WALLABY/DINGO kinematic pipeline
: A new Bayesian MCMC tilted-ring fitter

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with

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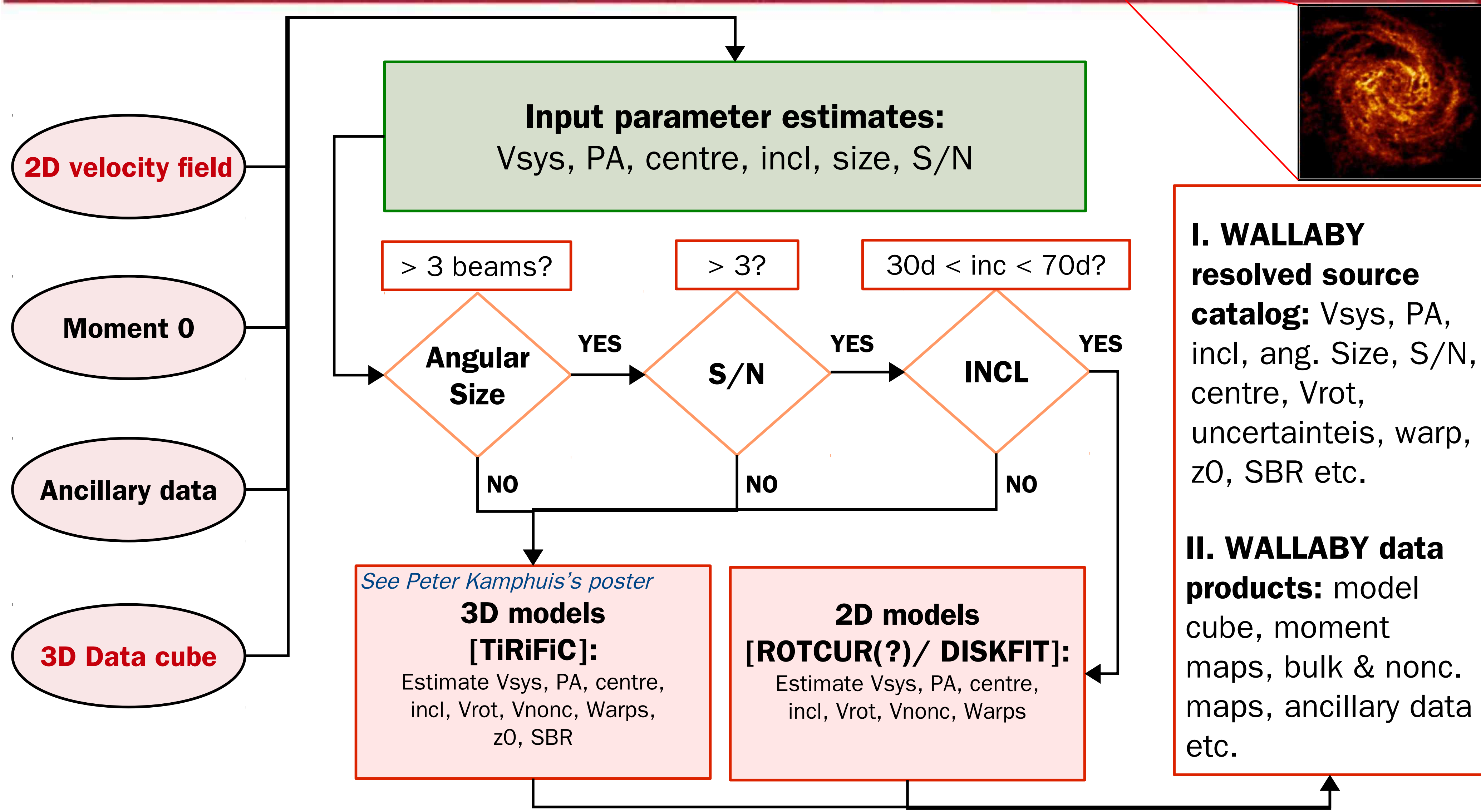
T. Westmeier (ICRAR), P. Serra(CSIRO) + WALLABY kinematics working group

Content

- An overview of WALLABY kinematic pipeline
- A new Bayesian MCMC 2D tilted-ring fitter
- Performance test using sample galaxies from LVHIS
- Summary & future works

Kinematic parameter extraction for WALLABY/DINGO:

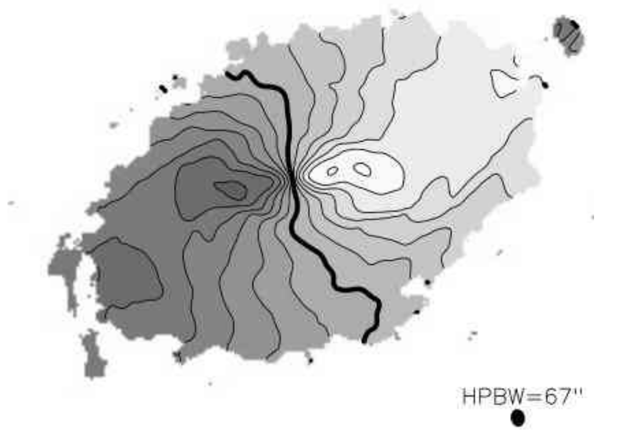
ASKAP WALLABY/DINGO (~5,000) + WSRT WNSHS (~7,000)

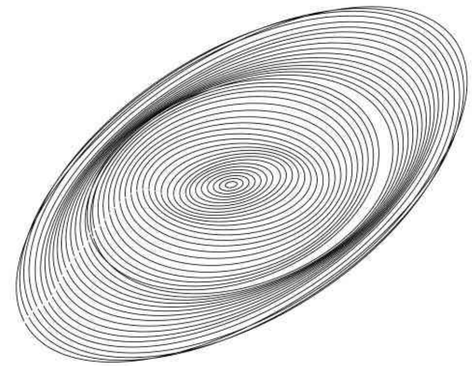


See posters + talks (Thursday) by Peter, Ed and Kristine for more details

2D tilted-ring model (Rogstad et al. 1974)

NGC 5055 (Battaglia et al. 2005)





Free: XPOS, YPOS, VSYS, PA, INCL, VROT
Fixed: VEXP

↓

Free: PA, INCL, VROT
Fixed: XPOS, YPOS, VSYS, VEXP

↓

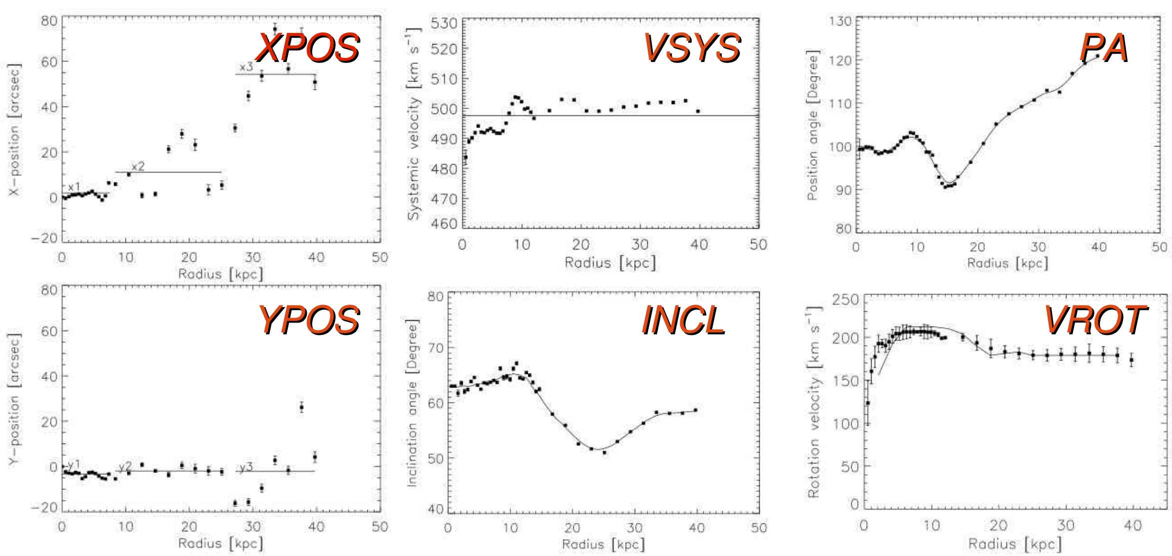
Free: XPOS, YPOS, VROT
Fixed: VSYS, VEXP, PA, INCL

↓

Free: VROT
Fixed: XPOS, YPOS, VSYS, VEXP, PA, INCL

↓

Derive final rotation curve



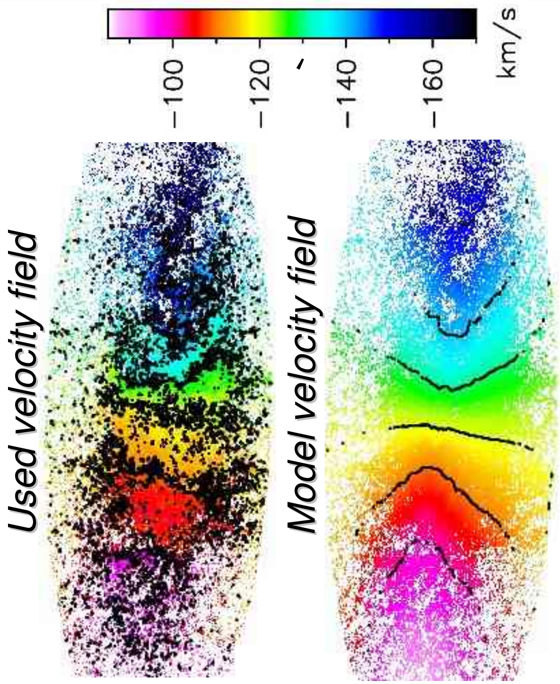
Galaxy Radius Galaxy Radius Galaxy Radius

