Compact structures of extragalactic radio sources in the cosmological context

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Angular size – redshift (θ–z) tests: the concept

- The idea:

  F. Hoyle, 1959, URSI Symp. No. 1, Paris

- **Many attempts at arc-second scale:**
- Radio structures as standard rods
  - Kapahi 1987
  - Barthel and Miley 1988,,
  - Nilsson et al 1993
    - + many others
  - Strong source evolution found !

  - Some encouraging results by
  - Buchalter et al. 1998
  - Daly et al. 2001, 2002

  (hand-picking “right” sources)

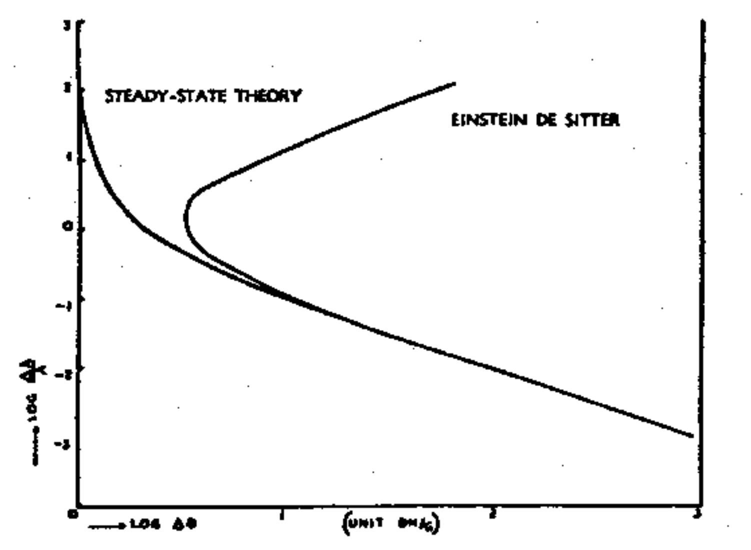
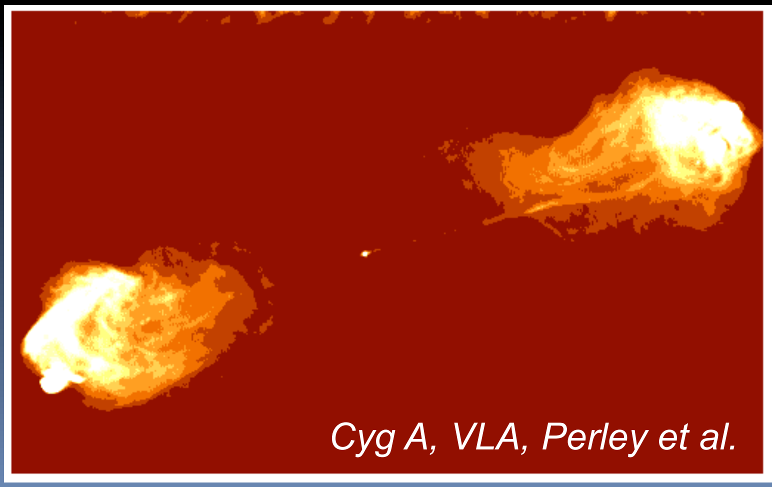
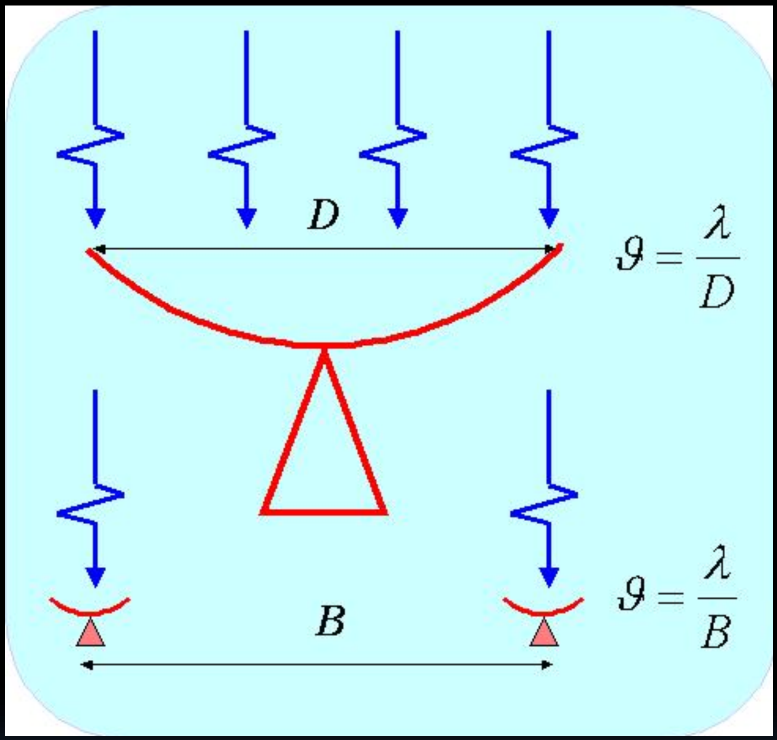


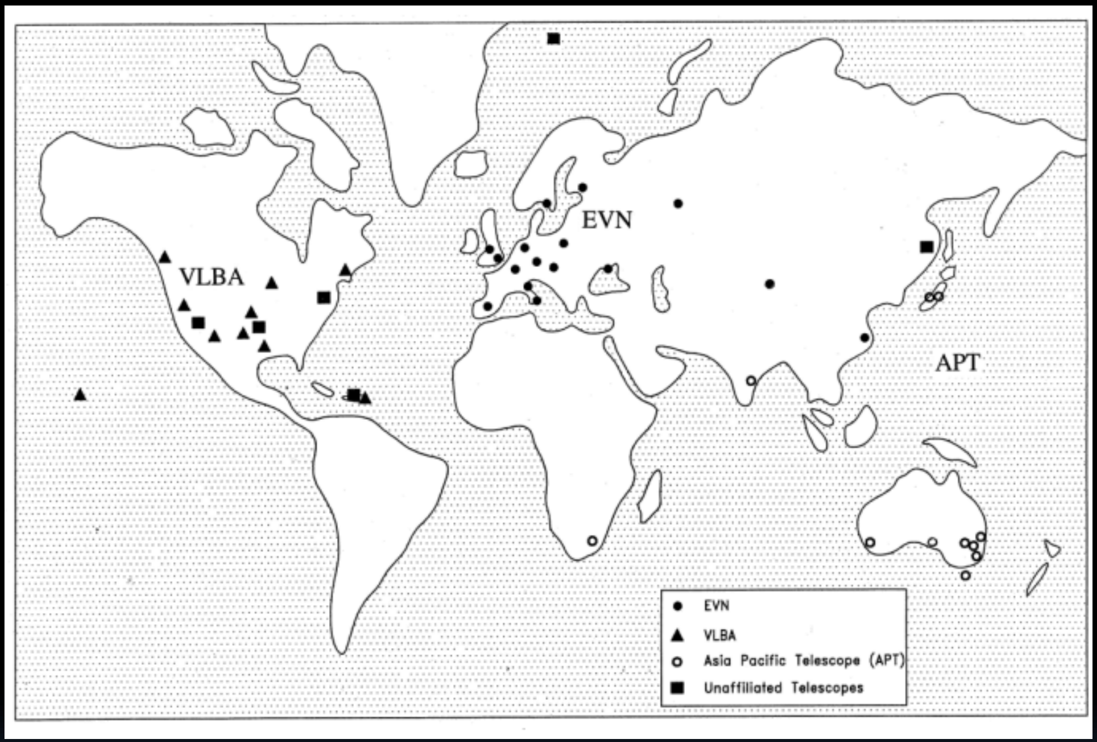
Fig. 5. Apparent diameter $\Delta\theta$ of a source of absolute diameter D, plotted against red-shift.



Cyg A, VLA, Perley et al.

