X-ray Observations of Cosmic Accelerators

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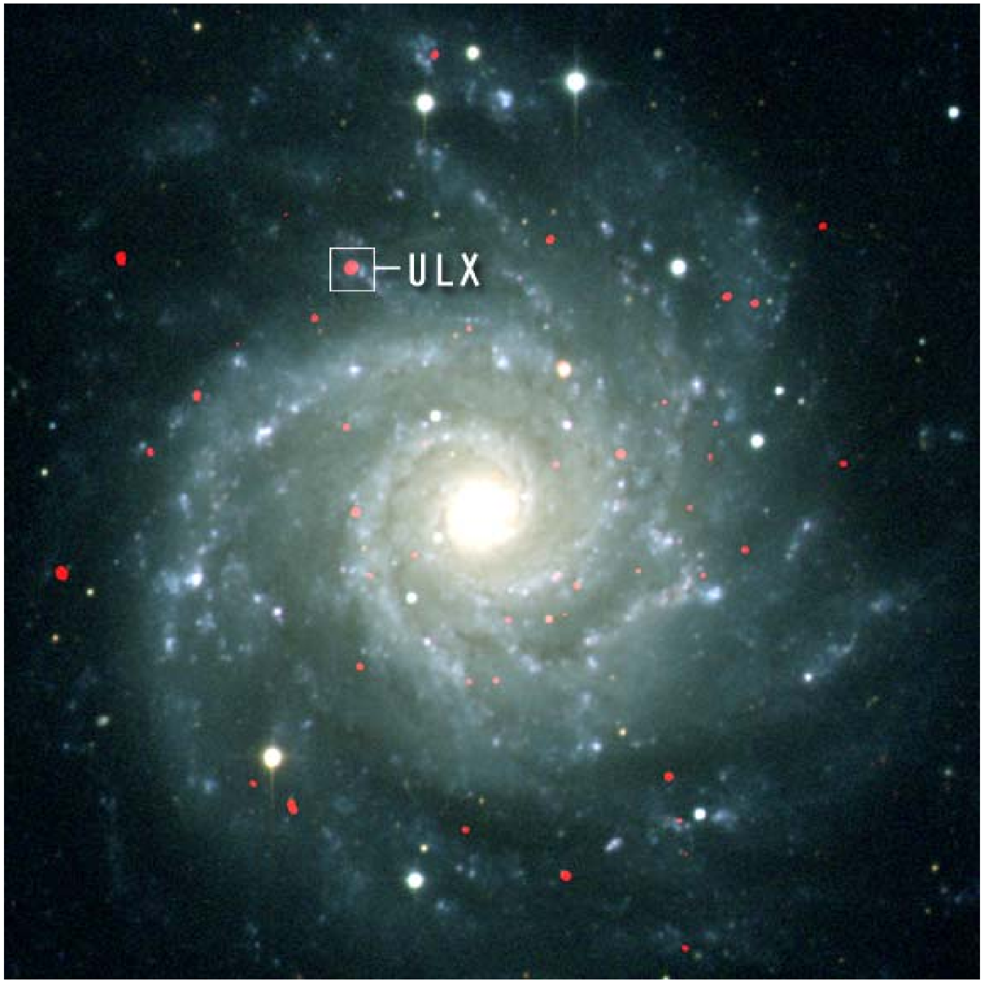
Outline:

- Continuing on the case studies and “X-ray insights”
  into the questions of particle acceleration in the cosmos

- Today: - active galaxies and relativistic jets
  - clusters of galaxies

Active galaxies and strong gravity



“Normal” galaxy M74

- Many galaxies contain exceptionally bright nuclei that are also point-like sources of radio and X-ray emission
- In some cases, the nuclei are so bright that the galaxy can be barely detected
- We now believe that the origin of this emission is the release of gravitational energy by matter flowing onto a supermassive black hole, with a mass of 10^6 or more times the Sun

Active Galactic Nuclei: the "working picture"

- Discovery of active galaxies – a.k.a. quasars - was one of the successes of astronomy outside of the visible band (optical IDs of radio sources, high redshifts -> large distances)
- Active galaxies are bright and given their large distances, very luminous
- Our best model for *all* active galaxies includes the same basic ingredients: a black hole accreting via disk-like structure, located in the center of a galaxy: this emission is mostly isotropic
- In *some* active galaxies the radiation is dominated by emission from relativistically boosted jet, so bright that the jet outshines the isotropic emission
- *Connection to the jet one of the central questions of the AGN research*

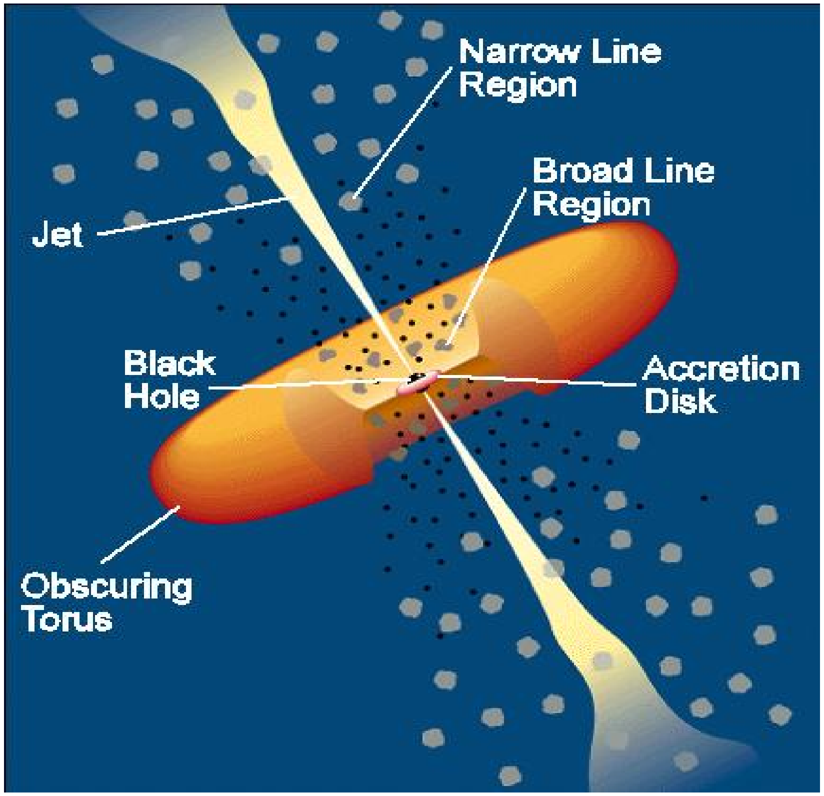
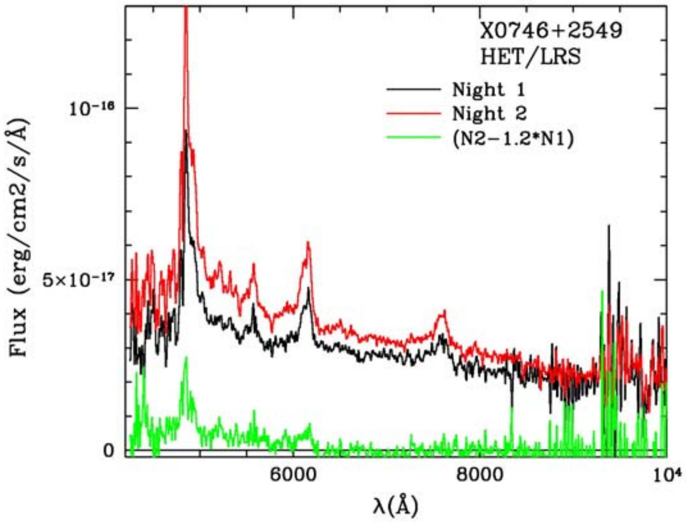
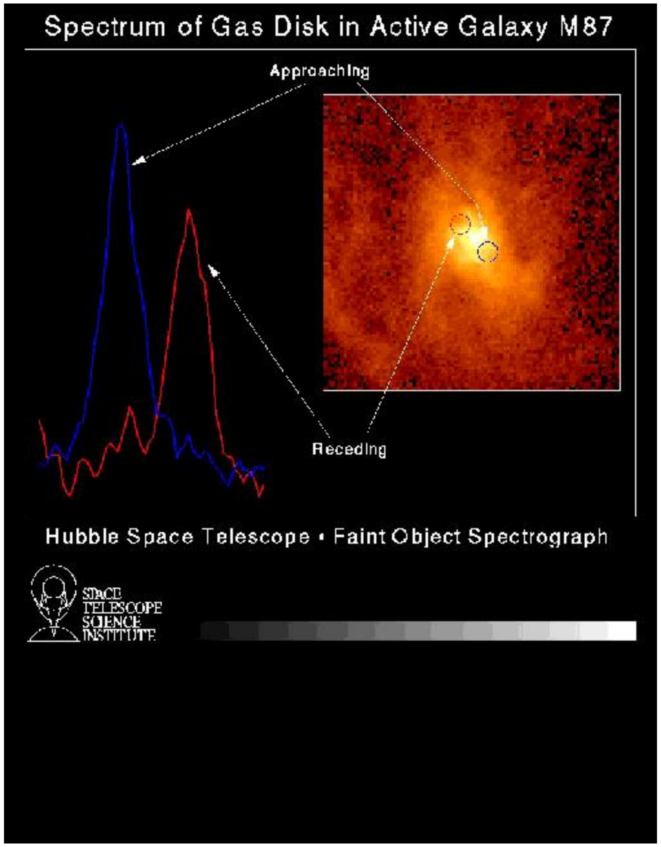


Diagram from Padovani and Urry

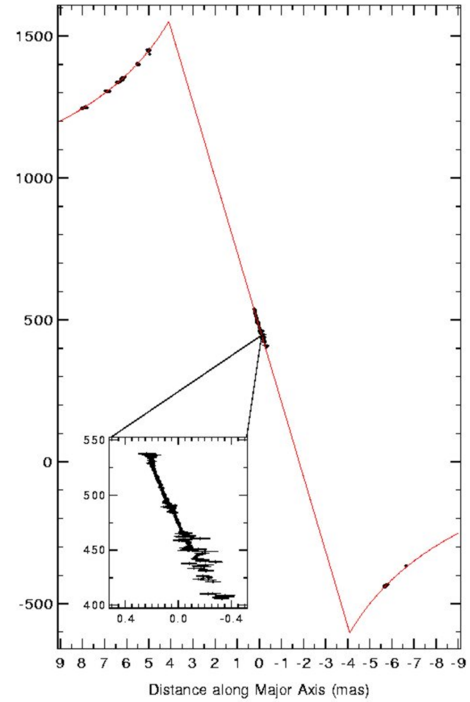


Optical spectrum of a high-redshift quasar 0746+25

Weighing the central black hole

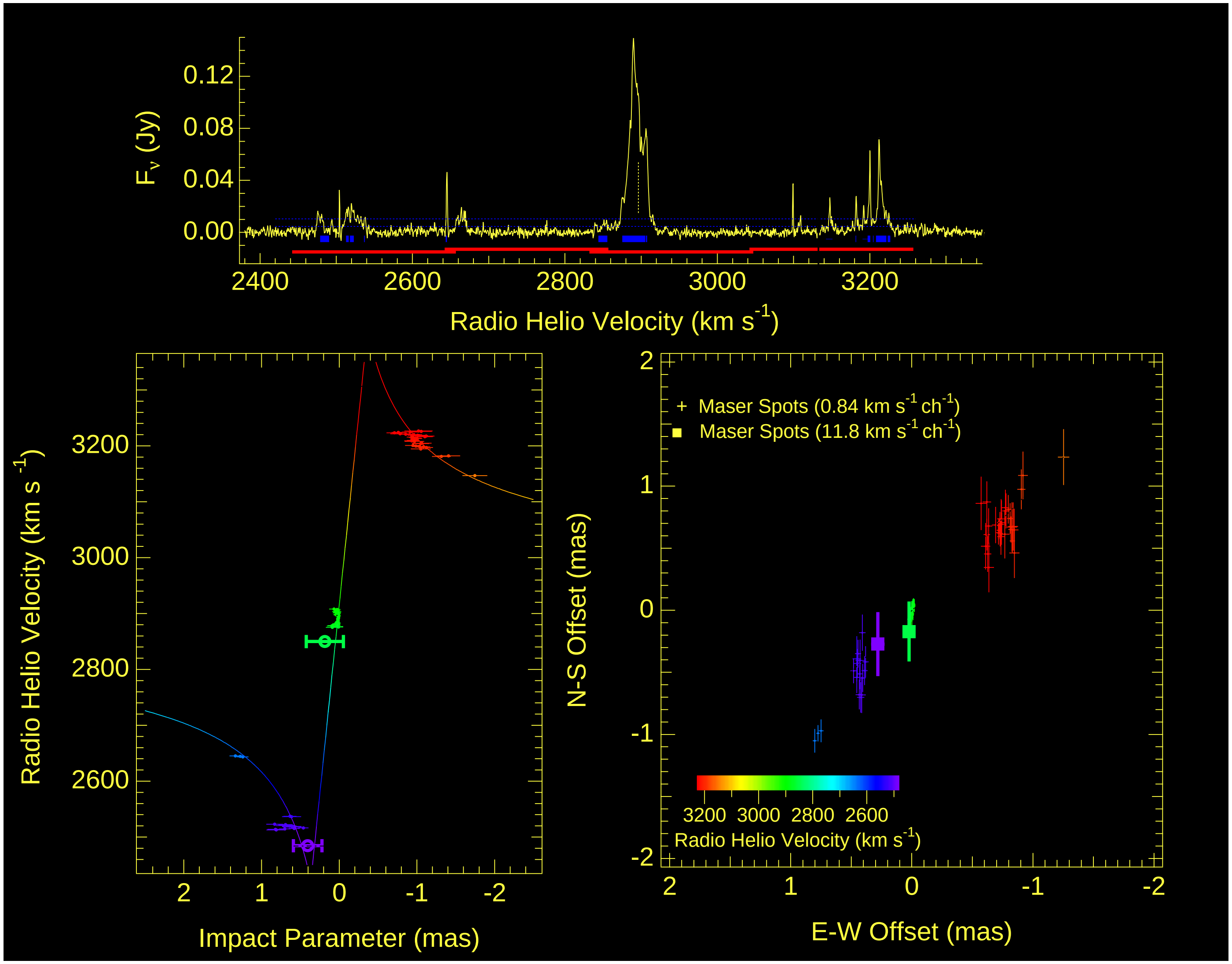


Radio galaxy M87 (Virgo-A) studied with the Hubble Space Telescope



Seyfert galaxy NGC 4258 studied using H_2O megamaser data (Miyoshi et al. 1995)

