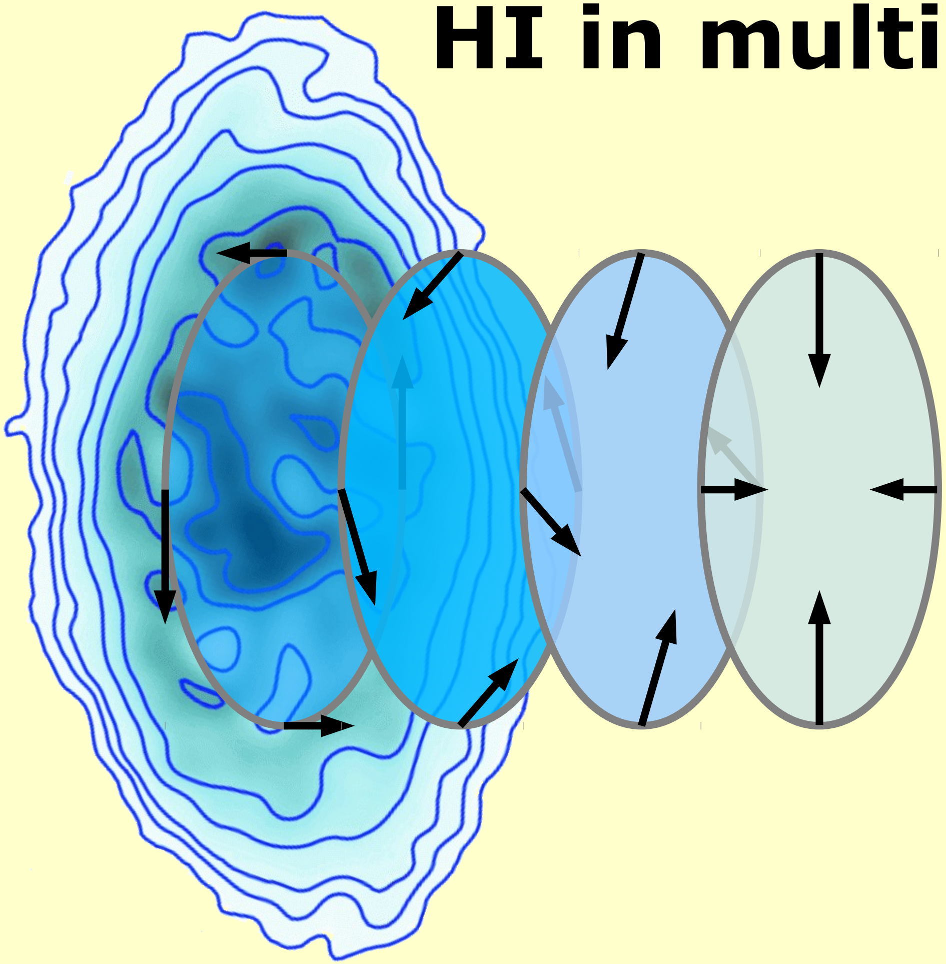
HI in multispin galaxies



Gyula I. G. Józsa

SKA Africa
Square Kilometre Array

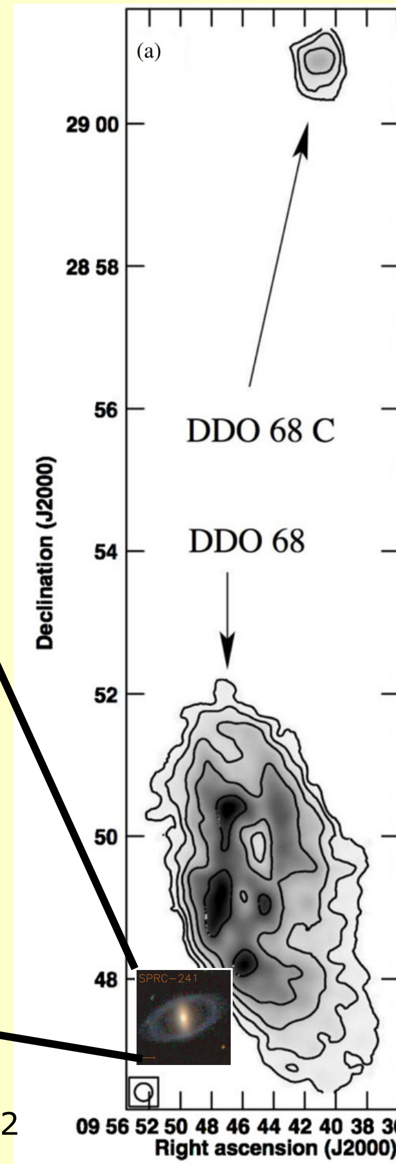
Rhodes University
Where leaders learn

Current problems for H I studies

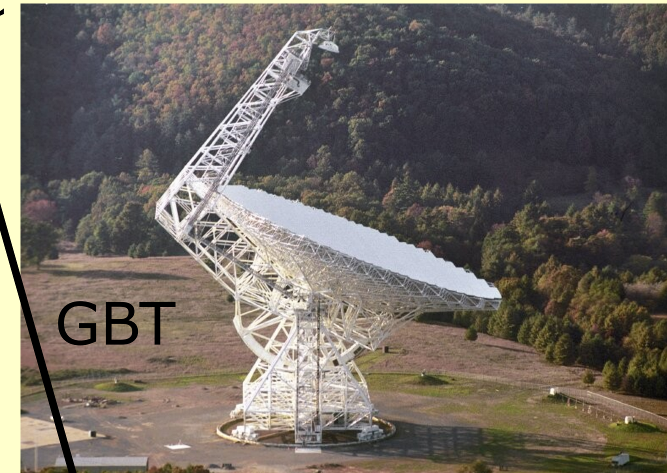
- Sensitivity: reaching down to n x 10^{20} atoms cm^{-2} at ~10'' resolution

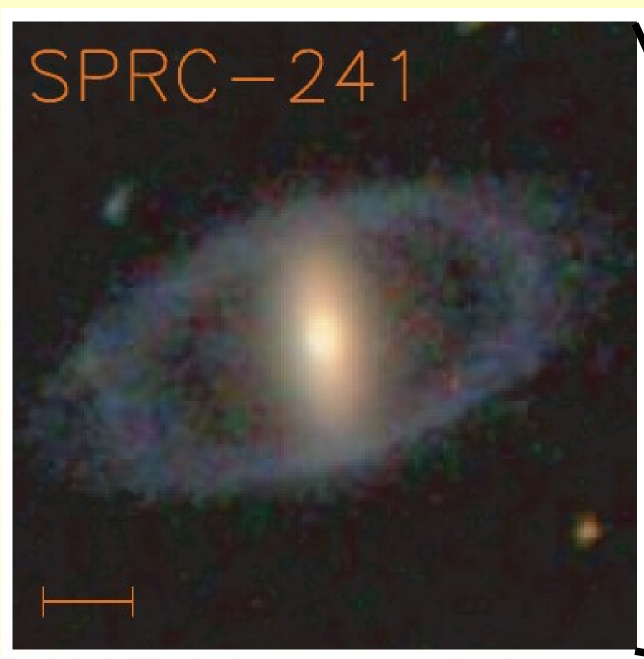
DDO 68 + DDO 68 C

VLA



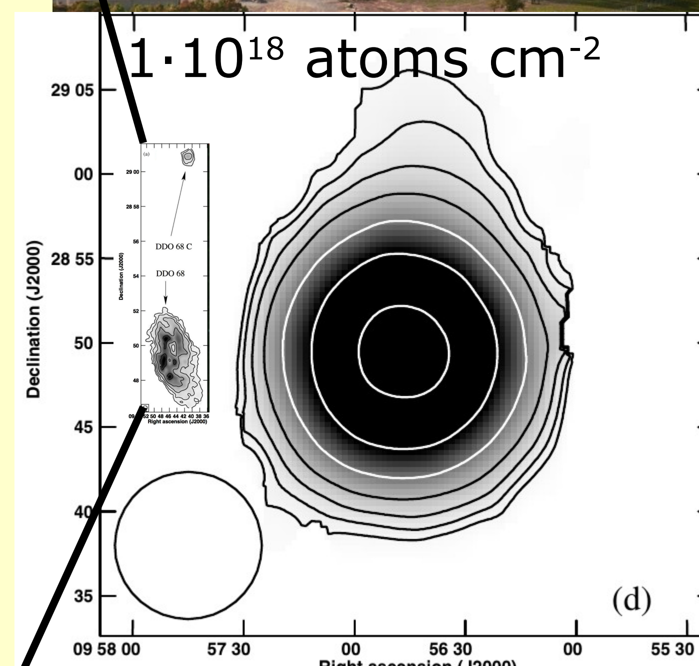
GBT





Moiseev et al. 2014

1.3·10^{20} atoms cm^{-2}



Cannon et al. 2014

Multi-spin aspects in galaxies

• Multi-spin galaxies are galaxies with two or more distinct subsystems of differing angular momentum

Absolute value of the angular momentum is different, e.g.

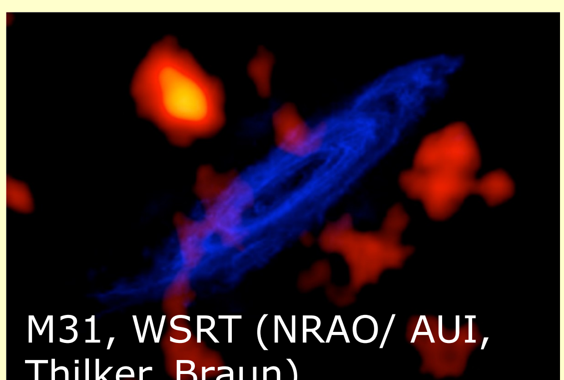
• Bulge-disk systems


M31, WSRT (NRAO/ AUI, Thilker, Braun)

• IGM-ISM connection, slowly rotating gas (through gas accretion)


NGC 5775 (Rand et al.)

• High-Velocity Clouds (HVCs, connected to gas accretion?)


M31, WSRT (NRAO/ AUI, Thilker, Braun)

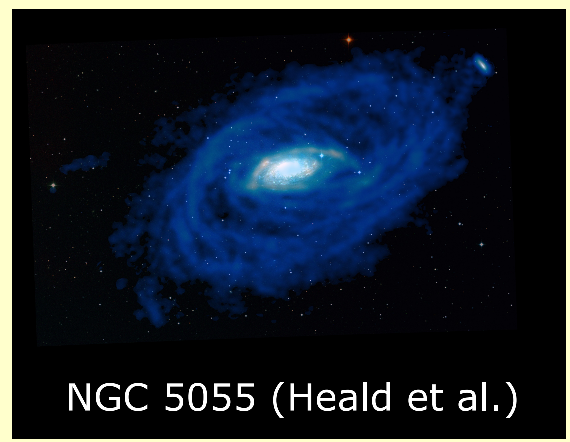
Normal vector of angular momentum is different, e.g.

• Polar-ring galaxies


NGC 4650A

(Gallagher et al.)

• Warps (not really distinct)


NGC 5055 (Heald et al.)

Multi-spin aspects in galaxies

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Absolute value of the angular momentum is different, e.g.

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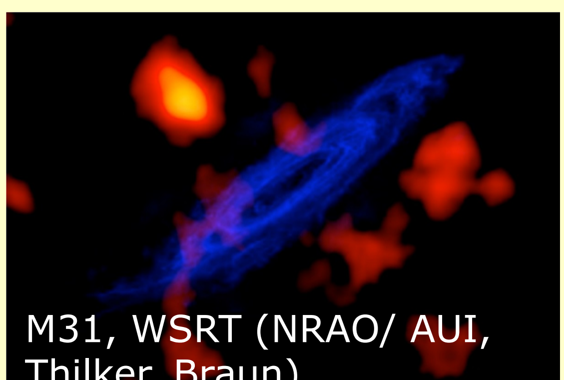
• High-Velocity **X** Clouds (HVCs, connected to gas accretion?)

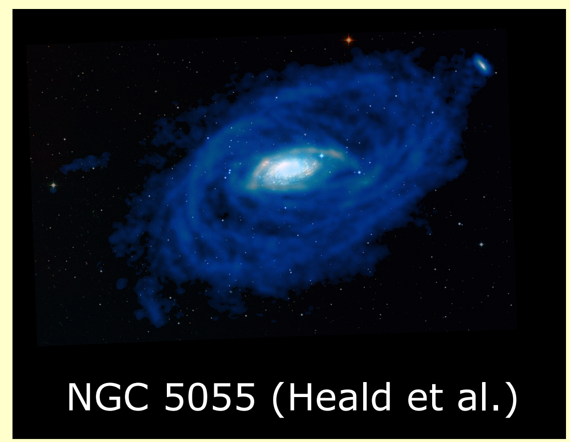

M31, WSRT (NRAO/ AUI, Thilker, Braun)


NGC 5775 (Rand et al.)


M31, WSRT (NRAO/ AUI, Thilker, Braun)


NGC 4650A

(Gallagher et al.)


NGC 5055 (Heald et al.)

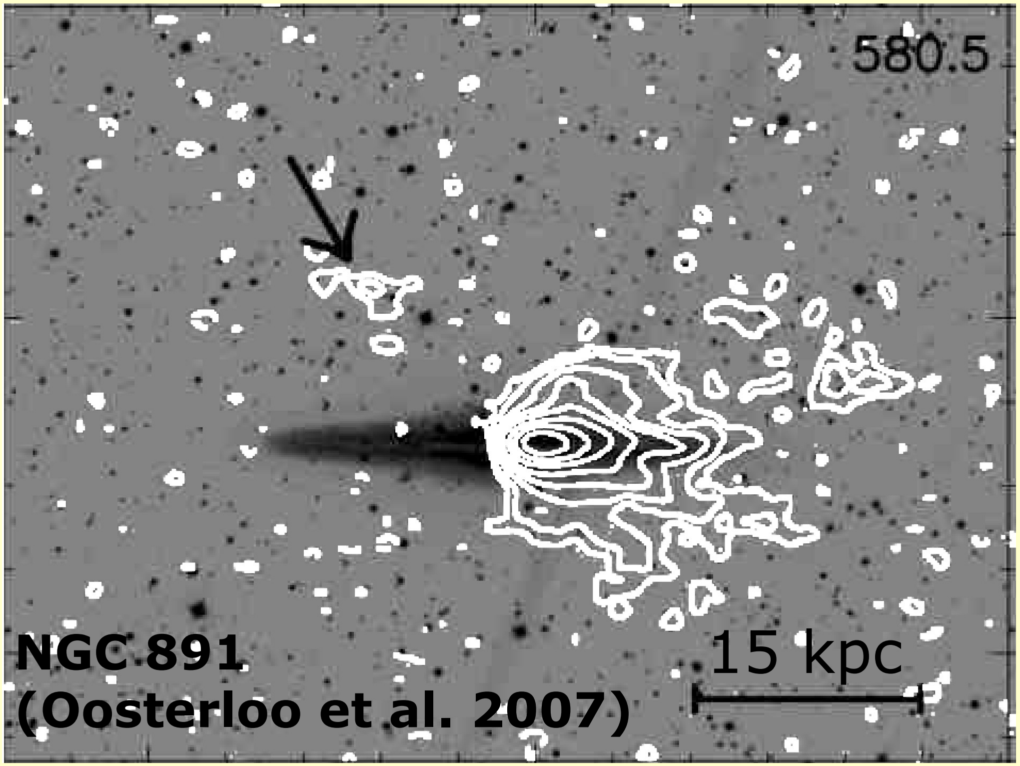
Normal vector of angular momentum is different, e.g.

