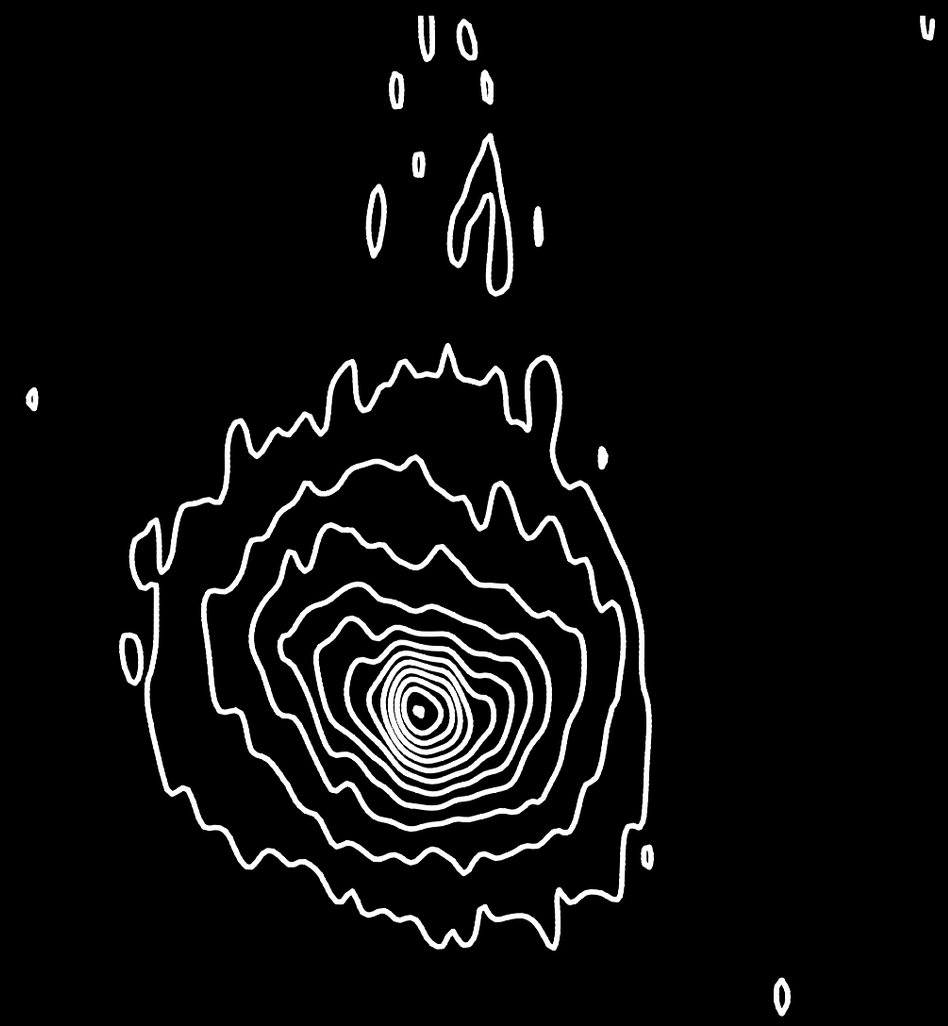
Current and future searches for the smallest galaxies

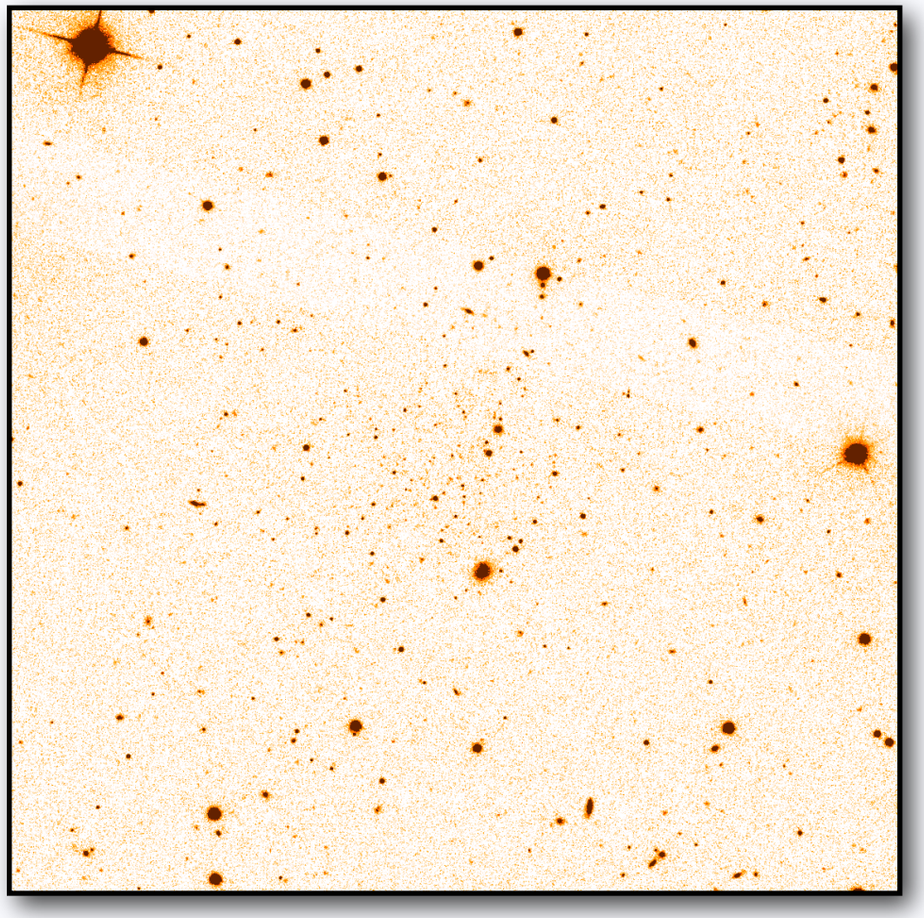


Tom Oosterloo
Netherlands Institute for Radio Astronomy - ASTRON, Dwingeloo
Kapteyn Astronomical Institute, Groningen

My talk

- Why are the smallest, ‘almost’ dark galaxies interesting?
- Ongoing projects
- The importance of SKA

How special is Leo T?



