VSOP-2

A Space VLBI Mission to Image Central Engines and Jet Launching Regions

Seiji Kameno（Kagoshima University）

VSOP-2 Science Working Group

- VSOP-2 Project Overview
- Scientific Specifications
- Science Case for AGN disks and Jets

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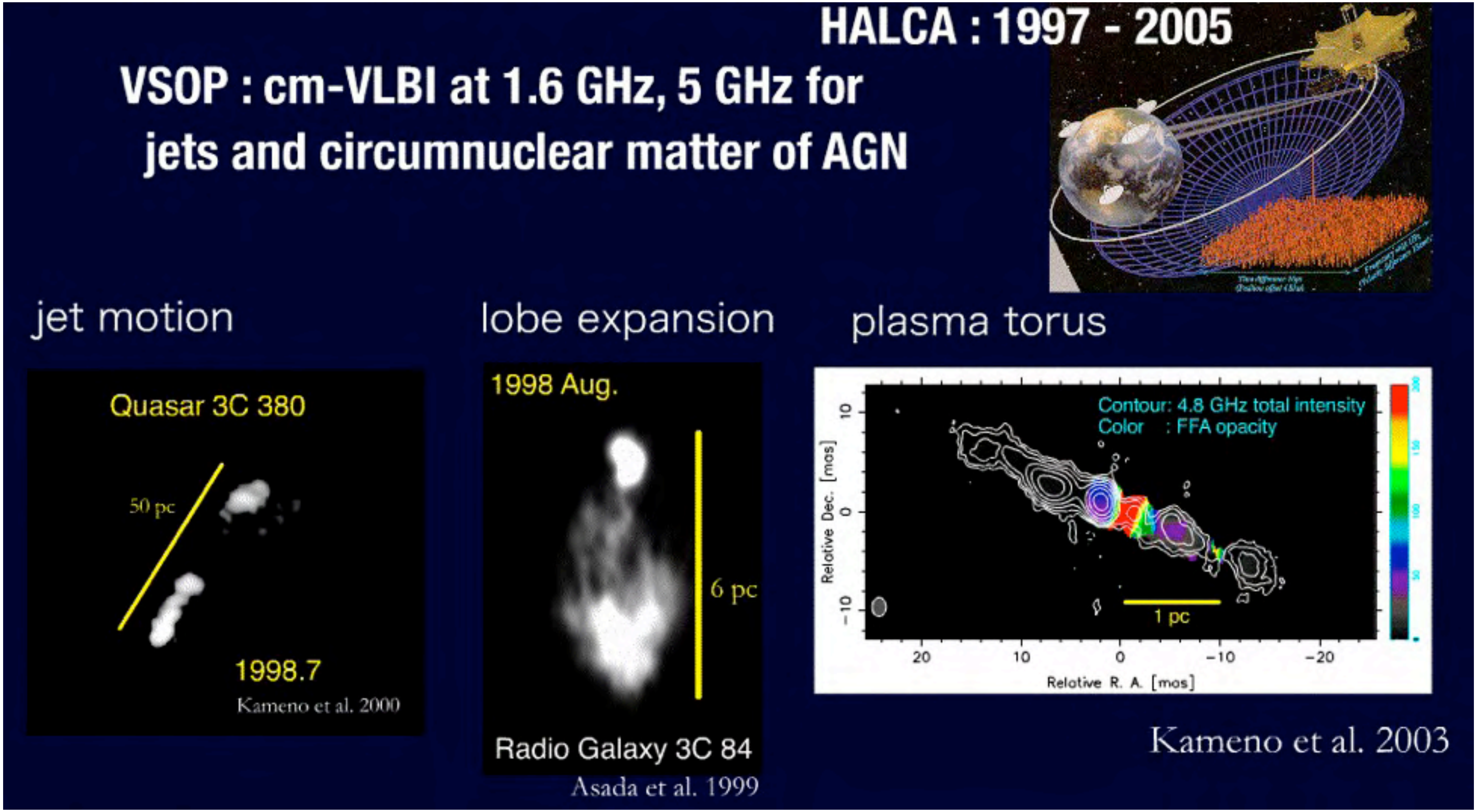
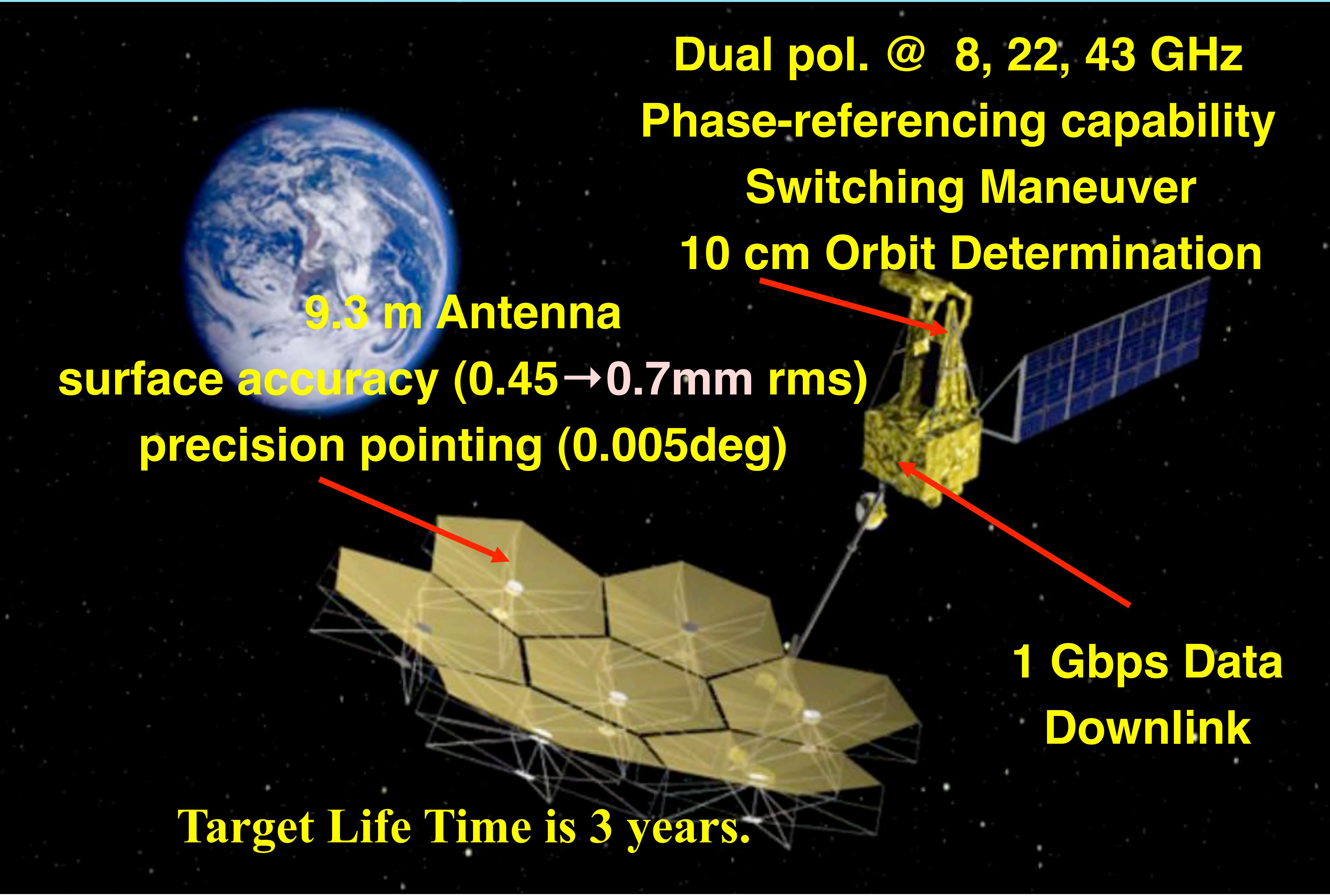
- Scientific Specifications
- Science Case for AGN

VSOP-2 to succeed the heritage of VSOP



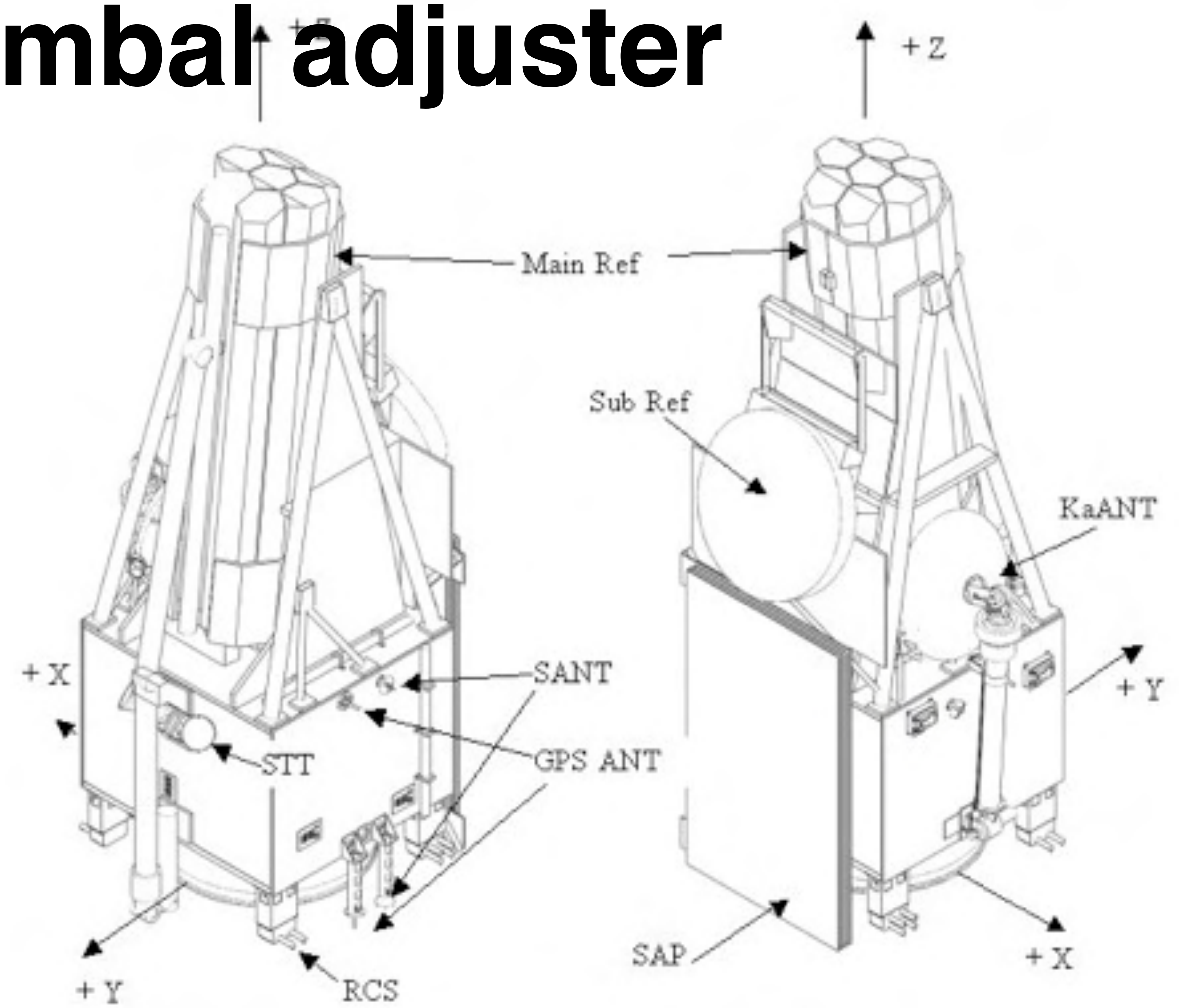
ASTRO-G satellite of the VSOP-2Mission

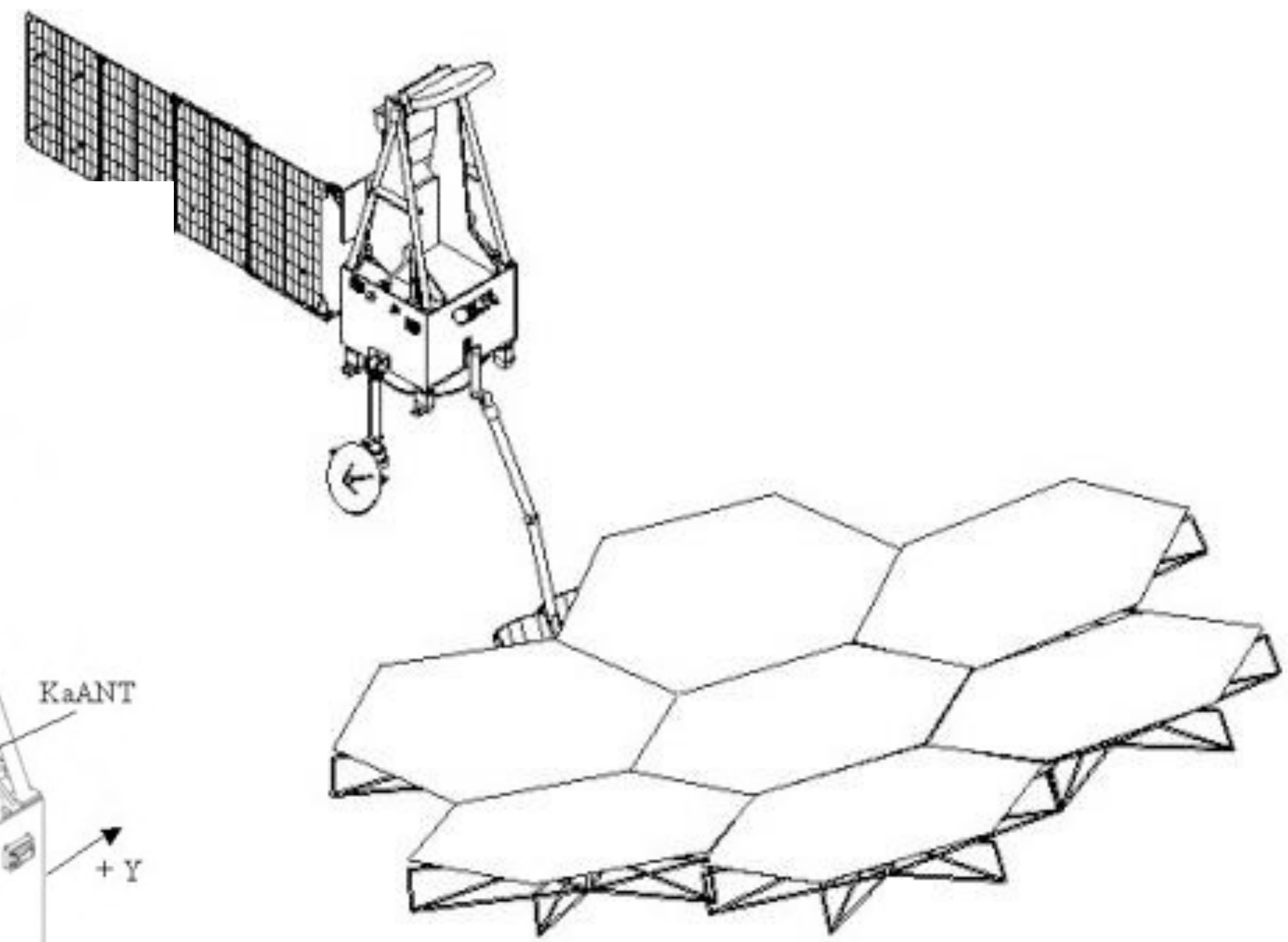


ASTRO-G Satellite Configuration

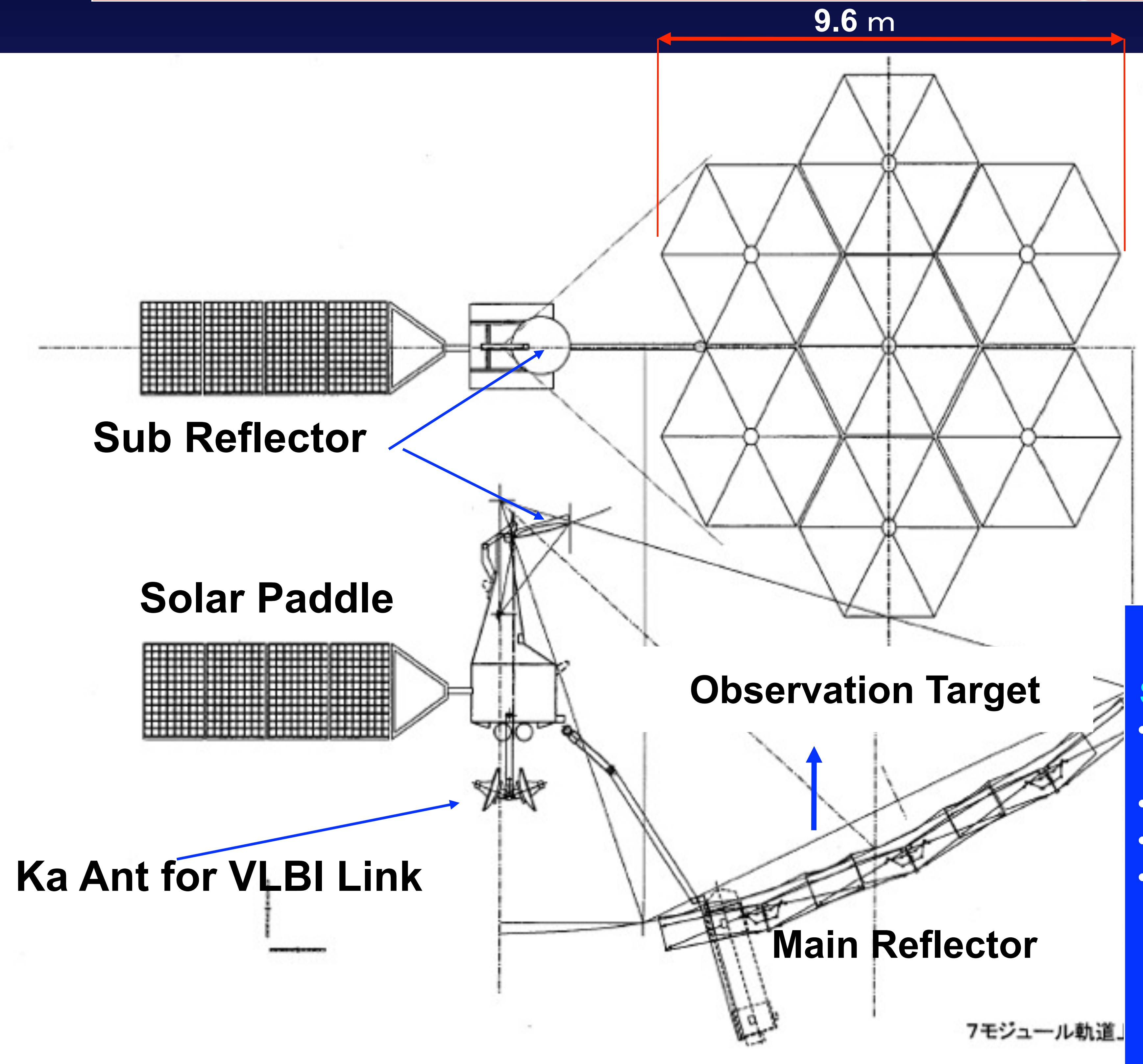
Mass (wet) 1200Kg
Power 2000W

- 9.3-m offset Cassegrain antenna with module structures
  - Light weight
  - gimbal adjuster





ASTRO-G　Configuration



Orbit

Apogee Height	25,000 km
Perogee Height	1,000 km
Inclination	31°
Orbit Period	7.5 h

Satelite Size

Mass	1,200 kg
Power	2,000 W

Satellite For VLBI

- 9 meter Deployable Antenna for 43GHz
- Cooled LNA（30 K ）
- 1 Gbps Down Link
- Phase Compensation Observation
  Target Switching
  (3deg manoeuvre in 15 sec)
  Orbit Determnation
  with 10 cm Accuracy

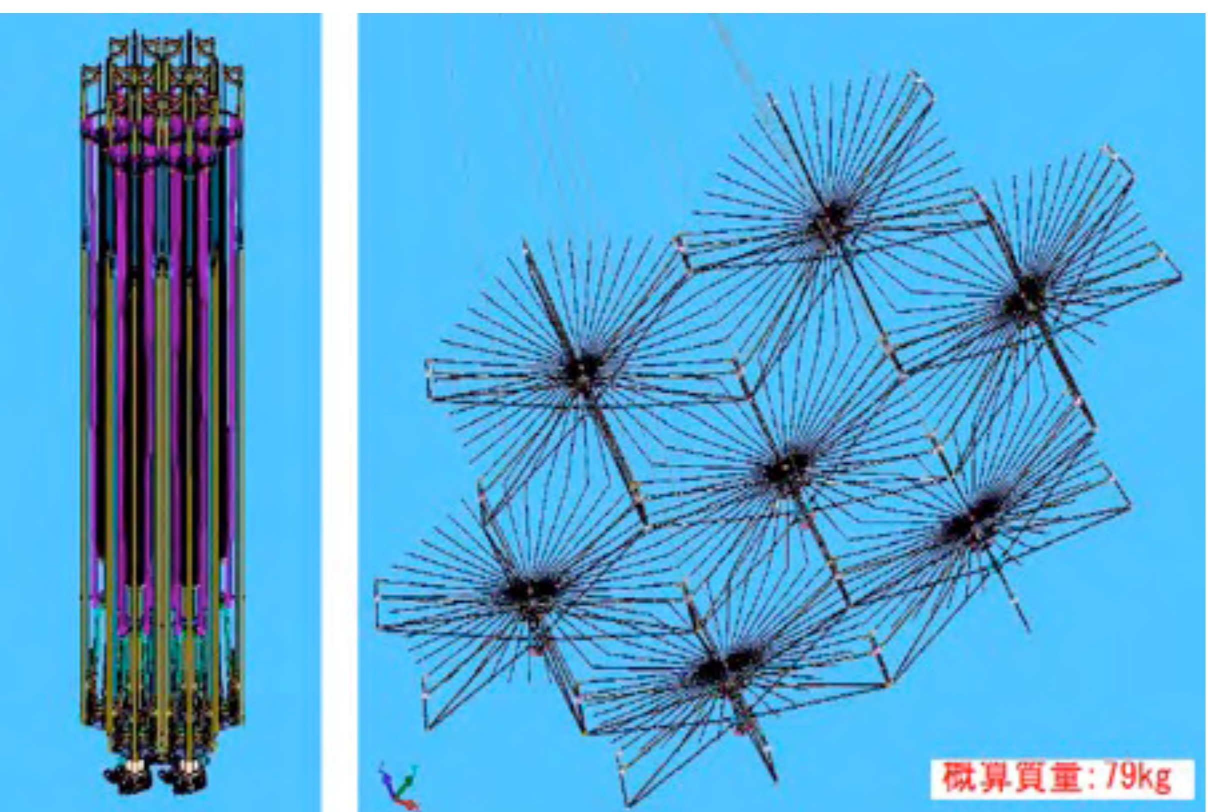
Large Deployable Antenna

… employs ETS-VIII Mechanism

Module-type offset-Cassegrain antenna

ETS-VIII (2006) deployment mechanism

Seven Modules (Stow / Deployment)



