Structural Transition in the NGC 6251 Jet

An Interplay with the SMBH and Its Host Galaxy

Tseng et al. 2016
submitted to ApJ

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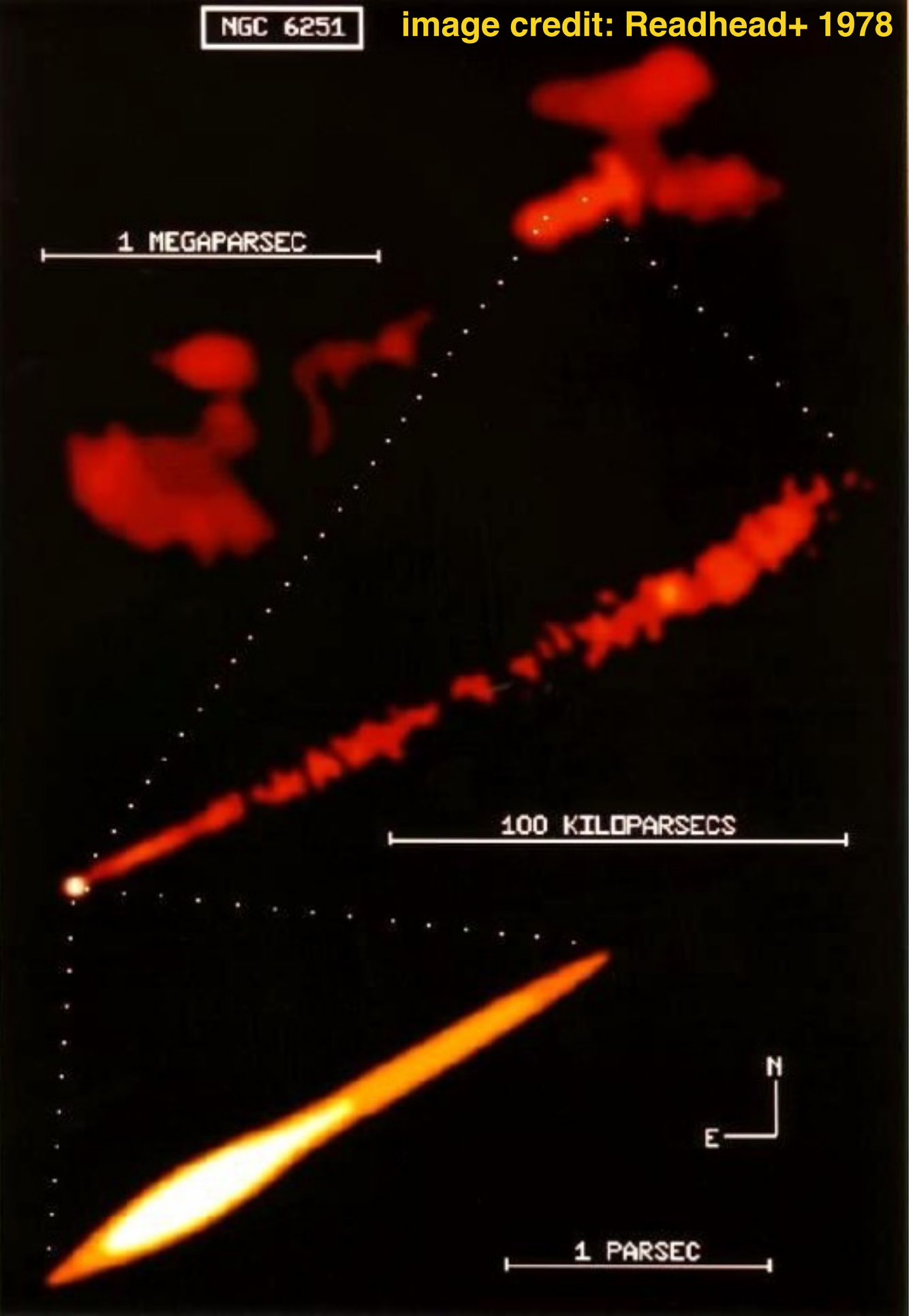
30 Sep 2016, EAMA10, Seoul N Univ.

Outline

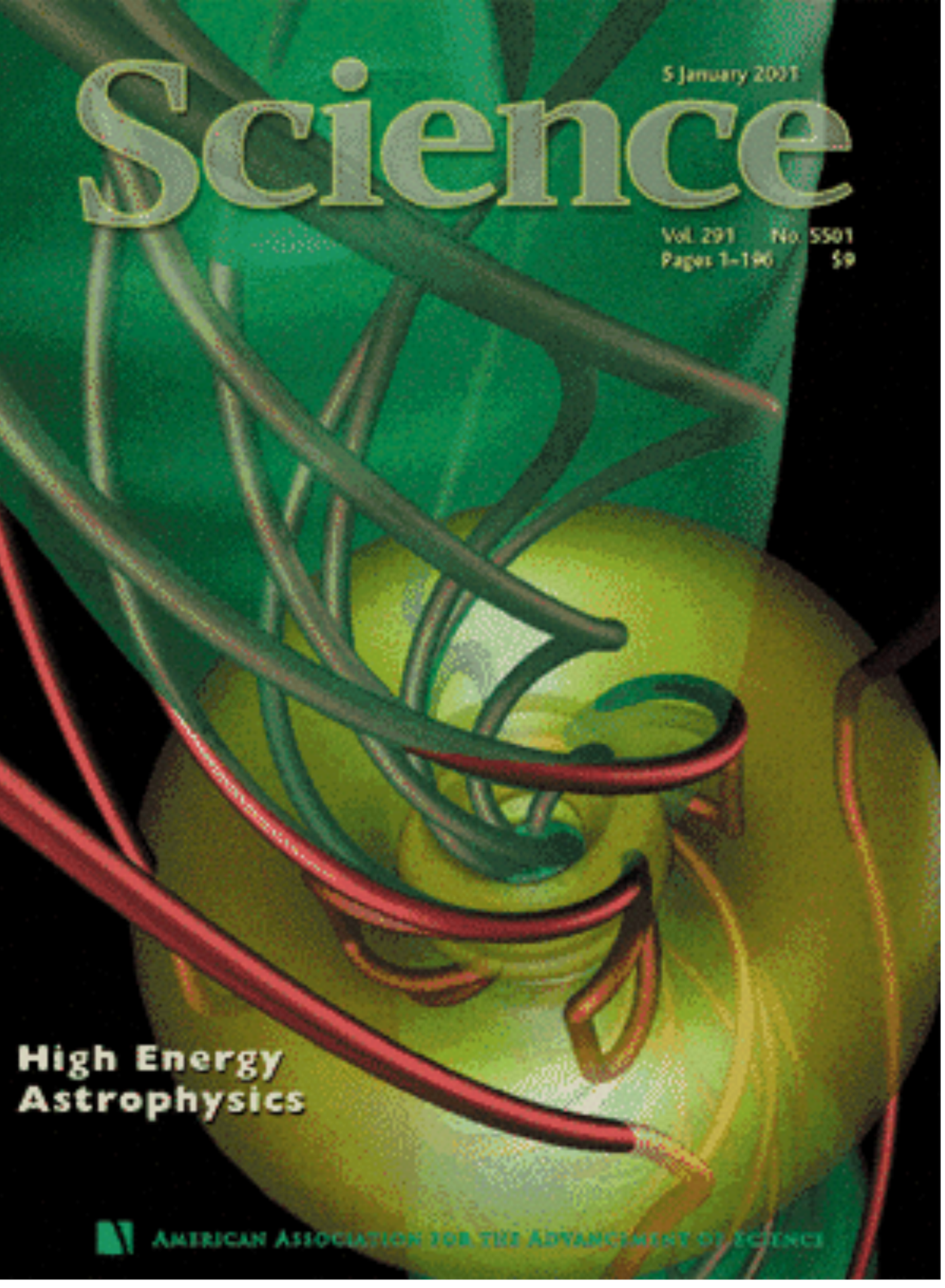
- **Introduction**: AGN jet, collimation process
- **Observation**: VLBI, EVN
- **Result**: Structural transition of the NGC 6251 jet
- **Discussion**: Compare to M87



AGN Jet

Energy/momentum transport from SMBH through the host galaxy to ISM/ICM

- Long (AU — Mpc)
- Collimated ($\theta_{open} \sim 1°$)
- Very fast ($\gtrsim 0.99c$)
- Powerful (10^{45} erg/s)



Meier+ 2001

How to collimate?