- Black holes are a common ingredient of nearly all (!) galaxies
- When “fed” by galaxian matter, they shine – or produce jets – or both
- The BH mass is very important to understand physical processes involved



Vital characteristics of AGN IC 2560:

***Distance: 26 Mpc**

******Inner radius*** **of megamaser spots: 0.07 pc**

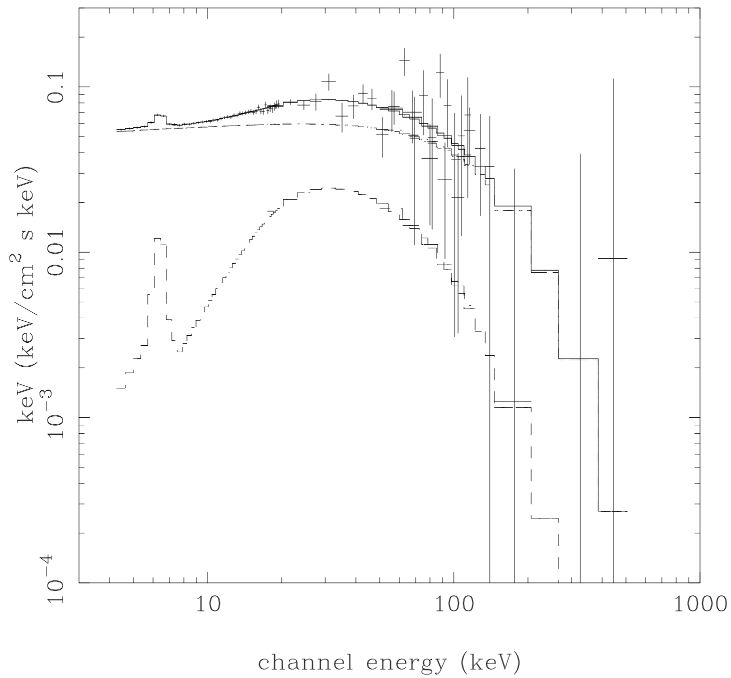
******Outer radius:*** **0.26 pc**

***Very disk-like (no warp)**

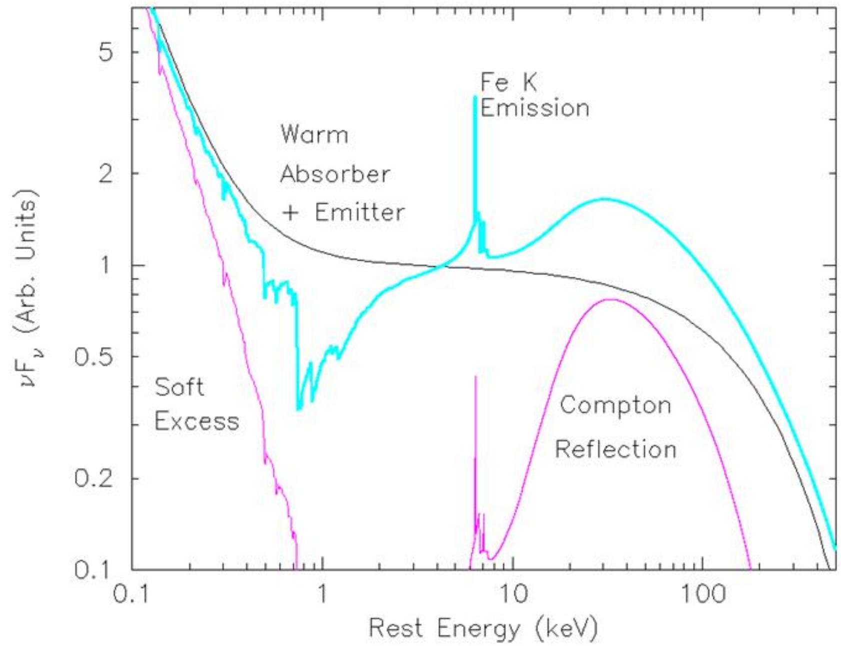
Second high-quality example: after the “archetypal” NGC 4258:
IC 2560 (Greenhill, Madejski, …) - black hole mass: 2.8×10^6 M_o

Megamasers important – can provide an independent measures of the Hubble constant

"Central engine" – clues from the X-ray spectra of AGN



Asca, XTE, OSSE data for bright AGN IC 4329a (from Done, GM, Zycki 2003); average spectrum of ~20 AGN looks essentially the same

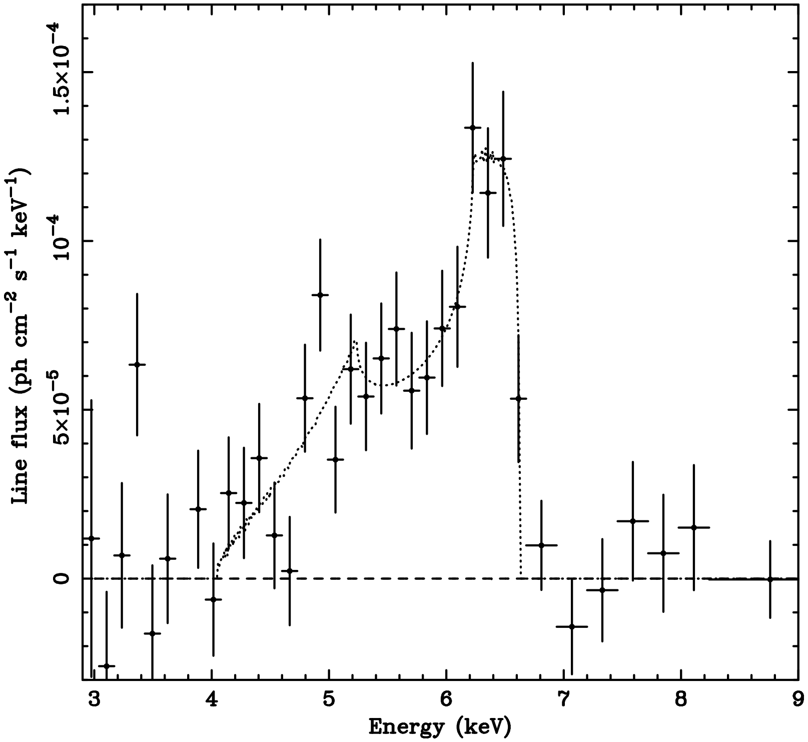


Origin of the individual ingredients of the X-ray spectrum

- General description of the broad-band intrinsic X-ray spectrum of a "non-jet" emission from an AGN is a power law w/photon index ~ 2 & exponential-like cutoff at ~ 200 keV, modified by "environmental effects" (absorption, Compton reflection from the accretion disk, …

Iron K line as a probe of the innermost regions of the accretion region

Asca X-ray spectrum of the Fe K line region for an active galaxy MCG-6-30-15
(from Tanaka et al. 1995)

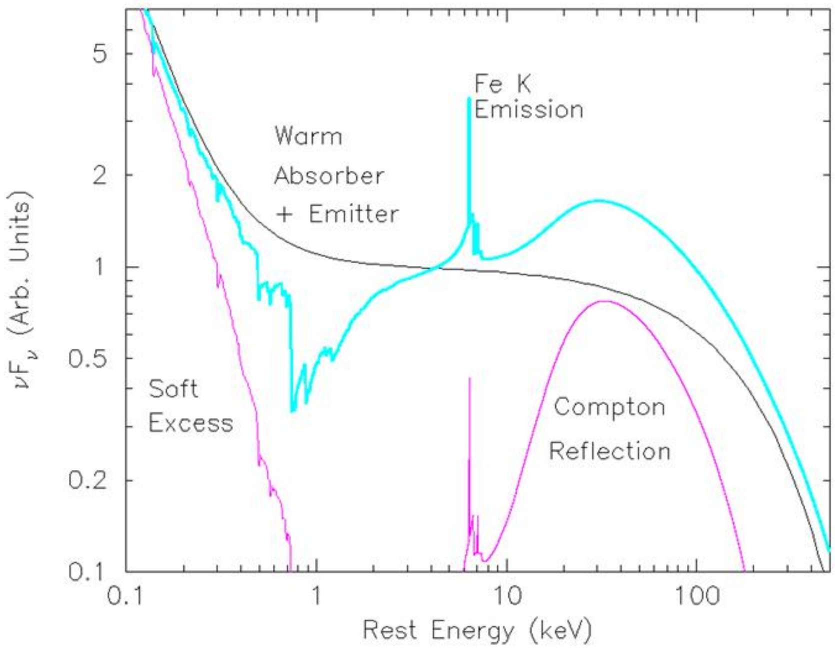


Fe K emission line (n=2 -> n=1) is a great tool to study the kinematics of the accreting material:

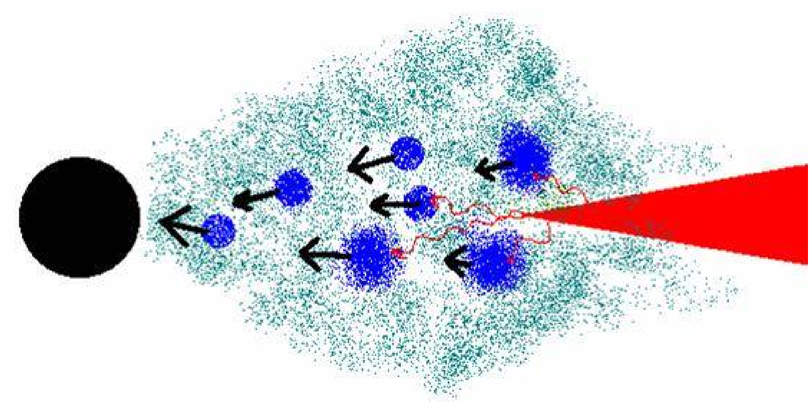
* relatively simple atomic physics,
* high fluorescence yield with appreciable abundances,
* no contamination by other elements, ...

Profile of the Fe K line in the active galaxy MCG-6-30-15 measured with the ASCA satellite (Tanaka et al. 1995) shows a red wing expected in strong gravity

“Central engine” – clues from the X-ray spectra of AGN



Origin of the individual ingredients of the X-ray spectrum



Model: black hole, (red) disk, (blue) corona

* Spectral formation: multiple Compton scattering of soft accretion disk photons by trans-relativistic corona with kT ~ 100 keV:

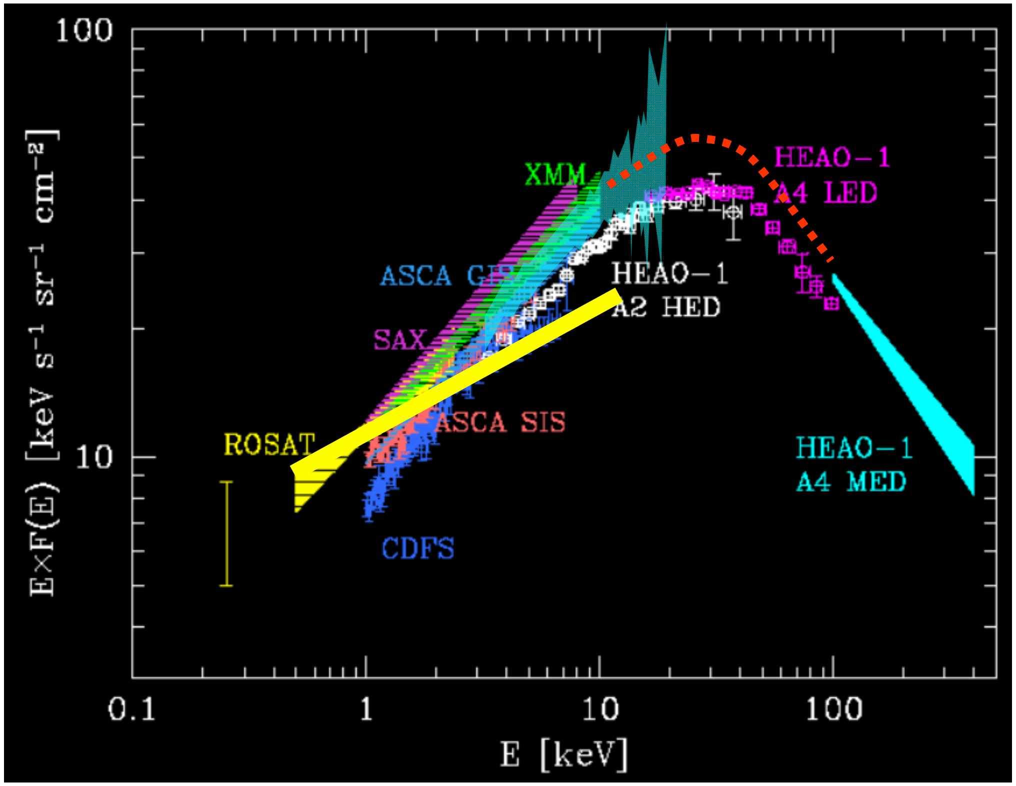
  -> “scaled-up” Galactic black hole binaries

