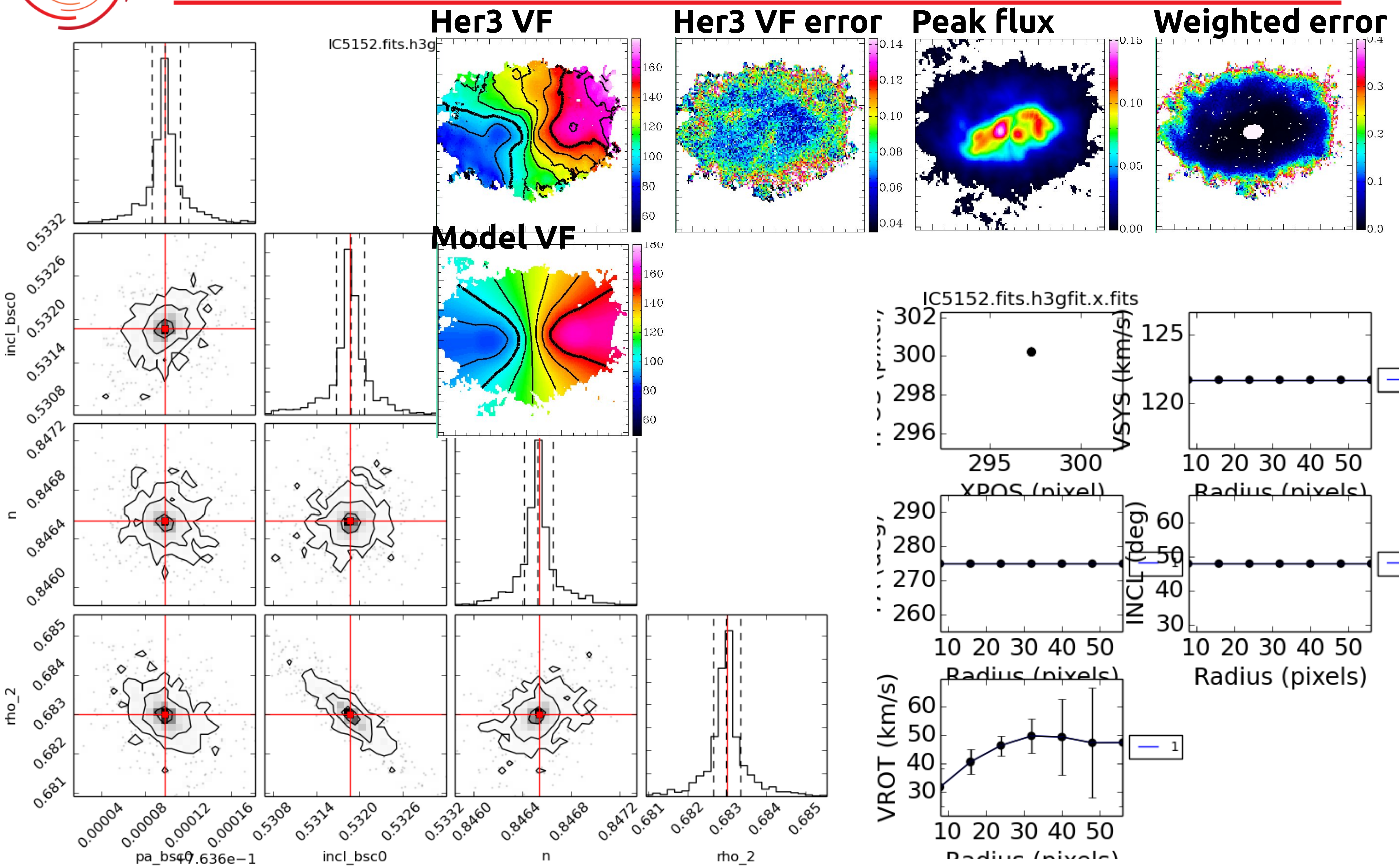


Australia Telescope Compact Array (ATCA)

Performance test (LVHIS)



Performance test (LVHIS)