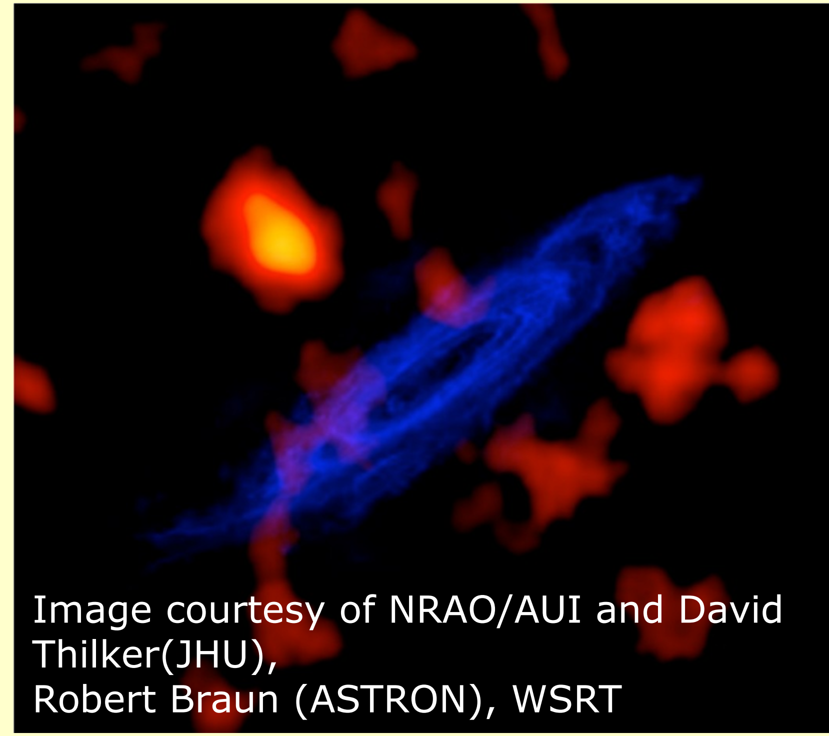
• Polar-ring **X** galaxies

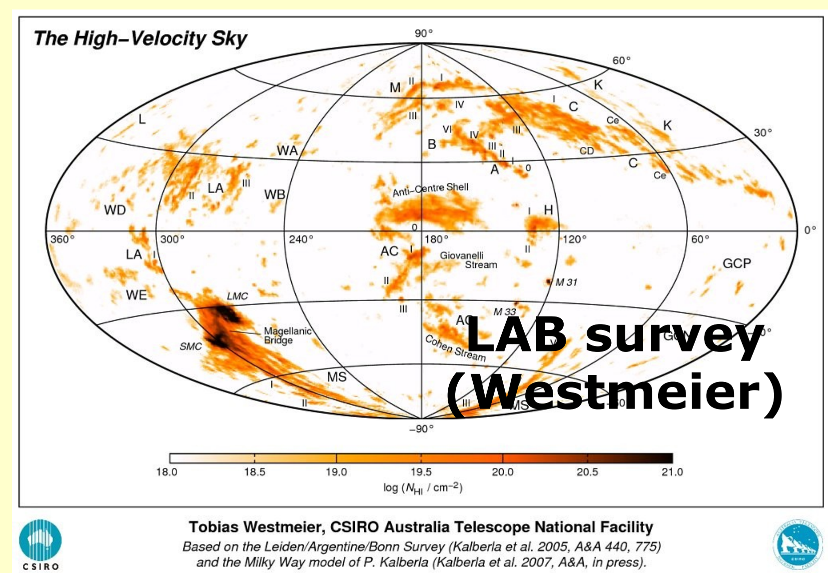
• Warps (not really distinct) **X**

Faint neutral gas

- HVCs/clouds



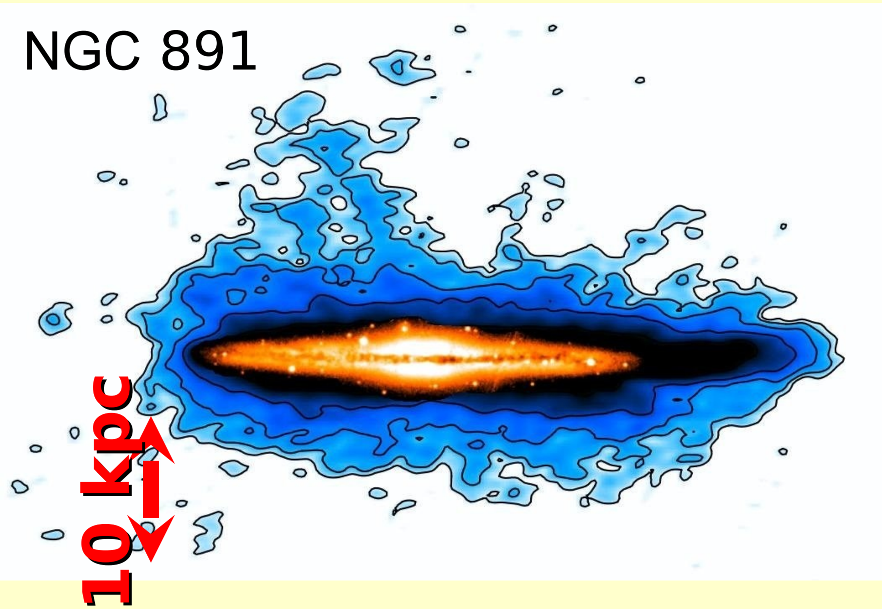




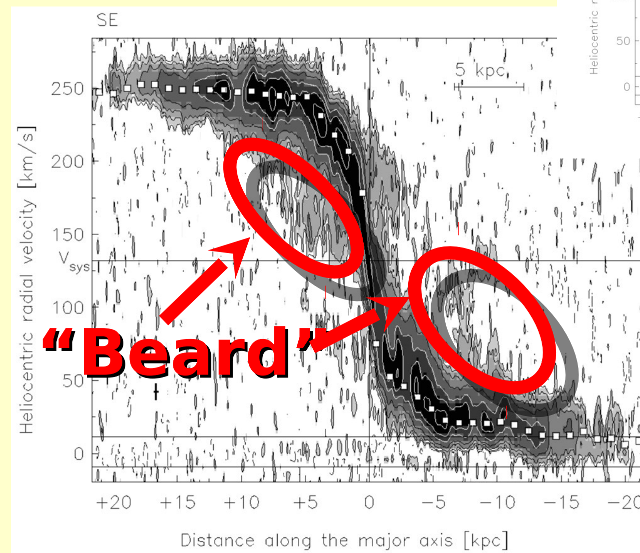
- Large cloud complexes and smaller clouds detected in a few galaxies (D < 50 kpc for MW and M31)
- Mass: 10^5 - 10^7 $M_\odot$
- **How much accretion from neutral clouds?**

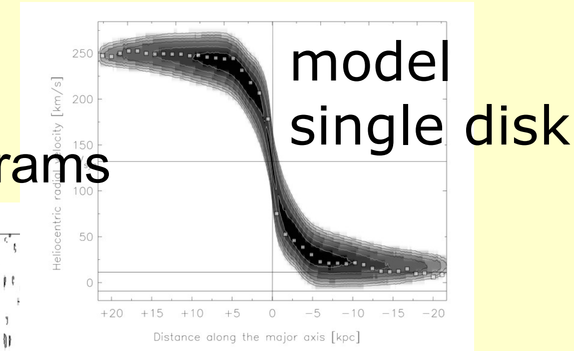
Faint neutral gas

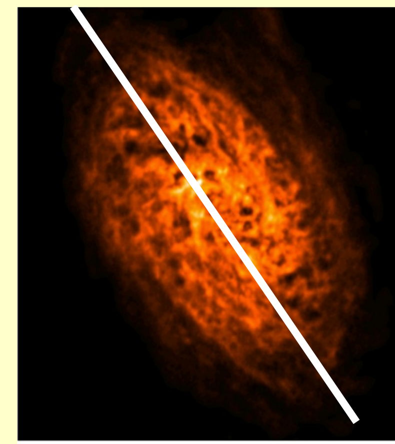
- Thick disks

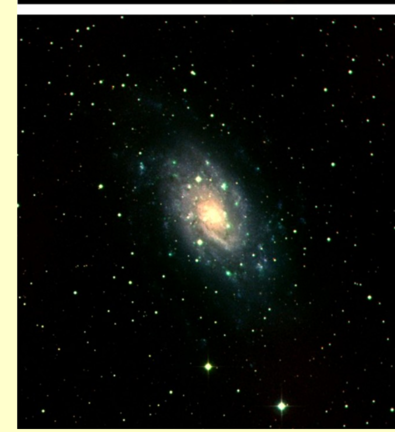


NGC 2403
position-velocity diagrams









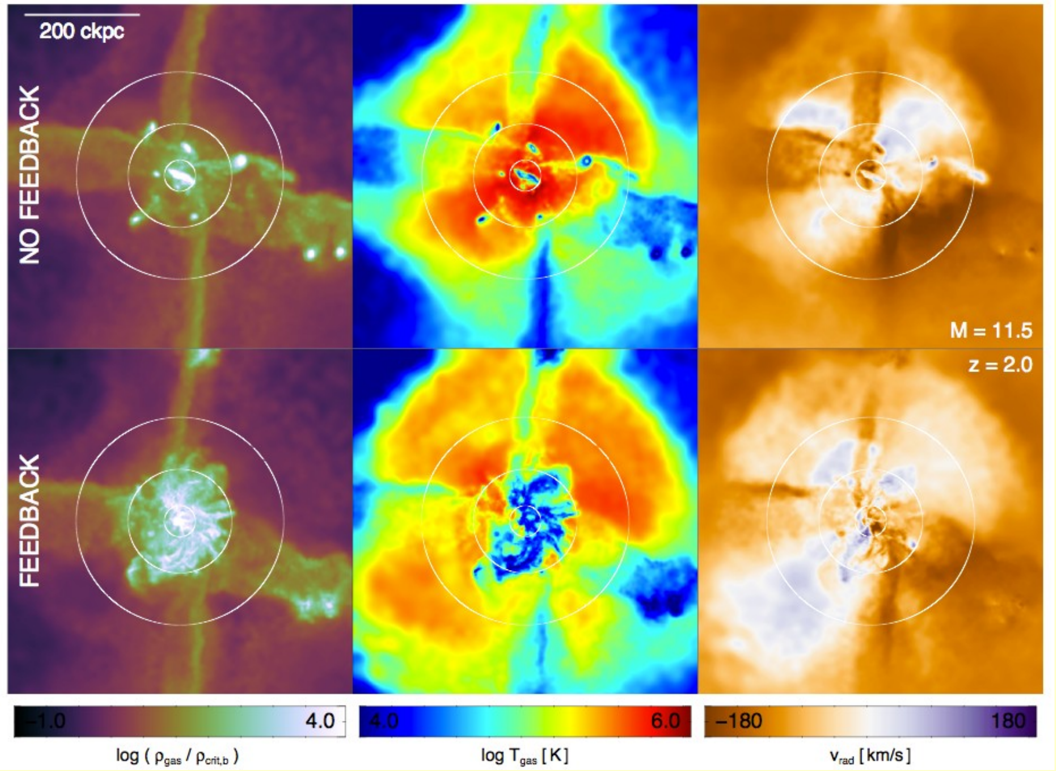
- NGC 891 (Oosterloo et al. 2007):
30% (~1.2 x 10^9 $M_\odot$) of the gas in extraplanar halo component

- NGC 2403 (Fraternali et al. 2002):
10% (~3 x 10^8 $M_\odot$) of the gas in extraplanar component (+ radial flow in extraplanar component)

- Few cases studied well enough to establish presence of gaseous halo: **How common are they?**

Gas accretion

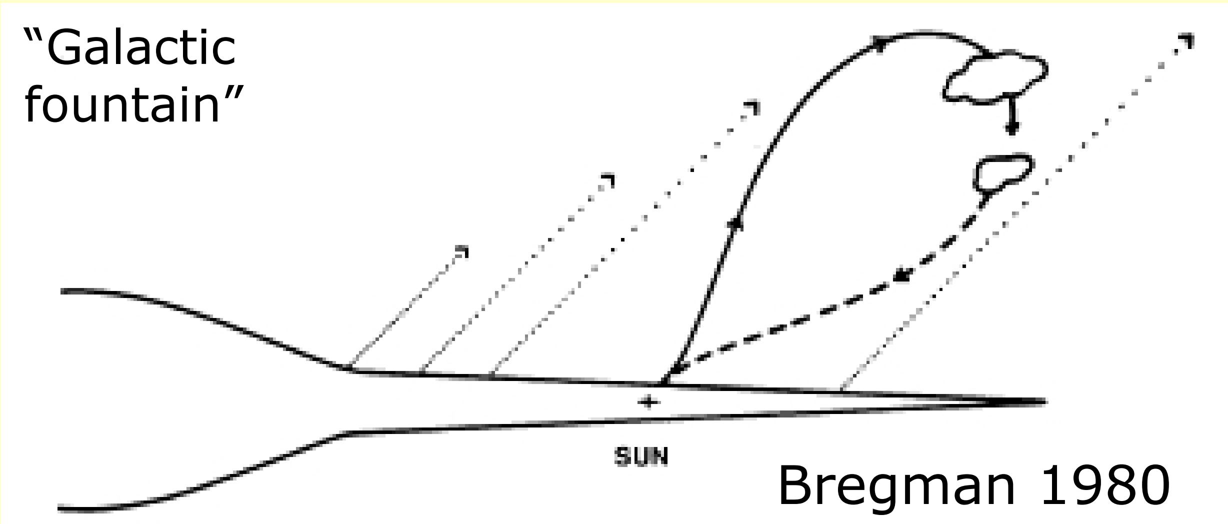
- Accretion of cold material needed to replenish star forming material: 3 $M_{\odot}$/yr (e.g. Bothwell et al. 2011)
- Infall of low-metallicity gas (0.1 solar) needed to explain stellar metallicity abundances (e.g. “G-dwarf problem”, Wakker et al. 1999)
- Observed: ≥ 0.2 $M_{\odot}$/yr (HVCs, minor mergers, Sancisi et al. 2008)
- Could be much more if an unseen, cold accretion takes place (Kereš et al. 2005)
- Is it there? How can it be observed?

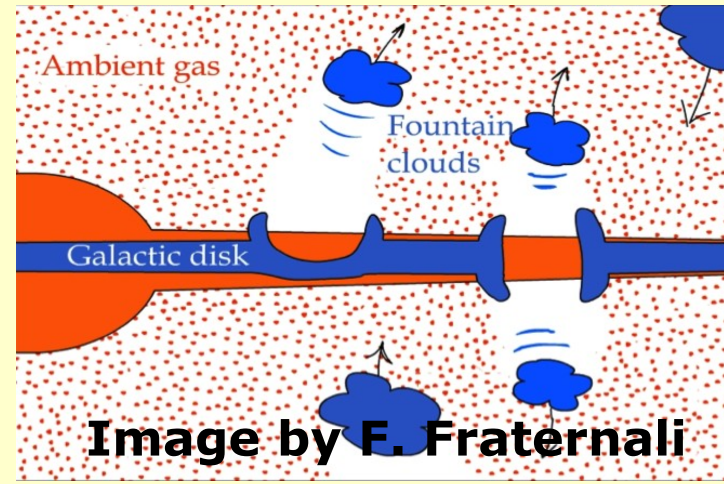


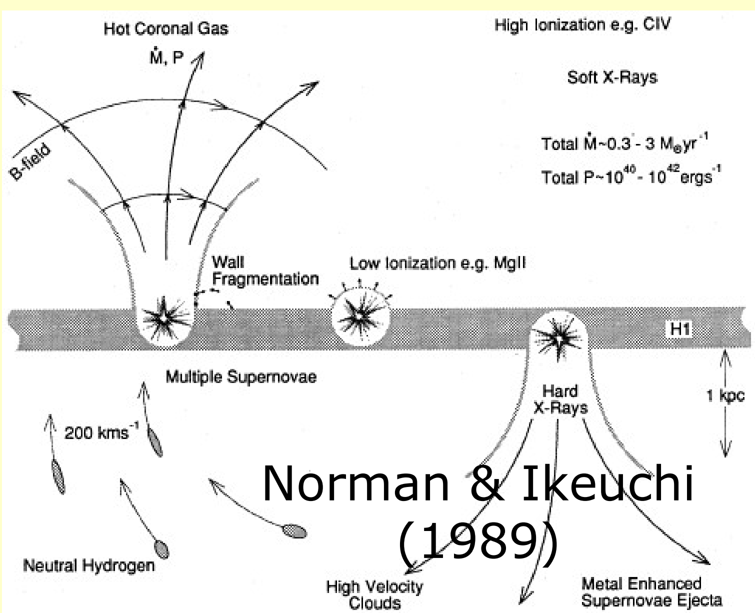
Nelson et al. 2014

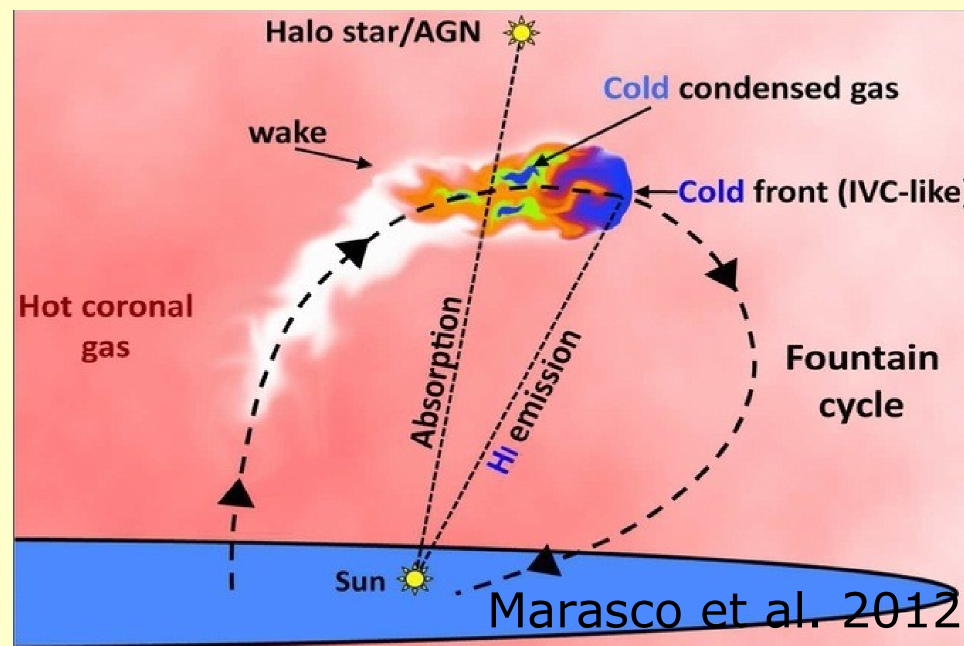
Galactic fountain and accretion

- Neutral extraplanar gas is expected, but not with the observed lag





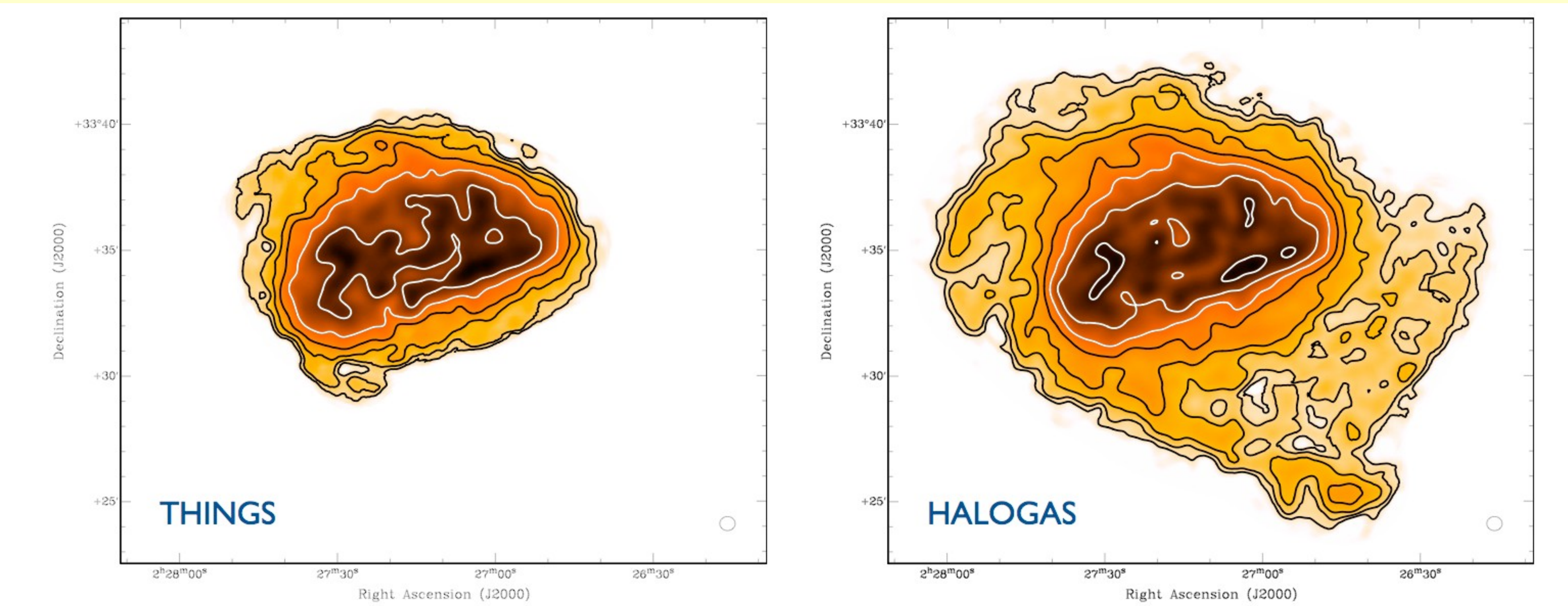




The HALOGAS survey

• Deep H I observations mostly biased → how does the H I halo population look like in general? → need for unbiased sample →

