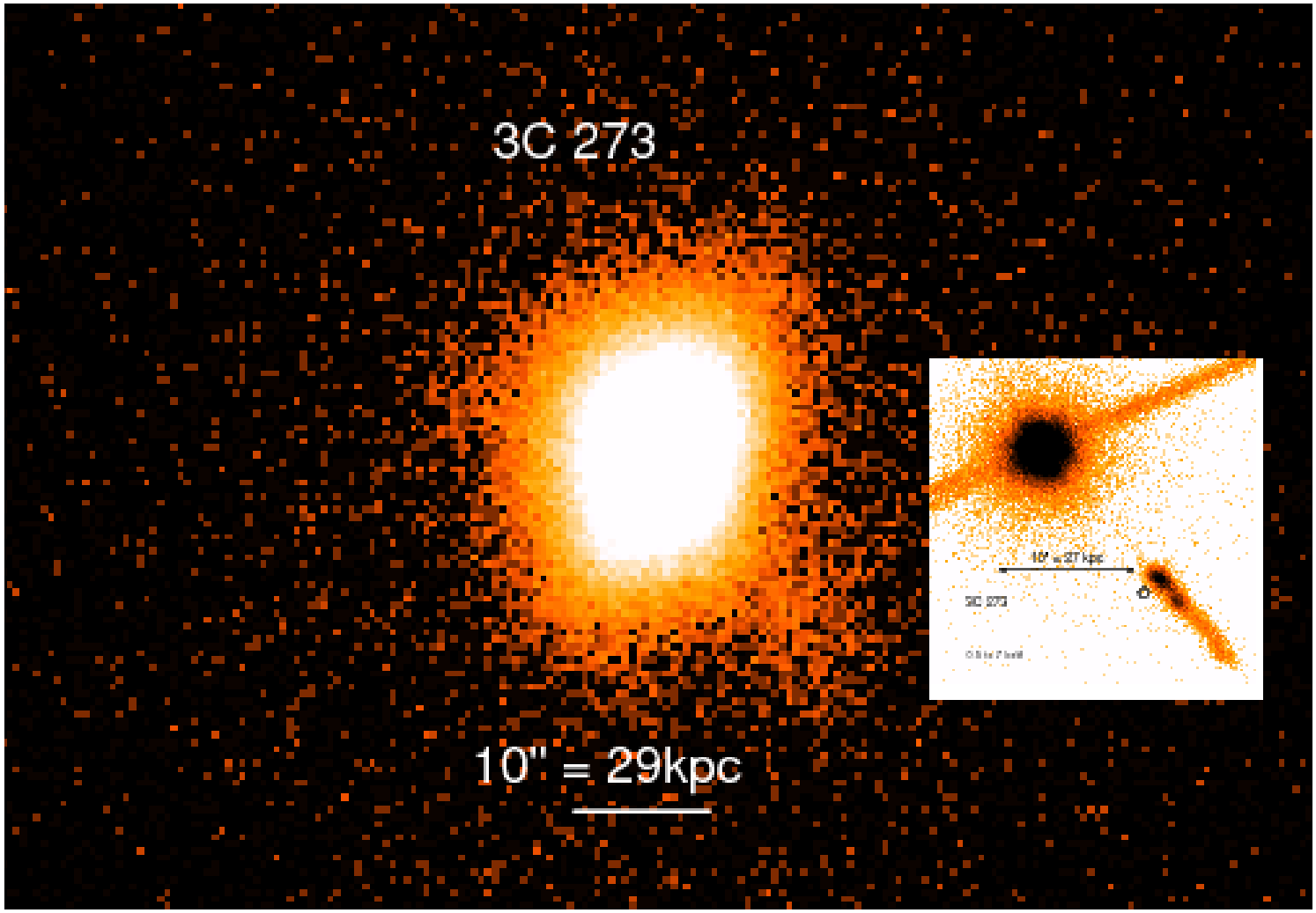
Resolved Jet Structures

Dan Schwartz (SAO)

Ten Years (and 44 days) of Science with *Chandra*

2009 September 25

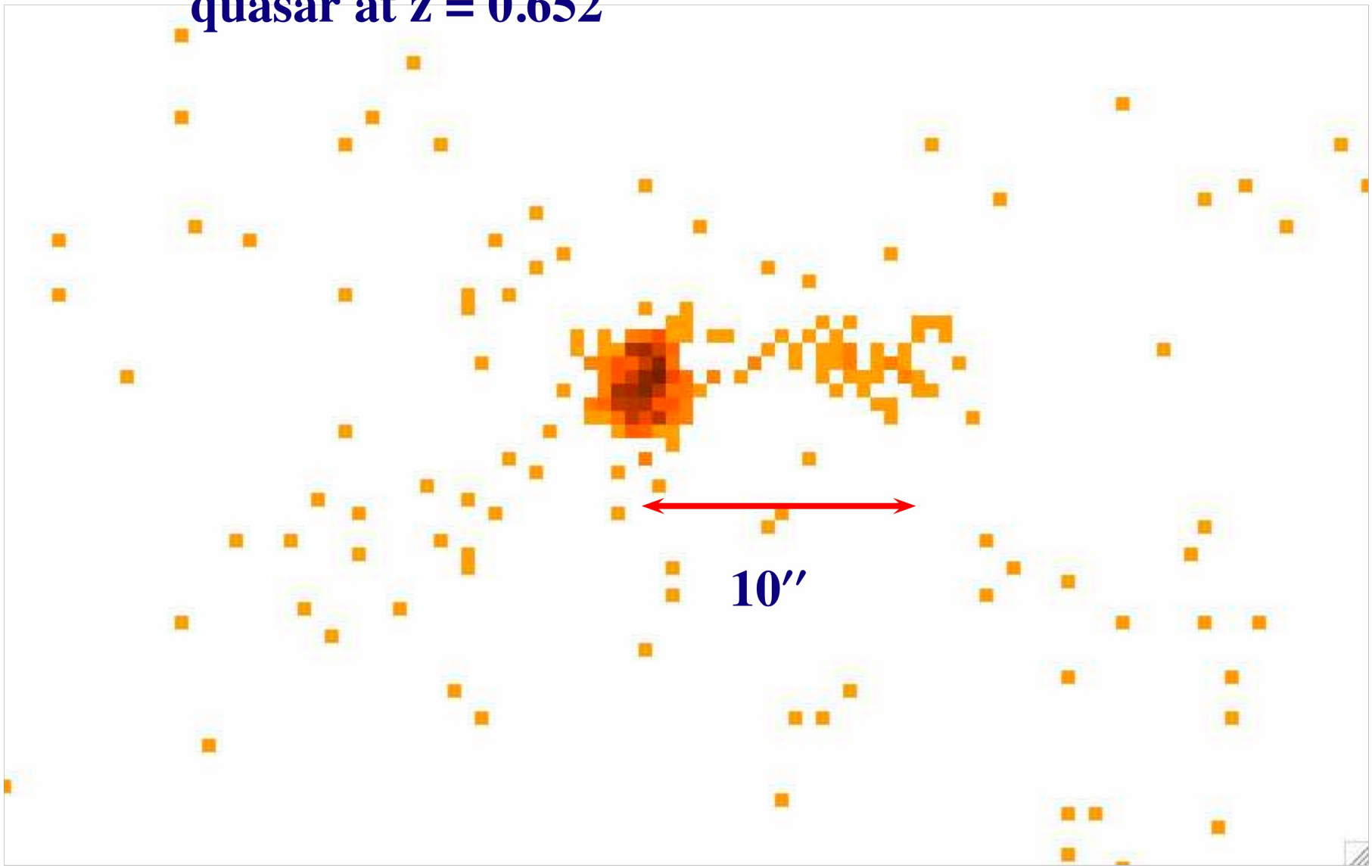
3C 273: Rosat and Chandra to Scale



Study of Jets Requires Angular Resolution!

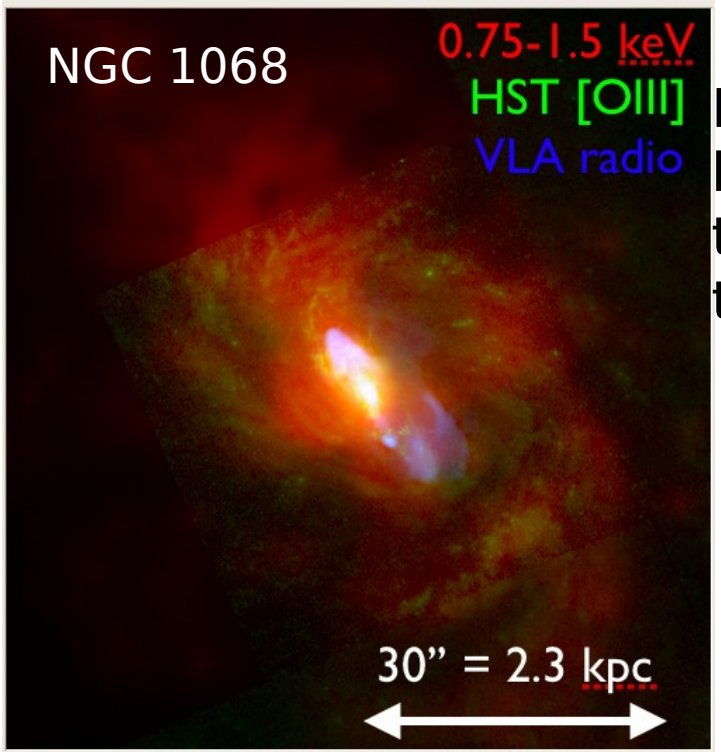
PKS 0637-752: First Chandra Pointing

quasar at z = 0.652



INTRODUCTION

- **What Do Jets Do?**
  - **Carry large quantities of energy, to feed radio lobes**
  - **Significant part of black hole energy generation budget**
  - **Interact with gas in galaxies and clusters of galaxies**



Dan Evans talk, to follow, will use high resolution HETG spectroscopy to address whether jets can effect the evolution in NGC 1068

INTRODUCTION

- **What Do We Want to Learn**
  - **Particle composition and acceleration**
  - **Jet acceleration and collimation**
- **Why Do We Need X-Ray Data?**
  - **Spectral Energy Distribution (SED) gives mechanism**
  - **Particle lifetimes change with observed band**

Ten Years of *Chandra:*

The TOP 10 Jet List

(In no particular order)

#10 3 Pre-*Chandra* Jets

Cen A
Feigelson et al.
1981ApJ...

HRI Raw Data

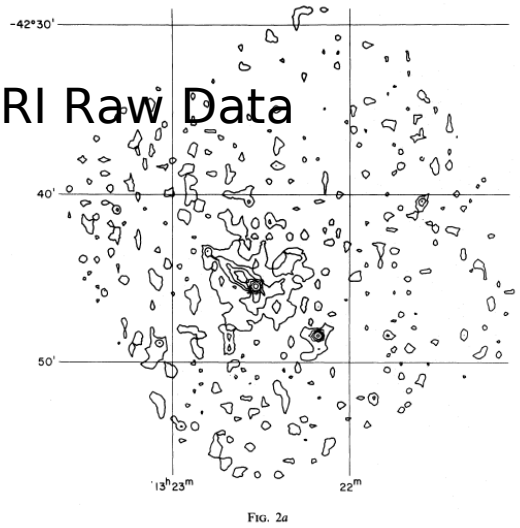
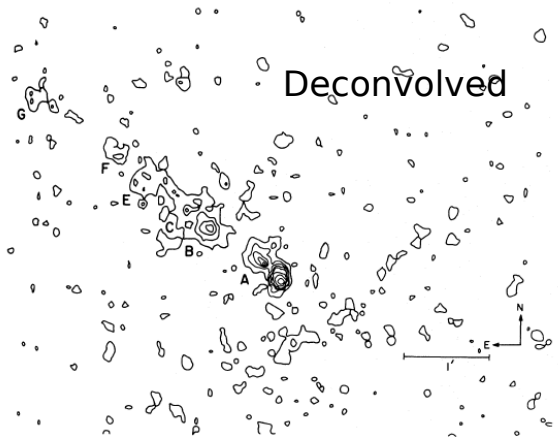
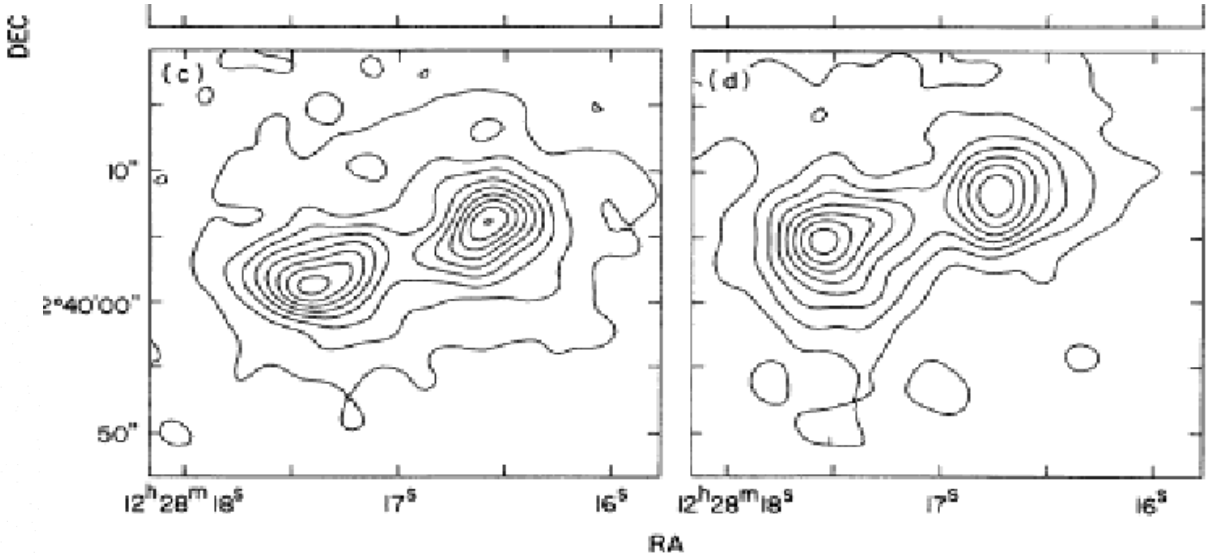


