Interferometric Radio Science

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5th European Radio Interferometry School – Dwingeloo 9th September 2013

Outline

Atmospheric observing windows

Angular resolution and the need for interferometry

Basic introduction to interferometry – details in following presentations

What do we look at with interferometers

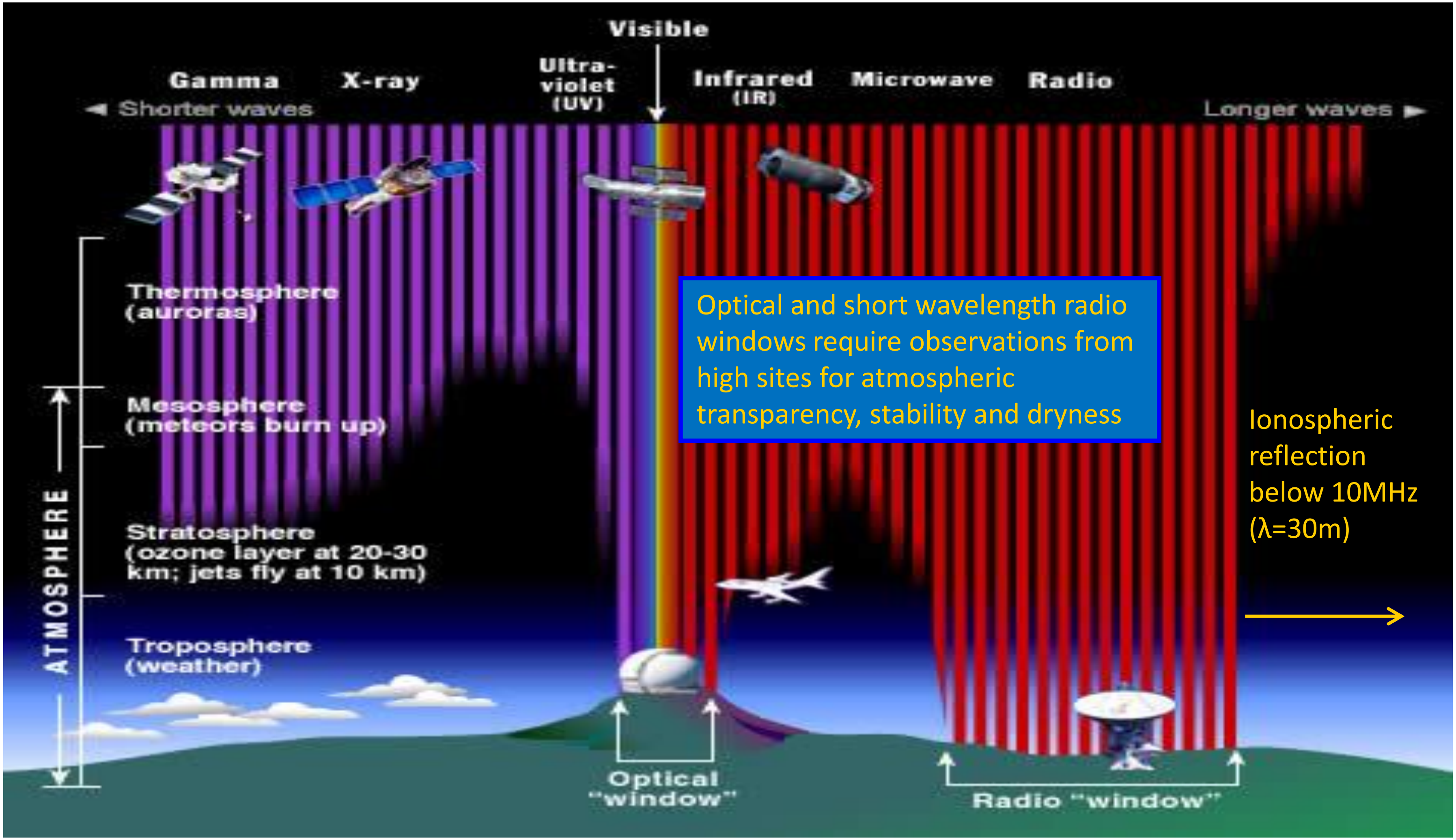
Some recent examples of interferometry science….

Atmospheric Observing Windows

Just two observing bands are available for ground-based astronomical observations – Optical & Radio "windows"

Visible light: 400 – 700 nm

Radio: 0.3mm – 30m



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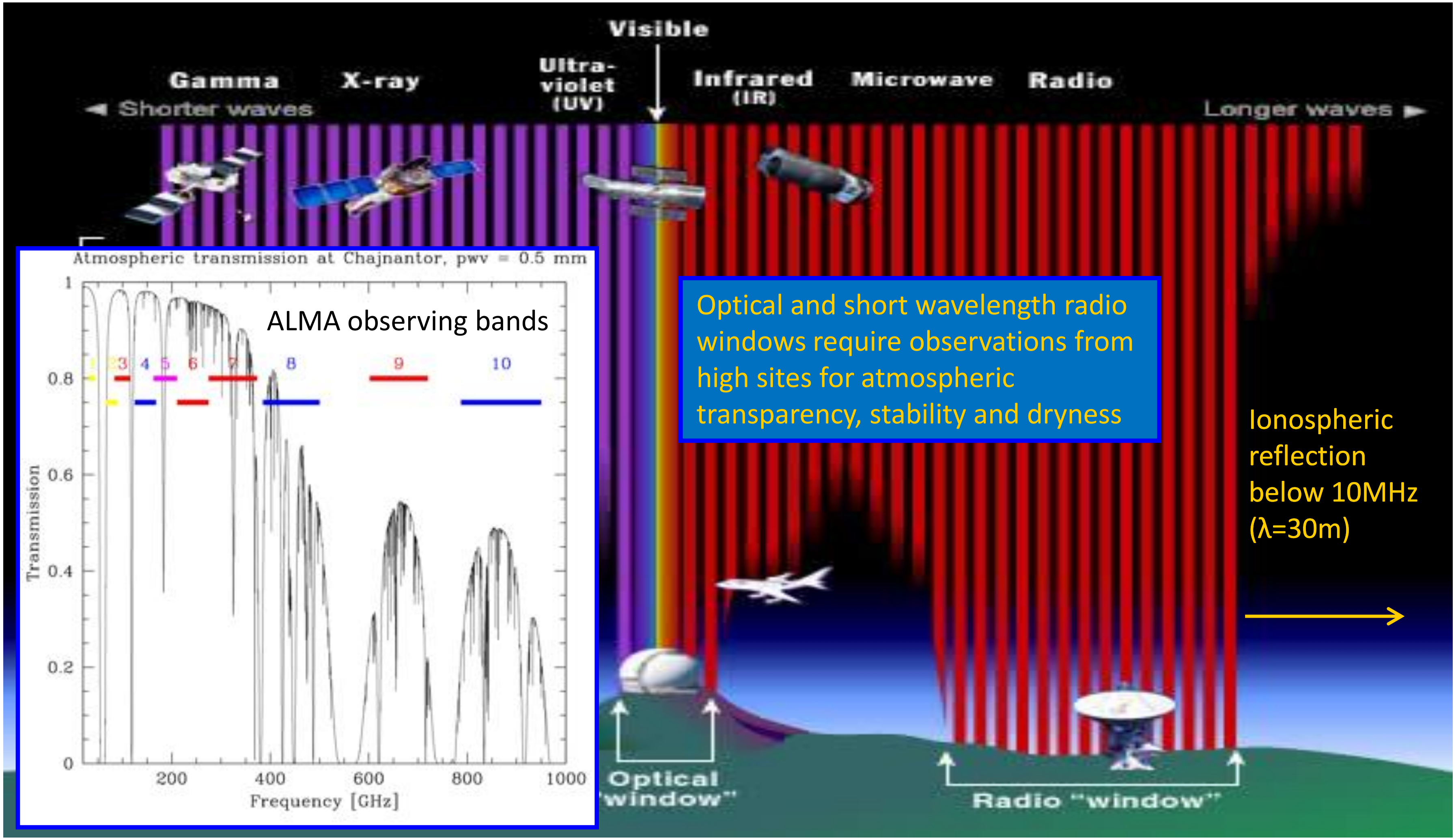

Apertures – Sensitivity and Resolution

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RadioNet

Large reflecting telescope – Arecebo (d=300m)

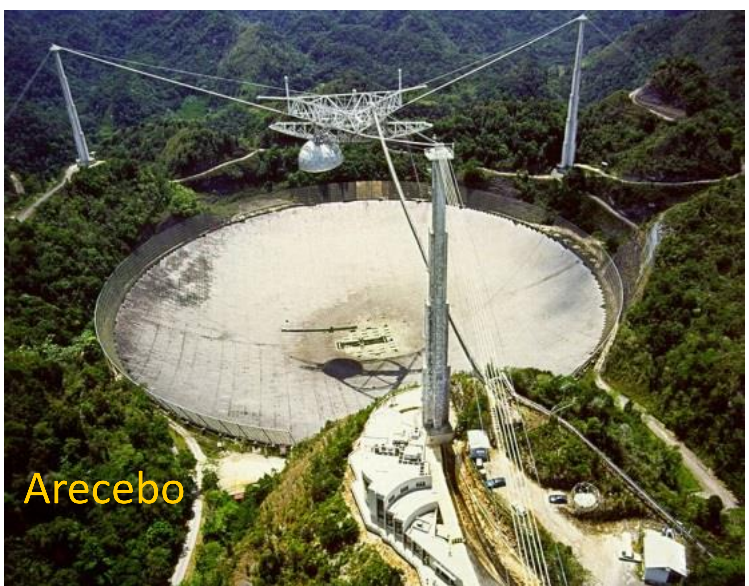
Large steerable radio telescope – Green Bank Telescope (d=100 x 110m)

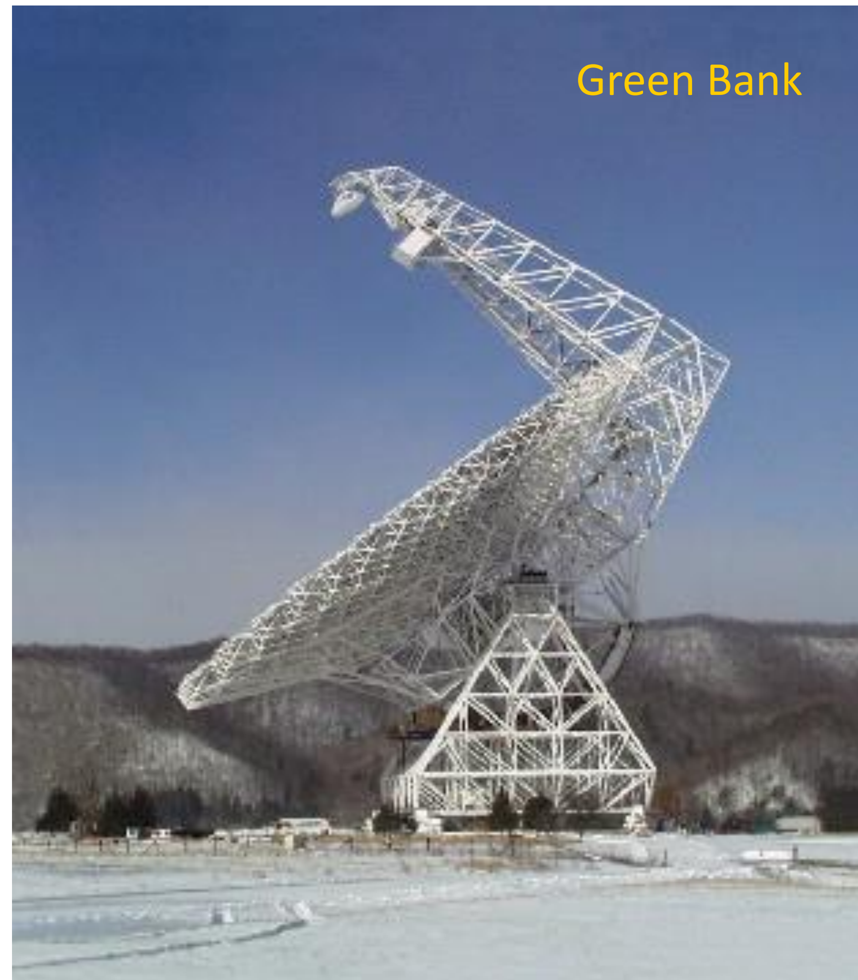
Resolution = ~wavelength / Diameter (radians) → few arcmins at centimeter λ

Excellent sensitivity from collecting area

Optical telescope has resolution ~ 1 arcsec

At λ=20cm, need Diameter ~35km!





Apertures – Angular resolution & psf

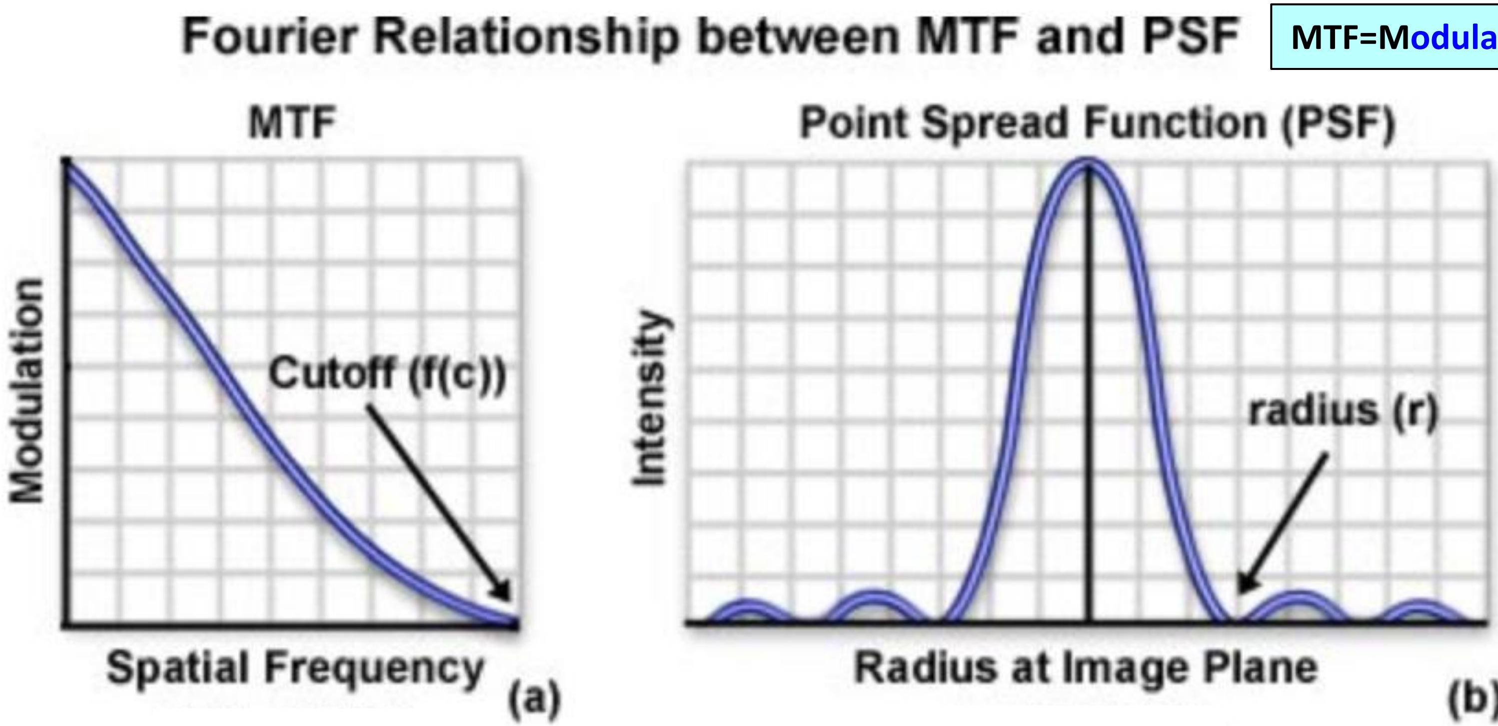
A fully filled aperture (diffraction-limited refracting telescope)

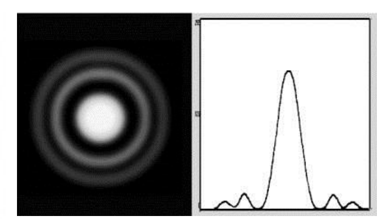
Samples image spatial frequencies out to a cut-off set by objective diameter

Image contrast (modulation) is highest at low spatial frequencies, decreasing to a value of zero as the spatial frequency increases → $f(c)=D/\lambda$.

Resolution set by PSF I[st] minimum → $\theta=1.22\lambda/D$

MTF=Modulation Transfer Function





Airy Disc

Apertures – Angular resolution & psf

A fully filled aperture (feed-horn illuminated radio telescope)
Samples image spatial frequencies out to a cut-off set by objective diameter

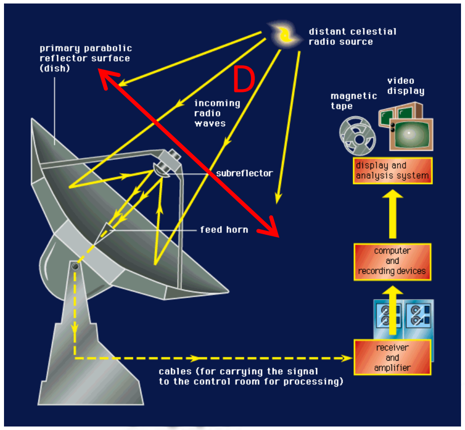
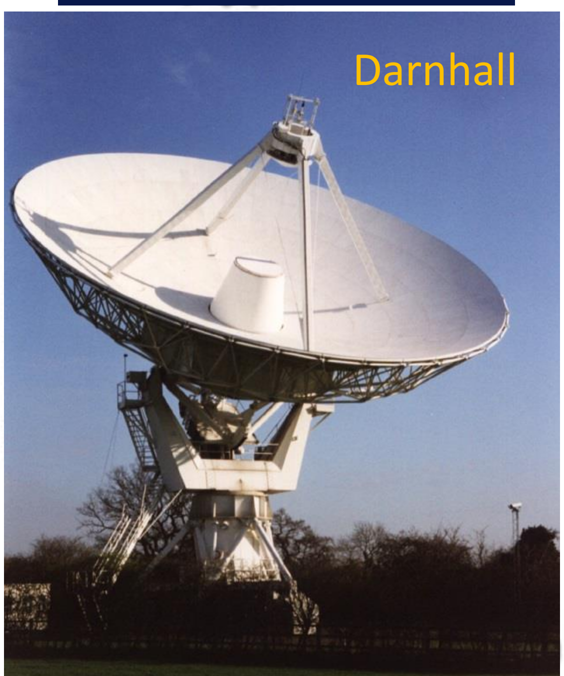
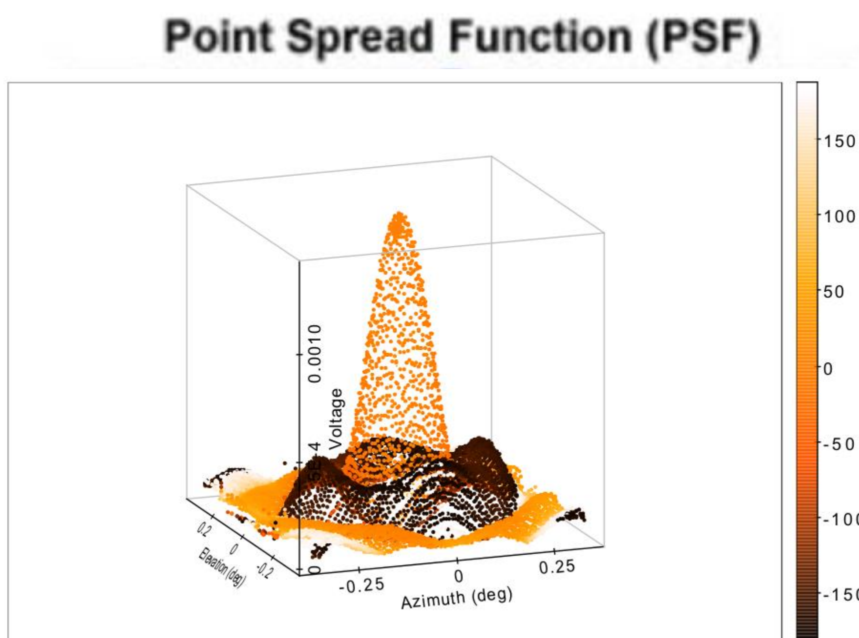


Image contrast (modulation) is highest at low spatial frequencies, decreasing to a value of zero as the spatial frequency increases → $f(c)=D/\lambda$.

