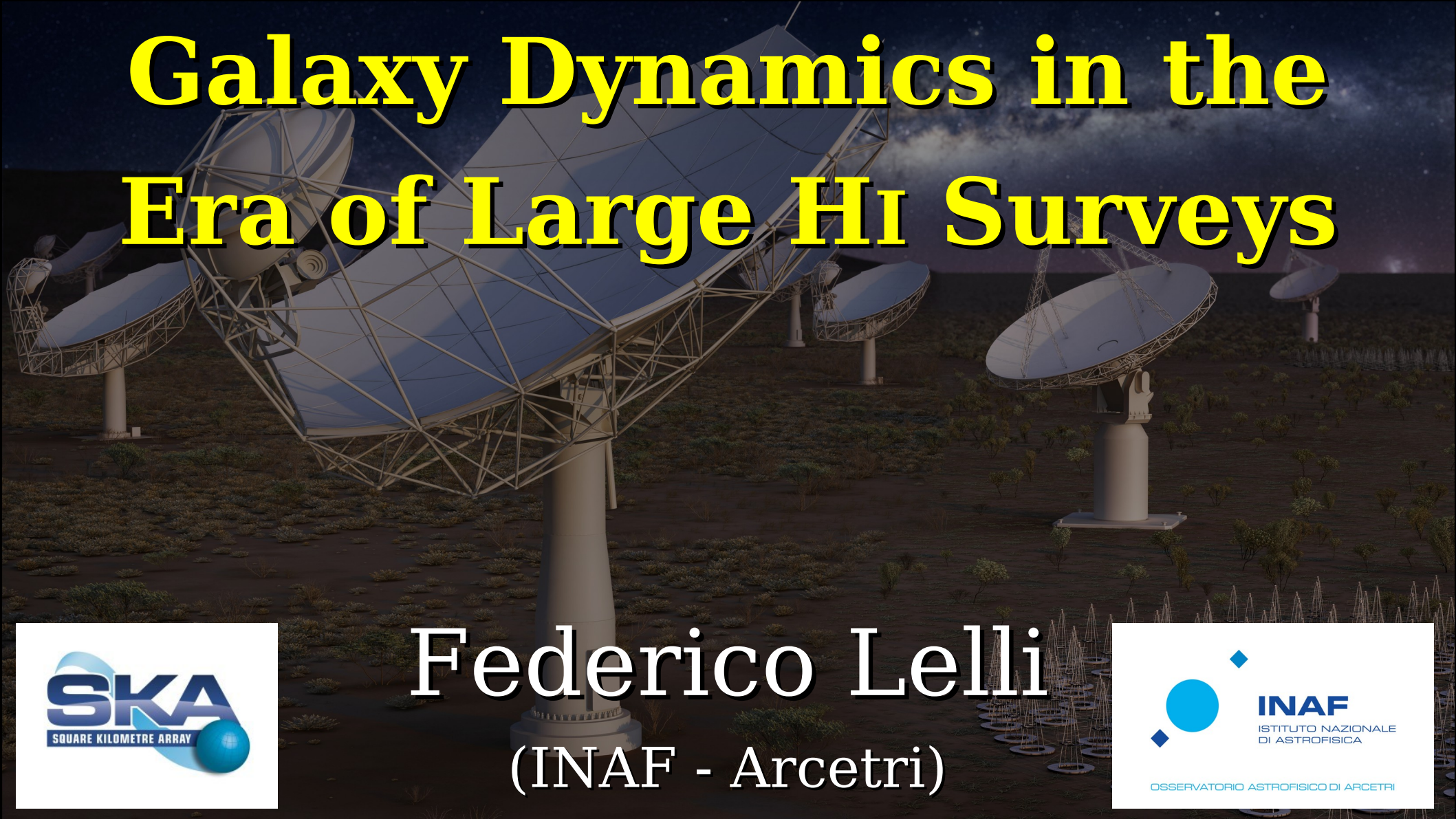
Galaxy Dynamics in the Era of Large HI Surveys



Federico Lelli

(INAF - Arcetri)

Talk Outline

1. Role of HI data in galaxy dynamics & dark matter

2. BHINGO: preparing for large HI galaxy samples

3. WALLABY with ASKAP: kinematic pipeline

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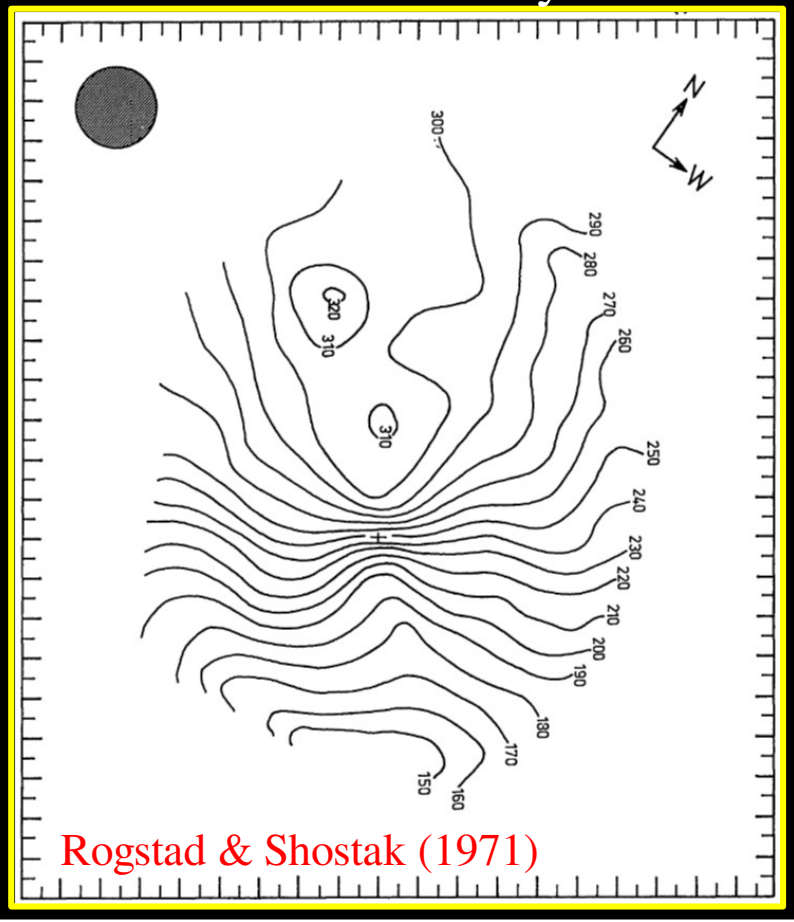
Long-Standing Role of HI in Galaxy Dynamics

M101 - HI Velocity Field



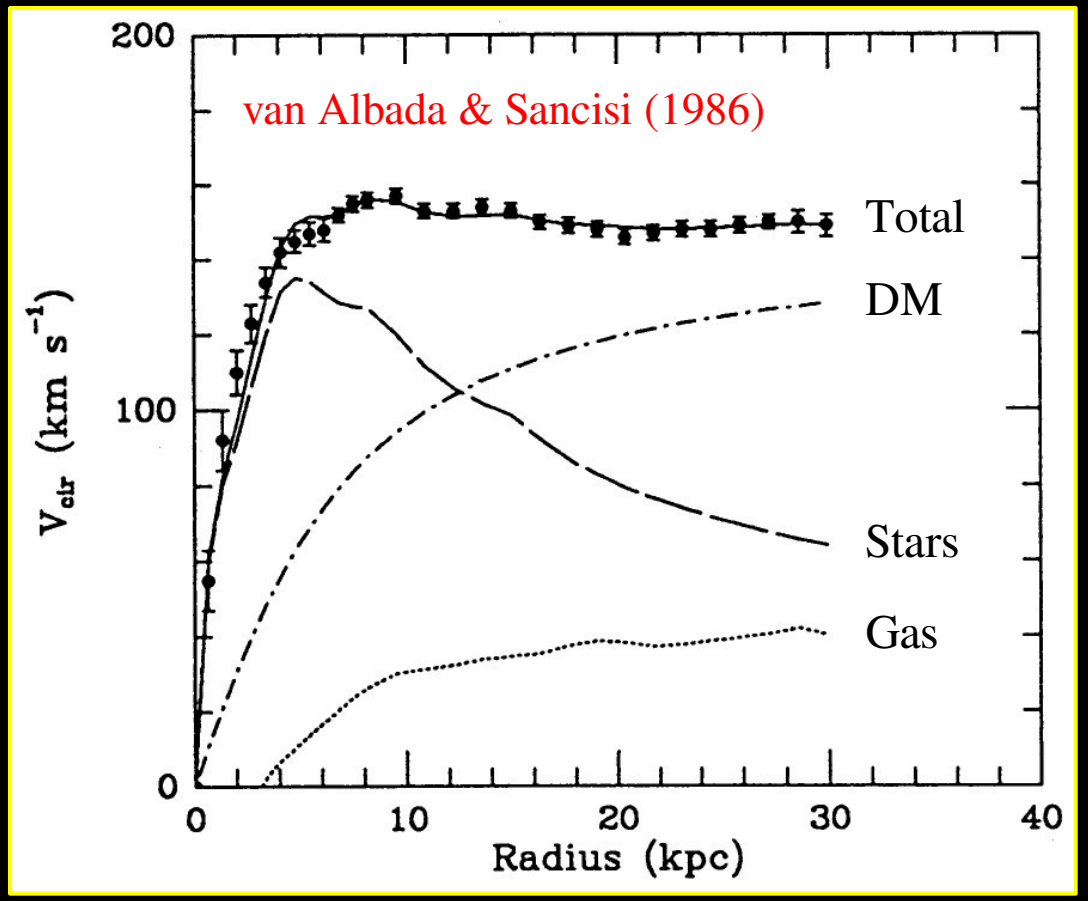
Rogstad & Shostak (1971)

Key Topics in Galaxy Evolution

- Angular Momentum ↔ Galaxy Morphology
- Disk Stability ↔ Star Formation
- Gas Turbulence ↔ Stellar & AGN Feedback
- Galaxy Interactions & Mergers
- Gas Removal (outflows, stripping, etc.)
- Gas Accretion (inflows, mergers, etc.)
- And much more...

