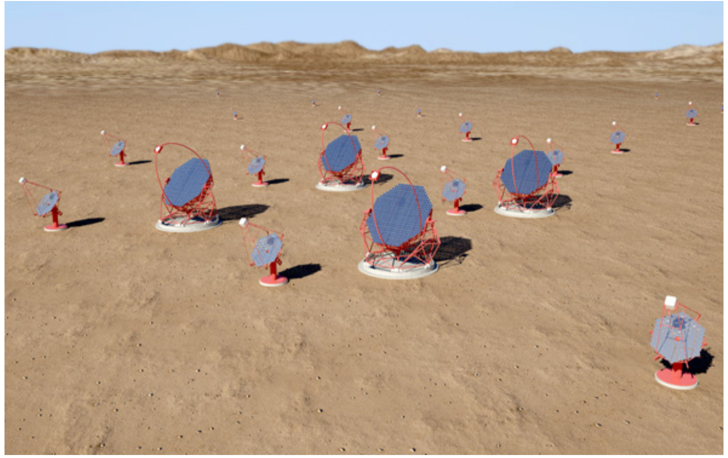


Active Galactic Nuclei: a CTA perspective

Paolo Padovani, ESO, Germany

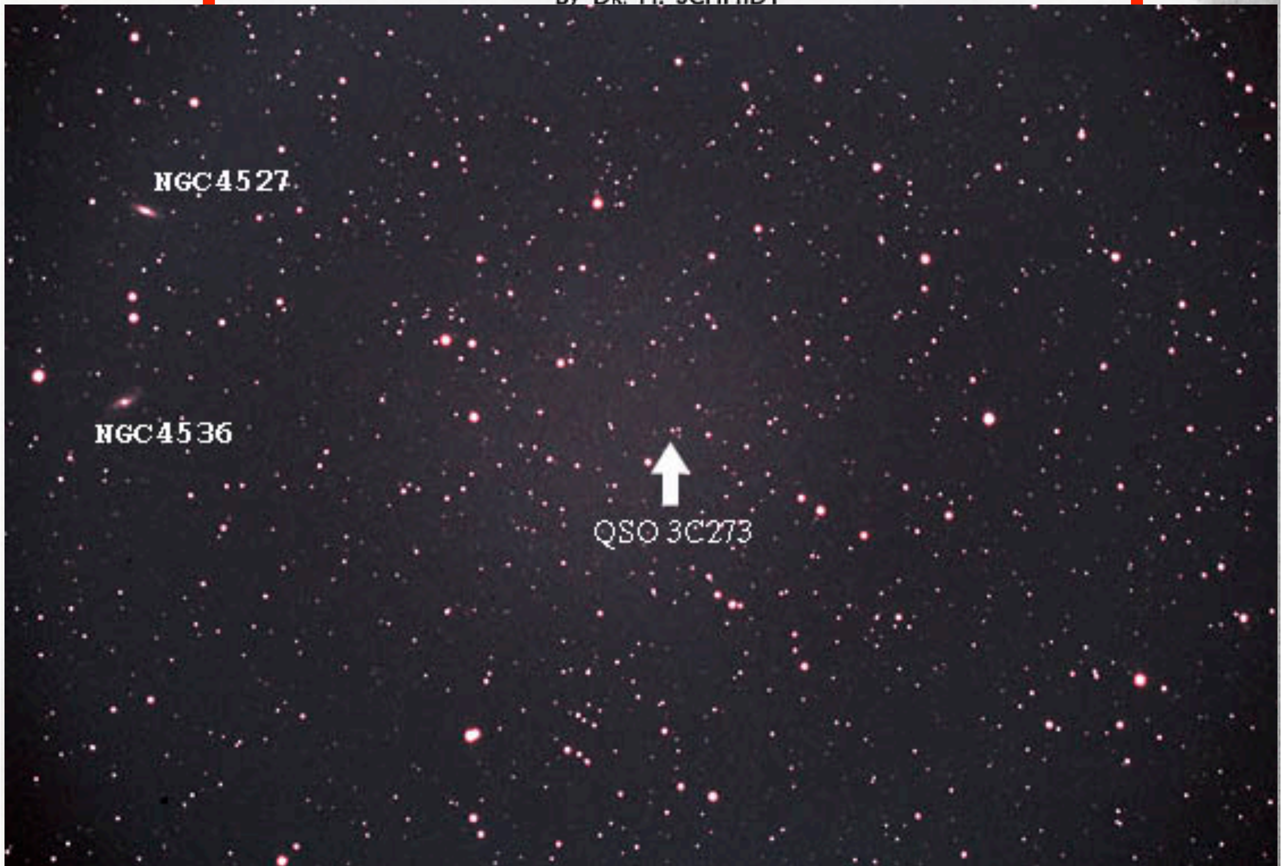
- Active Galactic Nuclei (AGN): a short introduction
- AGN open questions and CTA
- AGN as cosmic ray (and neutrino) sources

1963: the discovery of quasars

1040 NATURE March 16, 1963 Vol. 197

3C 273: A STAR-LIKE OBJECT WITH LARGE RED-SHIFT

By Dr. M. SCHMIDT



offered for the three very wide emission bands.

It thus appears that six emission bands with widths around 50 Å can be explained with a red-shift of 0·158. The differences between the observed and the expected wave-lengths amount to 6 Å at the most and can be entirely understood in terms of the uncertainty of the measured wave-lengths. The present explanation is supported by observations of the infra-red spectrum communicated by

Only the detection of an irrefutable proper motion or parallax would definitively establish *3C* 273 as an object within our Galaxy. At the present time, however, the explanation in terms of an extragalactic origin seems most direct and least objectionable.

I thank Dr. T. A. Matthews, who directed my attention to the radio source, and Drs. Greenstein and Oke for valuable discussions.

1963: the discovery of quasars

3C 273: A STAR-LIKE OBJECT WITH LARGE RED-SHIFT

By Dr. M. SCHMIDT
Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena

THE only objects seen on a 200-in. plate near the positions of the components of the radio source 3C 273 reported by Hazard, Mackey and Shimmins in the preceding article are a star of about thirteenth magnitude and a faint wisp or jet. The jet has a width of 1″–2″ and extends away from the star in position angle 43°. It is not visible within 11″ from the star and ends abruptly at 20″ from the star. The position of the star, kindly furnished by Dr. T. A. Matthews, is R.A. 12h 26m 33·35s ± 0·04s, Decl. +2° 19′ 42·0″ ± 0·5″ (1950), or 1″ east of component *B* of the radio source. The end of the jet is 1″ east of component *A*. The close correlation between the radio structure and the star with the jet is suggestive and intriguing.

Spectra of the star were taken with the prime-focus spectrograph at the 200-in. telescope with dispersions of 400 and 190 Å per mm. They show a number of broad emission features on a rather blue continuum. The most prominent features, which have widths around 50 Å, are, in order of strength, at 5632, 3239, 5792, 5032 Å. These and other weaker emission bands are listed in the first column of Table 1. For three faint bands with widths of 100–200 Å the total range of wave-length is indicated.