PSF set by detailed illumination pattern (how it samples the aperture)





'Shaped' aperture illumination increases aperture efficiency at the expense of PSF near side-lobe pattern

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Angular Resolution – Large Apertures

Resolution = ~ Diameter/wavelength (radians)

Optical telescope has resolution ~ 1 arcsec -- how to match this in the radio?

At λ=20cm, need Diameter ~35km!

→ Use smaller antennas to synthesize ~ 35km telescope

→ Can 'fill' an aperture up to ~ 1km

Angular Resolution – Unfilled Apertures

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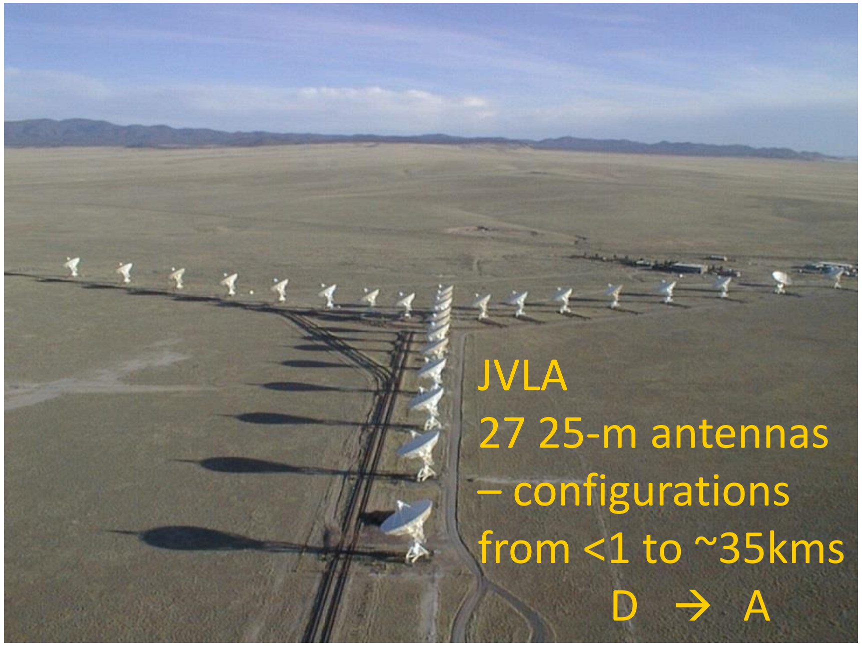
Allow Earth rotation to populate the sampled aperture

Unfilled apertures do not sample all spatial frequencies present in the image
→ Limits the image quality & produces strong instrumental psf

Sampled spatial frequencies from the set of projected antenna spacings (in λ)

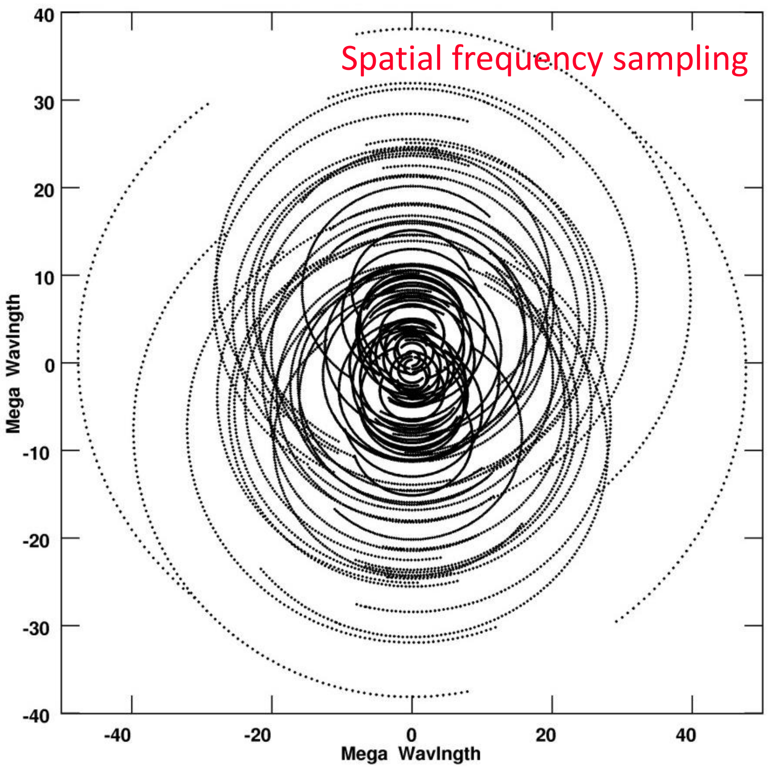
Large numbers of antennas + Earth rotation aperture synthesis
→ High quality images

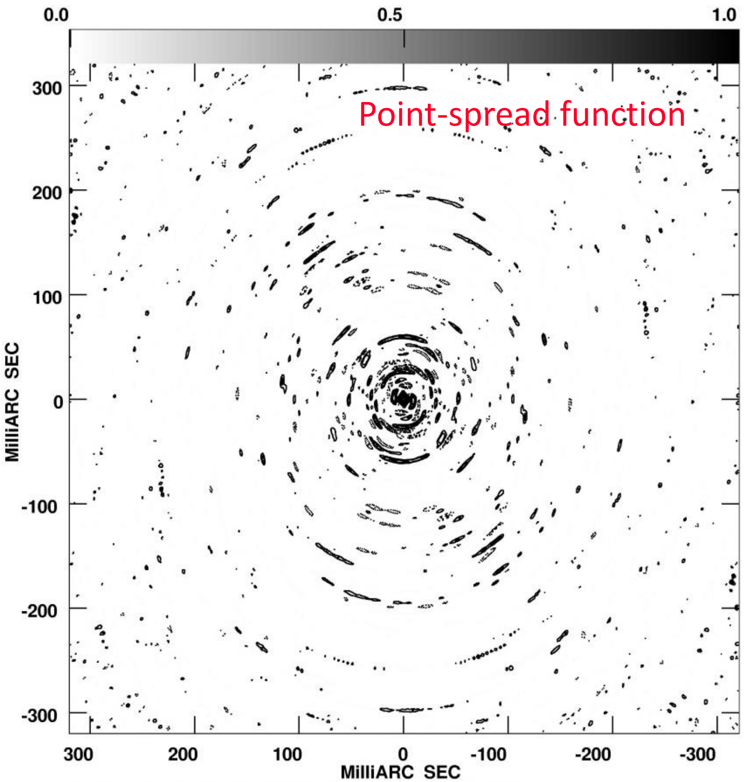


Angular Resolution – Unfilled Apertures

Spatial frequency sampling ⟺ point-spread function

Monochromatic 6-hr 10-element simulated observations of Virgo-A



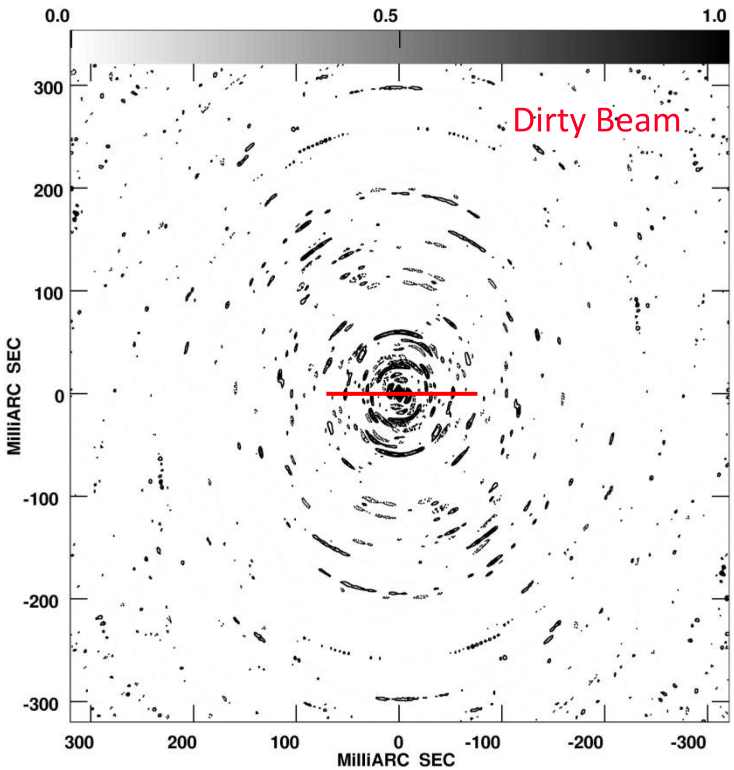


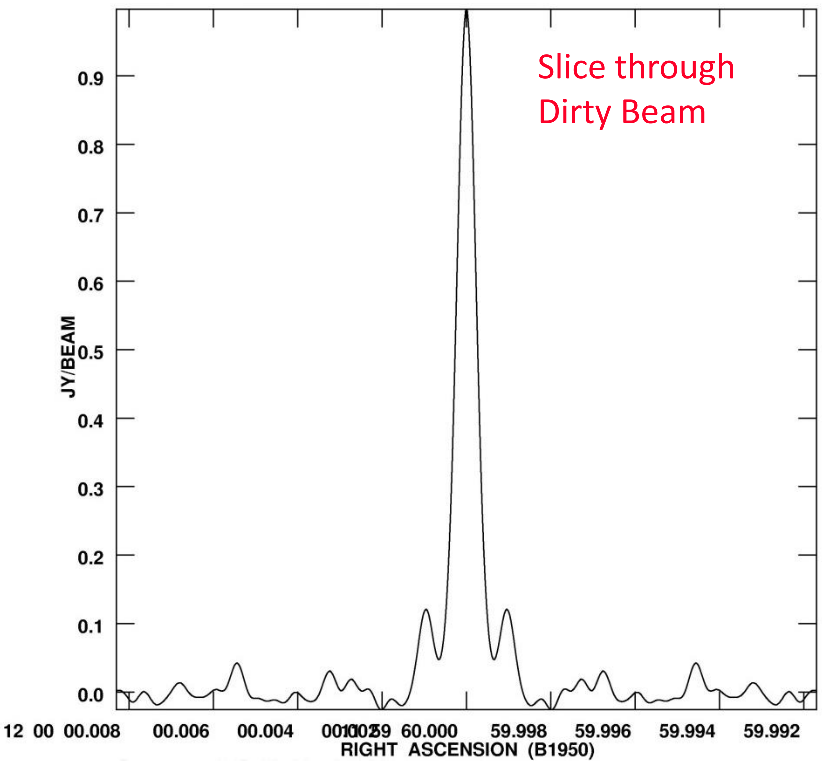
Holes in the spatial frequency sampling distribution produce a significant side-lobe response in the associated point spread function

Angular Resolution – Unfilled Apertures

Spatial frequency sampling ⟺ point-spread function

Monochromatic 6-hr 10-element simulated observations of Virgo-A



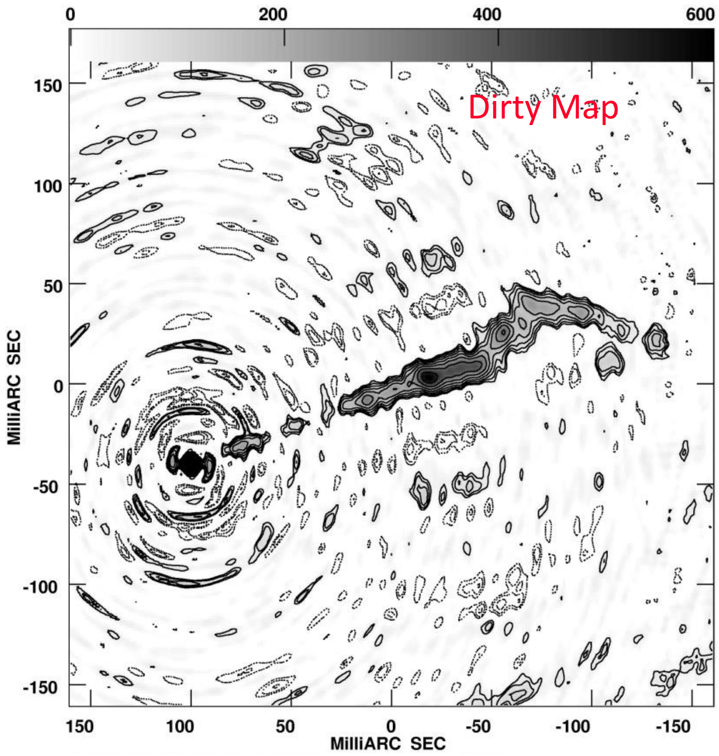


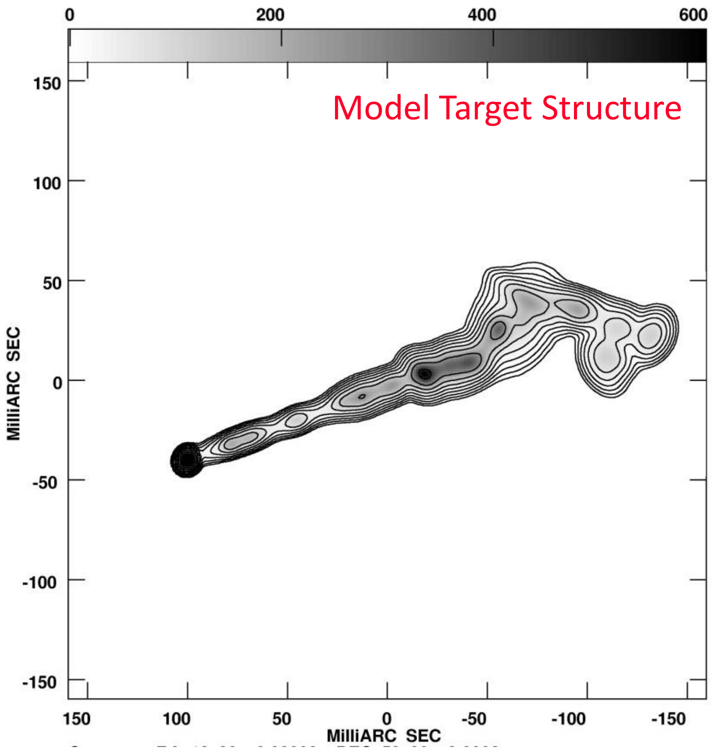
Point-spread function (Dirty Beam) has complex side-lobe structure

Angular Resolution – Unfilled Apertures

Spatial frequency sampling ⟺ point-spread function

Monochromatic 6-hr 10-element simulated observations of Virgo-A





Every element of the target source radio structure is convolved with the Dirty Beam side-lobe structure to produce a raw image (Dirty Map)

Angular Resolution – Unfilled Apertures

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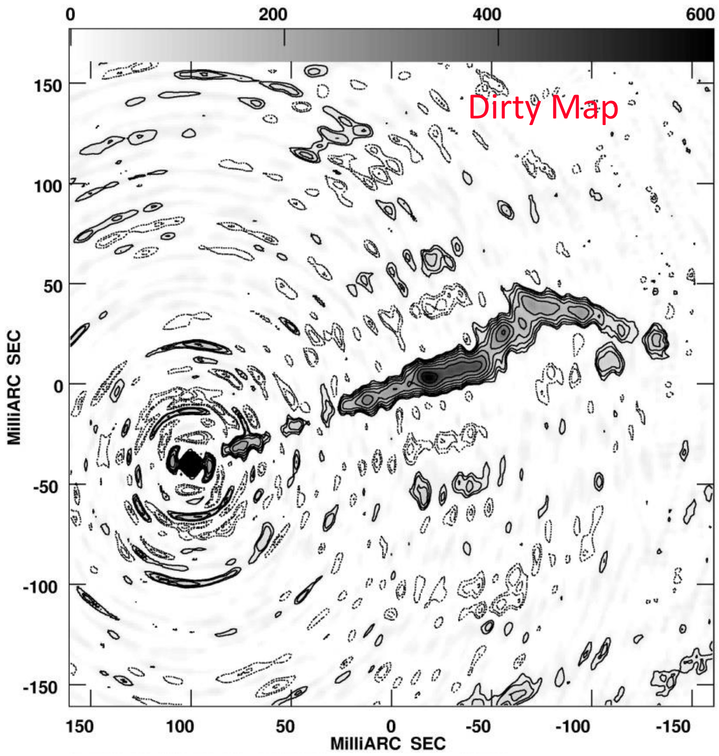
Spatial frequency sampling ⟺ point-spread function

Monochromatic 6-hr 10-element simulated observations of Virgo-A



Limitations: Can only reliably image radio structures smaller than the FT of the largest holes in the sampled aperture

Imaging software can de-convolve the Dirty Beam response from the Dirty Map to produce the Clean Map – interpolates between sampled points in the aperture

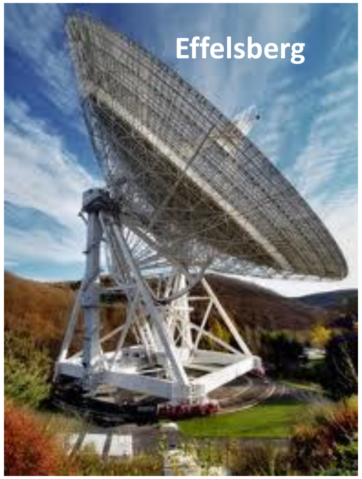
Angular Resolution – Unfilled Apertures

Large numbers of antennas + Earth rotation + adding data from several configurations → Detailed extended radio images

Angular Resolution

20cm imaging (arcmin → mas)

Allows astronomers to trace astronomical phenomena over orders of magnitudes in scale size



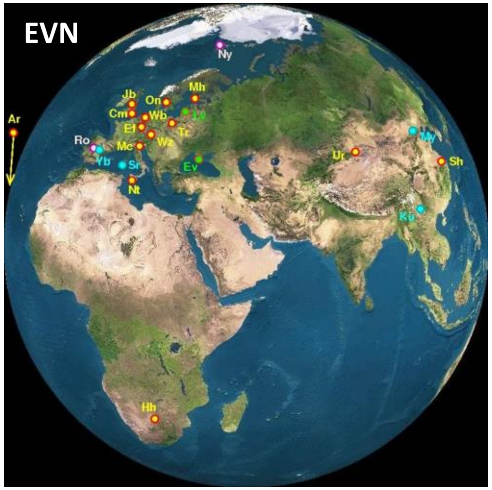
D=100m θ ~ 9.4’

D=1km θ ~ 44”

D=28km θ ~ 1.2”

D=35km θ ~ 1”

D=217 km θ ~ 150 mas



D~10000 km θ ~ 5 mas

θ≈fraction of mas

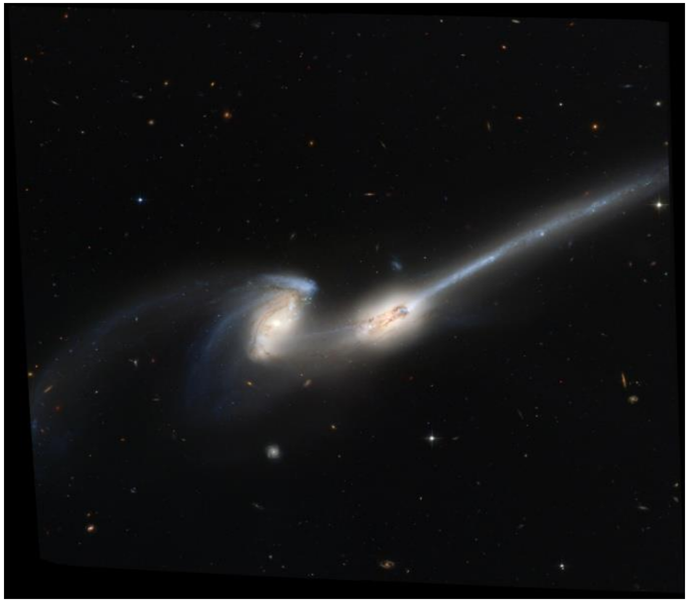
Angular Resolution

Matched imaging

Chandra, Gemini

θ ~ 1”

- angular resolution of the JVLA A-Array & GMRT



HST

θ ~ 50 mas

(angular resolution of *e*-MERLIN at 5 GHz aperture ~220km)

