CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

2D tilted-ring fitting of disk galaxies in large HI galaxy surveys

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with

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Content

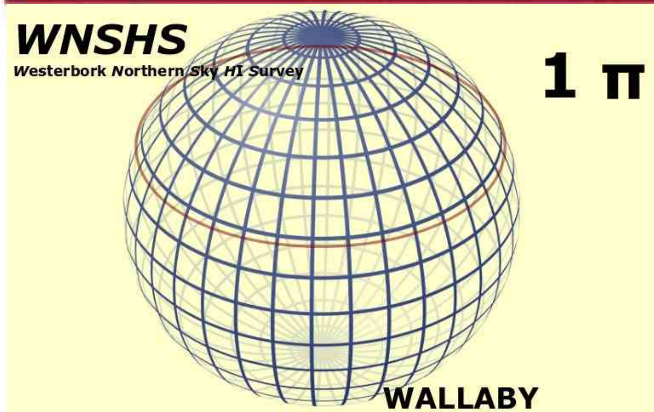
- An overview of WALLABY kinematics pipeline
- A new Bayesian MCMC 2D tilted-ring fitter
- Performance test (model & observed galaxies)
- Summary & future works

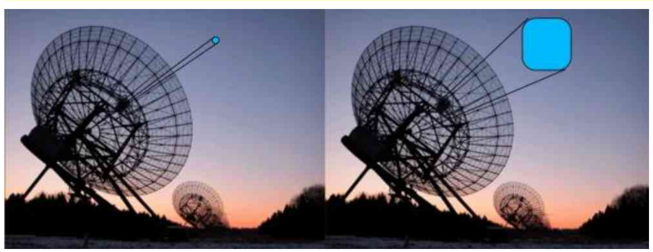
ASKAP WALLABY (Koribalski & Staveley-Smith)

- ASKAP 3π HI galaxy survey
- ~5,000 hours of ASKAP time
- ~500,000 galaxies out to z~0.26

→ ~6,000 galaxies within 200 Mpc, spatially resolved by > 6 beams (Duffy et al. 2012)

WSRT Apertif WNSHS (Gozsa et al.)





- The Westerbork Northern Sky 1π HI Survey (WNSHS) with the WSRT Apertif

- ~1400 pointings of the sky (δ > +27 deg) with 15”~30” angular resolution

- WALLABY-like channel resolution (0.1 MHz), number (16,384) and rms sensitivity (~0.6 mJy/beam)

- Redshift range of 0 ~ 0.26

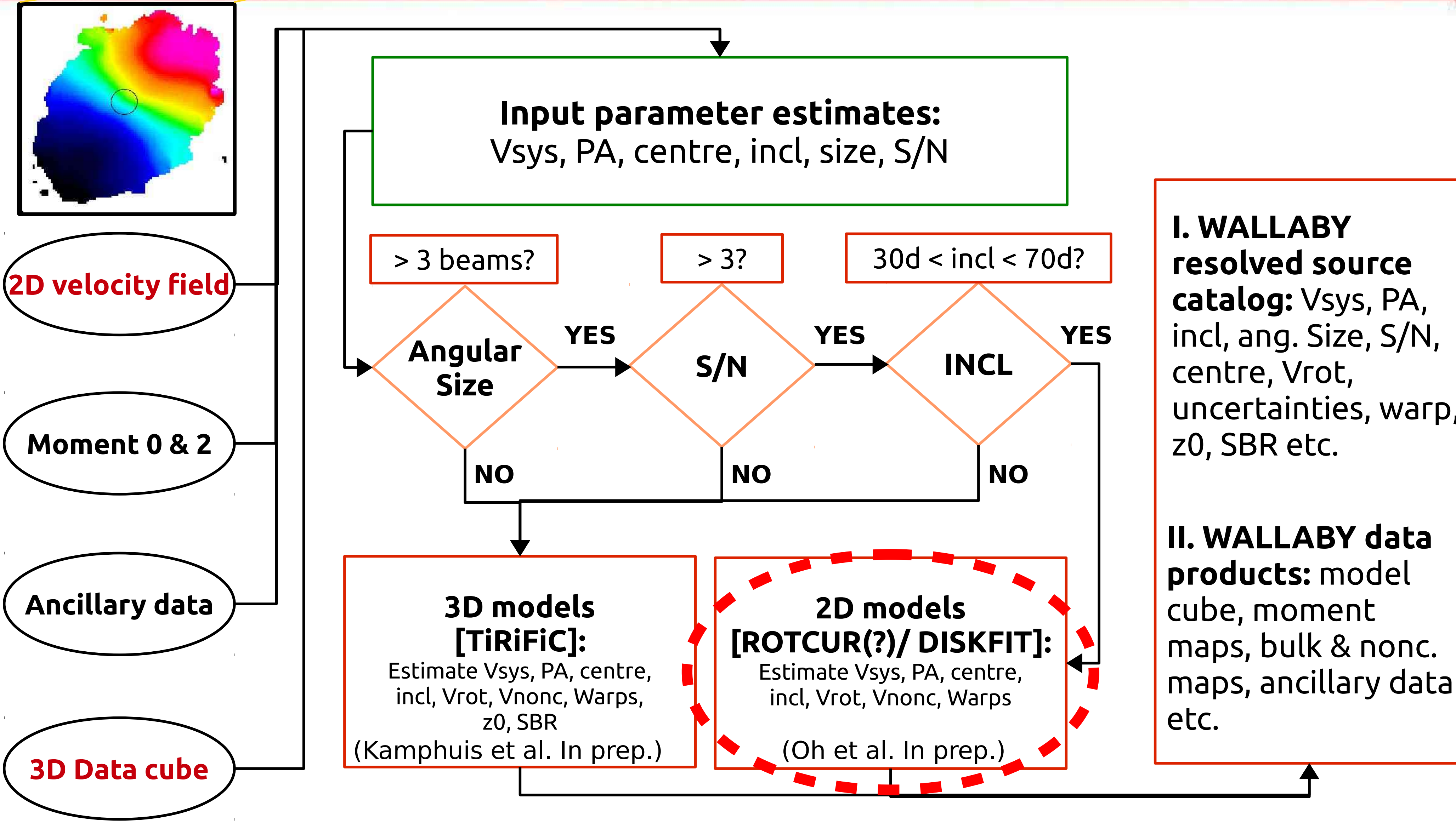
→ If combined with WALLABY, the expected number of galaxies for resolved kinematics is >13,000

: Mass distribution in galaxies, interplay between ISM and star formation on (sub-) kpc scales, dynamical morphology and structure (bars, warps, spiral arms, tidal interaction etc.), angular momentum etc.

→ How to do source characterisation and parameterisation?

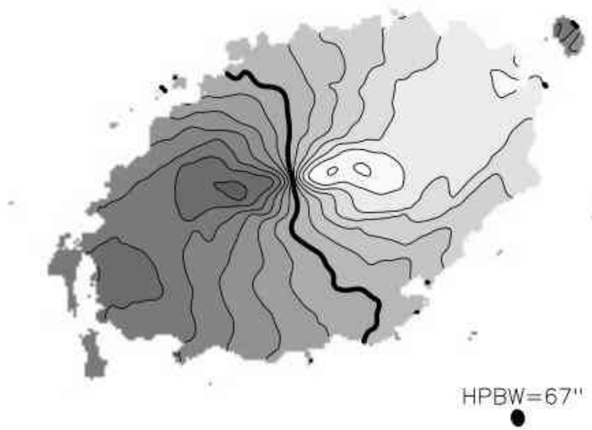
Automated kinematic parameterisation

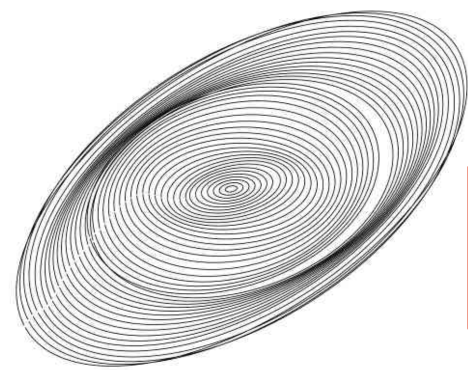
ASKAP WALLABY/DINGO (~6,000) + WSRT WNSHS (~7,000)



