A New Age in Radio Astronomy

Upgrades : From the aperture to the user

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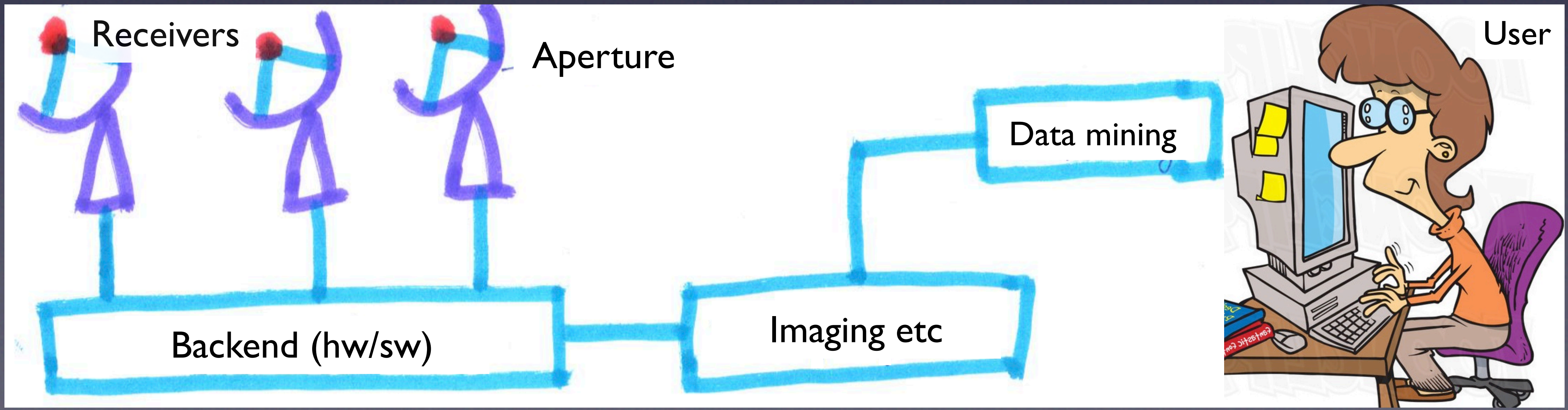
NCRA-TIFR, 2013

Outline

- Current scenario
- Telescope aperture
- Telescope receivers
- Telescope backend
- Data processing
- Data usage

Caveat : No polarisation, pulsar processing or ME



Current scenario

Apertures

Single dishes : cant do too much better than now

Largest steerable : 100 m (with active surface)

Largest immoveable : 305 m (but will increase)

100-m Greenbank

305-m Arecibo

530X30 m Ooty

Current scenario

Apertures

Interferometers

Number of elements (<70) : cost and computation

Size of elements : cost and structural stability

Baselines : cost, networking, logistics (30-100 km + VLBA)

30 X 45m GMRT

27 X 25m

VLA

48 X 50m

eLOFAR

Current scenario

Backends and post-processing

Correlators and beam formers :

- Traditionally done in hardware (BWs < 50 MHz)
- Increasingly being done in software (BWs ~ 200 MHz)

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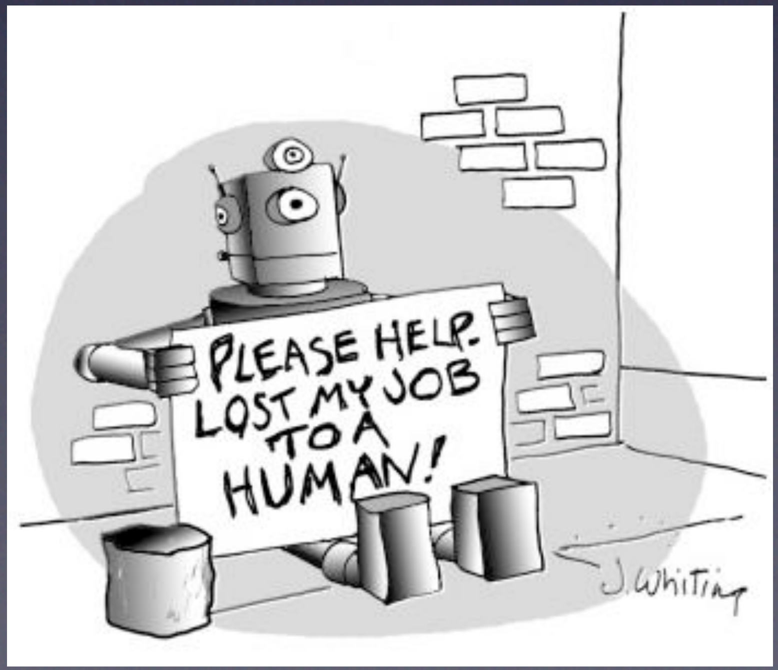
Calibration and imaging

- Done manually, pre-industrial revolution style
- Automated pipelines exist for pulsar searches

Post-processing

- Still done manually, except for new surveys (TGSS etc)



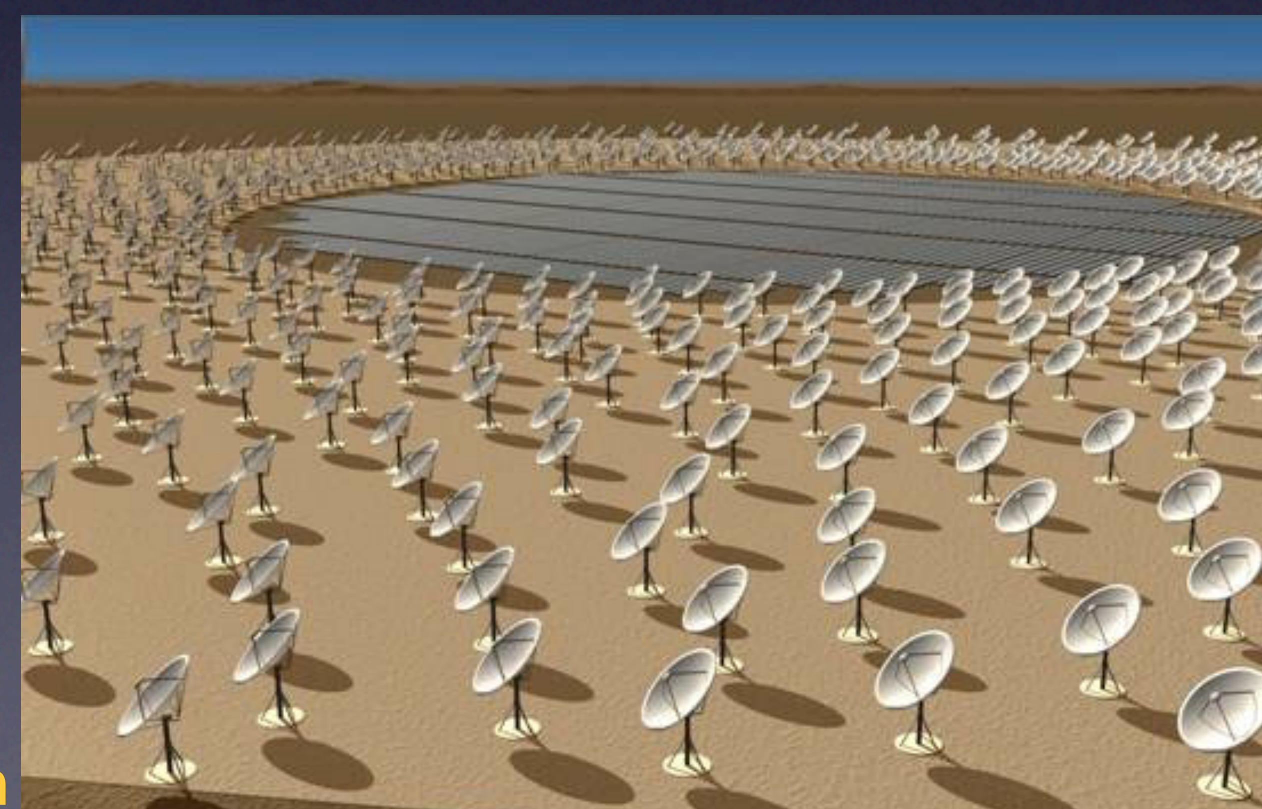
Square Kilometre Array - the future

The SKA will be built in 10 yrs time, based in South Africa and Australia

Will be the most powerful radio telescope, 30-50 more than any other !

The SKA will generate 50 PetaBytes of data every hour. This will require ~1 Peta Flop of computation

- Frequency : 70 MHz - 10 GHz
- FOV : 200 deg^2 (70 MHz) to 1 deg^2 (L)
- Survey speed > 10^5 times GMRT/VLA
- Baseline : 100 km + outer arms to 1000 km



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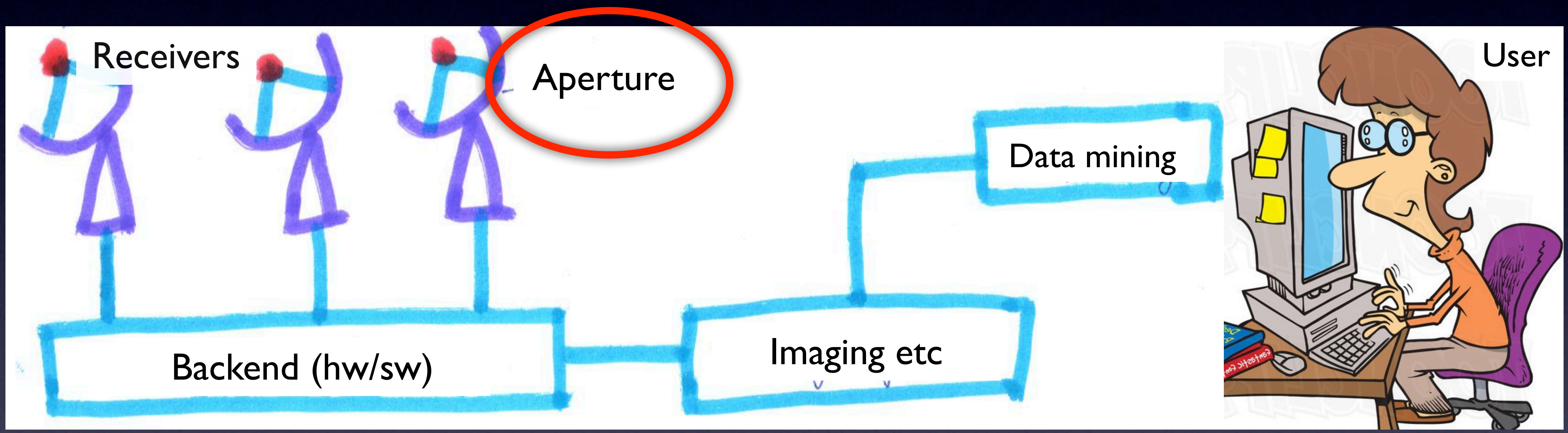
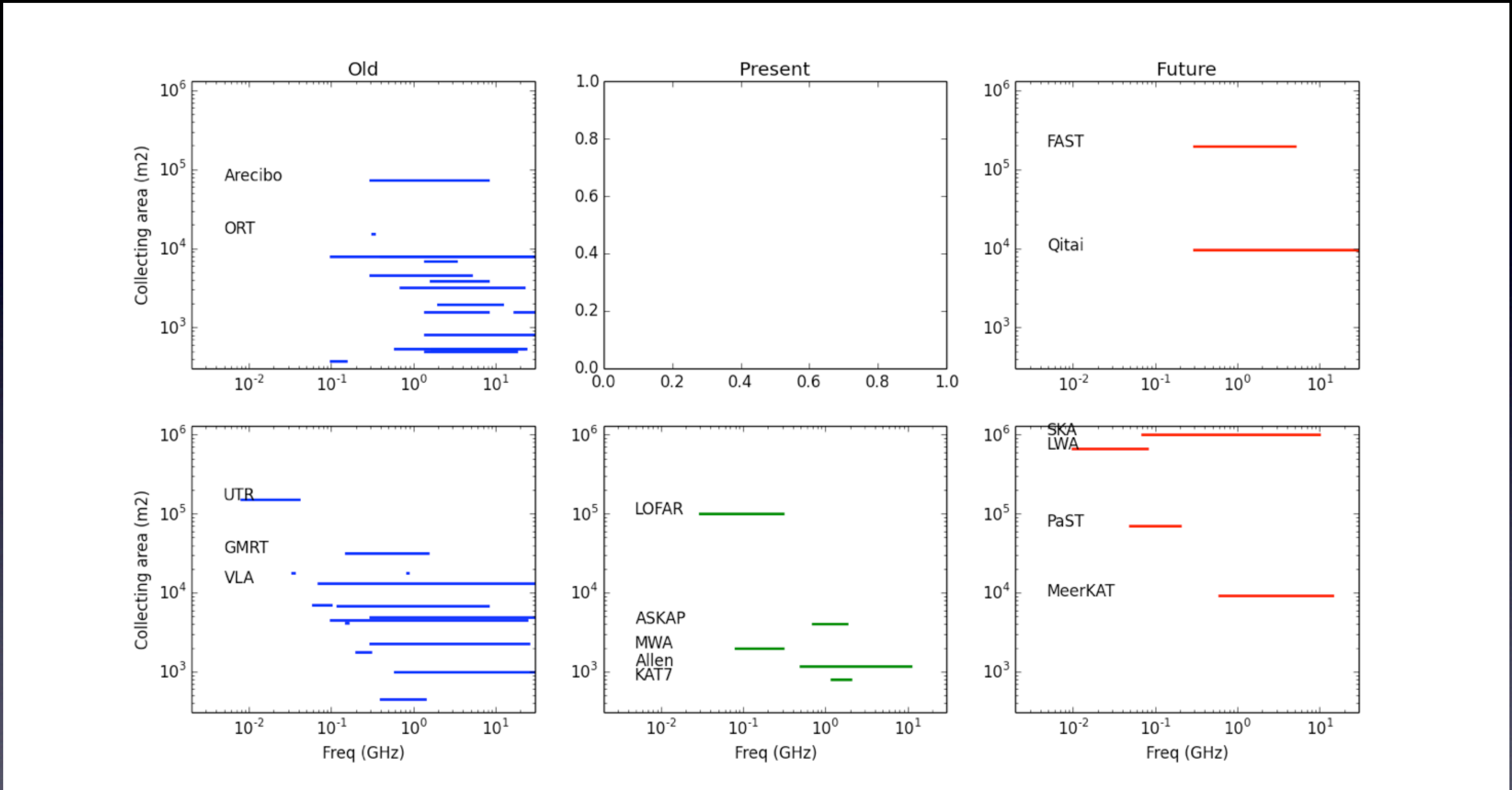


Increasing collecting area

Need to increase collecting area for sensitivity



Geometric area plotted vs frequency.

Top : single dishes; Bottom : interferometers

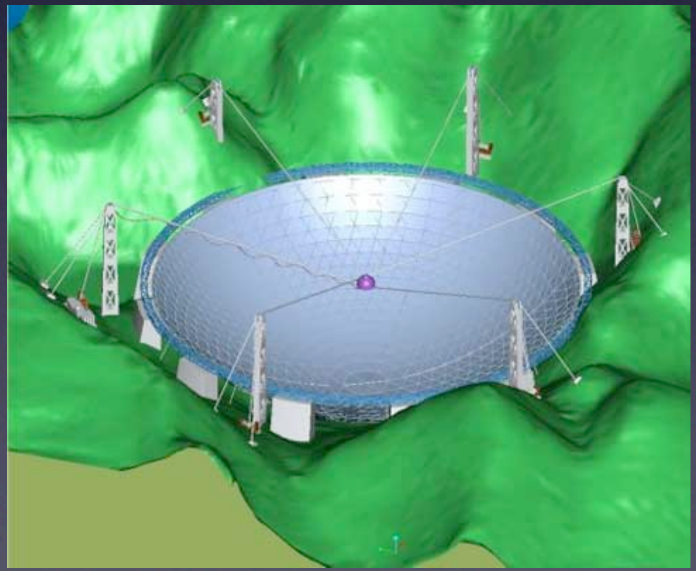
Caveat : this is not effective area, and hence not proportional to sensitivity

Increasing collecting area

Need to increase collecting area for sensitivity

Single dishes

- Use active surface (GBT)
- Don't steer the primary (Arecibo)
- Use natural contours (Arecibo)



FAST : 500-m, active surface, 0.3-5 GHz

Built in a Karst (natural bowl), in China

Zenith angle of 40 degrees, immoveable

Qitai Telecope

- 110-m, 0.3-117 GHz
- to be built in China
- active surface
- fully steerable

Increasing collecting area

Interferometers

- Need to compromise between number and size of elements
- Increasing use of small elements for larger FOV
  - Survey speed ~ FOV x sens^2
- Dishes for higher frequencies
  - Steerable - maintain sensitivity
  - Off-axis receivers (eg MeerKAT)
- Aperture Arrays for lower frequencies
  - not steerable
  - AAs have become the standard now

Off-axis MeerKAT dishes

Aperture Arrays

Aperture arrays are in fashion once again

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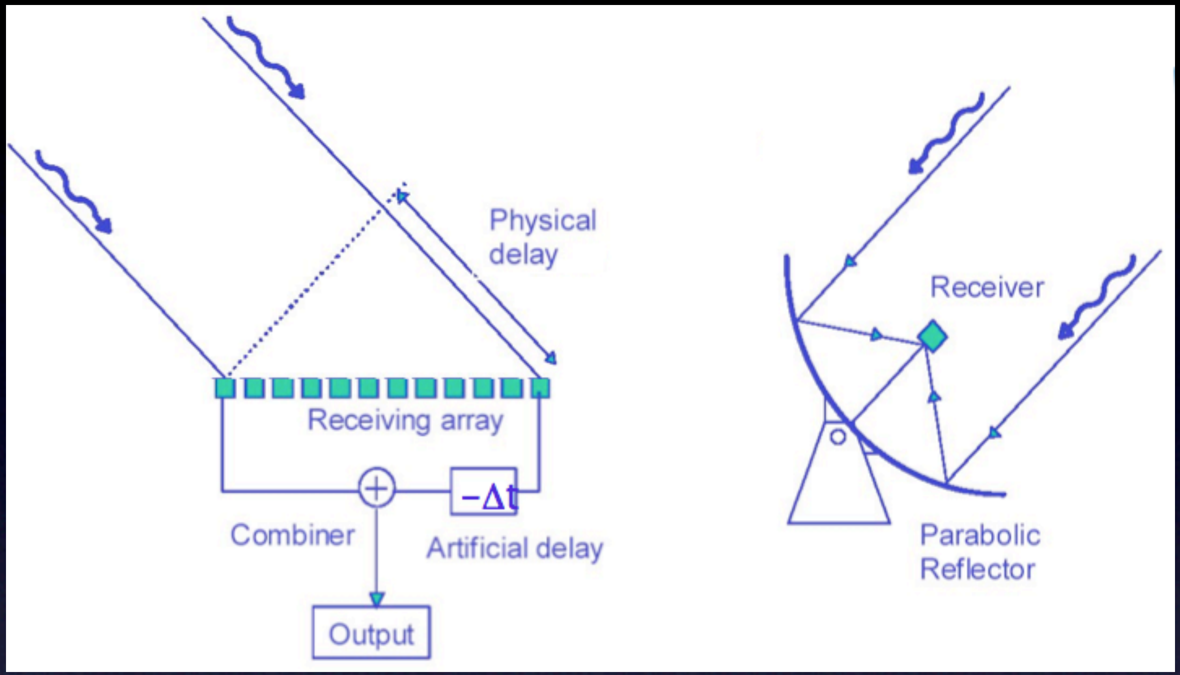