Hydrogen **A**ccretion in **LO**cal **GA**laxie**S** Survey



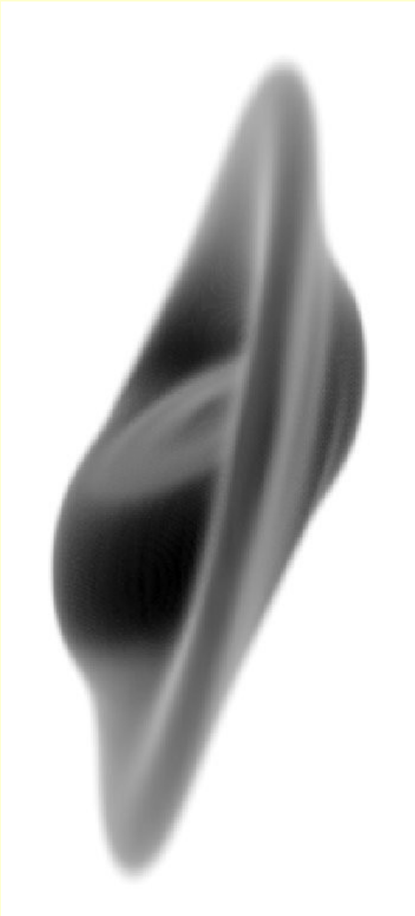
→ 22 spiral galaxies (24 including archive galaxies)

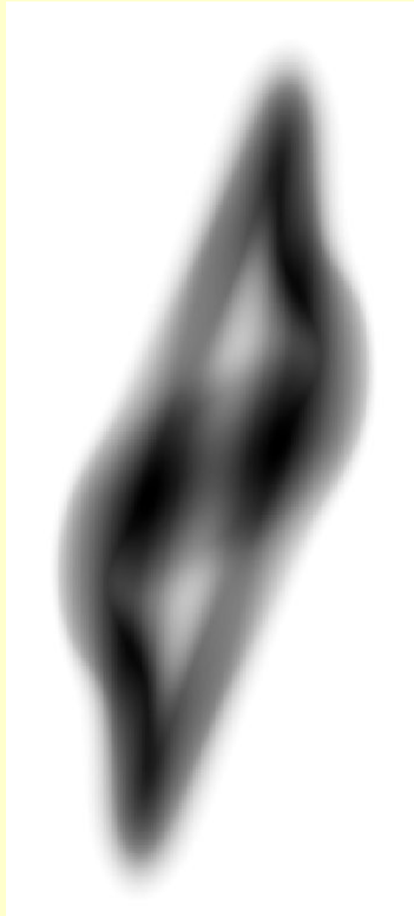
Requirement:

• 3-σ detection of column density of 10^{19} cm^{-2} → 10 x 12h (on-source) observing time per galaxy (detection limit 2.7×10^5 (D/10 Mpc)^2 $M_\odot$)

→ ~2900 h WSRT telescope time (finished)

Analysis using the tilted-ring model

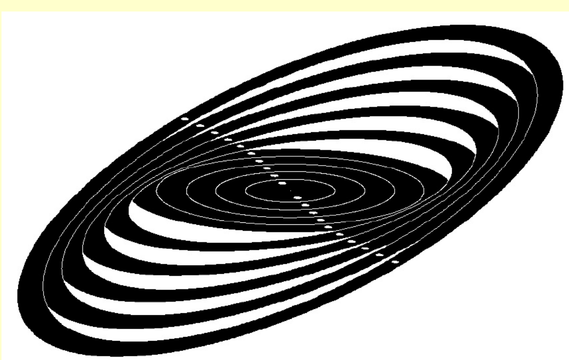




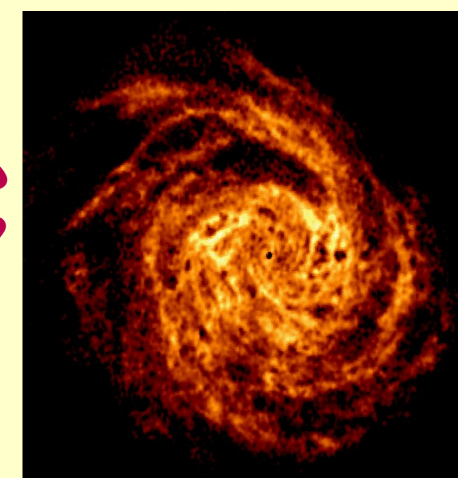
Tilted-Ring-Model
(Rogstad et al. 1974):

parametrise rings at different radii by

- two orientation parameters (inclination, position angle)
- central position
- surface brightness (thickness)
- rotation velocity



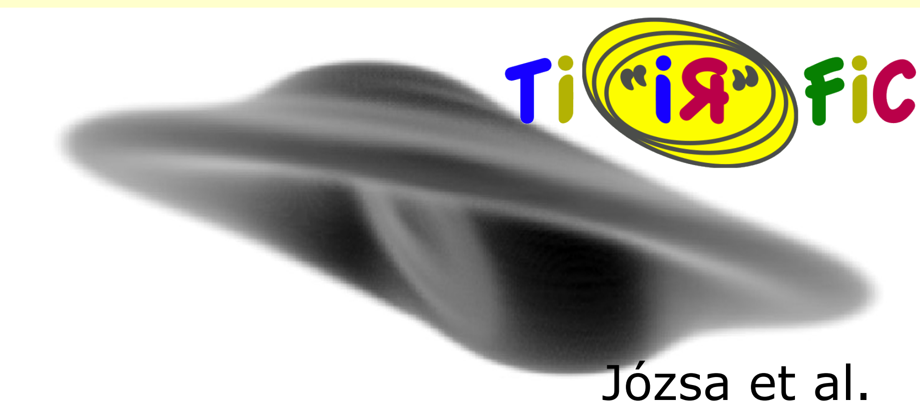
García-Ruiz 2001



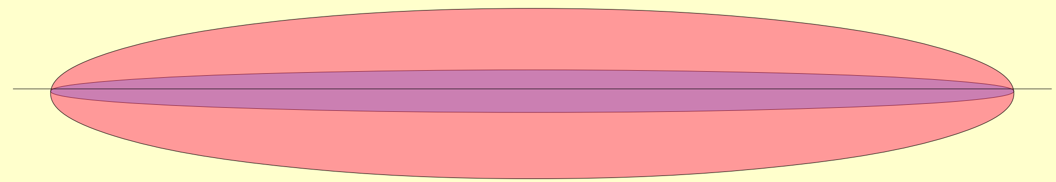
Boomsma et al. 2008

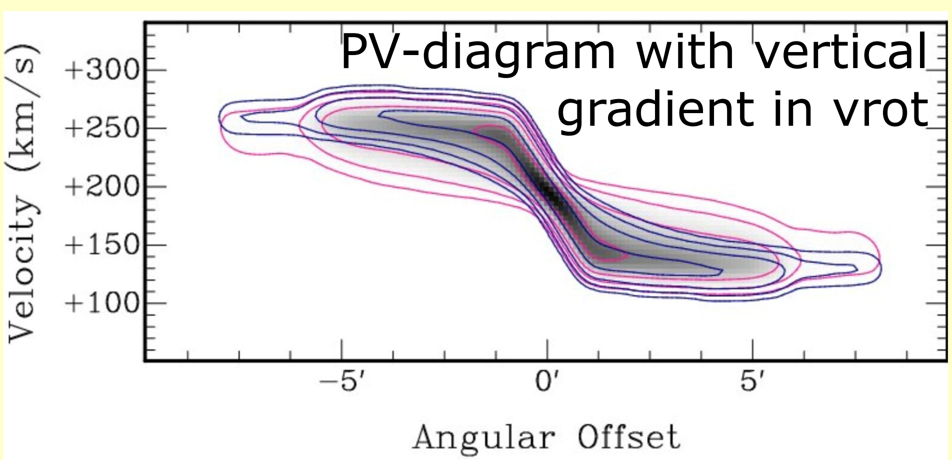
Analysis strategy

- Goals: Statistics of H I masses and kinematic description of disk, gaseous halo, H I clouds, companions
  - -> in-depth detailed tilted-ring modelling of each galaxy
  - -> search for companions/"HVCs"
  - -> estimates of extraplanar gas mass using global scheme

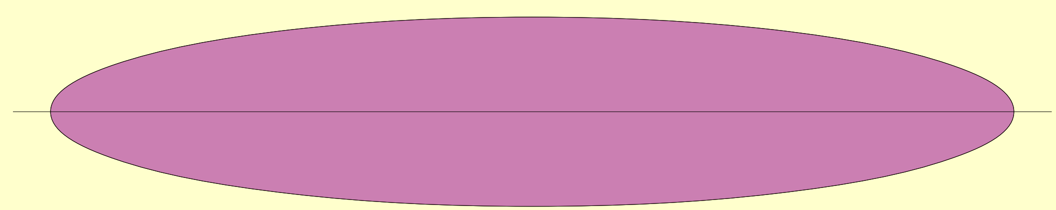


Thin+thick disk required?



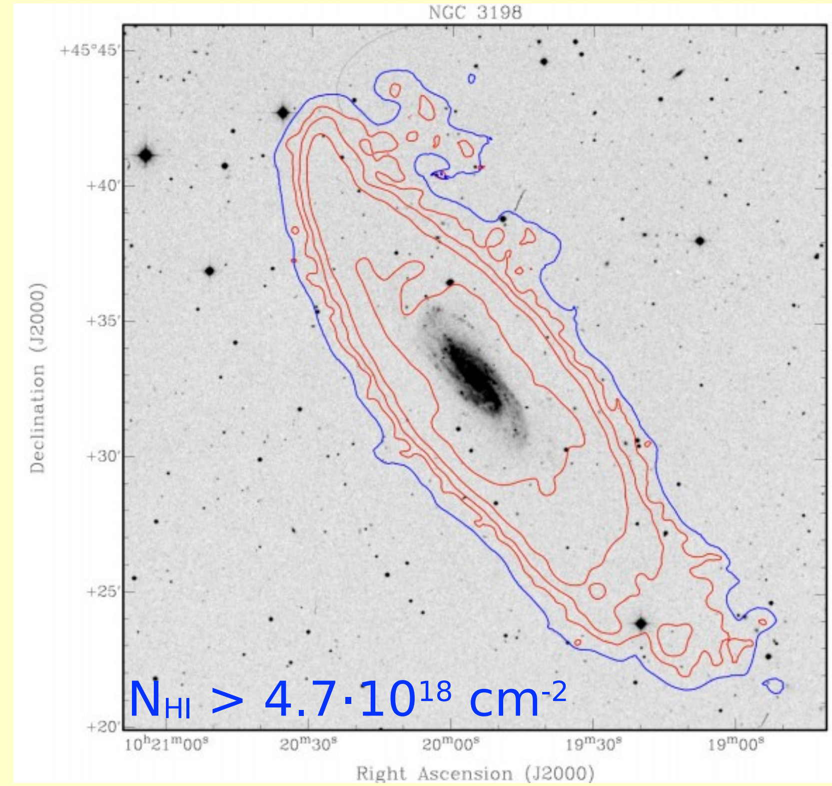


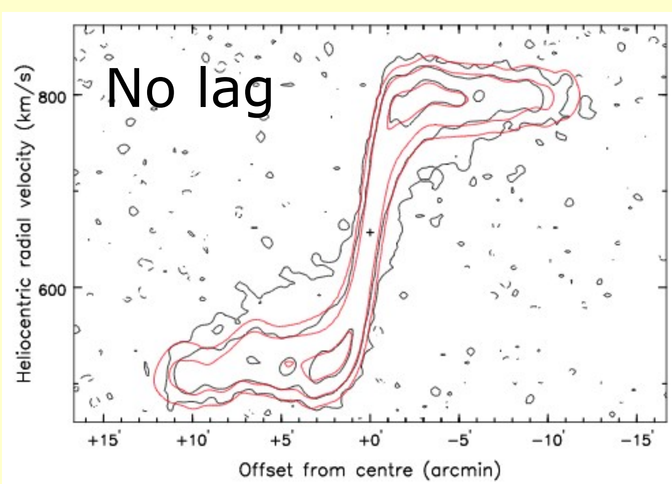
or for given scale height single disk sufficient?

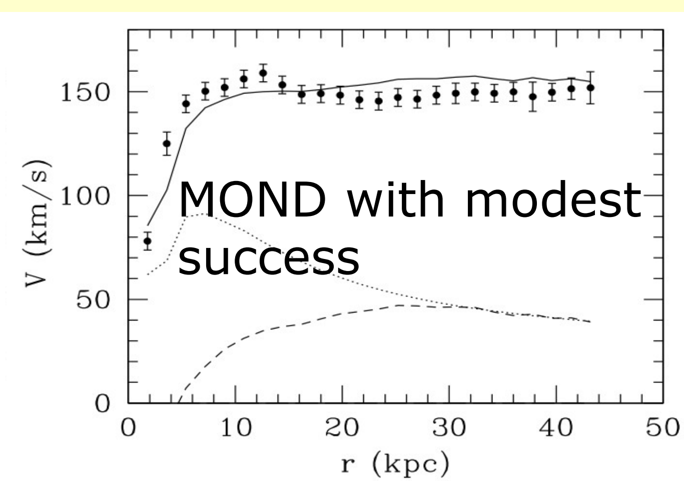


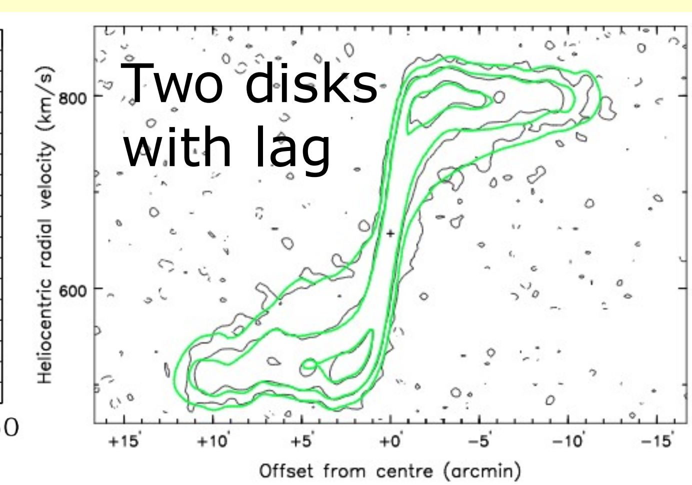
NGC 3198 (Gentile et al. 2013)

- Two disks required (thick disk scale height 3 kpc)
- Extraplanar component 10% - 20% of total H I mass
- Lagging: 7 km s^{-1} (app), 15 km s^{-1} (rec)
- m = 2 harmonic distortion in tangential velocity (bar-like distortion)

