# *e*–VLBI

## A real-time telescope spanning Europe

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*&*

*Sterrewacht Leiden*

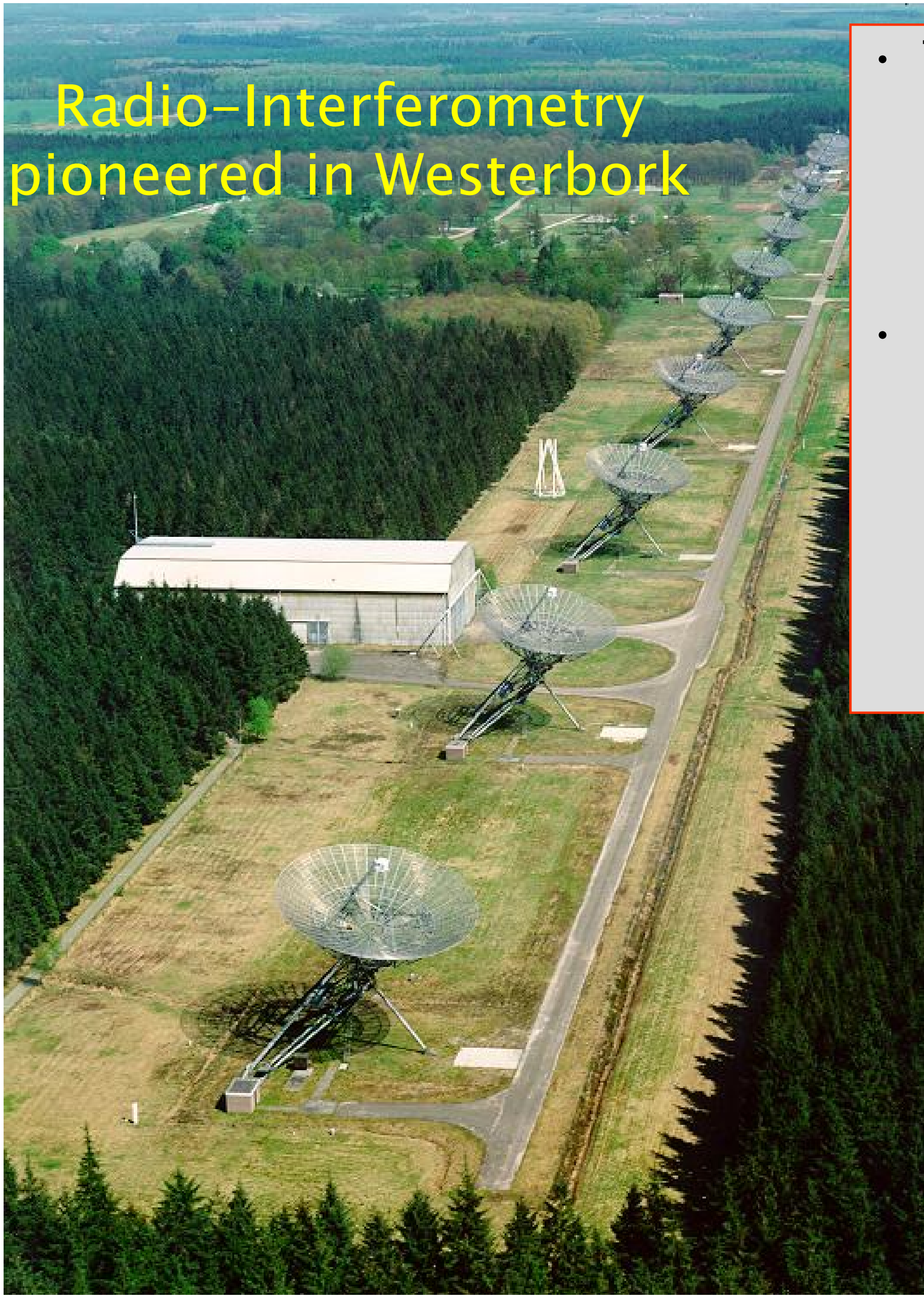
# Introduction

- Even voorstellen…

- Wetenschap & Techniek, Sterrenkunde & Informatica
  - NWO funded project SCARIe
  - EC funded project EXPReS::FABRIC

- It's about e-VLBI and "distributed correlation"
  - Introduction to radio-interferometry
  - Explaining Very Long Baseline Interferometry
  - Show how it is limited by bandwidth
  - Progress in eVLBI
  - And introduce distributed correlation on the Grid

  - Astronomical applications




- To reach interesting resolution:

$$\theta \approx \frac{\lambda}{D}$$

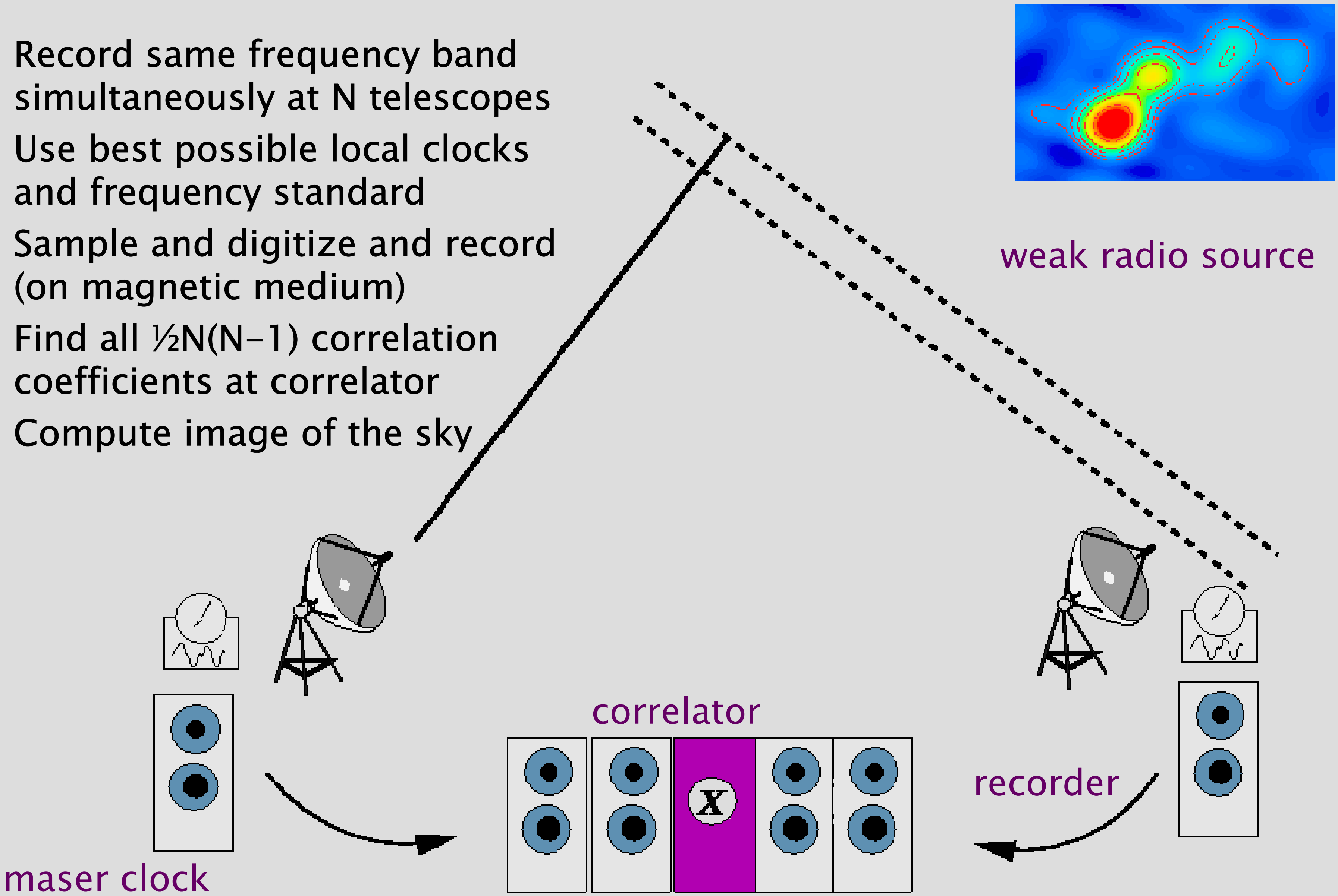
- Interferometer measures Fourier components of the sky brightness
  - Can be done as electronics can be used in phase stable manner
  - Requires common clock
  - Calibrated cables
  - And central correlator


EUROPEAN
vlbi
NETWORK
Jodrell Bank Lovell (UK)
Onsala 20m (SE)
Onsala 25m (SE)
Dwingeloo (NL)
JIVE
JOINT INSTITUTE FOR VLBI IN EUROPE
Jodrell Bank Mk2 (UK)
Metsähovi (FI)
Arecibo (PR)
Cambridge (UK)
Torun (PL)
Urumqi (CN)
Hartebeesthoek (ZA)
Westerbork (NL)
Wettzell (DE)
Seshan (CN)
Effelsberg (DE)
Medicina (IT)
Robledo (ES)
Yebes (ES)
Noto (IT)

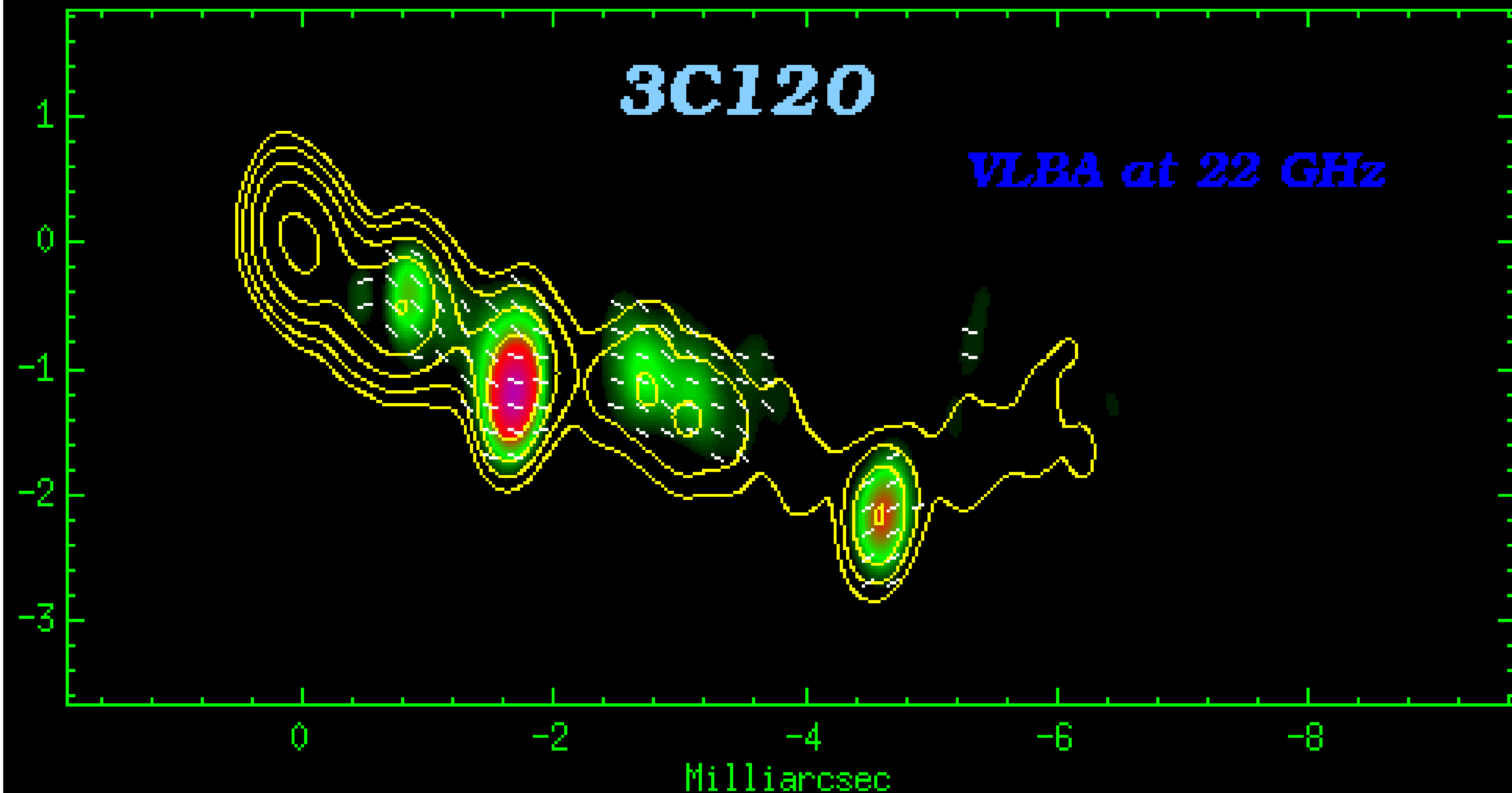

JIVE

# Principle of VLBI

- Record same frequency band simultaneously at N telescopes
- Use best possible local clocks and frequency standard
- Sample and digitize and record (on magnetic medium)
- Find all ½N(N−1) correlation coefficients at correlator
- Compute image of the sky



