Evolution of the AGN jet energetics revealed with the *Suzaku* observations of giant radio galaxies

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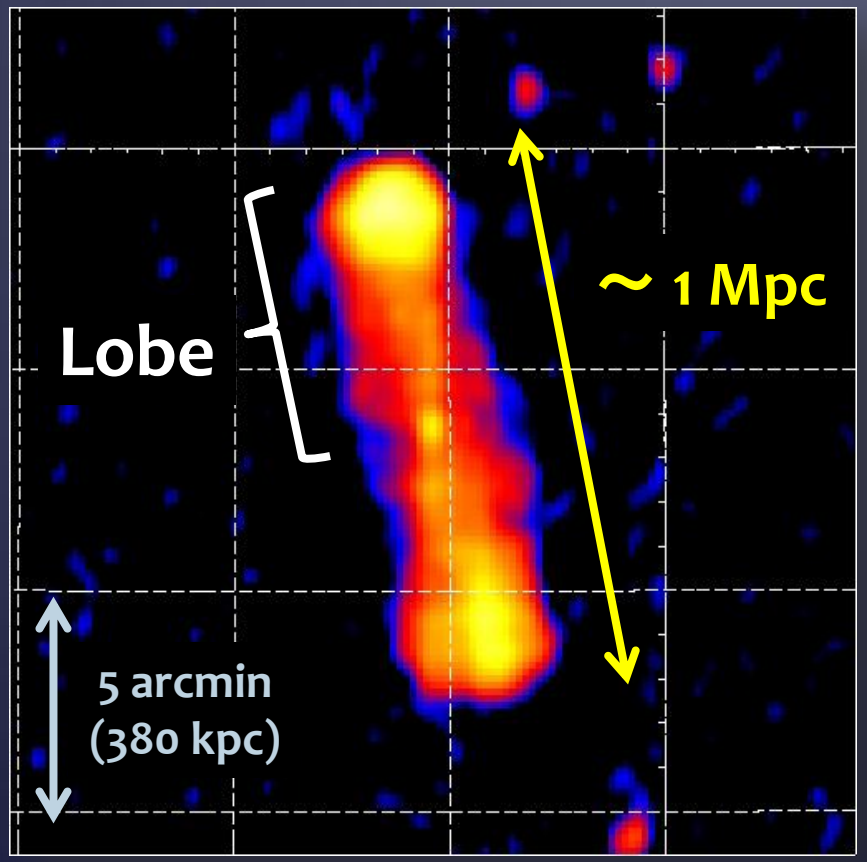
Giant Radio Galaxies (GRGs)

- Giant Radio Galaxies (GRGs)
  - Total linear size $D \gtrsim 1$ Mpc
  - Age $\tau_{age} \sim 100$ Myr (Schoenmakers et al. 2000)
  - The late phase in the evolution of jets can be explored from GRGs.

  How long does an AGN jet continue to be in an active phase ?

- Lobes of FR II radio galaxies
  - The bulk jet power is integrated, in the forms of non-thermal-particle and magnetic-field energies.
  - **An important indicator of the past jet activity**

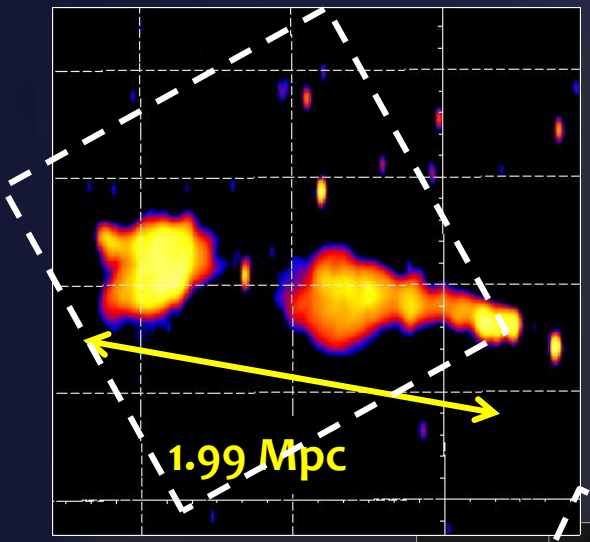


3C 35 @ 608.5 MHz
(http://www.hj.man.ac.uk/atlas/)

