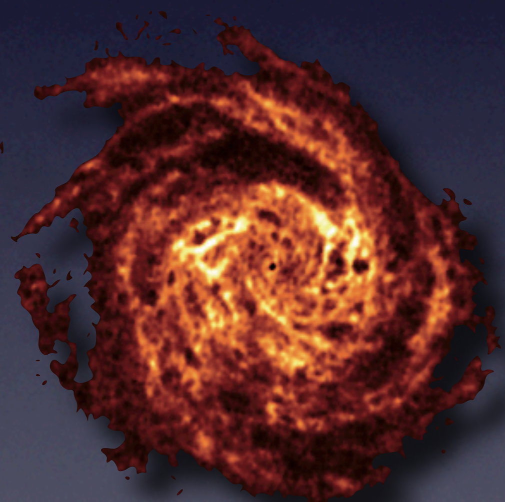
HI Surveys with APERTIF

Marc Verheijen
Tom Oosterloo



Boomsma

Panoramic Radio Astronomy - Groningen, 2-5 Jun 2009

university of groningen / Kapteyn Astronomical Institute
ASTRON
NWO Netherlands Organisation for Scientific Research

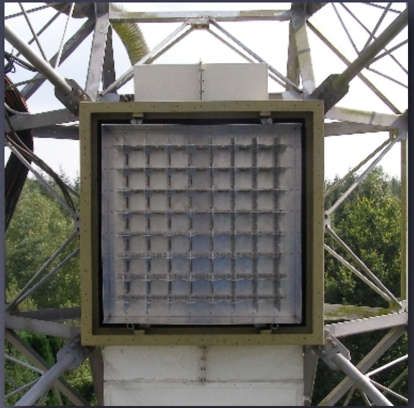
outline

- APERTIF on the WSRT
- Selected surveys
- Role and fate of gas in galaxy evolution
- Examples of existing blind HI synthesis surveys
- Challenges

Salient features of WSRT & APERTIF

- Westerbork Synthesis Radio Telescope
  - 14x25m dishes
    0.7% of collecting area of SKA
  - 3km regular east-west array
    baseline redundancy , no w-term in FFT
  - equatorial mounts
    excellent calibration & polarisation characteristics

- APERture Tile In Focus
  - T_{sys}= 50K , 8 deg^2 FoV , A_{eff}/T_{sys}= 88 m^2/K
  - 1000–1700 MHz , BW=300 MHz , ΔV=16 km/s



Imaging & Survey speeds

APERTIF versus other SKA pathfinders

	T_{sys}	FoV	BW	$(A_{eff}/T_{sys})^2$	$(A/T)^2$ FoV	$(A/T)^2$ FoV BW
	K	deg^2	MHz	$m^4 K^{-2}$	$m^4 K^{-2} deg^2$	$m^4 K^{-2} deg^2$ MHz
				$x10^3$	$x10^4$	$x10^6$
WSRT−14	30	0.28	160	16	0.45	0.72
APERTIF−12	50	8	300	7.8	6.2	19
ASKAP−36	50	30	300	3.7	11	33
MeerKAT−80	30	1.2	1024	40	4.8	49
ATA−42	40	4.9	200	0.43	0.21	0.42

Not *all* SKA pathfinders can do *all* the science...

➥ Specific surveys for APERTIF on WSRT:

- Efficient pulsar survey machine

  intersecting multiple fan-beams in 8gr8 mode

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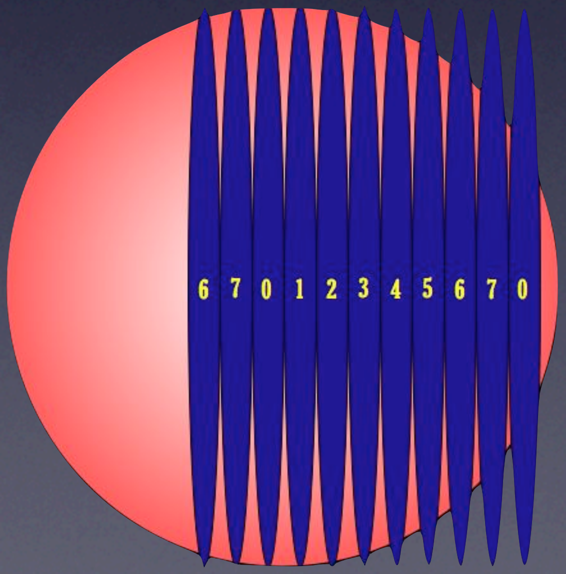
regular 'multi-slit' diffraction grating →



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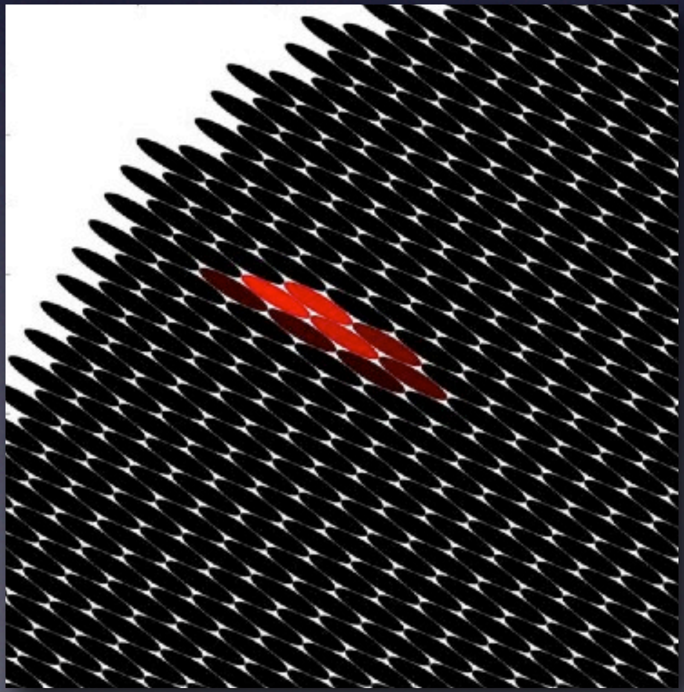

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- Overlap with LOFAR surveys

  all-sky continuum & polarisation survey at 1.4 GHz

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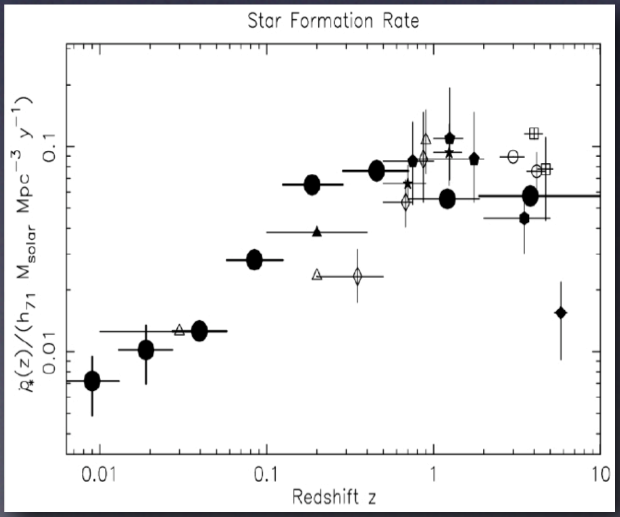
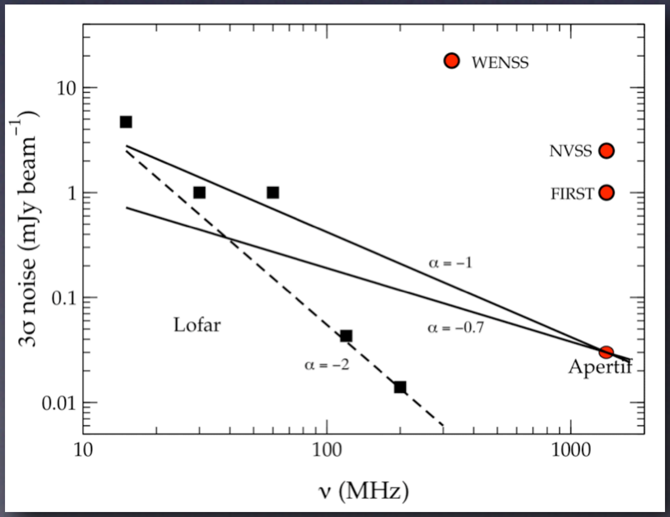


Heavens et al 2004



APERTIF will detect the same star forming galaxies as LOFAR.

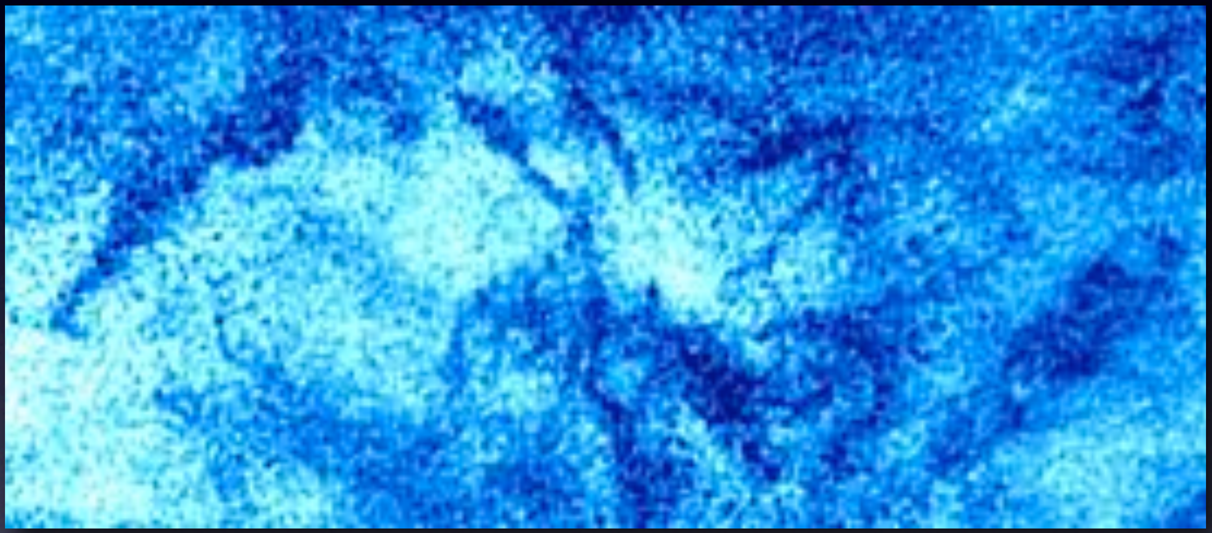
Not *all* SKA pathfinders can do *all* the science...

➥ Specific surveys for APERTIF on WSRT:

- Efficient pulsar survey machine
  - intersecting multiple fan-beams in 8gr8 mode
- Overlap with LOFAR surveys
  - all-sky continuum & polarisation survey at 1.4 GHz
- Selected HI surveys
  - Galactic Plane survey of the outer galaxy
  - Extragalactic HI surveys out to z=0.5

HI self-absorption
in DRAO and VLA Galactic Plane Surveys

DRAO - Canadian Galactic Plane Survey

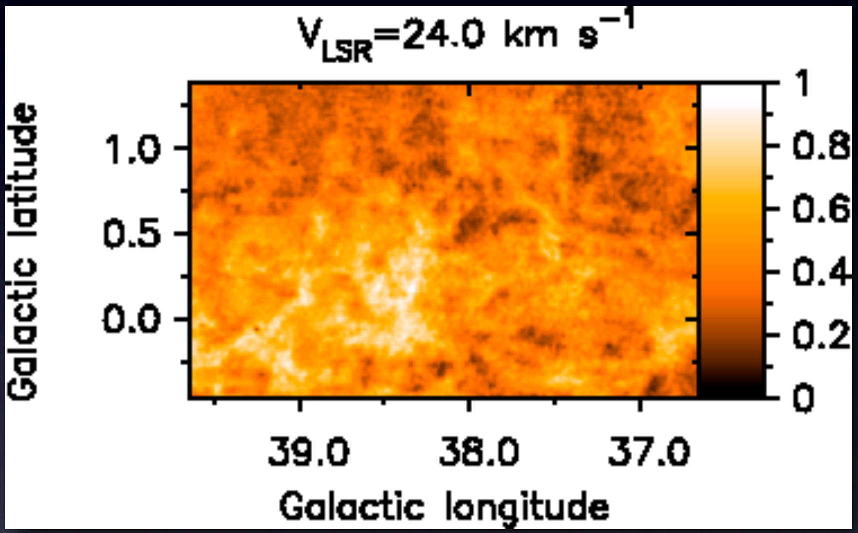


Taylor et al, 2003

θ =1 arcmin , ΔV=1.2 km/s , FoV=107′

T_{int} = 12x12^{hr}/field, 7x9m dishes, $A_{eff}/T_{sys} \approx 5.7$

VLA



Stil et al, 2006

θ =1 arcmin , ΔV=1.5 km/s , FoV=32′

T_{int} = 9^{m}/field, 27x25m dishes, $A_{eff}/T_{sys} \approx 210$

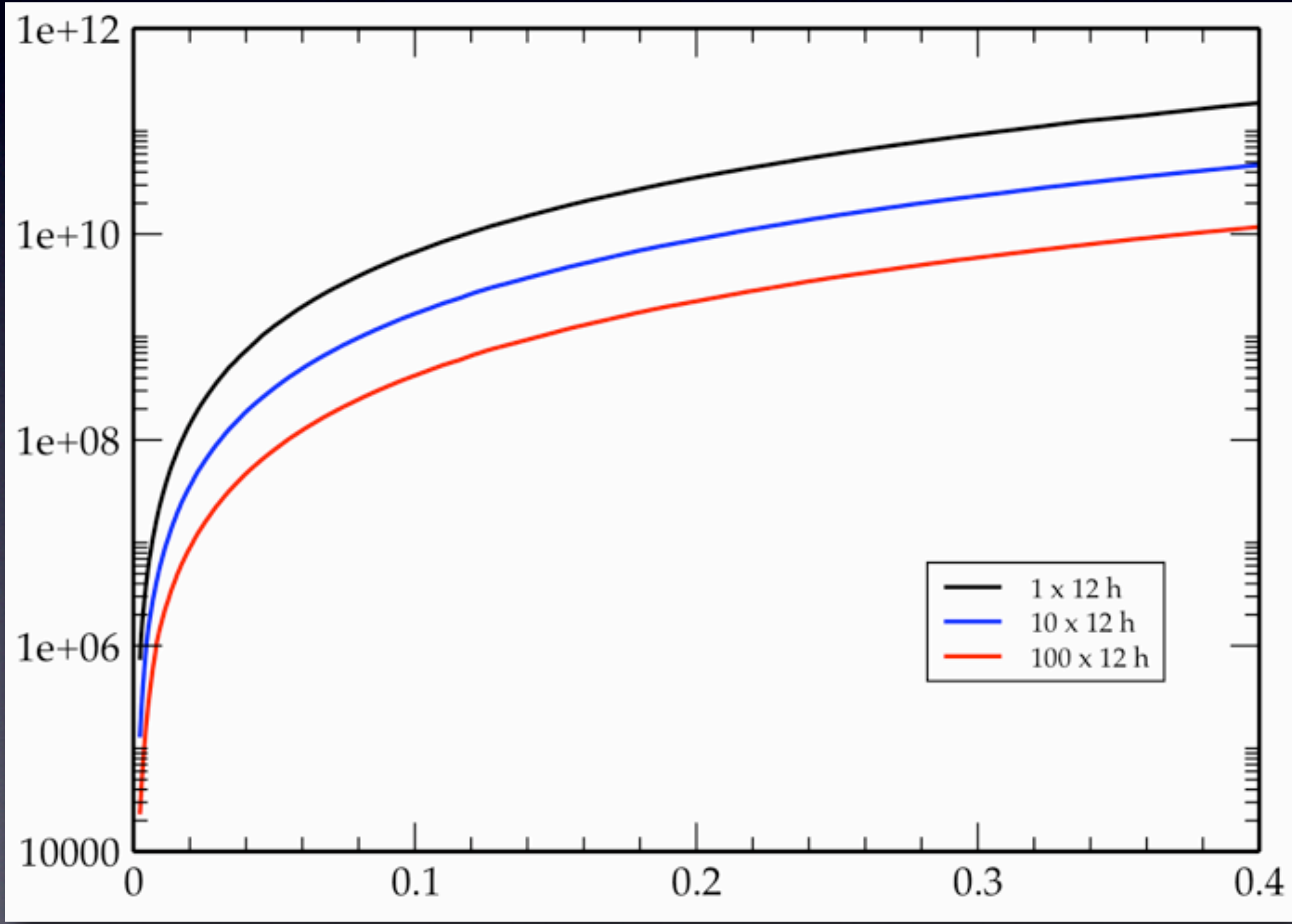
Based on $(A_{eff}/T_{sys})^2\, \Omega_{FoV}$: APERTIF survey speed ≈ 550 x DRAO

5 x VLA

Extragalactic large-area blind HI surveys

APERTIF HI mass limits versus redshift

5σ detection in HI mass dependent linewidth



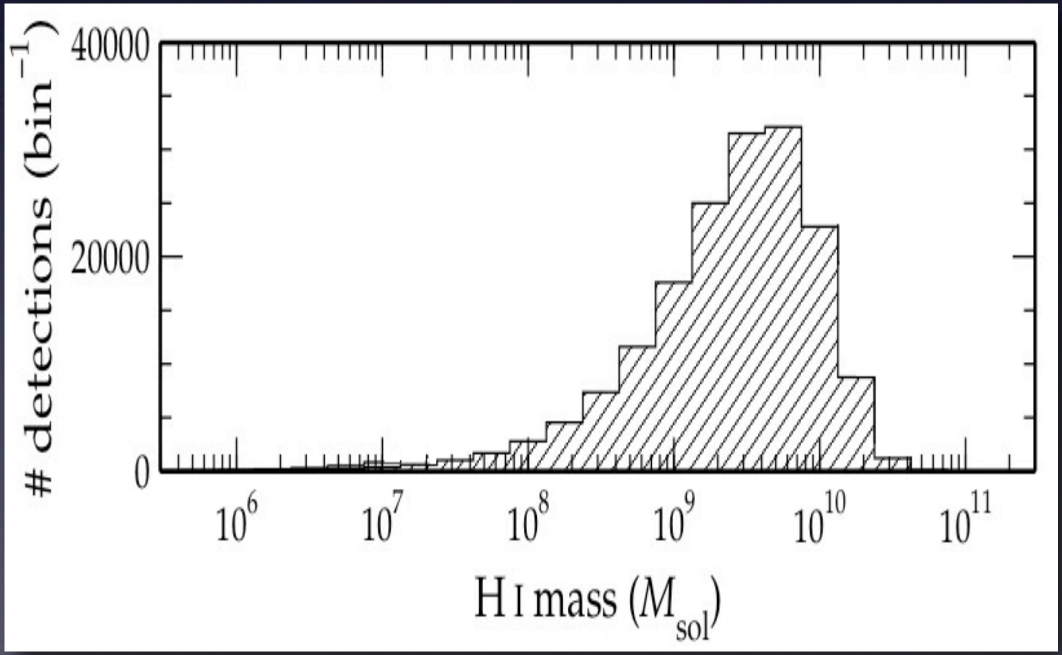
M_{HI} (M_{sun})

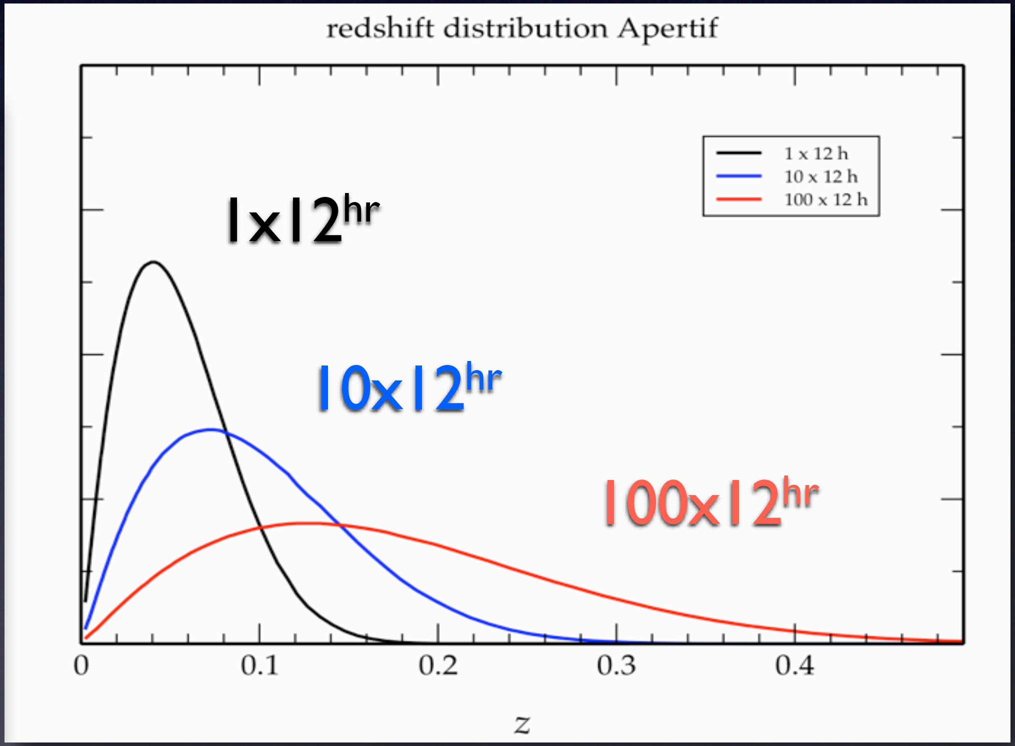
Redshift

Extragalactic large-area blind HI surveys

APERTIF HI detected mass & redshift distributions

all-sky survey, 1x12^{hr} per pointing





Extragalactic large-area blind HI surveys

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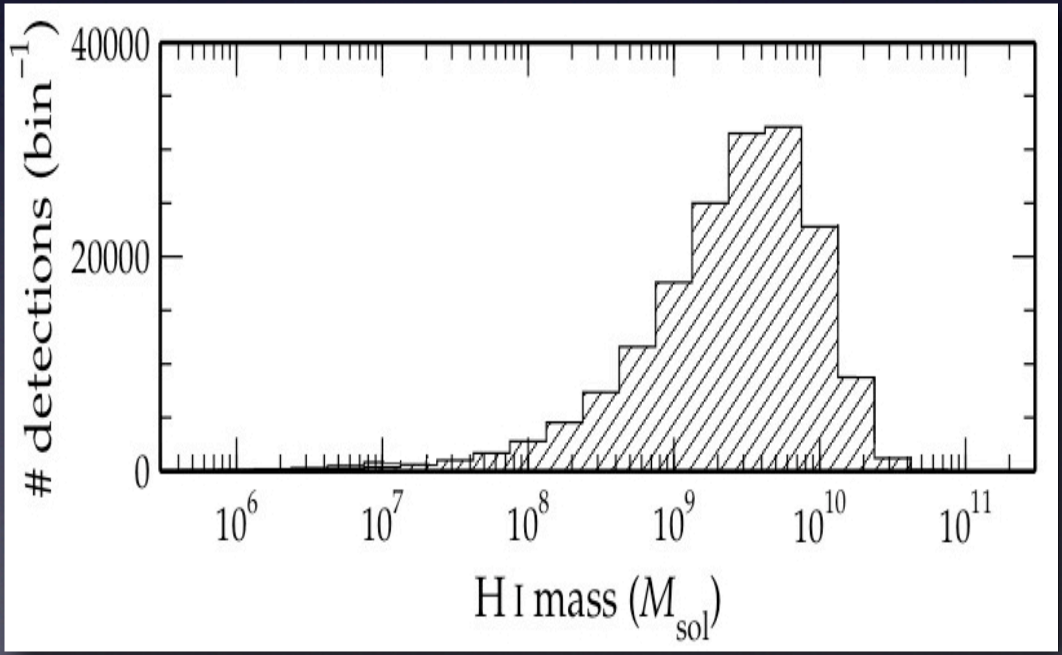
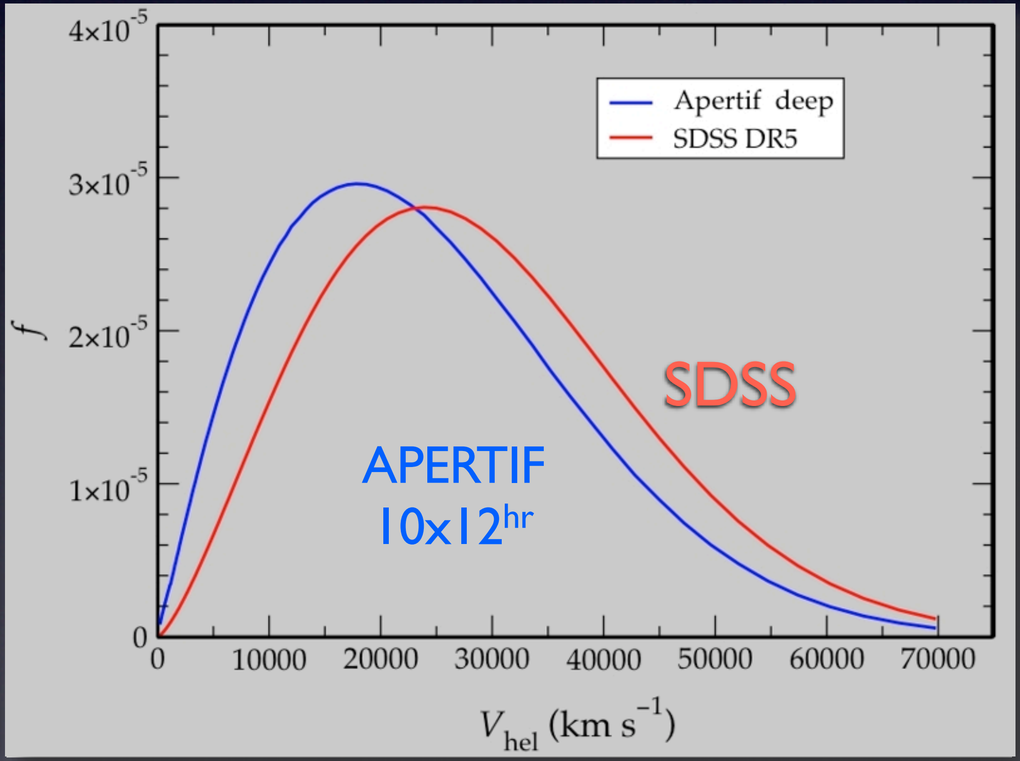


Matching SDSS redshift distribution

Z=0.0 0.1 0.2



WSRT + APERTIF located in northern hemisphere

Take advantage of SDSS

$8^{hr} < \alpha < 16^{hr}$, $15° < \delta < 60°$

4100 deg^2 → ~500 pointings

4 years @ 30% of time

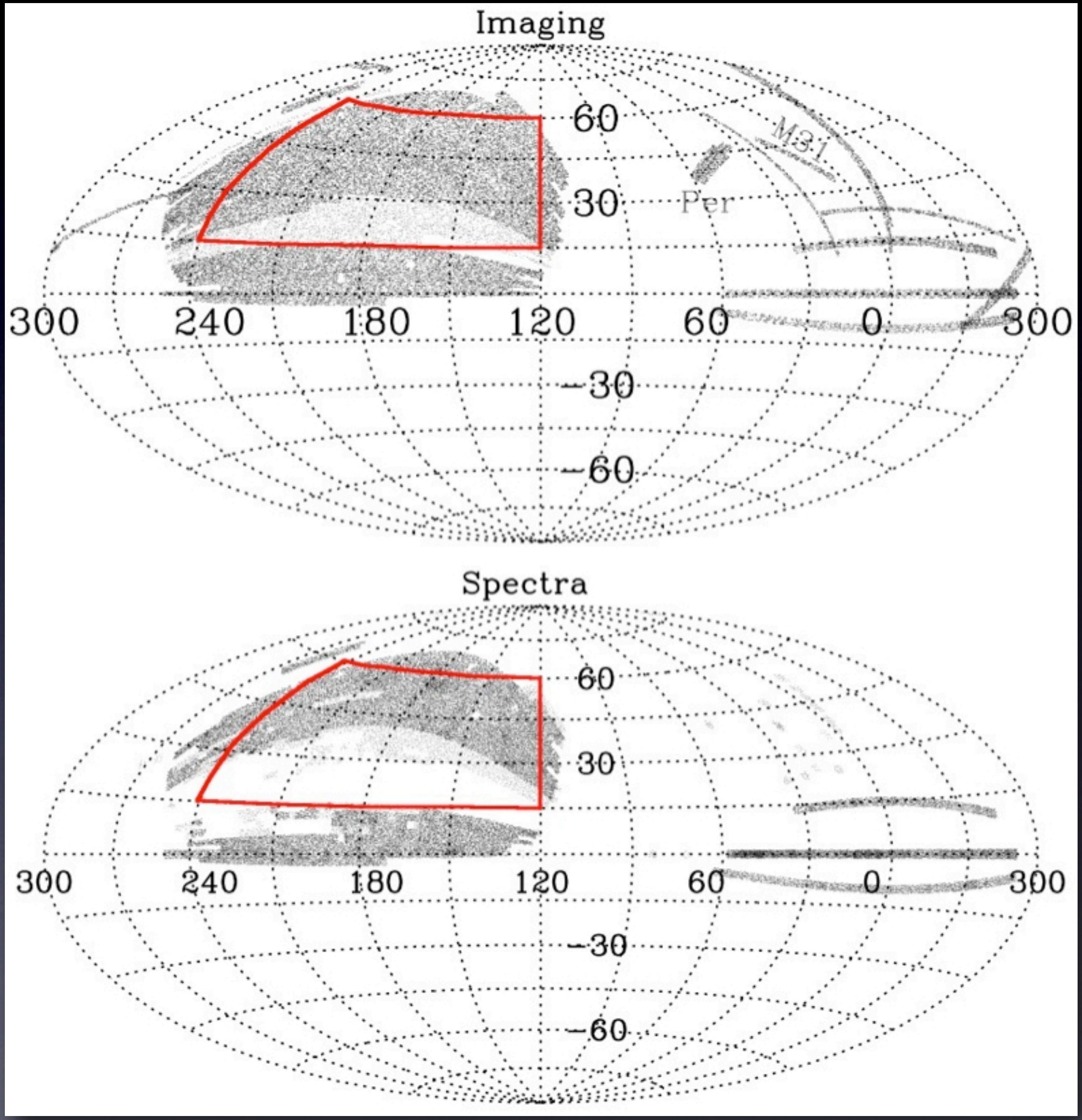
$0 < Z < 0.25$ (300 MHz)

203,425 optical SDSS redshifts

at $z < 0.2$ (DR5)

M^*_{HI} at $z = 0.08$

expect ~10^5 HI detections



SDSS-Data Release 5 paper

Spectroscopy completed with DR7

The promise of blind HI synthesis imaging surveys

- Nature of galaxy bimodality

  How to sustain star formation in the 'blue cloud'?

  What happens to galaxies when they migrating to the red sequence?

  What can we learn from 'fossil records' of cold gas in 'red & dead' galaxies?

  Examine cold gas in relation to SFR, age of stellar populations, dust (IRAS) etc

- Environmental dependence of gas content

  What is the HI Mass Function in different environments

  What is the origin of HI deficiencies in high density regions (stripping, harassment, ...)?

  How effective is pre-processing in cluster outskirts and galaxy groups (tidal)?

  What physical processes dominate gas removal where?

- Resolved galaxy structure and kinematics

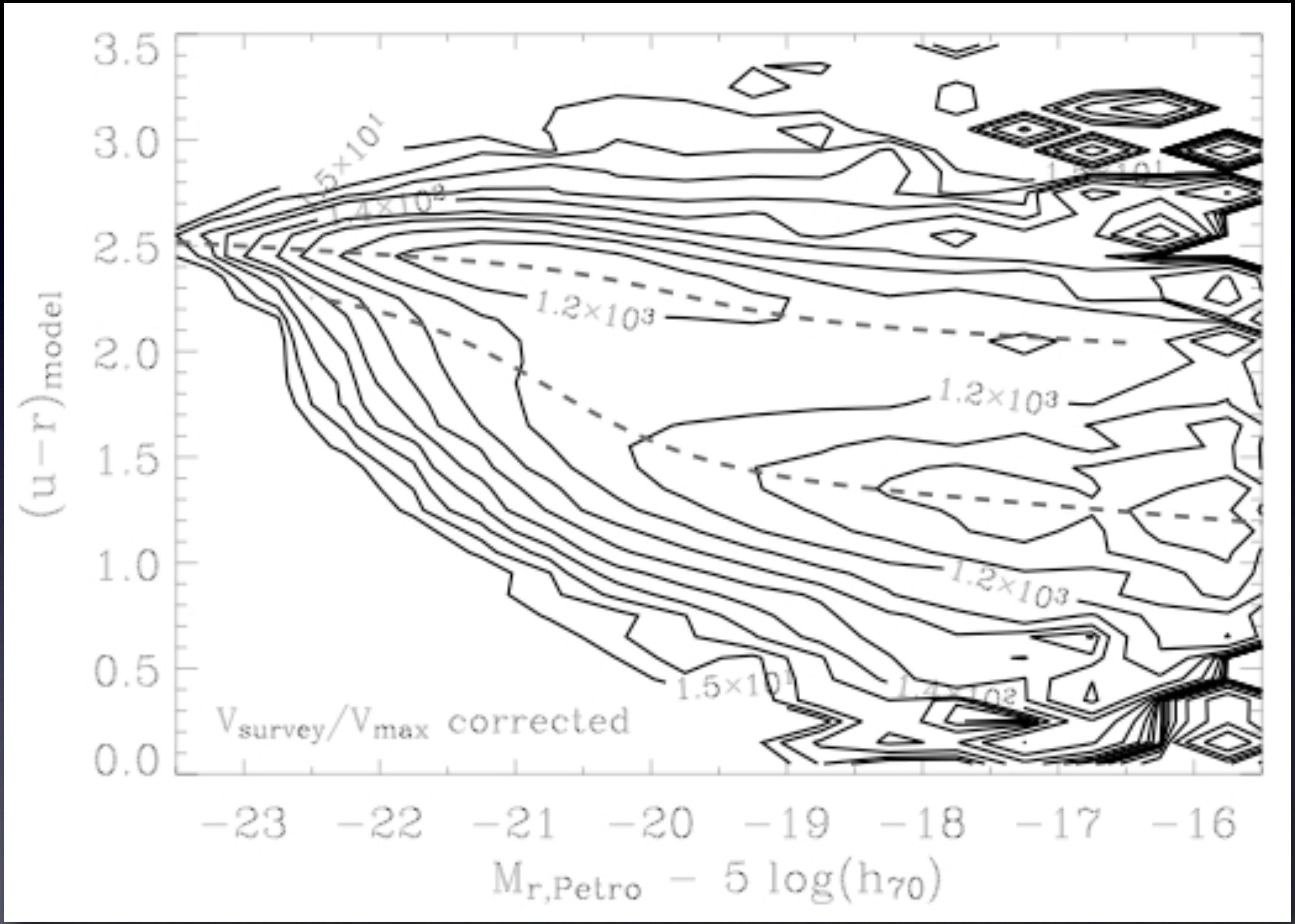
  Obtain an unbiased census of warps, lopsidedness, interactions

  Determine rotation curves and mass profiles probing dark matter halos

  Measure spin vectors & angular momentum (cosmic shear, structure formation)

  ....

central question: What is the role and fate of gas in galaxy formation & evolution?



