VLBI and Blazars (and other AGN): What have we learned?

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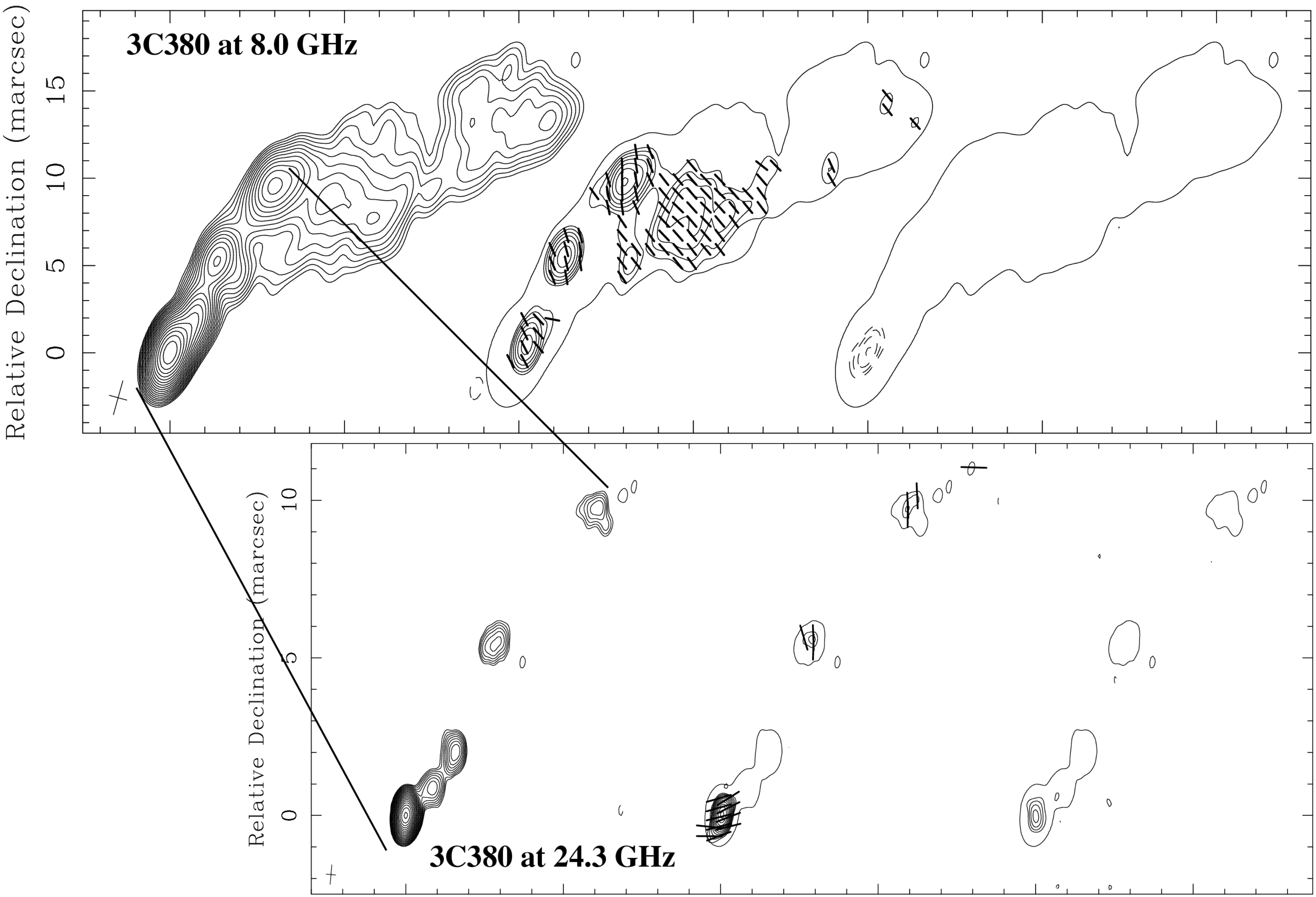
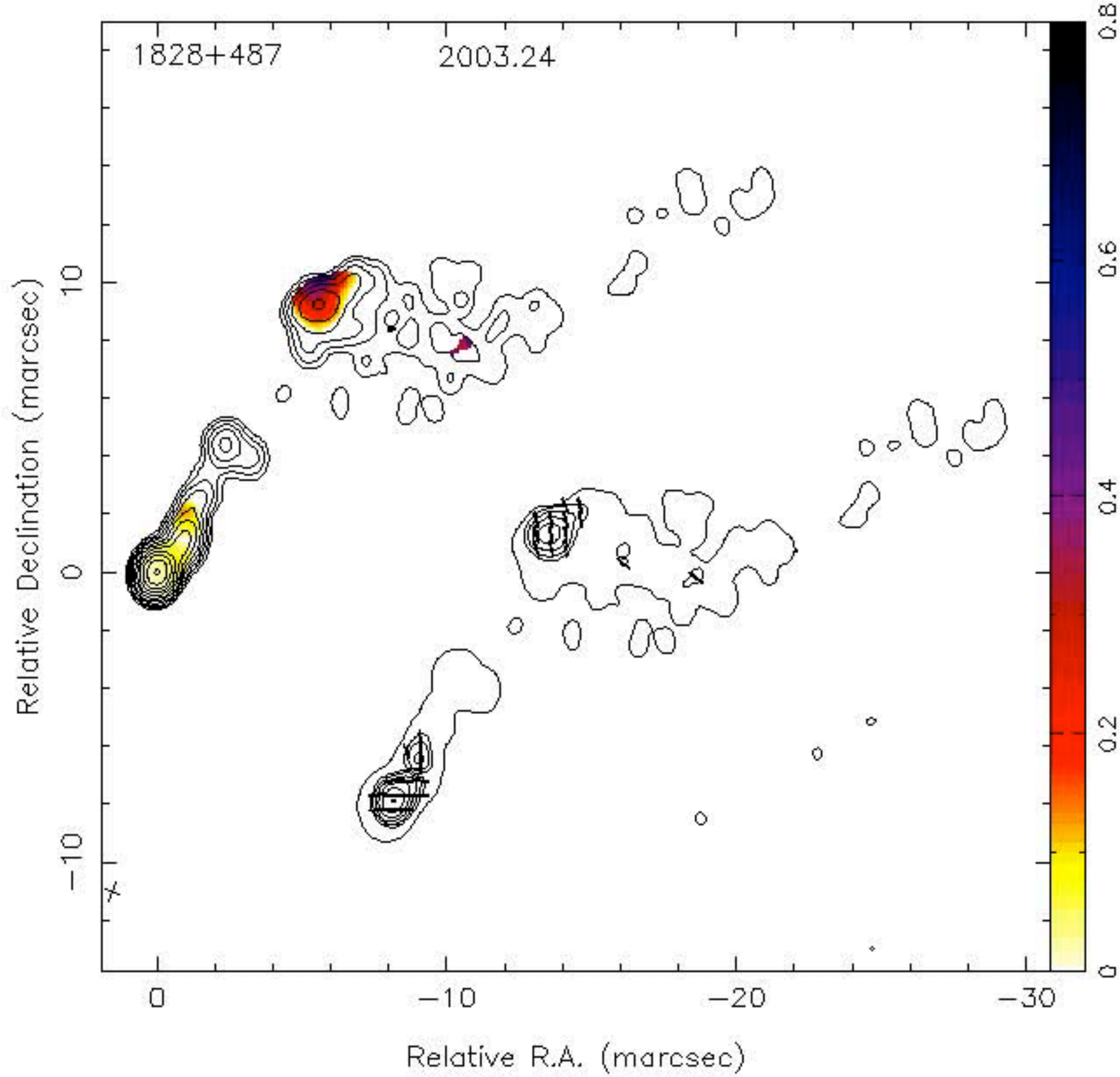
What Can VLBI Tell Us?