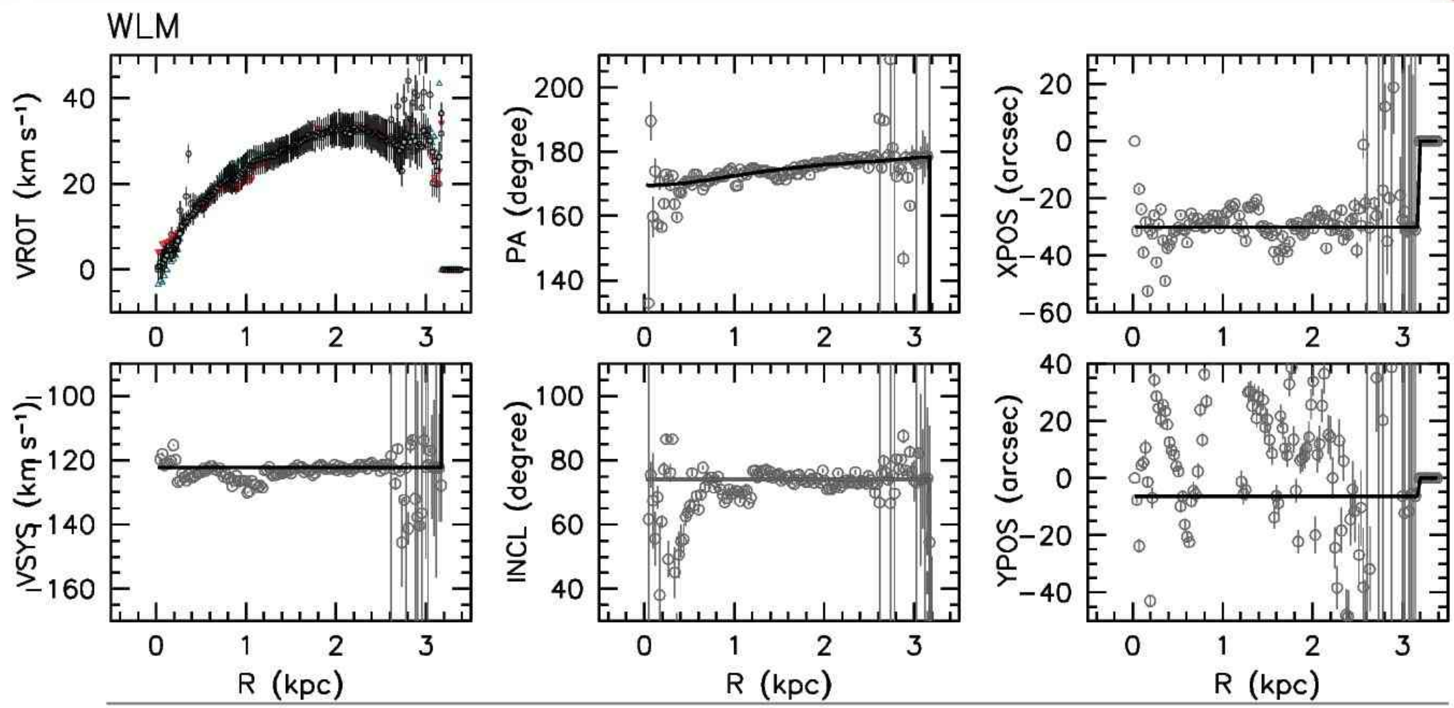
$$V_{\rm obs}(x,y) = V_{\rm sys}(x,y) + \sin i\{V_t(x,y)\cos\theta + V_r(x,y)\sin\theta\}$$

$$\cos\theta = \frac{-(x-{\rm XPOS})\sin({\rm PA}) + (y-{\rm YPOS})\cos({\rm PA})}{r}$$

$$\sin\theta = \frac{-(x-{\rm XPOS})\cos({\rm PA}) - (y-{\rm YPOS})\sin({\rm PA})}{r\cos({\rm INCL})}$$

Some issues on 2D tlted-ring fits





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

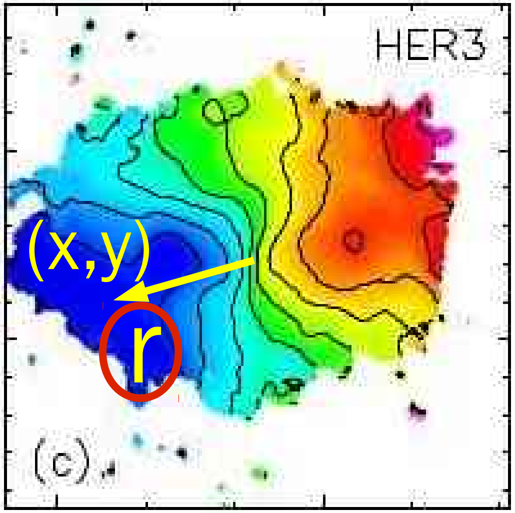
→ **difficult to make the fit atutomatic**

→ Why don't we fitting a tilted-ring model to all pixels at one time rather than dividing them into tilted-rings?

Fitting a 2D tilted-ring model to the velocity field

$$V_{MODEL}(x,y) = V_{SYS}(x,y) + \underline{V_{ROT}(r)} \times \cos\theta \sin I + Vexp(r) \times \sin\theta \sin I$$

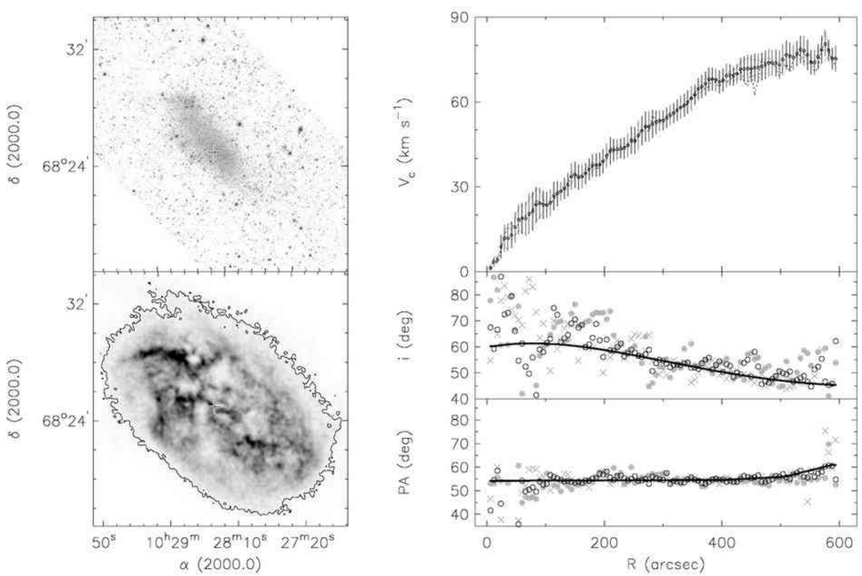
$$\begin{cases} \cos\theta = \dfrac{-(x-XPOS)\times\sin PA + (y-YPOS)\times\cos PA}{r} \\ \sin\theta = \dfrac{-(x-XPOS)\times\cos PA - (y-YPOS)\times\sin PA}{r\cos I} \\ \underline{r} = \sqrt{[-(x-XPOS)\times\sin\theta + (y-YPOS)\times\cos PA]^2 + [\dfrac{(x-XPOS)\times\cos PA + (y-YPOS)\times\sin PA}{\cos I}]^2} \end{cases}$$



