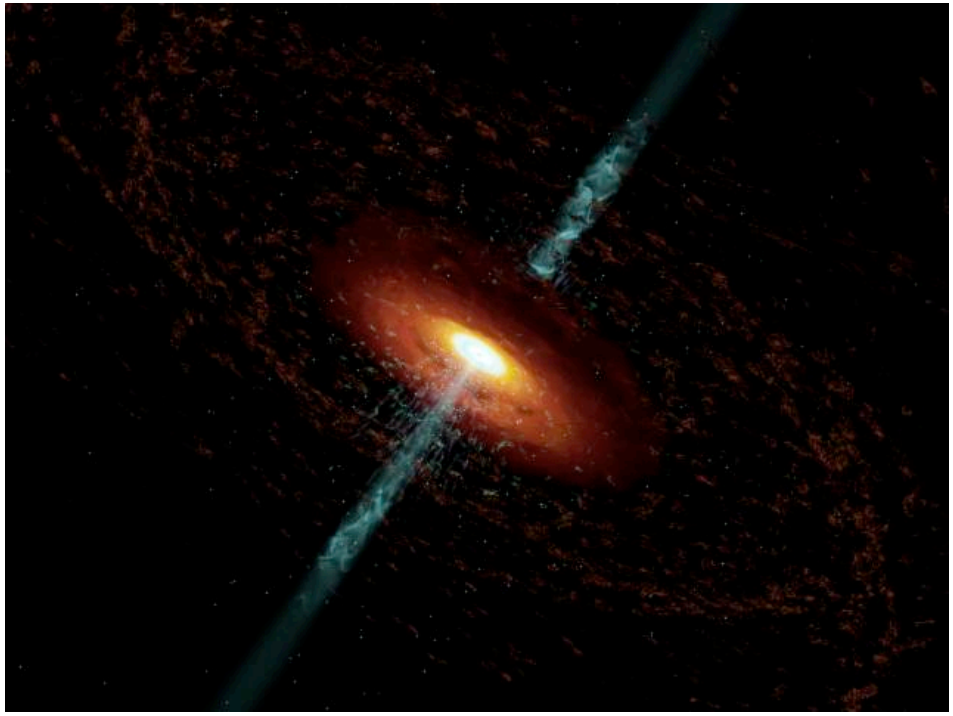


Jets from Black Holes in Quasars

Alan Marscher

Department of Astronomy, Boston University

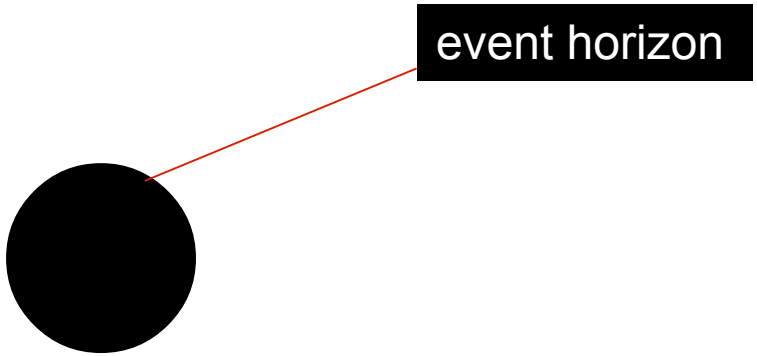
Research Web Page: www.bu.edu/blazars

Free downloads of songs: www.soundclick.com/cosmosii

BLACK HOLE

Gravity so strong that nothing - not even light - can escape from inside the boundary

→ event horizon

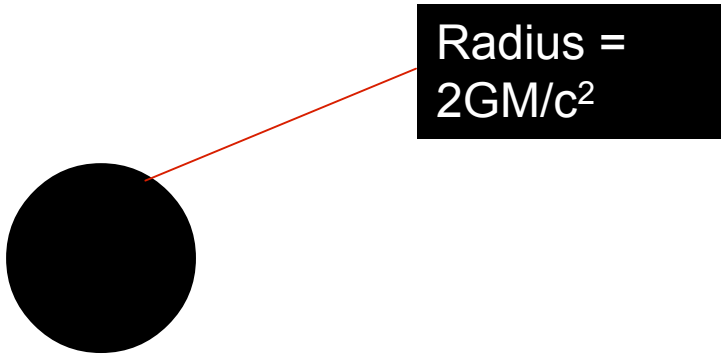


How big is a BLACK HOLE?
- Depends on its mass

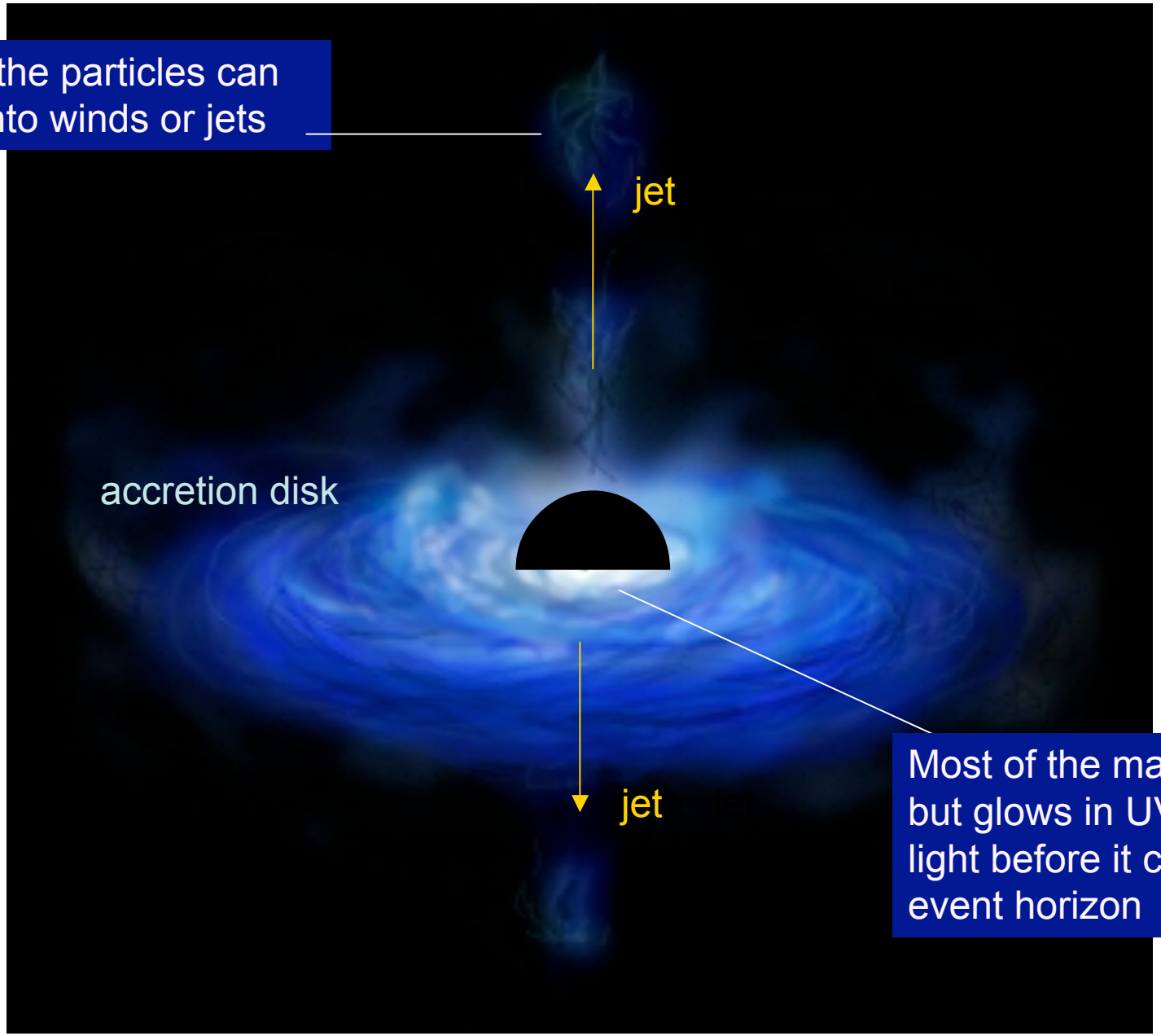
Human-mass black hole: much smaller than the nucleus of an atom

Black hole with sun's mass: 6 km (about the size of downtown)

1 billion times sun's mass: about the size of the solar system



ACCRETING BLACK HOLES ARE BRIGHT!



