HI emission and absorption diagnostics

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Plan for this lecture

- 21-cm emission/absorption line of neutral atomic hydrogen
- Parameters from HI observations

- How to carry out the observations
- Calibrating the data: what is the difference with radio continuum observations?
- Looking at HI data

- Examples of studies of associated HI

- Going further (toward SKA): blind/large surveys: why?
- SKA pathfinders: Apertif, EMBRACE.....Meerkat, ASKAP......
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 $6 \times 10^{-6}$ 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 $\rightarrow T_s$ 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 $2.85 \times 10^{-15} \text{ sec}^{-1}$
(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 $\sim 1 \text{ km/sec}$
  the observed lines are always much larger $\Rightarrow$ Doppler effect $\Rightarrow$ kinematics!

- Optically thin
HI emission and absorption diagnostics

HI cloud

HI emission

Vel km/s
HI detected in emission

\[ T_B(\nu) = T_{\text{spin}} [1 - e^{-\tau(\nu)}] \]

\[ N_H = 1.82 \cdot 10^{18} \int T_B dV \]

where \( \theta \) is beam size (arcmin)
\( dV \) km/s
\( S \) mJy/beam

[3.1 \cdot 10^{17} S dV / \theta^2 \text{ atoms/cm}^2]

To derive the mass of the neutral hydrogen

\[ M_{\text{HI}} = 2.365 \cdot 10^5 D^2 F \text{ (M}_{\odot}\text{)} \]

where \( F \sim \int S dV \text{ Jy km/s} \)
\( D \) distance in Mpc

\( 1 \text{ Jy} = 10^{-26} \text{ W/m}^2/\text{Hz} \)
HI emission and absorption diagnostics

- HI cloud
- HI emission
- HI absorption

Graph showing HI emission and absorption patterns over frequency (GHz).
HI detected in absorption
Particularly common in radio galaxies given the strong underlying radio continuum

Optical depth

\[ \Delta S = S_{cont} c_f (1 - e^{-\tau}) \]

Column density

\[ N_H = 1.823 \times 10^{18} T_{spin} \int \tau dv \quad \text{cm}^{-2} \]

\( T_{spin} \) accounts for the electrons that are in the upper state (i.e. those that do not absorb)

Higher \( T_{spin} \) \( \rightarrow \) more electrons in the upper state \( \rightarrow \) higher column density

From galactic studies, typical \( T_{spin} = 100 \) K

Typical column densities:

- in emission \( \rightarrow \) up to \( \sim 10^{21} \) cm\(^{-2} \) in a disk of a spiral galaxy
- in absorption \( \rightarrow \) from \( 10^{19} \) cm\(^{-2} \) against the core of some radio galaxies
Some (biased!) example of studies of neutral hydrogen

- Galactic stuff, high velocity clouds, satellites of the Milky Way.....
- Nearby galaxies and gas accretion
- Dark matter

- Interacting systems (including the stream in our own Galaxy)

- Galaxies in cluster \(\rightarrow\) effect of the dense environment on the interstellar medium (ISM) of the galaxies in the cluster (e.g. stripping etc.)

- Gas and Active Galactic Nuclei (AGN) \(\rightarrow\) HI in absorption tracing circumnuclear disk/tori fast gas outflows

- Intervening HI

The choice of the setup of the observations depends on the project.......

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HI emission and absorption diagnostics
HI observations

Standard radio observations

Some critical parameters to be set

- Central frequency
- Width of the observing band
- Number of channels (velocity resolution)

\[ S(\nu) \]

\[ \nu_0 \]

\[ A \]

\[ S_c \]
Planning an HI observation

- Redshift of the target $\rightarrow$ frequency

- Expected kinematics of the HI $\rightarrow$ bandwidth

- Velocity resolution requested $\rightarrow$ number of channels

- Sensitivity needed depending on the redshift

- Spatial Resolution: estimate from the typical column density
**Frequency and bandwidth**

\[ V_{hel} = 13500 \text{ km/s} \quad z = 0.045 \]

\[ V_{hel} = c \left( \frac{v_0 - v}{v} \right) \]

\[ v = 1359.2 \text{ MHz} \]

this will be the central frequency of your band to be able to detected HI at \( z = 0.045 \)

- Line must be in tunable range of receiver
- Not all telescopes cover all frequencies
- Sometimes non-standard frequencies
- Or high red-shifts move signal out of band

**Case of the WSRT**

From 1420 MHz to 1160 MHz (\( z \sim 0.22 \))

Very sensitive system.

