Array Spectrographs for Radio and (Sub)Millimeter Wavelength Astronomy

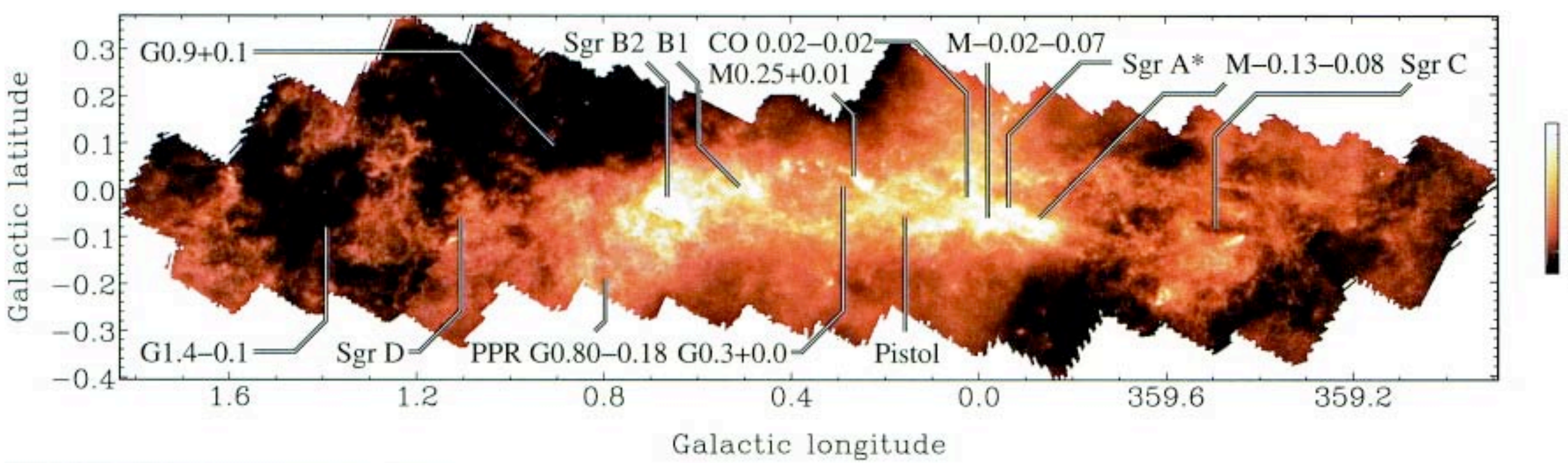
Karl M. Menten

Max-Planck-Institut für Radioastronomie

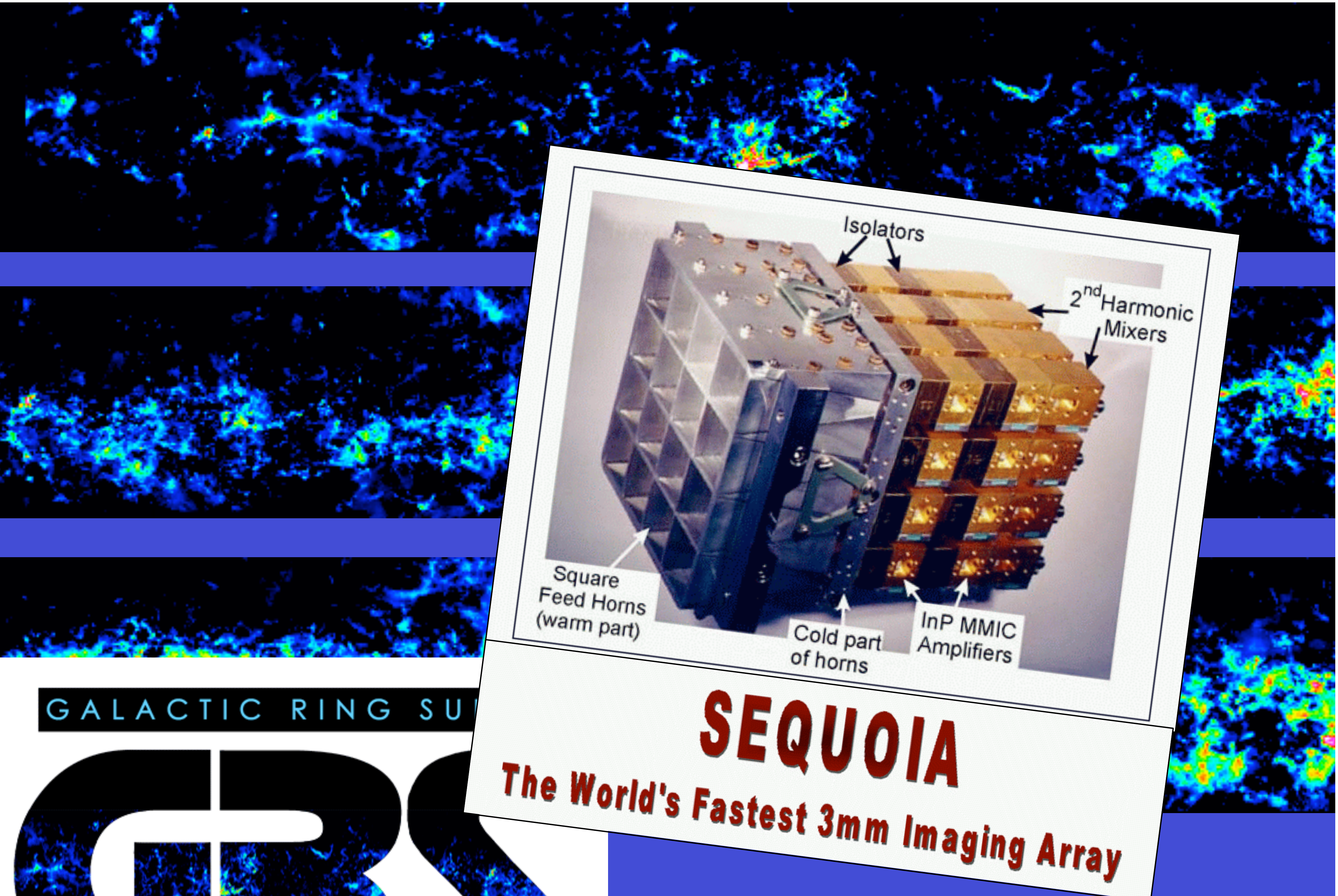
Bolometer arrays have completely dominated the field of submillimeter *continuum* observations for ~20 years now

The power of (bolometer) array science

The Galactic Center Region as seen by SCUBA at 850 μm



Pierce-Price et al. 200



GALACTIC RING SU

GRS

BOSTON UNIVERSITY-FCRAO

Pasadena, 23 March 2

Heterodyne arrays are becoming available just now:

A&A 423, 1171–1177 (2004)
DOI: 10.1051/0004-6361:20034179
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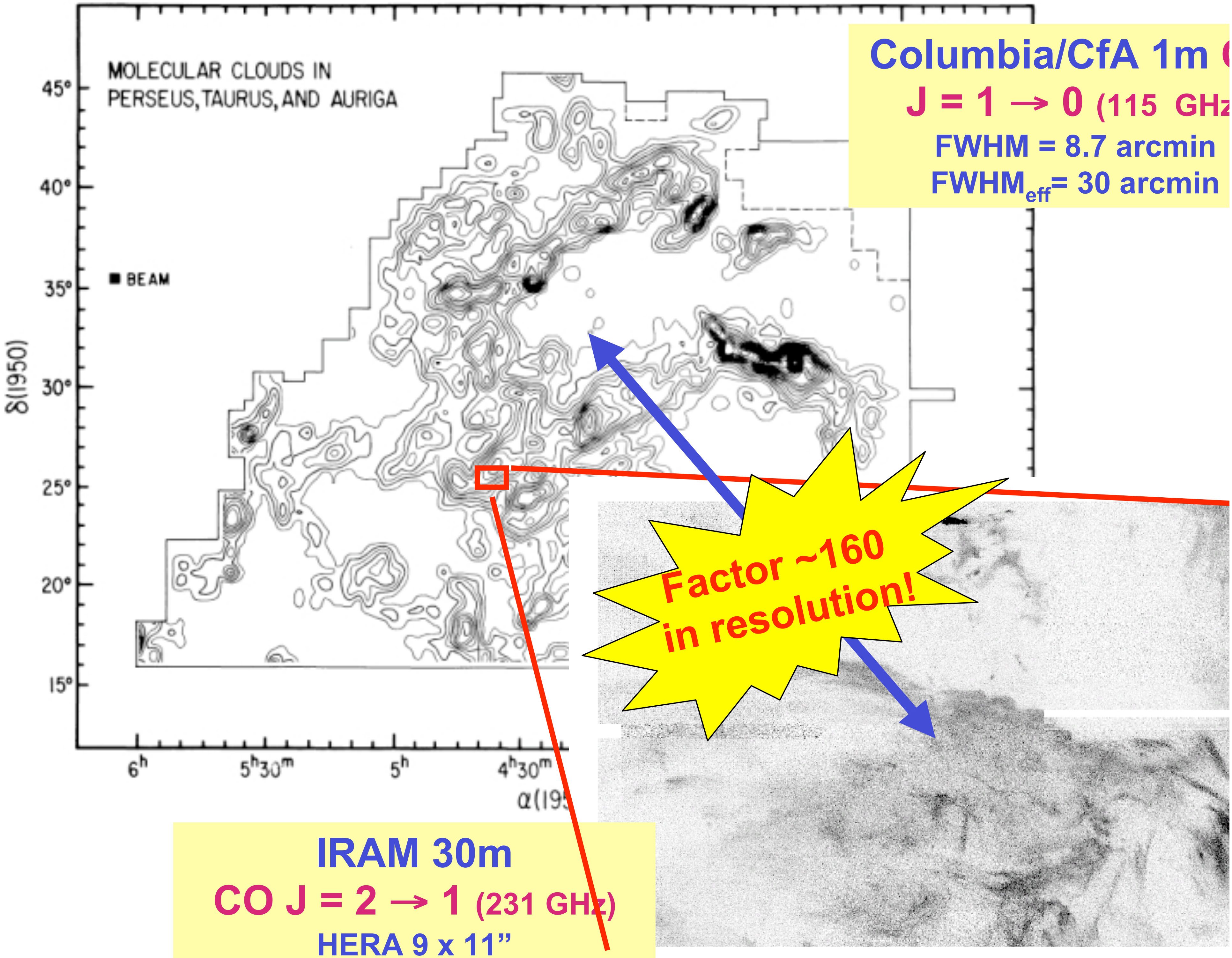
Astronomy & Astrophysics

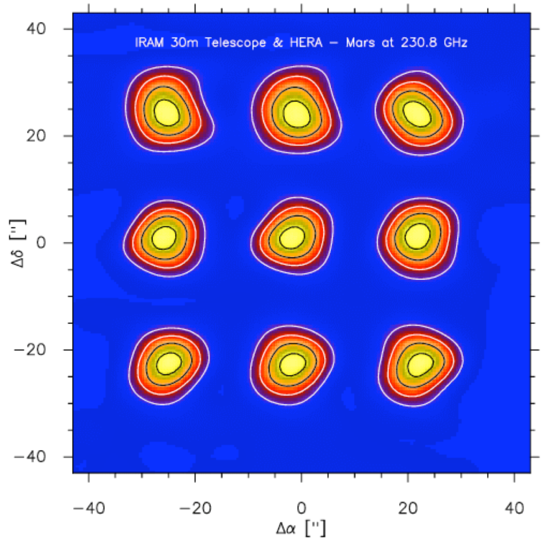
A 230 GHz heterodyne receiver array for the IRAM 30 m telescope

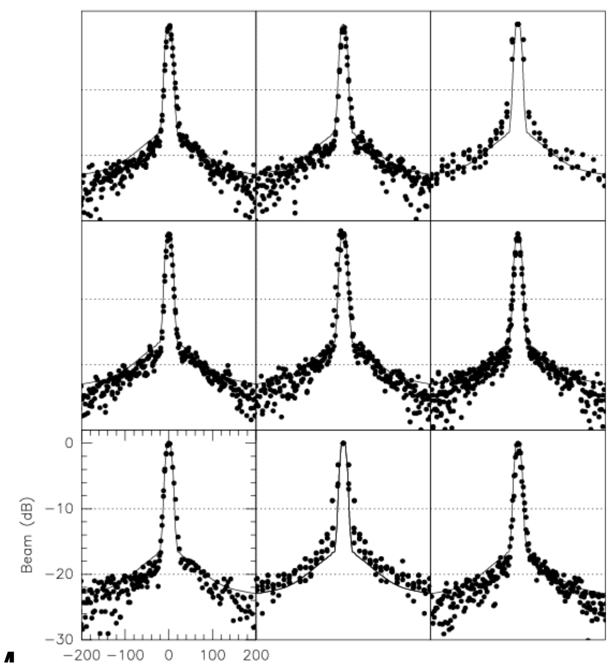
K.-F. Schuster[1], C. Boucher[1], W. Brunswig[1], M. Carter[1], J.-Y. Chenu[1], B. Foullieux[1,2], A. Greve[1], D. John[1], B. Lazareff[1], S. Navarro[1], A. Perrigouard[1], J.-L. Pollet[1], A. Sievers[1], C. Thum[1], and H. Wiesemeyer[1]