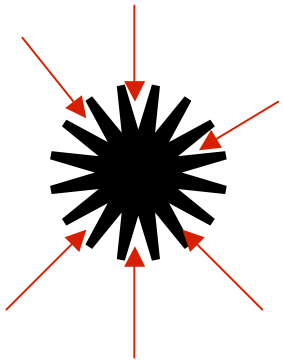
How Nature Makes BLACK HOLES

A star more than 10 or 20 times as massive as the sun uses up all of the nuclear fuel in its core

→ gravity contracts the star's core

Resistance is too weak to stop collapse

→ black hole forms



And then it just grows!

How many BLACK HOLES are there in our Galaxy?

Can estimate by number of very massive stars that have lived & died:

→ about 100 million!

Nearly all of them are starving

Don’t worry - there is a negligible chance that we’ll run into one for trillions of years

Black-hole Binary Star Systems

Most stars have companions (binary star)

If more massive one becomes a black hole, it can suck gas from its companion

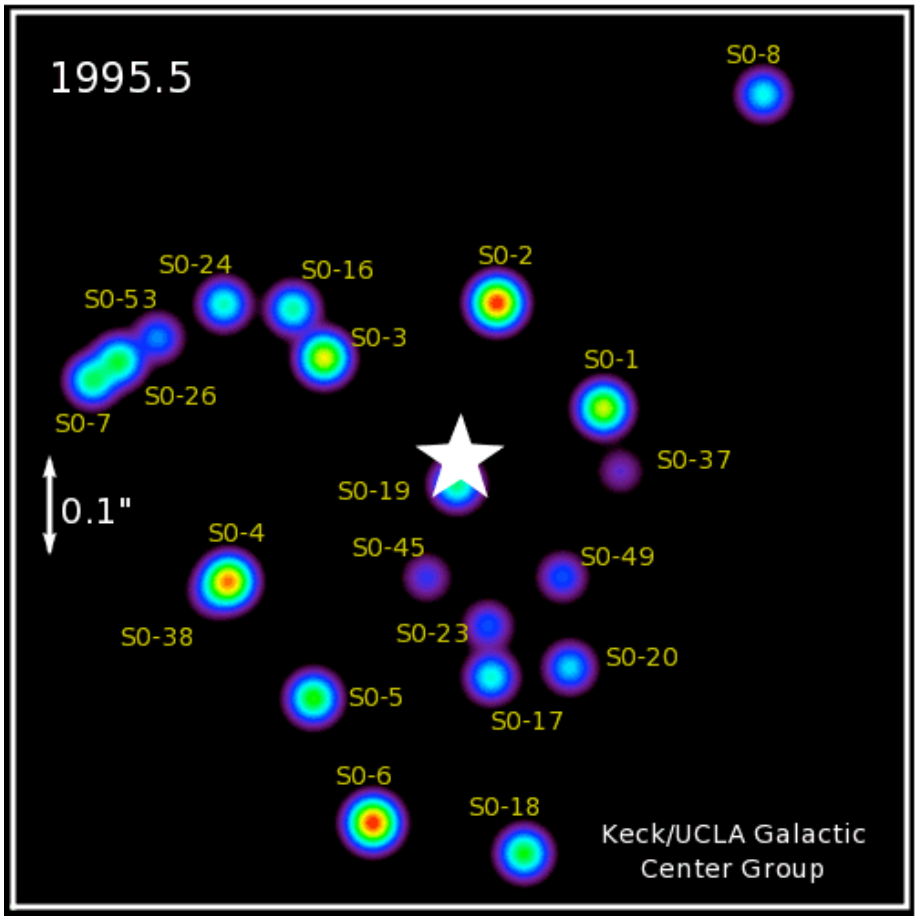
→ X-ray binary system

About 20 such systems known in our Galaxy, another 20 suspected

The Monster at the Center of Our Galaxy

Massive stars orbit a point in space in Sagittarius at center of Milky Way

→ Black hole 4 million times mass of the sun



Very little material is currently falling into the black hole

Otherwise, it would be a very luminous source of X-rays

View animation at
http://www.astro.ucla.edu/~ghezgroup/gc/pictures/orbitsMovie.shtml

Well-fed Monsters: Active Galaxies & Quasars

- **Ultraluminous nucleus of a galaxy**
- **Supermassive black hole being fed constantly**
- **Quasars are the most luminous variety**

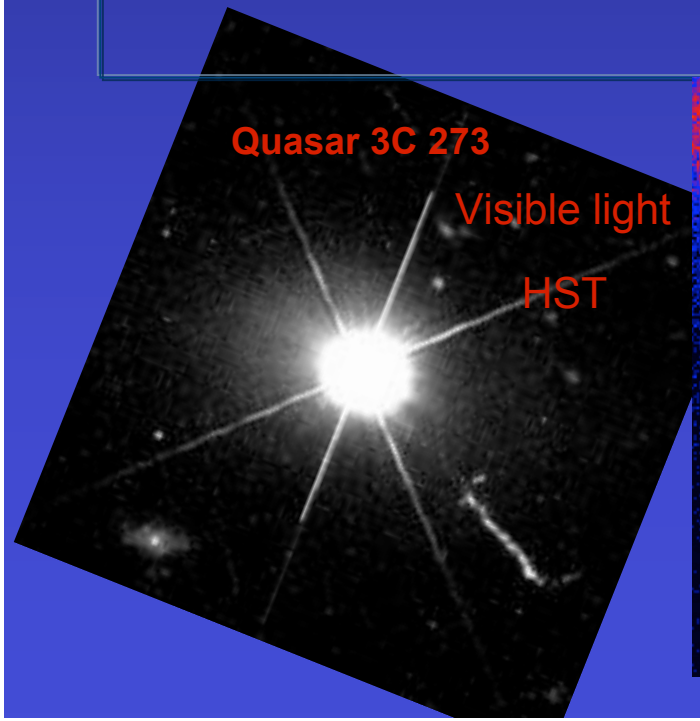
The radio galaxy 3C 120 (distance = 500 million light-years)

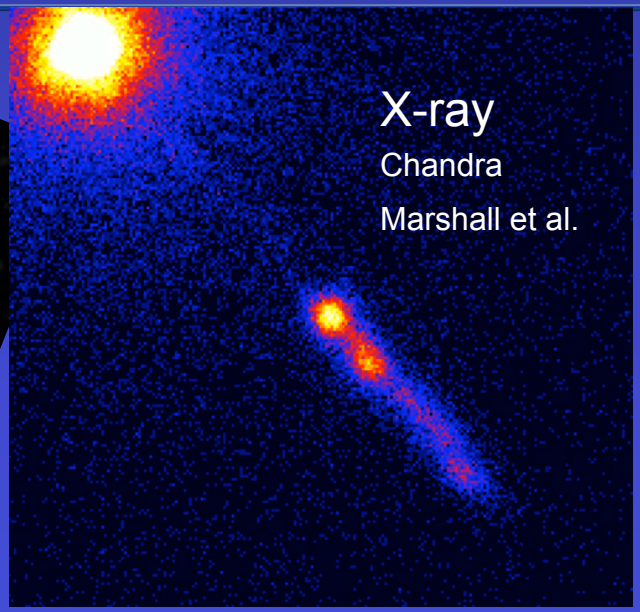
Hubble Space Telescope image (Harris & Cheung)

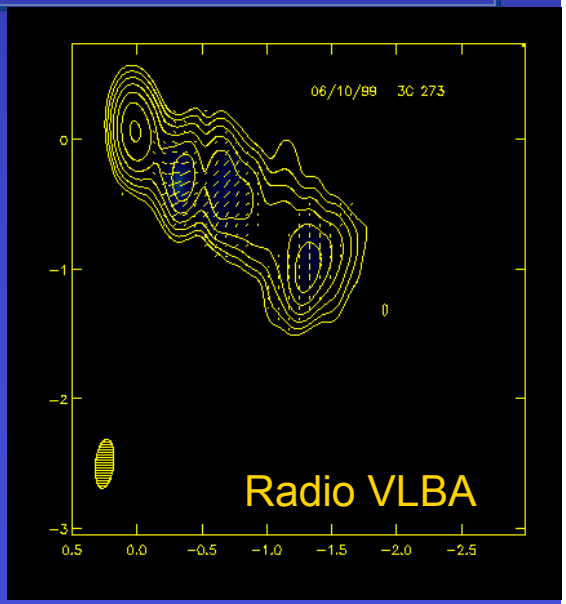
Blazars

Subclass (5-10%) of Quasars

- **Prominent jet of magnetized, ultra-hot gas (plasma)**
- **Flows out of nucleus at nearly the speed of light**
- **If jet points toward us, it beams radiation in our direction**
- **Jet is bright across entire electromagnetic spectrum**
- **Bright spots <u>appear</u> to move faster than light (illusion)**