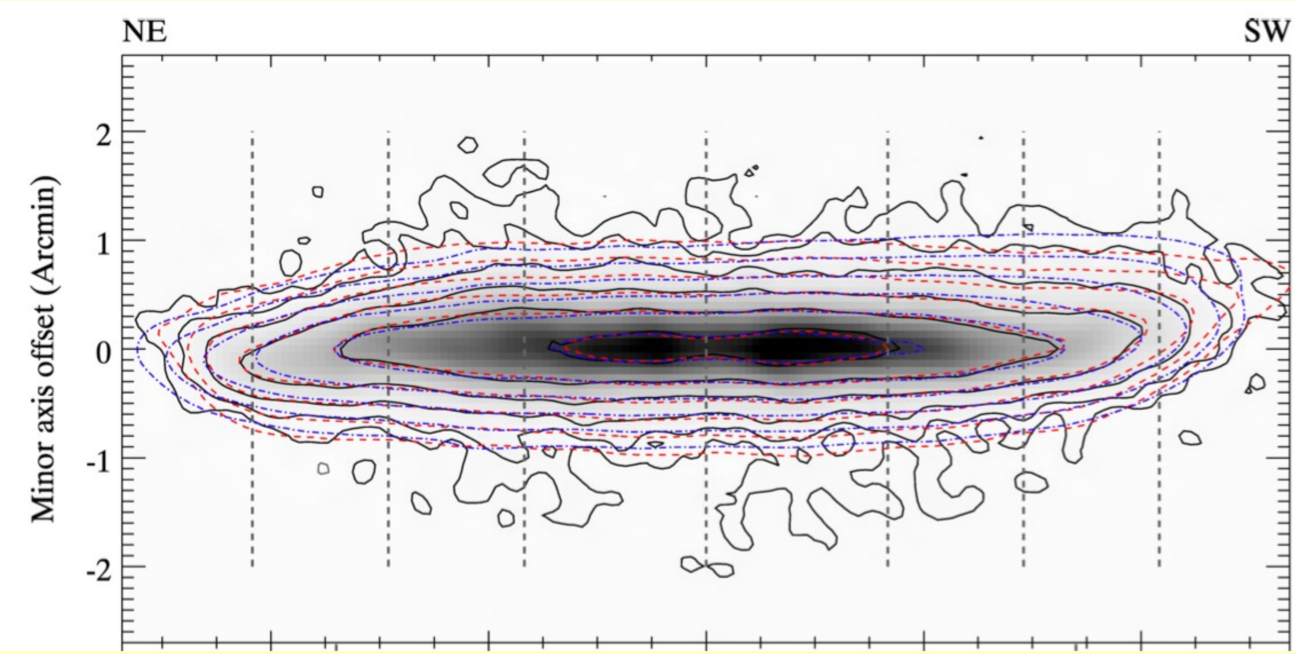


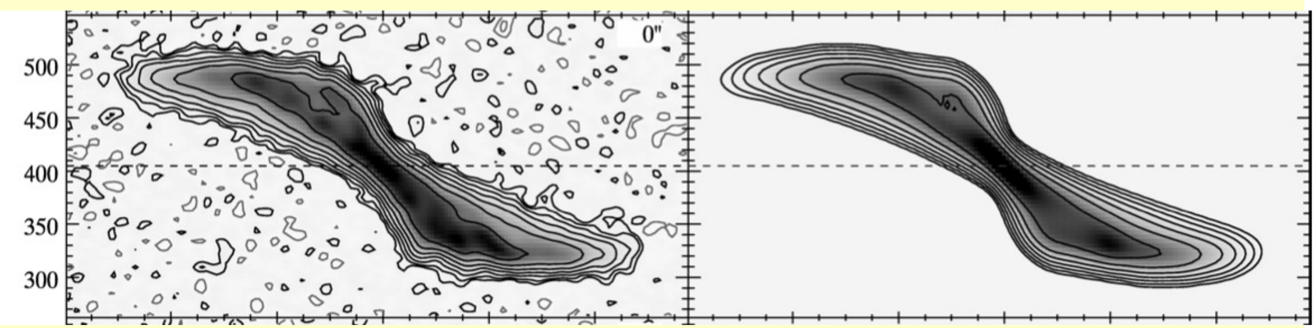


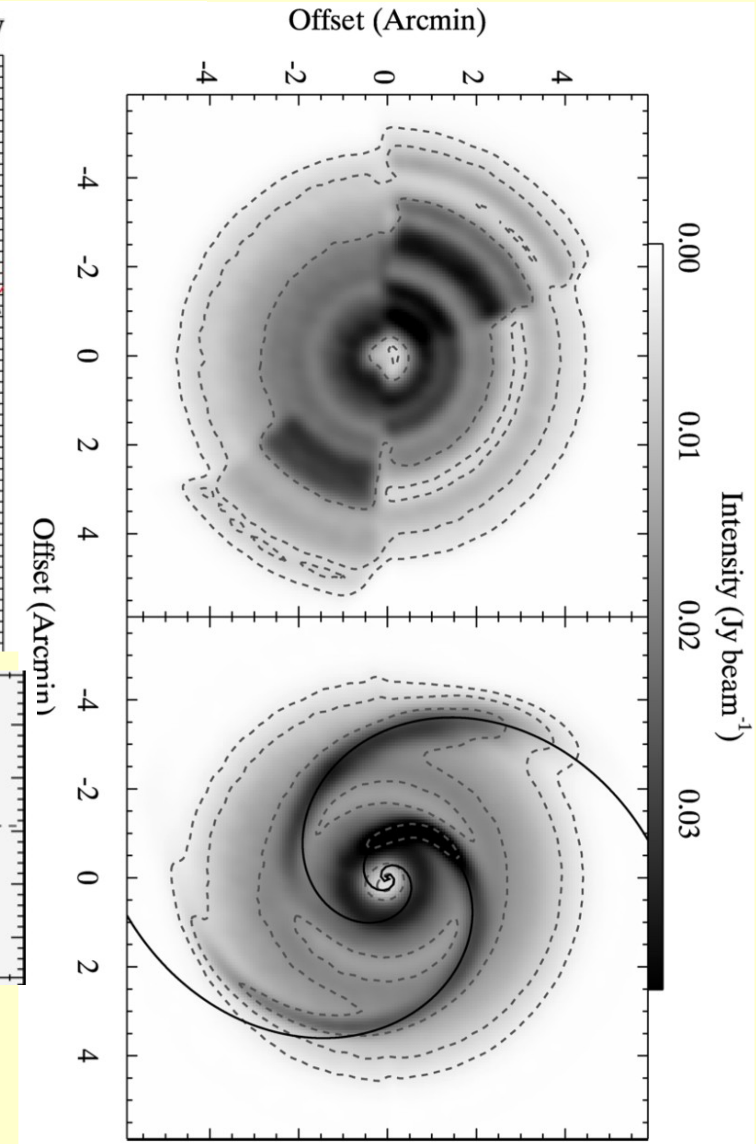




NGC 5023 (Kamphuis et al. 2013)







- Inhomogeneities well represented by spiral arms
- No extra vertical component required
- Vertical gradient in velocity: dV/dz = -9 km/s/kpc

NGC 5023

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- No extra vertical component required
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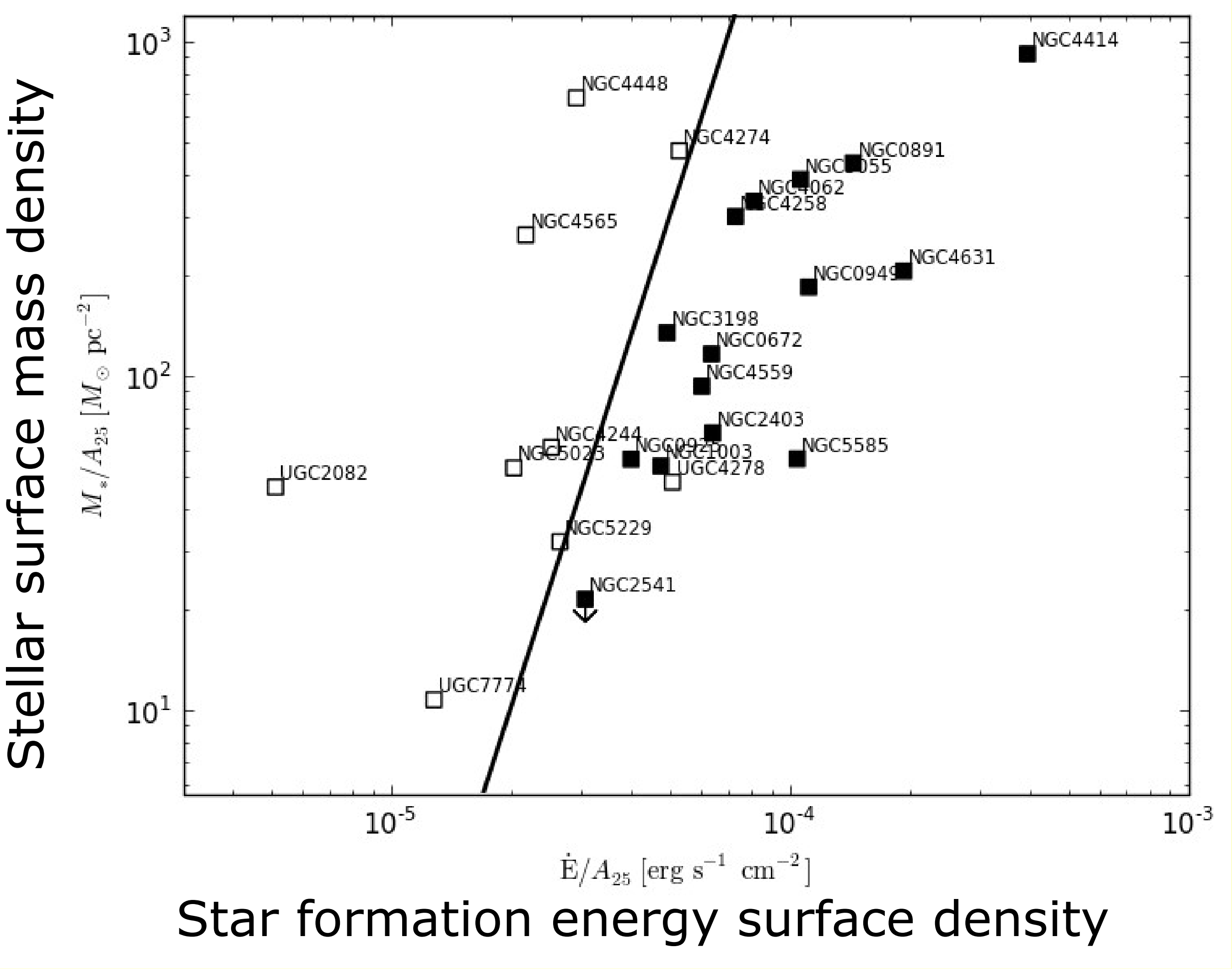
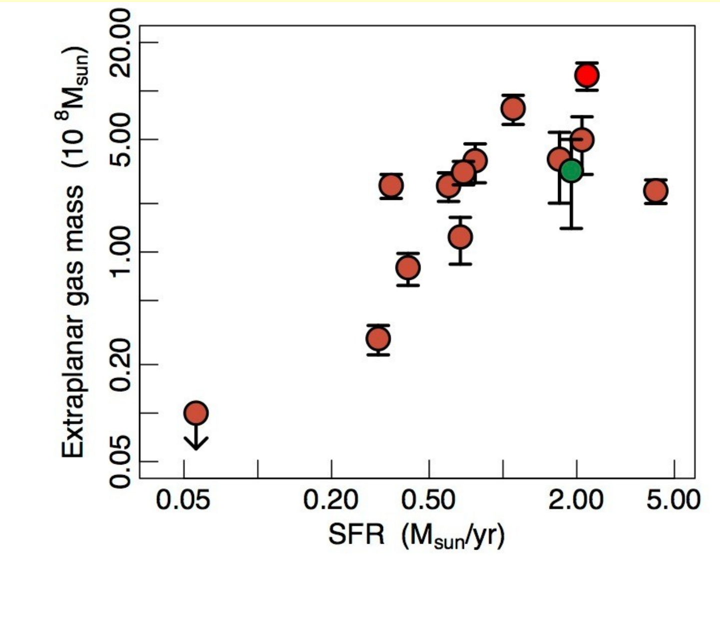
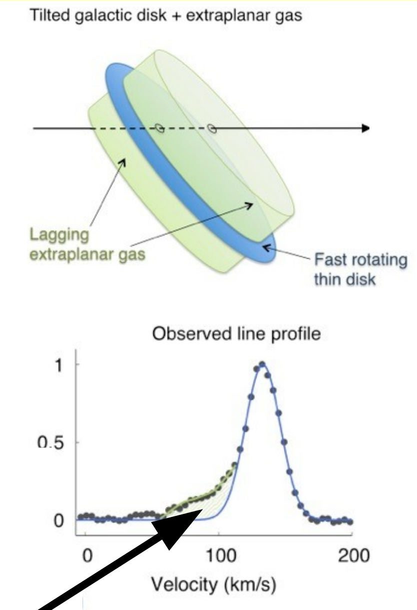
Thick disks and star formation (Heald et al.)

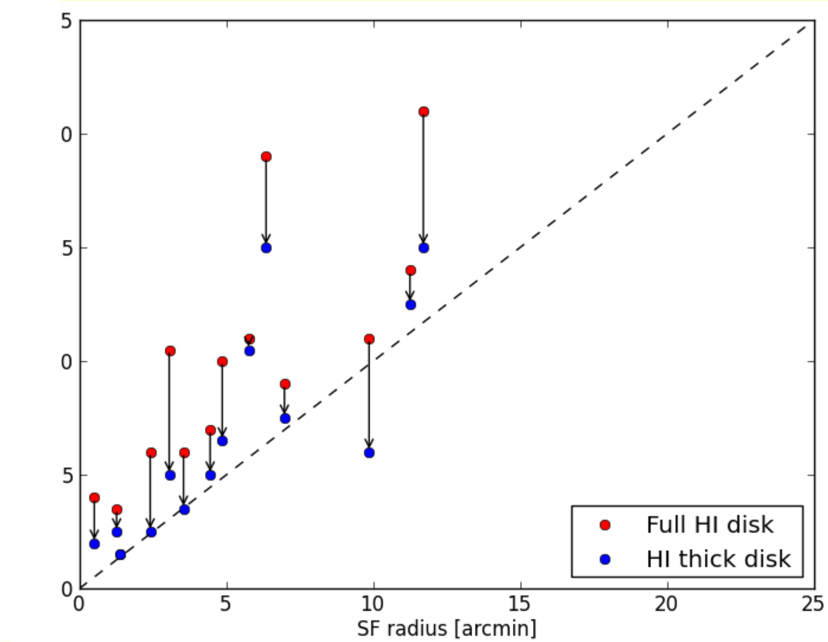


• Separation between galaxies with extraplanar H I (filled boxes) and without extraplanar H I (empty boxes) by star formation surface density

Thick disks and star formation







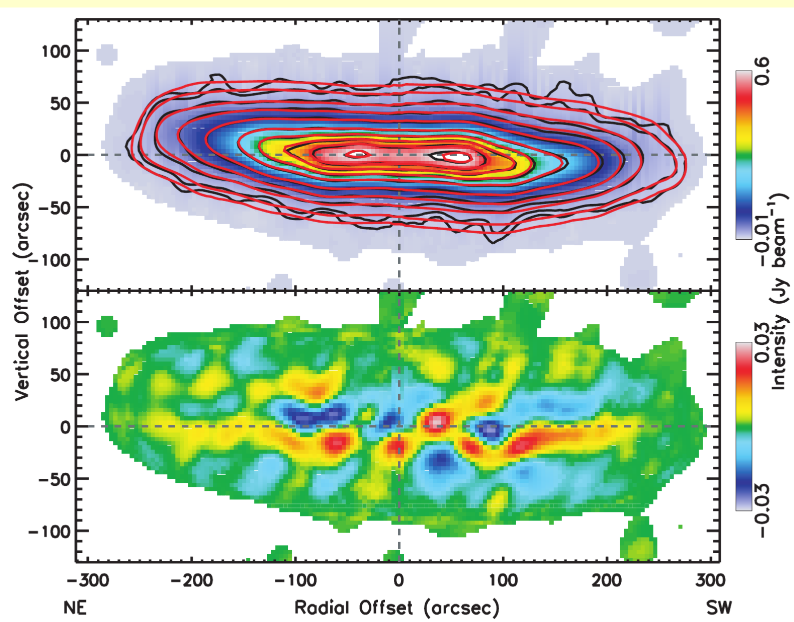
"Anomaleous" gas

- Correlation between star formation rate and extraplanar gas mass
- Star formation radius and thick H I disk radius similar
- Further investigations show: estimated fountain mass correlates with extraplanar gas mass (Fraternali et al.)

Dwarfs: kinematic structure

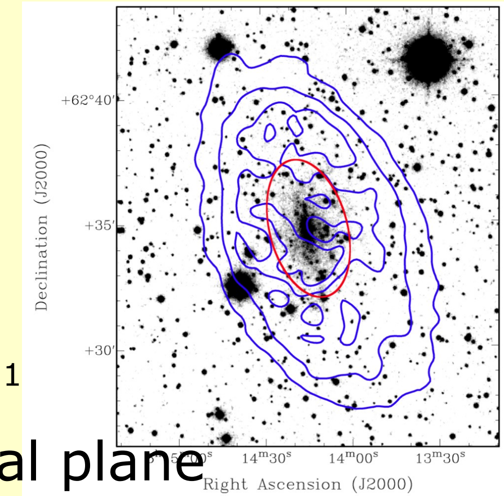
UGC 1281
Kamphuis et al. 2014, A&A

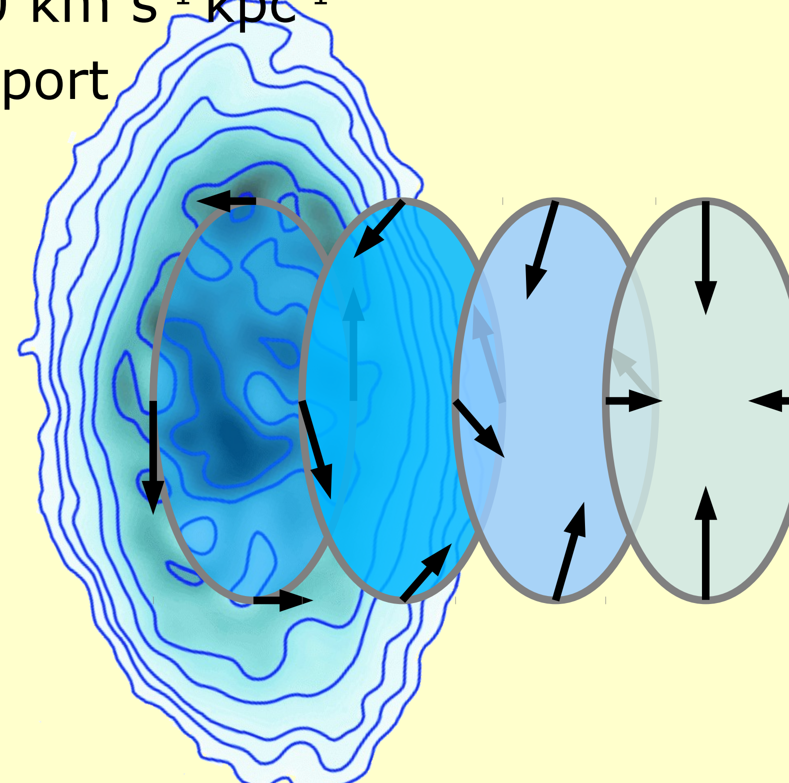
- M_B = -15.8
- v_{max} = 60 km s^{-1}
- SFR = 0.008 $M_\odot y^{-1}$
- Data consistent with no extraplanar gas