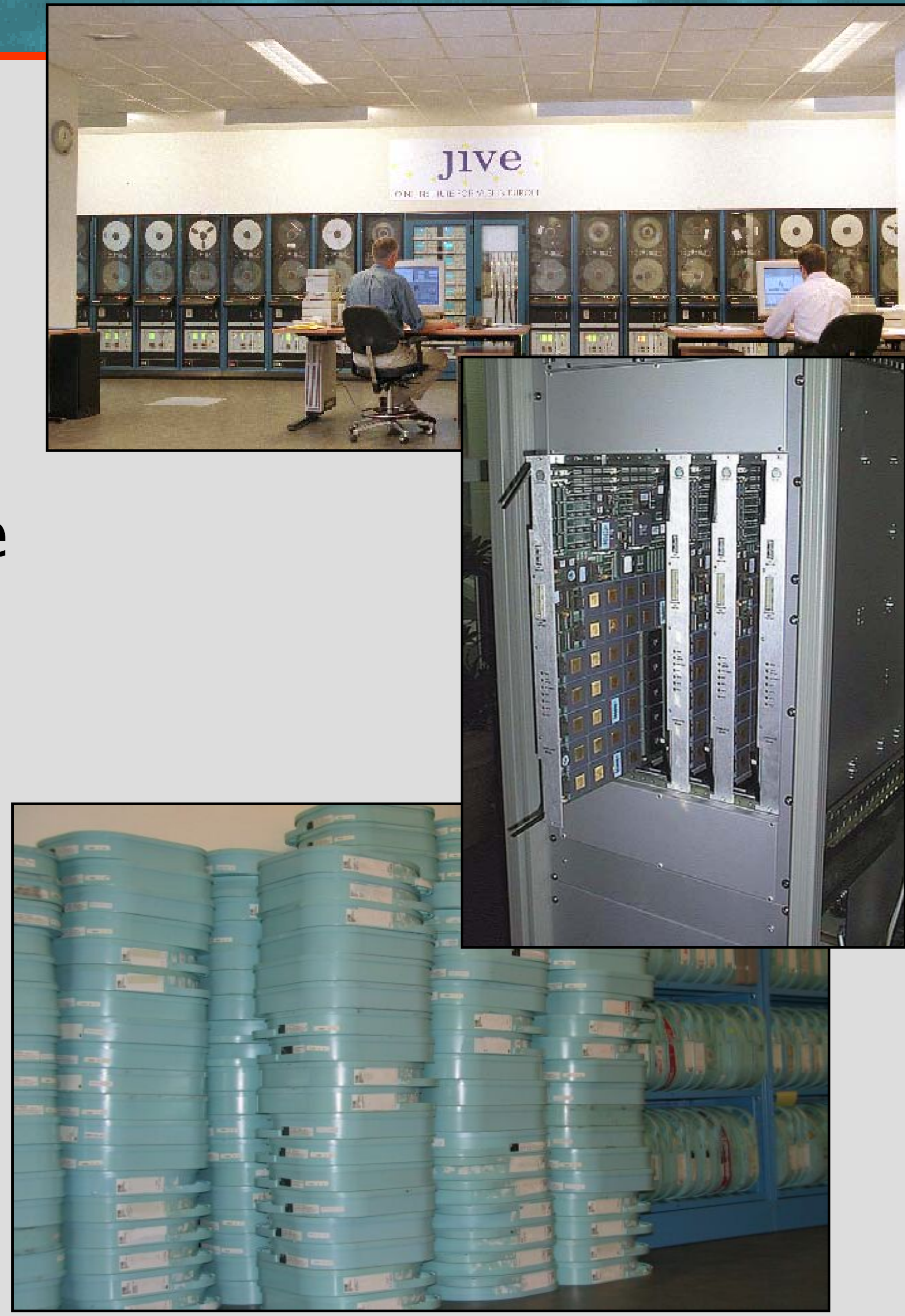
Results in extraordinary high resolution (for bright objects)




High enough to see things move at cosmological distance...

# VLBI in practice

- EVN observes with 6 – 10 telescopes
  - Global observations with 16 – 20 telescopes
  - Three session per year
    - Session of 250 – 350 hour
- Correlation requires close quality control
  - For example calibration of clocks better than 0.1µs
  - Correlation based on geodetic model
- Time granted on scientific merit
  - Investigator receives output data
  - And support for processing

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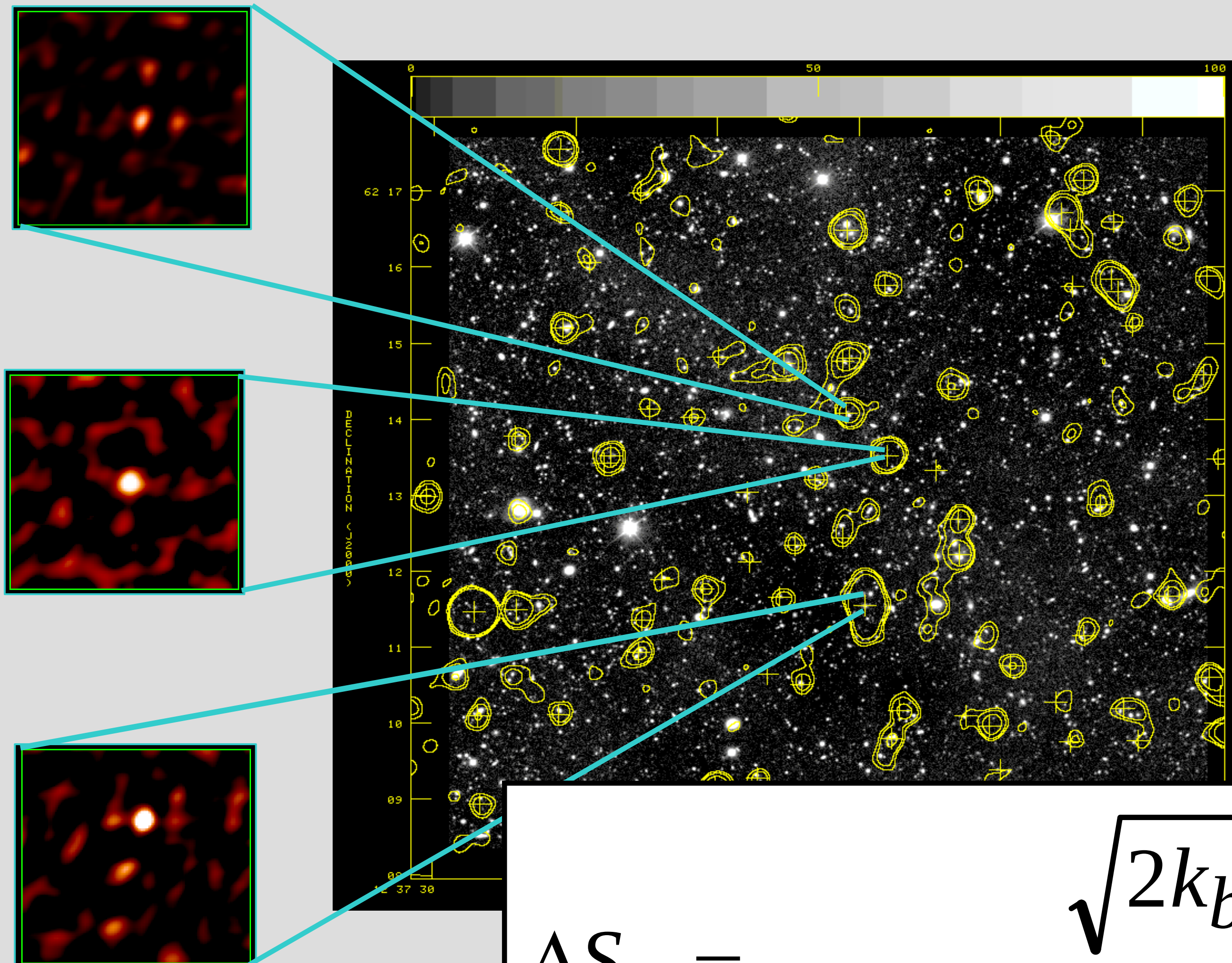
# Astronomy: always pushing for sensitivity




radio sources in the Hubble deep field require several days of integration (Garrett et al., 2000)

$$\Delta S_{\upsilon} = \frac{\sqrt{2 k_b T_{sys}}}{\eta_a \eta_c A \sqrt{\Delta t \boxed{\Delta \nu}} \sqrt{\frac{1}{2} N(N-1)}}$$

