Space VLBI in the era of LOFAR, ALMA and SKA

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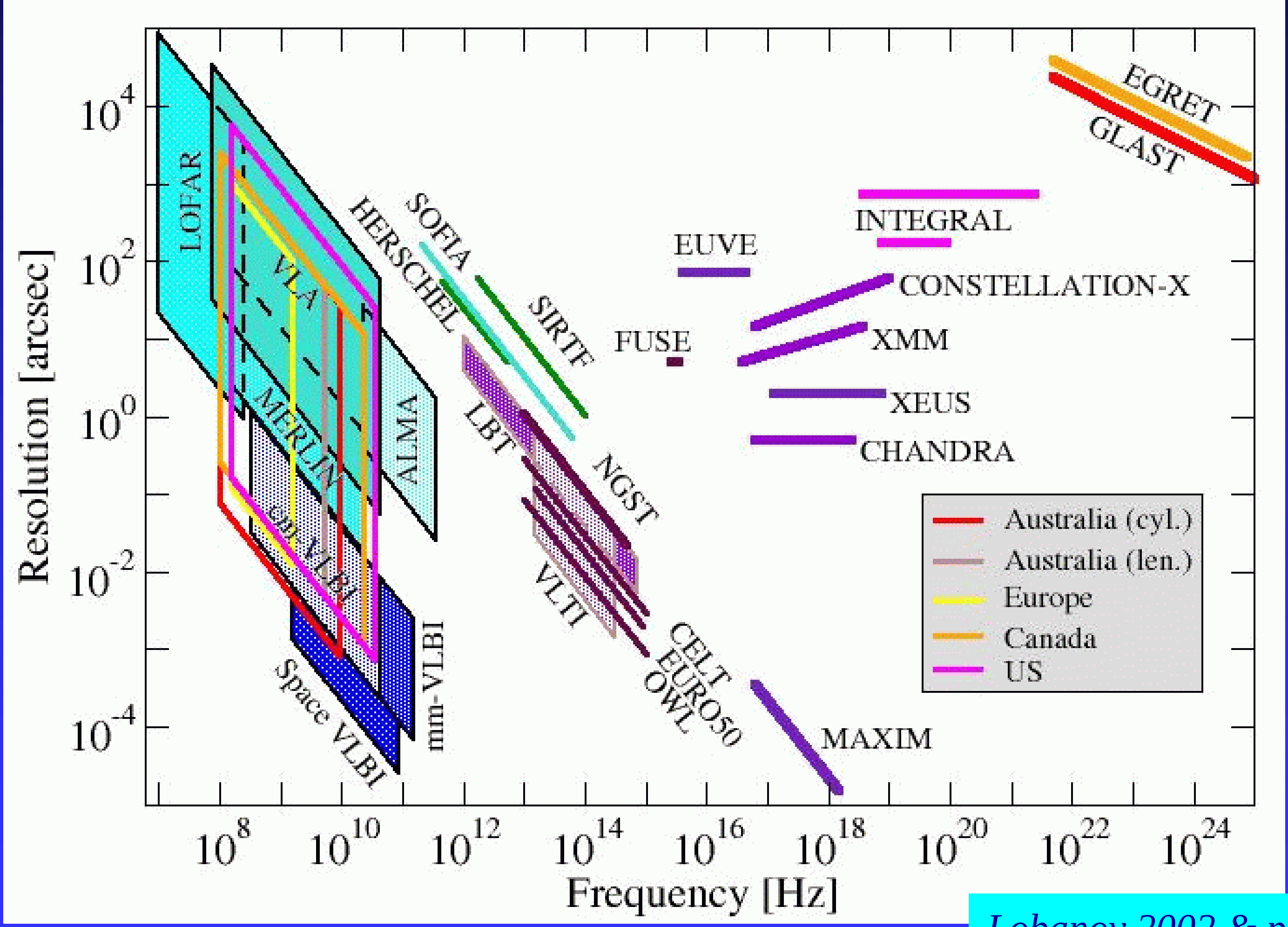
JOINT INSTITUTE FOR VLBI IN EUROPE

Why VLBI in Space?

$$\vartheta = \frac{\lambda}{B}$$



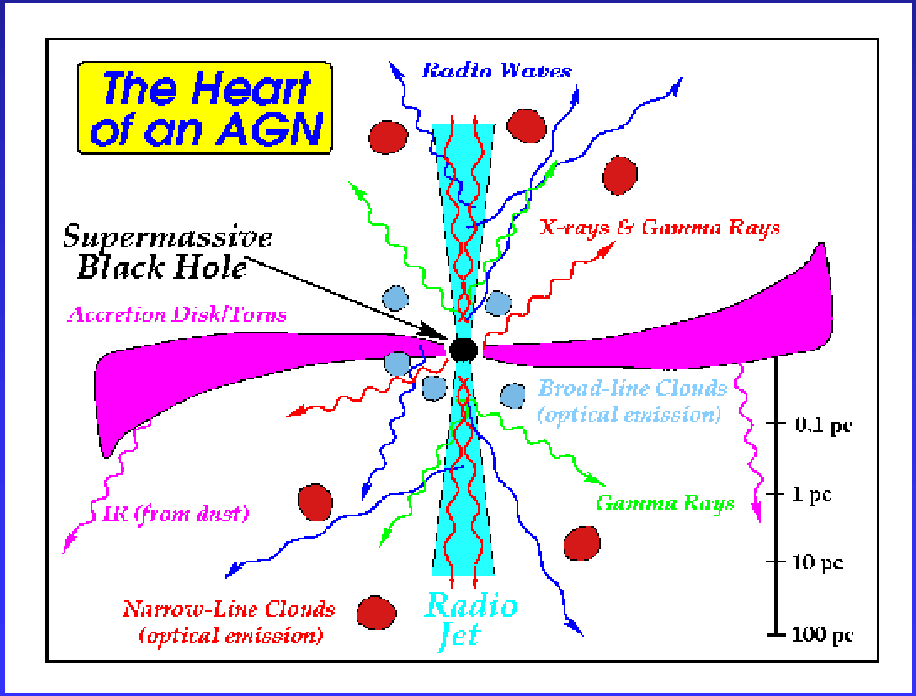
Lobanov 2002 & poster #52

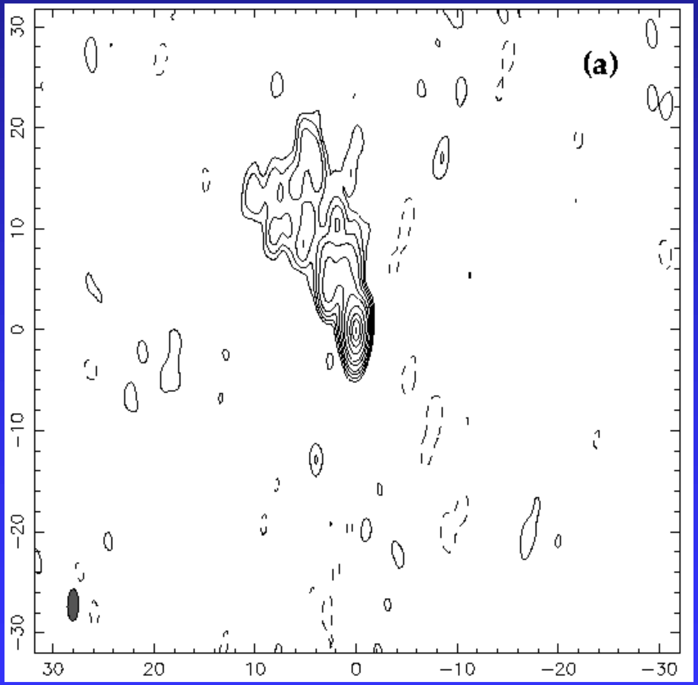
λ ⟵ 3 cm 3 μm 3 Å

The question: what's going on at $10^{12} < T_B < 10^{16}$ K?