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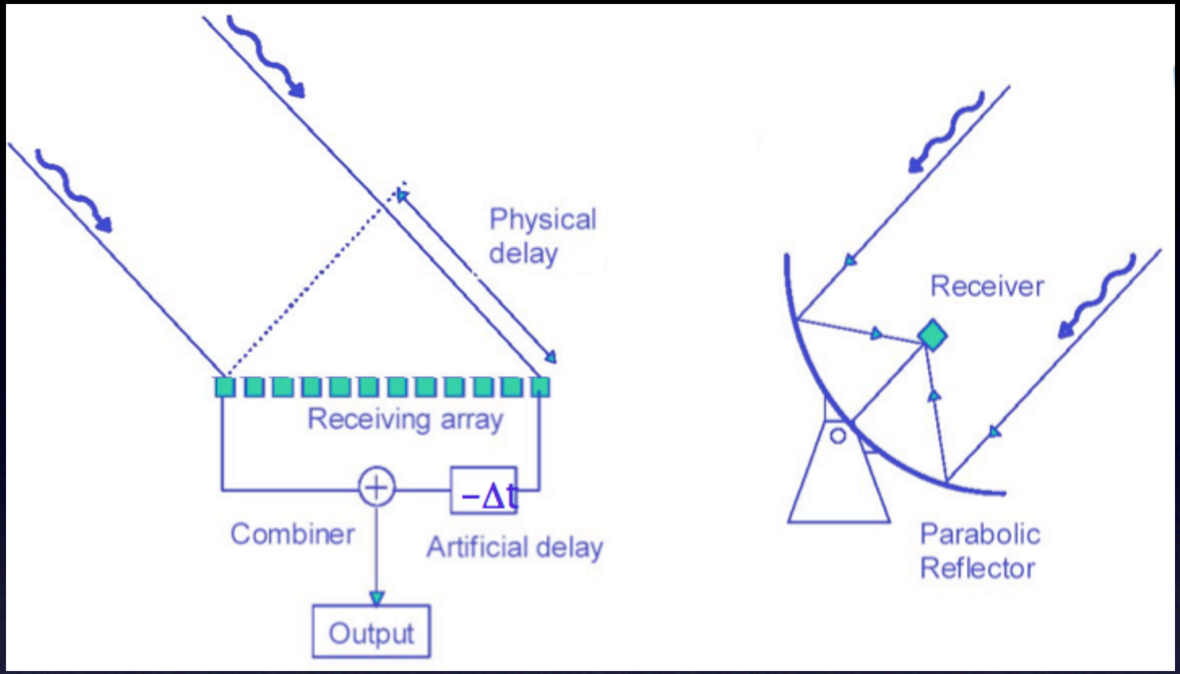
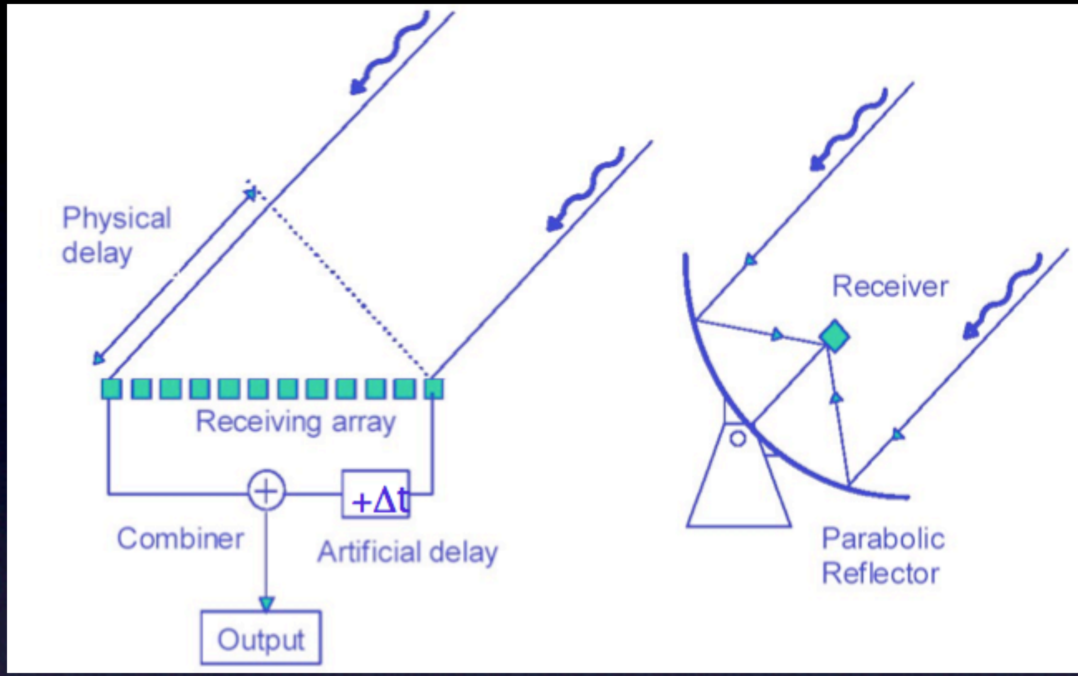
Aperture arrays are in fashion once again





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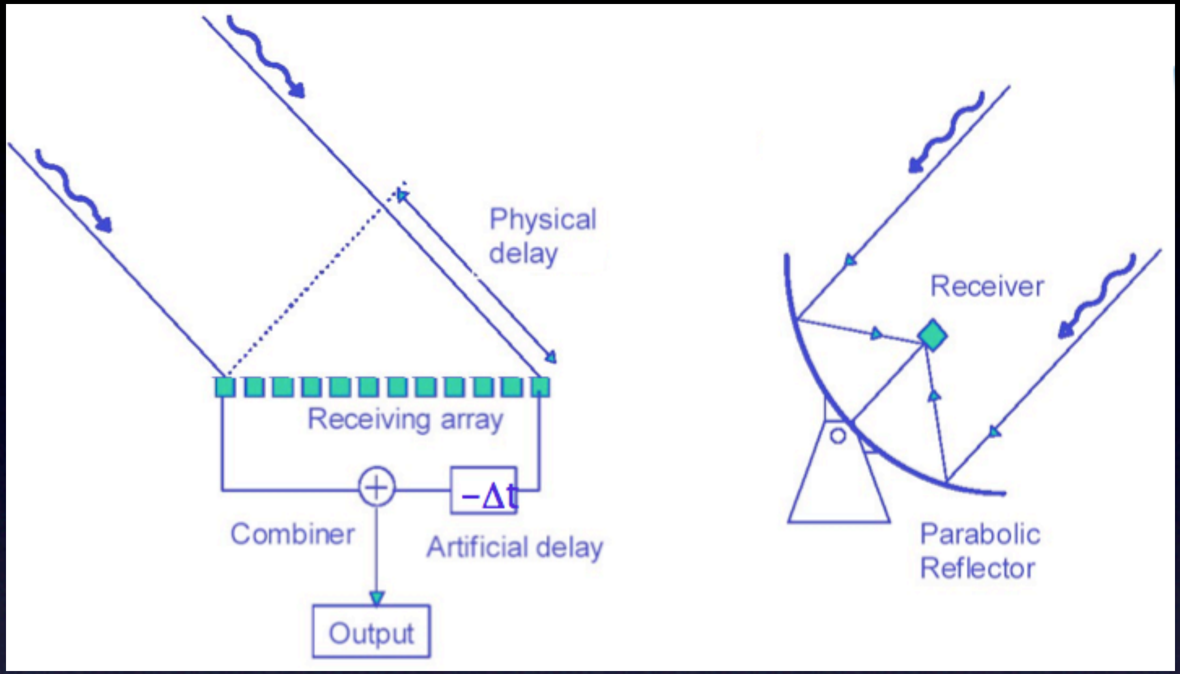

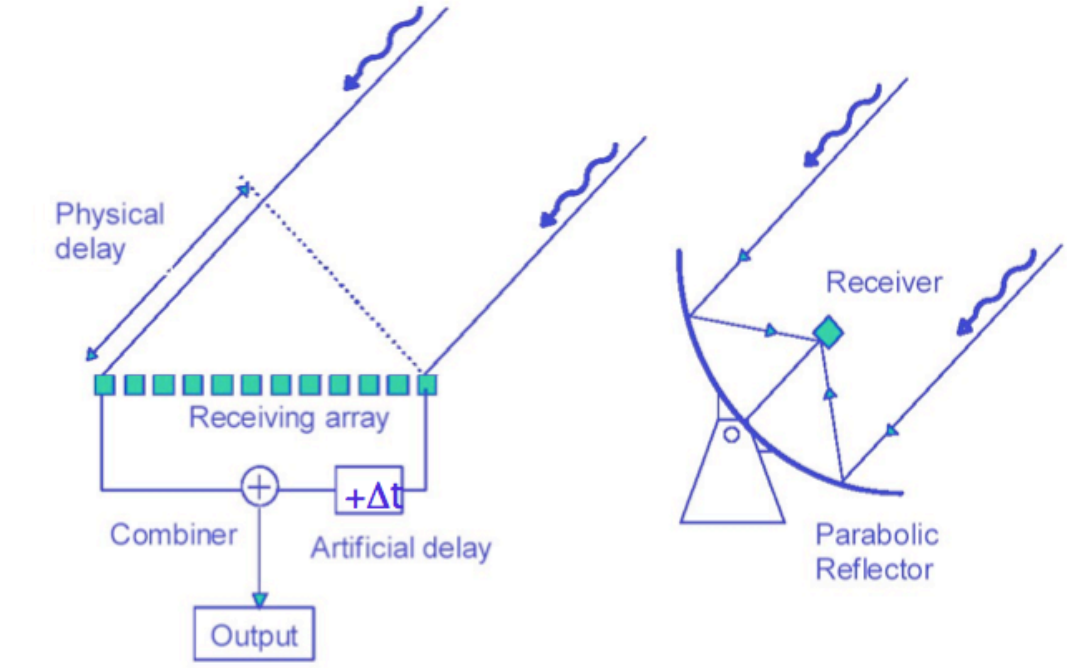

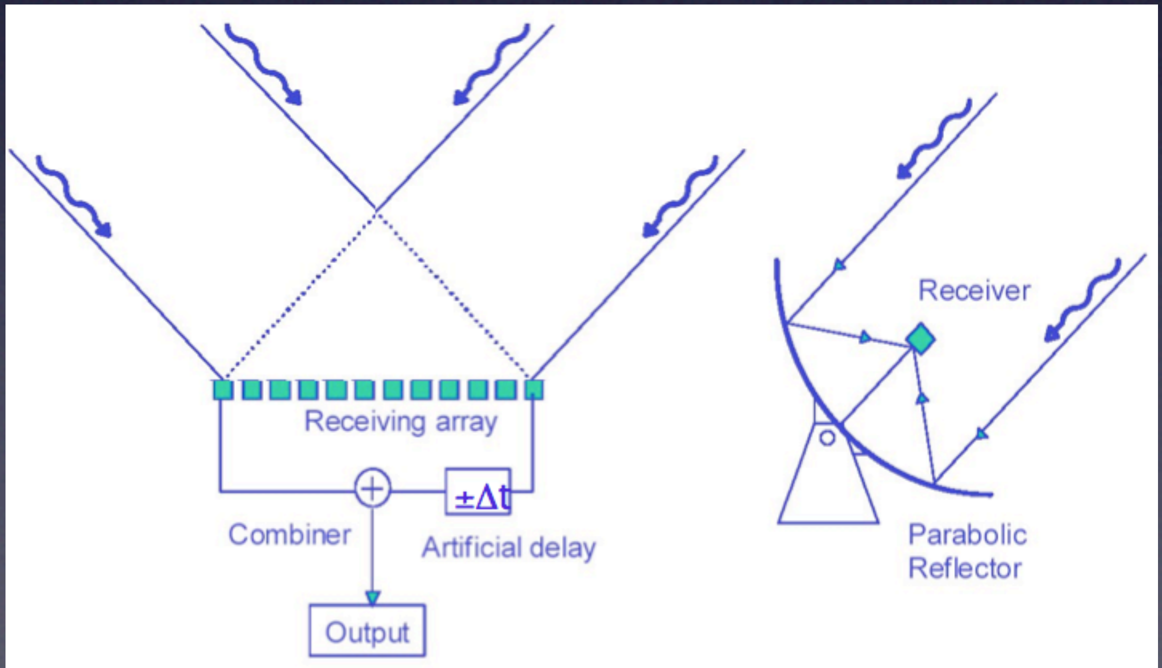

(from Garrett)

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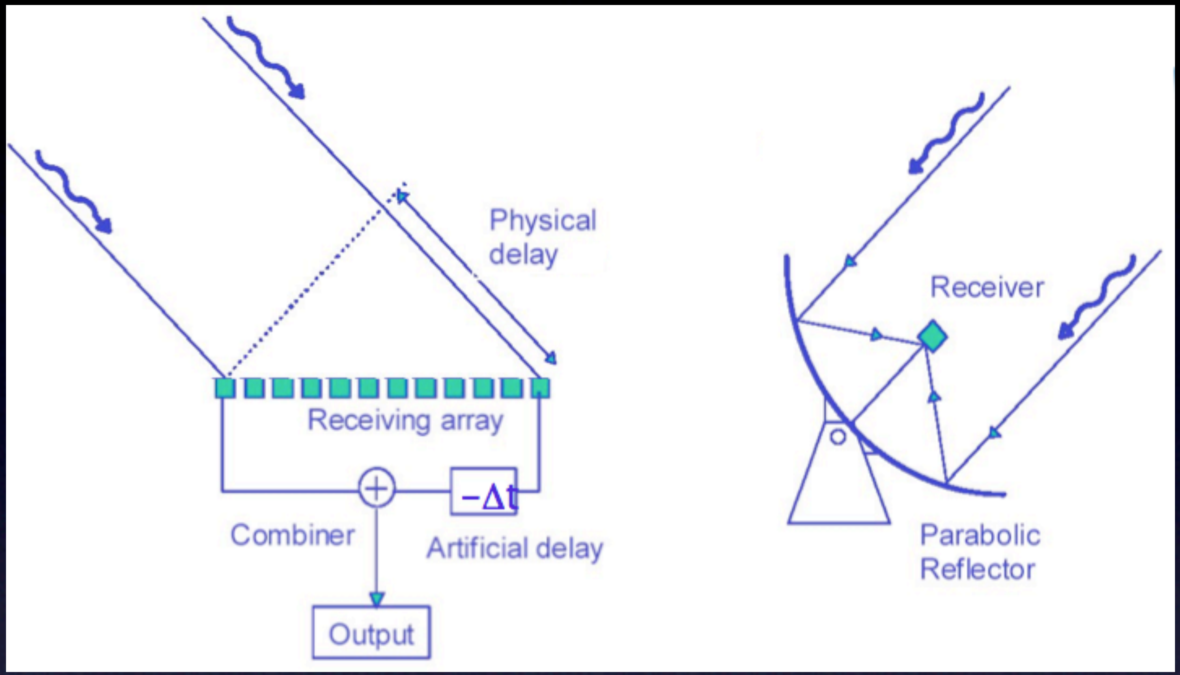

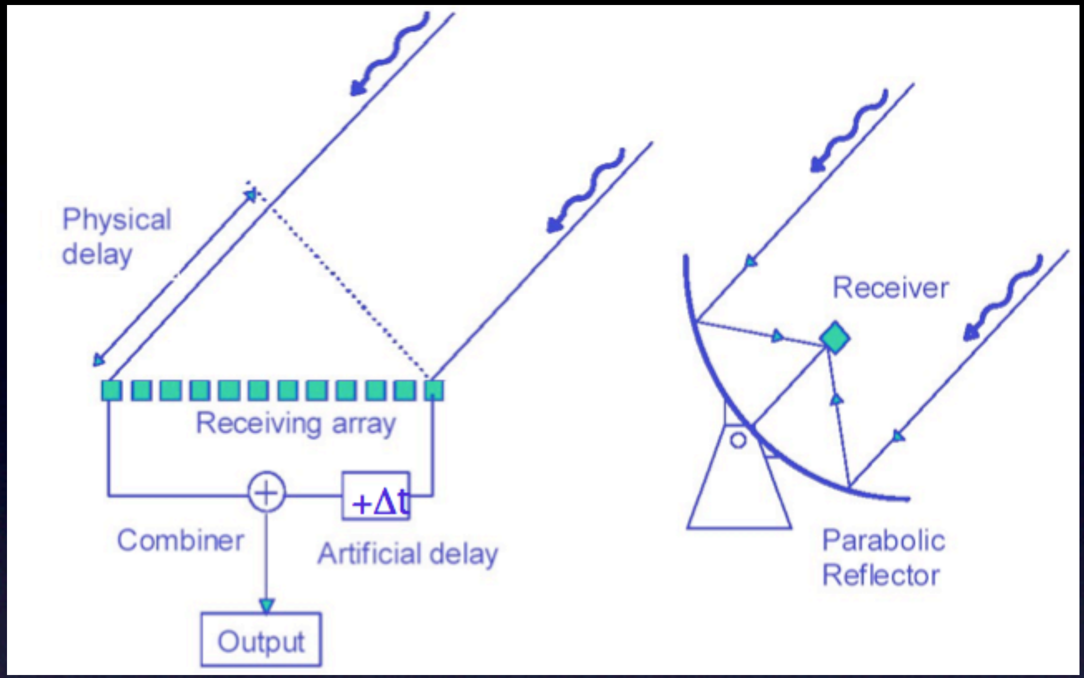

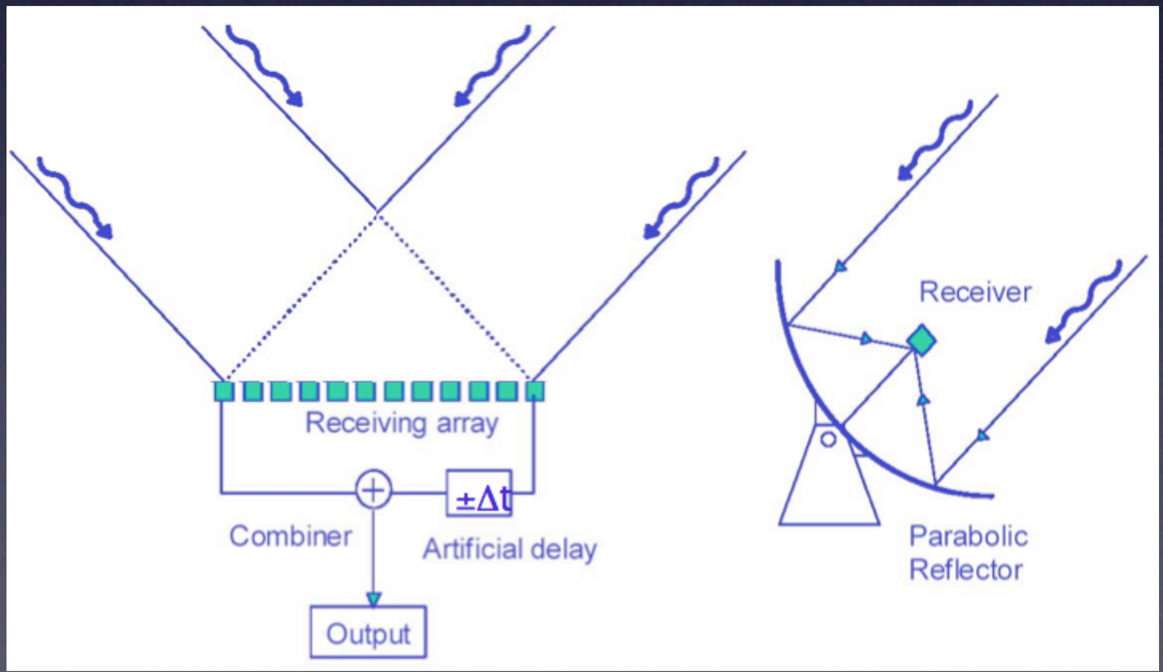

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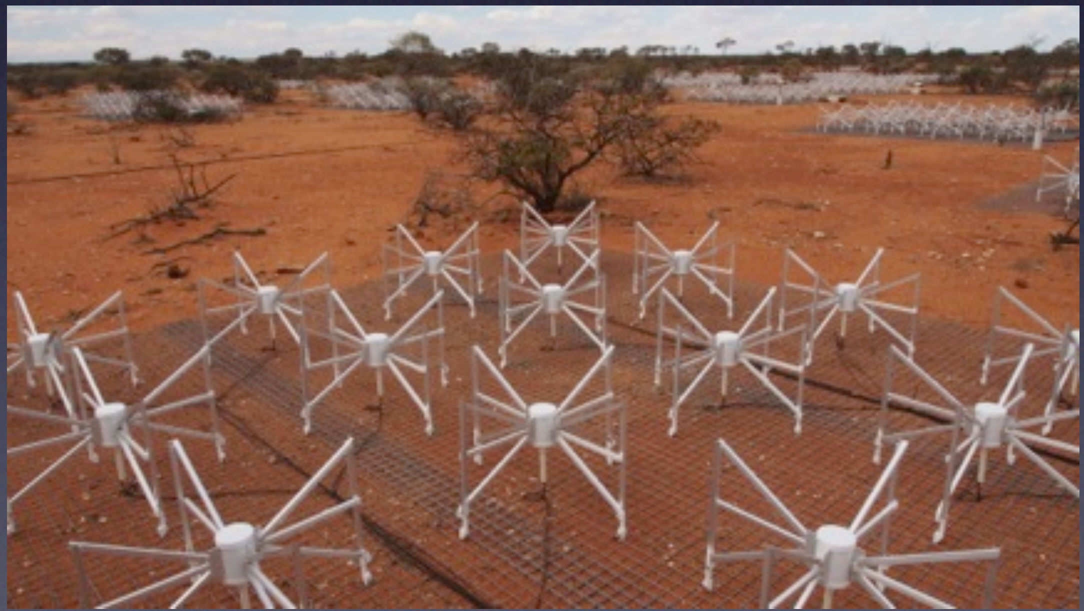


