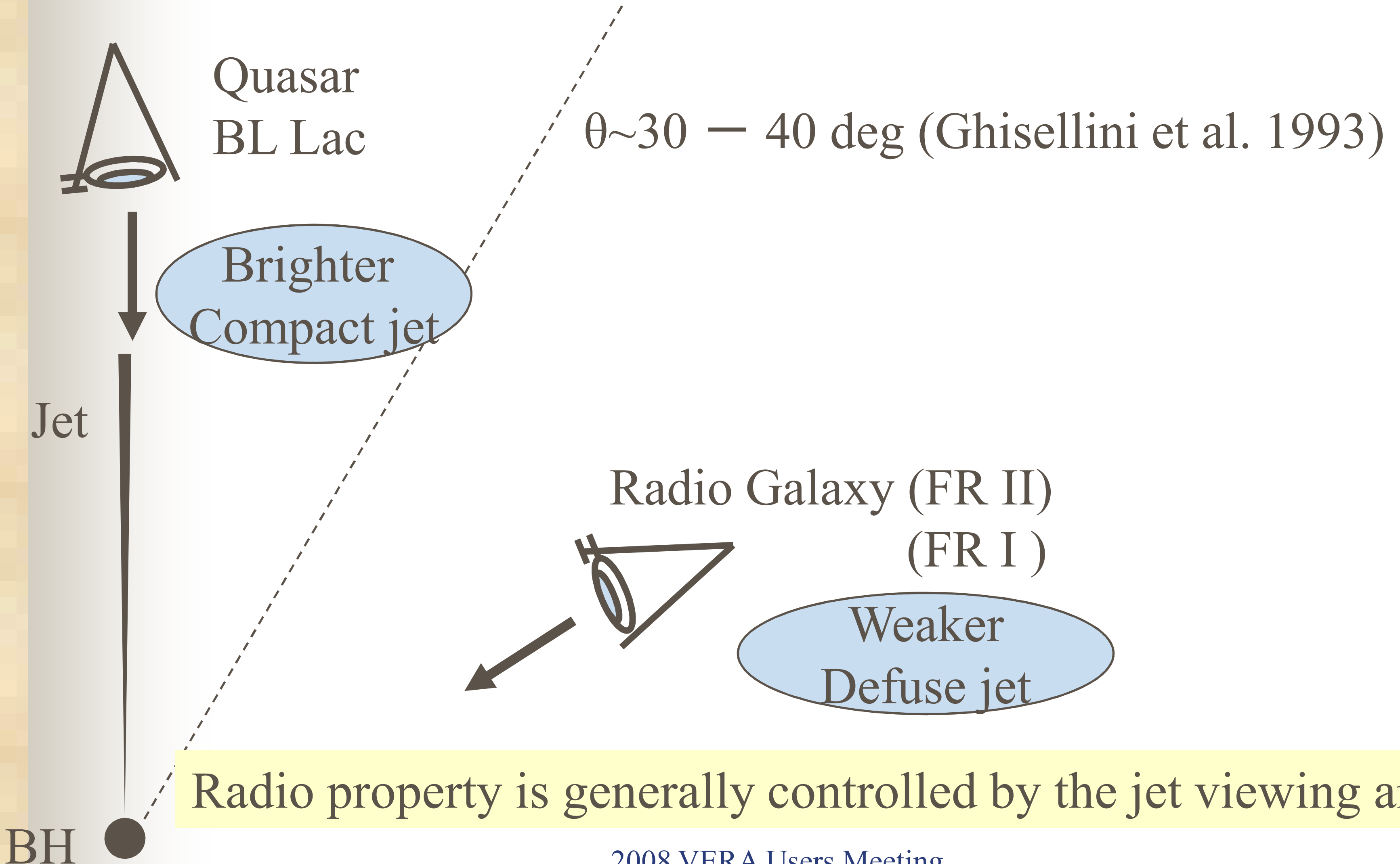
Proper Motion of Seyfert 1 Galaxy PKS 2201+044