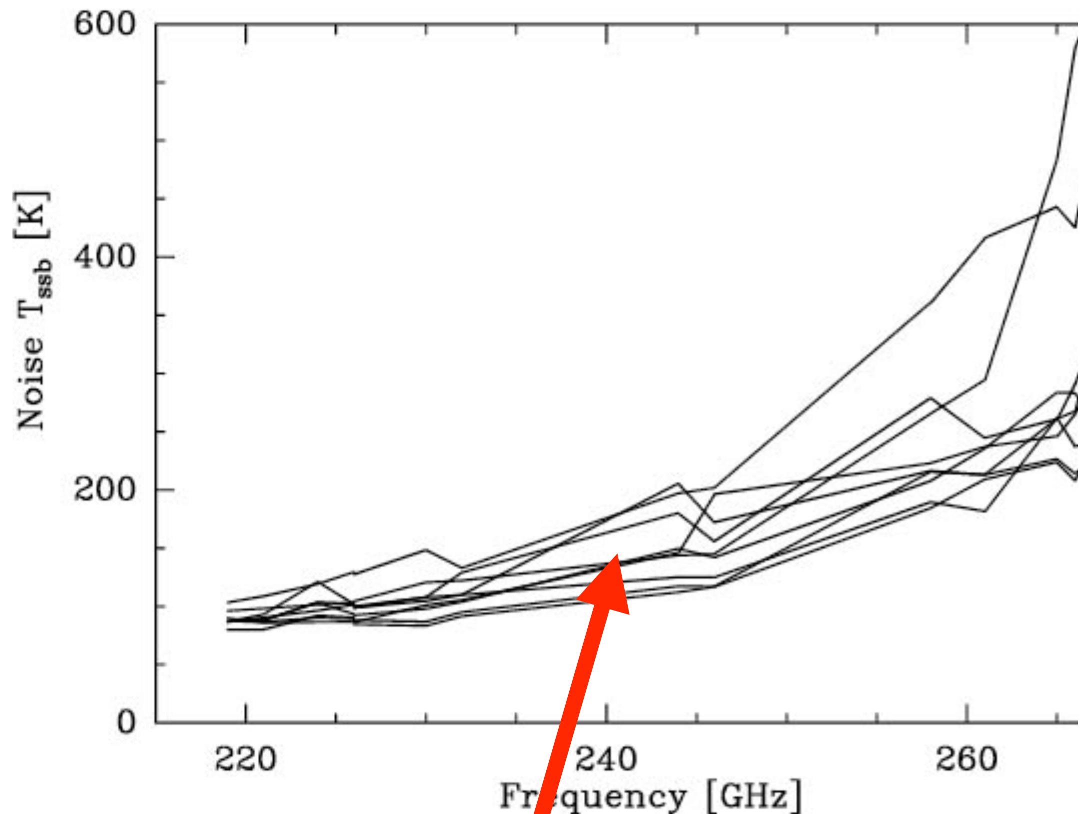
HERA = HEterodyne Receiver Array


MOLECULAR CLOUDS IN
PERSEUS, TAURUS, AND AURIGA
BEAM
45°
40°
35°
30°
25°
20°
15°
δ(1950)
6h
5h30m
5h
4h30m
Columbia/CfA 1m
J = 1 → 0 (115 GH
FWHM = 8.7 arcmin
FWHMeff = 30 arcmin
Factor ~160
in resolution!
IRAM 30m
CO J = 2 → 1 (231 GHz)
HERA 9 x 11”

Common sense requirements:





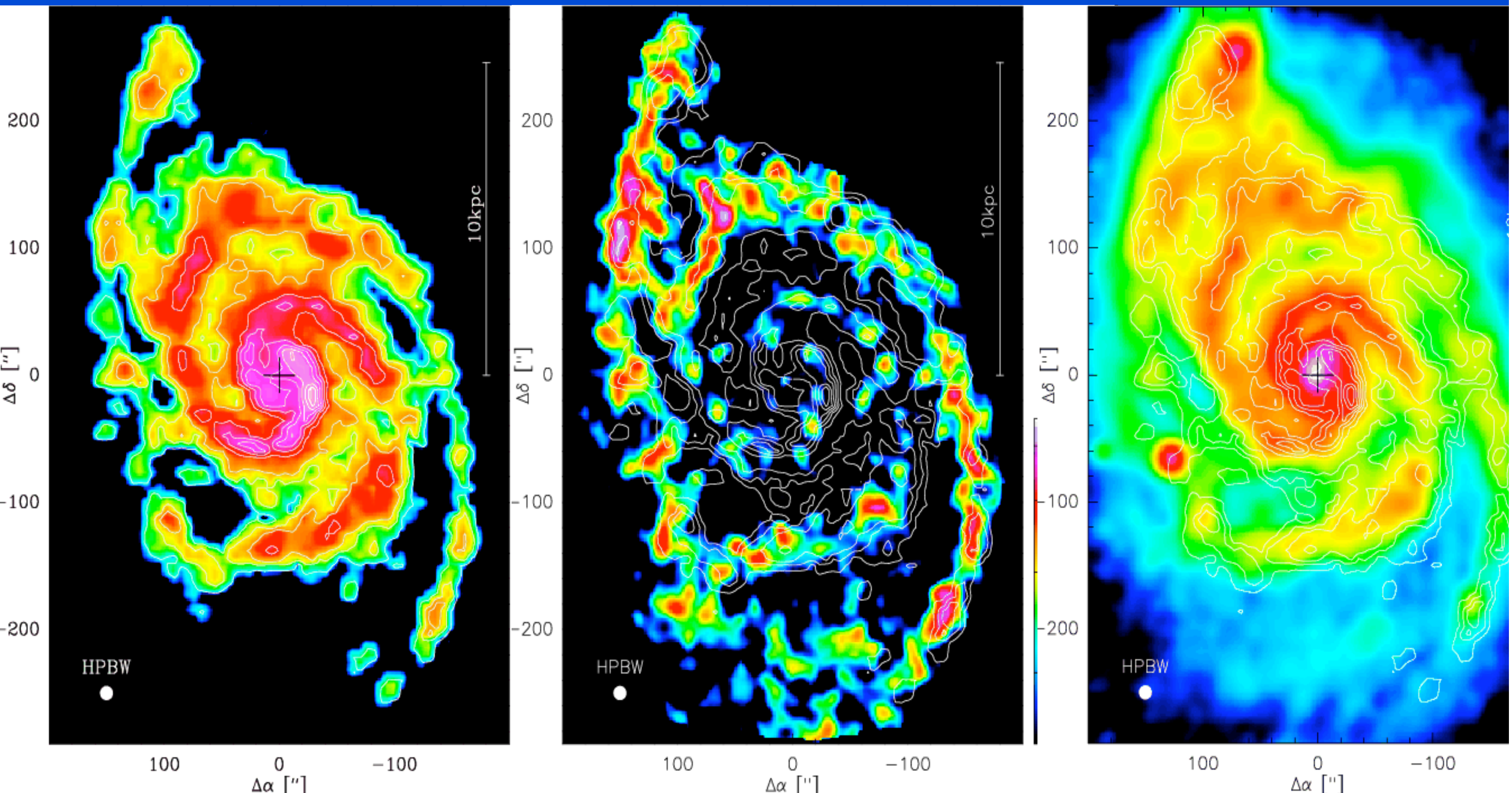


Important:

- **Uniform beams**
- **Uniform T_{RX}**

and

T_{RX} not "much" worse than T_{RX} of state-of-the-art single pixel RX

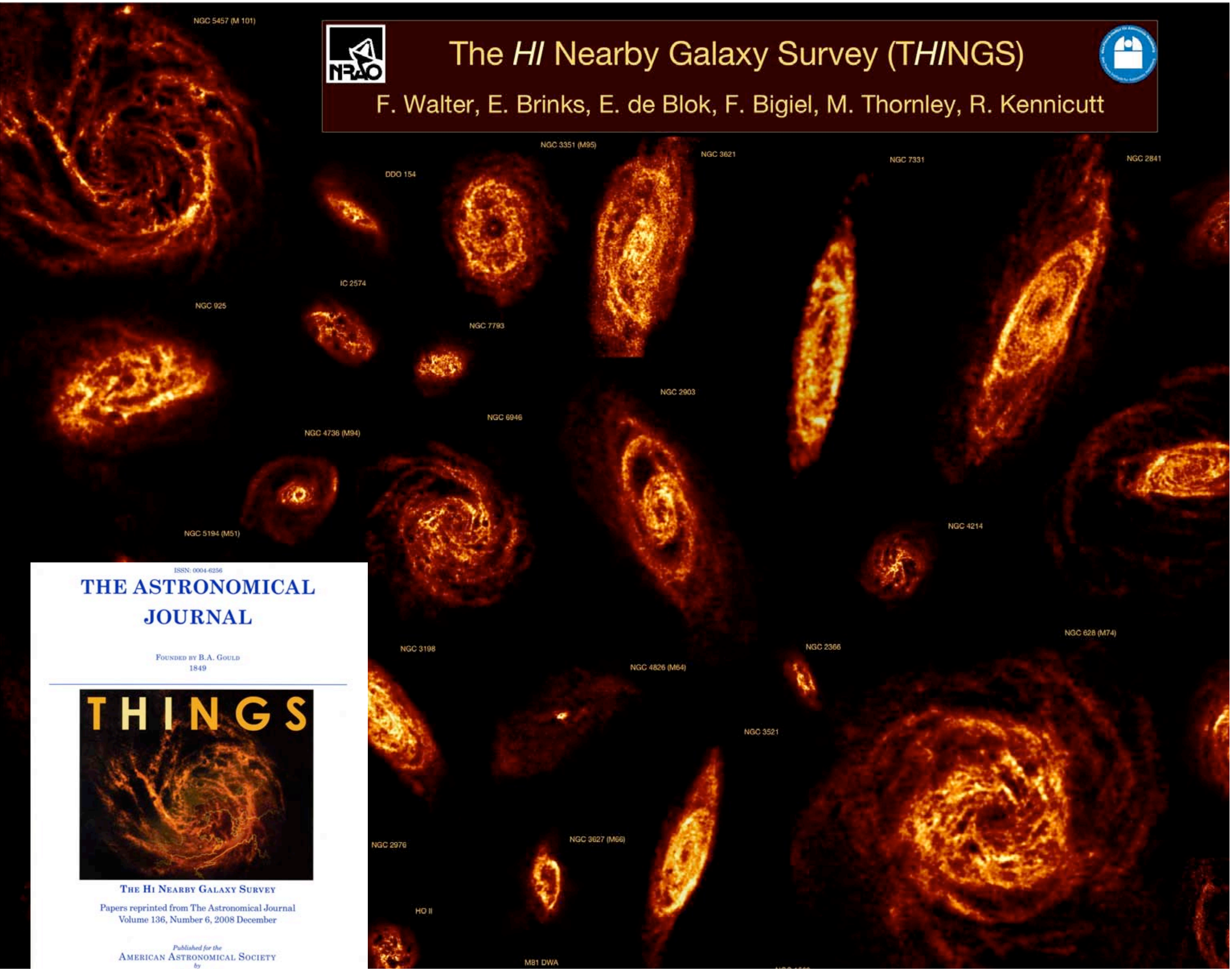


CO J = 2 – 1
FWHM = 11"
HERA@IRAM 30m

HI 21 cm
FWHM = 13"
VLA

Radio 20 cm
FWHM = 15"
VLA

Schuster et al.


The HI Nearby Galaxy Survey (THINGS)
F. Walter, E. Brinks, E. de Blok, F. Bigiel, M. Thornley, R. Kennicutt
NGC 5457 (M 101)
DDO 154
NGC 3351 (M95)
NGC 3621
NGC 7331
NGC 2841
IC 2574
NGC 925
NGC 7793
NGC 2903
NGC 6946
NGC 4736 (M94)
NGC 5194 (M51)
NGC 4214
NGC 628 (M74)
NGC 3198
NGC 2366
NGC 4826 (M64)
NGC 3521
NGC 2976
NGC 3627 (M66)
HO II
M81 DWA
ISSN: 0004-6256
THE ASTRONOMICAL JOURNAL
Founded by B.A. Gould
1849
THINGS
The HI Nearby Galaxy Survey
Papers reprinted from The Astronomical Journal
Volume 136, Number 6, 2008 December
Published for the
American Astronomical Society
by

Concentrate here an molecular line astronom

Advantages of array receivers:

- **Mapping speed**
- **Mapping homogeneity (map lage areas with similar weathe conditions/elevation) → minimize calibration uncertainties.**

Common sense requirements for any array RX:

Important:

- **Uniform beams**
- **Uniform T_{RX}**

and

T_{RX} not “much” worse than T_{RX} of state-of-the-art single pixel

All of the above superbly met by MMIC array spectrographs!

Heterodyne array molecular line astronomy

- Study large-scale distribution of gas an various scales → CO
- Unbiased imaging to find "interesting" regions (= star formation). In particular: probe protostars and their environments)
    - Signposts (= masers)
        - CH_3OH 6.7 and 12.2 GHz, H_2O 22.2 GHz
    - Regions of high density/column density/temperature
        - Ob serve thermal emission from "tracer" molecules
        - Once found, *map column* density

        → model calculations ⇒ temperature/density

K-band-Science (18 – 26 GHz)

• For temperature and column density determinations ideal: Ammonia (NH_3)

• Multiple K-band lines (23.6 – 25 GHz) that car be done simultaneously

and

• simultaneously with 22.2 GHz H_2O maser line

and

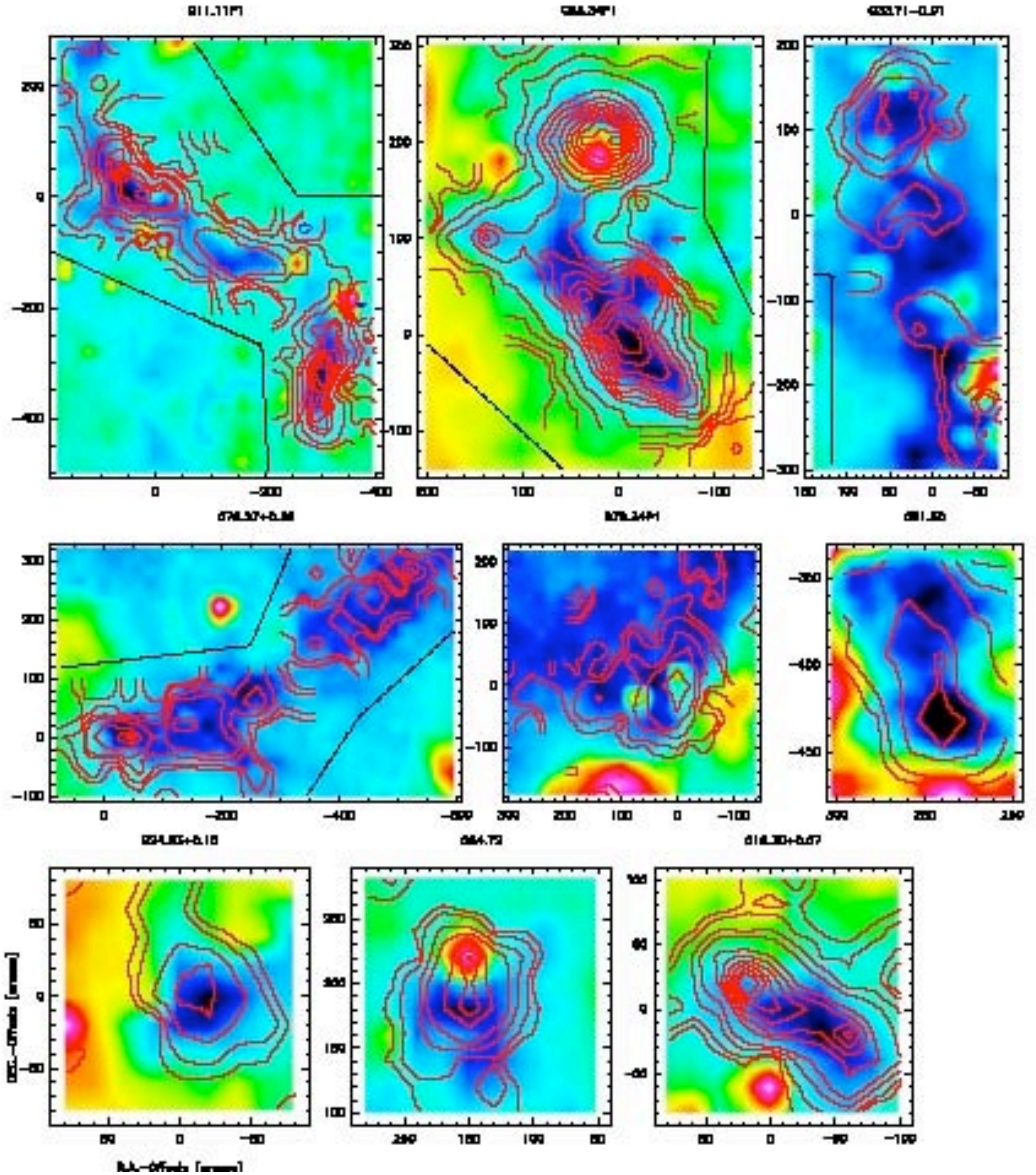
• simultaneously with 25 GHz series of CH_3OH lines (maser and thermal)

⇒ K-band RX array would be **VERY** interesting!

