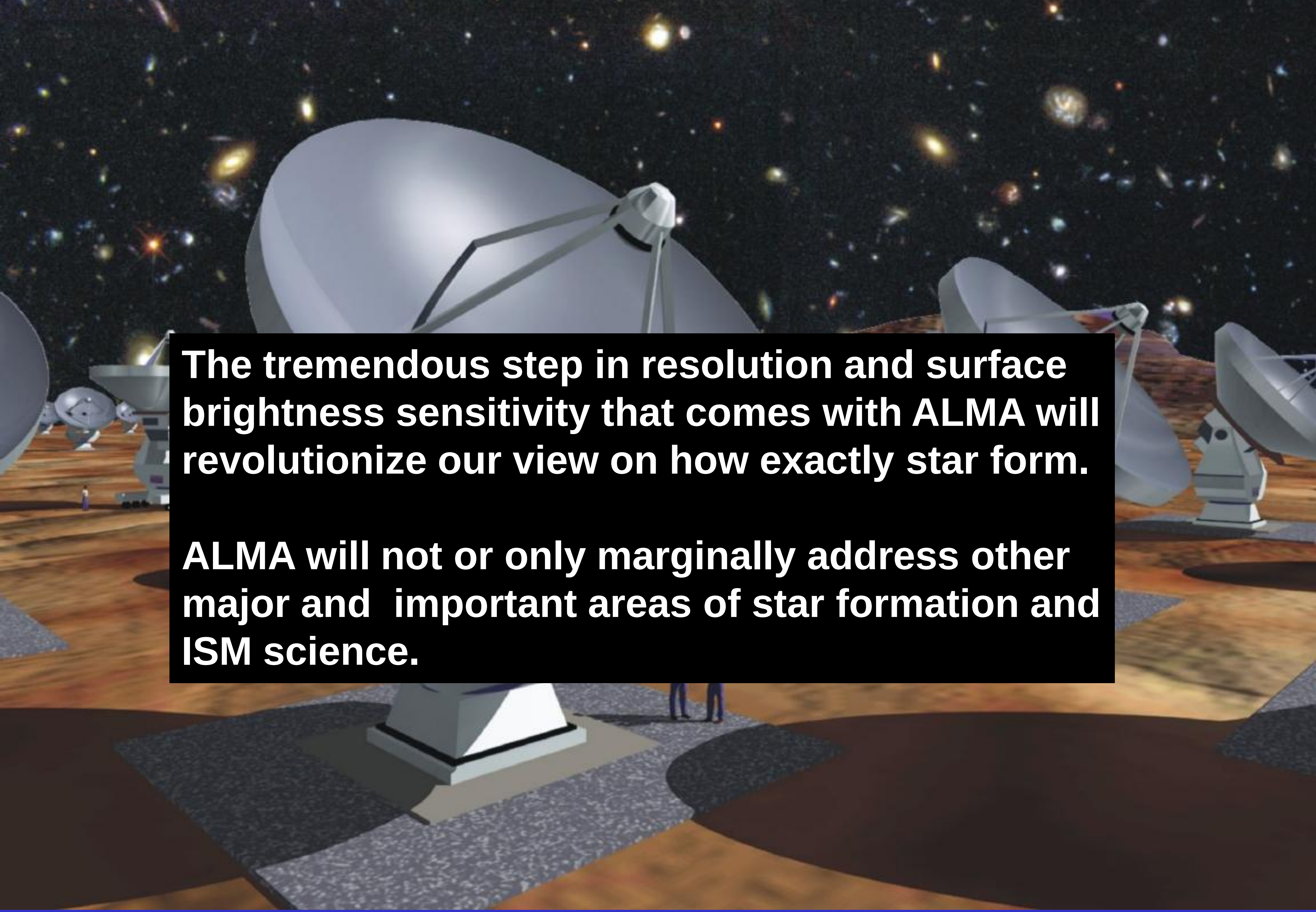
Array Spectrographs
for Radio and (Sub)millimeter Astronomy

Karl M. Menten
Max-Planck-Institut für Radioastronomie



The tremendous step in resolution and surface brightness sensitivity that comes with ALMA will revolutionize our view on how exactly star form.

ALMA will not or only marginally address other major and important areas of star formation and ISM science.

Interferometer Field of view: 1.22 λ/D

VLA (25 m)

ALMA (12m)

(At 345 GHz) ALMA really doesn't see anything that is larger than ~10 arcseconds

θ_B = 18″ @ 345 GHz

…st Angular scale

~1/2 θ_B **for a full 12 h synthesis**

~1/4 θ_B **for a snapshot**

The importance of massive stars in the Universe comes from multifold reasons which are related mostly to the large energy output during their life time, and the energetic events, and heavy elements (chemical elements heavier than the H, He and Li) they produce near and at the end of their lives.

The ultraviolet (UV) radiation and the strong stellar winds from massive stars shape the interstellar [redacted]ium (ISM) in one way, and the supernova ex[redacted]ntly mix the ISM in another way.

Feedback

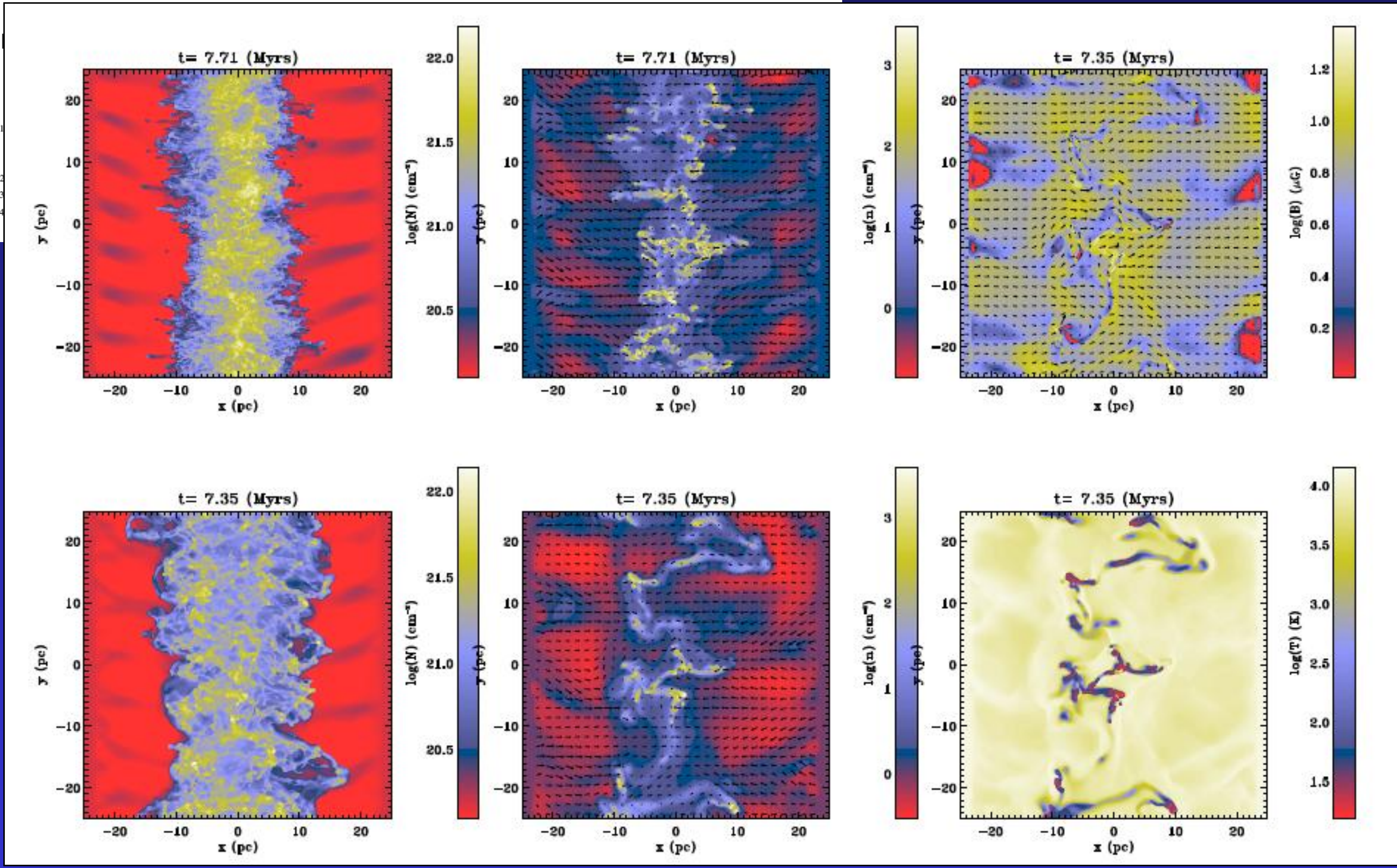
Black holes, s[redacted]ons, gamma-ray bursts (GRBs), the most dram[redacted]vents in galaxies are all connected to massive stars. **Massive stars, hence, play a key role in shaping the structure and modulating the evolution of galaxies.**

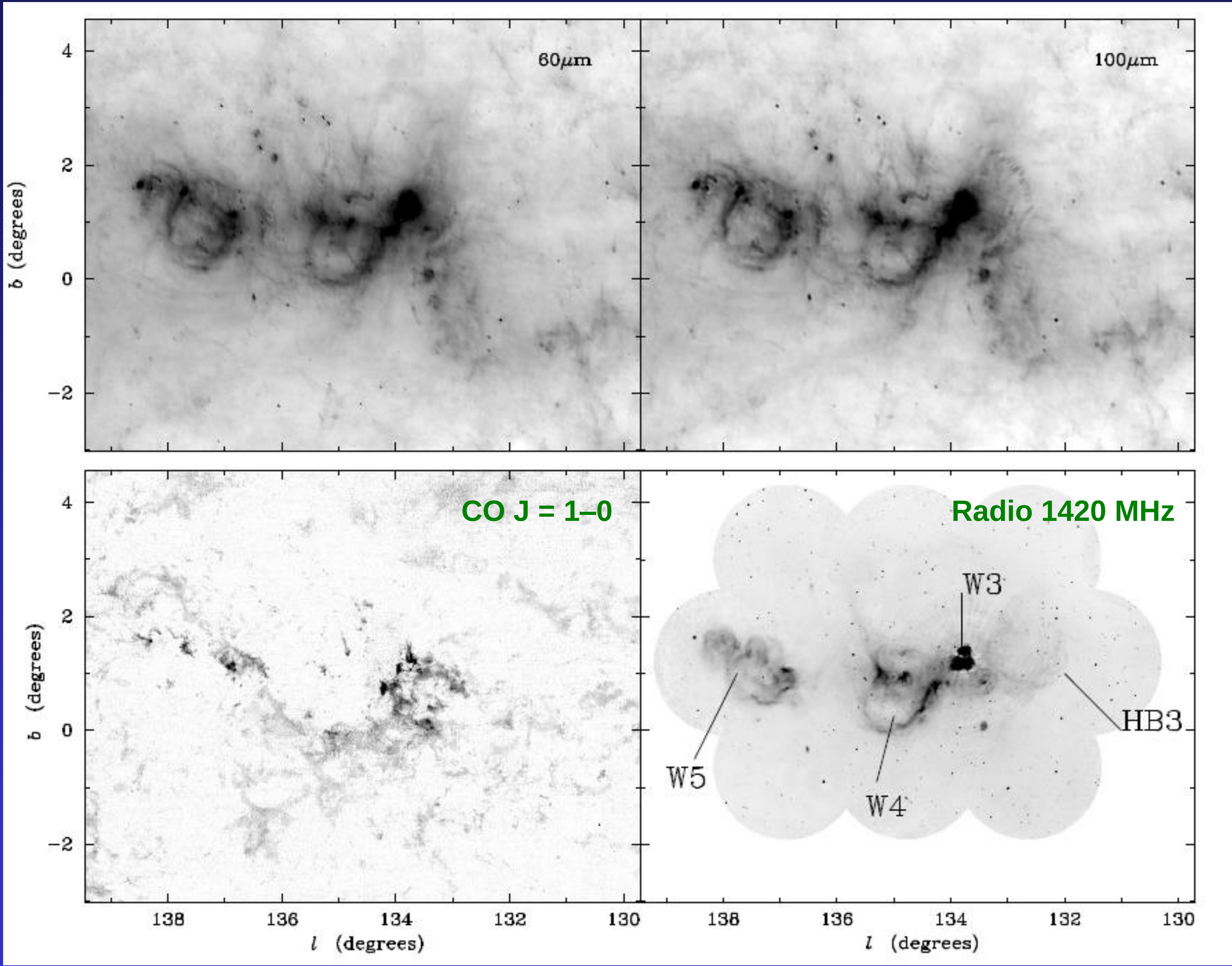
T.-C. Peng, Dissertation Bonn University/MPIfR 2010