The only explanation found for the spectrum involves a considerable red-shift. A red-shift $\Delta\lambda/\lambda_0$ of 0·158 allows identification of four emission bands as Balmer lines, as indicated in Table 1. Their relative strengths are in agreement with this explanation. Other identifications based on the above red-shift involve the Mg II lines around 2798 Å, thus far only found in emission in the solar chromosphere, and a forbidden line of [O III] at 5007 Å. On this basis another [O III] line is expected at 4959 Å with a strength one-third of that of the line at 5007 Å. Its detectability in the spectrum would be marginal. A weak emission band suspected at 5705 Å, or 4927 Å reduced for red-shift, does not fit the wave-length. No explanation is offered for the three very wide emission bands.

It thus appears that six emission bands with widths around 50 Å can be explained with a red-shift of 0·158. The differences between the observed and the expected wave-lengths amount to 6 Å at the most and can be entirely understood in terms of the uncertainty of the measured wave-lengths. The present explanation is supported by observations of the infra-red spectrum communicated by

Table 1. Wave-lengths and Identifications

λ	λ/1·158	λ_0	
3239	2797	2798	Mg II
4595	3968	3970	Hϵ
4753	4104	4102	Hδ
5032	4345	4340	Hγ
5200–5415	4490–4675		
5632	4864	4861	Hβ
5792	5002	5007	[O III]
6005–6190	5186–5345		
6400–6510	5527–5622		

Oke in a following article, and by the spectrum of another star-like object associated with the radio source 3C 48 discussed by Greenstein and Matthews in another communication.

The unprecedented identification of the spectrum of an apparently stellar object in terms of a large red-shift suggests either of the two following explanations.

(1) The stellar object is a star with a large gravitational red-shift. Its radius would then be of the order of 10 km. Preliminary considerations show that it would be extremely difficult, if not impossible, to account for the occurrence of permitted lines and a forbidden line with the same red-shift, and with widths of only 1 or 2 per cent of the wave-length.

(2) The stellar object is the nuclear region of a galaxy with a cosmological red-shift of 0·158, corresponding to an apparent velocity of 47,400 km/sec. The distance would be around 500 megaparsecs, and the diameter of the nuclear region would have to be less than 1 kiloparsec. This nuclear region would be about 100 times brighter optically than the luminous galaxies which have been identified with radio sources thus far. If the optical jet and component *A* of the radio source are associated with the galaxy, they would be at a distance of 50 kiloparsecs, implying a time-scale in excess of 10^5 years. The total energy radiated in the optical range at constant luminosity would be of the order of 10^{59} ergs.

Only the detection of an irrefutable proper motion or parallax would definitively establish 3C 273 as an object within our Galaxy. At the present time, however, the explanation in terms of an extragalactic origin seems most direct and least objectionable.

I thank Dr. T. A. Matthews, who directed my attention to the radio source, and Drs. Greenstein and Oke for valuable discussions.

1965: not all quasars are radio sources

THE EXISTENCE OF A MAJOR NEW CONSTITUENT OF THE UNIVERSE: THE QUASI-STELLAR GALAXIES

Allan Sandage
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington, California Institute of Technology
Received May 15, 1965

ABSTRACT

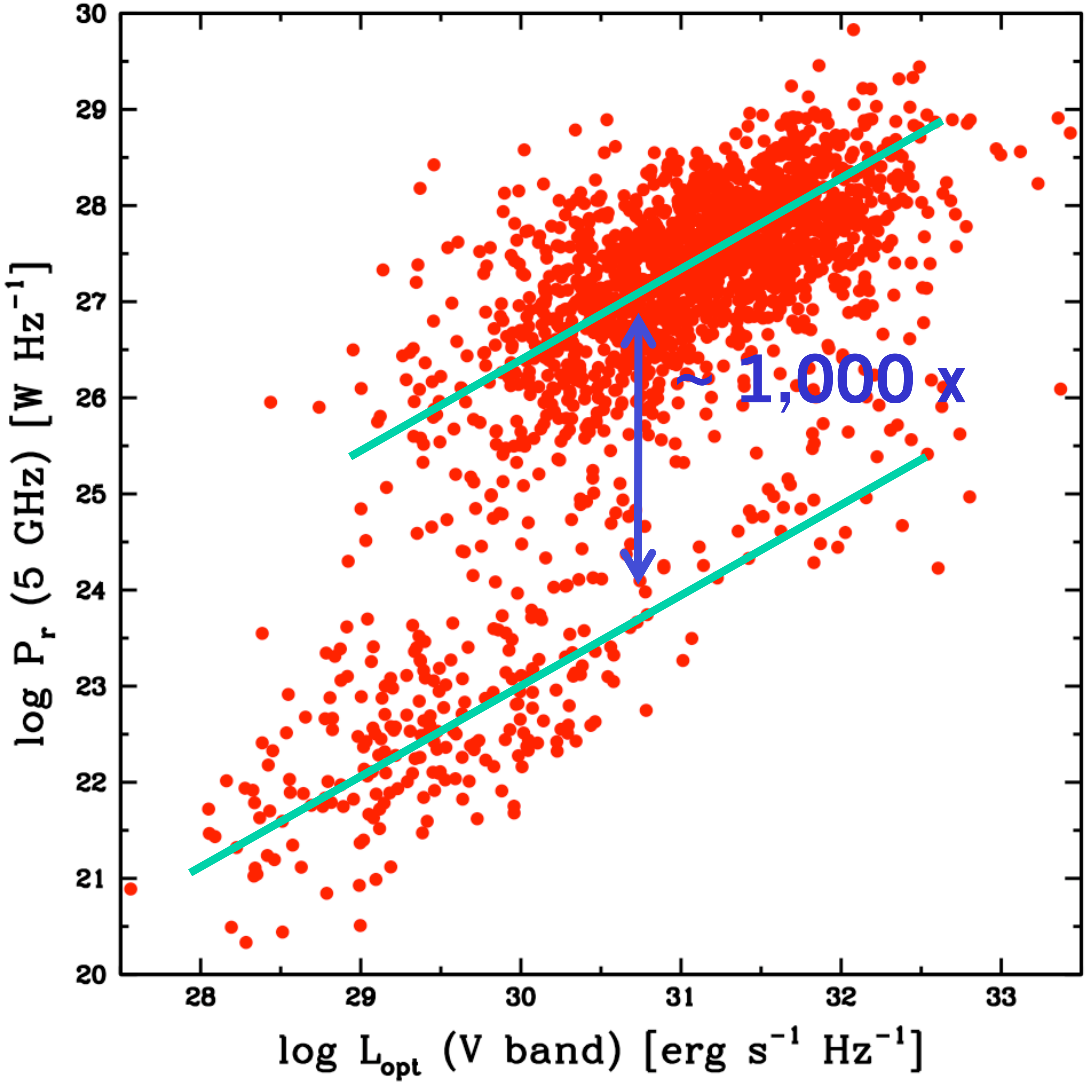
Photometric, number count, and spectrographic evidence is presented to show that most of the blue, starlike objects fainter than $m_{pg} = 16^m$ found in color surveys of high-latitude fields are extragalactic and represent an entirely new class of objects Members of the class called here quasi-stellar galaxies (QSG) resemble the quasi-stellar radio sources (QSS) in many optical properties, but they are radio-quiet. The QSG brighter than $m_{pg} = 19^m$ are 10^3 times more numerous per square degree than the QSS that are brighter than 9 flux units. The surface density of QSG is about 4 objects per square degree to $m_{pg} = 19^m$.