Very Long Baseline Interferometry (VLBI):
the highest [imaging] angular resolution in astronomy



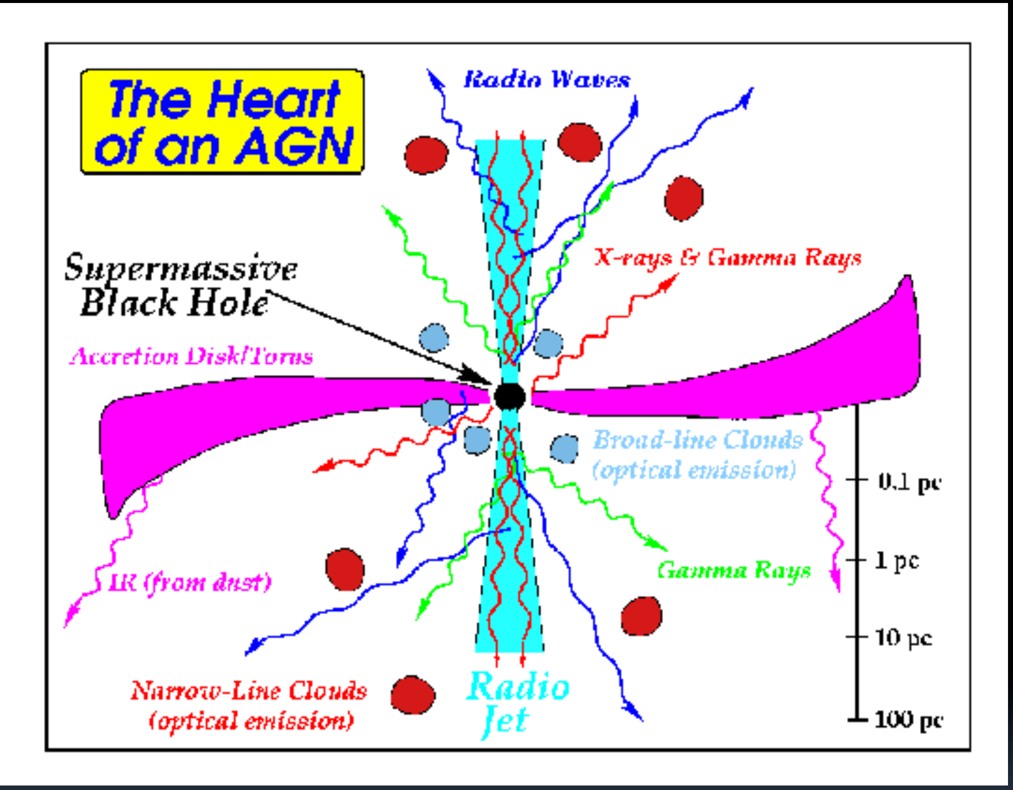


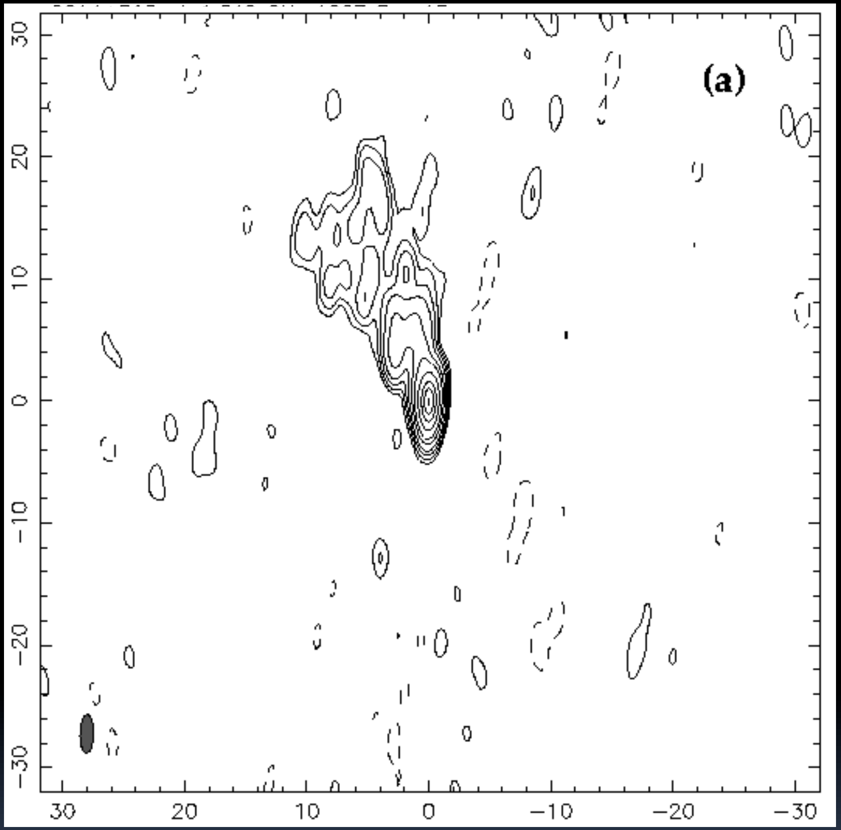
At present:

- **VLBI covers wavelengths from ~0.9 m (~327 MHz) to ~1 mm (~300 GHz);**
- **Angular resolution from 100 to 0.1 milliarcsecond (mas).**

- **Plus: Space VLBI – baselines up to ~30 Earth diameters**

What you [want to] get versus what you see:

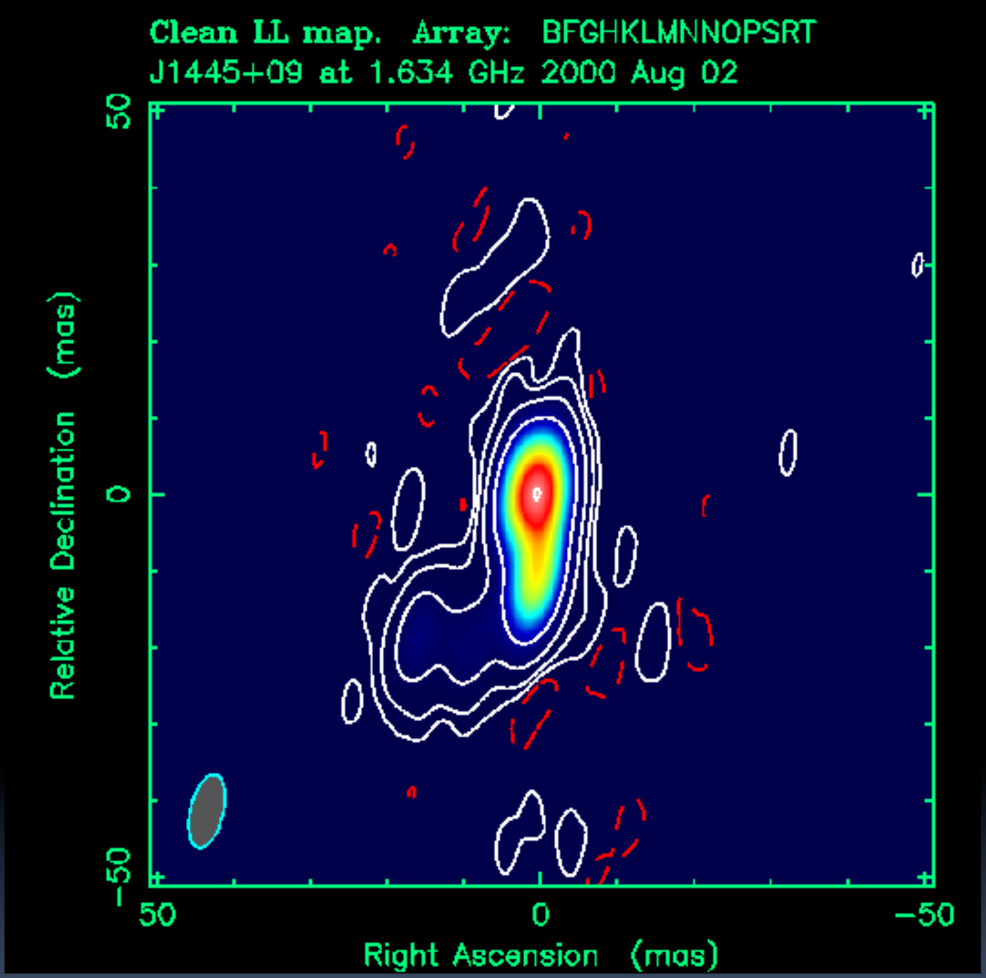




ARISE, 1999, JPL Publ. 99-14

- What is the correspondence between the two pictures (jets, cores, etc.)?
- How much deeper in the "core" can one go (a hunt for the highest T_B)?