IC/CMB technique

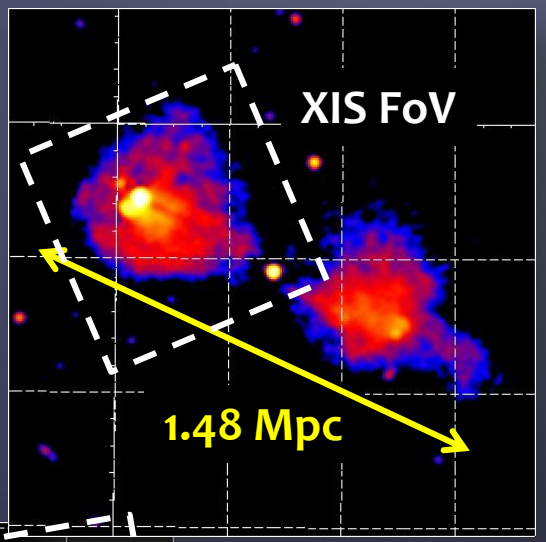
- Evaluation of the electron and magnetic energy densities (*U*e and *U*m) in lobes
  - Synchrotron radio flux $\propto$ *U*e *U*m
  - CMB-boosted Inverse-Compton (IC/CMB) X-ray flux $\propto$ *U*e U_{CMB}
- Previous Studies
  - *ASCA* (e.g., Kaneda et al. 1995)
  - *Chandra* (e.g., Isobe et al. 2002, Croston et al. 2005)
  - *XMM-Newton* (e.g., Isobe et al. 2005, 2006)
  - Limited to radio galaxies with $D \lesssim 500$ kpc
- Advantages of *Suzaku* XIS
  - Low and stable instrumental background (Tawa et al. 2008)
  - Well-calibrated response (rmf and arf), even for diffuse X-ray sources
  - Reasonable field of view (17'.8 x 17'.8)

Our Suzaku targets

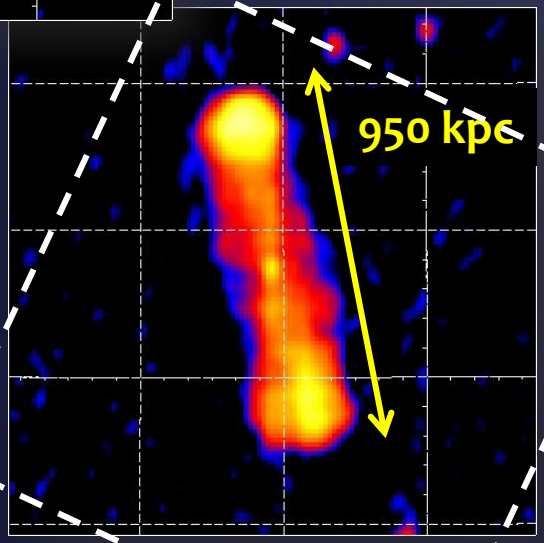


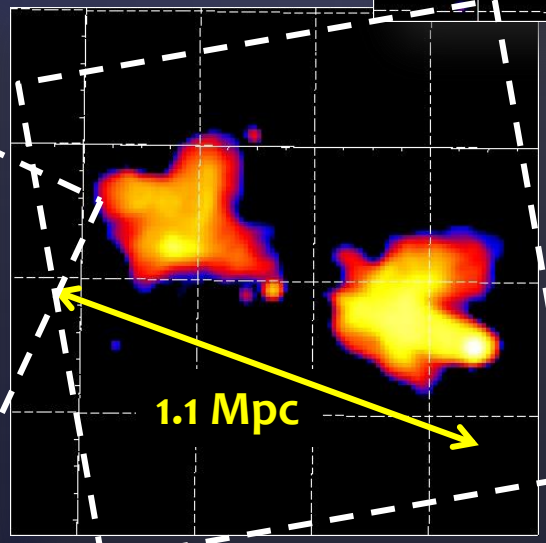
3C 326
(1.4 GHz)
z = 0.0895

DA 240
(608.5 MHz)
z = 0.03566



Radio images from 3CRR ATLAS
(Leahy, Bridle, & Strom;
http://www.jb.man.ac.uk/atlas)