3C380, z=0.692, Epoch = Nov. 2005 1 mas = 7 pc

3C380: 15.4 GHz from MOJAVE Program. Speeds up to 13c (Lister et al., in prep.)



What do we want to know?

- What are the basic intrinsic properties of Jets?
  - Bulk Lorentz factor

$$\Gamma = \frac{1}{\sqrt{1-\beta^2}}$$

  - Intrinsic Luminosity, L_{int}
  - Intrinsic Brightness Temperature, T_{int}
  - Energy budget of Jet
    - Bulk K.E.
    - Particle vs. Field Energy

What do we want to know?

- Other questions
  - How are jets accelerated/collimated?
  - How do jets interact with their environment?
  - Shocks in Jets
    - Role in Gamma-Ray emission?
    - How are they formed/propagate?
    - Sites of active conversion of bulk K.E. into particle/field energy
    - Standing shocks at the base of jet?
  - What is the transverse structure of jets?
  - B-Field structure and Particle population of Jets

Relativistic Complications

- Jets are fast ($\Gamma > 1$) and close to our line of sight
  - Apparent Speed: $$\beta_{app} = \frac{\beta \sin\theta}{1 - \beta\cos\theta}$$

$$\beta_{app\_\max} \approx \Gamma$$ when $$\theta = \Gamma^{-1}$$

  - Doppler Beaming: $$\delta = \frac{1}{\Gamma(1 - \beta \cos\theta)}$$
    - Observed Luminosity $$L_{obs} = L_{\text{int}}\delta^{n+\alpha}$$ n = 2, 3
    - Observe Brightness Temp. $$T_{obs} = T_{\text{int}}\delta$$

Distributions of Observed Speeds

- EGRET Blazars ($\lambda\lambda$ 0.7cm, 1.3cm) (Jorstad et al. 2001)
  - 33 Jets – Distribution peaks at ~ 12c with a tail up to ~ 40c
- 2cm Survey (Kellermann et al. 2004) – 110 jets
  - Most speeds range from 0 – 15c with a tail up to 34c
- RRFID analysis (λ = 4 cm) (Piner et al. 2007) – 54 jets
  - Consistent with 2 cm Survey with tail up to 30c
- CJ Survey (λ = 6 cm) (Vermeulen et al. 2003) – 262 jets
  - Most speeds range from ~ 0 – 11c with a tail up to ~22c

All 'converted' to use ~ H_0 = 70 km/s/Mpc, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$

Lessons from Speed Distributions?

- Many jets have $\beta_{app} > 10$ → $\Gamma > 10$ are common
- Max observed Speed ~ Maximum Γ

  (e.g. Lister & Marscher 1997)

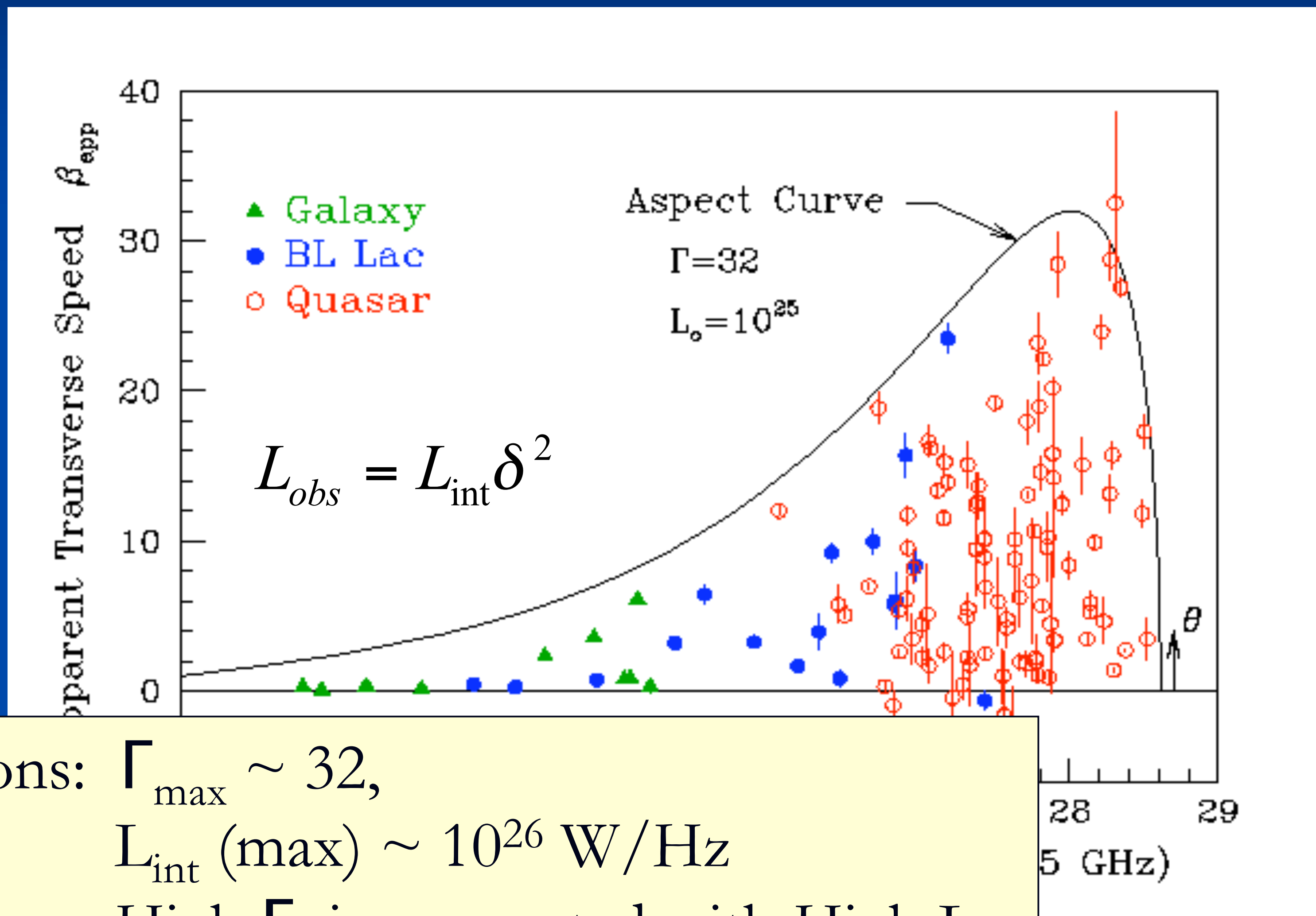
  → $\Gamma_{max} \sim 40$ for Blazar Jet Population

- Comparison with studies of individual components…

  Jorstad et al. (2005) estimated δ from fading times of components in 15 jets: δ and β_{app} → Γ
  - Found Γ ranged from 5 to 40
  - for most quasar components $\Gamma \sim 16$ -18

β_{app} vs Observed Luminosity

Cohen et al. 2007



Conclusions: $\Gamma_{max} \sim 32$,

L_{int} (max) $\sim 10^{26}$ W/Hz

High Γ is connected with High L_{int}

Observed Brightness Temps.

