SEVENTH FRAMEWORK PROGRAMME

2nd Engineering Forum Workshop

RadioNet

Radio and (Sub)Millimeter Wavelength Multi-Beam Spectral Line Astronomy

Karl M. Menten

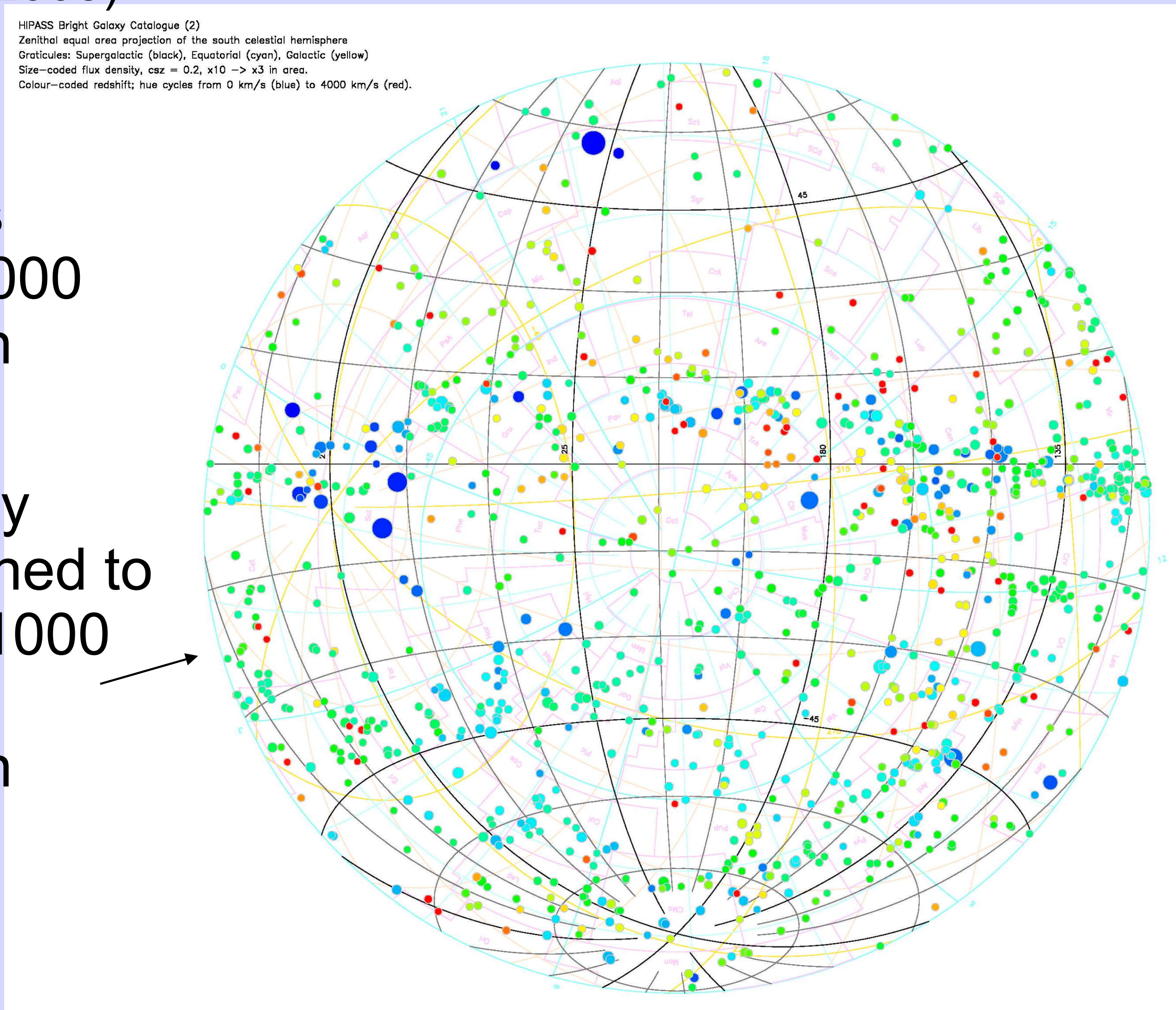
Max-Planck-Institut für Radioastronomie


Welcome to the
PARKES 21cm MULTIBEAM
Project
Overview
Events
Research
Documents
Status
Observations
Data
HIPASS data available here
Interface V2
Parkes Observatory
64 metre Telescope

HIPASS Bright Galaxy Catalog (BGC)

Koribalski et al. (2003)

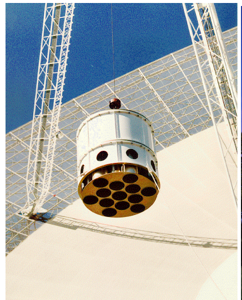
- HIPASS has detected ~7000 galaxies with Decl.<25^{o}
- Bright Galaxy Catalog defined to contain the 1000 HI-brightest galaxies with Decl.<0^{o} (S>116mJy)



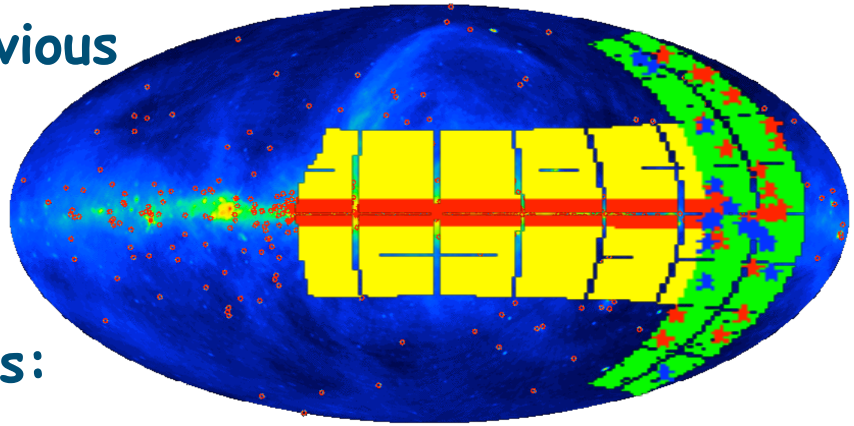
Unbiased surveys deliver surprizes!

New sources & phenomena

Parkes Multibeam Survey(s):

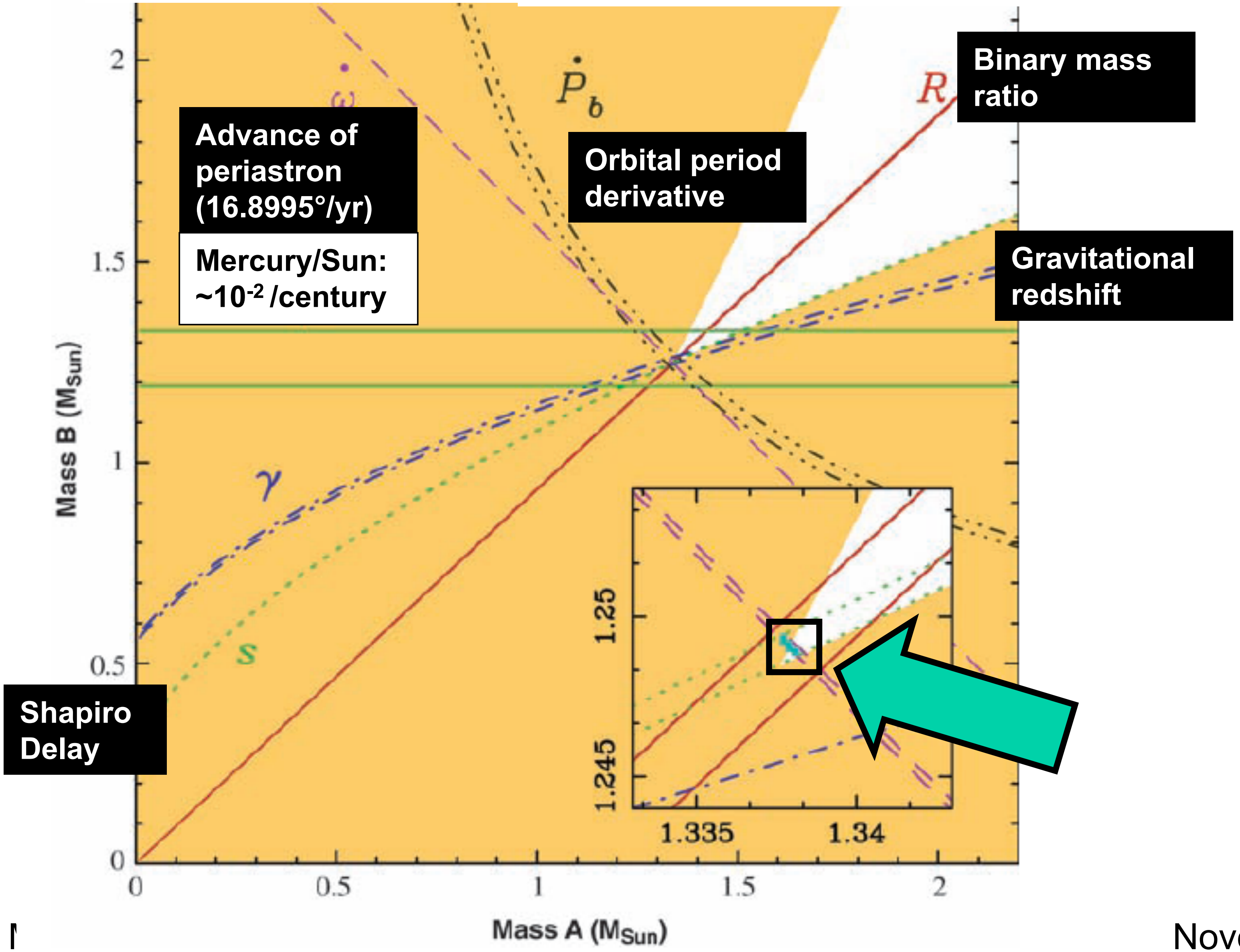




- Led by JBO
- Collaboration with ATNF and partners
- Receiver amplifiers, filterbanks and software infrastructure designed & built by JBO
- Survey at Parkes, follow-up producing science with Lovell telescope
- Most sensitive large-scale survey ever
- More successful survey than all previous surveys put together
- More than 800 new pulsars
- Still counting…
- Very exciting discoveries of all kinds:



Pulsars with massive companions, in SNRs, magnetar-like, young and millisecond pulsars and some previously unknown types of sources

Tests of General Relativity from Timing the Double Pulsar
M. Kramer, *et al.*
Science **314**, 97 (2006);