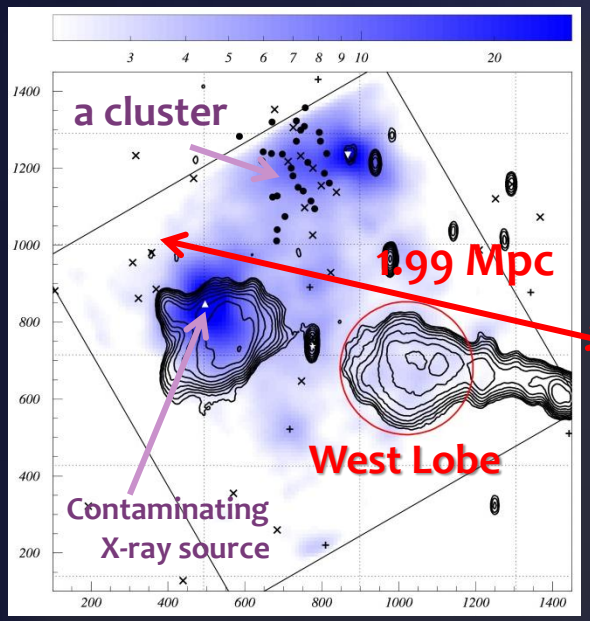




3C 35
(608.5 MHz)
z = 0.0670

4C 73.08
(1.4 GHz)
z = 0.0581

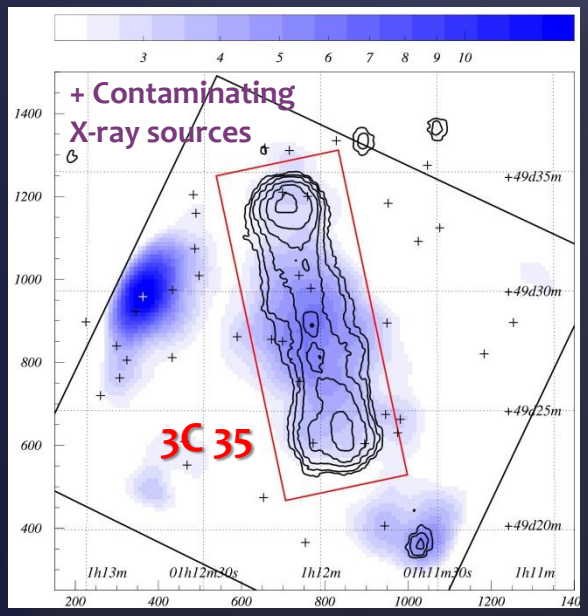
Suzaku XIS Images

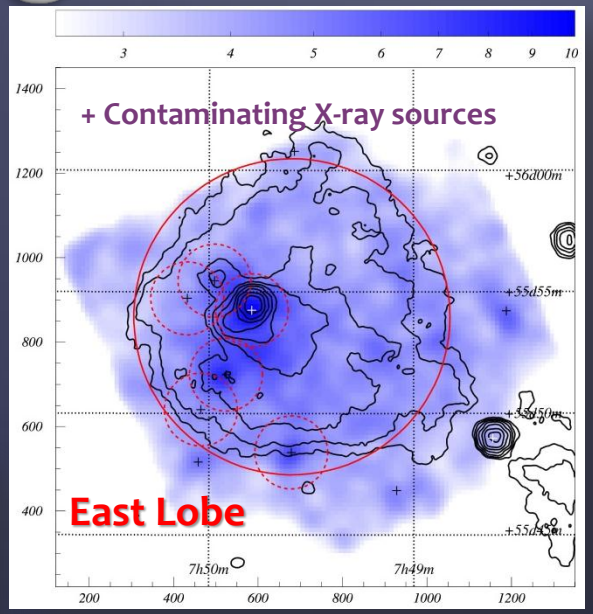


3C 35

(Isobe et al. 2011a, ApJ, 727, 82)

- XIS 0.5 – 5.5 keV (blue)
- 608.5 MHz (contours)





3C 326

(Isobe et al. 2009, ApJ, 706, 454)

- XIS 0.5 – 5 keV (blue)
- 1.4 GHz (contours)