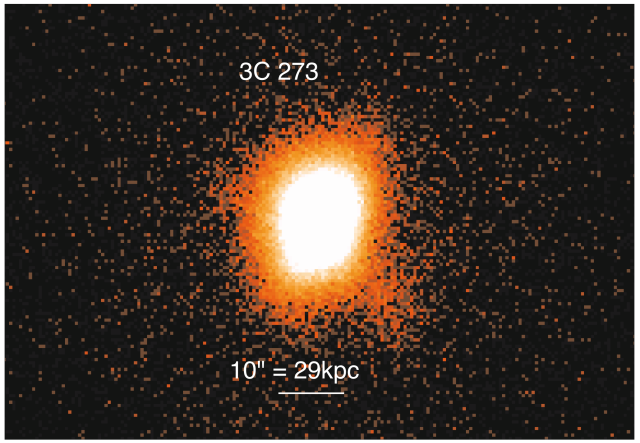
FIG. 2a

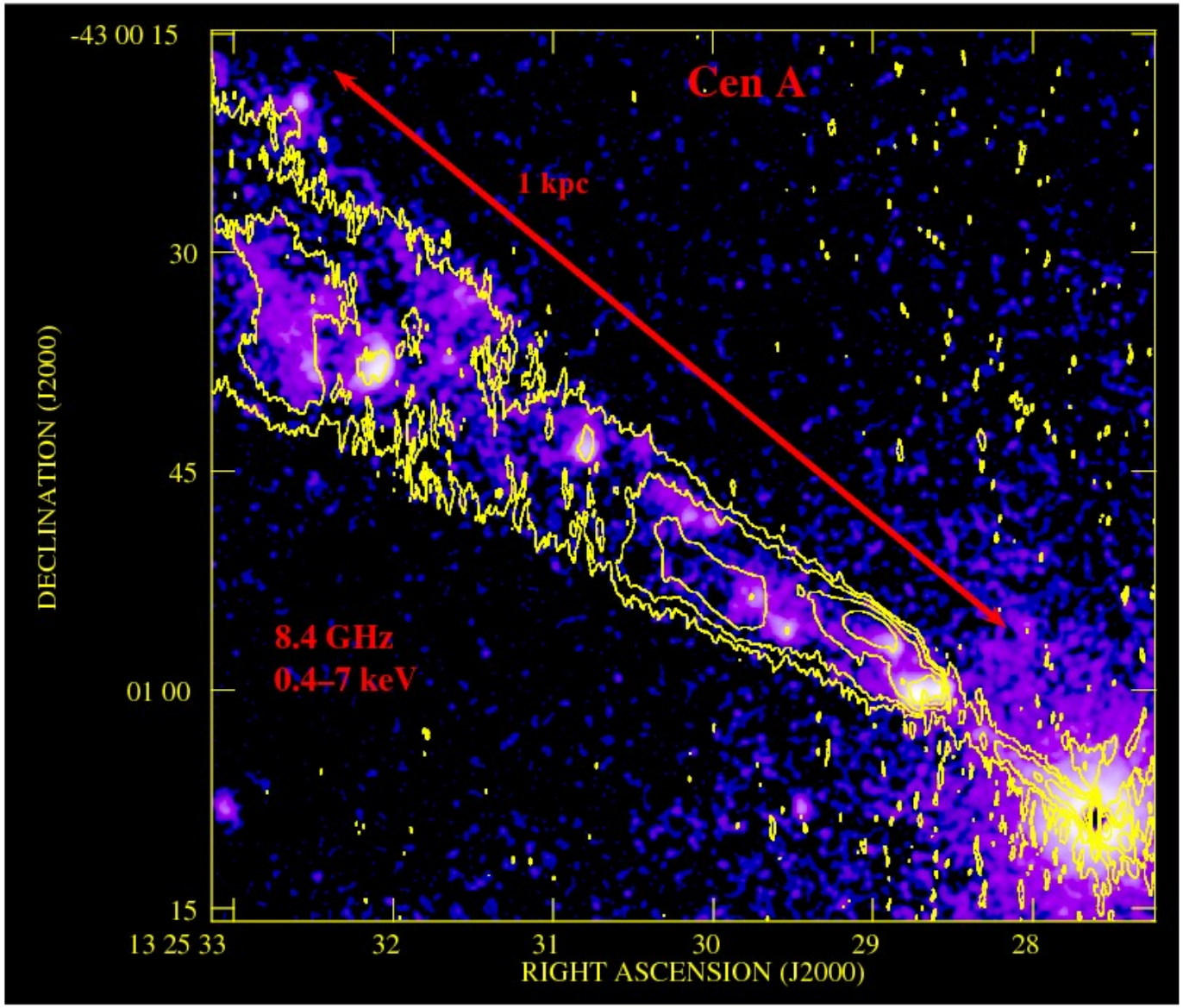


Deconvolved

M87 Biretta et al. 1991AJ....101.1632B





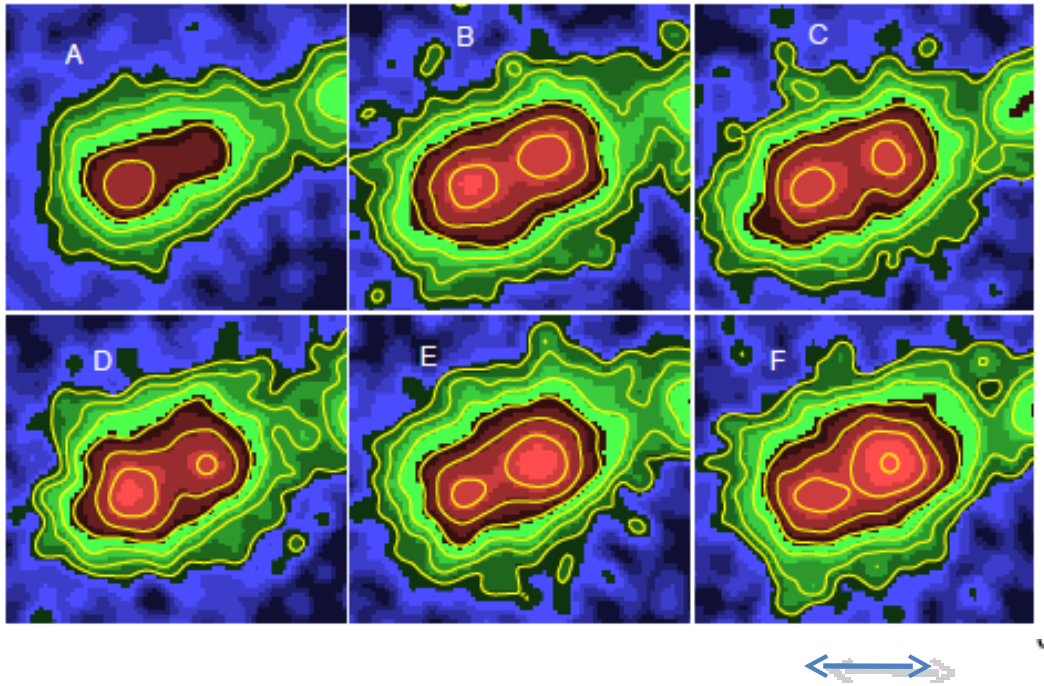


Hardcastle et al., 2003ApJ...593..169H

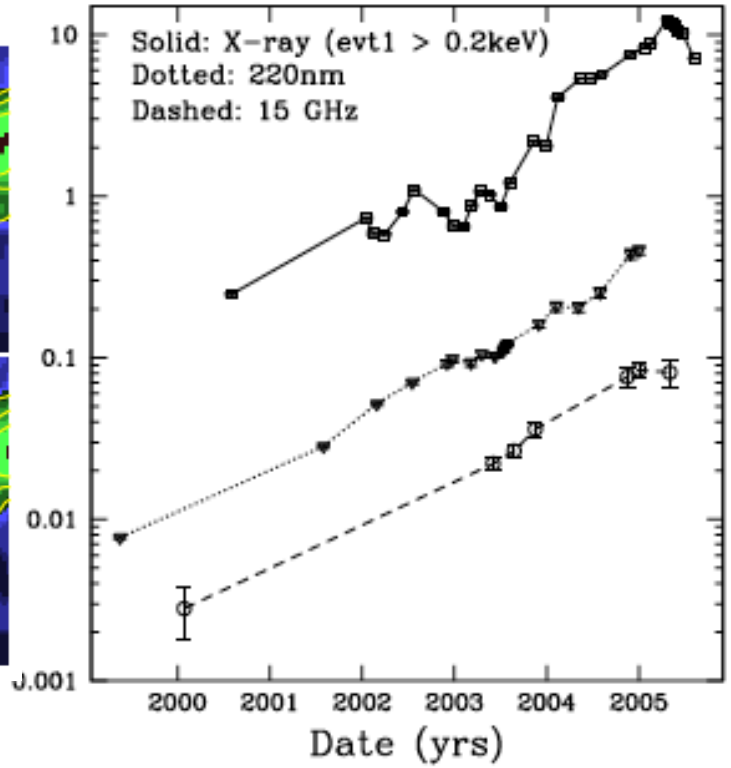
Synchrotron X-rays. Irregular structure. Interaction with ISM

Talk by Paul Nulsen to follow

M87: Variability of HST-1 Knot



1” = 77pc

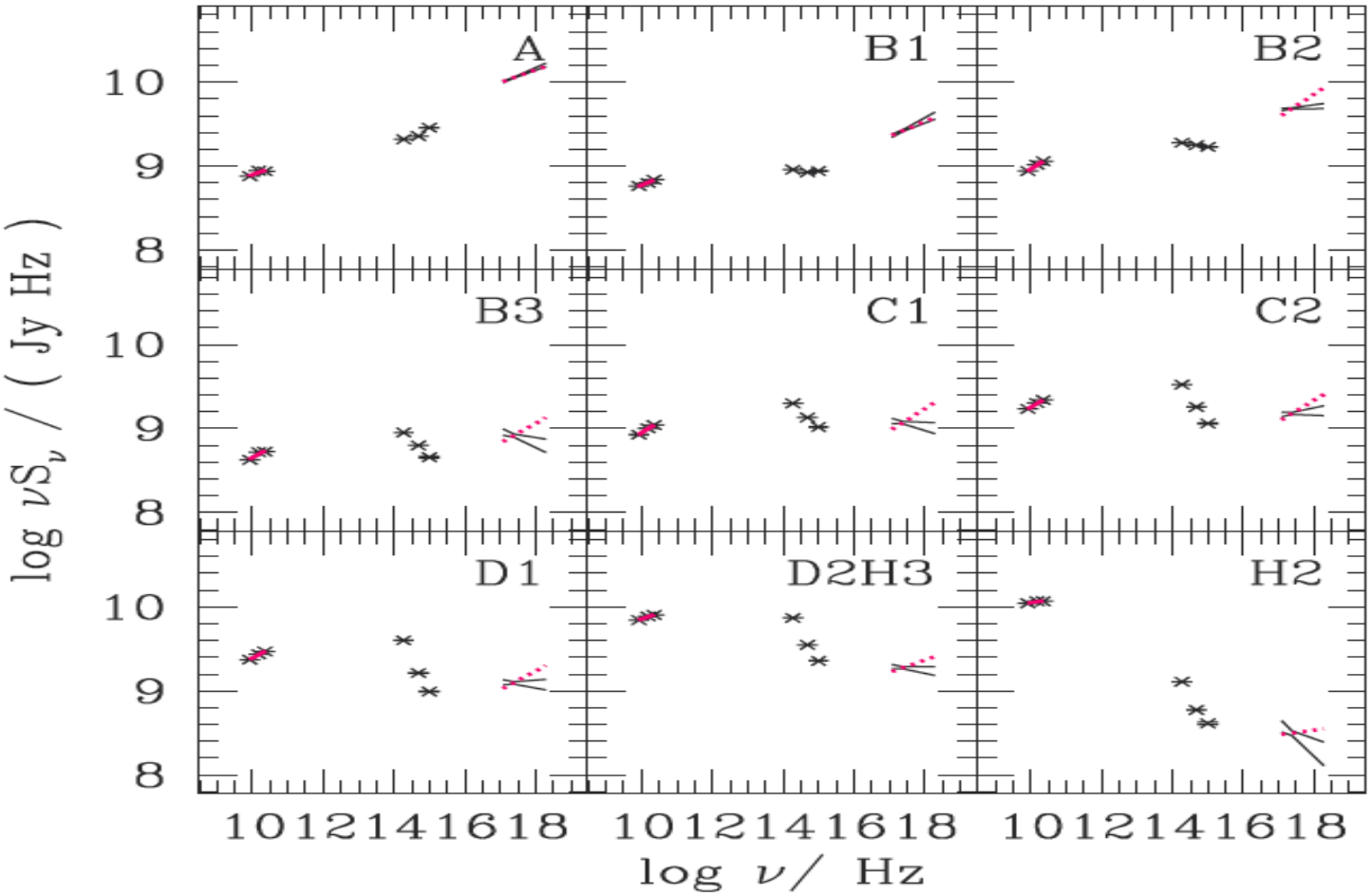


Harris, D. 2003NewAR..47..617

Harris et al. 2006ApJ...640..211H

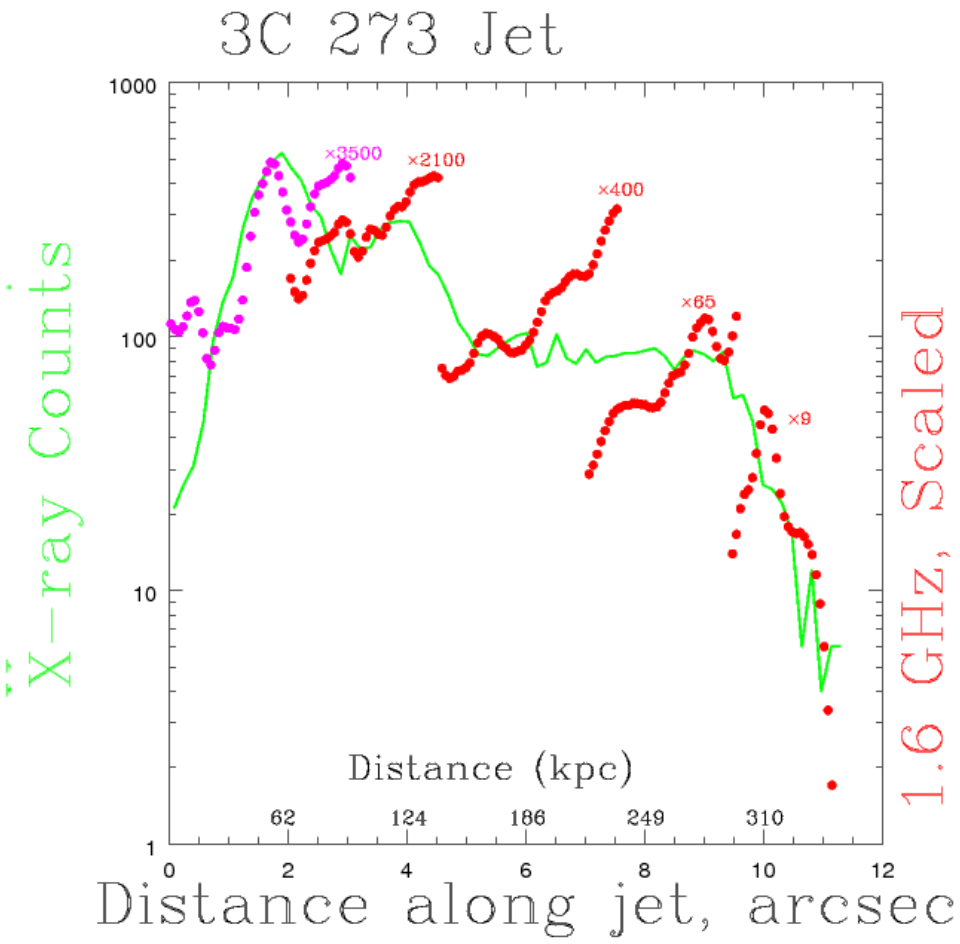
Short time scale rises and falls requires synchrotron X-ray emission.
Irregular structure in jets.