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

↓

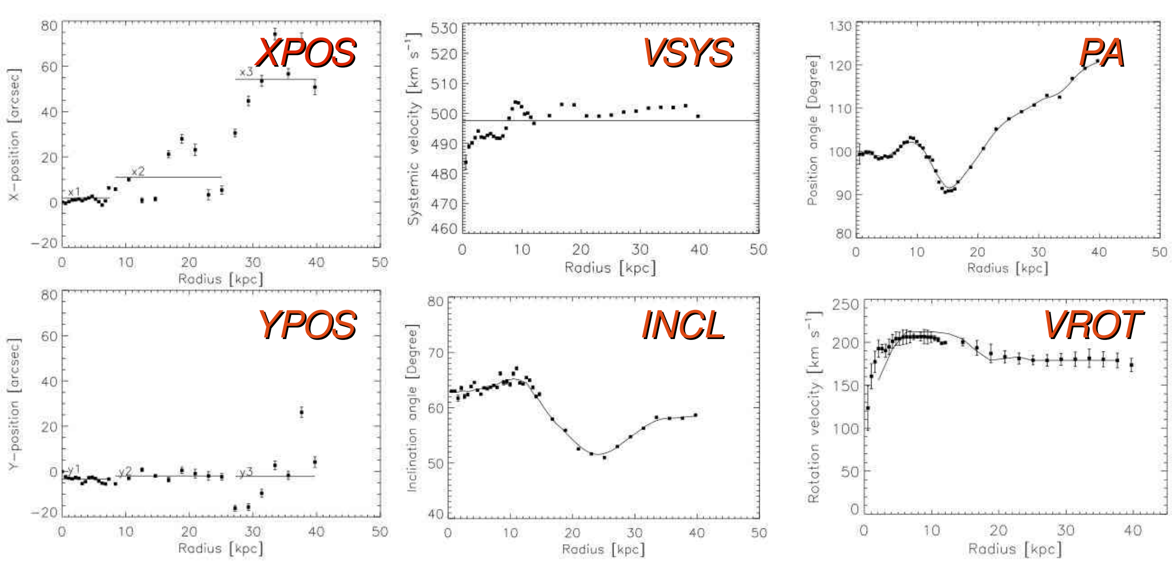
Free: XPOS, YPOS, VROT
Fixed: VSYS, VEXP, PA, INCL

↓

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

↓

Derive the final rotation curve



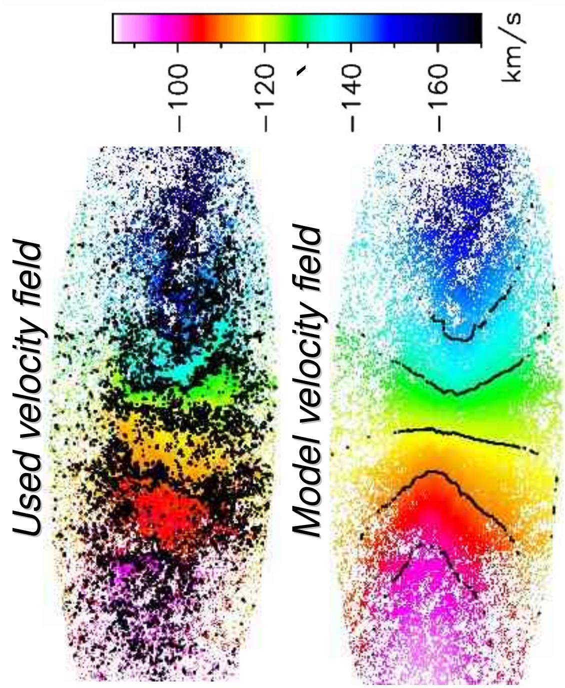
Galaxy Radius *Galaxy Radius* *Galaxy Radius*

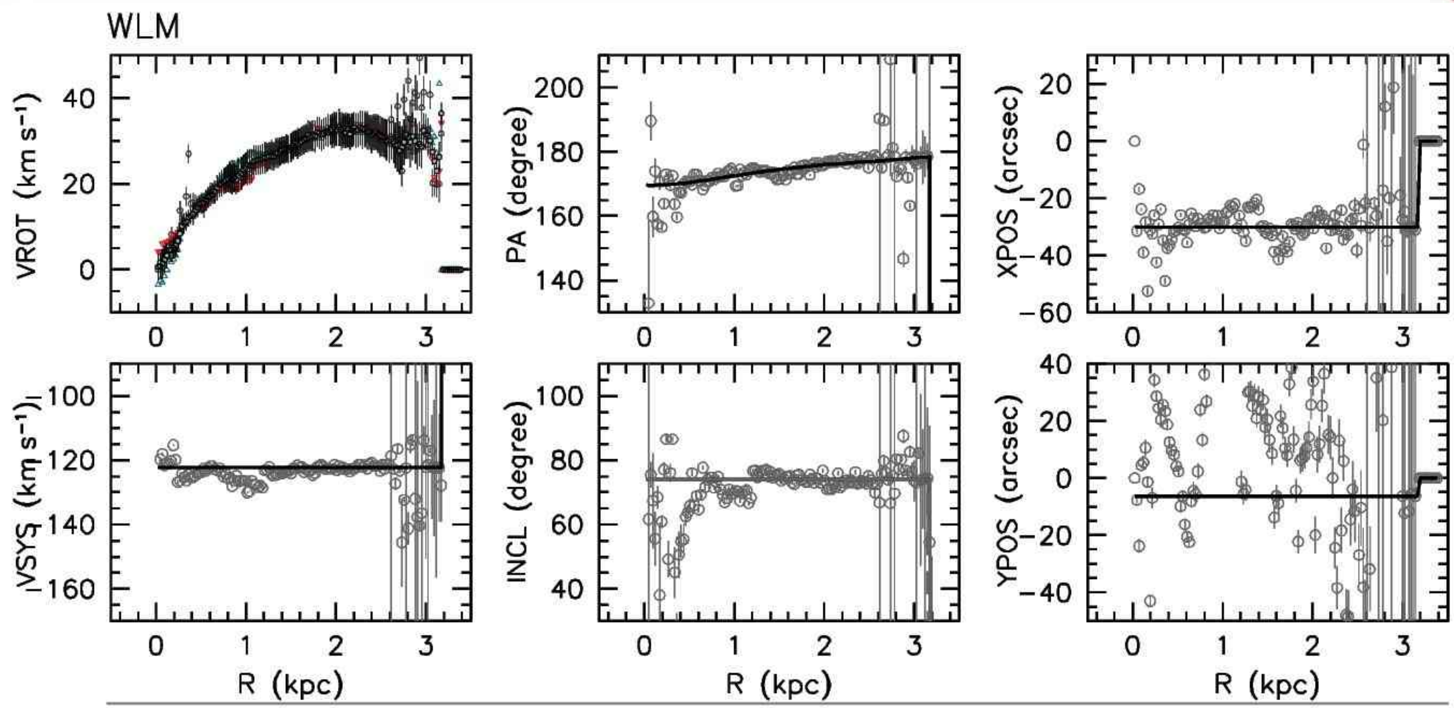
$$V_{\rm obs}(x,y) = V_{\rm sys}(x,y) + \sin i \{V_t(x,y)\cos\theta + V_r(x,y)\sin\theta\}$$

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

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

Some issues on 2D tlted-ring fits





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

→ ***difficult to make the fit automated***

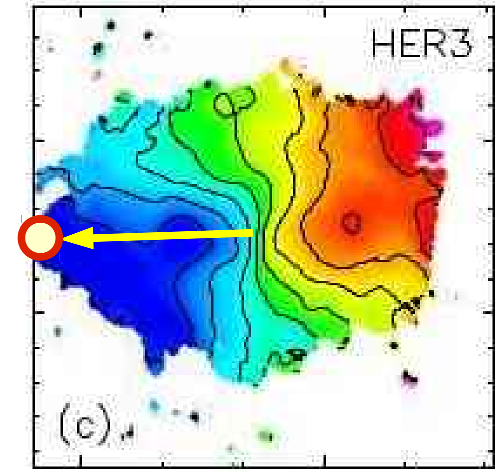
→ Why don't we fitting a 2D model to the velocity field at one time rather than dividing it into tilted-rings?

2D tilted-ring model

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

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

r(x,y)



: If PA and INCL vary with galaxy radius (not constant), the galaxy radius can be derived in an iterative way by solving the above equation with given functional forms of *PA(r)* and *INCL(r)*

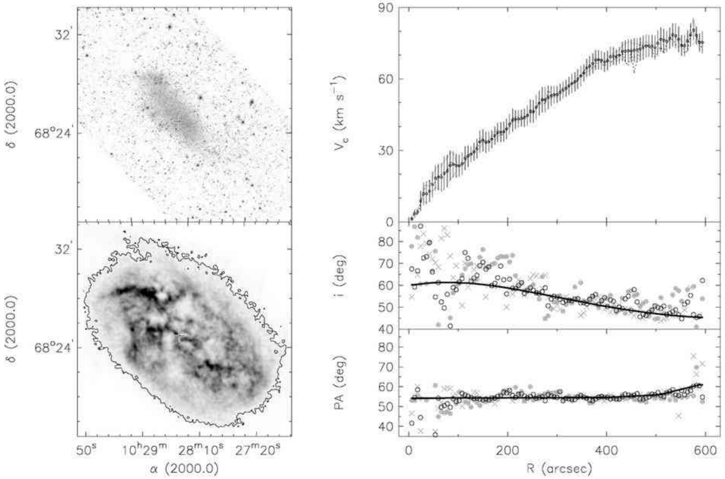
Kinematic position angle

- Kinematic PA often varies with galaxy radius due to dynamical structures in galaxies (e.g., lopsideness, bar-like potential, spiral arms, non-circular motions etc.)