Largest "IC/CMB-X-ray" lobe

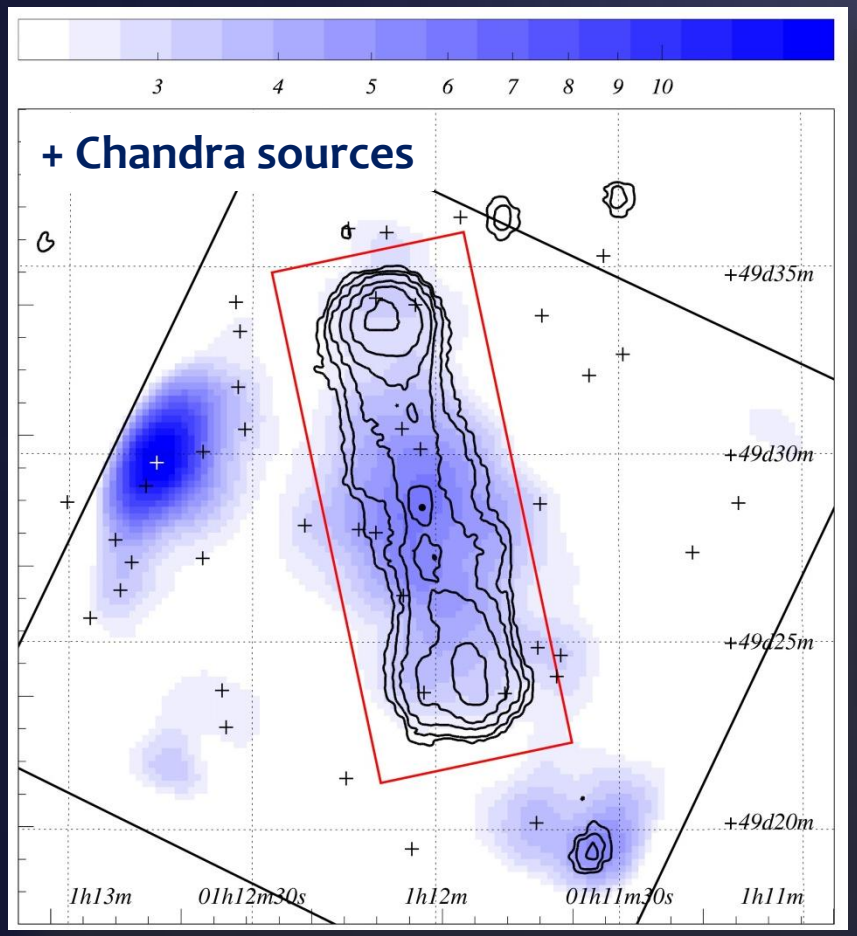
DA 240

(Isobe et al. 2011b, arXiv:1105.3473, PASJ 4th Suzaku issue)

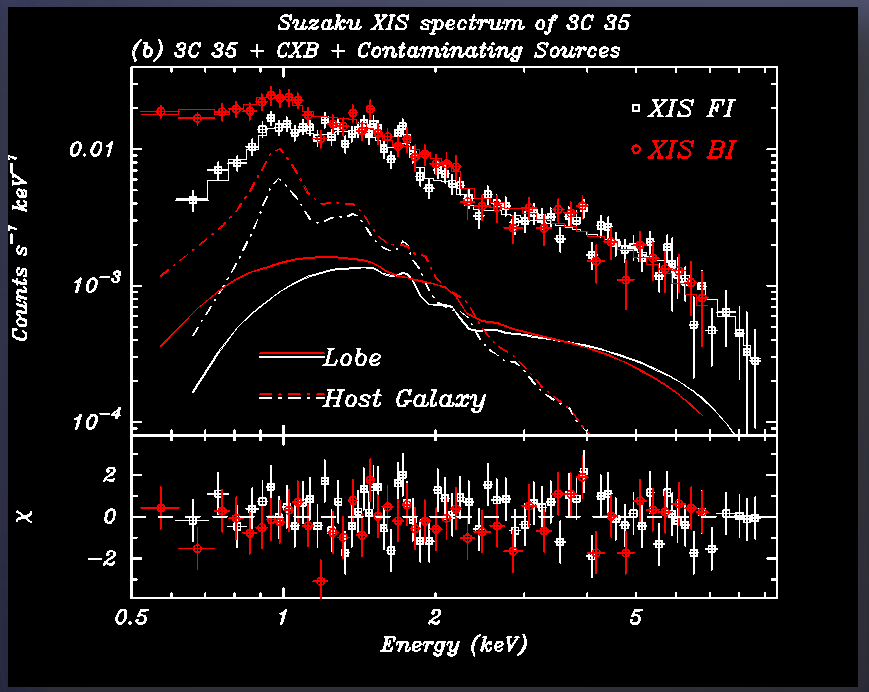
- XIS 0.5 – 10 keV (blue)
- 608.5 MHz (contours)