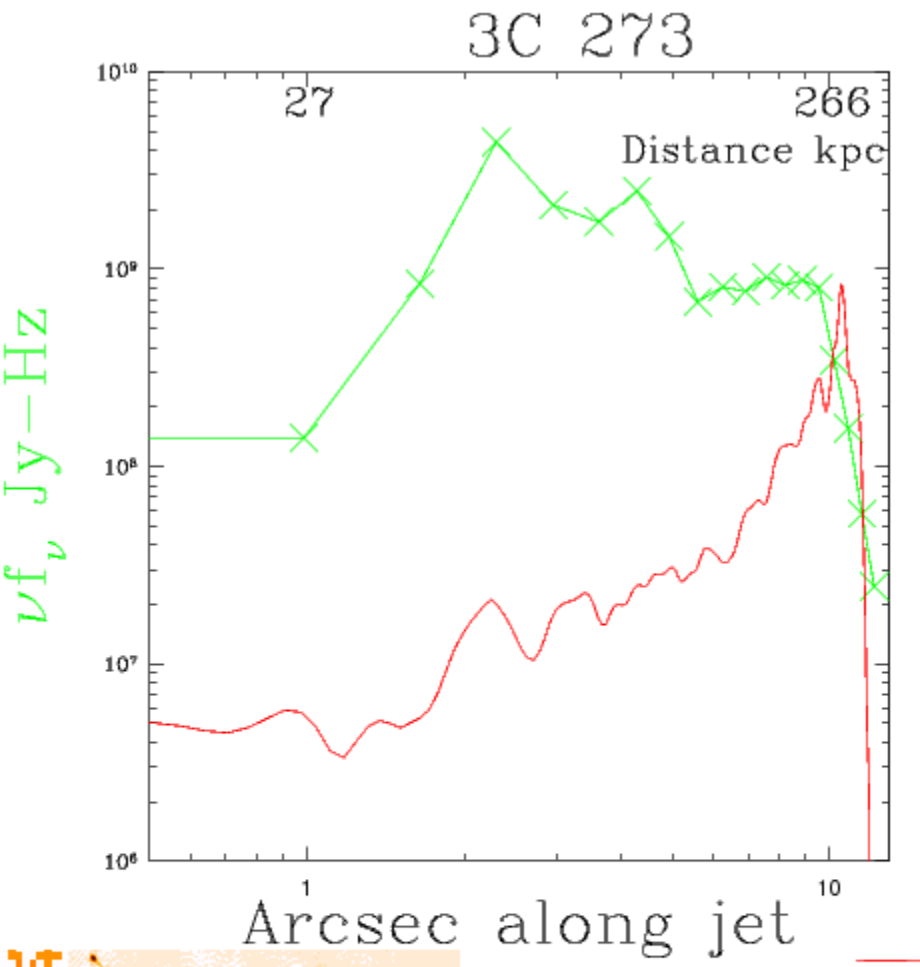
SED of the 3C 273 knots

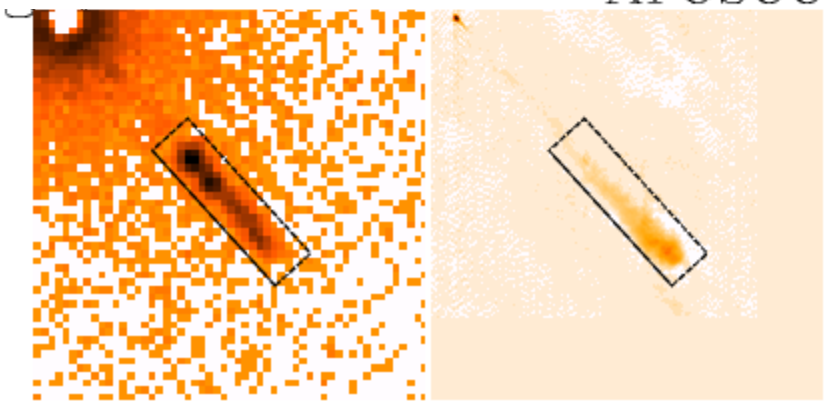


Jester et al. 2006ApJ...648..900

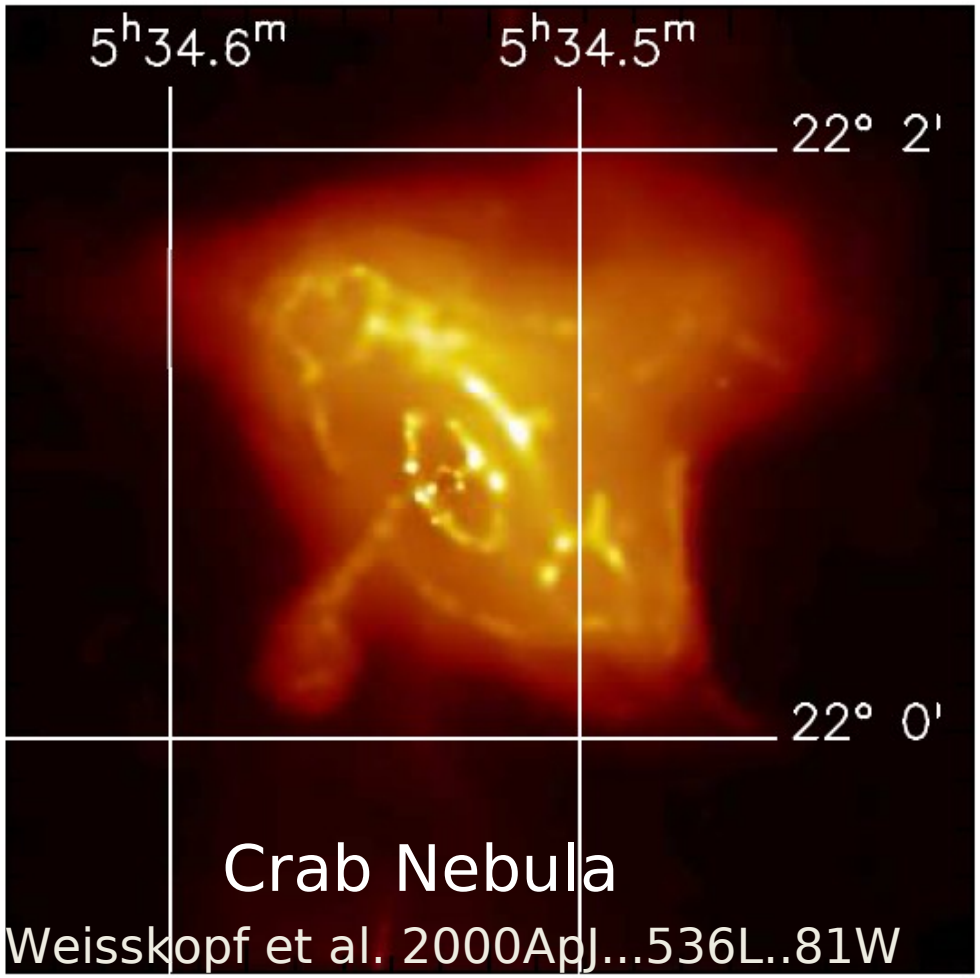
Softer X-ray spectra imply synchrotron origin.
Discord with optical implies second $N_e(\gamma)$.

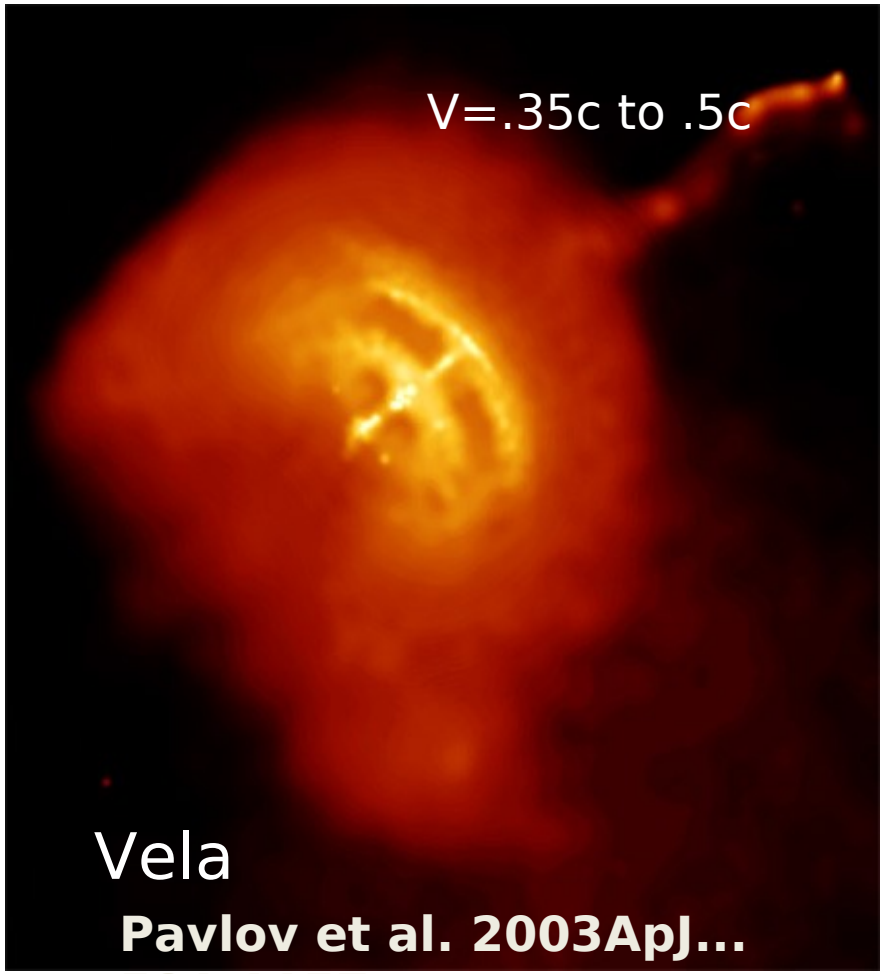

3C 273 Jet
X-ray Counts
1.6 GHz, Scaled
1000
100
10
1
×3500
×2100
×400
×65
×9
Distance (kpc)
62
124
186
249
310
0
2
4
6
8
10
12
Distance along jet, arcsec


3C 273
νf_ν, Jy−Hz
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
27
266
Distance kpc
1
10
Arcsec along jet