Long-Standing Role of HI in Galaxy Dynamics

NGC 3198 – Mass Model



The Dark Matter Problem

- HI Rotation Curves → DM Halos:

  Baryonic Mass ↔ Halo Mass

  Cusp *vs* Core problem

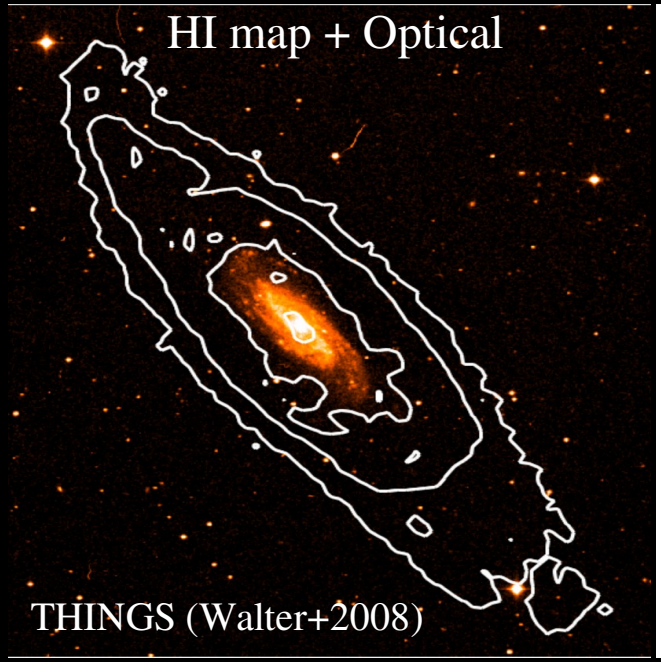
- Dynamical Scaling Laws:

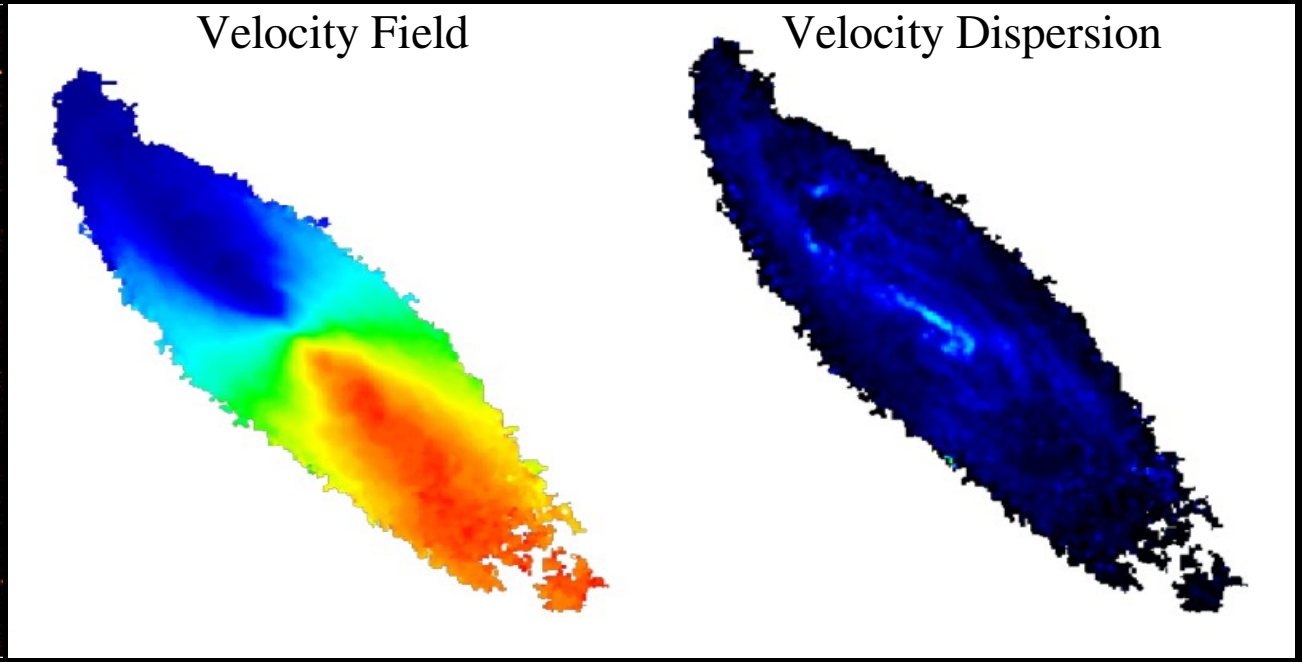
  Tully-Fisher Relation & others

- Test Alternatives to Dark Matter:

  MOND, Emergent Gravity, etc.

HI Emission Line: Optimal Dynamical Tracer



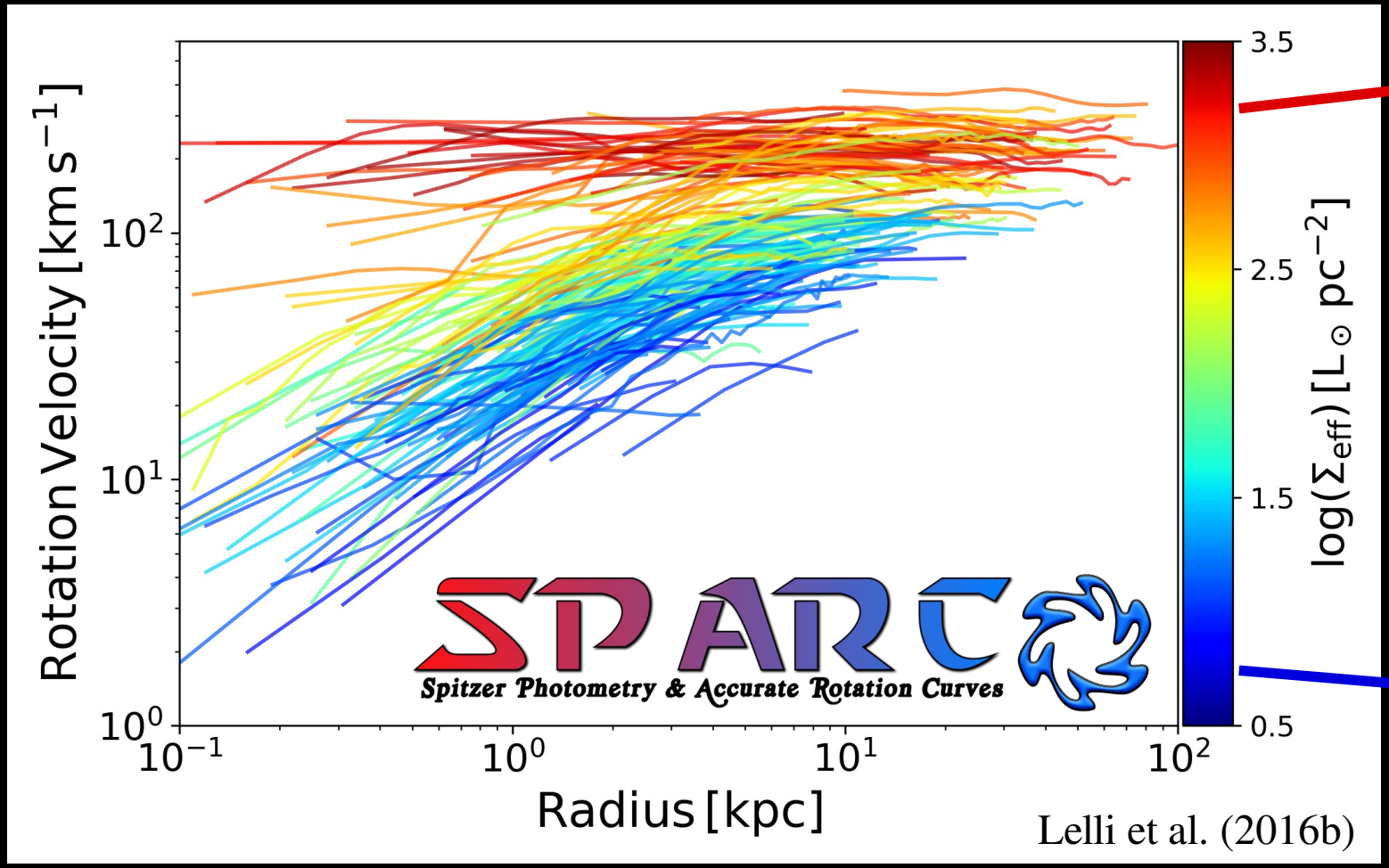


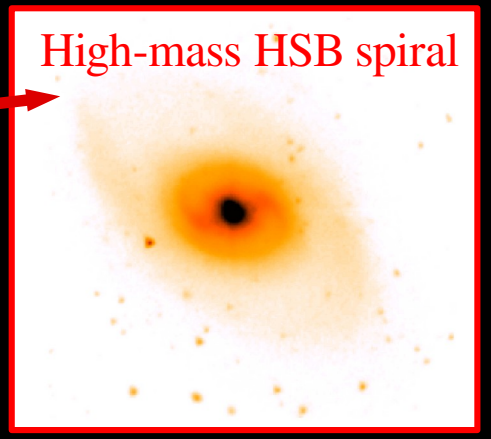
✔ Very extended (~2 stellar size) → probe outermost galaxy regions

✔ Dynamically cold → σ_{HI} ~ 5-10 km/s, $V_{rot}/\sigma_{HI} \gg 1$ → No pressure support

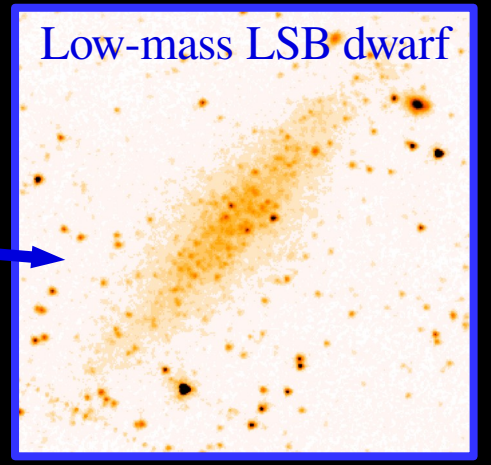
→ $V_{rot} \simeq$ circular velocity of a test particle in a given gravitational potential

SPARC: 175 galaxies with HI rotation curves

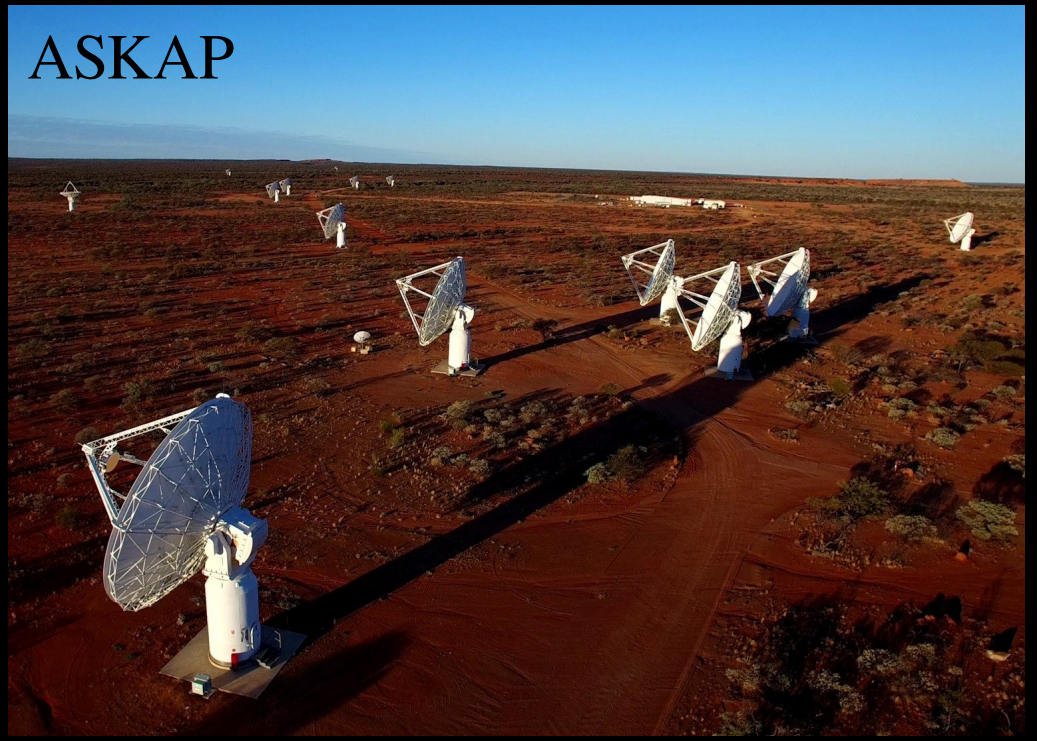




Spitzer [3.6] images



SKA-mid & Pathfinders →
First Statistical Samples for HI Galaxy Dynamics



Challenge: automated & reliable software for 3D kinematic modeling

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1. Role of HI data in galaxy dynamics & dark matter