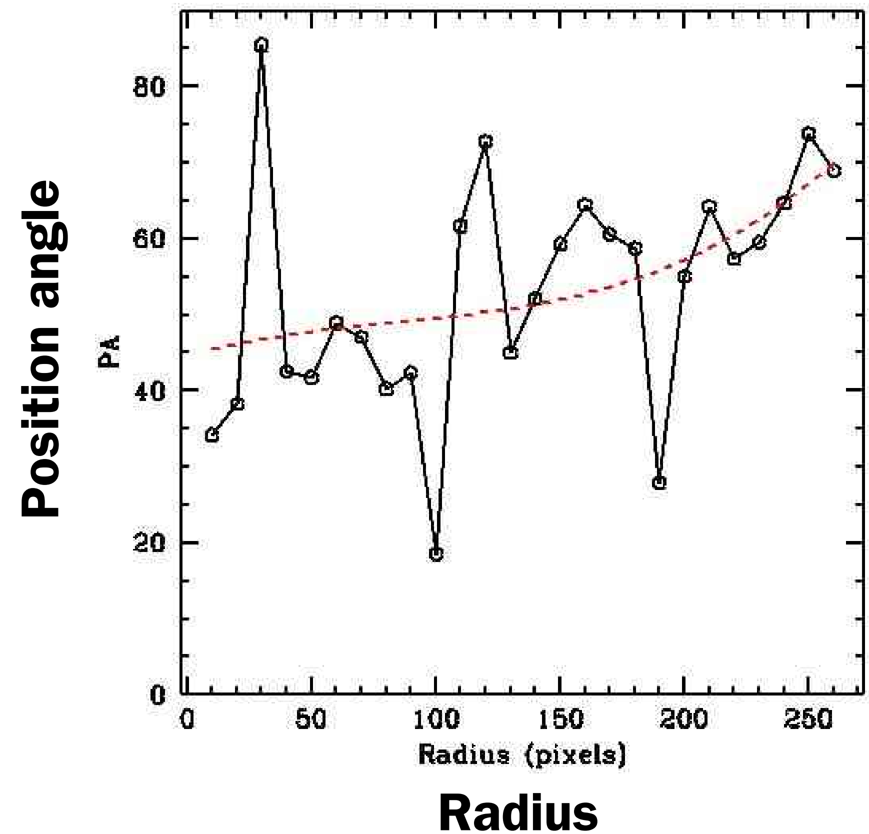
Kinematic position angle

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

$$PA = \sum_{i=0}^{m} p_i r^i$$



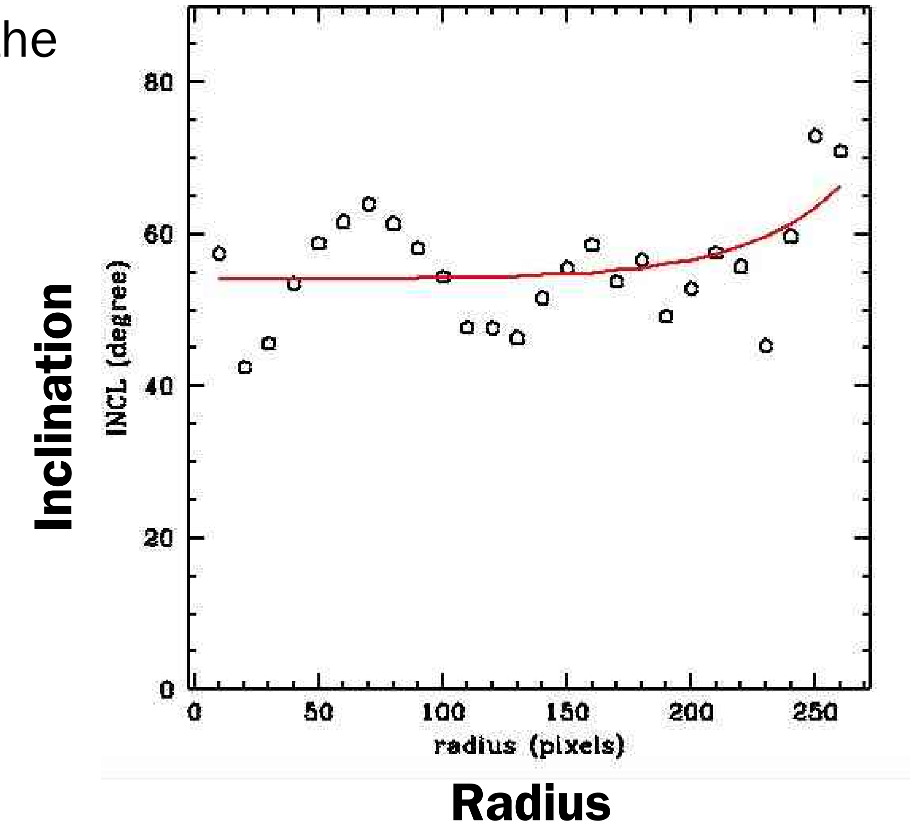
de Blok et al. (2008)



Kinematic inclination

- Kinematic INCL change is often seen in galaxies but its sudden change in the inner region (probably due to non-circulr motions or low filling factor) is unphysical except for outer regions where warps may exist.
- A modified Sersic profile is used for INCL
- Constant or linear variation of INCL in the inner region (e.g., n=0 or 1)

$$I = \sum_{i=0}^{n} i_i r^i + \kappa \exp\left(\left[\frac{r}{\alpha}\right]^{\beta}\right)$$



Fitting a 2D tilted-ring model to the velocity field

$$V_{MODEL}(x,y)=V_{SYS}(x,y)+\underline{V_{ROT}(r)}\times\cos\theta\sin I+Vexp(r)\times\sin\theta\sin I$$

$$\cos\theta=\frac{-(x-XPOS)\times\sin PA+(y-YPOS)\times\cos PA}{r}$$

$$PA=\sum_{i=0}^{m}p_i r^i$$

$$\sin\theta=\frac{-(x-XPOS)\times\cos PA-(y-YPOS)\times\sin PA}{r\cos I}$$

$$I=\sum_{i=0}^{n}i_i r^i+\kappa\exp([\tfrac{r}{\alpha}]^{\beta})$$

$$r=\sqrt{[-(x-XPOS)\times\sin PA+(y-YPOS)\times\cos PA]^2+[\frac{(x-XPOS)\times\cos PA+(y-YPOS)\times\sin PA}{\cos I}]^2}$$

→ $$r=f(x,y,XPOS,YPOS,p_0,p_1,\ldots,i_0,i_1,\ldots,\kappa,\alpha,\beta)$$

→ Solve this non-linear equation and derive the radius, r in the galaxy plane for given (x, y), XPOS, YPOS, p0, p1, ⋯, i0, i1,..., κ, α, β (e.g., Newton-Rapson method etc.)

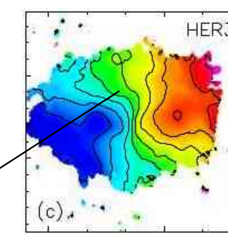
Fitting a 2D tilted-ring model to the velocity field

$$V_{MODEL}(x,y)=V_{SYS}(x,y)+V_{ROT}(r)\times\cos\theta\sin I+Vexp(r)\times\sin\theta\sin I$$

$$r=f(x,y,XPOS,YPOS,p_{0},p_{1},\ldots,i_{0},i_{1},\ldots,\kappa,\alpha,\beta)$$

$$V_{ISO}(r)=\sqrt{4\pi G\rho_0 r_c^2[1-\frac{r_c}{r}\arctan(\frac{r}{r_c})]}$$

$$\rightarrow V_{MODEL}=F(XPOS,YPOS,VSYS,VEXP,\underbrace{r_c,\rho_0,}_{VROT}\underbrace{p_{0},p_{1},\ldots,}_{PA}\underbrace{i_{0},i_{1},\ldots,\kappa,\alpha,\beta}_{INCL})$$



$$\log\mathcal{L}=-\frac{N}{2}log2\pi-\sum_{i=0}^{NAX1}\sum_{j}^{NAX2}\log\sigma_{ij}-\frac{1}{2}\sum_{i=0}^{NAX1}\sum_{j=0}^{NAX2}[\frac{V_{OBS}(i,j)-V_{MODEL}(i,j)}{\sigma_{ij}}]^2$$

Log likelihood

Bayesian Analysis

- **Bayesian parameter estimation**

  - Markov Chain Monte Carlo (MCMC) sampling (see Mackay 2003 and refs therein)

  - less sensitive to initial values and gives good error estimation

  - MCMC sampling (e.g., Metropolis-Hastings algorithm and its variants, Gibbs or Hamiltonian samplings)

  - CPU intensive and sampling problems in multimodal posteriors

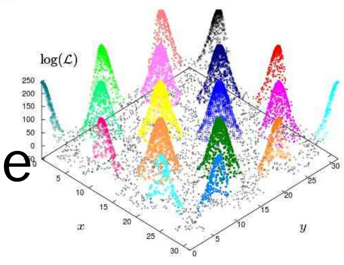
- **Bayesian model selection**

  - 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

MultiNest (Feroz & Bridges 2007, 2008) : a Bayesian inference tool



- 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 to 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
- Successfuly implemented in astrophysics and cosmology (e.g., CosmoMC, SuperBayeS, SUSY, gravitational lensing, exo-planet detection, ASKAP FLASH absorption line finder (Allison et al. 2012))

WALLABY 2D tilted-ring fitter

- Standalone C program for 2D tilted-ring fits based on Bayesian MCMC

  - MultiNest v2.18, CFITSIO, standard ANSI C libraries

  - fully automatic: estimation for initial values, convergence check and derivation of the final rotation curve for a given 2D velocity field

  - several builtin rotation curve shape functions are provided (e.g., pseudo-isothermal, Burkert, polynomial rotation curves etc.)

  - the larger number of sampling, the higher quality of fits but the more cpu time

  → supports MPI which enables us to do parallel computing

Program run

```
seheon@darkmatter rotcur.develop.mpi]$
seheon@darkmatter rotcur.develop.mpi]$ mpirun -np 1 --bysocket -loadbalance ./wallaby_2D_TRfitter

+ ---------------------------------------------------------------------------------------------- +
+ WALLABY 2D TILTED-RING FITTER                                                                  +
+ by SE-HEON OH (ICRAR/UWA) + WALLABY KINEMATICS WORKING GROUP                                   +
+ ---------------------------------------------------------------------------------------------- +
+                                                                                                +
+ Development history                                                                            +
+ : V.1.0 14/Sept/2013                                                                           +
+                                                                                                +
+ Usage                                                                                          +
+ : mpirun -loadbalance -np [0. N-cpus= 8] ./wallaby_2D_TRfitter                                 +
+                                                                                                +
+ A. Input 2D velocity field to fit ------------------------------------------------------------ +
+  [1. 2D VELOCITY FIELD= vf.fits)]                                                              +
+  [2. NAX1= 1024] [3. NAX2= 1024]                                                               +
+  [4. XLOWER= 200] [5. YLOWER= 200] [6. XUPPER= 800] [7. YUPPER= 800]                           +
+                                                                                                +
+ B. Binning option ---------------------------------------------------------------------------- +
+  [8. grid_X_ISOFIT= 5] [9. grid_Y_ISOFIT= 5] [10. BIN_X_TRFIT= 1] [11. BIN_X_TRFIT= 1]         +
+                                                                                                +
+ C. Uniform priors of ring parametres --------------------------------------------------------- +
+  [12. XPOS= 512] [13. xpos0= 500] [14. xpos1= 520]                                             +
+  [15. YPOS= 512] [16. ypos0= 500] [17. ypos1= 520]                                             +
+  [18. VSYS= 0]   [19. vsys0= -10] [20. vsys1= 10]                                              +
+  [21. PA= 45]    [22. pa0= 0.1]   [23. pa1= 0.9]                                               +
+  [24. INCL= 45]  [25. incl0= 0.1] [26. incl1= 0.9]                                             +
+  [27. VROT= 10]  [28. vrot0= 0.0] [29. vrot1= 200]                                             +
+                                                                                                +
+ D. Tilted rings ------------------------------------------------------------------------------ +
+  [30. RING_start= 4] [31. RING_end= 100] [32. RING_width= 4]                                   +
+  [33. RING_inner_regrad= 20] [34. PIXEL_scale= 5]                                              +
+  [35. PA_Poly-Order= 5] [36. INCL_Poly-Order= 1]                                               +
+                                                                                                +
+ E. MULTINEST parameters ---------------------------------------------------------------------- +
+  [37. nlive= 100] [38. efr= 0.8] [39. tol= 0.1] [40. fb= 0] [41. outfile= 0] [42. maxiter= 0]  +
+ ---------------------------------------------------------------------------------------------- +
+                                                                                                +
+ ! EXAMPLE ------------------------------------------------------------------------------------ +
 mpirun -loadbalance -np 8 ./wallaby_2D_TRfitter \
 test.VF1024.fits \
 1024 1024 \
 200 200 800 800 \
 5 5 1 1 \
 512 490 530 \
 512 490 530 \
 0 -20 20 \
 45 0.1 0.9 \
 60 0.1 0.9 \
 10 0.0 120 \
 3 100 3 \
 20 5 \
 5 1 \
 100 0.8 0.1 0 0 0
+ ---------------------------------------------------------------------------------------------- +

seheon@darkmatter rotcur.develop.mpi]$
seheon@darkmatter rotcur.develop.mpi]$
seheon@darkmatter rotcur.develop.mpi]$
```

