ASTRON

Netherlands Institute for Radio Astronomy

The WSRT HALOGAS Survey

Erwin de Blok

Local Gas 2015

on behalf of the Halogas team

ASTRON is part of the Netherlands Organisation for Scientific Research (NWO)

Context & survey design

Typical disk results

Results & work in progress

- Occurrence of thick HI disks in galaxies
- Prevalence of HI clouds

The future

de Blok et al (2014)

HALOGAS team members

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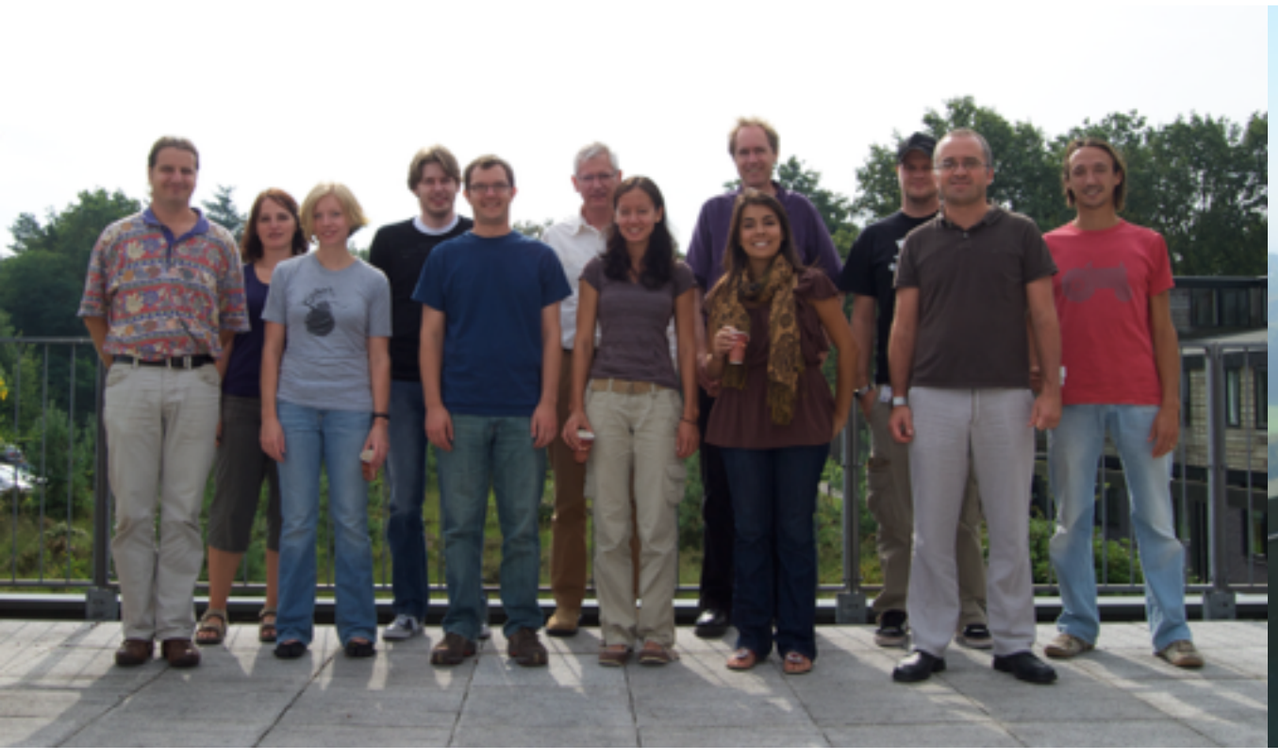
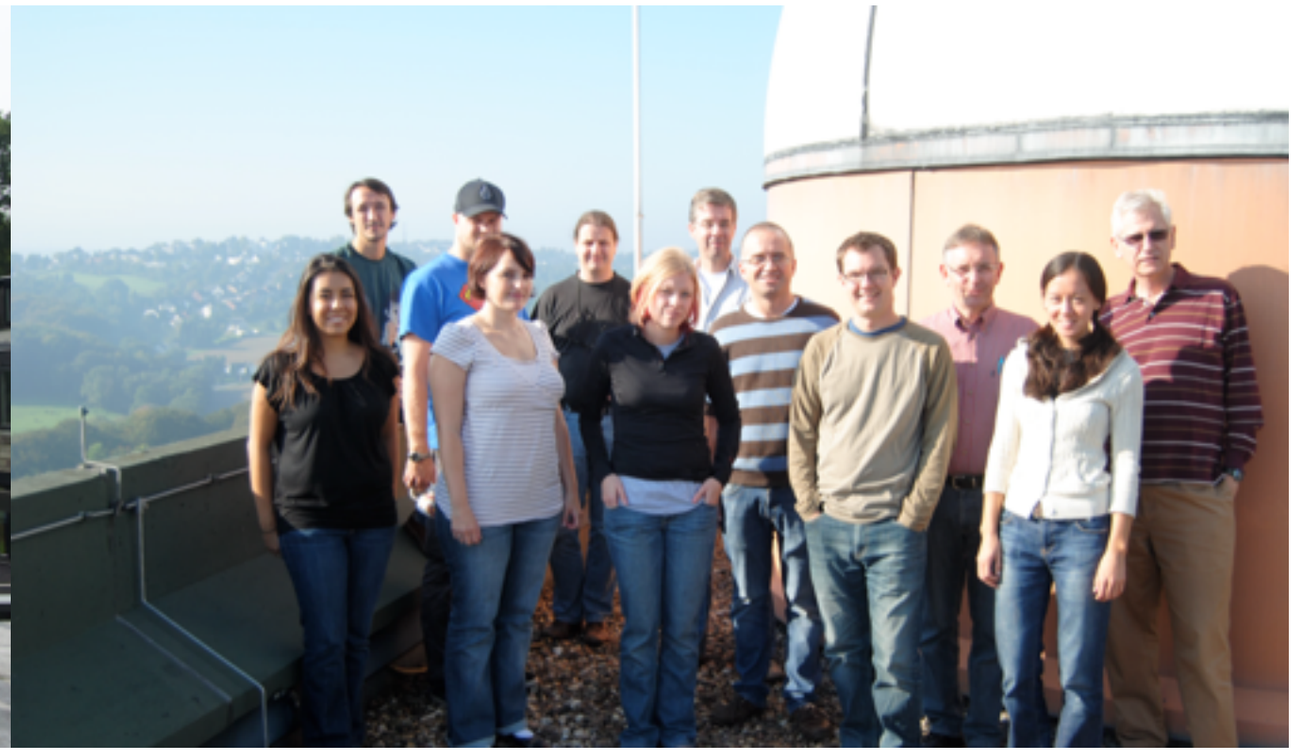
Paolo Serra (CASS) — Carlos Vargas (New Mexico State University)
Rene Walterbos (New Mexico State University) — Benjamin Winkel (MPIfR)
Cat Wu (New Mexico State University) — Laura Zschaechner (MPIA)

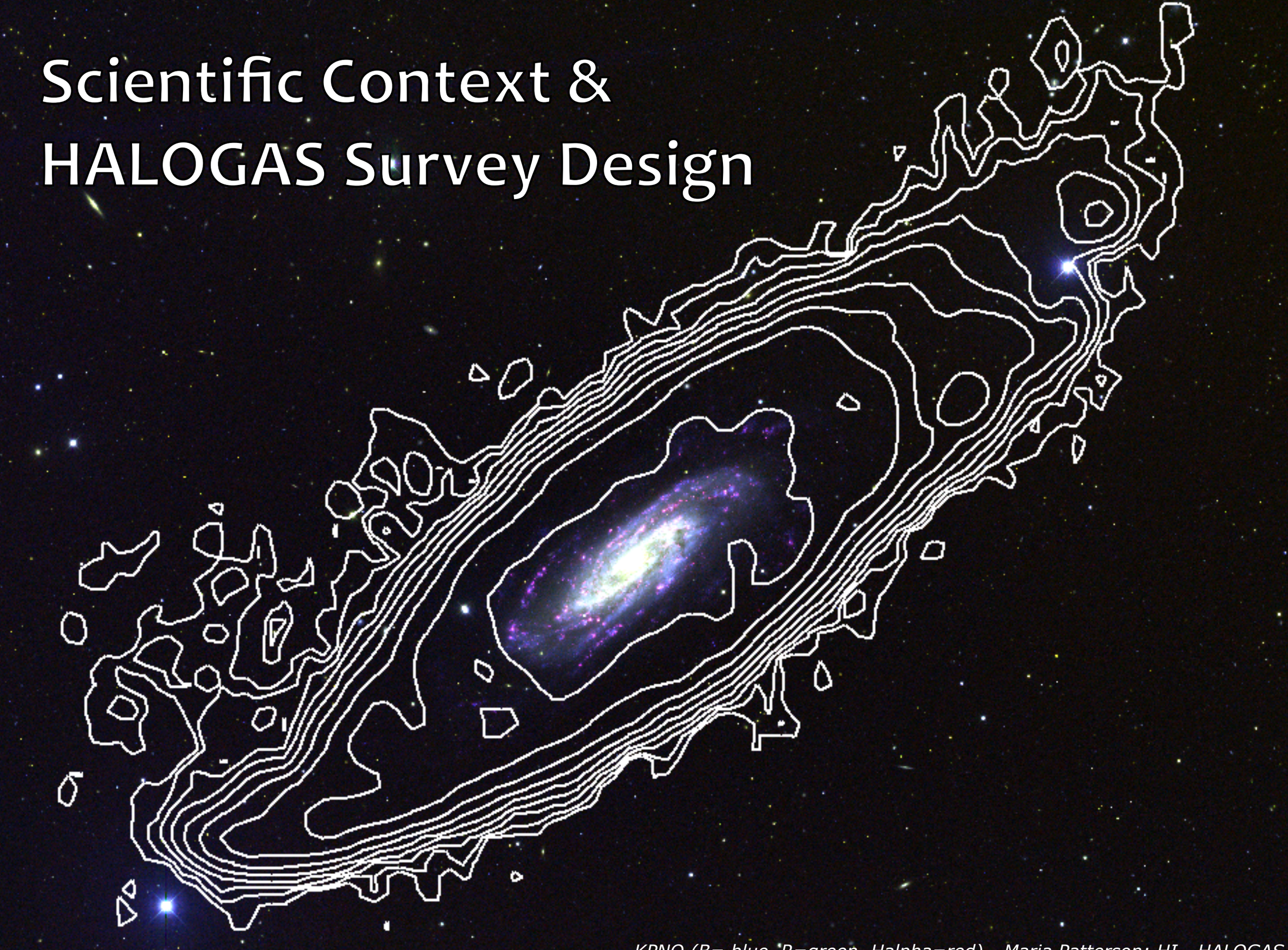


HALOGAS Meeting: Dwingeloo, August 2010



HALOGAS Meeting: Bochum, September 2011

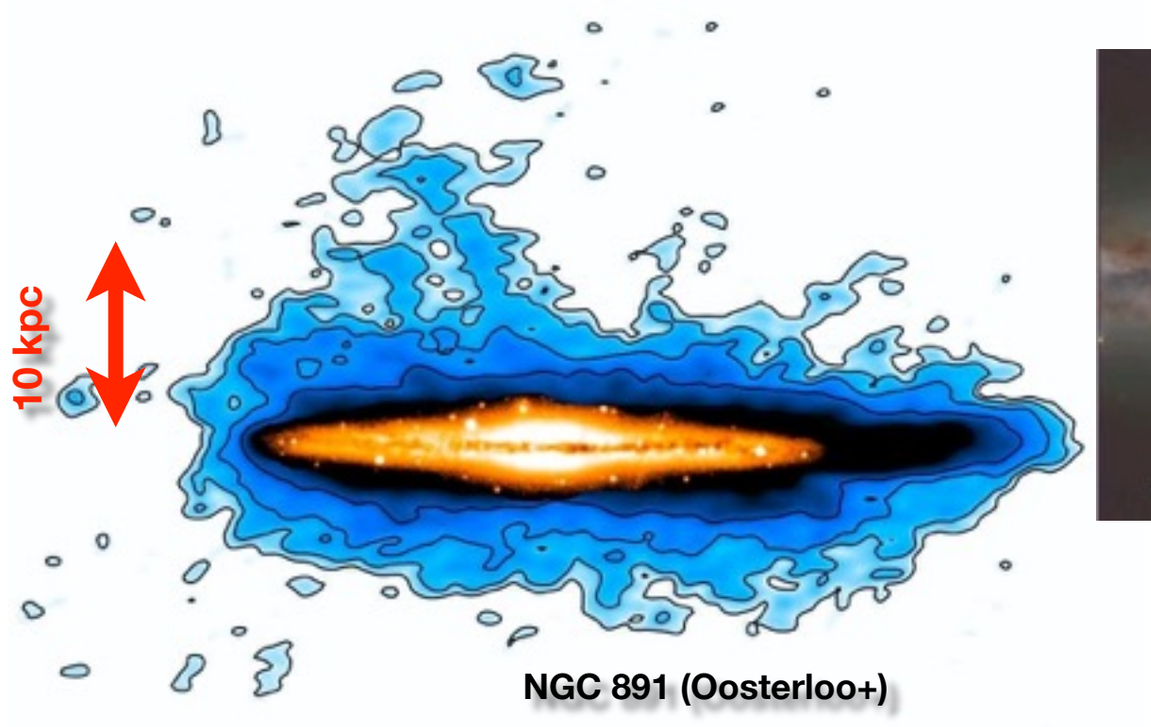
Scientific Context & HALOGAS Survey Design

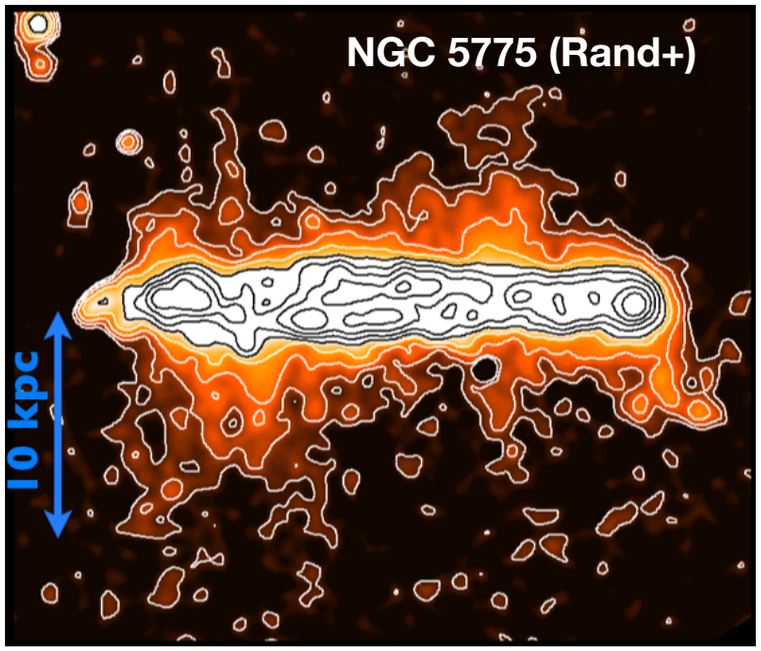


KPNO (B= blue, R=green, Halpha=red) - Maria Patterson; HI - HALOGAS

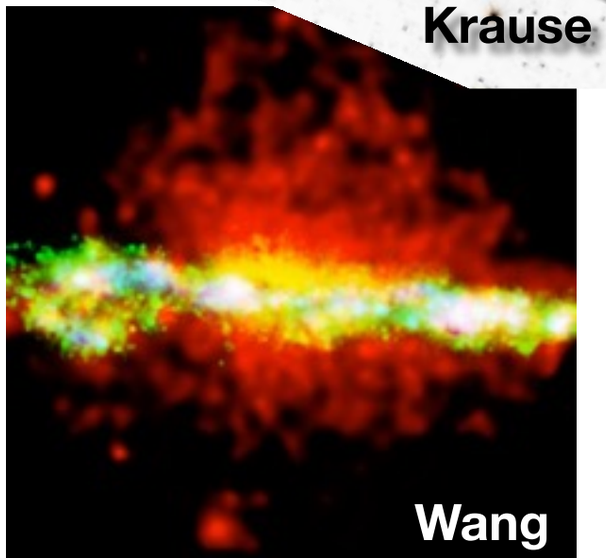
Multiphase extraplanar regions

- Deep observations of (edge-on) spirals show thick, vertically extended, multi-phase layers of gas, dust, and magnetic fields