Suzaku Results on 3C 35

✓ Suzaku XIS image in 0.5 – 5.5 keV



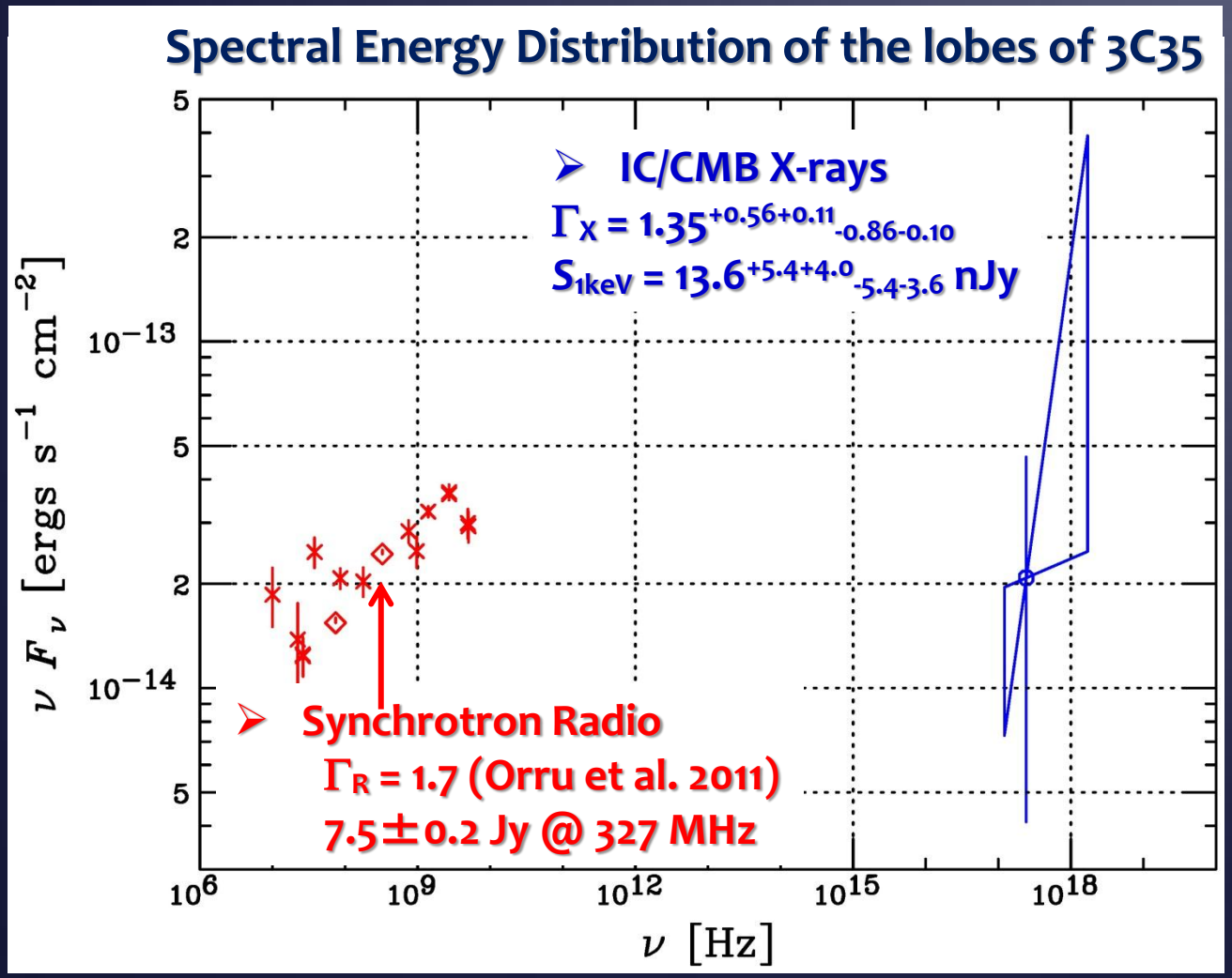
✓ NXB-subtracted XIS spectrum



Lobe Component

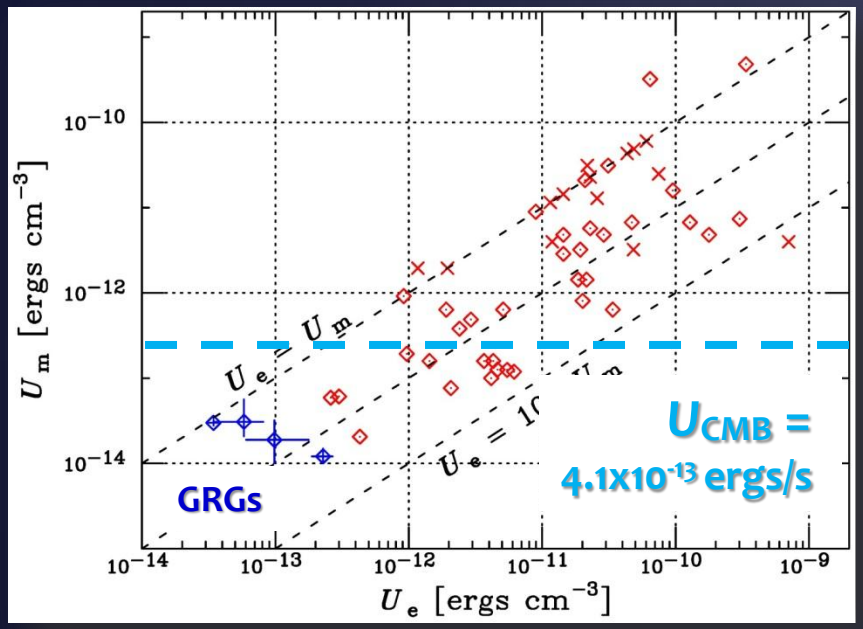
- Photon Index $\Gamma = 1.35^{+0.56+0.11}_{-0.86-0.10}$
- Flux density $S_{1keV} = 13.6^{+5.4+4.0}_{-5.4-3.6}$ nJy