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3. WALLABY with ASKAP: kinematic pipeline

BHINGO: BBarolo HI Nearby Galaxies Overview

- Lead by *Enrico Di Teodoro & Federico Lelli*
- Collection of ~1000 HI cubes from public archives

Literature Source	Telescope	Resolution	N_{cubes}	N_{gal}
LARGE SURVEYS				
WHISP	WSRT	25″ – 50″	270	259
ATLAS^{3D}	WSRT	25″ – 100″	142	161
BLUEDISK	WSRT	15″ – 40″	50	67
LVHIS	ATCA	40″ – 350″	82	64
VIVA	VLA	16″ – 45″	45	46
PPZoA	WSRT	24″	1	46
URSA MAJOR	WSRT	30″	42	42
HALOGAS	WSRT	18″ – 45″	22	35
VGS	WSRT	20″ – 160″	65	29
THINGS	VLA	5″ – 15″	32	27
SAURON	WSRT	30″ – 45″	10	25
FIGGS	GMRT	25″ – 55″	23	23
HIX	ATCA	25″ – 70″	23	22
LITTLE THINGS	VLA	10″ – 20″	40	19
VLA-ANGST	VLA	7″ – 15″	29	11
SHIELD	VLA	10″ – 30″	12	5
OTHER SAMPLES				
Richards et al. (2016, 2018)	VLA	30″ – 50″	25	30
Spekkens & Giovanelli (2006)	VLA	18″	8	12
Saburova et al. (2013)	WSRT	25″	2	7
van der Hulst et al. (1993)	VLA	25″	8	5
Allaert et al. (2015)	VLA-WSRT	15″ – 25″	4	4
Pickering et al. (1997)	WSRT	20″	3	3
Mishra et al. (2017)	GMRT	50″	3	3
Trachternach et al. (2009)	WSRT	30″	3	3
Individual Studies	VLA-WSRT	10″ – 50″	15	19
		TOTAL	959	967

BHINGO: BBarolo HI Nearby Galaxies Overview

- Lead by *Enrico Di Teodoro & Federico Lelli*
- Collection of ~1000 HI cubes from public archives
- BBarolo software (*Di Teodoro & Fraternali 2015*) improving automation, efficiency & reliability

Step 1 – Source Finder

→ Identified ~1200 individual galaxies

→ Moment maps & integrated HI profiles

Step 2 – Kinematic 3D Fitting

→ 967 good kinematic fits (~5 × SPARC)

→ Geometric parameters

→ Kinematical parameters

Literature Source	Telescope	Resolution	N_{cubes}	N_{gal}
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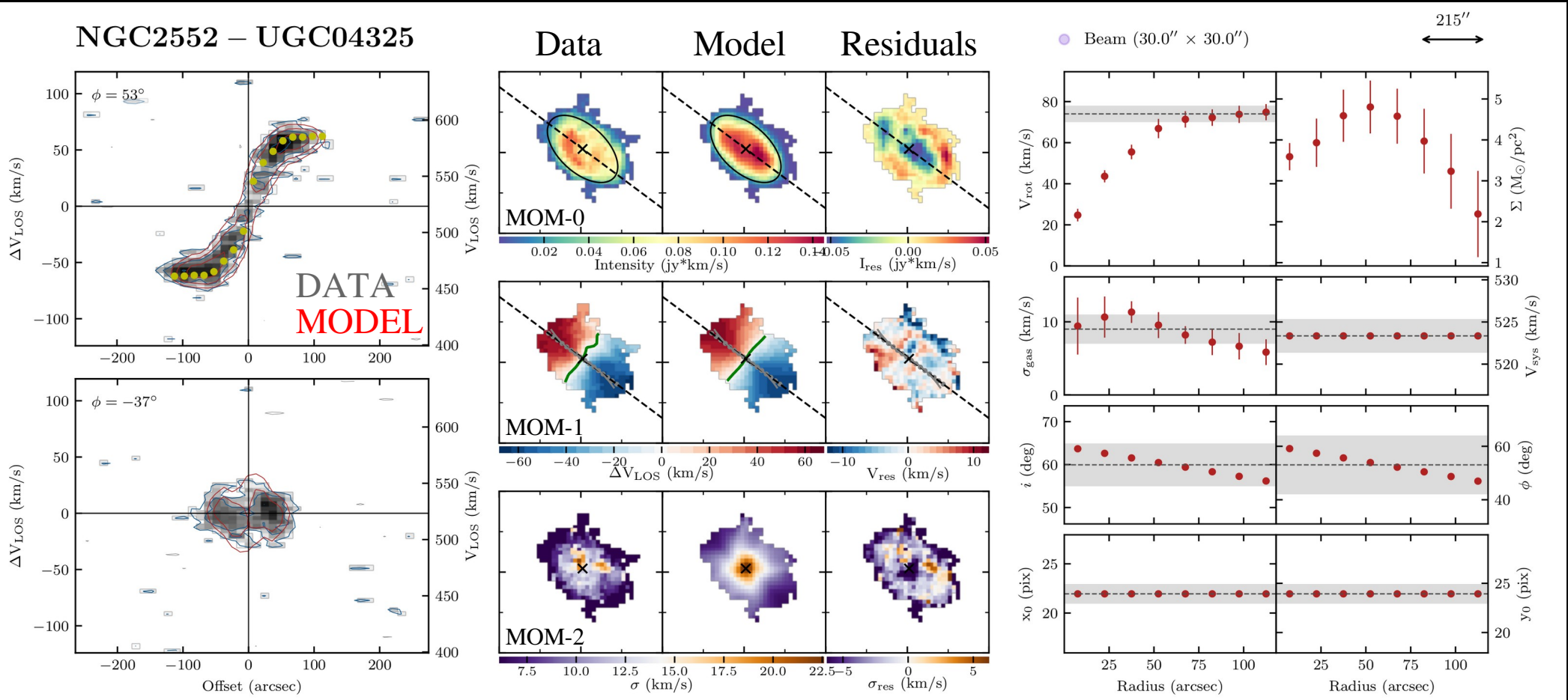
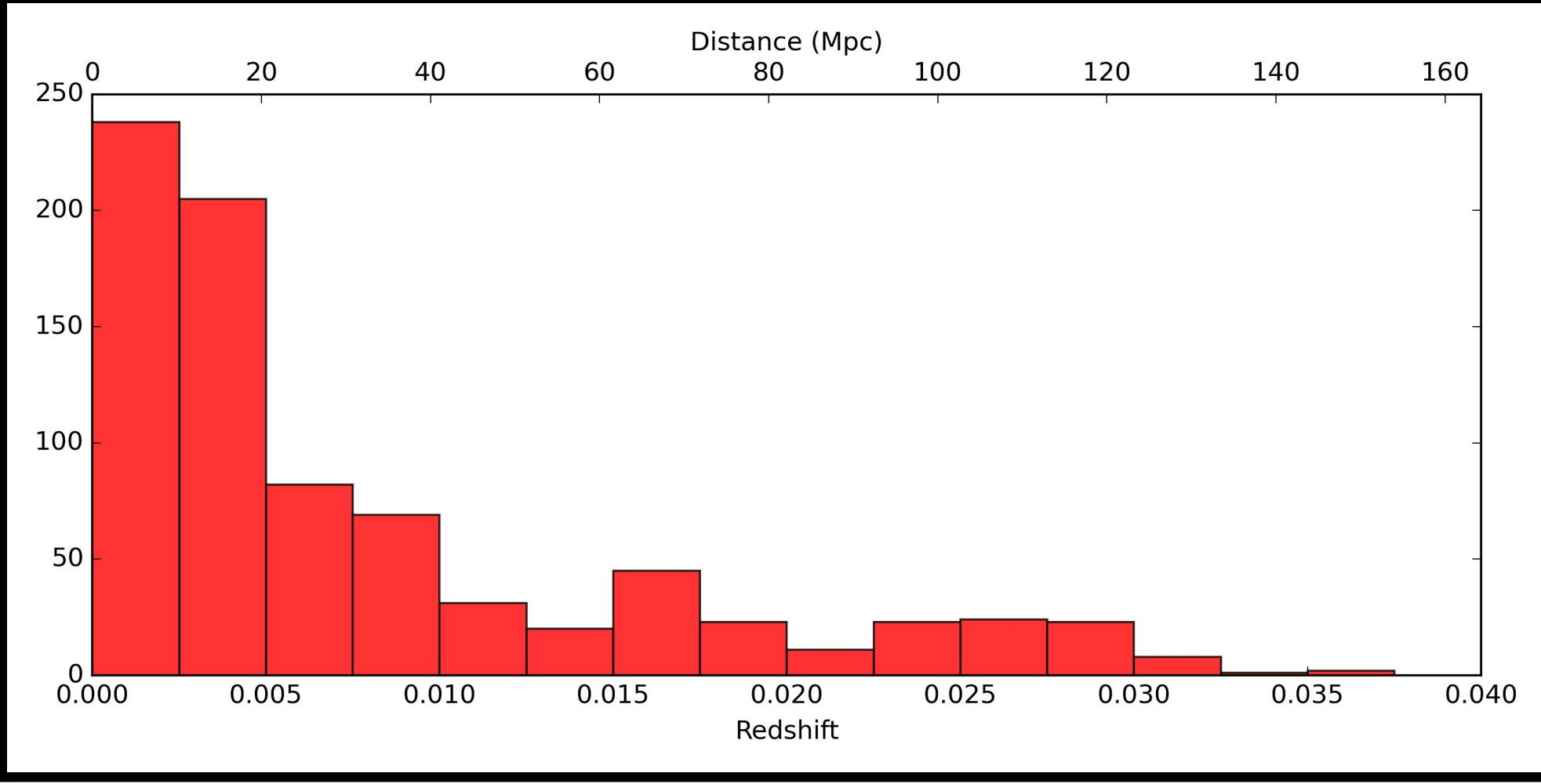
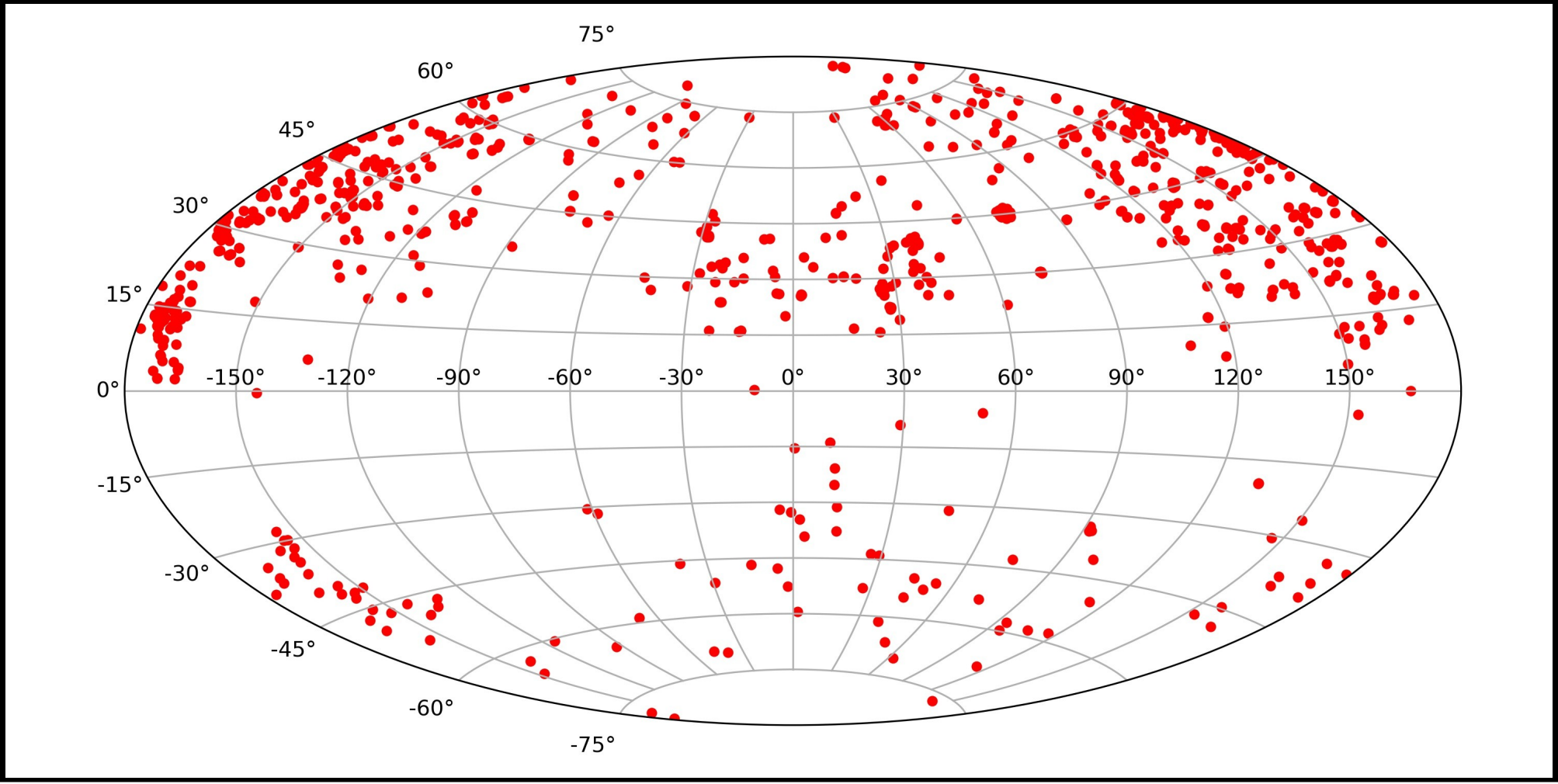
Typical Output from BHiNGO