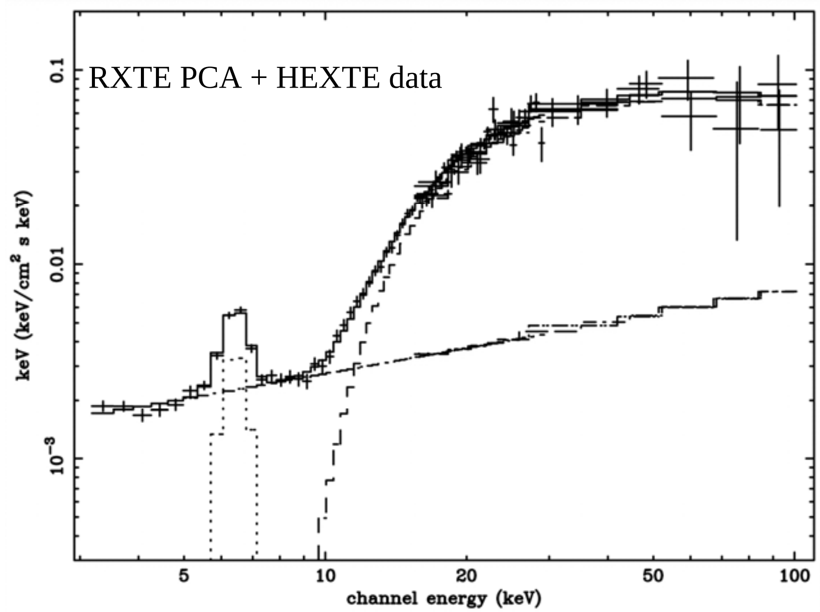
* As in the Galactic binaries: what heats / accelerates the electrons in the corona?

Heavily obscured AGN "hiding in the dust": Important ingredient of the Cosmic X-ray Background?

Spectrum of the CXB at E> 5 keV is hard, cannot be due to soft, unobscured AGN ("Seyfert 1s")
-> but it (presumably) *can* be due to superposition of AGN with a broad range of *absorption* in addition to a range of L_X, z

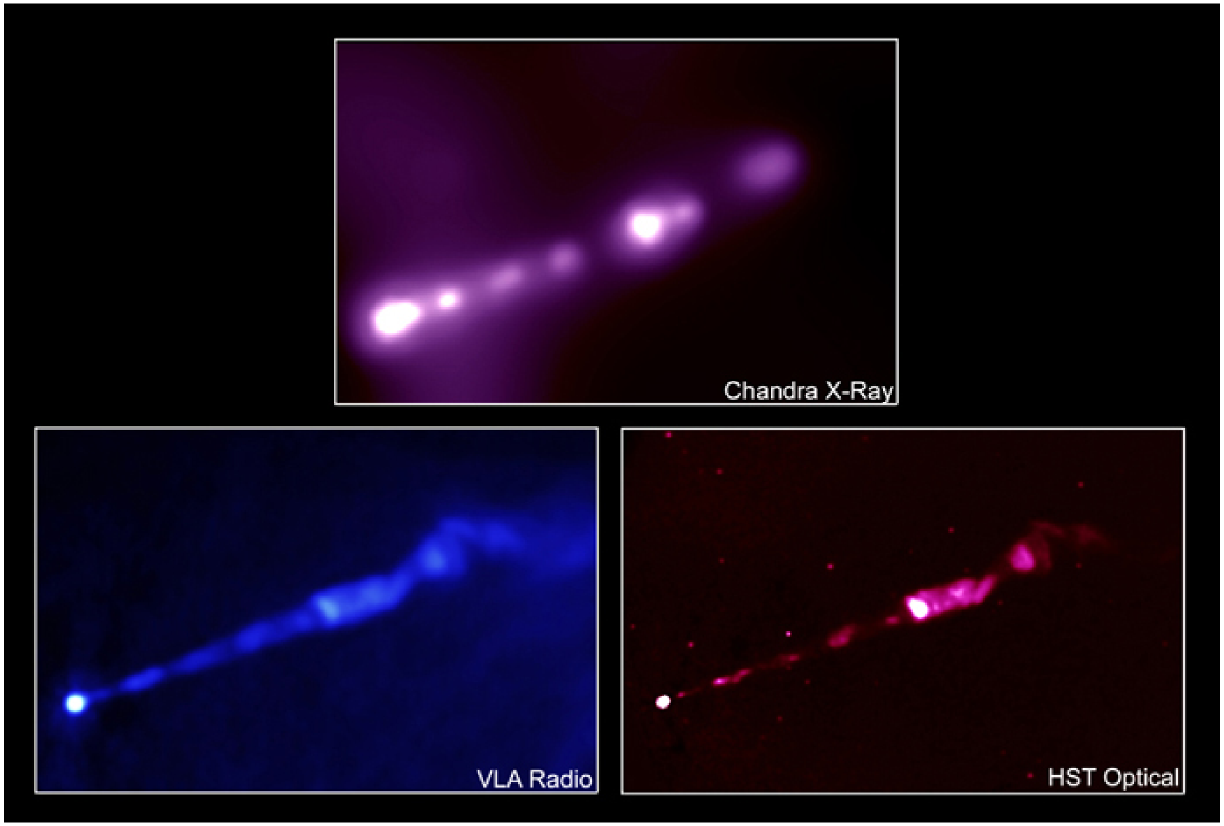
Is there a need for truly diffuse component contributing to the hard X-ray Cosmic Background?





Example: absorbed ("Seyfert 2") active galaxy NGC 4945

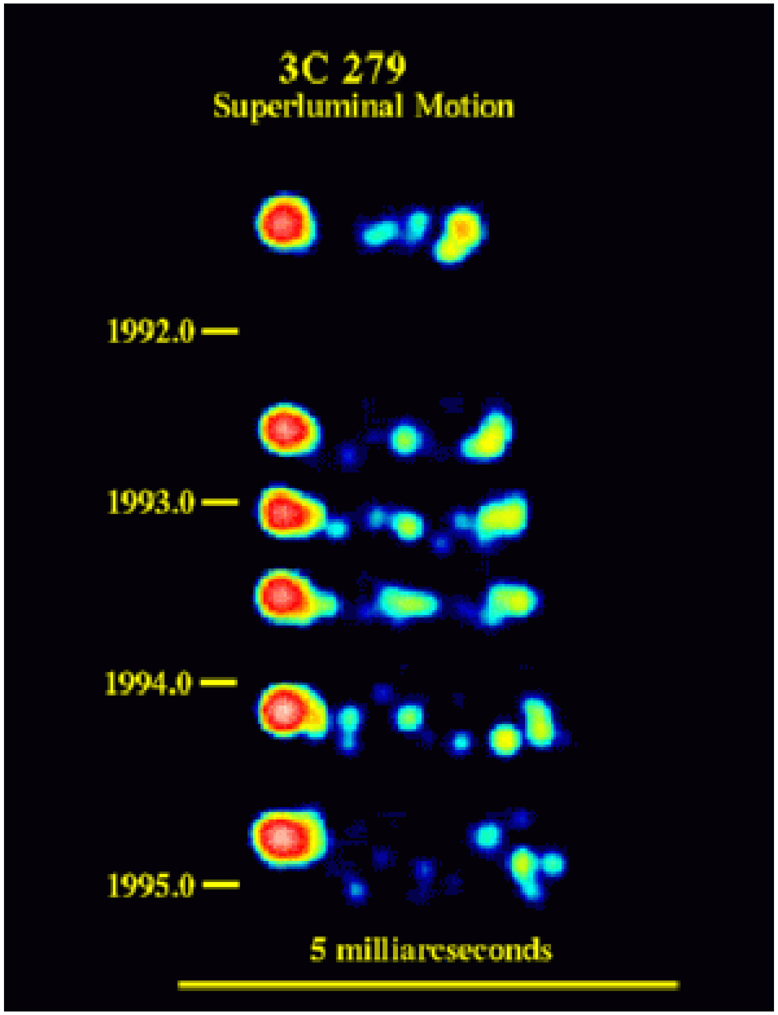
Jets in active galaxies



X-ray, radio and optical jets in the active galaxy M87

- Jets are common in AGN – and radiate in radio, optical and X-ray wavelengths
- Blazars are the objects where jet is pointing close to the line of sight
- In many (but not all) blazars, the jet emission dominates the observed spectrum
  - which can extend to the highest observable energy (TeV!) gamma-rays
- Connection of the jet to the central source not fully understood

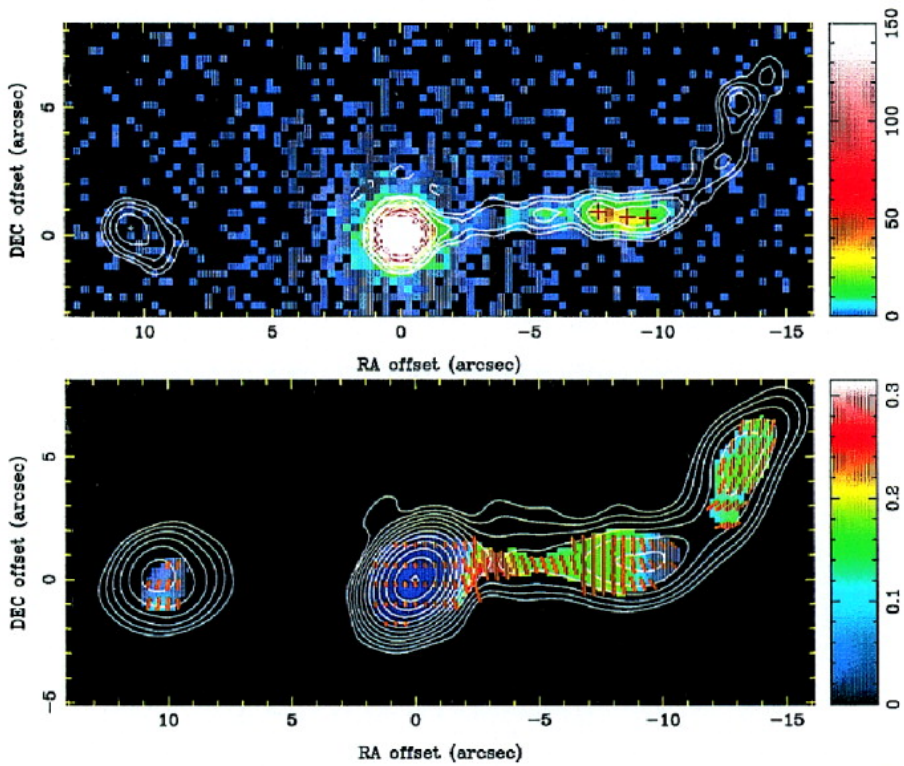
AGN jets are relativistic



Example of VLBI superluminal expansion of a 3C279 (Jorstad et al. 2001)

- Large scale images (arc-sec, corresponding to ~ 1,000 light years) reveal jets, but small-scale (milliarcsec, or ~ 1 light year) reveal co-aligned time-variable outflows
- Those are “faster than the speed of light” – but this is just a projection effect
- 3C279 (z~0.5) is just one such “superluminal” example - most bright blazars are monitored with VLBI
- Such monitoring reveals Lorentz factors $\Gamma_{jet} \sim 10$