Angular Resolution

Matched imaging – 1 arcsec

→ Facilitates multiband research

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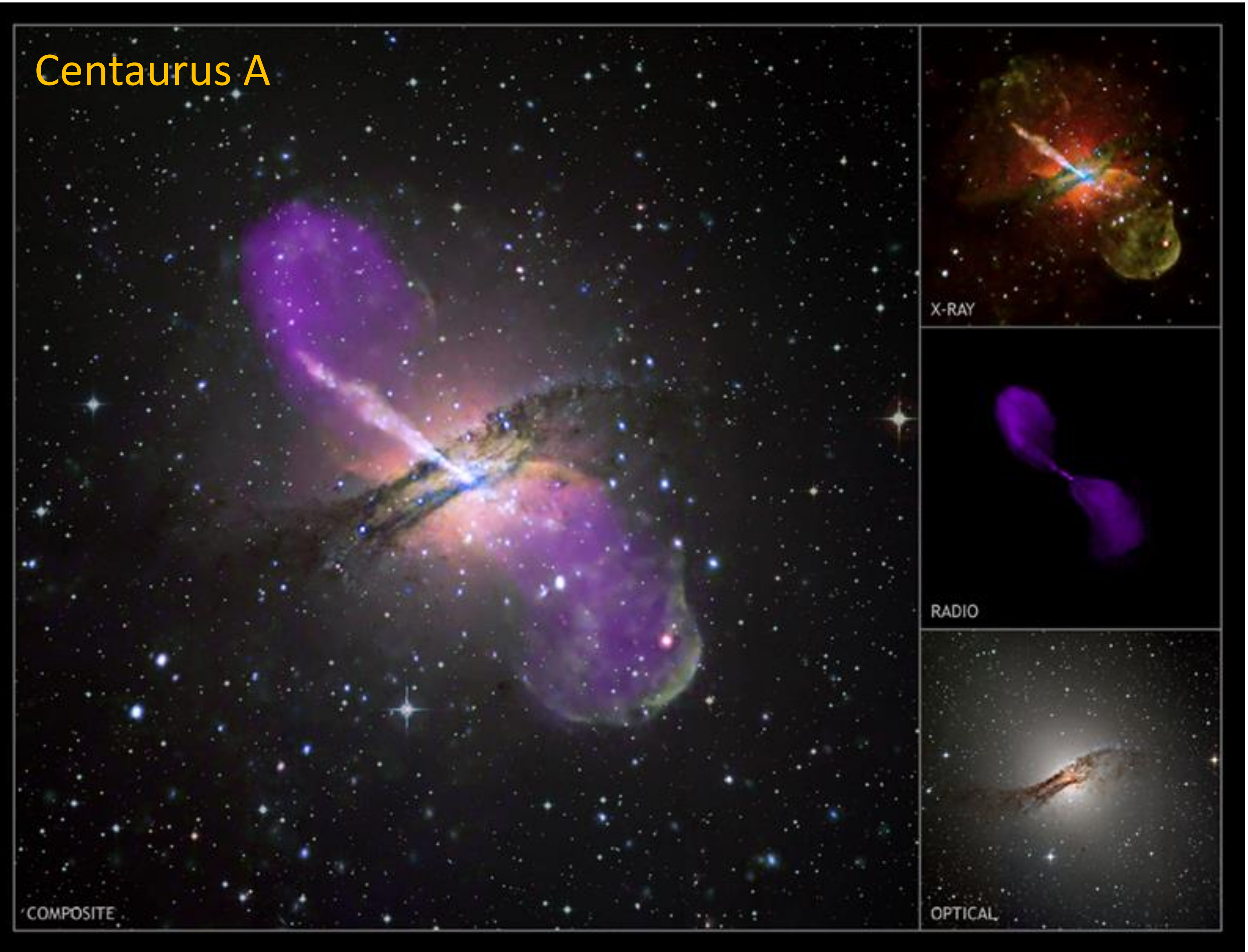

Chandra
720ks

VLA-A 5GHz
Hardcastle et al. 2008

ESO VLT

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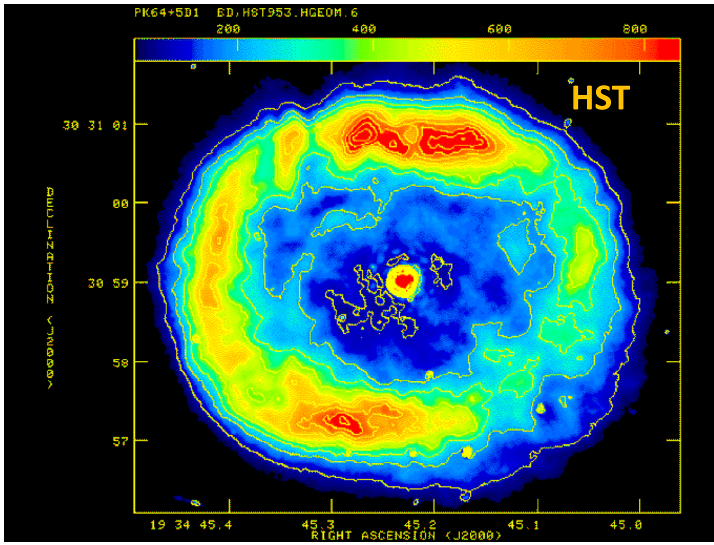
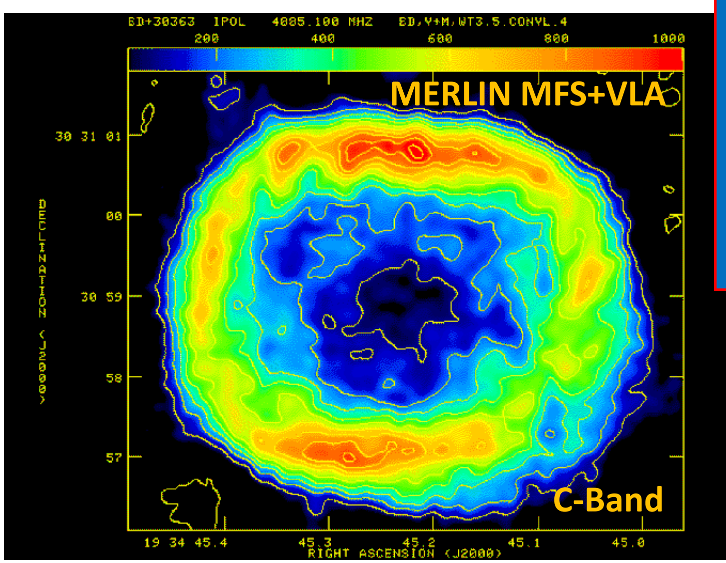
Angular Resolution

Matched imaging – HST (50mas)

D=1.2 kpc

Planetary nebula BD+303639

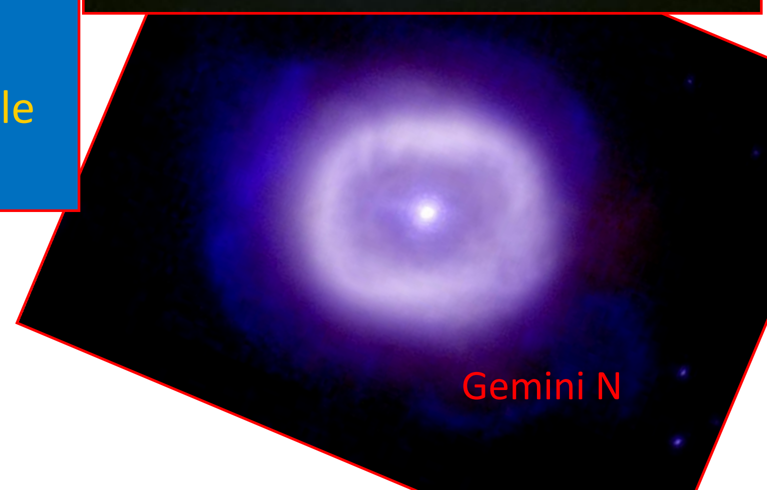




Although superficially very similar – differences show nebula contains small-scale dusty clumps & filaments

– particularly in the northern limb of the ring

Central star not visible in the radio image



Angular Resolution

The best of both worlds…

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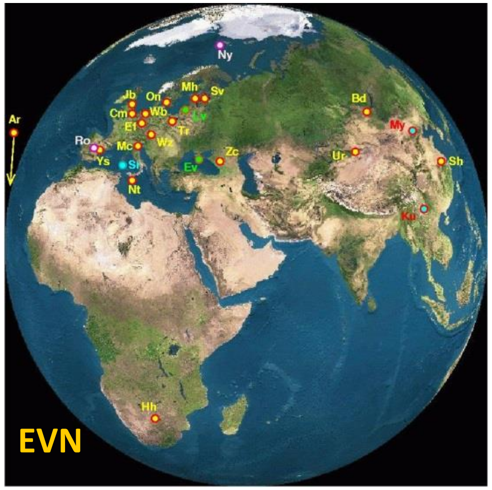
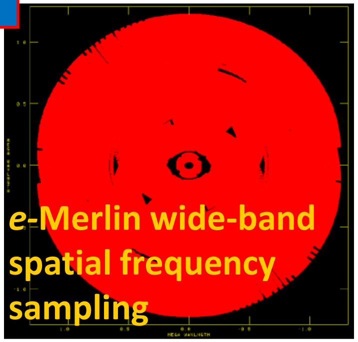
Multi-band imaging – from arcminute resolution to <100mas

Large numbers of antennas + Earth rotation
+ large fractional bandwidths + sophisticated imaging software
→ Very high quality images



Allows astronomers to investigate different physical phenomena and emission mechanisms present in any one object and their interactions
– imaged at matching angular resolution

From metre to sub-mm wavelengths



Angular Resolution

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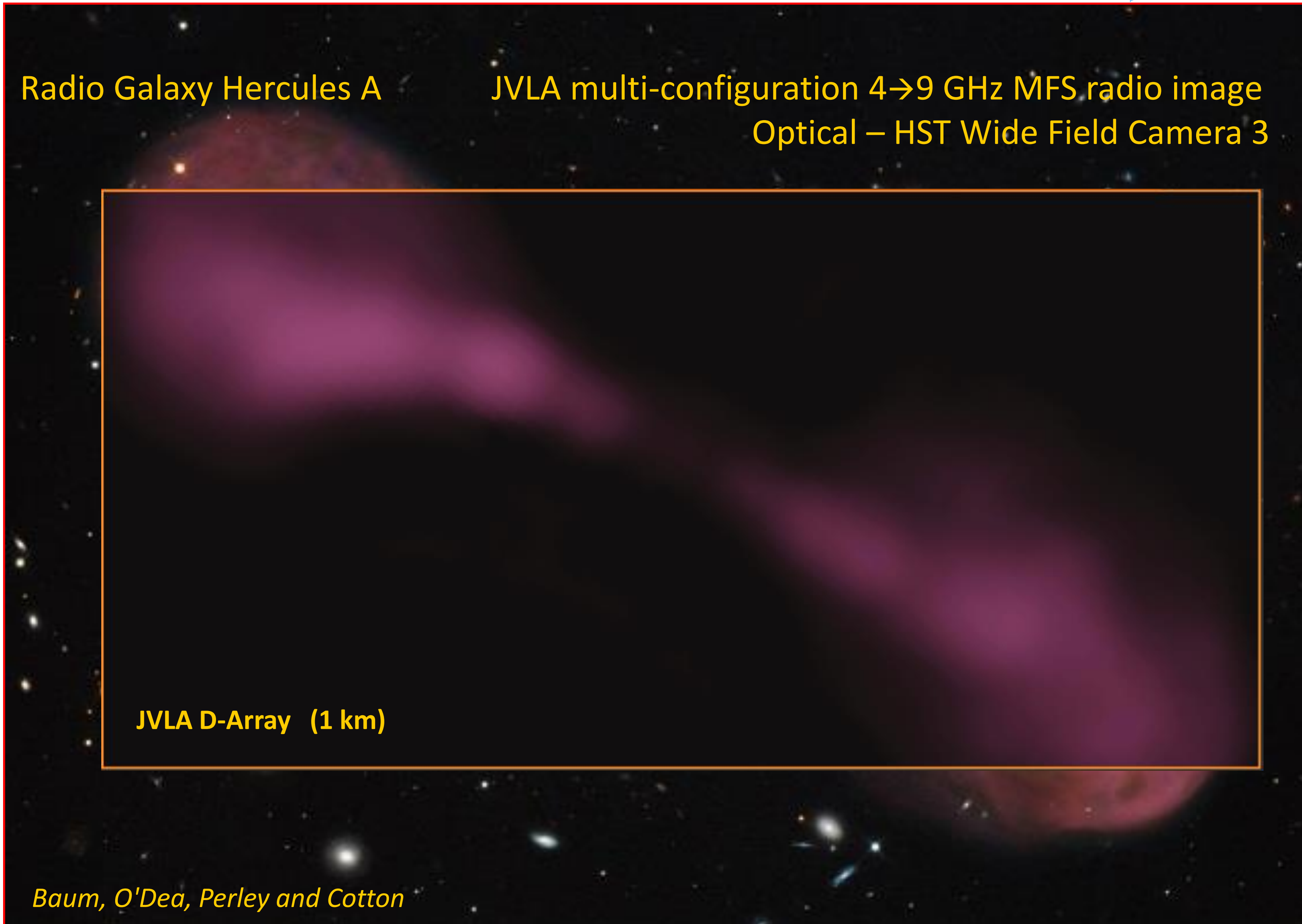
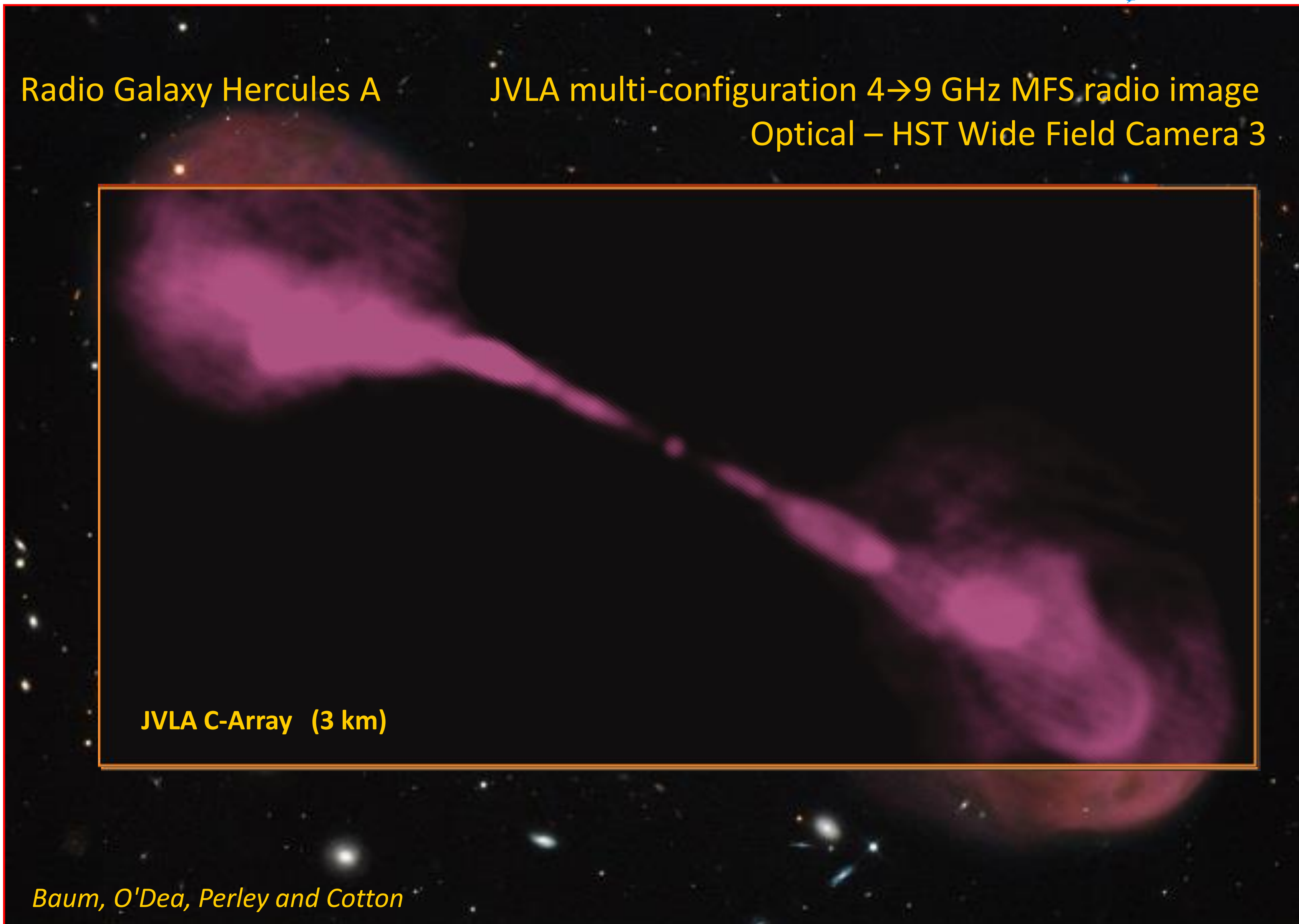


Angular Resolution



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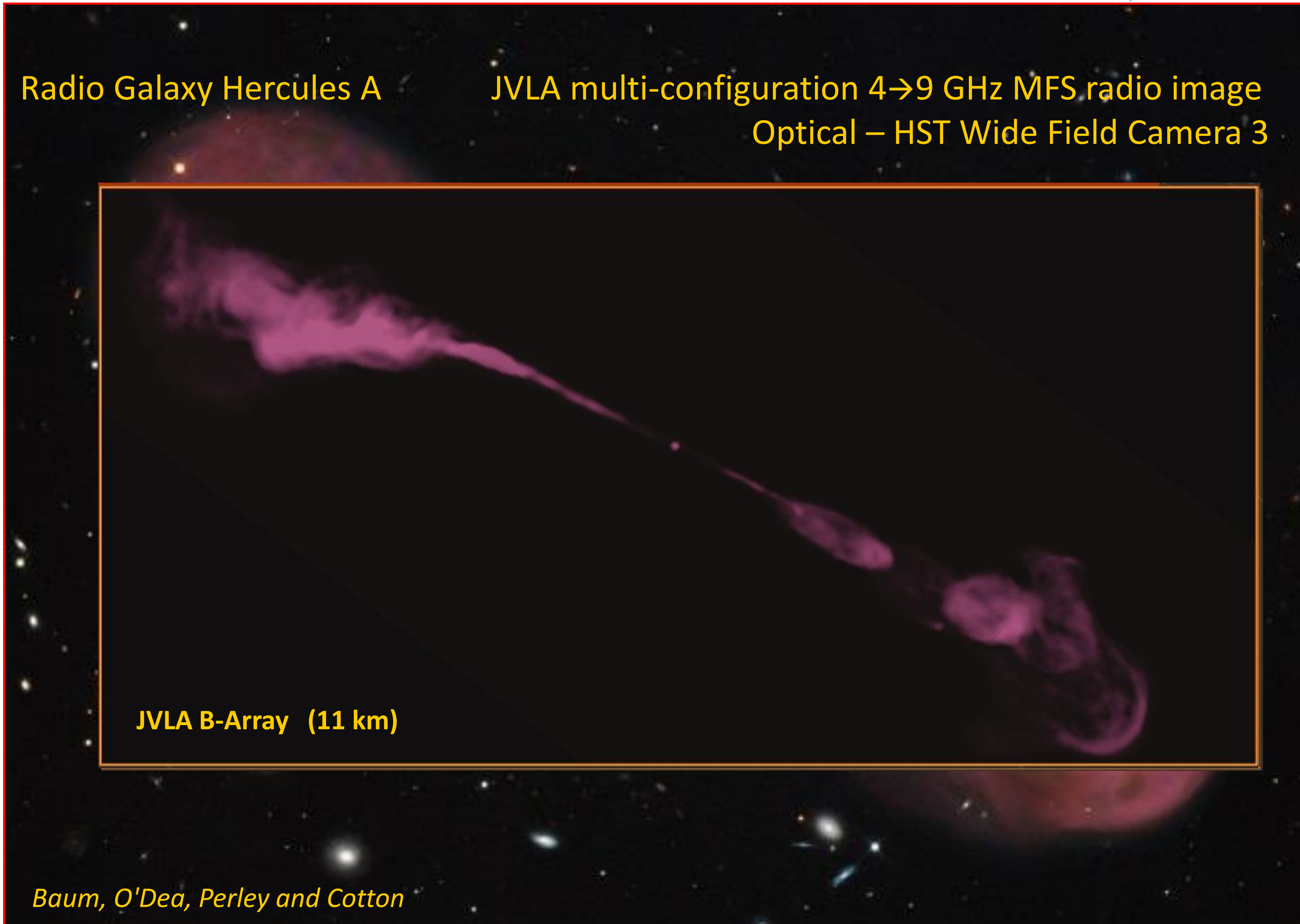