BHINGO Sample: Redshift Distribution



BHINGO Sample: Sky Distribution



The Road to the BHINGO Data Release

✔ Source Finder & Moment Maps Creation

✔ Automated Kinematic Fitting + Visual Inspection

✗ Manual Fitting for Problematic Cases (~5%)
(due to asymmetries, warps, interactions, etc.)

✗ WISE & Spitzer Photometry (→ stellar mass distribution)

✗ Mass Models (→ dark matter halos, MOND, etc)

STAY TUNED!

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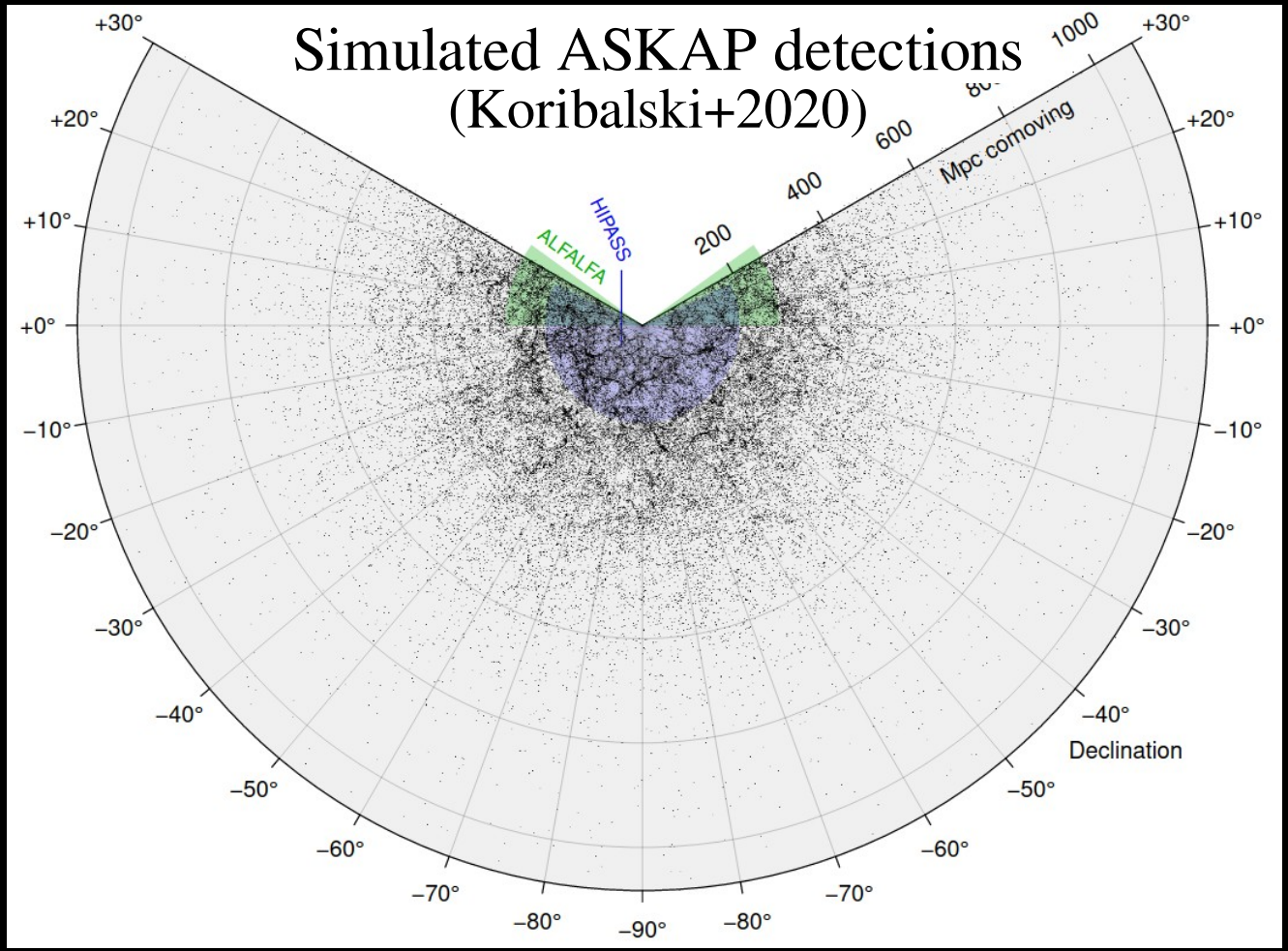
WALLABY: Key Survey with ASKAP



Large Blind HI Survey:

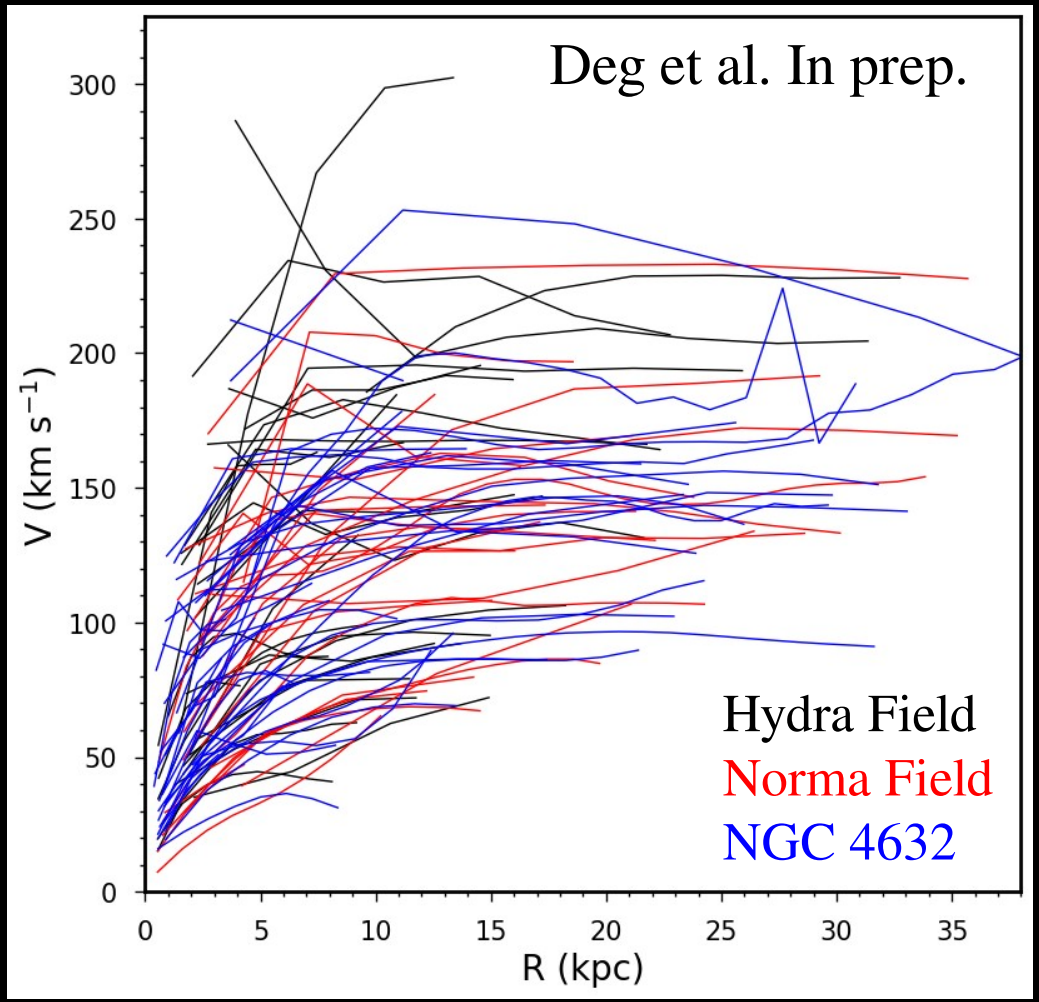
- All-Sky Declination < 30°
- Coverage up to z < 0.26
- Angular Resolution ~ 30”
- Velocity Res. ~ 4 km/s
- Expected 500k detections

