

WALLABY kinematic parametre extraction: A sub-pipeline for 2D tilted-ring fits

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with

WALLABY kinematics working group

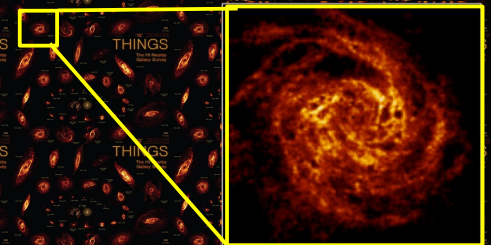
- A brief recap of WALLABY rotation curve pipeline
- 2D tilted-ring fit and its long-standing issues
- Efficient and robust Bayesian inference (MultiNest)
- WALLABY 2D tilted-ring fitter based on Bayesian MCMC
- Test on simulated and real galaxies
- Summary & future works

- **2D velocity fields**

- **diskfit** (Spekkens & Sellwood 2007): circular+non-circular (lopsided or bar-like) flows + a symmetric outer disk warp
- **rotcur** (Begeman 1989): concentric 2D tilted-ring models

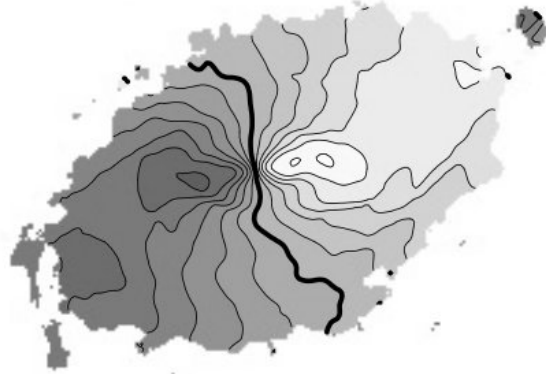
- **3D data cube**

- **tirific** (Jozsa et al. 2007): concentric 3D tilted-ring models

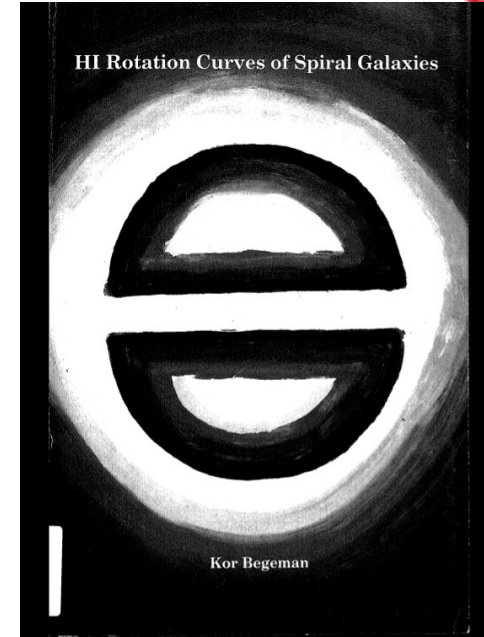
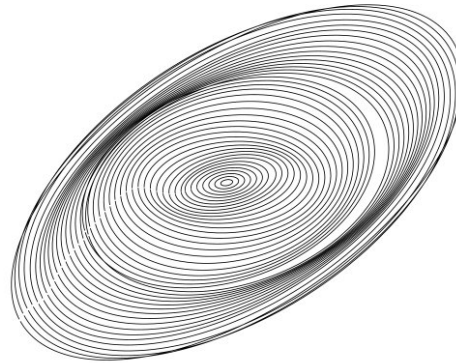


2D tilted-ring model (Begeman 1987)

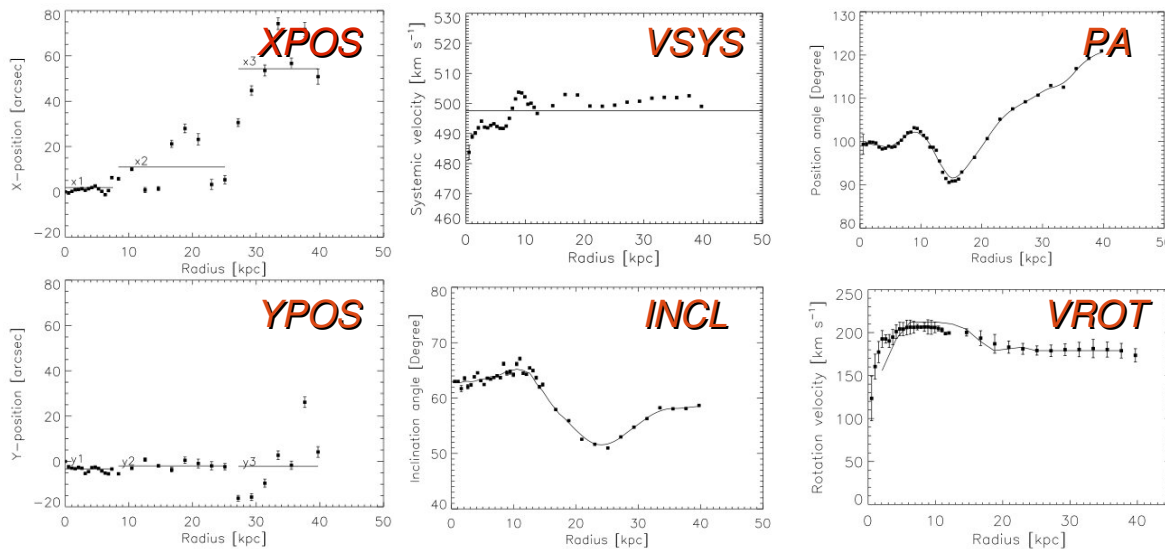
NGC 5055 (Battaglia et al. 2005)



HPBW=67"



Begeman (1987)



Galaxy Radius

Galaxy Radius

Galaxy Radius

$$V_{\text{obs}}(x, y) = V_{\text{sys}}(x, y) + \sin i \{ V_t(x, y) \cos \theta + V_r(x, y) \sin \theta \}$$

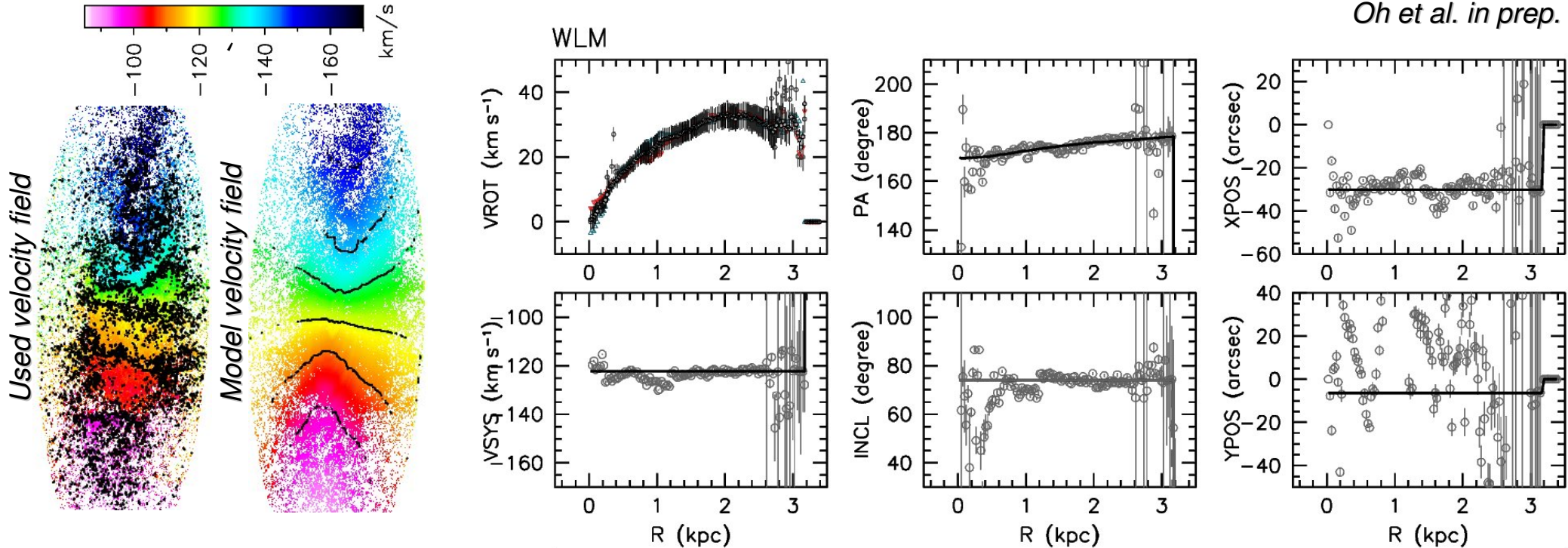
$$\cos \theta = \frac{-(x - X\text{POS}) \sin(\text{PA}) + (y - Y\text{POS}) \cos(\text{PA})}{r}$$

$$\sin \theta = \frac{-(x - X\text{POS}) \cos(\text{PA}) - (y - Y\text{POS}) \sin(\text{PA})}{r \cos(\text{INCL})}$$

- Non-model based
- Relatively fast and reliable if correct velocity fields are given
- Used as a standard tool for deriving HI kinematics of galaxies
: WHISP, FIGGS, THINGS, LITTLE THINGS, LVHIS etc.
- Do not take the effect of gas-disk thickness into account (e.g., dwarfs)
: assuming infinitely thin disk

Some issues on 2D tilted-ring fits

Oh et al. in prep.