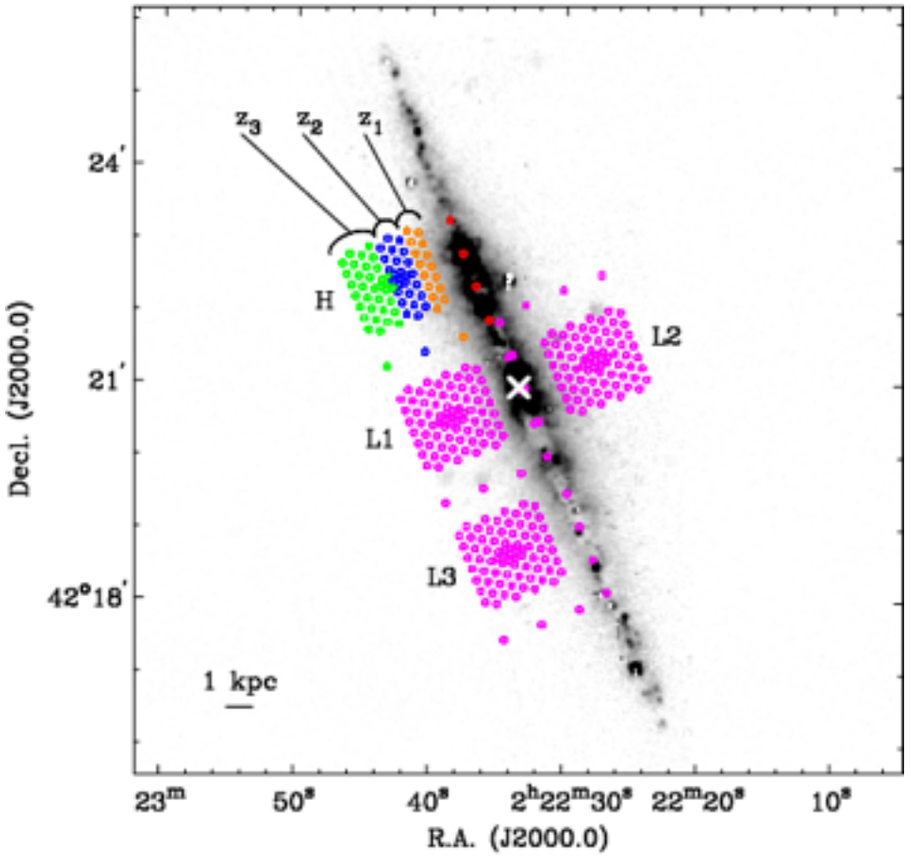


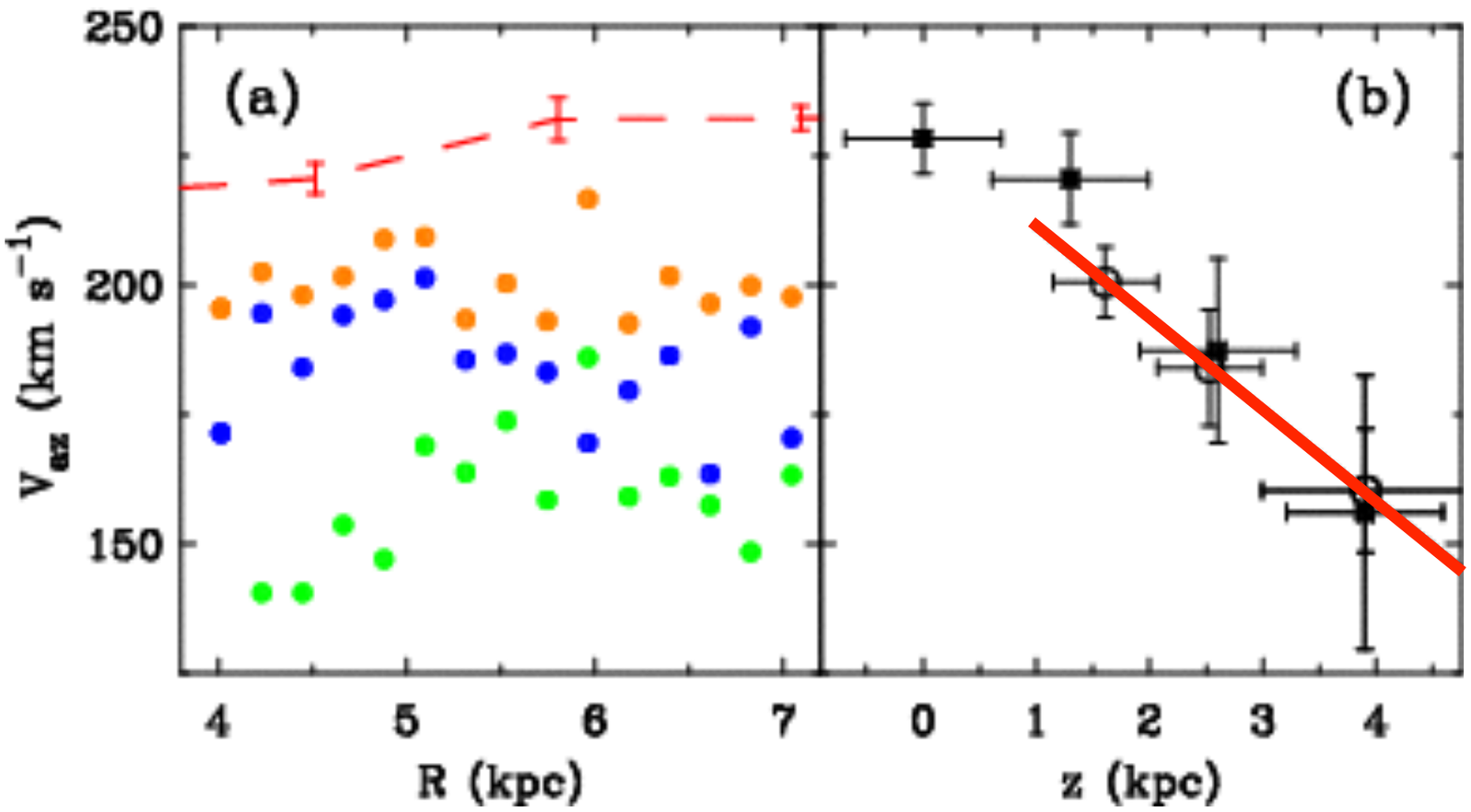
Local Gas 2015



Extraplanar kinematics

- Extraplanar kinematics "lag" the disk rotation curve
  - This means that thick disks can be identified *kinematically* in inclined galaxies



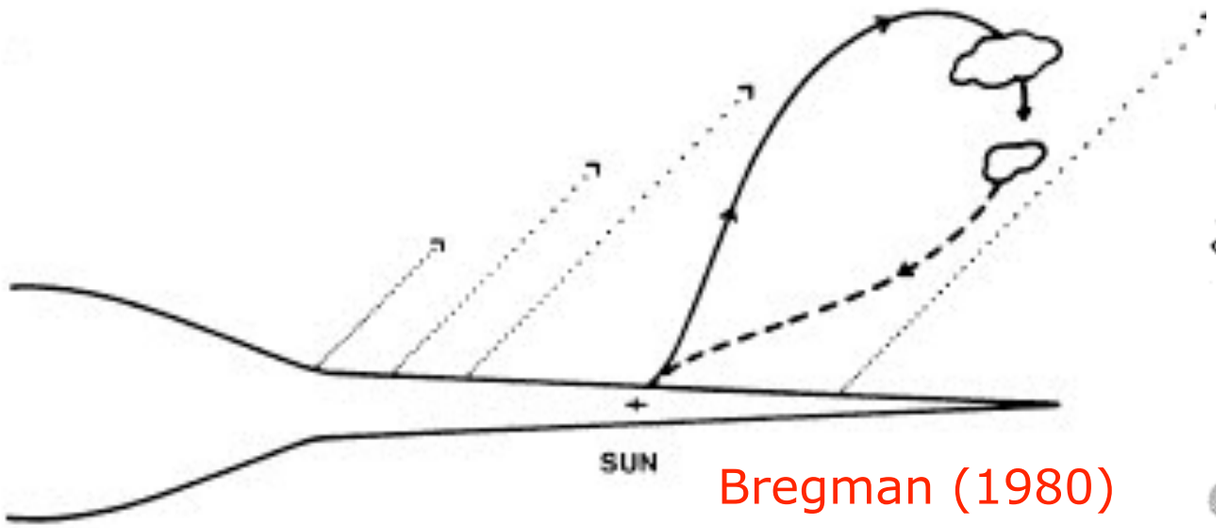


Heald et al. (2007)

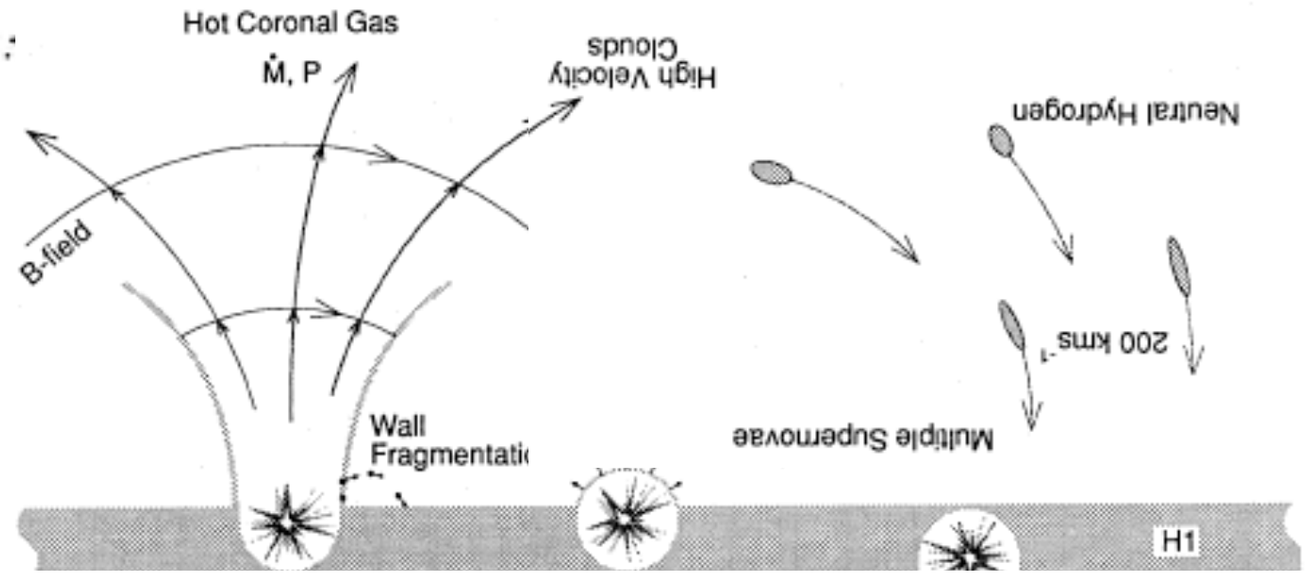
Ionized gas kinematics match HI kinematics from Fraternali et al. (2005)

Understanding extraplanar gas

- Origin thought to be a mixture of galactic fountain / chimney



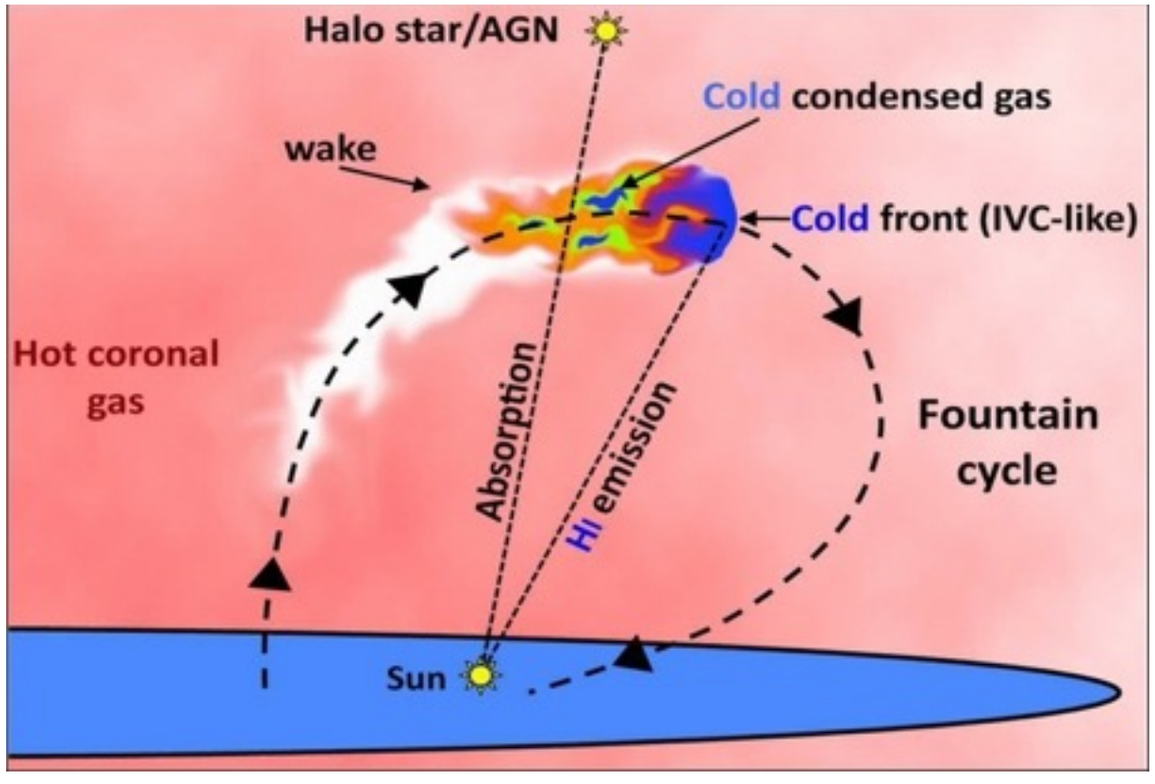
Bregman (1980)



Norman & Ikeuchi (1989)

and swept-up coronal gas:

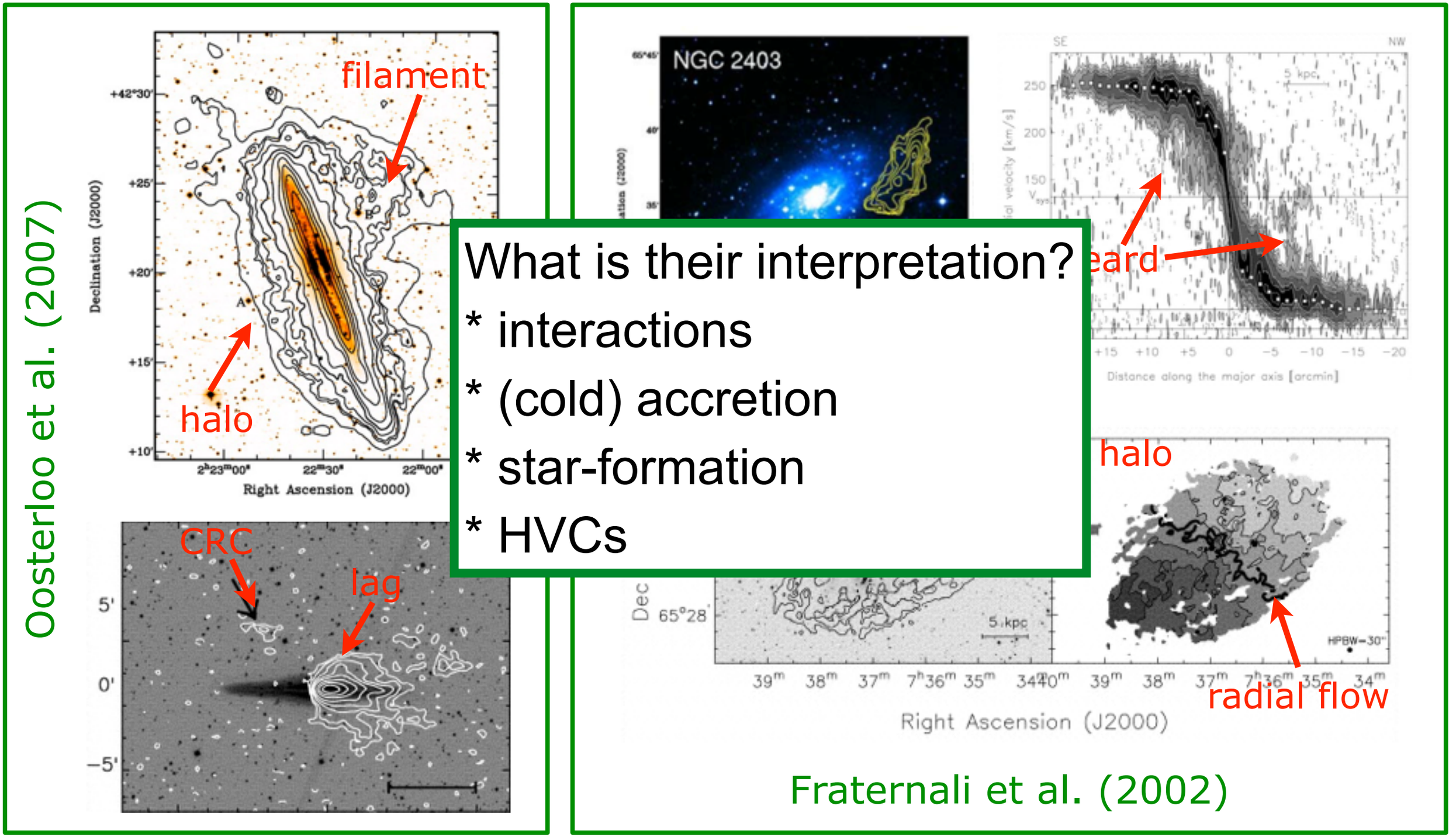
This combination can explain the kinematics, and appears to imply a reasonable accretion rate



Fraternali et al (2013)

