

- Jets are highly-structured, containing blobs or **knots** that are less than 1 light year across and that (in the radio) can vary on timescales of 3-10 years. They are seen in the optical, X-rays and even gamma-rays.

**Plot:** VLBI Images of Radio Galaxy NGC 6251

- \* Each knot displays similar broad-band spectra, suggesting local generation of the relativistic electron population. This inference is reinforced by images in X rays closely resembling those in radio.

**Plot:** Radio and X ray images of M87 and PKS 1127-145 Jets

- The knotty structure is attributed to MHD instabilities in dynamic outflows, with **entrainment** of external material as the jet propagates outward. Radio images on the kpc scale indicate that the jet structure may consist of a fast moving central column or **spine** of low plasma density, surrounded by a slower-moving (but still relativistic), denser **sheath** that captures the entrainment. Shocks may develop at the spine-sheath interface, and may seed acceleration of electrons to relativistic energies.

**Plot:** Relativistic Hydrodynamic Jet Simulations

- \* The magnetic field morphology in jets is not precisely known, but may be quasi-helical as opposed to sheet-like in character.

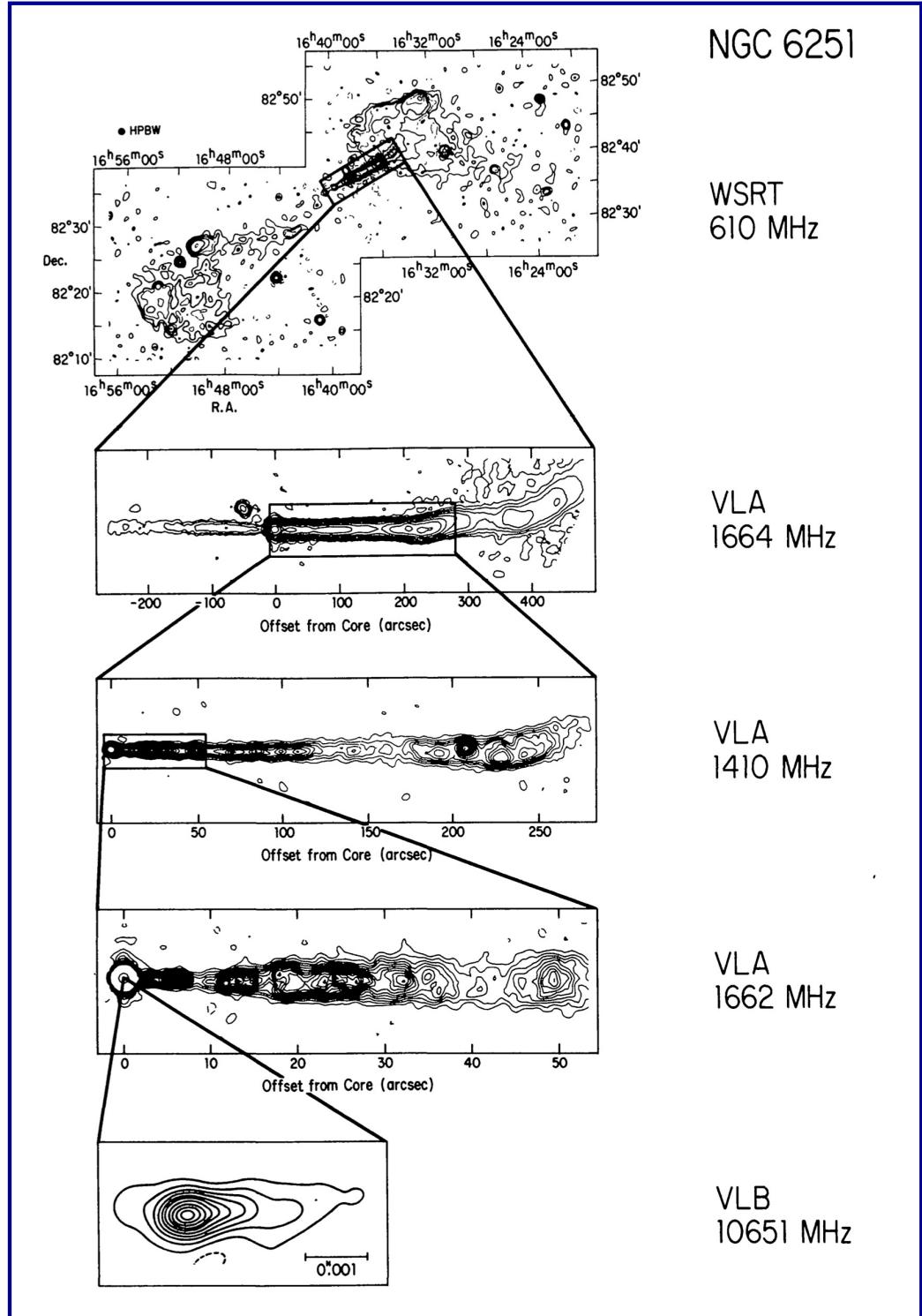
- Fine-scale mapping of structures in radio jets is achieved through **very-long baseline array interferometry** (VLBI/VLBA). The diameter  $d_{\oplus}$  of the Earth establishes the baseline, and the phase difference  $\delta$  of signals at wavelength  $\lambda$  from two points separated by  $r$  (perpendicular to the line of sight - *draw a diagram*) a source at distance  $d = d_{\oplus}/\theta$  is

$$\delta = \frac{r}{\lambda} \theta \sim \frac{r}{\lambda} \frac{d_{\oplus}}{d} , \quad (5)$$