- For jet cores, T_{obs} measurements and limits range from 10^{11}K to 5 x 10^{13} K, a few > 10^{14} K

(Hirabayashi et al. 2000; Frey et al. 2000; Tingay et al 2001; Horiuchi et al. 2004; Kovalev et al. 2005)

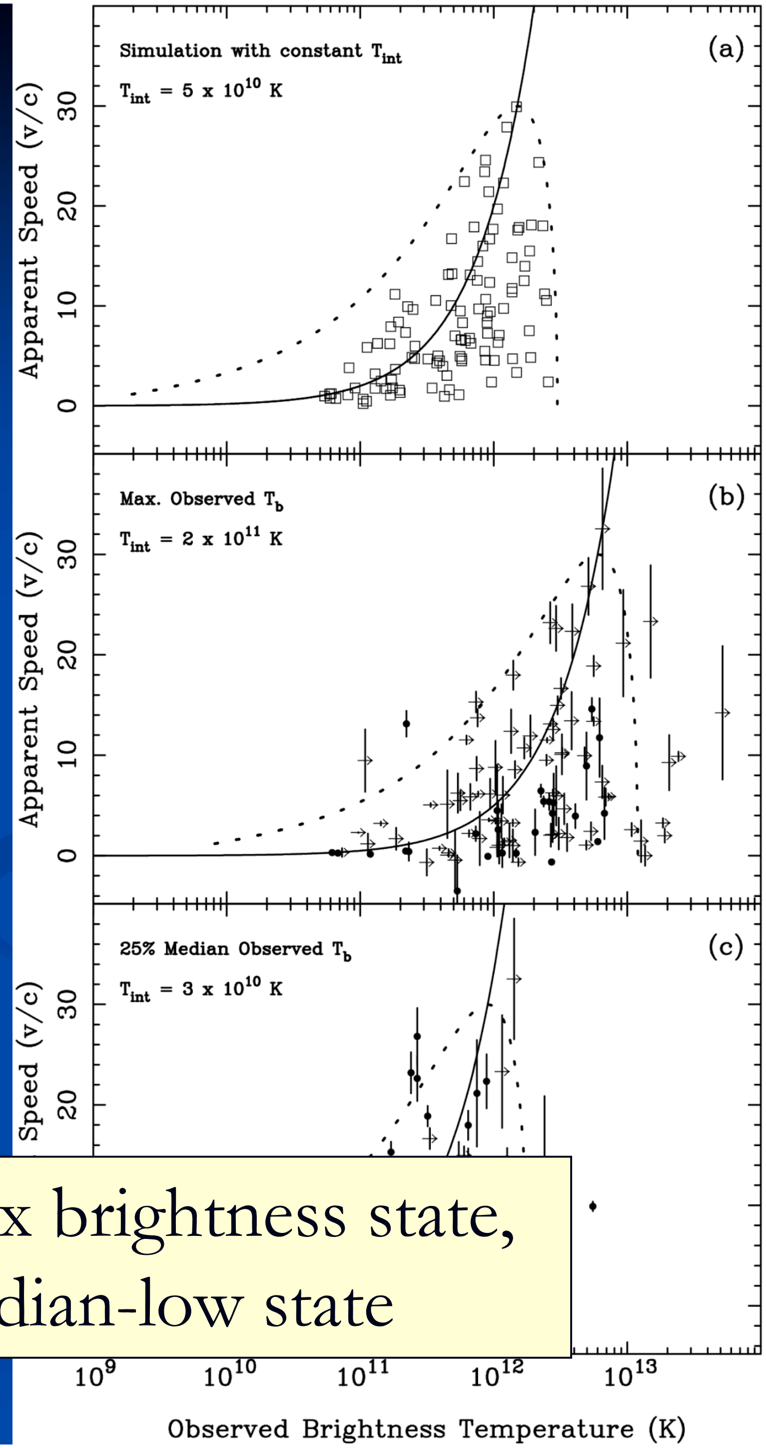
- Compare to the equipartition value of ~$10^{10.5}$ K (Readhead 1994) and the inverse compton limit of ~$10^{11.5}$ K (Kellermann & Pauliny-Toth 1969)