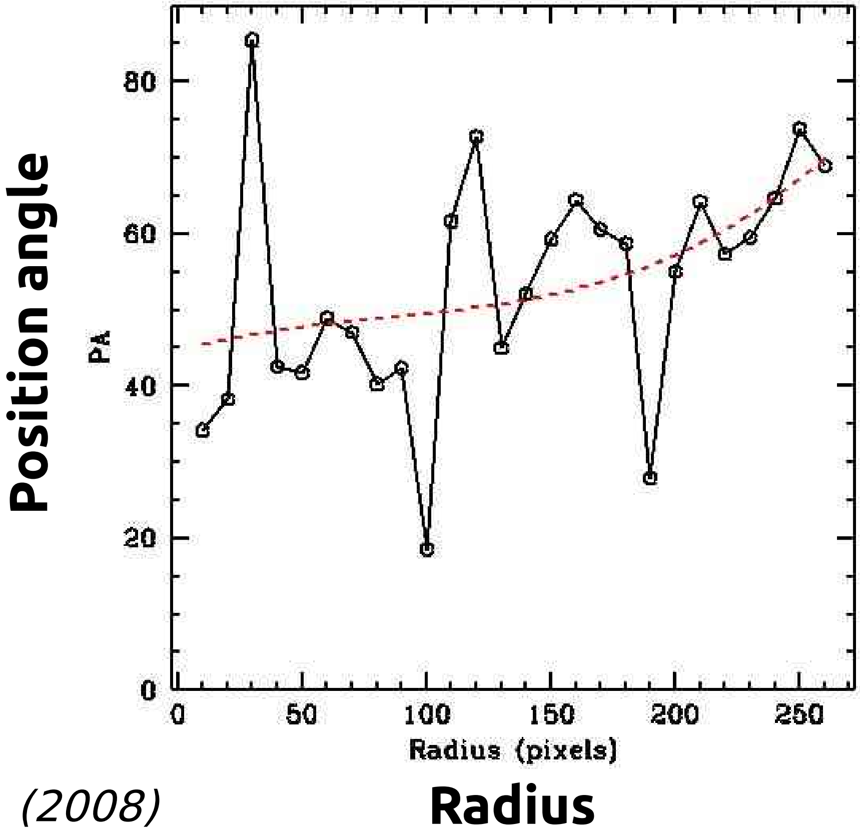
- Kinematic PA can be modelled by polynomials or Fourier series

$$PA(r) = \sum_{n=0}^{m} p_n r^n$$

$$PA(r) = \sum_{n=0}^{m} [a_n \cos(nwr) + b_n \sin(nwr)]$$



de Blok et al. (2008)

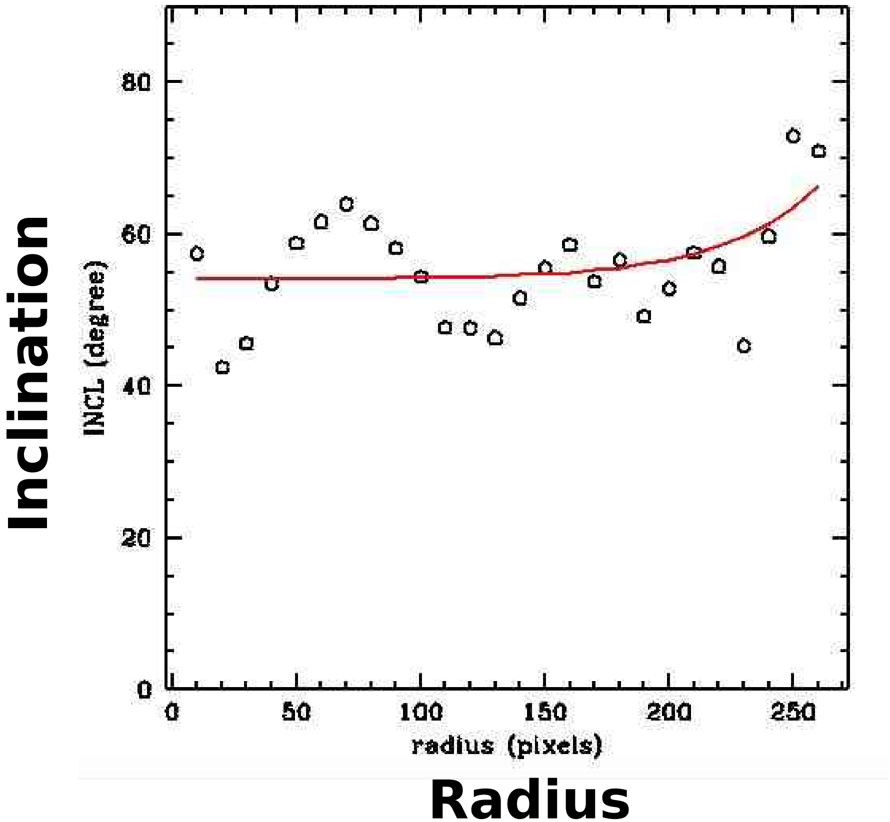


Kinematic inclination

- Kinematic INCL often varies with galaxy radius, particularly in the outer region where warps may exist
- A modified Sersic profile or Fourier series can be used for taking such radial variation into account

$$INCL(r)=\sum_{n=0}^{m} i_n r^n+\kappa \exp\left(\frac{r}{\alpha}\right)^{\beta}$$

$$INCL(r)=\sum_{n=0}^{m}\left[a_n \cos(nwr)+b_n \sin(nwr)\right]$$



2D tilted-ring model

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

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

$$PA = PA(r, a_n, b_n, w \| r, p_n)$$

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

$$INCL = INCL(r, a_n, b_n, w \| r, i_n, \kappa, \alpha, \beta)$$

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

$$\boxed{r = r(x, y, XPOS, YPOS, PA(a_n, b_n, w \| p_n), INCL(a_n, b_n, w \| i_n, \kappa, \alpha, \beta))}$$

→ Solve this non-linear equation and derive the galaxy radius, r in the galaxy plane with given kinematic center (XPOS, YPOS), PA and INCL at sky coordinates (x, y) (e.g., Newton-Rapson method etc.)

2D tilted-ring model

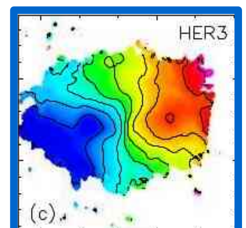
$$V_{MODEL}(x,y)=V_{SYS}(x,y)+V_{ROT}(r)\times\cos\theta\sin I+Vexp(r)\times\sin\theta\sin I$$

$$r=r(x,y,XPOS,YPOS,PA(a_n,b_n,w\|p_n),INCL(a_n,b_n,w\|i_n,\kappa,\alpha,\beta))$$

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

(e.g., Pseudo-isothermal halo model rotation curve)

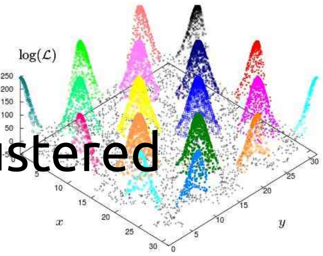
$$\boxed{V_{model}=V(XPOS,YPOS,VSYS,VEXP,\overbrace{PA(a_n,b_n,w\|p_n)}^{PA},\overbrace{INCL(a_n,b_n,w\|i_n,\kappa,\alpha,\beta)}^{INCL},\overbrace{V_{rot}(r_c,\rho_0)}^{VROT})}$$



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

Likelihood

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 degeneracy 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

- Successfully 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 fitting based on Bayesian MCMC

  - MultiNest v3.7, CFITSIO, GNU & standard ANSI C libraries

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

  - less sensitive to initial estimates and good error estimation

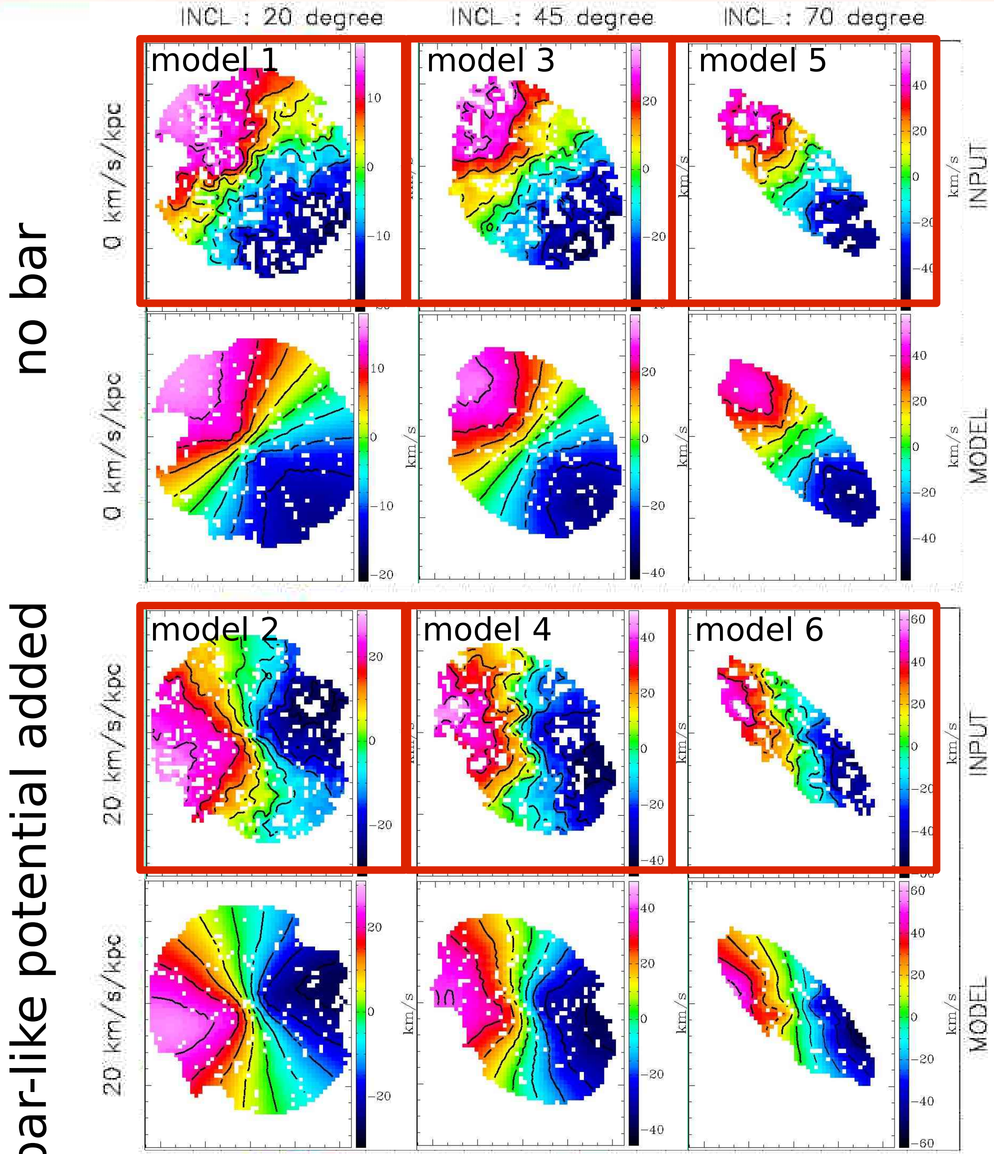
  - several builtin rotation curve shape functions (e.g., pseudo-isothermal, Burkert, polynomial rotation curves etc.)