Input velocity field

Binning factors

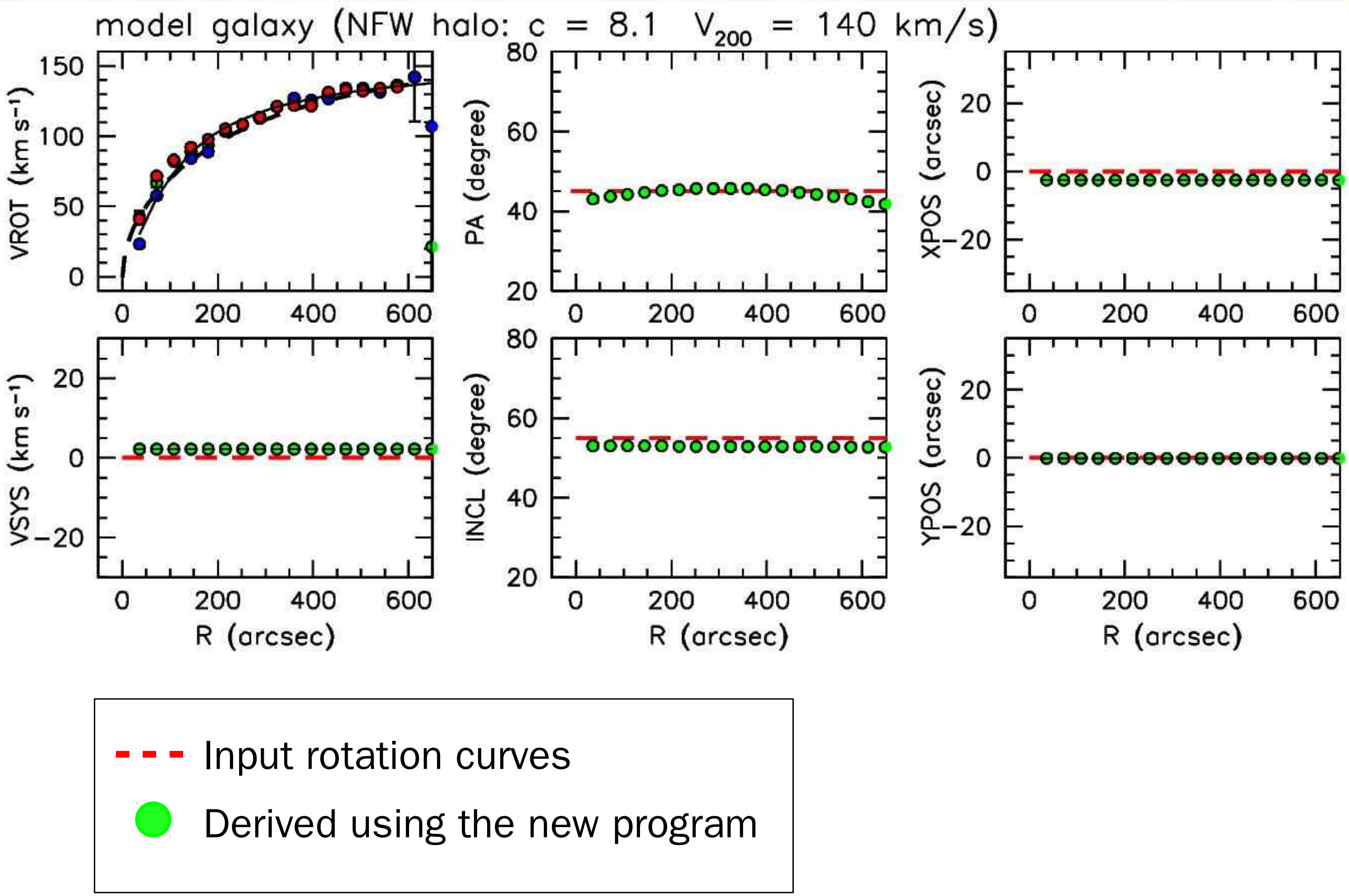
Uniform priors of tilted-ring parametres

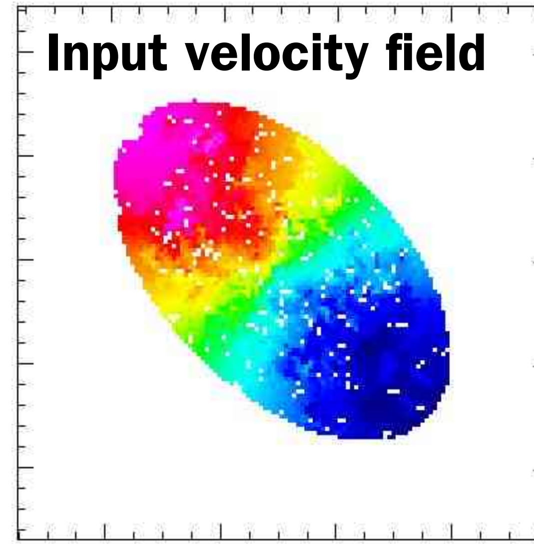
radii, width, pixel-scale, PA/INCL p-orders