What is seen in AGN at the milliarcsecond scale?



- "Core-jet" structures composed of components with $T_B \sim 10^8 - 10^{13}$ K
- These components are "short-leaving" (comparing with the cosmological scale): 10^3 vs 10^{10} yrs
- Central engines of AGN powered by supermassive black holes
- Physics on the sub-pc scale is likely to be dominated by the gravitational potential of the central BH

Physical size (scale) of AGN as a class is more or less the same?

Why mas-scale cosmology?

- The age of "precision cosmology" (M. Longair, IAU GA 2000)
- VLBI – the leading edge of (imaging) precision in astronomy
  - Parsec/sub-parsec linear resolution ANYWHERE in the Universe;
  - Objects – the most powerful "engines" of the Universe, AGN
    - *Their physics supposed to be "governed" by gravitation*
      - Well understood?
- Cosmological "utilisation" of existing VLBI data possible
- In combination with other techniques, VLBI provides unique tools for measuring cosmologically meaningful phenomena (e.g. H_0 from the megamaser in NGC4258)
- "Angular size–redshift" (θ-z) milliarcsecond scale test
  - *"in action" since ~1992* *(Sahni & Starobinsky 2000, Int. J. Mod. Phys D, 9, 373)*

Standard rod at mas scale: *phenomenology*

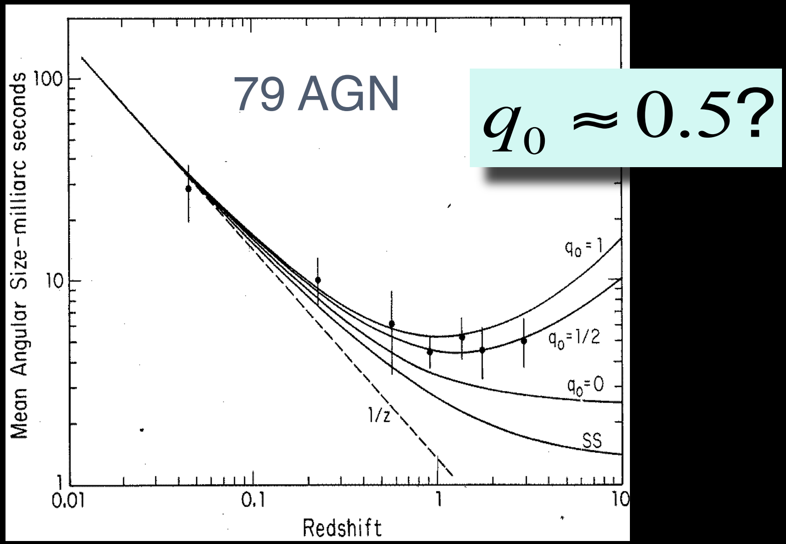
$$\theta = \frac{H_0}{c} l \left(\frac{L_c}{L_0} \right)^{\beta} (1+z)^n D$$

$$D = D(z, \mathrm{cosmology})$$

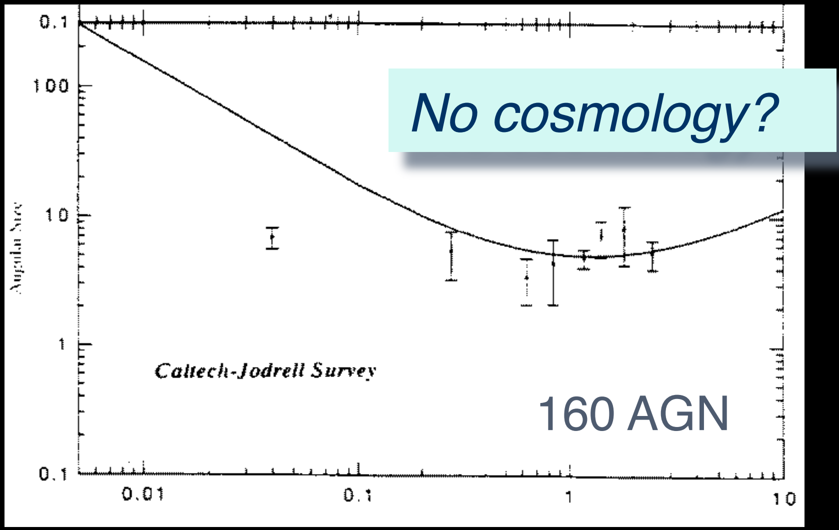
- β – physics of AGN (after all, AGN are different)
- n – a blend of (class) evolution and AGN physics
- θ and z are measurables =>
  - a fit of "θ–z" enables estimates of D

NB: *Collecting "θ–z" data can be done in ad hoc fashion, not a special project/mission*

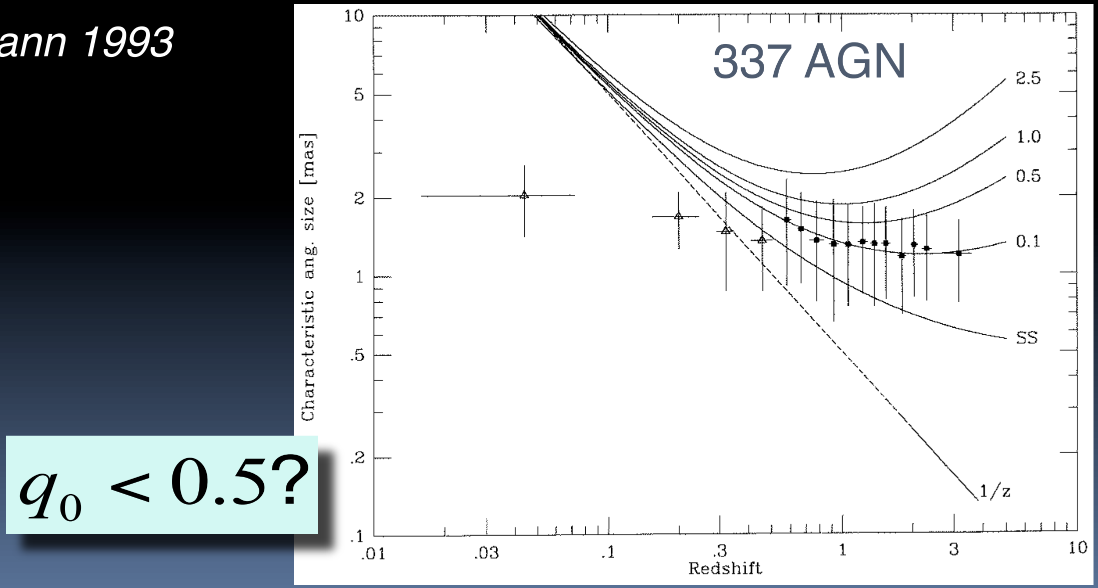
Demonstration mas-scale θ-z tests (1990s)