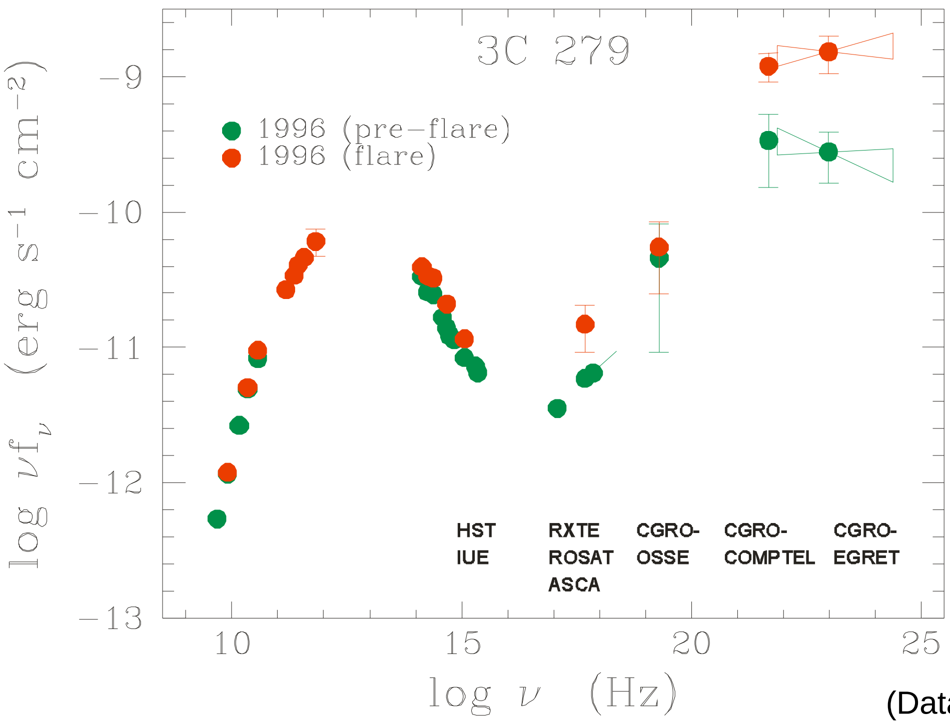
Particle acceleration in AGN jets must be "local"

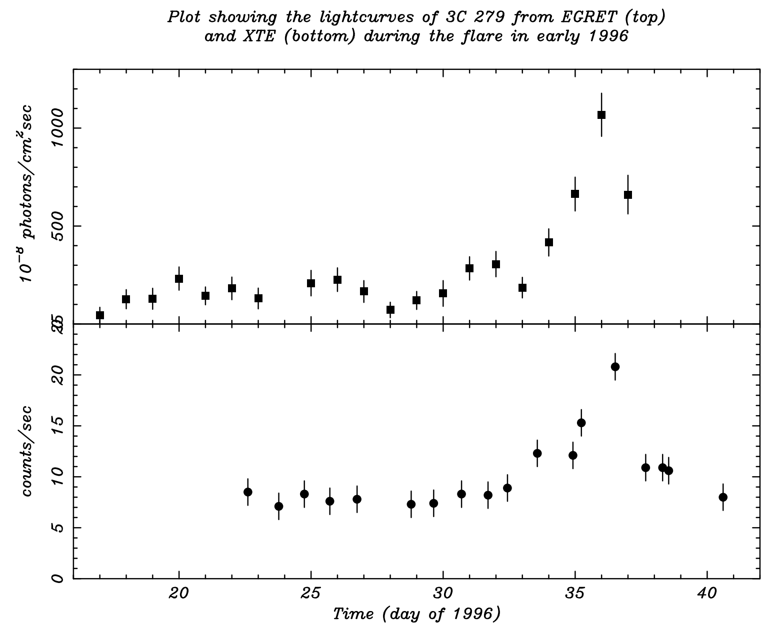


Example of a large-scale (~kiloparserc, ~ 10^{21} cm) X-ray emitting jet in
PKS 0637-752 (top panel) with radio contours; bottom panel shows radio polarization

- The time scale for energy loss by radiating particles are much shorter than the light travel time from the central engine (as much as ~ 300,000 y)

Broad-band spectrum and time variability of the jet in the archetypal EGRET GeV blazar 3C279





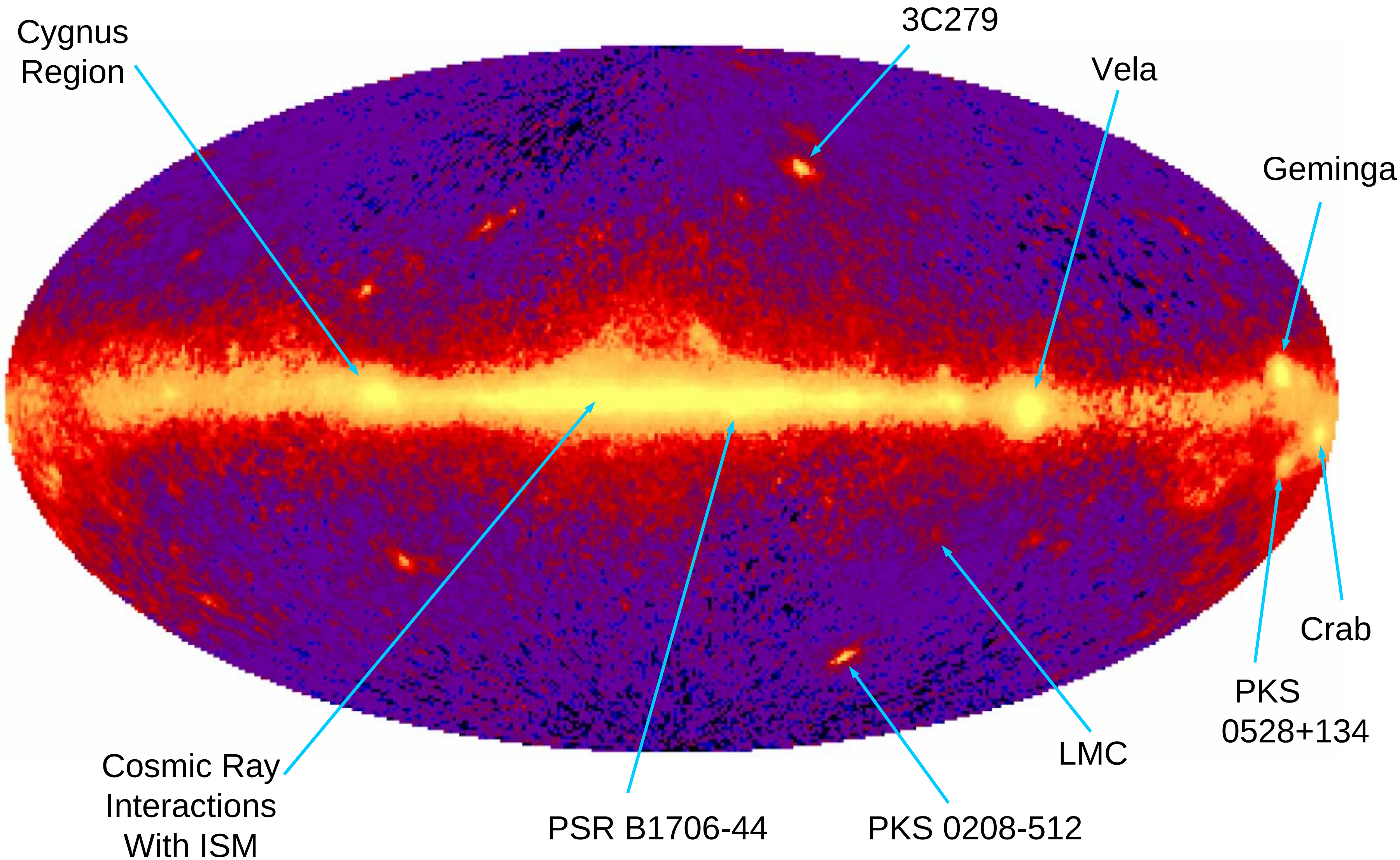
(Data from Wehrle et al. 1998)

* GeV emission dominates the observed flux -> blazars are “extreme accelerators”

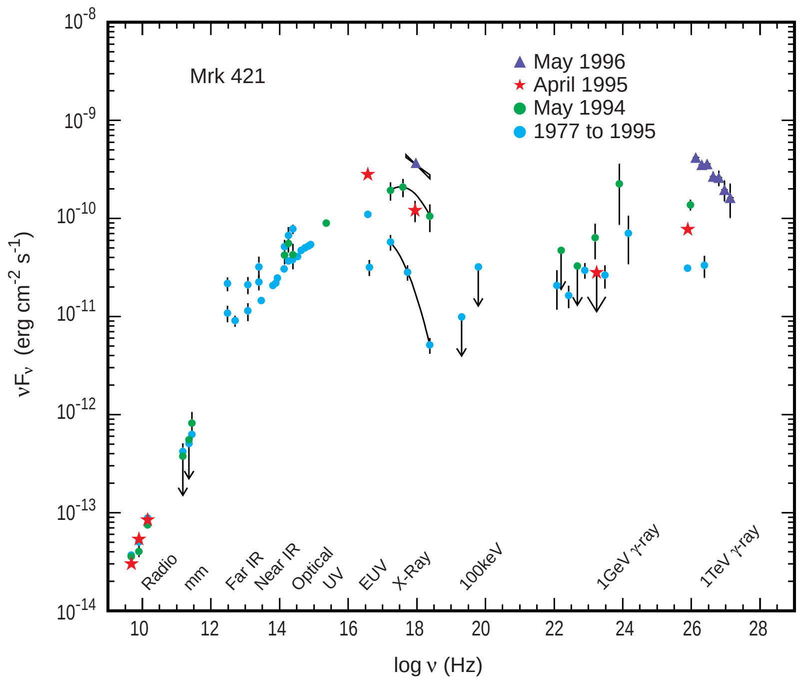
* Correlated variability on day time scales is common

* Variability in X-ray and γ-ray bands puts constraints on the minimum relativistic boost (Γ_j) of the innermost region (via γ–γ absorption to e+/e- pair production)

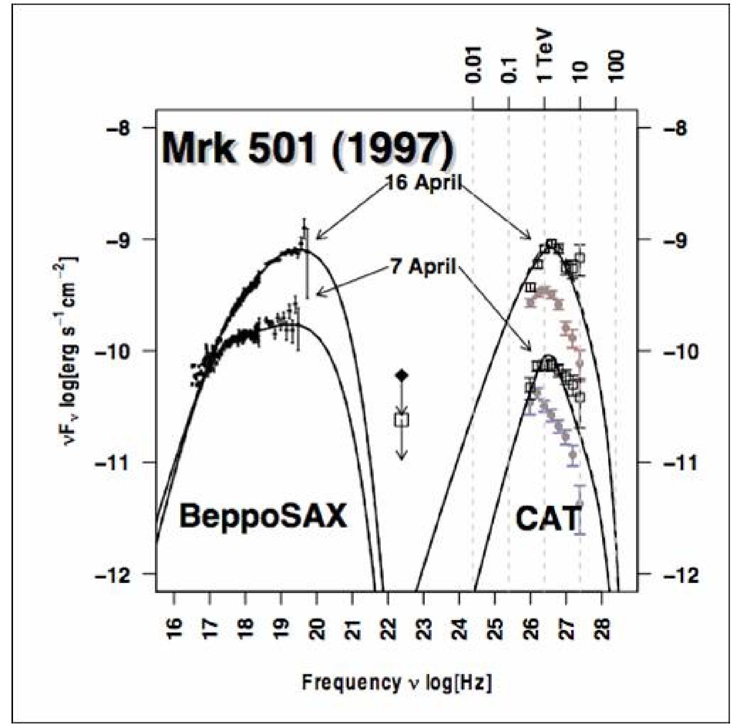
EGRET All-Sky γ-ray Map (>100 MeV)



AGN jet emission can extend to the TeV band



Mkn 421 (data from Macomb et al. 1995)



Mkn 501 observation by the MAGIC telescope (Albert et al. 2007)

An Exceptional VHE Gamma-Ray Flare of PKS 2155−304 5

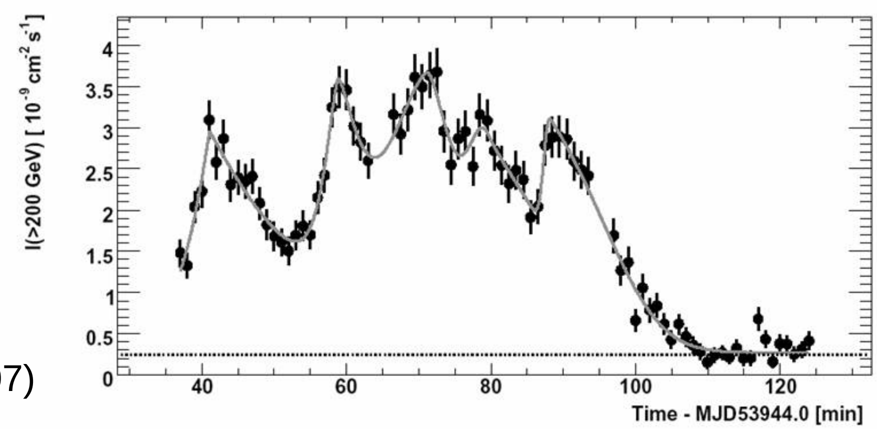


FIG. 1.— The integral flux above 200 GeV observed from PKS 2155−304 on MJD 53944 versus time. The data are binned in 1-minute intervals. The horizontal line represents I(>200 GeV) observed (Aharonian et al. 2006) from the Crab Nebula. The curve is the fit to these data of the superposition of five bursts (see text) and a constant flux.