Deployment Test of ETS-VIII

Rocket & Orbit

Launch Rocket is H2A

- **Launch epoch; 2012→2016+**

due to technical uncertainty pointed out in the JAXA's critical review

	HALCA / VSOP	ASTRO-G / VSOP-2
Apogee Height	21,300 km	25,000 km
Perigee Height	560 km	1,000 km
Inclination	31°	31°
Orbit Period	6.3 hr	7.5 hr

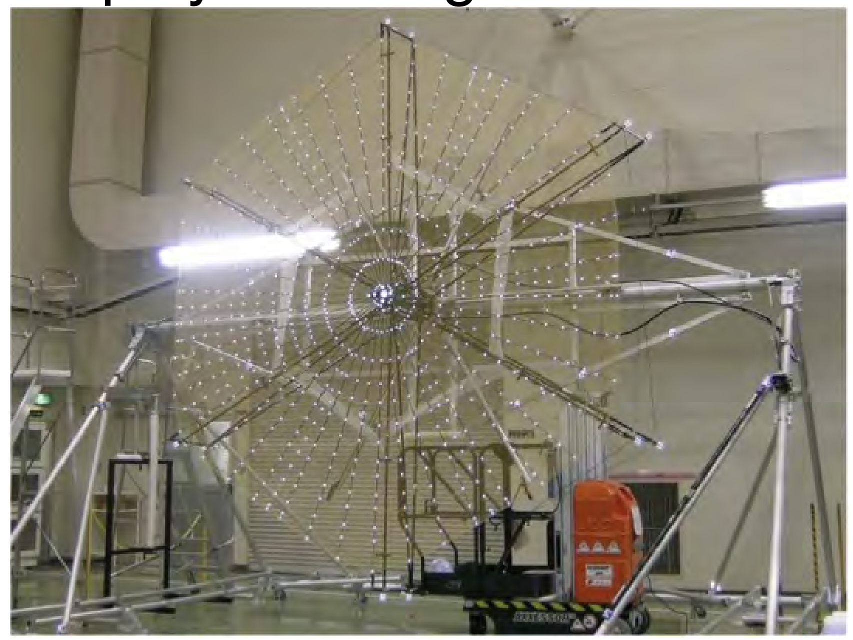
Antenna Deployment tests

Surface error after deployment

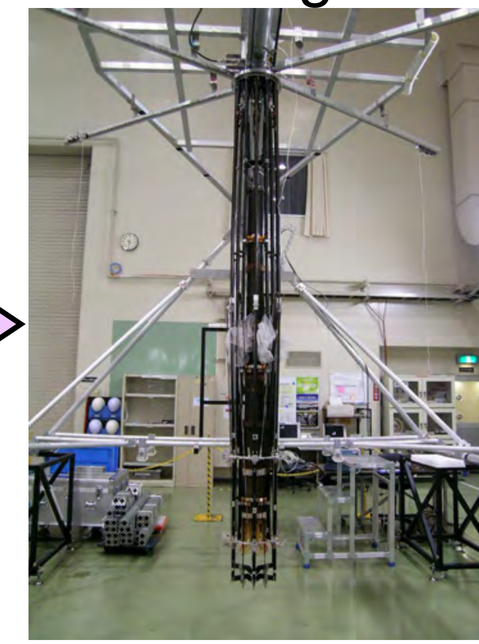
…doesn't meet the requirement of 1.0 mm rms

due to creep of the hoop cable

Deployed configuration



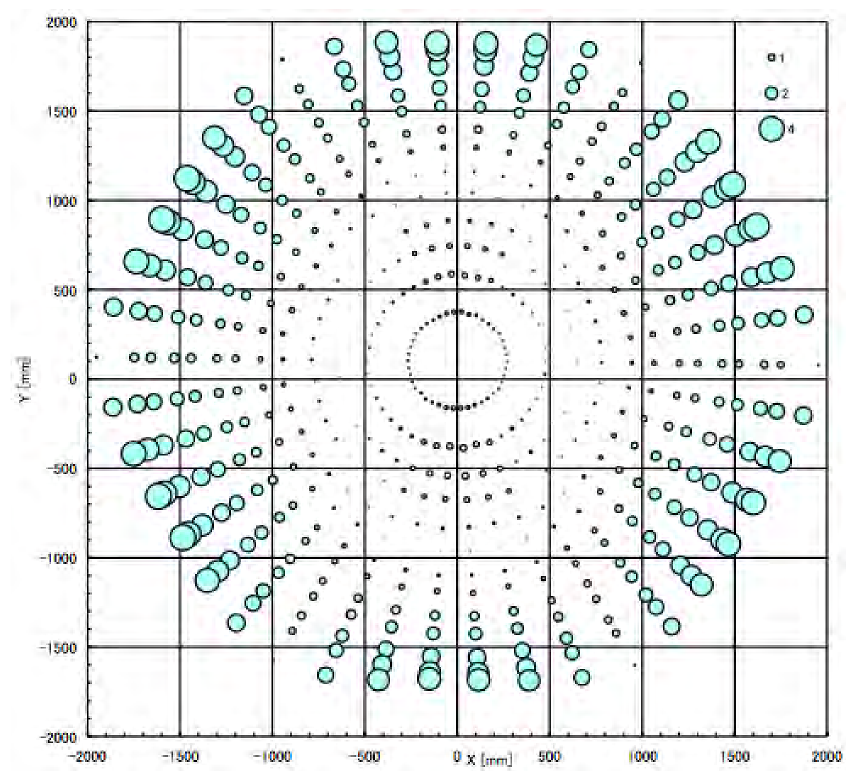
Launch configuration



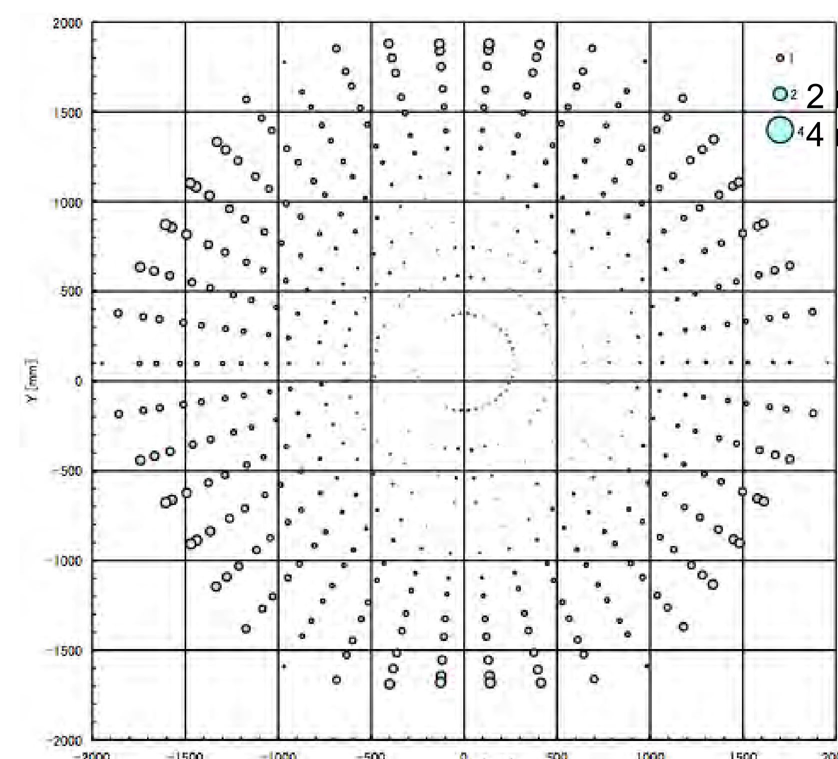
We tested a new cable material;
Quartz → Carbon Fibre

This modification results in

- rms = 0.57 mm (nominal)
  0.78 mm (worst)
- 43 GHz obs. possible
- Delay in the schedule



Quartz cable

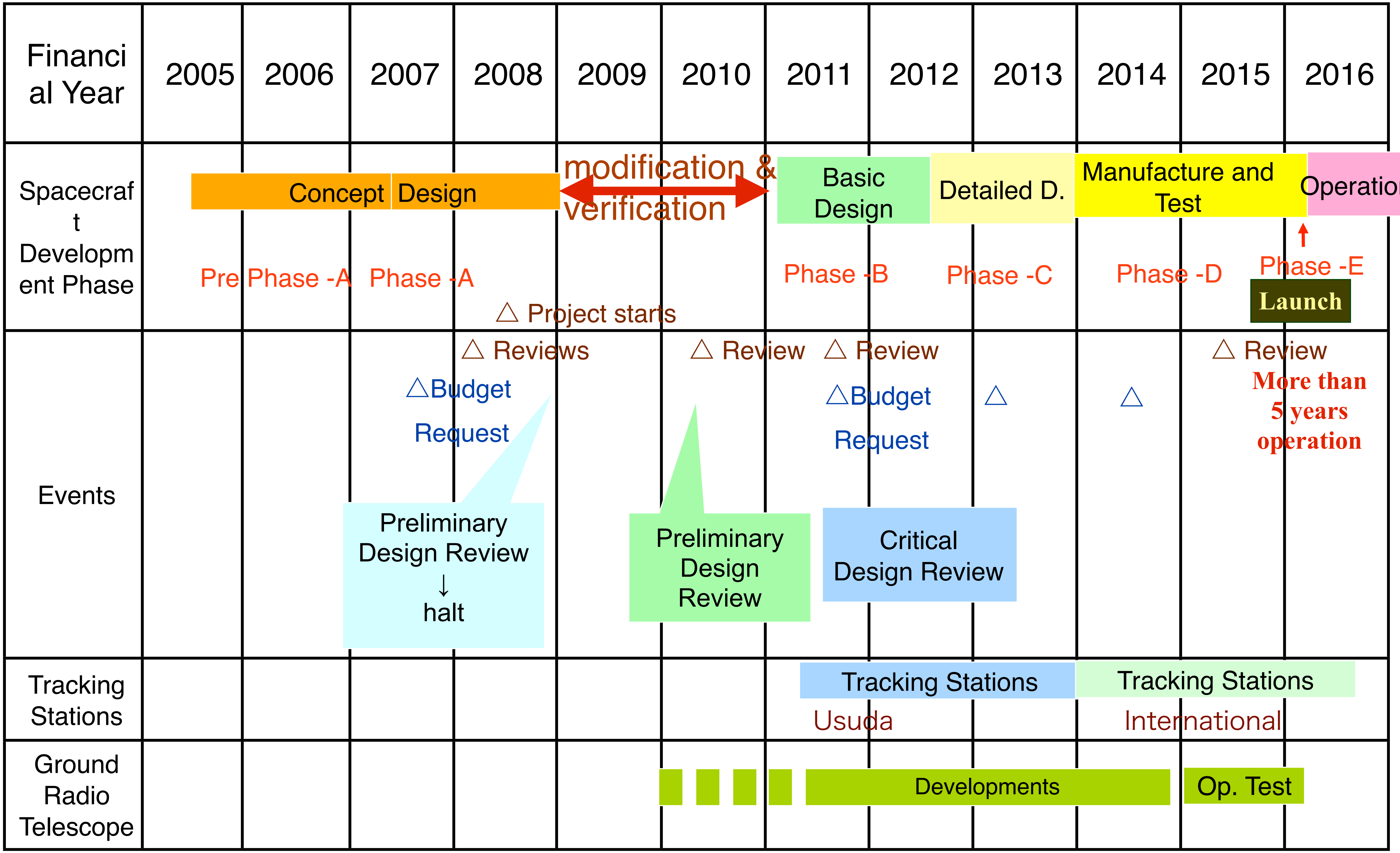


Carbon Fibre

ASTRO-G Development schedule (previous)

Financial Year (Apr-Mar)	2000～ 2005	2006	2007	2008	2009	2010	2011	2012 ～
Spacecraft Development Phase	Concept Pre Phase -A	Design Phase -A	Basic Design Phase -B △ Project starts	Detailed D. Phase -C	Manufacture and Test	Phase -D		Operation Phase -E Launch
Events	Selection of the science mission in ISAS	Approval of project preparation △Budget Request	△ Reviews △ △System I/F Fixed Design of PFM Structure Antenna, Obs.system Attitude control system	△ Review △	△ Review △	△	△	△ Review More than 5 years operation
Tracking Stations			Ground Tracking Stations Usuda		Ground Tracking Stations International			
Ground Radio Telescopes.				▪ ▪ ▪ ▪	Developments		Op. Test	

ASTRO-G Development schedule (current)



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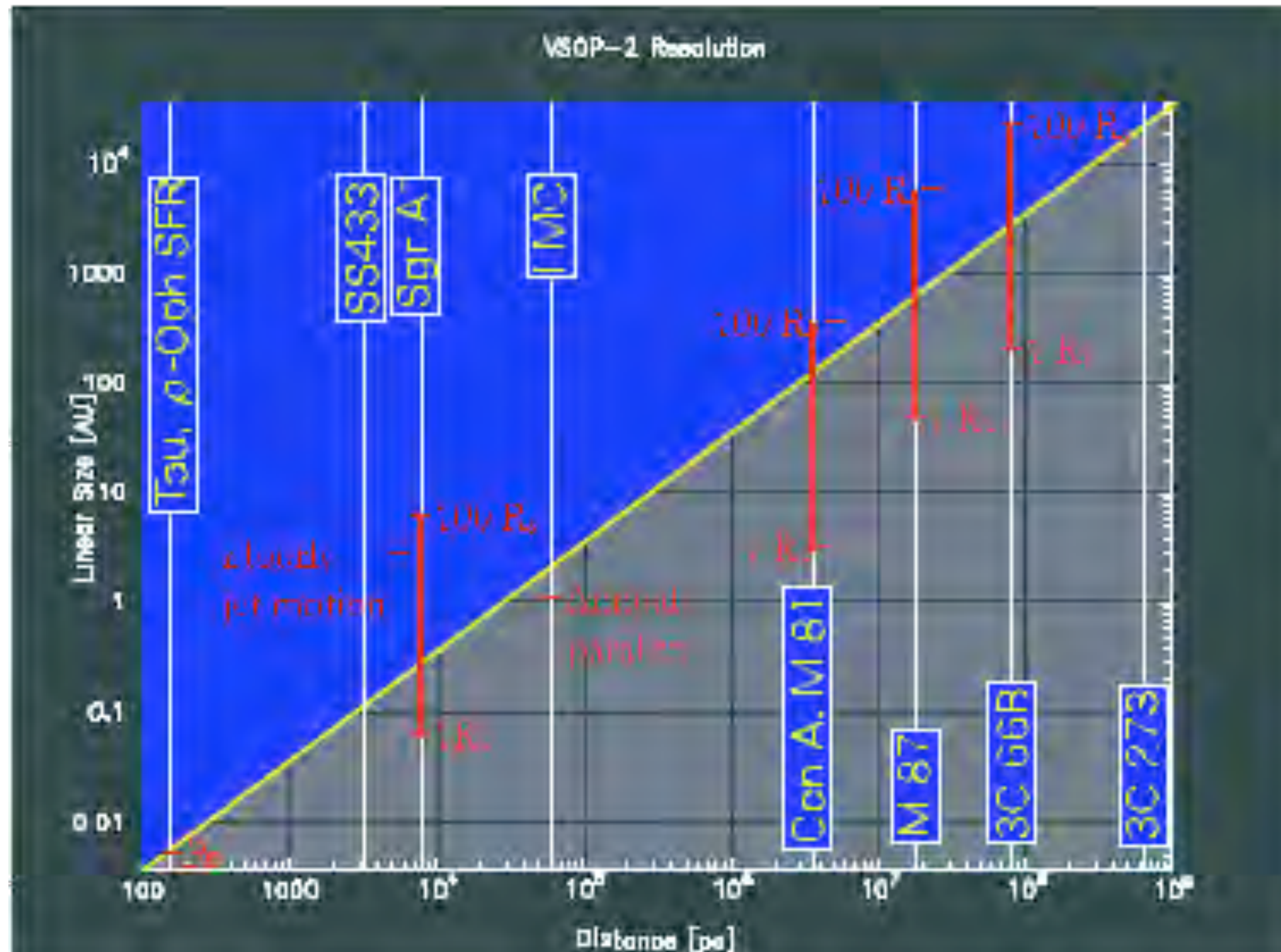
Improvements of VSOP-2

10x frequency, 10x resolution, 10x sensitivity

Resolution

Frequecy	Resolutoin	@10 Mpc
8 GHz	200 μas	0.01 pc
22 GHz	80 μas	0.004 pc
43 GHz	40 μas	0.002 pc

Linear scales of 40 μas



Sensitivity

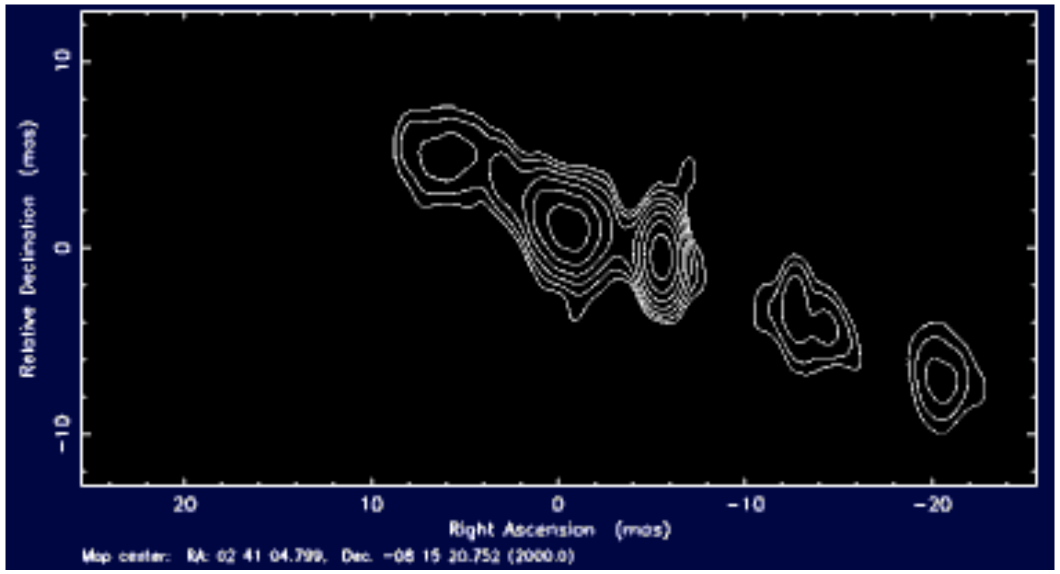
Frequency	Flux density	Tb
8 GHz	25 mJy	
(phase-ref)	6 mJy	6.8×10^{7} K
22 GHz	50 mJy	
(phase-ref)	8 mJy	1.3×10^{8} K
43 GHz	110 mJy	
(phase-ref)	11 mJy	2.1×10^{8} K