SDSS r

Leo T: M_V = -8

M_{HI} = 4.1 x10^5 $M_\odot$

$M_{gas}/(M_{gas}+M_{star})$ = 0.73

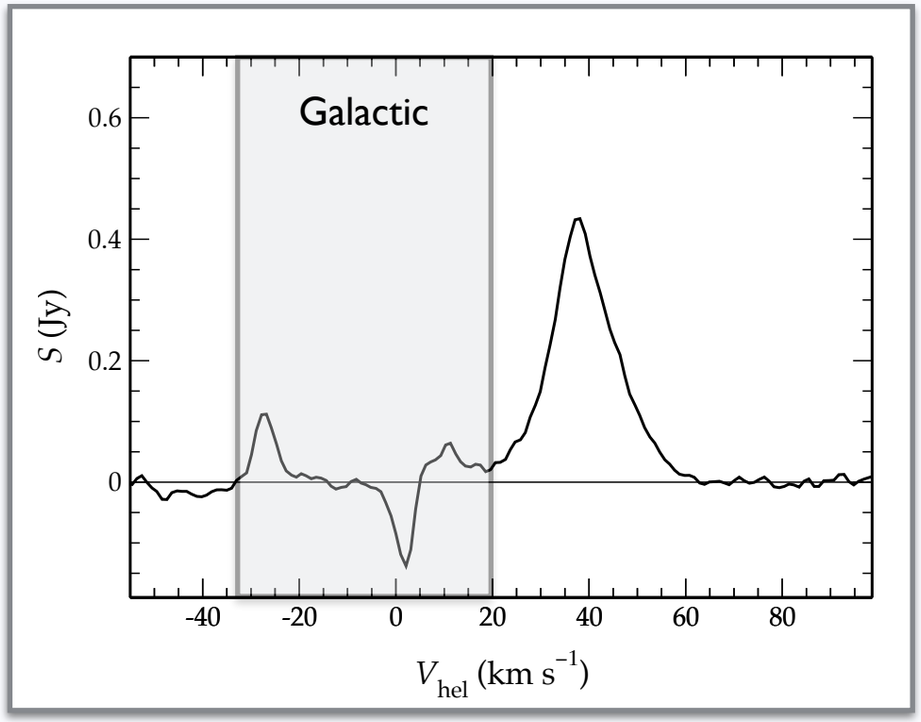
r_{HI} ~ 300 pc

$N_{HI,peak}$ = 5 x10^{20} cm^{-2}

Mostly warm HI

Small core of cold HI

D = 420 kpc

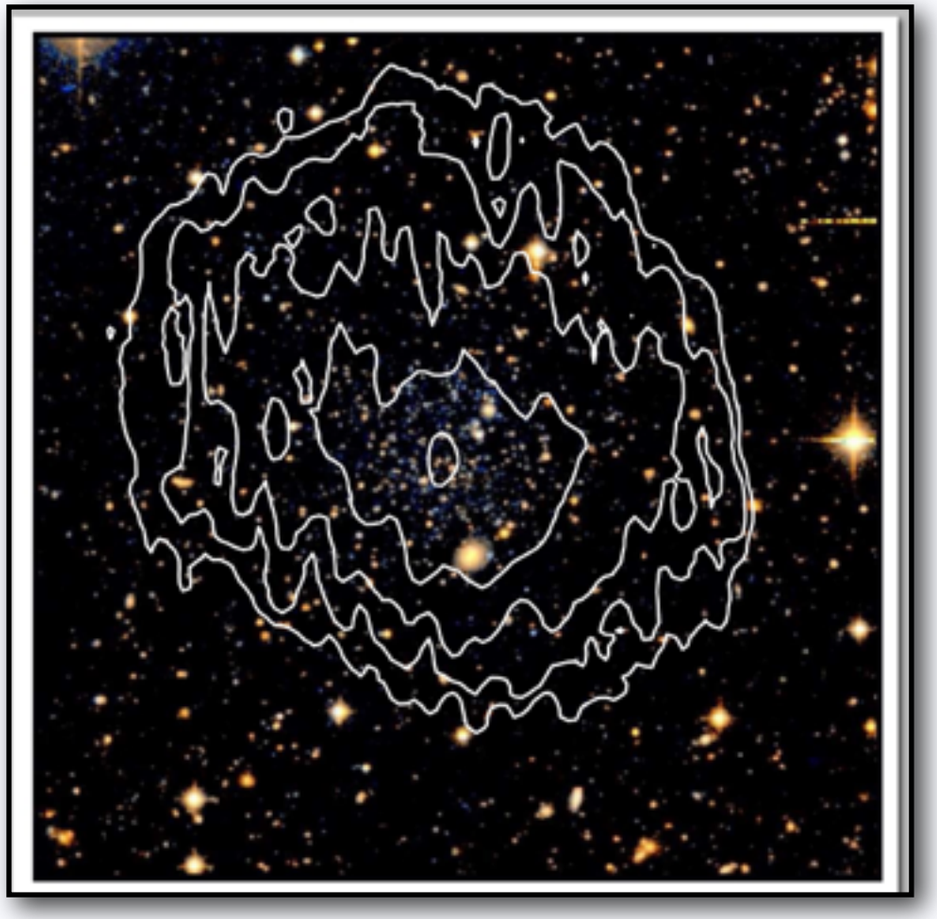


WSRT - HI

Very faint in the optical, very bright in the radio

Even detected with Dwingeloo 25-m dish in 90's

(but not recognised as being extragalactic)



HI contours on INT image

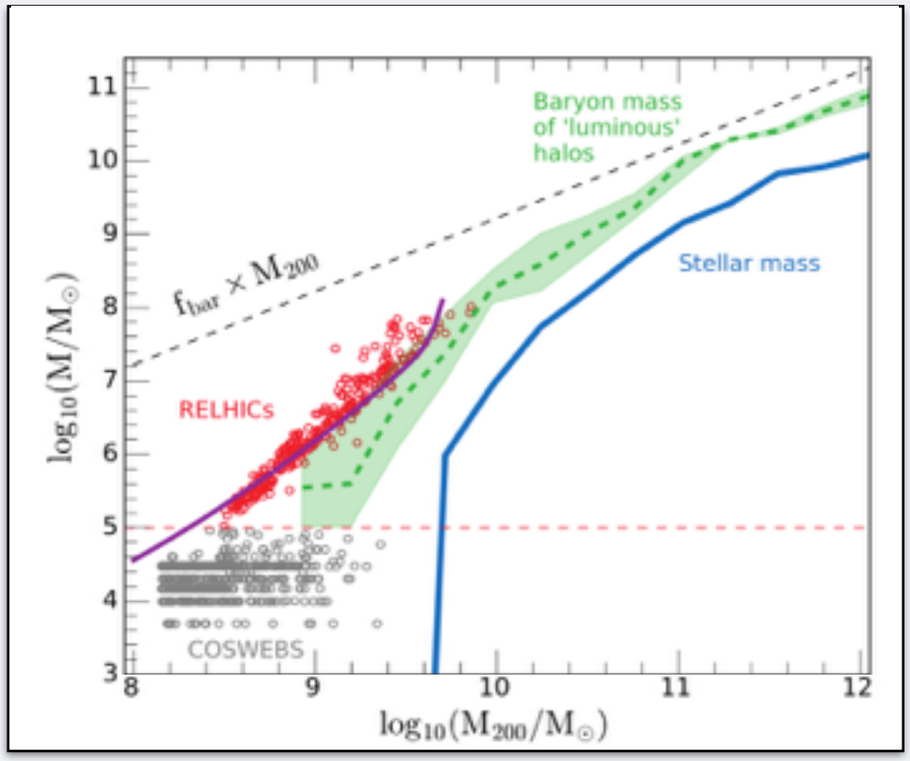
Ryan Weber+ 2008

Are small dwarfs expected to be gas rich?

- They should not exist!!!!

  - Epoch of re-ionisation imposes lower limit
  - it is easy to expel gas from shallow potential well
  - it is harder for gas to cool and form stars
  - effects due to environment & cosmic web
  - late (re-)accretion of gas?

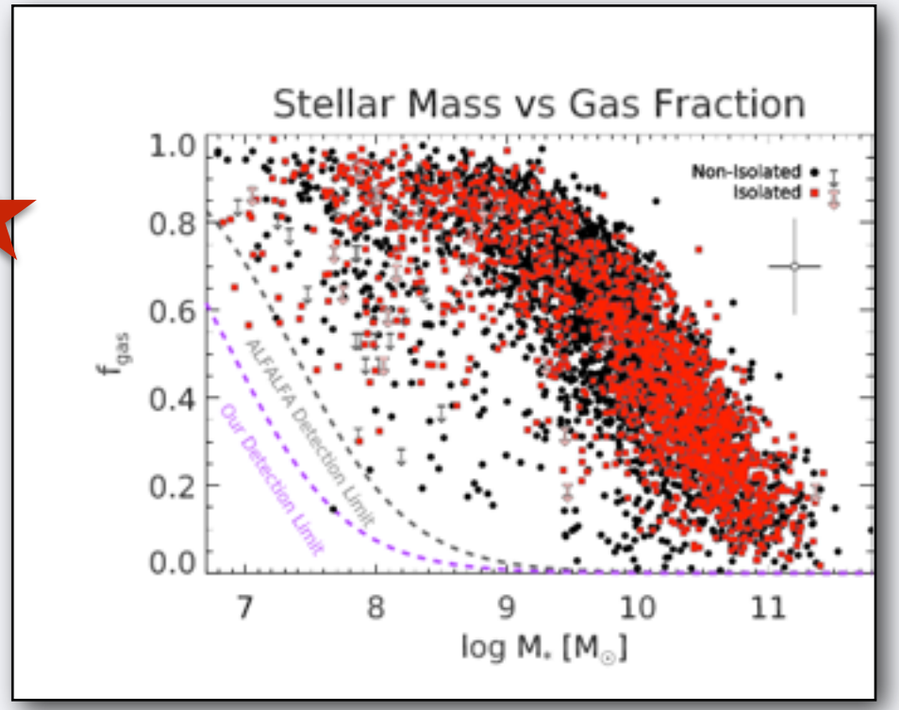
  - very delicate systems,
    properties depend very much on local circumstances.
  - may help understanding the formation of the earliest galaxies
    and what the early Universe looked like



Benítez-Llambay+ 2017

  - what is the lower limit to gas bearing galaxies?
  - how many galaxies like Leo T's are there?
  - are there objects even more extreme?