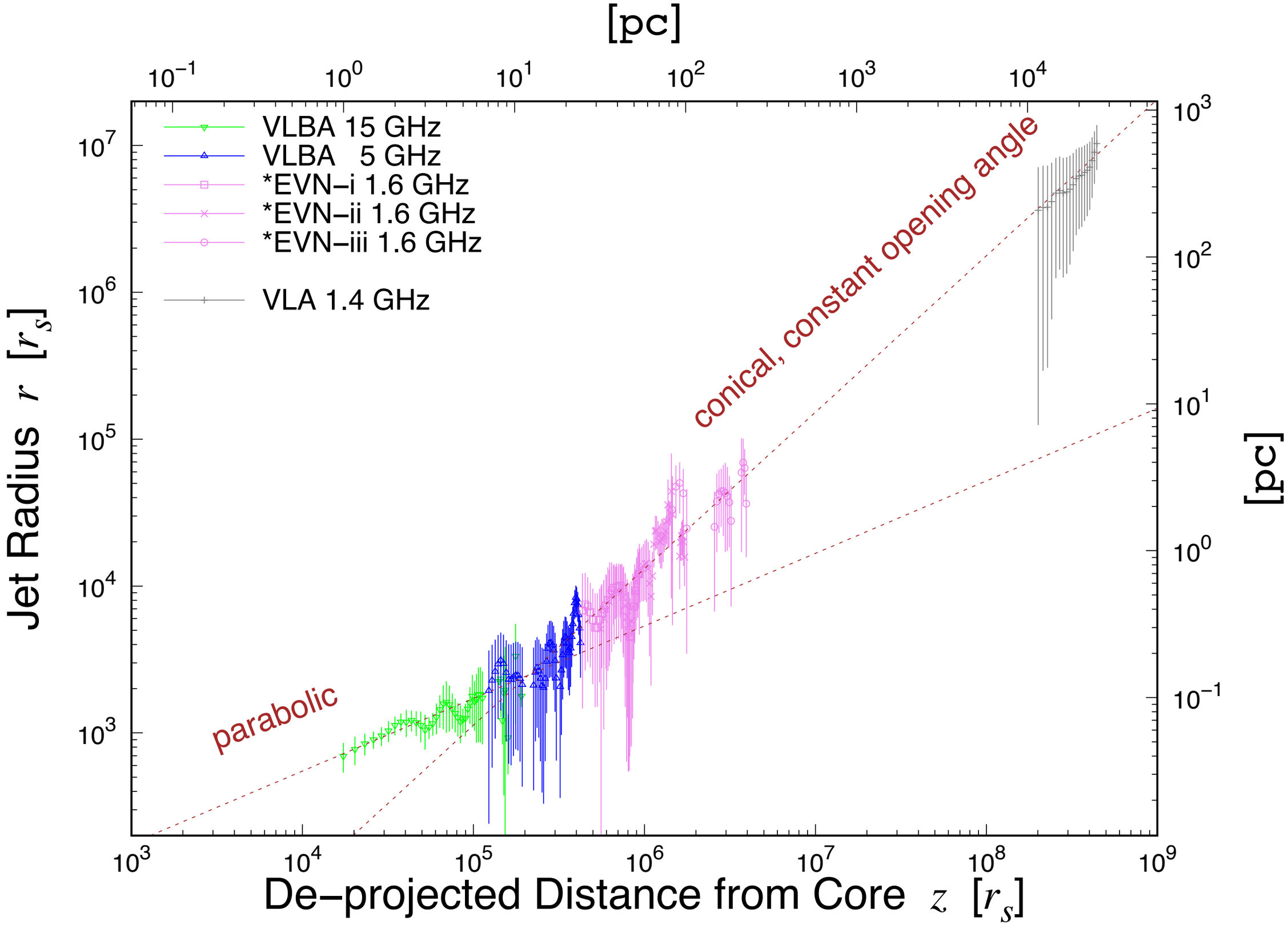
- In MHD simulations, jet structure correlates with the bulk acceleration ($\Gamma\,\theta_{open} \sim 0.1$)

➡ Self-collimation by B_ϕ (hoop stress)

➡ External confinement (by thermal gas)