Kellermann 1993



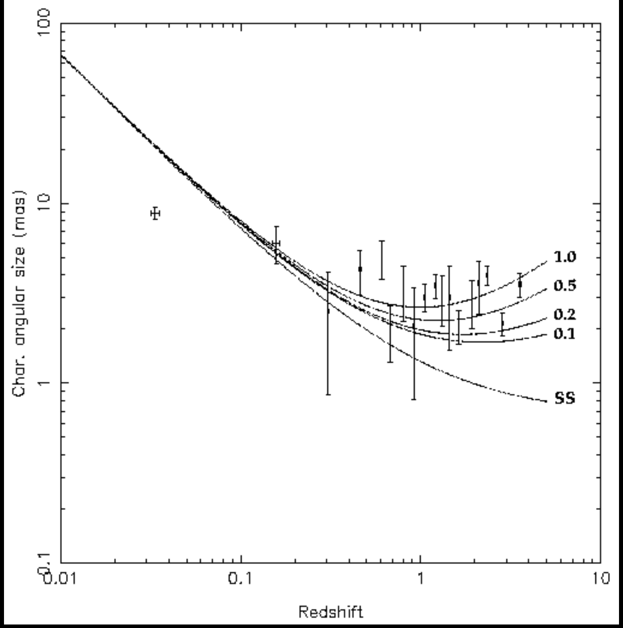
Pearson et al. 1996
Wilkinson et al. 1998

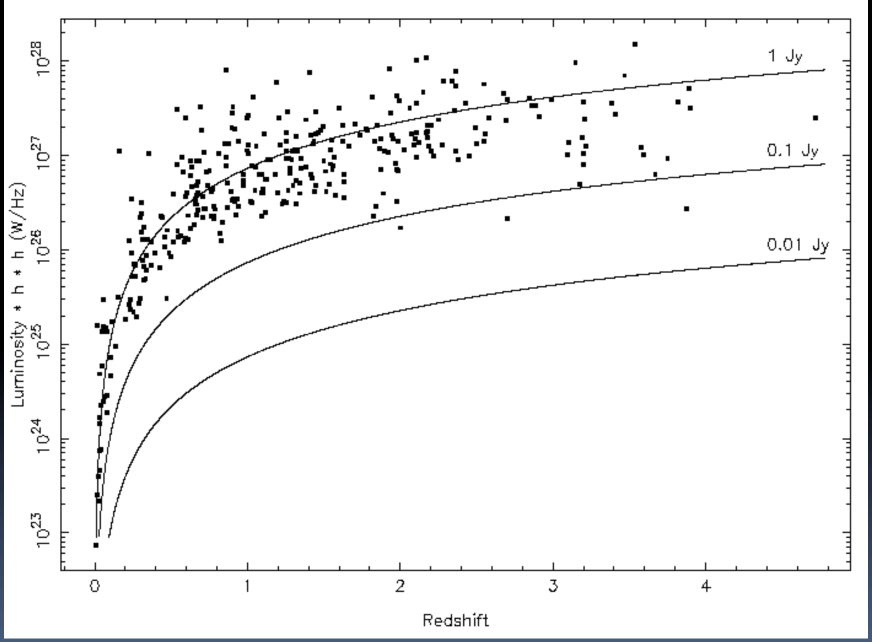


LIG 1994

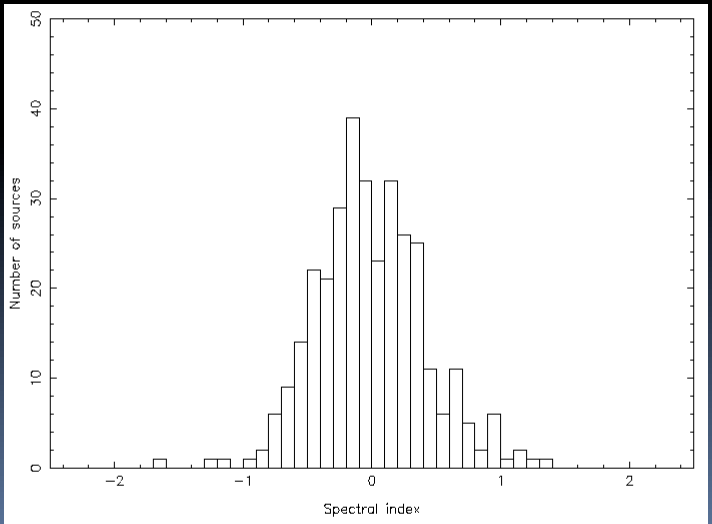
θ-z 2000: "maximum" use of ad-hoc data

- 330 sources with known redshift and mas images at 5 GHz better than 100:1
- 4-parameter regression model ("proof of suitability")





LIG, Kellermann, Frey 1999



Naïve results

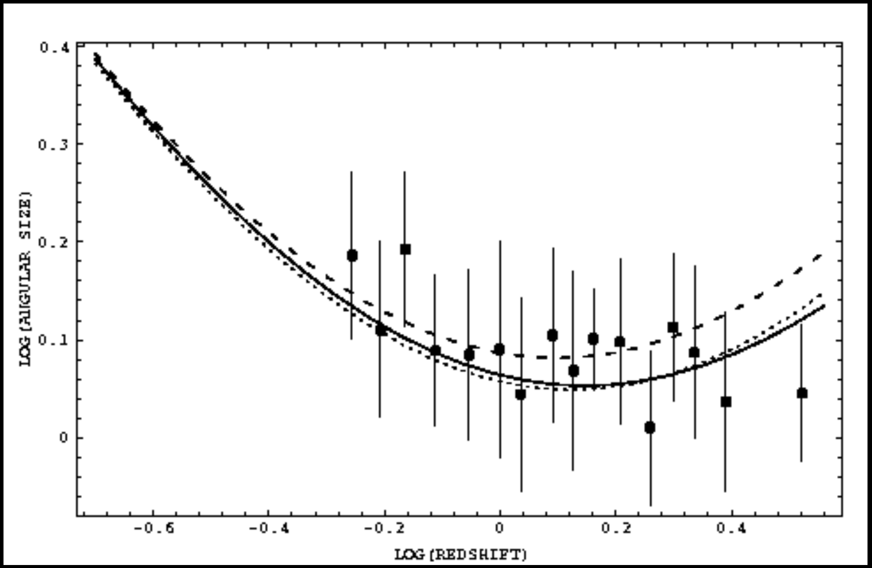
Table 1: Two-parameter (l_h and q_0) regression model results with 1σ errors for different, fixed values of β and n for the sample of 145 sources ($Lh^2 \le 10^{26}$ W/Hz, $-0.38 \le \alpha \le 0.18$).

n		$\beta=-0.20$	$\beta=-0.10$	$\beta=-0.05$	$\beta=0.0$	$\beta=0.05$	$\beta=0.10$	$\beta=0.20$
−0.3	l_h (pc)	13.98±4.71	16.48±4.82	17.56±5.22	18.48±6.79	19.20±9.09	19.90±1.81	20.84±2.54
	q_0	1.78±0.83	1.04±0.51	0.81±0.51	0.64±0.73	0.51±1.59	0.41±0.27	0.26±0.06
−0.2	l_h (pc)	14.64±4.03	16.76±4.14	17.68±4.50	18.42±6.07	19.00±4.02	19.60±1.93	20.28±2.44
	q_0	1.22±0.43	0.73±0.30	0.57±0.32	0.45±0.53	0.36±0.71	0.28±0.15	0.17±0.03
−0.1	l_h (pc)	15.02±3.48	16.82±3.58	17.58±3.87	18.16±5.42	18.70±2.06	19.00±1.98	19.60±2.30
	q_0	0.86±0.23	0.52±0.18	0.40±0.20	0.31±0.40	0.24±0.33	0.19±0.09	0.10±0.02
0.0	l_h (pc)	15.15±3.04	16.68±3.12	17.22±3.36	17.72±4.83	18.10±1.62	18.33±1.95	18.66±2.14
	q_0	0.60±0.13	0.36±0.11	0.28±0.13	0.21±0.30	0.16±0.18	0.12±0.05	0.05±0.01
0.1	l_h (pc)	15.14±2.69	16.36±2.74	16.80±2.92	17.14±4.30	17.30±1.56	17.56±1.89	17.68±1.99
	q_0	0.42±0.08	0.25±0.07	0.19±0.09	0.14±0.23	0.10±0.11	0.07±0.03	0.01±0.01
0.2	l_h (pc)	14.92±2.40	15.88±2.43	16.20±2.56	16.46±3.81	16.60±1.55	16.74±1.79	16.24±2.05
	q_0	0.29±0.05	0.16±0.05	0.12±0.06	0.08±0.18	0.05±0.07	0.02±0.02	2e-6±1e-3
0.3	l_h (pc)	14.52±2.16	15.30±2.16	15.54±2.26	15.69±3.38	15.80±1.53	15.40±1.65	14.63±1.29
	q_0	0.20±0.03	0.10±0.03	0.06±0.04	0.03±0.15	7e-3±0.04	5e-3±0.02	1e-7±1e-6

