CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

Kinematics of Nearby Galaxies in preparation for WALLABY

Se-Heon Oh (ICRAR/UWA)

With

LITTLE THINGS team & WALLABY WG2

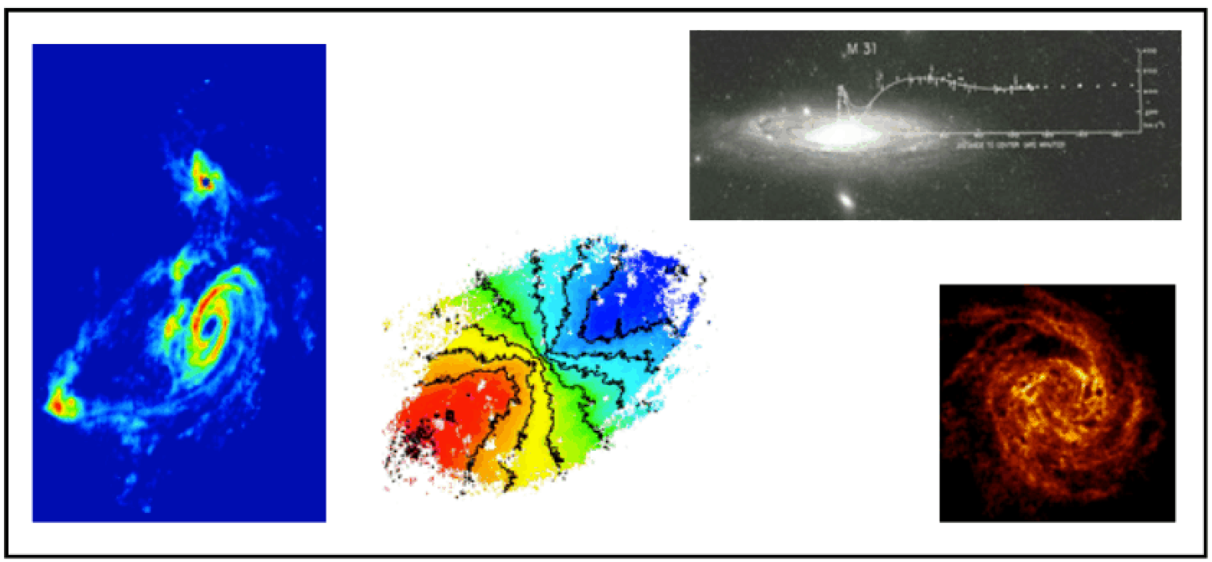
ICRAR

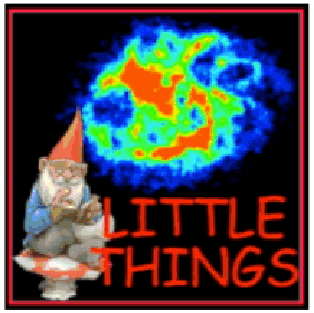
Contents

- HI kinematics of galaxies
- Dark matter distribution in dwarf galaxies
- Progress on WALLABY rotation curve pipeline
- A new approach for extracting bulk velocity fields
- Summary & future works

HI kinematics of resolved galaxies

- **Dynamical structure** : (dark) matter distribution in galaxies
- **Interplay between ISM and star formation** on small (sub-kpc) scales
- **Dynamical information about galaxy evolution** : warps, bars, spiral arms, tidal interaction, HVCs etc.

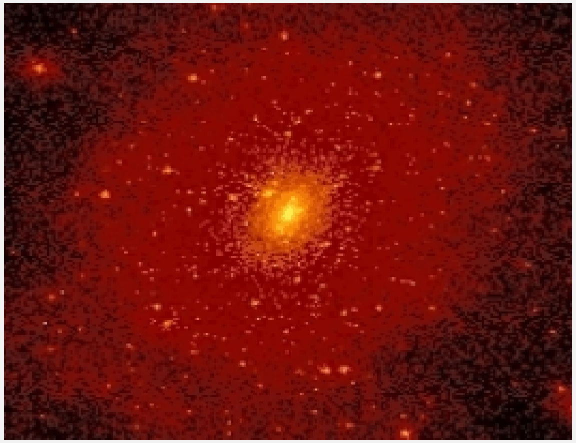


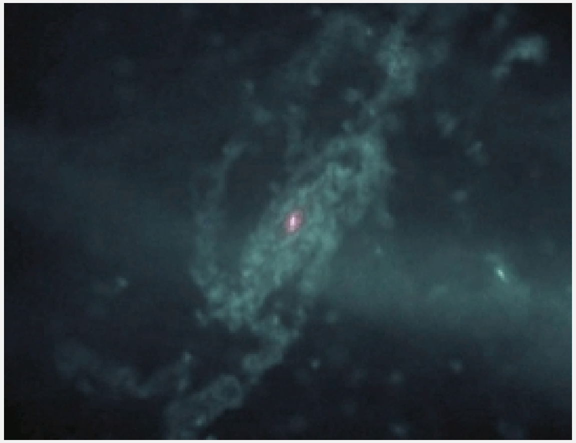


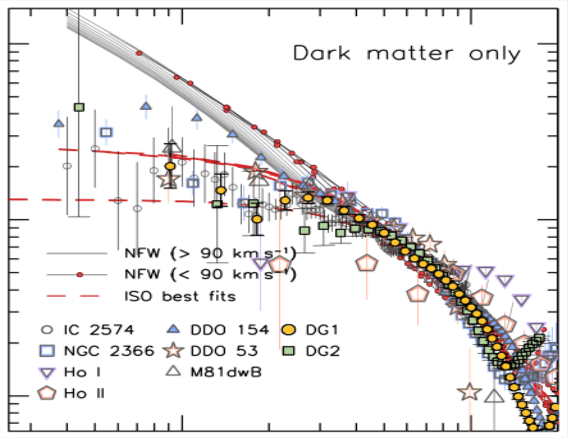
WALLABY

Widefield ASKAP L-band Legacy All-sky Blind surveY

Small-scale problems in ΛCDM simulations



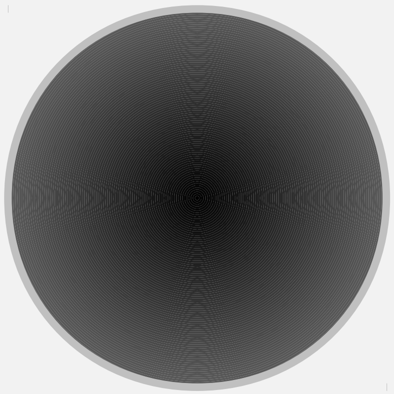




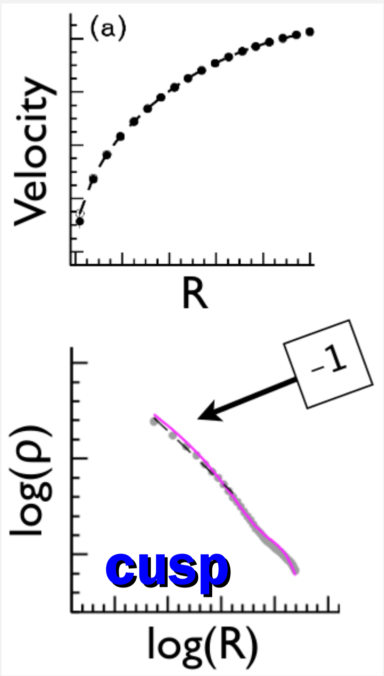
- Missing satellites problem
- Angular momentum problem
- "cusp/core" problem

"cusp/core" problem in galaxies

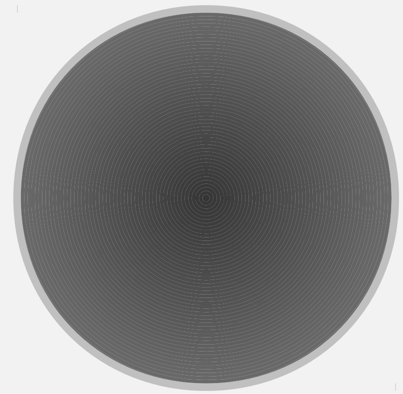
ΛCDM simulations

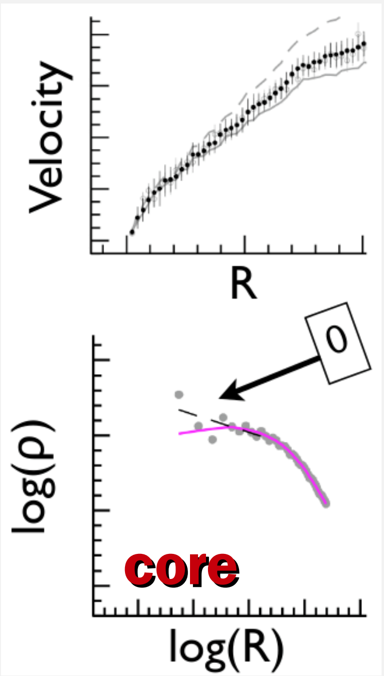


Moore (1994)
Flores & Primack (1994)
Navarro, Frenk & White (1995)
Navarro, Frenk & White (1996)
Moore et al. (1998)
Ghigna et al. (2000)
Klypin et al. (2001)
Power et al. (2002)
Navarro et al. (2004)
Diemand et al. (2008)
Stadel et al. (2009)
Navarro et al. (2010)
etc.



Observations

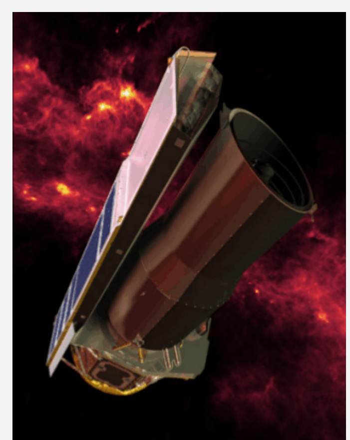
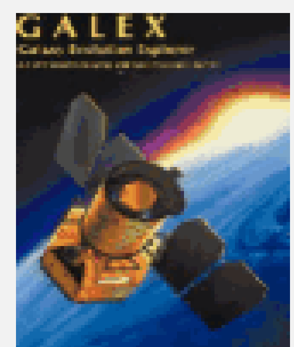


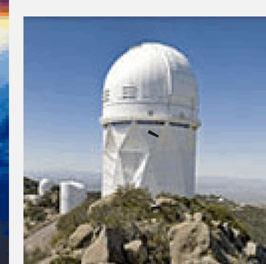


Flores & Primack (1994)
Moore (1994)
de Blok et al. (2001)
de Blok & Bosma (2002)
Bolatto et al. (2002)
Weldrake et al. (2003)
Simon et al. (2003)
Swaters et al. (2003)
Kuzio de Naray et al. (2006)
Gentile et al. (2007)
Oh et al. (2008)
Trachternach et al. (2008)
de Blok et al. (2008)
Oh et al. (2011a, b)
etc.

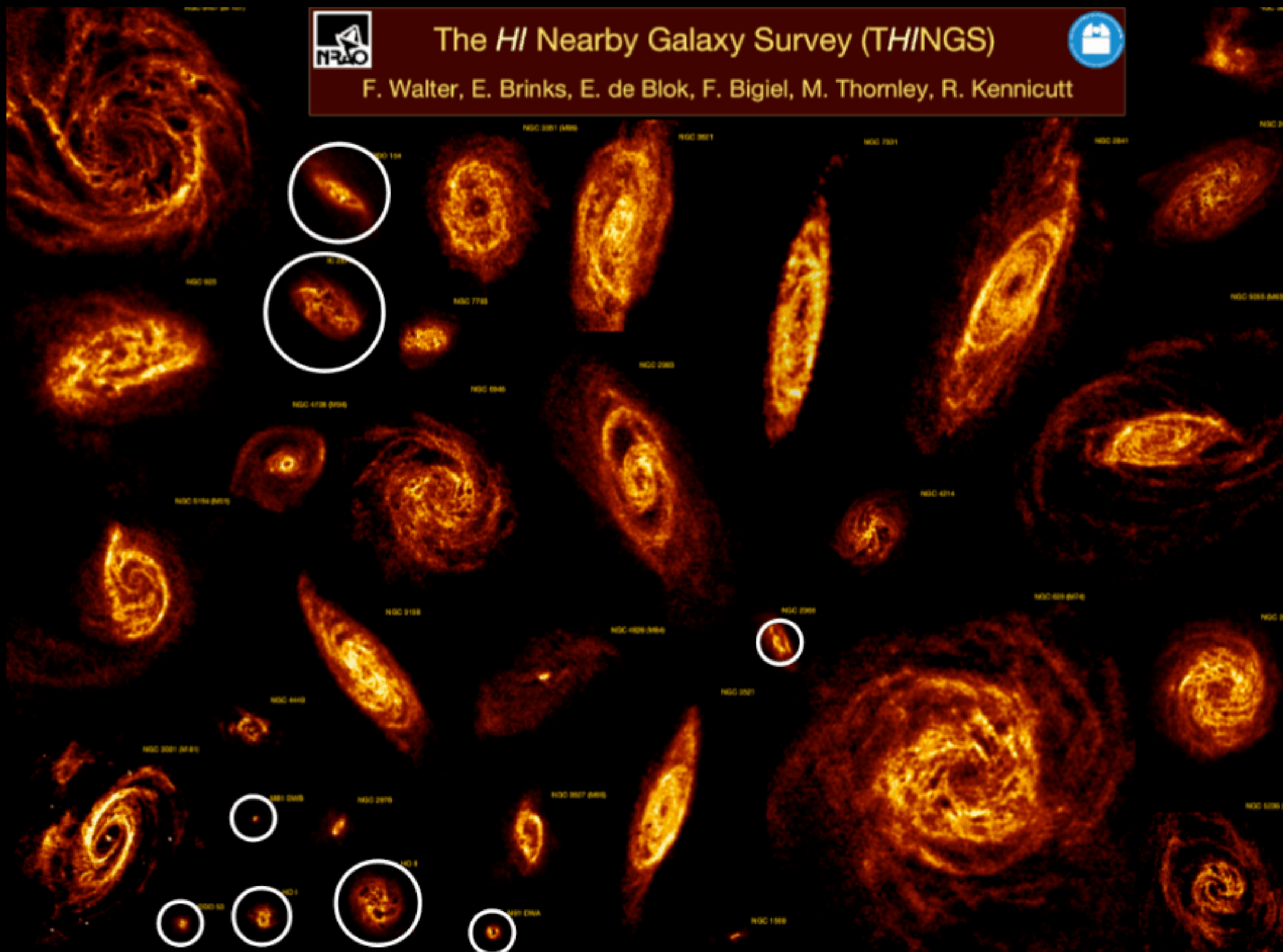
The HI Nearby Galaxy Survey (THINGS)

- VLA HI 21-cm survey (~6”; 5.2 km/s; ~500 hours) of nearby (< 10 Mpc) 34 galaxies
- Commensality with optical, Spitzer SINGS, GALEX uv, CO data etc.)
- All observations ended in late 2005
- Data available at http://www.mpia.de/THINGS

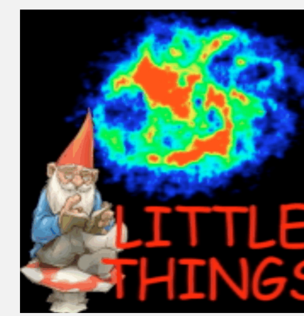


The HI Nearby Galaxy Survey (THINGS)



LITTLE THINGS (Local Irregulars That Trace Luminosity Extremes The HI Nearby Galaxy Survey)

- THINGS-like (~6”; < 5.2 km/s) high-resolution VLA HI 21cm survey (B+C+D; 376 hours) for 41 nearby (< 10 Mpc) dwarf (dIm, BCD) galaxies
- Commensality with Spitzer (+ Herschel) optical, GALEX uv, CO data etc.)
- VLA observations ended in 2008
- Further observations with EVLA, CARMA, APEX etc.



CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

LITTLE THINGS

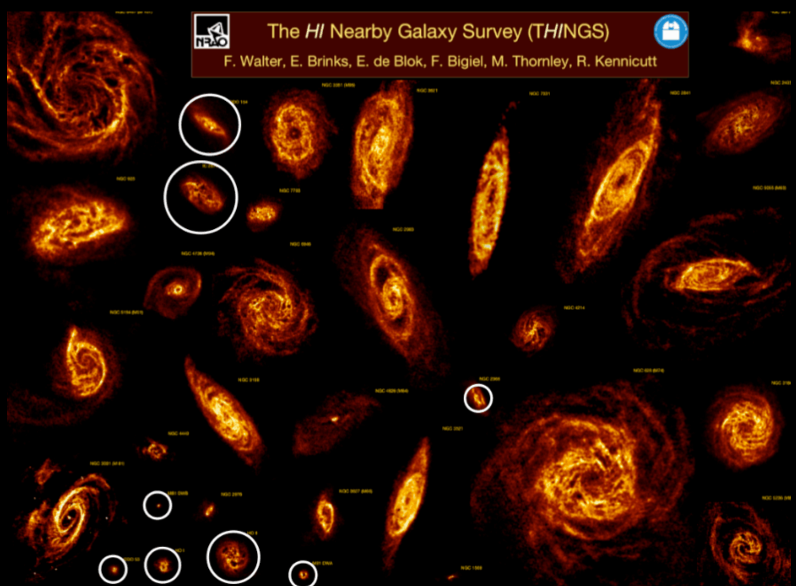
Deidre Hunter (PI. Lowell obs)
Elias Brinks (Univ. of Hertf.)
Bruce Elmegreen (IBM)
Michael Rupen (NRAO)
Caroline Simpson (Florida Univ.)
Fabian Walter (MPIA)
David Westpfahl (NMT)
Lisa Young (NMT)
Trisha Ashley (Florida Int. Univ.)
Sandipan Basu (Florida Int. Univ.)
Phil Cigan (NMT)
Dana Ficut-Vicus (Univ. of Hertf.)
Volker Heesen (Univ. of Hertf.)
Kim Herrmann (Lowell Obs)
Megan Jackson (Lowell Obs)
Se-Heon Oh (ICRAR/UWA)
Andreas Schruba (MPIA)
Hongxin Zhang (Lowell Obs)

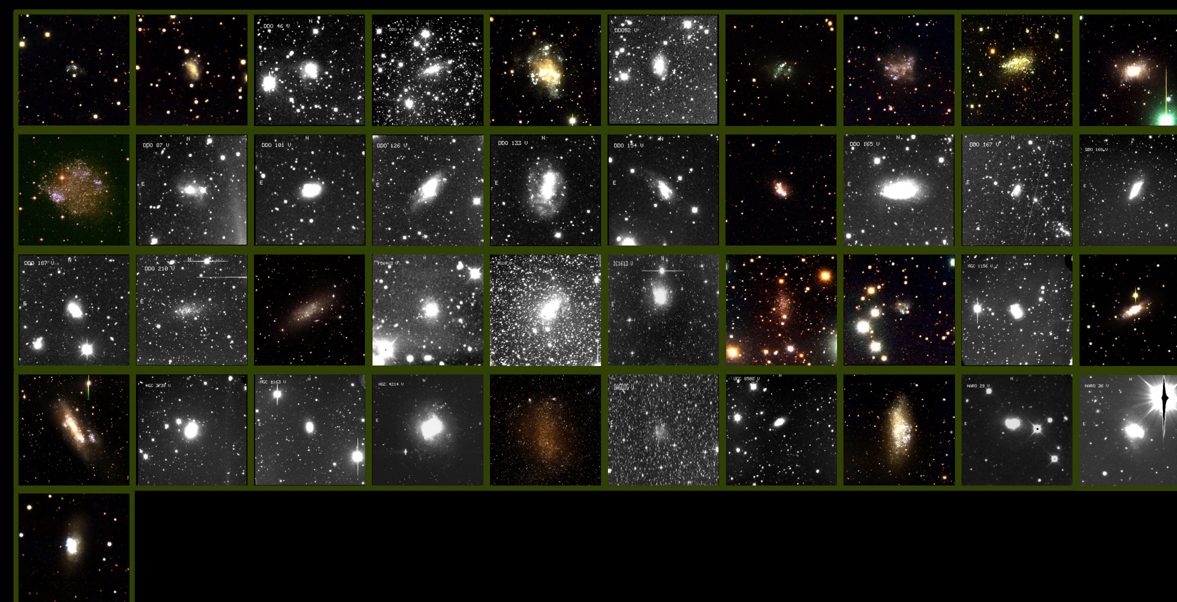
3rd team meeting in Socorro 27-29 Mar 2011