~5-10k for dynamical work

WALLABY

ASKAP
Australian SKA Pathfinder

WALLABY Kinematic Pipeline



Preliminary Results from Pilot Fields:

- 3 Fields: Hydra, Norma, NGC 4632
- 92 kin. models out of 563 detections

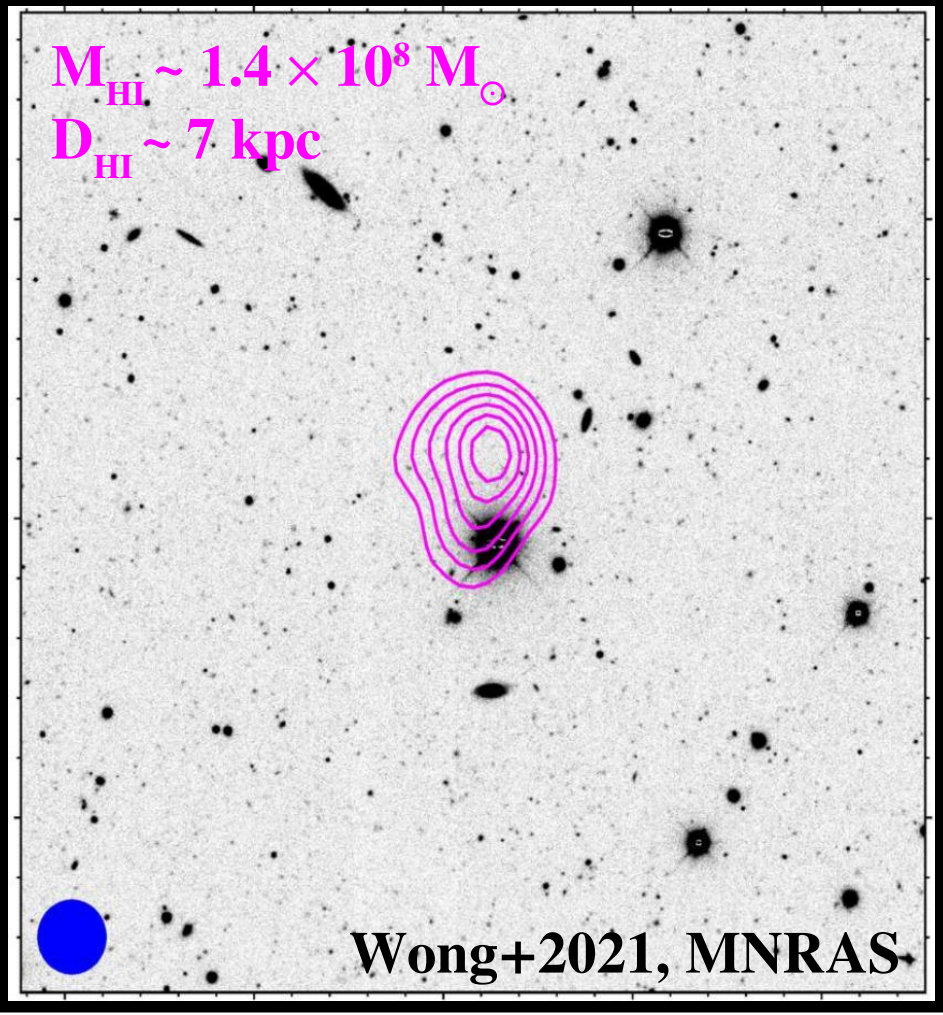
  ~15% success rate for kinematic fits

  Rest: unresolved or low S/N galaxies
- Mean of two codes: BBarolo & FAT
- Public release planned in March 2022

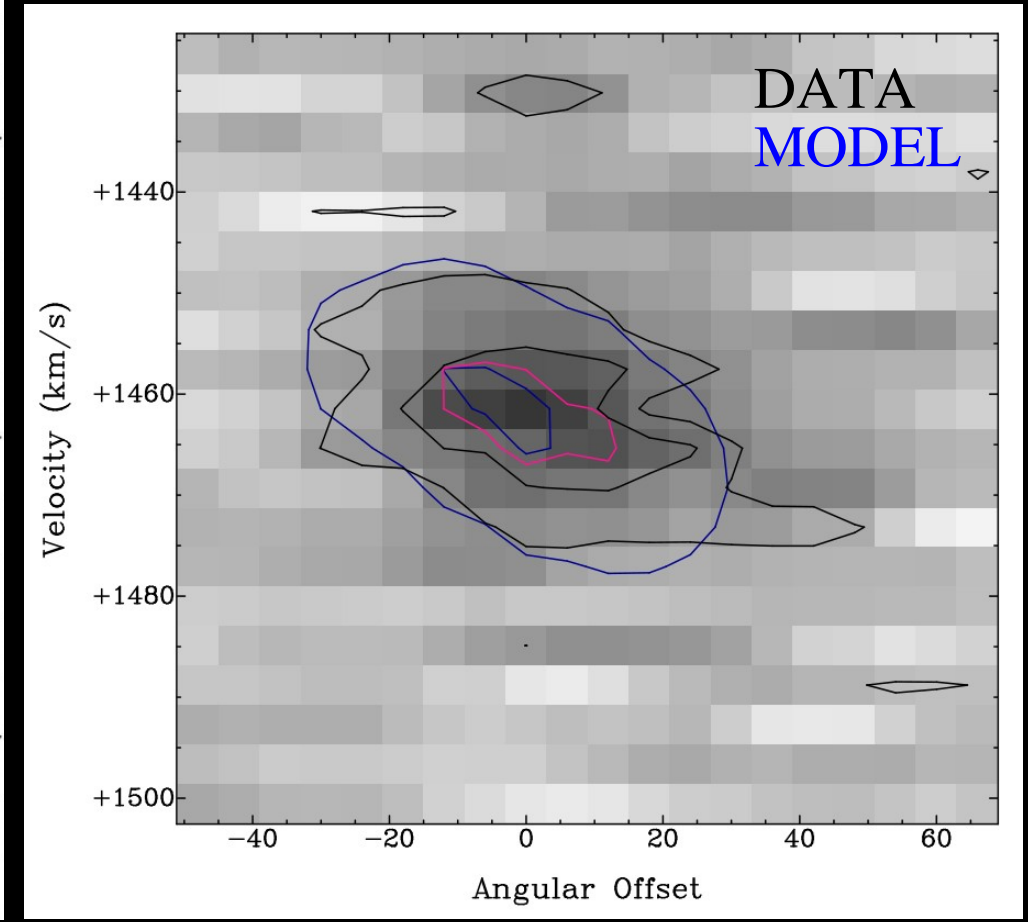
WALLABY

ASKAP
Australian SKA Pathfinder

WALLABY will detect optically dark galaxies!



Major-Axis PV Diagram: Rotation?



Conclusions:

1. New era for galaxy dynamics with large HI samples

→ Key science goal for SKA & pathfinders – Italian expertise!

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→ Factor 5 increase over existing samples (SPARC, Lelli+16)

Conclusions:

1. New era for galaxy dynamics with large HI samples

→ Key science goal for SKA & pathfinders – Italian expertise!

2. BHINGO: 3D kinematic models for ~1000 galaxies

→ Factor 5 increase over existing samples (SPARC, Lelli+16)

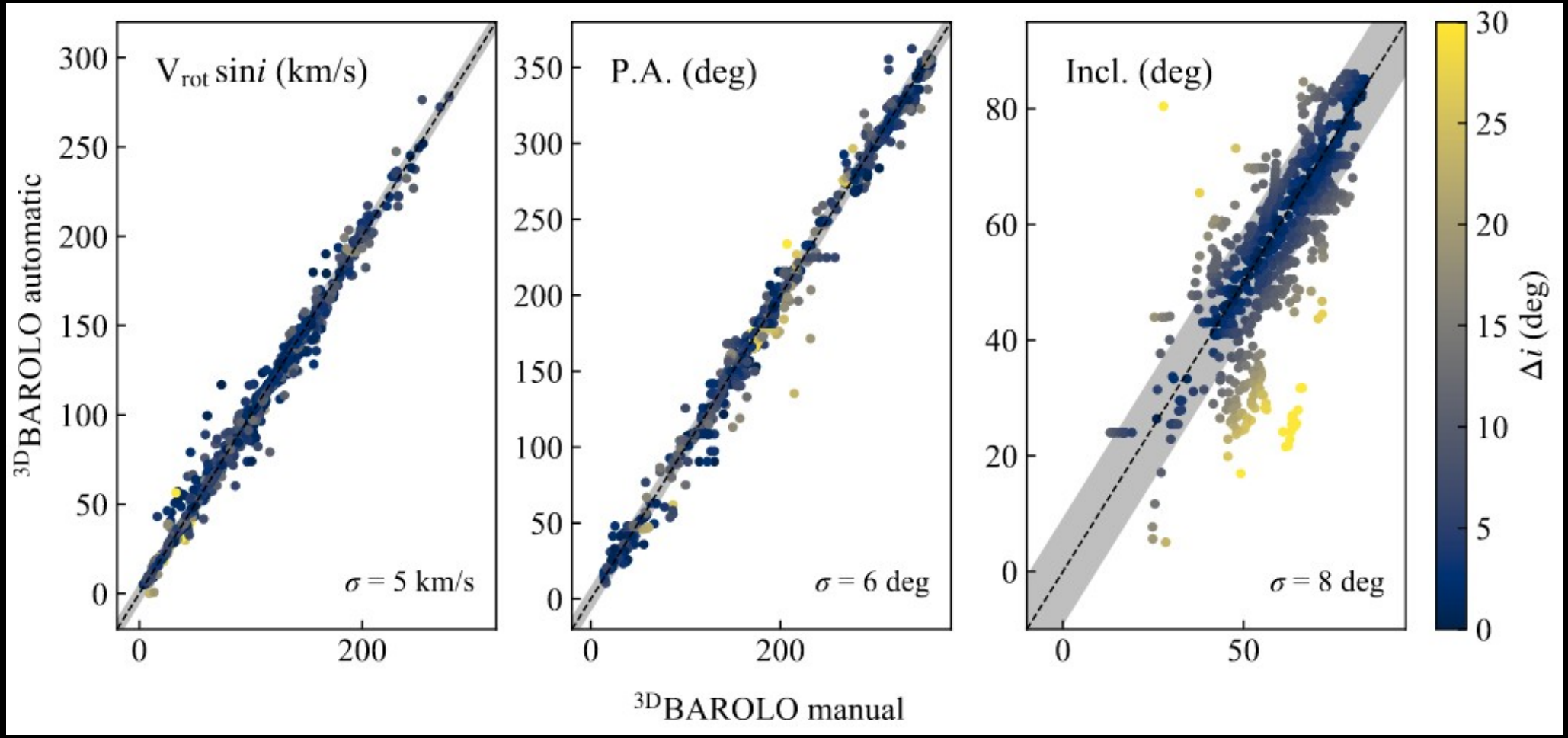
3. WALLABY@ASKAP is proceeding well

→ Kinematic models for ~100 galaxies (a few 1000s by the end)