- 6 free parameters
- VROT/INCL degenerated
- sensitive to initial estimates
- non-parametric models for PA/INCL
- affected by non-circular motions

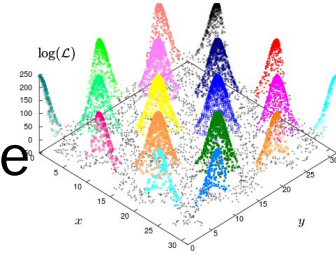


- iteration
- user defined radial models for PA/INCL
- sometimes too subjective
- **difficult to make it automatic**

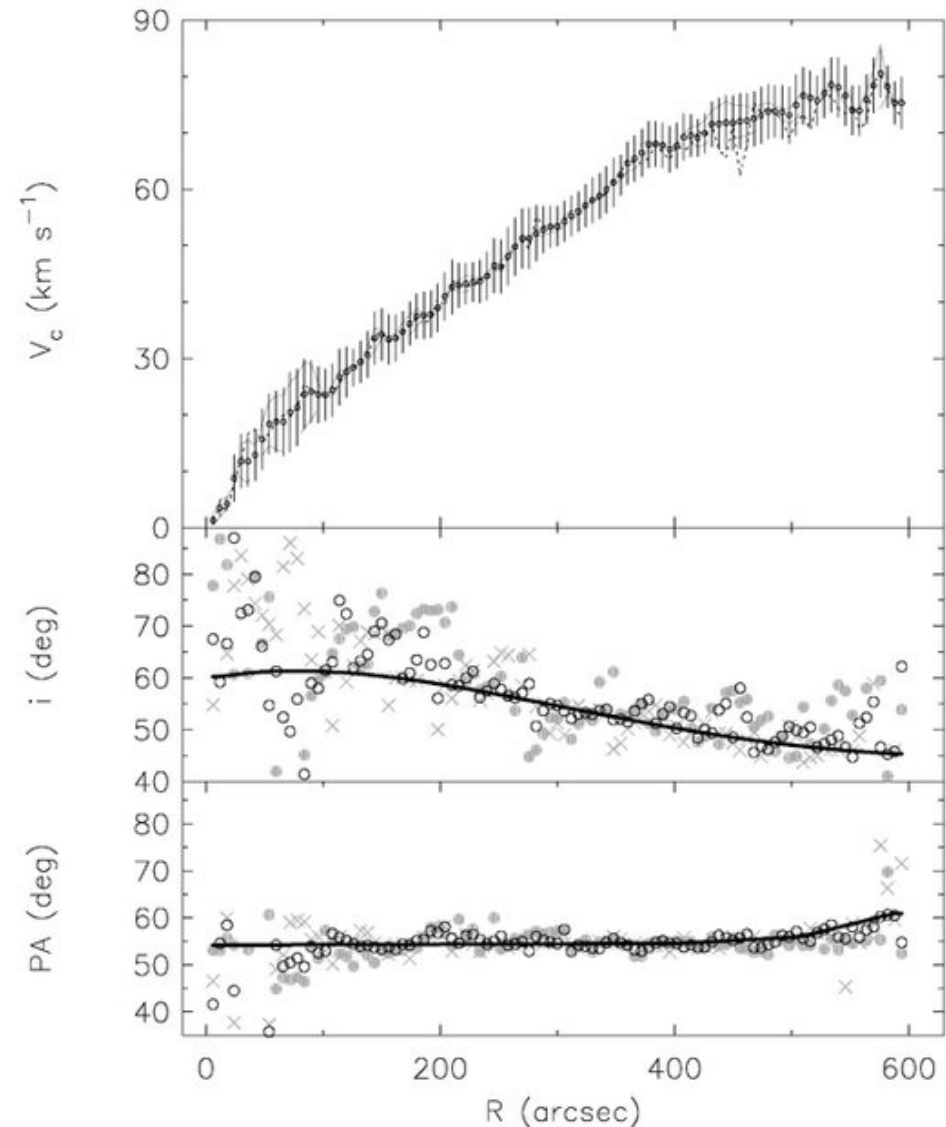
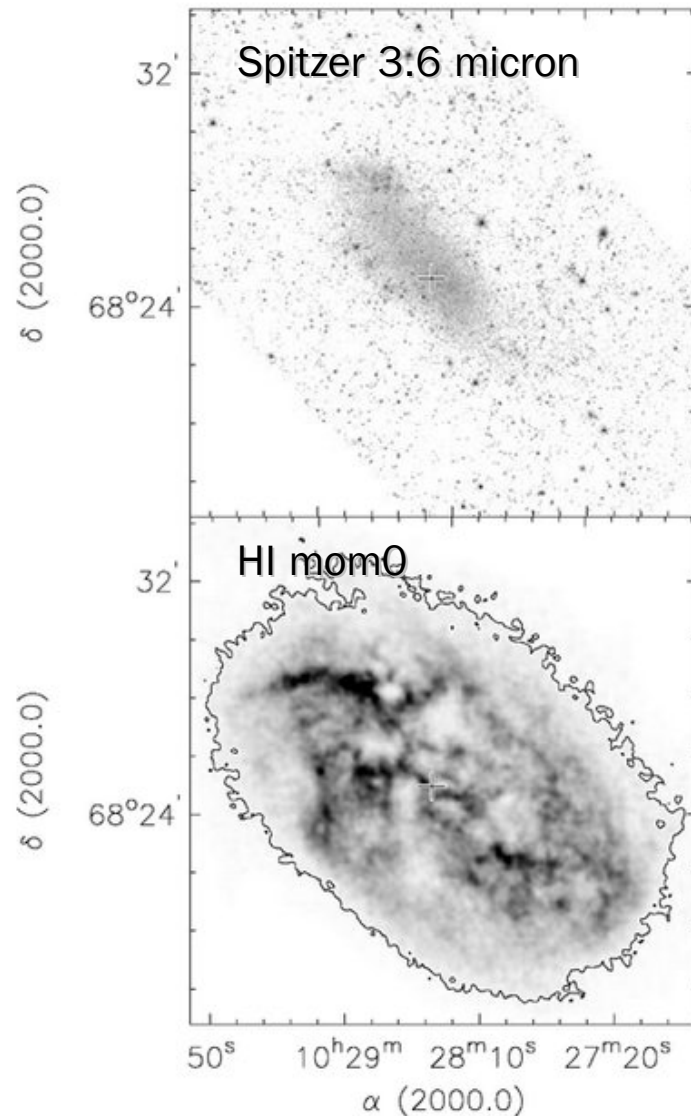
- Robust estimation of tilted-ring parameters
 - robust extraction of 2D velocity fields of bulk motions from 3D cubes
 - Peak, IWM, single Gaussian, Gaussian-Her3 or multiple Gaussian velocity components (e.g., Oh et al. 2008)
 - robust initial estimates for ring parameters
 - efficient removal of outliers in PA/INCL radial models

- **Bayesian parameter estimation**
 - using Markov Chain Monte Carlo (MCMC) sampling (see Mackay 2003 and refs therein)
 - less sensitive to initial values and gives good error estimation
 - Metropolis-Hastings algorithm and its variants
 - Gibbs or Hamiltonian samplings
 - CPU intensive and sampling problems in multimodal posteriors
- **Bayesian model selection**
 - CPU expensive for the calculation of the Bayesian evidence which is used to assign relative probabilities to different models
 - thermodynamic integration method (e.g., O Ruanaidh & Fitzgerald 1996)
 - inefficient sampling in multimodal posteriors

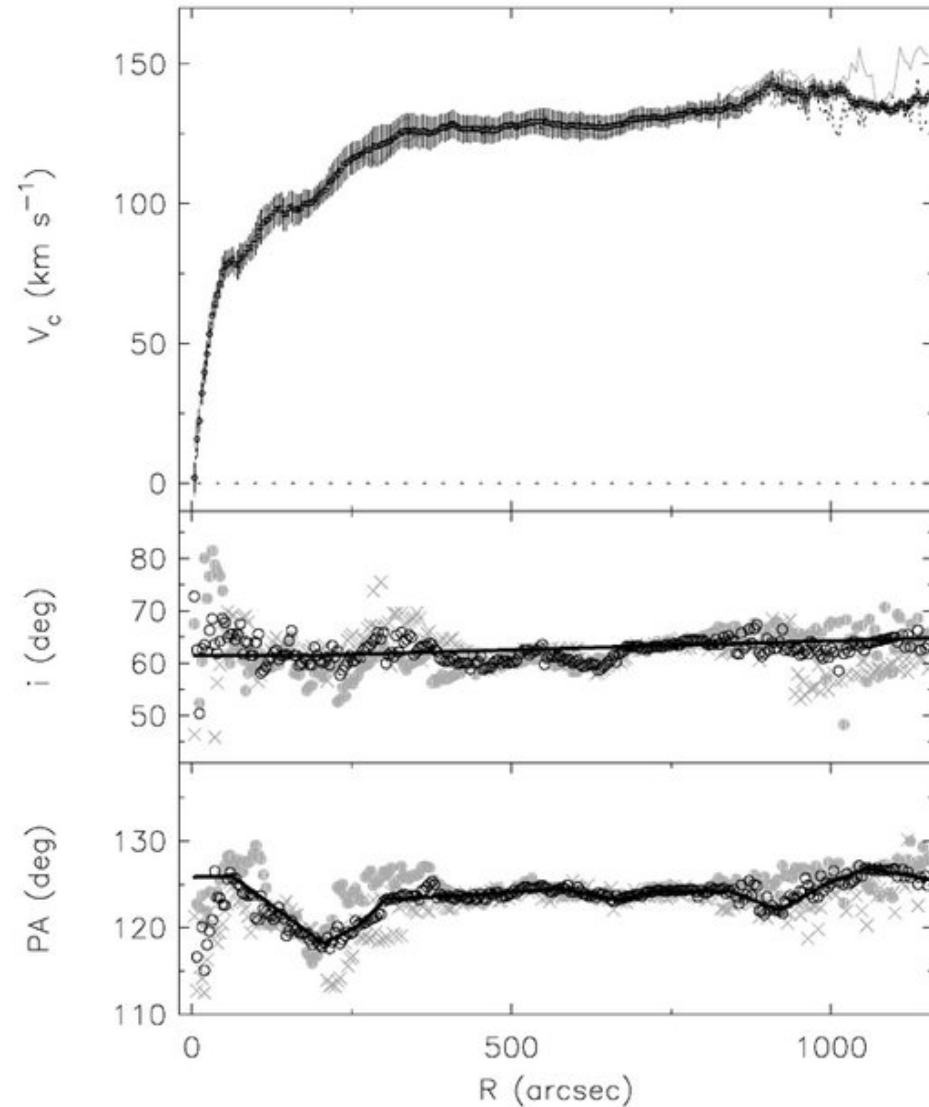
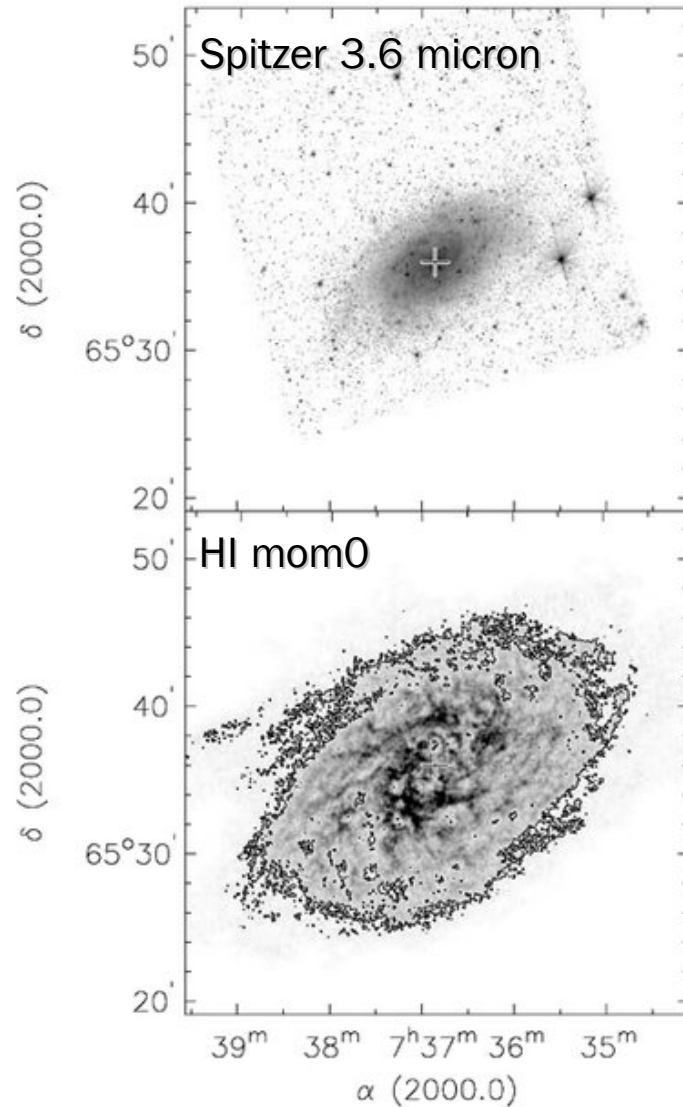
- Improves the sampling efficiency and robustness based on the clustered nested sampling in Shaw et al. (2007)
- Calculates the evidence and explores parameter space even with multimodals and curving degeneracies in high dimensions
- Refer Feroz & Bridges (2008) for a complete discussion on the new sampling scheme, “the improved simultaneous ellipsoidal nested sampling method”
 - a fully parallelized algorithm using MPI
- Successfully implemented in astrophysics and cosmology (e.g., CosmoMC, SuperBayeS, SUSY, gravitational lensing, exo-planet detection, **ASKAP FLASH absorption line finder** (Allison et al.))



