Resolved kinematics of galaxies from Australia SKA Pathfinder (ASKAP) WALLABY

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+ ASKAP WALLABY kinematics working group

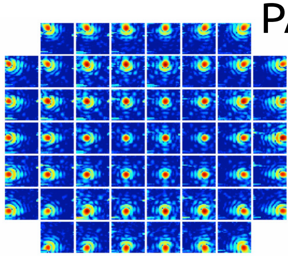
'<u>Resolved</u>' kinematic analysis for galaxies (from HI surveys)

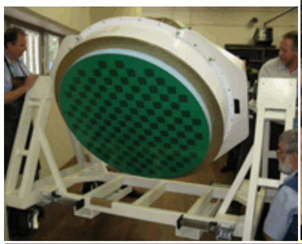
1970s	• **25** spiral galaxies from **WSRT observations** (Bosma 1978)
1990s	• **21** spirals in the center of Virgo Cluster from **VLA observations** (Guhathakurta & van Gorkom 1988) • **25** late-type and dwarf galaxies from **WSRT WHISP** (Swaters 1999) • **30** spirals in the Ursa Major Cluster from **WSRT observations** (Verheijen 1997)
2010s	• **21** late-type and dwarf galaxies from **VLA THINGS** (de Blok et al. 2008; Oh et al. 2008) • **52** dwarf galaxies from **GMRT FIGGS** (Begum et al. 2008) • **33** dwarf galaxies from **VLA THINGS + LITTLE THINGS** (Oh et al. 2011; Oh et al. 2015) • **24** spirals from **WSRT HALOGAS** (Heald et al. 2011) • **26** late-type and dwarf galaxies from **ATCA LVHIS** (Kamphuis et al. 2015; Oh et al. 2018) • **35** dwarf galaxies from **VLA-ANGST** (Ott et al. 2012) • **12** dwarf galaxies from **VLA SHIELD** (McNichols et al. 2016) • **300 SAMI galaxies** from **GMRT follow-up observations** (Kamphuis et al.) • **28** sprial galaxies from **ATCA IMAGINE** (Popping et al.)
2020s onwards	• > **10,000** *resolved* galaxies from **SKA pathfinders' surveys** (ASKAP, MeerKAT & Apertif)

→ need to prepare for the unprecedented data flow from the upcoming 3D spectroscopic galaxy surveys including SKA pathfinders' large surveys

ASKAP large survey proposals

PAF (radio camera)

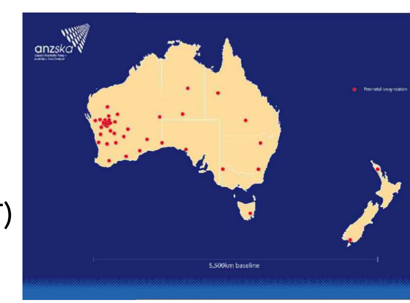




- 12m x 36 dishes, 10–30" beam (up to 6 km baseline)
- 700 MHz – 1.8 GHz (32,768 channels over 300 MHz BW)
- 188 phase array elements → 30 deg^2 FOV
- Continuum & spectral lines
- 12 Phased Array Feeds (PAFs) installed → *ASKAP-12 early science observations have been on-going since Oct/2016*

10 ASKAP Large Survey Projects

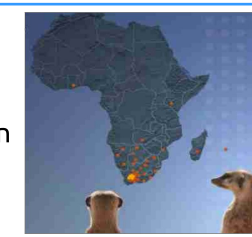
- Evolutionary Map of the Universe (EMU)
- **Widefield ASKAP L-Band Legacy All-Sky Blind Survey (WALLABY)**
- The First Large Absorption Survey in HI (FLASH)
- An ASKAP Survey for Variables and Slow Transients (VAST)
- The Galactic ASKAP Spectral Line Survey (GASKAP)
- Polarization Sky Survey of the Universe's Magnetism (POSSUM)
- The Commensal Real-time ASKAP Fast Transients survey (CRAFT)
- **Deep Investigations of Neutral Gas Origins (DINGO)**
- The High Resolution Components of ASKAP: Meeting the Long Baseline Specifications for the SKA (VLBI)
- Compact Objects with ASKAP: Surveys and Timing (COAST)



MeerKAT large survey proposals

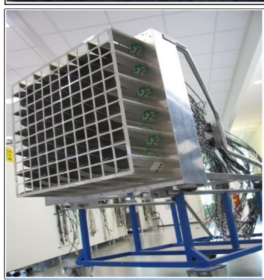
- 13.5m x 64 dishes, 8" beam over <u>1.8 deg² FOV</u>
- Antenna layout: a dense inner component (70%) + an outer component (30%) <u>over 30m to 8 km</u>
- 580 MHz – 14.5 GHz (32,768 channels over 300 MHz BW)
- Continuum & spectral lines
- *MeerKAT AR1 (16 dishes) has started its early science observation from early 2017*

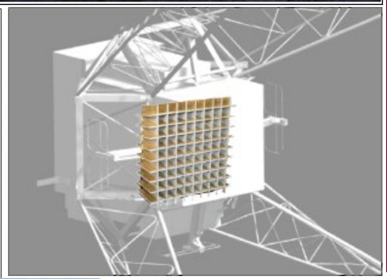
<u>10 MeerKAT Large Survey Projects</u>



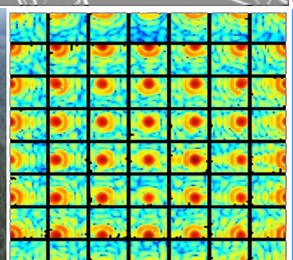
- Radio Pulsar Timing: Testing Einstein's theory of gravity and gravitational radiation
- **<u>LADUMA (Looking at the Distant Universe with the MeerKAT Array)</u>**
- MESMER (MeerKAT Search for Molecules in the Epoch of Re-ionisation)
- MeerKAT Absorption Line Survey for atomic hydrogen and OH lines in absorption against distant continuum sources
- **<u>MHONGOOSE (MeerKAT HI Observations of Nearby Galactic Objects: Observing Southern Emitters)</u>**
- TRAPUM (Transients and Pulsars with MeerKAT)
- A MeerKAT HI Survey of the Fornax Cluster (Galaxy formation and evolution in the cluster environment)
- MeerGAL (MeerKAT High Frequency Galactic Plane Survey)
- MIGHTEE (MeerKAT International GigaHertz Tiered Extragalactic Exploration Survey)
- ThunderKAT (The Hunt for Dynamic and Explosive Radio Transients with MeerKAT)