Komissarov+ 2007, 2009
Zakamska+ 2008,
Pu+ 2015

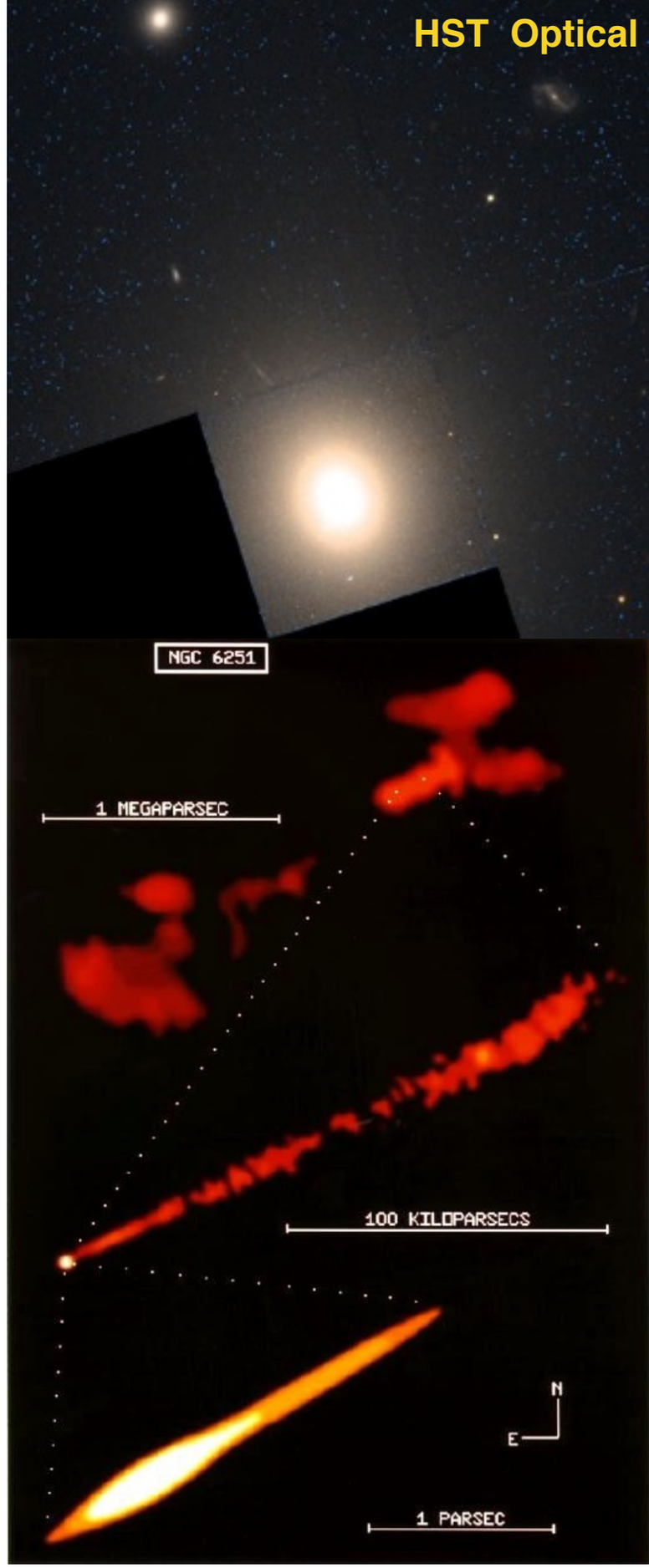
Collimation Profile of NGC 6251



$r_s = 2GM/c^2$

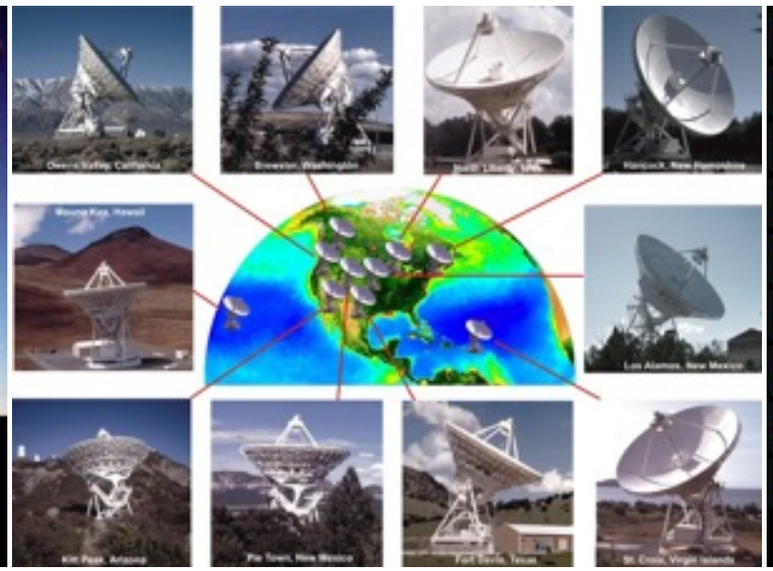
NGC 6251

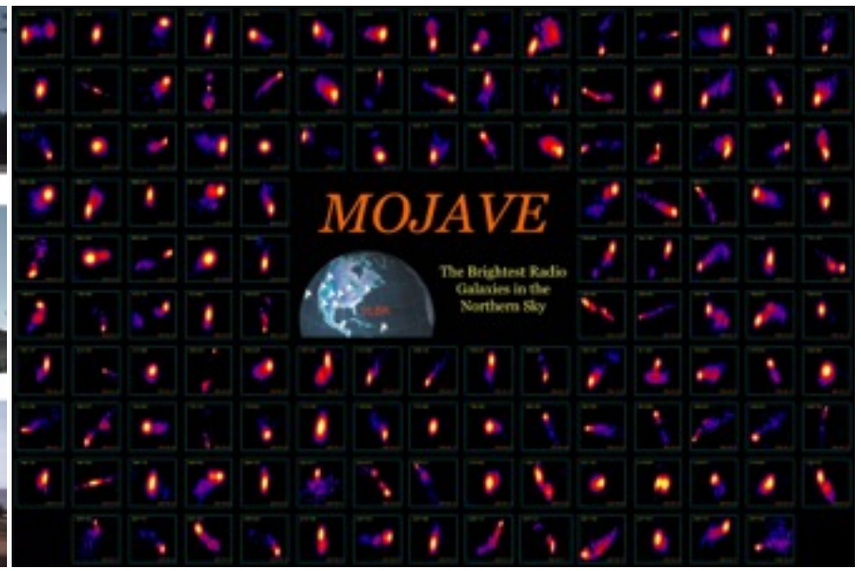
- Giant elliptical galaxy
- Exceptionally long (3 Mpc), straight jet.
  Waggett+ 1977
- SMBH mass ~ 6 x 10^8 $M_\odot$
  Ferarrese & Ford 1999, gas dynamics
- Distance ~ 100 Mpc
  Wegner+ 2003, redshift
- Viewing angle ~ 20°
  Sudou+ 2000, Chiaberge+ 2003
- Scales:
  1 mas = 0.5 pc = 8,700 r_s
  1 mas = 1.5 pc = 26,800 r_s (orientation effect)



Data Summary

Telescope	*v* (GHz)	Resolution (mas)	Jet length (mas)
VLA **Sambruna+ 2004**	1.4	2000	7500-
VLBA **Archival Data**	5	1	5 - 16
VLBA **MOJAVE, Lister+ 2009**	15	0.5	0.6 - 7
EVN **Our observation 2013**	1.6	3-15	10 -150