NH_3 in Infrared Dark Clouds

Effelsberg 100m

Dissertation of T. P



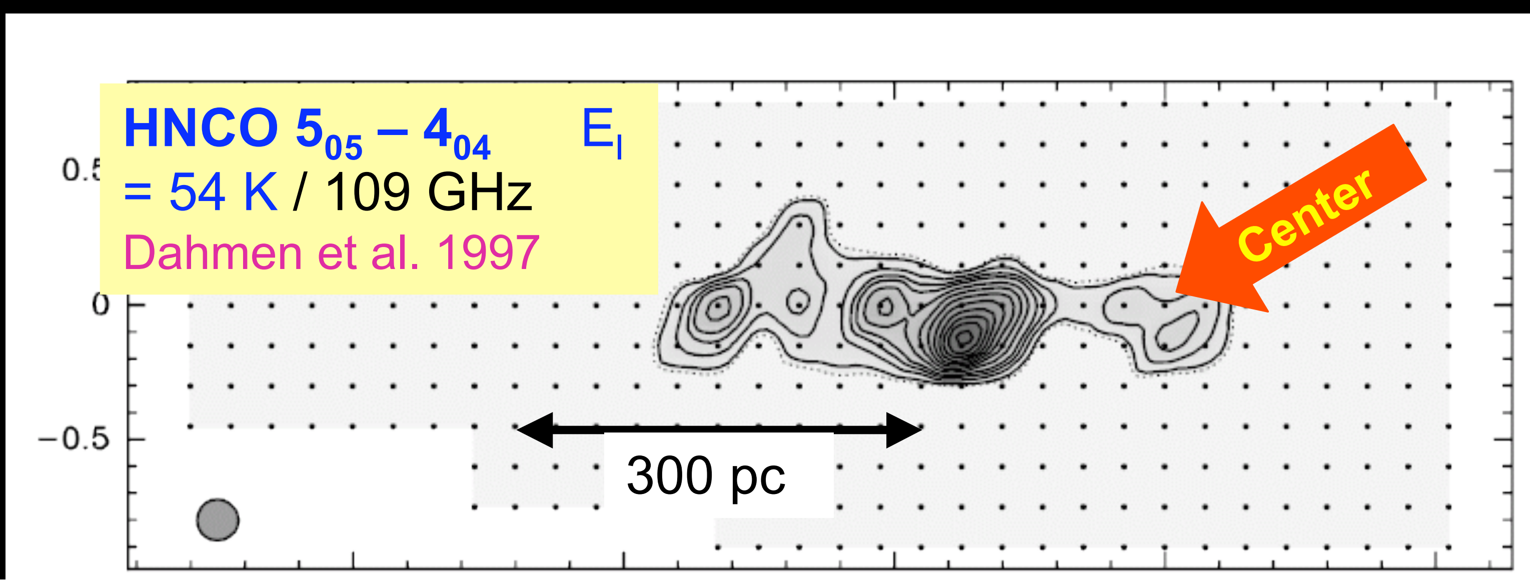
W-band-Science (80 – 116 GHz)

- Apart from CO J=1-0 lines there are ground- or near-ground-state transitions of HCN, HNC, CN, N_2H^+, HCO^+, CH_3OH, SiO… all between 80 and 115 GHz
- Because of their high dipole moments, these species trace high density gas ($n > 10^4$ cm^{-3}) (↔ CO: $n > 10^2$ cm^{-3})
- Large-scale distribution of these molecules on larger GMC scales poorly known
- Strong emission in these lines, as well as in rare $C^{18}O$ isotope, traces high column densities *(→ star formation*
- These lines are very widespread (= everywhere) over the whole Galactic center region ($-0.5^0 < l < 2^0$)

The interstellar medium in the Central Molecular Zone of our Galaxy

The Central Molecular Zone (CMZ)

- huge Giant Molecular Cloud (GMC) complex:
  - ~0.3º broad band around the center of our Galaxy from *l* = +1.9º to -1.
- GMCs in CMZ have properties that are quite different from "normal" (i.e. spiral arm) clouds: they are much
  - denser (n ~ 10^4 cm^{-3} vs. 10^2 cm^{-3}),
  - much warmer (60 K < T < 120 K vs. 10 – 20 K),
  - and much more turbulent (Δv ~ 10 – 20 km/s vs. a few km/s).



Sensitivity

$$rms = \frac{const \cdot T_{\text{sys}}}{\sqrt{\Delta\nu \cdot t_{\text{int}}}}$$

For Fast Fourier Transform Spectrometers (FFTS), $const \approx 1$

Assume

T_{sys} **= 100 K and**

Δv = 1 km/s

$\Rightarrow$ **Δν = 300 kHz@90GHz**

= 80 kHz@24 GHz

$\Rightarrow$ **rms(1 sec) = 0.2 K at 90 GHz and 0.35 K at 24 GHz**

Mapping speed

⇒ **rms(1 sec) = 0.2 K at 90 GHz and 0.35 at 24 GHz**

IRAM 30m	**Effelsberg 100m**
24” FWHM@90 GHz	**40”@24 GHz**

Positions to observe for a Nyquist-sampled map of 1 square degree

90000	**32400**

Time needed for a map with an N pixel array

25/N hours	**9/N hours**

Mapping speed and sensitivity estimates indicate that very larg sections (if not all) of the Galactic plane can be imaged

HUGE advantage over SiS arrays: Many lines in HEMT band ca be imaged *simultaneously*

Necessary Spectrometer capability:

Example W-Band:

- **Want to do 20 lines simultaneously**
    - **need ~300 km/s (= 100 MHz) each**

⇒ Need N × 20 × 100 MHz = N × 2 GHz

2 GHz FFTS bandwidth cost ~ a few kEU today

At today's prizes, an FFTS for a 100 element array would "only cost a few hundred kEU

***HOWEVER:* Above is the *de luxe* correlator. To save money, could do fewer lines, use narrower bandwidths**

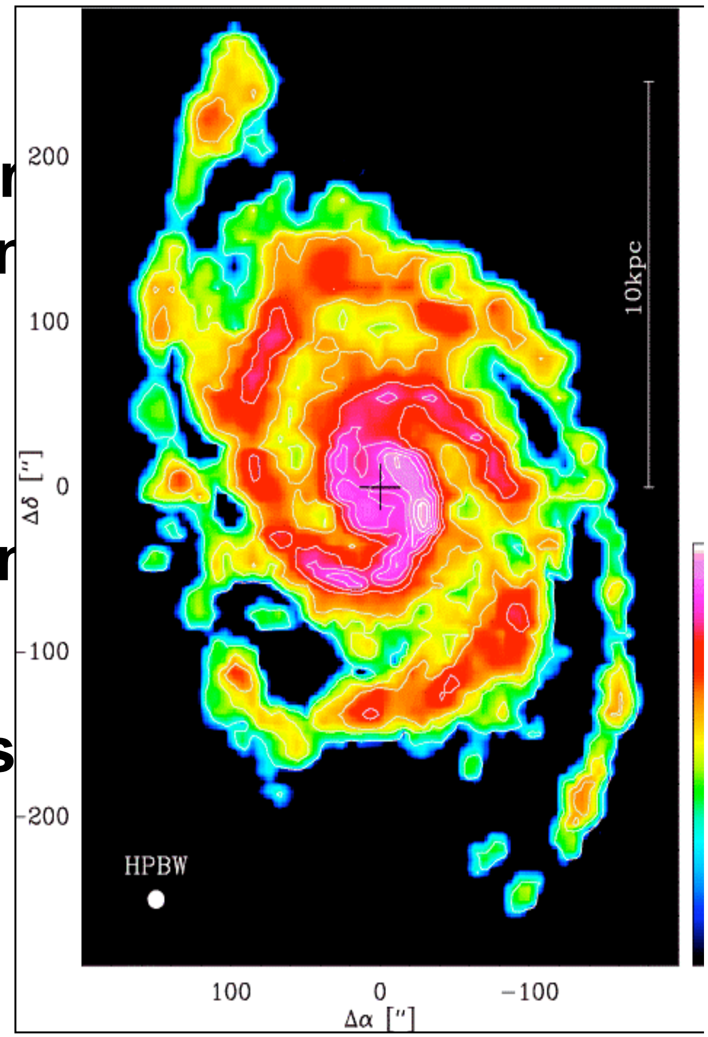
Other *most interesting* projects include complete (mostly) ^{12}CO and ^{13}CO mapping of nearby galaxies.

These are HUGE (many square arc minutes)!

Such maps would be interesting in their
***absolutely necessary* as zero spacing in**
the PdBI, and ALMA.

***REALLY FANTASTIC* would be MASs on**

… and they would make these facilities
ALMA era, as ALMA will not have MASs



Subject: Fwd: MMIC Array Receivers and Spectrographs Workshop 2: program
From: Tim Pearson <tjp@astro.caltech.edu>
Date: 19.03.2009 23:12
To: Karl Menten <kmenten@mpifr-bonn.mpg.de>
Cc: Charles Lawrence <charles.r.lawrence@jpl.nasa.gov>, Tony Readhead <acr@astro.caltech.

Dear Karl,

I hope you will be able to give us a short presentation on current developments at MPIfR, APEX, etc., and provide a European perspective for our workshop. We look forward to seeing you in Pasadena on Sunday!

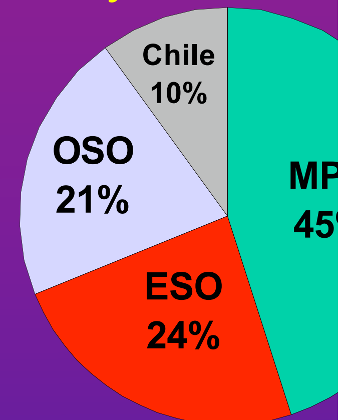
Regards

Tim

The Atacama Pathfinder Experiment (APE

Built and operated by
- Max-Planck-Institut fur Radioastronomie
- Onsala Space Observatory
- European Southern Observatory

on
Llano de Chajnantor (Chile)
Longitude: 67° 45’ 33.2” W
Latitude: 23° 00’ 20.7” S
Altitude: 5098.0 m

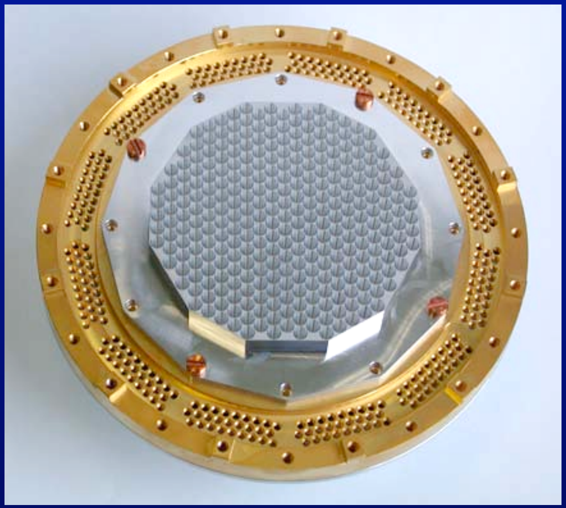


- **∅ 12 m**
- λ = 200 μm – 2 mm
- 15 μm rms surface accuracy
- currently (June 2005) in final testing phas
- PI and facility instruments:
  - 345 GHz heterodyne RX
  - 295 element 870 μm Large Apex Bol meter Camera (LABOCA)

http://www.mpifr bonn.mpg.de/div/mm/apex/

The need for large area mapping:

Bolometer arrays are getting ever larger:

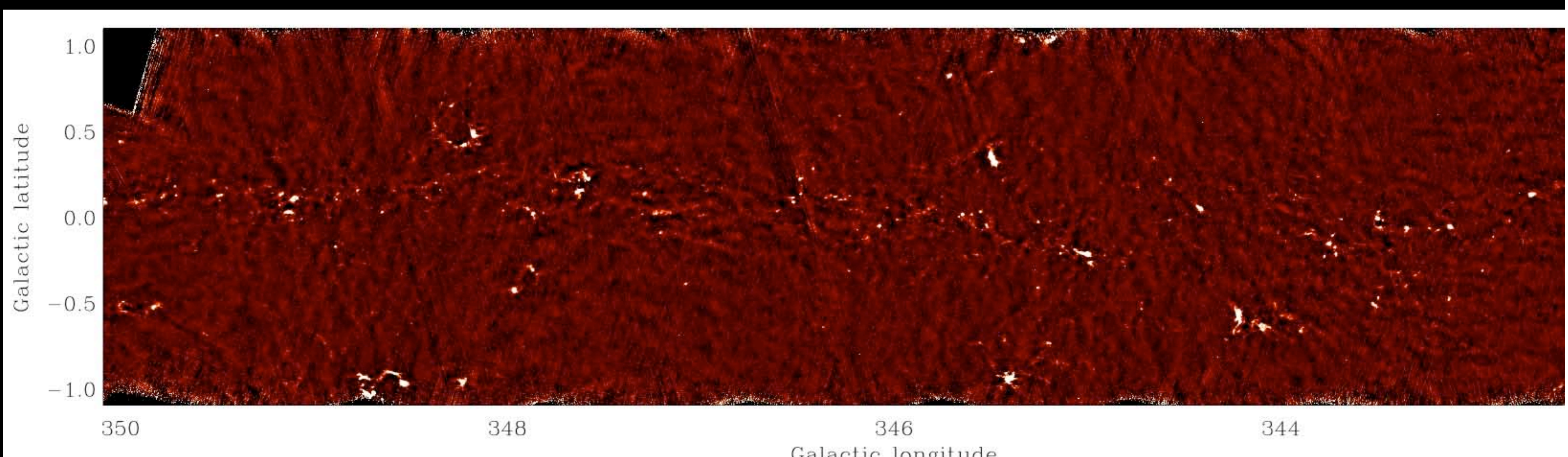
SCUBA	LABOCA	SCUBA-2
		
37 bolometers	295 bolometers	2 × 5128 bolometers
yesterday	**since 2007**	**2010?**