#9 Pulsars

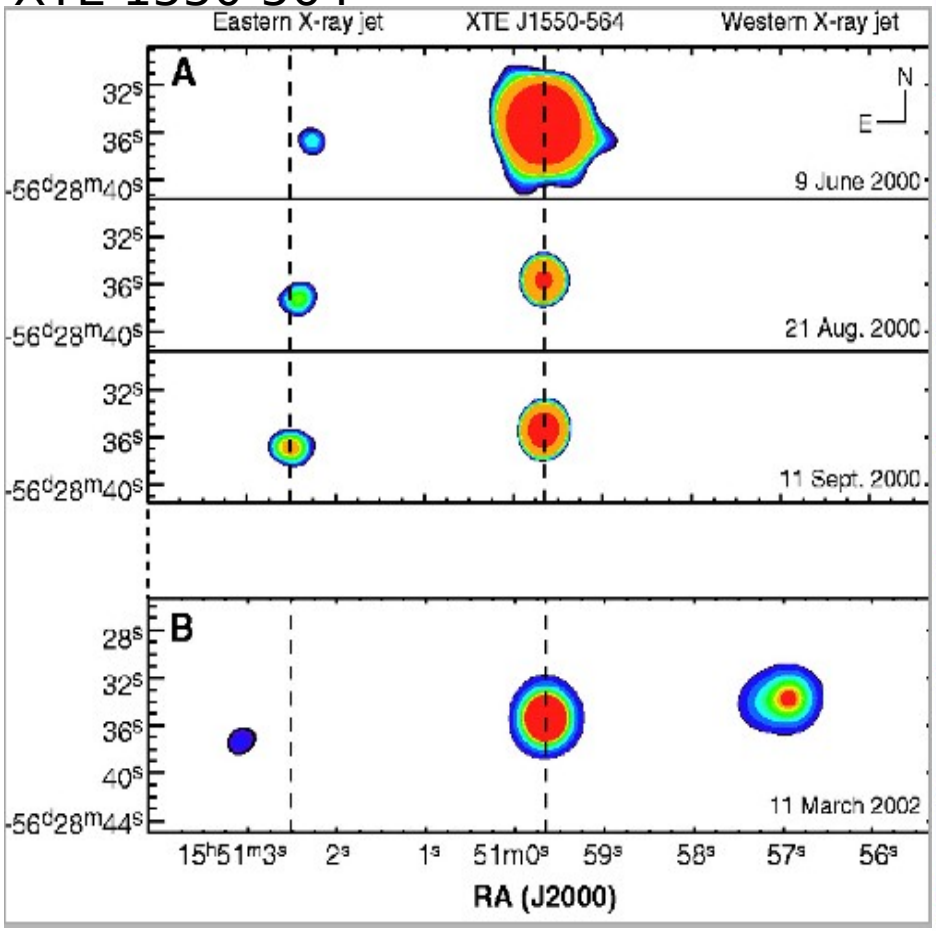




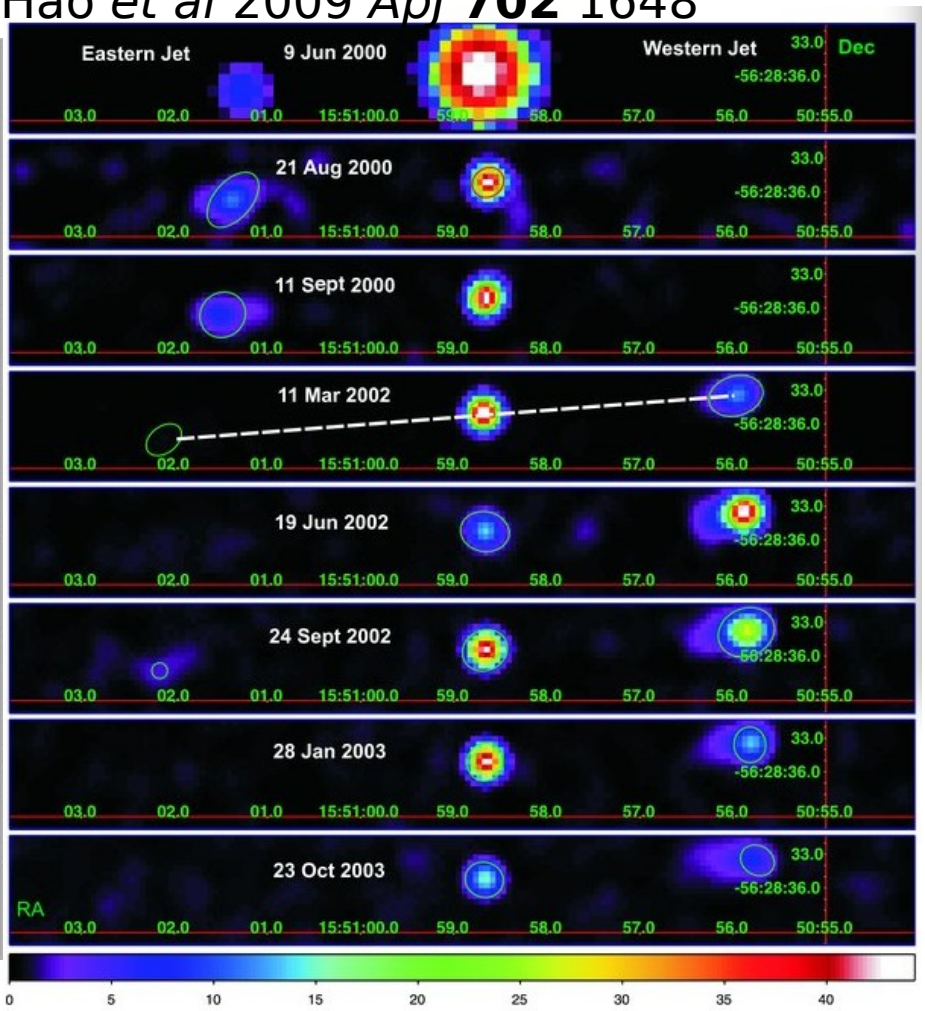
Jet must be aligned with spin axis.
Alignment of Spin & Proper Motion restricts initial kick.

#8. Stellar Mass Black Holes

Corbel et al. 2002Sci...298..196
XTE 1550-564

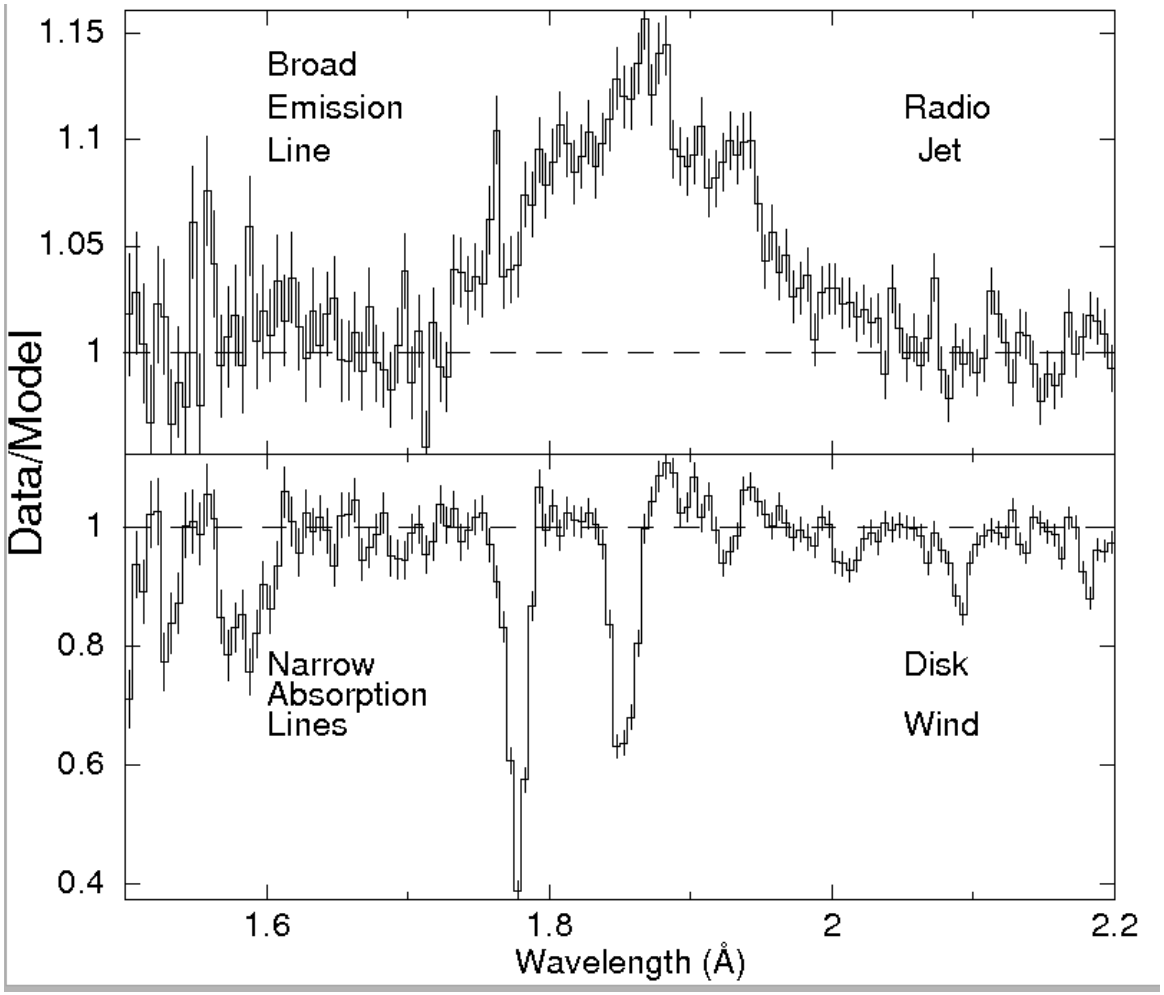


Hao *et al* 2009 *ApJ* **702** 1648



Relativistic ejection. Deceleration. Interaction with ISM.

GRS 1915+105 Neilsen and Lee, 2009Natur.458..481



Jet associated with hard spectral state, and Fe emission

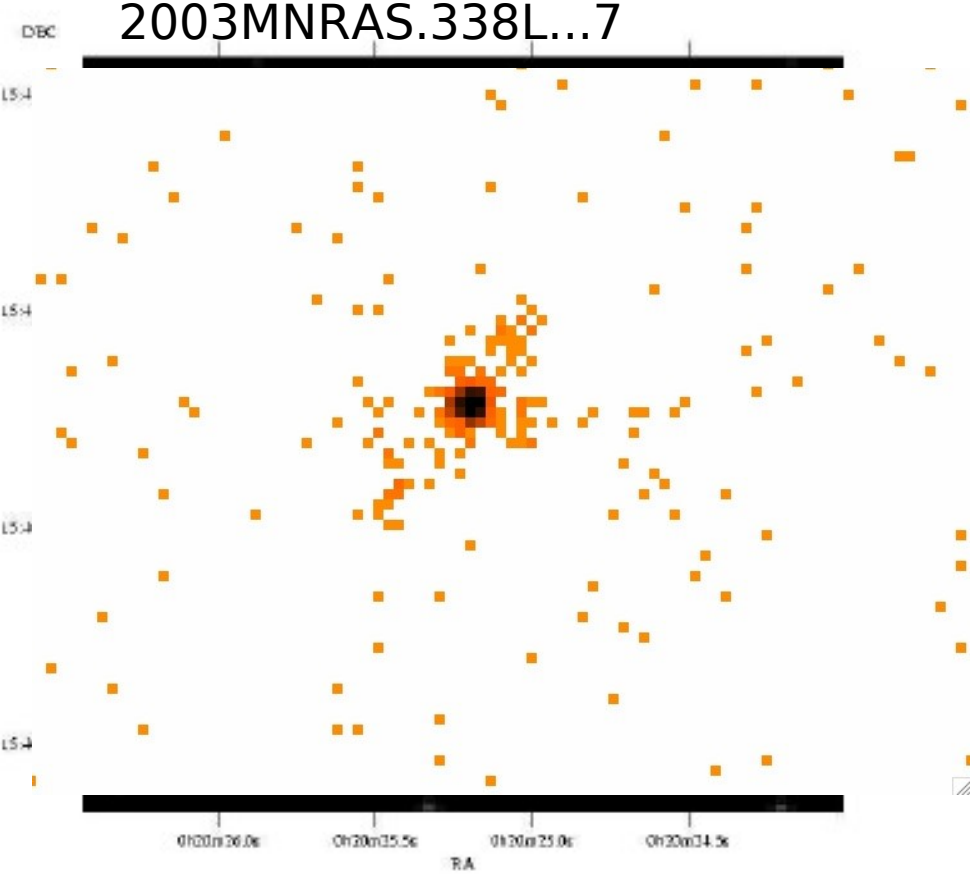
(talk by Joey Neilsen to follow)

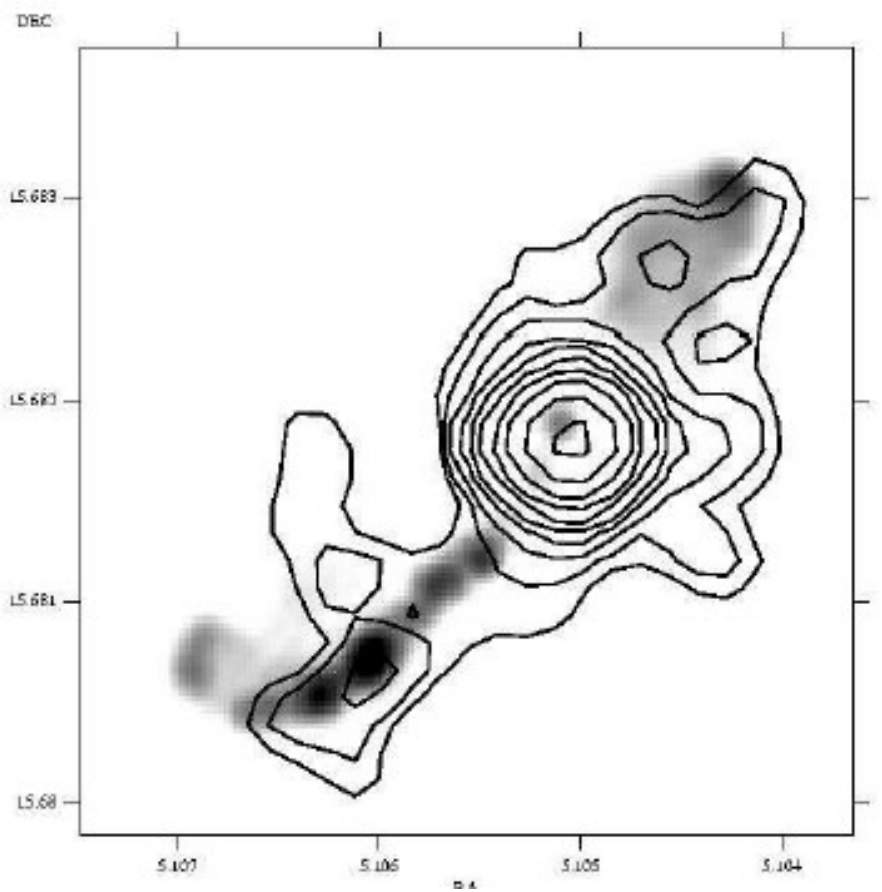
#17. Two sided ...

A.C. Fabian, A. Celotti & R.M. Johnstone

2003MNRAS.338L...7

3c9: Quasar at z=2.012

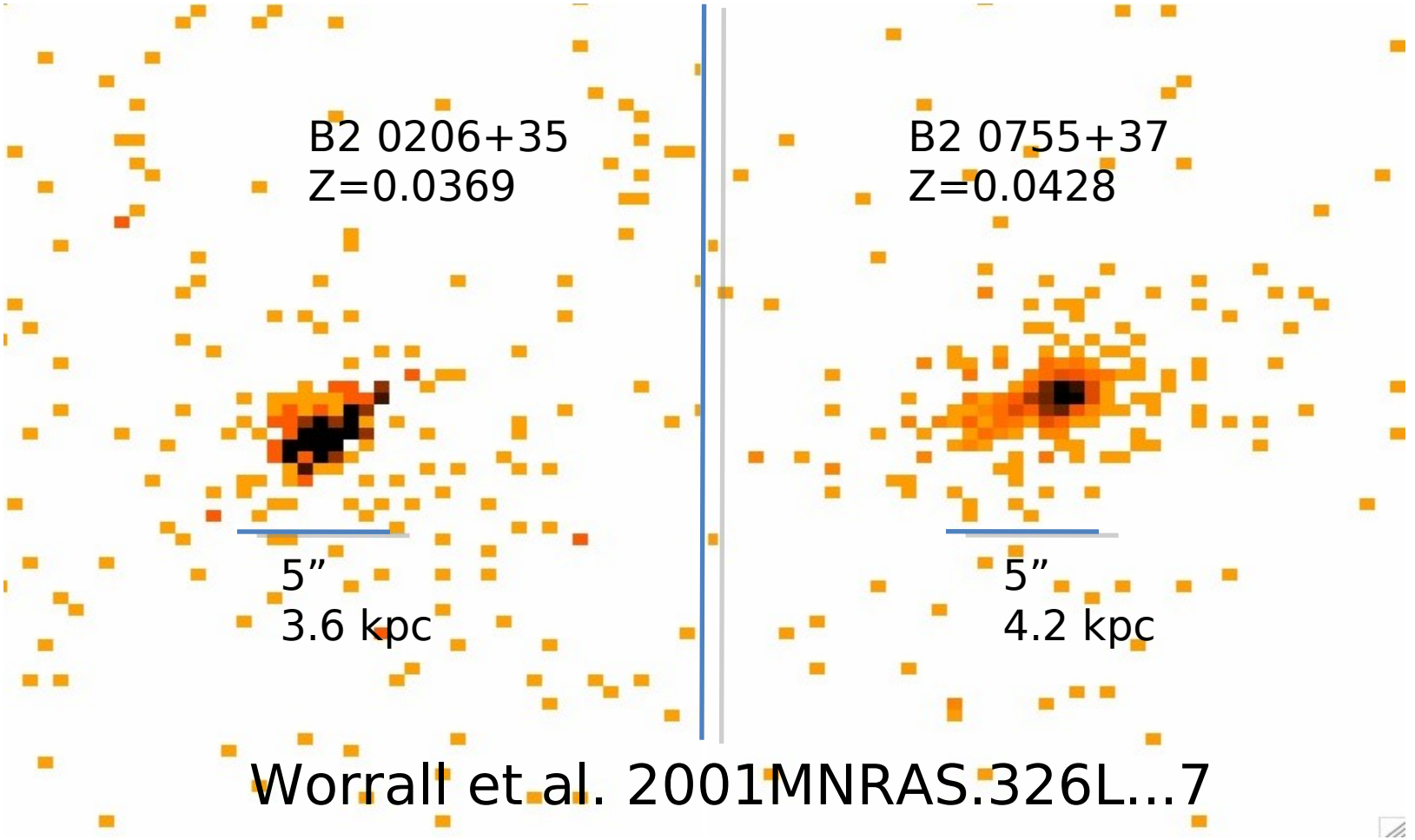




Modest Doppler factor, larger angle to LOS.
May be IC off of the core radiation.