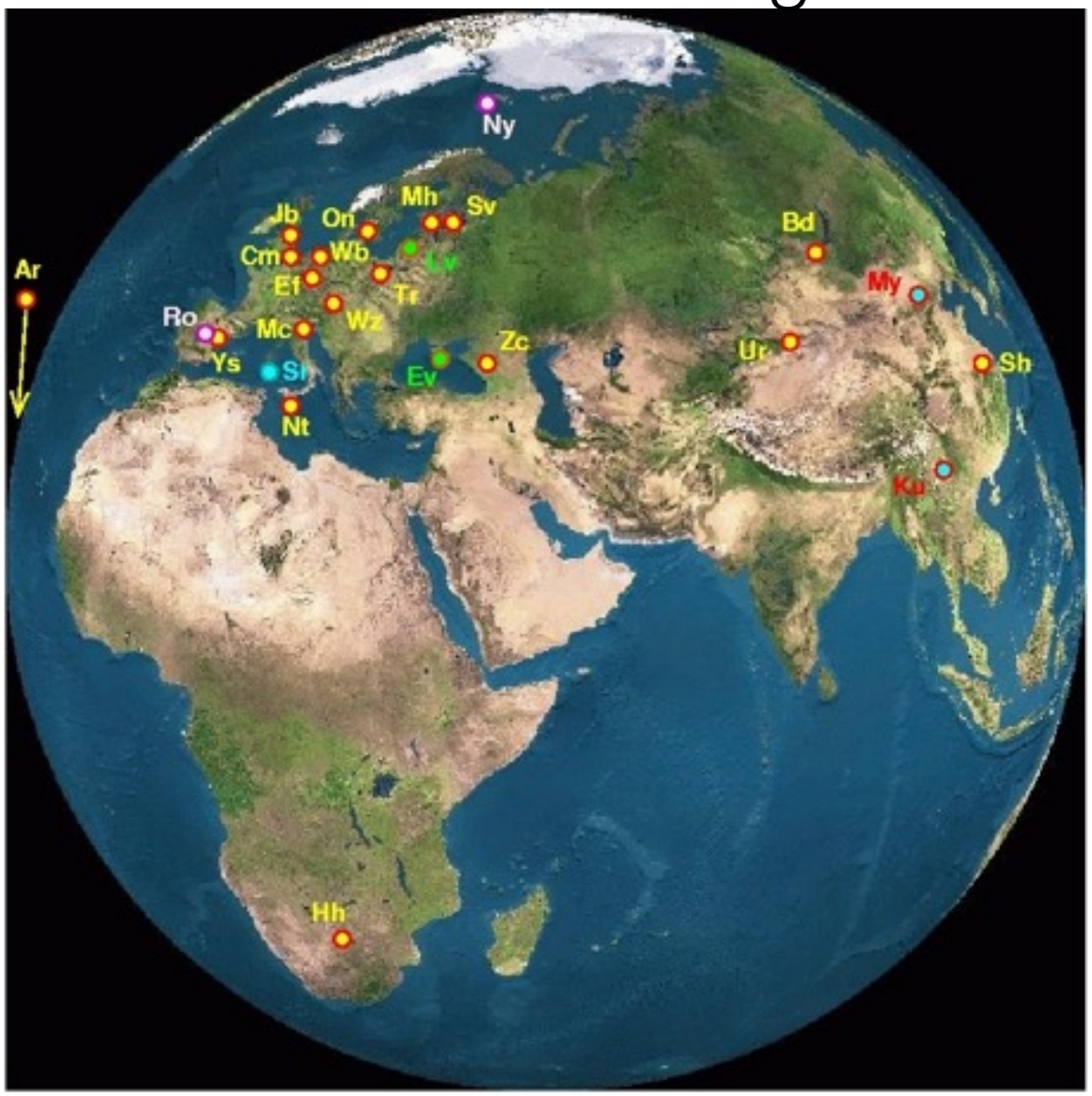


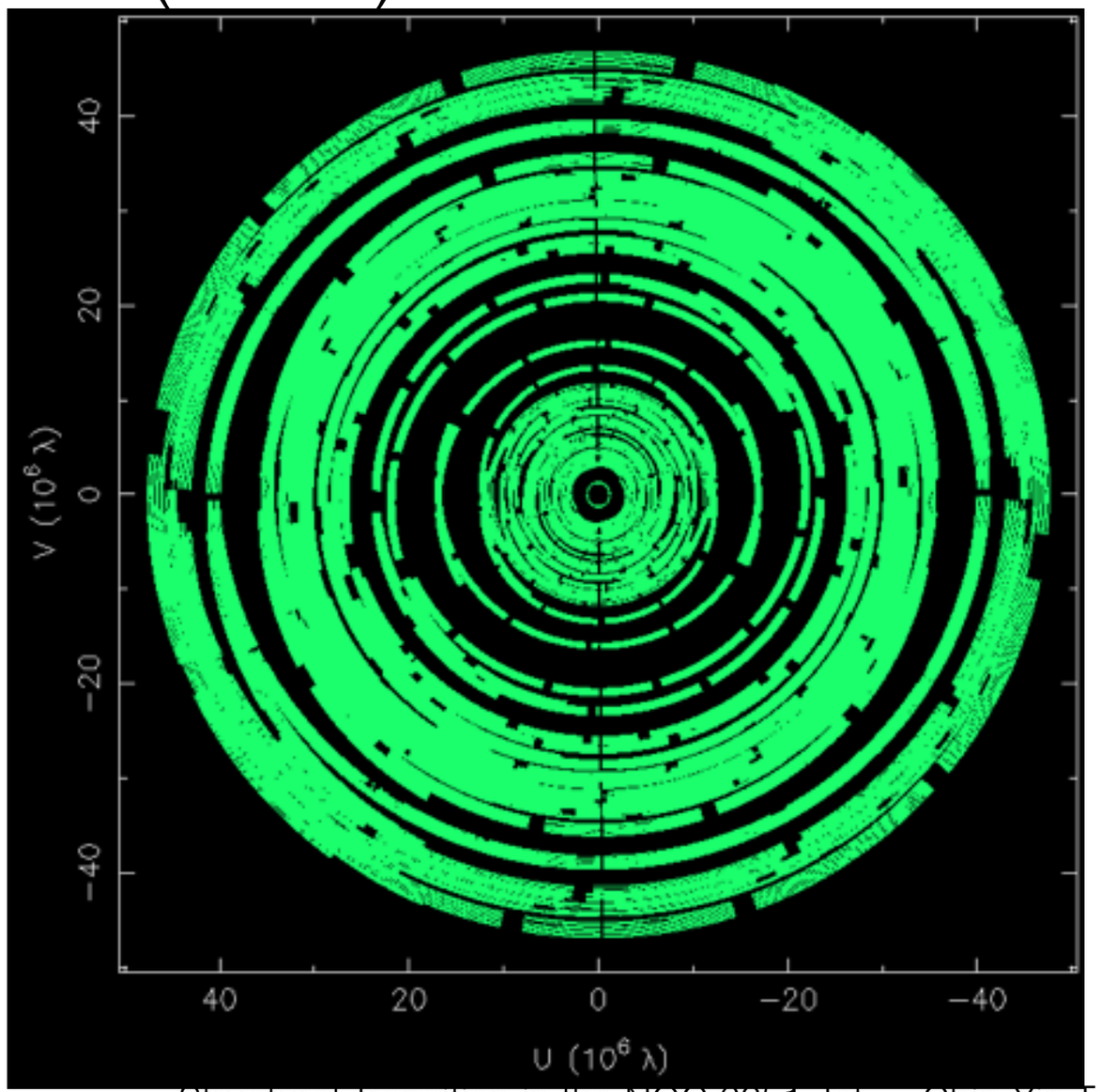


EVN Observation

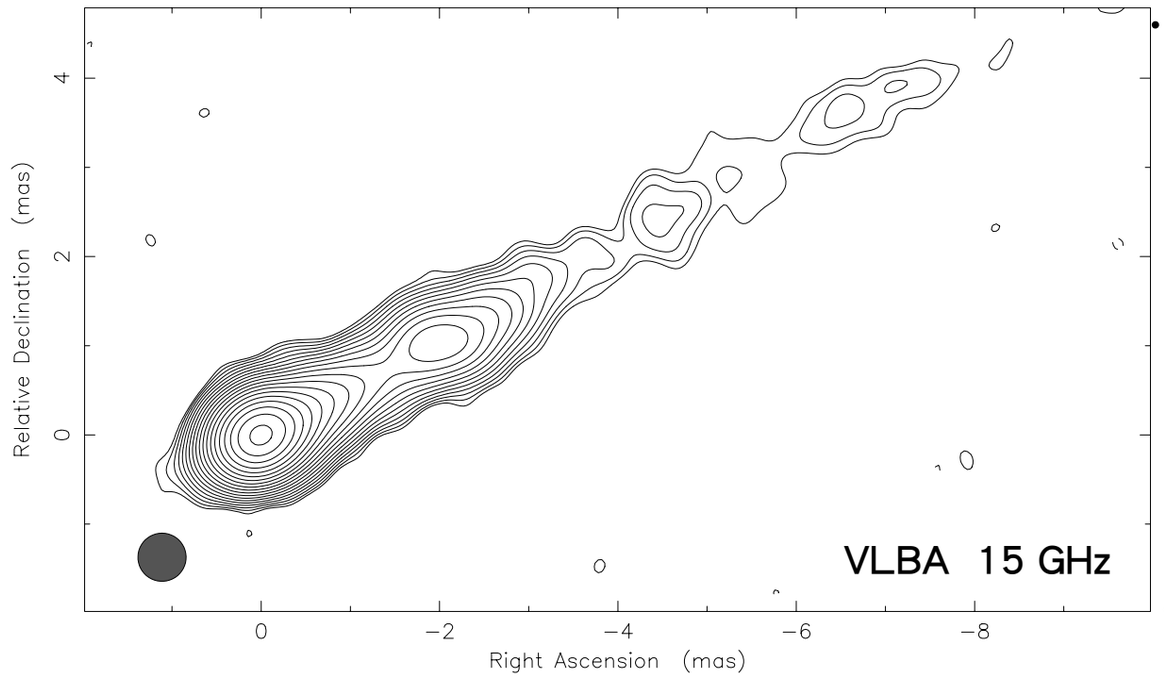
EVN: European VLBI Network

- 12 antennas, including Shanghai, Urumqi, Jodrell bank
  Max. baseline length: ~**9000 km** (Jb-Sh)



