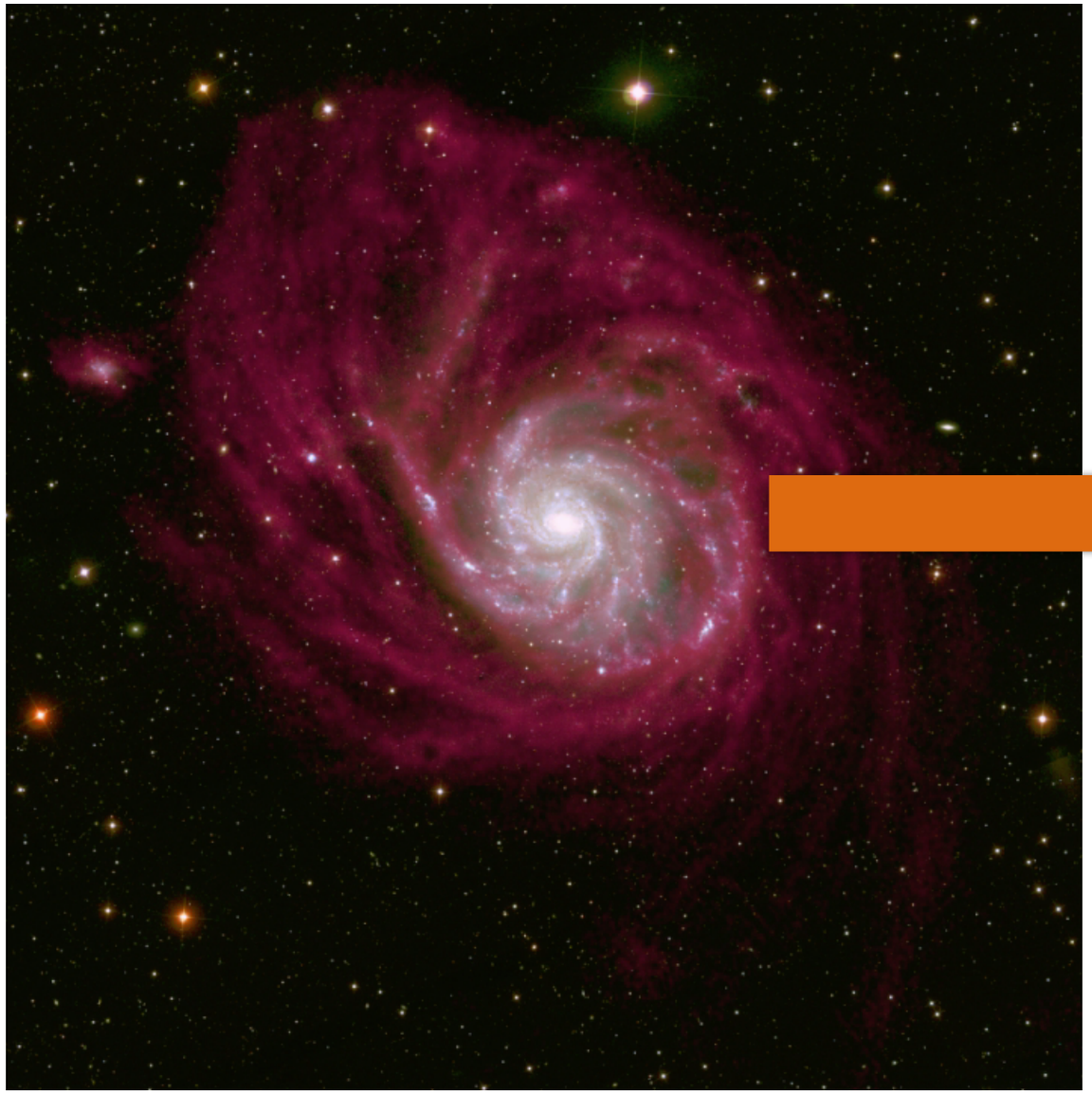
accretion and low-column density HI in nearby galaxies:

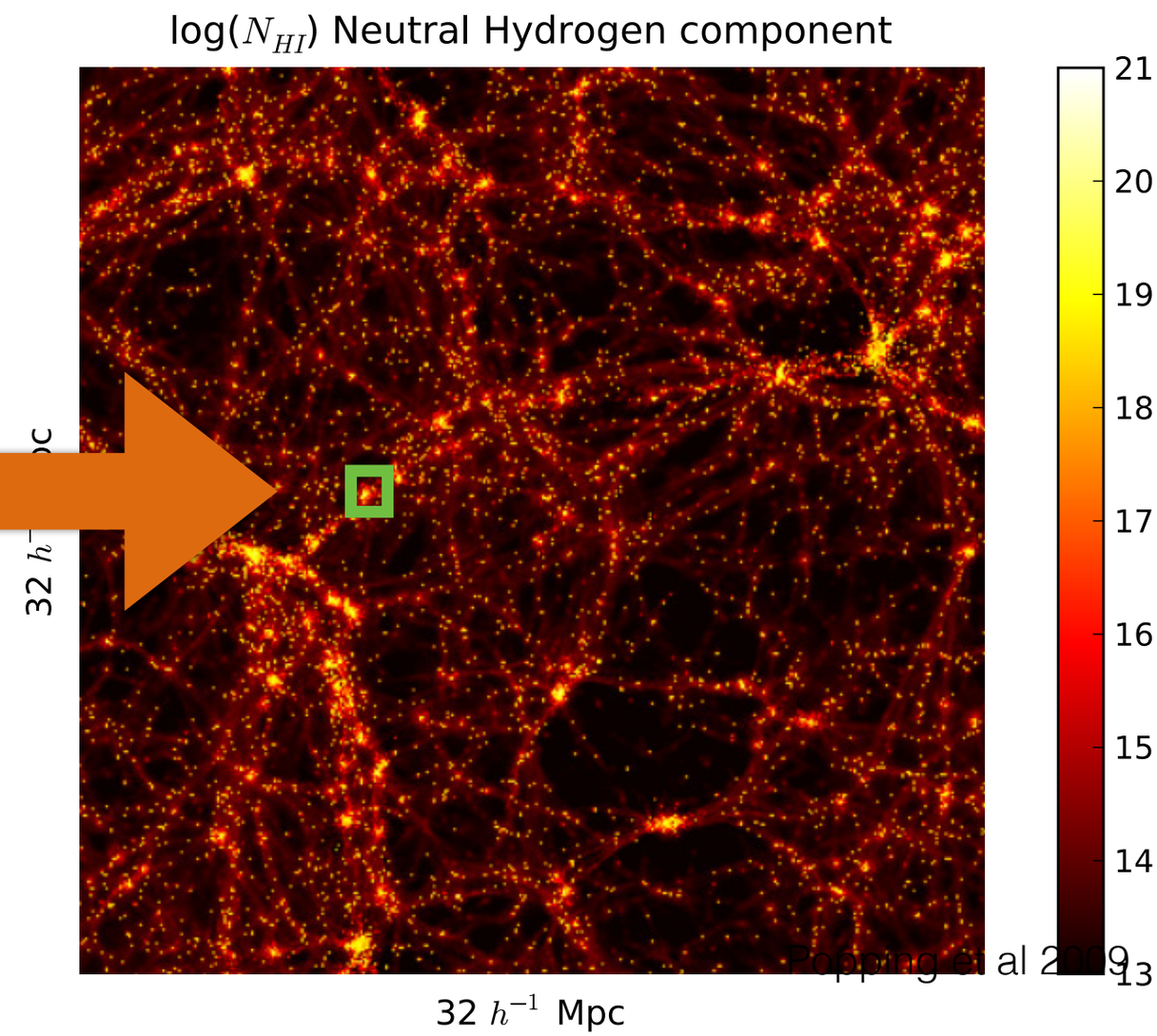
prospects for SKA

Erwin de Blok
(ASTRON/UCT/Kapteyn)

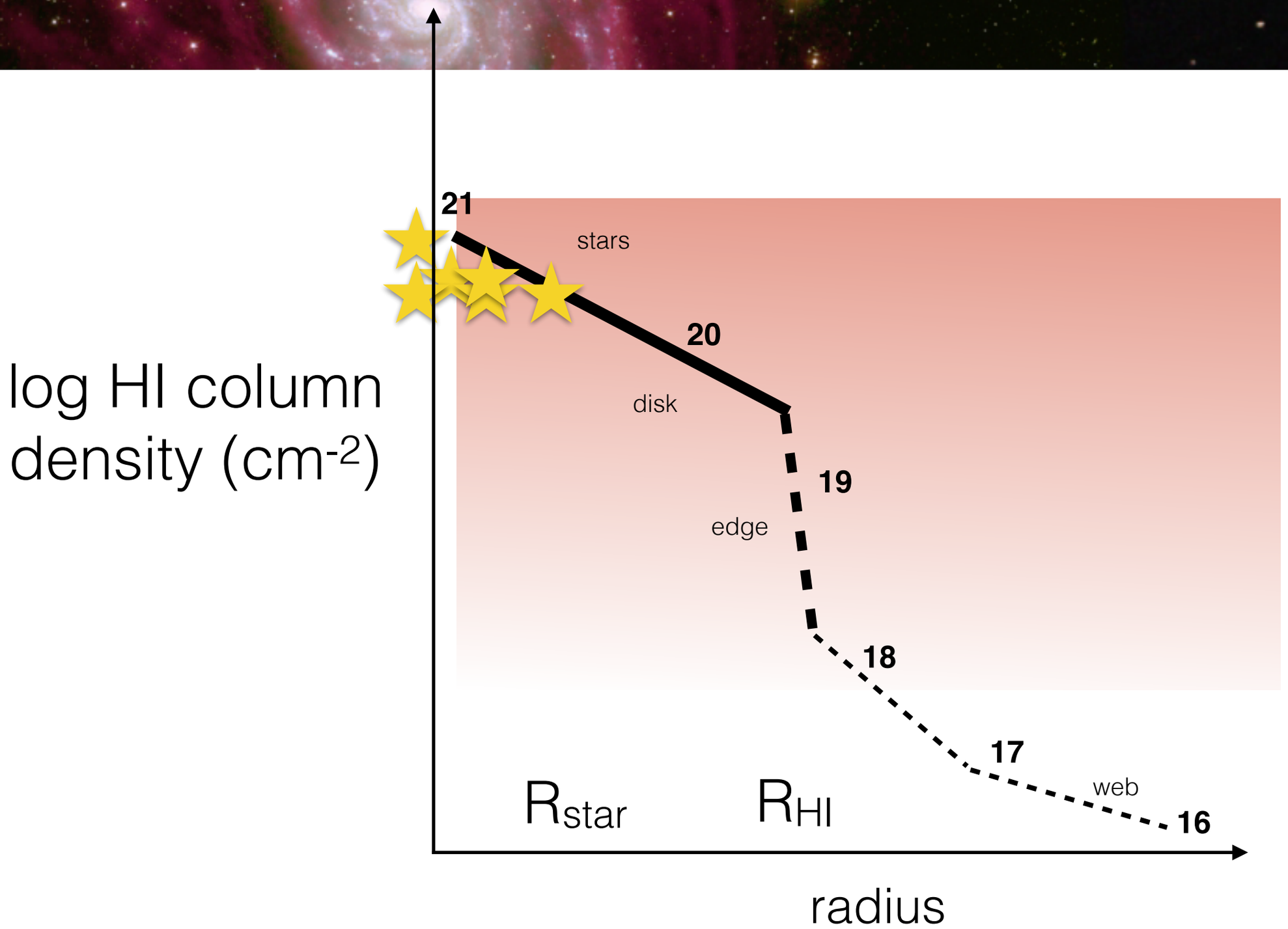
SKA meeting Goa
7 Nov 16

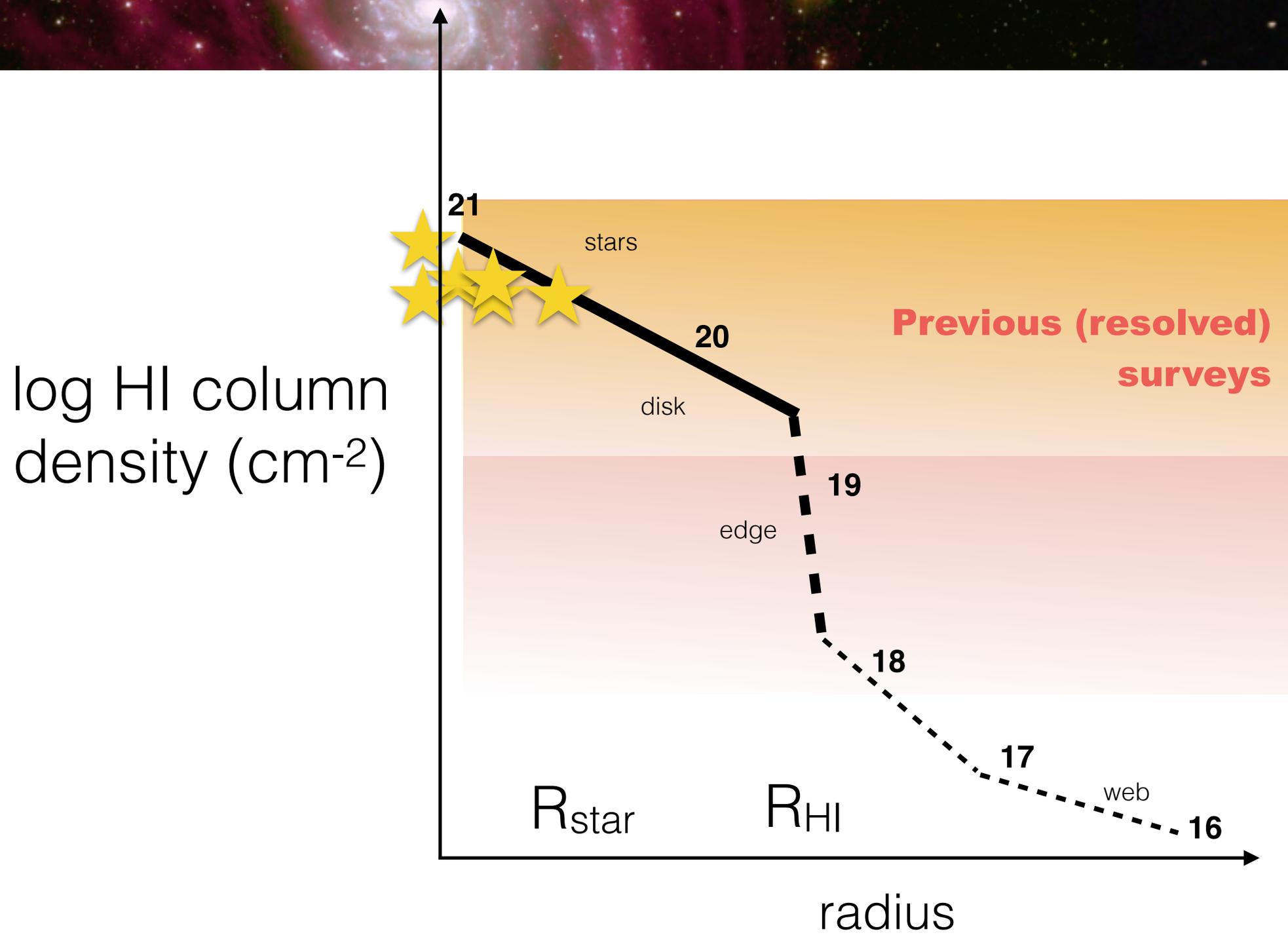
Galaxies in the cosmic web





Popping et al 2009


log HI column density (cm-2)
21
20
19
18
17
16
stars
disk
edge
web
Rstar
RHI
radius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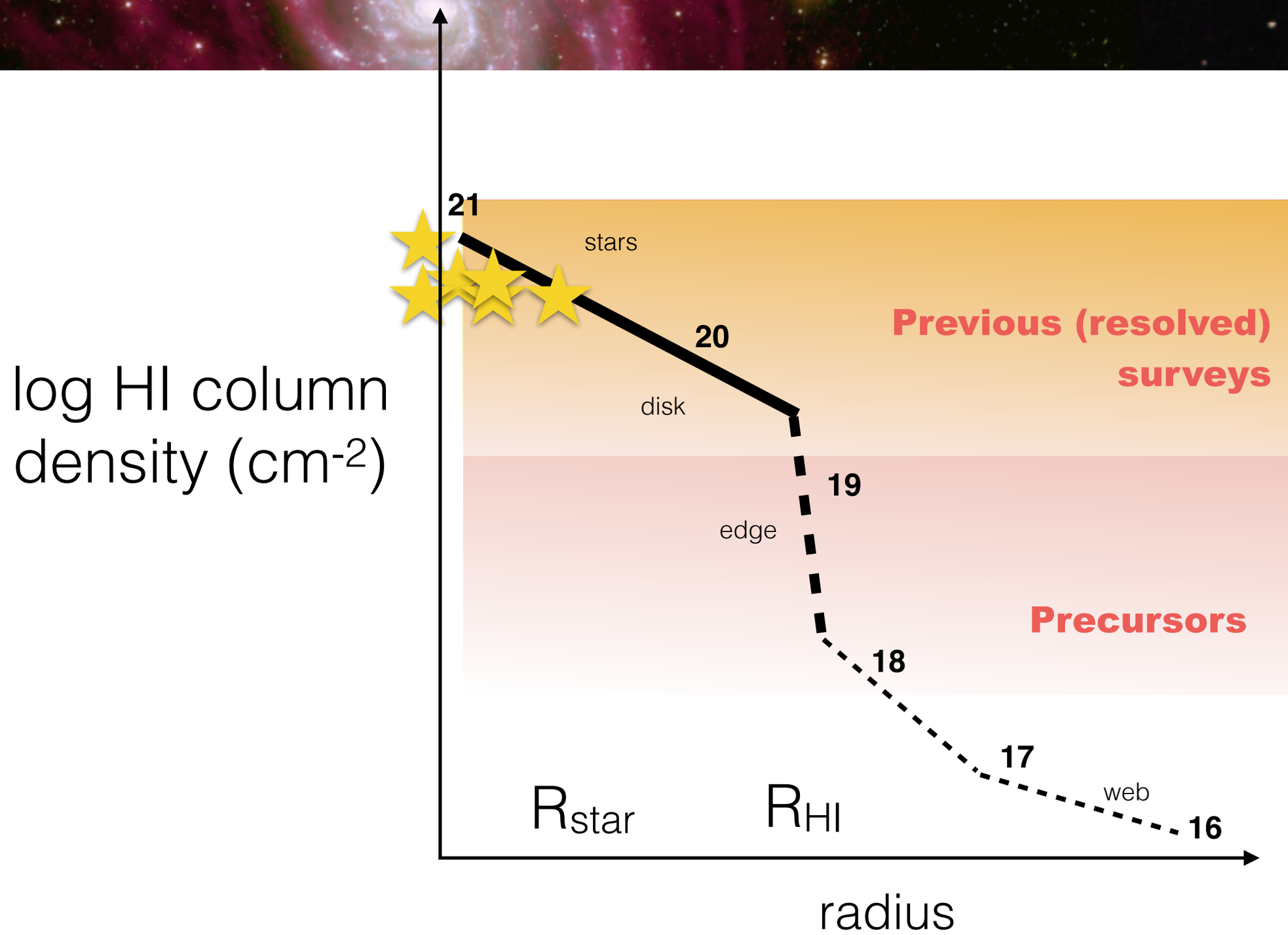
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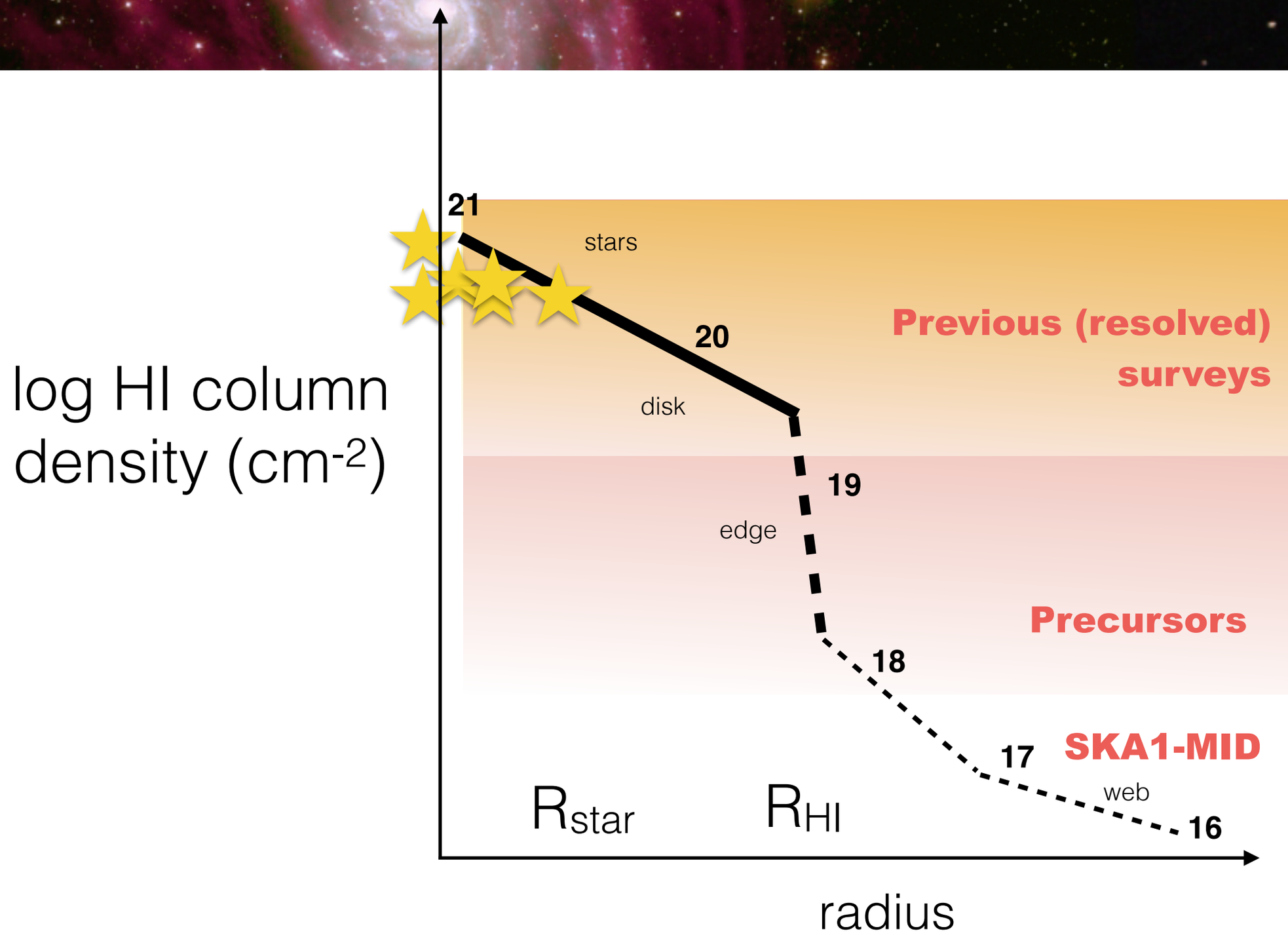
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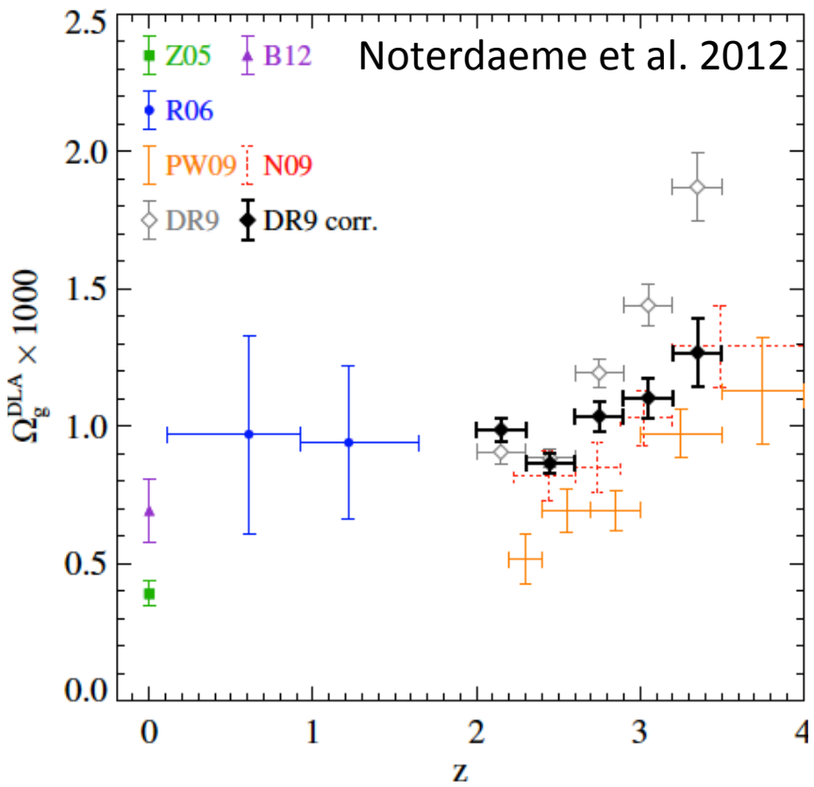
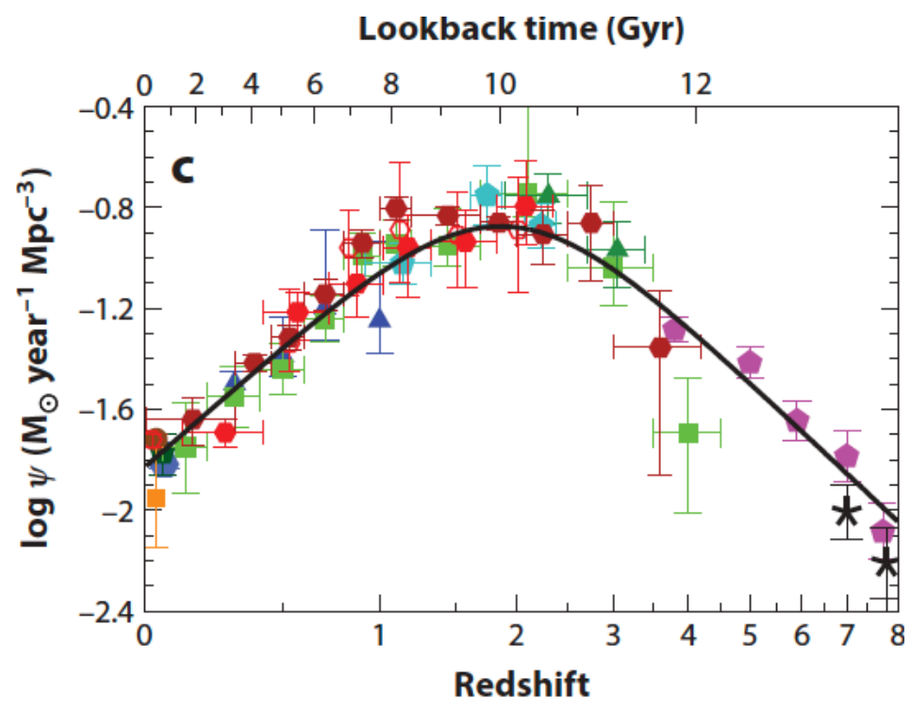
HI Content and SFR