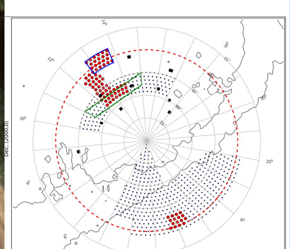
WSRT Apertif large survey proposals





- 25m x 14 dishes with Apertif : being upgraded to an HI survey telescope with FOV of ~8 deg2; ~15” beam
- 1.0 – 1.7 GHz (16,384 channels over 300 MHz)
- *Commissioning is under way*



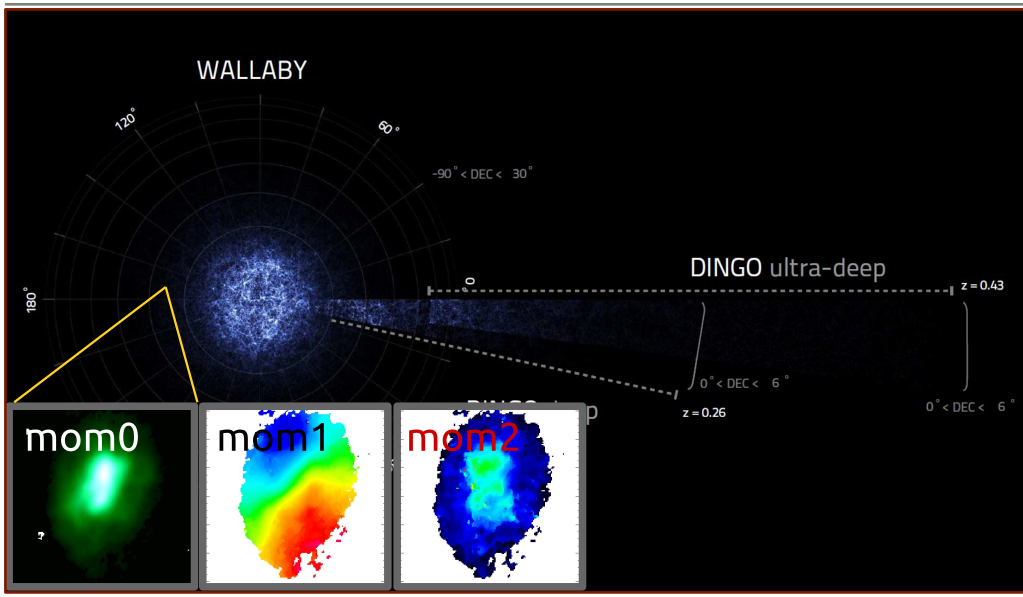


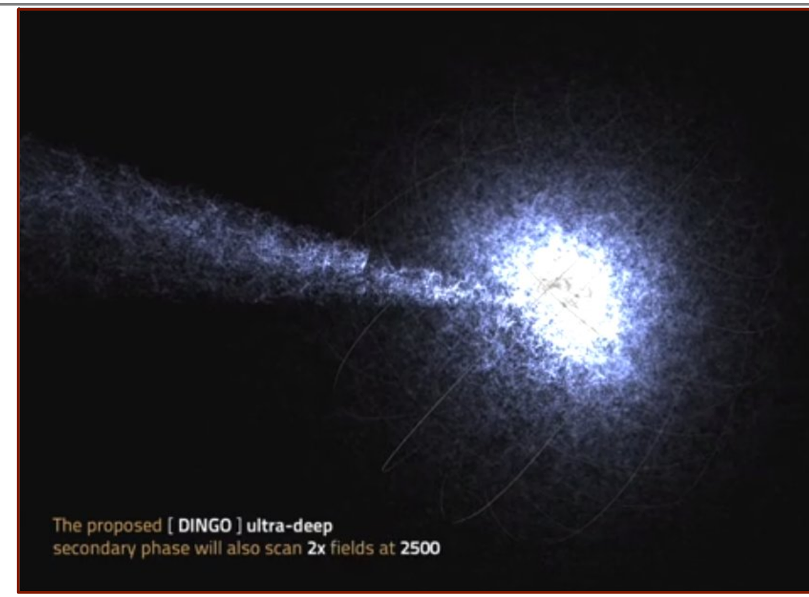
Apertif large surveys

- An HI survey telescope in northern sky comparable to ASKAP
- A large area, **shallow imaging survey** of HI and polarised radio continuum emission covering ~3500 deg^2
- A **medium-deep imaging survey** of HI and polarised radio continuum emission covering ~450 deg^2
- A time domain survey for **pulsars and fast transients** over 15,000 deg^2
- Follow-up of some LOFAR fields

ASKAP all-sky HI survey (WALLABY)

: Baerbel Koribalski (CASS/CSIRO) & Lister Staveley-Smith (ICRAR/UWA)





- ASKAP 3Π HI galaxy survey
- ~**5**,000 hours of ASKAP time
- > ~**5**00,000 galaxies out to **z~0.26** (~1 million if combined with Apertif observations)
- > ~**5**,000 galaxies within **200 Mpc** are spatially resolved: Resolved galaxy kinematics!

→ Galaxies in local Universe / (dark) mass distribution in galaxies / Galaxy environments / Intergalactic HI / HI mass function / Galaxy clusters / High-velocity clouds / Multi-frequency synergies etc.