Possibility for direct imaging of accretion disks for the first time

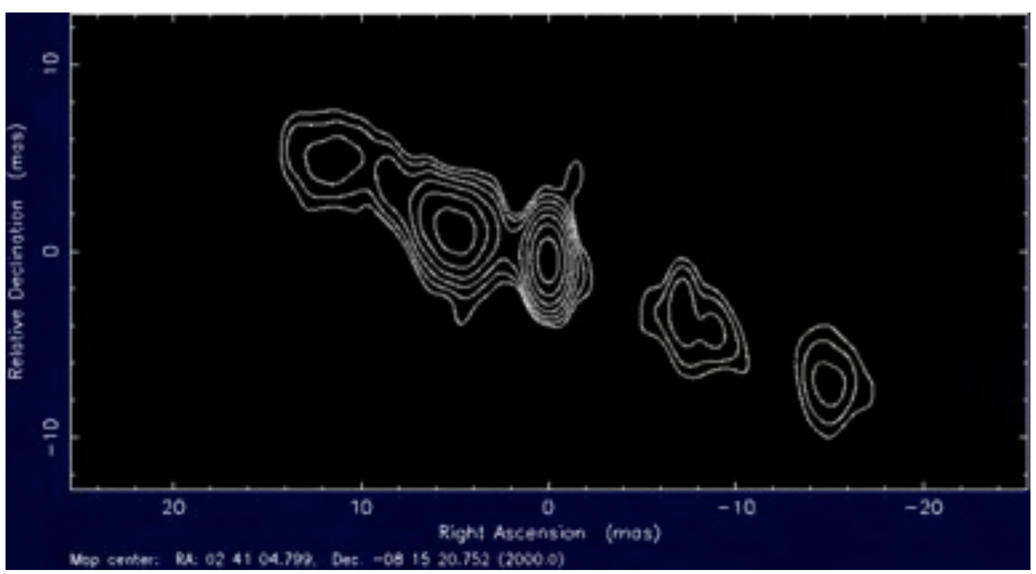
Phase Referencing Capability

VSOP-2 offers position-switching phase referencing capability

60-sec-cycle switch for 3˚ separation



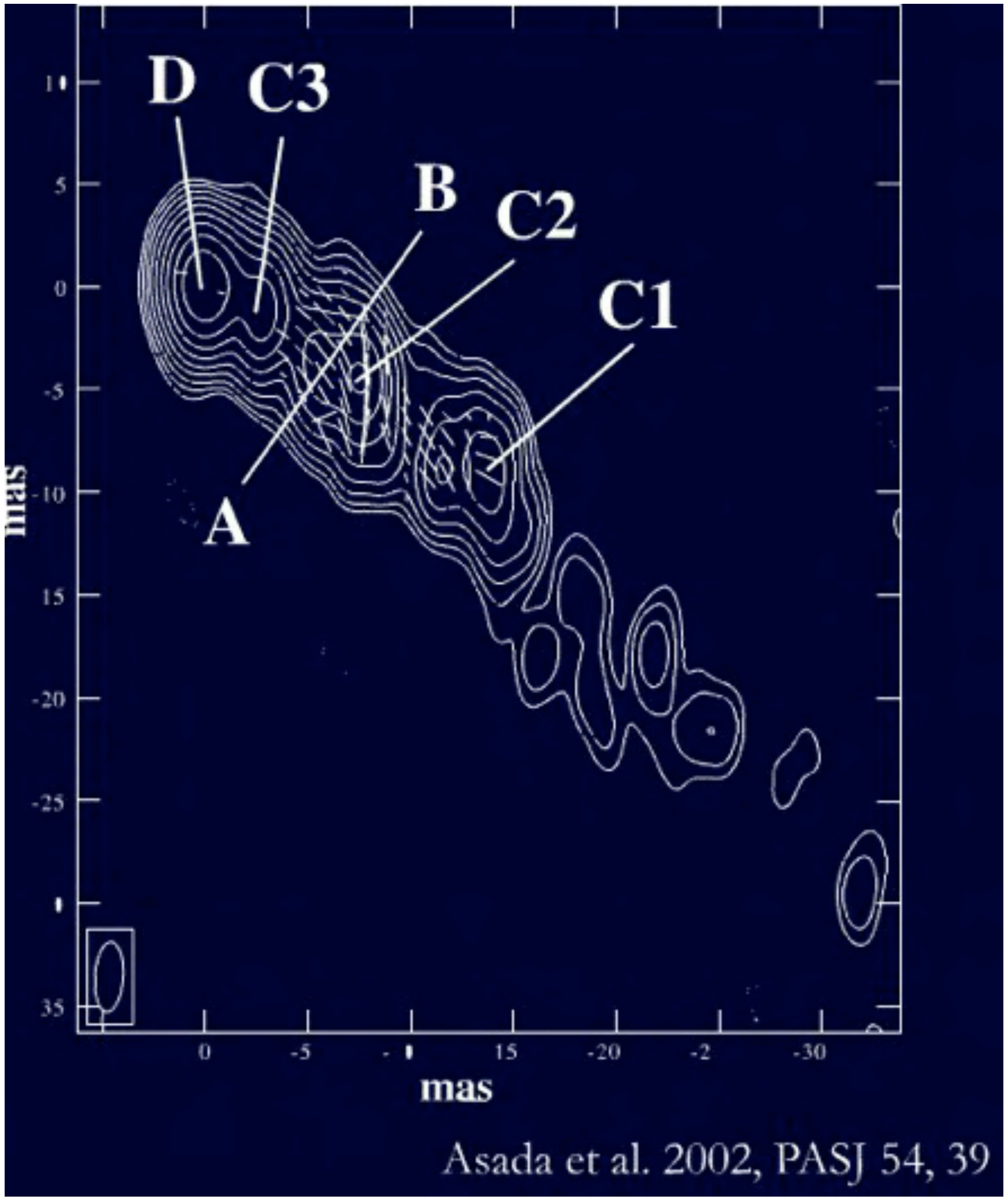
Phase-ref OFF



Phase-ref ON

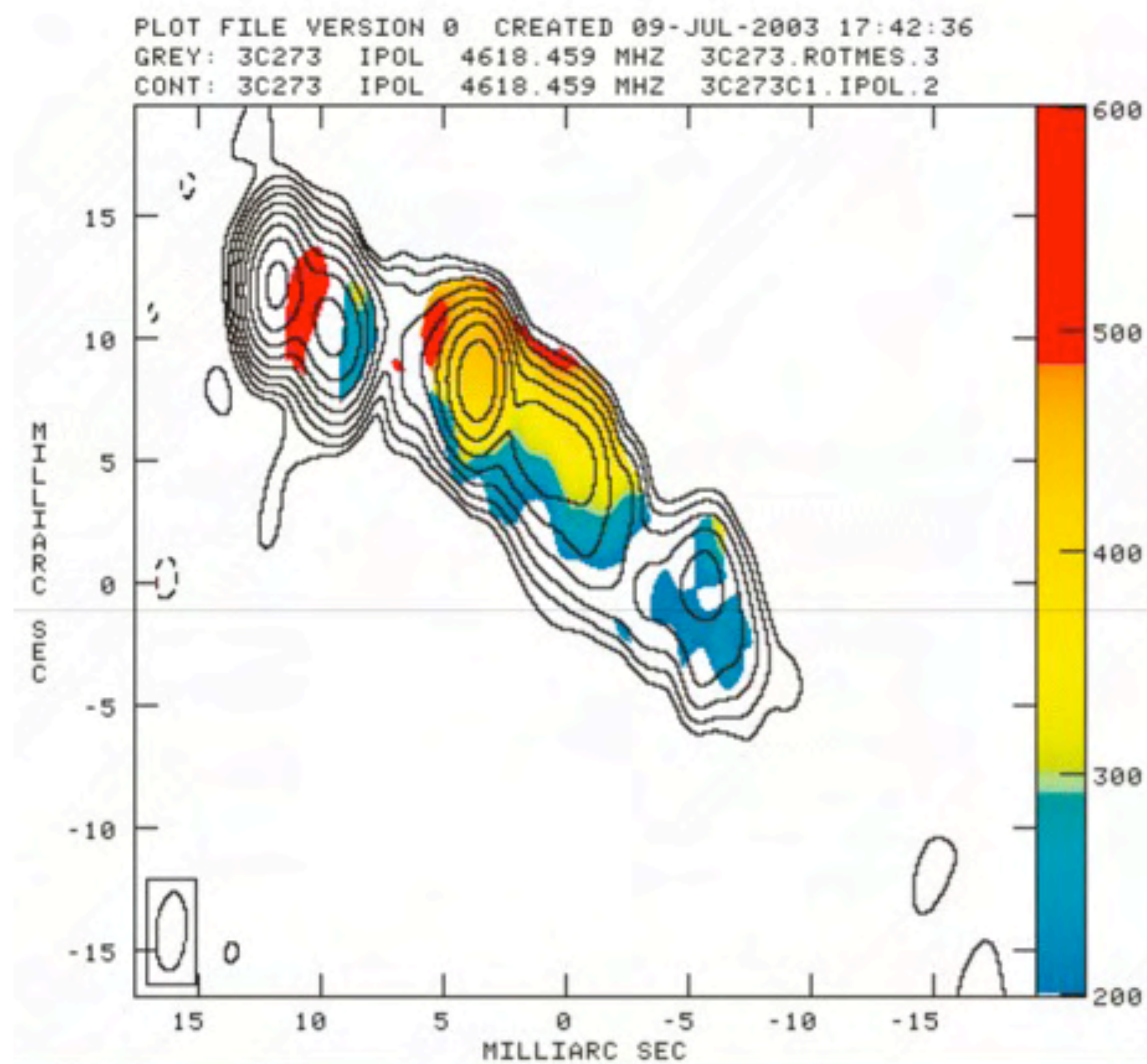
- Longer coherent integration → higher sensitivity
- Positioning
  - Astrometry
  - Multi-frequency registration
  - Multi-epoch registration

Dual Polarization Capability



LHCP and RHCP at 8, 22, and 43 GHz

- Linear polarization → $B_{\perp}$
- Faraday rotation measure → $B_{\parallel}$



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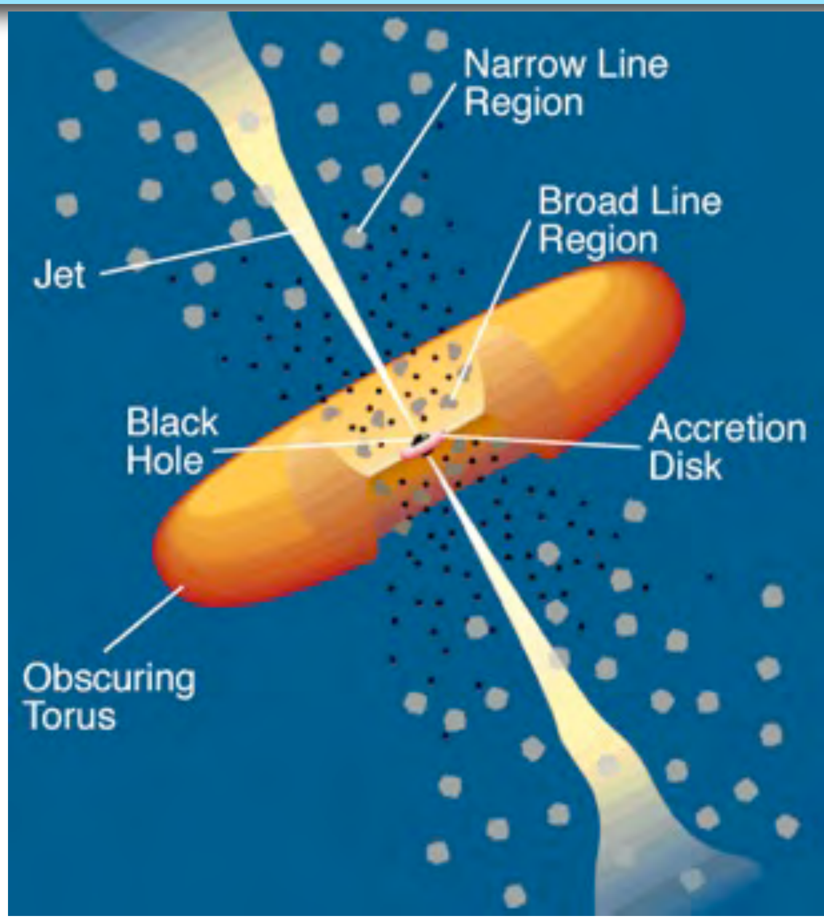
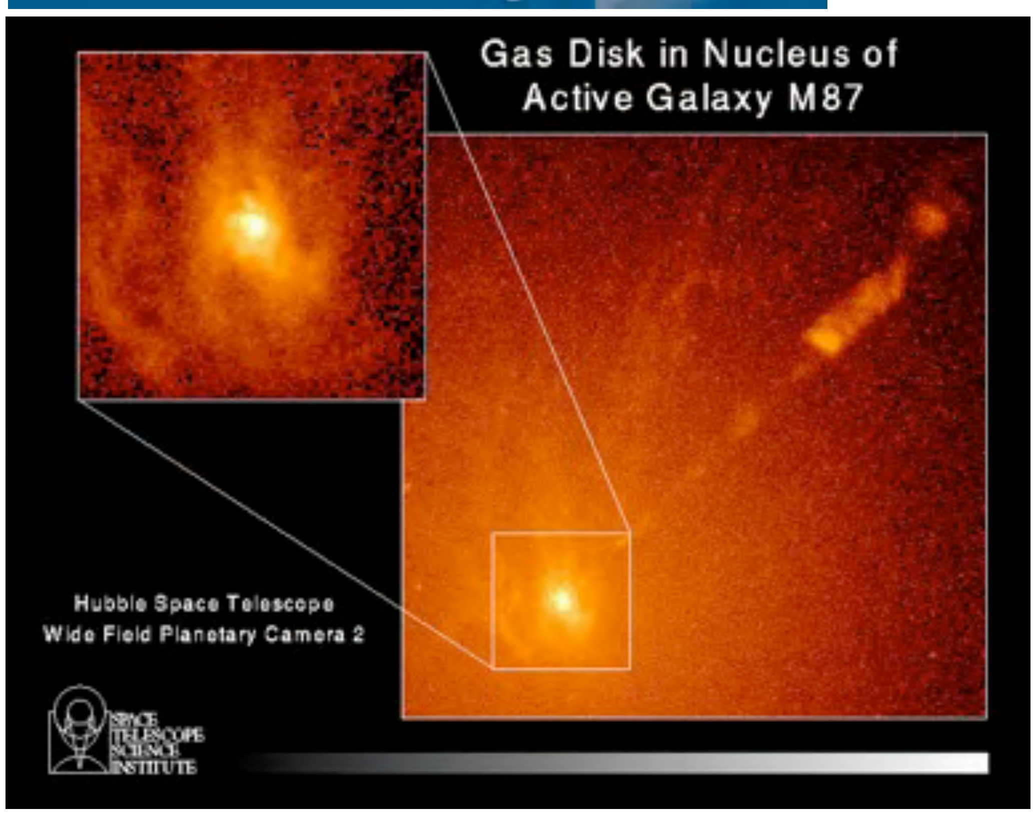
Zooming up on the central engine

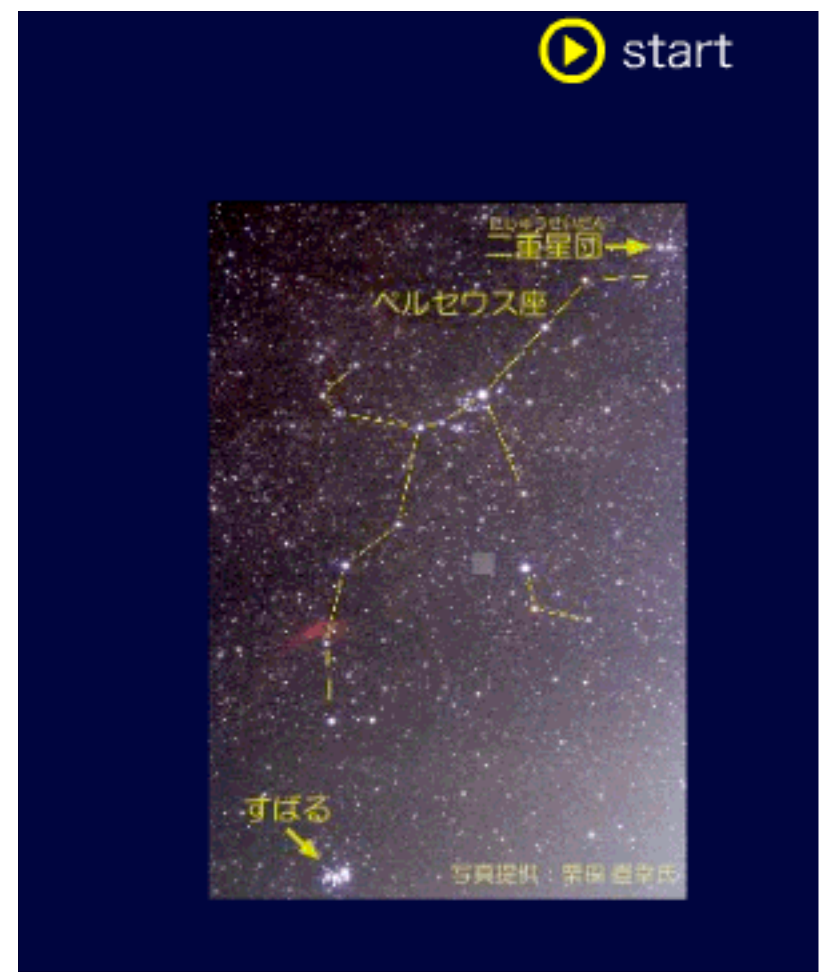


Power Source of Active Galactic Nuclei

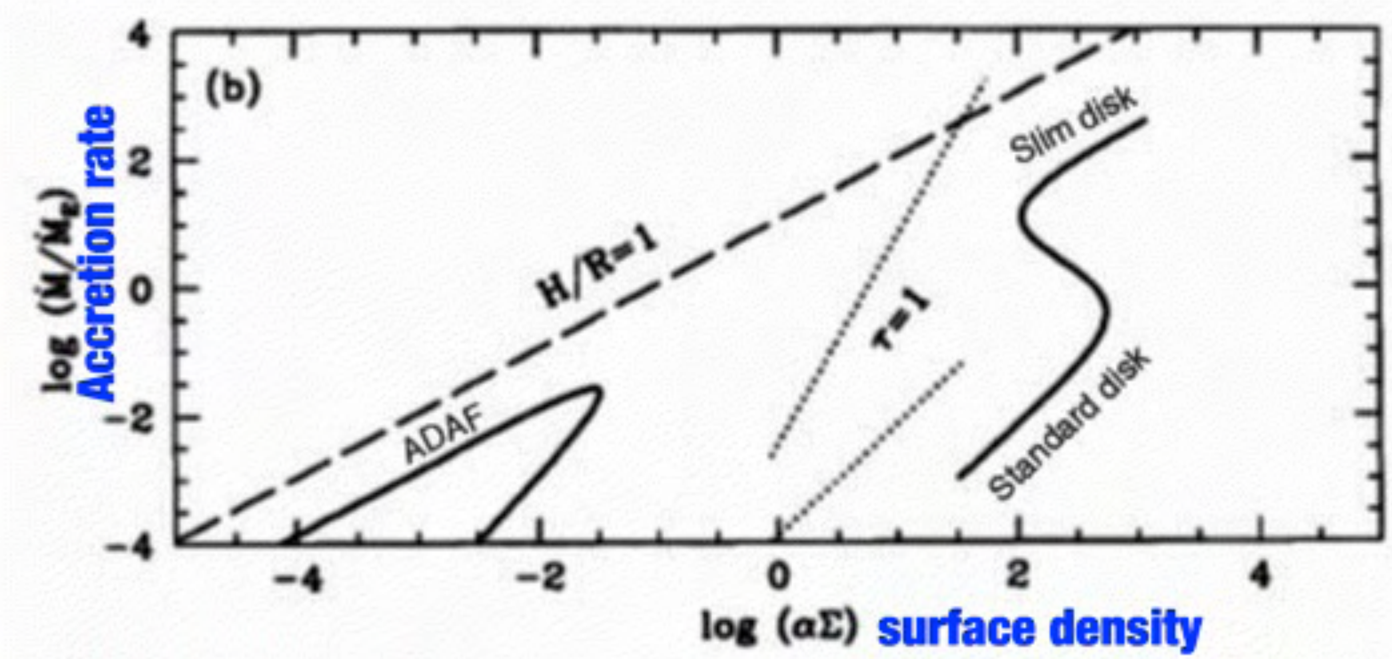
… considered to be accreting power onto massive black hole

The key is to resolve the central engine:
- Black hole
- Accretion disk
- Jet-launching region





Accretion disk types to image



Slim Disk (Abramowicz et al. 1988)

- $T_e \sim 10^6$ K
- $dm/dt > 1$
- Narrow-Line Sy1

Too faint for VSOP-2

Standard Disk (Shakura & Sunyaev 1973)

- $T_e \sim 10^{4\text{-}5}$ K
- $dm/dt << 1$
- Quasars

VSOP-2 Detectable

- $T_b >$ detection limit of 10^8 K
- ~ 40% population of AGNs

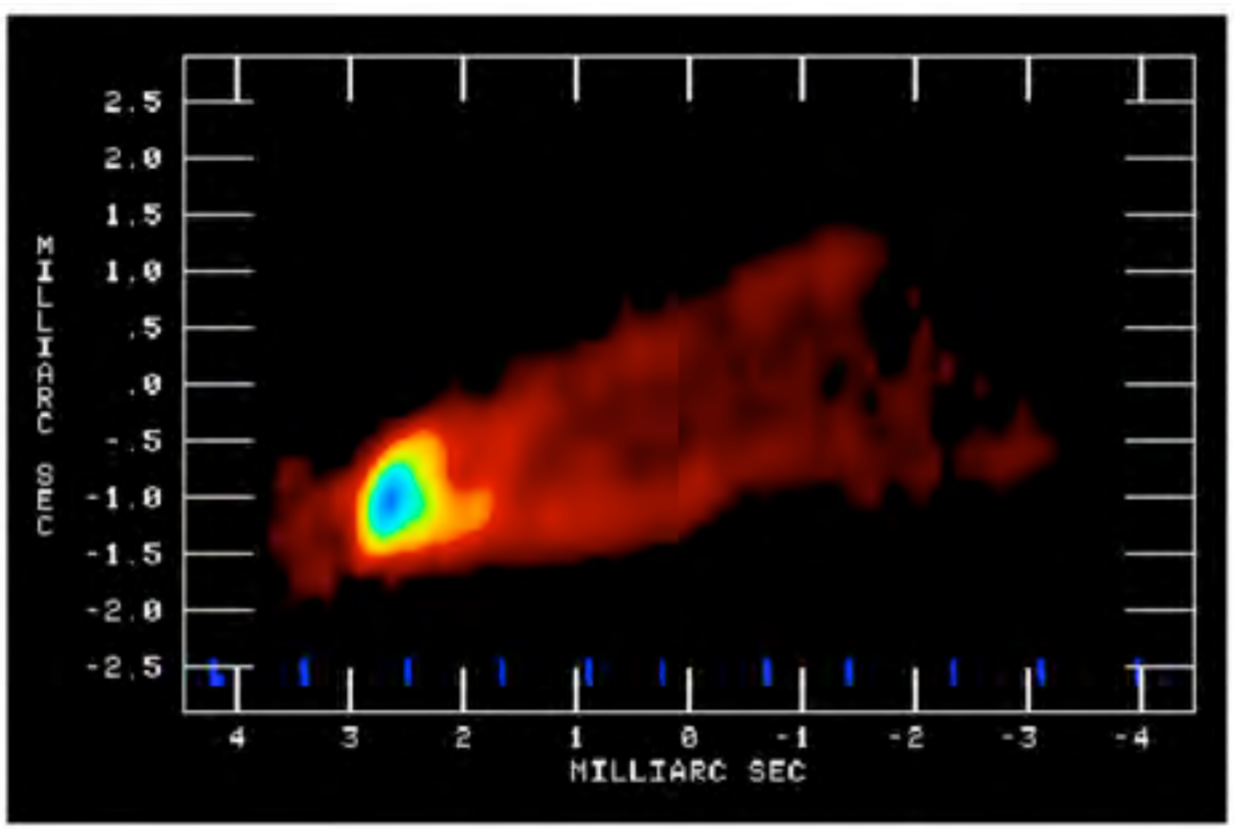
ADAF / RIAF (Narayan & Yi 1994)

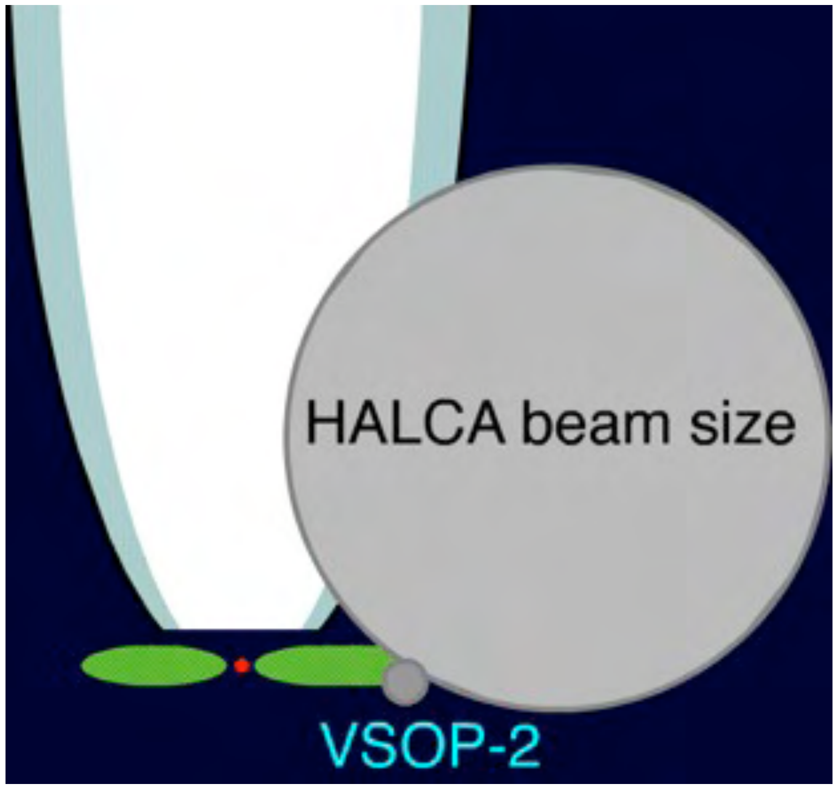
- $T_e \sim 10^{9\text{-}11}$ K
- $dm/dt << 1$
- Low-luminosity AGNs

Imaging accretion disks and jets with VSOP-2

Distinctly important source : M 87

- *R*s ~ 3.8 µas : VSOP-2 resolution ~ 10 *R*s
- The root of the jet can be imaged
- Separated by 1.5° from M 84 … phase ref.