CAASTRO
ARC CENTRE OF EXCELLENCE
FOR ALL-SKY ASTROPHYSICS

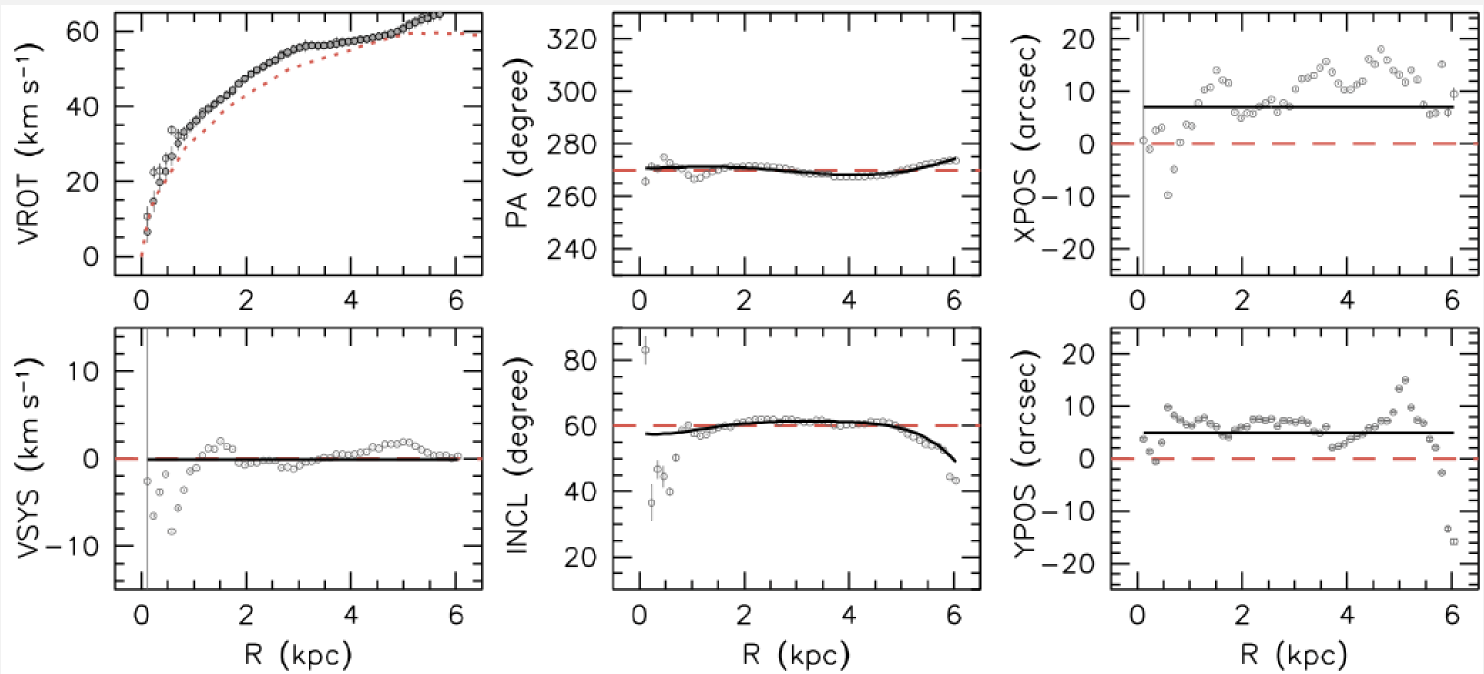
LITTLE THINGS sample galaxies

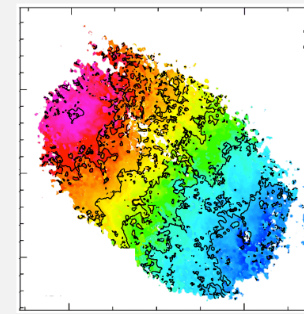
Dark matter distribution in (LITTLE) THINGS dwarf galaxies





I. Deriving rotation curves





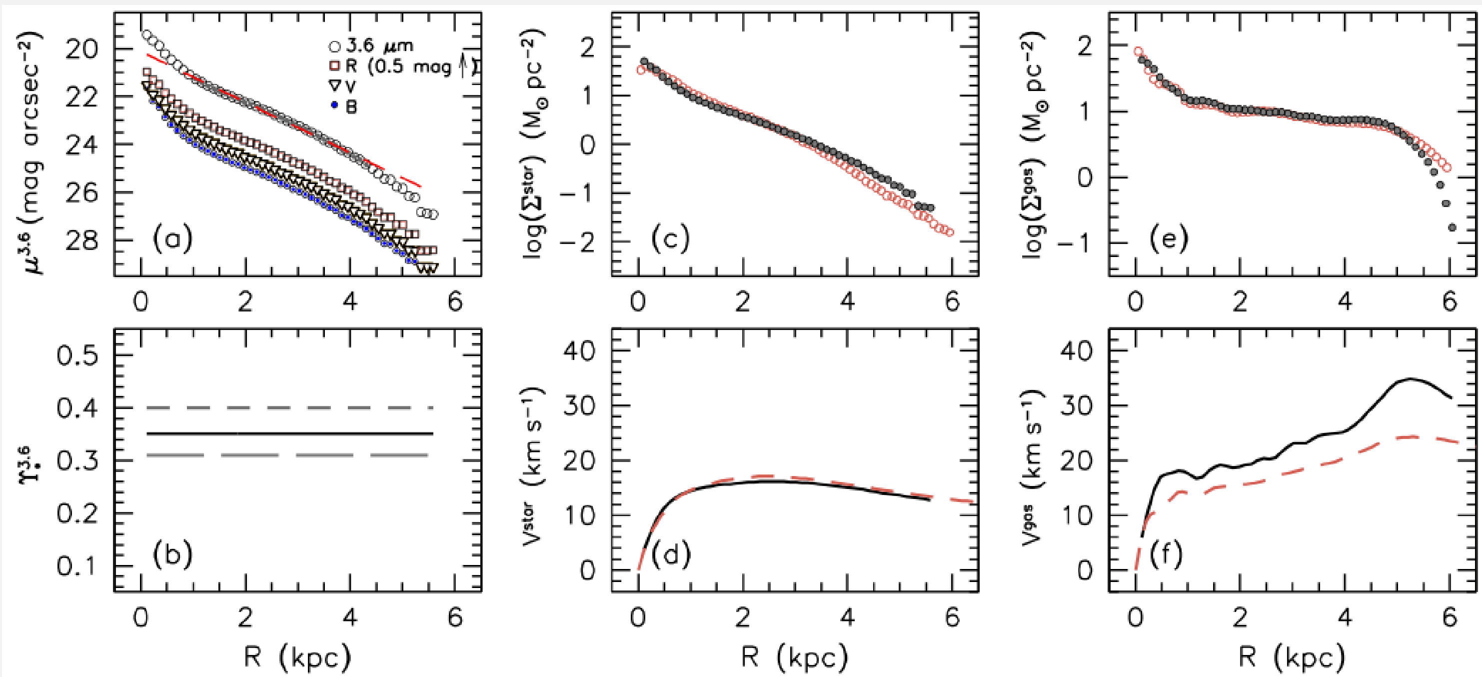
Velocity field

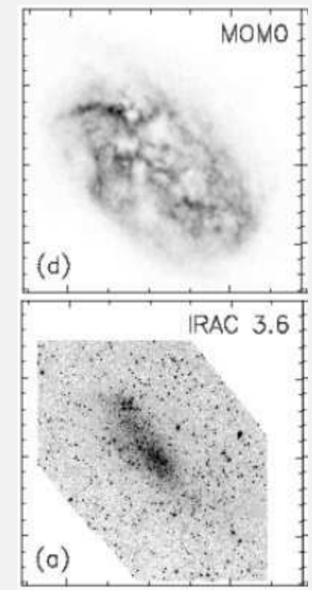
TR models

- **Fit tilted-ring models to 2D velocity fields**
  (e.g., Rogstad et al. 1974; “rotcur” in GIPSY)

II. Deriving mass models of baryons

stars **gas**





Gas

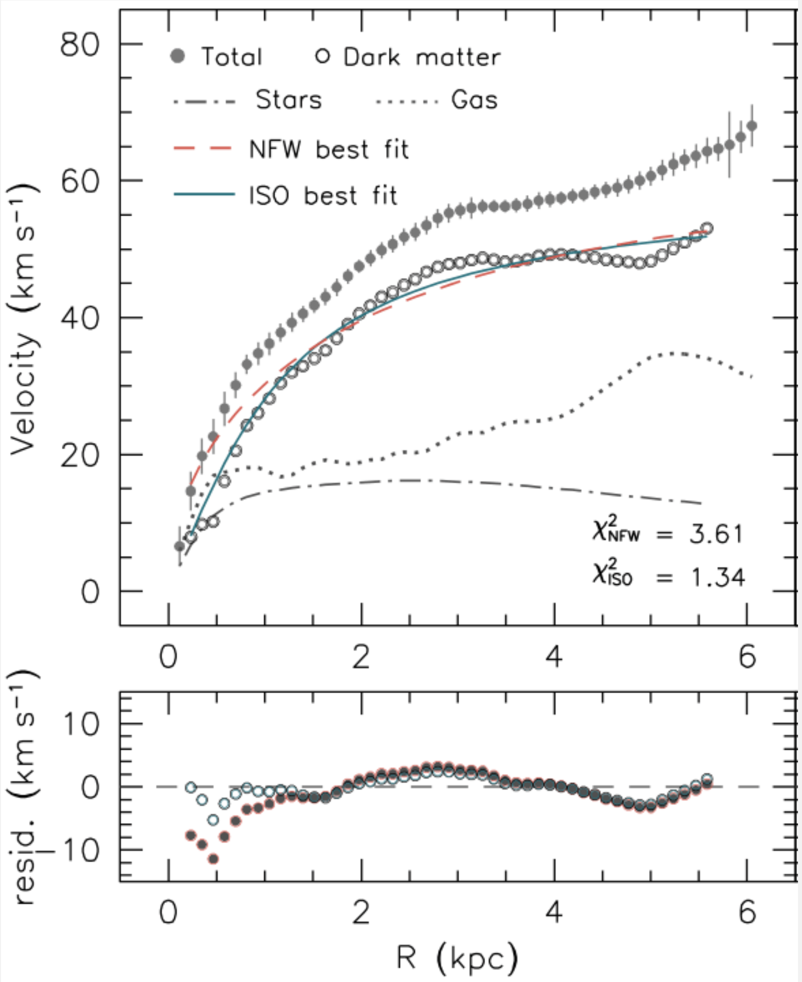
stars

TR models

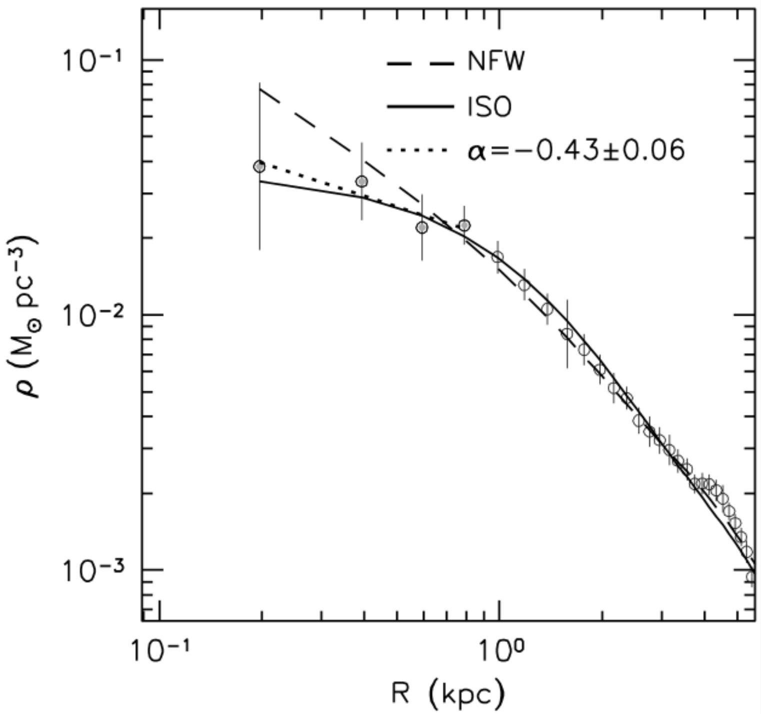
- **Mass modelling of 7 THINGS and 15 LITTLE THINGS dwarf galaxies using VLA HI data, Spitzer 3.6 micron images and ancilliary optical images**

III. Deriving dark matter density profiles

Disk-halo decomposition



Dark matter density profile

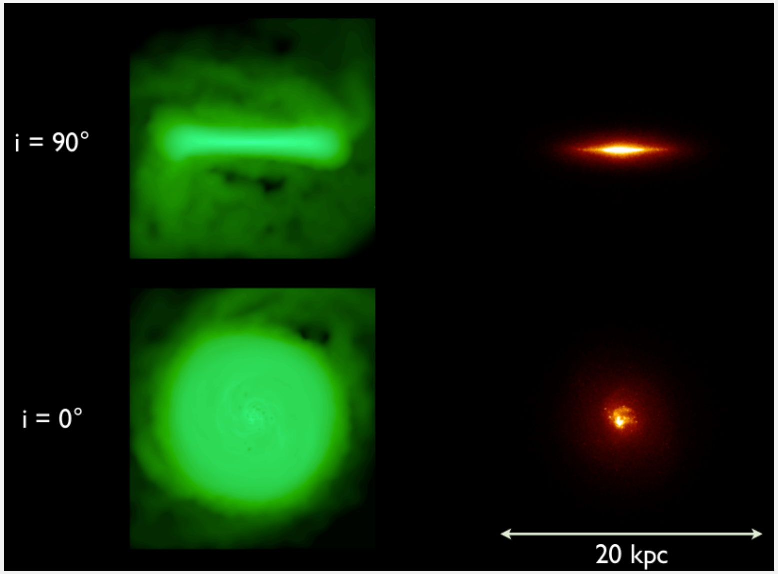


$$\rho(R) = \frac{1}{4\pi G}\left[2\frac{V}{R}\frac{\partial V}{\partial R} + \left(\frac{V}{R}\right)^2\right]$$

New high-resolution SPH-ΛCDM simulations of dwarf galaxies (Governato et al. 2010)

- N-body+SPH tree-code GASOLINE
- Flat Λ-dominated cosmology
- Baryonic processes are included, such as
  - gas cooling
  - cosmic UV field heating
  - star formation
  - SNe-driven gas outflows

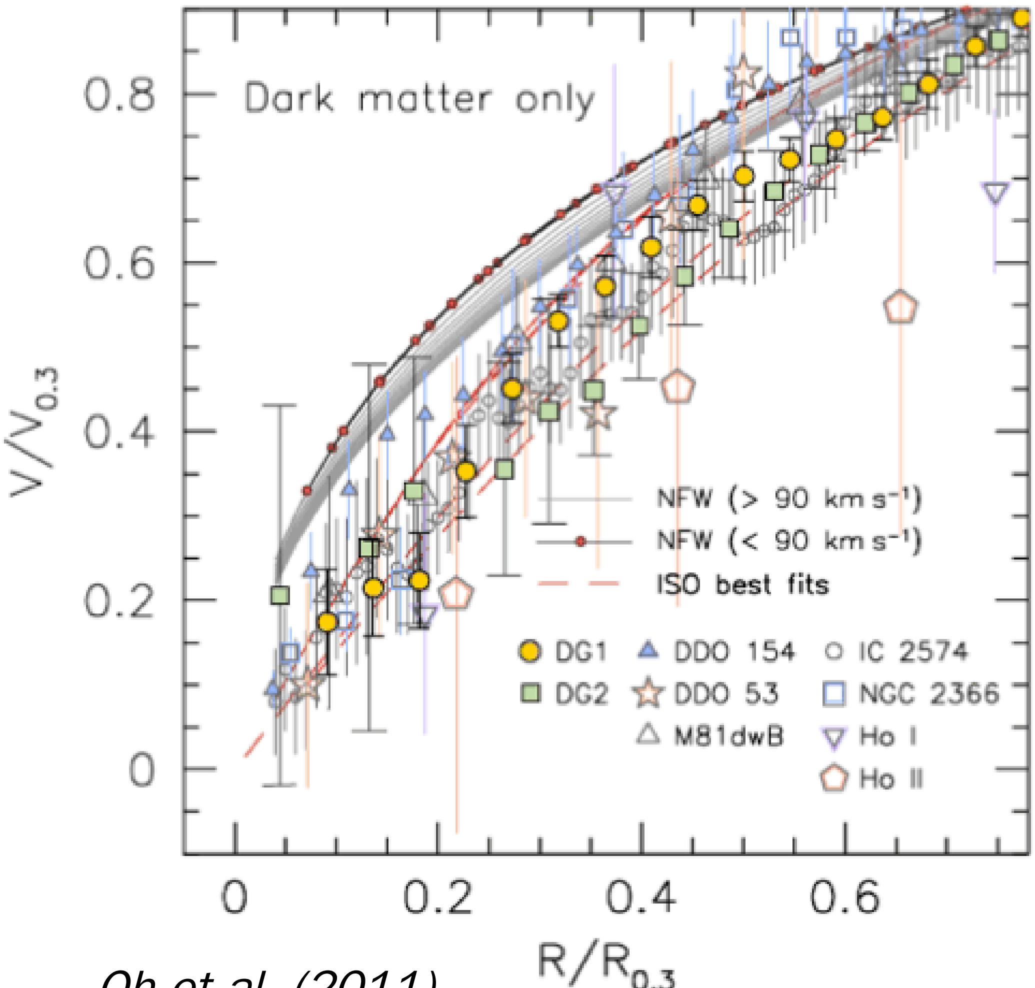
HI 21cm 3.6 micron



- ~3.3 million particles within the virial radius at z = 0.
- DM ~ 1.6×10^4 $M_\odot$; gas particle ~ 3.3×10^3 $M_\odot$
- The force resolution (gravitational softening) ~ 86 pc.