Hiroshi Sudou (Gifu University),
Phil Edwards (CISRO),
& Japanese VLBI team

Unified Scheme for radio-loud AGNs



Radio property is generally controlled by the jet viewing angle

PKS 2201+044

- Elliptical galaxy at $z \sim 0.02$
- Optical property
  - Violent variability　Δm ～2 mag
  - Recent spectroscopy ➔ Seyfert 1 Galaxy
  - Previous spectroscopy ➔ BL Lac Object
- Radio property
  - FR I type
  - Apparent size ~ 50 kpc
  - Showing optical jet as well as radio one

Measuring the viewing angle of the radio jet
➔ Which is likely BL Lac or Seyfert (Radio Galaxy) ?

How to measure the viewing angle

- Proper motion of the jet $\beta_{app}(\beta, \theta) = \beta\sin\theta/(1-\beta\cos\theta)$
- Doppler factor $\delta(\beta, \theta) = 1/\{\gamma(1-\beta\cos\theta)\}$
  - From Synchrotron self-Compton model

    Estimate from the comparison between observed and predicted X-ray flux
  - From Compton catastrophy of Brightness temperature

    Brightness temperature of > 1012[K] leads to catastrophic inverse Compton losses and forces the radiation to have a lower value
- Jet/counter-jet intensity ratio

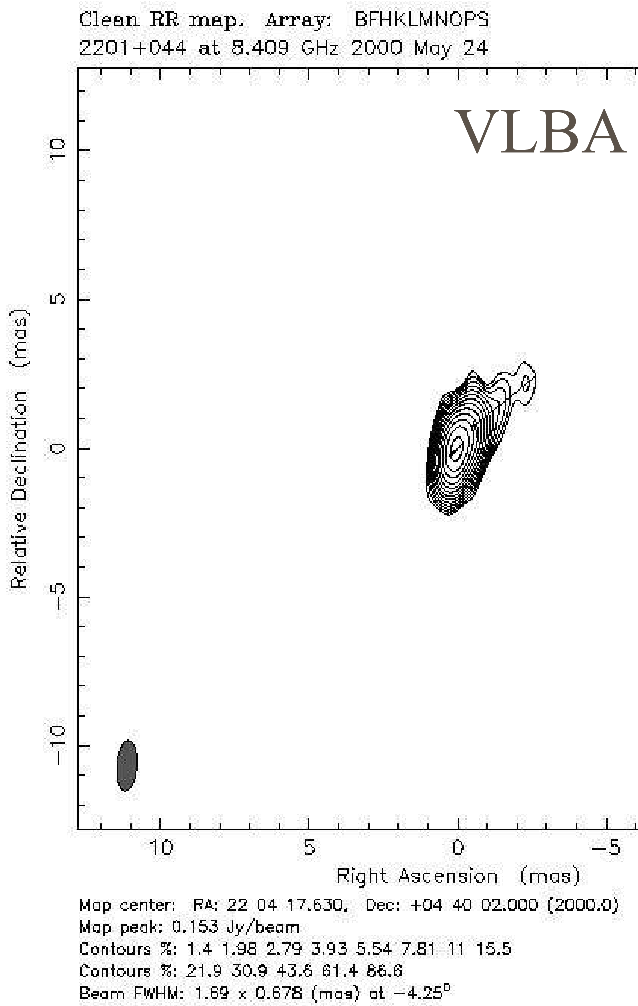
$$R(\beta, \theta) = \{(1+\beta\cos\theta)/(1-\beta\cos\theta)\}^{3+\alpha}$$