  → Doppler boosted observed values: $T_{obs} = T_{\mathrm{int}}\delta$

β_{app} vs Observed Brightness Temp

Homan et al. 2006

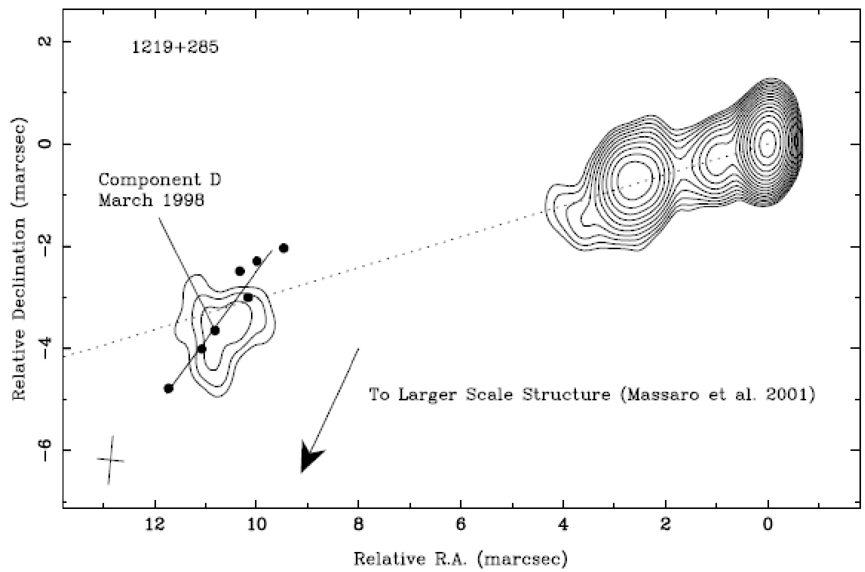
T_{obs} from Kovalev et al. 2005

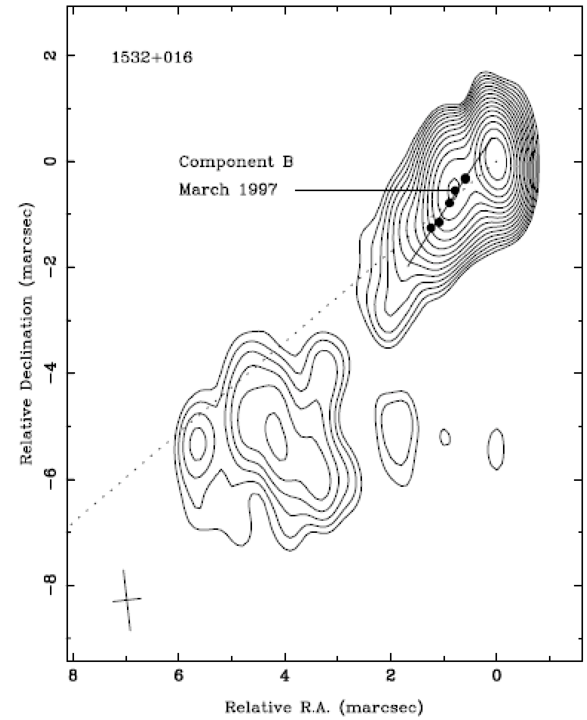


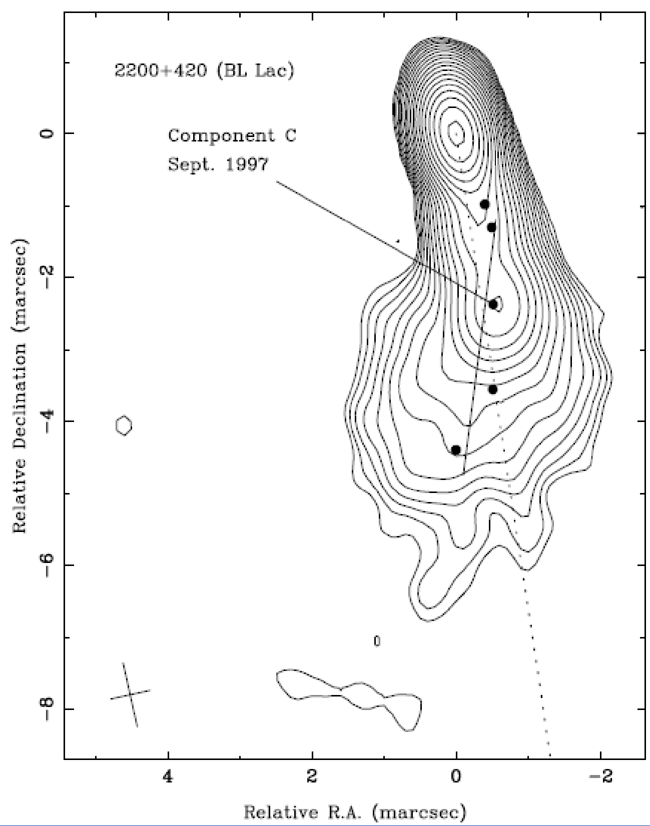
Conclusions: $T_{int} > 2 \times 10^{11}$ K in max brightness state,
$T_{int} \approx 3 \times 10^{10}$ K in median-low state

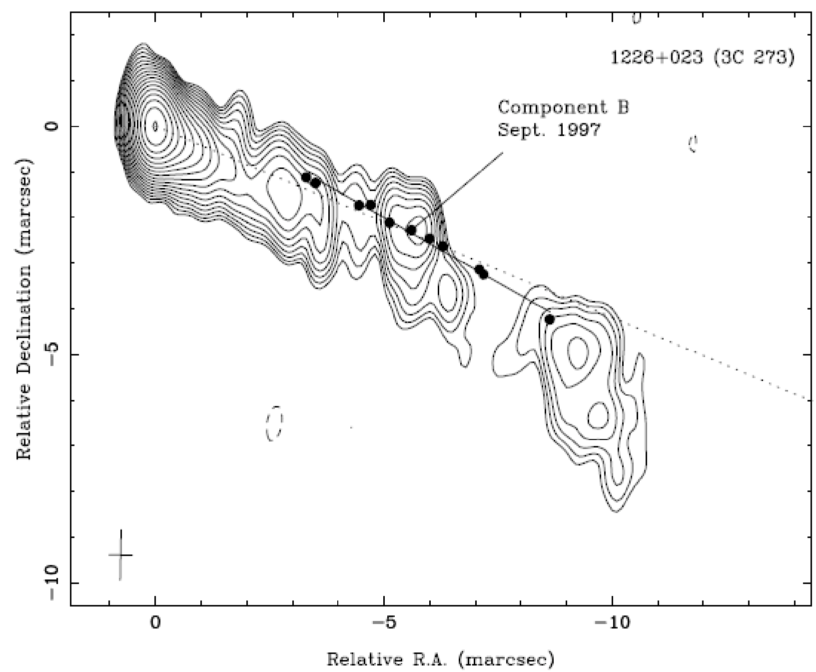
Jets aren't Straight

Kellermann et al. 2004







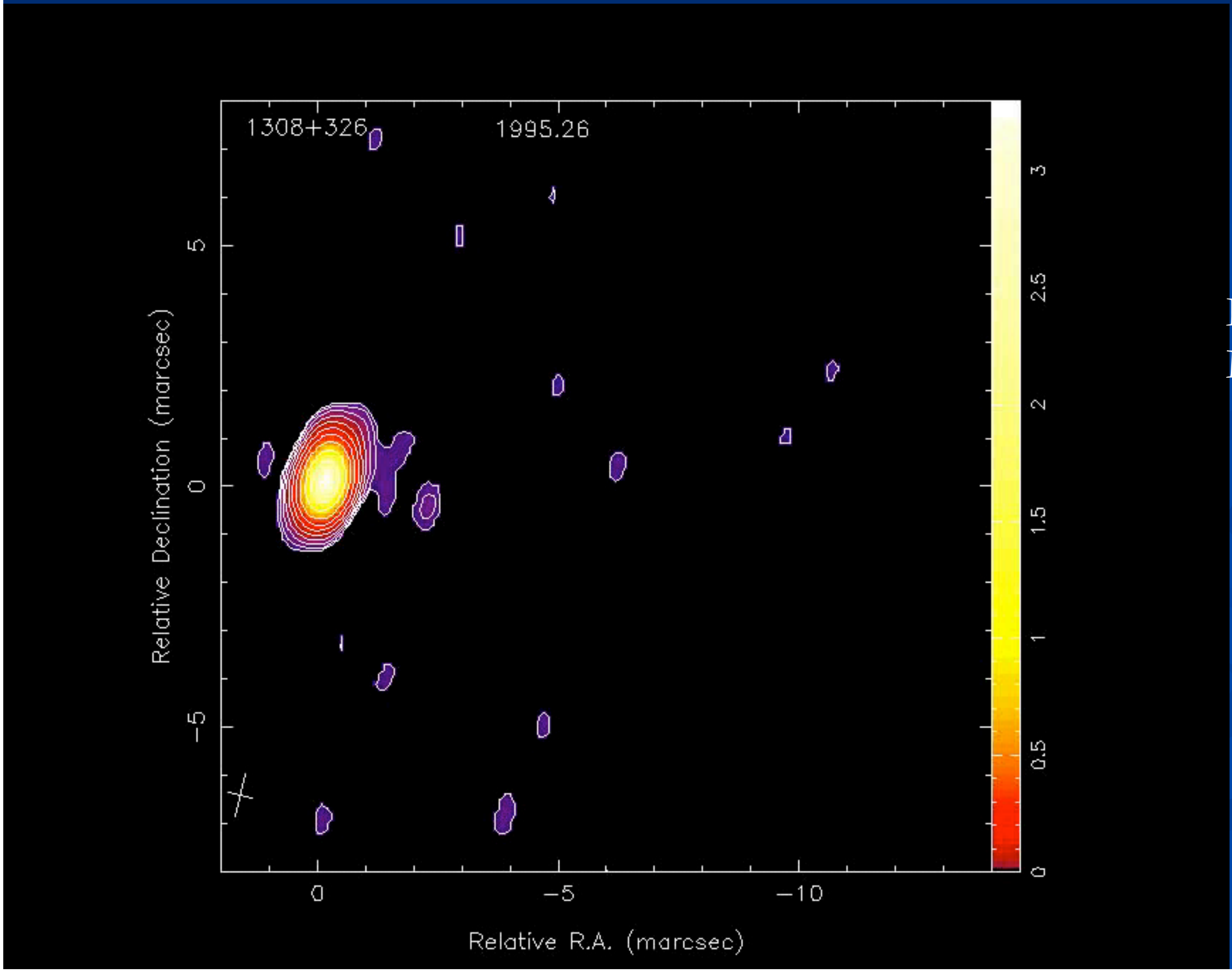


Non-Ballistic Motions

- ~1/3rd of features are moving “non-radially”
  (Kellermann et al. 2004; Piner et al. 2007)

- Tend to be in direction of next jet structure
  (Kellermann et al. 2004)
  → Motion along pre-determined channels?