Leo T

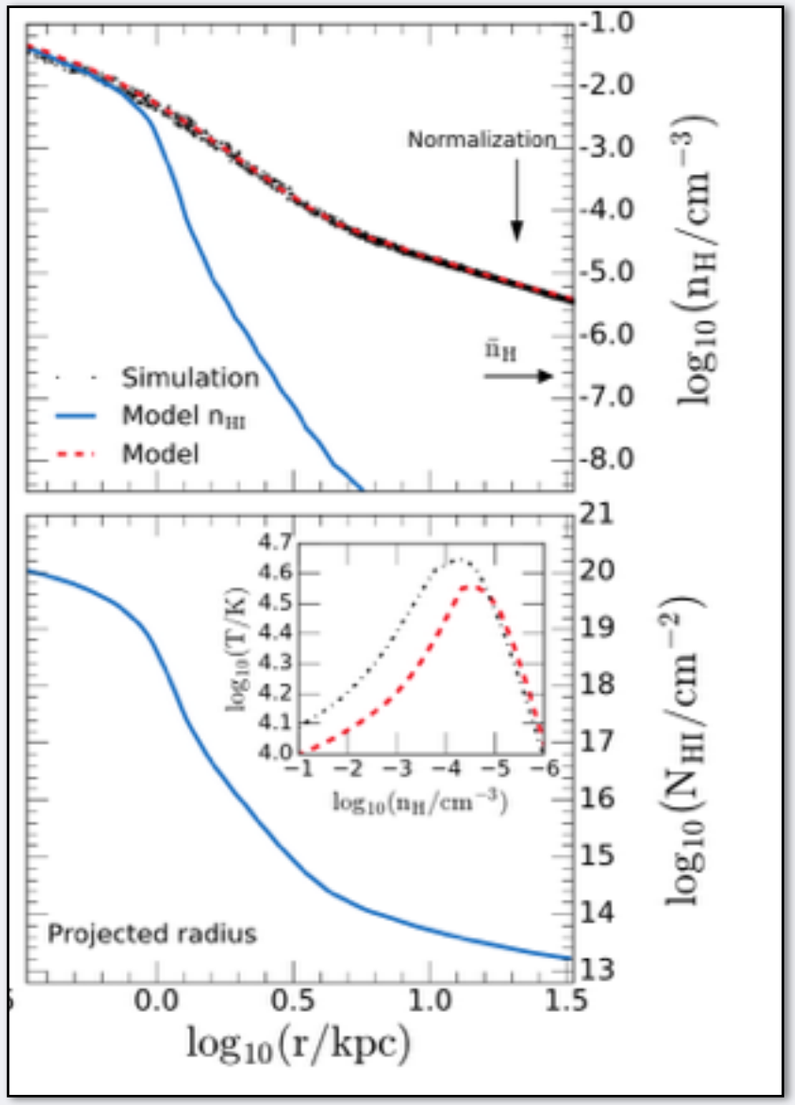


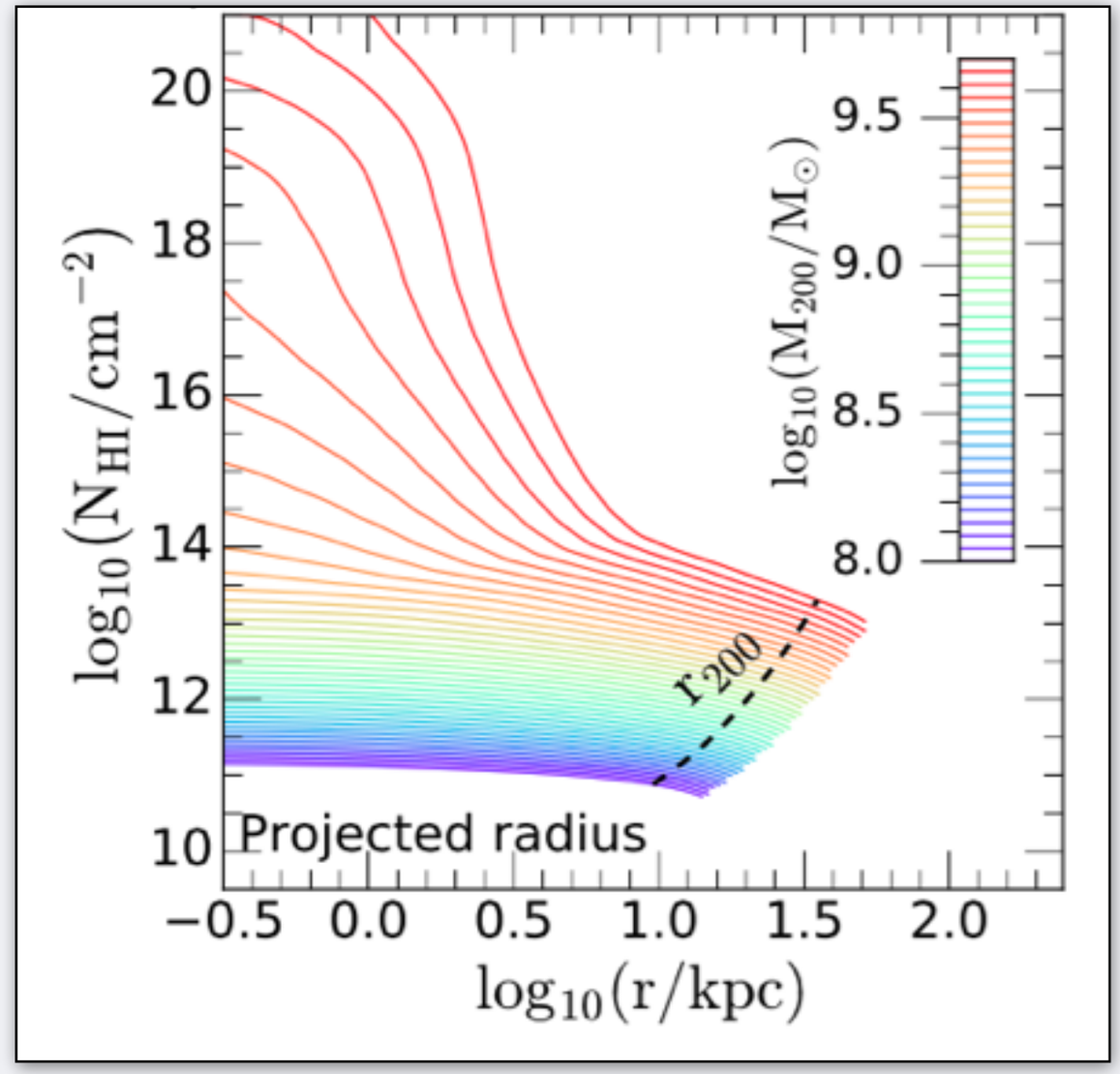
Bradford+ 2015

  - most isolated dwarfs are (very) gas rich
  - not much known about statistics of small, gas rich galaxies

What to look for?

- models of DM minihalos:
  - contain little gas: all gas is ionised by radiation field
  - more gas: self-shielding: core with Warm Neutral Medium forms, sharp transition
  - even more gas: small core with Cold Neutral Medium forms, clumps of high density
  - still more gas: some stars will form