Suzaku Results on 3C 35



Energetics in Lobes

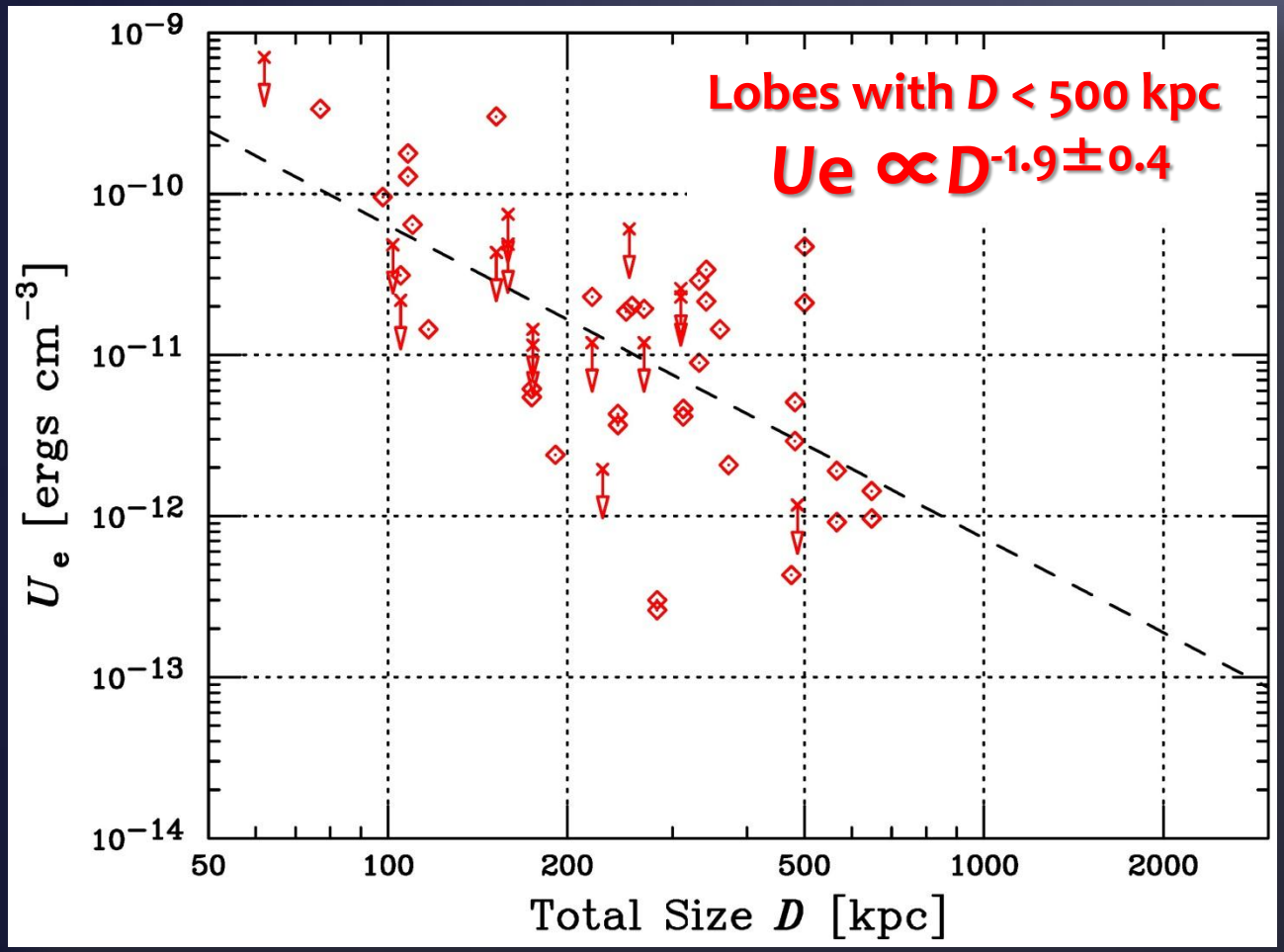
✓ *Ue-Um* relation in Lobes



(Isobe et al. 2009, 2011a, 2011, Croston et al. 2005, and reference therein)