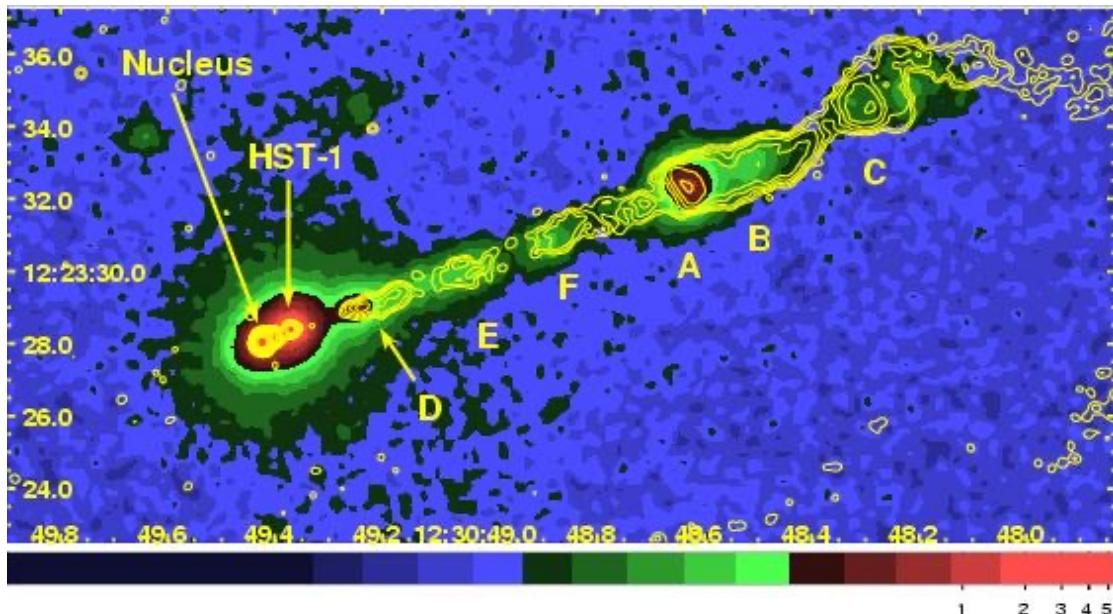
for a parallax  $\theta/2$ . Therefore, to obtain resolution on small scales  $r$  in the sky one requires large baselines  $d_{\oplus}$  (i.e., VLBI) at a fixed wavelength. The ultimate radio interferometer is the Event Horizon Telescope (EHT) in the mm band (shorter  $\lambda$  than GHz band), which has obtained the spectacular images of the environs of the SMBHs of M87 and the Milky Way.

# High Resolution Radio View of a Jet

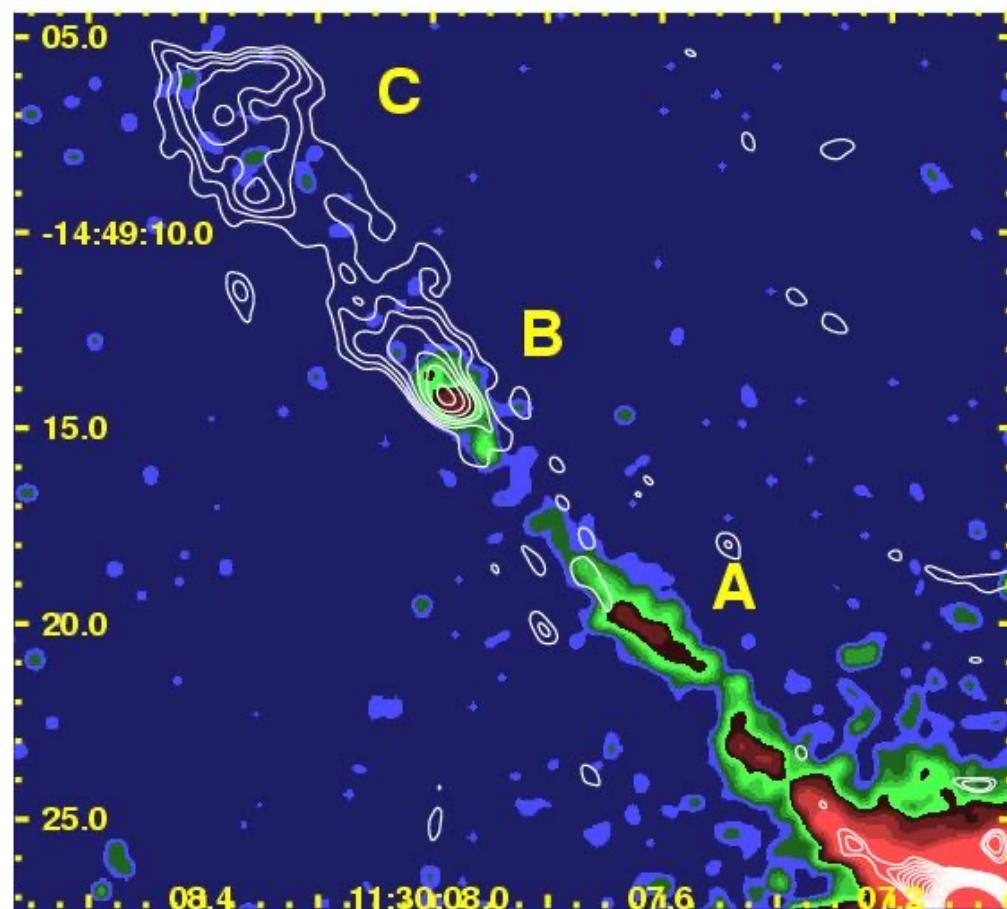
- Radio intensity contours for the [NGC 6251 jet](#) at different wavelengths, demonstrating both multi-scale and knotty structure.
- Lower resolution data (top) are from the [Westerbork \(WSRT\)](#) facility in the Netherlands. Higher resolution views are from the [Very Large Array \(VLA\)](#) in NM, and the enlarged view of the core (bottom) was obtained using multi-facility [Very-Long Baseline Interferometry \(VLBI\)](#).
- Fig. 2 from classic review of [Bridle & Perley \(1984, Ann. Rev. Astron. Astrophys. 22, 319\)](#).