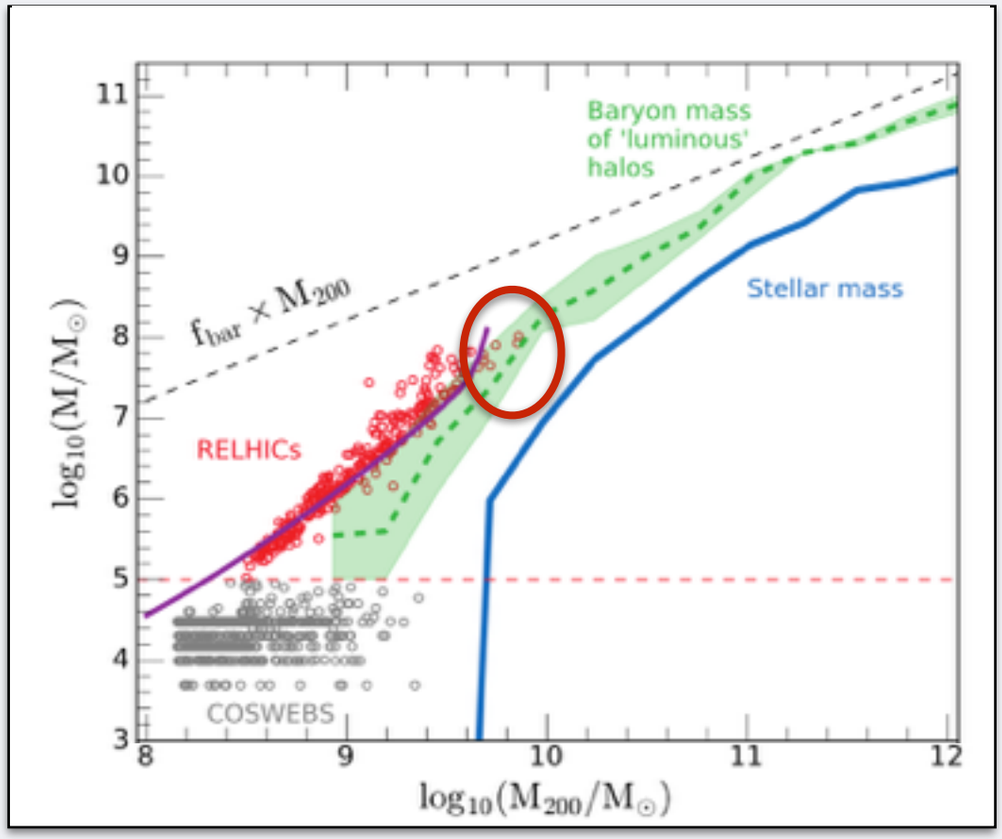


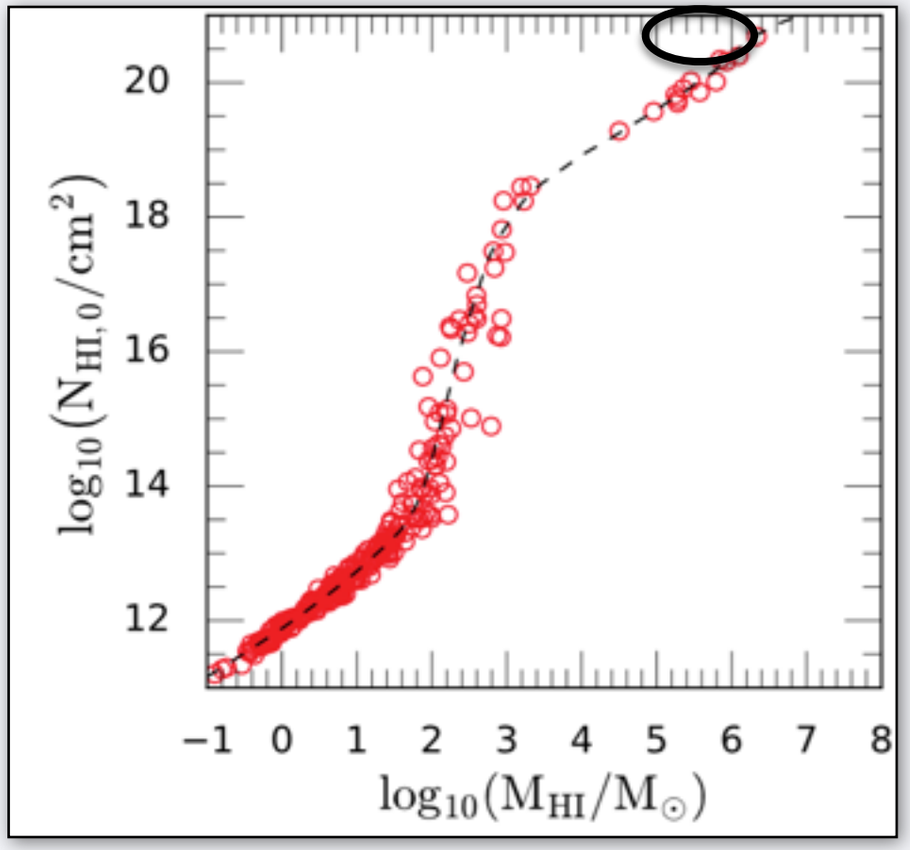
Benítez-Llambay+ 2017

- Expected properties
  - size up to ~ 1 kpc
  - $N_{HI,peak}$ up to a few x10^{20} cm^{-2}
  - Round, no structure

  - D > 300 kpc from big galaxies

- The largest ones look (in HI) very similar to Leo T!





Benítez-Llambay+ 2017

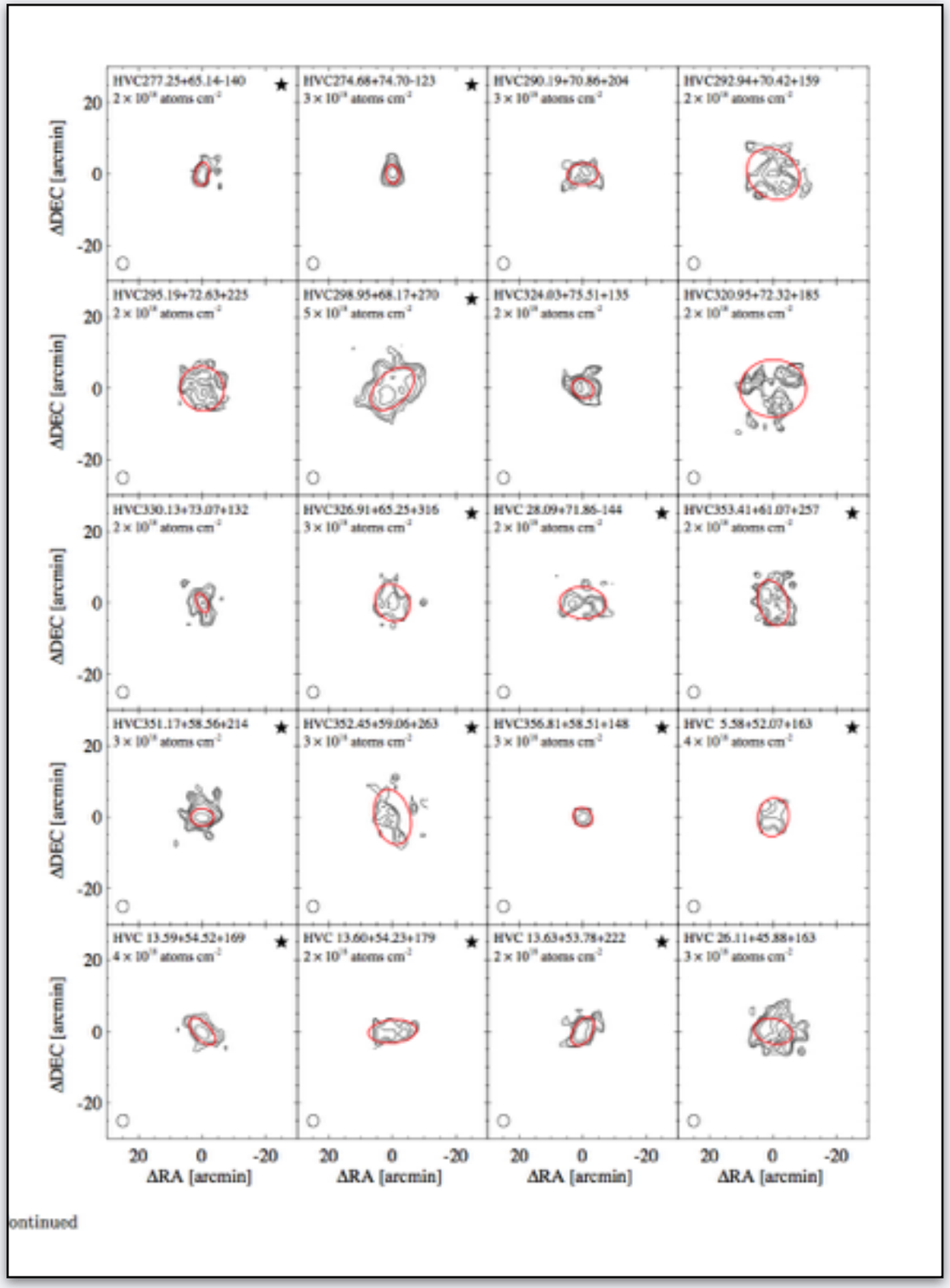
Searches for ‘dark’ galaxies: Local Group

- ALFALFA/GALFA revealed population of Ultra Compact HVCs

  (Giovanelli+, Adams+, Saul+)