The evidence is developed in three parts: (1) Photoelectric photometry shows that a fundamental change occurs in the color distribution of high-latitude blue objects at about $V = 14.^m5$. Brighter than this, the objects fall near the luminosity class V line of the $U - B$, $B - V$ diagram. Fainter than this, 80 per cent of the objects lie in the peculiar region known to be occupied by the quasi-stellar radio sources. (2) The observed integral-count-curve, log $N(m)$, for objects in the Haro-Luyten catalogue undergoes a profound change of slope between $m_{pg} = 12^m$ and $m_{pg} = 15^m$, steepening and reaching a constant slope for m_{pg} fainter than 16^m. This magnitude interval is the same as that in which the color distribution changes, as discussed above. The slope fainter than 16^m is $d \log N(m)/dm = 0.383$. It is shown that this is the expected value from the theory of cosmological number counts for uniformly distributed objects with large redshifts. (3) Spectra of five of the faint blue objects are similar to spectra of quasi-stellar radio sources Intense, sharp emission lines of forbidden [O III], [O II], and [Ne III], together with very broad (35 Å wide) lines of $H\beta$, $H\gamma$, $H\delta$, $H\epsilon$, and [Ne V] are present in two of the five. Two broad emission lines are present in another at λ 3473 and λ 4279, identified as C IV (1550) and C III (1909). The other two objects have featureless spectra with only a blue continuum showing. The redshifts ($\Delta\lambda/\lambda_0$) for the three objects with lines are 0.0877, 0.1307, and 1.2410. The position of the objects in the redshift–apparent-magnitude diagram shows each of the three to be superluminous.

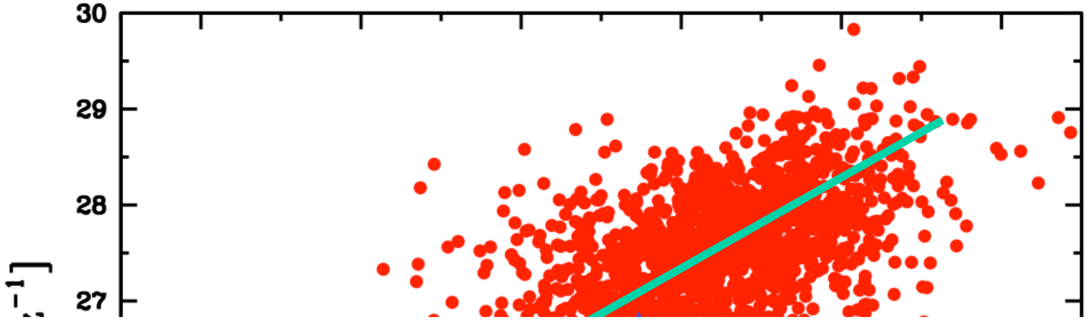
The space density of the quasi-stellar galaxies is estimated to be about 5×10^{-80} QSG/cm^3, which is to be compared with the space density of normal galaxies of about 1×10^{-75} galaxies/cm^3. The ratio, per unit volume, of QSG to QSS is estimated to be 500, which gives a lifetime of the QSG phase as 5×10^8 years if the lifetime of the radio source is 10^6 years.

The objects would seem to be of major importance in the solution of the cosmological problem. They can be found at great distances because of their high luminosity. QSG at $B = 22^m$ are estimated to have a mean redshift of $\Delta\lambda/\lambda_0 \simeq 5$ for a model universe of $q_0 = +1$. At these redshifts, we are sampling the universe in depth to 0.63 of the distance to the horizon (for $q_0 = +1$), and are looking back in time more than 0.9 of the way to the "creation event" in an evolutionary model. Study of the $[m, z]$- and log $N(m)$-curves using the QSG should eventually provide a crucial test of various cosmological models. But even more important, comparative study of the quasi-stellar galaxies and the intimately connected quasi-stellar radio sources is expected to shed light on the evolutionary processes of the violent events that characterize the two classes.

Radio quiet AGN

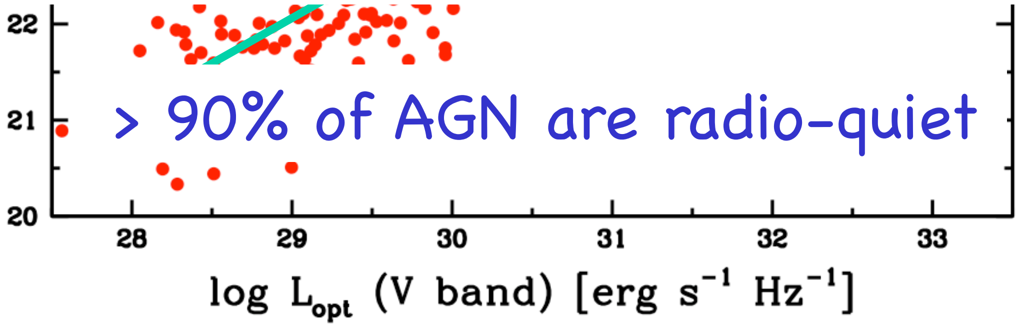


Radio quiet AGN



- Radio-loud AGN: most energy non-thermal: powerful relativistic jets (also thermal components [accretion disk])

- Radio-quiet AGN: jets not present or insignificant w.r.t total energy budget → thermal emission dominates



> 90% of AGN are radio-quiet

The AGN Zoo

- Quasars belong to the Active Galactic Nuclei (AGN) class
- AGN come in a large (and scary!) number of sub-classes:

Radio-quiet AGN

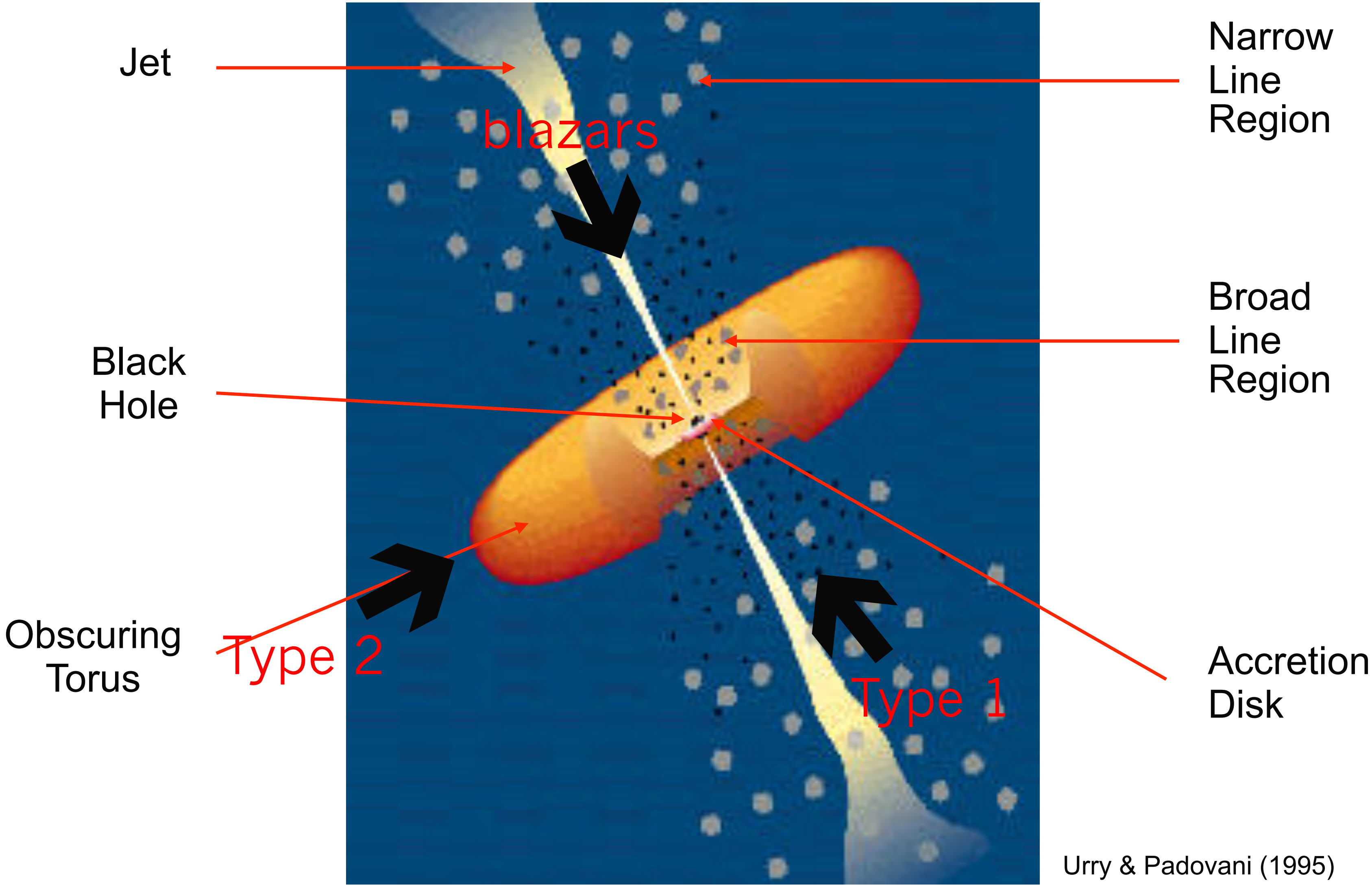
Type 1 & 2, Seyfert 1, Seyfert 2, Seyfert 1.5, Seyfert 1.8 ...
Narrow-line Seyfert 1, Liners

Radio-loud AGN

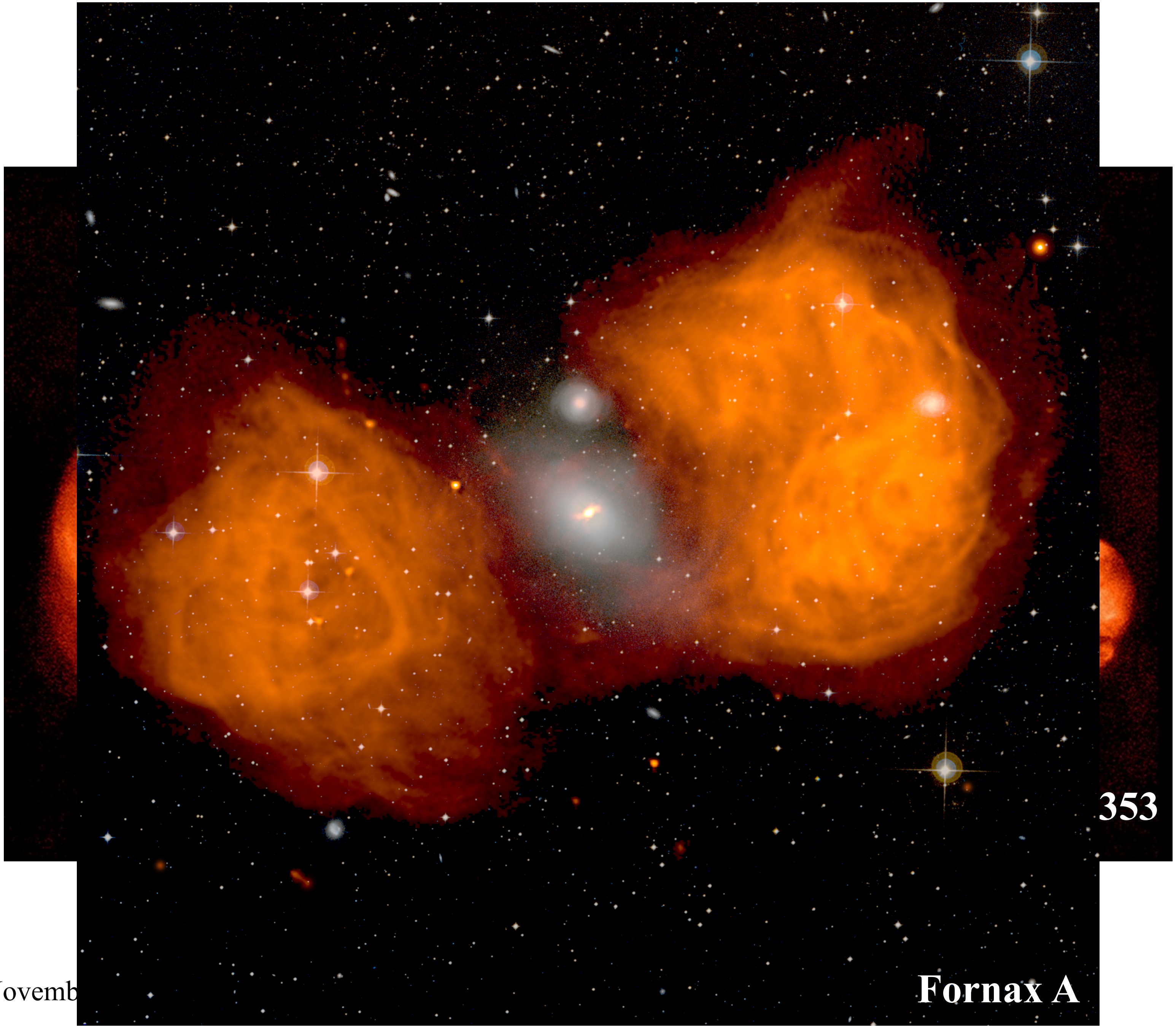
Type 1 & 2, blazars, flat- and steep-spectrum radio quasars, core-dominated, lobe-dominated, optically violent variable quasars, BL Lacertae objects (*high-peaked, low-peaked, radio-selected, X-ray selected*) high- and low-polarization quasars