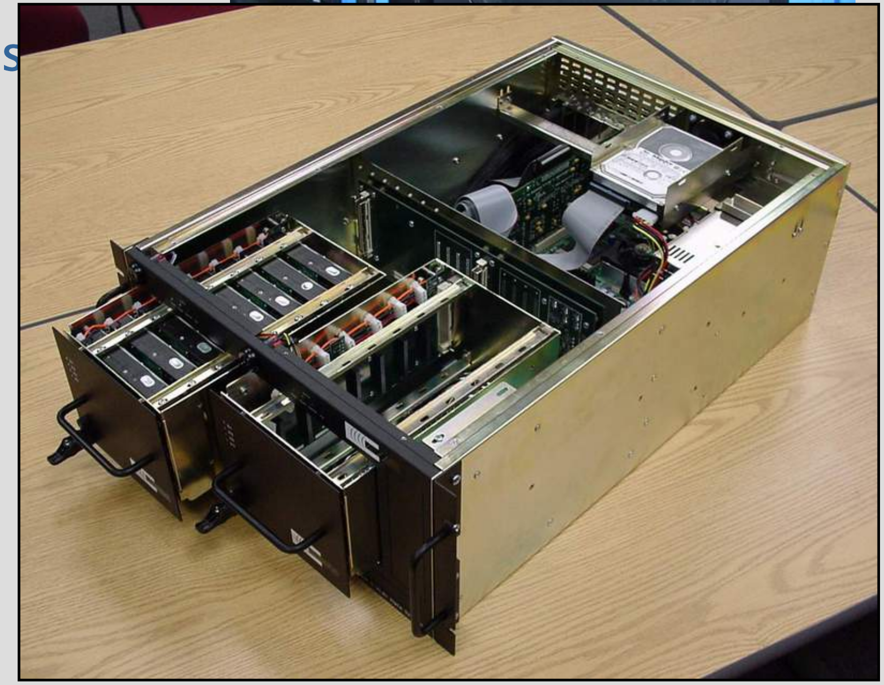
# New telescopes being built

40m antenna at Yebes, Spain
Radio and mm frequencies

Sardinia Radio Telescope
64m; radio to millimeter

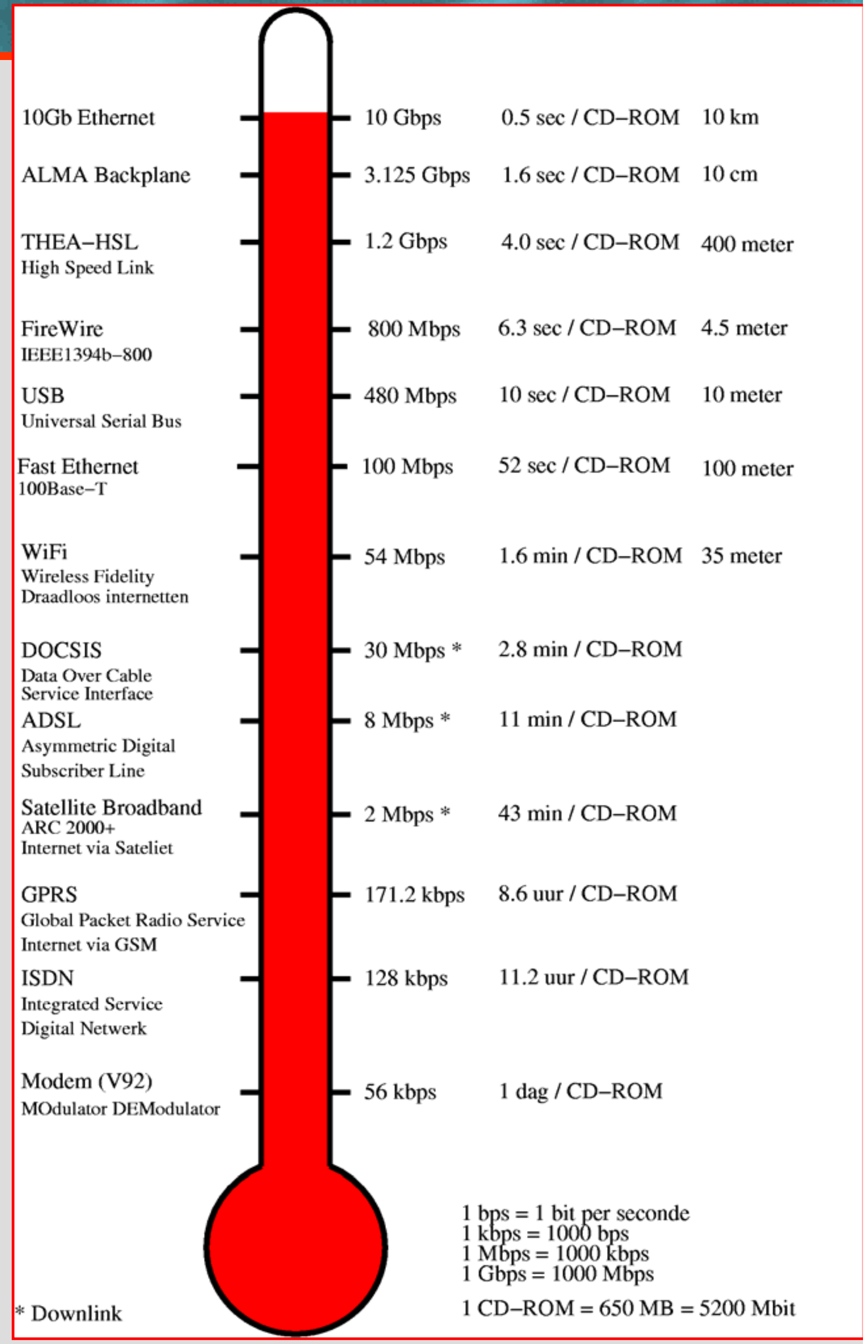
# tape recorders

- Tapes: Technology of the 80s
  - 6 km tape length, 32 tracks, 16 positions
  - Total capacity: ≈ 1 TB
    - 1.5 hour recording at highest bandwidth
  - Expensive and vulnerable
    - Operates at $10^{-3}$ to $10^{-6}$ error rate
- Nowadays disk recording
  - Uses parallel recording like hard disk recorder for video
  - More reliable, better data quality
  - More efficient to use
    - Direct access compared to tape
    - Unattended operations
  - Capacity grows with commercial demand
  - Step to larger bandwidth



# e-VLBI is connected

- Typical VLBI uses 64 MHz bandwidth in 2 pols
- Nyquist sampling: 2 x 2 x 64 MHz = 256 M samples/s
  - Fortunately these noisy signals can do with 2 bit representation
- Thus 512 Mbit/s
  - Which is hard enough through 1 Gb/s ethernet
- Need to sustain across Europe or the world
  - often the “last mile” is the bottleneck
  - Needs real digging…

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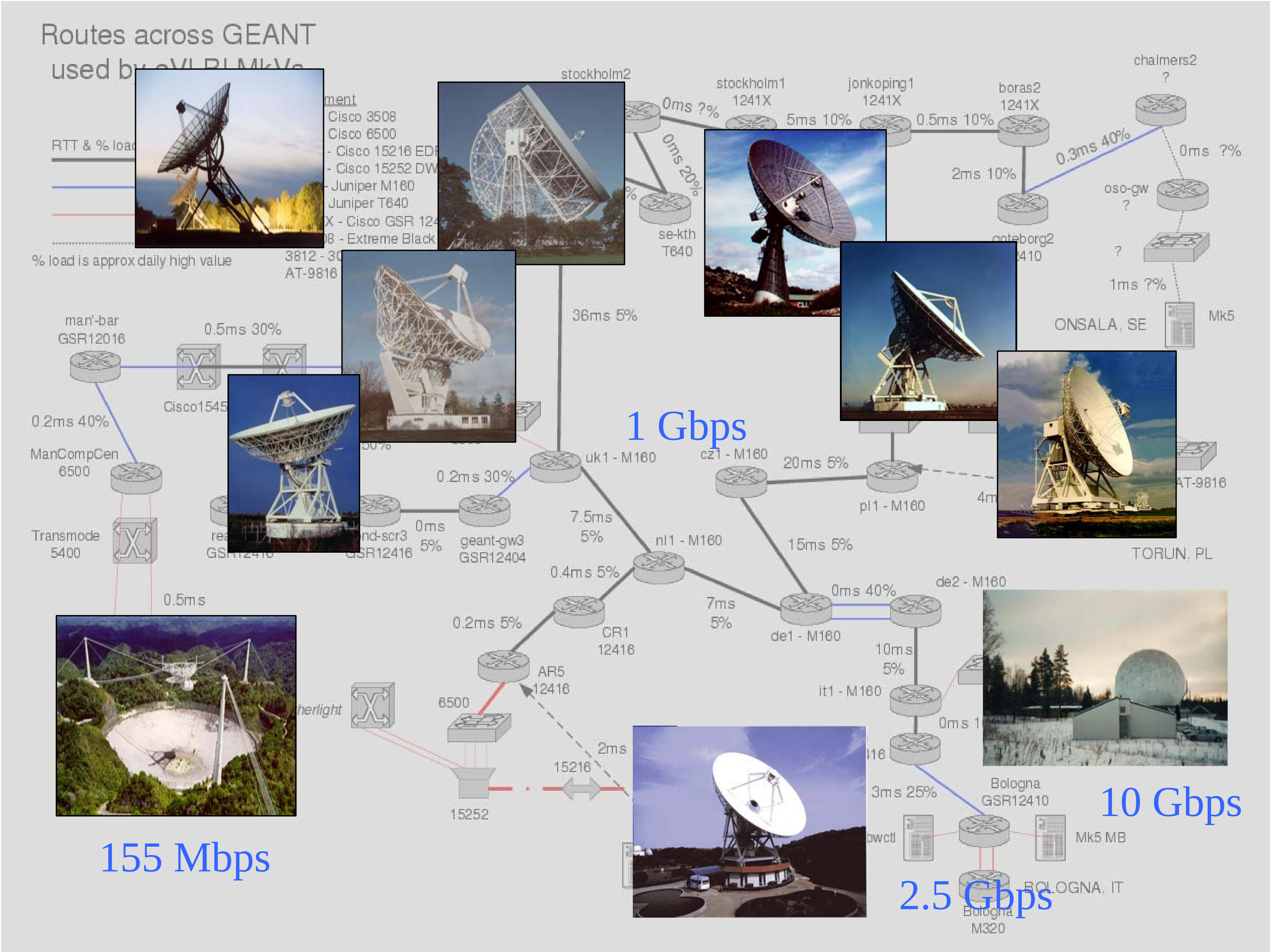
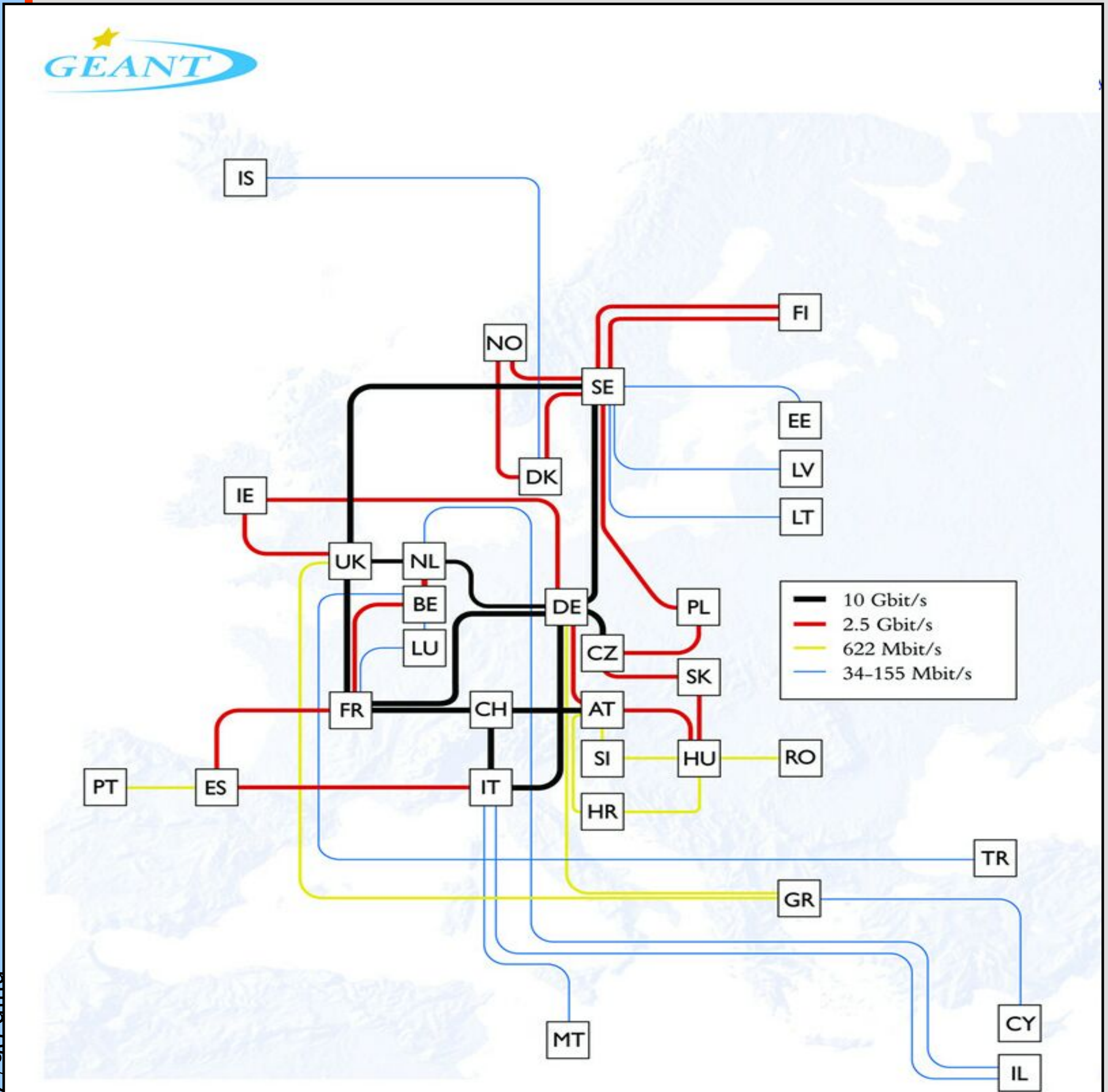
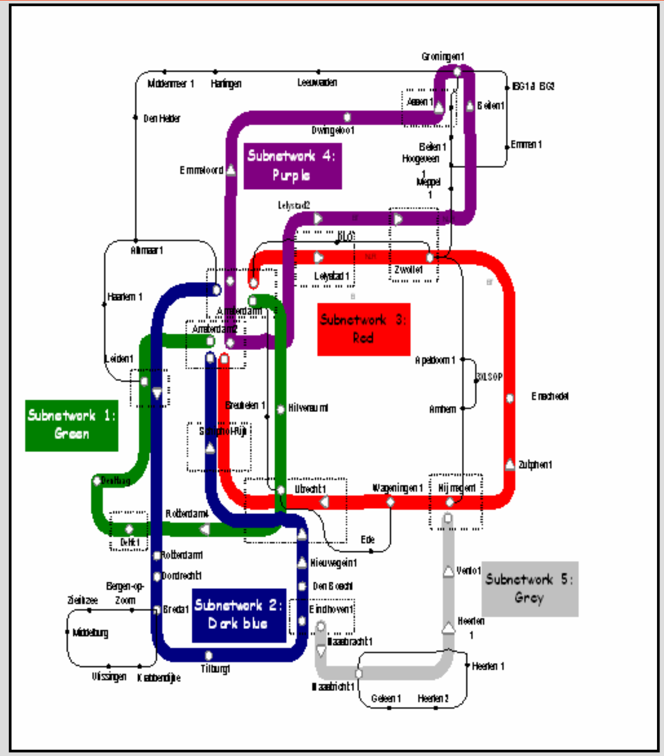