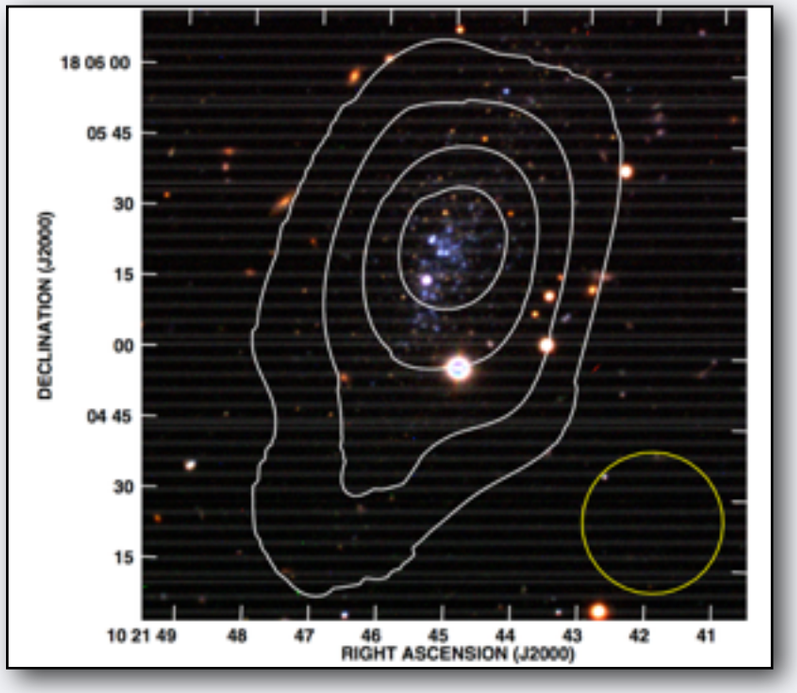
  Arecibo: resolution 3 arcmin
  so clouds are unresolved
  - Some of them could be ‘dark’ objects in and around the LG.

  - if at 1 Mpc: ~1 kpc in size
    M_{HI} ~$10^{5\text{-}6}$ $M_\odot$
    M_{dyn} ~$10^{7\text{-}8}$ $M_\odot$



Adams+ 2013

- Some of turn out to be real (gas dominated) galaxies!!! (just) beyond Local Group



Bernstein-Cooper+ 2014

Leo P

Discovered in HI
$D \sim 1.7$ Mpc
Diameter ~ 0.8 kpc
$M_V = -9$
$M_{HI} = \sim 10^6\ M_\odot$
$M_{gas}/(M_{gas}+M_{star}) = 0.8$
$N_{HI,peak} = 5 \times 10^{20}\ cm^{-2}$

just factor ~2 larger than Leo T

Suggests that an unknown population of nearby gas-rich dwarfs is still to be discovered through their HI emission

- Many HI clouds do not have an optical counterpart..

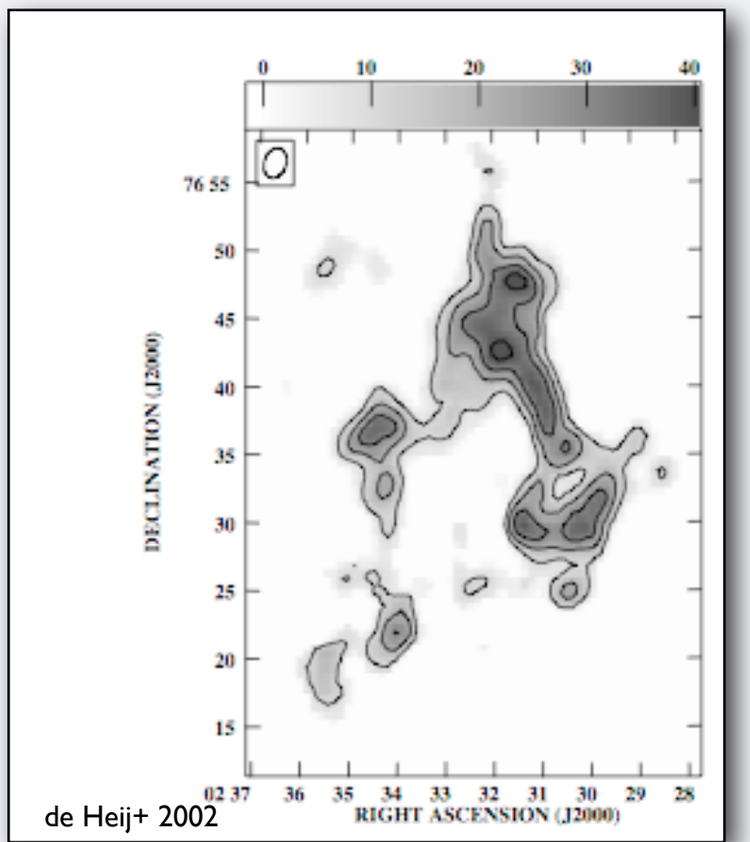
Not clear what they are… distance unknown!!!!

How to proceed?

Can learn more by imaging the HI

Compare HI structure and kinematics with Leo T
and with Galactic clouds

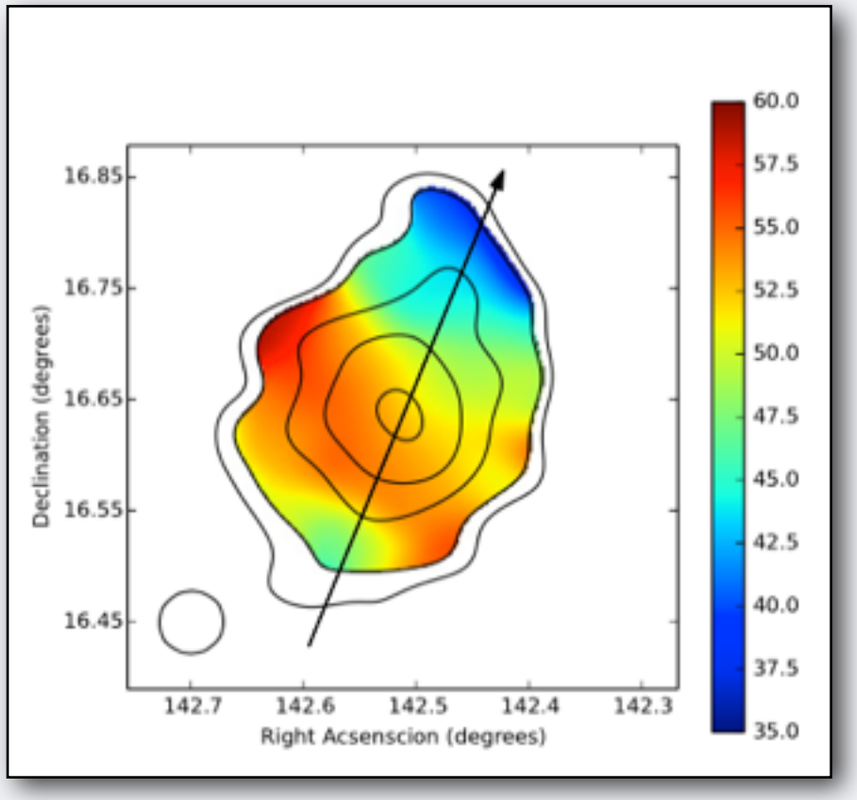
Galactic clouds break up into clumpy mess.
But others look similar to Leo T.
so perhaps some are 'dark' galaxies
but hard to confirm as long as we do not know distance