2D vs. 3D kinematic analysis

2D kinematic analysis

- Ring-by-ring or entire disk fit to velocity fields projected from 3D cubes
- Affected by projection effect and beam smearing
- Challenging for edge-on like galaxies
- Rotcur / kinemetry / diskfit / nemo

3D kinematic analysis

- Use full information of spectral observations without any compression
- Ring-by-ring or 3D kinematic model fit to 3D cubes
- Less affected by projection effect and beam smearing
- Even works for edge-on like galaxies
- Higher degree of flexibility but CPU expensive and often too sensitive to inhomogeneous gas distributions
- FAT(TiRiFiC) / 3DBAROLO / GBKFIT, GALACTUS

(2D) Tilted-ring analysis

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

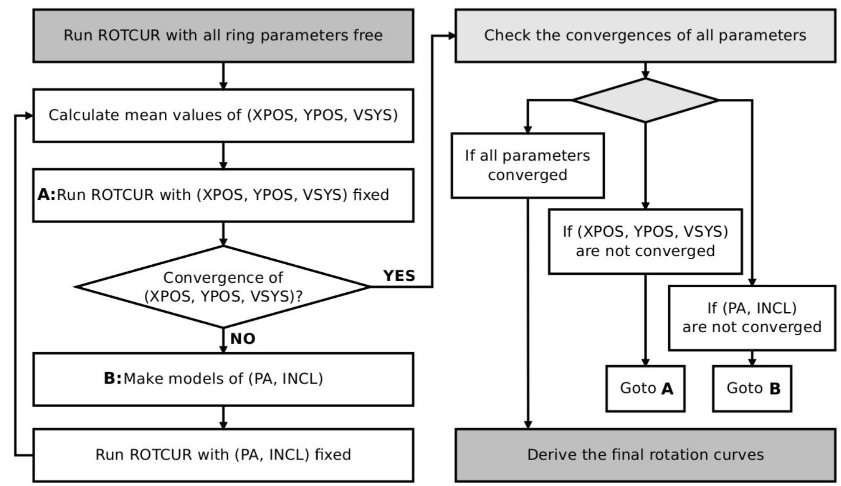
$$v_{\rm LOS}(x,y) = v_{\rm SYS} + \sin i\{v_{\rm ROT}(r)\cos\theta + v_{\rm EXP}(r)\sin\theta\}$$

where

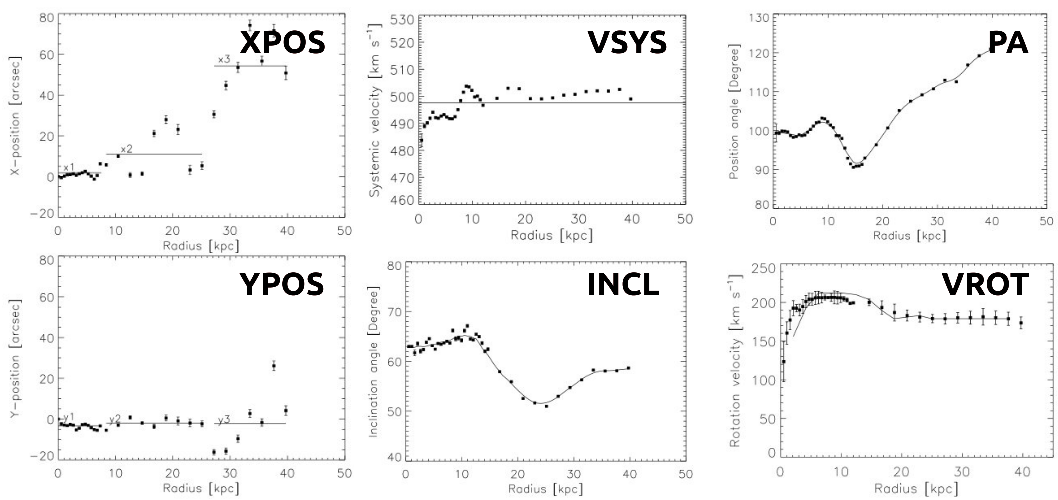
$$\cos\theta = \frac{-(x-x_C)\sin\phi + (y-y_C)\cos\phi}{r},$$

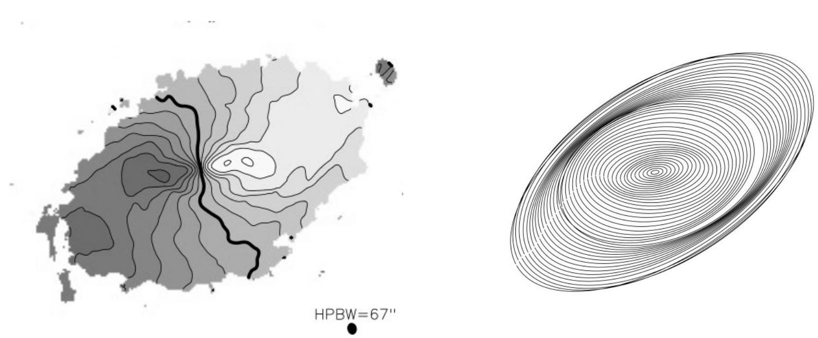
$$\sin\theta = \frac{-(x-x_C)\cos\phi - (y-y_C)\sin\phi}{r\cos i},$$

- An example of conventional TR analysis



Oh et al. (2009)





NGC 5055 (Battaglia et al. 2005)

Key requirements of the kinematic analysis for WALLABY : in a 2D perspective *(see Kamphuis et al. 2015 for a 3D view)*

- **Robustness**
  - insensitive to initial estimates
  - insensitive to localized outliers
  - flexible regularization for PA/INCL/VEXP/VROT
- **Efficiency**
  - fast but reliable fitting of the resolved disk galaxies from the massive WALLABY data stream
- **Automation**
  - determine initial priors
  - check convergence

→ Fit 2D kinematic disc models to the entire region of input velocity fields in a Bayesian framework at one time

→ Find the best fits via MCMC sampling given priors of the ring parameters

→ Parallel processing using multi-cores

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

- 2D kinematic model based on B-splines + Einasto rotation velocity

single values — **regularized by the below forms:**

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

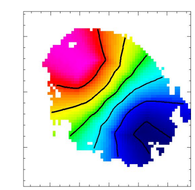
where

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

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

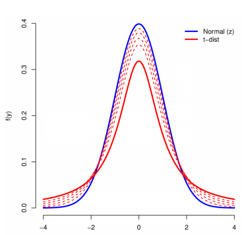
VEXP: $$v_{\rm EXP}(r) = \sum_{m=1}^{n} c_m^{v_{\rm EXP}} B_{m,k}^{v_{\rm EXP}}(r)$$