Madau & Dickinson 2014

- The HI content of galaxies appears to be relatively constant since z=2-5
- The SFR was 10 times higher at z ~ 2
- Galaxies must be accreting gas from the IGM

Feeding a galaxy

- Local universe galaxy gas consumption time scale ~2 Gyr (e.g. Bigiel et al 2008)
- Galaxies need refuelling over their lifetime
- Where does the gas come from?
- Very little direct evidence observationally

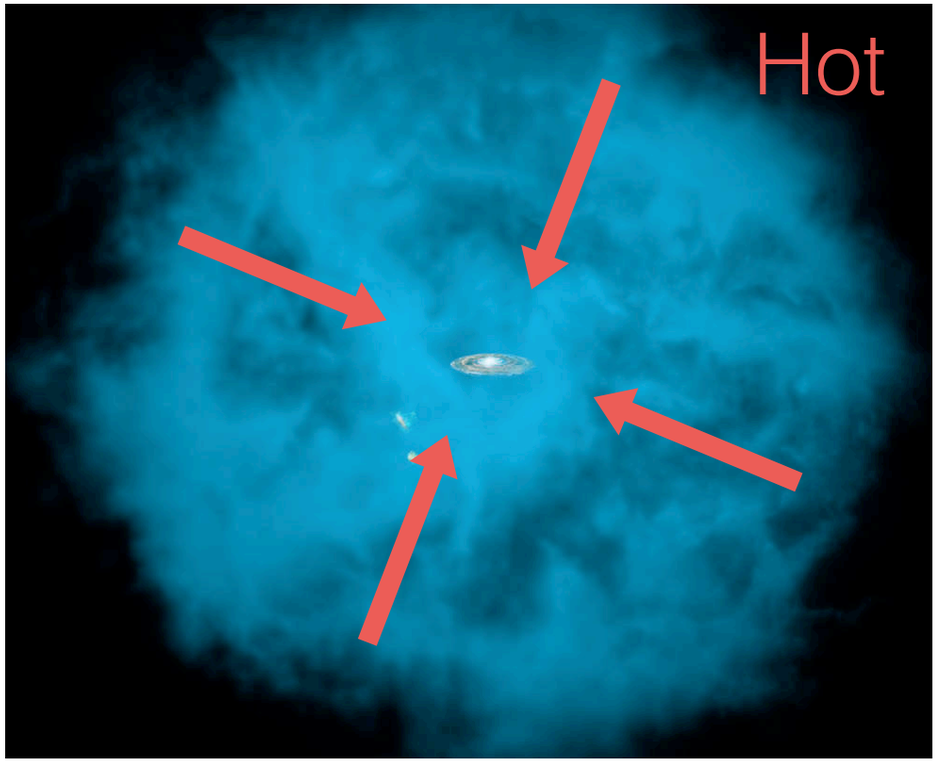
Forms of accretion

- Many simulations predict that gas is accreted by galaxies in two forms (e.g. Birnboim & Dekel 2003, Keres et al. 2005, 2009).

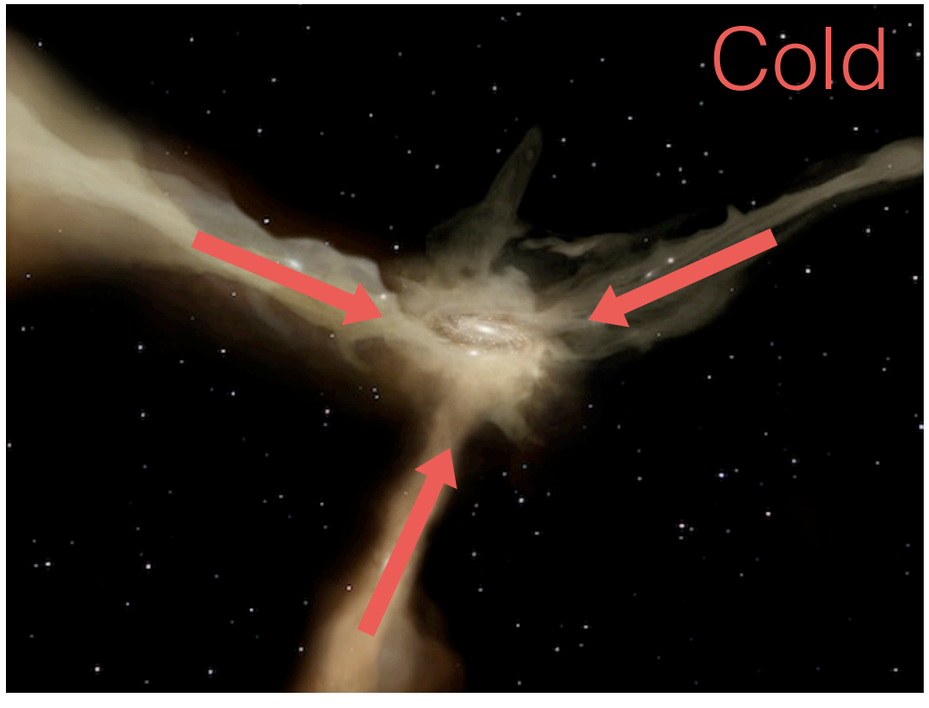
- Hot accretion flows are gas that is shock-heated to the virial temperature; $T > 10^5$ K

- Cold accretion flows remain below T_{vir}, $< 10^5$ K, and falls onto galaxy along filaments.

- At z=0, cold mode should be dominant for $M_{halo} \leq 10^{11} M_\odot$ and in low density environments.



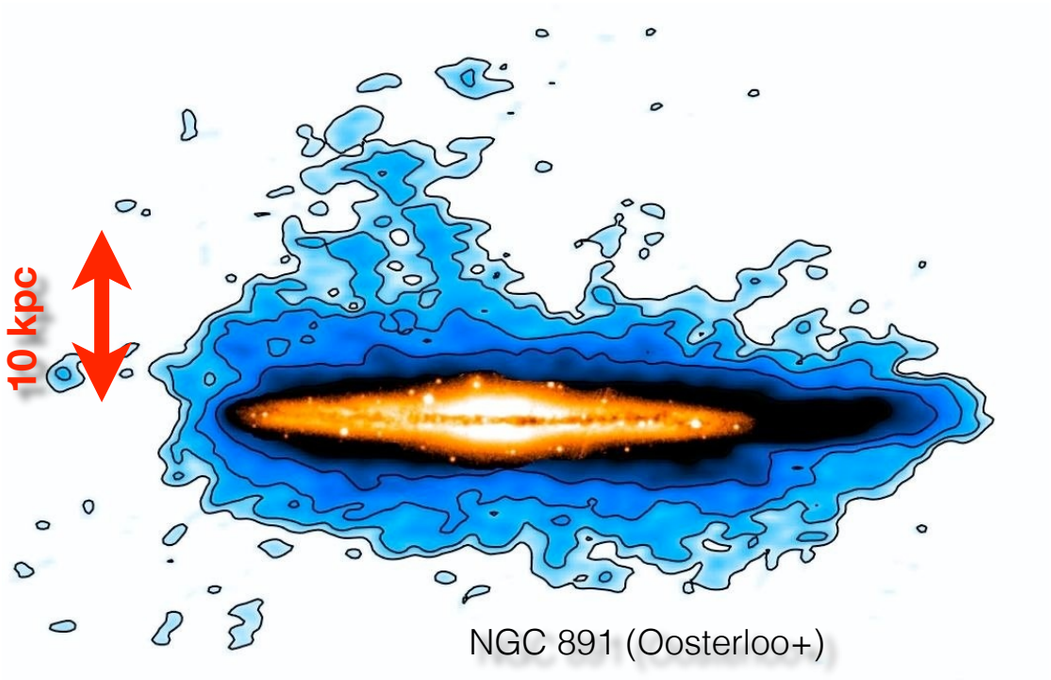
Credits: NASA/CXC/M.Weiss/Ohio State/A Gupta et al

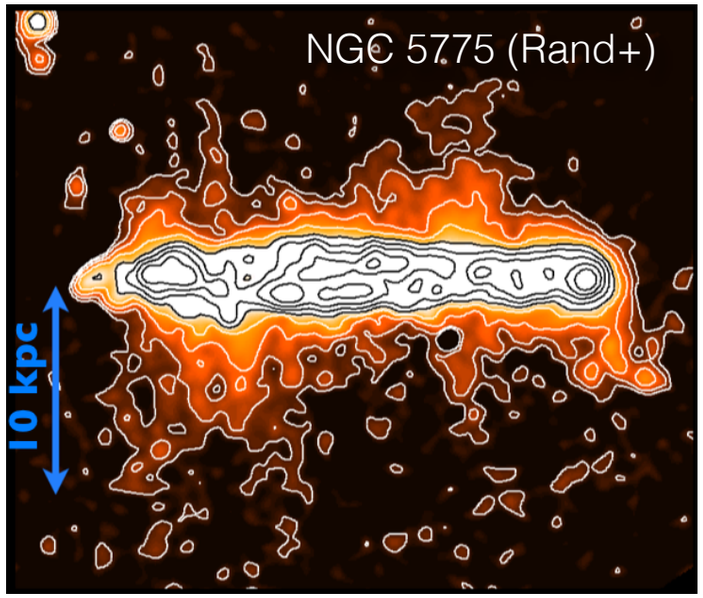


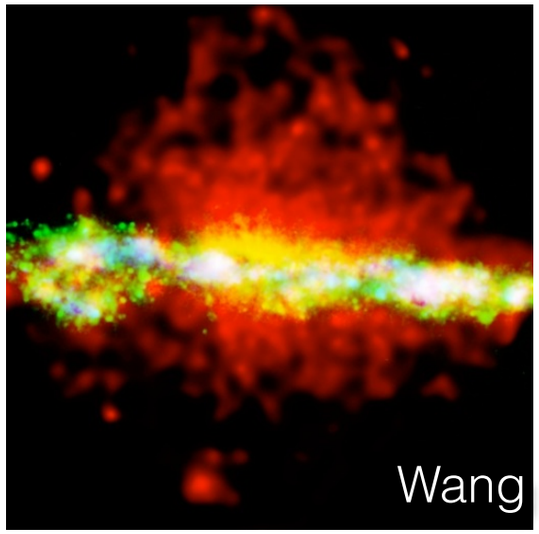
Credit: ESA-AOES Medialab

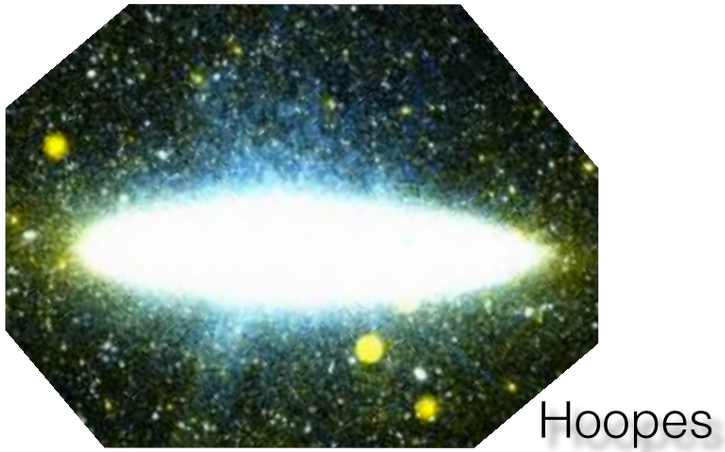
Multi-phase extraplanar gas

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





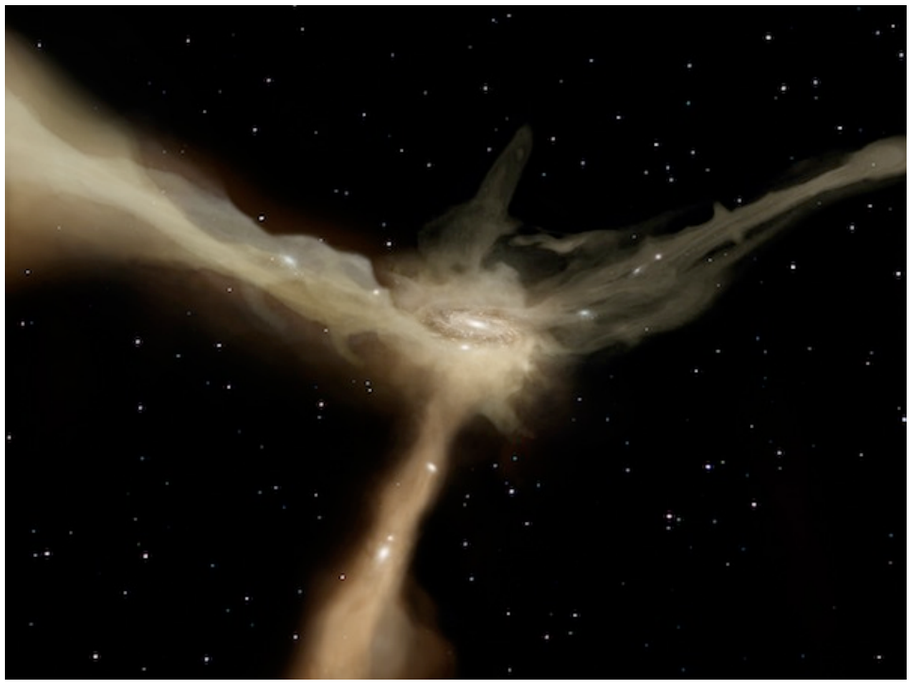




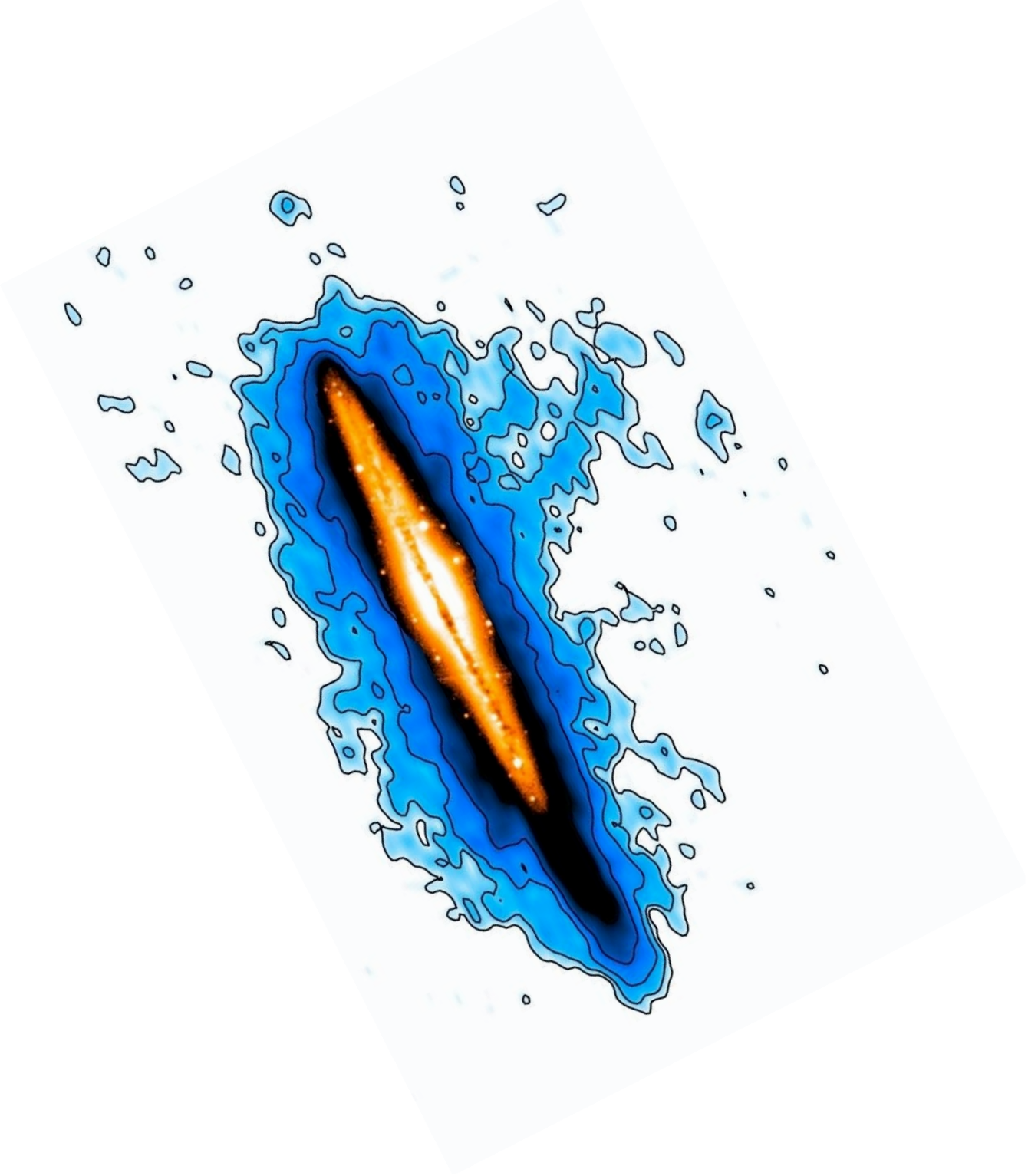
This talk

Questions:

- What is the nature of extra-planar gas in galaxies
- What is the importance of (cold) accretion and can we detect it



(ESA-AOES Medialab)



NGC 891 (Oosterloo+)

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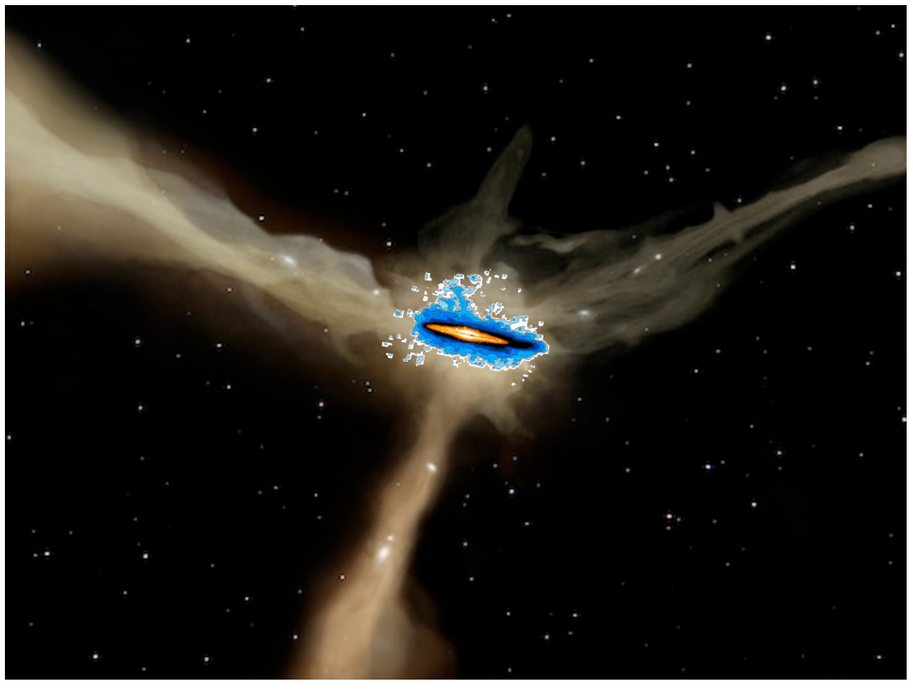

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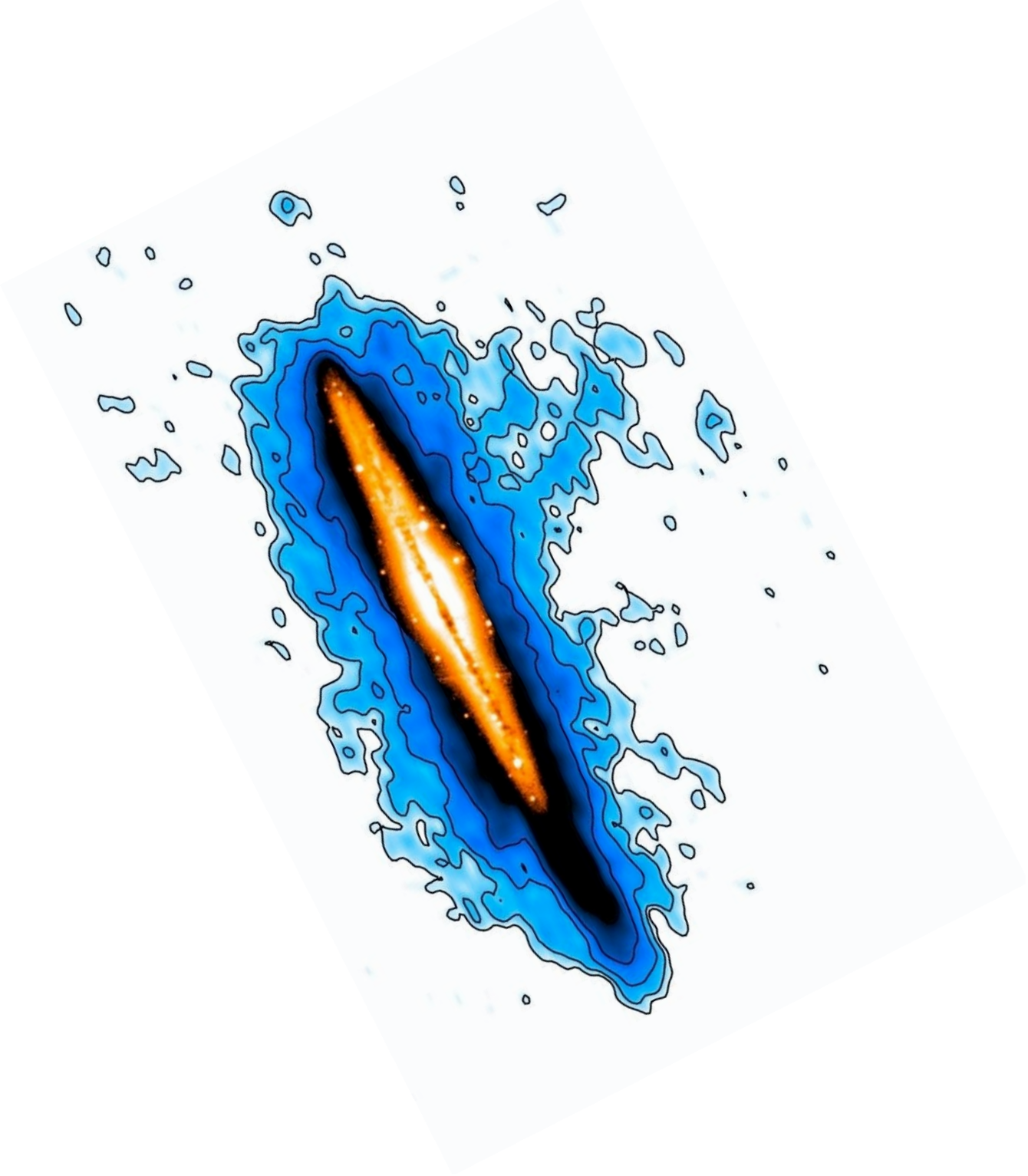