#7

FR I Jets



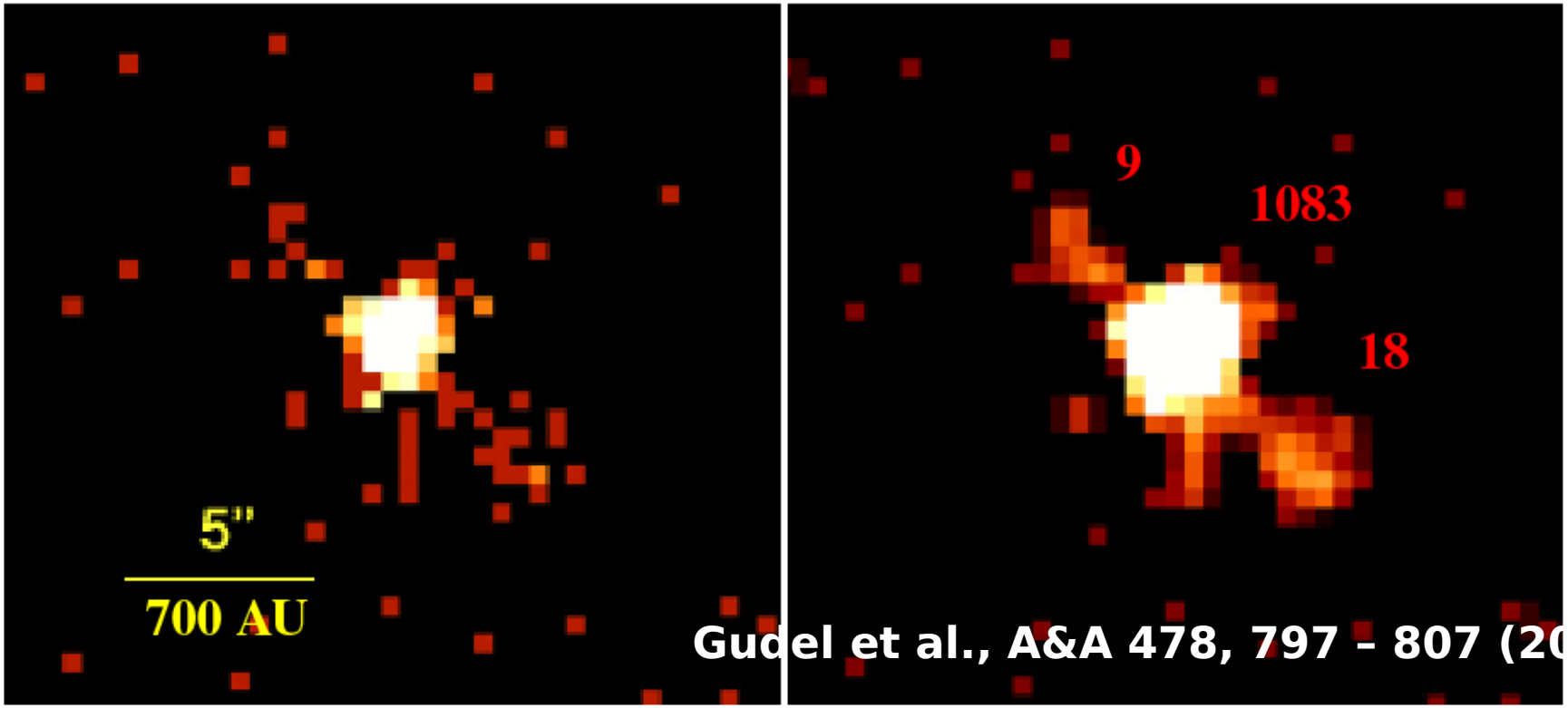
Worrall et al. 2001MNRAS.326L...7

Synchrotron X-rays, $L_x \approx 10^{41}$ergs/s.

Jet pressure ≈ gas pressure.

#6. Jets From Stars

DG Tau, a T Tauri Star



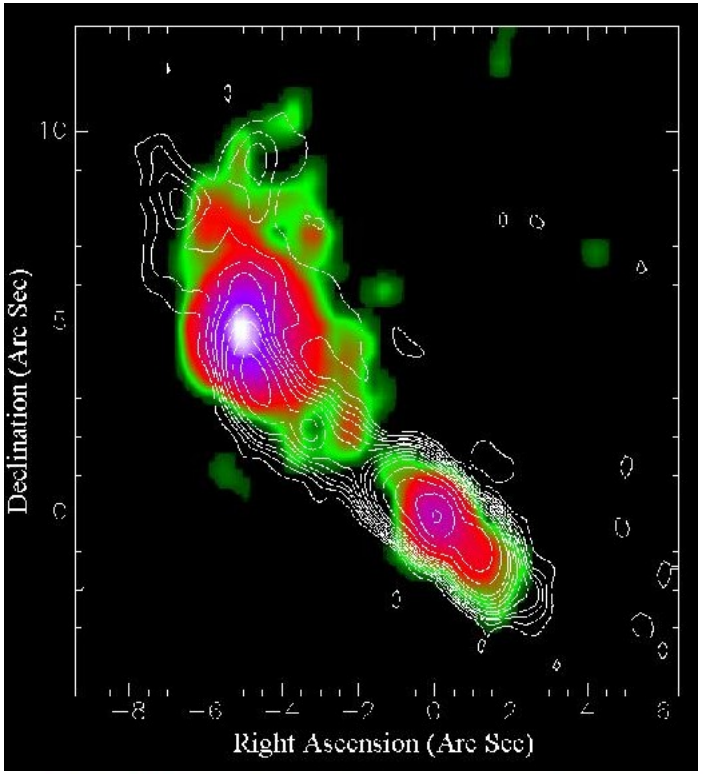
$L_x \approx 2.4 \times 10^{28}$ ergs s^{-1}.

KE flux $\approx 1.7 \times 10^{33}$ ergs s^{-1}.

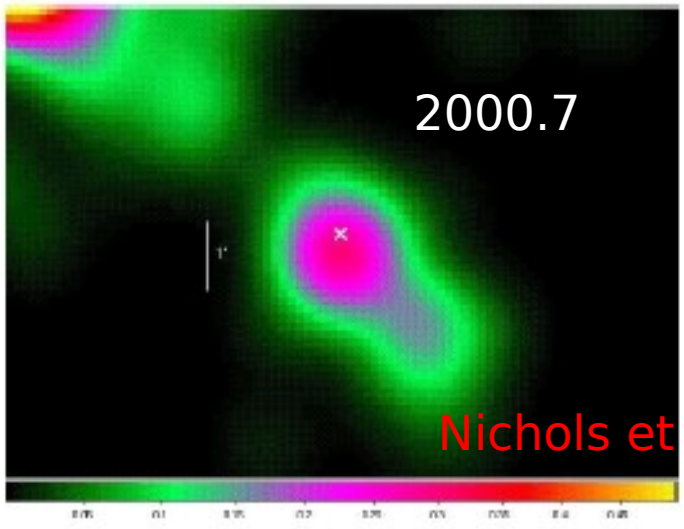
$\varepsilon \approx 1.4 \times 10^{-5}$

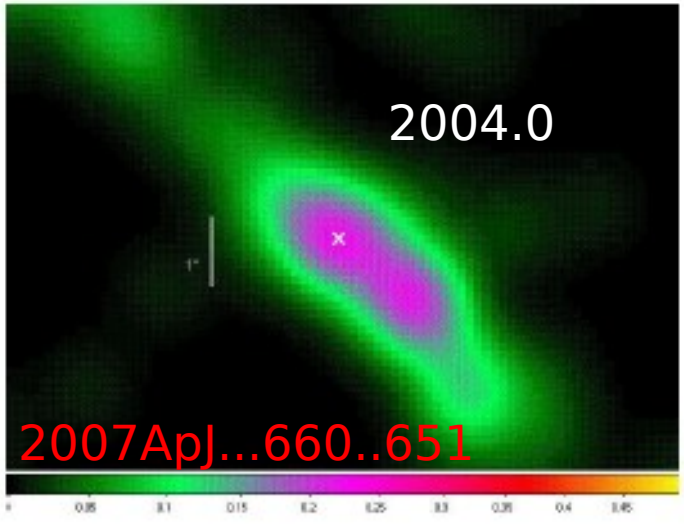
Kellogg et al. 2001ApJ...563L.151

R Aqr, a Symbiotic Binary



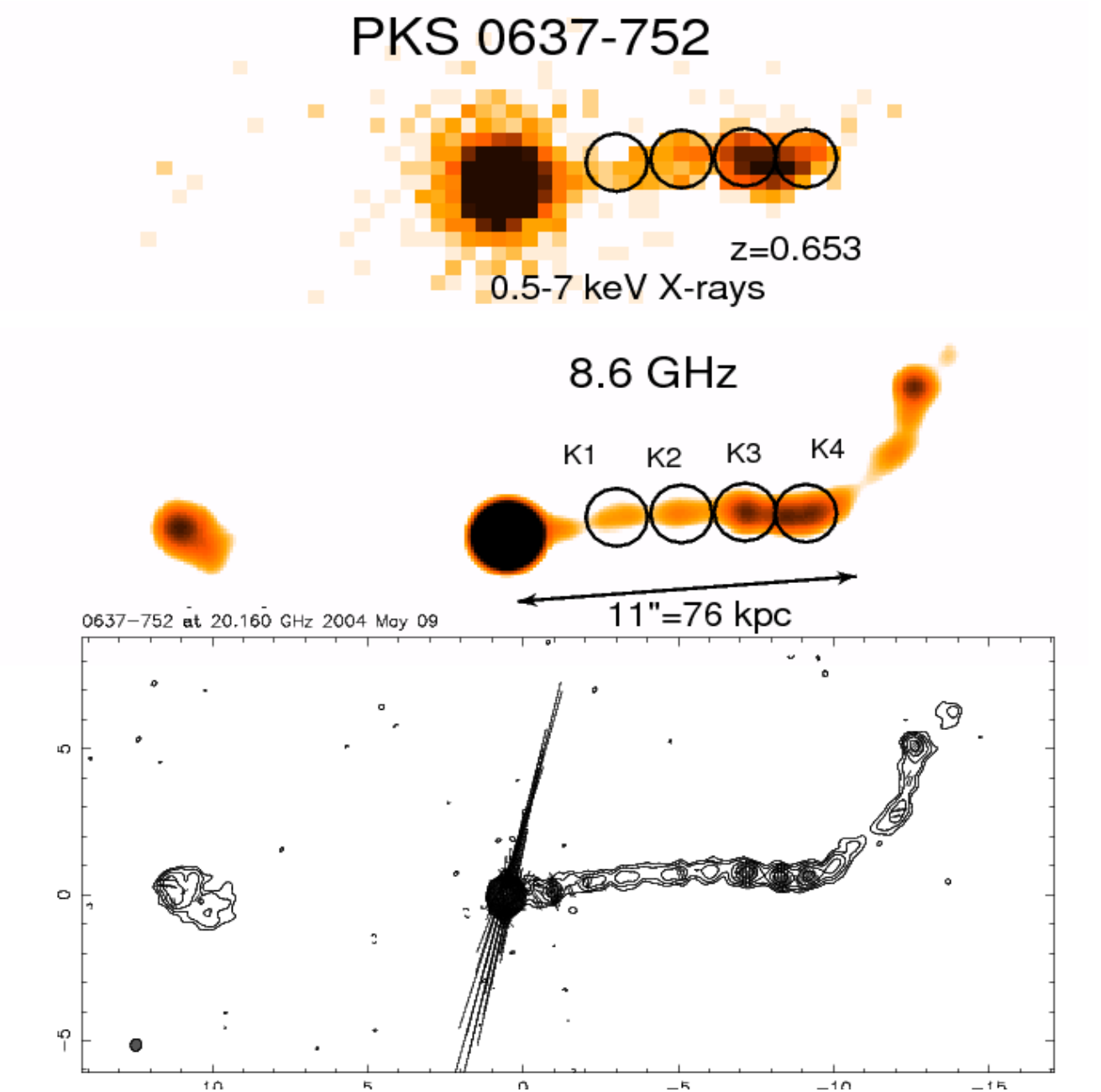
Non-relativisitic jets.
Interaction with circumstellar ejecta.
New jet outflow.