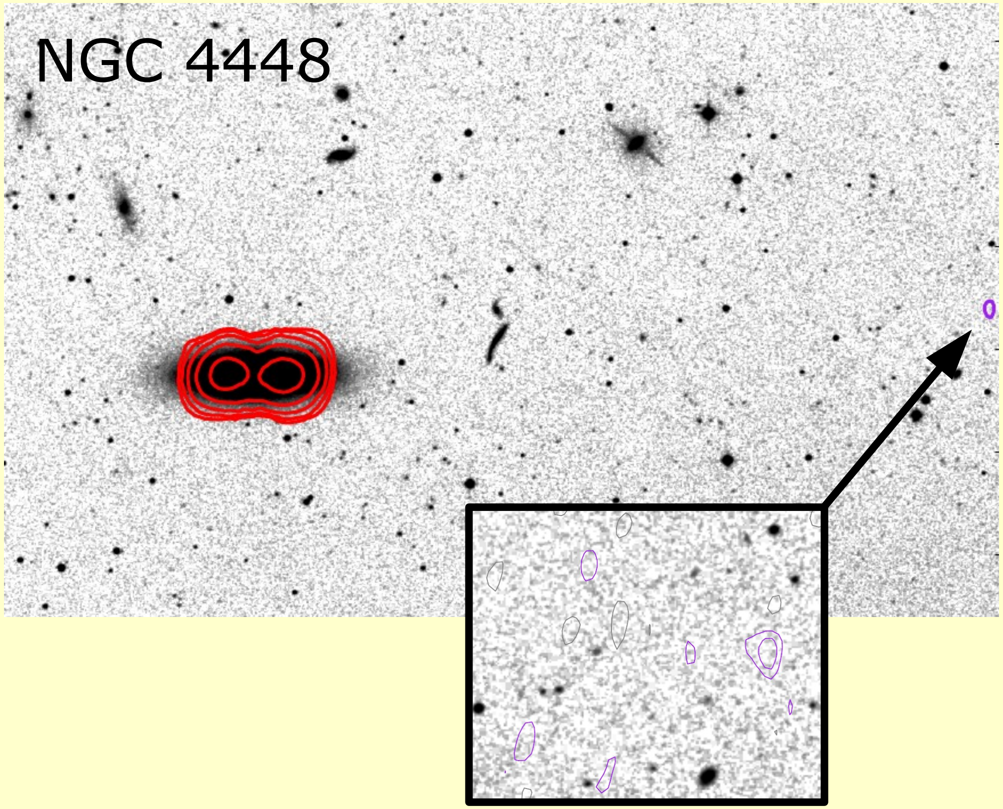
UGCA 105
Schmidt et al. 2014

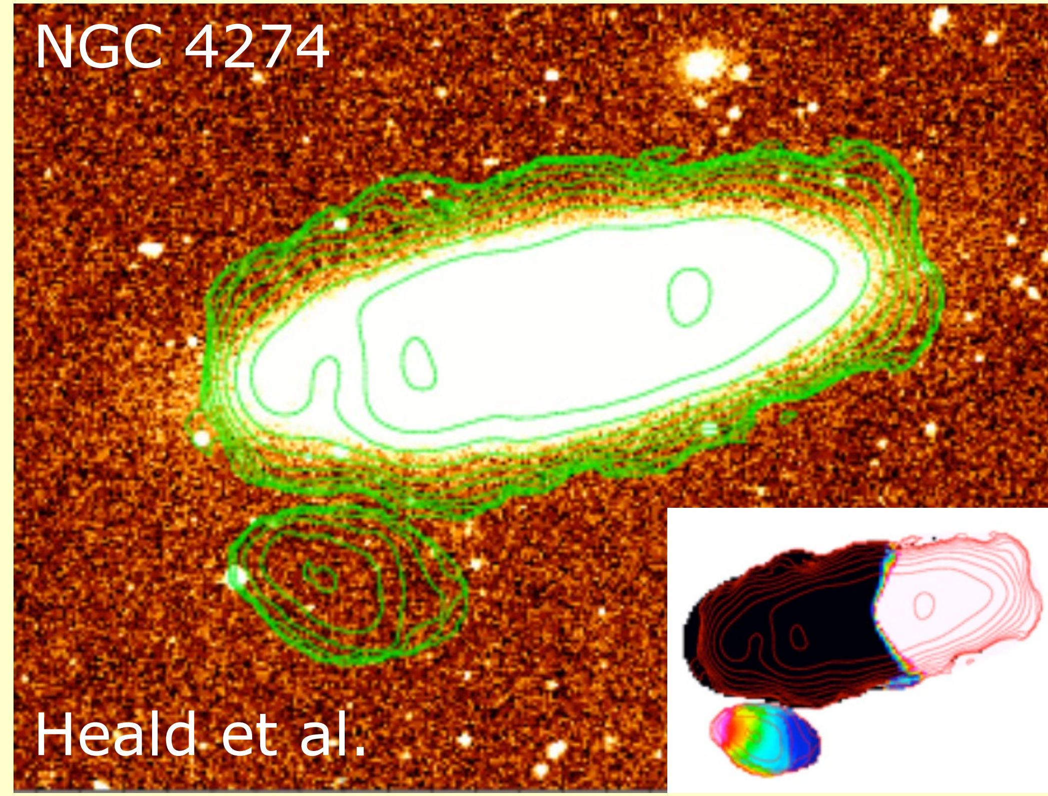
- M_B = -14.7
- v_{max} = 80 km s^{-1}
- SFR = 0.07 $M_\odot y^{-1}$
- dV_{rot}/dz = -60 km s^{-1} kpc^{-1}
- No radial motion in central plane
- dV_{rad}/dz = -70 km s^{-1} kpc^{-1}
- Inwards transport 0.05 $M_\odot$ y^{-1}





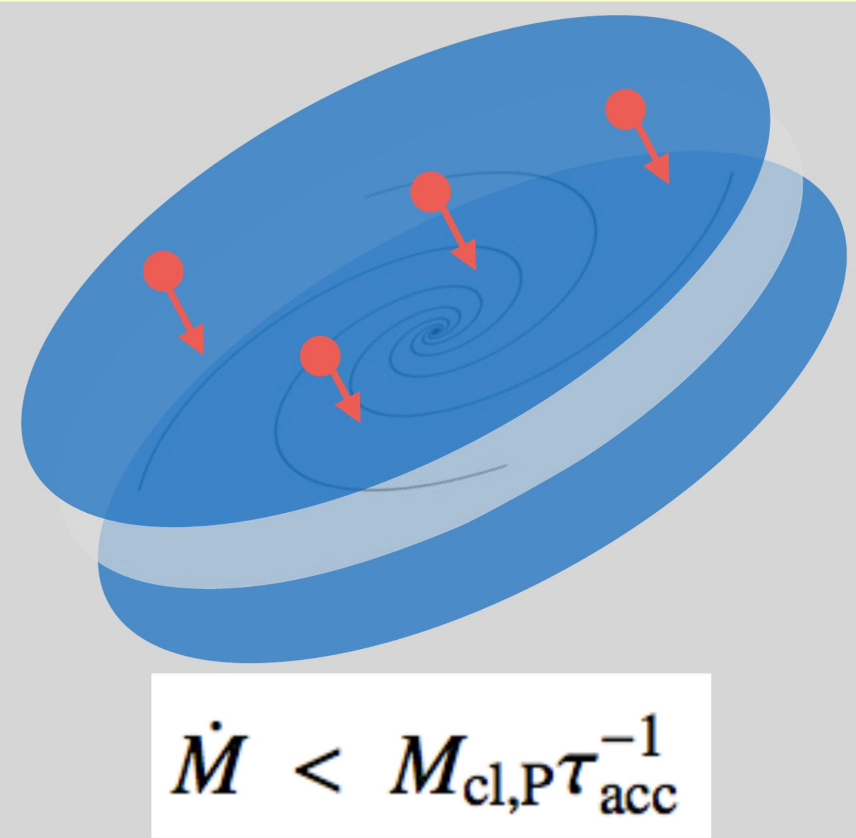
The HALOGAS cloud catalogue (Jütte et al.)



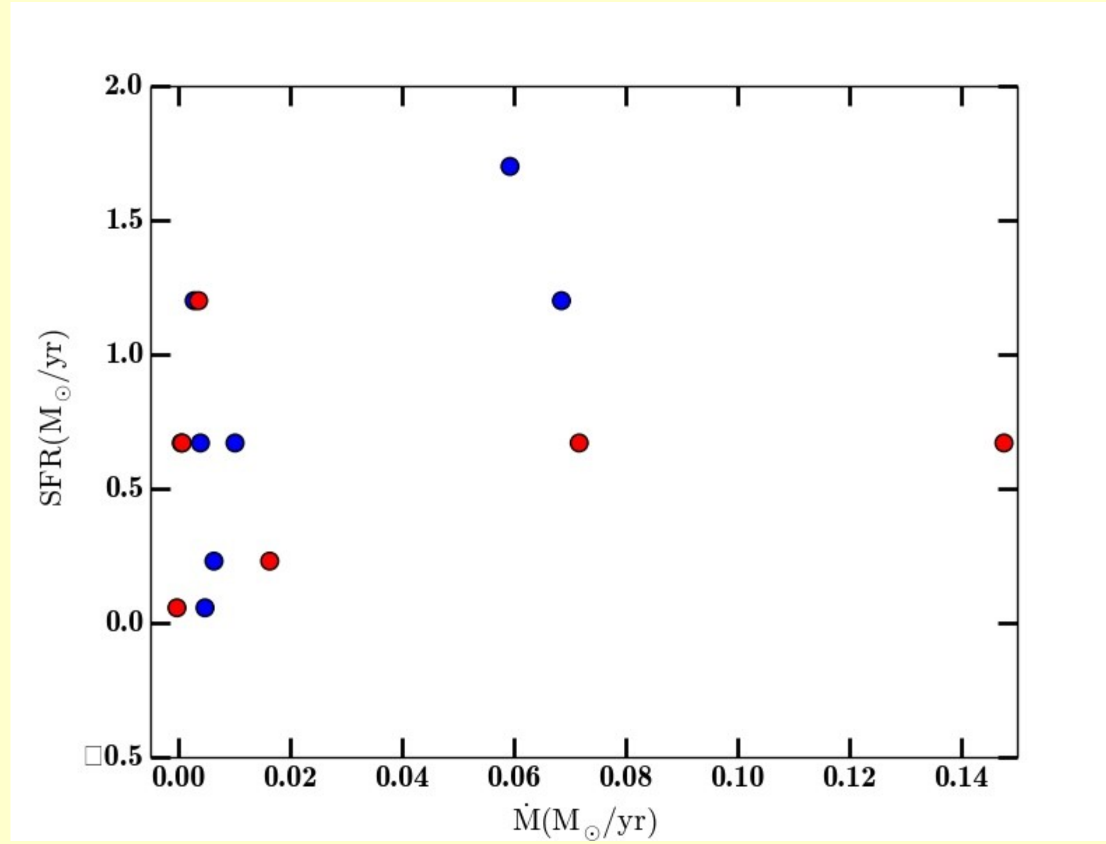


- Use 3DBarolo to detect 117 source candidates in cubes with 1024x1024x900 pixels
- Inspect data cubes to identify obvious false detections and be left with 22 clouds
- Identify potential companion galaxies as hosts in deep HALOSTARS (PI: Józsa) INT images and DSS
- The complete HALOGAS cloud catalogue consists of 8 clouds (some also rather interesting ones)

The HALOGAS cloud catalogue (Jütte et al.)



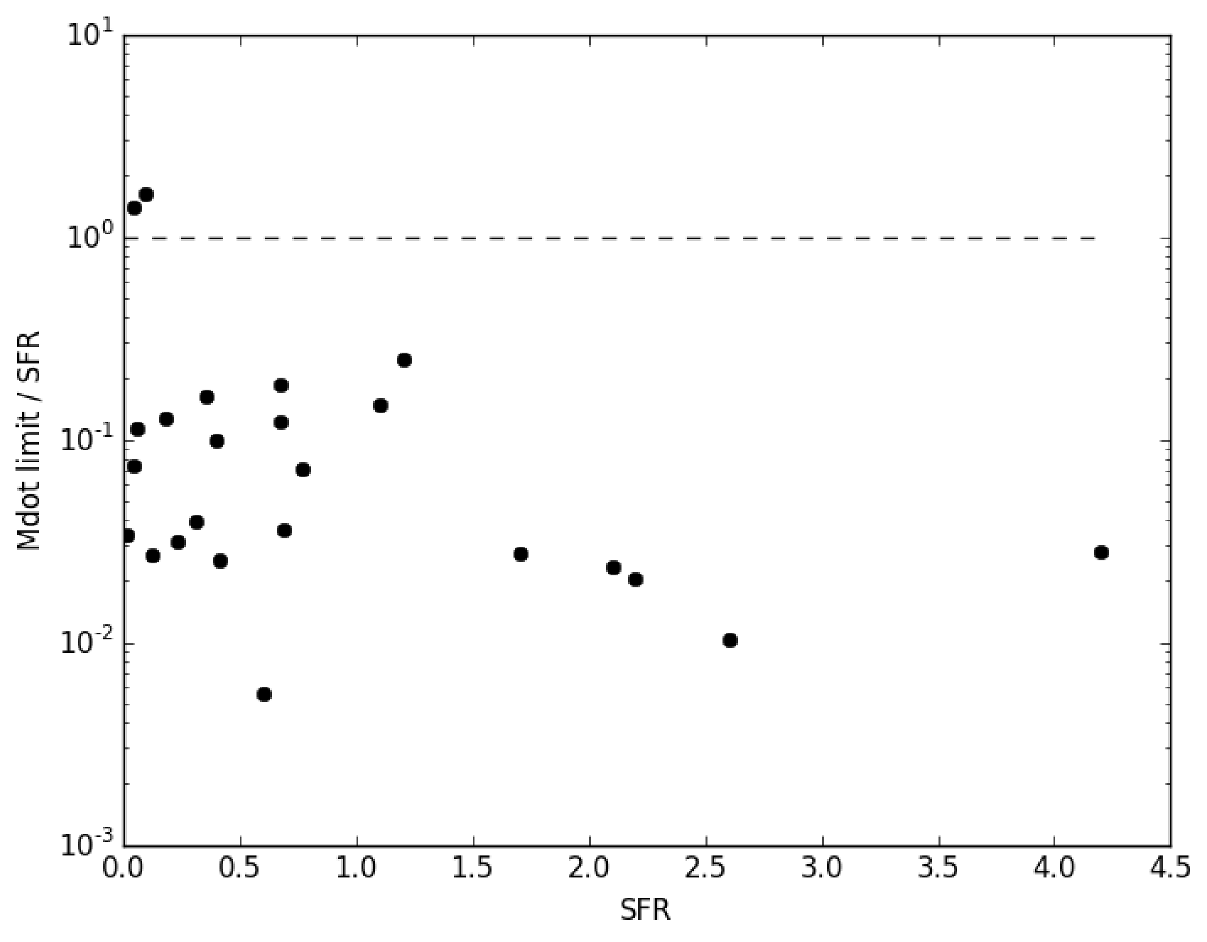
$$\dot{M} < M_{\mathrm{cl,P}} \tau_{\mathrm{acc}}^{-1}$$



- Bulk of gas thought to be within volume defined by ~0.5 R_{vir} (e.g. Nelson et al. 2014)
- Not all cubes cover that volume
- Assume direct infall on centre (or r_{25}) with escape velocity to calculate accretion time τ_{acc} and correct for volume to estimate upper limit to visible H I infall
- Induced visible accretion rate always much lower than SFR

Upper limits to HI accretion (Jütte et al.)