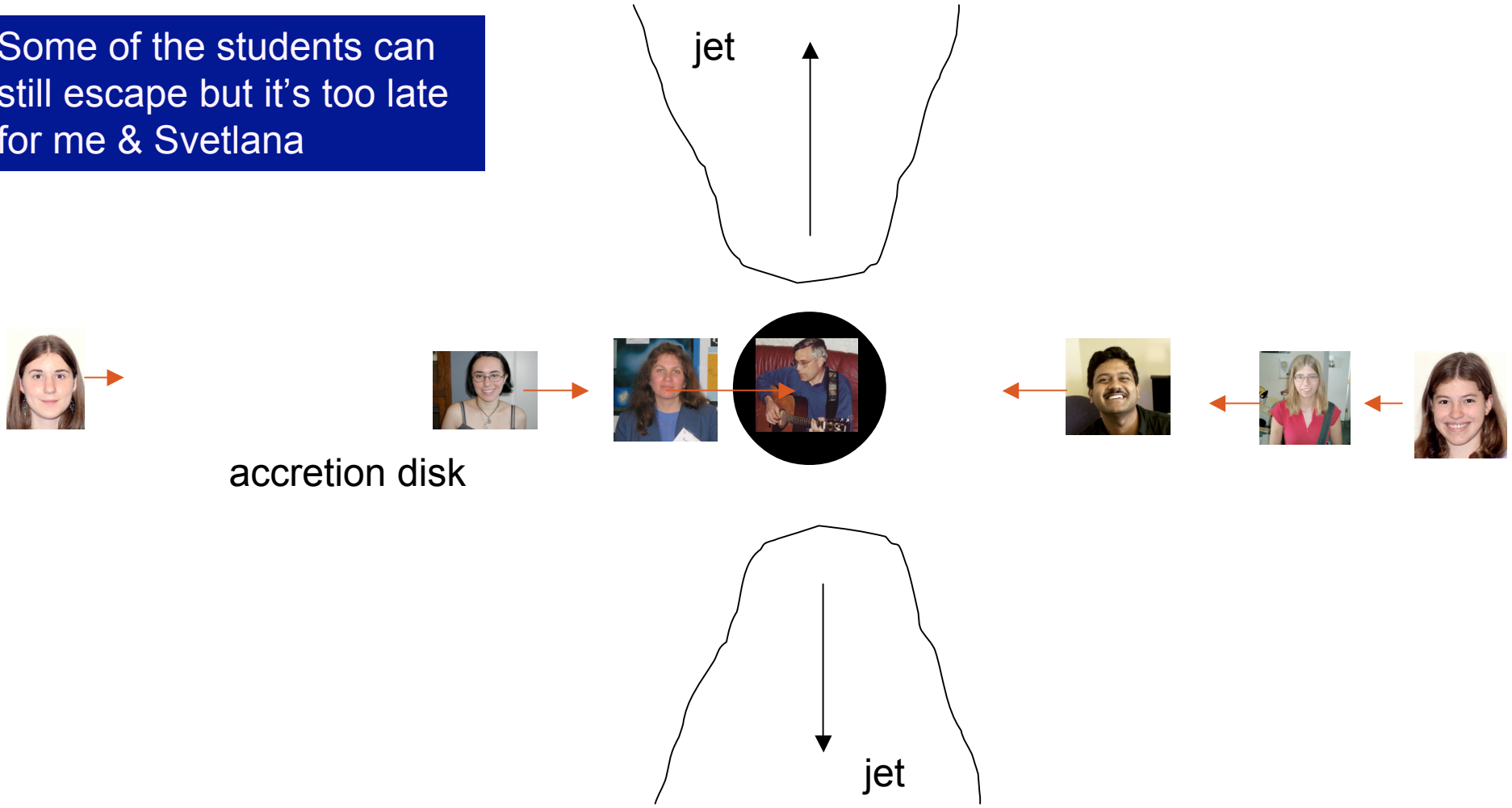






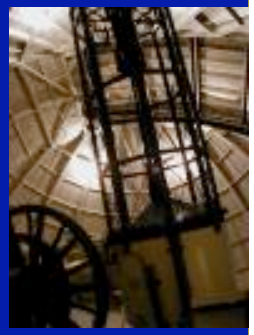
The Boston University Blazar Research Group

Some of the students can still escape but it's too late for me & Svetlana



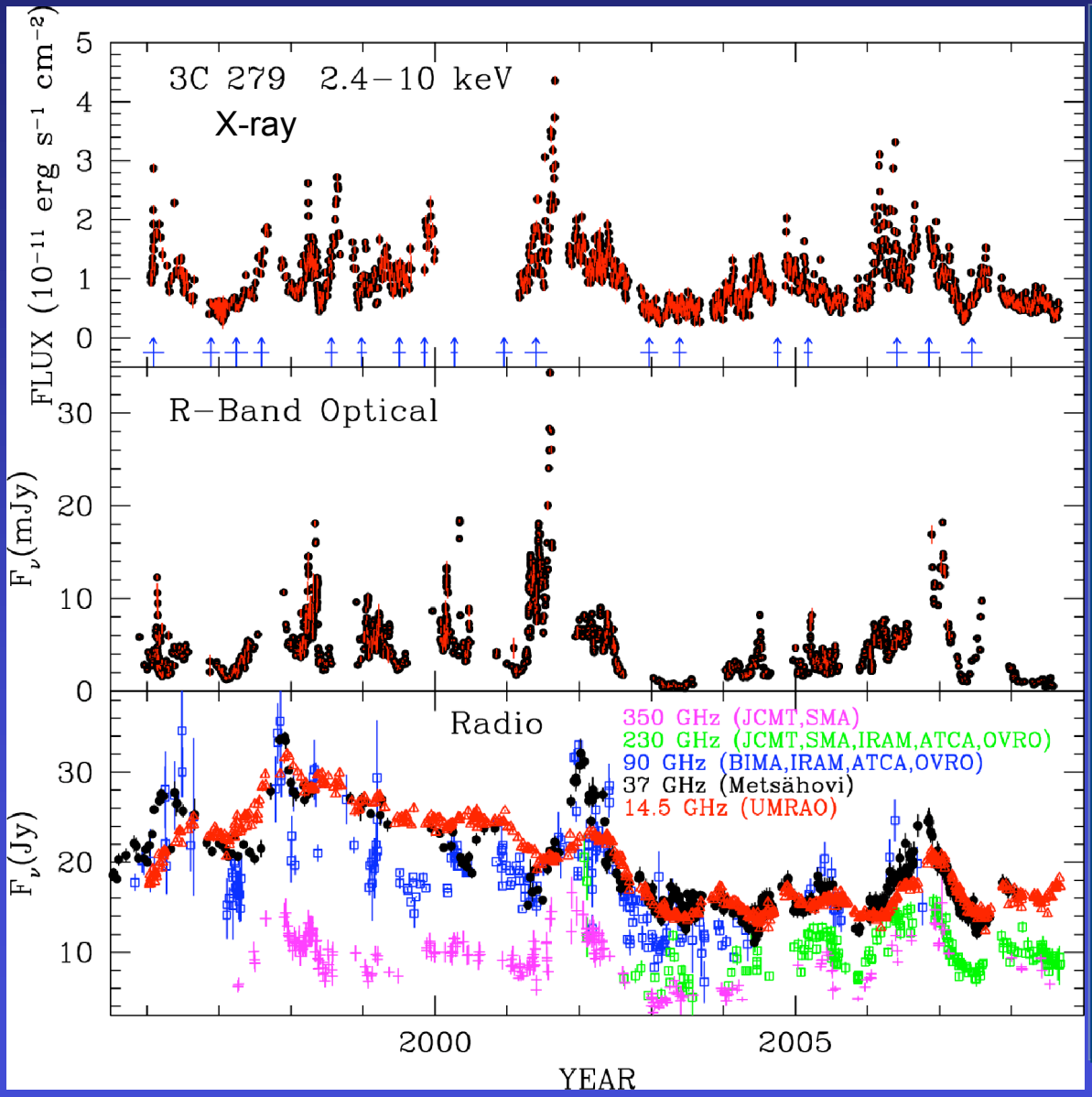
Telescopes We Use - Visible Light + Much More