Radio-galaxies: Fanaroff-Riley I & II, narrow-lined, broad-lined, high-excitation, low-excitation

AGN Unified Schemes



Urry & Padovani (1995)


353
Fornax A

TeV Sources

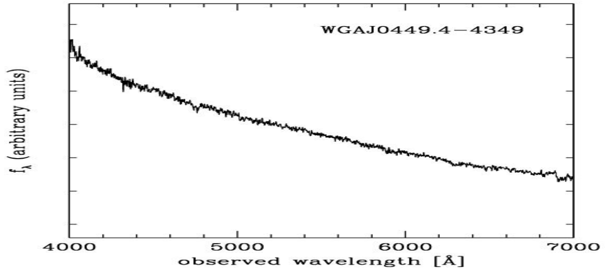
- > 150 sources detected at TeV energies by Cherenkov telescopes

Galactic sources (pulsars, etc.)	**76**	**49%**
Blazars	**45**	**29%**
Other AGN	**5**	**2%**
Star-forming galaxies	**2**	**1%**
Unclassified	**28**	**18%**

- AGN (blazars) make up ≈ 1/3 of the TeV γ-ray sky
- And ≈ 60% (< 90%) of the MeV – GeV γ-ray sky

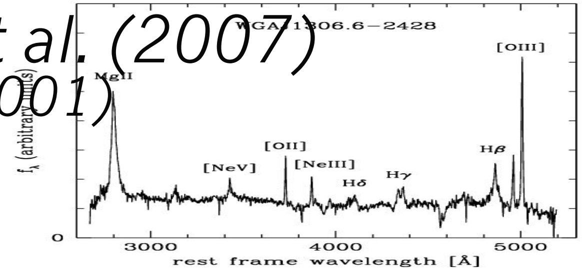
Blazar Properties

BL Lacs and Flat-Spectrum Radio Quasars



BL Lac: Albert et al. (2007)

Tavecchio et al. (2001)

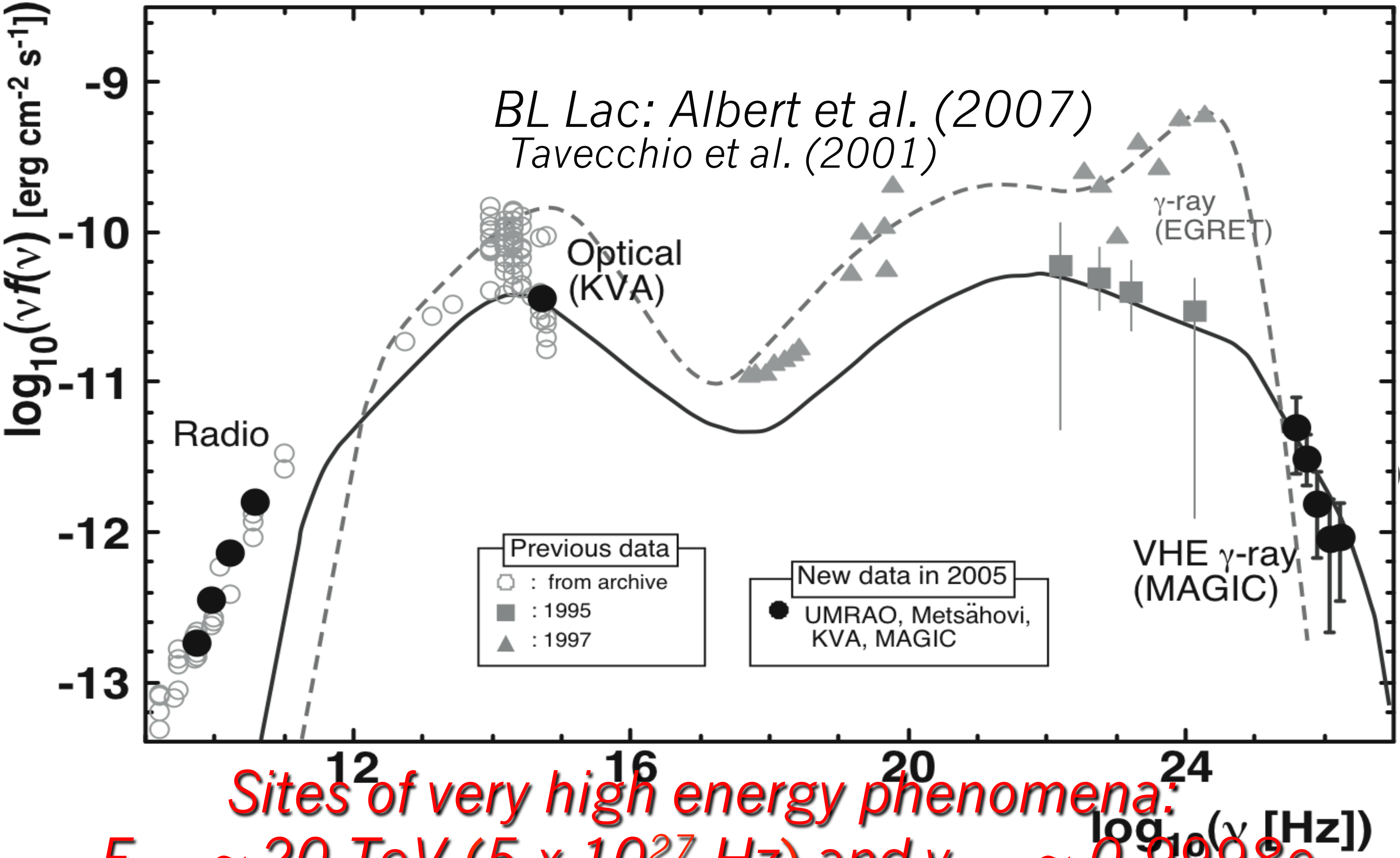


- Smooth, broad, non-thermal continuum (radio to γ-rays)
- Compact, strong radio sources ($f_{core} >> f_{extended}$)
- Rapid variability (high $\Delta L/\Delta t$), high and variable polariz. ($P_{opt} > 3\%$)
- Strong indications of "relativistic beaming" ⇒ bulk relativistic motion beams emission in forward direction in the observer's frame
- Amplification: $L_{obs} = \delta^{p+\alpha} L_{em}$, p ~ 2 - 3 → $\Gamma = 10$, $L_{obs} \sim 600\ L_{em}$, $\Gamma = 30$, $L_{obs} \sim 100{,}000\ L_{em}$