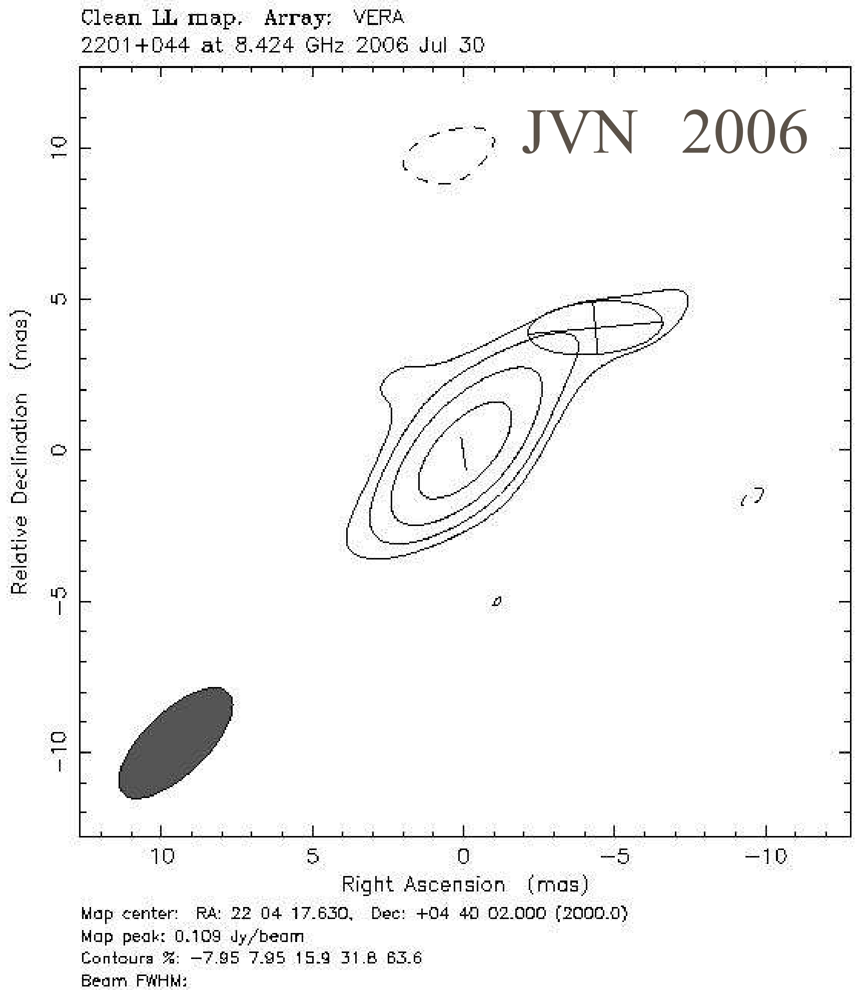
Observations

Date	Frequency [GHz]	Array [ant. num.]	Resolution [mas]
24 May, 2000	8.6	VLBA [10]	1
30 July, 2006	8.6	JVN [5]	3
28 May, 2007	8.6	JVN [8]	3

JVN [5] = VERA + Kashima
JVN [8] = VERA+ Kashima+ Yamaguchi+ Usuda + Gifu

Maps


Clean RR map. Array: BFHKLMNOPS
2201+044 at 8.409 GHz 2000 May 24
VLBA 2000
Relative Declination (mas)
Right Ascension (mas)
Map center: RA: 22 04 17.630, Dec: +04 40 02.000 (2000.0)
Map peak: 0.153 Jy/beam
Contours %: 1.4 1.98 2.79 3.93 5.54 7.81 11 15.5
Contours %: 21.9 30.9 43.6 61.4 86.6
Beam FWHM: 1.69 x 0.678 (mas) at −4.25°


Clean LL map. Array: VERA
2201+044 at 8.424 GHz 2006 Jul 30
JVN 2006
Relative Declination (mas)
Right Ascension (mas)
Map center: RA: 22 04 17.630, Dec: +04 40 02.000 (2000.0)
Map peak: 0.109 Jy/beam
Contours %: −7.95 7.95 15.9 31.8 63.6
Beam FWHM:

Direction of the jet

Scale	Position angle [deg]	Reference
50 kpc (VLA)	280	Laurent-Muehleisen et al. 1993
1 kpc (VLA, HST)	310	Scarpa et al. 1999 Laurent-Muehleisen et al. 1993
pc (VLBA, JVN)	315	This work

Proper motion (β_{app})

- Knot identification
  - Normal method ➔ Gaussion fitting of knots
  - The most likely positional shift of the knot component is (⊿x, ⊿y) = (−3.8, −3.5)
- Proper motion is estimated to be 5.1 [mas] for 6 yrs @position angle of 313 [deg]

In this case, we adopt β_{app}= 1.1

Doppler factor (δ)

- Synchrotron self-Compton
  - δ=0.2 ➔ consistent with Ghisellini et al. 1993
- Brightness temperature

$$\delta = \frac{T_{\mathrm{B,int}}}{T_{\mathrm{B,obs}}}$$

  - $T_{\mathrm{B,\,obs}} = 0.7 \times 10^{11}$ [K] was estimated from VLBA data
  - δ=0.07 − 0.7

    for $T_{\mathrm{B,int}} = 10^{12}$ and 10^{11}[K], respectively

➔ consistent with the SSC results

We adopt δ=0.2

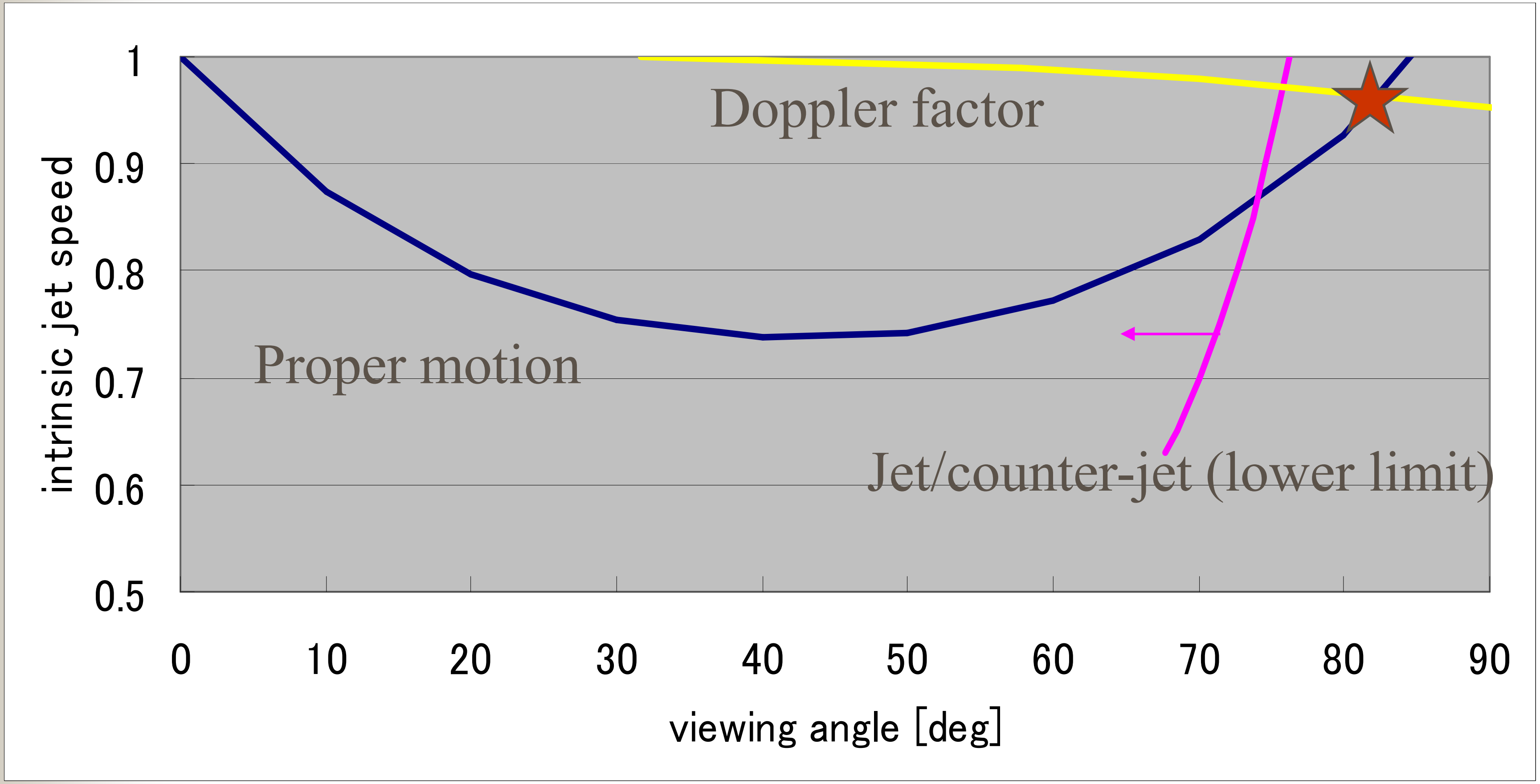
Jet/Counter-jet intensity ratio (*R*)