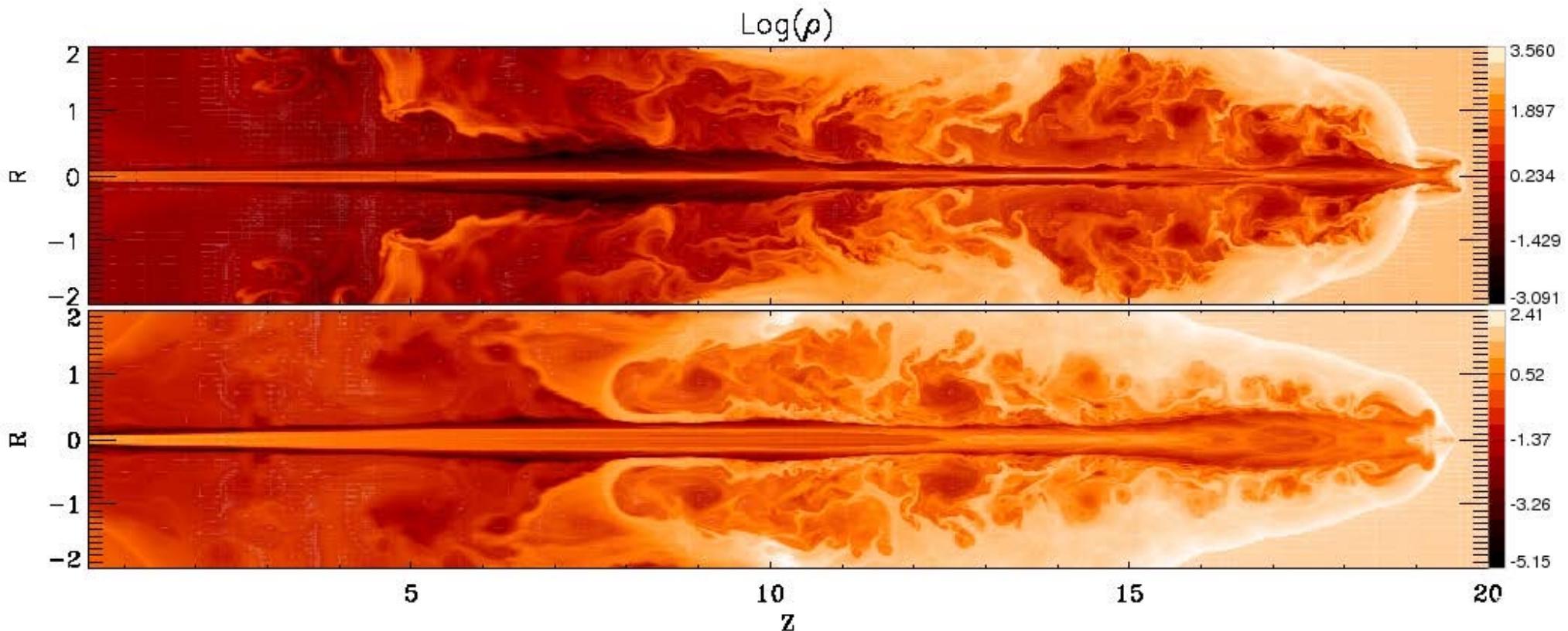
# Supermassive Black Hole Jet Morphology



- *Above:* M87 jet ( $z=0.0043$ ) as viewed by *Chandra* (0.2-6 keV), with *VLA* 8 GHz radio contours superimposed.
- *Right:* Combined *Chandra* X-ray and *VLA* 8 GHz radio data for the PKS 1127-145 jet ( $z=1.18$ ).
- Figures from extragalactic jet review by *Harris & Krawczynski* (2006, *ARA&A* 44, 463)



# Hydrodynamics of Relativistic Jets



- Density structure in hydrodynamic simulations of relativistic jets, revealing nozzle formation, turbulent eddies and sheath-spine morphology.
- Meliani, Keppens & Giacomazzo, *Astron. & Astrophys.* **491**, 321 (2008)

### 3.1 Superluminal Motion and Doppler Boosting

- Imaging over time of the jets reveals that the knots are moving outwards (the same is seen in galactic superluminal jet sources or **microquasars**), and with **apparent superluminal motion**  $v_{\text{app}} > c$  in the sky.

**Plot:** Superluminal Motion in 3C 273 and GRS 1915+105

- This deception is a geometrical projection effect on the sky (flashlight+wall analogy), and has no physical basis that contradicts Einstein's theory of special relativity.
- Consider two photons reaching Earth from a jet that are observed at times  $t_1$  and  $t_2$ . The propagation equations are

$$t_1 = \frac{d}{c}, \quad t_2 = t_e + \frac{d - vt_e \cos \phi}{c}, \quad (6)$$

where  $t_e$  is the time delay at the source for the emission of the second photon, and we define  $\Delta t = t_2 - t_1$  to be the arrival time difference.

Then the apparent speed  $v_{\text{app}}$  of the knot can be coupled to the time delay via

$$\frac{v_{\text{app}}}{c} = \frac{vt_e \sin \phi}{c \Delta t} = \frac{(v/c) \sin \phi}{1 - (v/c) \cos \phi}, \quad \Delta t = t_e \left(1 - \frac{v}{c} \cos \phi\right). \quad (7)$$

When  $\phi \ll 1$  and  $v \sim c$  this can yield  $v_{\text{app}} \gg c$ ! Specifically, in this domain,

$$\frac{v_{\text{app}}}{c} \approx \frac{2\phi}{\phi^2 + 2/\Gamma^2} \quad \text{with} \quad \Gamma = \frac{1}{\sqrt{1 - v^2/c^2}}. \quad (8)$$

If  $\phi$  is known (*difficult to measure*), this relation can be inverted to infer the relativistic speed  $v$ . Generally, bulk motions with  $\Gamma = 1/\sqrt{1 - v^2/c^2} \sim 5 - 100$  are determined for extragalactic jet sources (lower for microquasars).