de Heij+ 2002

typical Galactic HVC:
irregular, clumpy,
multi-phase structure

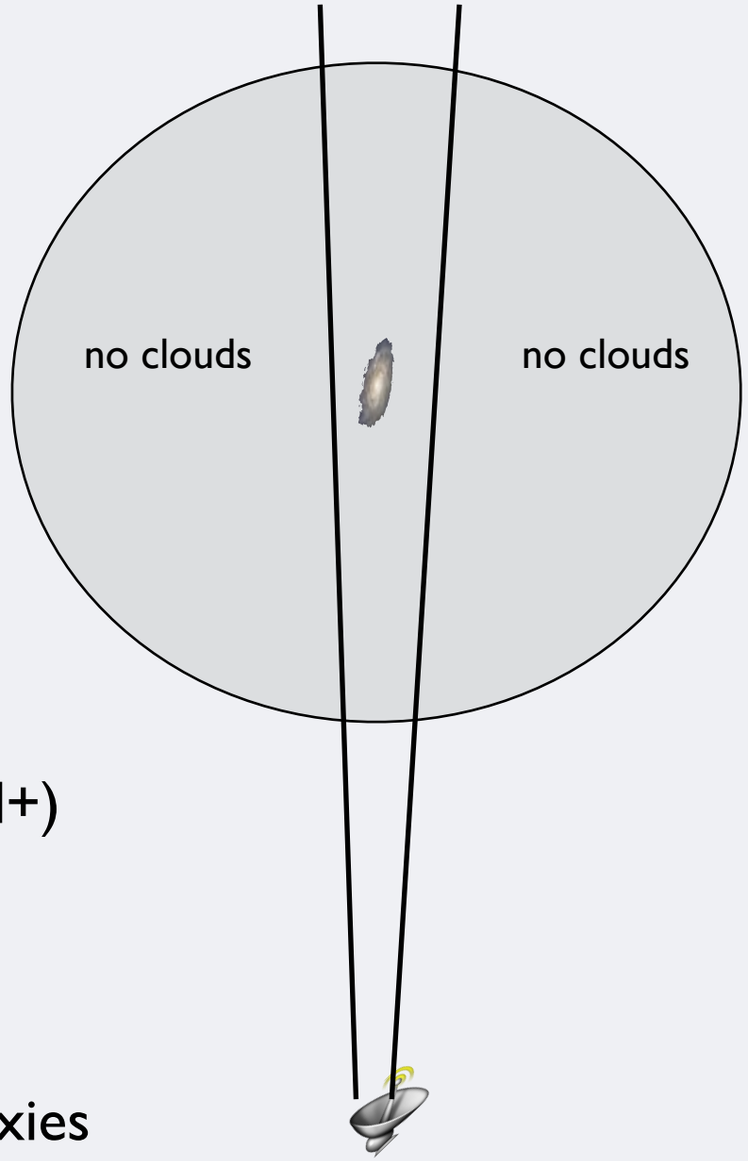
AGC198606
WSRT Adams+ 2015



Smooth, centrally concentrated.
'Friend of Leo T'.
Could have a very faint optical counterpart
at ~ distance of Leo T

Solve distance problem by searching near other galaxies

- Main problem with ALFALFA/GALFA clouds: we do not know the distances…
- Solve this problem by finding similar clouds around other large galaxies with known distances (find the Leo T's around other galaxies)



- Need:
  - sensitivity to detect $10^5\ M_\odot$ at several Mpc
  - clouds are possibly >100 kpc from main galaxy, need large field of view
  - takes a very large amount of observing time…

- earlier searches were over large area but not sensitive enough. some interesting objects found but >(>) $10^7\ M_\odot$ (ALFALFA, Zwaan+, Pisano+,…)

- or were sensitive enough but over too small area (e.g. Halogas; Heald+) none found…

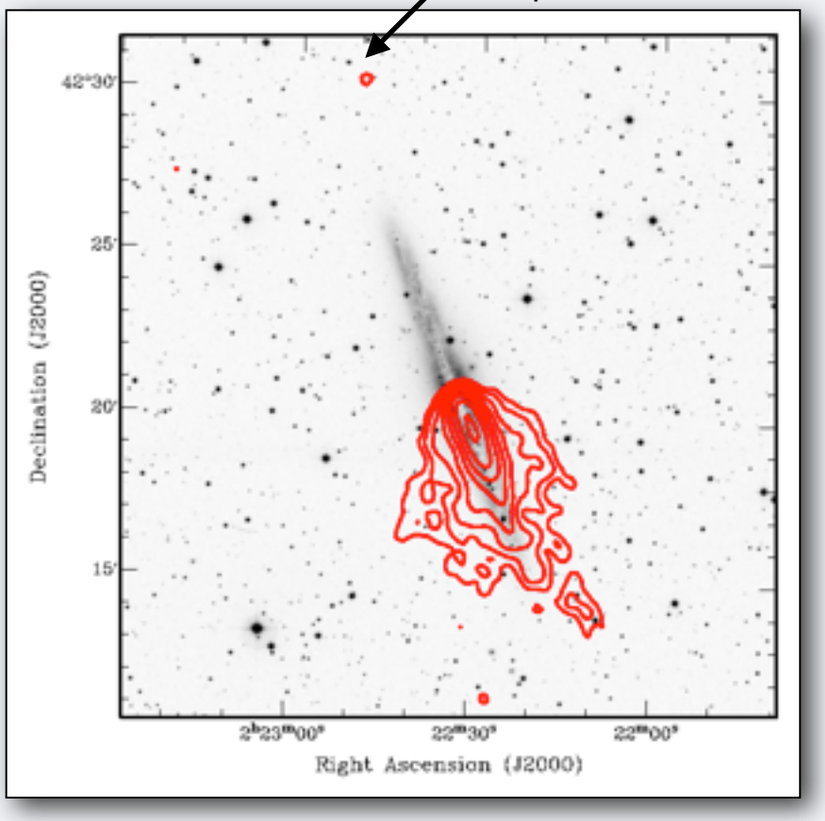
- No constraints yet on how many Leo T's etc exist around other galaxies

