ESSEA- Effelsberg Single Dish School
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Bonn - MPIfR

Why single dishes in future Radio Astronomy ?

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Outline

- Single Dishes: what are we talking of ?
- Single Dishes vs Arrays : intrinsic & practical differences
- Single Dish use: some scientific cases
- Requirements for Single Dishes in next decade
- The longer term perspectives

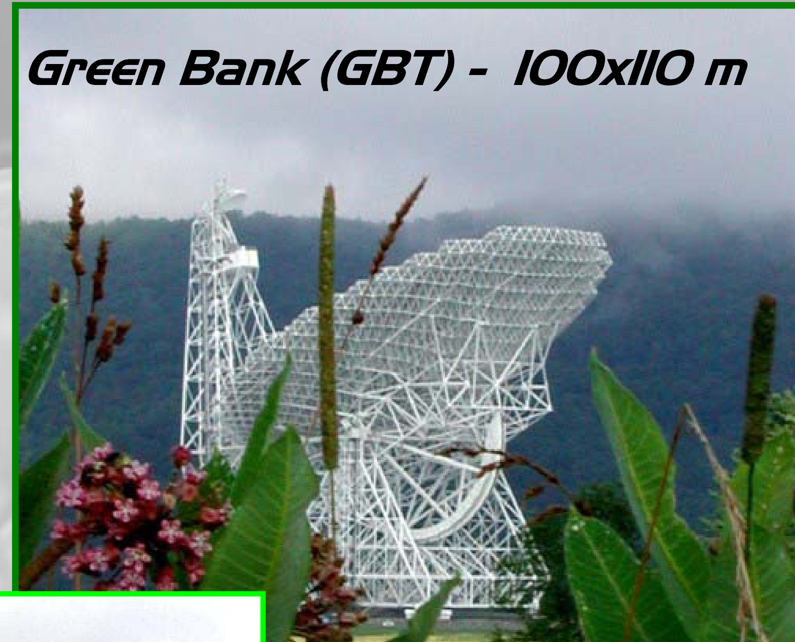
Acknowledgements & credits: M. .Burgay, P. Castangia, M. Murgia,, S. Poppi, A.Tarchi

Single dishes …

… what are we talking of ?

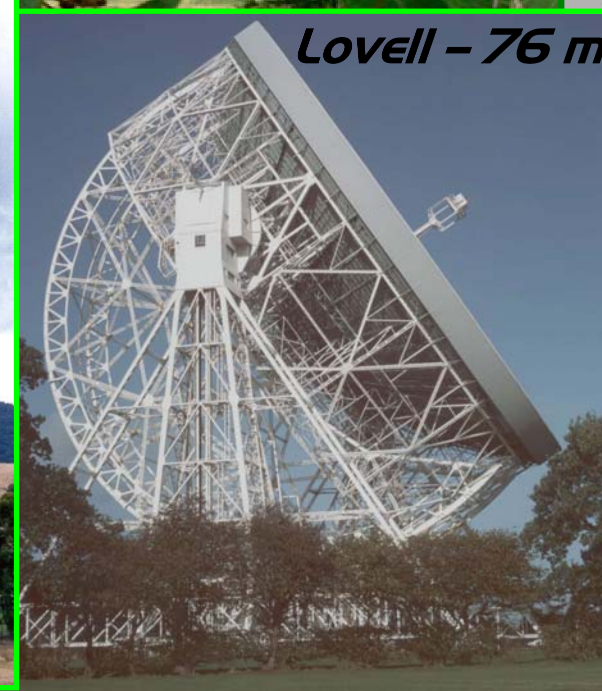
Metric to centimetric dishes (someone down to few mm)

Effelsberg – 100 m



Green Bank (GBT) - 100x110 m

Tidbinbilla – 70 m



Lovell – 76 m

Parkes – 64 m

Millimetric single dishes

Sub-Millimetric single dish

Not always really a fully steerable dish…

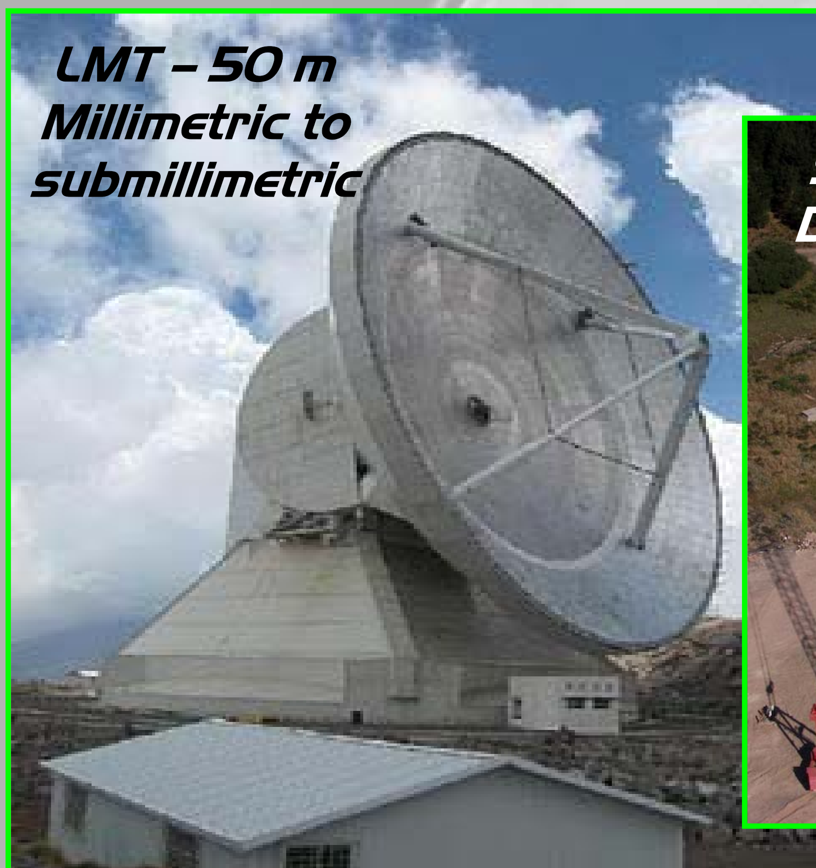
Decimetric radio telescopes

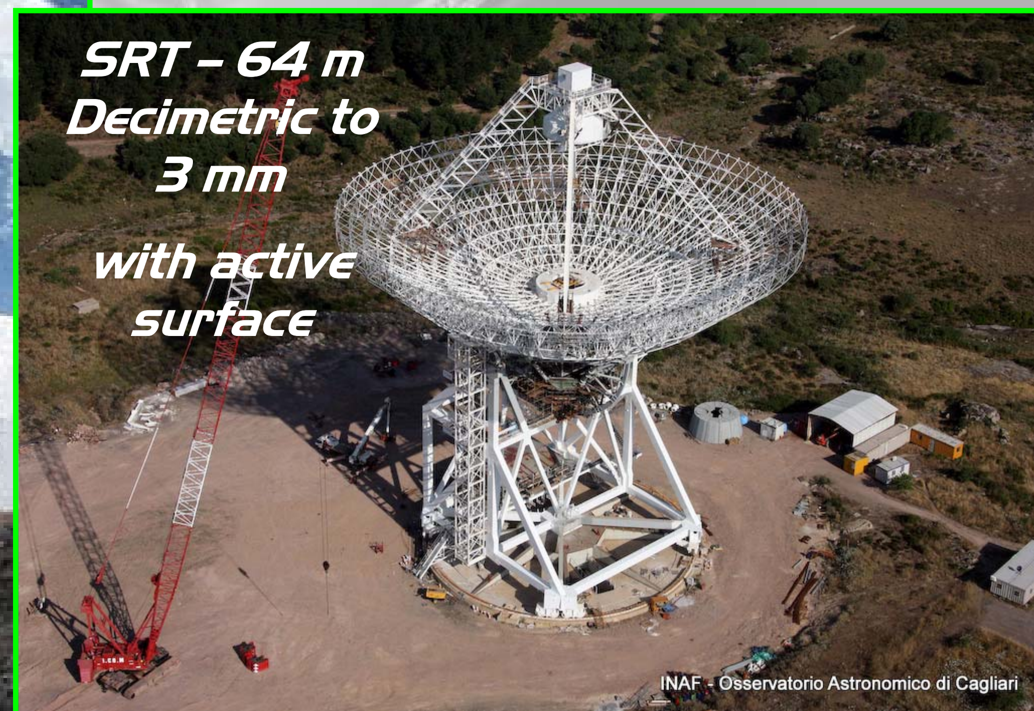
or not a dish at all…

More in general, better saying **filled aperture telescopes**

In the (hopefully nearly immediate...) future

few new large single-dishes, operating also in the millimeter band, will complete commissioning, e.g. SRT (64m, 0. 3-110 GHz) and LMT (50m, 75-275 GHz)