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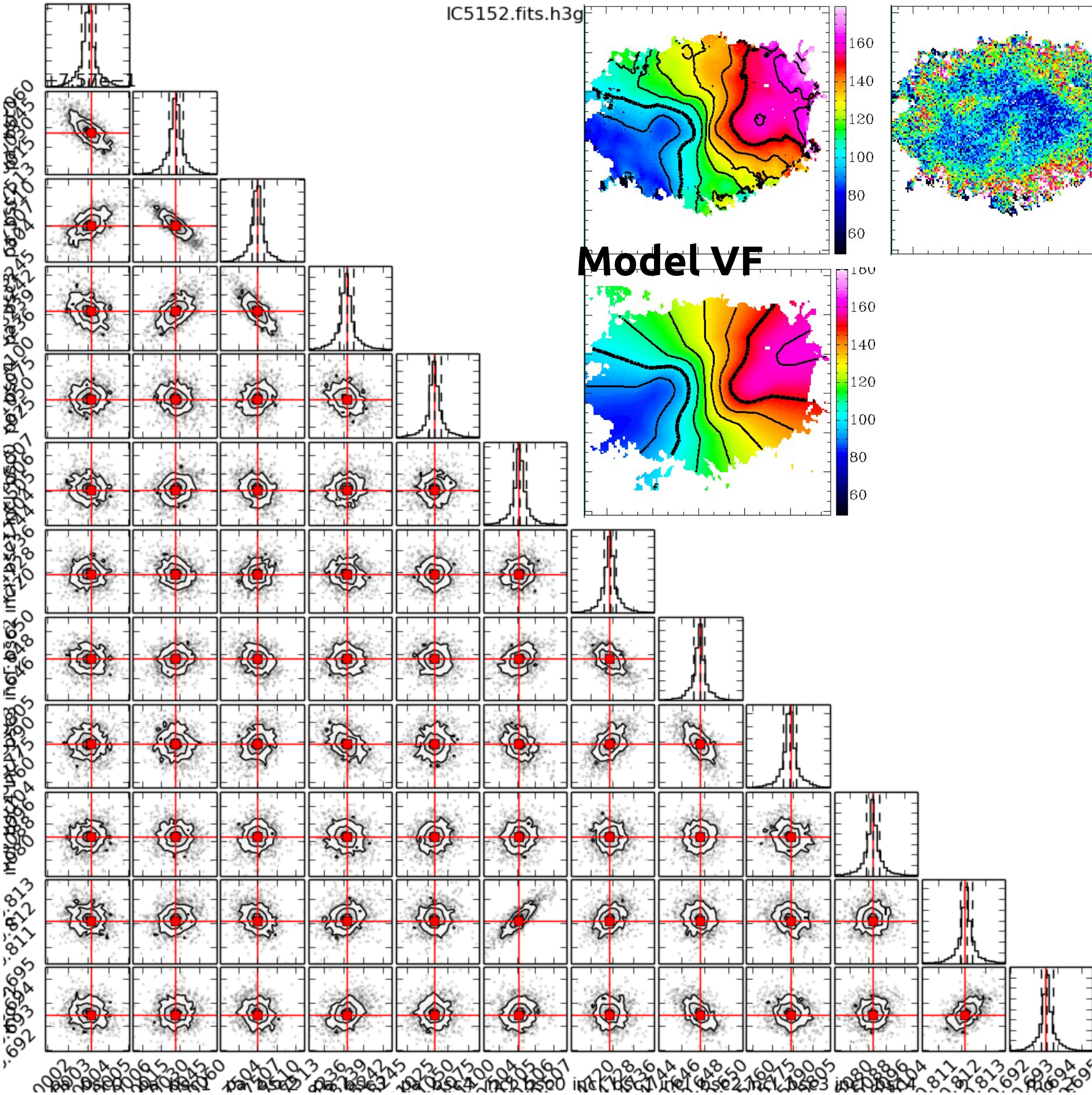