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

  → Massage Passing Interface (MPI) for parallel computing

Performance test

I. model velocity fields

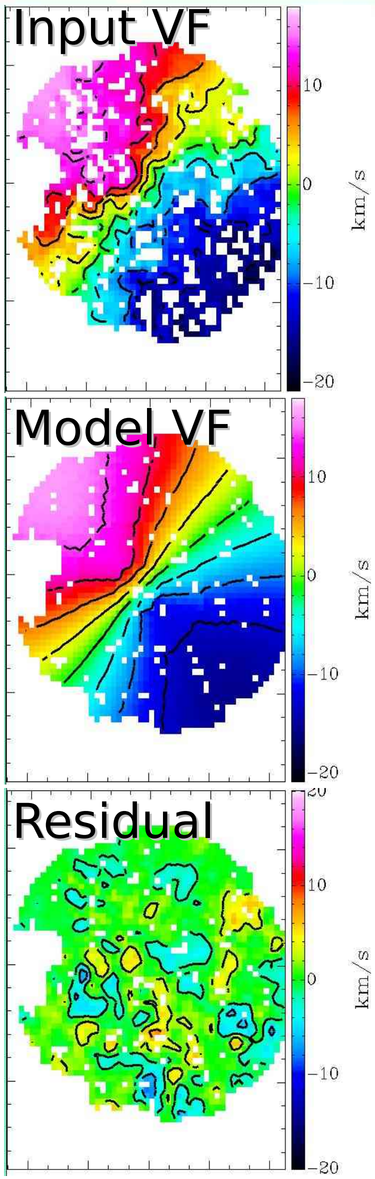


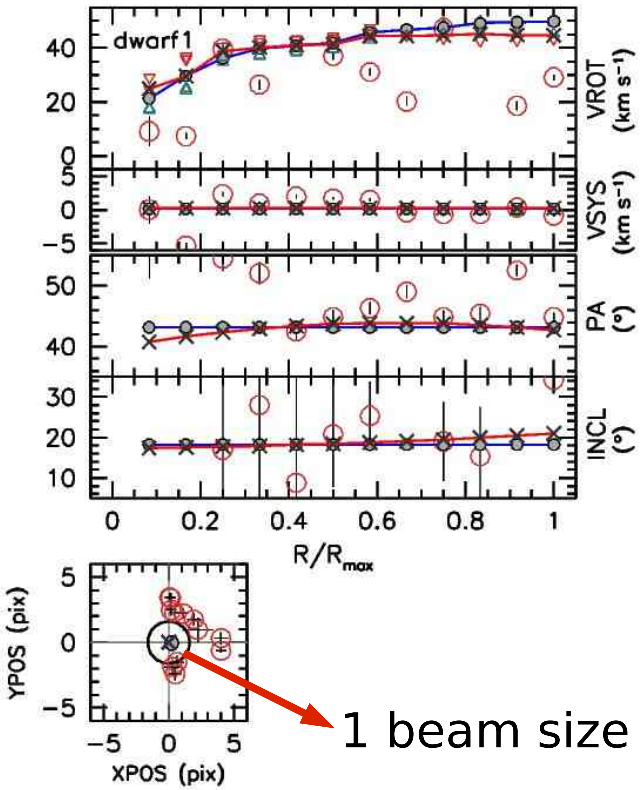
Model dwarf galaxies (ISO Halo)

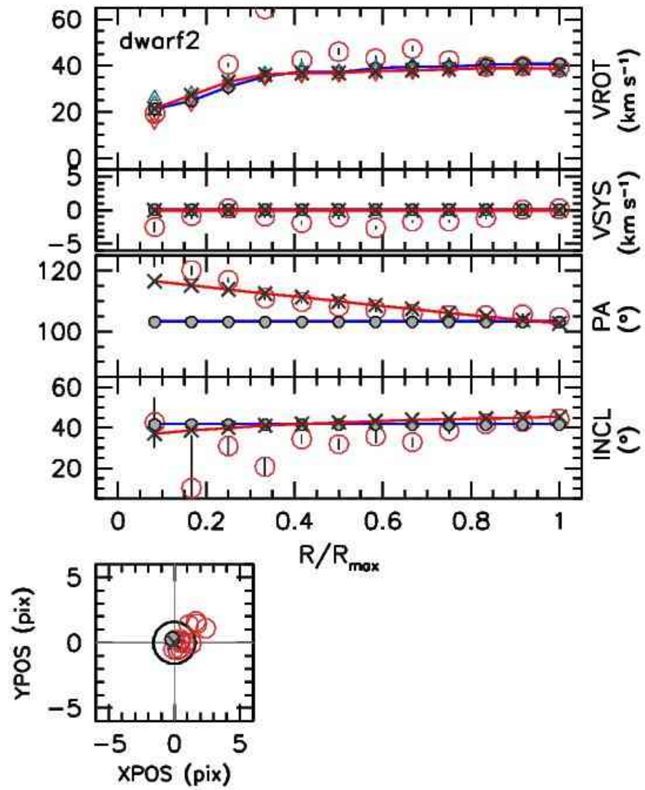
- Construct model data cubes based on galaxy properties from THINGS (e.g., HI column density, HI velocity dispersion, rotation curves etc.)
- Add small-scale random & large-scale bar-like non-circular motions
- Smooth the cubes with 24” beam
- Re-observe the cubes at 20, 45 & 70 degrees viewing angles
- Extract 2D velocity fields

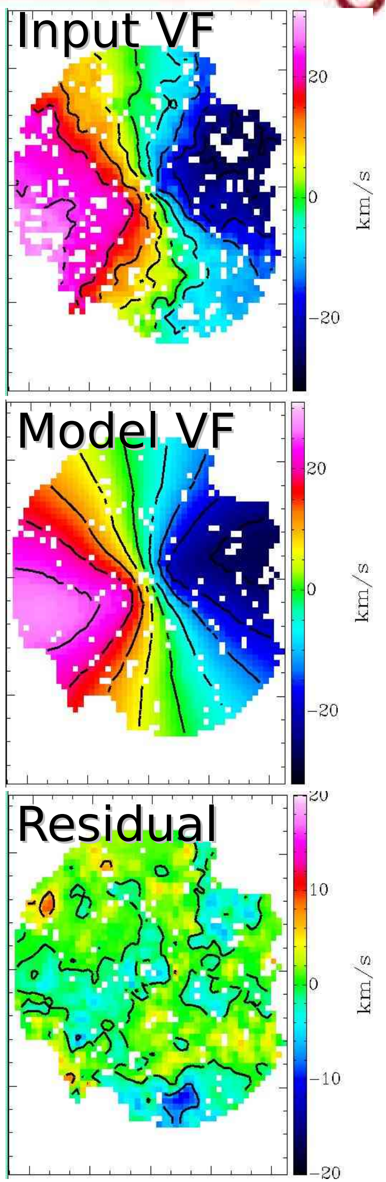
Performance test

Model 1 : 20° inclination + no bar
Model 2 : 20° inclination + bar









Oh et al. In prep.