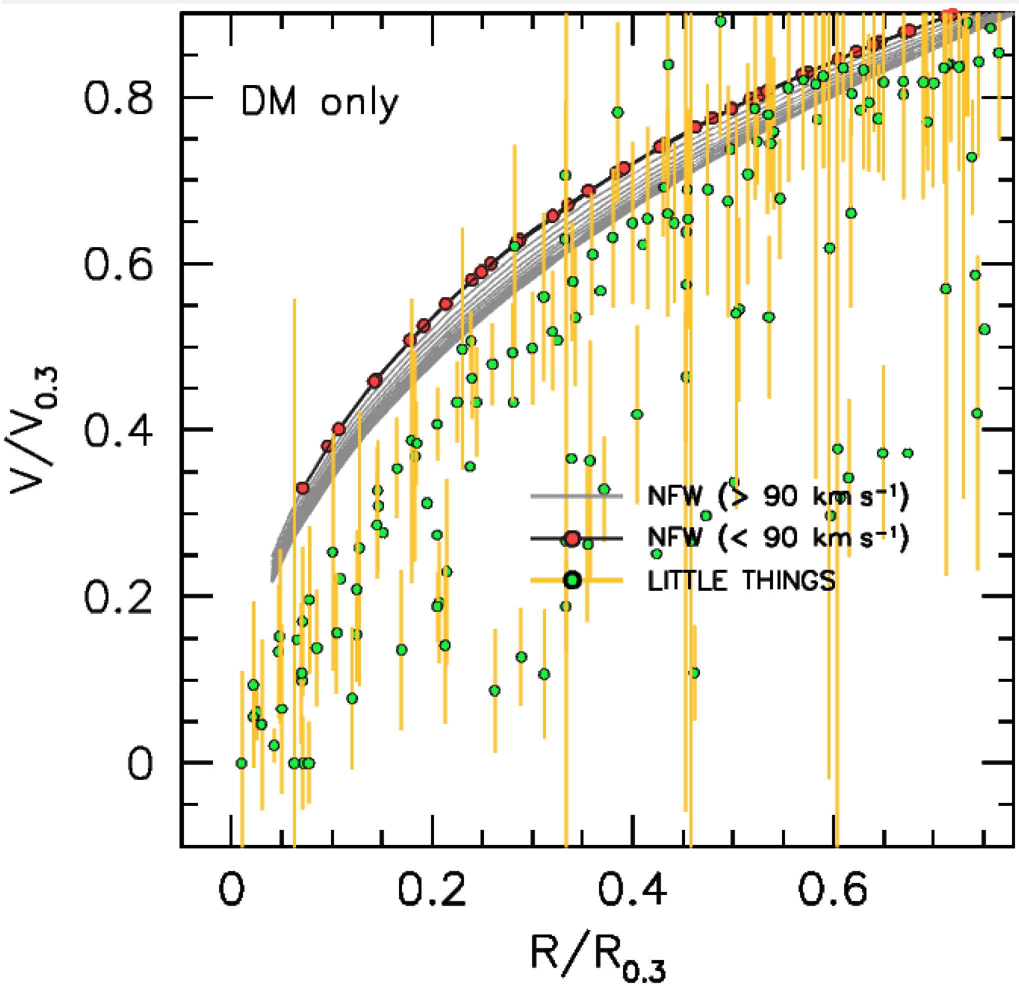
The rotation curve shape of THINGS & LITTLE THINGS

7 THINGS + new SPH simulations



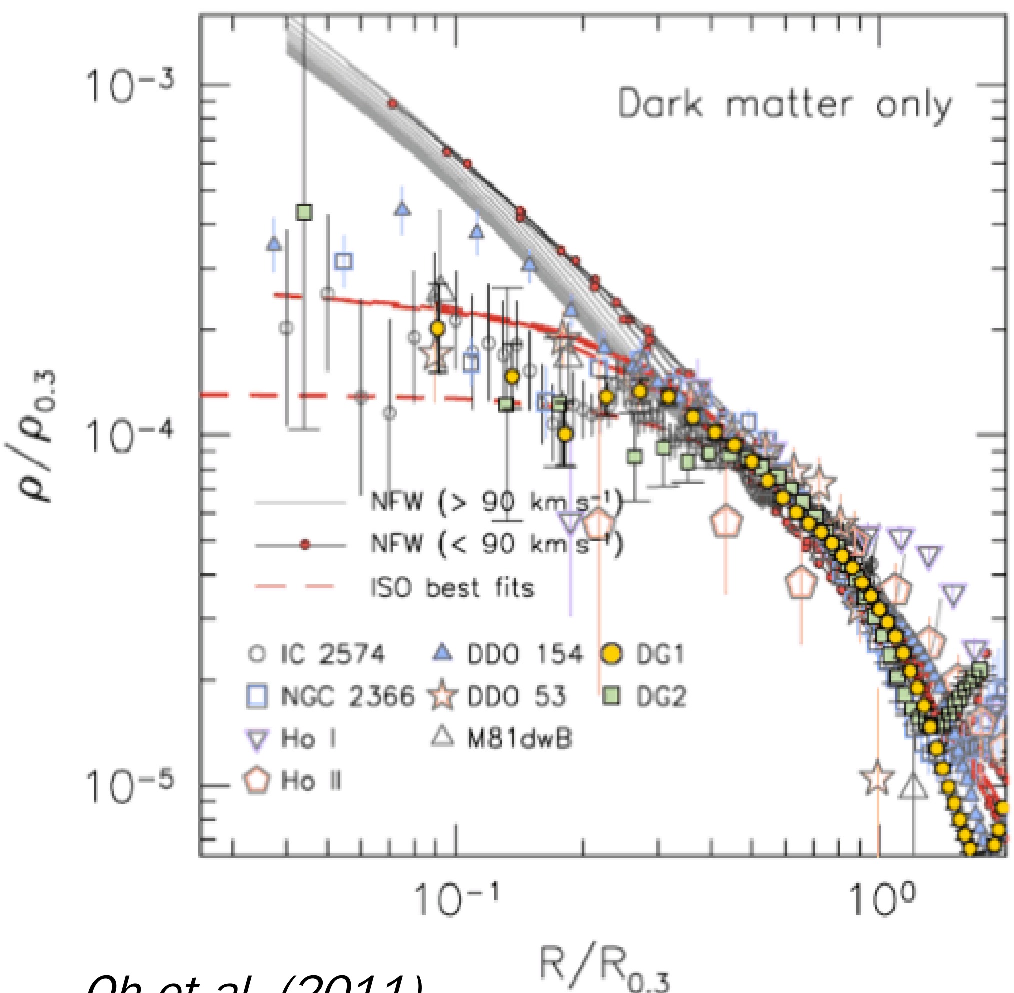
Oh et al. (2011)

15 LITTLE THINGS



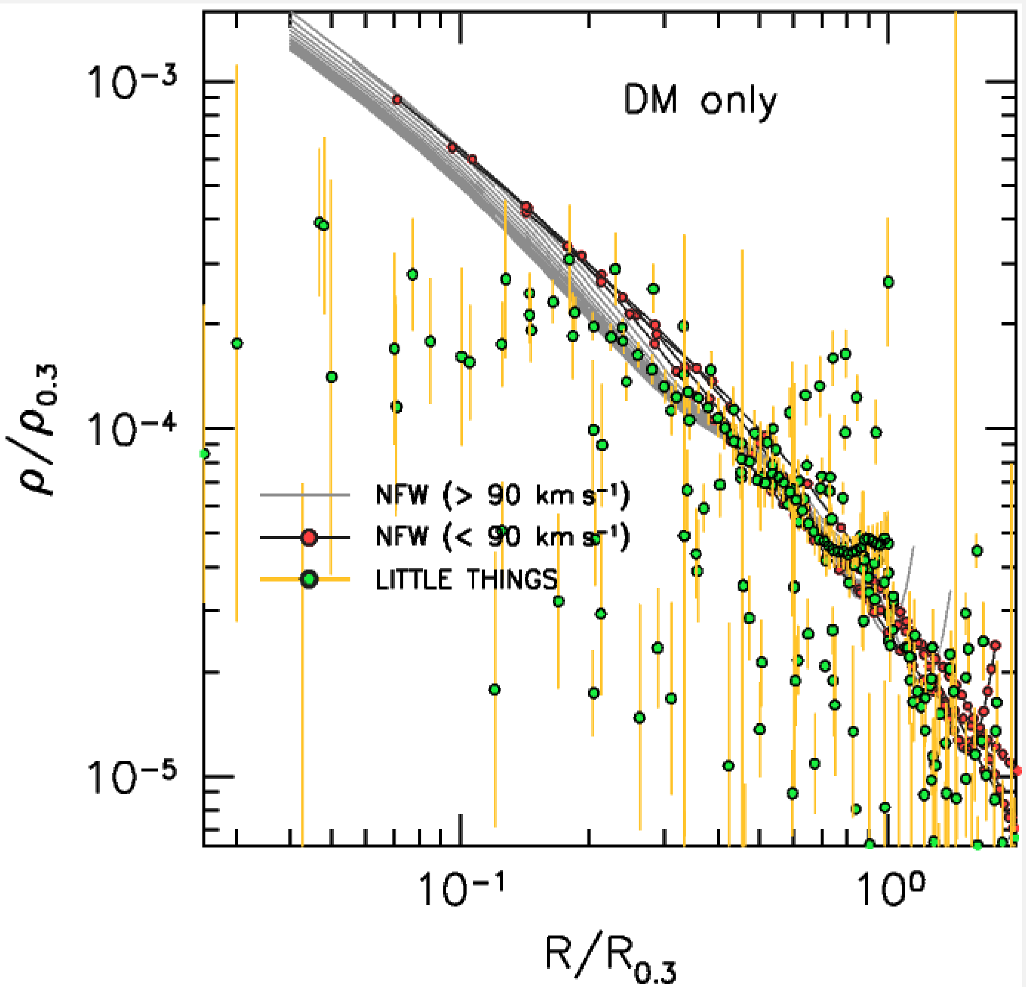
Dark matter density profiles of THINGS & LITTLE THINGS

7 THINGS + new SPH simulations

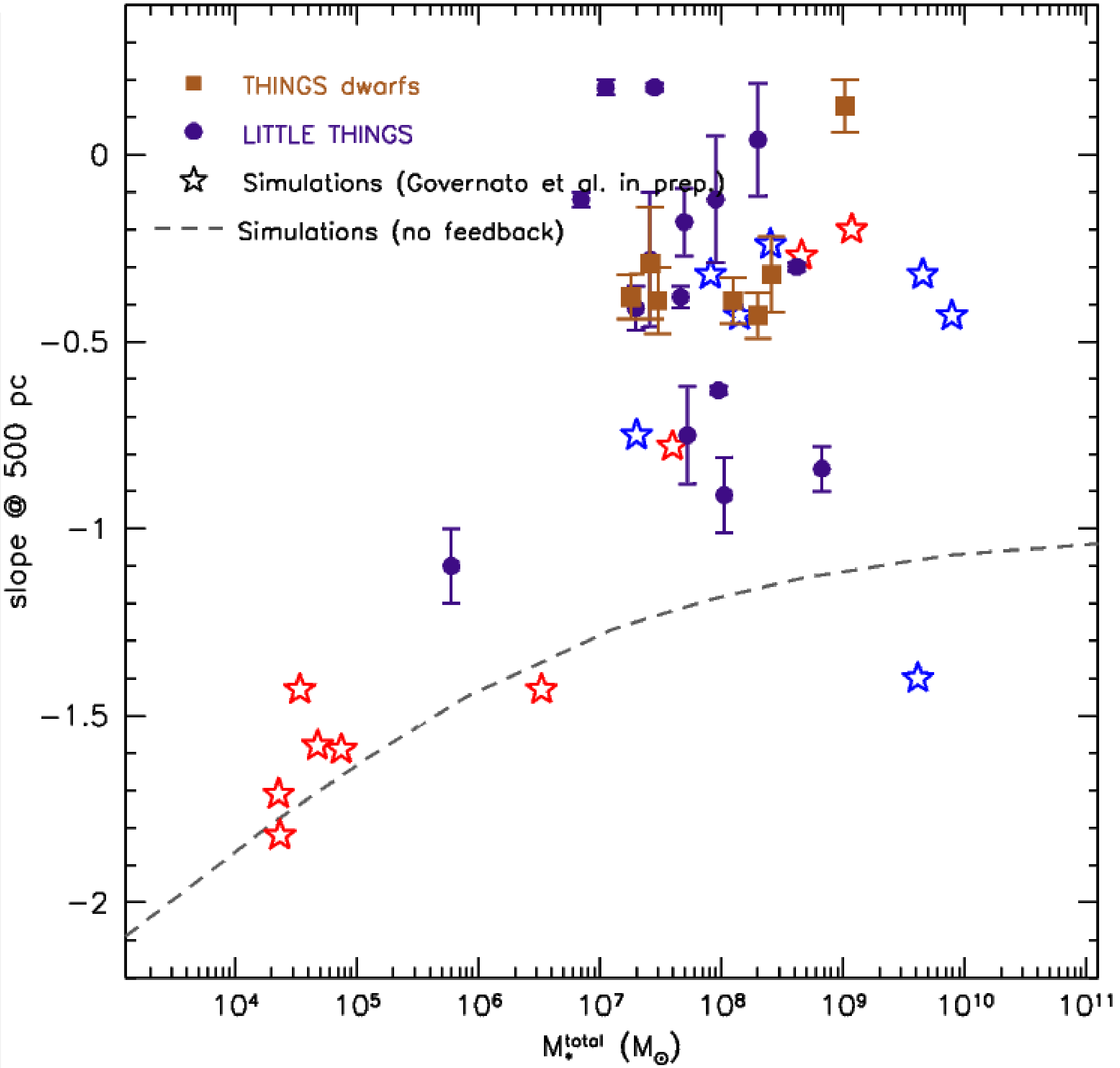


Oh et al. (2011)

15 LITTLE THINGS



DM slope as a function of stellar mass



DM slope

Stellar mass

- **Gas outflows get less efficient in smaller galaxies so cores at fixed radius get smaller…**
- **SN driven gas outflows in the early Universe can be a solution for the "cusp/core" controversy**

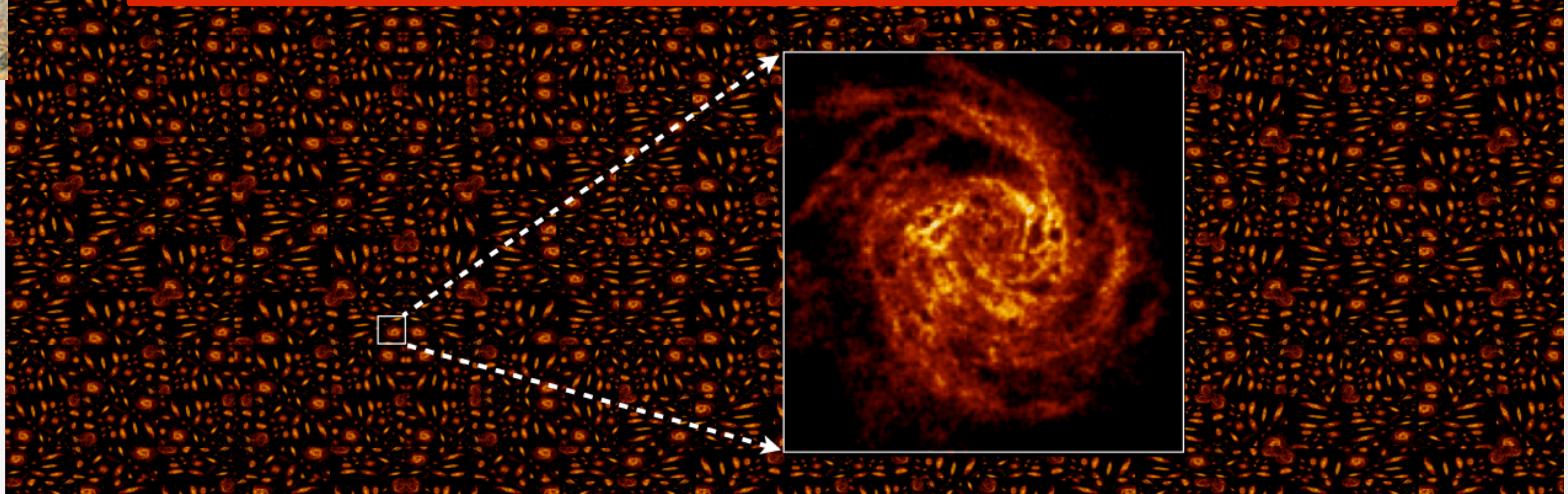
Oh et al. in prep.

CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

ASKAP WALLABY survey

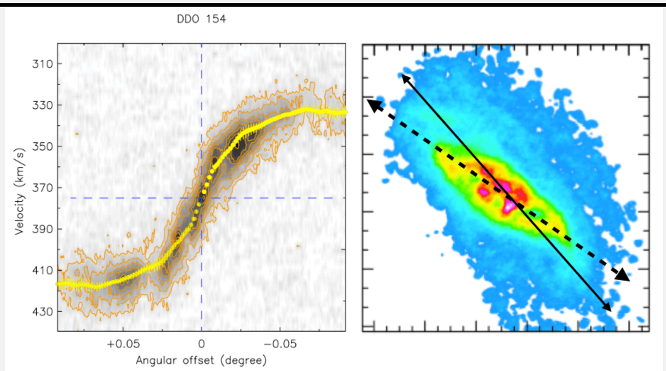
(Widefield ASKAP L-band Legacy All sky Blind surveY)

- Out of ~0.5 million galaxies up to z ~ 0.26
- ~85% poorly resolved (< 3 beams)
- ~14% marginally resolved (~ 3 beams)
- ~5,000 galaxies within 200 Mpc well resolved

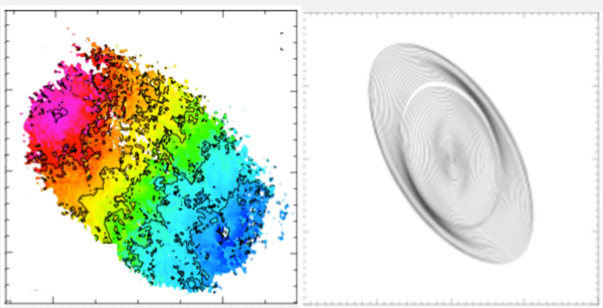


How to derive rotation curves of the resolved WALLABY galaxies?

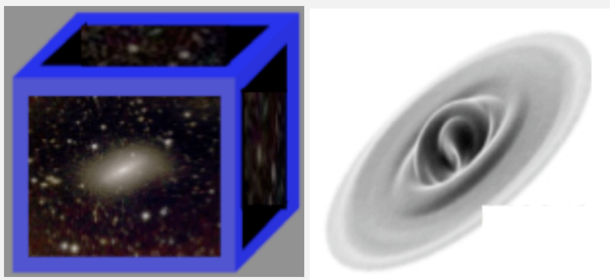
Deriving rotation curves of galaxies



- **1-D : long slit observations**
  - position-velocity diagram
  - major axis cut
  - affected by systematic effects (e.g., non-circular motions, beam smearing etc.)