Evidence for Ballistic Ejections

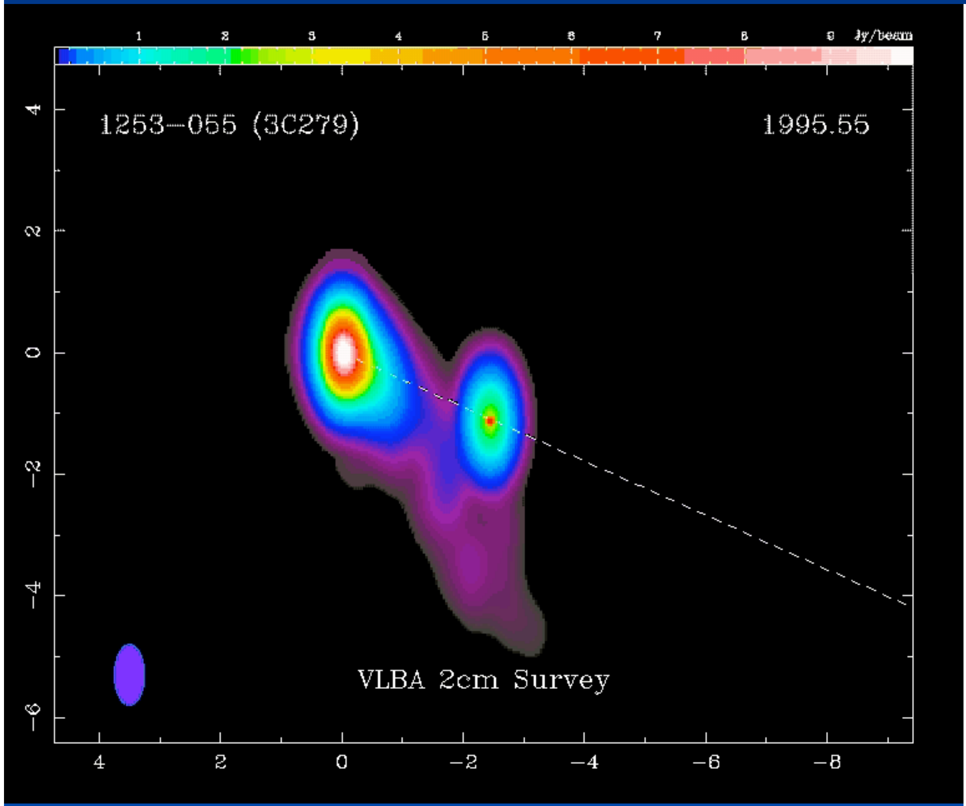


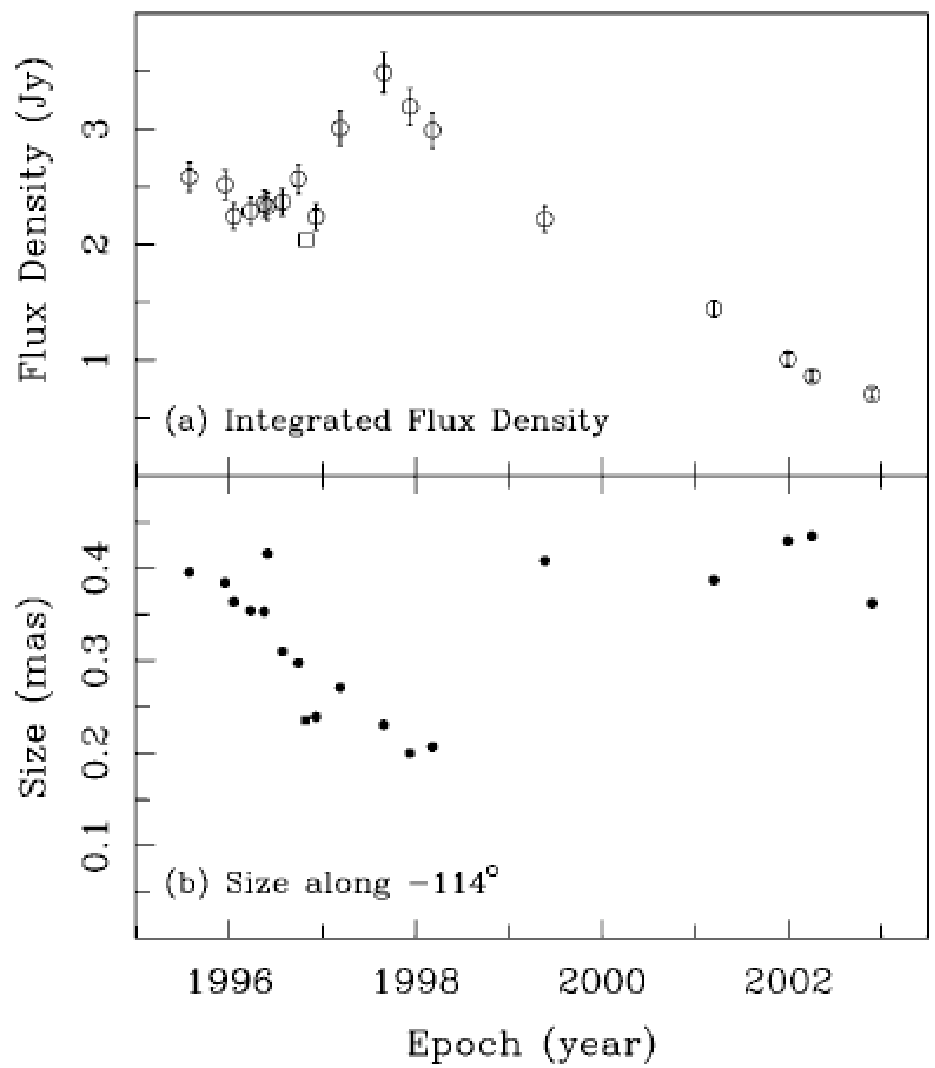
Lister et al, in prep.
MOJAVE program

Evidence for Multiple Ejection Angles

- 3C279 (Abraham & Cararra 1998, Wehrle et al. 2001, Jorstad et al. 2004), 3C345 (Caproni & Abraham 2004, Lobanov & Roland 2005), BL Lac (Stirling et al. 2003)
  - Precession?
- How do the jets become collimated further out?
  - Bends to give observed non-radial motions?

Caught in a Bend!