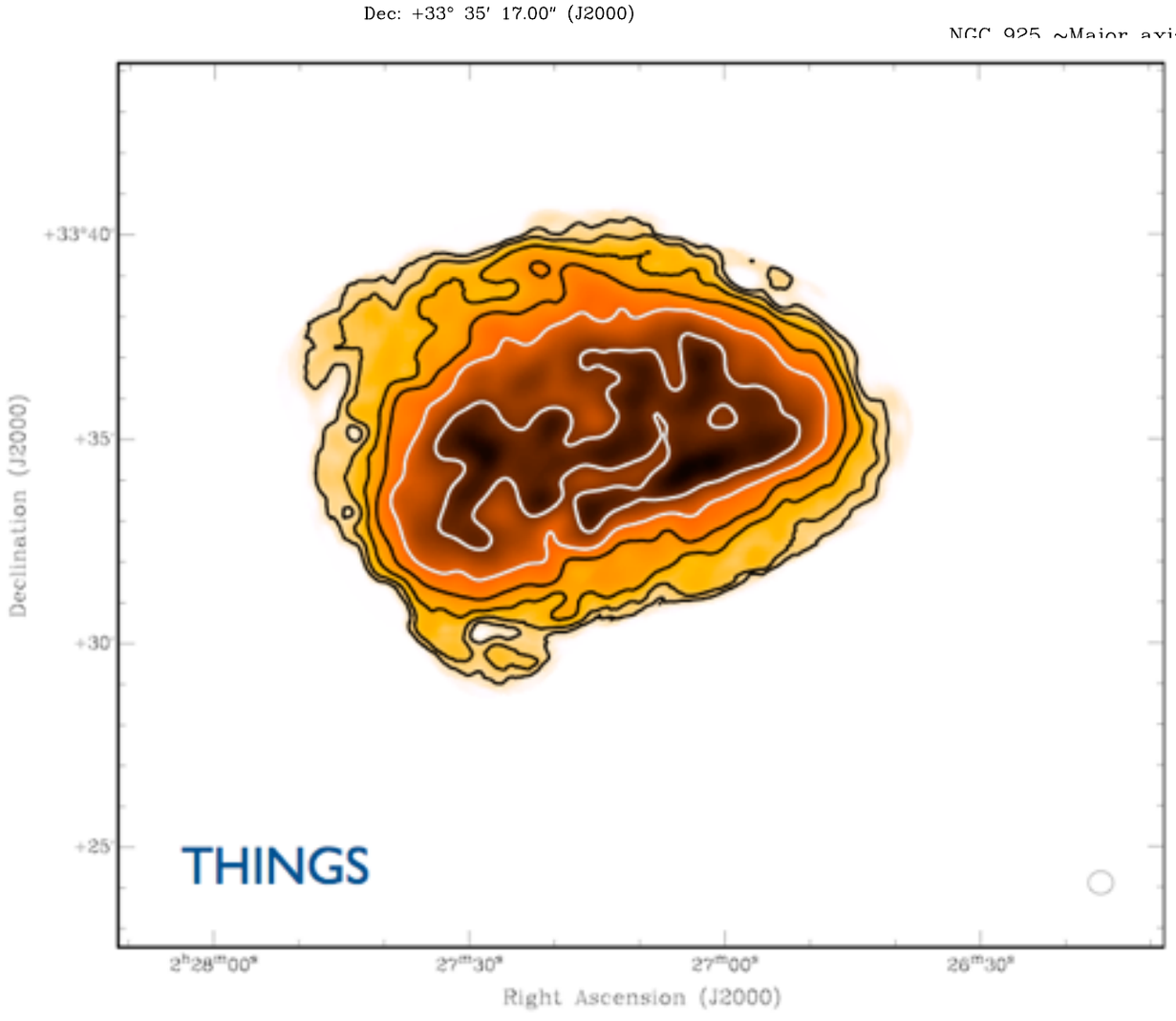
HALOGAS: Scientific motivation

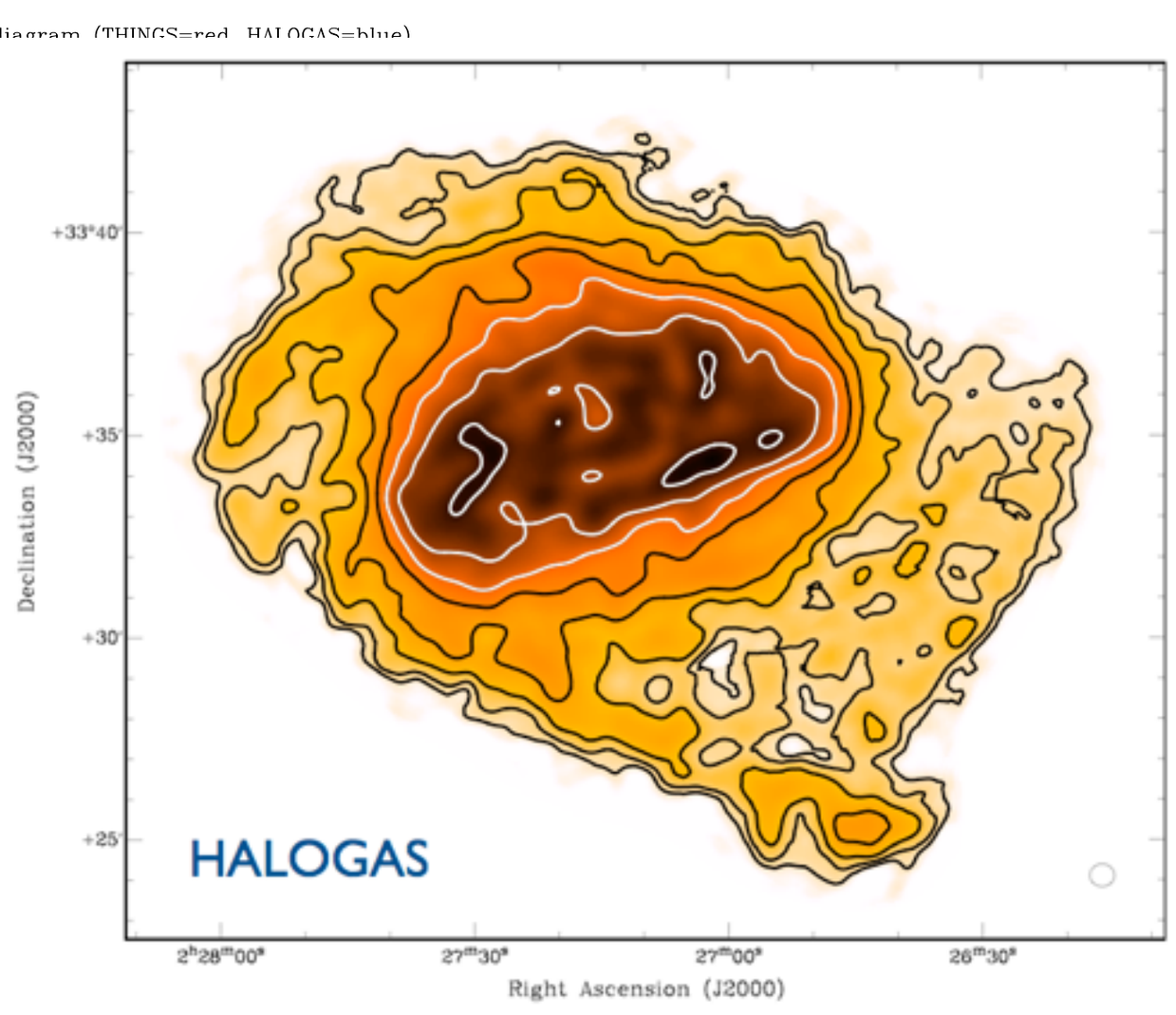
- How many nearby spiral galaxies show features like these?



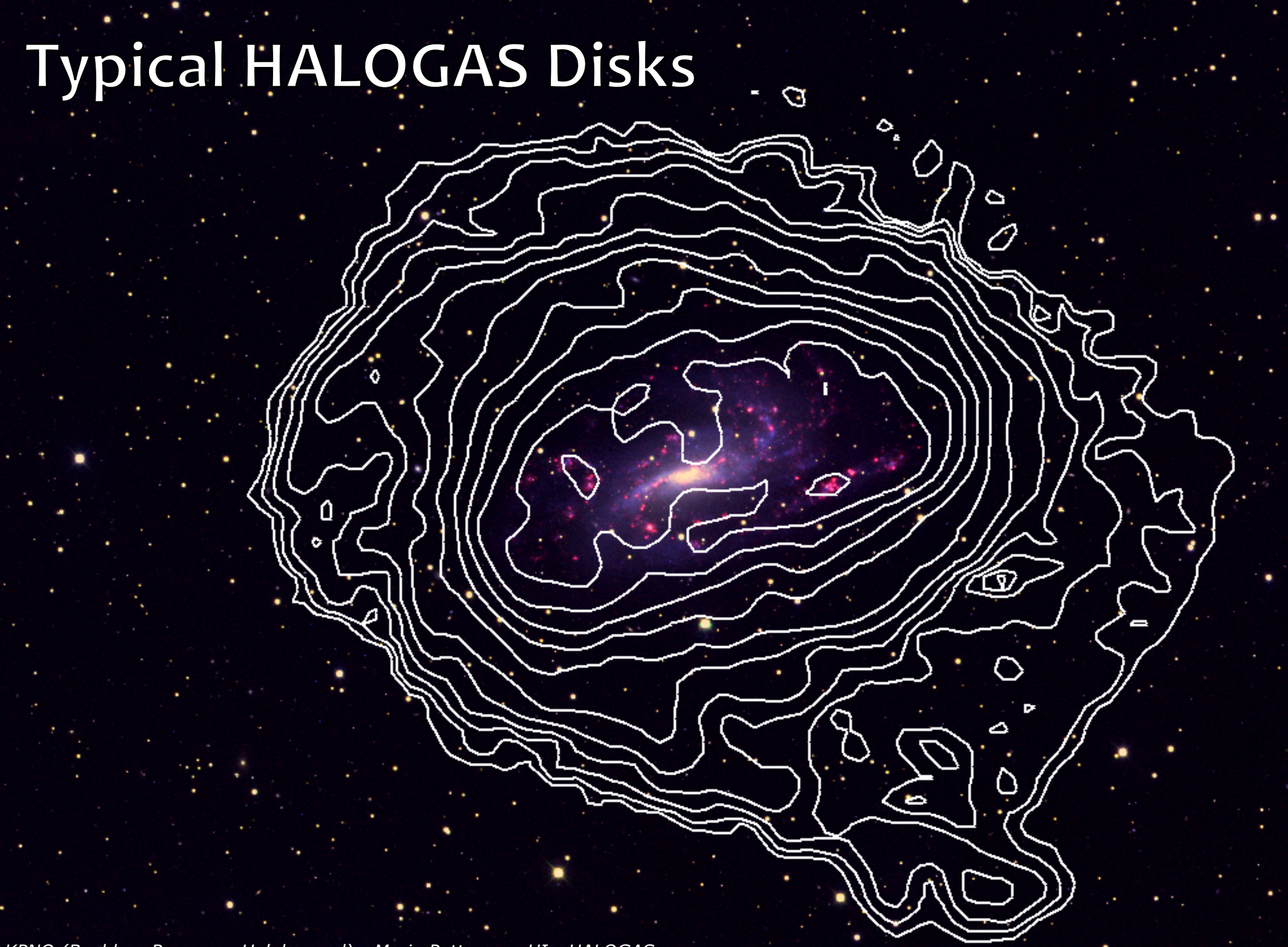
HALOGAS: WSRT observations

- 10x12 hr per target, to reach typical column density sensitivity of N_{HI} = 1x10^{19} cm^{-2} (3σ) at 30” resolution (cf. THINGS: 5x10^{19} cm^{-2}) and typical unresolved mass sensitivity $M_{\rm cl} \approx 2.7 \times 10^5 \left(\frac{D}{10\,{\rm Mpc}}\right)^2 M_\odot$
- Survey sample = 24 galaxies (including NGC 891 & NGC 2403)
- WSRT observations are complete as of early 2013.





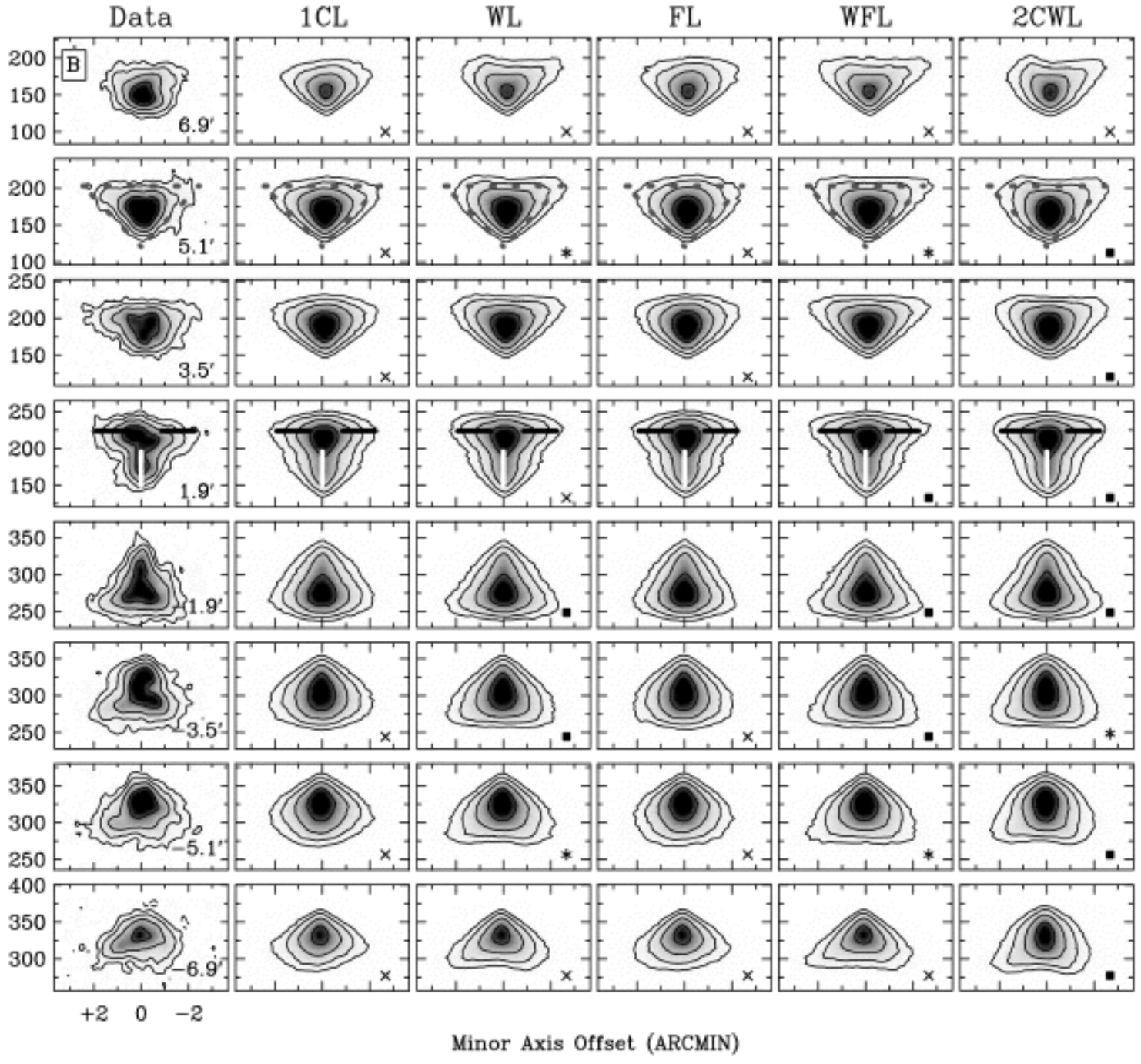
Typical HALOGAS Disks

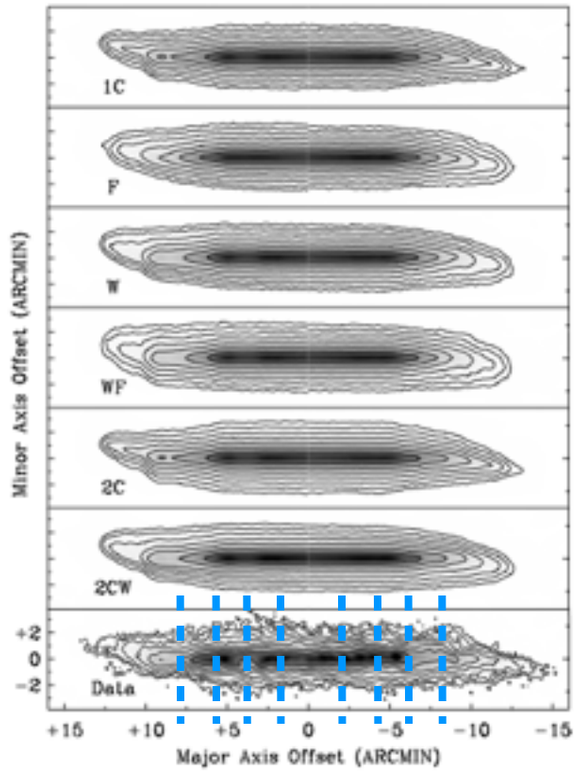


KPNO (B= blue, R=green, Halpha=red) - Maria Patterson; HI - HALOGAS

NGC 4244 (Zschaechner+ 2011)

- Key results:
  - no halo - *surprisingly thin*
  - radially varying rotational lag ~9 km/s/kpc

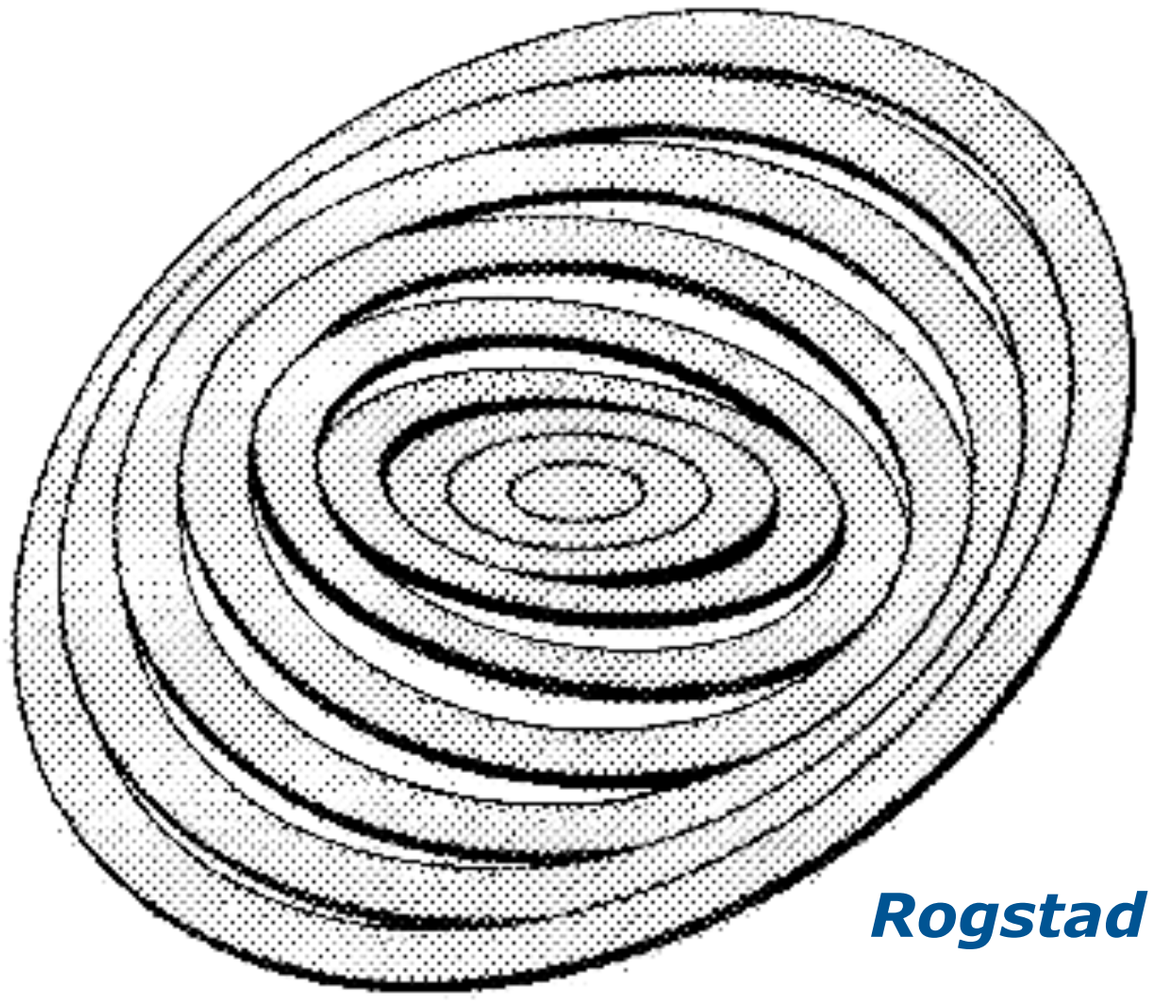




TiRiFiC (Jozsa et al 2007)

- Tilted Ring Fitting Code

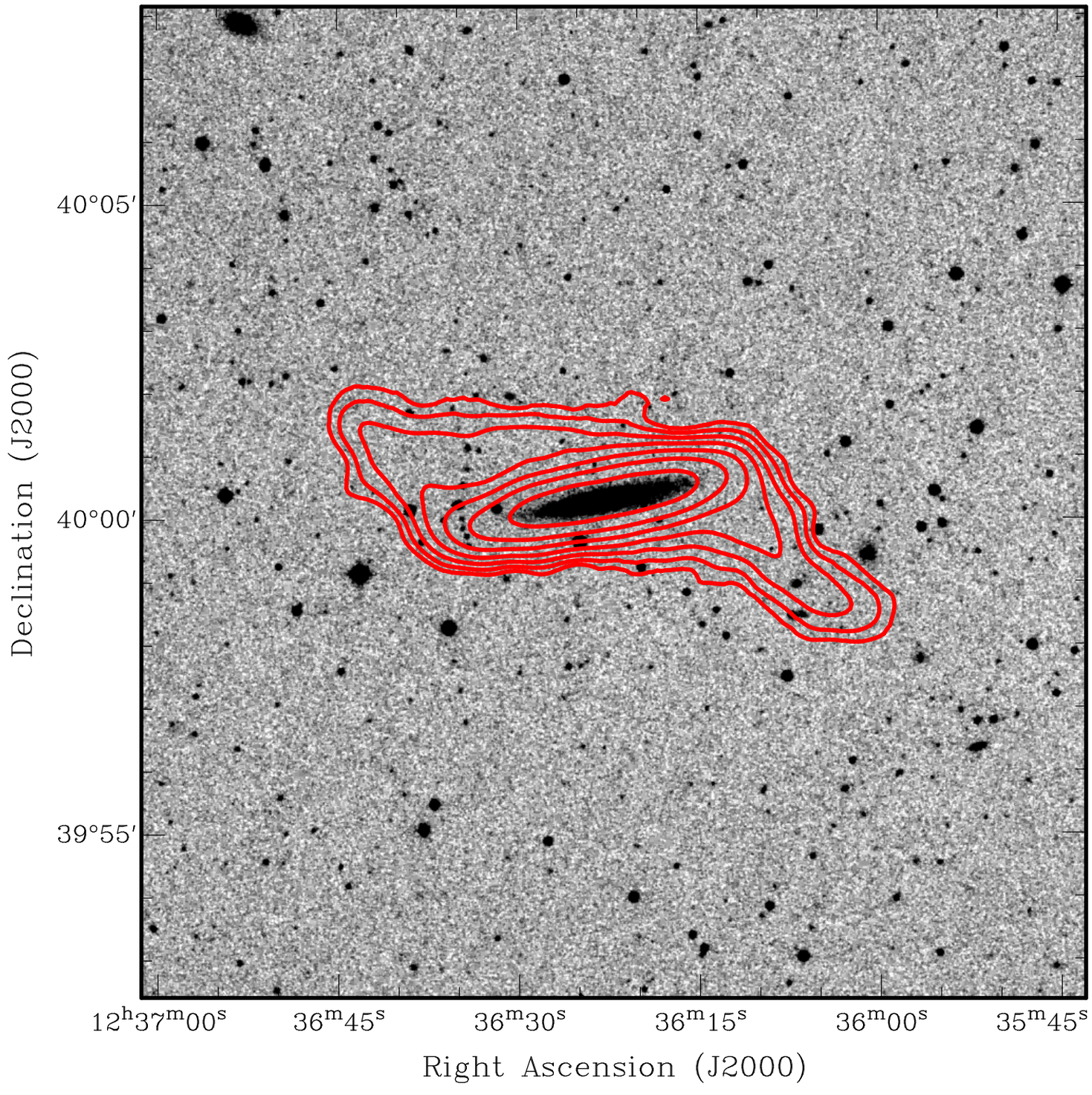
- Used to model in 3D: warps, flares, thick disks, spiral arms, ...
  Extraordinary ability to assess the effect of various features