In addition: MAMBO-II, Bolocam, SHARC-II, …

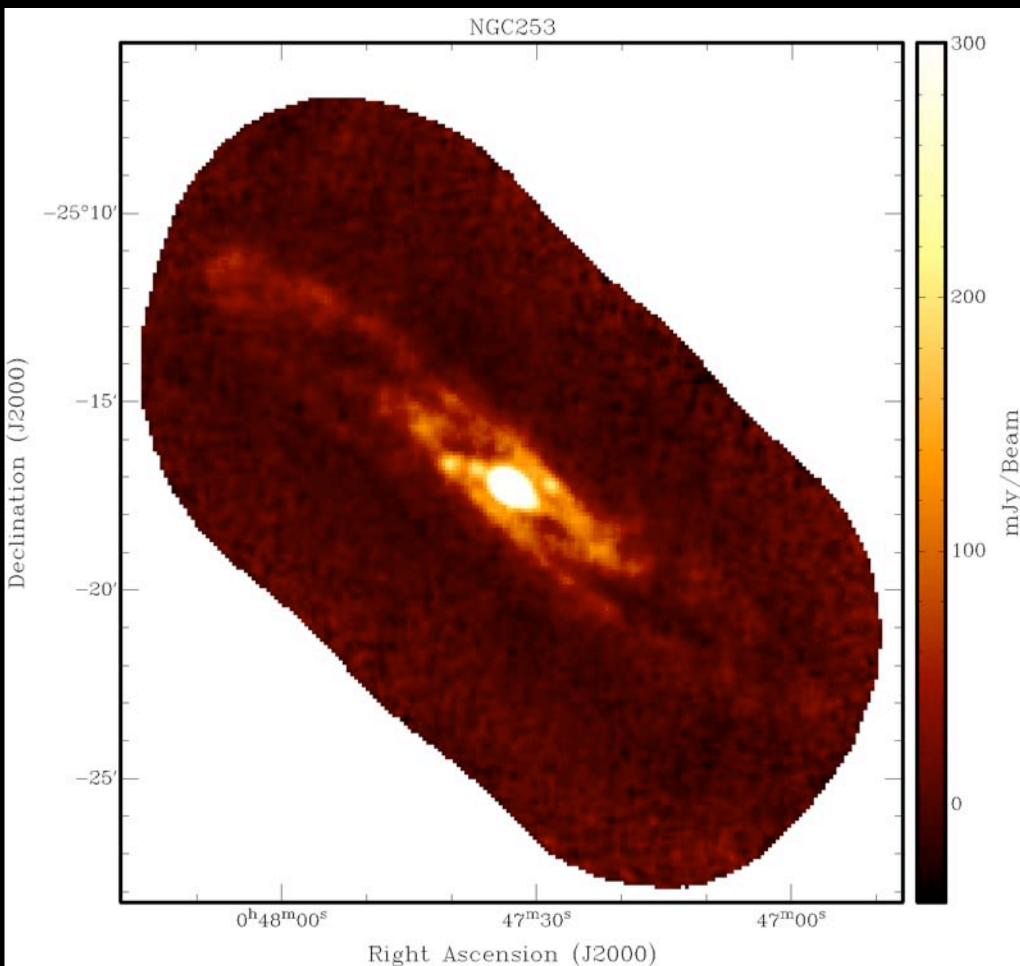
ATLASGAL
(APEX Telescope Large Survey: The Galaxy)

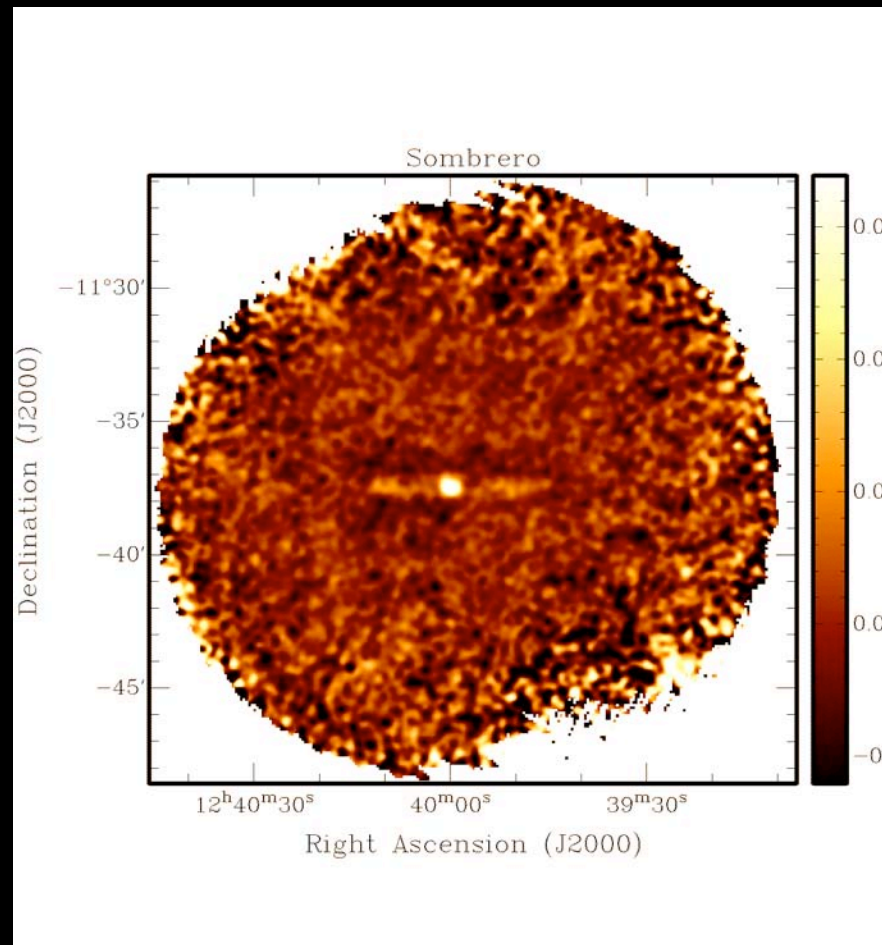
- **Main goals:**
  - **To have a complete 350 GHz census of high mass star formation in the Galaxy (= whole part of Galactic plane visible with APEX)**
  - **To detect protostellar condensations down tens of $M_{\odot}$ throughout the Milky Way**

Total observing time: ~1000 hours



Some LABOCA Results





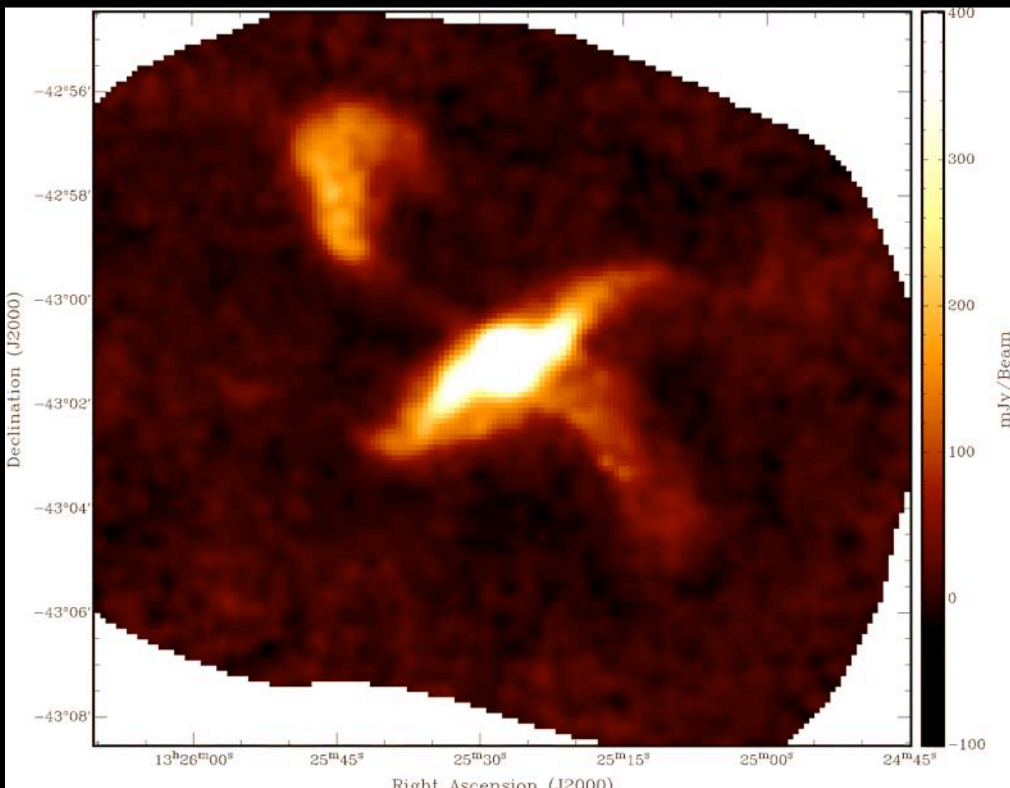
NGC 253

Weiss et al. 2008

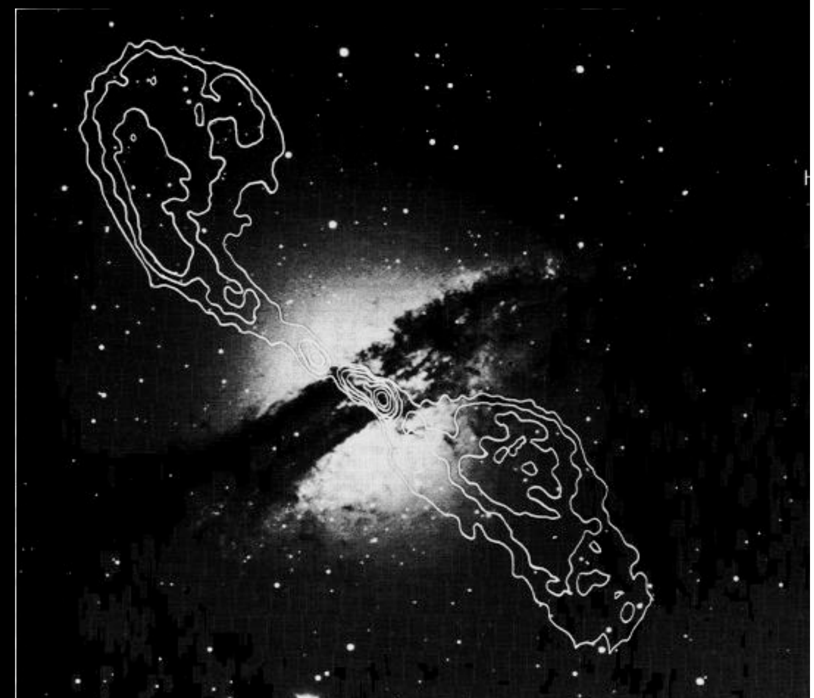
M104 (El Sombrero)

Vlahakis et al. 200

Centaurus A



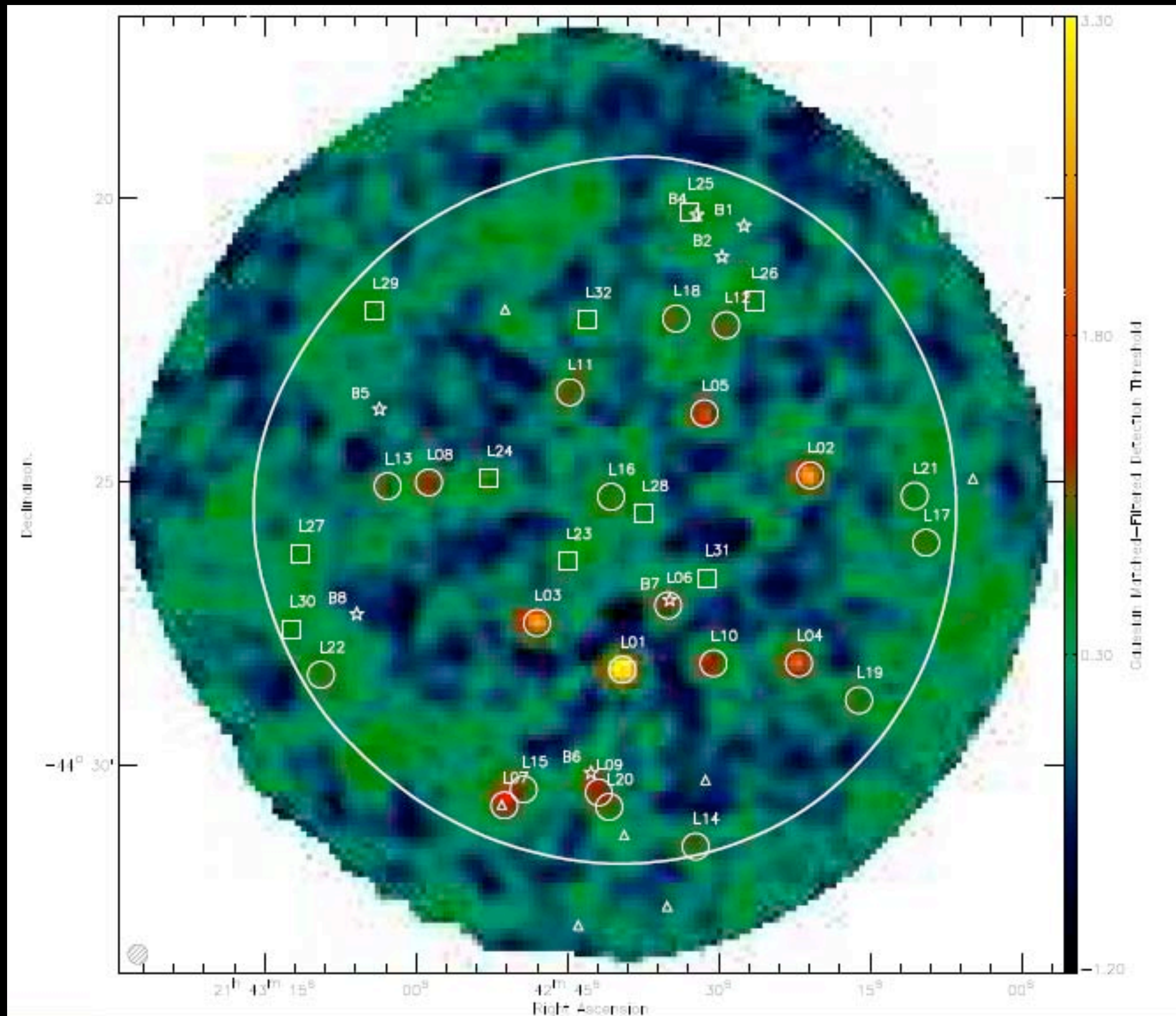
APEX 870 μm



Optical/VLA 6cm
(Burns e tal. 1983)