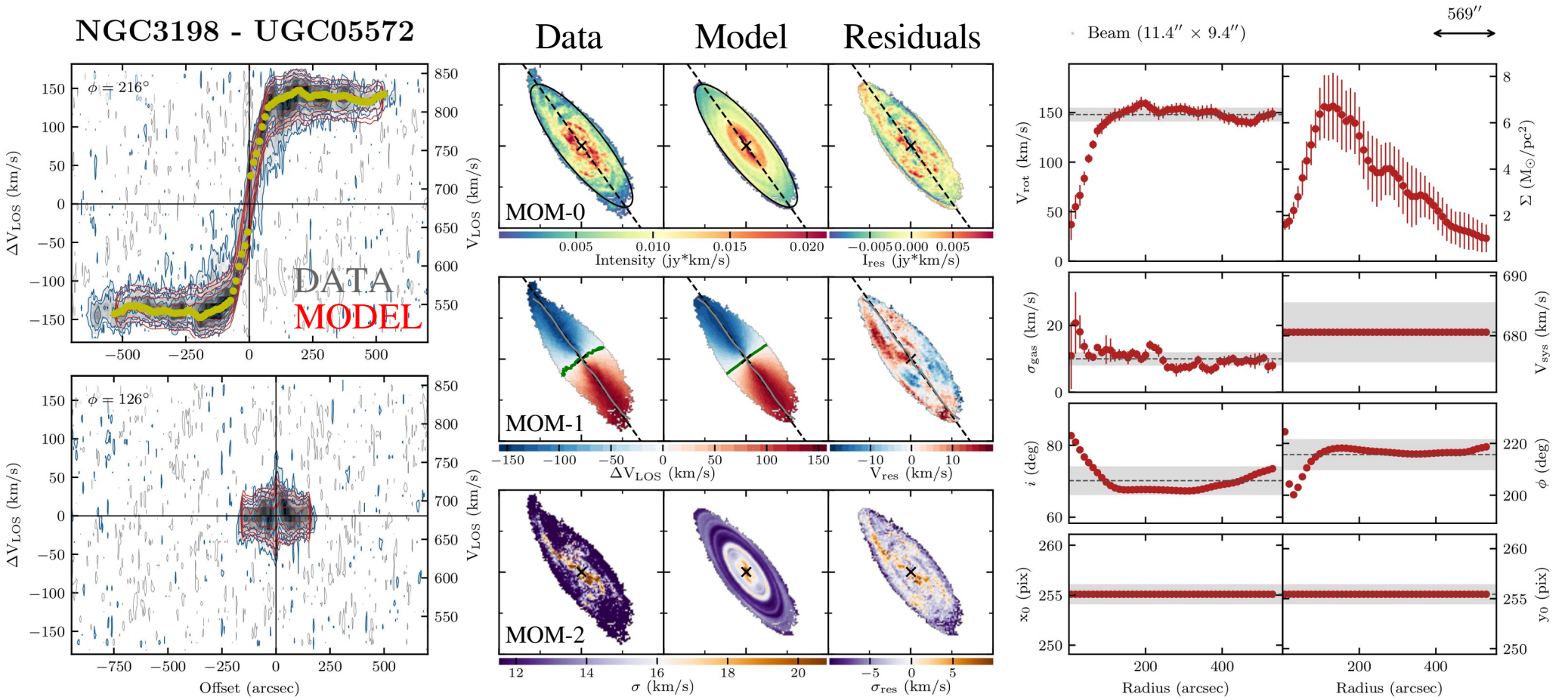
→ Potential to unveil optically-dark HI-rich galaxies

Thank you!

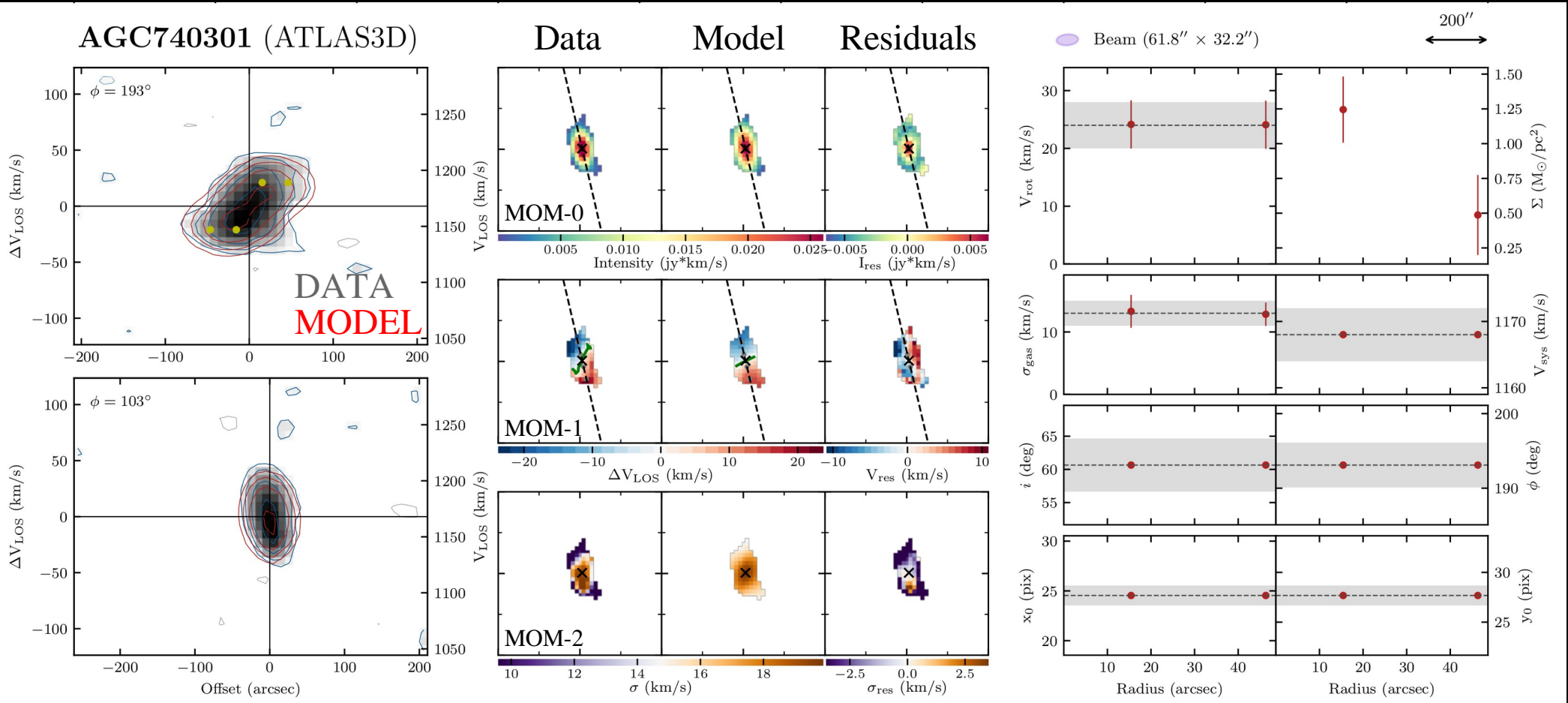
Automated versus Manual Fitting



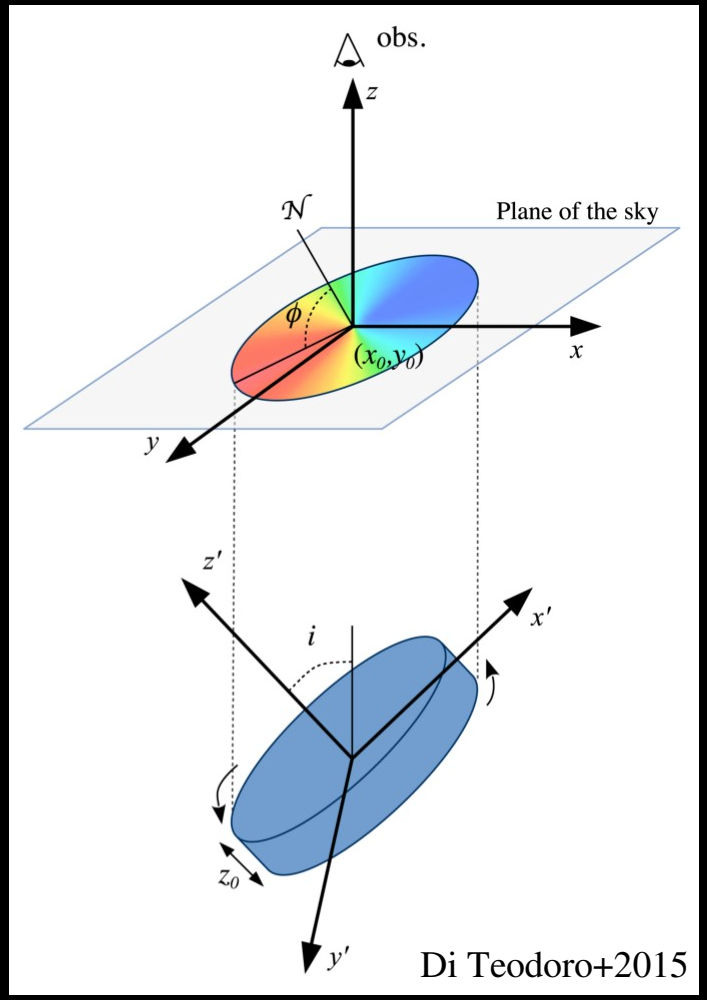
Example: Highly Resolved Galaxy



Example: Poorly Resolved Galaxy



Deprojection from Sky Plane to Galaxy Plane



For circular orbits in a plane:

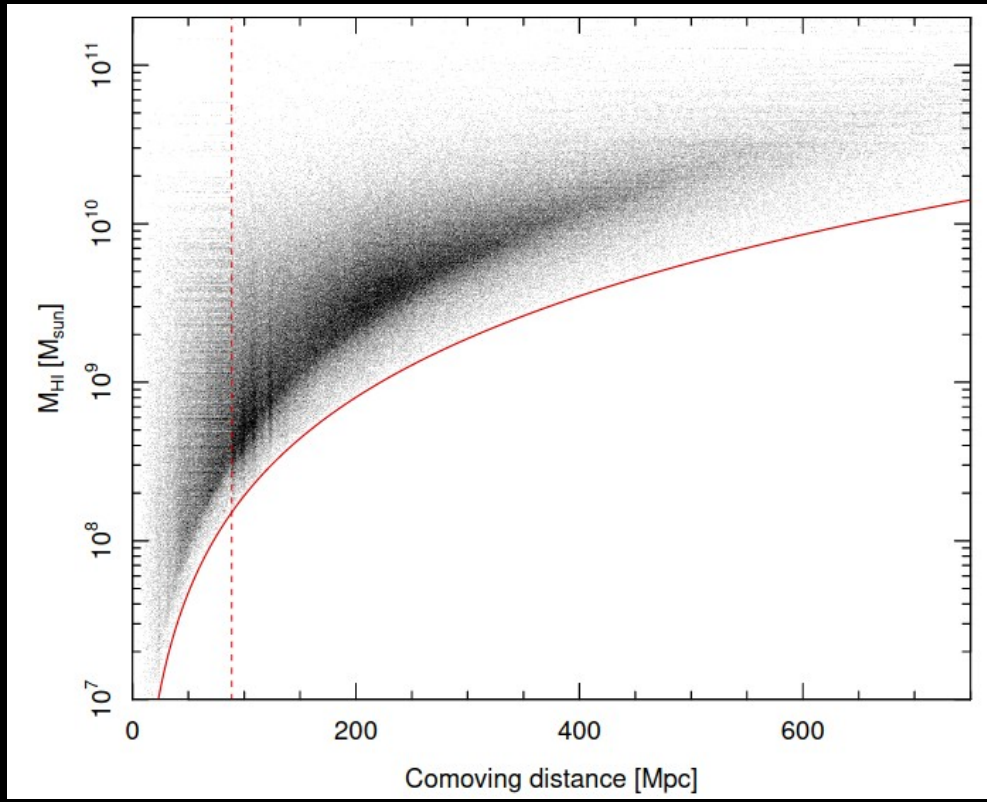
$V_{los}(x, y) = V_{sys} + V_{rot}(R) \sin(i) \cos(\theta)$