- Fits with all ring parametres free
- Fits with constant PA & INCL
- Fits with 2^{nd} order Fourier series

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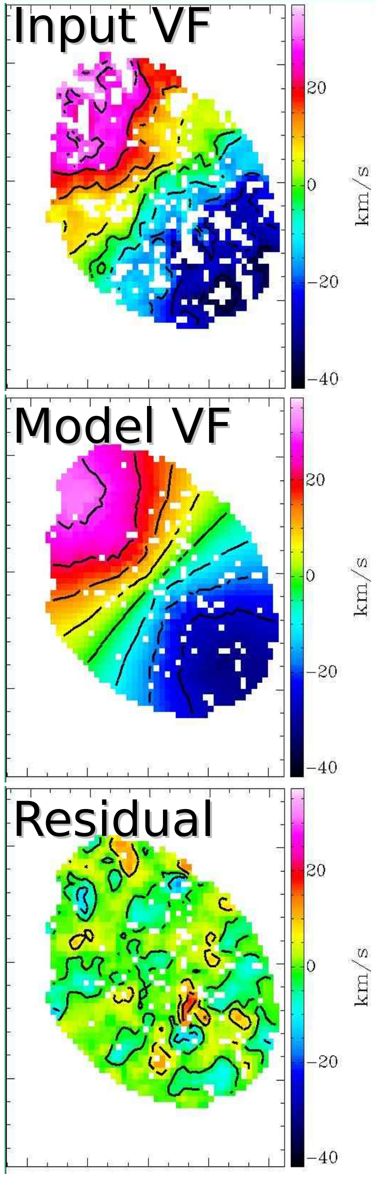
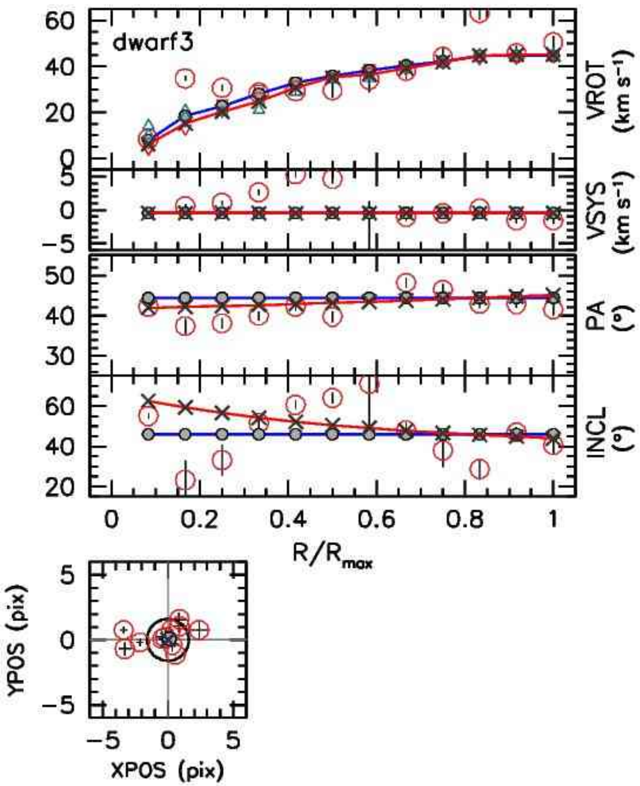
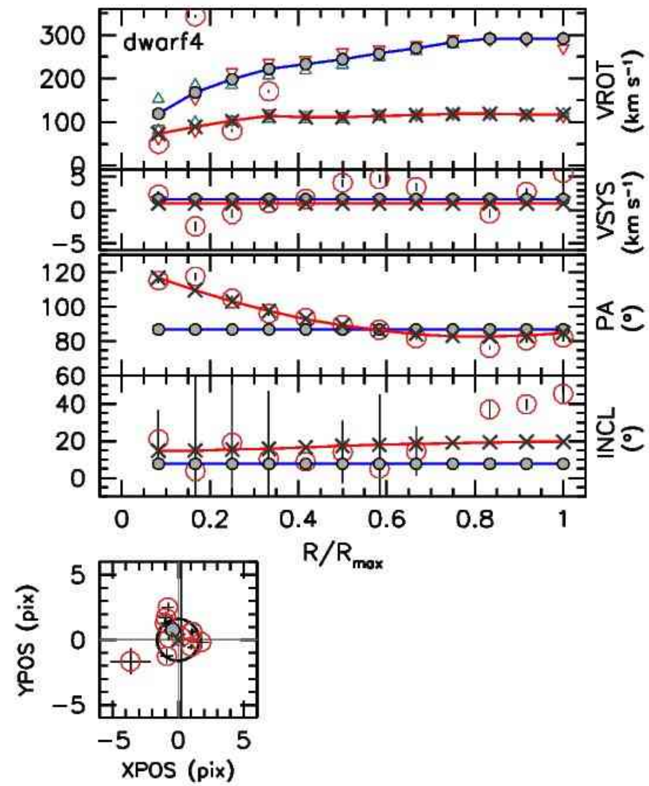
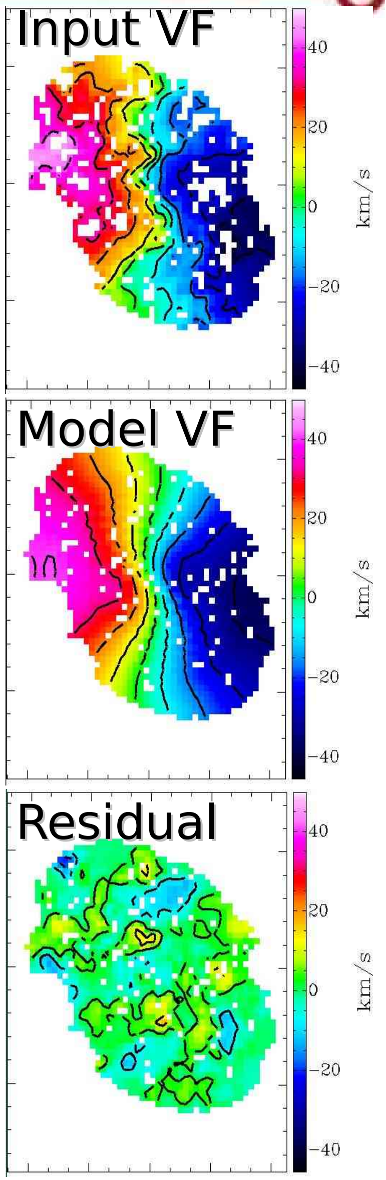
Performance test

Model 3 : 45° inclination + no bar
Model 4 : 45° inclination + bar









Oh et al. In prep.