A MWA tile, with more in the background

Aperture Arrays

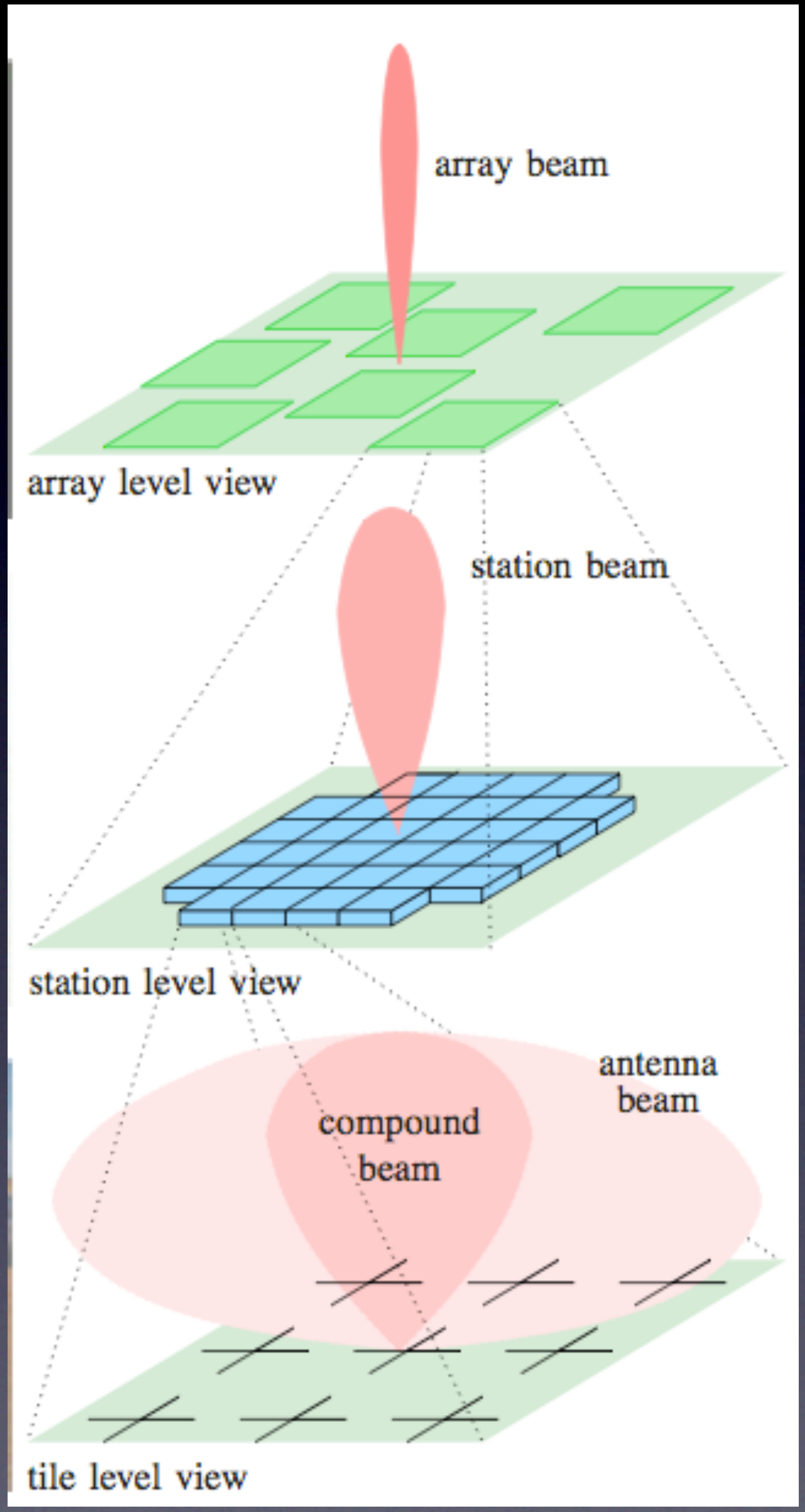
- Cheap
- No moving parts
- No blockage, nice beam
- Multiple beams
- Large FOV
- Largest A_{eff} at low f
- Can design for large BW

Dense AA : closely spaced

$(d < \lambda/2)$, $A_{eff} \sim A_{phys}$

Sparse AA : widely spaced

$(d > \lambda/2)$, $A_{eff} \sim$ const $(N \lambda^2/2)$



LOFAR

Stations	48 (40 in Netherlands, 8 in DE,SE,FR,UK+)
Frequency	LBA (10-90 MHz) and HBA (110-250 MHz)
Bandwidths	Upto 95 MHz, limited by data rate and software
Sensitivity	Upto 300000 m^2,
Baselines	83 km (NL) and 1300 km (EU)

LBA : 96 dipoles in a station

HBA : 48 aperture arrays

Elements in a station are phased to form a beam, or many beams !

Superterp (24 core stations)

LOFAR

A LBA dipole (10-90 MHz), part of the sparse aperture array

HBA (110-250 MHz) tiles with antenna elements within, forming a dense aperture array

Resolution and uv-coverage

Need to increase maximum baseline for resolution

Need to have short spacings for large diffuse emission

Technology has made it possible to have large bandwidths

Multi-frequency synthesis → better uv-coverage (but cost)

e.g. MWA (full monochromatic coverage); LOFAR (with large fr BW)

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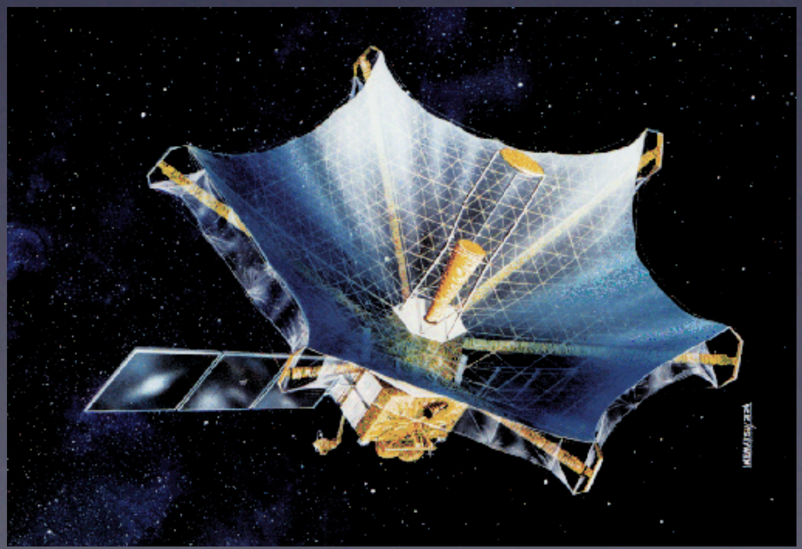
Global VLBI has given us baselines ~10000 km

Antennas in space can give us a factor of a few more



HALCA, part of VSOP

RadioAstron, partly built by NCRA

Bettering Sensitivity

$$\text{Sensitivity (1/rms)} \propto \frac{A_{eff}\sqrt{(B\,T_{int})}}{T_{sys}}$$

Increase A_{eff} → larger aperture + better efficiency

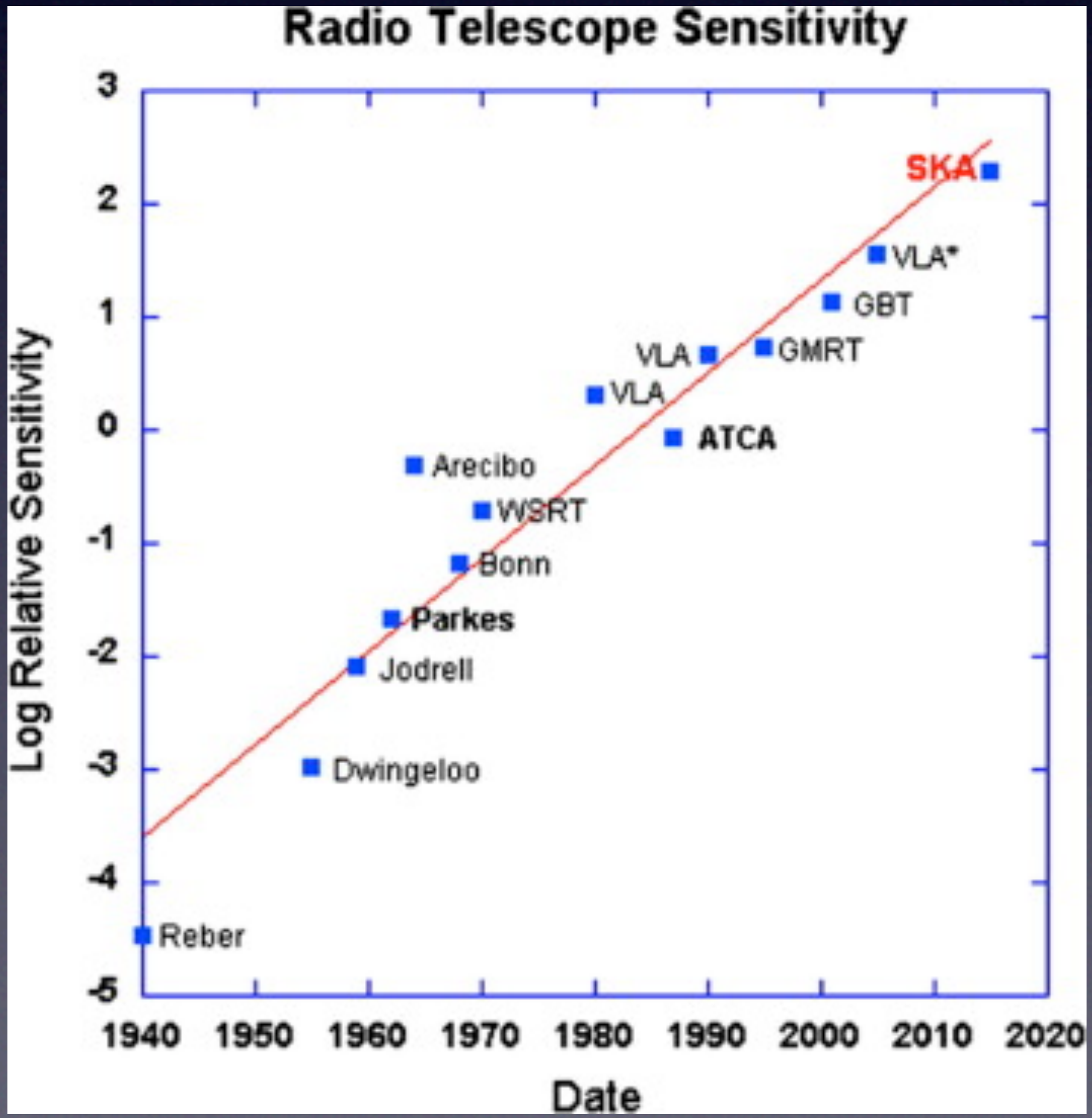
Increase BW → data rates, data processing complexity

Increase T_{int} → need to account for various effects

Decrease T_{sys} → better receivers

We have our own Moore's law for sensitivity !

(note: y-axis is in log)



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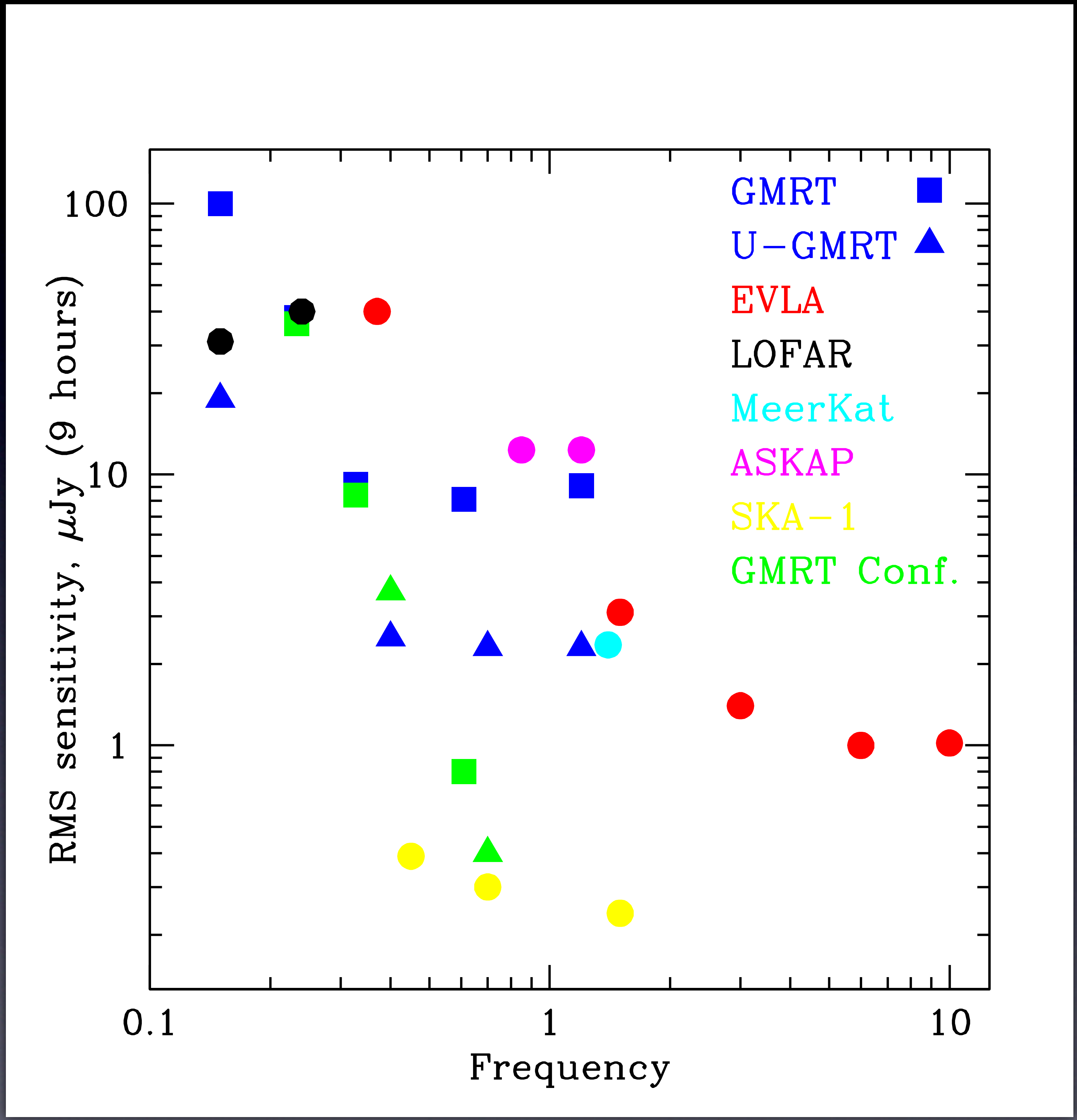


(Kanekar)

Survey instruments

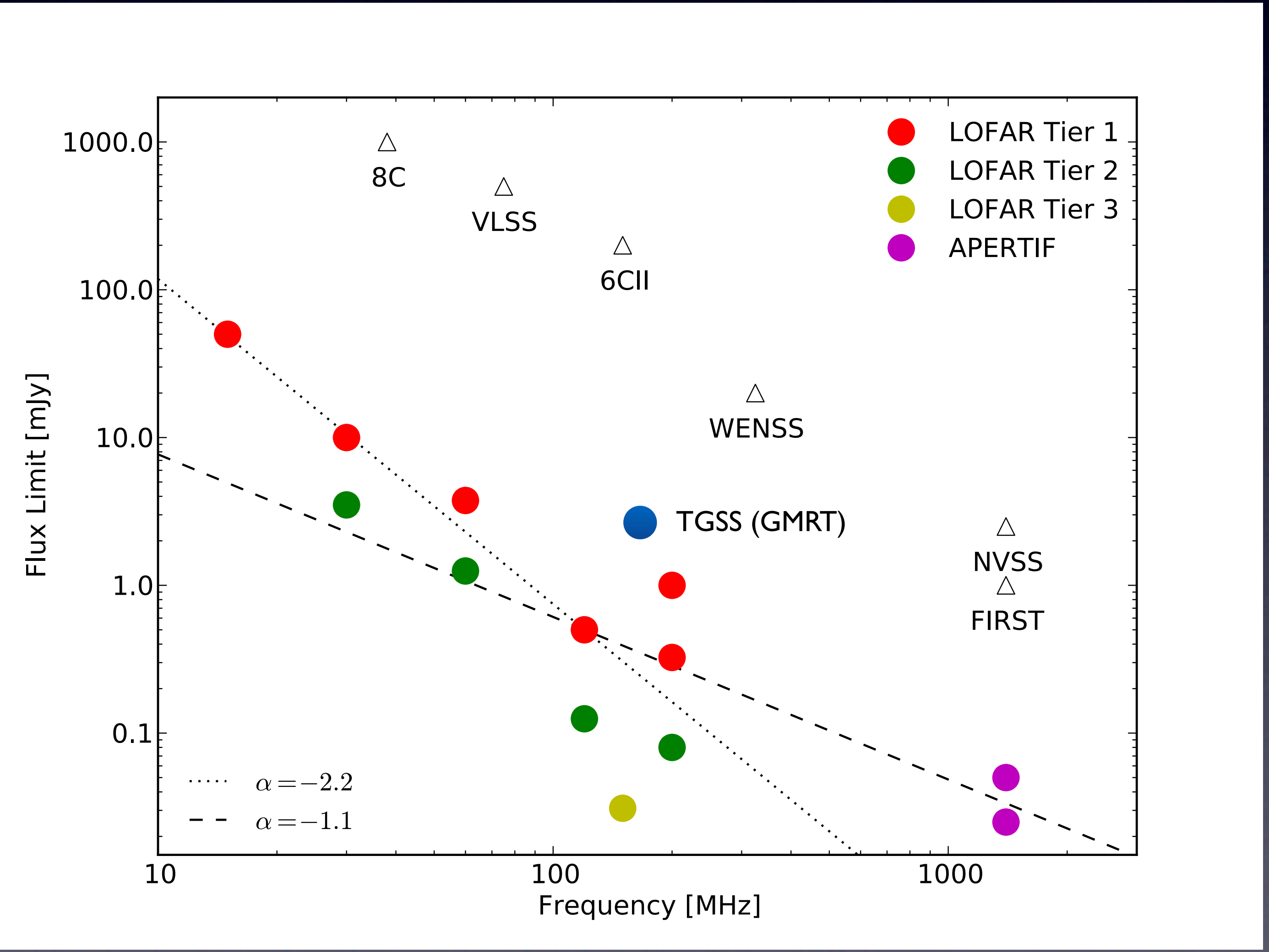
Cover maximum amount of sky in a given time with maximum sensitivity.

Survey speed $\propto$ (sensitivity)^2 x FOV

Can increase survey speed by increasing the number of beams !