Lower frequency (higher redshift) uncooled system \( \rightarrow \) lower sensitivity
Doppler tracking

- To catch a line, also need to set frequency accurate
  - Proper reference frame
  - And right approximation

- Significant differences, so be aware!
  - Observing time has been wasted!
  - Galactic radio-astronomers used to $V_{\text{lsr}}$ and radio
  - Extragalactic e.g. $V_{\text{hel}}$ and optical (redshift)

\[
v_{\text{los}} = c \frac{v_0^2 - v^2}{v_0^2 + v^2}
\]

\[
V_{\text{radio}} = c \frac{v_0 - v}{v_0}
\]

\[
V_{\text{optical}} = c \frac{v_0 - v}{\nu} = c \frac{\lambda - \lambda_0}{\lambda} = cz
\]
Rest Frames

- Is your source velocity measured in a heliocentric frame (corrected for the Earth’s motion around the sun) or with respect to the Local Standard of Rest (LSR)? The difference can be up to 20 km/s or so.

<table>
<thead>
<tr>
<th>Correct for</th>
<th>Amplitude</th>
<th>Rest frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nothing</td>
<td>0 km/s</td>
<td>Topocentric</td>
</tr>
<tr>
<td>Earth rotation</td>
<td>&lt; 0.5 km/s</td>
<td>Geocentric</td>
</tr>
<tr>
<td>Earth around Sun (incl barycenter earth-moon)</td>
<td>&lt; 30 km/s</td>
<td>Heliocentric</td>
</tr>
<tr>
<td>Sun peculiar motion (incl planets barycenter)</td>
<td>&lt; 20 km/s</td>
<td>Local Standard of Rest</td>
</tr>
<tr>
<td>Galactic rotation</td>
<td>&lt; 300 km/s</td>
<td>Galactocentric</td>
</tr>
</tbody>
</table>
Velocity Specifications (continued)

• Are you using the radio definition of velocity or the optical definition? (Both are approximations to the relativistic Doppler shift formula.)

\[ V_{\text{radio}} = c \frac{\nu_0 - \nu}{\nu_0} \]
\[ V_{\text{optical}} = c \frac{\nu_0 - \nu}{\nu} = c \frac{\lambda - \lambda_0}{\lambda} = cz \]

At large velocities, the difference between the two definitions can cause you to miss your line.
**Frequency and bandwidth**

\[ V_{hel} = 13500 \text{ km} / \text{s} \quad z = 0.045 \]

\[ V_{hel} = c \left( \frac{v_0 - v}{v} \right) \]

\[ v = 1359.2 \text{ MHz} \]

This will be the central frequency of your band to be able to detect HI at \( z = 0.045 \).

The typical bandwidth of HI observation is 5, 10 or 20 MHz:

- **10MHz**: 1354.2 \( \rightarrow \) 1364.2
  
  The range of velocities covered goes from 14665 to 12358 km/s

- for 10MHz \( \sim \) 2300 km/s velocity range covered

- for 20MHz \( \sim \) 4600 km/s velocity range covered

**Line must be in tunable range of receiver**

- Not all telescopes cover all frequencies
- Sometimes non-standard frequencies
- Or high red-shifts move signal out of band

**Case of the WSRT**

- from 1420 MHz to 1160 MHz (\( z \sim 0.22 \))
- very sensitive system.
- Lower frequency (higher redshift) uncooled system \( \rightarrow \) lower sensitivity

But see later for the need of much broader bandwidth!!
Velocity resolution

Typical velocity range observed in different systems:
- Small galaxies: 100 km/s
- Large galaxies: up to ~ 400 km/s
- Interacting systems: ~ 400 – 500 km/s
- Gas outflows: up to 2000 km/s

Channel width: $\frac{\Delta v}{v_0} \rightarrow 1$ MHz $\rightarrow$ ~ 200 km/s

Typical number of channels: 128, 256, 512, 1024

10 MHz, 512 channels $\rightarrow$ 0.02 MHz $\rightarrow$ 4 km/s
Column density and Mass for HI emission

- The rms noise per channel and the spatial resolution define the column density we can reach.