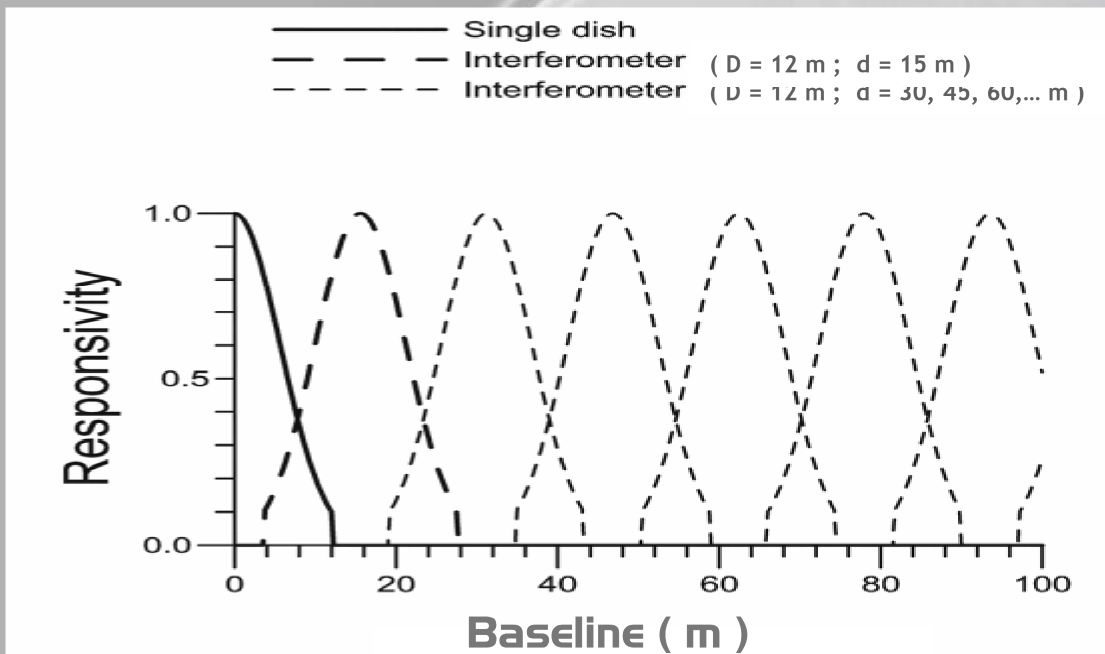
Single-Dishes

vs

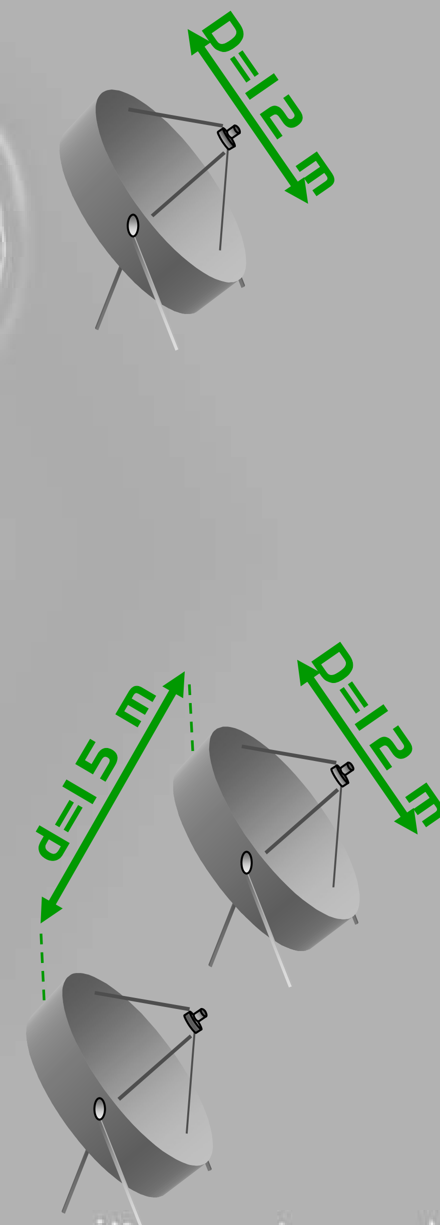
Arrays

Intrinsic differences I

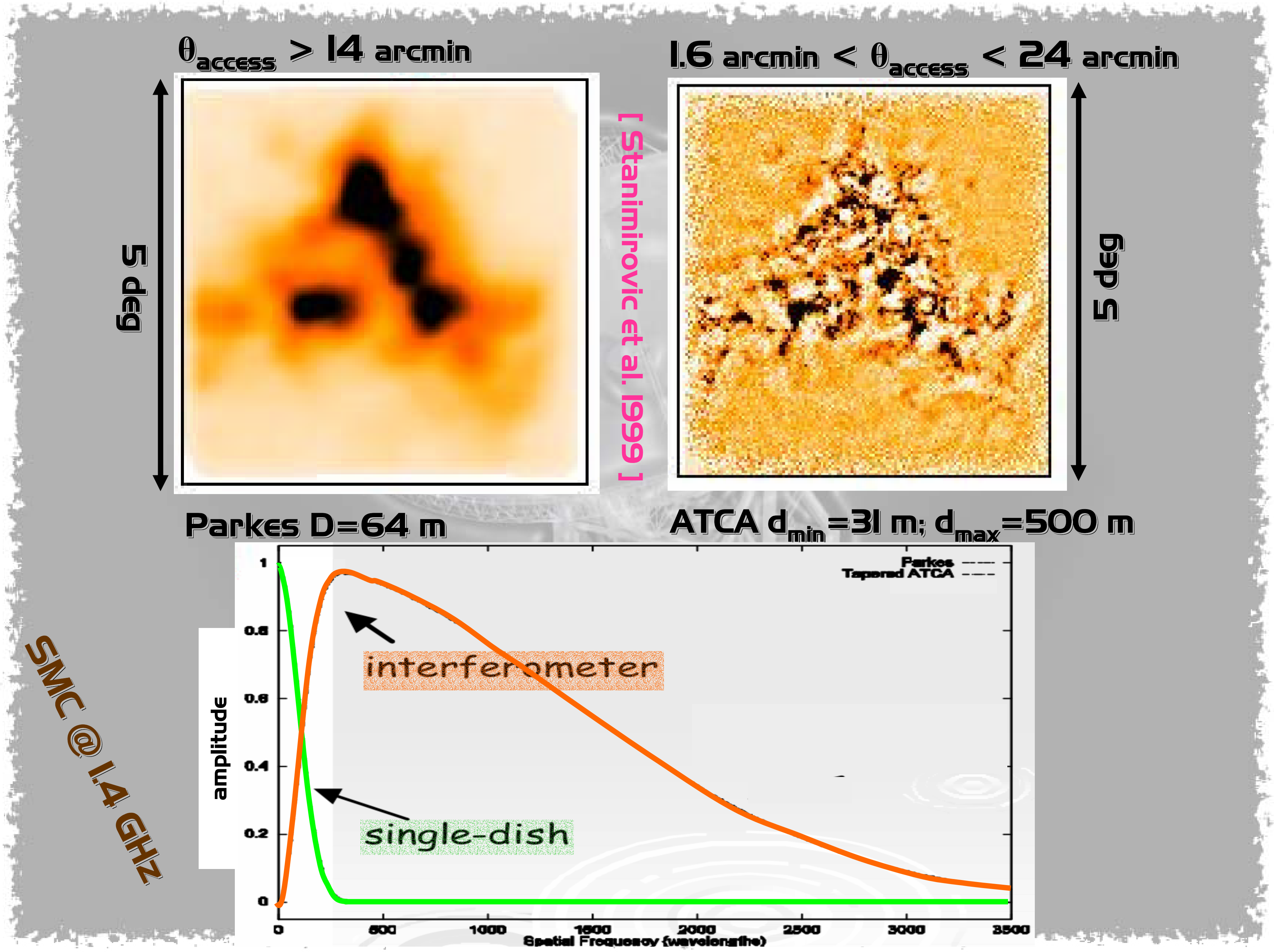
Single dish has a high spatial freq cut-off in resolution imposed by their diameter D ($\theta \approx \lambda/D$)



[Emerson 2002]