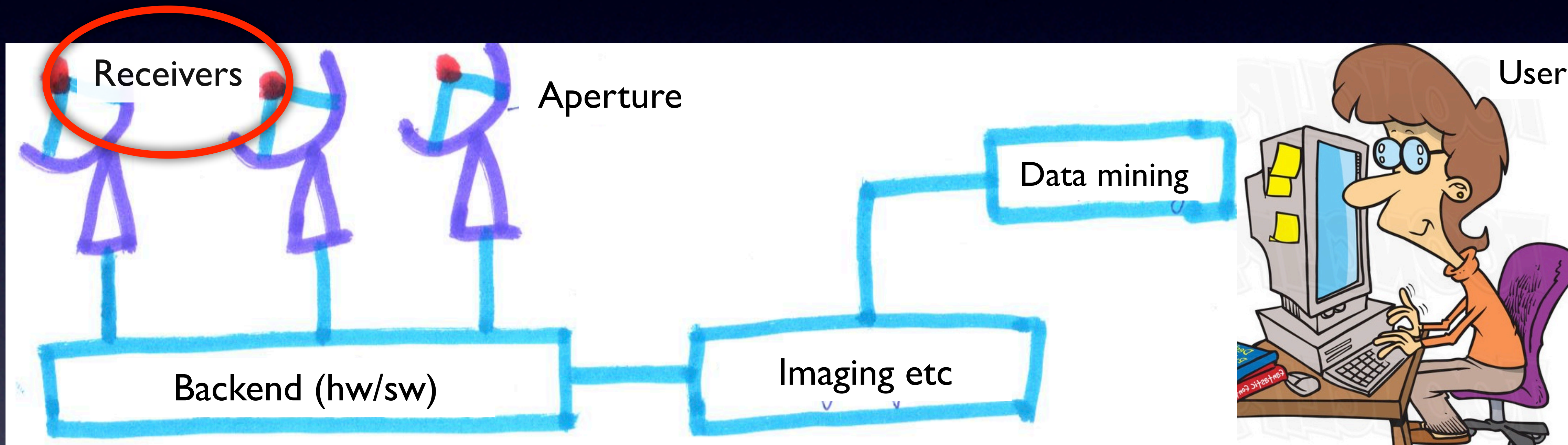
Dishes → Focal Plane Arrays

AA → Multiple Beamformers



(Röttgering)

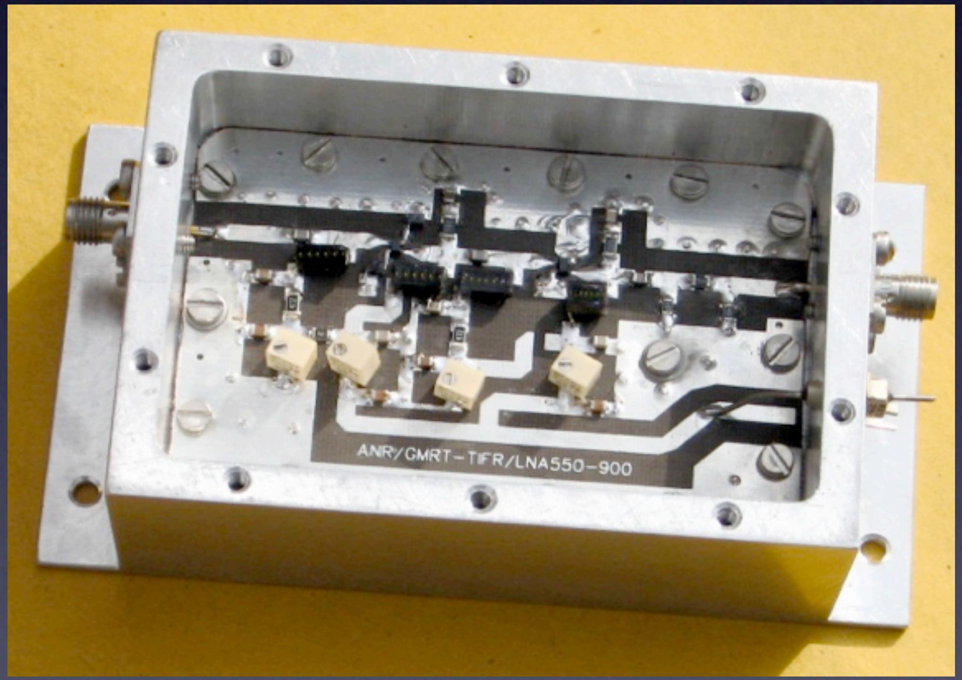
Upgrades : From the aperture to the user



Receivers (Frontend)

- Wide band receivers (200 MHz - 4 GHz)
- Low noise receivers (including cryogenics)
- Single pixel vs Multi-pixel feeds

New 550-900 MHz feed for the upgraded GMRT



New 500-900 MHz room temp LNA for the upgraded GMRT

Focal Plane Arrays on dishes

Optical telescopes have many detectors at focus

(many silver iodide grains, many CCD pixels)

$\Rightarrow$ can image many directions at the same time

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- Can we have many feeds at the focus ?

- Can we have many feeds on an interferometer ?

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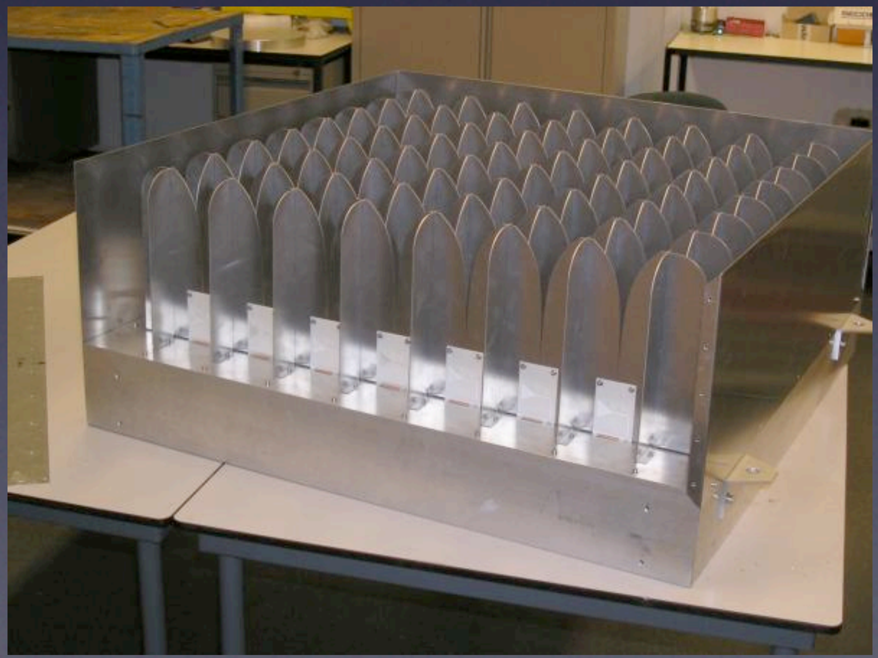
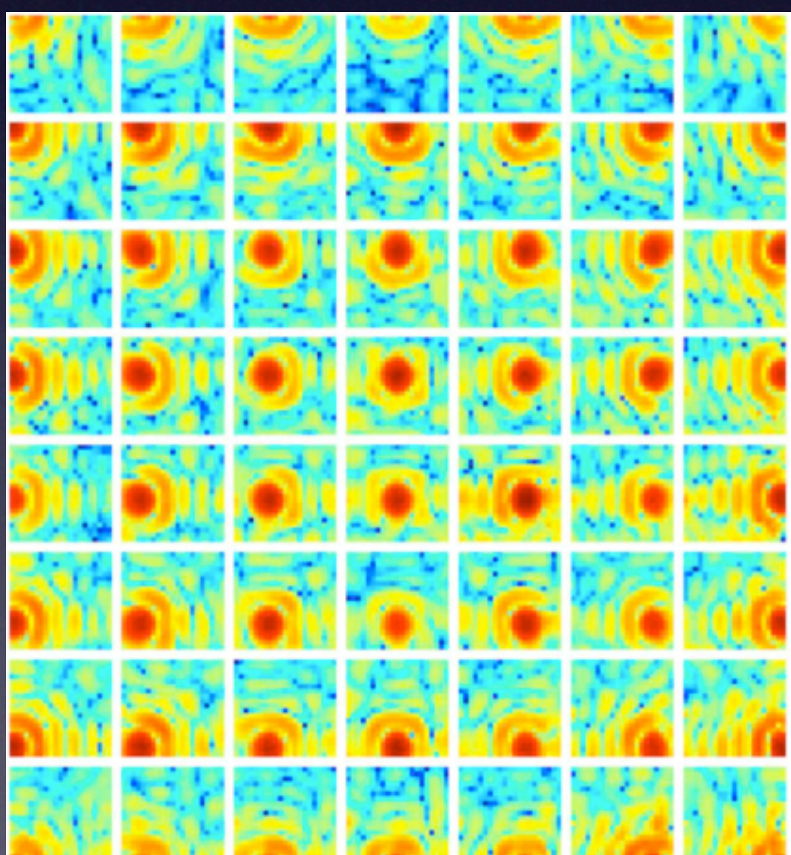


APERTIF : 112 pixel feed for WSRT

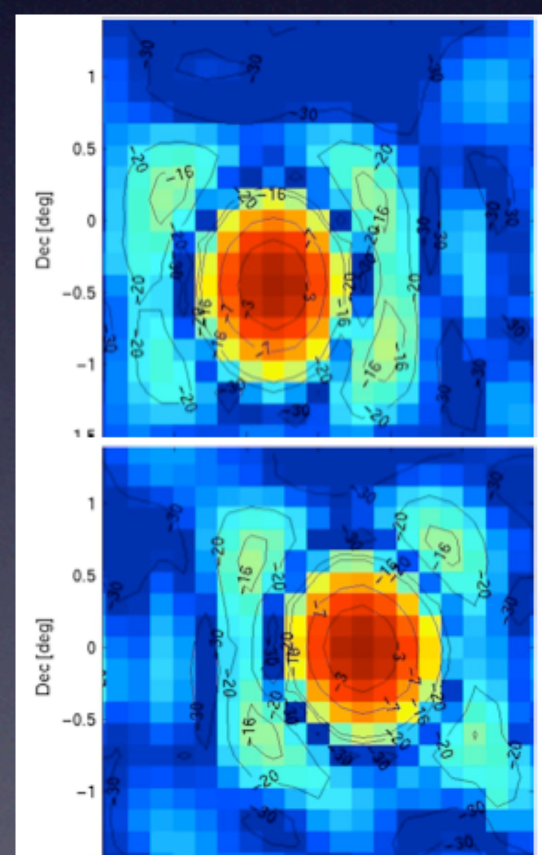
Focal Plane Arrays on dishes

Examples : Parkes multibeam survey, AlfaAlfa on Arecibo and APERTIF on WSRT

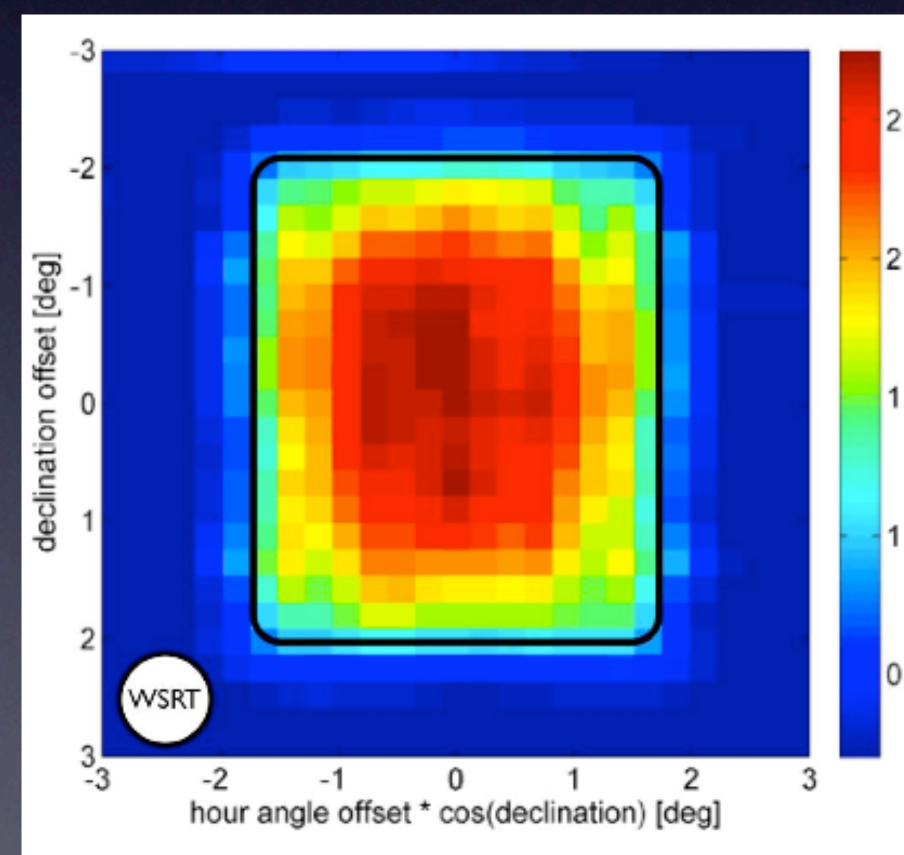
- Can have multi-feed arrays, each being independent
  - need to be widely spaced, hence at low frequencies



Beams of individual elements



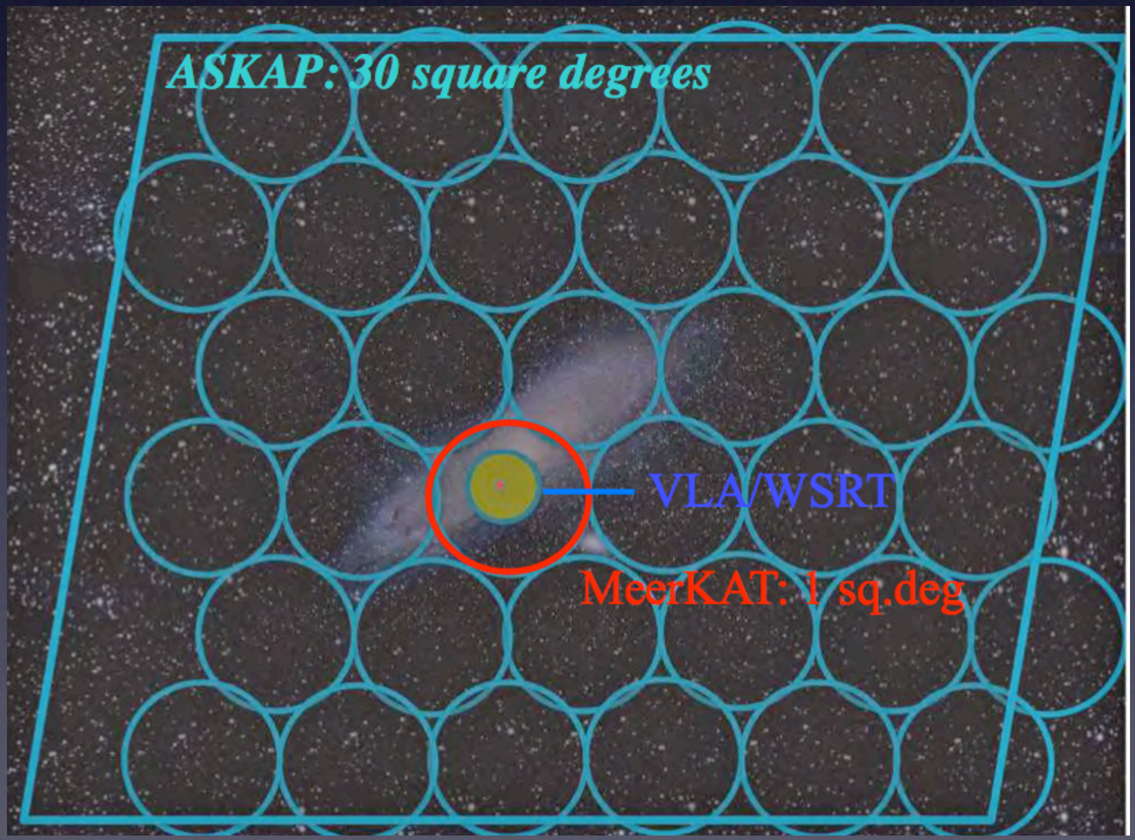
Two beams of the PAF



APERTIF vs SPF on WSRT (Oosterloo et al)

Focal Plane Arrays on dishes

- Can also form multiple phased beams out of many closely packed feeds, called Phased Array Beams
  - can then correlate each PAB across antennas !



ASKAP PAF beams on the sky

- Increases survey speed enormously
- Corresponding increase in processing cost

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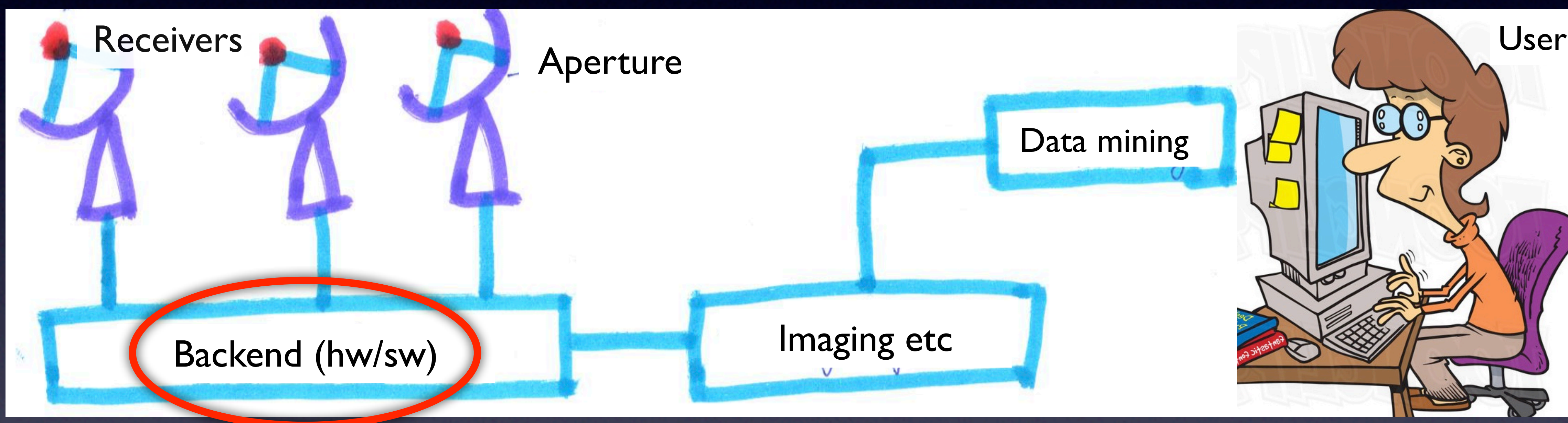


Data rates and correlators

Incoming data rates will increase hugely due to

- wider bandwidths (400 MHz - 4 GHz)
- multiple beams (4 - 64)
- aperture arrays and focal plane arrays (120 - 256)
- high time resolution for RFI and transients (10s of ns)

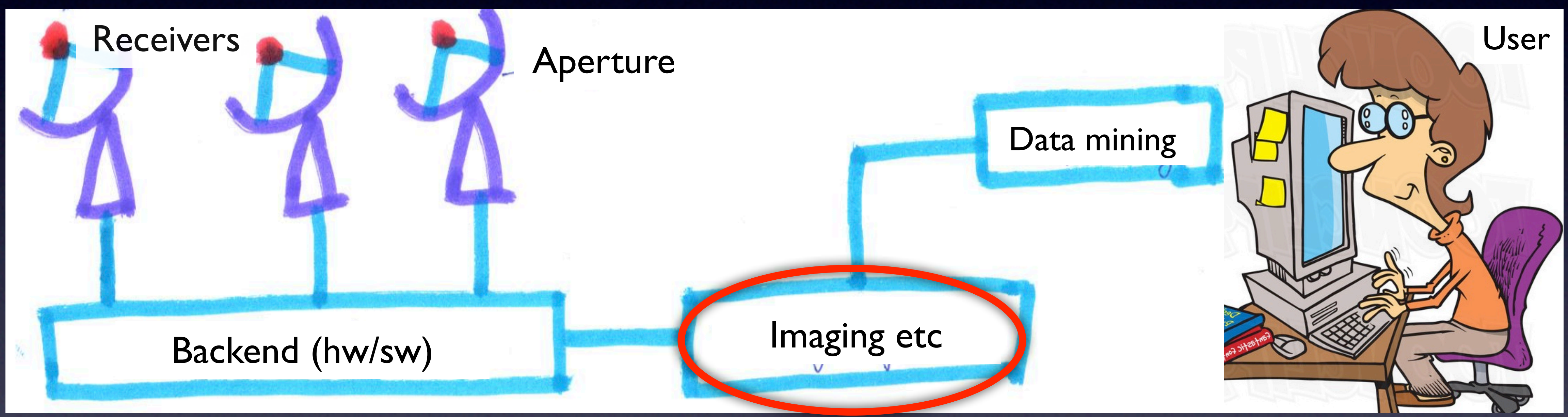
Data rates are huge: 10^{11}-10^{12} bps (upgraded GMRT) to 10^{15} bps (SKA-AA)

Ongoing research in

- Data I/O
- High Performance Computing (GPUs, FPGAs)

Software correlator (CPU-GPU) at GMRT

Upgrades : From the aperture to the user



Data processing

Current data processing techniques are highly inadequate for next generation telescopes (LOFAR, LWA, uGMRT ... SKA)

- Large fractional bandwidths ($\Delta\nu/\nu \sim 0.3$-0.6)

  for high sensitivity + good uv-coverage

- Large Fields of View (5 to 120 degrees) at low ν

  using Aperture Arrays, for high survey speed

Each of these lead to a number of issues, which are being tackled only now

- ongoing research in theory (for EVLA, LOFAR, SKA)
- ongoing work in software (pre-CASA insufficient)