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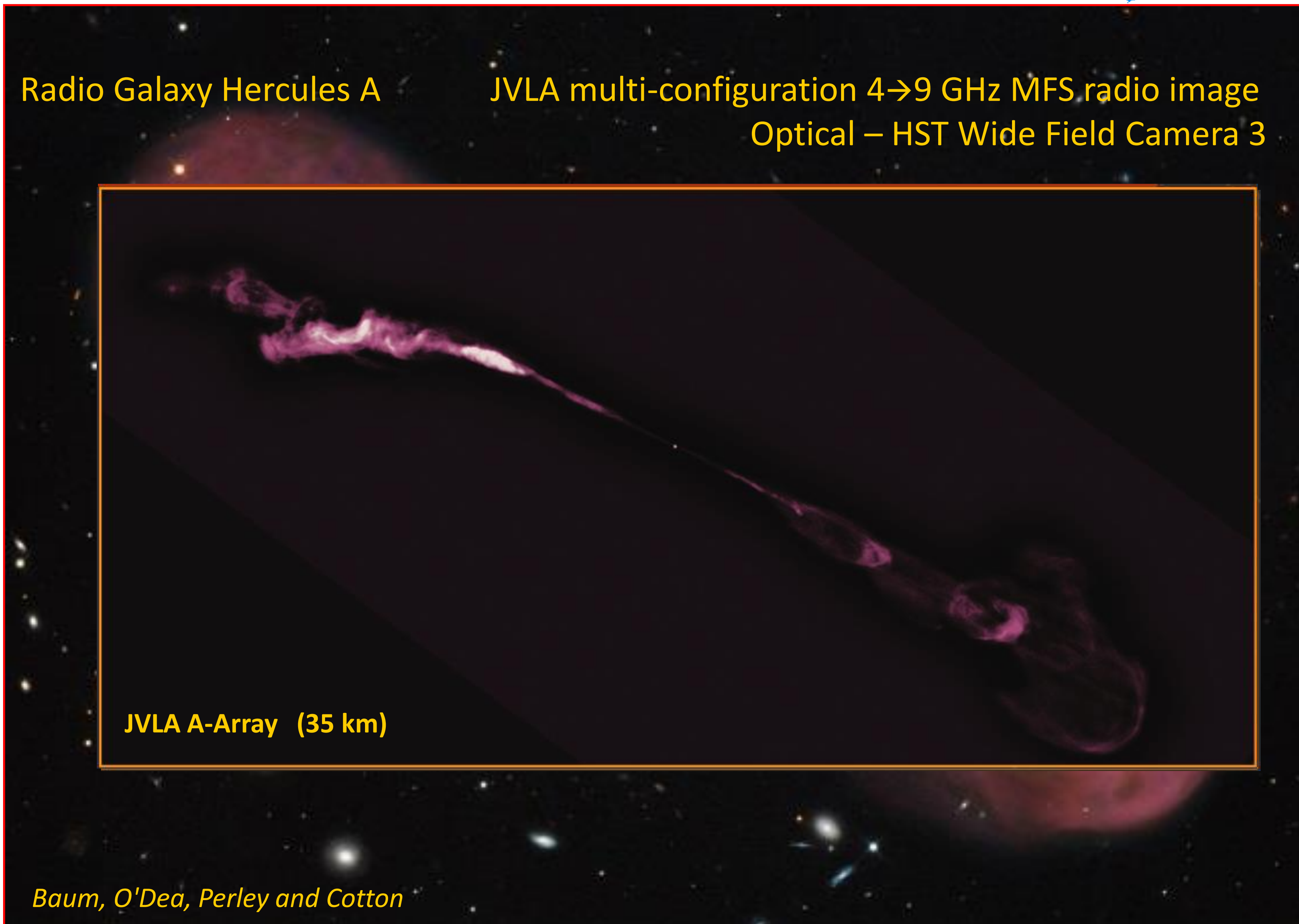
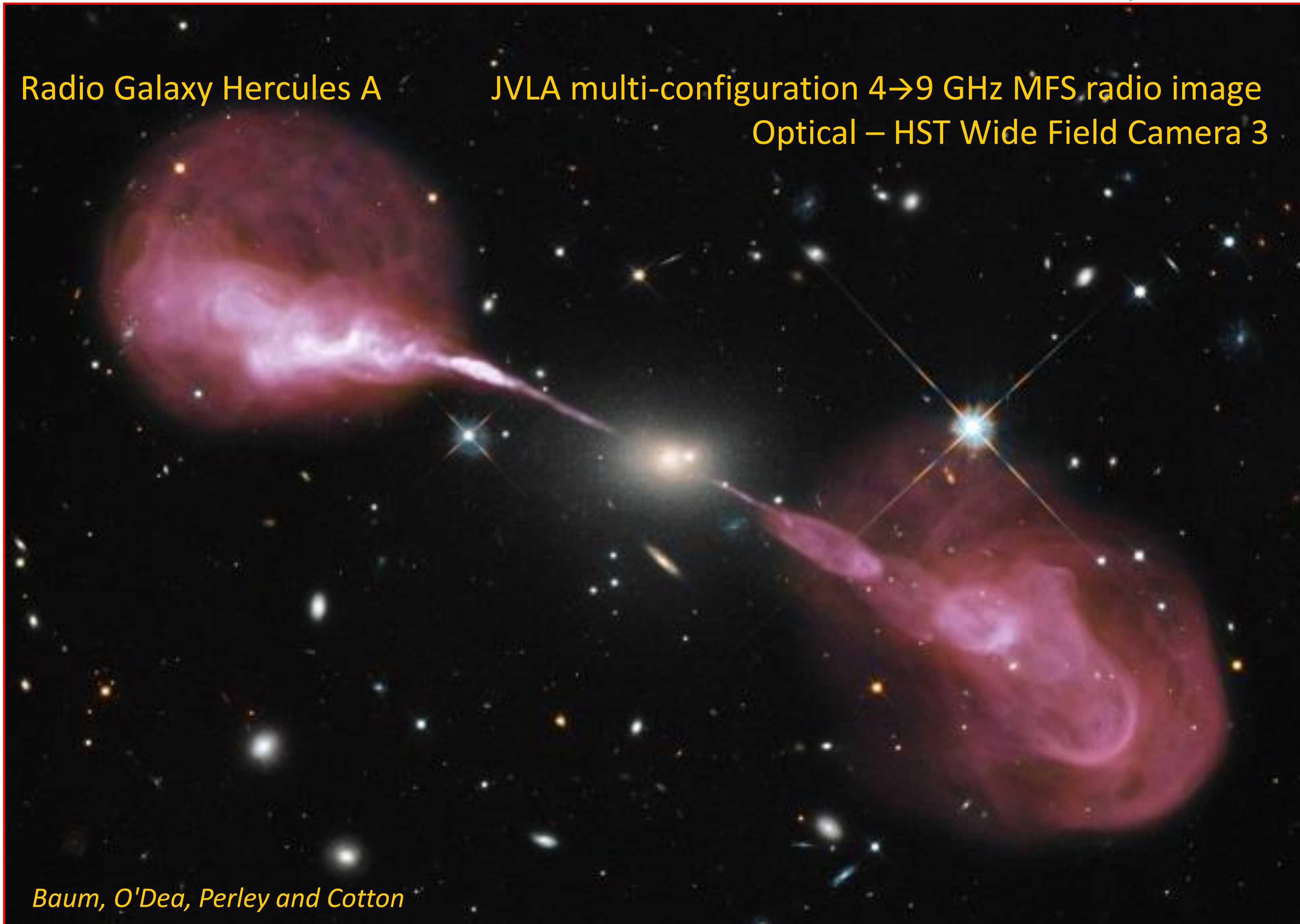


Angular Resolution



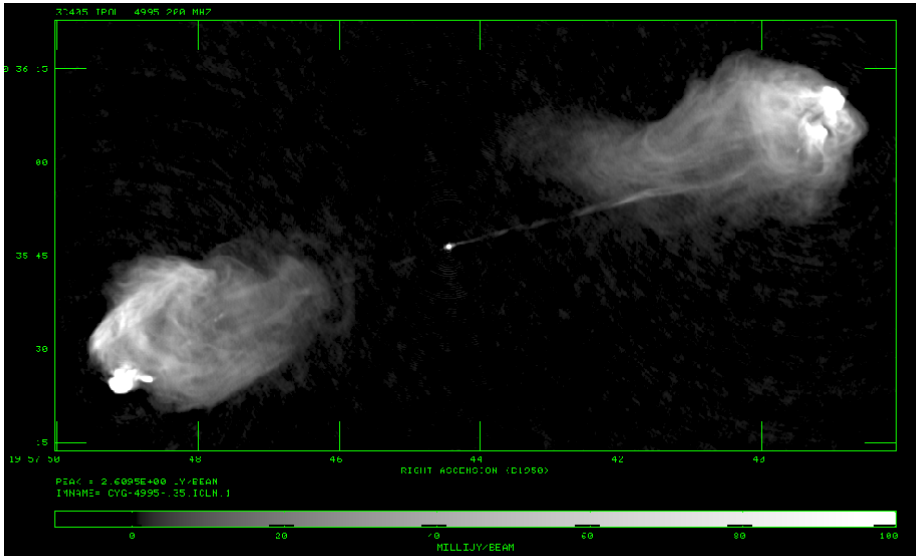
Radio Images

Interferometers are designed to make images of the sky brightness, at some frequency or range of frequencies, as a function of RA and Dec.

Brightness is defined as the power received per unit frequency at a particular frequency, per unit solid angle in a particular direction, per unit collecting area.

The units of brightness are in terms of (spectral flux density)/(solid angle): e.g:

watt/(m^2 Hz Ster)



VLA Image of Cygnus A at λ = 6cm.

The units are in Jy/beam.

1 Jansky (Jy) = 10^{-26} watt/(m^2 Hz)

Beam area = 0.16 $arcsec^2$

From R. Perley 2010

Radio Images

What are we looking at?

Blackbody radiation & CMB - Thermal properties

Thermal Bremsstrahlung - Ionized medium (T and ρ)

Radio Images

What are we looking at?

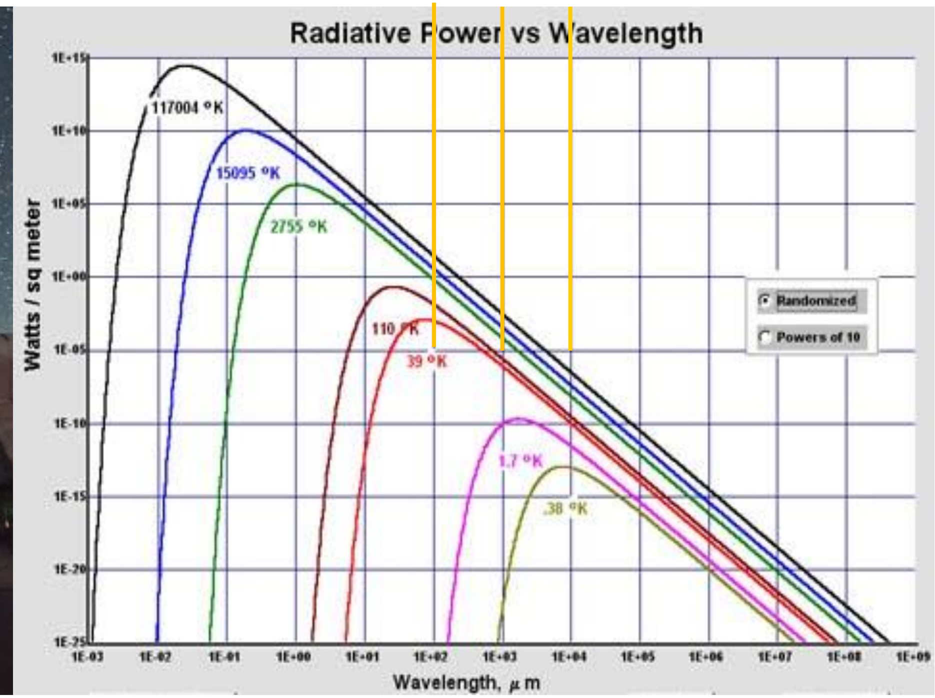
ASTRON Interferometric Radio Science

Blackbody radiation & CMB - Thermal properties

"Blackbody" radiation from warm bodies

Objects with temperatures of ~ 3-30 K (the cool Universe) emit in the mm & sub-mm bands – now becoming routinely visible in high resolution with ALMA

0.1 1 10 mm



Radio Images

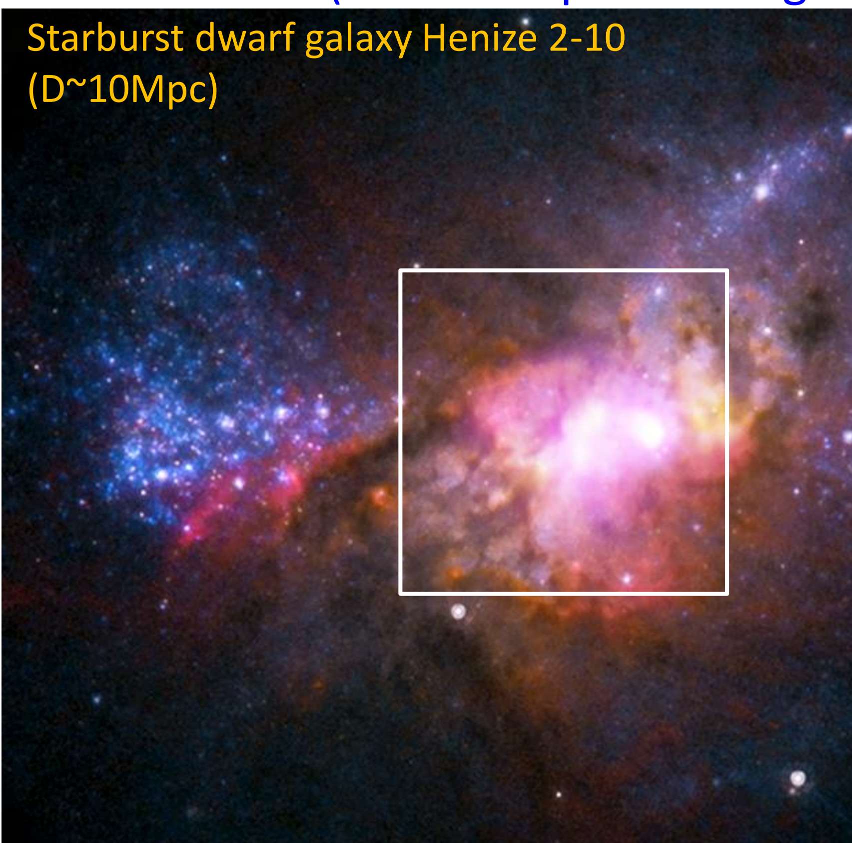
What are we looking at?

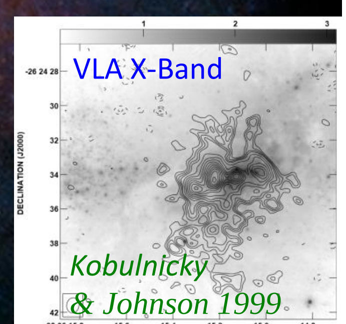
Thermal Bremsstrahlung - Ionized medium (T and ρ)

Emission from accelerating charged particles

- "Bremsstrahlung" or free-free emission from ionized plasmas

Signature of youngest starbursts – optically thick thermal Bremsstrahlung radio knots (Ultra-compact HII regions, each with ~750 O7 stars) – VLA 8.6GHz





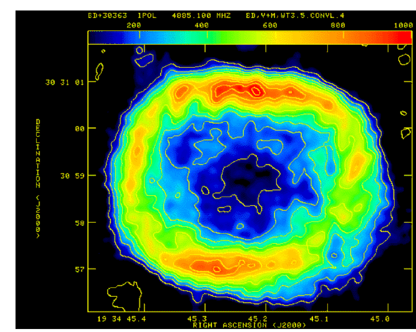
Size ~LMC $(3.7 \times 10^9 M_\odot)$

SF rate $\sim 1.9 M_\odot$/yr (~10xLMC)

SFRD ULIRG-like (but smaller)

Reines, Sivakoff, Johnson, & Brogan 2010

Free-free also from PNs

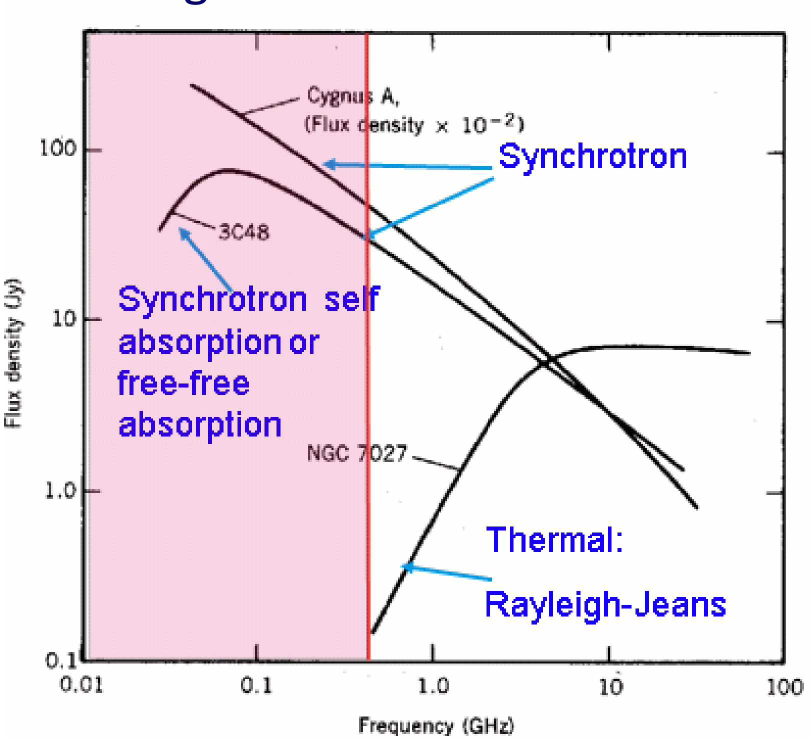


Radio Images

What are we looking at?

ASTRON Interferometric Radio Science
RadioNet

Blackbody radiation & CMB	- Thermal properties
Thermal Bremsstrahlung	- Ionized medium (T and ρ)
Synchrotron radiation	- Relativistic electrons and magnetic fields
Spectral lines from molecular and atomic gas clouds	- Composition (T and ρ) of the ISM/IGM



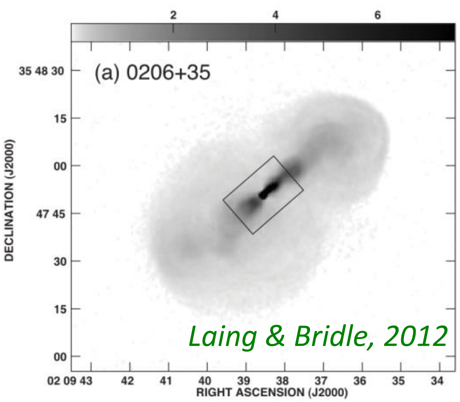
In radio images non-thermal and especially Synchotron processes are most easily detected at lower radio frequencies since the overall radio spectrum is steep.

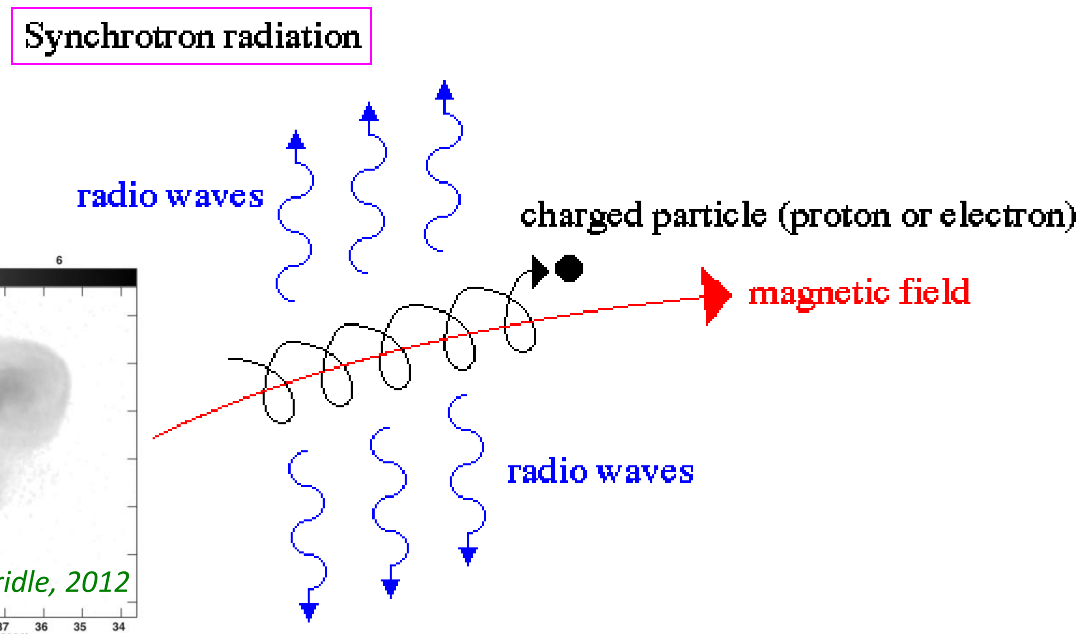
Thermal proceses are most easily detected at higher radio frequencies since they tend to exhibit rising spectra across the radio band.