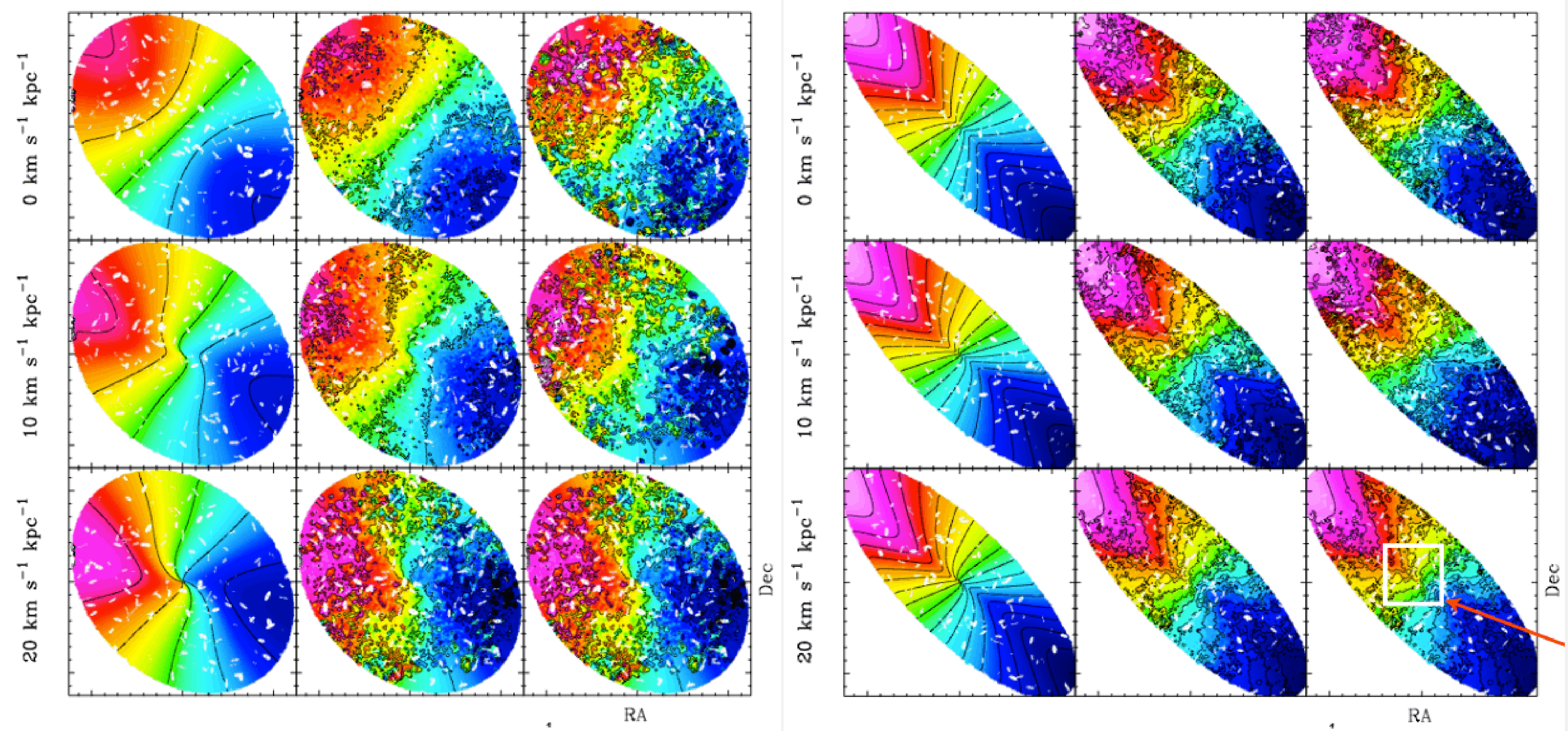
- **2-D : velocity fields**
  - tilted-ring model ("rotcur", Rogstad et al. 1974)
  - flat disk model ("velfit", Spekkens et al. 2007)
  - suited for well-resolved galaxies with moderate inclinations



- **3-D : data cubes**
  - direct fits to data cubes (e.g., "TiRiFiC", Jozsa et al. 2007)
  - fits a larger class of galaxies

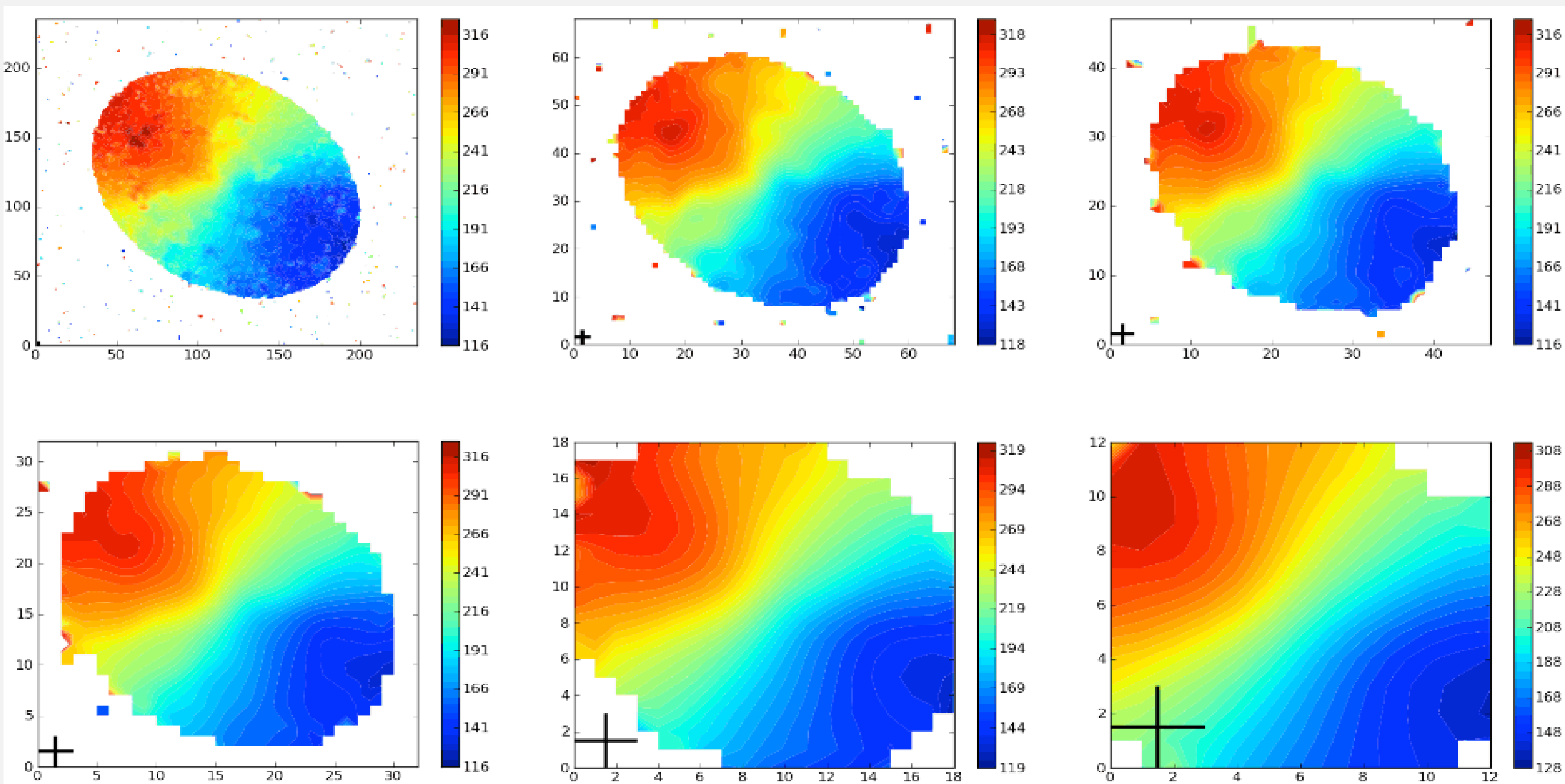
Performance comparison of RC programs
: Artificial data cubes

- **Based on THINGS (e.g., HI column density, velocity dispersion, rotation curves etc.), a suite of model data cubes created..**



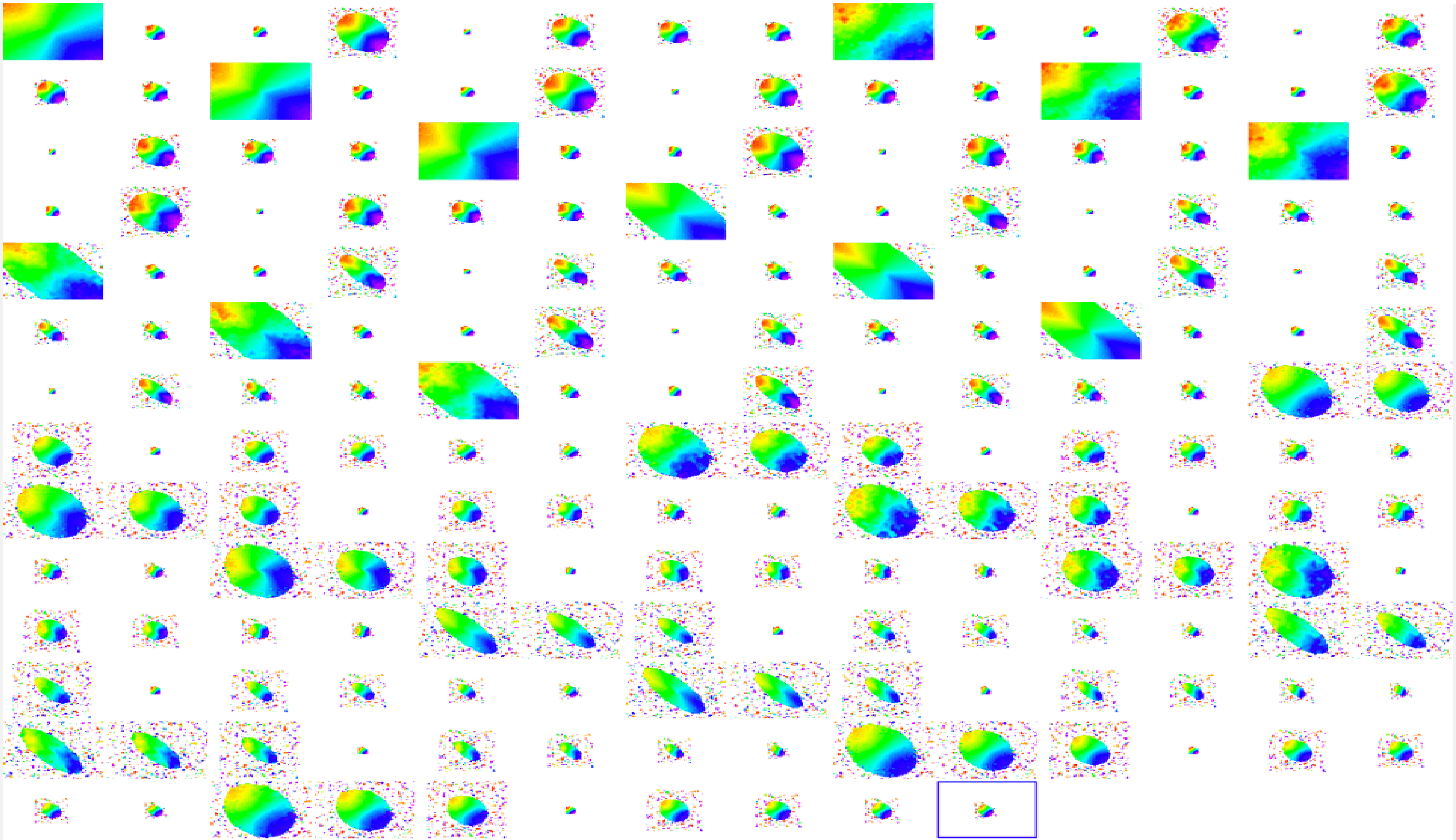
Shifting the model galaxies to 6 redshifts

- **Re-observe the model data cubes with the ASKAP beam (30”) and shift them to 6 different redshifts, and derive rotation curves…**

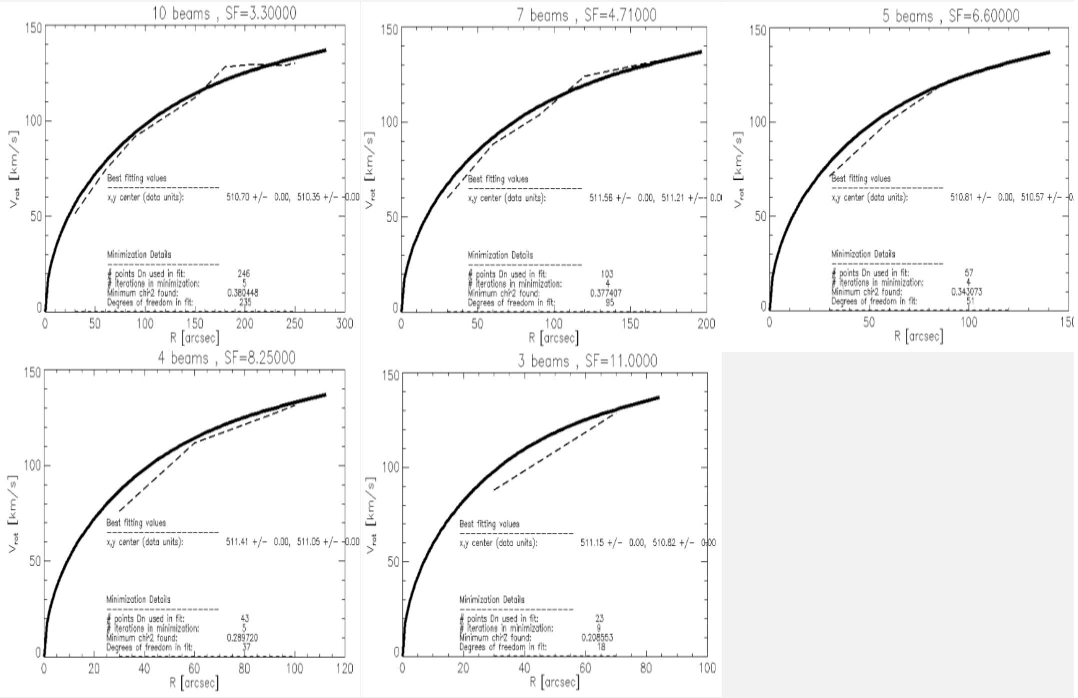


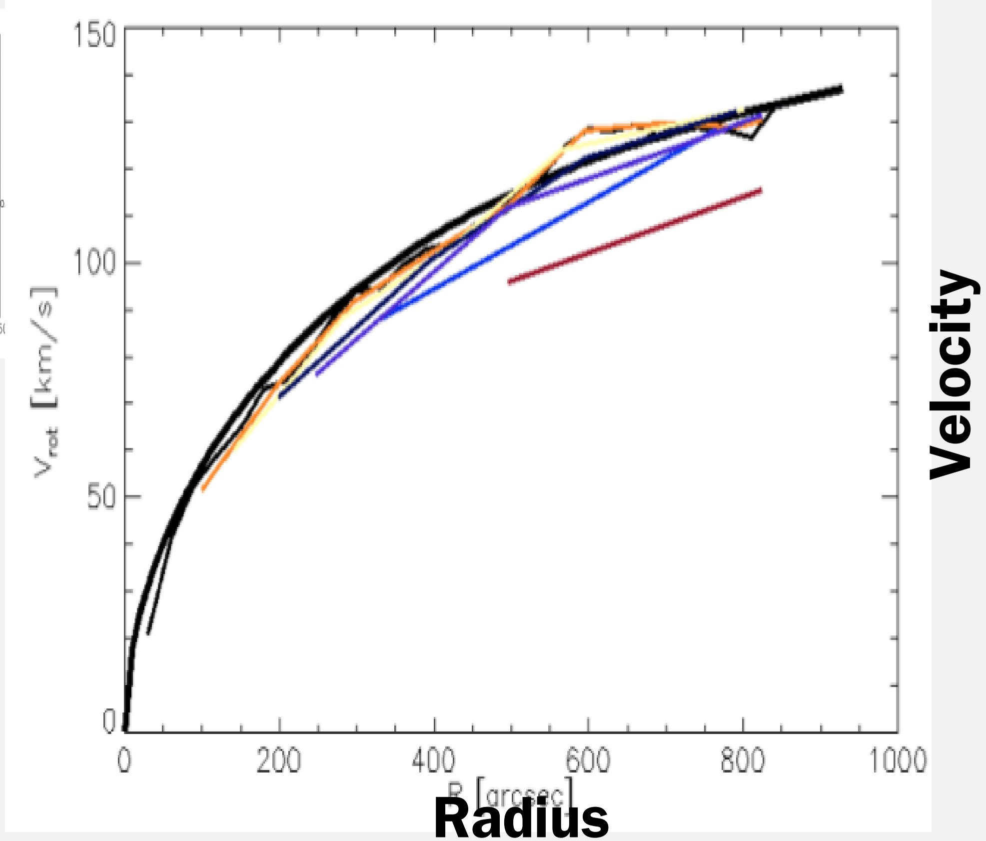
CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

196 model data cubes shifted



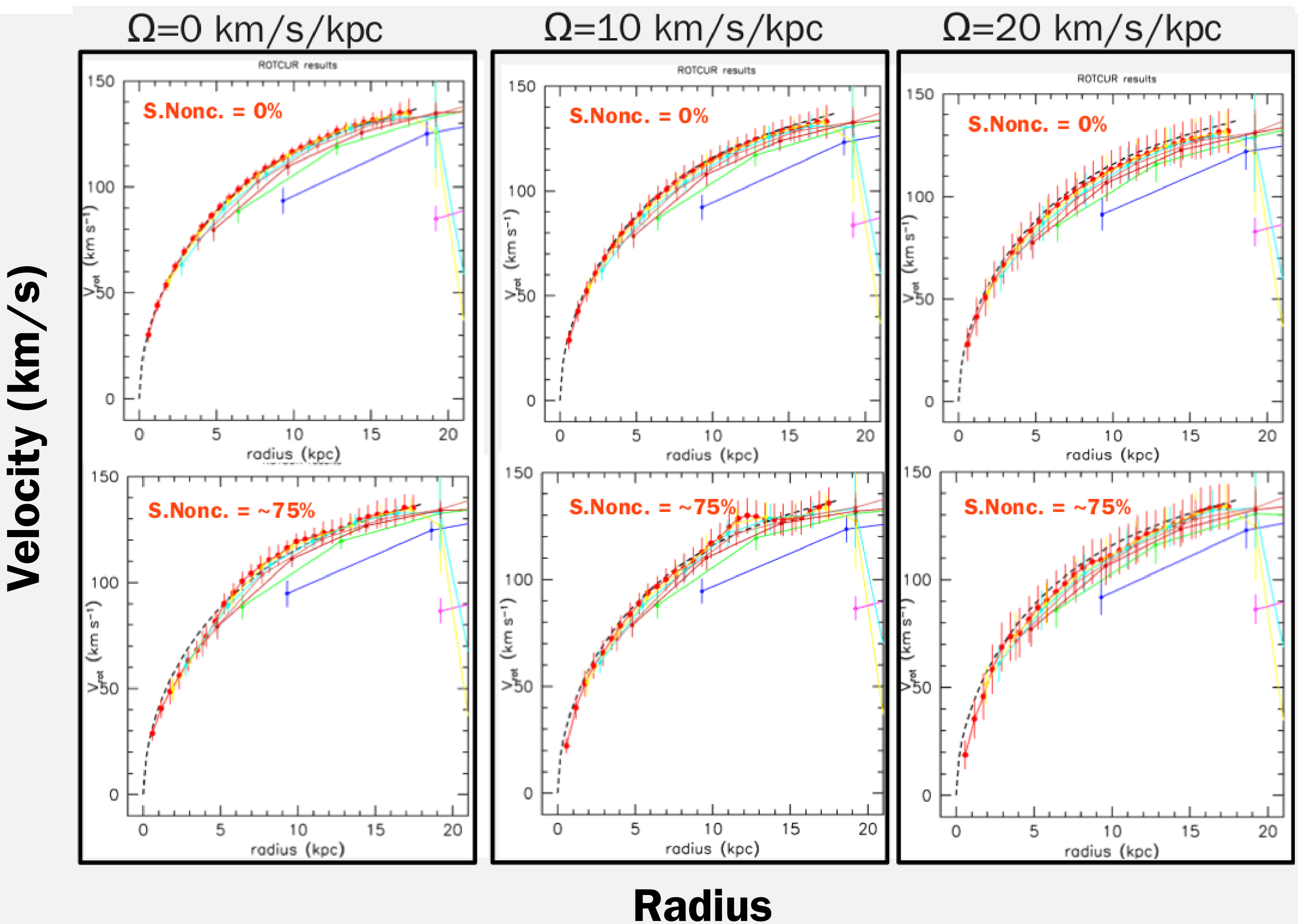
Performance comparison of RC programs : velfit