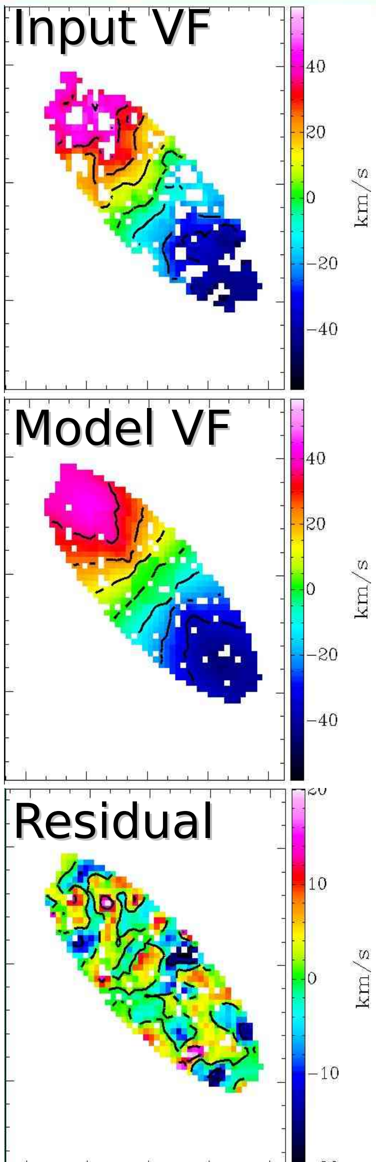
Fits with all ring parametres free

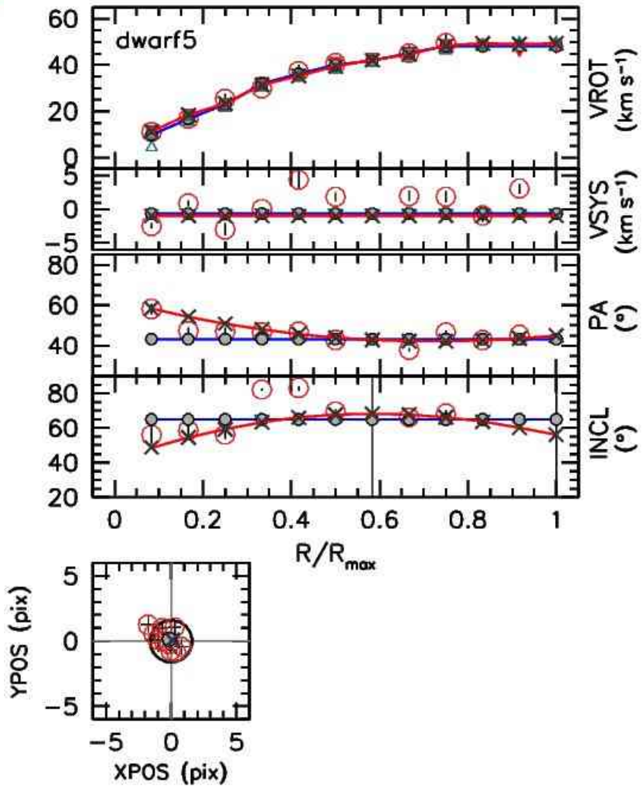
Fits with constant PA & INCL

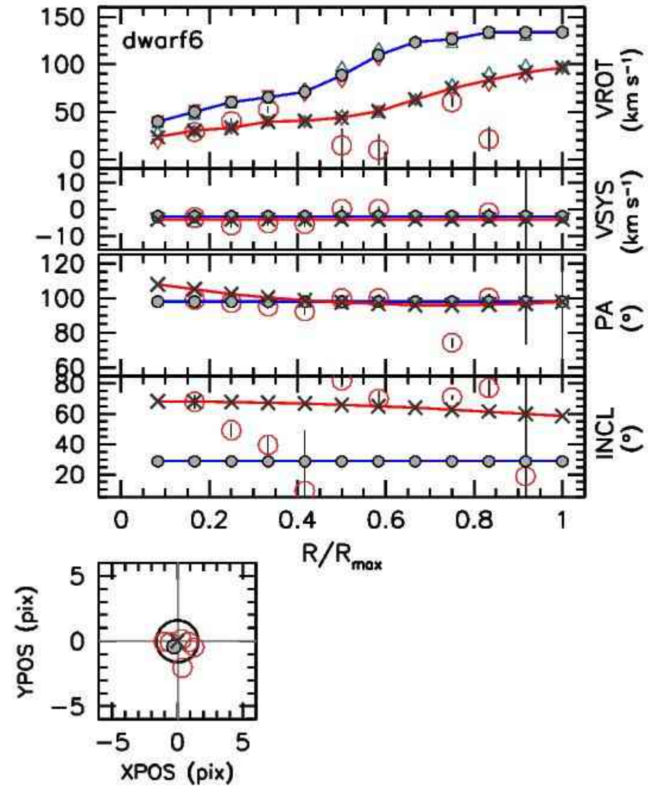
Fits with 2^{nd} order Fourier series

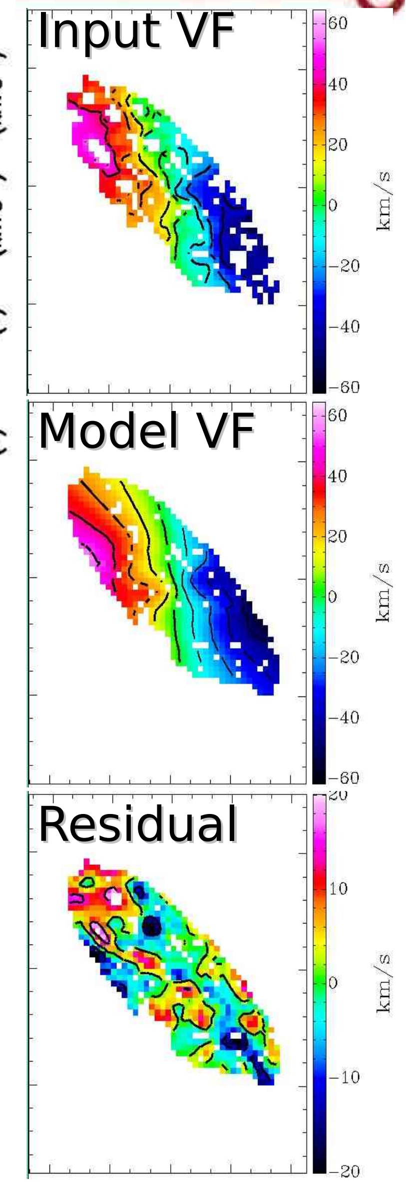
Performance test

Model 5 : 70° inclination + no bar
Model 6 : 70° inclination + bar





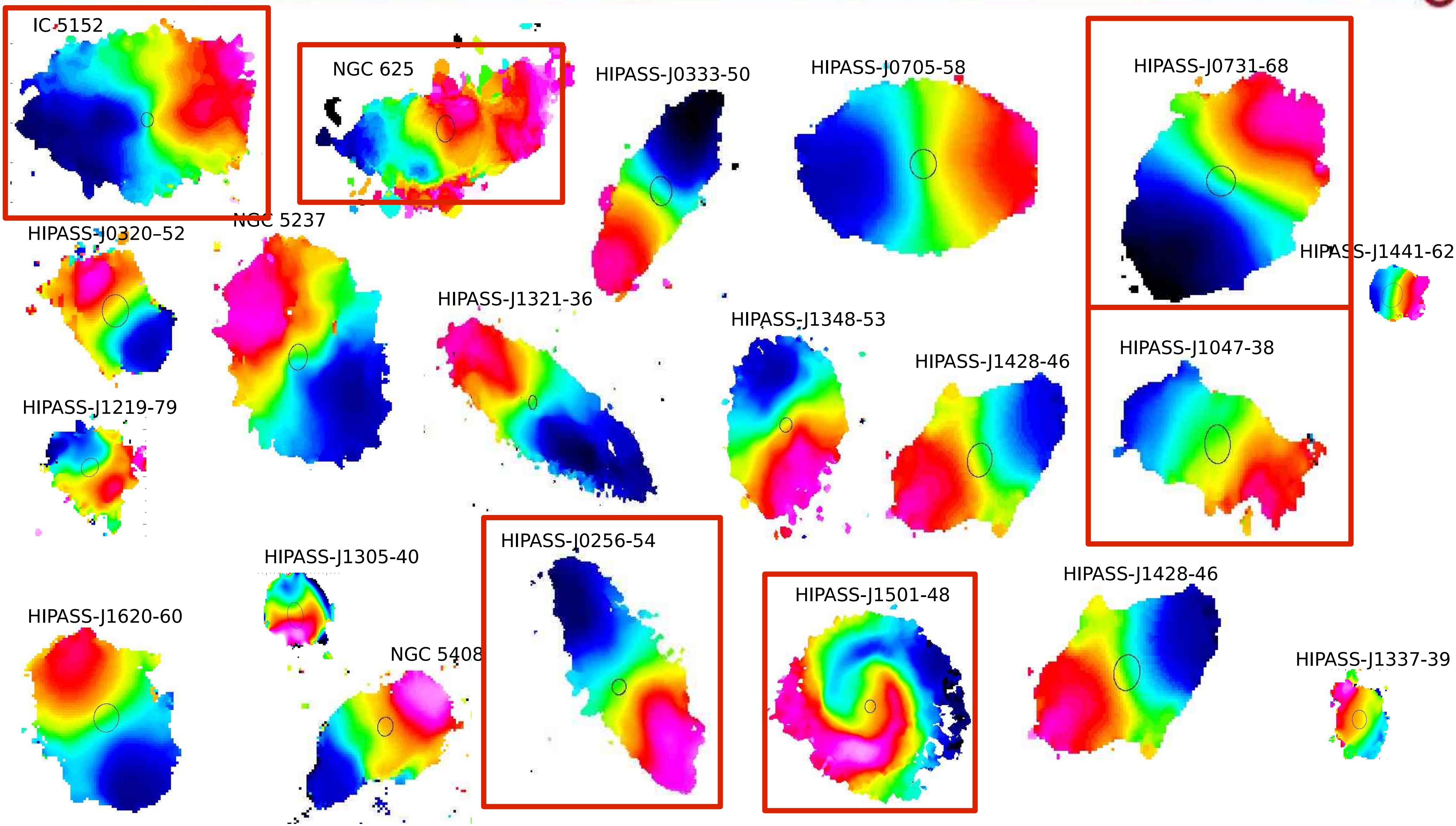




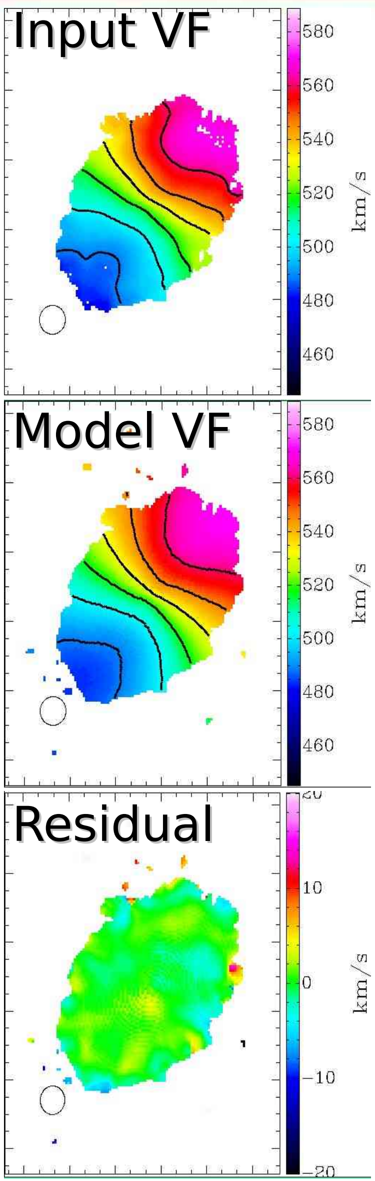
Oh et al. In prep.