Sites of very high energy phenomena:

$E_{max} \sim 20$ TeV (5×10^{27} Hz) and $v_{max} \sim 0.9998c$

Blazar Properties



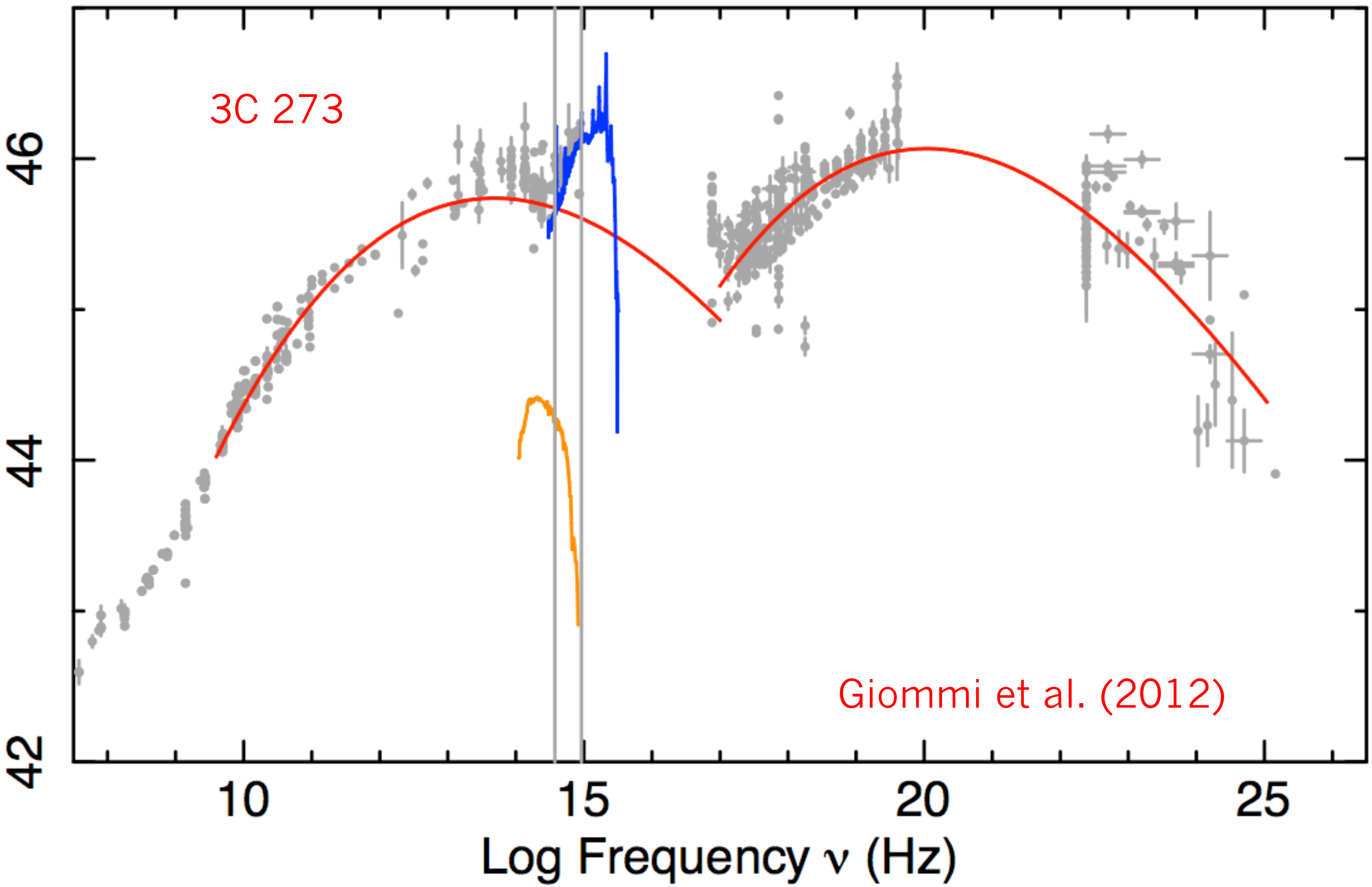
Sites of very high energy phenomena:

E_{max} ~ 20 TeV (5 x 10^{27} Hz) and v_{max} ~ 0.9998c

What does it take for an AGN to be detected in the TeV band?

1. To be looked at → target selection based on other bands
2. Non-thermal emission → radio-quiet AGN do not make it
3. Low redshift ($z \lesssim 0.54$) → high redshift γ-ray photons absorbed by the IR background (cf. the small # of quasars)
4. Right spectral energy distribution → peak in the γ-ray band is favoured (quasars are biased against)
5. Relativistic beaming to boost emission → only the closest radio galaxies are detected
6. Variability to boost emission → flaring targets more likely to be detected

What does it take for an AGN to be detected in



Why is CTA good for AGN? 1.

- Because some objects have their peak energy in the TeV band
- To study extreme cosmic accelerators (blazars): highest photon energies! (most promising way with cosmic rays and neutrinos)
- To constrain models of jet emission: e.g., leptonic [γ-rays from high-energy electrons] vs. hadronic [γ-rays from high-energy protons/nuclei]
  - ✓ different high-energy spectra
  - ✓ if hadronic, related to the origin of ultra-high-energy cosmic rays and neutrinos
- To probe regions very close to the black hole (rapid variability): $R \leq c\ t_{var} \delta /(1+z)$
- To give an unbiased view of the TeV sky

Why is CTA good for AGN? 1.