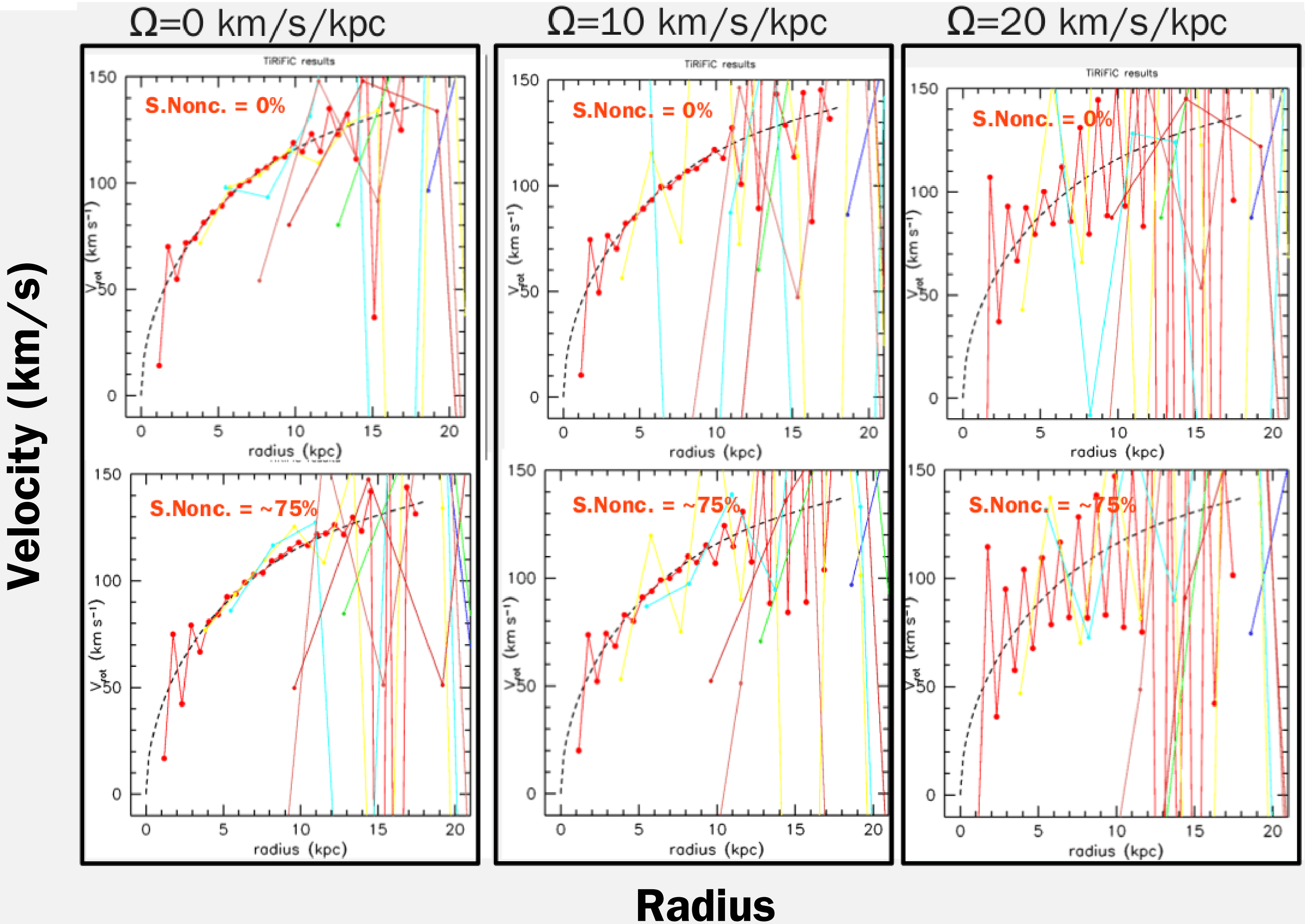


CAASTRO
ARC CENTRE OF EXCELLENCE
FOR ALL-SKY ASTROPHYSICS

Performance comparison of RC programs : rotcur



Performance comparison of RC programs : tirific



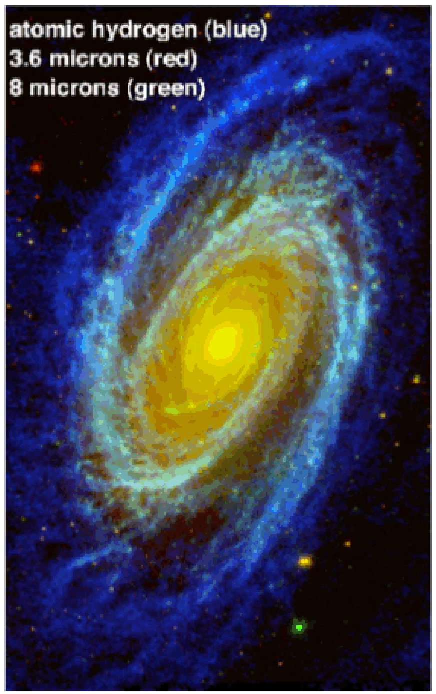
Preliminary results/findings...

- **We now have a machinery in place that will allow us to do:**

  - autonomously produce (realistic) model data cubes
  - autonomously parameterise (rotation curves) galaxies

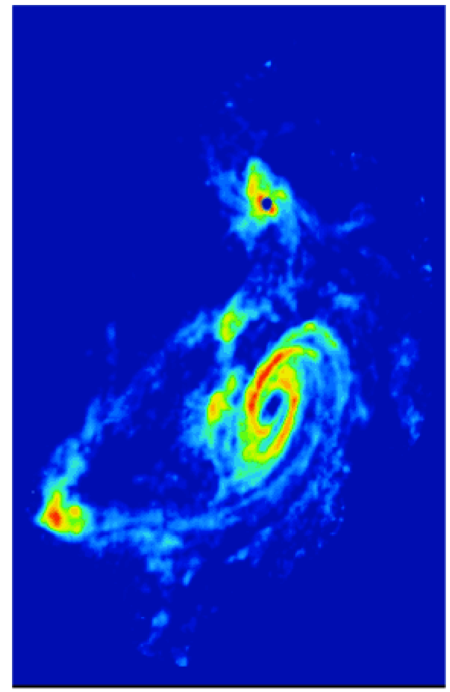
- **We will further expand the parameter space of the model data cube (e.g., inclinations, maximum rotation velocities, sizes etc.)**

The effect of non-circular motions on velocity fields

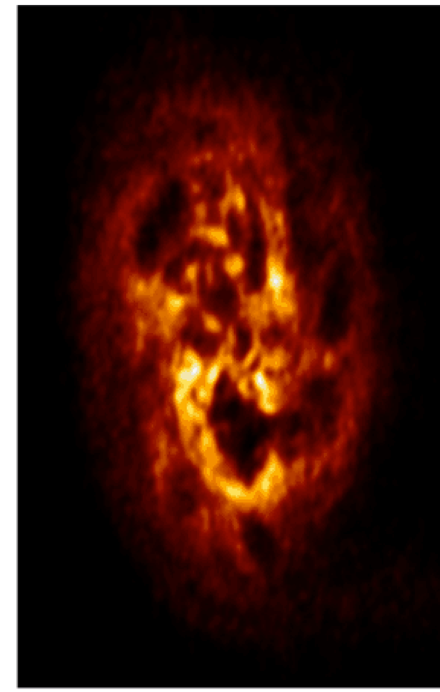


Streaming motions along spiral arms

Streaming motions along bars

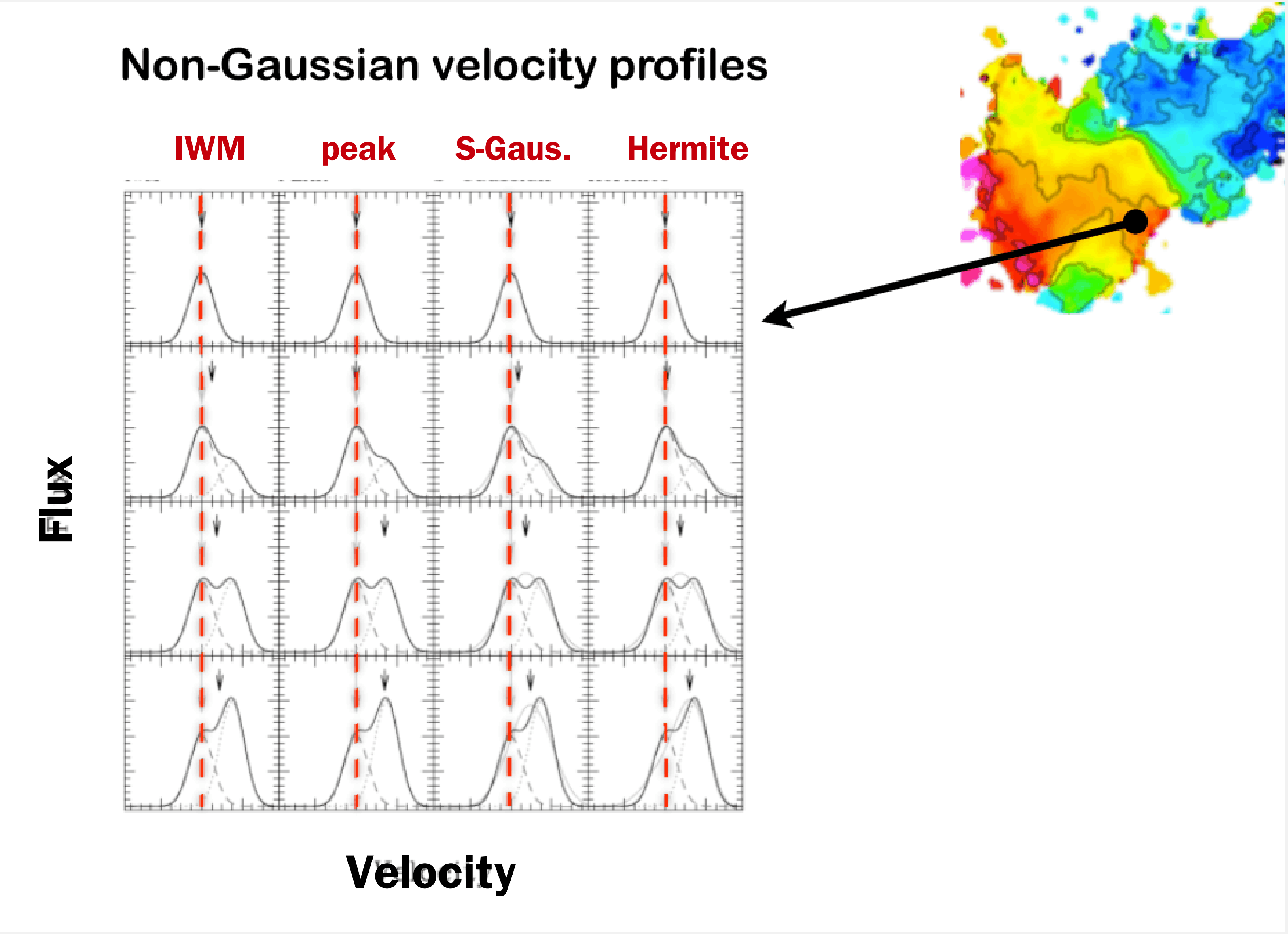


Large-scale asymmetric deviations

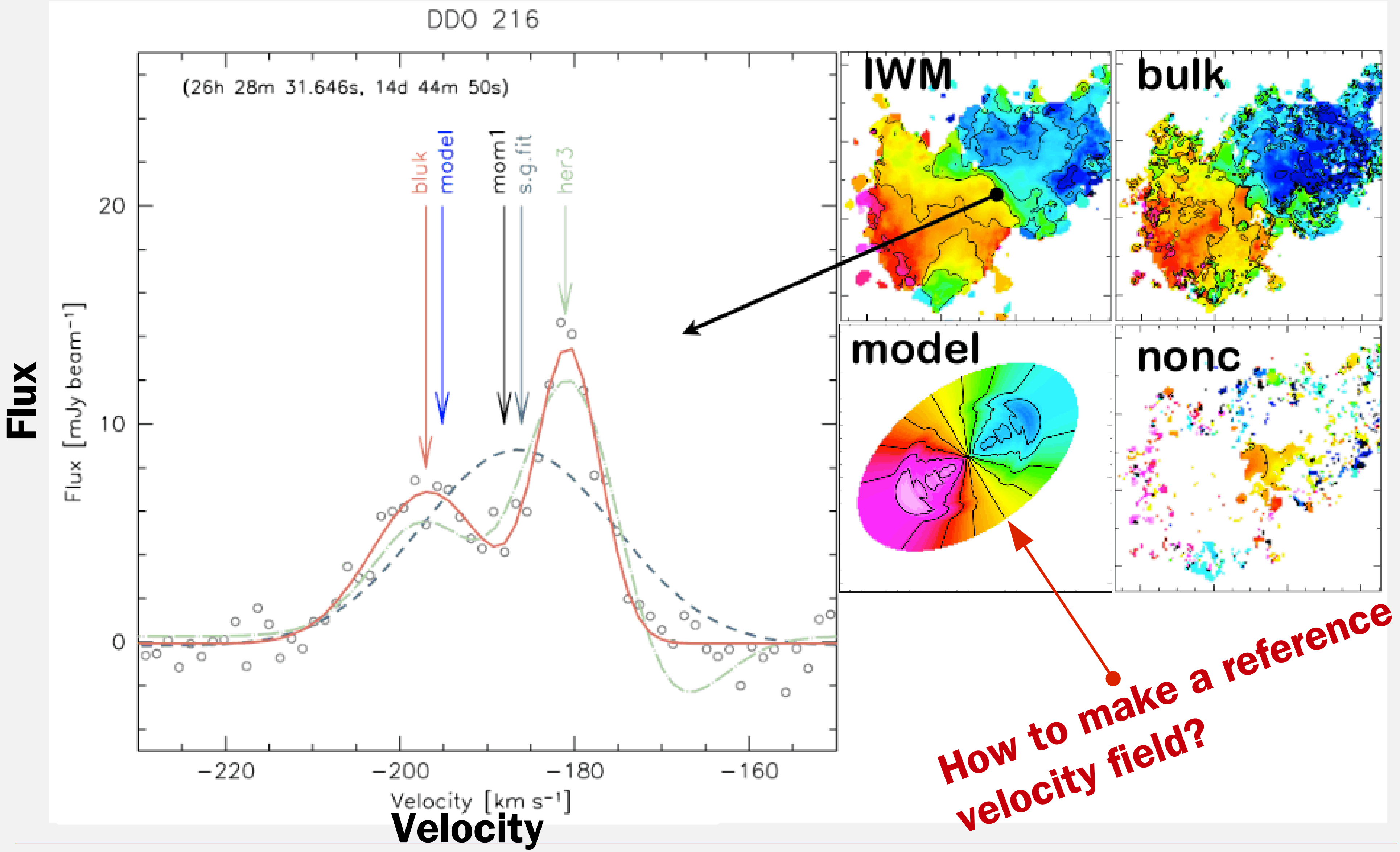


Small-scale asymmetric deviations

Non-Gaussian velocity profiles



Bulk velocity field



Reference velocity field

- **fit a set of general galaxy disk models**

  (e.g., Spekkens et al. 2007)

  - **Solid body model :**

    $$V_{\rm model} = V_{\rm sys} + \sin i \left(\bar{V}_t \cos\theta \right)$$

  - **Radial model :**

    $$V_{\rm model} = V_{\rm sys} + \sin i \left(\bar{V}_t \cos\theta + \bar{V}_r \sin\theta \right)$$

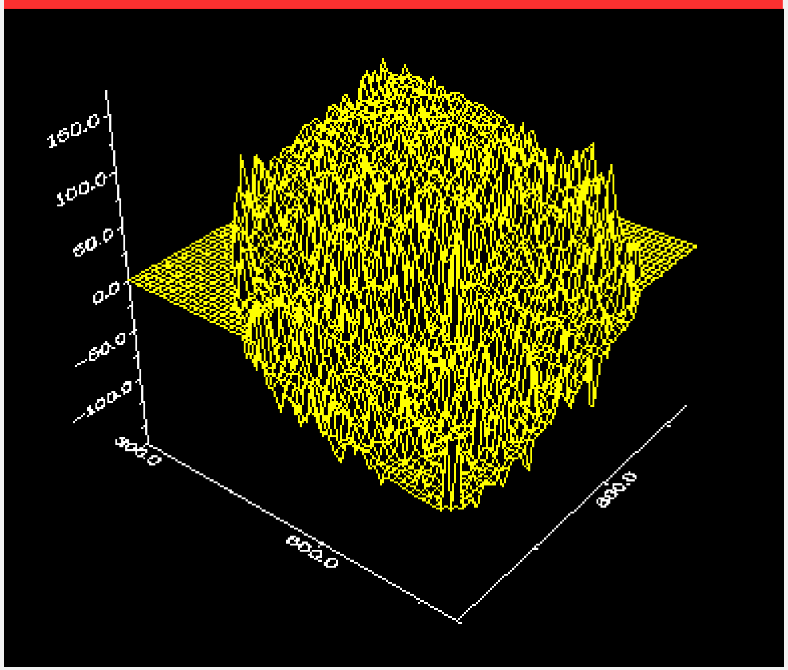
  - **Bisymmetric model :**

    $$V_{\rm model} = V_{\rm sys} + \sin i \left[\bar{V}_t \cos\theta - V_{2,t} \cos(2\theta_b) \cos\theta - V_{2,r} \sin(2\theta_b) \sin\theta \right].$$

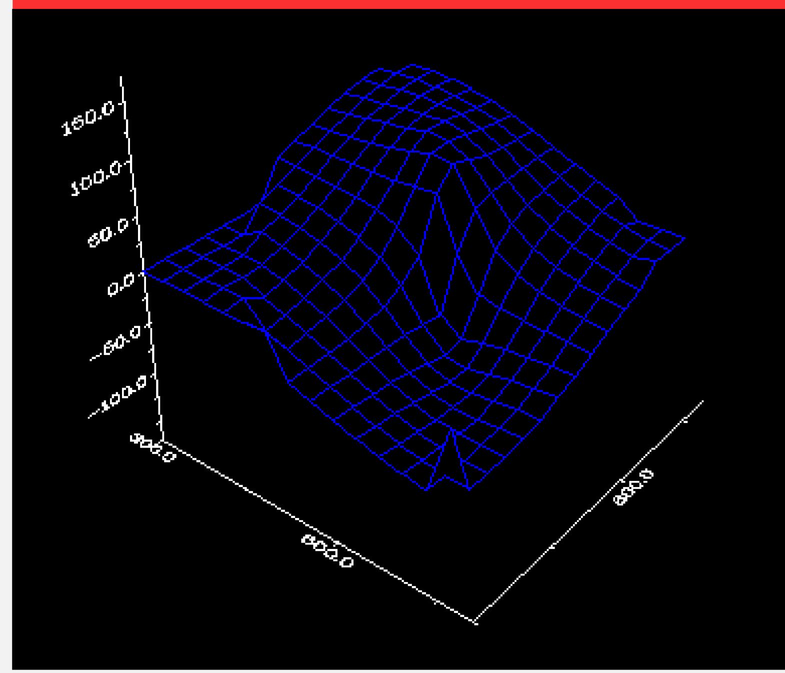
    

Reference velocity field

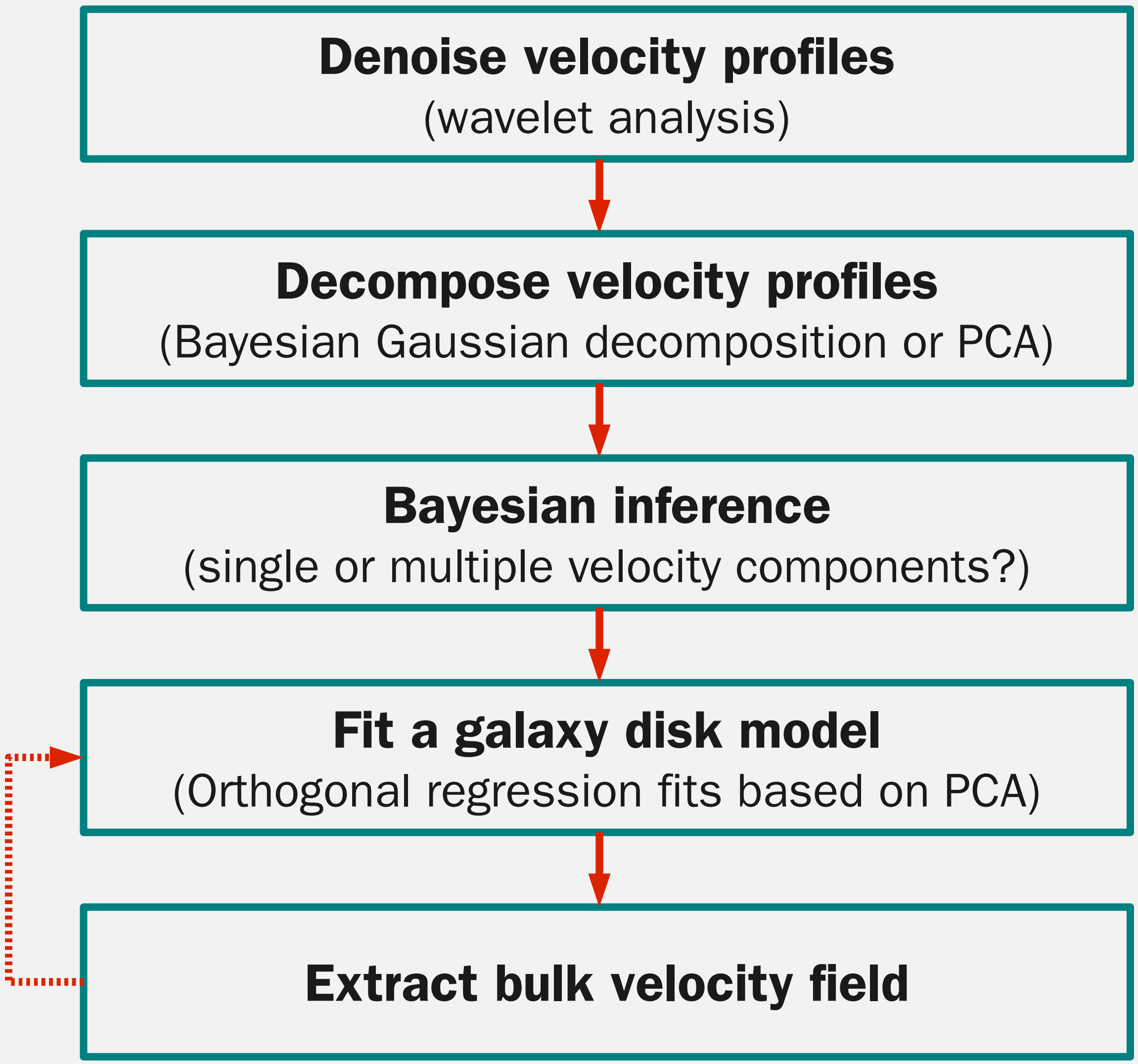
3D plot of the decomposed velocity components