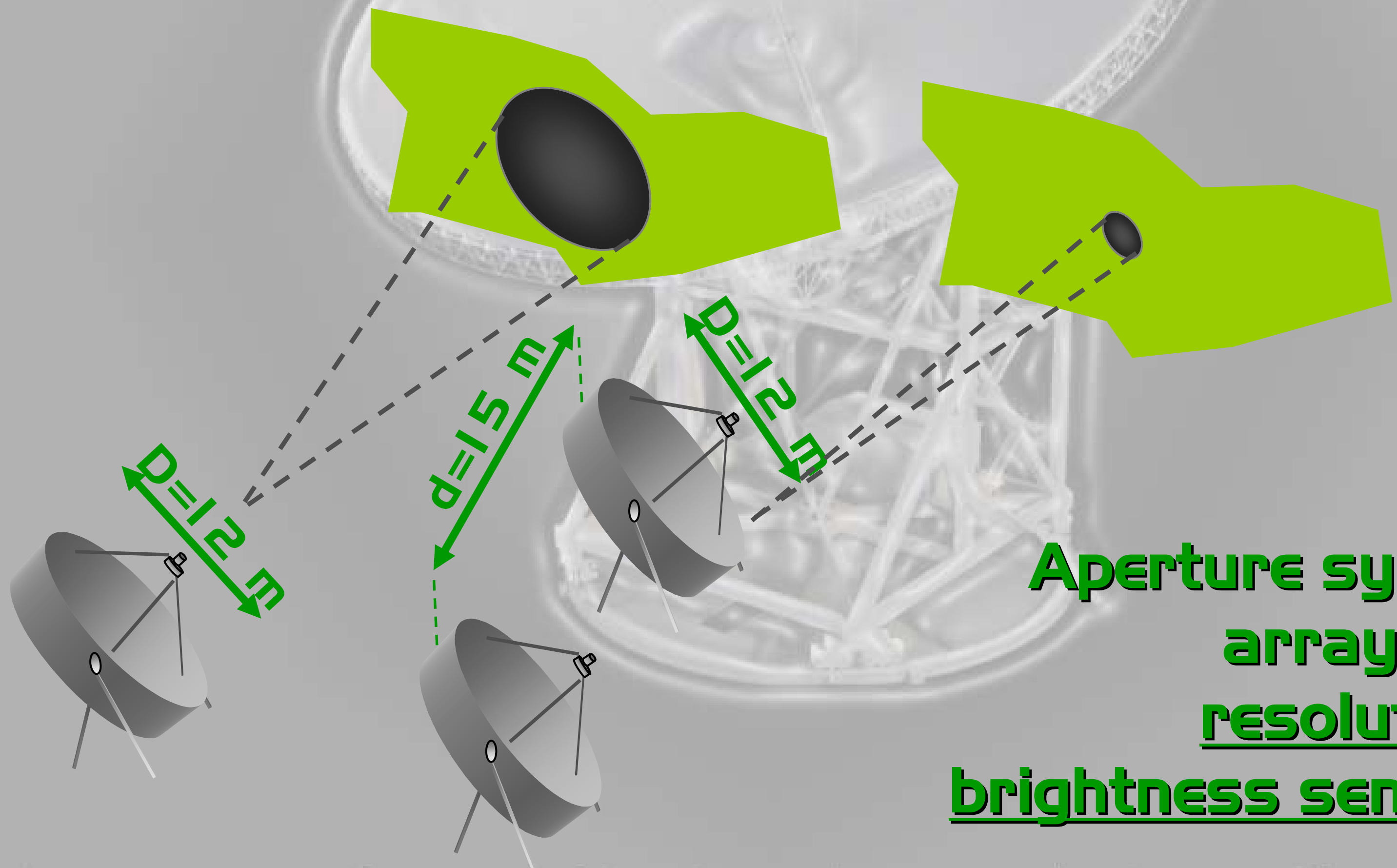


Aperture synthesis array has a high spatial freq cut-off imposed by their maximum baseline D+d and a low spatial freq cut-off imposed by the minimum antenna separation D-d


θaccess > 14 arcmin
1.6 arcmin < θaccess < 24 arcmin
5 deg
5 deg
[Staniminovic et al. 1999]
Parkes D=64 m
ATCA dmin=31 m; dmax=500 m
SMC @ 1.4 GHz
Parkes
Tapered ATCA
interferometer
single-dish
amplitude
1
0.8
0.6
0.4
0.2
0
0
500
1000
1500
2000
2500
3000
3500
Spatial Frequency (wavelengths)

Intrinsic differences II

Sensitivity to extended emission (in T_b) scales as $(d/D)^2$, Whence brigthness sensitivity of an aperture synthesis array is much worse than a single dish of equal collecting area.



Aperture synthesis arrays trade resolution for brightness sensitivity

Intrinsic differences III

[See e.g. Emerson 2002]

N_A = Noise of the amplifier of antenna A

S_A = Signal in antenna A

N_B = Noise of the amplifier of antenna B

S_B = Signal in antenna B

The "correlation" of data from two elements in an interferometer basically involves a multiplication and an averaging

$$(N_A + S_A) \times (N_B + S_B) = N_A \times N_B + N_A \times S_B + S_A \times N_B + S_A \times S_B$$

When averaging over a long enough time, uncorrelated products tend to zero and thus one is left with

$$< (N_A + S_A) \times (N_B + S_B) >_{ave} \;=\; S_A \times S_B$$

Since the averaged output from a correlation interferometer does not depend (barring side statistical effects) on the internally generated amplifier noise voltages, the correlation interferometers are almost immune to fluctuations in the receiver gain and noise

Whereas for a single dish, after detection and averaging, it holds

$$< (N_A + S_A) \times (N_A + S_A) >_{ave} \;=\; N_A^2 + S_A^2$$

and therefore single-dishes can be severely affected by instrumental fluctuations

Thus in summary, radio telescopes may come in many flavors:

1) Single-dishes

2) Phased-arrays=adding interferometers

3) Aperture synthesis arrays =correlation interferometers

+ various combinations of the above…

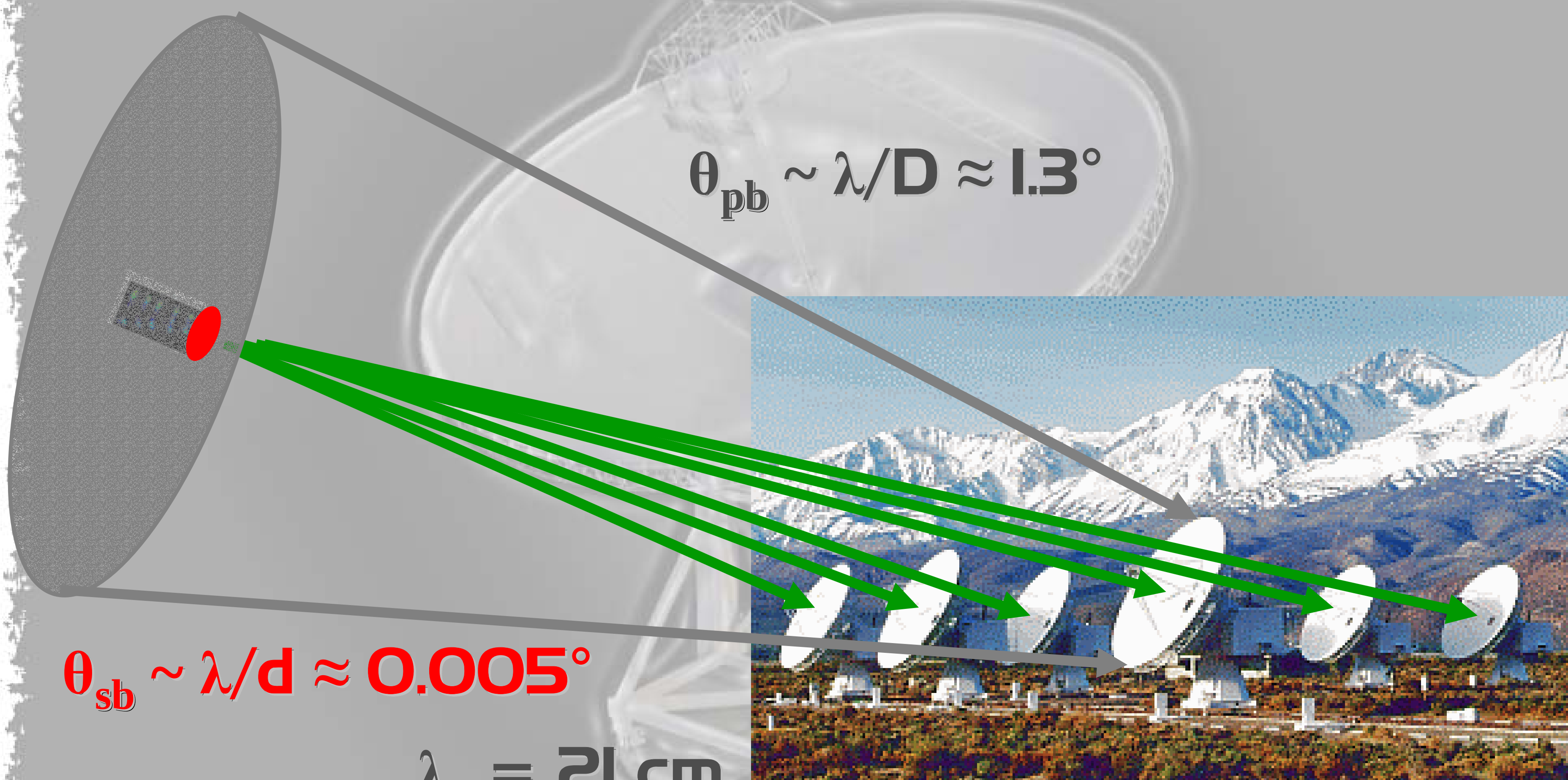
The single dish

$\theta_{pb} \sim \lambda/D \approx 0.5°$

K/Jy driven by the size of single dish

$\lambda = 21$ cm
$D = 64$ m

The aperture synthesis arrays



$\theta_{pb} \sim \lambda/D \approx 1.3°$

$\theta_{sb} \sim \lambda/d \approx 0.005°$

$\lambda = 21$ cm

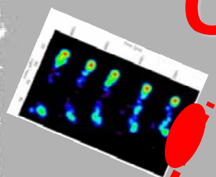
$d \approx 6.4$ km

$D = 25$ m

K/Jy dominated by that of the single element

The phased arrays

0.005°



$\theta_{sb} \sim \lambda/d \approx 0.005°$

λ = 21 cm

d ≈ 6.4 km

D = 25 m

K/Jy like a single dish of area equivalent to the sum of the areas of all elements

Why Single-Dish ?

i.e.: Why not arrays ?

Single Dish science & real life pros-cons

Pros

- Higher sensitivity (K/Jy) to extended structure (λ/D)
- Higher mapping speed
- Many receiver available at once
- Almost always the same config
- More avail telescopes, thus <u>in principle</u> less over-subscription
- Only one needed receiver for each freq and simpler electronics
- Easier upgrading
- Larger flexibility and tunability to a novel experiment
- Easy to install a transmitter
- Can be part of (and add a lot of sensitivity to) an array

Cons

- Poorer angular resolution
- Contamination from very large scale power
- More affected by instrumental variations of gain and noise
- Confusion limited
- Complex and costly mechanics
- Difficult to be scalable: i.e. construction in one shot only
- Budget ($\approx$size^3) and mechanical limited size for not transit-only instruments

…thus there are advantages and disadvantages for both flavours of the radio telescopes…

…the best choice depends on the target and/or the process to be investigated

in the past, still nowadays and certainly for few years onward…

often the best solution is exploiting a combination of the two systems

e.g. Maser - Galaxy Cluster radio halos – large scale mapping – high velocity clouds - all sky surveys - etc etc…

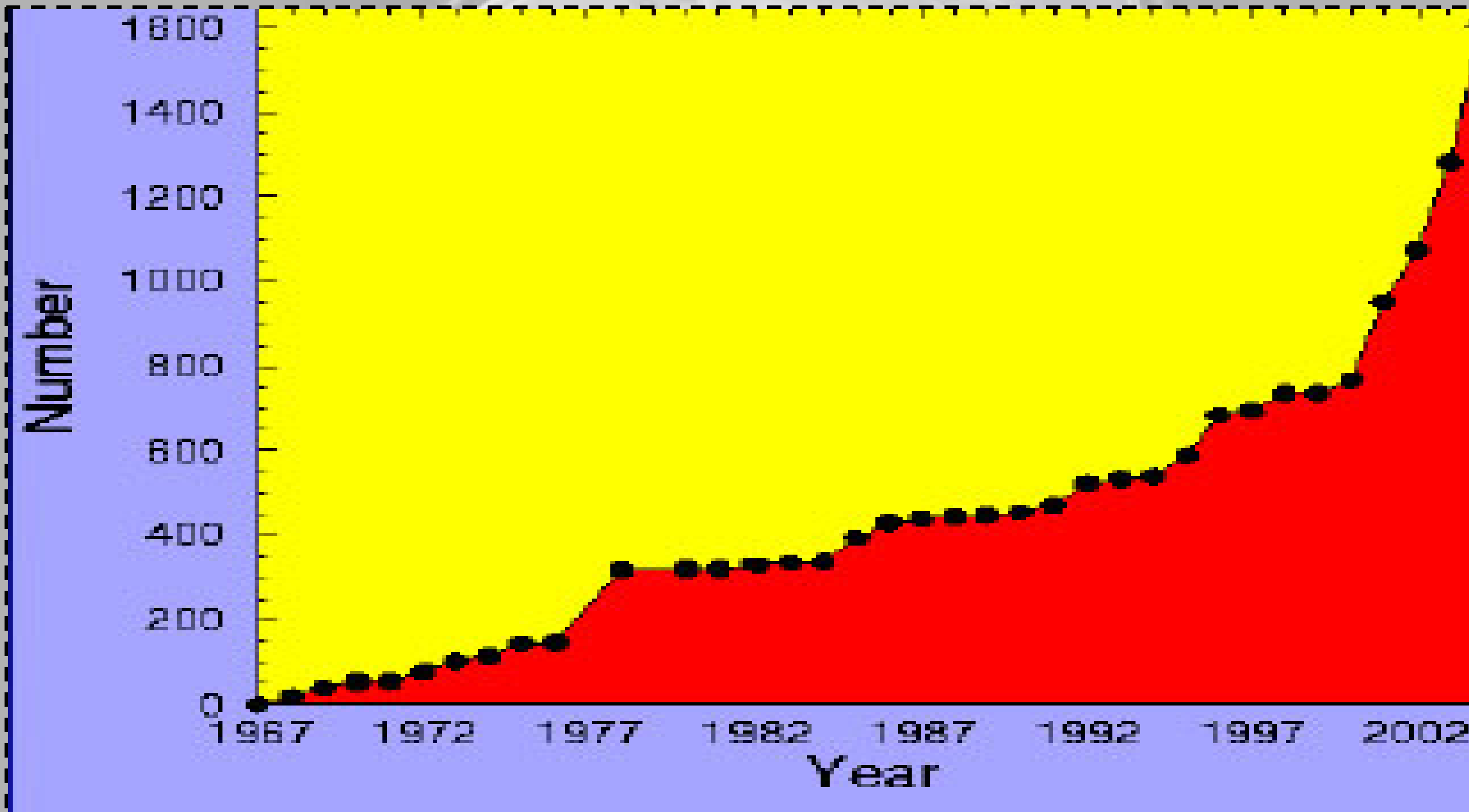
…but there are exceptions, some of which also in favor of the single-dishes