IC 2574 (de Blok et al. 2008)



NGC 2403 (de Blok et al. 2008)



- Finding the optimal data set for **a given model**: similar to model selection

- **Akaike information criterion (AIC)**

$$AIC = -2 \ln \mathcal{L} + 2 \eta$$

where \mathcal{L} is maximum likelihood and η is the number of parameters

→ tends to overfitting if the number of data is small

- **Bayesian information criterion (BIC)**

$$BIC = -2 \ln \mathcal{L} + \eta \ln N$$

where \mathcal{L} , η and N are maximum likelihood, the numbers of parameters and data

→ gives more penalties on the number of params to combat overfitting

- **The used model** is critical for calculating BIC

- Several dynamical structures in galaxies (e.g., lopsideness, bar-like potential, spiral arms, non-circular motions etc.) change kinematic PA in radial.
- Usually, well modeled by a polynomial function with a moderate order (e.g., $n=5$)

$$PA = \sum_{i=0}^n a_i r^i \quad : \text{PA filter function}$$

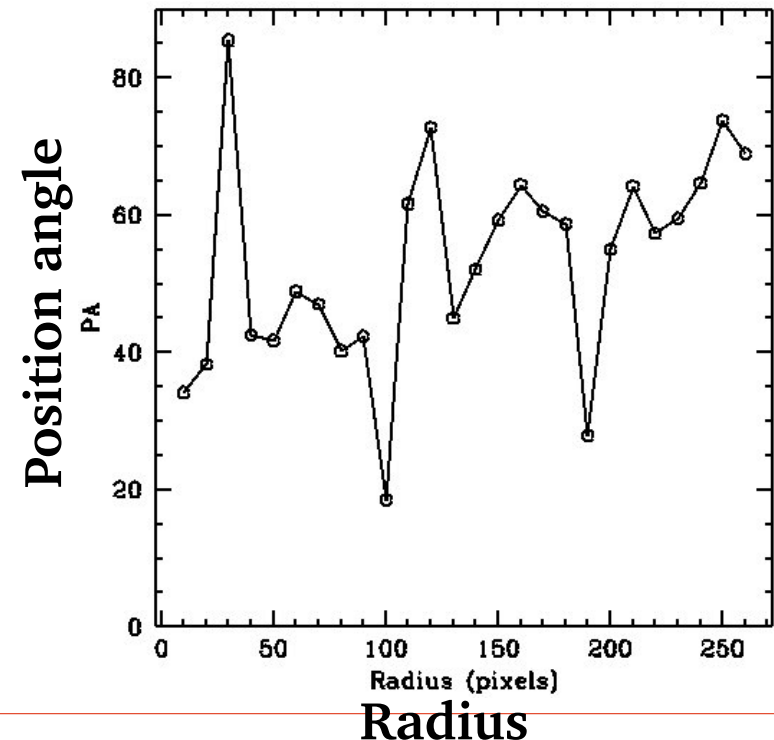
Fit a filter function and find outlier candidates with large residuals



Calculate BICs after removing the candidates, subsequently



Find the first local minimum: the most plausible number of outliers



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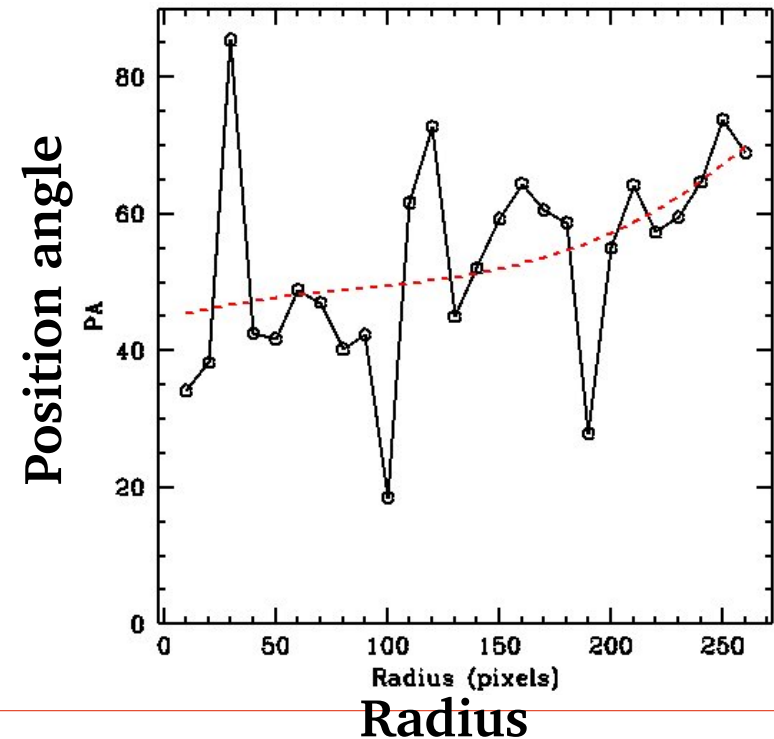
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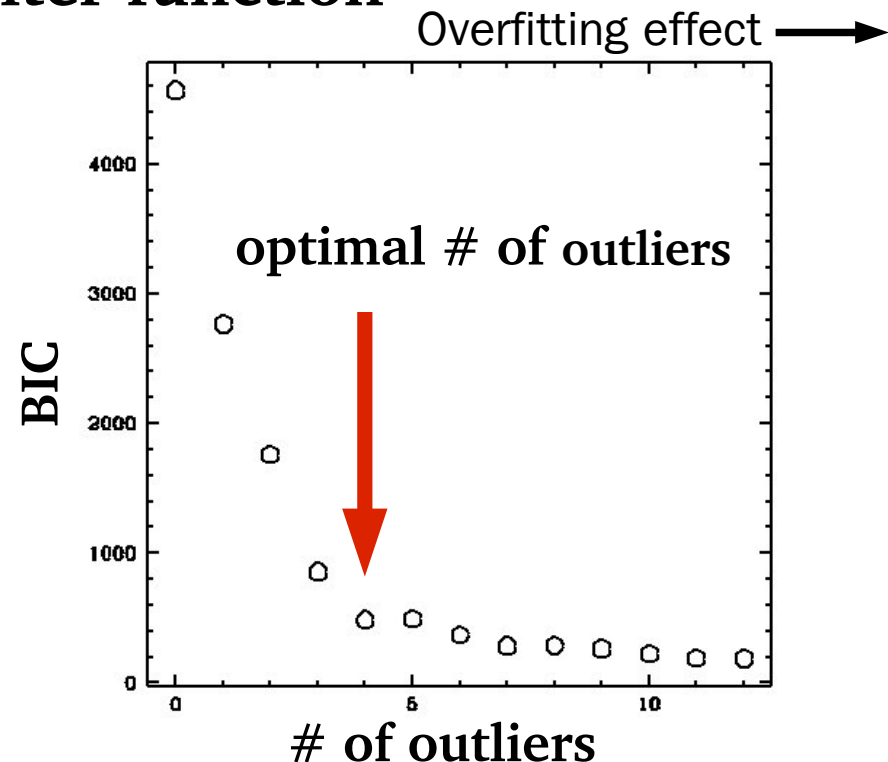
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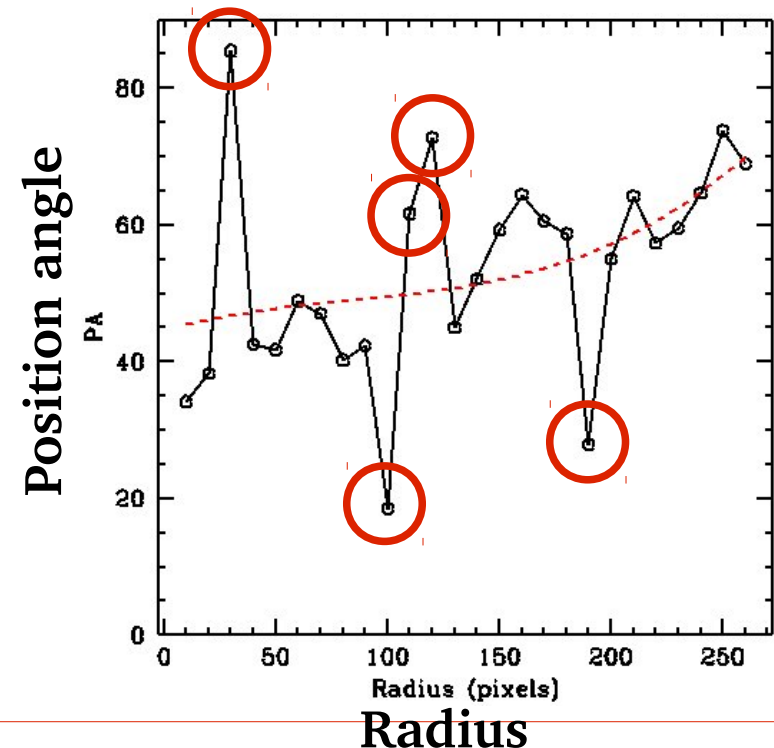
Fit a filter function and find outlier candidates with large residuals



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Find the first local minimum: the most plausible number of outliers



- Kinematic INCL change is often seen in galaxies but its sudden change in the inner region (e.g., non-circular motions?) is unphysical except for outer regions (e.g., warps?)
- A modified Sersic profile is used for INCL filter function (e.g., $m=0$ or 1)

$$INCL = \sum_{i=0}^m a_i r^i + \kappa \exp(r^{-n}) \quad : \text{INCL filter function}$$