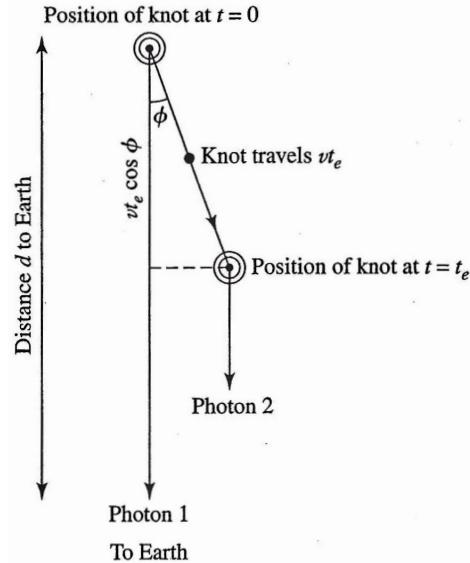
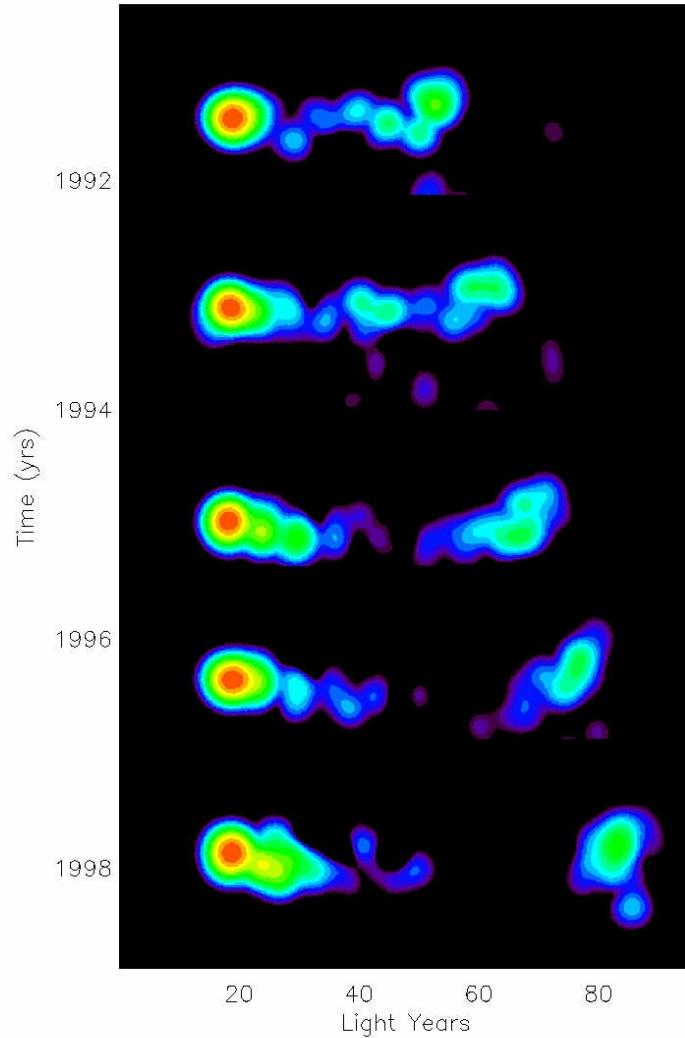


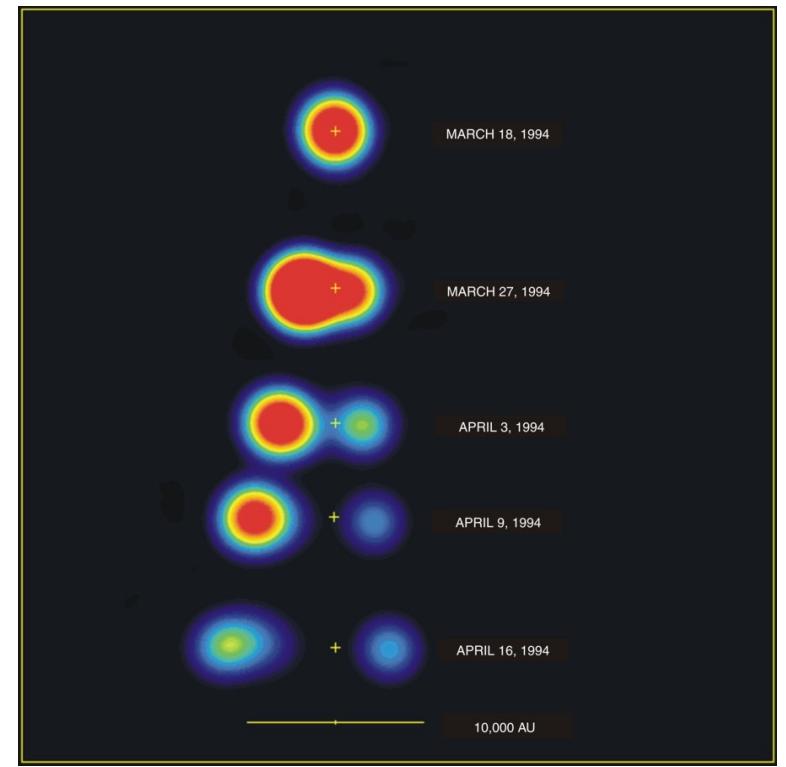
Figure 1: Superluminal motion geometry for two knots.

3C 279



# Superluminal Motion in Jets

GRS 1915+105



- Left Panel: Time-lapse VLBI images of quasar 3C 279 depicting evolving knot positions in a superluminal motion (from Wehrle et al. 2001, ApJ 133, 297);
- See NRAO gallery <http://images.nrao.edu/387>, image courtesy of NRAO/AUI.
- Right Panel: Time-laps for galactic superluminal jet in black hole candidate GRS 1915+105 (from Mirabel & Rodriguez 1994, Nature **371**, 46)

- At the same time, such relativistic motions induce an enhancement of the flux from radio jets. Relative to the intrinsic comoving jet luminosity,  $L_{\text{int}}$ , the apparent luminosity is **Doppler boosted** according to

$$L_{\text{app}} = \mathcal{D}^4 L_{\text{int}} , \quad \mathcal{D} = \frac{1}{\Gamma[1 - (v/c) \cos \theta]} , \quad (9)$$

for an angle  $\theta$  ( $\approx \phi$ ) between the line of sight and the bulk motion vector. Here  $\mathcal{D}$  is called the **Doppler factor** of the luminosity boosting.

- \* The breakdown of this formula is that relativistic solid angle collimation contributes two powers of  $\mathcal{D}$ , frequency blueshifting one power, and time dilation gives another power of  $\mathcal{D}$ .
- The sign of  $\cos \theta$  clearly proves critical, and leads to the jets **beamed** towards us being much more luminous than those beamed away from the observer. Hence, jets should overwhelming be **one-sided**, as is observed.
- N.B. If  $\Gamma \gg 1$  and  $\theta \approx 0$ , then small changes in  $\theta$  can yield large changes in  $\mathcal{D}$  and hence the apparent luminosity; this is the situation for **blazars**.