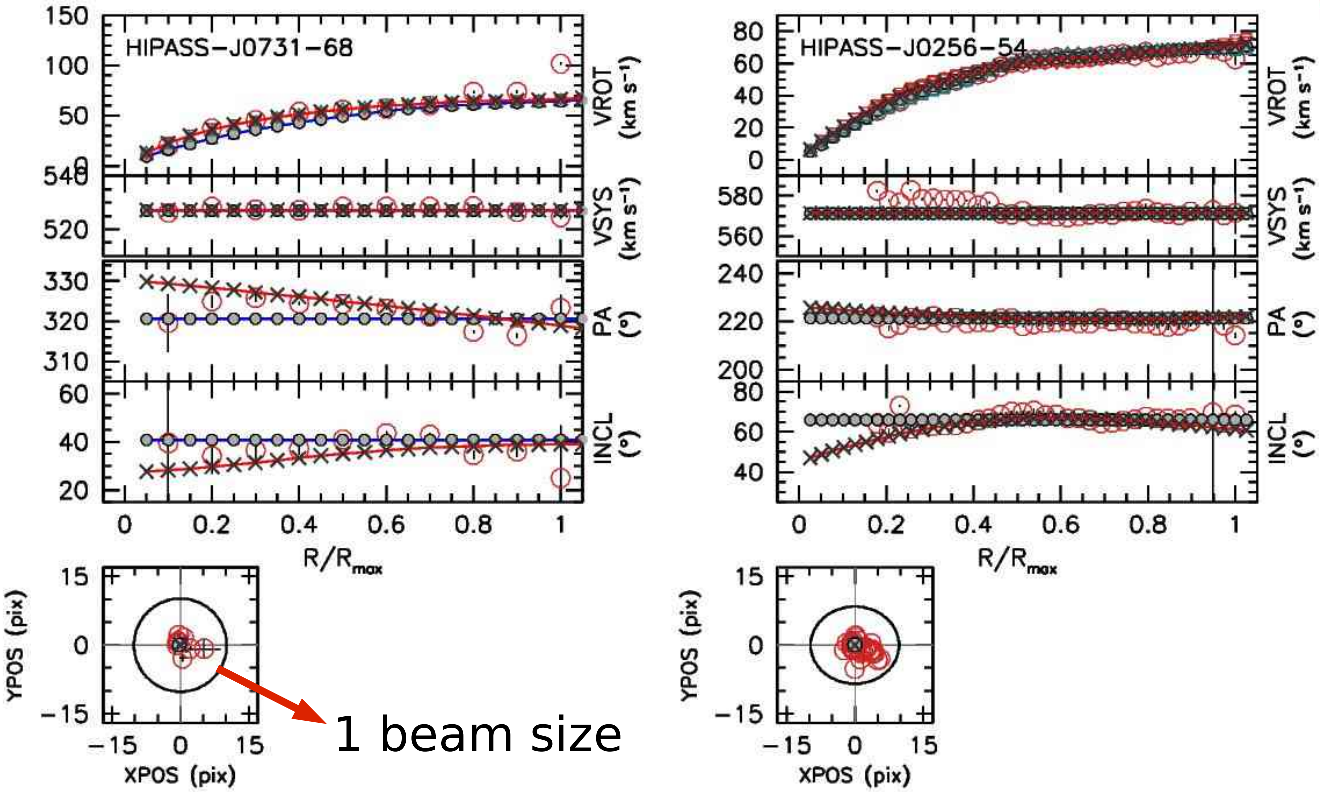
- Fits with all ring parametres free
- Fits with constant PA & INCL
- Fits with 2nd order Fourier series

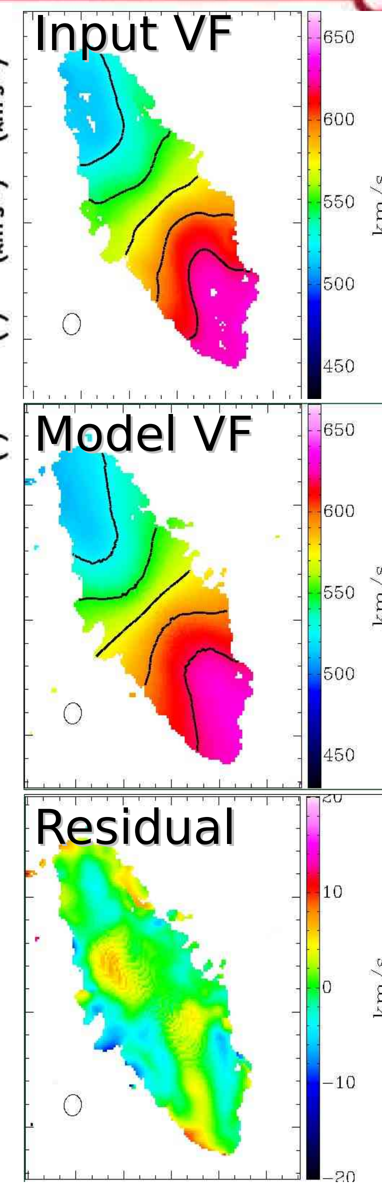
Performance test
II. Local Volume HI Survey (LVHIS; Koribalski et al.)



Performance test:
: LVHIS sample galaxies







Oh et al. In prep.

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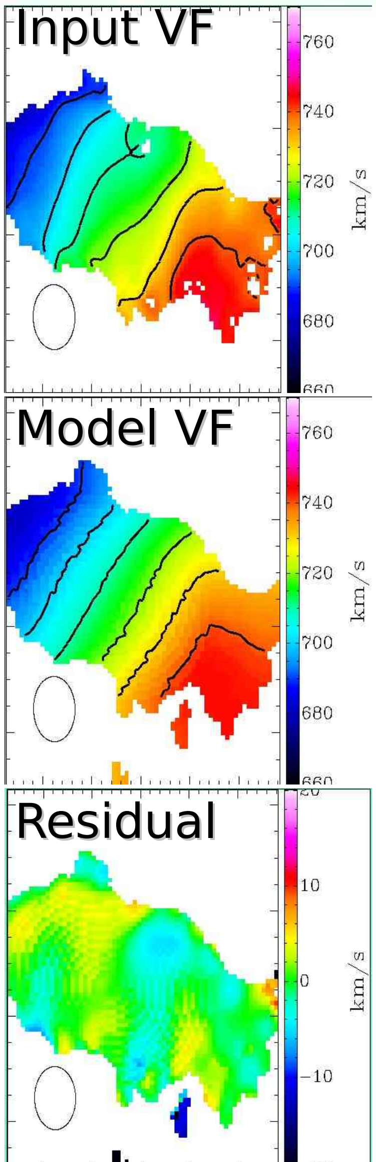
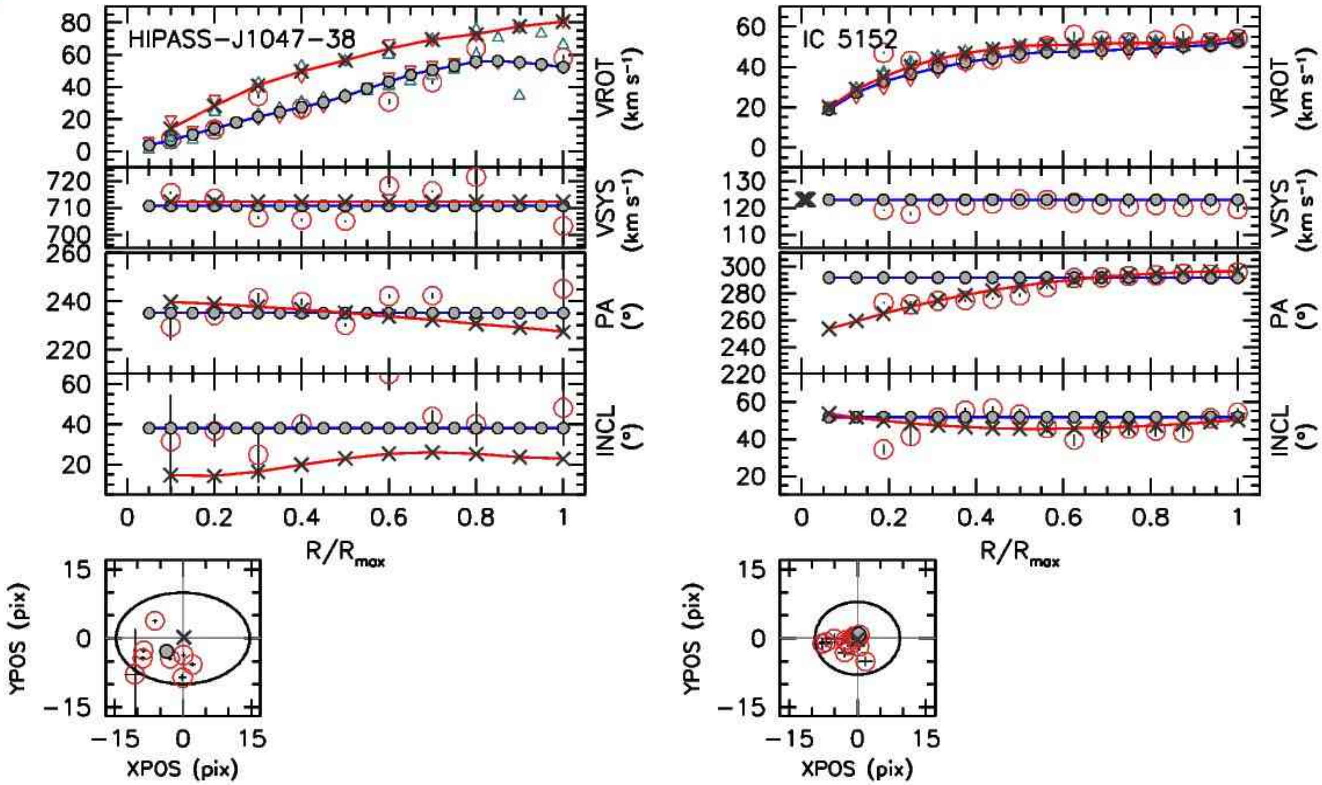
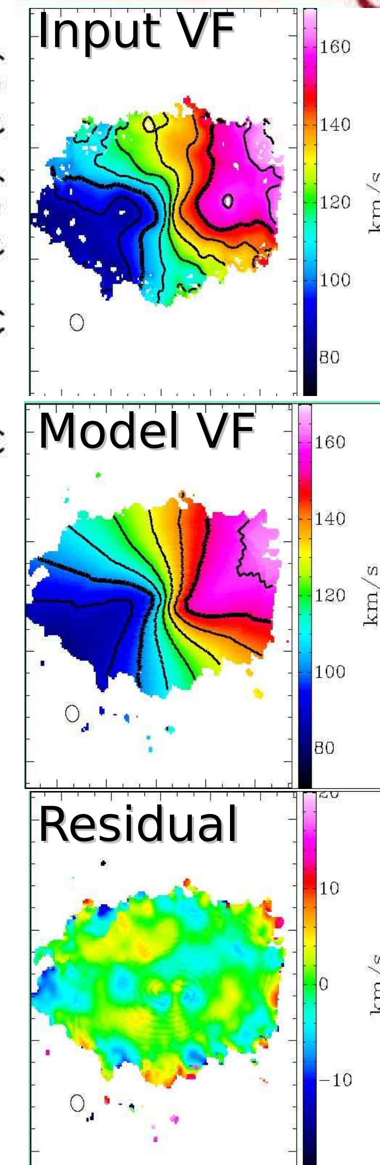
Performance test
: LVHIS sample galaxies