Routes across GEANT
used b
RTT & % loa
% load is approx daily high value
ment
Cisco 3508
Cisco 6500
- Cisco 15216 EDF
- Cisco 15252 DW
- Juniper M160
Juniper T640
X - Cisco GSR 124
08 - Extreme Black
3812 - 3
AT-9816
stockholm2
0ms ?%
0ms 20%
se-kth
T640
stockholm1
1241X
jonkoping1
1241X
5ms 10%
0.5ms 10%
boras2
1241X
2ms 10%
goteborg2
chalmers2
?
0.3ms 40%
0ms ?%
oso-gw
?
?
1ms ?%
ONSALA, SE
Mk5
36ms 5%
man-bar
GSR12016
0.5ms 30%
Cisco1545
0.2ms 40%
ManCompCen
6500
Transmode
5400
0.5ms
1 Gbps
uk1 - M160
0.2ms 30%
cz1 - M160
20ms 5%
pl1 - M160
AT-9816
TORUN, PL
0ms
5%
geant-gw3
GSR12404
7.5ms
5%
nl1 - M160
15ms 5%
0.4ms 5%
7ms
5%
de1 - M160
0ms 40%
de2 - M160
0.2ms 5%
CR1
12416
AR5
12416
10ms
5%
it1 - M160
6500
15216
2ms
15252
3ms 25%
Bologna
GSR12410
Mk5 MB
BOLOGNA, IT
Bologna
M320
155 Mbps
10 Gbps
2.5 Gbps

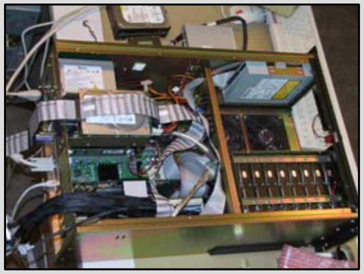
# Academic networks

## Across Europe: Dante

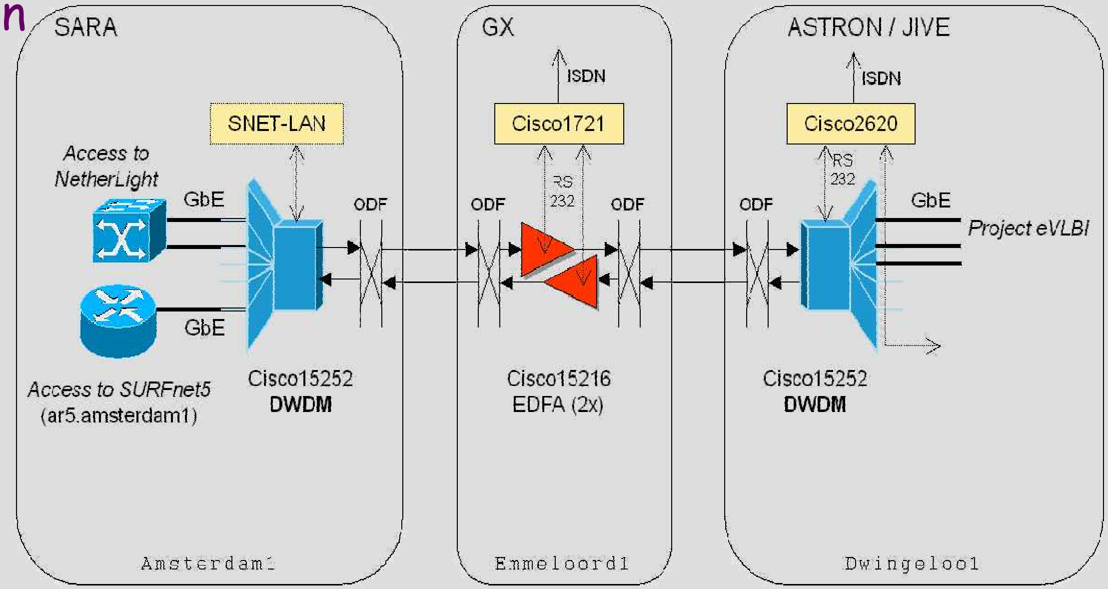



The Netherlands: SURFNet



## Mk5 at station



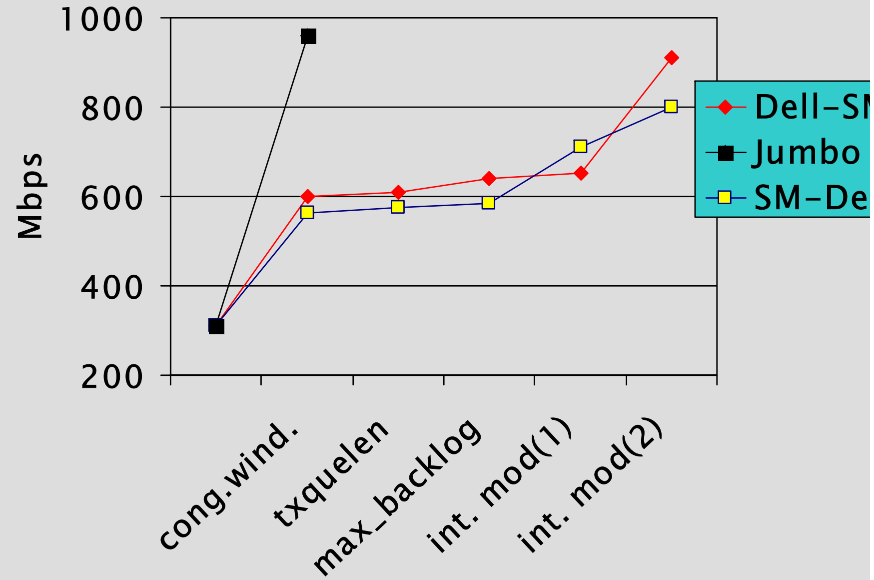

## By Fiber

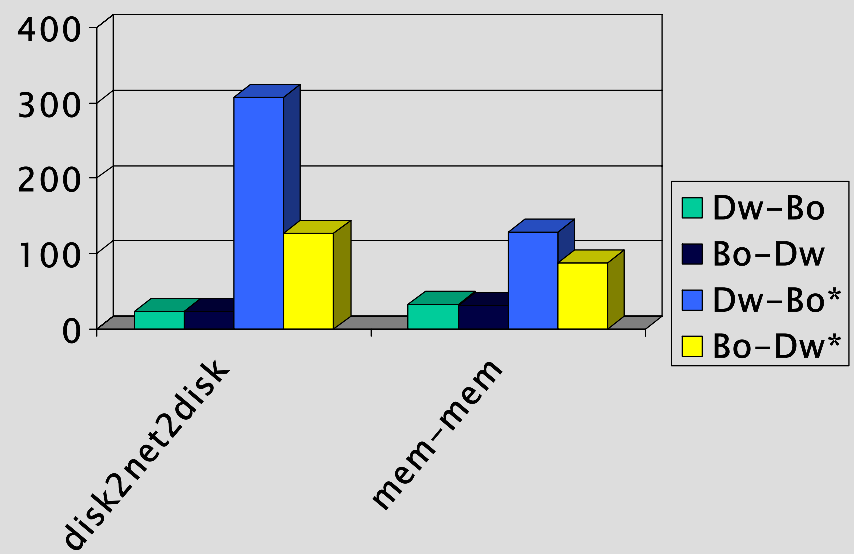
## Into local Gb Ethernet

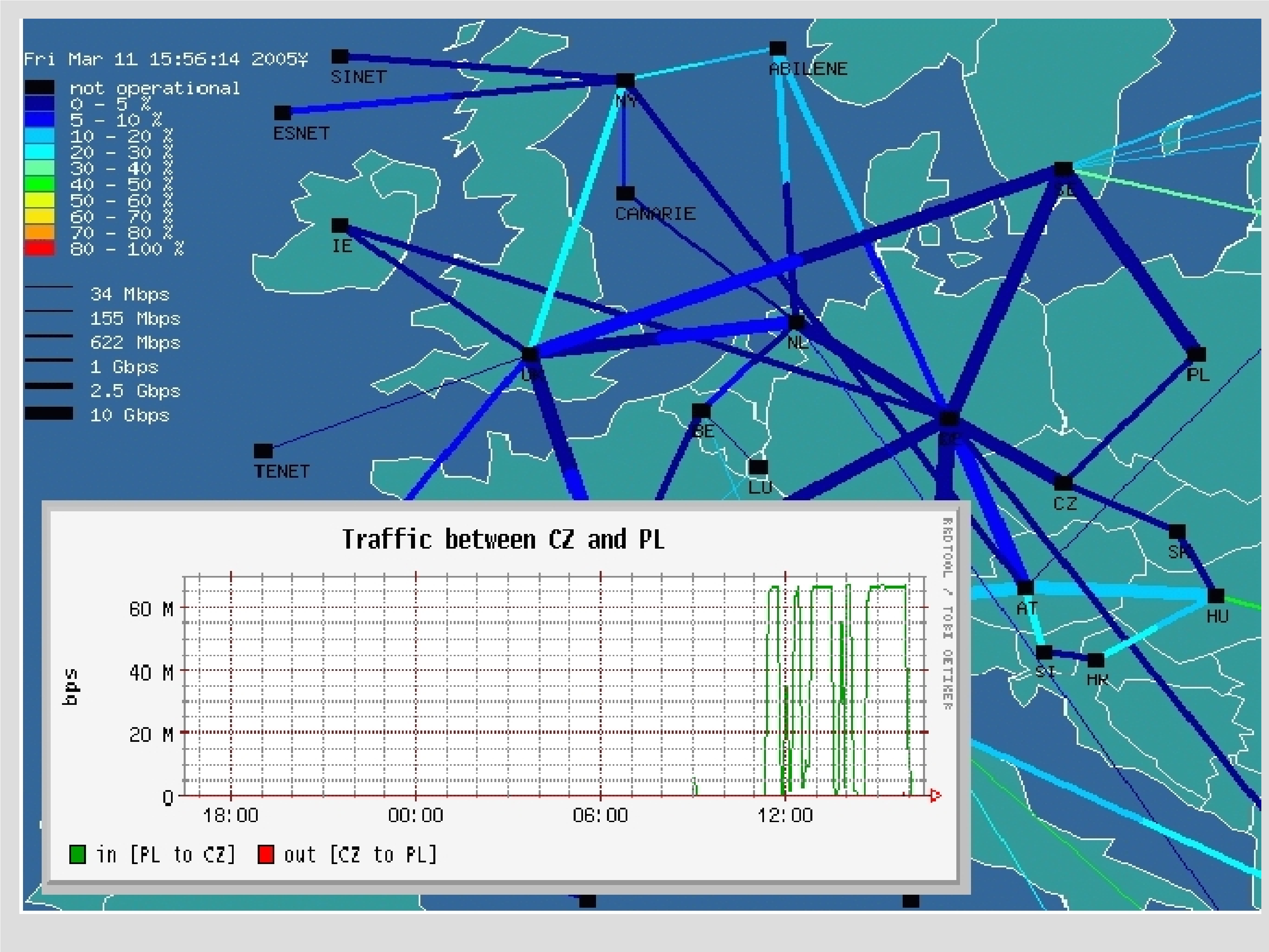
## Mk5 real-time correlation

# Lot of tweaking to get throughput

- Use existing protocols on currently available hardware
  - TCP maximal reliability
    - Sensitive to congestion
    - Lot of fine-tuning necessary
  - UDP connectionless
    - Faster but un-accountable
  - Tailor made protocols
  - Or Lambda switching or dedicated light paths
- Internet weather
  - Hard to control
  - Collaboration with Geant