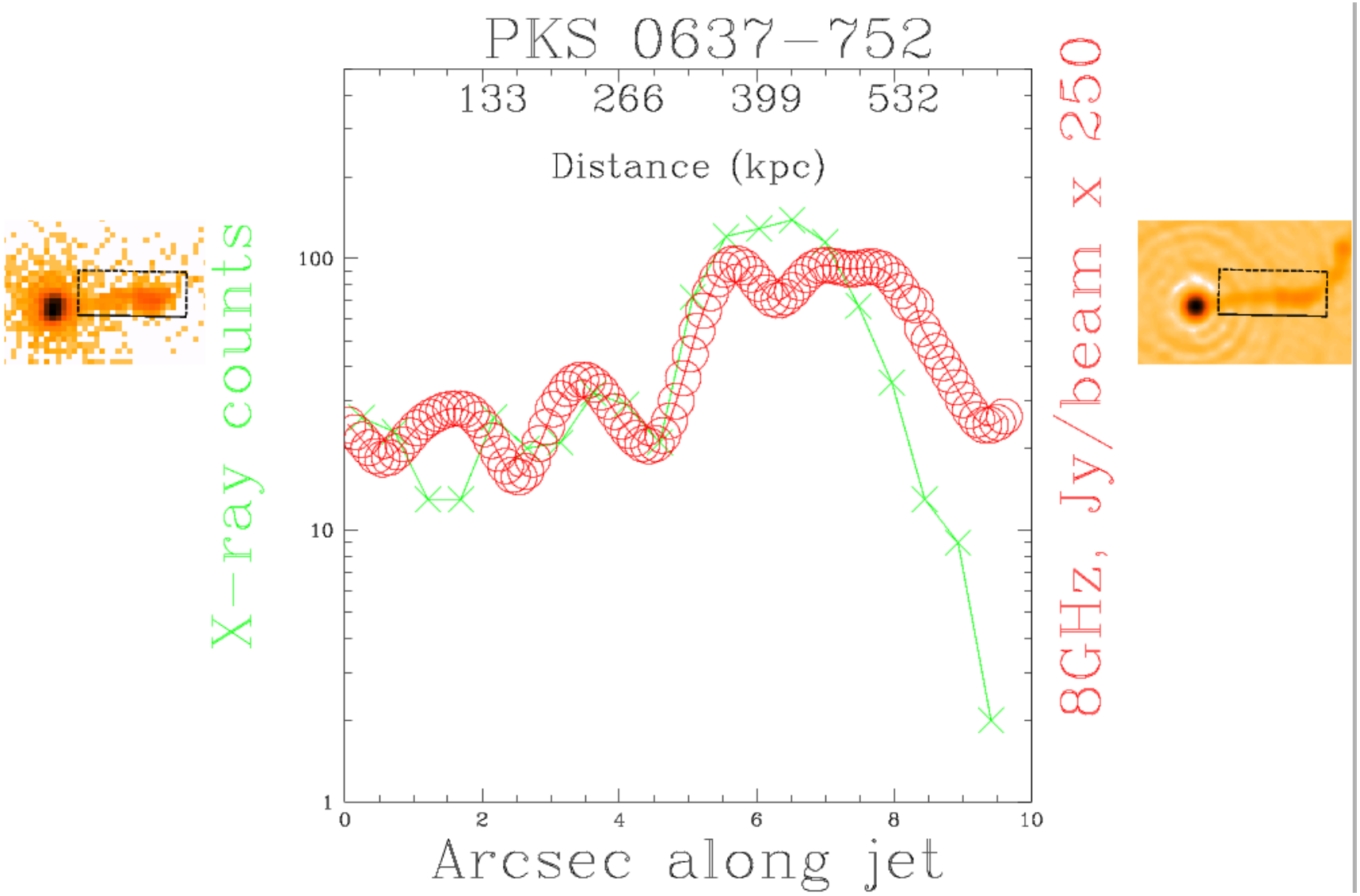




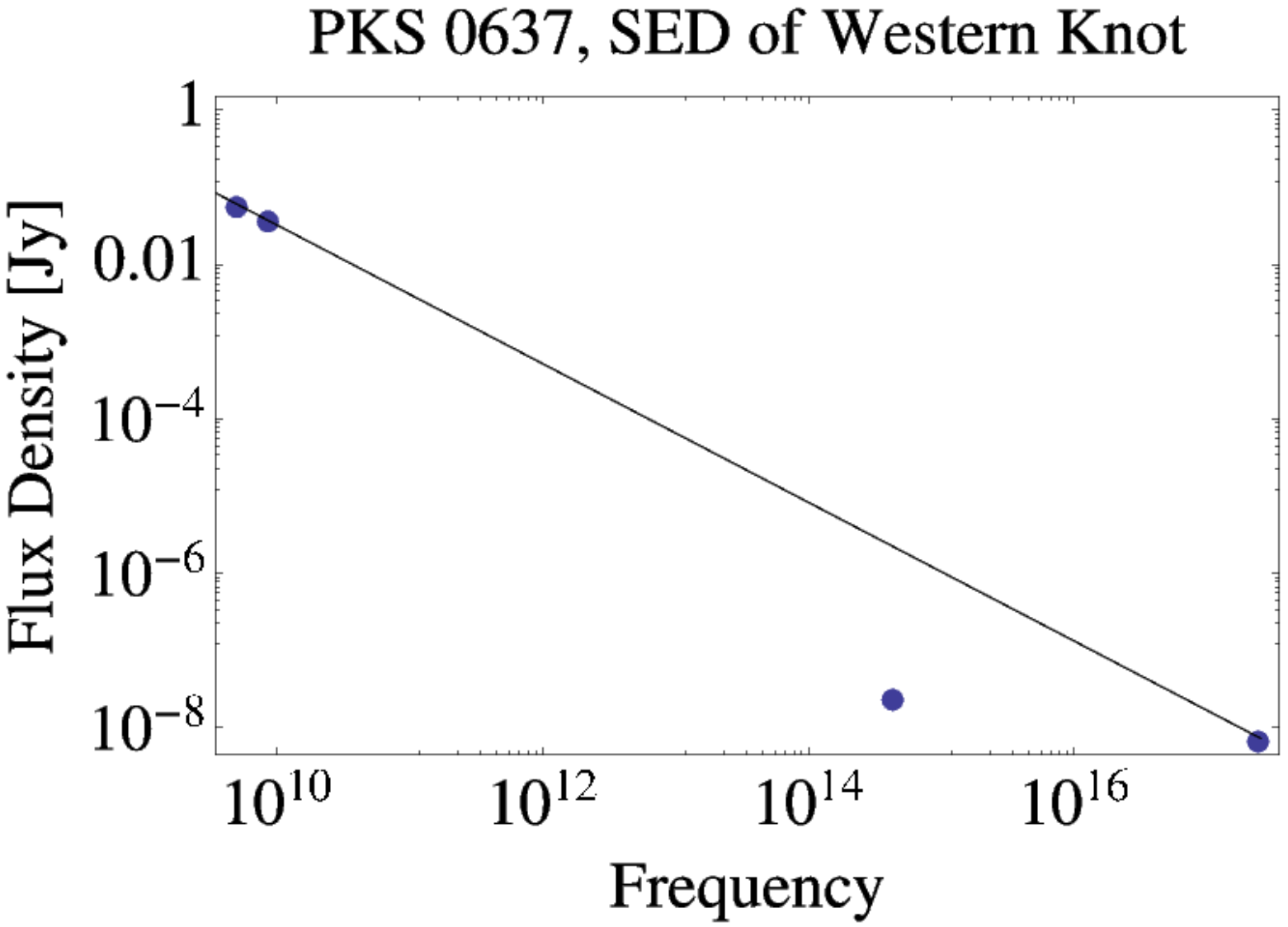
Nichols et al. 2007ApJ...660..651

#5.


PKS 0637-752
z=0.653
0.5-7 keV X-rays
8.6 GHz
K1
K2
K3
K4
11"=76 kpc
0637−752 at 20.160 GHz 2004 May 09



X-ray and radio track within x2.
Origin from a single electron population.



Optical flux prohibits a single synchrotron origin.
Solution is IC on the CMB from relativistic jet.

Deriving magnetic field, H, and Lorentz factor, Γ

Doppler factor $\delta = 1/(\Gamma(1-\beta\cos\theta))$

$H_{min} = H / \delta$

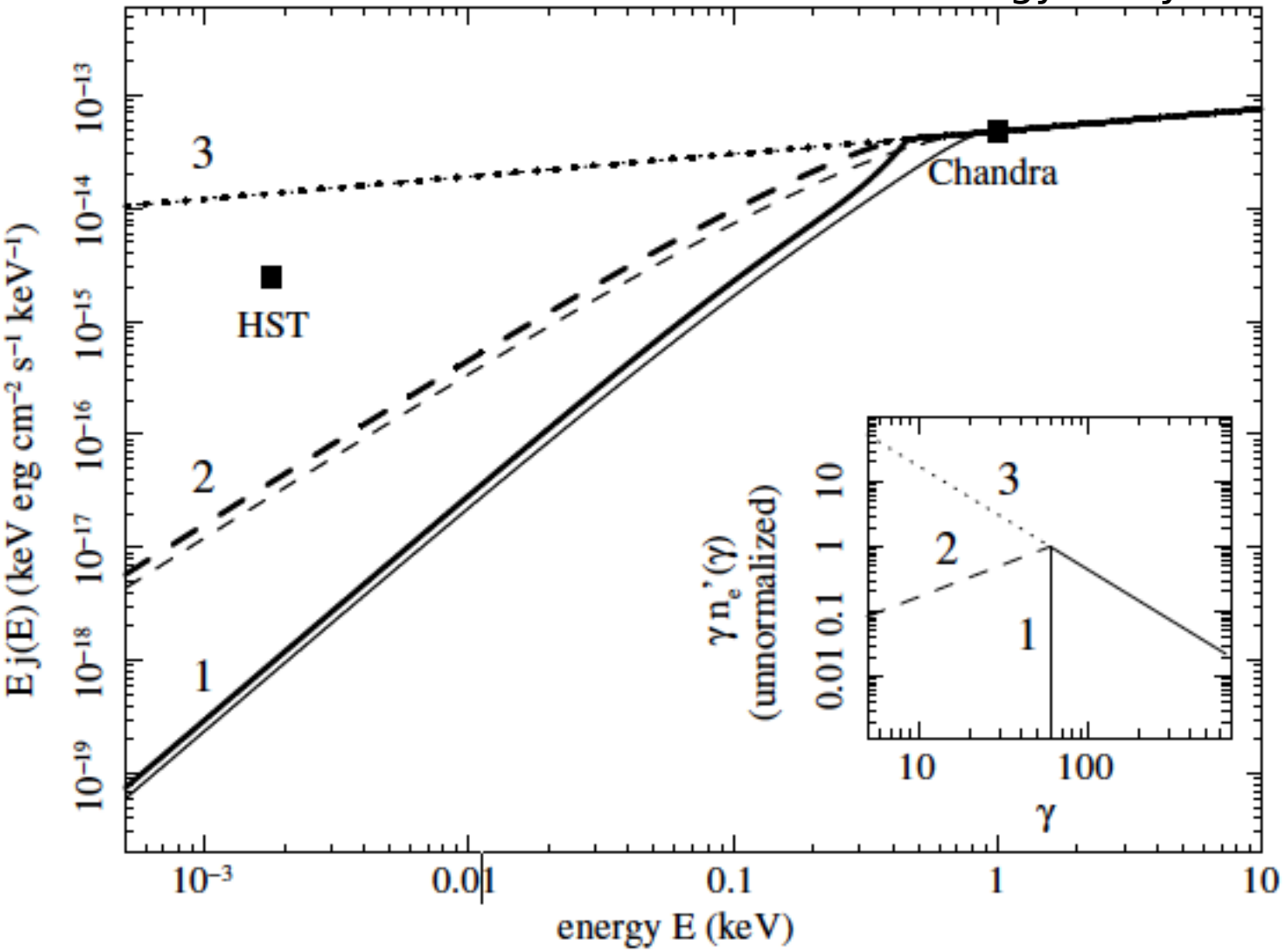
$H_{cmb} = \Gamma H_{FM}$

$H_{cmb} = H_{min}$

Unknown angle usually finessed by taking Γ=δ, or Γ= some fixed number.

Low energy cutoff to the relativistic electrons:

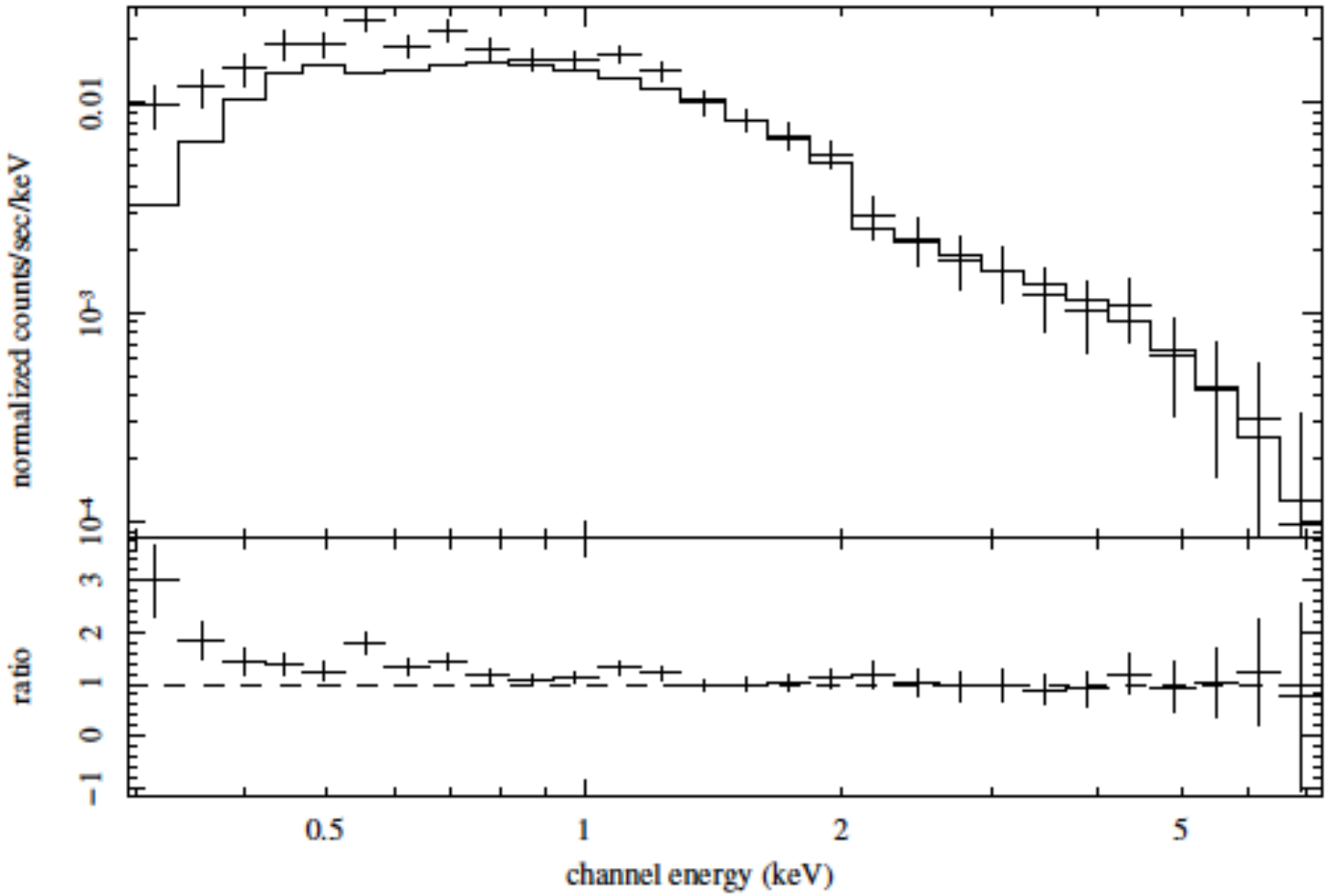
PKS 0637-752. Production of low energy X-rays.