z = 2.38 Protocluster with Ly α blobs

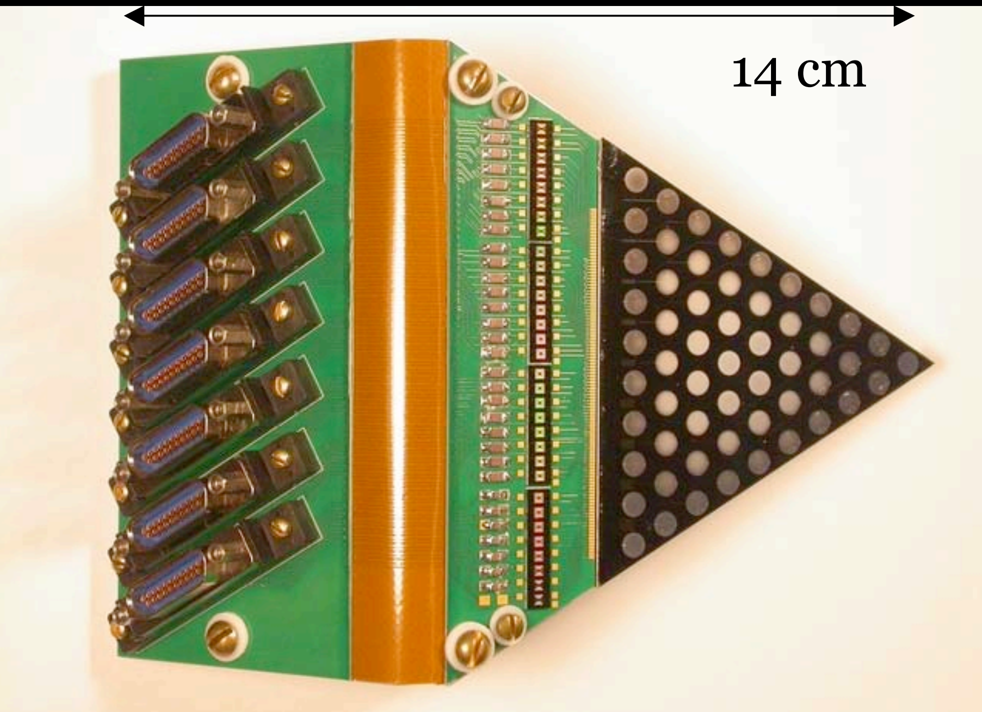
10 arcmin

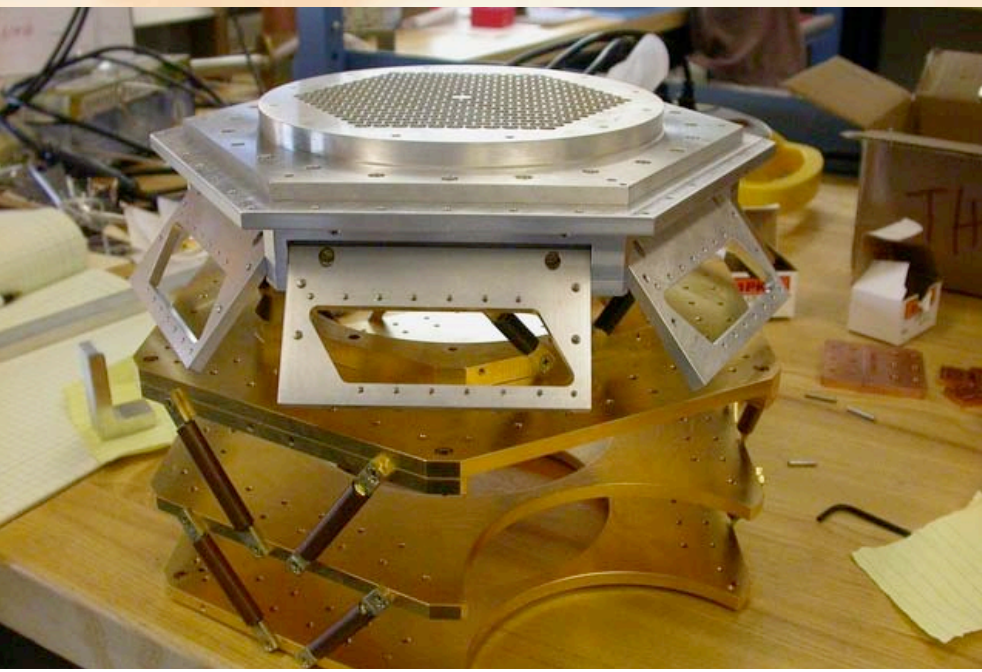


LABOCA 870 μm

Beelen et al. 2

UCB/APEX SZ Array

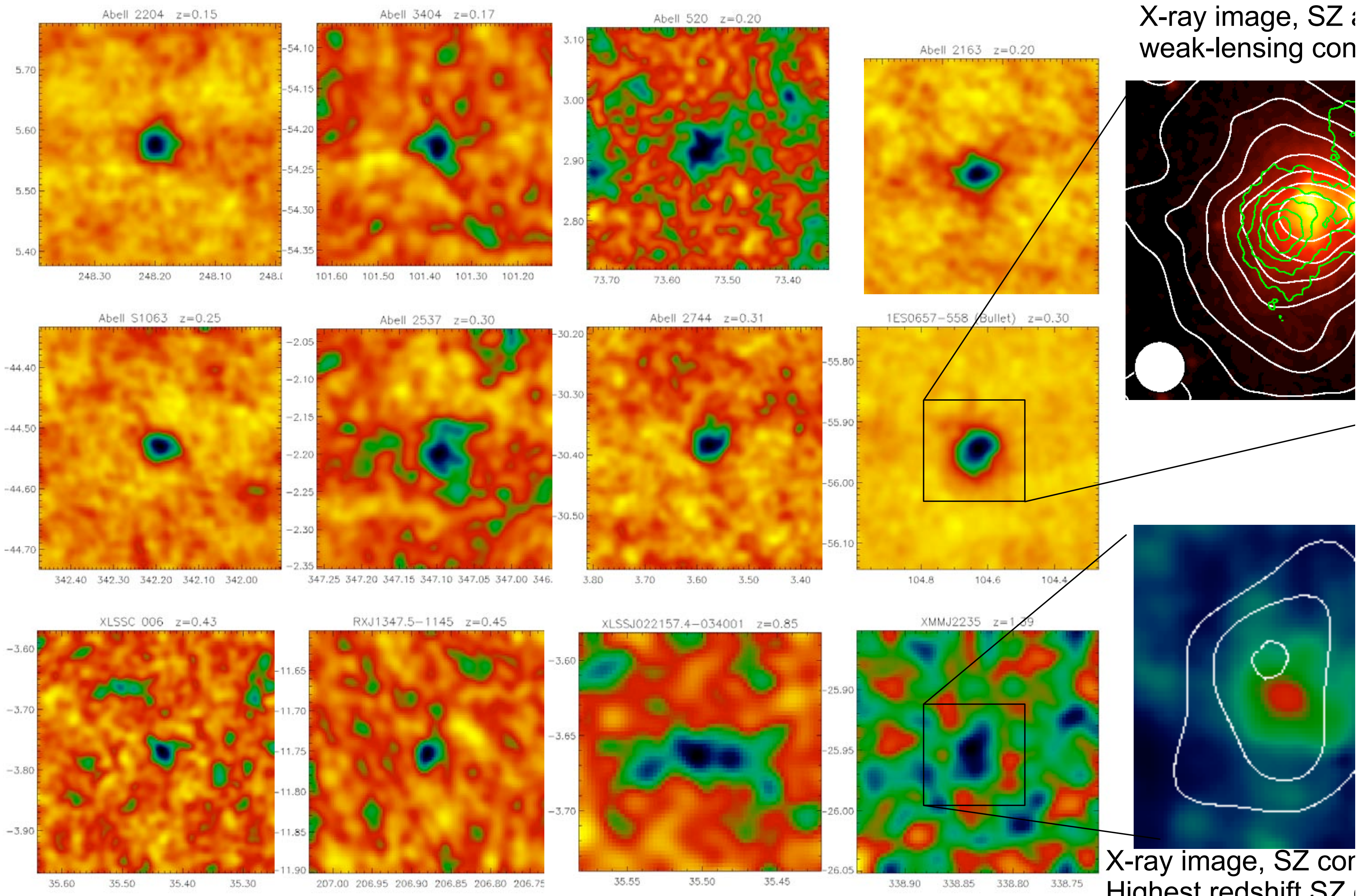




http://bolo.berkeley.edu/apexsz/

- horn coupled array
- 330 bolo's in 6 wedges
- Each TES bolometer coupled through resonant circuit to SQU readout
  - direct path to Multiplexing
- 150 GHz and 217 GHz b swapping horns & filte

SZ detections from APEX-SZ



Halverson et al. 2009 +

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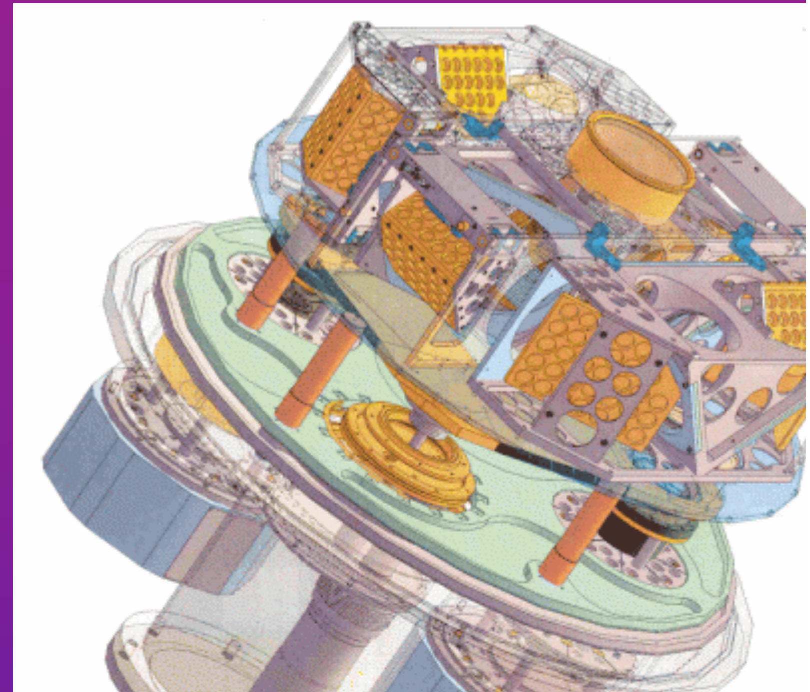
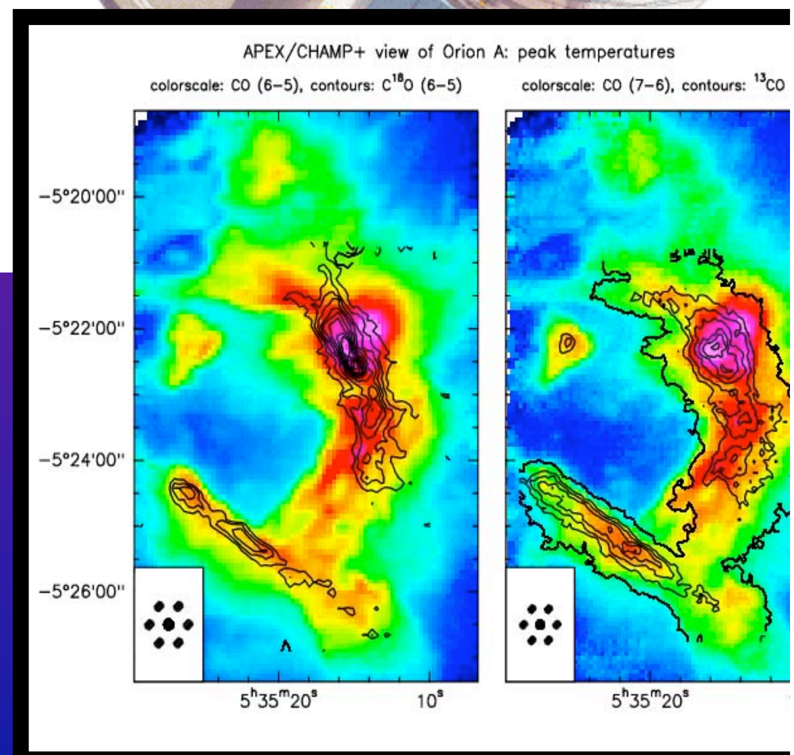
SRON