Rogstad+ (1974)

UGC 7774

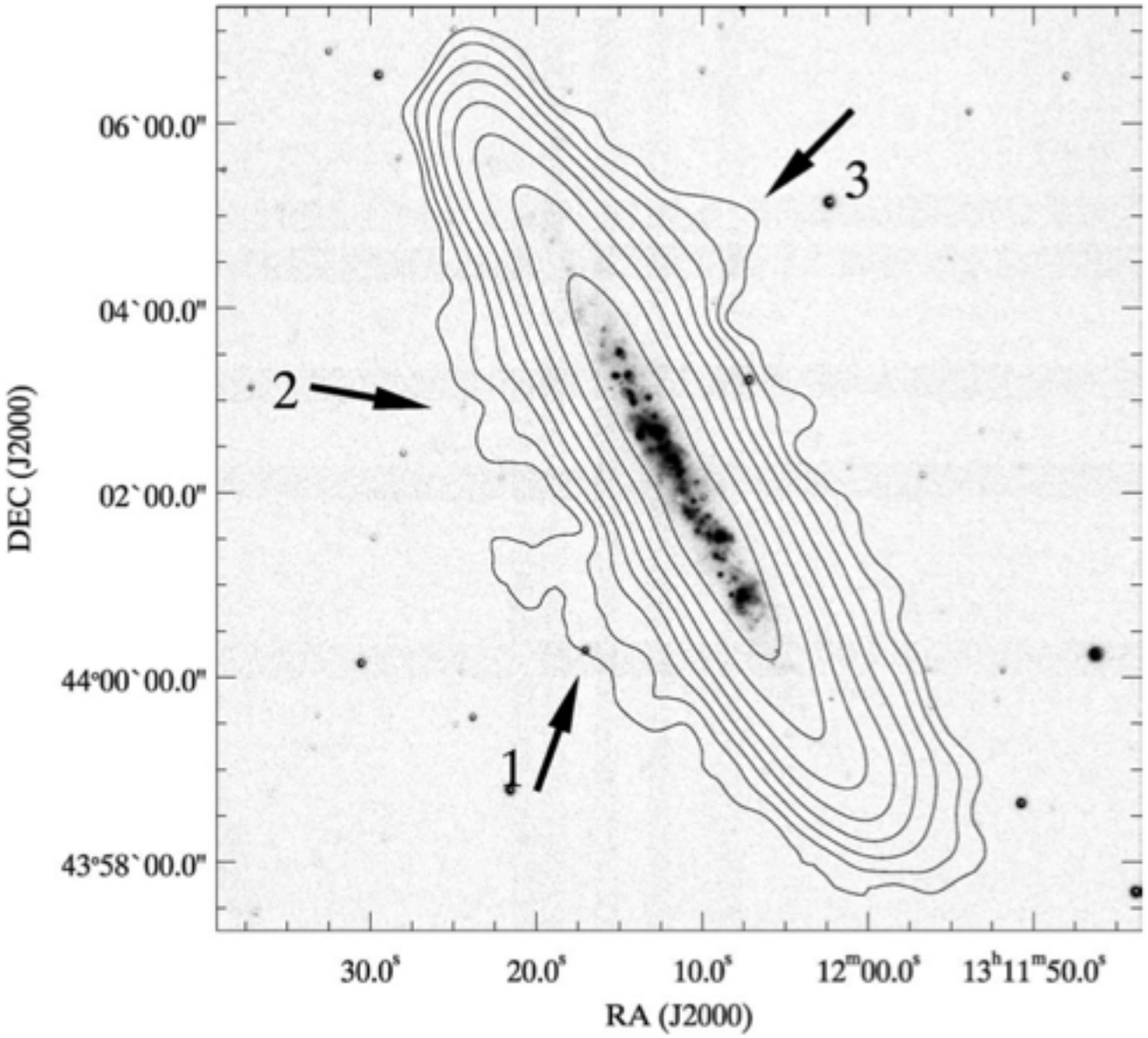
- Strongly warped! but no sign of extraplanar HI...



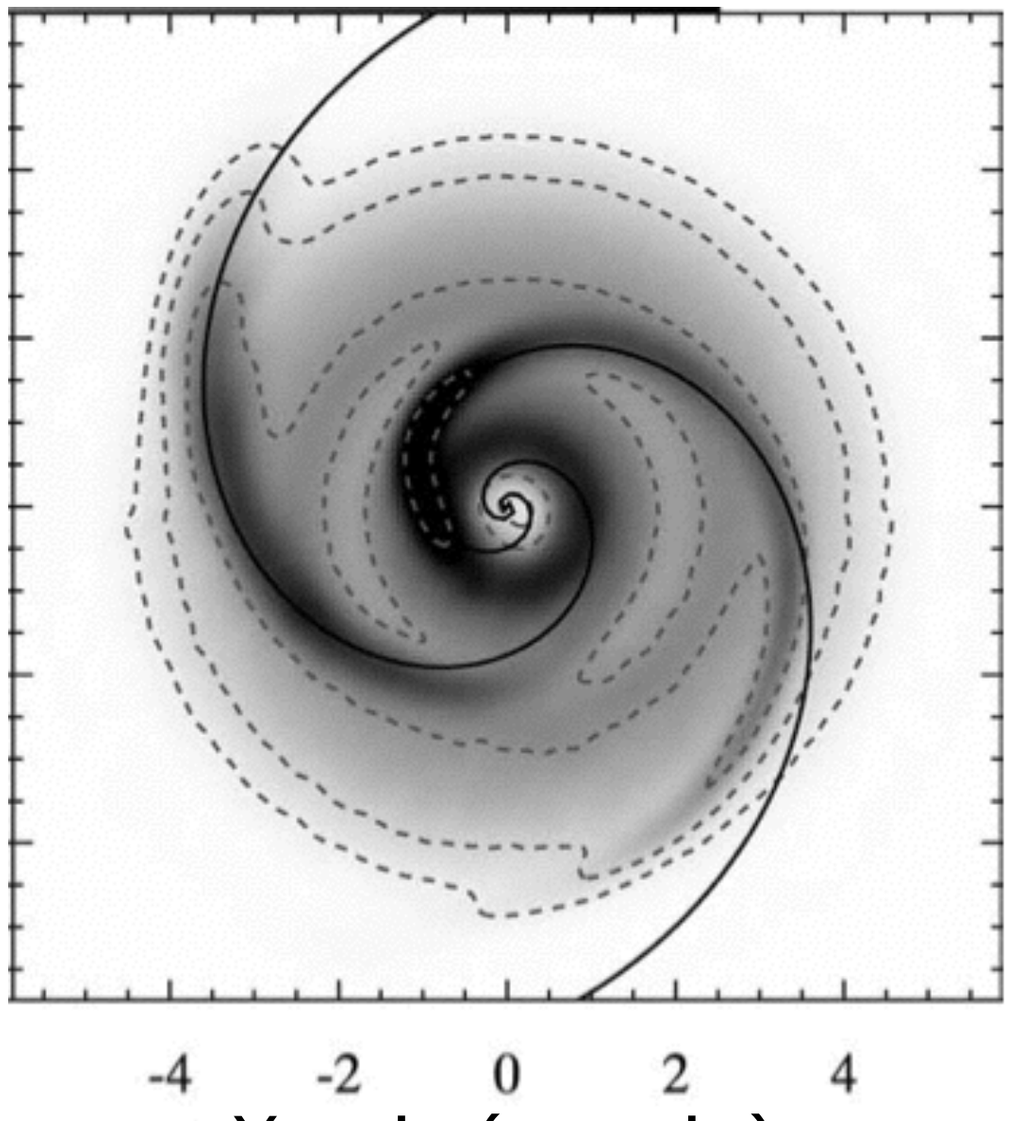
NGC 5023 (Kamphuis+ 2013)

- Need to model spiral structure in an edge-on galaxy....
  - Reduces contribution lagging thick disk, removes model asymmetries, lag does not radially vary, disk thins

Edge-on (sky) view

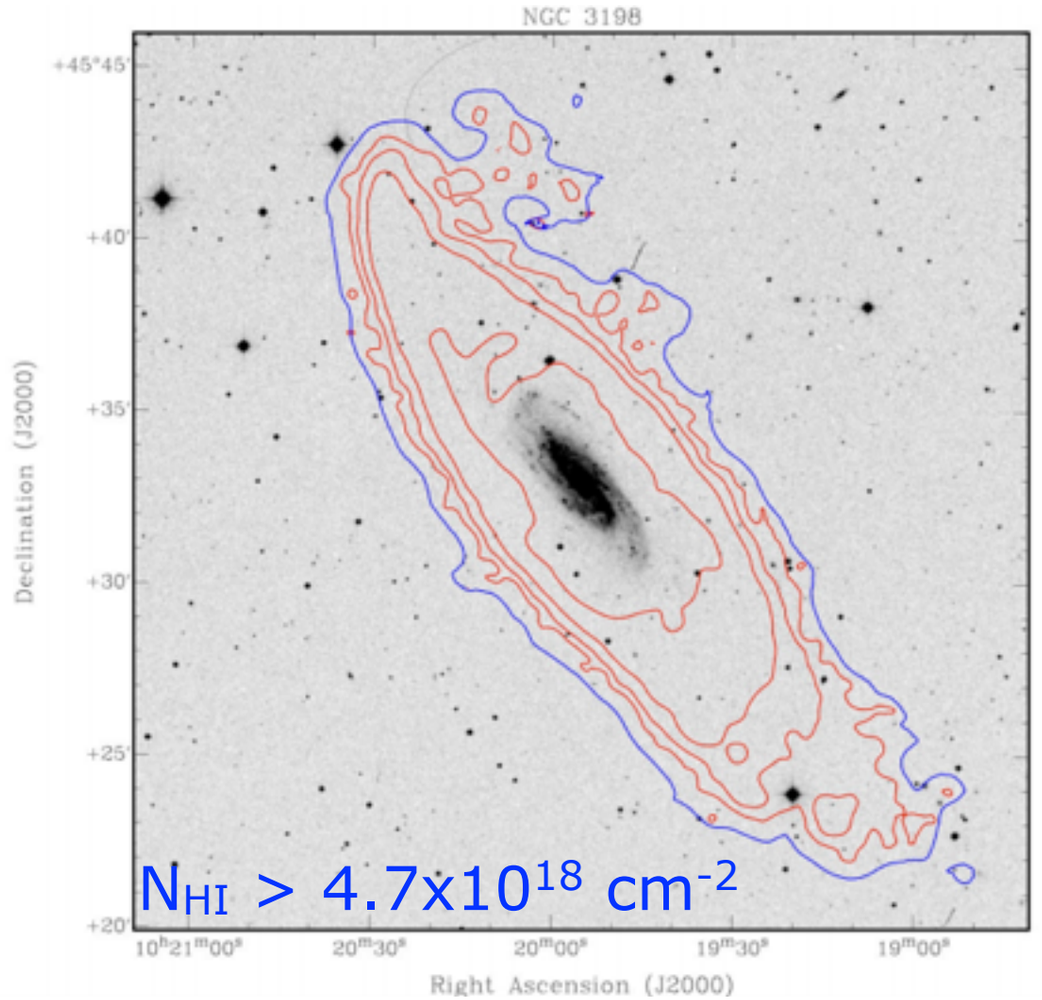


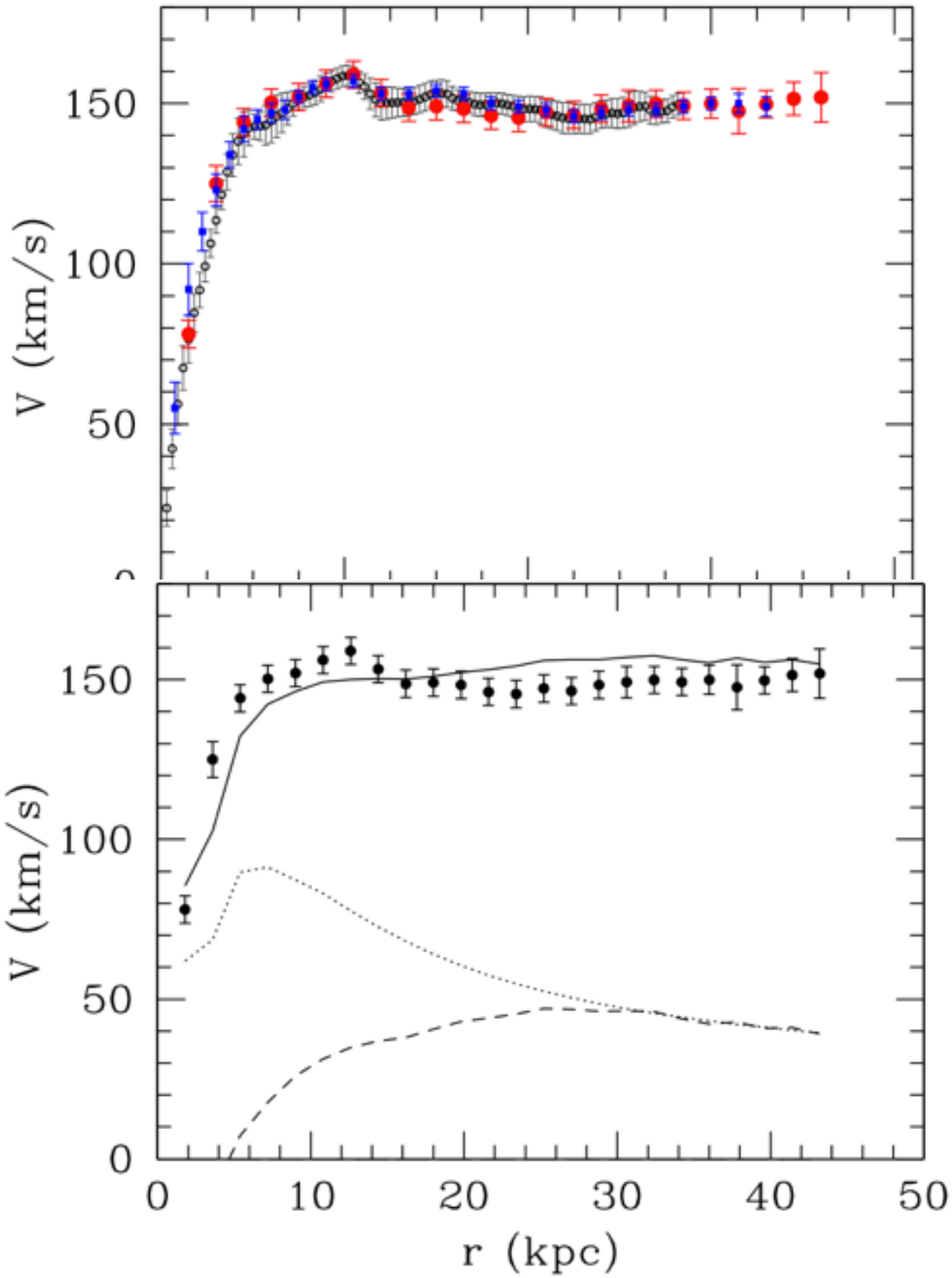
Face-on (model) view



NGC 3198 (Gentile+ 2013)

- Key result: lagging thick disk (~7-15 km/s/kpc) containing estimated ~15% of HI mass from disk-halo separation