- A collimation event at > 1

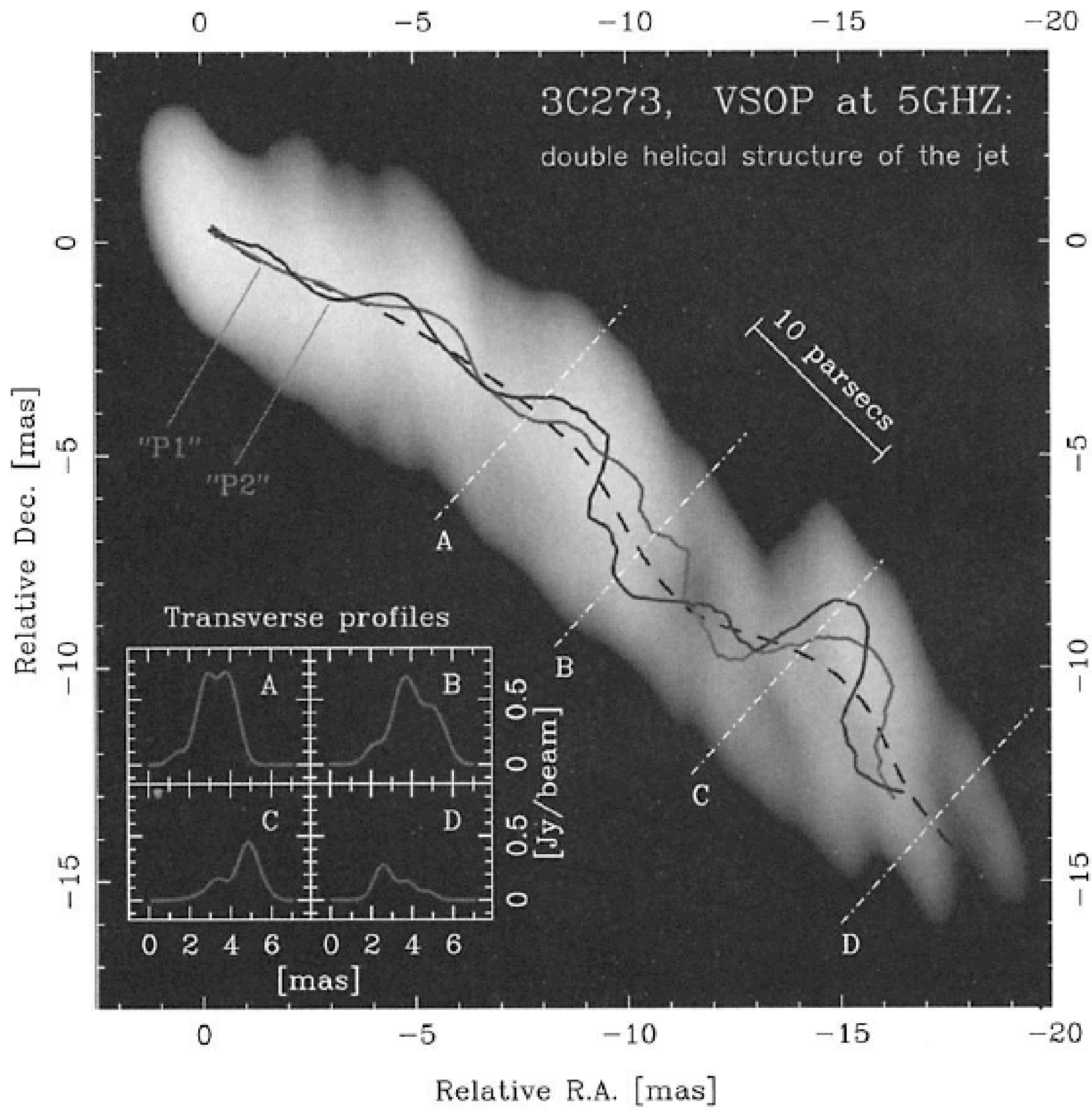
Acceleration of Jet Components?

- Contradictory Evidence
  - → Some indications of acceleration along jet
    (e.g. Hough et al. 1996; Unwin et al. 1997;
    Homan et al. 2001; Jorstad et al. 2005)
  - → But the fastest motions are observed at the highest frequencies which probe closest to jet "core"…
    (e.g. Jorstad et al. 2001; Kellermann et al. 2004)

Transverse Structure of Jets

Lobanov & Zensus (2001)

- Double Helical Structure in 3C273?
  - Consistent with K-H plasma instabilities



VLBI Polarization of Jets

- B-fields as a tracer of jet dynamics
  - Shocks, Shear, etc…
- 3-D field structures of jets?
  - Connection with SMBH/accretion disk system?
  - Do Jets carry a current?
- A probe of particle population in jets

Linear Polarization in Jets

- Fractional Polarization
  - Cores ~ few percent up to 10%
  - Jet features ~ 5-10% up to a few tens of percent

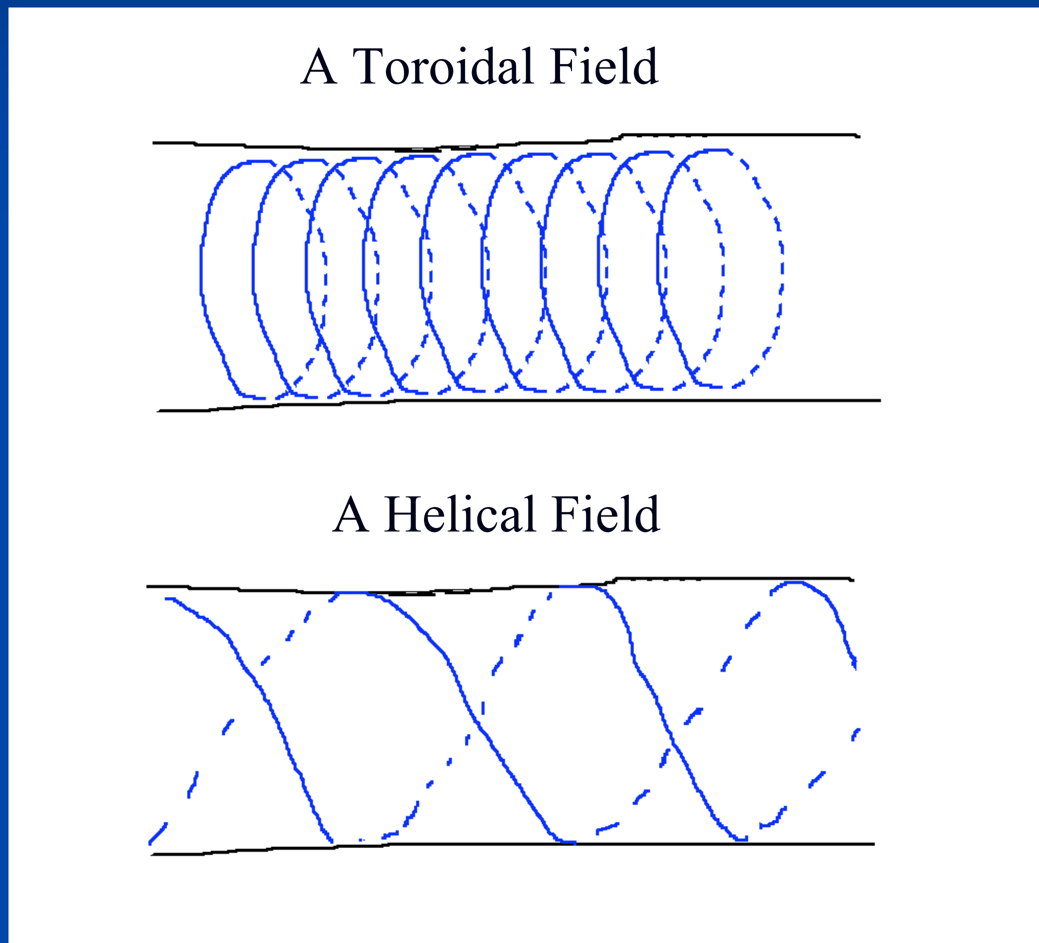
  - EGRET detected jets and jet components have higher average fractional polarization than non-EGRET jets

    (Lister & Homan 2005)
  - Also have brighter jet components by ~ x 2 (Lister & Homan)

  → Both related to higher Doppler factors for EGRET jets?

  → OR both related to stronger shocks in EGRET jets?

Possible Field Order in Jets



Evidence for Helical/Toriodal Fields

- Gradients in Faraday Rotation Across Jets…

  (Asada et al. 2002; Gabuzda et al. 2004; Zavala & Taylor 2005; Attridge et al. 2006)

  - Due to Toroidal field structures within jets or in a boundary layer surrounding them?