NGC 891 (Oosterloo+)

This talk

Questions:

- What is the nature of extra-planar gas in galaxies
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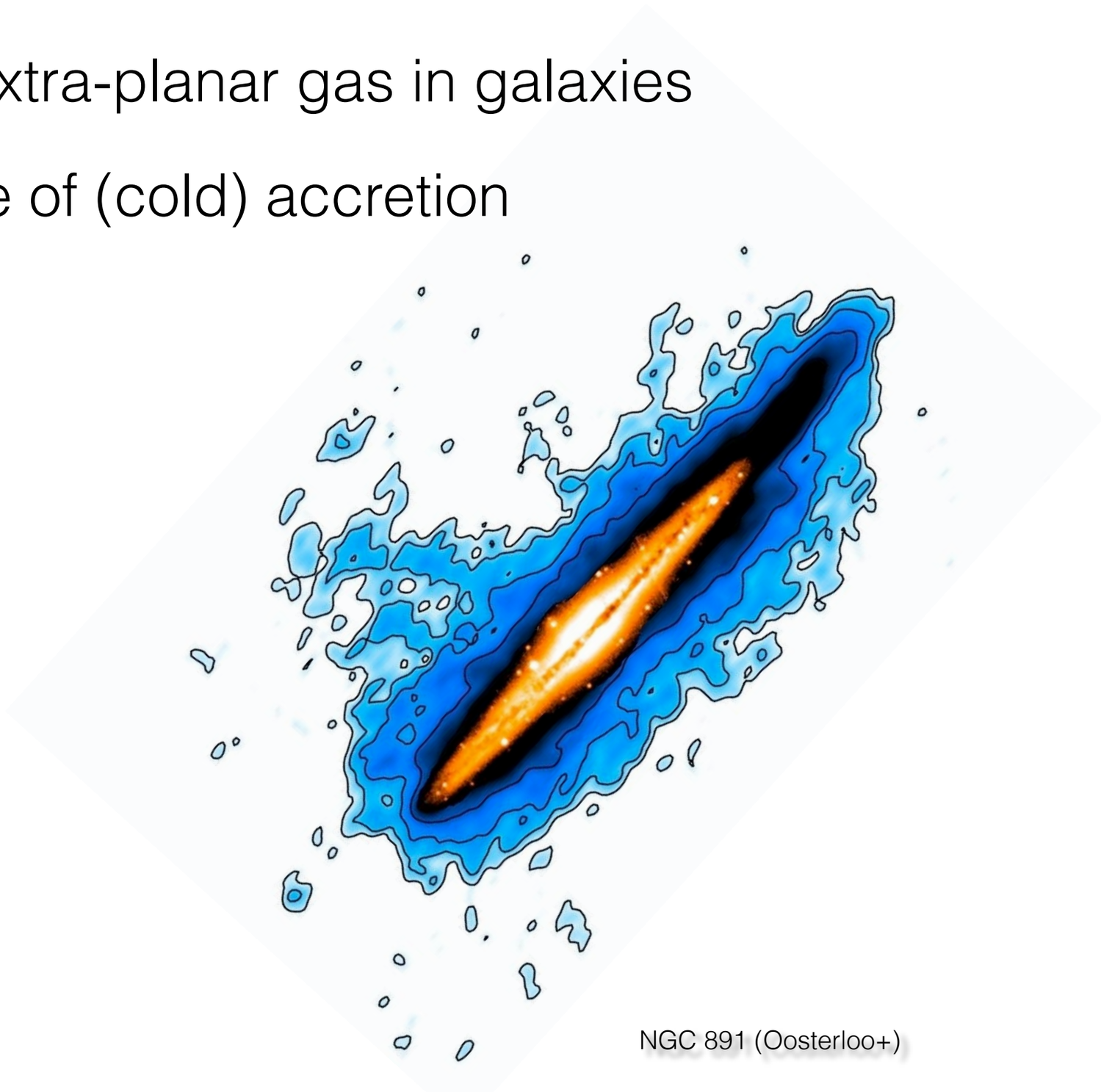
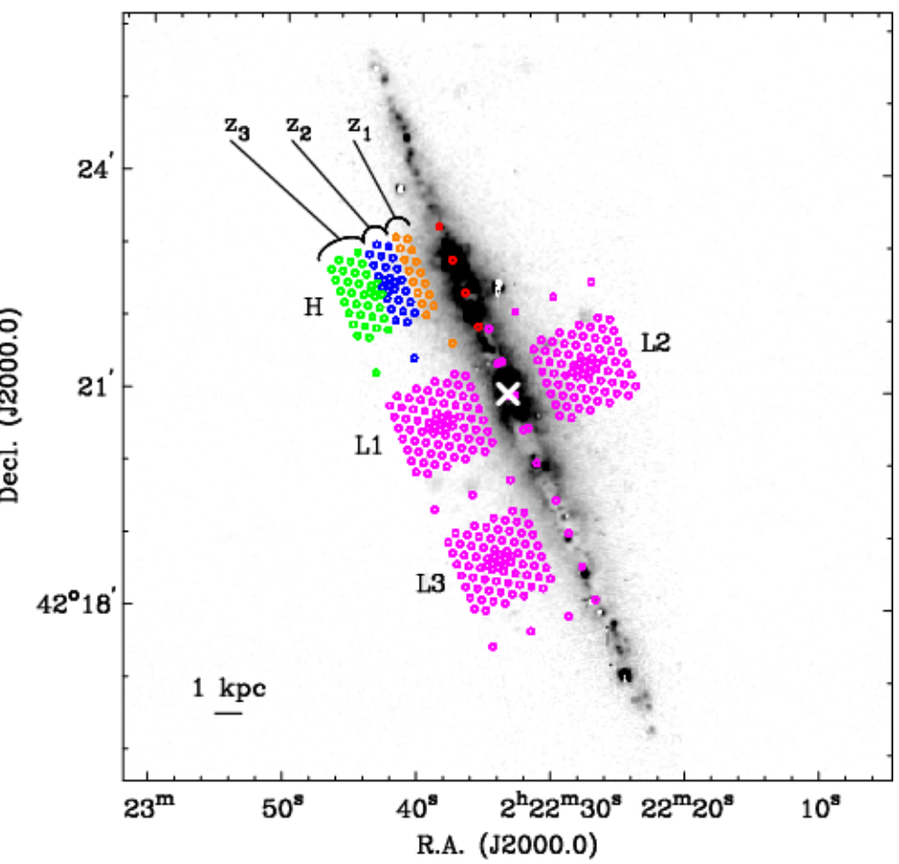
This talk

- HALOGAS (deep WSRT)
- GBT THINGS/HALOGAS
- Future surveys

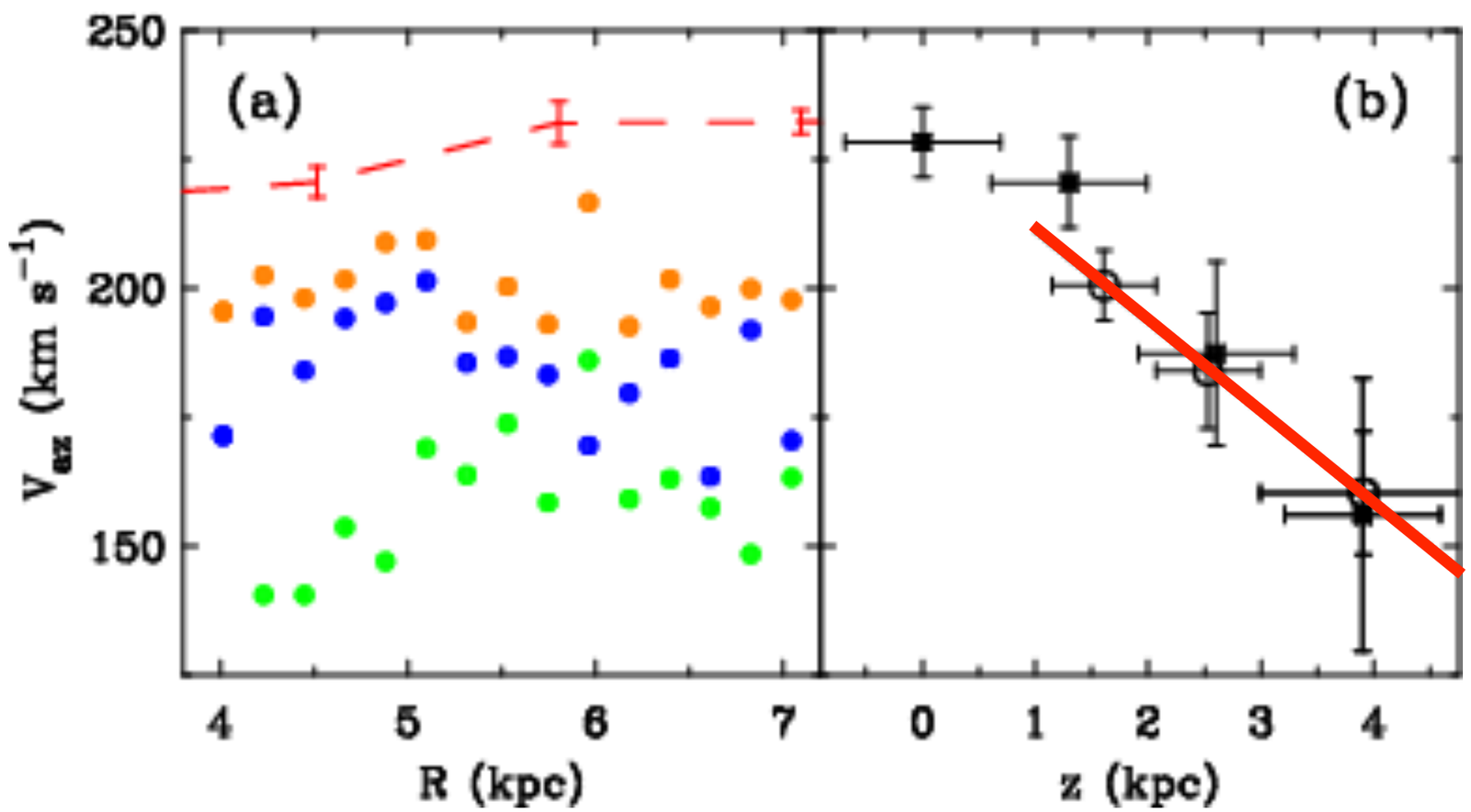


Extraplanar kinematics

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

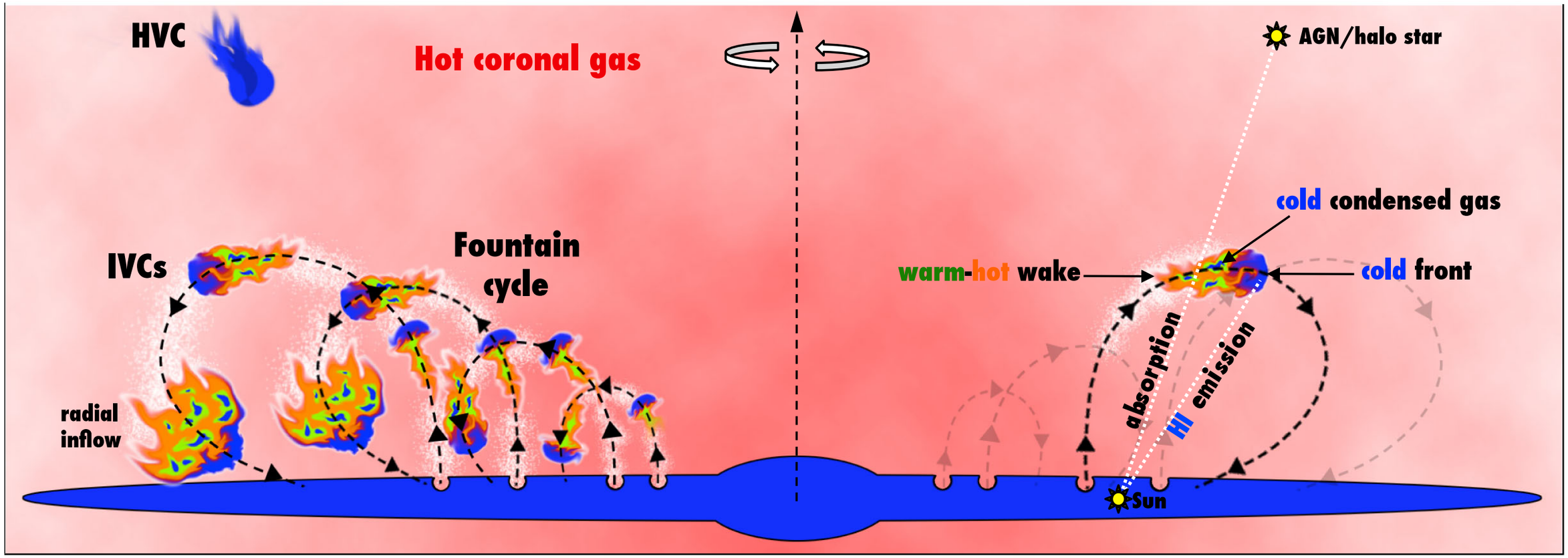


Heald et al. (2007)



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

Understanding extraplanar gas



Marasco et al 2013

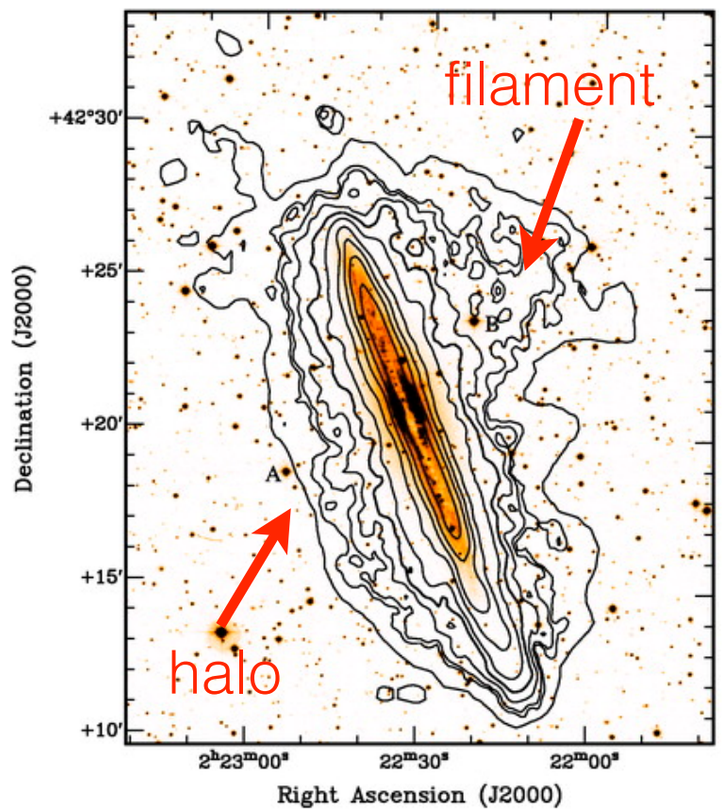
Origin thought to be a mixture of galactic fountain / chimney

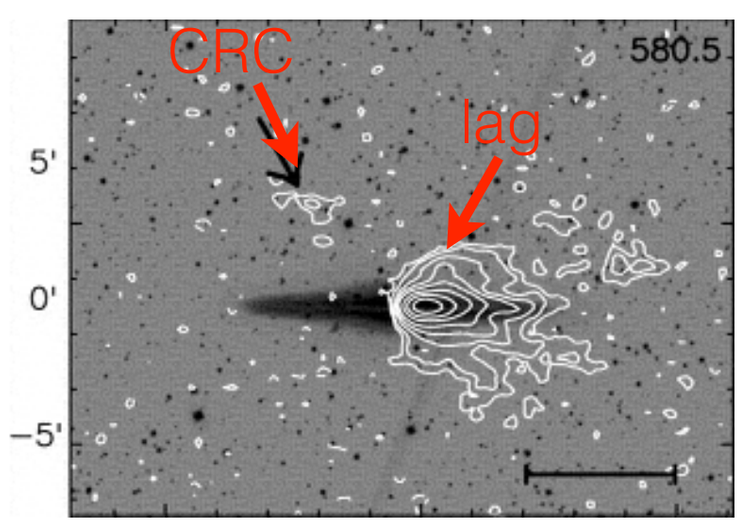
Can these disks also give us evidence for accretion?

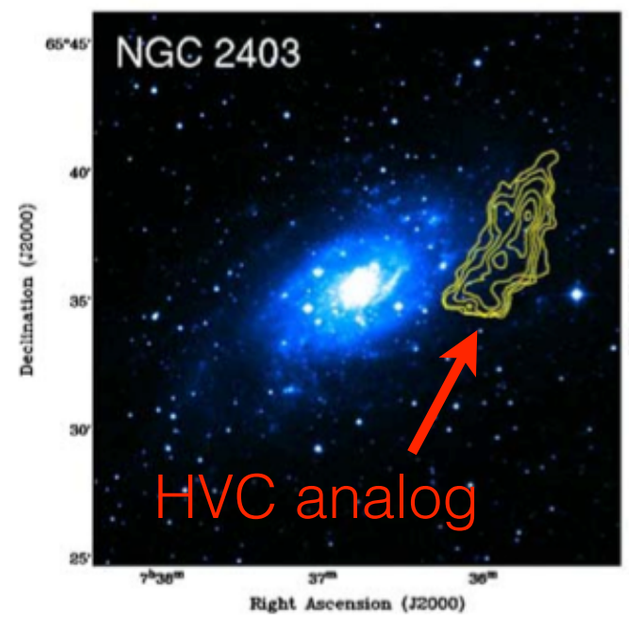
HALOGAS: Scientific motivation

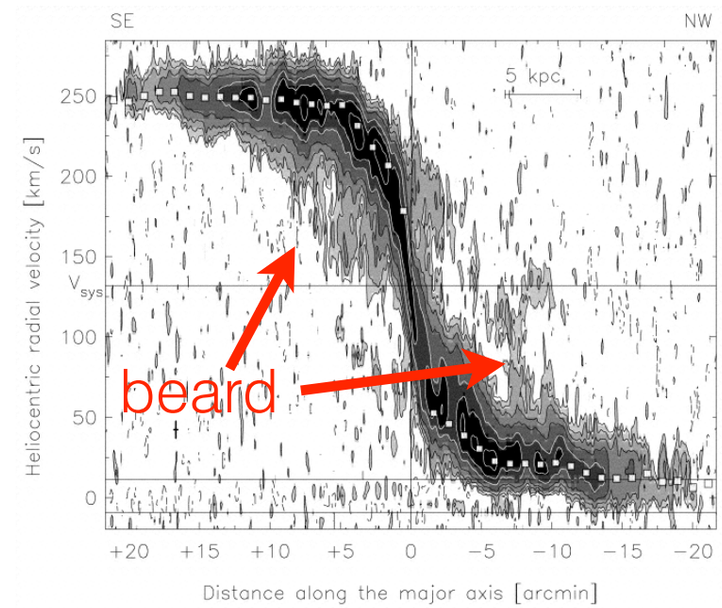
How many nearby spiral galaxies show features like these?

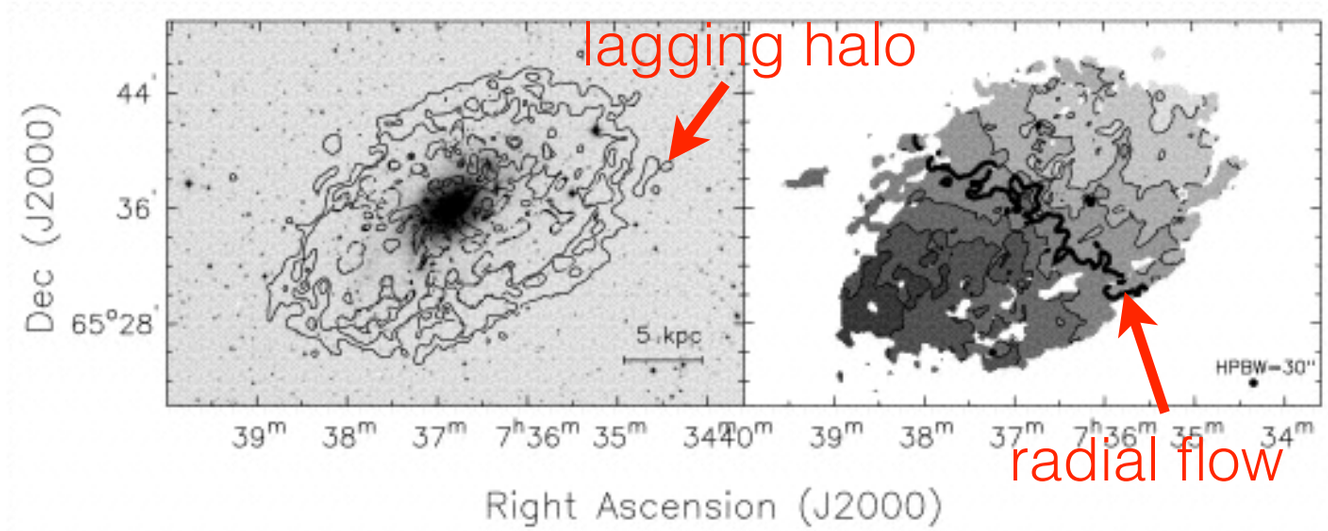
Oosterloo et al. (2007)











Fraternali et al. (2002)

HALOGAS: Scientific motivation

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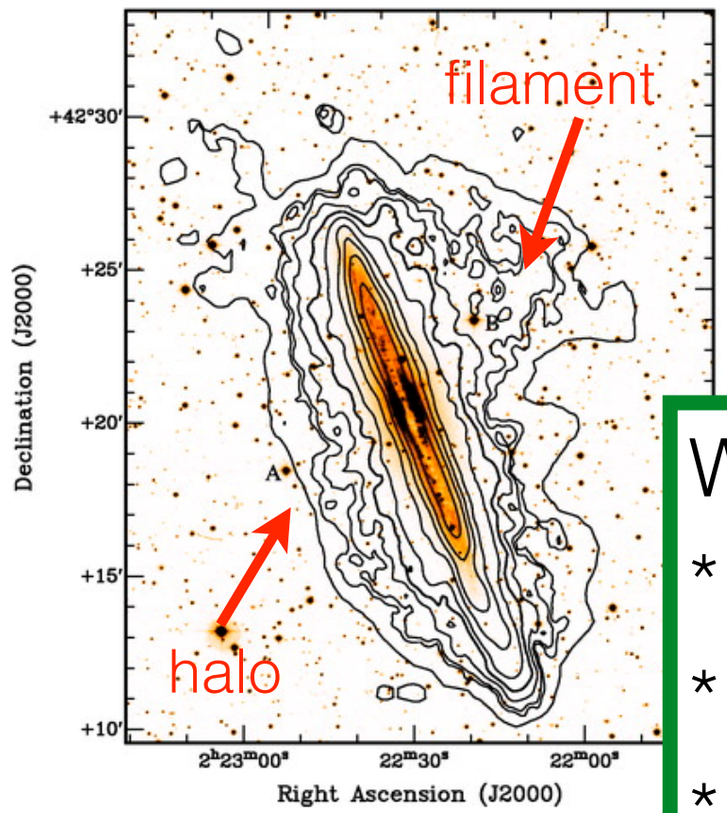