Lowell Obs. Perkins Telescope (visible & infrared light)
Calar Alto 2.2 m telescope (visible light)
Liverpool Telescope (visible & infrared light)
Very Long Baseline Array (VLBA) (radio images)
Crimean Astrophysical Observatory 70 cm telescope
St. Petersburg (Russia) State University 0.4 m telescope
Rossi X-ray Timing Explorer, XMM-Newton, & Swift (X-rays)
Chandra (X-rays), Hubble (visible light), Spitzer (infrared light)
University of Michigan Radio Observatory
IRAM 30 m (microwaves)
Metsähovi Radio Observatory
Fermi Gamma-ray Space Telescope



VLBA

Blazars

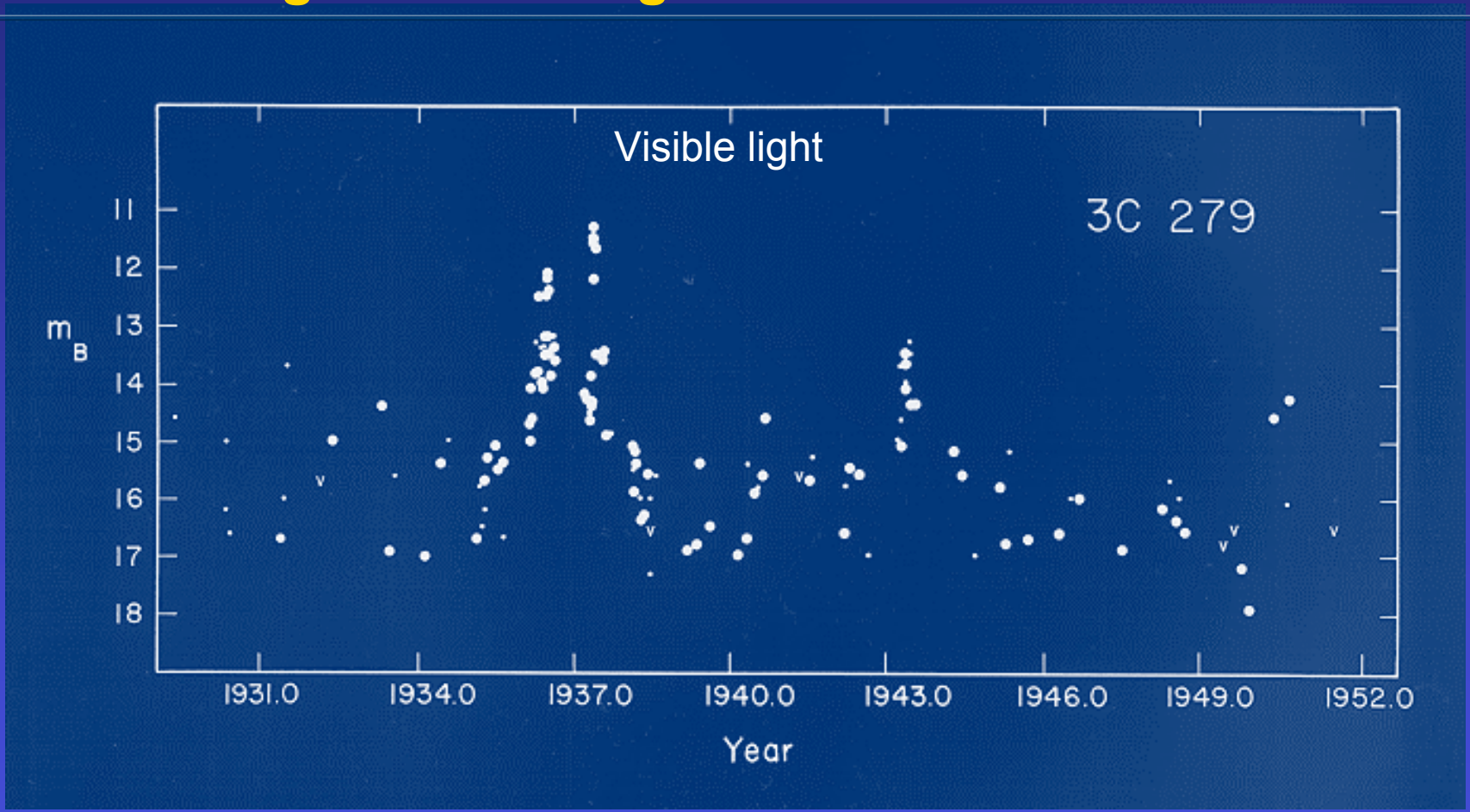


Rapidly changing brightness

Light from ultra-high energy electrons

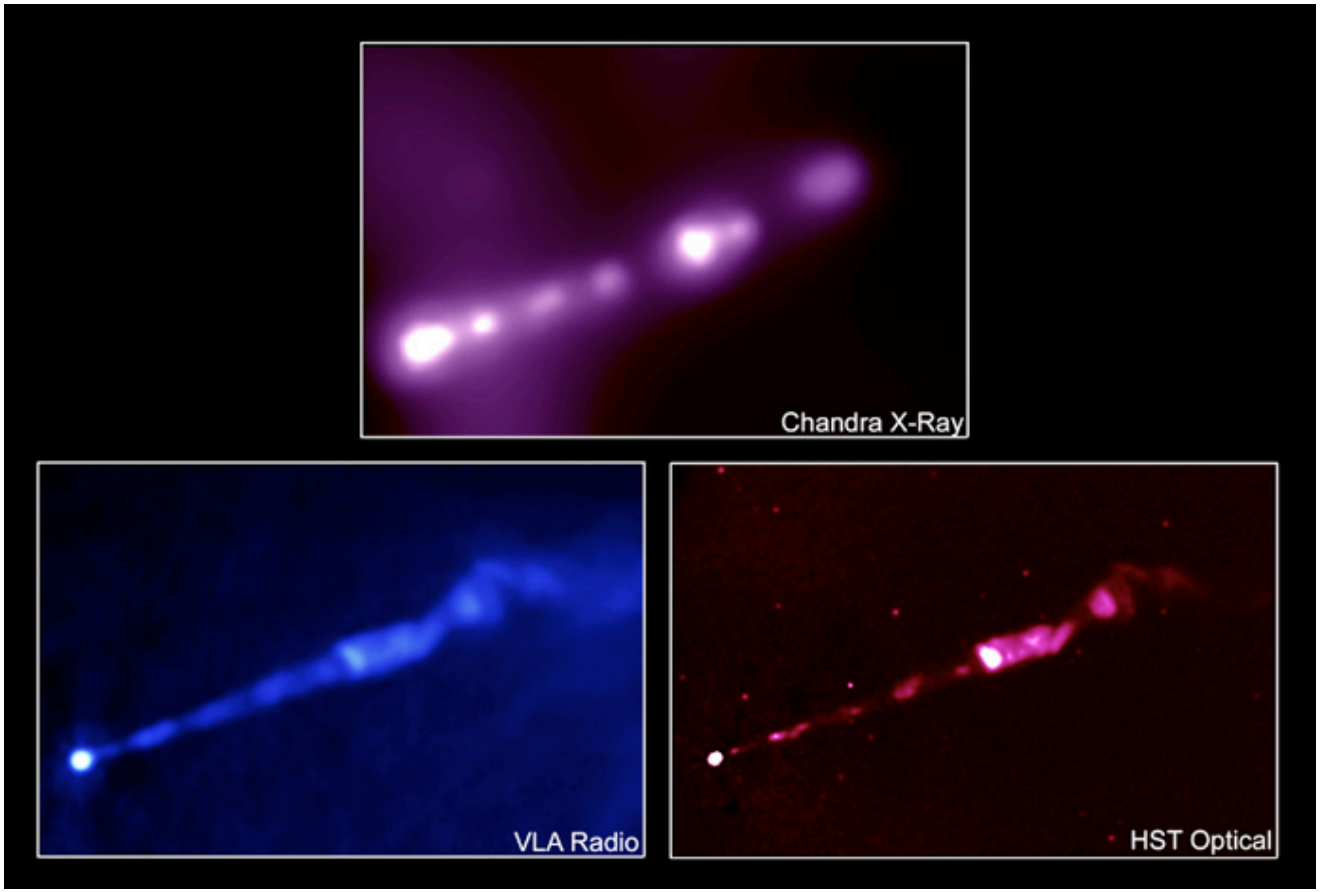
Blazars

Brightness changes over decades of time



The Jet in the Quasar-Like Galaxy M87

- **Hubble Space Telescope observations of motions of stars in nucleus: Black hole of 3×10^9 solar masses at center**