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



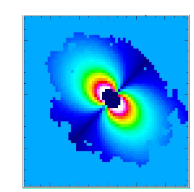
- A log-likelihood function for a Student-t distribution

$$\log L = \sum_{t=1}^{N} w_t \log\left[\frac{\Gamma(\frac{\nu+1}{2})}{\sqrt{\pi(\nu-2)}\Gamma(\frac{\nu}{2})}\right] - \frac{1}{2}\sum_{t=1}^{N} w_t \log\sigma_t^2 - \frac{\nu+1}{2}\sum_{t=1}^{N} w_t \log\left[1 + \frac{\epsilon_t^2}{\sigma_t^2(\nu-2)}\right]$$



where

$$w_t = \frac{l_{\rm outermost}}{l_t} \times \frac{|\cos(\theta_t)|^{\rm q}}{v_t^{\rm LOS-error}}$$



$$\epsilon_t = v_t^{\rm LOS} - v_t^{\rm MODEL}$$

Oh et al. (2018)

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

- A standalone code for 2D tilted-ring analysis based on Bayesian MCMC techniques

  - 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 given broadly defined ranges of initial priors for the ring parameters

  - parallelised: Message Passing Interface (MPI) supported

  - written in C with publicly available libraries: MultiNest v3.10 (Feroz & Bridges 2008, 2009), cfitsio, GSL & standard MPI libraries

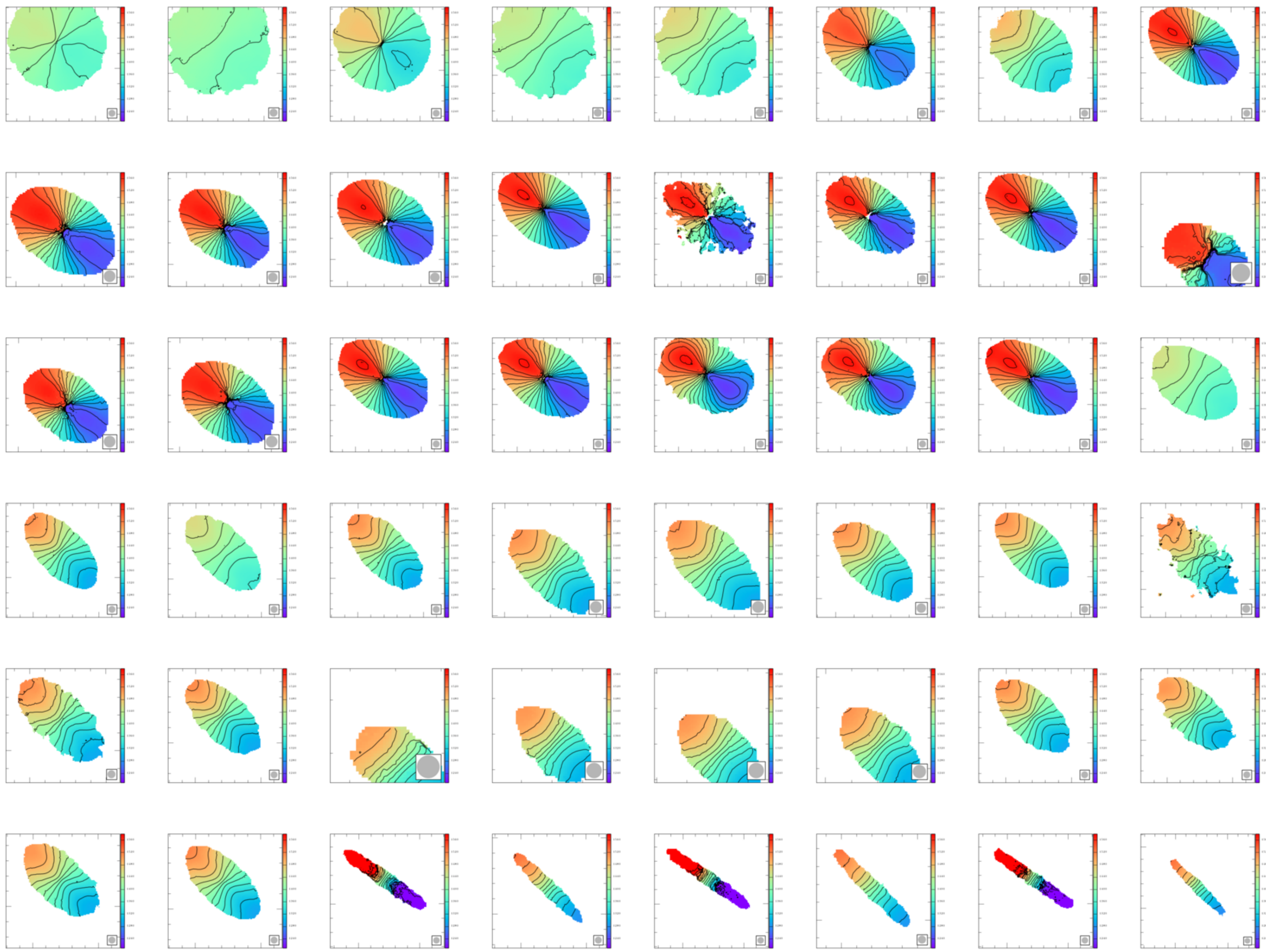
  - comprise the WALLABY kinematics pipeline together with the automated TiRiFiC (FAT)