Example: if we observe with 5 arcsec resolution, rms noise (per chan) 1 mJy/beam
dV~ 30 km/s →
the resulting column density is $4 \times 10^{21} \text{cm}^{-2} (1\sigma)$

If we observe at much lower resolution, e.g. 60 arcsec, We can detect HI emission of $2.8 \times 10^{19} \text{cm}^{-2}$

This is not the case for HI absorption!

- HI mass → distance dependent

$$M_{\text{HI}} = 2.365 \cdot 10^5 D^2 F \left( M_{\text{sun}} \right)$$

where $F \sim \int S \ dV$ Jy km/s D in Mpc ($D \sim cz/H_0$)

$z=0.005$ ($V_{\text{hel}}=1500 \text{ km/s}$) $D_L=21 \text{ Mpc} \rightarrow M_{\text{HI}} = 3 \times 10^7 M_{\text{sun}} (1\sigma)$

$z=0.1$ ($V_{\text{hel}}= 30000 \text{ km/s}$) $D_L=454 \text{ Mpc} \rightarrow 1.4 \times 10^{10} M_{\text{sun}}$

$z=1$ $D_L= 6634 \text{ Mpc} \rightarrow M_{\text{HI}} = 3 \times 10^{12} M_{\text{sun}}$
Performing the observations

• Main difference (compared to “radio continuum” observations) is the calibration of the shape of the band

• Bandpass calibration: requires the observation of a calibrator → point source of known intensity (and spectral index) in the center of the observed field.

• Depending how accurate the calibration of the band has to be, you need to observe a strong calibrator, few times during the observations → this allows to follow possible variations of the bandpass with time.

Note: in many radio telescopes also standard continuum observations are done in spectral line mode (better rejection RFI, reduced beam smearing for large fields, etc.)
Spectral Bandpass:

- Spectral frequency response of antenna to a spectrally flat source of unit amplitude

Perfect Bandpass

Bandpass in practice

- Shape due primarily to individual antenna electronics/transmission systems.
- Different for each antenna
- Varies with time, but much more slowly than atmospheric gain or phase terms
Observations of the calibrator interleaved with the target
Visibilities in 5h observations

calibrators

short baseline (144m)

long baseline (3km)
HI emission and absorpti

Spectrum of 3C48 - strong calibrator

Point source of known intensity and spectral shape at the center of the observed field.

short baseline (144m)  long baseline (3km)

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What do we get from the calibrated data? Not just a single image but a data cube ⇒ like integral field spectroscopy.

The data (and the cube) include both line and continuum ⇒ the two have to be separated.

Every channel is one plane of the cube.
Continuum Subtraction: basic concept

- Use channels with no line emission to model the continuum & remove it
- Iterative process: have to identify channels with line emission first!
Continuum Subtraction: Methods

- **Image Plane**: First map, then fit line-free channels in each pixel of the spectral line datacube with a low-order polynomial and subtract this.

- **UV Plane**: Model UV visibilities and subtract these from the UV data before mapping.
  - Clean line-free channels and subtract brightest clean components from UV datacube.
  - Fit line-free channels of each visibility with a low-order polynomial and subtract this.
Spectral Line Visualization and Analysis
HI emission and absorption diagnostics

but some 2D methods are required to visualize the data.
For illustrations, you must choose between many 2-dimensional projections

- 1-D Slices along velocity axis = line profiles
- 2-D Slices along velocity axis = channel maps
- Slices along spatial dimension = position velocity profiles
- Integration along the velocity axis = moment maps
Examples given using VLA C+D-array observations of NGC 4038/9: “The Antennae”
Greyscale representation of a set of channel maps
Emission from channel maps contoured upon an optical image
Position-Velocity Profiles

- Slice or Sum the line emission over one of the two spatial dimensions, and plot against the remaining spatial dimension and velocity.