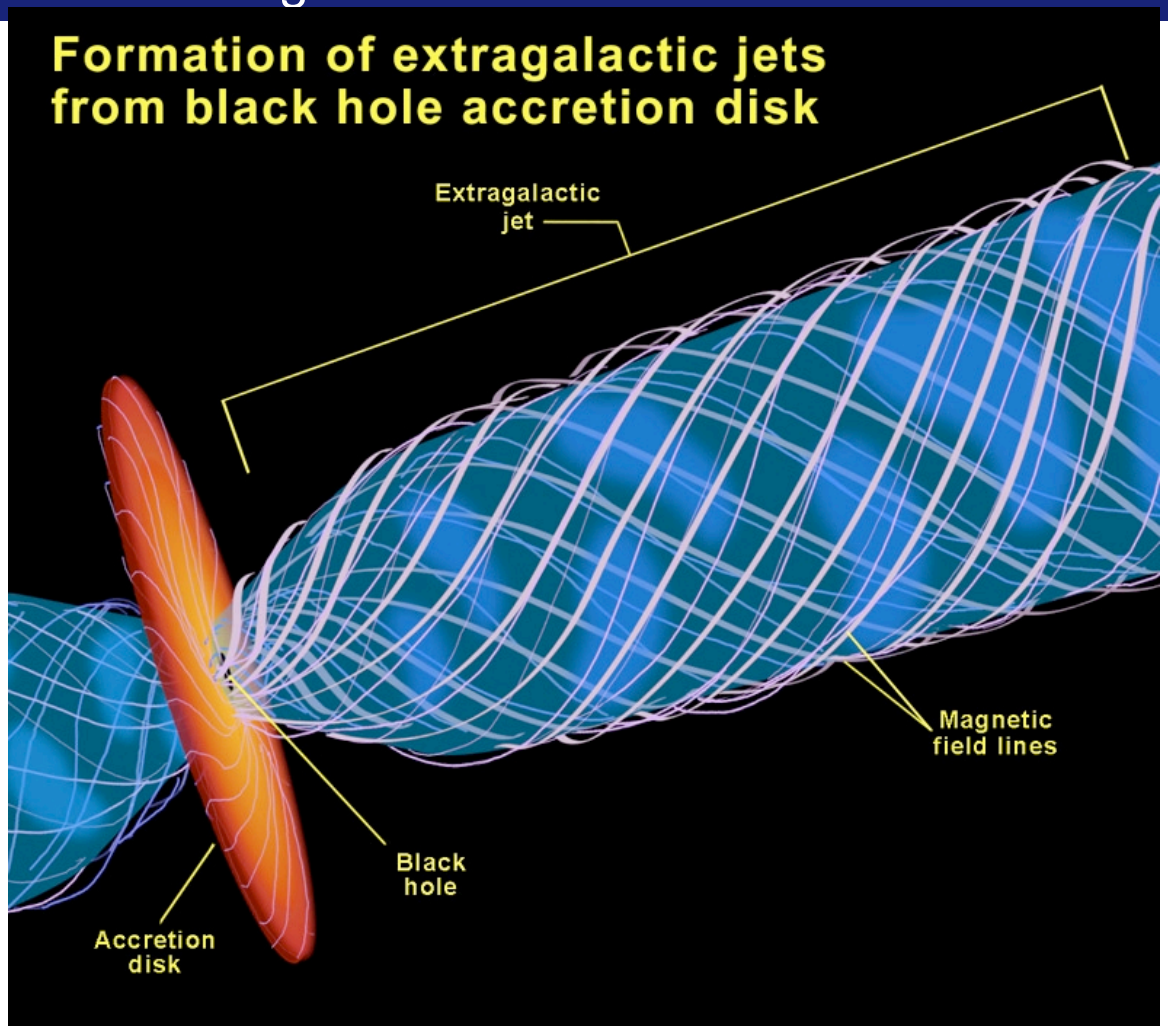
Goal: Probe jets as close to black hole as possible

Questions we want to answer:

How are jets accelerated to near the speed of light & focused?

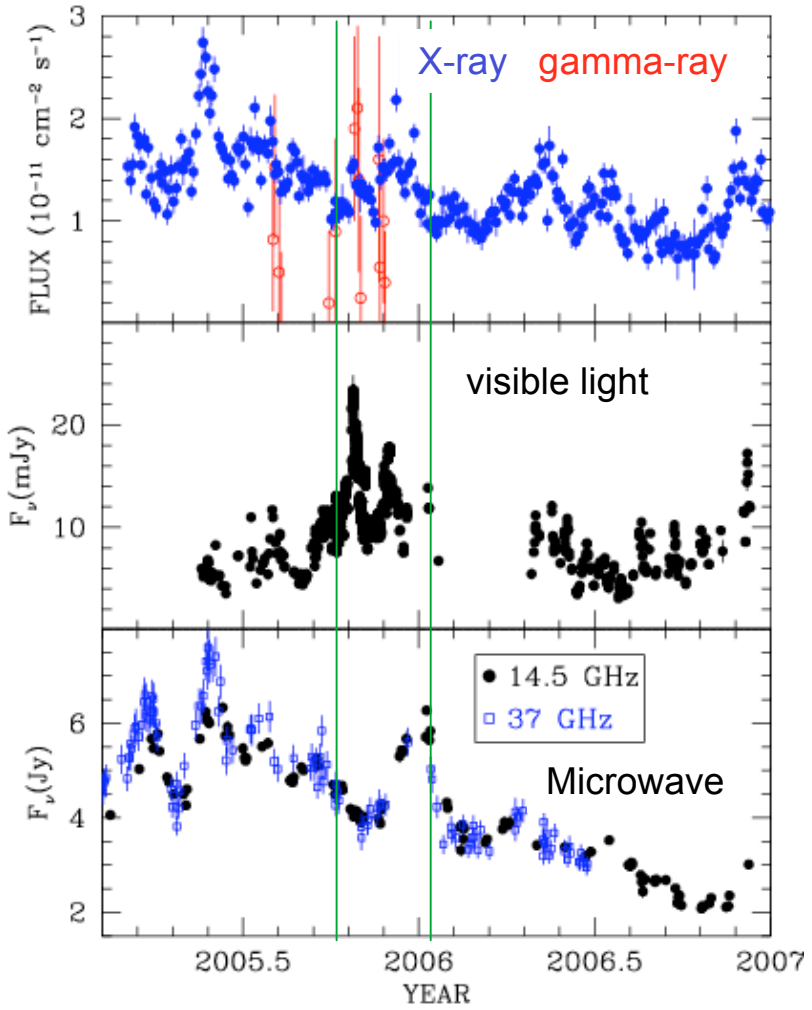
- Test theory that twisted magnetic fields propel the jets

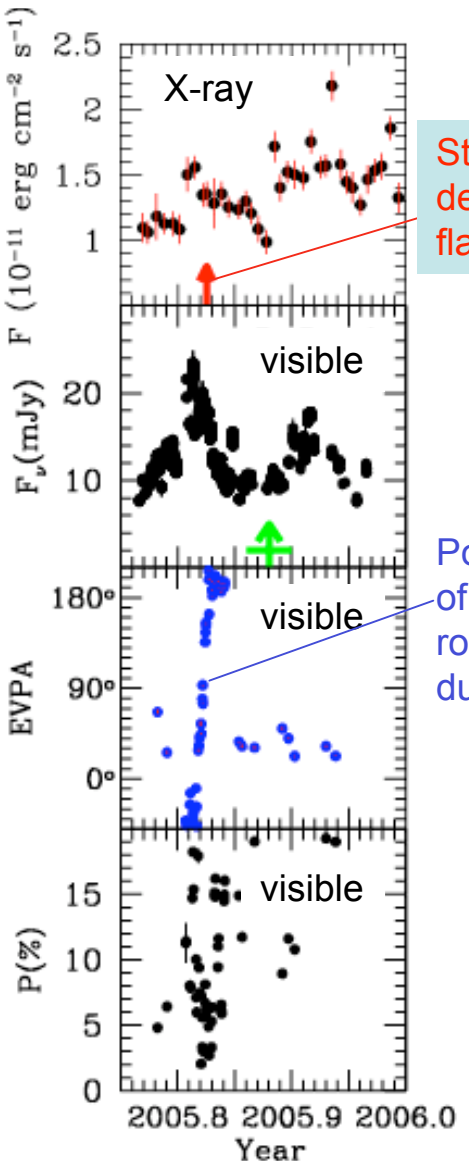
Where do the outbursts of light occur?