- Non-detections at the ~$3 \cdot 10^5$ $M_\odot$ level (3σ)
- Assume mass function of accreting clouds
  - Upper limit: detection threshold
  - Lower limit set by self-shielding density
- Accretion timescale
  - ~4 Myr (crossing time of an unresolved cloud at 200 km/s)
- Accretion surface of diameter D_{25} (in both directions)
- Filling factor of H I clumps within the accretion flow



$$\dot{M} < 8.2 \times 10^{-2} \left(\frac{D_{25}}{10\,\mathrm{kpc}}\right)^2 \left(\frac{D}{10\,\mathrm{Mpc}}\right)^2 \left(\frac{f}{0.1}\right) M_\odot\,\mathrm{yr}^{-1}.$$

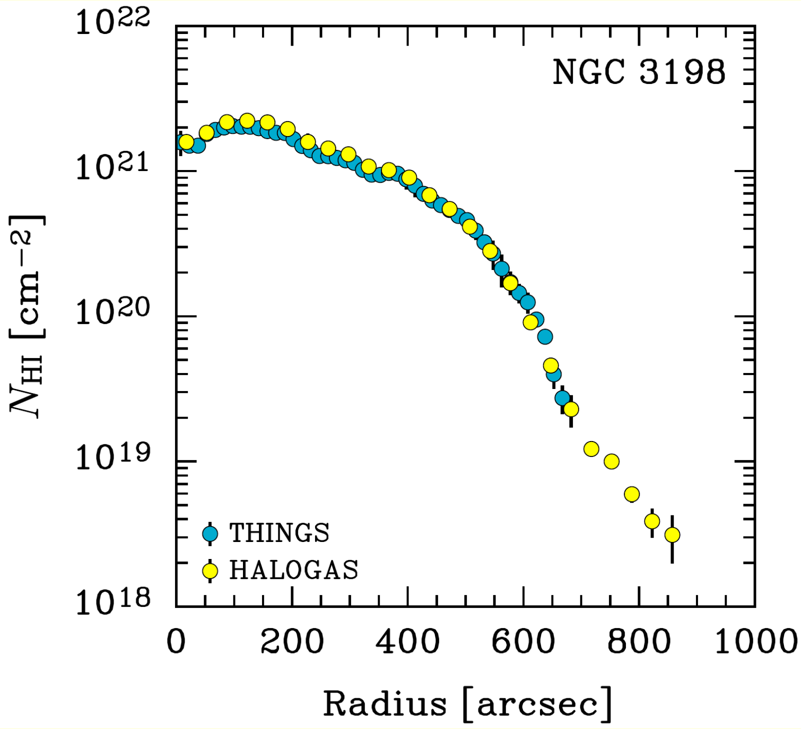
Summary and outlook

- Thick disks and anomalous gas are not ubiquitous
- NGC 891 is certainly an extreme case and not the rule
- Thick lagging disks are connected to the underlying star formation properties

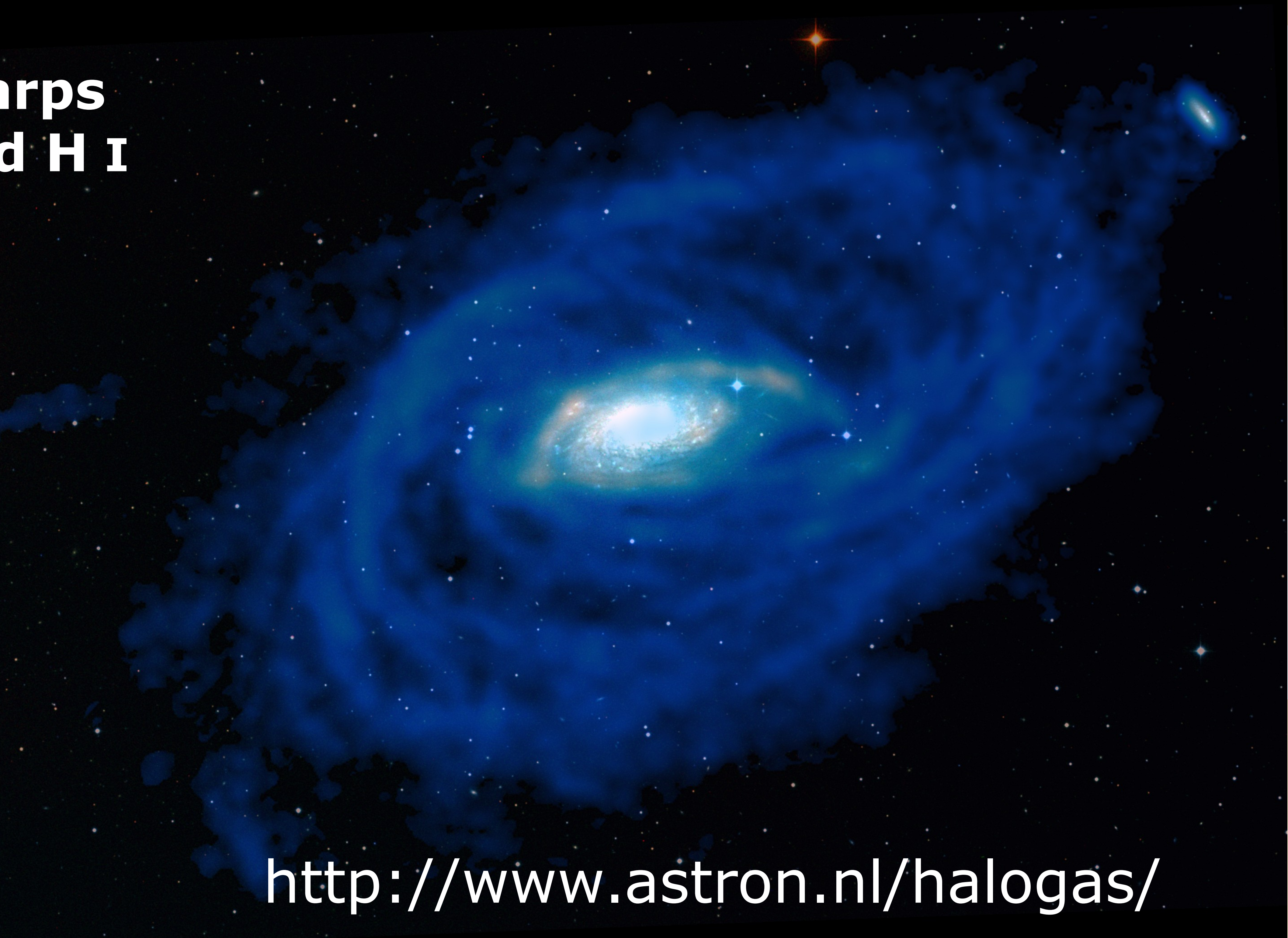
- Accretion of H I in the form of clouds is not the predominant form of accretion
    - Special time in the evolution of the universe?
    - Accretion closer to disk, mixing with fountain?
    - Accretion of hot gas through fountain?
    - Accretion of mostly ionised gas?
    - Further, more comprehensive search required

- Stacking underway (Ianjamasimanana et al.)

- Future: MHONGOOSE
    - MeerKAT (most sensitive and fastest H I telescope in near future, 1° FOV, ~15 times faster than WSRT)
    - 30 nearby galaxies

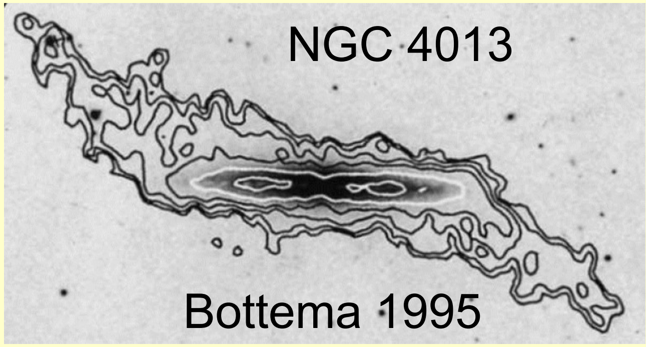


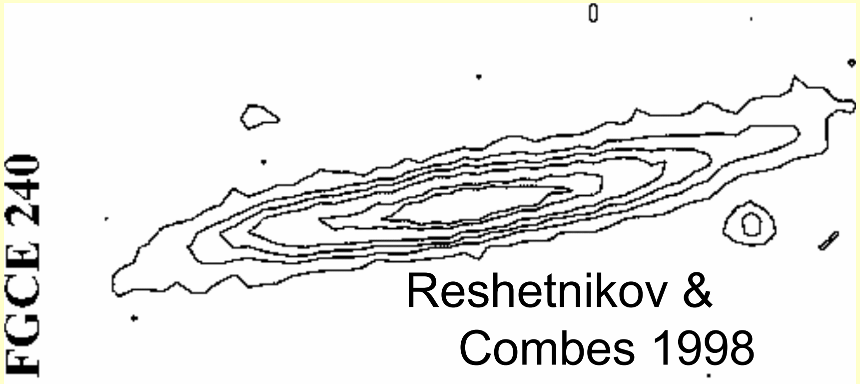
Ianjamasimanana et al.

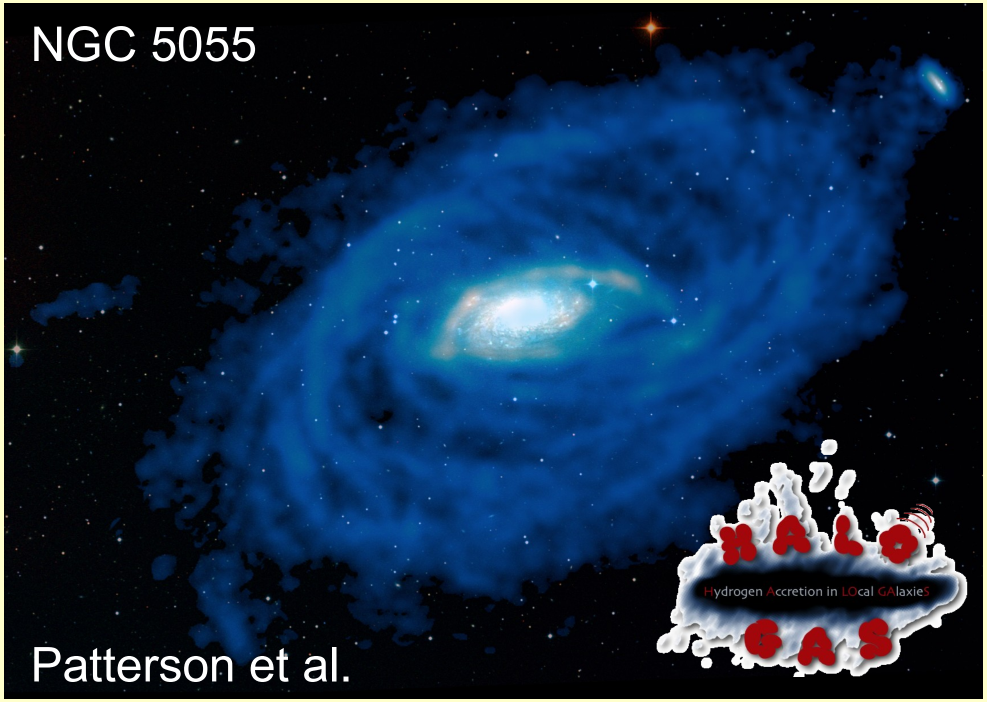

rps
d H I
http://www.astron.nl/halogas/

Warps: Properties

- Warps are **ubiquitous**
- Warps usually **start where the optical disk fades** (→ **H I best tracer)**
- Most warps are dominated by an **m=1** vertical displacement (they are S-shaped)
- Warps tend to **higher asymmetry** (mixing with m=0, m=2, ...) and amplitude **in denser environments**







Rules for the behaviour of (H I-) warps

Briggs (1990) rules:

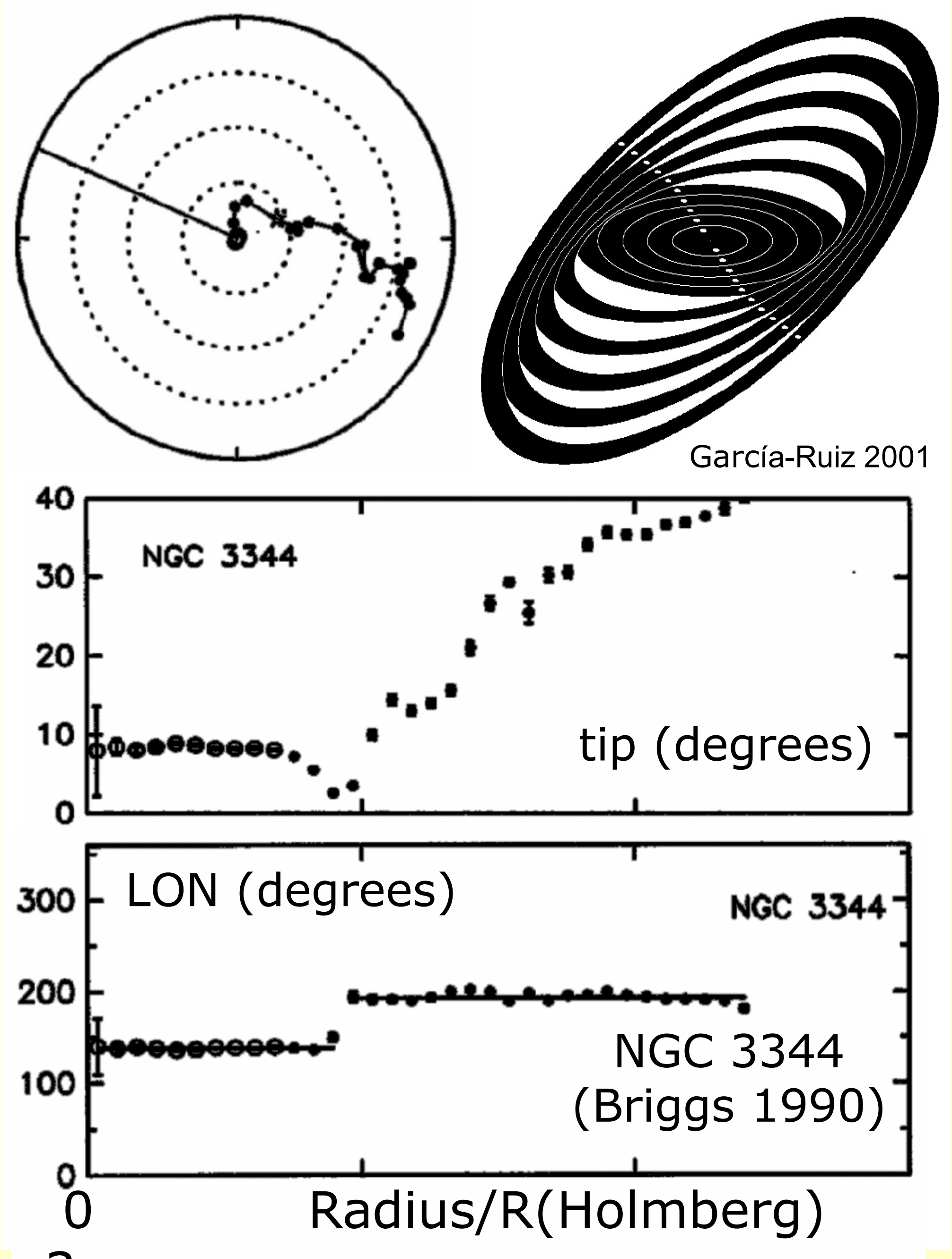
- The H I layer is **planar within R_{25}**, but warping becomes detectable within R_{25}

- **Co-precession** inside a radius $R_{tr} \approx R_{Ho}$

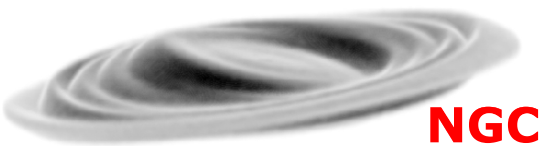
→ **self-gravity** of the disk is important

- **Differential precession** beyond R_{tr} (probably retrograde decreasing precession rate)

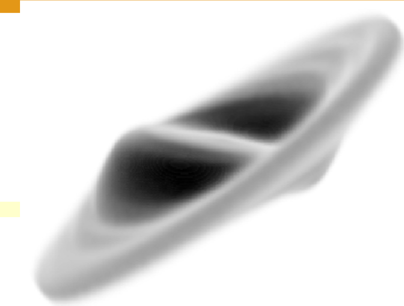
- Indication for **co-precession** at large radii?



More findings



NGC 2541



- **Two-disk structure in the H I disk**, the warp being a transition from one orientation to the other (Kuijken 1991, Corbelli & Schneider 1997, Józsa 2007)

- At the commencement of the warp in a few cases

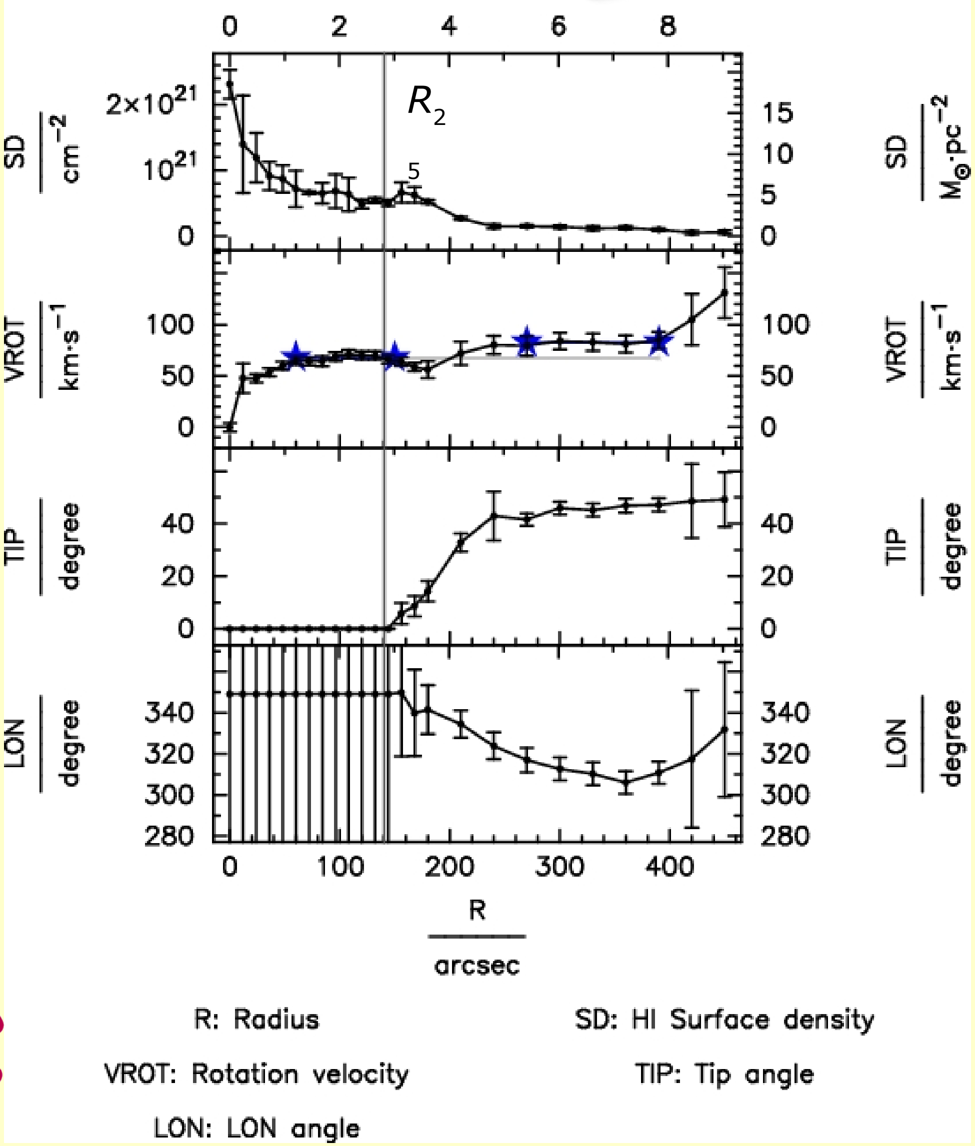
i) the **H I surface density profile drops** (García-Ruiz 2002, van der Kruit 2007, Józsa 2007)

ii) the **modelled rotation velocity changes** (Corbelli & Schneider 1997, van der Kruit 2007, Józsa 2007)