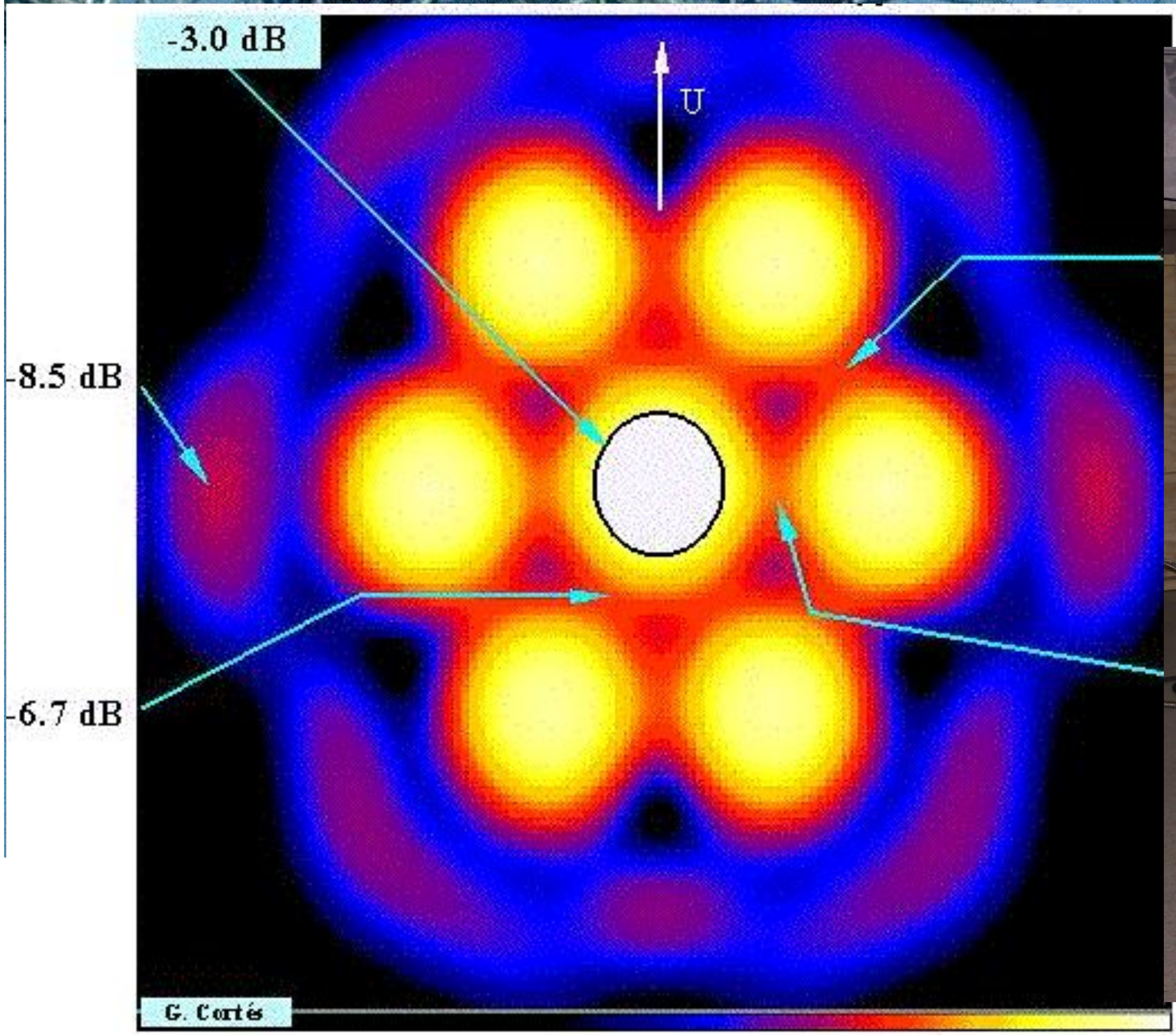


2001 radio astronomy papers cited in 2002–2004

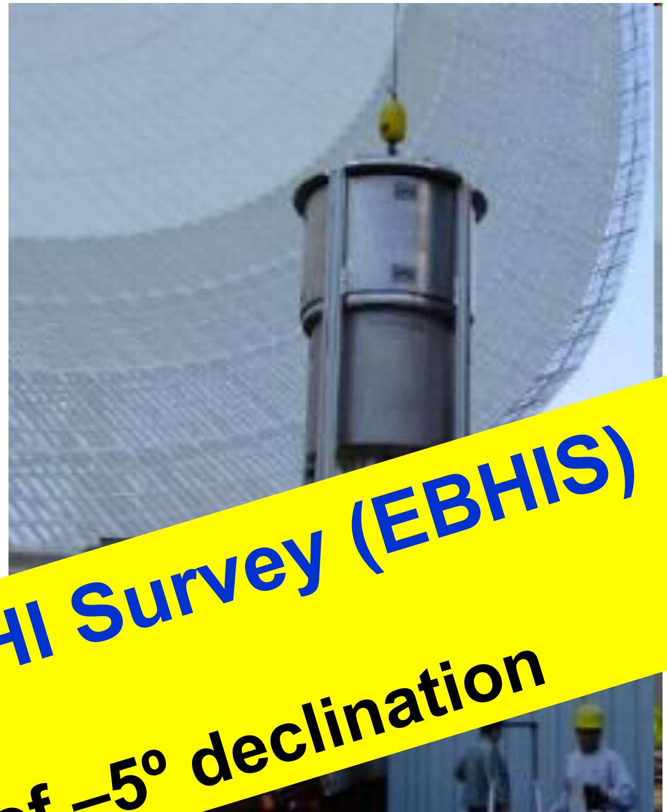
A.D. 1964

Facility	Citations	Papers	C/P
Interferometers, Parts Used Separately, and Single Dishes			
HALCA satellite	26	3.4	7.65
VLBI unspecified	38	5.1	7.45
VLBA+component dishes	482	38.25	10.01
VLA	3003	181.4	16.55
MERLIN	194	18.6	10.43
Australia Telescope Compact Array	525	46.8	11.22
Parkes	786	38.3	20.52
Other Australia+Deep Space Network	94	11.4	8.25
Arecibo	366	28.0	13.07
European VLBI Network	106	12.2	8.69
Jodrell Bank (several)	112	10.5	10.67
Westerbork	181	14.1	12.84
Effelsberg	183	21.0	8.71
Puschina	24	7.0	3.43
RATAN-600	6	6.0	1.00
Nançay	41	6.2	6.62
Other European	115	17.4	56.61
Giant Metrewave Radio Telescope	40	6.0	6.61
Ooty	10	6.0	1.67
Other Asian	26	9.4	2.77
Green Bank (several)	118	8.9	13.26
Dominion Radio Astrophysical Observatory	60	8.0	7.50
Other Western Hemisphere	53	6.3	8.41

ALFALFA/Arecibo 305 m



21 cm 7 Beam (1290 - 1430 MHz, Primary Focus) Receiver
Effelsberg 100 meter telescope



Effelsberg-Bonn HI Survey (EBHIS)

- **HI 21 cm line**
- **Whole sky north of –5º declination**

The PKS Methanol Multi-Beam Receiver

- 7 × 2 beams (RCP+LCP)
- 1 GHz BW HEMT
- 2 × 2 × 4 MHz detected with autocorrelatorrs:
    - around OH maser line at 6.0 GHz and CH_3OH lin… 6.7 GHz
- Survey started 2…
- JBO/ATNF (Graha…

(Southern) Galactic plane survey:
to find embedded high-mass protostars in their earliest evolutionary phases
- 800+ detections
- 350+ of them new
- ATCA follow-up

A real cool upgrade:

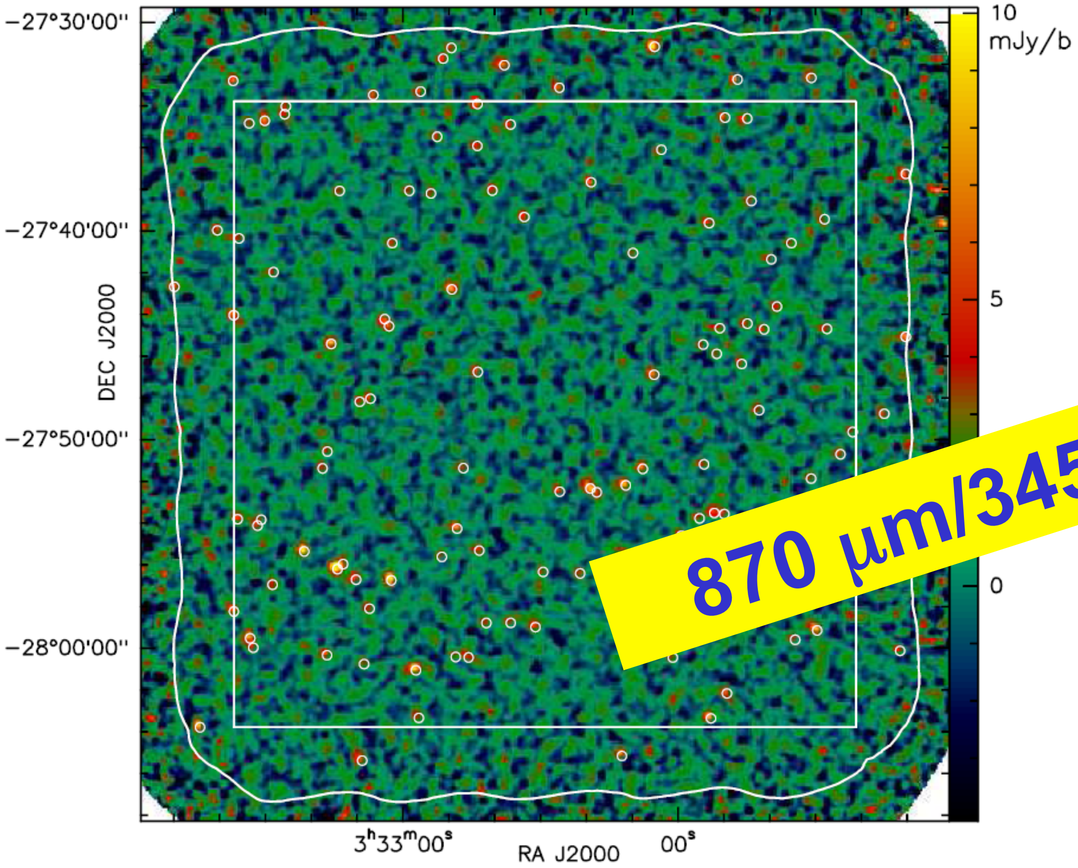
- replace 2 × 2 × 4 MHz BW with 2 × 4 GHz B… A-HEMTs)
- A Galactic plane surv…
  - incr… …ow
  - …ging, separation of thermal and …on emission
  - allow observations of
    - the 4.8 GHz H_2CO absorption line → kinematic distances
    - three 4.7 GHz OH lines
    - 24 Hα radio recombination lines

The ultimate radio wavelength single-dish Galactic plane survey (~1.3' –2.8‘ FWHM/100 m Ø)

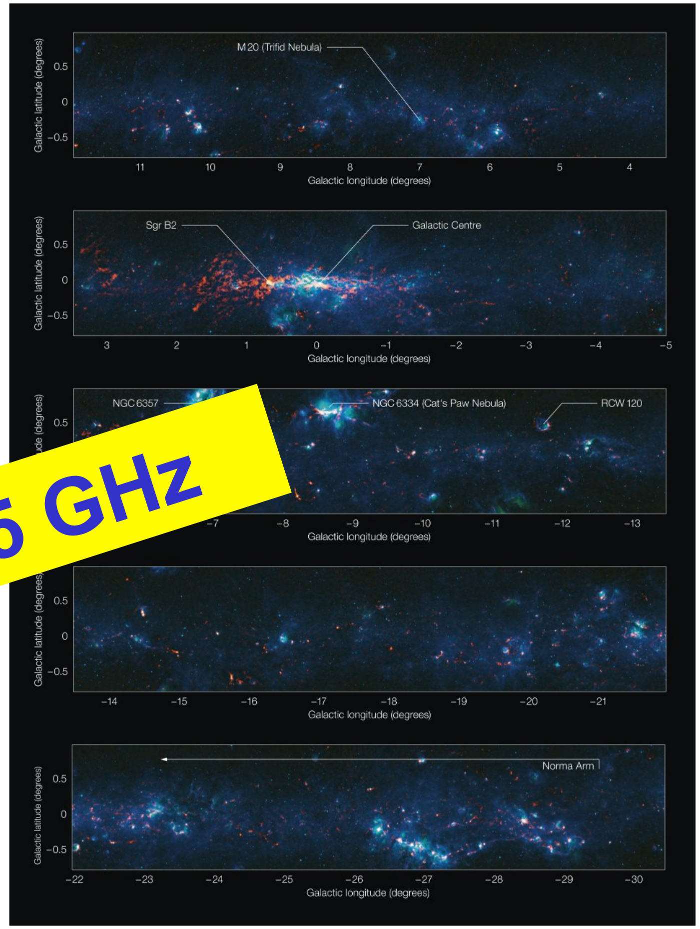
Would deliver 0 spacing information for future EVLA surveys

Shorter wavelengths:

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

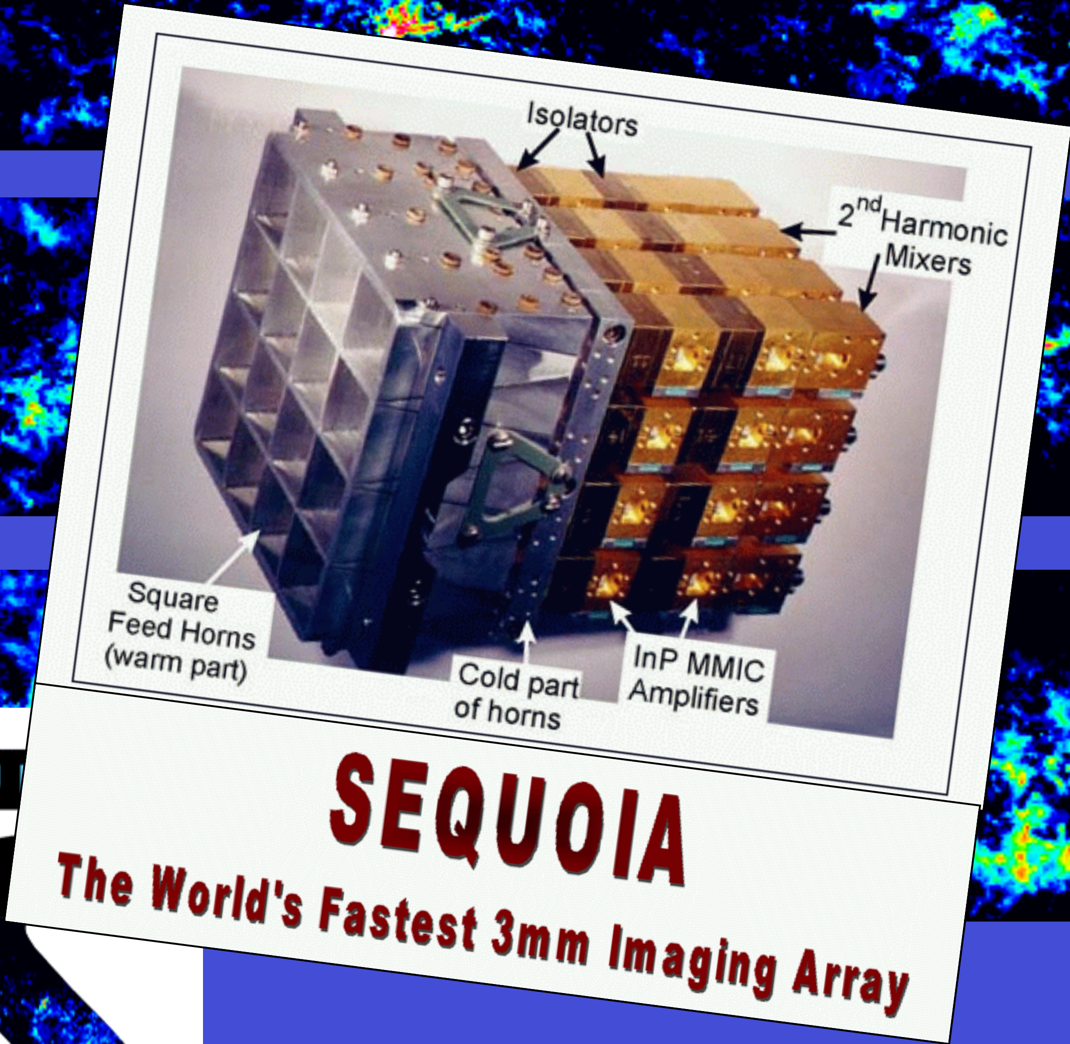


870 µm/345 GHz



Extended Chandra Deep Field South (APEX/Weiss et al. 2009)