Orthogonal regression surface fit using a solidbody disk model



A schematic flow chart for extracting "bulk" velocity fields



A test python code

- **Bayesian Gaussian fits**

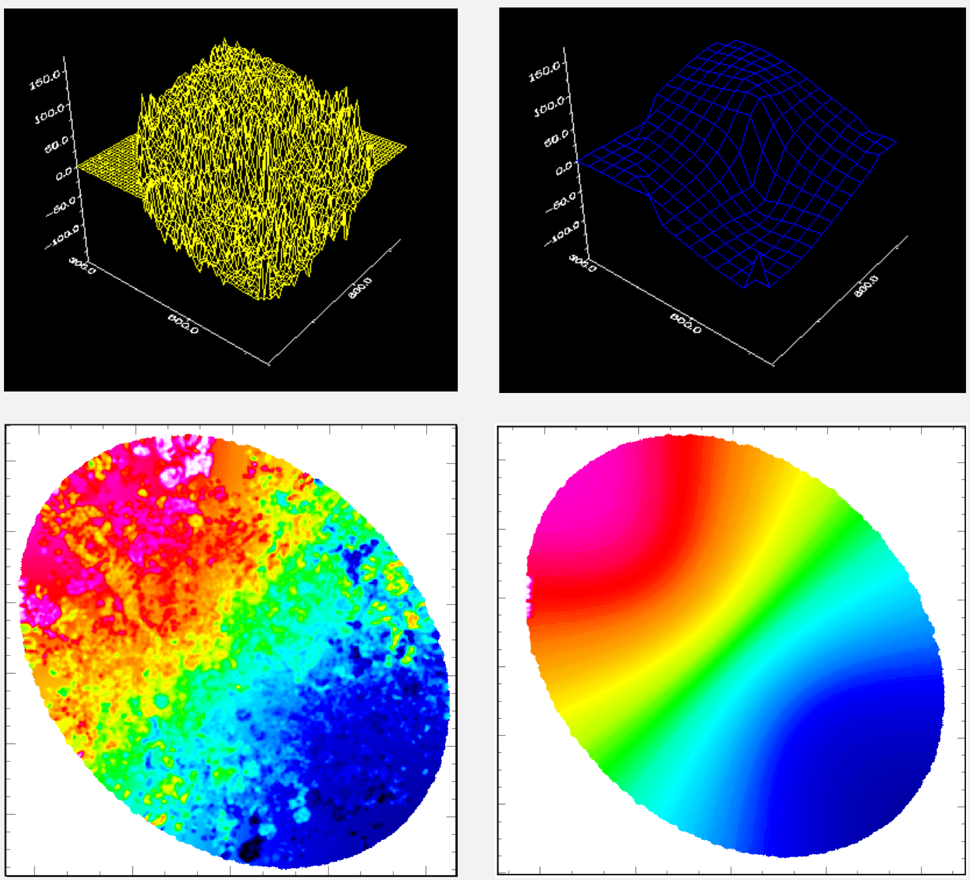
  → python modules: pymc, pyAstronomy

- **bulk_VF_wallaby_V0.9.py**

  → [usage] : python bulk_vf_wallaby_v0.9.py cube.fits 2

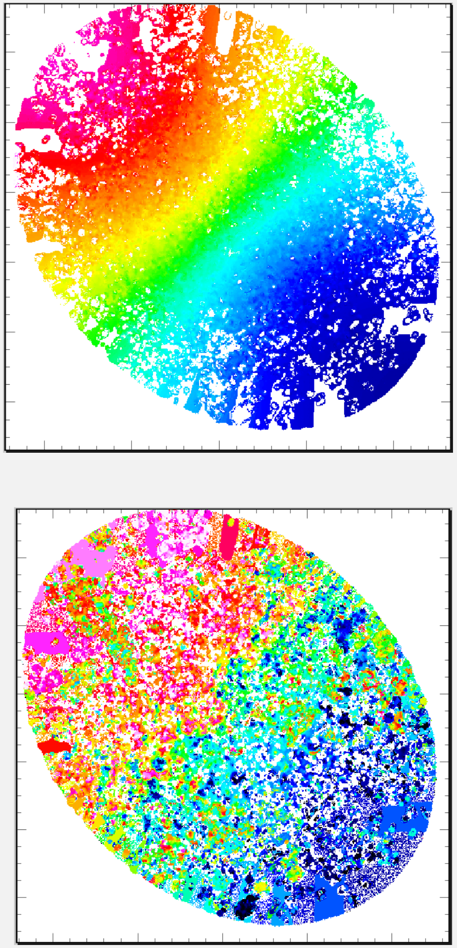
```
Thanks for flying Vim
seheon@darkmatter bayesian]$
seheon@darkmatter bayesian]$
seheon@darkmatter bayesian]$
seheon@darkmatter bayesian]$
seheon@darkmatter bayesian]$ python bulk_VF_wallaby_v0.9.py IA3.14B12X120X20C00S0P45I40D00.SS74.B6.fits 2
```

A test with a model data cube



IWM V.F.

Model V.F.



Bulk V.F.

Nonc V.F.

Summary & Future works

- **The dark matter distribution near the centres of dwarf galaxies are better described by core-like halo models unlike the prediction from dark-matter-only simulations**

- **New SPH simulations including baryonic feedback processes (e.g., SN-driven gas outflows) are better to explain the shallow DM distribution found in nearby dwarf galaxies**

- **More tests on rotation curve programs**

- **More tests on bulk velocity field business**
  - C/C++ modules for Bayesian analysis which is computationally expensive
  - Apply PCA techniques for a reliable profile decomposition
  - Develop bulk_VF_wallaby_v1.0.py

CAASTRO
ARC CENTRE OF EXCELLENCE
FOR ALL-SKY ASTROPHYSICS

Kinematics of Nearby Galaxies in preparation for WALLABY

Se-Heon Oh (ICRAR/UWA)

With

LITTLE THINGS team & WALLABY WG2

ICRAR

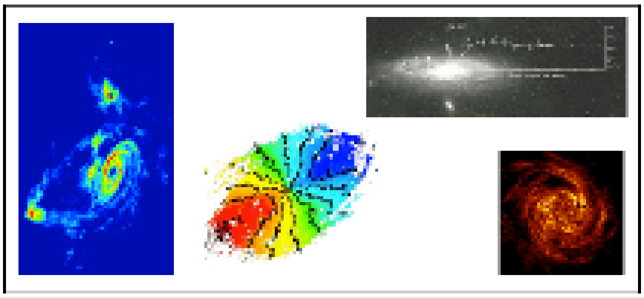
Contents

- HI kinematics of galaxies
- Dark matter distribution in dwarf galaxies
- Progress on WALLABY rotation curve pipeline
- A new approach for extracting bulk velocity fields
- Summary & future works

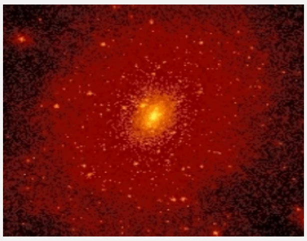
CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

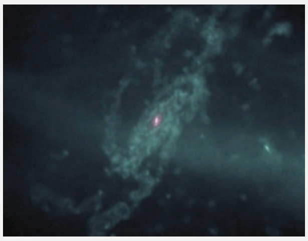
HI kinematics of resolved galaxies

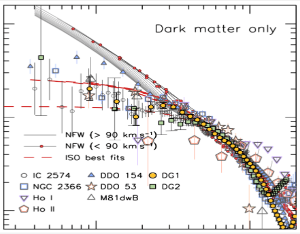
- **Dynamical structure** : (dark) matter distribution in galaxies
- **Interplay between ISM and star formation** on small (sub-kpc) scales
- **Dynamical information about galaxy evolution** : warps, bars, spiral arms, tidal interaction, HVCs etc.



Small-scale problems in ΛCDM simulations

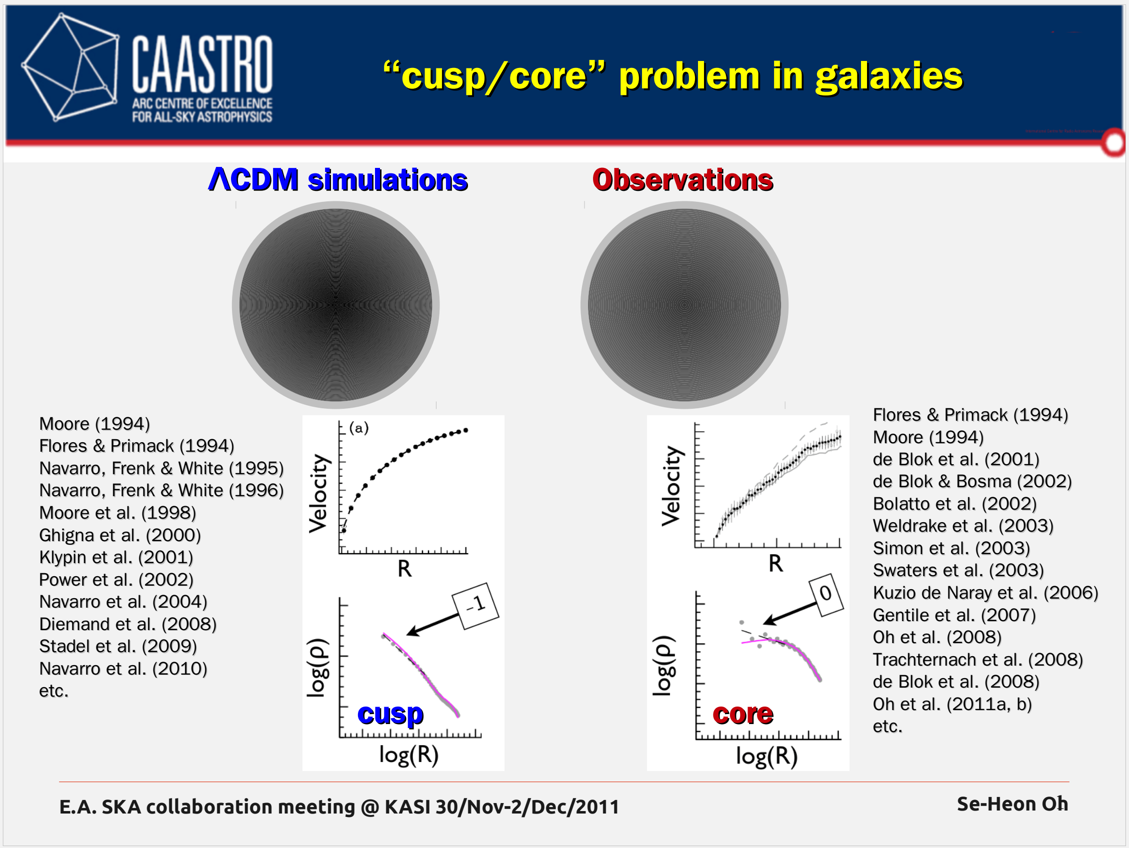






- **Missing satellites problem**
- **Angular momentum problem**
- **“cusp/core” problem**

▪

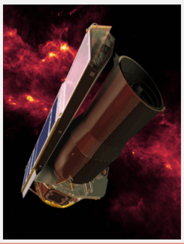

CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS
"cusp/core" problem in galaxies
ΛCDM simulations
Observations
Moore (1994)
Flores & Primack (1994)
Navarro, Frenk & White (1995)
Navarro, Frenk & White (1996)
Moore et al. (1998)
Ghigna et al. (2000)
Klypin et al. (2001)
Power et al. (2002)
Navarro et al. (2004)
Diemand et al. (2008)
Stadel et al. (2009)
Navarro et al. (2010)
etc.
Velocity
R
(a)
log(ρ)
log(R)
-1
cusp
Velocity
R
log(ρ)
log(R)
0
core
Flores & Primack (1994)
Moore (1994)
de Blok et al. (2001)
de Blok & Bosma (2002)
Bolatto et al. (2002)
Weldrake et al. (2003)
Simon et al. (2003)
Swaters et al. (2003)
Kuzio de Naray et al. (2006)
Gentile et al. (2007)
Oh et al. (2008)
Trachternach et al. (2008)
de Blok et al. (2008)
Oh et al. (2011a, b)
etc.
E.A. SKA collaboration meeting @ KASI 30/Nov-2/Dec/2011
Se-Heon Oh

s.

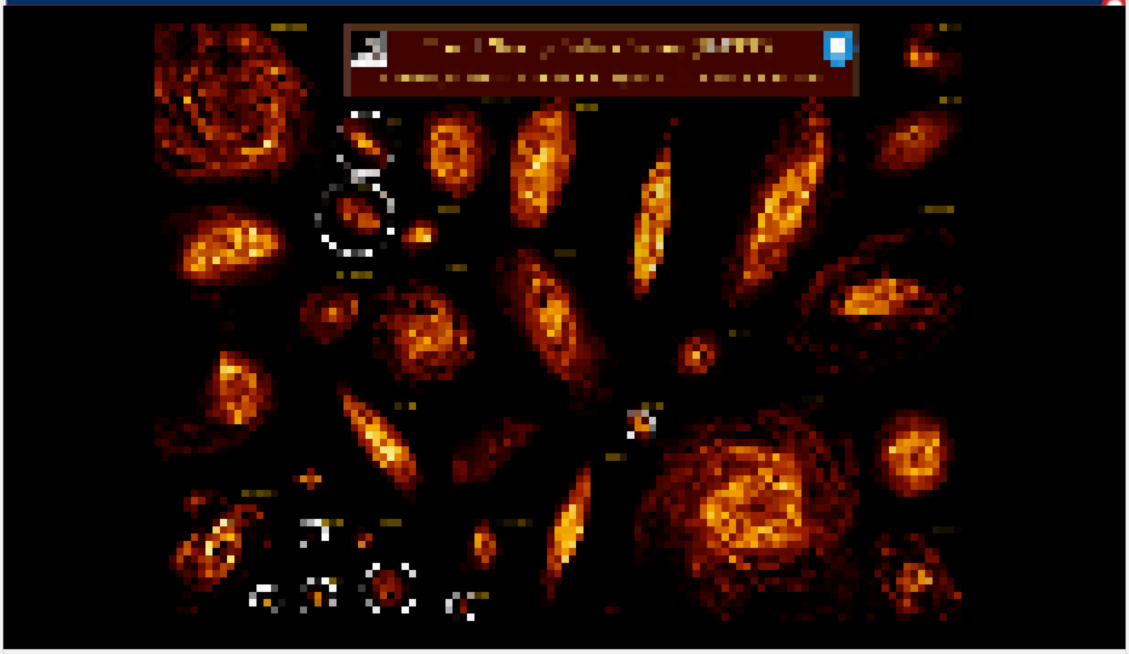
CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

The HI Nearby Galaxy Survey (THINGS)

- VLA HI 21-cm survey (~6"; 5.2 km/s; ~500 hours) of nearby (< 10 Mpc) 34 galaxies
- Commensality with optical, Spitzer SINGS, GALEX uv, CO data etc.)
- All observations ended in late 2005
- Data available at http://www.mpia.de/THINGS

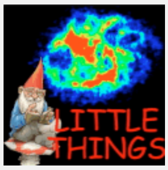


The HI Nearby Galaxy Survey (THINGS)



LITTLE THINGS (Local Irregulars That Trace Luminosity Extremes The HI Nearby Galaxy Survey)

- THINGS-like (~6”; < 5.2 km/s) high-resolution VLA HI 21cm survey (B+C+D; 376 hours) for 41 nearby (< 10 Mpc) dwarf (dIm, BCD) galaxies
- Commensality with Spitzer (+ Herschel) optical, GALEX uv, CO data etc.)
- VLA observations ended in 2008
- Further observations with EVLA, CARMA, APEX etc.