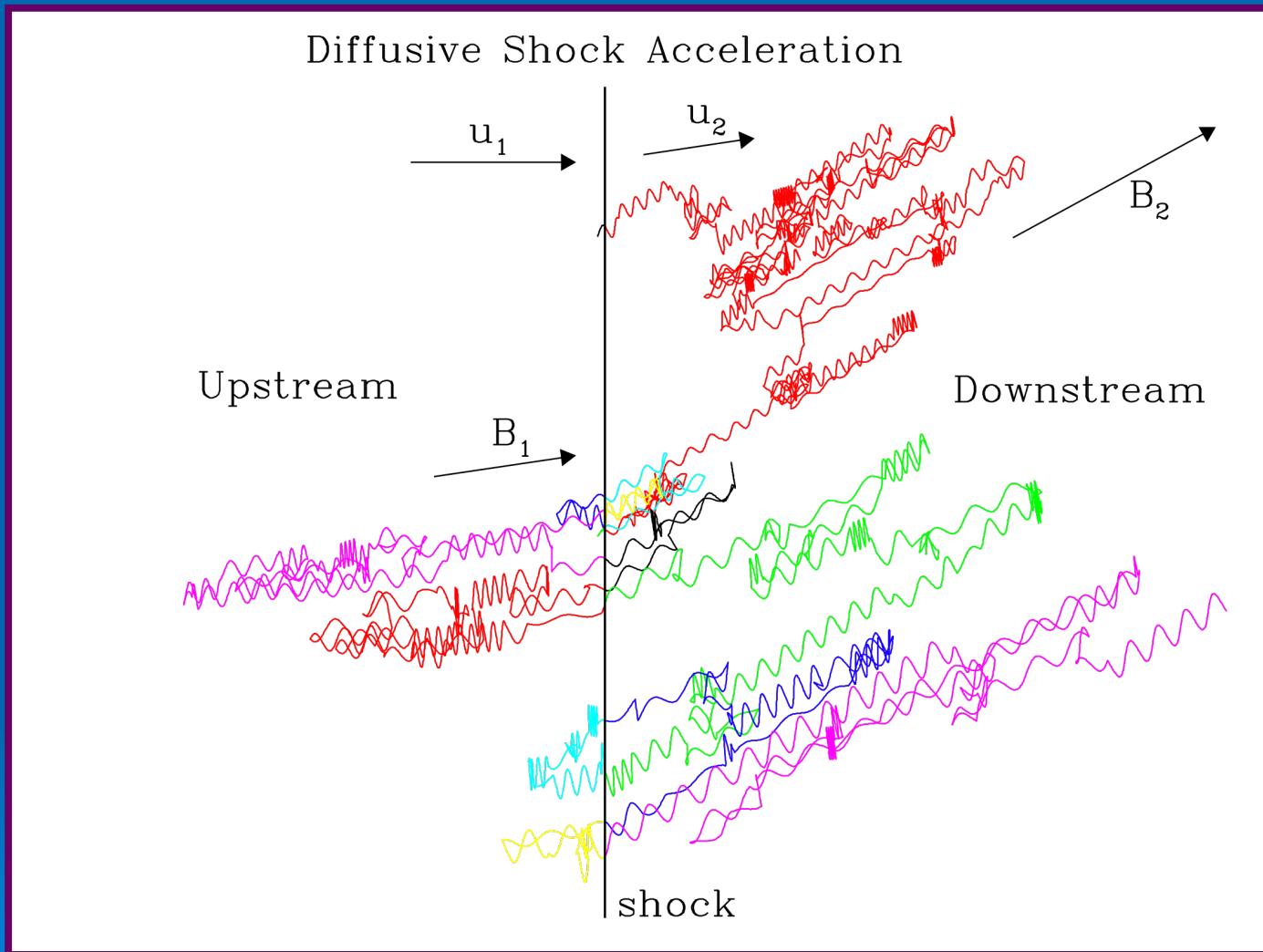
## 3.2 Shock Acceleration

- Inferences of relativistic electrons in jets require a process of acceleration. The observed turbulent structure of jets, coupled with eddying/turbulence in MHD jet simulations suggests that **shocks** are present in jets.
- Formation of shocks requires only the existence of a supersonic flow impacting on a subsonic one. This affords the opportunity for **diffusive shock acceleration** (ubiquitous in astrophysics) to be active.

**Plot:** Shock Acceleration Schematic

- Such diffusive acceleration, originally posited by Fermi in 1949, is widely invoked in sources such as supernova remnants, heliospheric shocks, gamma-ray bursts, intracluster gas shocks, etc., as the site for energization of non-thermal electrons and ions.

# Monte Carlo Simulation of Fermi Acceleration



- Gyration in B-fields and diffusive transport modeled by a Monte Carlo technique; color-coded in Figure according to fluid frame energy.
- Shock crossings produce net energy gains (evident in the increase of gyroradii) according to principle of first-order Fermi mechanism.

- \* Direct evidence for the action of shock acceleration is found by particle measurements at the Earth's bow shock, other planetary bow shocks, and interplanetary traveling shocks.

- In large systems, diffusive acceleration at shocks is scale-free for significant ranges of momenta, thereby generating **power-law distributions** that are seen in the **cosmic ray** spectrum, and also can be inferred from many non-thermal astronomical sources, such as blazars and radio galaxies.

**Plot:** The Cosmic Ray Spectrum

- Since diffusive shock acceleration in turbulent MHD plasmas avails itself of charged particle interactions with plasma wave turbulence, it is usually most efficient for **gyroresonant** wave-particle interactions. This then establishes a natural timescale for the acceleration process, namely the **gyroperiod** or inverse gyrofrequency (cyclotron frequency):

$$t_{\text{cyc}} = \frac{1}{\omega_B} \equiv \frac{m_e c}{e B} = \frac{5.7 \times 10^{-8}}{B} \text{ sec.} \quad (10)$$