- Counter-jet was not detected
- Lower limit of *R* can be estimated to be 5 from the VLBA map

We adopt $R > 5$

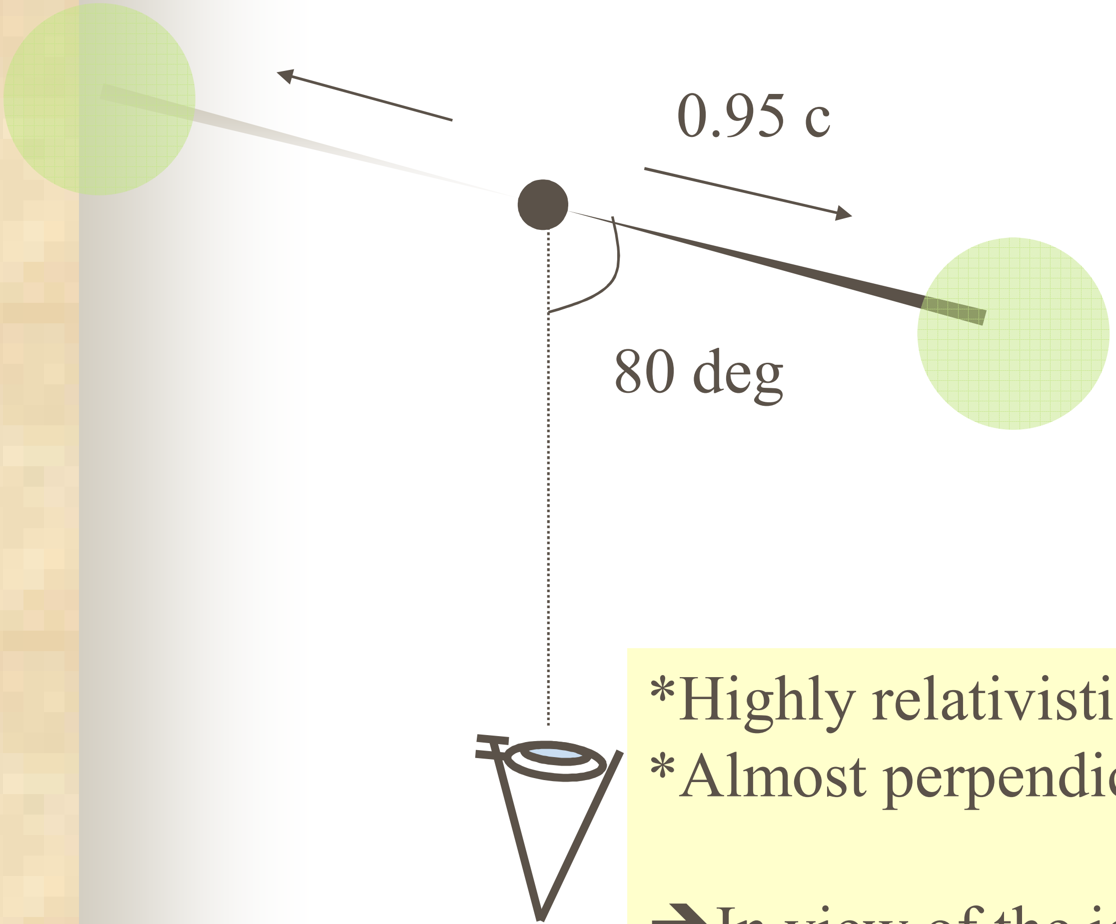
- Note
  - Counter-jet might be absorbed by dense plasma torus (e.g., Kameno et al. 2001),
  - Thus intrinsic *R* could be lower than observed one