$$q_0 \le 0.5 \text{ for } \beta + n \ge -0.15$$

Aftermath of the "maximum use" sample publication

Vishwakarma 2001 a,b
Astro-ph/9912105, -/0012492,



$$1+\Omega_{ko} = \Omega_0 + \Omega_{\Lambda 0}, \quad 2[q_0 + \Omega_{\Lambda 0}] = \Omega_0$$

- Re-analysed data from LIG 1994 (256 sources) and LIG, Kellermann and Frey 1999 (330 sources) in concurrence with the Type Ia SN (Riess 1998, Perlmutter et al. 1999)
- Various models analyzed:

models	Ω_0 flat	Ω_0 global	$\Omega_{\Lambda 0}$ global
$\Lambda \sim S^{-2}$	0.68	0.97	0.61
$\Lambda \sim H^2$	0.67	0.29	1.03
$\Lambda \sim \rho$	0.67	0.53	0.82
Λ=const	0.2	0.08	1.16

θ-z data favor accelerating and decelerating models with Λ=*var* or accelerating models with Λ=*const* (SN Ia data: acceleration in both cases)

Aftermath of the "maximum use" sample publication

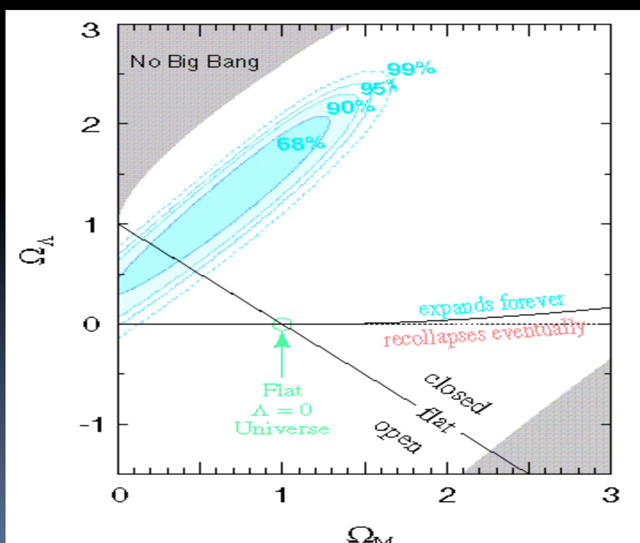
- Minimize

$$\chi^2(l,P) = \sum_{bins} \left[\frac{\theta(l,P,z_i) - \theta_{obs}(z_i)}{\sigma(z_i)} \right]^2$$

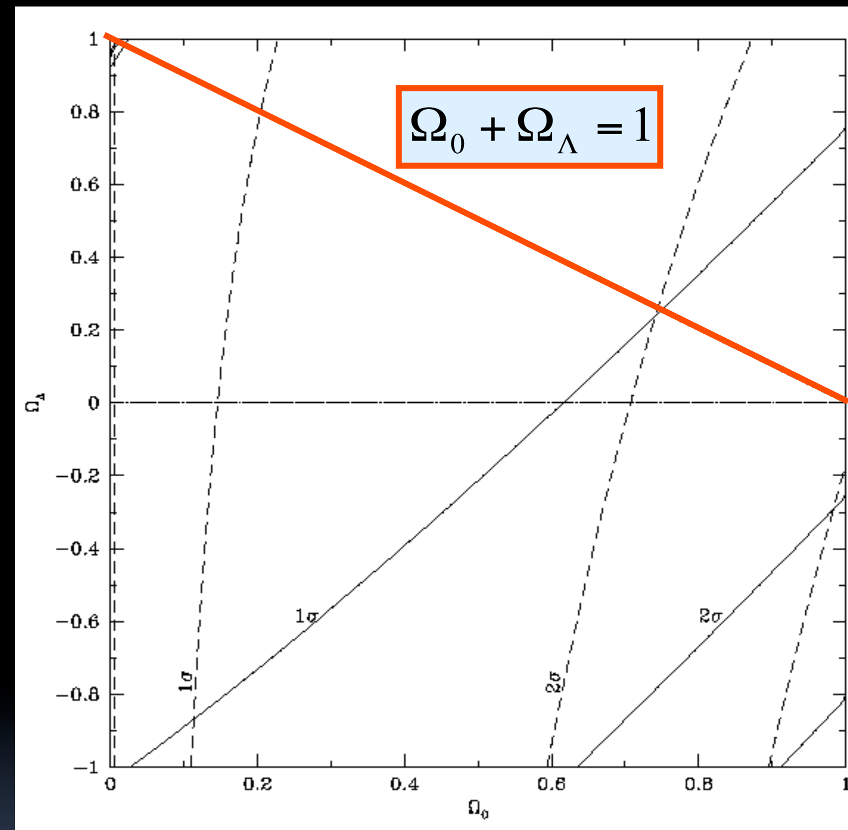
$$L(P) = \int dl\, e^{-\chi^2(l,P)/2}$$

- Treat linear size, *lh*, as a "nuisance" parameter

Perlmutter et al. 1998



Chen & Ratra 2002
Astro-ph 0207051



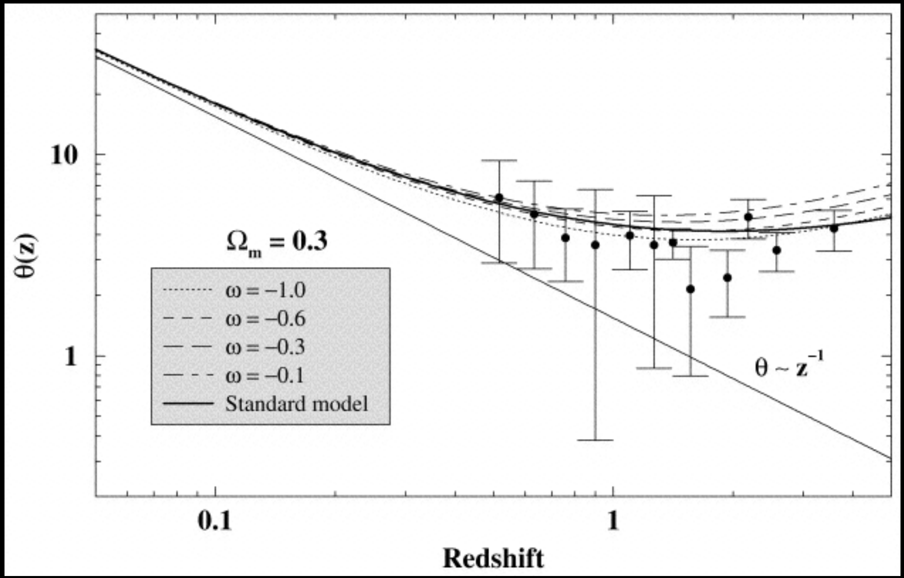
Constraints on cosmological model from *θ-z* data are consistent but less constraining than those of SN Ia.