- Susceptible to projection effects.
• Rotations emphasize kinematic continuity and help separate out projection effects

• However, not very intuitive
“Moment” Analysis

Integrals over velocity

- **0th moment** = Integrated flux (intensity integrated over all channels with HI detected)
- **1st moment** = intensity weighted (IW) mean velocity
- **2nd moment** = IW velocity dispersion
Moment 0 = \int S_v \, dv

Moment 1 = \langle V \rangle

= \frac{\int S_v \, v \, dv}{\int S_v \, dv}

Moment 2 = \langle V^2 \rangle^{1/2}

= \sqrt{\frac{\int S_v \, (v - \langle V \rangle)^2 \, dv}{\int S_v \, dv}}
Moment Maps

Zeroth Moment
Integrated flux

First Moment
mean velocity

Second Moment
velocity dispersion
Examples of extragalactic HI studies
(with current telescopes)
Some (biased!) example of studies of neutral hydrogen

- Galactic stuff, high velocity clouds, satellites of the Milky Way.....
- Nearby galaxies and gas accretion
- Dark matter

- Interacting systems (including the stream in our own Galaxy)

- Galaxies in cluster \(\rightarrow\) effect of the dense environment on the interstellar medium (ISM) of the galaxies in the cluster (e.g. stripping etc.)

- Gas and Active Galactic Nuclei (AGN) \(\rightarrow\) HI in absorption tracing circumnuclear disk/tori fast gas outflows

- Intervening HI
HI from the Milky Way

Column density of atomic hydrogen from radio surveys of the 21-cm spectral line of hydrogen. On a large scale the 21-cm emission traces the "warm" interstellar medium, which is organized into diffuse clouds of gas and dust that have sizes of up to hundreds of light years. Most of the image is based on the Leiden-Dwingeloo Survey of Galactic Neutral Hydrogen. This survey was conducted over a period of 4 years using the Dwingeloo 25-m radio telescope.
The nearest interacting galaxy: our Milky Way

Sagittarius dwarf

Magellanic Clouds

HI emission and absorption diagnostics
Dwarf galaxies “building blocks” of large galaxies.

According to models/simulations, the Milky Way has fewer dwarf companions than predicted (missing satellite problem)

Solution: small galaxies are less efficient in converting gas into stars, making them fainter than predicted

To form stars, the gas in a galaxy has to cool to very low temperatures. Do we see this gas?

The Universe around our Galaxy
**Dwarf galaxies around us**

- The recently discovered dwarf galaxy LeoT is a key object: it is (by far) the smallest galaxy that has a *nice* disk of hydrogen gas

- Best case to study properties of interstellar medium in relation to star formation

  - Why is this less efficient in small galaxies? Effect of re-ionisation? Effect of supernovae?

Distribution of hydrogen gas (contours) in the dwarf galaxy LeoT as observed by the WSRT (Oosterloo et al.)
Kinematics of the galaxies
Case of an undisturbed galaxy: rotating disk

Simple 2-D model: Rotating disk

HI observation (datacube) of NGC 4414

Mean Velocity Field

Channel Maps

QuickTime™ and a YUV420 codec decompressor are needed to see this picture.

RA

Dec

H I observation (datacube) of NGC 4414

HI emission and absorption diagnostics
Rotating disks

Mean Velocity Field

Channel Maps

Rotating Ring, top view

Front View, projected

Side View

HI emission and absorption diagnostics
The radio galaxy B2 0258+35

more than $10^{10}$ M$\odot$ of HI!

compact radio galaxies

young ($<10^7$ yr)

~1kpc

$125$ kpc

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.
Examples of parameters that can be derived from the HI data for the radio galaxy B2 0258+35

\[ M_{HI} = 2.35 \times 10^5 \times D^2 \times F \sim 10^{10} M_{\odot} \]

\[ M_{\text{dyn}} \Rightarrow G \frac{Mm}{r^2} = \frac{mV^2}{r} \Rightarrow 10^{11} M_{\odot} \]

\[ L = 1.4 \times 10^{10} L_{\odot} \Rightarrow M/L \sim 10 \]

the correct value of \( V_{\text{rot}} \) depends on the inclination that, very often, is not known or difficult to estimate.

rotation time \( \Rightarrow \frac{2 \cdot \pi \cdot 60 kpc}{250 km/s} = 1.5 \times 10^9 \text{ yr} \)

in order for the gas to settle it takes at least a few orbits so the HI must have been accreted a few \( \times 10^9 \) yrs ago (at redshift 0.5).
Neutral hydrogen so much more extended than the stars

The faster the neutral gas rotates (in regions as far as possible from the centre) the more mass is present inside that radius.

\[ M \approx RV^2 \]

This can be compared with the mass of the visible matter (stars or gas) to estimate whether the mass of the galaxy is all due to this (visible) matter or whether there is more. The gas keep on rotating fast even when there are no stars → DARK MATTER!
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.