Viewing angle and speed of the jet



★: (β,θ) ~ (0.95, 80)

Possible geometry of the jet



*Highly relativistic speed
*Almost perpendicular to the line of sight

➔In view of the jet geometry PKS 2201+044 is similar to Radio Galaxies, not to BL Lacs.

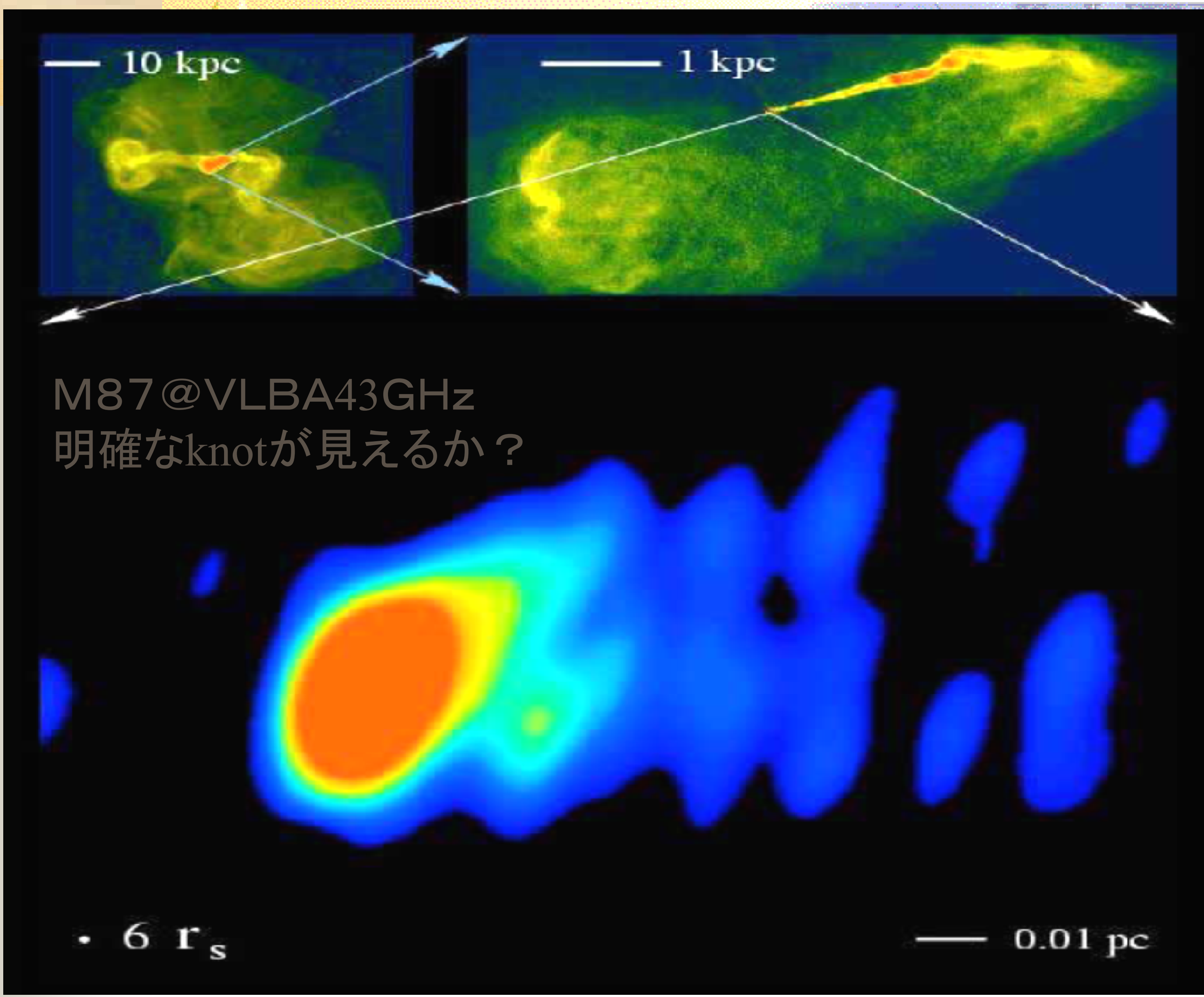
Summary (Science Part)