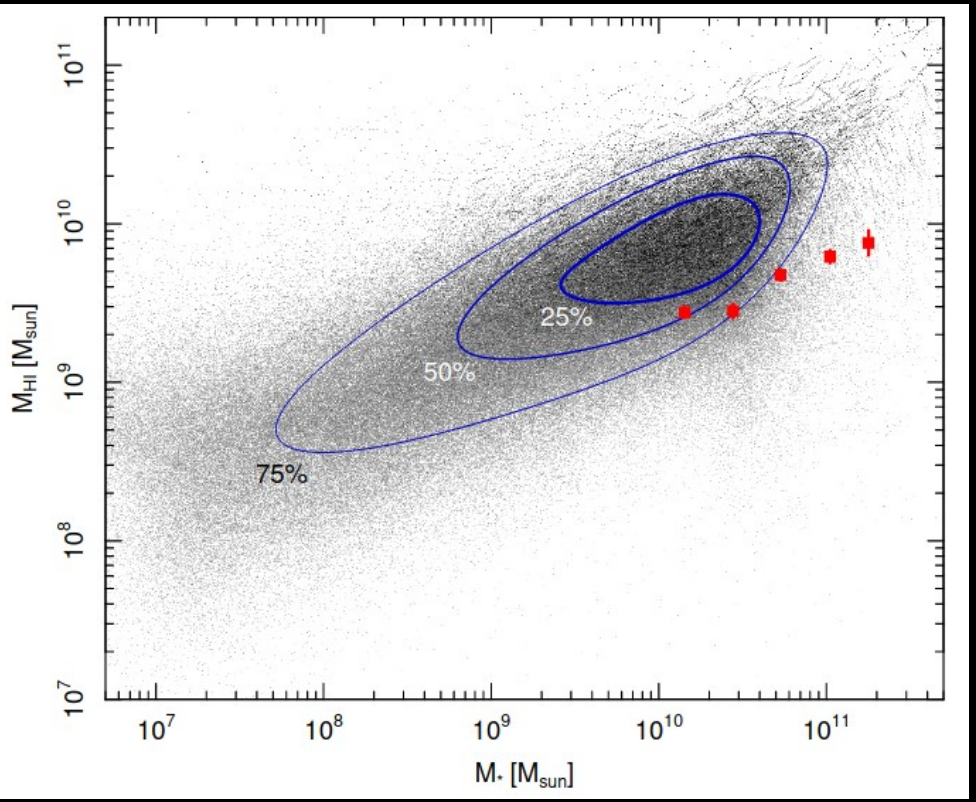
$\cos(\theta) = f\,(x_0, y_0, PA)$

3D codes fit directly the cube bypassing the 2D velocity field → strongly recommended to take observational effects into account:

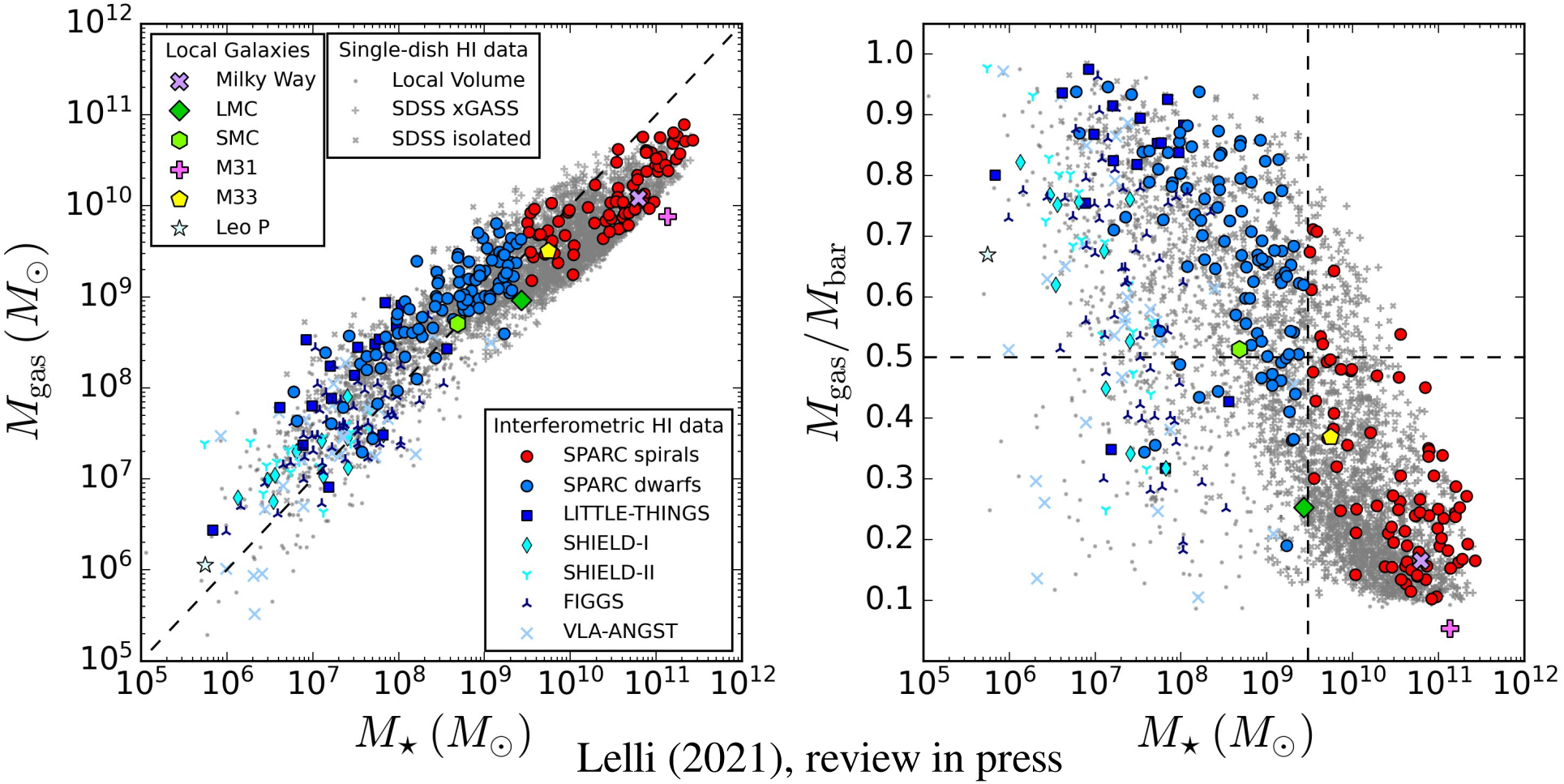
- BBarolo (Di Teodoro & Fraternali 2015)
- FAT (Józsa+2007; Kamphuis+2015)
- KinMS (Davis+2013)

WALLABY: Expected HI Mass Detections





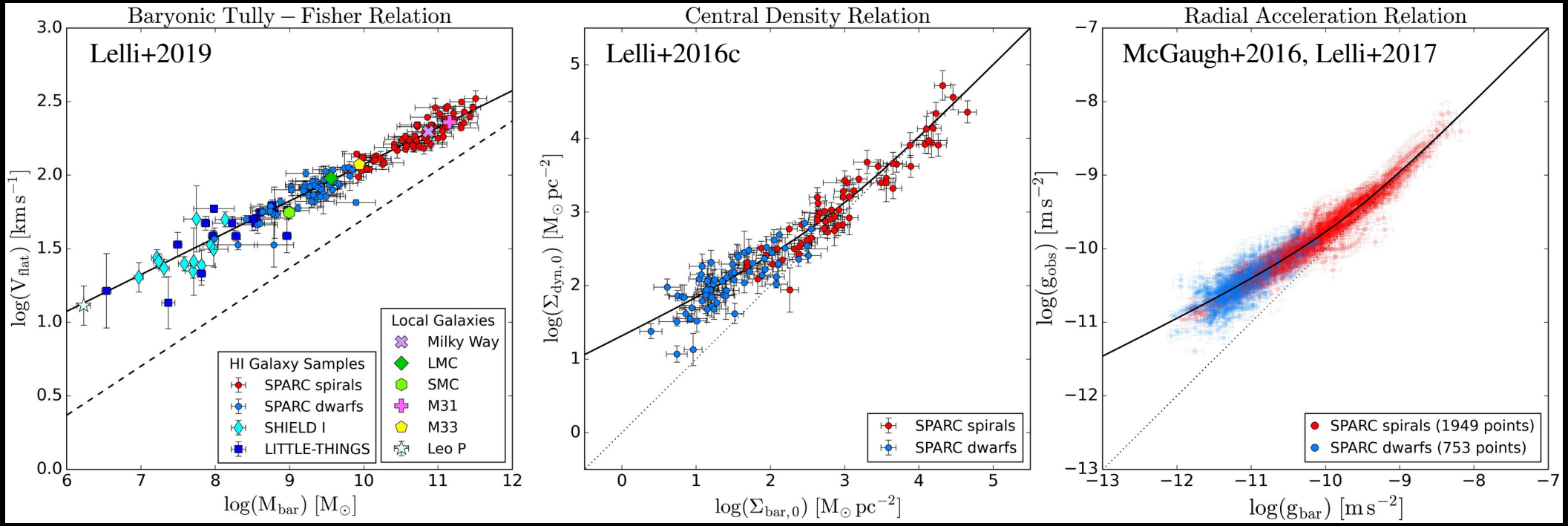
Gas Content in Star-Forming Galaxies (LTGs)



Lelli (2021), review in press

Dynamical Laws for Rotation-Supported Galaxies

Baryonic Property ↔ Dynamical Property (baryons + dark matter)



Outer Regions (R→ ∞):
Baryonic Mass *vs* Flat Velocity

Inner Regions (R→ 0):
Central Surface Densities

Spatially Resolved (∀R):
Centripetal Accelerations

Key Questions:

1 – Is there any intrinsic scatter in the dynamical laws?

2 – Do their properties (slope, etc) depend on environment?