20 nights of WSRT observations
- of the nearby galaxy NGC 891 have
- allowed to detect such gas for the first time
A “messy” case: NGC 4631
Early-type galaxies from major merger

The two galaxies merge in a few times $10^8$ yrs

Tails left over from major mergers
Example of interacting galaxies: the gas is a powerful tracer of interaction

The Antennae (Hibbard et al.)

Early-type galaxies from major merger

Numerical simulations of Barnes

QuickTime™ and a YUV420 codec decompressor are needed to see this picture.
Effect of the dense environment on the gas:

stripping by the hot cluster gas removes the neutral gas from galaxies falling into the cluster

NGC 4388, member of the Virgo cluster

Oosterloo, van Gorkom 2005
Case of Centaurus A
emission, absorption

ATCA observations
6'' resolution ® ~100 pc

Schiminovich et al. 1995

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 $-40 \text{ km/s}$ and black is $+40 \text{ km/s}$ from the mean HI absorption velocity.
Broad HI absorption in 3C293

broad, shallow absorption by *neutral gas*

**WSRT**

Broad absorption

$\tau \sim 0.0015$

$N_H \sim 2 \times 10^{21}$ cm$^{-2}$ (for $T_{\text{SPIN}} = 1000$ K)

Highly blueshifted HI absorption $\Rightarrow$ fast *outflow* ($> 1000$ km/s)
Not all the science comes from pointed observations!!!
H I surveys

- Low end of H I Mass function

Where are the small galaxies?

WSRT: 60 nights of observing of nearby volume (90 deg$^2$) to determine mass function down to $5 \times 10^6 \, M_\odot$

CVn survey; Kovac et al. 2007
H I surveys

• Galaxy evolution in rich clusters

Strong environmental effects on galaxies
Very time consuming with present day telescopes.....
HI surveys

- HI at high redshift

WSRT: 100 nights integration on **one** field (!).
At $z = 0.2$, this is the same volume as locally out to $V = 2000$ km s$^{-1}$

- Kinematics of cluster & environment
- Relate to e.g. star formation properties

Verheijen et al 2007
HI surveys

• The evolving gas content of galaxies

We need to detect in emission $M_*$ galaxy out to the highest possible redshift

The necessary sensitivity will be reached only by SKA!

How about absorption???
monitor the HI content of collapsed objects from the epoch of formation to the present day in emission will be difficult to go beyond a certain redshift.

HI 21-cm absorption measurements toward radio-loud background sources promising way

Absorption line studies done in optical/UV: Damped Ly\(\alpha\) (DLA) and sub-DLA. DLAs: Intervening absorbers with high HI column density, \(N_{\text{HI}} > 2 \times 10^{20} \text{ cm}^{-2}\)

Local Universe: HI in emission
Redshift higher than 1.7:
Damped Ly\(\alpha\) (DLA) absorption based on ground-based optical observations

Few cases at intermediate \(z\).
Origin still controversial:
- large, rapidly rotating massive disks
  (e.g. Prochaska & Wolfe 97)
- small, merging sub-galactic systems
  (Haehnelt et al 98)

Optical/UV studies tend to produce biased surveys...
Search of intervening HI via absorption in the radio band, 21-cm

Radio surveys particularly sensitive to cold HI (T < 200K)

\[ \frac{N_{\text{HI}}}{T_s \cdot \Delta V} \]

for observed optical depth

Probability of intercepting a DLA system?

number of DLA - with \( N_{\text{HI}} > 2 \times 10^{20} \) cm\(^{-2}\) per unit redshift

\[ \frac{dN}{dz} = 0.055 (1+z)^{1.11} \]

(Storrie-Lombardi & Wolfe 2000)

\[ z = 0 \quad \frac{dN}{dz} = 0.058 \]

(Ryan-Weber et al. 2003)

WSRT: Lane & Briggs 2001

not many cases known
How many intervening HI absorption systems?