Baldry et al 2004

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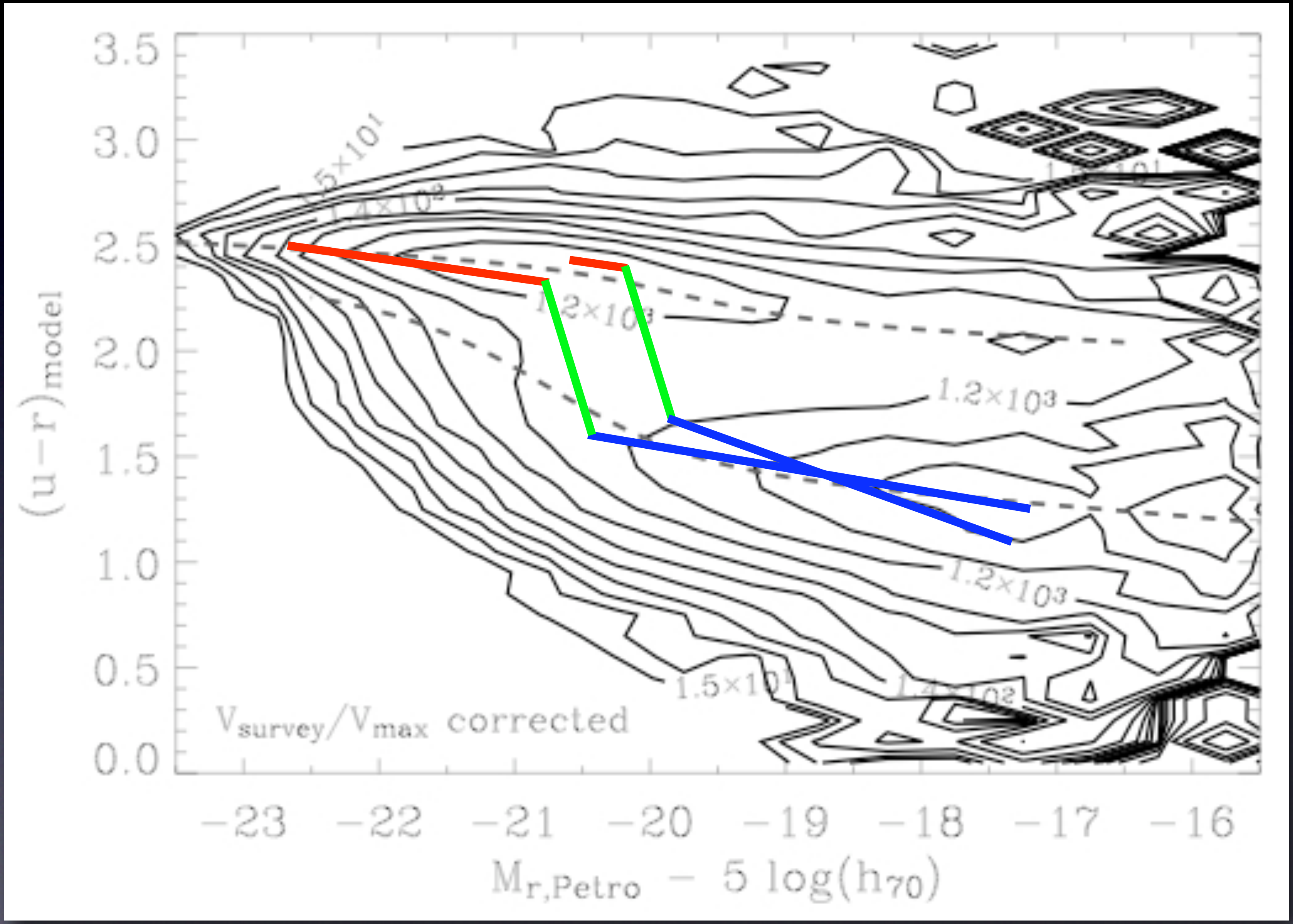

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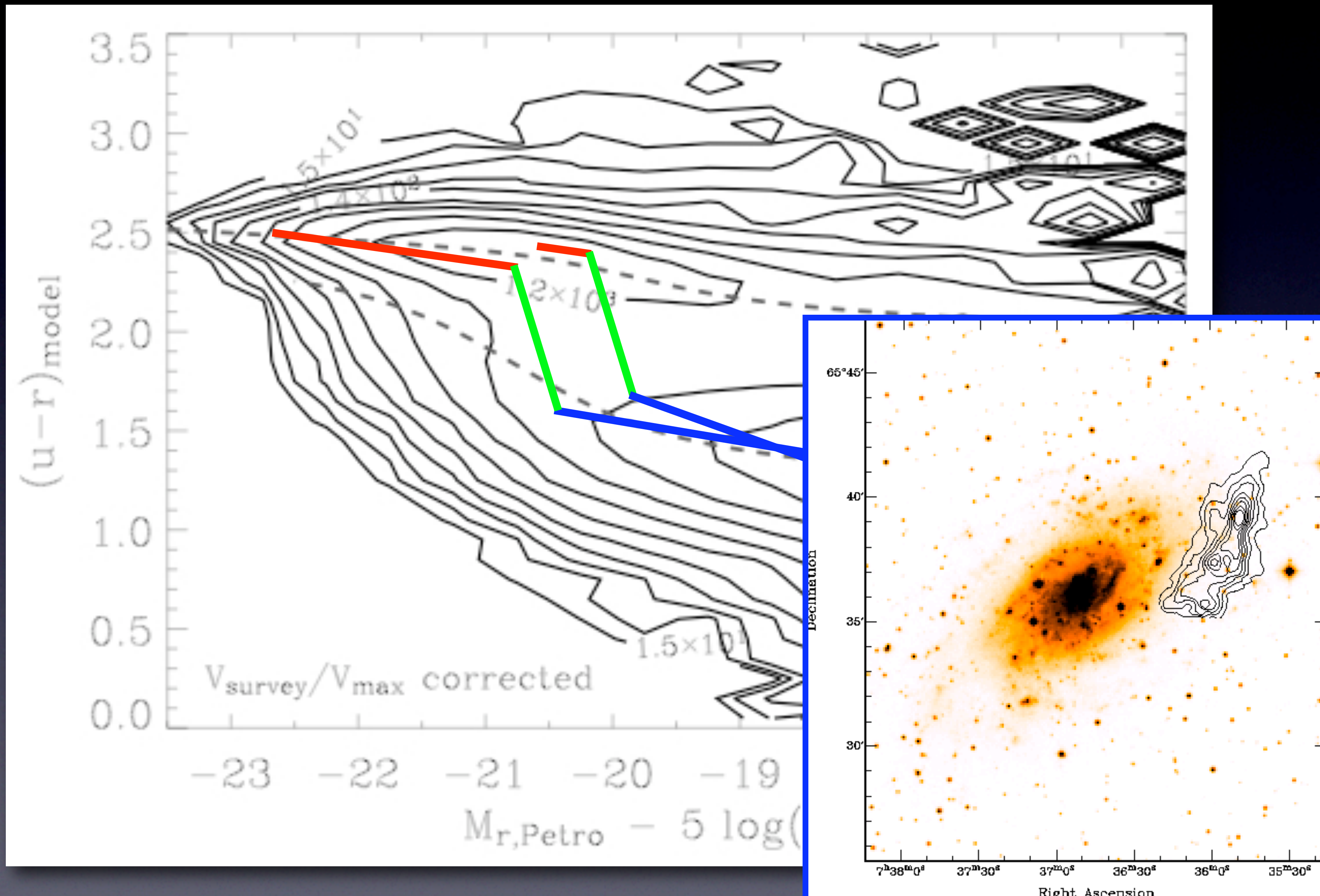

Fraternali et al 2002

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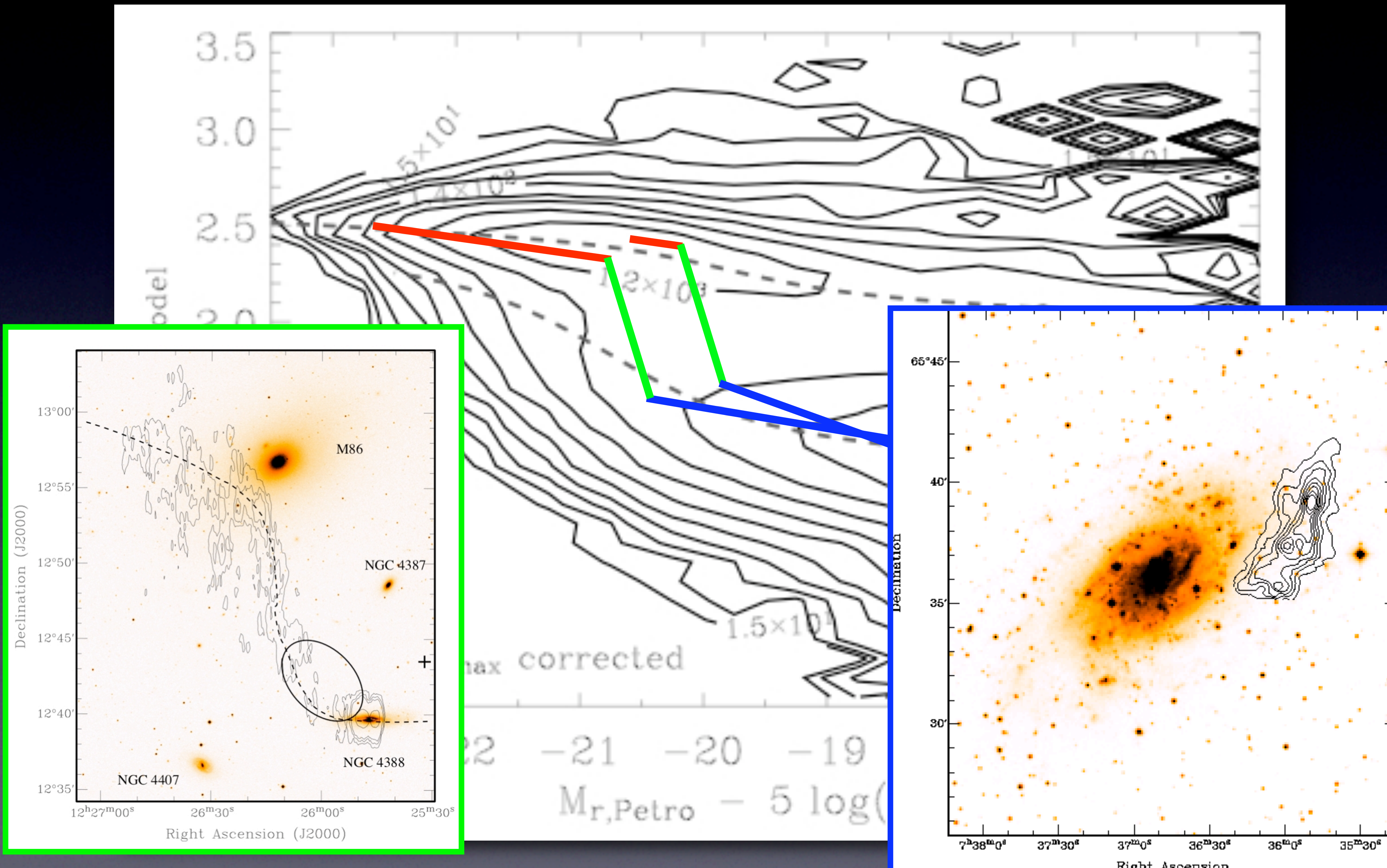
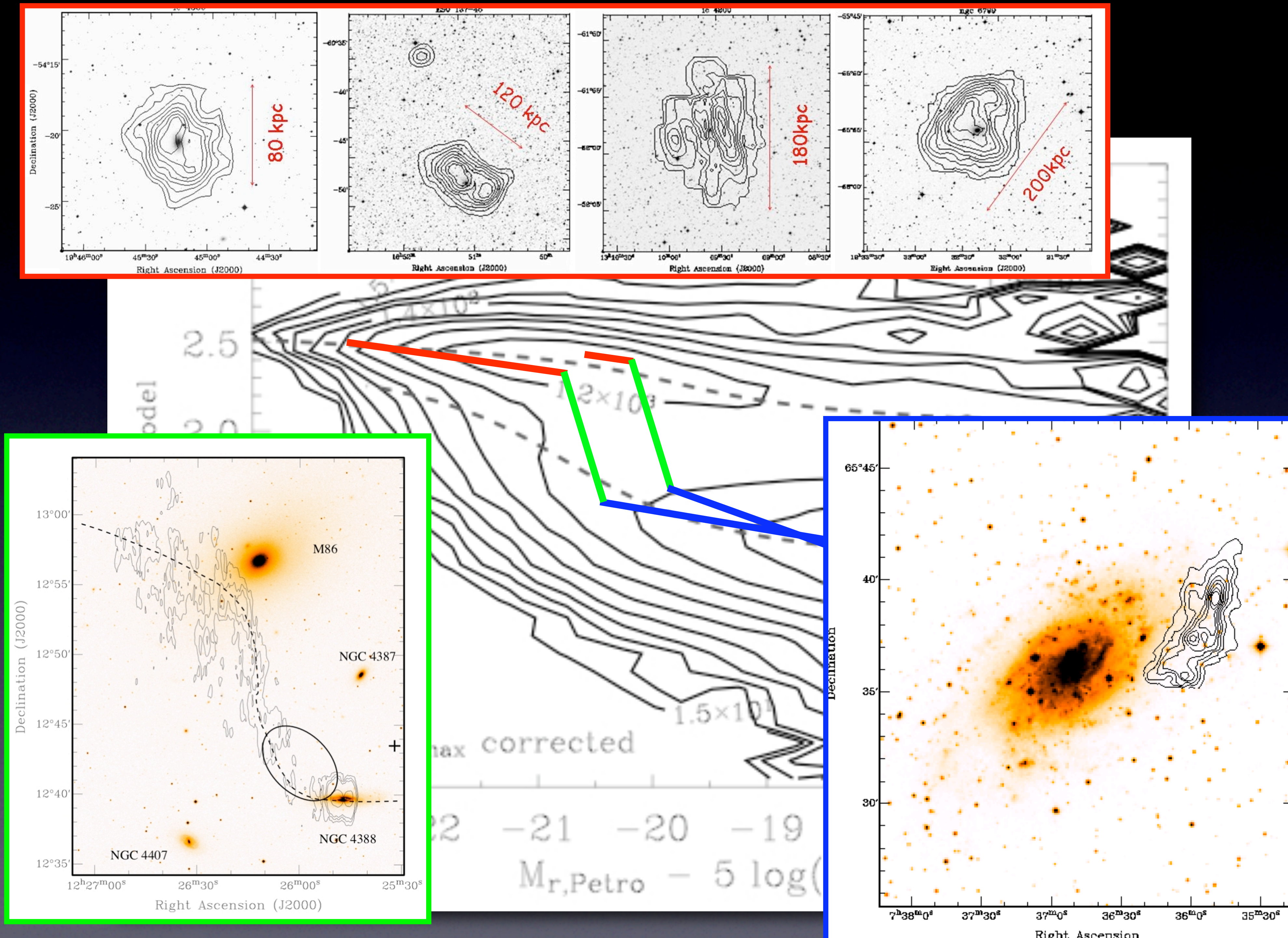


Oosterloo & van Gorkom 2005

Fraternali et al 2002

Oosterloo et al 2007



Oosterloo & van Gorkom 2005

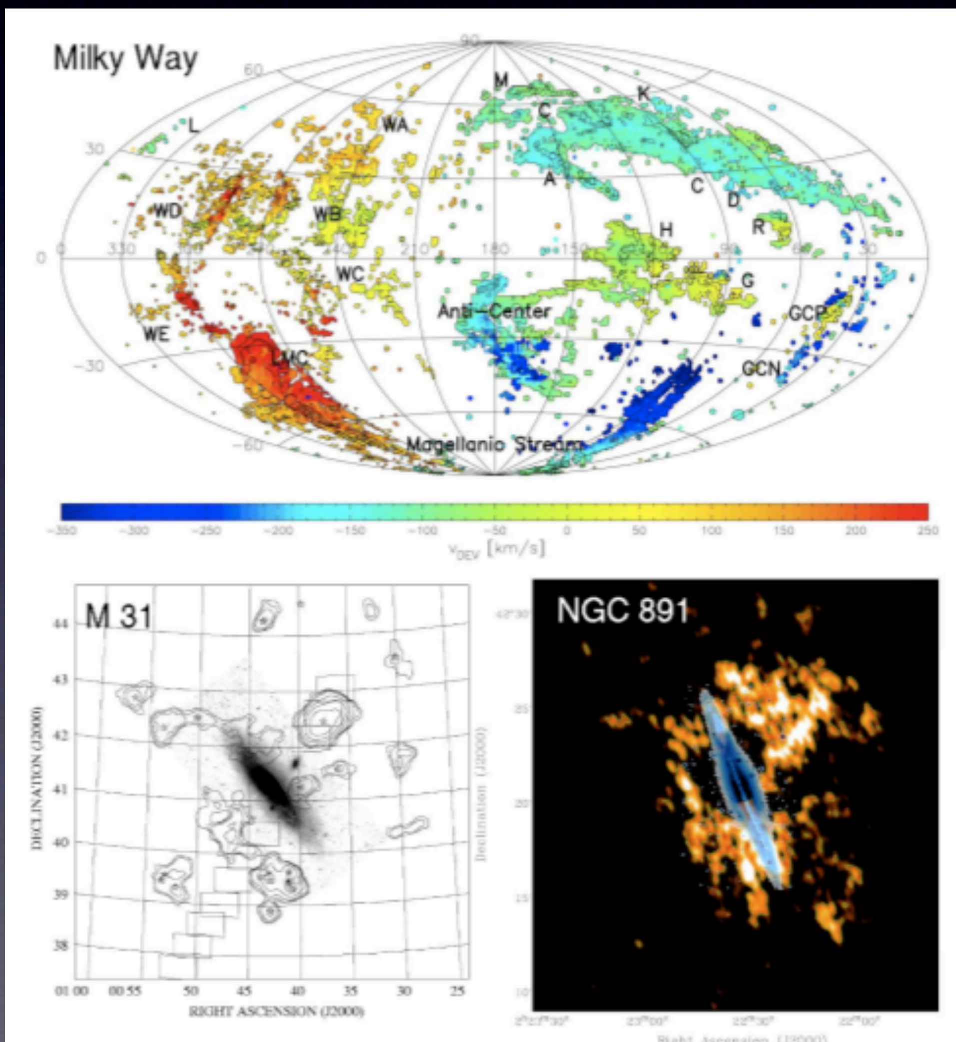
Fraternali et al 2002

Fueling the Blue Cloud
sustaining star formation
building up stellar mass

High Velocity Clouds
in MW and other galaxies

van Woerden et al 2004

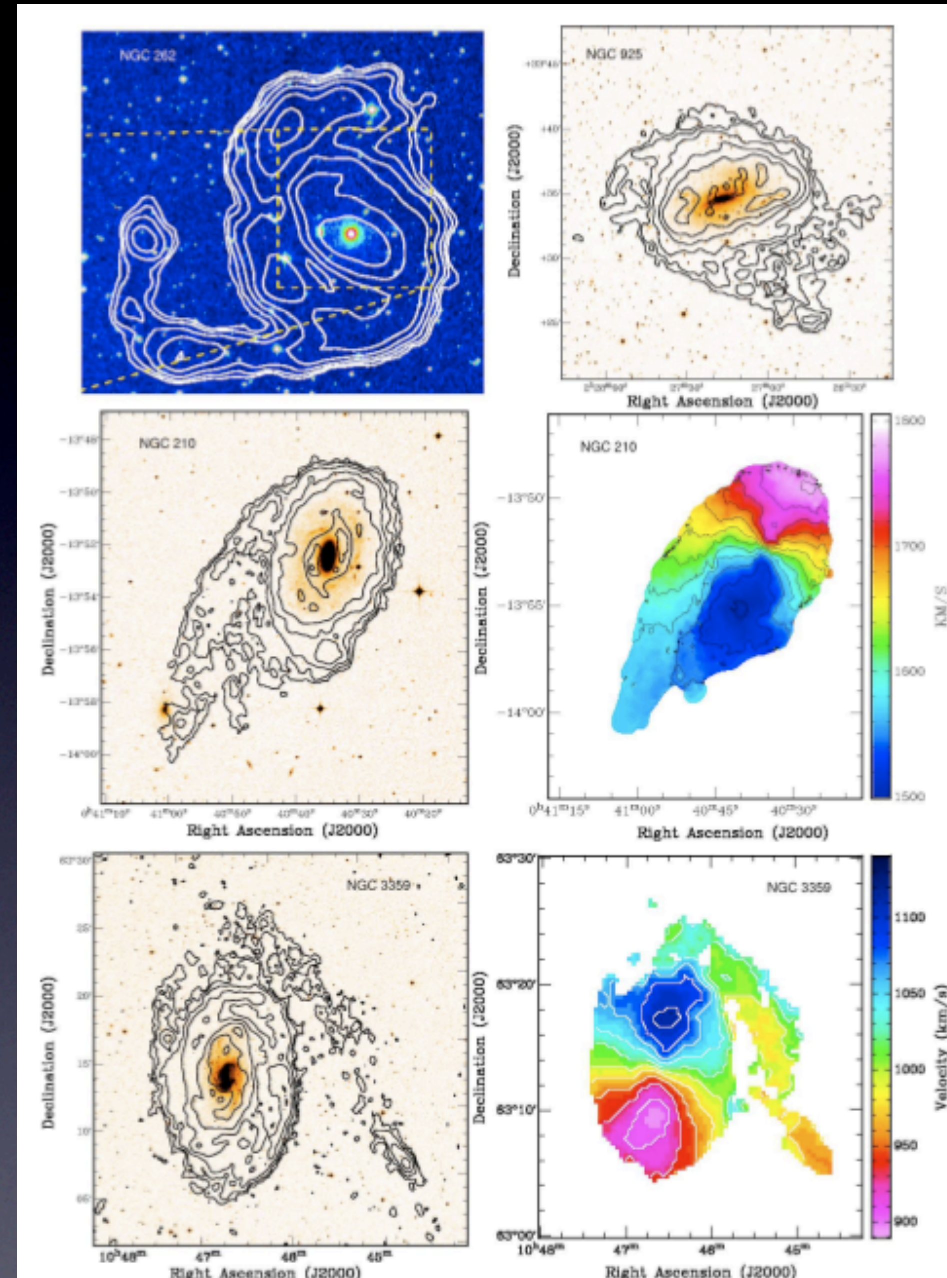
Thilker et al 2004



Oosterloo et al 2007

Late stages of gas accretion or
minor mergers

Simkin et al 1987



Sancisi et al 2008

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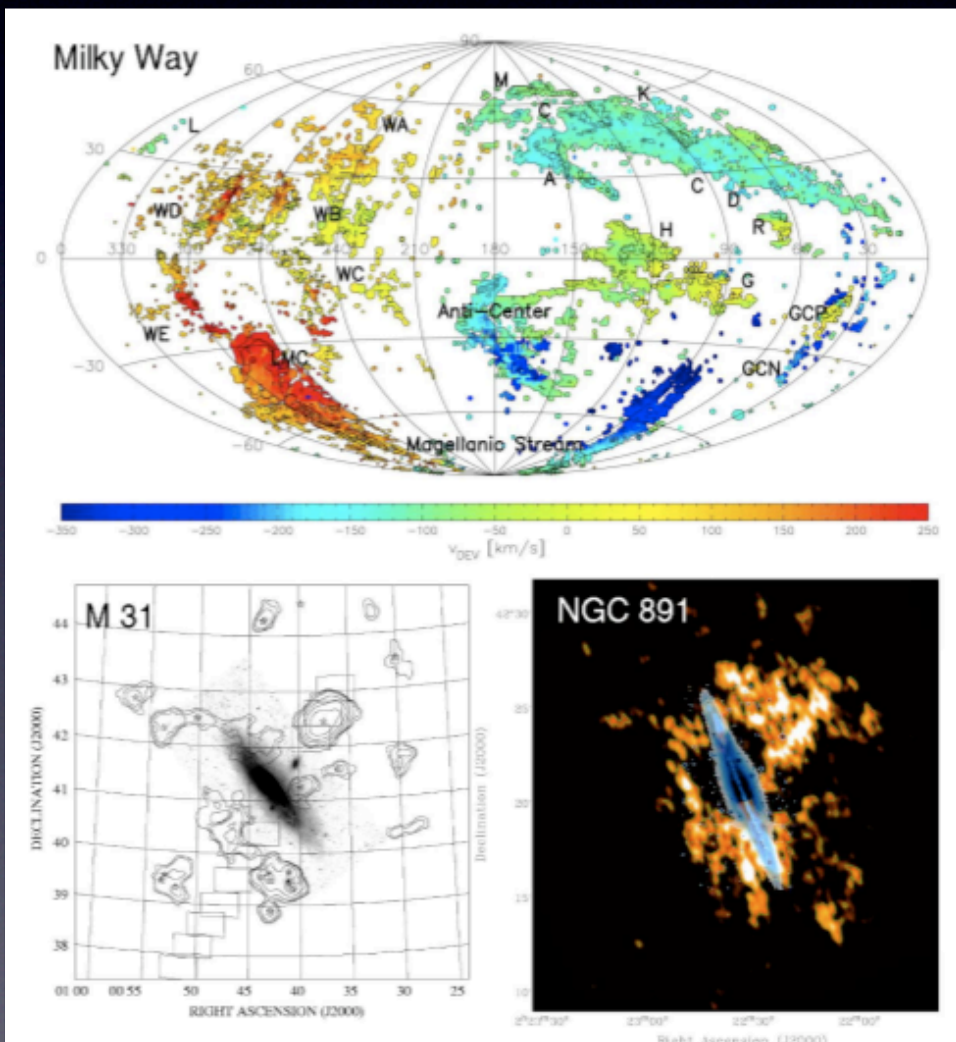

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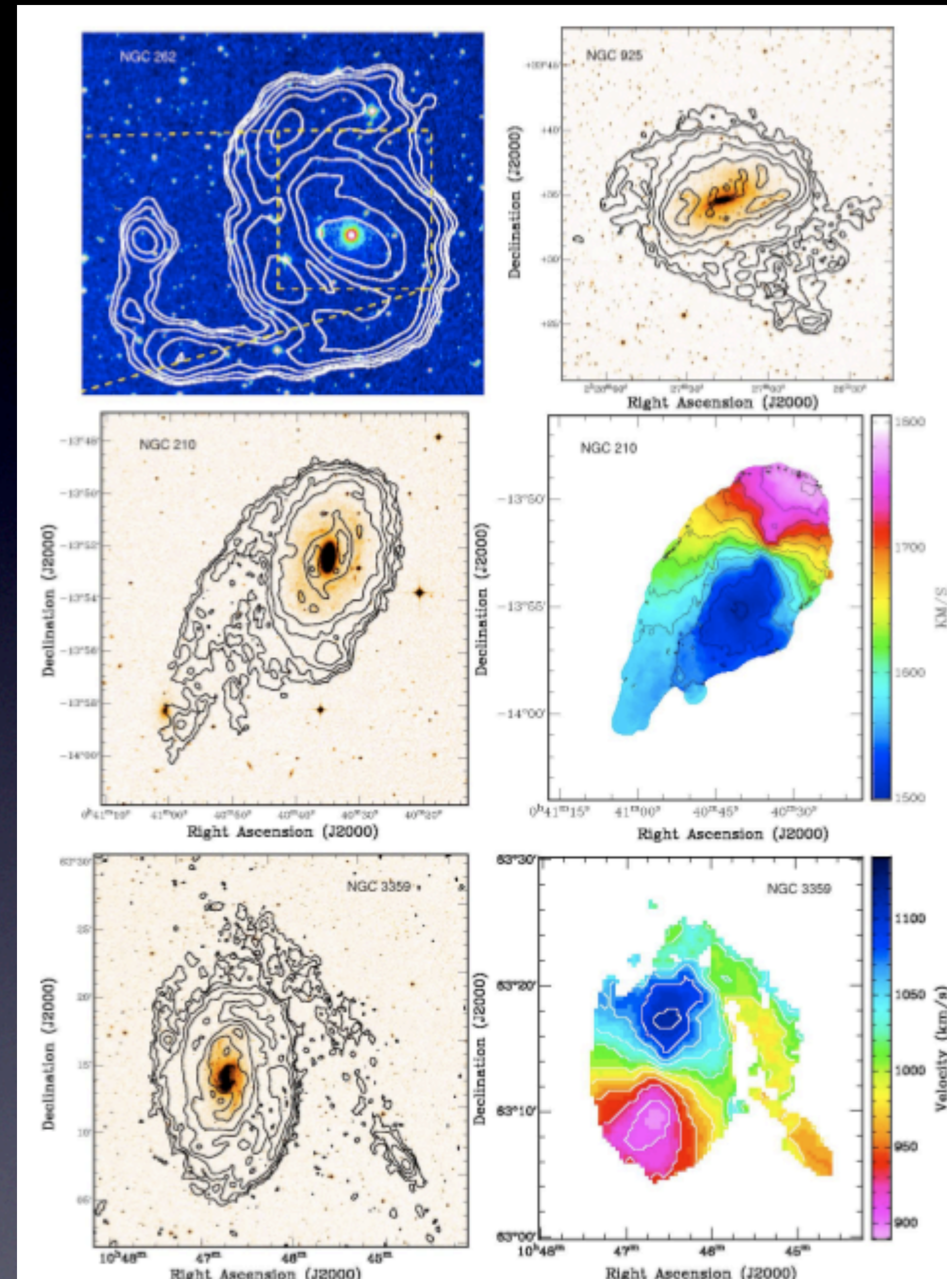


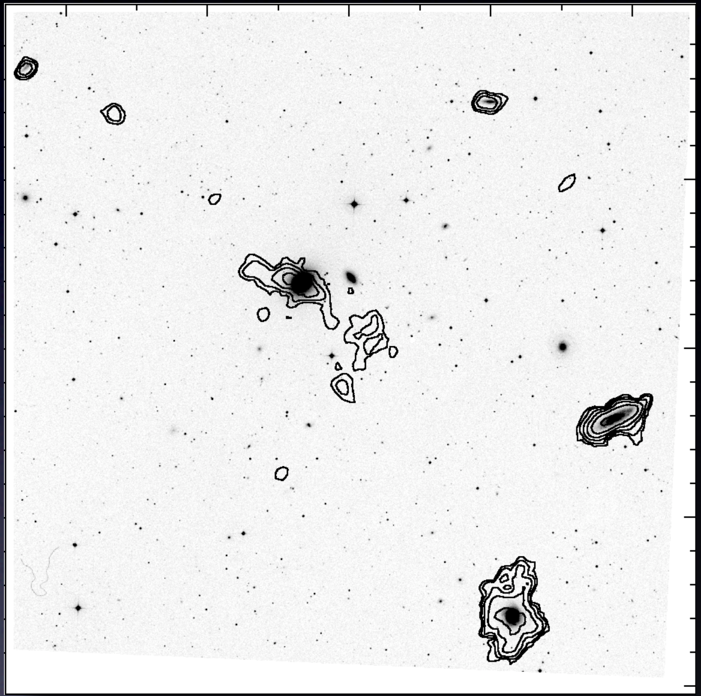
Sancisi et al 2008

APERTIF will provide a full census.

The brightest lenticulars in Ursa Major

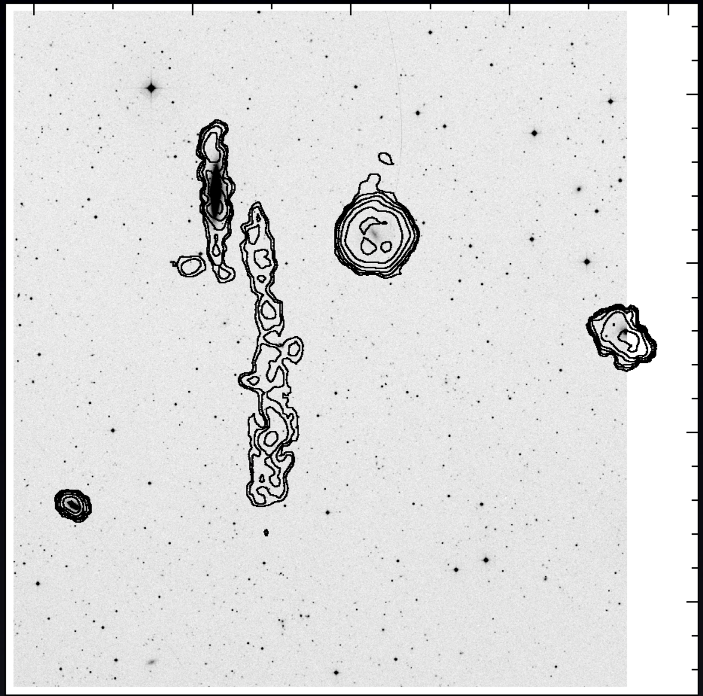
Hot action in a cool group

NGC 3998



$$M_R = -21.84 \text{ (mag)}$$
$$M_{HI} = 5.8 \times 10^8 (M_\odot)$$

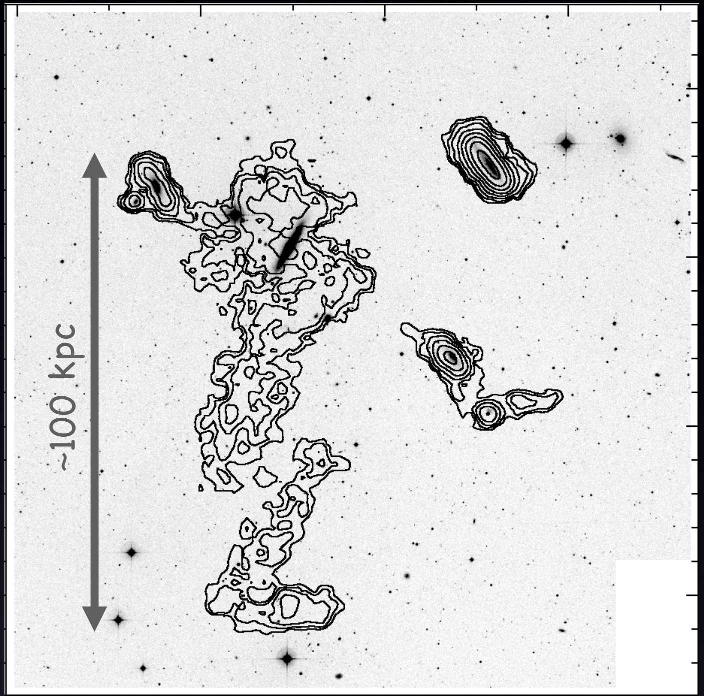
NGC 4026



$$M_R = -21.16 \text{ (mag)}$$
$$M_{HI} = 1.2 \times 10^9 (M_\odot)$$

NGC 4111

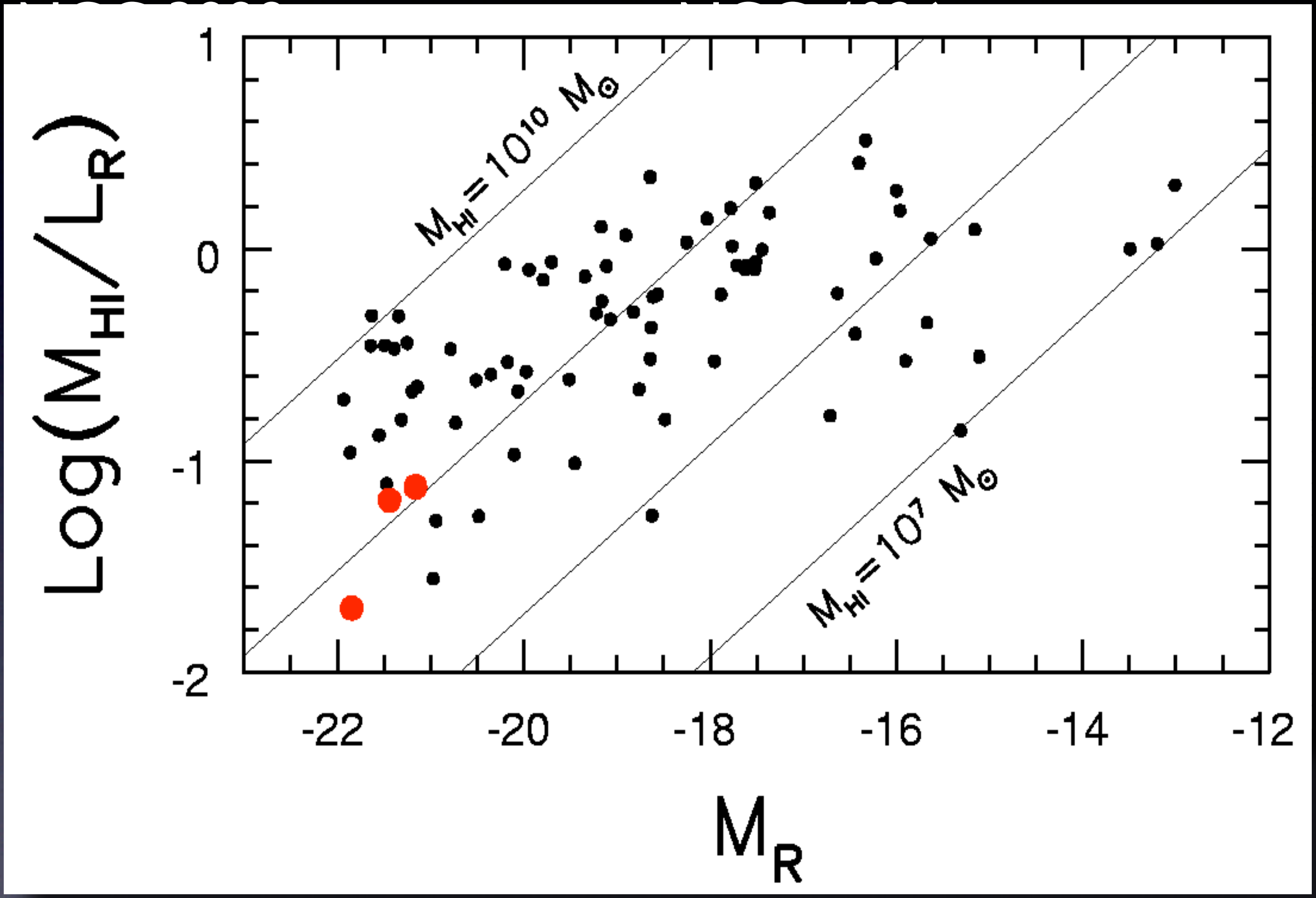
Verheijen et al, 2001



$$M_R = -21.44 \text{ (mag)}$$
$$M_{HI} = 1.3 \times 10^9 (M_\odot)$$

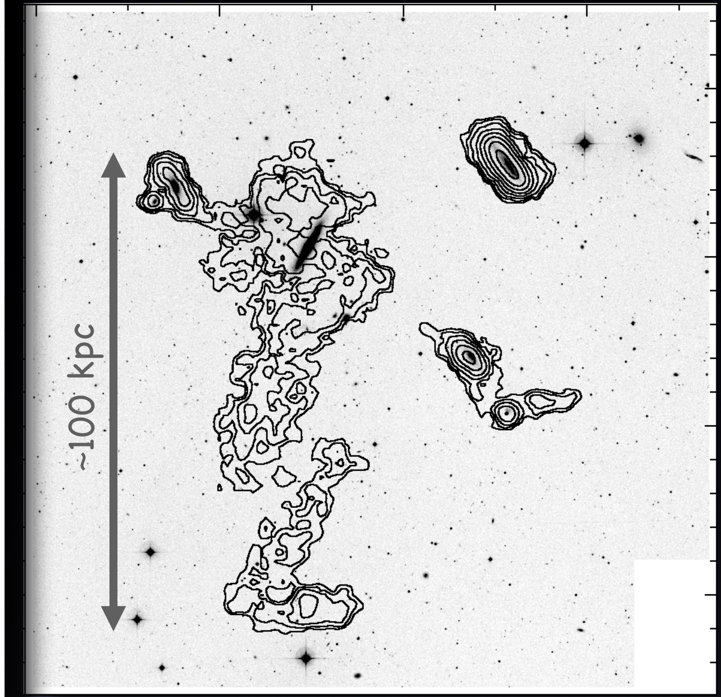
The brightest lenticulars in Ursa Major

Hot action in a cool group



NGC 4111

Verheijen et al, 2001



$$M_R = -21.44\ (\text{mag})$$
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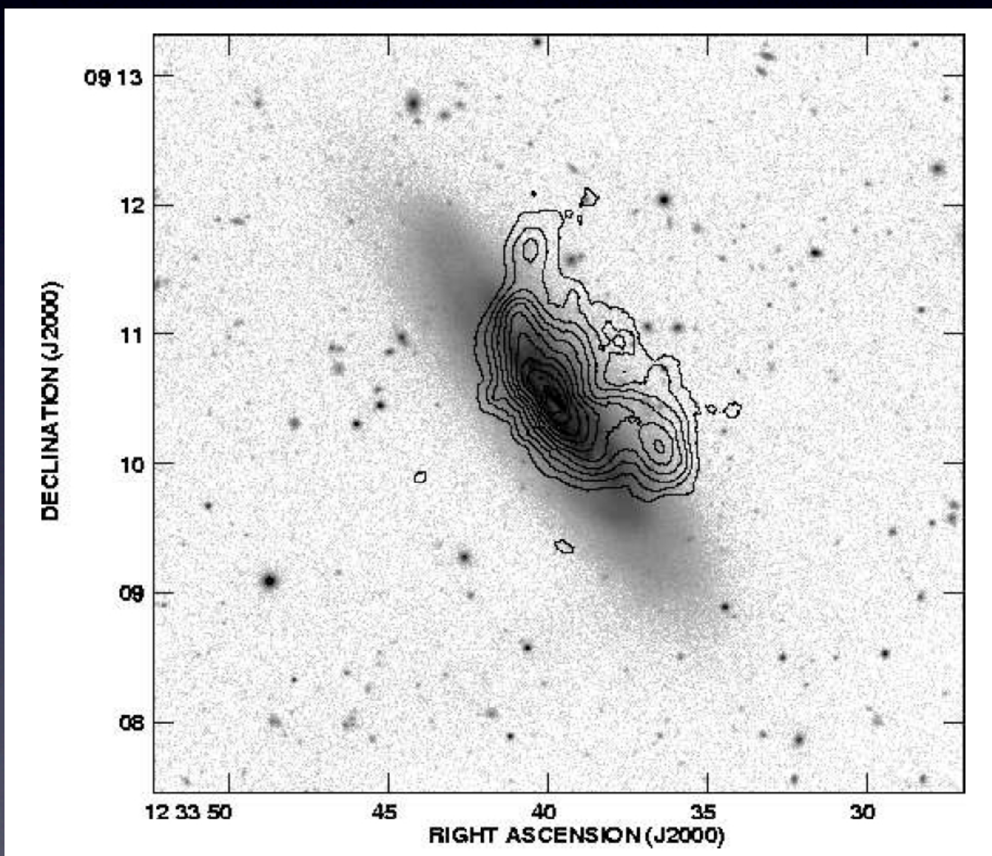
From Spiral to Lenticular through tidal interactions?