- Jets with long sections of transverse B-field
  - 1803+784 (Gabuzda 1999)

- If Toroidal Fields → jets carry a current

Tracing Jet Hydrodynamics

VLBA 22 GHz Observations

of

3C120

José-Luis Gómez	*IAA (Spain)*
Alan P. Marscher	*BU (USA)*
Antonio Alberdi	*IAA (Spain)*
Svetlana Marchenko-Jorstad	*BU (USA)*
Cristina García-Miró	*IAA (Spain)*

So what have we learned (from VLBI)?

- Apparent Speeds of jets range up to 30-40
  → Maximum Γ ~ 40 in jets
- Apparent speeds of jet features are connected with jet luminosity and brightness temp.
  - Through Doppler factor (?)
    → Can extract intrinsic values for L and T
- EGRET detected jets….
  - Are faster (?)
  - Are more compact (Kovalev et al. 2005)
  - Have brighter jet components with more polarization
  → Greater Γ, more favorable angle to l.o.s.? Both?

So what have we learned (from VLBI)?

- Jet structure and flow is complicated
  - Do (some) jets precess?
  - How are jets accelerated and collimated?
  - Will there be a connection between 'events' in jet features and Gamma-ray emission?
- Polarization data is rich and complicated
  - Do jets have Toroidal fields? Carry a current?
  - What can we learn about the particle population of jets?

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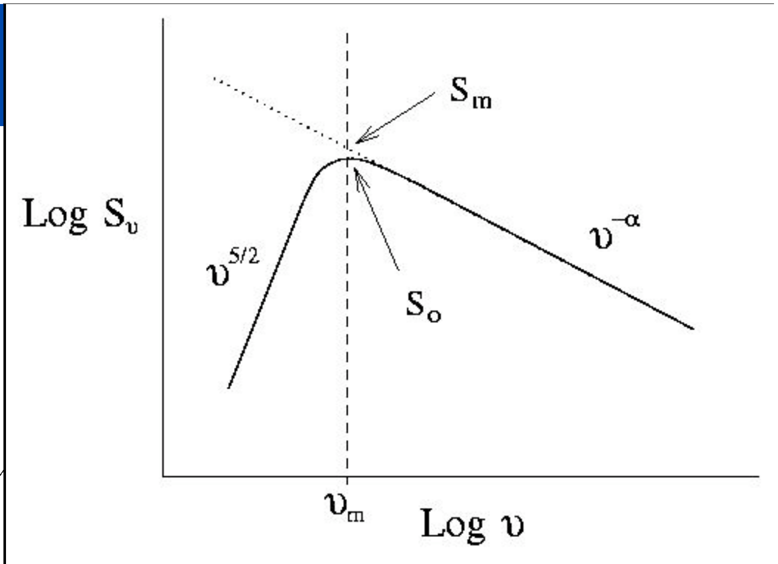
Power-Law Particle Distribution