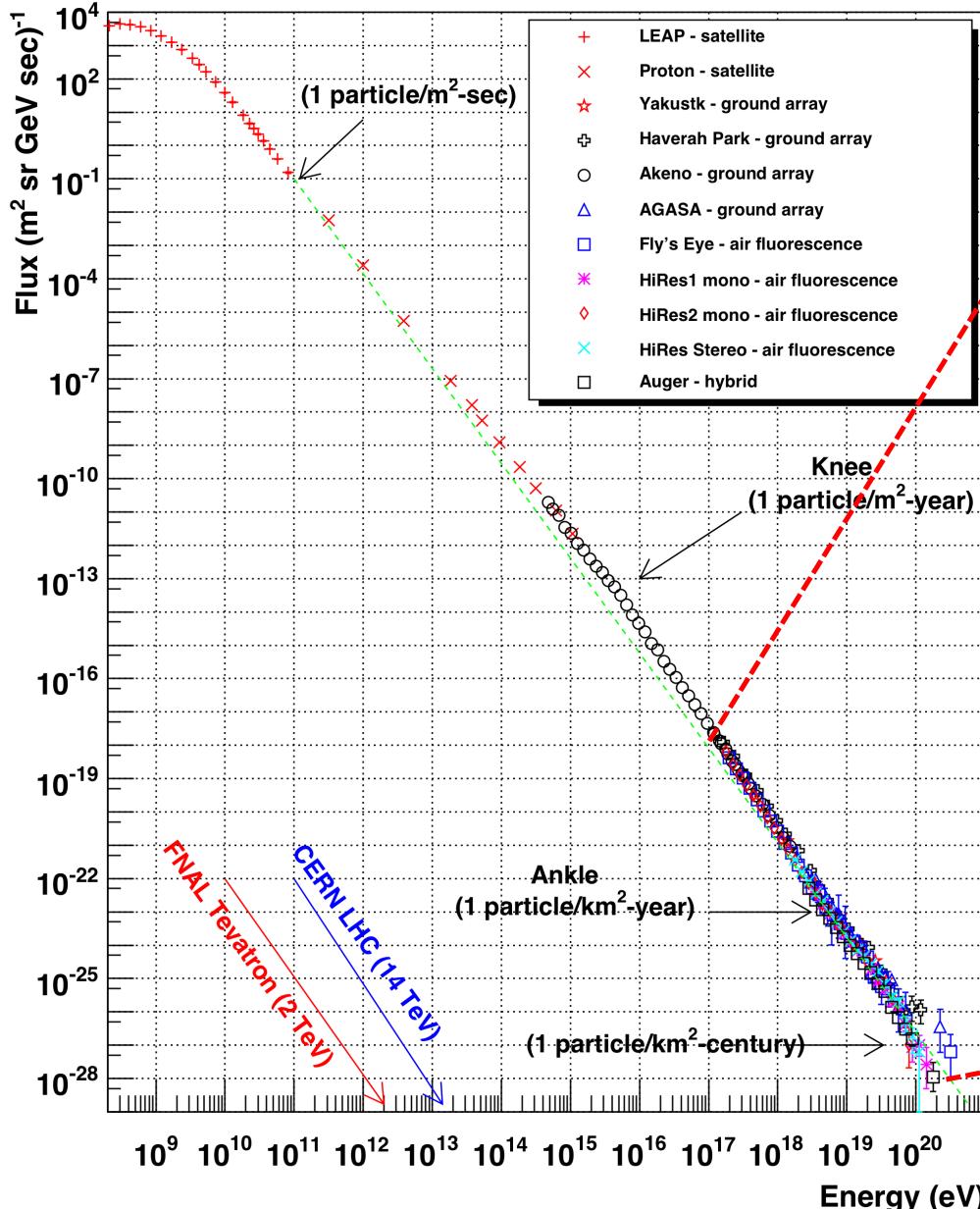
Since the acceleration to electron Lorentz factor  $\gamma_e$  is just time-dilated, i.e.  $t_{\text{acc}} \sim \gamma_e t_{\text{cyc}}$  ( $= \gamma_e / \dot{\gamma}_e$ ), the energy gain rate can be written

$$\frac{dE_e}{dt} \sim 3 \times 10^7 \text{ GeV/sec} \quad . \quad (11)$$

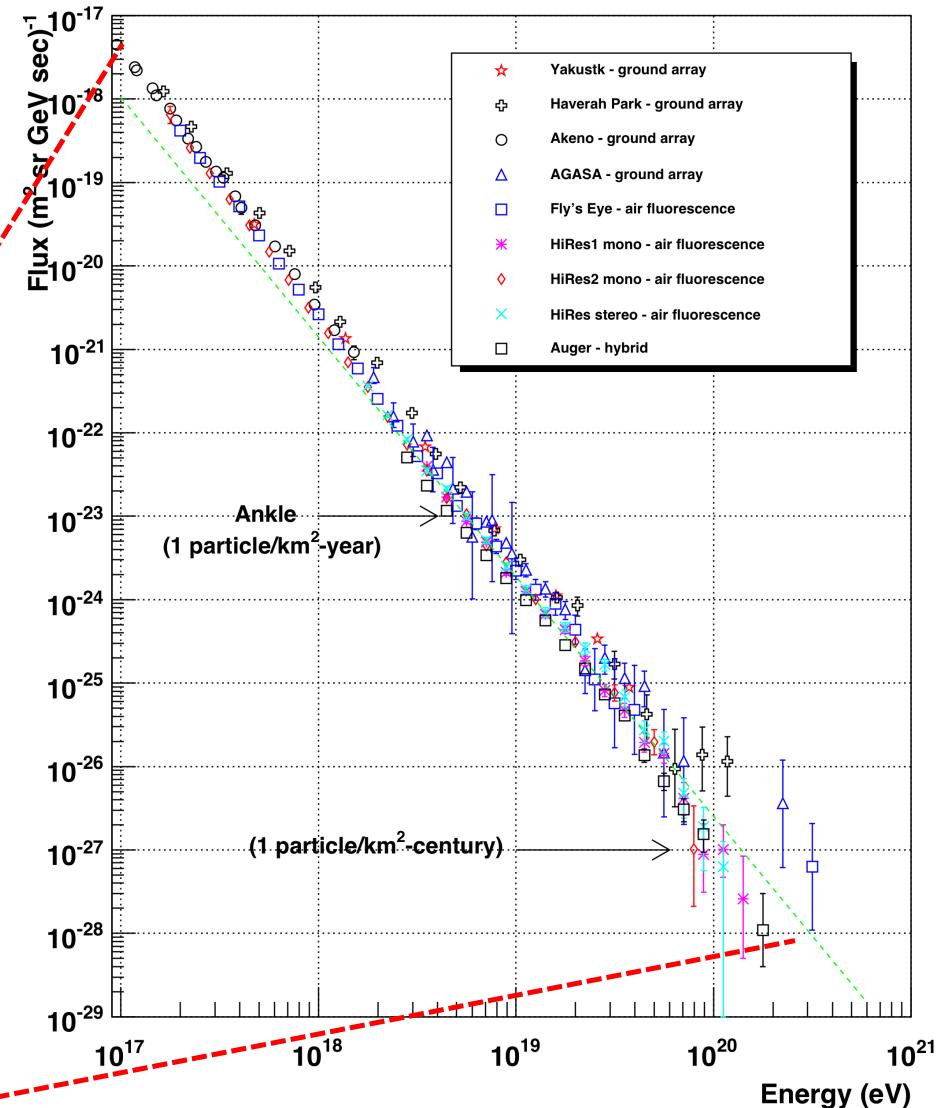
Hence, an AGN flare that varies on timescales around 1 hour can generate  $E_{\text{max}} \sim 10^{11} \text{ GeV} = 10^{20} \text{ eV}$  for typical magnetic field strengths,  $B \sim 10^3 \text{ G}$ . This promotes the possibility that AGN jets can generate **ultra-high energy cosmic rays** (talk about these a bit).