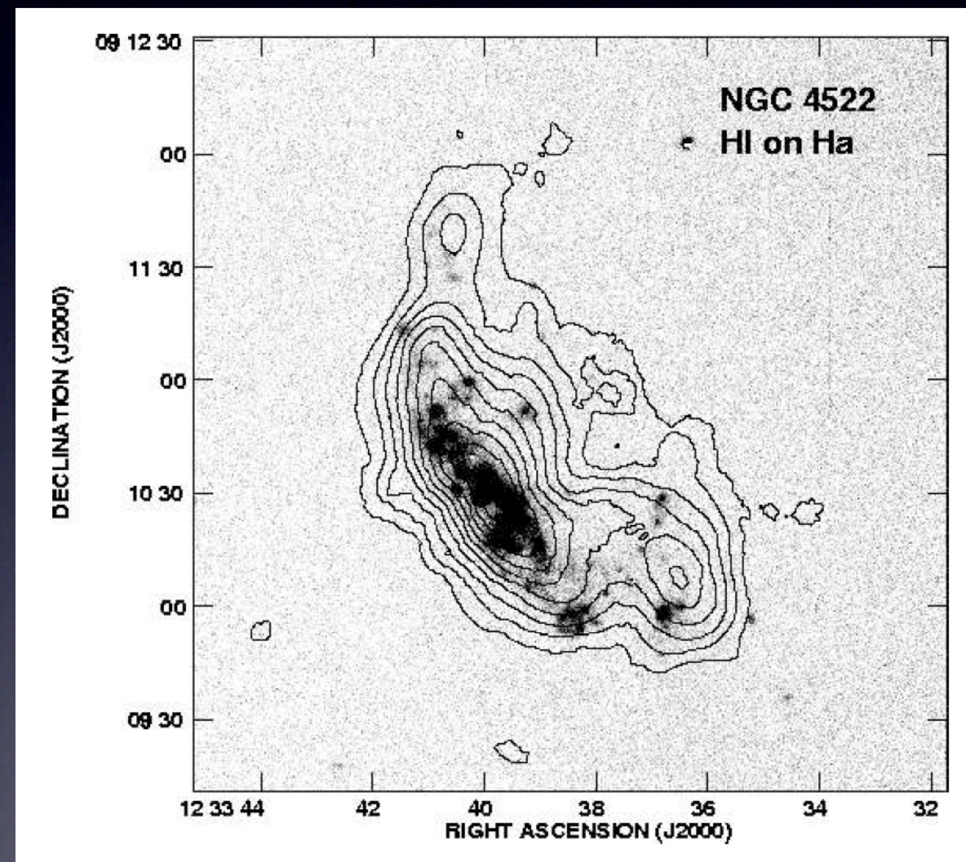
Stripping in action

NGC 4522 in Virgo

HI contours on optical image



HI contours on Hα image

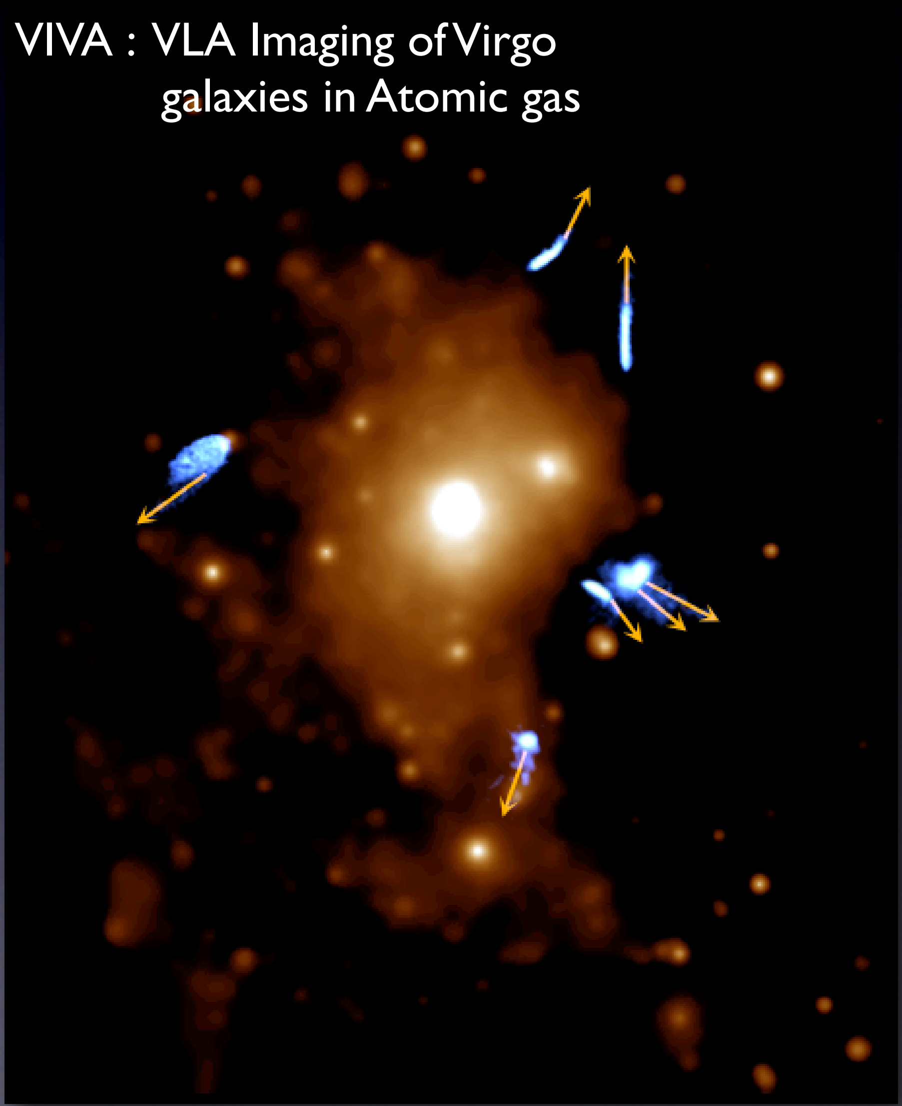


Kenney et al, 2004

➢ Ram-pressure induced (and truncated?) star formation

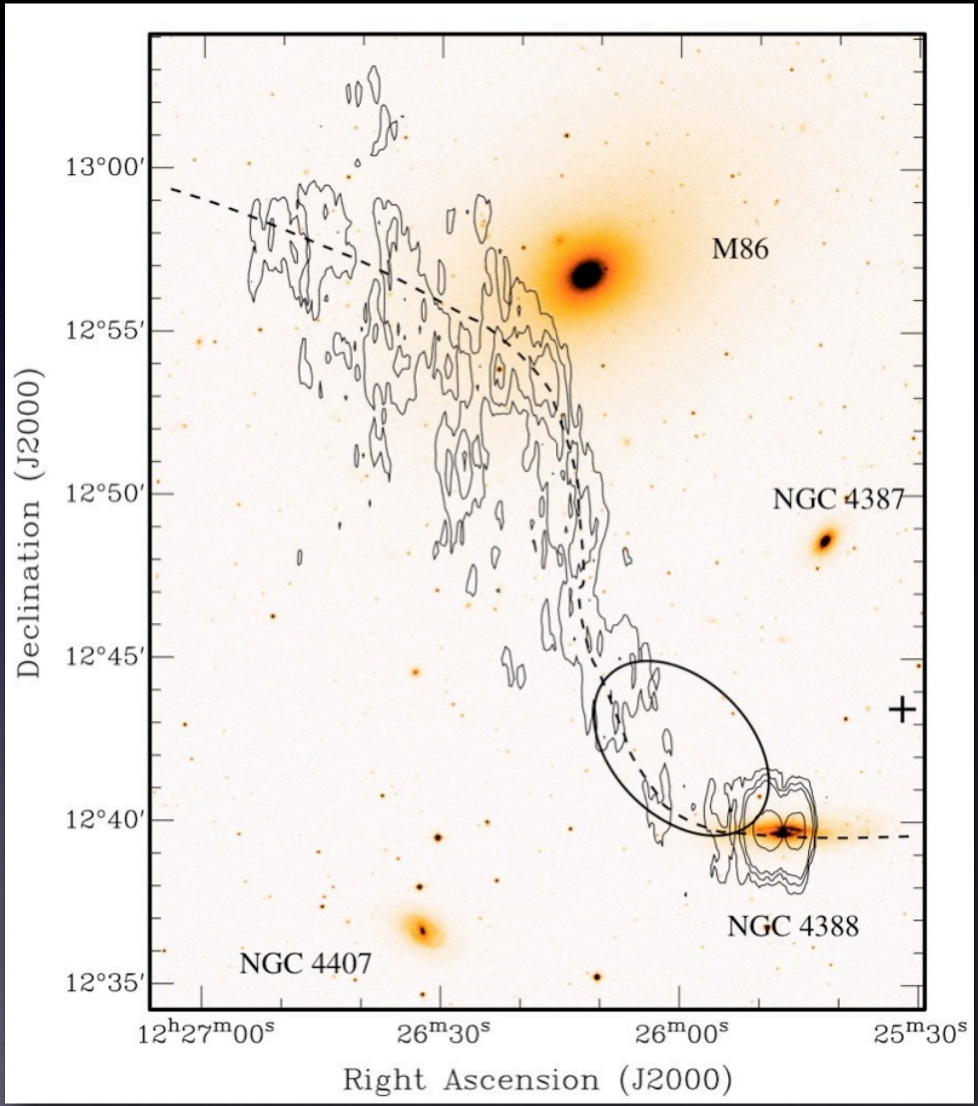
HI in the Virgo cluster

VLA



Chung, van Gorkom, Kenney & Vollmer, 2007

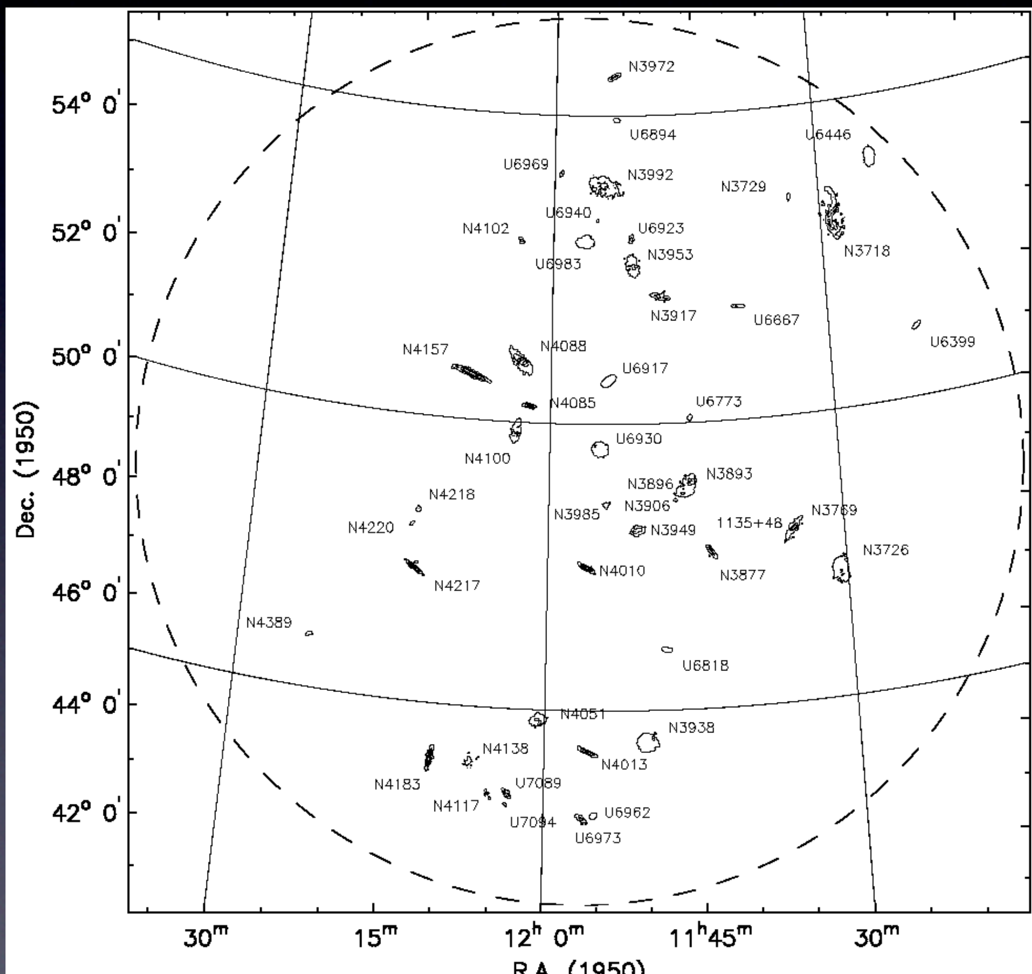
WSRT



Oosterloo & van Gorkom, 2005

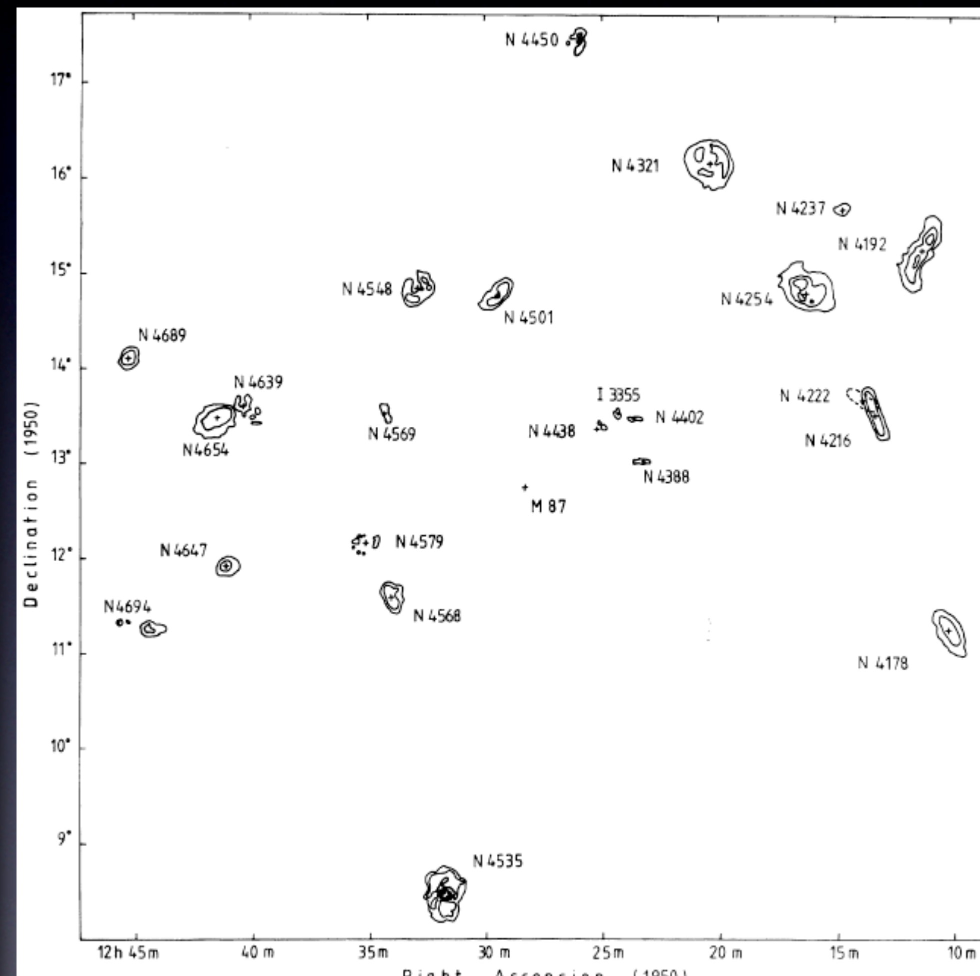
Environmental dependence of gas content.

Ursa Major



Verheijen & Sancisi 2001 Westerbork

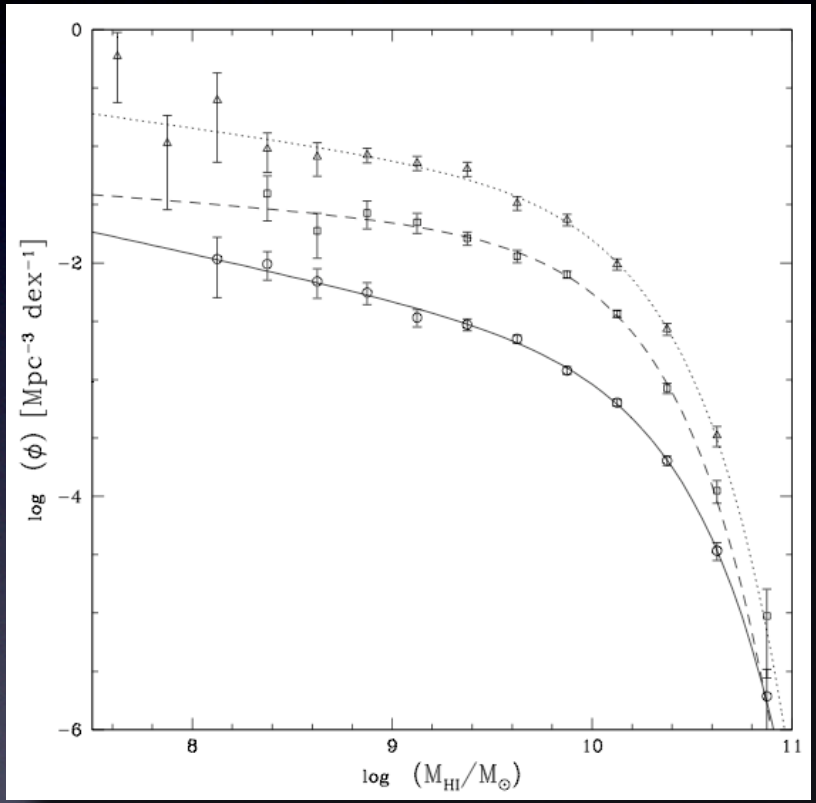
Virgo



Cayatte et al 1993 Very Large Array

Environmental dependence of HI Mass Function?

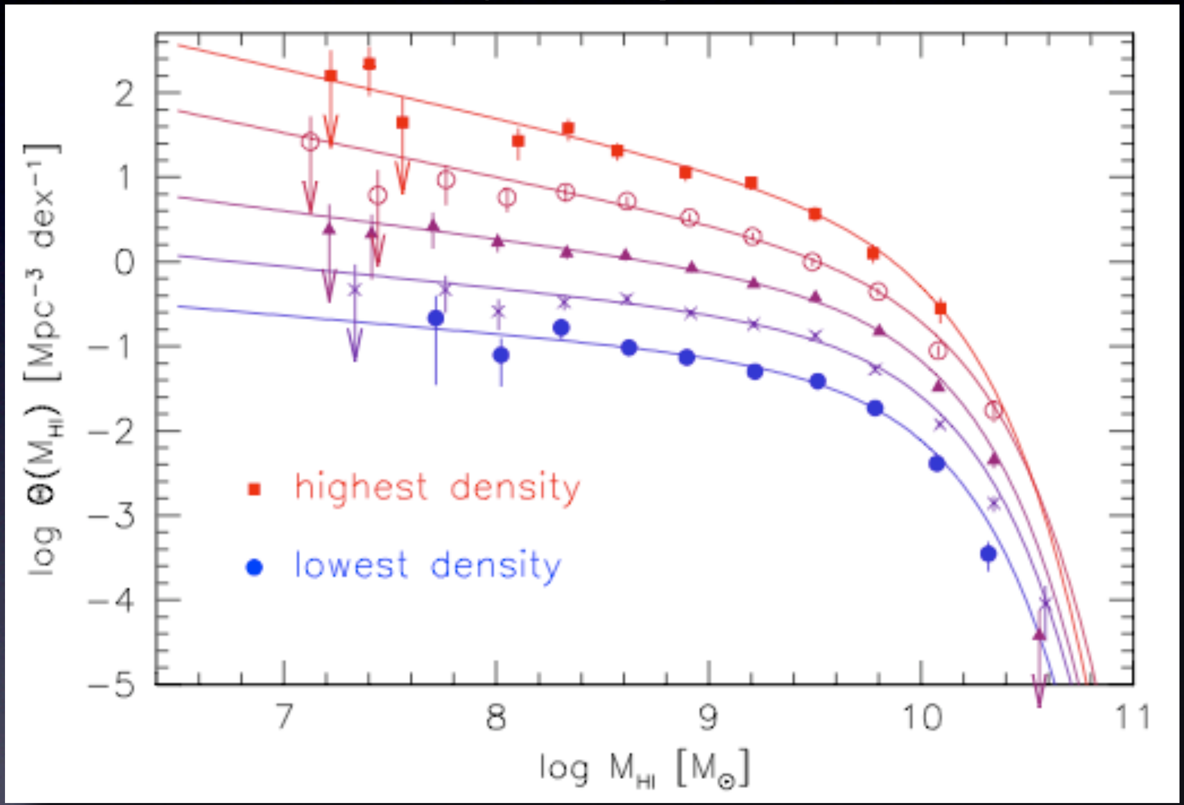
HIMF flattens
with increasing density



Springob et al, 2005

Arecibo General Catalogue

HIMF steepens
with increasing density



Zwaan et al, 2005

HIPASS

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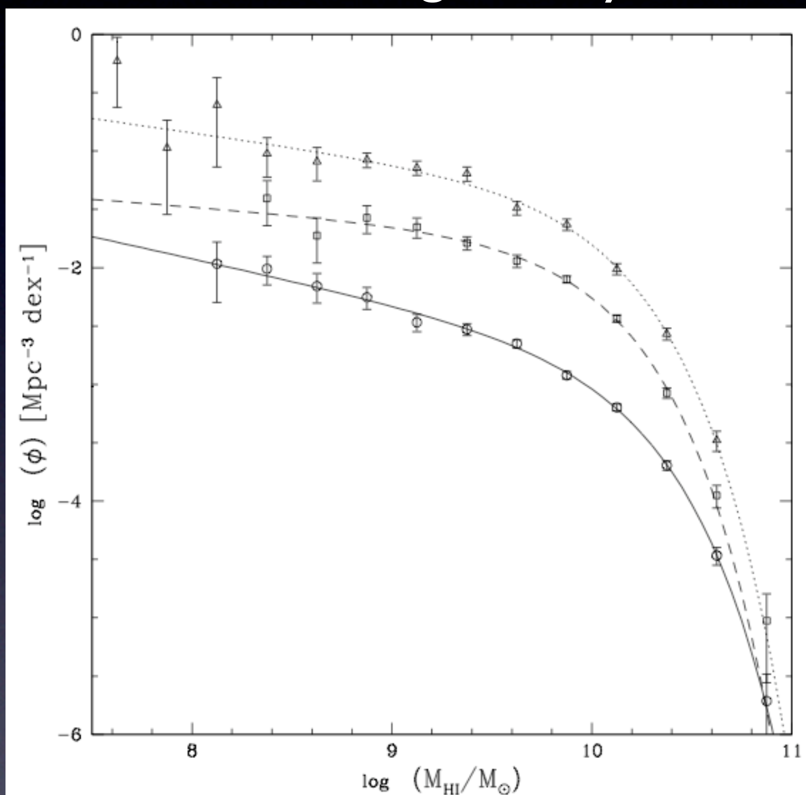
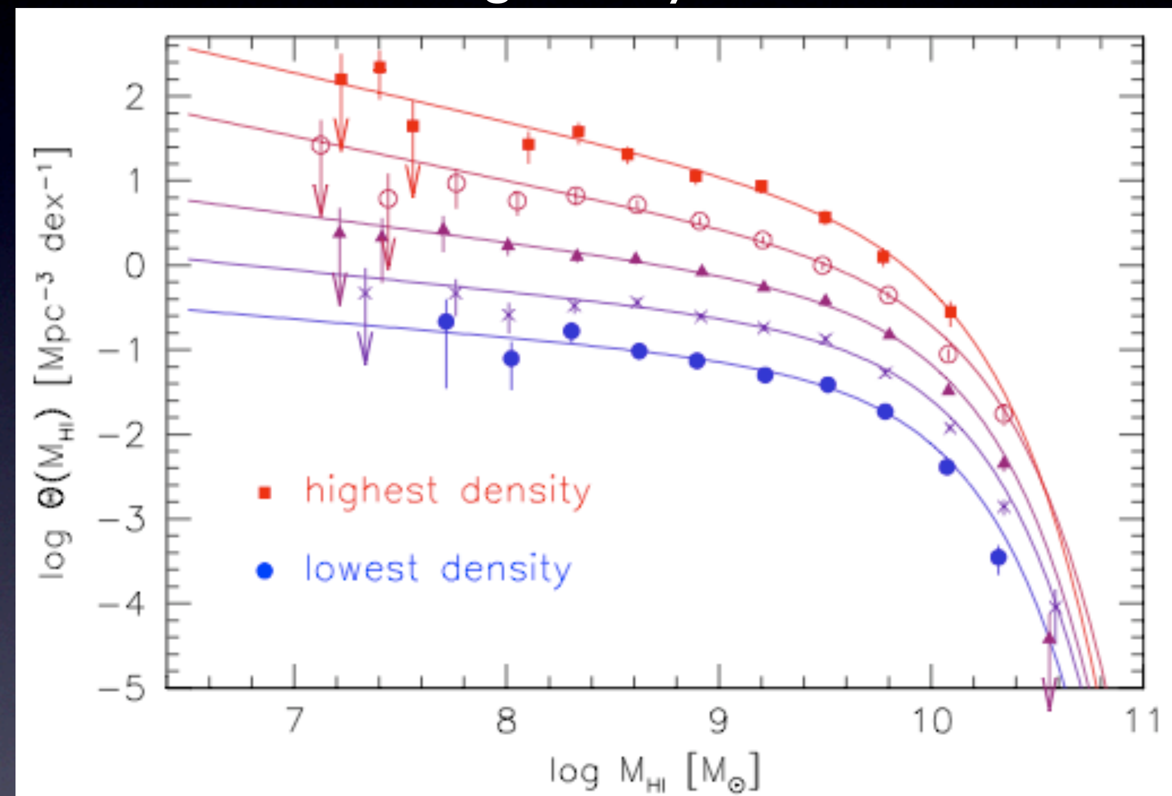




Springob et al, 2005

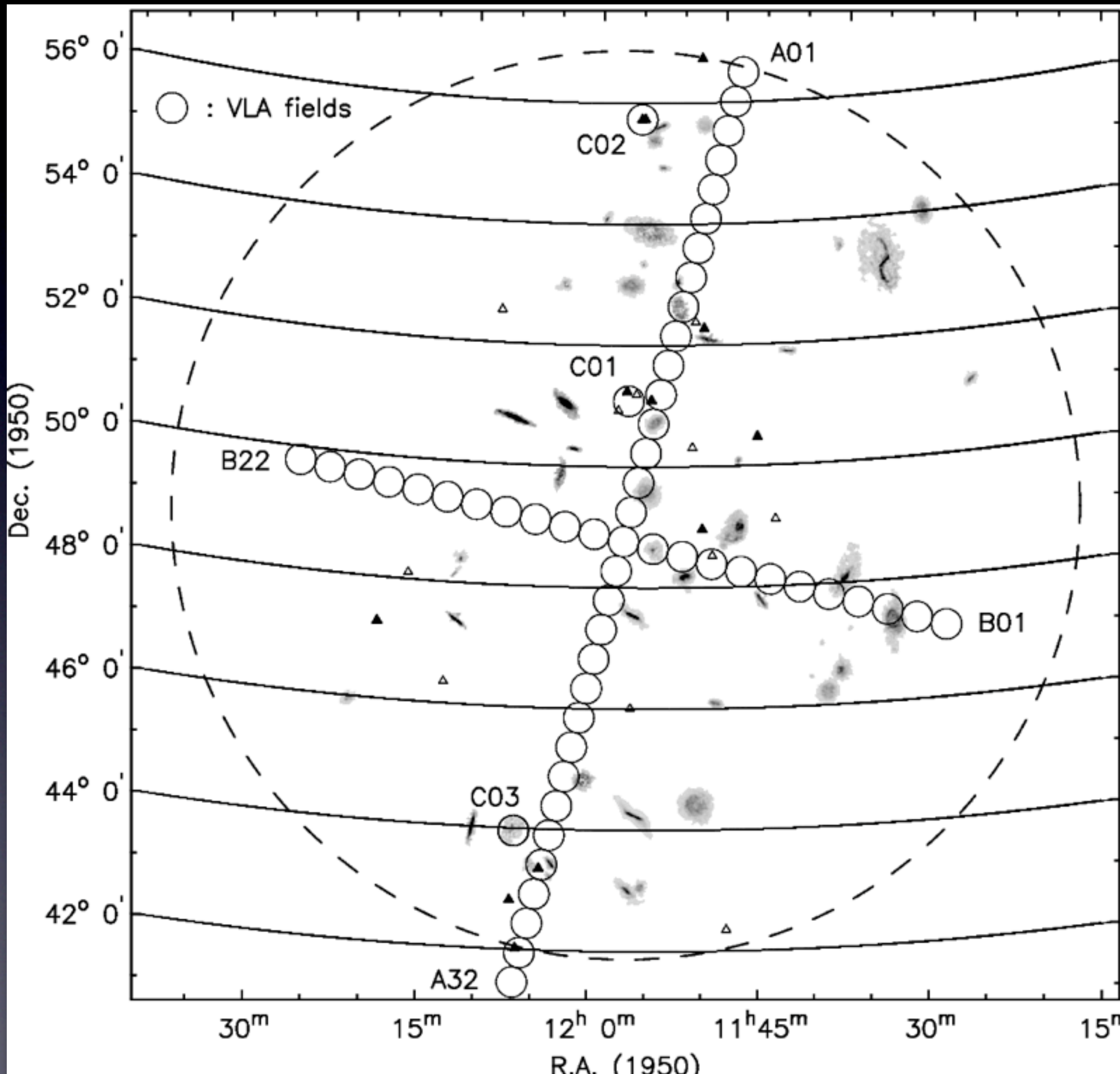
Zwaan et al, 2005

Arecibo General Catalogue

HIPASS

APERTIF will blindly survey all densities beyond the local universe.

Blind VLA-D HI survey of Ursa Major.



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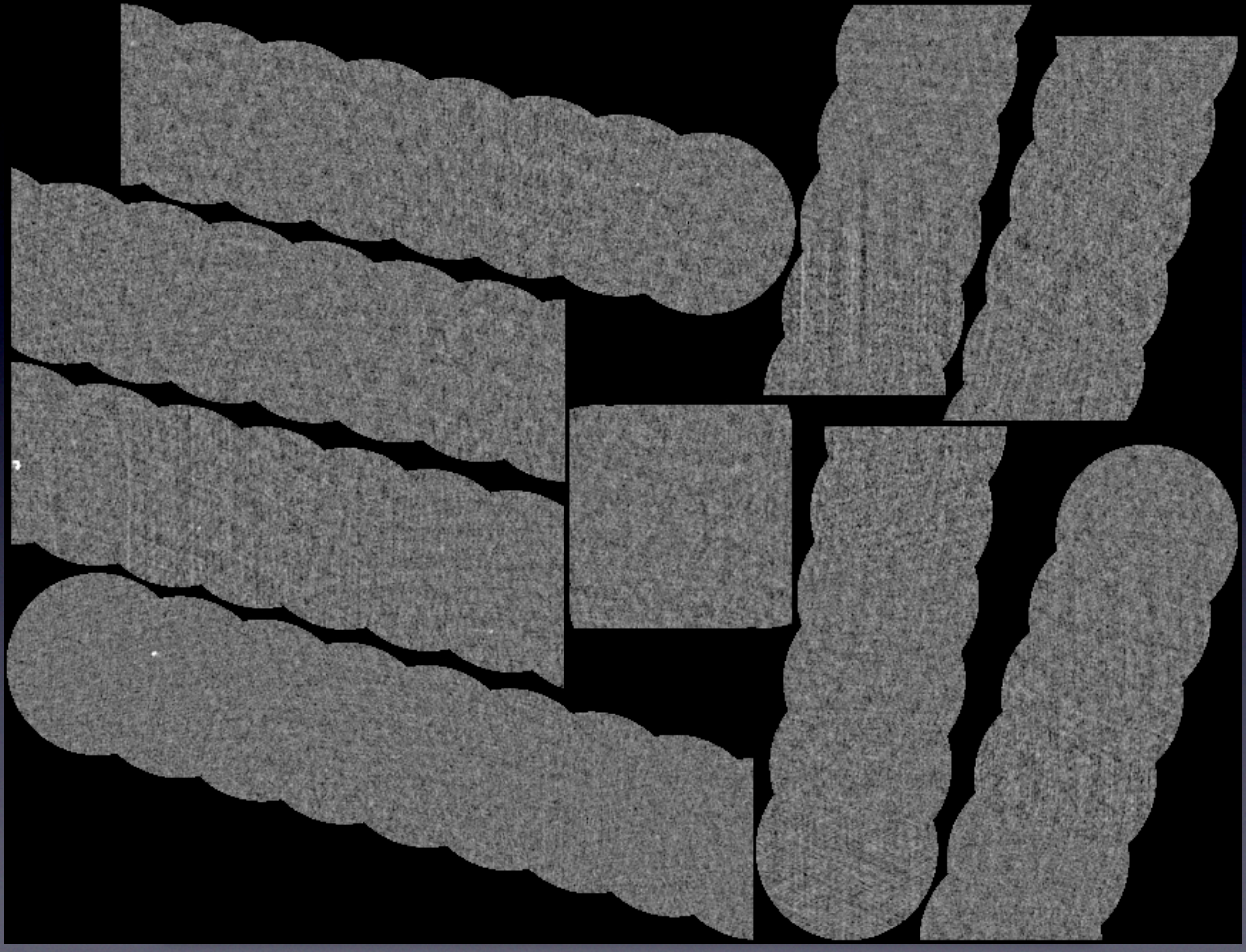

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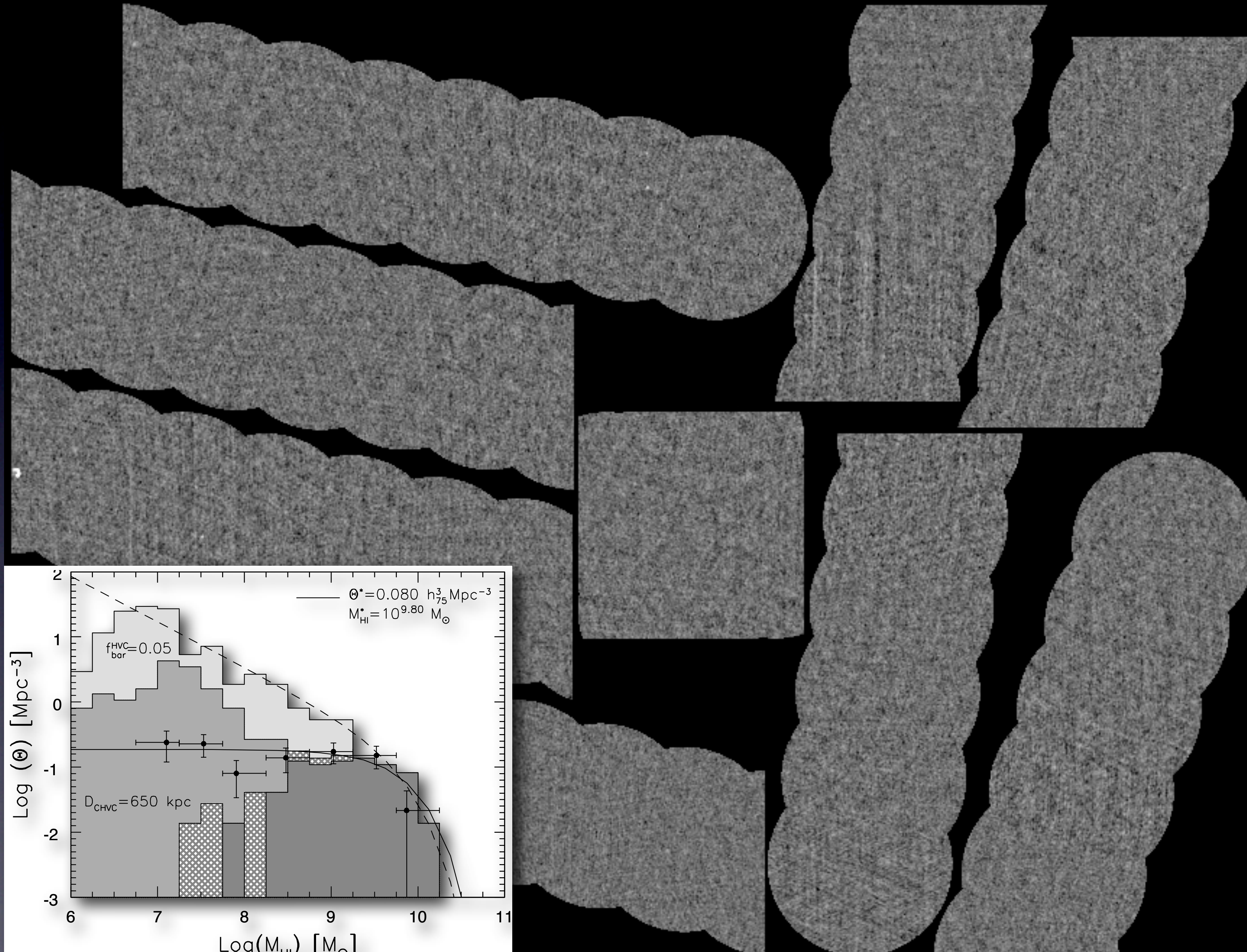
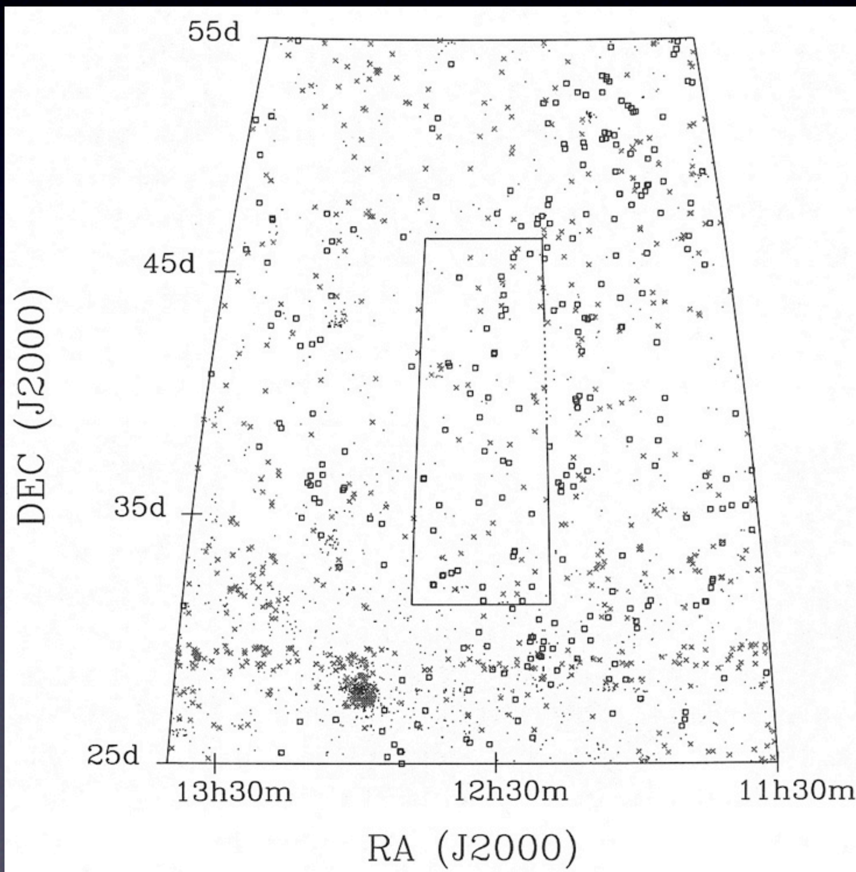
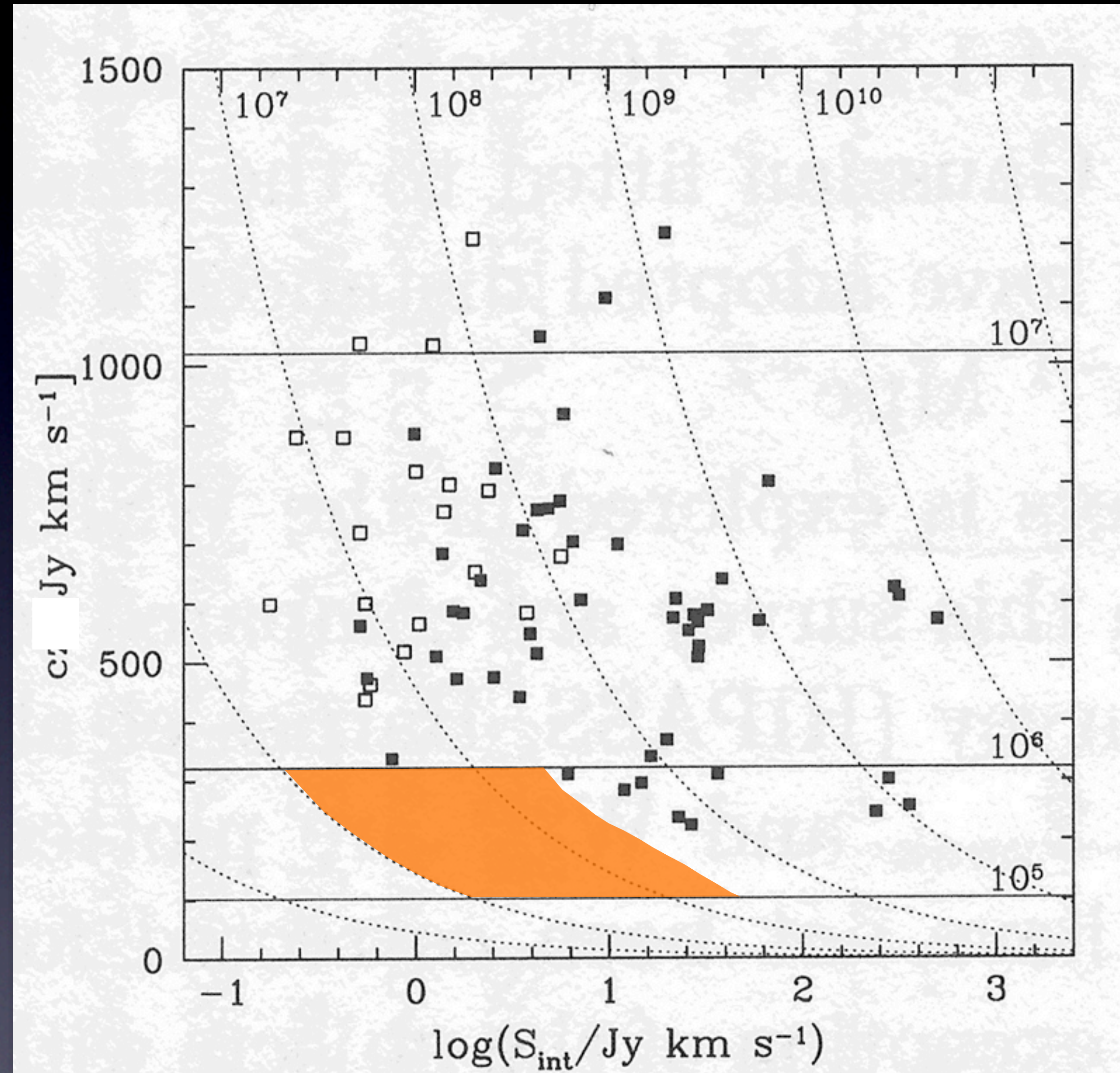


collapsing HIMF at M(HI)<$10^7 M_{sun}$?