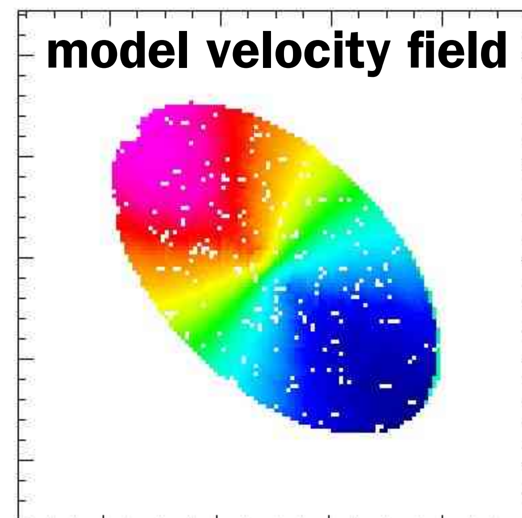
Multinest parametres

Performance test

: a model galaxy (NFW halo: c=8.1 V200=140 km/s + non-circular motions

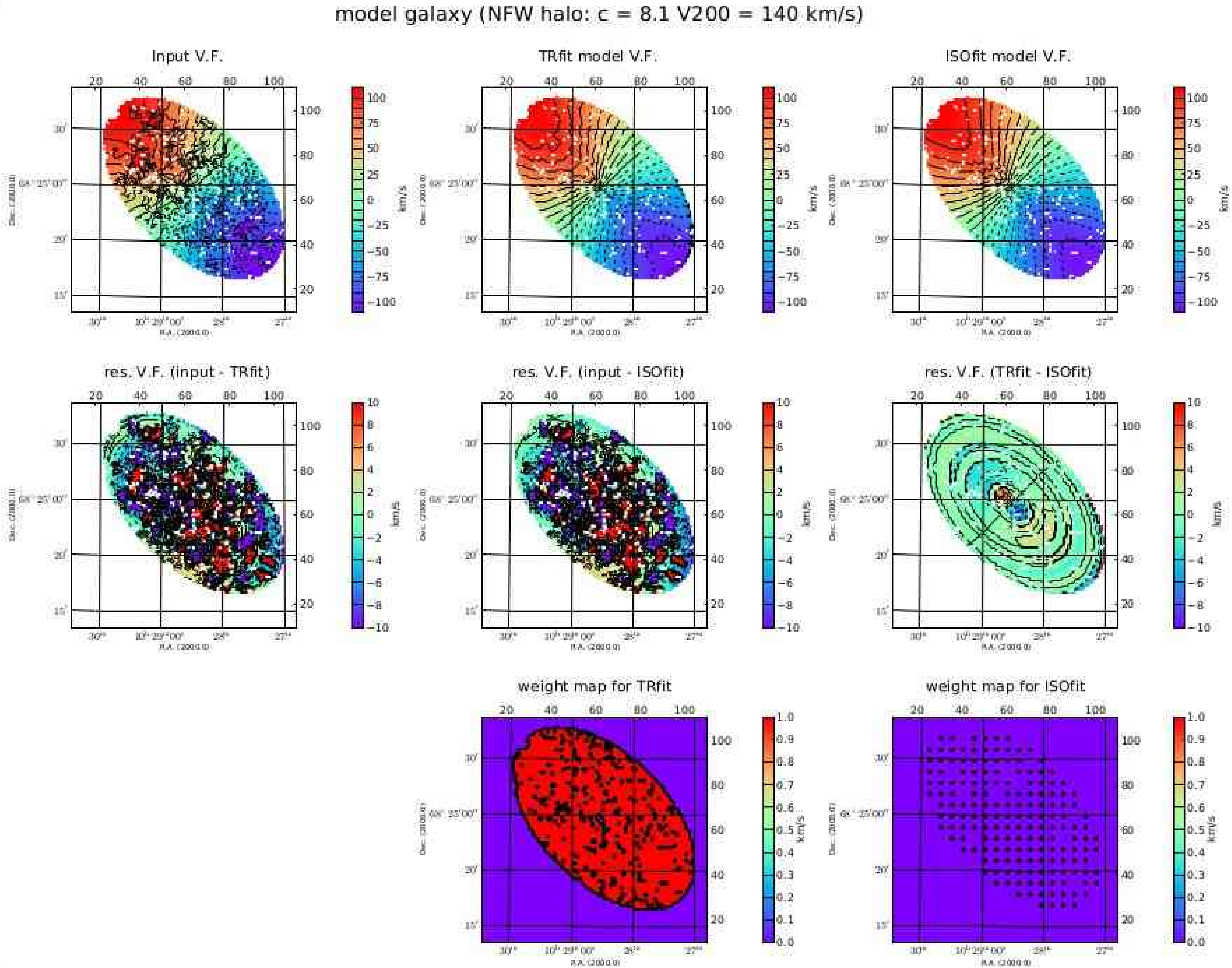






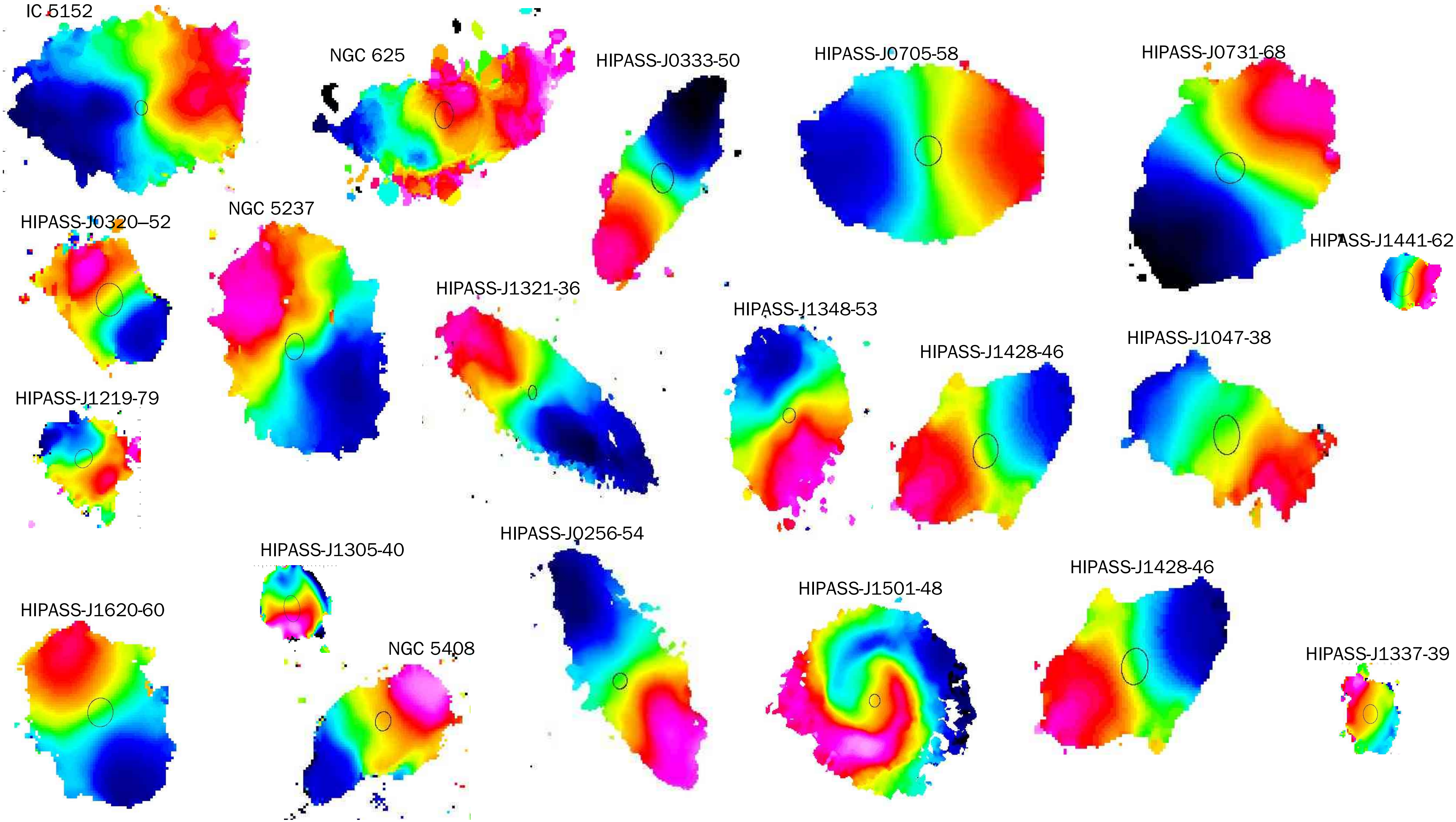
Performance test

: model galaxy (NFW halo: c=8.1 V200=140 km/s + non-circular motions

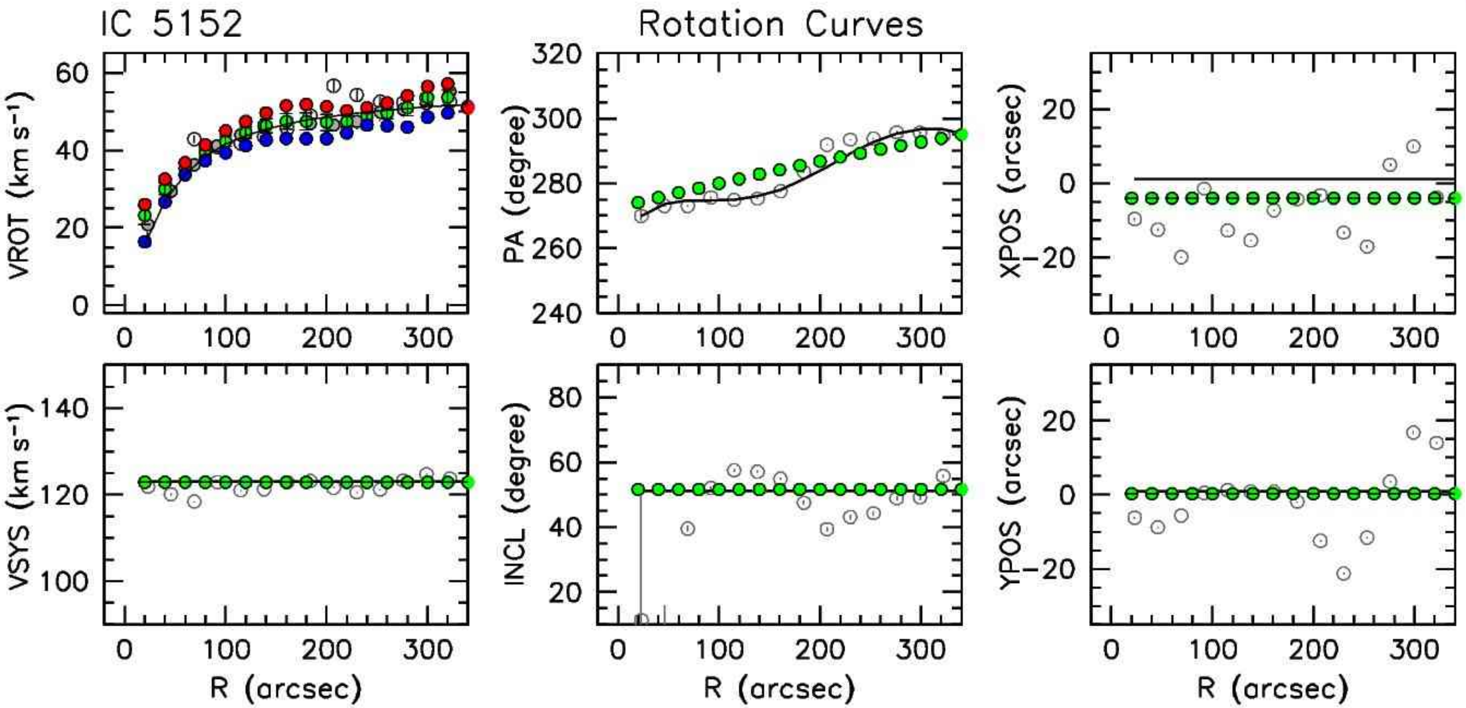


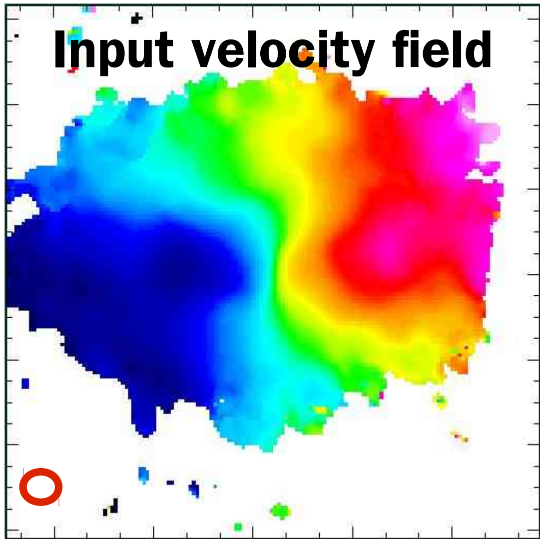
CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

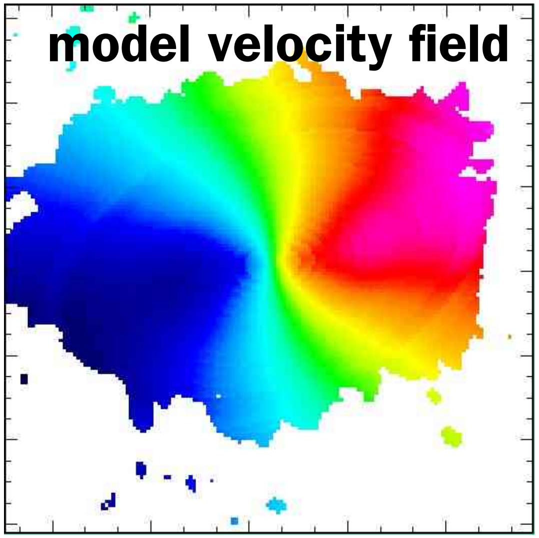
Local Volume HI Survey (LVHIS) : *Koribalski et al.*
: HI velocity field



Performance test
: IC 5152 (> 5 beams)