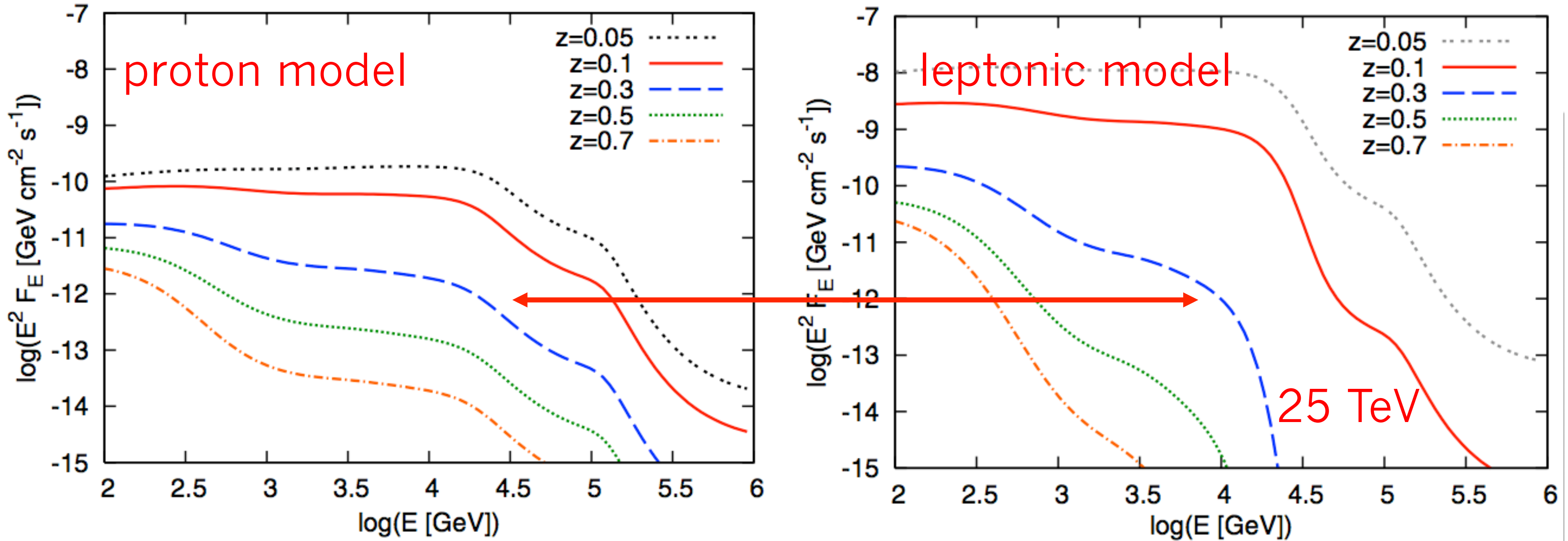
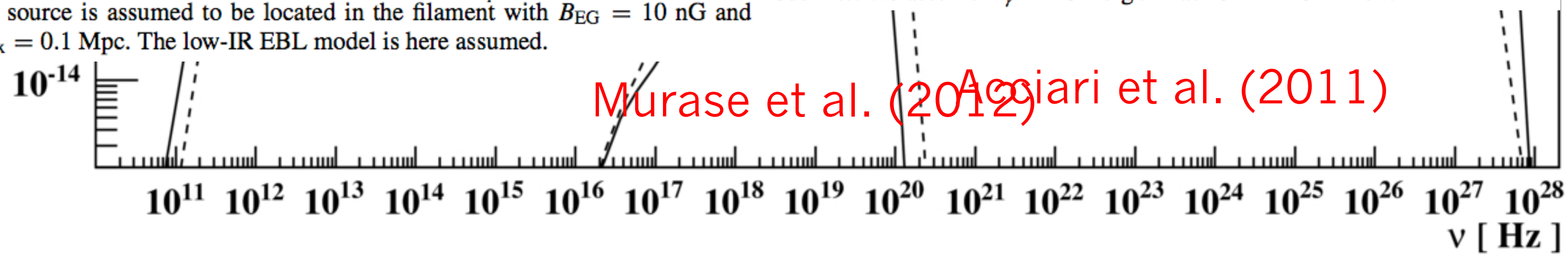


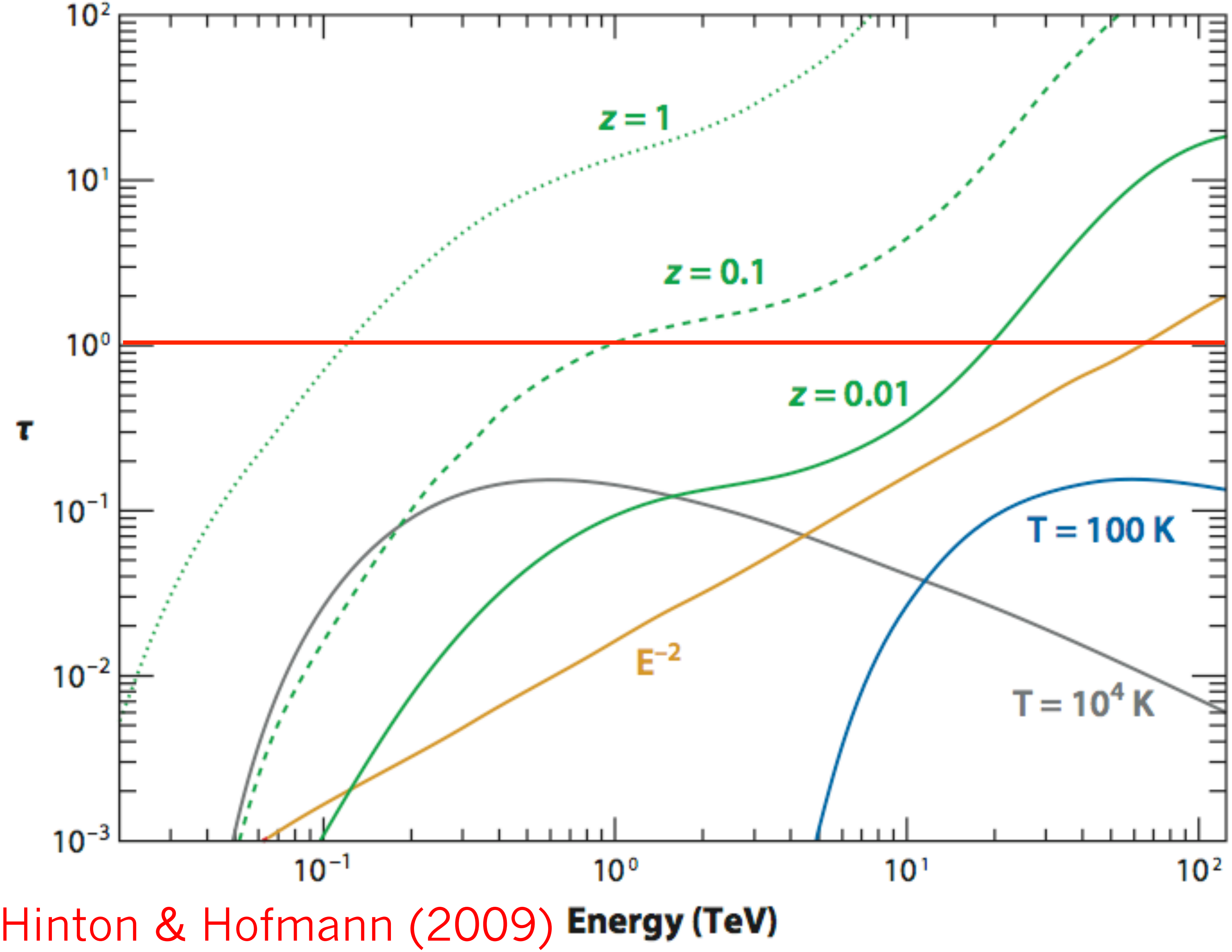
Figure 7. Spectra of UHE proton-induced cascade emission for various source redshifts. We assume $L_{\rm UHECR} = 10^{45}$ erg s^{-1} with $E_p^{\rm max} = 10^{19}$ eV and $p = 2$. The source is assumed to be located in the filament with $B_{\rm EG} = 10$ nG and $\lambda_{\rm max} = 0.1$ Mpc. The low-IR EBL model is here assumed.