Fri Mar 11 15:56:14 2005
not operational
0 - 5 %
5 - 10 %
10 - 20 %
20 - 30 %
30 - 40 %
40 - 50 %
50 - 60 %
60 - 70 %
70 - 80 %
80 - 100 %
34 Mbps
155 Mbps
622 Mbps
1 Gbps
2.5 Gbps
10 Gbps
SINET
ESNET
NY
ABILENE
CANARIE
IE
UK
NL
BE
LU
TENET
PL
CZ
SK
AT
HU
SI
HR
Traffic between CZ and PL
bps
60 M
40 M
20 M
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18:00
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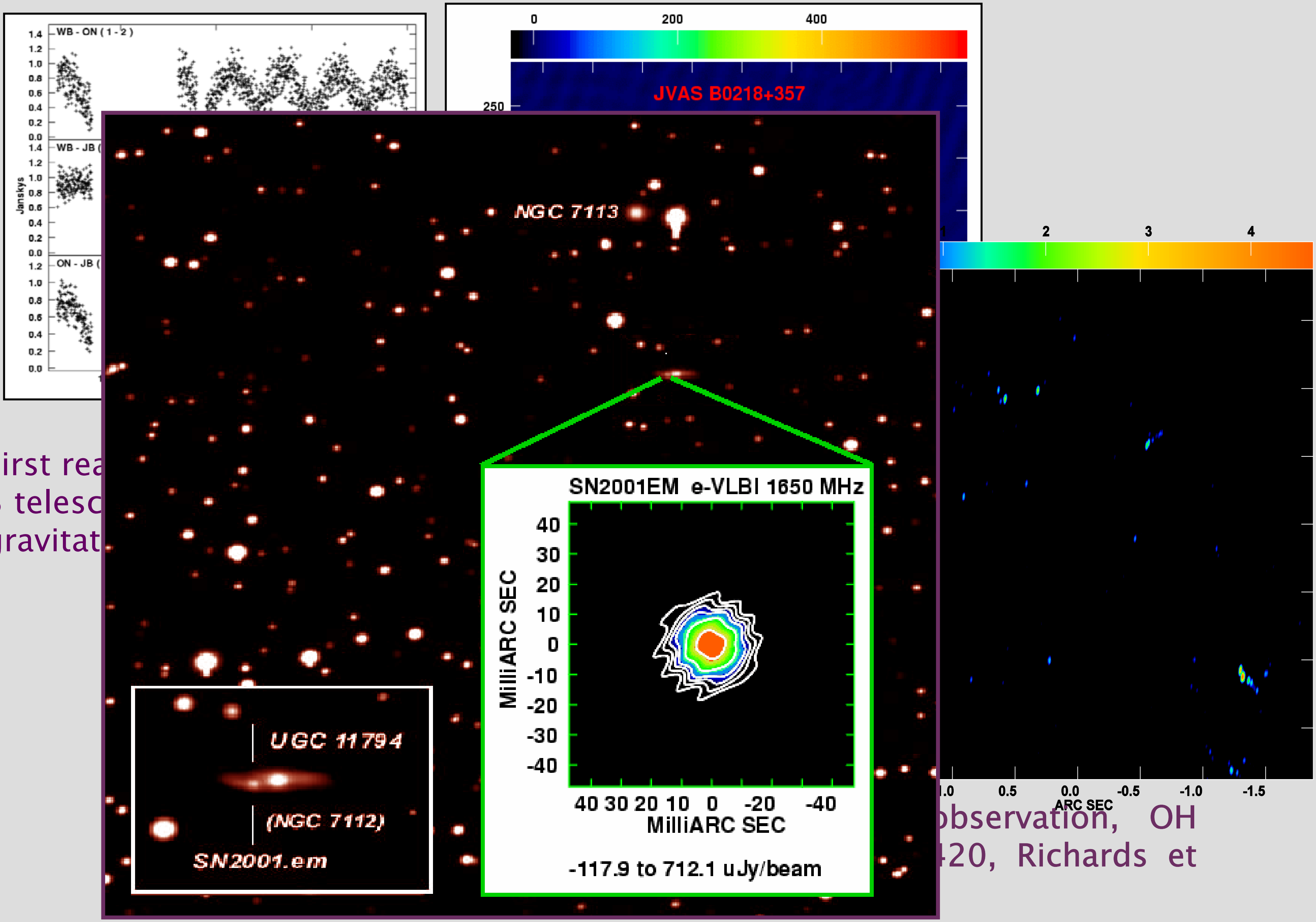
06:00
12:00
in [PL to CZ]
out [CZ to PL]
RRDTOOL / TOBI OETIKER

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20, Richards et

First broadband eVLBI science, detection of the Hypernova SN2001em, Paragi et al, astro-ph/0505468

# Now an operational system

- Offered for astronomical use 1 day / month
  - Using telescopes in the UK, Poland, Sweden, Netherlands, Italy
  - At 256 Mb/s, sometimes reaching 512 Mb/s
- Aimed at time critical observations
  - For example flaring stars
- Will be the standard in 2009

Mon. Not. R. Astron. Soc. 000, 1–?? (2006) Printed 16 September 2006 (MN LaTeX style file v2.2)

## First e-VLBI observations of Cygnus X-3

V. Tudose,[1,2*] R.P. Fender,[3,1] M.A. Garrett,[4] J.C.A. Miller-Jones,[1] Z. Paragi,[4] R.E. Spencer,[5] G.G. Pooley,[6] M. van der Klis[1] and A. Szomoru[4]

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Accepted XXXXXX. Received XXXXXX; in original form XXXXXX

**ABSTRACT**

We report the results of the first two 5 GHz e-VLBI observations of the X-ray binary Cygnus X-3 using the European VLBI Network. Two successful observing sessions were held, on 2006 April 20, when the system was in a quasi-quiescent state several weeks after a major flare, and on 2006 May 18, a few days after another flare. At the first epoch we detected faint emission probably associated with a fading jet, spatially separated from the X-ray binary. The second epoch in contrast reveals a bright, curved, relativistic jet more than 40 milliarcsecond in extent. In the first, and probably also second epochs, the X-ray binary core is not detected, which may indicate a temporary suppression of jet production as seen in some black hole X-ray binaries in certain X-ray states. Spatially resolved polarisation maps at the second epoch provide evidence of interaction between the ejecta and the surrounding medium. These results clearly demonstrate the importance of rapid analysis of long-baseline observations of transients, such as facilitated by e-VLBI.

**Key words:** accretion, accretion discs – stars: individual: Cygnus X-3 – ISM: jets and outflows – radiation mechanisms: non-thermal – techniques: interferometric.

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## First e-VLBI observations of GRS1915+105

A. Rushton,[1*] R. E. Spencer,[1] M. Strong,[1] R. M. Campbell,[2] S. Casey,[1] R. Fender,[3,4] M. Garrett,[2] J. Miller-Jones,[4] G. Pooley,[5] C. Reynolds,[2] A. Szomoru[2] and V. Tudose[4,6]

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Accepted XXXX XXX XX. Received XXXX XXX XX; in original form XXXX XX XX

**ABSTRACT**

We present results from the first successful open call e-VLBI run on the X-ray binary GRS1915+105. e-VLBI science makes possible the rapid production of VLBI radio maps within hours of an observation rather than weeks, facilitating a decision for follow-up observations. 6 telescopes observing at 5 GHz across the European VLBI Network (EVN) were correlated at Joint institute for VLBI in Europe (JIVE) in real time. Data rates of 128 Mbit $s^{-1}$ were transferred from each telescope, giving 4 TB of raw sampled data over the 12 hours of the whole experiment. Throughout this, GRS1915+105 was observed for a total of 5.5 hours, producing 2.8 GB of recorded visibilities of correlated data. A weak flare occurred during our observations, and we detected a slightly resolved single component of 2.7 by 1.2 milliarcsecond was detected at a position angle of $140° \pm 2°$. The peak brightness was 10.2 mJy per beam, with a total integrated radio flux of 11.1 mJy.

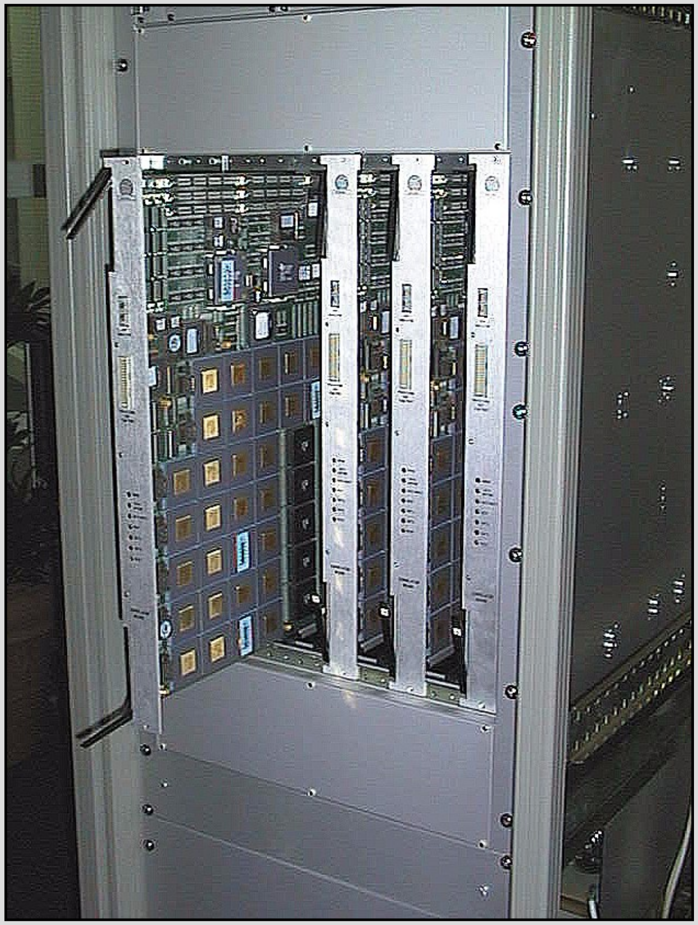
**Key words:** ISM: jets and outflows - X-ray binaries: individual (GRS1915+105).