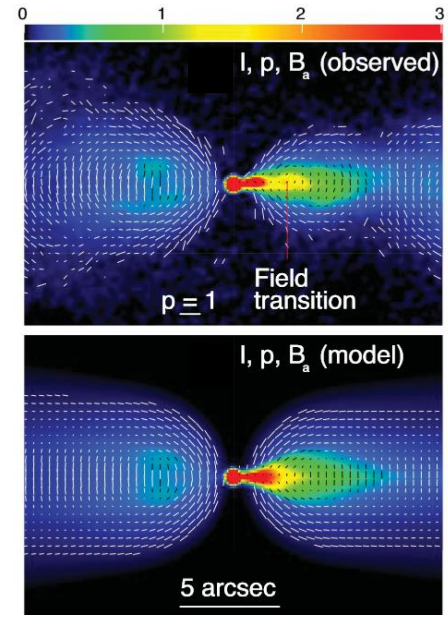
Radio Images

Synchrotron radiation

Interferometric Radio Science







synchrontron radiation occurs when a charged particle encounters a strong magnetic field – the particle is accelerated along a spiral path following the magnetic field and emitting radio waves in the process – the result is a distinct radio signature that reveals the strength of the magnetic field

Polarization provides information on the magnetic field → Direction of magnetic field is perpendicular to E-field direction in linearly polarized radio images

e.g. Role of magnetic fields in relativistic jet models to investigate backflow in the radio galaxy 0206+35

Radio Images

Spectrum of synchrotron radiation

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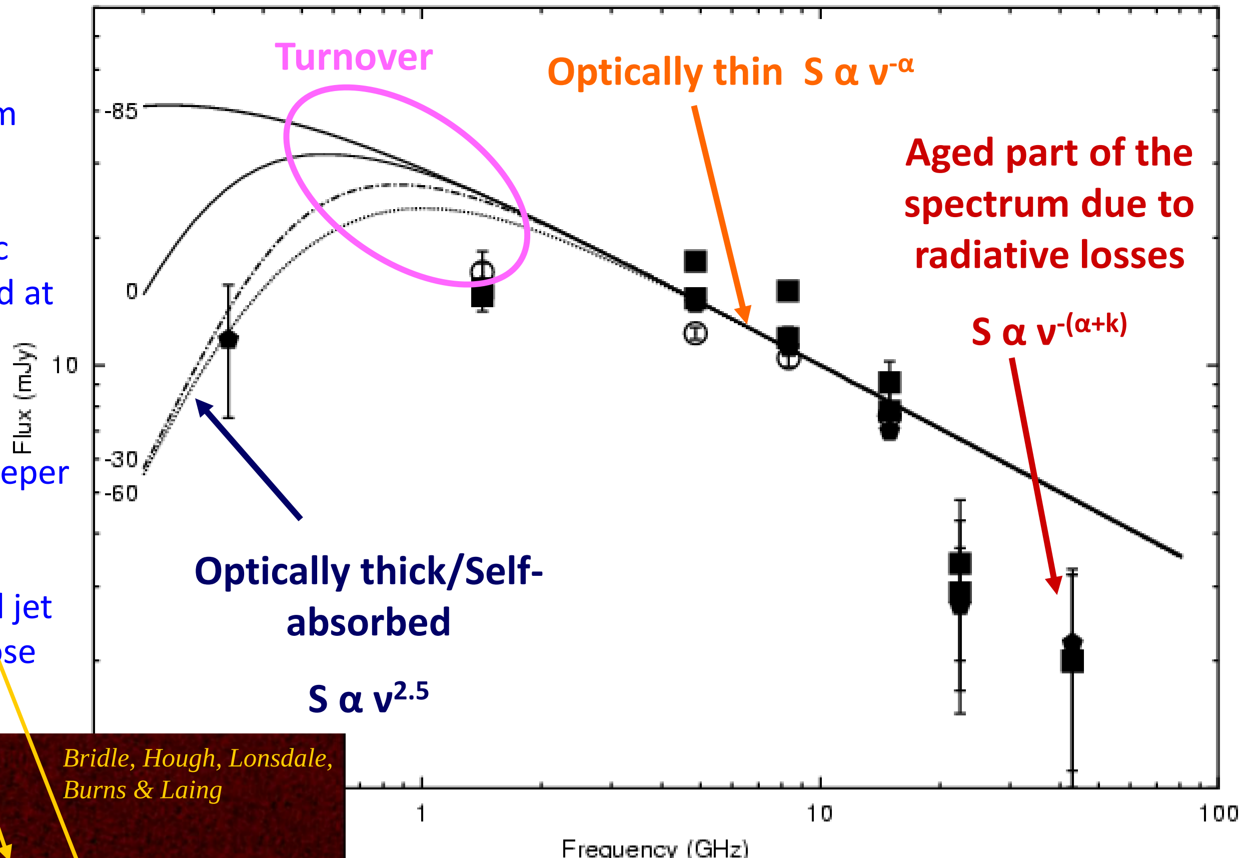
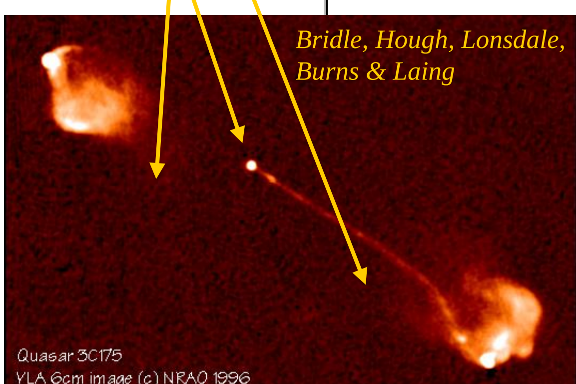
Steep-spectrum jets & lobes

Fresh energetic plasma injected at hot-spots

Aging inner lobes show steeper spectrum

+Self-absorbed jet component close to AGN





The most energetic electrons radiate at higher radio frequencies and lose their energy more rapidly unless re-accelerated

Shocked regions can re-energise electrons and produce bright flatter-spectrum knots of emission

Different parts of the synchrotron spectrum provide different information on the radio source and on the population of radiating relativistic electrons

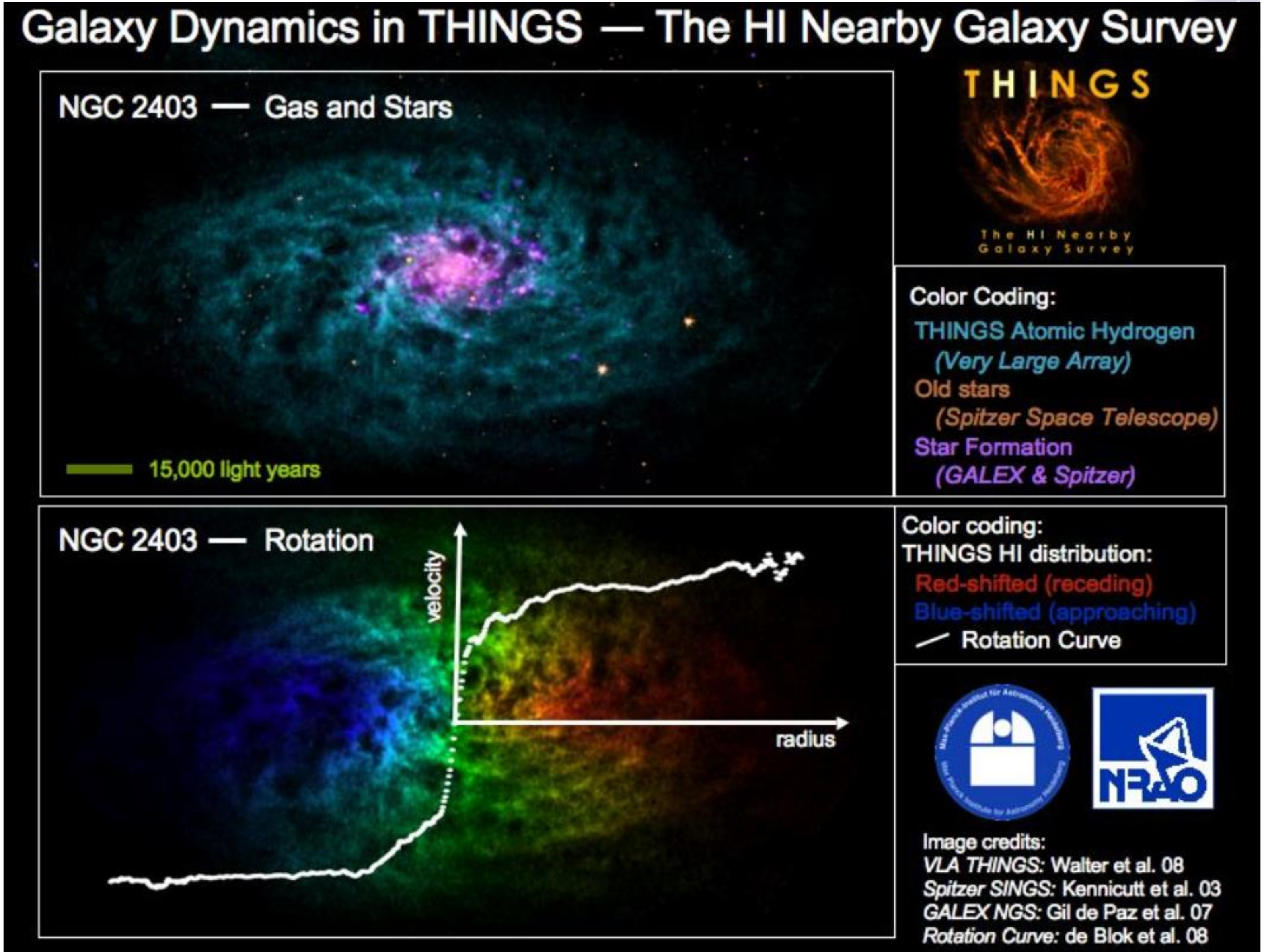
Radio Images

Neutral hydrogen (HI) emission

HI can be used to study the dynamics and gas flow within galaxies

THINGS VLA combined B+C+D-array mapping of HI emission from several thousand nearby galaxies

Walter et al. 2008



Radio Images Neutral hydrogen (HI) in distant galaxies

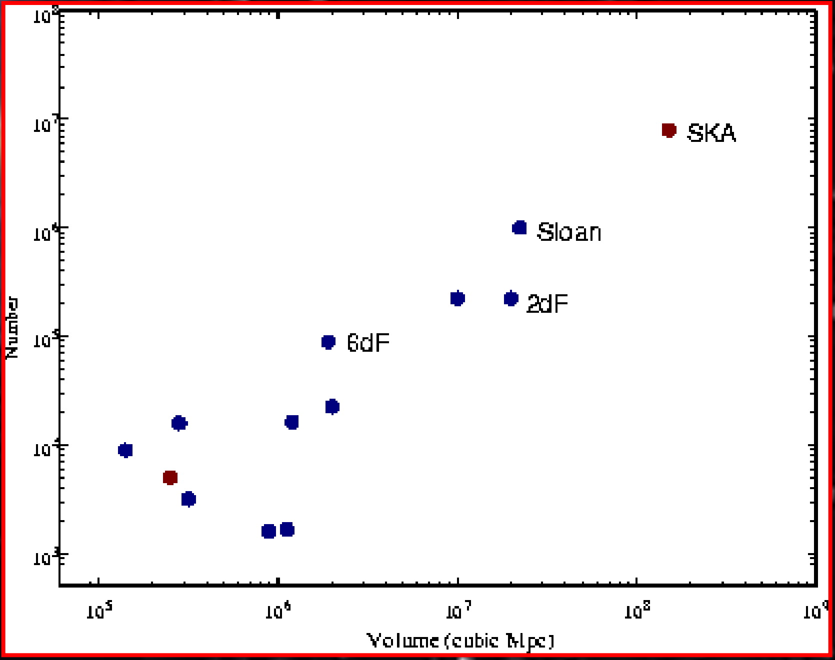
HI in emission is very low surface brightness
→ high-resolution imaging of even nearby galaxies problematical.

Line emission sensitivity does not benefit from wide-band interferometer upgrades – requires better receivers and/or more collecting area

The SKA will transform this field:

SKA will detect HI in >5 million galaxies at a median redshift of 0.1 and increase the sizes and sampled volumes of galaxy surveys by more than an order of magnitude

Before the SKA, we can study distant neutral Hydrogen in absorption against bright continuum background radio sources



Radio Images

Neutral hydrogen (HI) in absorption

→ probe small scale structure

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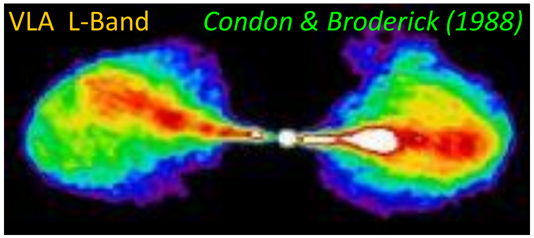
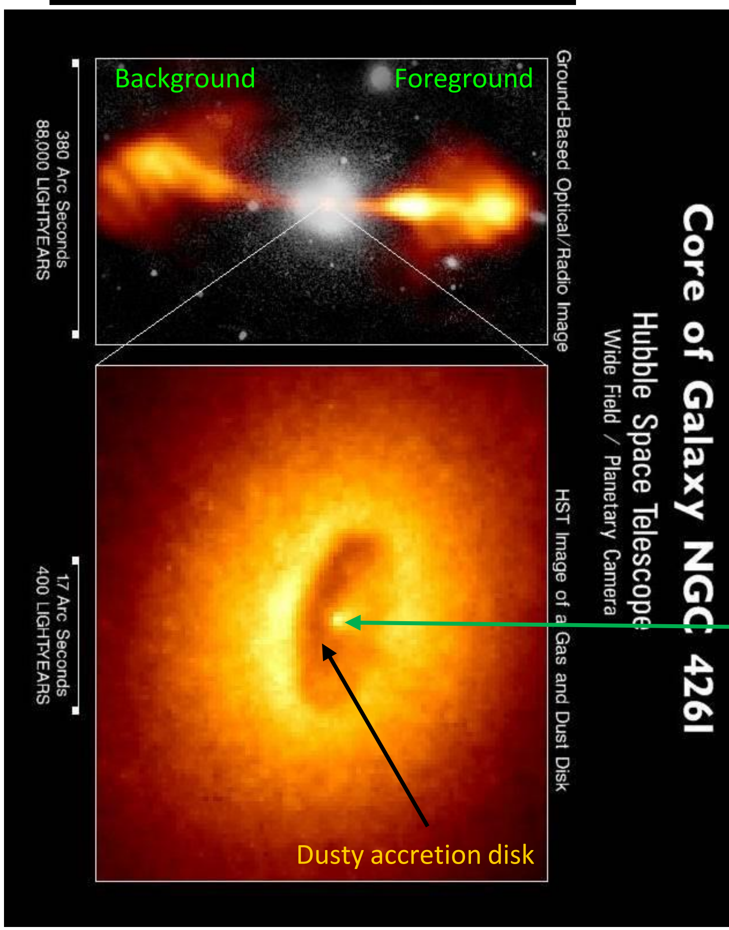
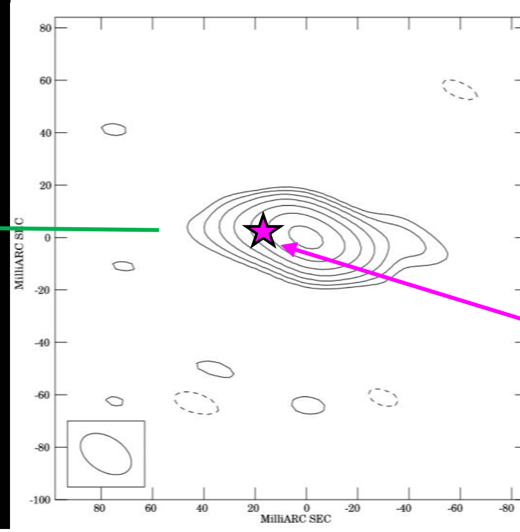


NGC 4261 (3C270) – FR-I type radio galaxy, z=0.00737

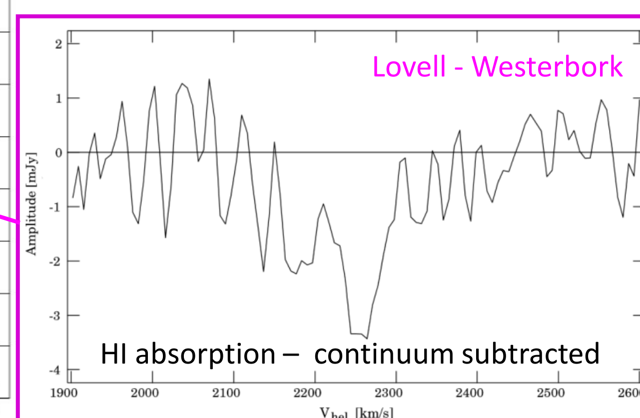
Sensitive EVN L-Band observations of the compact core detect HI in absorption on the most sensitive spacing (Lovell-Westerbork) 18mas East of the peak of core emission at the counter-jet side.