A&A 486, L43–L46 (2008)
DOI: 10.1051/0004-6361:200810165

Astronomy & Astrophysics

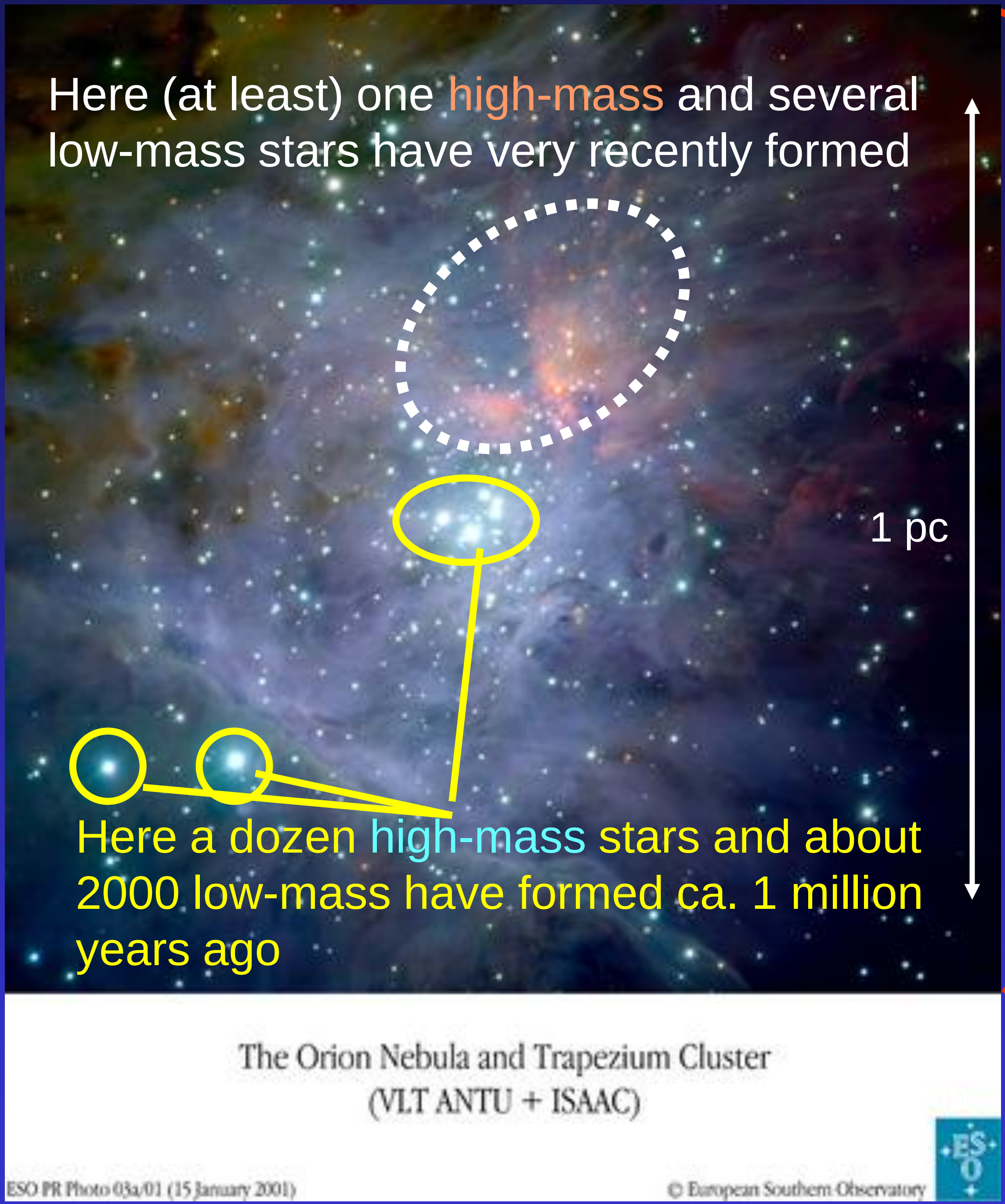
Letter to the Editor



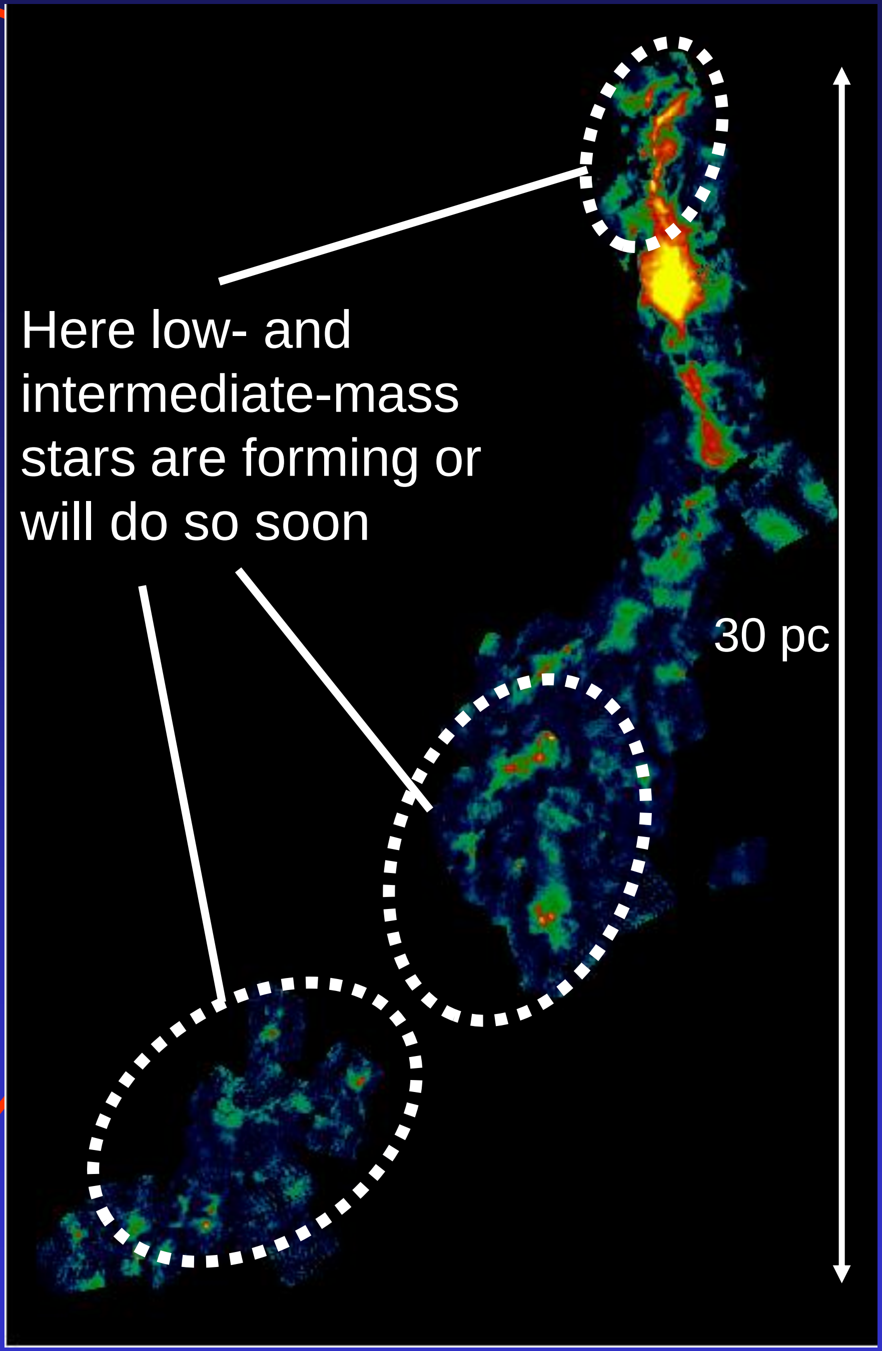


Heyer & Terebey 1998/Quabbin 14m

Normandeau et al. 1997 /CGPS

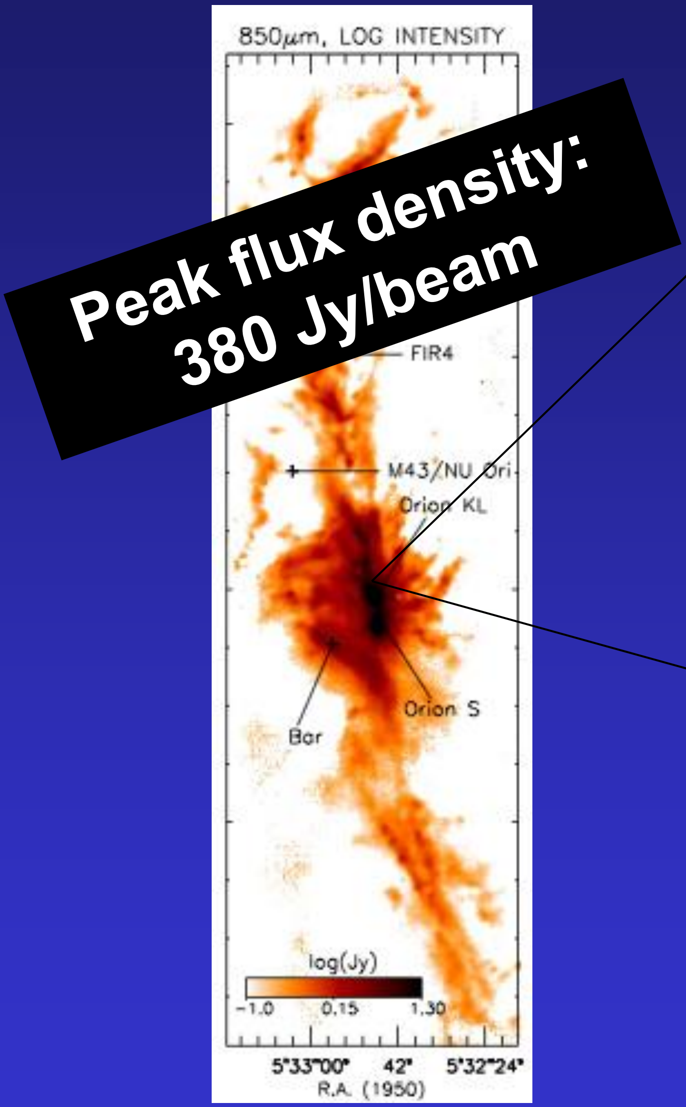


2.2 microns

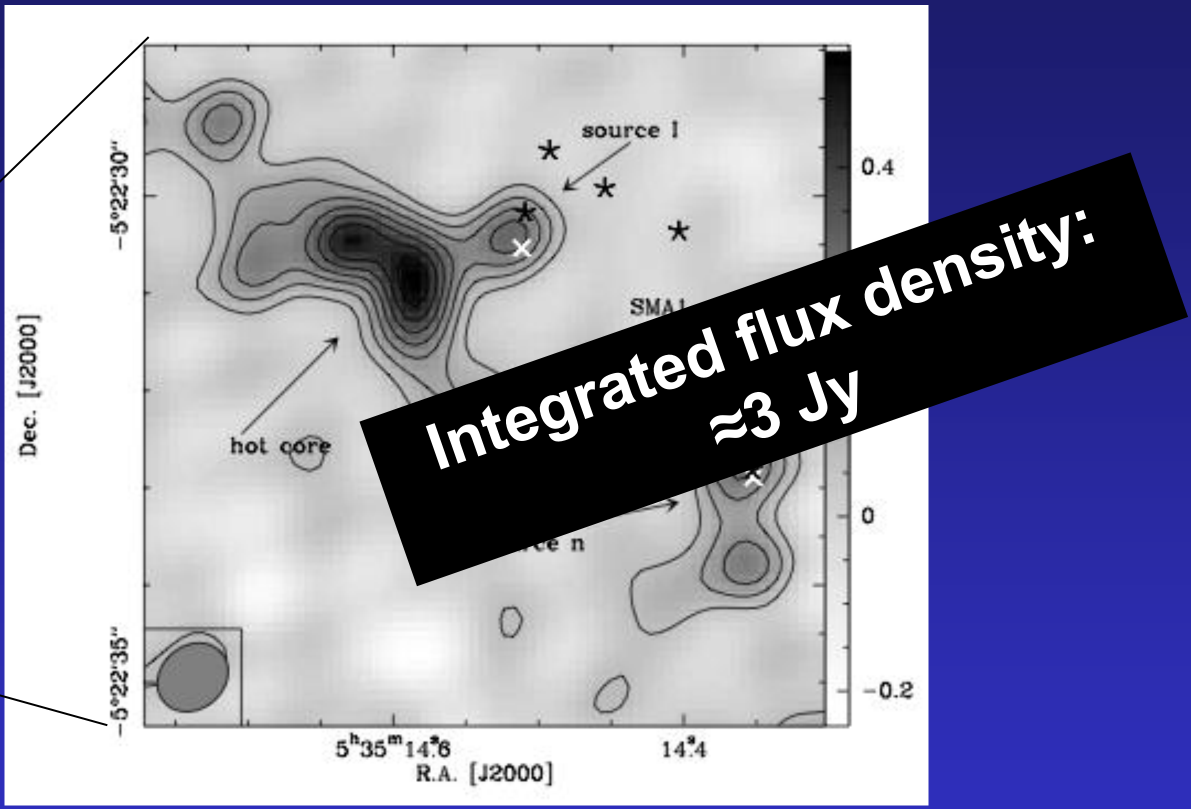


1.2 mm dust emisson
(T. Stanke/IRAM 30 m/ 37 element MAMBO array)

Two views of Orion at 870 µm (= 345 GHz)



SCUBA@JCMT: Johnstone & Bally 1999

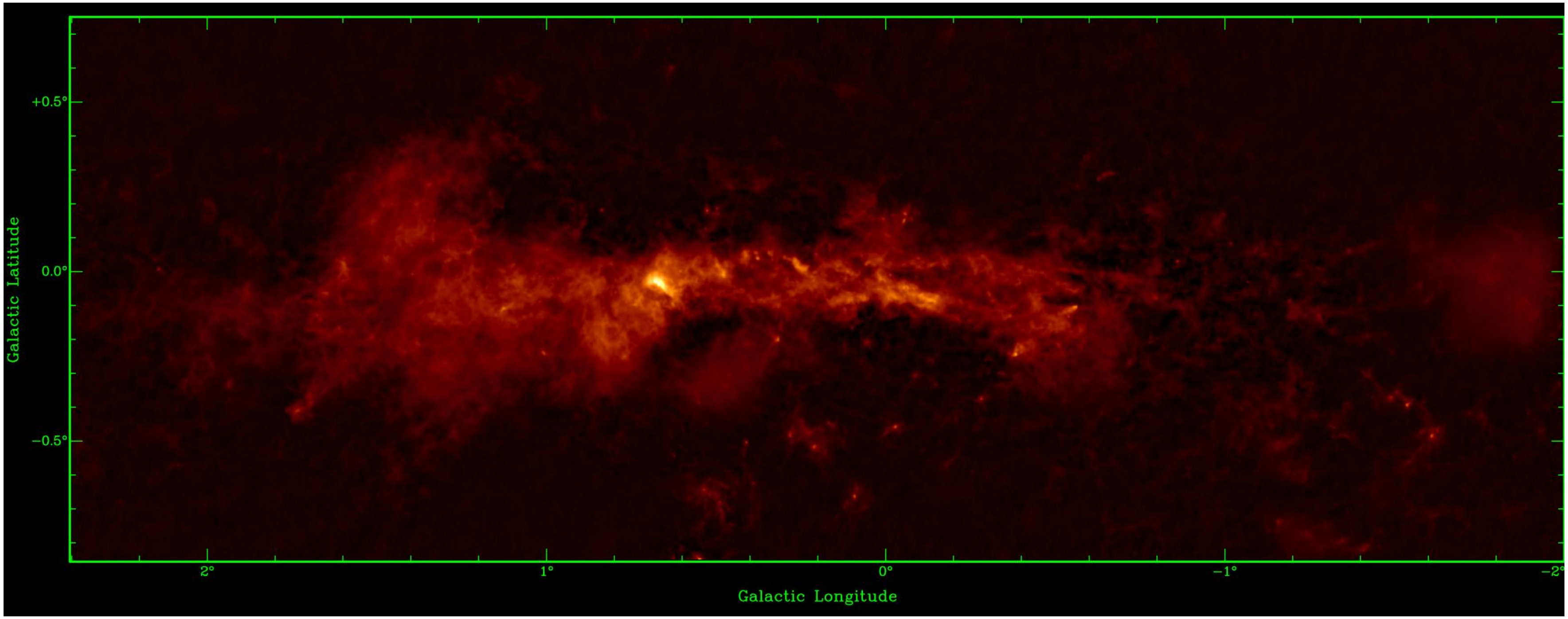


SMA: Beuther et al. 2004/5

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

The power of (bolometer) array science:

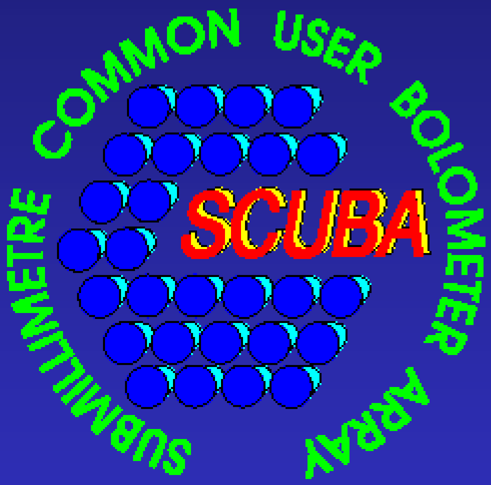
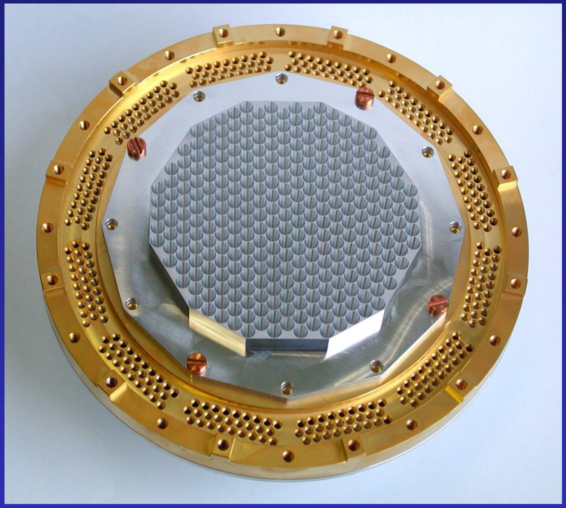
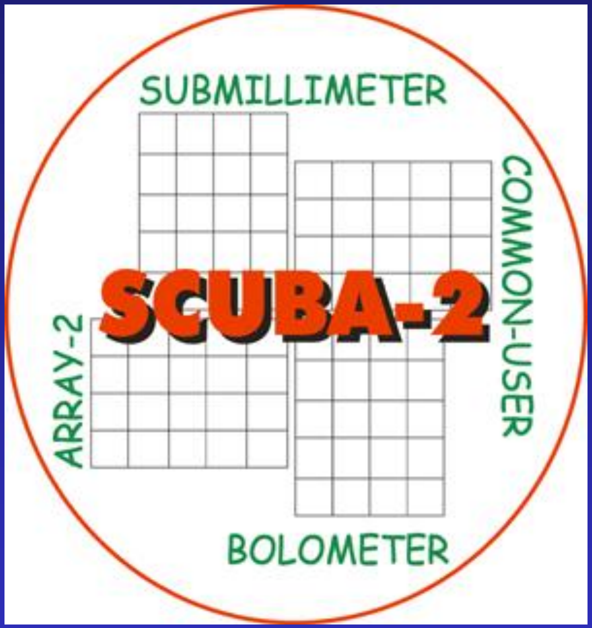
The Galactic Center Region as seen by LABOCA at 870 μm