- **What are the most compact radio structures in AGN?**
  - ***What is the highest brightness temperature in AGN?***
- **Note: the highest LOWER LIMIT of T_B measured directly to date:**

5.8 x 10^{13} K (*AO0235+164, VSOP, Frey et al. 2000)*

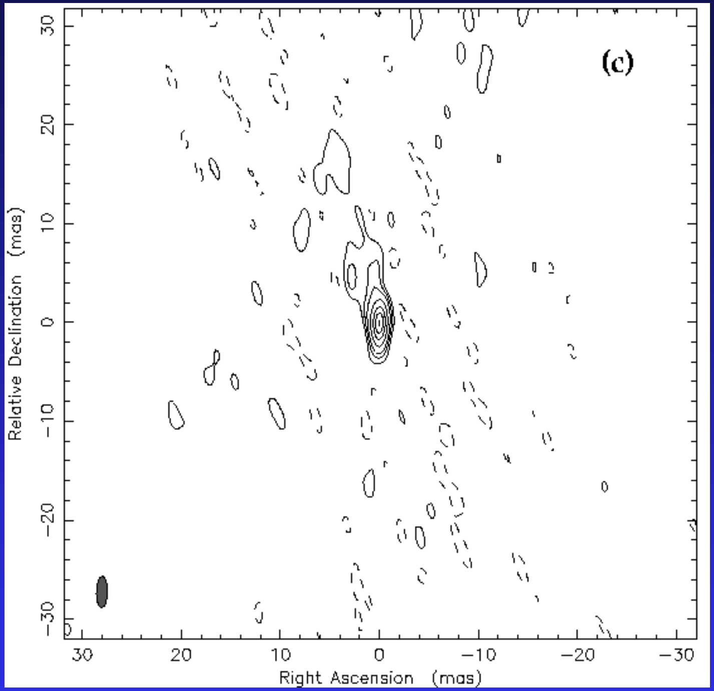




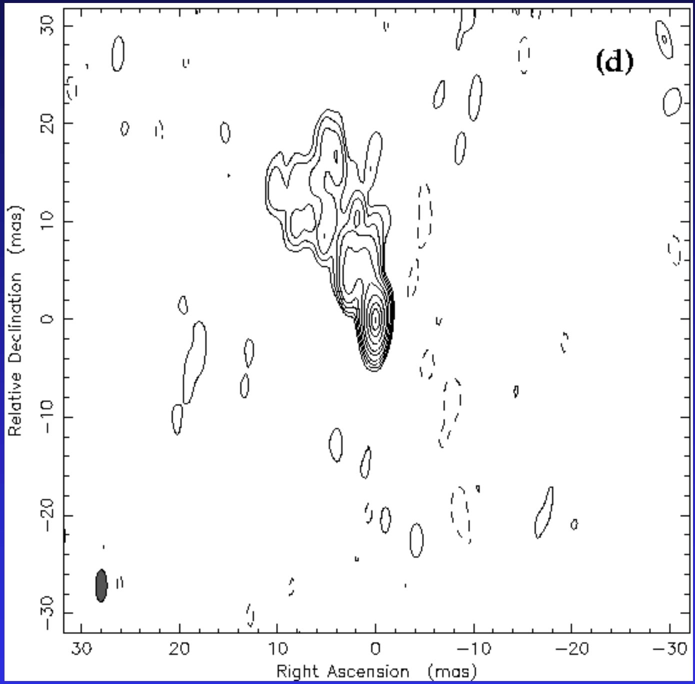
ARISE, 1999, JPL Publ. 99-14

Space VLBI at λ versus ground-based Global VLBI at λ /3

Simulated images with similar angular resolution and comparable sensitivity



Global VLBI at λ/3 cm



Space VLBI at λ cm, α=-1.5

Longer baselines at lower frequencies are
COMPLEMENTARY
to shorter baselines at higher frequencies

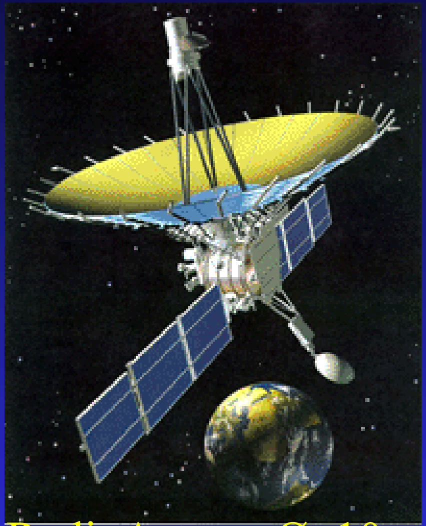
See also posters #39 by Agudo et al and #43 by Krichbaum et al.