# What’s next? The correlator…

- Receives the data inputs (on Internet?)
    - Decodes the time stamps and aligns the data
- Correlator calculates ½N(N−1) baseline outputs
    - after compensating for the geometry of array
    - Integrates output signal to something relatively slow
    - and samples with delay/frequency resolution

# EVN MkIV data processor at JIVE

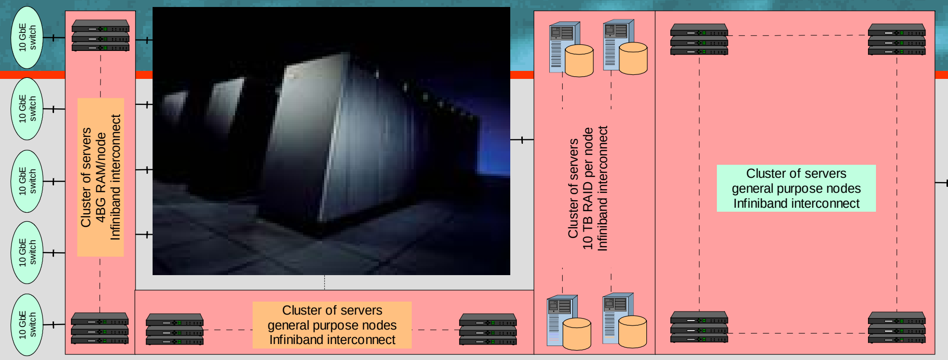
- Implements this in custom silicon
  - 16 stations input from tapes
  - now hard-disks and fibres
- Input data is 1 Gb/s max
  - 1 or 2 bit sampled
  - up to 16 sub-bands
  - format includes time codes
- "Super computer" 1024 chips
  - 256 complex correlations each
  - at 32 MHz clock
- Around 100 T-operations/sec
  - 2 bit only!
  - Depends a bit how you do it



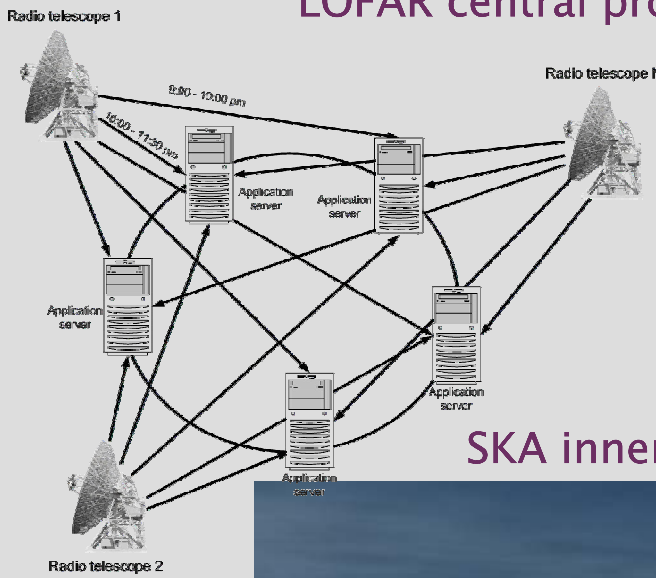
Should next correlator also use special hardware?

# Next generation…

- Can be implemented on standard computing?
  - Time critical, keep up with input
    - example: LOFAR on BlueGene
  - Higher precision and new applications
    - Better sensitivity, interference mitigation, spacecraft navigation
- Can CPU cycles be found on the Grid?
  - From 16 antenna @ 1Gb/s (eVLBI)
    - And growing…
  - To 1000s at 100 Gb/s (SKA)
  - Pilot projects FABRIC & SCARIe
    - Connectivity, workflow
    - Real-time resource allocation




LOFAR central processor

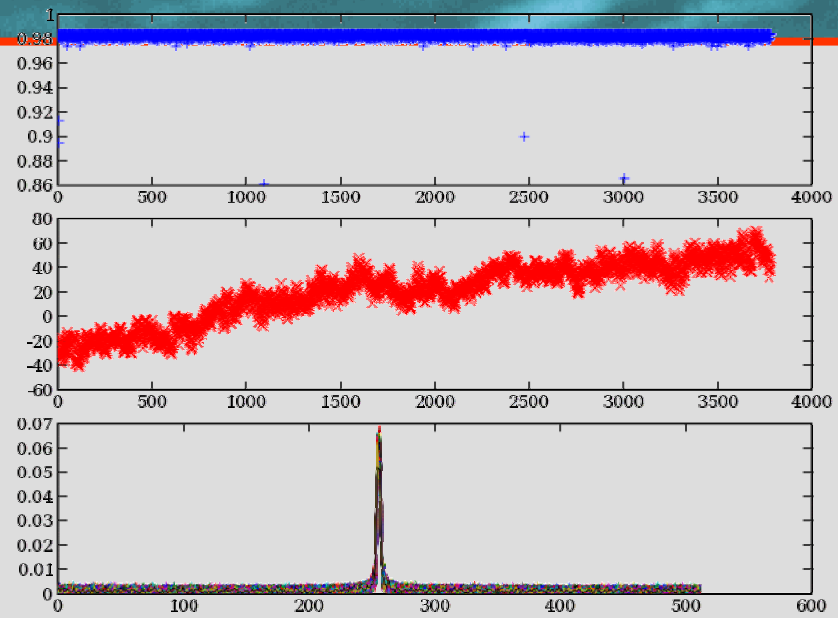



FABRIC eVLBI

SKA inner core (5km)

# Tflops, Pflops…

- 2 bit operations ⇒ floating point
  - Results in enormous computing tasks
  - Very few operations / bit
  - Some could be associated with telescope



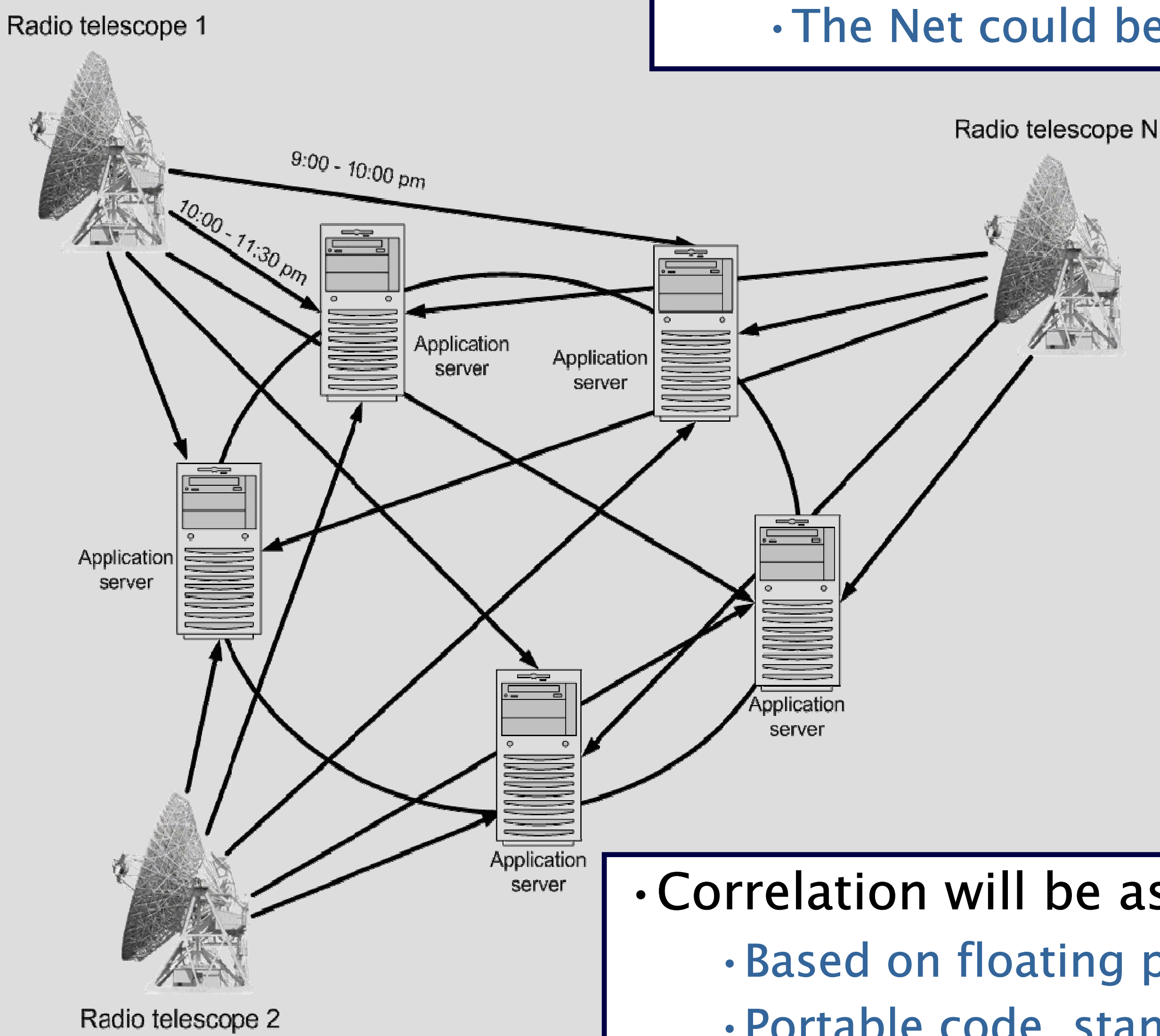
| typical VLBI problems | | | | | |
|---|---|---|---|---|---|
| description | N telescopes | N subbands | data-rate [Mb/s] | N spect/prod | Tflops |
| 1 Gb/s full array | 16 | 16 | 1024 | 16 | 83.89 |
| typical eVLBI continuum | 8 | 8 | 128 | 16 | 2.62 |
| typical spectral line | 10 | 2 | 16 | 512 | 16.38 |
| FABRIC demo | 4 | 2 | 16 | 32 | 0.16 |
| future VLBI | 32 | 32 | 4096 | 256 | 21474.84 |

SKA not even in here…

*Rough estimate based on XF correlation*

# Basic idea

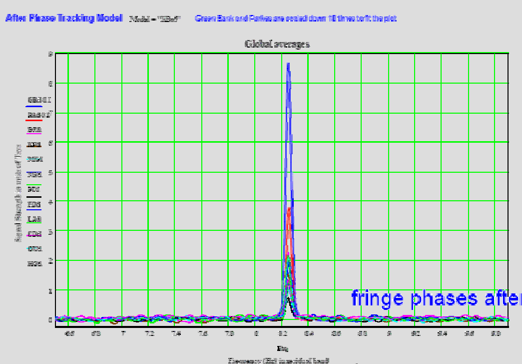
- Use the Grid for correlation
  - CPU cycles on compute nodes
  - The Net could be crossbar switch?