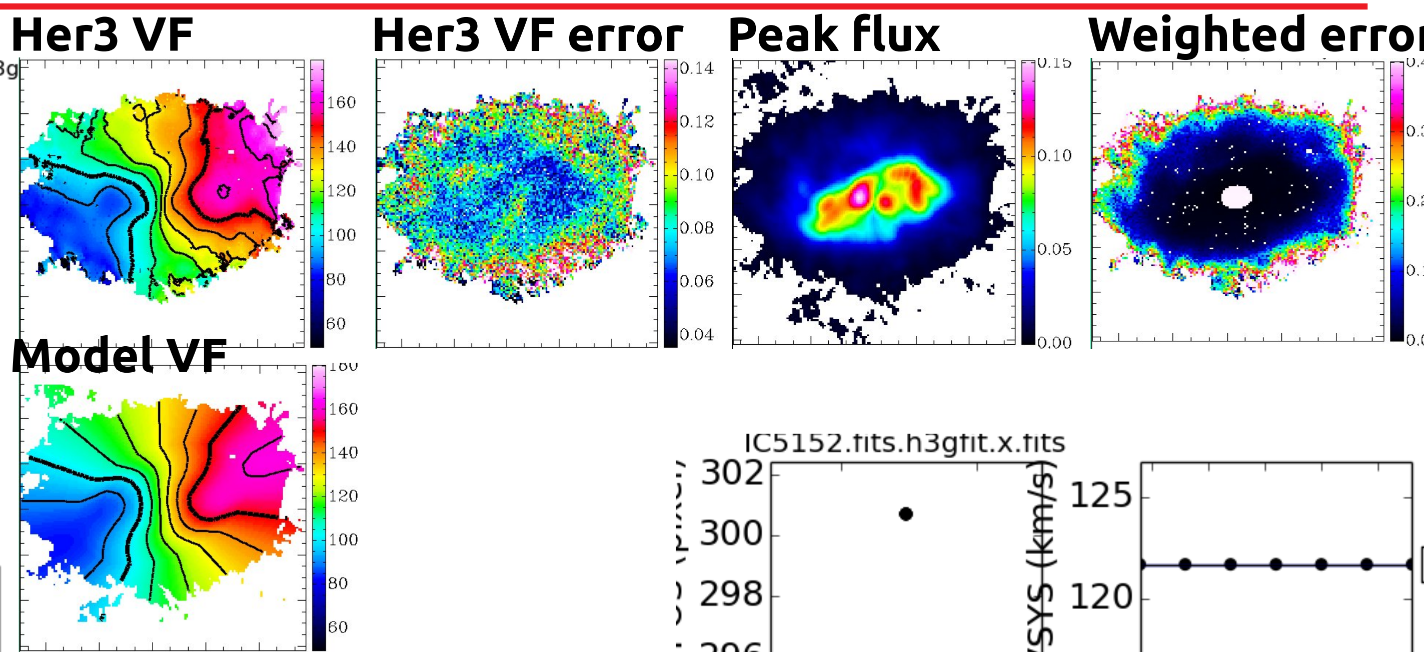

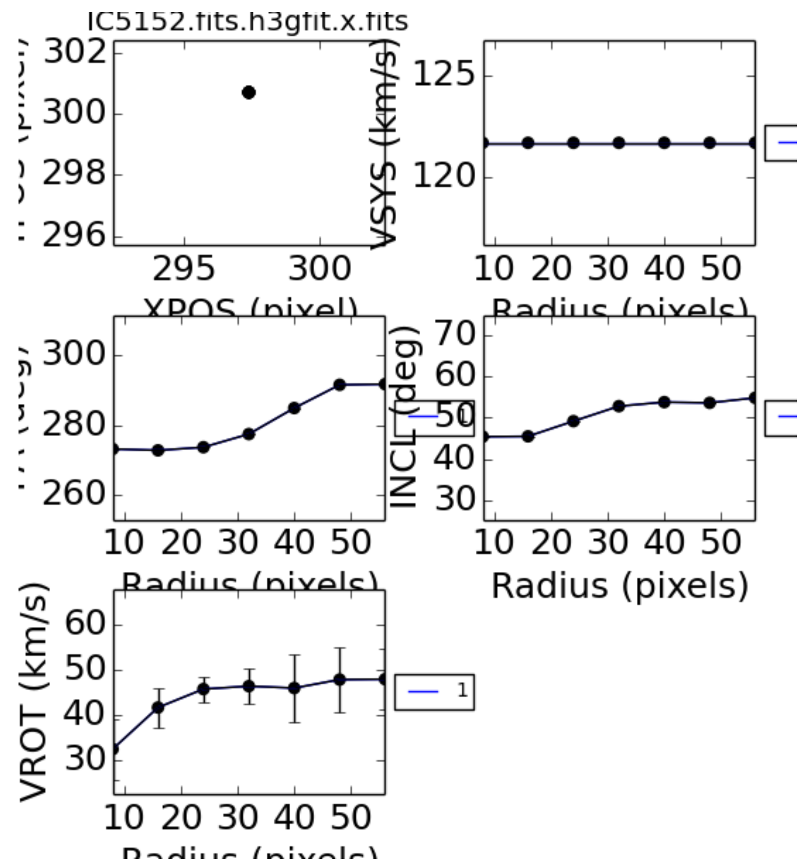