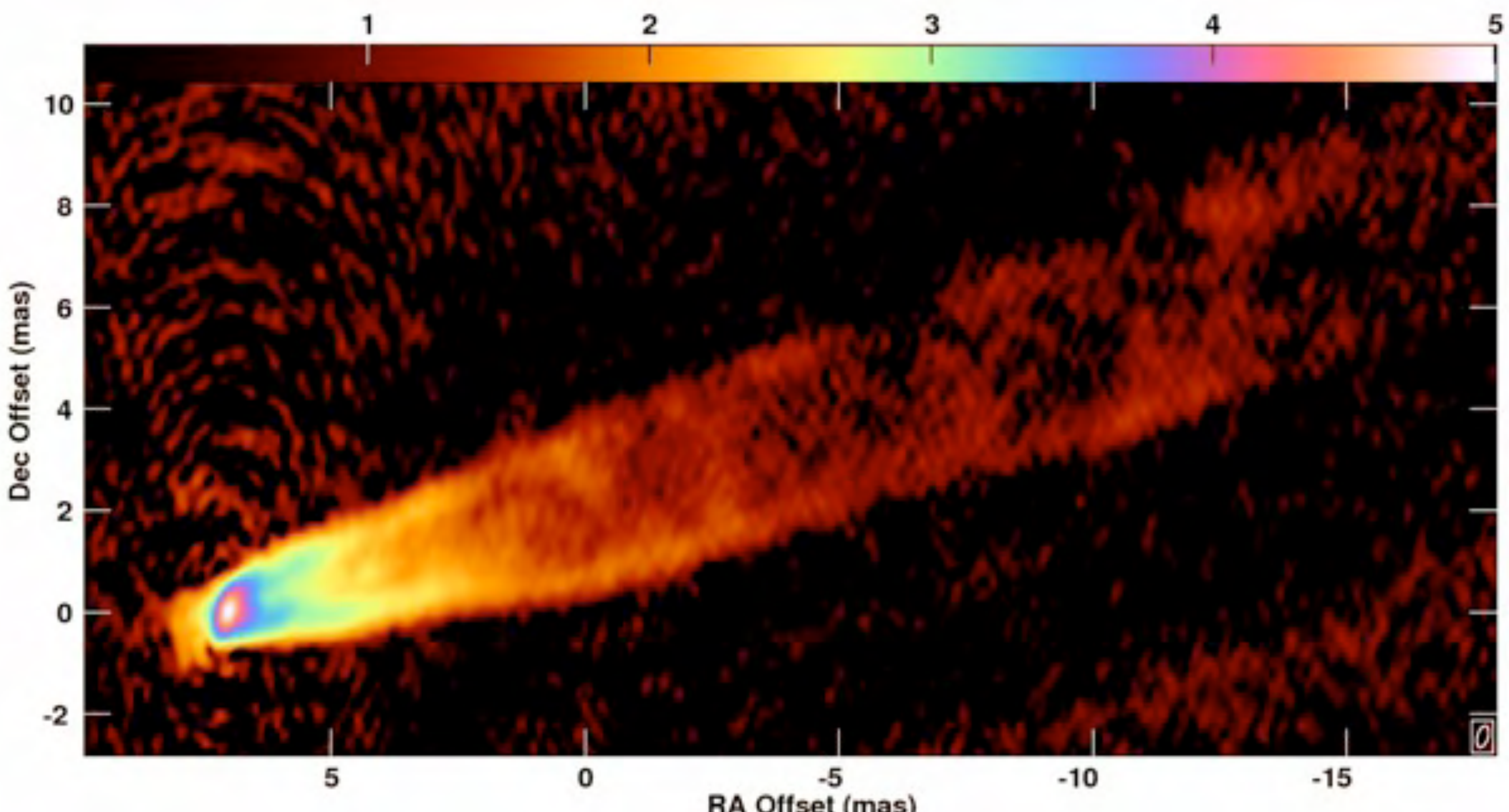


Movie : courtesy of C. Walker

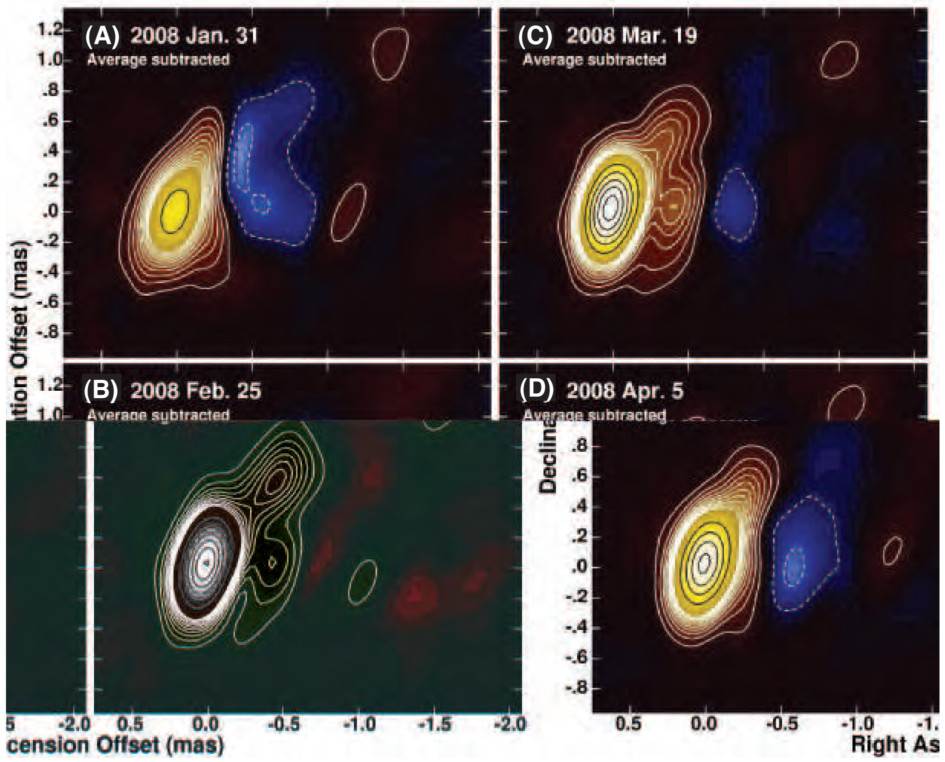
Disk imaging in M 87

Most probable source for disk imaging

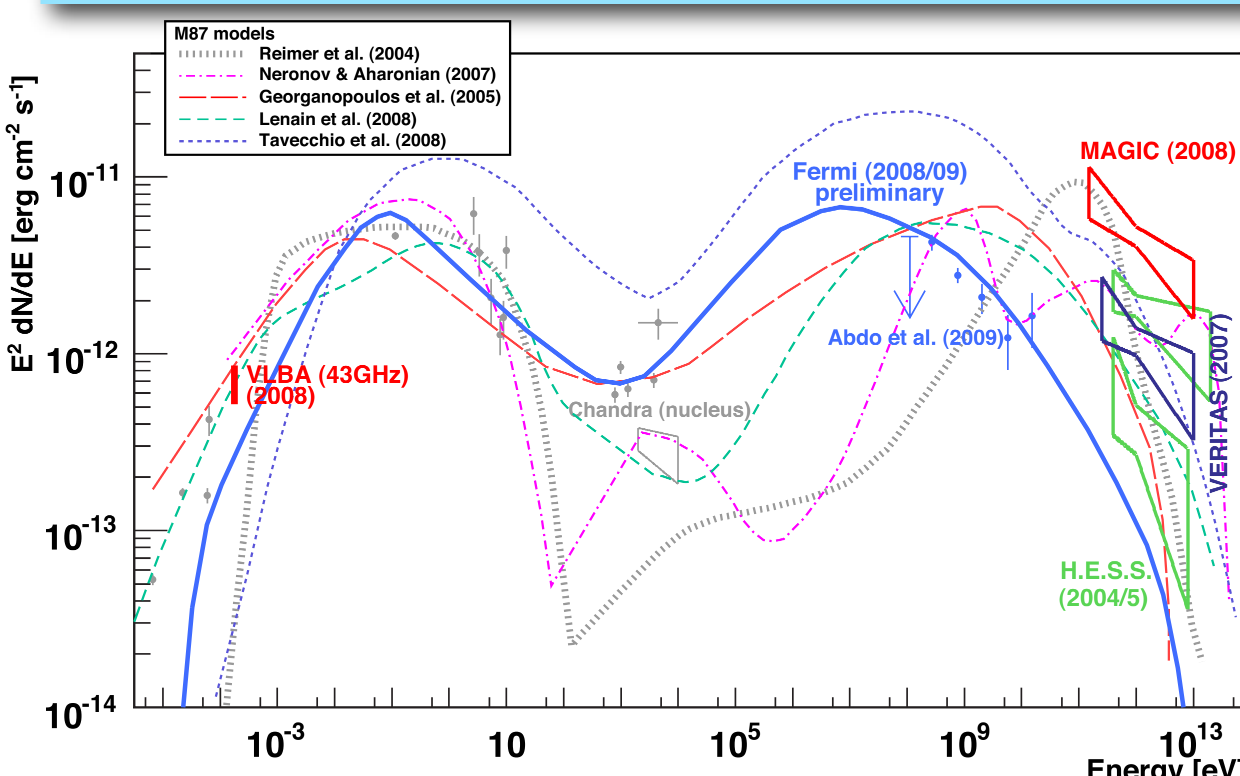
- Goal : image the core that is unresolved with ground VLBI
- Extra : detection of the disk discriminated from jets, distribution of brightness, spectral index, and time evolution



Walker et al. (2009)



Prediction from models and simulations



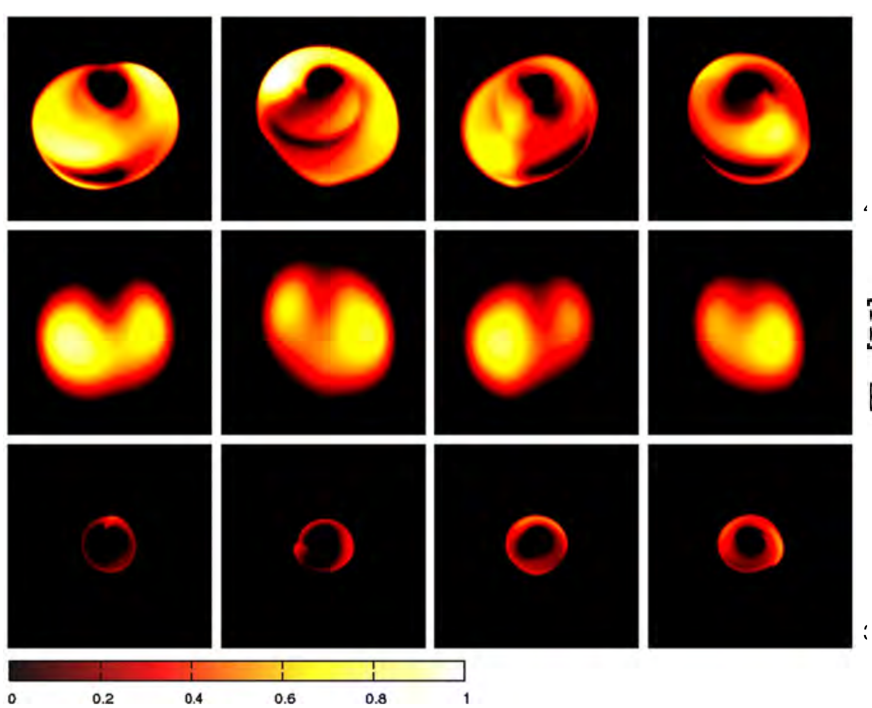
Wagner et al. (2009)

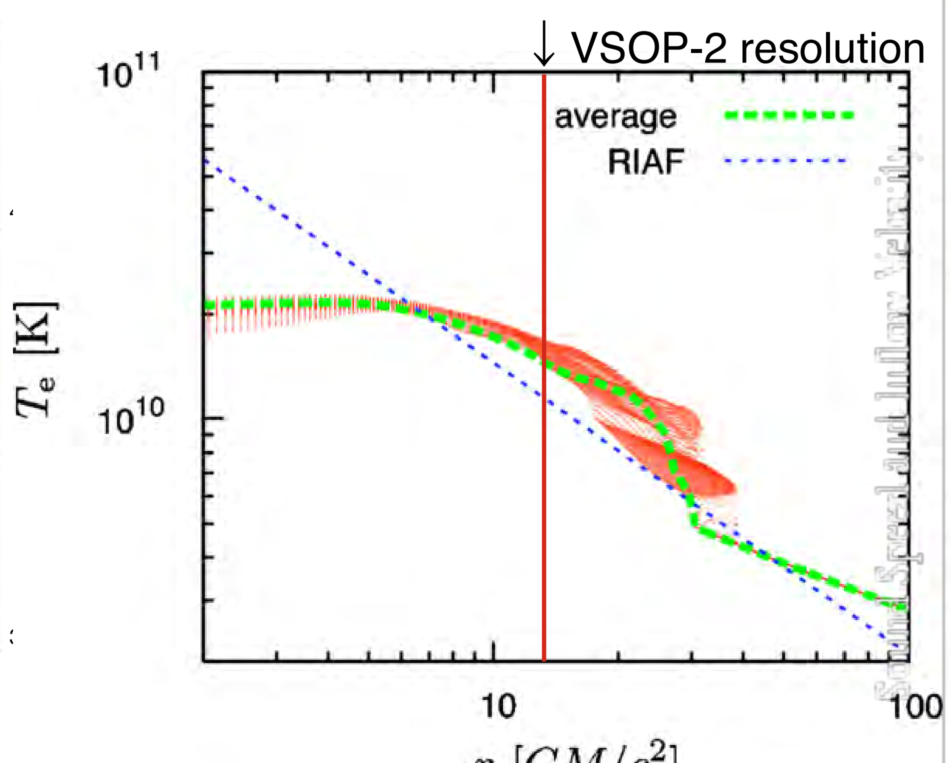
- **RIAF (Radiative Inefficient Accretion Flow)**
- **SASI (Standing Accretion Shock Instability)**

prediction

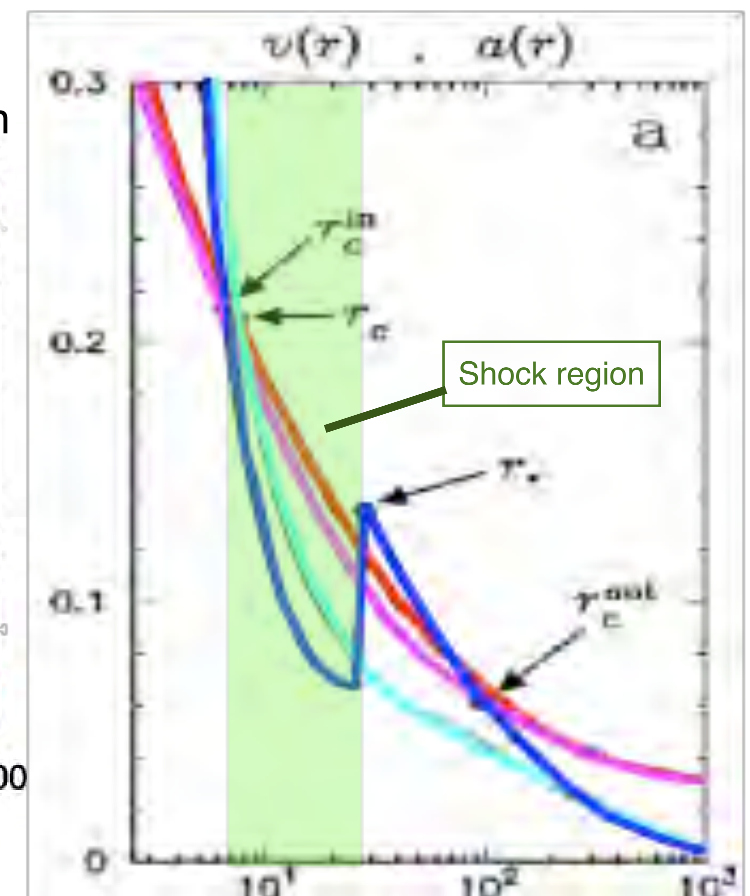
$T_e \sim 10^{9\text{-}10}$ K

$r \sim 30\ R_g$



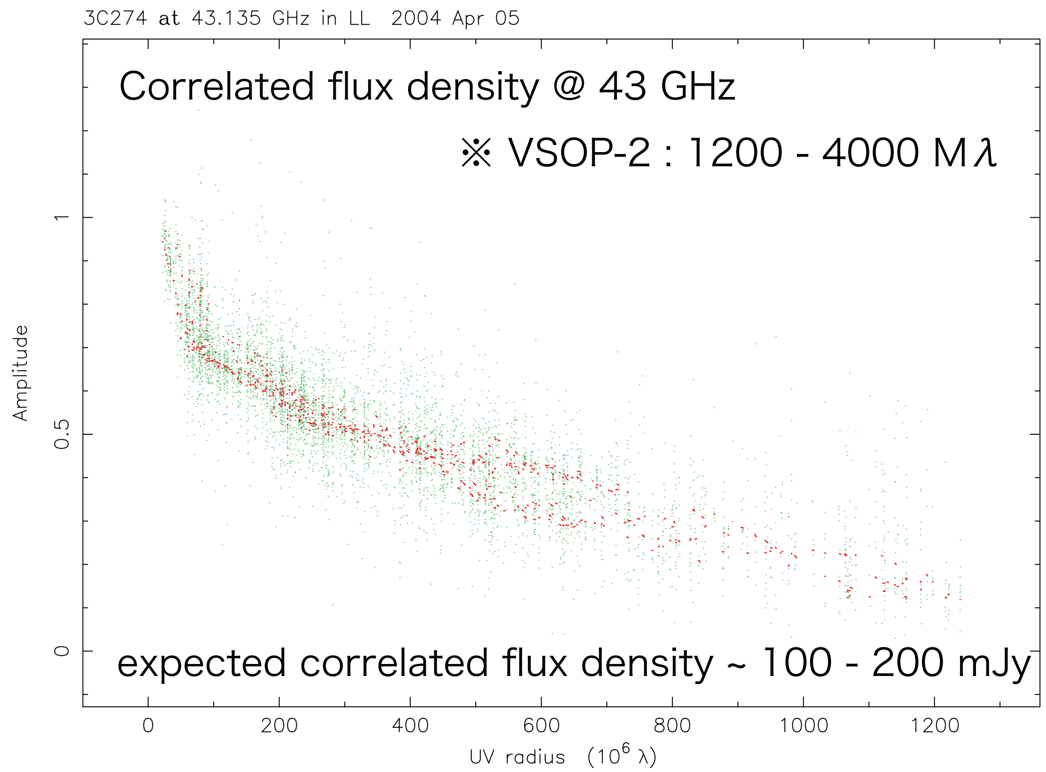


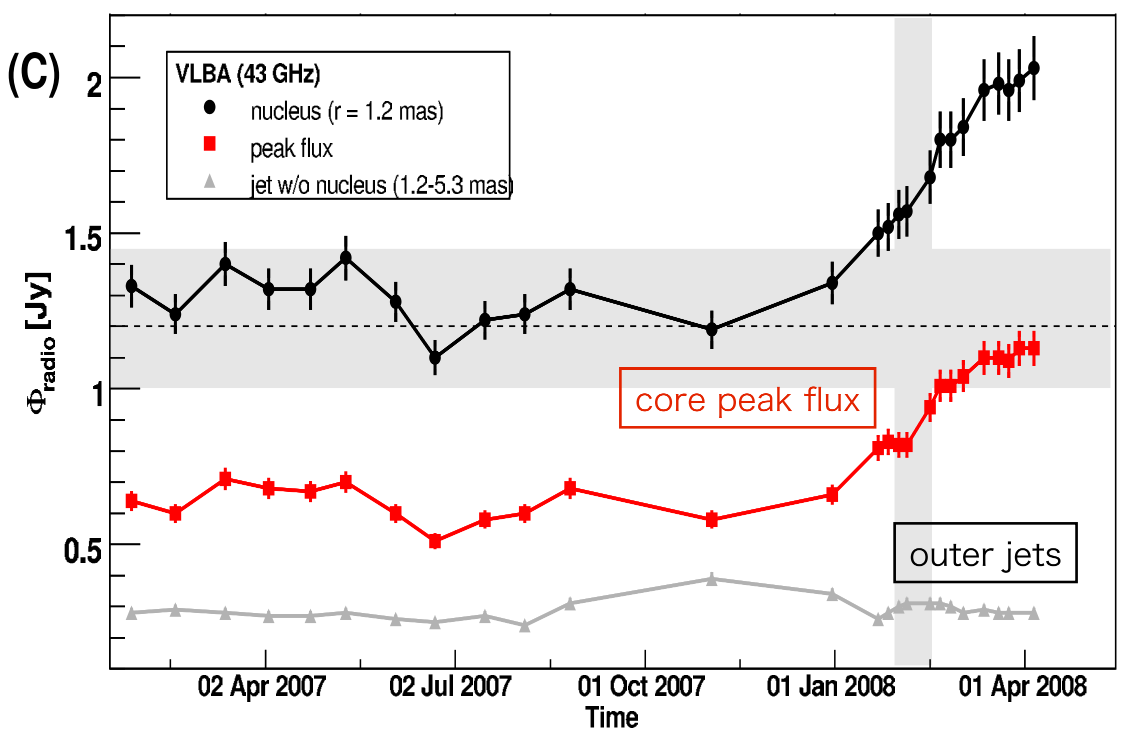
Nagakura & Takahashi (2010)