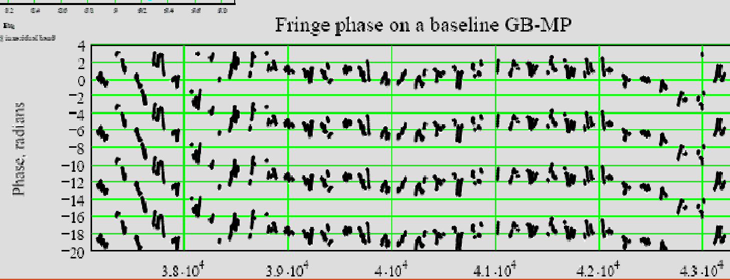

- Correlation will be asynchronous
  - Based on floating point arithmetic
  - Portable code, standard environment

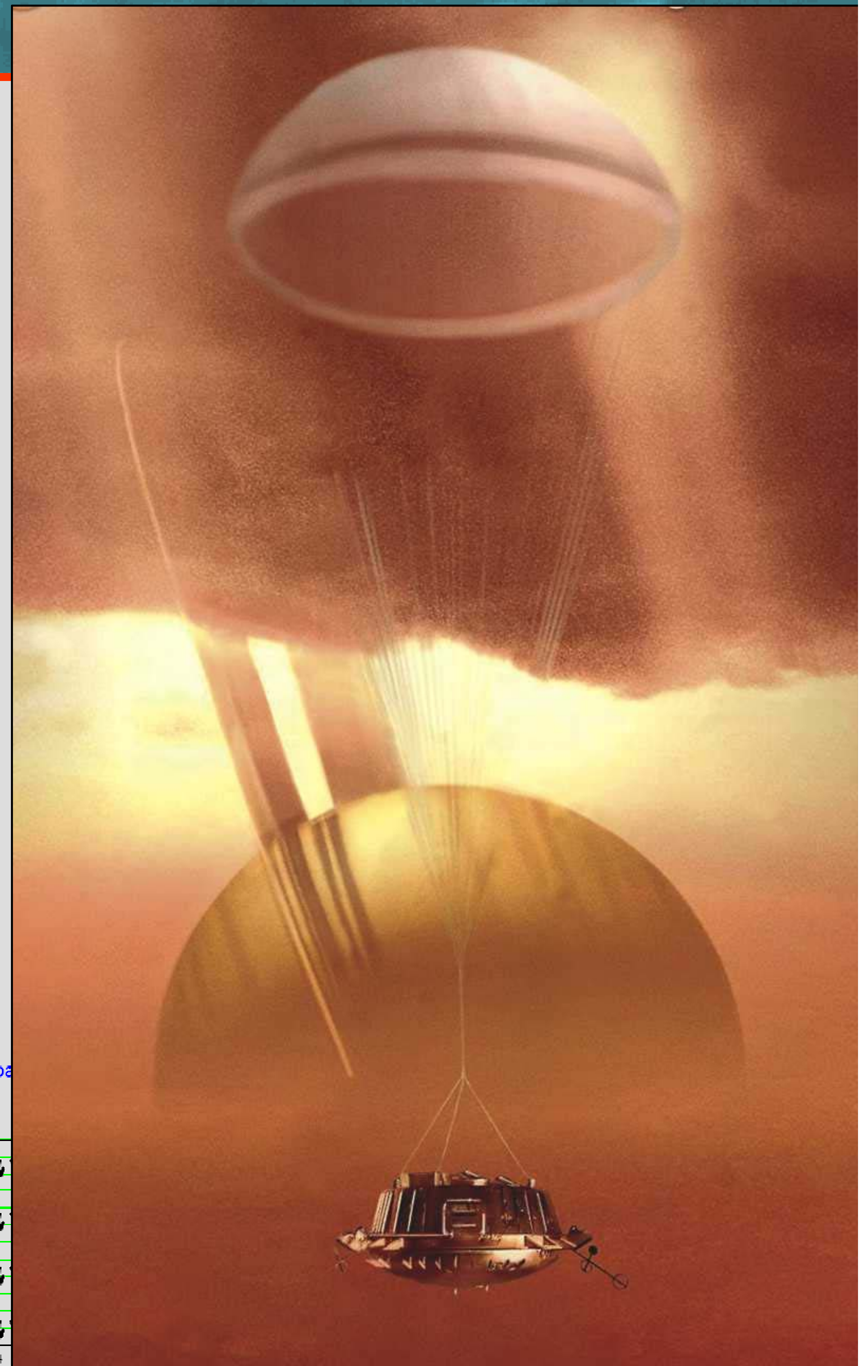
# Software correlation

- Builds on previous experience at JIVE
  - regular and automated network performance tests
    - Using Japanese software correlator from NICT
  - Huygens extreme narrow band correlation
    - Home grown superFX with  sub-Hz resolution




Huygens carrier signal
fringe phases after cross-correlation in 30 mHz wide phase tracking ba



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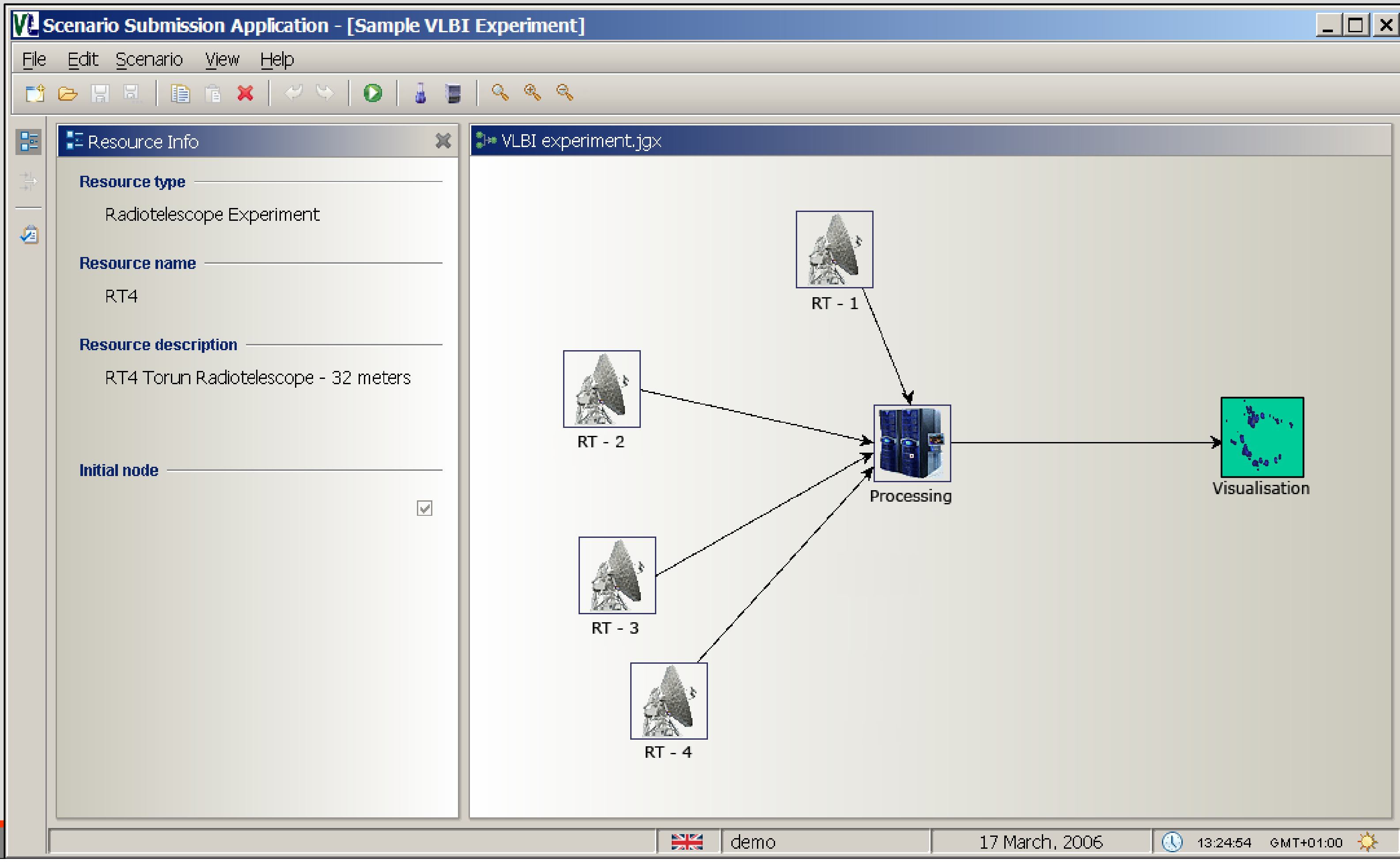
# Workflow Management

- Must interact with normal VLBI schedules
  - Divide data, route to compute nodes, setup correlation
  - Dynamic resource allocation, keep up with incoming data!

Effort from Poznan, based on their Virtual Lab.

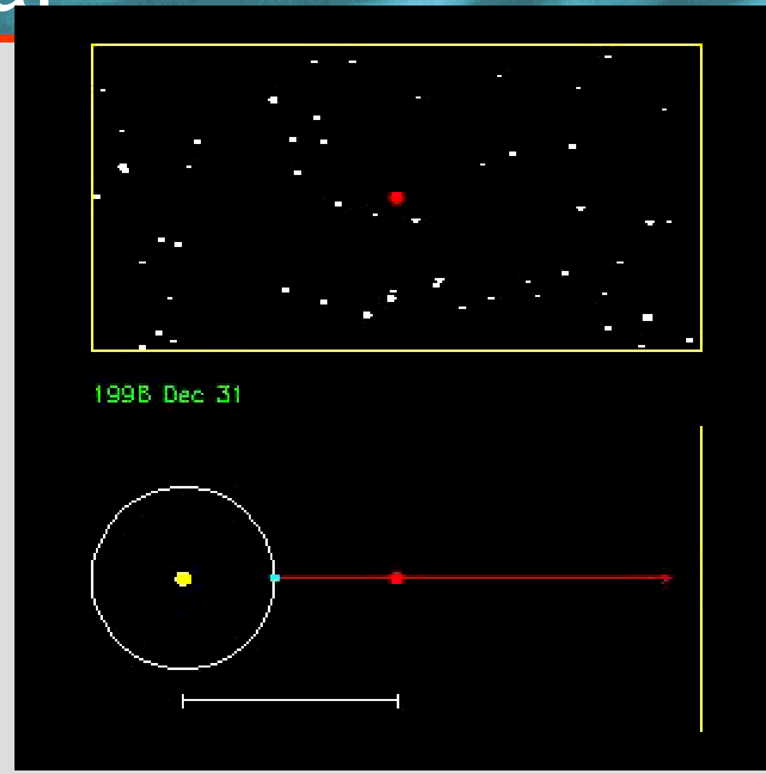


# Distributed correlation

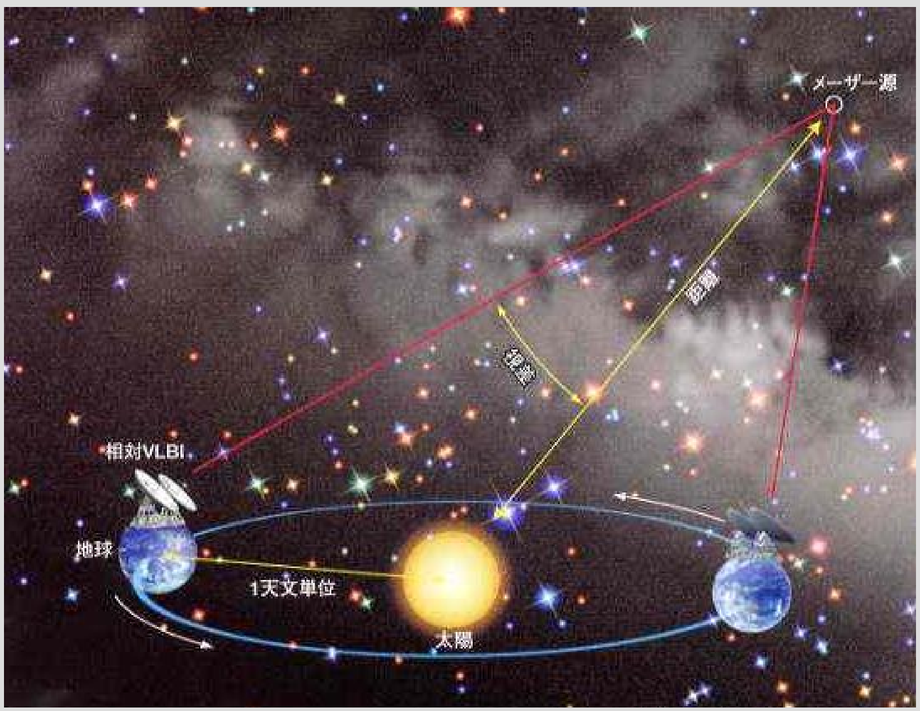
- Deploy algorithm on standard computing
  - Using the interfaces for Grid computing
  - Interesting issues with quality of service and load balancing
- Pilot project in Dutch contact using StarPlane
  - Cluster computers with ultra high connectivity
  - Stream data from disk pool in Dwingeloo
- Or real-time processing in European context
  - EC funded project with international partners
  - Requires guaranteed access to a number of European Grid nodes

- Scientific application of pilot demonstator
  - “Gated” correlation for pulsars
  - Space craft navigation of extremely narrow signals
  - Continuous available high precision VLBI