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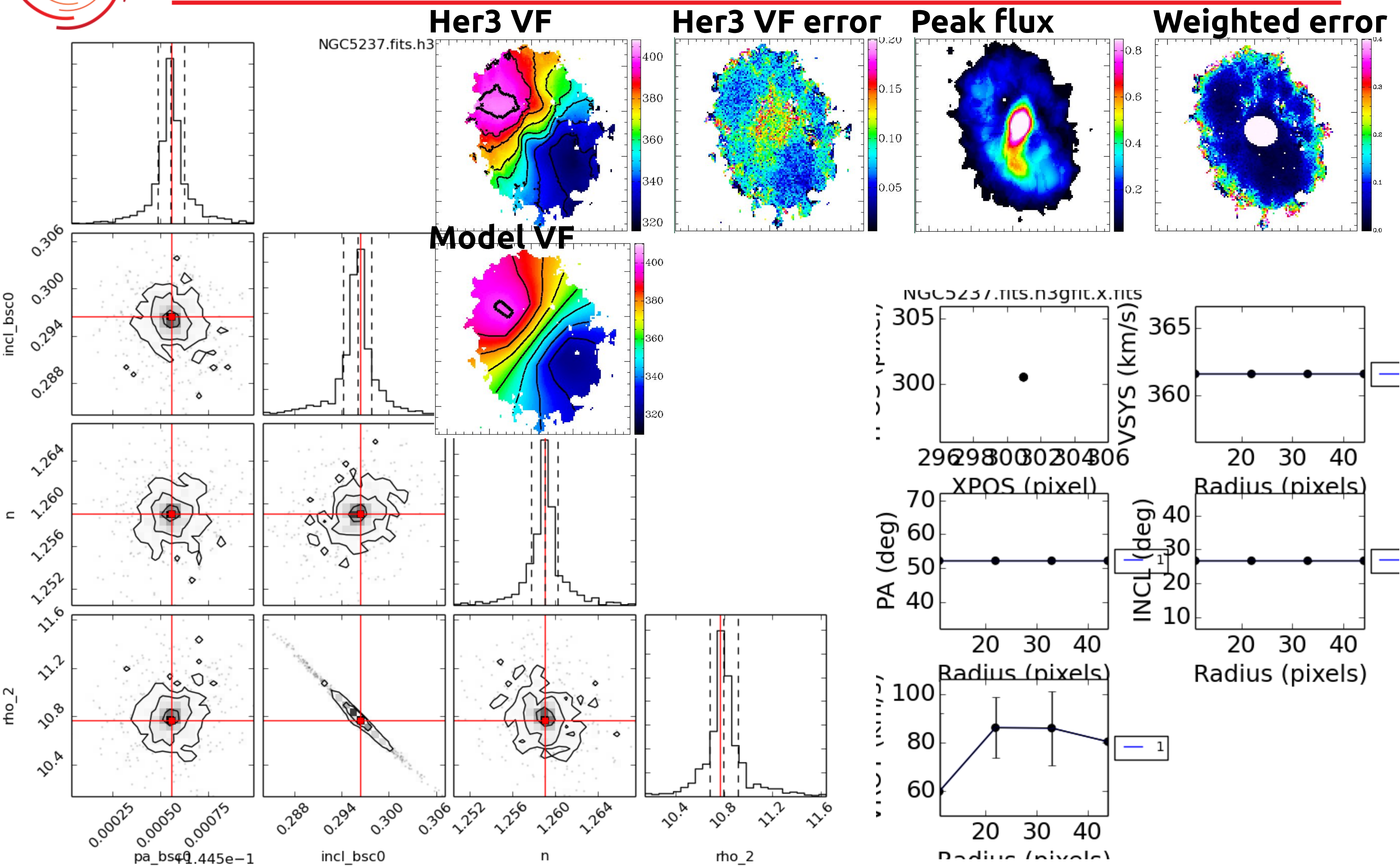