Blind WSRT Survey of CVn
86 deg^2, 1372 pointings
60x12 hrs, 80 min/pointing



Kovač, 2007 (thesis, Groningen)



Where are these low HI-mass dwarfs?

collapsing HIMF at $M(HI)<10^7 M_{sun}$?

Blind WSRT Survey of CVn
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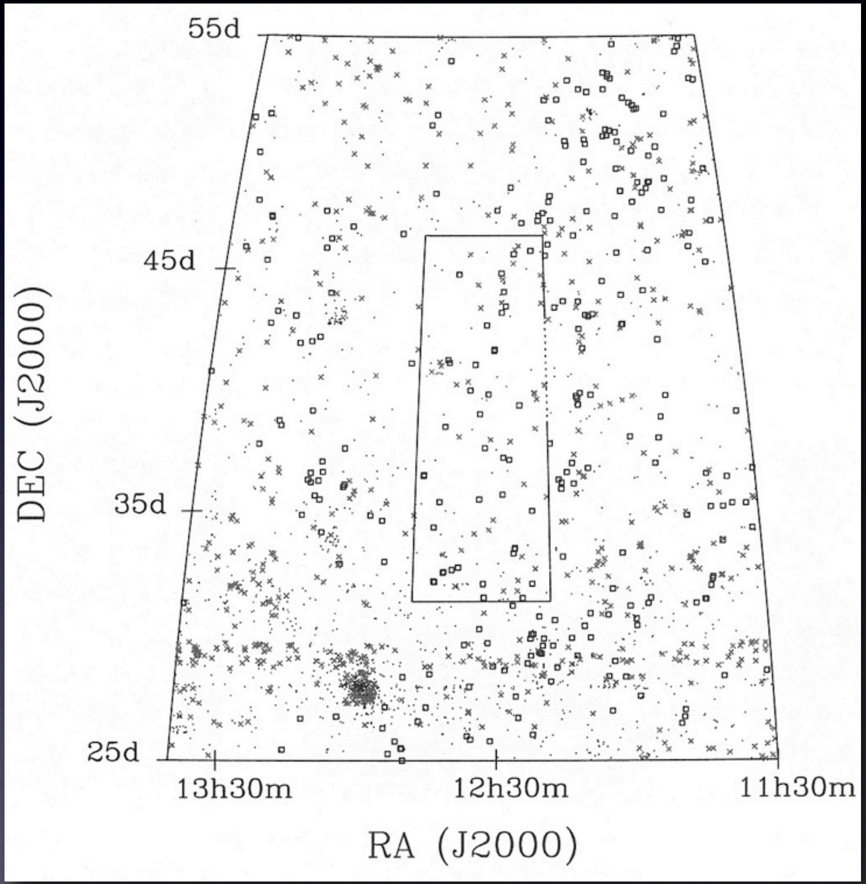

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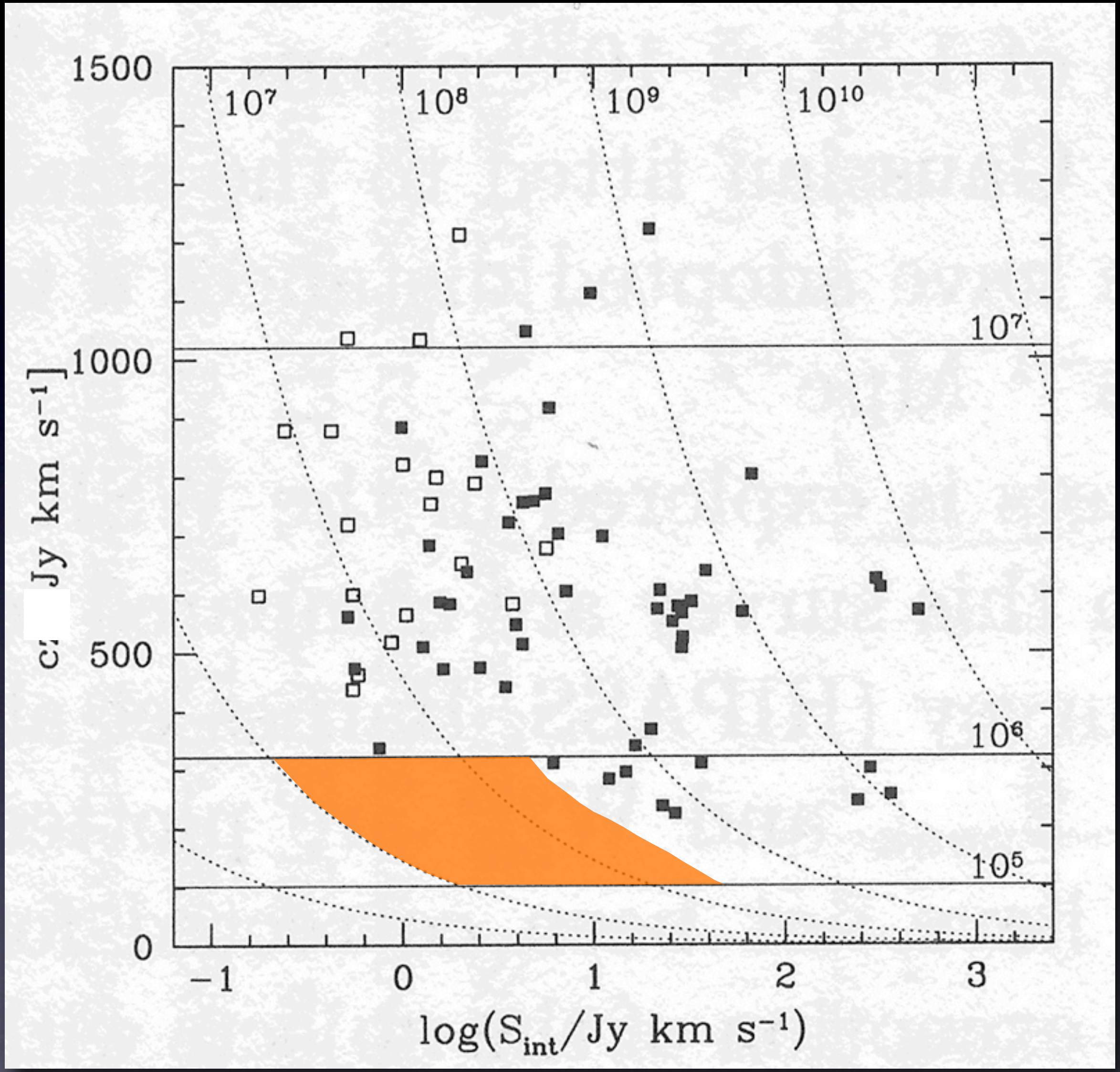
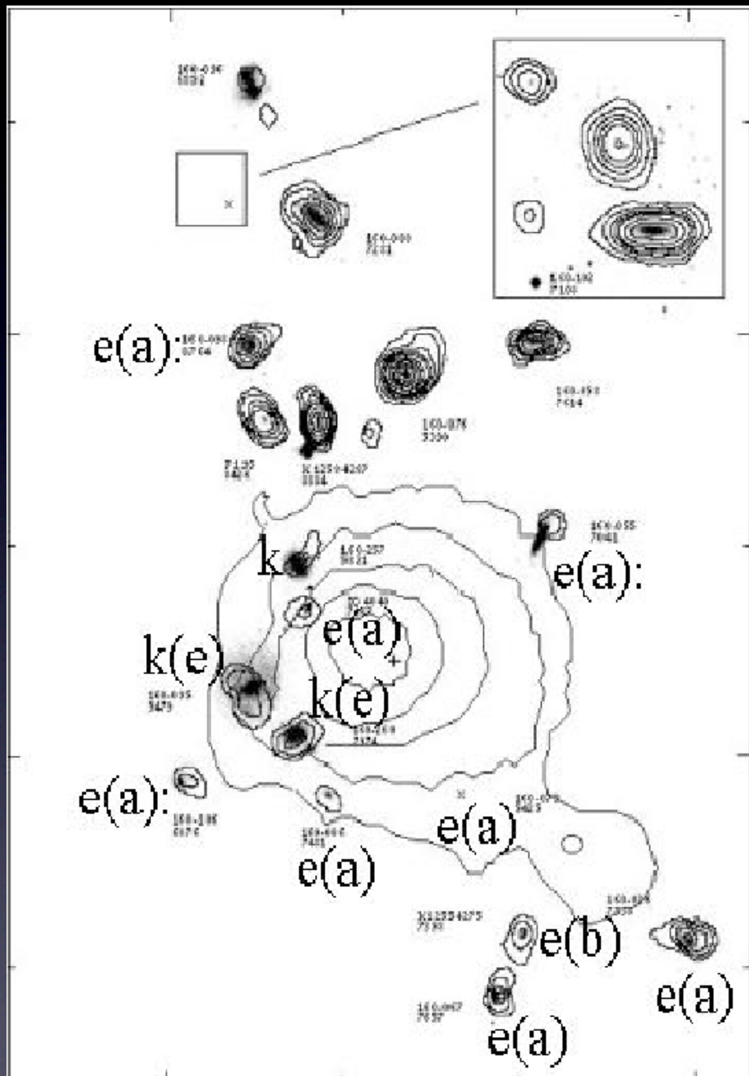


Where are these low HI-mass dwarfs?

APERTIF will efficiently survey local volumes to greater depth.

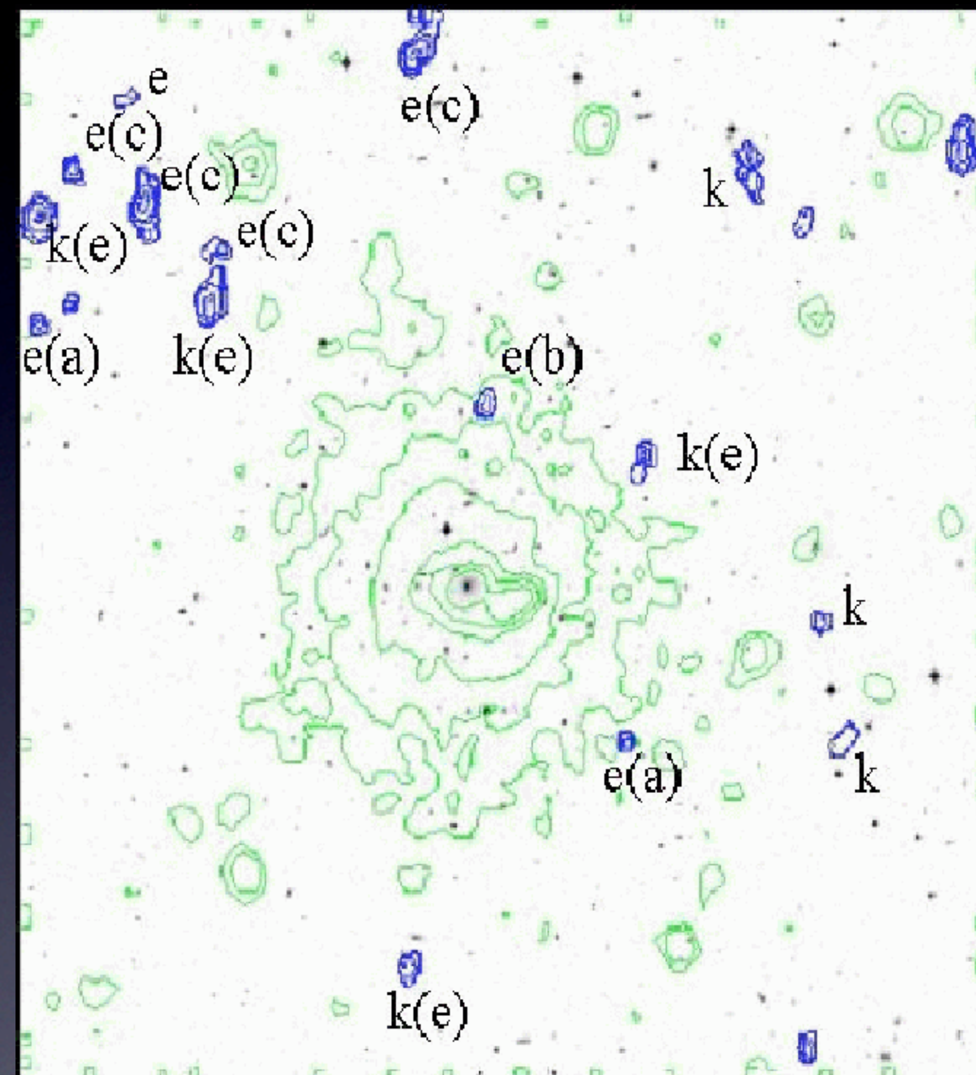
HI, ICM, SFR, SP interrelations

Coma



Bravo-Alfaro et al, 2001

Abell 2670



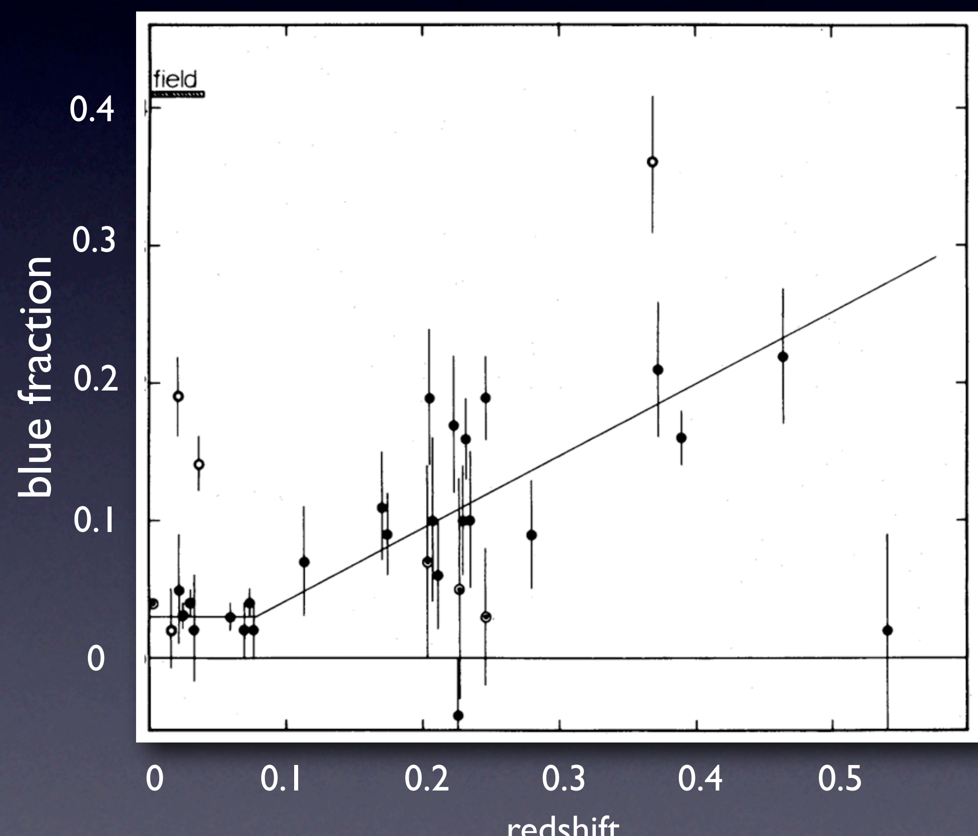
Poggianti & van Gorkom, 2001

Infalling galaxies are clustered in space and velocity

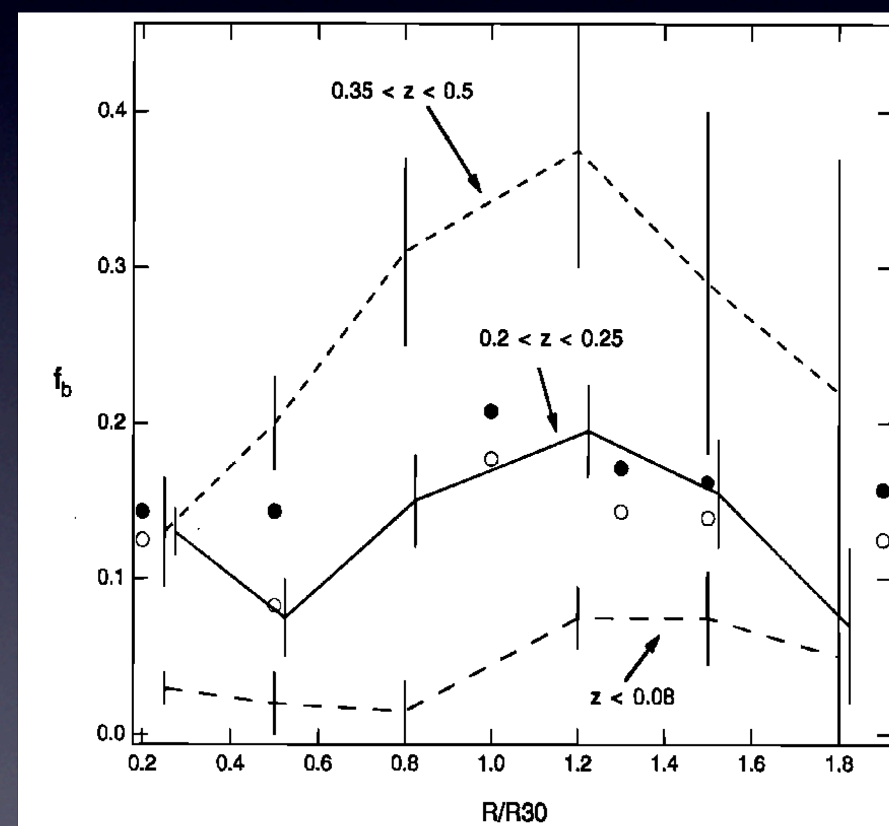
- ➢ relates to substructures in redshift space

Butcher-Oemler effect

The fraction of blue (starforming?) galaxies in clusters increases with redshift and peaks in cluster outskirts.



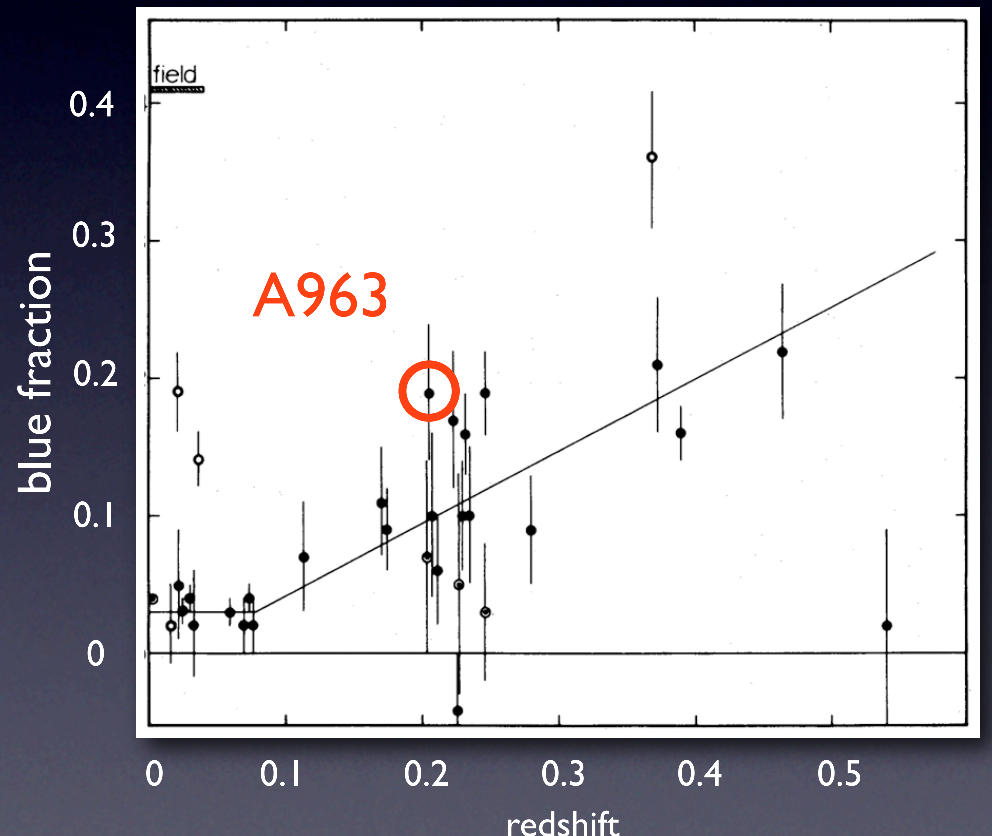
Butcher & Oemler, 1984



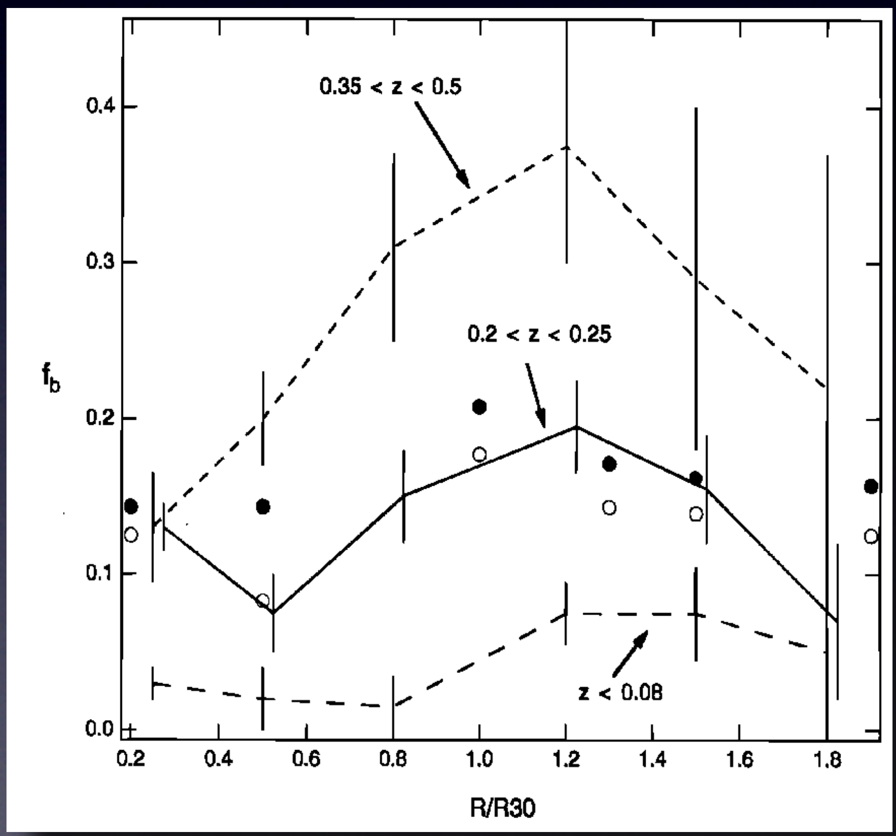
Abraham et al, 1996

Butcher-Oemler effect

The fraction of blue (starforming?) galaxies in clusters increases with redshift and peaks in cluster outskirts.



Butcher & Oemler, 1984



Abraham et al, 1996

A tale of two clusters

Abell 963

Abell 2192

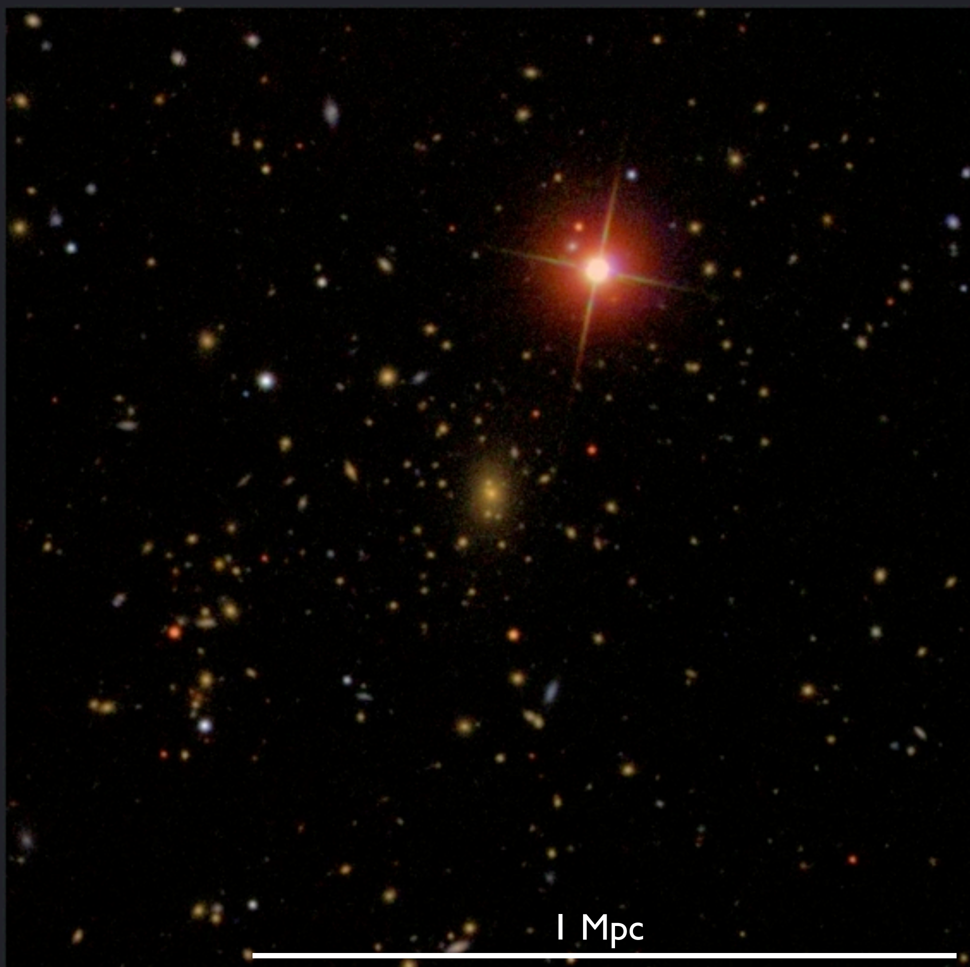
SDSS images

z=0.206

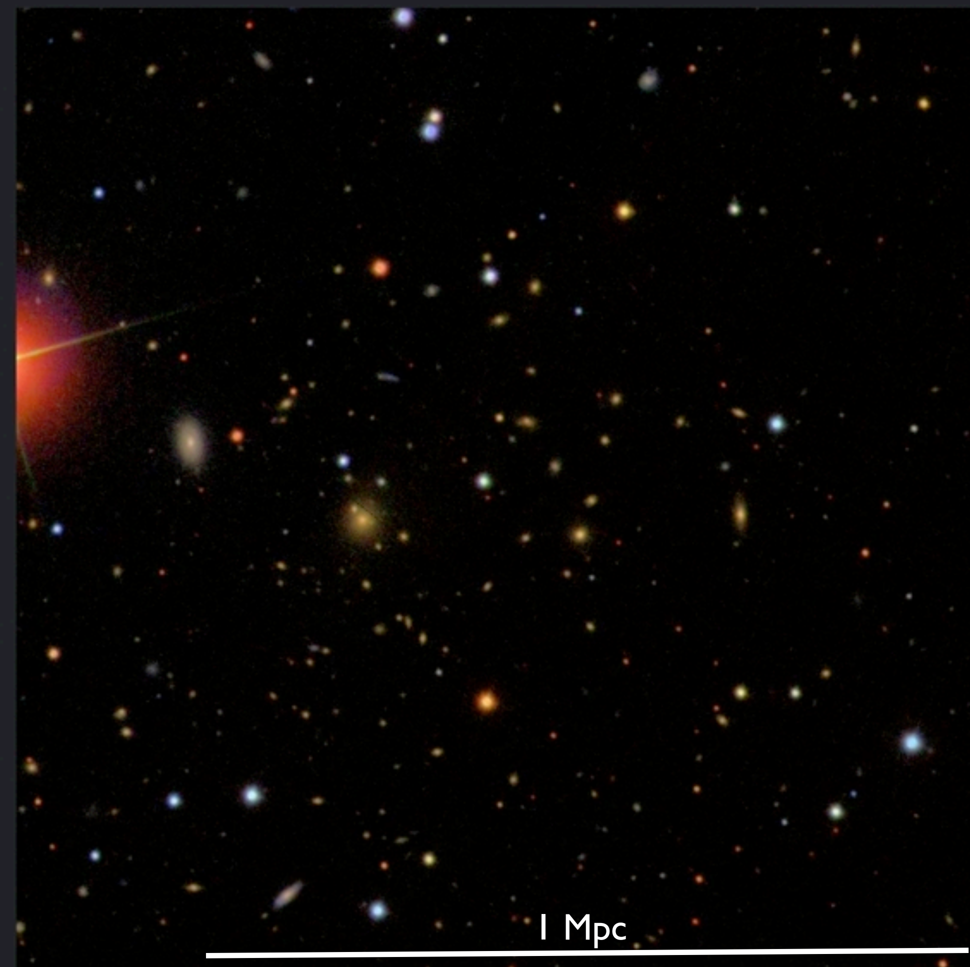
z=0.188

A tale of two clusters

Abell 963



Abell 2192



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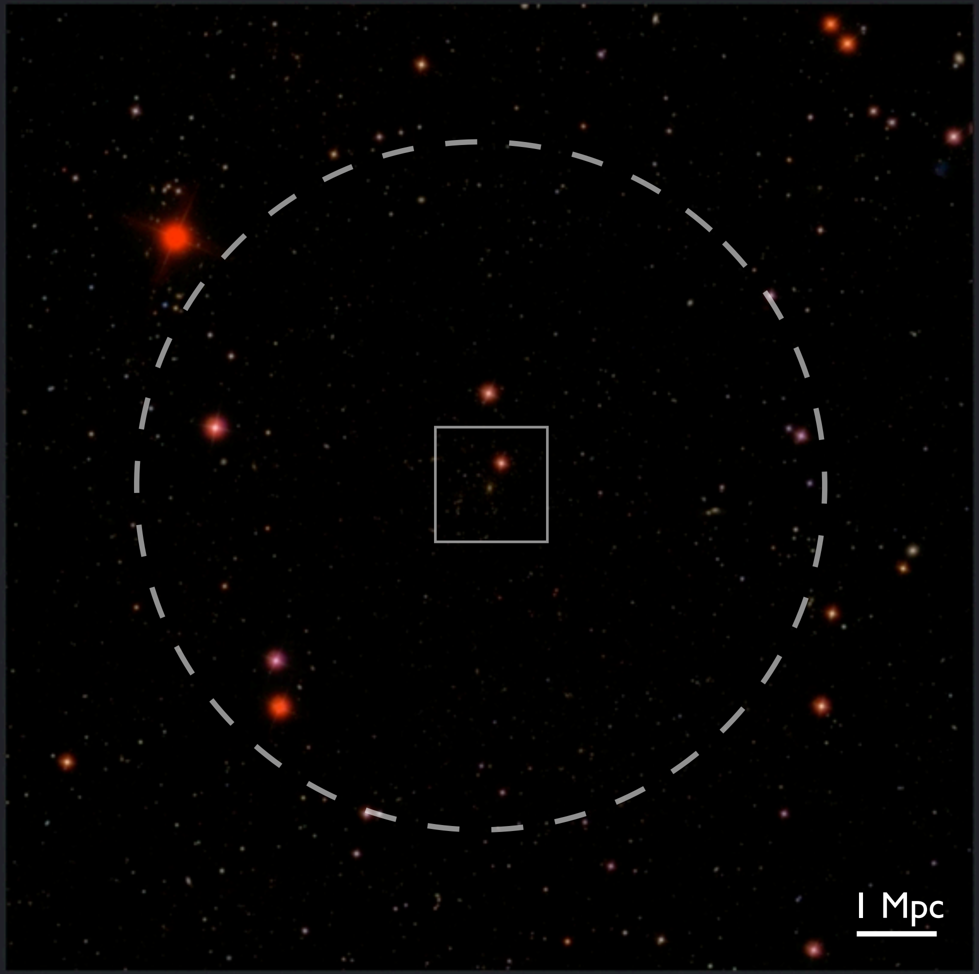
z=0.206

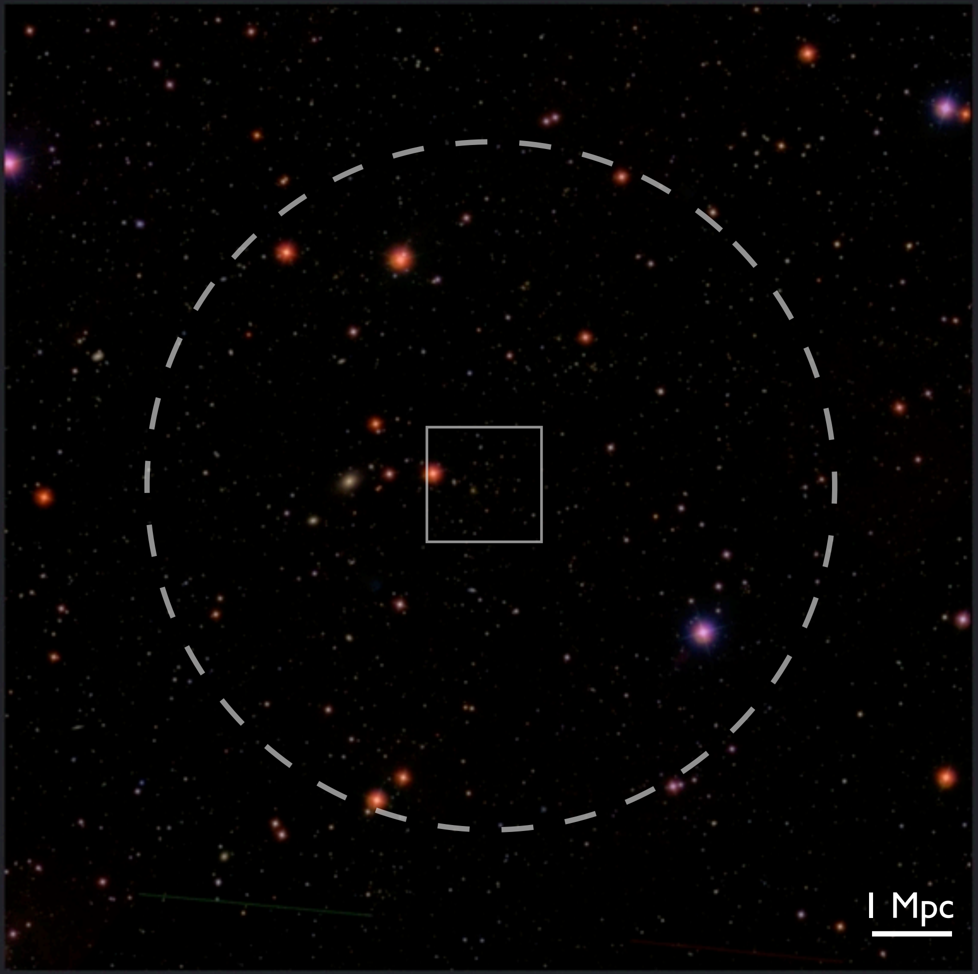
z=0.188

A tale of two clusters

Abell 963



Abell 2192



SDSS images

z=0.206

z=0.188

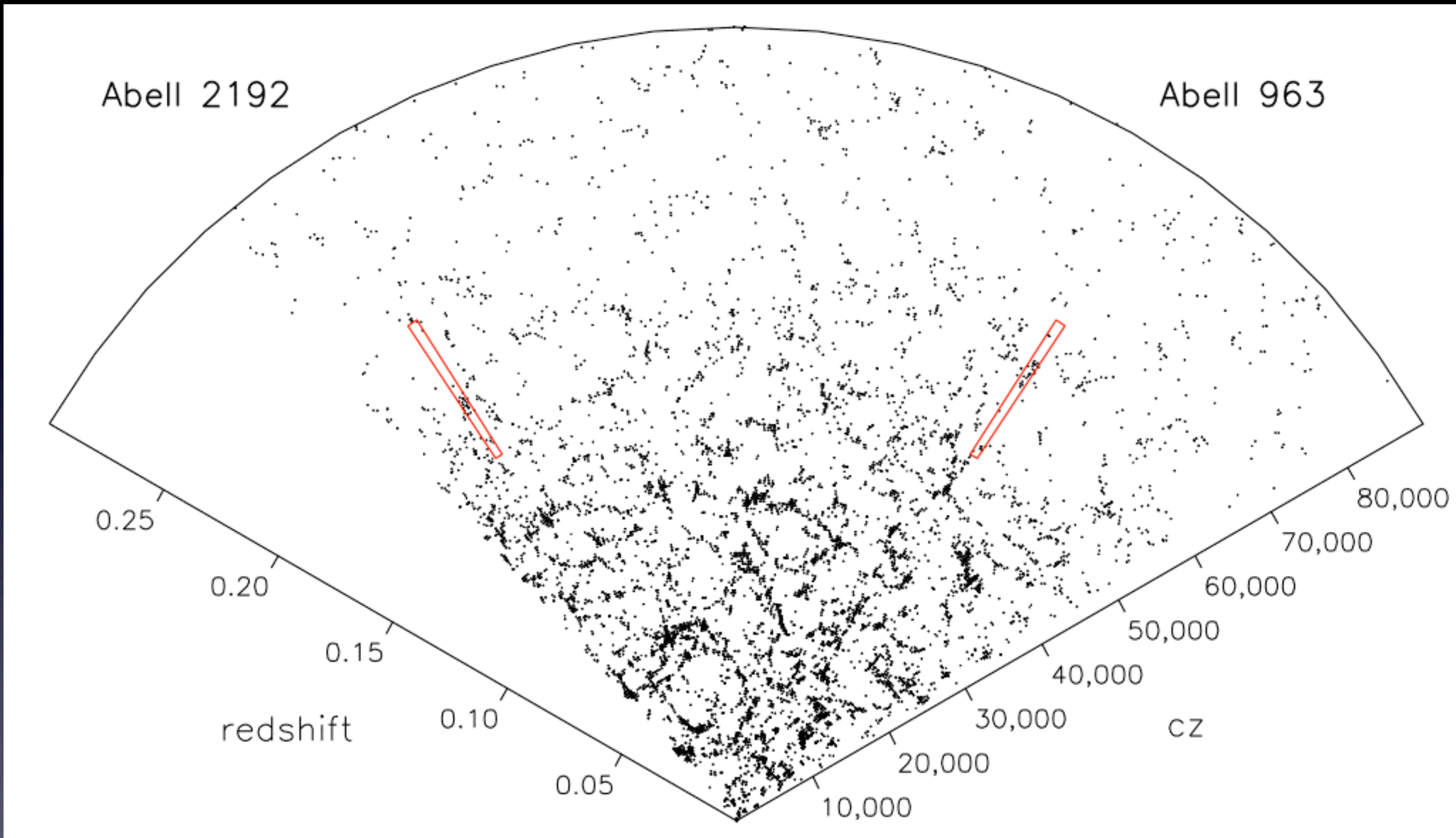
Ultra-deep WSRT observations

- 8x10MHz bands, overlapping to cover 1160−1220 MHz
  Z = 0.164−0.224 , surveyed volume ≈ 70,000 Mpc^3
- 1600 channels, covering 18,000 km/s velocity range
  22 km/s velocity resolution (after Hanning smoothing)
- 117x12^{hr} on Abell 963 , 73x12^{hr} on Abell 2192 (5−10% lost to RFI)
- Measured rms noise : 30 μJy and 36 μJy at R=22 km/s.