ATLASGAL+ (reprocessed)
Schuller/Weiß

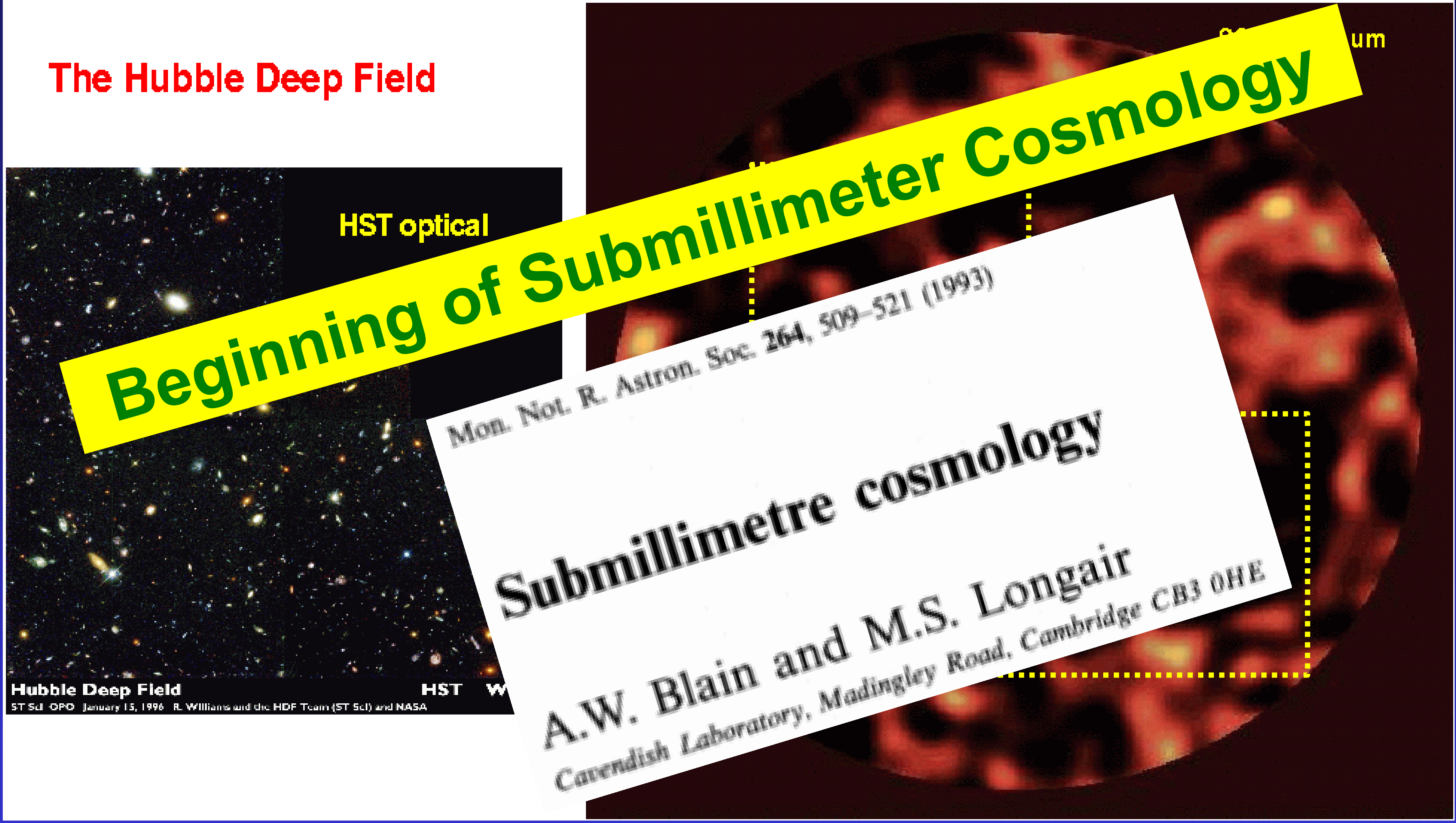
The need for large area mapping:

Bolometer arrays are getting ever larger:

SCUBA	LABOCA	SCUBA-2
		
37 bolometers	295 bolometers	2 × 5128 bolometers
yesterday	**since 2007**	**2011???**

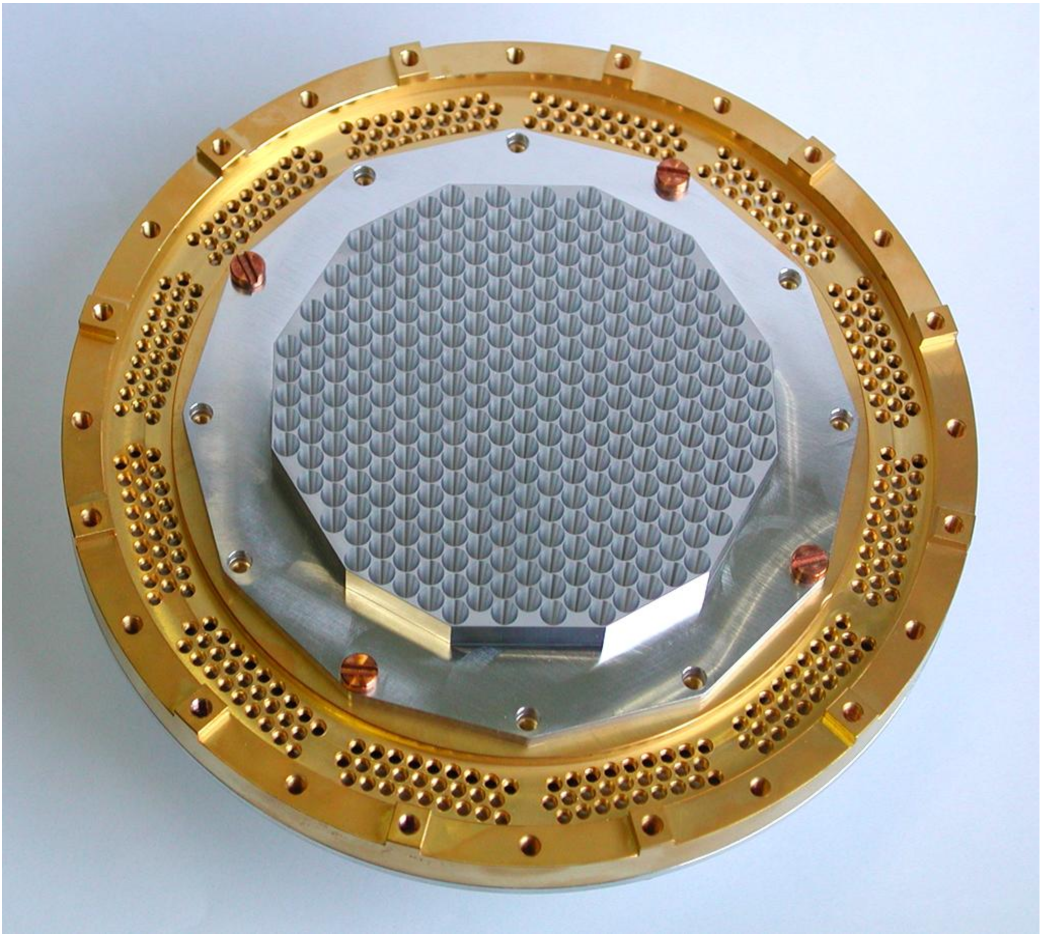
In addition: MAMBO-II, Bolocam, SHARC-II, …

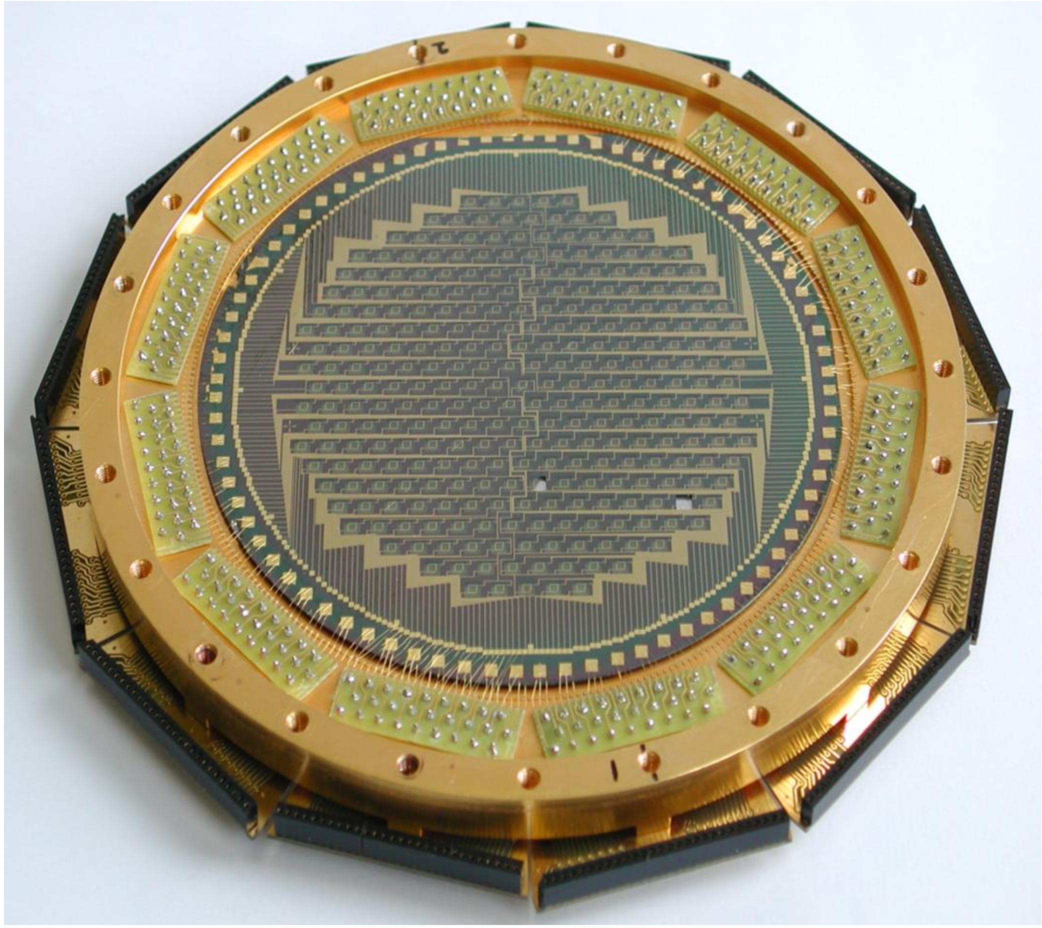
The sub-mm Extragalactic Background resolved:

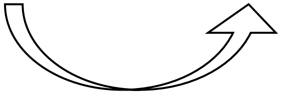


Hughes et al. 1998, Nature,

The Large APEX Bolometer Camera – LABOCA



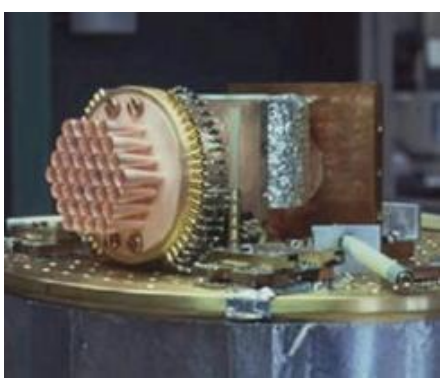




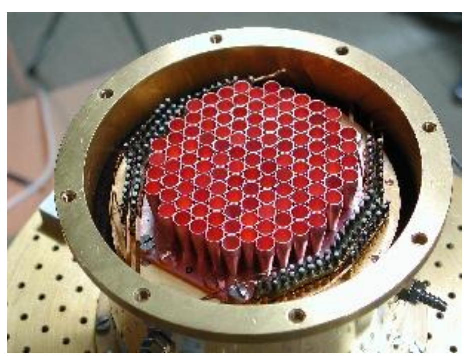
MPIfR Bolometer Array Cameras

Teleskop	Name	Elem.	λ/mm	Debut
IRAM 30m	MAMBO	7 $\rightarrow$ 117	1.2	1991- 2002
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	2007
APEX		37	0.35	2007
APEX	LABOCA-II	295(TES)	0.87	2010

SIMBA

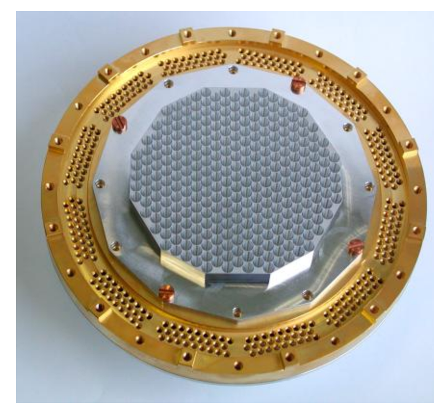


MAMBO-37



MAMBO-117

HUMBA

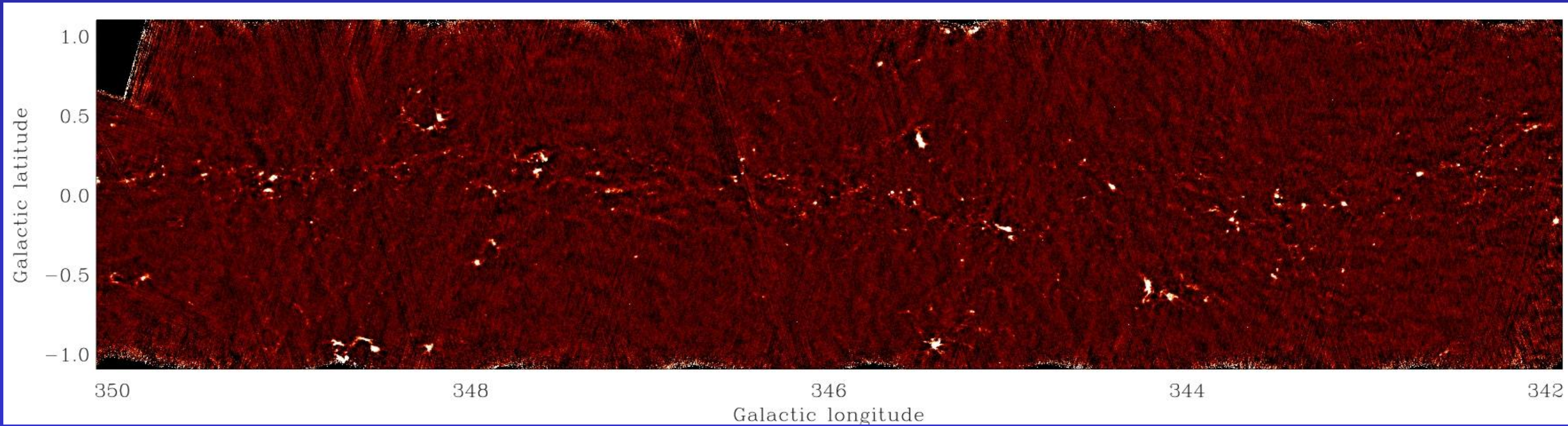


LABOCA-295 on APEX

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



Schuller et al. 2009

The University of Manchester

MANCHESTER 1824

The Methanol Multibeam Survey

J. A. Green (1), R. J. Cohen (1), J. L. Caswell (2), G. A. Fuller (1), S. Breen (5), K. Brooks (2), M. G. Burton (3), A. Chrysostomou (4), P. J. Diamond (1), S. Ellingsen (5), M. D. Gray (1), M. G. Hoare (6), M. R. W. Masheder (7), B. N. McClure-Griffiths (2), M. Pestalozzi (4), C. Phillips (2), L. Quinn (1), M. Thompson (4), C.M. Voronkov (2), A. Walsh (10), D. Ward-Thompson (8), D. Wong-McSweeney (1), J. A. Yates (9), J. Cox (8)

CSIRO

Goals:

- 7 beam RX on Parkes radio telescope cover whole southern Galactic plane searching for
  - 6.7 GHz CH_3OH masers – excellent tracers for high-mass protostars
  - 6.0 GHz OH masers – magnetic field probes in high-mass star forming regions
- Use ATCA for precise positions of detected sources

Results:

- Mission accomplished, > 1000 masers found, ~1/2 new ones
- Magellanic Cloud
- Northern extension unclear

Surveys for compact sources (masers, AGN, radio stars…) can be done much more efficiently with many element interferometers than with multi-beam arrays with a moderate number of elements

Single dish vs. interferometer

Basic facts:

- (*If* you can calibrate your phases) an interferometer is much better to detect faint (point-like) sources

- Single dish observations are necessary to provide short-spacing information

- Bolometer arrays will become very large (thousands of elements)

→ Many dozen times the collecting area of ALMA and, thus, ***very much faster*** if noise not dominated by systematics (atmosphere) and if the confusion limit is not reached