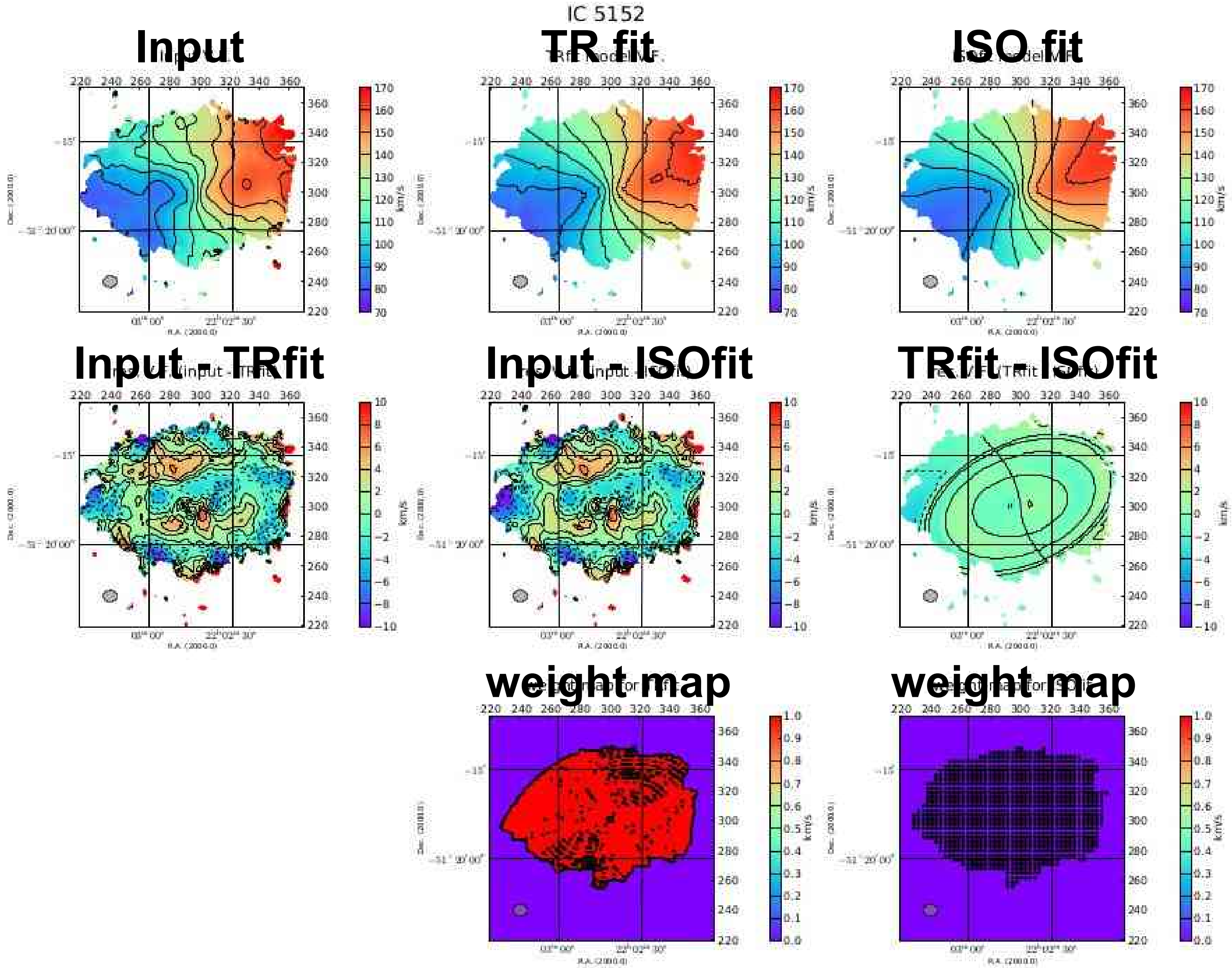




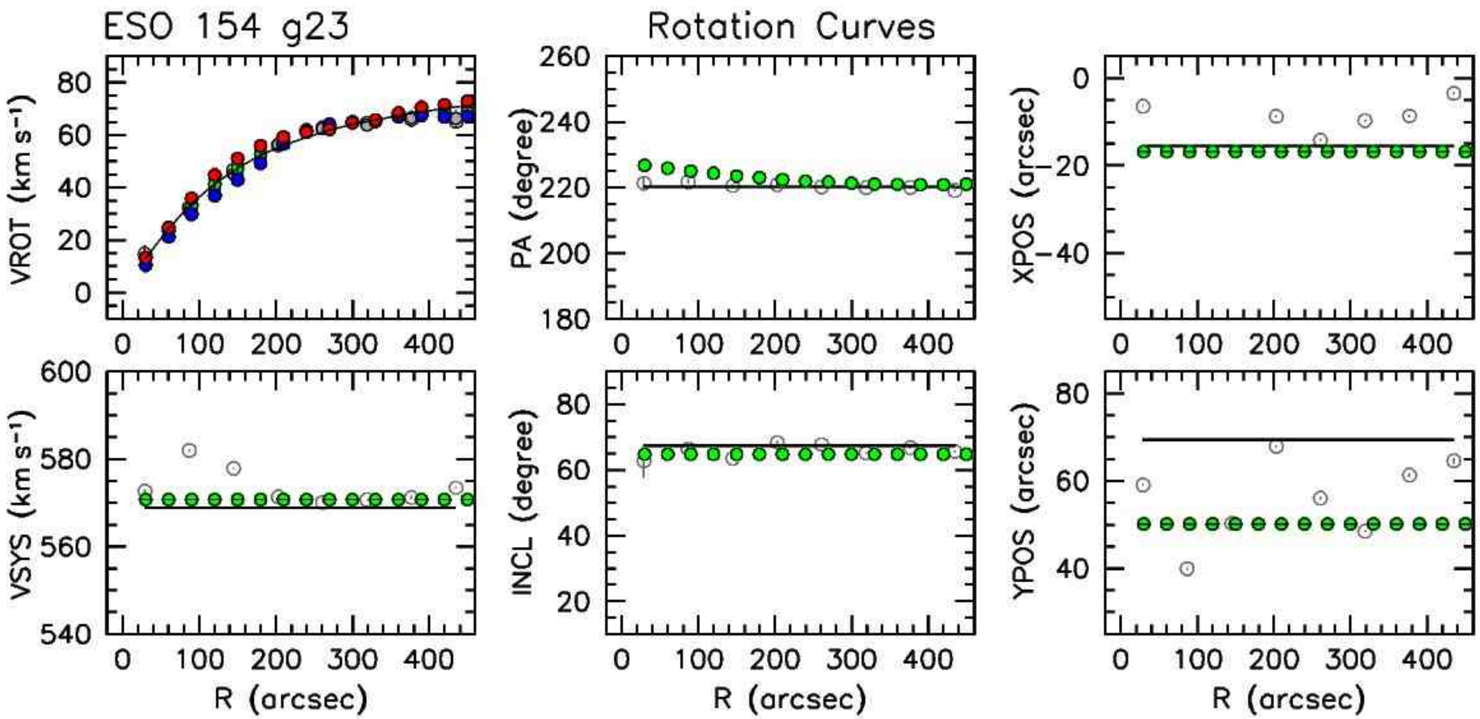
— Derived in manual using rotcur program

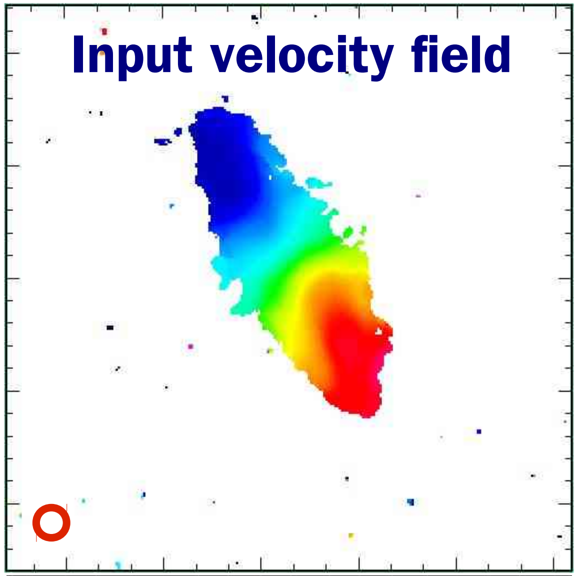
● Derived using the new program

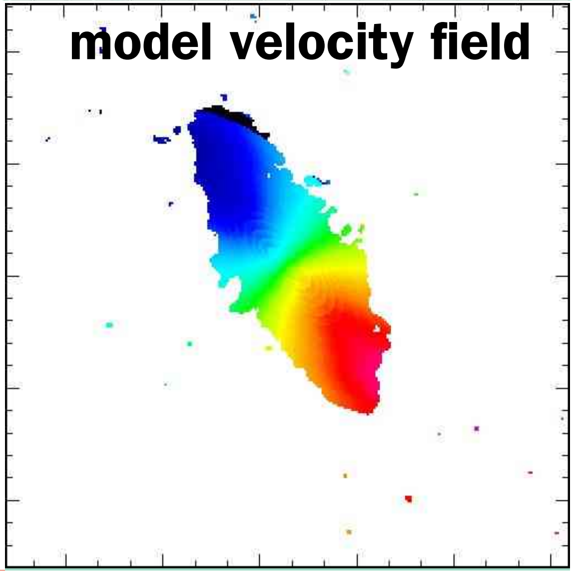
Performance test
: IC 5152 (model velocity fields)



Performance test
: ESO 154 g23 (~5 beams)