M_{HI} (min) = 2×10^9 ($M_\odot$) over 150 km/s profile width.
(4σ in each of 3 resolution elements)

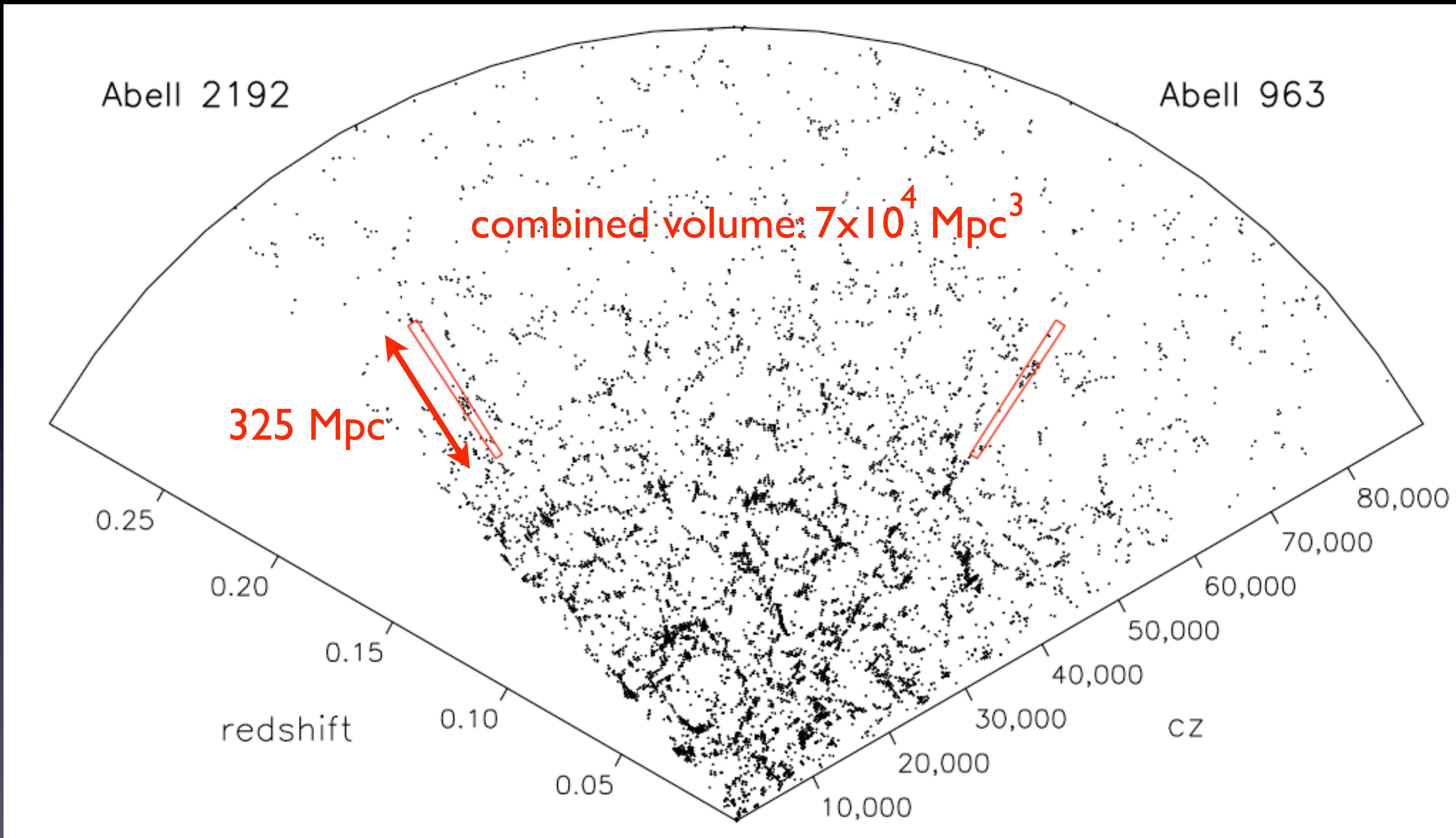
N_{HI} (min) = 3×10^{19} (cm^{-2}) over 75 km/s profile width at 7σ.

Survey Volume & Large Scale Structure



SDSS redshift cone

Survey Volume & Large Scale Structure



SDSS redshift cone

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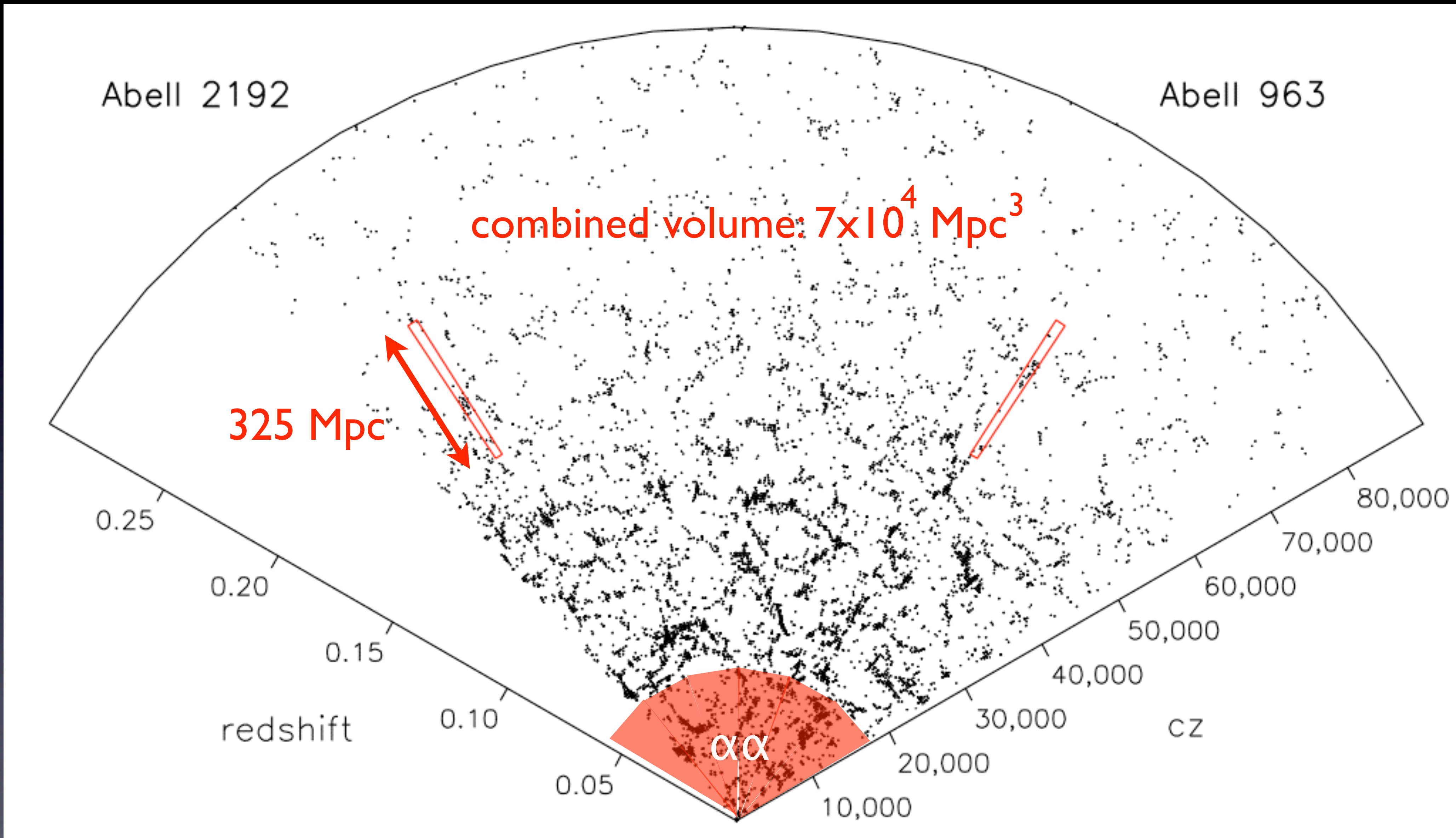
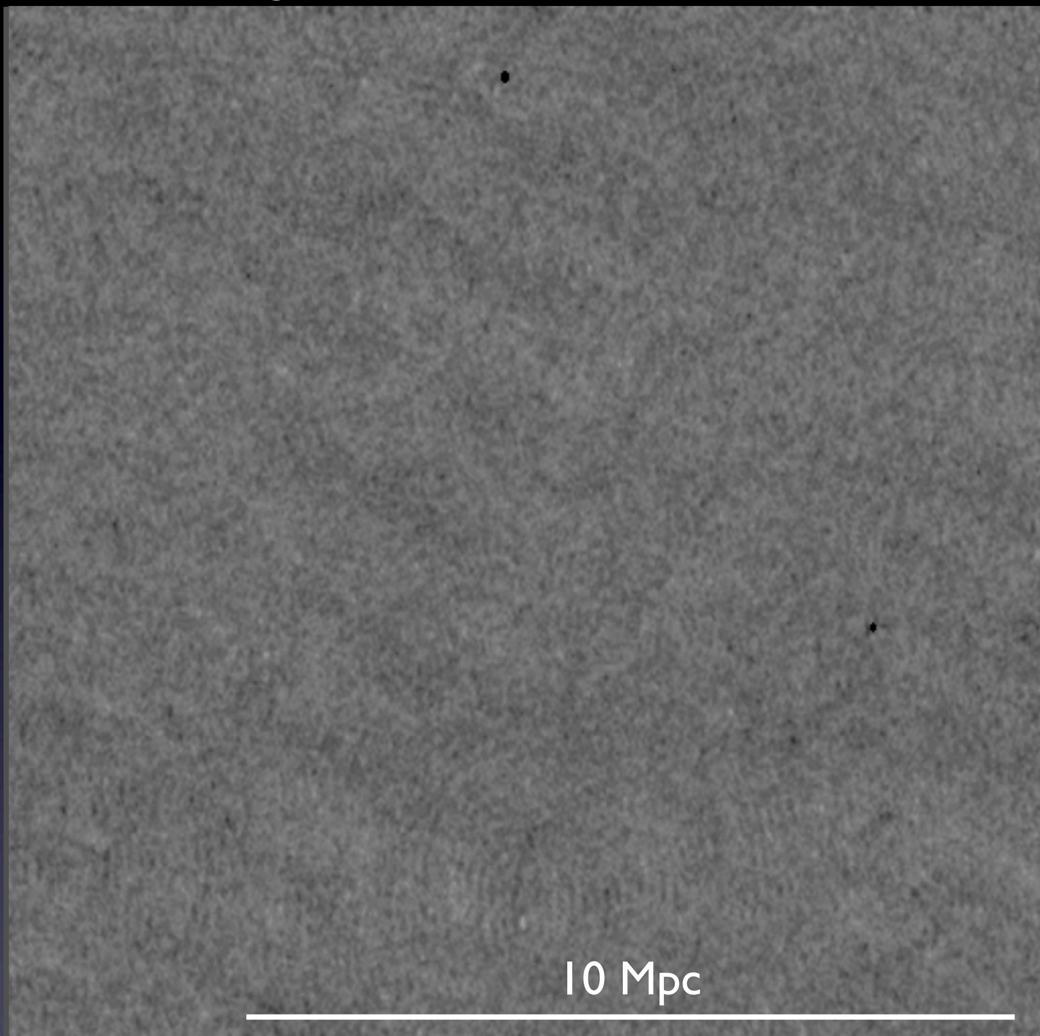


SDSS redshift cone

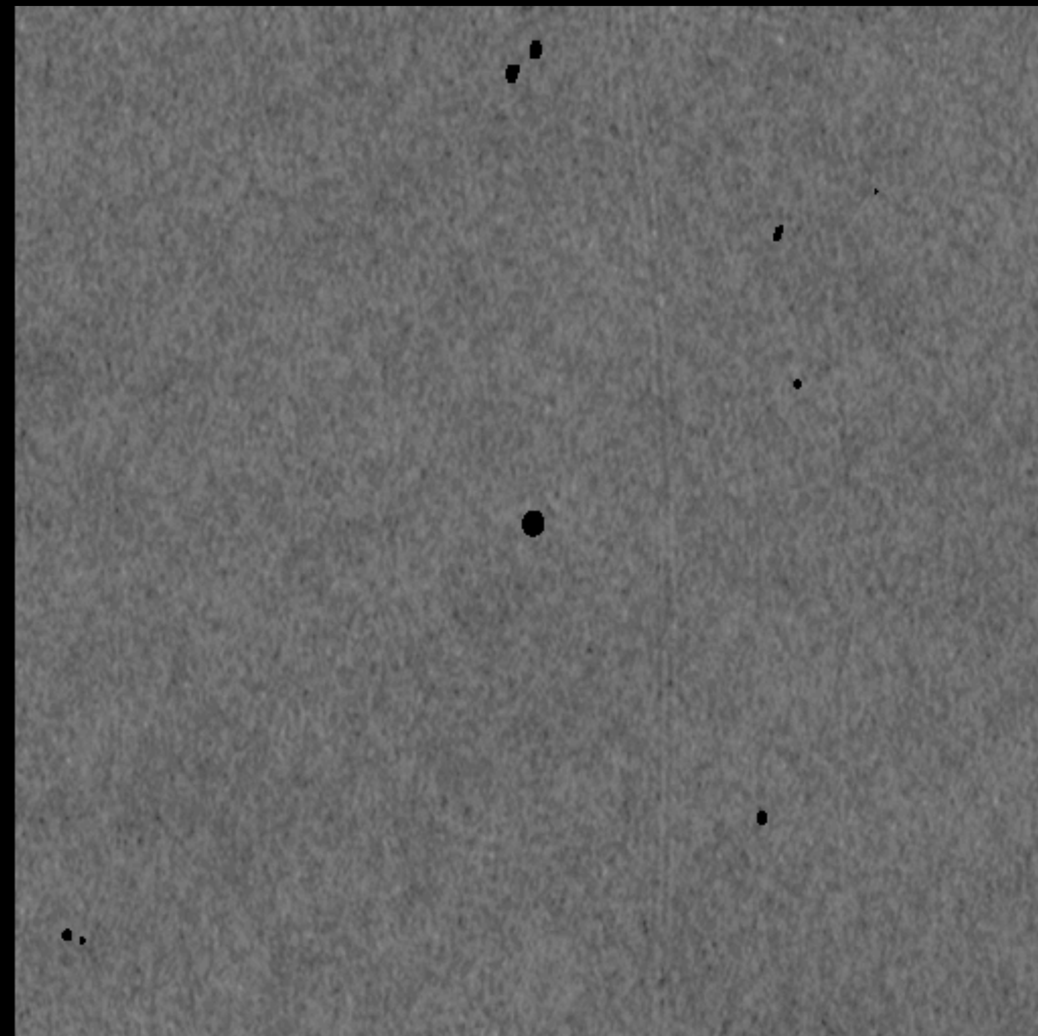
Abell 2192

1.14x1.14 deg^2 σ =17 μJy



Abell 963

σ =14 μJy



6 IFs

ν = 1205 −1160 MHz

z = 0.179−0.224

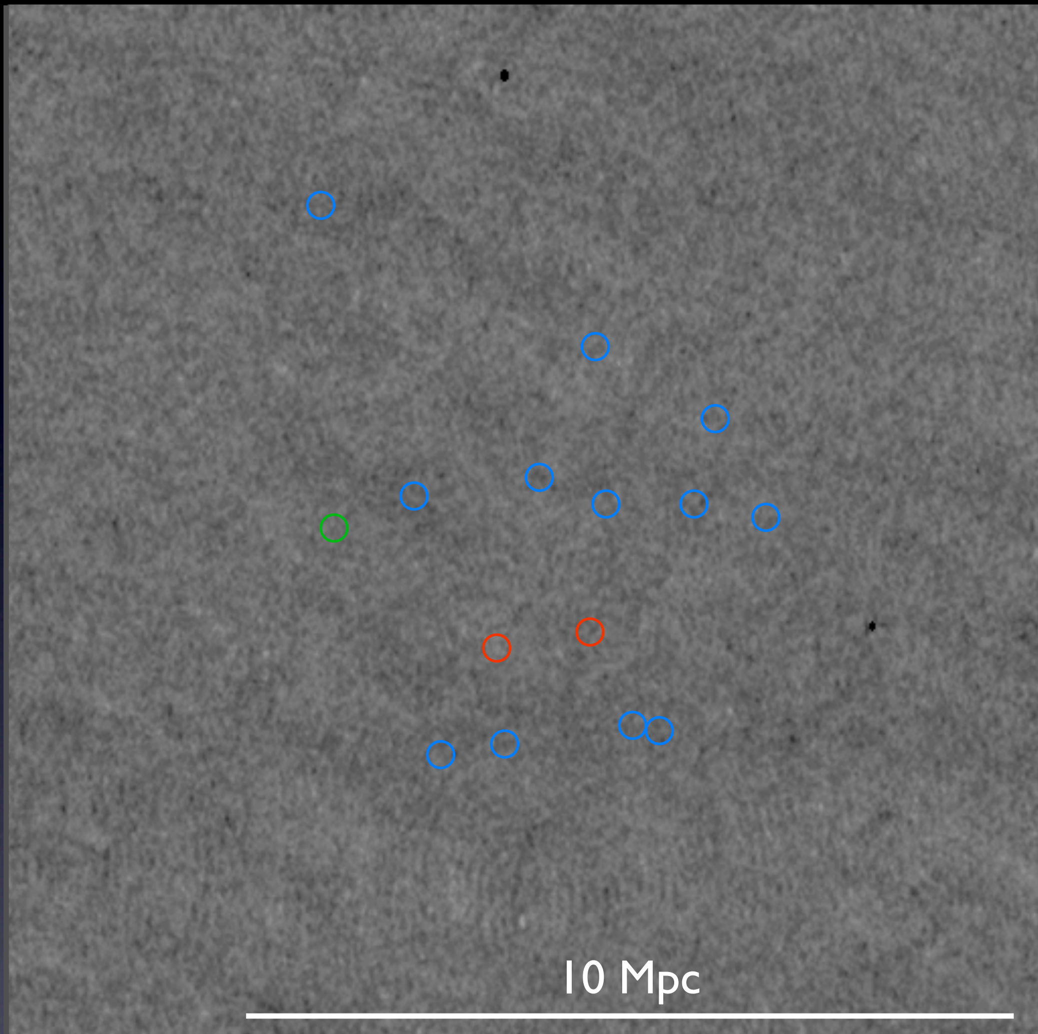
cz = 53.617−67.230 km/s

R = 88 km/s

99 preliminary 5σ HI detections with optical counterparts.

Abell 2192

1.14x1.14 deg^2 $\sigma = 17\ \mu\text{Jy}$



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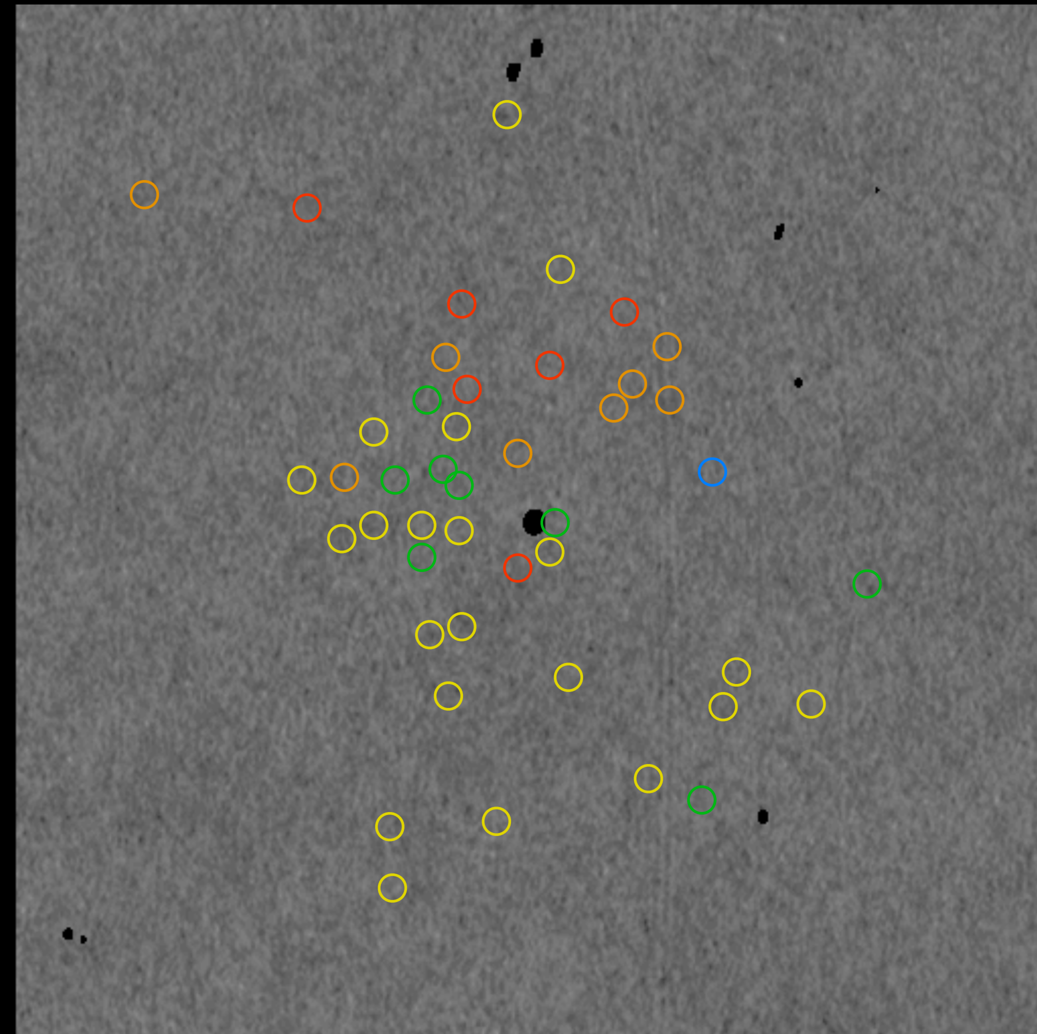

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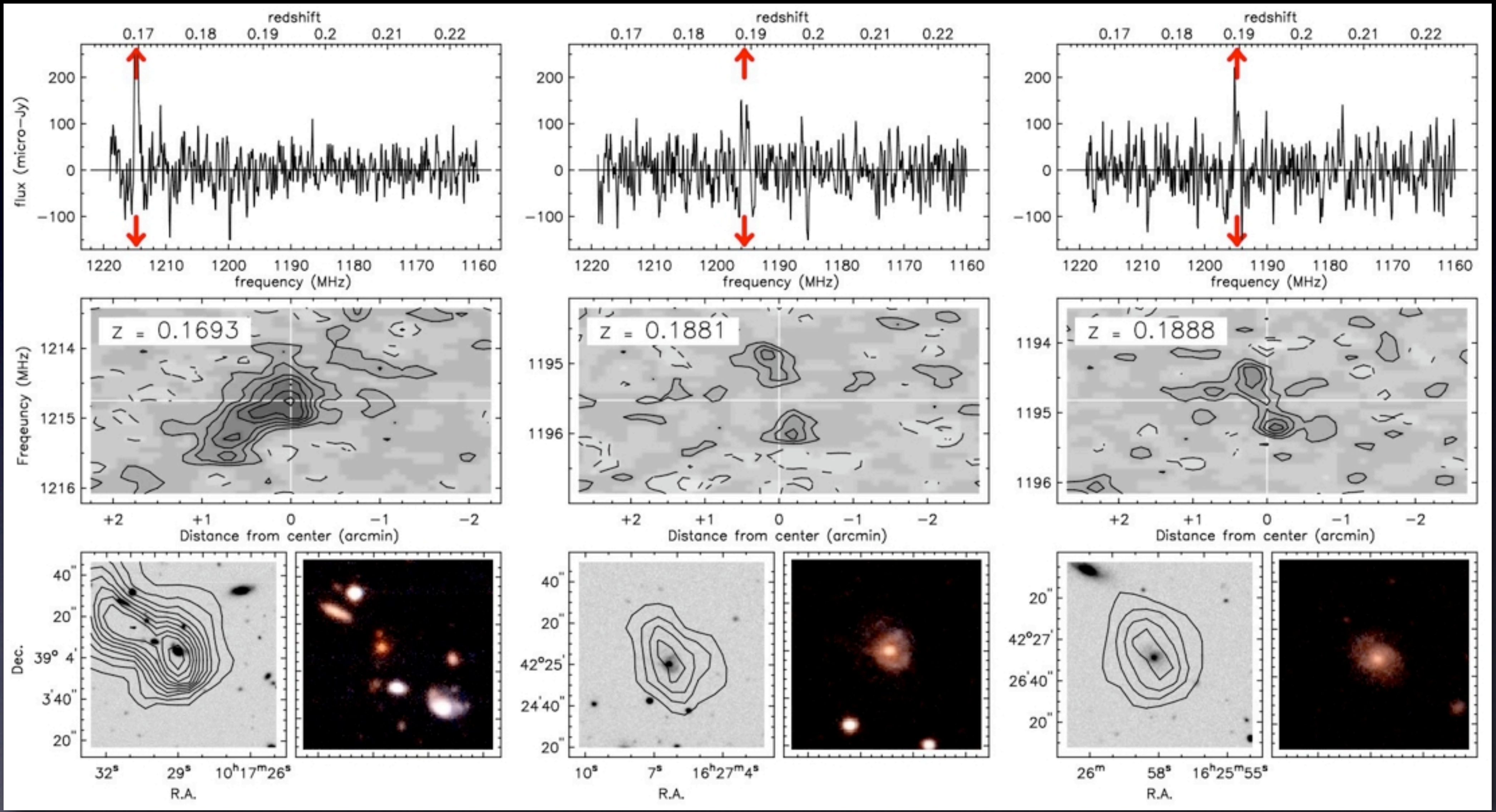
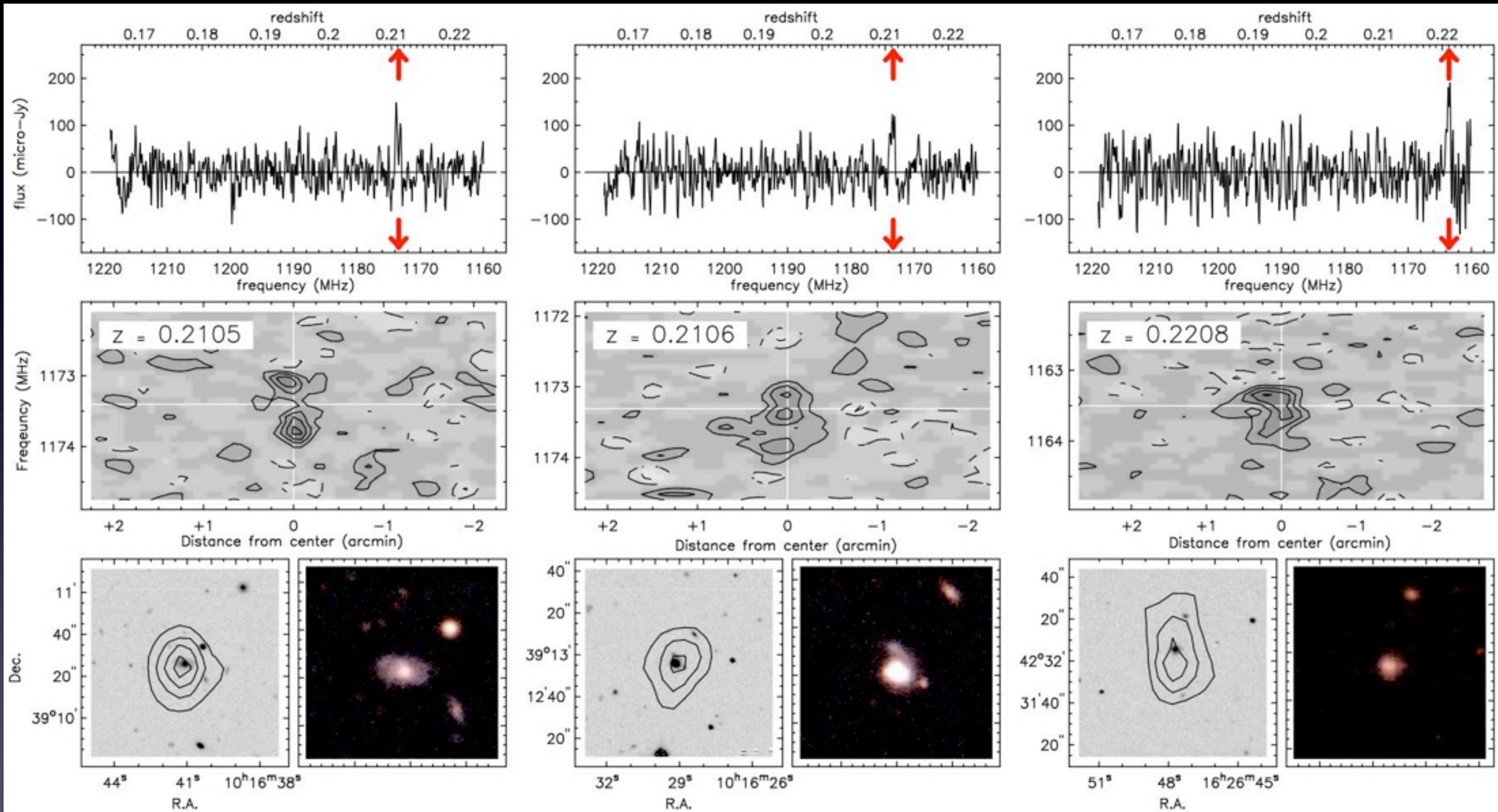
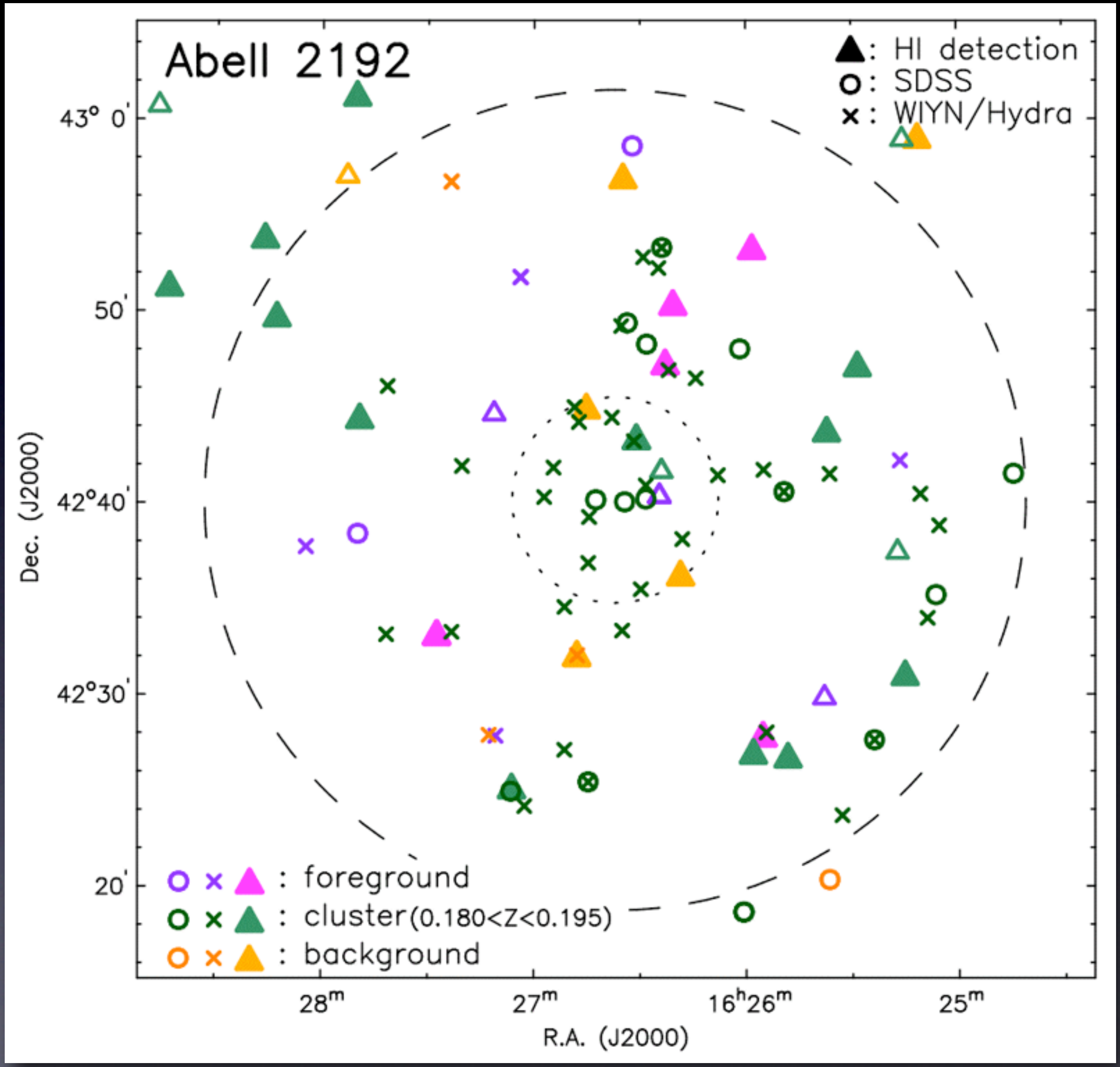
Detections in pilot observations



Detections in pilot observations



Revealing the surrounding field



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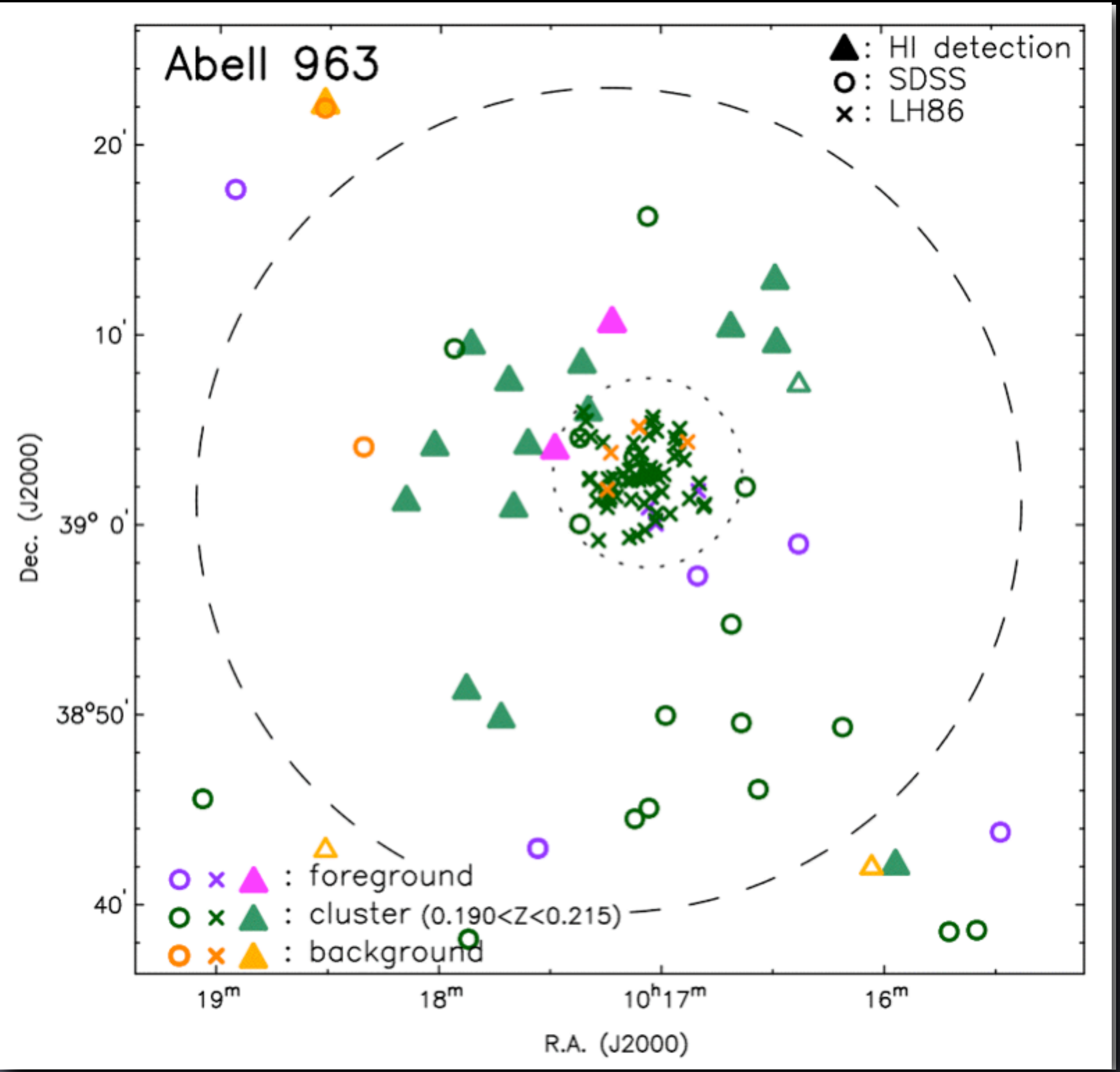