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Performance test
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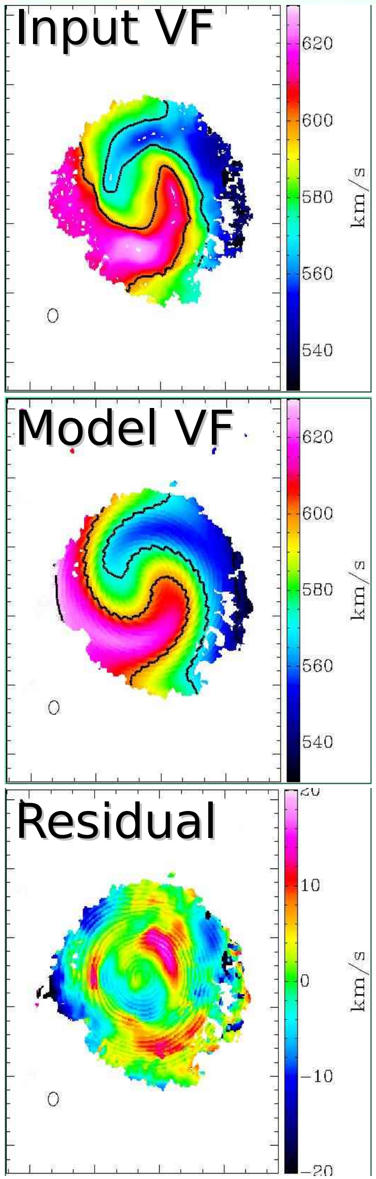

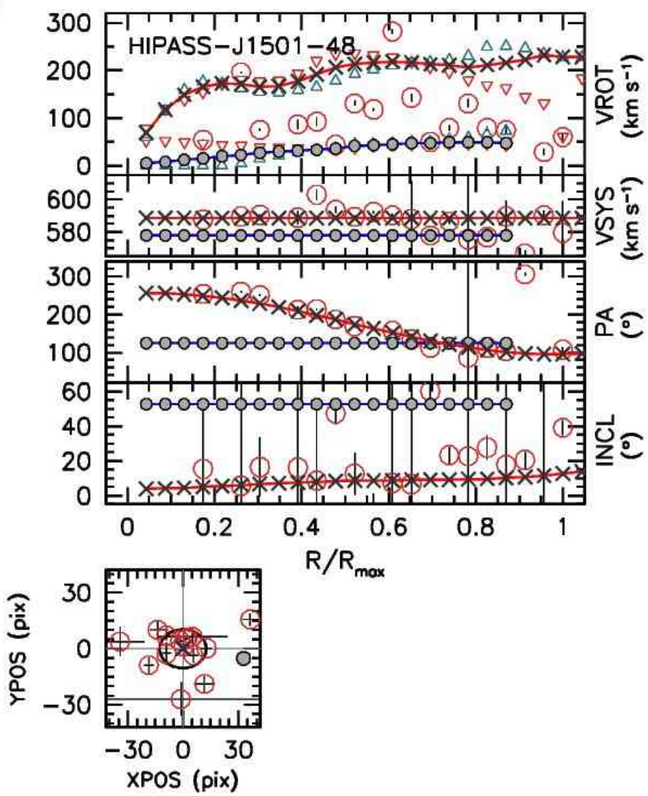

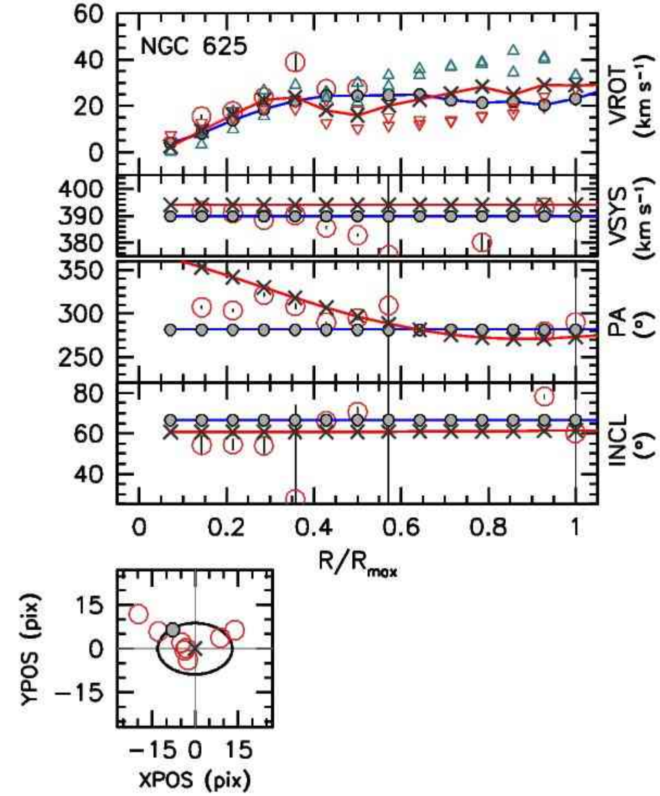

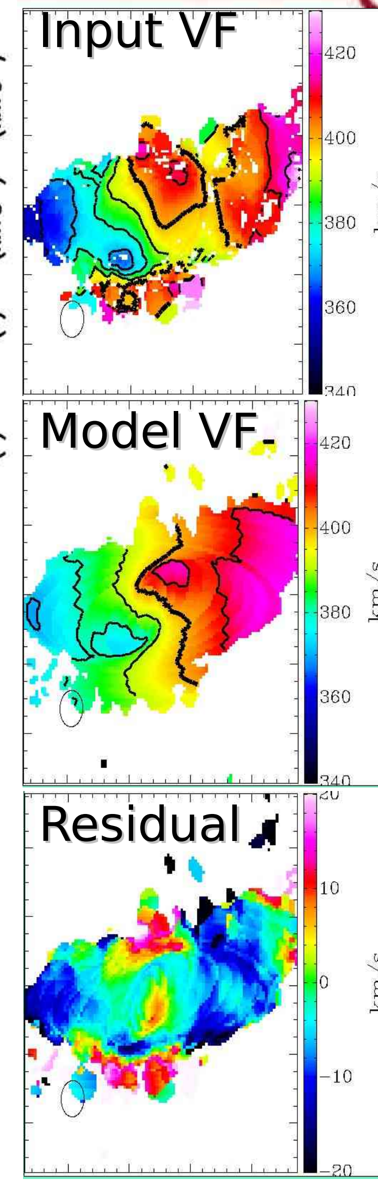

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Summary & future direction

- **A new 2D tilted-ring fitting algorithm** based on Bayesian MCMC developed
- **A standalone C program employing MultiNest** (a Bayesian inference tool) developed:

  - fully automated: broadly defined ranges of priors of t parameters are only required for a given 2D velocity field; provide good fit results comparable to those derived using standard tilted-ring fitting code even without exhaustive manual iterations
  - MPI supported: written in MPI for the parallel implementation of MultiNest either on a multi-core single (tested) or a cluster system (will be tested using Pleiades, a cluster machine at ICRAR)

- **Successfully tested using WALLABY-like 13 LVHIS sample galaxies as well as numerous model velocity fields (extended test using THINGS + LITTLE THINGS sample galaxies)**
- (Will) estimate optimal initial priors, derive rotation curves and visualise the results of **> 10,000 resolved galaxies from ASKAP WALLABY/DINGO + WSRT WNSHS (+ also useful for MeerKAT MHONGOOSE)**
- **Also applicable to velocity fields from IFU observations** (e.g., SAMI, MANGA etc.)
- Implications: e.g., **statistical revisit of HI rotation curve** of galaxies from all available literature data (rotation curve shape, cusp/core, etc.)
- Will be publicly available after the internal release to team members (stay tuned...)