Mueller and Schwartz, 2009ApJ...693..648

PKS 0637-752 Inverse Compton Spectrum

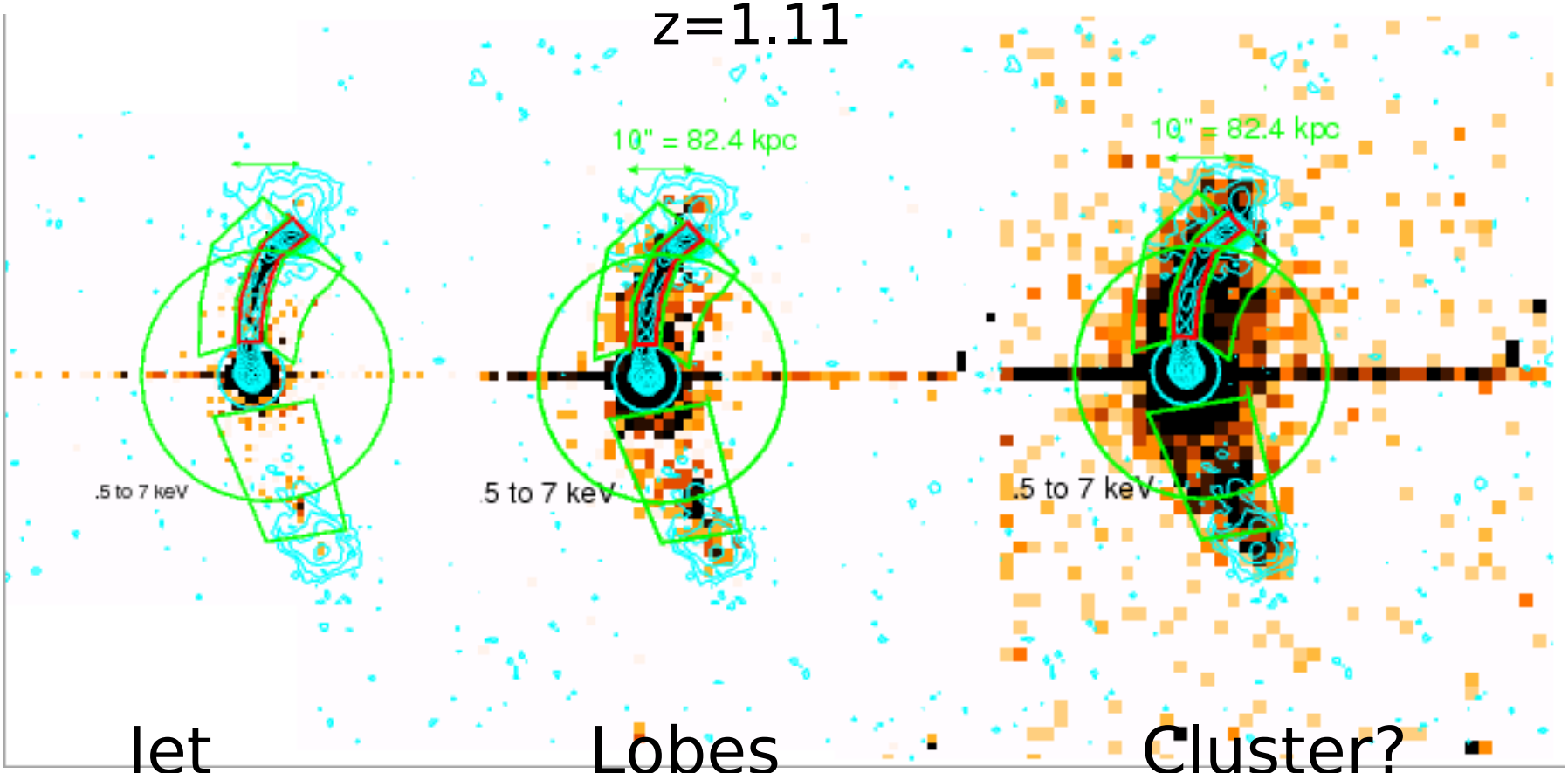
ACIS S3, pre-contamination



Mueller and Schwartz, 2009ApJ...693..648

#4. PKS 1055+210

z=1.11

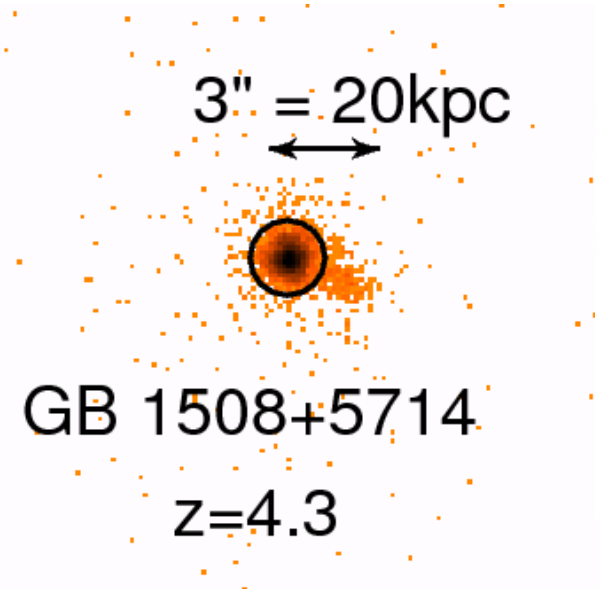


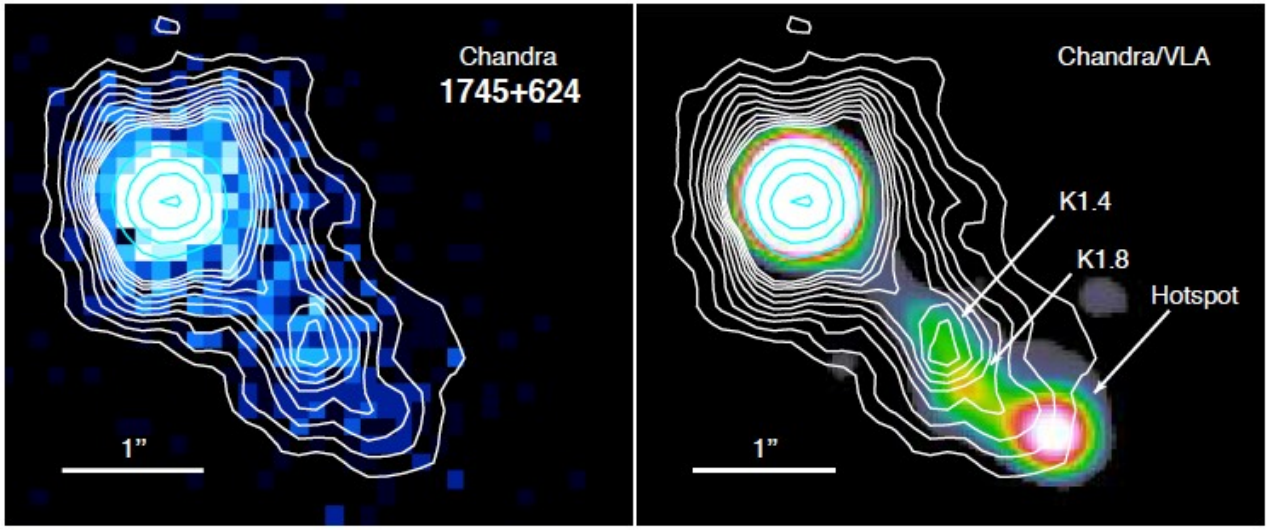
Symmetric lobes show the existence of "invisible," symmetric counterjet.

Flatter jet spectrum shows acceleration in terminal hotspot.

#3. High Redshift Jets

Cheung et al., 2006ApJ..650..679

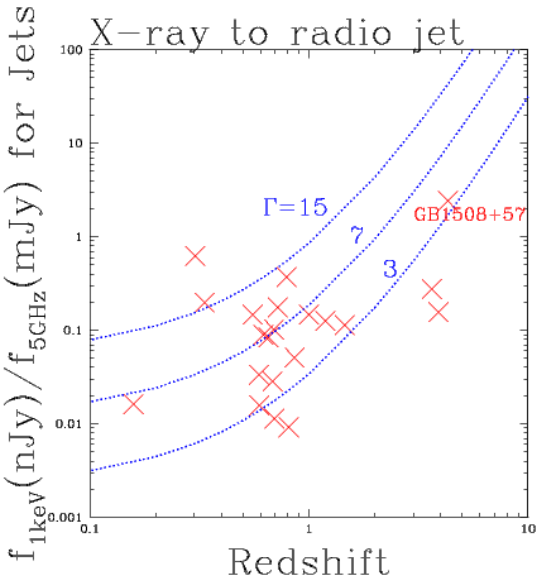




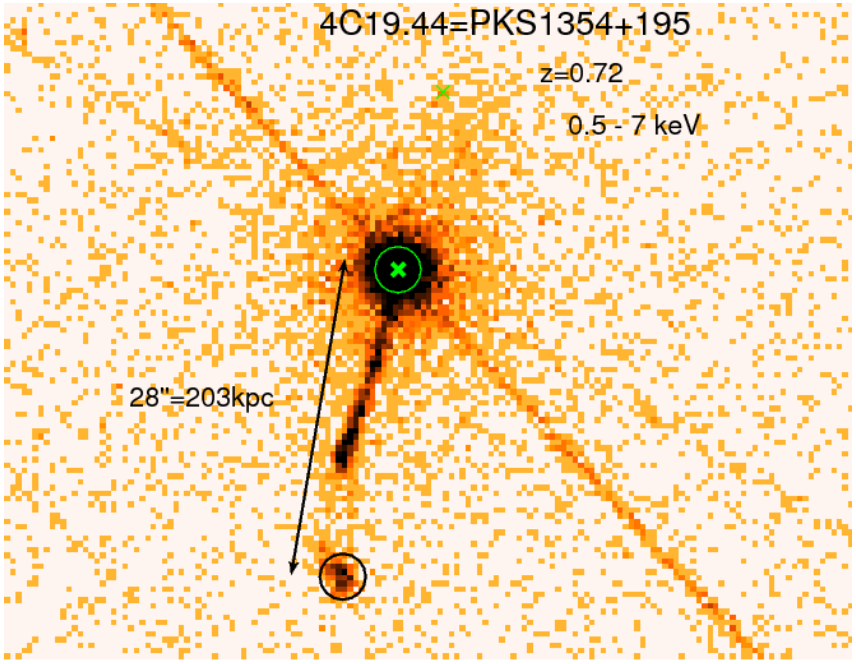
z=3.89

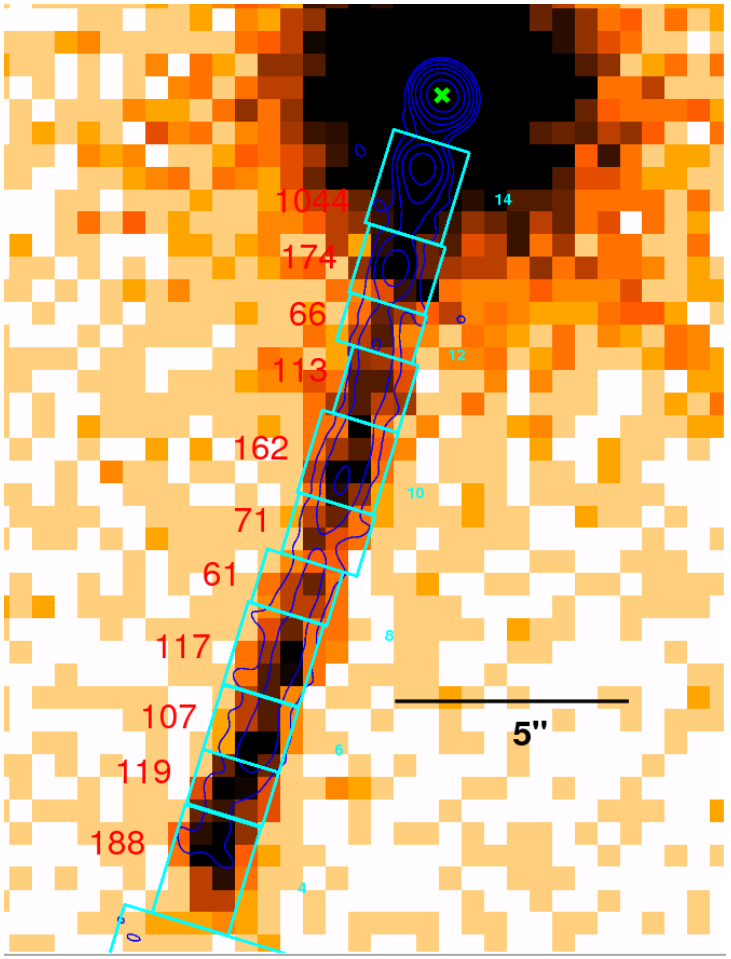
Siemiginowska et al. 2003ApJ... 598L..15