Three generations of VLBI in Space

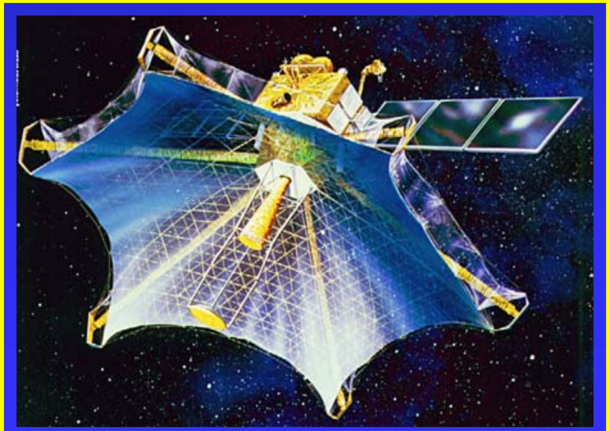
1986-88

TDRSS-OVLBI, Ø 5m

1990s

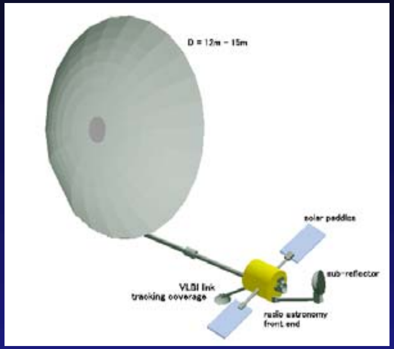


RadioAstron, Ø 10m

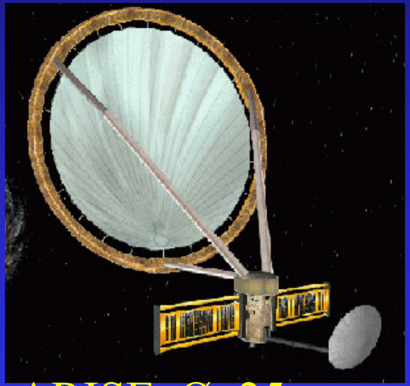


VSOP, Ø 8m

2000s



VSOP-2, Ø 12m



ARISE, Ø 25m

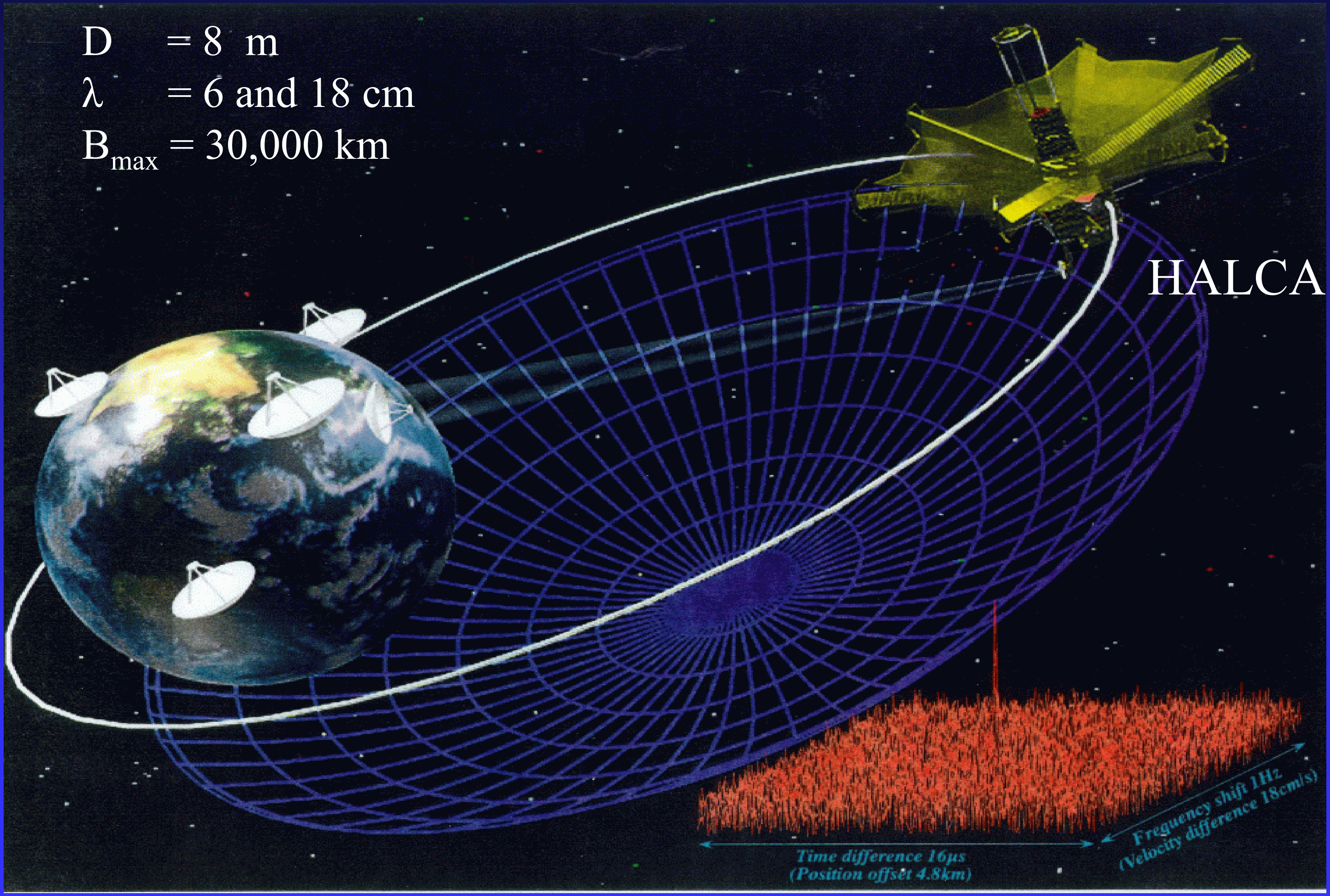
ISS-SVLBI, Ø ≥30m

Plus:

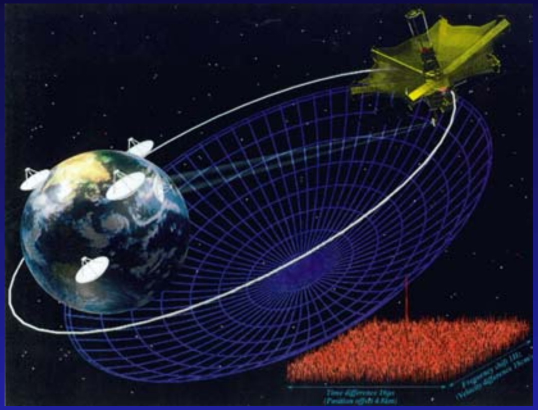
- **KRT-30 (1978-82)**
- **QUASAT (1980s)**
- **IVS (1987-91)**
- **ALFA (1990s)**

VLBI Space Obsrvatory Programme (VSOP)

ISAS, Japan + world-wide collaboration (in orbit since 1997)



VSOP AGN Survey at 5 GHz (1997-2004)



- **402 extragalactic radio sources (mostly AGN)**
- **Selection criteria:**

$$S_5 \geq 0.95 \text{ Jy}$$

$$\alpha \geq -0.45 \quad (S \propto \nu^{\alpha})$$

$$|b| \geq 10^{o}$$

- **Plus all** $S_5 \geq 5$ Jy **sources in the visible part of the sky**

More info on VSOP Survey:

http://www.vsop.isas.ac.jp

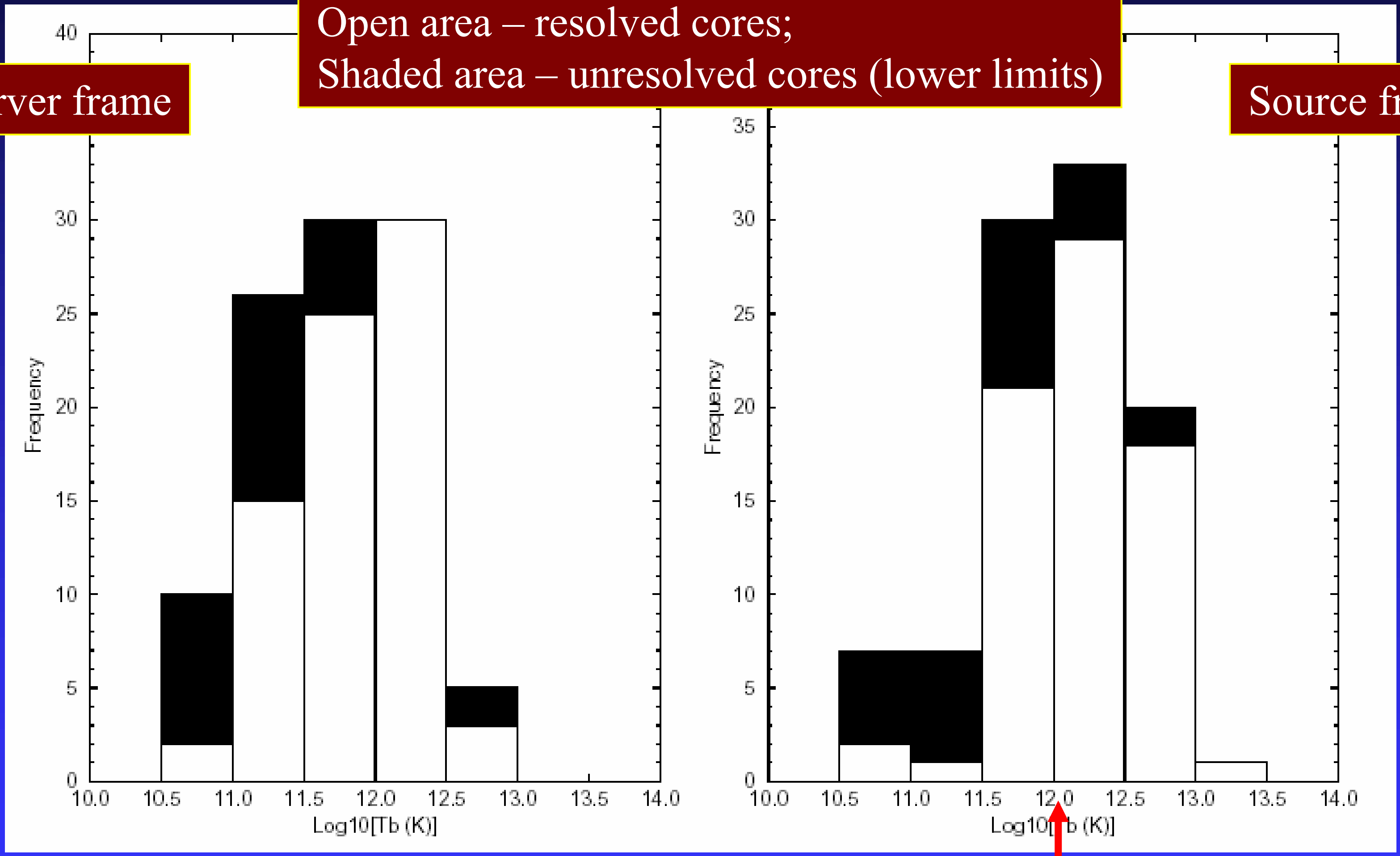
Hirabayashi et al. 2000, PASJ 52, 997
Lovell et al, 2004, ApJ Suppl, in press
Scott et al. 2004, ApJ Suppl, in press
Horiuchi et al. 2004, ApJ, submitted

