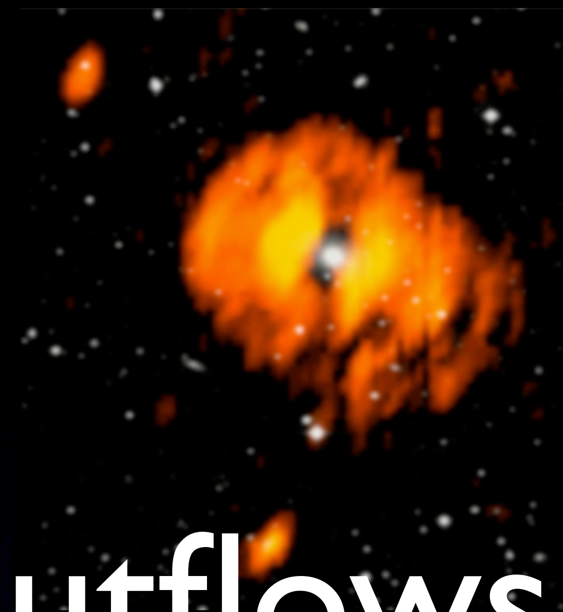
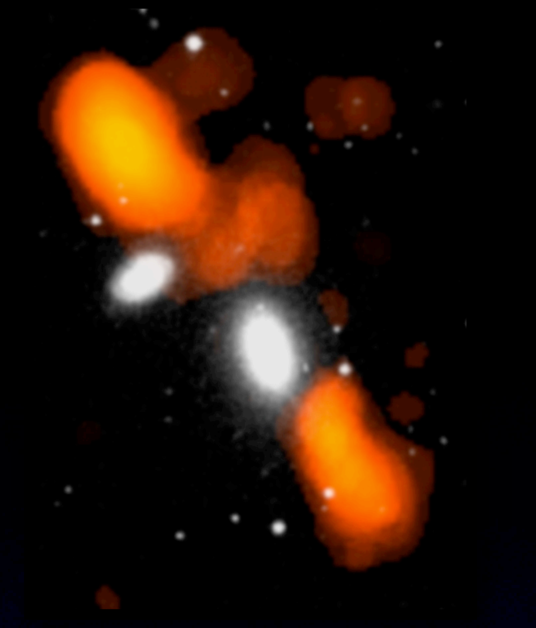


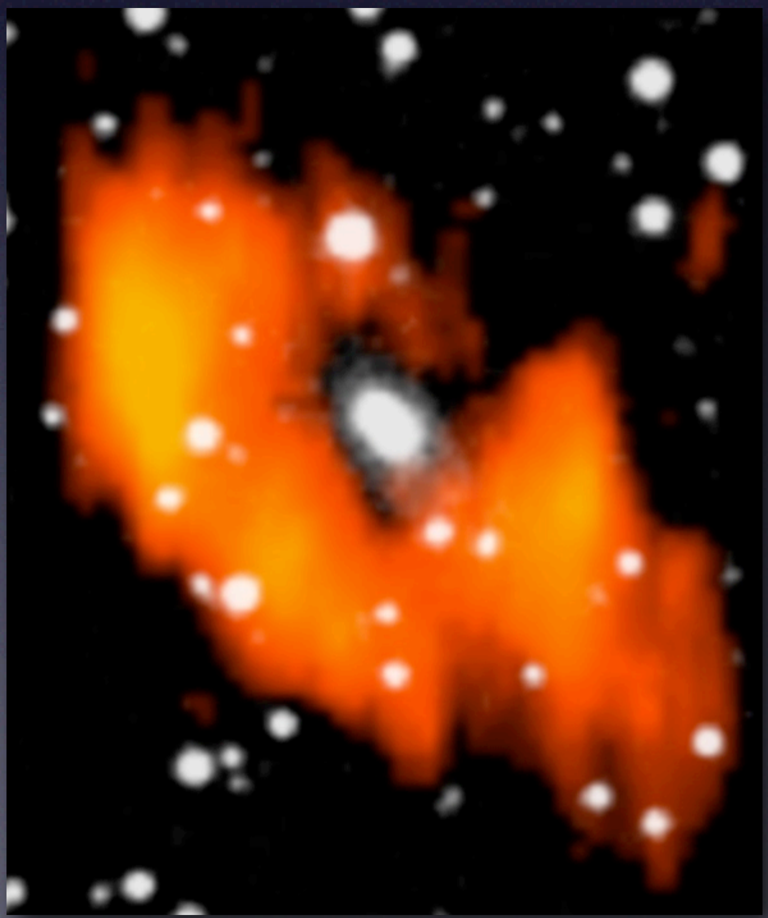


HI accretion and outflows in early-type galaxies

recent results and future prospects

Raffaella Morganti

ASTRON (Dwingeloo, NL)
and
Kapteyn Institute, Groningen



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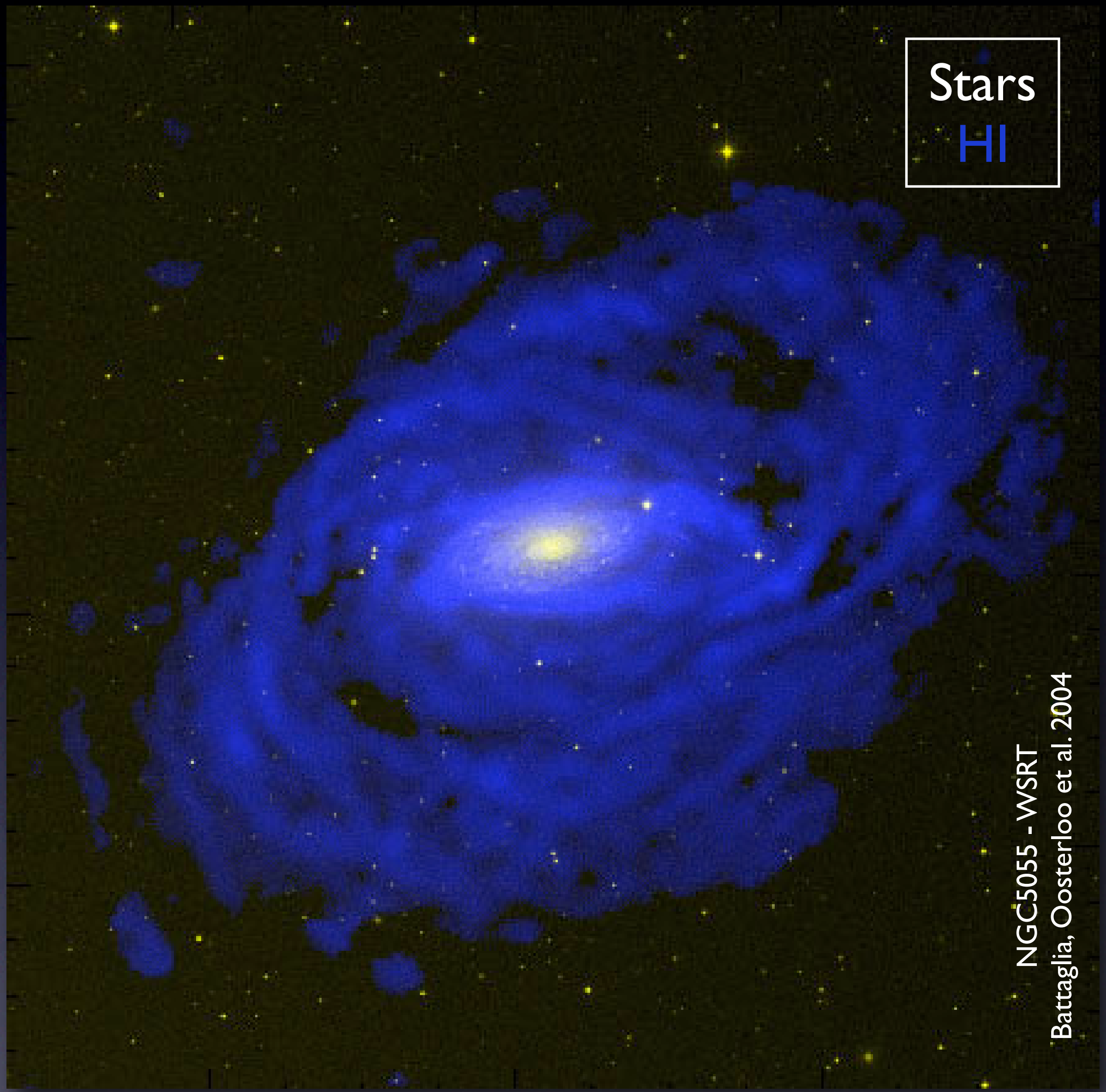
Why neutral hydrogen?

- hydrogen most abundant element
- fuel for star formation
- tracer for kinematics
- tracer for evolutionary stage of galaxies
- tracer for effects environment

best way through the 21-cm line

(emission or absorption)



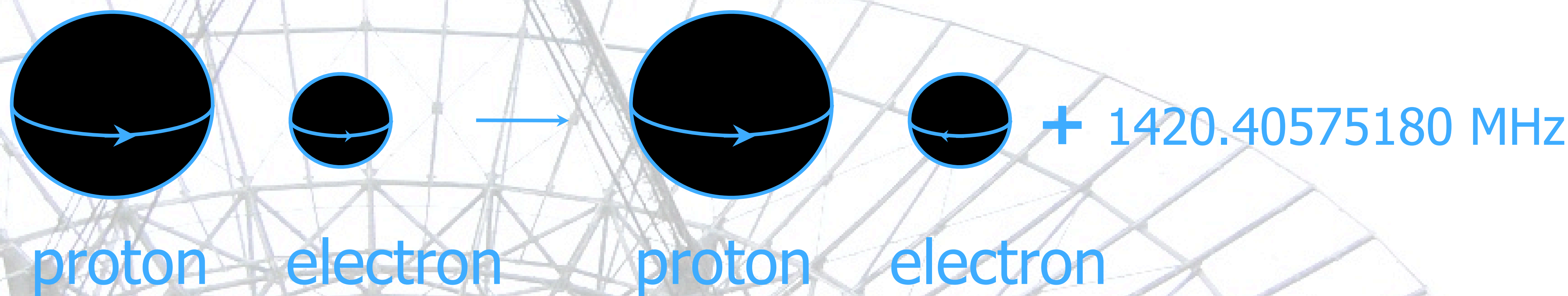
SKA as an HI radio telescope

- in its original idea: *telescope that would provide two ordes of magnitude increase in collecting area compared to existing radio telescopes allowing the study of the neutral hydrogen content of galaxies to cosmologically significant distances (i.e. to z~2)*
- HI still plays a major role in two key science projects: *Galaxy evolution and cosmology* and *Probing the dark ages*

21-cm emission line of neutral hydrogen

The ground state can undergo a hyperfine transition,
reverse the spin of the electron→ higher energy state when the spin of electron and proton are parallel (difference 6 x 10^{-6} eV)

Frequency of the transition: 1420.405752 MHz (21.105 cm)



The temperature T_s (spin or excitation temperature) accounts for the distribution of the atoms between the two states. The population of the two states is determined primarily by collisions between atoms → T_s equal to the kinetic temperature (with some exceptions!)

Predicted by van de Hulst (1944) and later confirmed by observations (US, australian & dutch teams)

probability of a spontaneous transition 2.85×10^{-15} sec^{-1}
(1 event per atom per 11 million years!)
this rate increases to one transition per 400 years due to collisions

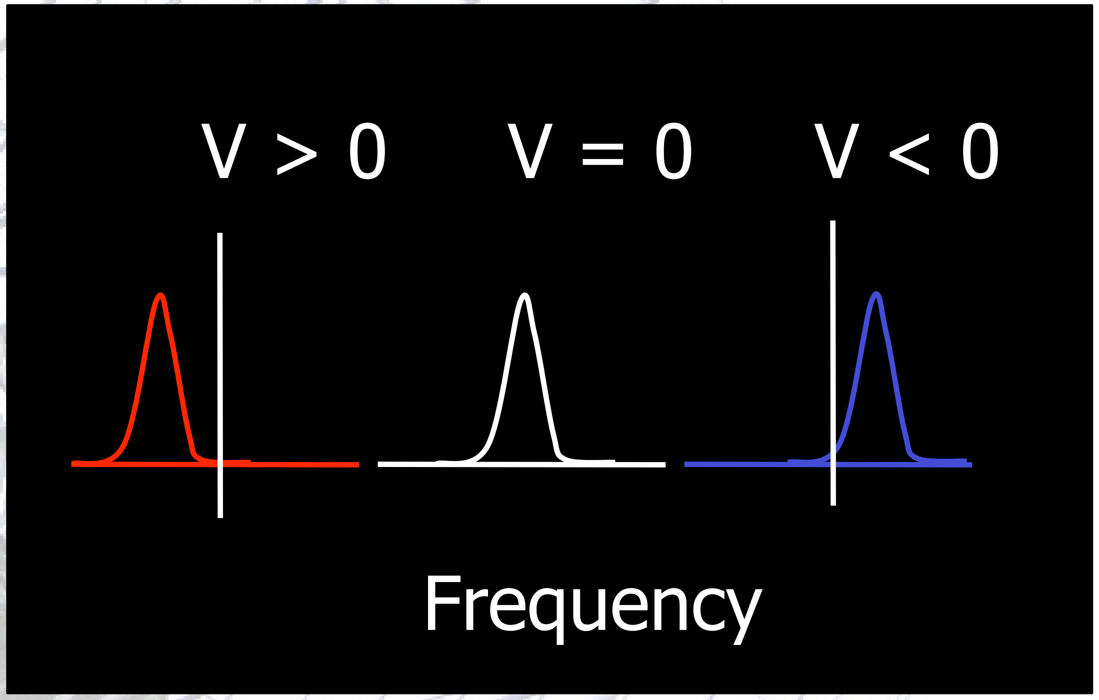
BUT

- Hydrogen most common element in the universe
  $\Rightarrow$ present “everywhere”!

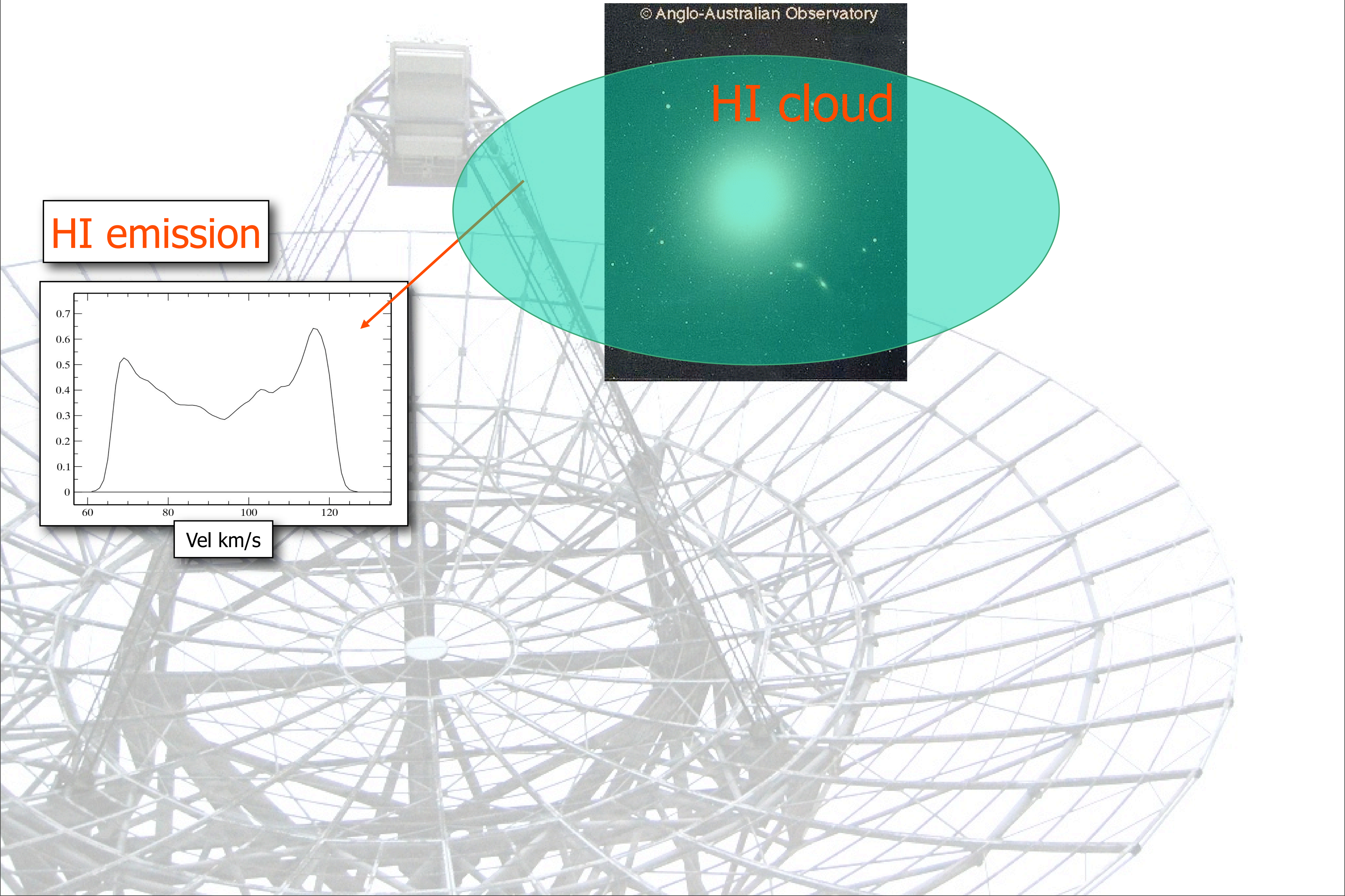
- Narrow spectral line

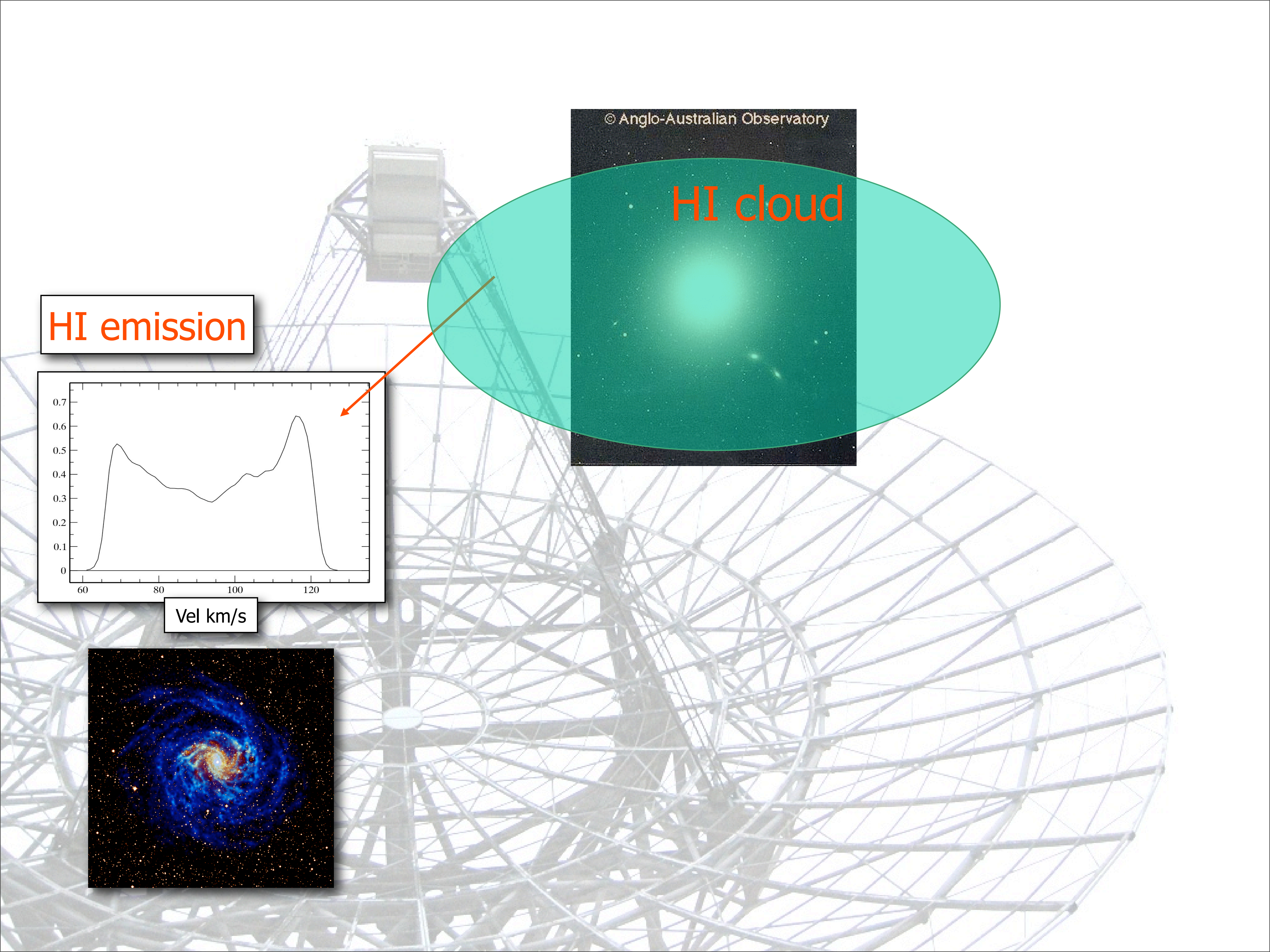
for a temperature of the gas of 100 K the width of the line is ~ 1 km/sec

the observed lines are always much larger → Doppler effect ⇒ kinematics!



- Optically thin


© Anglo-Australian Observatory
HI cloud
HI emission
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
60
80
100
120
Vel km/s



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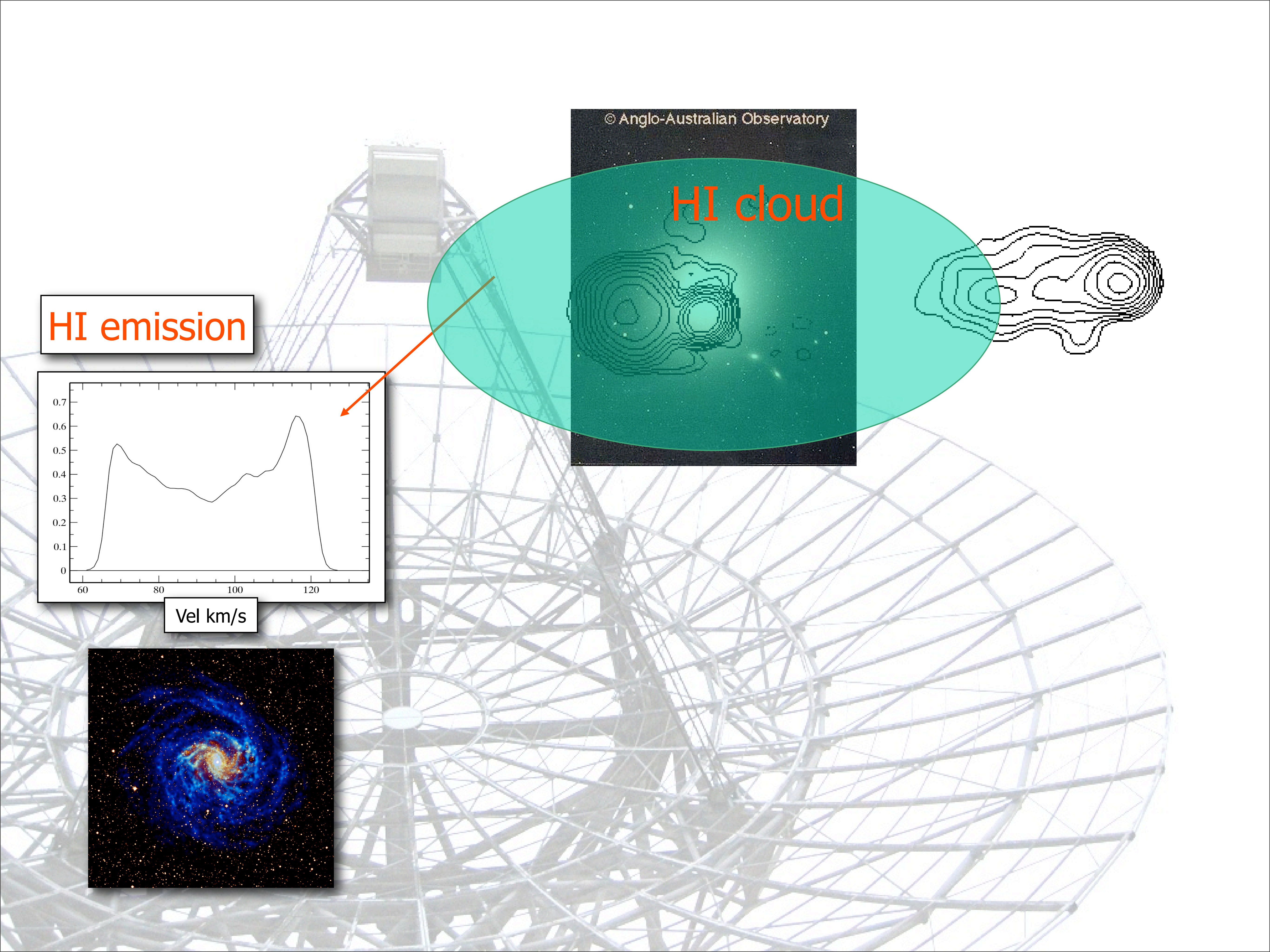
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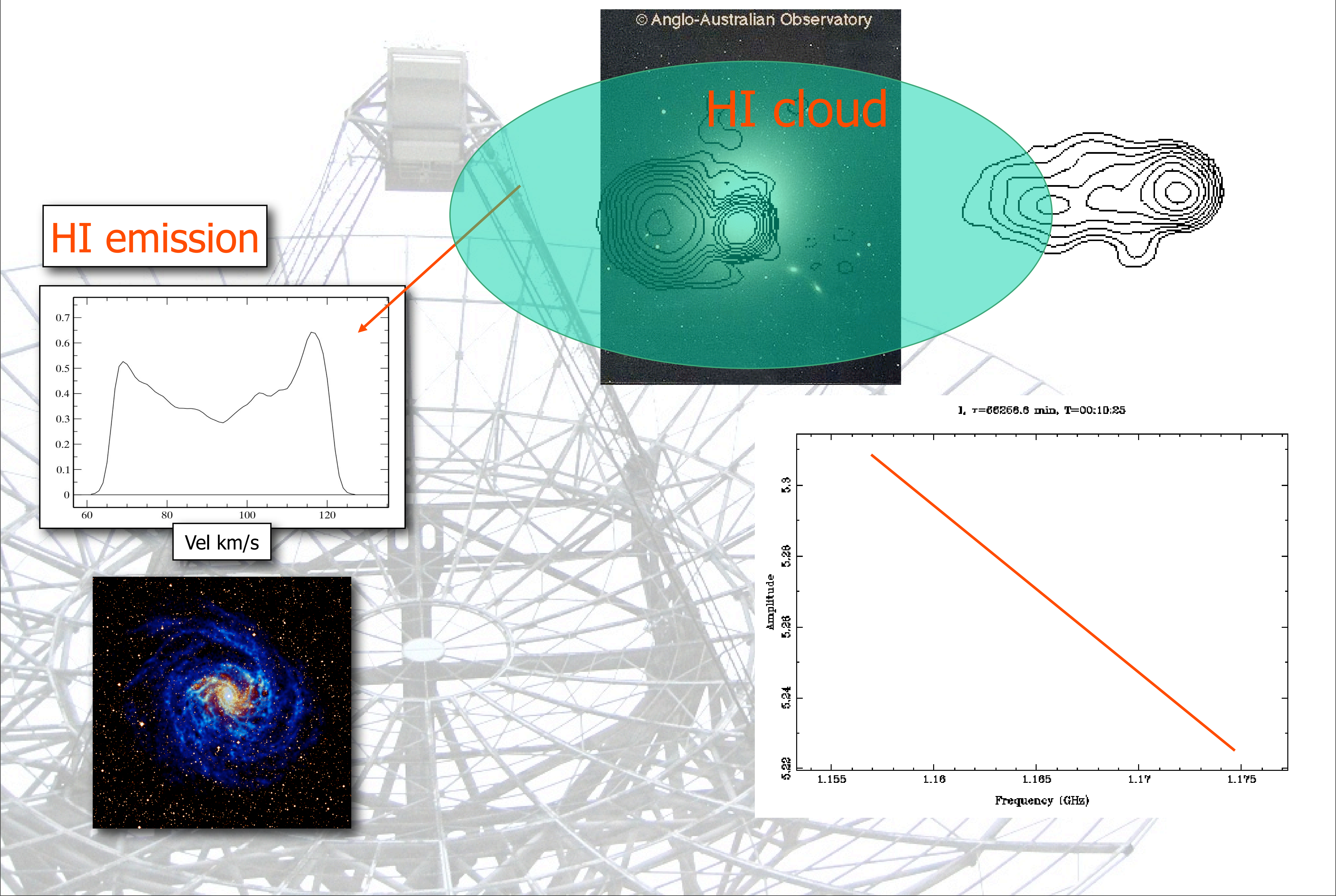

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0.6
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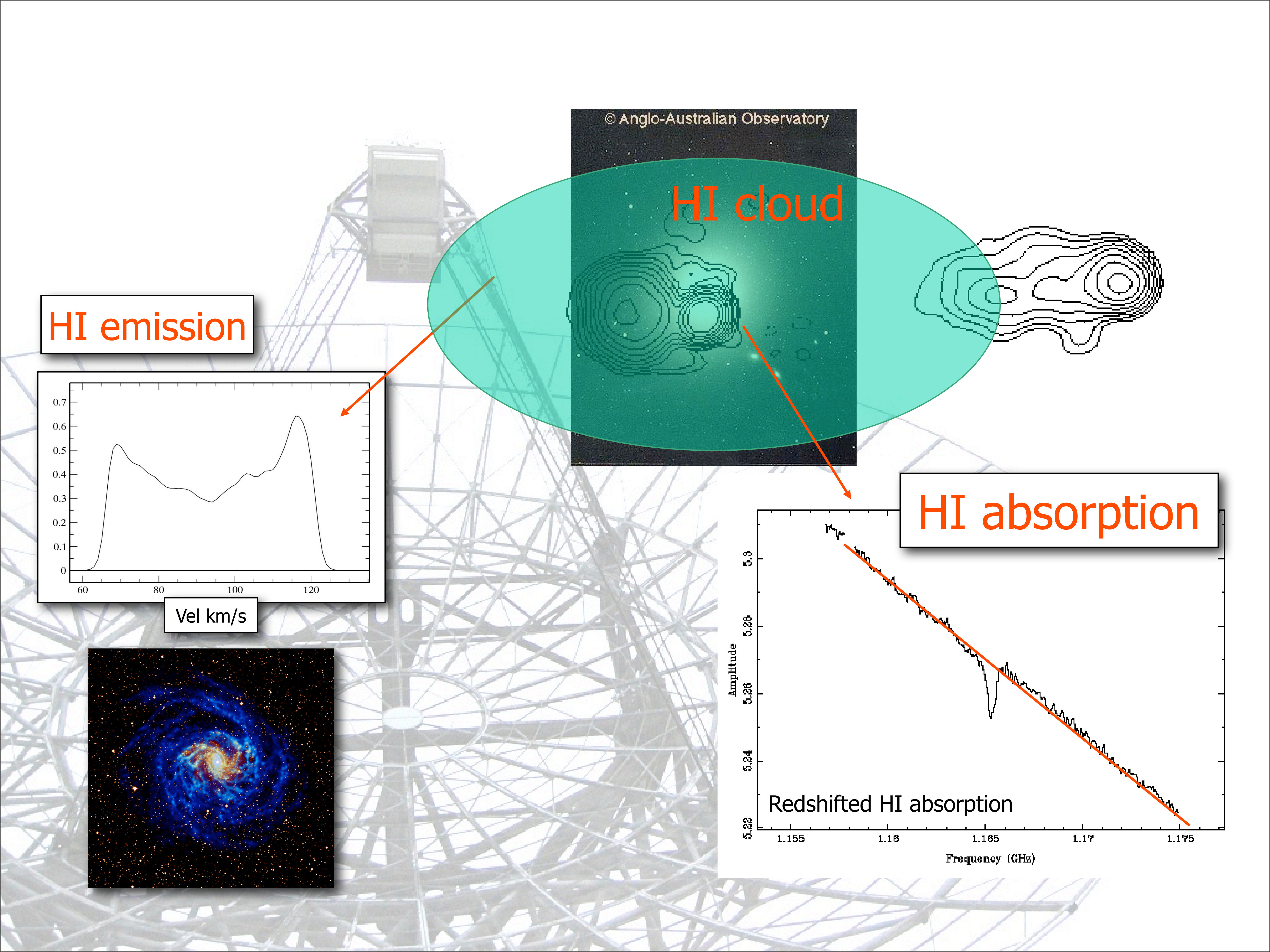
0
60
80
100
120
Vel km/s
1, τ=66256.6 min, T=00:10:25
Amplitude
5.3
5.28
5.26
5.24
5.22
1.155
1.16
1.165
1.17
1.175
Frequency (GHz)


© Anglo-Australian Observatory
HI cloud
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60
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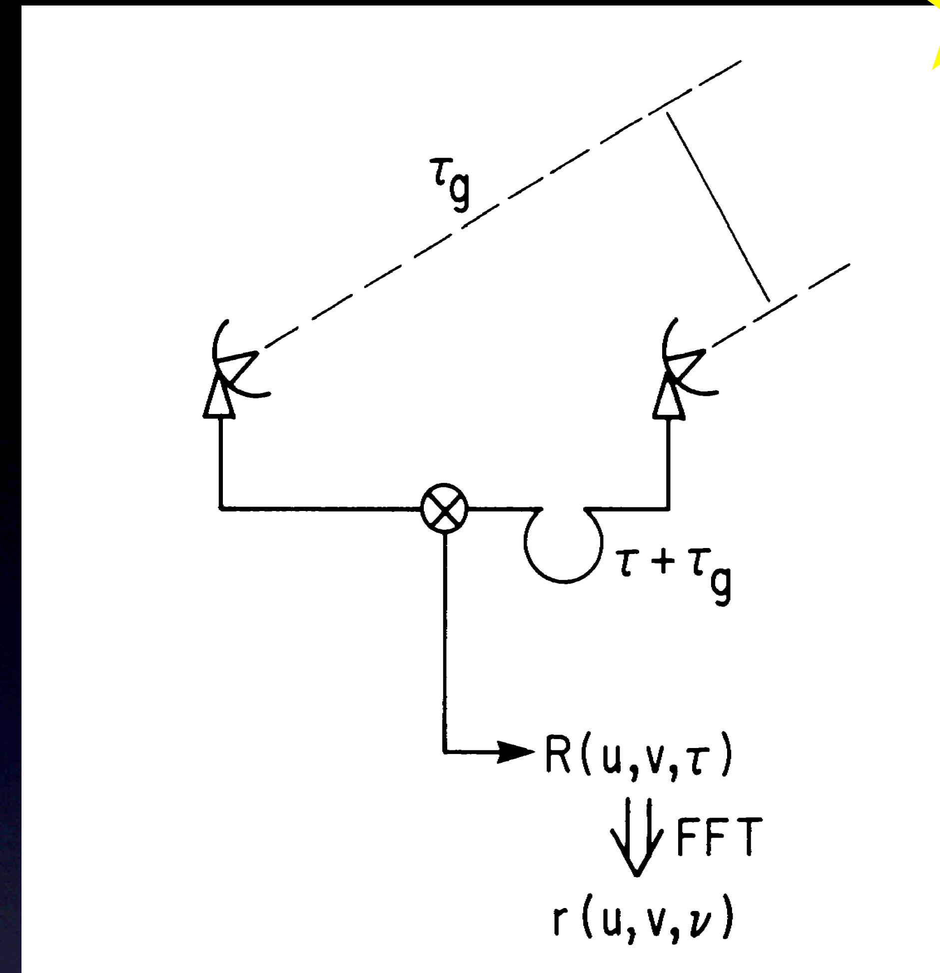
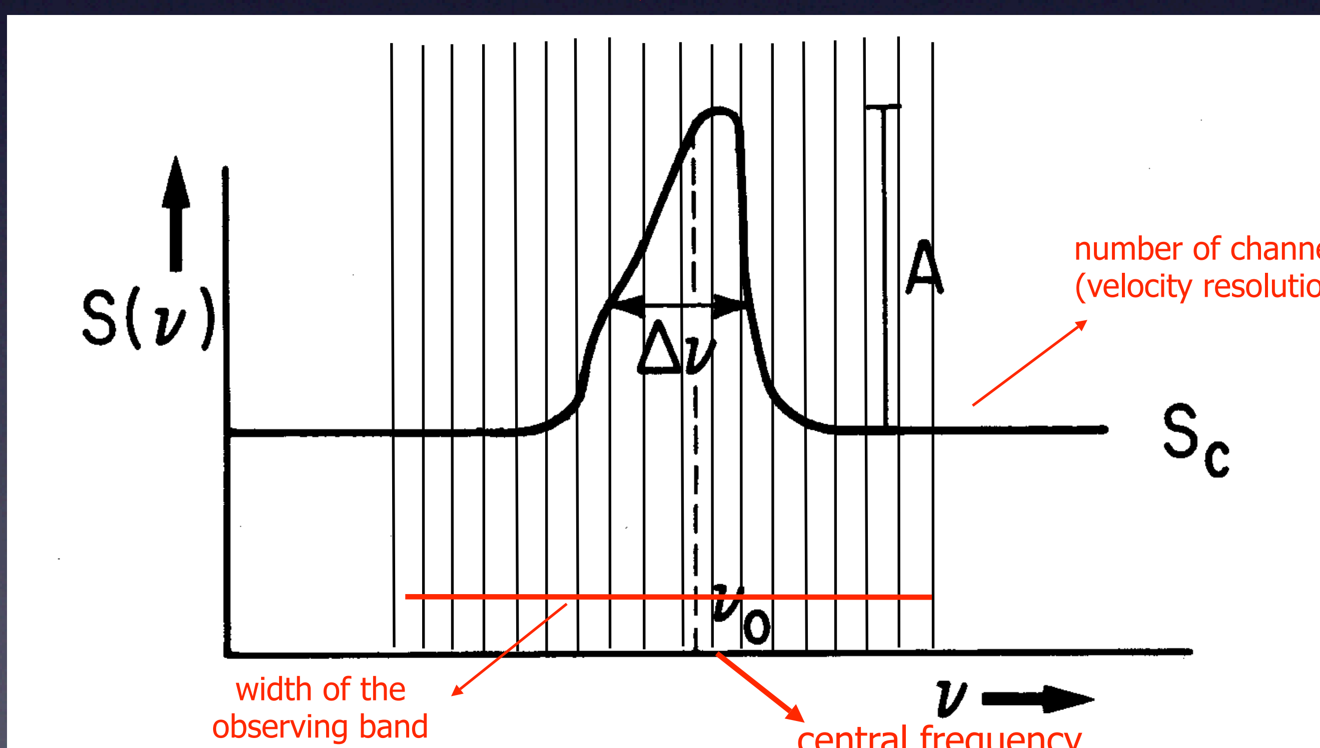
Vel km/s
HI absorption
Amplitude
5.3
5.28
5.26
5.24
5.22
1.155
1.16
1.165
1.17
1.175
Frequency (GHz)
Redshifted HI absorption

HI observations

Standard radio observations



Some critical parameters to be set



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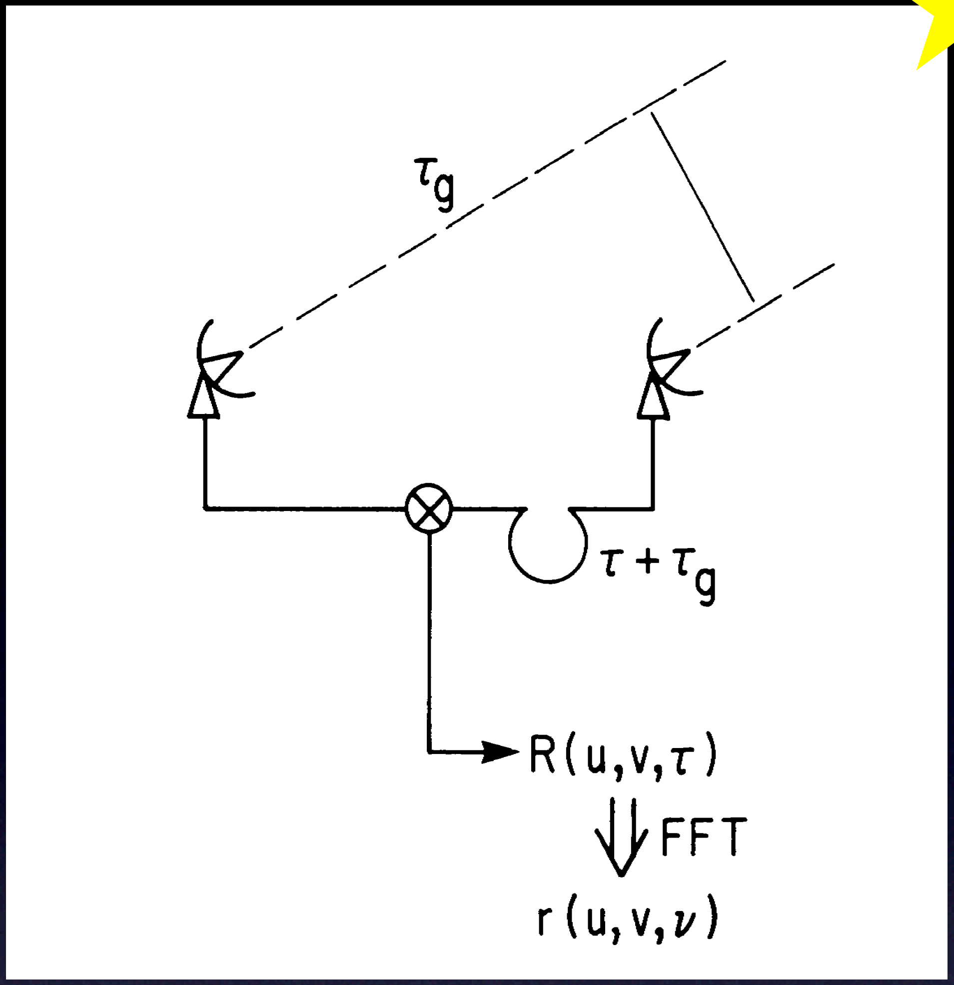