Becker et al. (2008)

M87 disk imaging capability





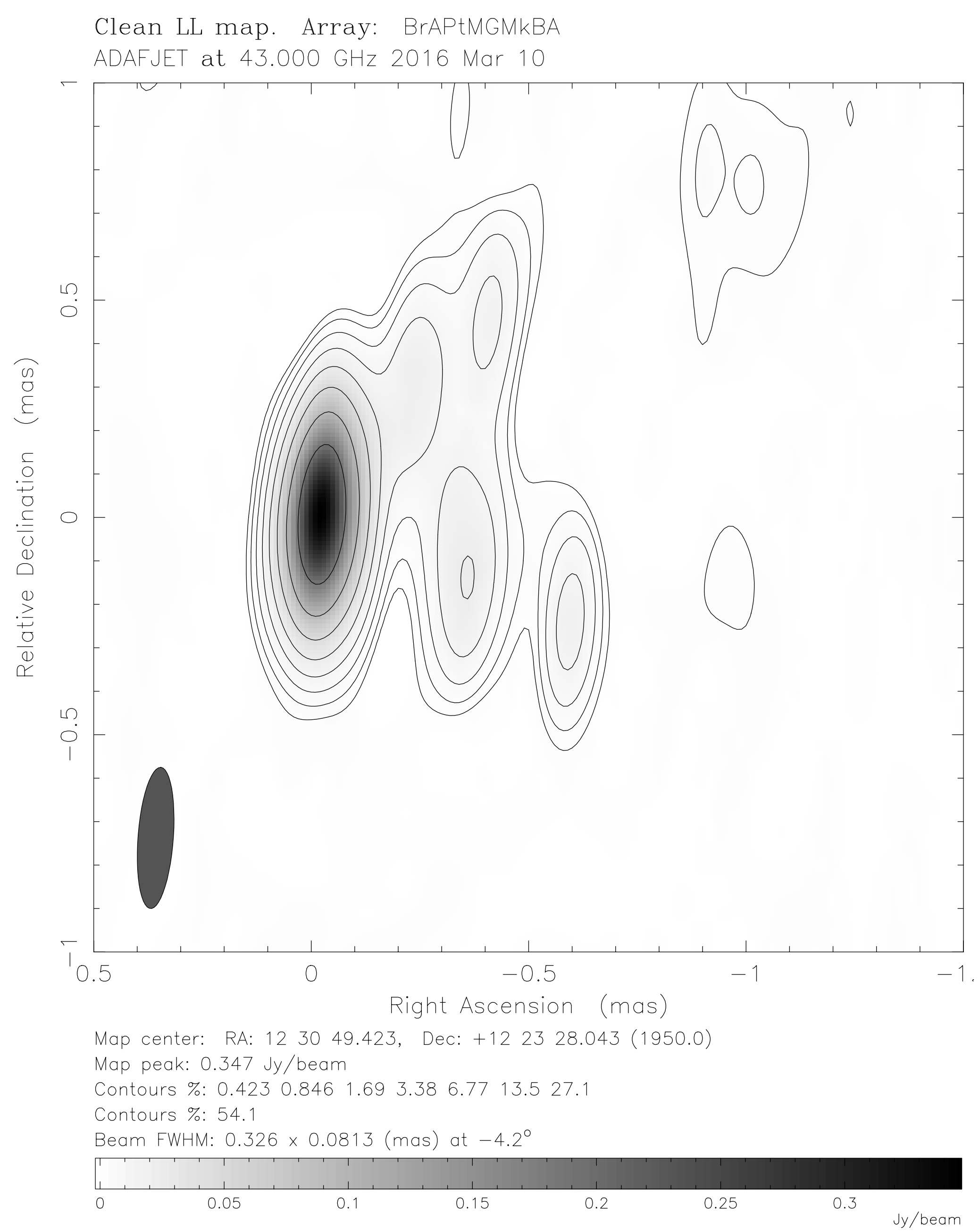
- Fringe detection in M 87
  - visibility amp. > 100 mJy@43 GHz, 24 mJy@22 GHz
  - 22 GHz : OK. 43 GHz : requre rms < 0.7 mm
- Resolutipn
  - FWHM = 12 Rs@43 GHz, 24 Rs@22 GHz
- Tb > image r.m.s.
  - Tb ~ Te ~ 10^{9-10} K > r.m.s. = $5x10^8$ K
- Electron scattering << disk size
  - core size@5 GHz < 0.3 mas （VSOP）

    → λ^2 scattering < 14 μas@22 GHz, 4 μas@43 GHz
- Brightness ration to jets < dynamic range
  - Tb in jets ~ 10^{11} K → require D.R. ~ 100

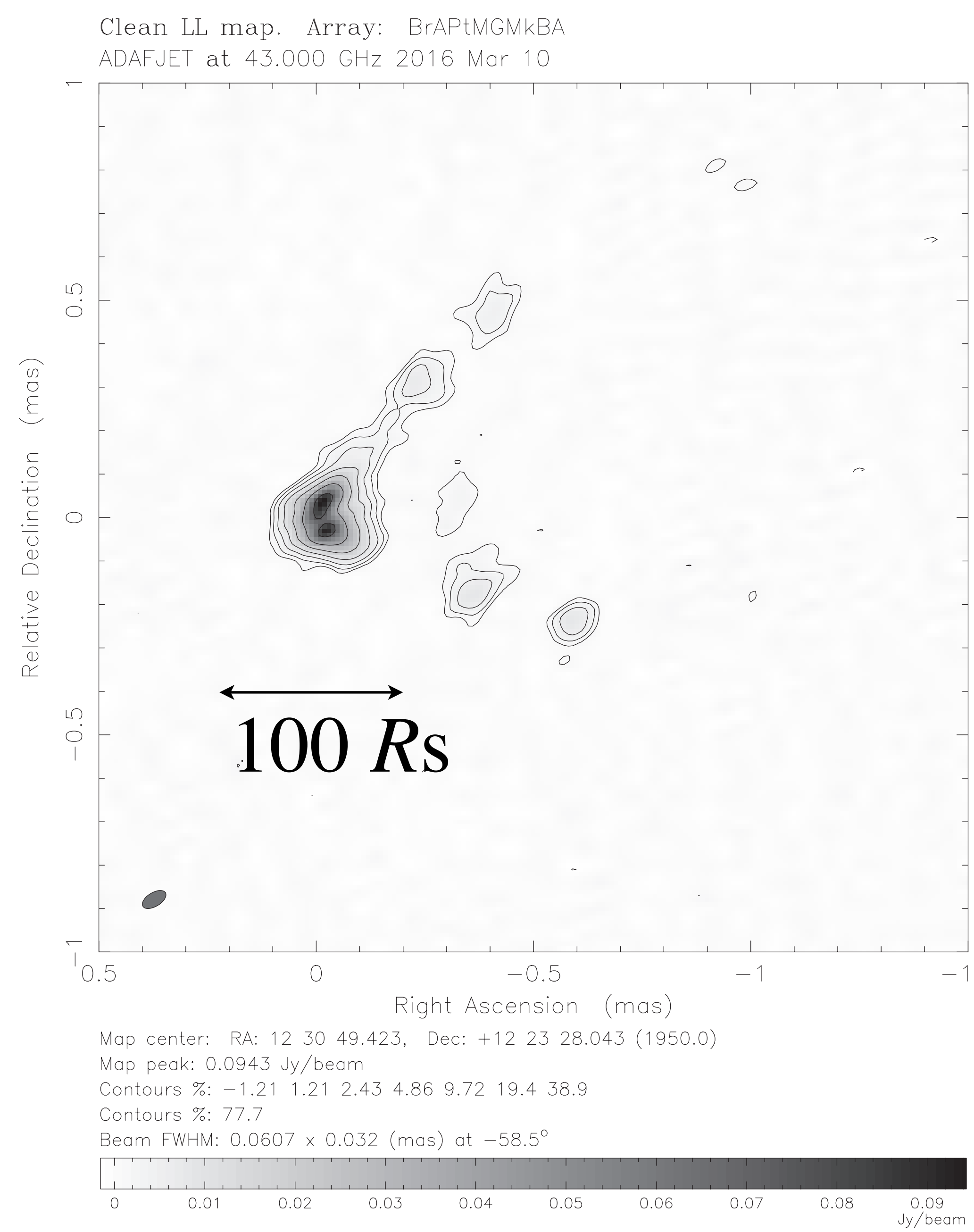
VSOP-2 results impact to accretion disk models

Imaging simulations

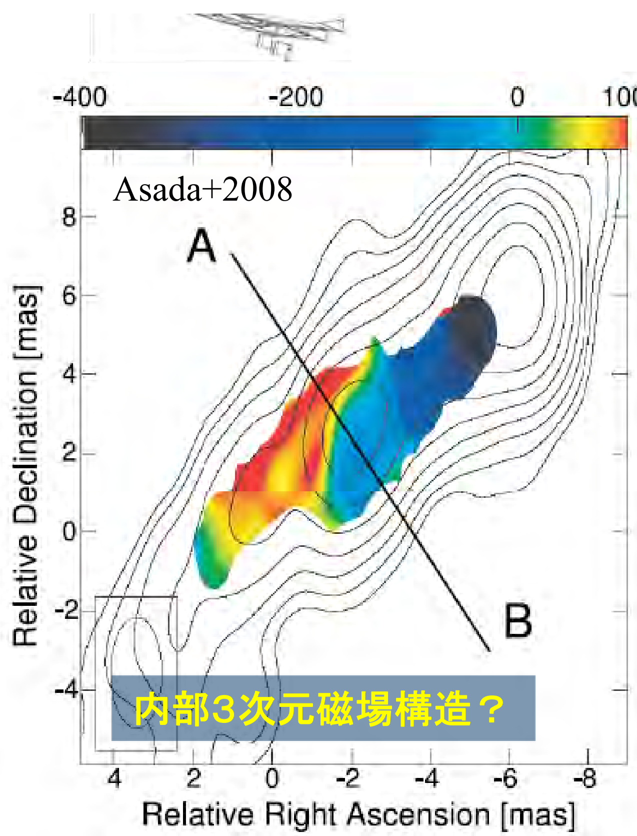
Ground-VLBI

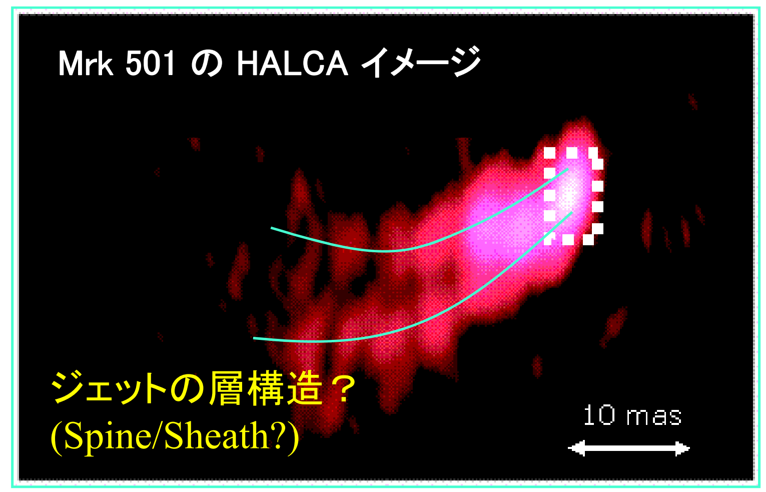


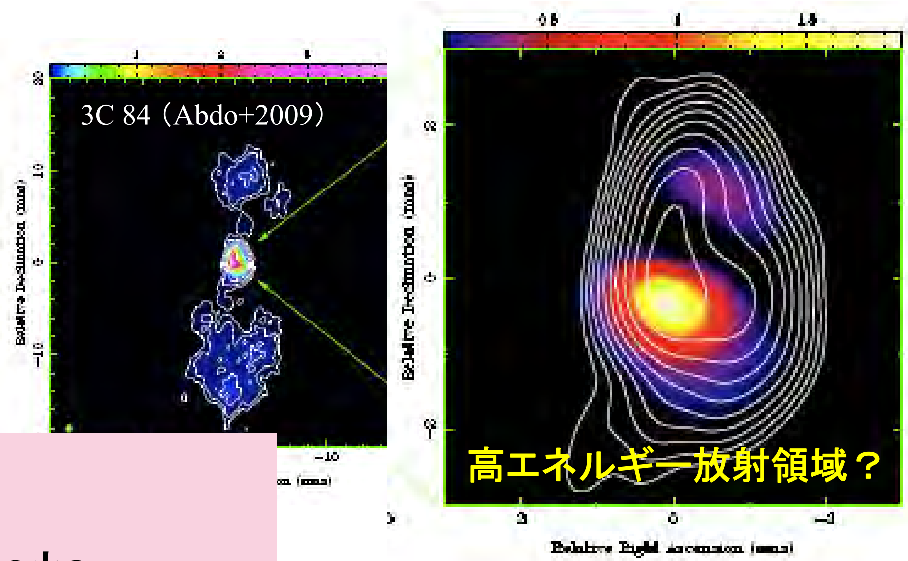
VSOP-2

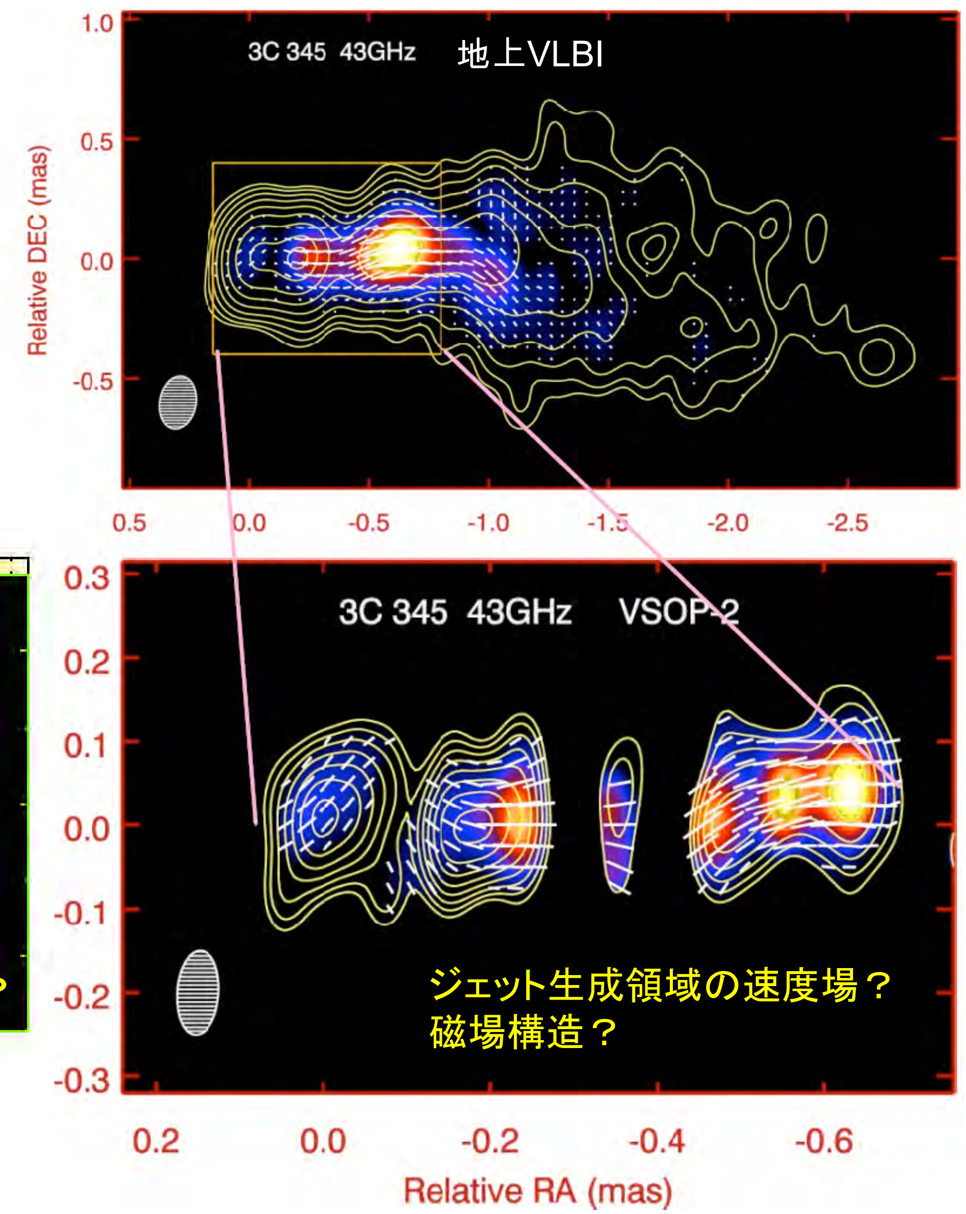


Jet acceleration and high-energy emission







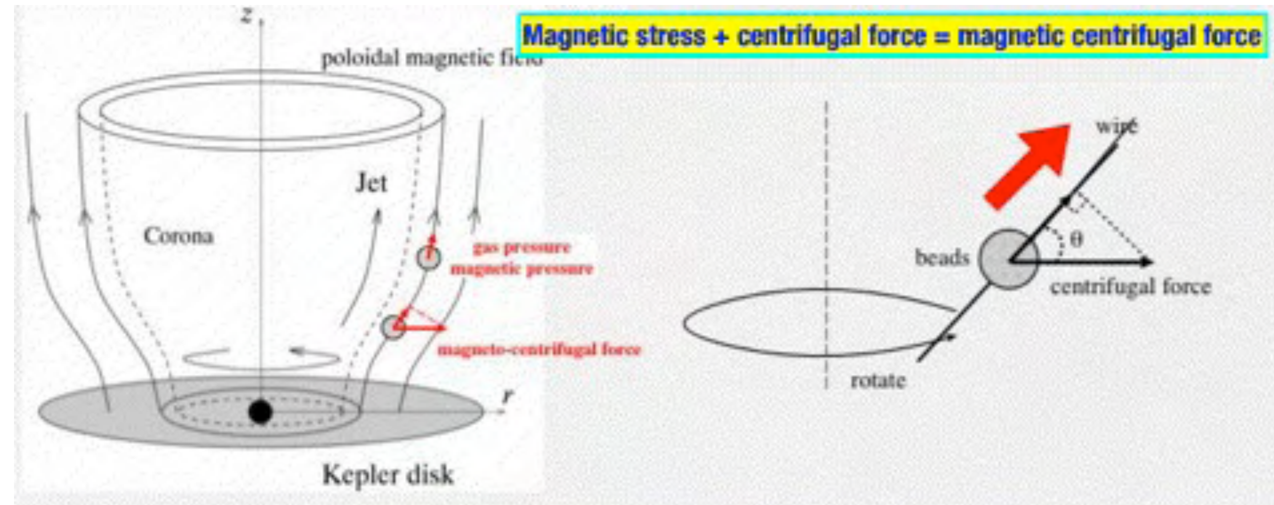


- Jet velocity fields
- Inner structure of jets
- 3-D magnetic fields
- High-energy emission component