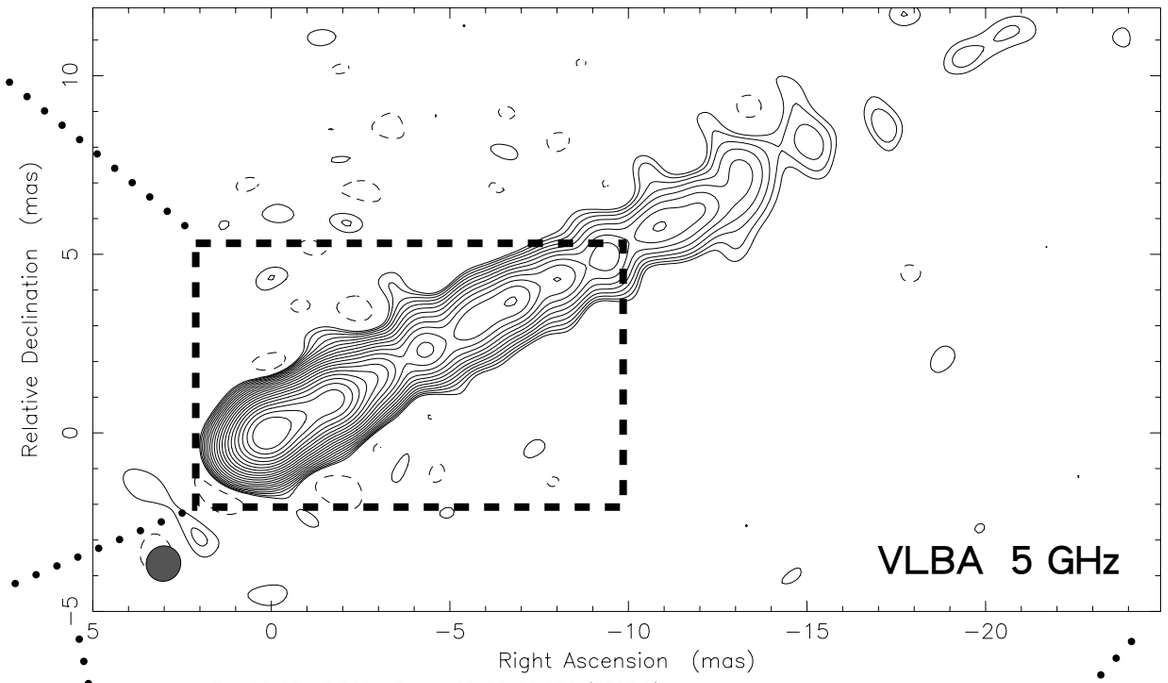


Clean LL map. Array: BFHKLMNOPS
N6251 at 15.365 GHz 1998 Jun 02



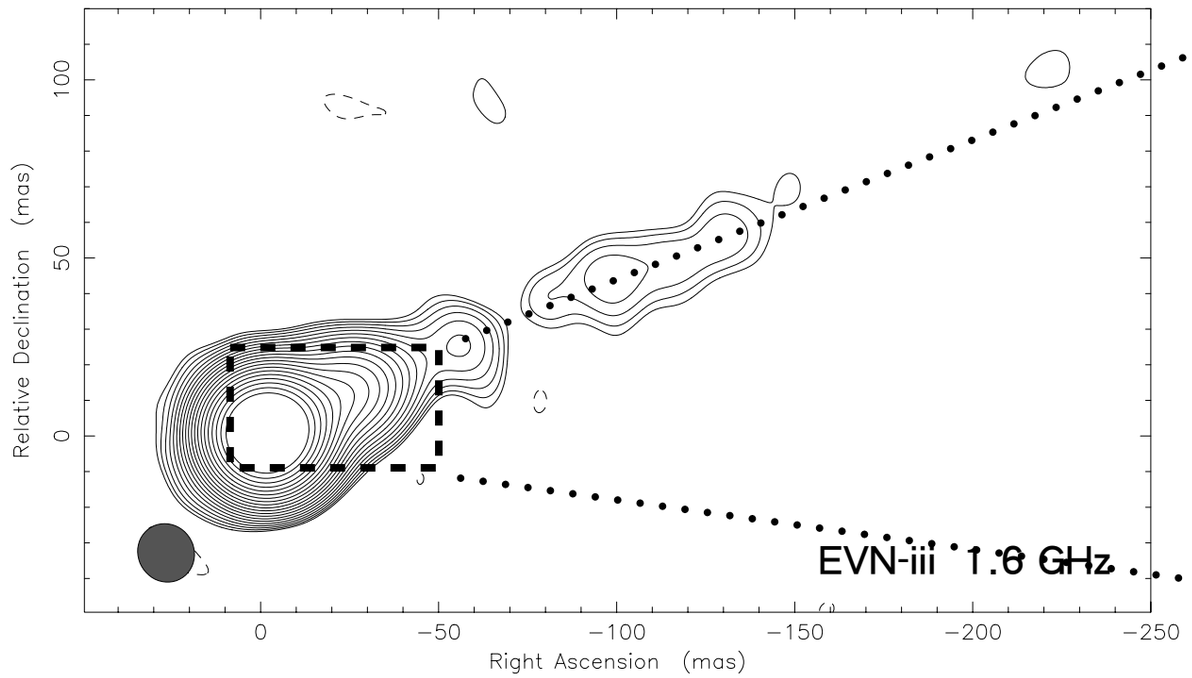
Map center: RA: 16 32 32.013, Dec: +82 32 16.404 (2000.0)
Map peak: 0.347 Jy/beam
Contours: 0.000204 Jy/beam x (−3 3 4.24 6 8.49 12
Contours: 17 24 33.9 48 67.9 96 136 192 272 384
Contours: 543 768 1.09e+03 1.54e+03)
Beam FWHM: 0.54 x 0.54 (mas) at 0°