What Happens He

We See These Particles

Gamma of Particles

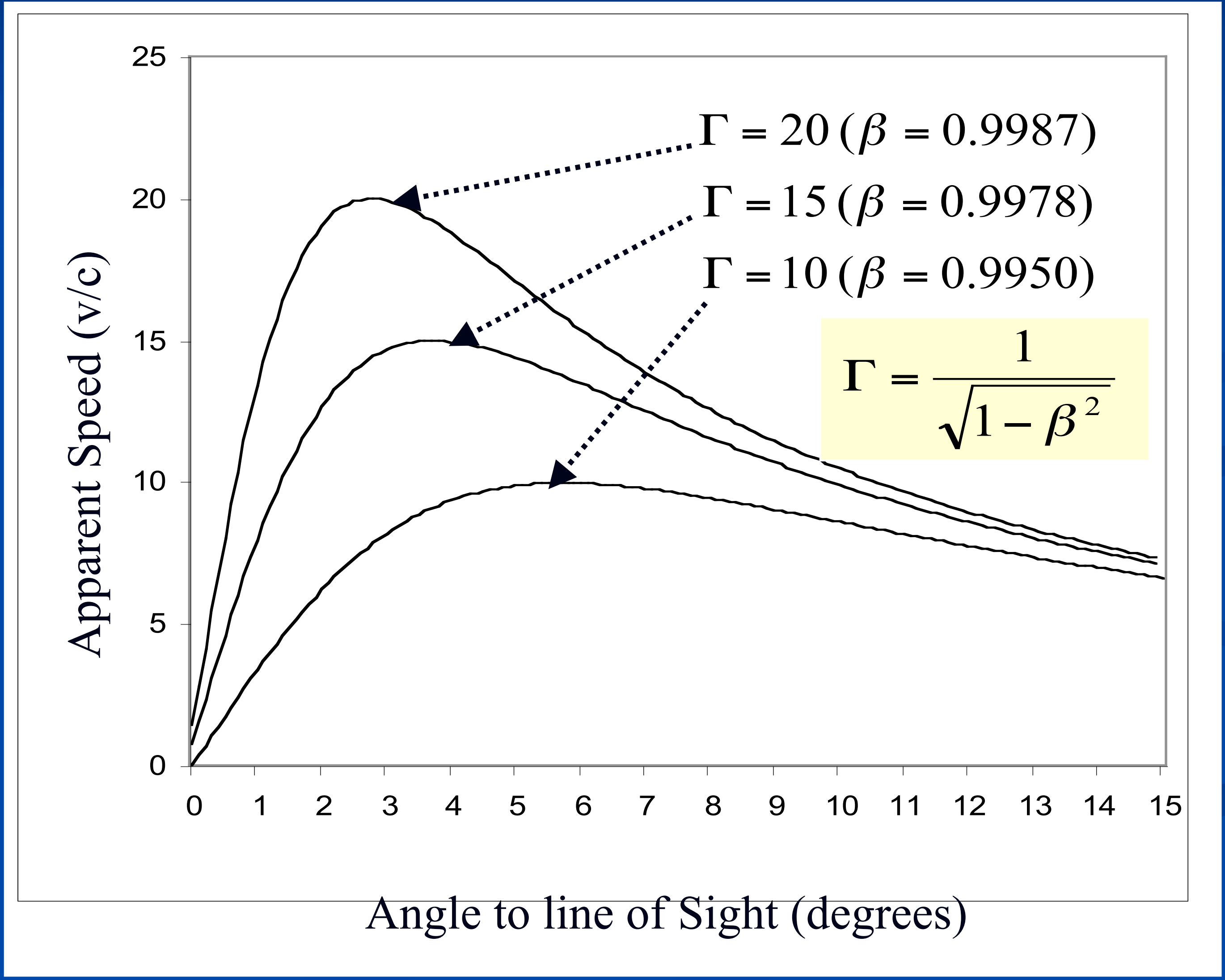
10

$$N_{total} \propto 1/\gamma_{min}^{2\alpha}$$

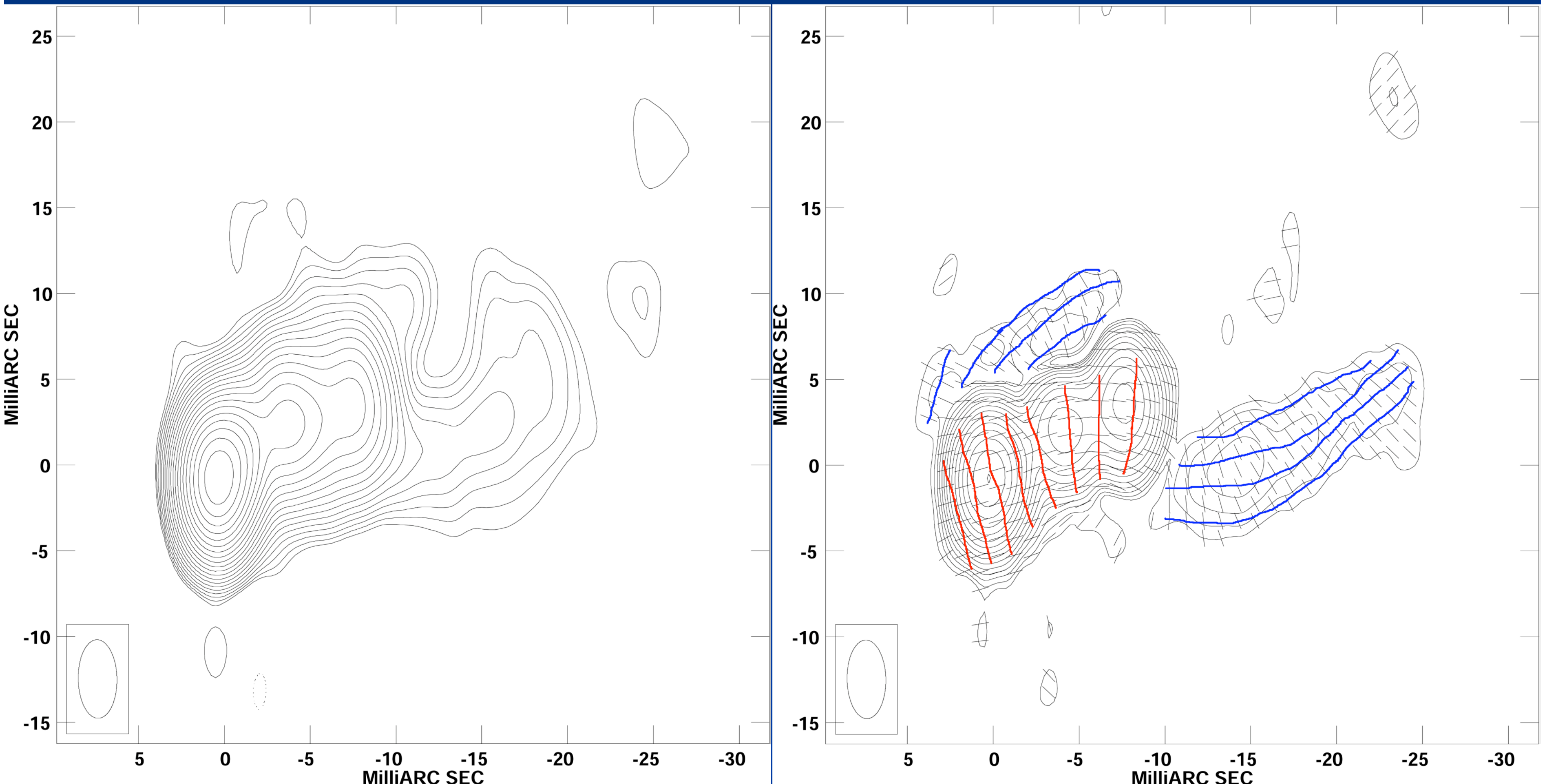
$$N_\gamma d\gamma = N_0 \gamma^{-(2\alpha+1)} d\gamma$$

Apparent Speed:

$$\beta_{app} = \frac{\beta \sin\theta}{1 - \beta\cos\theta}$$



Quasar 1055+018, λ = 6 cm



Attridge 1998; Attridge, Roberts, & Wardle 1999

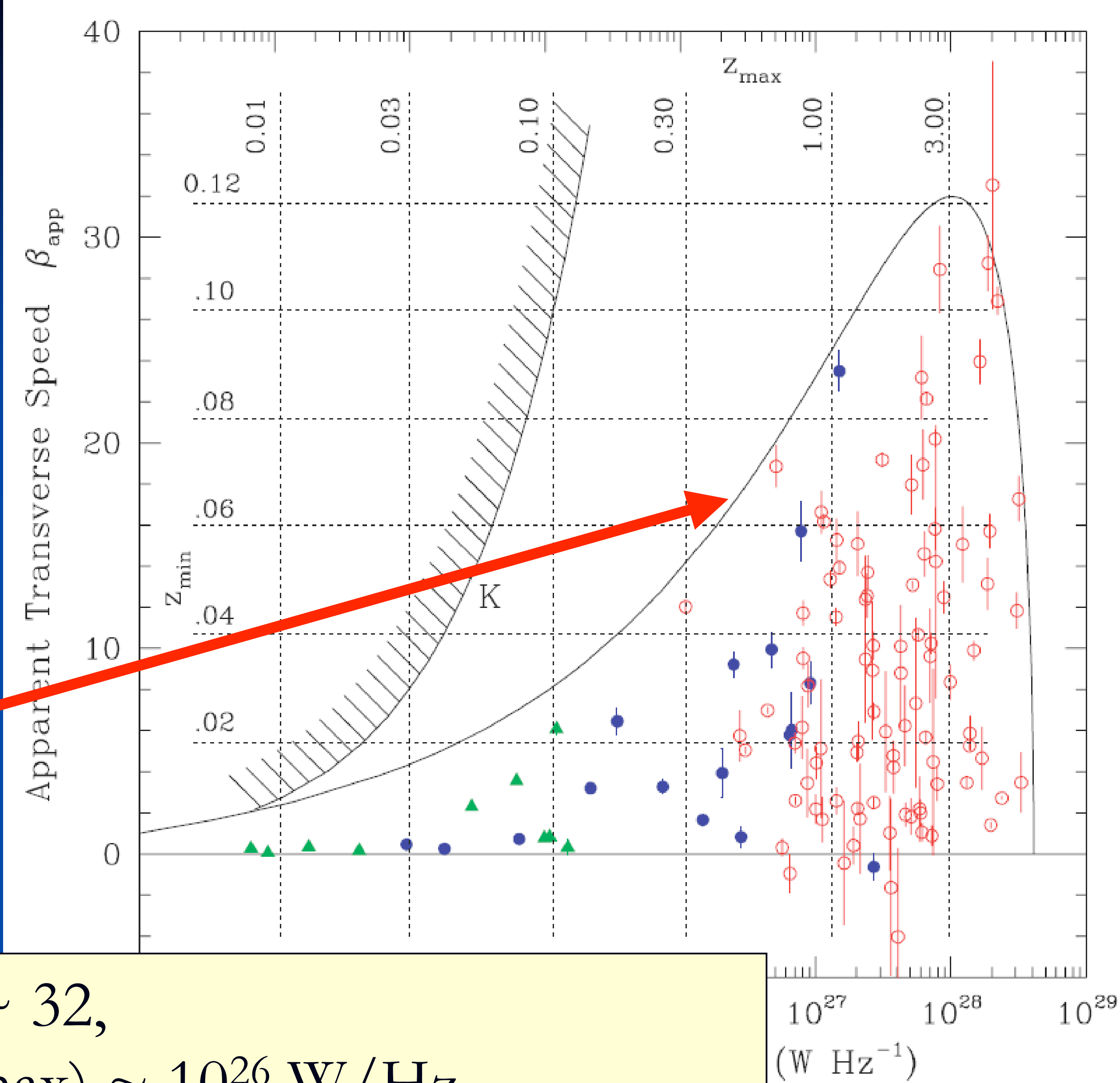
z = 0.889

β_{app} vs Observed Luminosity

Cohen et al. 2007

$$L_{obs} = L_{int}\delta^2$$

Aspect Curve
$\Gamma = 32$
$L_{int} = 10^{25}$ W/Hz



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