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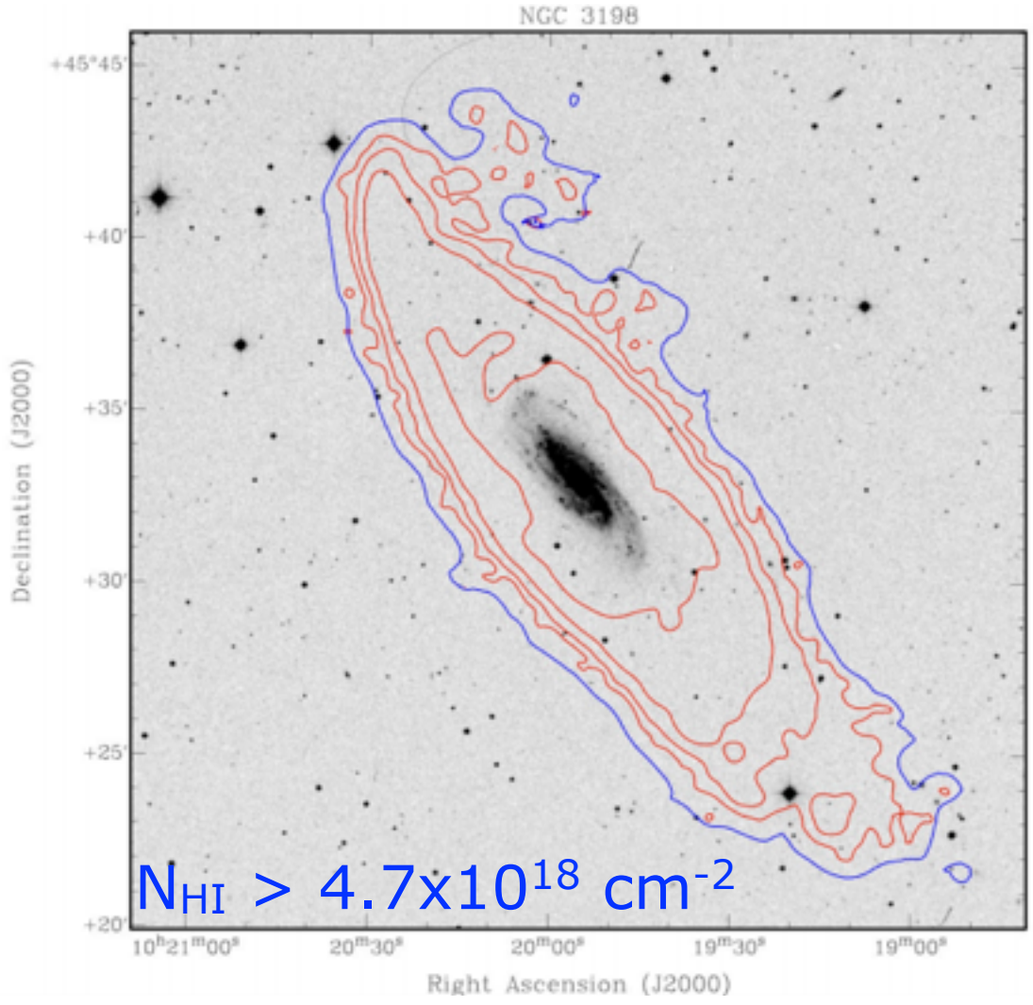
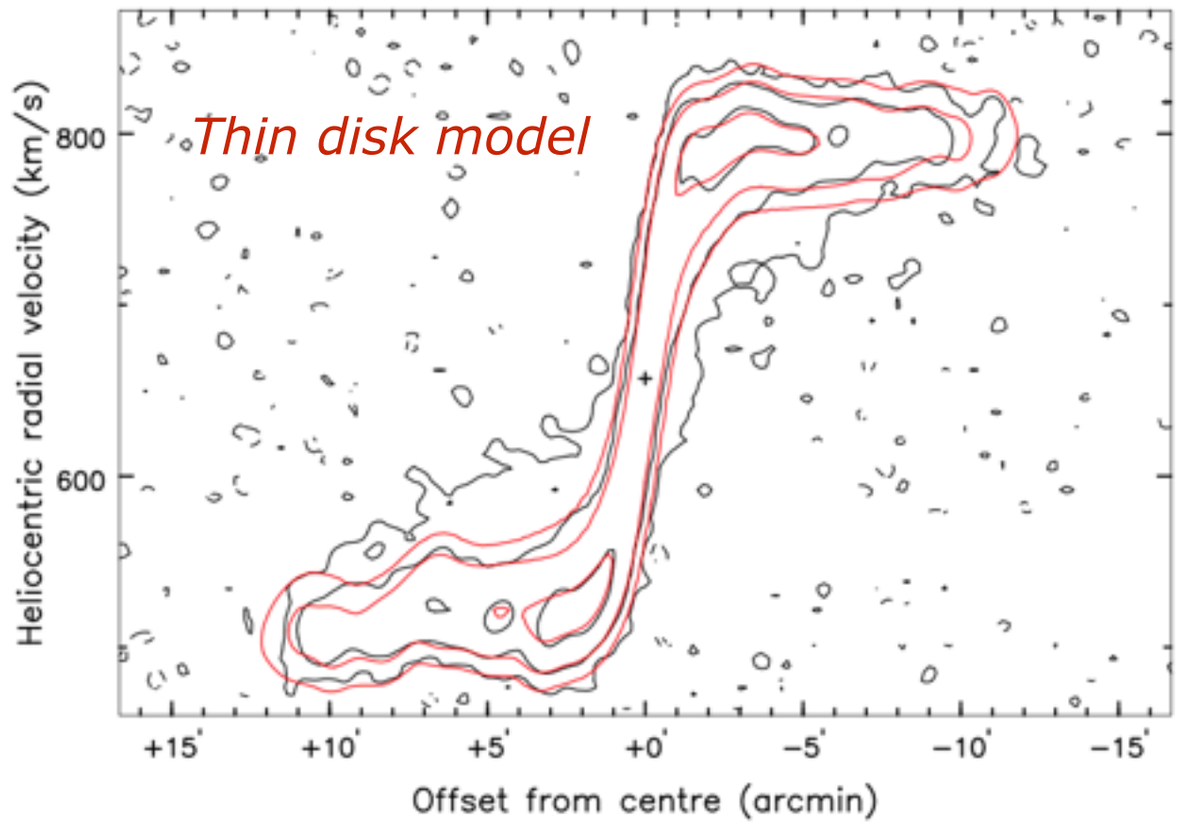
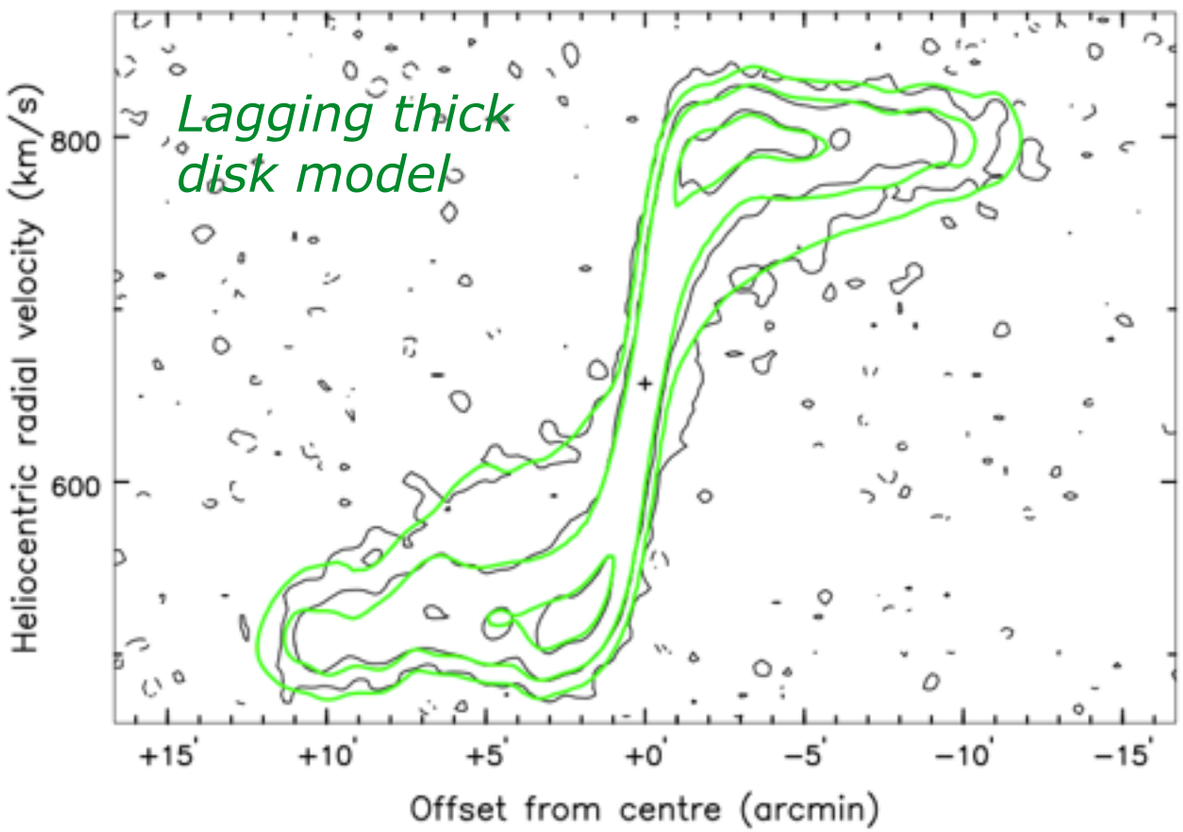




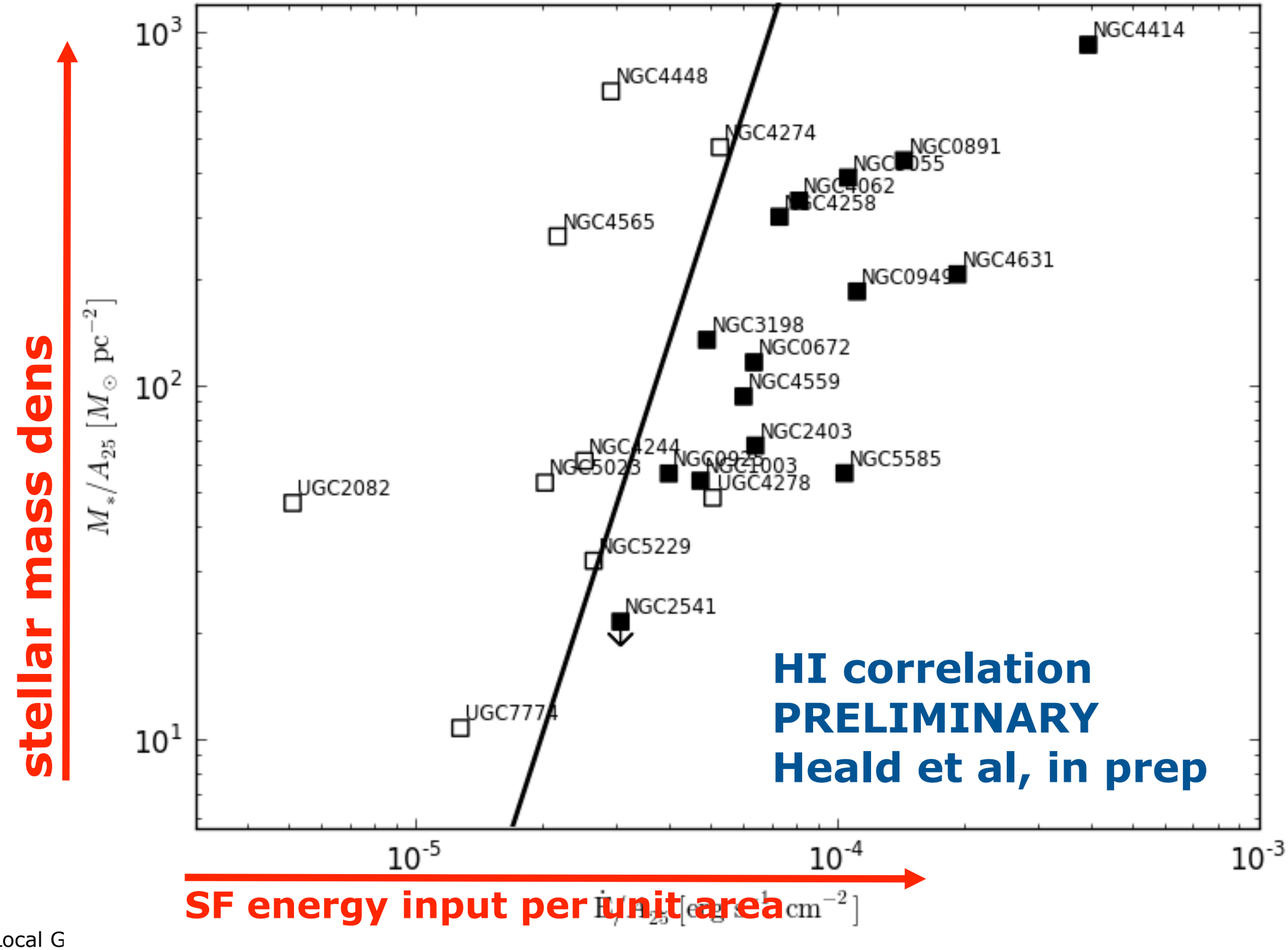


HALOGAS Survey Results

KPNO (B= blue, R=green, Halpha=red) - Maria Patterson; HI - HALOGAS

Thick HI disks

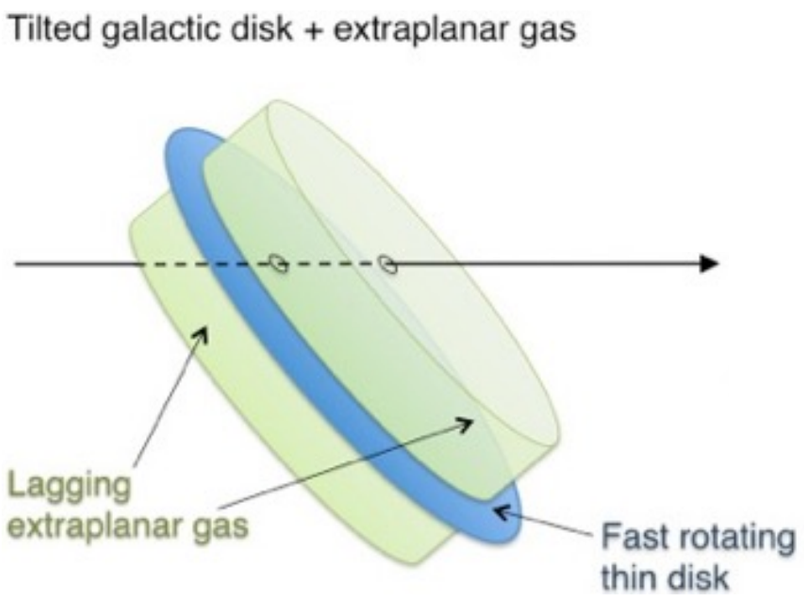
Multiphase thick disks: correlations

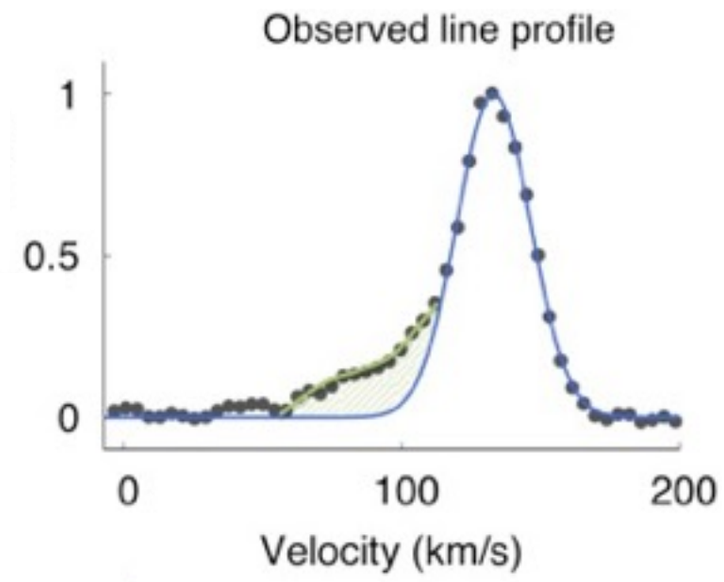


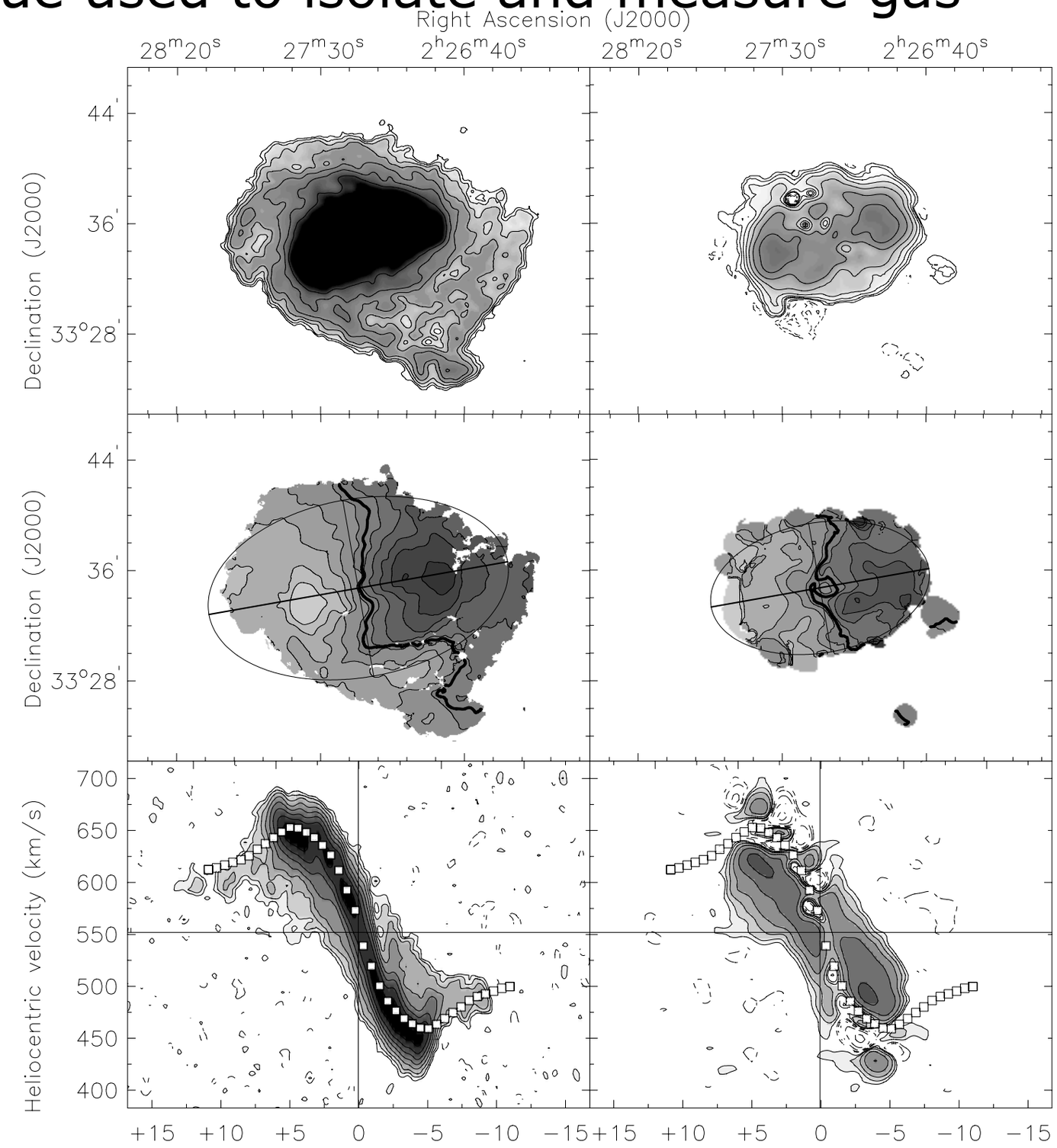
Local G

Quantifying multiphase thick disks

- Disk-halo separation technique used to isolate and measure gas above the thin disk