Proposed MHD models for jet formation

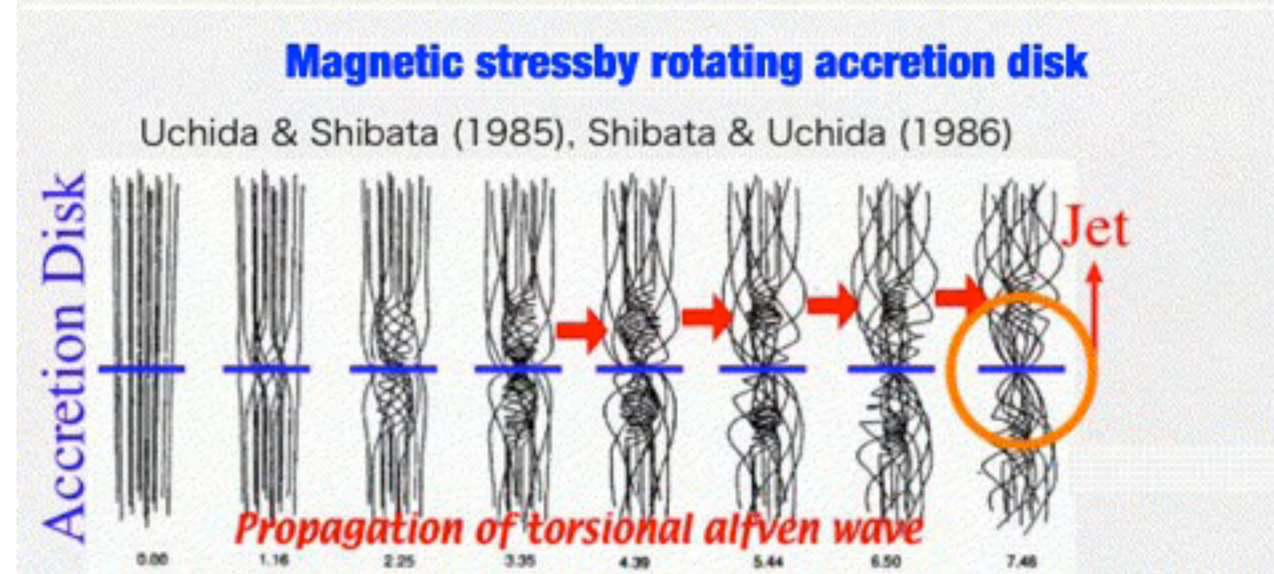
- **•Magnetic centrifugal force**

Blandford & Payne (1982)



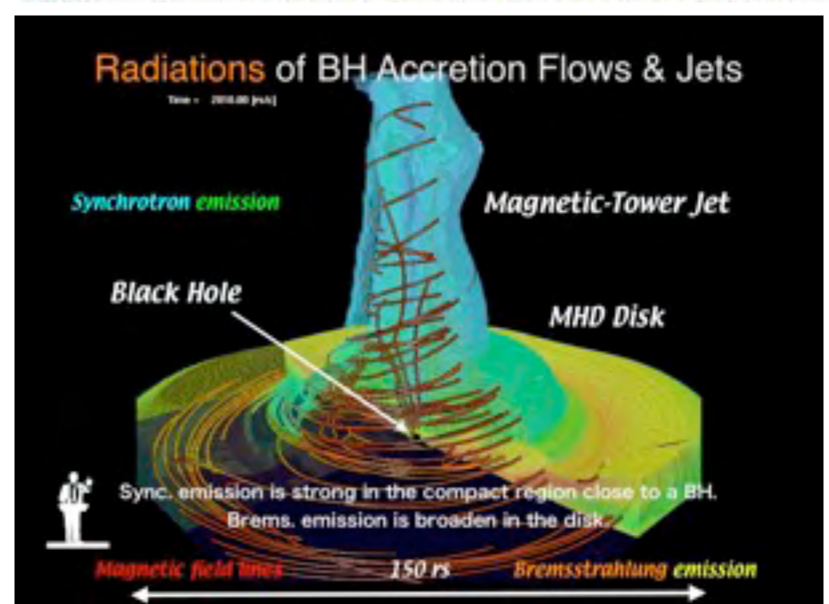
- **•Magnetic stress by rotating disk**

Uchida & Shibata (1985)



- **•Magnetic tower jets**

Kato, Y. (2007)

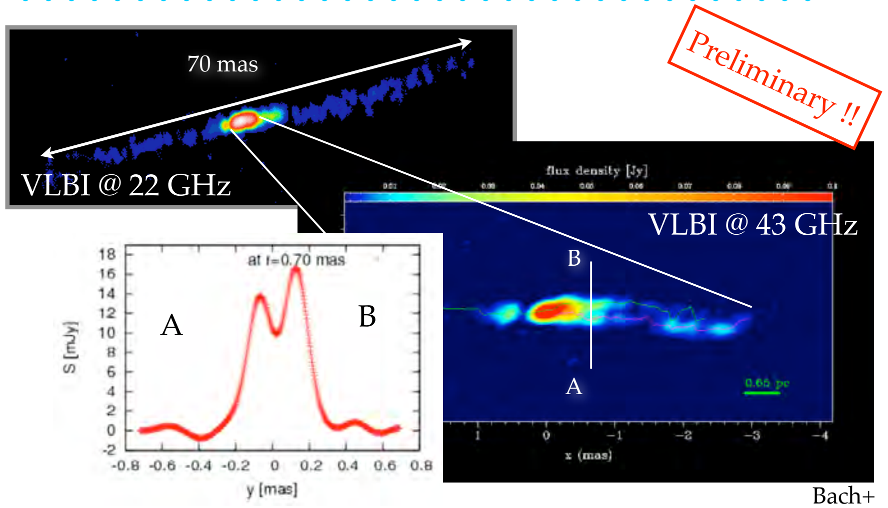


Kato, Y. (2007)

3-D magnetic structure in the jet-launching region

Velocity fields in Jet acceleration region

internal structure of Cyg A jet

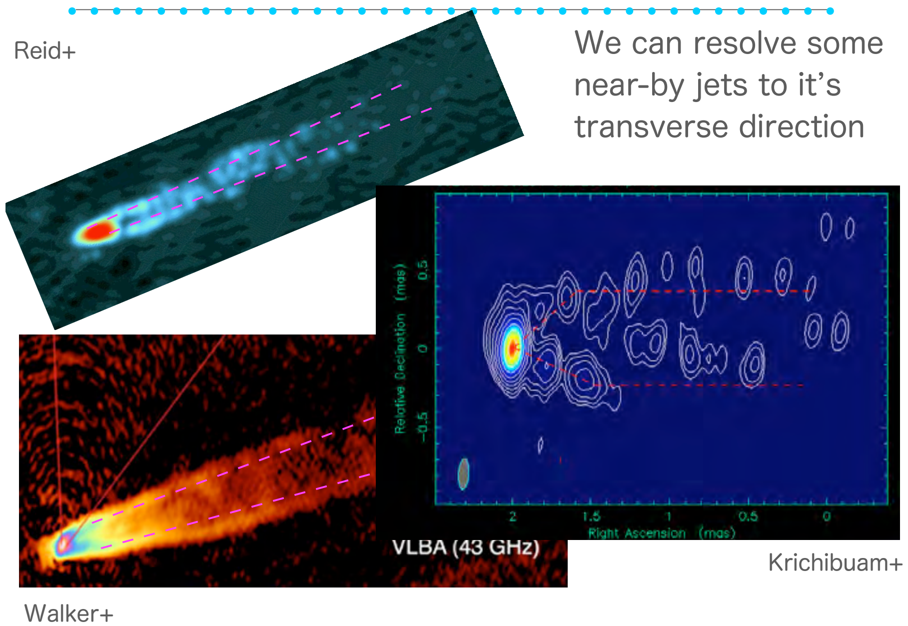


Apparent acceleration in ~ 0.1 pc (!?)

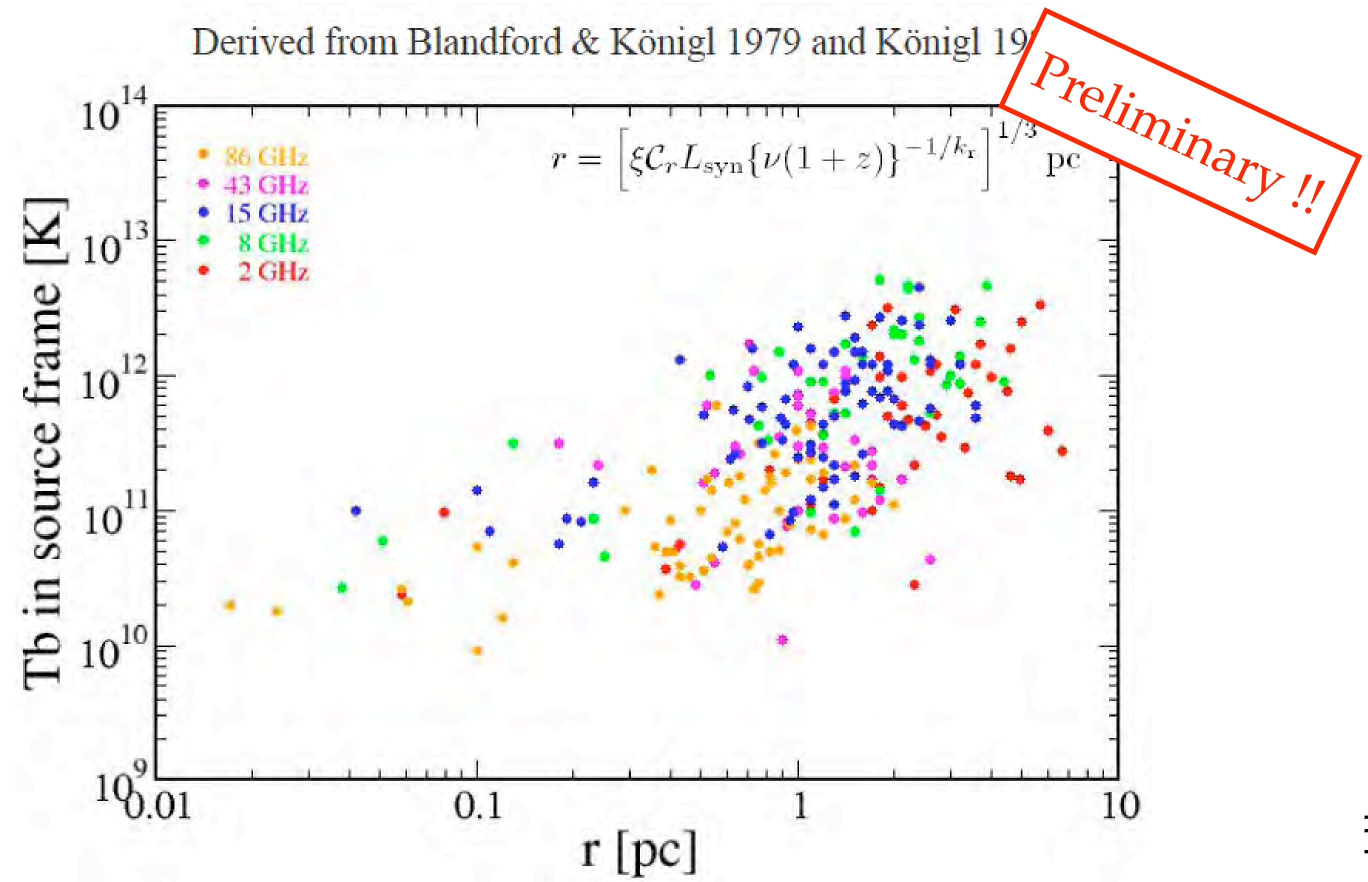
- **collimation of jet opening angle**
- **increase of Doppler factors**

To clarify what happens in inner sub-pc region
→ magnetic fields in ~100 Rg

internal structure of M87 jet

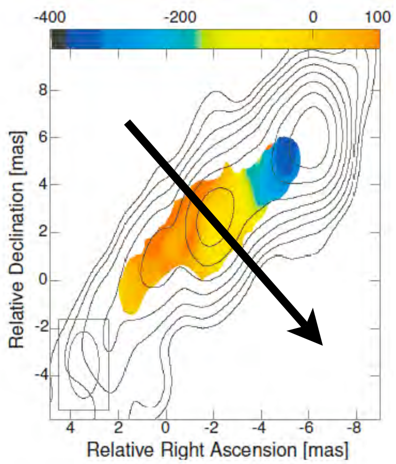


Brightness temperature @ 86 GHz



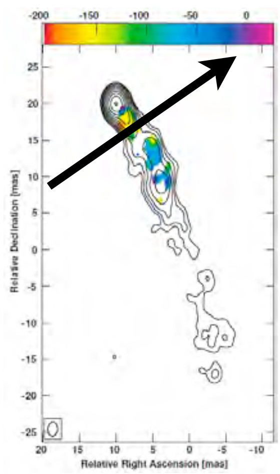
Inner-Jet Structure

0333+321



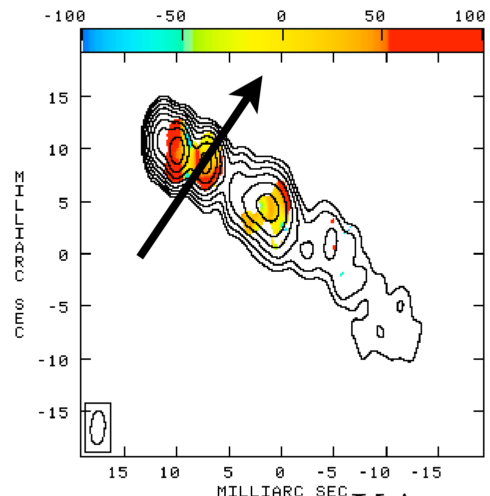
KA+

0836+710



KA+

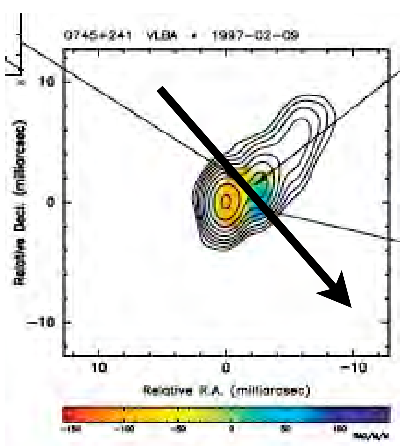
1150-002



KA+

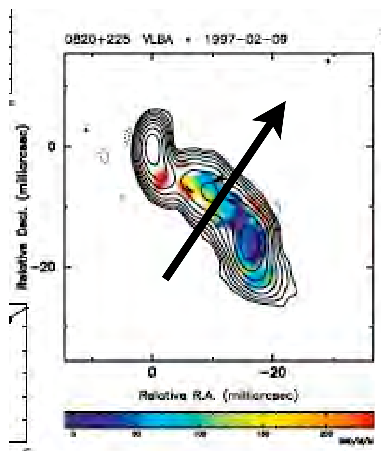
- •3-D magnetic fields by polarization observations
  - Linear pol. → $B_{\perp}$
  - Faraday RM→$B_{//}$