— Derived in manual using rotcur program

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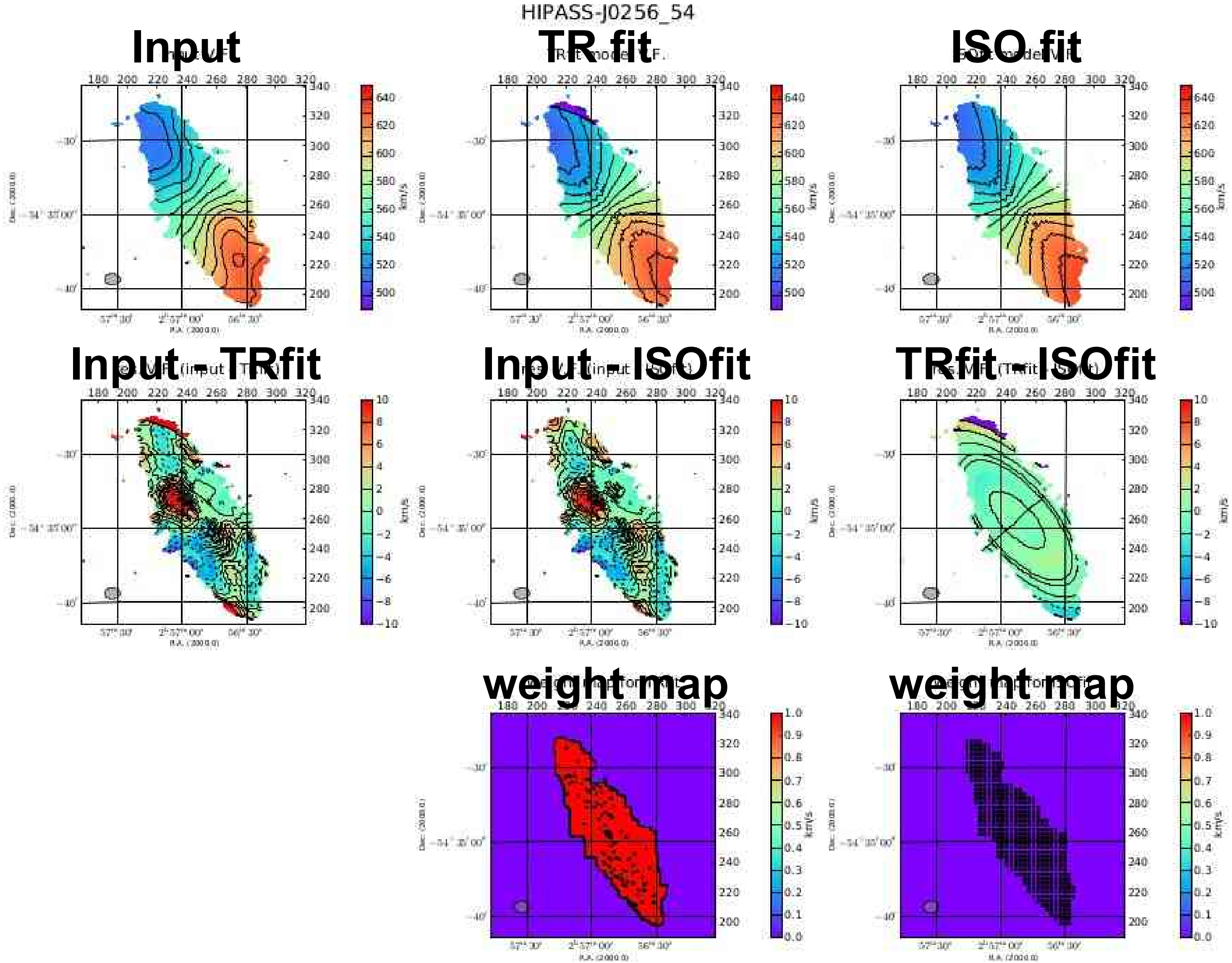
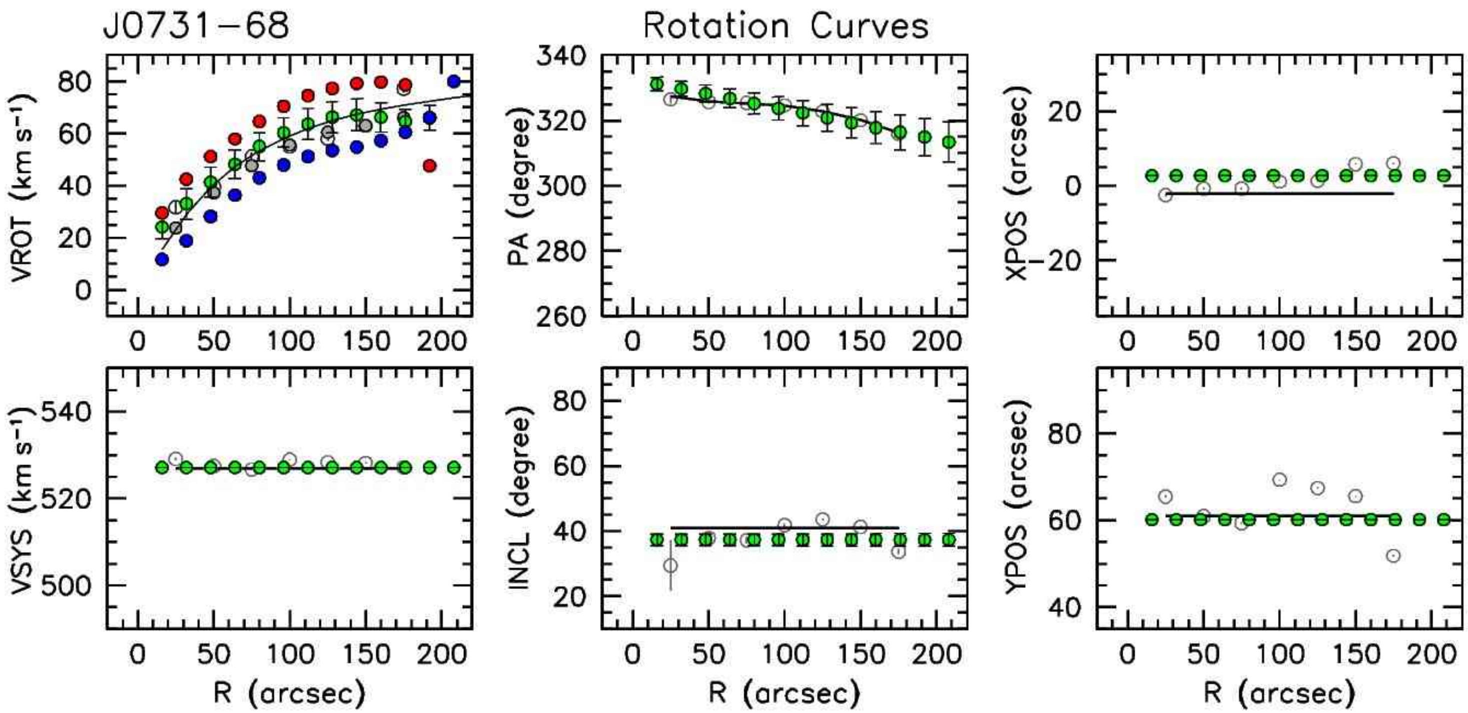
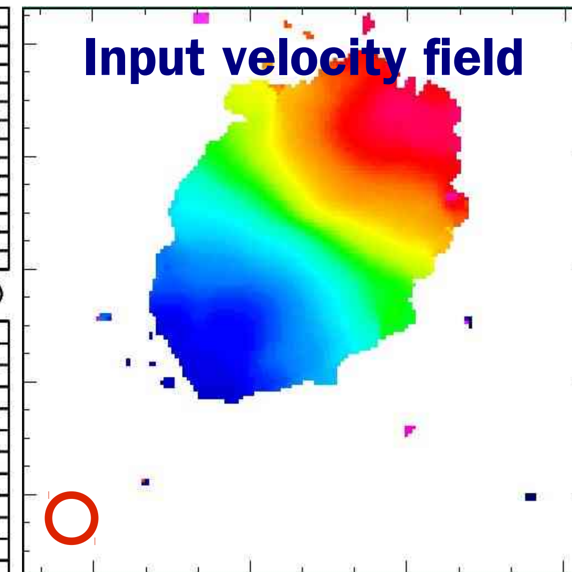
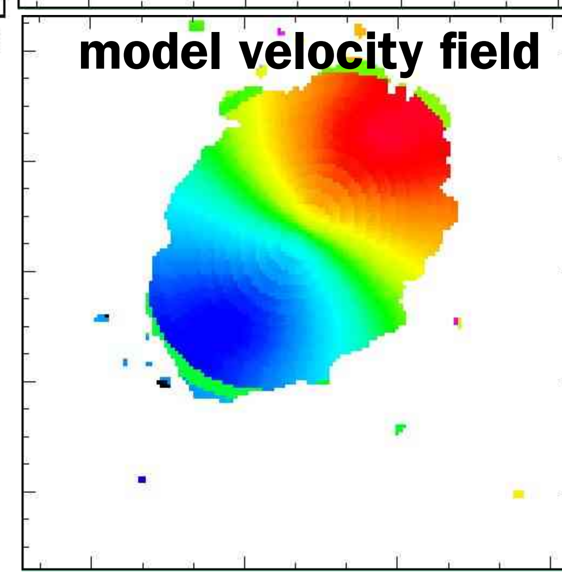
Performance test
: ESO 154 g23 (model velocity fields)



Performance test
: HIPASS-J0731-68 (~ 4 beams)