Our study of AGN BL Lacertae (Marscher et al. 2008, *Nature* 4/24/08)

Late 2005: Double optical/X-ray flare, radio outburst starts during 2nd flare



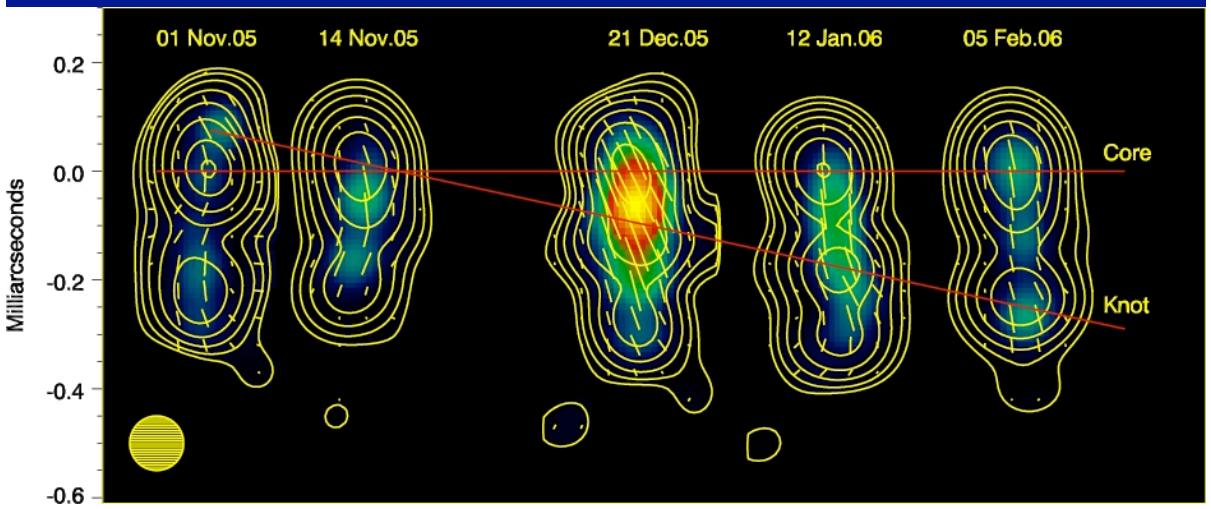


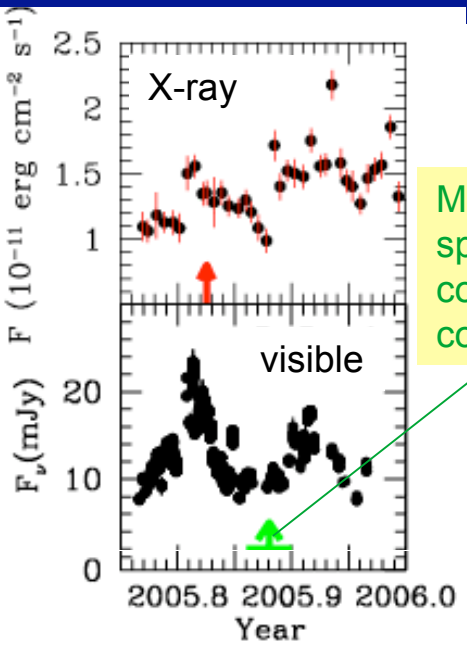
Strong gamma-ray detection during 1st flare

Polarization angle of visible light rotates smoothly during 1st flare

BL Lacertae (cont.)

New moving bright spot (“blob”) appears after 1st flare, 2nd flare occurs as blob passes through the “core”





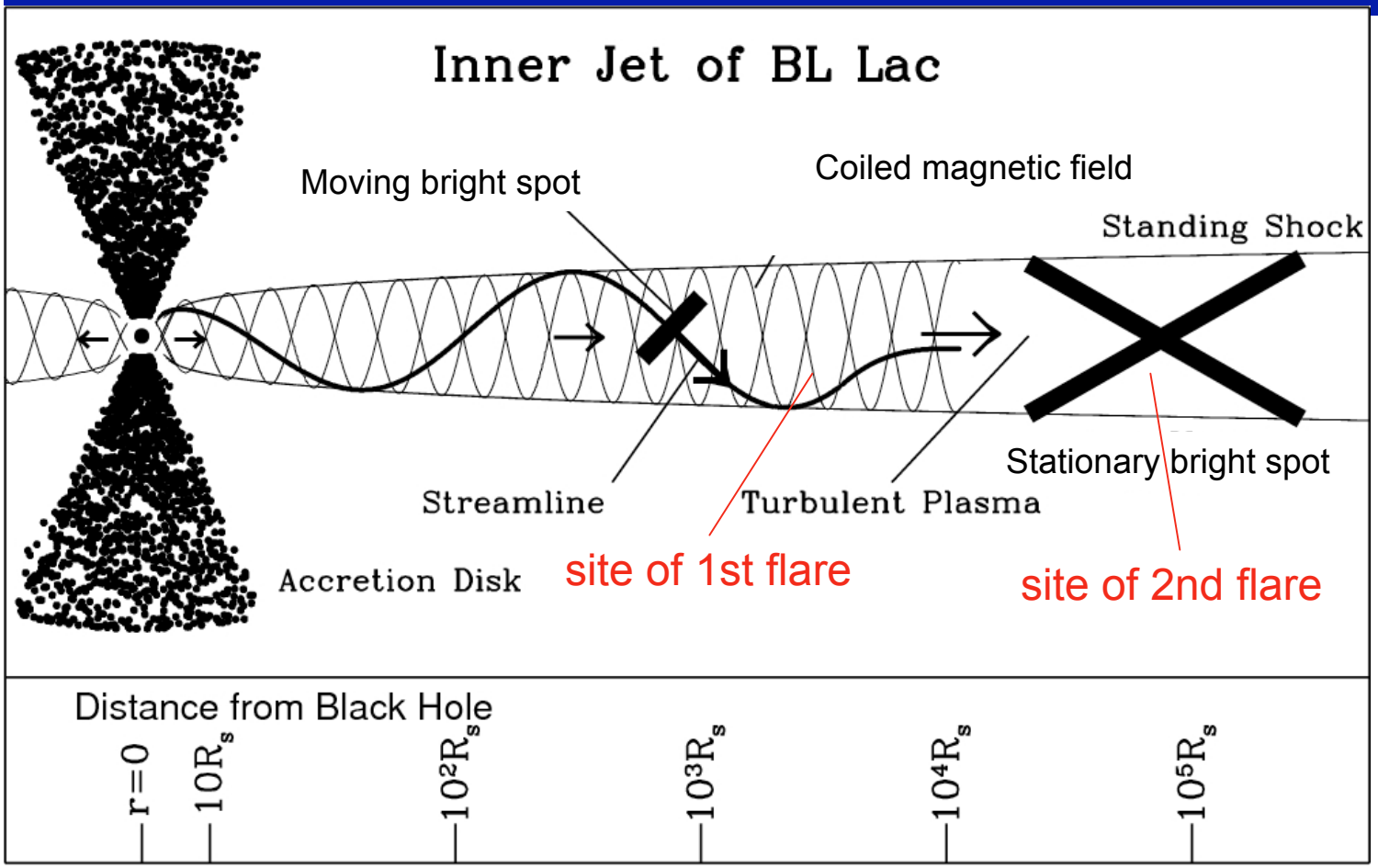
Moving bright spot (“blob”) coincident with core