HI absorption from thin atomic circum-nuclear disk – a continuation of dusty accretion disk seen by HST





van Langevelde, Pihlstròm, Jaffe, & Schilizzi (2000)



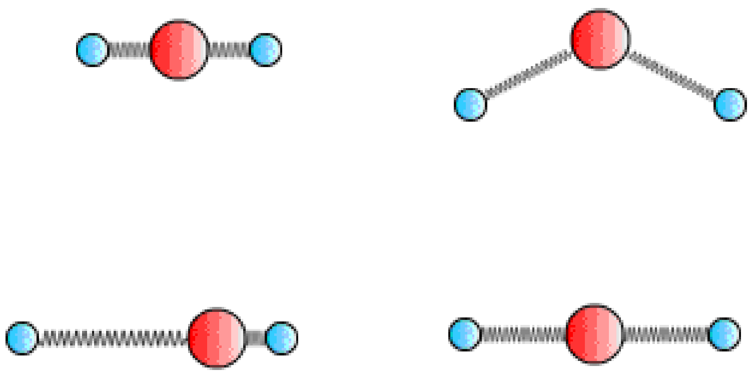
Radio Images

Line emission

Molecular, vibrational & rotational modes

Commonly observed molecules in space:

- Carbon Monoxide (CO)
- Water (H_2O), OH, HCN, HCO^+, CS
- Ammonia (NH_3), Formaldehyde (H_2CO)



Less common molecules:

- Sugar, Alcohol, Antifreeze (Ethylene Glycol), …

Many such lines are visible in the mm and sub-mm region of the spectrum
→ Imaging by ALMA

Radio Images

Molecular line emission

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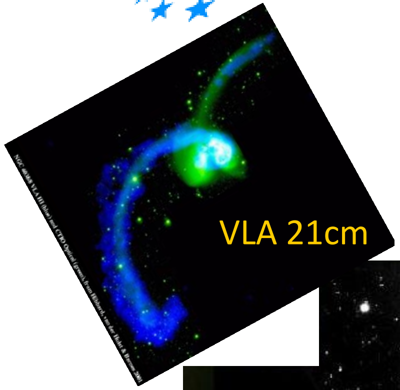
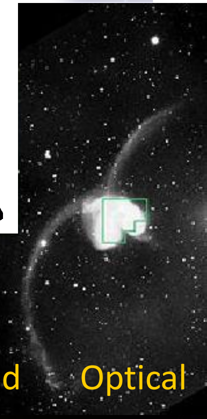
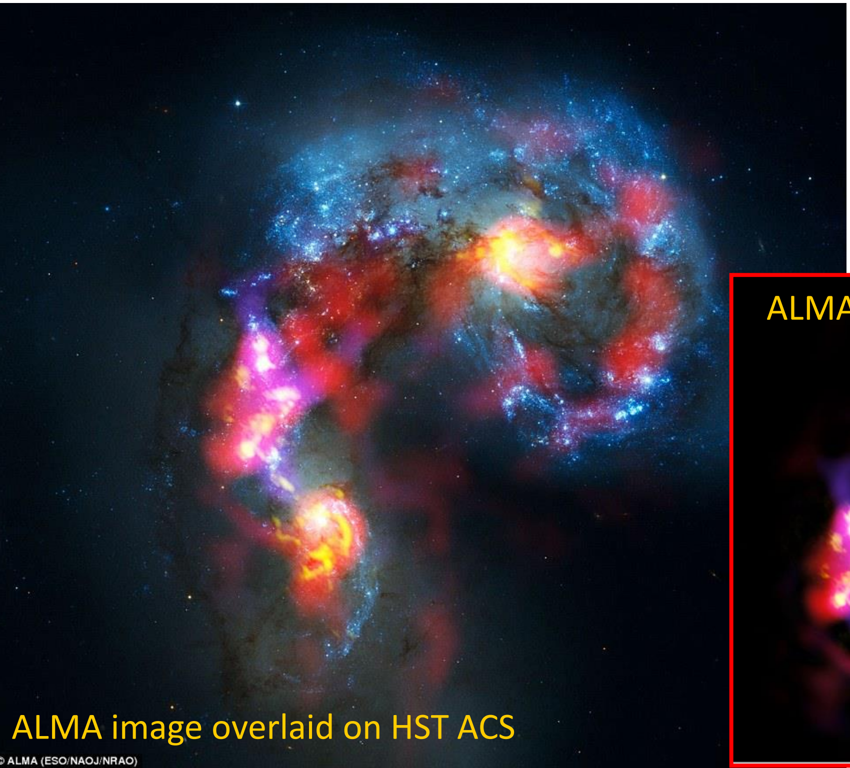
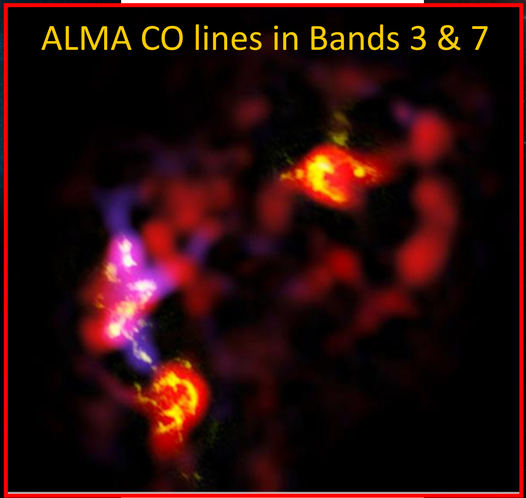
ALMA images of molecular line emission from CO – tracing areas of intense star-formation – Bands 3 & 7 showing CO(1-0) 115GHz [3] & (3-2) 230GHz [7]

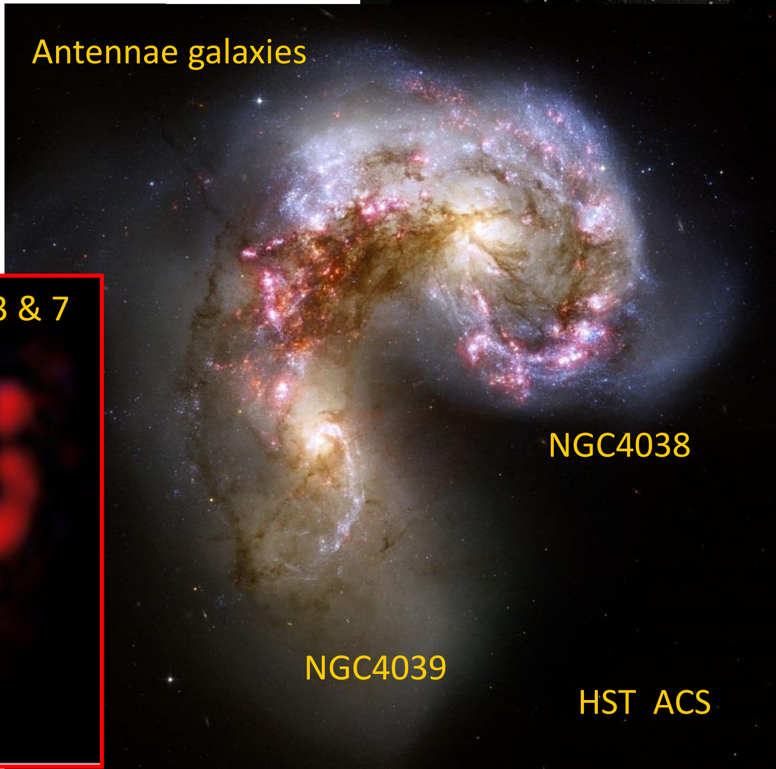
Early science verification data from only 12 antennas











Radio Images

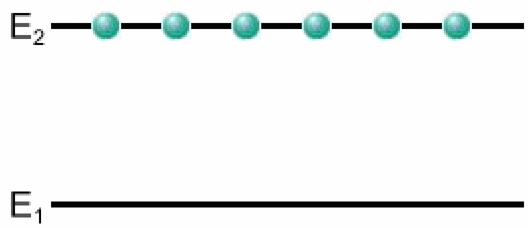
Maser mission

ASTRON Interferometric Radio Science

RadioNet

Needs population inversion & low column turbulence

- traces the dynamics of molecular material



Several maser species found associated with young stars (methanol, water masers). OH and SiO masers found associated with late stages of stellar evolution

Several excitation methods

Most common:

IR excitation (radiative)

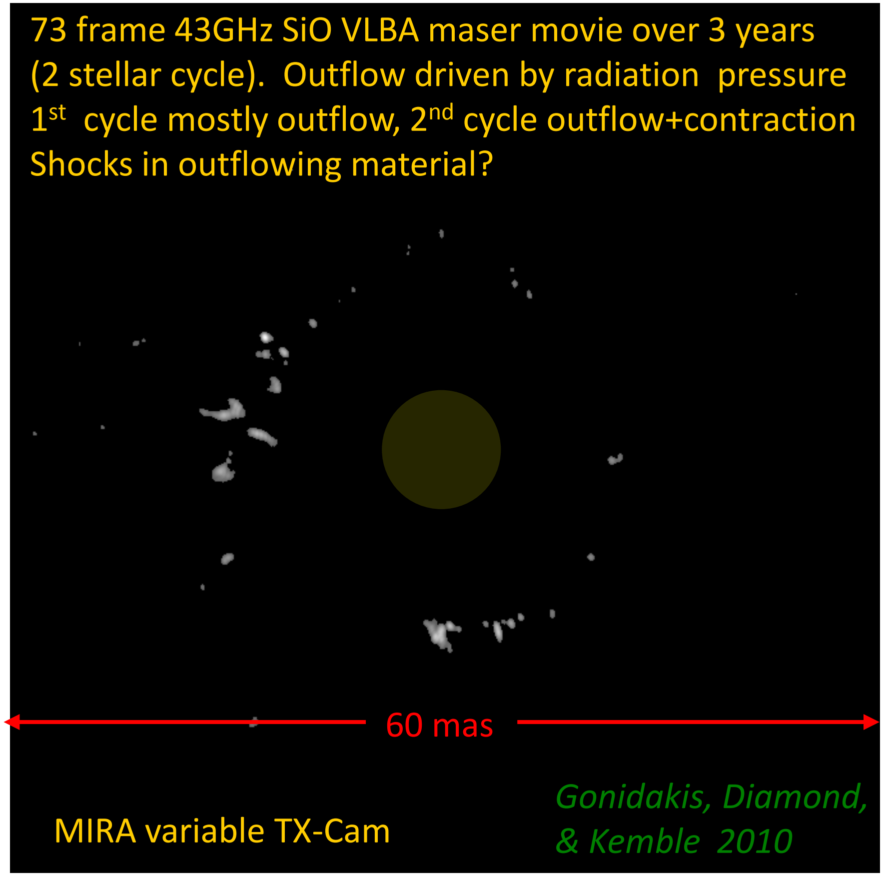
- Selective cascade transitions over-populate some low level energy states
- Common for OH masers

Also

Shocks (collisional)

- Selective decays pile-up in certain states
- H_2O masers mostly pumped by shocks

SiO 43GHz masers – could be either/both…



Radio Images

Maser emission – H_2O masers in NGC4258

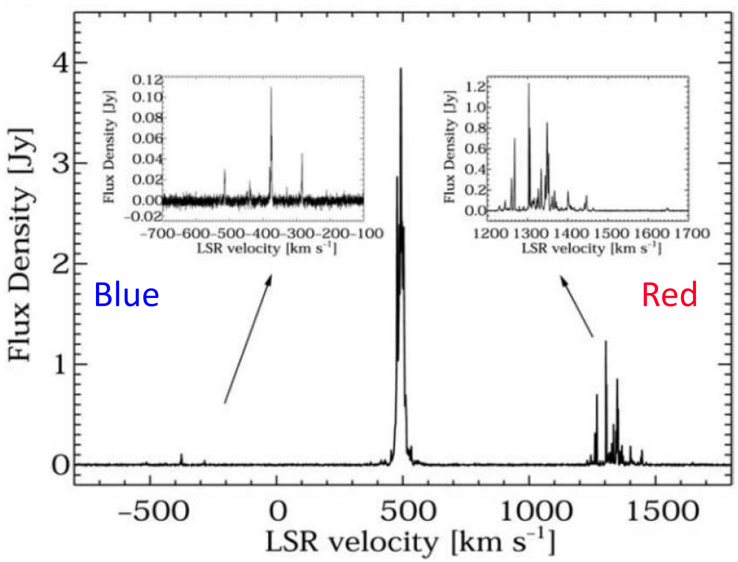
Masing from molecular material in circum-nuclear accretion disk

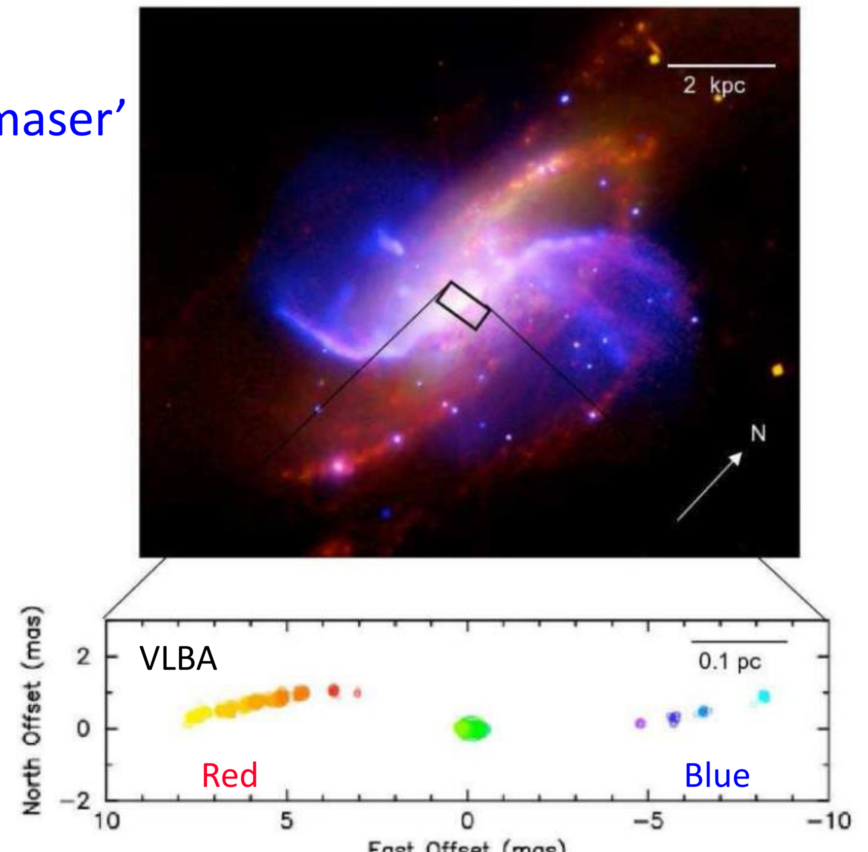
Argon et al. 2007

18 epoch 22GHz H_2O maser 3-yr VLBA study

Resolution 200μas, 1 km/s   3 groups of maser spots - systemic + red & blue lines

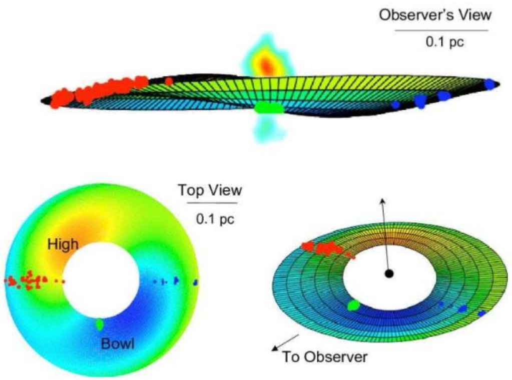
'Mega-maser'





Radio Images

Maser emission – H_2O masers in NGC4258

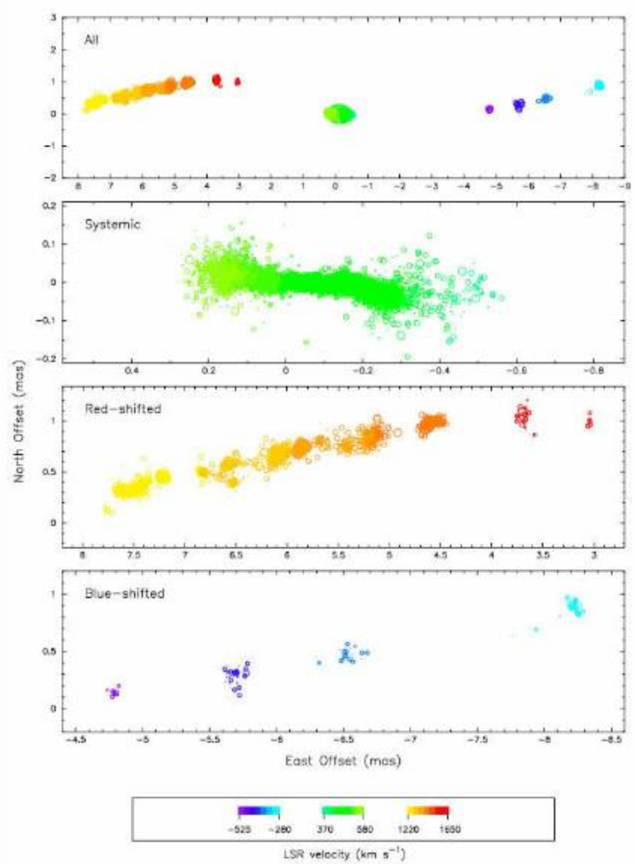


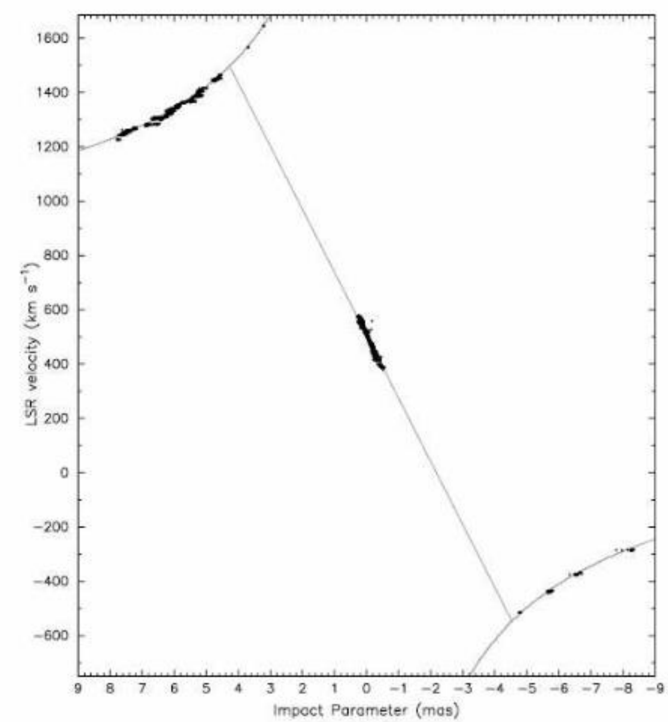
Argon et al. 2007

Warped Keplarian disk, diameter ~0.5pc (inner diameter ~0.13pc). Thin disk ~0.003pc Edge-on, i=83° → Black hole mass = $3.6x10^7 M_{\odot}$

Continuing programme to measure geometric distance from the geometry of the warped disk and measurements of acceleration or proper motion for masing spots (velocity drift has seen)

Plan to measure distance to better than 3% to calibrate distance ladder





Radio Images

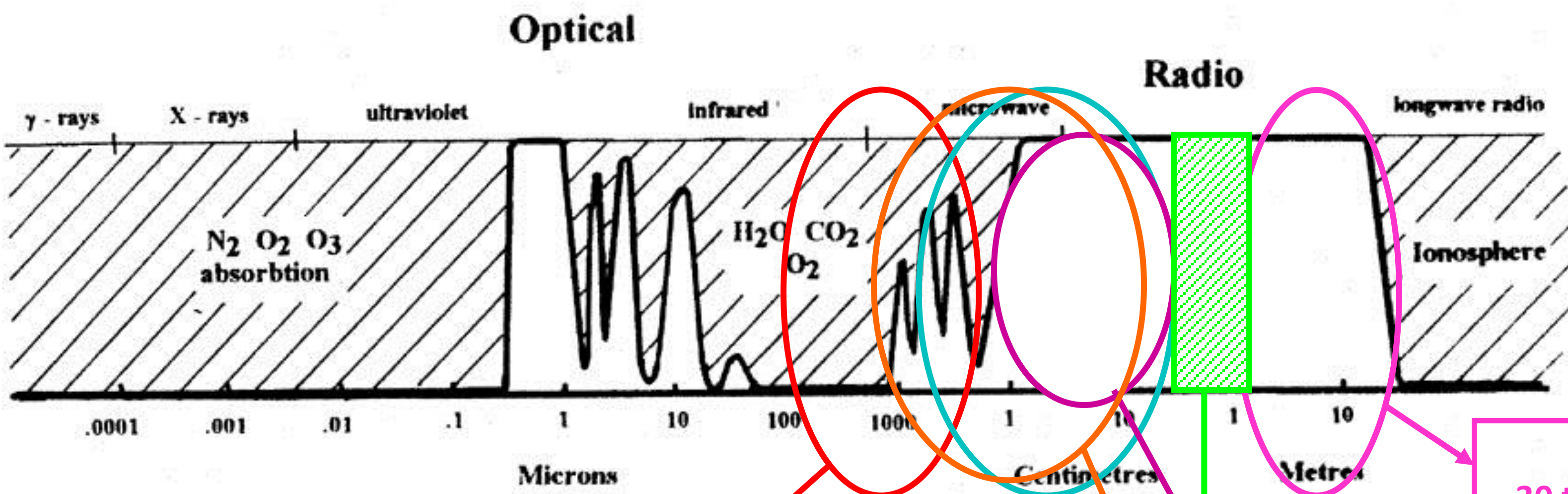
ASTRON Interferometric Radio Science

RadioNet

Present and future radio facilities

Wide fields, wide bandwidths, high sensitivity

New and upgraded observational facilities covering the whole radio window are now operational



The whole of the radio window is now available to you!!