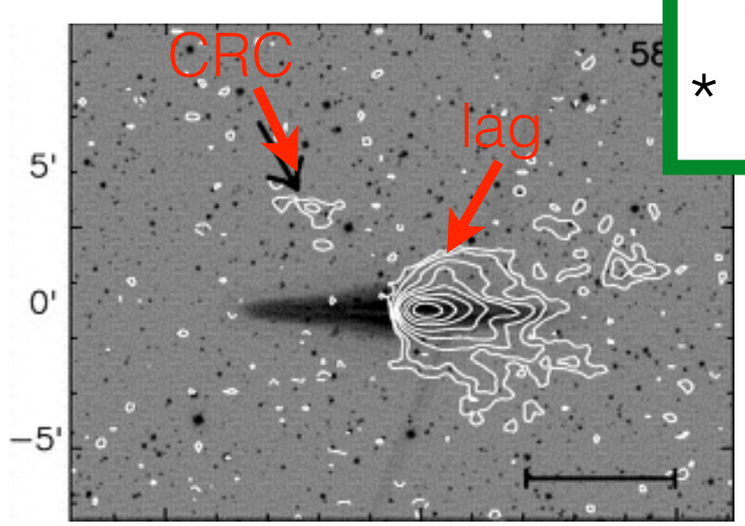

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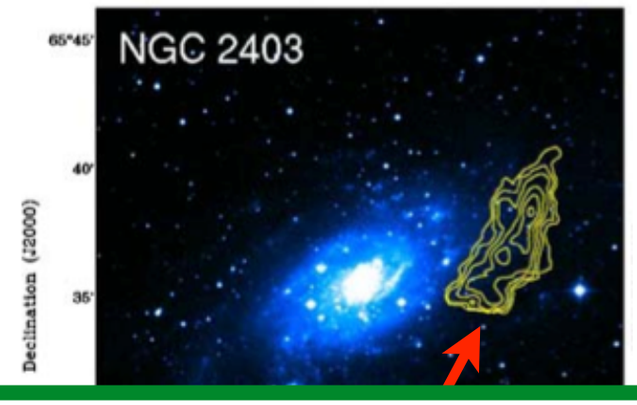
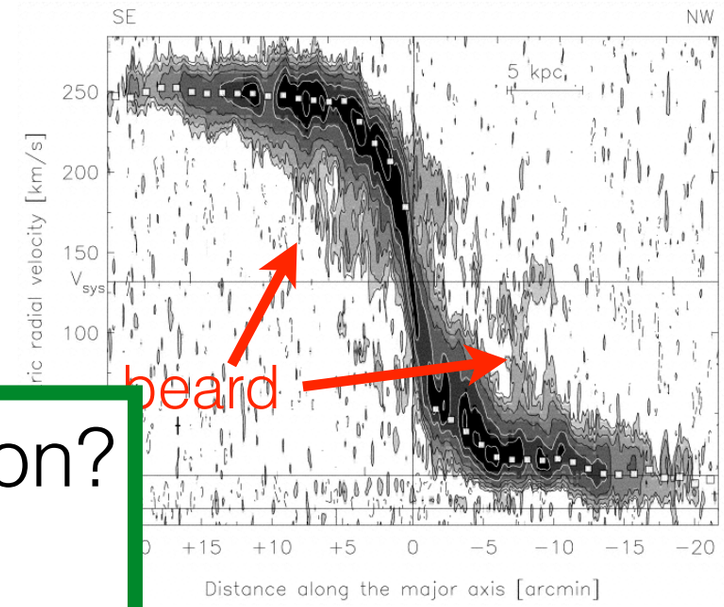
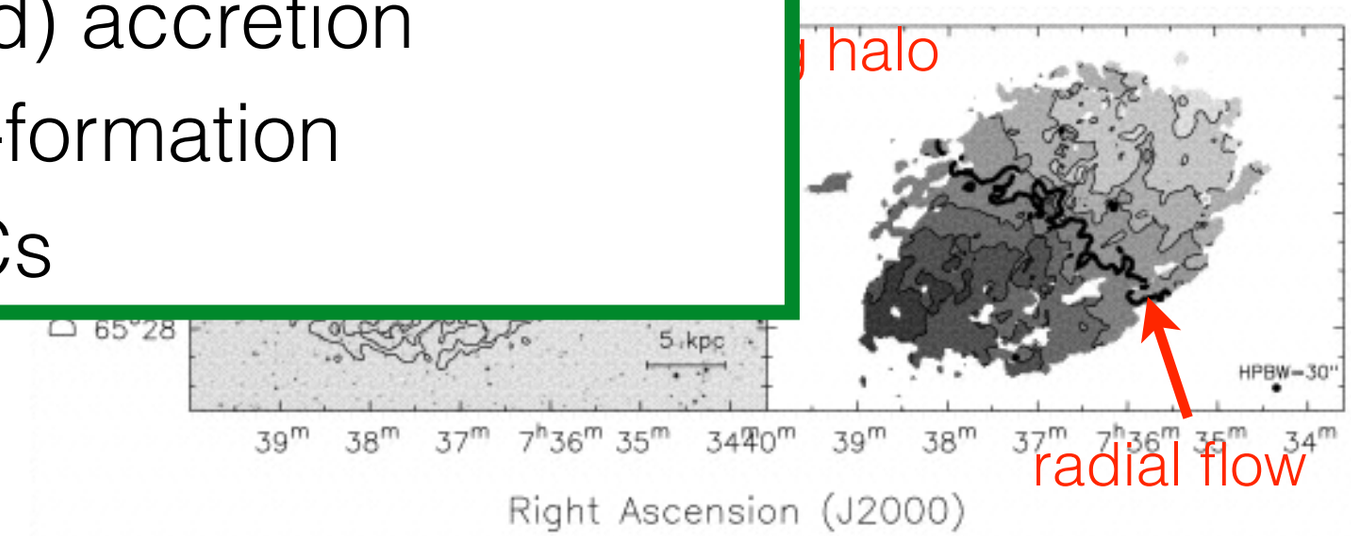




What is their interpretation?

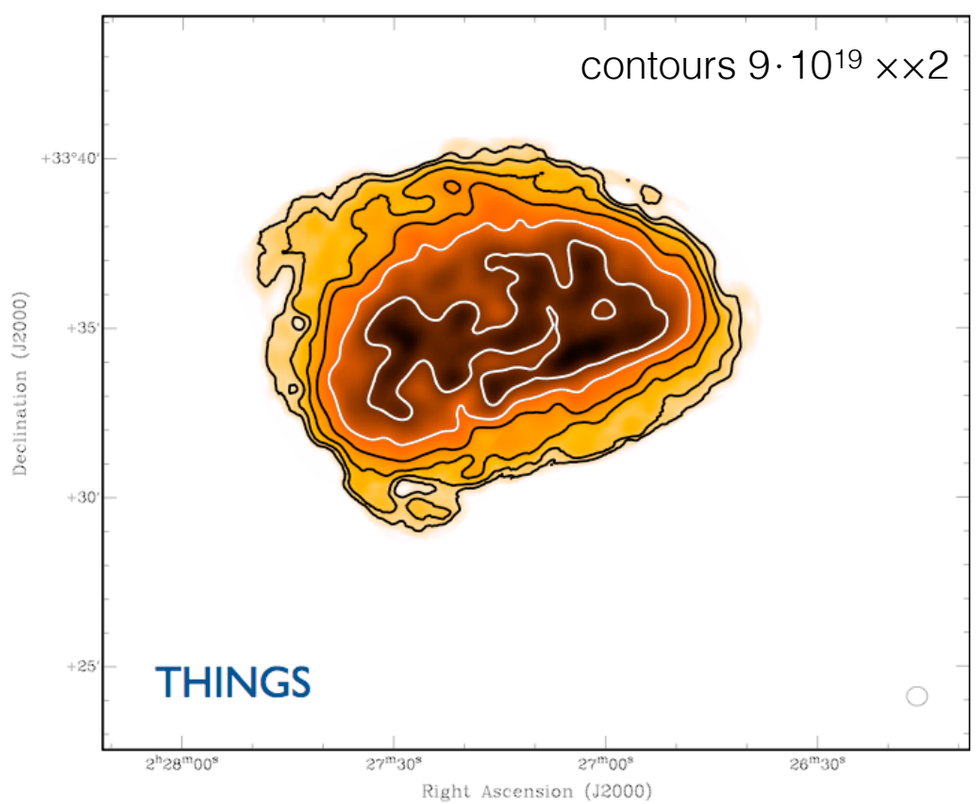
* interactions
* (cold) accretion
* star-formation
* HVCs

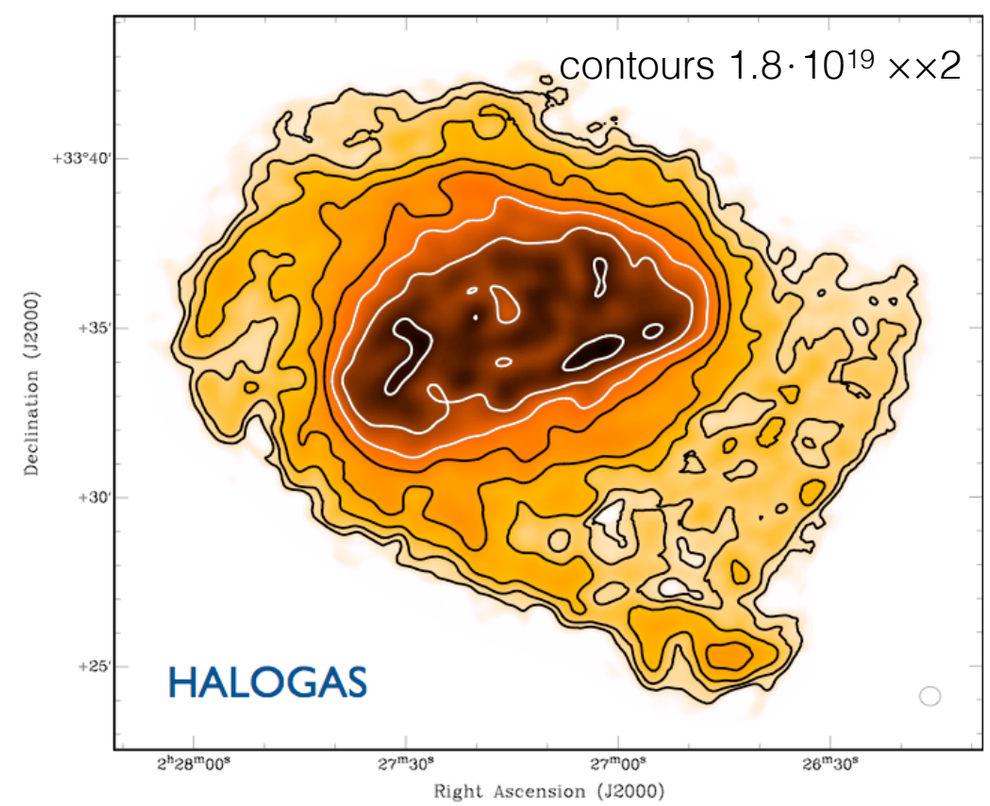


Fraternali et al. (2002)

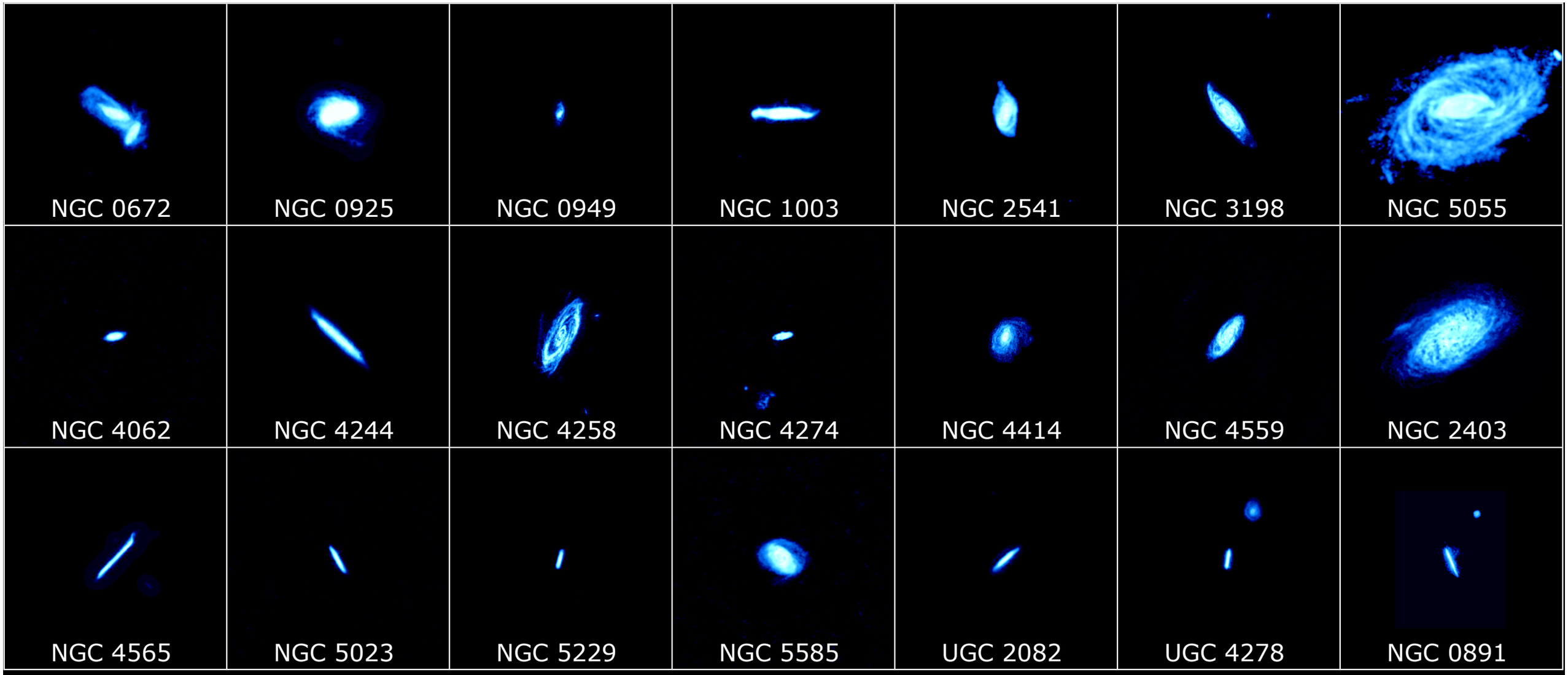
HALOGAS: WSRT observations

- PI George Heald (Heald et al 2011)
- 10 ×12h per target, to reach N_{HI} = **1x10^{19} cm^{-2}** (3σ, 16 km s^{-1}) at 30" resolution (cf. THINGS: 5x10^{19} cm^{-2})
- unresolved cloud mass sensitivity of **2.7x10^{5}** (D/10 Mpc)^{2} $M_{\odot}$
- Survey sample 24 galaxies (including NGC 891 & NGC 2403)
- Survey complete and summary papers in progress





HALOGAS Sample: Overview



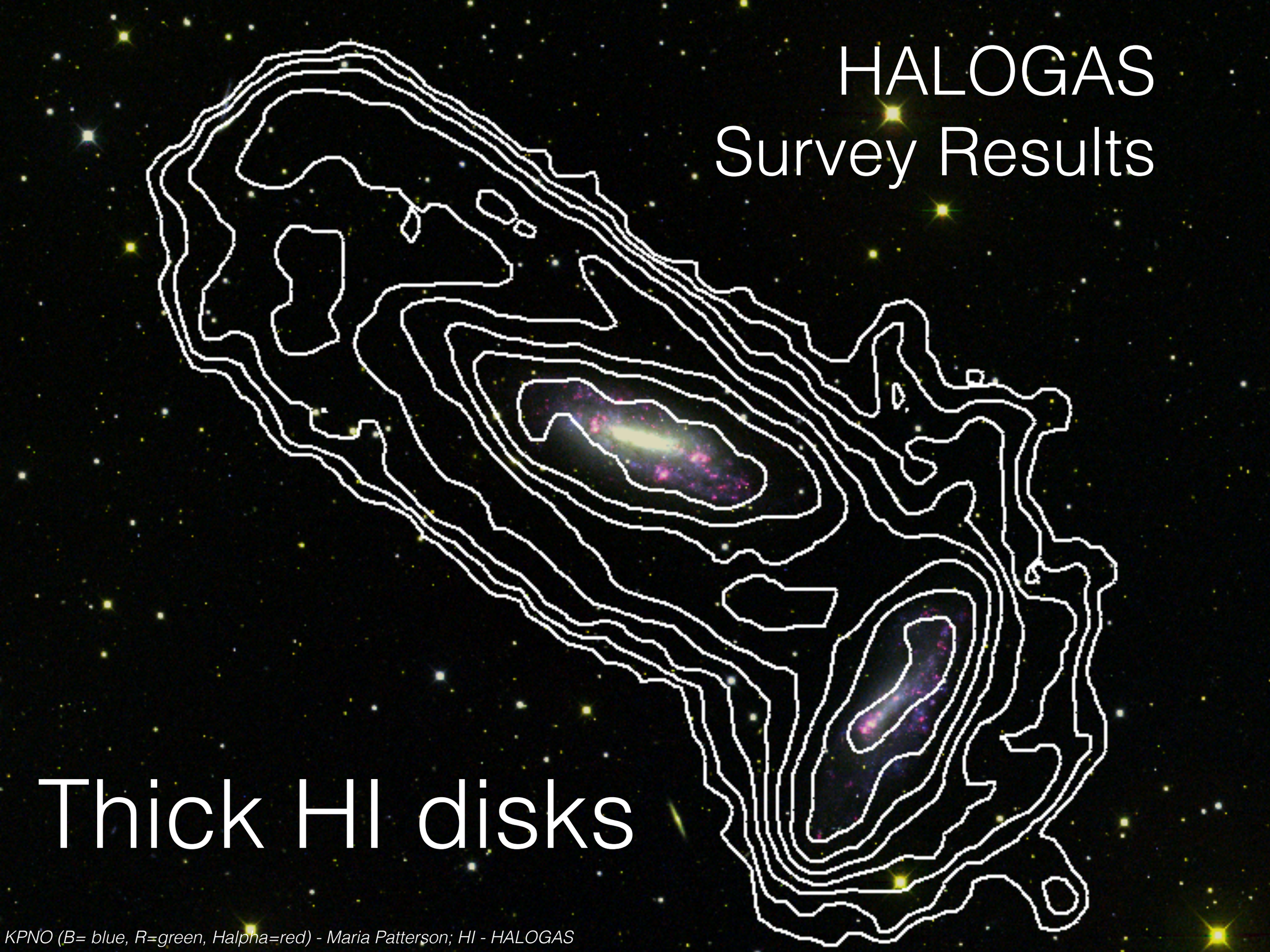
The WSRT HALOGAS Survey is the first systematic investigation of cold gas accretion in nearby spiral galaxies. It consists of deep (120 hours) WSRT observations of 22 edge-on and moderately-inclined nearby galaxies. Images of the galaxies are shown here, at the same angular scale. The HALOGAS Survey probes neutral hydrogen down to a column density of about 10^{19} cm^{-2}, and allows the characterisation of faint extra-planar and anomalous-velocity neutral gas with excellent spatial and velocity resolution. HALOGAS data reveal the presence of lagging thick-disk gas, and counterparts to the Milky Way's high velocity clouds. The data also allow us to study the disk structure and dynamics in unprecedented detail for a sample of this size.

ASTRON

Netherlands Institute for Radio Astronomy

G. Heald for the HALOGAS Team

HALOGAS
Survey Results

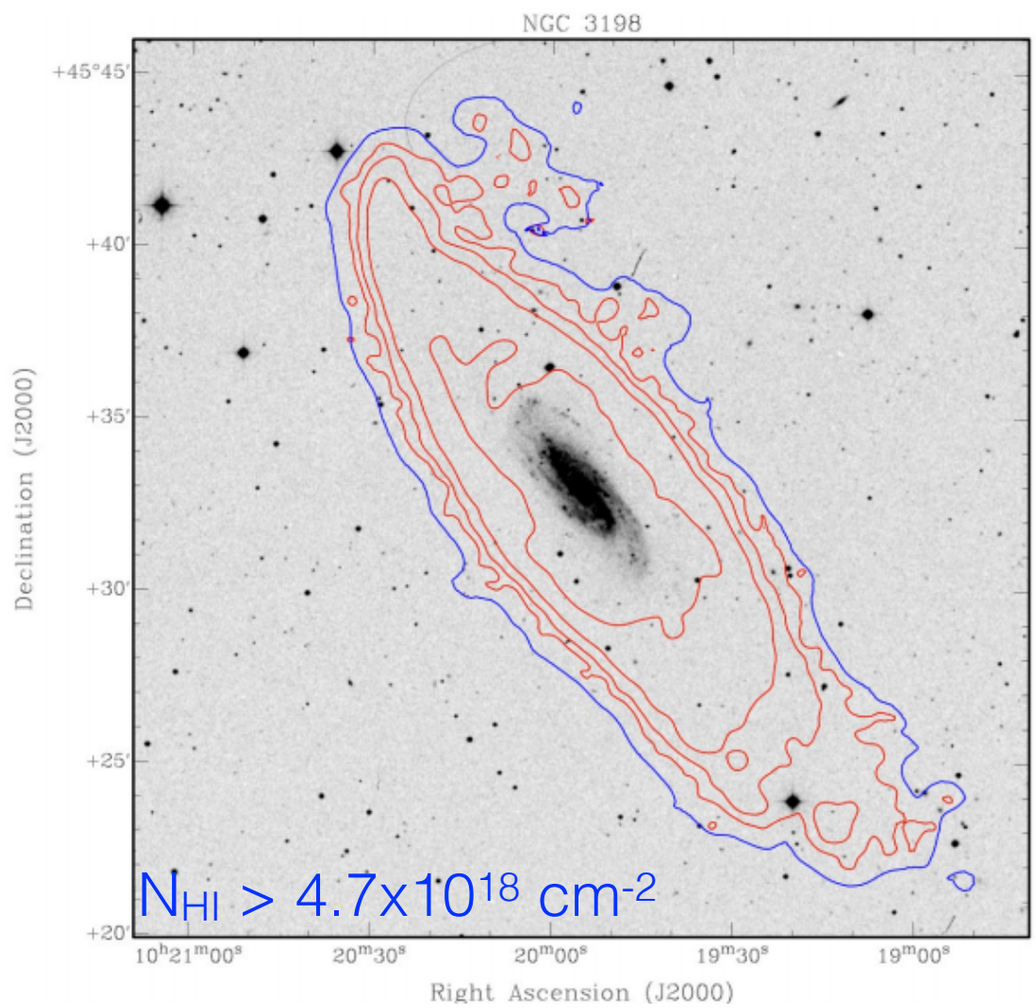


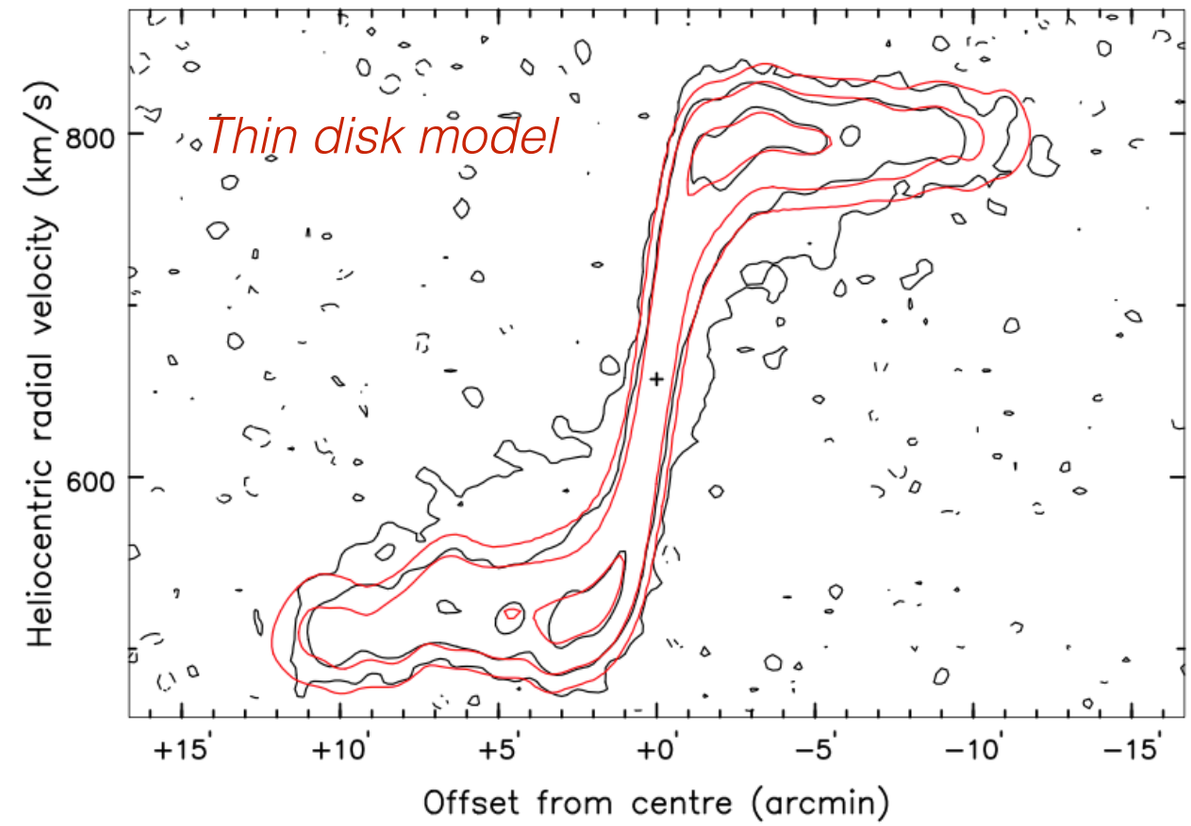
Thick HI disks

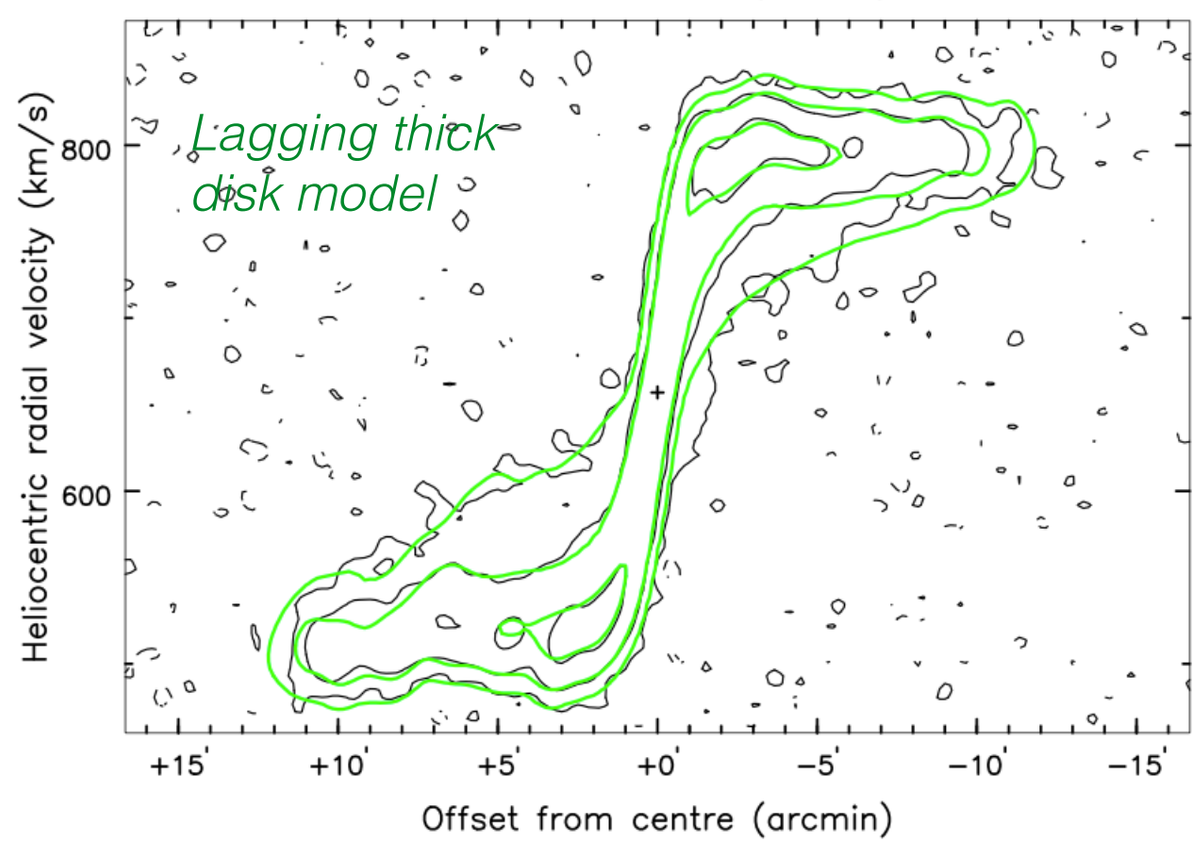
KPNO (B= blue, R=green, Halpha=red) - Maria Patterson; HI - HALOGAS