  - downloadable at http://github.com/seheonoh/2dbat

  - cross-platform (linux/mac/windows) "*DOCKERIZED*" version available

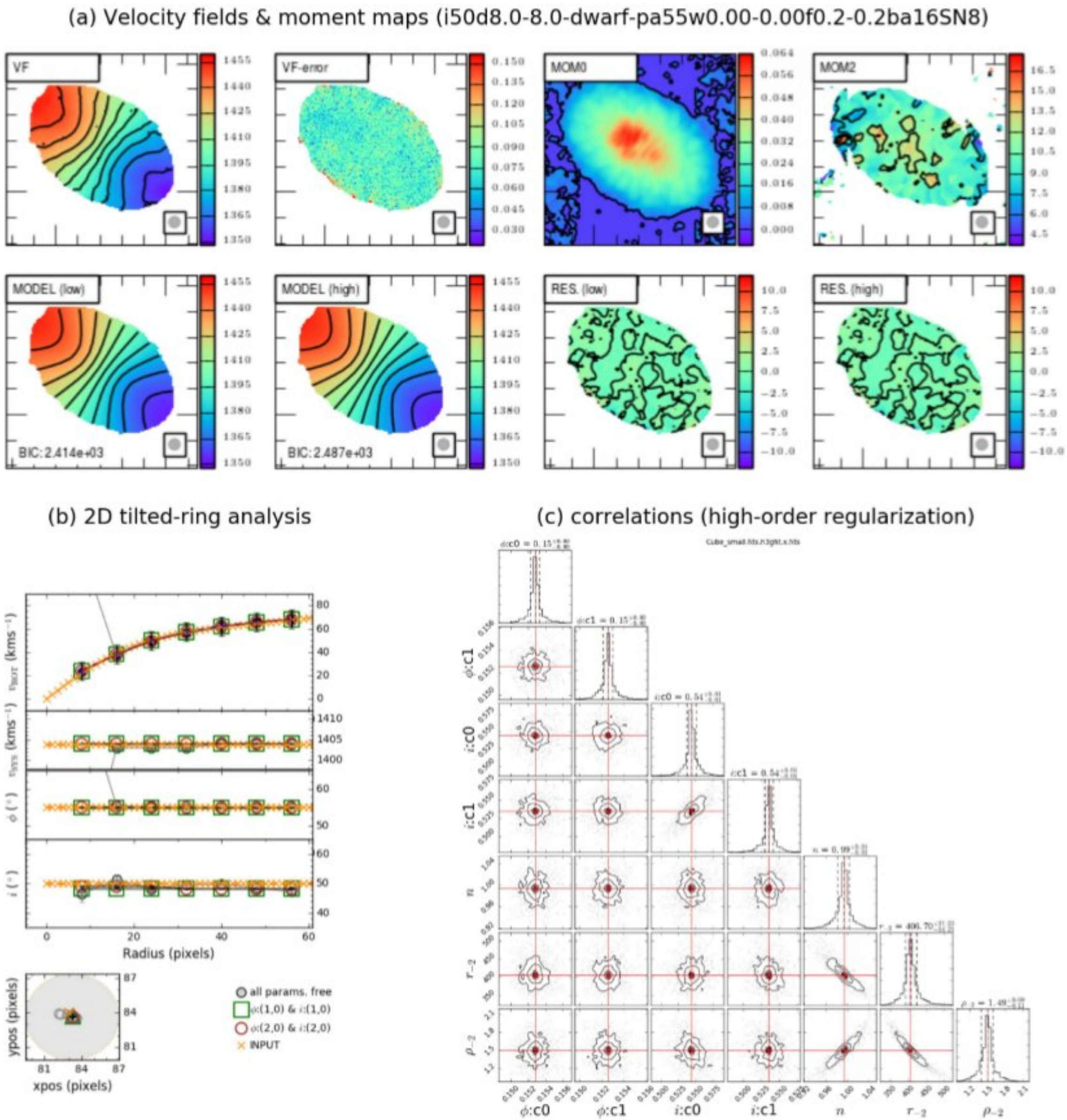
  - See Oh et al. (2018) for a complete description of the code

2DBAT analysis for artificial galaxies



Korea Astronomy and Space Science Institute

2DBAT analysis for artificial galaxies



- 52 artificial galaxies in Kamphuis et al. (2015)

  - two representative rotation curves of intermediate-mass and massive disk galaxies as well as a solid body-like rotation curve of dwarf galaxies

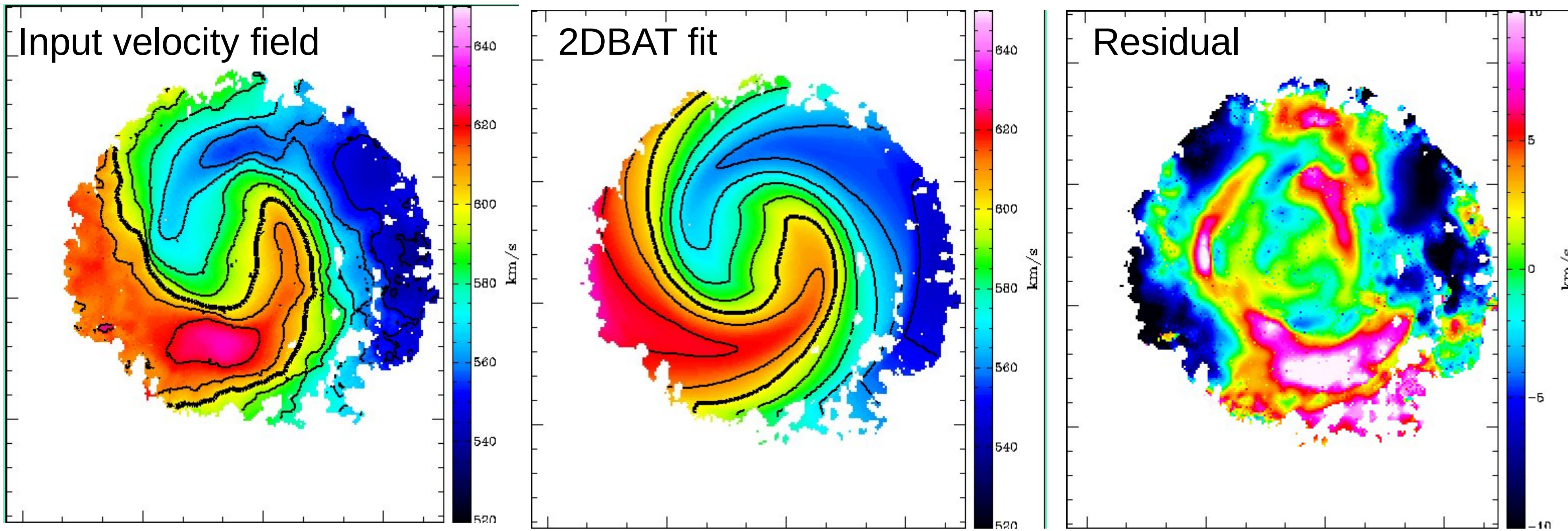
  - 4 km/s of channel resolution

  - white noise added

  - smoothing the cubes with a Gaussian beam with FWHM of 30”