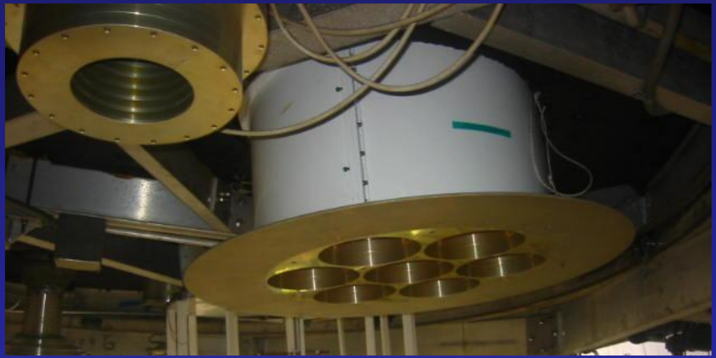
- Heterodyne arrays will have ~100 elements at 3 mm and dozens at submm and radio wavelengths

The **HI Parkes All Sky Survey (HIPASS)**

HIPASS:
- 13 beam cooled 21 cm system
- Between 1997 and 2002 using Parkes RT
    - covered 71% of the sky
    - redshift range: -1,280 to 12,700 km s^{-1}
    - identified 5317 HI sources
    - discovered:
        - leading arm of the Magellanic Stream
        - gas clouds devoid for stars
    - also used for all-sky pulsar survey

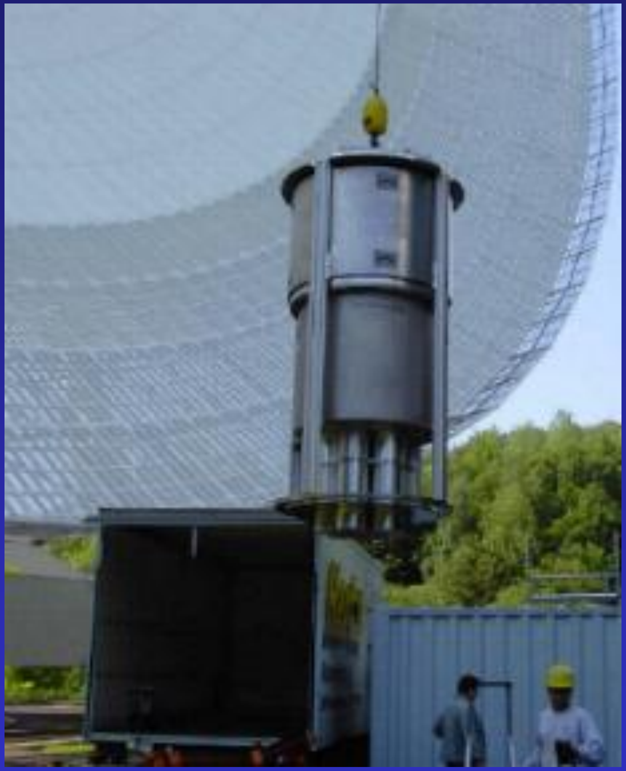
ALFA: Arecibo L-Band Feed Array

ALFA:
- CSIRO-built 7 beam cooled 21 cm system
- Since 2005 in operation at the Arecibo 300 m telescope
- Galactic and extragalactic HI surves
- continuum and polarization surveys
- also used for pulsar surveys



Effelsberg L-Band 7 Feed Array

Major project:
THE EFFELSBERG–BONN H I SURVEY
• Northern sky (decl. > 5 deg)



Spectral line imaging with heterodyne receiver multi-beam arrays

Concentrate now an molecular line astronomy

Advantages of array receivers:

- Mapping speed
- Mapping homogeneity (map lage areas with similar weather conditions/elevation) $\rightarrow$ minimize calibration uncertainties.

SIS arrays have only recently become available:

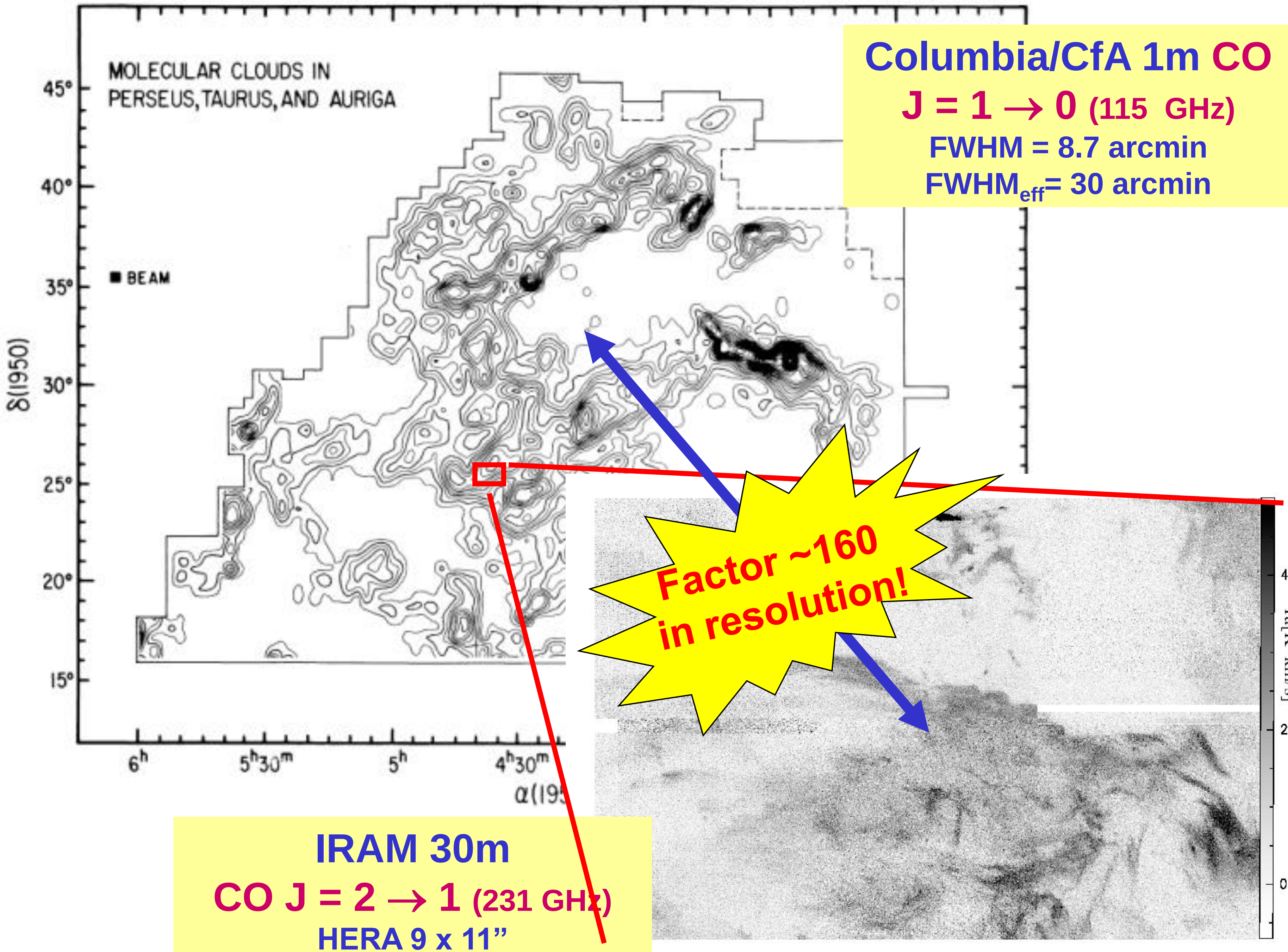
A&A 423, 1171–1177 (2004)
DOI: 10.1051/0004-6361:20034179

Astronomy & Astrophysics

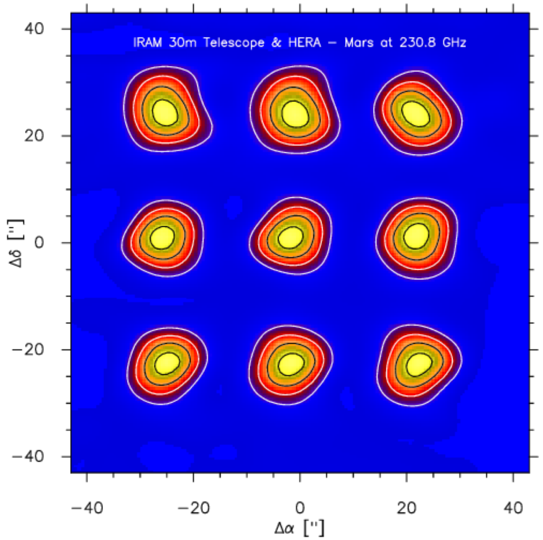
A 230 GHz heterodyne receiver array for the IRAM 30 m telescope

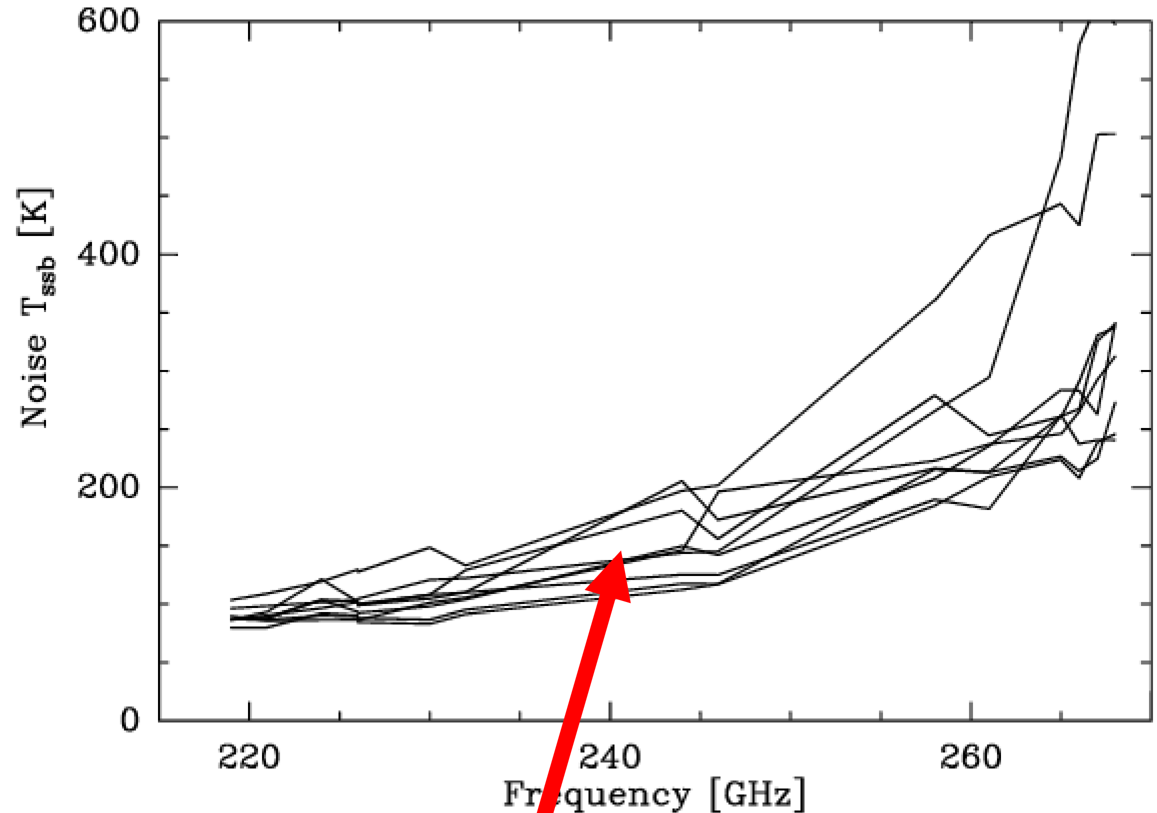
K.-F. Schuster[1], C. Boucher[1], W. Brunswig[1], M. Carter[1], J.-Y. Chenu[1], B. Foullieux[1,2], A. Greve[1], D. John[1], B. Lazareff[1], S. Navarro[1], A. Perrigouard[1], J.-L. Pollet[1], A. Sievers[1], C. Thum[1], and H. Wiesemeyer[1]

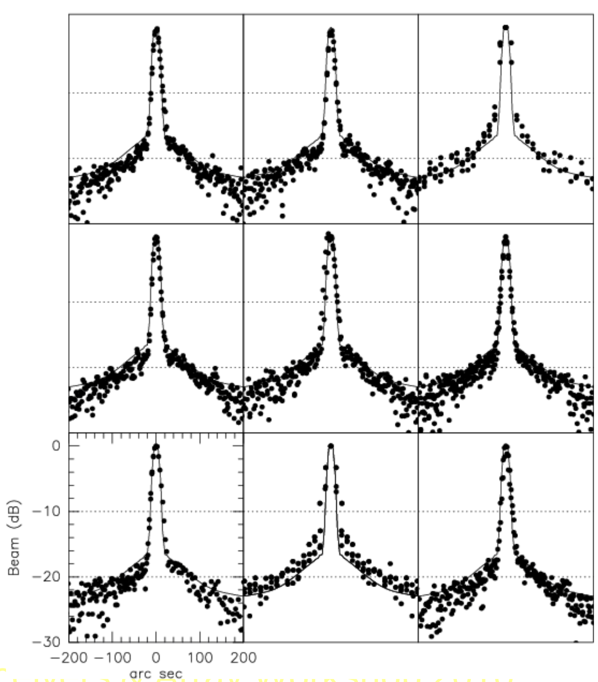
HERA = HEterodyne Receiver Array


MOLECULAR CLOUDS IN
PERSEUS, TAURUS, AND AURIGA
BEAM
45°
40°
35°
30°
25°
20°
15°
δ(1950)
6h
5h30m
5h
4h30m
α(19
Columbia/CfA 1m CO
J = 1 → 0 (115 GHz)
FWHM = 8.7 arcmin
FWHMeff= 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:





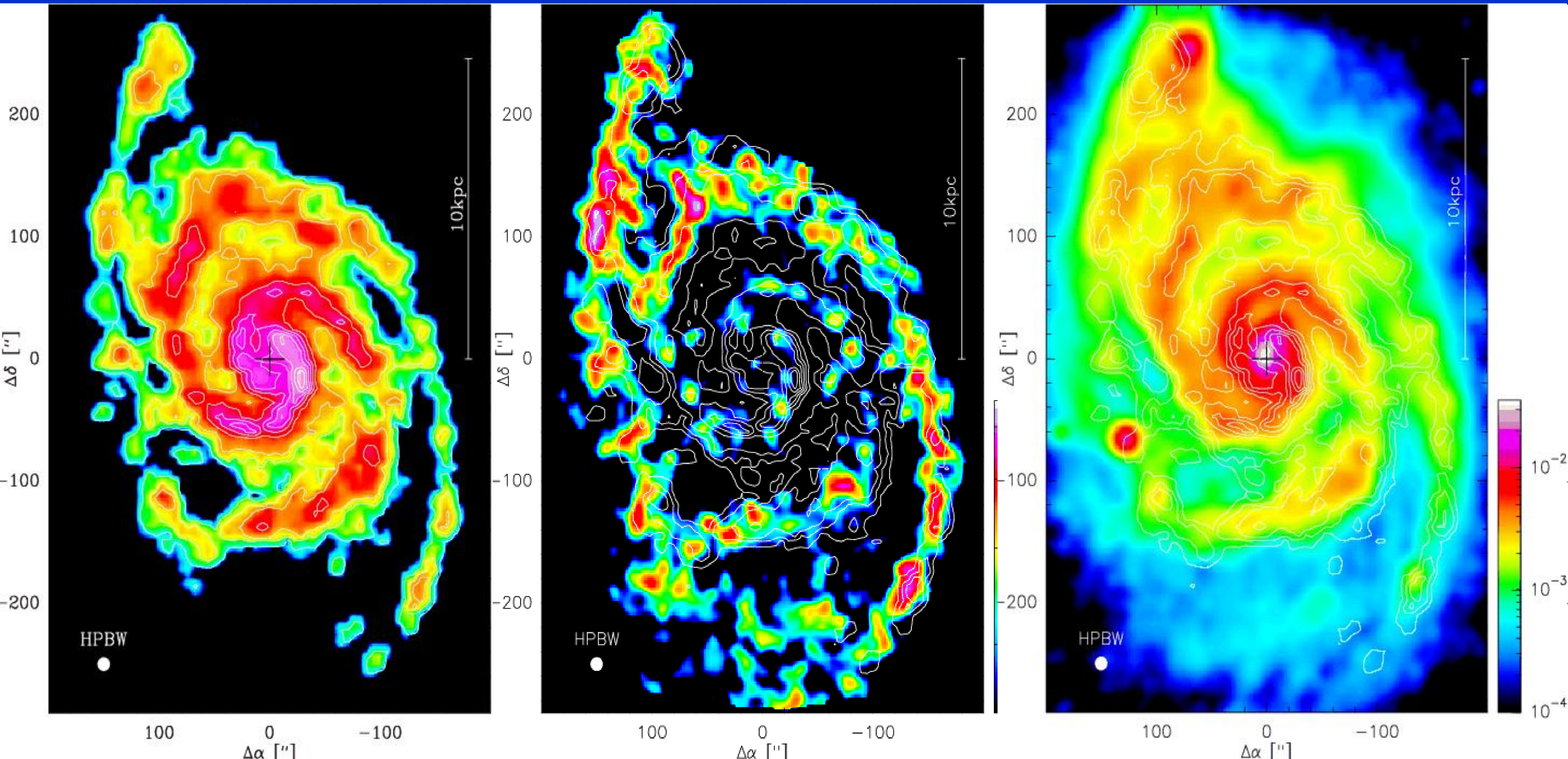


Important:

- **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

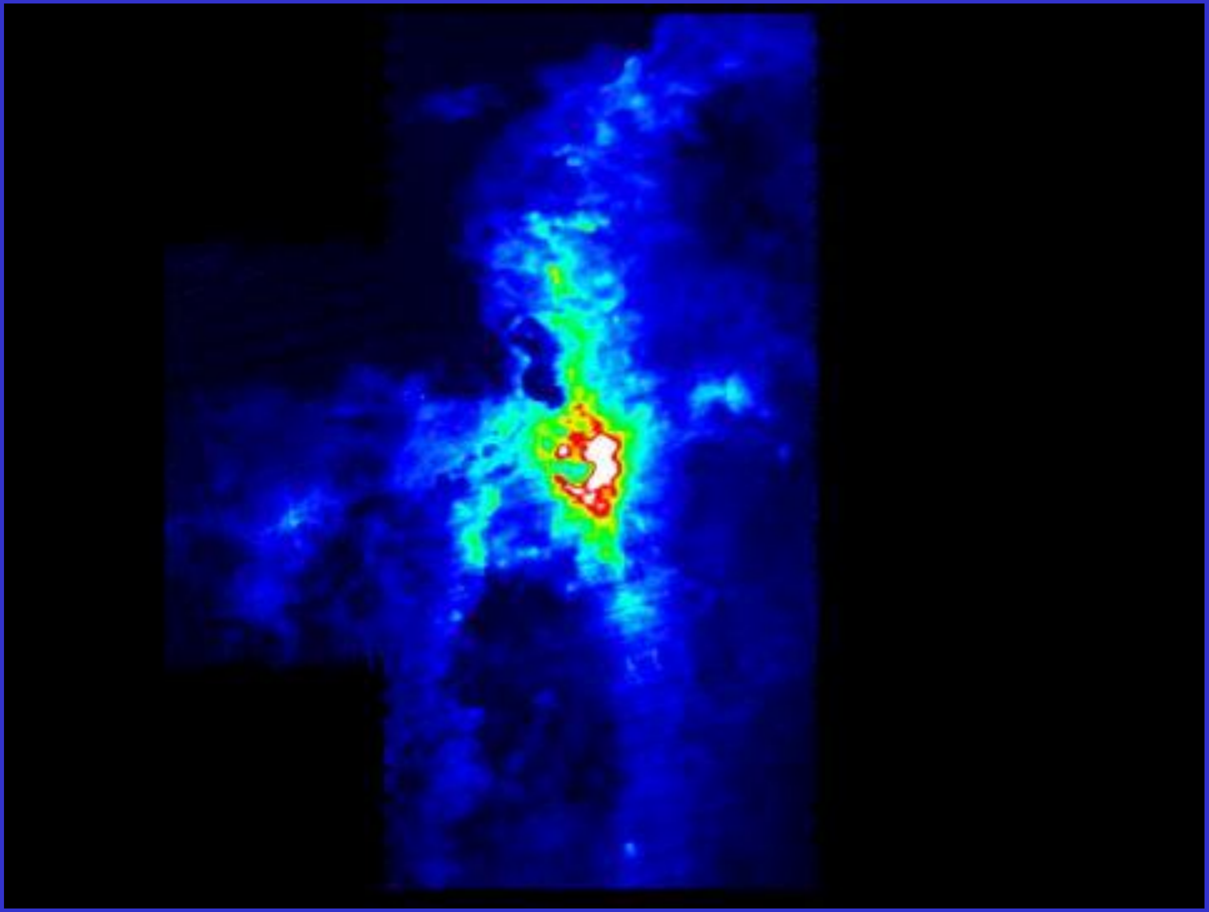
HI 21 cm
FWHM = 13"
VLA

Radio 20 cm
FWHM = 15"
VLA

Schuster et al. 2007

JCMT Heterodyne Array Receiver Programme

- 16 elements
- 325 – 375 GHz
- 14" FWHM

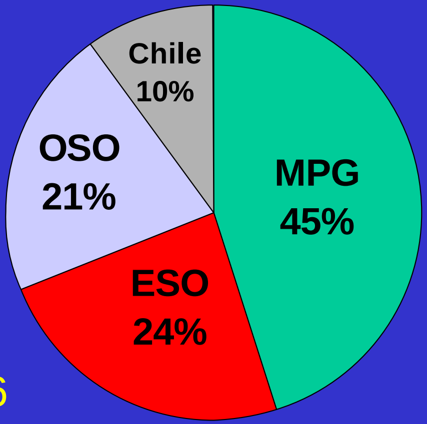


http://www.mrao.cam.ac.uk/projects/harp/

The Atacama Pathfinder Experiment (APEX)

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

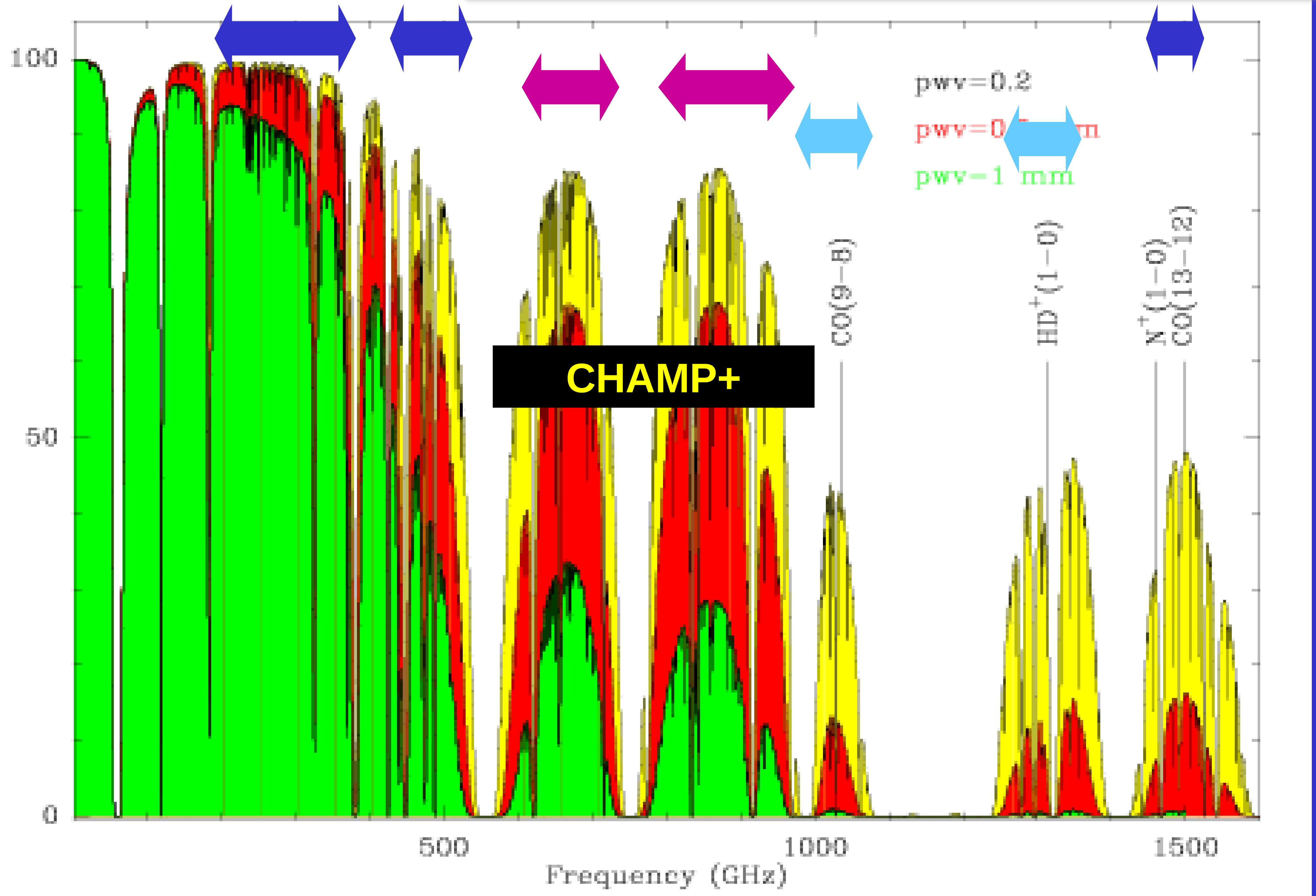
on
Llano de Chajnantor (Chile)
Altitude: 5098.0 m



- ∅ 12 m
- λ = 200 μm– 2 mm
  ν = 200–1400 GHz
- 15 μm rms surface accuracy
- In operation since September 2006
- Instruments:
  - Heterodyne RXs:
    - single pixel covering all "windows" 200–1400 GHz
    - CHAMP+ 7x450+7x350 μm array
  - Bolometer Arrays:
    - ~300 element 870 μm Large Apex Bolometer Camera (LABOCA)
    - 37 element 350 μm Submillimter Apex Bolometer Camera (SABOCA)
    - ~300 element 1.3 mm APEX SZ Camera

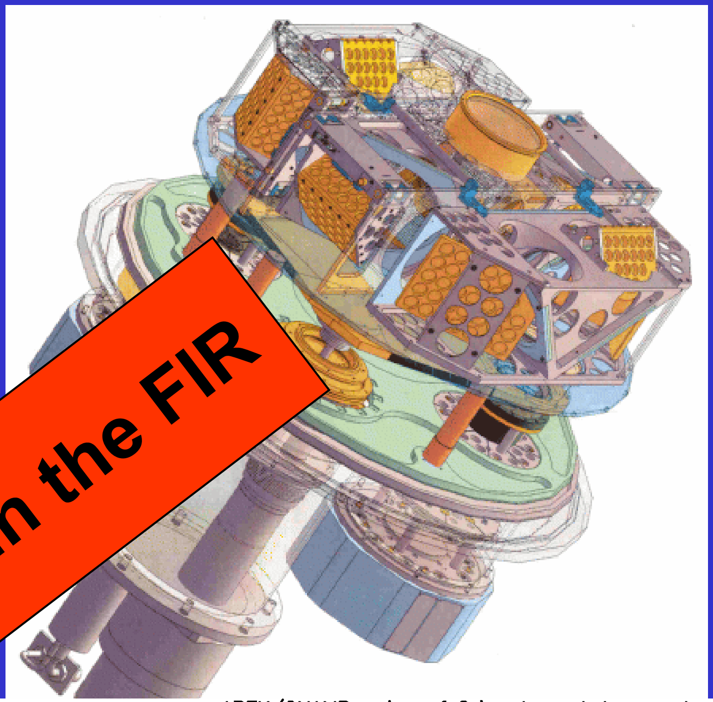
http://www.mpifr-bonn.mpg.de/div/mm/apex/
http://www.apex-telescope.org

APEX Heterodyne Instrumention



Max-Planck-Institut für Radioastronomie

SRON

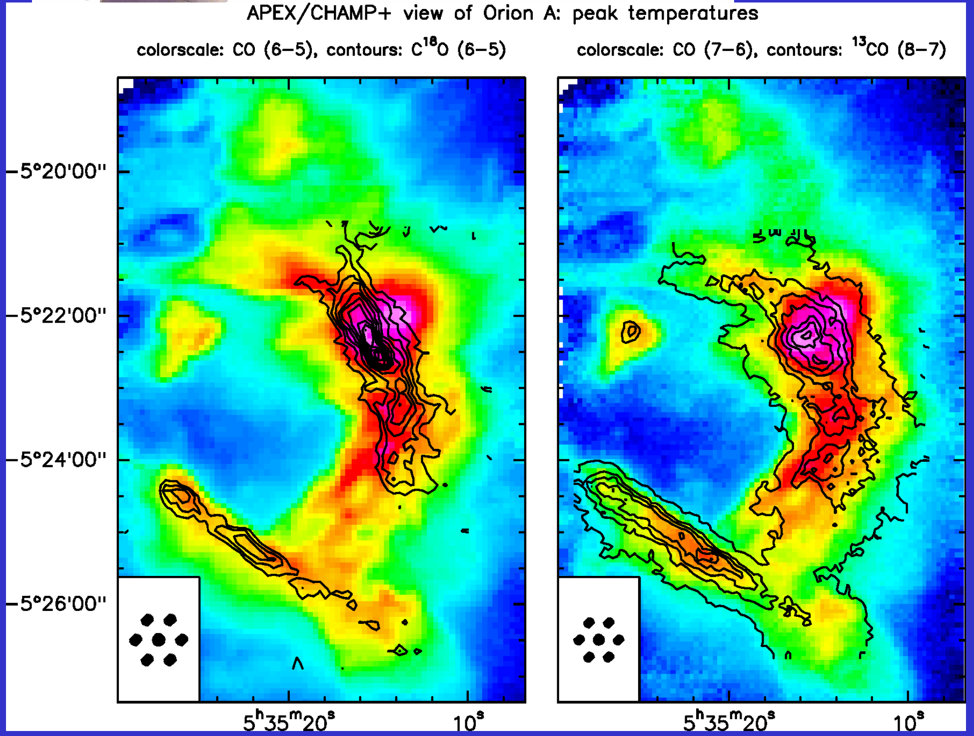


CHAMP+

Carbon Heterodyne Array of the MPIfR

Same as Herschel in the FIR

- 2 x 7 pixels
- frequency ran… 20 and 790 – 950 sim… sly
- beamsize 9" – 7" and 7" – 6"
- IF band 4 – 8 GHz