Performance test (LVHIS)

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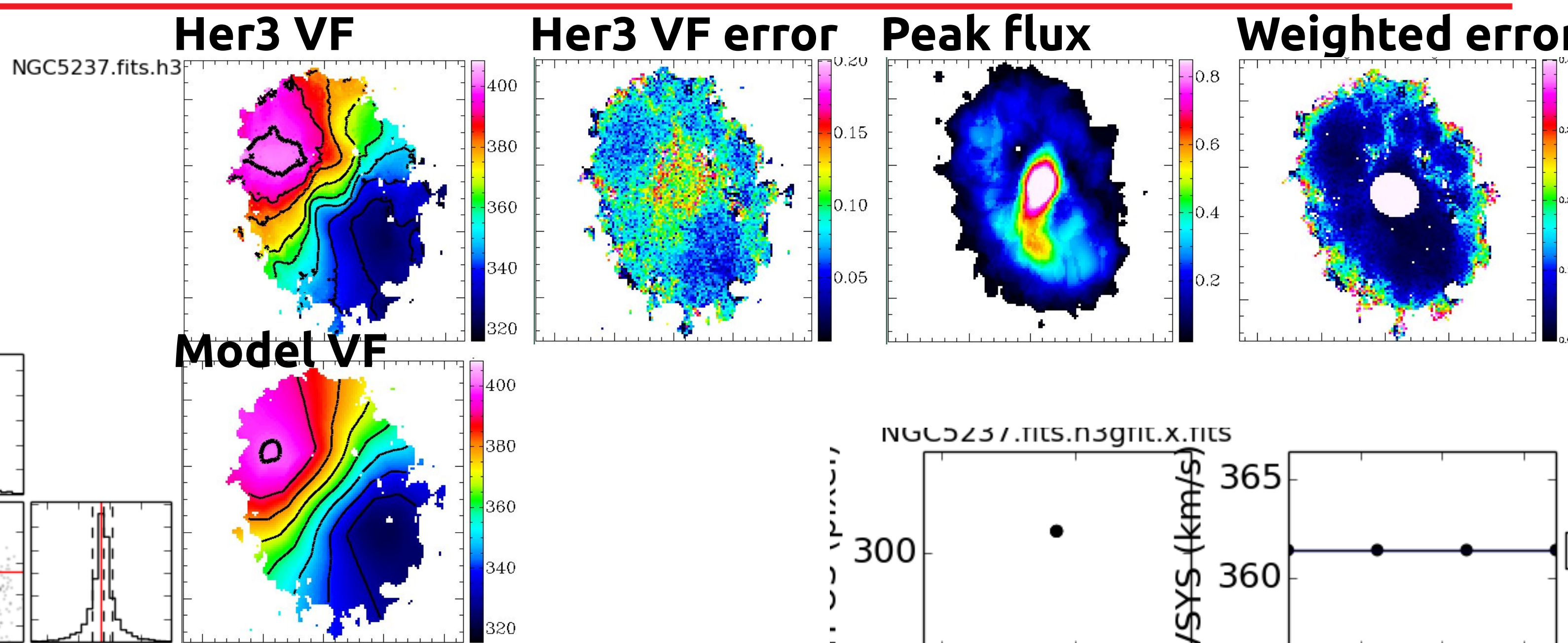