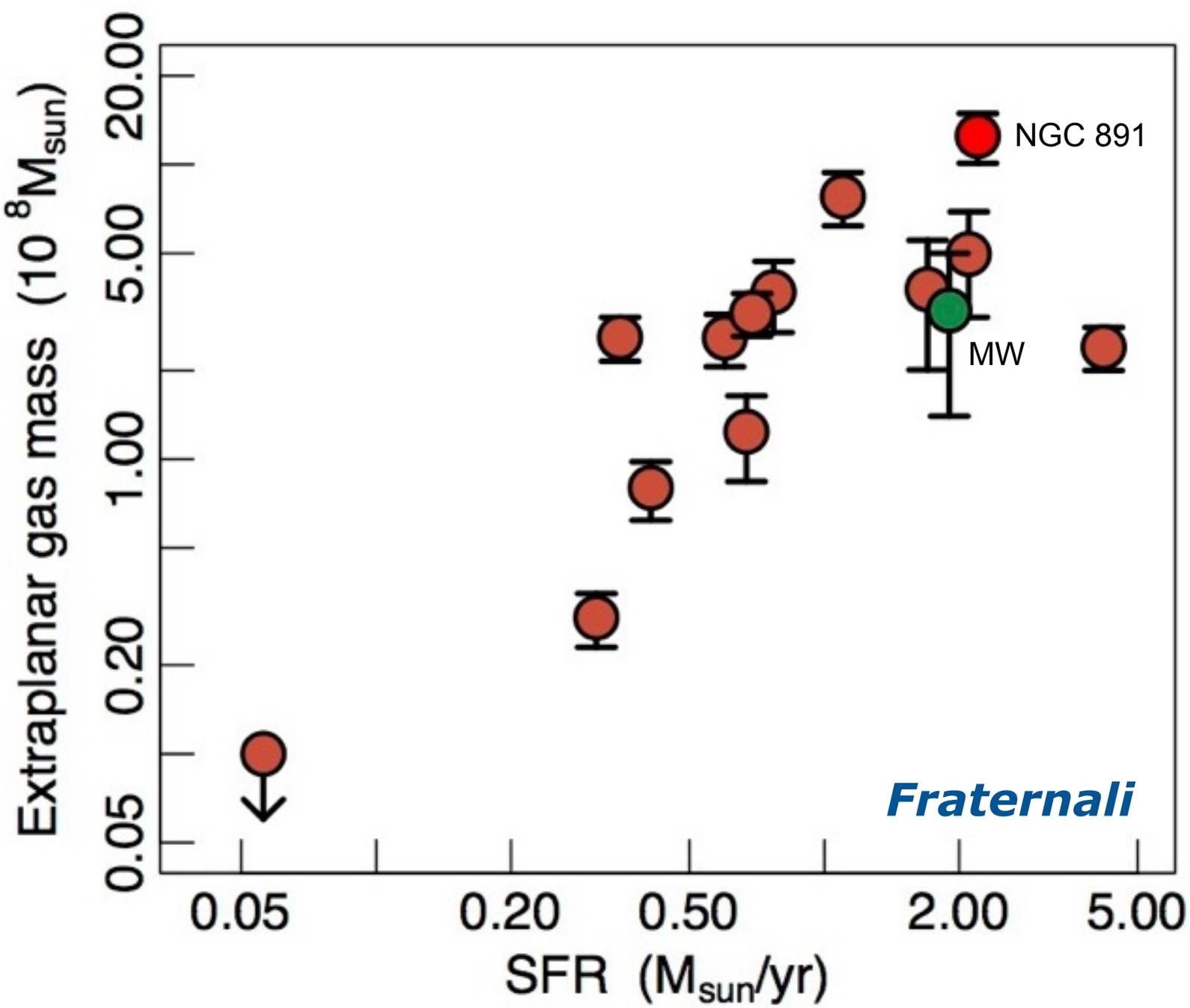




Fraternali

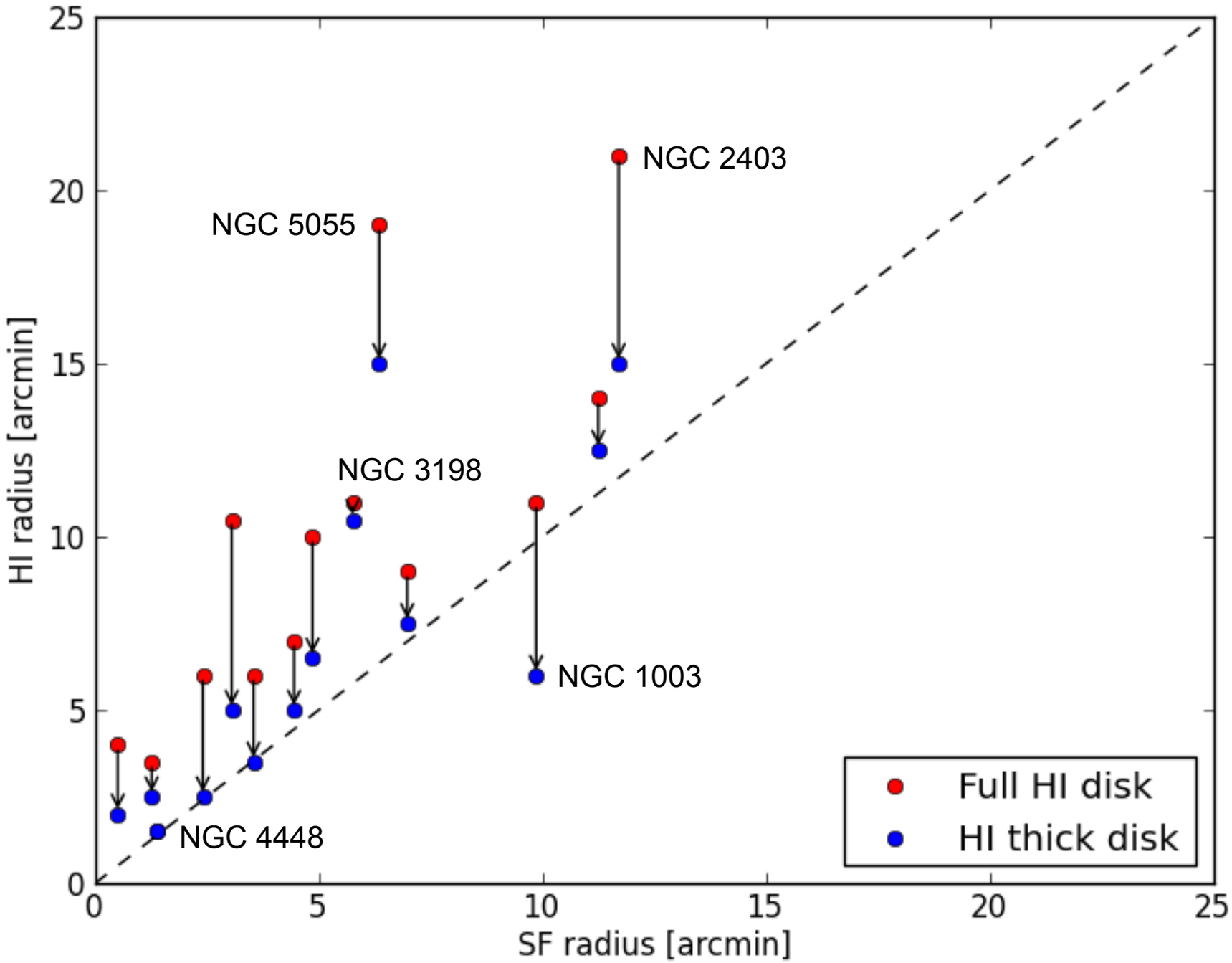
Quantifying multiphase thick disks

- Disk-halo separation technique used to isolate and measure gas above the thin disk
- Thick disk HI mass appears to correlate with host galaxy SFR



Quantifying multiphase thick disks

- Disk-halo separation technique used to isolate and measure gas above the thin disk
- Radial extent of thick disk gas correlates well with SF radius



Local Gas 2015

Fraternali & Heald

Fountain mass model

- A fountain mass estimate

$$M_{fount} = 2\pi \int_0^{R_{max}} \Sigma_{fount}(R) R dR$$

$$\Sigma_{fount}(R) = \alpha\, SFRD(R) \times t_{orb}(R)$$

$$SFRD(R) = SFRD_0 \exp(-R/R_{SF})$$

$$t_{orb}(R) \simeq A(v_{flat})R$$

flat rotation curve

$$A = 25(v_{flat}/100km/s)$$

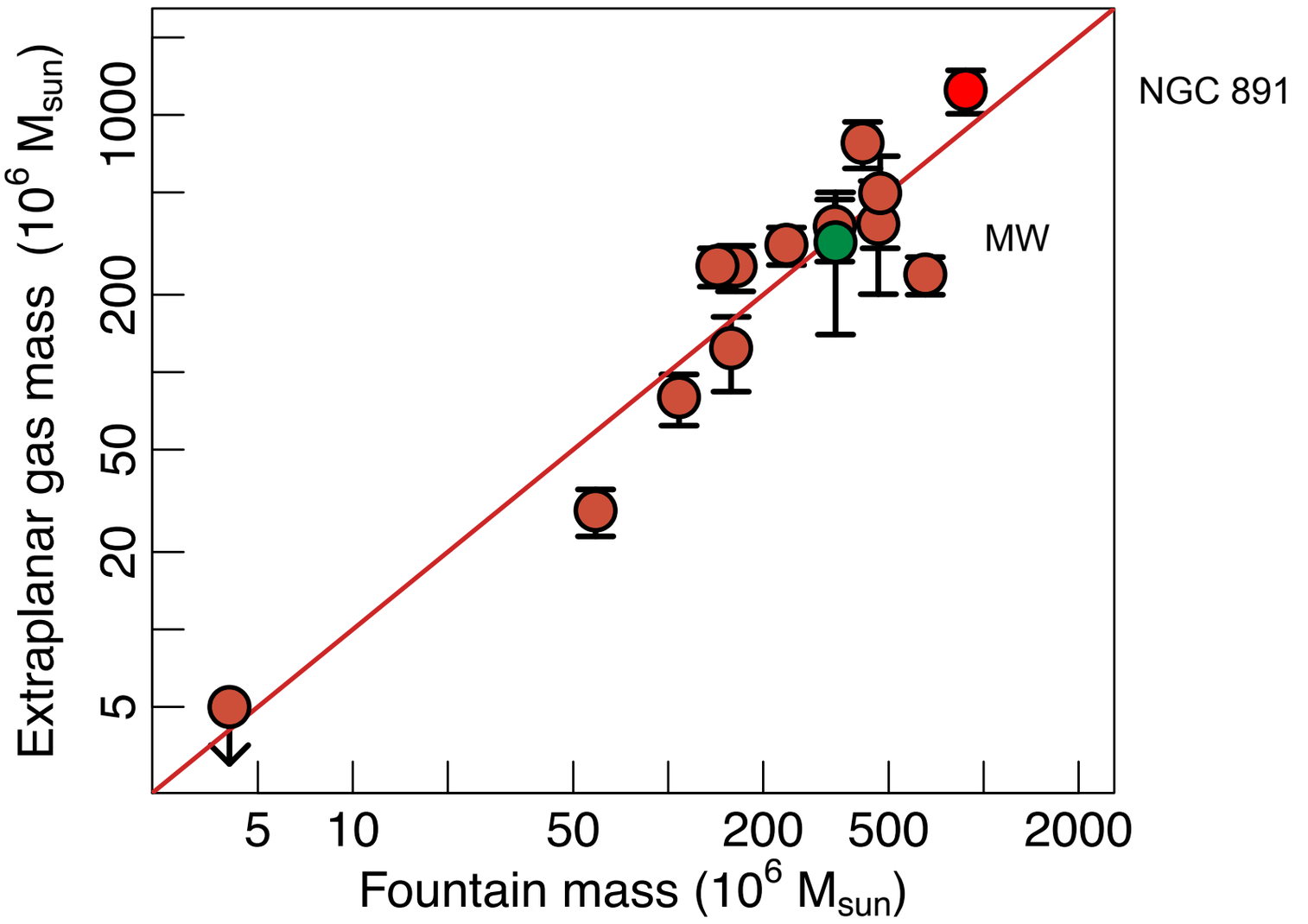
t(orb) in Myr and R in kpc

$$M_{fount} = 2\alpha \cdot A \cdot SFR \cdot R_{SF}$$

Fraternali

Quantifying multiphase thick disks

- Disk-halo separation technique used to isolate and measure gas above the thin disk
- Thick disk HI mass appears to correlate with fountain gas mass



Fraternali

HI Clouds

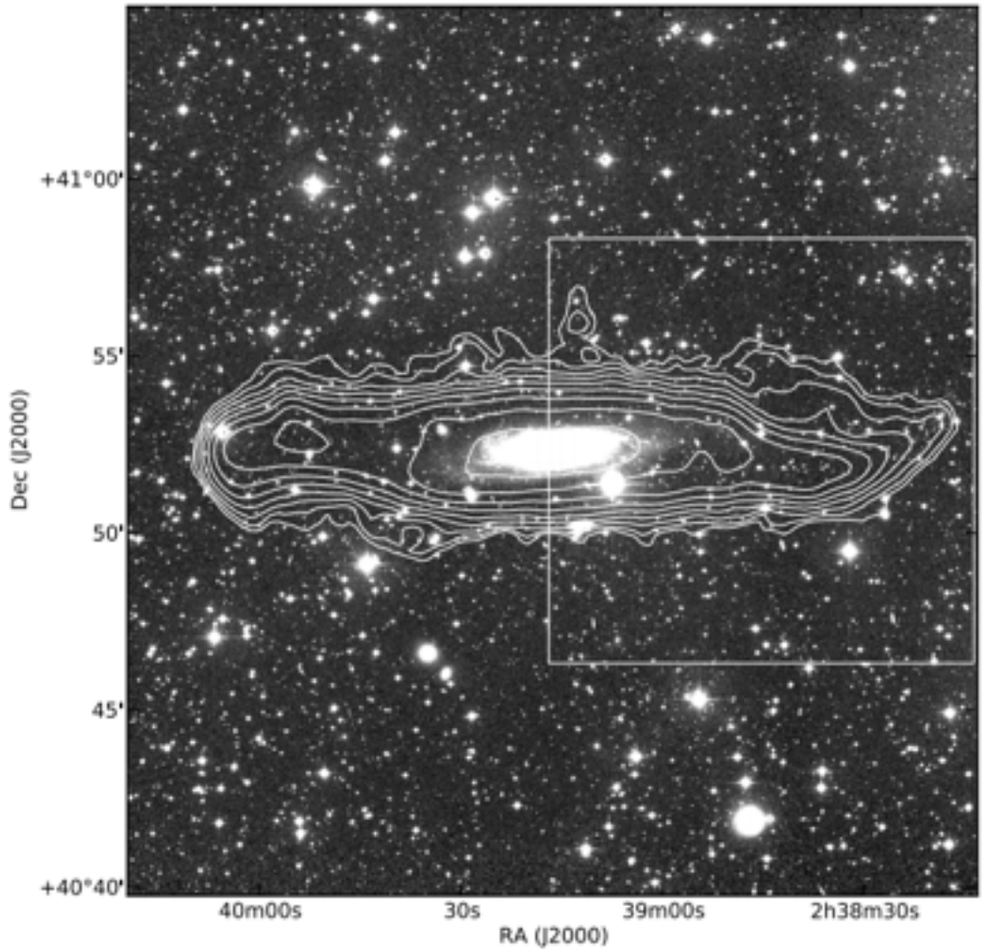
HALOGAS Accretion Catalog

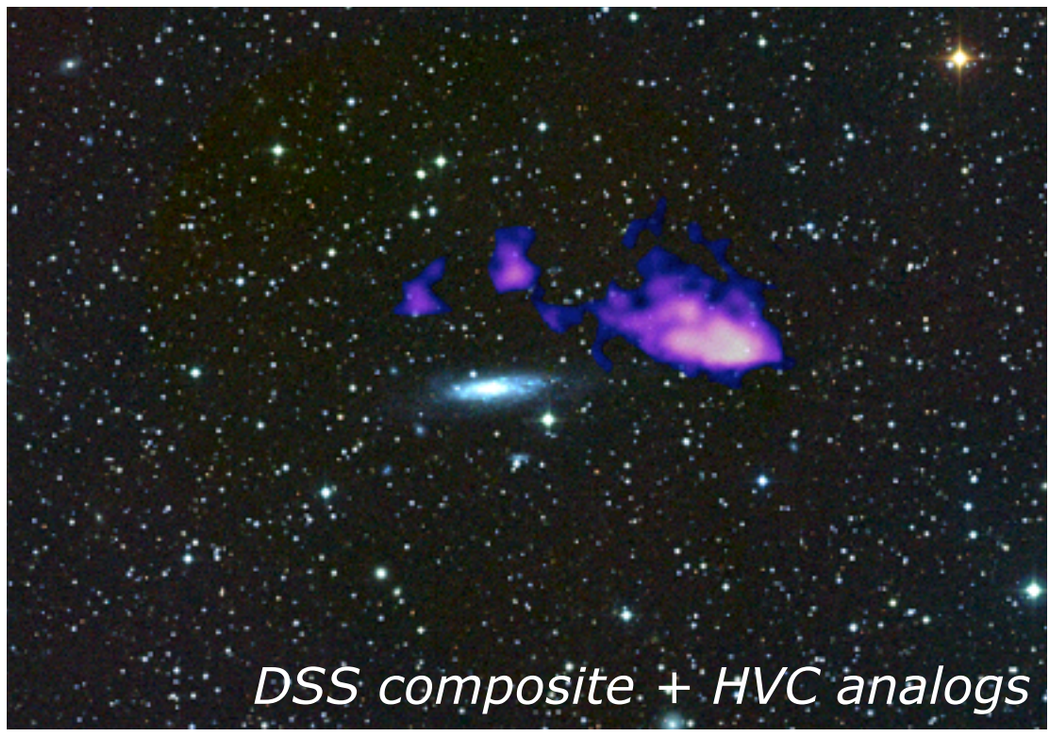
- Effort underway to collect full list of all clouds and streams in HALOGAS target fields
  - Formation of master catalog
  - How many galaxies show signs of accretion? How much (and at what rate)? Clouds or diffuse? Corotating with the galaxy? Associated with star formation? …

- Preliminary result already clear:
  Some features attributable to cold accretion (in the form of HI)
  but insufficient to fully balance SFR in a typical galaxy
  - See also Di Teodoro & Fraternali (2014)
    Minor mergers do not significantly contribute to fuelling SFR

NGC 1003

- Key results:
  - HVC analogs detected at 11 Mpc distance
  - Contributing ~4x10^6 $M_\odot$ of the HI in the system
  - over a dynamical time, these features contribute only ~2% SFR