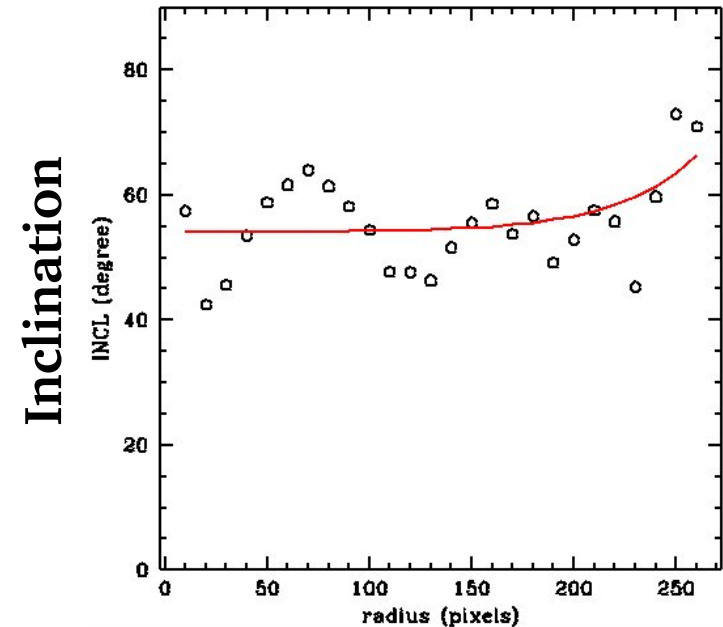
Fit a filter function and find outlier candidates with large residuals



Calculate BICs after removing the candidates, subsequently



Find the first local minimum: the most plausible number of outliers



Radius

- Standalone C program for 2D tilted-ring fit based on Bayesian MCMC
 - MultiNest v2.18, CFITSIO, standard ANSI C libraries
 - **fully automatic**: initial value estimation, convergence check and derivation of the final rotation curve for a given 2D velocity field
 - **several builtin rotation curve shape functions** are optional (e.g., pseudo-isothermal and Burkert rotation curves; **Burkert rotation curve is currently used for deriving the initial estimates for ring parameters**)
 - the larger number of sampling, the higher quality of fits but the more cpu time consuming
 - multinest supports MPI which enables us to do **parallel computing**

```
Terminal
seheon@darkmatter rotcur]$
seheon@darkmatter rotcur]$
seheon@darkmatter rotcur]$
seheon@darkmatter rotcur]$ ./wallaby_2D_TRfits
+-----+
+ WALLABY 2D TILTED-RING FITTER                                     +
+ by SE-HEON OH (ICRAR/UWA) + WALLABY KINEMATICS WORKING GROUP   +
+-----+

usage: mpirun -np 1 ./wallaby_2D_TRfits

I. VELOCITY FIELD AREA : DECIMAL PARAMETRES
[1-velocityfield::vf.fits] [2-nax1::1024] [3-nax2::1024] [4-xlower::200] [5-ylower::200] [6-xupper::800] [7-yupper::800]
[8-decimX_ISOfit::30] [9-decimY_ISOfit::30] [10-decimX_TRfit::1] [11-decimY_TRfit::1]

II. RING PARAMETRES
[12-xposF::512] [13-xpos1::500] [14-xpos2::520] [15-yposF::512] [16-ypos1::500] [17-ypos2::520] [18-vsystF::0] [19-vsyst1::-20] [20-vsyst2::20]
[21-paF::45] [22-pa1::0] [23-pa2::90] [24-inclF::45] [25-incl1:0] [26-incl2::90] [27-vrotF::5] [28-vrot1::0] [29-vrot2::100]

III. TILTED RINGS
[30-ring_s::10] [31-ring_e:200] [32-ring_w::10] [33-pixelScale::1.5]

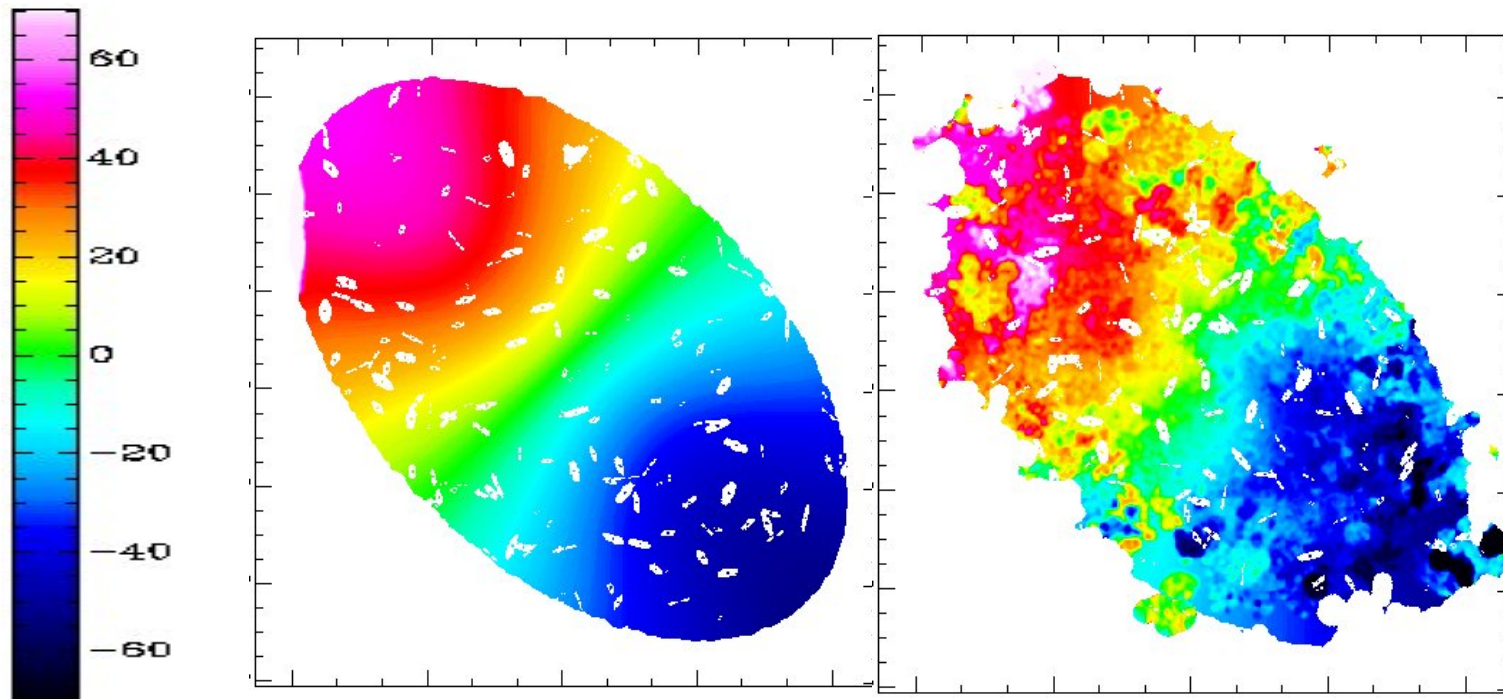
IV. CONVERGENCE LIMITS
[34-xy_radial_diff_limit::5] [35-xy_bic_diff_limit::10]
[36-vsystlimit::3] [37-vsyst_stepsize::1] [38-vsyst_bic_diff_limit::10]
[39-pa_filter_polyorder::5] [40-pa_max_polyorder::5] [41-pa_nlive_polyfit::50] [42-pa_bic_diff_limit::15] [43-palimit::5]
[44-incl_filter_sersicpolyorder::1] [45-incl_max_polyorder::1] [46-nlive_SersicPolyfit::50] [47-incl_bic_diff_limit::15] [48-incllimit::5]

V. MULTINEST PARAMETRES
[49-nlive::20] [50-efr::0.8] [51-tol::0.5] [52-fb::0] [53-outfile::0] [54-maxiter::0]

+-----+
seheon@darkmatter rotcur]$
```


Model 1

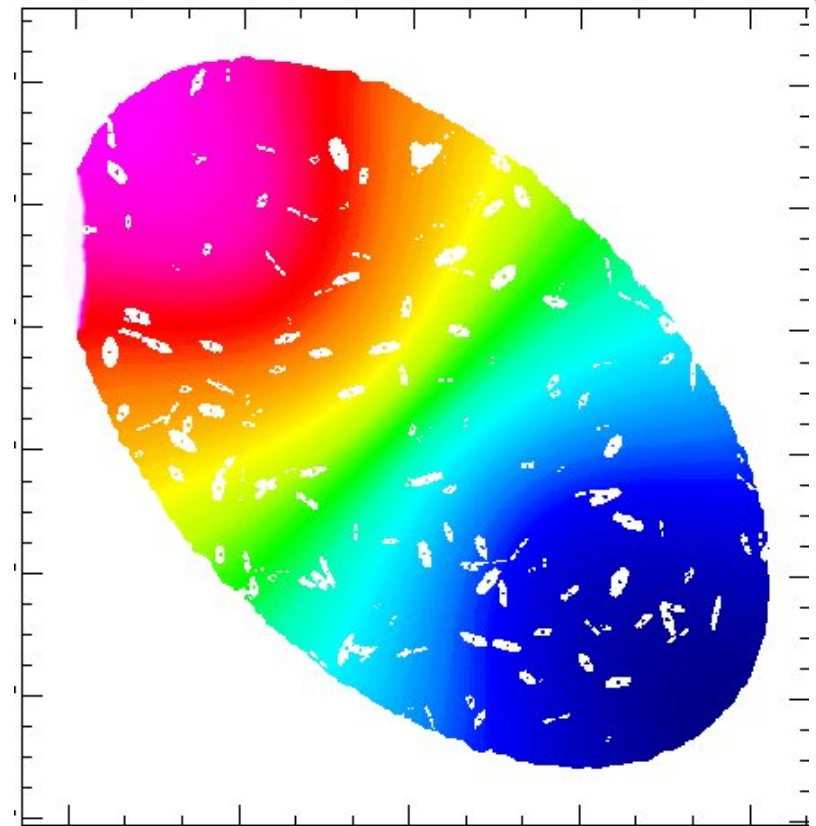
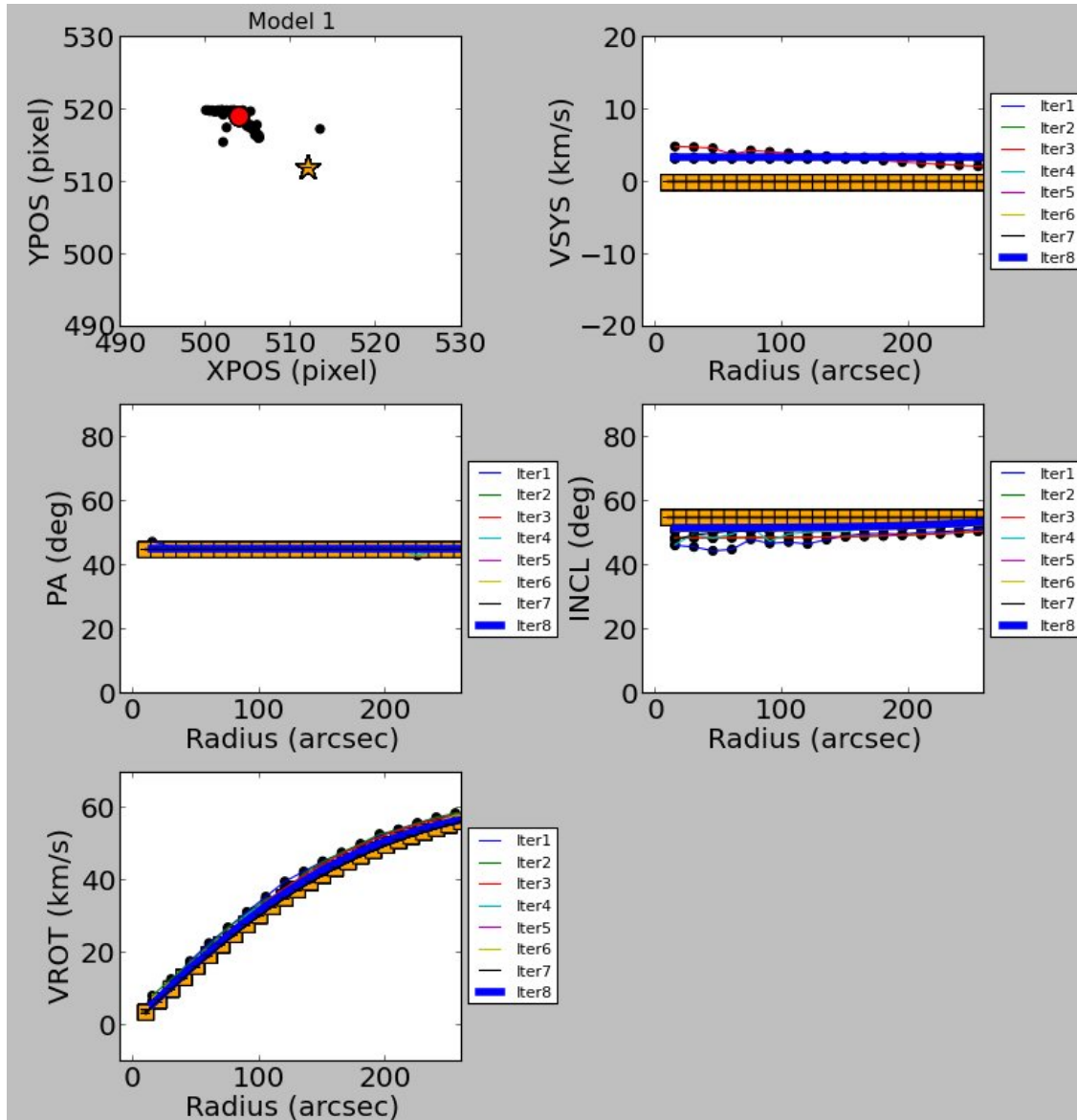
Model 2