CHAMP+

Carbon Heterodyne Array of the MPIfR

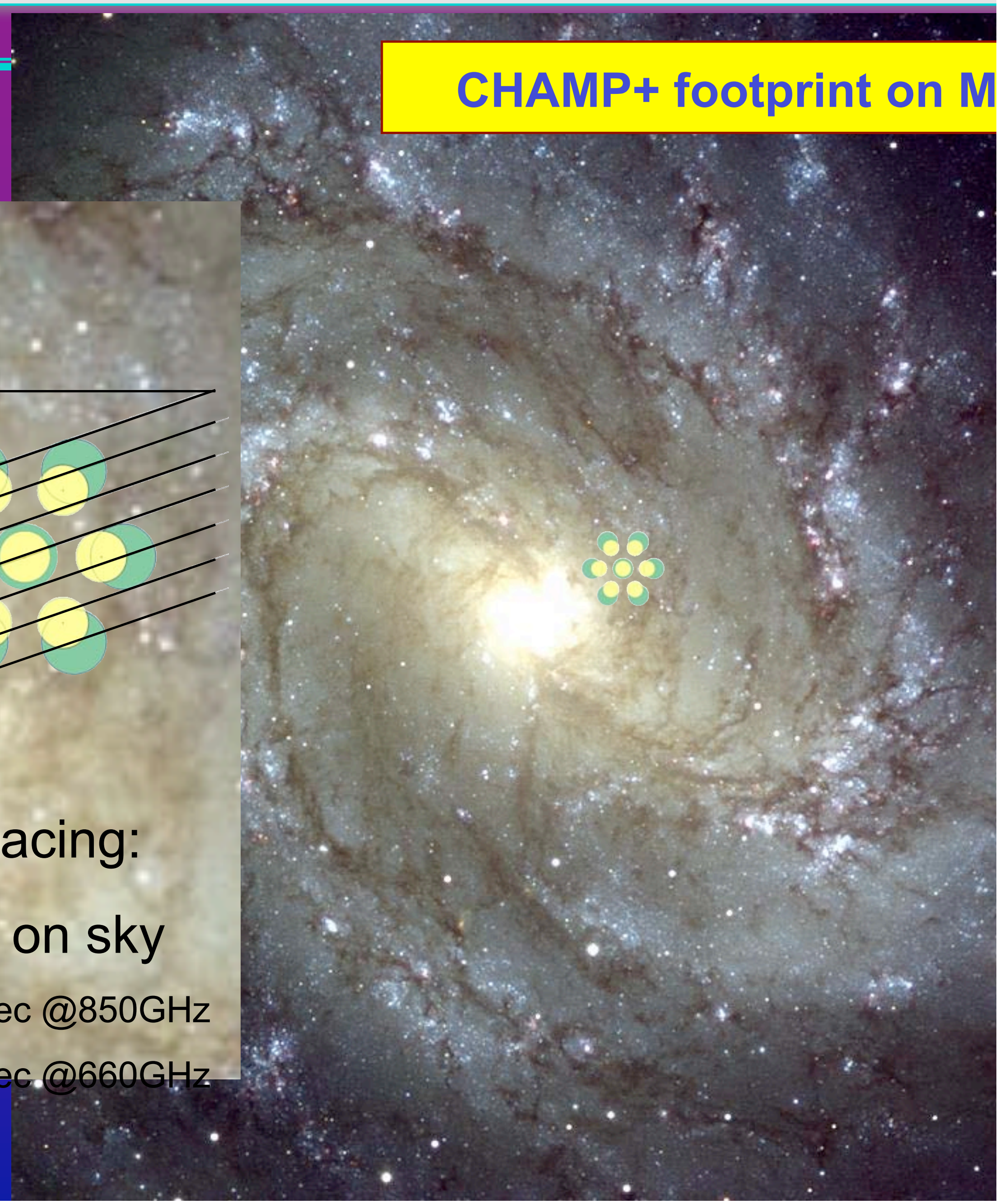
- 2 × 7 pixels
- frequency ranges 602 – 720 and 790 – 950 GHz simultaneously
- beamsize 9" – 7" and 7" – 6"
- IF band 4 – 8 GHz

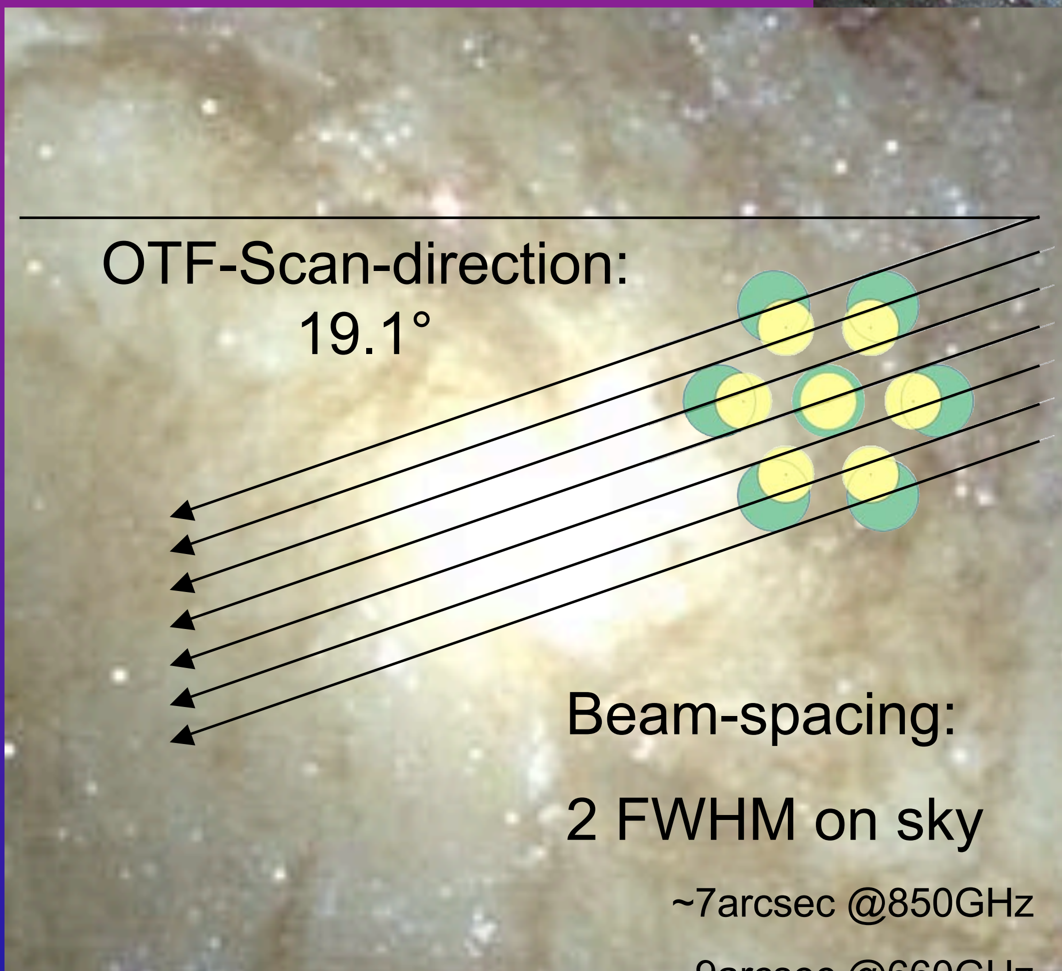


http://www.mpifr-bonn.mpg.de/div/mm/tech/het.html#champ

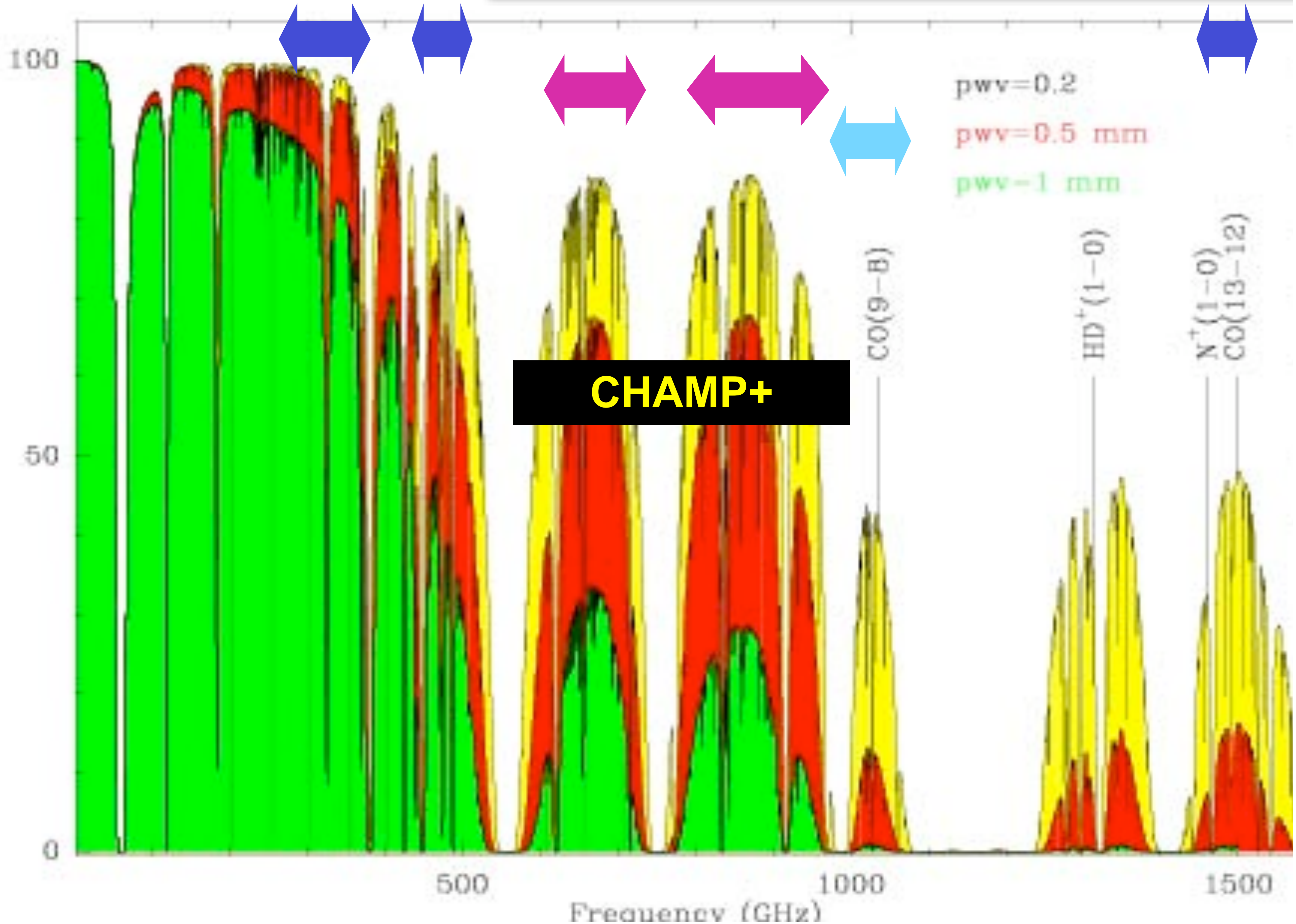
http://www.strw.leidenuniv.nl/~champ+/

APEX Instrumentation: CHAMP+ mappin





APEX Heterodyne Instrumention



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AFFTS :: *Array-FFTS for APEX*

Bandwidth: 32 x 1.5 GHz = 48 GHz (option 58 GHz)
Spec. channels: 32 x 8k = 256k channels @ 212 kHz

Similar size to what's needed for a 100 element MAS

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Broadband

Fast Fourier Transform Spectrometer

(FFTS)

- state-of-the-art and future prospects -

Bernd Klein

Max-Planck-Institut für Radioastronomie,
Bonn
- Germany -

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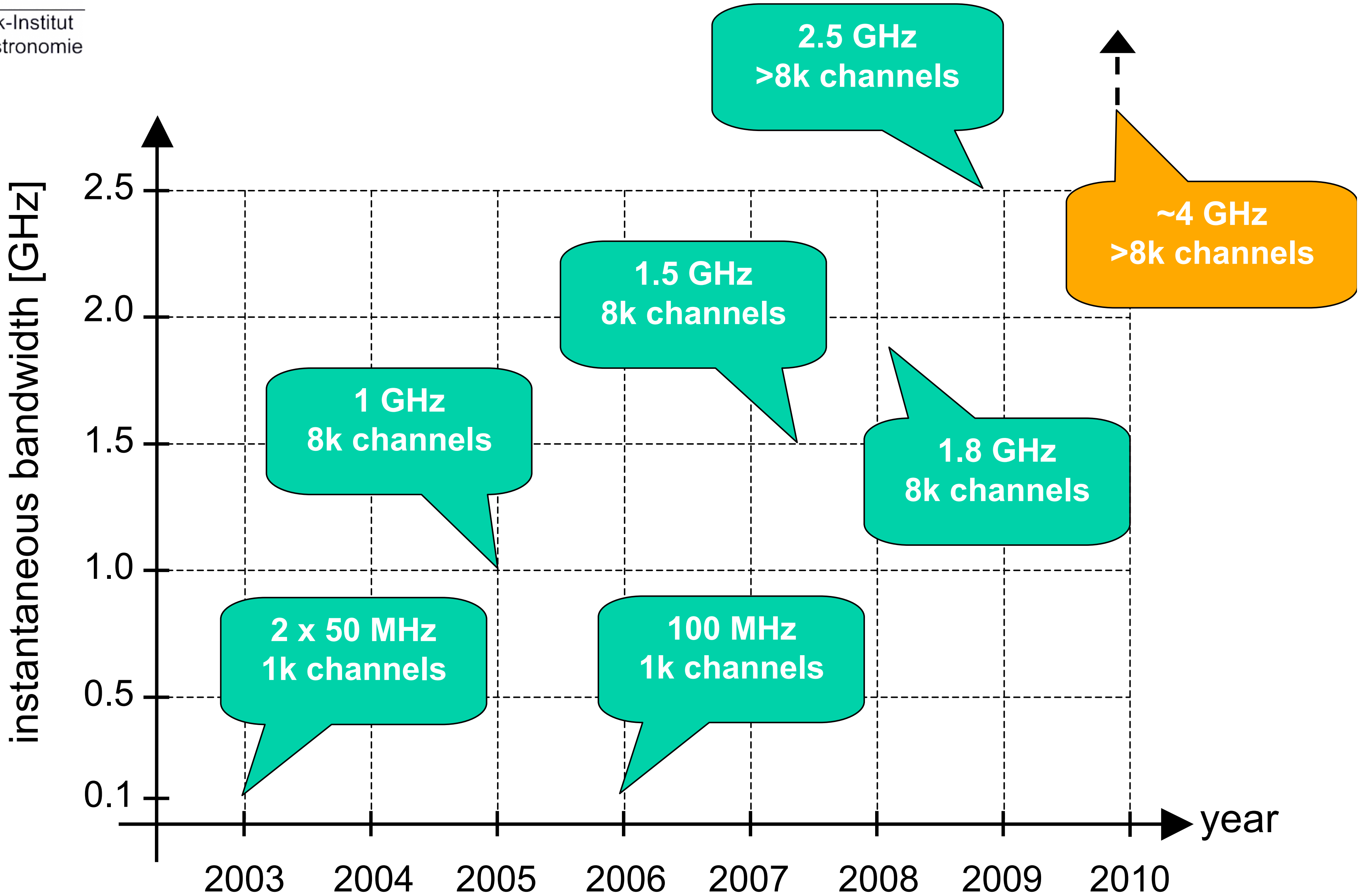
FFTS :: *A short "history" ...*