VSOP AGN Survey: imaging results (Scott et al. 2004)

Open area – resolved cores;
Shaded area – unresolved cores (lower limits)

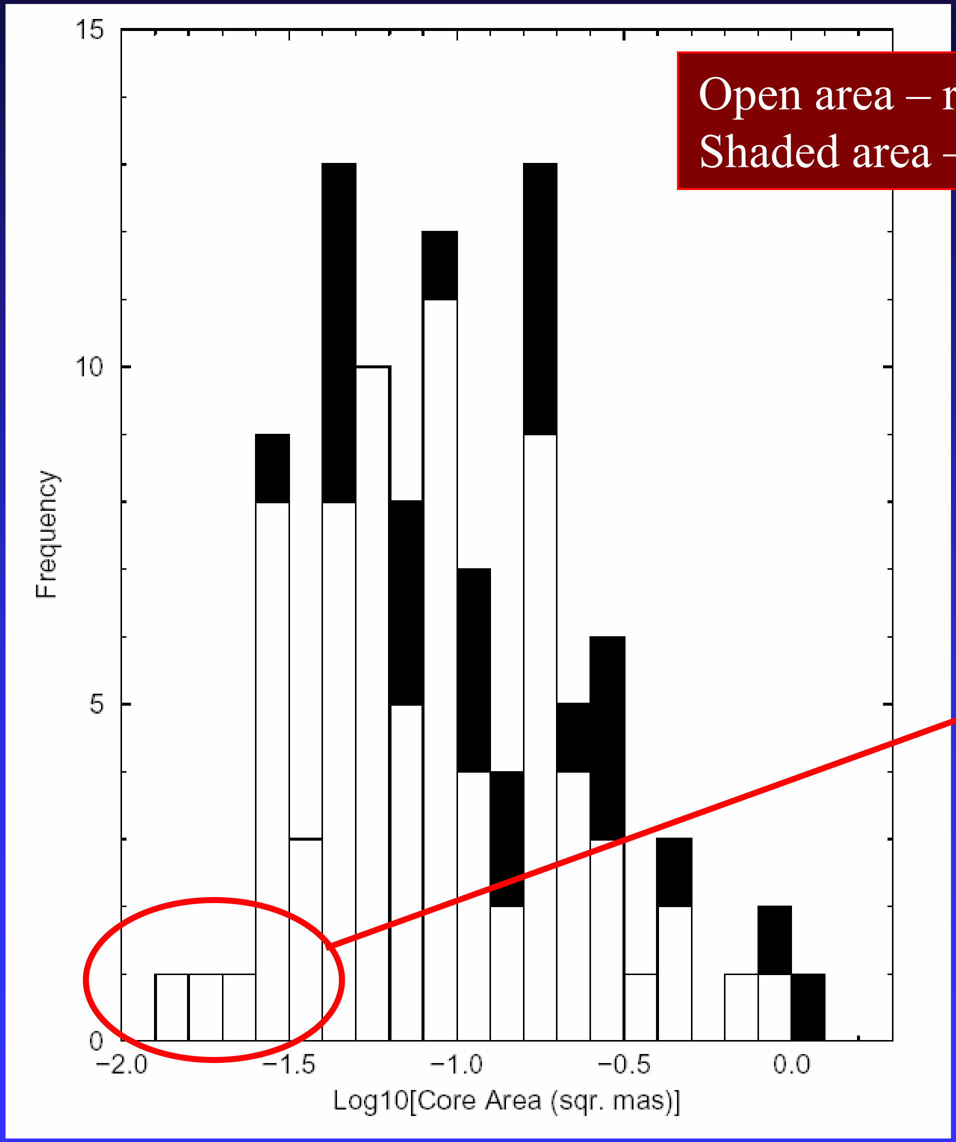
Observer frame

Source frame



Inverse Compton limit of 10^{12} K (Kellermann & Pauliny-Toth 1969) exceeded

AGN "cores" in VSOP AGN Survey (Scott et al. 2004)