e.g. Pulsars

Pulsars can be fully studied using single-dish only observations

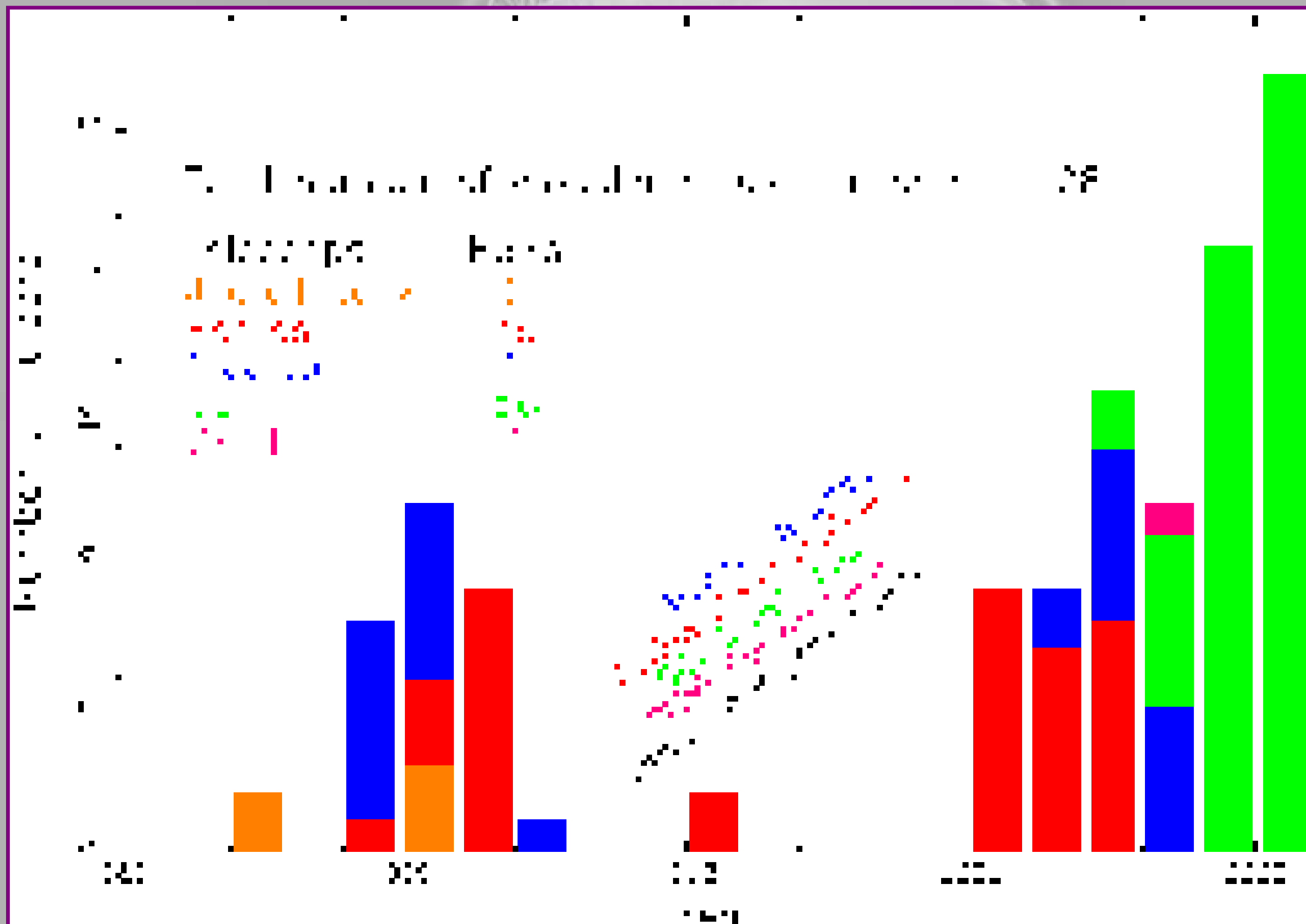
A <u>PULSAR</u> is a rapidly rotating and highly magnetized neutron star, emitting a pulsed radio signal as a consequence of a light-house effect

Doubled the Pulsars' sample with the Parkes Multibeam Surveys



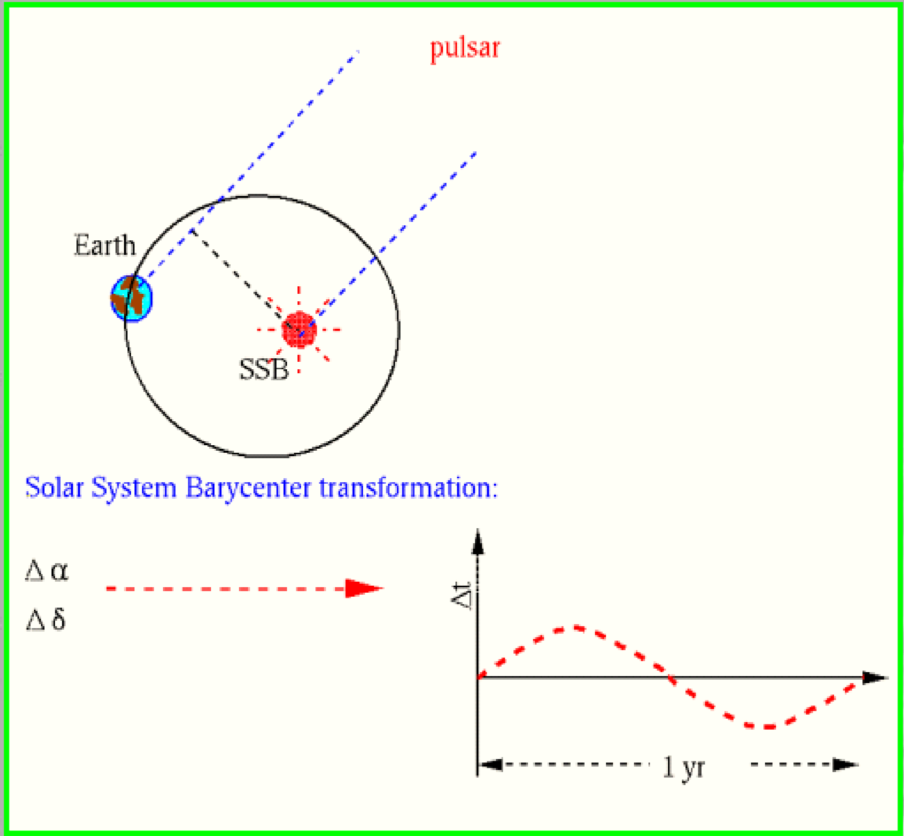
[@ Lyne - JBO]

The impact of the GBT+Parkes on Globular Cluster searches



[@ Ransom - NRAO]

[based on the web based GC pulsar catalog - Freire 2007]



...repeated observations of the times of arrival of the pulses with large single-dishes lead to accurately measure the spin period ... e.g. for PSRJ0437-4715 on 16 jan 1999

P_{spin} = 5.757451831072007(8) sec

...and exploiting the clock-like nature of the signal, one can very accurately position the source,e.g.

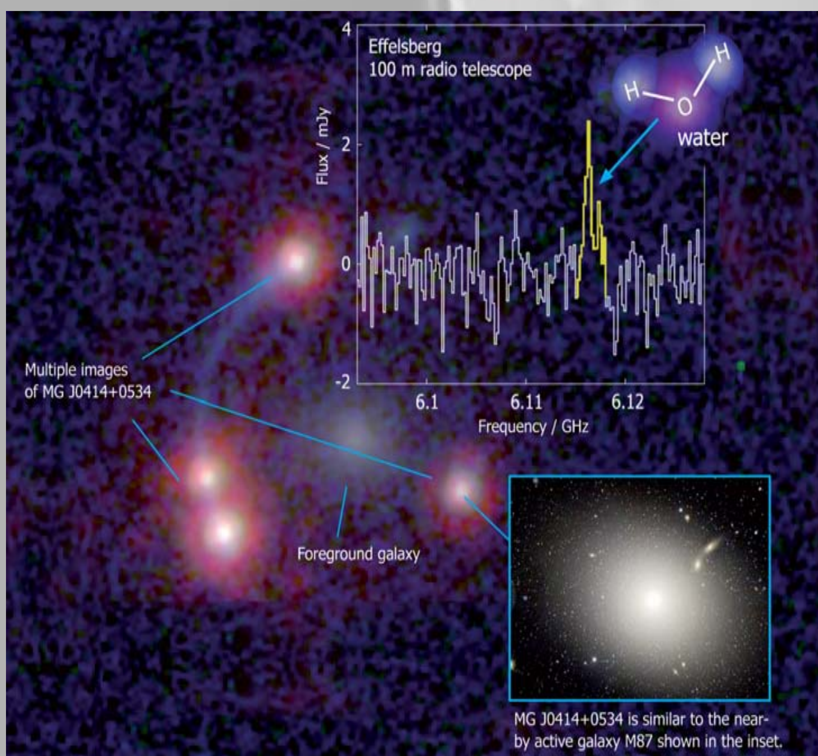
RAJ = 04:37:15.883250(3)

DECJ = -47:15:09.03186(4)

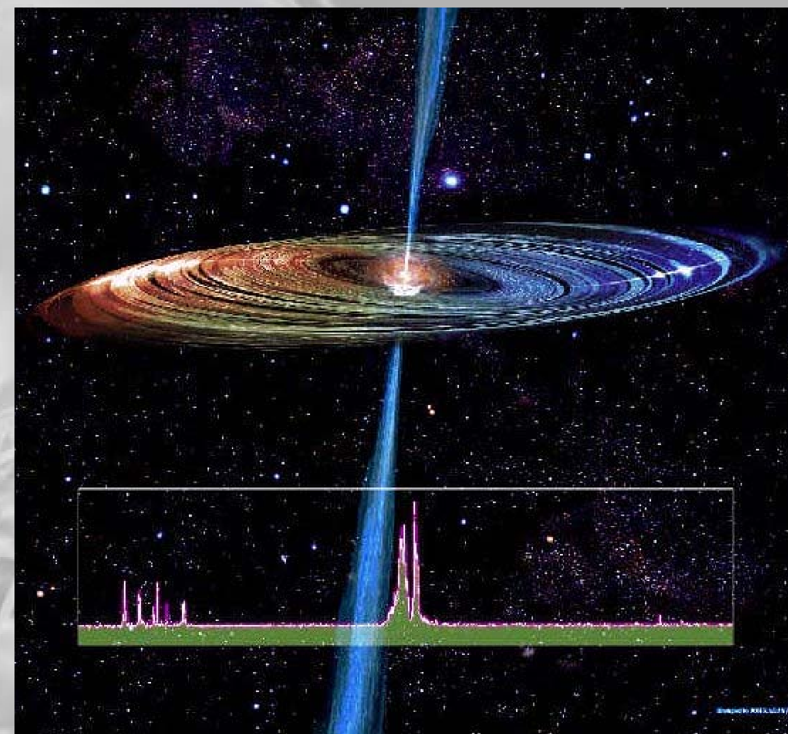
...as well as measuring (for suitable pulsars) proper motion, parallax, and keplerian and post-keplerian parameters, thus making some pulsars magnificent tools for investigations in fundamental physics