Clean LL map. Array: BEFHKLMNOPRSNTG
NGC6251 at 4.816 GHz 1998 Apr 30



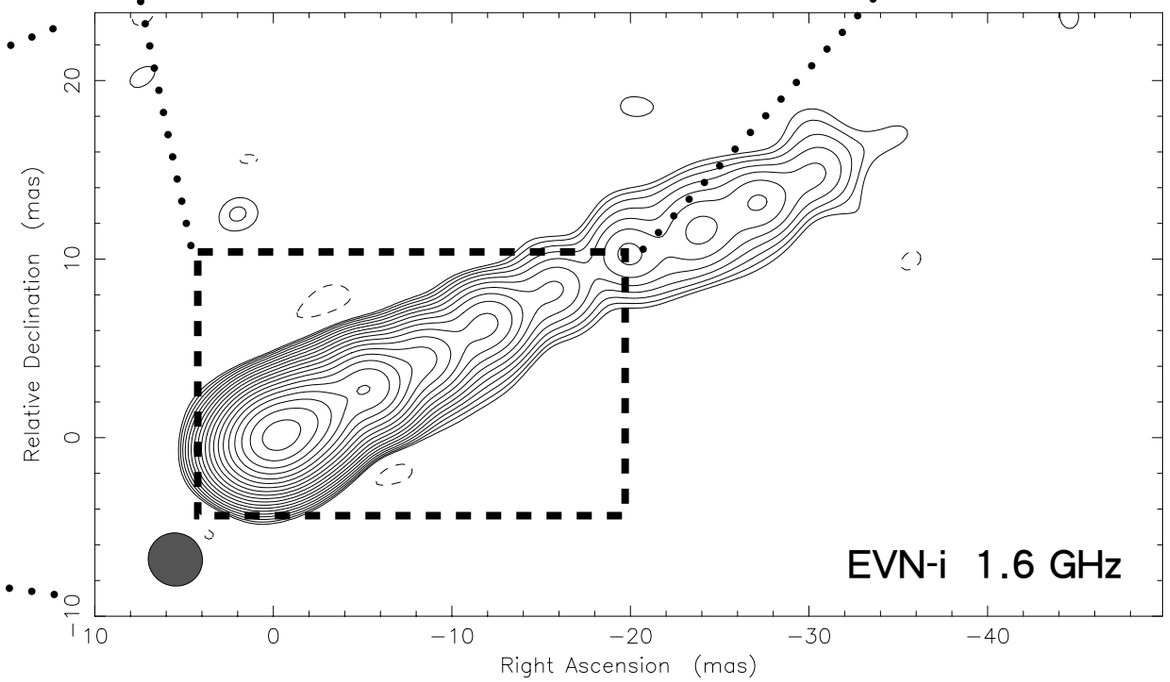
Map center: RA: 16 32 32.013, Dec: +82 32 16.404 (2000.0)
Map peak: 0.218 Jy/beam
Contours: 6.3e−05 Jy/beam x (−3 3 4.24 6 8.49 12
Contours: 17 24 33.9 48 67.9 96 136 192 272 384
Contours: 543 768 1.09e+03 1.54e+03 2.17e+03)
Beam FWHM: 0.997 x 0.962 (mas) at −24.1°

Clean LL map. Array: EVN
NGC6251 at 1.658 GHz 2013 Mar 10



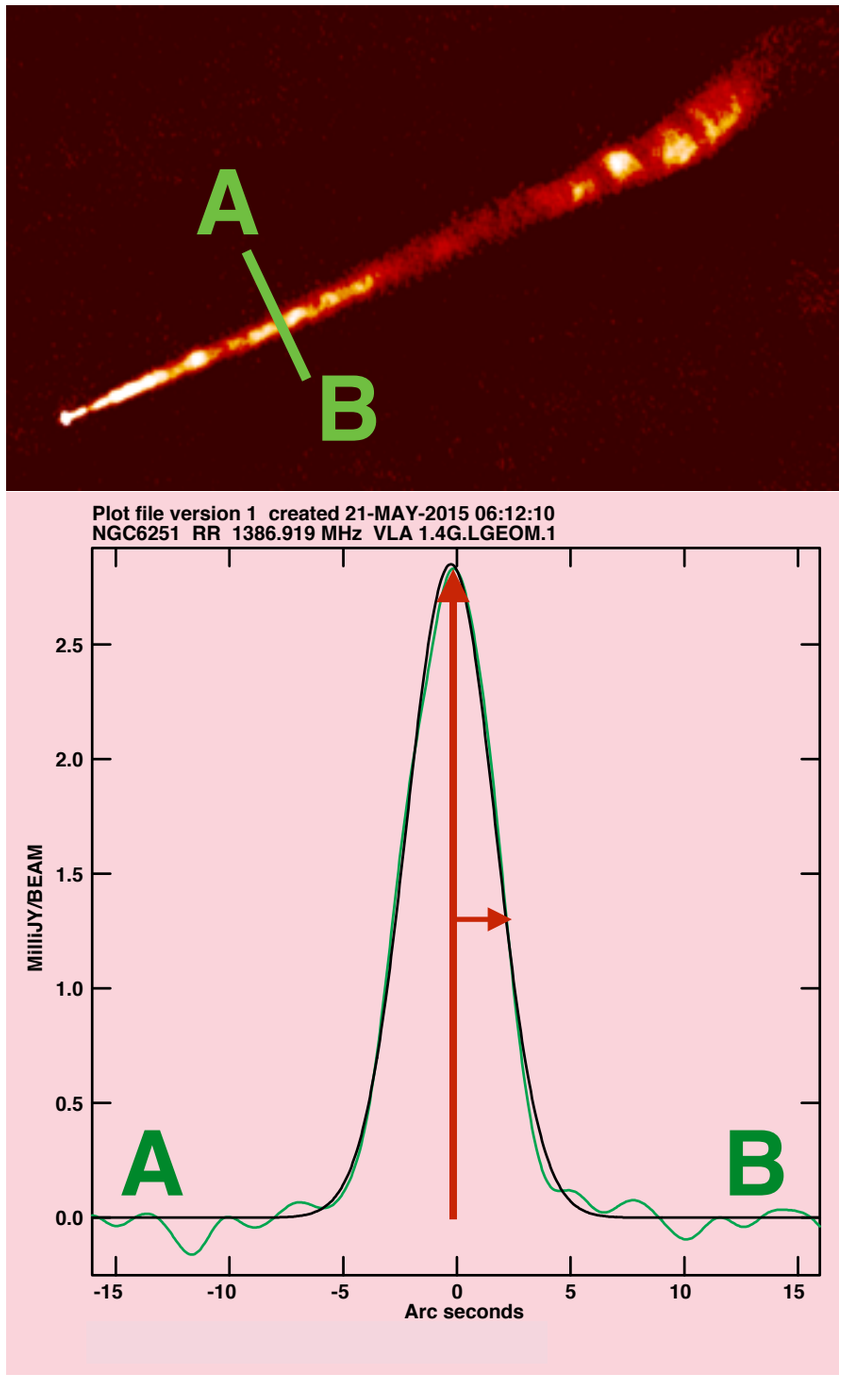
Map center: RA: 16 32 31.970, Dec: +82 32 16.400 (2000.0)
Map peak: 0.418 Jy/beam
Contours: 5.5e−05 Jy/beam x (−3 3 4.24 6 8.49 12
Contours: 17 24 33.9 48 67.9 96 136 192 272 384
Contours: 543 768 1.09e+03 1.54e+03 2.17e+03)
Beam FWHM: 16.7 x 15.7 (mas) at 31°

Clean LL map. Array: EVN
NGC6251 at 1.658 GHz 2013 Mar 10



Map center: RA: 16 32 31.970, Dec: +82 32 16.400 (2000.0)
Map peak: 0.238 Jy/beam
Contours: 0.000129 Jy/beam x (−3 3 4.24 6 8.49 12
Contours: 17 24 33.9 48 67.9 96 136 192 272 384
Contours: 543 768 1.09e+03 1.54e+03)
Beam FWHM: 3.06 x 2.96 (mas) at 65.1°