Variability of the TeV blazar
PKS 2155-304 (Aharonian et al. 2007)

Modeling the blazar emission

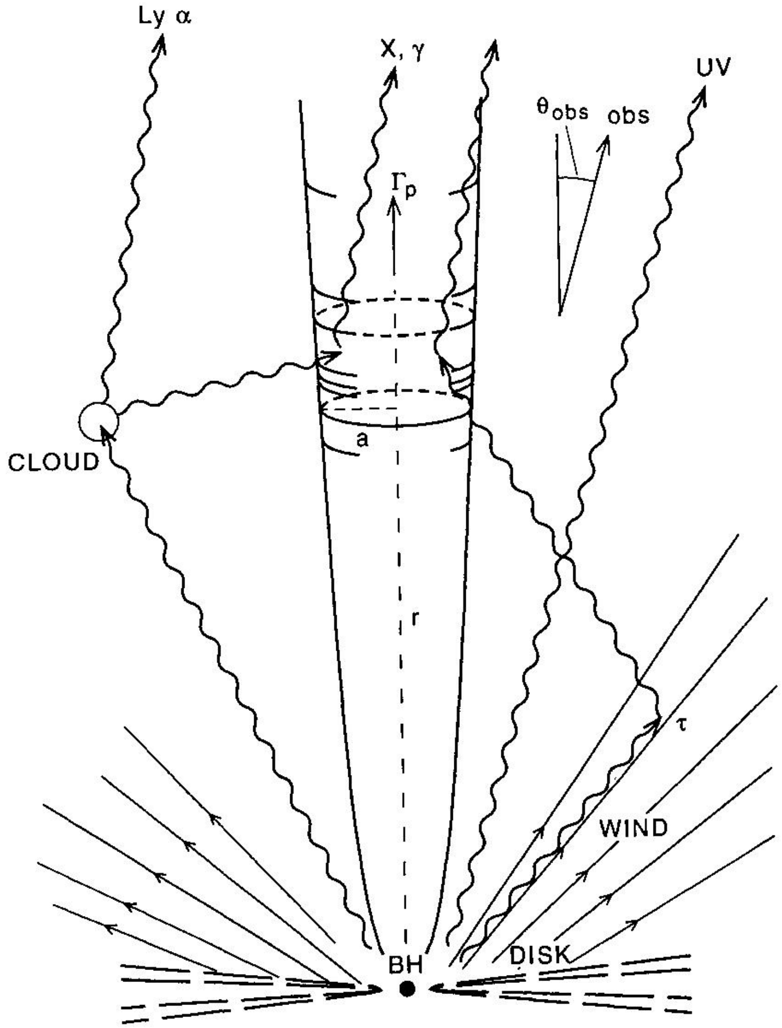


FIG. 2.—Geometry of the source. The radiating region, denoted by short cylinder of dimension a, moves along the jet with pattern Lorentz factor Γ_p. Underlying flow moves with Lorentz factor Γ, which may be different.

From Sikora, Begelman, and Rees 1994

- Approach here is the common in astrophysics "onion peeling":
  - start with the models for radiation spectrum
  - infer the radiating particle population / geometry,
  - deduce the source structure
- Most viable models are "leptonic" –
  - synchrotron emission for the low-energy peak (polarization!)
  - inverse Compton emission for the high energy peak
- "Seed" photons for inverse Compton scattering can depend on the environment - internal to the jet ("Synchrotron self-Compton") or external to the jet ("External Radiation Compton")

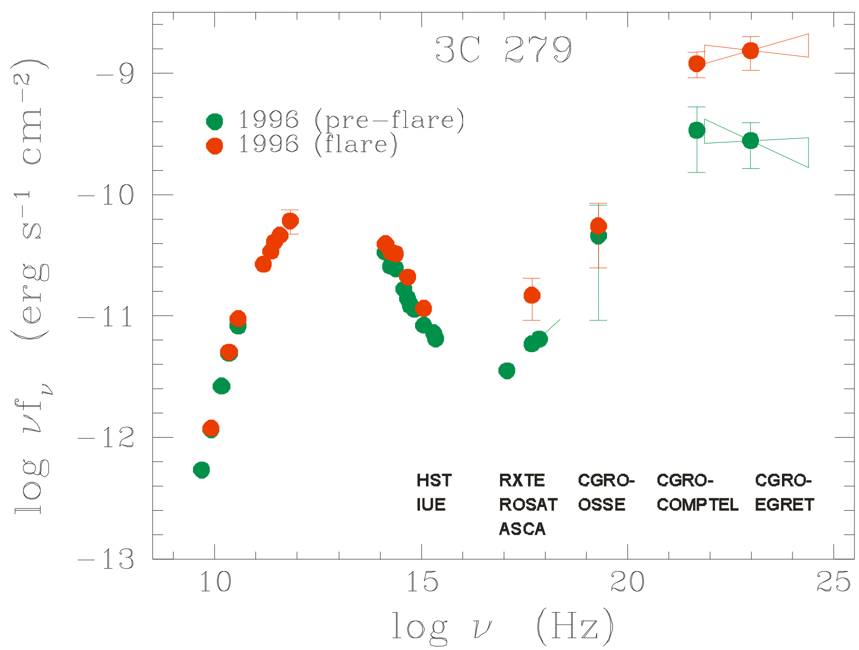
Modeling of radiative processes in blazars

- In the context of the synchrotron models, emitted photon frequency is
  $\nu_s = 1.3 \times 10^6 \ B \times \gamma_{el}^2$ Hz
  where B is the magnetic field in Gauss
  and γ_{el} is the electron Lorentz factor
- The best models have B ~ 1 Gauss, and γ_{el} for electrons radiating at the peak of the synchrotron spectral component of ~ $10^3 – 10^6$, depending on the particular source
- The high energy (Compton) component is produced by the same electrons as the synchrotron peak and $\nu_{compton} = \nu_{seed} \times \gamma_{el}^2$ Hz
- Still, the jet Lorentz factor Γ_j is ~ 10, while Lorentz factors of radiating electrons are γ_{el} ~ $10^3 – 10^6$
- *What converts the bulk motion of the jet to the ultrarelativistic particle energies?*

Why is the X-ray band important?

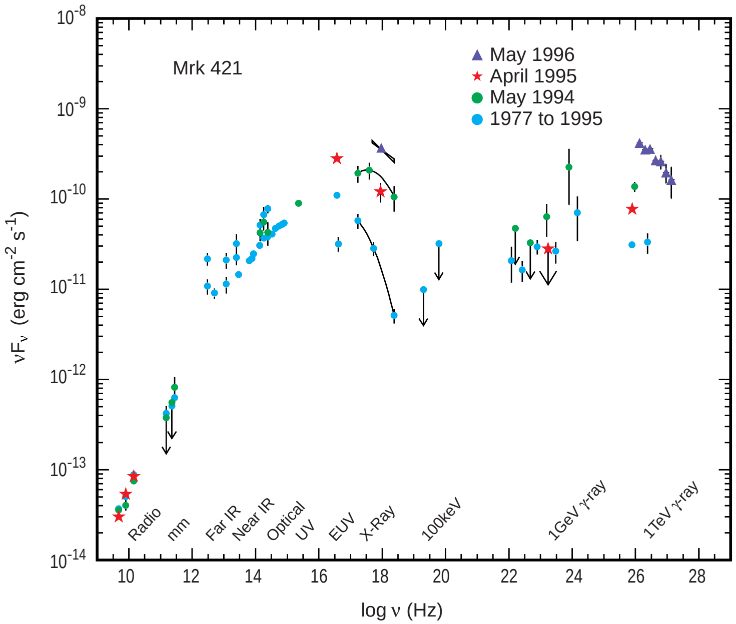
Broad-band spectra of two classes of blazars:

3C279 (data from Wehrle et al. 1998)



Compton component: X-rays probe the total jet content (particles radiating at the low end of the distribution are most numerous)

Mkn 421 (data from Macomb et al. 1995)



Synchrotron component: X-rays probe the most energetic end of particle distribution

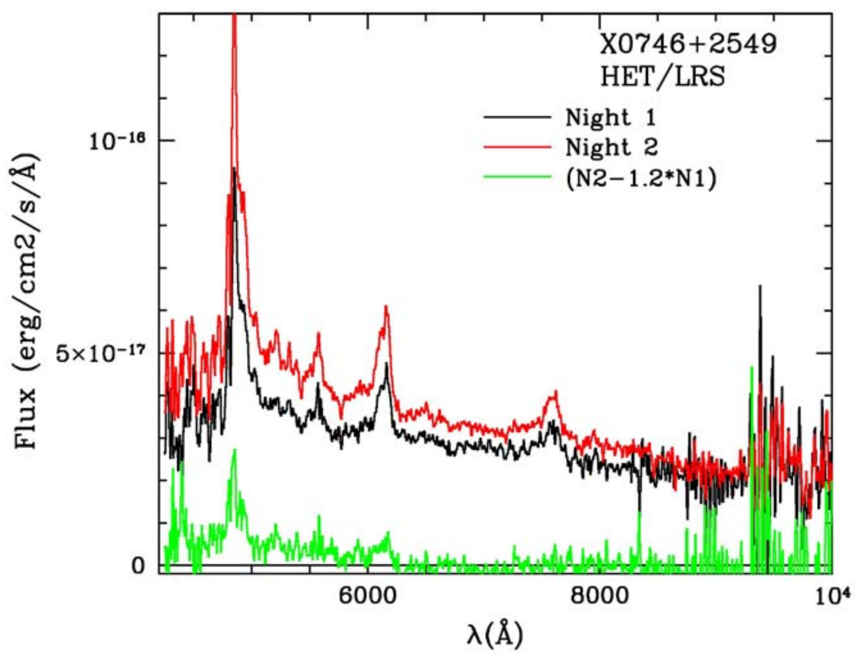
Content of jets in active galaxies

* Are blazar jets dominated by kinetic energy of particles from the start, or are they initially dominated by magnetic field (Poynting flux)? (Blandford, Vlahakis, Wiita, Meier, Hardee, …)

* There is a critical test of this hypothesis, at least for quasar-type ("EGRET") blazars:

* *If the kinetic energy is carried by particles*, the radiation environment of the AGN should be bulk-Compton-upscattered to X-ray energies by the bulk motion of the jet

* If Γ_{jet} = 10, then the ~10 eV H Lyα photons should appear bulk-upscattered by Γ_{jet}^2 - to 10^2 x 10 eV ~ 1 keV

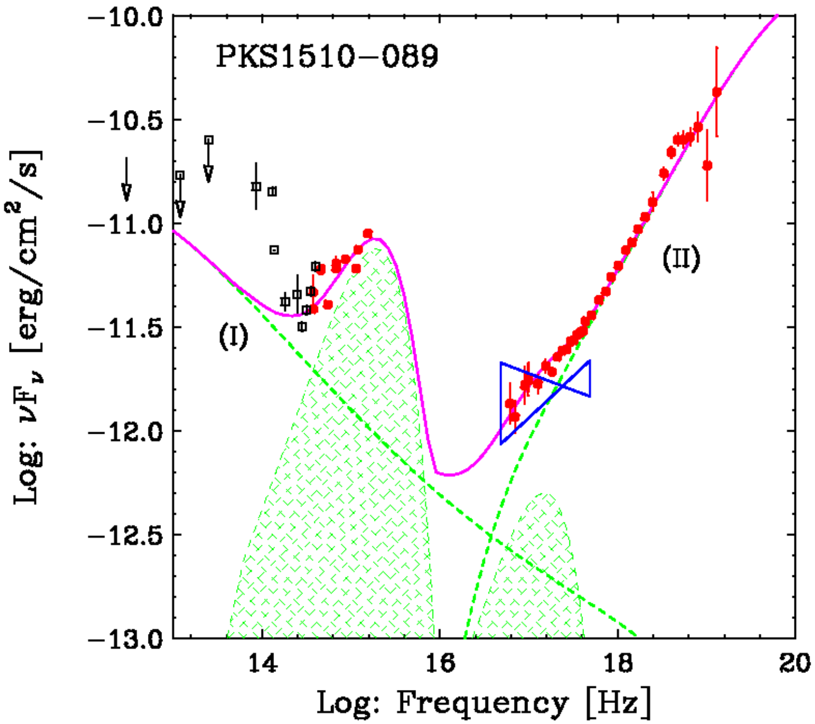


Optical spectrum of a distant blazar: the Ly α line is redshifted to λ ~ 5000 A

Jet content cont'd

Suzaku data for PKS 1510-089: possible evidence for "bulk-Compton" bump?