Masers are effectively studied using a combination of single-dishes and interferometers

High sensitivity, broad bandwidth, and flat baseline of the biggest single-dishes is very important for increasing the population of the rare extragalactic masers



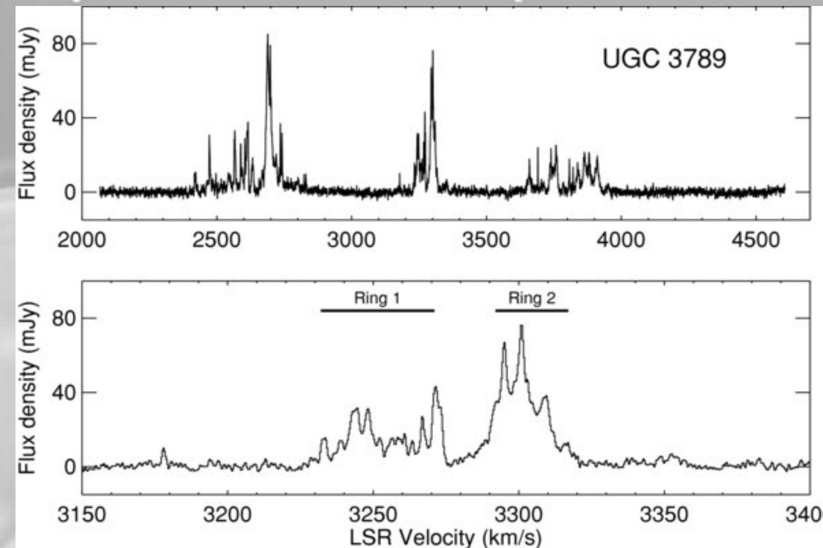
MG J0414+0534 © MPI



NGC 4258 © J. Kagaya

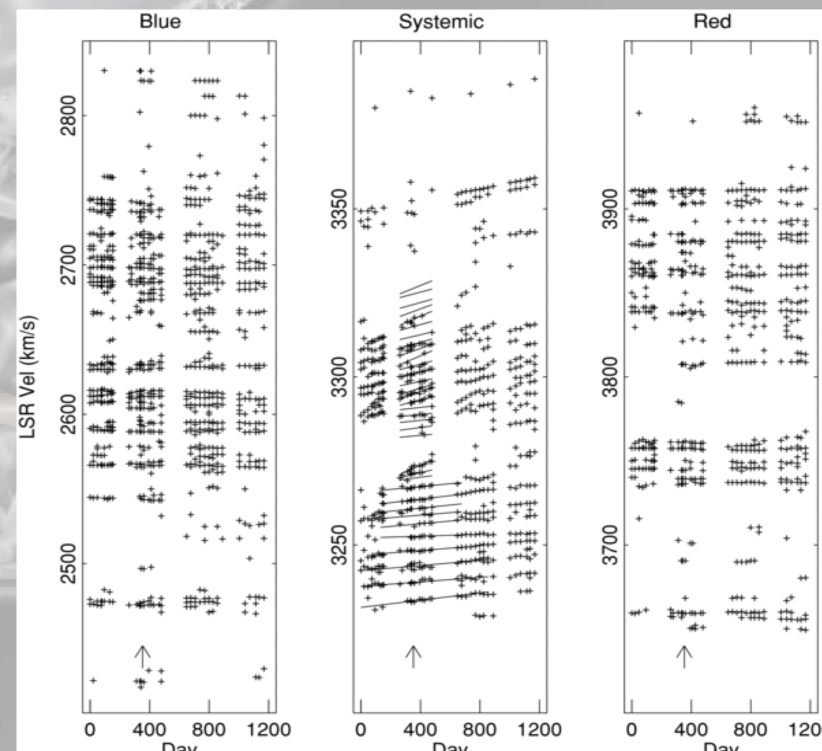
Large sensitive single-dishes (equipped with suitable multibeam systems, e.g. Parkes, GBT, SRT) are very useful for searching masers in the Galaxy or in extended nearby galaxies

Then interferometers enters in play for a detail mapping and possibly precise localization of the maser emission in the sky

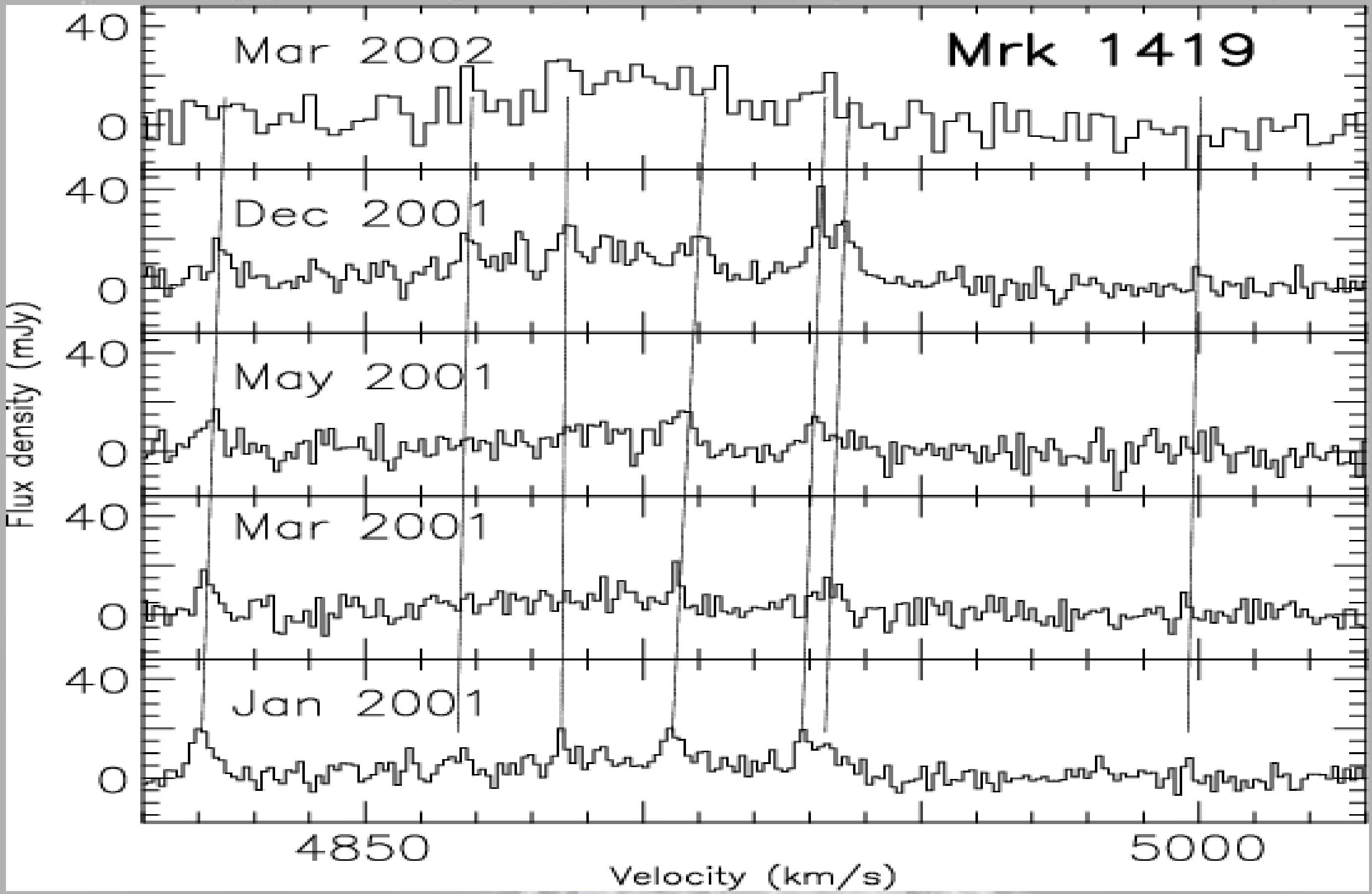


[Braatz et al 2010]

Once the association of the maser lines with a given source is done, single-dishes come again in play for monitoring the kinematics (whence inferring the dynamics) of the maser lines [for this job using the interferometers may be an overkill, and maybe also more complicated: better having very large bandwidth, identical configurations...]