# Ultra-High Energy Cosmic Rays

Cosmic Ray Spectra of Various Experiments



Cosmic Ray Spectra of Various Experiments



- Adapted from Simon Swordy plots by Hanlon.  $E > 10^{14}$ eV measurements require large collecting area => air shower arrays.

### 3.3 Hot Spots in Radio Lobes

- Jets blast into the intergalactic medium (IGM), eventually dispersing in lobes (with  $L_{\text{lobe}} \sim 10^{44}$  erg/sec) which exhibit filamentary structure indicative of shocks. **Hot spots** define cores for the impact of jets on the lobe.
  - \* The common bending of jets shows that galaxies move through the IGM. The net mass required to bend a jet is usually only sampled on large scales, i.e.,  $> 100 - 200$  kpc.

**Plot:** Observed Bending of Extragalactic Jets

- A consideration of hot spot dynamics can provide estimates of the matter density in the jet, and the magnetic fields in lobes. In the frame of the hot spot, non-relativistic **ram pressure** can be balanced between jet and IGM contributions:

$$\rho_{\text{IGM}} v_{\text{H}}^2 \approx \rho_{\text{J}}(v_{\text{J}} - v_{\text{H}})^2 \Rightarrow \frac{\rho_{\text{J}}}{\rho_{\text{IGM}}} = \frac{1}{(v_{\text{J}}/v_{\text{H}} - 1)^2} . \quad (12)$$

For  $v_{\text{J}} \sim c$  and  $v_{\text{H}} \lesssim c/30$  as a general virial estimate for the IGM flow speed (say from cluster dynamics), this establishes that  $\rho_{\text{J}} \lesssim 10^{-3} \rho_{\text{IGM}}$ . Thus, jets are quite under-dense; their key impact is that they carry a lot of momentum (and angular momentum).

**Plot:** Bow Shock Geometry for Hot Spots

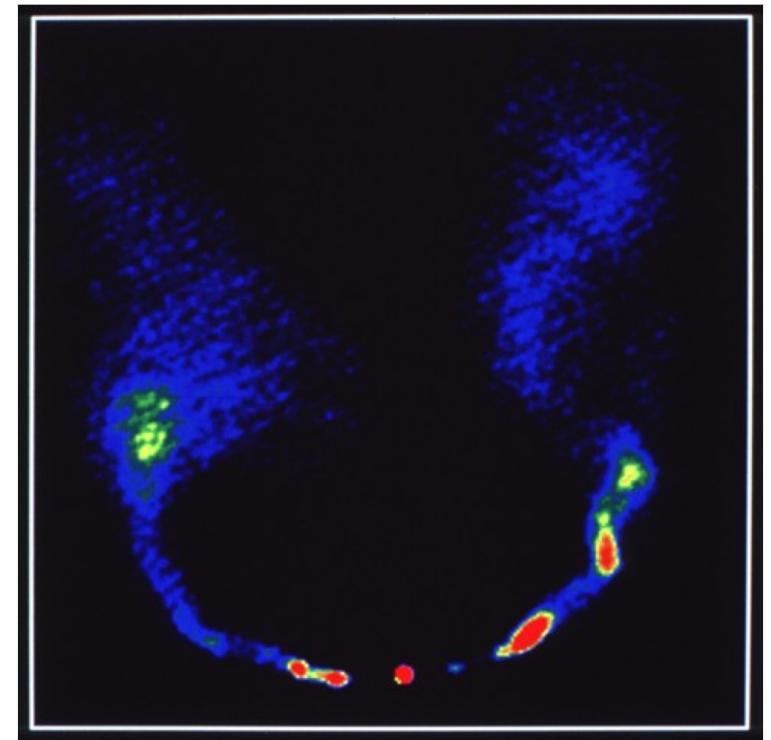
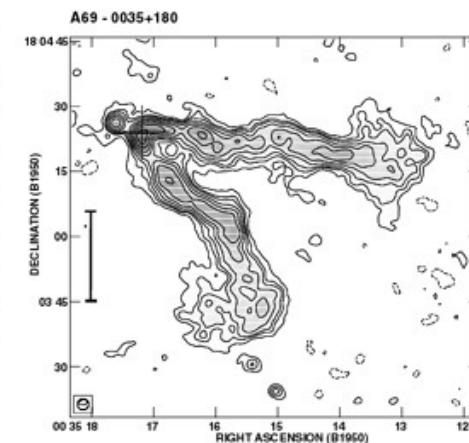
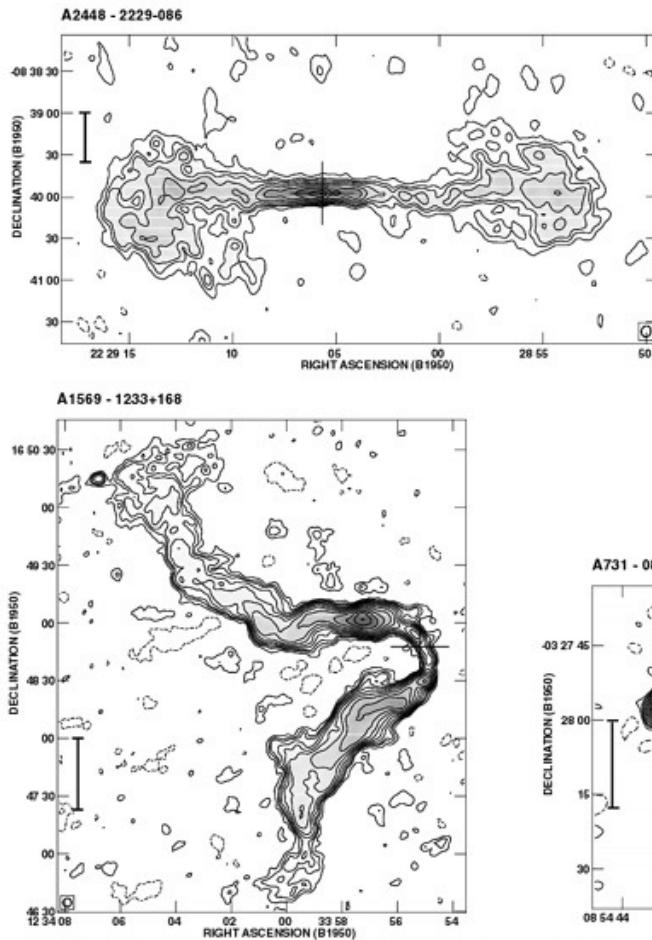
- Assuming an equipartition magnetic field then yields