# Example scientific potential



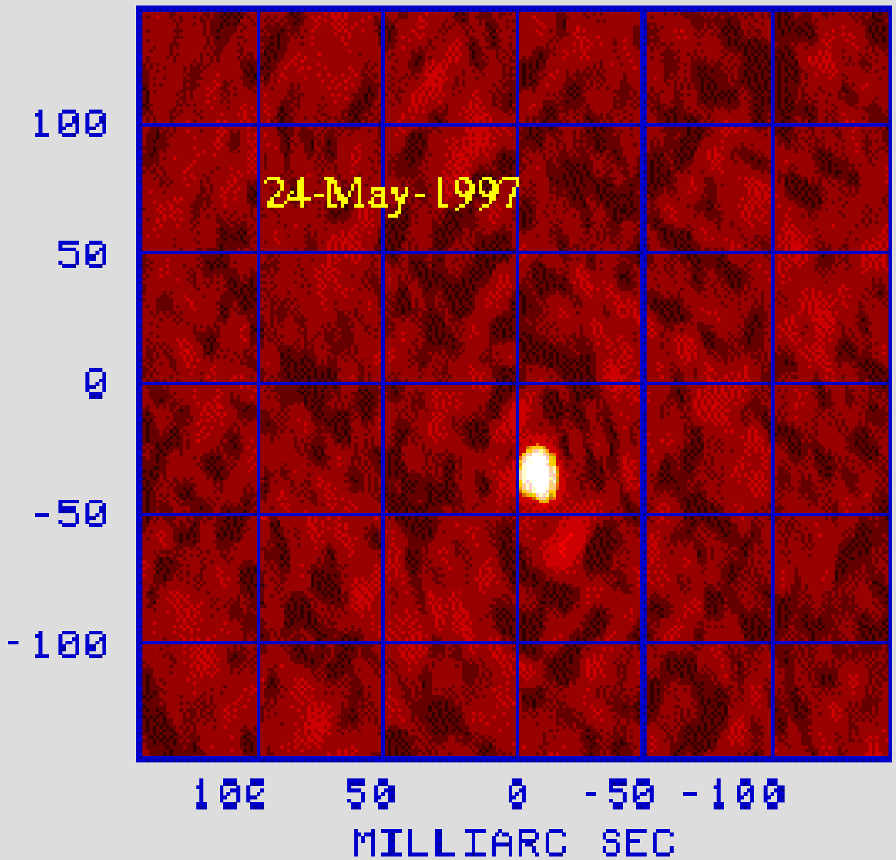

Direct stellar distances through parallax measurement



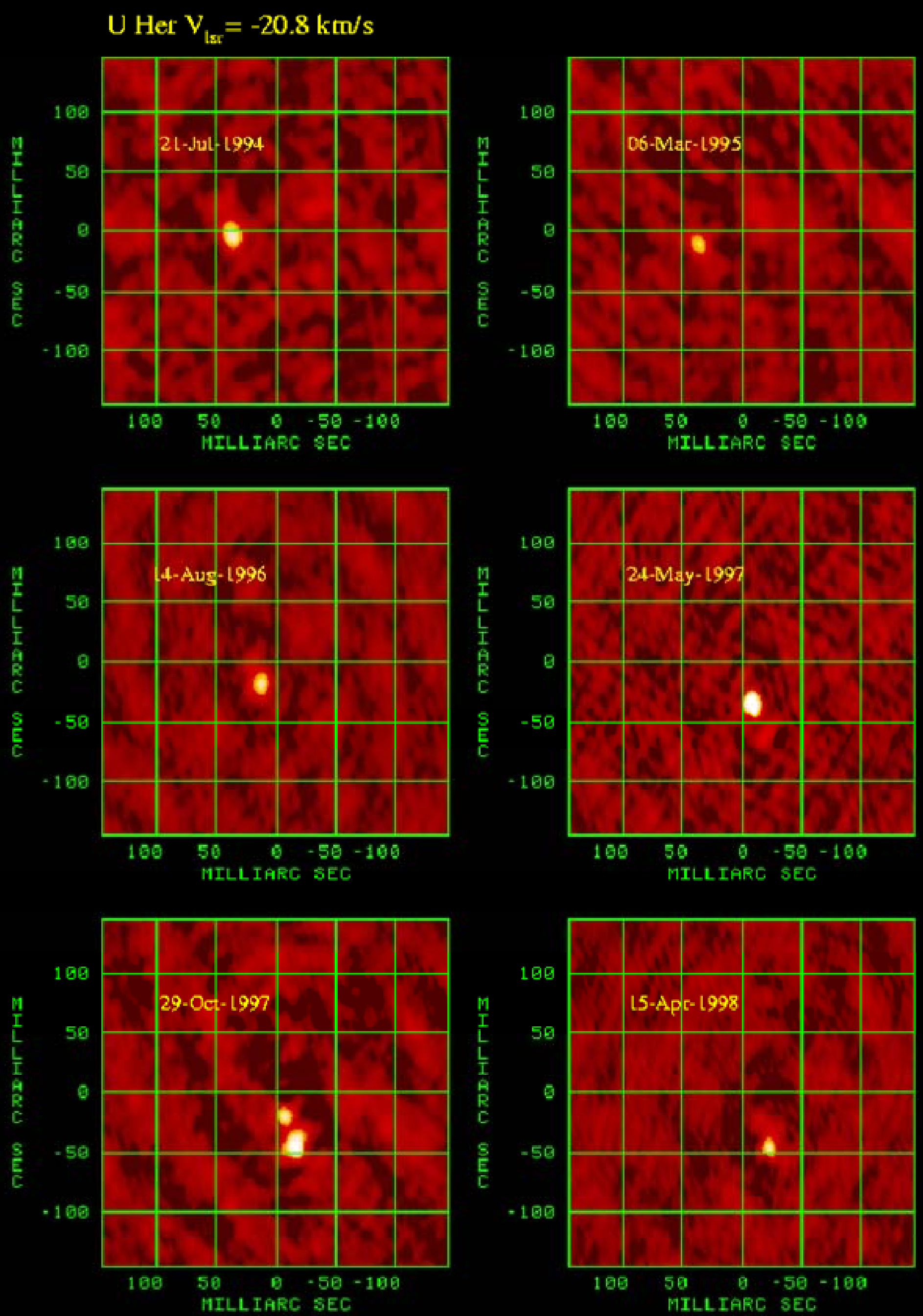

Extremely small wobble on top of stellar proper motion

# OH masers around Mira star

- Old star surrounded by envelope of gas and dust
- Such that MASER emission occurs
- Bright image of the star
- At ≈ 200 pc
  - Parallax $\Pi$ = 5 mas
  - $R_*$ = 2AE = 10 mas
  - $R_{shell}$= 2000 AE = 10.000 mas
  - $V_*$ ≈ 50 km/s = 50 mas/yr
- Resolutie VLBI
  - Image 10 mas
  - Relative accuracy 1 – 5 mas
  - Absolute accuracy +1–2 mas

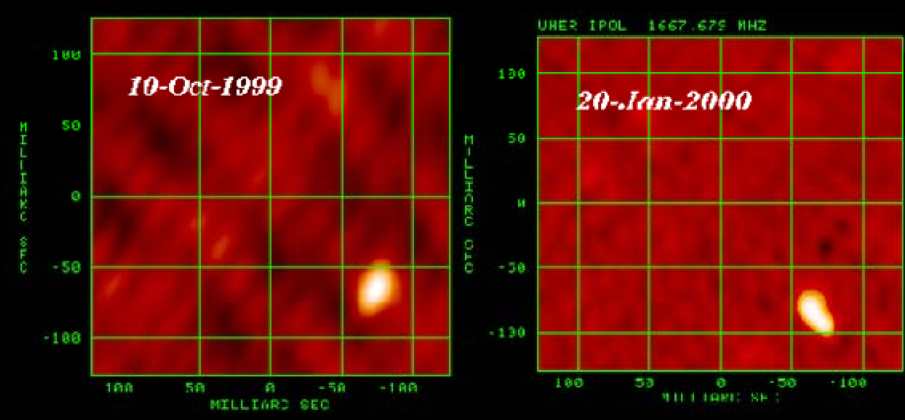



- Where mas = milliarcsecond
- = 1/1000 x 1/3600 degree



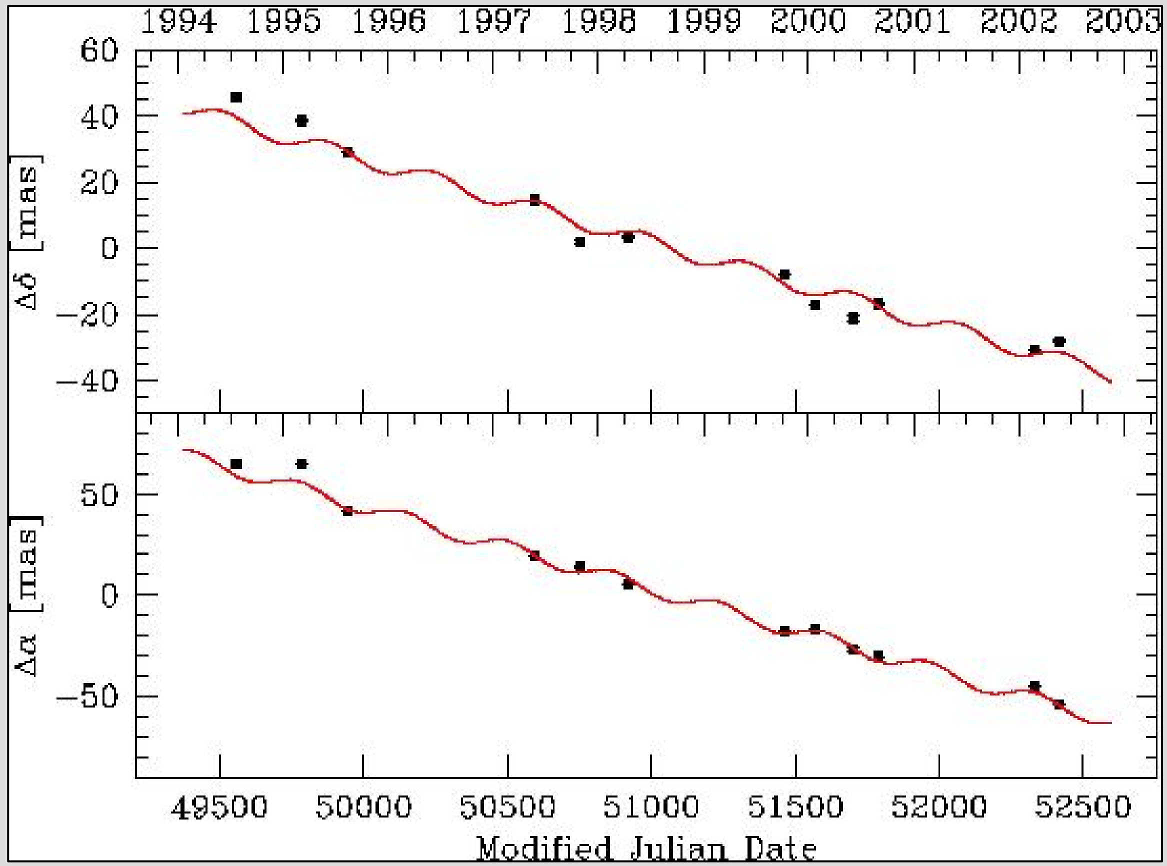

VLBI images of the bright OH maser in the variable star U Herculis

Proper motion of star through Galaxy is clearly detected



# As is its parallax

- 12 observations in 8yr
- Measured with respect to distant and fixed quasars
- Requires a lot of special techniques
- Ionospheric conditions unstable during solar maximum
- Will be much better and more routine when done with e-VLBI and software correlator




$\Pi_{vlbi}$ = 3.61 ± 1.04 mas, $\mu_{vlbi}$ = -14.94 ± 0.38, -9.17 ± 0.42 mas/yr

$\Pi_{hip}$ = 1.64 ± 1.31 mas, $\mu_{hip}$ = -16.84 ± 0.82, -9.83 ± 0.92 mas/yr