APEX Telescope Large Area Survey: The Galaxy (Schuller et al. 2009)



GALACTIC RING SU

GRS

BOSTON UNIVERSITY-FCRAO

November 16, 2009

Shorter (submm) wavelength heterodyne arrays are becoming available just now:

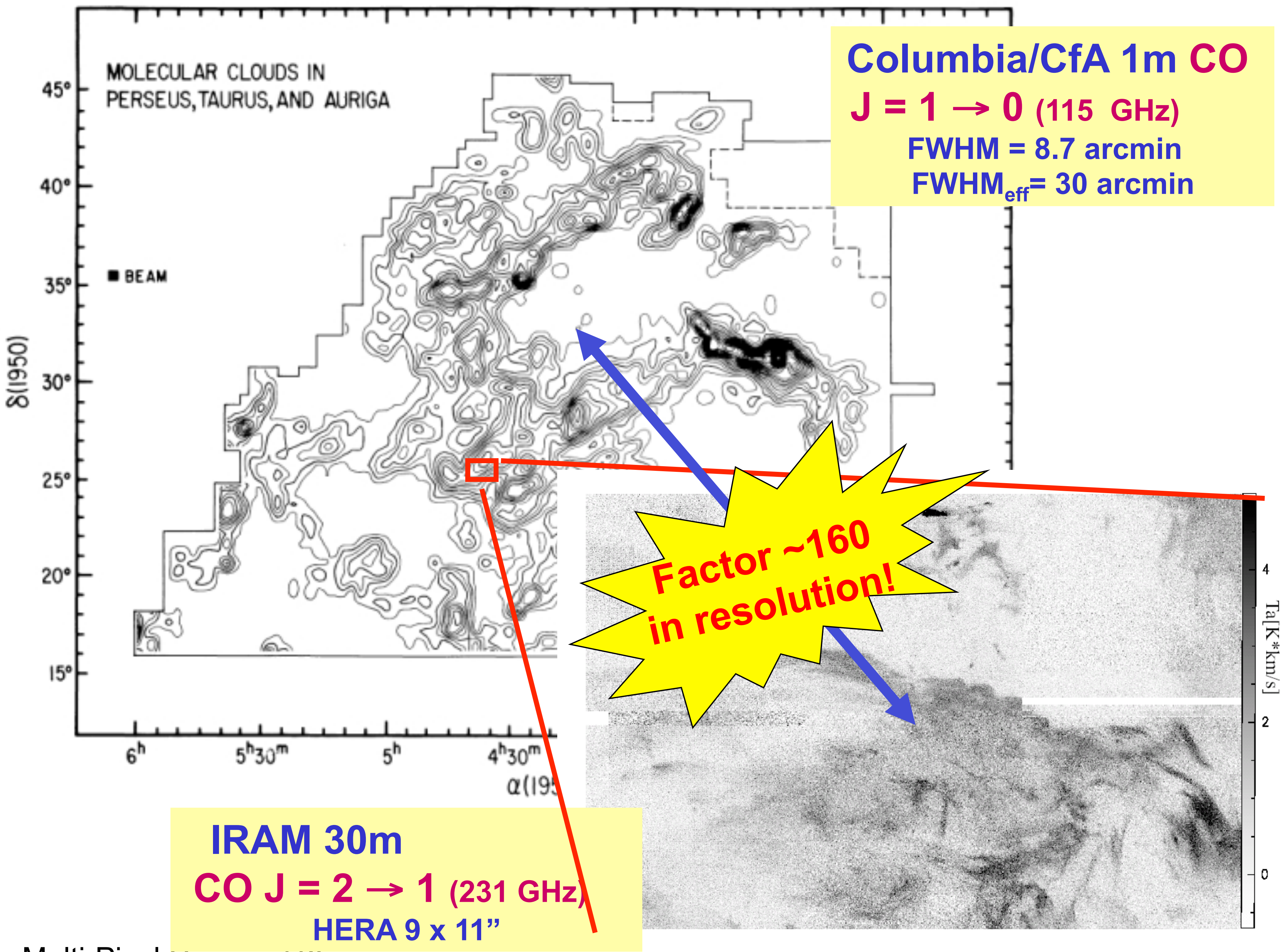
A&A 423, 1171–1177 (2004)
DOI: 10.1051/0004-6361:20034179

Astronomy & Astrophysics

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

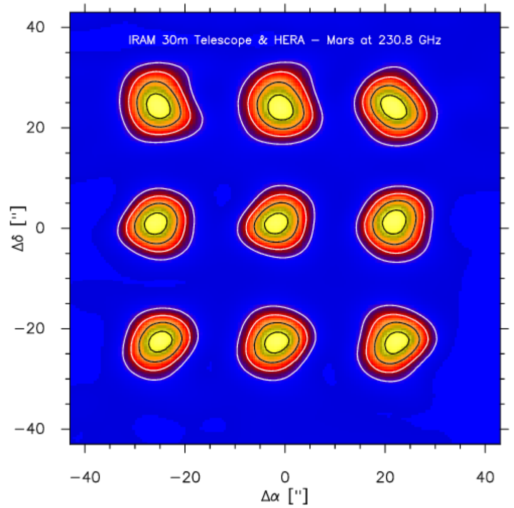
K.-F. Schuster[1], C. Boucher[1], W. Brunswig[1], M. Carter[1], J.-Y. Chenu[1], B. Foullieux[1,2], A. Greve[1], D. John[1], B. Lazareff[1], S. Navarro[1], A. Perrigouard[1], J.-L. Pollet[1], A. Sievers[1], C. Thum[1], and H. Wiesemeyer[1]

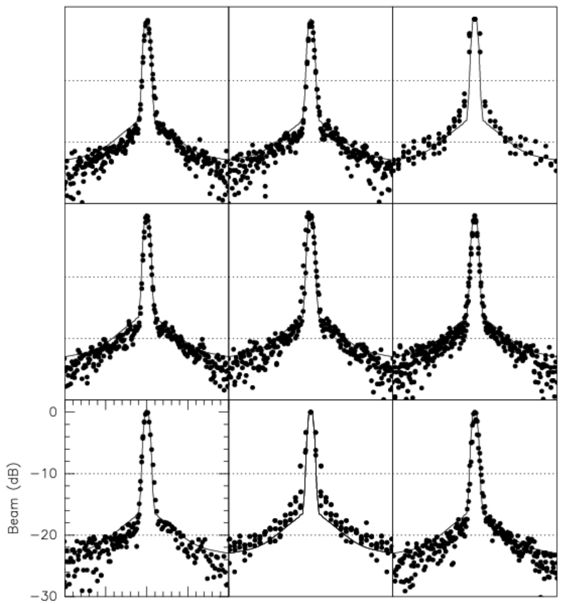
HERA = HEterodyne Receiver Array

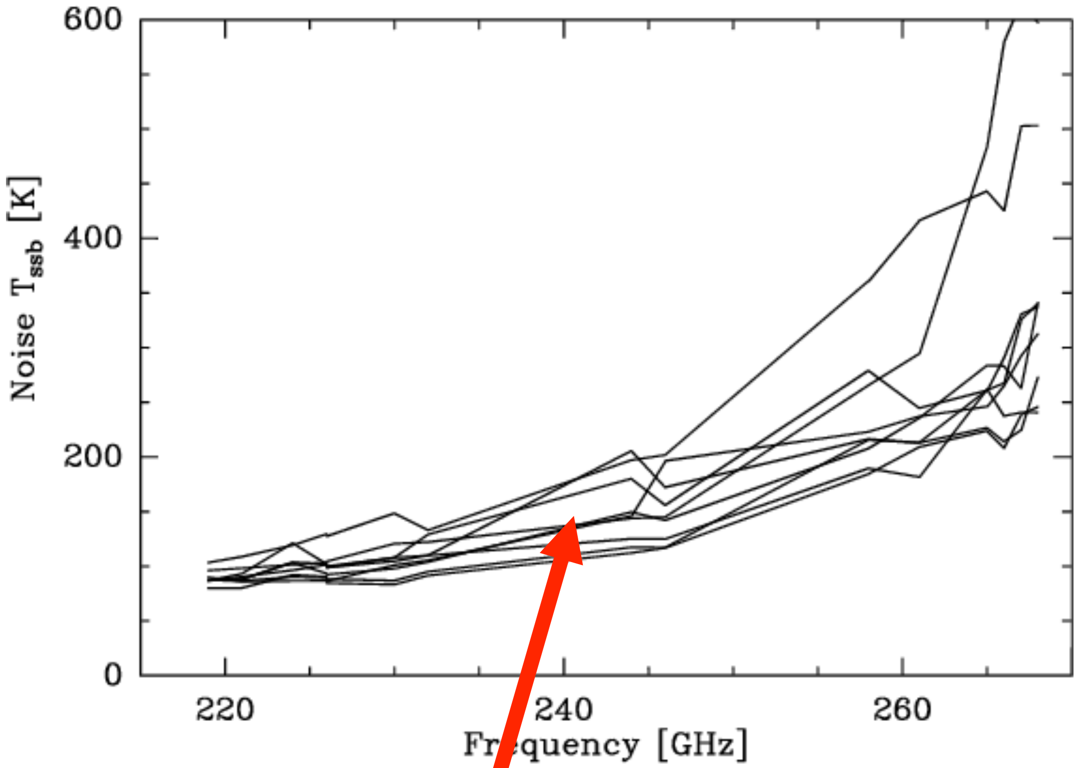


MOLECULAR CLOUDS IN
PERSEUS, TAURUS, AND AURIGA
BEAM
δ(1950)
45°
40°
35°
30°
25°
20°
15°
6h
5h30m
5h
4h30m
Columbia/CfA 1m CO
J = 1 → 0 (115 GHz)
FWHM = 8.7 arcmin
FWHM$_{eff}$= 30 arcmin
Factor ~160
in resolution!
Ta[K*km/s]
4
2
0
IRAM 30m
CO J = 2 → 1 (231 GHz)
HERA 9 x 11”

Common sense requirements:





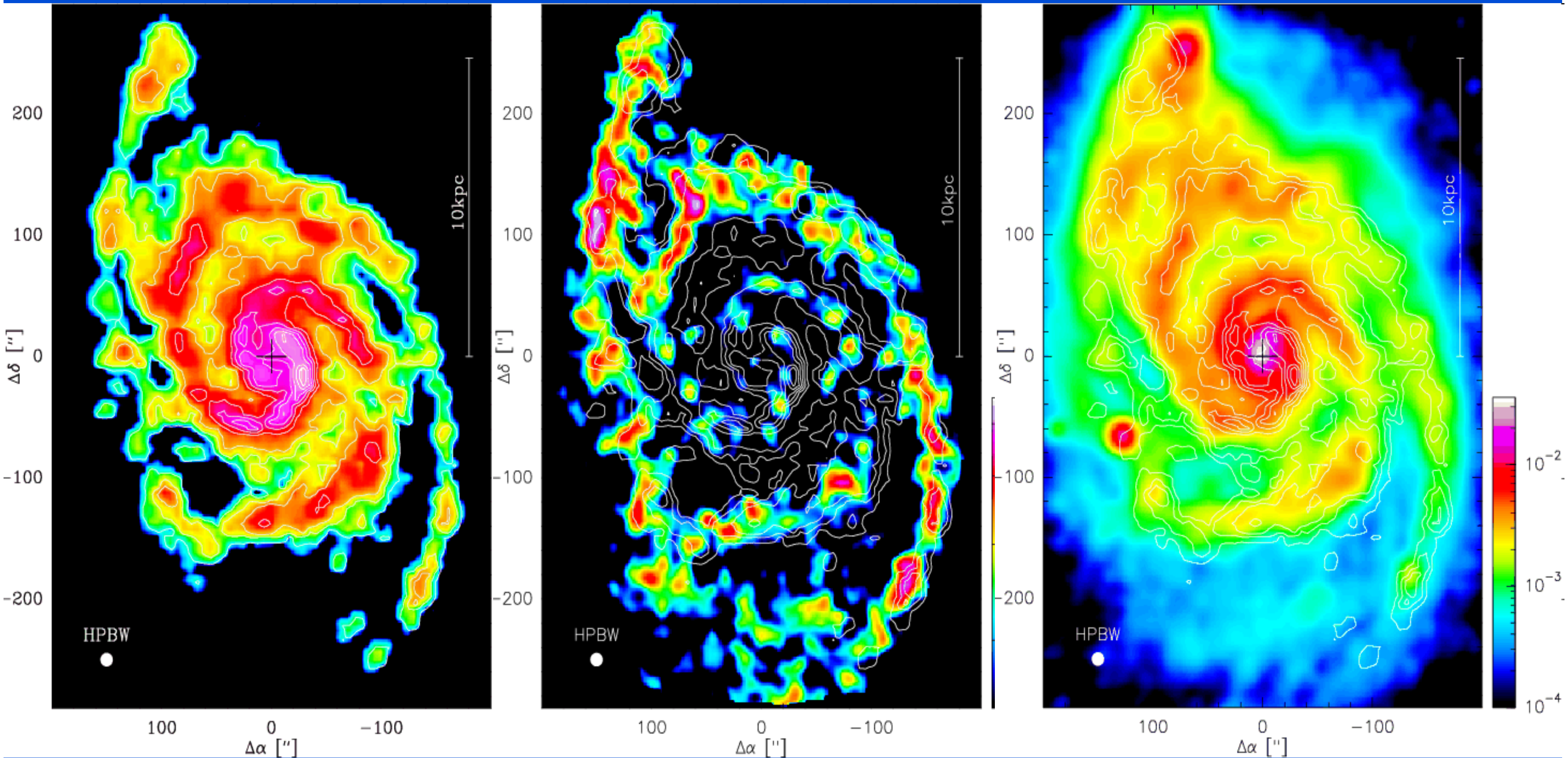


Important:

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

and

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

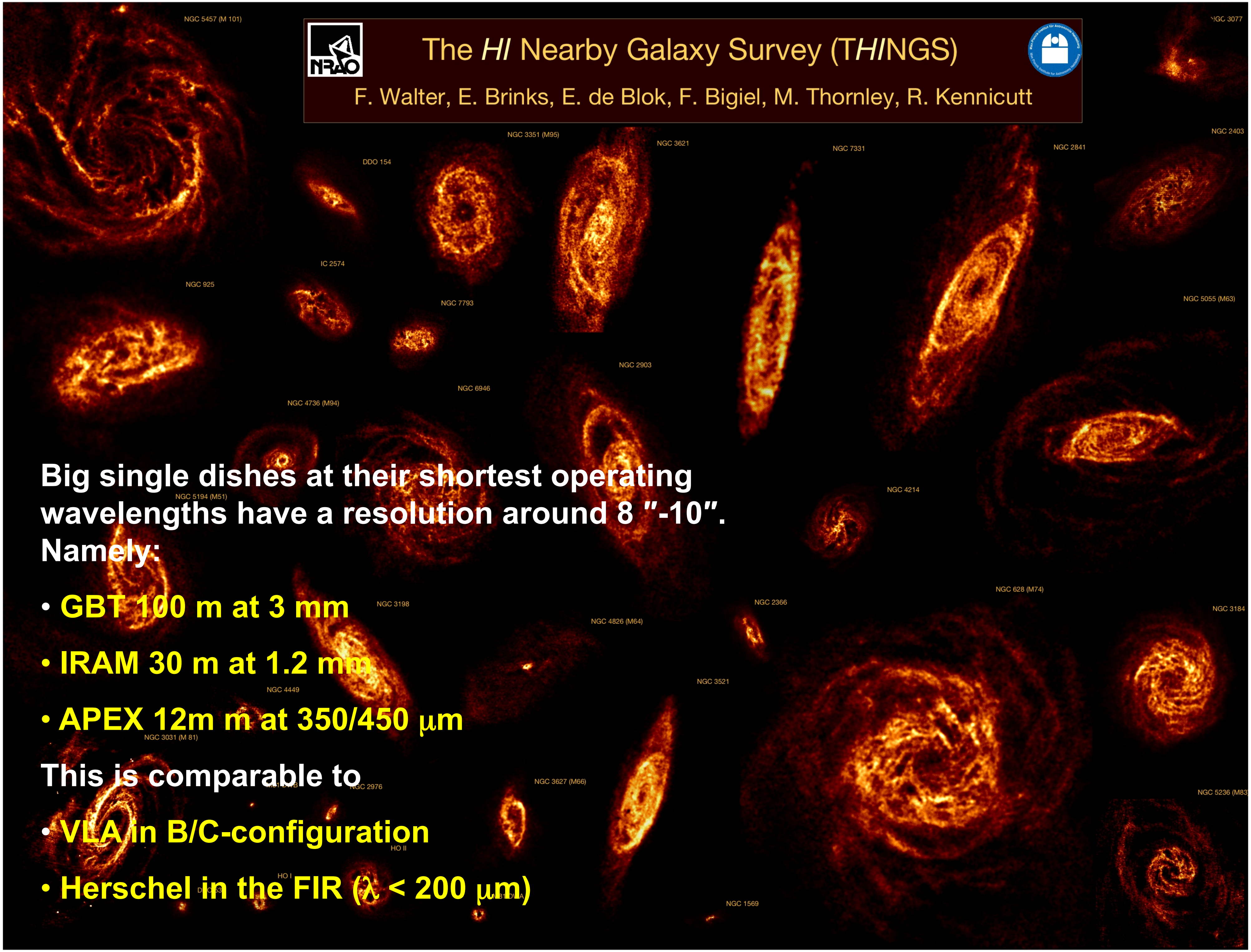


CO J = 2 – 1
FWHM = 11"
HERA@IRAM 30m

HI 21 cm
FWHM = 13"
VLA

Radio 20 cm
FWHM = 15"
VLA

Schuster et al. 2007



Big single dishes at their shortest operating wavelengths have a resolution around 8″-10″. Namely:

- **GBT 100 m at 3 mm**
- **IRAM 30 m at 1.2 mm**
- **APEX 12m m at 350/450 μm**

This is comparable to

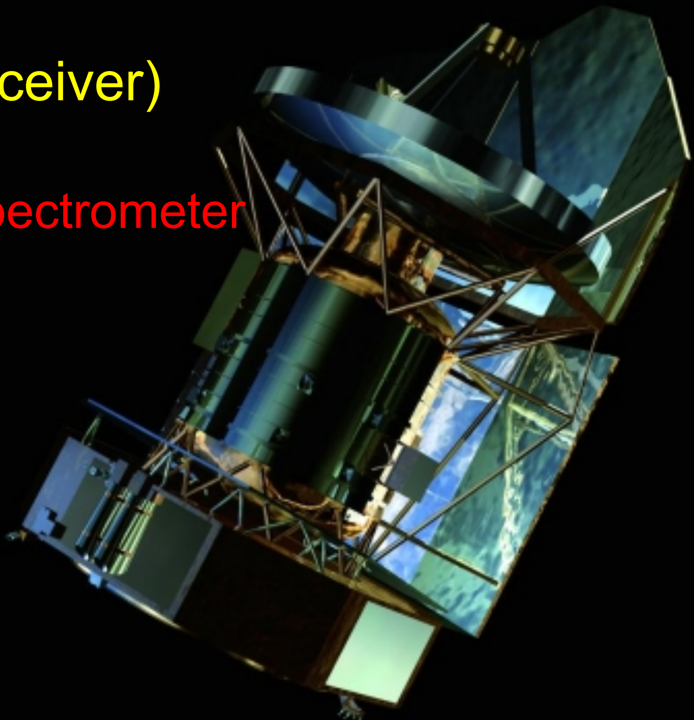
- **VLA in B/C-configuration**
- **Herschel in the FIR (λ < 200 μm)**

HERSCHEL

HIFI (**H**eterodyne **I**nstrument for the **F**ar **I**nfrared)
480 – 1910 GHz, 157 – 625μm, 7 bands
Very high resolution heterodyne spectrometer

PACS (**P**hotodetector **A**rray **C**amera and **S**pectrometer)
60 – 210 μm: photom. 1.75 x 3.5’ / spec 50×50” @ 5”, 1500 km/s
Imaging photometer / medium resolution grating spectrometer

SPIRE (**Sp**ectral and **P**hotometric **I**maging **R**eceiver)
250, 360, 520 μm, R3, 4×4’
Imaging photometer / imaging Fourier transform spectrometer



Concentrate here an molecular line astronomy

Advantages of array receivers:

- **Mapping speed**
- **Mapping homogeneity (map lage areas with similar weather 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 RX

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 can be done simultaneously

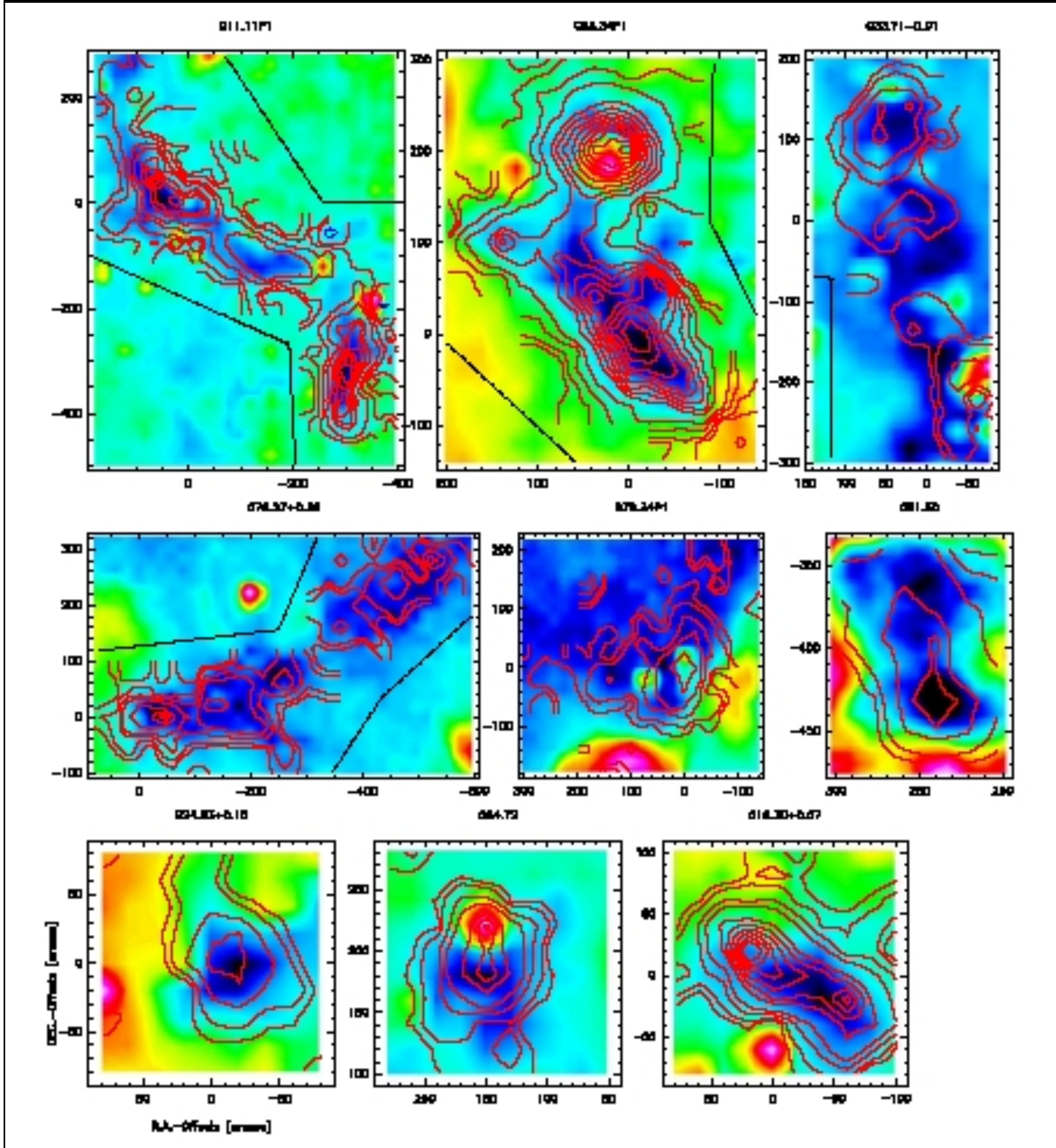
and

- 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. Pillai

Talks at this Workshop:

K-band Focal plane array for NRAO GBT:

- S. White
- M. Morgan
- G. Watts

FARADAY (18 –26.6 GHz MF RX) for the Sardinia Telescope:

- A. Cremonini

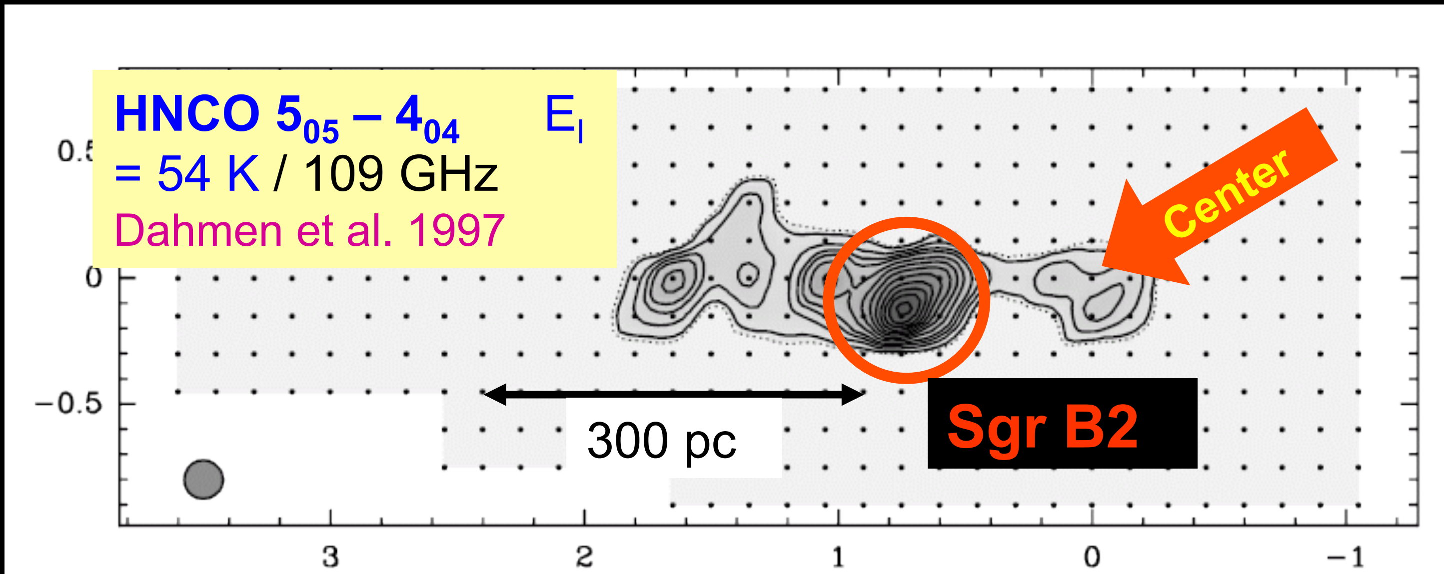
W-band-Science (80 – 116 GHz)

- 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** ($-0.5^0 < l < 2^0$)

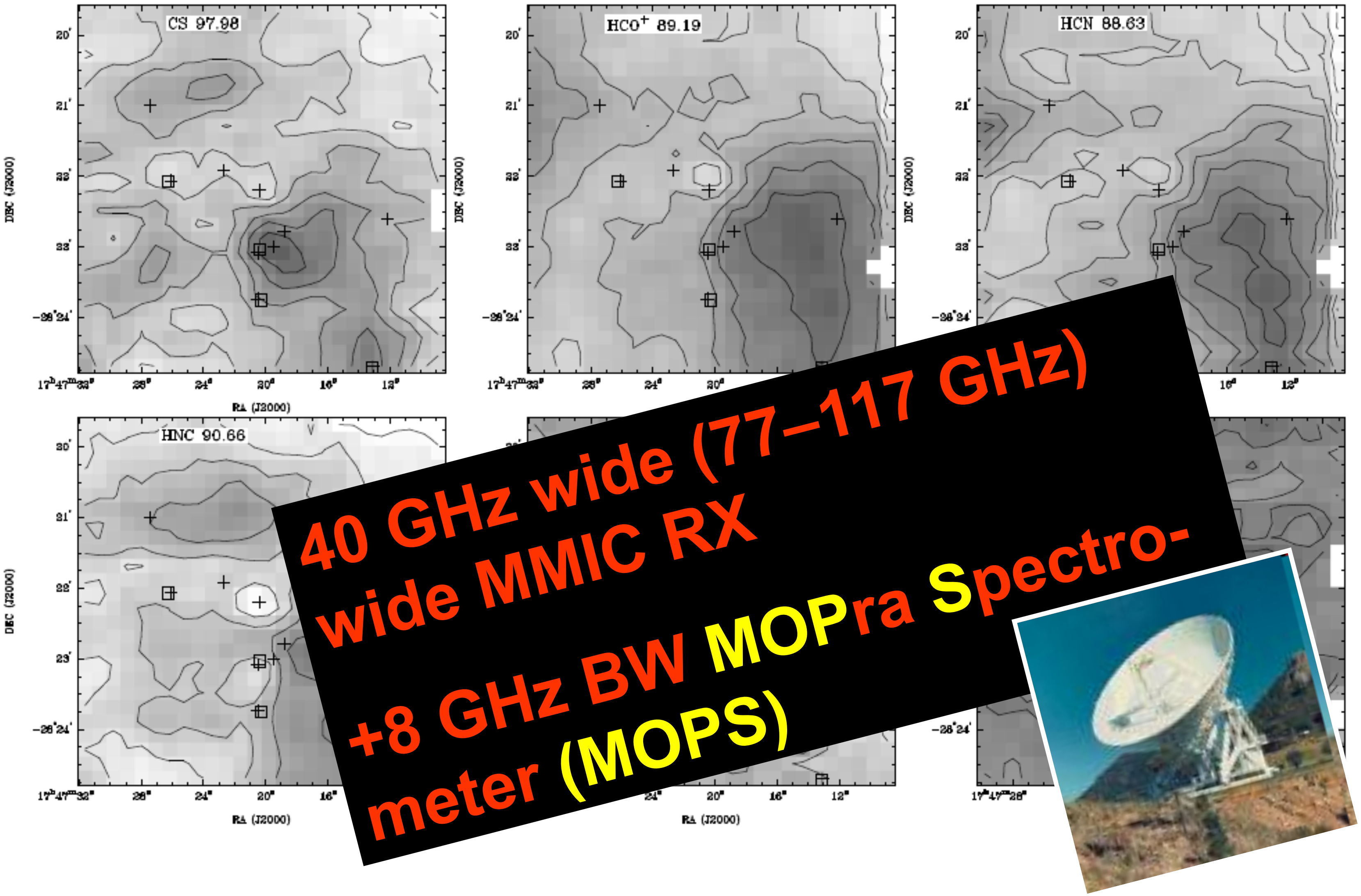
The interstellar medium in the Central Molecular Zone of our Galaxy

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 -1.1º.
- 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).



10 *P. A. Jones et al.* (2008)



40 GHz wide (77–117 GHz) wide MMIC RX

+8 GHz BW MOPra Spectro-meter (MOPS)

Sensitivity

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

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

Assume

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

Δv = 1 km/s

$\Rightarrow$ **Δv = 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

$\Rightarrow$ **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 large sections (if not all) of the Galactic plane can be imaged

Big advantage over SiS arrays: Many lines in HEMT band can 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**

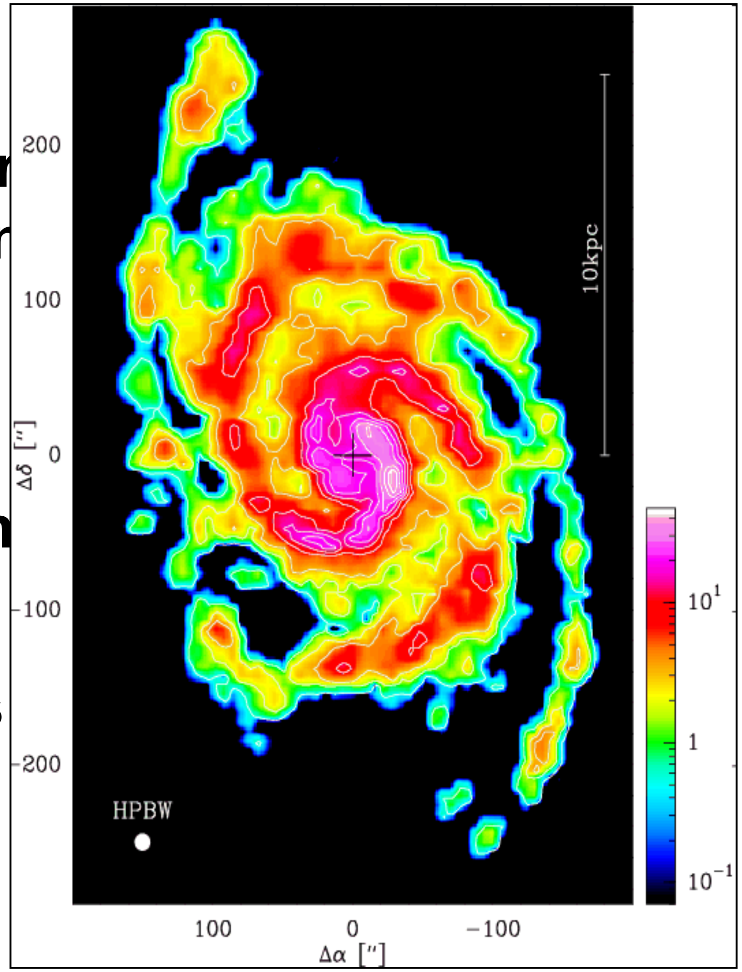
Other *most interesting* projects include complete (mostly) ^{12}CO and ^{13}CO mapping of nearby galaxies.

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

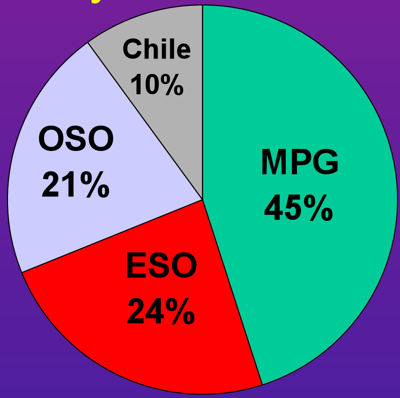


Even shorter (submm) wavelenghts

The Atacama Pathfinder Experiment (APEX)

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

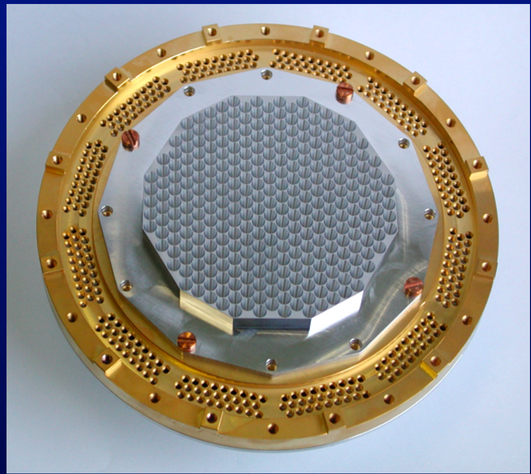


- **∅ 12 m**
- λ = 200 μm – 2 mm
- 15 μm rms surface accuracy
- currently (June 2005) in final testing phase
- PI and facility instruments:
  - 345 GHz heterodyne RX
  - 295 element 870 μm Large Apex Bolo- meter Camera (LABOCA)

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, …

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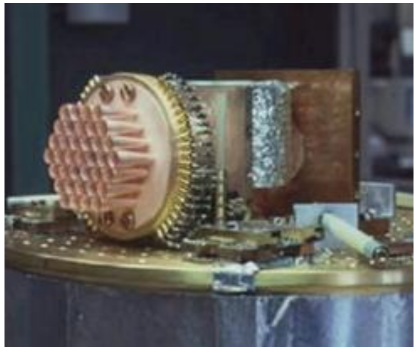
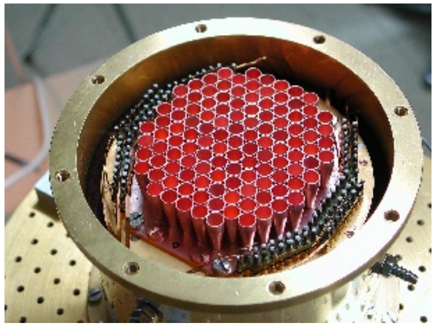
MPIfR Bolometer Array Cameras

Telescope	Name	Elem.	λ/mm	Debut	
Several, incl. 30m		1	1.2	<1983	
IRAM 30m	MAMBO	7–117	1.2	1991	
IRAM 30m	HUMBA	19	2	1999	(50 mK)
HHT (Arizona)		19	0.87	1999	
SEST (Chile)	SIMBA	37	1.2	2000	
30m/HHT	Polarimeter	37/19	1.2/0.87	2003	
30m/APEX	TES-Test	7	1.2	2003	
APEX	LABOCA	295	0.87	2006	
APEX		37	0.35	2008	