[Braatz et al. 2010 @ GBT]



[Henkel et al. 2002 @ Effelsberg]

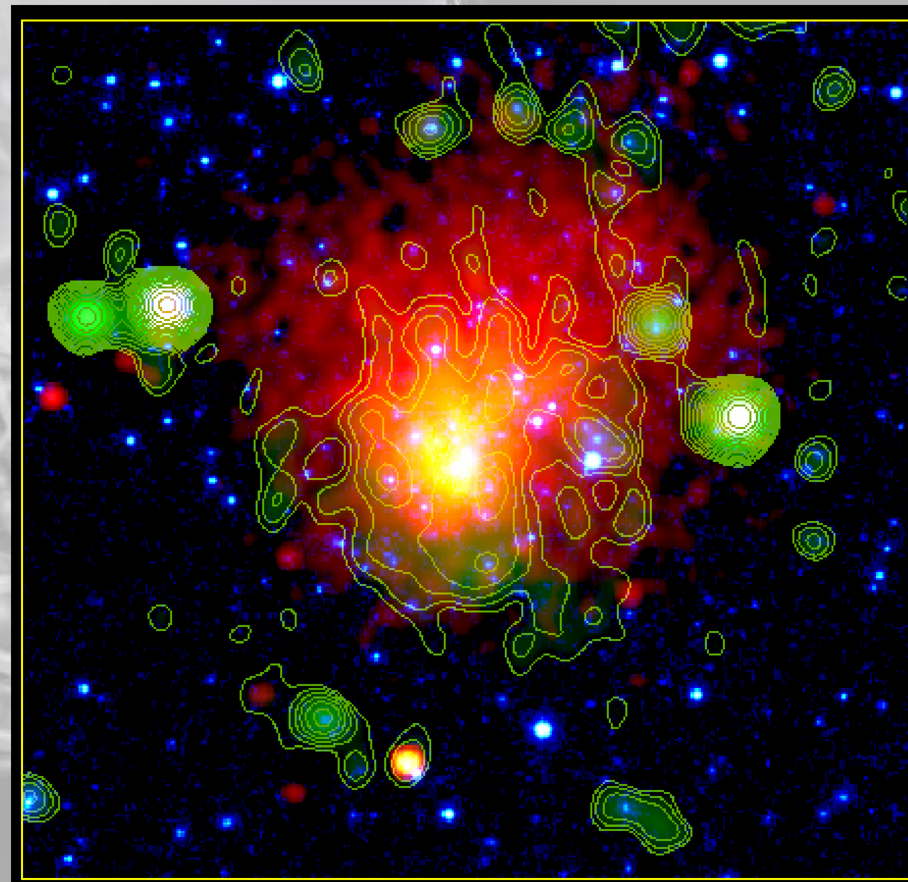
The single-dish monitoring of the maser lines, coupled with the (often VLBI) interferometric determination of the location of the maser emission lead to the most exciting scientific outcomes, like e.g.

rotation velocity of accretion disk, central black-hole mass, distance of the host galaxy, evolution of jet-maser, etc.

Studying Radio Halo in galaxy clusters requires a combination of interferometers and single-dishes

- -Low surface brightness (often < 1 μJy/arcsec^2)
- -Large angular extension (often > 10 arcmin)
- -Steep spectrum (often idx > 1)

Radio
Optical
X-ray



10 arcmin

[Vacca et al 2010 @ VLA 1.4 GHz (15 hrs)]

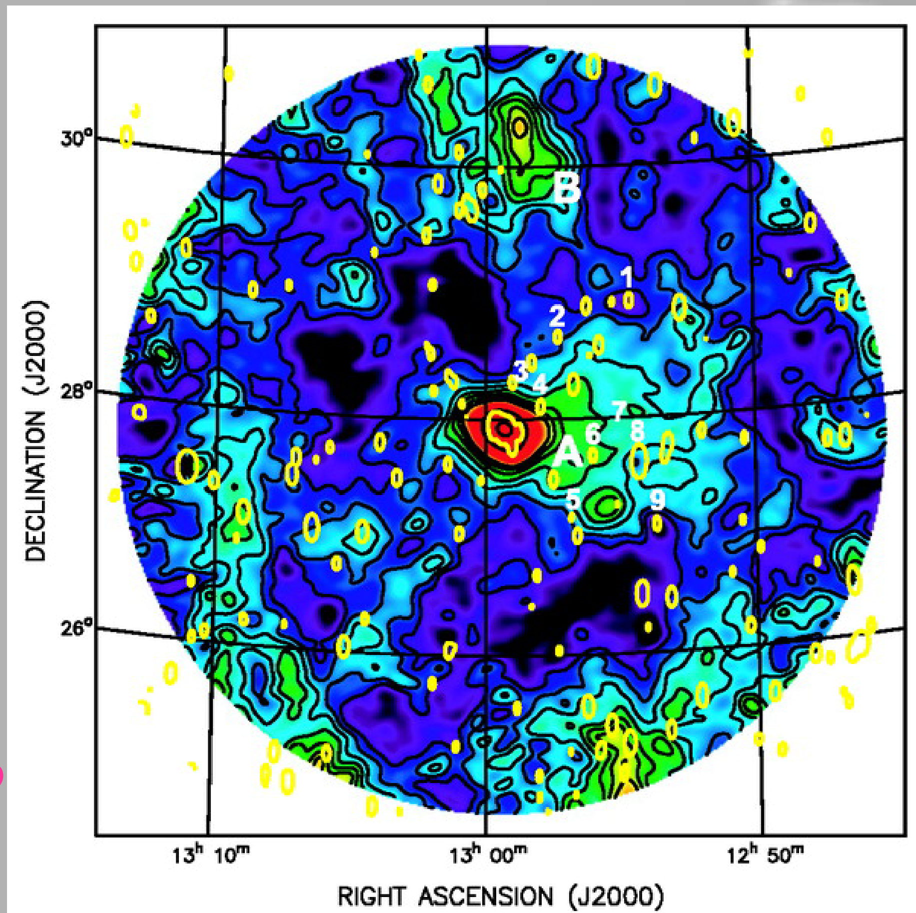
The radio halo certainly extends well beyond the border of the image...

...but even the most compact (C/D) configurations of VLA at 1.4 GHz cannot unveil structures larger than ~10-15 arcmin...

...single dish data are mandatory !

Res ≈ 10 arcmin

[Kronberg et al 2006 @ Arecibo + DRAO 0.4 GHz]



8 deg

Combination of single-dish scans with interferometric data in the Fourier space allows one to produce maps with detailed resolution over large portion of the sky in a reasonable observation time (tens of days)

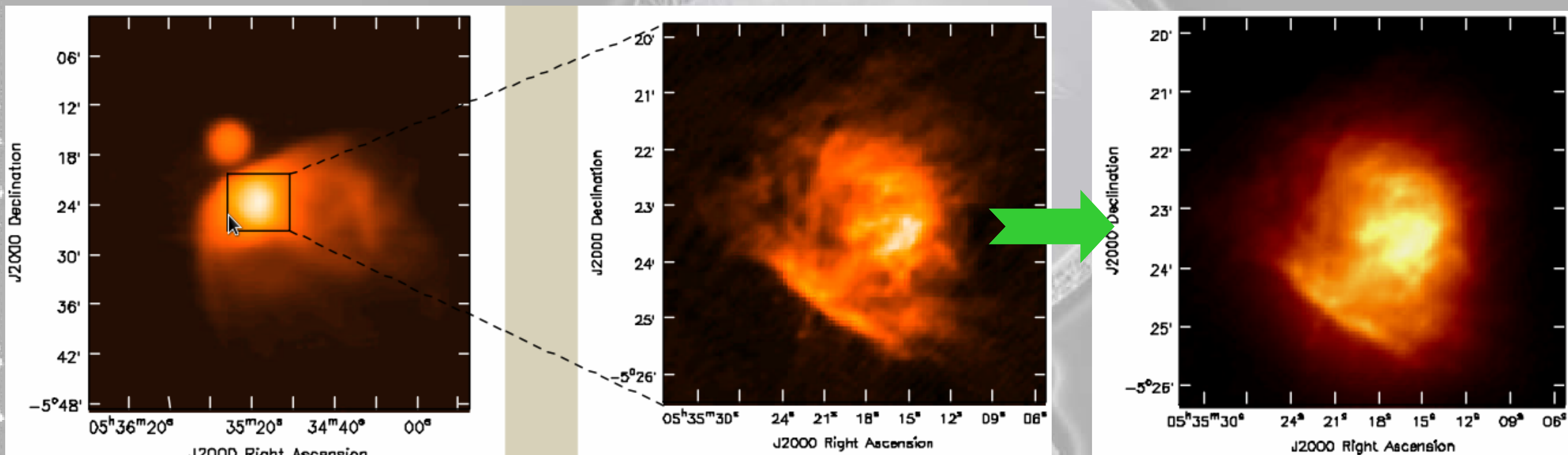
COMA CLUSTER

See also Brown & Rudnick 2010

...in fact combination of single-dish and interferometer data is a well established technique, used since a while