Measuring Jet Radius



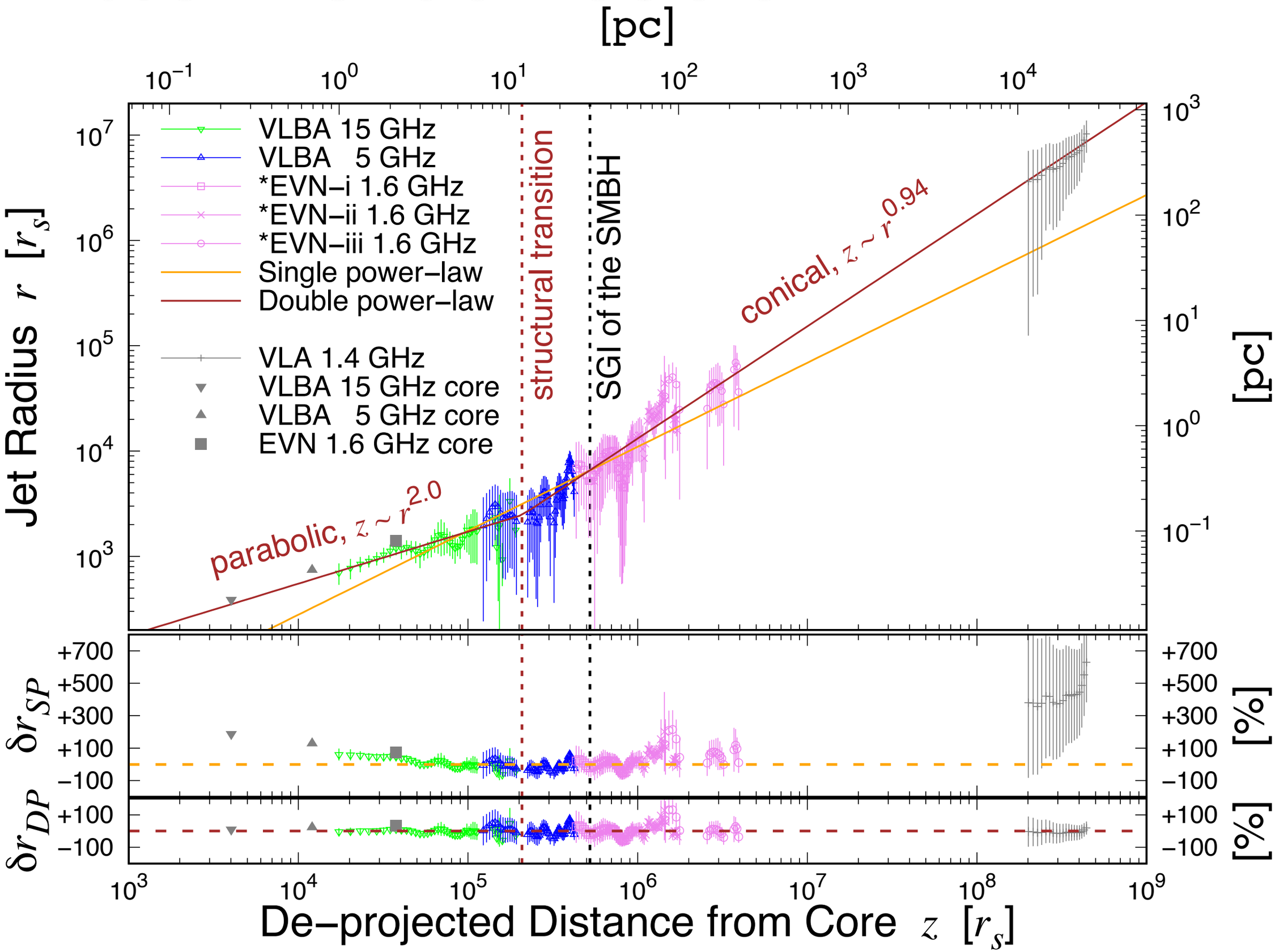
1. Measure the intensity profile transverse to jet axis **A—B**

2. Fit by Gaussian function, and take **FWHM** as 2x jet radius **r**

3. Deconvolution from the beam.

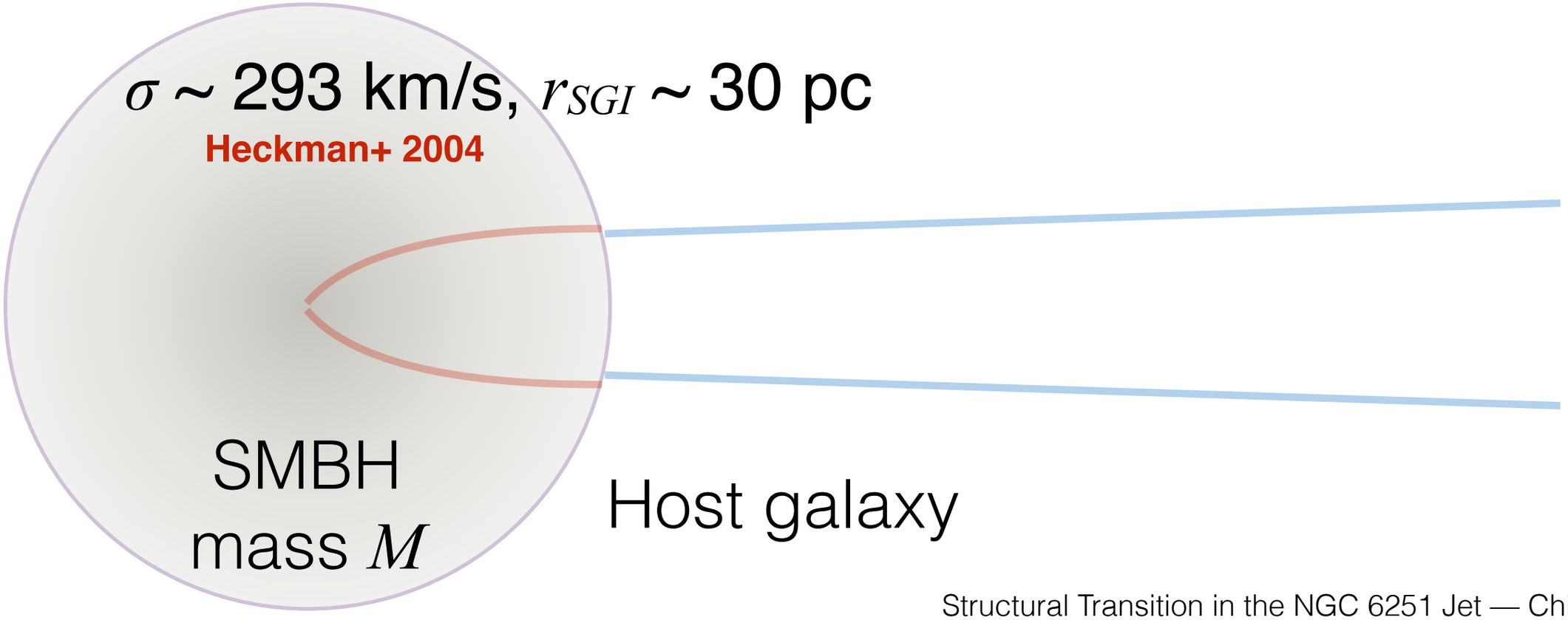
4. Examine collimation profile: “radius **r**—distance **z**” figure