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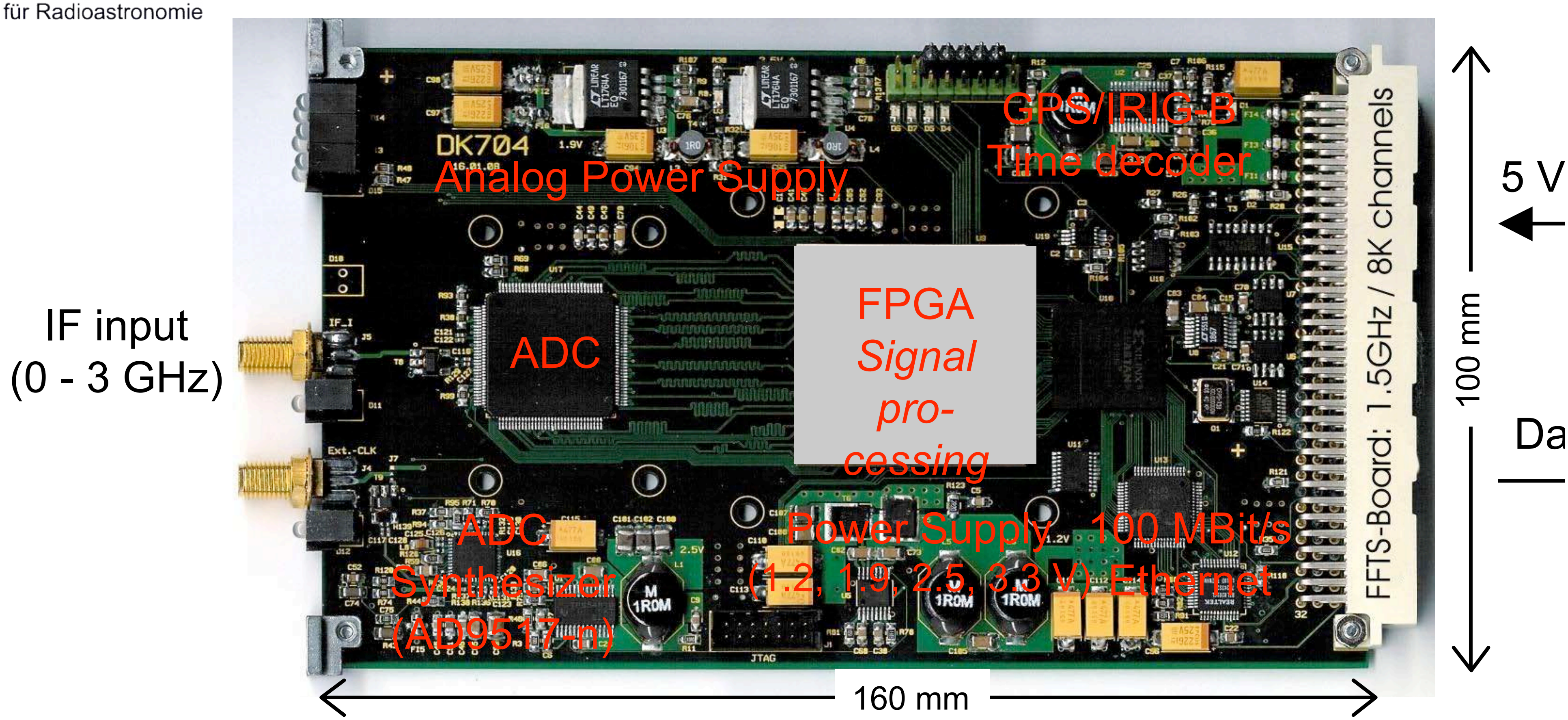
FFTS :: *The MPIfR-Board*



- Instantaneous bandwidth: 0.1 – 1.8 GHz
- Spectral resolution @ 1.5 GHz: 212 kHz
- Stability (spec. Allan Variance): > 1000 sec.
- Calibration- and aging free digital processing

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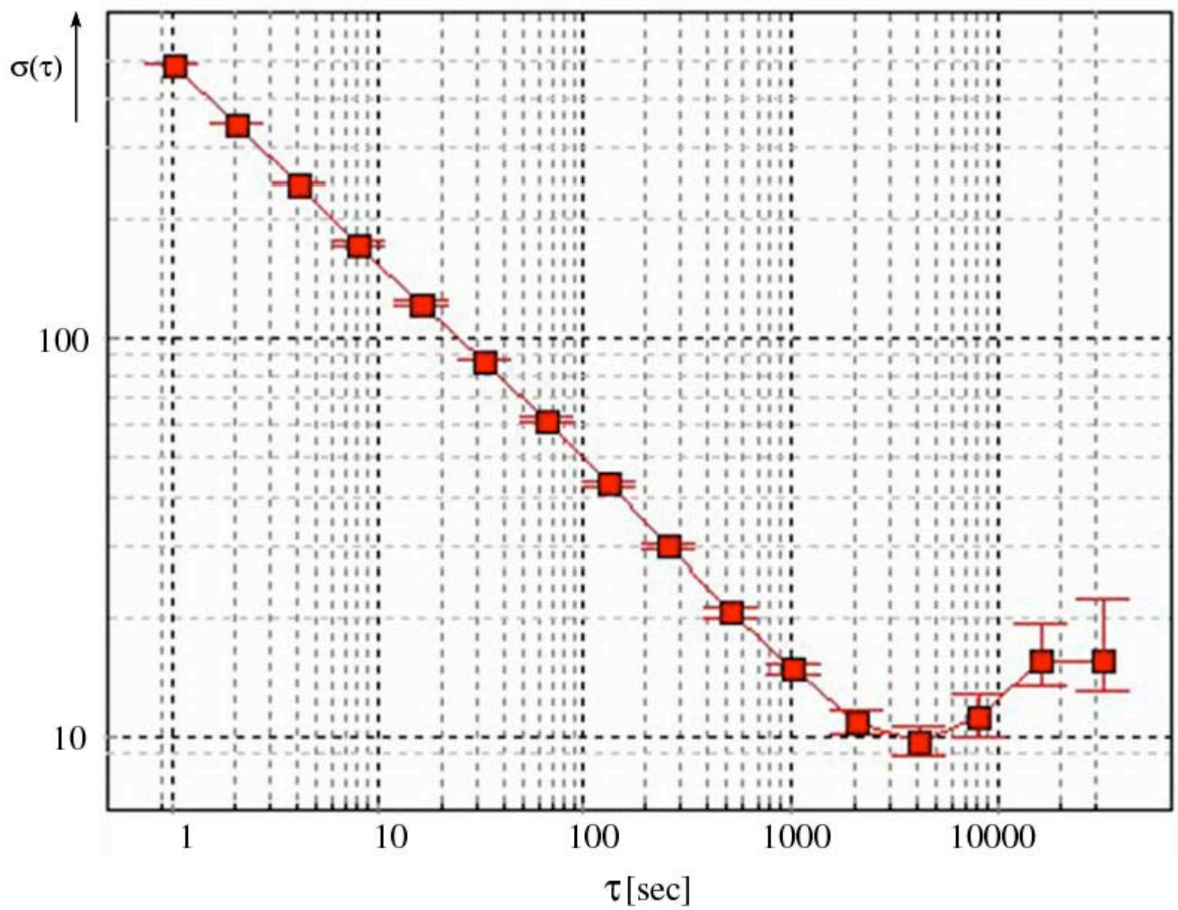
AFFTS :: *Array-FFTS for APEX*

Bandwidth: 32 x 1.5 GHz = 48 GHz (option 58 GHz)
Spec. channels: 32 x 8k = 256k channels @ 212 kHz

FFTS :: *Stability*



The spectroscopic variance between two 1 MHz broad channels, separated b
800 MHz within the band, was determined to be stable on a timescale of ~4000

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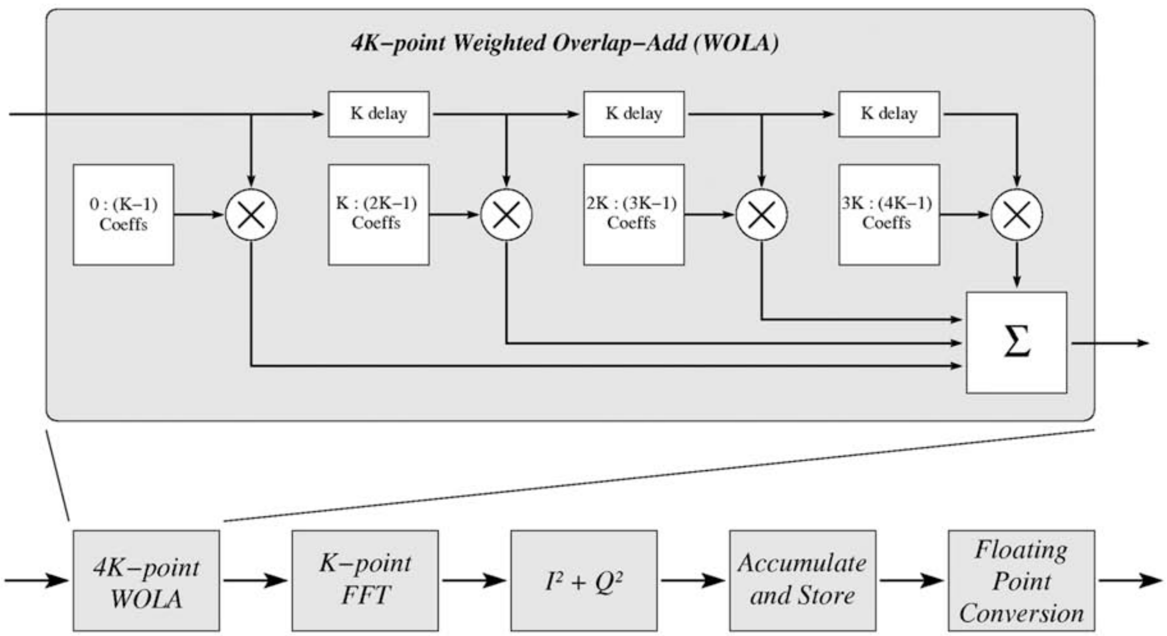
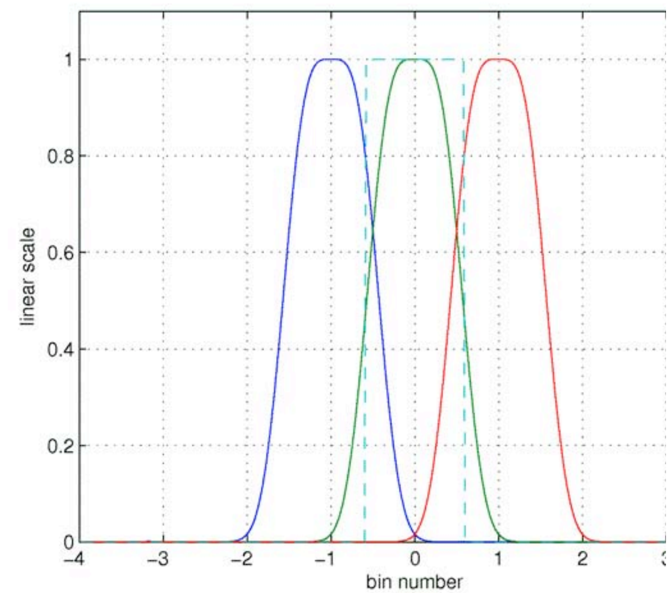
FFTS :: *Signal Processing*

Unlike the conventional windowed-FFT processing, a more efficient polyphase pre-processing algorithm has been developed with significantly reduced frequency scallop, less noise bandwidth expansion, and faster sidelobe fall-off.





Frequency response of the optimi
FFT signal processing pipeline

Equivalent noise bandwidth = 1.16 x frequency spacing

FFTS :: *FPGA configurations*

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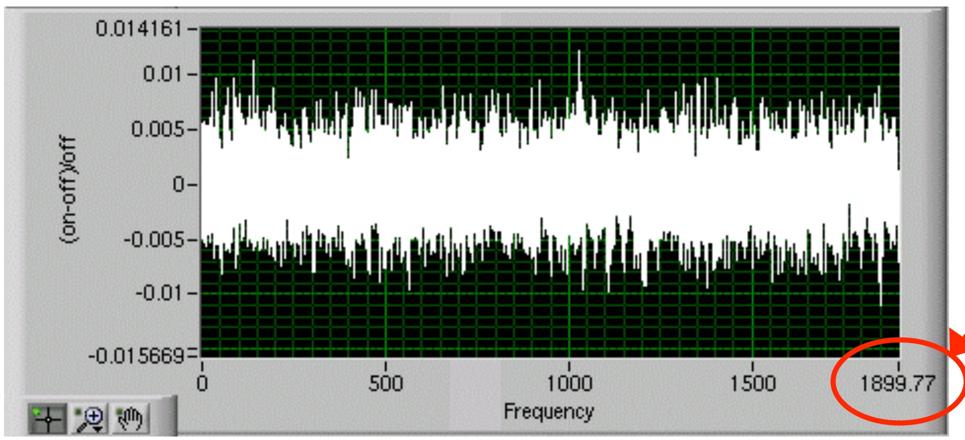
Today, implemented FFTS board / FPGA configurations are:

- 1 x 1.5 GHz bandwidth, 1 x 8192 spectral channels, ENBW: 212 kHz (default core)
- 1 x 1.8 GHz bandwidth, 1 x 8192 spectral channels, ENBW: 255 kHz



1.9 GHz is poss
by using selecte
FPGAs with higl
speed grades!

- 1 x 750 MHz bandwidth, 1 x 16382 spectral channels, ENBW: 53 kHz
- 1 x 500 MHz bandwidth, 1 x 16384 spectral channels, ENBW: 35 kHz
- 1 x 100 MHz bandwidth, 1 x 16384 spectral channels, ENBW: 7 kHz
- 2 x 500 MHz bandwidth, 2 x 8192 spectral channels, ENBW: 71 kHz (in lab test)

The Equivalent Noise Bandwidth (ENBW) is the width of a fictitious rectangular filter such that the power in that rectangular band is equal to the (integrated) response of the actual filter.