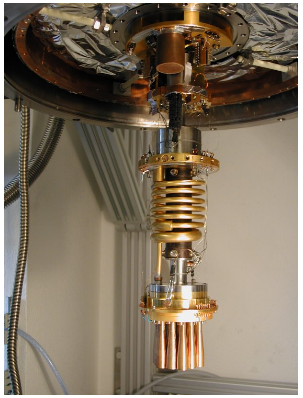
SIMBA



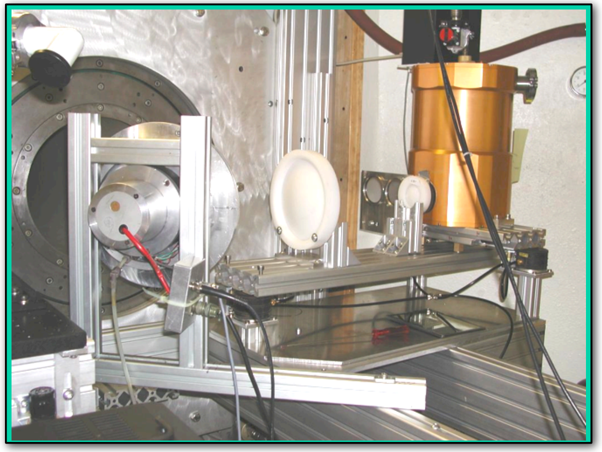
MAMBO-37



MAMBO-117



HUMBA

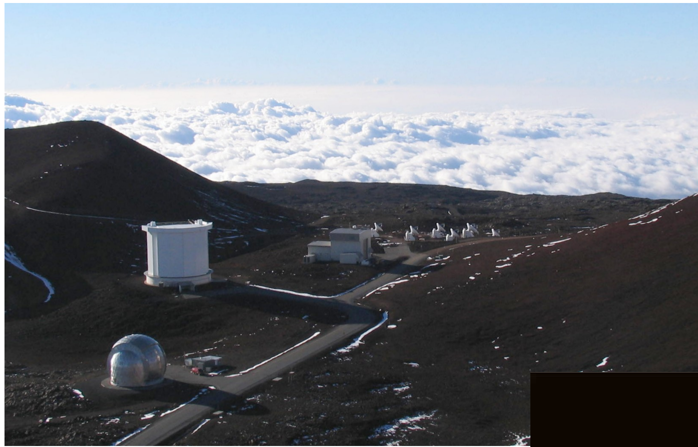


Polarimeter at HHT

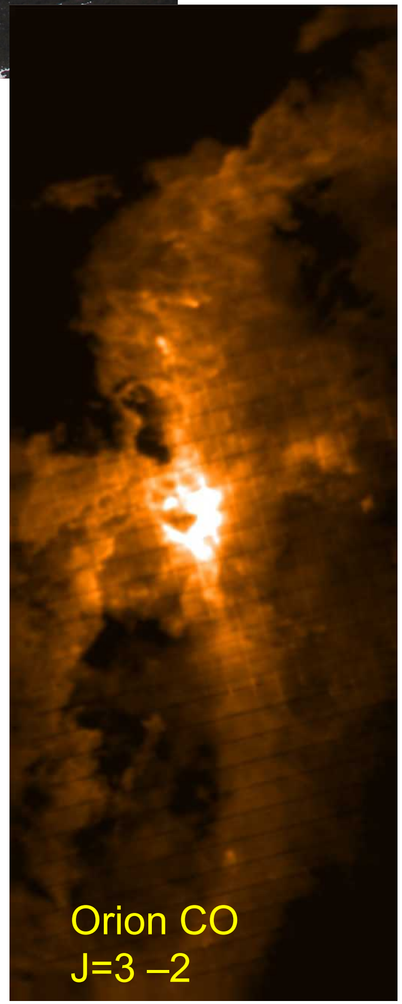
Multi-Pixel Camera RXs

November 16, 2009

HARP-B@JCMT



- 4×4 beams
- Range 324–376 GHz
  - Automated SSB tuning
- ACSIS spectrometer backend (DRAO)



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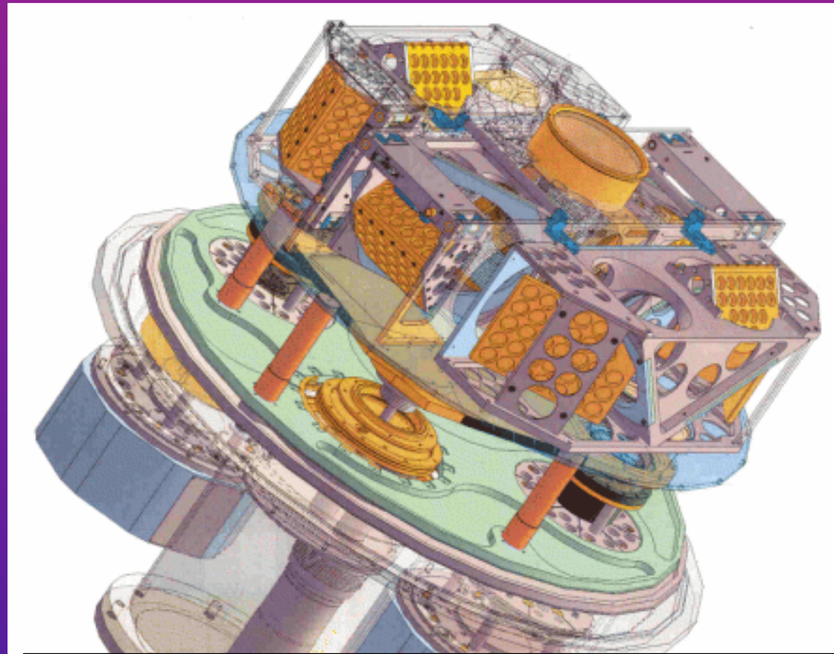
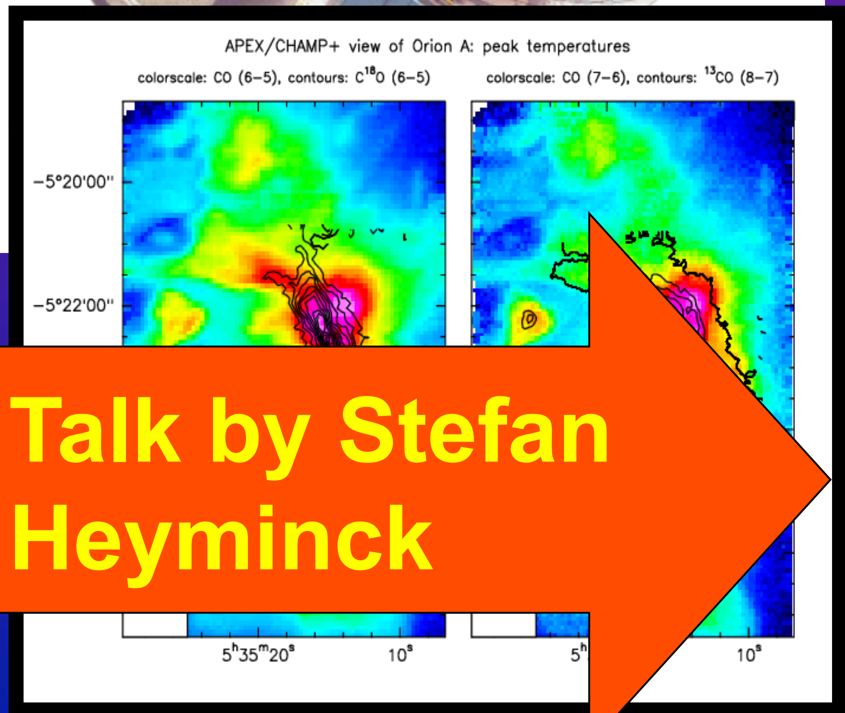
SRON



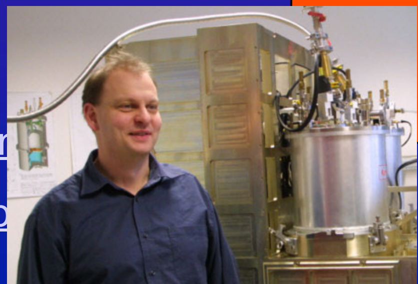
CHAMP+

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**



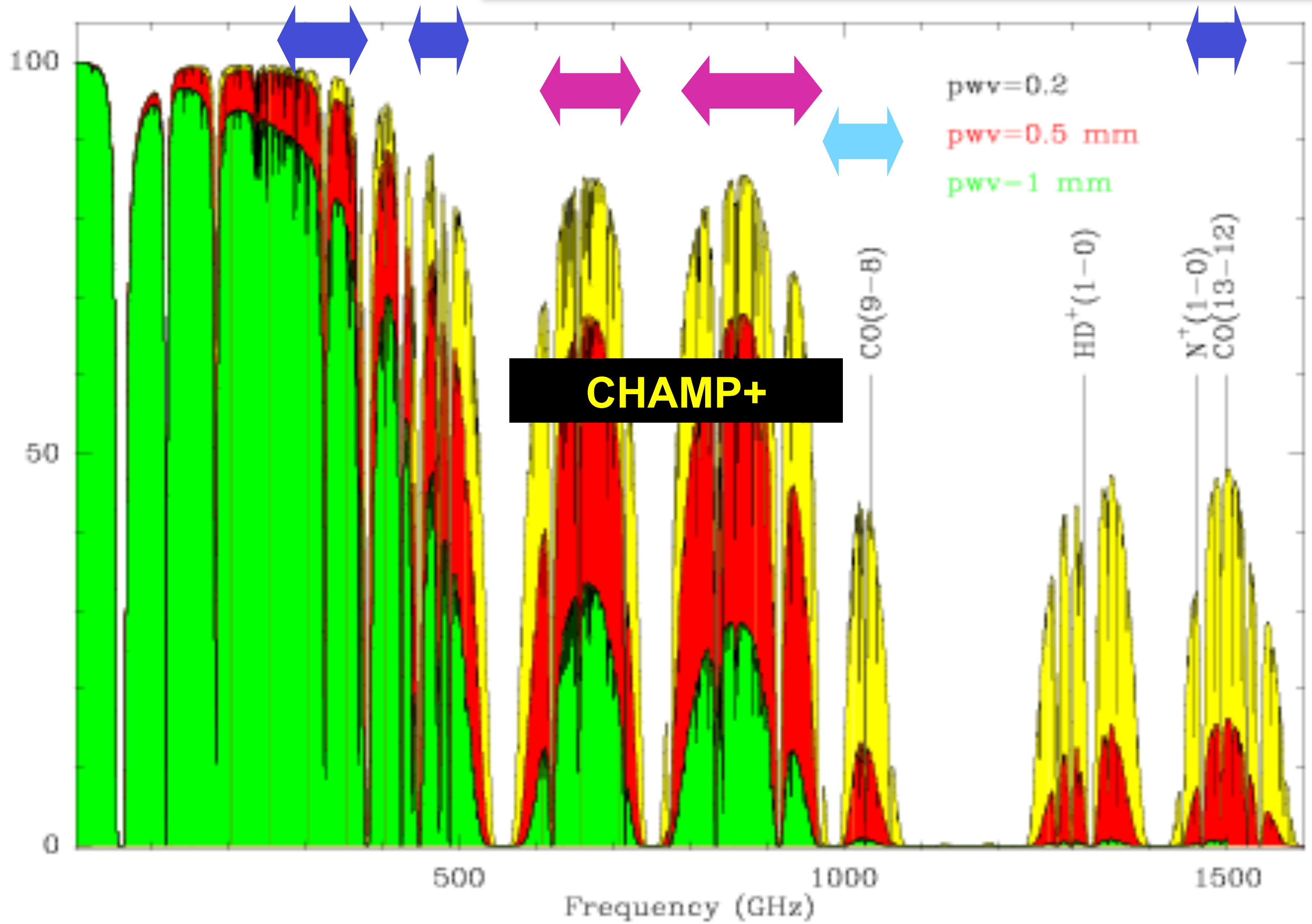
Talk by Stefan Heyminck



http://www.mpifr-bonn.mpg.de/div/mr

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

APEX Heterodyne Instrumention



Even a few years ago, even thinking of affordable backends to serve large format/wide bandwidth/ large number of channels spectrometric multi-beam receivers with a would have been frustrating…

Enter the super-Moore's Law world of FPGA driven Fast Fourier Transform Spectrometers!

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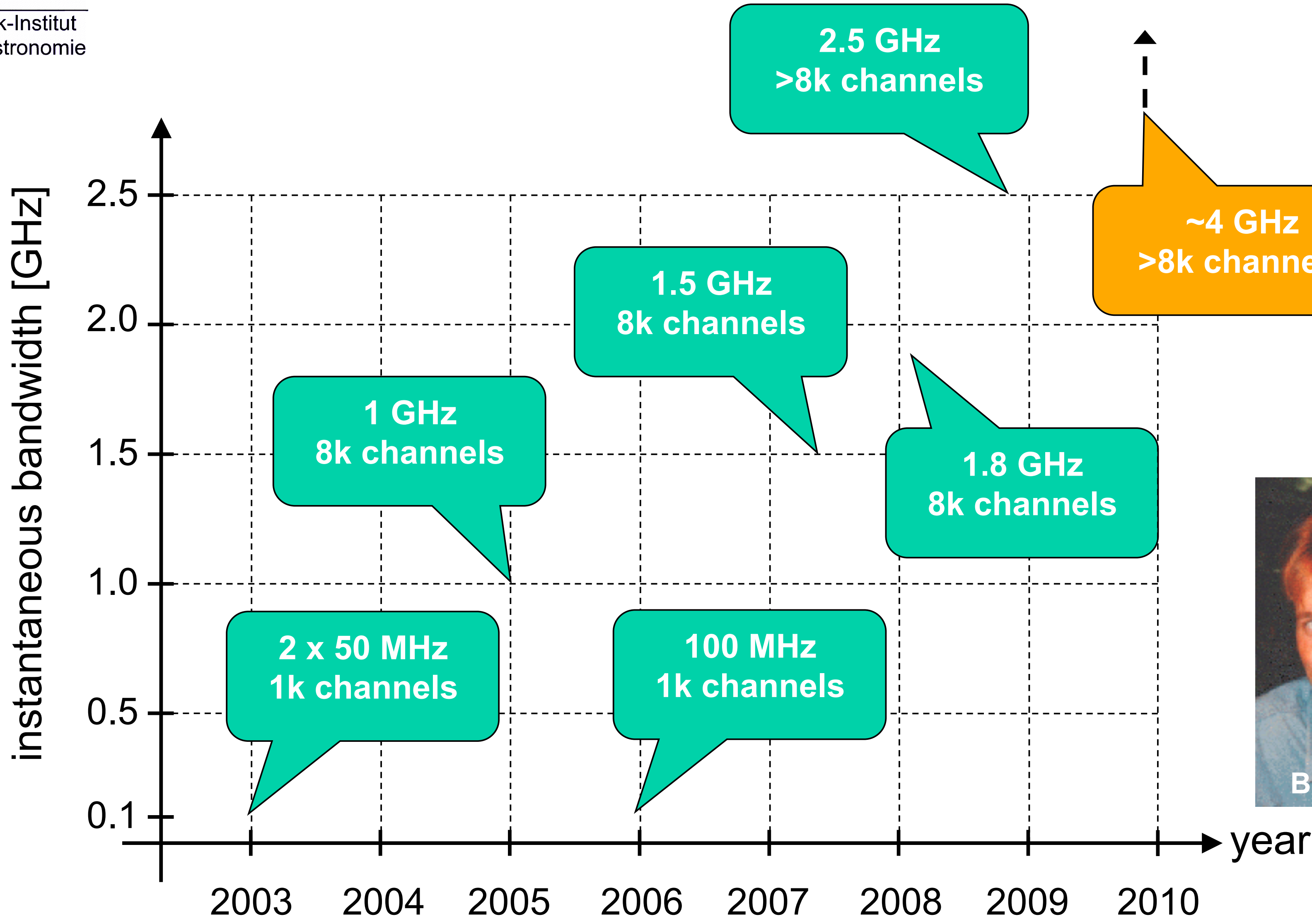
für Radioastronomie