- Lobes with $D \lesssim 500$ kpc
  - $Ue = 2 \times 10^{-13} - 10^{-9}$ ergs/cm^3
  - $Um = 2 \times 10^{-14} - 10^{-9}$ ergs/cm^3
  - $Ue/Um \sim 10$ (1 - 100)
    ($B/Beq = 0.3 - 1.3$)
- GRGs lobes with $D \gtrsim 1$ Mpc
  - $Ue \lesssim 3 \times 10^{-13}$ ergs/cm^3
  - $Um \lesssim 3 \times 10^{-14}$ ergs/cm^3
  - $Ue/Um \lesssim 10$
  - $Um < U_{cmb} = 4.1 \times 10^{-13} (1+z)^4$ ergs/cm^3
    (equiv. to $B = 3.2 (1+z)^2$ μG)
    - IC/CMB is the dominant cooling process in the lobes of GRGs

Evolution of Jet/Lobe Energetics



Evolution of Jet/Lobe Energetics

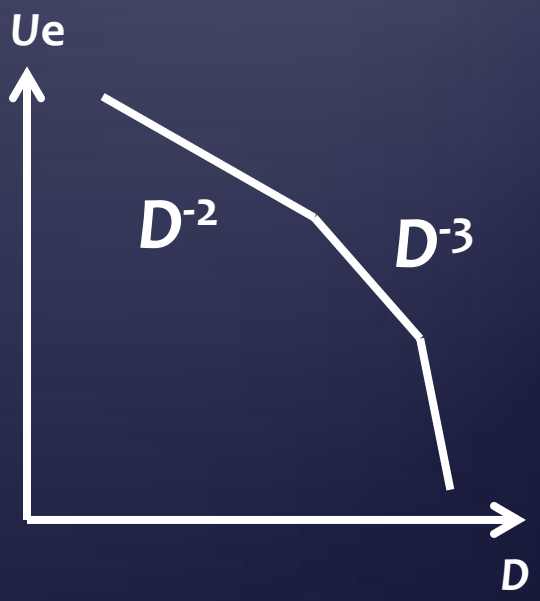
- Phase 1 : Lobe expansion with a constant jet power P_{jet}
  - Total Energy in the lobe $E \propto \tau_{age} P_{jet}$
  - Size $D \propto v_{jet} \tau_{age}$ (v_{jet} : jet velocity)

  $\Rightarrow Ue + Um = E / V \propto E / D^3 \propto \tau_{age}^{-2} P_{jet} \propto D^{-2} P_{jet}$