Figure 3. Spectra of UHE γ-ray-induced cascade emission for various source redshifts. We assume $L_\gamma = 10^{45}$ erg s^{-1} at $10^{18.75}$–$10^{19.25}$ eV.



Why is CTA good for AGN? 2.

- To constrain intrinsic high-energy blazar spectra through possible detections of sources at high z
  - ✓ $\gamma_{TeV} + \gamma_{IR/O/UV} \rightarrow e^{+} + e^{-}$ σ_{max} for $\lambda \sim 1.33\ \mu m\ (E/TeV)$
- To help solve the paradox of VLBI sub-luminal speeds in TeV BL Lacs:
  - ✓ fast γ-ray variability → $\Gamma \approx 50$
  - ✓ for typical angles → superluminal motion in the radio band expected: none is observed



Hinton & Hofmann (2009)

Wh… ? 2.

- To constrain int… …a through possible detectio…
  - ✓ $\gamma_{TeV} + \gamma_{IR/(}$… …1.33 μm (E/TeV)
- To help solve t… …speeds in TeV BL Lacs:
  - ✓ fast γ-ray …
  - ✓ for typical … …n the radio band expected:

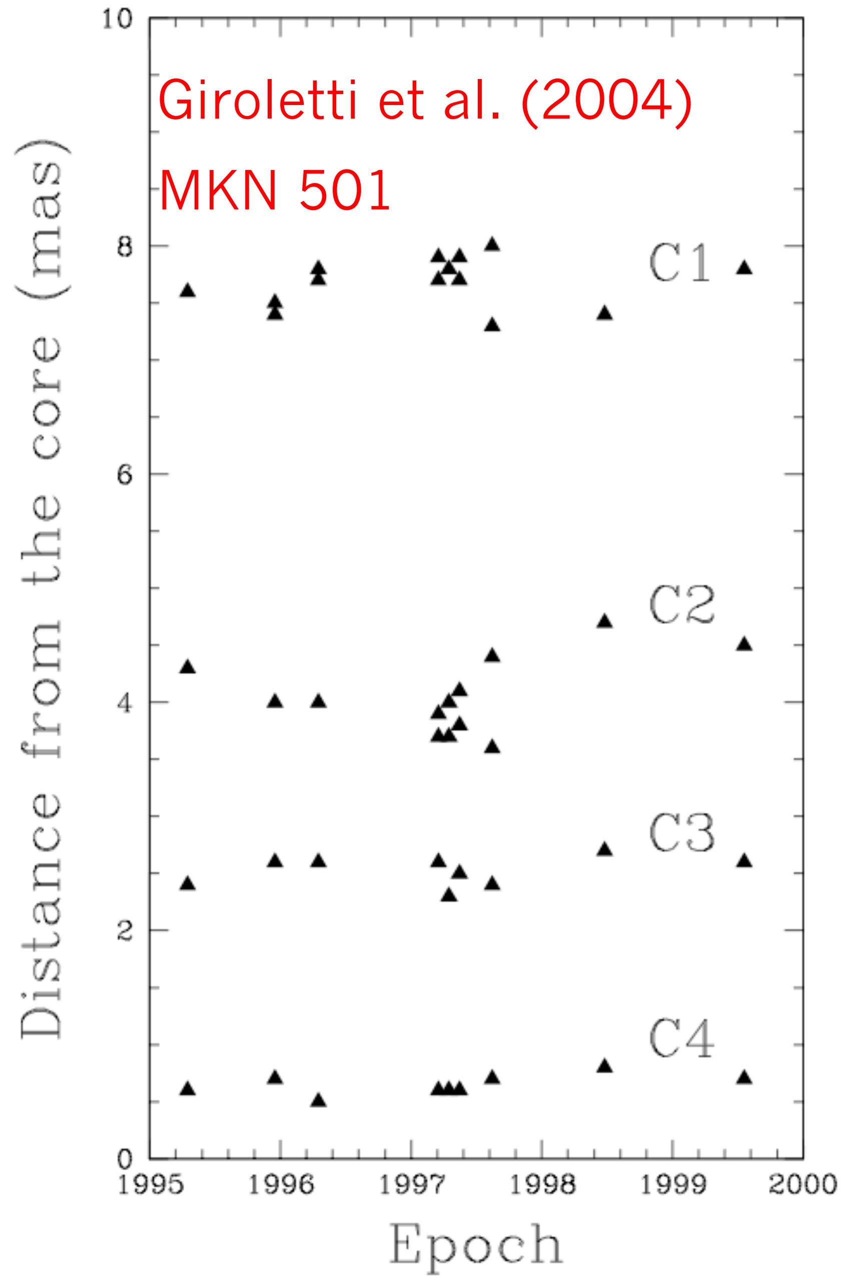


FIG. 13.—Component positions from model fitting. Distances are given in milliarcseconds. All points are at 15 GHz with the exception of the 1998.48 epoch, which is at 8.4 GHz.

AGN as ultrahigh energy cosmic ray (and neutrino) sources

- Restricted to radio-loud sources (in my opinion!):
  - ✓ no radio-quiet AGN detected in the γ-ray (MeV – TeV) band (e.g., Ackermann et al. 2012) [two Seys, star-formation related]
  - ✓ radio emission in radio-quiet AGN mostly star-formation related (synchrotron emission from SN remnants: PP et al. 2011)

  → *should not be using whole Véron-Cetty & Véron AGN catalogue to look for the sources of cosmic rays*
- Need hadronic jets (standard leptonic models only reach $\approx 10^{19}$ eV: e.g., Murase et al. 2012) [important also for neutrino emission]
- Need magnetic luminosity $L_B \gtrsim 10^{45}\ Z^{-2}\ (E/10^{20} \mathrm{eV})^2$ erg/s to accelerate protons/nuclei (e.g., Lemoine & Waxman 2009):
  - ✓ if $Z = 1$, only powerful radio galaxies and quasars can make it but GZK suppression limits the redshift ($\lesssim$ 0.03–0.05)
  - ✓ if $Z \gg 1$, $L_B \downarrow$, more potential sources but isotropic distribution (e.g., Hardcastle 2010, Lemoine 2012)
- Delay between arrival of particles and photons (e.g., Olinto 2012)

Summary

- CTA to be very important for AGN: should be fundamental for the solution of quite a few open problems
- Requirements for AGN as cosmic ray and neutrino sources: radio-loud, hadronic jets, large power → few candidates (if protons) OR lower power → more candidates (if heavier nuclei) [but loss of correlation with astronomical counterparts]