- Some tentative candidates
  - NGC 891
  - M101

A few tentative detections of dark objects of the right size

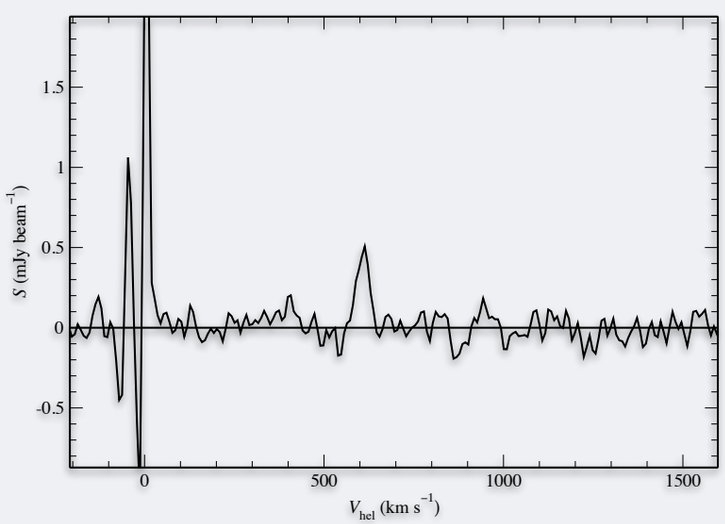
cloud counter rotating

channel from data cube; one of the deepest observations ever

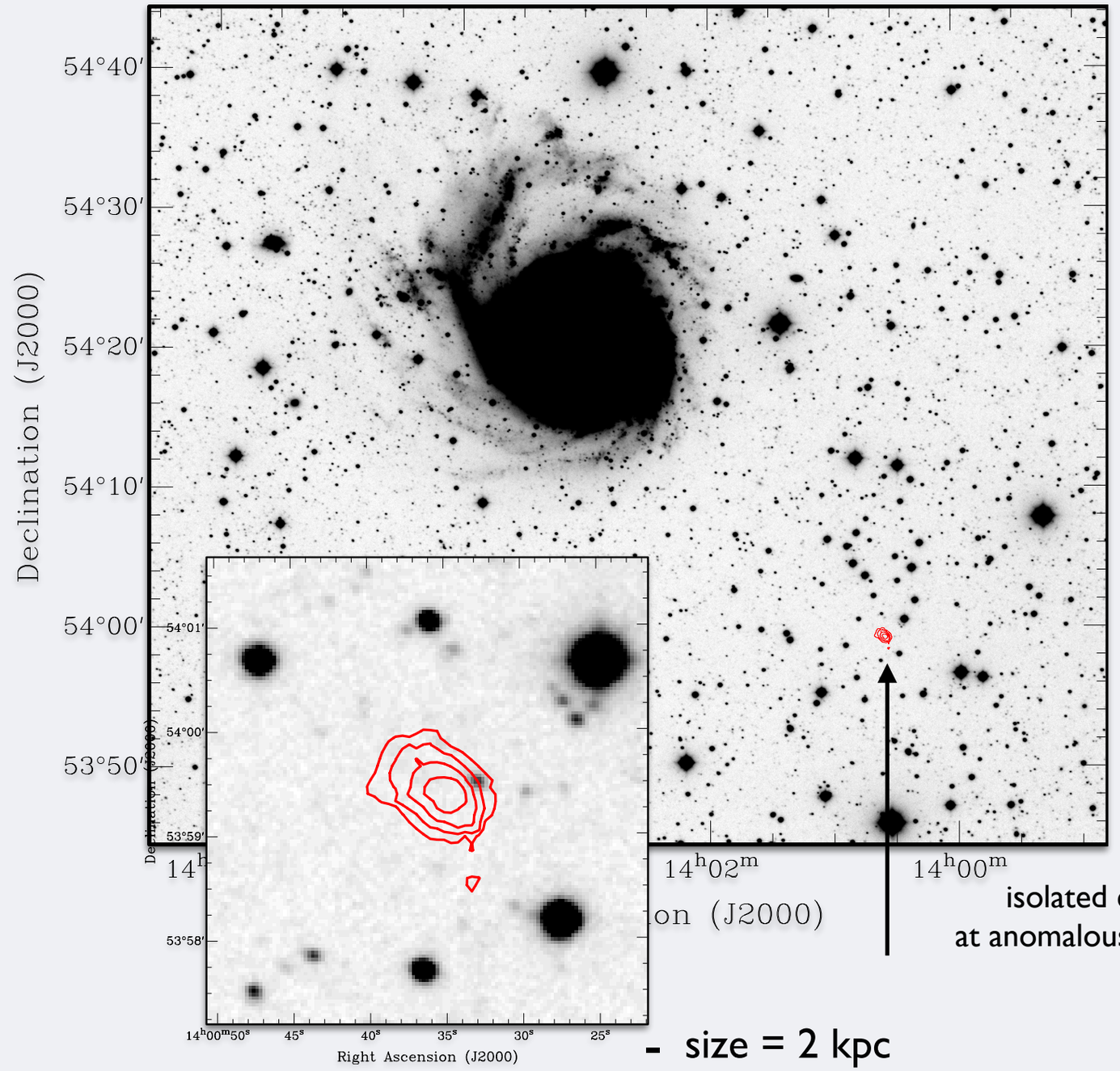


Oosterloo+ 2007

- size = 1 kpc
- M_{HI} = 5 x10^5 $M_\odot$
- $N_{HI,peak}$ = 3 x10^{19} cm^{-2}



Oosterloo+ 2015



isolated cloud
at anomalous velocity

ultra-deep *r*-band image
μ_r >30 mag arcsec^{-2}
Dragonfly (van Dokkum+)

- size = 2 kpc
- M_{HI} = 2 x10^6 $M_\odot$
- $N_{HI,peak}$ = 7 x10^{19} cm^{-2}

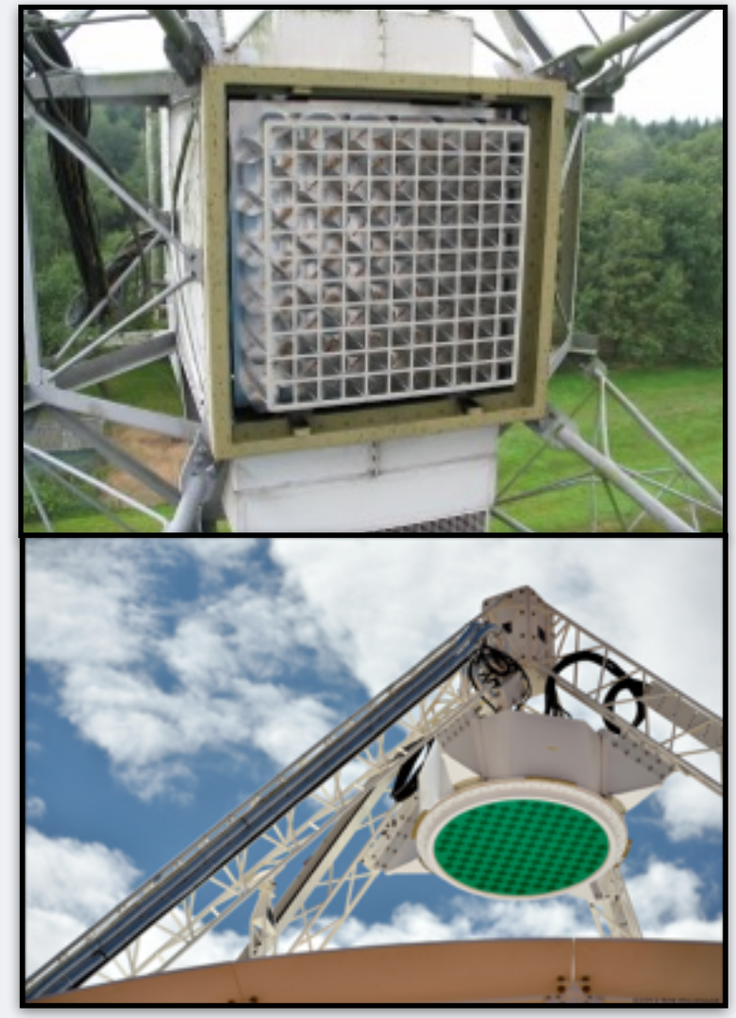
If other galaxies have many gas-rich companions, we soon will find them

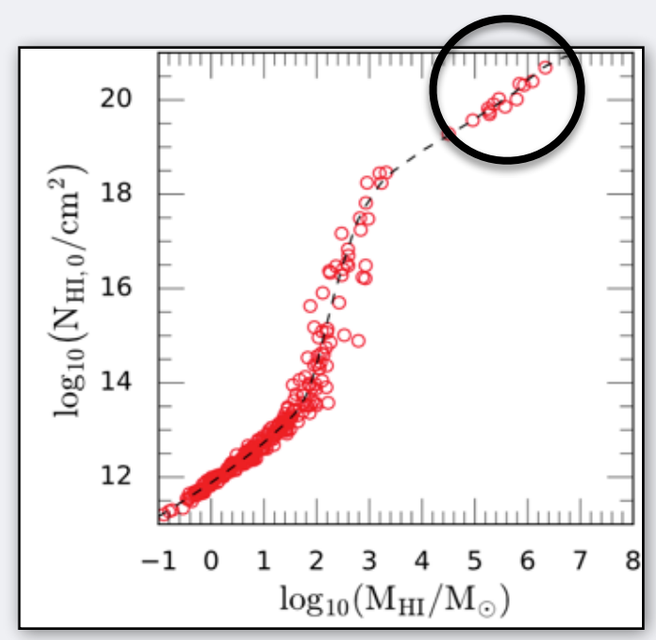
ASKAP (AUS) & Apertif (NL)

phased-array feeds: replace 'single-pixel' detector with an array:
large increase in field of view (x30-60) without (much) loss of sensitivity

Huge improvement in survey speed makes it possible to do 'deep' large-area surveys of local Universe.
10-20 x deeper and 10x better resolution than ALFALFA.
No need for 'expensive' follow up.