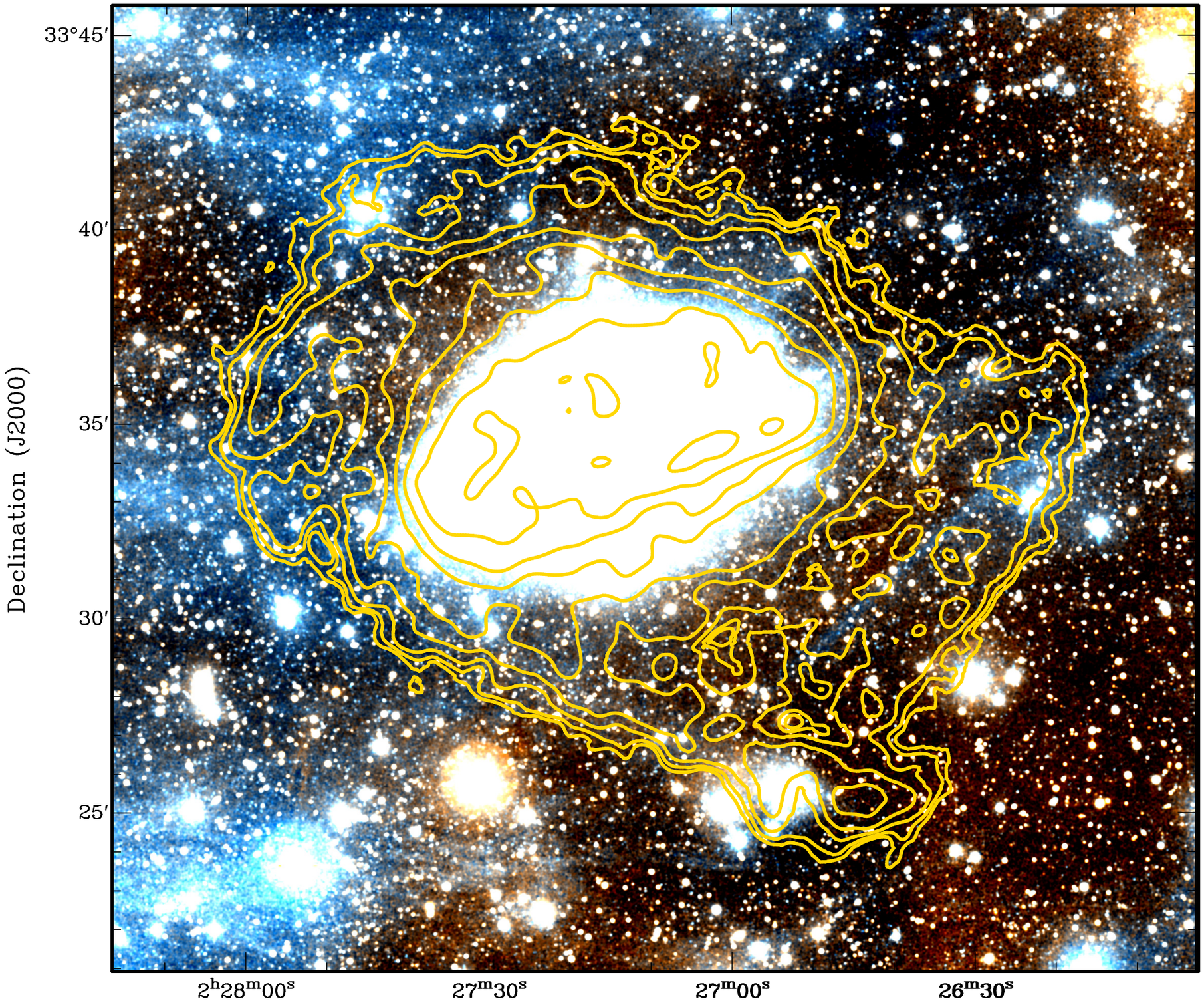


Heald et al. (in prep) *HALOGAS + HALOSTARS*

Cloud	Mass	Height
1	2 x 10^5 $M_\odot$	10 kpc
2	3.3 x 10^5 $M_\odot$	10 kpc
3	3 x 10^5 $M_\odot$	5 kpc
AC (excl #3)	2.9 x 10^6 $M_\odot$	-

NGC 925

- Powerful combination of deep optical and HI reveals tidal remnants

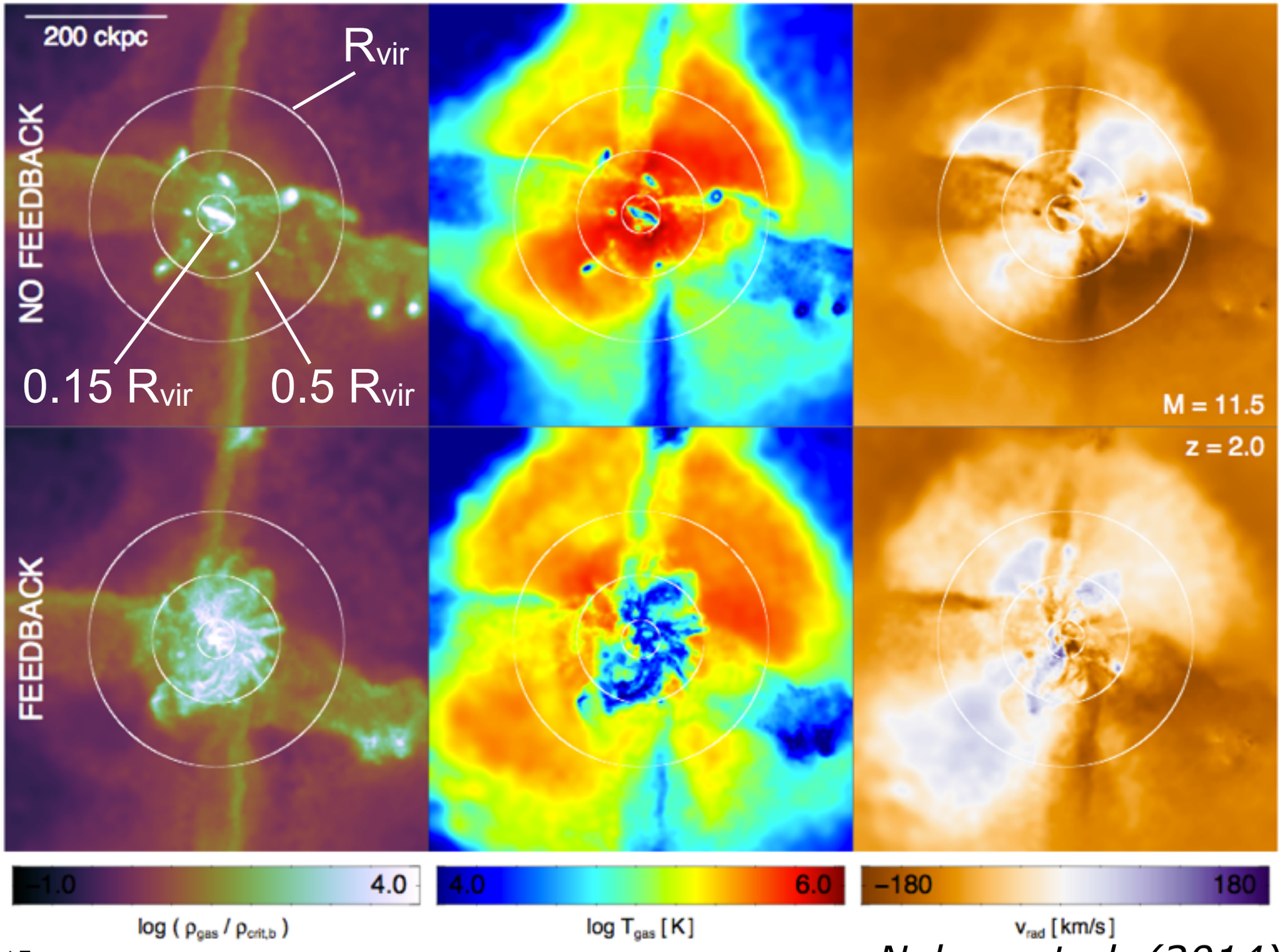


Heald, Patterson et al.

Vogelsberger et al. (2012)

HALOGAS Accretion Catalog

- Current observational capability does not permit a search for accreting gas in each galaxy, over the full virial volume



Nelson et al. (2014)

HALOGAS Accretion Catalog

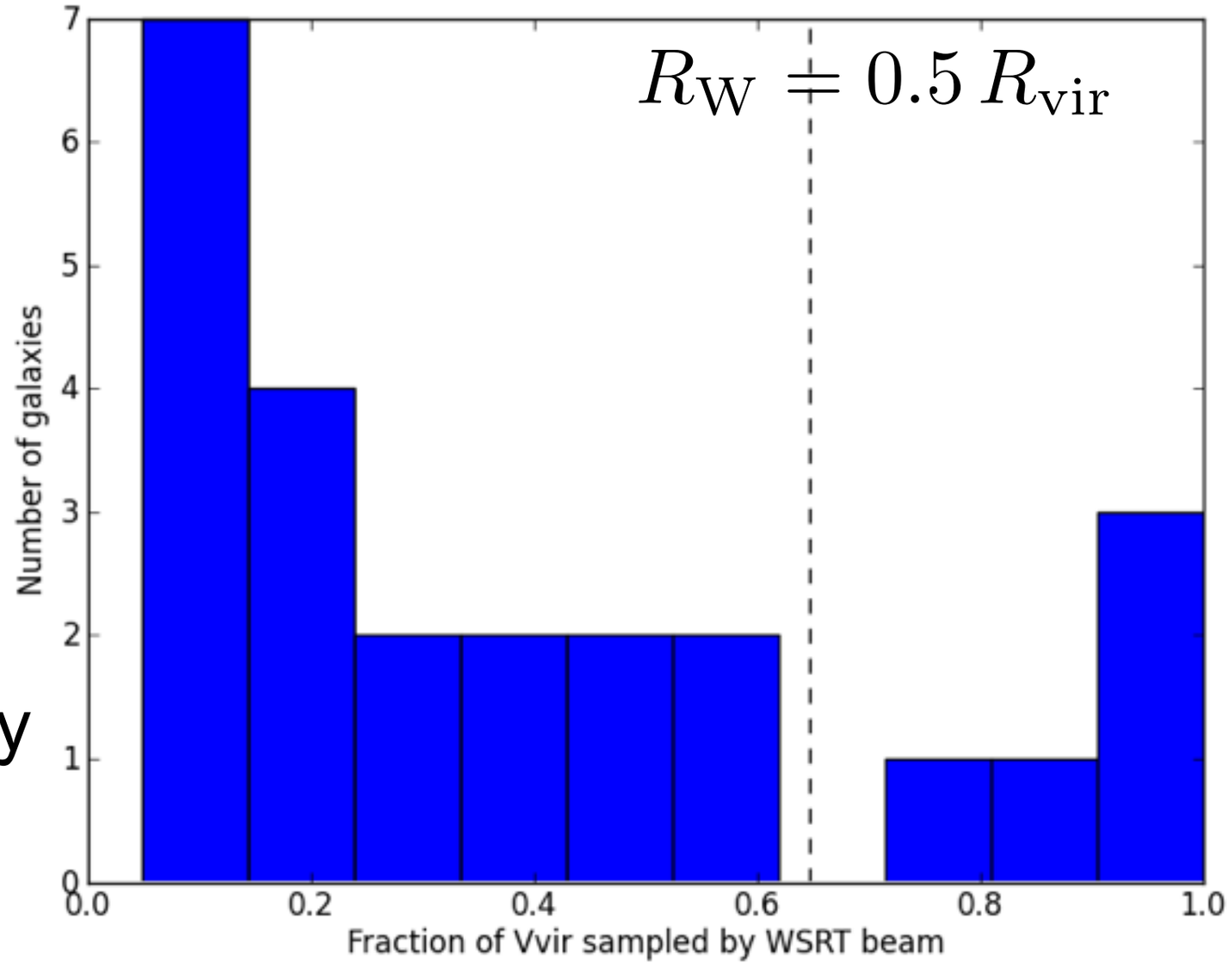
- Current observational capability does not permit a search for accreting gas in each galaxy, over the full virial volume
  - Bulk of gas thought to be within volume defined by ~0.5 R_{vir} (e.g. Nelson et al 2014)
  - That volume is not always fully probed with single pointings:

$$V_{\rm W} = \frac{4\pi}{3}(R_{\rm vir}^3 - \zeta^3),$$

$$\text{where} \quad \zeta = \sqrt{R_{\rm vir}^2 - R_{\rm W}^2}$$

virial radius

WSRT primary beam size



HALOGAS Accretion Catalog

- Current observational capability does not allow for a full census of accreting gas in each galaxy
- Using human searches along with SoFiA (Serra et al.) to do uniform cloud detection within PBs … but almost nothing is seen!
- We detect hardly any HI clouds that are not associated with the main disks or tidal interactions

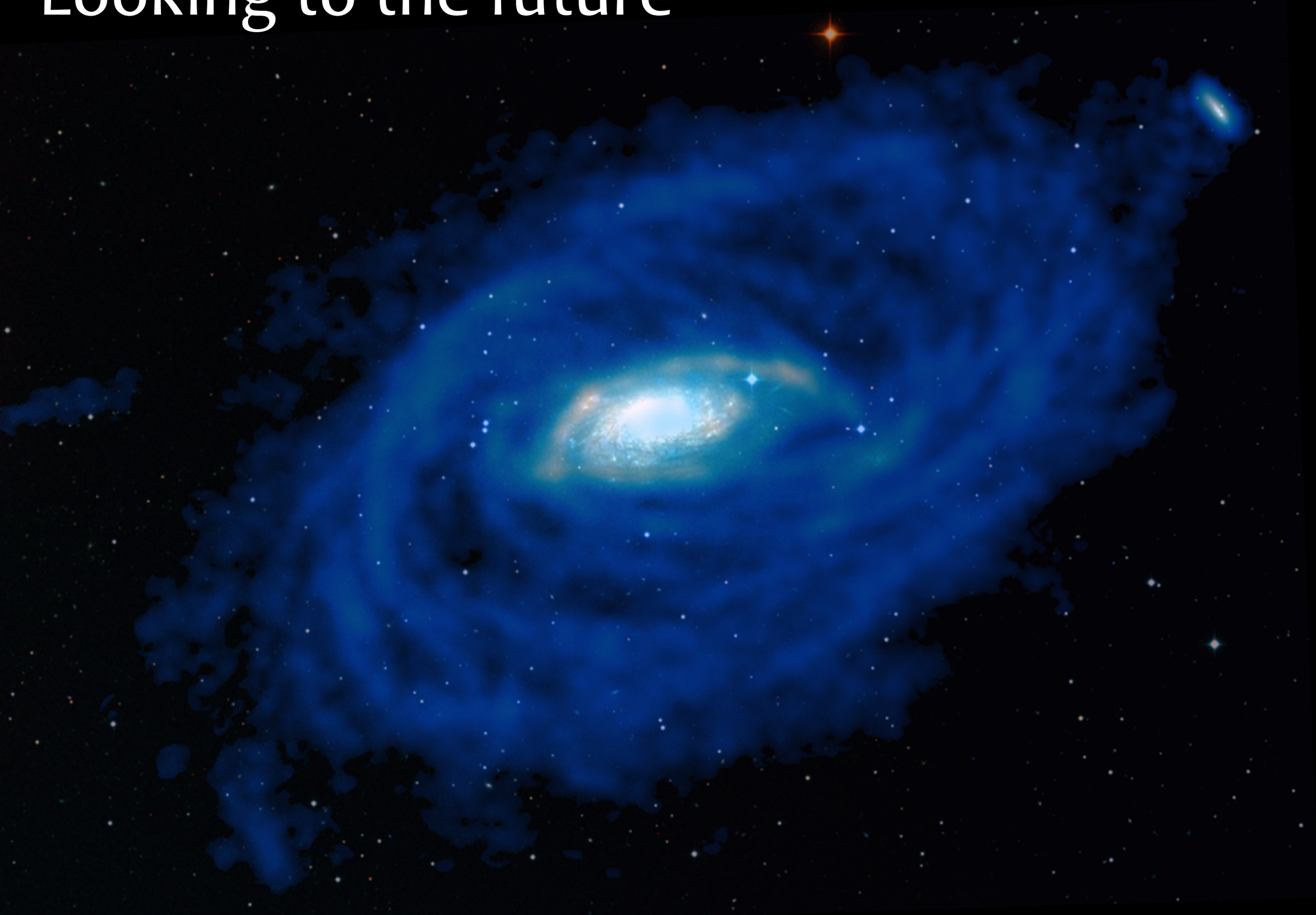
- **HALOGAS detects insufficient amounts of (cold) accretion in HI emission**
- See Eva Jütte's and Filippo Fraternali's talks this afternoon for interpretation

Implications

- HI thick disks are not ubiquitous, but have properties that seem to align with underlying galaxies
  - Detections vs non-detections gives important leverage
  - SF seems to be at the root of HI thick disk properties

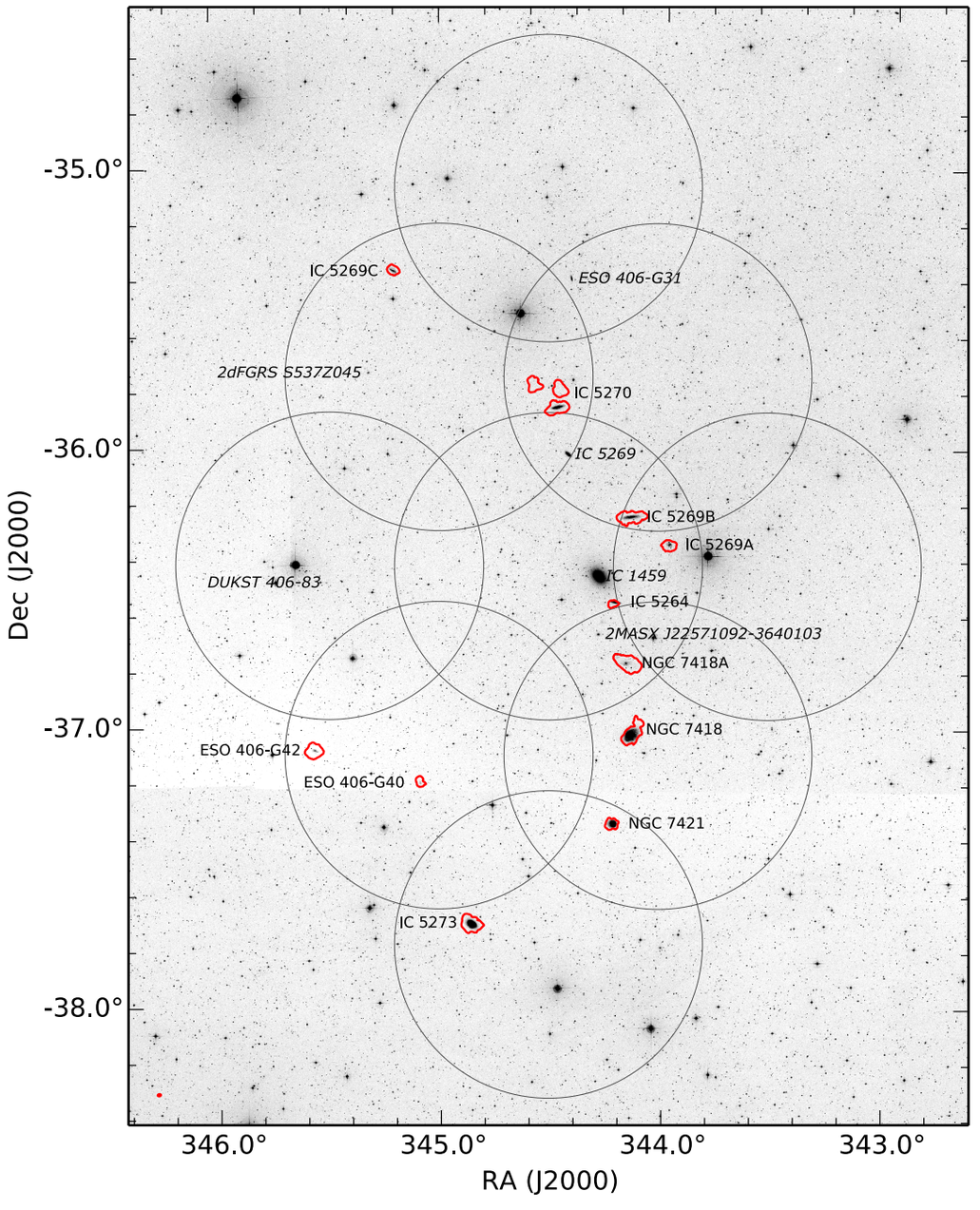
- Accretion seemingly not predominantly in the form of clouds, and not in the form of minor mergers (Di Teodoro & Fraternali 2014)
  - Era of galaxy SFR decline?
  - In the form of hot gas, and brought to the disk via fountain?
  - Need for a better search out at the virial radius?