Peng et al. 2010

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

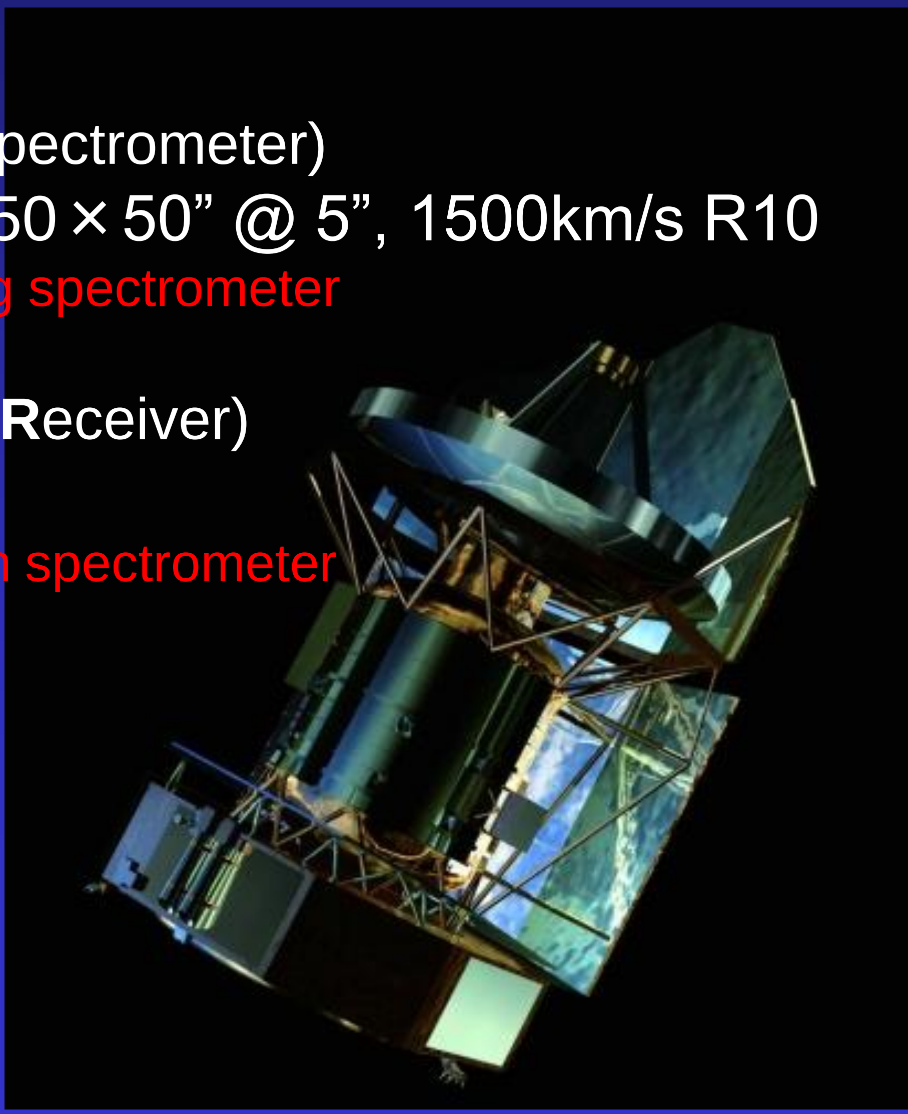
http://www.strw.leidenuniv.nl/~champ+/

HERSCHEL

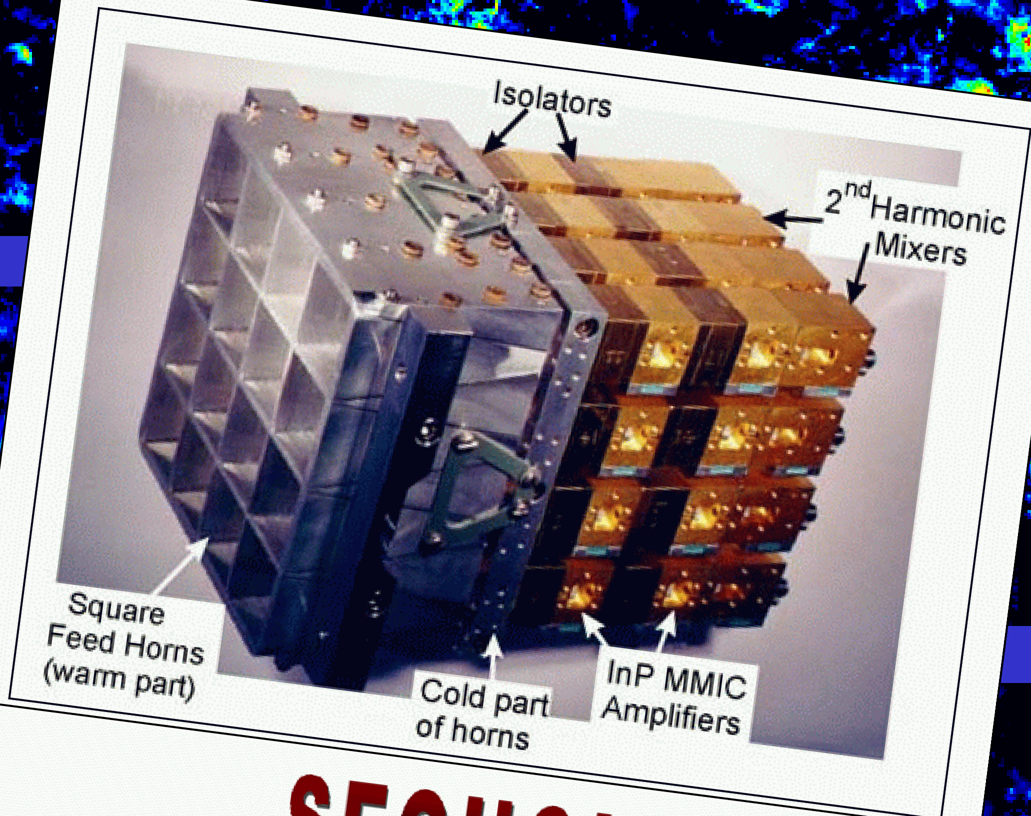
HIFI (**H**eterodyne **I**nstrument for the **F**ar **I**nfrared)
480 – 1910 GHz, 157 – 625μm, 7 bands
Very high resolution heterodyne spectrometer

PACS (**P**hotodetector **A**rray **C**amera and **S**pectrometer)
60-210 μm: photom. 1.75' x 3.5' / spec 50 × 50” @ 5”, 1500km/s R10
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



MMIC Array Spectrographs



SEQUOIA

The World's Fastest 3mm Imaging Array

GALACTIC RING SU

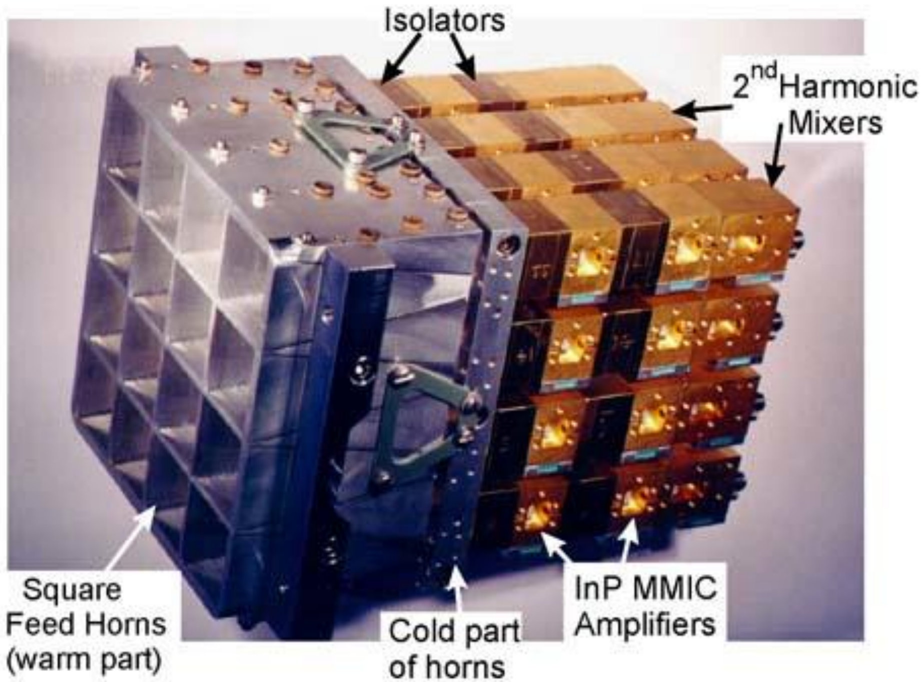
BOSTON UNIVERSITY-FCRAO

MPIfR Bonn, 19 September 2010

SEQUOIA

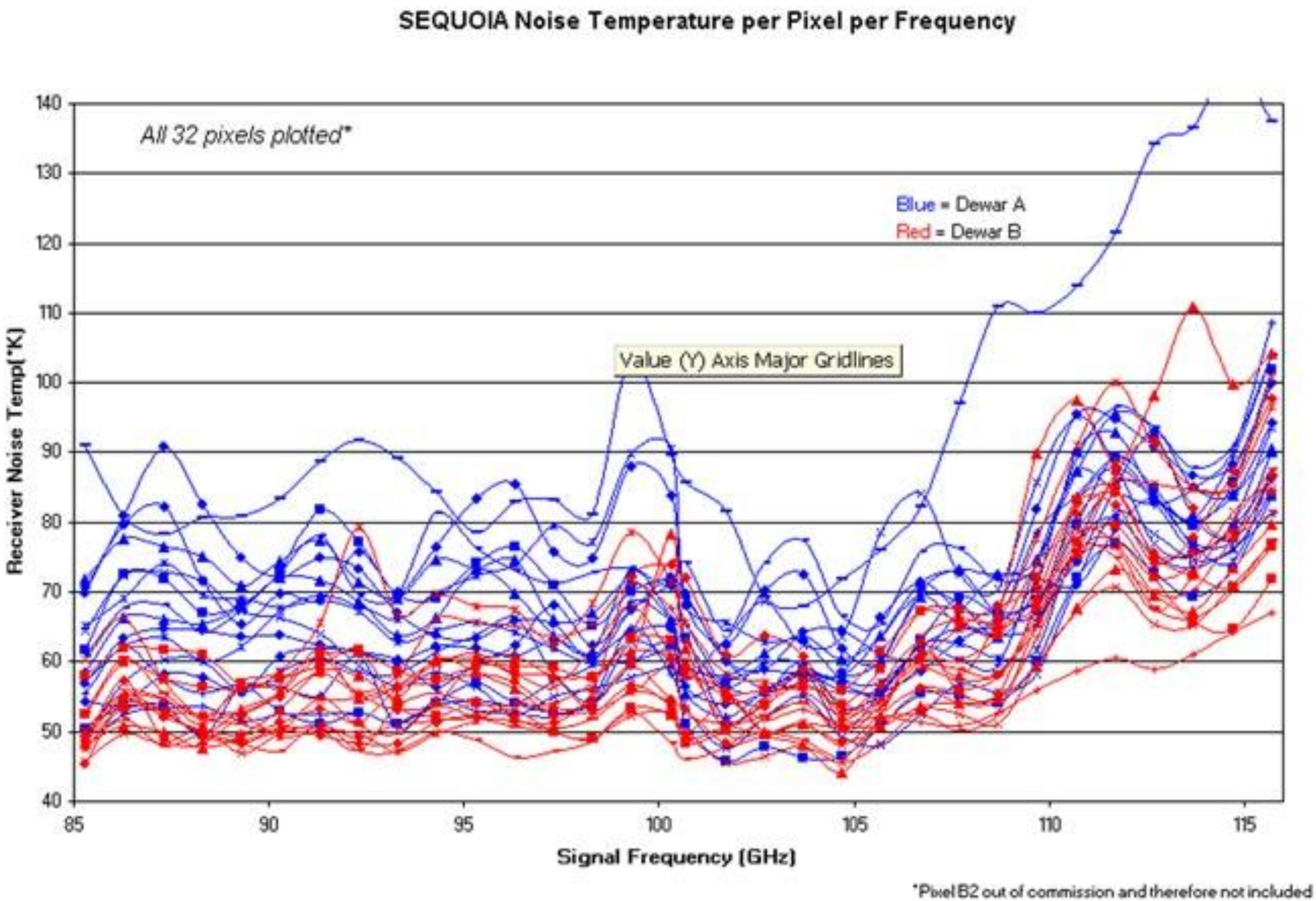
The World's Fastest 3mm Imaging Array

SEQUOIA
• is a cryogenic focal plane array
• 85–115.6 GHz range
• 32 pixels are arranged in a dual-polarized 4x4 array.
• InP MMIC preamplifiers with 35-40dB gain
• noise temperature ranges from 50–80K over most of the band
• No mechanical or electrical tuning
• In each pixel, the preamplifier is followed by a subharmonic mixer with an IF band from 5–20GHz
• The entire signal band is covered with single sideband response using just two LO's, at 40GHz and 60GHz.



SEQUOIA System Performance

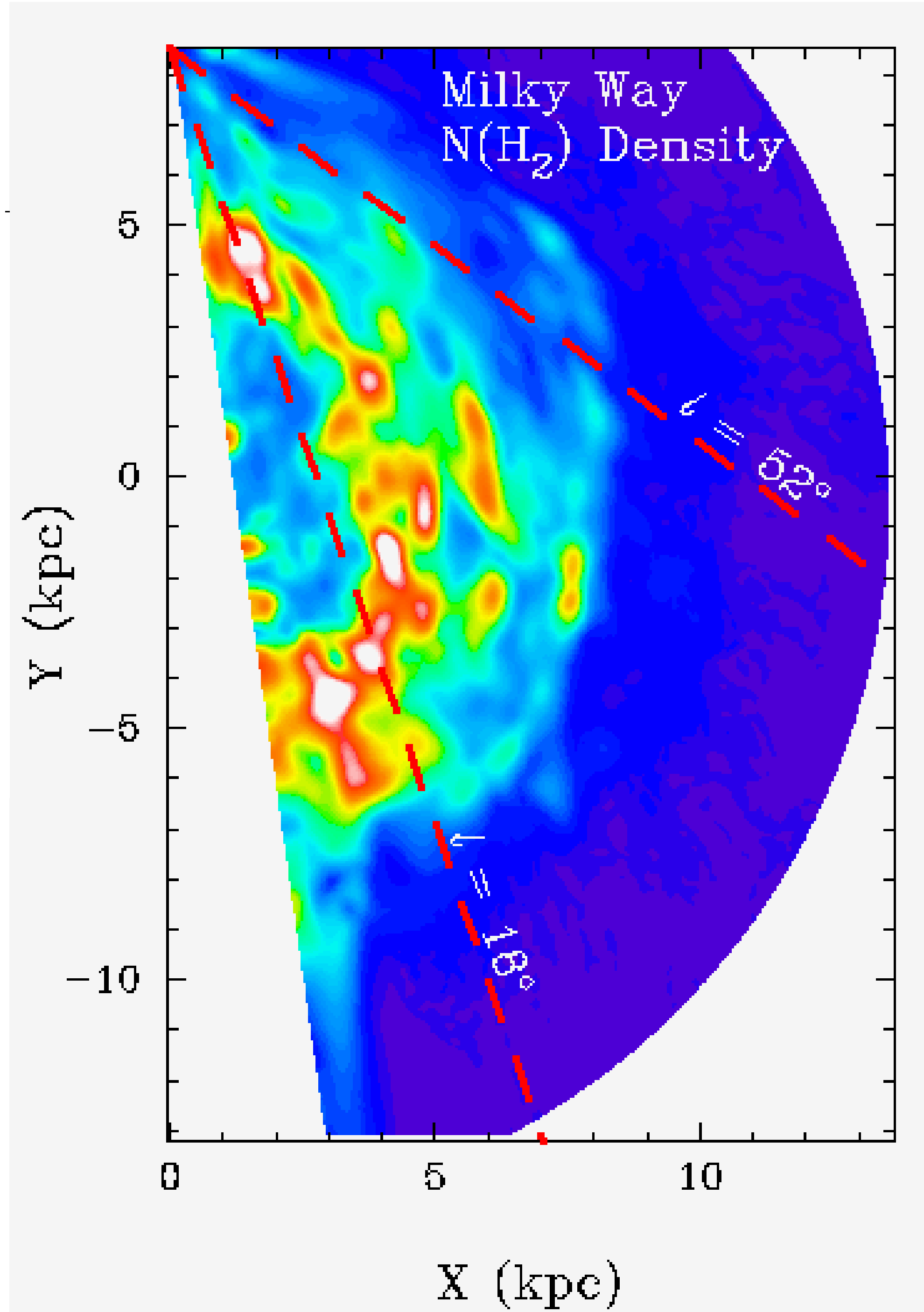
- **competitive with wideband SIS receivers, and much simpler to use.**
- **The receiver is cooled by a single 3.5W (at 18K) refrigerator**
- **excellent spectral line baseline stability**
- **excellent system reliability**



GALACTIC RING SURVEY

GRS

BOSTON UNIVERSITY-FCRAO



Heterodyne array molecular line astronomy

- Study large-scale distribution of gas an various scales $\rightarrow$ 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

        $\rightarrow$ model calculations $\Rightarrow$ 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