0745+241



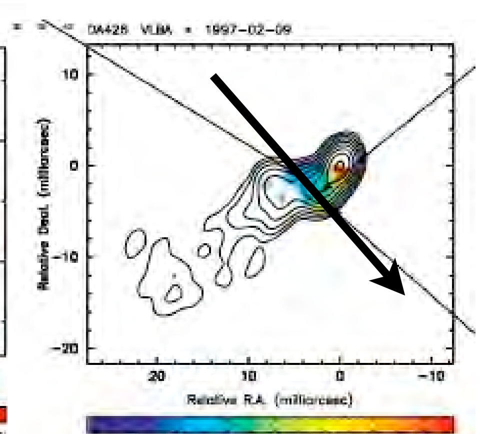
Gabuzda+

0820+225



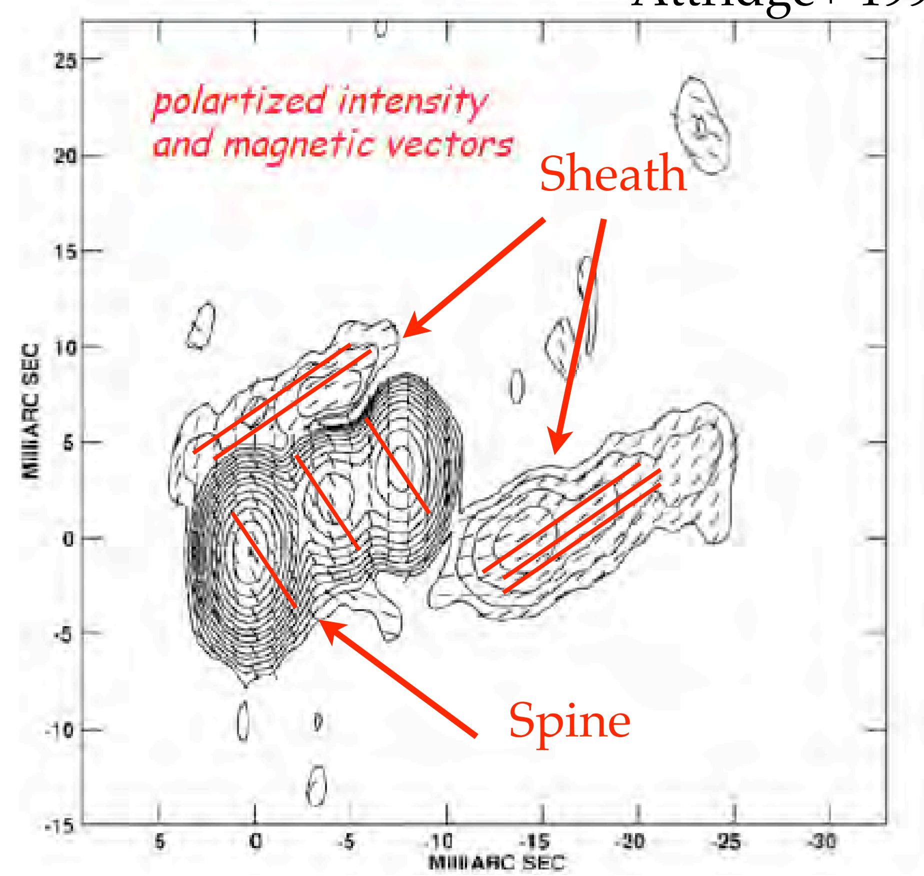
Gabuzda+

Mrk 501



Gabuzda+

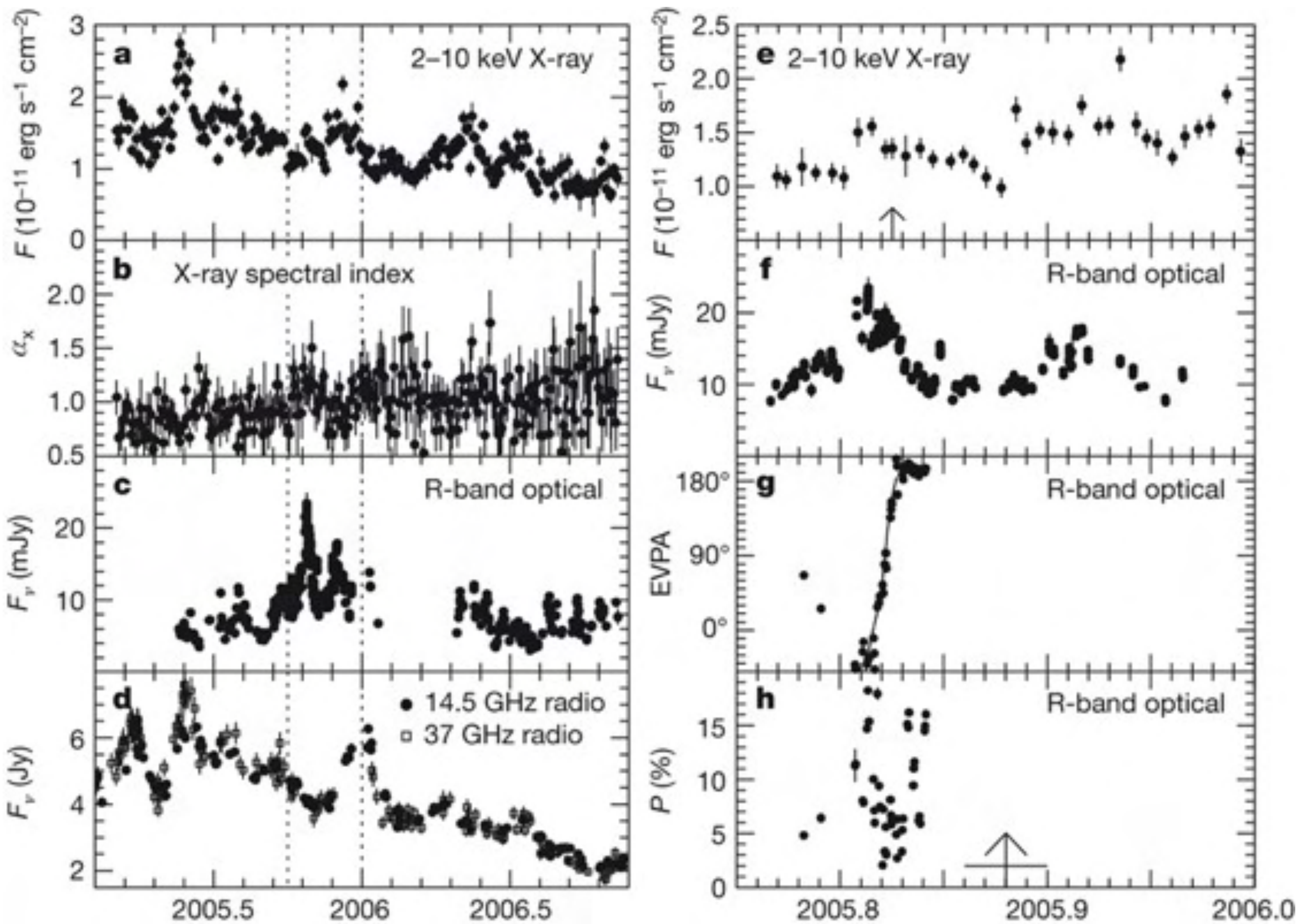
Attridge+ 1999

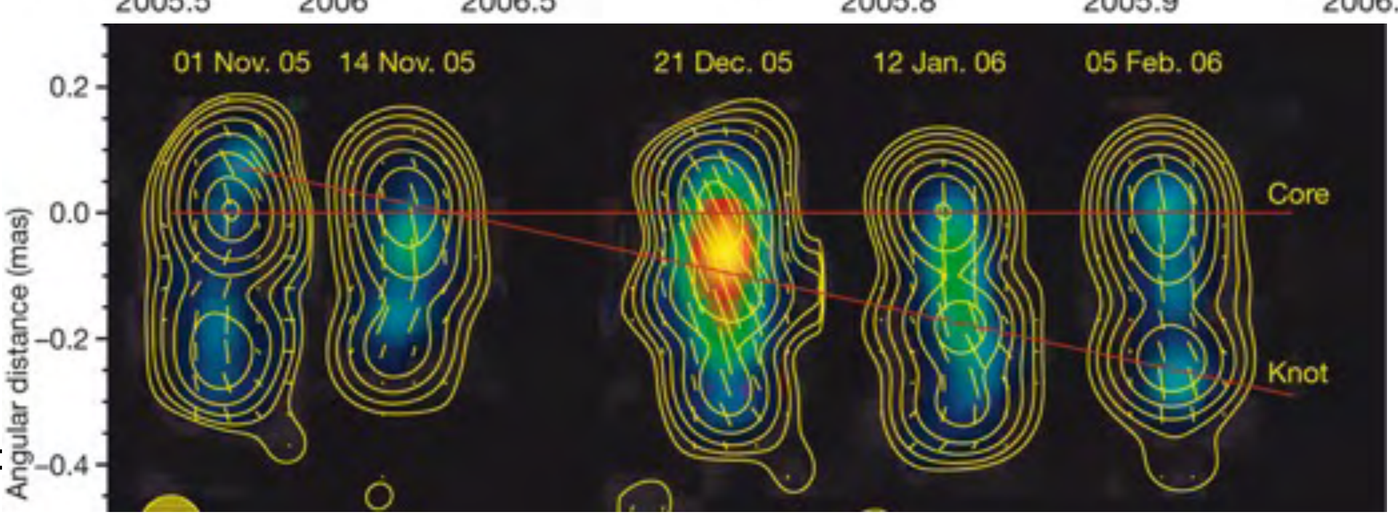


High-energy emission region

Identification of the γ / X / optical component

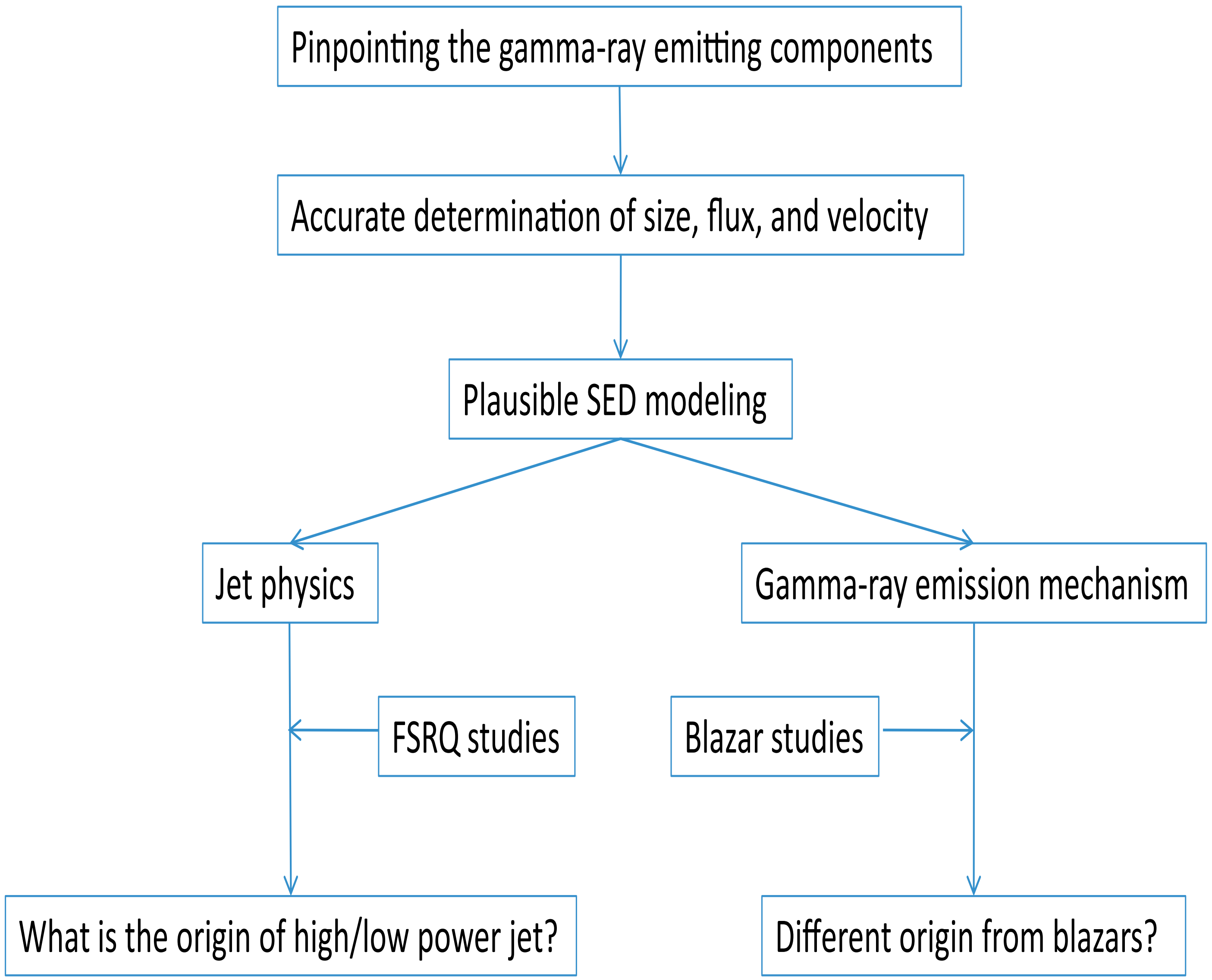
BL Lac Marscher et al. (2008)

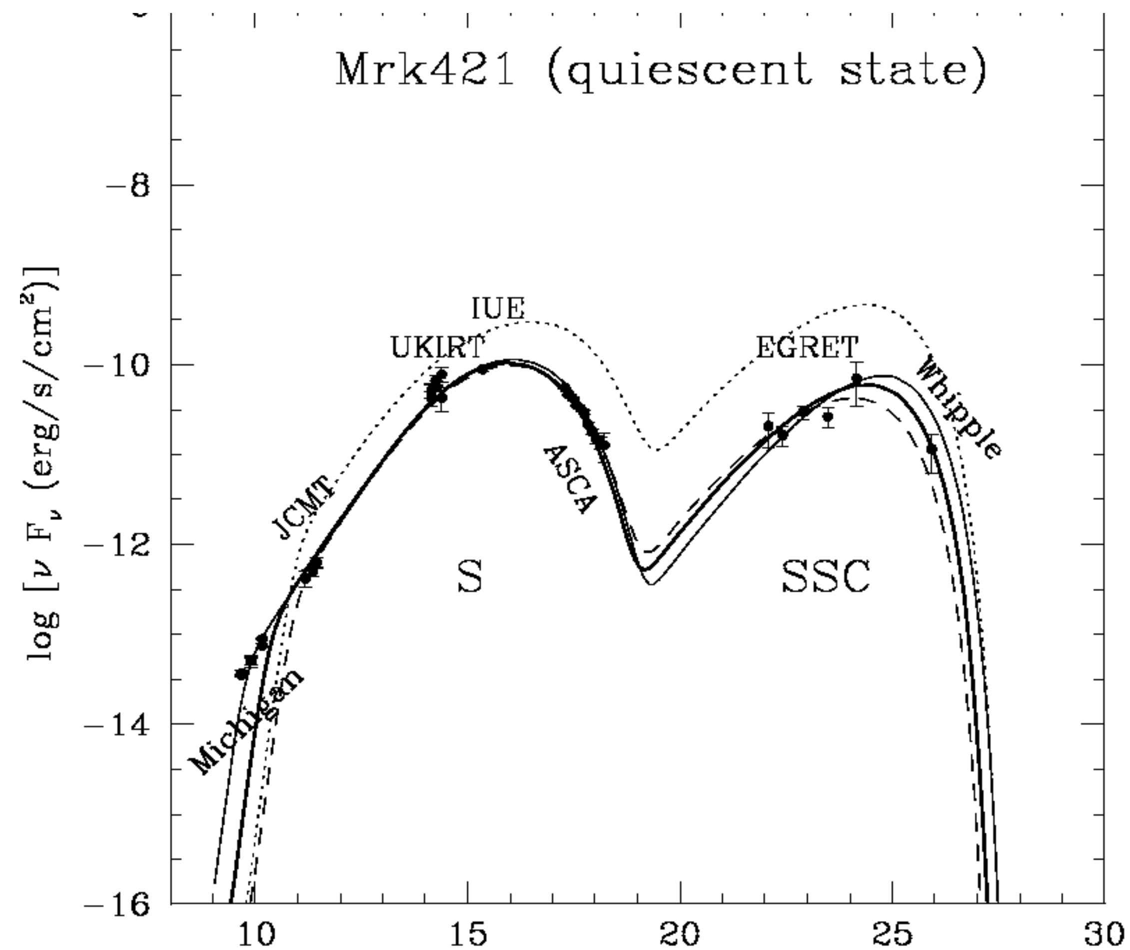




VSOP-2 resolution corresponds to 0.03 pc at 100 Mpc

Probing high-energy emitting region





ToO coordinated with γ-ray obs.

such as ASTRO-H, CTA, IXO

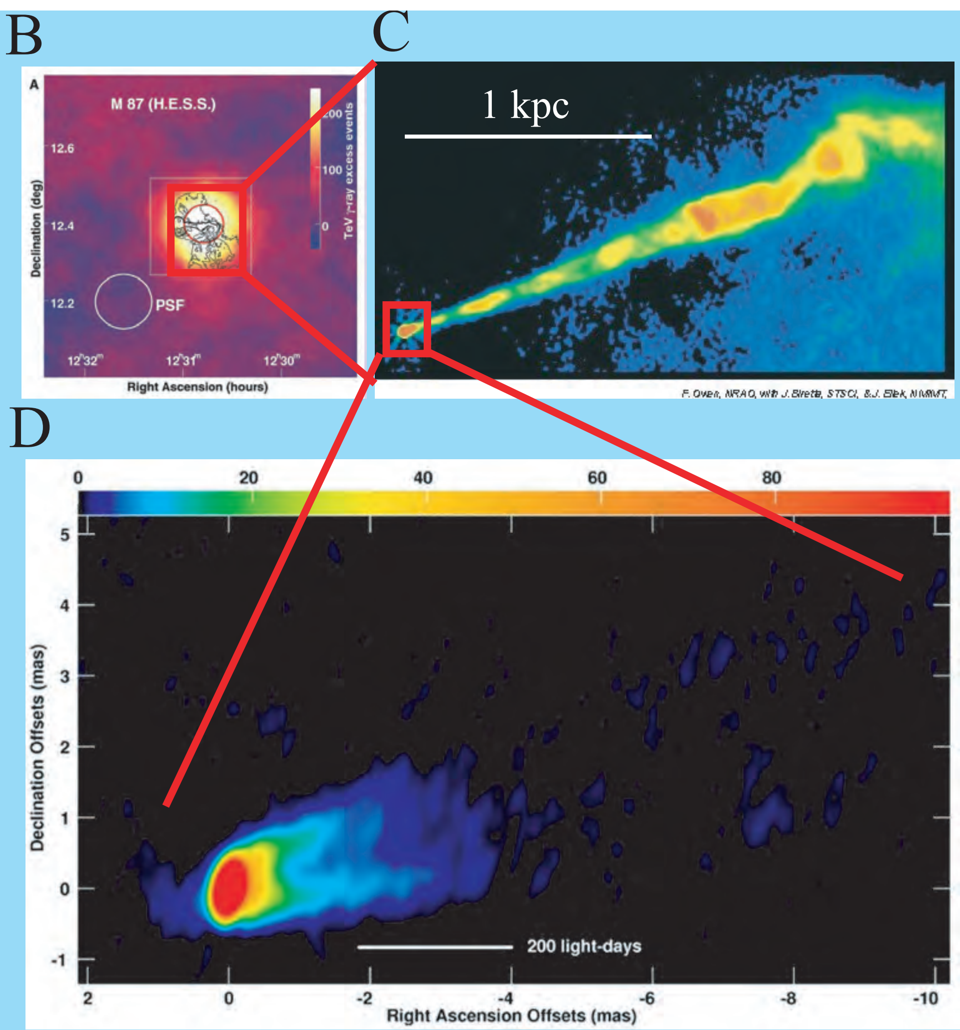
Identify γ-ray components w/ ~0.01 - 0.03 pc resolution

High-energy emission region

EGRET era : Blazars are γ-ray emitting AGNs

Fermi era : γ-ray from FR-I radio galaxies

→imaging high-energy acceleration region

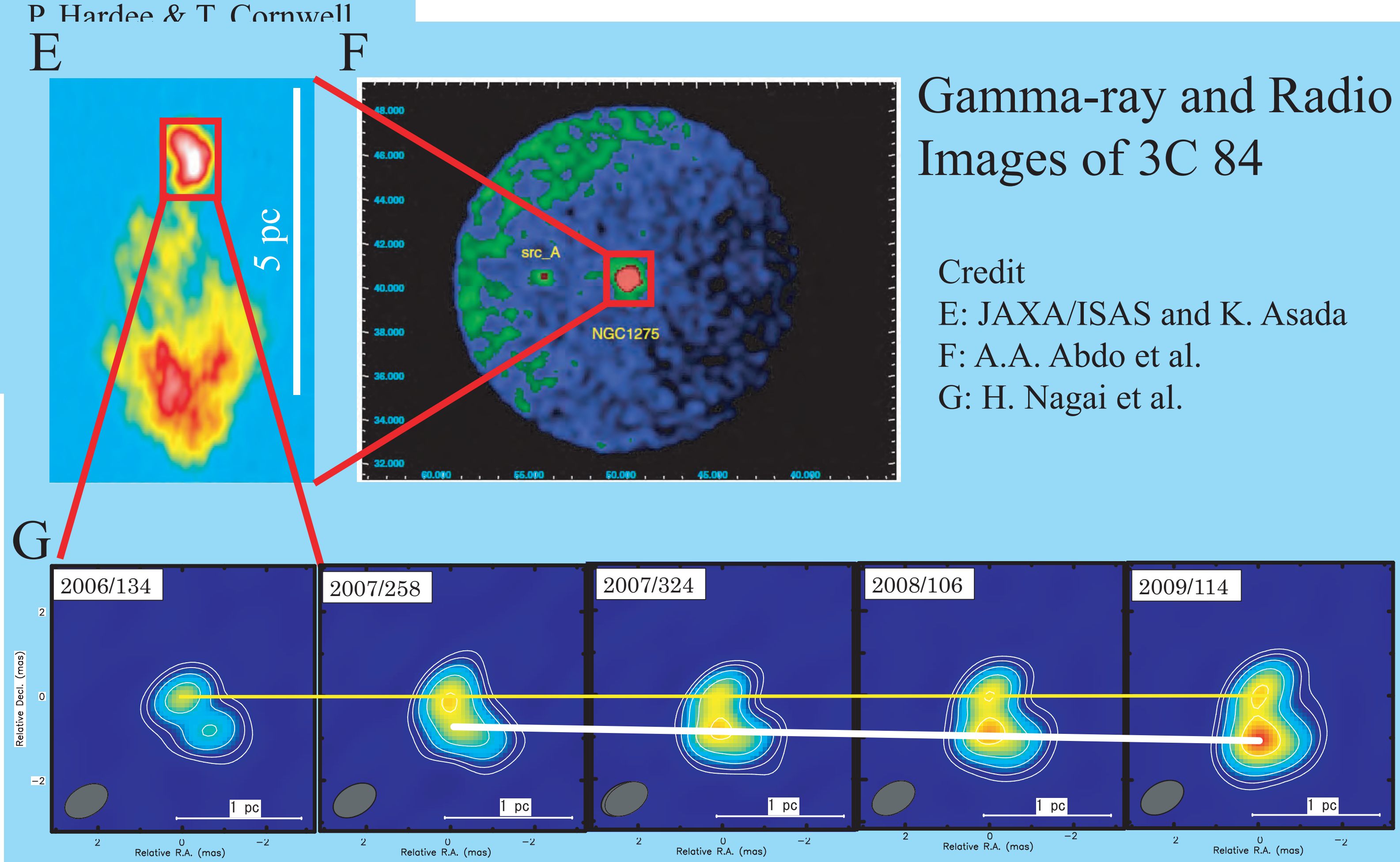


Gamma-ray and Radio Images of M 87

Credit:
B. A.F. Aharonian et al.
C. NRAO/AUI and F. Owen,
P. Hardee & T. Cornwell
D.

Less-affected by opacity

- larger viewing angle
- better linear resolution



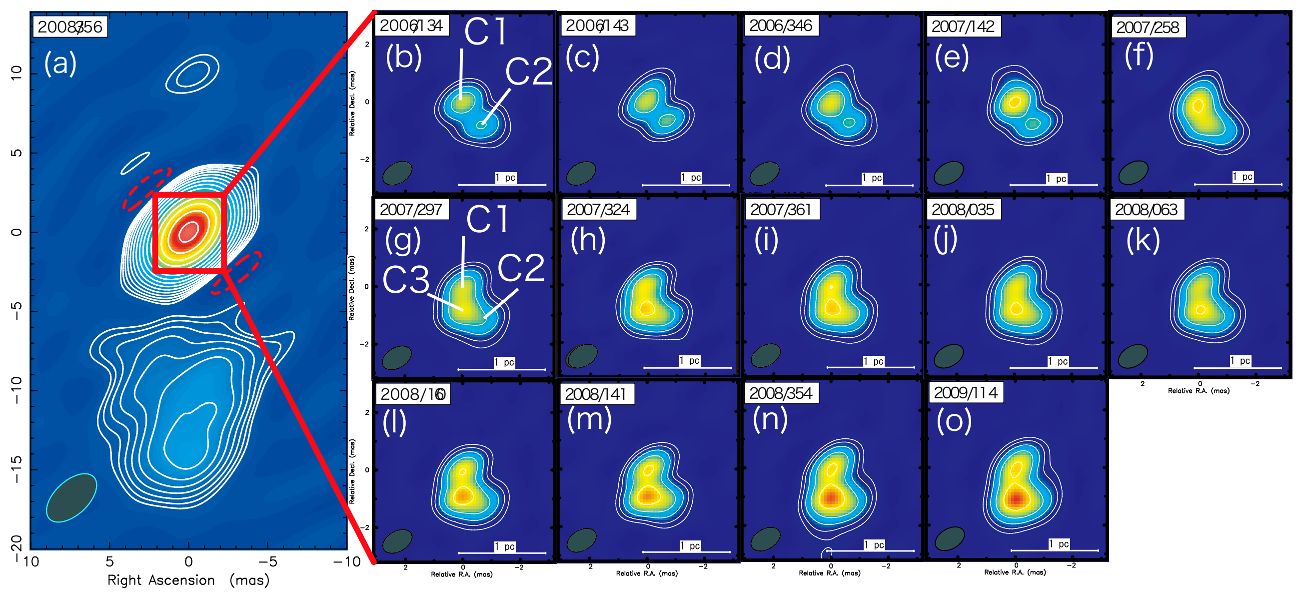
Gamma-ray and Radio Images of 3C 84

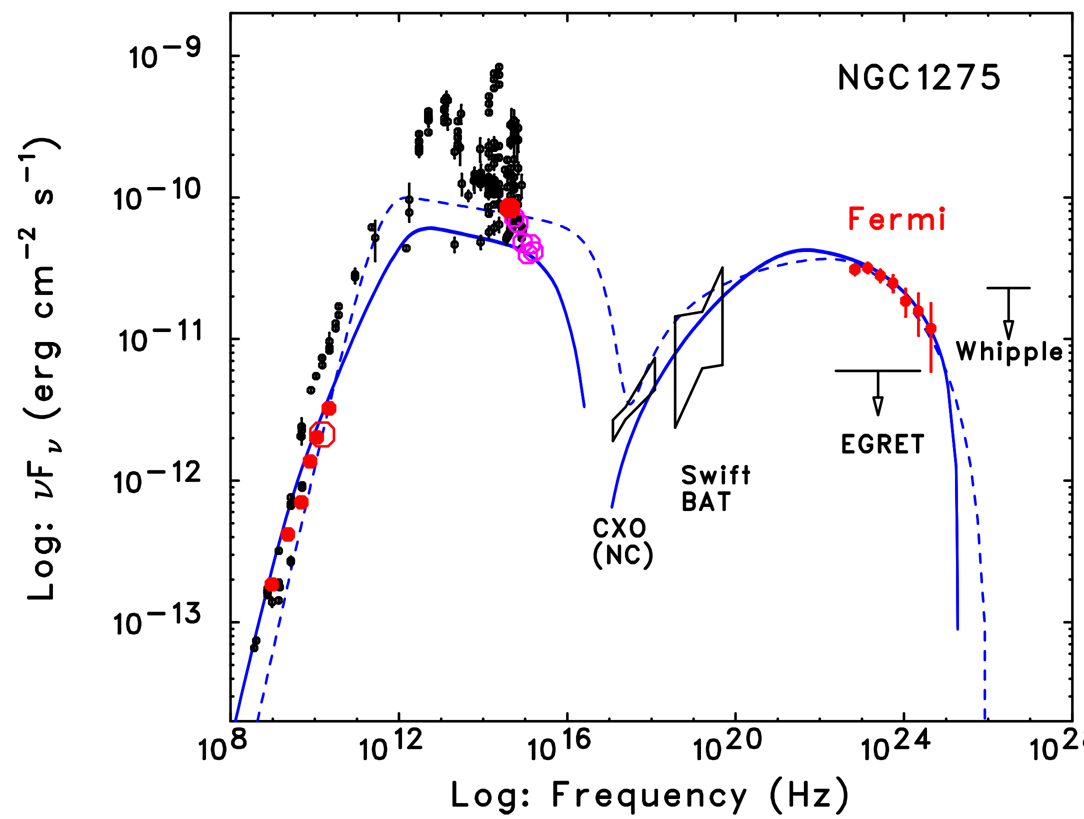
Credit
E: JAXA/ISAS and K. Asada
F: A.A. Abdo et al.
G: H. Nagai et al.