Colour-Magnitude diagrams

Galaxies with known redshifts only

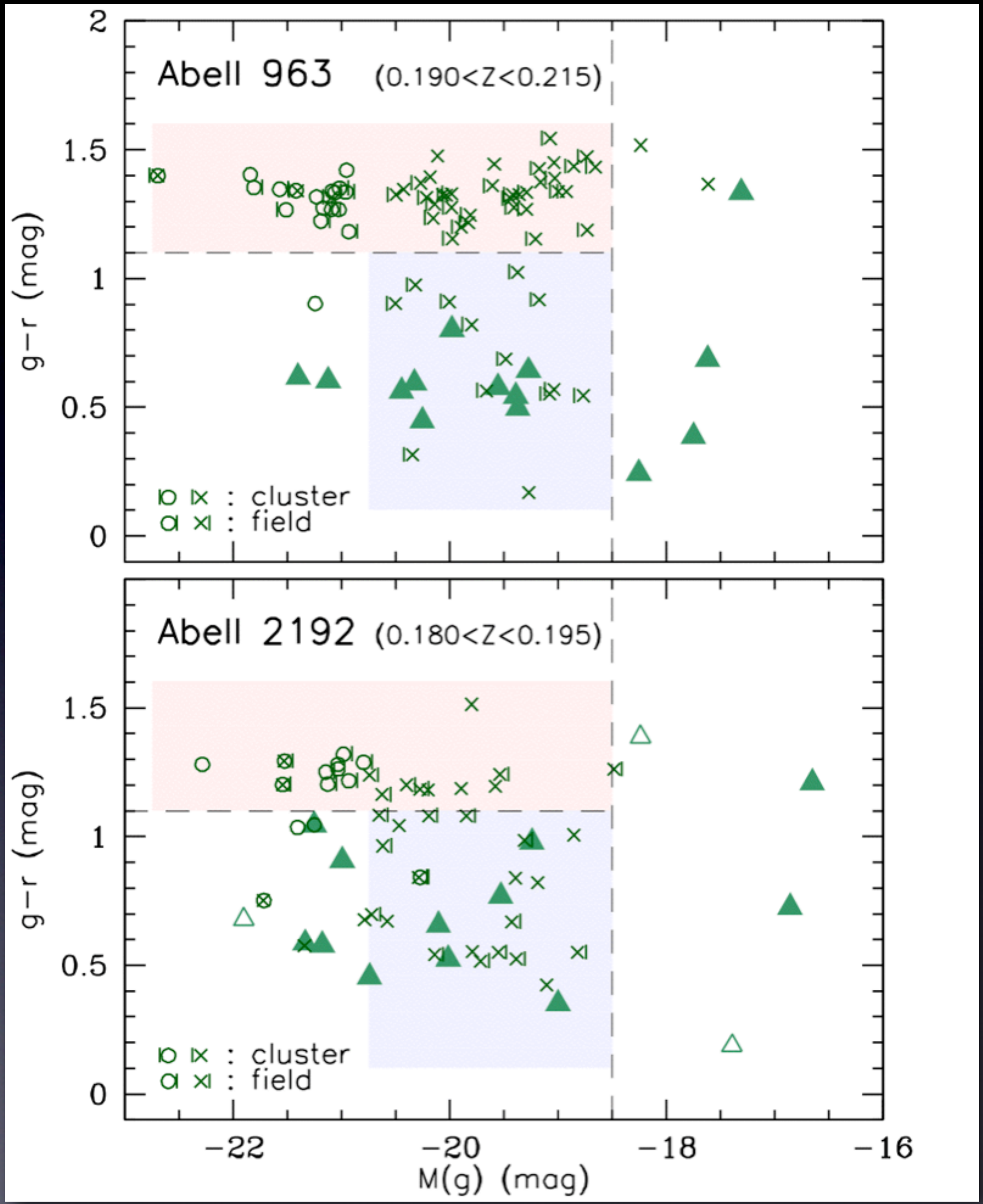
optical redshifts

O : SDSS

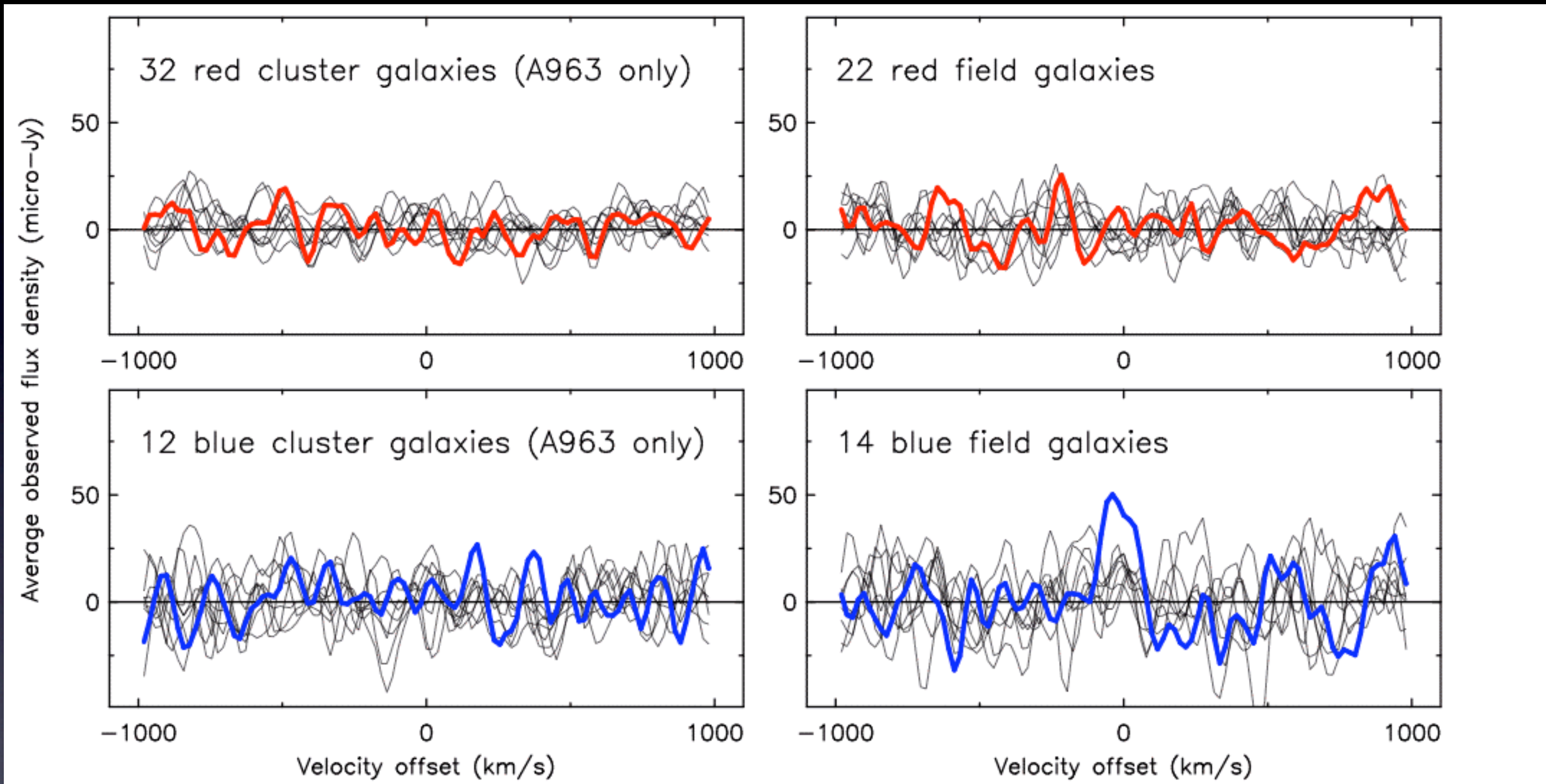
× : other

HI redshifts

▲ : WSRT



Stacking HI spectra

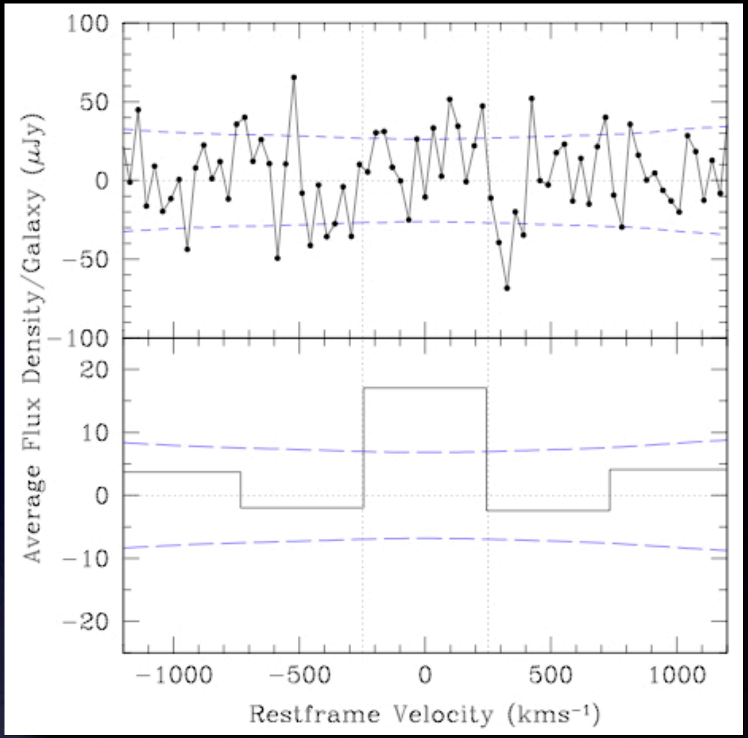


Average HI mass: ~ $2x10^9\ M_{\odot}$

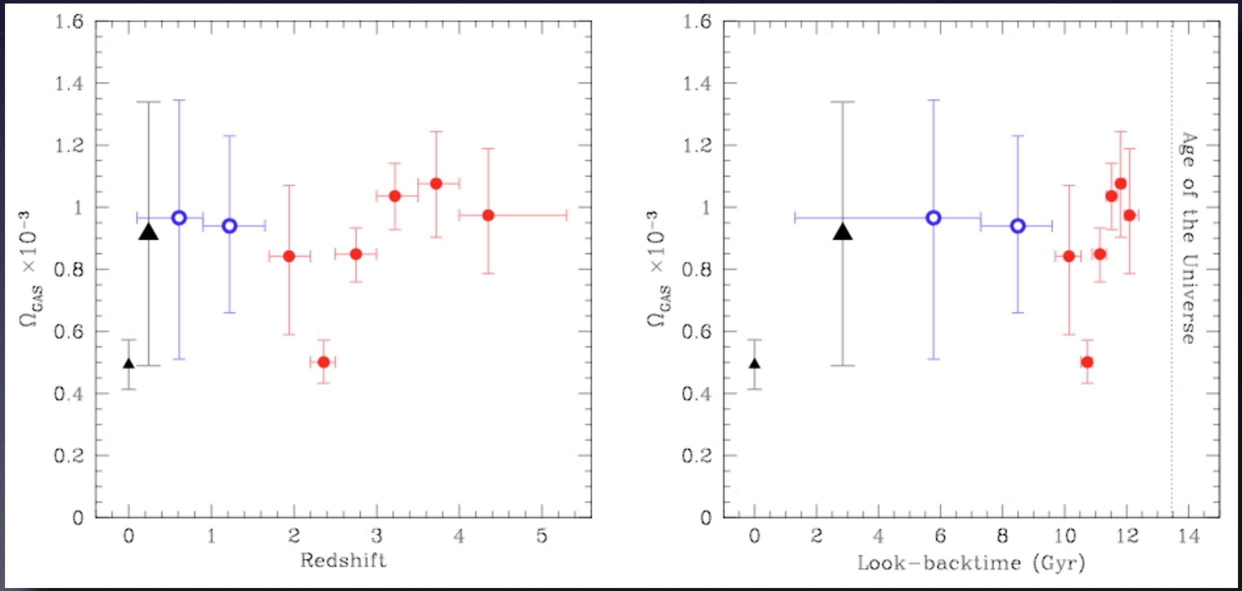
Probing $\Omega_{HI}(z)$ of the universe

Ω_{HI} at z=0.2 from stacking GMRT HI spectra of starforming galaxies with optical redshifts.

(Lah et al, 2007 ; Blyth this meeting)

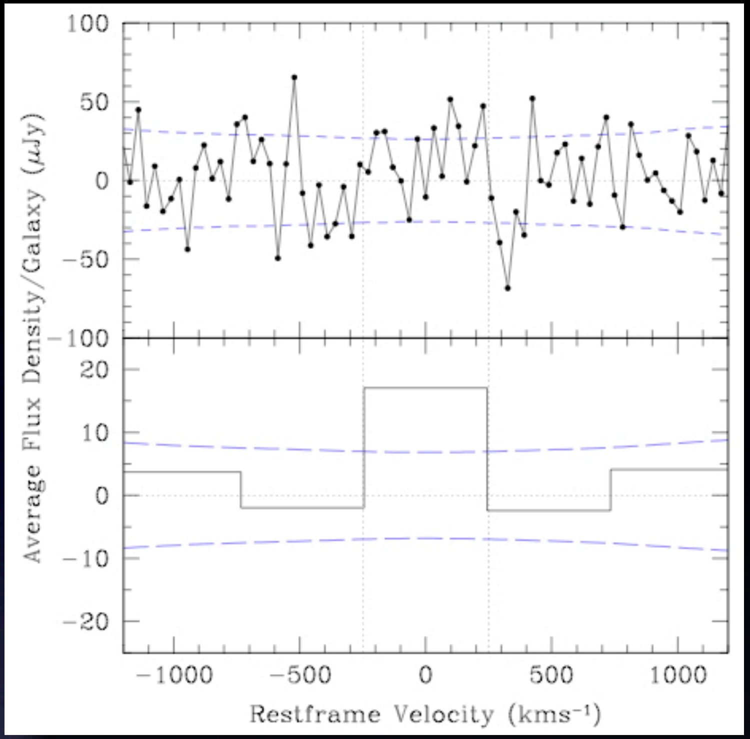


Lah et al, 2007



Soon to be measured from WSRT data, but surveyed volume too small?

Probing $\Omega_{HI}(z)$ of the universe



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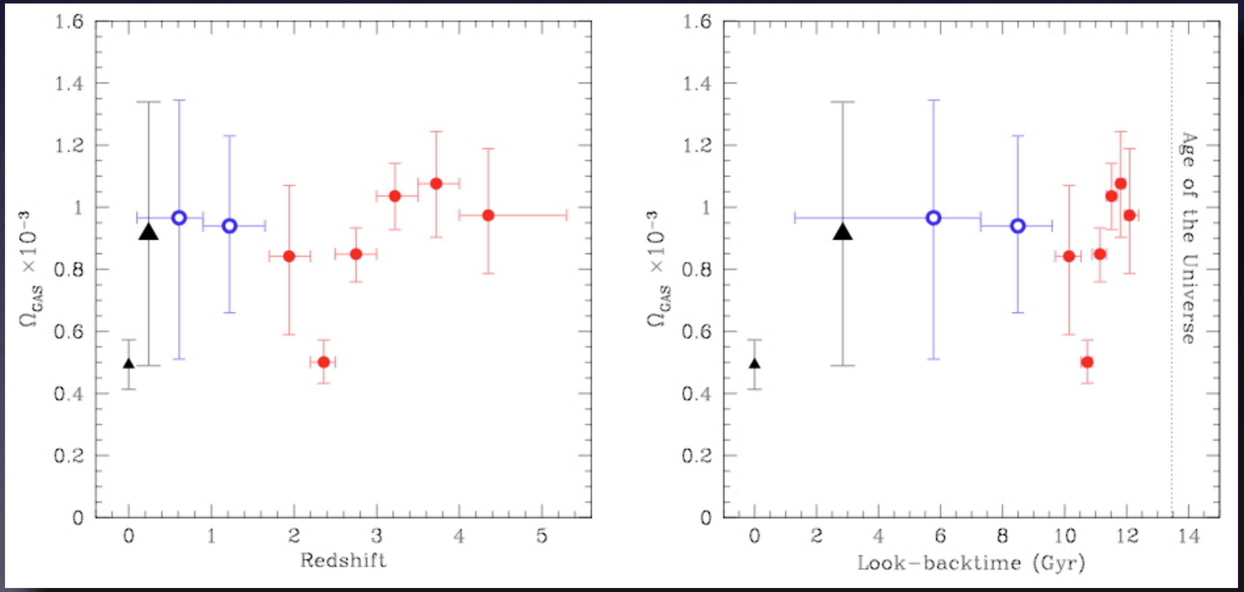


Soon to be measured from WSRT data, but surveyed volume too small?

Still a tough job for APERTIF and ASKAP given A_{eff}/T_{sys} .

Challenges

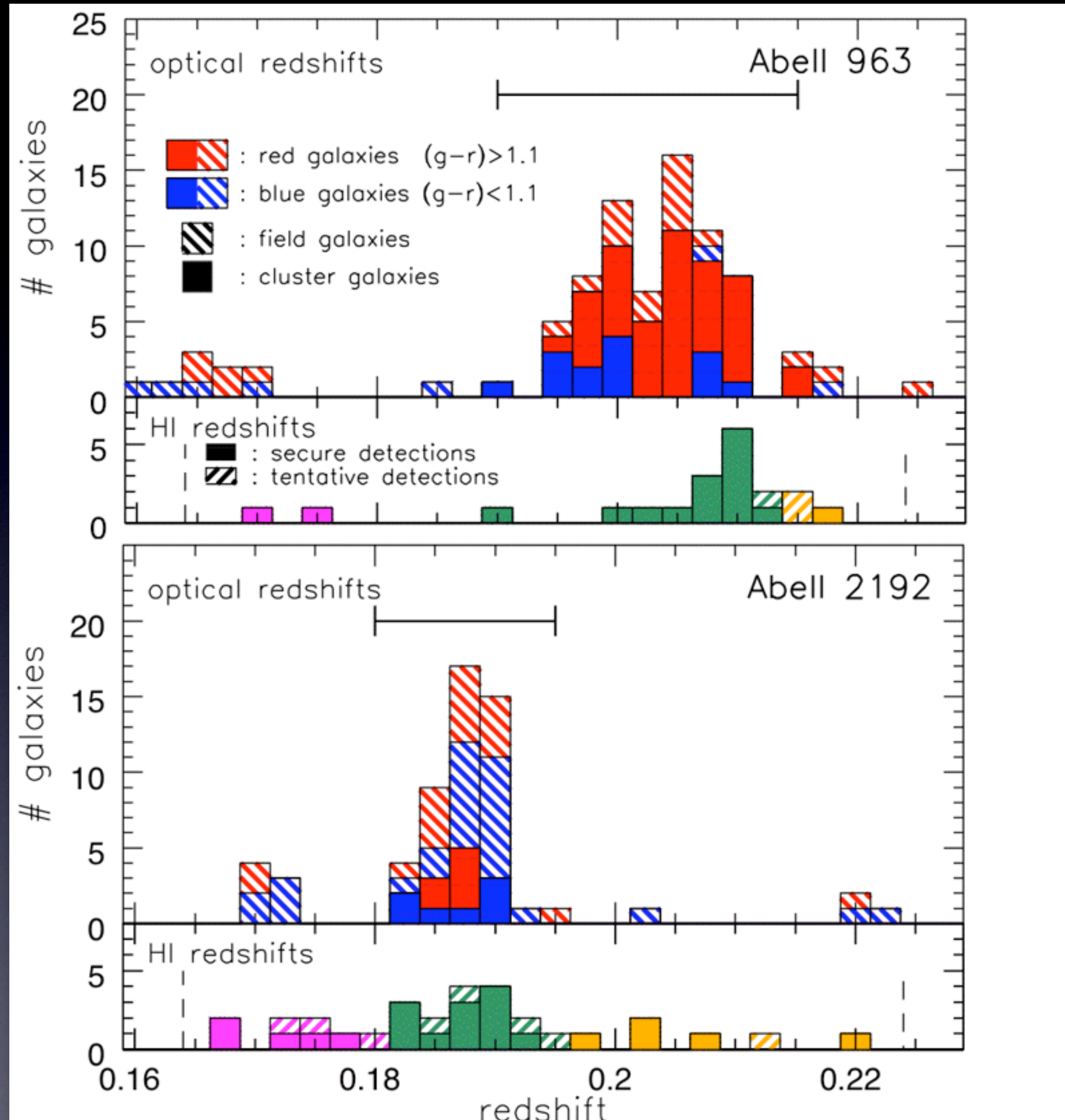
Correlator and pipelined calibration solutions?

How to keep up with the huge data flow?

How to extract HI maps, velocity fields and rotation curves for 10^4 galaxies and recognize 'anomalies'?

How to serve the data to the public?

Redshift distributions



trade-offs: Imaging/Survey speeds & costs

Ntel	Nbm	BW		ISpeed		SSpeed		dish	total
		MHz		line	cont			k€	M€
14	1	160		1	1	1		0	0
12	25	160		0.36	0.36	9		217	2.60
		300		0.36	0.67	17		262	3.15
	30	160		0.36	0.36	11		225	2.70
		300		0.36	0.67	20		280	3.36
14	25	160		0.49	0.49	12		217	3.03
		300		0.49	0.92	23		262	3.67
	30	160		0.49	0.49	15		225	3.15
		300		0.49	0.92	28		280	3.92

Trade-offs: Imaging/Survey speeds & costs

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Imaging & Survey speeds

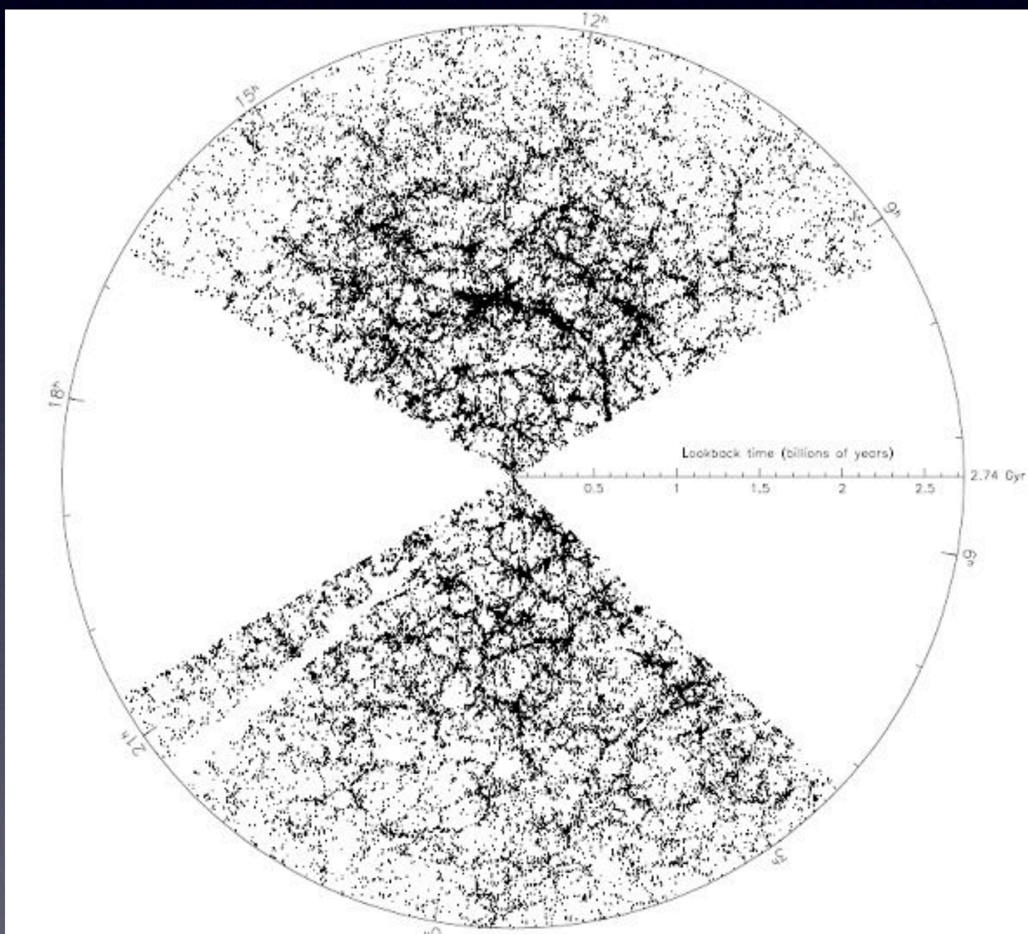
APERTIF versus other SKA pathfinders

	T_{sys}	FoV	BW	$(A_{eff}/T_{sys})^2$	$(A/T)^2$ FoV	$(A/T)^2$ FoV BW
	K	deg	MHz	$m^4\ K^{-2}$	$m^4 K^{-2} deg^2$	$m^4 K^{-2} deg^2 MHz$
				$x10^3$	$x10^4$	$x10^6$
APERTIF-12	57	10	300	6	6.0	17
ASKAP-50	35	30	300	12	35	105
MeerKAT-50	30	1.2	512	18	2.1	11
ATA-42	40	4.9	200	0.43	0.21	0.42

SKA all-sky HI survey

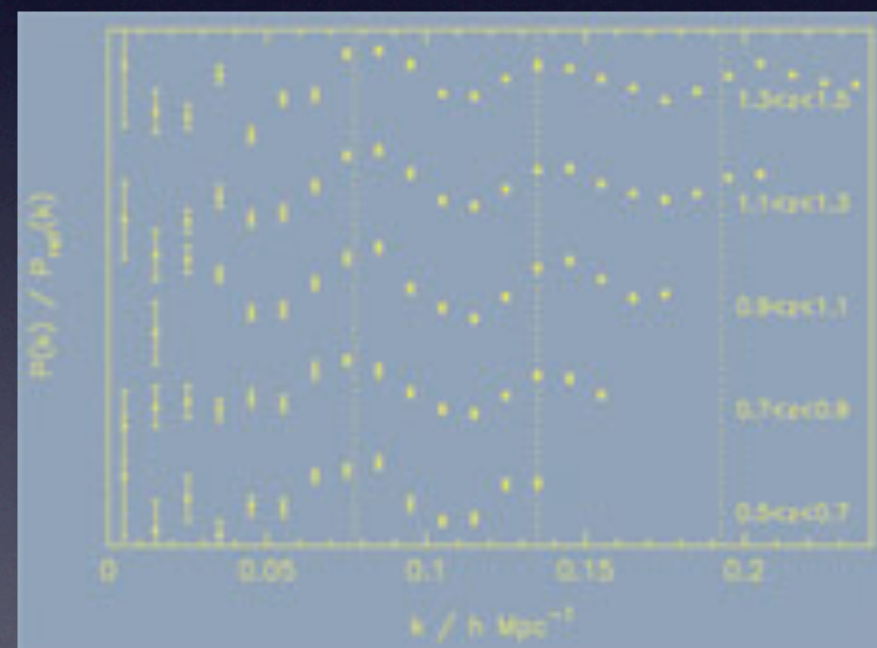
a billion galaxies detected in HI out to z=3

Cosmic large scale structure



SDSS

Baryonic Acoustic Occilations
from the clustering power spectrum



Chris Blake, 2007

APERTIF

APERture Tile In Focus

A Focal Plane Array for the WSRT

Principal Investigators: Tom Oosterloo
Marc Verheijen

Program Manager: Wim van Cappellen

Engineering team: Laurens Bakker, Marianna Ivashina, Oleg Smirnov, Stefan Wijnholds, Bert Woestenburg, Jan Noordam

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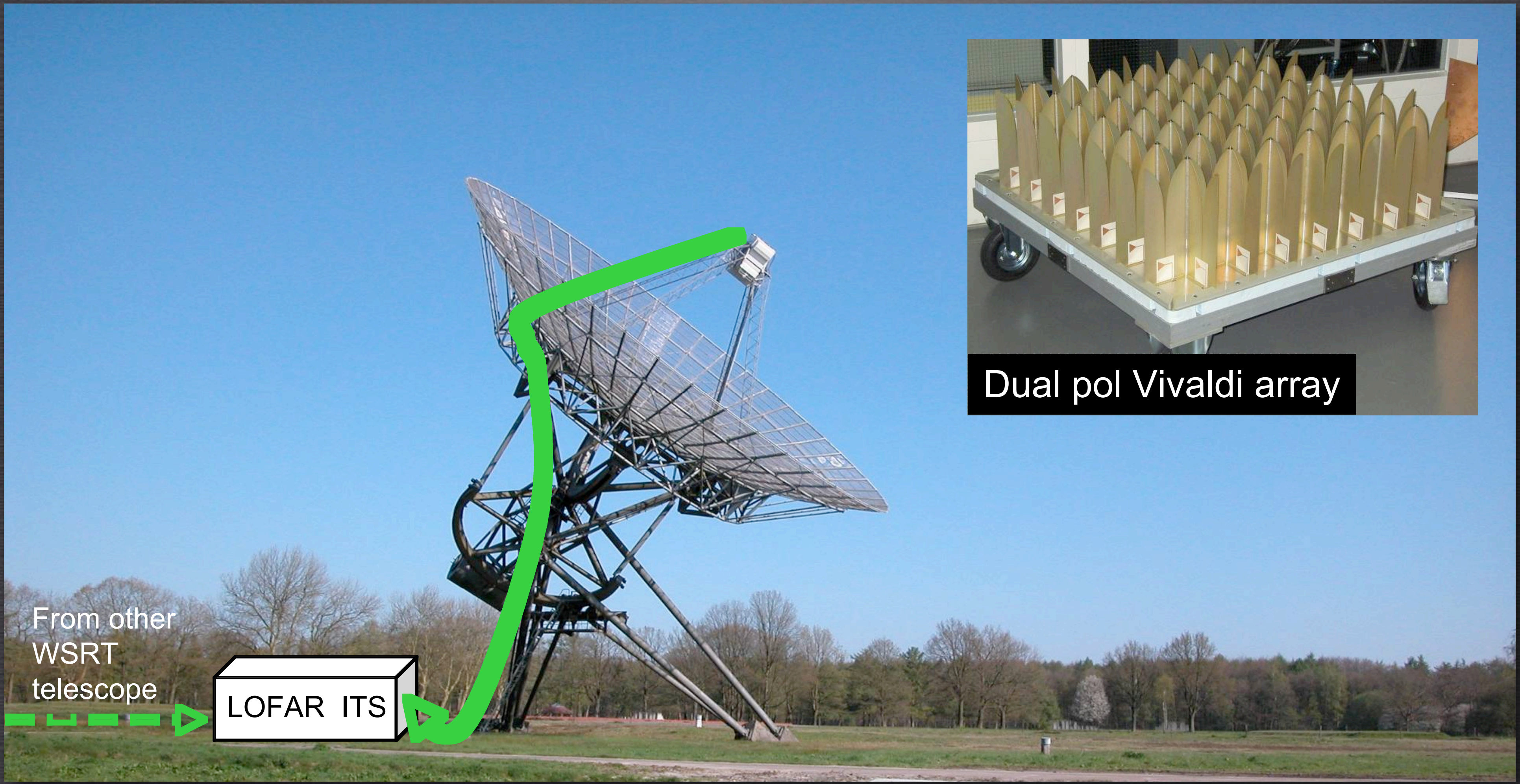
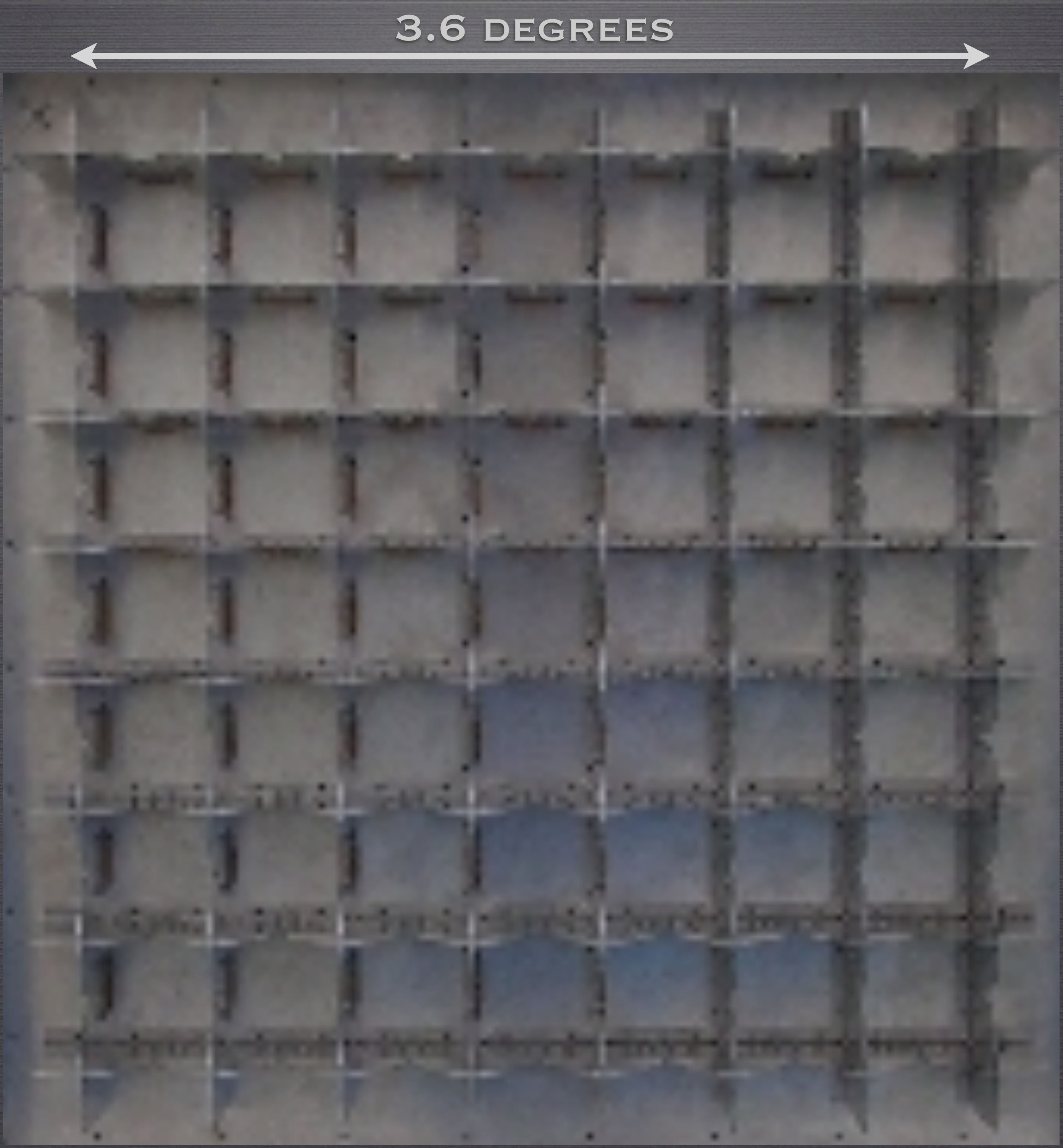
Prototype installed in RT5, using the modified LOFAR Initial Test Station

ITS can accept 60 signal chains



future APERTIF beamforming below apex



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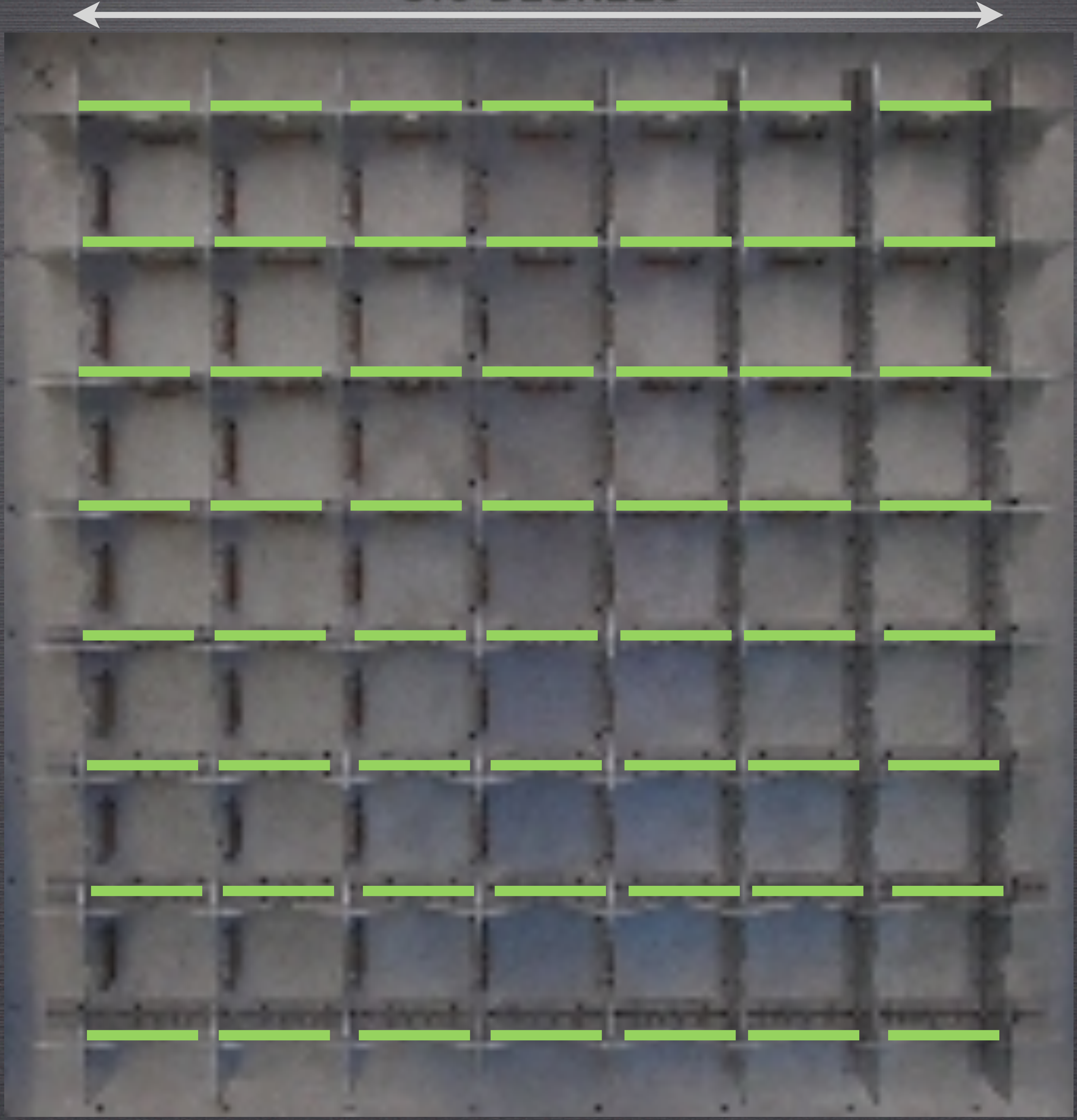
3.6 DEGREES



7x8 X

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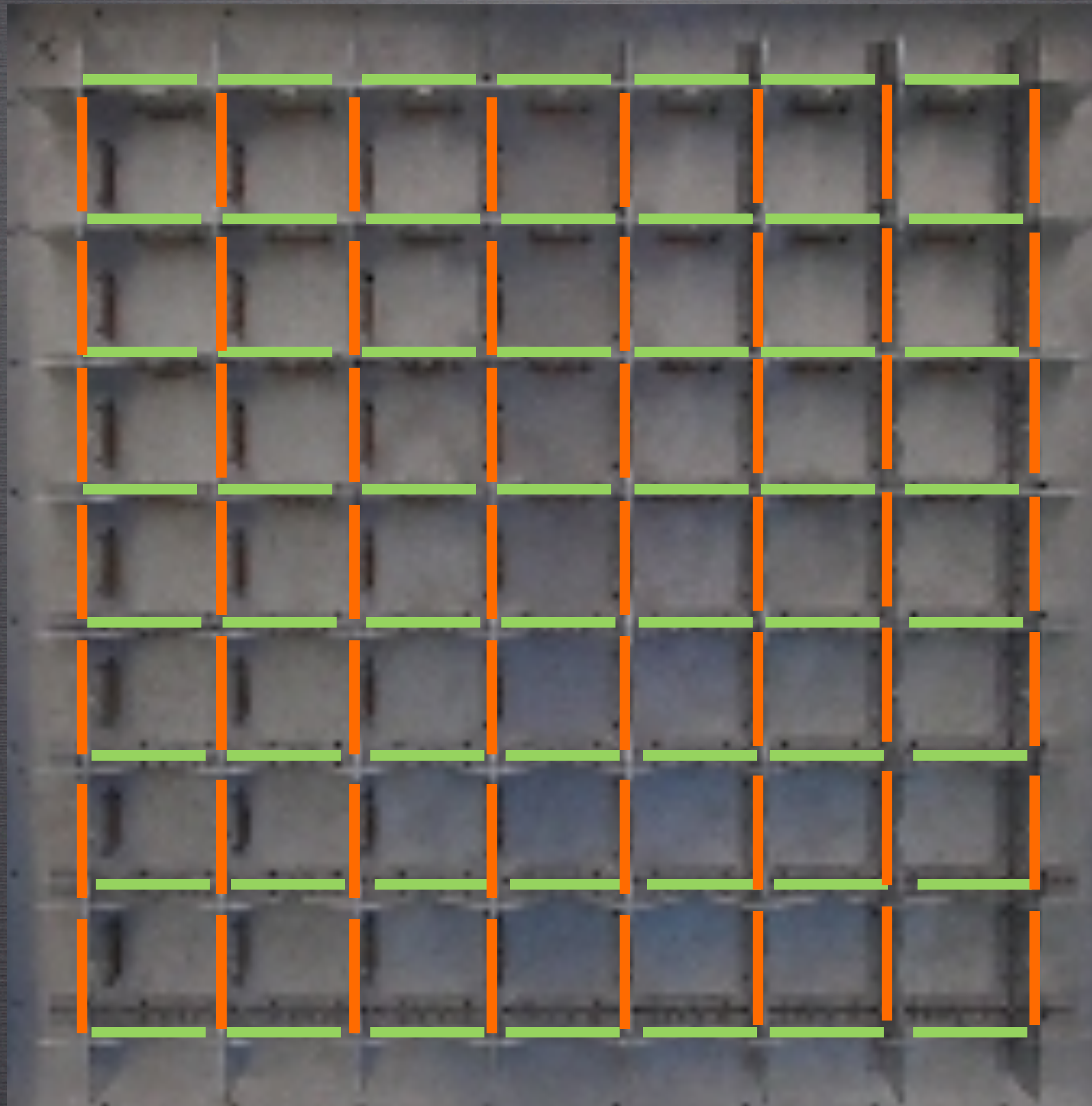
3.6 DEGREES