- Proper motion of PKS 2201+044 is estimated to be 1.1 c
- Together with Doppler factor, the jet viewing angle is estimated to be ~80 deg
- This indicates that this source should be a Seyfert (radio) galaxy, rather than an BL Lac
- Difference between optical and radio classification should be considered

Appendix: Methods of Knot Identification

- 2つのマップがあったとする
  - ジェットの固有運動を計りたい
- しかし、2つのマップは異なる望遠鏡で(つまり異なる分解能、感度)で得られている
- または、ジェットの形状が非常に複雑(e.g., M87 @VLBA 43GHz)
  - ＶＳＯＰ－２ではよりこの傾向が強まる

➔ knot同定の精度を上げるには？


10 kpc
1 kpc
M87@VLBA43GHz
明確なknotが見えるか？
6 r_s
0.01 pc

General Methods

1. Local Peak： ピークの1ピクセルのみ
2. Gaussian Peak： 明確なガウス型ピークを構成する複数のピクセル（通常の方法）
3. Correlation： ある強度レベル以上の全てのピクセル

- 画像情報をできるだけ多く取り込むことで、精度を向上させる

Two Correlation Methods

$$A(j) = \int X(i)Y(i+j)di$$

$$B(j) = \int \frac{X(i)Y(i+j)}{Q(j)} di$$

$$Q(j) = \int X^2(i)Y^2(i+j)di$$

A:通常の相関
B:自己相関による規格化

Case of PKS 2201+044 (preliminary)

・各マップ3σでカット(3σ以下の強度は0とおいた)
・マップごとに重みはかけていない
（より精度のいいVLBAデータに重みをかけることも今後検討）

	ΔX [mas]	ΔY [mas]
ガウスフィット (No.8参照)	4.5	4.3
相関A(j)	4	3
相関B(j)	4	7

・いくつかのパラメータ(e.g., カットオフ、重み関数)にて再検討したい
・疑似データを使ったシミュレーションでも検証してみたい

Next Step

- この手の画像処理の一般的手法は？
- 多少ノイズが大きくても、精度良く固有運動を検出する最適手法を見つける（SNR等、ケースごとに異なるかもしれない）
- ＶＳＯＰ－２に向け、複雑な構造のジェットの固有運動の同定方法の検討
- ビームに埋もれた複数の成分を検出できるアルゴリズムもほしい（e.g., Double core）