Circular motion only

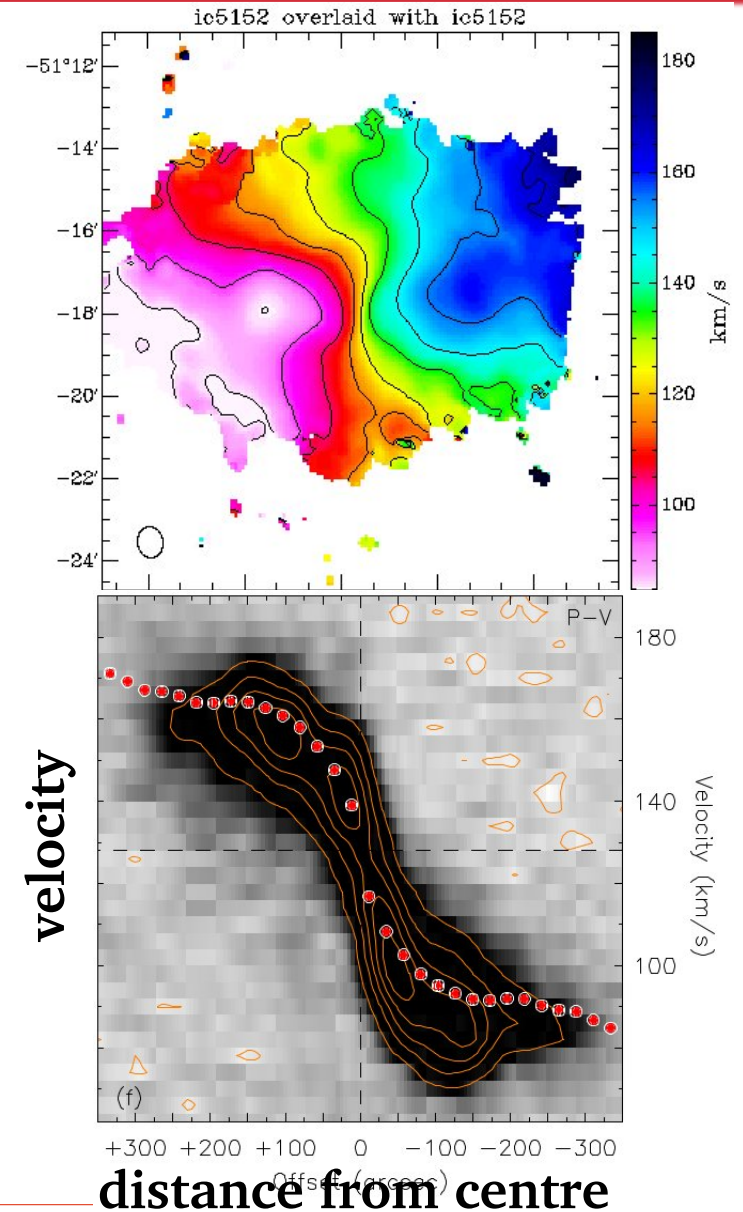
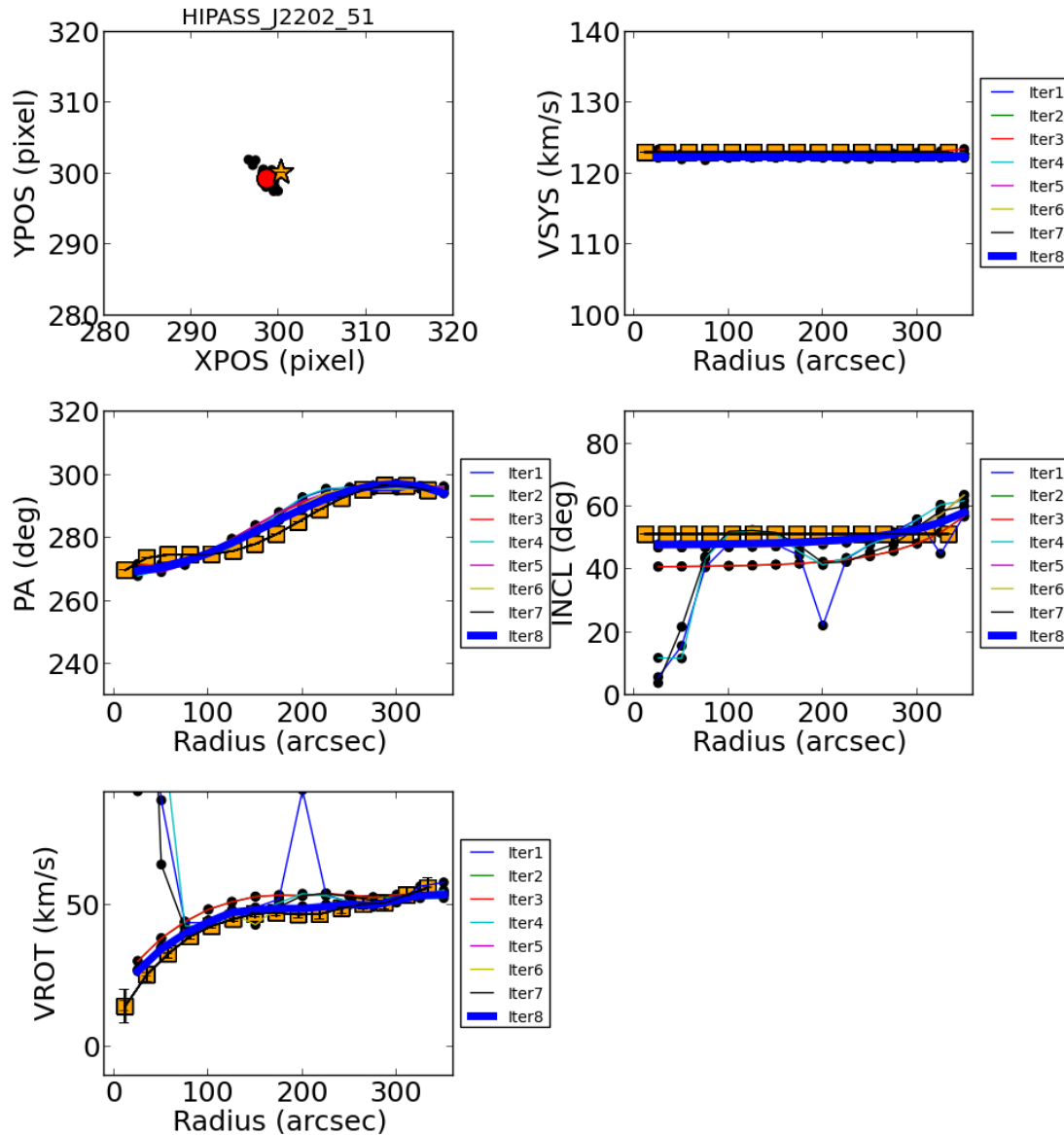
Circular motion +
Random motions +
Bar-like flow (10/km/s/kpc)