NGC 3198 (Gentile+ 2013)

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

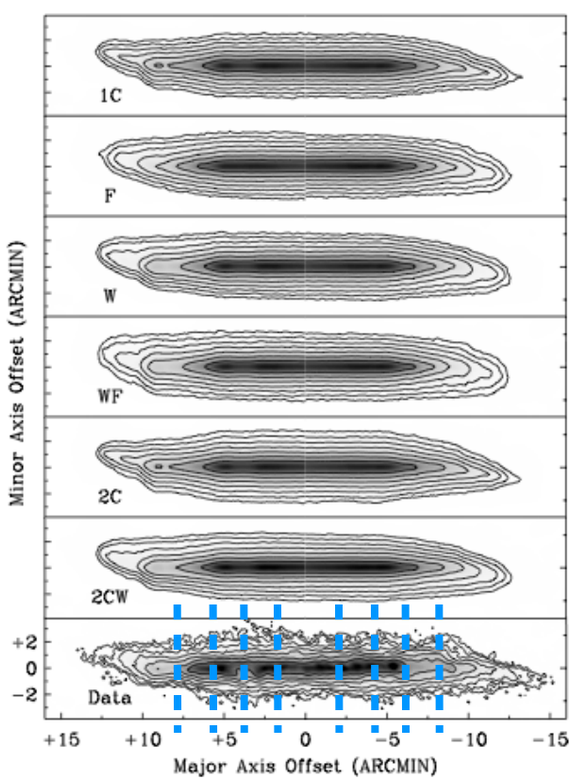


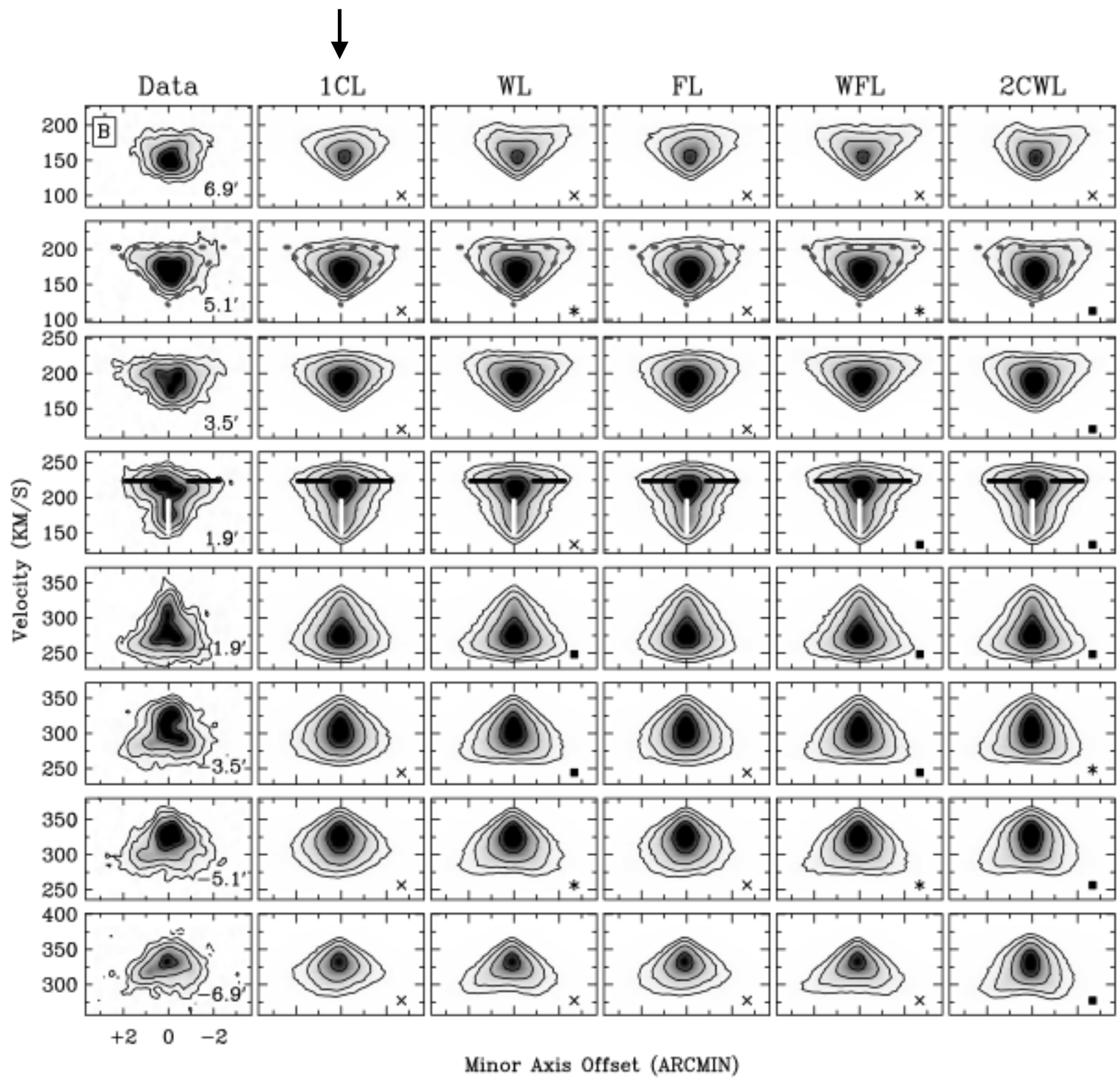




NGC 4244 (Zschaechner+ 2011)

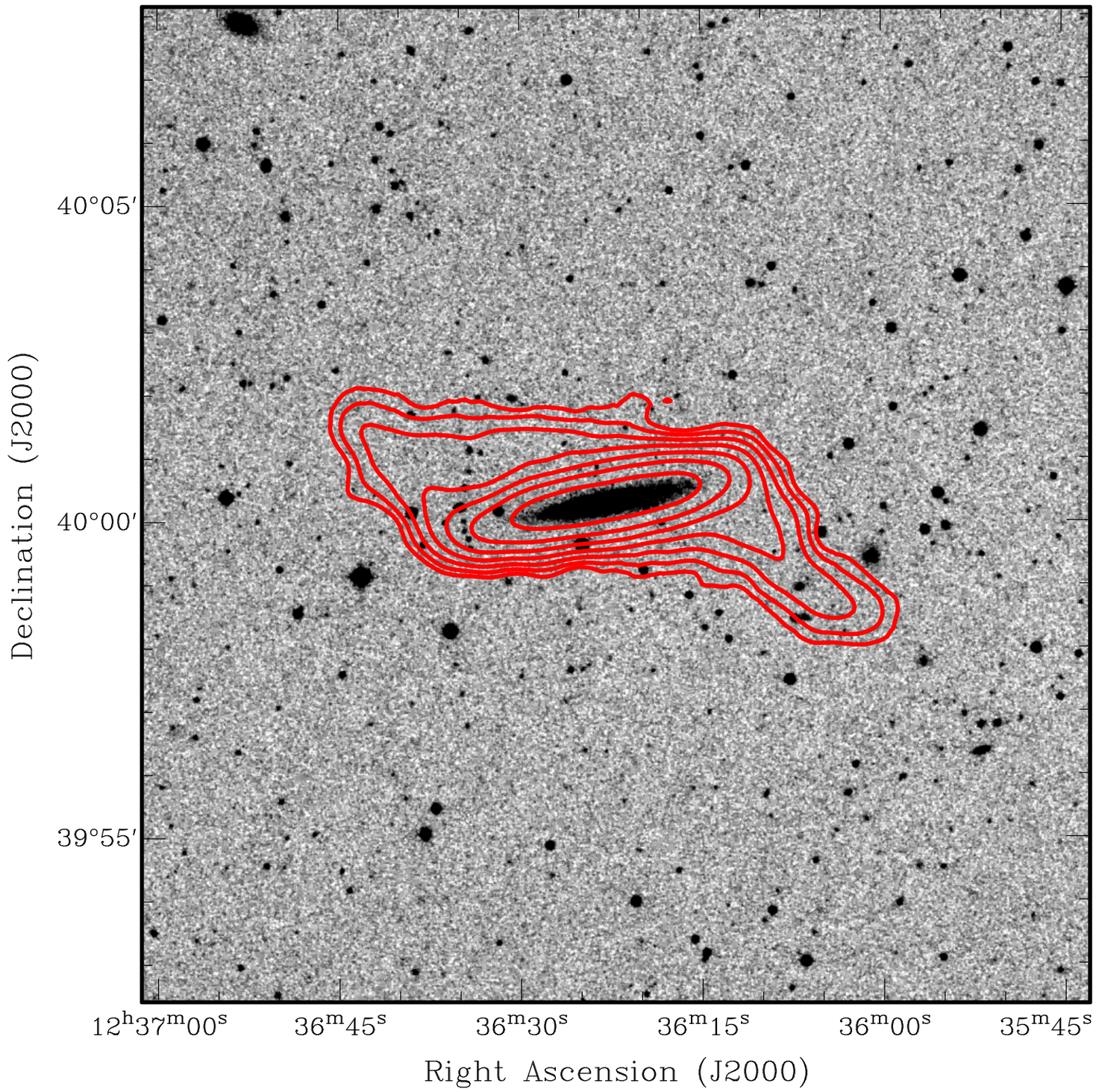
- Key results:
  - no halo - *surprisingly thin*
  - radially varying rotational lag ~9 km/s/kpc