Looking to the future



HALOGAS Accretion Catalog

- Current observational capability does not allow for a full census of accreting gas in each galaxy
- But this is bound to change with ASKAP & APERTIF!
- NB: Typical virial radius for HALOGAS galaxies is ~250 kpc
  - For ASKAP, FoV = 5.5 deg x 5.5 deg; APERTIF 3 deg x 3 deg
  - ASKAP = full V_{vir} for galaxies D > 5 Mpc with full sensitivity
  - APERTIF = full V_{vir} for galaxies D > 10 Mpc with full sensitivity



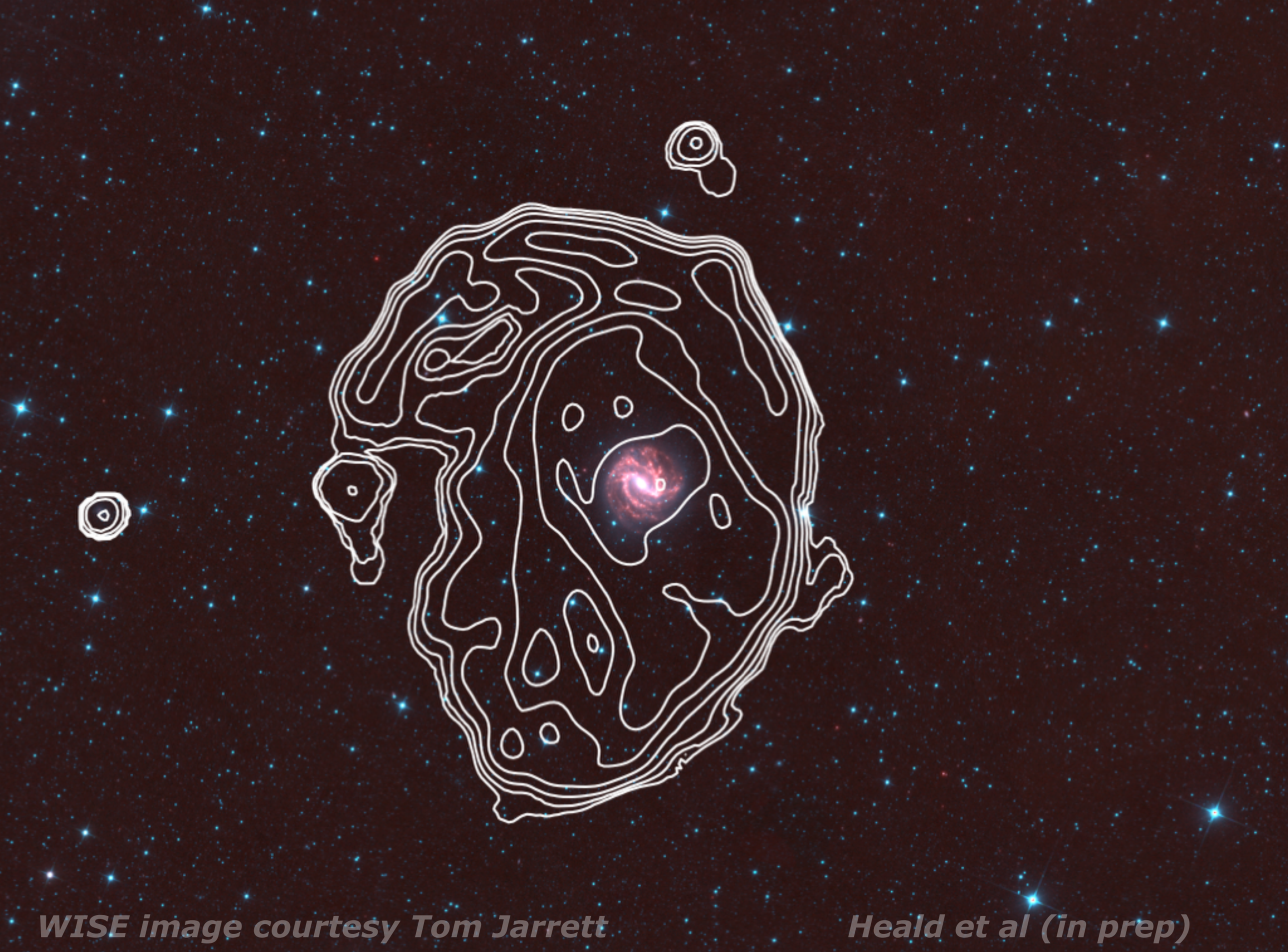
ASKAP (BETA): Serra et al 2015

Preparation for MHONGOOSE

- MHONGOOSE (de Blok et al)
  MeerKAT HI Observations of Nearby Galactic Objects: Observing Southern Emitters

Talk by Yiannis Bagetakos on Fri

- Deep HI observations of nearby galaxies, with commensal polarized continuum to investigate magnetic fields
- First look at M83 with KAT-7 in 2013
- Initially in full-Stokes continuum mode
  Produced intriguing HI map despite poor velocity resolution
- Recent reobservation (reduction ongoing) in line mode
  - 6/7 antennas operational for first scan, all 7 for the rest
  - 3 pointing mosaic, in total ~60h on source
  - Data reduced in miriad using standard bandpass and interleaved gain (phase) calibrators

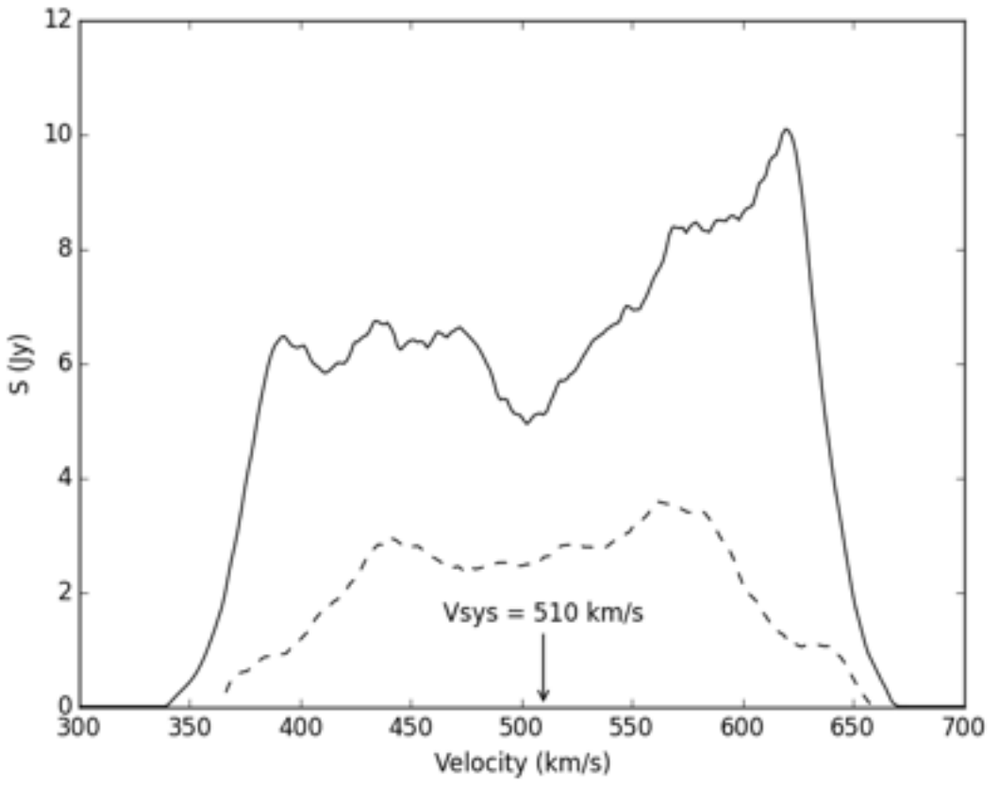


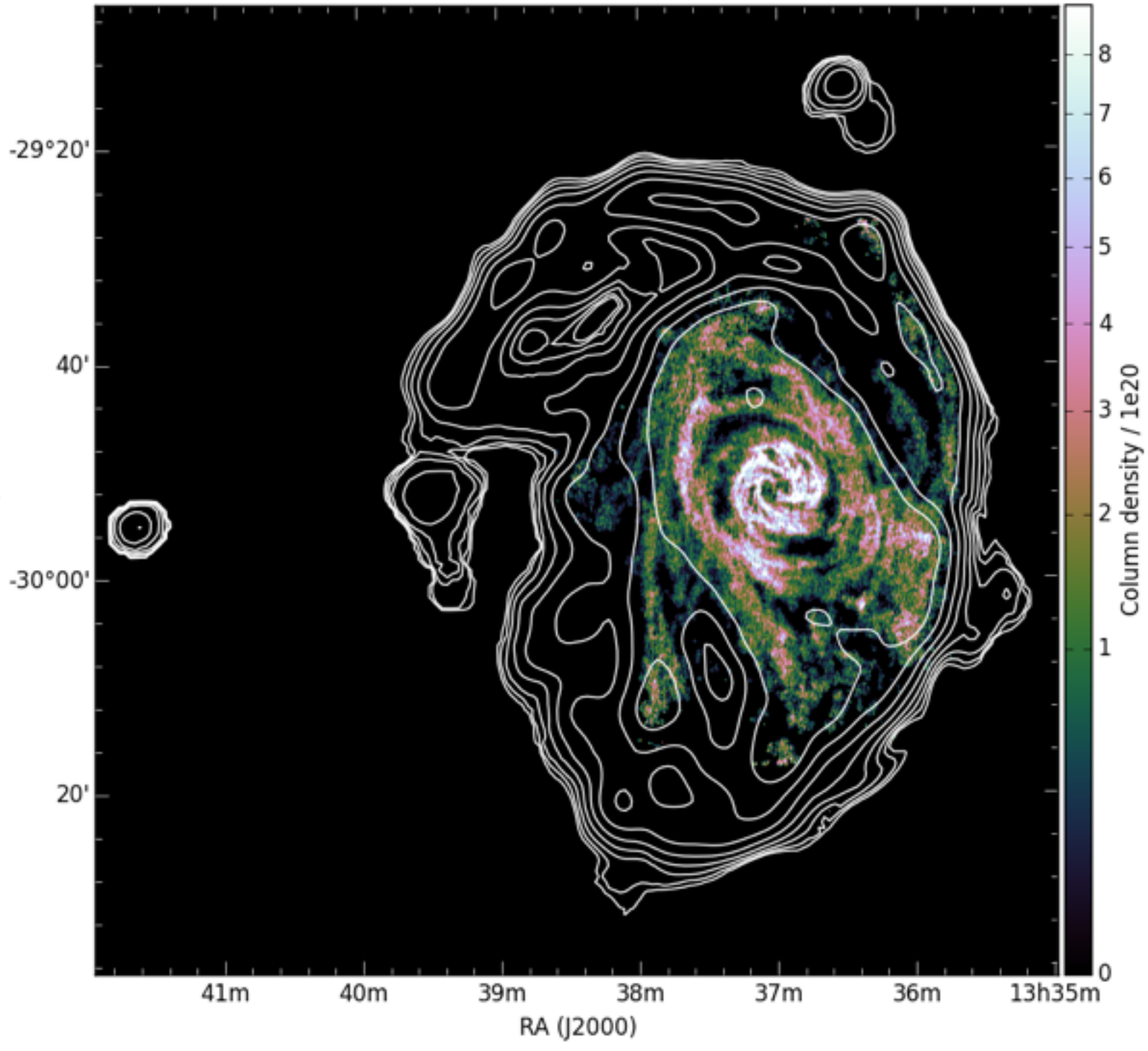
WISE image courtesy Tom Jarrett

Heald et al (in prep)

KAT-7 view of M83

- Column density threshold similar to HALOGAS, with ~3’ resolution

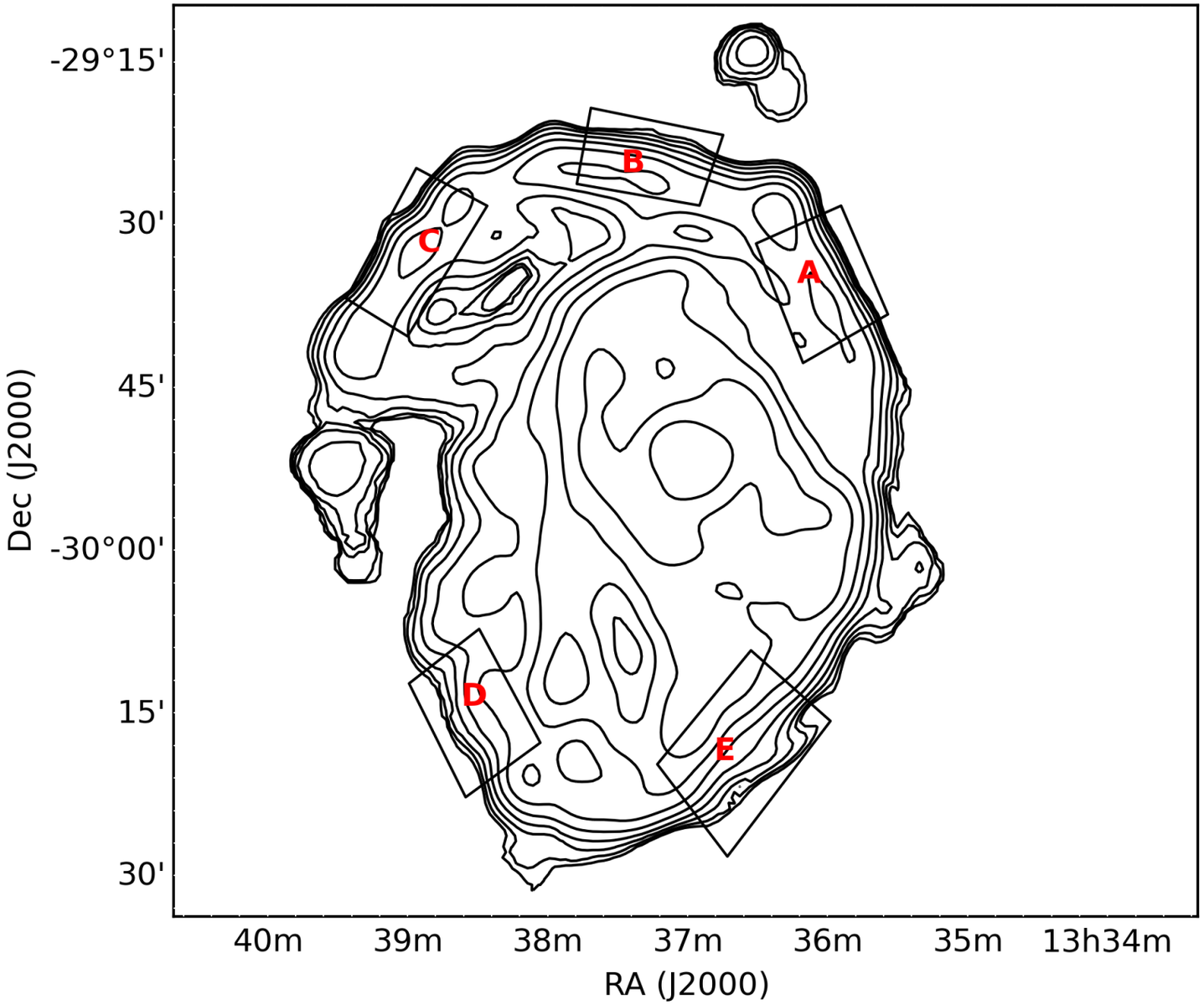


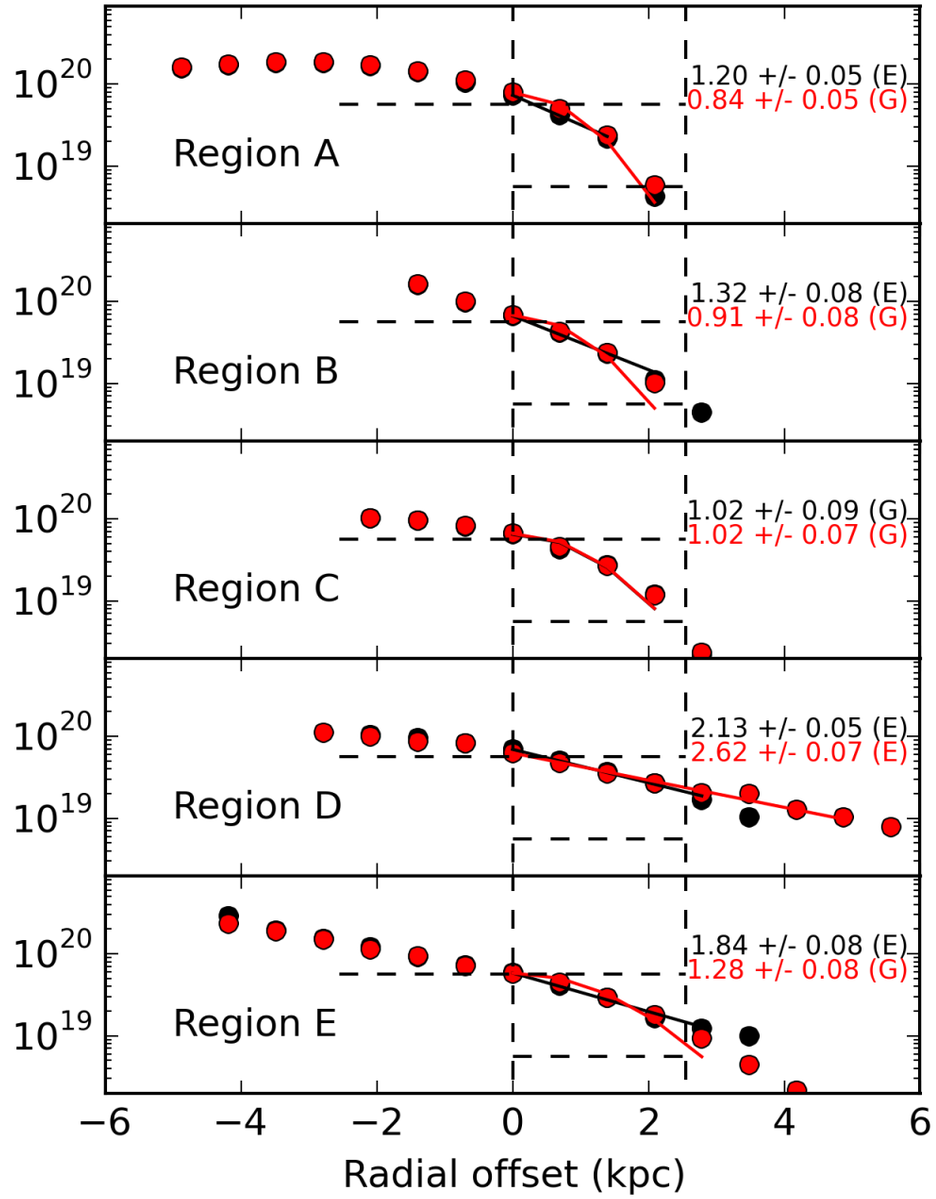


Heald et al (in prep)

KAT-7 view of M83

- Edge of the disk?





Heald et al (in prep)

Summary

- HALOGAS: Interpretation underway
  - Providing access to a broad range of extraplanar characteristics (including *important* non-detections...)
  - SF origin of extraplanar HI layers and role in gas accretion
  - HALOGAS accretion catalog

- Near-term prospects for extending lessons from HALOGAS
  - APERTIF Medium-deep survey, MeerKAT/MHONGOOSE
  - Preliminary work with KAT-7 is already providing new access to low column density (diffuse) HI!
  - More to come…