Performance test using model galaxies : Model 1

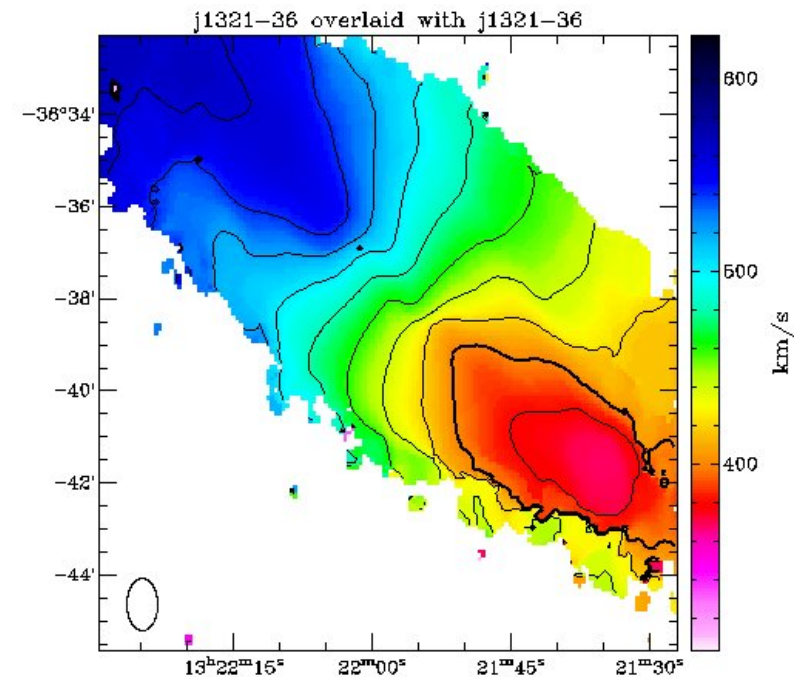
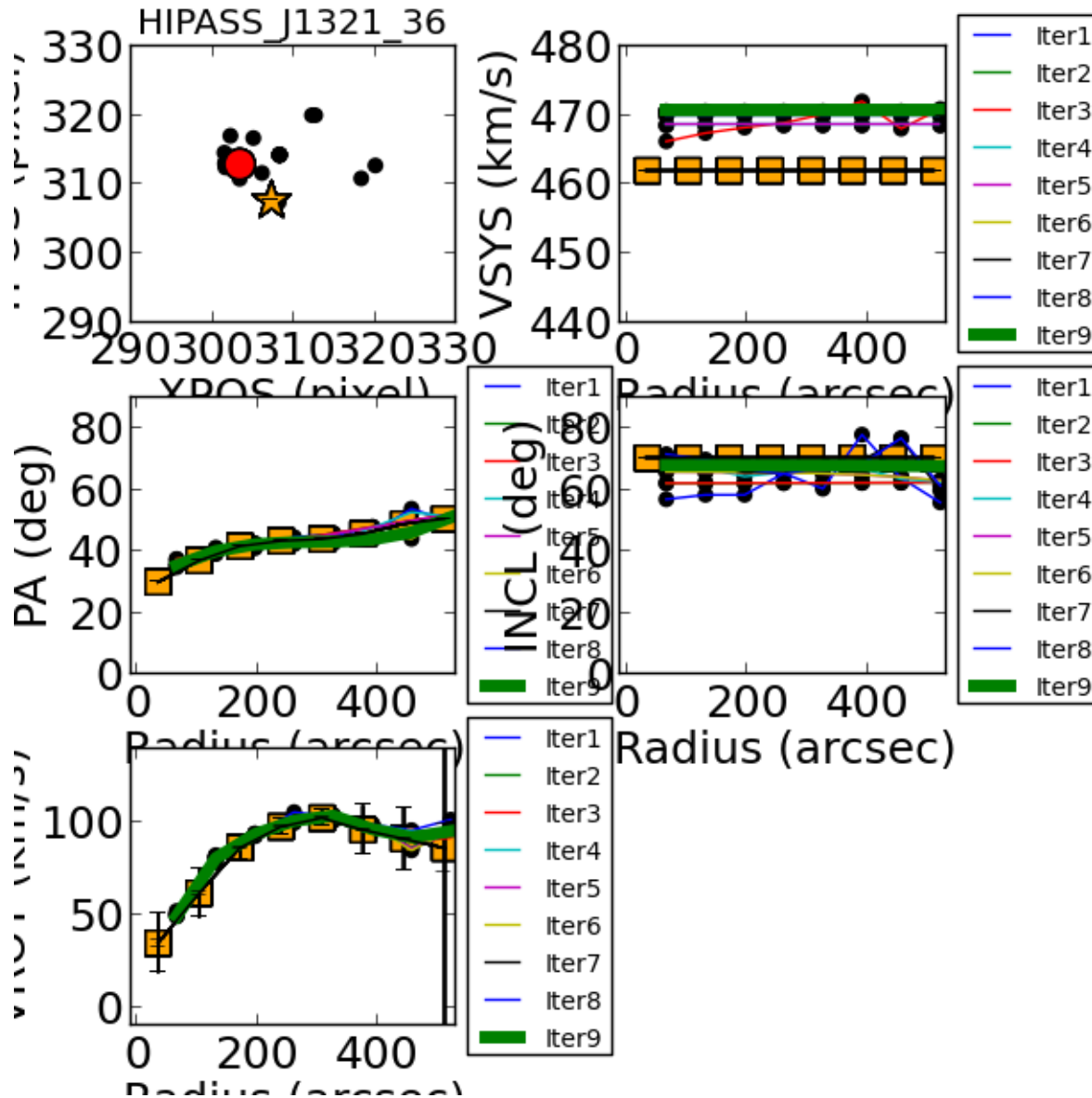


+ Circular motions

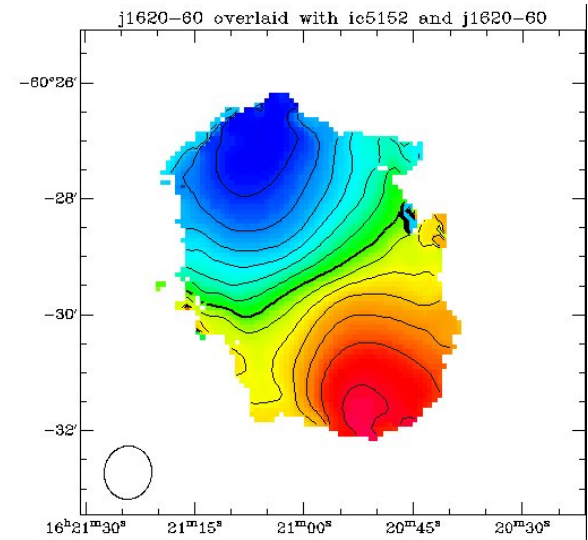
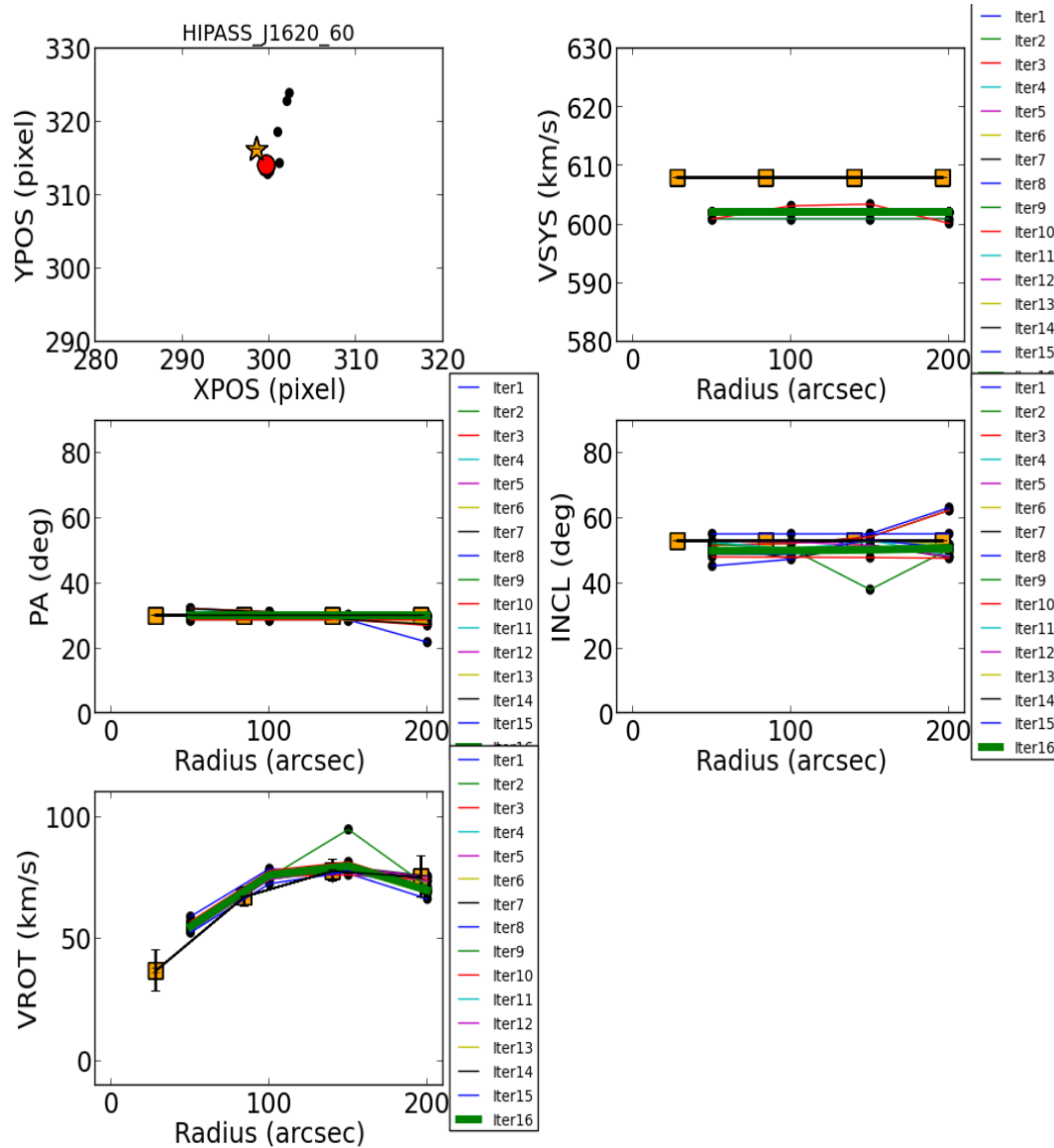
Performance test using real galaxies : Local Volume HI Survey (LVHIS)