7x8 X
8x7 Y

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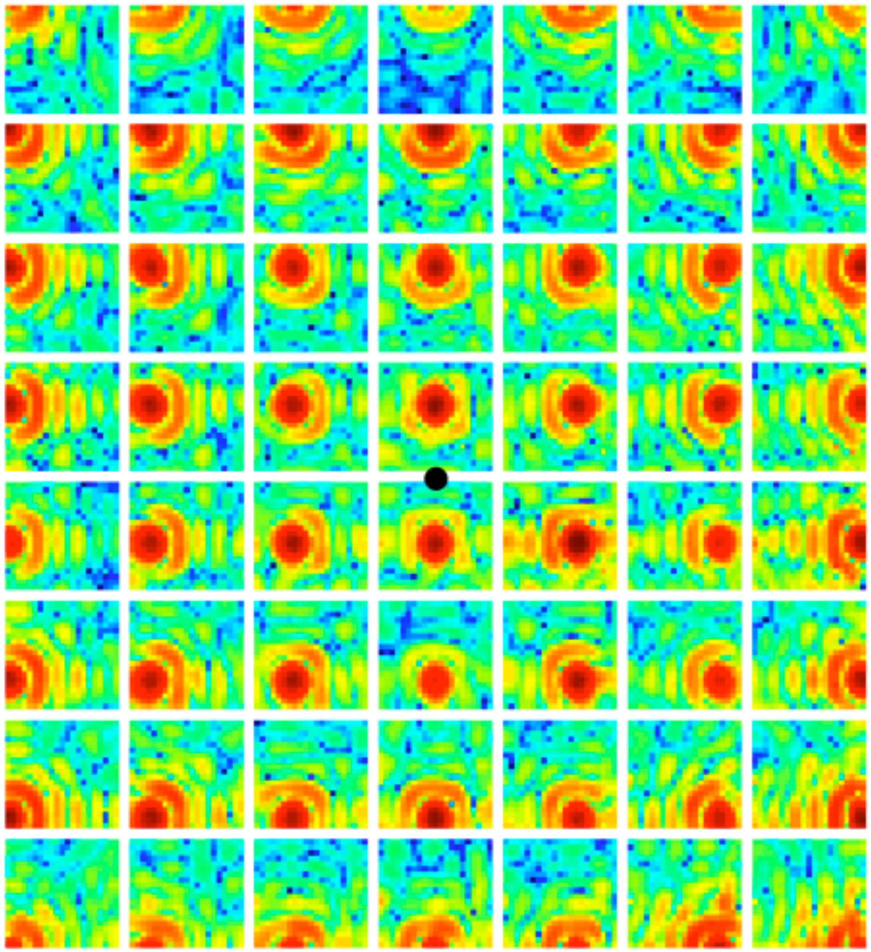
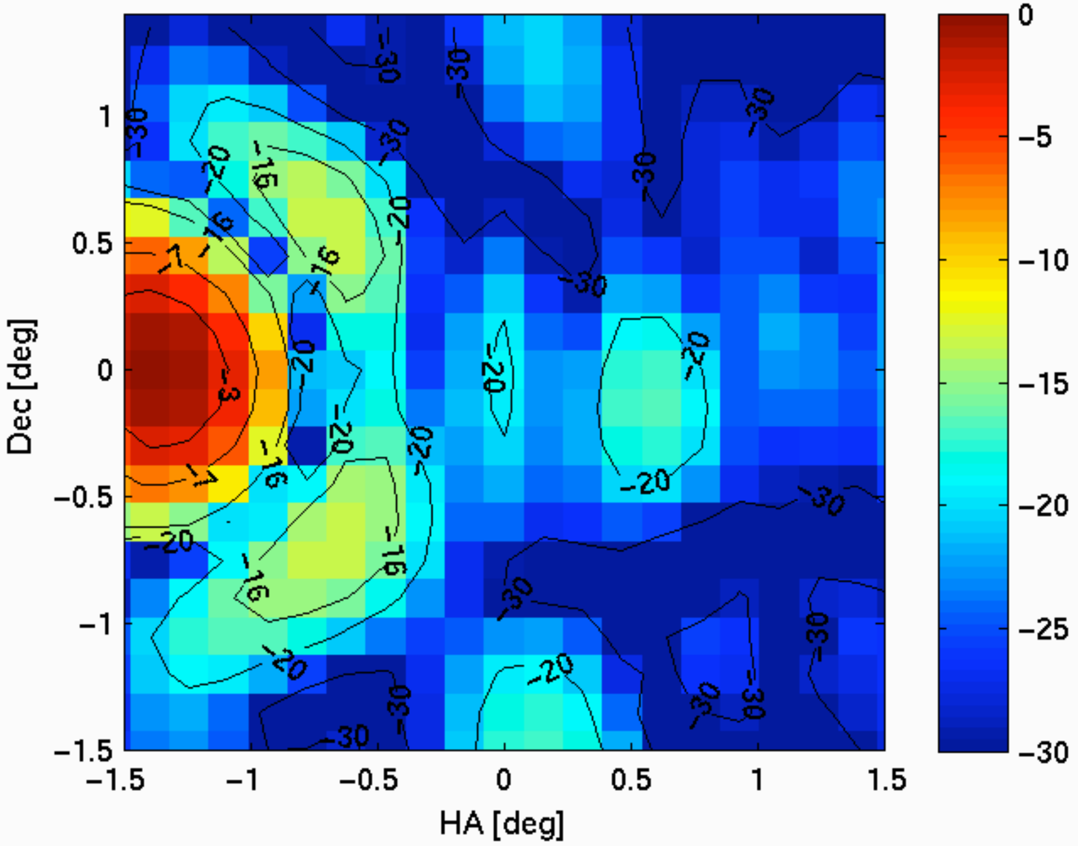
APERTIF prototype results

Element patterns



Steerable compound beam



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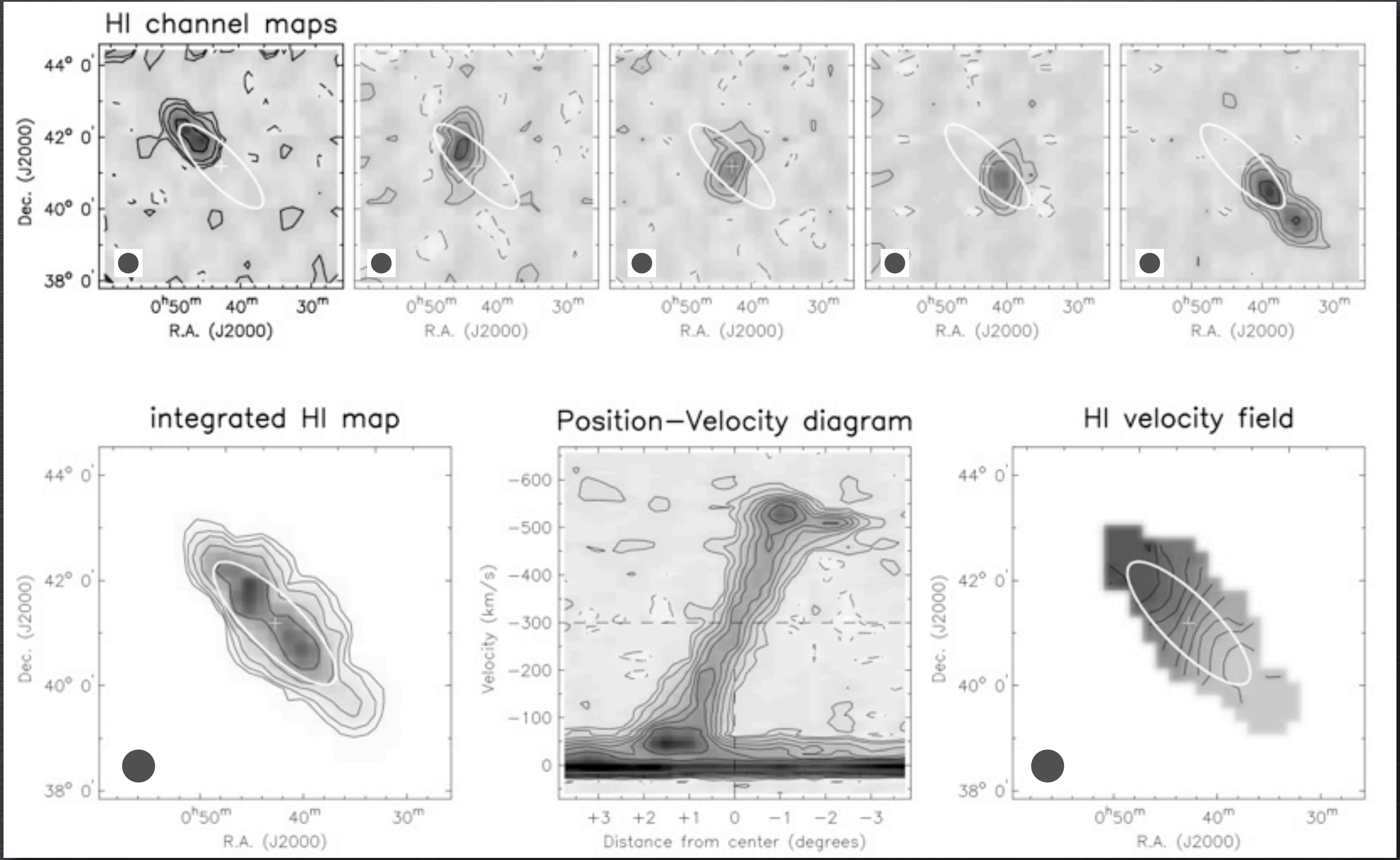
Messier 31

3x3 pointings, 9x20 sec integration time, 6.5° x 6.5° FoV



Messier 31

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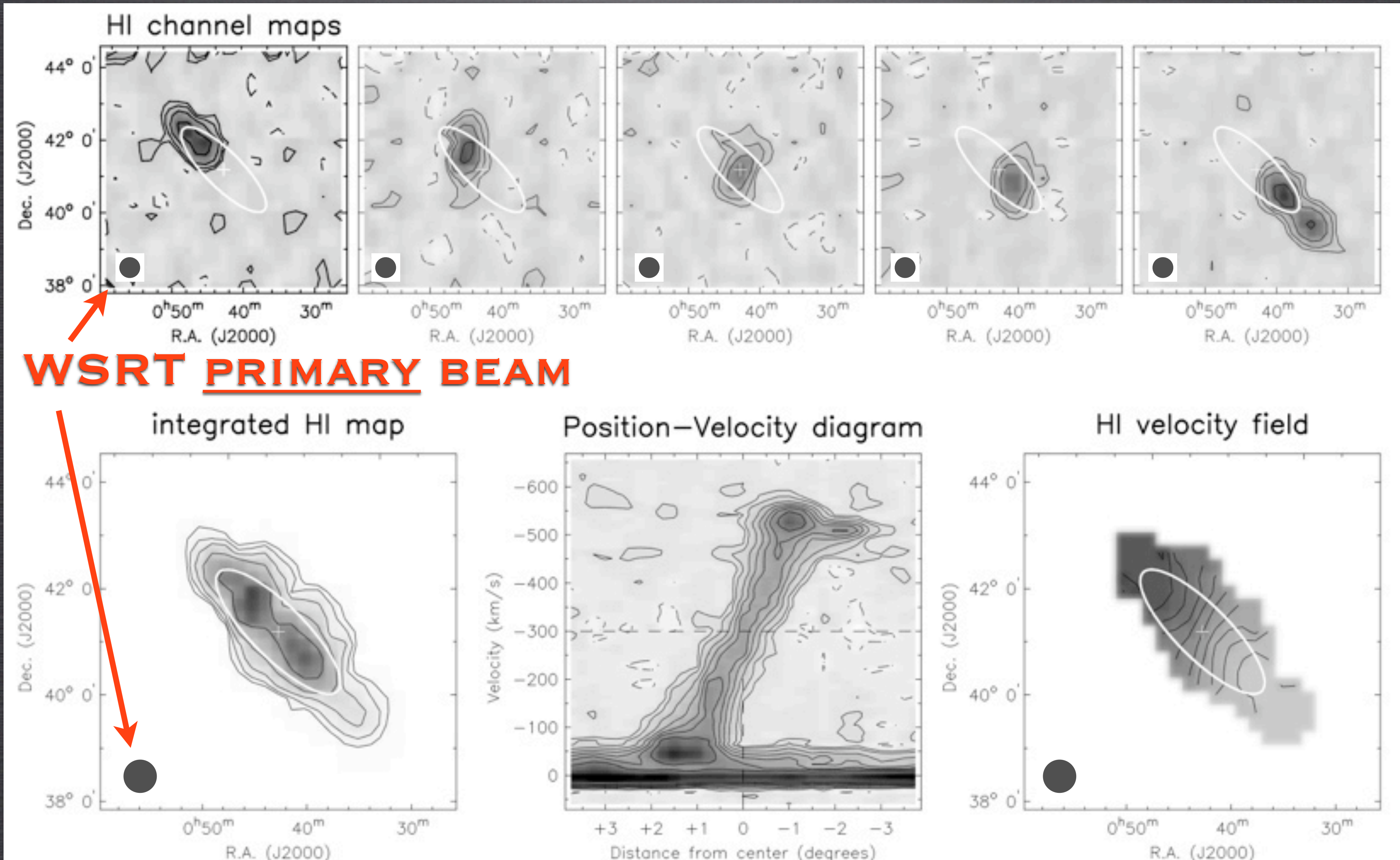

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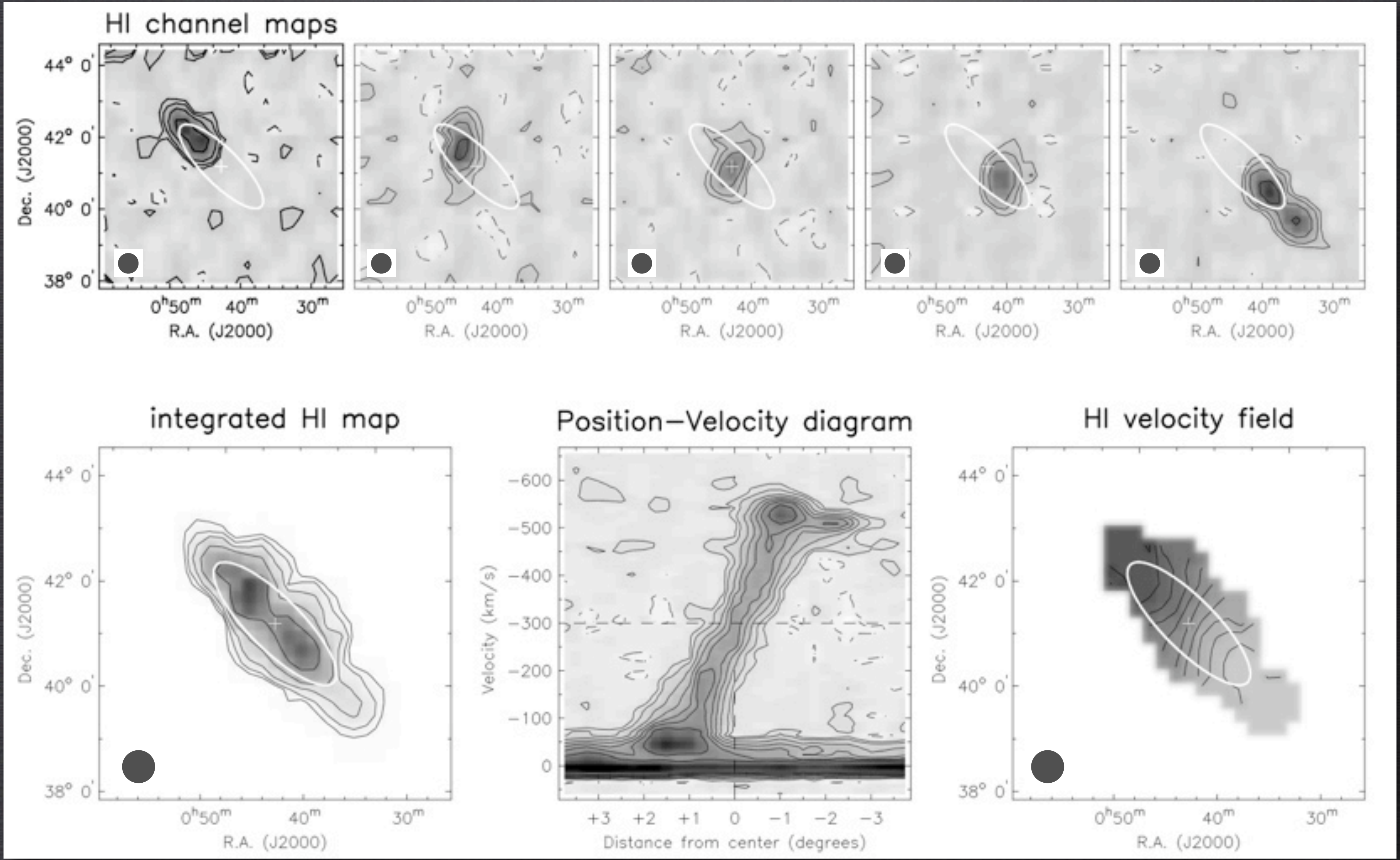

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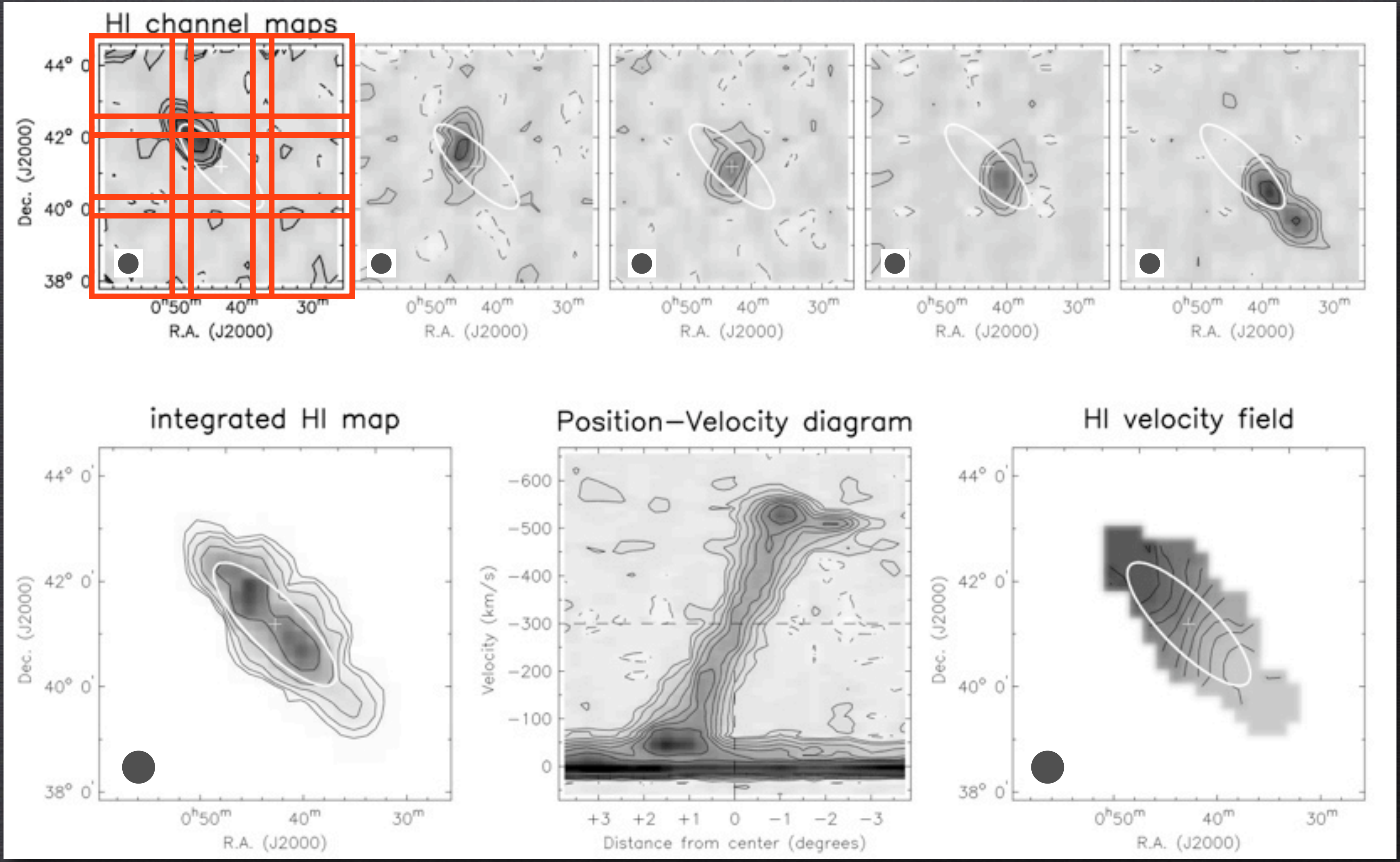

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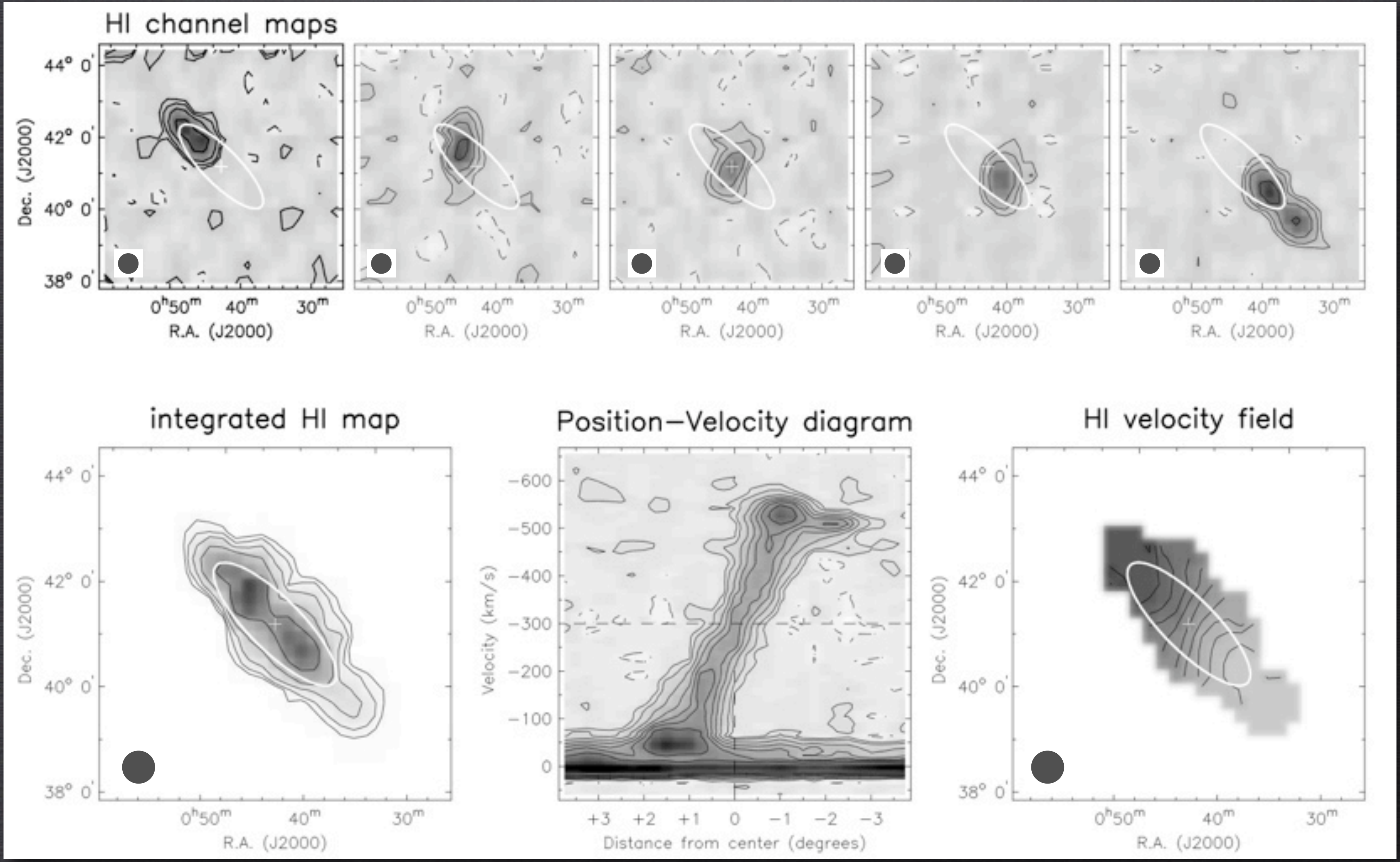

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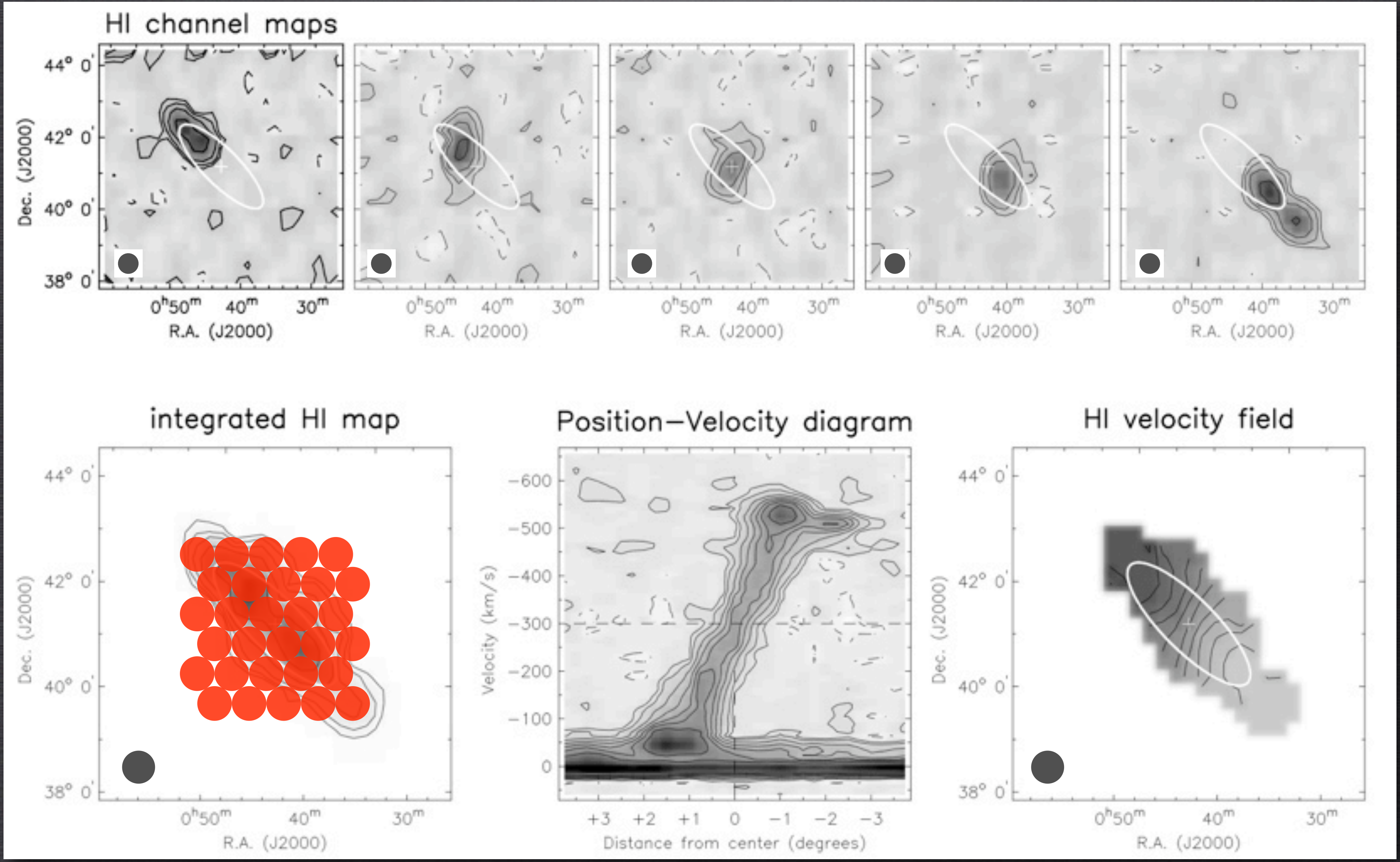

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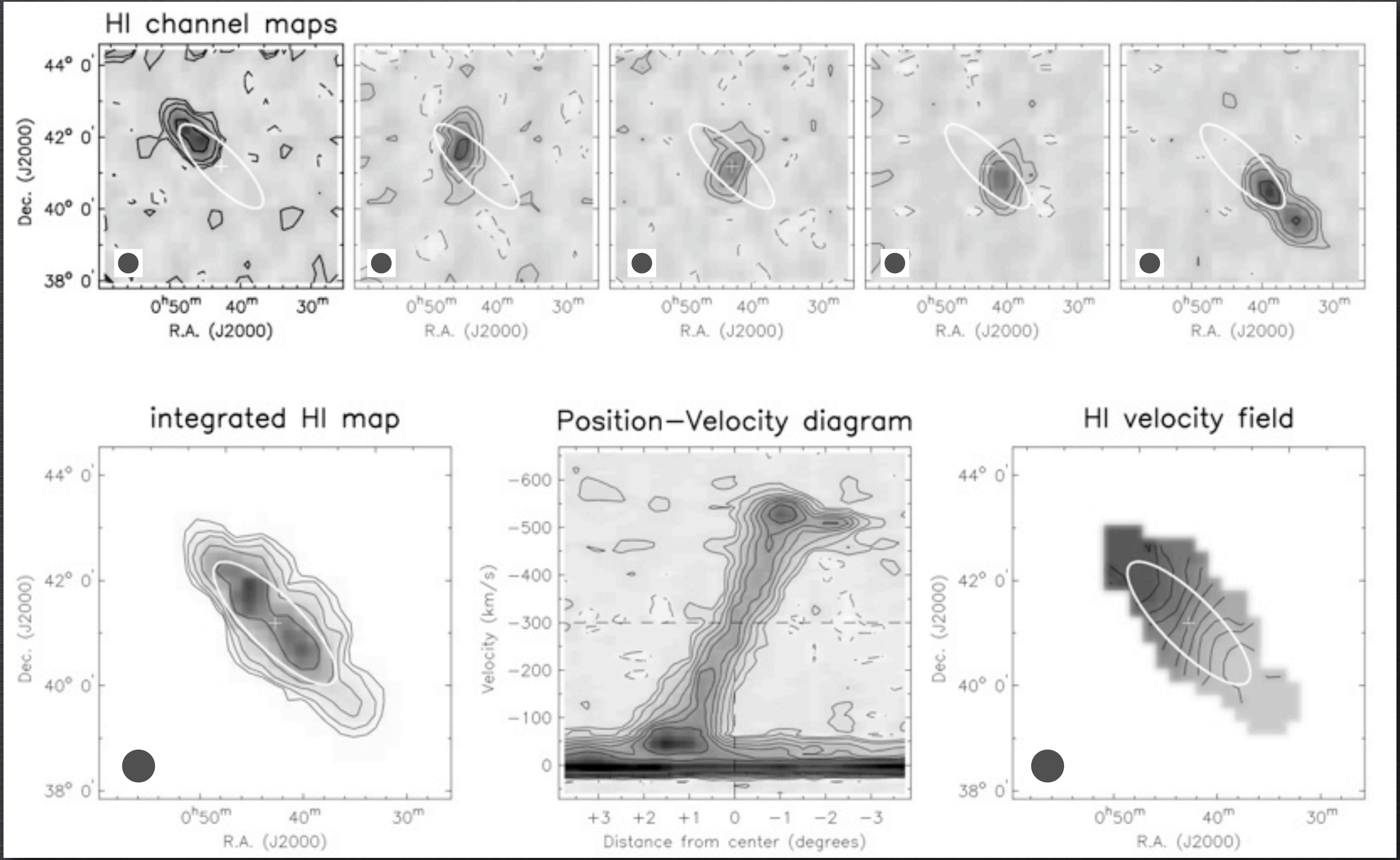

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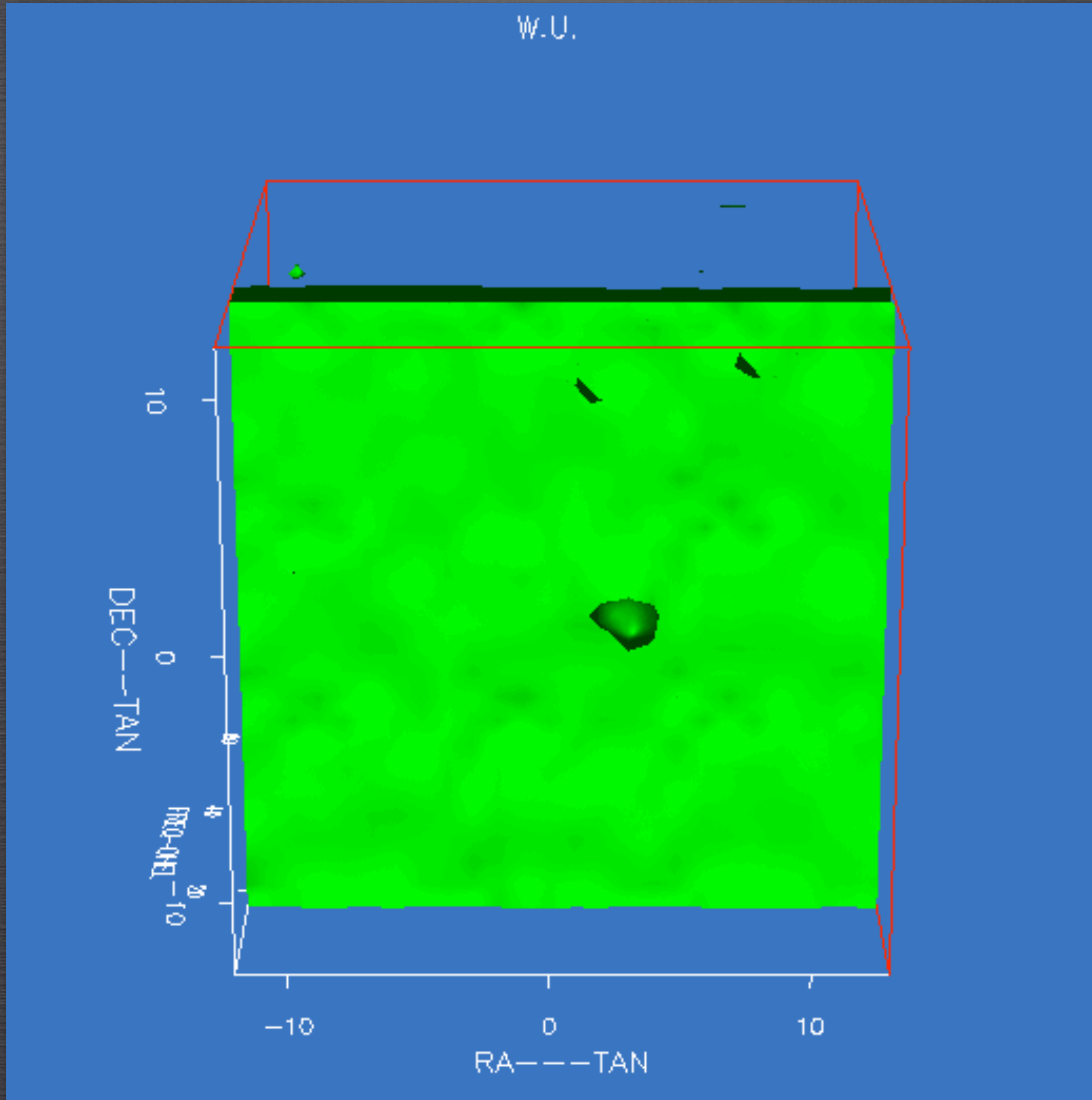

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Imaging & Survey speeds

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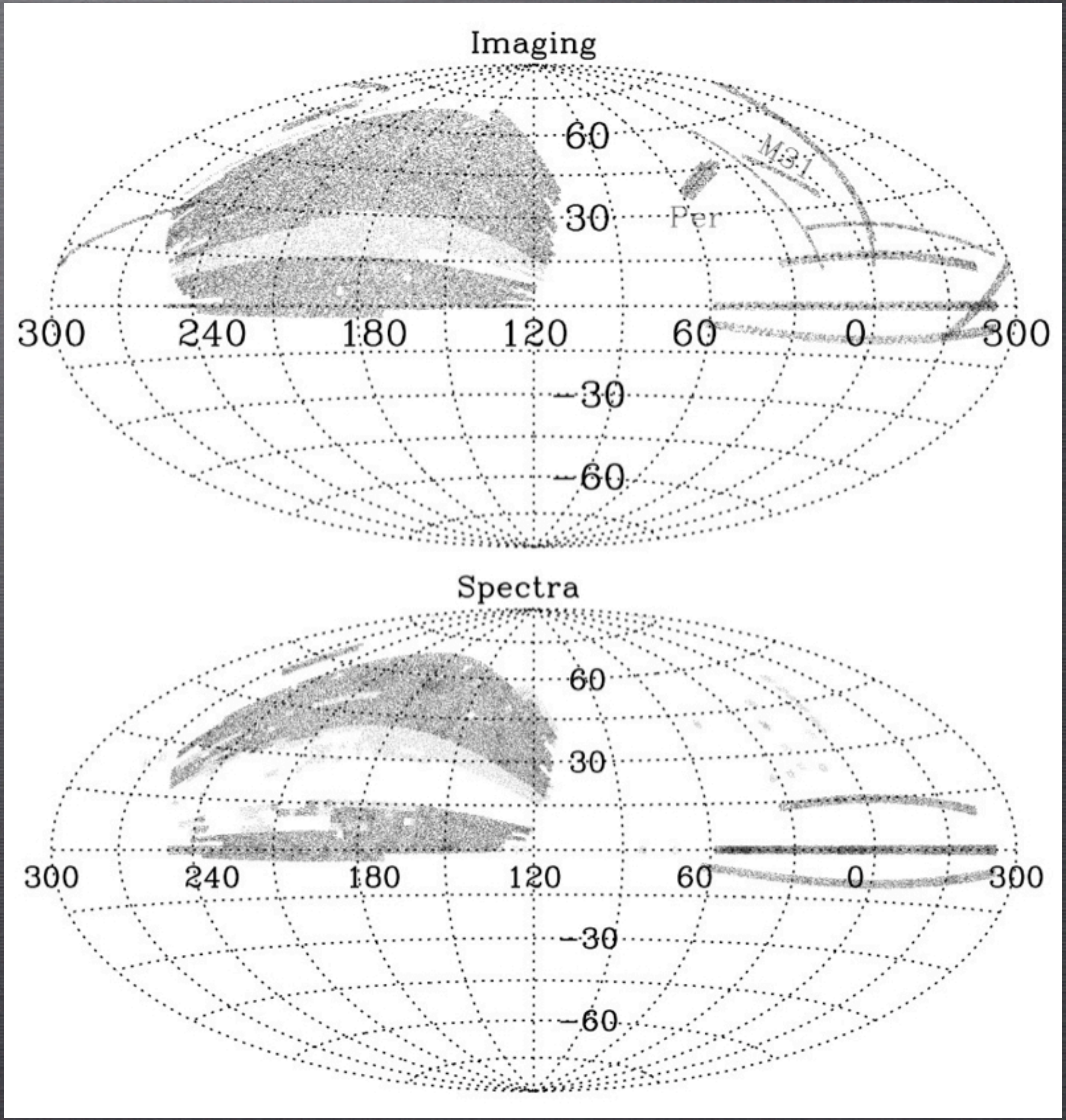
HI surveys of SDSS area

- $8^{HR} < \alpha < 16^{HR}$, $15^{\circ} < \delta < 60^{\circ}$
- 0<Z<0.25   (300 MHz)
- 4177 deg^2
- ~ 450 x 12^{HR}
- 4 years @ 30% of time
- 203,425 optical SDSS redshifts at z<0.2 (DR5)
- M(HI)* at z=0.08
- 1.5x10^5 HI detections