Physical Picture of BL Lac: Exactly as Expected Theoretically*

*N. Vlahakis (2006)

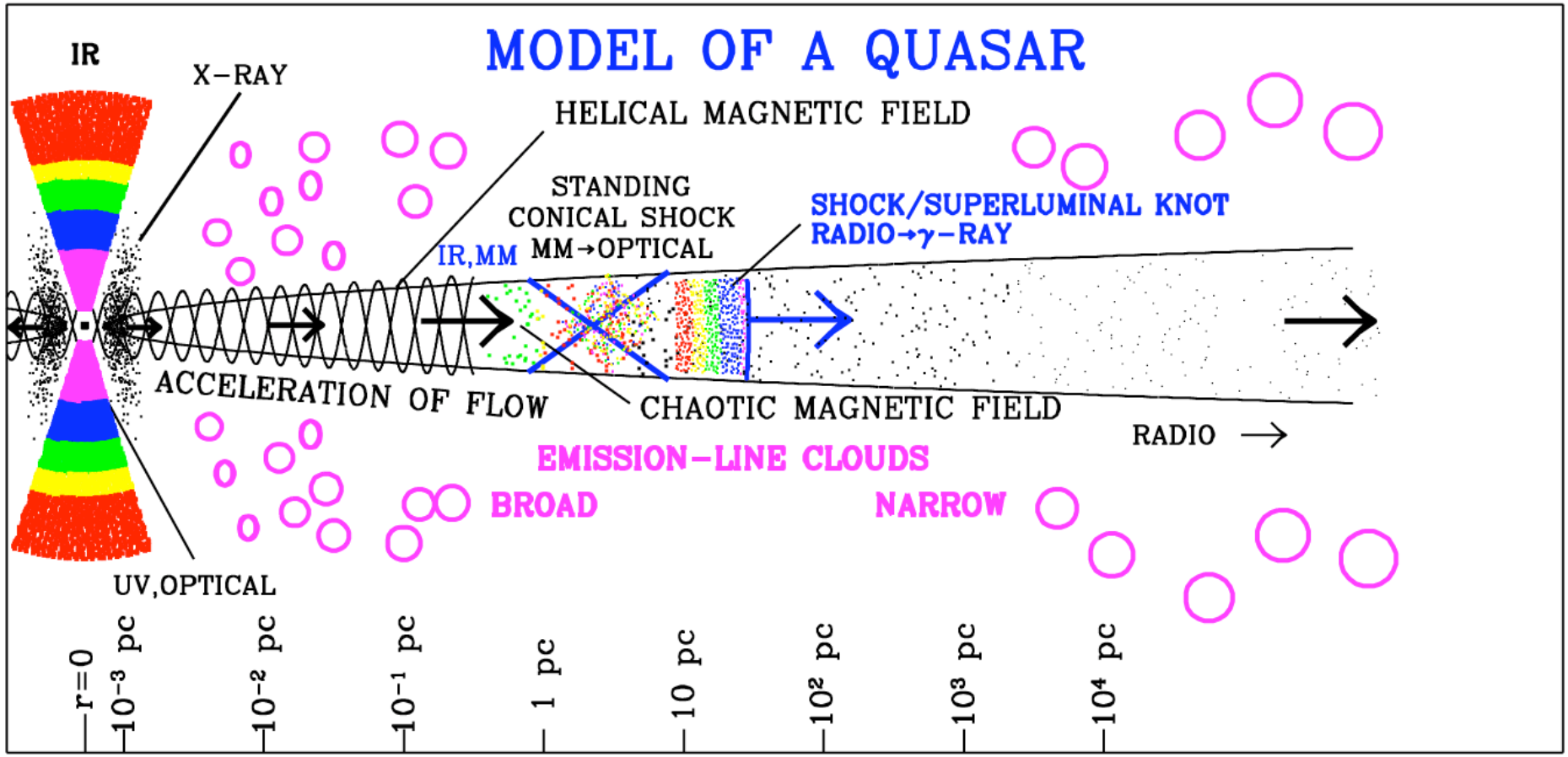
Moving bright spot follows spiral path

Passes through coiled magnetic field pattern where jet accelerates & focuses



Our Picture of a Quasar

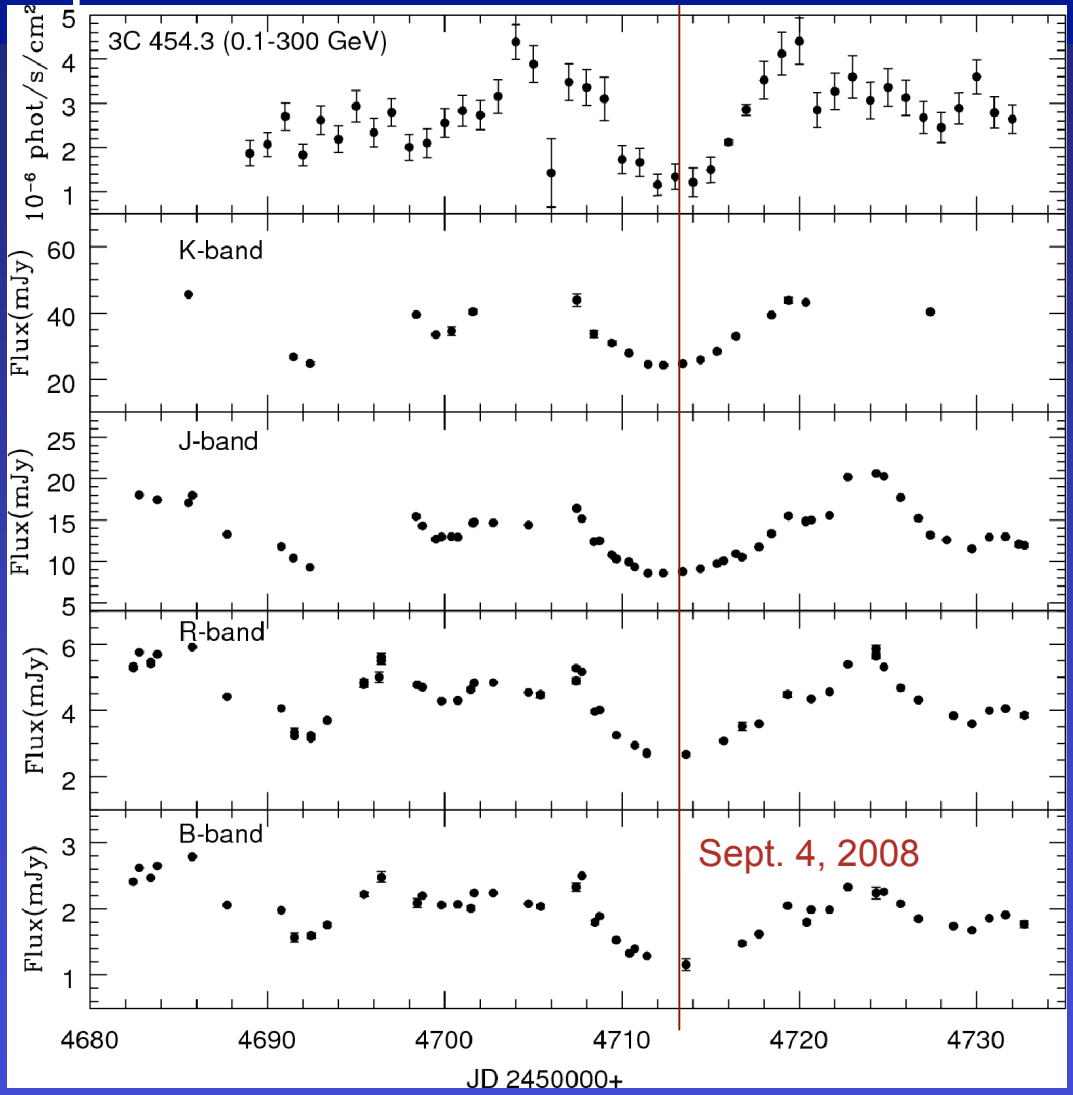
- Complex but we have confirmed reality of most of the components
- Can test this further + continue to explore inner jet with comprehensive observations of all forms of light, including gamma-rays now that *Fermi* is in orbit



On to the Movie!