- Run 2DBAT on their extracted Hermite h3 velocity fields given the degree of regularization in a fully automated manner

Cases of 2DBAT application:
(1) Revisit of galaxy kinematics from HI archival data



Oh et al. (2018)

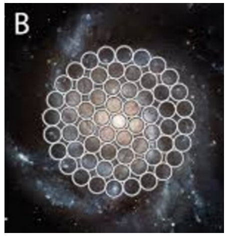
- 24 sample galaxies from LVHIS (Koribalski et al.)

  - taken out of a sample of 82 (< 10 Mpc), gas-rich galaxies undertaken with the ATCA

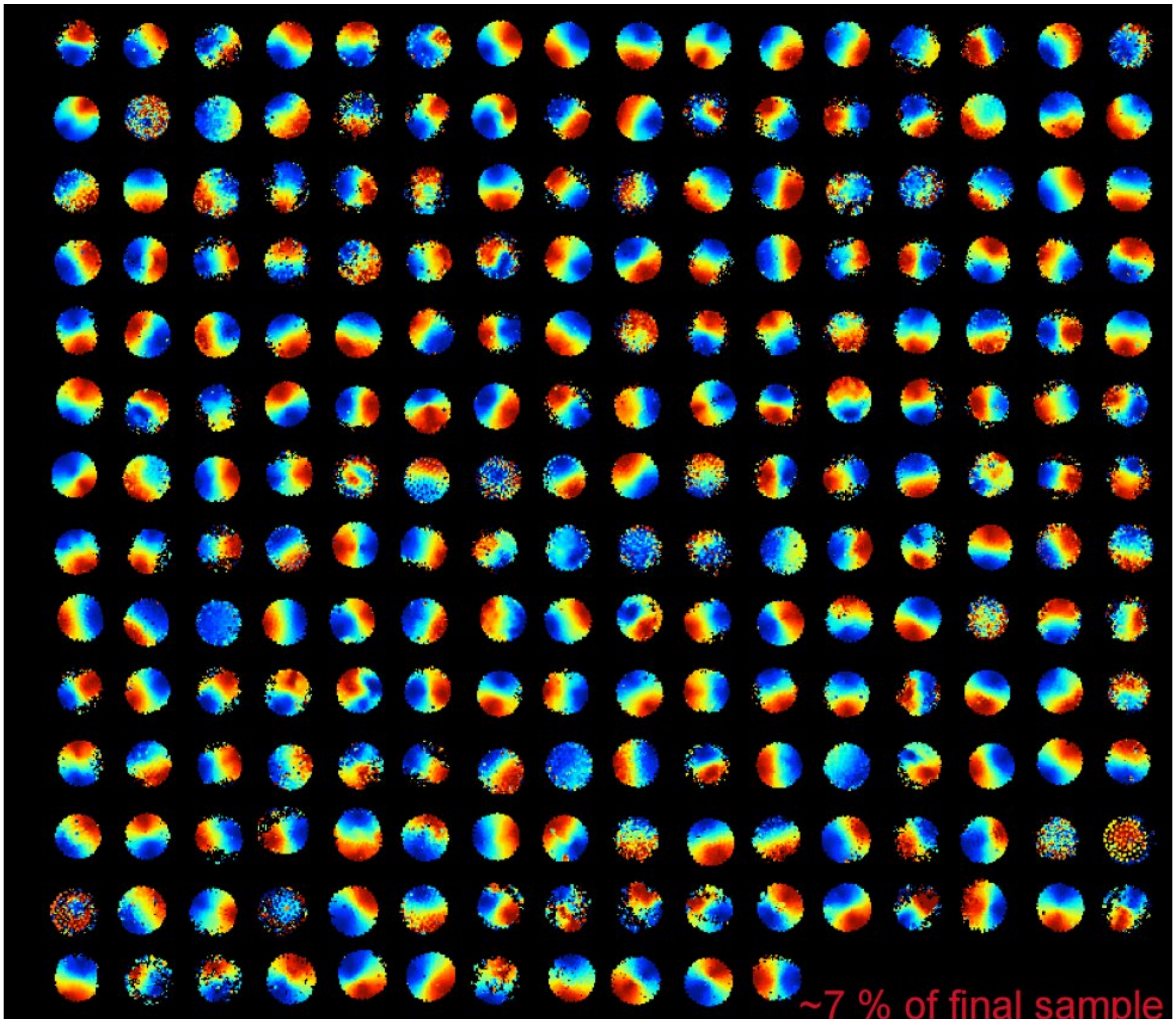
  - more or less like those of WALLABY resolved galaxies in terms of the spatial (20-60") and spectral (4 km/s) resolutions as well as the number of resolved elements across the major axis

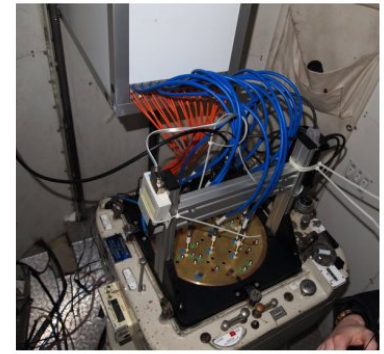
  - also used for testing the performance of FAT in Kamphuis et al. (2015)