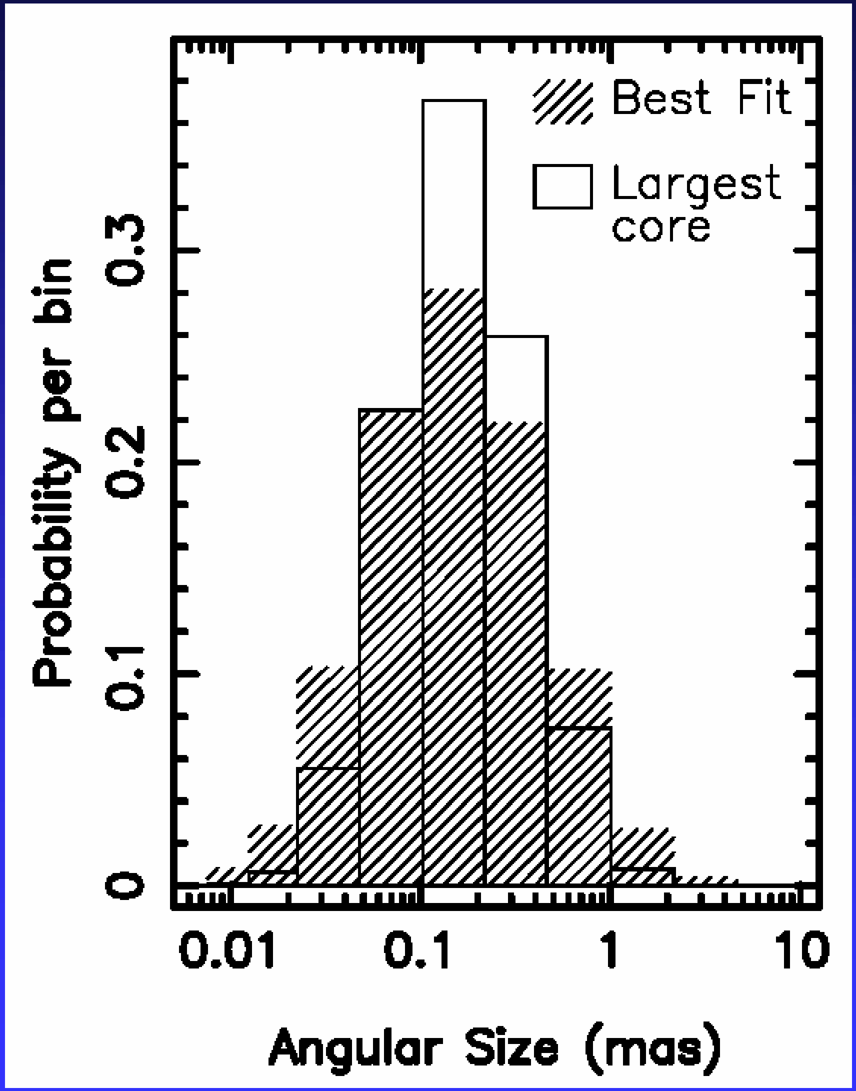


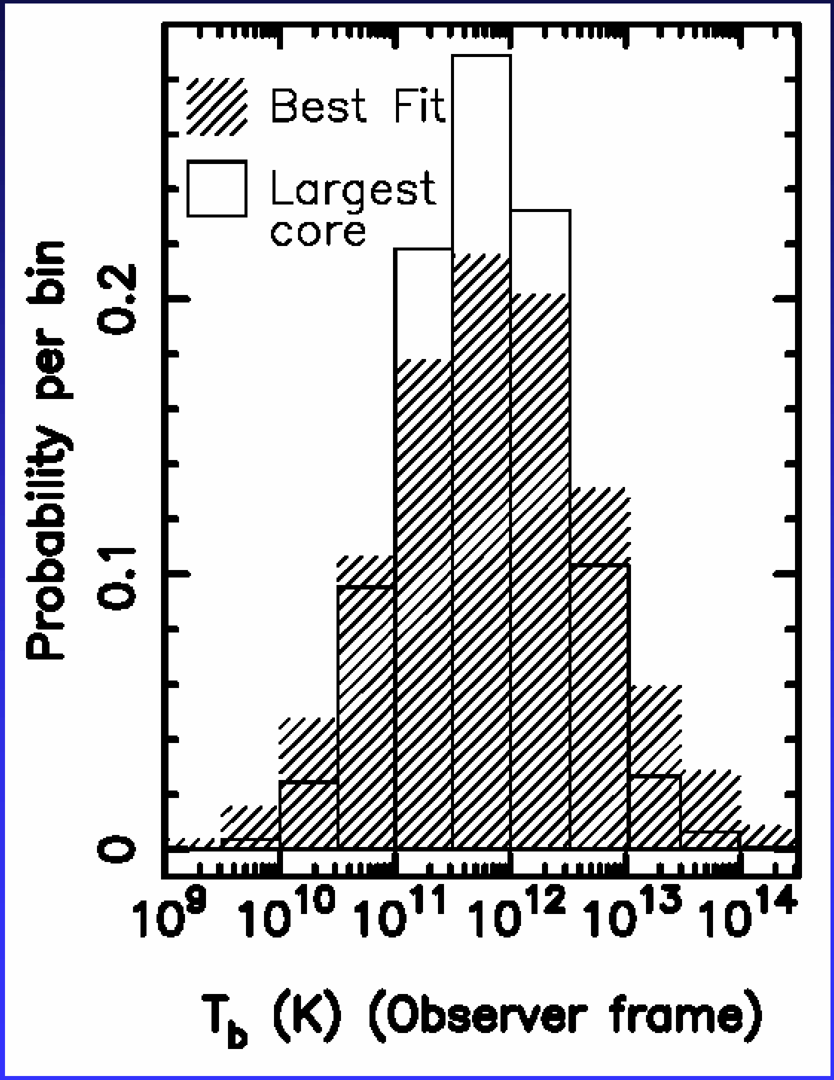
Open area – resolved cores;
Shaded area – unresolved cores (upper limits)

Random sub-set of 101 AGN from the VSOP Survey list

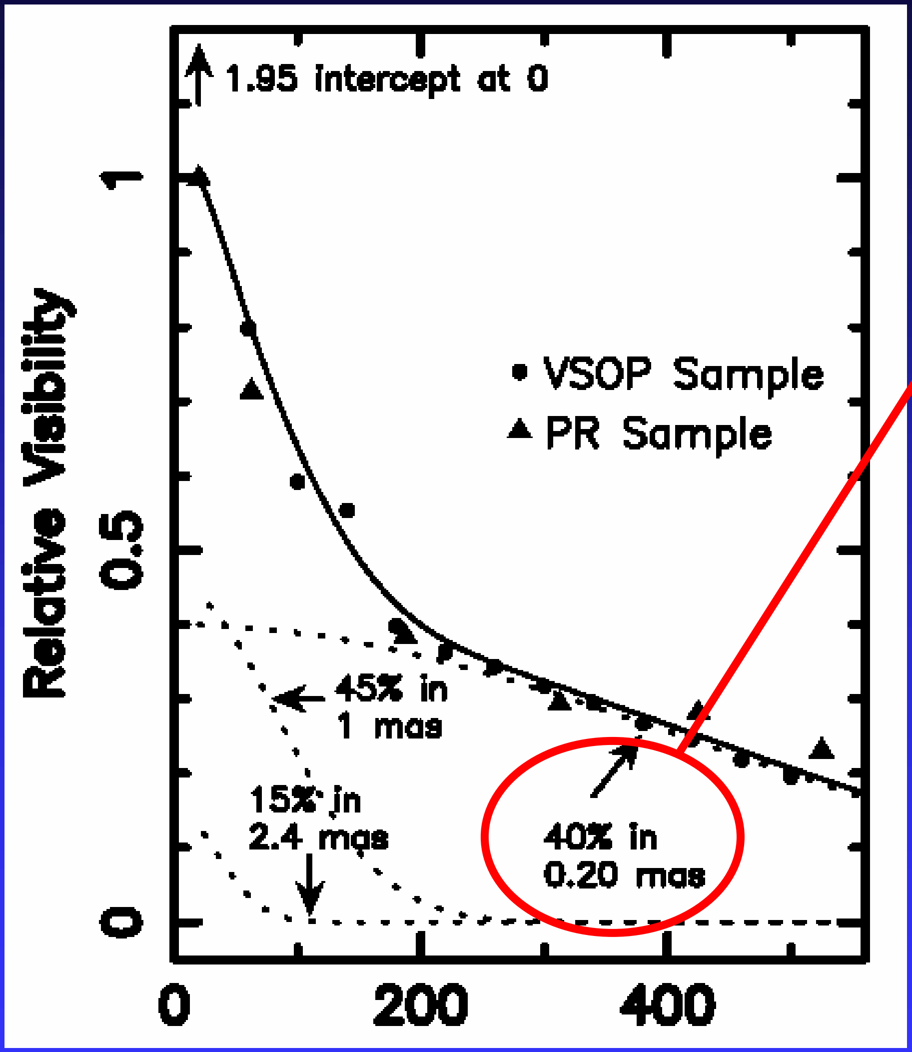
Less than 10% of the cores are < 0.1 mas in diameter

VSOP AGN Survey: non-imaging analysis (Horiuchi et al. 2004)





VSOP AGN Survey: non-imaging analysis ***(Horiuchi et al. 2004)***



Averaged normalised visibility

The most compact (i.e. the brightest) radio-emitting region?