- The soft X-ray excess might be the tentative evidence for the "Sikora bump" – arising by the inverse Compton scattering of BEL light by the cold electrons in the jet – but even if it is not "bulk-Compton"…
- From its isotropic luminosity of $L_{BC} < 3 \times 10^{44}$ erg/s - we can set a limit on the energy flux $L_{e,cold}$ carried by the cold electrons and the e+/e- pair content of the jet:



-since $L_{BC} = (4\sigma_T/3m_ec^2)\, U_{BEL}\, r_{BLR}\, \Gamma_j^3\, L_{e,cold}$

we have

$L_{e,cold}$

$< 2.7\times10^{43}\, (r_{BLR}/0.1\mathrm{pc})\, (\Gamma_j/10)^{-3}\, (L_{BEL}/10^{45}\mathrm{erg/s})^{-1}$ erg/s

- Significantly less than the required kinetic luminosity of the jet
- Now the total power delivered by the jet must be 8×10^{44} erg/s

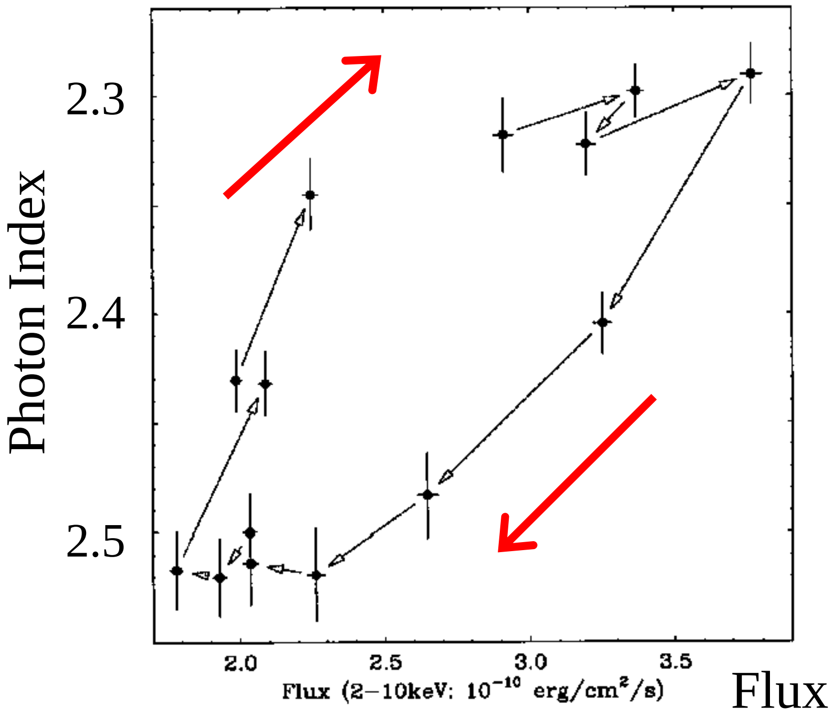
-With more realistic parameters, n_e/n_p in the jet is < 5

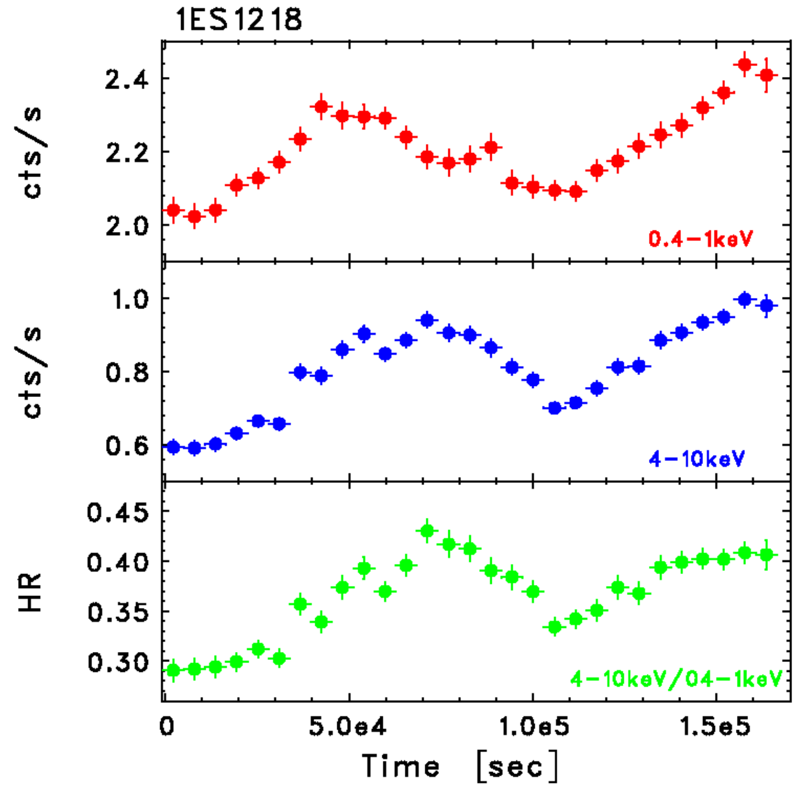
--> Jet contains more pairs than protons, but cannot be *dynamically* dominated by e+/e- pairs

-For details, see Kataoka, GM, + 08

Recent results from Suzaku X-ray variability of TeV-emitting blazars

Asca data for Mkn 421



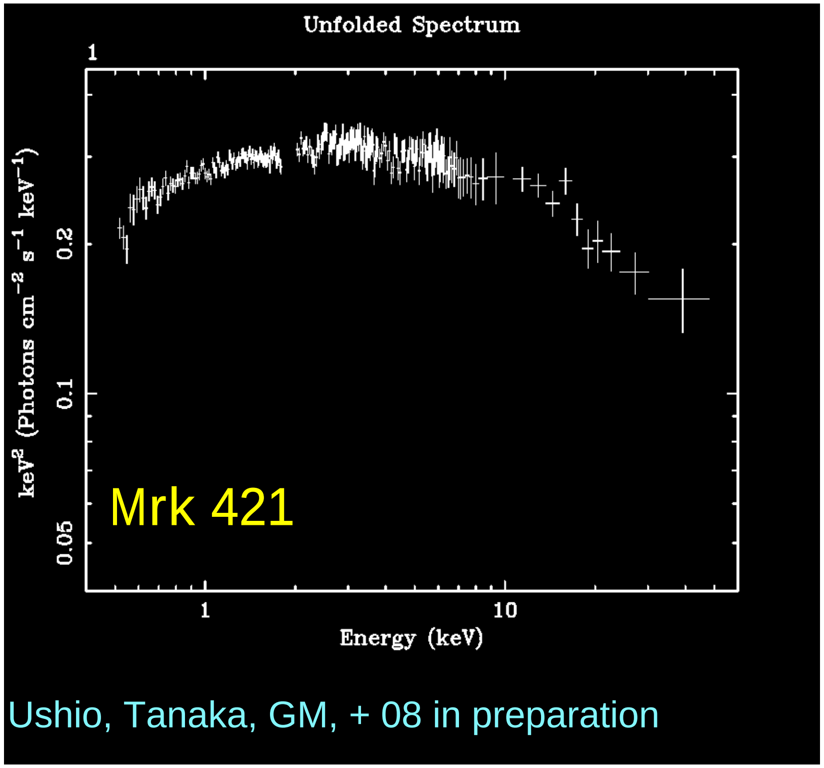


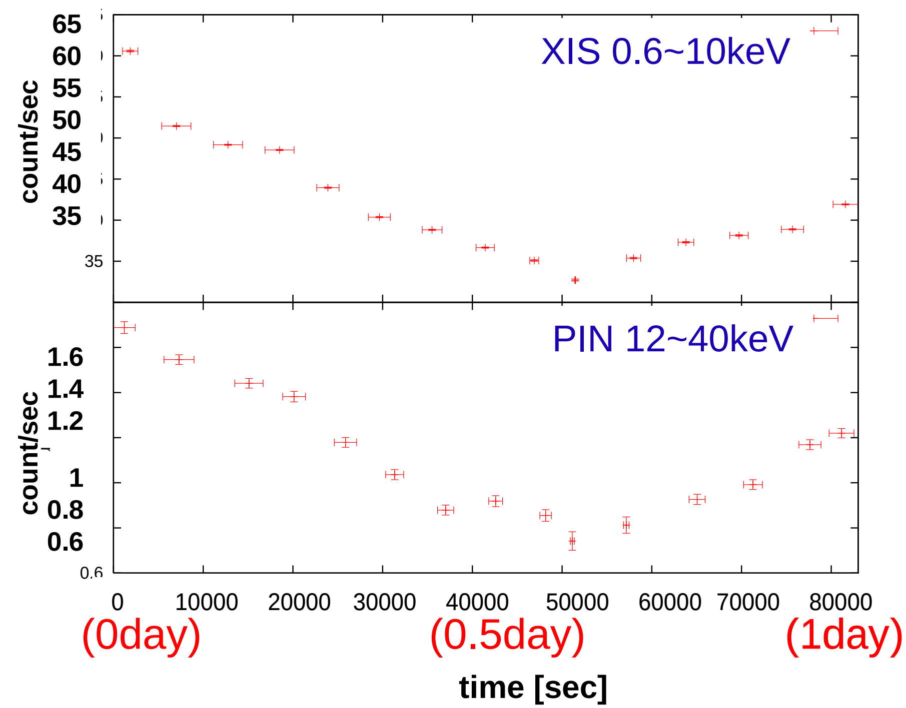
From Asca data: Mkn 421 showed that during flares the spectrum gets “hard” very quickly, then if softens as the source gets fainter: signature of energy-dependent electron cooling time scale (Takahashi, GM, +, 1996)

Suzaku observed another TeV blazar, 1218+304, reveals that *hard X-rays lag soft X-rays:*
20 ks delay of 6 keV vs. 0.6 keV X-rays -
clear energy-dependent *acceleration* time scale?
(Sato et al. 2008)

-> Implications on the structure of B-field

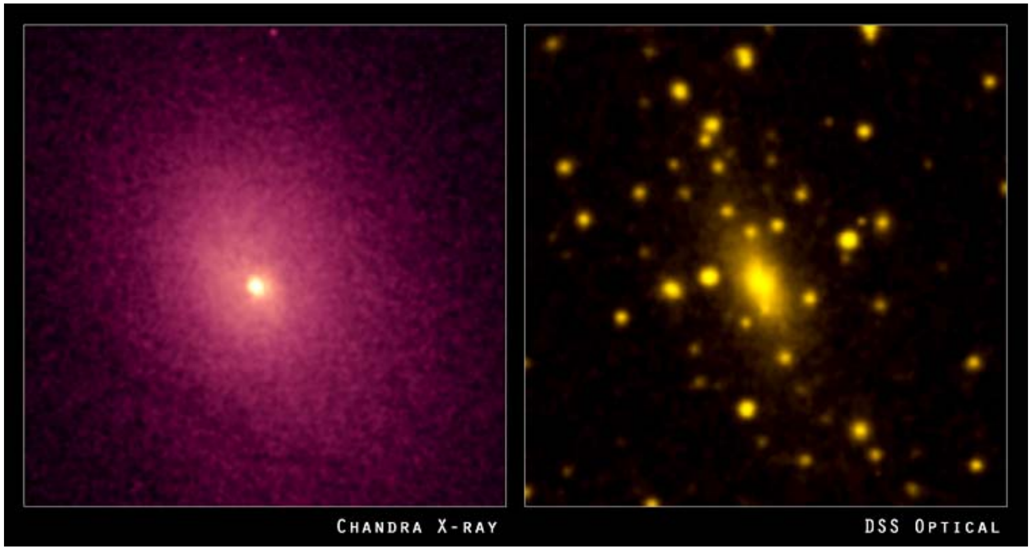
Another recent example: Mkn 421 observed with Suzaku

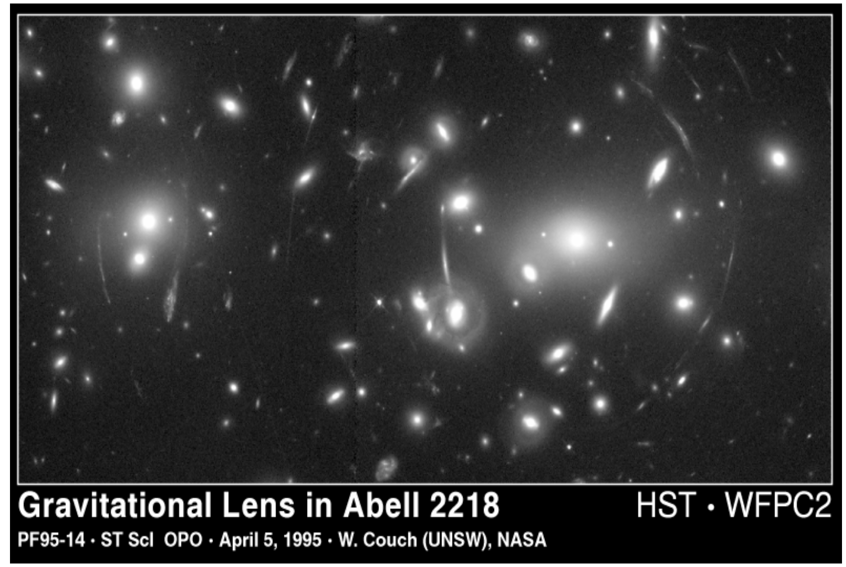




- Broad-band X-ray spectrum measured by Suzaku cannot be described as a simple power law
- Instead, the index steepens with increasing energy
- Assuming constant B field, steepening electron distribution is implied
- Best fitted with power-law electron distribution (index ~ 2.2), with super-exponential cutoff (as inferred for some SNR; Tanaka et al. 2008)
- Such a cutoff is predicted in, e.g., radiating relativistic electrons that were accelerated in turbulent B field (see, e.g., Stawarz and Petrosian 2008)
- Applicable to many blazars where the X-ray band represents the high-energy tail of the synchrotron peak (often the “TeV blazars”)