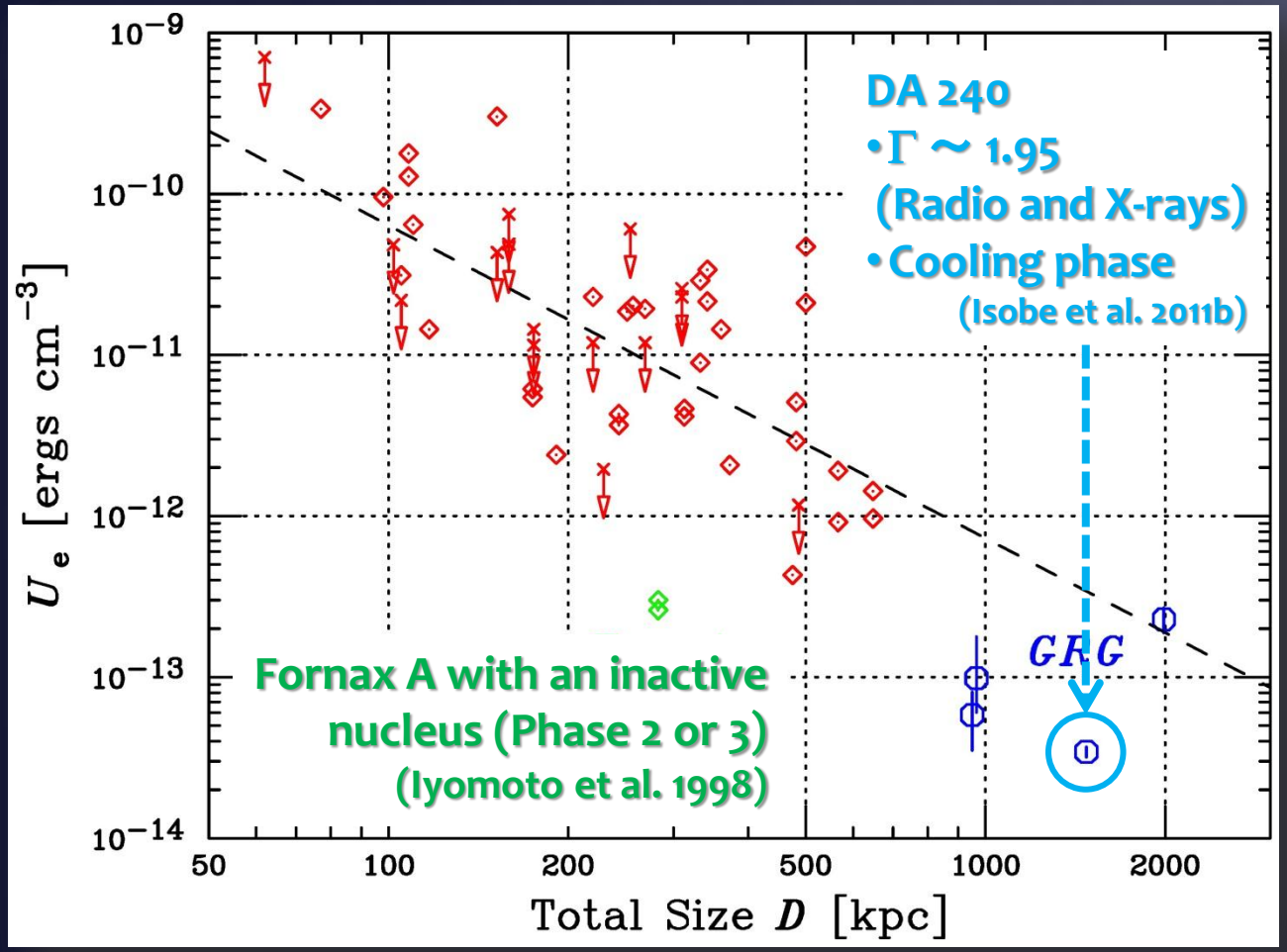
- Phase 2 : Lobe expansion with no input
  - Total energy E is conserved

  $\Rightarrow Ue + Um = E / V \propto D^{-3}$

- Phase 3 : Cooling dominant
  - *Ue* and *Um* should rapidly decrease.



Evolution of Jet/Lobe Energetics



- GRGs tend to exhibit lower *Ue* in comparison with the trend of the radio galaxies with $D \lesssim 500$ kpc.
- This indicates that GRGs reside in Phase 3 (or 2).
- A significant decrease in the jet activity typically from D = 500 kpc to 1 Mpc

Other support for the declined jet/nuclear activity in GRGs

- **Low nuclear X-ray luminosity**
  - $L_X < 10^{41}$ ergs s^{-1} for 3C 35, DA 240 (This work, Evans et al. 2008)
  - $L_X < 10^{42}$ ergs s^{-1} for 3C 326
- **No significant [OIII] line**
  - 3C 326 (Saunders et al. 1998)
- **No significant jet feature in radio**
  - 3C 35 (Mullin et al. 2008)

Summary and Conclusions

- *Suzaku* observations of 3 GRGs ($D \gtrsim 1$ Mpc)
  - IC/CMB X-ray emission was significantly detected from their lobes, thanks to the low and stable BGD of the *Suzaku* XIS
- *U*e and *U*m in the lobes of GRGs, estimated from the IC/CMB technique
  - *Ue*/*Um* $\lesssim 10$
    - *Ue*/*Um* $\sim$ 10 for radio galaxies with D < 500 kpc
  - *Um* < U_{CMB}
    - IC/CMB is the dominant cooling process in the lobes of GRGs
- Evolution of Jet/Lobe energetics, examined from the *D*-*Ue* relation.
  - *Ue* $\propto D^{-1.9\pm0.4}$ for the radio galaxies with *D* < 500 kpc.
    - Consistent with expansion with a constant jet power.
  - *Ue* in the lobes of GRGs is by an order of magnitude lower than the value estimated from the *Ue*-*D* relation for the *D* < 500 kpc sources.
    - A significant reduction in the jet power, as radio galaxies evolve from *D* = 500 kpc to 1 Mpc
    - Low X-ray luminosity of the GRG nucleus supports this idea.