DIGITALLABOR

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



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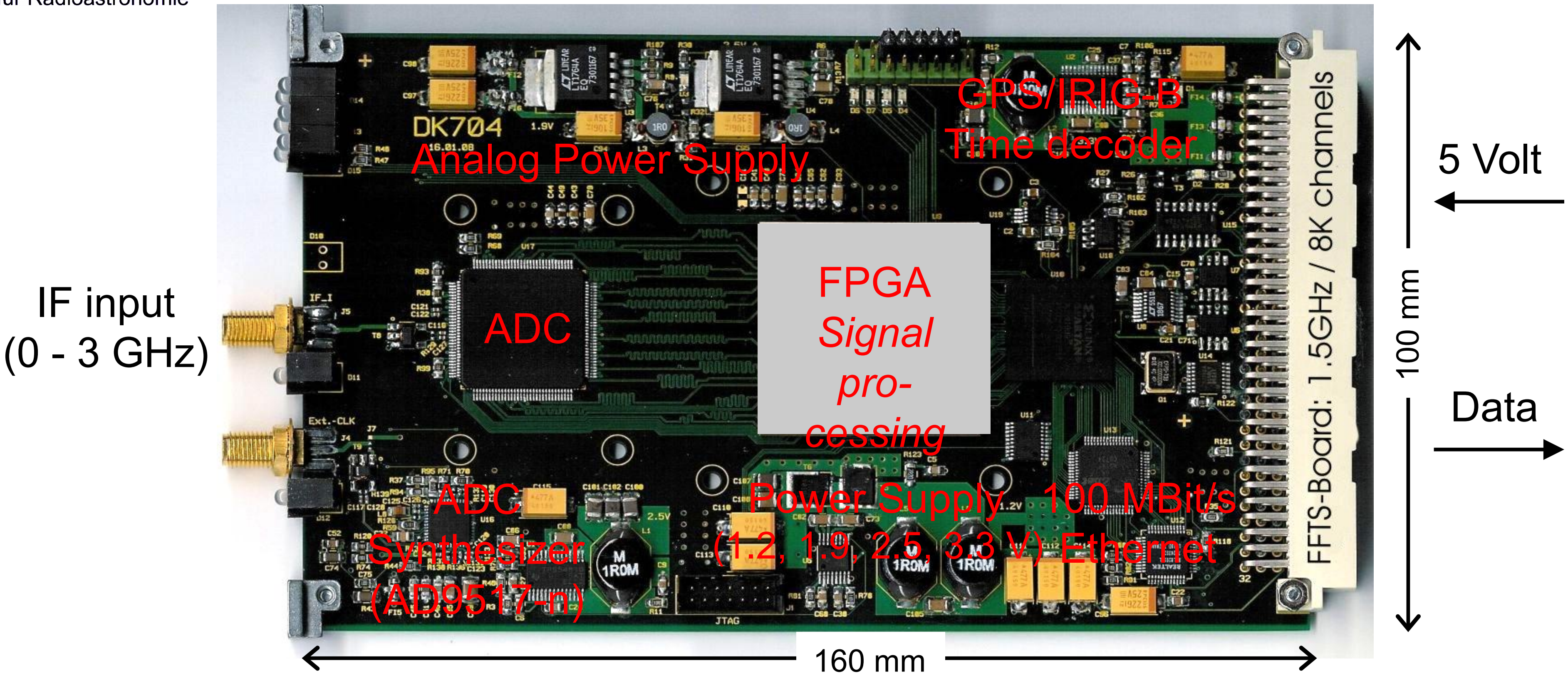
DIGITALLABOR

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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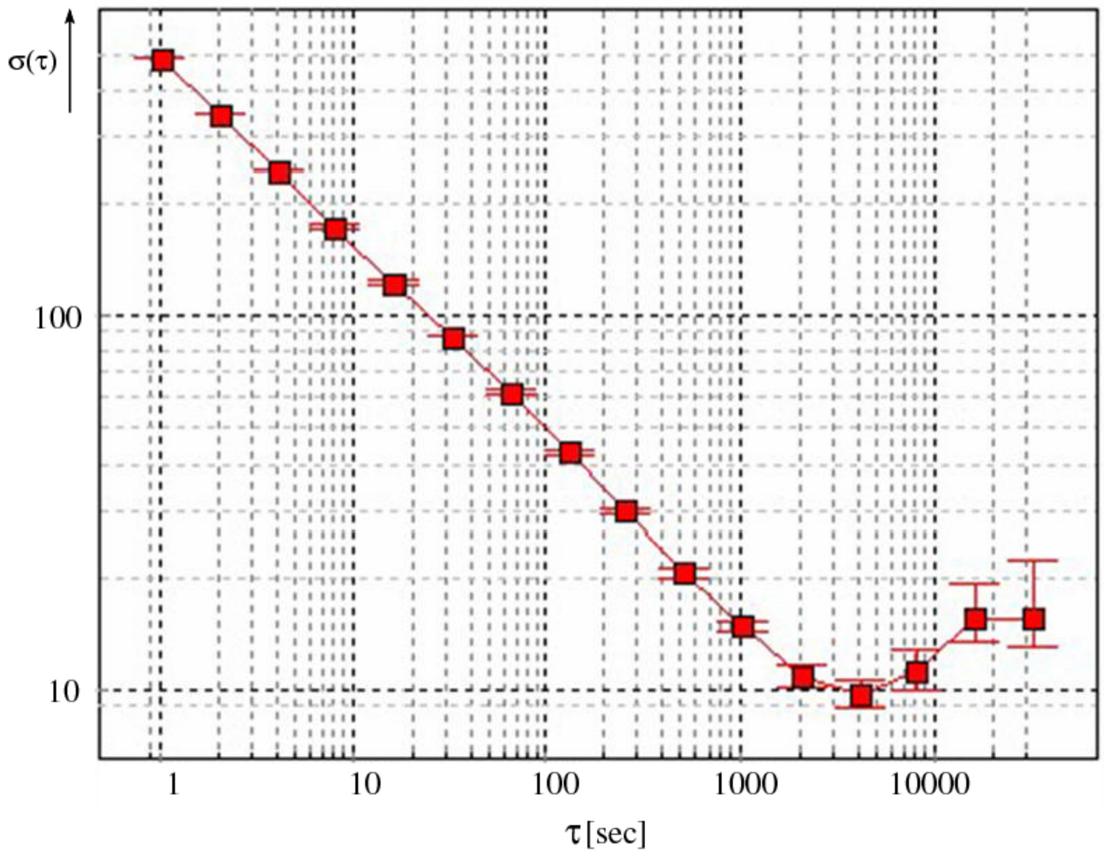
AFFTS :: *Array-FFTS for APEX*

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

Similar size to what's needed for a 100 element mmλ FPA

FFTS :: *Stability*



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

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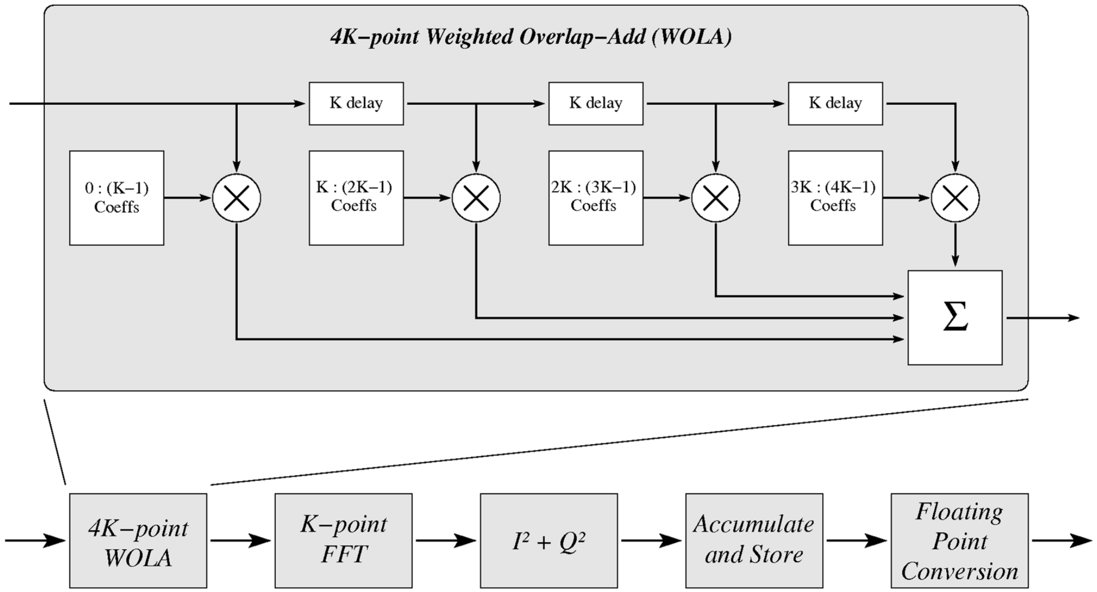
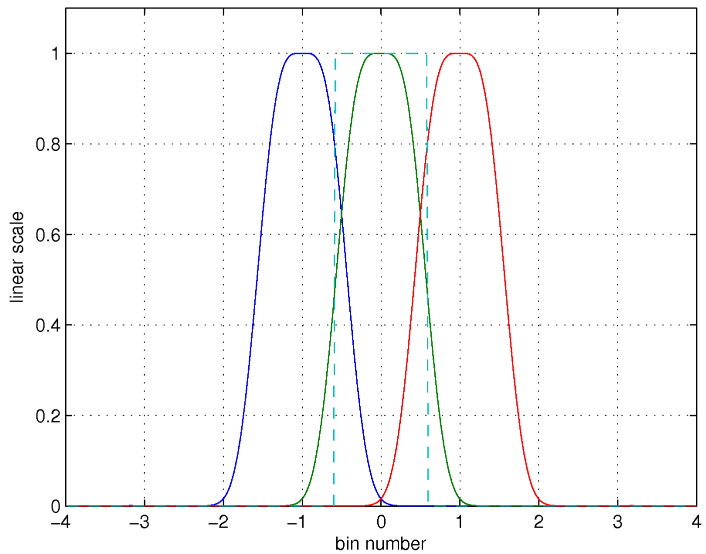
FFTS :: *Signal Processing*

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 optimized FFT signal processing pipeline

Equivalent noise bandwidth = 1.16 x frequency spacing

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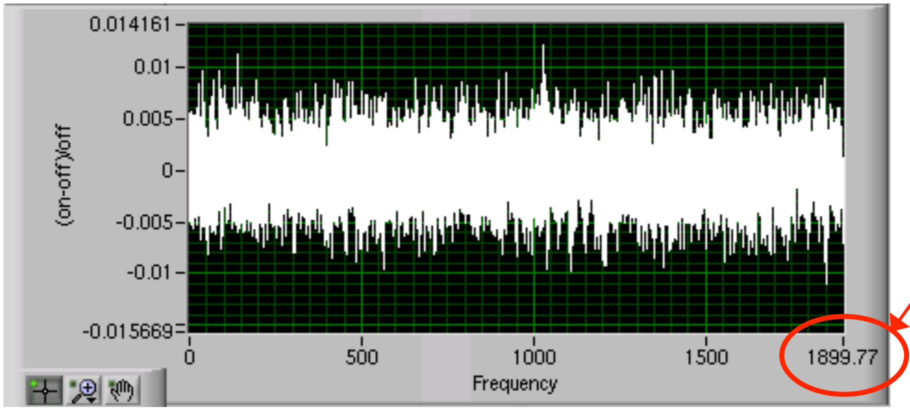
FFTS :: FPGA configurations