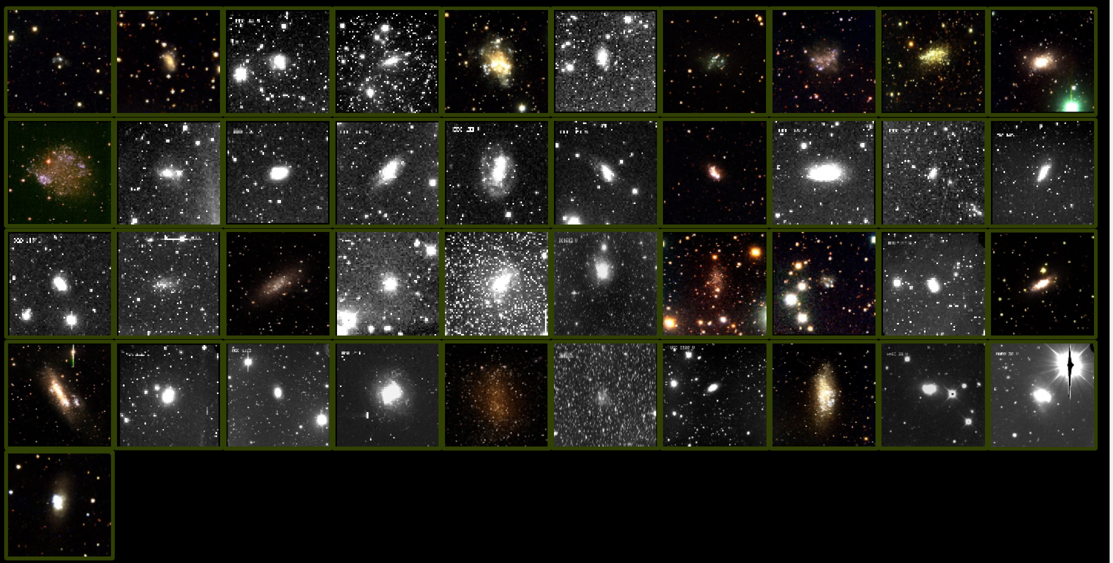


LITTLE THINGS

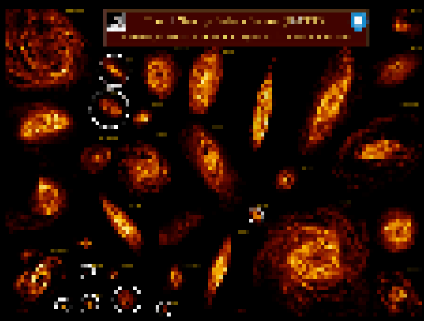
Deidre Hunter (PI. Lowell obs)
Elias Brinks (Univ. of Hertf.)
Bruce Elmegreen (IBM)
Michael Rupen (NRAO)
Caroline Simpson (Florida Univ.)
Fabian Walter (MPIA)
David Westpfahl (NMT)
Lisa Young (NMT)
Trisha Ashley (Florida Int. Univ.)
Sandipan Basu (Florida Int. Univ.)
Phil Cigan (NMT)
Dana Ficut-Vicus (Univ. of Hertf.)
Volker Heesen (Univ. of Hertf.)
Kim Herrmann (Lowell Obs)
Megan Jackson (Lowell Obs)
Se-Heon Oh (ICRAR/UWA)
Andreas Schruba (MPIA)
Hongxin Zhang (Lowell Obs)

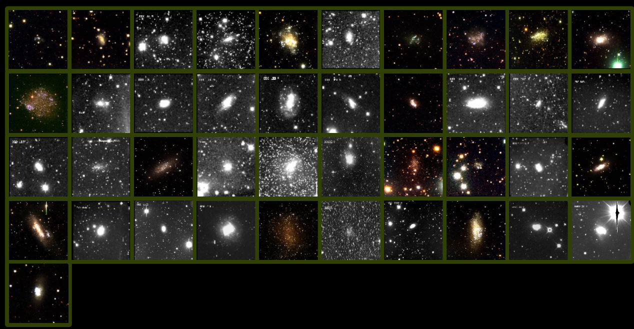
3rd team meeting in Socorro 27-29 Mar 2011

LITTLE THINGS sample galaxies



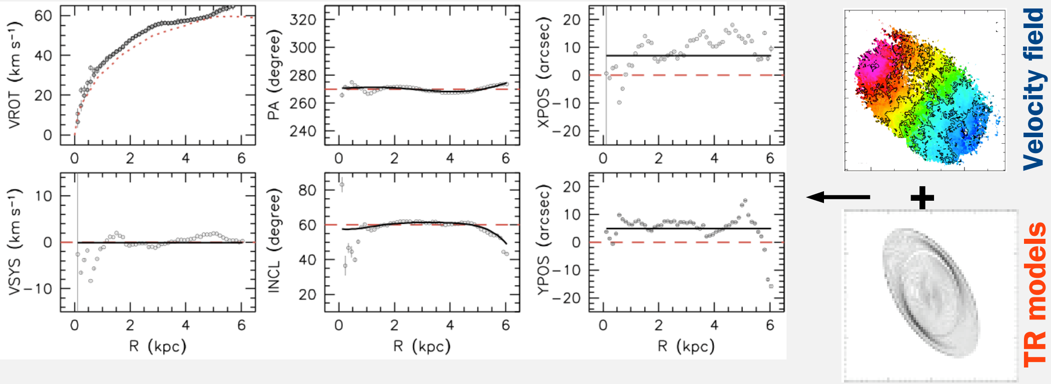
Dark matter distribution in (LITTLE) THINGS dwarf galaxies





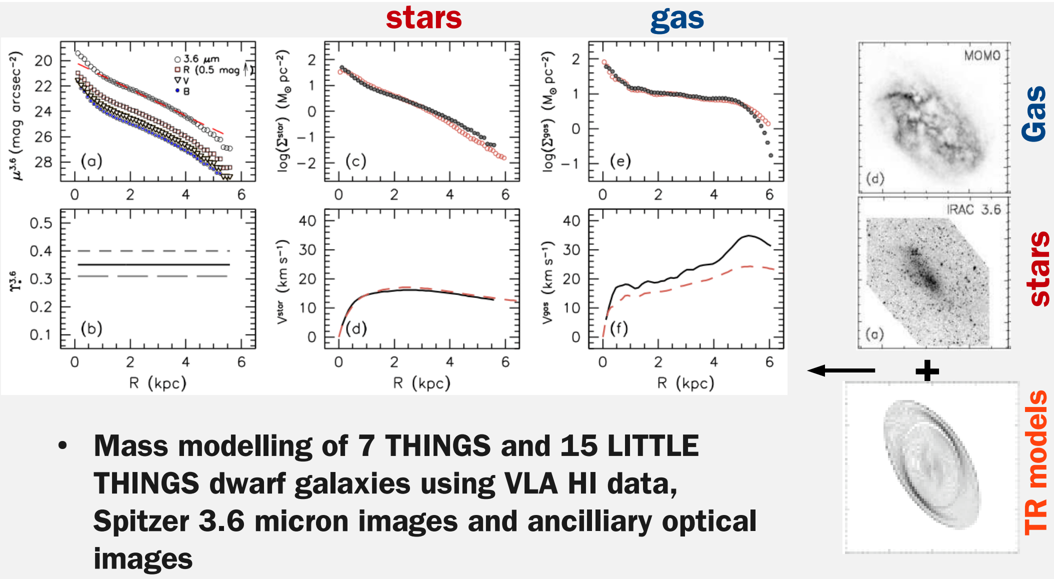
CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

I. Deriving rotation curves



- **Fit tilted-ring models to 2D velocity fields**
  (e.g., Rogstad et al. 1974; "rotcur" in GIPSY)

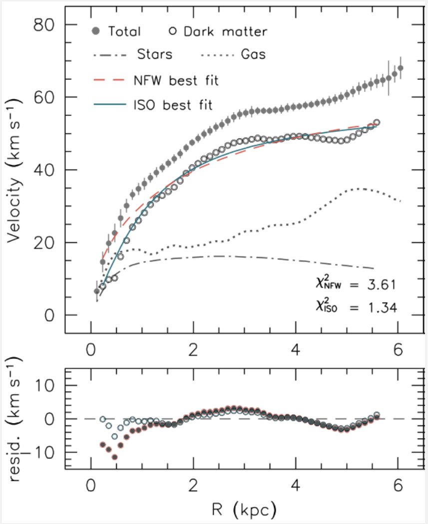
II. Deriving mass models of baryons



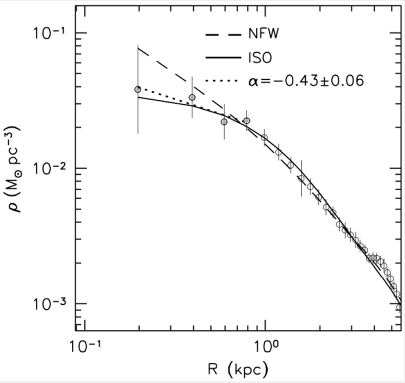
- **Mass modelling of 7 THINGS and 15 LITTLE THINGS dwarf galaxies using VLA HI data, Spitzer 3.6 micron images and ancilliary optical images**

III. Deriving dark matter density profiles

Disk-halo decomposition



Dark matter density profile

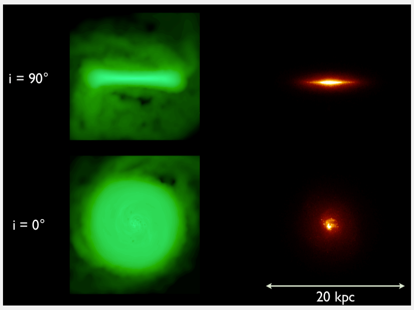


$$\rho(R) = \frac{1}{4\pi G}\left[2\frac{V}{R}\frac{\partial V}{\partial R} + \left(\frac{V}{R}\right)^2\right]$$

New high-resolution SPH-ΛCDM simulations of dwarf galaxies (Governato et al. 2010)

- N-body+SPH tree-code GASOLINE
- Flat Λ-dominated cosmology
- Baryonic processes are included, such as
  - gas cooling
  - cosmic UV field heating
  - star formation
  - SNe-driven gas outflows

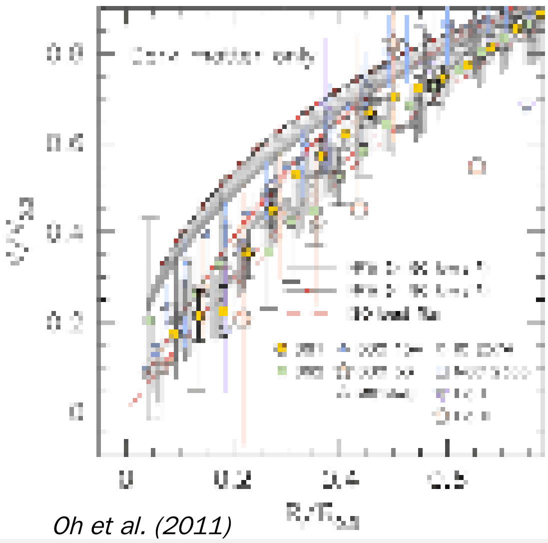
HI 21cm   3.6 micron



- ~3.3 million particles within the virial radius at z = 0.
- DM ~ $1.6\times10^4\ M_\odot$; gas particle ~ $3.3\times10^3\ M_\odot$
- The force resolution (gravitational softening) ~ 86 pc.

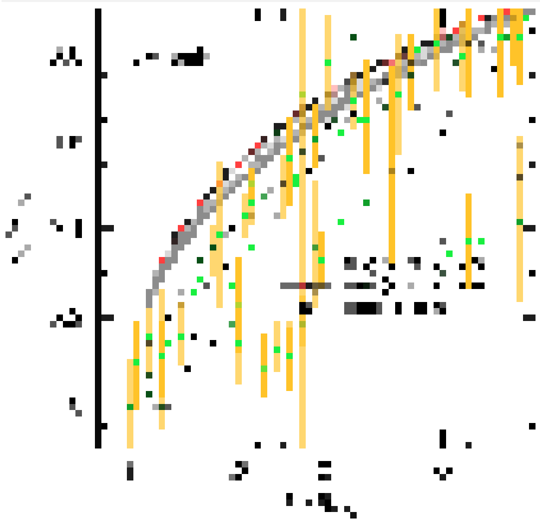
The rotation curve shape of THINGS & LITTLE THINGS

7 THINGS + new SPH simulations



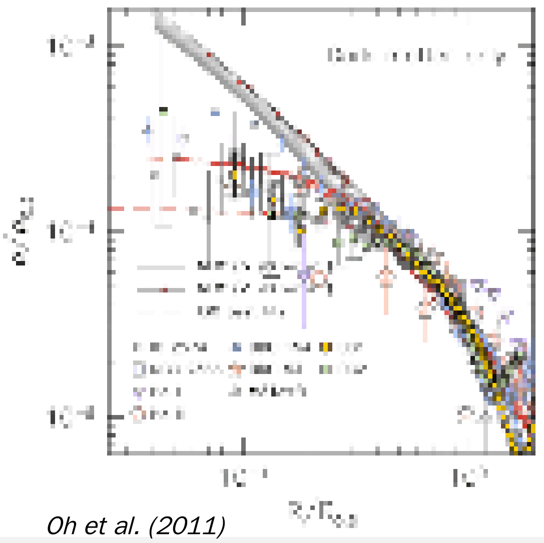
Oh et al. (2011)

15 LITTLE THINGS



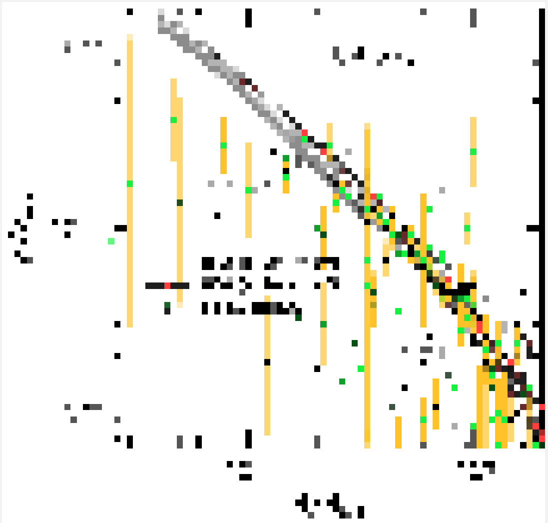
Dark matter density profiles of THINGS & LITTLE THINGS

7 THINGS + new SPH simulations

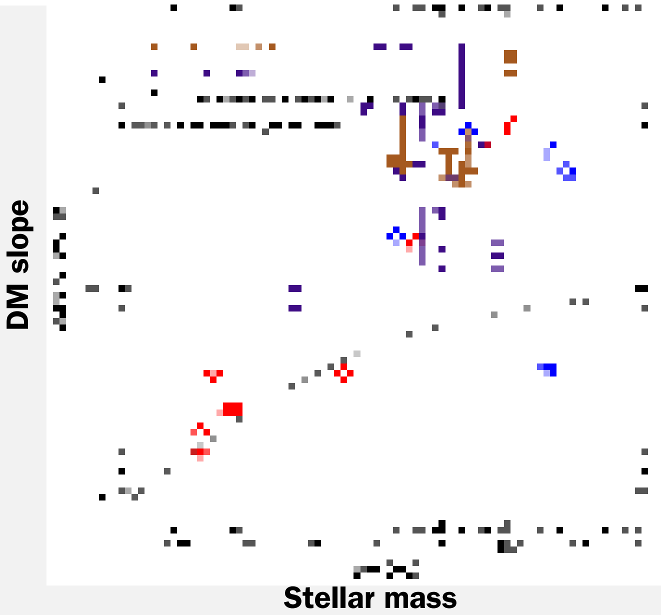


Oh et al. (2011)

15 LITTLE THINGS



DM slope as a function of stellar mass



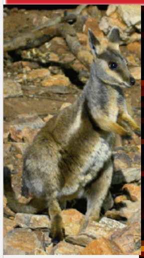
- Gas outflows get less efficient in smaller galaxies so cores at fixed radius get smaller…

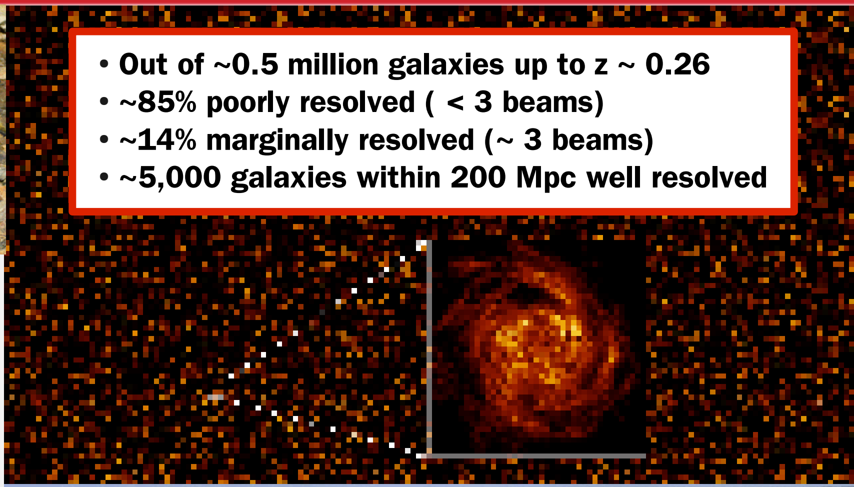
- **SN driven gas outflows** in the early Universe can be a solution for the "cusp/core" controversy

Oh et al. in prep.

ASKAP WALLABY survey

(Widefield ASKAP L-band Legacy All sky Blind surveY)

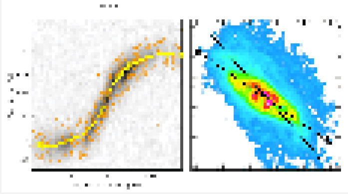




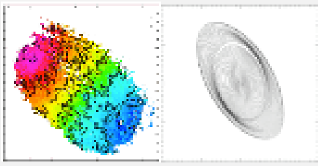
- Out of ~0.5 million galaxies up to z ~ 0.26
- ~85% poorly resolved (< 3 beams)
- ~14% marginally resolved (~ 3 beams)
- ~5,000 galaxies within 200 Mpc well resolved

How to derive rotation curves of the resolved WALLABY galaxies?

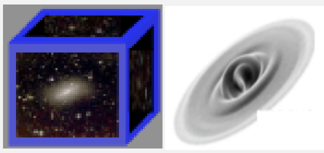
Deriving rotation curves of galaxies



- **1-D : long slit observations**
  - position-velocity diagram
  - major axis cut
  - affected by systematic effects (e.g., non-circular motions, beam smearing etc.)