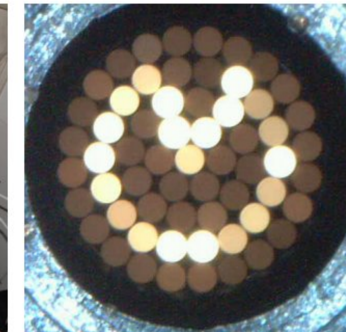
- Run 2DBAT on their extracted Hermite h3 velocity fields given the degree of regularization in a fully automated manner



Cases of 2DBAT application: (2) 2D kinematics of SAMI galaxies







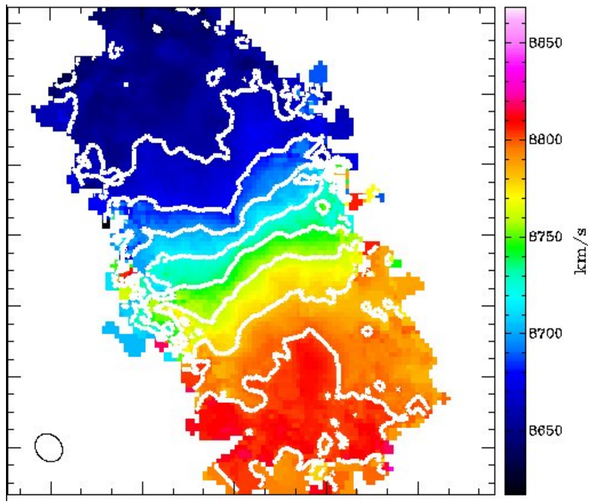
The Sydney-AAO Multi-object Integral field spectrograph

Scott Croom (for the SAMI team)

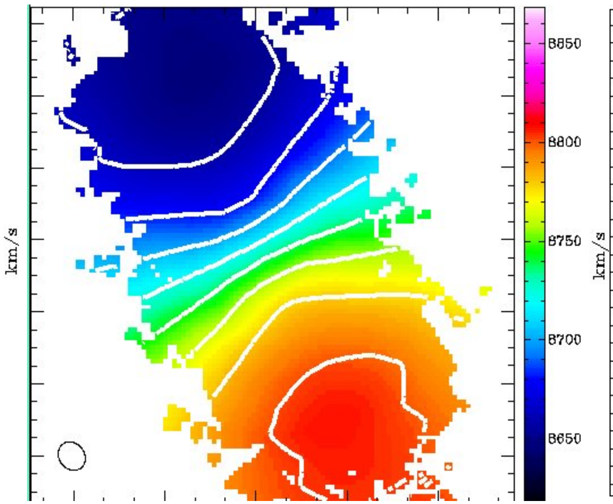
Sydney Institute for Astronomy (SIfA)
CAASTRO ARC Centre of Excellence
University of Sydney