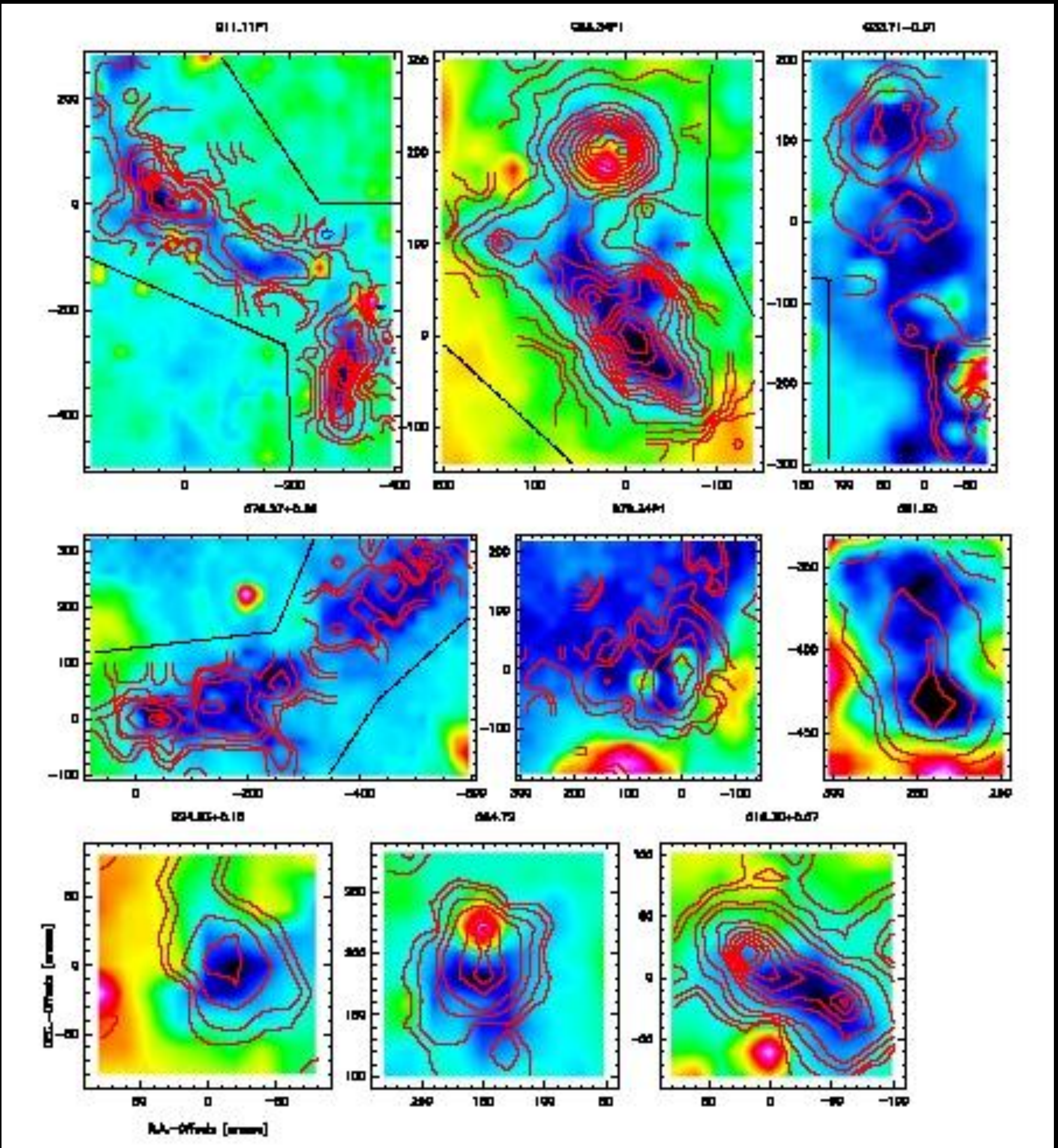
and

- 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!

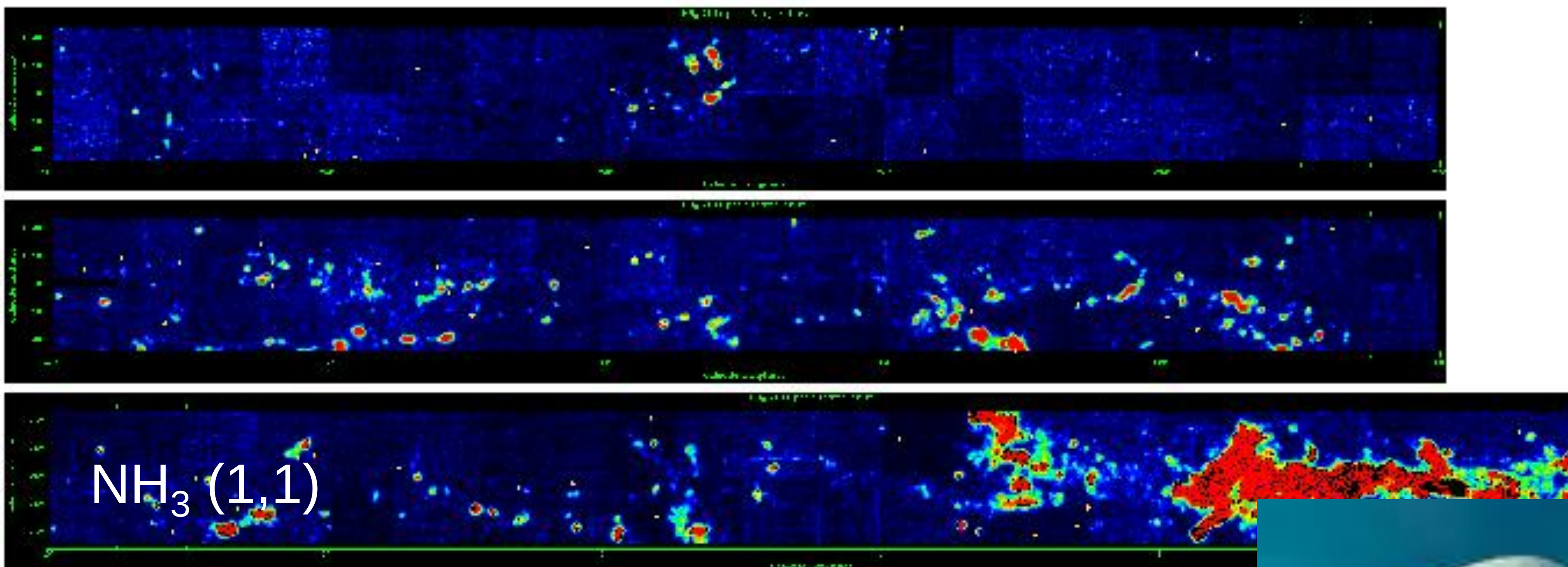


NH_3 in Infrared Dark Clouds

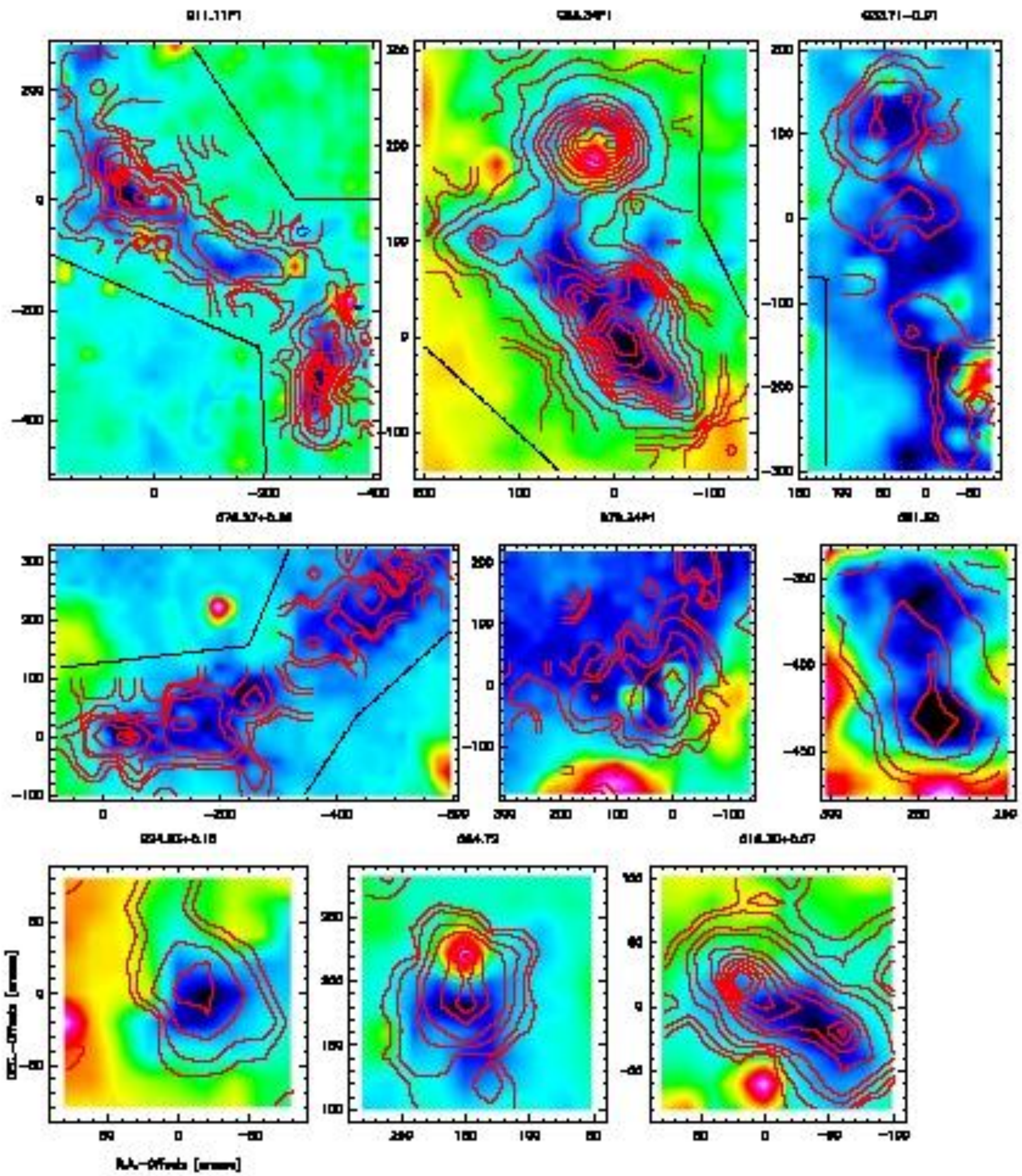
Effelsberg 100m

Dissertation of Thushara Pillai (2007)

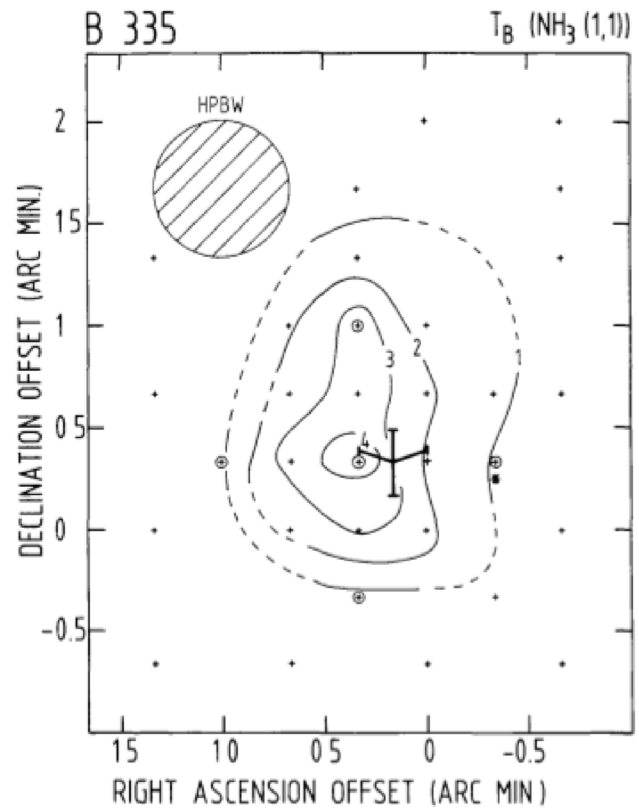
HOPS - The H_2O southern Galactic Plane Survey



In the cm range, the large separation between beams has a strong impact on science case!



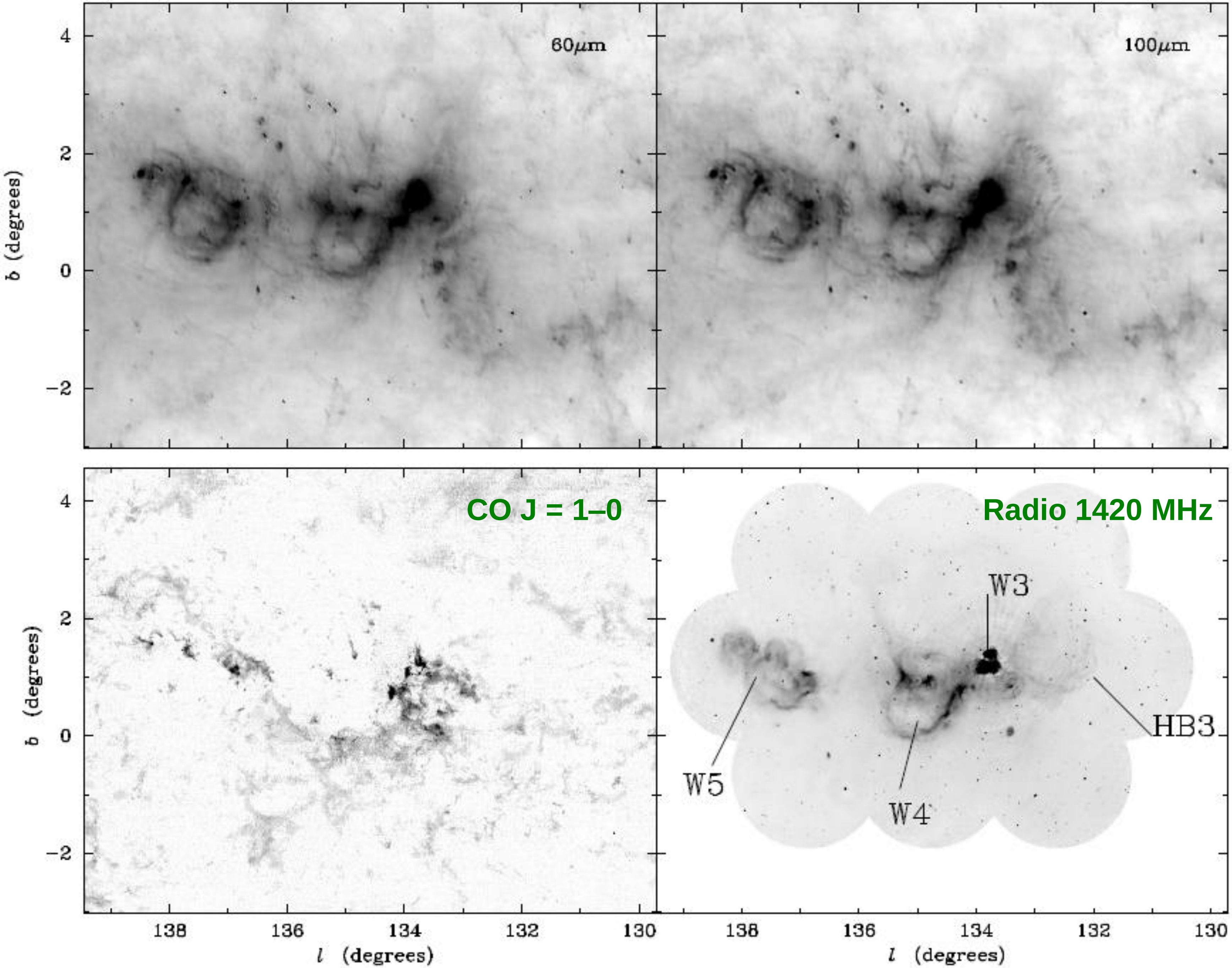
Pillai et al. 2006



Menten et al. 1984

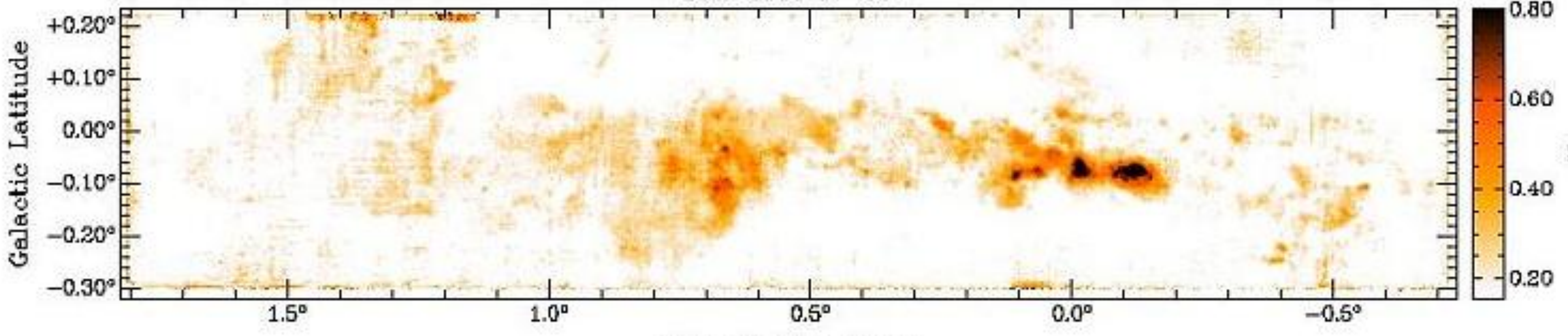
W-band-Science (80 – 116 GHz)