In ΛCDM: dynamical laws emerge from galaxy formation process

→ scatter & environment are key to distinguish different models

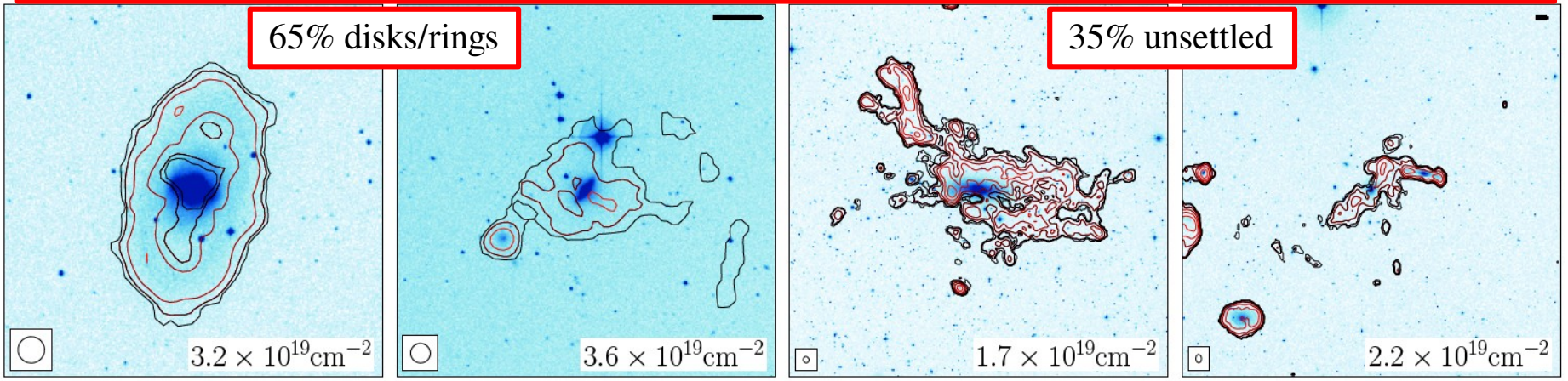
In MOND: new fundamental Laws of Nature (akin Kepler's Laws)

→ scatter null or tiny, environment plays a role (Chae+2020, 2021)

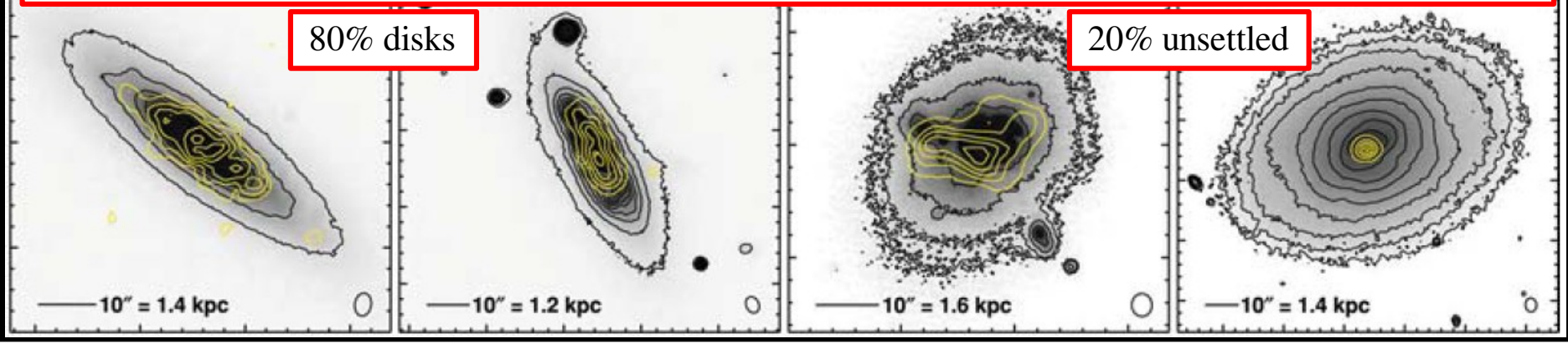
Challenge: build large, homogeneous, unbiased kinematic samples

Gas Content in Early-Type Galaxies (ETGs)

Serra+2012: HI detected in 40% of ETGs outside galaxy clusters; 10% inside Virgo cluster



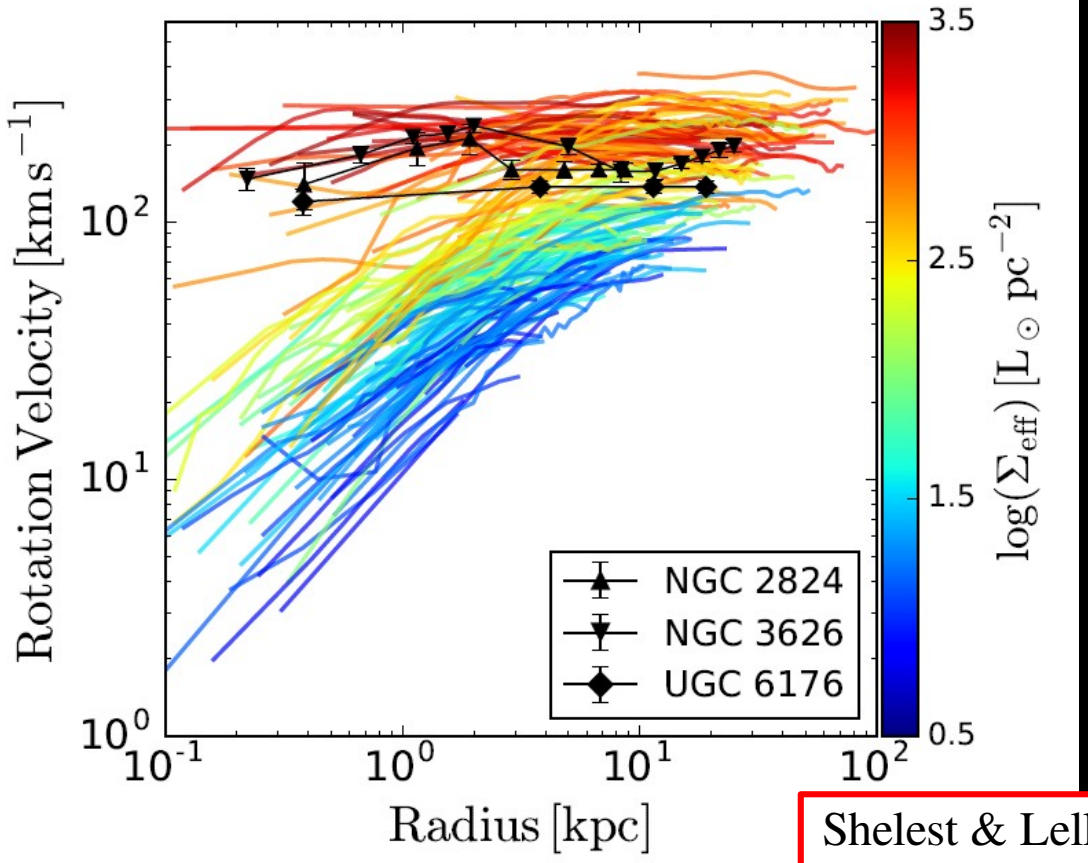
Young+2012: CO detected in 30% of ETGs outside galaxy clusters; 20% inside Virgo cluster

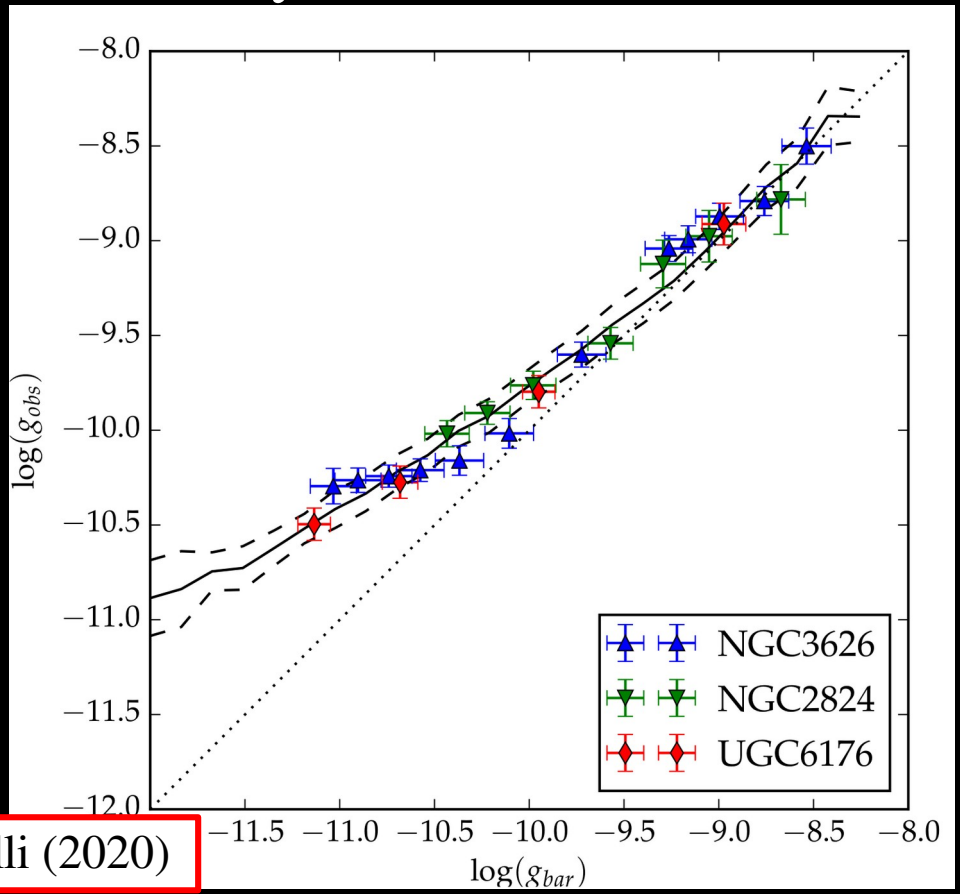


CO+HI Rotation Curves for three Lenticulars

Similar rotation curves as HSB spirals

Same Dynamical Laws as LTGs





Shelest & Lelli (2020)

Jeans Equations (e.g. Binney & Tremaine 1987)

For a stationary axisymmetric system embedded in $\Phi(R, z)$:

$$V_c^2 \equiv R\frac{\partial \Phi}{\partial R} = \overline{v_\theta}^2 + \sigma_R^2\left[\frac{\sigma_\theta^2}{\sigma_R^2} - 1 - \frac{\partial \ln \rho}{\partial \ln R} - \frac{\partial \ln \sigma_R^2}{\partial \ln R} - \frac{R}{\sigma_R^2}\frac{\partial \overline{v_R v_z}}{\partial z}\right]$$

$\overline{v}_\theta = V_{rot}$ (rotation velocity) $\sigma_R \sim \sigma_{los}$ (line-of-sight velocity dispersion)

Australian Square Kilometre Array Pathfinder

ASKAP capabilities:

- 36 x 12-m dishes
- Baselines: up to ~6 km
- Phased Array Feeds

→ 36 primary beams

→ F.o.V ~ 30 sq deg

- ν_{obs} = 0.7 – 1.8 GHz

ASKAP
Australian SKA Pathfinder