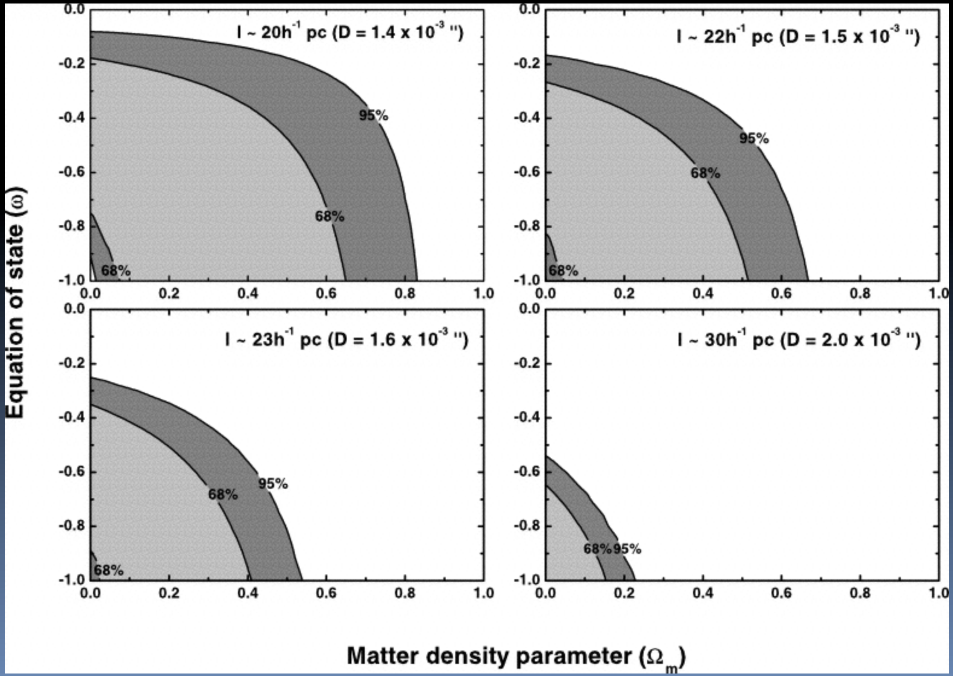
Aftermath of the "maximum use" sample publication

Lima & Alcaniz 2002

- FRW model driven by non-relativistic matter and a smooth "dark energy" component $p_x = \omega \rho_x$
- Best fit:

$$\Omega_m \le 0.62, \quad \omega \le -0.2, \quad lh = 20 \ \text{pc}$$
$$\Omega_m \le 0.17, \quad \omega \le -0.65, \quad lh = 20 \ \text{pc}$$





Conventional flat ΛCDM model (ω= -1) with Ω_m=0.2 is the best fit.

Better statistics –

– more ata needed!

Shocks in jet as standard rods: θ/τ_{int} versus z

- Linear size of shocks depends on the variability time-scale, τ_{int}
- Angular size of the shocks, θ, measured by VLBI (typically 0.1 mas)
- The ratio, θ/τ_{int}, serves as a standard object
- The method requires both VLBI data and monitoring (at high frequencies)

$$q_0 \approx 0, \quad \Omega_m \approx 0$$
$$\Omega = \Omega_m + \Omega_\Lambda = 1$$

Wiik & Valtaoja, 2001

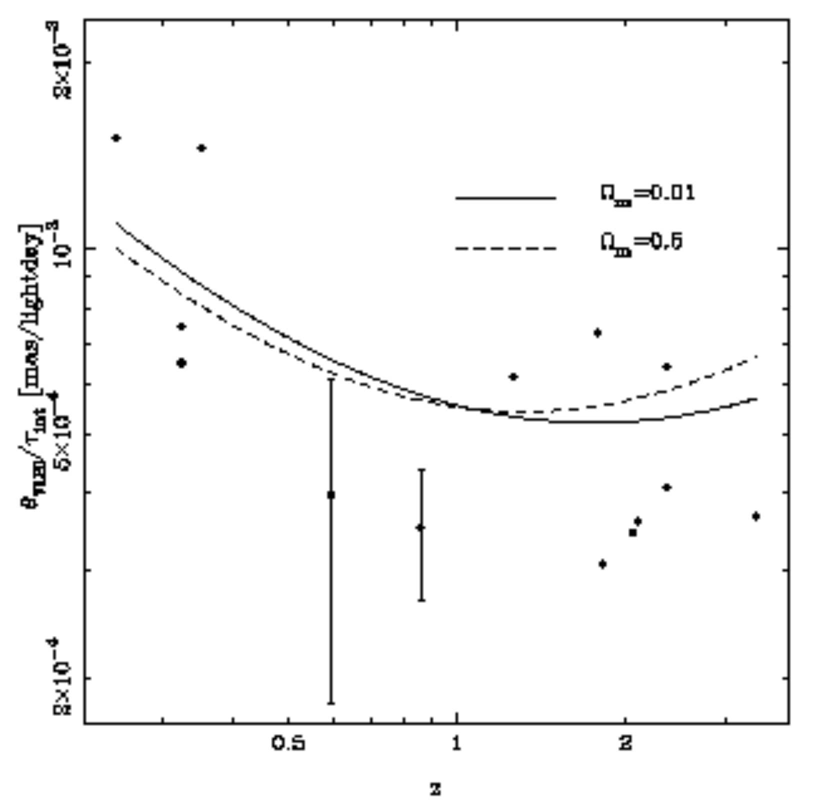


Fig. 2. Normalized datapoints and fitted models with $\Lambda \neq 0$ (Eq. (7)). Ω_m was fixed and best fit was found with $2^{-2/3}KH_0$ as the free parameter

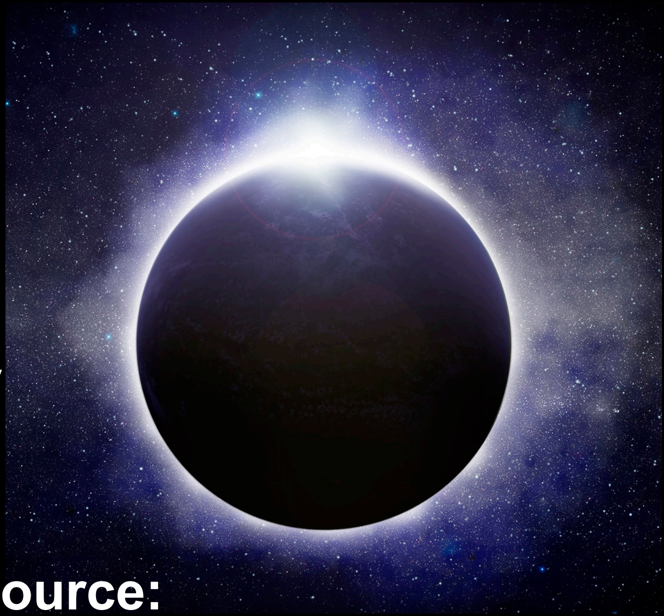
Half a century of quasars

- 3C 273, 1963 – (the story by Hazard et al. 2015)
- AGN of all kinds
- Central SMBH
- Known through z~7

  (cf. SN I, z~2)

- Earth-based VLBI offers parsec-scale imaging
  - but deals with a "smoking gun" only….
- VLBI surveys provide images of several 10^3 sources
  - including ~30 sources at z>5
  - cover received frequency range 1.6 – 22 GHz
  - push the radio brightness envelope…
- Key improvements for θ–z tests with AGN VLBI images
  - *Higher z (efforts underway; several z>6 QSOs imaged)*
  - *Higher sensitivity (efforts underway; single-digit mJy sources imaged)*
  - ***Sharper view (higher brightness temperature) – needed!***

Cosmic conspiracy:
Earth, a very special place



But not because of this only

Brightness temperature of a slightly resolved source:

$$T_b = \frac{2\ln 2}{\pi k}\frac{S_{core}\lambda^2(1+z)}{\theta_{maj}\,\theta_{min}}$$

$\sim B^2$

For a "typical" AGN:

$z \sim 1$

$S_{core} \sim 500$ mJy

$T_b \sim 10^{12}$ K (Inverse Compton limit, Kellermann & Pauliny-Toth 1969)

$\Rightarrow$ $B \sim 10^4$ km

Earth, a very special VLBI system!