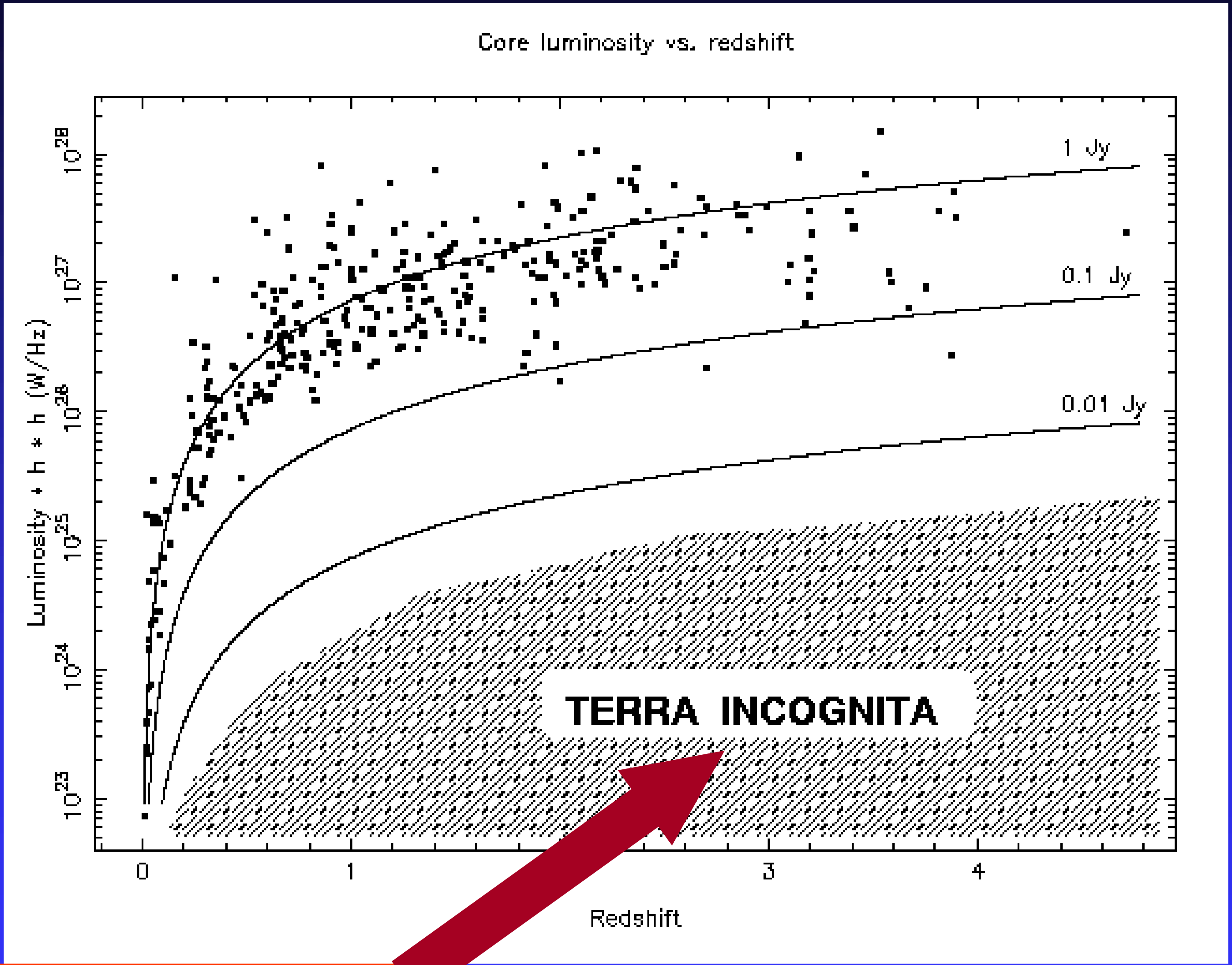
NB1: ….but beware of IDV sources
(i.e.J1819+3845, core ~0.01 mas)

NB2: The highest directly measured value of T_B ~5.8 x 10^{13} K (VSOP data on AO 0235+164, Frey et al. 2000)

Toward 10,000 sources

Data points: 300 AGN
Imaged @ 5 GHz
(ad-hoc) with mas
angular resolution
(Gurvits et al. 1999)

De-facto flux density selection!

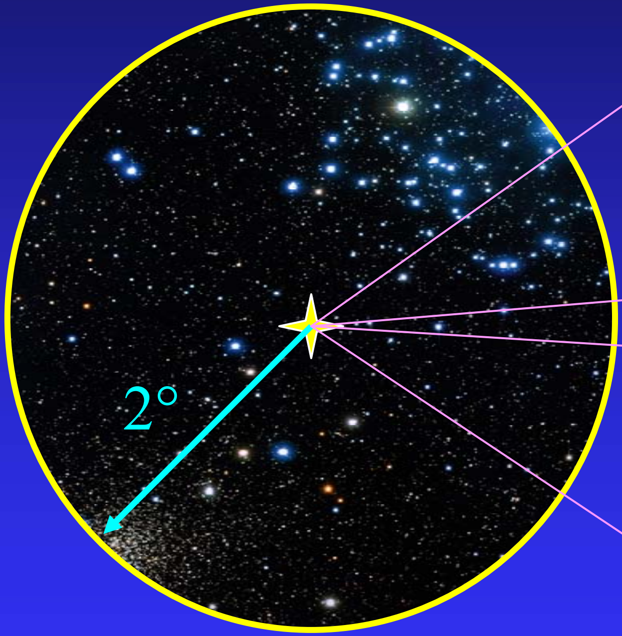


New territory for new radio telescopes, especially "Global" SKA!

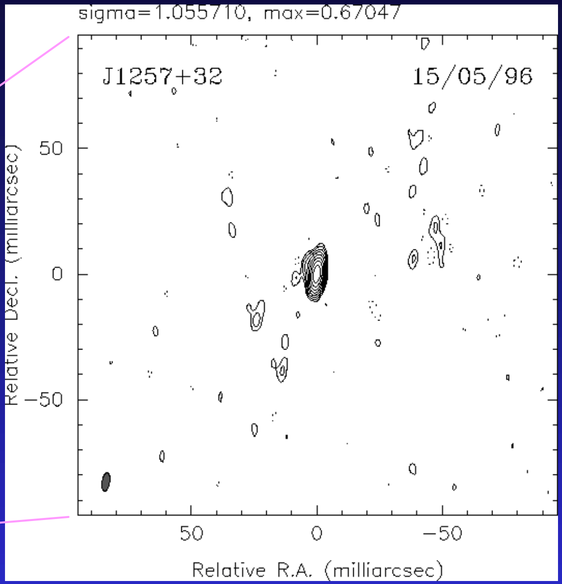
Need to observe mJy-level sources with 10^{23} – 10^{25} W/Hz objects at z>0.5

The sky area of DEVOS NGP (North Galactic Pole)

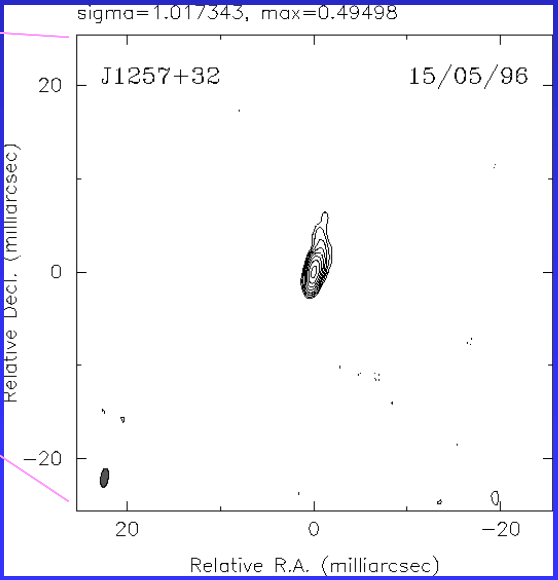
The reference source: J1257+3229
VLBA Calibrator source