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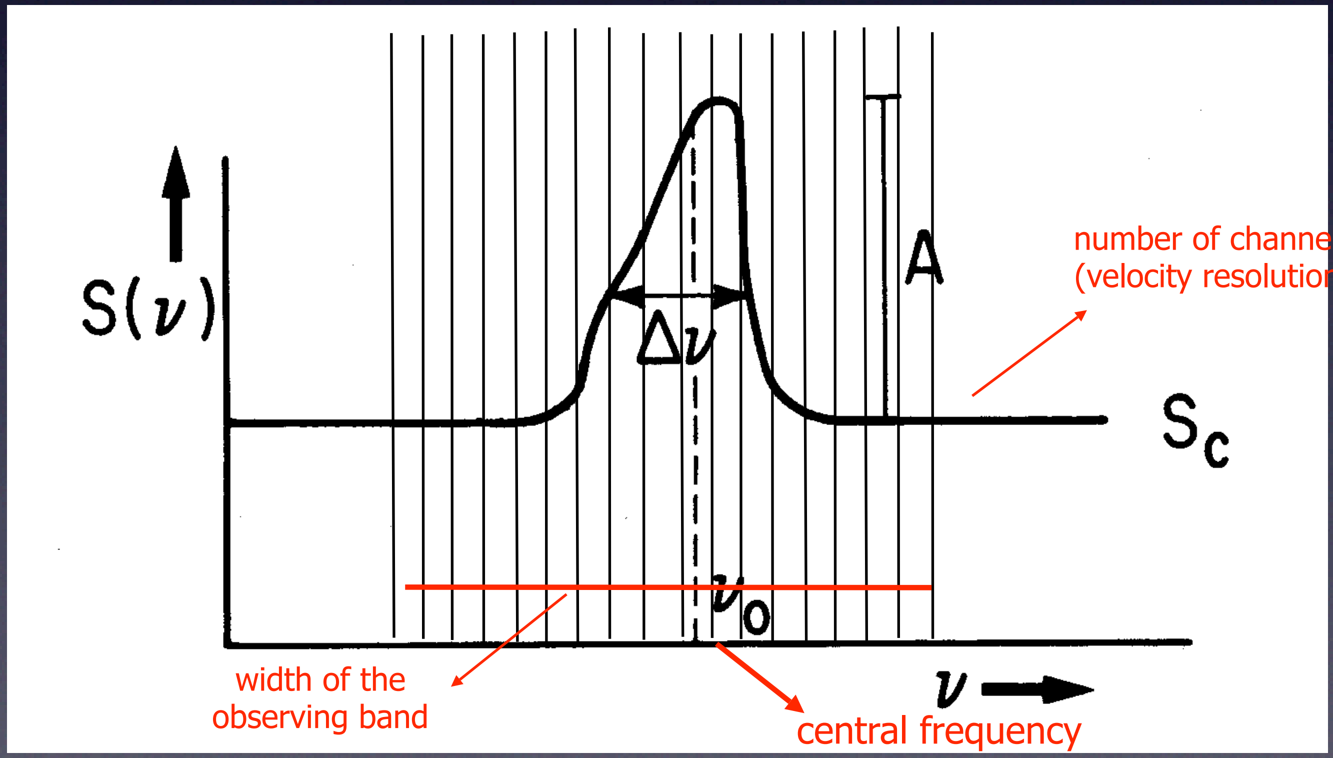
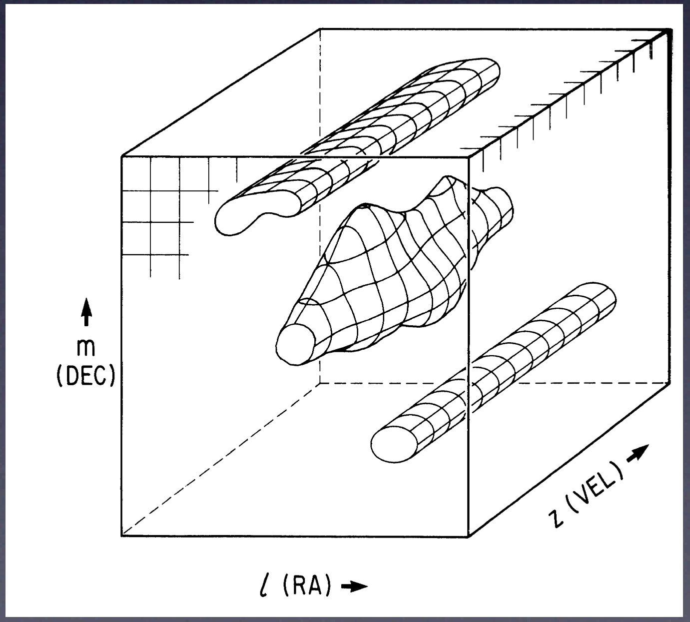
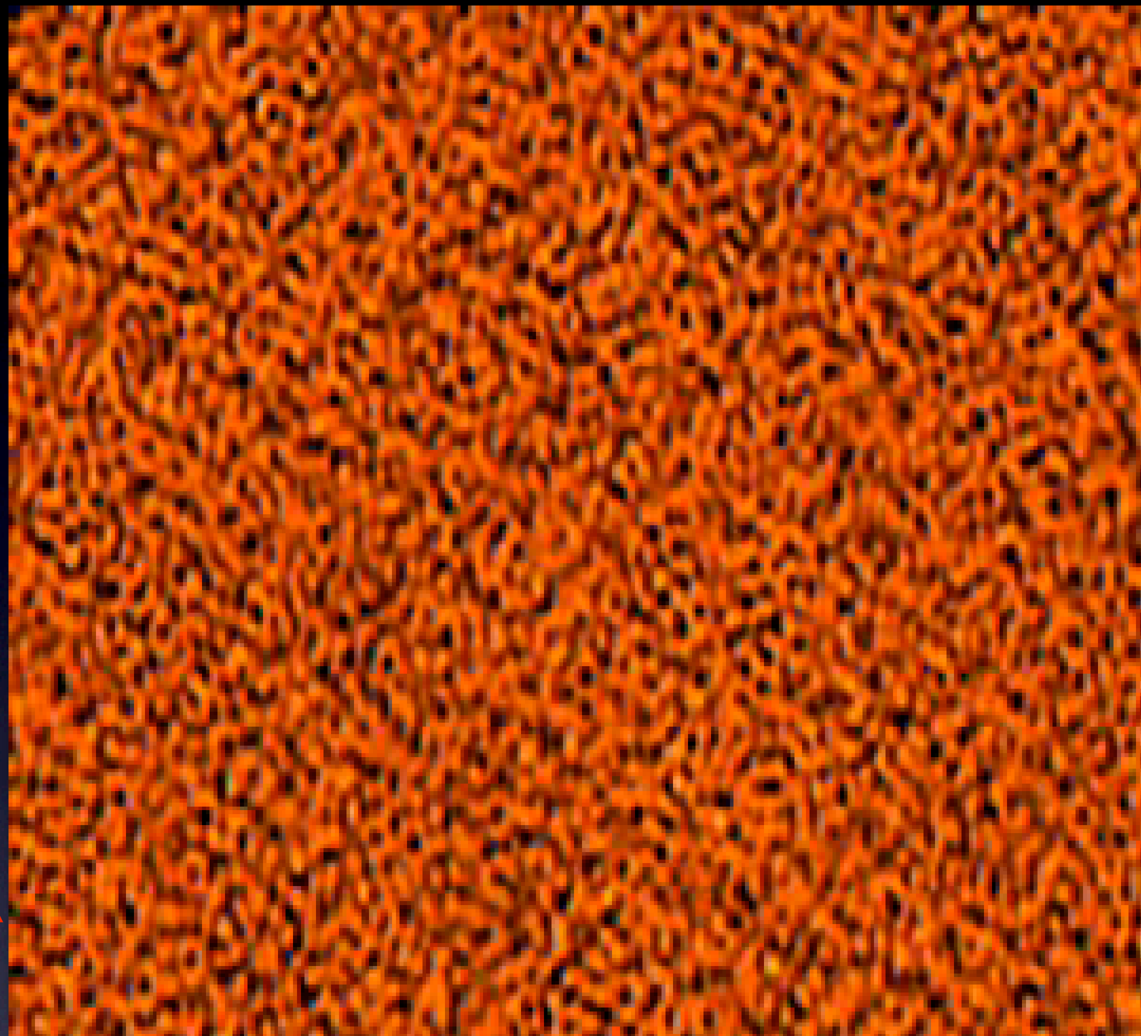


Every channel → a plane in the cube



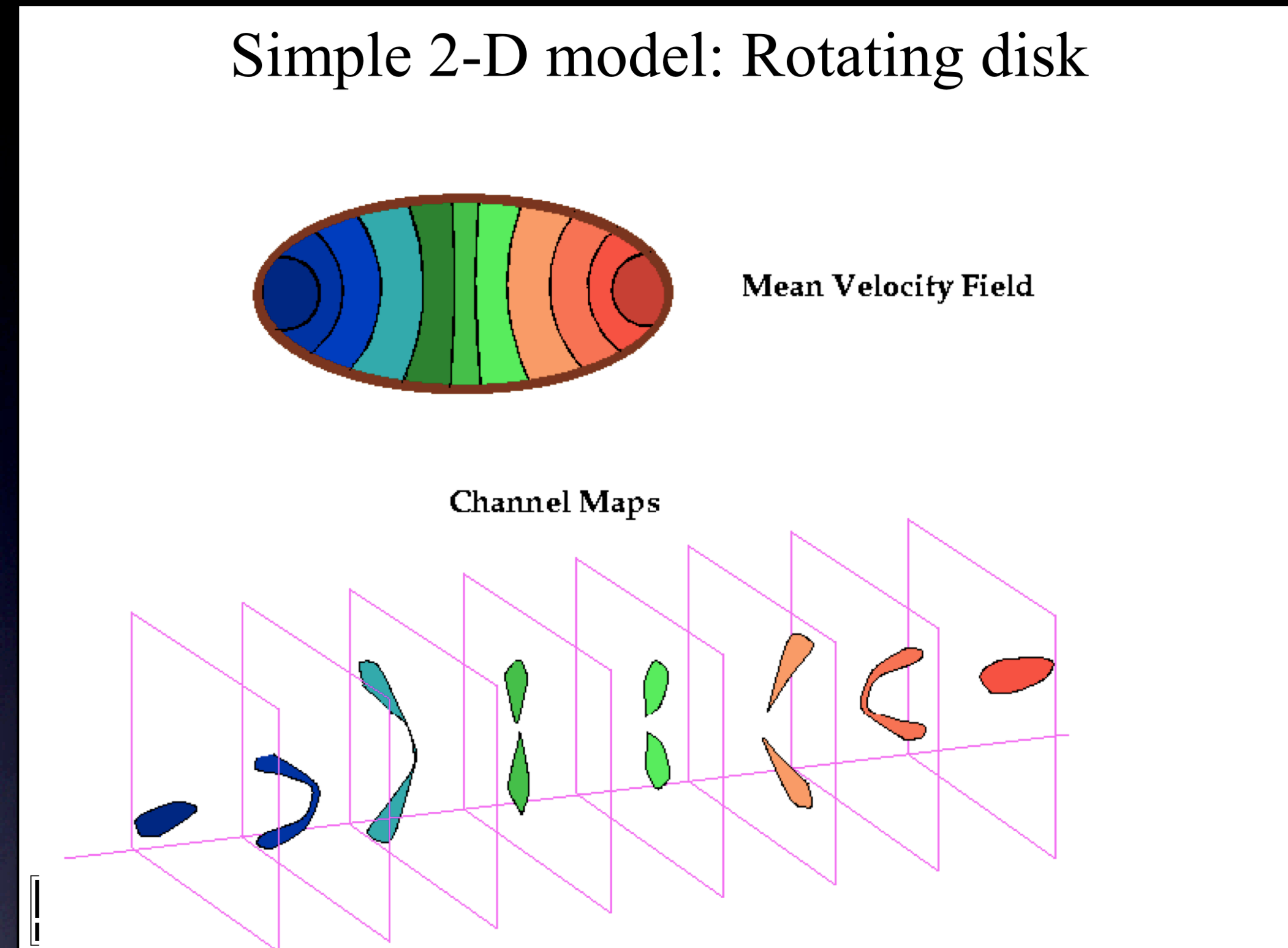
Kinematics of the galaxies

Case of an undisturbed galaxy: rotating disk

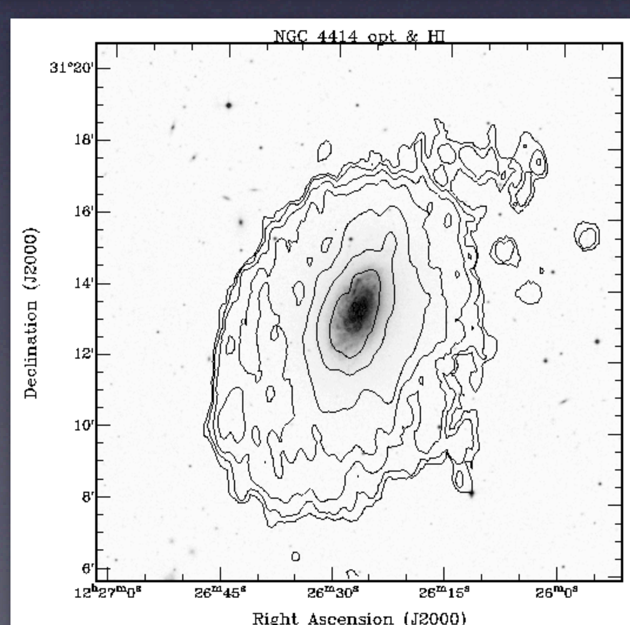


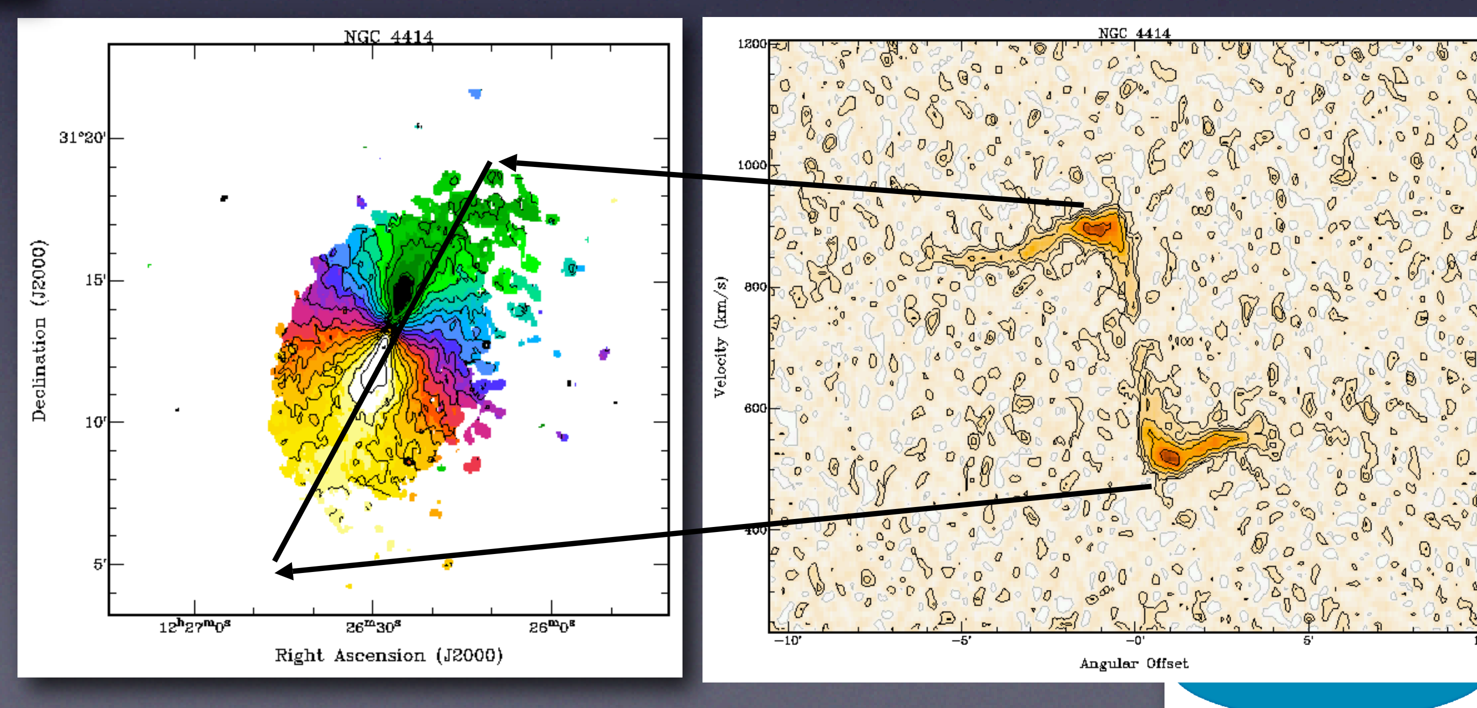
Dec

RA



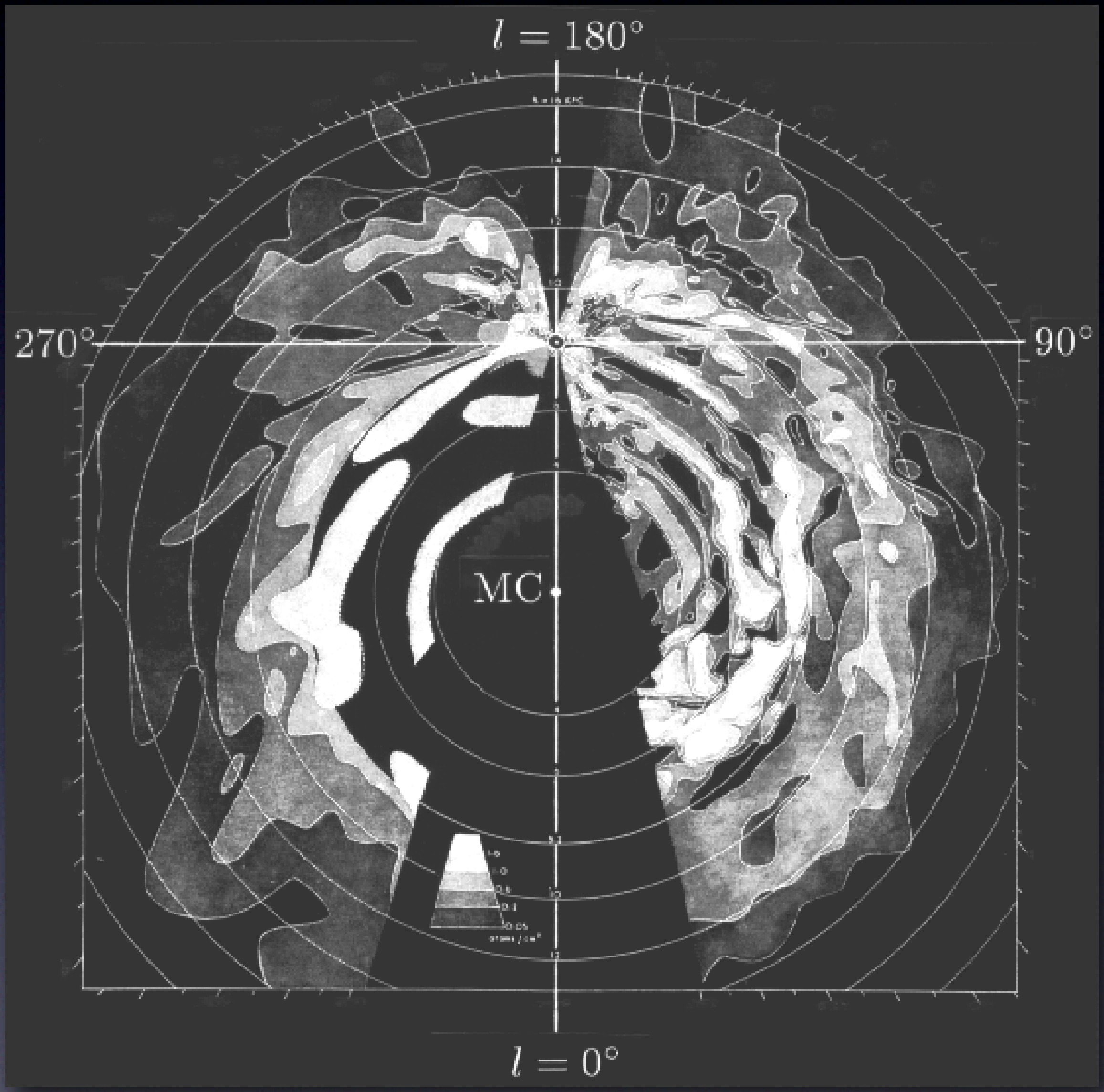
H I observation (datacube) of NGC 4414





HI for galaxy structure and evolution

- Milky Way - structure and kinematics of our galaxy
- Tracing streams and high velocity clouds around our galaxy
- HI accretion/merger
- Dark matter



from Oort, Kerr & Westerhout (1958)

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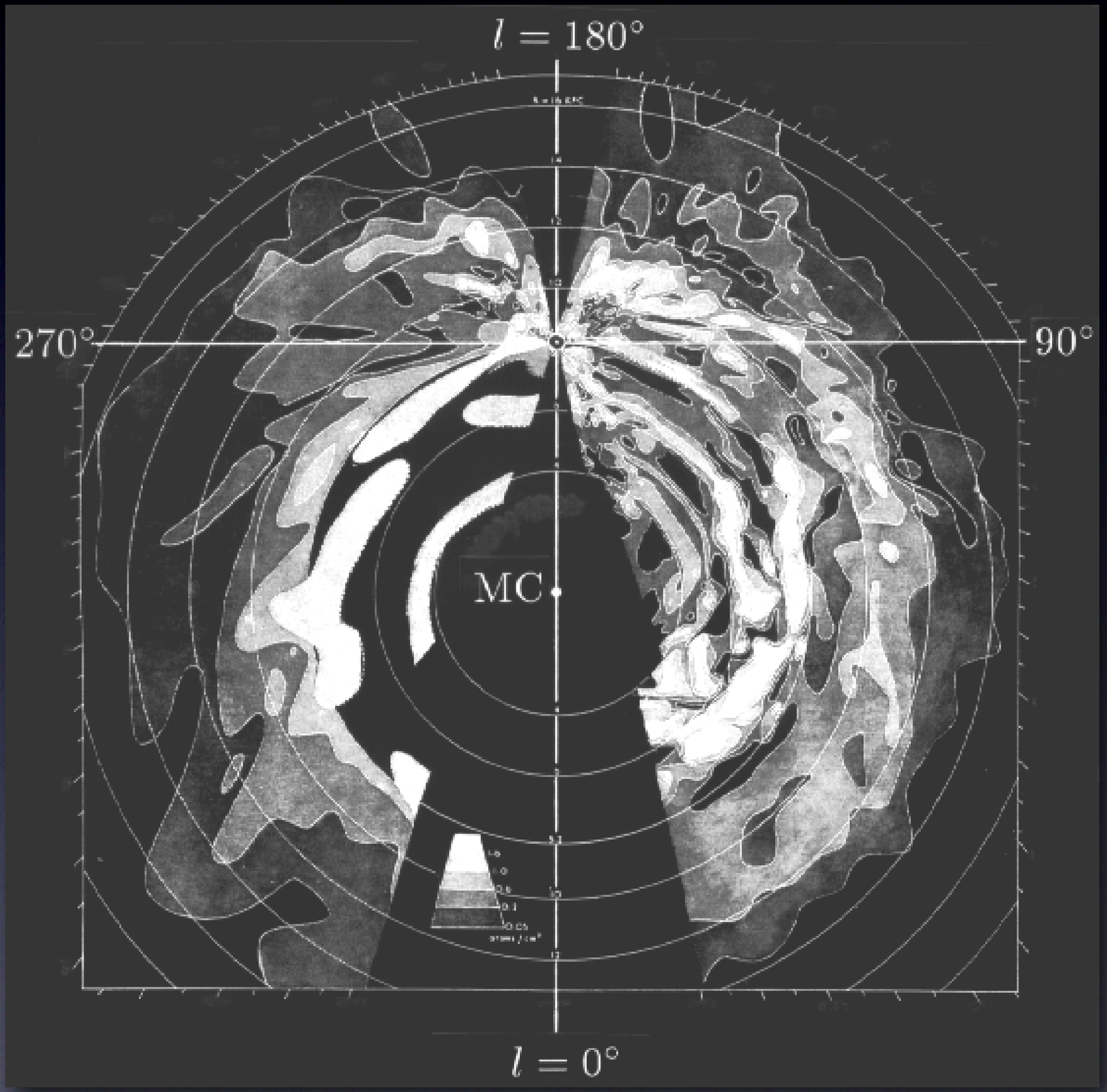

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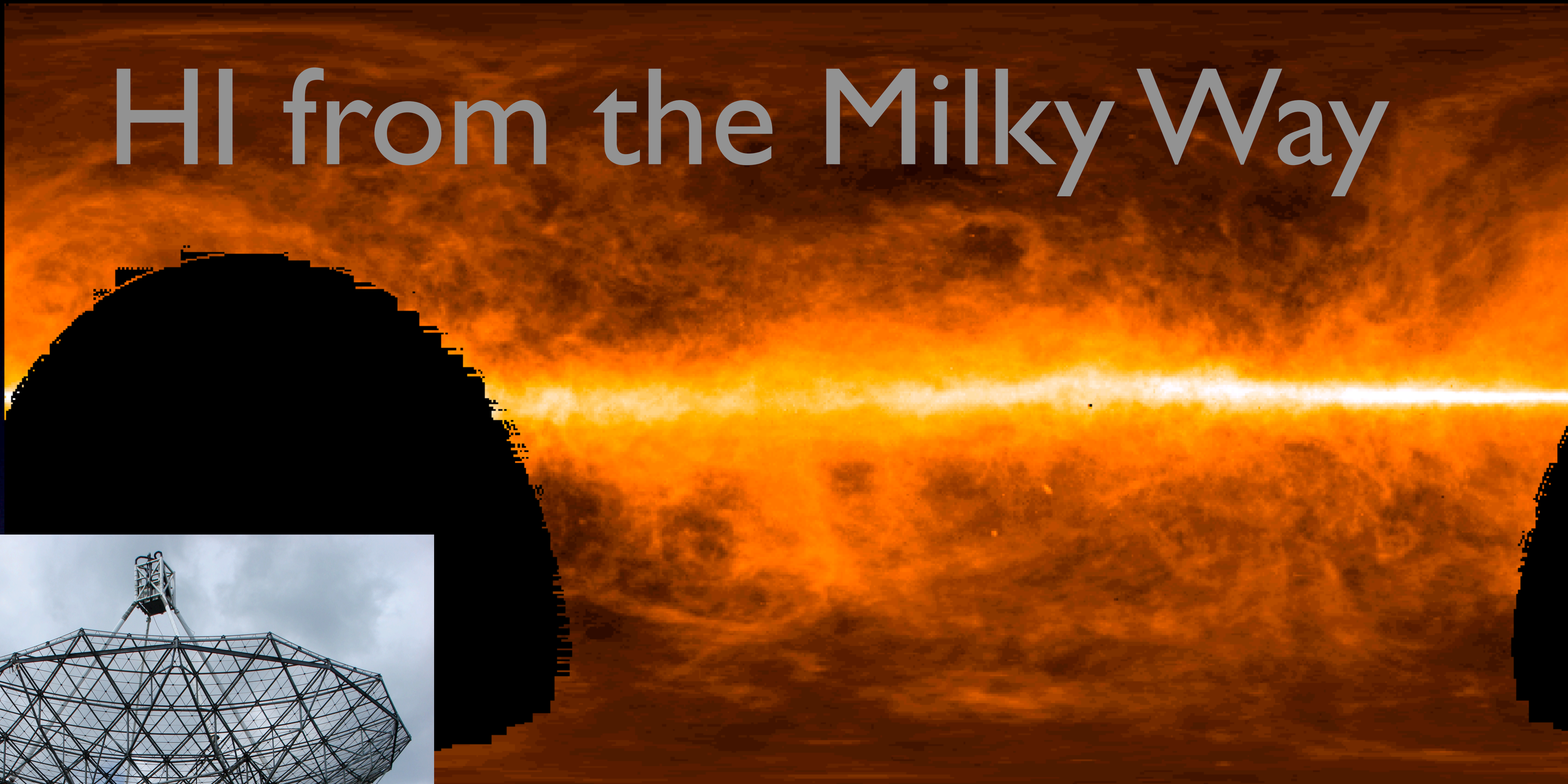
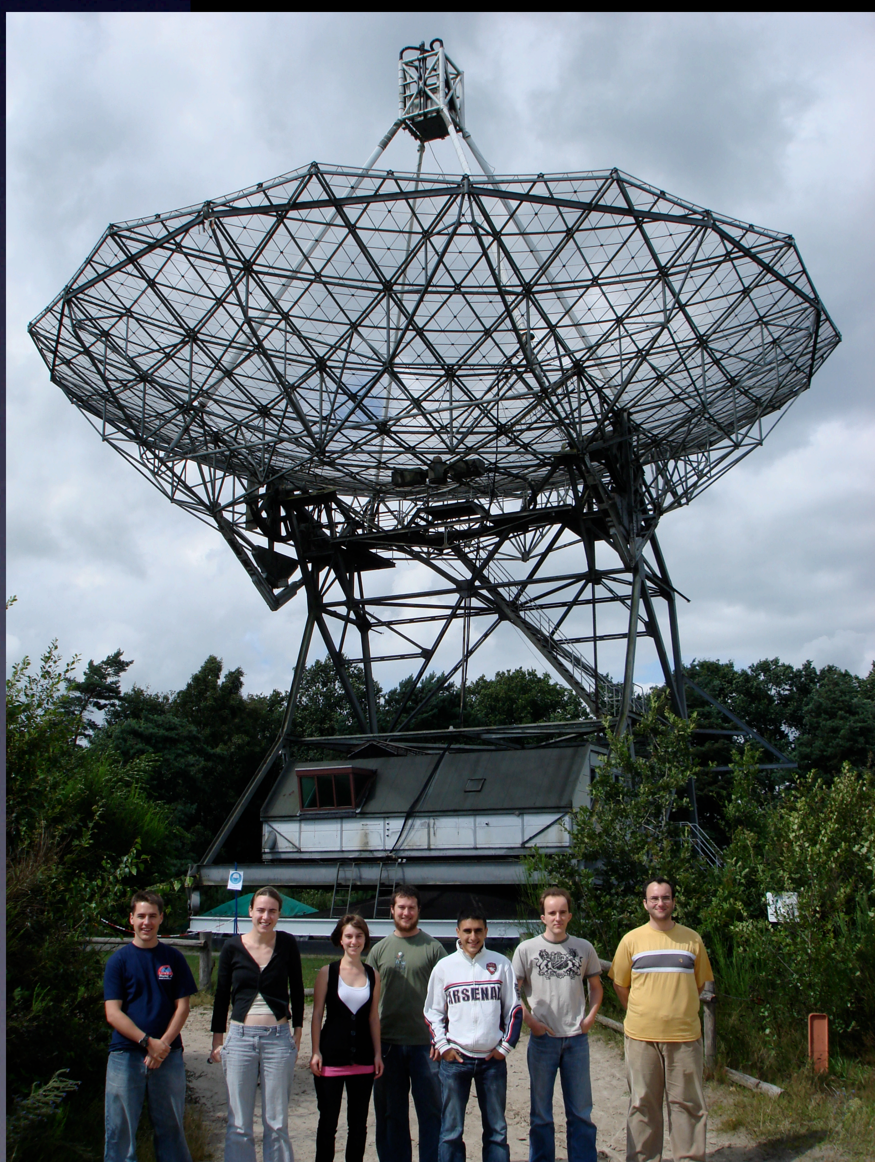
HI from the Milky Way



All-sky image of the HI column density in the Milky Way - from the Dwingeloo- Leiden survey



Approximately 5-10% of the mass of the Milky Way is in the form of interstellar atomic hydrogen

On a large scale the 21-cm emission traces the "warm" interstellar medium, which is organised into diffuse clouds of gas and dust that have sizes of up to hundreds of light years.

This survey was conducted over a period of 4 years using the Dwingeloo 25-m radio telescope.

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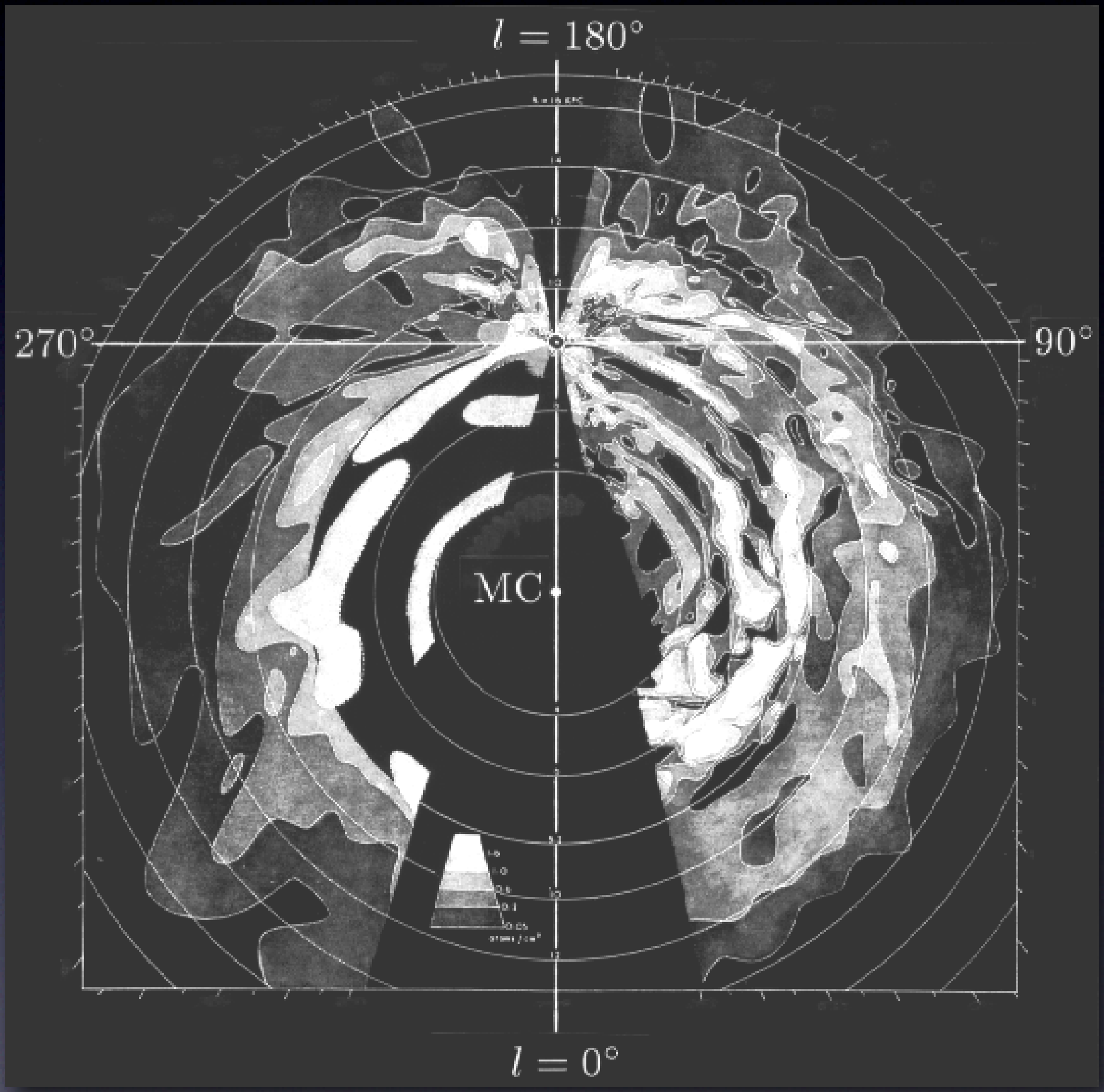

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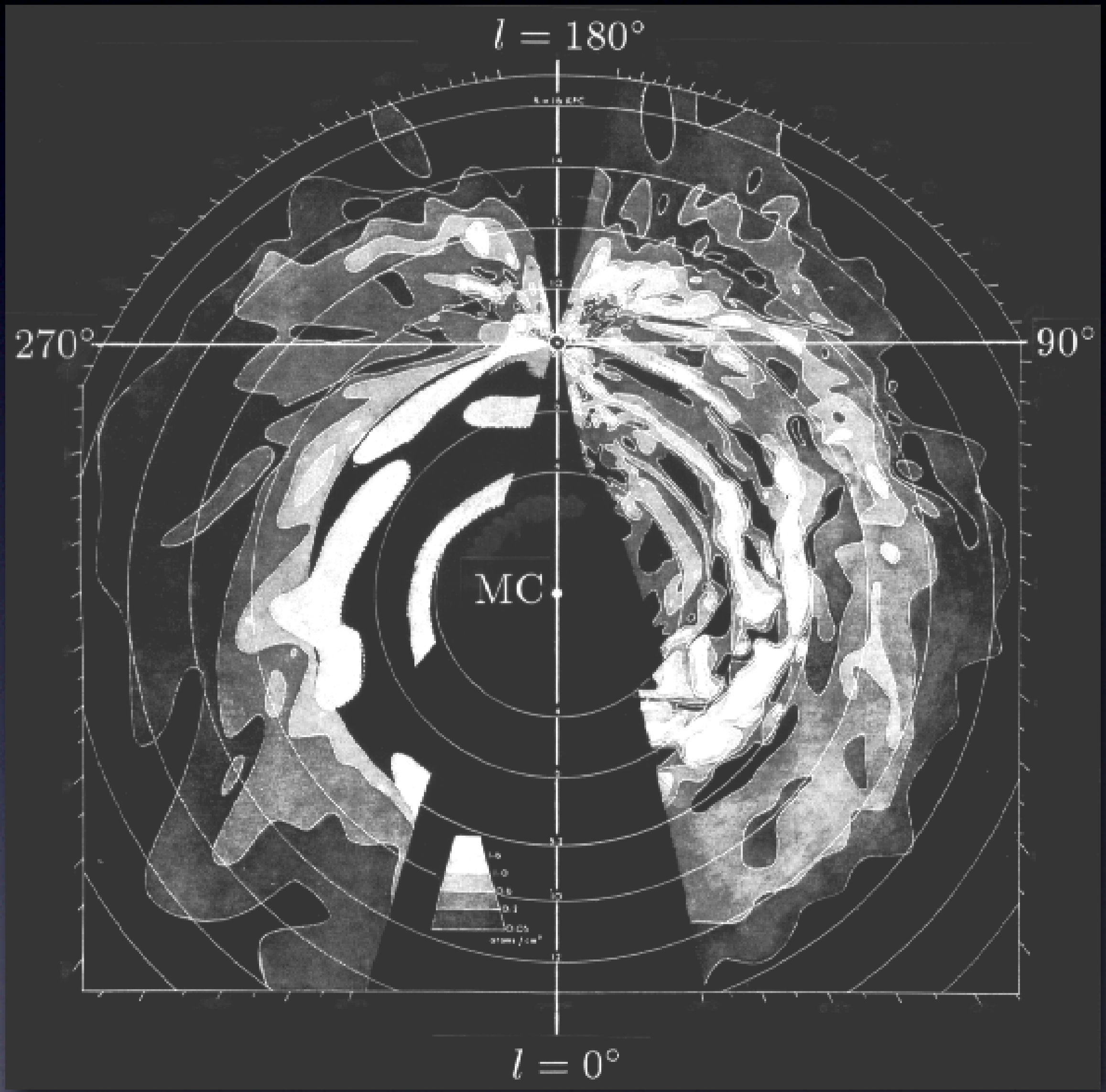
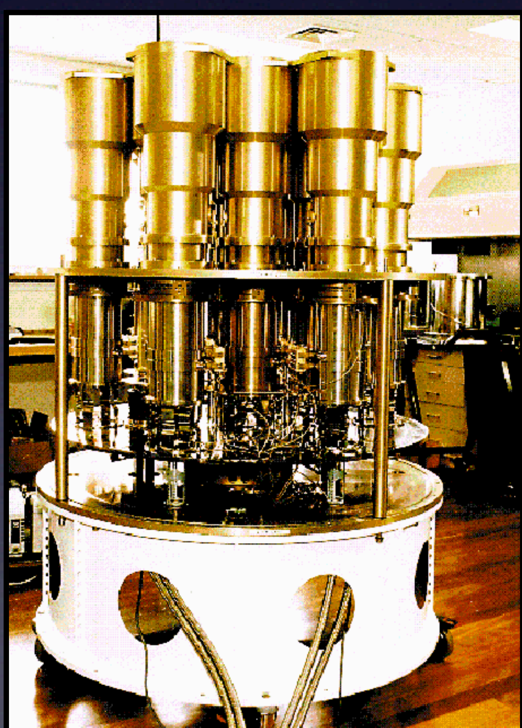


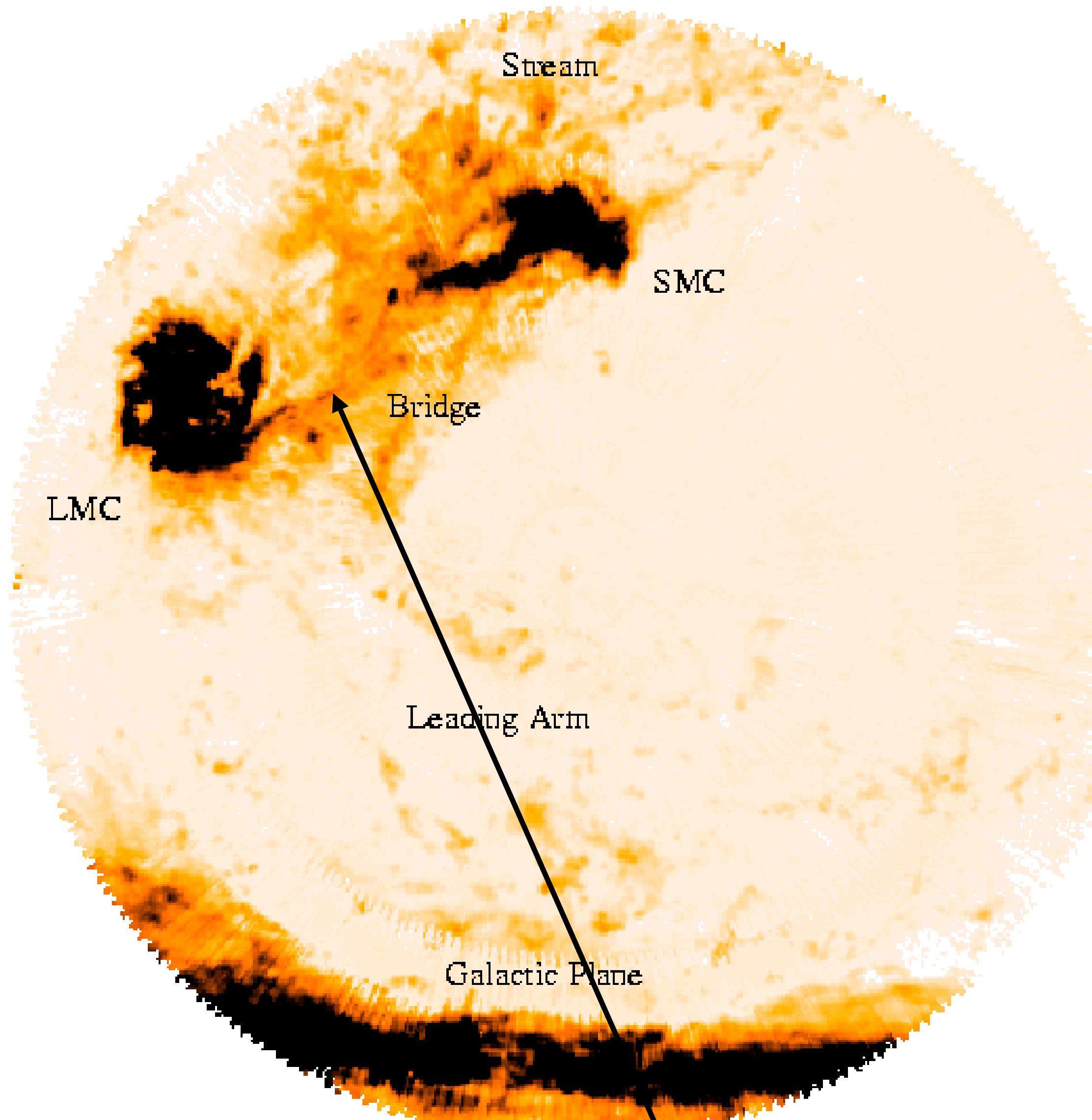
from Oort, Kerr & Westerhout (1958)

The nearest interacting galaxy: our Milky Way

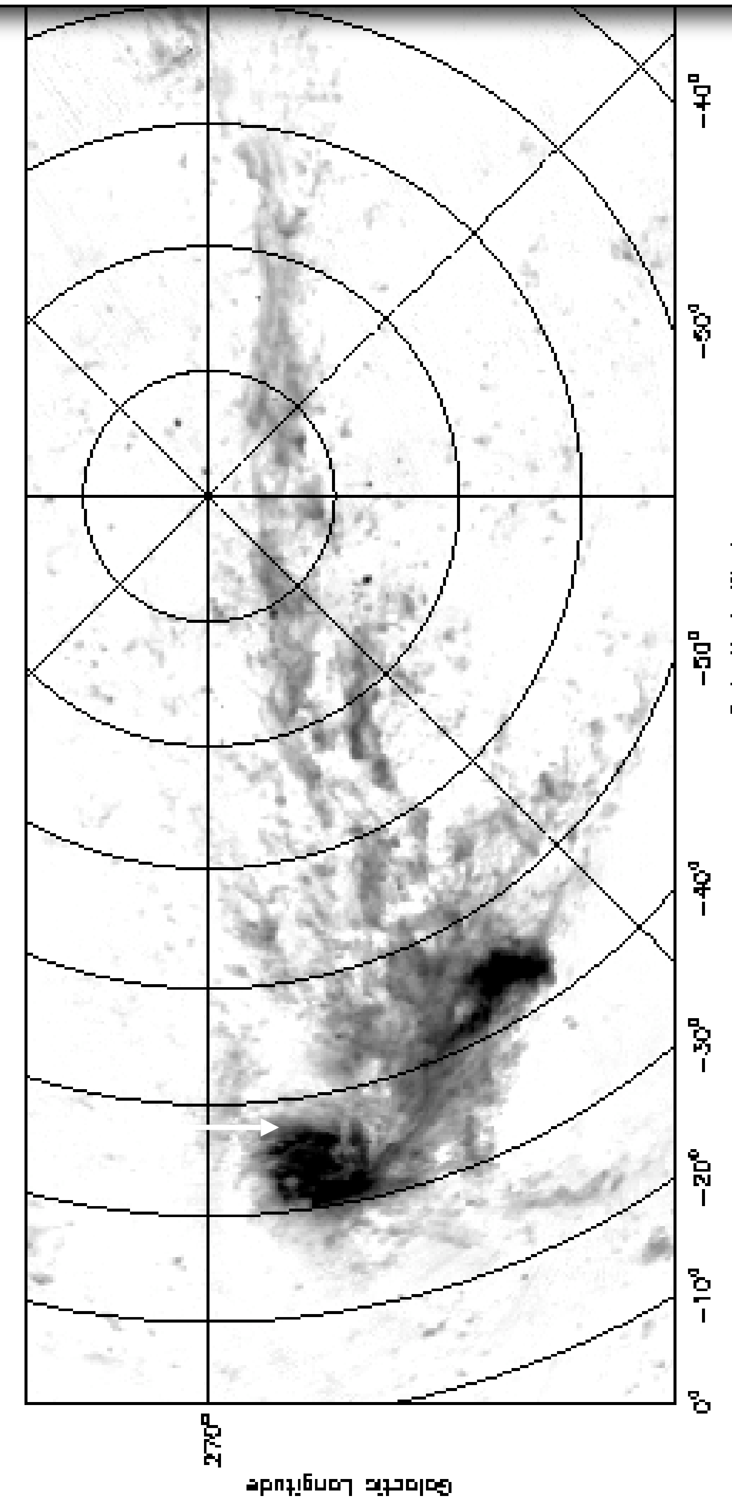
13-beam 21-cm receiver at prime focus



Example of interaction with our neighbours: hydrogen in the Magellanic stream



Magellanic Clouds



M. Putman

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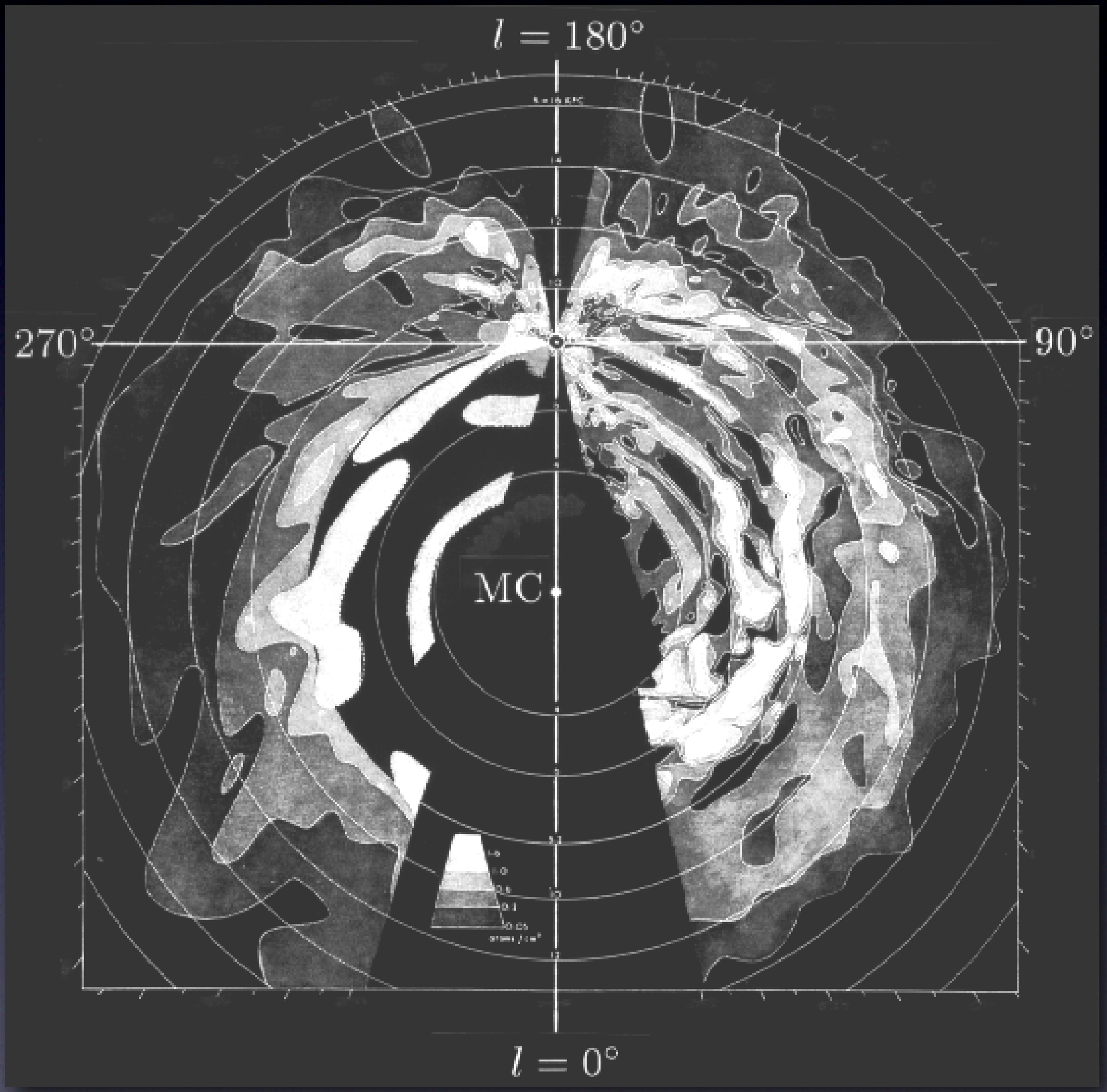