- 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}) ($\leftrightarrow$ 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 *($\rightarrow$ star formation)*
- These lines are very widespread (= everywhere) over the whole Galactic center region ($-0.5^0 < \ell < 2^0$)

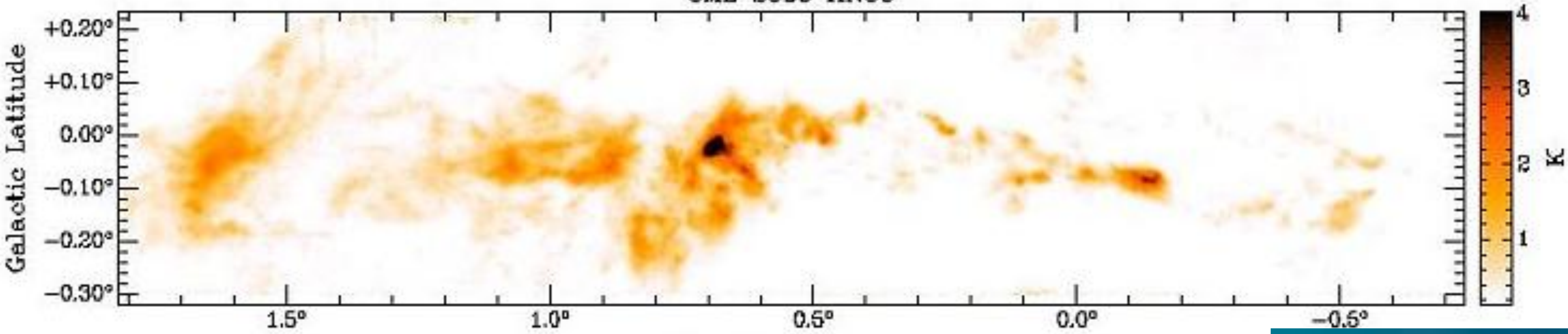

60μm
100μm
CO J = 1–0
Radio 1420 MHz
W3
W5
W4
HB3
b (degrees)
l (degrees)
4
2
0
−2
138
136
134
132
130

The Central Molecular Zone as seen with Mopra at 3 mm

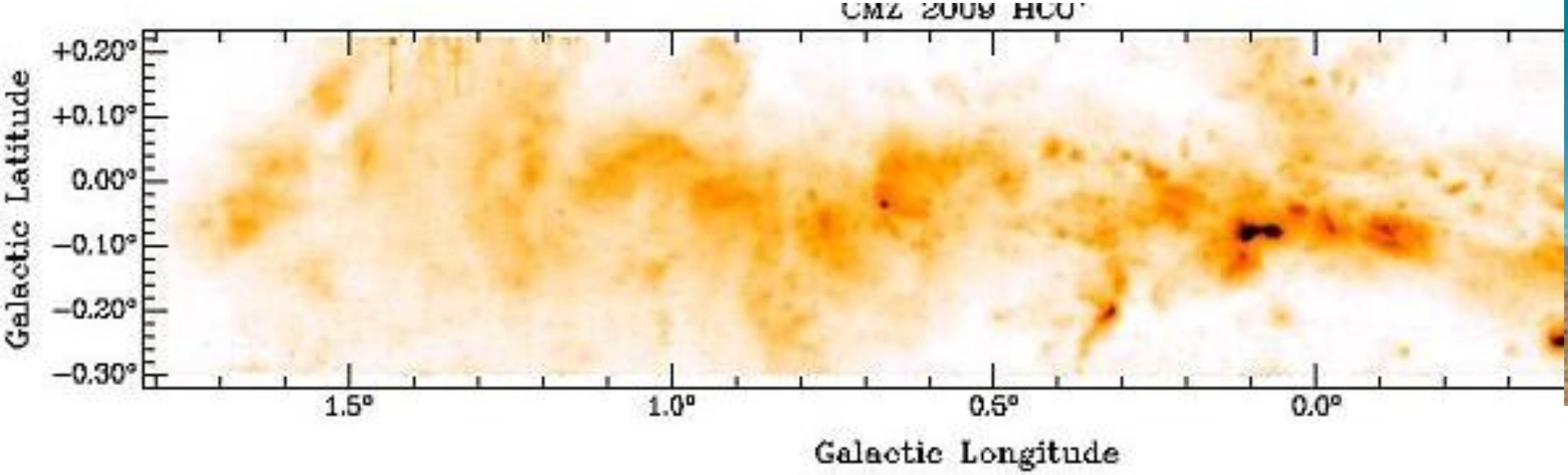
CMZ 2009 $H^{13}CN$



CMZ 2009 HNCO



CMZ 2009 HCO^+



Sensitivity

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

For Fast Fourier Transform Spectrometers (FFTS), *const* ≈ 1

Assume

T_{sys} = 100 K and

Δv = 1 km/s

$\Rightarrow$ $\Delta\nu$ = 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

HUGE 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**

$\Rightarrow$ Need N $\times$ 20 $\times$ 100 MHz = N $\times$ 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**

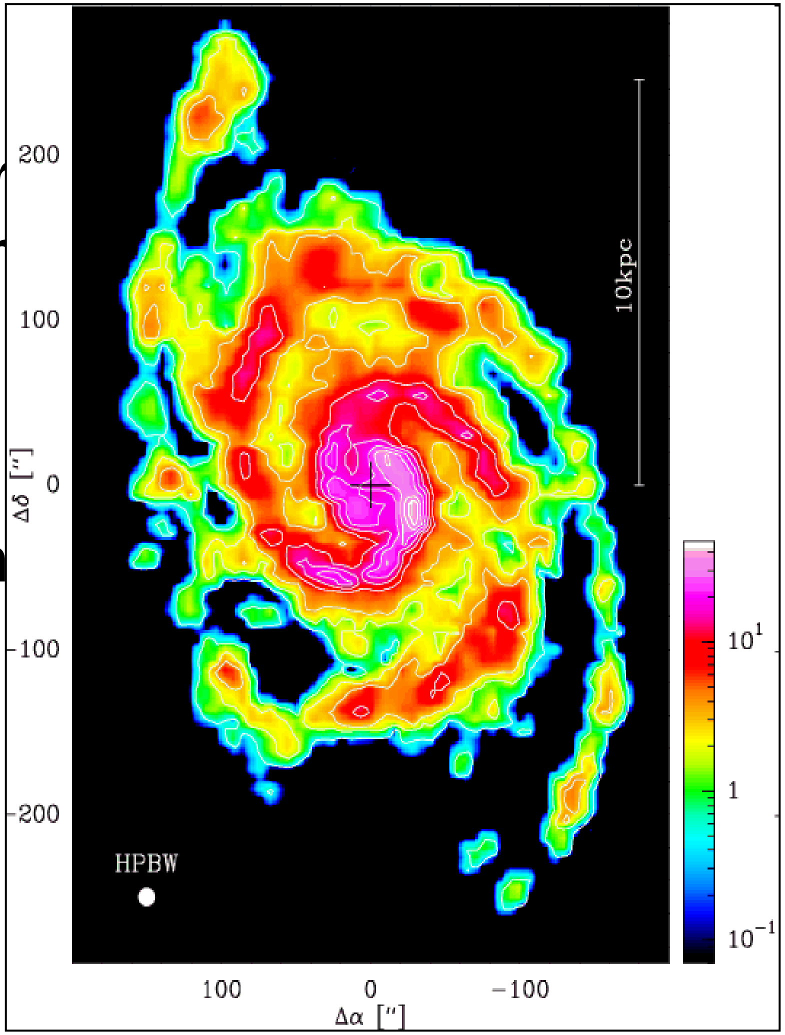
Other *most interesting* projects include complete (mostly) ^{12}CO and ^{13}CO mapping of nearby galaxies.

These are HUGE (many square arc minutes)!

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

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

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



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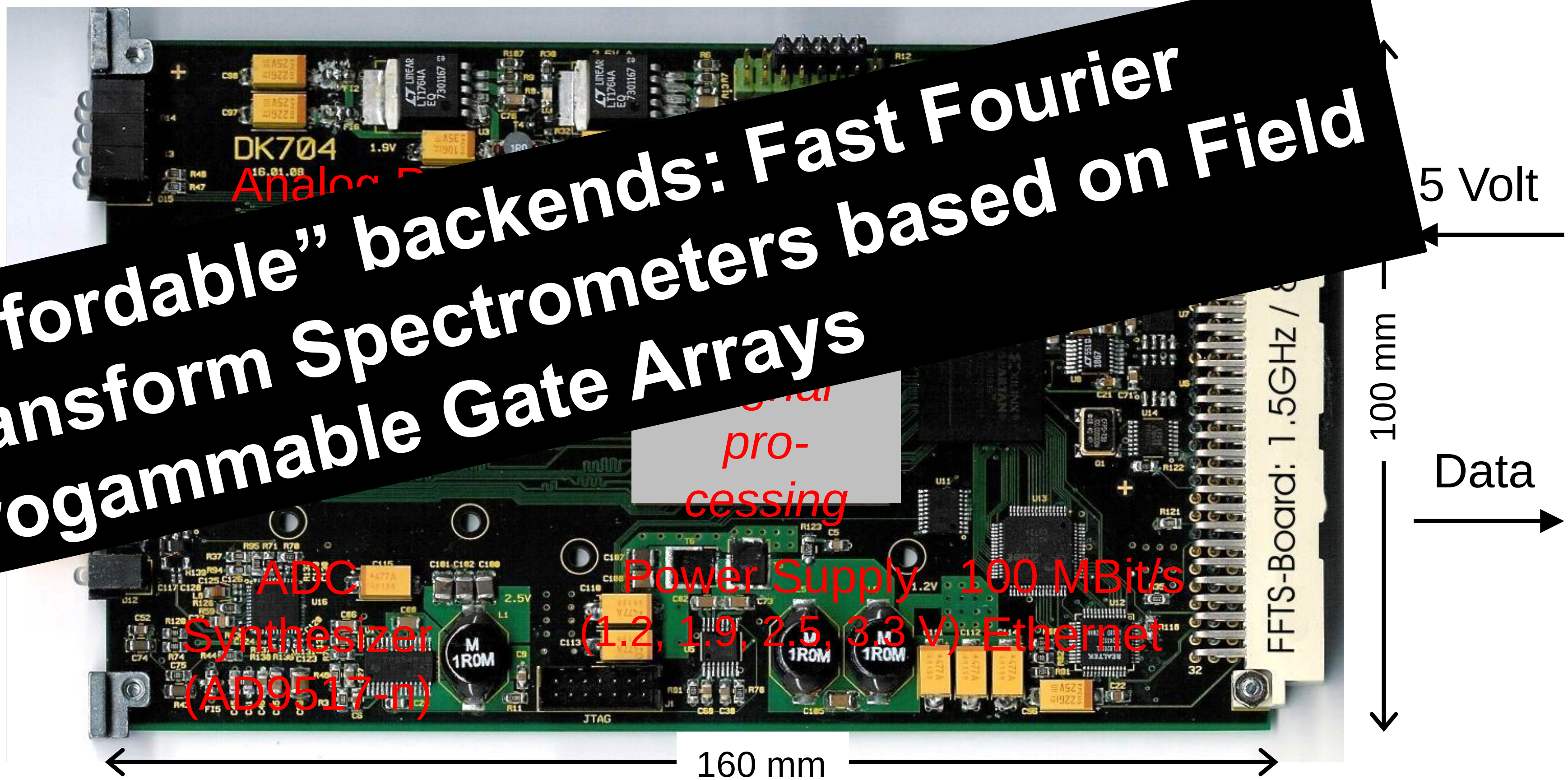
DIGITALLABOR

FFTS :: *The MPIfR-Board*

"Affordable" backends: Fast Fourier Transform Spectrometers based on Field Progammable Gate Arrays

IF i
(0 - 3



- 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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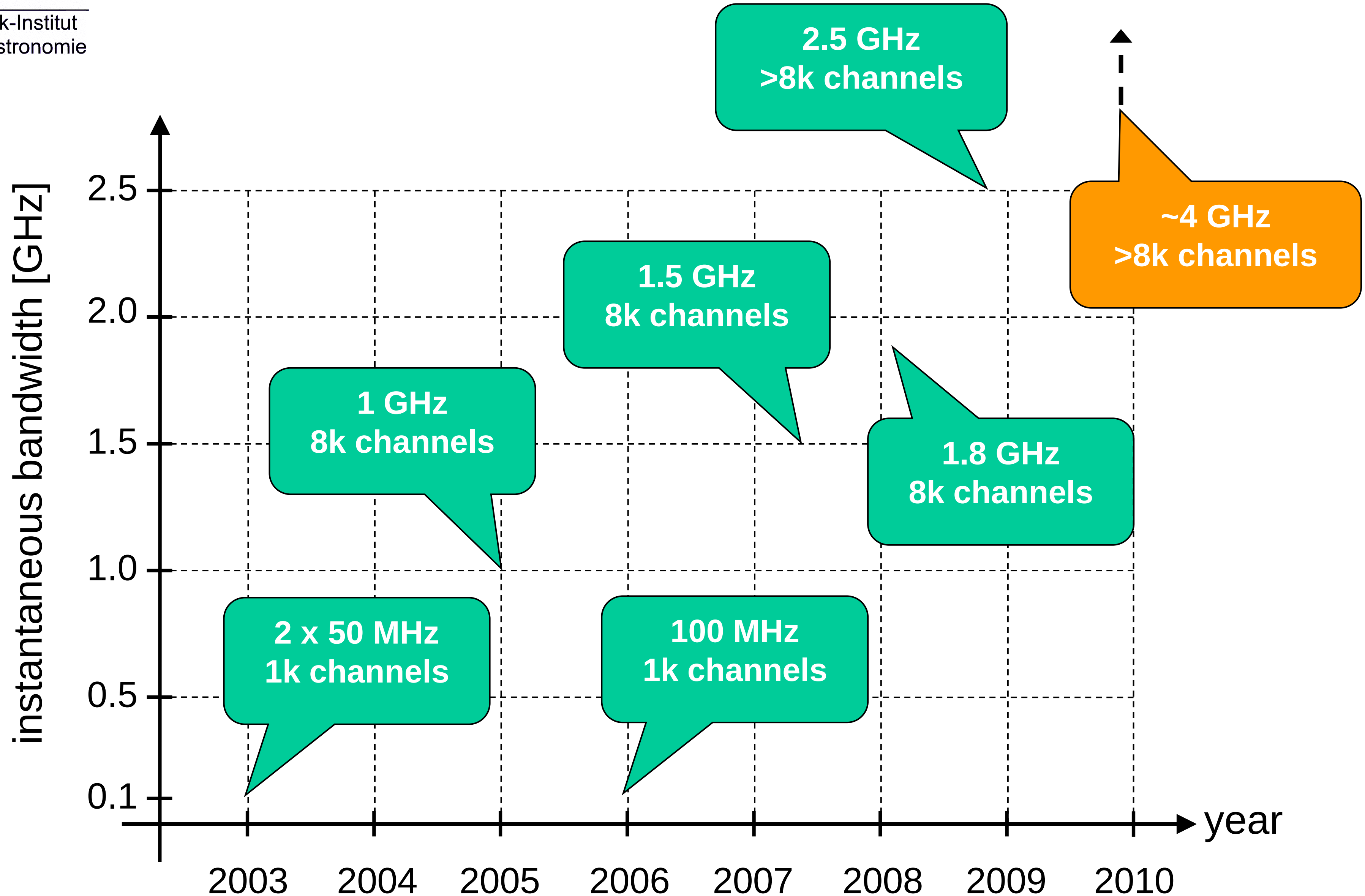
DIGITALLABOR

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



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Atacama Pathfinder EXperiment
APEX

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 MB arrays

Conclusion:

Even in the brave new world of ALMA and the EVLA, single dish telescopes equipped with large format RX arrays, allowing large scale imaging, will make crucial contributions to star formation and interstellar medium science

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
- Shanghai radio telescope

+ ...

Thank You