RadioAstron – Spektr-R

- 10-m antenna
- 0.327, 1.6, 5 and 22 GHz
- Dual-polarization
- 128 Mbps
- 2 on-board H-masers
- Apogee (initial) – 343,000 km
- Data reception – Pushchino
  – Green Bank

In orbit since 18 July 2011 *(under development since 1978)*

Н.С. Кардашев[1], В.В. Хартов[2], В.В. Абрамов[3], В.Ю. Авдеев[1], А.В. Алакоз[1], Ю.А. Александров[1], С. Анантакришнан[4], В.В. Андреянов[1], А.С. Андрианов[1], Н.М. Антонов[1], М.И. Артюхов[2], В. Баан[5], Н.Г. Бабакин[1], В.Е. Бабышкин[2], К.Г. Белоусов[1], А.А. Беляев[6], Б.Ф. Бёрк[7], А.В. Бирюков[1], А.Е. Бубнов[8], М.С. Бургин[1], Дж. Буска[9], А.А. Быкадоров[10], В.С. Бычкова[1], В.И. Васильков[1], К. Веллингтон[11], И.С. Виноградов[1], П.А. Войцик[1], А.С. Гвамичава[1], И.А. Гирин[1], Л.И. Гурвиц[5], Р.Д. Дагкесаманский[1], Л. Д'Аддарио[13], Г. Джиованини[14], Д. Джонси[11], А.А. Дьяков[15], Р. Екерс[11], В.Е. Жаров[16], В.И. Журавлёв[1], Г.С. Заславский[17], М.В. Захваткин[17], А.Н. Зиновьев[1], А.В. Ипатов[15], Б.З. Каневский[1], И.А. Кнорин[1], К.И. Келлерманн[18], Ю.А. Ковалев[1], Ю.Ю. Ковалев[1], А.В. Коваленко[1], Б.Л. Коган[19], Р.В. Комаев [2], А.А. Коноваленко[20], Г.Д. Копелянский[1], Ю.А. Корнеев[1], В.И. Костенко[1], Б.Б. Крейсман[1], А.Ю. Кукушкин[8], В.Ф. Кулишенко[20], А.М. Кутькин[1], В.Х. Кэннон[21], М.Г. Ларионов[1], М.М. Лисаков[1], Л.Н. Литвиненко[20], С.Ф. Лихачев[1], Л.Н. Лихачева[1], А.П. Лобанов[12], С.В. Логвиненко[1], Г. Лэнгстон[18], С.Ю. Медведев[6], М.В. Мелёхин[2], Д. Мерфи[13], Т.А. Мизякина[1], Н.Я. Николаев[1], Б.С. Новиков[1,8], И.Д. Новиков[1], В.В. Орешко[1], Ю.К. Павленко[6], И.Н. Пащенко[1], Ю.Н. Пономарёв[1], М.В. Попов[1], А. Правин-Кумар[4], Р. Престон[13], В.Н. Пышнов[1], И.А. Рахимов[15], В.М. Рожков[22], Дж.Д. Ромни[18], П. Роша[9], В.А. Рудаков[1], А. Рэйзенен[23], С.В. Сазанков[1], Б.А. Сахаров[6], С.К. Семенов[2], В.А. Серебренников[2], Р.Т. Скилици[5], Д.П. Скулачев[8], В.И. Слыш[1], А.И. Смирнов[1], Дж. Смит[13], В.А. Согласнов[1], К.В. Соколовский[1], Л. Сондаар[5], В.А. Степаньянц[17], М.С. Турыгин[3], С.Ю. Турыгин[3], А.Г. Тучин[17], С. Урпо[23], С.Д. Федорчук[1], А.М. Финкельштейн[15], Э.Б. Фомалонт[18], И. Фэйеш[24], А.Н. Фомина[25], Ю.Б. Хапин[8], Г.С. Царевский[1], Дж.А. Цэнзус[12], А.А. Чуприков[1], М.В. Шацкая[1], Н.Я. Шапировская[1], А.И. Шейхет[2], А.Е. Ширшаков[2], А. Шмидт[12], Л.А. Шнырева[1], В.В. Шпилевский[15], В.Е. Якимов[1]

Baikonur,
18 July 2011
02:31 UTC

RadioAstron AGN Survey

- 270 brightest AGN from Earth-based surveys
  - S_{corr} > 600 mJy at the longest Earth-based baselines (8 GHz)
  - Plus several tragets of special interest (IDV and high-z sources)
  - Plus 20 highest kinematics AGN from 15 GHz MOJAVE (Lister+ 2003)

- Status as of April 2015:
  - 1100 segments (experiments) processed;
  - 360 detections on **90 sources**

- Detection records:
  - 18 cm: 0048–097 27 D_{Earth}
  - 6 cm: 0716+714 23 D_{Earth}
  - 1.35 cm: OJ287 15.5 D_{Earth} (fringe spacing ~14 μas)

How high can be T_B in AGN?

Theory:

Inverse Compton Cooling: $T_B \leq 10^{11.5}$ K

Kellermann & Pauliny-Toth 1969

Equilibrium ($E_p = E_m$): $T_B \leq 10^{10.5}$ K

Readhead 1994

Observations:

TDRSS OVLBI: $T_B \geq 10^{12}$ K

Linfield et al. 1989

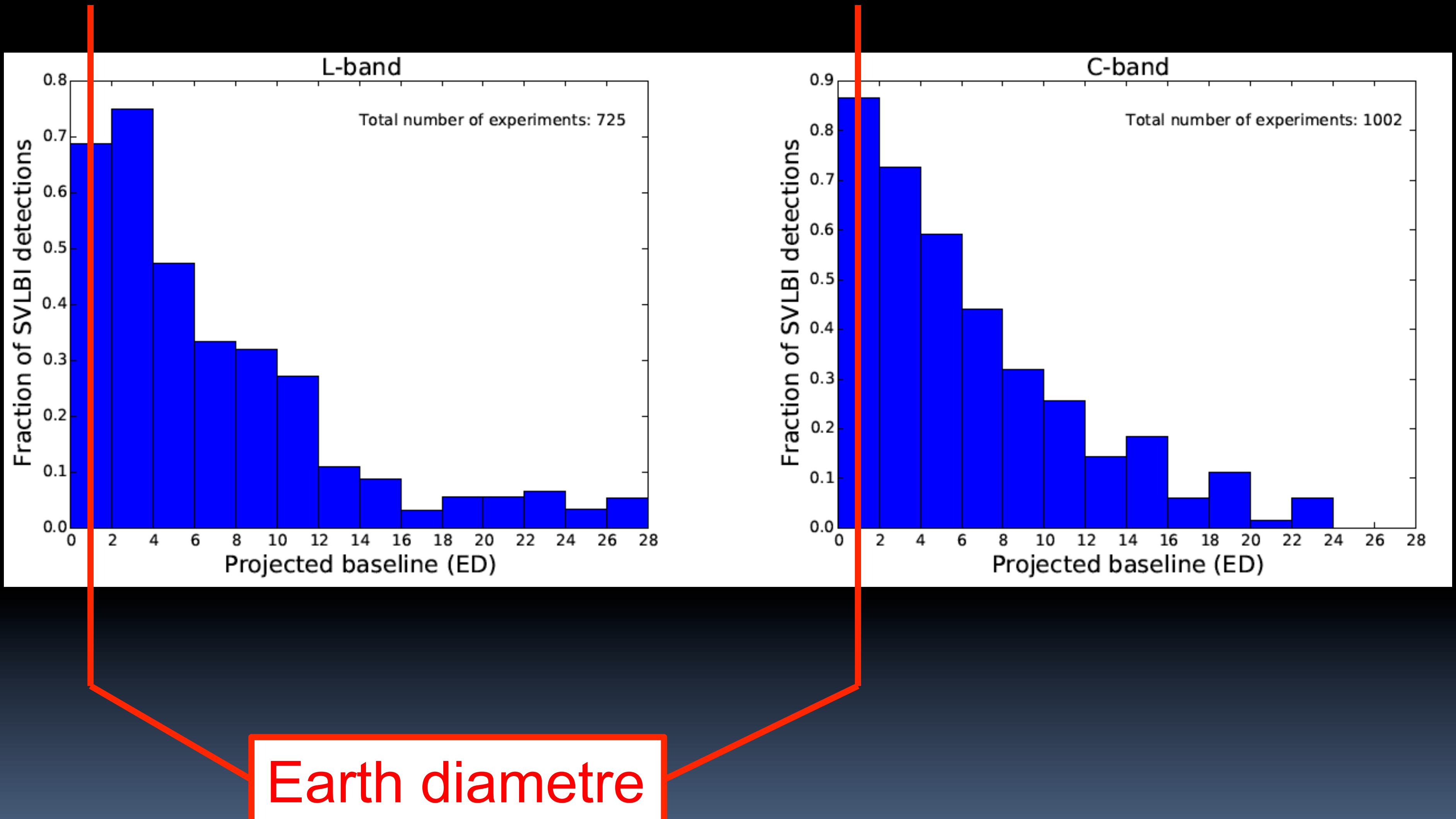
VSOP, AO0235+164: $T_B \geq 6\text{x}10^{13}$ K