Collimation Profile of NGC 6251

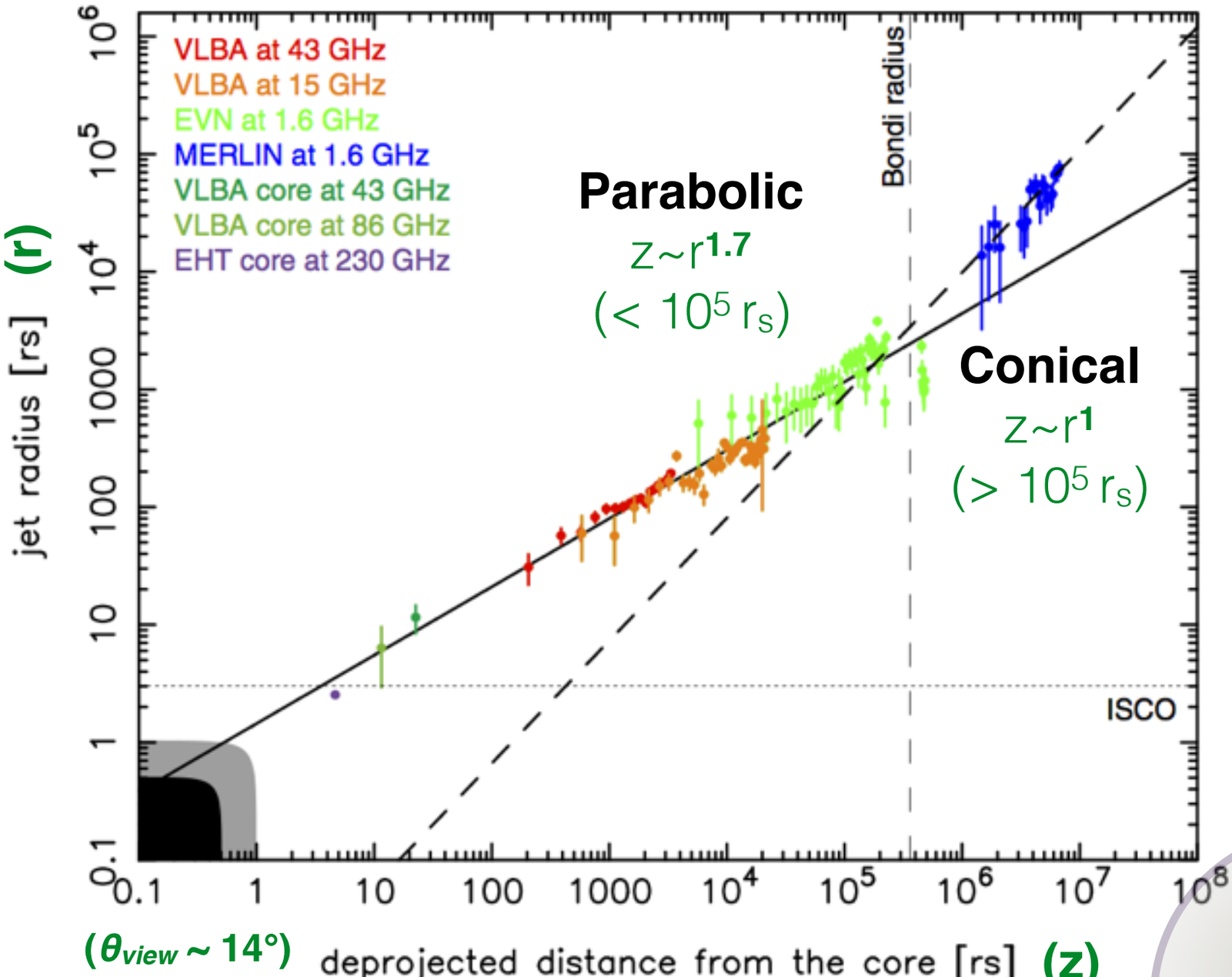


Sphere of Grav. Influence (SGI) vs Bondi radius

- Virial equilibrium
  - Stellar motion, with velocity dispersion σ $\quad r_{SGI} = \dfrac{GM}{\sigma^2}$
- Gas motion, with local sound speed c_s $\quad r_B = \dfrac{2GM}{c_s^2}$



Environment (BH—Galaxy) plays a role in determining jet structure



(θ_{view} ~ 14°)

Asada & Nakamura 2012
Nakamura & Asada 2013

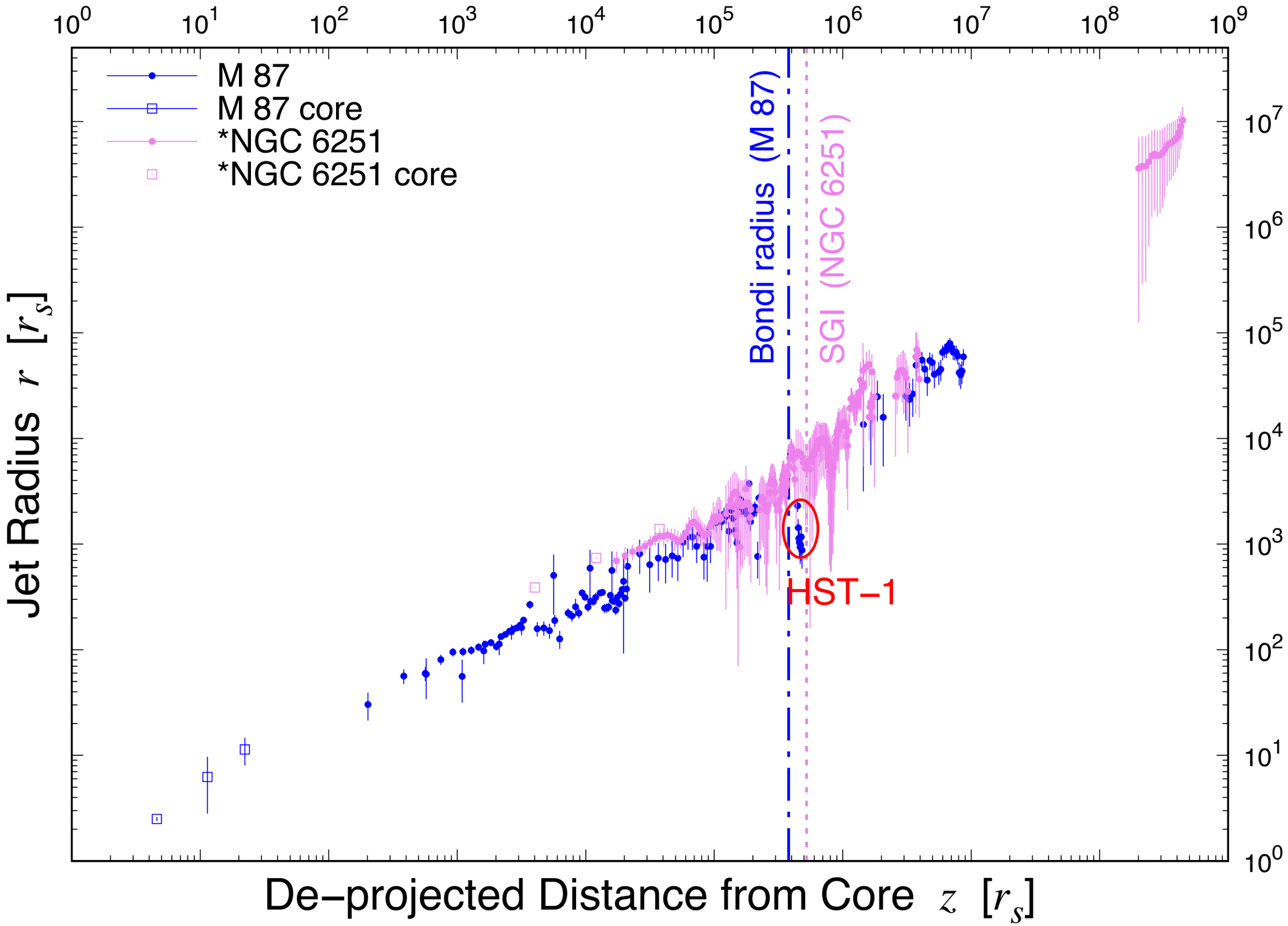
- **M 87, First discovery of structural transition in an AGN jet!**

- Jet geometry is described by 2 power-law lines

➡ A structural transition takes place at ~10^5 r_s (Bondi radius or SGI: gravity from BH wins that from galaxy)

rs = $2GM/c^2$

Combined Collimation Profile of NGC 6251 & M 87



Summary

- We find a structural transition in the NGC 6251 jet, a 2nd case following M 87, which may be a fundamental phenomena of an AGN jet, showing an interplay with its SMBH—galaxy system.

- The collimation process of AGN jets is characterized by thermal pressure of the external gas, and eventually terminates at around the SGI of the SMBH.