Activity in the early universe.
Ratio f_x/f_R should increase as $(1+z)^4$



#2. Calculation of Kinetic Flux: PKS 1354+195

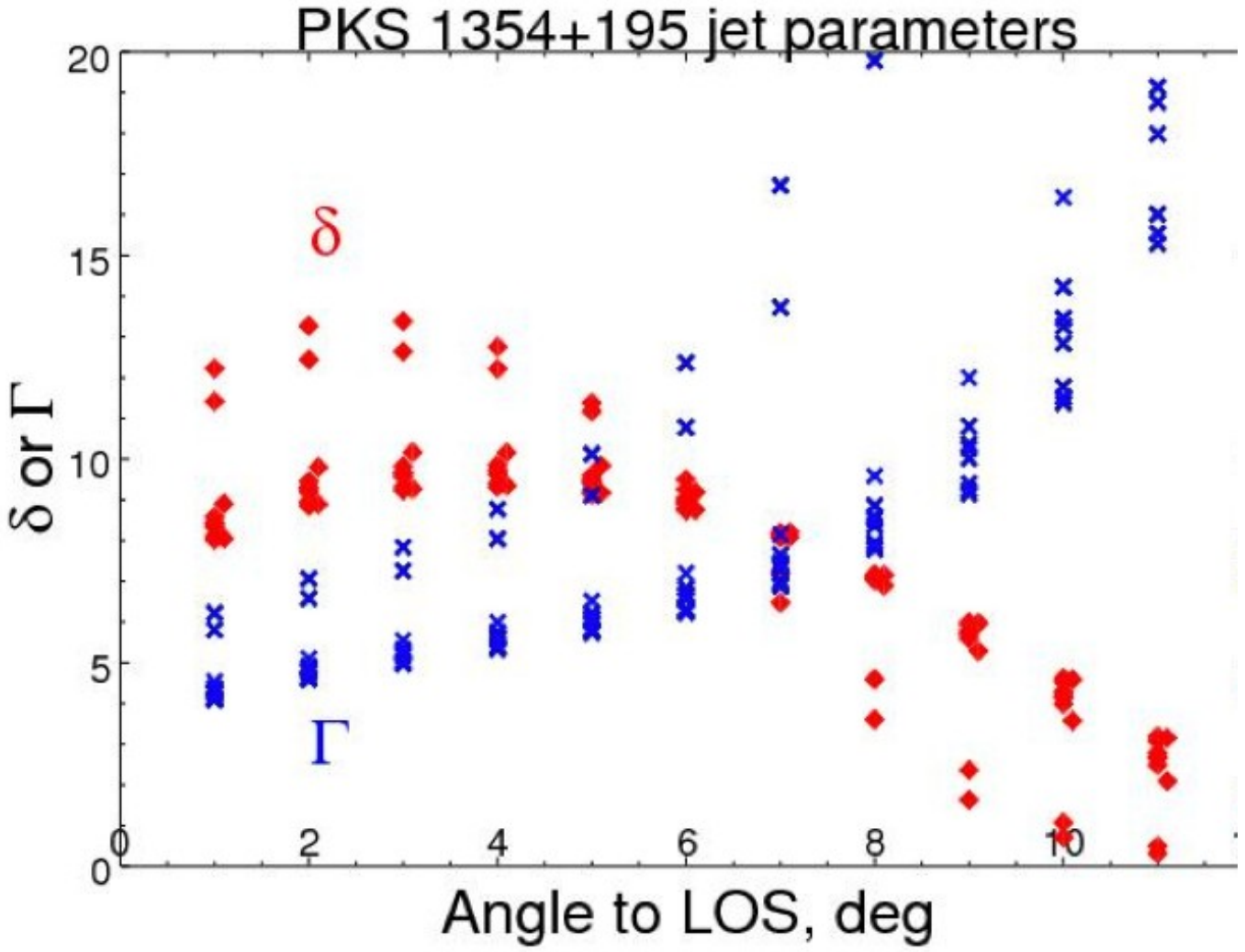




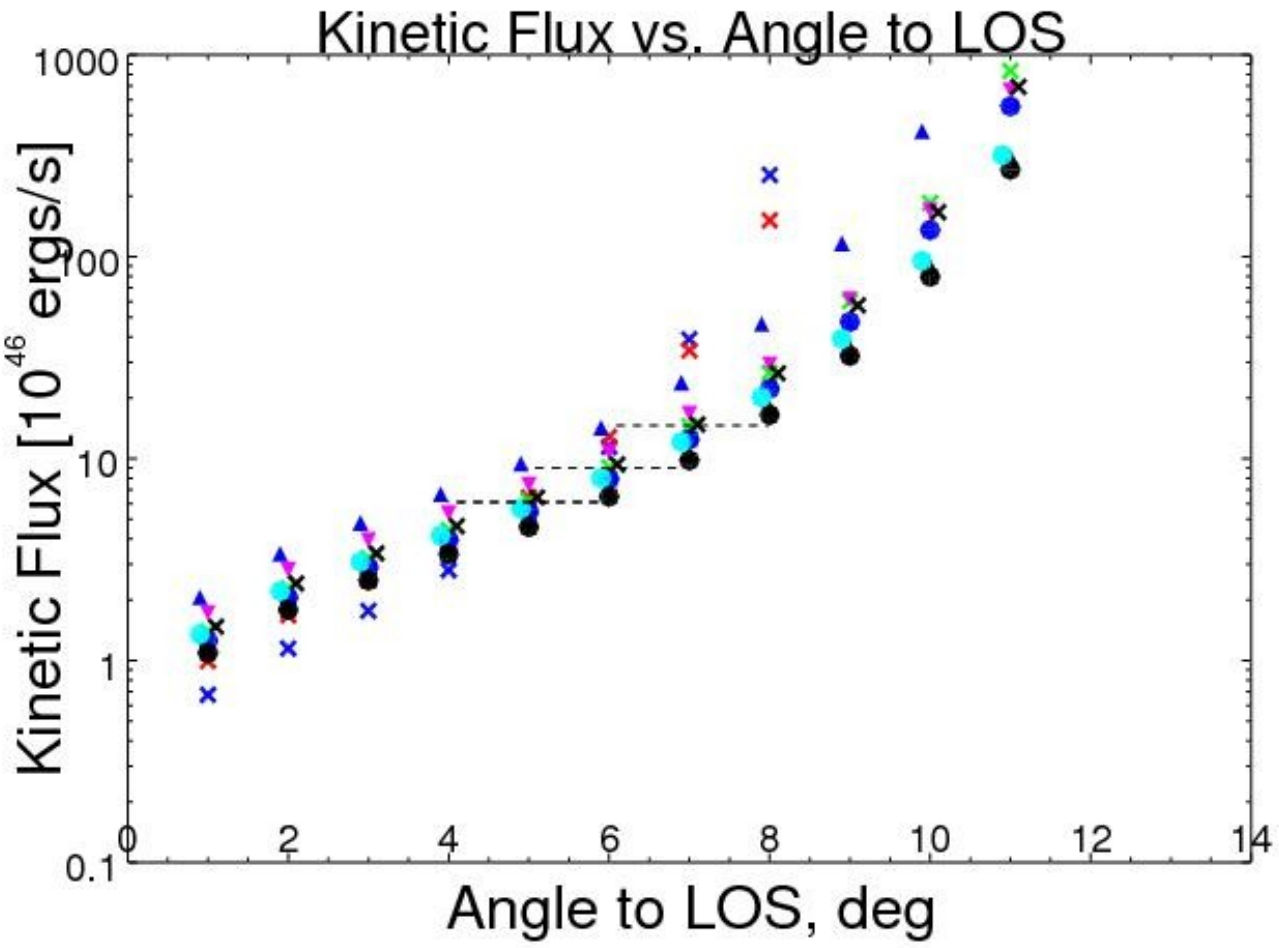
Harris et al, in preparation
Schwartz et al., in preparation

Long, straight jet. Angle and geometry may be nearly constant along jet. Allow $\Gamma \neq \delta$, assume kinetic flux is constant!

Possible Γ and δ values



Kinetic Flux: PKS 1354+195



Mean angle, 5° to 7°. Angle deviation δθ ≈ ±1°. Kinetic Flux = 9×10^{46}

Significance of the X-ray Emission

1. X-rays dominate power radiated by jet
2. SED through X-ray band provides clues to structure.
   - Acceleration sites
   - Deceleration of bulk motion
   - Proton content

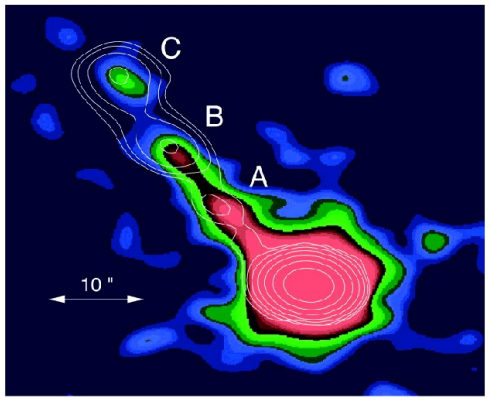
Significance of the X-ray Emission

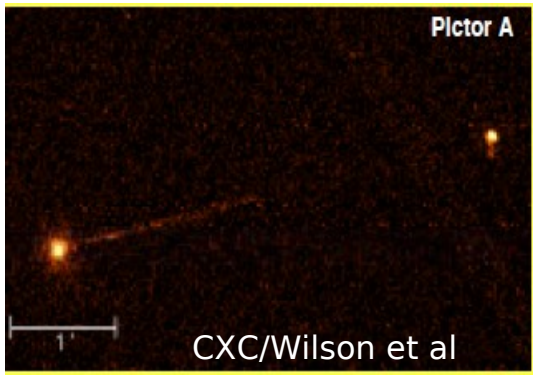
If emission is inverse Compton on the Cosmic Microwave Background:

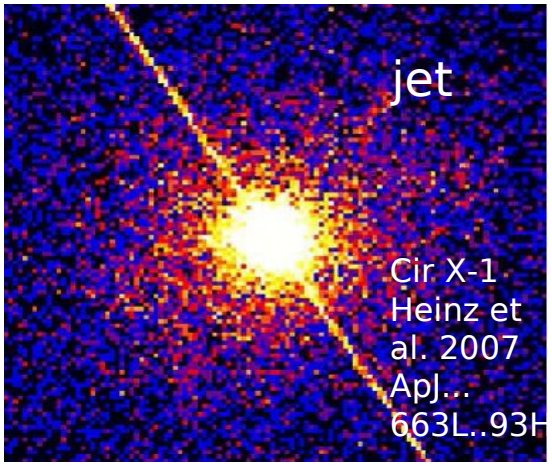
3. X-rays can give the effective Lorentz factor, rest frame B, and electron spectrum cutoff γ_{min}

4. X-ray jets will be detectable at arbitrarily large redshift!

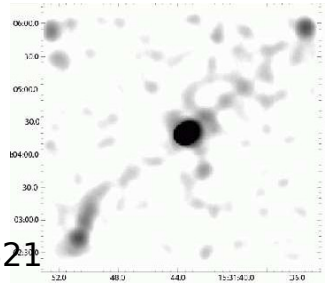
And the #1. Chandra Jet?





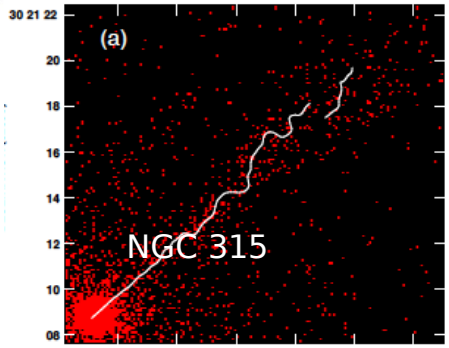


Siemiginowska et al. 2002 ApJ...570..543S
PKS 1127-145 at z=1.187

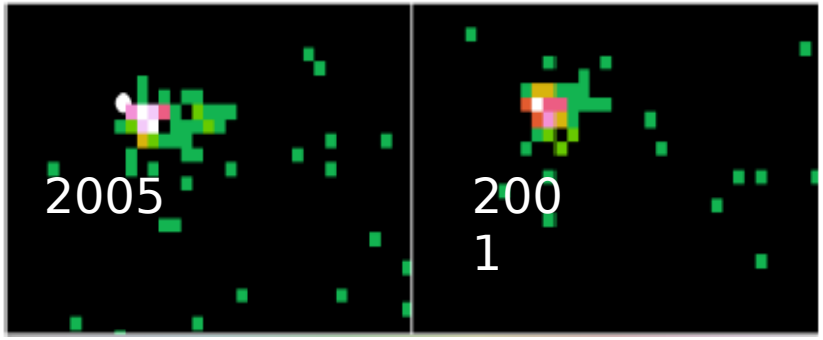


3C321

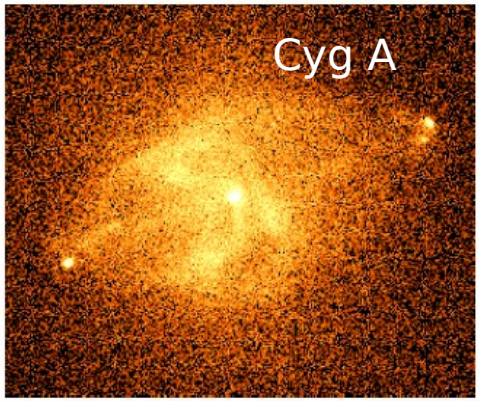
Evans et al.2008ApJ...675.1057



Worrall et al. 2007MNRAS.380....2

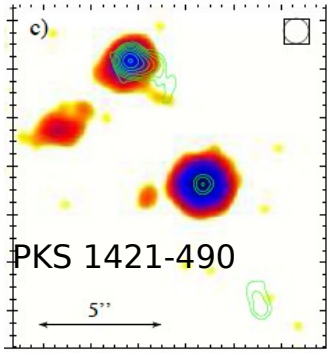


Favata et al., 2006A&A...450L..17

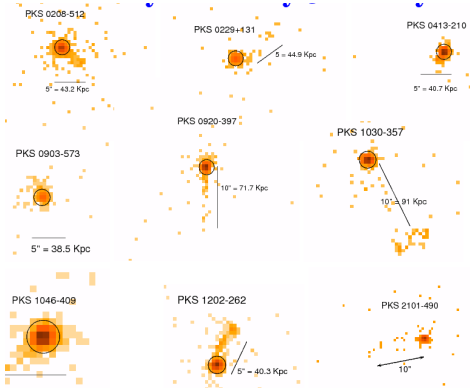


Wilson et al. 2006ApJ...644L...9

IS



Gelbord et al., 2005ApJ...632L..75



Marshall et al., 2005ApJS..156...13

YOUR NEXT OBSERVATION!

STARTING THE SECOND DECADE OF DISCOVERY WITH *CHANDRA*

Thank you!

NORTHROP GRUMMAN ITT

Smithsonian Astrophysical Observatory

Chandra X-ray Center

NASA

Harvard College Observatory
Harvard University