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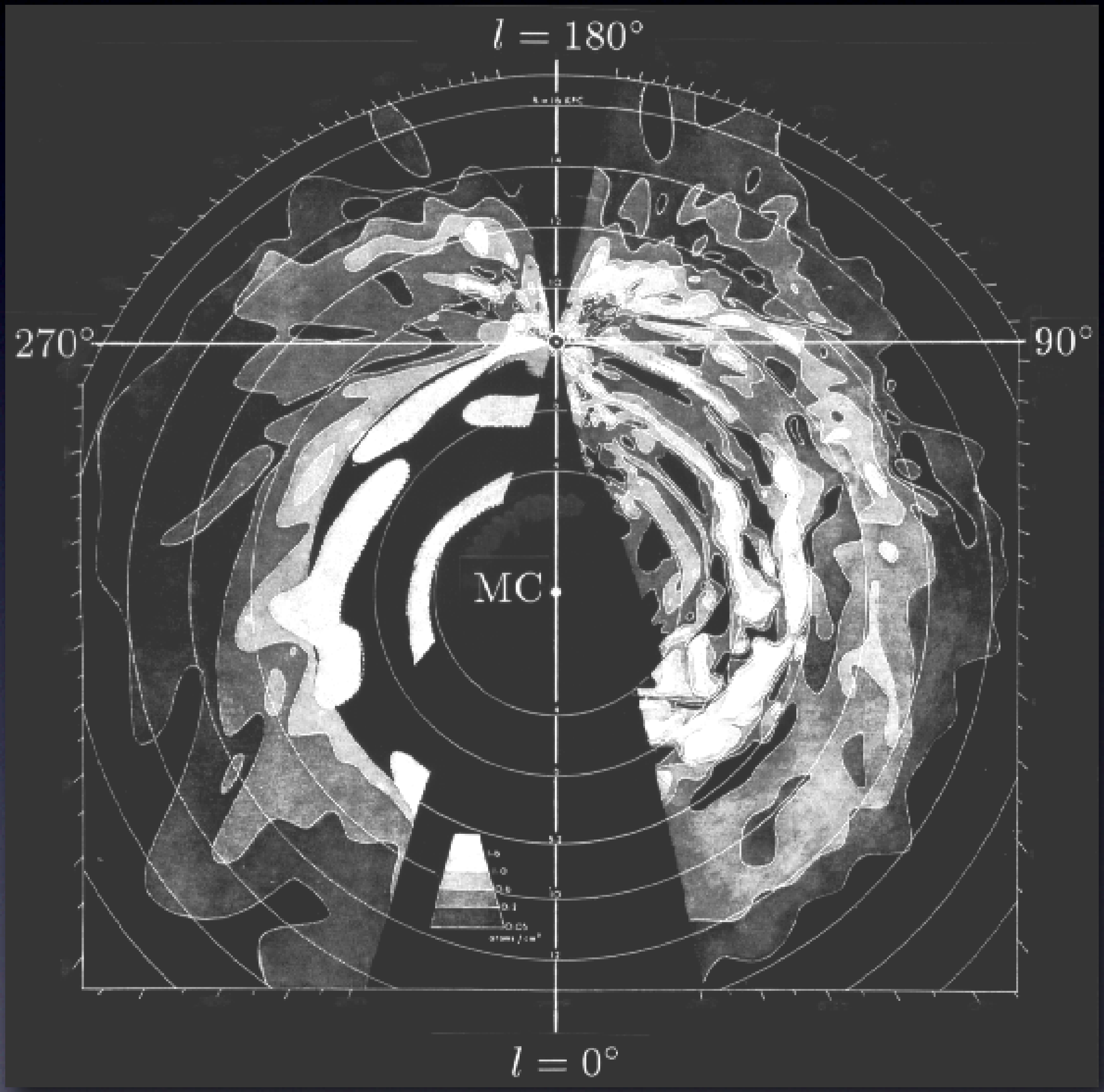

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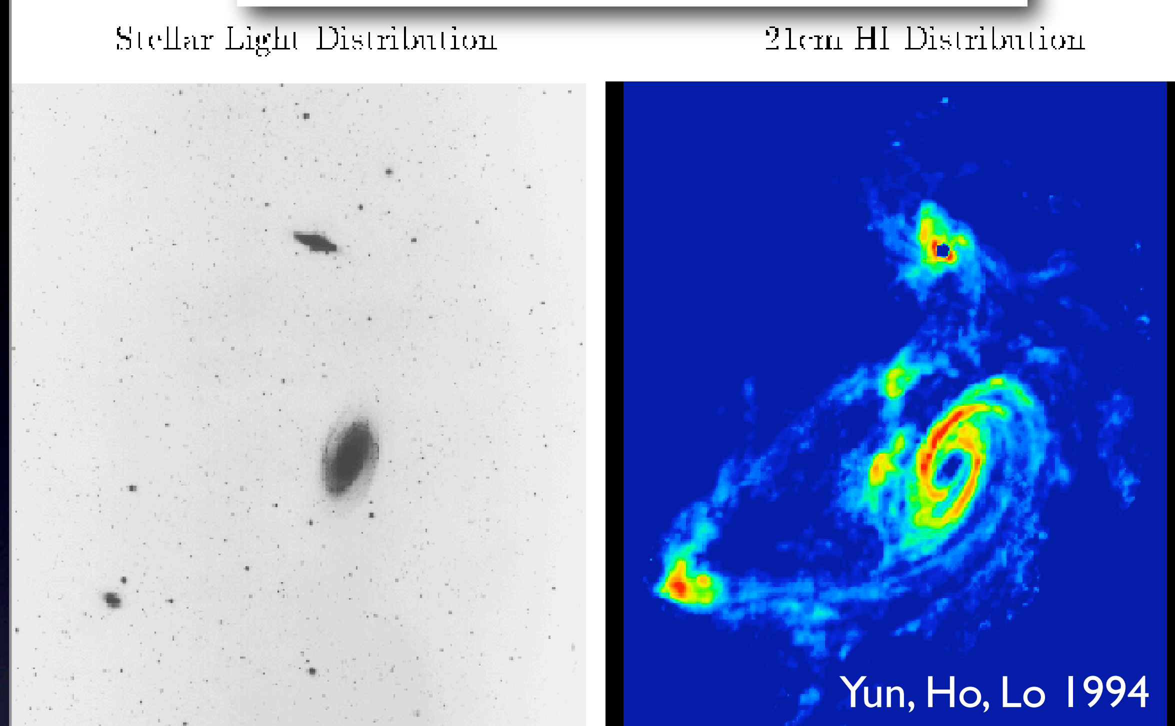
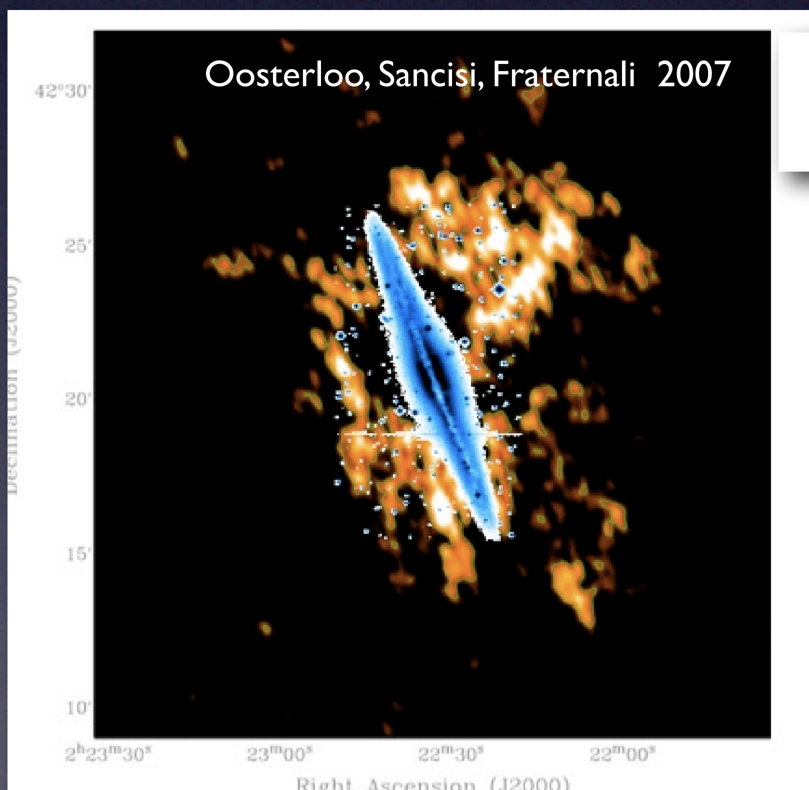
HI and the farther away Universe

Tracing interaction

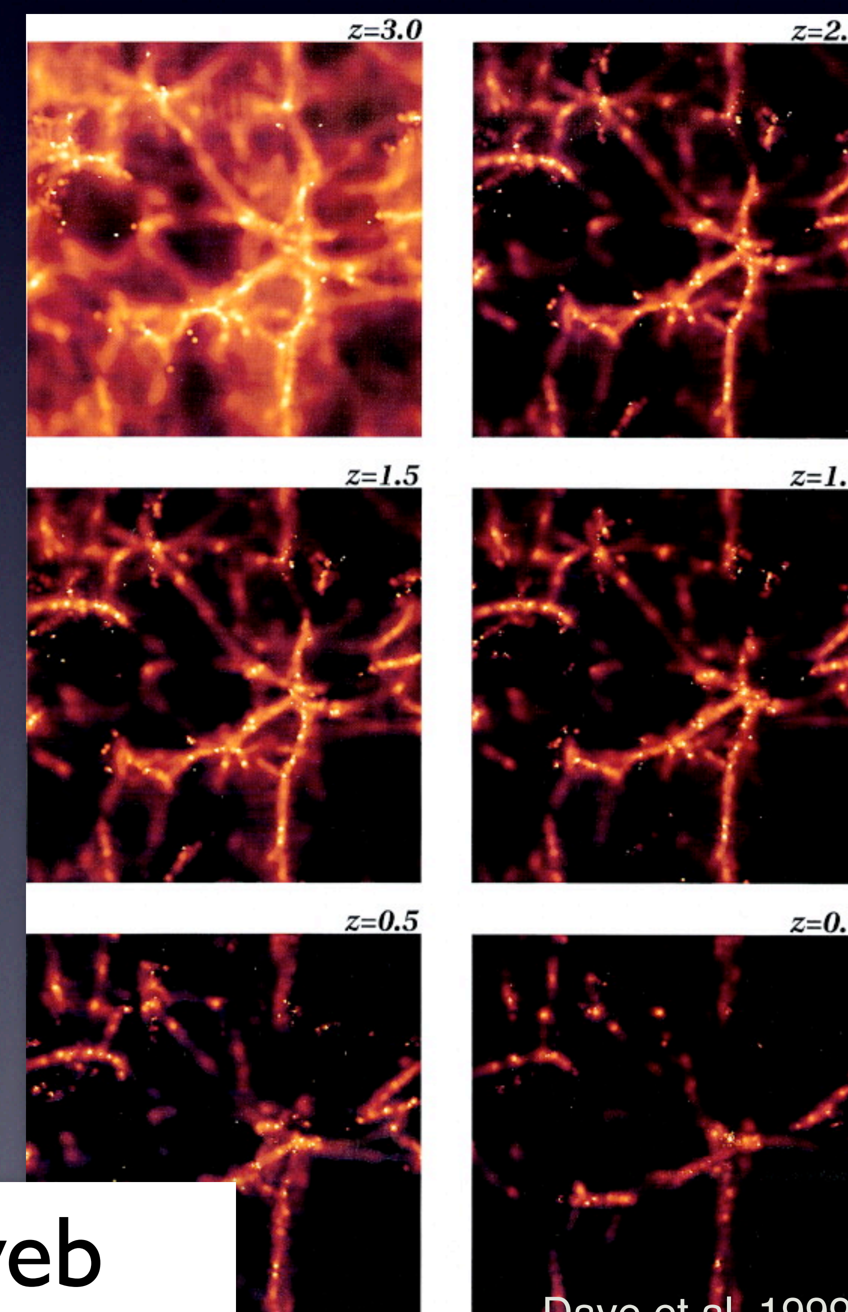


Gas accretion



The gas falling onto NGC 891
as detected with the WSRT

Cosmic web



HI and early-type galaxies: why?

- Early-type (elliptical and S0) galaxies are considered gas poor: so why bother?

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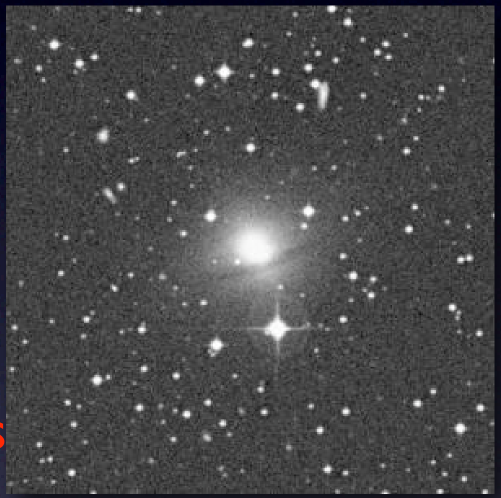

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Can we use the gas to trace the process that turns a black hole in an active nucleus ➡ feeding the monster?

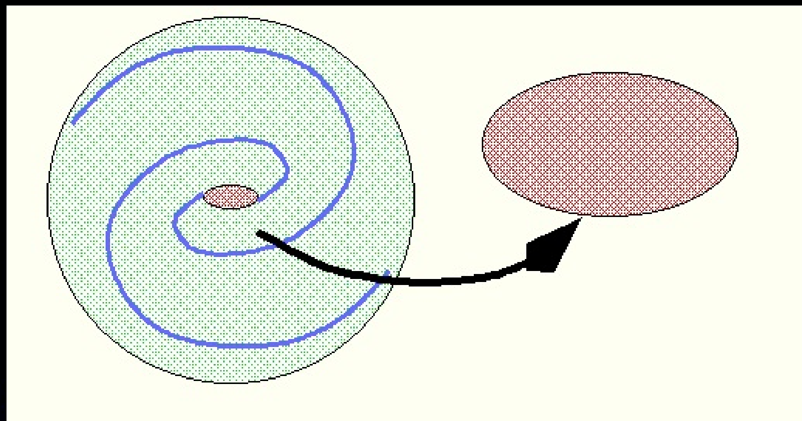
- Gas in the surrounding of the active nucleus: structure of the central regions

- Is the energy (jets?) released by the AGN affecting this gas

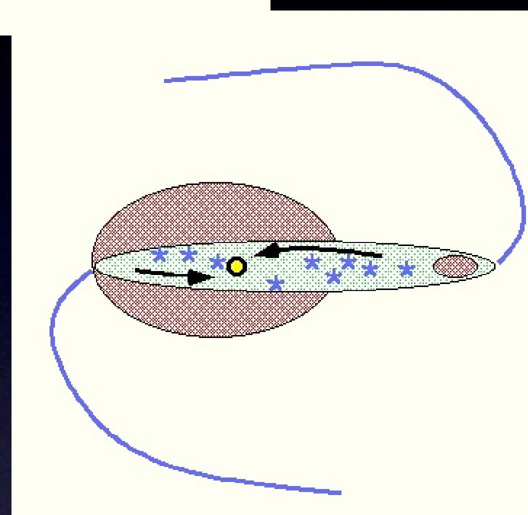
ASTRON

onset of radio activity related to accretion or merger -> but variety of conditions in the merger

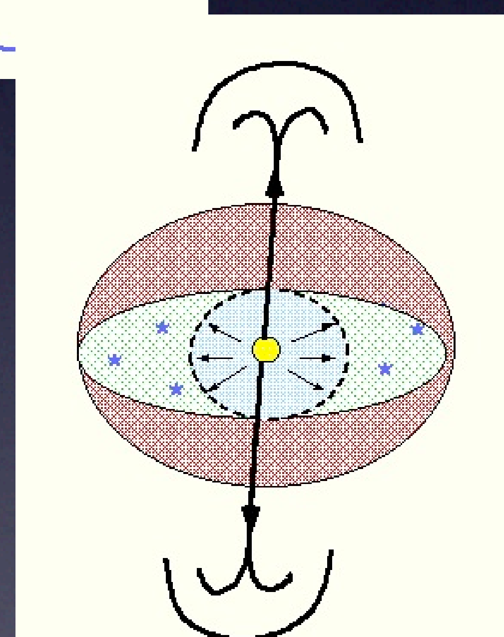
from Clive Tadhunter



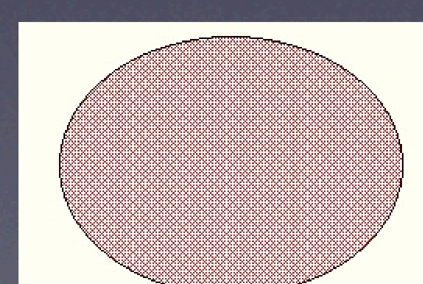
Start of merger
-1 billion yr



Advanced merger: gas driven towards nucleus; starburst
-0.5 billion yr



Quasar and jet activity drives gas out of galaxy
Now



Relaxed
E-galaxy
+1 billion yr

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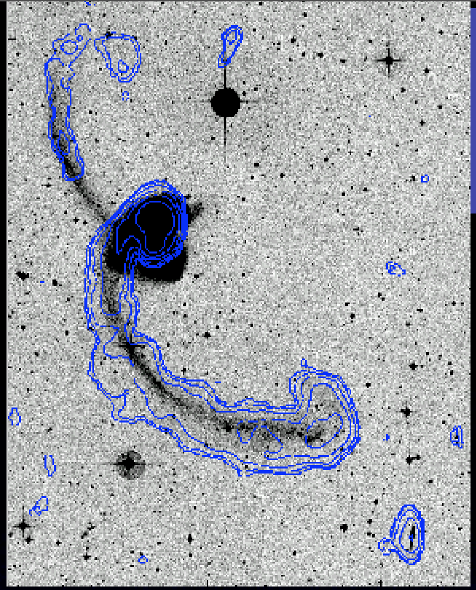

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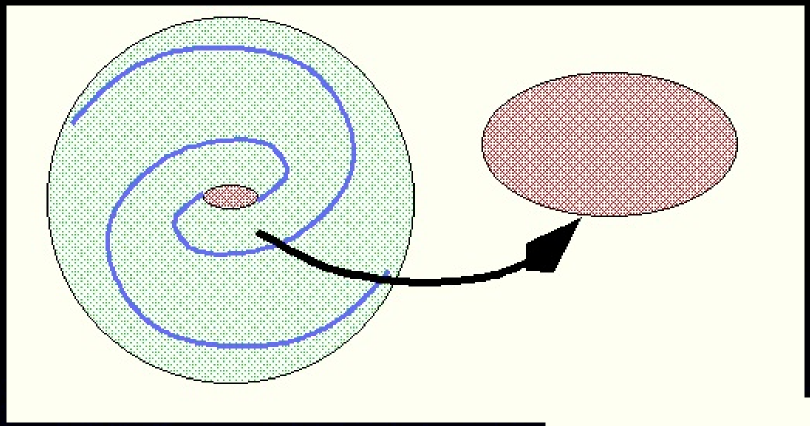

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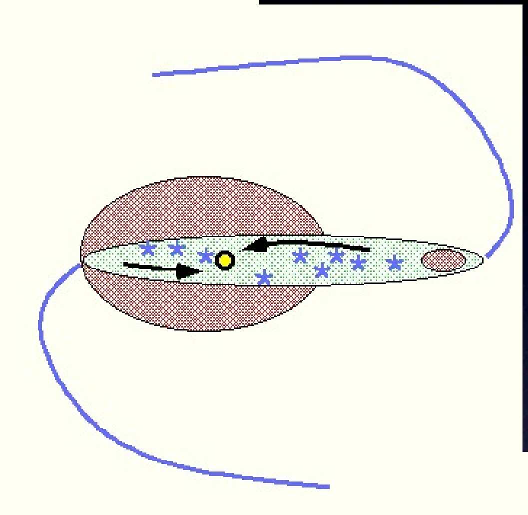

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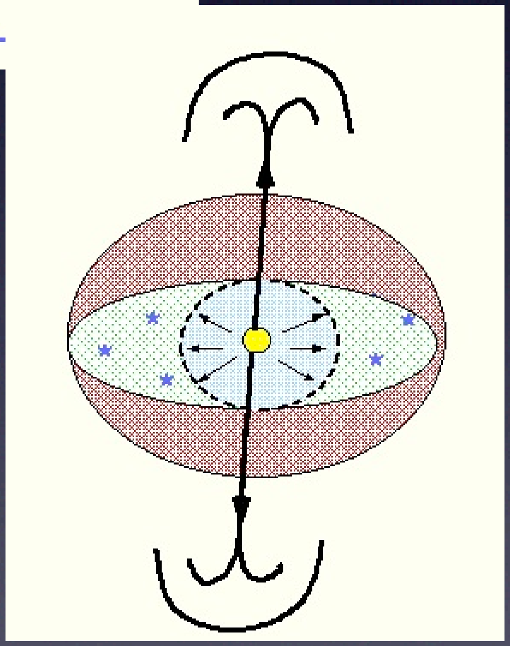

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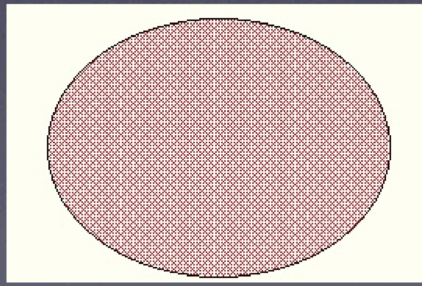

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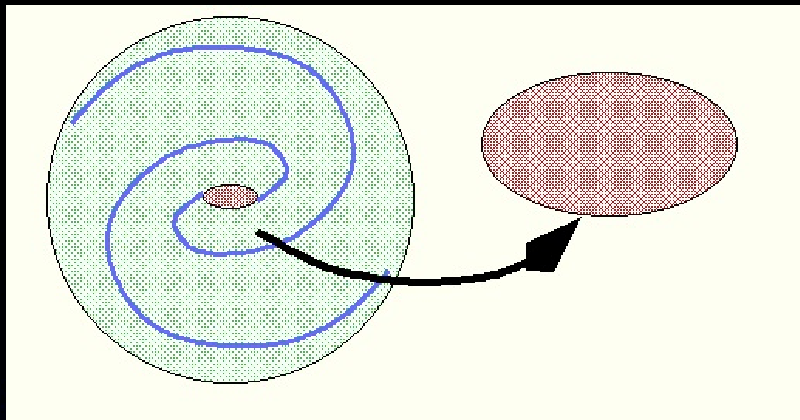

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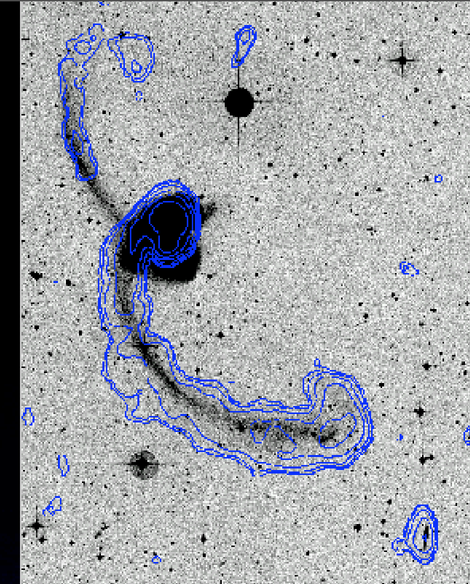

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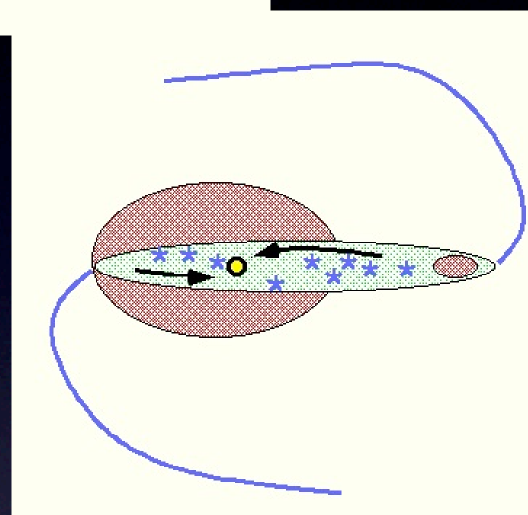

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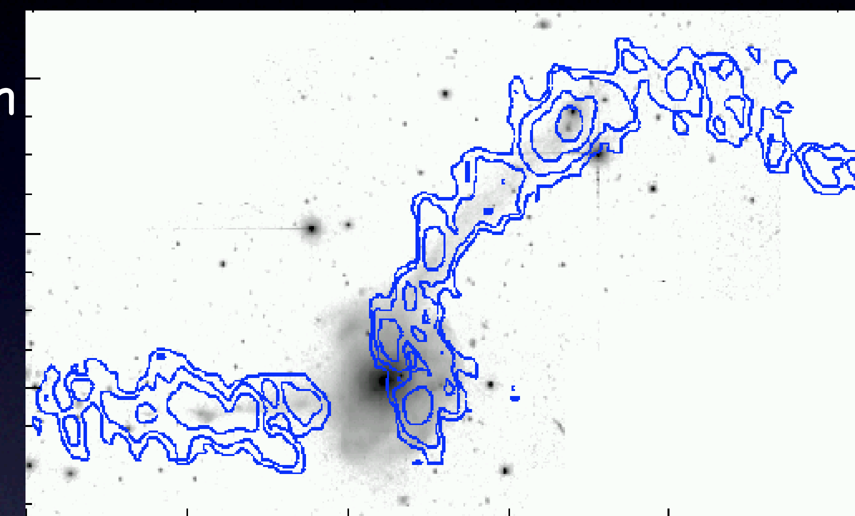

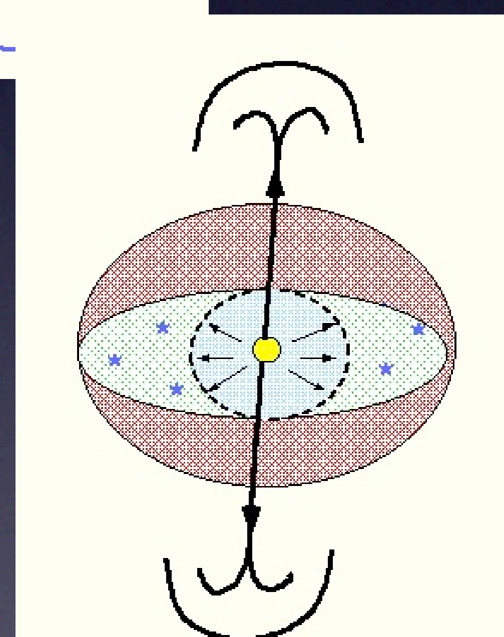

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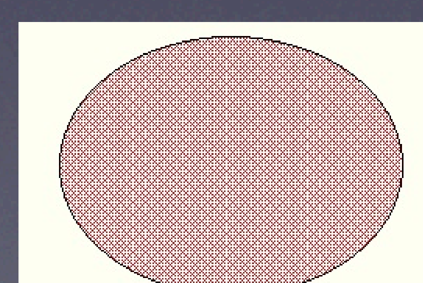

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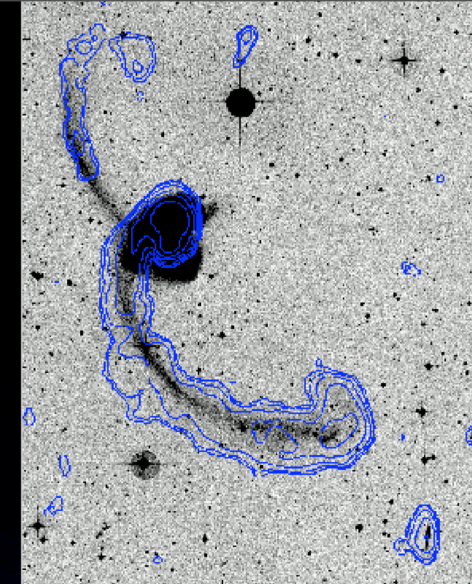
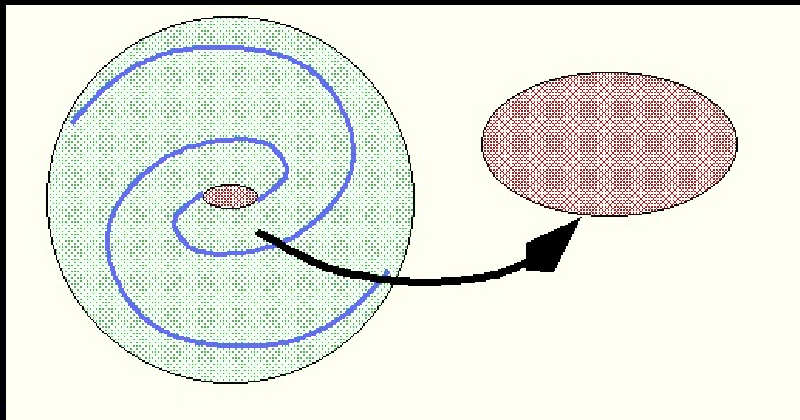
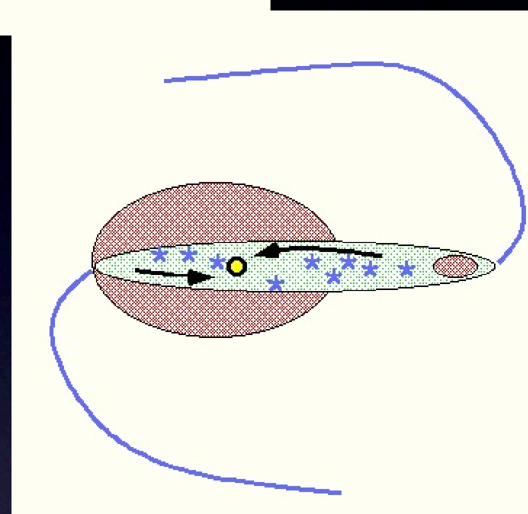


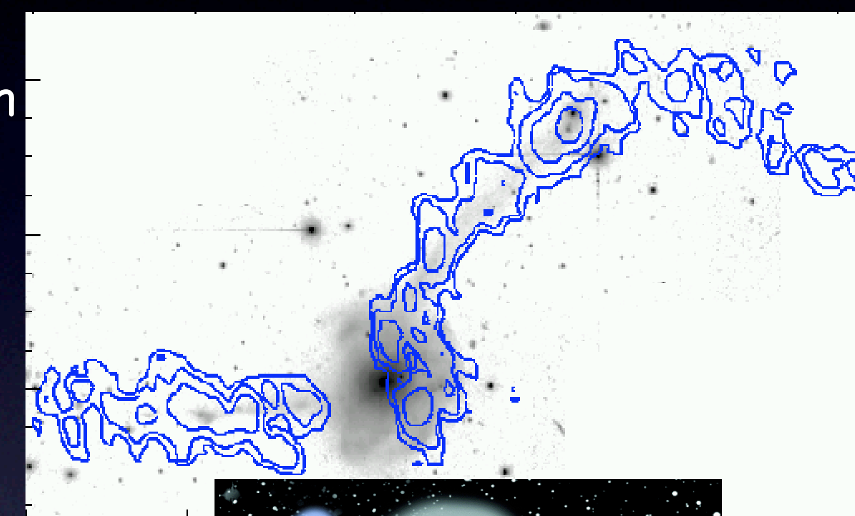
from Clive Tadhunter

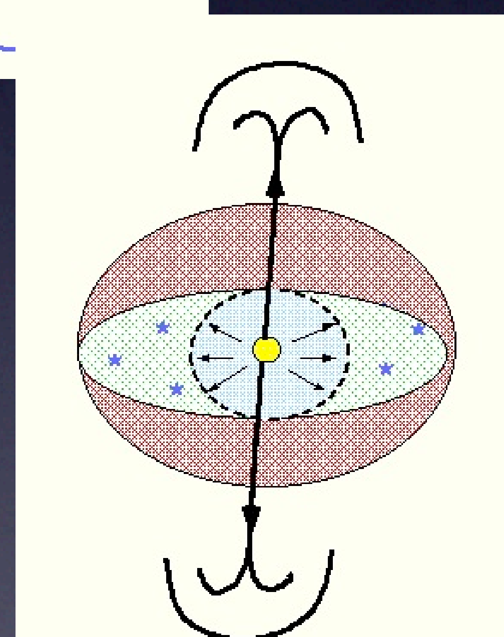


Start of merger
-1 billion yr

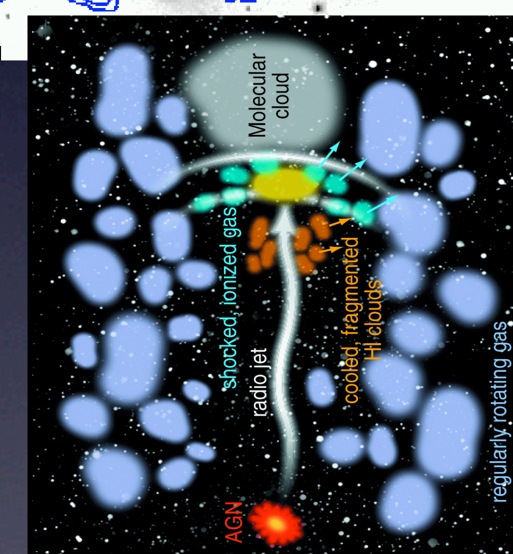


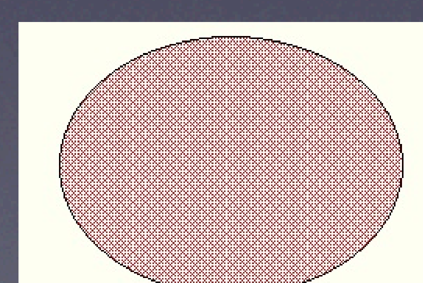
Advanced merger: gas driven towards nucleus; starburst
-0.5 billion yr





Quasar and jet activity drives gas out of galaxy
Now

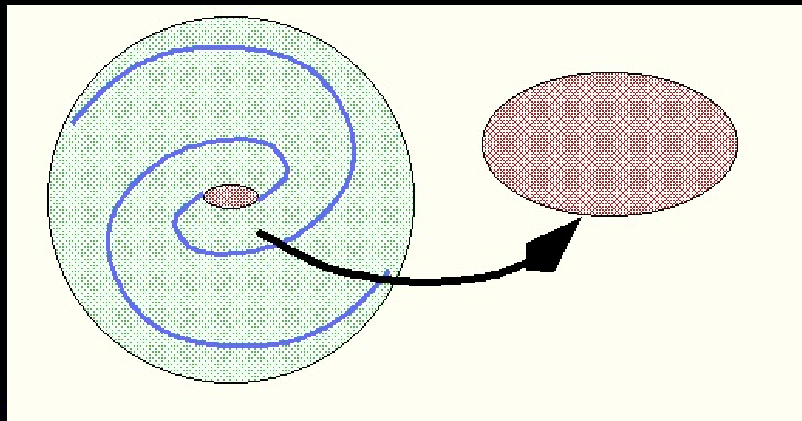




Relaxed
E-galaxy
+1 billion yr

onset of radio activity related to accretion or merger -> but variety of conditions in the merger

from Clive Tadhunter



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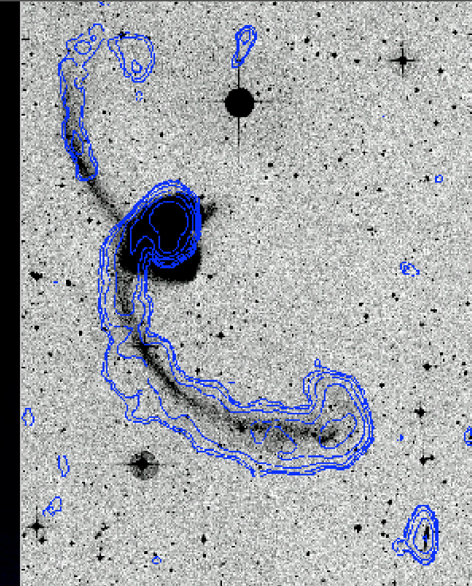

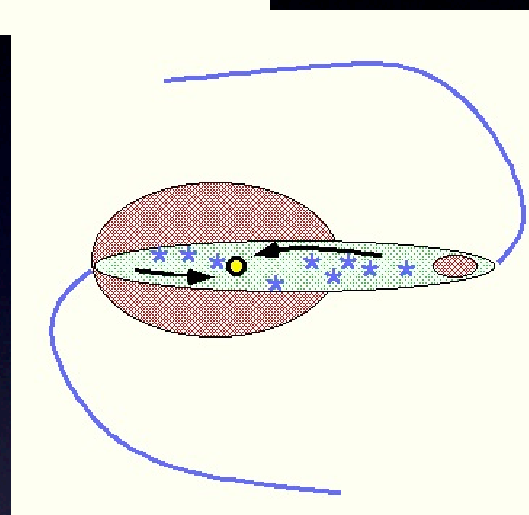

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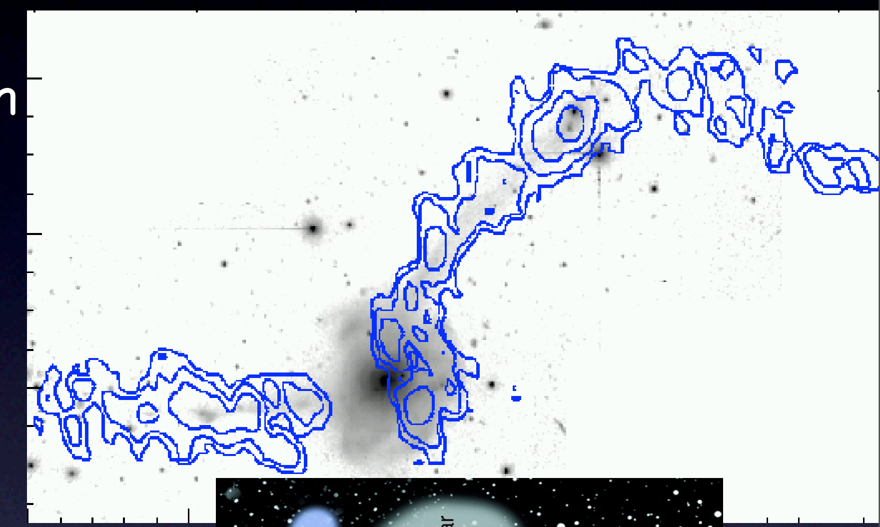

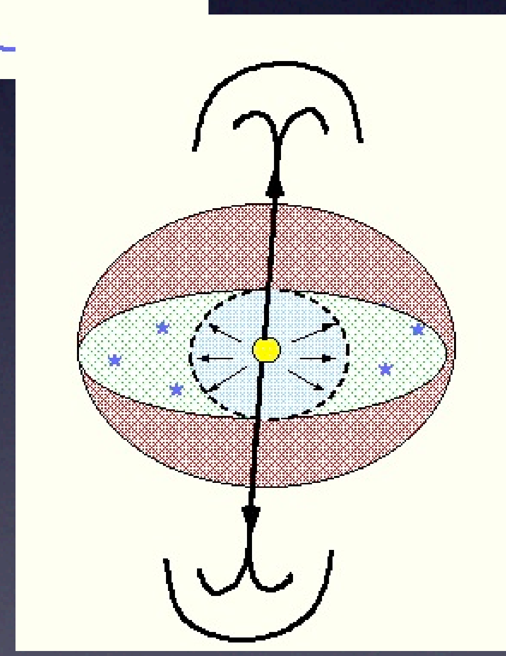

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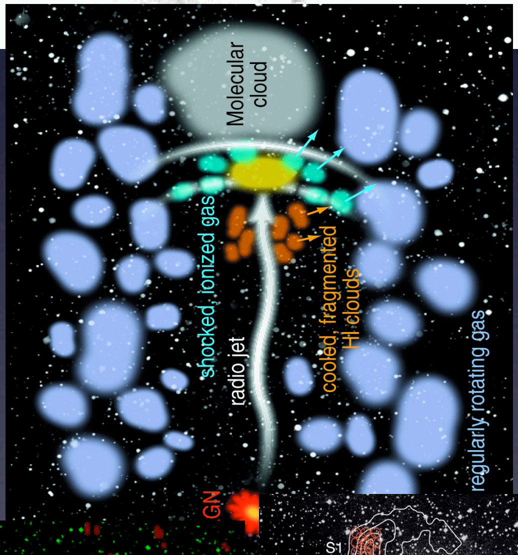

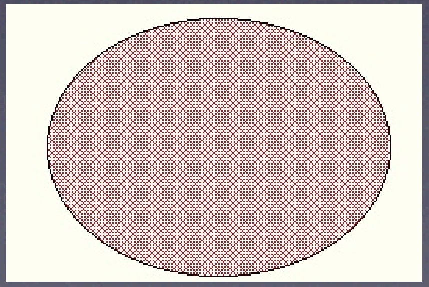

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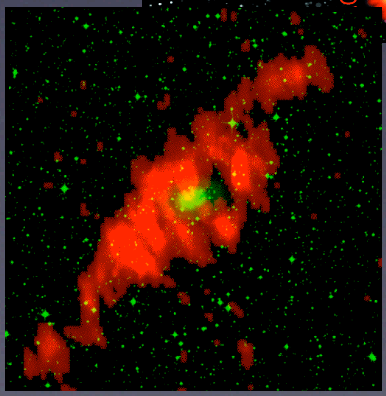
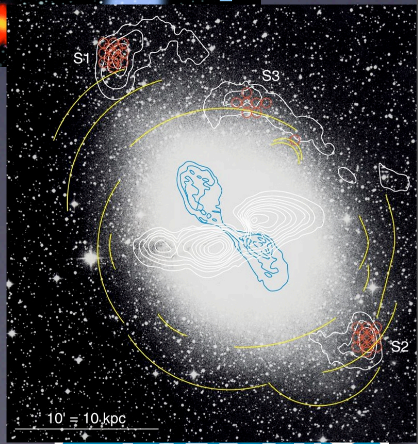
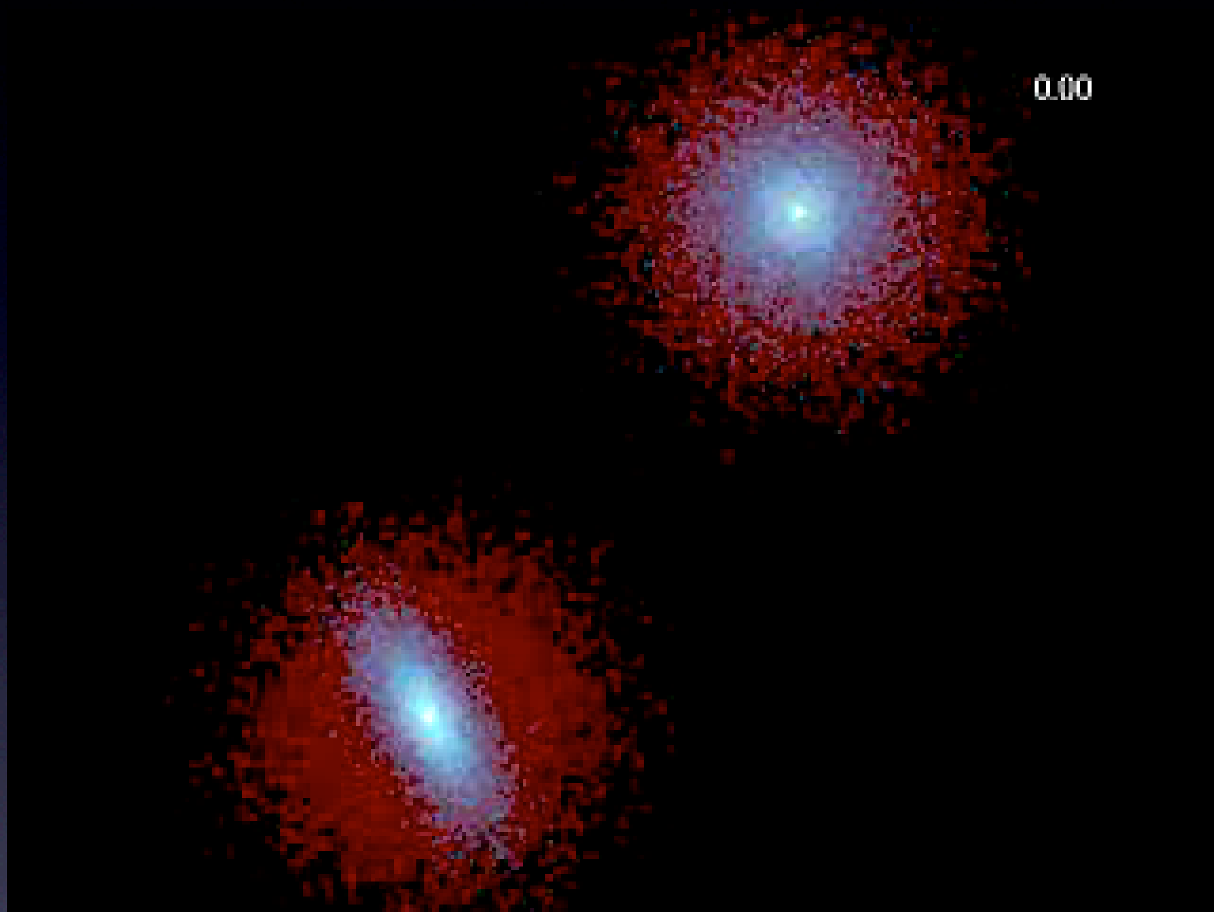


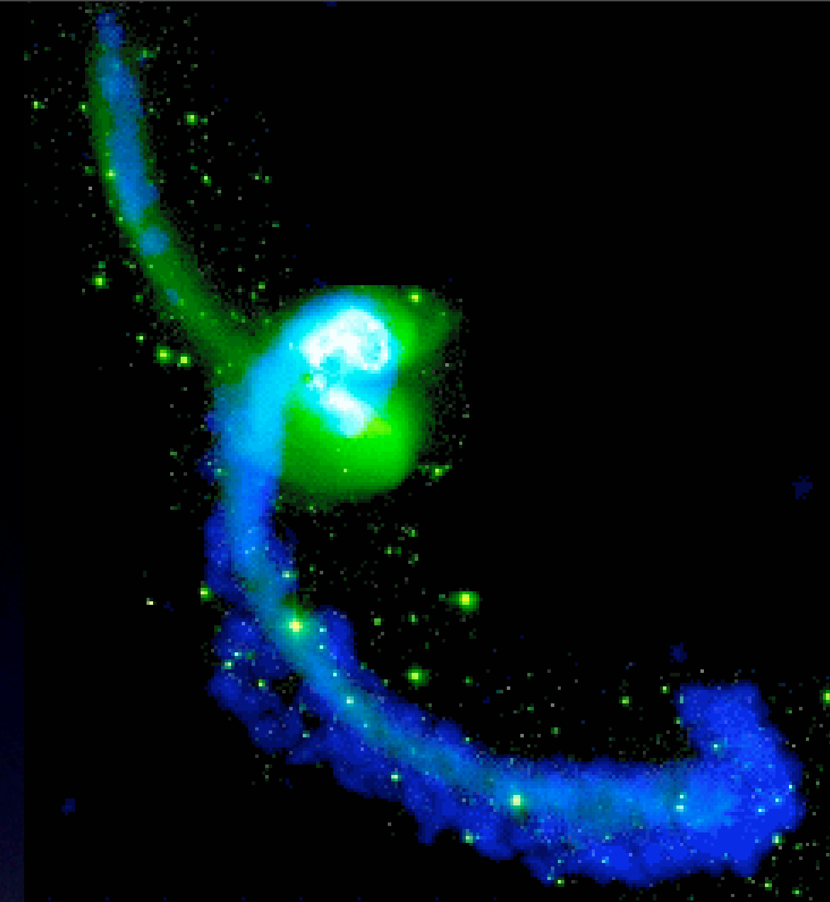


Example of interacting galaxies: the gas is a powerful tracer of interaction

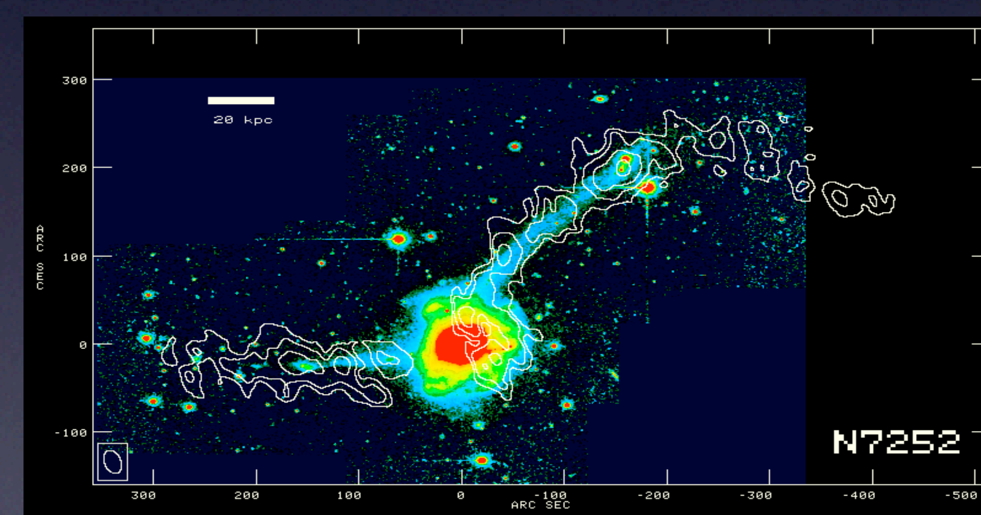
Numerical simulations of Barnes



Early-type galaxies from major merger



The Antennae (Hibbard et al.)