2.3 GHz

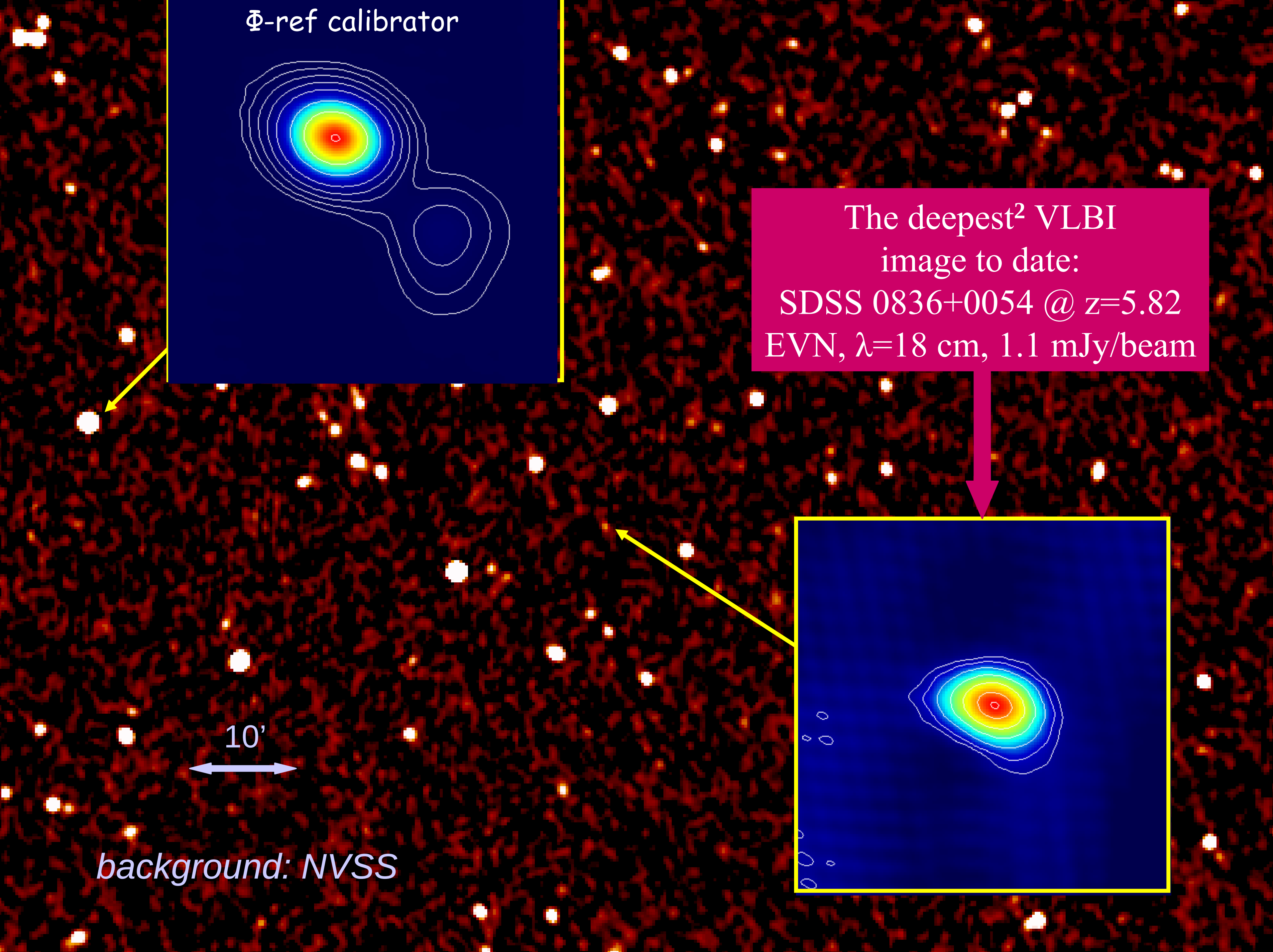


8.4 GHz



47 FIRST/SDSS sources within 2°
from J1257+3229

DEVOS – Deep Extragalactic VLBI-Optical Survey


Φ-ref calibrator
The deepest² VLBI
image to date:
SDSS 0836+0054 @ z=5.82
EVN, λ=18 cm, 1.1 mJy/beam
10'
background: NVSS

VSOP Survey conclusions: compactness of the cores

- **Strange coincidences – cosmic conspiracy?**
  - ***10^{12} K is about the maximum measurable brightness temperature with the baseline ~10,000 km.***

    We happen to live on the "interferometrically" correct planet!
  - ***The most compact structures in AGN begin to appear at baselines ~200 Mλ (1 mas), just a bit longer than available on the Earth at 5 GHz, the most popular VLBI frequency of the recent past.***

    Again, we live on a very special planet!
- **Both the items above have become known to us essentially owing to baselines longer than the Earth diameter (VSOP). Baselines 10,000 – 100,000 km (Space VLBI) and sub-mJy sensitivity are crucial!**
- **Radio structures < 1 mas are likely to be the last bastion on the way to complete resolution of the cores – definitive diagnostics of the "SMBH – accretion disc – jet" system.**

What is next?

- <u>**Sensitivity!**</u>

  ~microjansky per mas-scale beam

- <u>**Angular resolution at VARIOUS frequencies (matched with sensitivity)**</u>

  ~10 microarcseconds at mm and cm wavelengths

- <u>**Full sky coverage**</u>

  In-beam phase-referencing – phase calibrators ANYWHERE on the sky

VSOP-2, proposal by ISAS/JAXA(Japan)

- **VSOP-2 is a mission for the highest resolution imaging of AGN and young stellar objects.**
- **Improvements over VSOP by factors of ~10**
  - ***Higher frequency***
    - Highest observing frequency 43GHz
  - ***Higher resolution***
    - 38 micro arcsecond @43GHz
  - ***Higher sensitivity***

- **The angular resolution is approaching the dimensions of**
  - ***accretion disk and black hole in nearby AGN***
  - ***jet launching site***
  - ***Structure of magnetospheres of protostar***

See also poster #4 by Hirabayashi et al.

Summary of VSOP-2 Science Goals

- **Key science :**
  - ***Jet structure, collimation and acceleration regions***
  - ***Structure of accretion disks around AGN***
  - ***Structure of magnetic fields in protostars***

- **Other targets:**
  - ***Galactic masers in star-forming region***
  - ***Extragalactic Megamasers***
  - ***Radio quiet quasars***
  - ***X-ray binaries, SNR, gravitational lenses etc.***

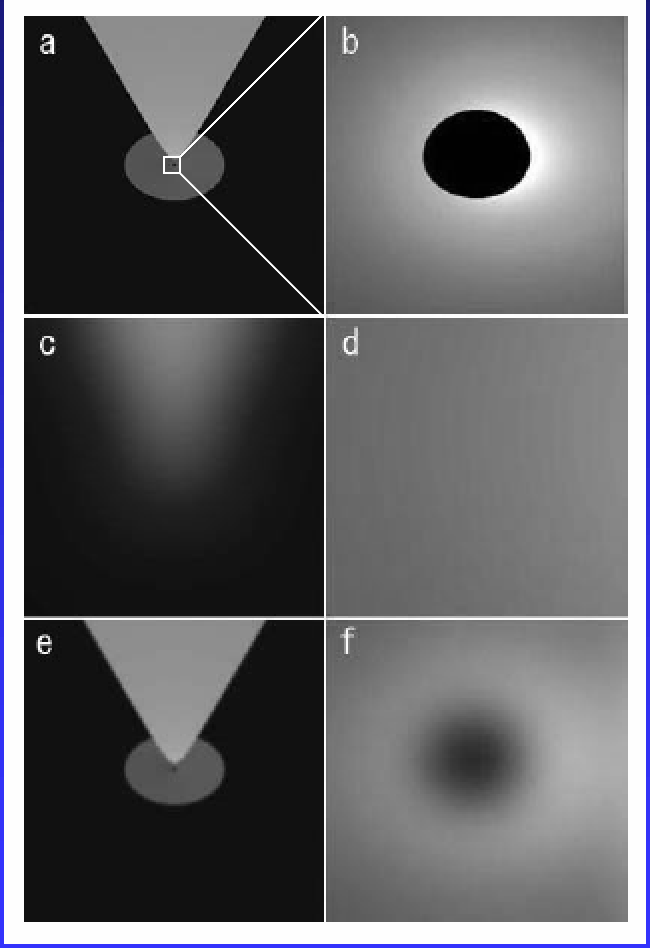
"Direct" view at a super-massive black hole