Wide band interferometry

Bandwidth smearing

$\Rightarrow$ radial smearing of sources

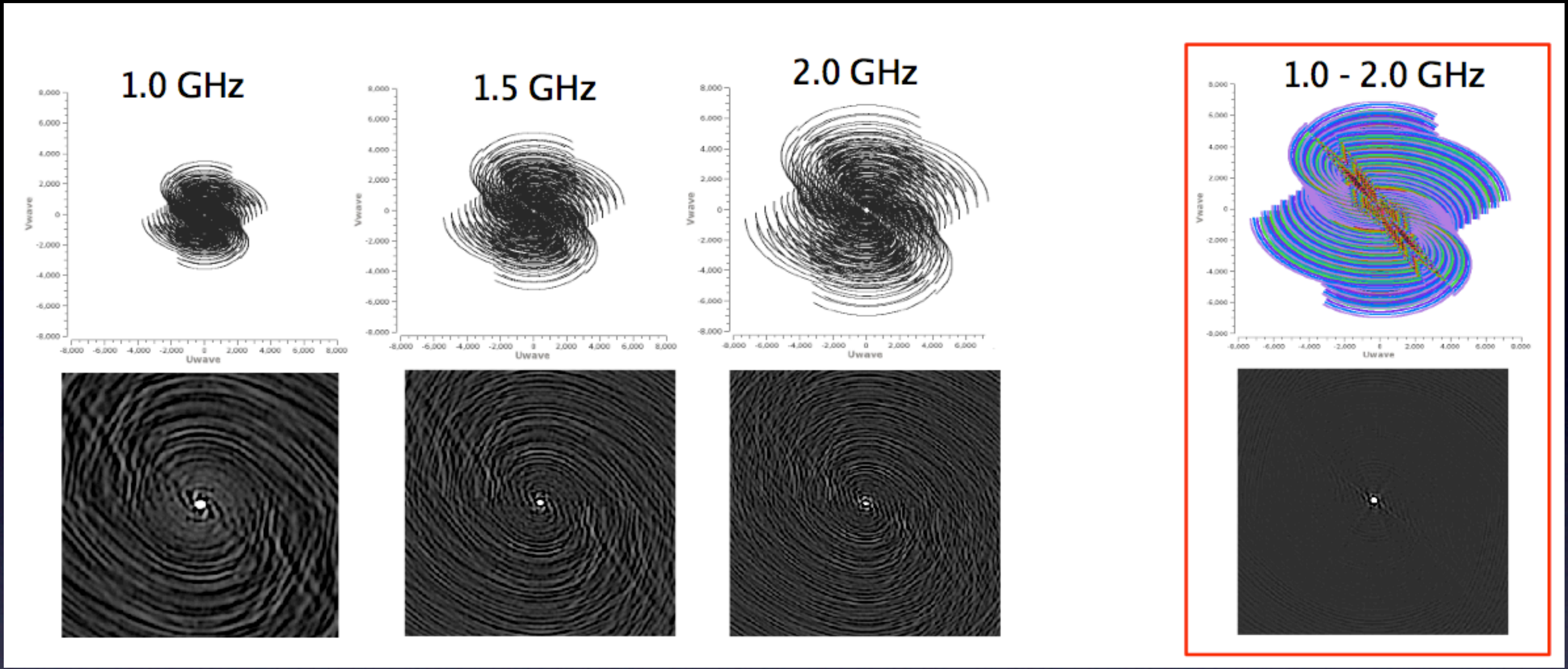
To image the full GMRT beam, can't go beyond 0.1-1 MHz BW. Upgraded GMRT will have 400 MHz BW !

Use MFS (Multi Frequency Synthesis)

Grid each channel visibility correctly onto a single image. This leads to a number of complexities for wide bands

- The sky will vary with frequency
  (i.e., different sources have different spectral indices)
- The primary beam will vary with frequency
  (this is predictable, only as a scaling)

Wide band interferometry



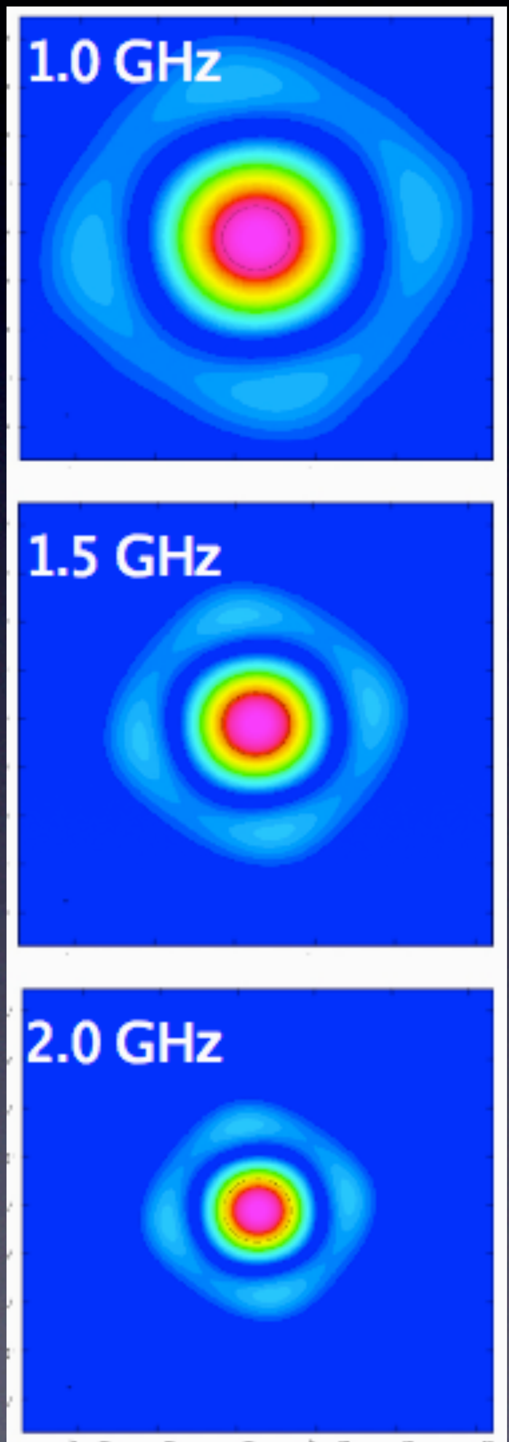
PSF (Dirty Beam) for VLA at 3 frequencies, versus combining 1-2 GHz band (simulation, U. Rau et al)

Hence, wide bandwidth can compensate

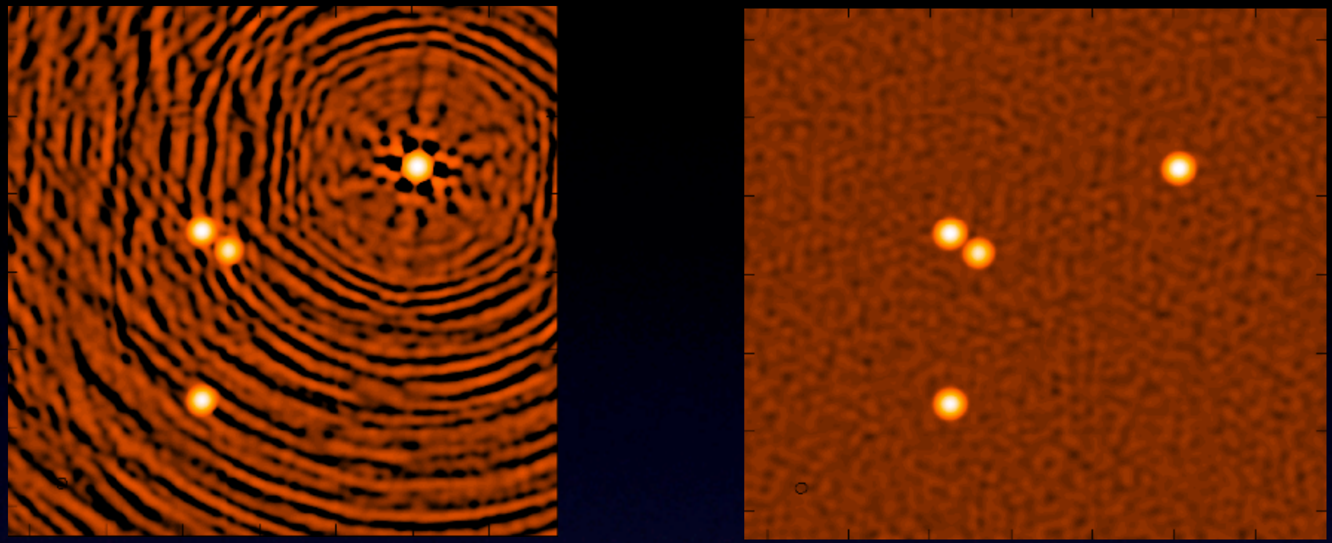
for sparse uv-coverage (eg LOFAR)

Wide band interferometry

Primary beam varies with frequency



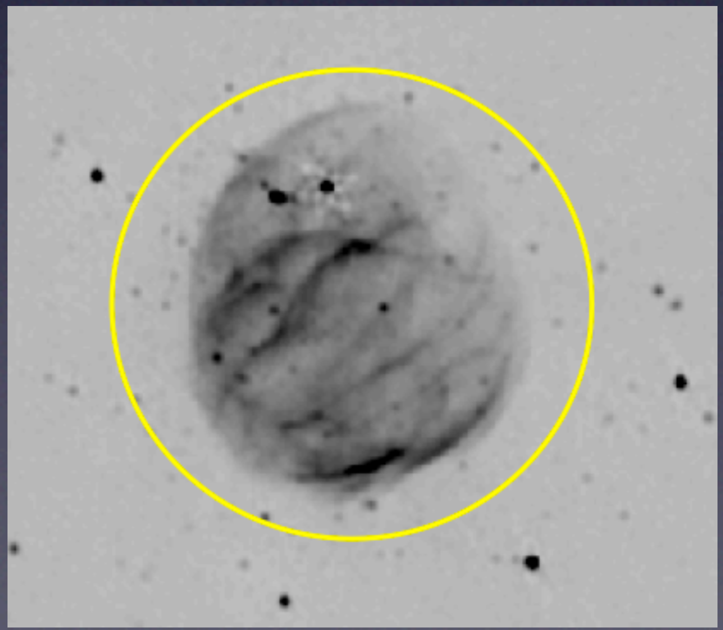
Simulations for EVLA antennas (from U. Rau)



MFS without (left) and with (right) solving for spectral index of each source

(simulation, from U. Rau)

For extended sources, need to do a Multi-Scale MFS to model spectral indices of the entire source



SNR G55.7+3.4, with MS-MFS + Wproj. Note the primary beam (yellow) ! (U. Rau + D. Green)

Wide field imaging

Imaging and selfcalibration assume :

- the sky is constant in time as seen by each antenna

  (the sky, the ionosphere and the antenna beam)

- instrumental response is multiplicative on the image

  ⇒ one gain per antenna for the whole sky

This is not true for wide band imaging at low freq

⇒ Direction Dependent Effects (DDE)

Difficult to solve for DDEs

- both theory and software are just catching up
- visibilities can be corrected only for ONE direction!

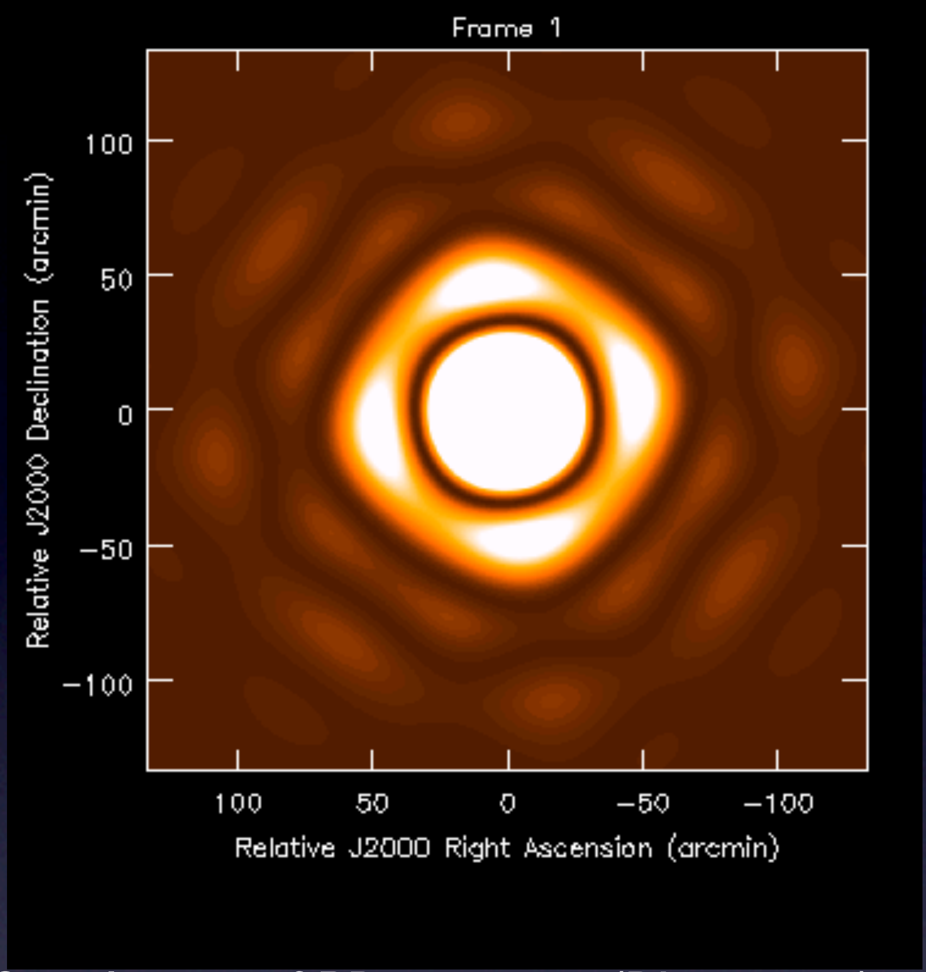
Wide field imaging

Primary Beam PB(t)

- rotates for alt-az dishes
- dish deforms (gravity+thermal)

  ⇒ pointing errors

- frequency dependence
- geometric effects (for AAs)



Simulation of PB rotation (Bhatnagar)

Strong sources not close to the centre will become 'variable' with time, as seen through PB(t)

But, this variation is different for different sources, and for different antennas !

Wide field imaging

Primary Beam PB(t)

Algorithms : Pointing Selfcal & A-projection (Bhatnagar, Cornwell)

These assume a parametrised form of the beam variation.

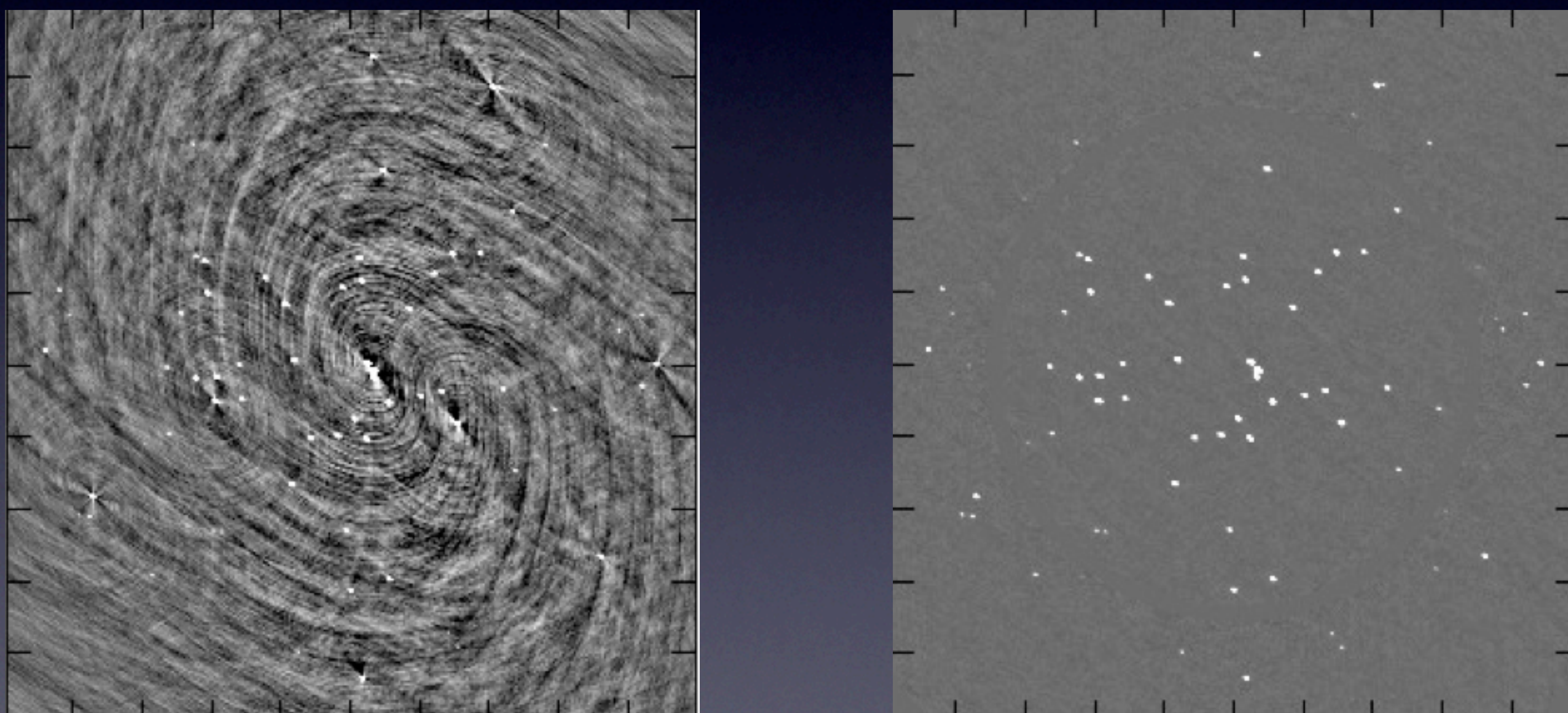


Image before Primary Beam corrections (left) and after corrections (right). Simulations from Bhatnagar S.