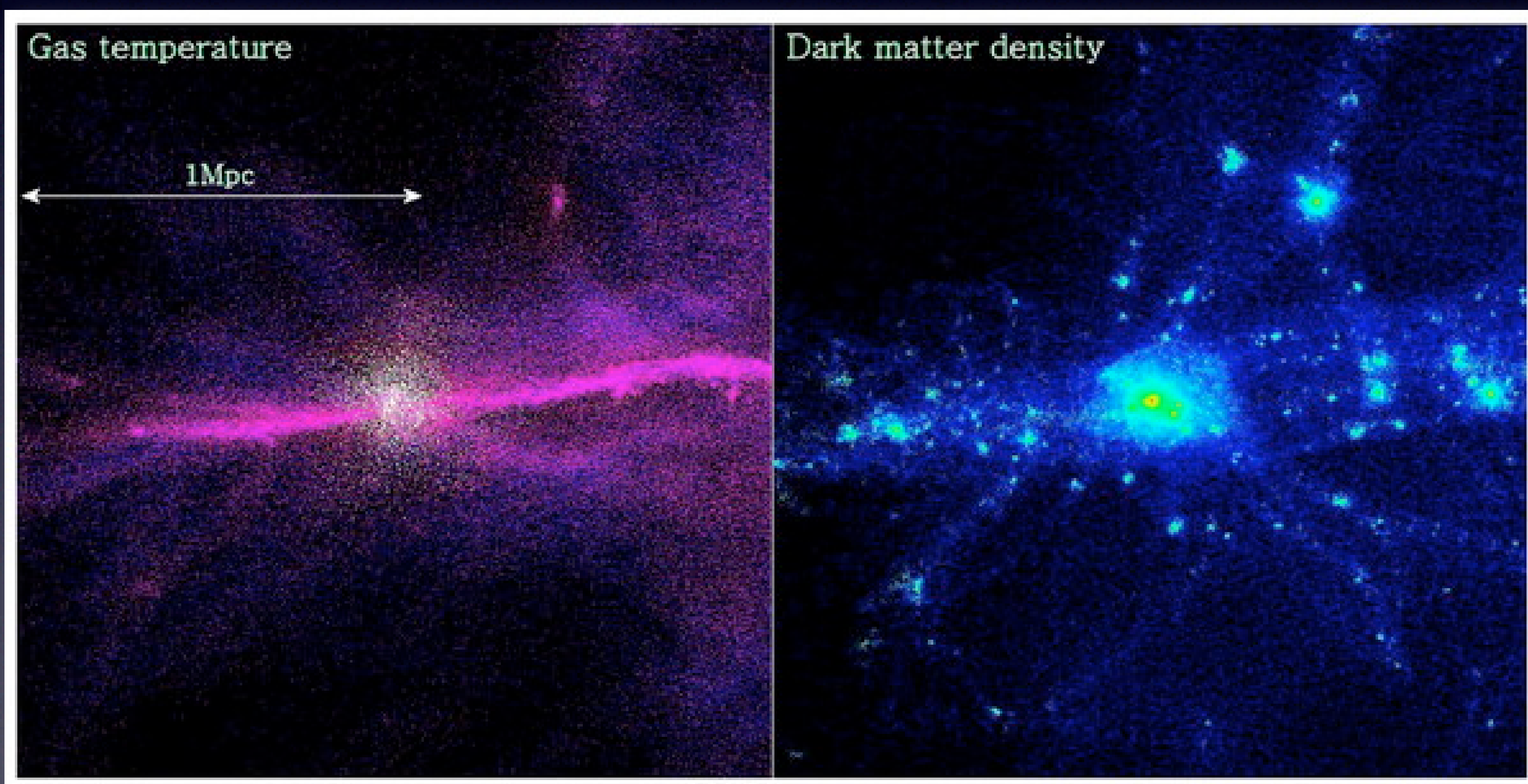


(Hibbard et al.)

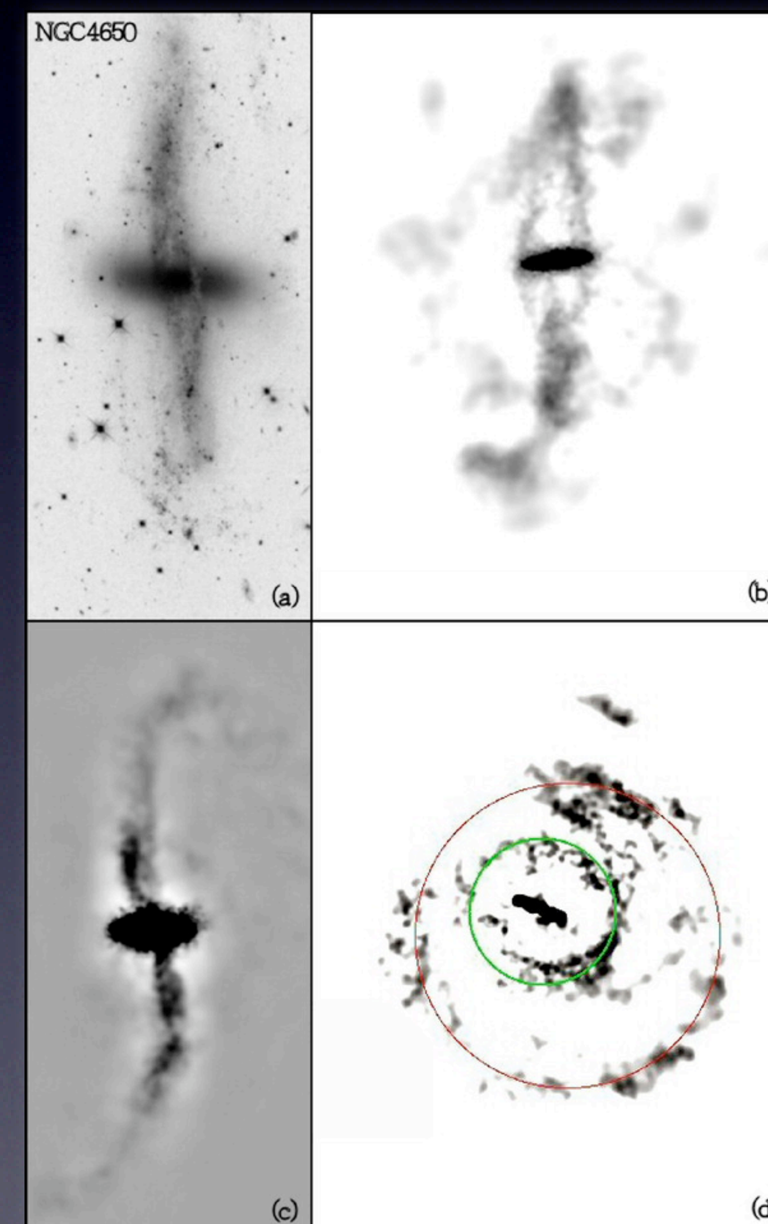
Cold accretion?

Slow but long-lasting accretion of significant amounts of (primordial) gas. Some of the gas can remain cool (not all gets shock ionized)

Not clear predictions about distribution and amount of HI but, unlike mergers, it should not leave a clear signature in the stellar population....



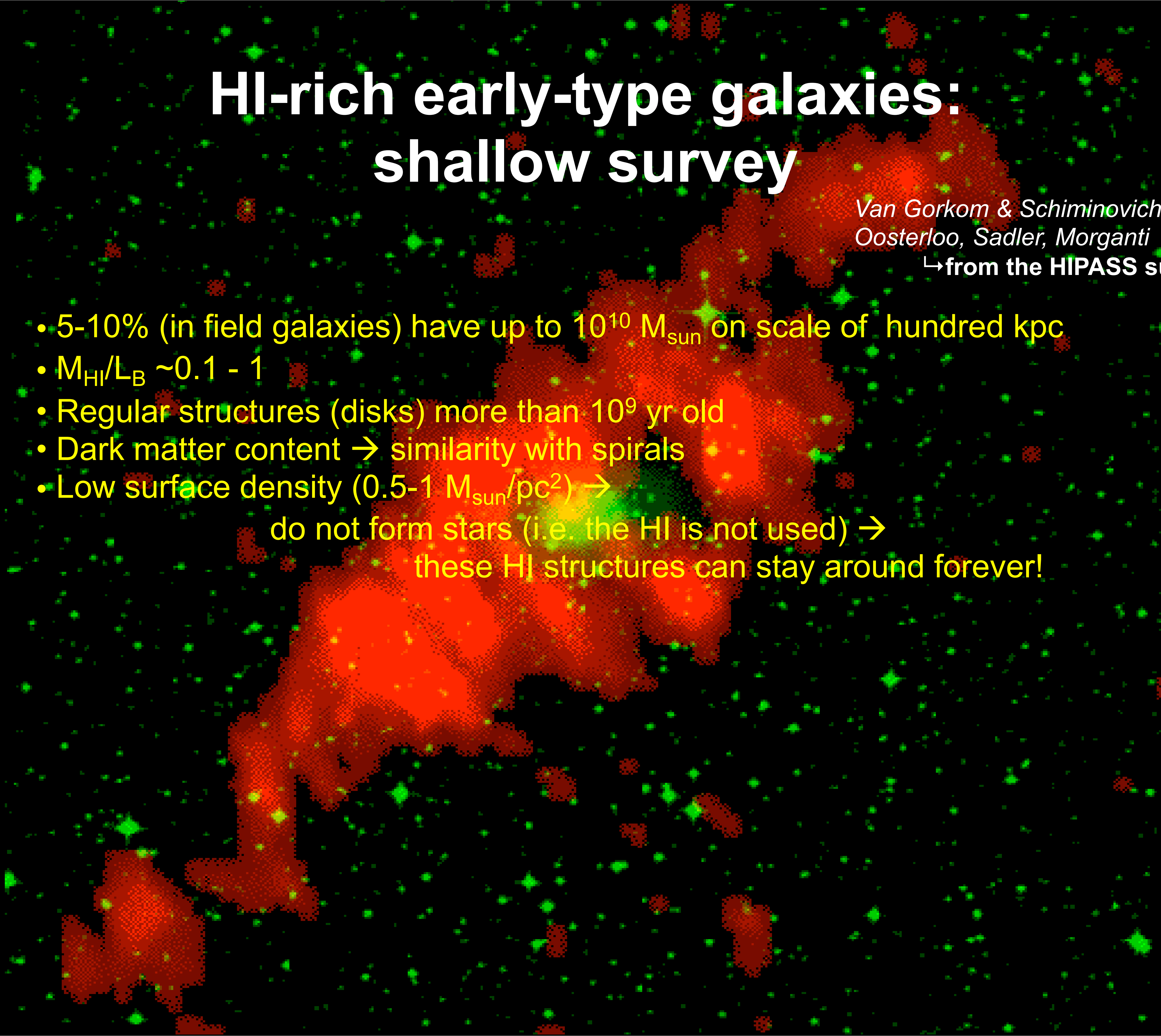
Macciò, Moore, Stadel 2006



HI-rich early-type galaxies: shallow survey

Van Gorkom & Schiminovich
Oosterloo, Sadler, Morganti
↳**from the HIPASS survey**

- 5-10% (in field galaxies) have up to 10^{10} M_{sun} on scale of hundred kpc
- M_{HI}/L_B ~0.1 - 1
- Regular structures (disks) more than 10^9 yr old
- Dark matter content → similarity with spirals
- Low surface density (0.5-1 M_{sun}/pc^2) →
  do not form stars (i.e. the HI is not used) →
  these HI structures can stay around forever!



Morganti, Sadler, Oosterloo, Pizzella, Bertola 1997 AJ

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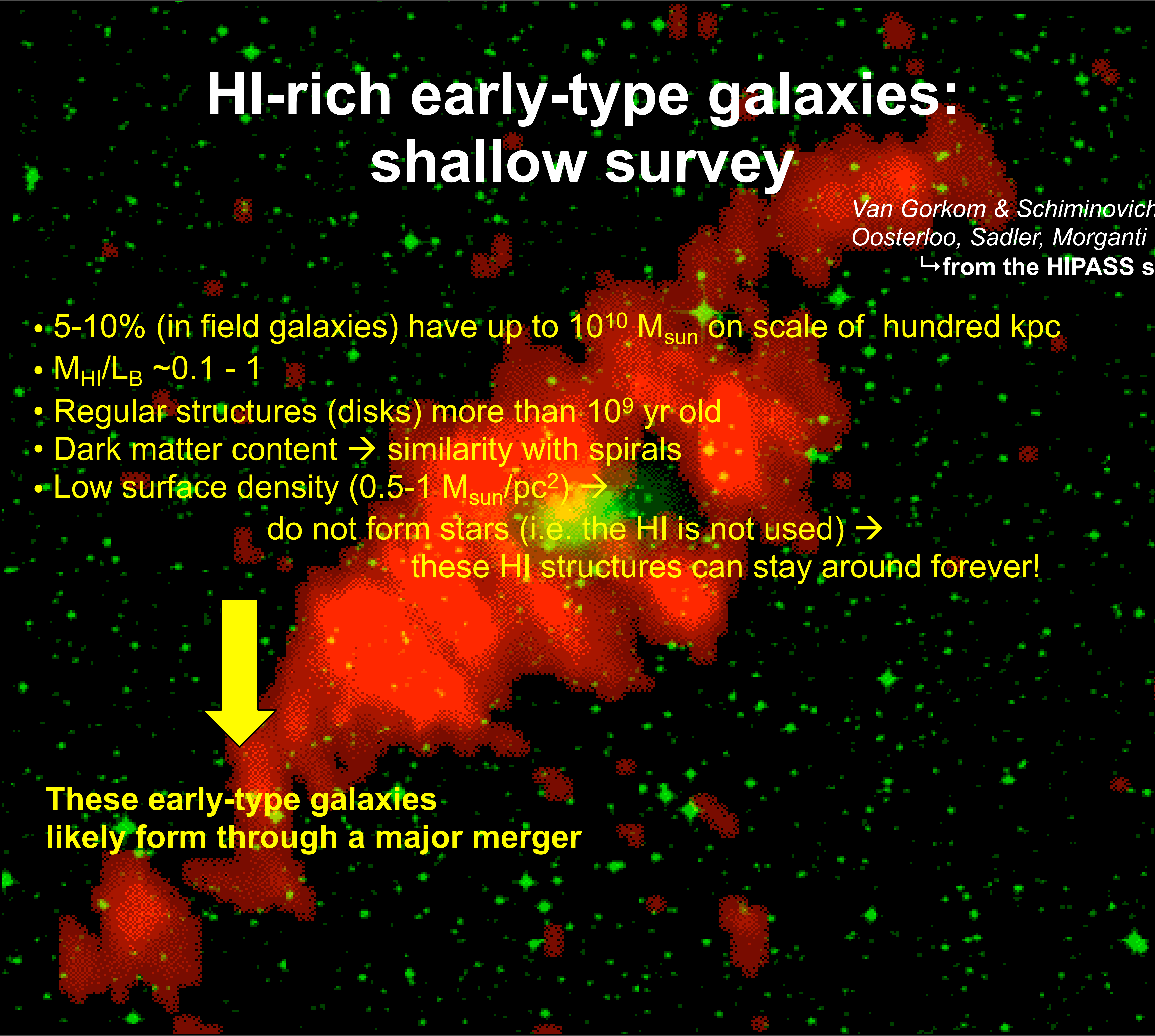

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Morganti, Sadler, Oosterloo, Pizzella, Bertola 1997 AJ

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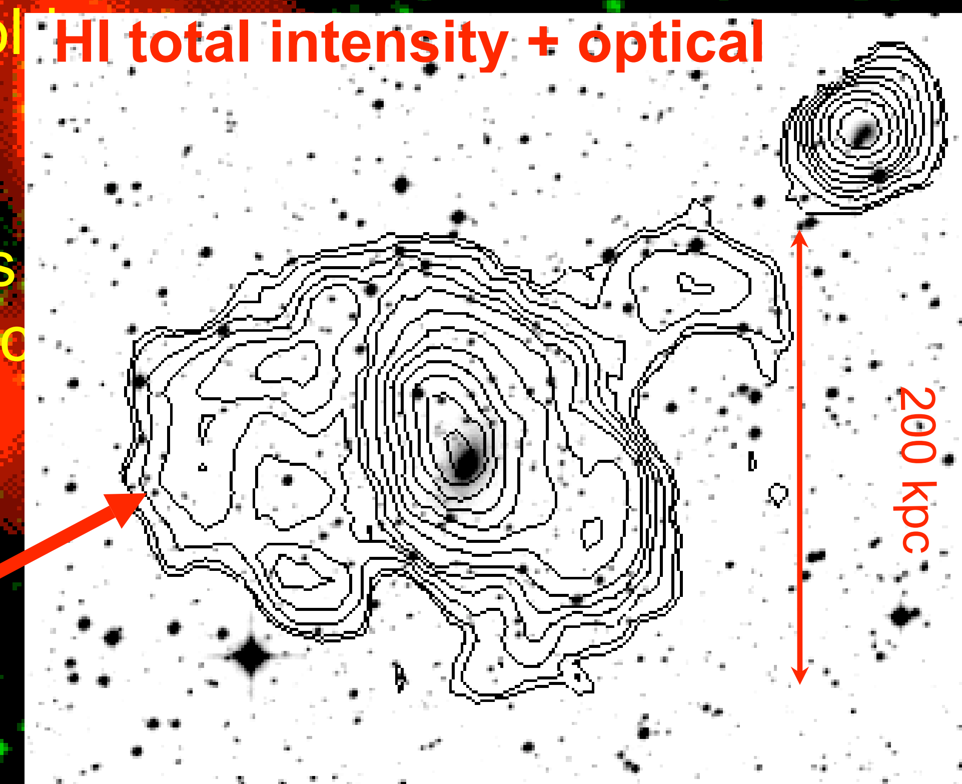


These early-type galaxies likely form through a major merger

IC4200 → Event that happened about 2 Gyr ago and originated both the HI structure and the central starburst: major merger – time not long enough for accretion of IGM.

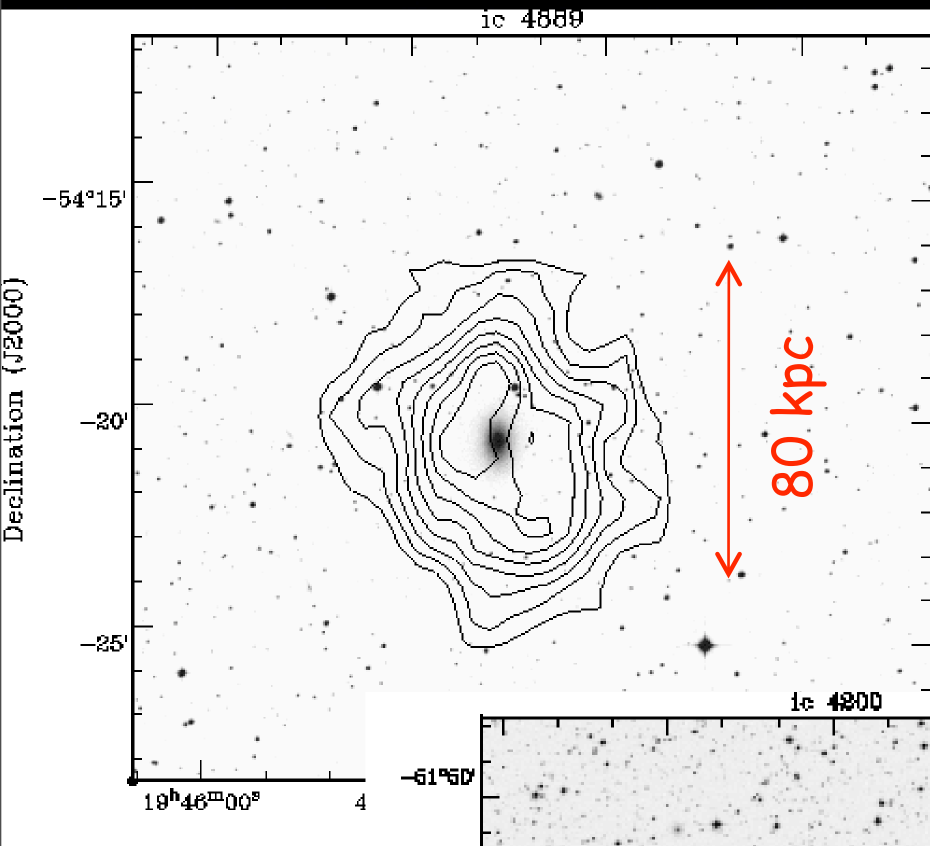
Serra et al. A&A in press

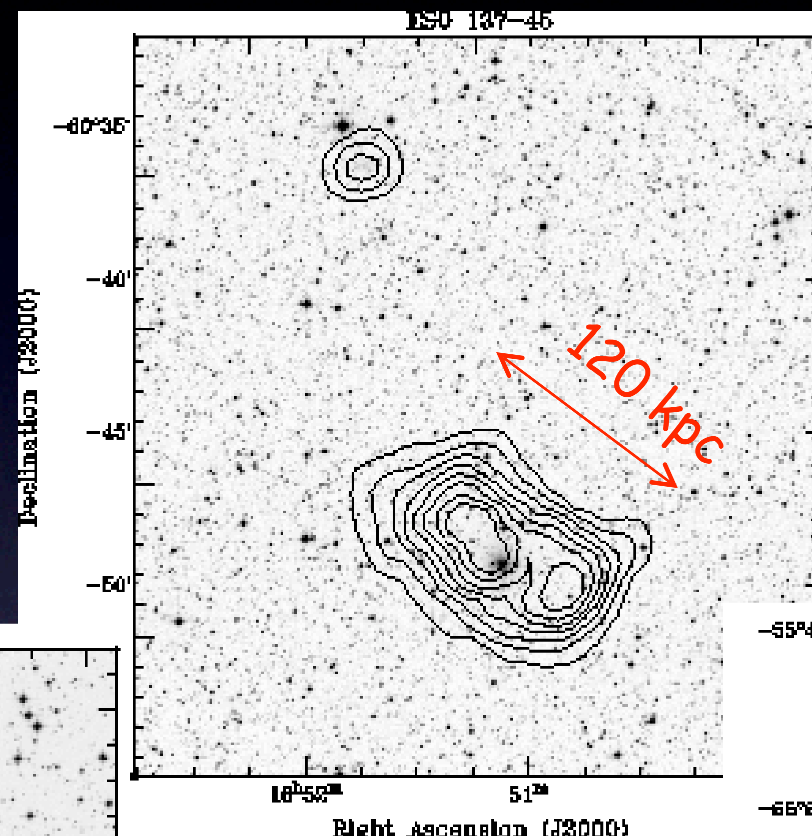
Morganti, Sadler, Oosterloo, Pizzella, Bertola 1997 AJ

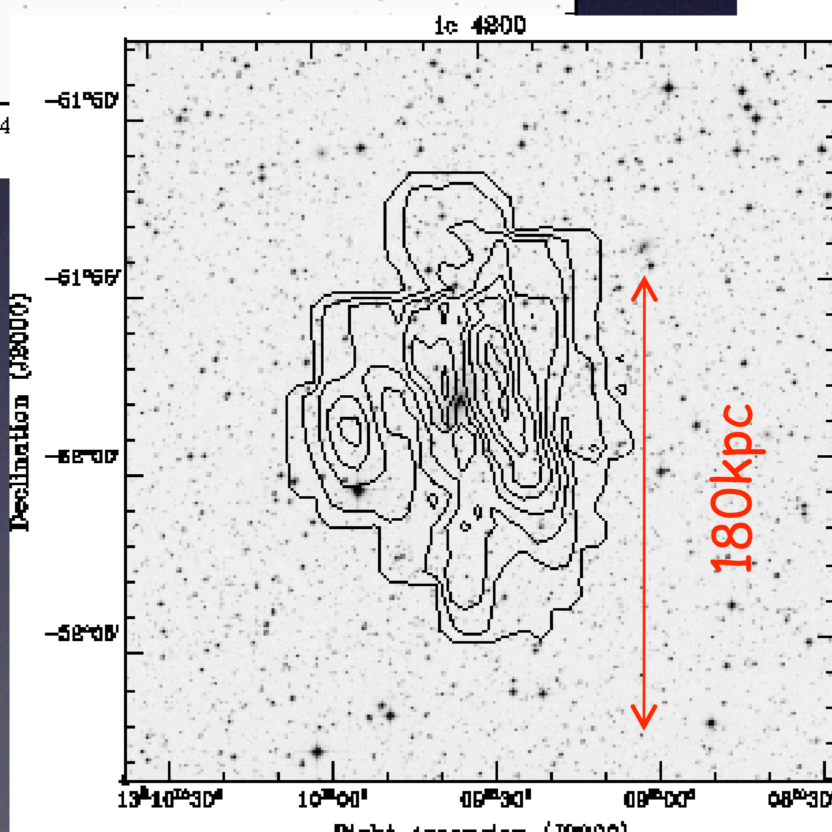
HI rich, early-type galaxies: very large H I disks of low column density

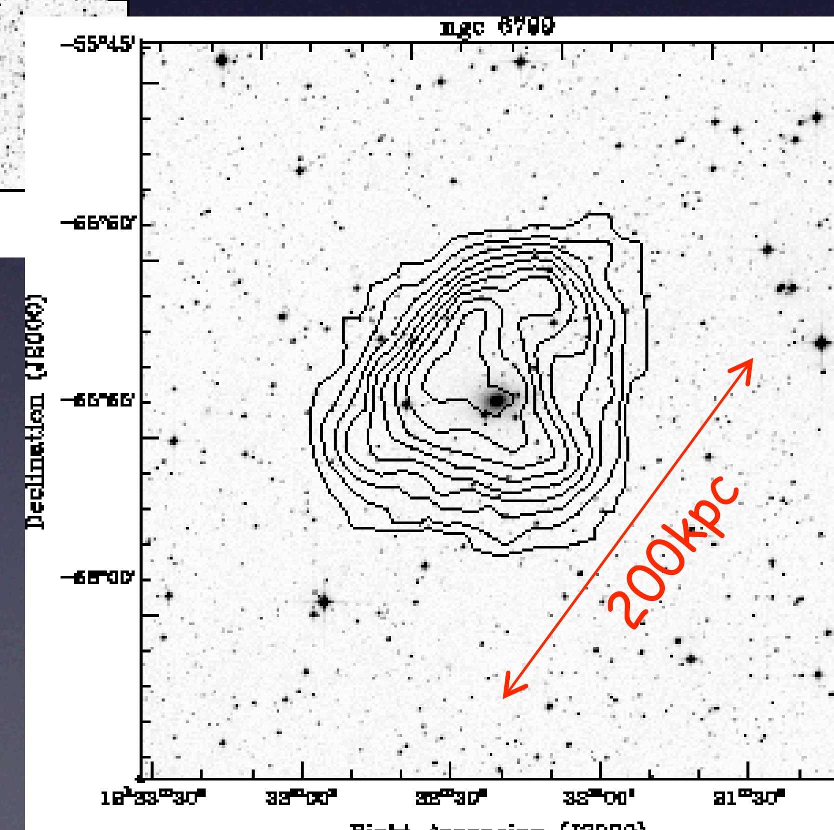
$\sigma_{HI} < 2 \cdot 10^{20}$ cm^{-2}

"no" star formation









HI in early-type galaxies: deep survey

- Deep HI observations with the WSRT
- Down to upper limits of $M_{HI} \sim 2x10^6 M_{sun}$
- **In 8 of the 12 cases, HI is detected in or around the galaxy**
- HI masses between $4x10^6$ and $10^9 M_{sun}$

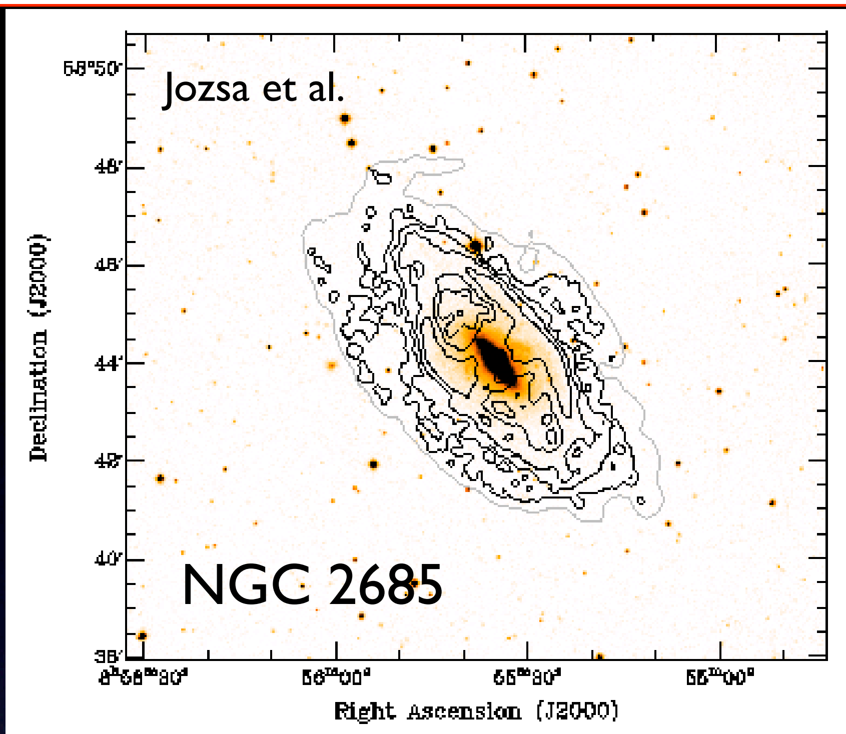
  → **~70% galaxies detected**
- M_{HI}/L_B: **wide range** from <0.0003 up to 0.3
- For the first time (for these low HI masses) we have also the morphological information: variety of morphologies
- Four cases of HI in disk-like structures, three (possibly 4) cases of offset clouds/tails → the presence of regular disk-like structures is therefore as common as HI "floating" around galaxies

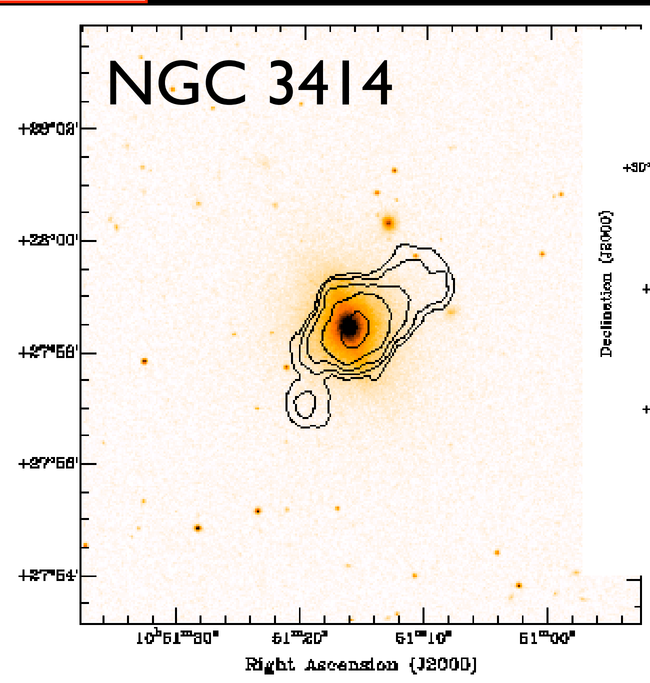
Morganti, de Zeeuw, Oosterloo et al. MNRAS 2006

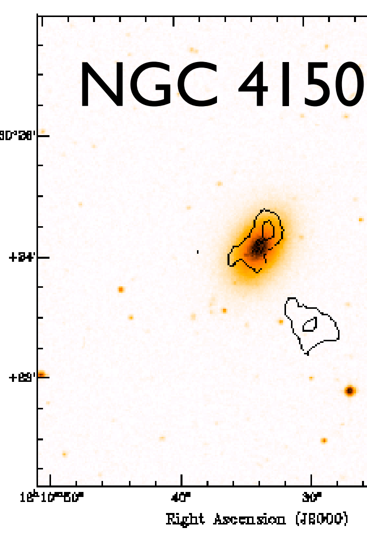
A lot of telescope time but only 12 objects!