- **With an angular resolution for M87 of 10 R_g (Schwarzschild radius) , detection of the black hole shadow may be possible**

model Rg~3μasec

VSOP ~100Rg

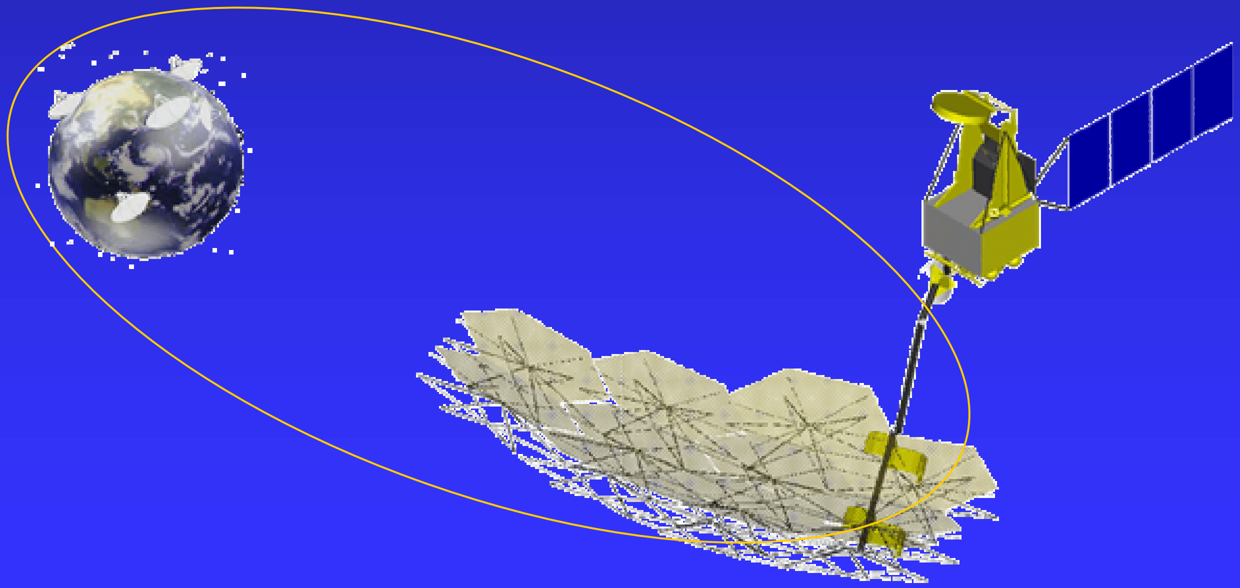
VSOP2 ~12Rg



Takahashi et al. 2003

VSOP-2

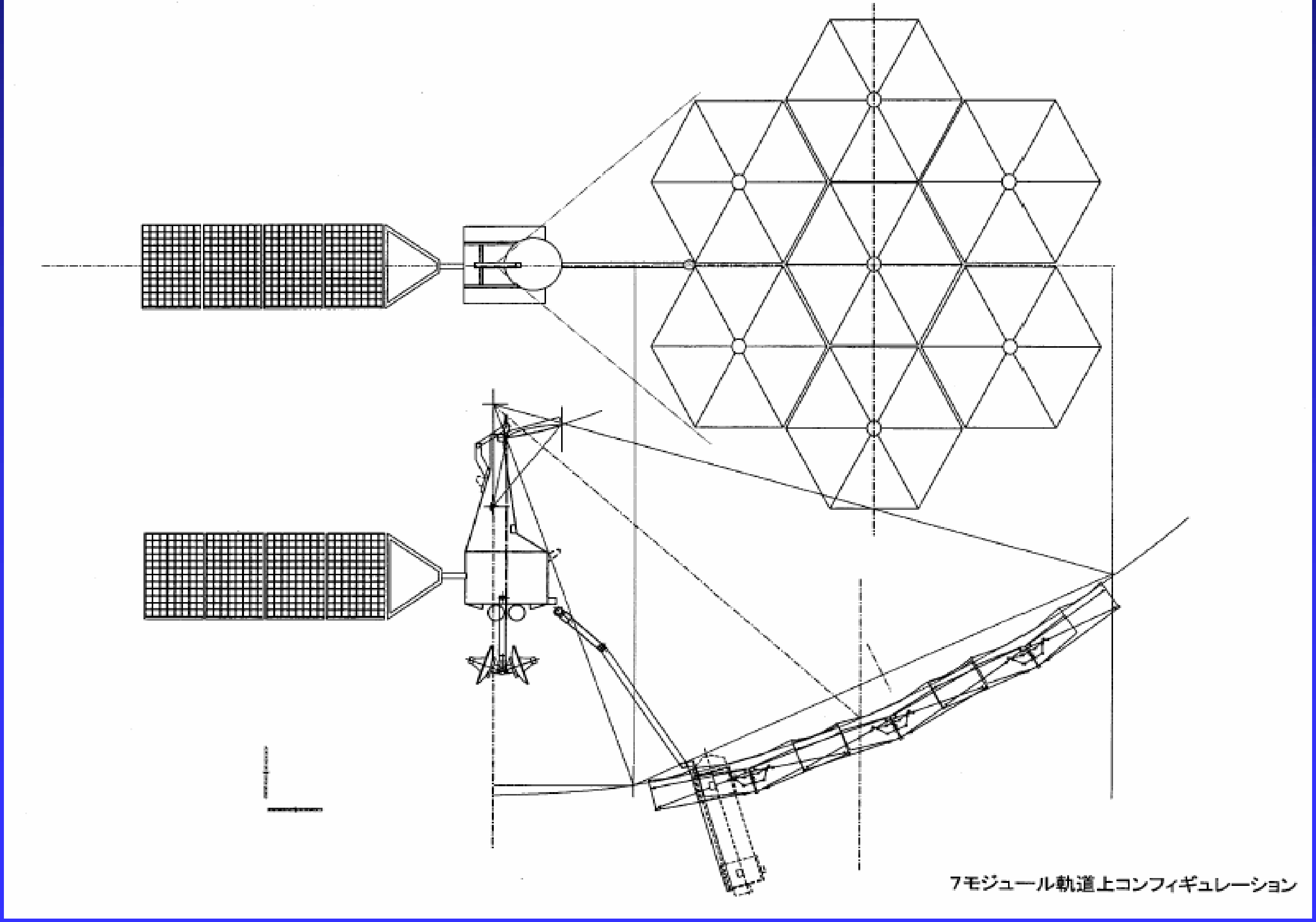
- **Observing Freq.: 8, 22, 43 GHz**
- **Cooled receivers (22 and 43 GHz)**
- **Wide band data downlink (1 Gbps)**
- **Apogee height 25000 km**
    - ***75 μasec @ 22 GHz***
    - ***38 μasec @ 43 GHz***
- **Dual polarization**
    - ***LCP/RCP***
- **Phase-referencing capability**
    - ***Switching the main reflector***



VSOP-2 satellite

- **9-m offset cassegrain antenna with module structures**
  - ***Light weight***
  - ***Easy adjustment***

- ***Mass (wet) 910Kg***
- ***Power 1800W***

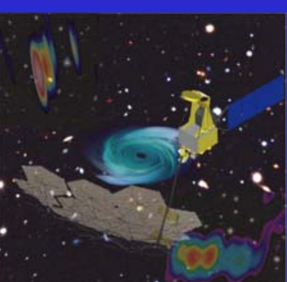


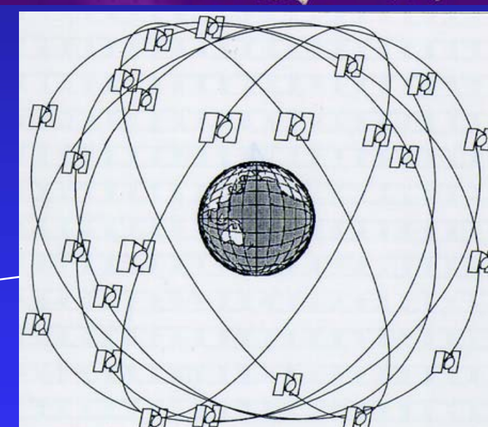
Forward look

Space Sub-mm Array
(ALMA in space)

VSOP-2

BH imager

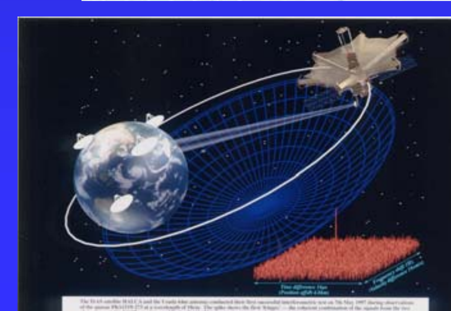




VSOP-4

VSOP-3

Sub-mm Telescope



VSOP