Cases of 2DBAT application:
(3) ASKAP Early Science Observations

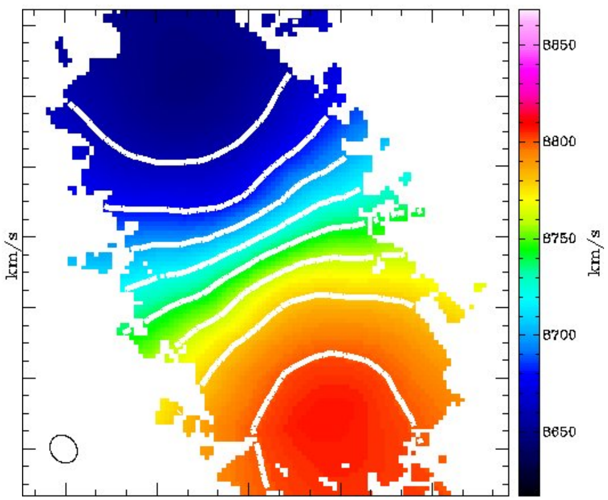
MOM1

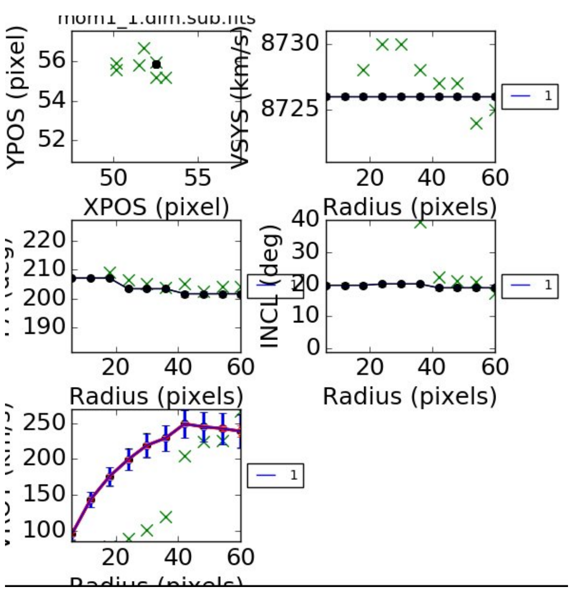


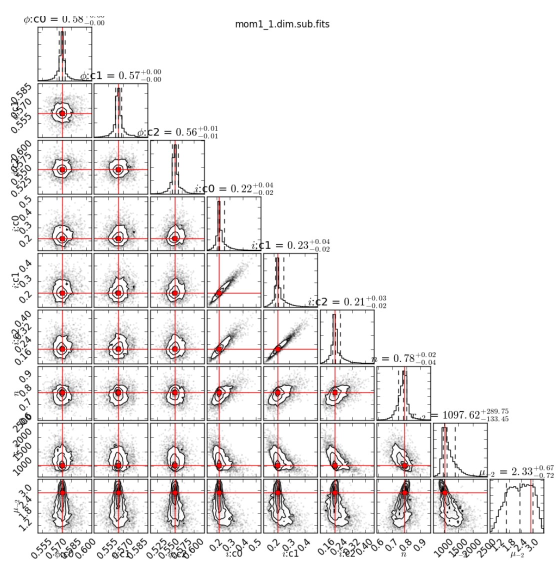
Model1: constant PA/INCL



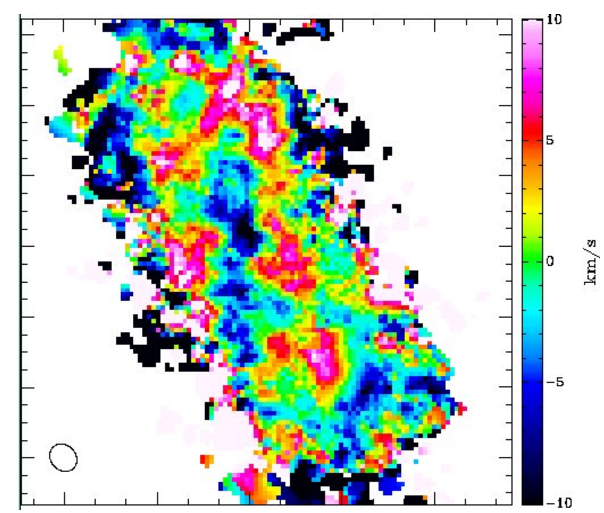
Model2: higher order PA/INCL



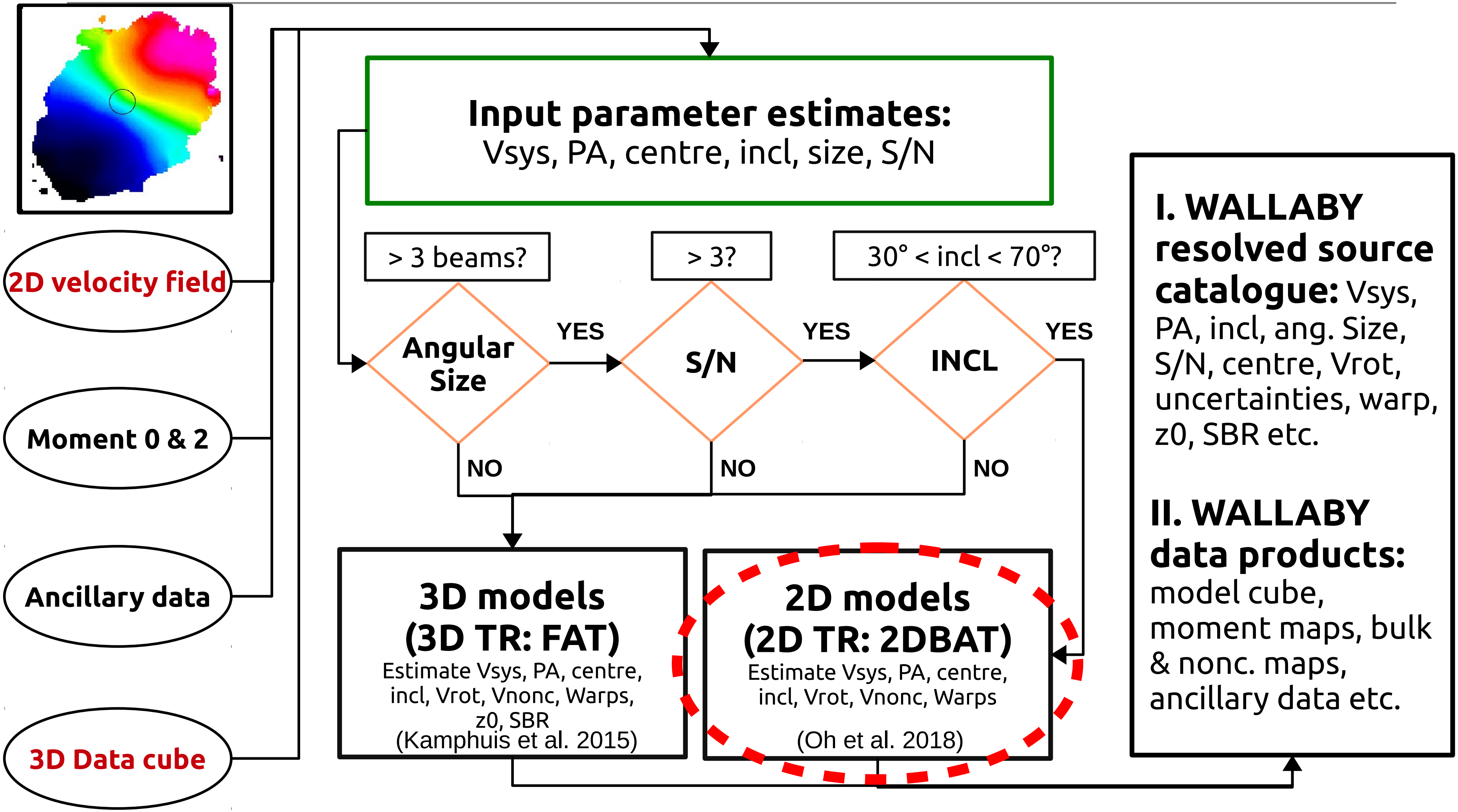




Residual: input - Model2



Kinematic parametre extraction for WALLABY
: ASKAP WALLABY/DINGO (~5,000) + WSRT Apertif (~7,000) galaxies



Summary & (near) future directions

- A new standalone 2D tilted-ring analysis tool (2DBAT) on hand
- Fully automated given broadly defined ranges of initial priors
- Written in C with publicly available libraries: MultiNest v3.10 (Feroz & Bridges 2008), cfitsio, GSL & standard MPI libraries
- Parallelised: Message Passing Interface (MPI) supported
- Comprise the WALLABY kinematics pipeline together with the automated TiRiFiC (FAT)
- See Oh et al. (2018) for a complete description of the code
- Downloadable at http://github.com/seheonoh/2dbat
- Cross-platform (linux/mac/windows) "DOCKERIZED" version available
- Evolution to 3DBAT?

- Applications (e.g.):

  - statistical revisit of resolved galaxy kinematics from all the available archival data

  - Resolved kinematics for ASKAP Early Science Observations

  - 2D kinematic baseline for SAMI

Thank you!