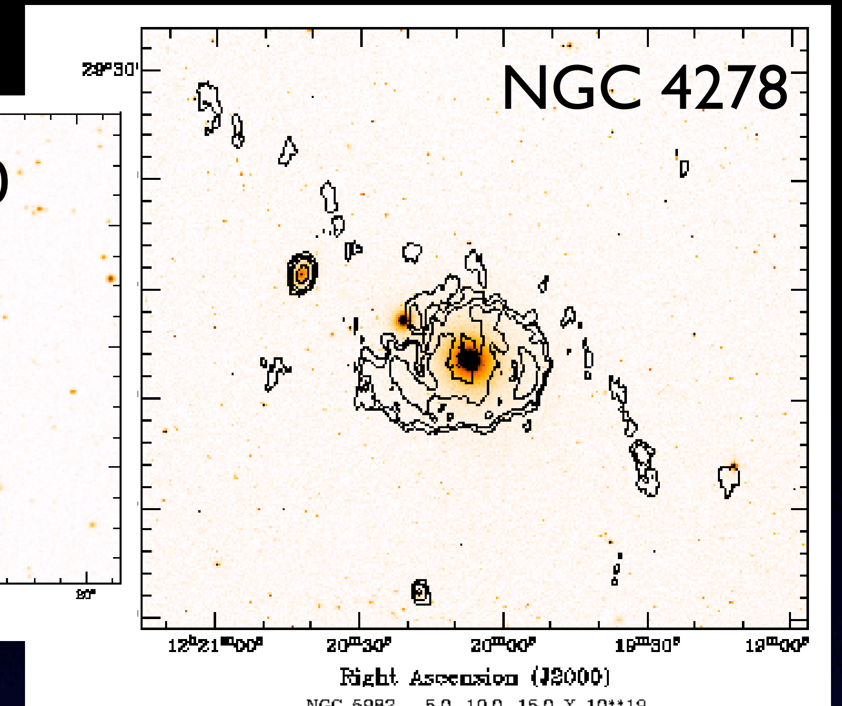
ASTRON

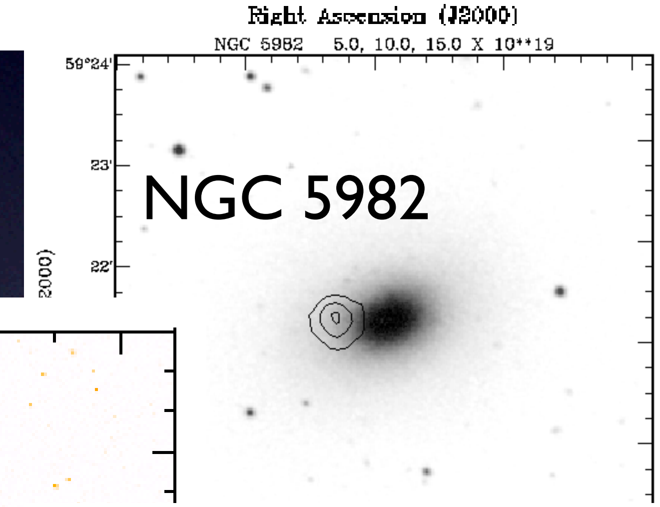
Regularly rotating HI structures



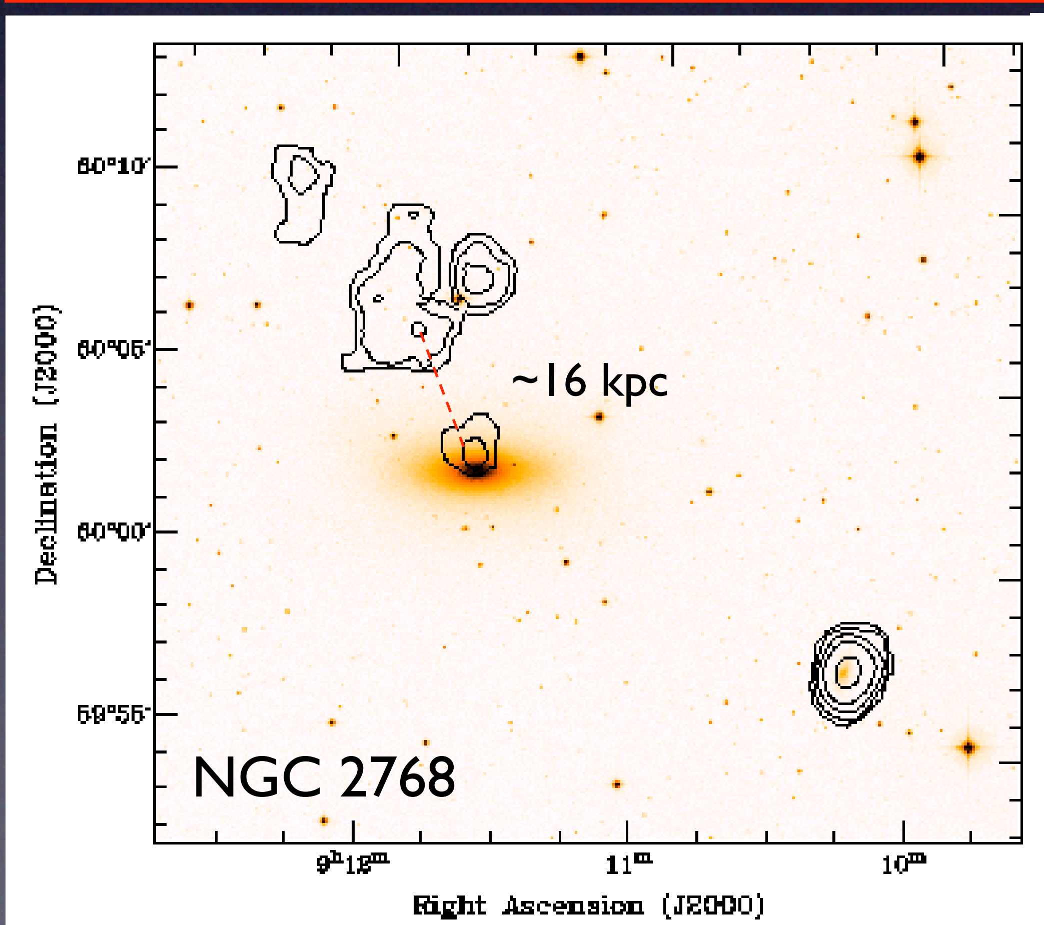


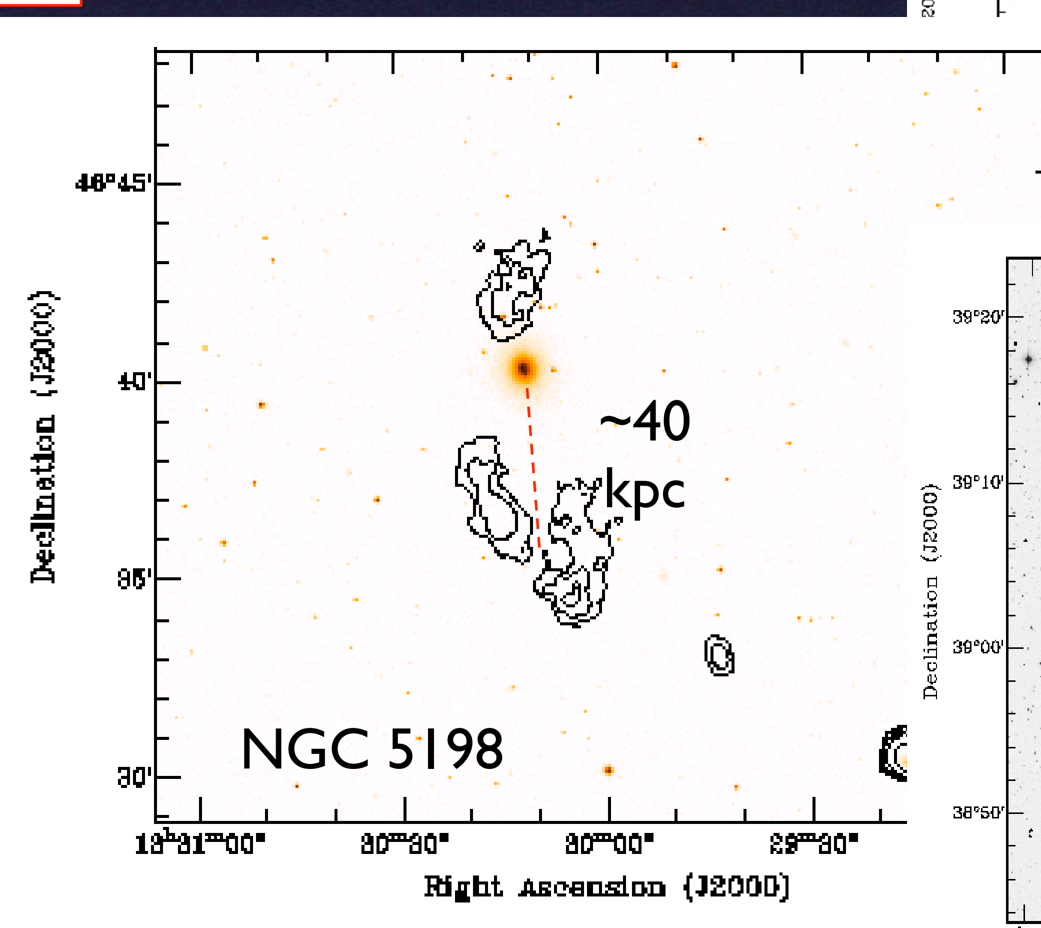


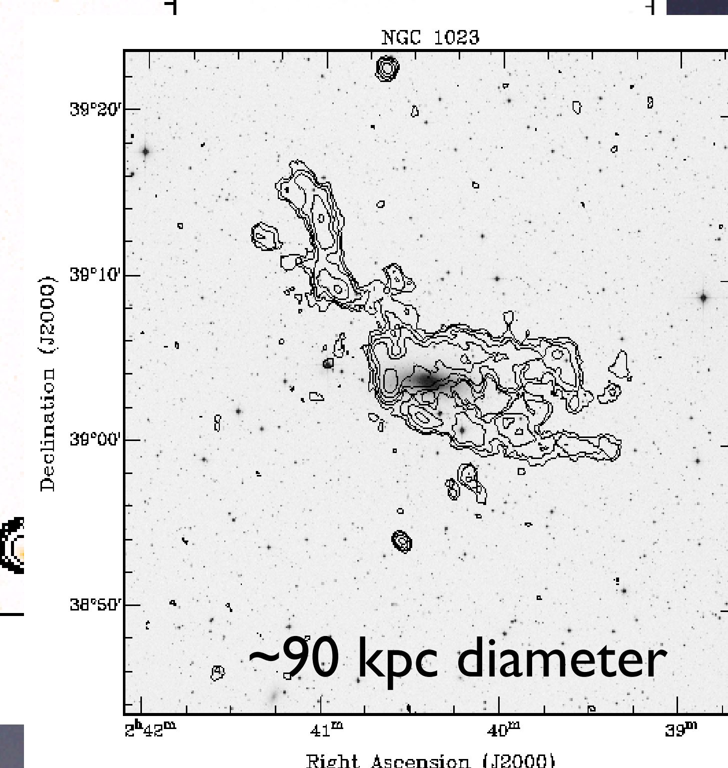




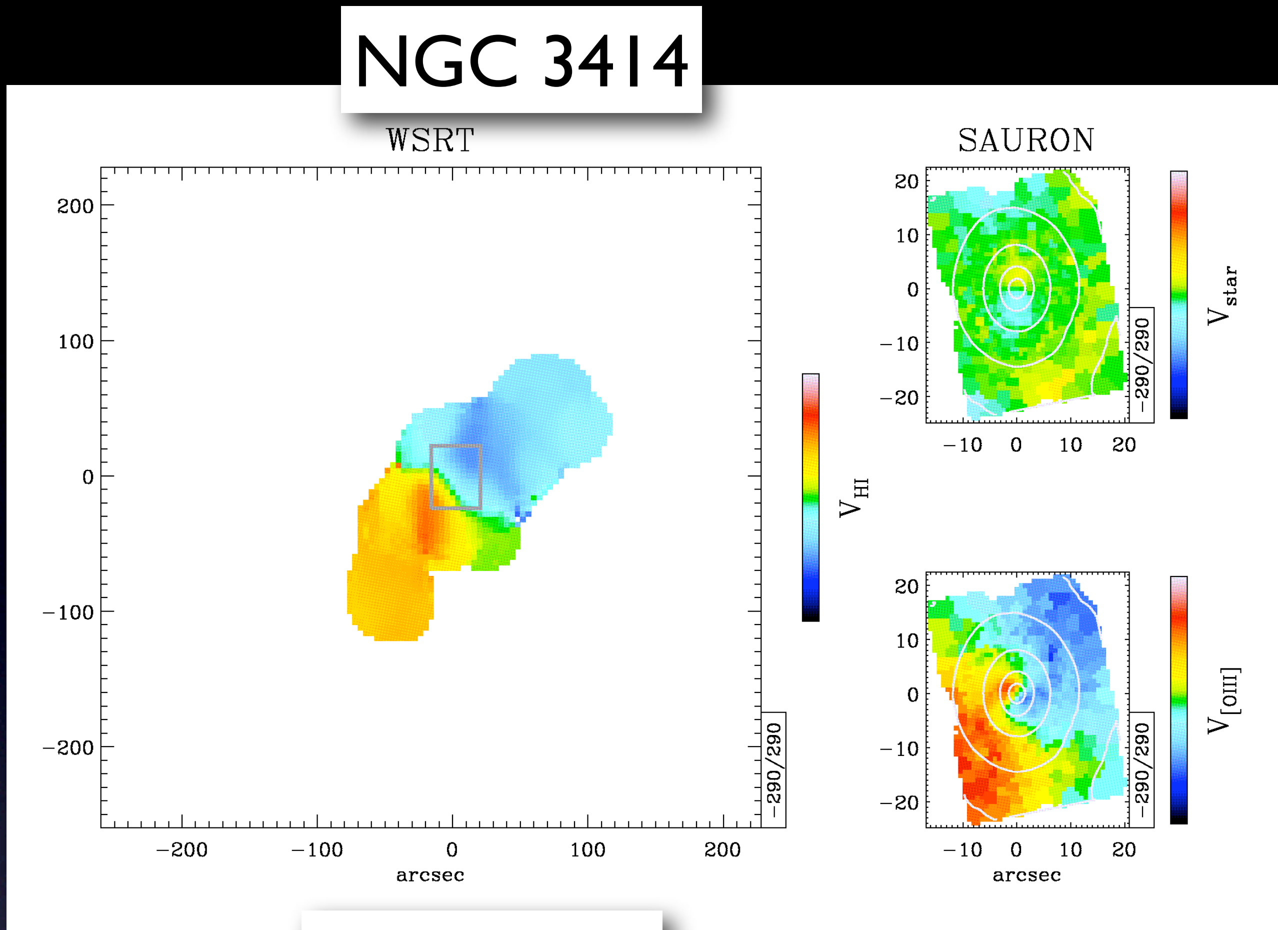
HI structures offset from the galaxy

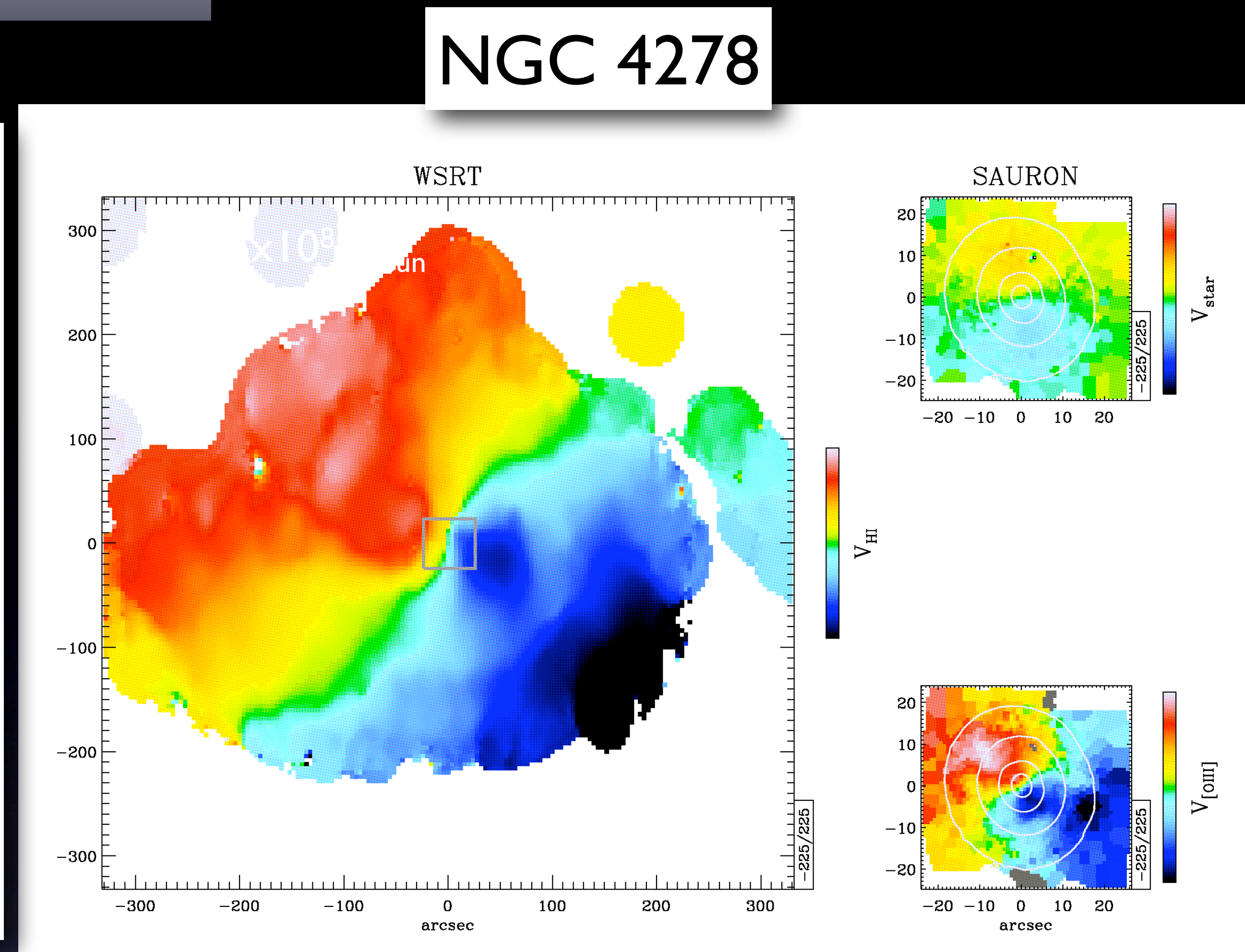


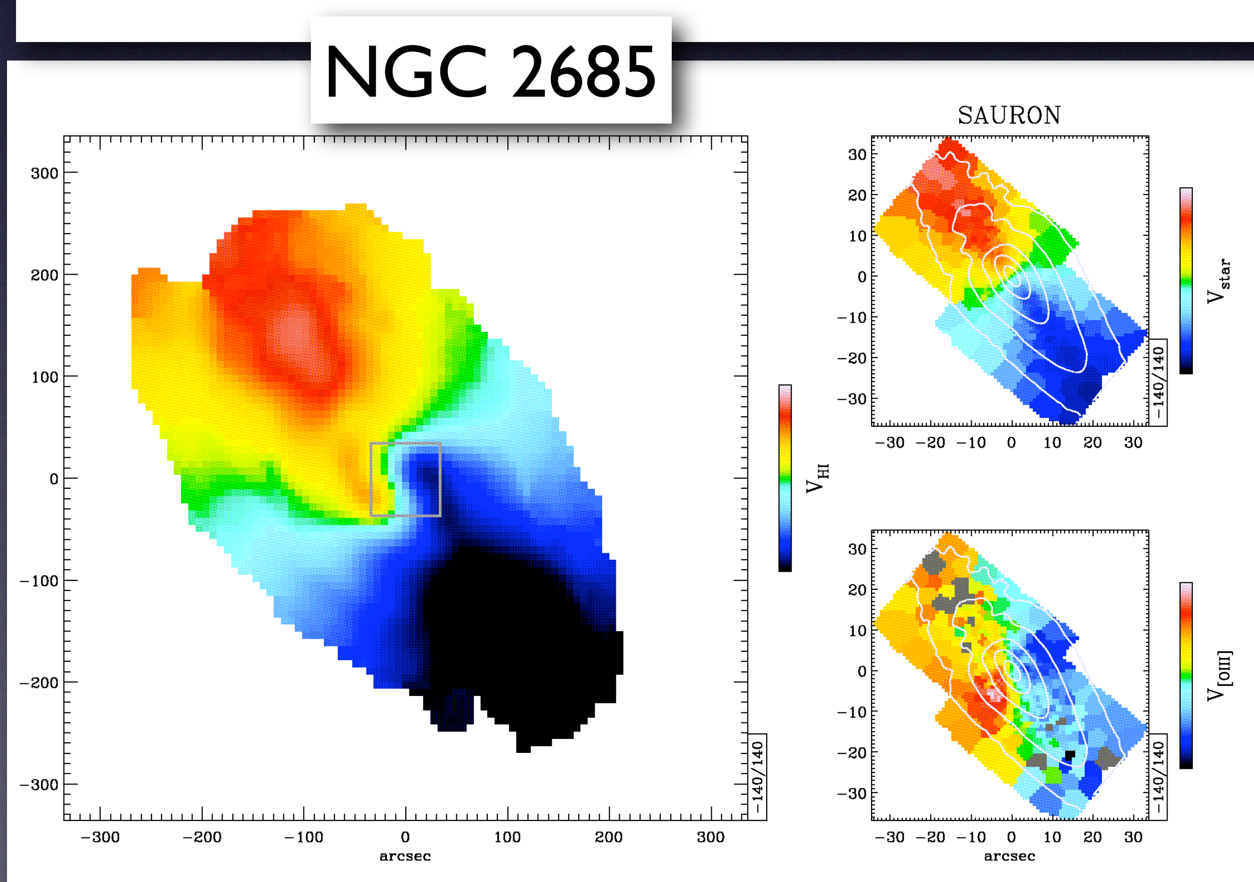


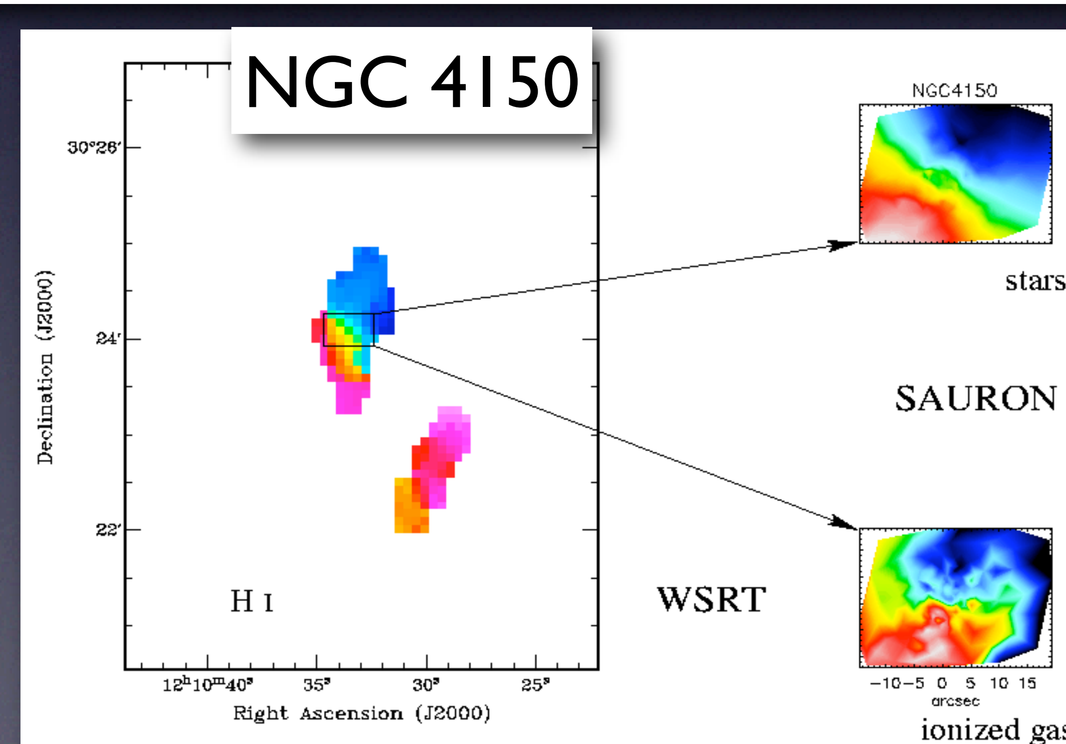


Kinematics of the gas and the stars









What did we learned.....

- At *deep levels*, many (most?) field early-type galaxies contain neutral gas. ***Gas also important for gas-poor galaxies***
- Not the case in dense environments
- The *tip of the HI distribution*:

  often in disks, sometimes ***very large disks*** ⇒ ***OLD***

- Low column density gas, very little star formation.

  ⇒ galaxies ***remain gas rich***

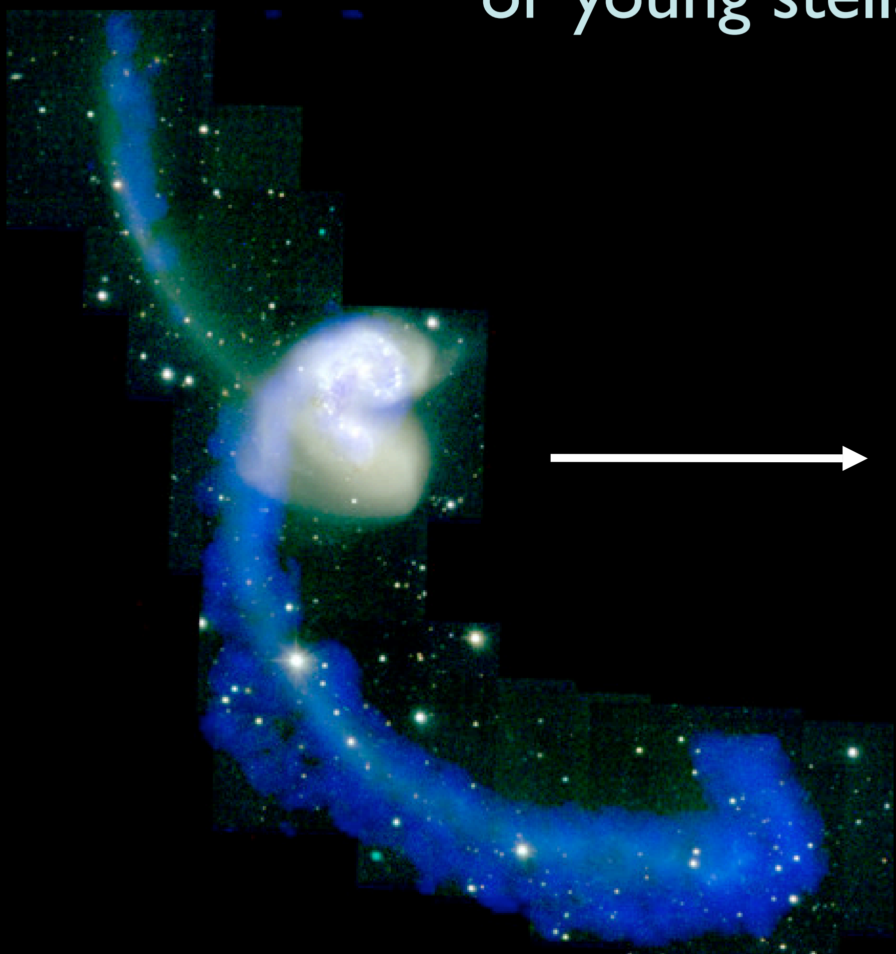
- H I disks and ionised gas disks are ***part of the same structure***
- No strong correlation of neutral gas content on large scales with dynamics nor stellar population. Every combination possible
- (Major) mergers in some cases, but not obvious in others.

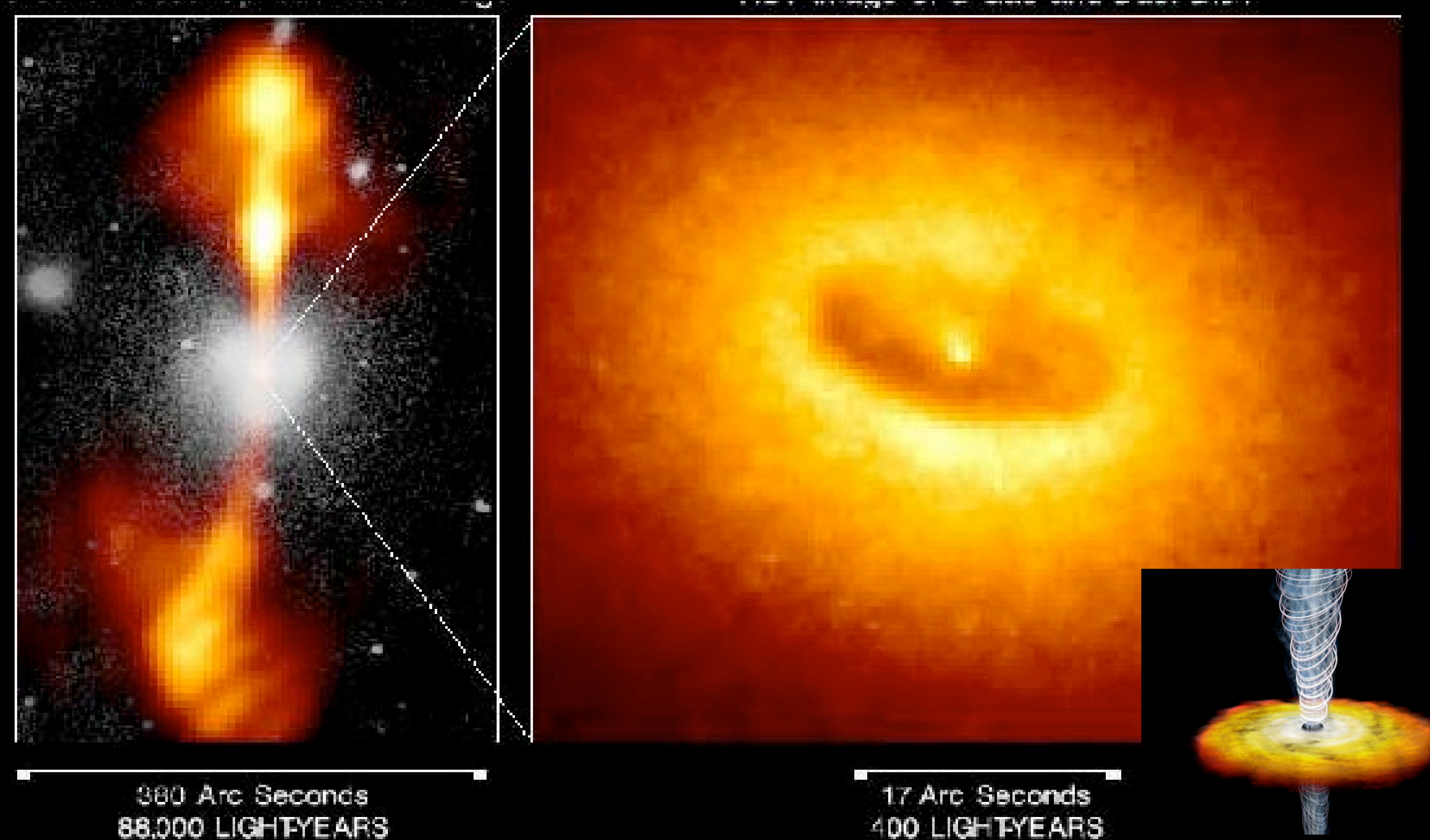
  Cold accretion?

  Internal origin?

Radio Galaxies

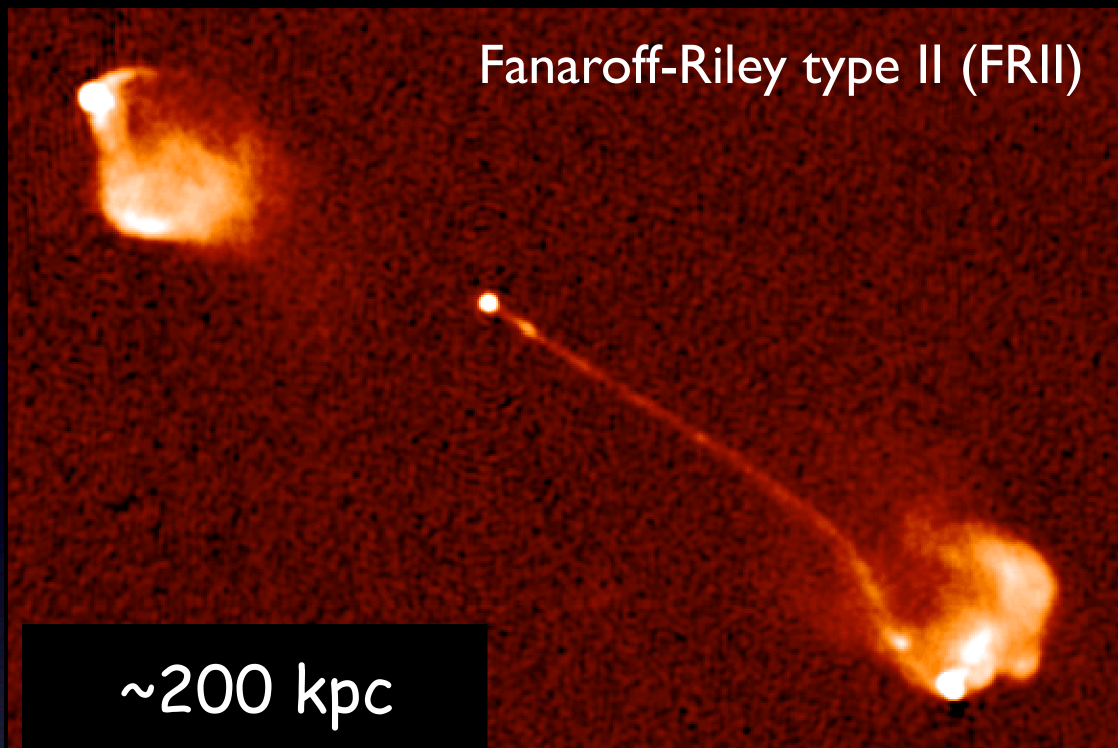
- Generally hosted by *early type* galaxies
- Many powerful radio galaxies show optical tails, shells, dust-lanes, etc. *(e.g. Smith & Heckman 1989, Heckman et al. 1986)* or young stellar populations *(e.g. Tadhunter et al. 2005, Holt et al. 2007)*



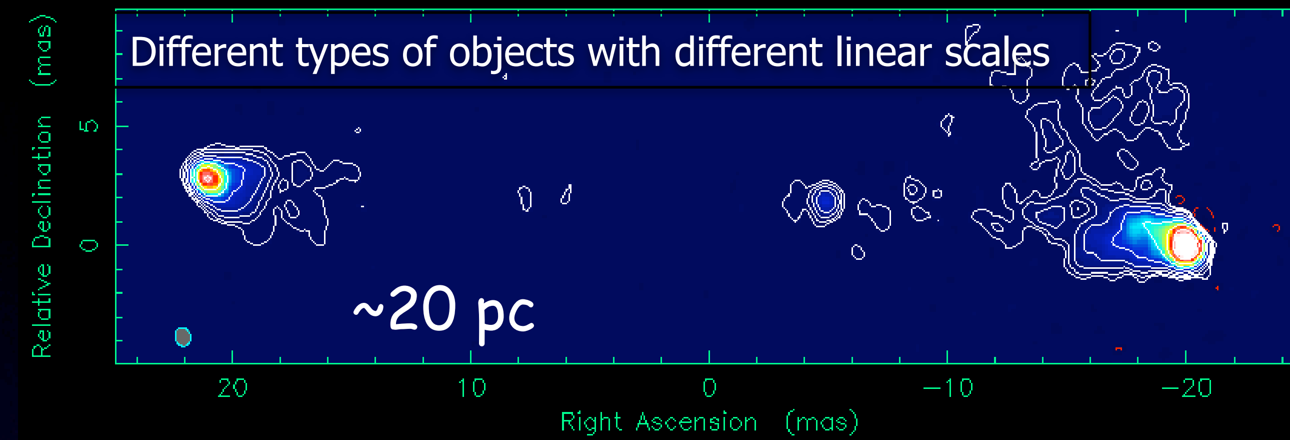


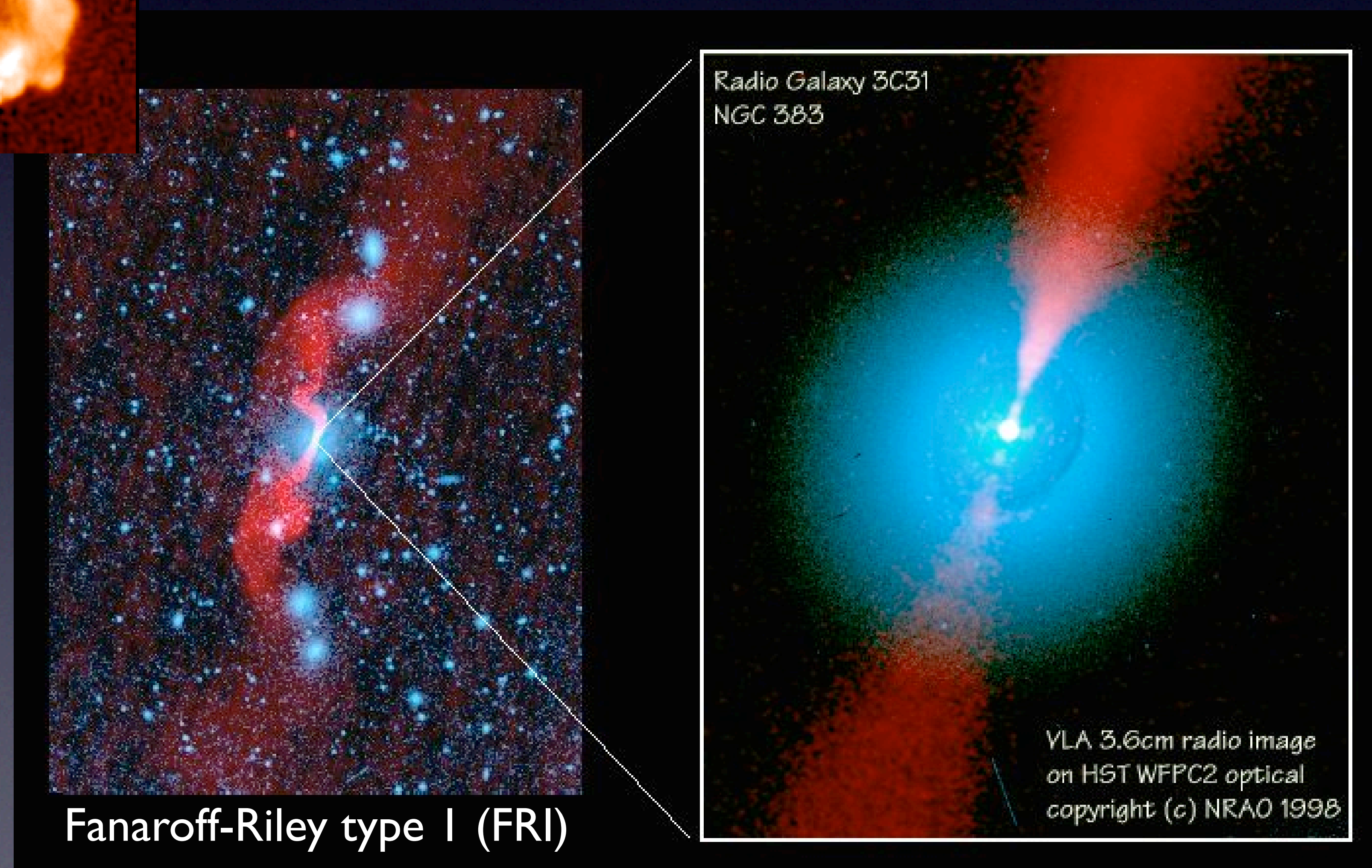
Mergers / interactions as trigger for AGN?
Do we see this in the neutral hydrogen?

HI in different type of radio galaxies



typical radio power > 10^{25} W/Hz
rare at low redshift: **problem for the HI**





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relatively common at low redshift

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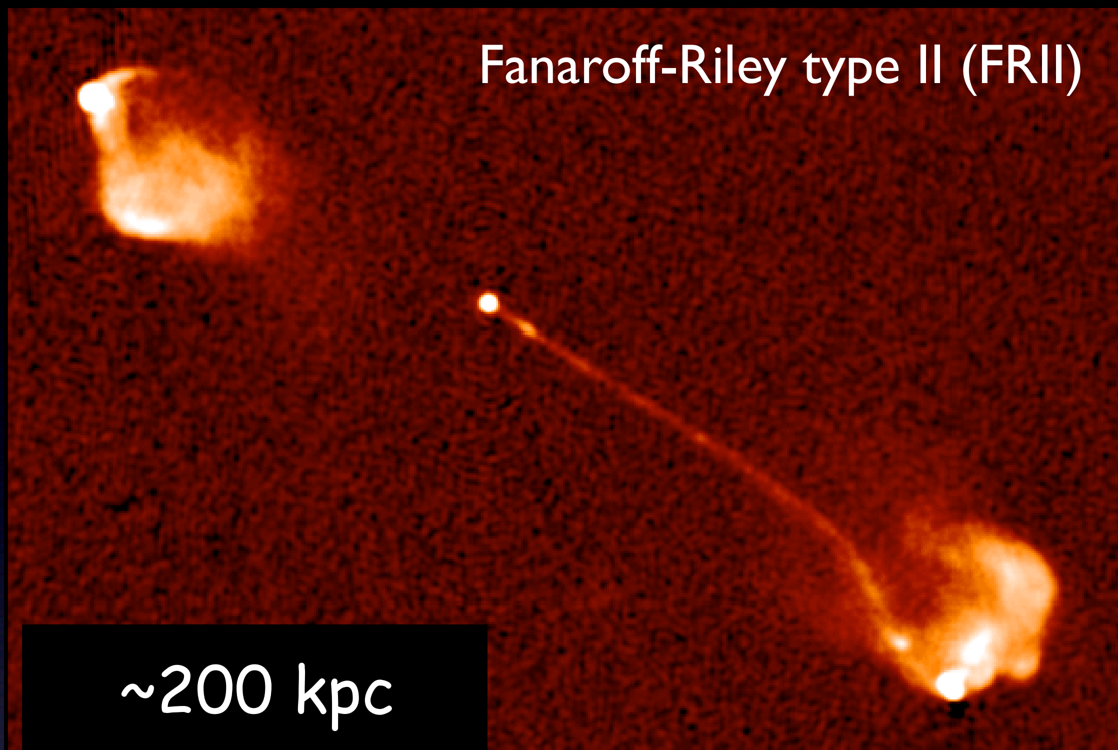

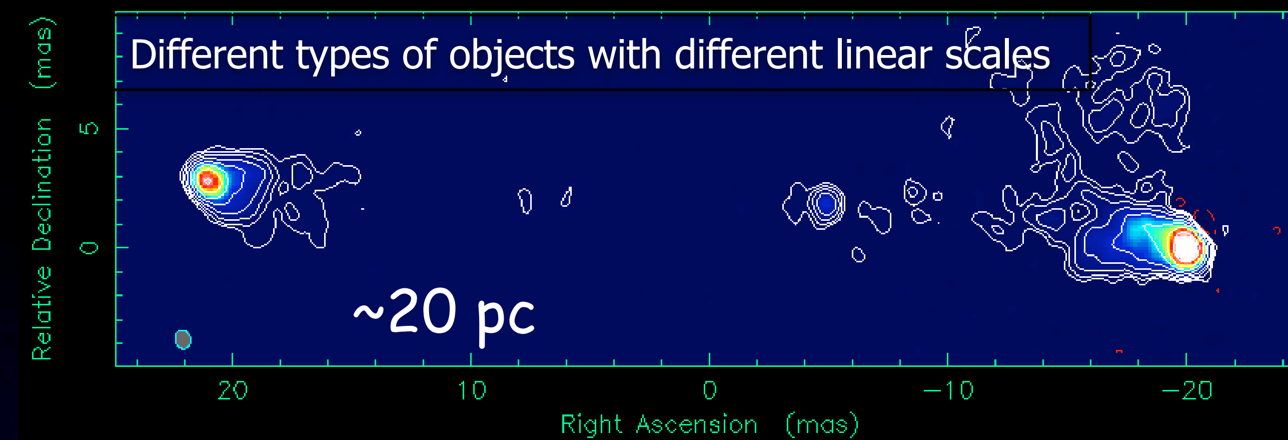

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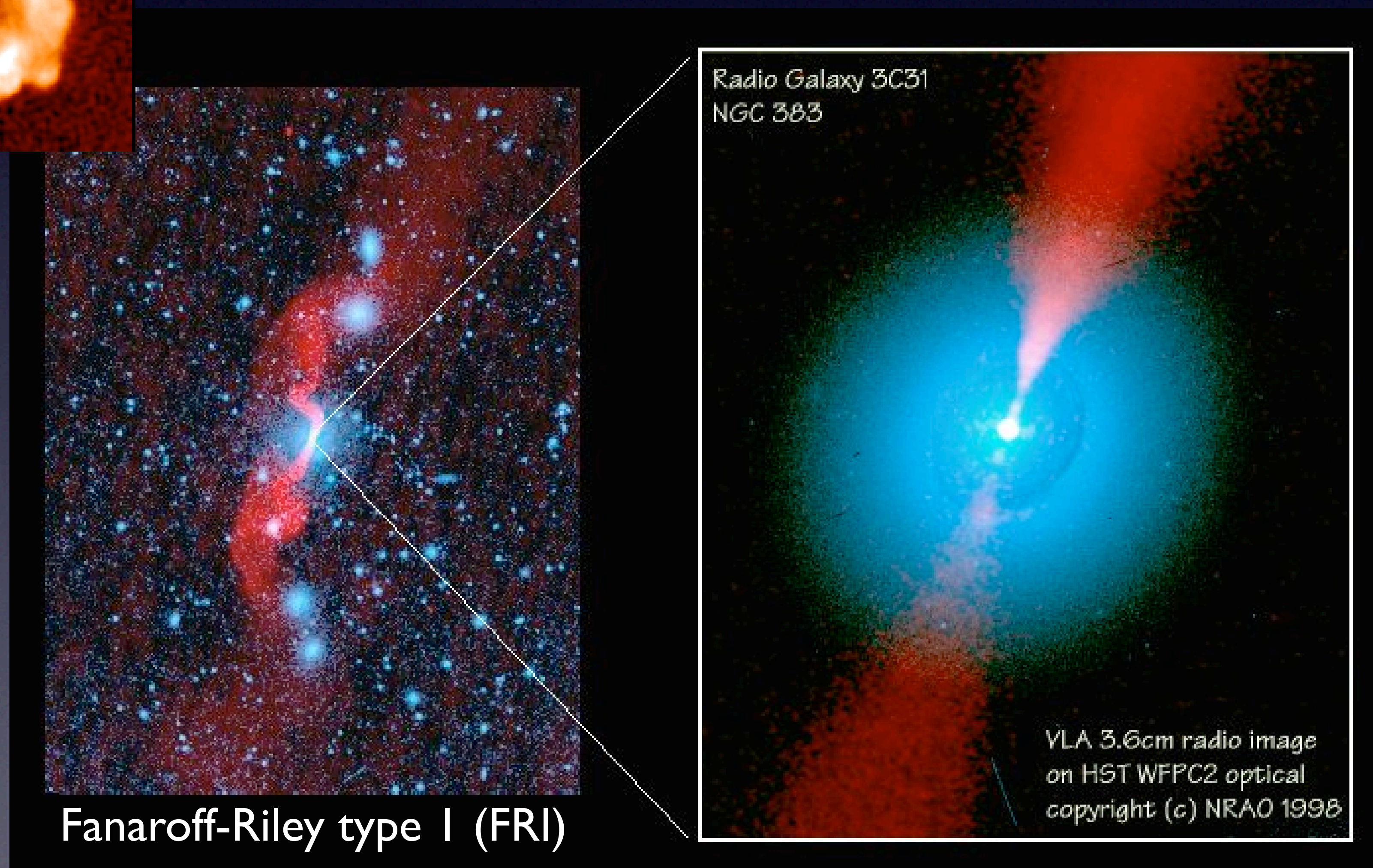
Different accretion mode between FRI and FRII sources?

High-luminosity (FRII) ➠ accretion disk, radiatively efficient

Low-luminosity (FRI) ➠ radiatively inefficient accretion flow (spherically symmetric Bondi accretion?)