[Shepherd et al. 2003]

ORION NEBULA



GBT @ 8.4 GHz

VLA @ 8.4 GHz

VLA+GBT @ 8.4 GHz

it is basically required at least in the following cases:

- mapping of extended objects (much larger than the interferometer primary beam)
- mosaicing with an interferometer
- when total power information is needed

…and data combination will take a key role in ALMA

where aperture synthesis array data will be combined with the observations of the 12m single-dishes

As to the future …

many new arrays will enter in play in next decade or will be refurbished/improved

Their common distinctive feature with respect to the "traditional" arrays will be the

larger or much larger Field-of-View

obtained thanks to smaller elementary dishes ($\theta \sim \lambda/D$) or with the adoption of focal plane arrays (multi-beaming) and/or exploiting multi-beam forming techniques

[@ Astron]

[@ CSIRO]

However

LOFAR (≈10 MHz-240 MHz), **ALMA** (35 GHz-950 GHz) will often operate <u>outside the bands</u> of most of the <u>major large single dishes</u>

While e.g.

ATA, Apertif-WSRT, ASKAP, MeerKAT will have a

1) **collecting area comparable** to that of the largest single dishes
2) **larger or much larger Field-of-View** than all previous aperture synthesis arrays

A challenge for single-dishes even in some of their "battlefields"

Requirements for single-dishes in next decade

Cooled large "multibeams" or "focal plane arrays" to counterbalance the wider FoV of new arrays

Very large Rx and IFs Bandwidth (≈ 30% central freq) as well as State-of-art digital back-ends for fully exploiting the relative simplicity of the electronics wrt that of very complex arrays

RFI rejection and commensual observing to fully exploit the enlarged bandwidth and FoV

…with (at least some of) those features in place, the current "complementarity" between the interferometers and the single-dishes ***of similar collecting AREA*** will be mantained

Moreover the largest single-dishes will likely have also to start focusing their use on a smaller number of specific and WELL TAILORED AIMS…

…as well as exploring new opportunities/ideas for maximising their "advantages" wrt the arrays of smaller dishes, e.g. by combining observations

Sensitivity equivalent to illuminated Arecibo

Telescope	Diameter (m)	ϵ	T_{sys}	$\epsilon A/T_{sys}$	Allocated time (h/mo)
Arecibo	305	0.5	30	5.0	8
GBT	100	0.7	20	1.1	18
Parkes	64	0.6	25	0.3	100
LEAP	**200**	**0.7**	**30**	**3.0**	**24**

EPT LEAP

In summary, with suitable investments in upgrading front-ends and back-ends and new observational strategy…

the scientific role of the Largest Single-Dishes in radio astronomy in next decade (and further on) will be warranted

…with particular emphasis on…

- Studying point-like sources
- Mapping large scale structures
- Investigating pulsars
- Radar mapping

…implying many scientific applications…

HI, OH and CO content of millions galaxies for studying dynamics and evolution of internal properties

Polarization surveys for studying galactic magnetic fields and facilitating CMB measurements

Evolution of clusters and superclusters of galaxies

Origin of the cosmic magnetic fields

Mapping of Solar System bodies and Near Earth Objects

Gravitational waves detection via pulsar timing arrays

Gravity theories tests via high precision pulsar timing

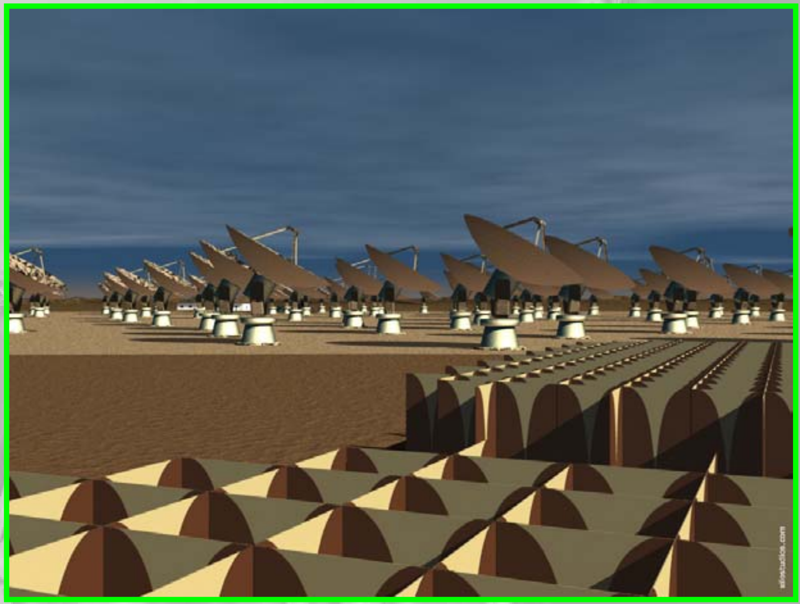
Mass of central black-hole and host galaxy distance via maser searches and monitoring

+ …

On a longer time-scale…

what really matters the most is the size:
i.e. the collecting area!

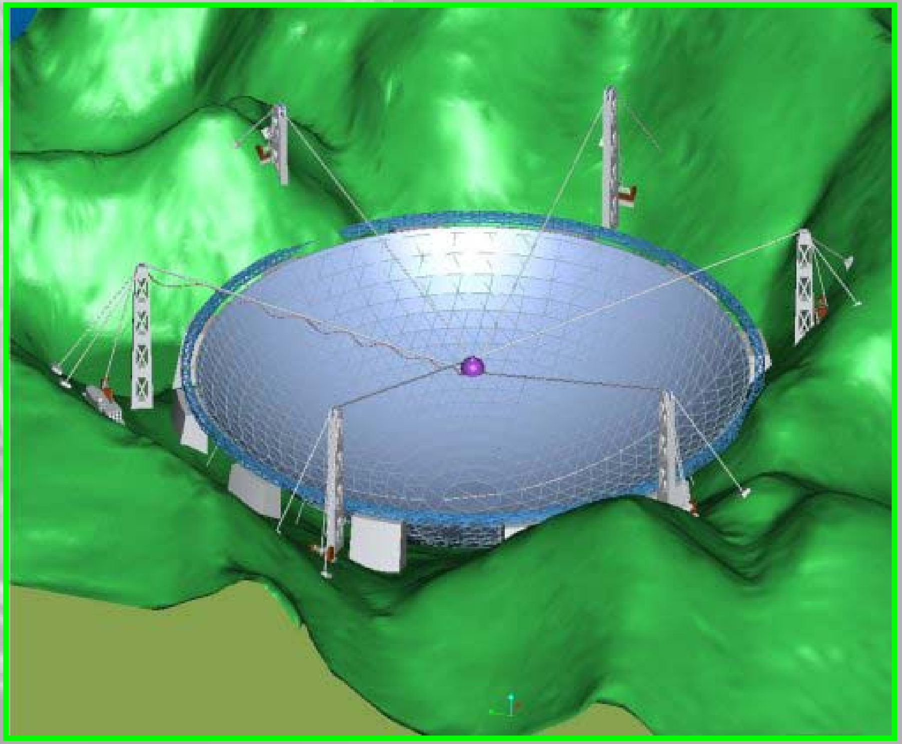
Square
Kilometer
Array



The ultimated radio telescope will likely be a combination of all the arrays' technologies…

However, the case of the single-dishes will be still represented by…

Five-hundred meter
Aperture
Spherical
Telescope



..and already investigated some projects for which FAST may be better/easier-to-use/less-costly than SKA…

e.g. Pulsar searches with a 100 pixel focal plane array at FAST would have a "survey speed" twice that at SKA [Smits et al 2009]

+

Much easier cabling

Much less data rate and requested computational power

Survey Speed ≈ (A_{eff}/T_{sys})^2 x FoV

Thank you!