Clusters of galaxies as particle accelerators

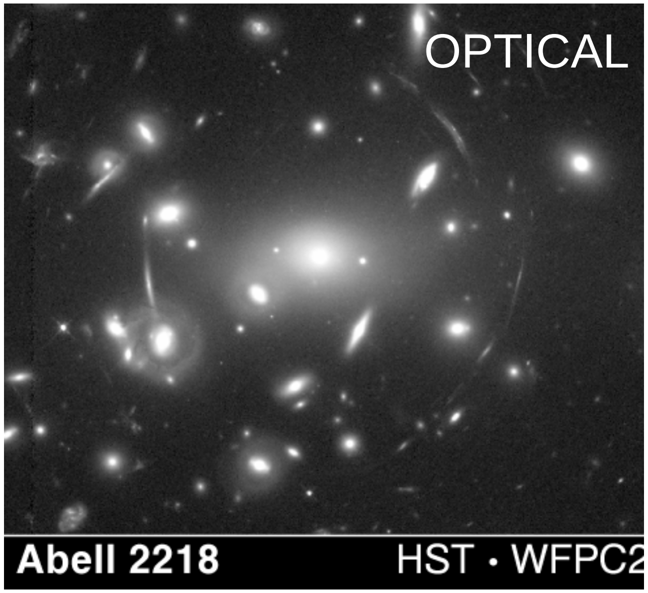


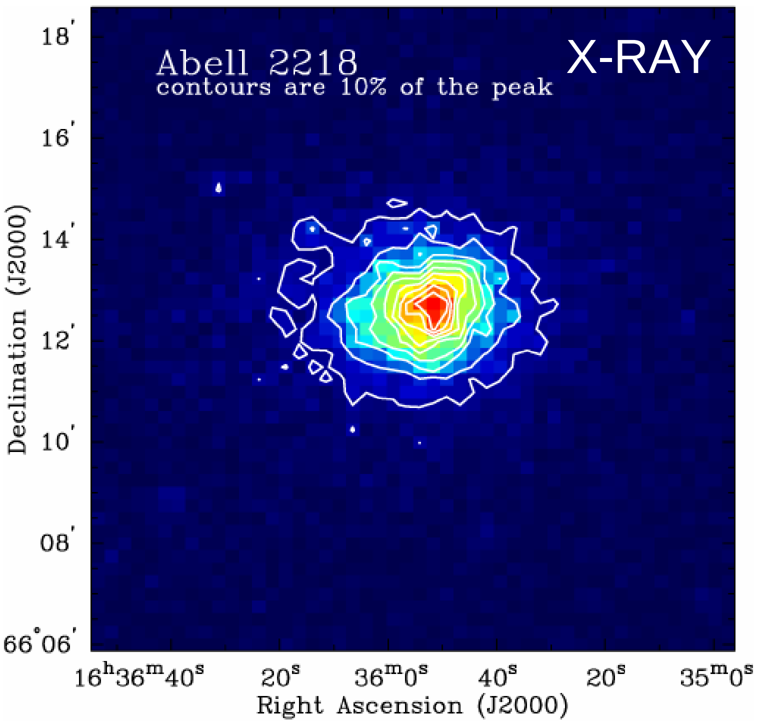


Cluster of galaxies Abell 2029

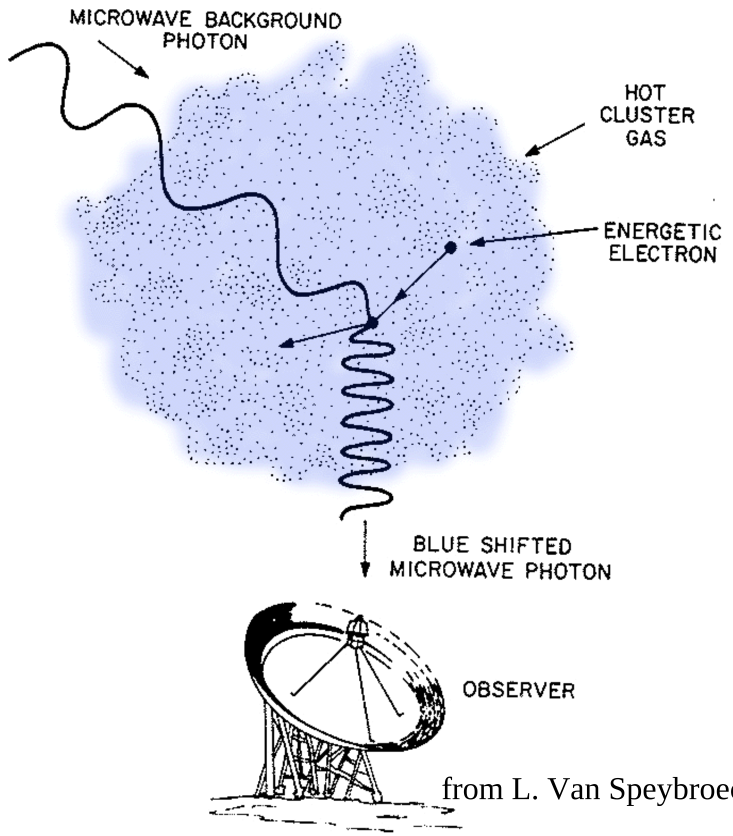
• Clusters of galaxies are largest gravitationally bound and relaxed structures in the Universe
• They are strong X-ray emitters -> X-rays provide measure of their total mass
• Keeping clusters gravitationally bound requires unknown form of non-baryonic but gravitating material ("dark matter")
• Mass distribution inferred from gravitational lensing data generally (but not always!) agree with the X-ray data
•They are great cosmological probes: their mass/number density as function of cosmic time is an excellent probe of cosmological parameters

The Sunyaev-Zel'dovich Effect

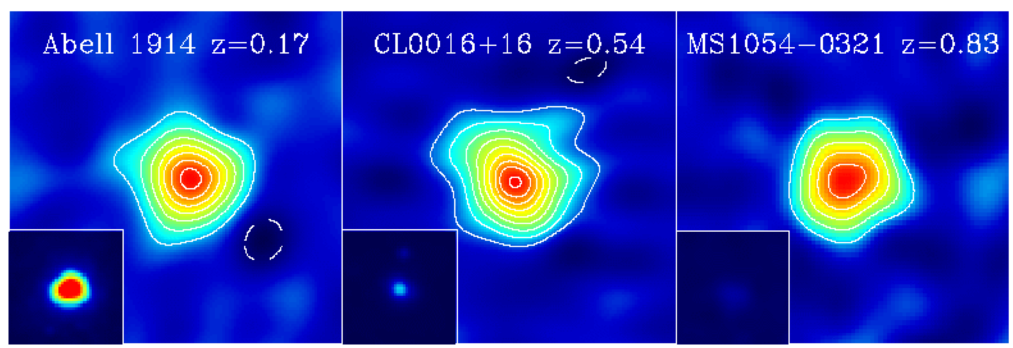




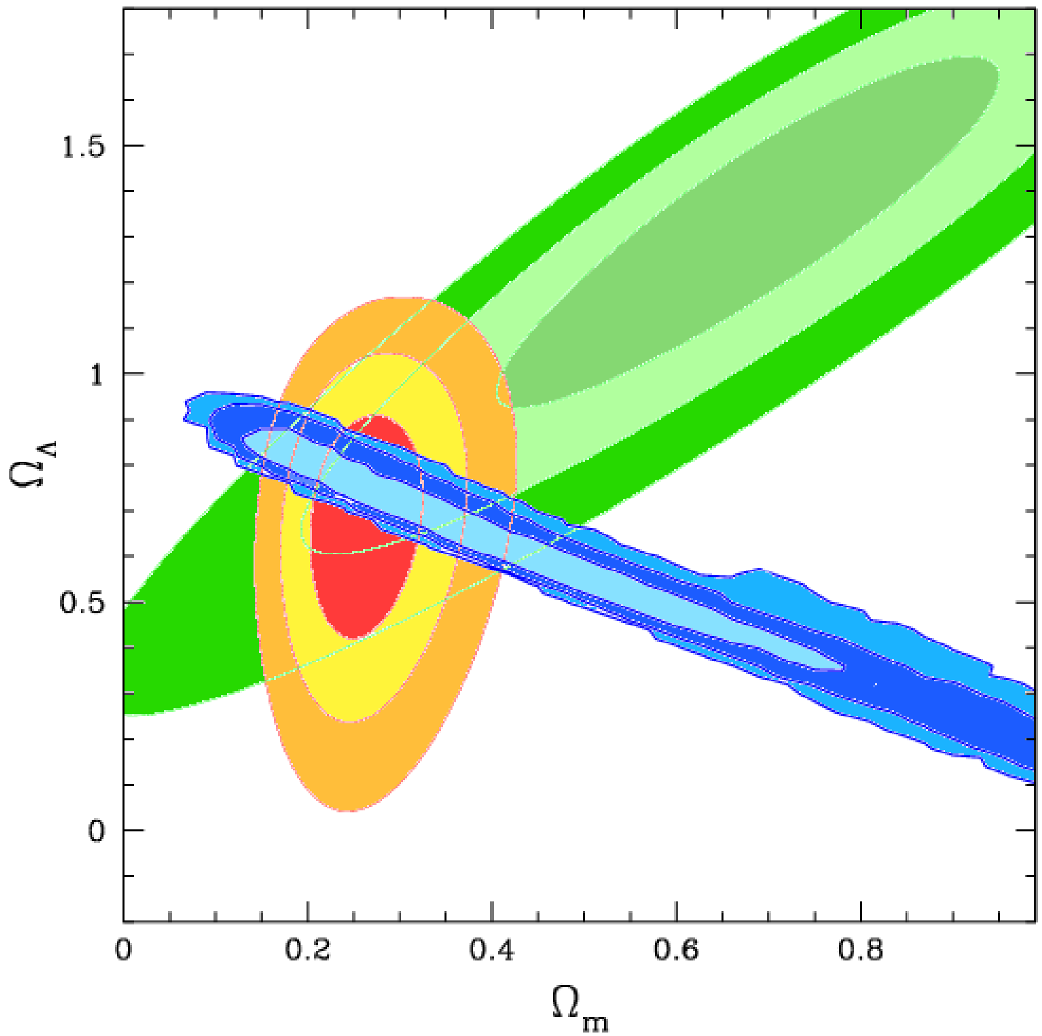
Clusters and the CMB



from L. Van Speybroeck



Comparison of independent cosmological constraints: cluster f_{gas} method and supernovae (ΛCDM)



Color coding:

Cluster f_{gas} analysis including standard $\Omega_b h^2$, h and b priors (Allen et al. 2004)

CMB data (WMAP +CBI + ACBAR) weak prior 0.3<h<1.0

Supernovae data from Tonry et al. (2003)

IMPORTANT: cluster data "orthogonal" to other methods

Figure and analysis from Allen et al. (2004)
More up-to-date results for a larger sample are in Allen+ 2007

Cosmological constraints from X-ray observations of clusters (from Mantz et al. 2007)

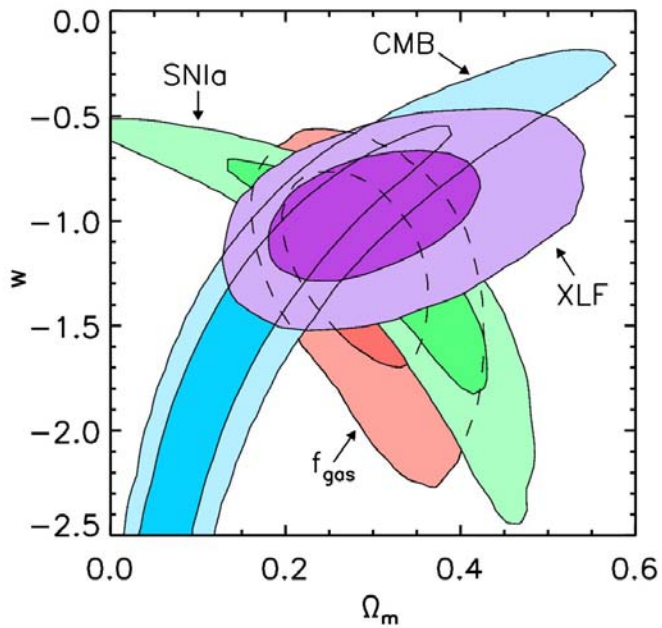


Figure 10. Joint 68.3 and 95.4 per cent confidence constraints on Ω_m and w for a constant-w model using the luminosity function data (purple) and our standard priors (Table 1). Also shown are independent constraints from CMB data (blue; Spergel et al. 2007), SNIa (green; Davis et al. 2007) and cluster f_{gas} data (red; Allen et al. 2007).