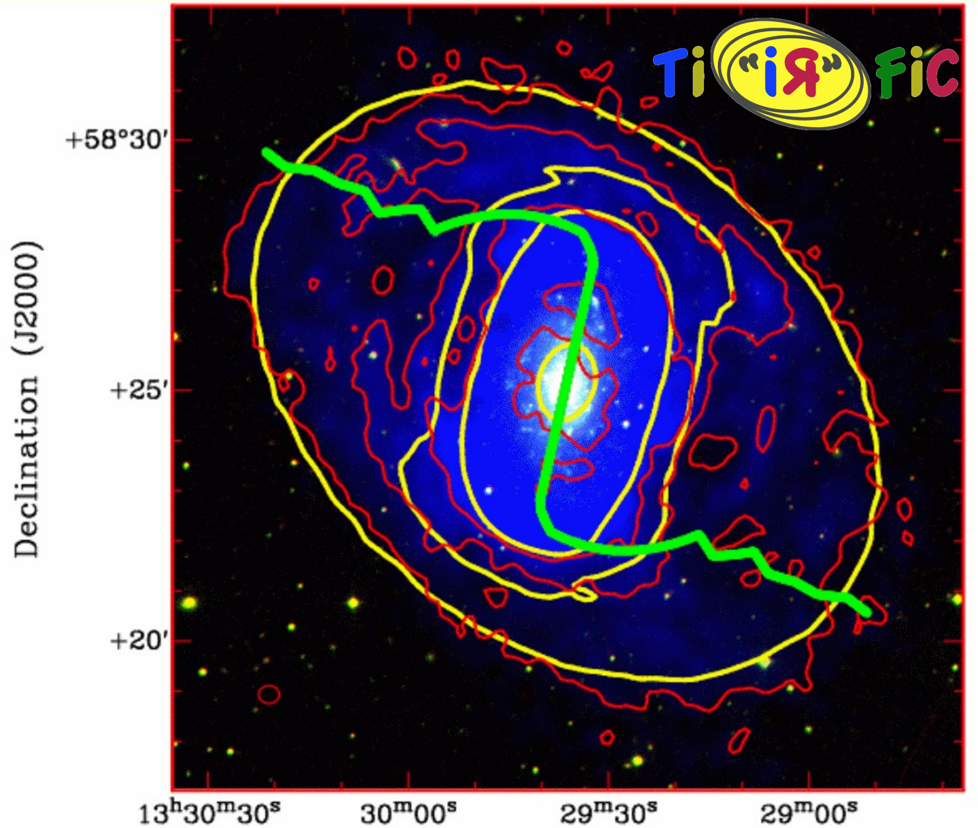
- Late cosmic infall does a reasonable job describing the observed features

TiRiFiC

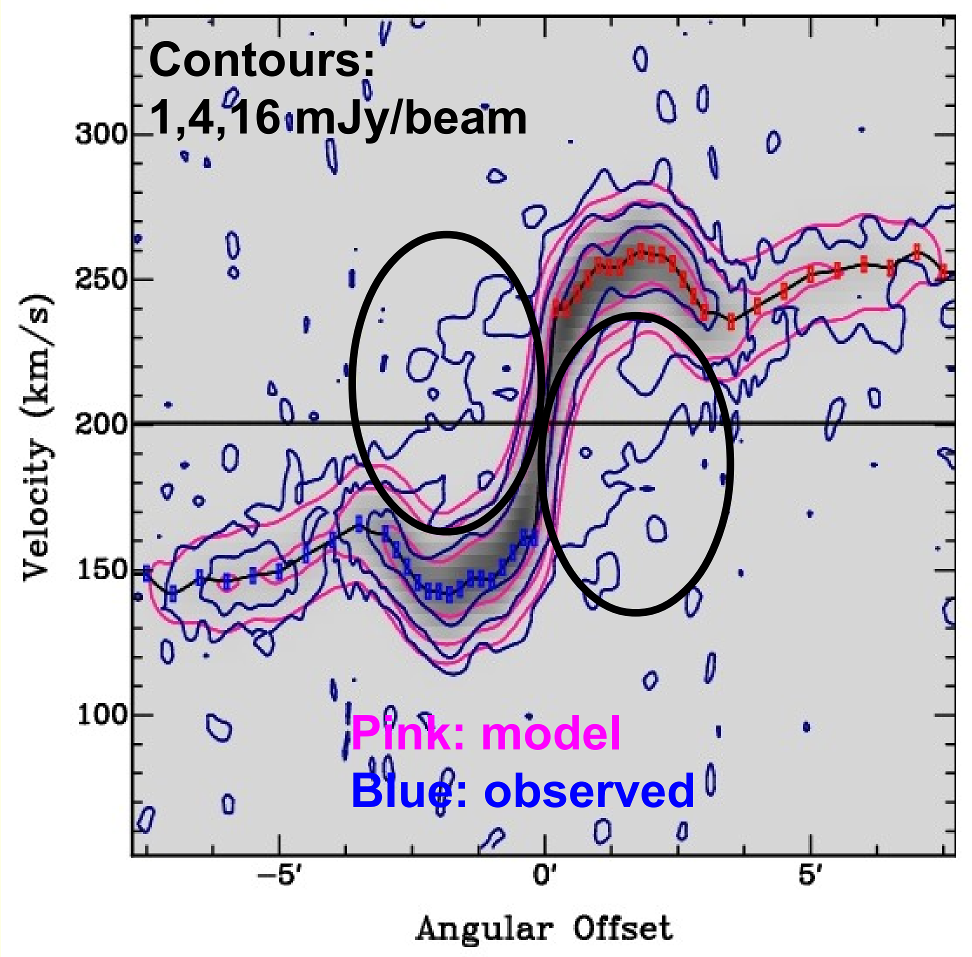
NGC 5204



NGC 5204: anomalous gas



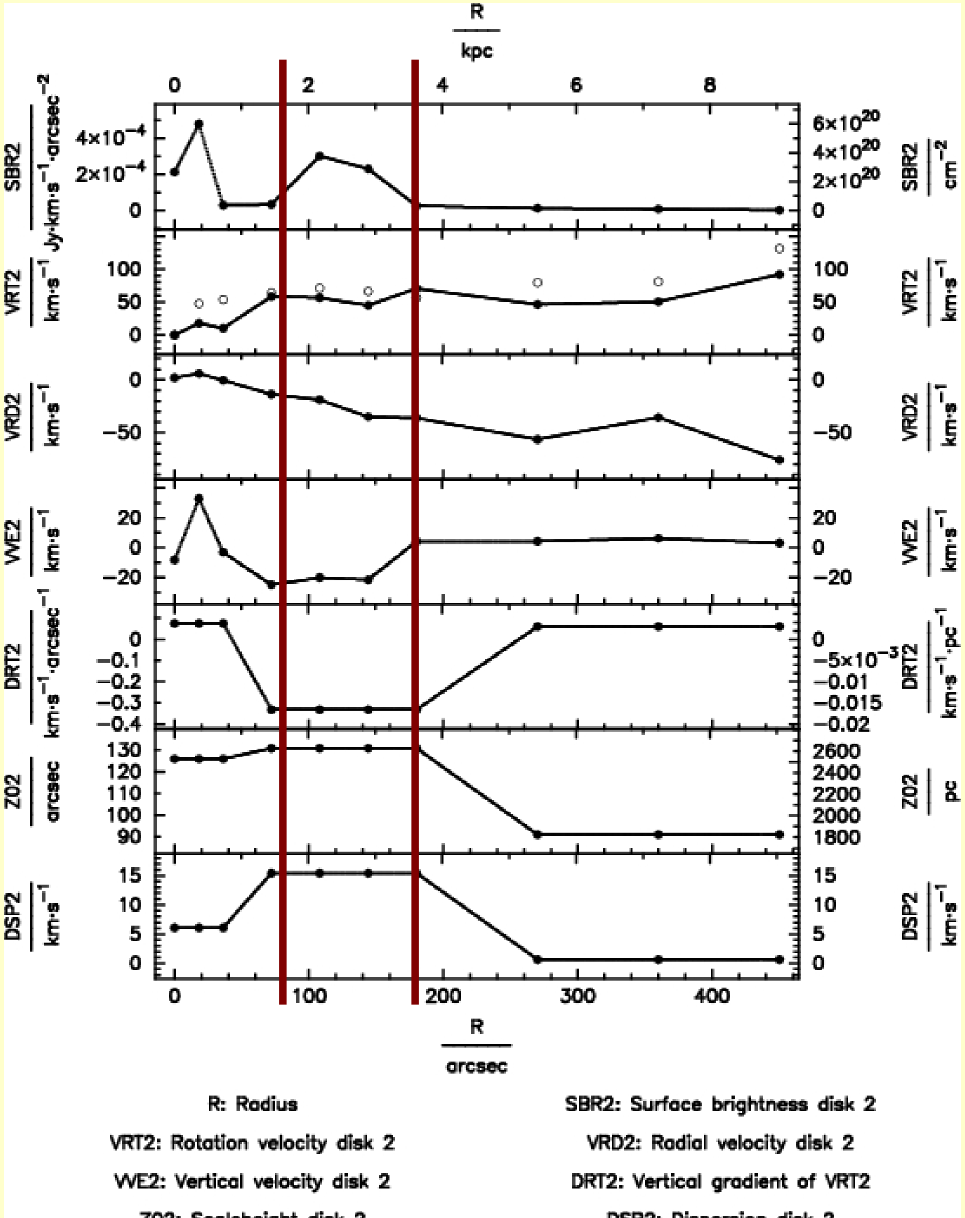
Contours:
8, 25, 45, 145 · 10^{19} atoms cm^{-2}

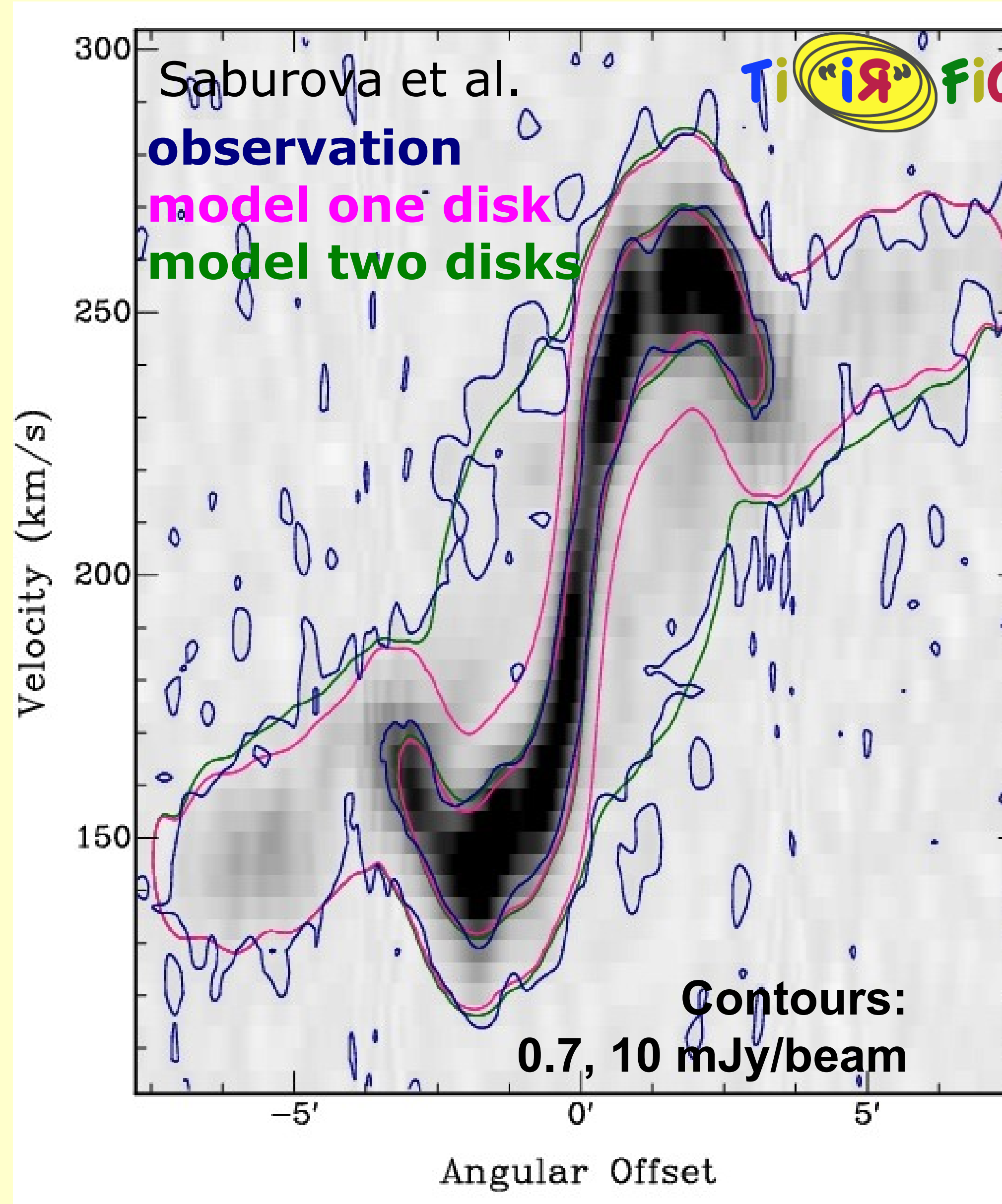


Type:	SA(s)m
Distance:	4.1 Mpc
L_B:	$8.1 \cdot 10^8$ L$_\odot$
M_{HI}:	$5.4 \cdot 10^8$ M$_\odot$

Position-Velocity (PV) diagram along the kinematical major axis.

NGC 5204: anomaleous gas





NGC 5204 H I mass: $5.4 \cdot 10^{8}\ M_{\odot}$ Thick disk mass: $9.1 \cdot 10^{7}\ M_{\odot}$

Status: warps

- Models invoking late infall work well to reproduce the kinematics and the morphology of (symmetrically) warped galaxies **but** we also observe other formation mechanisms at work (e.g. gas capture, merger)

- Indication of characteristic kinematic signatures for DM sub-structure (at the commencement of the warp) **and/or** anomaleous gas

- Large amounts of extraplanar gas observed in galaxies with regular warps (indication of inwards motion: NGC 5204) **but** not dependent on warp amplitude, might be a coincidence.

- Waiting for simulations and statistics in H I

Polar ring galaxies

- Galaxies with **two distinguished**, rotating **sub-systems** of similar size, with **orthogonal angular momentum** vectors. The complete system must be in **equilibrium** (Whitmore et al. 1990).

NGC 4650A (BVI composite, Gallagher et al.)

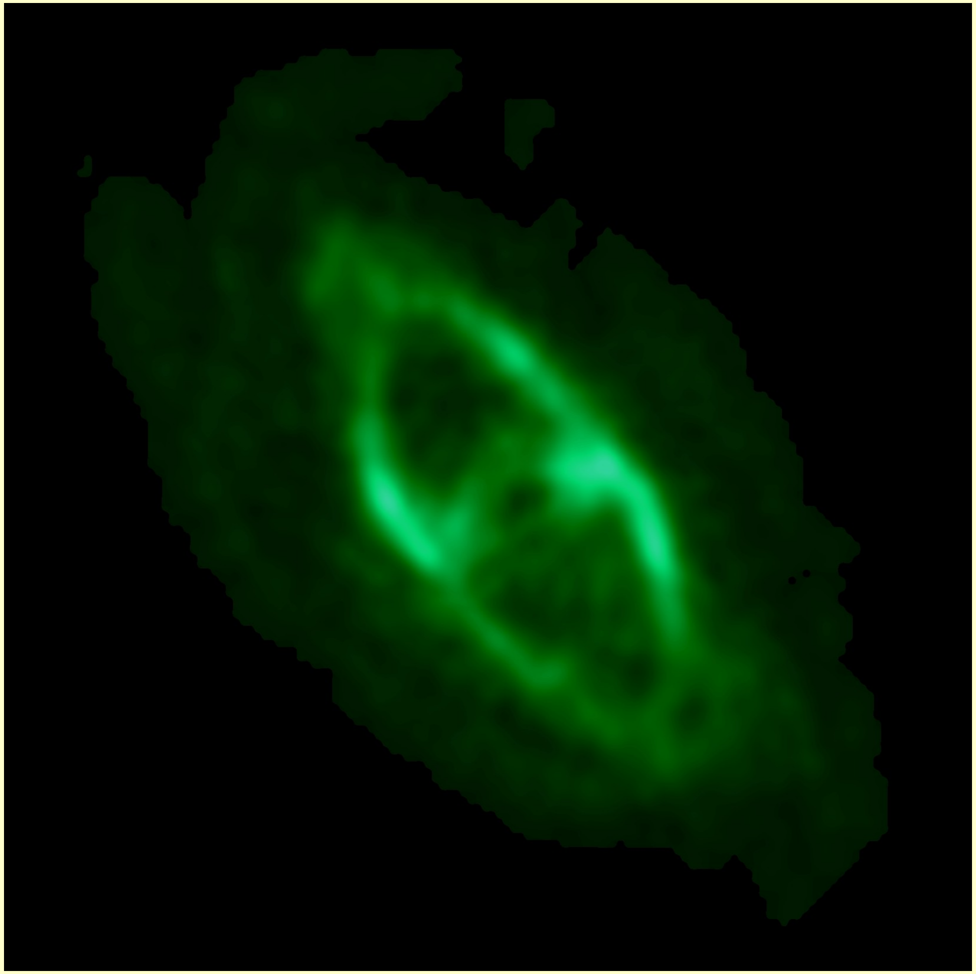
NGC 2685

Type:	(R)S0 pec
Distance:	15.2 Mpc
Luminosity L_B:	$7.0 \cdot 10^9 L_\odot$
HI Mass M_{HI}:	$1.7 \cdot 10^9 M_\odot$
Optical radius r_{25}:	150'' ≙ 10.8 kpc
HI radius r_{HI}:	420'' ≙ 31.0 kpc

INT i'-band observations
13350s on-source

- Former HI studies concluded that NGC 2685 is a polar ring galaxy
- “Helix” consisting of gas, dust, stars
- Age of helix 2-5 Gyr