ALMA
10 bands from 35 to 850 GHz

JVLA
Complete frequency coverage from 1 to 50 GHz

VLBI and *e*-MERLIN from 1.4 to 22 GHz

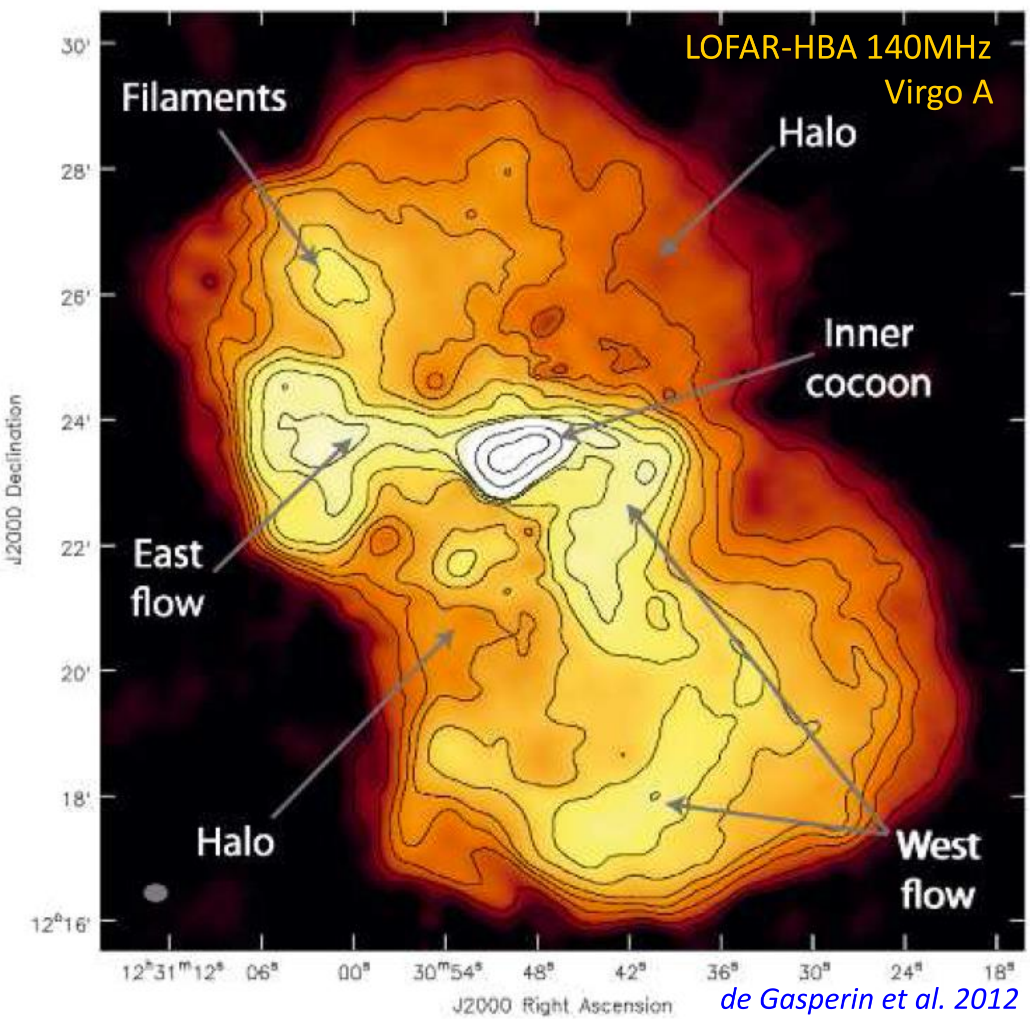
ATCA from 2 to 86 GHz

LOFAR
30 to 80 MHz
120 to 240 MHz

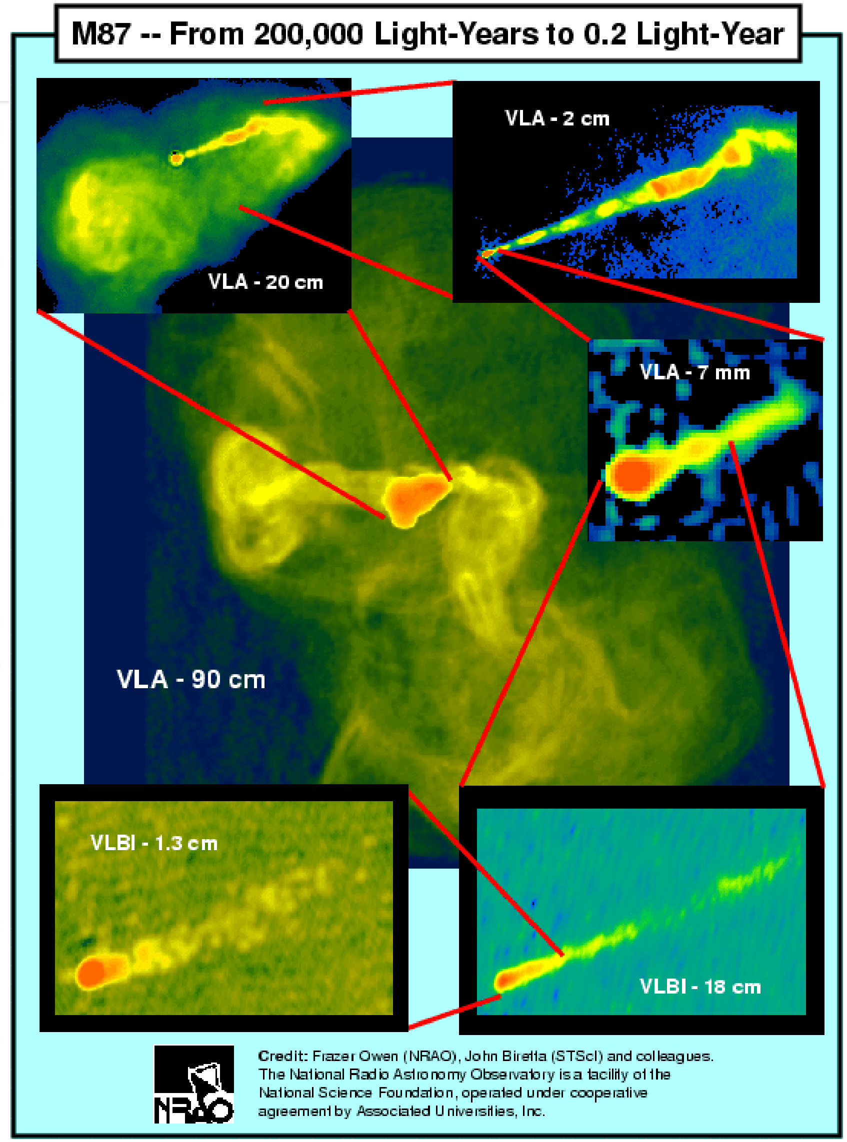
GMRT
240 MHZ to 1.4 GHz

Radio Images

Wide-band high fidelity imaging study of the M87 jet



de Gasperin et al. 2012

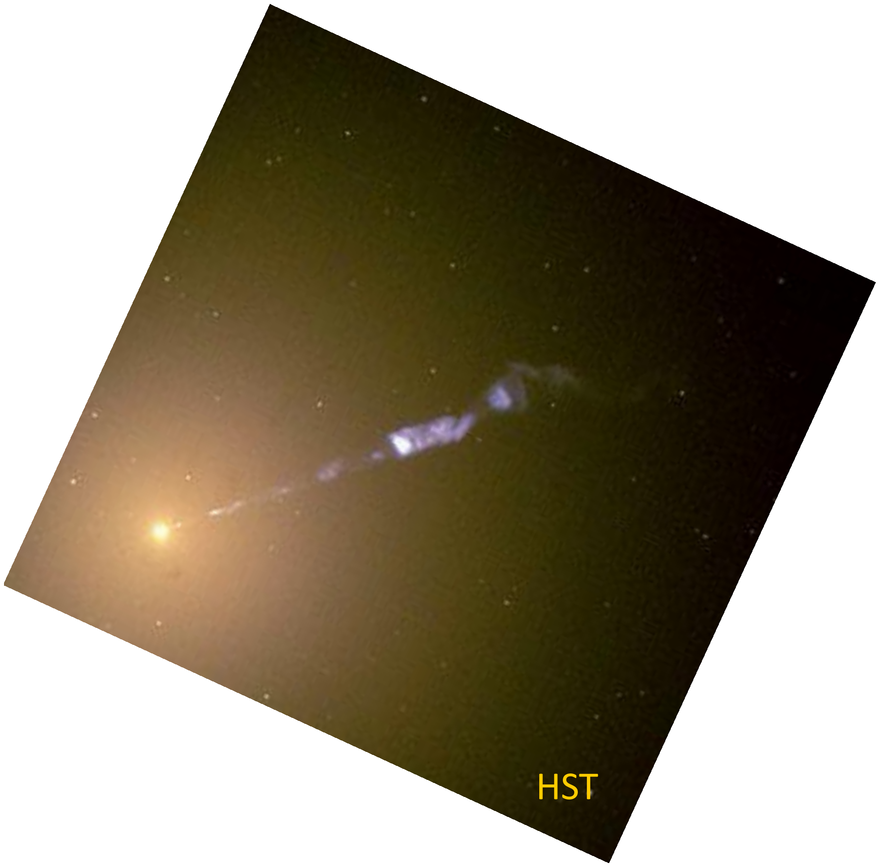


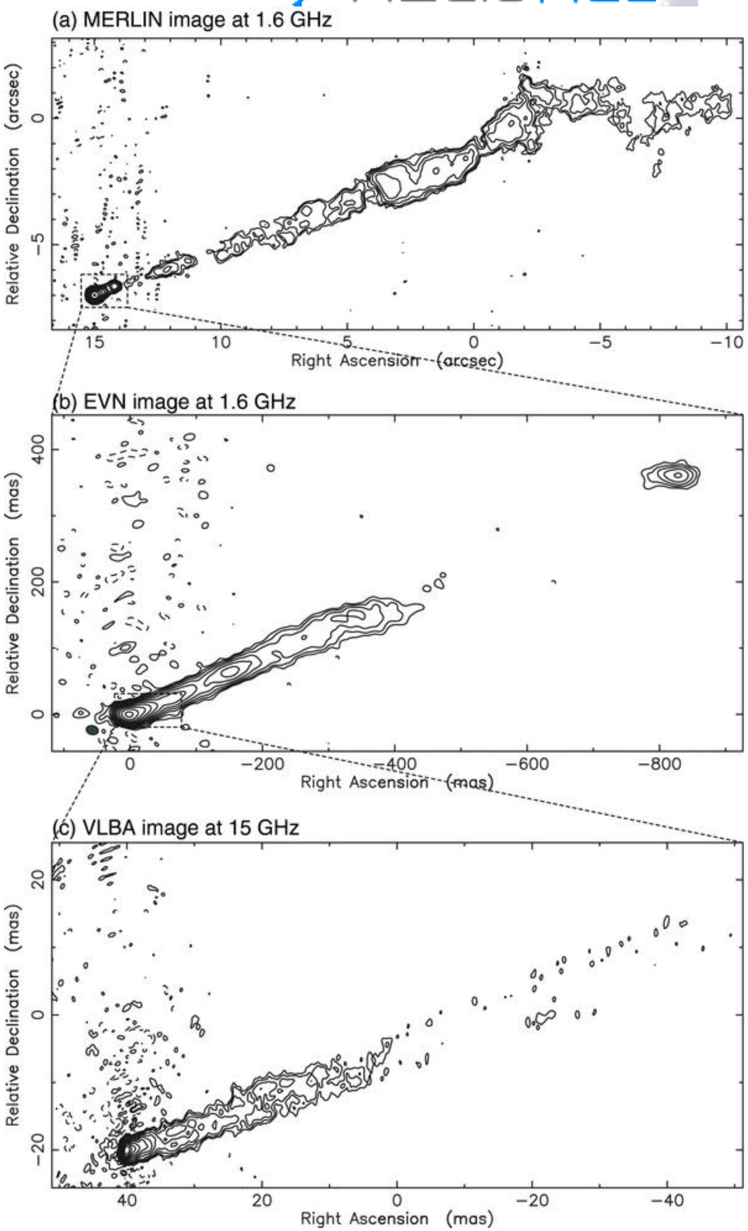
Radio Images

High resolution imaging of M87

- Merlin 1.6GHz data from March 2007
- EVN 1.6GHz data from March 2009
- VLBA 15GHz data from January 2000
- VLBA 43 GHz data from January 2007

→ approaching the region of jet collimation?





Radio Images

High resolution imaging of M87

ASTRON Interferometric Radio Science RadioNet

Merlin 1.6GHz data from March 2007

EVN 1.6GHz data from March 2009

VLBA 15GHz data from January 2000

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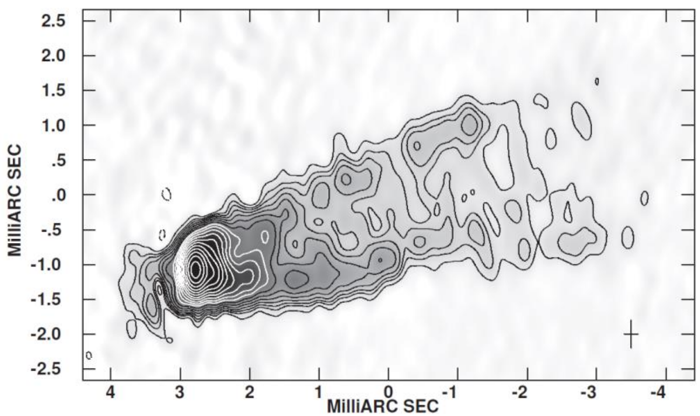
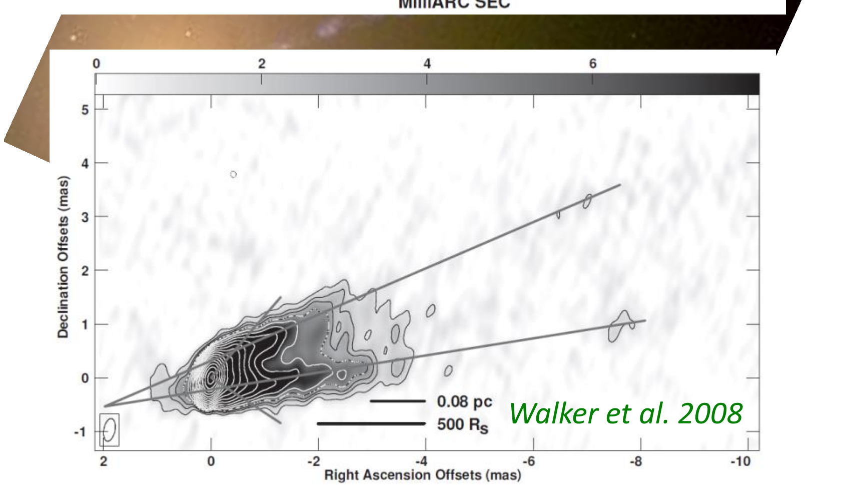
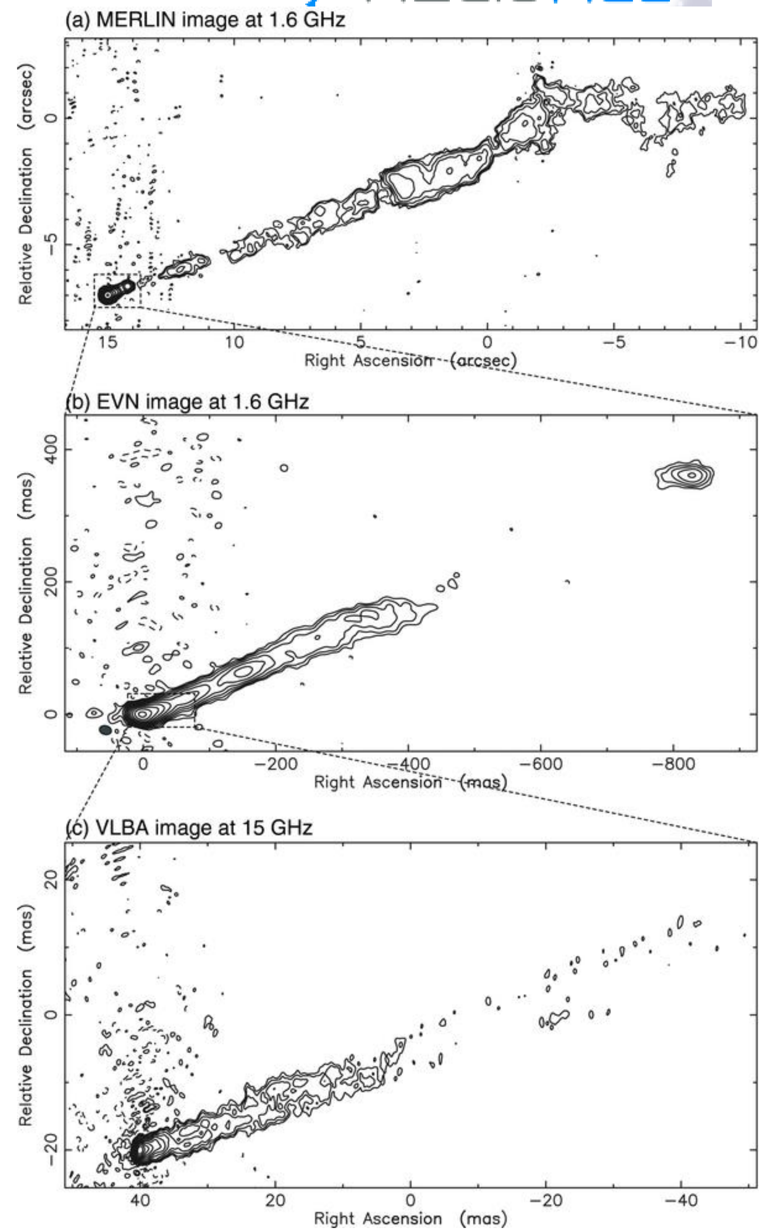






Radio Images

High resolution imaging of M87

ASTRON *Interferometric Radio Science*

RadioNet

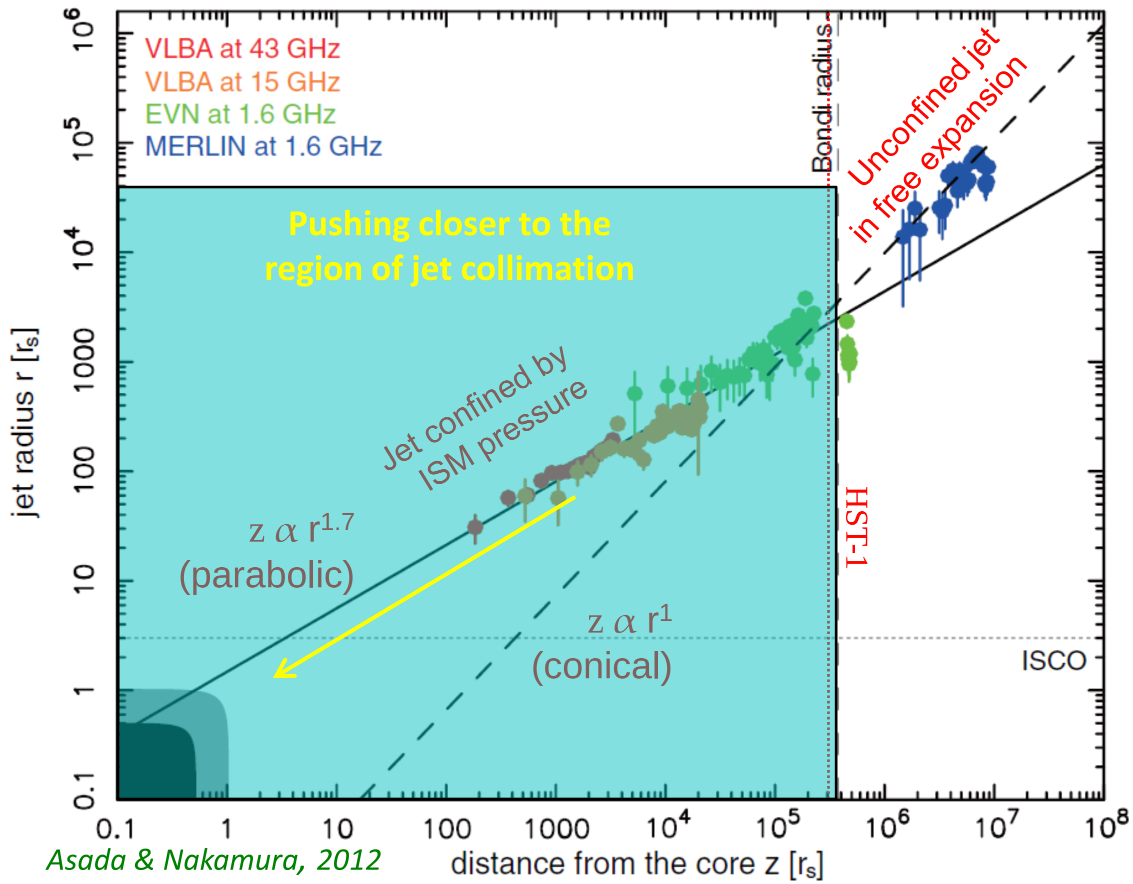
Gaussian fits to get jet widths

HST-1 lies near Bondi radius → accreting gas goes supersonic

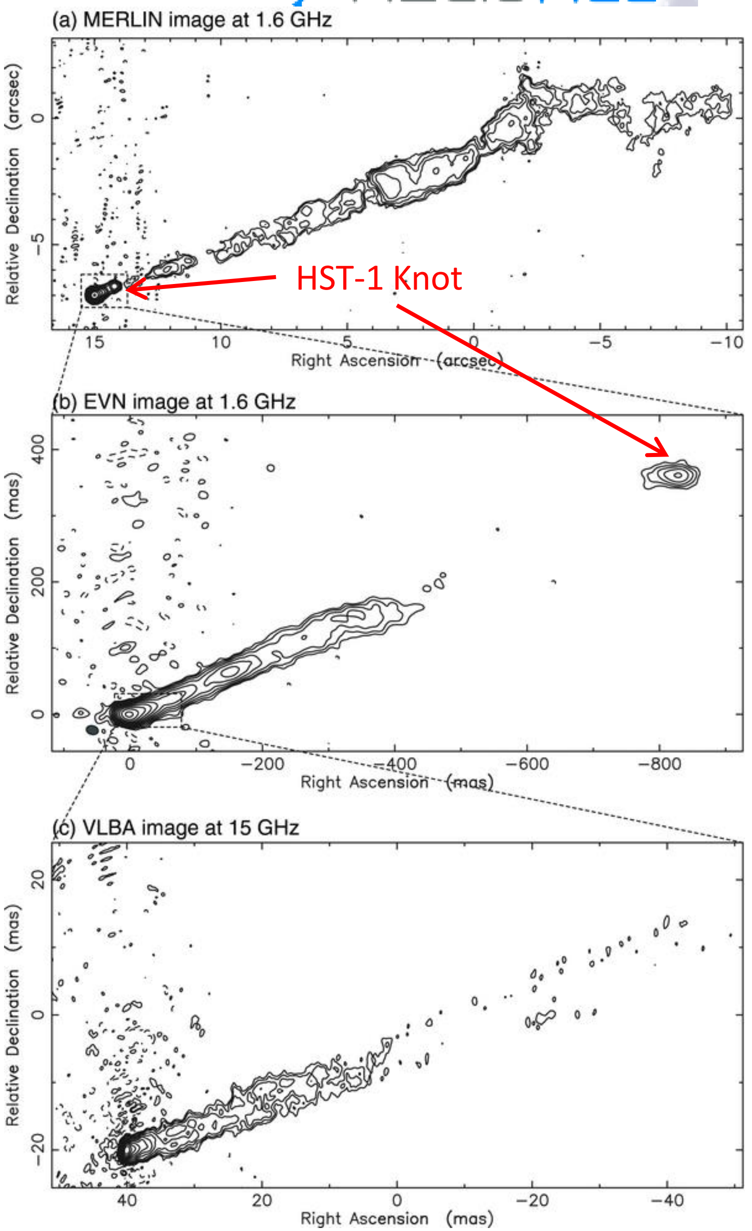
Upstream of HST-1 streamlines parabolic, downstream conical