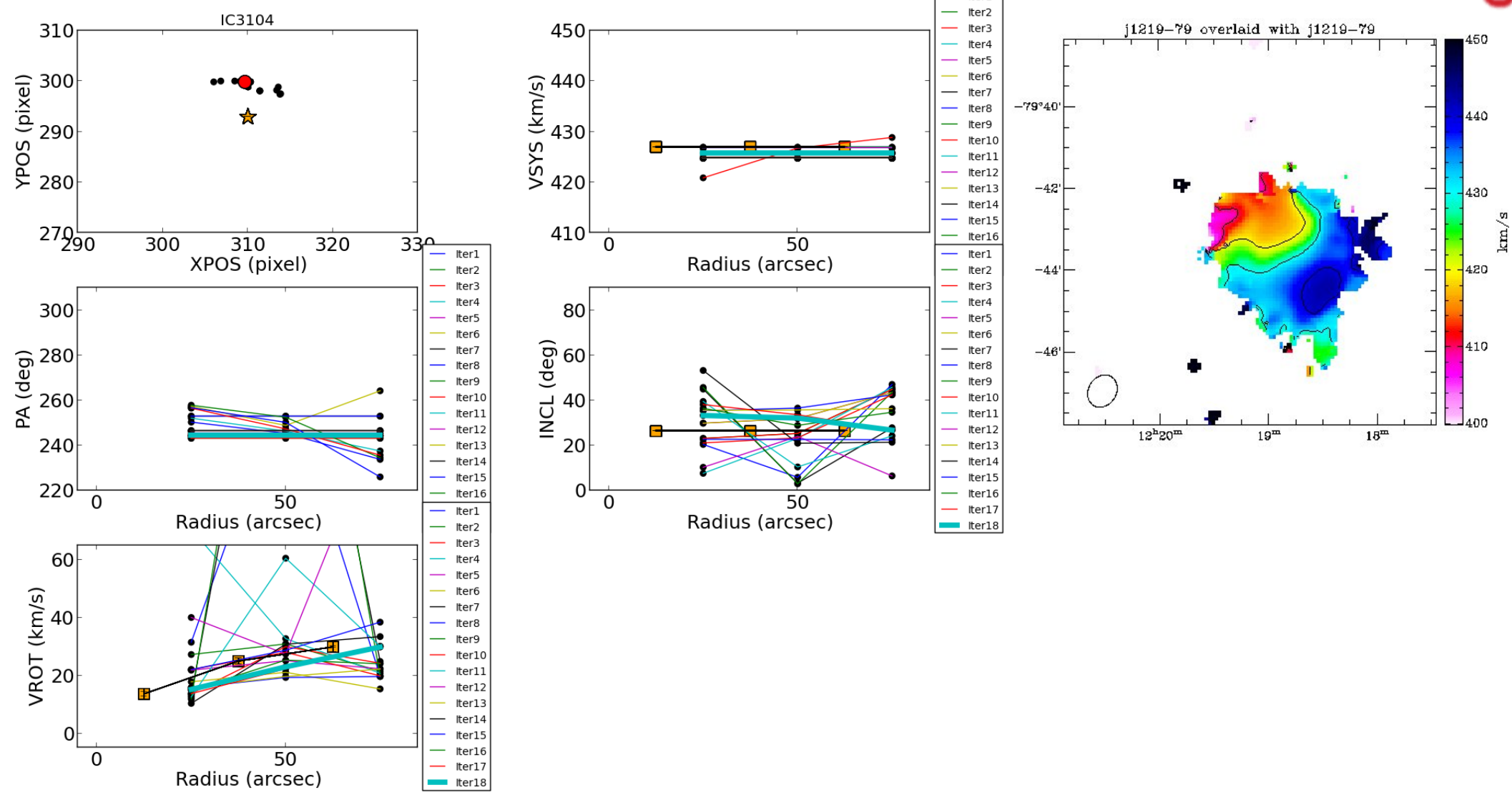
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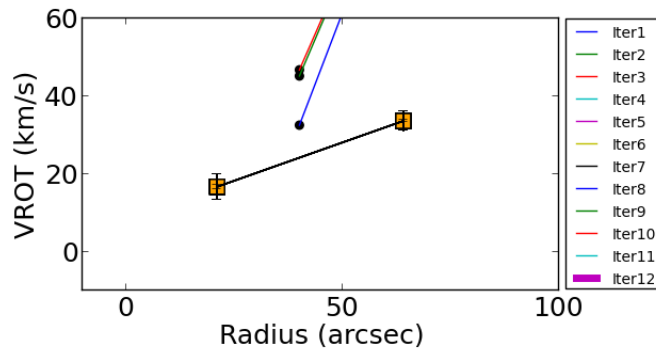
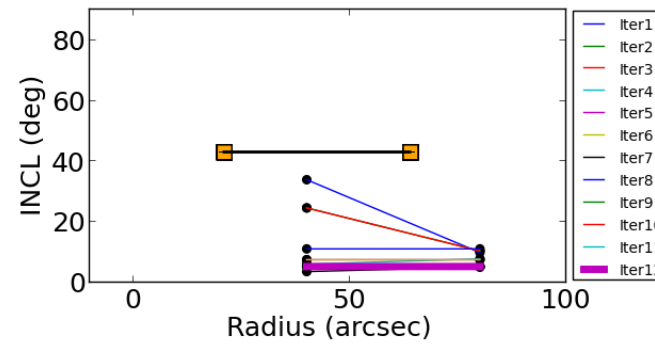
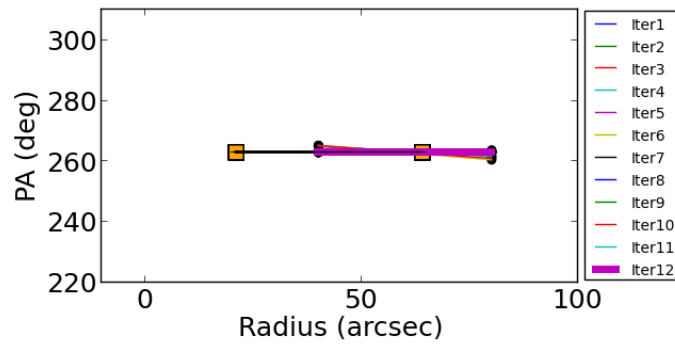
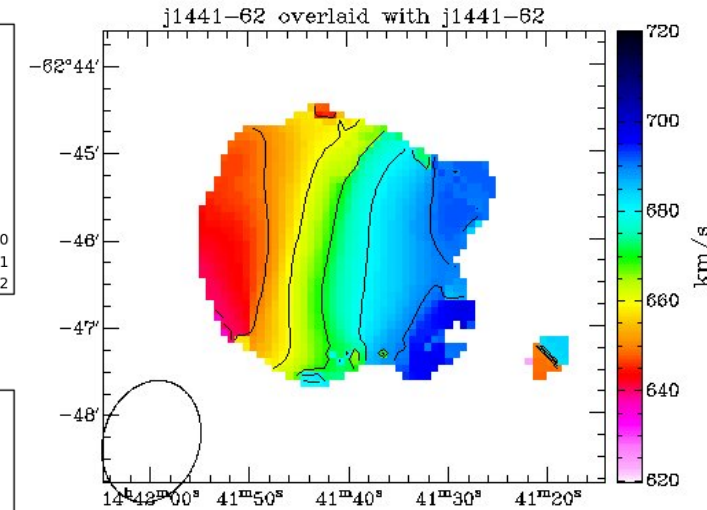
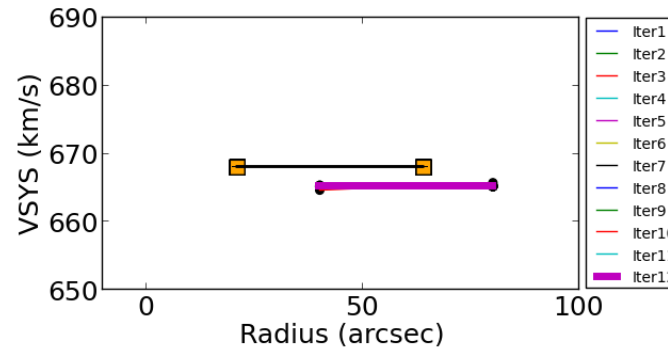
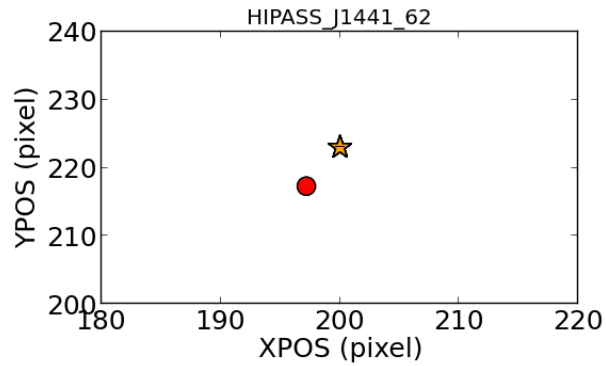


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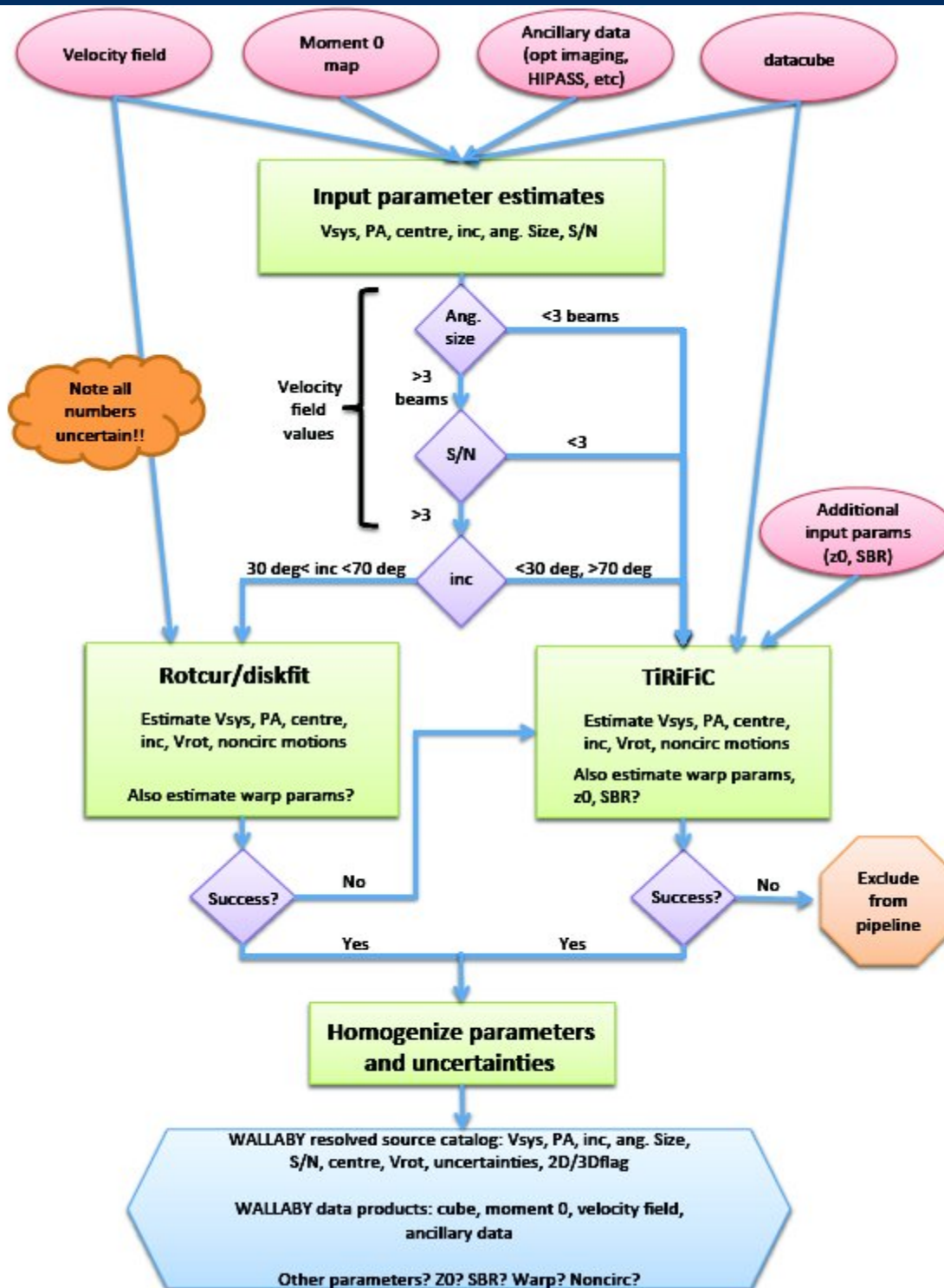


Performance test using real galaxies

: Local Volume HI Survey (LVHIS)