Frey et al.. 2000

VLBA, 2 cm survey: $T_B \geq 3\text{x}10^{12}$ K

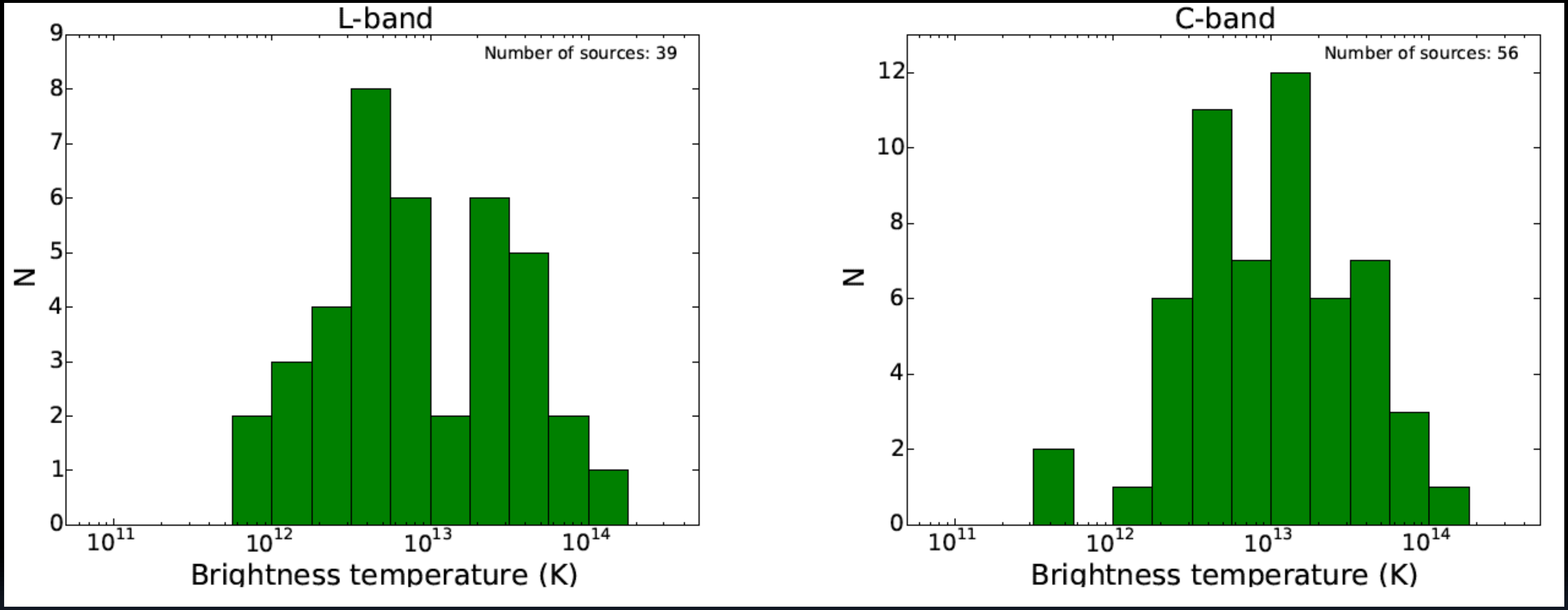
Kovalev et al.. 2006

AGN Survey detectability statistics so far



Qualitative conclusion: no surprises, but…

Brightness temperature in RA AGN Survey



- RadioAstron can detect $T_B \sim 10^{15} - 10^{16}$ K
- So far – no such detections

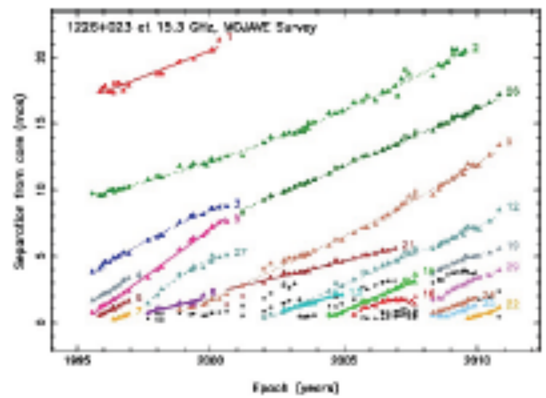
RadioAstron measurements of 3C273

λ [cm]	GRT	B	S_B [mJy]	θ µasec	T_B [K]
18	GBT Arecibo	165,000 km 0.9 Giga λ	65±10	270±10	10^{14}
6	Arecibo	84,500 km 1.6 Giga λ	130±20	150±10	3×10^{13}
1.3	GBT/ VLA	99,300 km 7.6 Giga λ	250±40	22±2	2×10^{13}

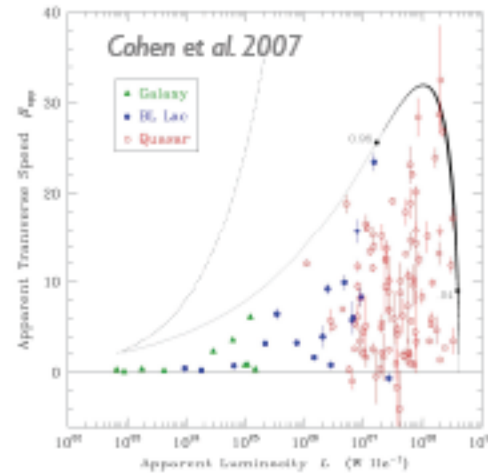
Observed T_B is 10^2 to 10^3 times higher than the theory predictions

How can this be?!

- Relativistic Doppler boosting
  - $T_{obs} \equiv \delta T_{int} \sim \gamma T_{int}$
  - $\gamma \sim 15$
  - $v_p \neq v_b$? NO!



- Complex geometry
- Non Stationary Processes (acceleration/injection)
- Proton synchrotron radiation
  - $T_b(p)/T_b(e) = (m_p/m_e)^{9/7} \sim 10^4$
- Coherent emission
- Stimulated (maser) emission



In lieu of conclusions

- AGN cores are compact enough to require B~10 D_{Earth}
- For ~70 AGN observed so far, $T_B \sim 10^{12} - 10^{14}$ K
  - *very high Doppler boosting?*
  - *(en-mass) exotic explanations?*
  - *truly new physics?*
- Completion of RadioAstron AGN Survey in combination with massive (thousands of sources) Earth-based AGN VLBI surveys will offer a reliable "θ–z" database for ad hoc cosmology tests – at least consistency check.
- **Wanted**: insight by cosmology community