Change in ISM pressure profile → re-collimation shock

HST-1 knot is a stationary feature



Asada & Nakamura, 2012

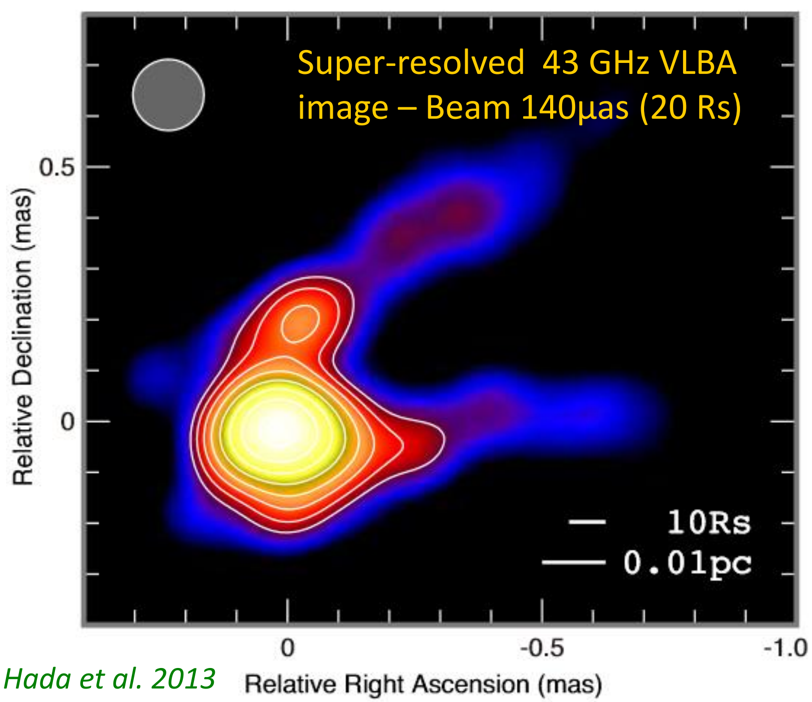


Radio Images Ultra-high resolution imaging of M87

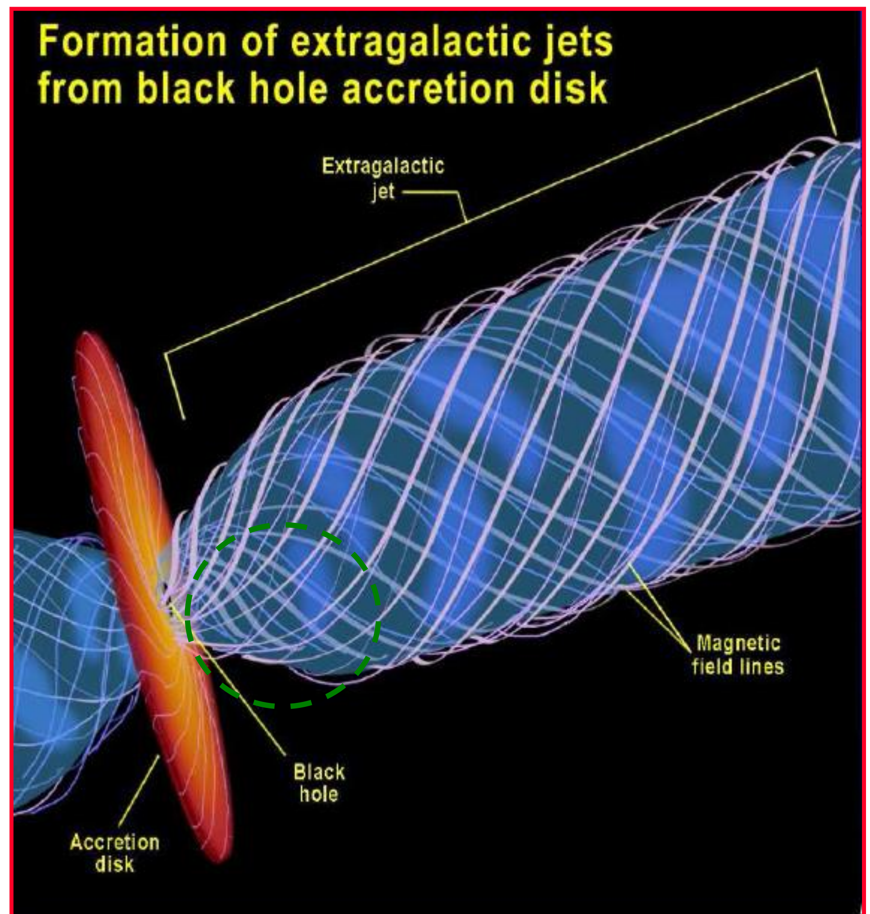
Jet collimation region within ~35 Rs de-projected distance along jet

Confirmed by 86 GHz VLBA

and 230 GHz mm VLBI imaging



Hada et al. 2013



ASTRON *Interferometric Radio Science*

RadioNet

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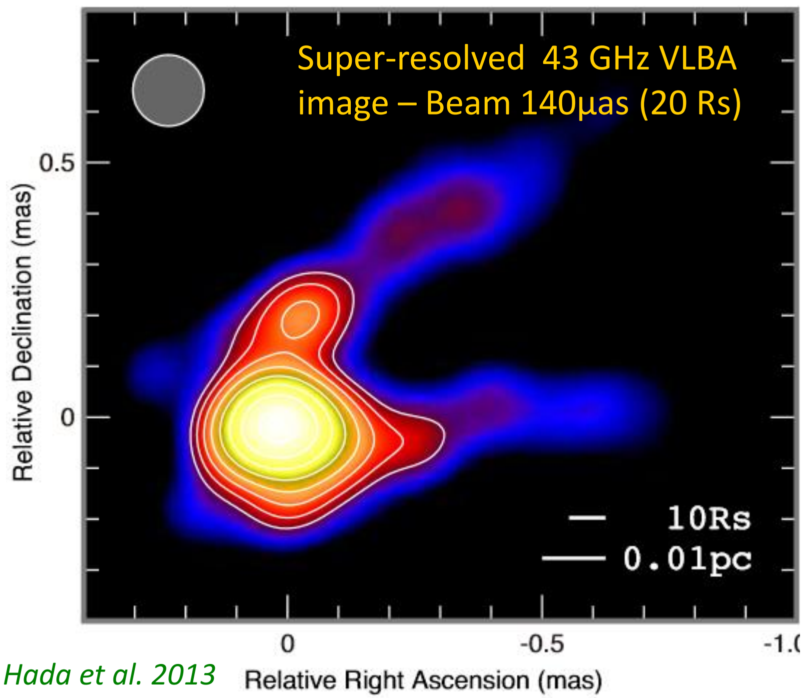
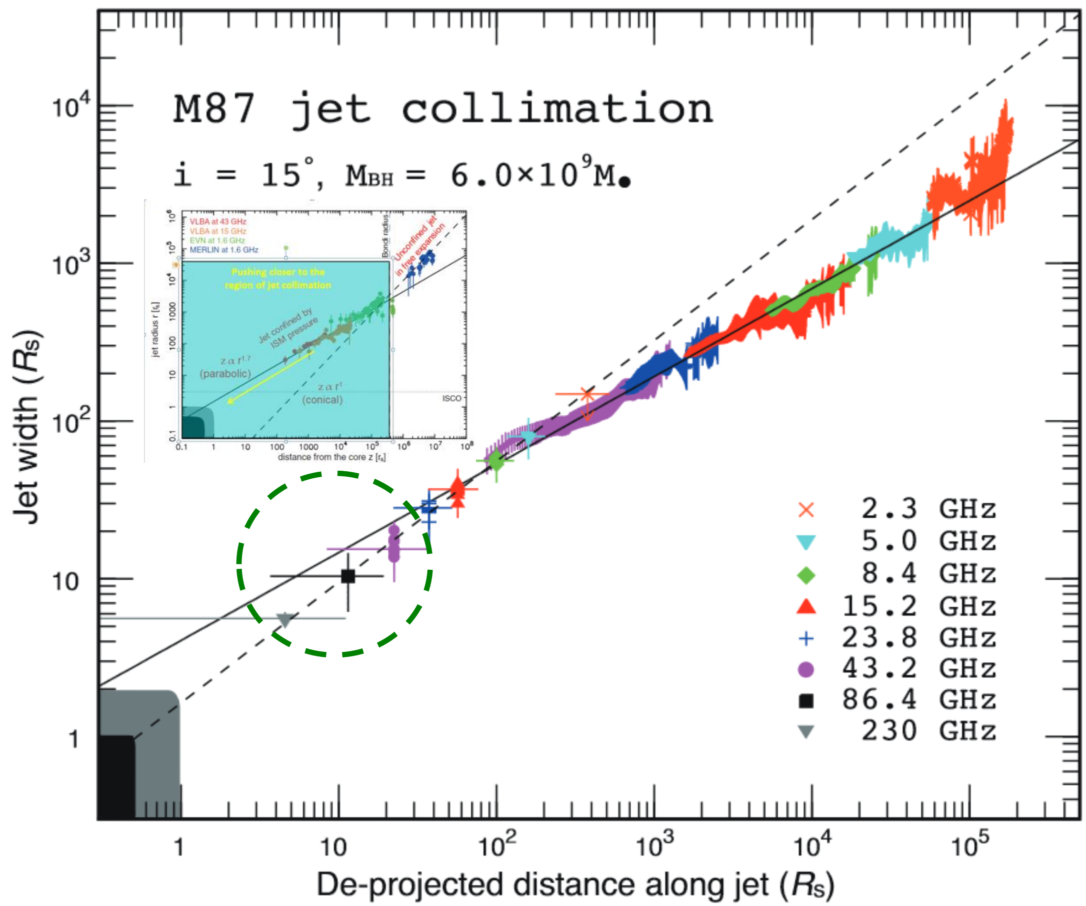


Hada et al. 2013



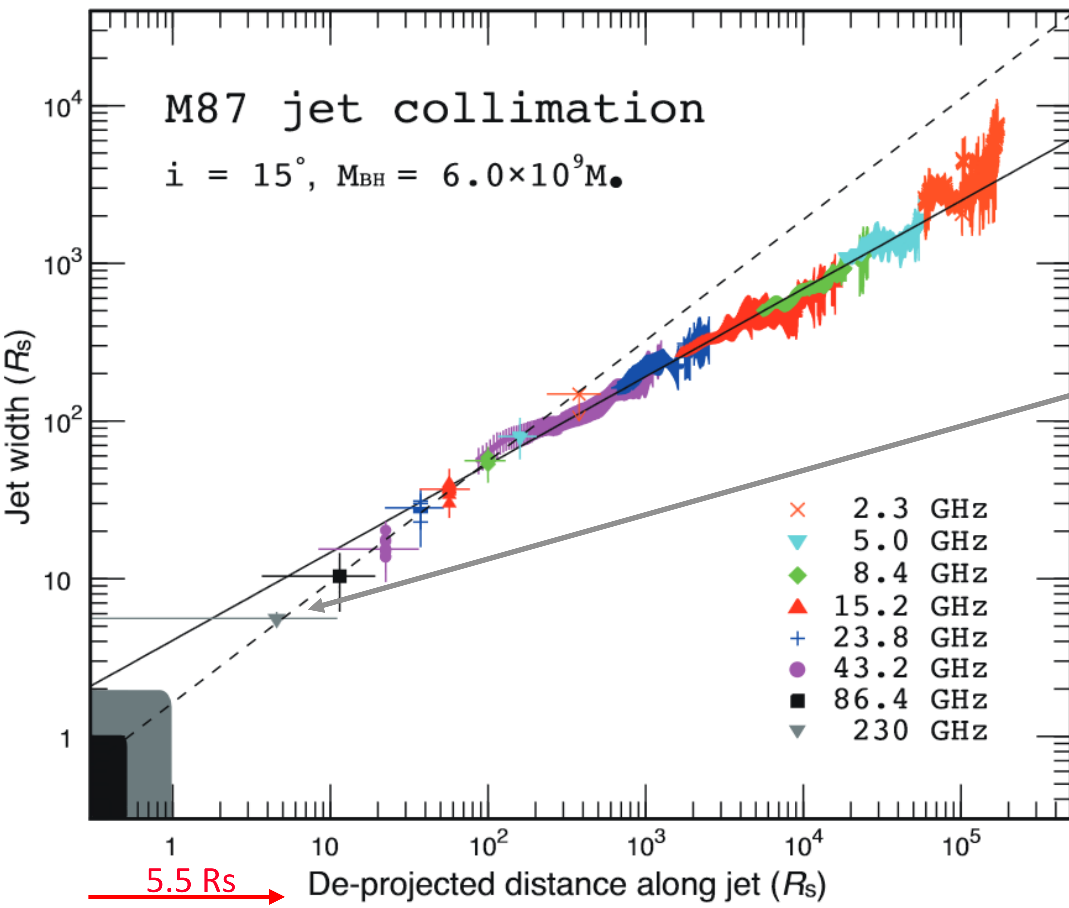
Radio Images Ultra-high resolution imaging of M87

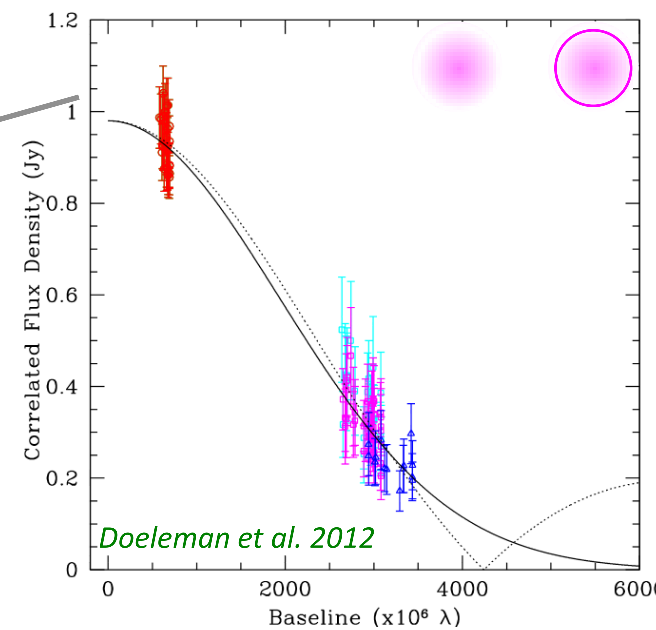
CARMA 10.4 m Cedar Flat, California
HHSMT 10m Mount Graham, Arizona
JCMT 15m Mauna Kea, Hawaii
CARMA-SMT
CARMA-JCMT
SMT-JCMT

Highest angular resolution study of M87 ever attempted (3.5B λ at 1.3mm)

Fits to Amplitude
(No phase - only closure-phase)

→ 40μas FWHM Gaussian (solid) &
→ 40μas Gaussian + thin ring (dashed)





Radio Images

Event horizon telescope

ASTRON Interferometric Radio Science RadioNet

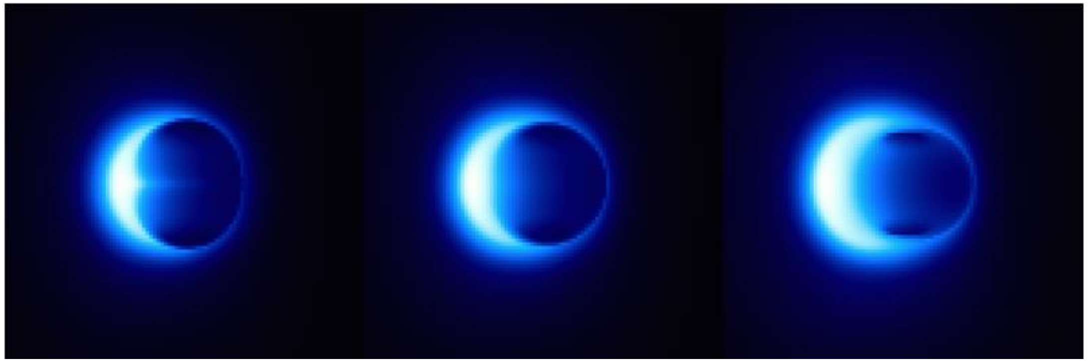
Global sub-mm VLBI studies of nearby AGN systems (Sgr A* & M87)

Several mm-telescopes combined across the Earth

ALMA array to be phased-up for extreme sensitivity imaging

M87 Rs = 7μas – with should be able to image shadow of BH against background counter-jet with 15μas resolution

Baseline	Resolution at 230 GHz	Resolution at 345 GHz
CARMA - SMT	300 μas	200 μas
Hawaii - SMT	58 μas	39 μas
Hawaii - ALMA	28 μas	19 μas
Plateau de Bure - South Pole	23 μas	15 μas



GR predicts that the shadow of a black hole should be circular (middle), but a black hole that violates the no-hair theorem could have a prolate (left) or oblate (right) shadow.

Future EHT images of nearby supermassive black holes will be able to test this prediction

Radio Images

Event horizon telescope

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Global sub-mm VLBI studies of nearby AGN systems (Sgr A* & M87)

Several mm-telescopes combined across the Earth

No hair conjecture: Black holes can be completely characterized by only three externally observable classical parameters – mass, electric charge, and angular momentum.

image shadow of BH against background counter-jet with 15µas resolution

[illegible]	[illegible]	[illegible] 5 GHz
[illegible]	[illegible]	[illegible]
Hawaii - SMT	[illegible]	[illegible]
Hawaii - ALMA	28 µas	19 µas
Plateau de Bure - South Pole	23 µas	15 µas

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Radio Images

Event horizon telescope

Interferometry provides the highest angular resolution available to astronomers together with mas or sub-mas astrometric positional accuracy

15µas resolution → a grape on the lunar surface when viewed from the Earth

Plateau de Bure - South Pole	23 µas	15 µas

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