Computer animation made by Dr. Wolfgang Steffen of UNAM in Mexico - his visualization group is COSMOVISION

Early Fermi/Optical Observations: The Quasar 3C 454.3



Gamma-ray - optical - infrared varied simultaneously

Role of Optical Monitoring Observations

1. Optical light curves of selected blazars known to be strong gamma-ray emitters
2. Compare optical light curves (filled in with data from other telescopes) with gamma-ray light curves (Fermi) & X-ray light curves (RXTE, Swift)
3. Link flares with new superluminal “blobs” seen in VLBA images (www.bu.edu/blazars + www.physics.purdue.edu/MOJAVE)
4. Figure out where flares occur relative to the “core” on VLBA images & what this means for models of the jet

Join the fun! Magnitudes of blazars vs. time needed for Global Telescope Network; visit website

http://gtn.sonoma.edu/resources/observing_program.php

Superluminal Blazar [original song by A. Marscher]

1. Attracted by strong gravity, the mass is so compact, Pulling me inward, prepare for close contact
No strength to resist, spinning out of control, Falling toward the abyss, approaching the black hole

2. Full of twisting magnetism, feeling hot inside, Bursting forth with energy, ready for a high-speed ride
Acceleration growing, focusing my beam, The jet starts flowing, plasma shoots downstream

Drawing closer . . . faster . . . closer . . . faster . . . closer . . . faster . . . Poloidal field! . . . Magnetic spring! . . .
PROPULSION!!!

Chorus: I'm a superluminal blazar, emission beamed into the night
Check out my relativistic jet, it seems faster than the speed of light
I'm beaming as a blazar into your line of sight
Watch as my relativistic jet goes faster than the speed of light!

3. Don't mind the illusions, it's just relativity, Pardon the intrusions into the naked singularity
Enjoy the time dilation, relax and take it slow, Beam the radiation, make the central engine glow

4. I shine as a quasar, with brilliant intensity, Powered by the black hole's ultra-strong gravity
I get energized with a shock wave, I get turbulent inside, The magnetic propulsion just can't be denied

Drawing closer . . . faster . . . closer . . . faster . . .
[chorus]

End of Presentation

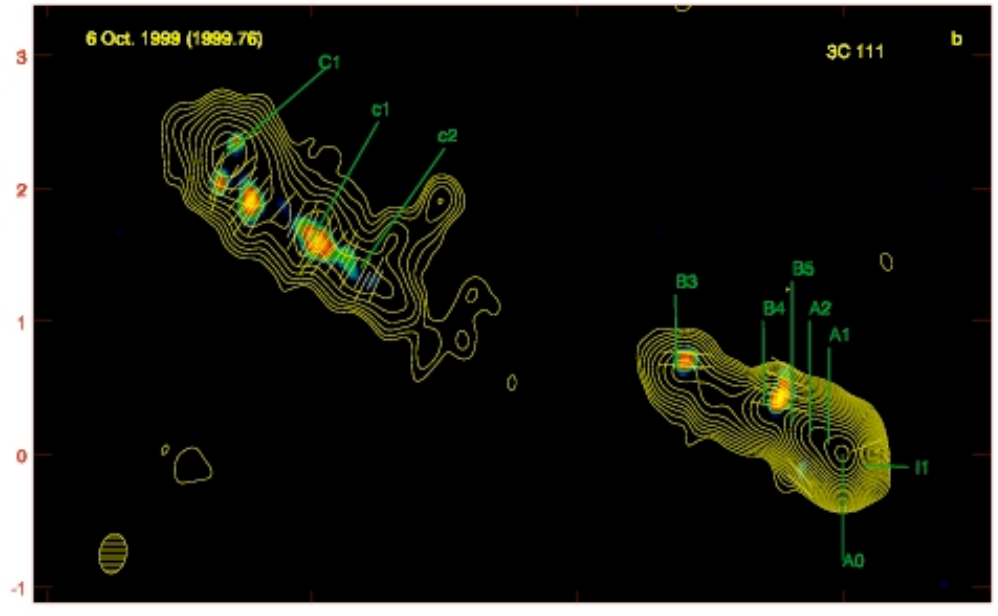
Extra slides follow

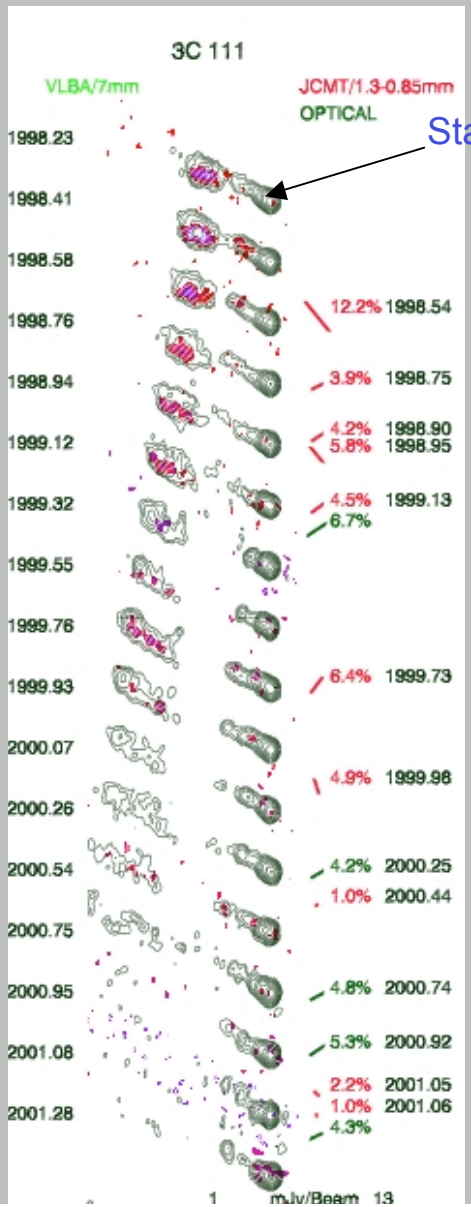
The Quasar-Like Galaxy 3C 111 (z=0.0485)

Clear example of one-sided jet structure with faster-than-light apparent motion at 5c (1.5 milliarcsec/yr)

Jet propagates through galaxy and into intergalactic space, where it feeds giant twin radio "lobes"

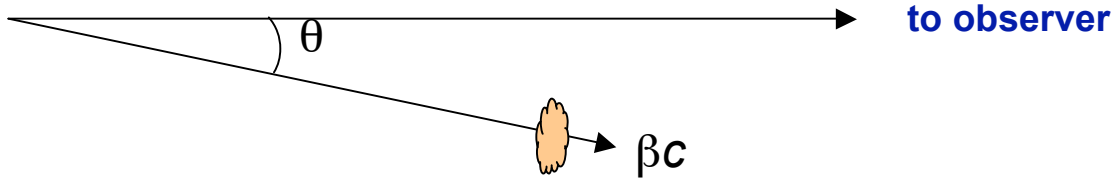
Scale: 1 mas = 0.92 pc = 3.0 lt-yr (H_o=70)





Observations made at 43 GHz with the Very Large Array (VLBA) of the National Radio Astronomy Observatory

Faster-than-light (Superluminal) Motion (An Illusion)



Velocity transverse to line of sight: $\beta c \sin\theta$; $\Gamma = (1-\beta^2)^{-1/2}$

But, in observer's frame, source of radio waves keeps getting closer, so arrival times of radio waves are compressed

Time required for source to move distance Δr is $t' = (\Delta r/\Gamma)/(\beta c)$ in source frame (length contraction) → $\Delta r = \Gamma\beta c t'$
Transformation to observer's frame: $t = t'[\Gamma(1-\beta\cos\theta)]$ (Doppler effect)

So, $\beta_{app} c = (\Delta r \sin\theta)/t = \Gamma\beta c(t'/t)\sin\theta = (\beta c \sin\theta)/(1-\beta\cos\theta)$
→ Maximum value: $\beta_{app} = \Gamma\beta$ [occurs at angle $\theta = \sin^{-1}(1/\Gamma)$]