NGC 2685: observations



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INT i'-band observations
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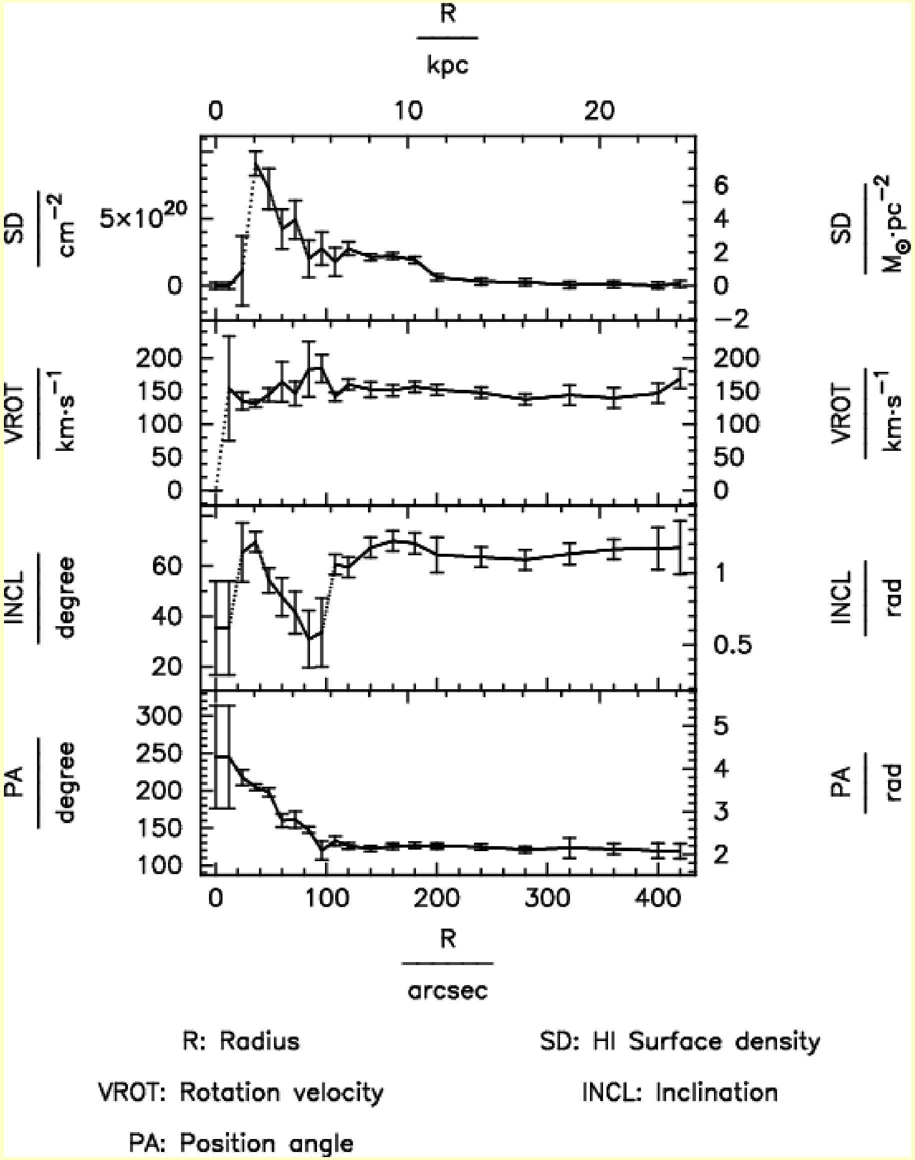
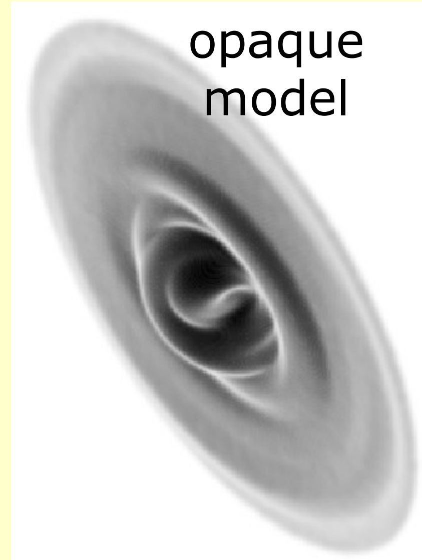
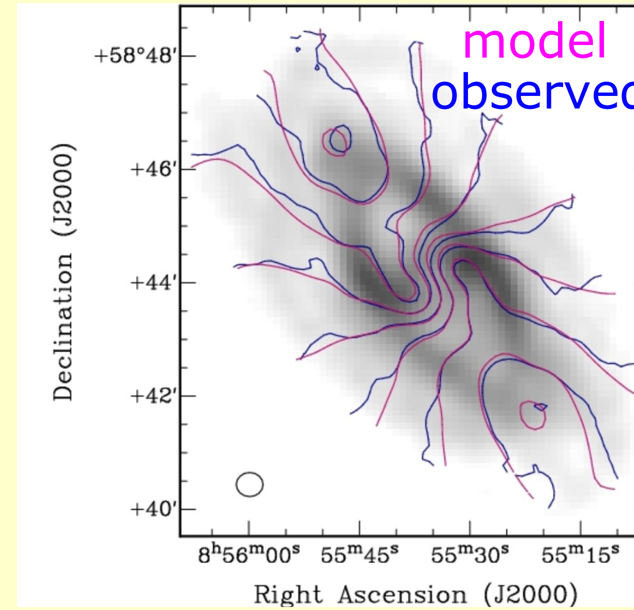
- Former HI studies concluded that NGC 2685 is a polar ring galaxy
- “Helix” consisting of gas, dust, stars
- Age of helix 2-5 Gyr
- Outer stellar- and gaseous ring, aligned with main stellar body







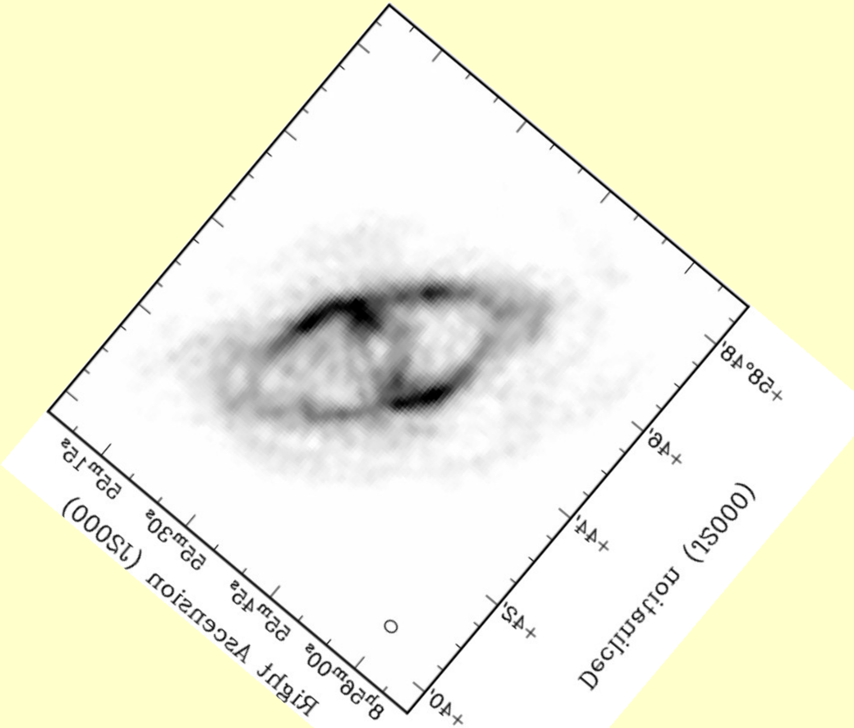
TiRiFiC

velocity field
Contours:
$v_{sys}\pm$0,15,30,45,60 km s $^{-1}$

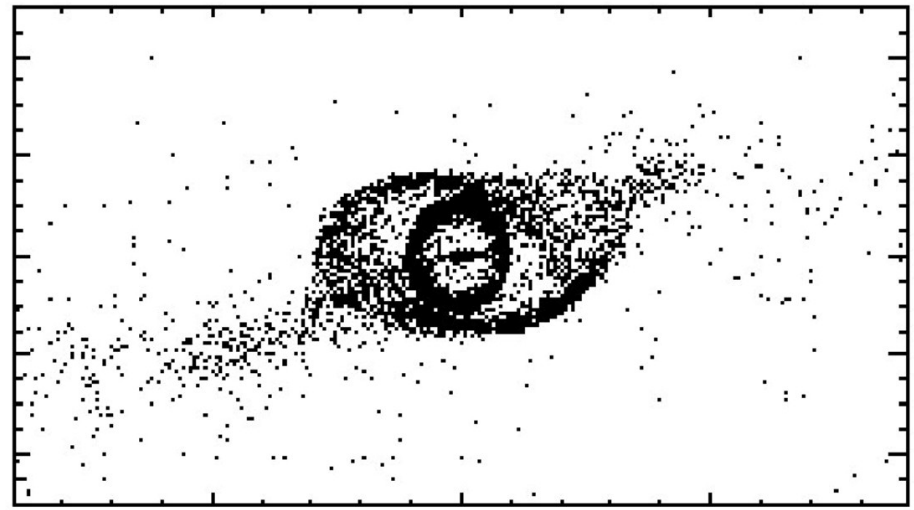
- Outer HI disk is planar, shares orientation with lenticular stellar body (Morganti et al. 2006)
- ~ flat rotation curve

NGC 2685: formation

NGC 2685, HI



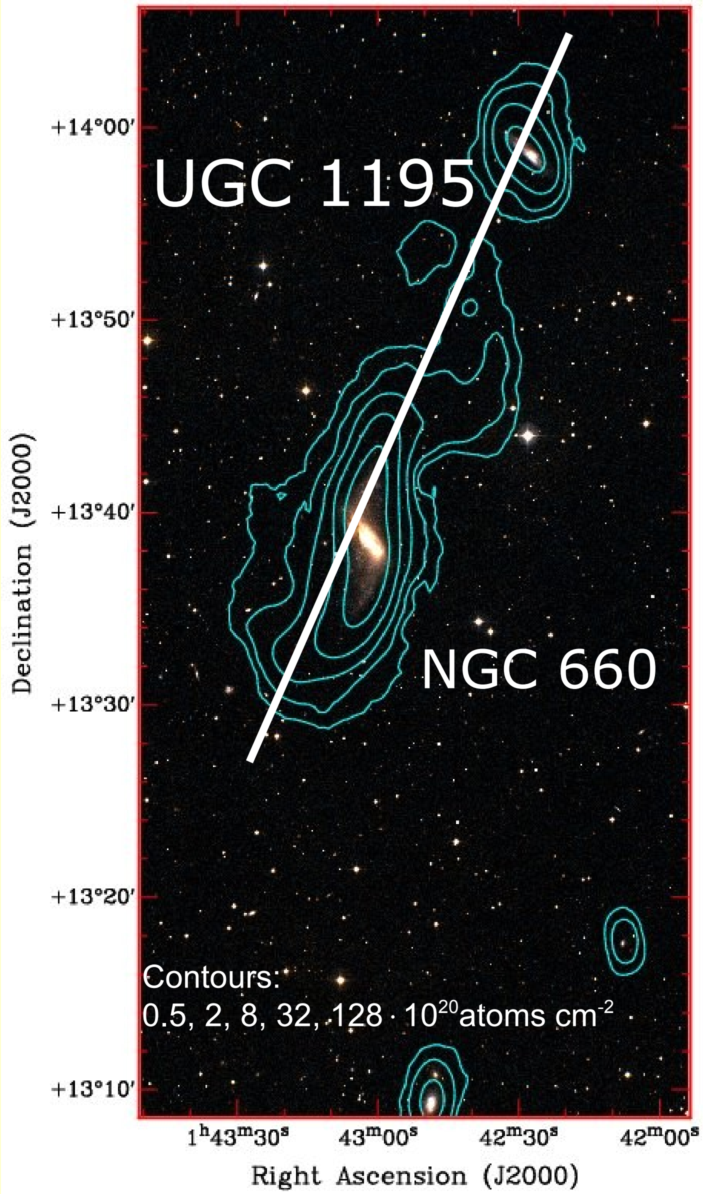
1:1 merger simulation remnant, gas



Naab et al. 2006

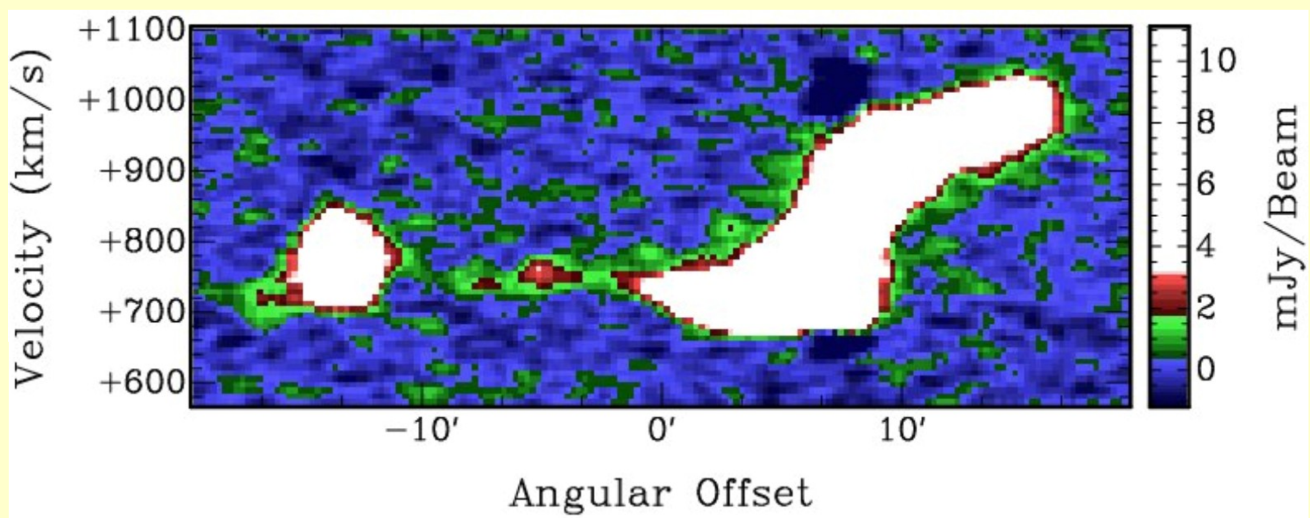
- Could be remnant of a **wet merger** event (Barnes 2002, Naab et al. 2006)
- Should be unequal-mass merger to result in fast rotating stellar body

NGC 660



- Formed by **gas capture from a companion**?
(Arnaboldi & Galetta 1993, Bournaud & Combes 2002)

- Data show a gaseous **connection/bridge to UGC 1195** → suggestive



3 x 12h WSRT HI observation

NGC 660

- Formed by **gas capture from a companion**? (Arnaboldi & Galetta 1993, Bournaud & Combes 2002)

- Data show a gaseous **connection/bridge to UGC 1195**

3 x 12h WSRT HI observation + image by I. Gerber

Want statistics...

- Current detailed observational **HI warp studies rely on observations of less than ~100 galaxies, studies of polar ring or multi-spin galaxies less than ~10**

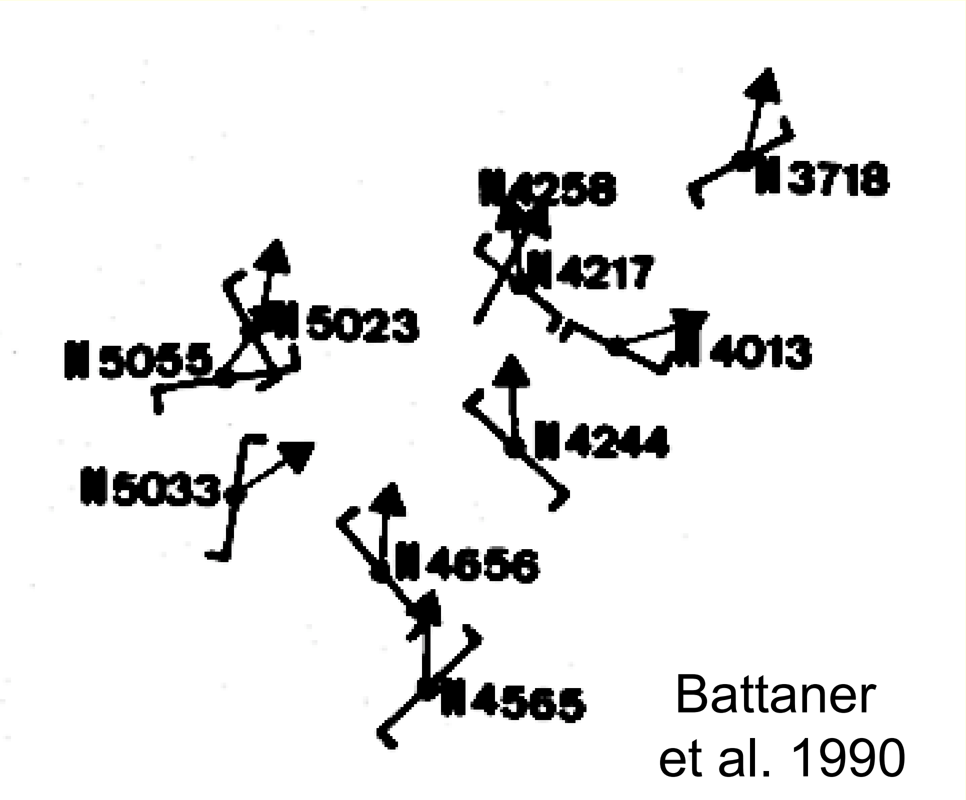
But we want a **statistical sample** to investigate

- Environmental effects (amplitude, symmetry)

- Variations with galaxy type

- Relative spin orientation of inner and outer disk with respect to the large-scale structure

- Statistical studies: best on multi-spin galaxies is Serra et al. 2014 (on ATLAS^{3D}), kinematical misalignment of stars and H I in 49 ETGs



Battaner et al. 1990

Outlook

• Upcoming H I surveys with SKA progenitors make statistical (3d !!!) studies possible, high sensitivity possible, high resolution

• ASKAP (WALLABY), **MEERKAT** (MHONGOOSE, MALS), APERTIF (MDS) ... **SKA**