$$\frac{B^2}{8\pi} \sim \rho_{\text{IGM}} v_{\text{H}}^2 \Rightarrow B \sim 3 \times 10^{-3} \text{ Gauss} \quad (13)$$

for an estimate of the lobe's field. This is much lower than that of the field in the inner, active portions of the jet that yield their most intense emission.

- \* Note that combining this  $B$  value with the approximate radius of a lobe can yield a rough estimate of the number density of non-thermal electrons via synchrotron emissivity formalism.

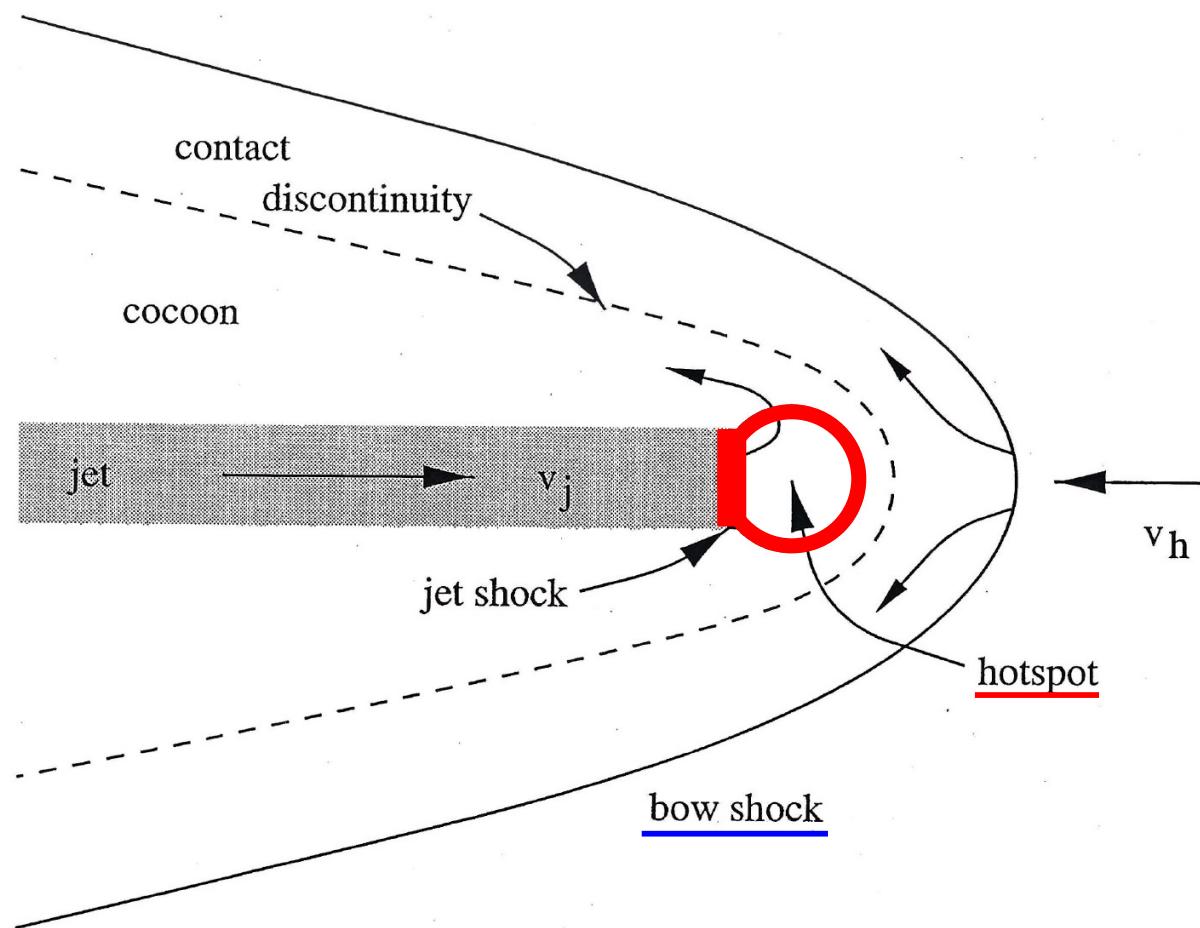
# Bent Jets in Radio Galaxies



NGC 1265

- *Left:* four 20cm VLA images of radio galaxies, two with bent jets (due to M. Ledlow, from Spark & Gallagher book). *Right:* VLA image of NGC 1265 in Perseus cluster. Courtesy: O'Dea & Owen (after original in ApJ 1986).

# Bow Shock Geometry for Radio Lobes



- Geometry of a jet of speed  $v_j$  colliding with plasma from the IGM of speed  $v_h$ . The hot spot abuts the jet and is behind the bow shock.