- A new 2D tilted-ring fitter based on Bayesian MCMC developed
 - Robust fitting and efficient outliers removal using MultiNest library
- The standalone C program: (will be) fully automatic for initial estimates, convergence check and derivation of rotation curves
- Gives similar results as Se-Heon did for moderately or well resolved galaxies
- The final WALLABY 2D tilted-ring fitter wrapped in Python will include additional sub-routines:
 - processing log files, plots for statistics and results, generating model velocity fields using the derived tilted-ring parameters, constructing data cubes + HI intensity map (for tirific comparison), quantification of warps etc.
- Needs to be further tuned for optimal Open MPI parallel processing
- Other priors (e.g., Gaussian) which can be set by the first fit results with uniform priors (speed up?)
- Being under test using model & real galaxies: WALLABY-like model galaxies, LVHIS(**26**/80), THINGS(**25**/34), LITTLE THINGS(**27**/41) and SAMI?
- Other types of galaxy kinematic 2D or 3D models can be plugged into the platform by defining their likelihood function and priors



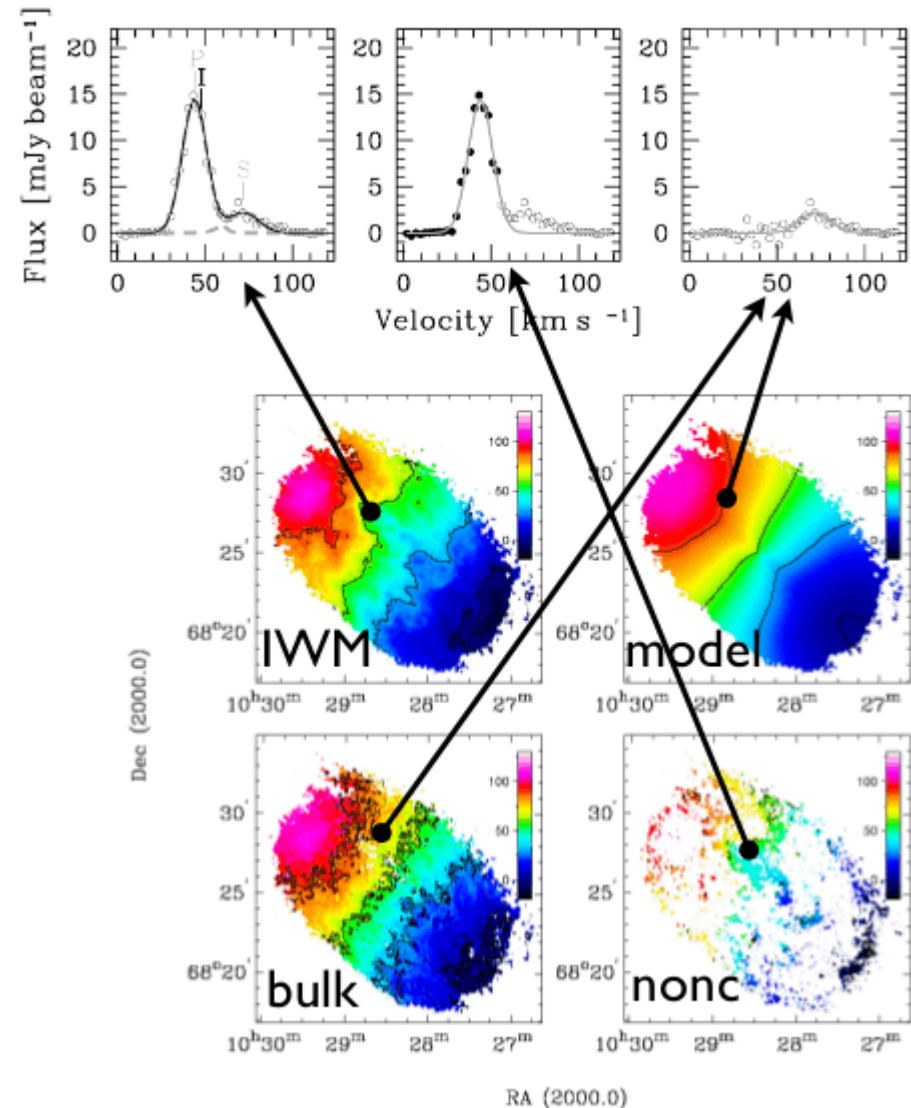
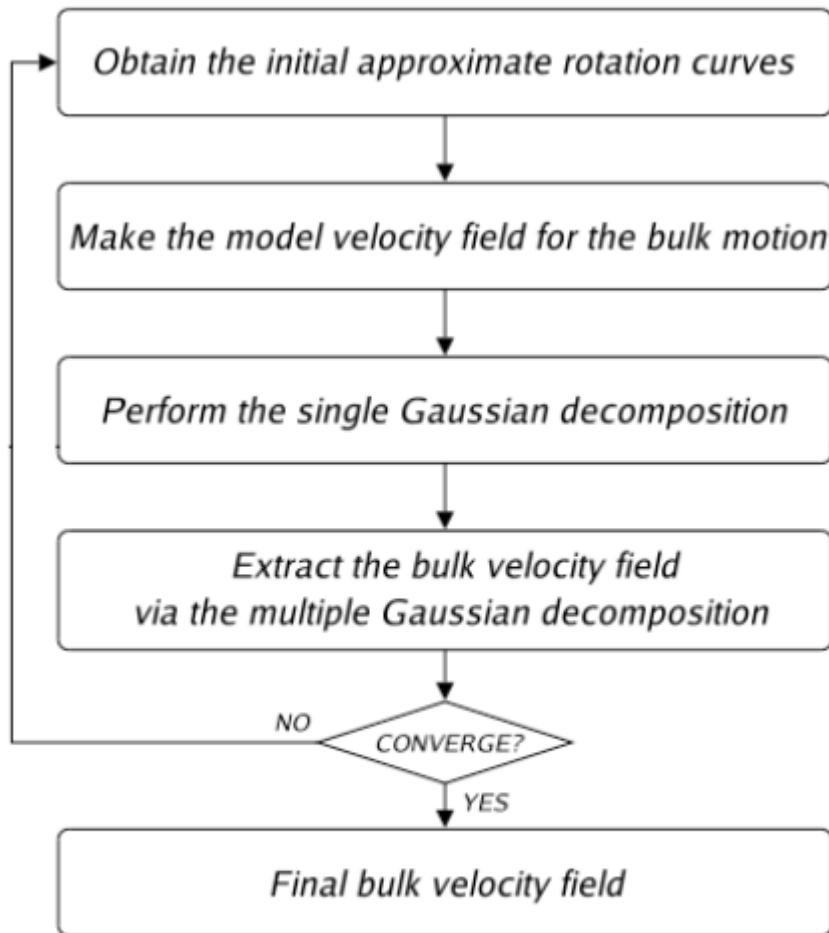
Note all numbers uncertain!!

Additional input params (z0, SBR)

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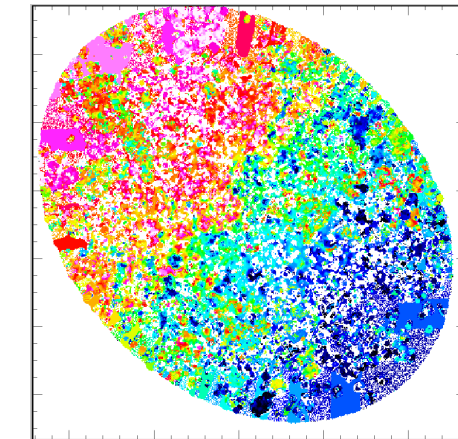
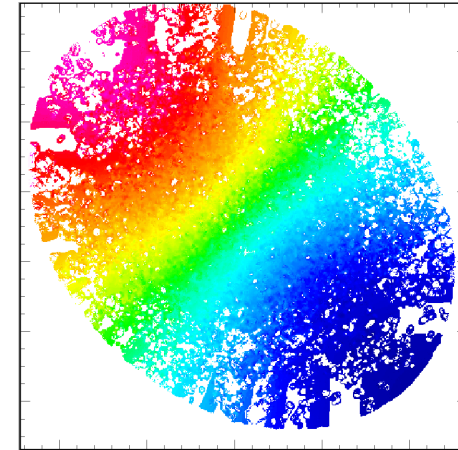
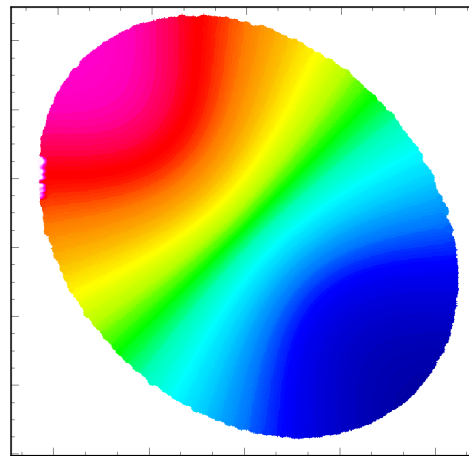
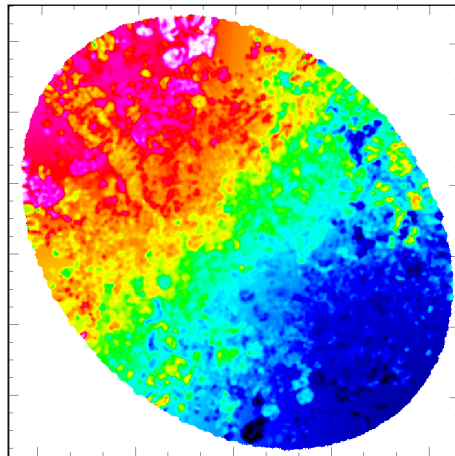
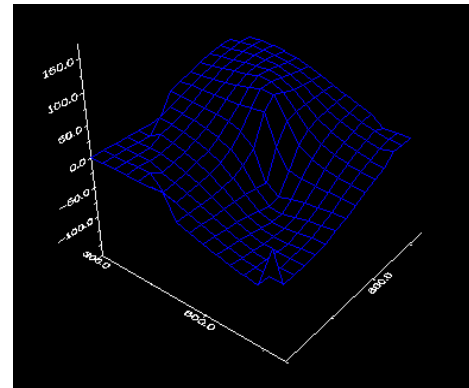
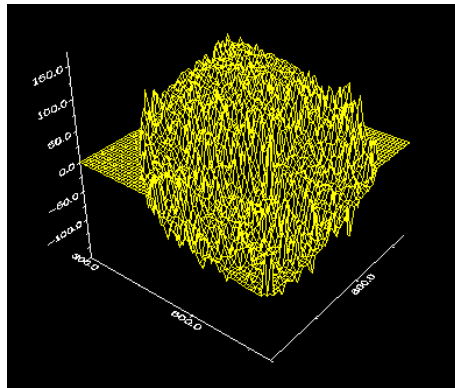
ut pecnoc A

Bulk velocity field



Oh et al. (2008)

A test with a model data cube



IWM V.F.

Model V.F.

Bulk V.F.

Nonc V.F.

**Derive initial estimates using builtin rotation curve function
(e.g., Burkert profile) : constant ring parameters**



**Perform tilted-ring fits using Bayesian MCMC
: outliers removal, optimal model fits**



Make output files and plots for fitting results

A schematic flow for 2D tilted-ring fit pipeline : BIC used for convergence check