will start next year

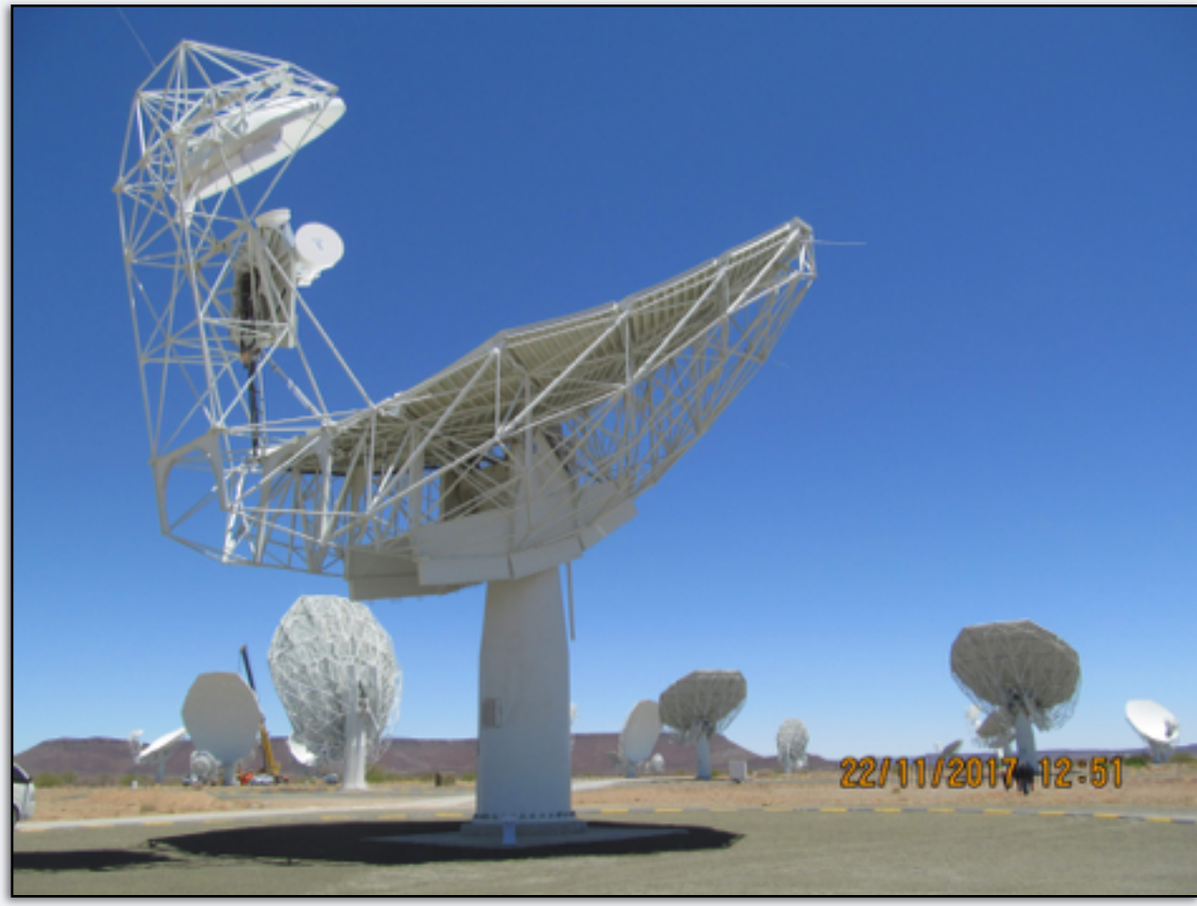




- will give:
  - sensitivity to detect 10^5 $M_\odot$ at several Mpc
  - column density sensitivity ~10^{19} cm^{-2} at <1 kpc resolution
  - large field of view to cover large volume
  - will survey many thousands of deg^2
  - may find the more massive, dark galaxies

Next step: Meerkat

64 dishes of 13.5 m.
Field of view 1 degree^2
First observations with all 64 dishes have been done, expected to start doing real science very soon

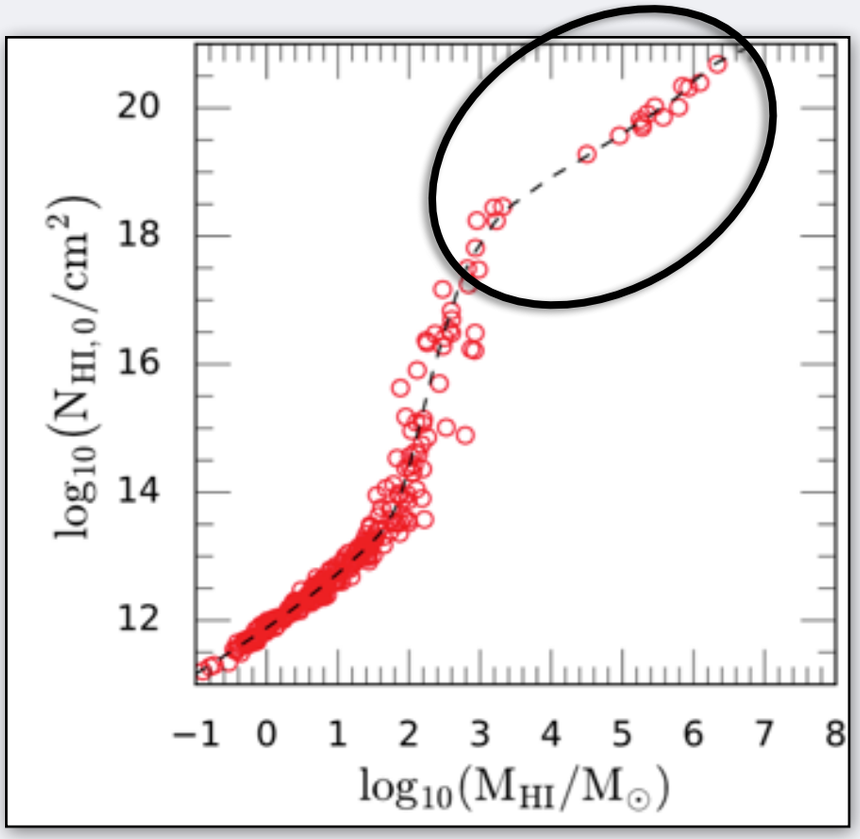


> 10 x more sensitive than ASKAP/Apertif, somewhat better resolution

Because of array layout Meerkat has excellent column density sensitivity $<10^{18}$ cm^{-2} at <1 kpc at several Mpc.

Could detect the fainter population, if it exists

But survey plans not optimal for searching for small galaxies (survey area a bit too small)



The real thing: SKA-mid

~200 dishes of 13.5 - 15 m
Field of view 1 degree^2

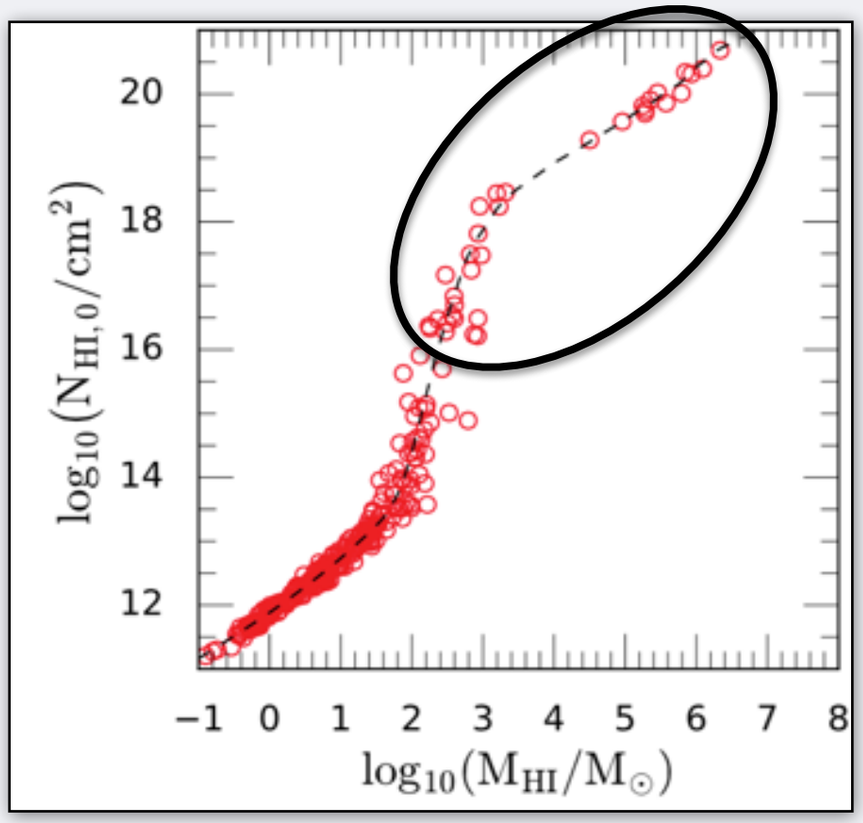
~3 x more sensitive than Meerkat,
(much) higher resolution

SKA surveys not yet defined, but
likely (very) large-area surveys will be done

SKA may detect the lower bound to 'dark' HI galaxies
and tell us what the high-z Universe looked like

Survey	Area (deg^2)	Frea MHz	HI Resolution	<z> (z_{lim})	T (hrs)
Medium wide	400	950-1420	10"	0.1 (0.3)	2000
Medium deep	20	950-1420	5"	0.2 (0.5)	2000
Deep	1 pointing	600-1050	2"	0.5 (1)	3000
Targeted ISM	30 targets	1400-1420	3"-30"	0.002 (0.01)	3000
Targeted Accretion	30 targets	1400-1420	30"-1"	0.002 (0.01)	3000
Galaxy/MS	500	1418-1422	10"-1'	0 (0)	4.500
Galaxy Abs	(5000)	1418-1422	2"	0 (0)	(10.000)
Absorption	1000+	350-1050	2"	1 (3)	1,000+
	1000	200-350	10"	4 (6)	1.000

Updated from Staveley-Smith & Oosterloo, 2015, PoS, AASKA14, 167



Summary

- Most isolated dwarf galaxies are very gas rich
- Very little known about the statistics of objects with $M_{HI} < 10^7\ M_\odot$
  - are they completely gas dominated like Leo T & P?
  - or even optically invisible?
  - or Leo T & P are an exception?

- ALFALFA/GALFA
  - many gas-rich dwarfs still to be discovered near Local Group
  - some interesting candidates for 'dark' galaxies near Local Group have been found
  - main problem: only know the distance if there is a sufficient number of stars

- Have to search near external galaxies
  - currently basically impossible to do
    - but a few tentative candidates found
  - new generation of radio telescopes (Apertif & ASKAP) will make it possible to find the 'tip of the iceberg' objects

  - SKA may detect the lower bound to HI galaxies and tell us about how the smallest galaxies formed at high redshift and how they evolved