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 possible by using selected FPGAs with highest 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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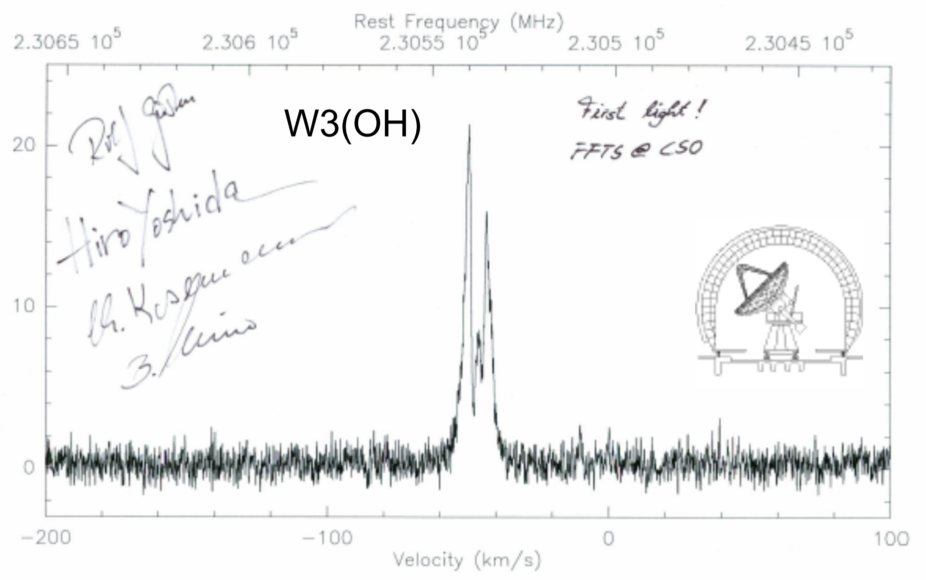
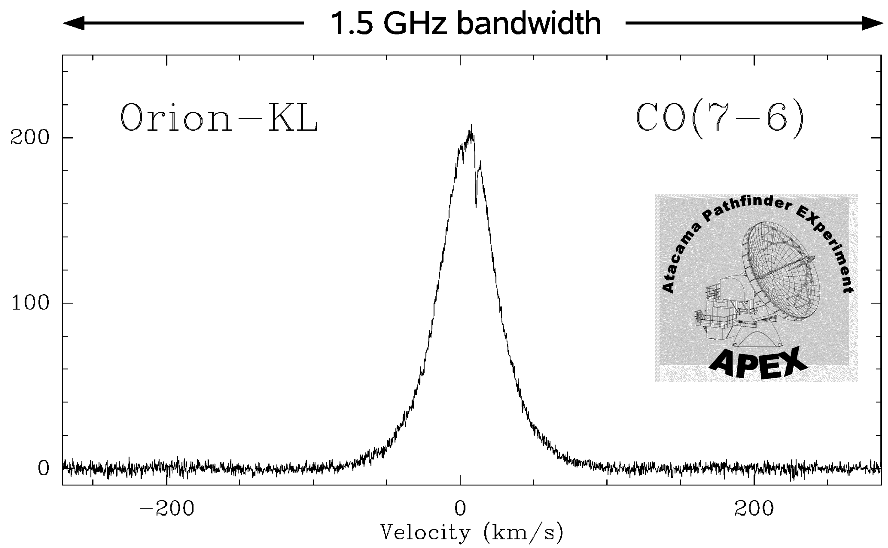
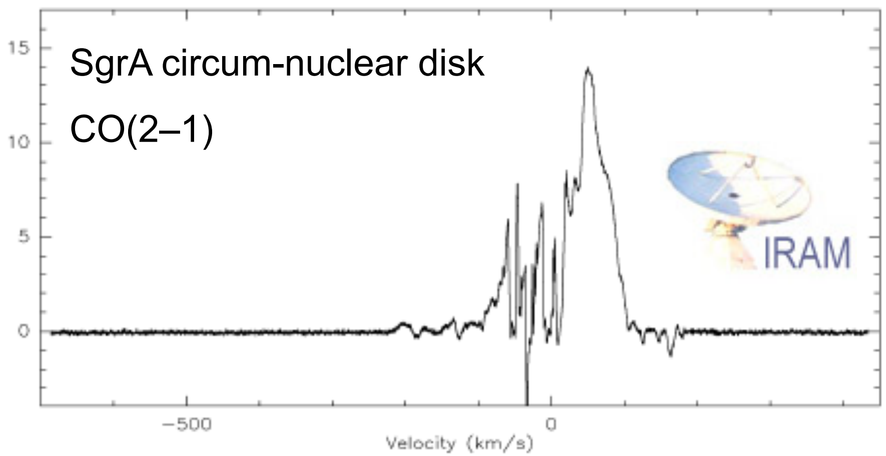
FFTS :: *in world-wide use*

The superior performance, high sensitivity and reliability of MPIfR FFT spectrometers 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*

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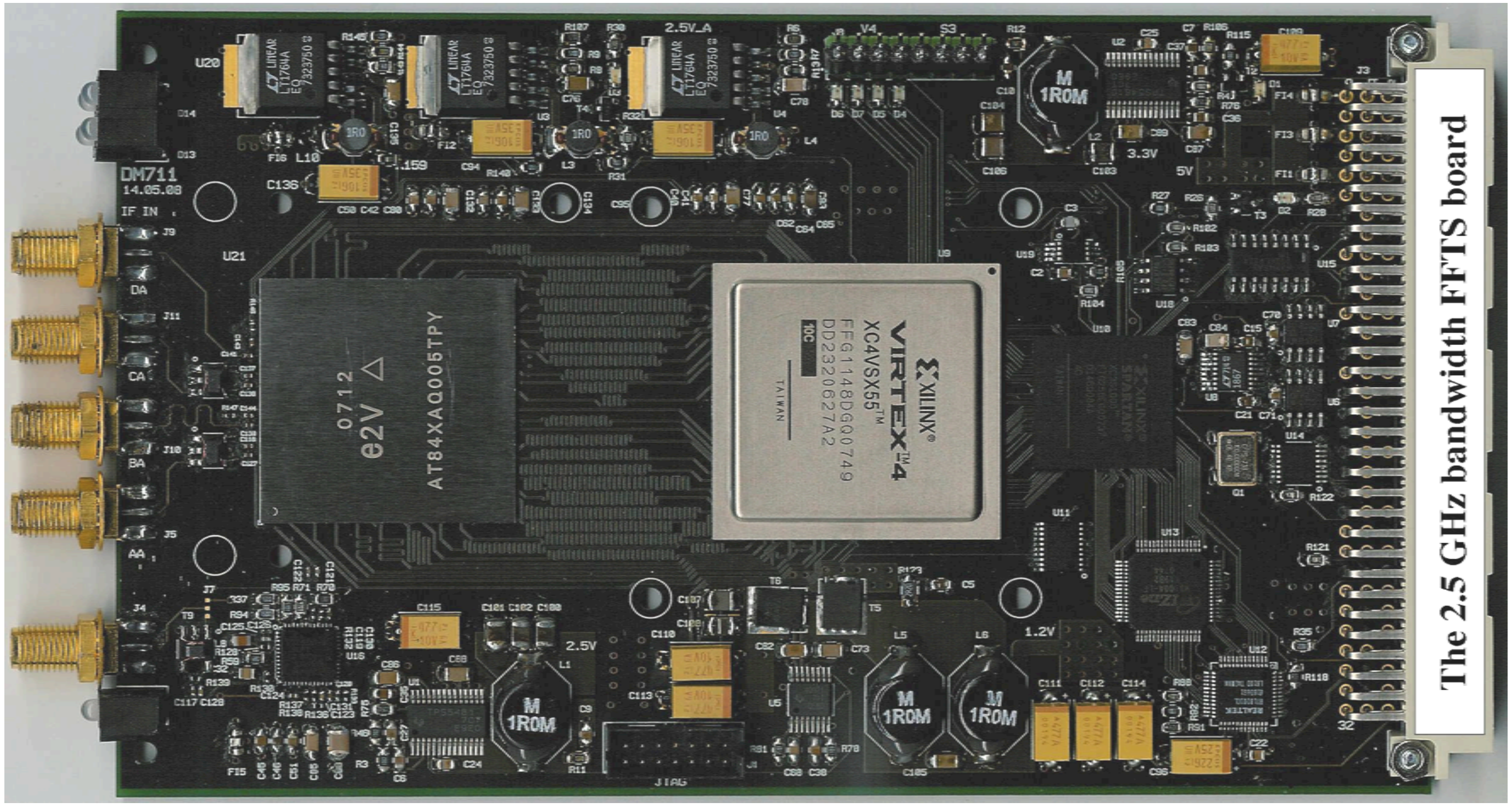
GREAT

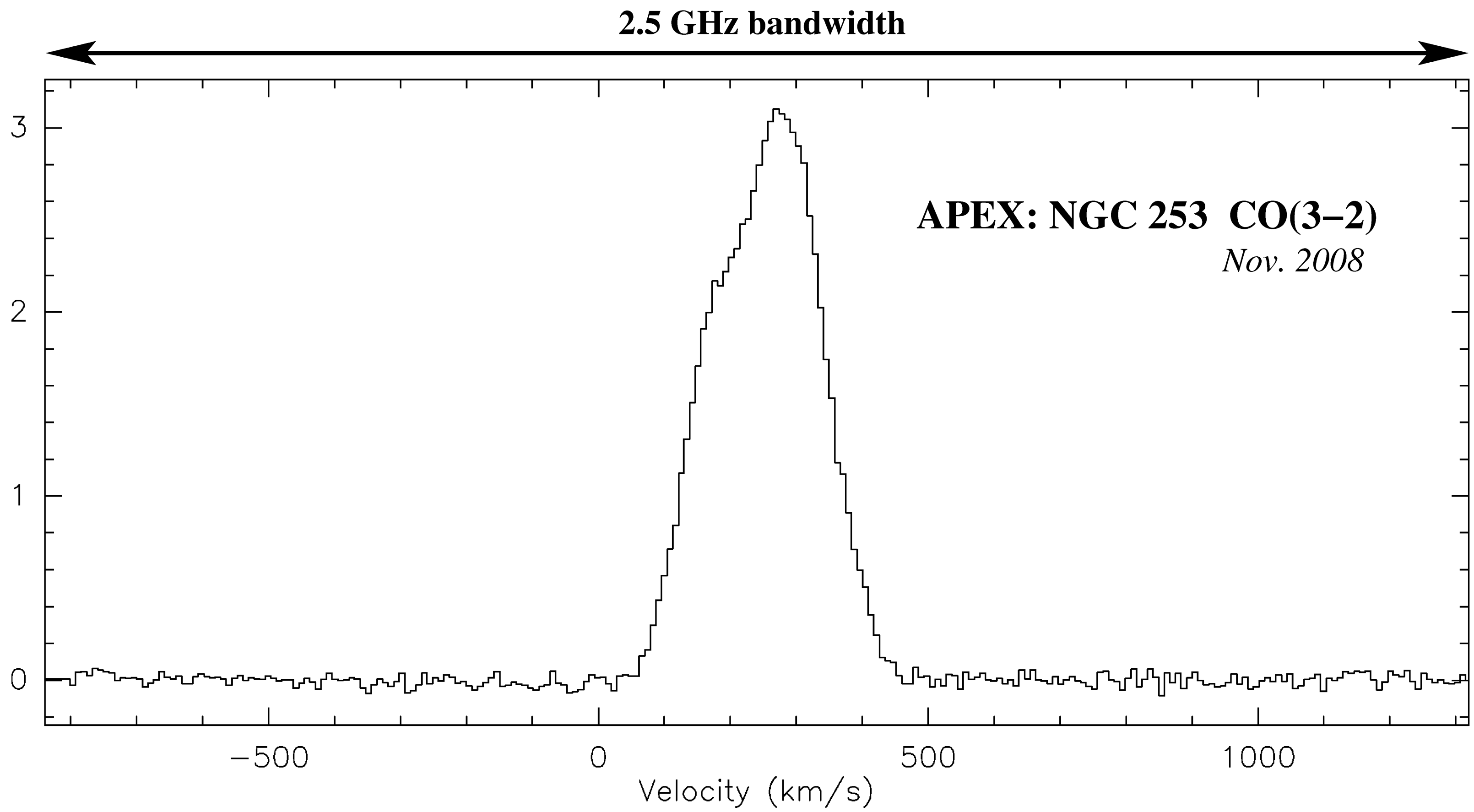
Currently in development: **The 2.5 GHz bandwidth FFTS for GREAT**



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

XFFTS :: The 2.5 GHz development

APEX: First Spectra …



MPIfR FFTS :: *Summary*

Advantages of our new generation of compact FFT spectrometers:

- ✓ 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 complexity 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, with calibration- and aging-free digital processing boards, which are swiftly re-configurable 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.

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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:

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Radiometer Physics GmbH

http://www.radiometer-physics.de

NEW!

MB Array RXs 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

+ ...

Some conclusions:

- Even in the upcoming era of vastly more powerful synthesis arrays (ALMA, EVLA) there will be a demand for vastly increased single dish observations
- Large format multibeam arrays with very wide band digital backends will revolutionize interstellar medium and star formation research
- These arrays will
  - deliver zero-spacing data for ALMA and the EVLA
  - (Sub)mm images will have comparable resolution to the EVLA at 21 cm and Herschel in the FIR
- And eventually:
  - We shall want to operate multi-beam arrays on interferometers. (Future for CARMA and IRAM PdBI in the age of ALMA?)