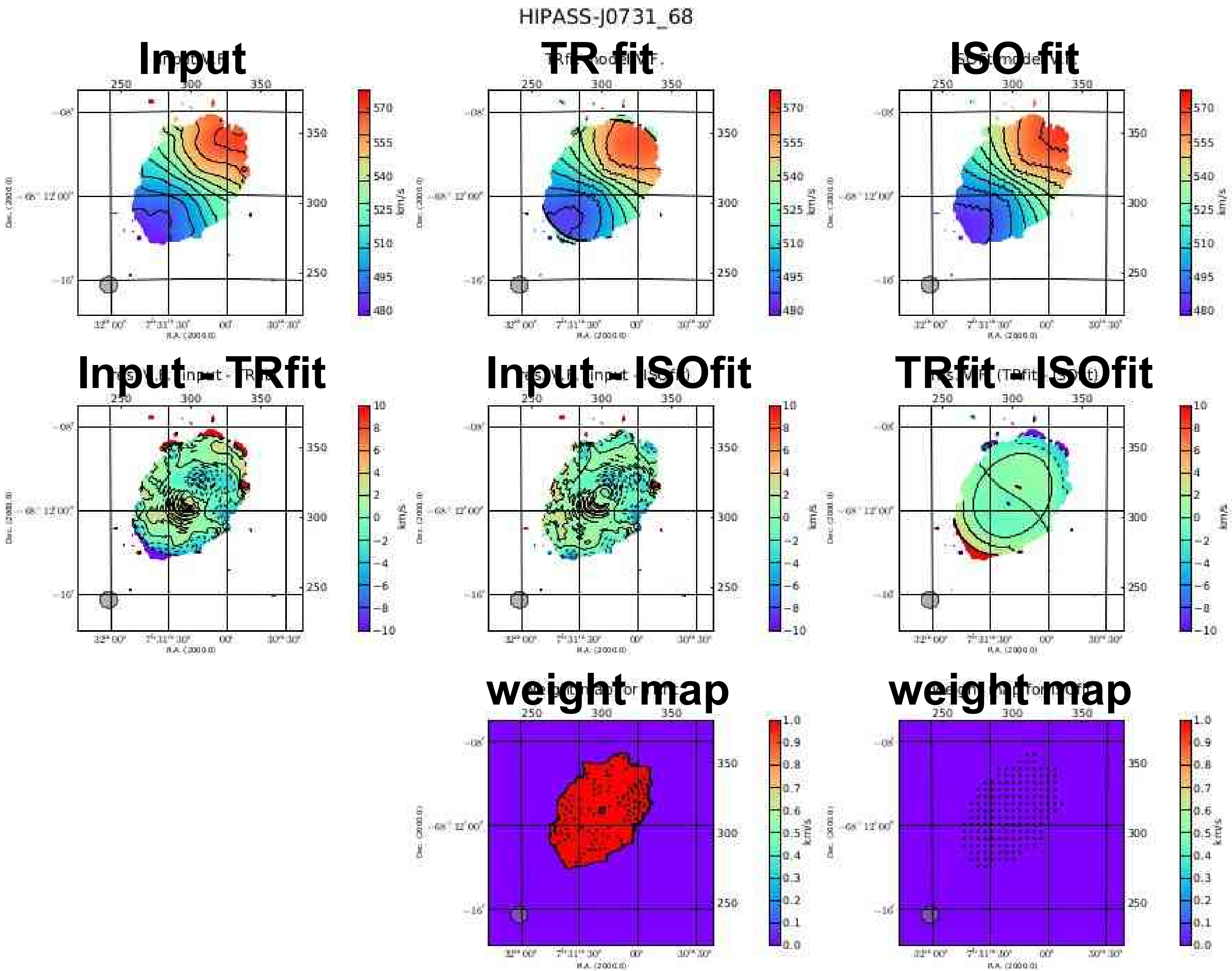




— Derived in manual using rotcur program

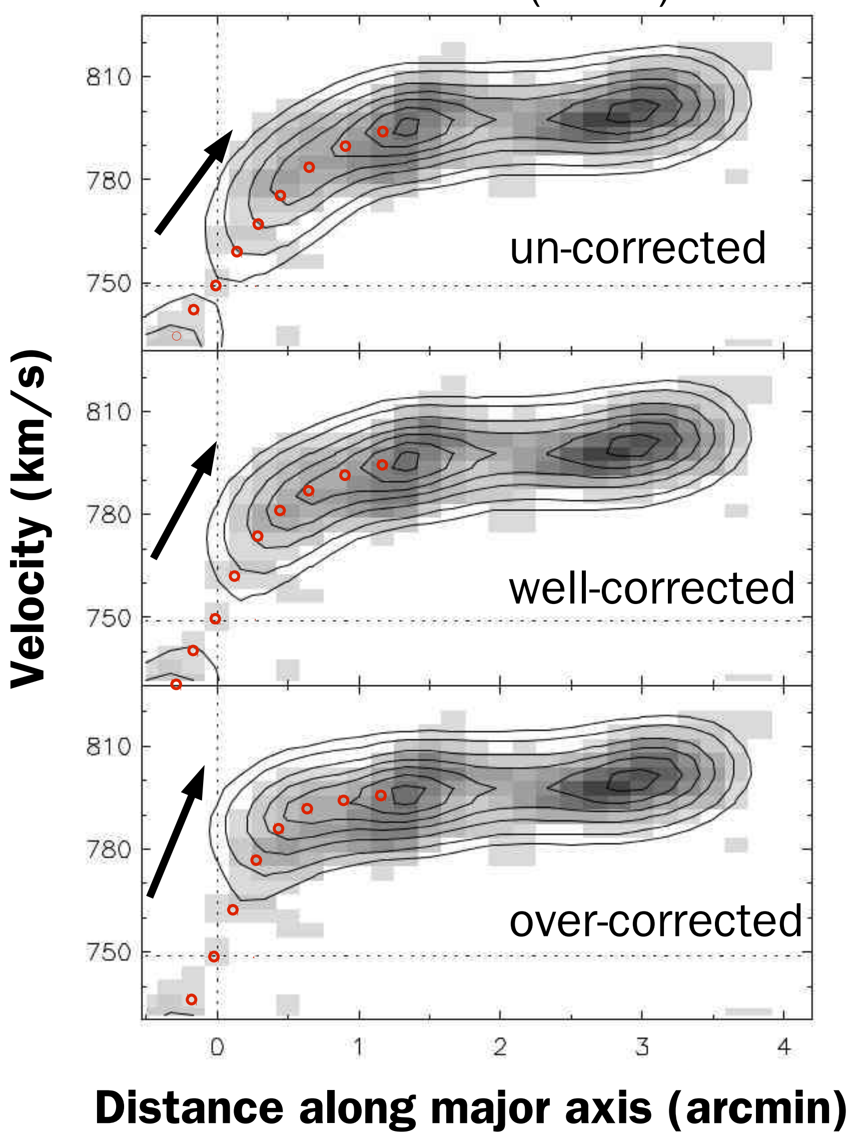
● Derived using the new program

Performance test
: HIPASS-J0731-68 (model velocity fields)



Correcting for beam smearing effect

Swaters et al. (2009)



Construct a model cube using the derived ring params (VROT+ΔV)

Calculate x^2 values of residual cubes between models and the observation

Find the optimal ΔV(R) minimising the x^2 value

- **Time consuming work**
  - manual adjustment of ΔV (e.g., galmod)
  - regularised x^2 minimisation (e.g., TiRiFiC)
  - → Bayesian search for ΔV?

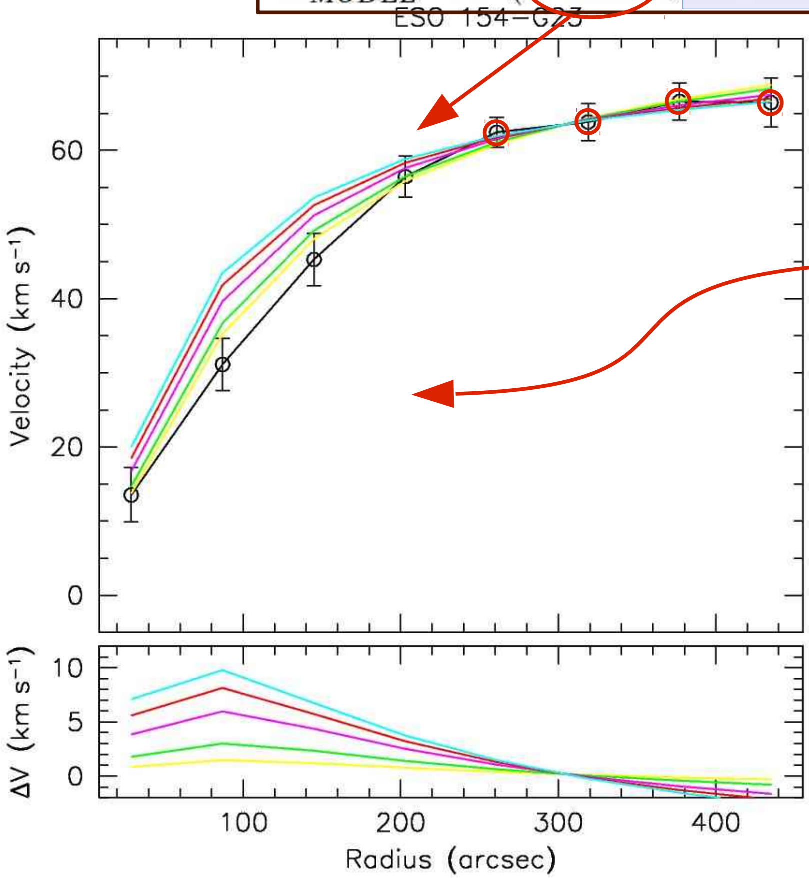
Bayesian search for beam smearing correction (work in progress...)

Log likelihood **Observed cube** **Model cube**

$$\log \mathcal{L} = \frac{-M}{2} \log 2\pi - \sum_{i=0}^{NAX1} \sum_{j=0}^{NAX2} \sum_{k=0}^{NAX3} \log \sigma_{i,j,k} - \frac{1}{2} \sum_{i=0}^{NAX1} \sum_{j=0}^{NAX2} \sum_{k=0}^{NAX3} \left[\frac{F_{OBS}(i,j,k) - F_{MODEL}(i,j,k)}{\sigma_{i,j,k}} \right]^2$$

$$F_{MODEL} = F(VROT, XPOS, YPOS, VSYS, VEXP, PA, INCL, VDISP, DENS, z0)$$

(from 2D tilted-ring model) (from mom0 & mom2)



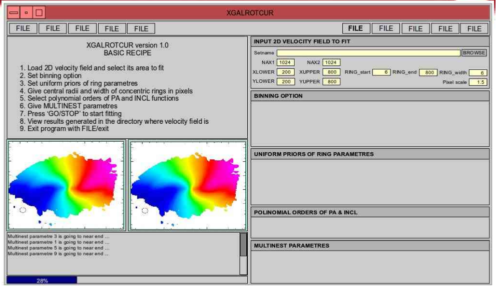
$$V_{ISO}(r) = \sqrt{4\pi G \rho_0 r_c^2 [1 - \frac{r_c}{r} \arctan(\frac{r}{r_c})]}$$

$$F_{MODEL}(r_c, \rho_0) \leftrightarrow F_{OBS}$$

→ Find the optimal ΔV [r_c, ρ_0] to provide the best matching model cube

- Work in progress: standalone galmod made; will be linked into the Bayesian platform of the main body

Summary & future direction



- **A new 2D tilted-ring fitting program** based on Bayesian MCMC developed
- Gives similar results as Se-Heon did for moderately or well resolved galaxies
- (will be) **fully automatic** for estimating initial priors, deriving rotaiton curves and visualising the results of **> 10,000 resolved galaxies from ASKAP WALLABY/DINGO + WSRT WNSHS (+ also useful for MeerKAT MHONGOOSE)**
- **Under test using sample galaxies from LVHIS(26), LITTLE THINGS(27), and THINGS(25)**

  → will include sub-routines for deriving mass models of baryons + DM halo
- Beam smearing correction will be added...
- **Also applicable to velocity fields from IFU or CO observations** (e.g., SAMI, Wifes, MANGA etc.)
- Other types of galaxy kinematic 2D or 3D models can be plugged into the platform by defining their likelihood functions (**evolution to 3D tilted-ring fits?**)
- Will be **tuned for open MPI** using a cluster machine at ICRAR, and **GUI** (with PyQT) will be provided
- **Statistical revisit of HI rotation curves** of galaxies from all available literature data (e.g., rotation curve shape, cusp/core, etc.)