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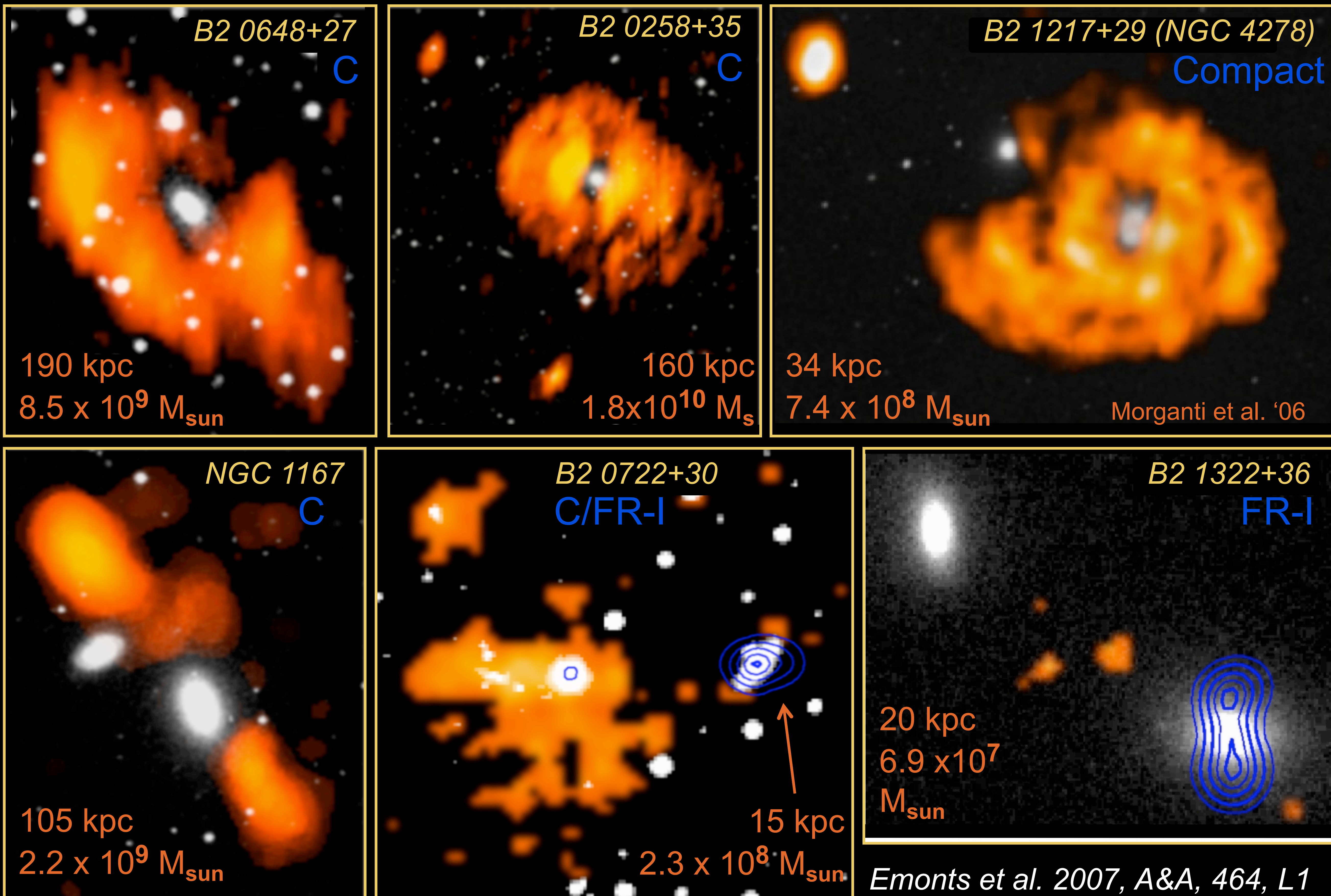
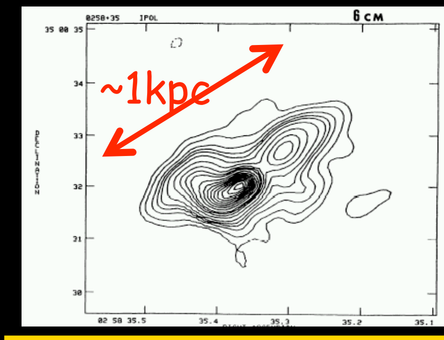
Low-luminosity radio galaxies

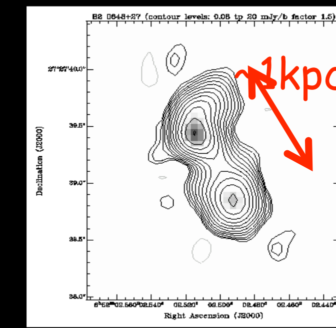


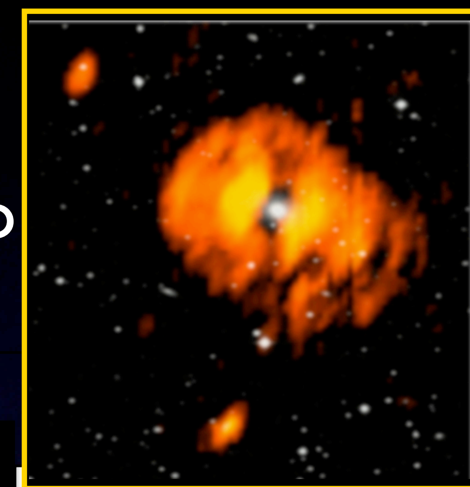
Emonts et al. 2007, A&A, 464, L1

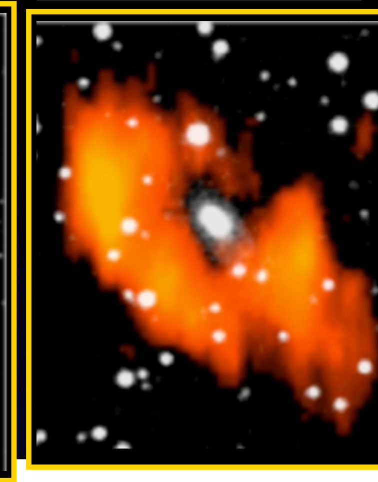
Remarkable trend:

radio galaxies with large amounts ($M_{HI} > 10^9$ M_{sun}) of extended (many tens of kpc up to 200 kpc!) HI disks all have a **compact** radio source

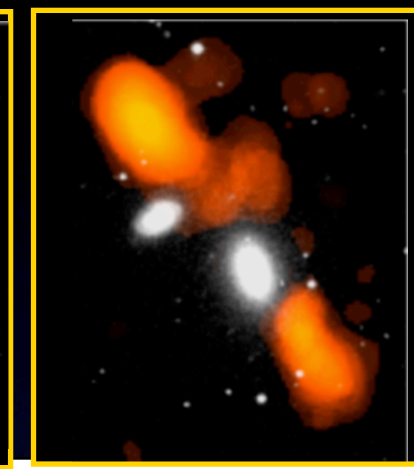


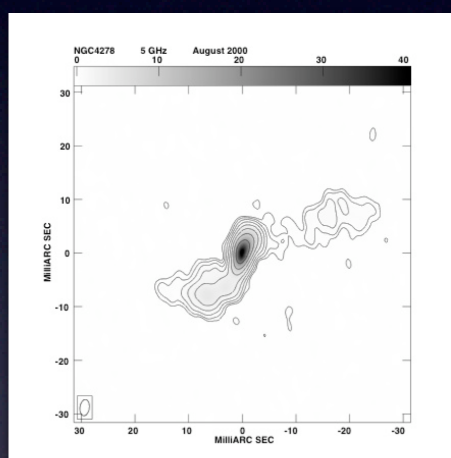




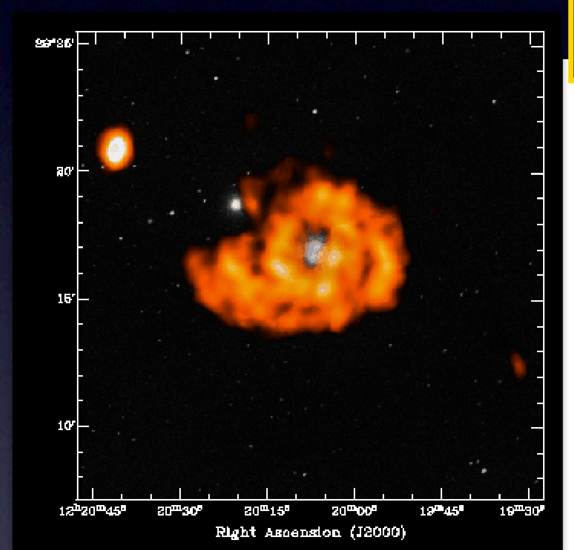


NGC 3894

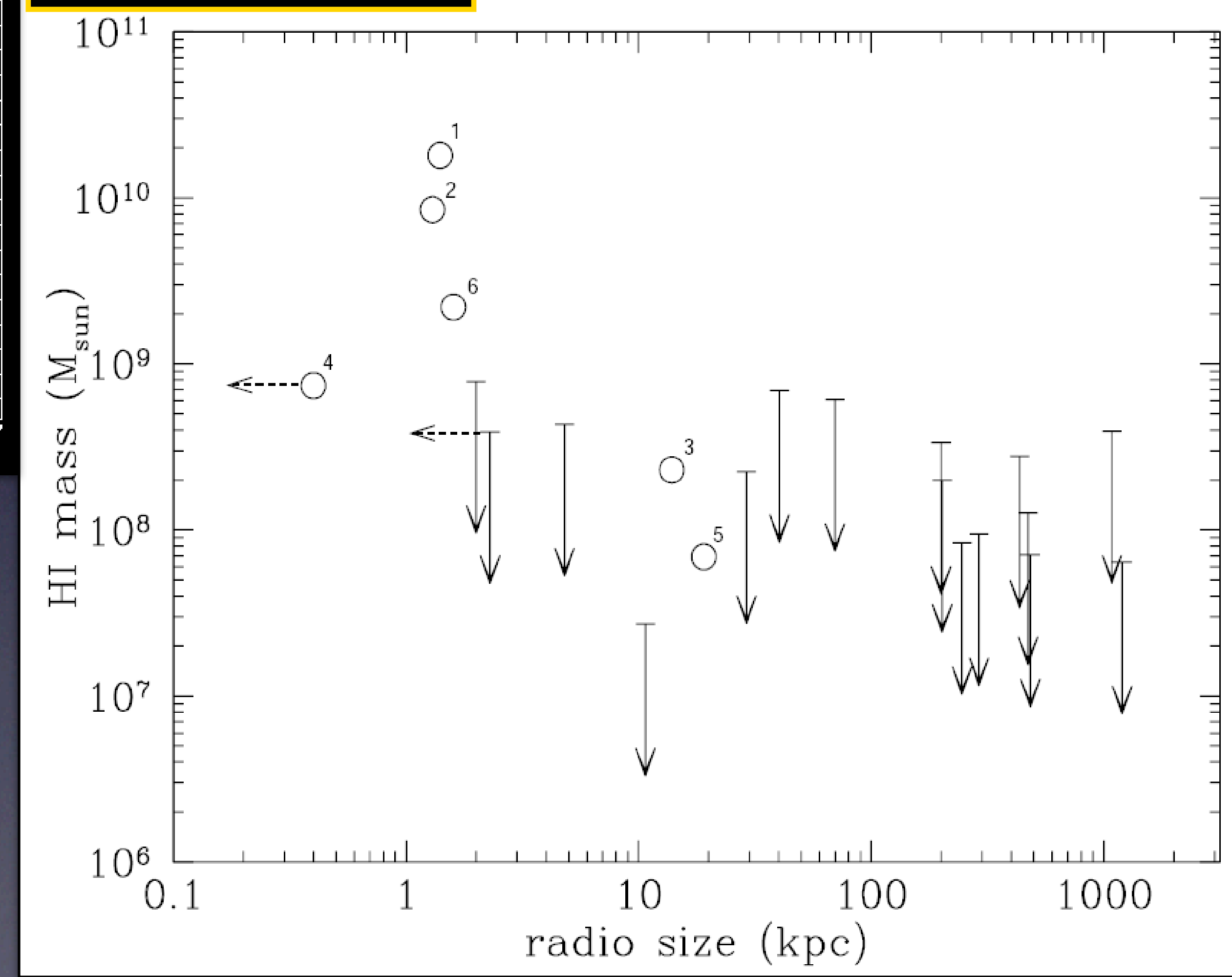




Giroletti et al. 2004



Morganti et al. 2006



Emonts et al. 2006, astro-ph/0701438

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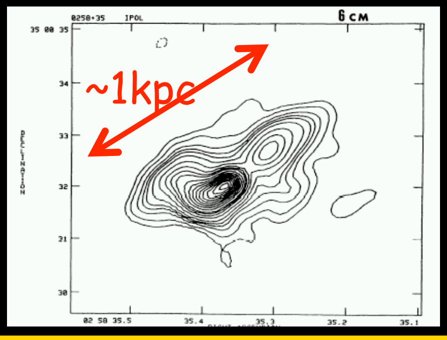
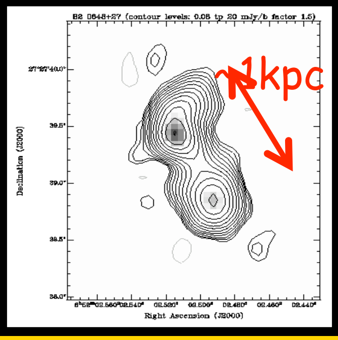
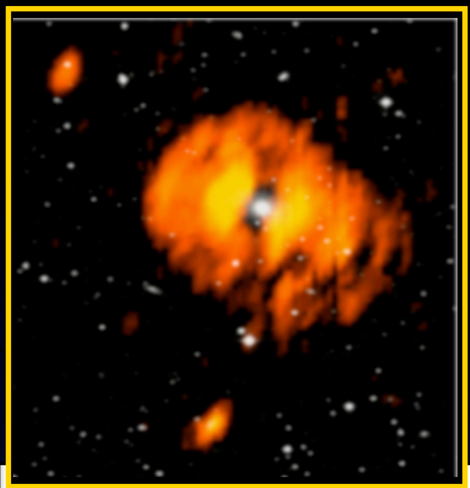
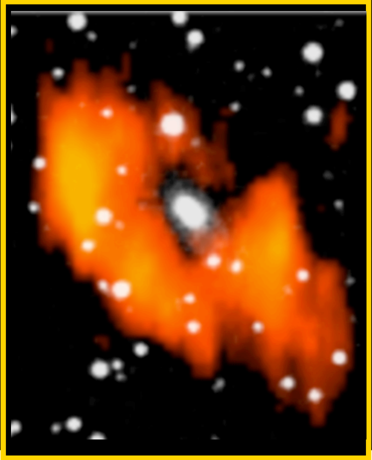
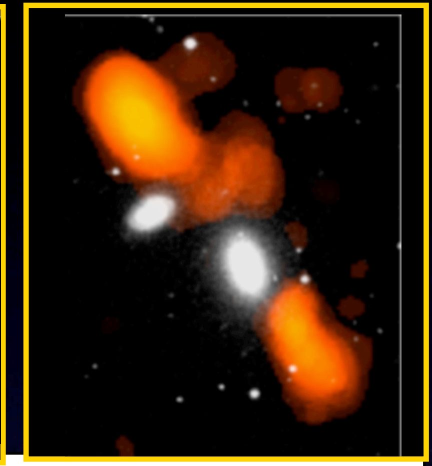


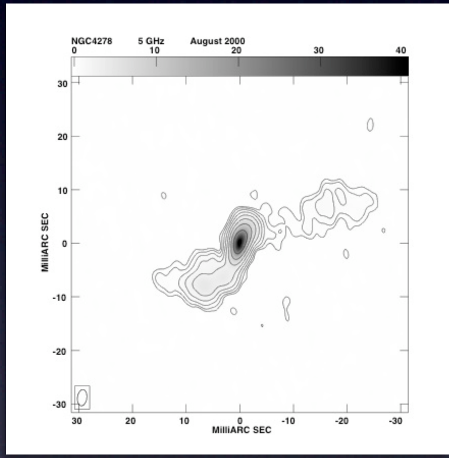




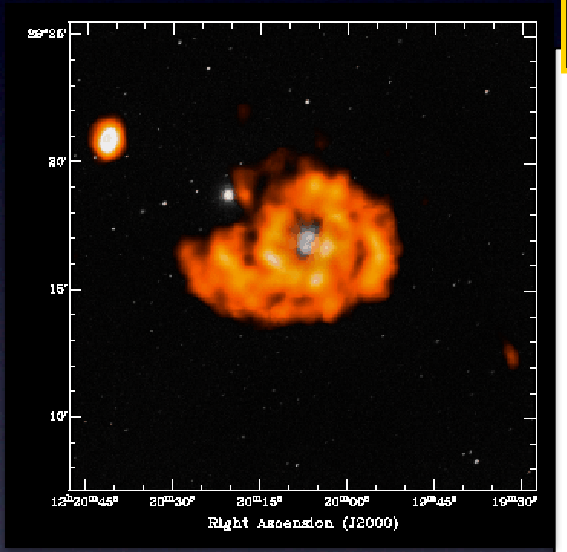


NGC 3894

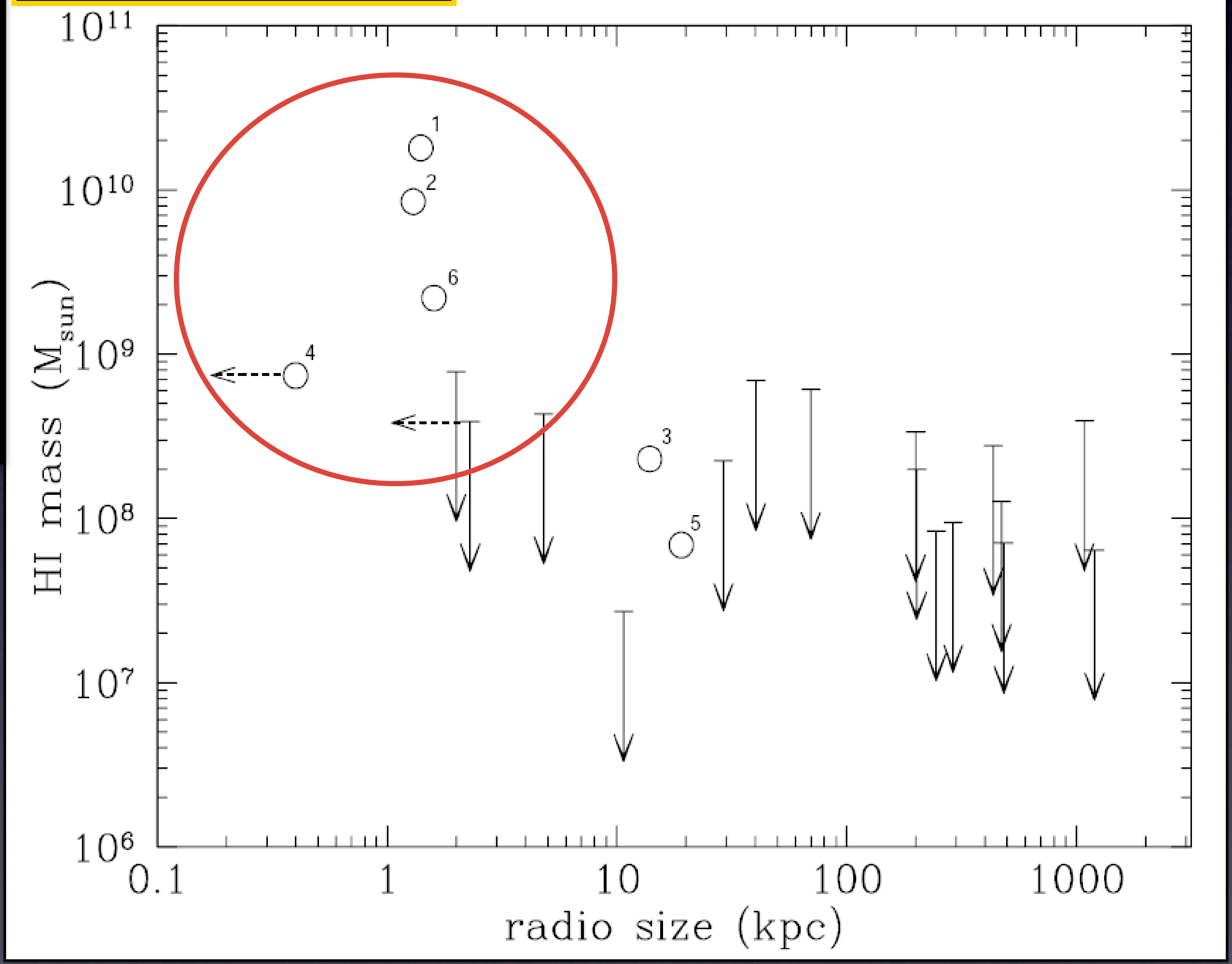




Giroletti et al. 2004



Morganti et al. 2006

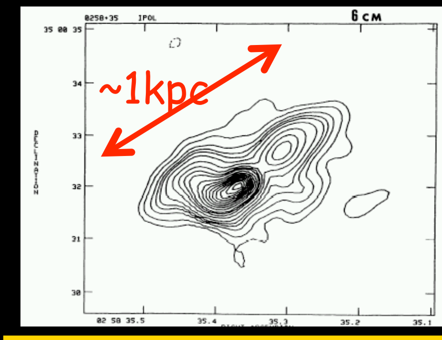


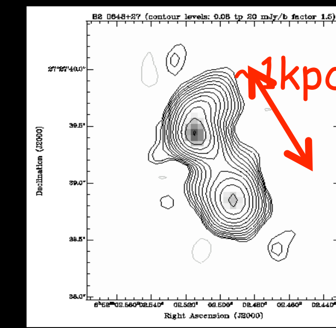
Emonts et al. 2006, astro-ph/0701438

ASTRON

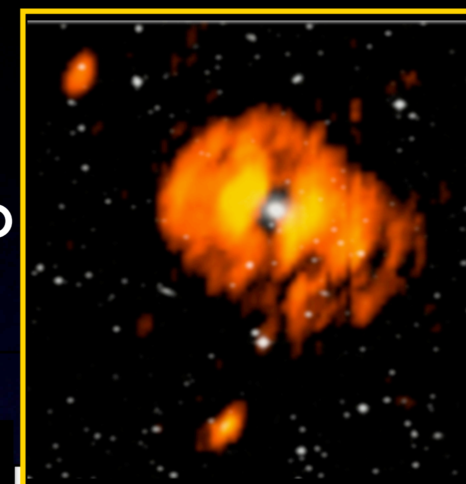
Remarkable trend:

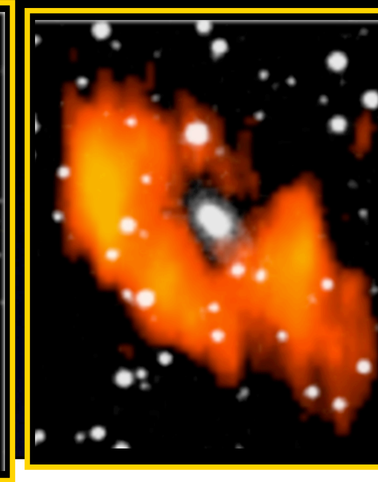
radio galaxies with large amounts ($M_{HI} > 10^9$ M_{sun}) of extended (many tens of kpc up to 200 kpc!) HI disks all have a **compact** radio source

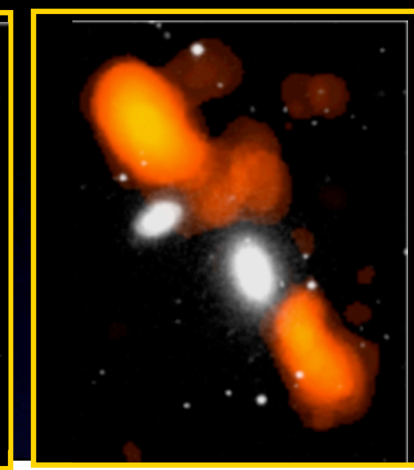


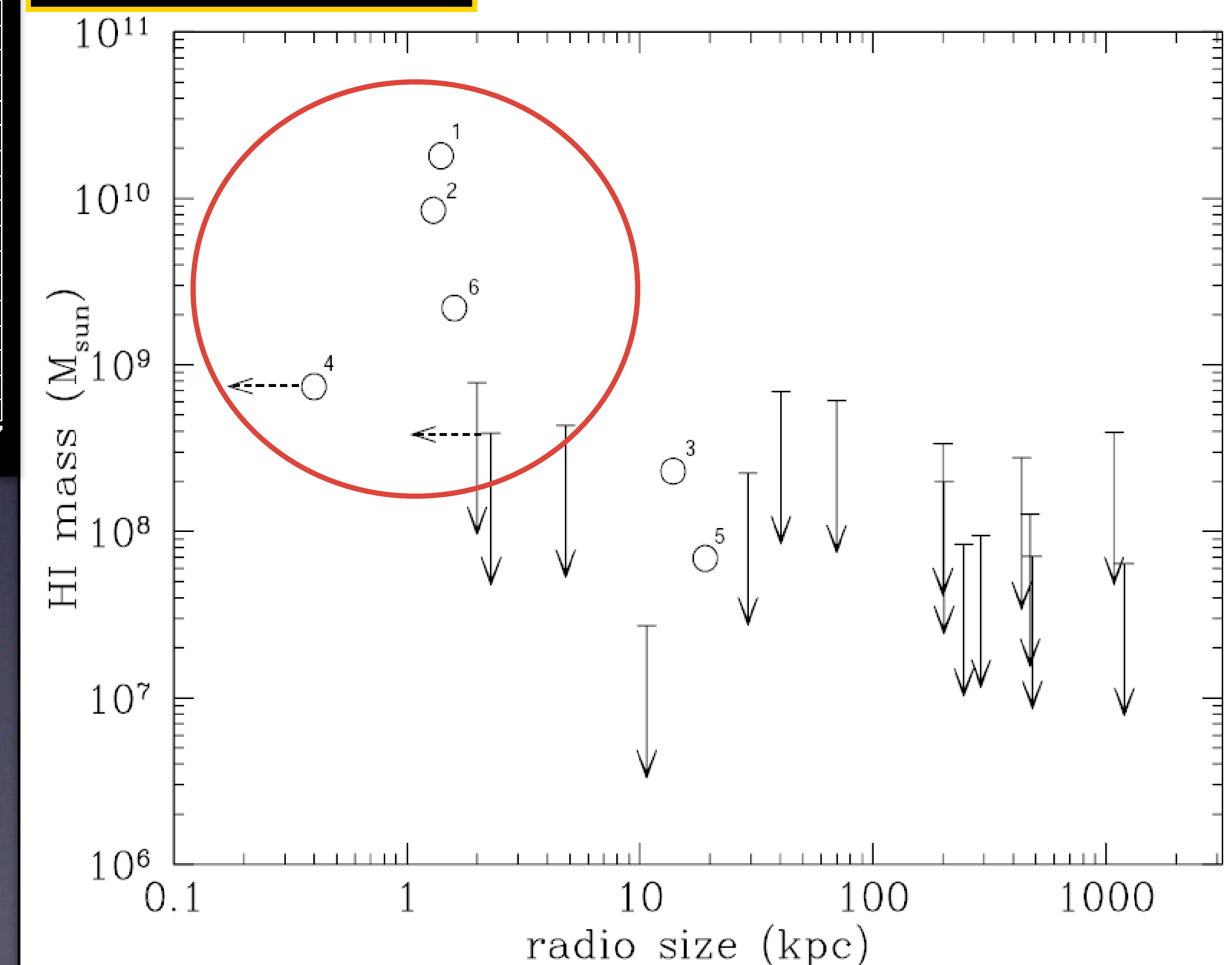


NGC 3894









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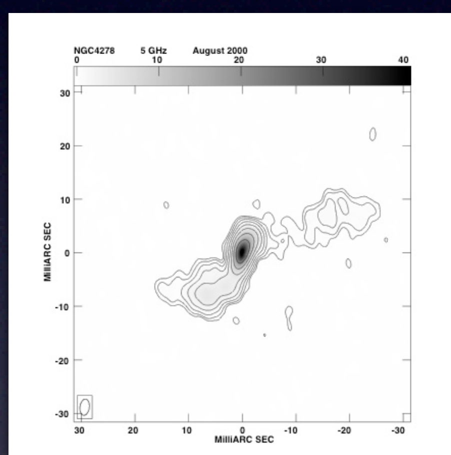
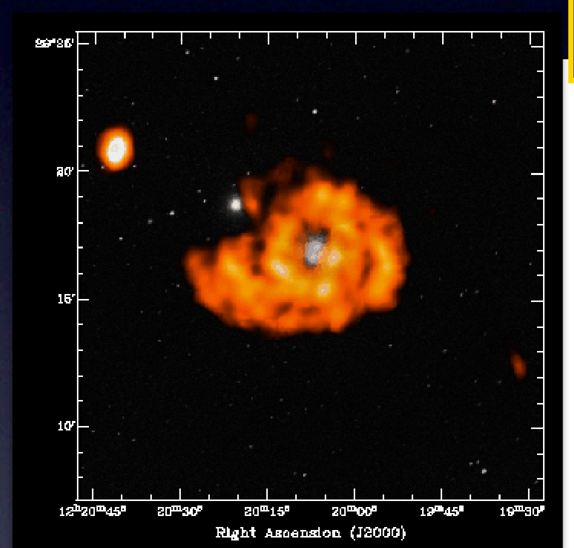


Giroletti et al. 2004



Morganti et al. 2006

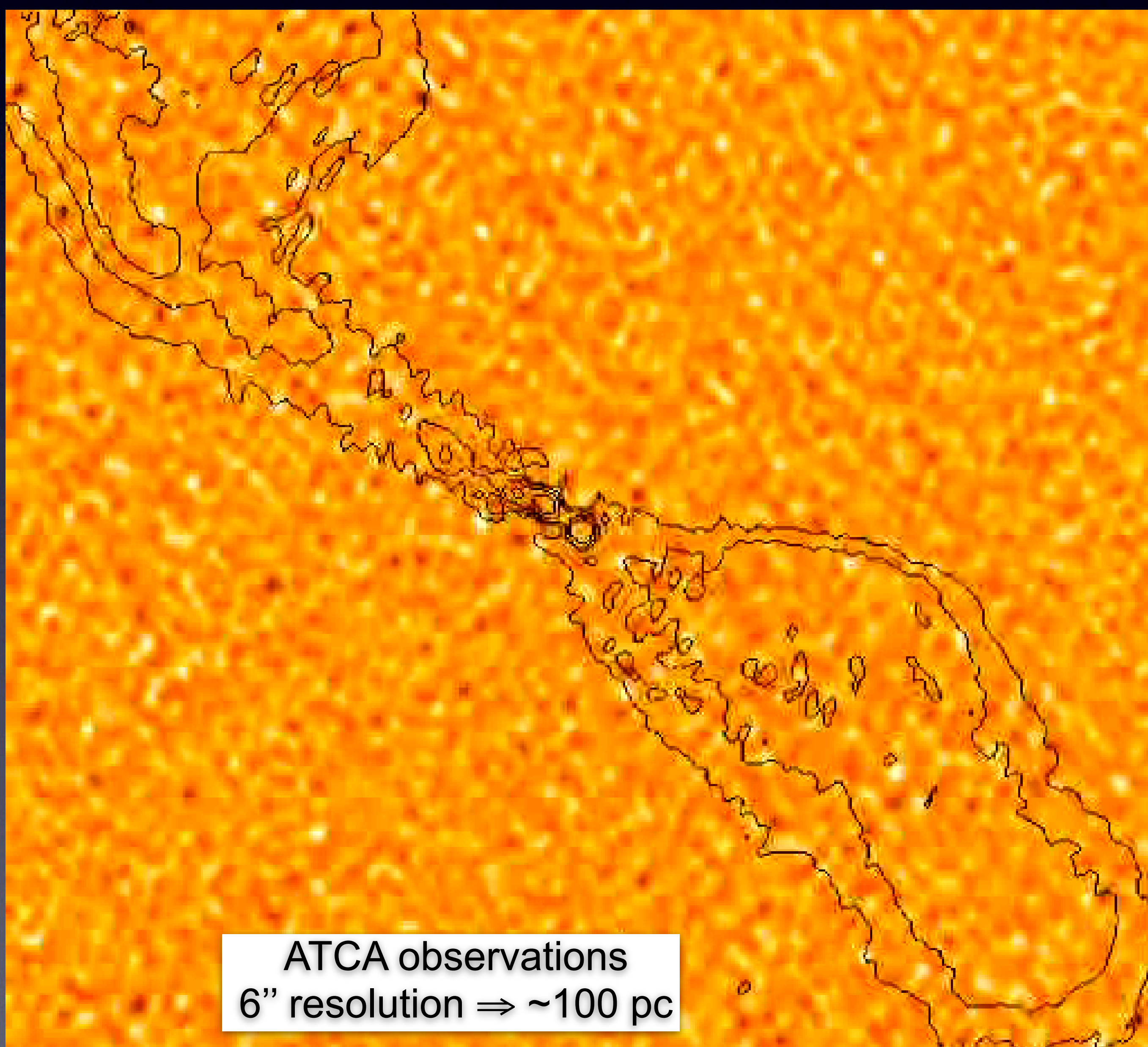
- HI-rich compact radio sources do not grow into extended sources

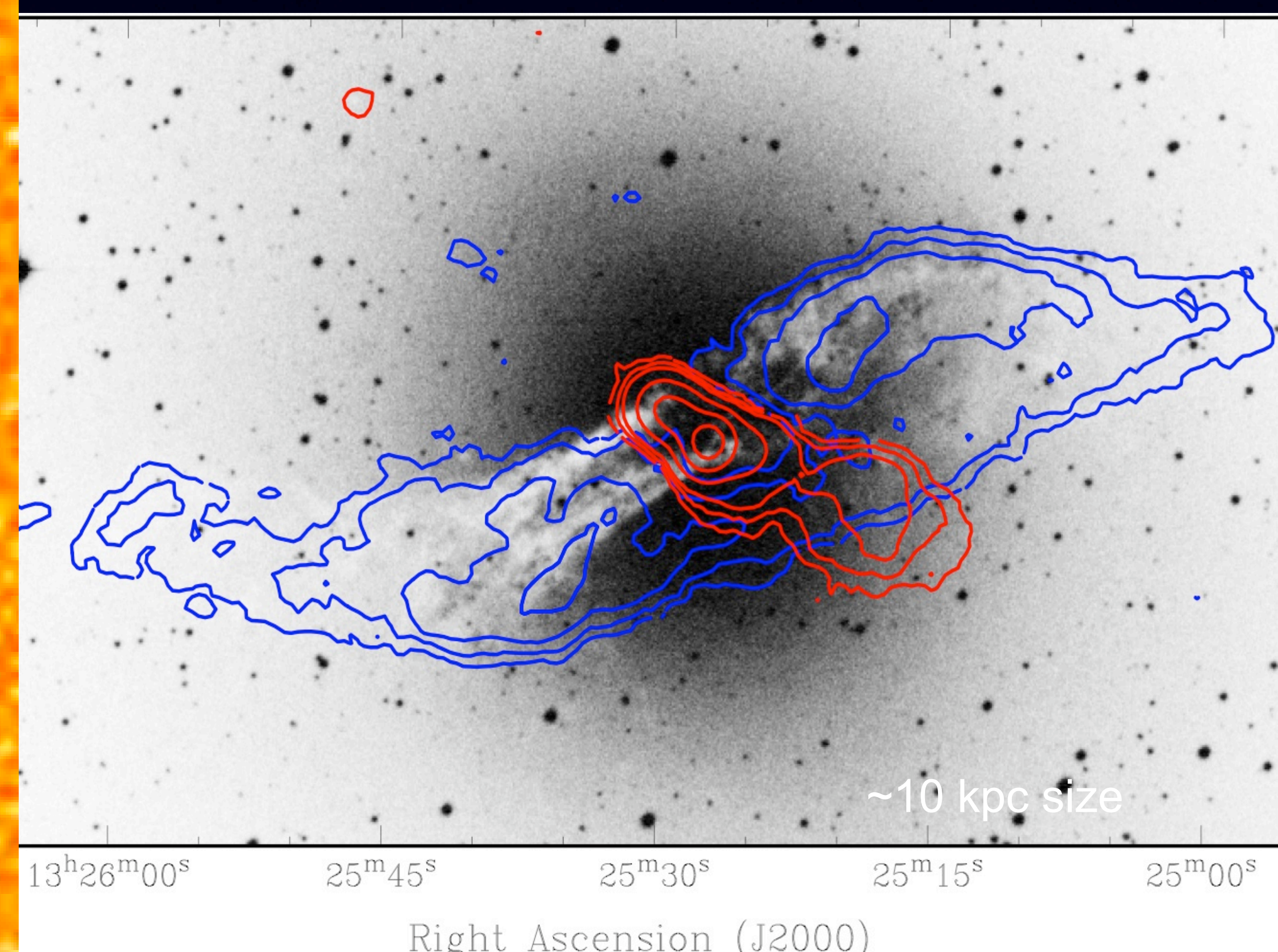
either because "frustrated" by the ISM in the central region of the galaxy or because the fuel stops before the source expands

- FRI sources not originating via major mergers but via accretion of hot or cold gas

Case of Centaurus A

HI emission and absorption

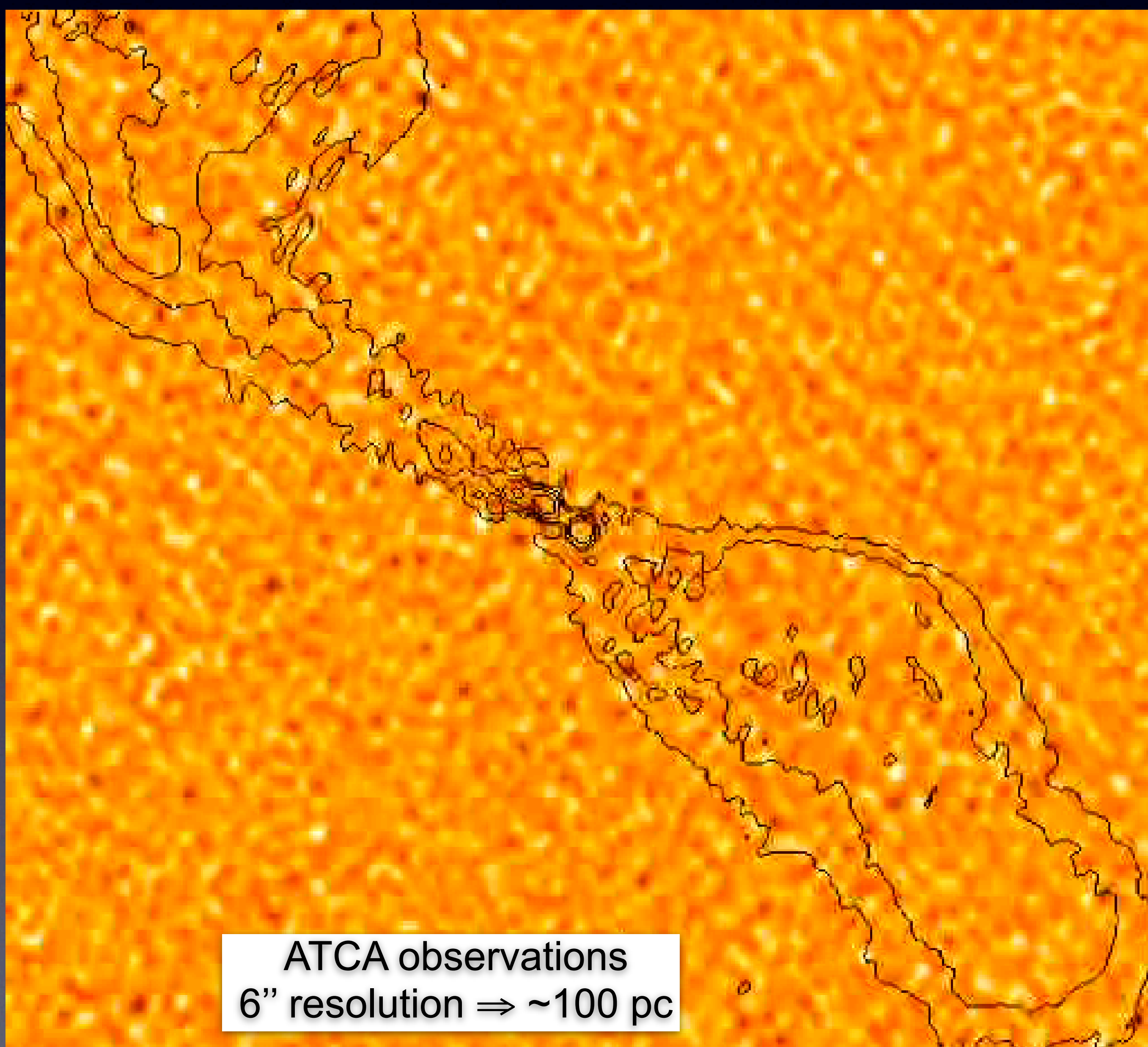


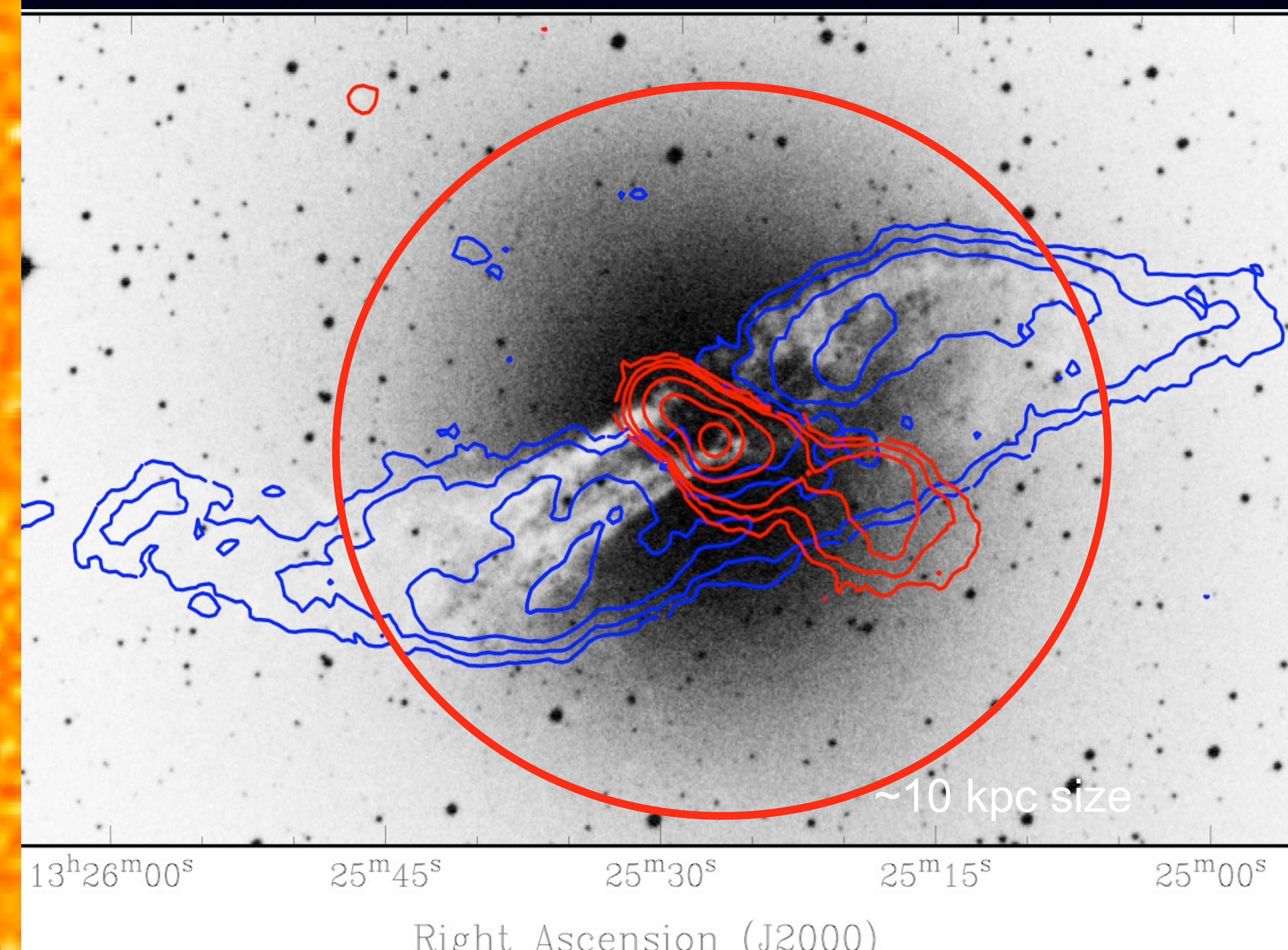


C. Struve PhD project (RuG)

Case of Centaurus A

HI emission and absorption

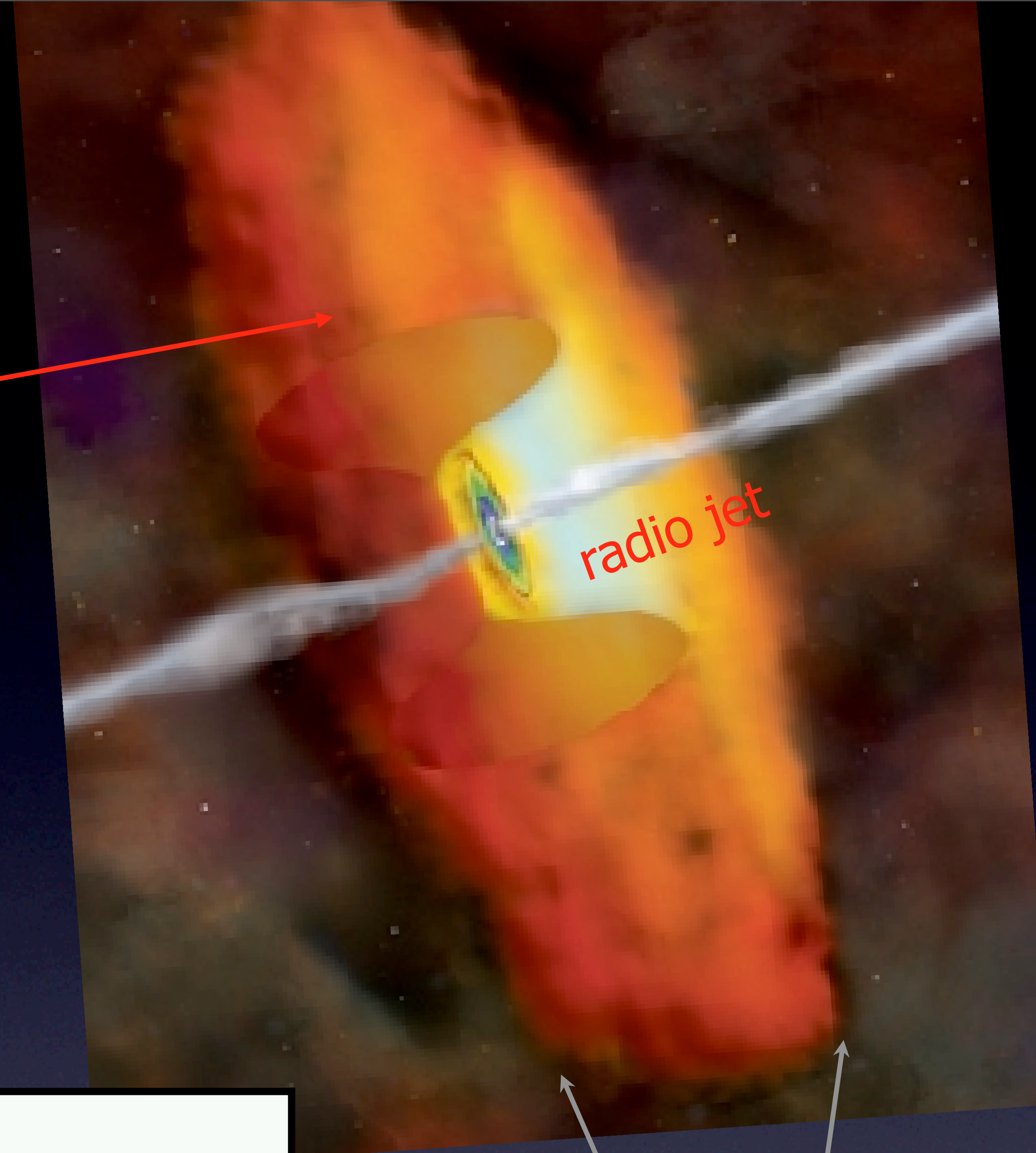


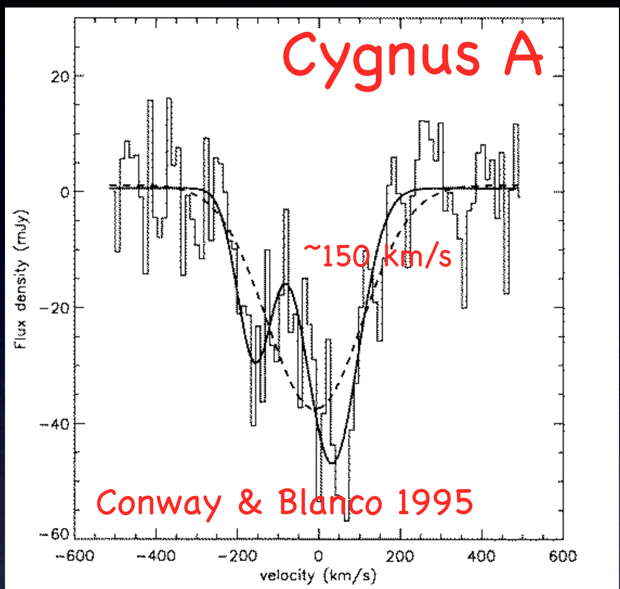


C. Struve PhD project (RuG)

The nuclear regions probed by the HI

HI absorption from the torus or from circumnuclear disks





The case of Cygnus A

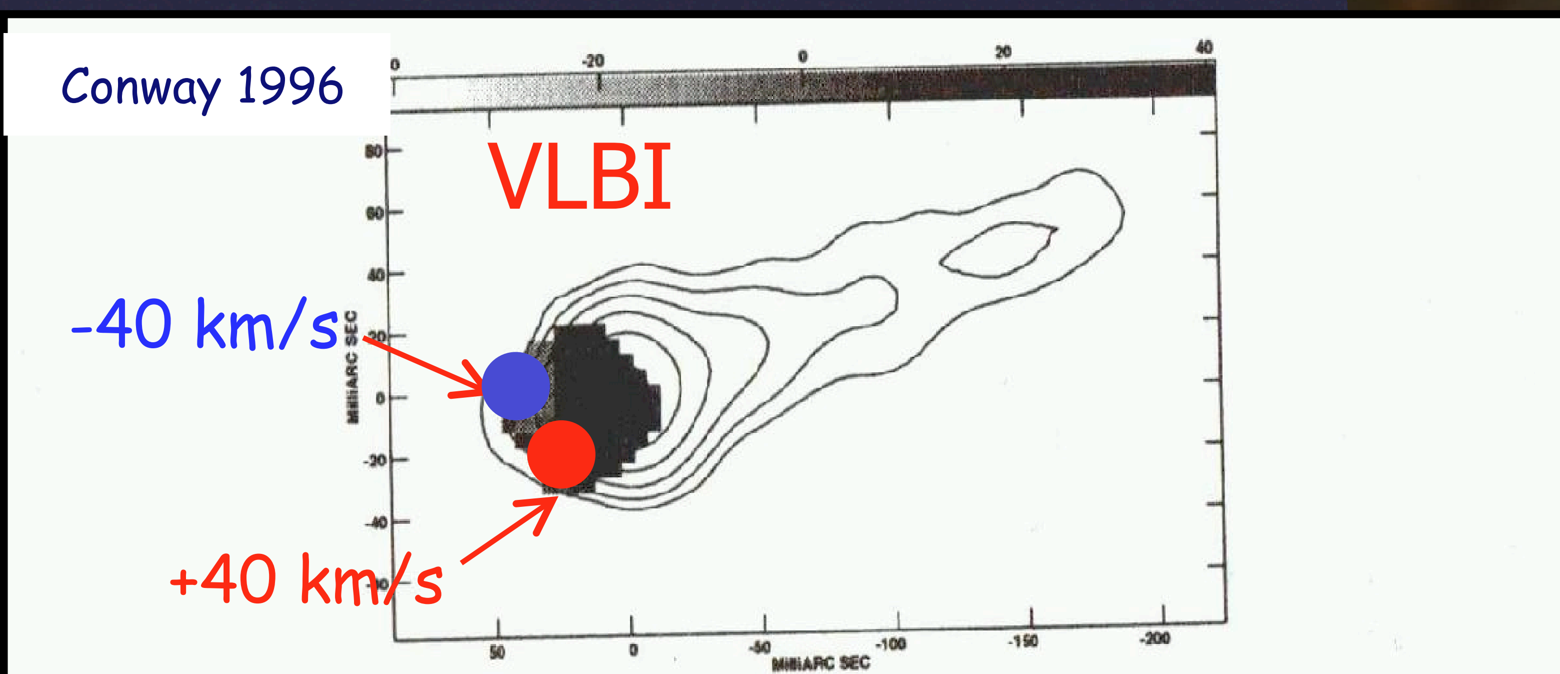
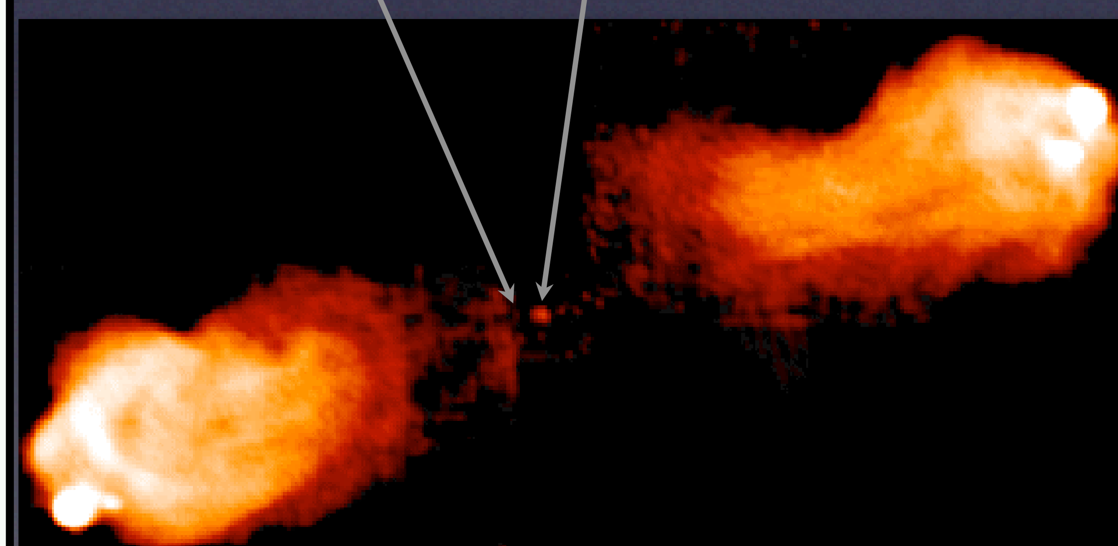