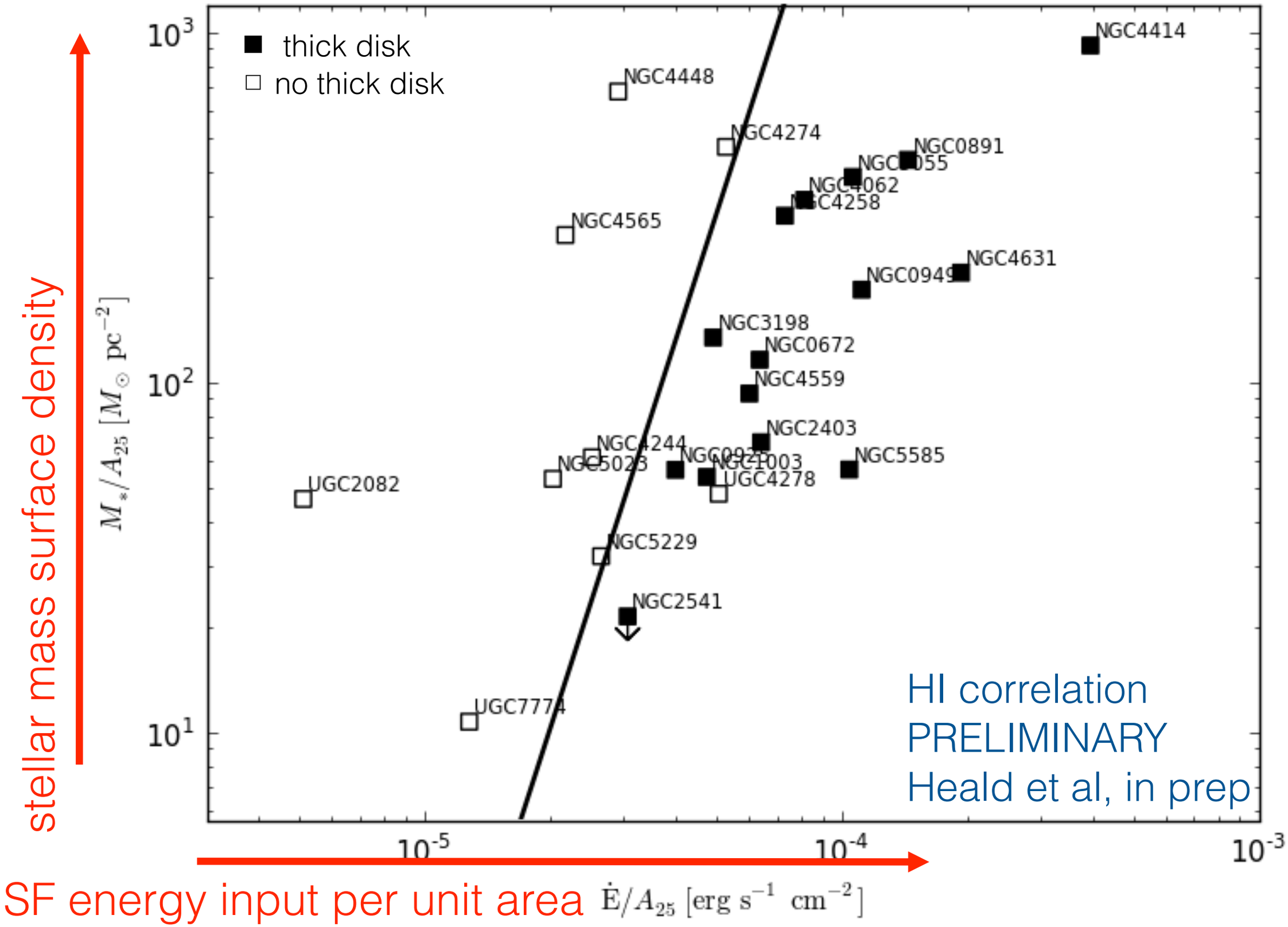


UGC 7774

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

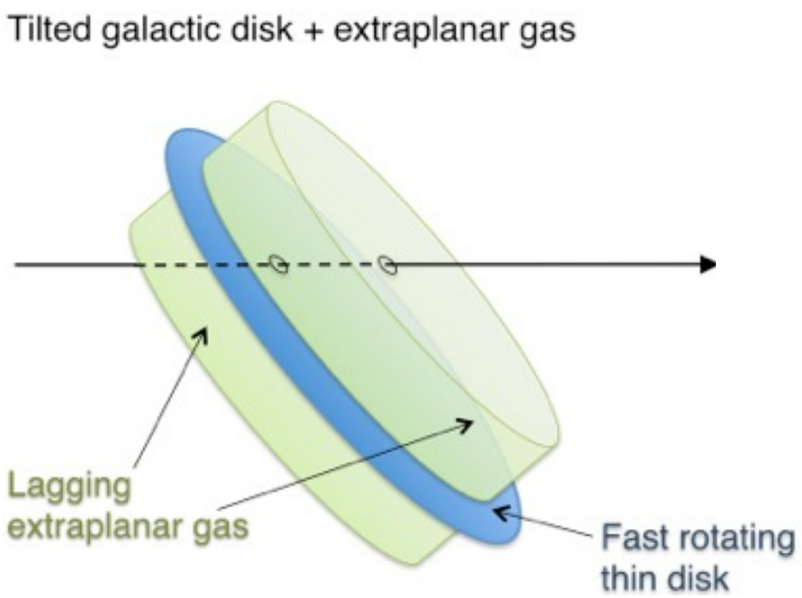


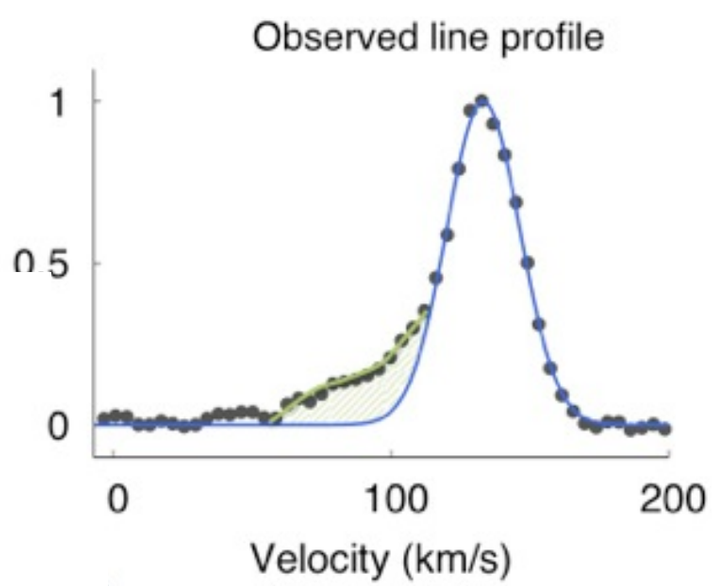
HI thick disks: correlations

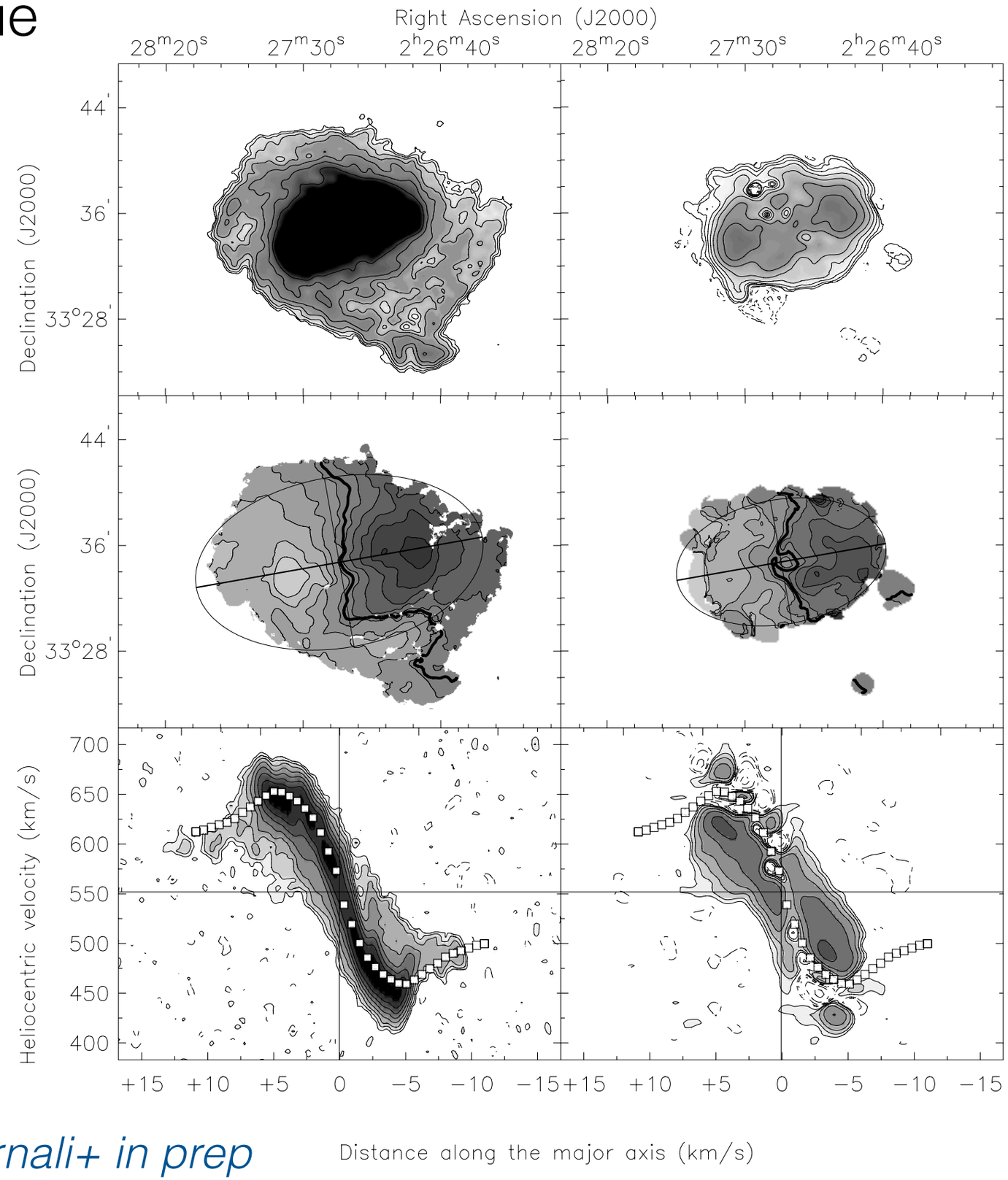


Quantifying HI thick disks

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



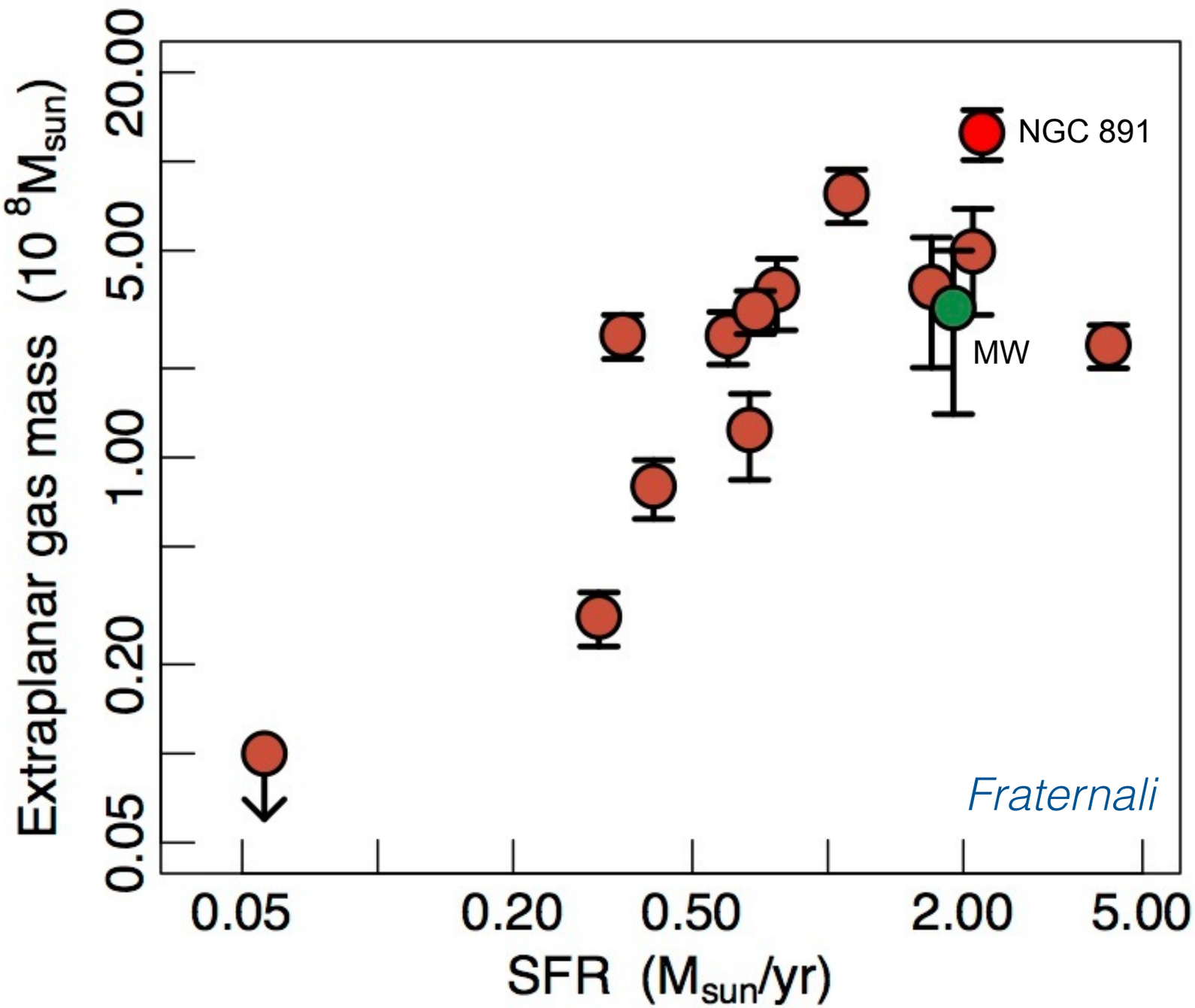




Fraternali+ in prep

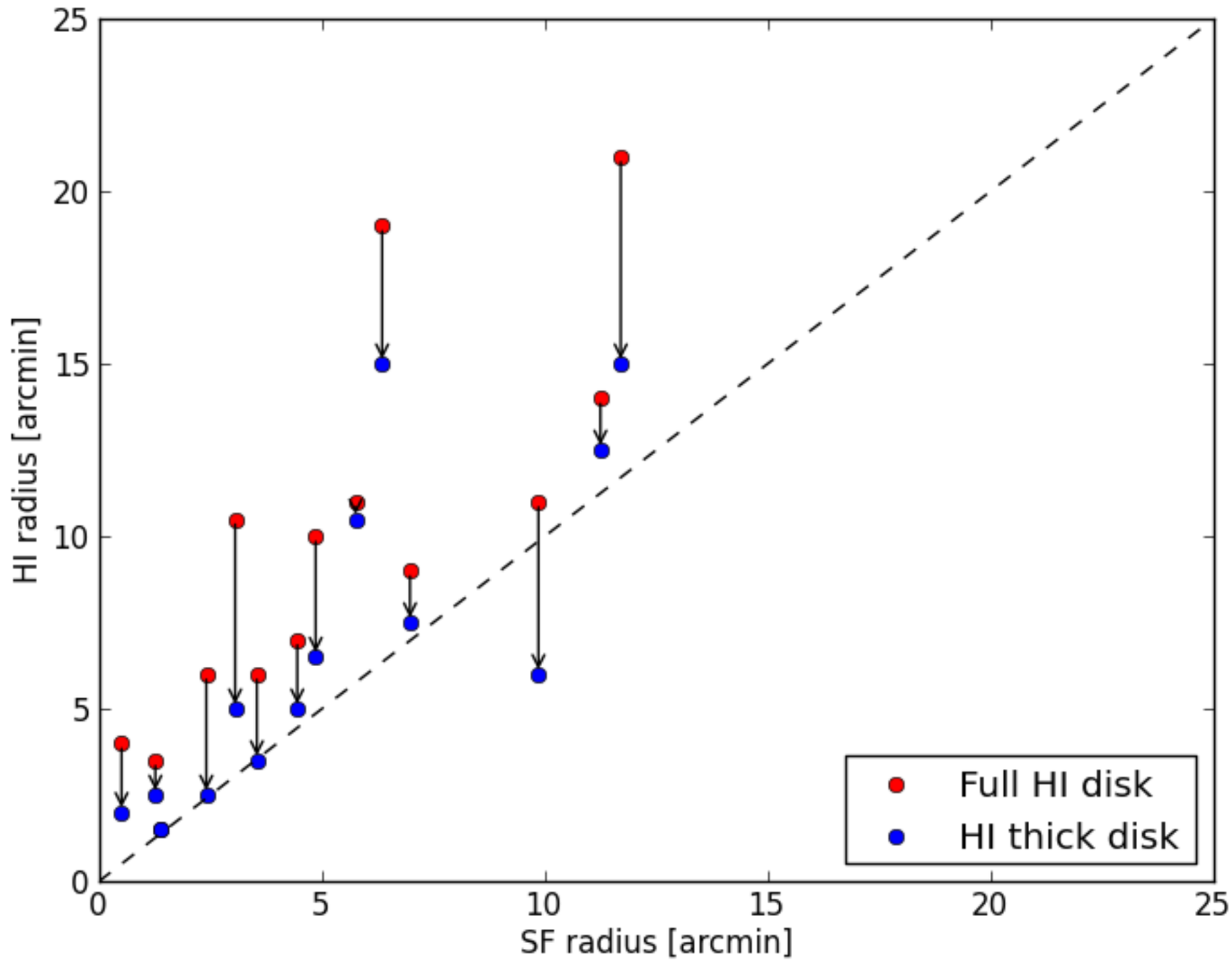
Quantifying HI thick disks

- 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 HI 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



Fraternali & Heald

Quantifying HI thick disks

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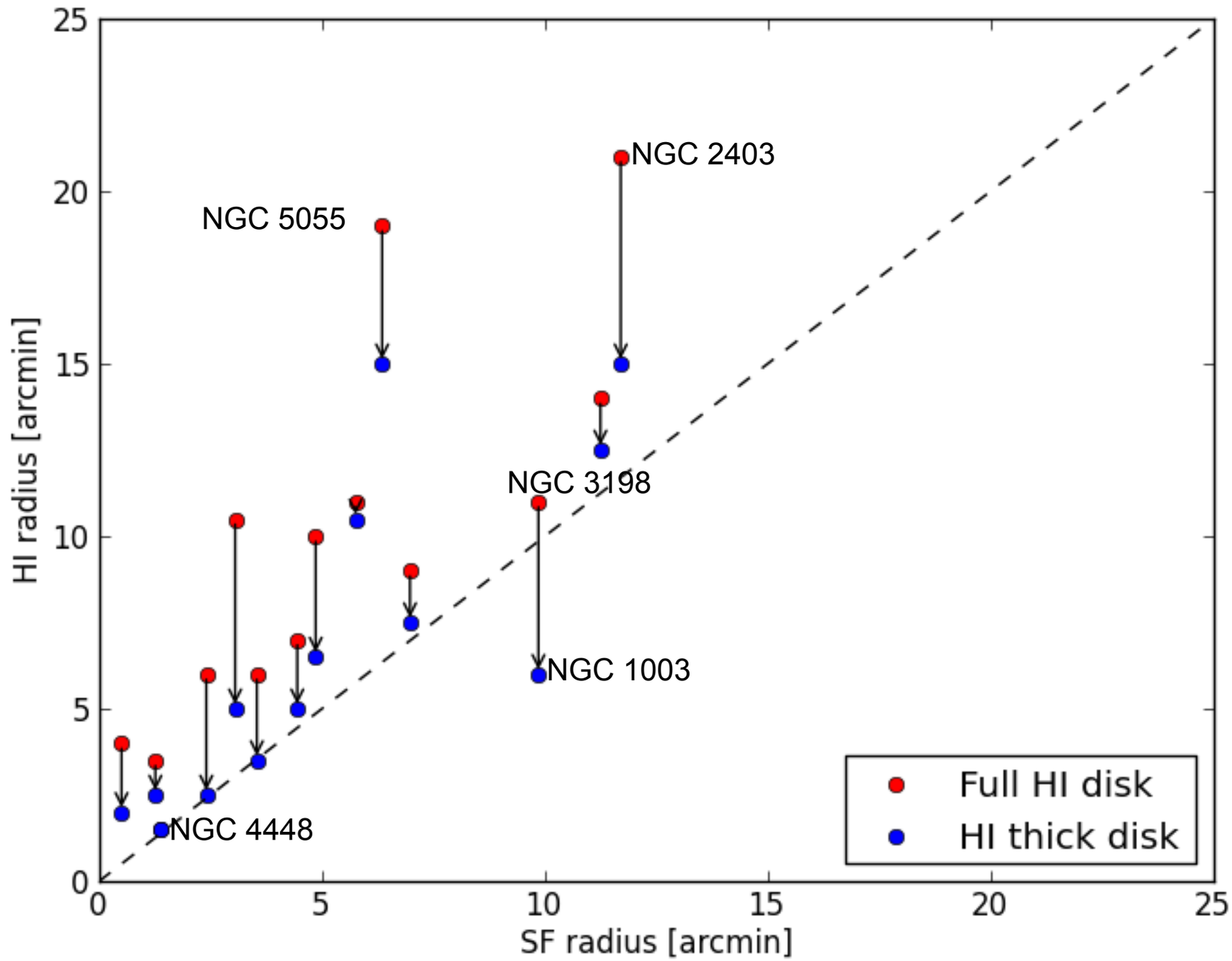
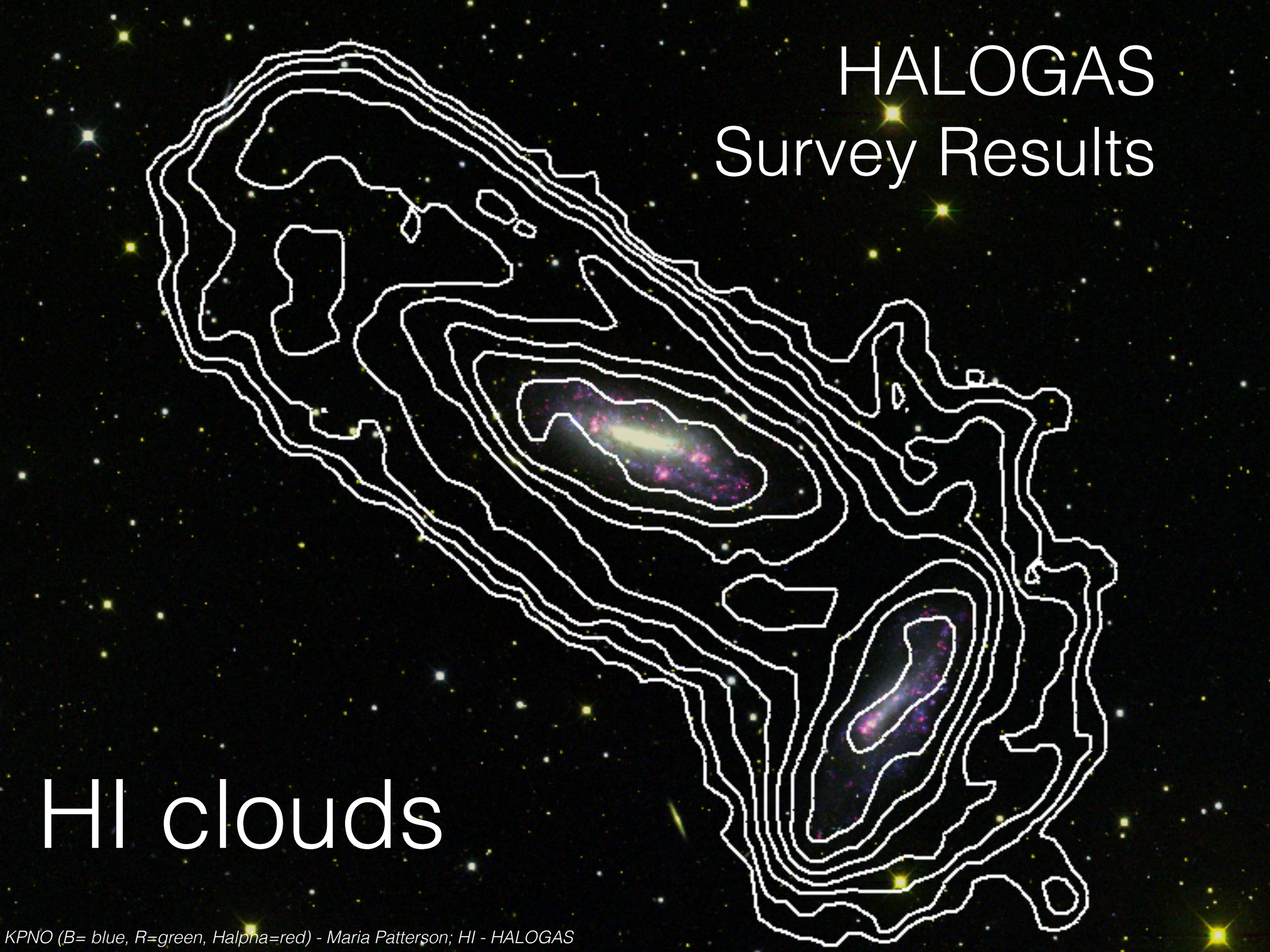


Fraternali & Heald

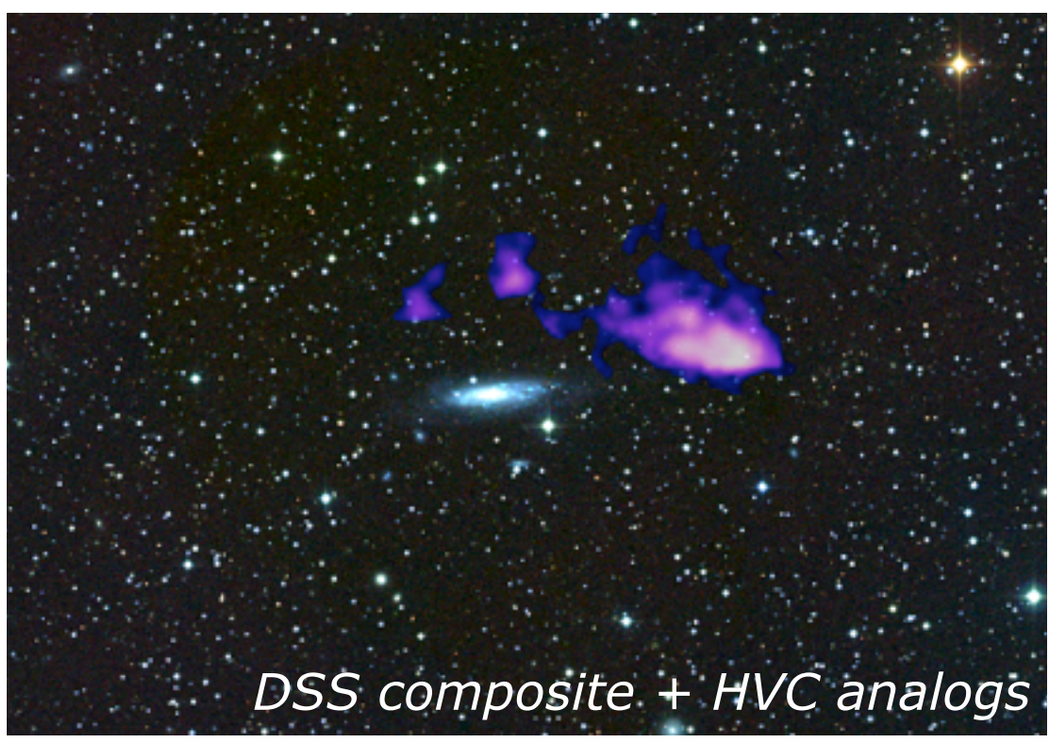
HALOGAS
Survey Results

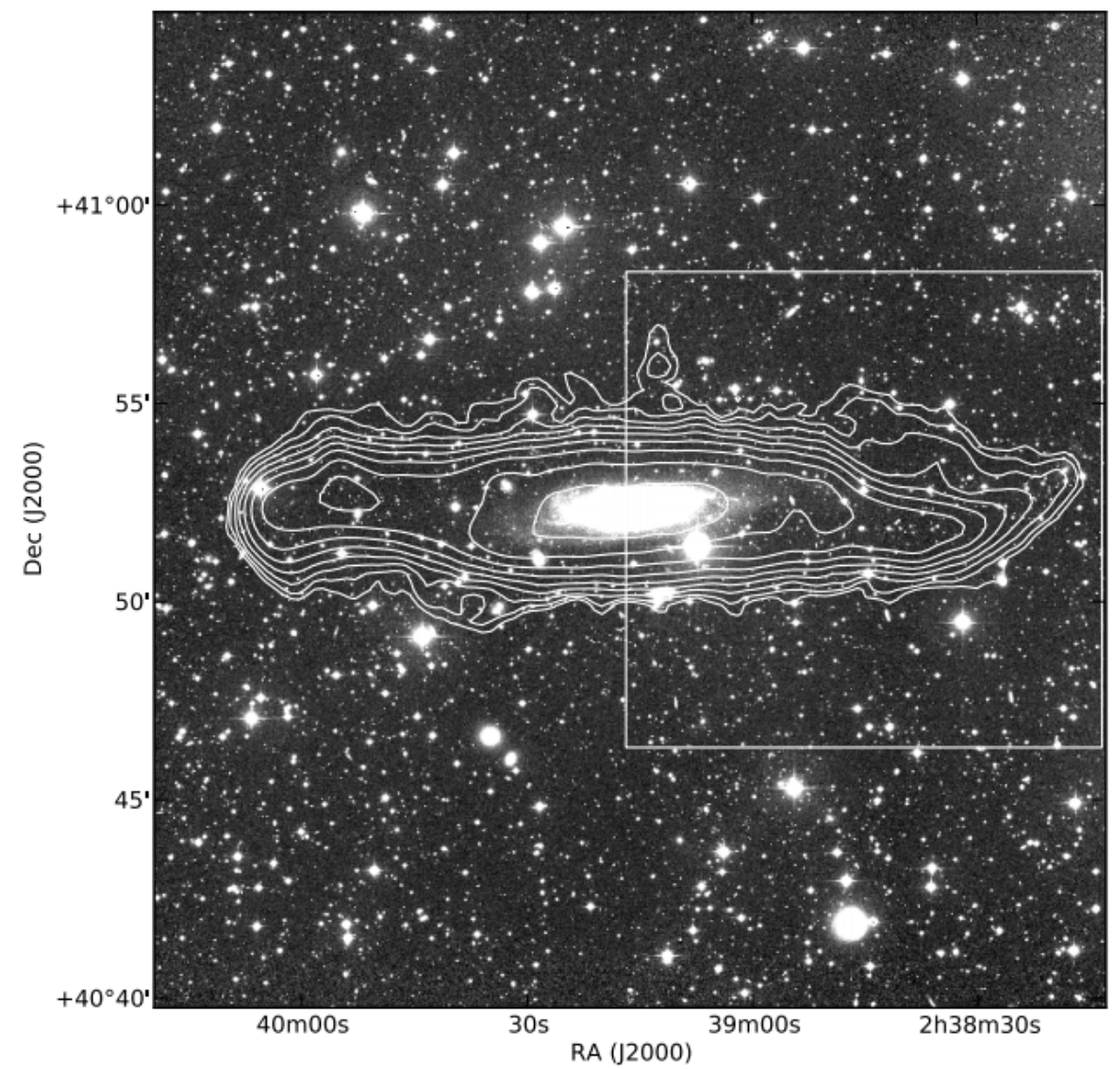


KPNO (B= blue, R=green, Halpha=red) - Maria Patterson; HI - HALOGAS

NGC 1003

- Key results:
  - HVC analogs detected
  - Contributing ~4 x 10^6 $M_\odot$ of the HI in the system
  - over a dynamical time, these features contribute only ~2% SFR





HALOGAS Accretion Catalog

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

HALOGAS Accretion Catalog

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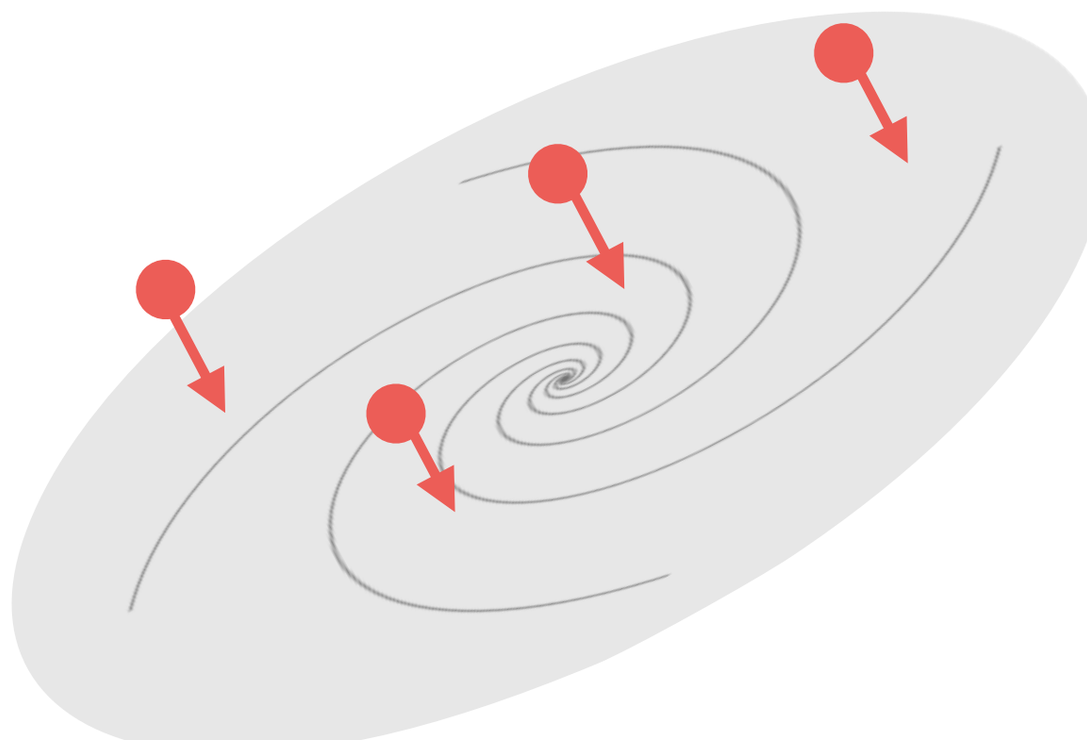
  - How many galaxies show signs of accretion? How much (and at what rate)? Clouds or diffuse? Co-rotating with the galaxy? Associated with star formation? …
- Preliminary result already clear:
  A few features possibly attributable to cold accretion (in the form of HI)
  - *but insufficient to fully balance SFR in a typical galaxy;*
  - *HALOGAS has not detected a large population of clouds with* $M_{HI} > 10^5\ M_\odot$
  - *HALOGAS has not found significant amounts of low-column density HI* <u>*not*</u> *associated with SF (down to* $10^{19}\ cm^{-2}$*)*
  - *NGC 891 is an extreme, atypical case*

Halo gas in HALOGAS?

Non-detections at the ~3 10^5 $M_\odot$ level (3σ)

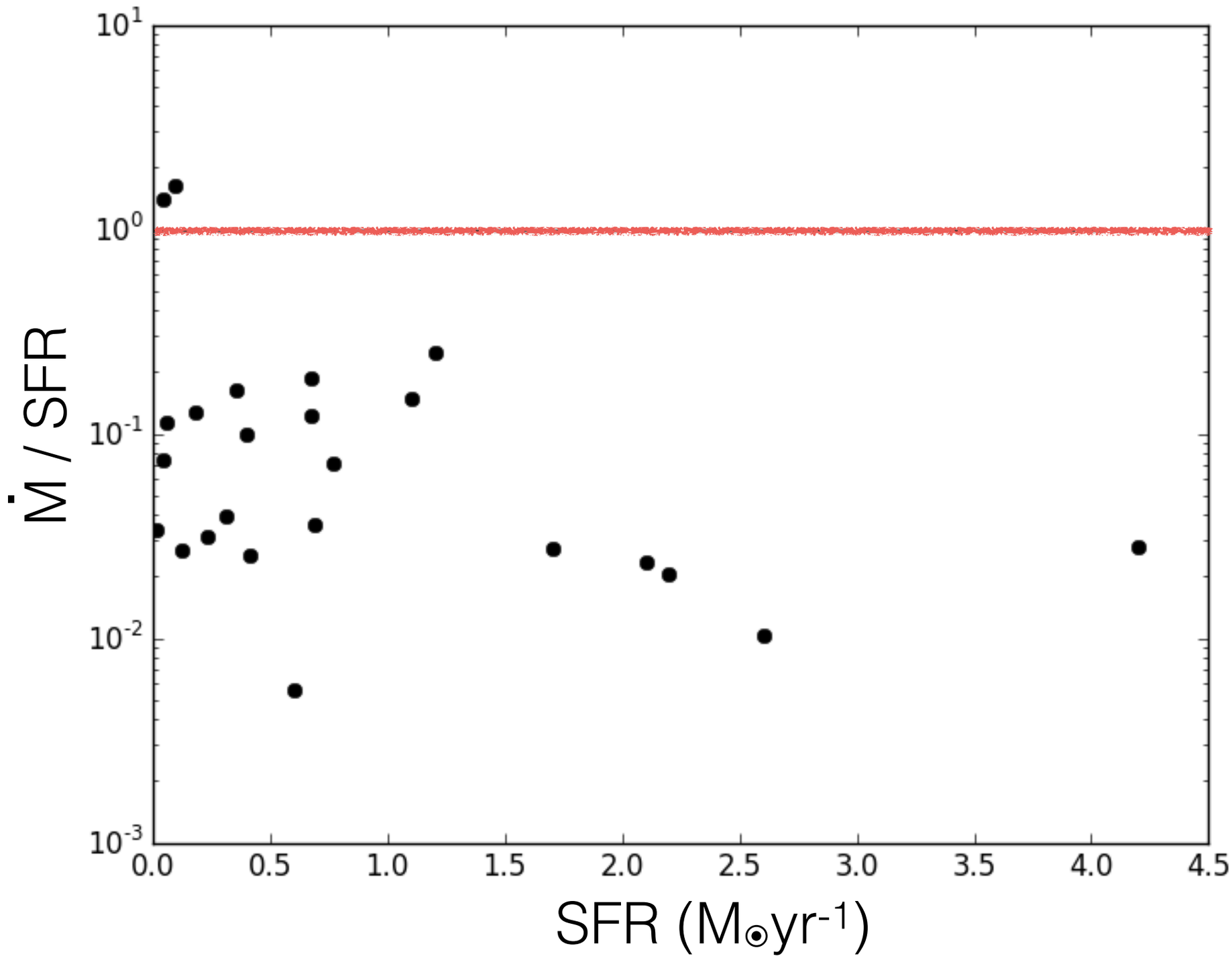
What are the implications for accreting gas?