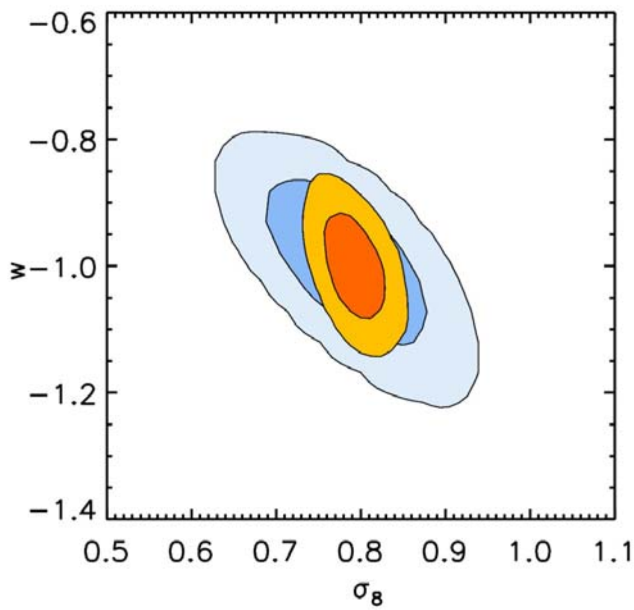
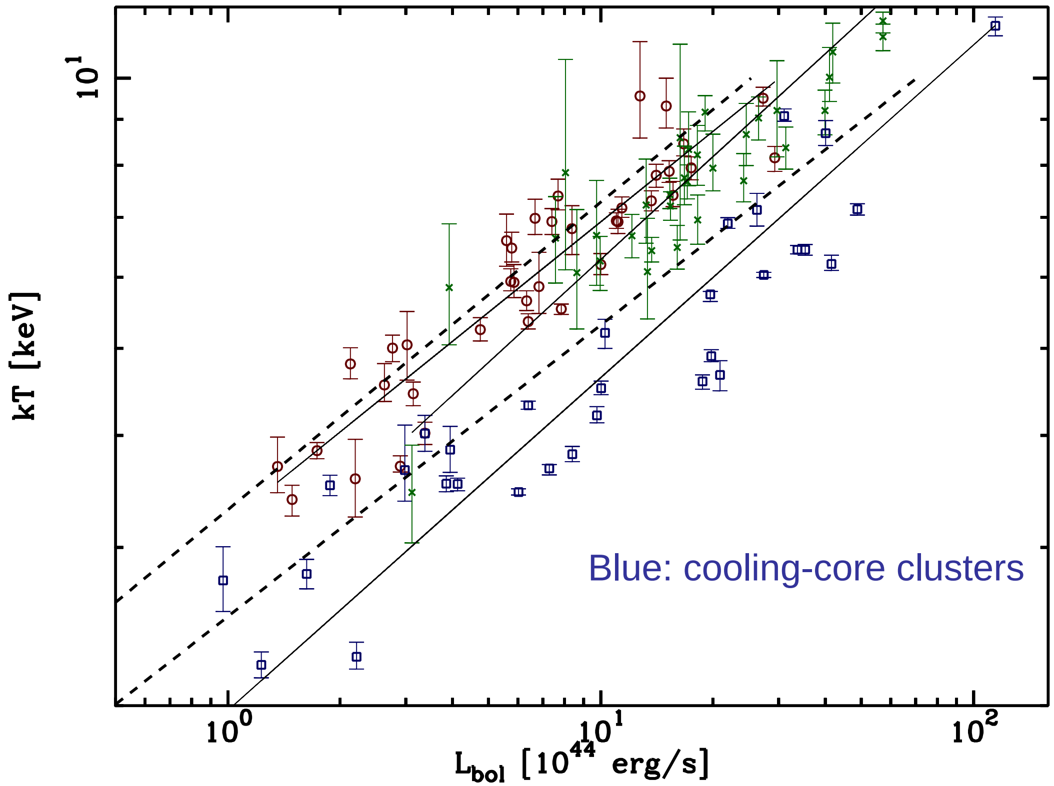


Figure 12. The joint constraints (68.3 and 95.4 per cent confidence) on σ_8 and w obtained from a combined SNIa+f_{gas}+CMB analysis (blue) and the improved constraints obtained by combining this with the XLF results using importance sampling (gold). No priors on h, $\Omega_b h^2$ or n_s are imposed in either analysis.

- Future observations should provide more and better data – following up on complete samples from S-Z surveys, E-Rosita, … (but lots of observing time will be needed…)
- It is important that we understand the systematic effects

Cluster masses via scaling relations

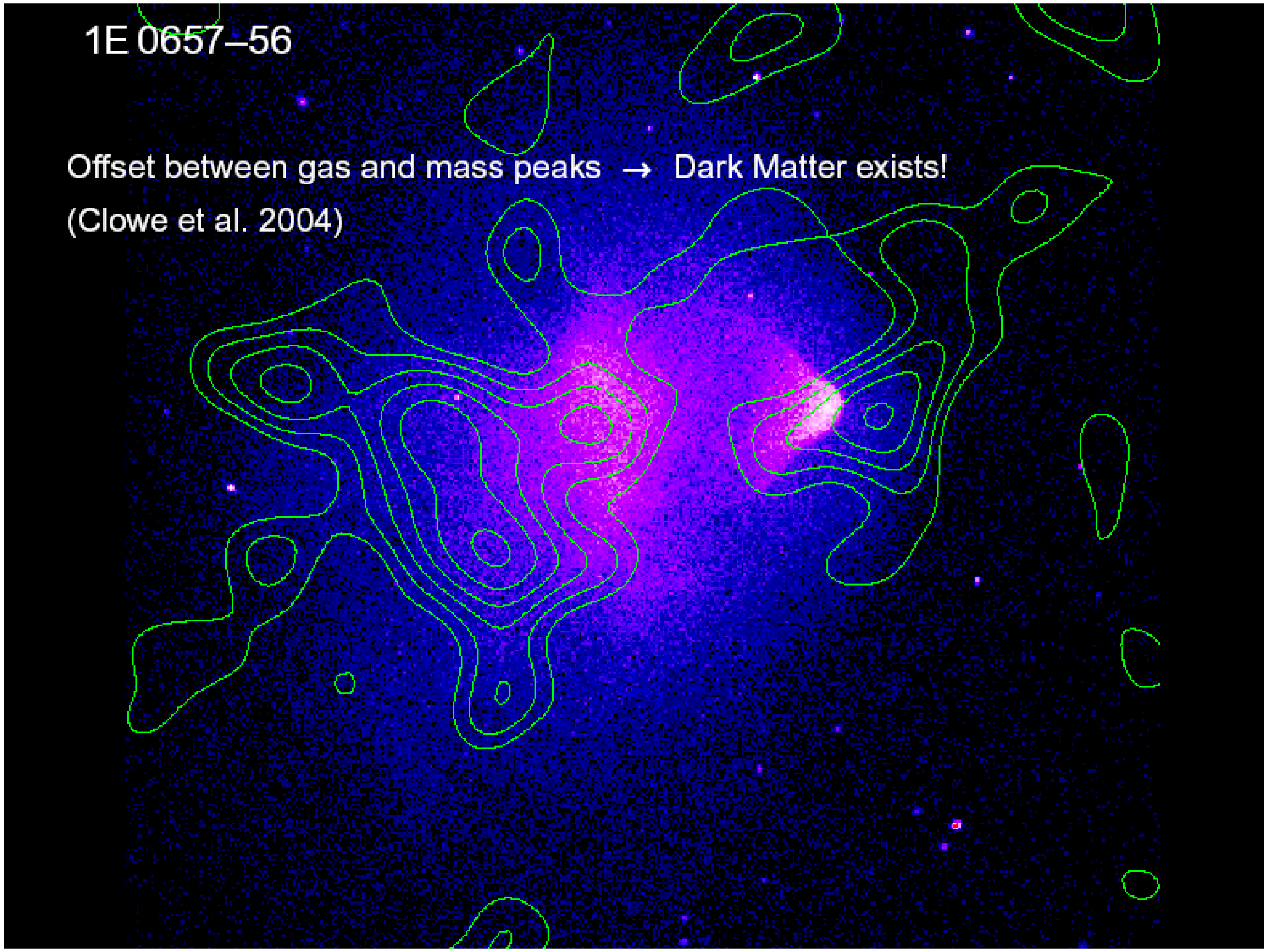


XMM data:

from Andersson, Peterson, GM, & Goobar 2008

- Clear relationship between L_x and T_x –> in principle can get the gas mass and total mass via hydrostatic equilibrium
- Normalization very different for relaxed vs. merging vs. "cooling core" clusters
- Robust mass determination requires knowledge of the dynamical state ("relaxedness") of the X-ray emitting gas
- Non-thermal processes and bulk gas motion are likely in disturbed clusters…

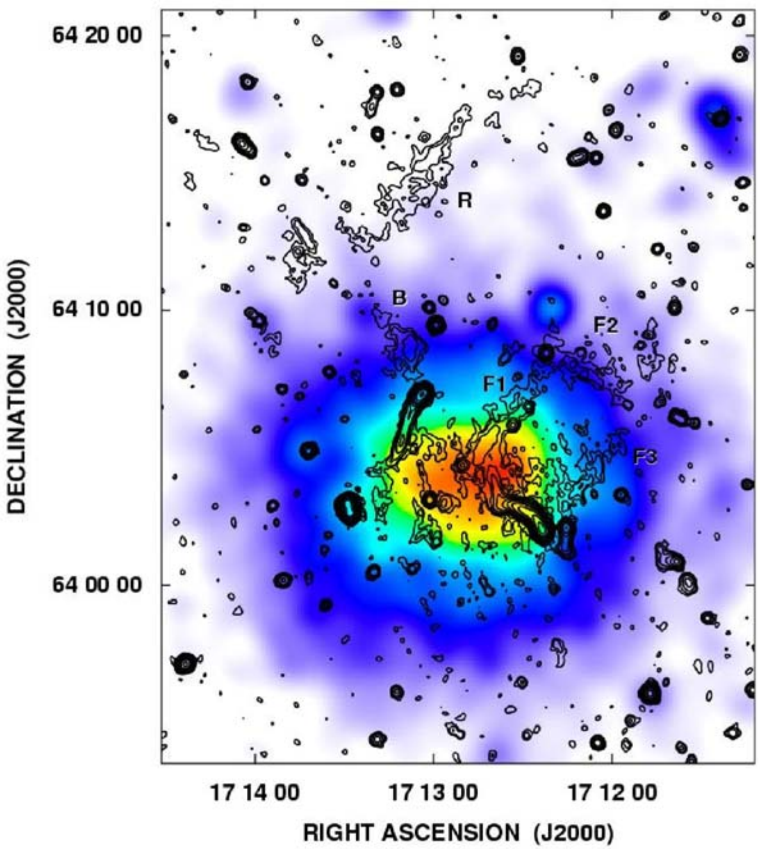
Truly disturbed ("bullet") cluster…



From Markevitch et al. (X-ray data: 2004, 2005); Clowe et al. (lensing data: 2004), and Bradac et al. 2006 (S+W lensing)

What are details of formaton of clusters? Non-thermal processes? Best studied in hard X-rays: inverse Compton of CMB photons against cluster's relativistic particles

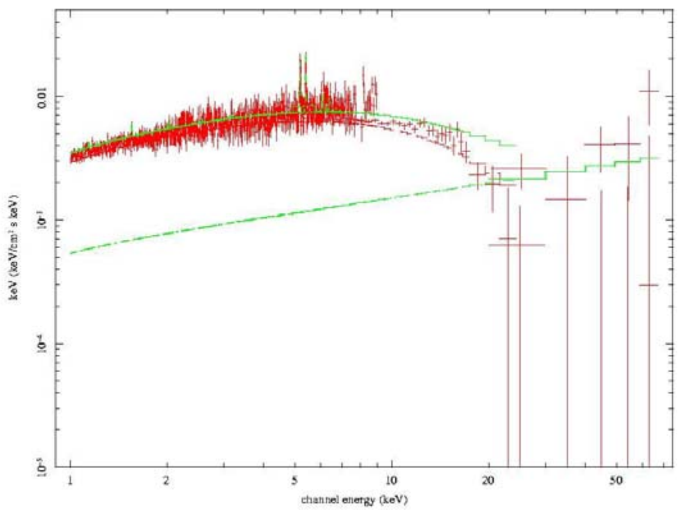
Radio observations reveal non-thermal particles in clusters



Cluster of galaxies Abell 2255
X-ray data (Rosat, color) + radio data (contours), from Govoni + 2005
Radio emission is polarized!

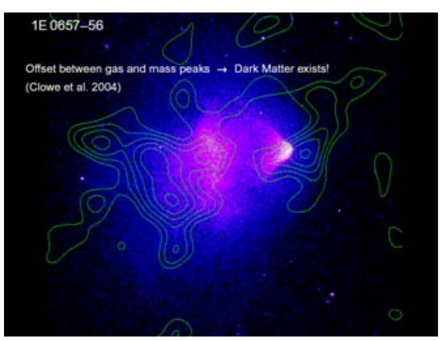
* Clusters are often radio emitters
* Radio emission -> synchrotron (relativistic electrons in *B* field)
* Cannot easily break the degeneracy between the B field and electron distribution from radio data alone

Hard X-ray observations as probes of *B* field in clusters



Example of hard X-ray measurements of the Bullet Cluster with XMM and RXTE (Petrosian, Madejski, Luli 2006)

Need this



in hard X-rays!

* Relativistic electrons IC-scatter the Cosmic Microwave Background and produce non-thermal X-ray flux

* Cannot use *soft* X-ray data – *thermal* emission dominates in the soft X-ray band

* Comparison of radio and hard X-ray data can break the degeneracy between the B field and distribution of γ_{el} and map B-field in clusters

* RXTE as well as the current Suzaku HXD data suggest that the *B* field is relatively strong (~ μGauss), γ_{el} ~ 1000

* Particle lifetimes relatively short -> continuous/distributed acceleration needed

* Detailed measurements require X-ray imaging instruments!

Hard X-ray imaging satellite NuSTAR

- NASA's Small Explorer mission, led by Caltech (PI F. Harrison), slated to fly in 2011-2012
- Two identical coaligned, multi-layer grazing incidence hard X-ray telescopes + actively shielded solid state CdZnTe pixel detectors
- Extendable mast provides 10-m focal length; energy bandpass 6 – 80 keV