Figure 2. Greyscale shows centroid of absorption velocity, white is −40km/s and black is +40km/s from the mean HI absorption velocity



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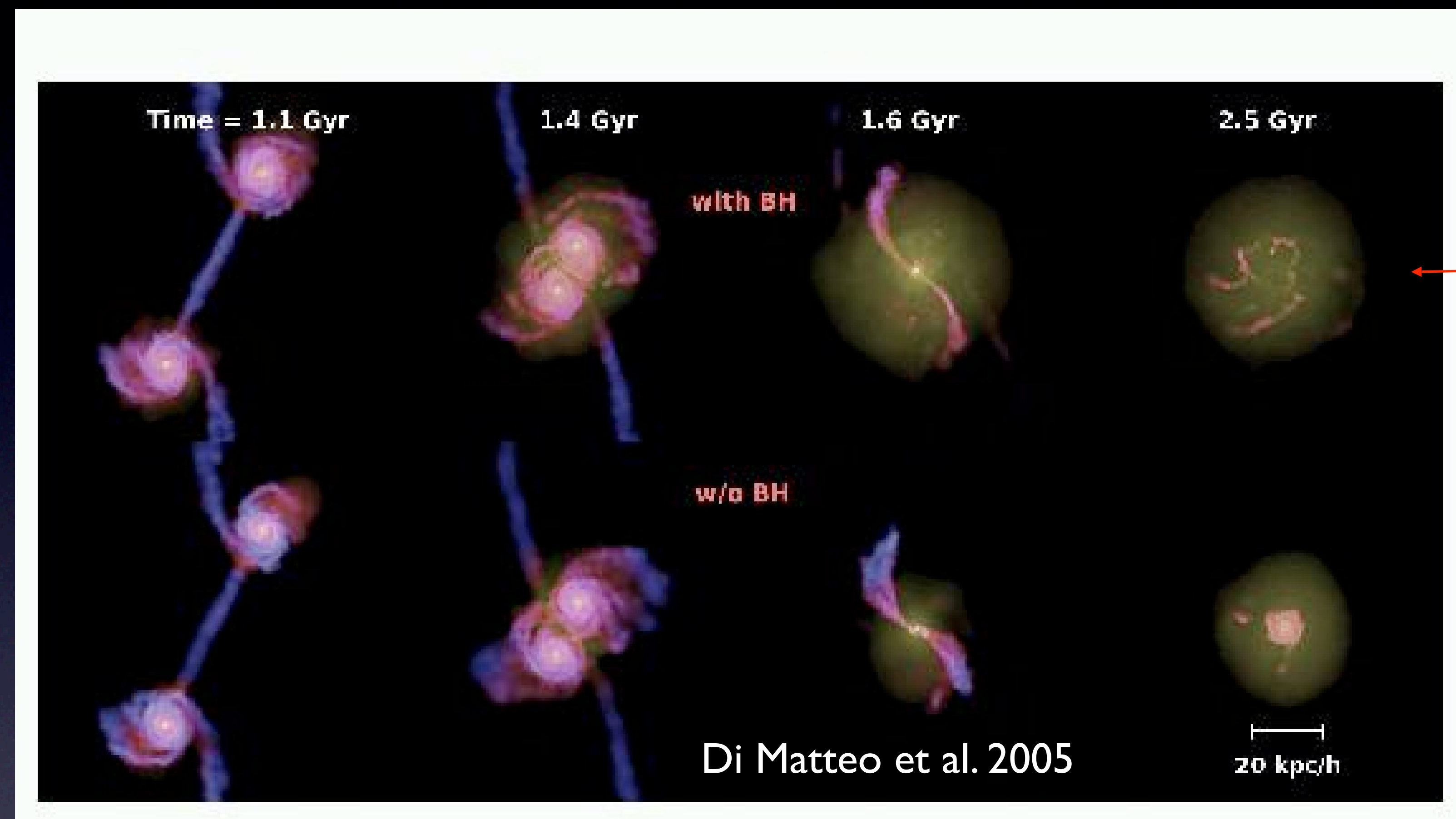
The impact of the active nucleus

- Effect of nuclear activity on the ISM
- Mass outflows (from starburst - and AGN-driven) are important in evolution of galaxies and growth of super-massive black-holes

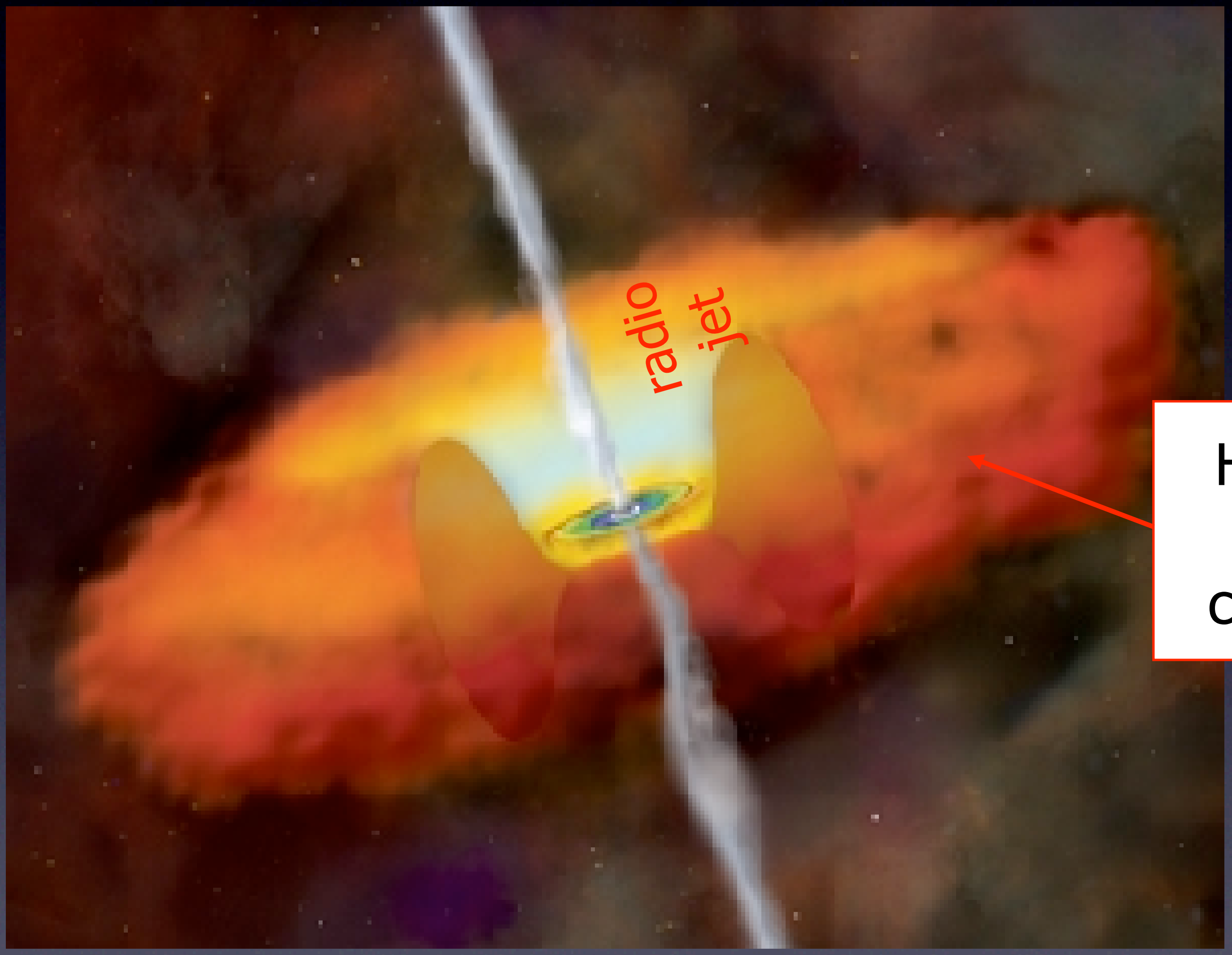


- Important for the evolution
  → inhibit starformation

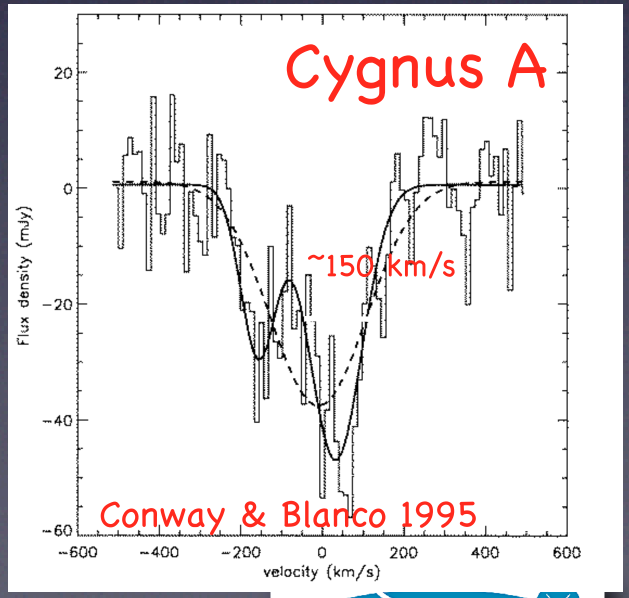
  → correlation BH-host

Starformation with and w/o central Black-Hole
Simulation with BH: after the final coalesce of the galaxies, a strong wind driven by feedback energy from the accretion expels much of the gas from the inner regions
→ gas poor remnant
Starformation suppressed by the presence of an active BH (di Matteo et al. 2005, Springel et al. 2005)

The nuclear regions probed by the gas

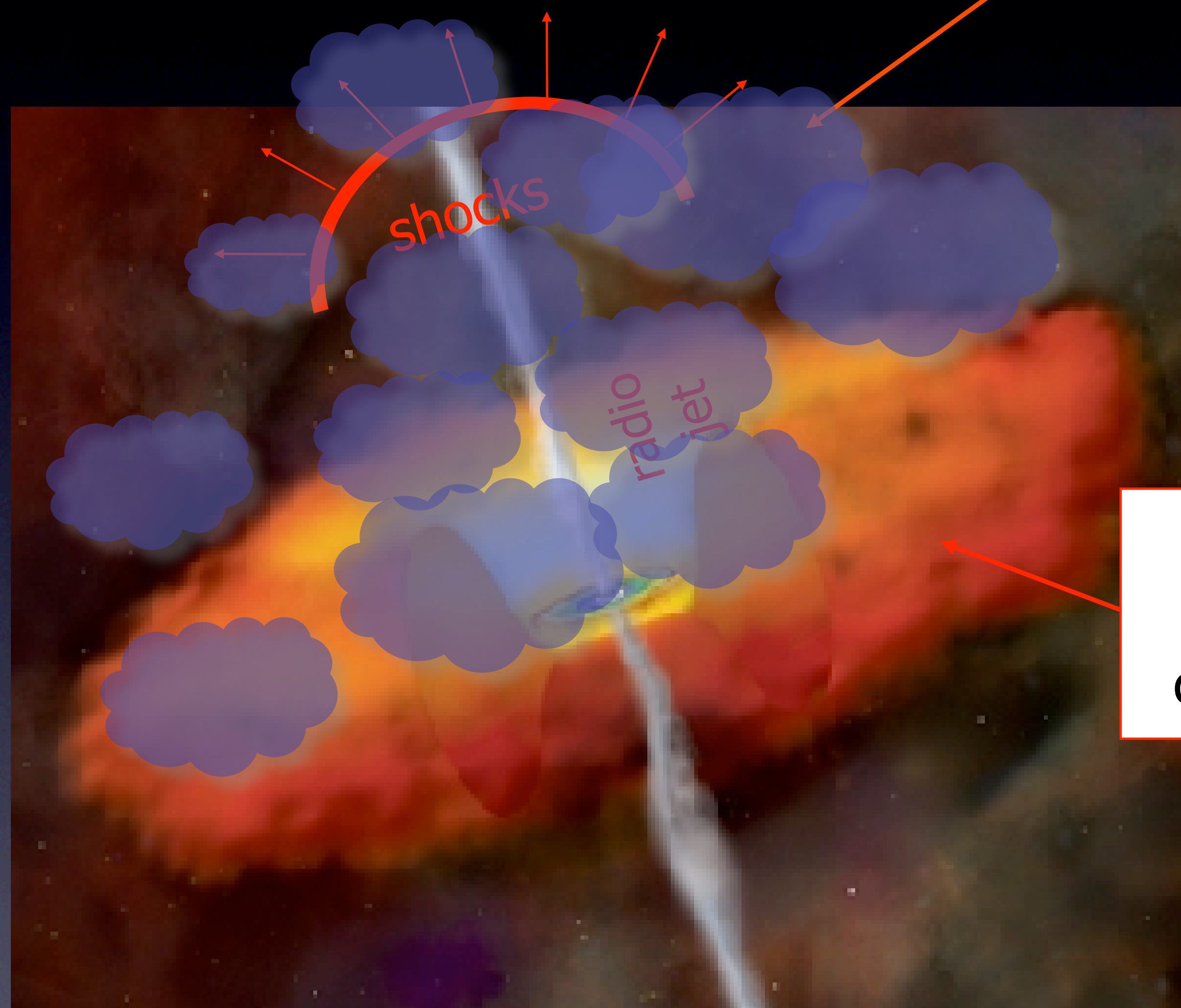


HI absorption from the torus or from circumnuclear disks

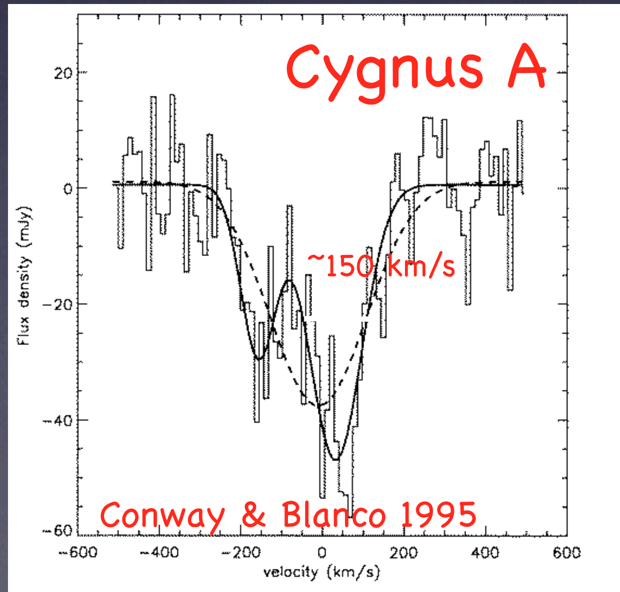


The nuclear regions probed by the gas

extra-gas surrounding the AGN, e.g. left over from the merger that triggered the AGN



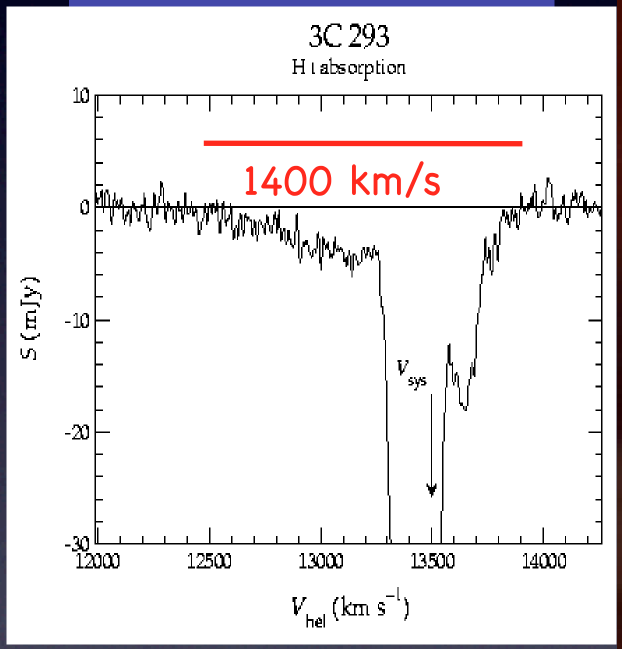
HI absorption from the torus or from circumnuclear disks

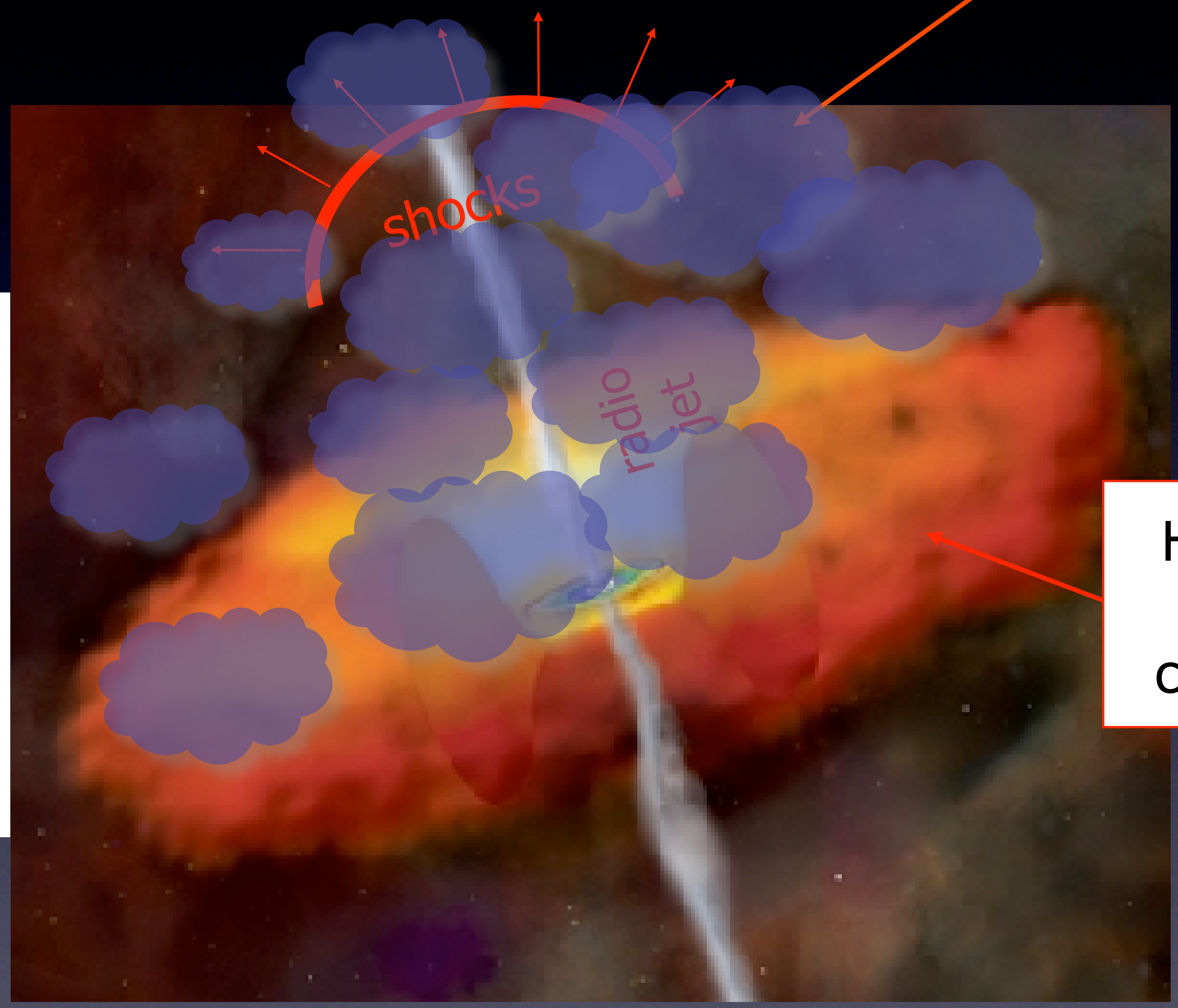


The nuclear regions probed by the gas

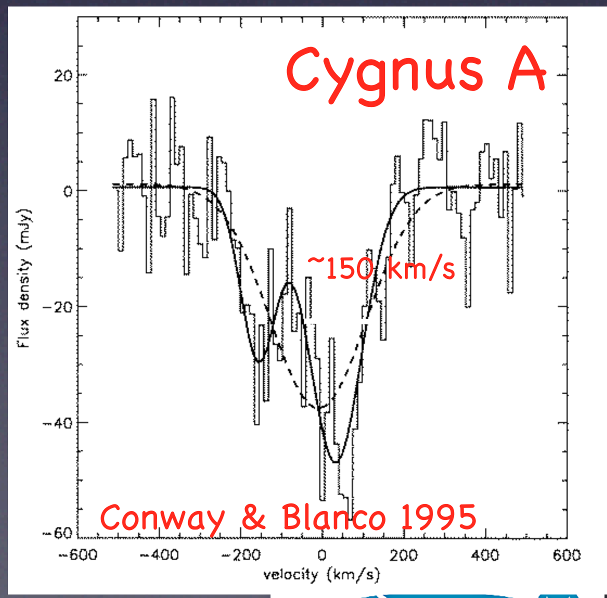
extra-gas surrounding the AGN, e.g. left over from the merger that triggered the AGN

Fast outflows: observed in ionised gas and HI
How important is the radio jet?



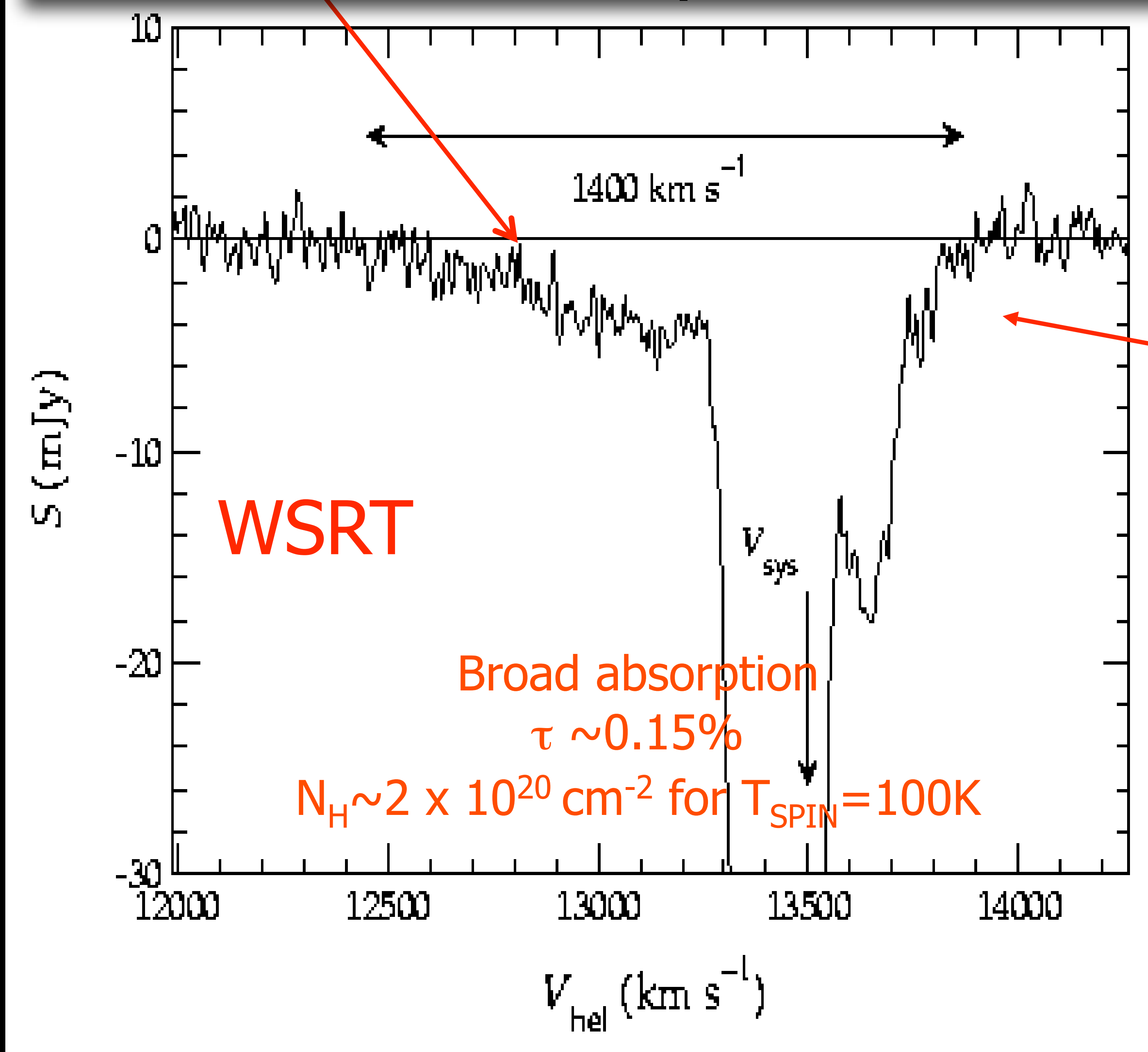


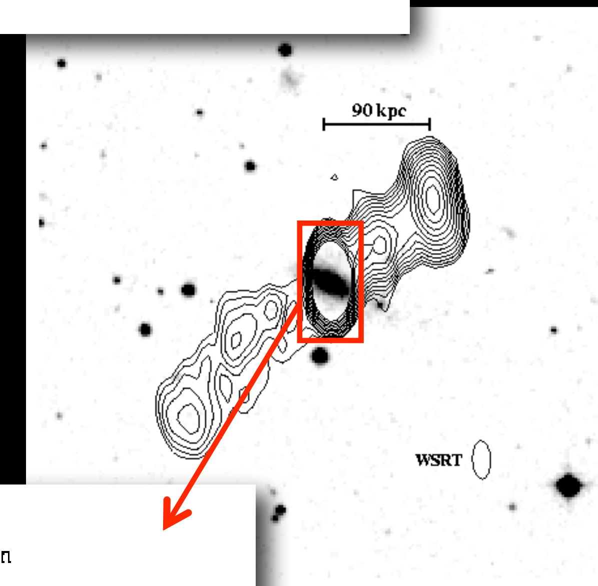
HI absorption from the torus or from circumnuclear disks

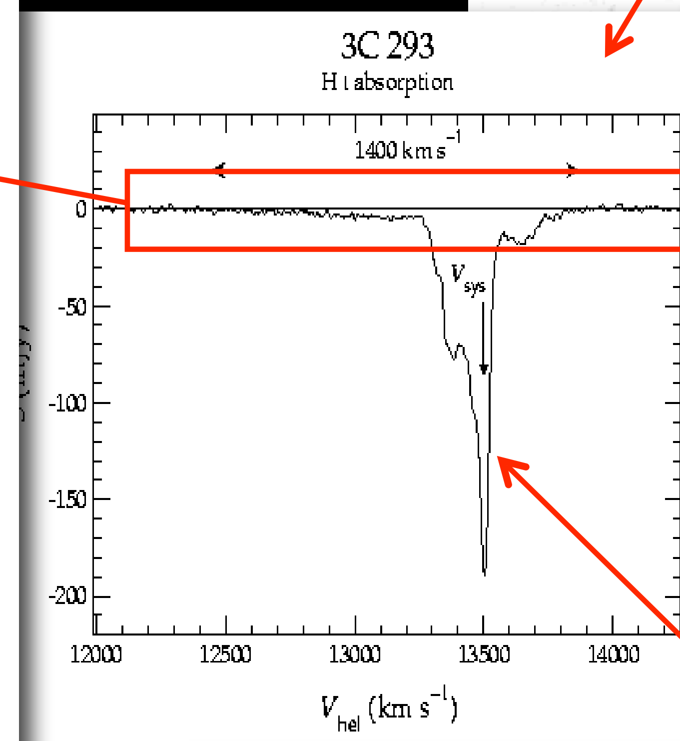


Broad HI absorption in 3C293

broad, shallow absorption by neutral gas





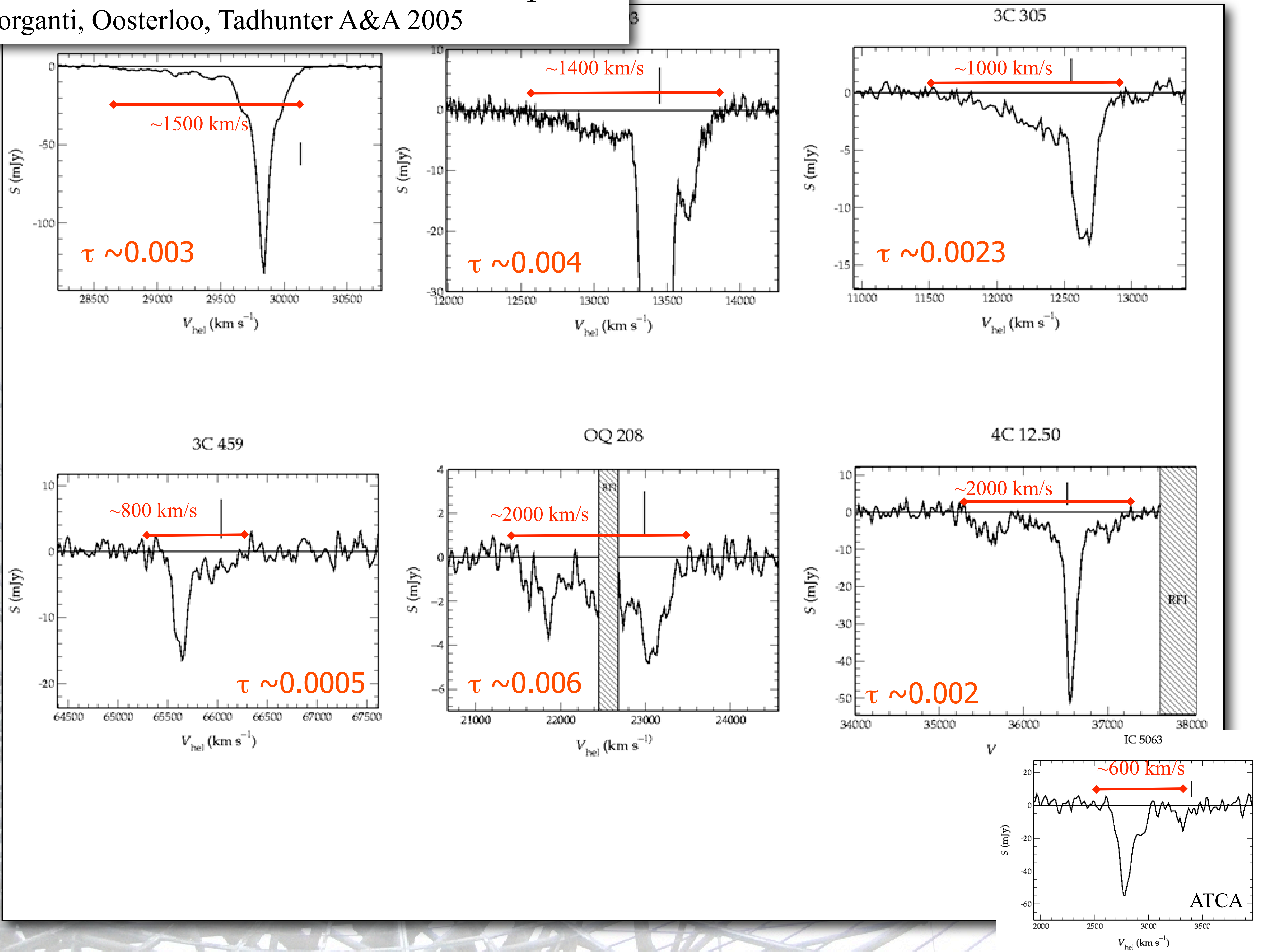


Deep absorption: Haschick & Baan (1985)
Beswick et al. (2002

Morganti, Oosterloo, Emonts, van der Hulst, Tadhunter ApJL 2003
Emonts et al. A&A 2005

WSRT observations of broad HI absorption

Morganti, Oosterloo, Tadhunter A&A 2005



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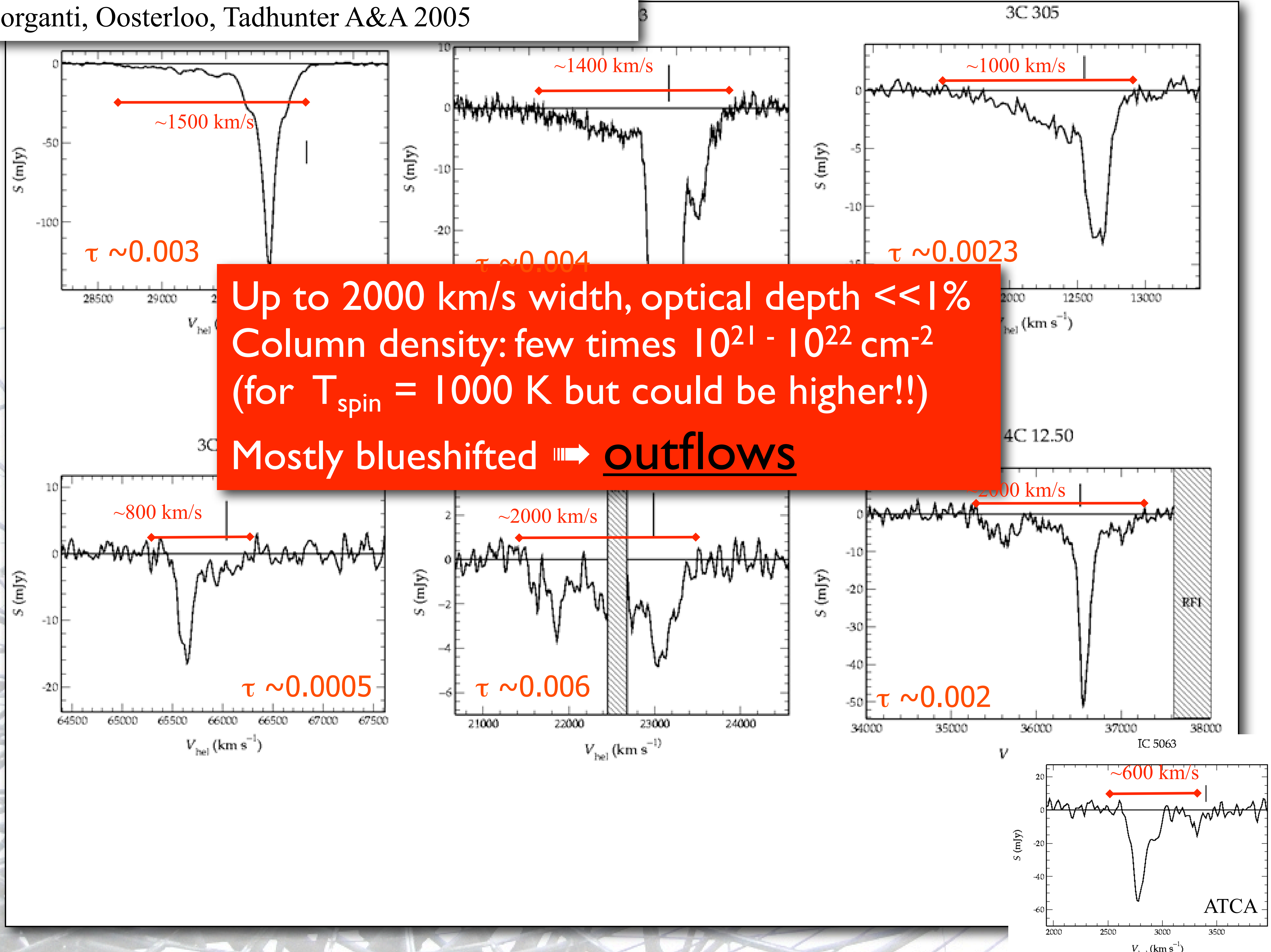
Morganti, Oosterloo, Tadhunter A&A 2005



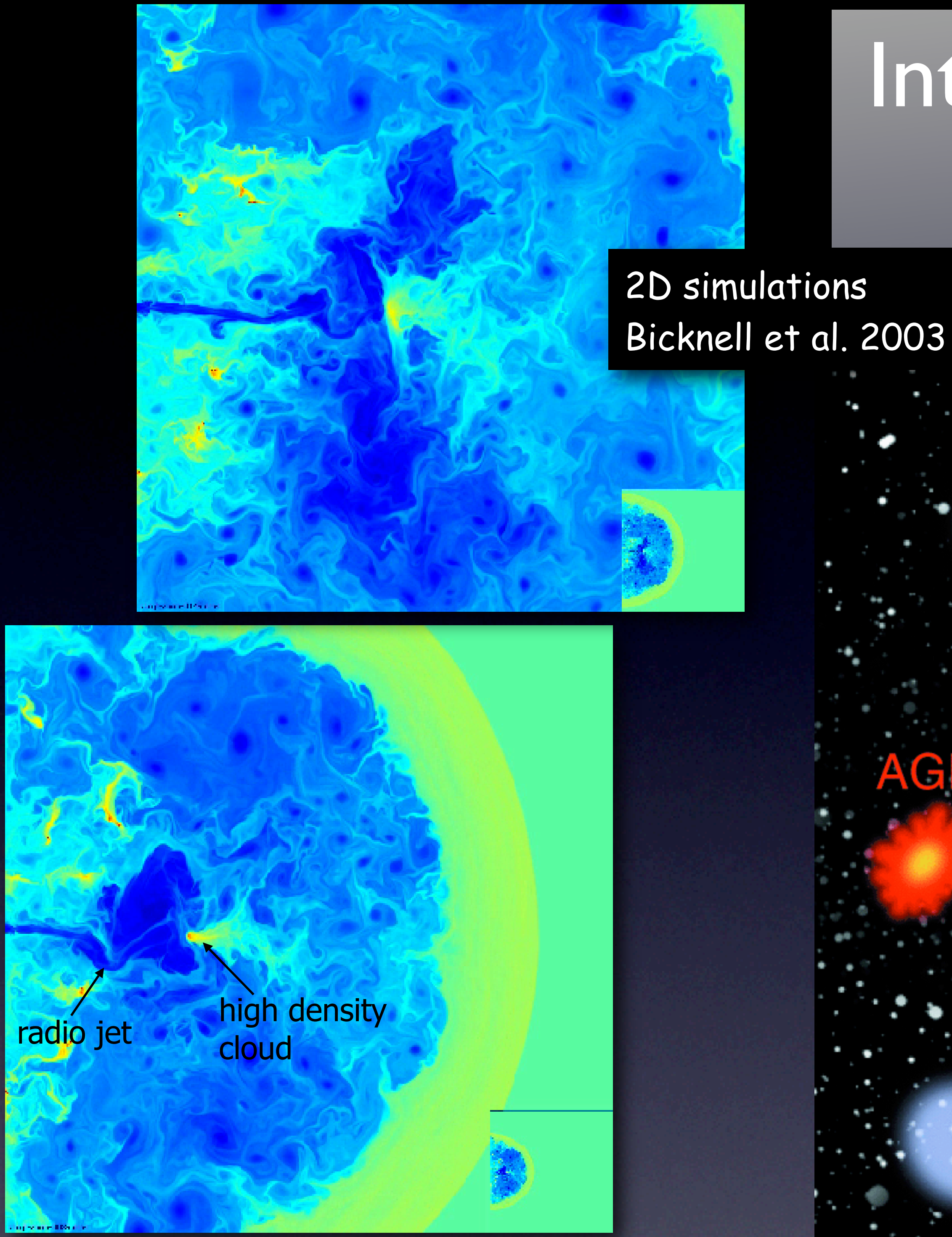
Up to 2000 km/s width, optical depth <<1%

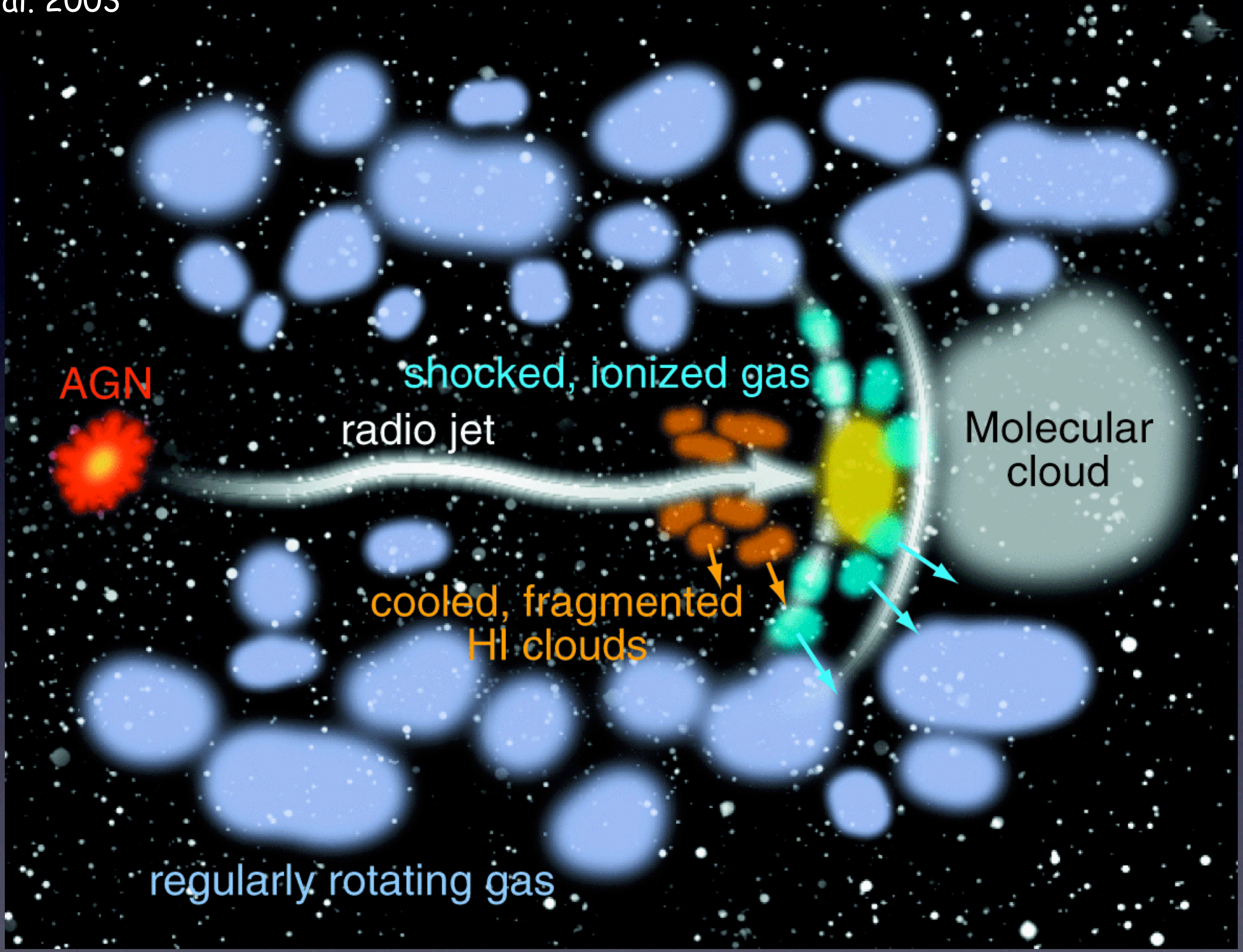
Column density: few times 10^{21} - 10^{22} cm^{-2}

(for T_{spin} = 1000 K but could be higher!!)