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

HALOGAS accretion rate limits

Tends to constrain the HI accretion rate to $\lesssim$ 0.1 SFR

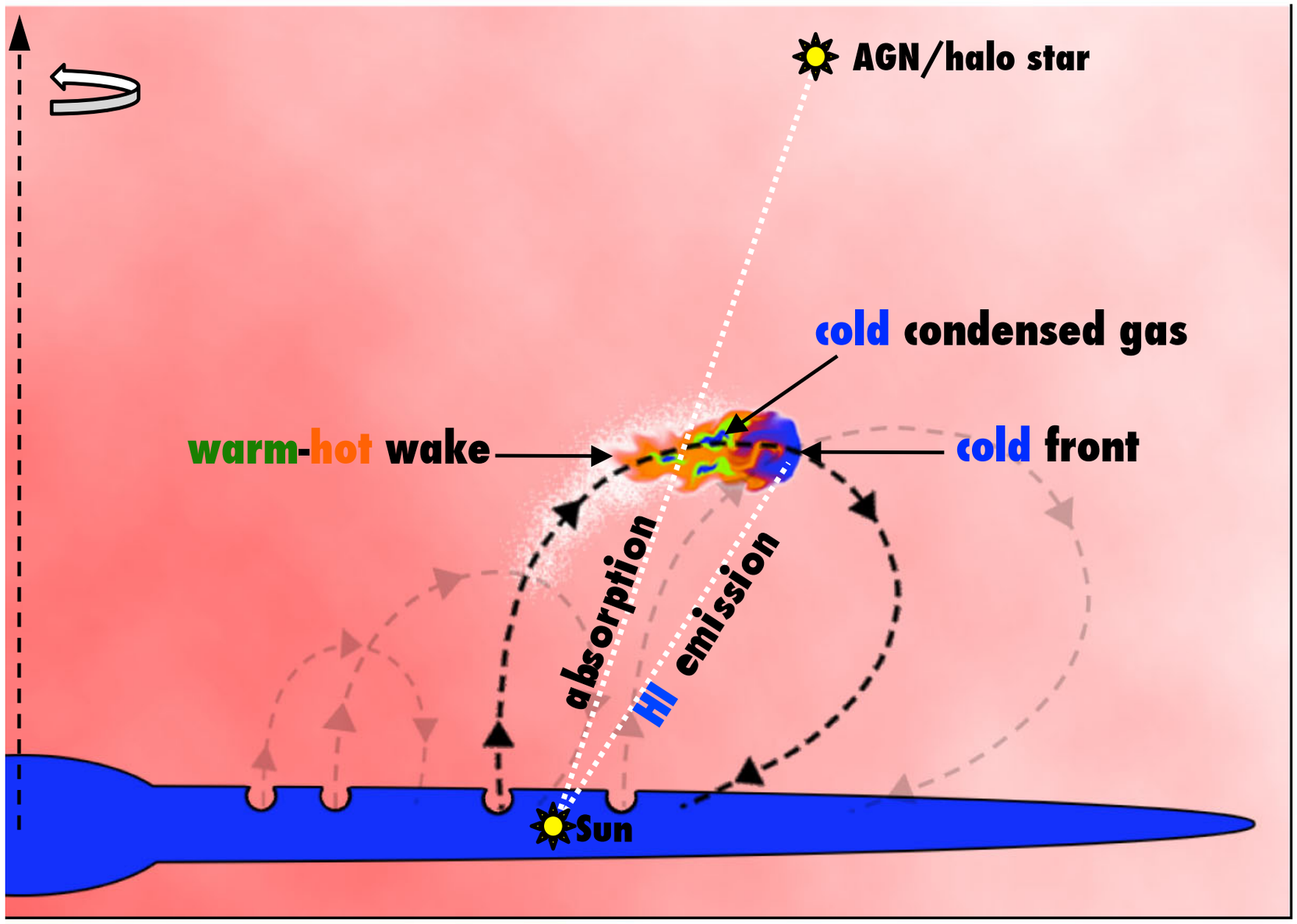


Implications

- 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 (down to current observational limits).
  - Era of galaxy SFR decline?
  - In the form of hot gas, and brought to the disk via fountain?
  - Happening at lower column densities?

Understanding extraplanar gas



Marasco et al 2013

Implications

- HI thick disks are not ubiquitous, but have properties that seem to align with underlying galaxies
  - Detections vs non-detections gives important leverage
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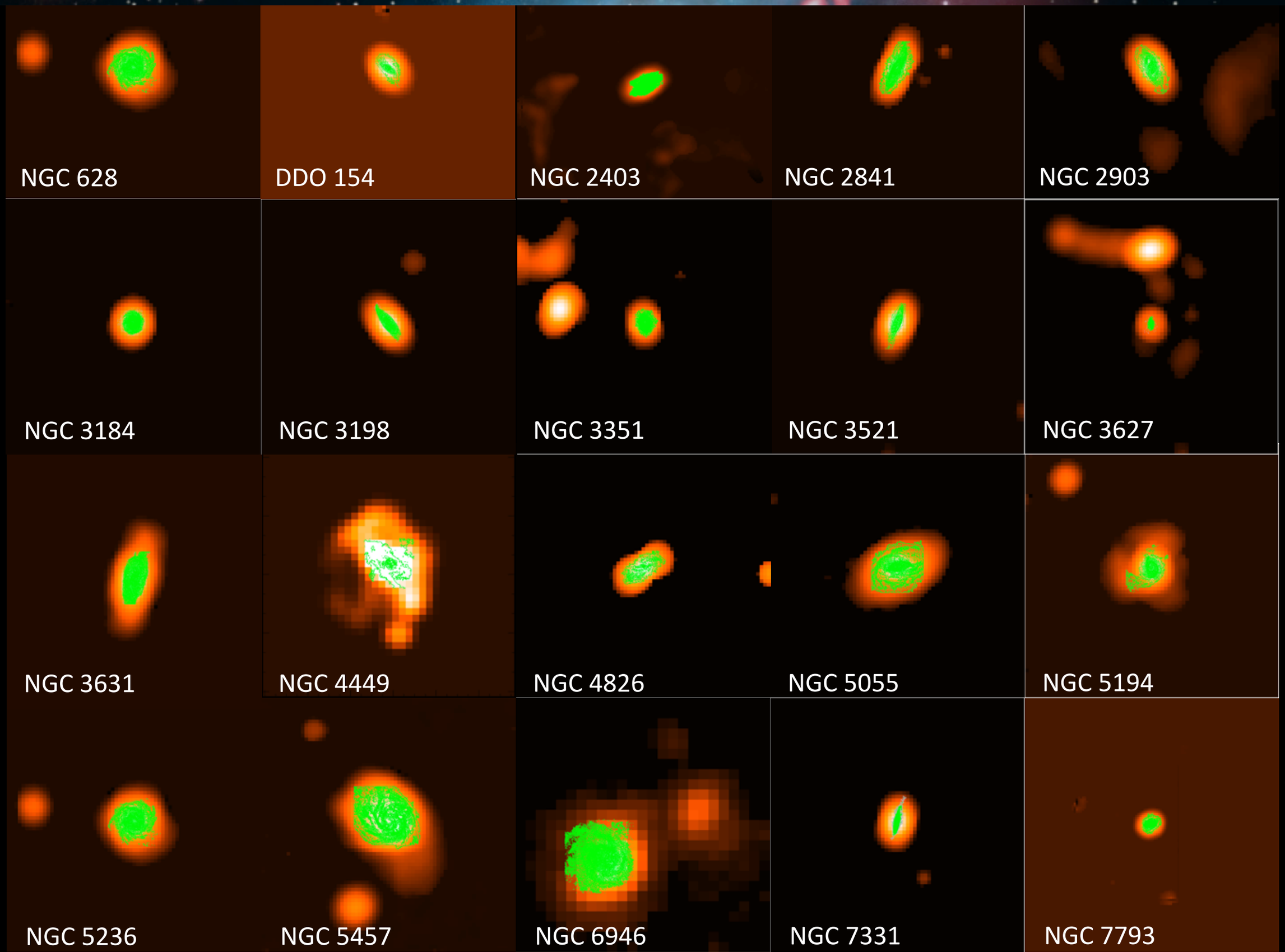
  - Happening at lower column densities?

Deep GBT Observations

- Accretion happening at even lower column densities?
- 21 THINGS and 20 HALOGAS galaxies followed up with GBT (PI D.J. Pisano)
- $4^{o} \times 4^{o}$ mapped
- 10 h per galaxy giving 5σ, 20 km s^{-1} column density limit of $2 \cdot 10^{18}$ cm^{-2}

Deep GBT Observations



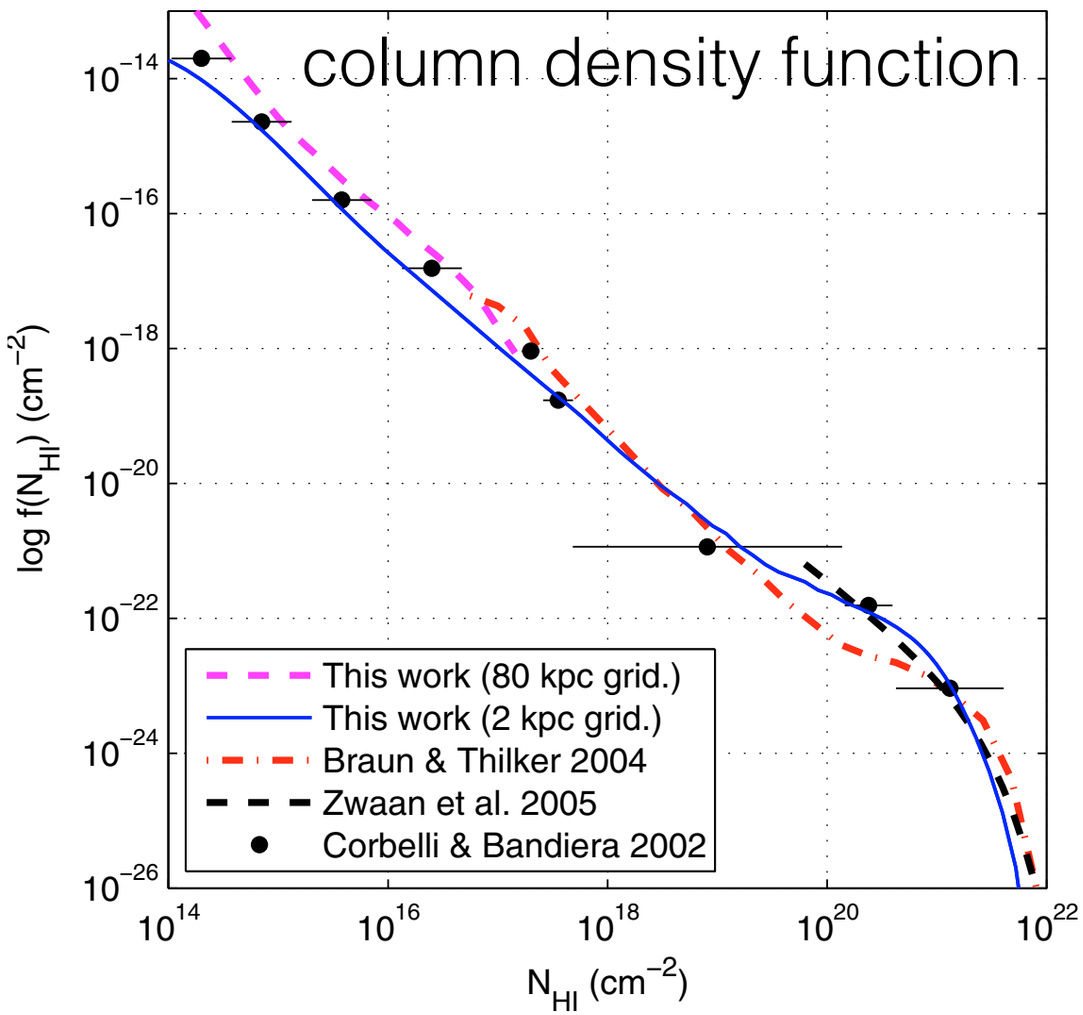
Slide courtesy D.J. Pisano

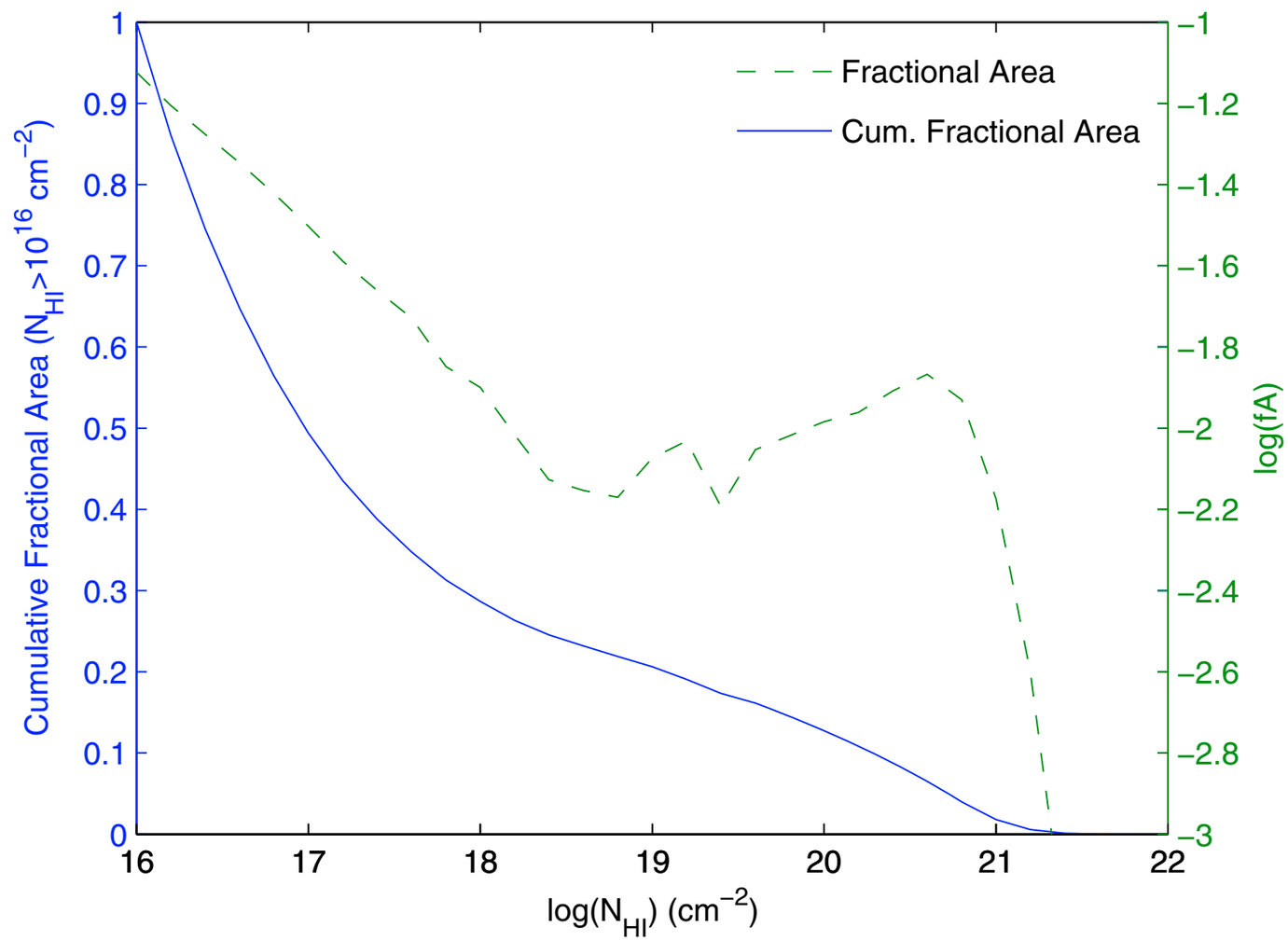
Deep GBT Observations

- THINGS and HALOGAS galaxies followed up with GBT (PI Pisano)
- Column densities (5σ, 20 km s^{-1}) ~ $2 \cdot 10^{18}$ cm^{-2}
- Between 10 and 30% more HI than HALOGAS
- However, resolution (9’) is big limitation
- Can establish presence, but no information on nature, morphology or dynamics, except absence of large-scale flows
- Higher resolution…

Looking to the future

Deeper Higher Resolution Surveys



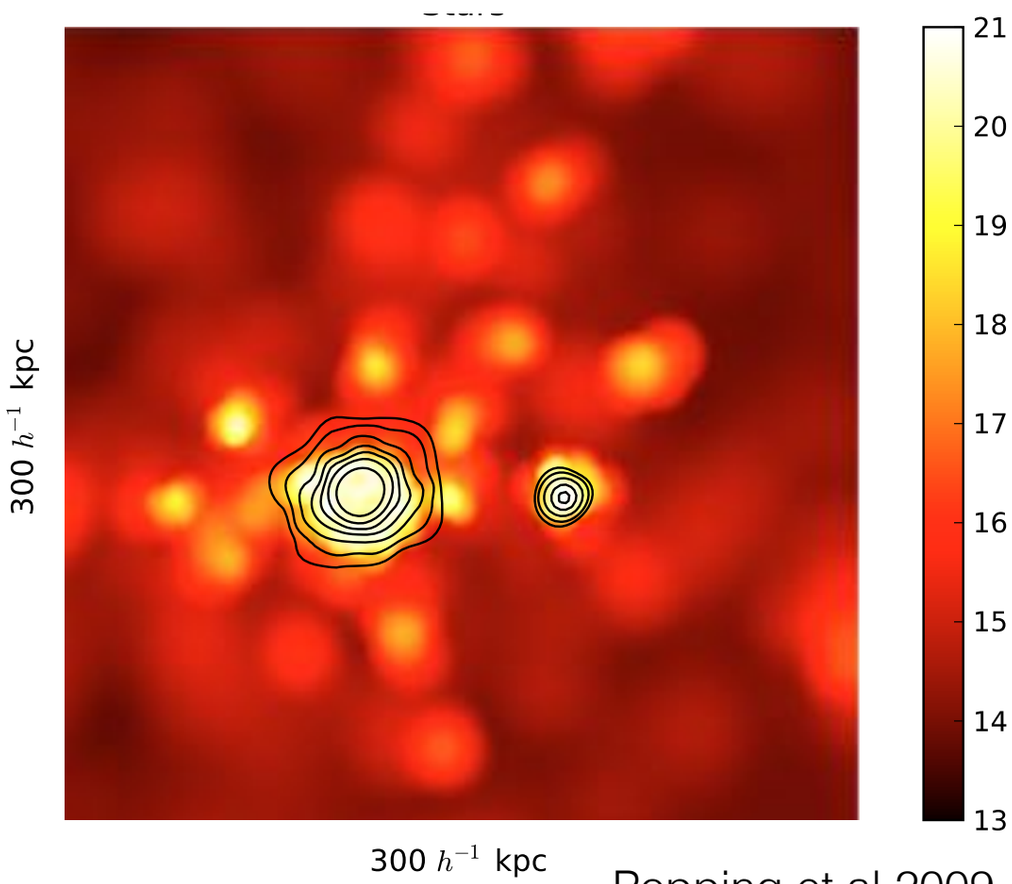


Popping et al 2009

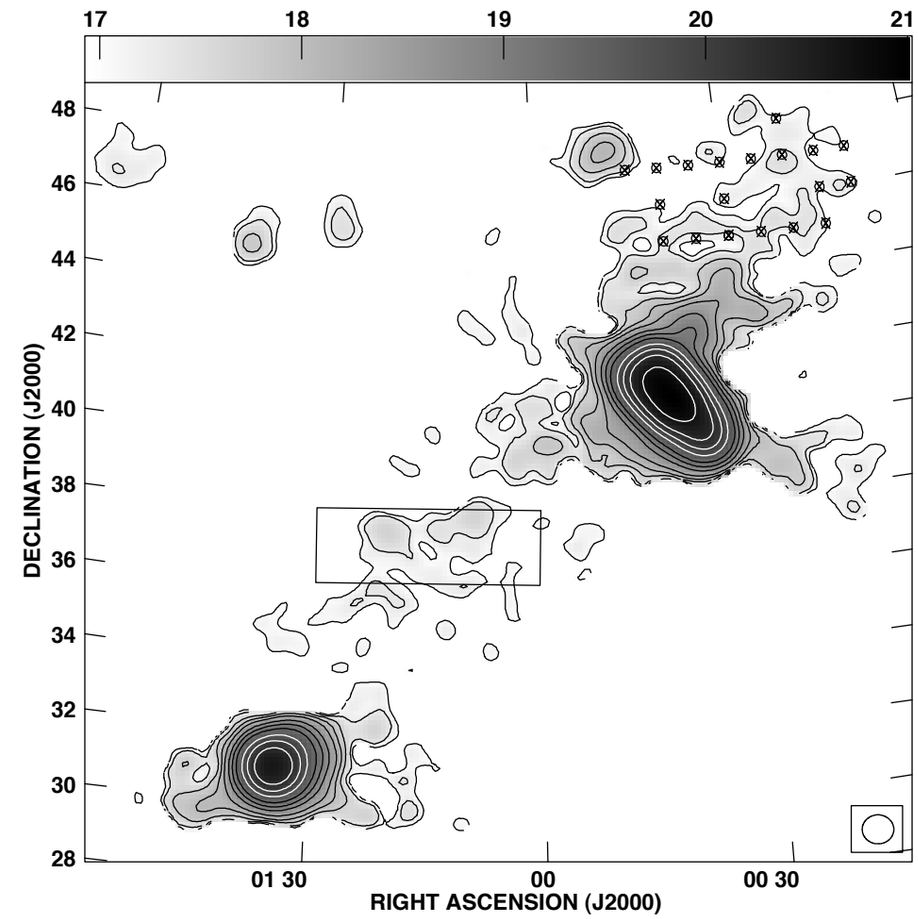
At 10^{17} cm^{-2} area is twice that at 10^{19} cm^{-2}

but virtually nothing is known about the morphology

Morphology

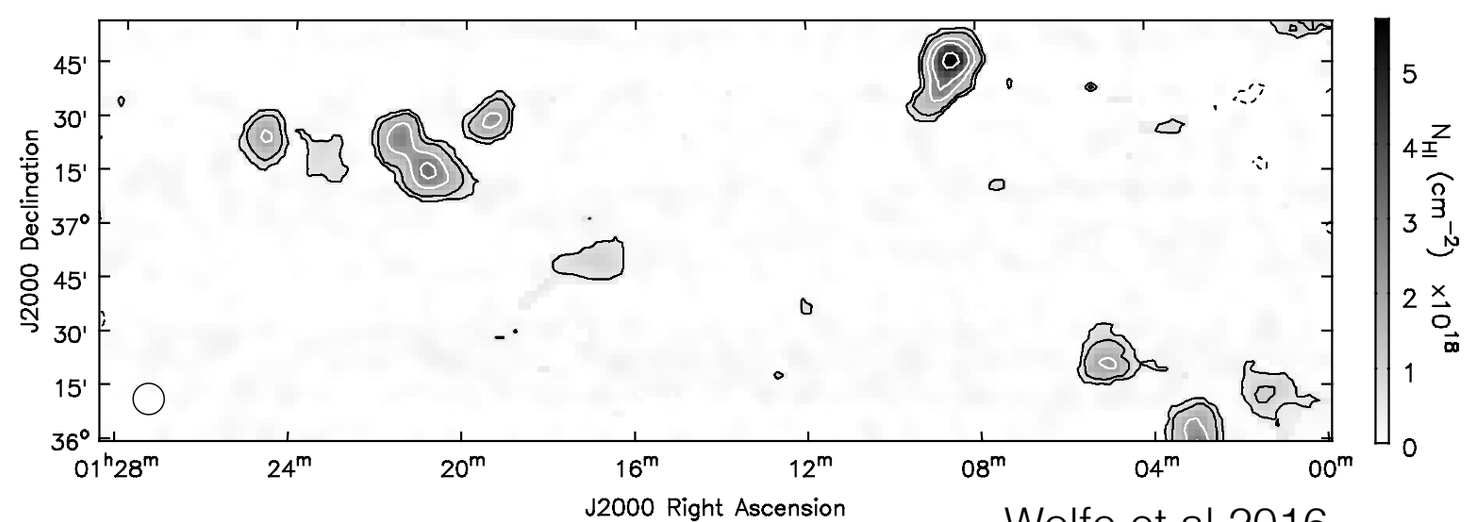


Popping et al 2009



Braun & Thilker 2004 map from Wolfe et al 2016

Clumpy low-column density material



Wolfe et al 2016

MHONGOOSE on MeerKAT

- Nearby Galaxies Large Survey Project on MeerKAT (PI: EdB)
- 25 times sensitivity of THINGS
- 30 galaxies taken from SINGG/SUNGG (Meurer et al 2006)
- multi-wavelength largely available
- equal numbers per log M_{HI}
- 1500h observing time (new MeerKAT sensitivies)
- accretion, cosmic web, dynamics beyond disk
  - $5\sigma = 3.0 \cdot 10^{18}$ cm^{-2} at 30” for 4.2 km s^{-1} channel spacing or 5.10^{17}-10^{18} cm^{-2} at 90”
  - 0.5-6 kpc resolution at 15 Mpc