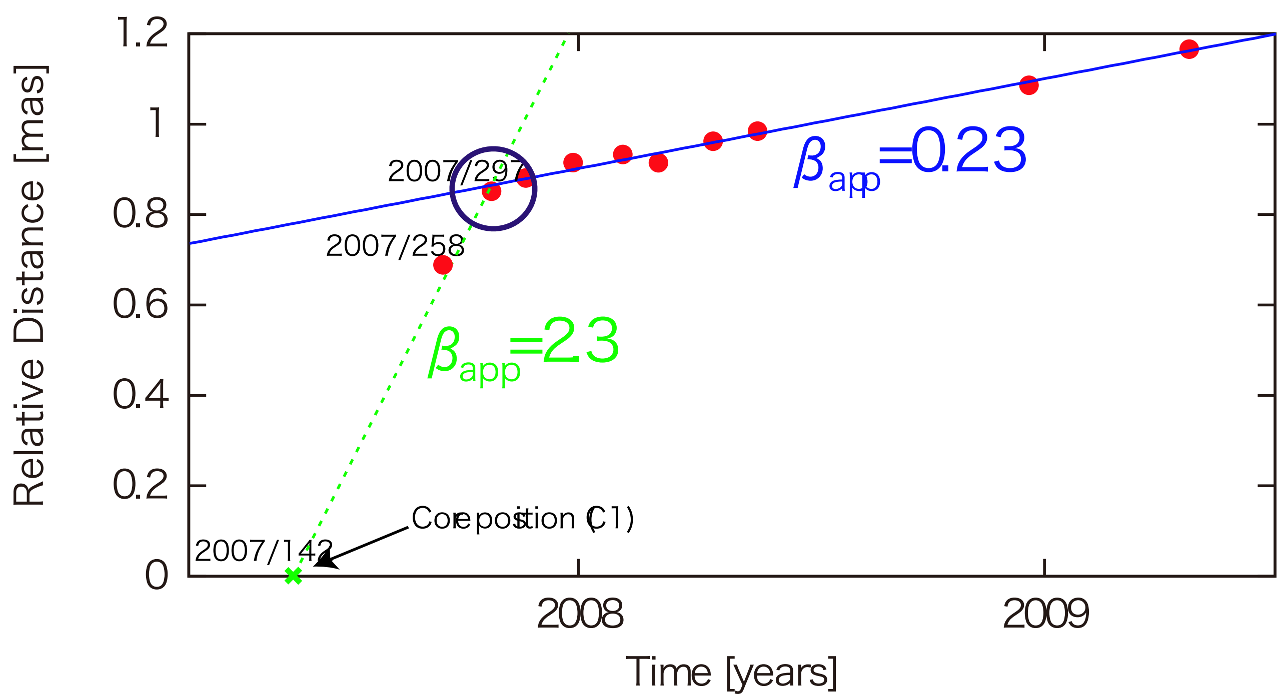
COSPAR 2010

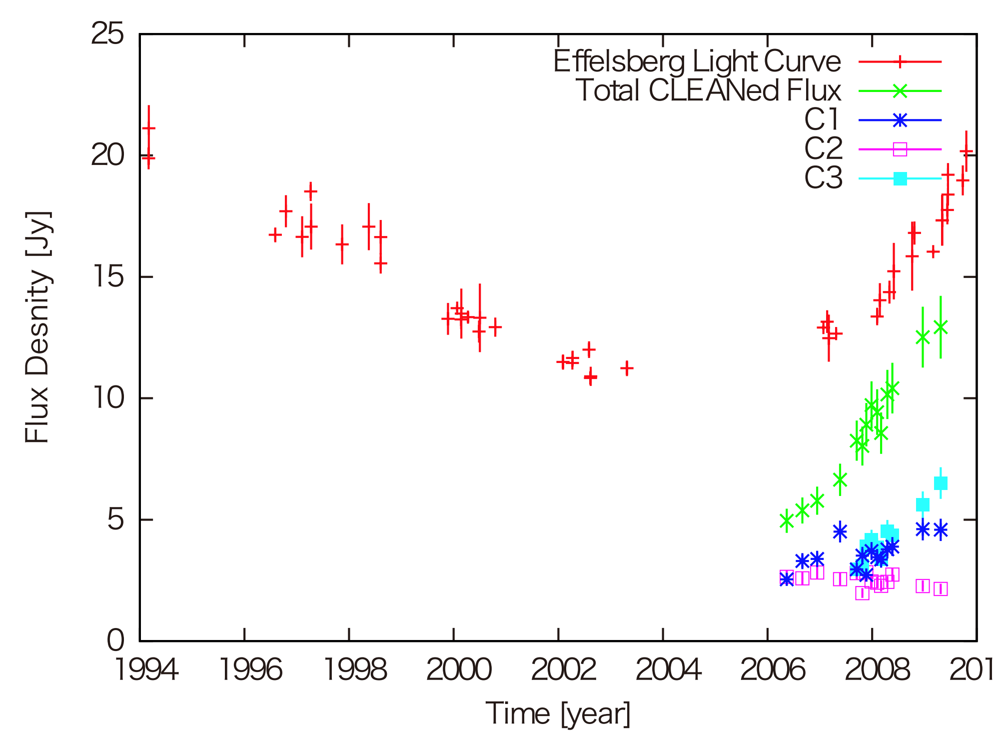
3C 84 flare and new component

Nagai et al. (2010)









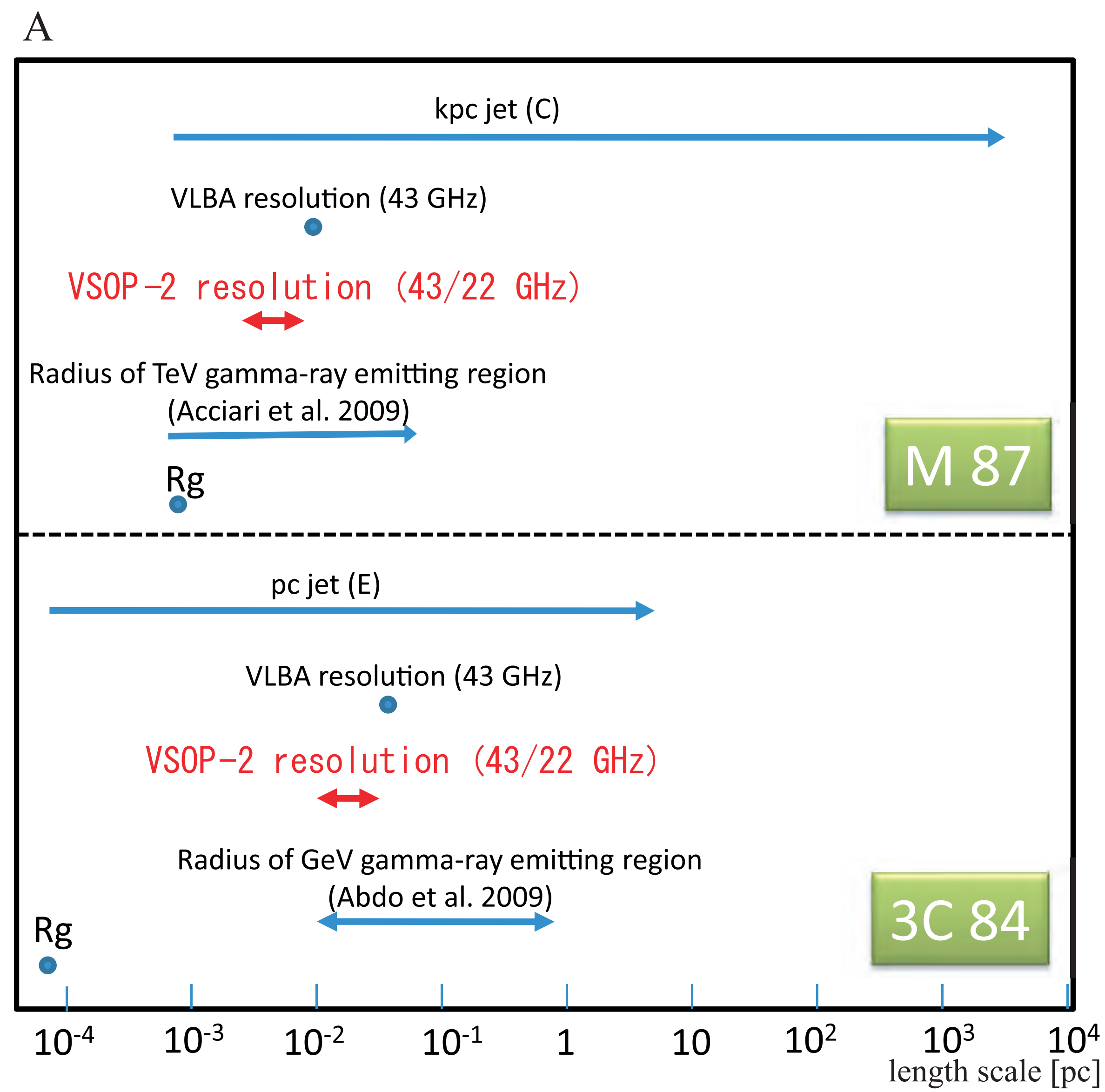
Probing high-energy emitting region

Broadband SED
- γ-ray : Fermi(?) CTA
- X-ray : ASTRO-H, IXO
- Optical
- Radio

Timing observations
- Fermi / CTA / MAXI / IXO

Polarization
- Kanata / VSOP-2

Imaging and positioning
- VSOP-2



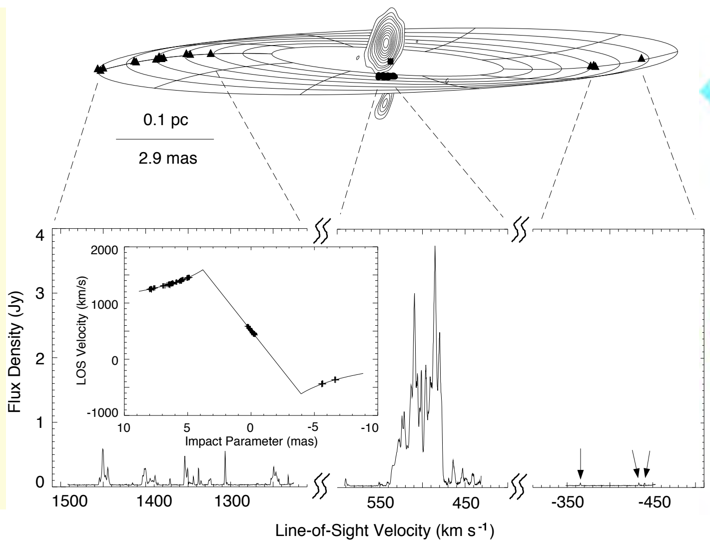
New coverage of observable space to open new window

32

AGN sub-pc-scale structure

Maser disk structure

- disk rotation→BH mass
- non-circular motion →accretion
- dispersion in P-V diagram →turbulence



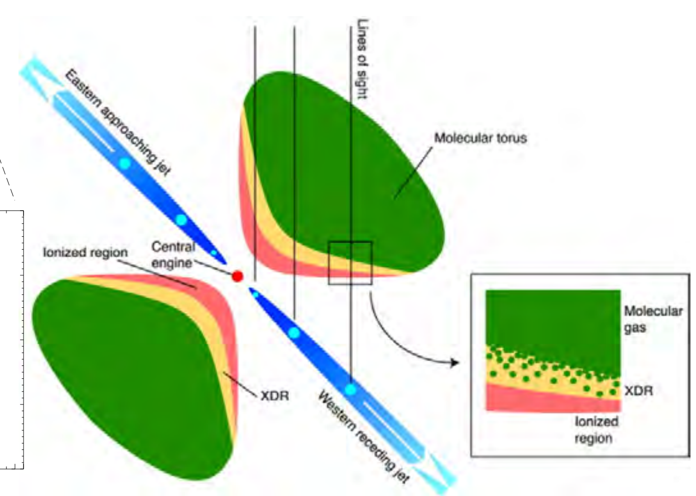
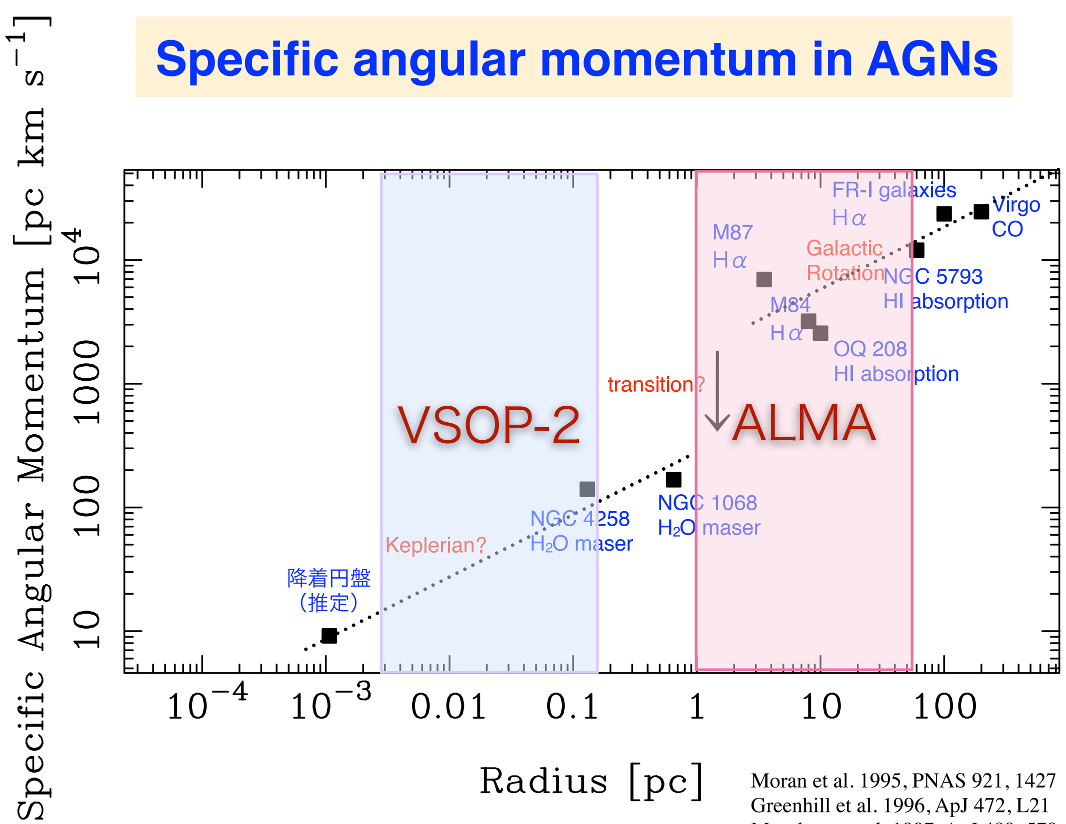


Table 5.2: Key sources for AGN sub-structure study

galaxy	Scale (pc/100μas)	disk type
NGC4258[1]	0.0039	Thin[1]
NGC1068[2]	0.0074	Thick[2]
NGC1052[3]	0.0086	Thick [3]or Jet[4]?

(1) Miyoshi et al.. 1995; (2) Greenhill et al.,1996; (3)Kameno et al. 2005; (4) Claussen et al. 1997



Moran et al. 1995, PNAS 921, 1427
Greenhill et al. 1996, ApJ 472, L21
Macchetto et al. 1997, ApJ 489, 579
Bower et al. 1998, ApJ 492, L111
Pihlström et al. 2003, A&A 404, 871
Pihlström et al. 2000, A&A 357, 7
Noel-Storr et al. 2003, ApJS 148, 419
Sofue et al. 2003, PASJ 55, 59

Summary

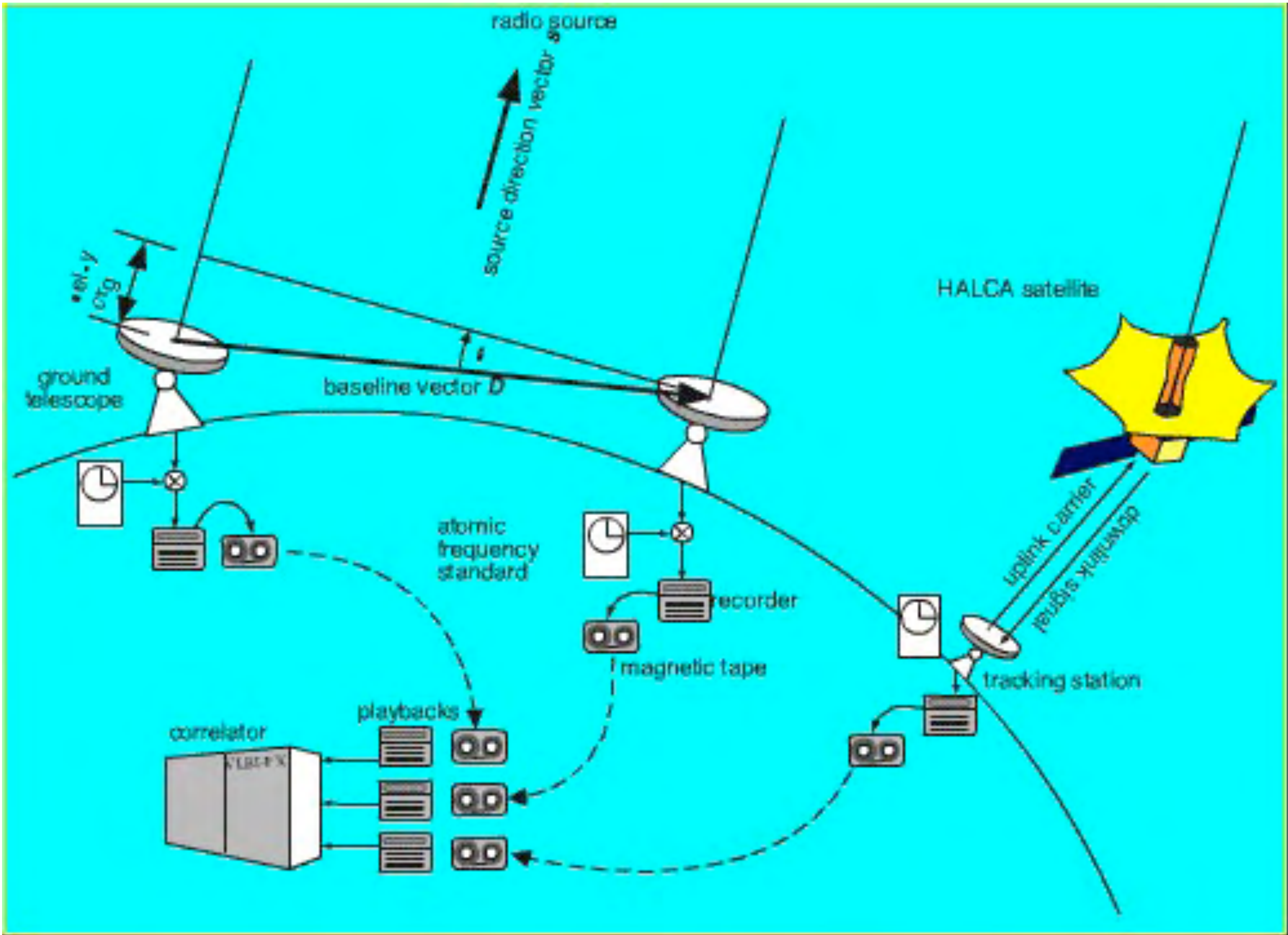
- VSOP-2 survives … to be launched 2016 (or later)
- 40-μas resolution to image disks and jets in nearby AGNs
- Synergy with high energy astrophysics
    - Broad-band SED, Timing at γ-ray, X-ray, and optical
    - Positioning, kinematics, and magnetic fields with VSOP-2

Visit and give your contribution to VSOP-2 science working group activity

http://hotaka.mtk.nao.ac.jp/groups/astrogswg/

Backup Slides

Concepts of Space VLBI



Updates in 2005→2010

Sensitivity degradation due to realistic Tsys and surface accuracy

Impacts at 43 GHz

SEFD

0.7 mm rms

1.0 mm rms

Spec in 2005

Frequency	8 GHz	22 GHz	43 GHz
SEFD (nominal)	5600 Jy	5000 Jy	28000 Jy
T_{sys}	89 K	56 K	98 K
A_e	44 m^2	31 m^2	9.7 m^2
SEFD (requirement)	5900 Jy	8200 Jy	190000 Jy
T_{sys}	89 K	56 K	98 K
A_e	42 m^2	19 m^2	1.4 m^2
SEFD (obsolete)	4080 Jy	2200 Jy	3170 Jy
T_{sys}	60 K	30 K	40 K
A_e	40 m^2	38 m^2	35 m^2

Fringe detection limit

	2005 nominal		0.7 mm rms		1.0 mm rms	
	22 GHz	43 GHz	22 GHz	43 GHz	22 GHz	43 GHz
7σ / GBT / Cont.	12 mJy	22 mJy	24 mJy	100 mJy	30 mJy	280 mJy
7σ / VLBA / Cont.	50 mJy	107 mJy	74 mJy	421 mJy	95 mJy	1100 mJy
7σ / GBT / Maser	0.7 Jy	0.9 Jy	1.4 Jy	4.2 Jy	1.8 Jy	12 Jy
7σ / VLBA / Maser	3.0 Jy	4.6 Jy	4.4 Jy	18 Jy	5.6 Jy	46 Jy

Updates in Key Science Area

	Proposal 2005	New Science Case
Accretion disks	Goal : Imaging accretion disks in plural nearby AGNs Extra : Distribution of brightness and spectral indices, imaging a black-hole shadow	Goal : Image the ‘core’ to verify accretion-disk models in more than 1 AGN (at 22 or 43 GHz) Extra : Disks in plural AGNs, Distribution of brightness and spectral indices
Jets	Goal : Inner-jet structure, Velocity fields, Magnetic field structure in jet acceleration and collimation region Extra : Magnetic fields in disks and jet-launching region	Goal : Velocity fields in jets, Imaging γ-ray emitting region, magnetic fields in jets in some nearby AGNs Extra : Those in ~10 - 20 AGNs, Motion of γ-ray emitting components
Extragalactic masers	Goal : Imaging masers in galactic SFRs, proper motion and annual pallarax,, Imaging megamasers in 20 Mpc, LMC/SMC annual pallarax Extra : H_0 measurements in 4% accuracy	Goal : Sub-pc structure of megamasers, LMC/SMC proper motion Extra : LMC/SMC annual pallarax, Calibration of the distance ladder
YSO magneto-spheres	Goal : Time-development of flares Extra : Magnetic field structure in YSO flares	Goal : - Extra : -

Red：deleted
Blue：degrade
Green：New!