Mostly blueshifted ➠ <u>outflows</u>

Interaction of the radio jet with the surrounding medium





The radio jet may have a major impact on the nuclear medium ➠ feedback ➠ impact of the evolution of the galaxy

The future
SKA and SKA pathfinders

- Sensitivity ➠ to detect fainter HI structures to expand the studies to higher z (evolution of the structures with redshift)
- Volume (i.e. bandwidth & field-of-view) ➠ to expand the statistics using a "limited" amount of observing time

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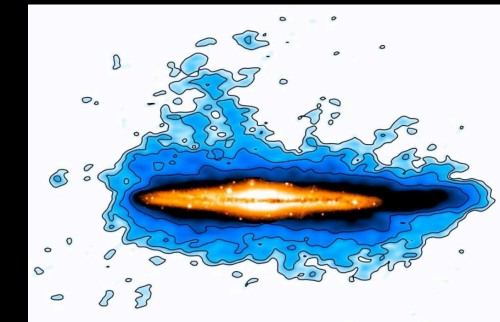
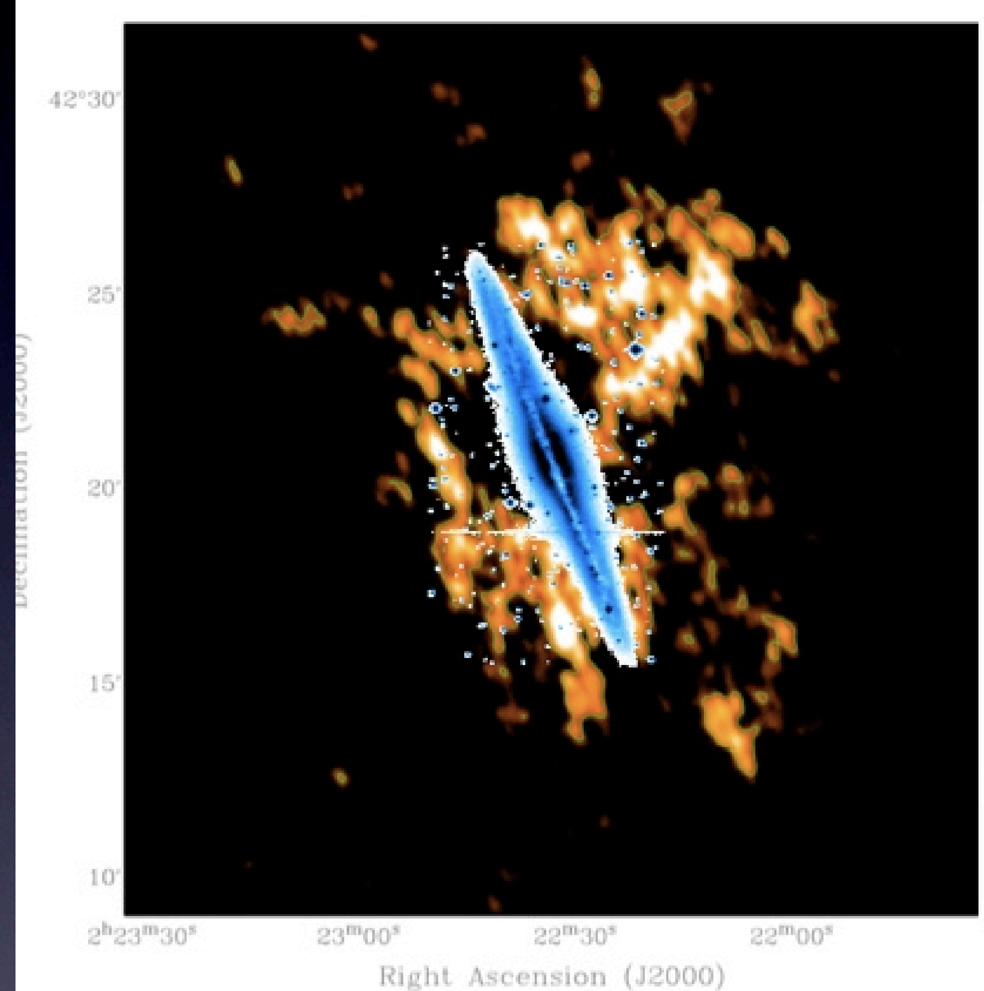
Example: need for high sensitivity ➠ Cosmic Drizzle



All stars, gas and dust together account for only 1/3 of all normal matter in the Universe.

The other 2/3 is in warm and hot, primordial gas floating in the large space between galaxies. There has to be a continuous "drizzle" of this intergalactic material onto galaxies because otherwise all galaxies would have no gas (and would not be able to form stars!)

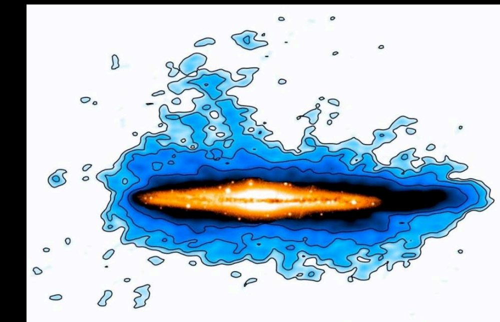
The infalling clouds are quite small and extremely difficult to observe.



The gas falling onto NGC 891
as detected with the WSRT

The cold gaseous halo of NGC 891 Oosterloo, Fraternali & Sancisito appear in The Astronomical Journal

Example: need for high sensitivity ➠ Cosmic Drizzle



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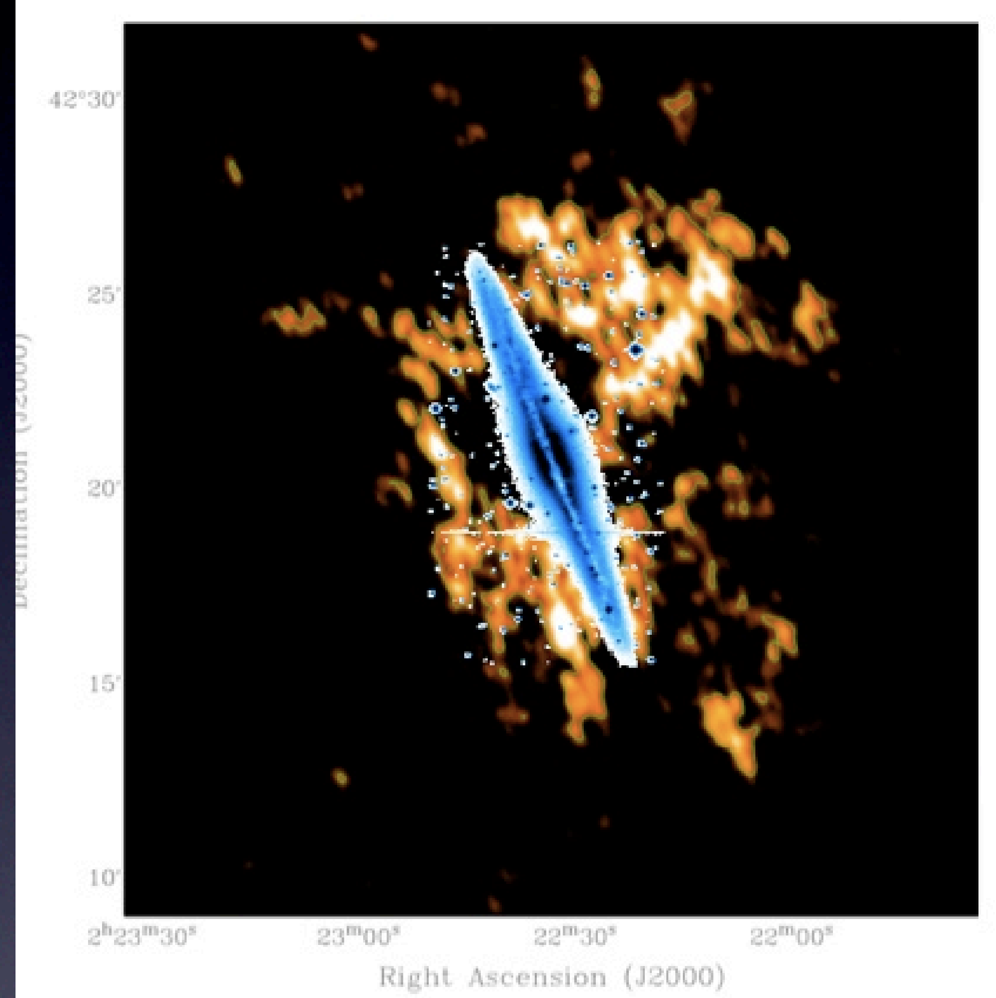

The gas falling onto NGC 891 as detected with the WSRT

The cold gaseous halo of NGC 891 Oosterloo, Fraternali & Sancisito appear in The Astronomical Journal

20 nights of WSRT observations
of the nearby galaxy NGC 891 have
allowed to detect such gas for the first time

How long does it take now to observe a sample of early-type galaxies?

- WSRT Large Project (search for HI emission):

  100 galaxies ($z < 0.016$, all next door!!)

  mass limit that we can reach: few x 10^6 to 10^7 $M_\odot$

  needed ➠ ~ 1300 h of WSRT time spread over 1.5 yr

- Ideally ➠ All sky survey

  HIPASS very shallow, only the very gas rich galaxies (M_{HI}> few x10^9 $M_\odot$) are detected

↪ a lot of telescope time to extend these studies

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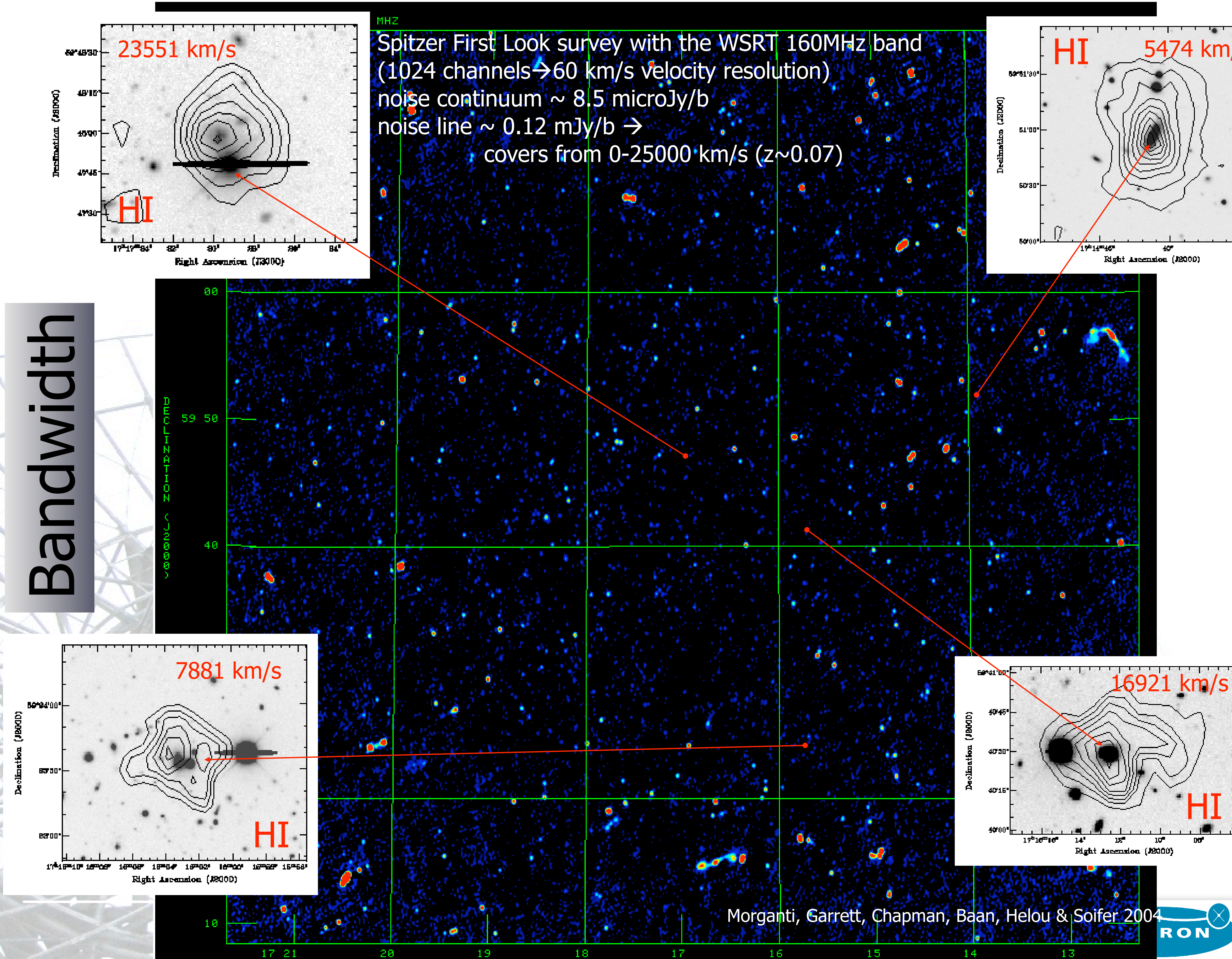
Bandwidth



MHZ
Spitzer First Look survey with the WSRT 160MHz band
(1024 channels→60 km/s velocity resolution)
noise continuum ~ 8.5 microJy/b
noise line ~ 0.12 mJy/b →
covers from 0-25000 km/s (z~0.07)
23551 km/s
HI
Right Ascension (J2000)
5474 km/s
HI
Declination (J2000)
Right Ascension (J2000)
16921 km/s
HI
Declination (J2000)
Right Ascension (J2000)
DECLINATION (J2000)
59 50
40
10
00
17 21
20
19
18
17
16
15
14
13
Morganti, Garrett, Chapman, Baan, Helou & Soifer 2004
7881 km/s
HI
Declination (J2000)
Right Ascension (J2000)

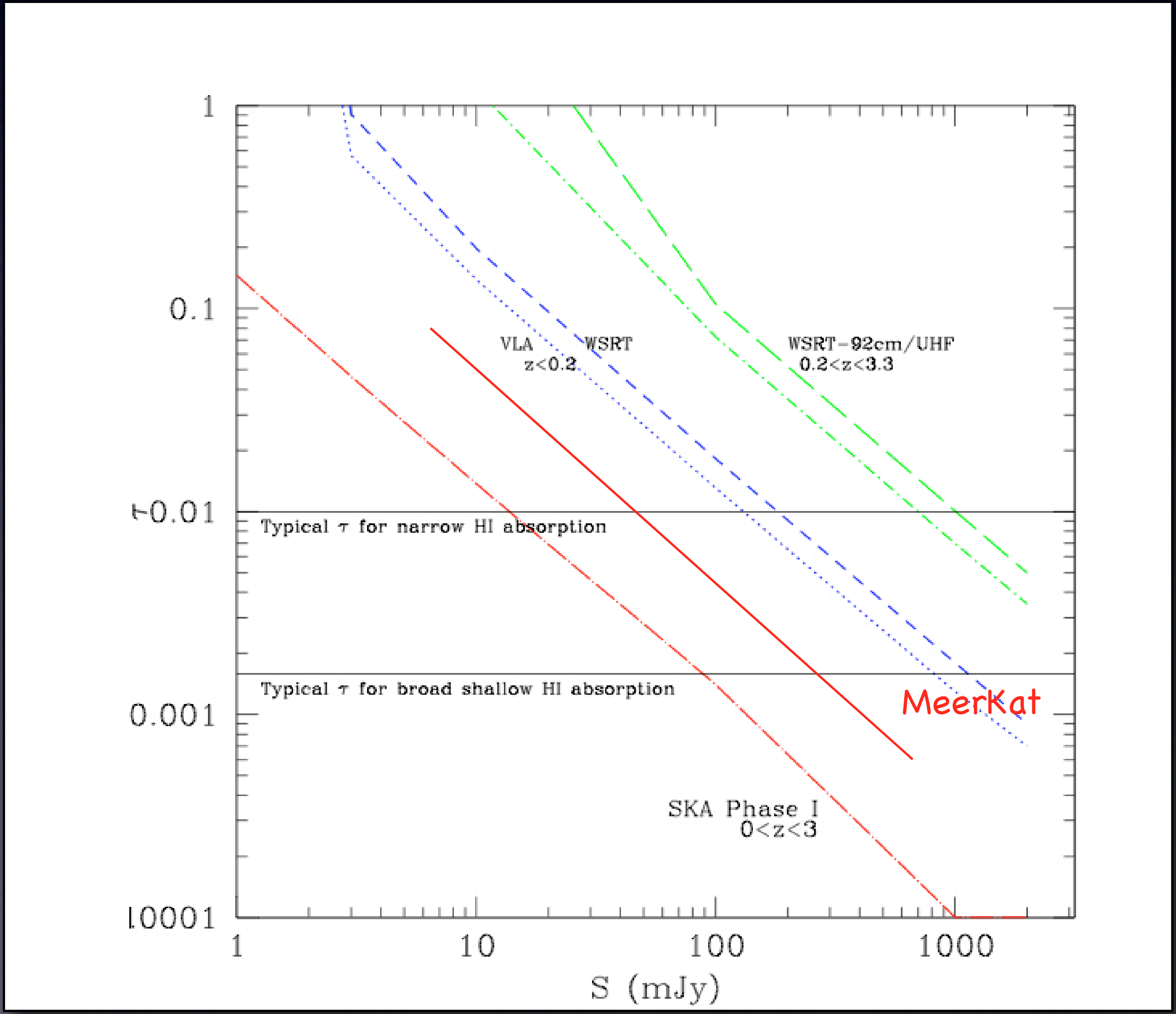
Extend the HI absorption studies

- Outflows τ~ 0.003 - we will need sources with flux ~200-300 mJy: sensitivity and stability of the bandpass crucial!
- Circum-nuclear disks τ > 0.01: interesting for sources with flux > 50 mJy
- Better sensitivity for low frequencies (compared to available systems) ➠ to study sources at higher z

Assumptions for MeerKat: 400 A_{eff}/T_{sys}

Same T_{sys} in the freq range: 1400-700 MHz

For 1x12h 20km/s velocity resolution



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Associated absorption: circumnuclear disks

- It becomes interesting for sources with F_{ν_HI} > 50mJy

(HI absorption detected at 5σ for A_{eff}/T_{sys} MeerKat = 400 $m^2\,K^{-1}$)

- How many of these sources? ~300 per 100 deg^2

How many of these sources will be in the observed redshift range?

- MeerKat will reach z~1 (0.7 GHz) and will have a bandwidth of 256 MHz

- This redshift range can be covered in three steps: 0-0.2/0.2-0.5/0.5-1

$z < 0.5$ ~ 80 sources per 100 deg^2 (~23%)

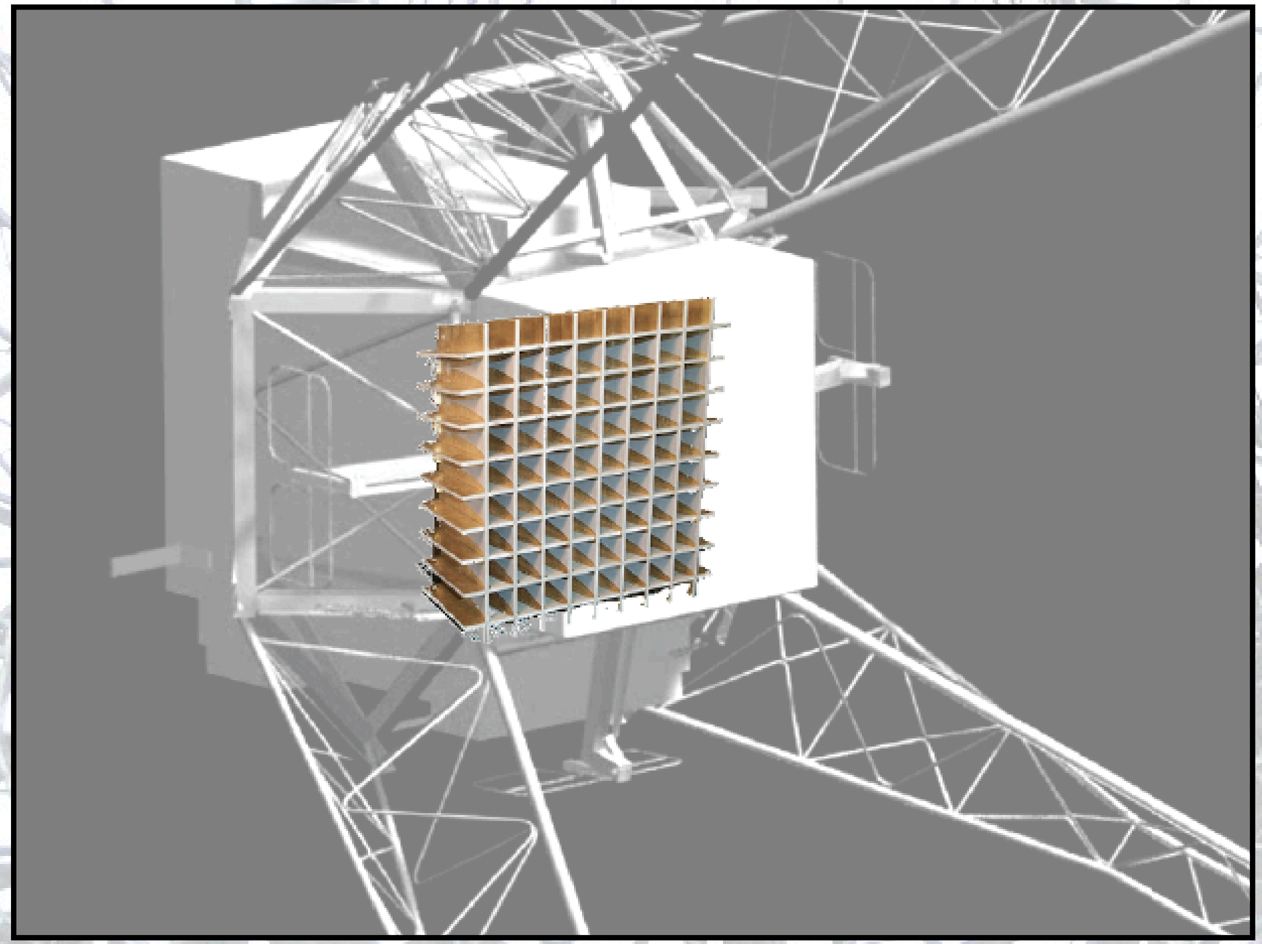
$0.5 < z < 1$ ~100 sources per 100 deg^2

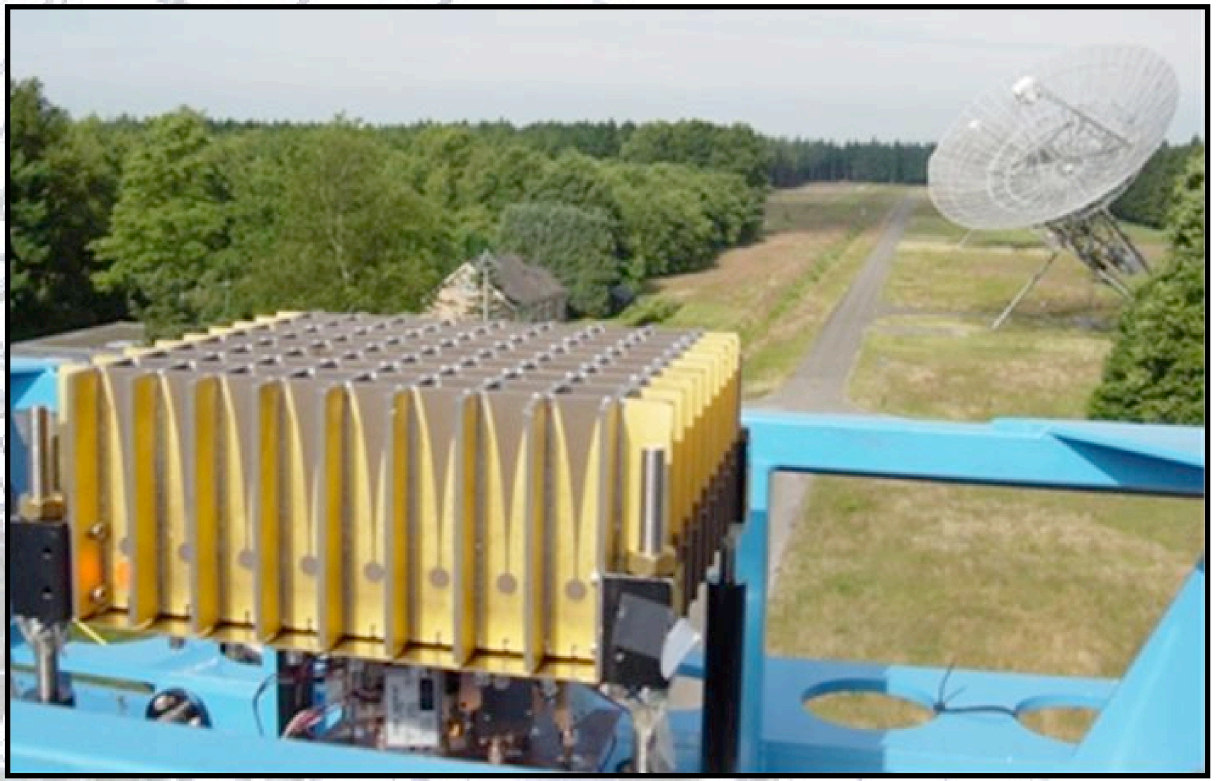
NOT A HUGE SAMPLE! and takes already ~140 *12h!!

Survey speed important!

Focal plane array

- Instead of using horns, use array of small antennae
- Combine signals to form several beams
- Can form good beam over about 5 FWHM





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Apertif

APERture Tile In Focus

Receptor array in each WSRT antenna

Apertif

- 8x8 (x2) elements
- 25 beams on the sky
- Frequency range: 850 – 1700 MHz
- T_{sys} 50 K
- Bandwidth 300 MHz
- Aperture efficiency 75%

WSRT

1

117 – 8650 MHz

30 K

160 MHz

55%

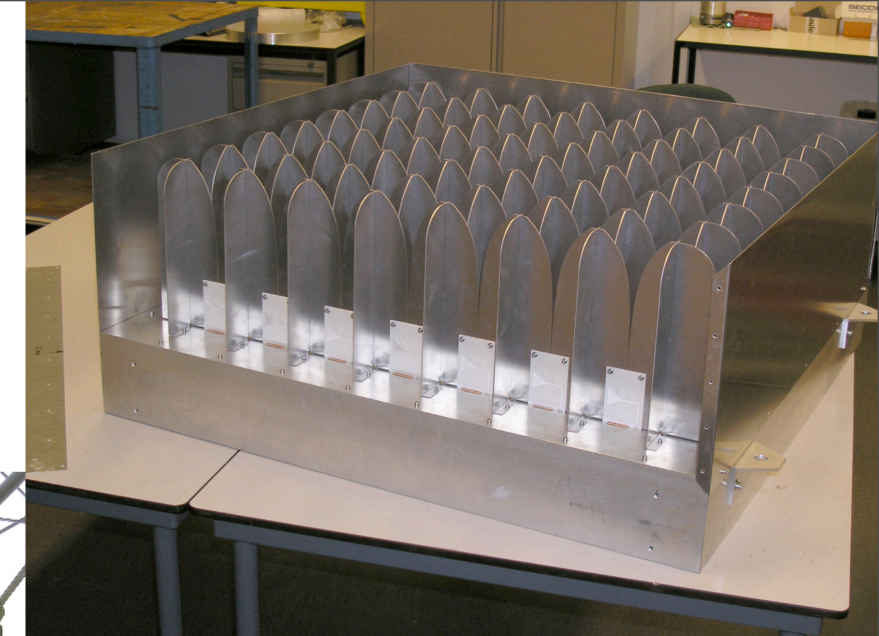
Survey speed increases with factor 32 (continuum)

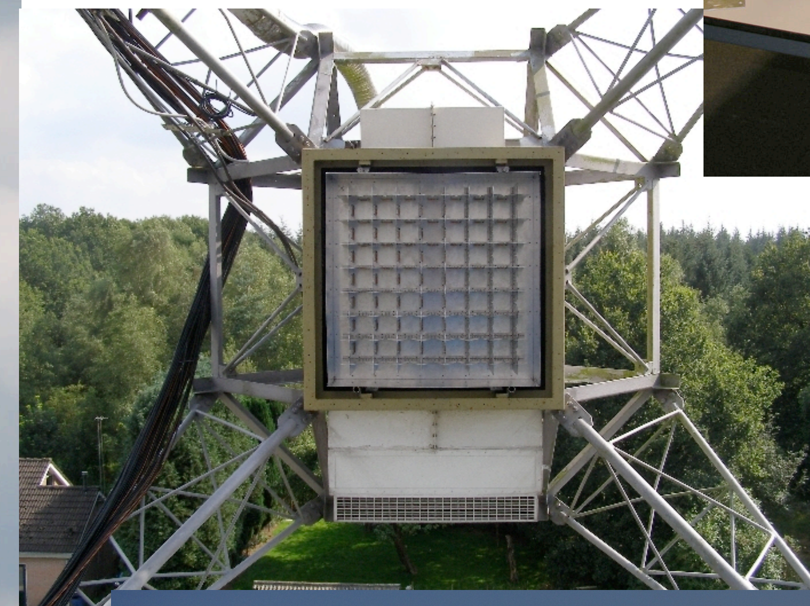
16 (line)

ASTRON

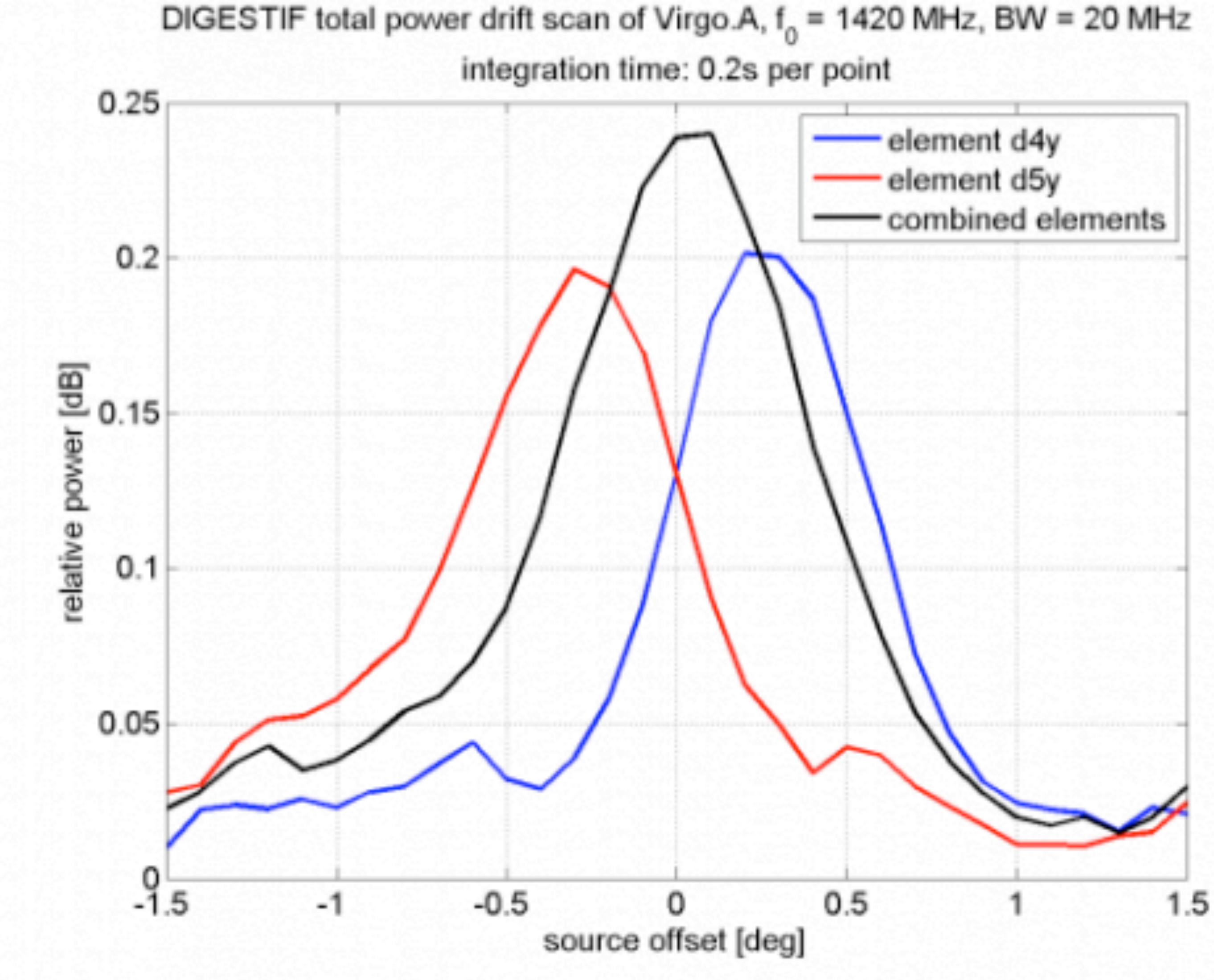
Apertif prototype: Digestif!

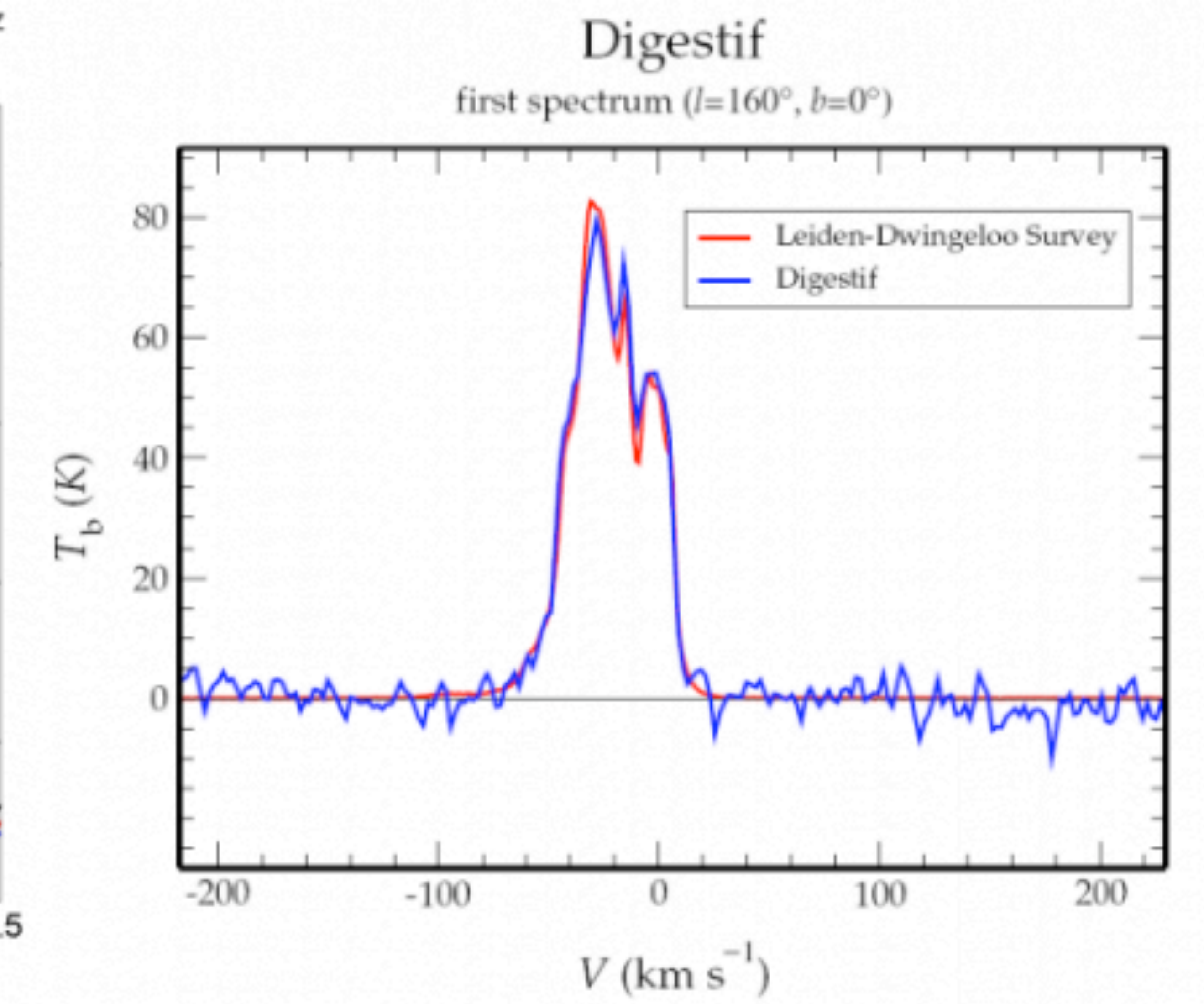
mounted on telescope #5 (WSRT)



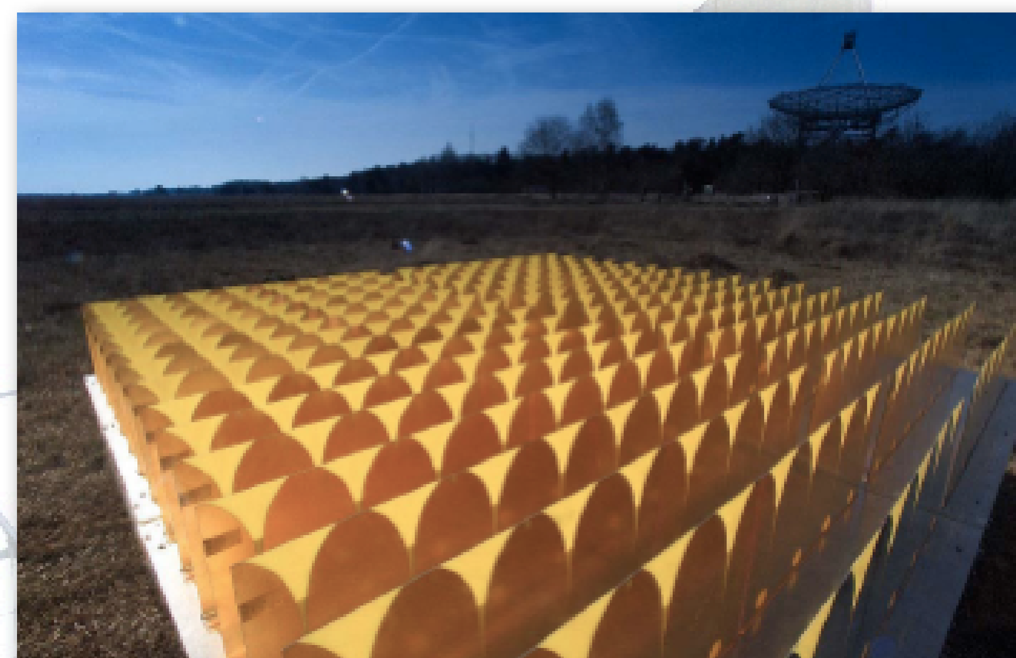


Fist astronomical observations: Digestif first light!

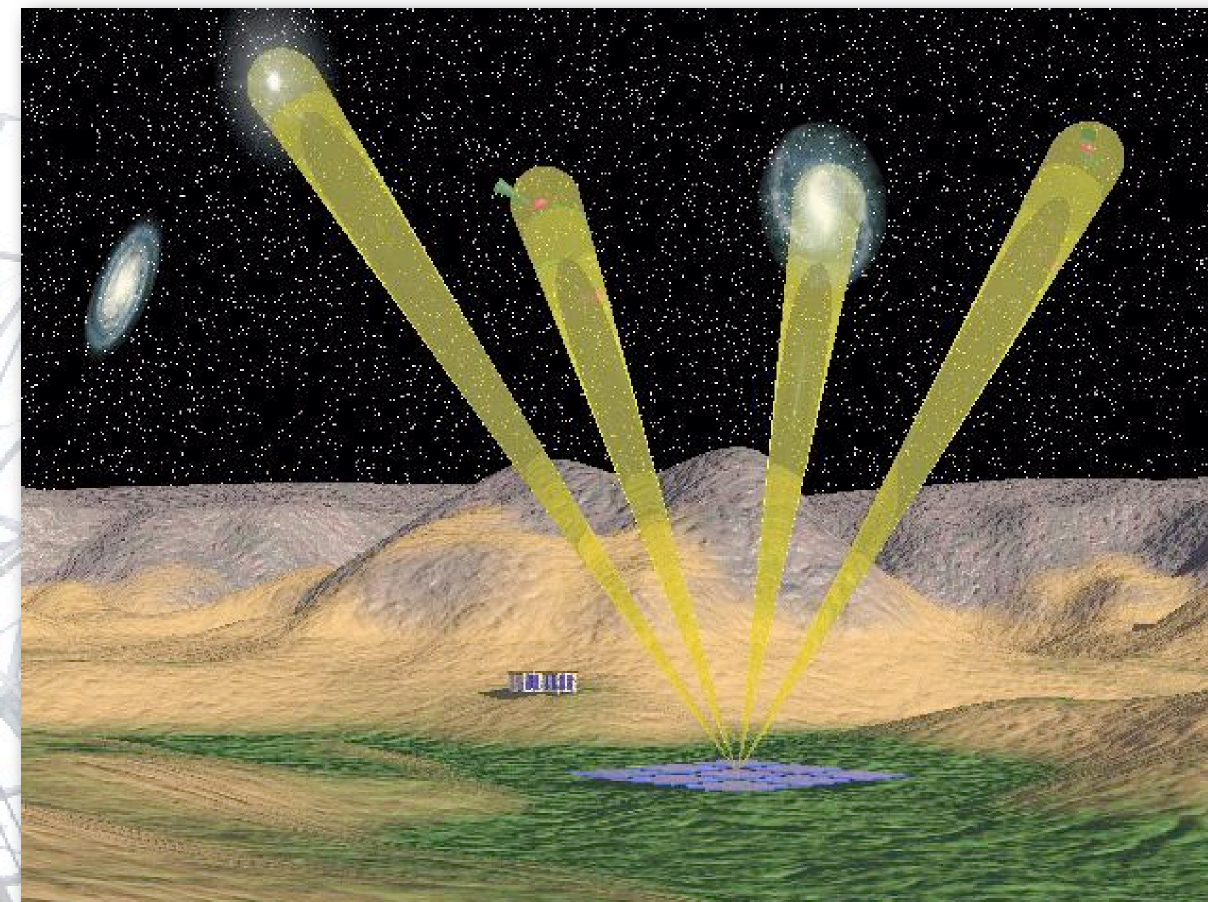




Technology relevant for SKA



Not only applicable in focus of dish



Instead of using a collector, place them in the aperture plane: Aperture array

↓

Embrace

Conclusions

- A lot of interesting science to be done with the HI !!!! even in gas poor galaxies...
- Key to understand early-type galaxies formation and evolution and radio loud AGN
- The major improvement in sensitivity will come with the SKA ➠ crucial for the study of evolution with z (HI in emission)
- but with the SKA pathfinders we can already foreseen some interesting new expansion of this work