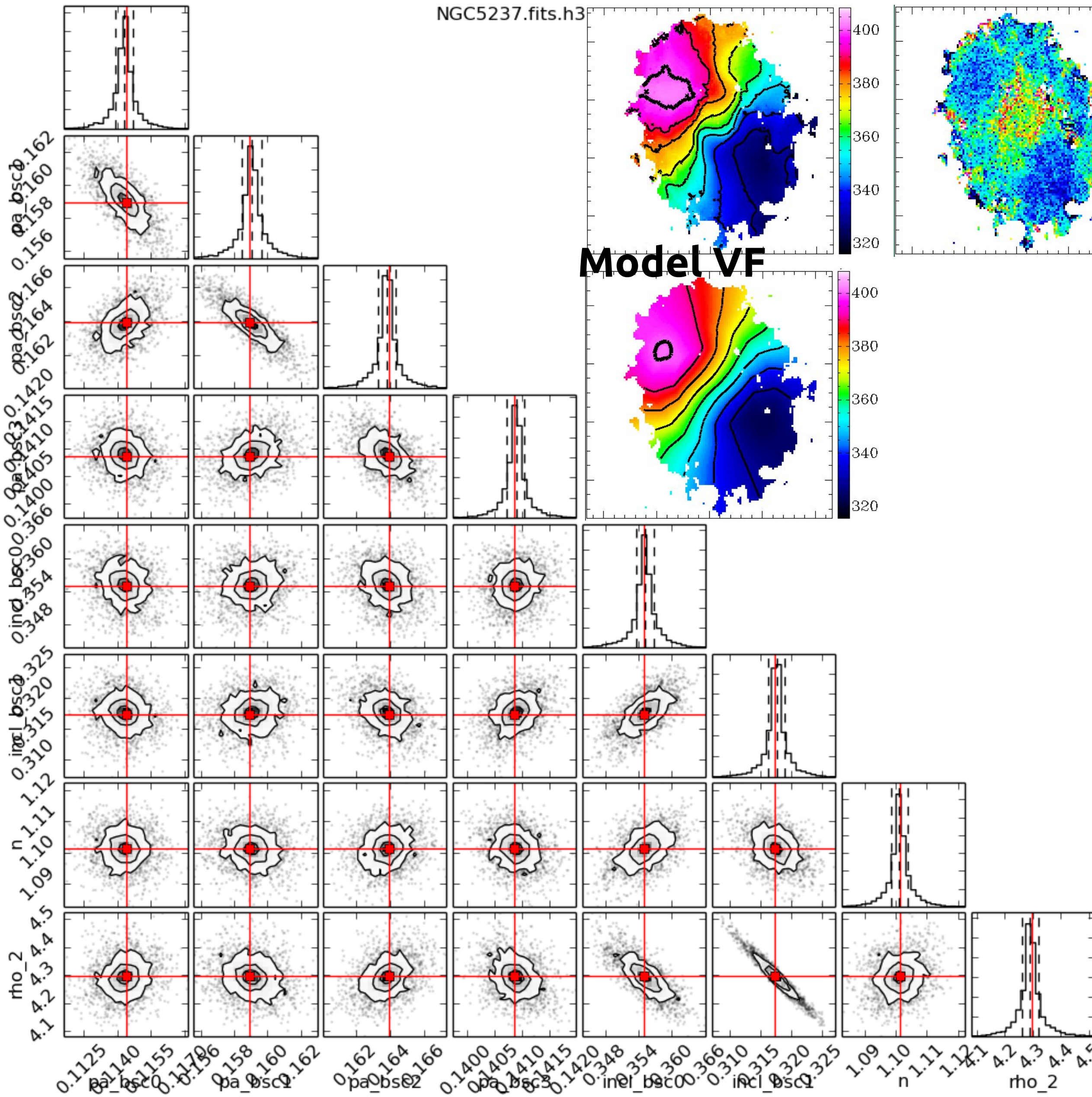

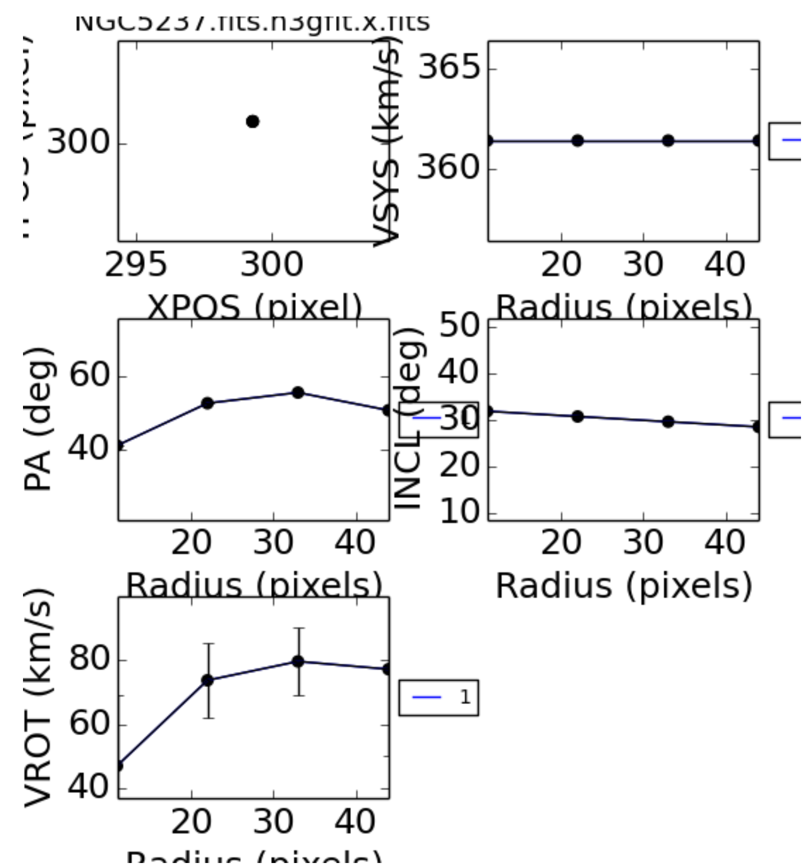

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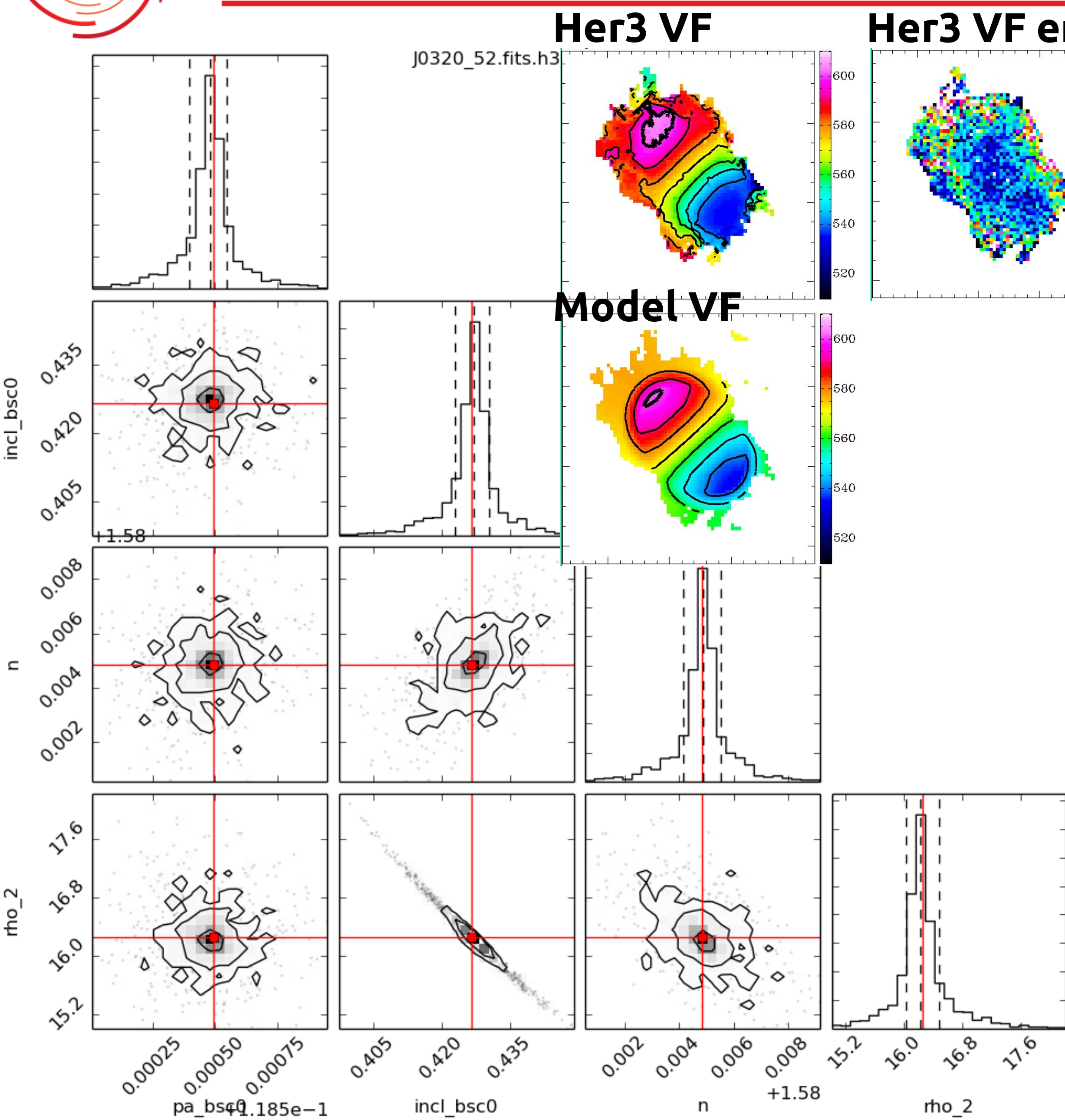
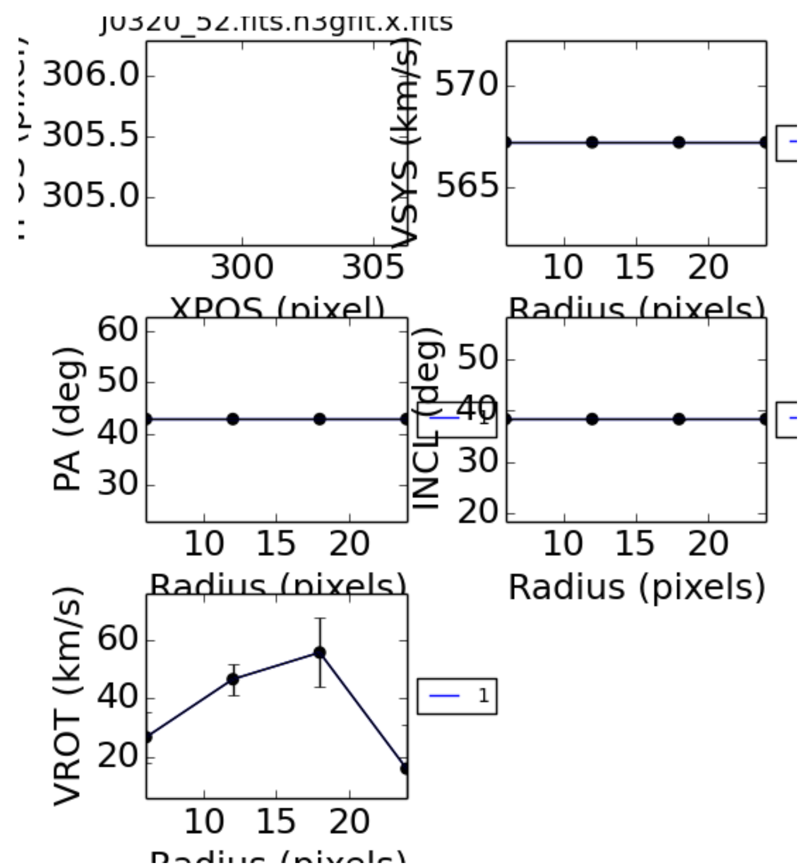
2DBAT





Summary & future works

- 2D Bayesian Automated Tilted-ring fitter (2DBAT)
- Fully automated & parallelised
- Successfully tested using artificial and observed (WALLABY-like) galaxies
- Applications (e.g.,):

  - statistical revisit of all the HI rotation curves of galaxies available in the literature

  - might be useful for optical velocity fields (e.g., SAMI etc.)
- GUI / 3DBAT?