mhongoose.astron.nl

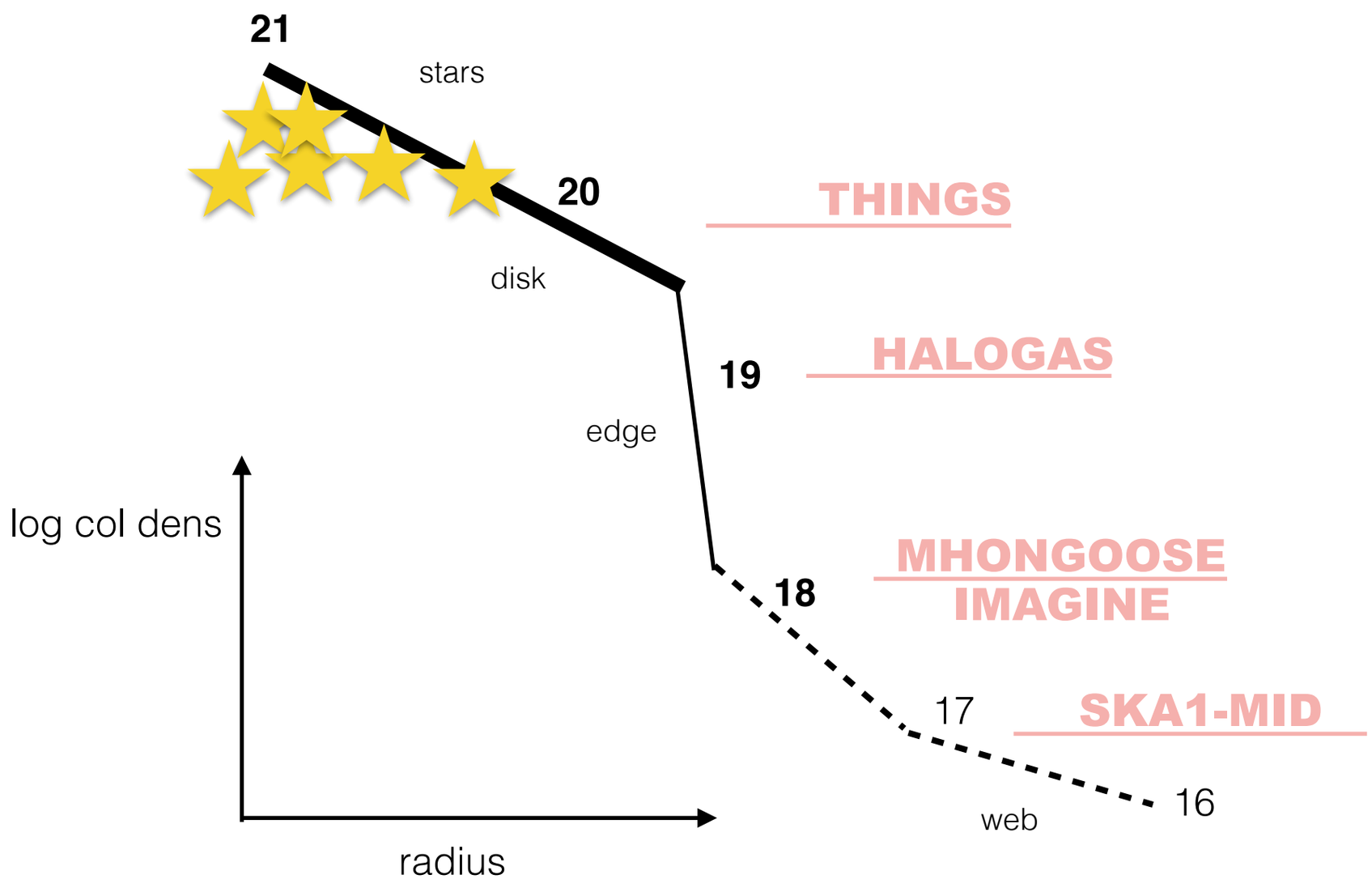
MHONGOOSE

IMAGINE

- *IMAGINE**, (PI Attila Popping, ICRAR)
- ATCA, 2500 hours, 28 galaxies, 96 h per galaxy
- 7.5 10^{17} (3σ over 20 km/s) at 2.5’ (factor 3.6 better spatially than GBT)
- observing started last month

*) IMAging Galaxies’ Intergalactic and Near Environment

Comparing limits



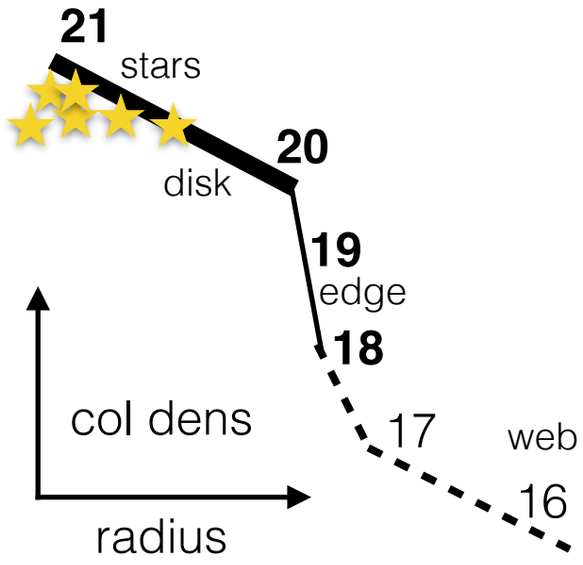
SKA1-MID capabilities

- HALOGAS: 120h:
  5σ over 4.2 km/s at 30”: 5 x 10^{18} cm^{-2}

- SKA-MID: 10h:
  5σ over 4.2 km/s at 30”: 2.4 x 10^{18} cm^{-2}

- SKA-MID can do HALOGAS+ observations in 10h

- Much improved statistics on relevance of accretion in relatively short time



SKA1-MID capabilities

- SKA-MID: 100h:
  5σ over 5 km/s at 30”: 7.5 x 10^{17} cm^{-2}

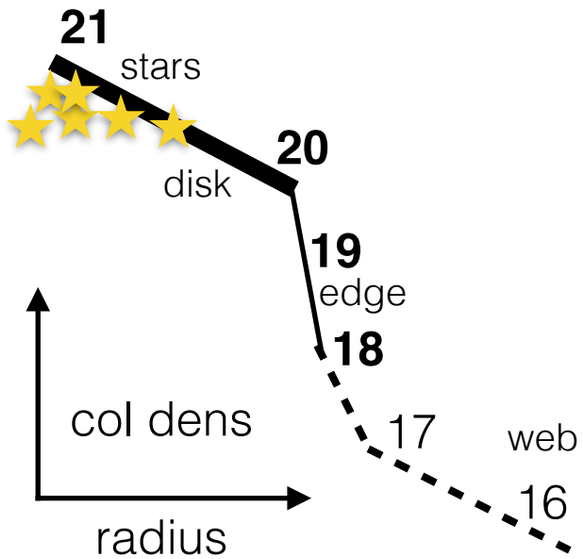
- Comparable to deep GBT single dish observations, but at ~20 times better resolution

- MID also allows higher resolutions

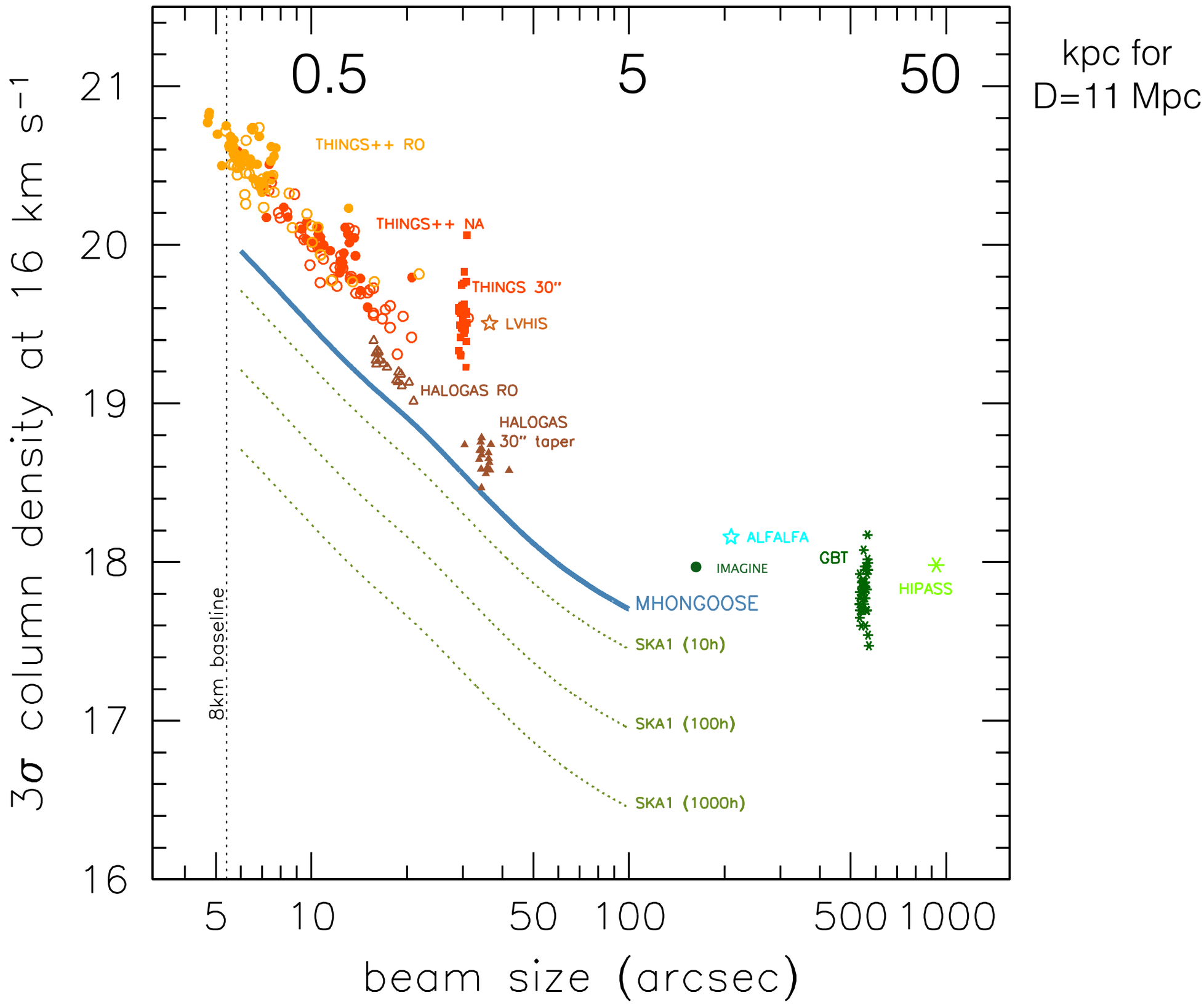
- 100h at 5σ over 5 km/s at 3”: 1.3 x 10^{20} cm^{-2}

  3” at 10 Mpc = 150 pc

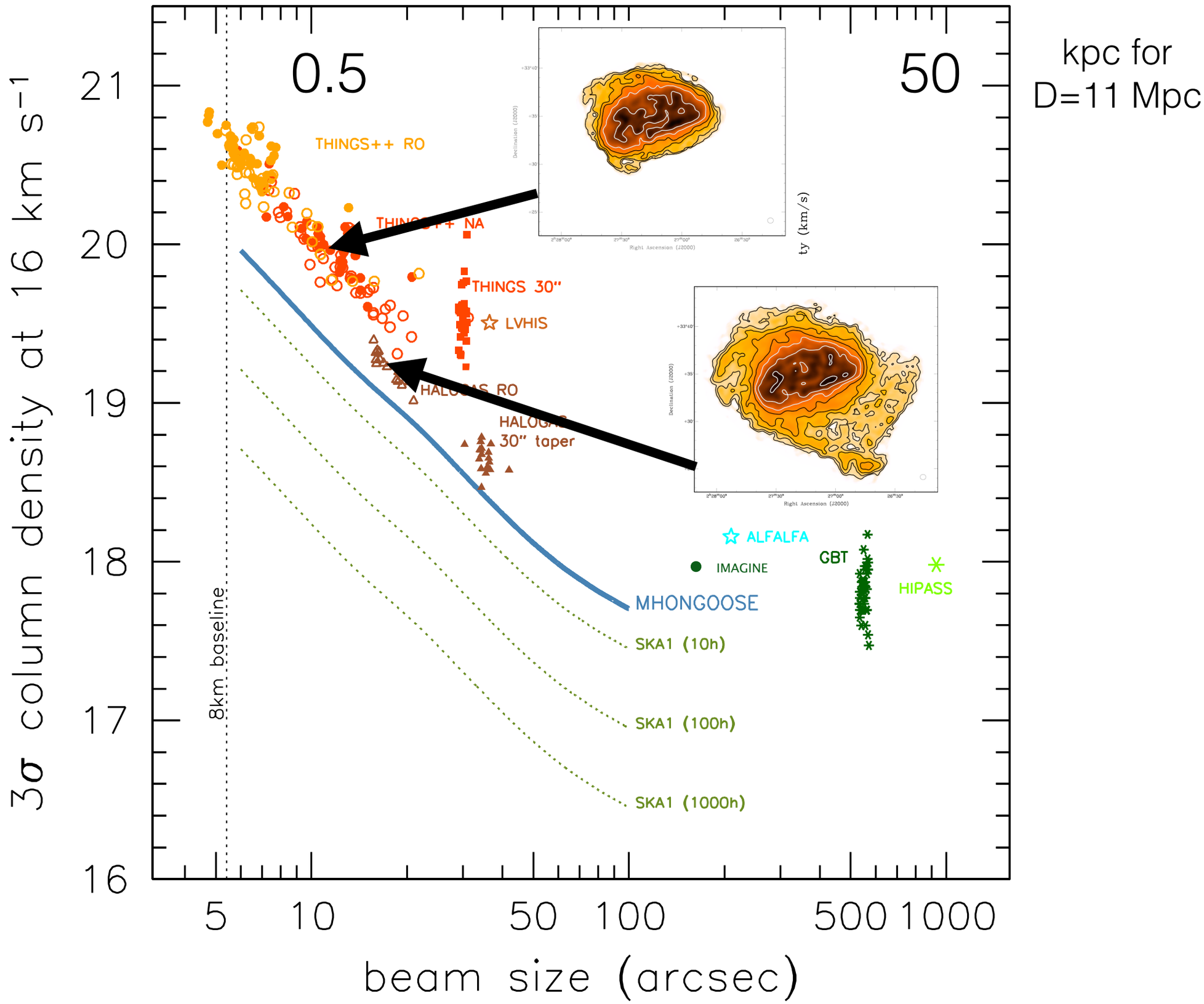
- Resolve the thick disk and test accretion models



Sensitivity comparison



Sensitivity comparison



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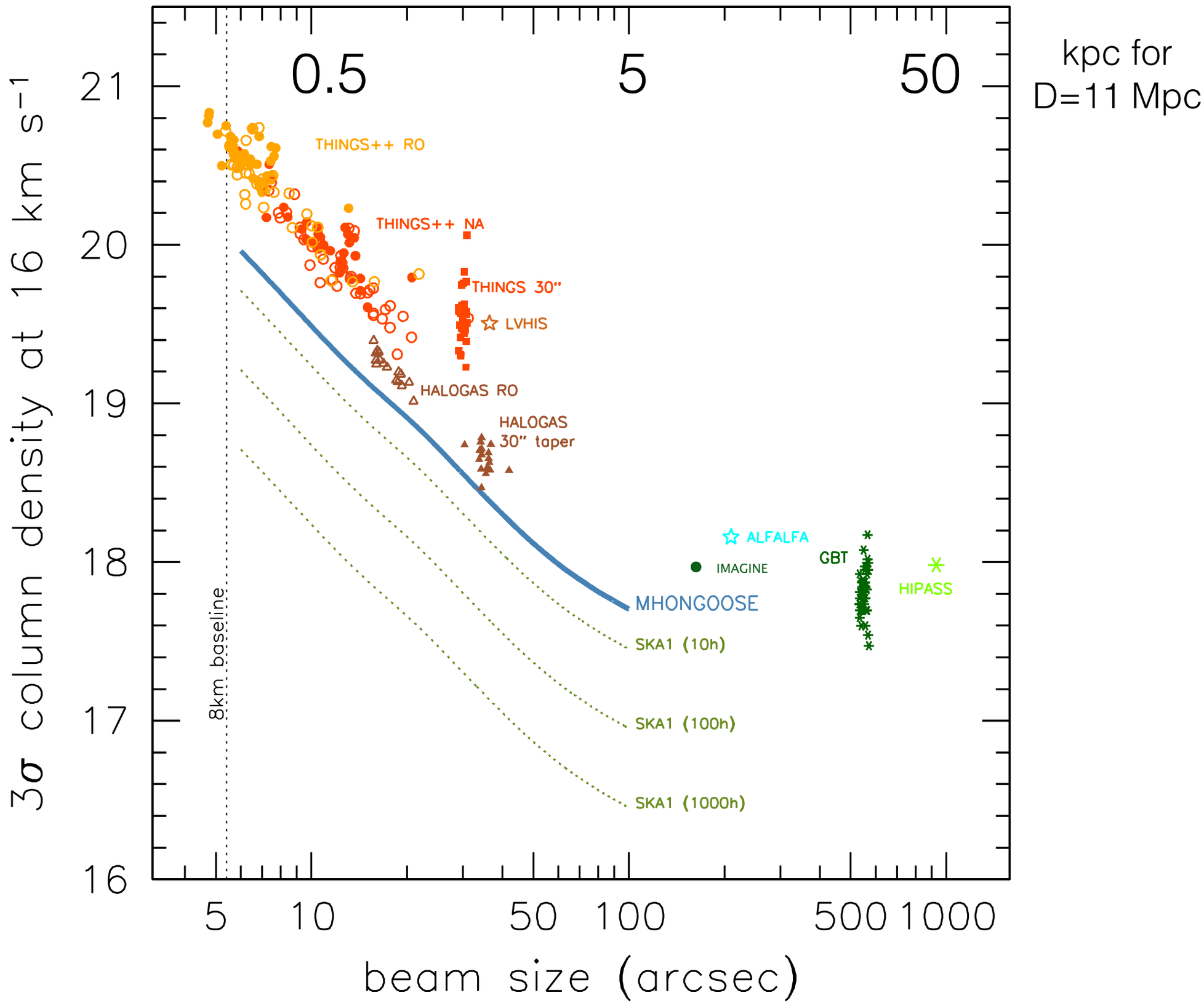

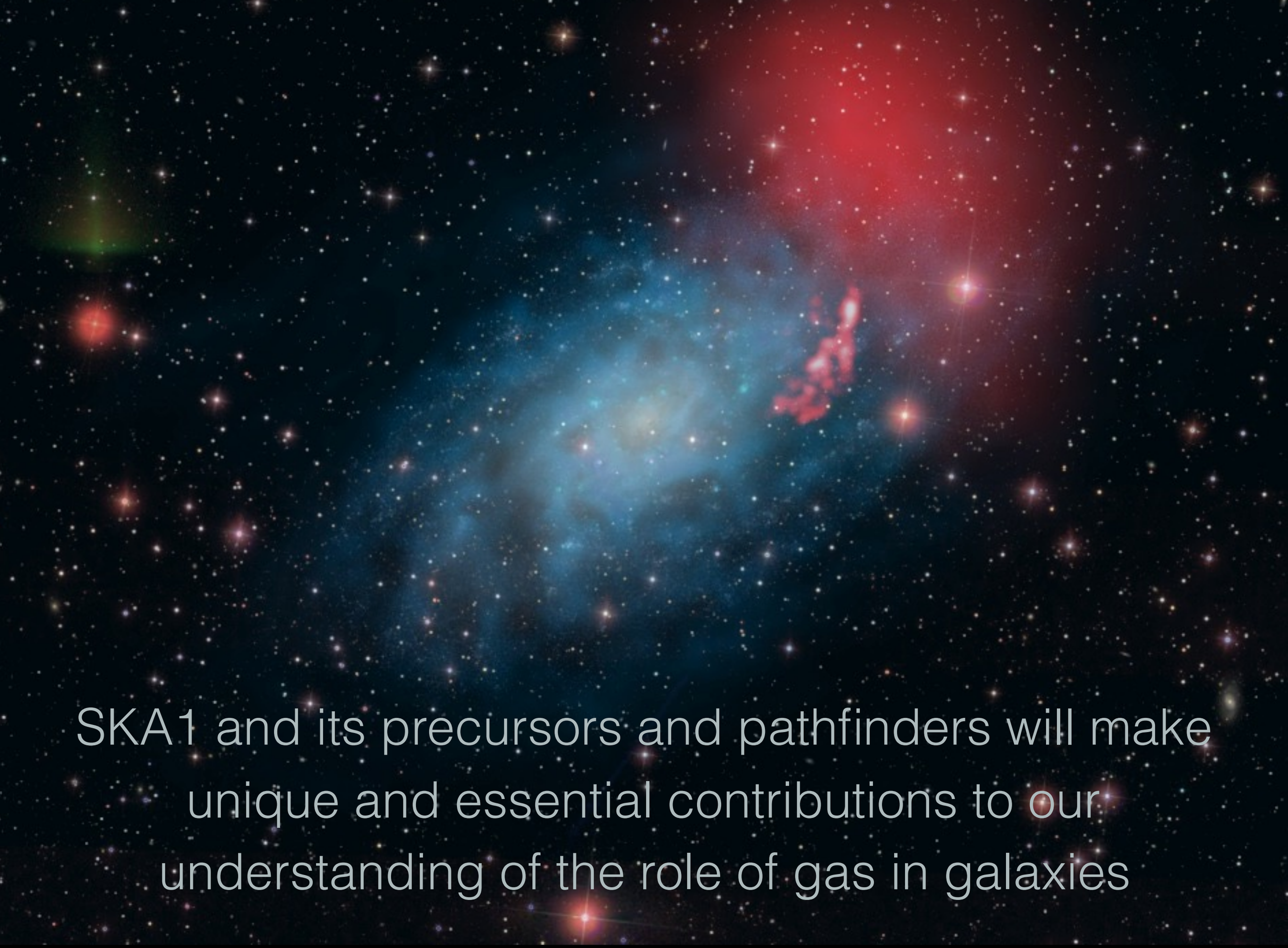
SKA1 and its precursors and pathfinders will make
unique and essential contributions to our
understanding of the role of gas in galaxies

http://web.ncra.tifr.res.in/PHISCC/

NCRA • TIFR

NATIONAL CENTRE FOR RADIO ASTROPHYSICS, PUNE

2017 PHISCC Workshop : Exploring First Light

February 6 -11, 2017

PHISCC-2017

The Pathfinders HI Science Co-ordination Committee (PHISCC) has been holding regular science meetings to discuss the HI-21cm science projects being planned and carried out with the various SKA Pathfinder telescopes and instruments, such as the upgraded GMRT, MEERKAT, ASKAP, WSRT-APERTIF, FAST, JVLA, etc.. The 10th such PHISCC meeting will be held at NCRA-TIFR, Pune, India, over February 6 -11, 2017. The PHISCC-2017 meeting will mark a turning point in HI-21cm studies, since many of the SKA Pathfinders will have achieved first light and begun their initial HI-21cm studies by late 2016. The exciting first science results from many of the pathfinders are hence expected to be presented at this meeting.

For PHISCC-2017, we aim to bring together the astronomers involved in carrying out the cutting-edge large HI-21cm programmes on the various SKA pathfinders, as well as those developing the software tools to enable the detailed science with the large datasets. Thus, while the major part of the meetings programme will be focused on the science that is beginning to emerge from the new observations, we plan to also have mini-workshops on the software tools. These will enable participants to share their experience with the different tools, allowing the community to make progress in both understanding and using the tools, as well as identifying areas that need further refinements.

The science topics at the PHISCC-2017 will cover all issues related to HI-21cm studies of neutral gas in galaxies, including HI-21cm emission and absorption studies, line surveys, intensity mapping, stacking, etc.. The software tools would include RFI mitigation, calibration/imaging pipelines, post-processing pipelines for source detection, extraction of kinematical information, etc.

Abstracts of proposed talks should be submitted by November 17, 2017.

Ganeshkhind, Pune University Campus, Pune 411 007, INDIA

:+91 20 2571 9000/ 2571 9111; Fax: +91 20 2569 2149; l:phiscc@ncra.tifr.res.in