- **2-D : velocity fields**
  - tilted-ring model ("rotcur", Rogstad et al. 1974)
  - flat disk model ("velfit", Spekkens et al. 2007)
  - suited for well-resolved galaxies with moderate inclinations

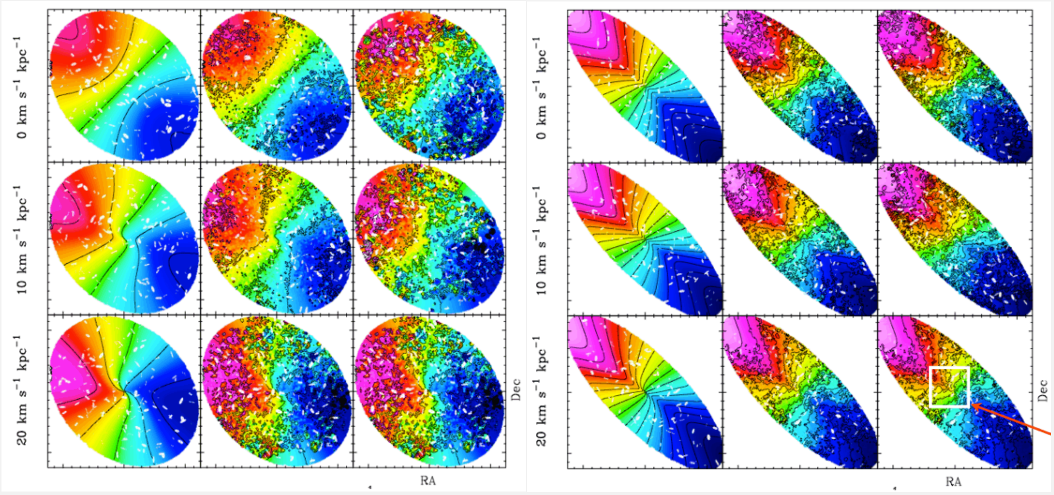


- **3-D : data cubes**
  - direct fits to data cubes (e.g., "TiRiFiC", Jozsa et al. 2007)
  - fits a larger class of galaxies

Performance comparison of RC programs : Artificial data cubes

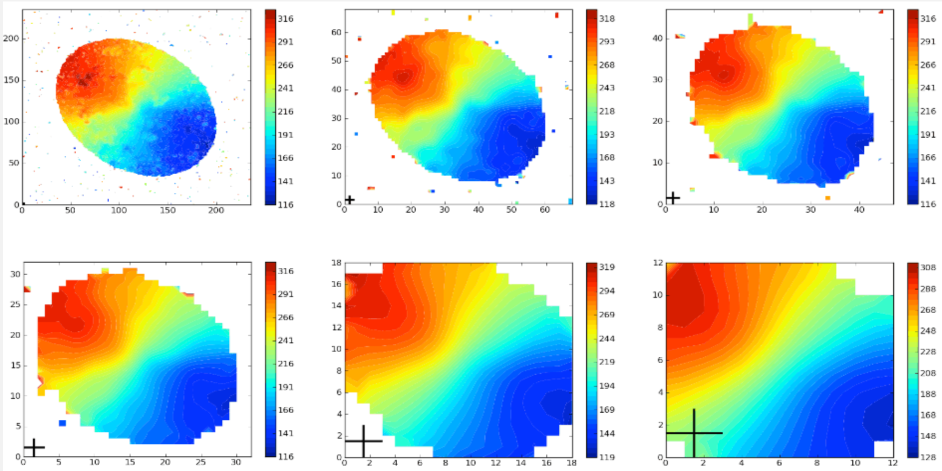
CAASTRO ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

- **Based on THINGS (e.g., HI column density, velocity dispersion, rotation curves etc.), a suite of model data cubes created..**

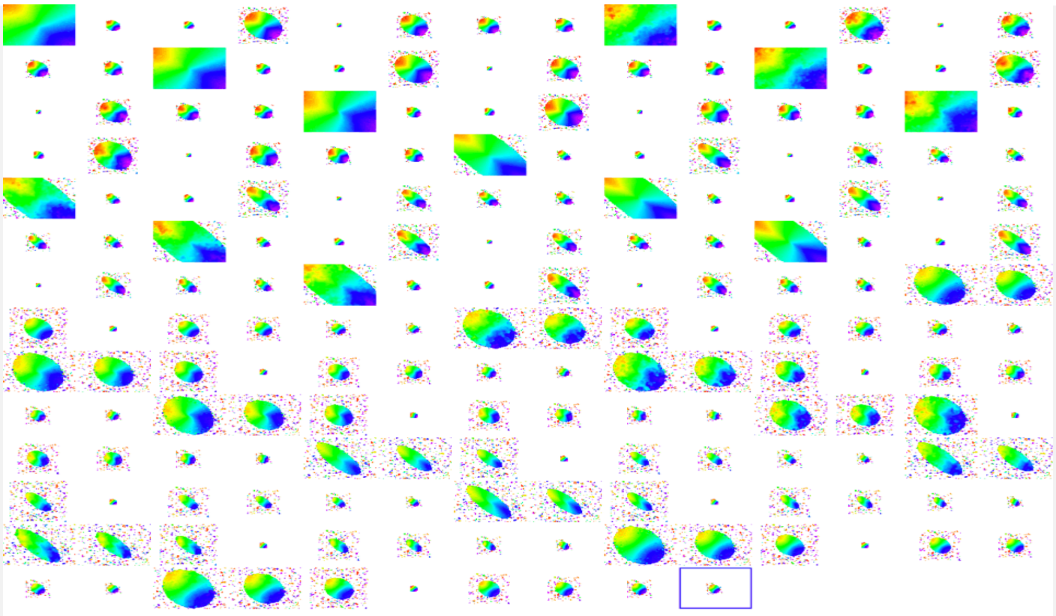


Shifting the model galaxies to 6 redshifts

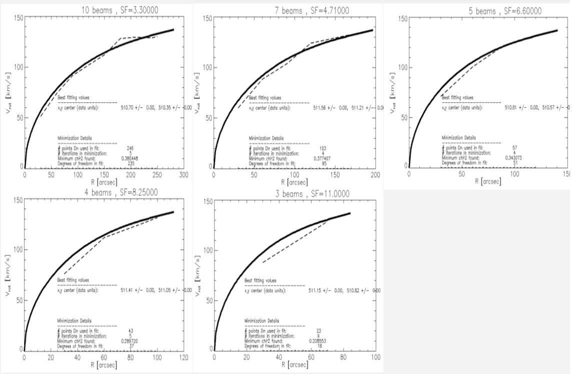
- **Re-observe the model data cubes with the ASKAP beam (30”) and shift them to 6 different redshifts, and derive rotation curves…**

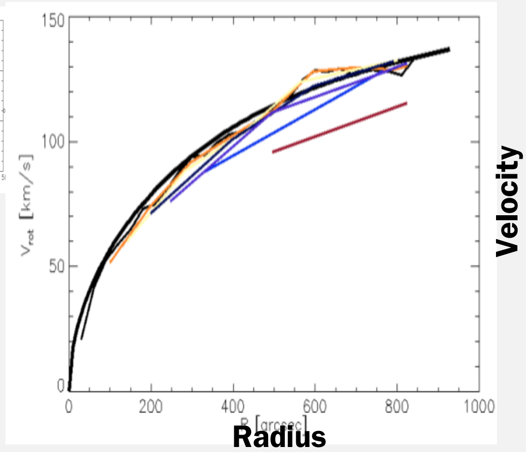


196 model data cubes shifted

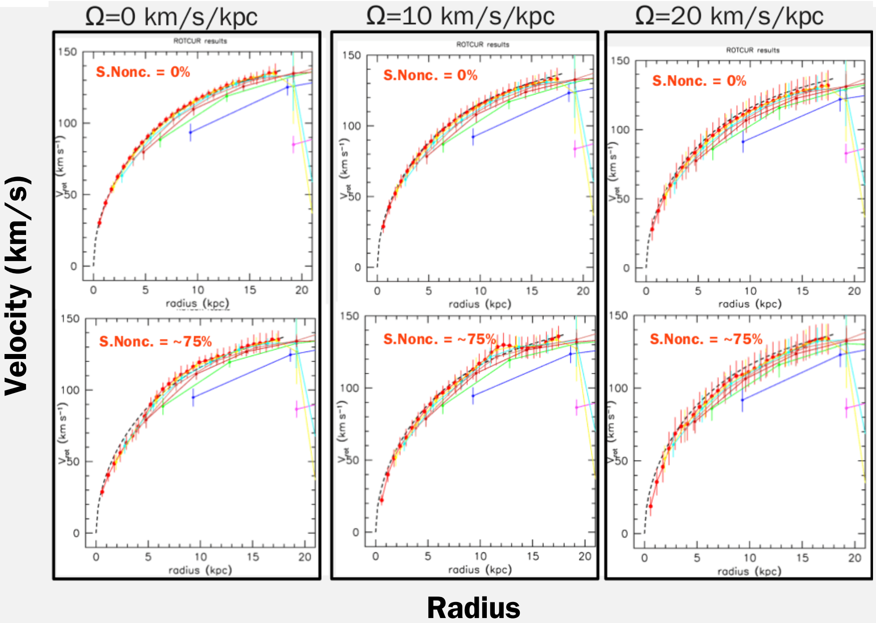


Performance comparison of RC programs : velfit

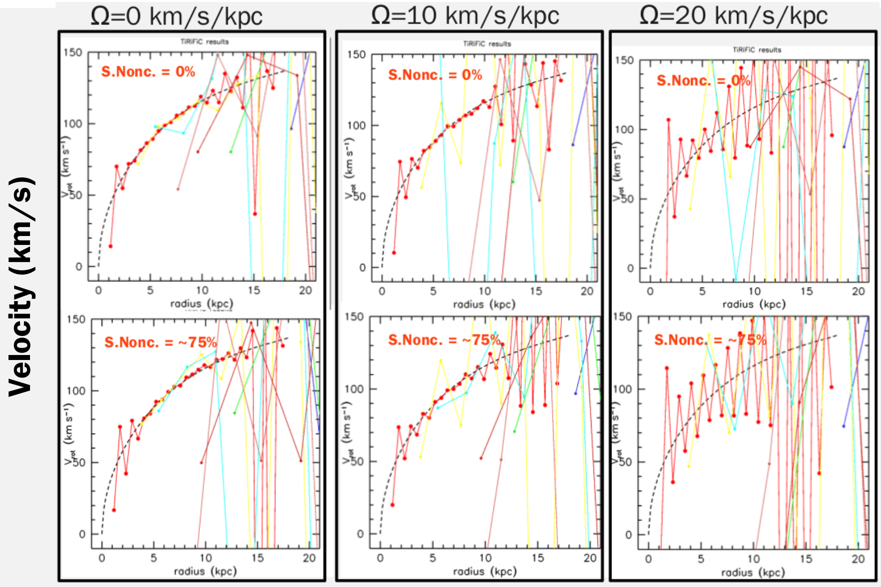




Performance comparison of RC programs : rotcur



Performance comparison of RC programs : tirific



CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

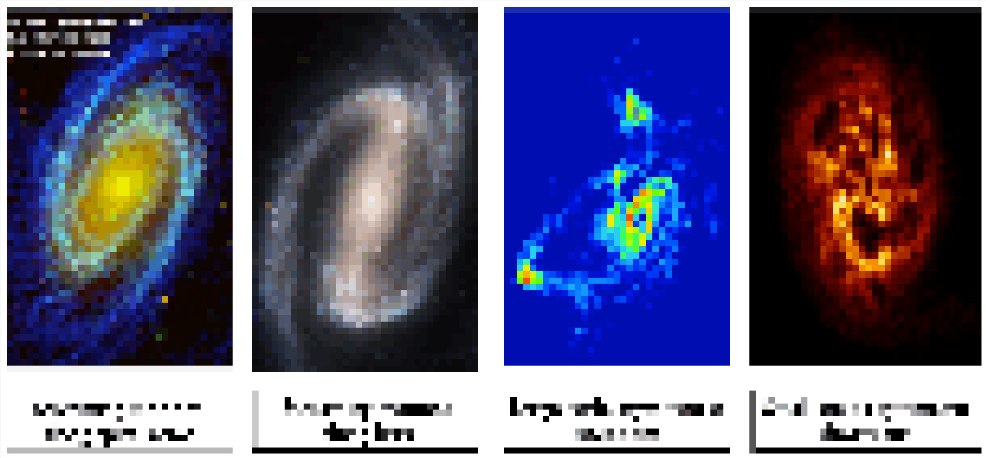
Preliminary results/findings...

- **We now have a machinery in place that will allow us to do:**

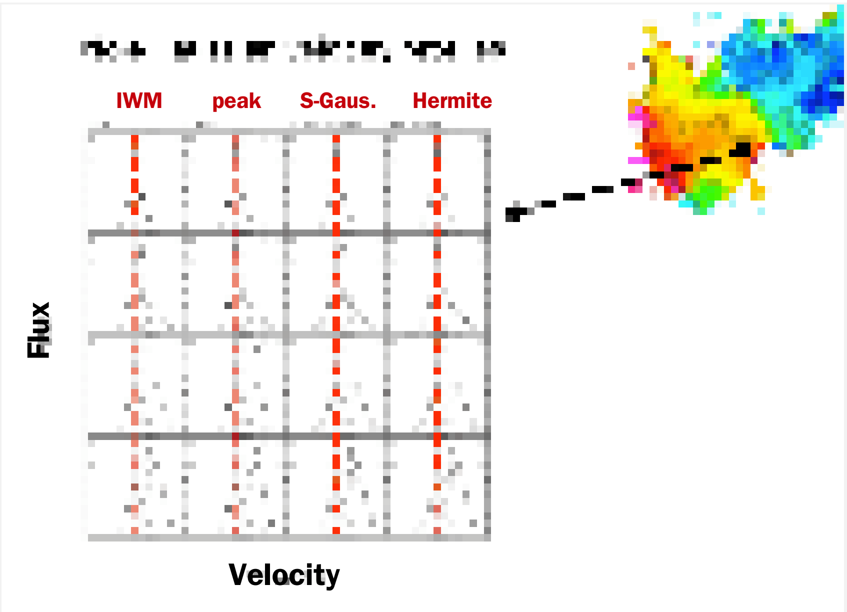
  - autonomously produce (realistic) model data cubes
  - autonomously parameterise (rotation curves) galaxies

- **We will further expand the parameter space of the model data cube (e.g., inclinations, maximum rotation velocities, sizes etc.)**

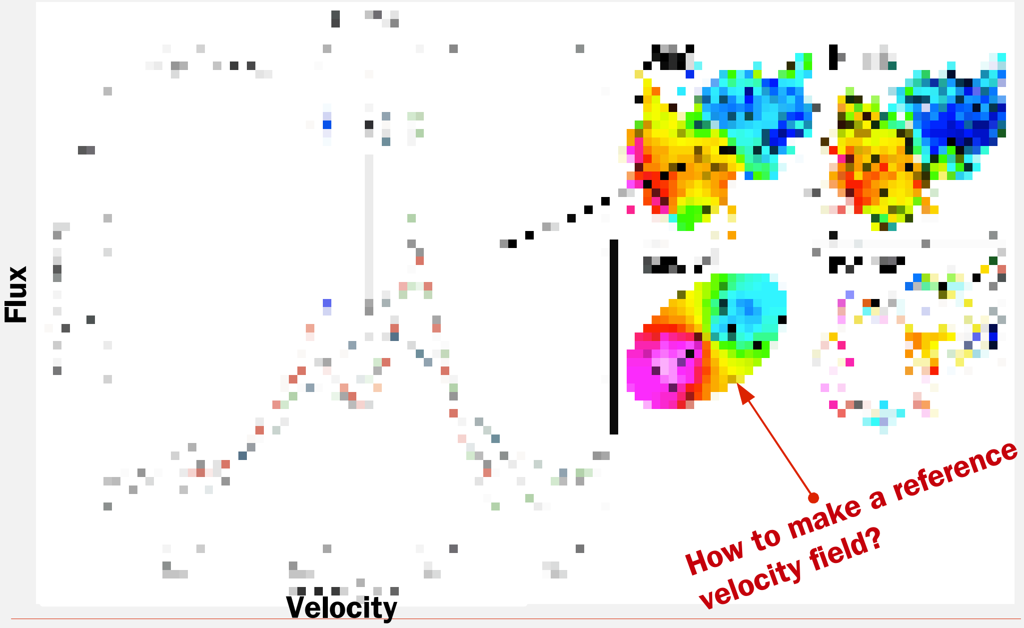
The effect of non-circular motions on velocity fields



Non-Gaussian velocity profiles



Bulk velocity field



Reference velocity field

- **fit a set of general galaxy disk models**
  (e.g., Spekkens et al. 2007)

  - **Solid body model :** $V_{\mathrm{model}} = V_{\mathrm{sys}} + \sin i\left(\bar{V}_t \cos\theta\right)$

  - **Radial model :** $V_{\mathrm{model}} = V_{\mathrm{sys}} + \sin i\left(\bar{V}_t \cos\theta + \bar{V}_r \sin\theta\right)$

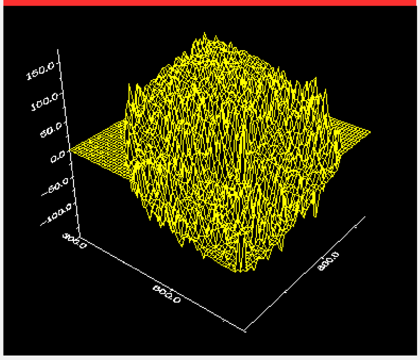
  - **Bisymmetric model :**

$$V_{\mathrm{model}} = V_{\mathrm{sys}} + \sin i\left[\bar{V}_t \cos\theta - V_{2,t} \cos(2\theta_b)\cos\theta - V_{2,r} \sin(2\theta_b)\sin\theta\right].$$

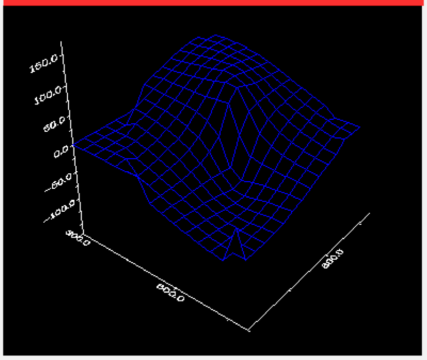
Reference velocity field

Bayes factor < 1

3D plot of the decomposed velocity components

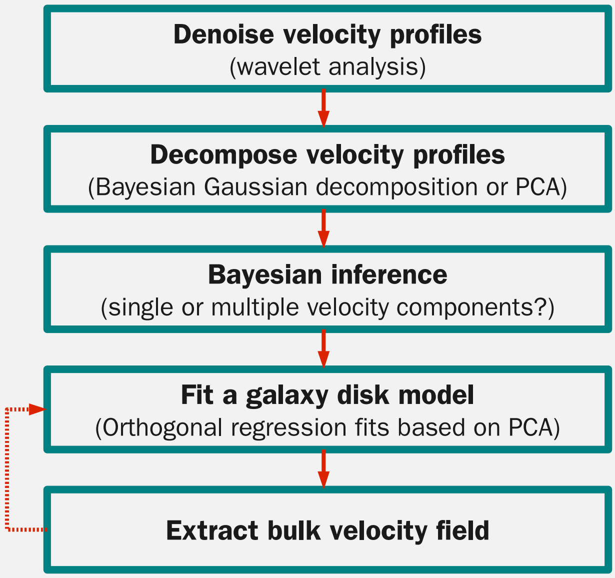


Orthogonal regression surface fit using a solidbody disk model



CAASTRO ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

A schematic flow chart for extracting “bulk” velocity fields



A test python code

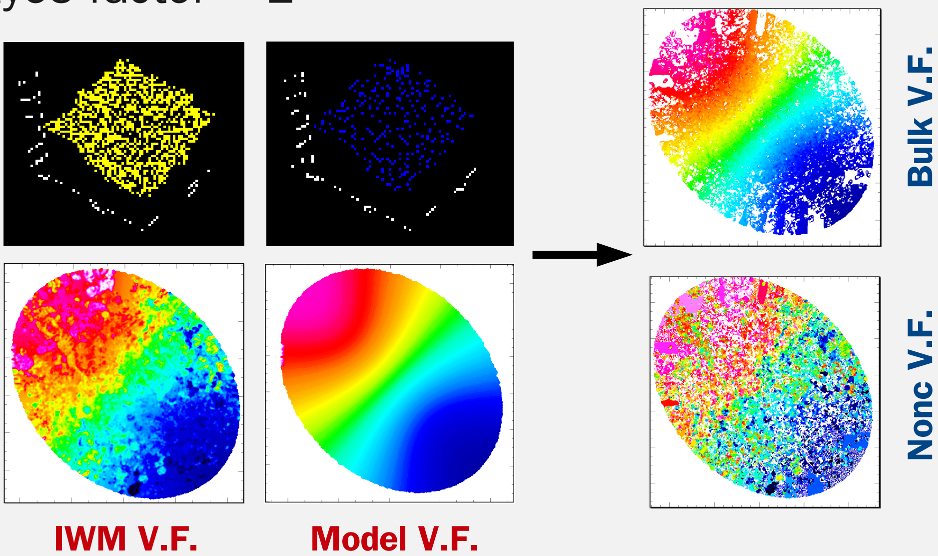
- **Bayesian Gaussian fits**
  → python modules: pymc, pyAstronomy

- **bulk_VF_wallaby_V0.9.py**
  → [usage] : python bulk_vf_wallaby_v0.9.py cube.fits 2

```
seheon@darkmatter bayesian]$
seheon@darkmatter bayesian]$
seheon@darkmatter bayesian]$
seheon@darkmatter bayesian]$
seheon@darkmatter bayesian]$ python bulk VF wallaby v0.9.py IA3.14B12X120X20C00S0P45I40D00.SS74.B6.fits 2
```

A test with a model data cube

Bayes factor < 1



CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

Summary & Future works

- **The dark matter distribution near the centres of dwarf galaxies are better described by core-like halo models unlike the prediction from dark-matter-only simulations**

- **New SPH simulations including baryonic feedback processes (e.g., SN-driven gas outflows) are better to explain the shallow DM distribution found in nearby dwarf galaxies**

- **More tests on rotation curve programs**

- **More tests on bulk velocity field business**
  - C/C++ modules for Bayesian analysis which is computationally expensive
  - Apply PCA techniques for a reliable profile decomposition
  - Develop bulk_VF_wallaby_v1.0.py