Wide field imaging

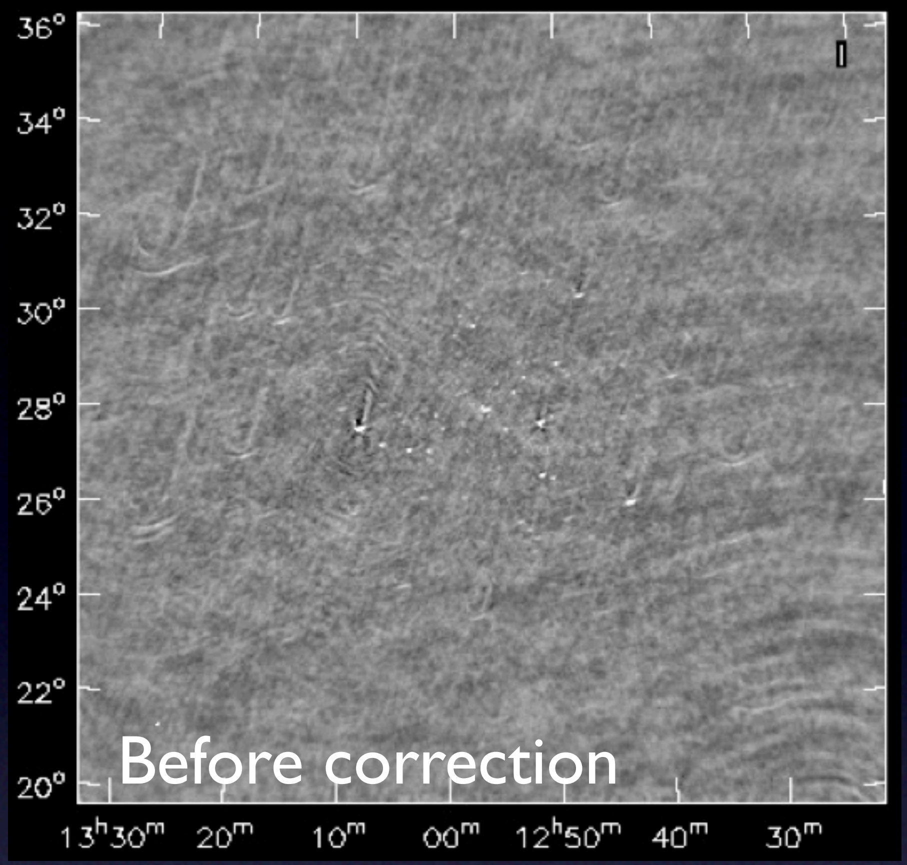
<u>Non-coplanarity (w-term)</u>

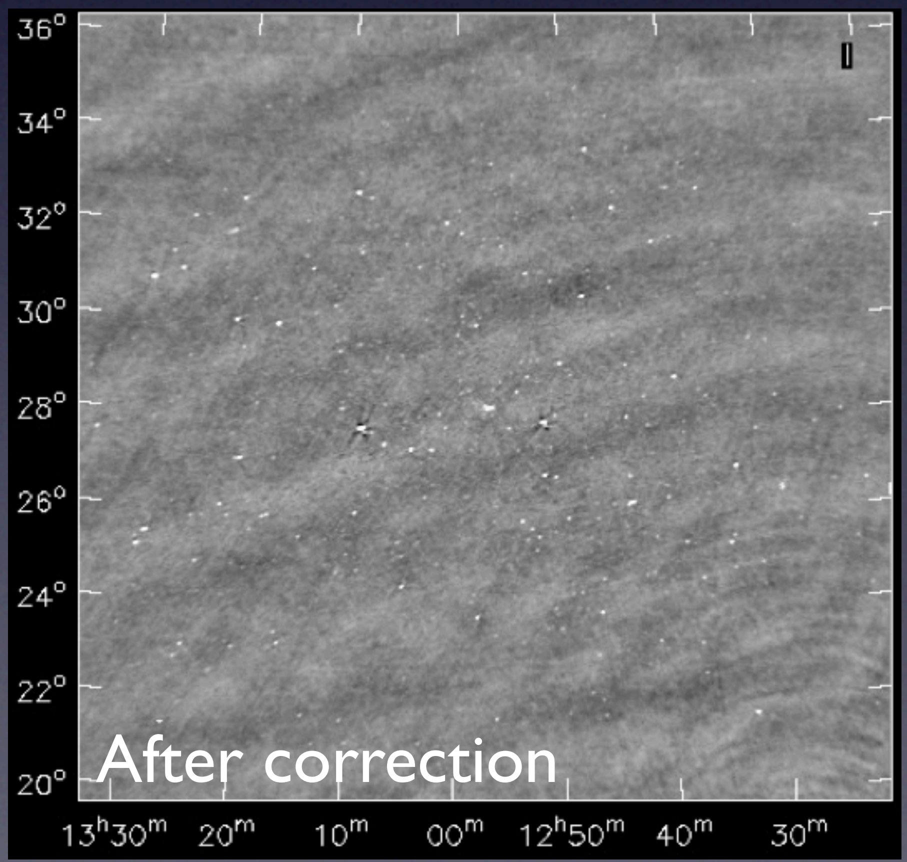
Errors due to

- projecting a 3d celestial sphere onto a 2d plane
- non-coplanar array

Algorithms are now known

- Facet imaging (slow, complex, limited)
- W projection (fast, can combine with A proj)





Coma cluster, 74 MHz (Bhatnagar)

Wide field imaging

Non-isoplanaticity (ionosphere)

Changing refractive index of the ionosphere leads to changing path (and phase) difference, function of time, freq, sky, antenna

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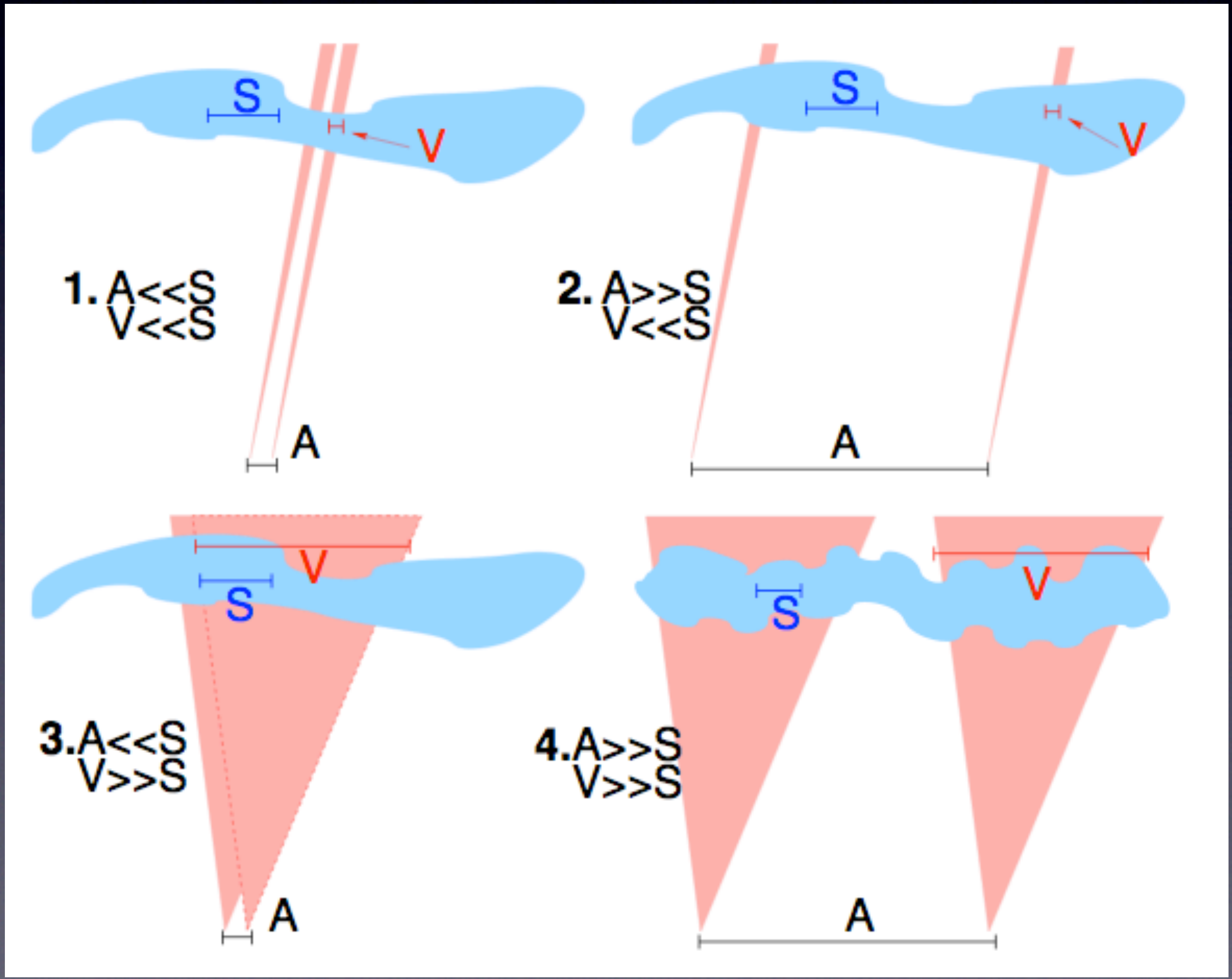

A : Array size

V : Field of View

S : Isoplanatic size

(from Lonsdale)

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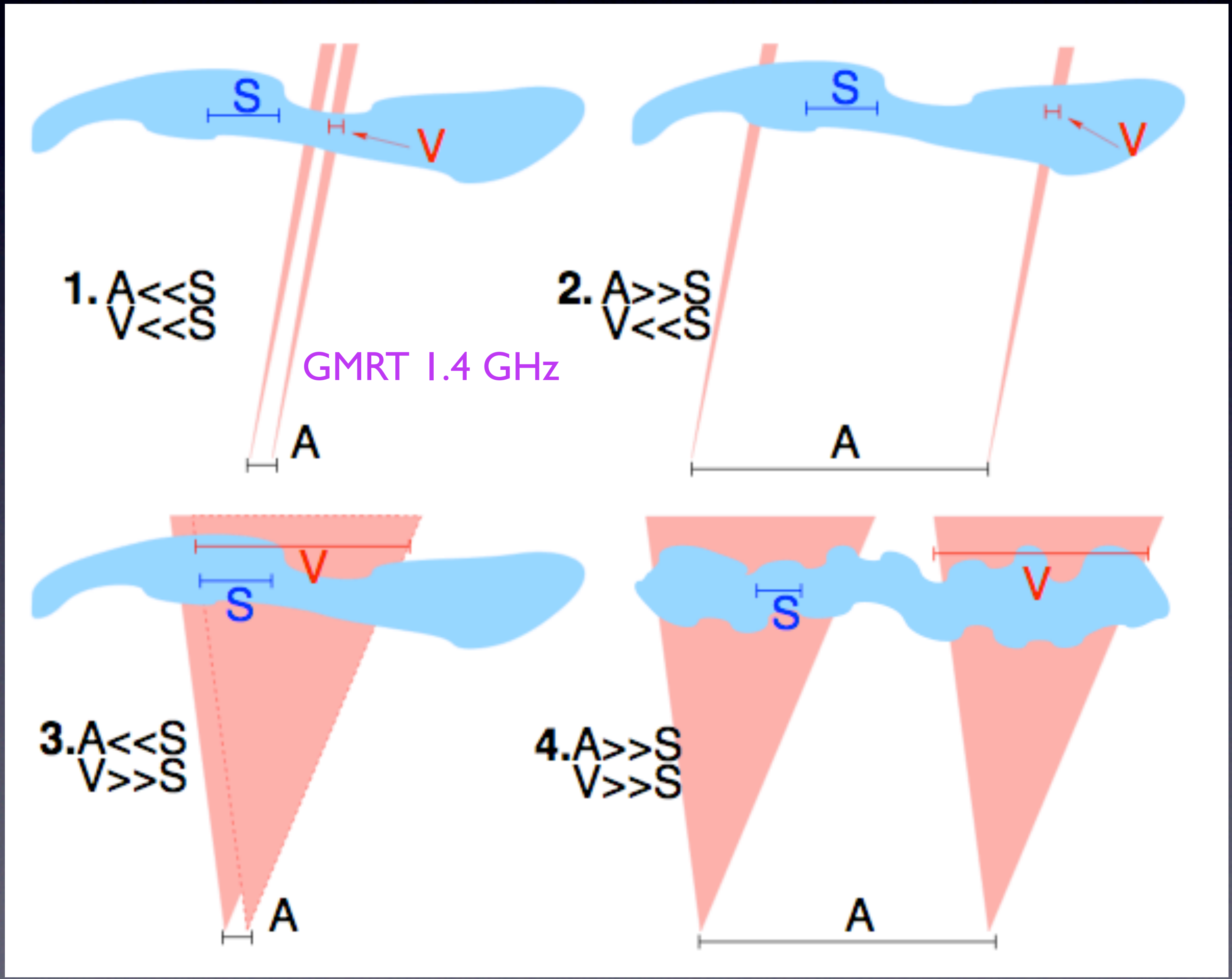

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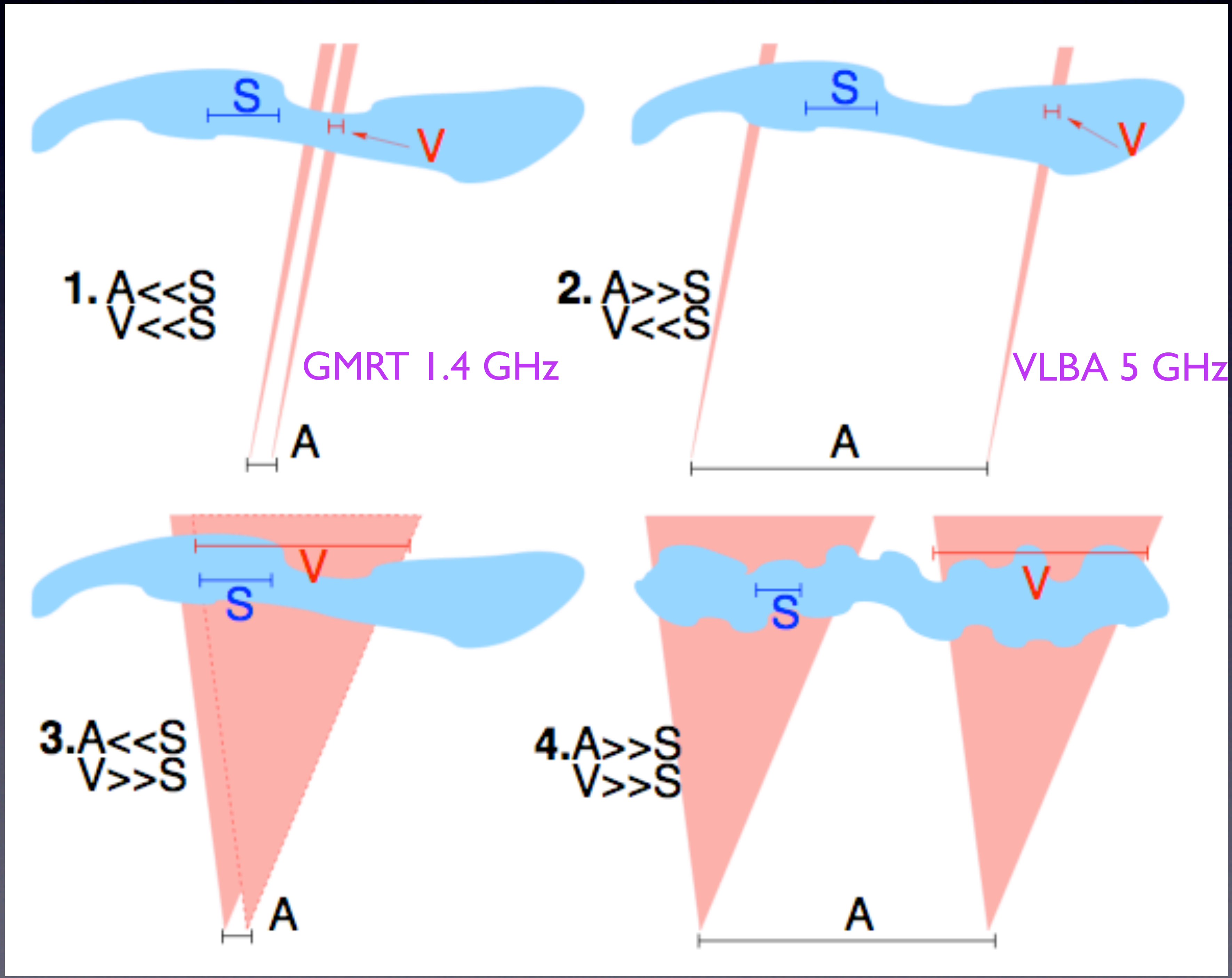

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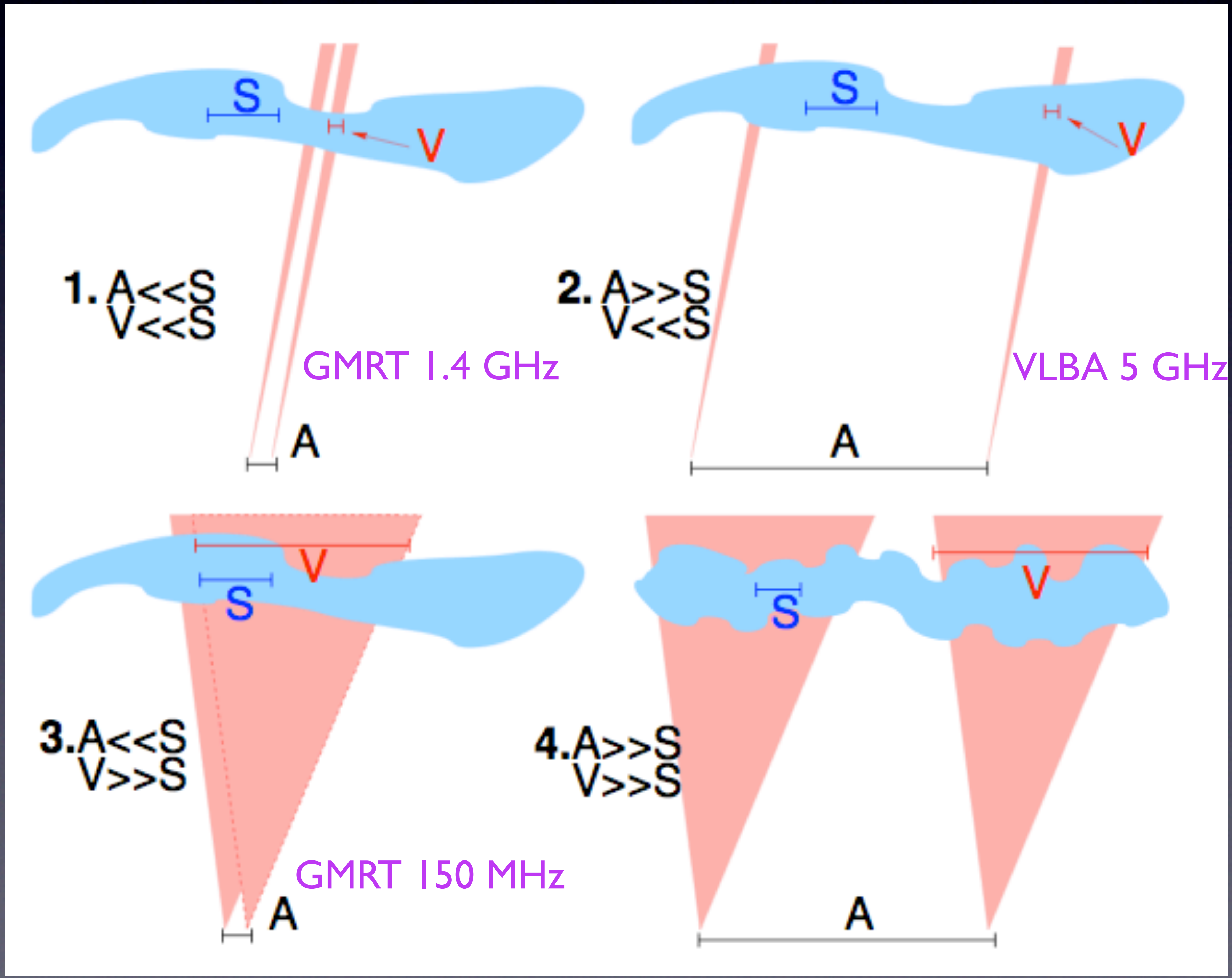

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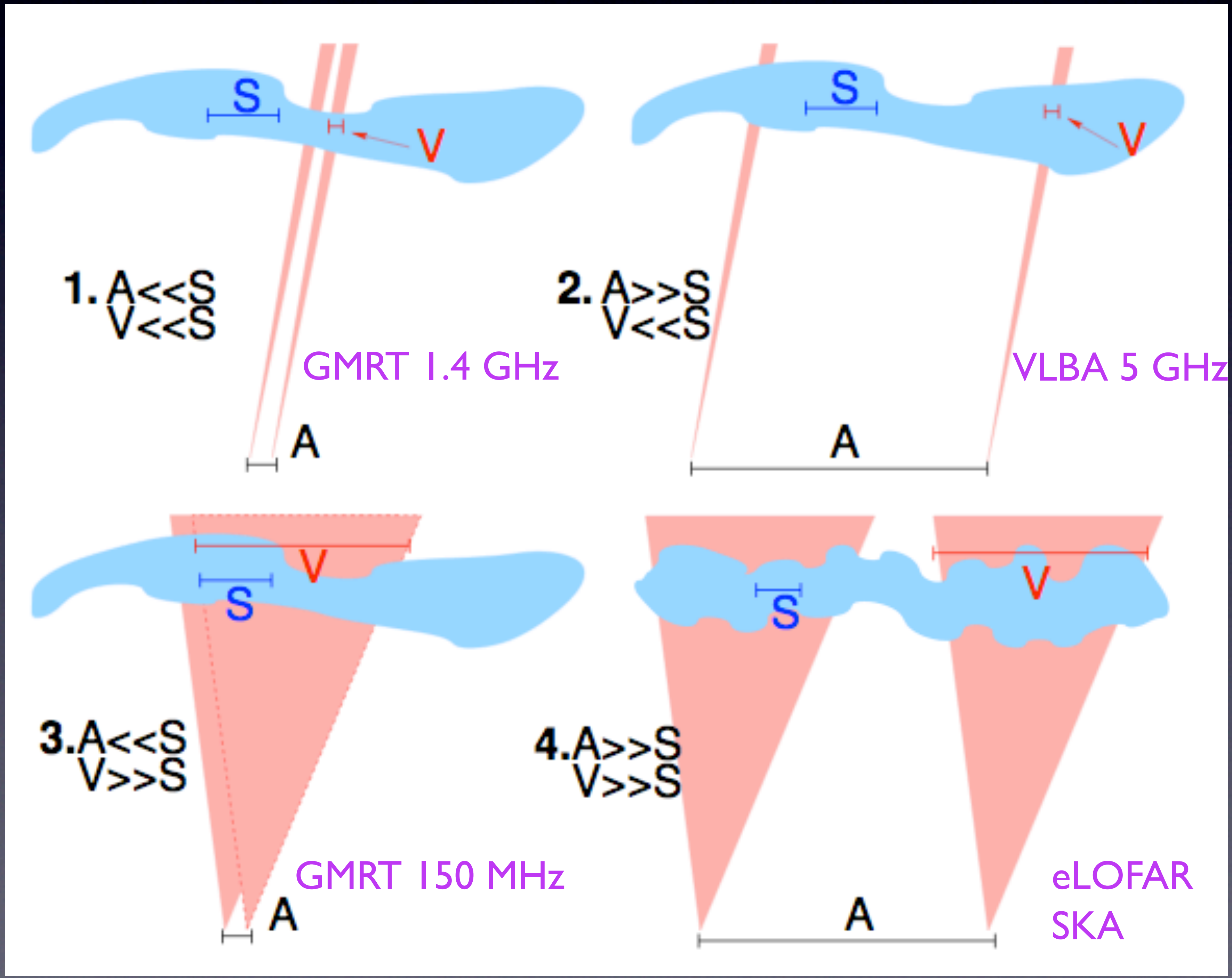