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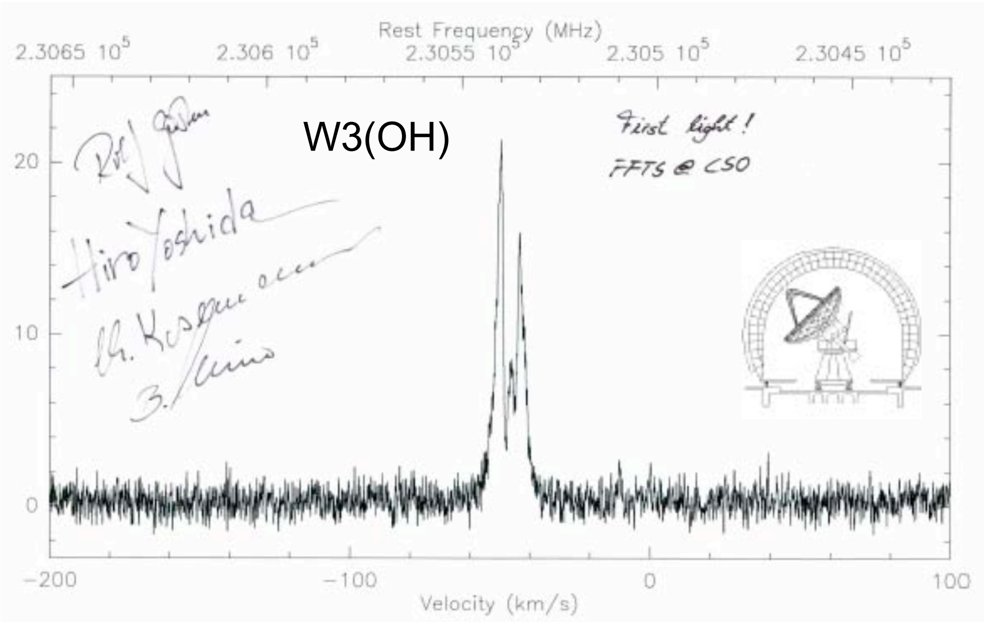
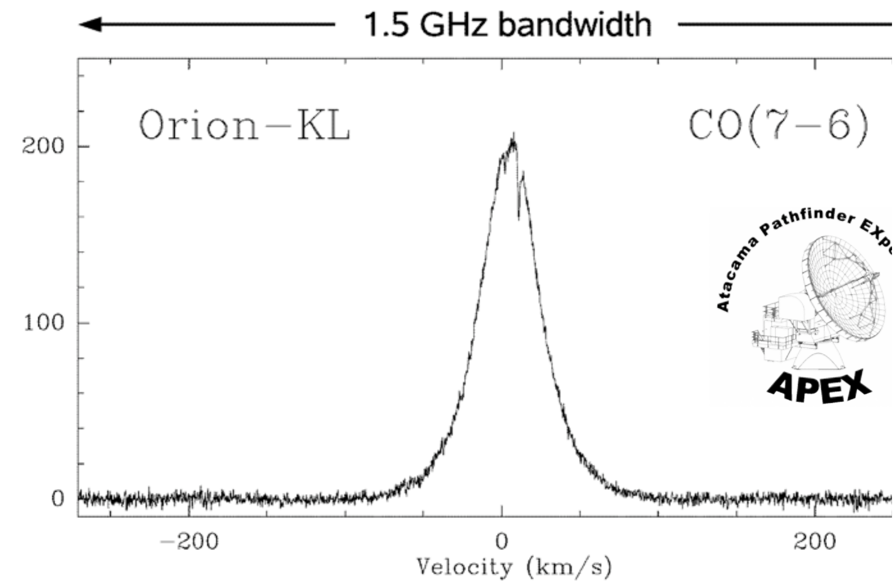
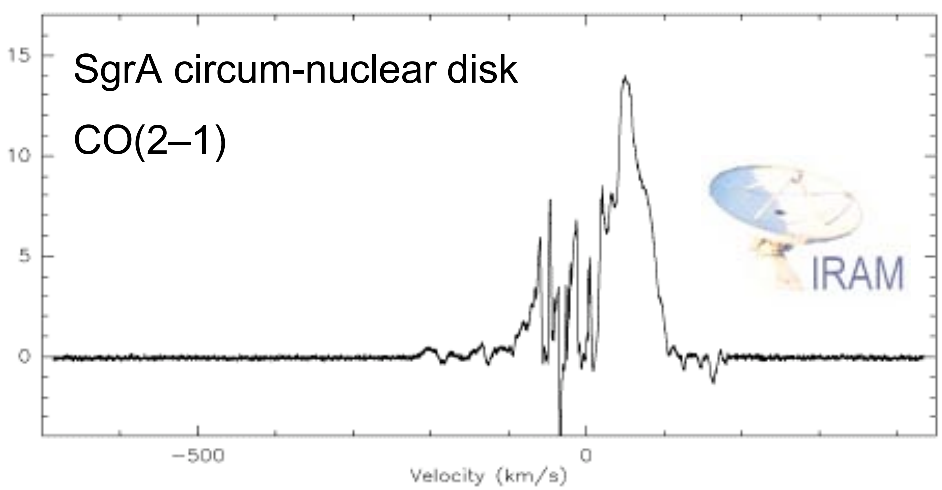
FFTS :: *in world-wide use*

The superior performance, high sensitivity and reliability of MPIfR FFT spectrc has now been demonstrated at many telescopes world-wide.





Spectrum towards Orion-KL. The high-excitation CO(7-6) transition at 806 GHz was observed with the central pixel of the CHAMP+ array.



Further details:

- B. Klein, et al., Proc. of ISSTT 19th, page 192, Groningen 28-30 April 2008
- http:://www.mpifr-bonn.mpg.de/staff/bklein

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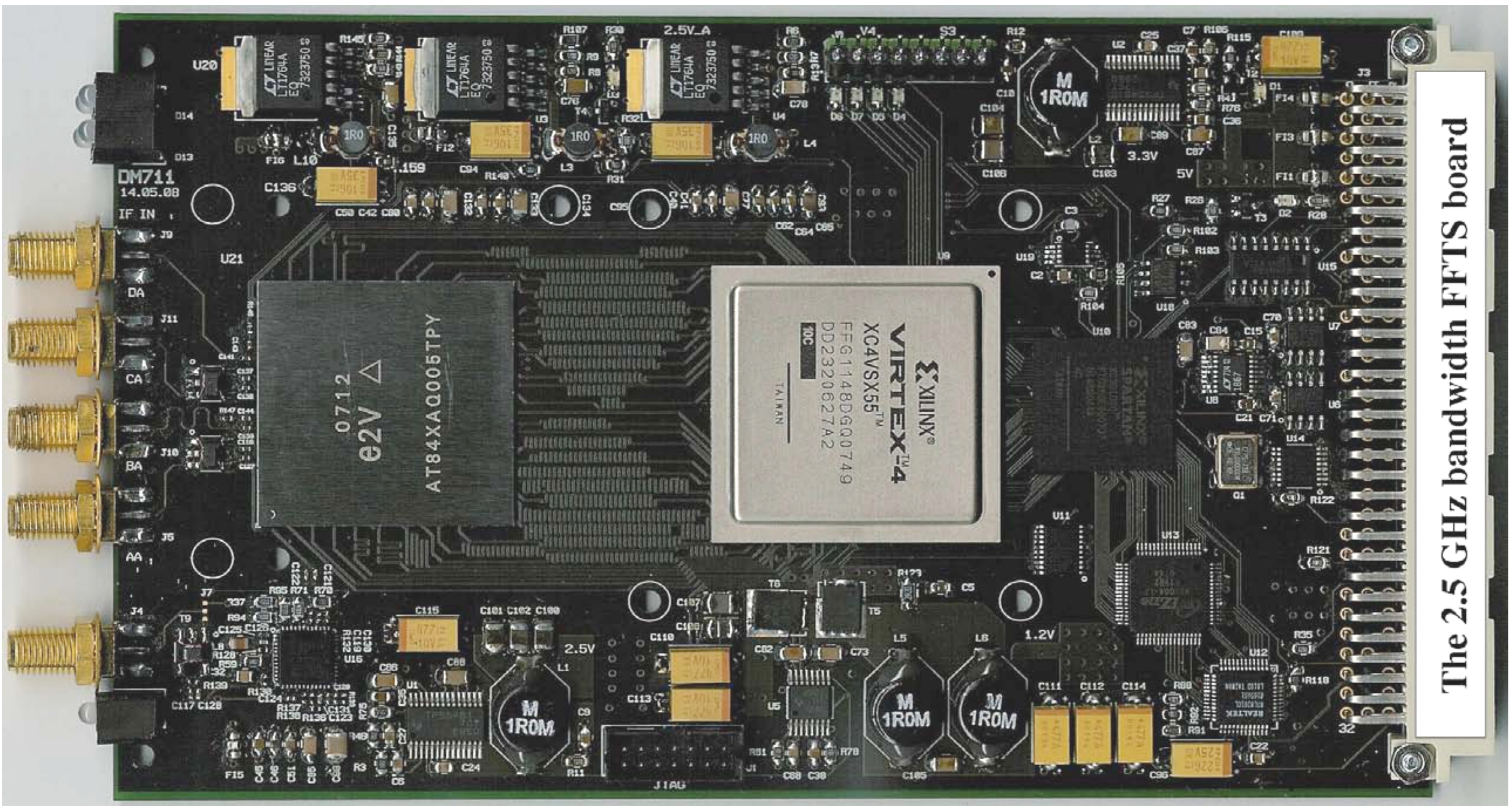
XFFTS :: *The 2.5 GHz development*

Currently in development: **The 2.5 GHz bandwidth FFTS for GREAT**



Goal: 2.5 GHz instantaneous bandwidth with adequate spectral resolution (~100 kH:
to be operational in time for SOFIA's early science flights in summer 2009!

XFFTS :: *The 2.5 GHz development*

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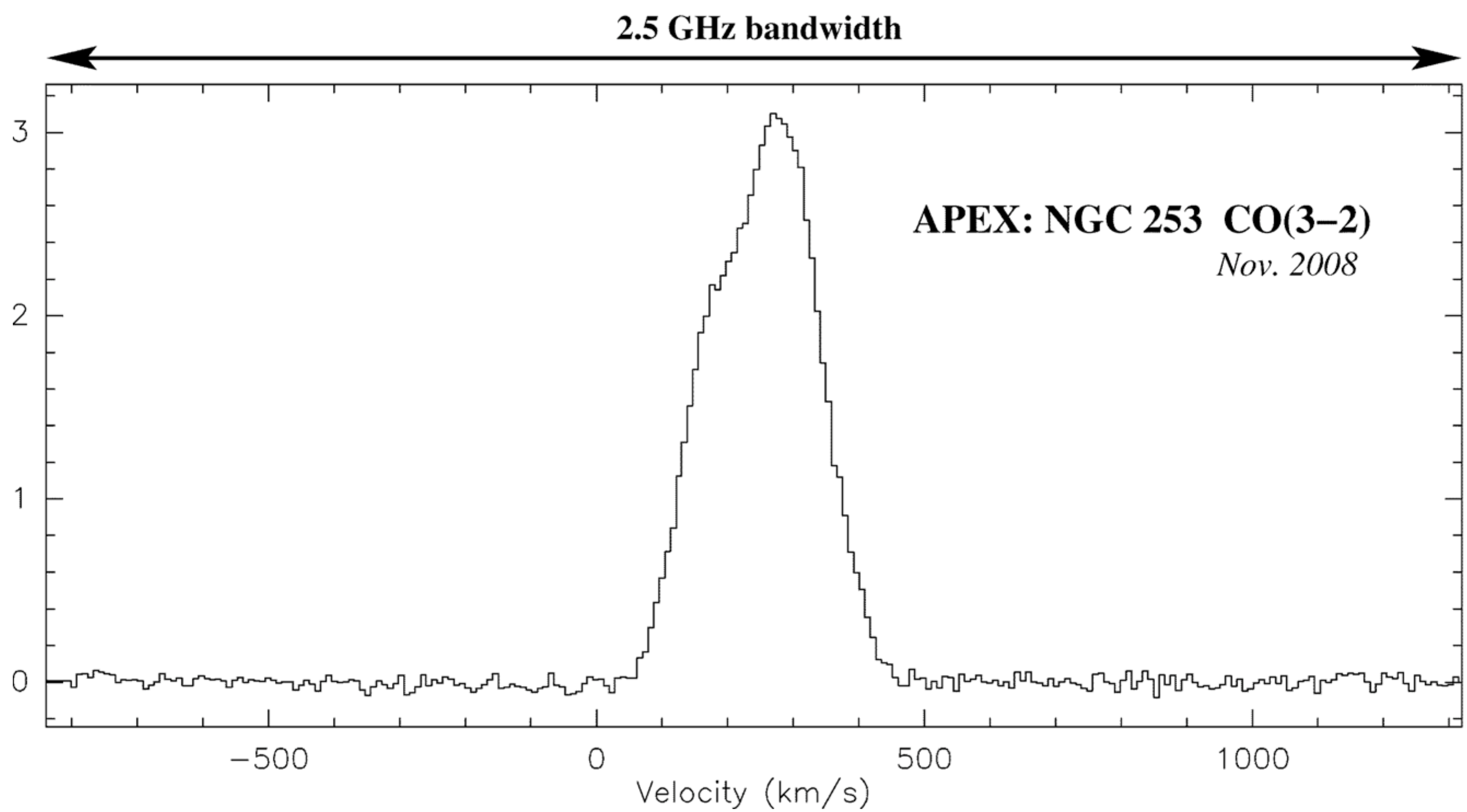
APEX: **First Spectra …**



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MPIfR FFTS :: *Summary*

Advantages of our new generation of compact FFT spectrometer

- ✓ FFTS provide high instantaneous bandwidth (2.5 GHz demonstrated in field tests) with many thousands frequency channels
  → offering wideband observations with high spectral resolution without the compl
  of the IF processing in a hybrid configuration.
- ✓ They provide very high stability by exclusive digital signal processing. Allan stability times of > 1000 seconds have been demonstrated routinely.
- ✓ Field-operations of our FFTS over the last 3 years have proven to be very reliable, w
  calibration- and aging-free digital processing boards, which are swiftly re-configurab
  by Ethernet for special observation modes.
- ✓ Low space and power requirements – thus safe to use at high altitude (e.g. APEX at
  5100-m) as well as (potentially) on spacecrafts and satellites.
- ✓ Production cost are low compared to traditional spectrometers through use of only commercial components.

Max-Planck-Institut
für Radioastronomie

DIGITALLA

FFTS :: *Contact, Distribution*

Contact:

For further information about the MPIfR FFT spectrometer, future developments and applications, please contact Dr. Rolf Güsten (rguesten@mpifr.de) or Dr. Bernd Klein (bklein@mpifr.de) at the Max-Planck-Institut für Radioastronomie in Bonn, Germany.

Distribution:

Radiometer Physics GmbH

http://www.radiometer-physics.de

MASs and FFTSs

Synergy – Pooling resources

Potential "users" for FFTSs **and** MASs

(= possible co-financers):

- IRAM
- APEX
- LMT
- Effelsberg 100m telescope, GBT
- GBT
- Madrid 40m telescope
- Sardinia Telescope

+ ...