SDSS-Data Release 5 paper

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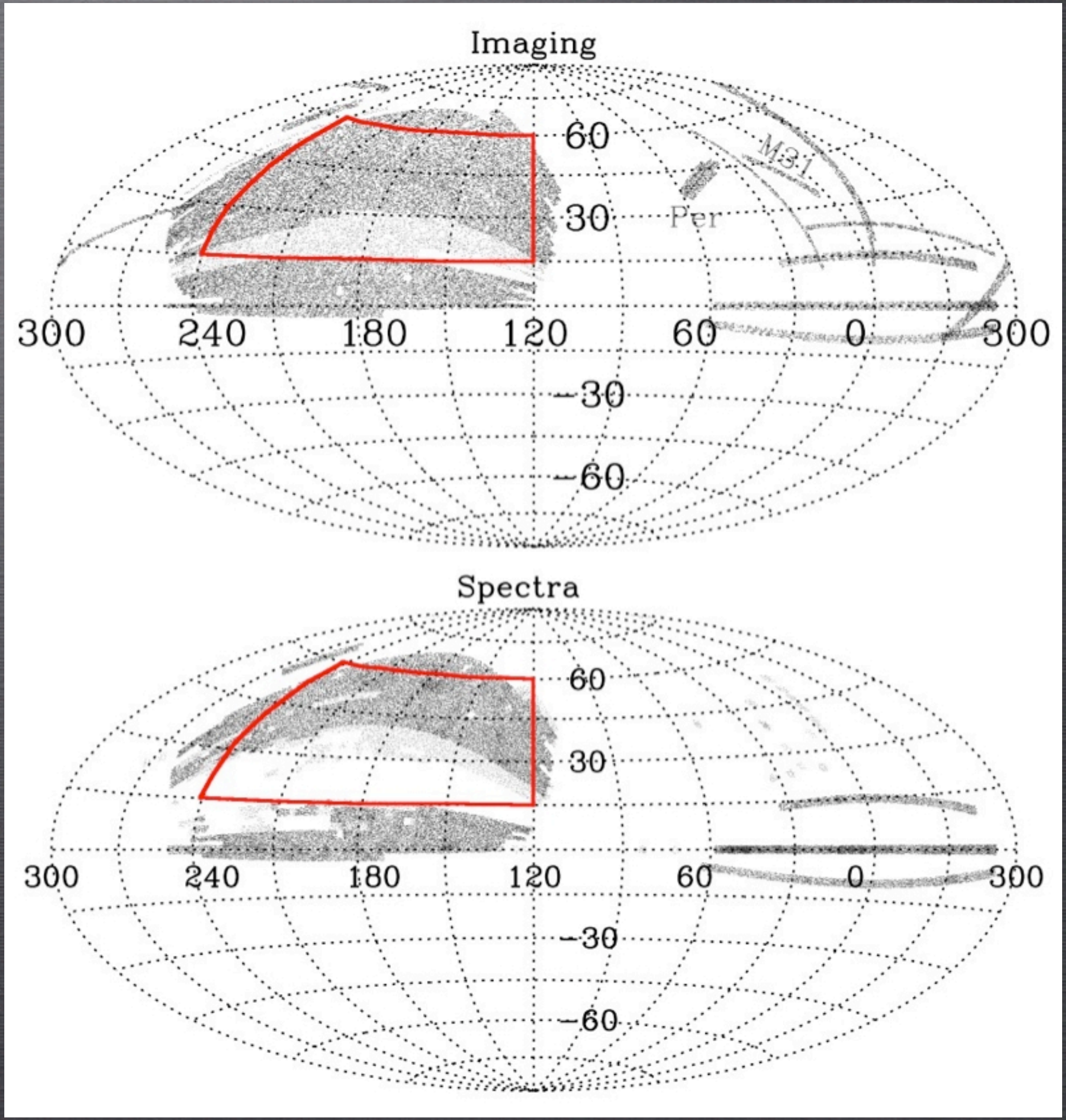

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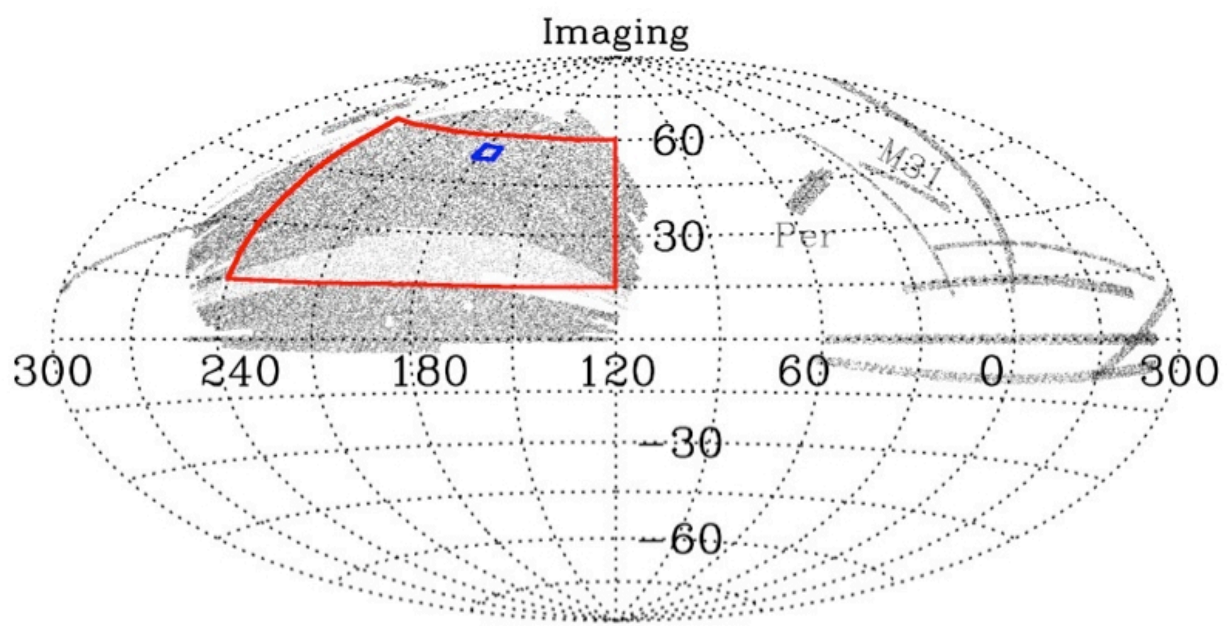

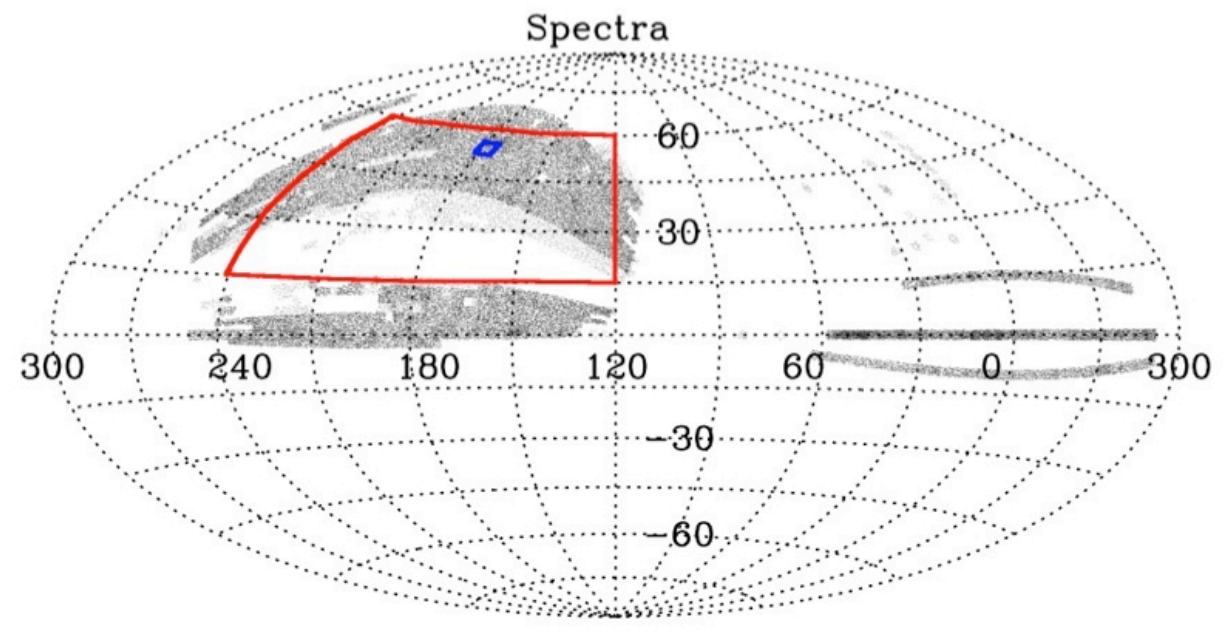

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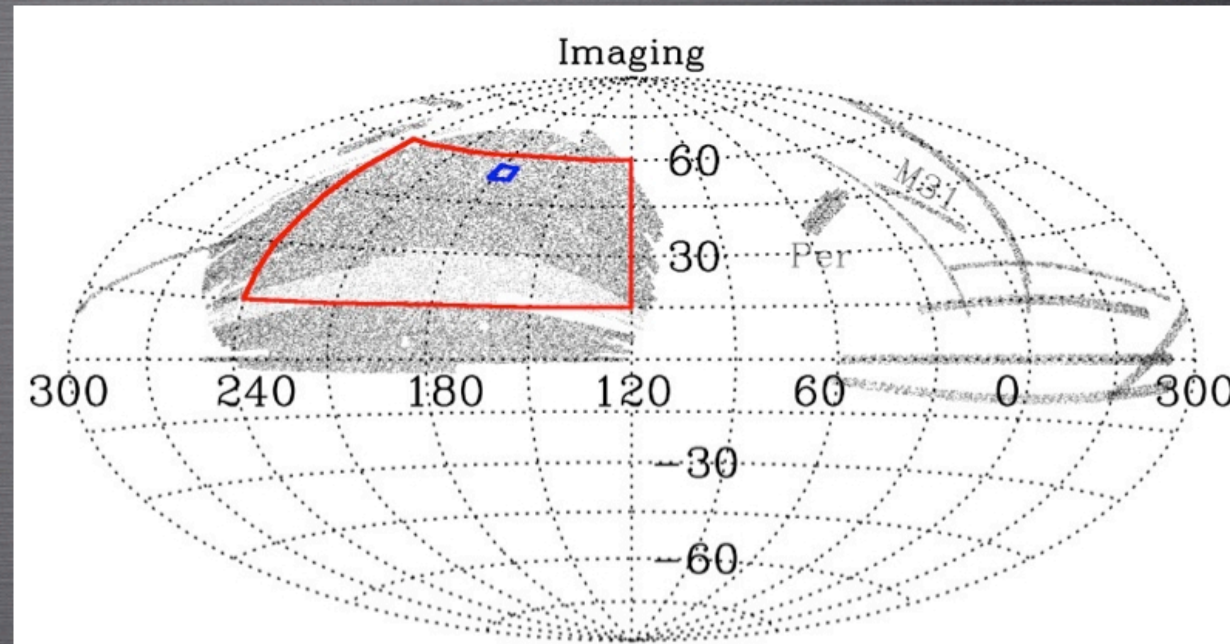

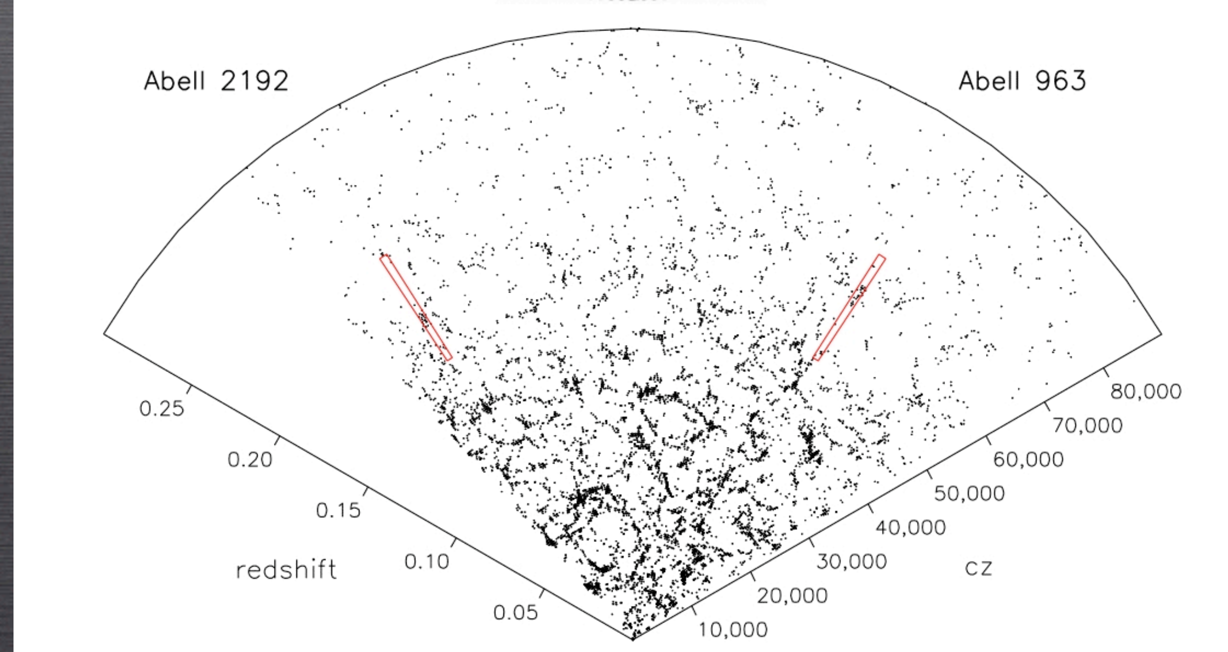

SDSS-Data Release 5 paper

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Summary & Outlook

- HI reveals physical processes unseen otherwise
- HI emission from 41 galaxies at z≈0.2
  (need SKA for larger redshifts)
- Blind HI survey uncovers LSS not seen by SDSS
- Blue 'BO-galaxies' gas-poor wrt similar field galaxies
- Long-term program on WSRT completed
  (>200 detections expected)
- APERTIF will enable all-sky
  survey at 15" resolution

Summary & Outlook

- HI reveals physical processes unseen otherwise
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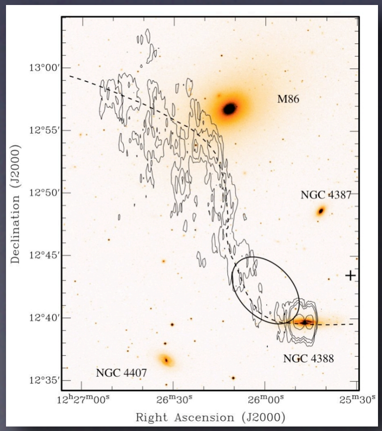
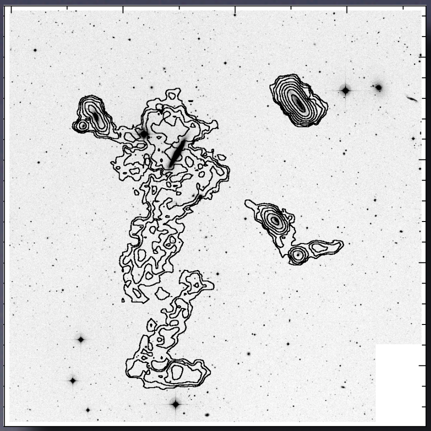
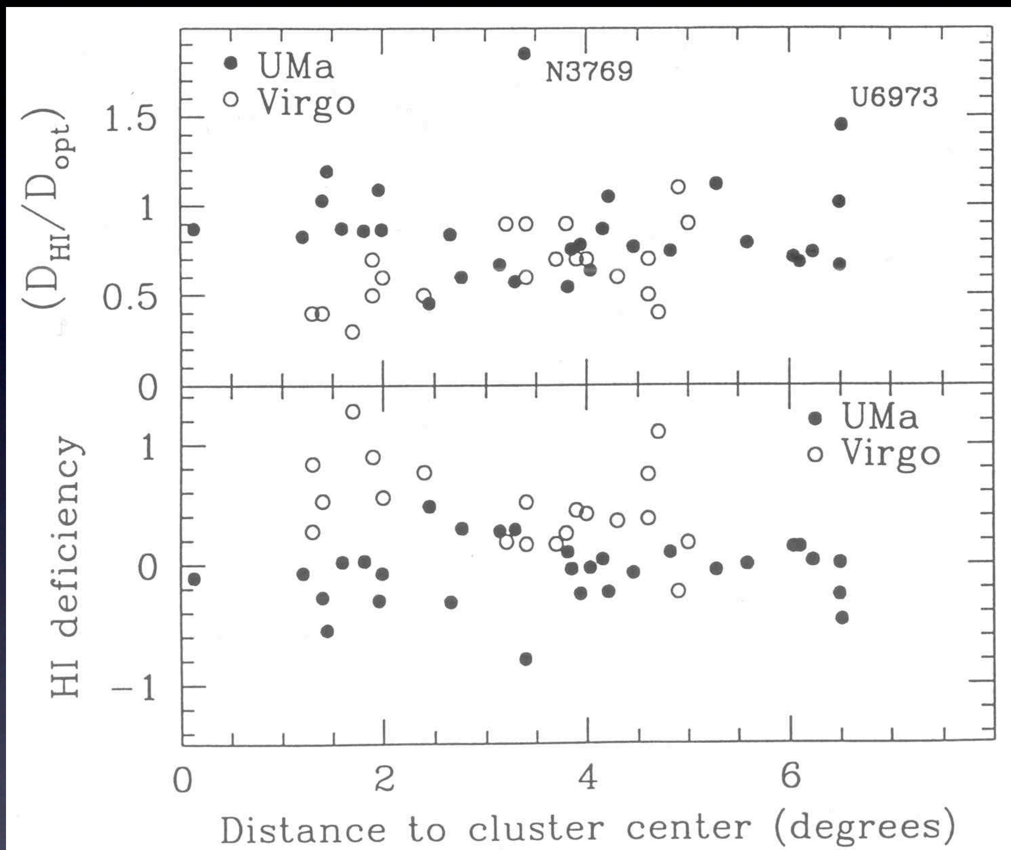
  (need SKA for larger redshifts)
- Blind HI survey uncovers LSS not seen by SDSS
- Blue 'BO-galaxies' gas-poor wrt similar field galaxies
- Long-term program on WSRT completed
  (>200 detections expected)
- APERTIF will enable all-sky
  survey at 15" resolution

Only SKA can image this at z=1





HI deficiencies



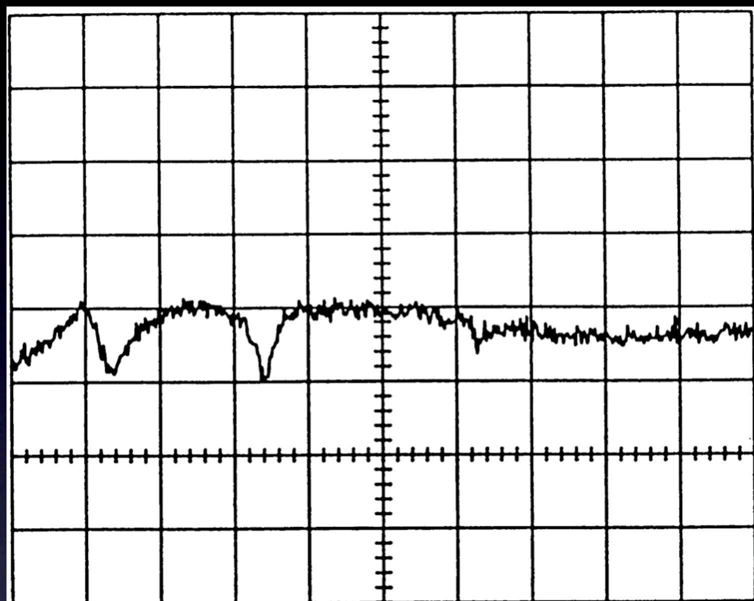
- D_{HI} at $N_{HI} = 10^{20}$ atoms/cm^2
- D_{opt} at $\mu(B) = 25$ mag/arcsec^2

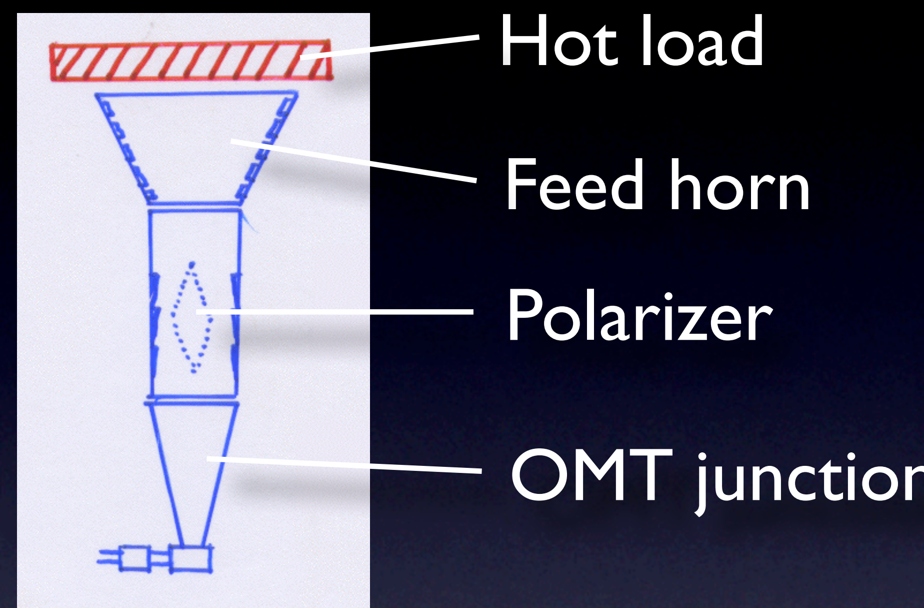
$$\mathrm{Def} = \langle \mathrm{Log}\ \sigma_{\mathrm{HI}} \rangle_{\mathrm{T}} - \mathrm{Log}\ \sigma_{\mathrm{HI}}$$

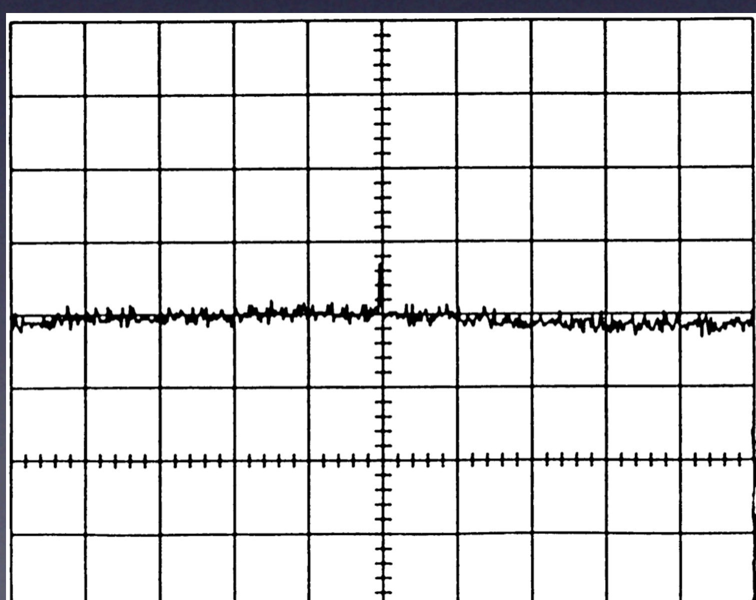
$$\sigma_{\mathrm{HI}} = \frac{\mathrm{M_{HI}}}{\pi(\mathrm{D_{opt}}/2)^2}$$

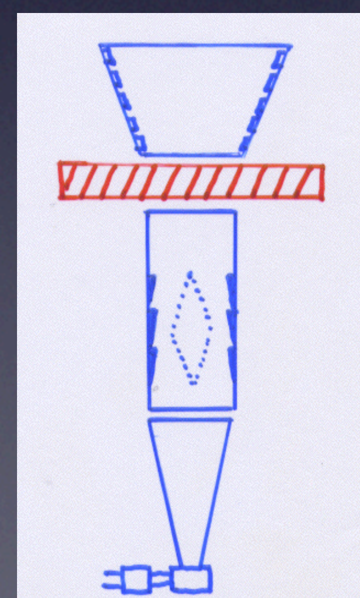
$D_{HI}/D_{opt} \ll 1$: enhanced central N_{HI} ➞ ram-pressure stripping
$D_{HI}/D_{opt} \sim 1$: overall lowered N_{HI} ➞ turbulent viscous stripping
$D_{HI}/D_{opt} > 1$: normal N_{HI} ➞ never traveled close to center

So here's the problem...







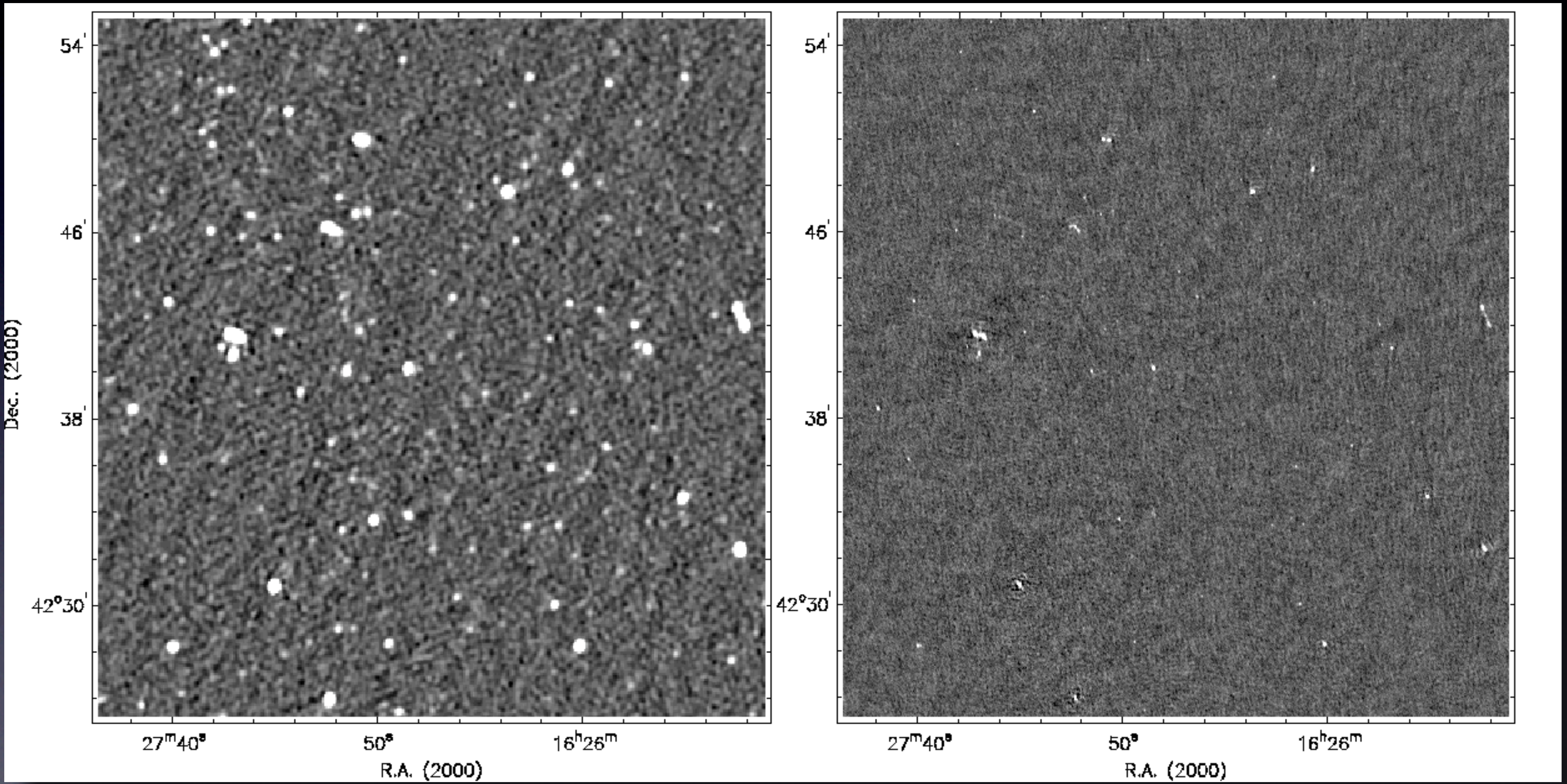


We have to live with these bandpass notches...

Radio continuum imaging

VLA-Cs σ = 24 μJy/bm, Θ = 16″x15″= 50x47 kpc

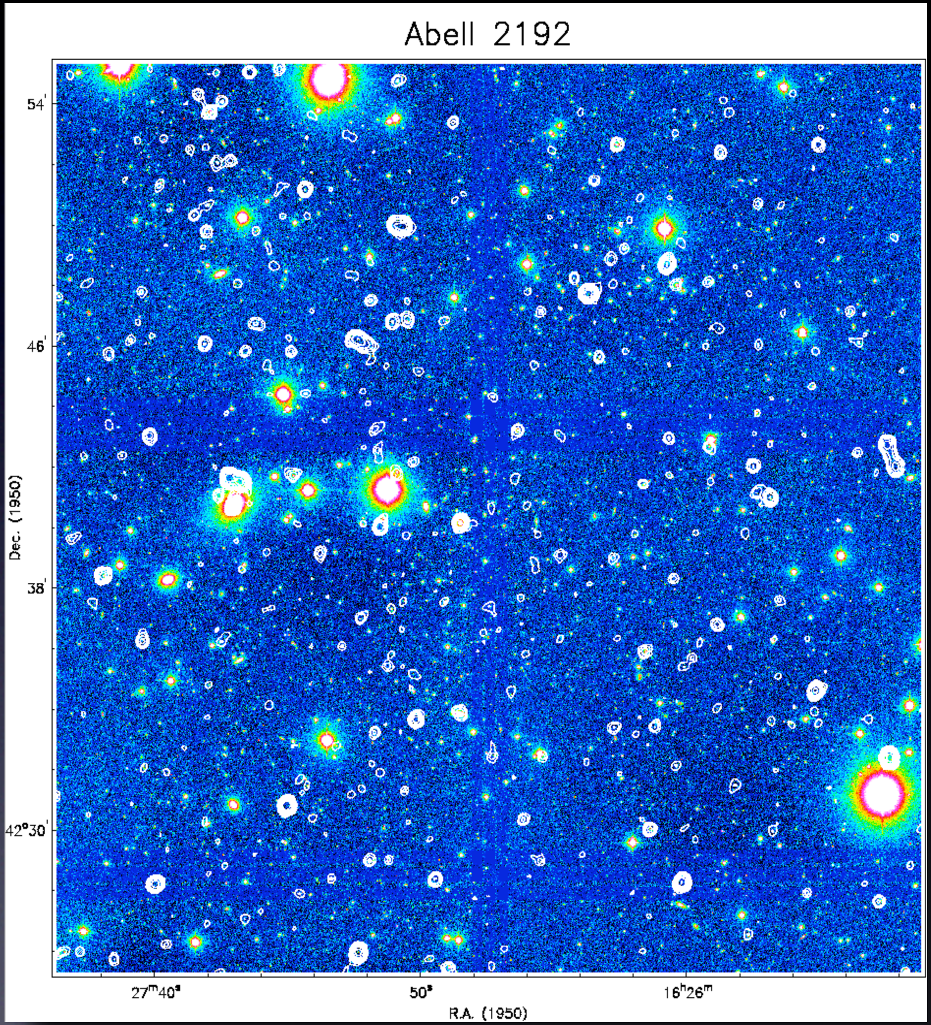
GMRT σ = 23 μJy/bm, Θ = 5″x4″= 15x12 kpc



$$\mathrm{SFR}\,^{3\sigma}_{\min} = 5.5 \times \frac{\mathrm{L}_{21}}{4.0 \times 10^{21}\mathrm{WHz}^{-1}} = 9.8\ \mathrm{M}_{\odot}/\mathrm{yr}$$ (at field center)

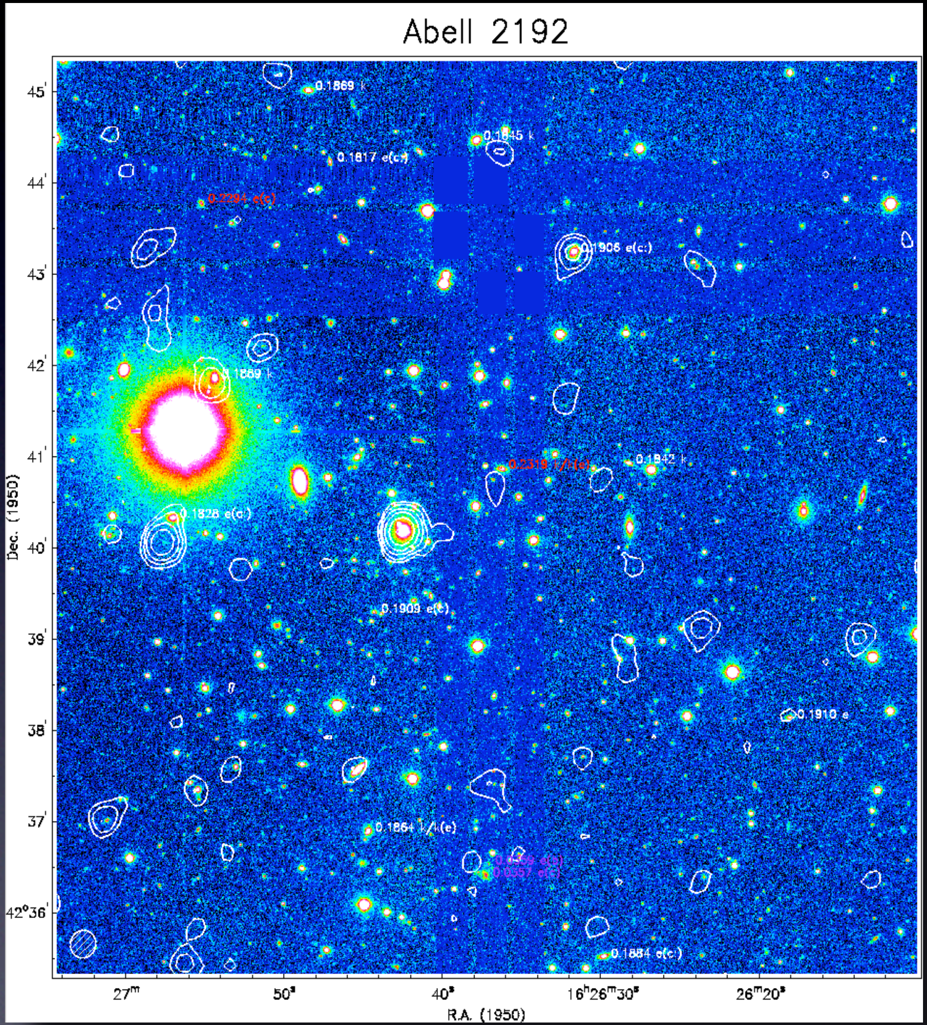
Radio contours on R-band image

30x30 arcmin



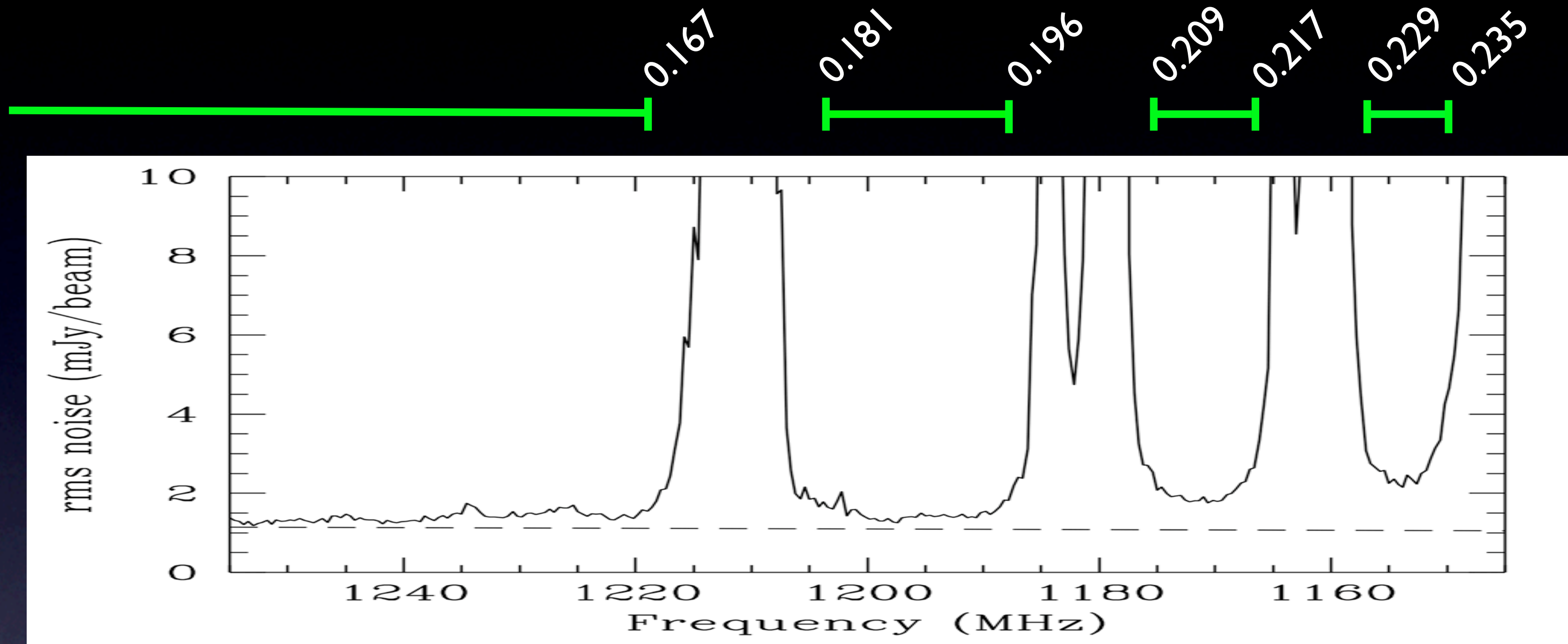
6.3x6.3 Mpc

10x10 arcmin



2.1x2.1 Mpc

The power of a fully upgraded WSRT

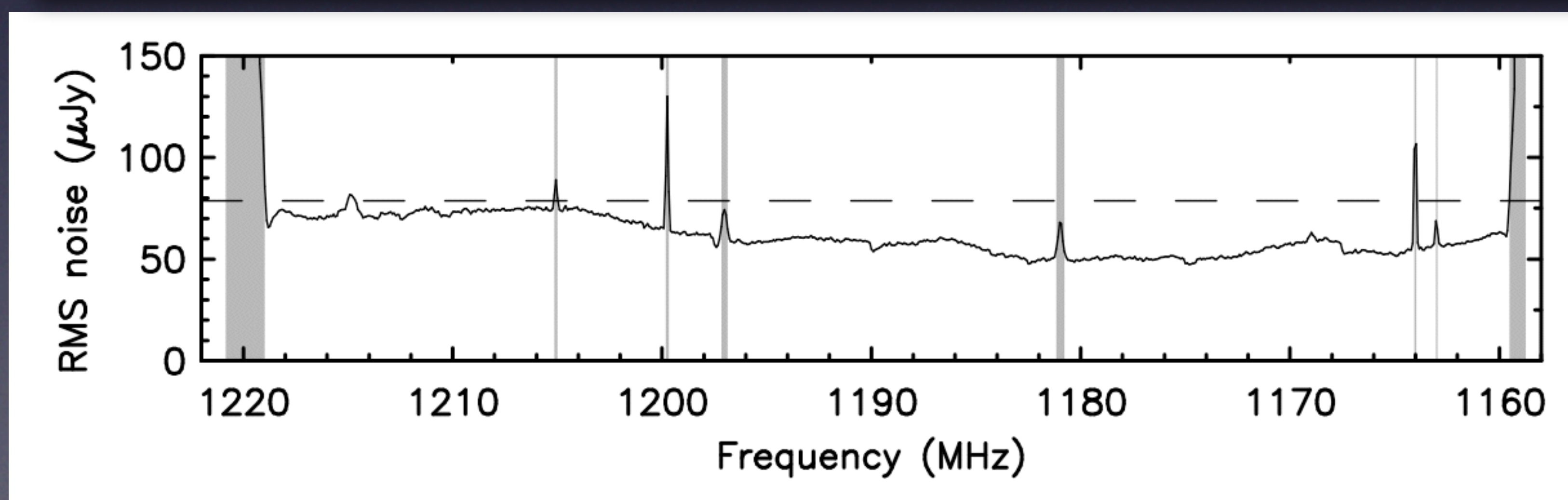


old VLA

A_{eff}/T_{sys} =

182 m^2/K

2x6.25 MHz



new WSRT

A_{eff}/T_{sys} =

140 m^2/K

8x10 MHz