A : Array size
V : Field of View
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(from Lonsdale)

Wide field imaging

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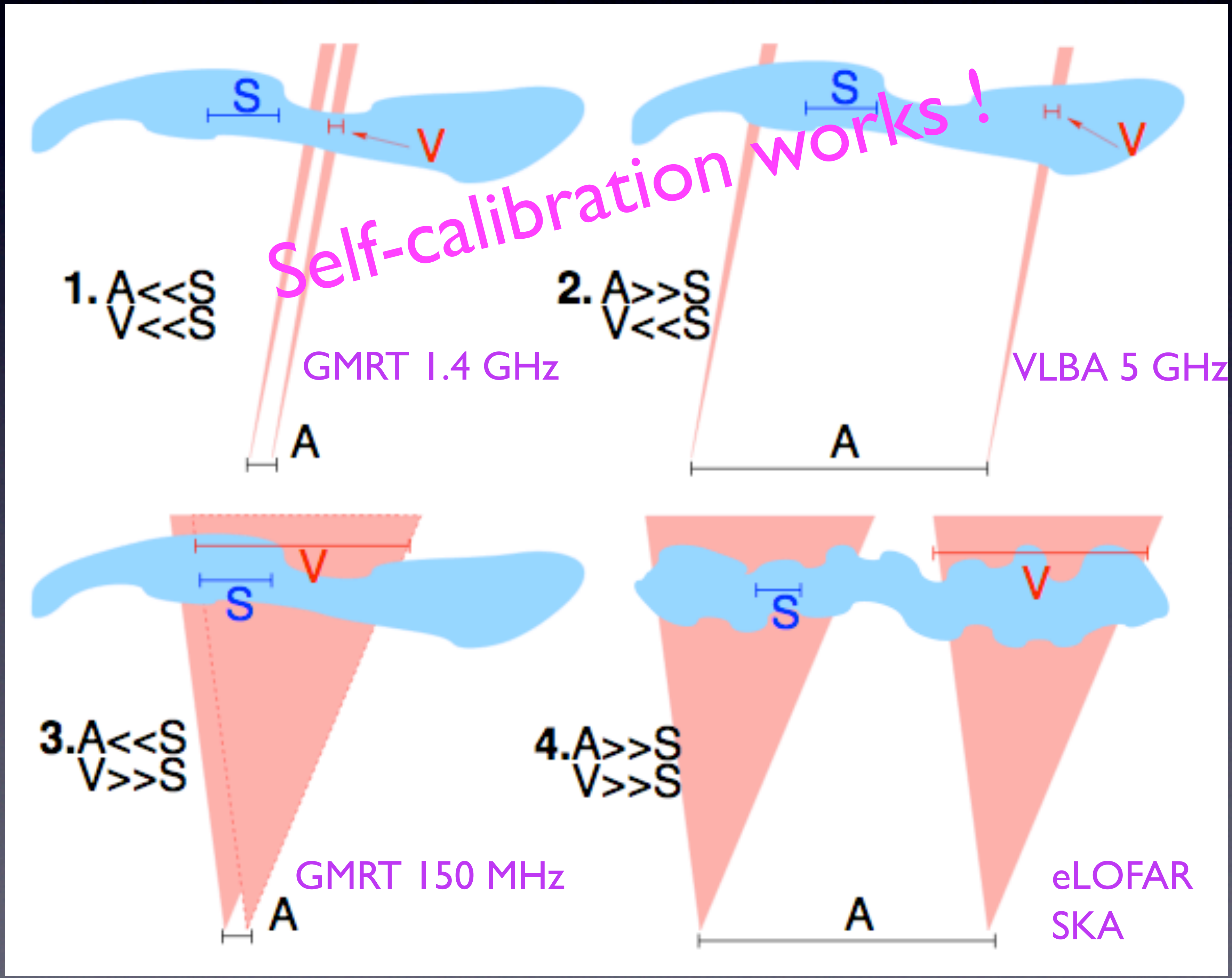

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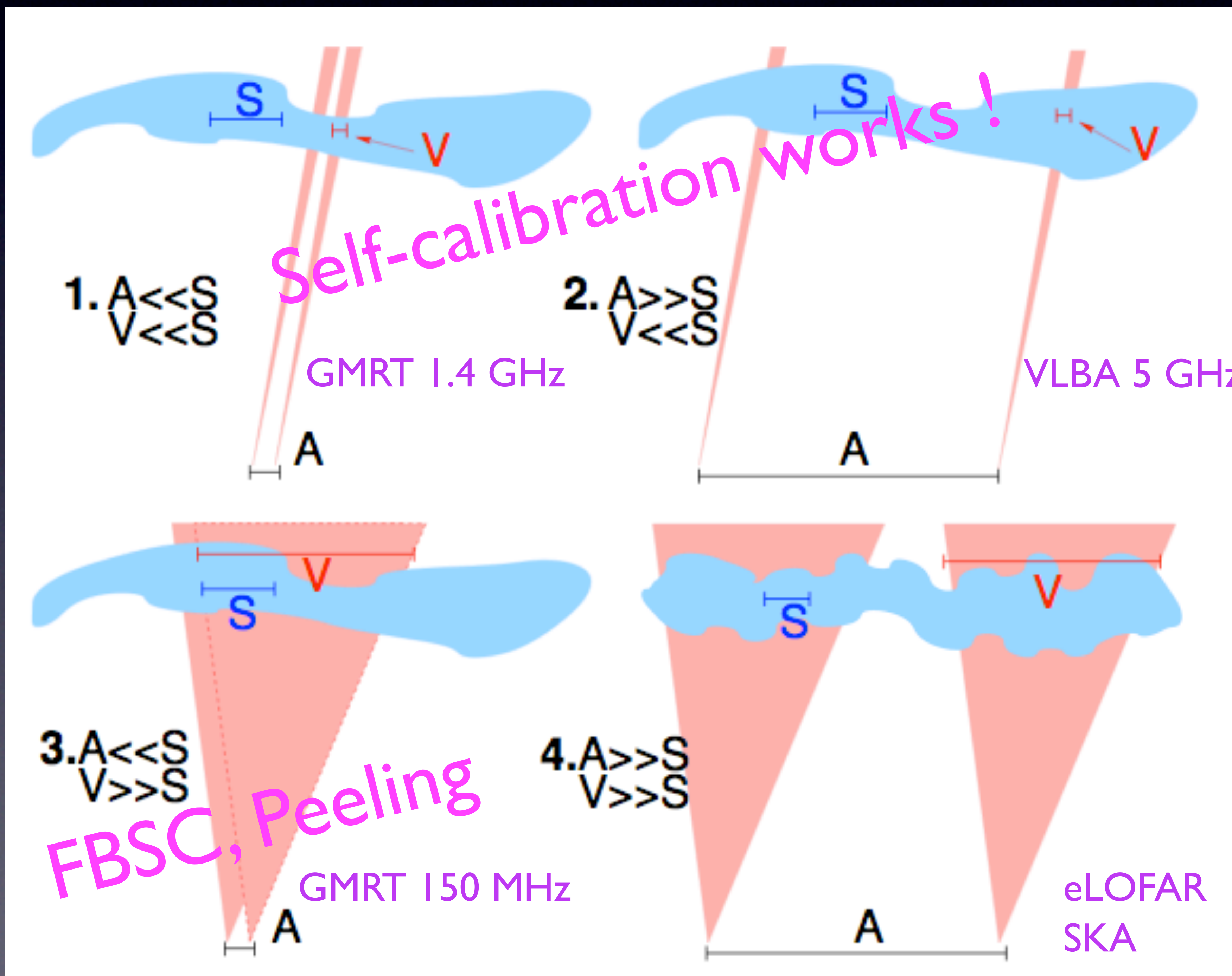

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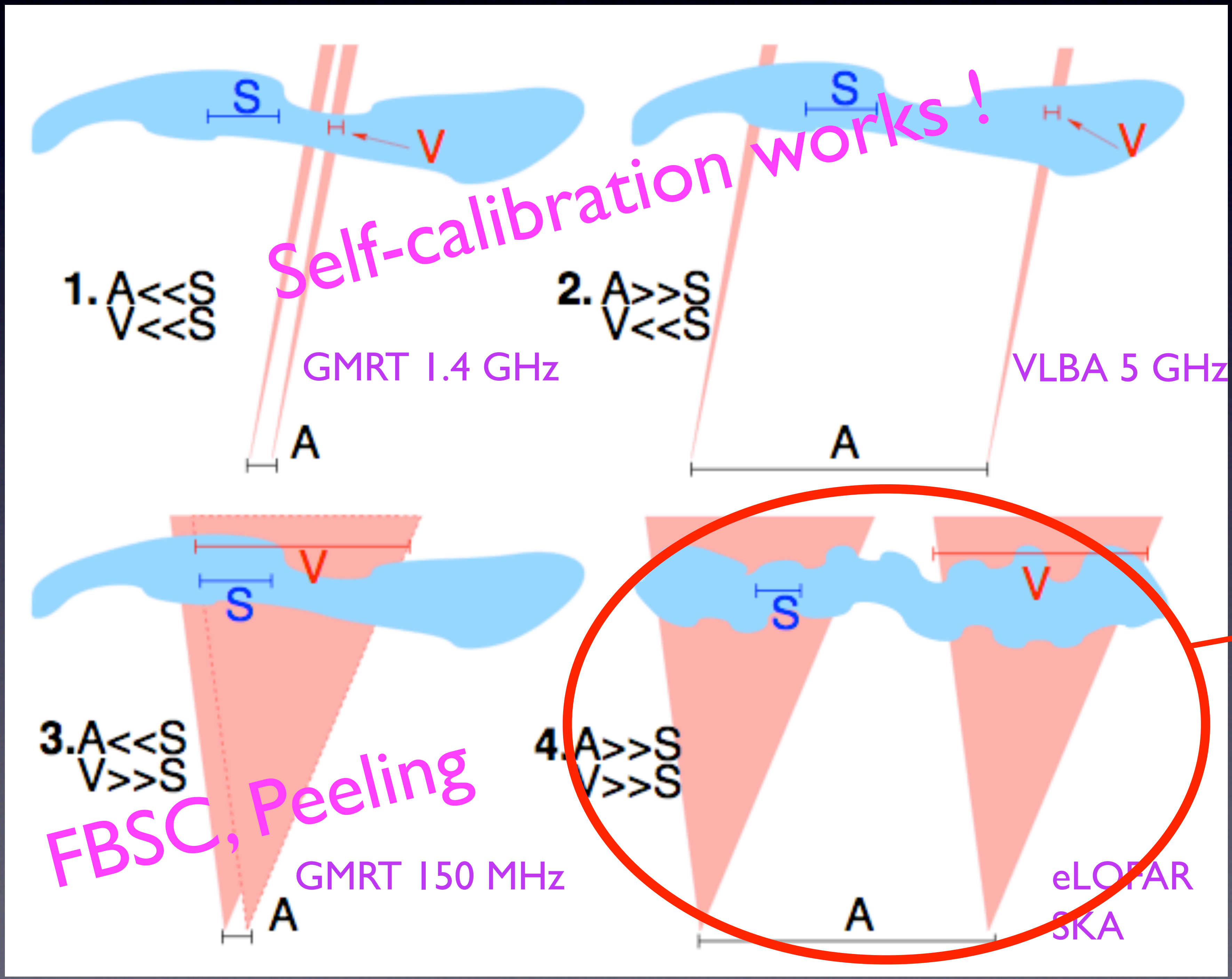

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Algorithms being developed !

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Timelapse movie of snapshot images of two sources far from the phase centre.

Data : 150 MHz GMRT, full FOV (Vir Lal & Röttgering)

Wide field imaging

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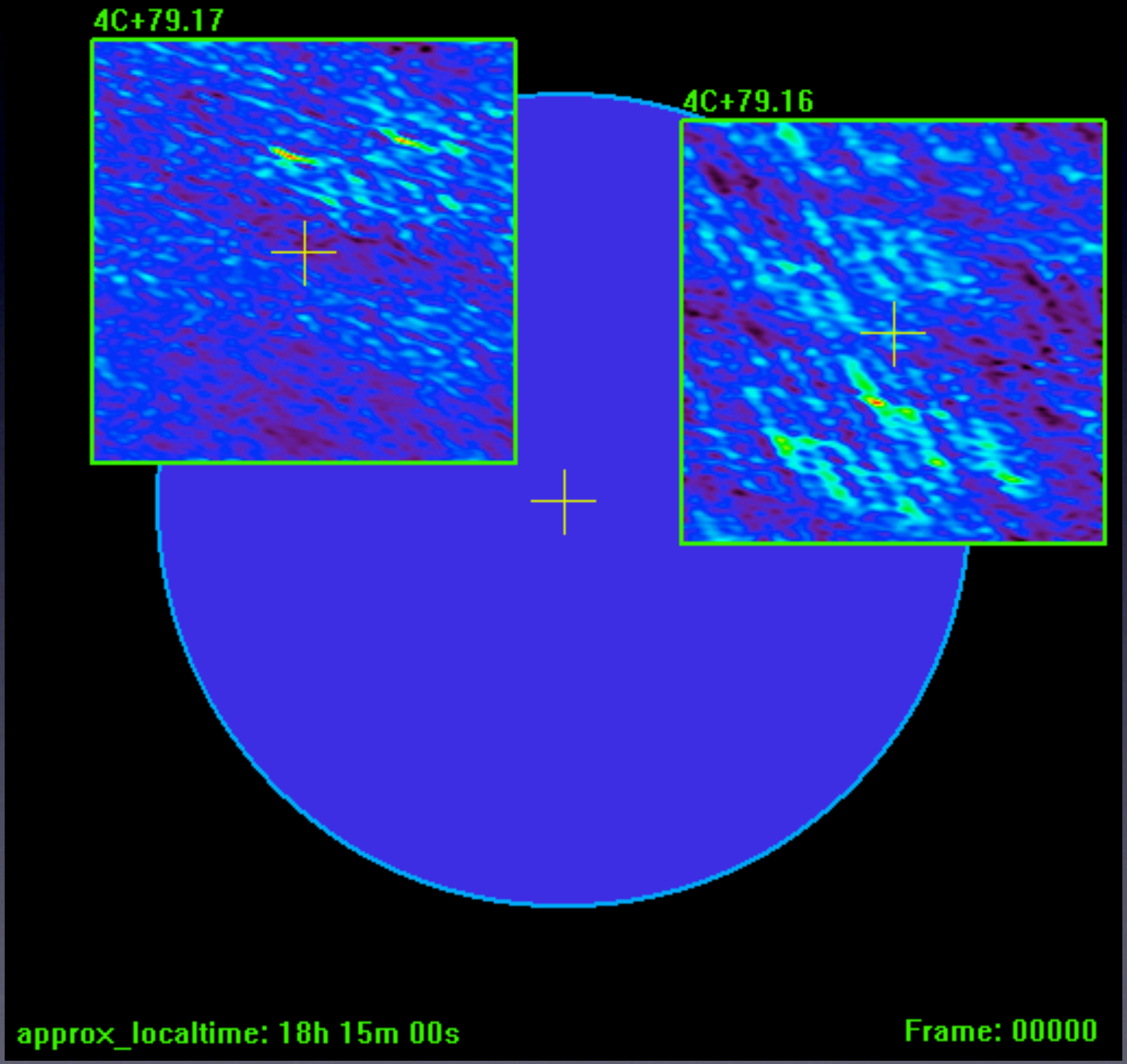

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Wide field imaging

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- Normal self calibration
- Field Based SC - Selfcal for a few directions (Cotton)
  - fit phase screen with Zernike polynomials (eg VLSS)
- Peeling algorithms (Noordam)
  - remove source one by one, in decreasing order of flux (contamination from other sources limits the method)
- SPAM (Intema) - FBSC + Peeling, use Karhunen Loève basis
- Demixed Peeling (van der Tol)
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"If a source is strong enough to cause errors, it is strong enough to correct with" (Noordam)

Radio Frequency Interference (RFI)

RFI is the biggest problem for low frequency astronomy, and is only going to get worse

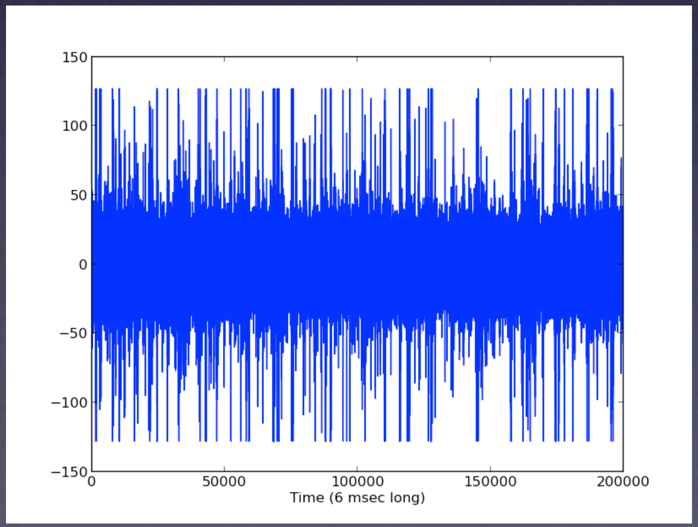
- Go to a radio quiet site
  - increasingly difficult to find one
- Repair/fix RFI sources
  - slow, Sisyphian
- Legal protection (eg GMRT)
  - limited in scope
- Go to the far side of moon
- Prevent RFI entering antenna
  - adaptive, filters, nulling (difficult)
- RFI excision algorithms
  - most feasible

(from Subhasis)

Radio Frequency Interference (RFI)

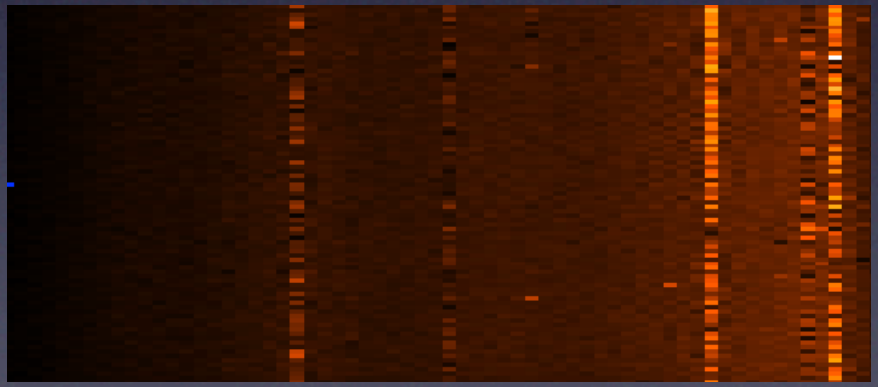
- Manual flagging (mindless, soul-destroying, for small datasets)
- Semi-automated flaggers
  - clip at constant level, but need to manually choose threshold
  - more complex algorithms, but need to fine-tune parameters
- Fully automated flaggers - being developed

Flag raw voltages



Raw voltage data from GMRT

Flag visibilities



CasaPy (from U. Rau)