Example for MeerKat

- about 900 continuum sources x 100 sq^2 ->
  - more than 70% of them with z > 1
- in the redshift range 0.5 - 1
  - expected 0.06 possible interceptions per object -> ~40 x 100 sq^2

- with the FOV of 0.73 deg^2 (~3 x times the WSRT):
  - about 0.2 intervening abs x 12h

-> 500 x 12h to get 100 absorption systems!! Large Field of View needed!
What do we need to make this science possible?

✓ Increased sensitivity for a major improvement we have to wait for SKA

✓ Increased volume that we can observe:
  - increased field of view (FoV)
  - increased bandwidth (i.e. range in distance covered)

SKA pathfinders
Blind HI surveys: First Look Spitzer with the WSRT
a mini experiment
Blind HI surveys

160MHz band \(\rightarrow\) covers from 0-25000 km/s (\(z\sim 0.07\))

1024 channels\(\rightarrow\) 60 km/s velocity resolution
noise line \(\sim 0.12\) mJy/b

Morganti, Garrett, Chapman, Baan, Helou, & Soifer 2004
HI emission and absorption diagnostics

Galaxy at velocity 5374 km/s

8 bands of 20MHz with the WSRT
Galaxy at velocity 23551 km/s
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)
Several telescopes planned with (a.o) much larger field of view ASKAP (Australia), MeerKAT (South Africa), ATA (US), Lofar, Apertif — Embrace

A focal-plane array for the WSRT An appetizer for SKA

EMBRACE: Aperture Array
How to enlarge the field of view?

Field of view for single detector is set by diffraction limit \( \frac{\lambda}{D} \)

- Use multiple receivers to increase area in focus that is sampled (single pixel \( \rightarrow \) array of pixels)
  - multiple horns (e.g. Multibeam)
  - focal-plane arrays
  - small dishes: but MANY of them! large correlator also necessary!
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
- $T_{\text{sys}}$ 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)
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
Apertif prototype: Digestif!
mounted on telescope #5 (WSRT)
Off-axis beam
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
## EMBRACE Requirements Specification

<table>
<thead>
<tr>
<th>Frequency range</th>
<th>500 MHz - 1500 MHz.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polarisation</td>
<td>Single polarisation</td>
</tr>
<tr>
<td>Physical Collecting area</td>
<td>~300 m² WSRT (100 m² Nançay)</td>
</tr>
<tr>
<td>Aperture Efficiency</td>
<td>&gt; 80%</td>
</tr>
<tr>
<td>Electronic Scan Range</td>
<td>+/-45 deg</td>
</tr>
<tr>
<td>$T_{sys}$</td>
<td>&lt;100K @ 1GHz (aim for 50K)</td>
</tr>
<tr>
<td>Element phase control accuracy</td>
<td>3 bit (also time delays)</td>
</tr>
<tr>
<td>Instantaneous bandwidth</td>
<td>40 MHz (increased further with time delays)</td>
</tr>
<tr>
<td>Dynamic range A/D Converter</td>
<td>60dB (effective # of bits)</td>
</tr>
<tr>
<td>Number of independent FoV (RF beams)</td>
<td>2</td>
</tr>
<tr>
<td>No of digital beams</td>
<td>8+</td>
</tr>
</tbody>
</table>
Baseline design of the radiators

- Design Vivaldi with a stripline feed configuration
- Similar design to THEA – safe approach
Actu\nal tile
System level Overview

EMBRACE multi-beam rake

Analogous links

Clock Subsystem

Filter bank

Control Subsystem

Digital Beam Former+

Receiver & A/D Conversion

WAN Interface

Towards WH2T emulator

Filter Cycle Data Link

HI emission and absorption diagnostics
Embrace siting at WSRT

Embrace 300 M²
EMBRACE location
The study of the neutral hydrogen gives important insights on many aspects of e.g. the structure, origin and evolution, nuclear activity etc. of galaxies.

These studies are now limited by the sensitivity of present day radio telescopes (but we are very creative!)

We are working toward SKA (but it will take a while!) with pathfinders that hopefully will give also some useful data in the near future.

A lot of fun......and new (challanging) instruments coming online!...even more fun!