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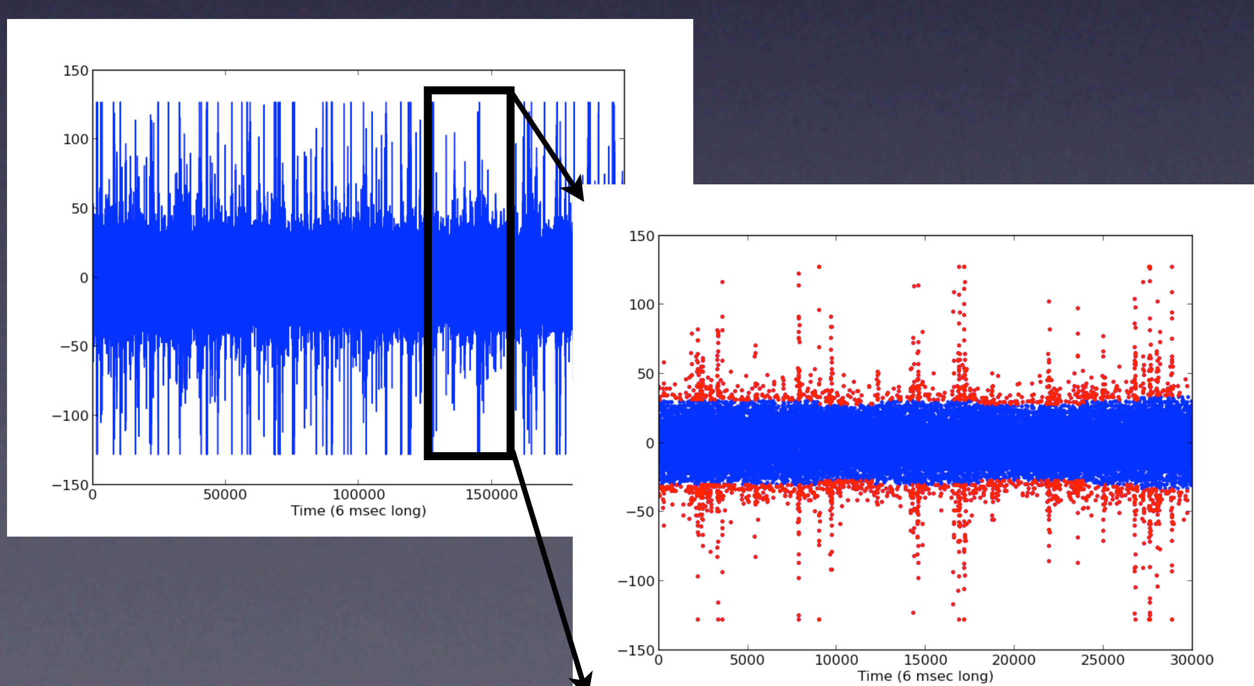

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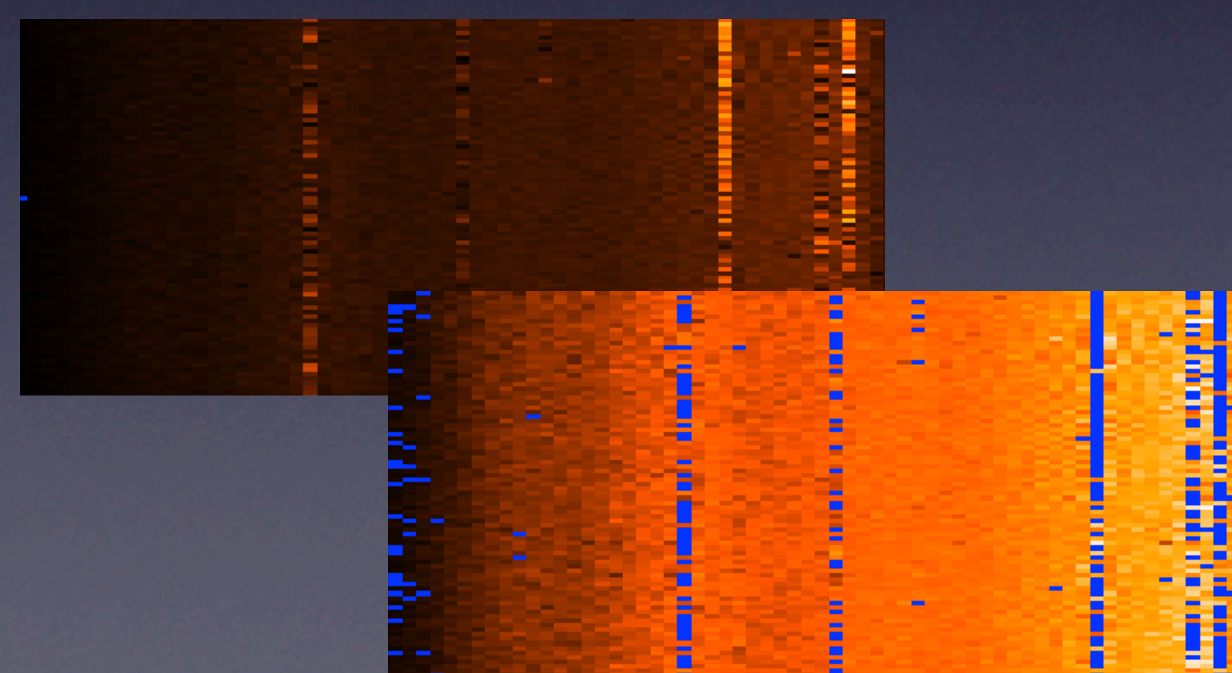
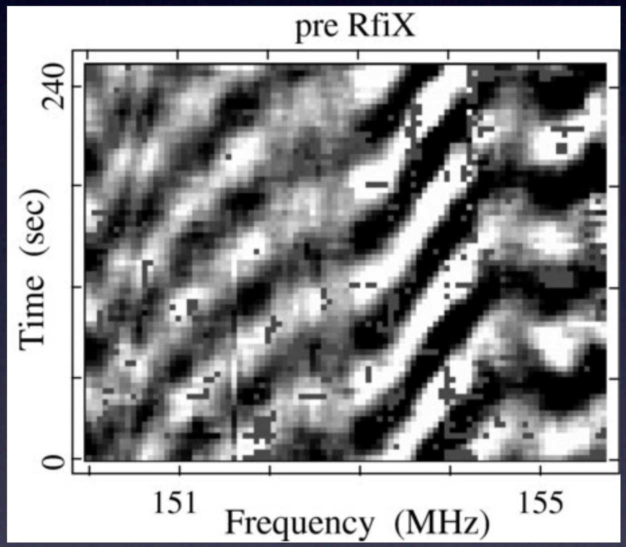


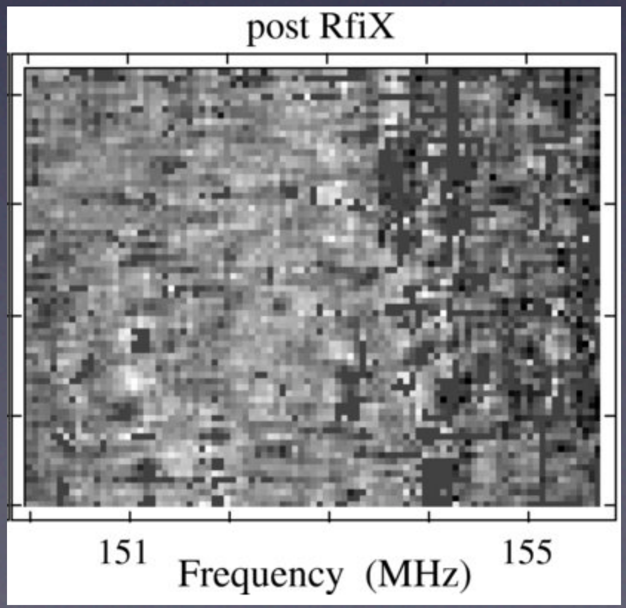
CasaPy (from U. Rau)

Radio Frequency Interference (RFI)

Detect RFI through different fringe rate (Athreya)

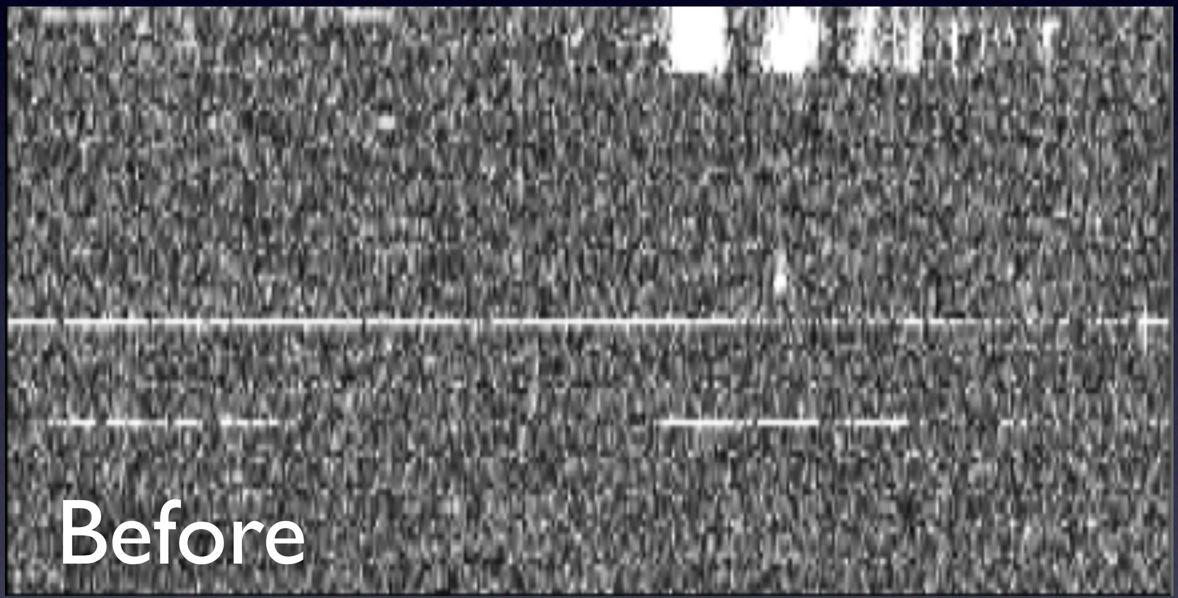
Stationary source will oscillate at fringe stopping rate

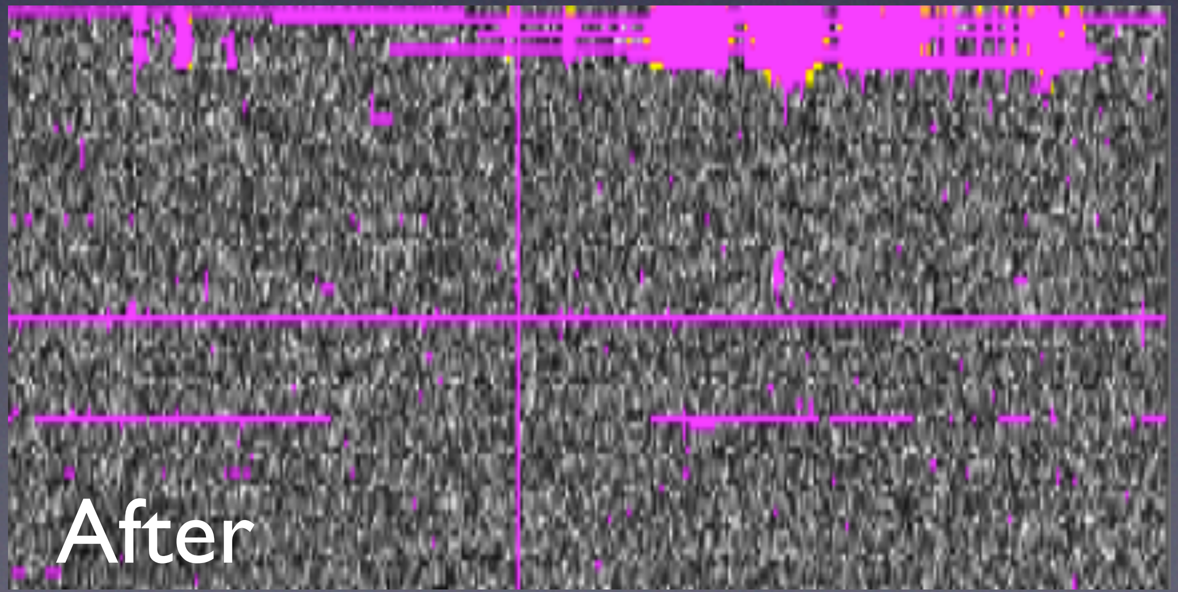




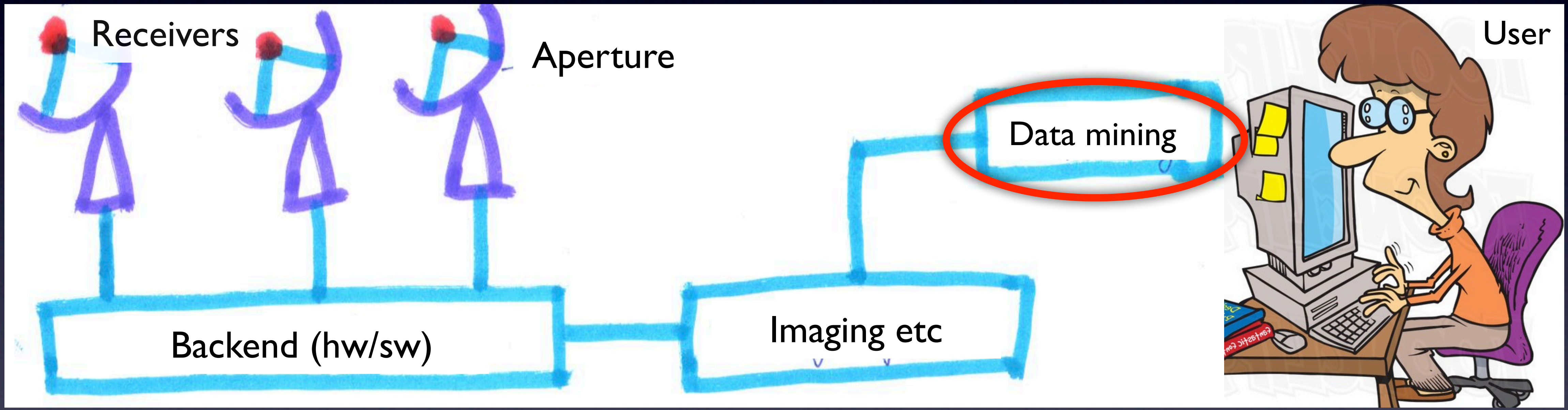
Detect RFI as outliers in time-frequency plane

Various algorithms for detecting outliers (Offringa)





Upgrades : From the aperture to the user



Data usage

All-Sky Surveys : Image data can be huge (10s of Terabytes)

- storage, retrieval, source extraction, multi-wavelength etc
- need automated pipelines
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- accept and generate triggers for other wavebands
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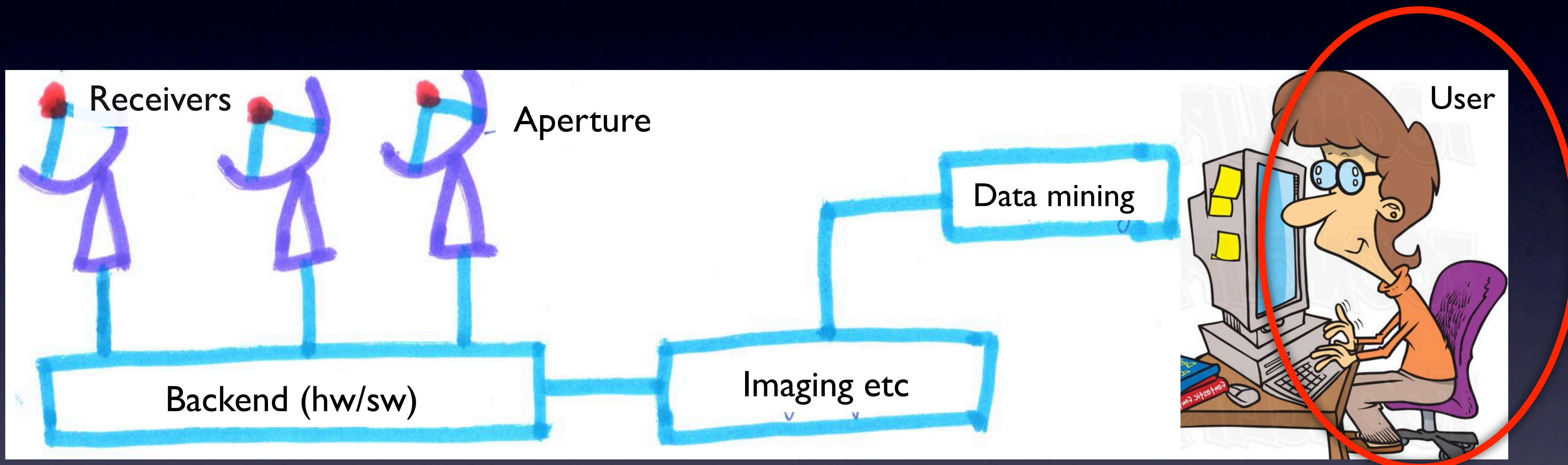
Need to understand instrument and data - automate 'art'

Upgrades : From the aperture to the user



Upgrading the Astronomer

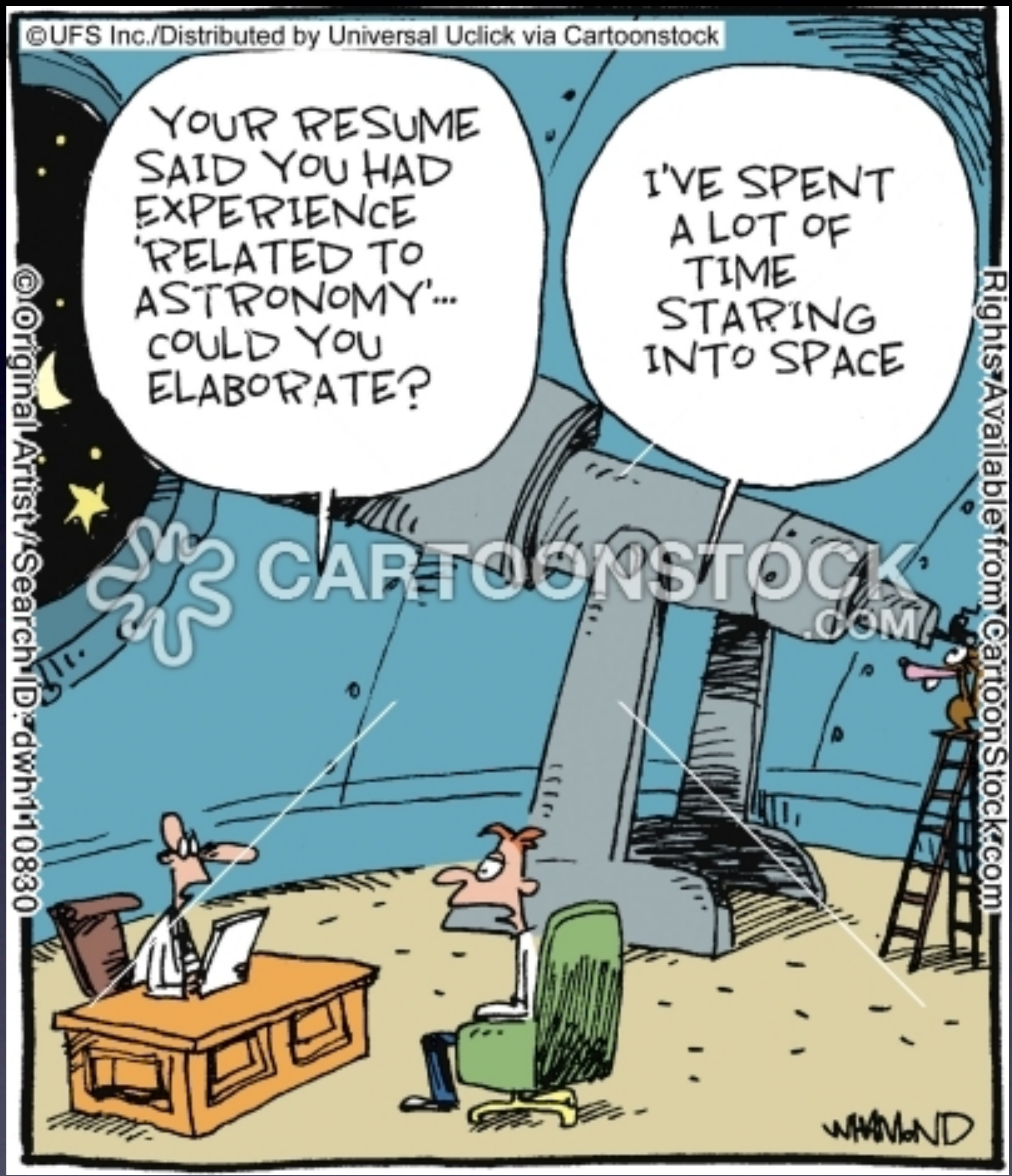
There is plenty to do !

Many new telescopes being built around the world

need ~100 engineers per telescope

need 10s of astronomers to test and use

⇒ job opportunities are plenty



Need people trained in

Engineering (mechanical, civil, electronic)

High performance computing

Mathematicians (algorithms)

Astronomers (designing + usage)

Era of multiwavelength astronomy

Era of automated pipelines

No more sitting with your own data for weeks

All major telescopes will have automated pipelines

Public data, Virtual Observatories etc

Credits : Images taken from all over the internet

There is plenty to do !

Go forth and experiment