Six Decades of Active Galactic Nucleus Research – the Legacy of Ernst Apushevich (“Eric”) Dibai (1931 – 1983)

Наследие Эрнста Апушевича Дибая в исследованиях активного ядра галактики

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General remarks

- I give the dates of the Russian publication of papers (sometimes the English translation is the following year)
- Note: the ADS does not have the abstracts of *Soviet Astronomy* (English translation of Астрономический журнал)
- Also, the ADS has the names of authors and the titles in English of papers from Астрономический Циркуляр, *but no access to the papers themselves* (and no abstracts).

Если бы кто-нибудь обновил ADS, это очень помогло бы наследию советской астрономии. Для этого в ADS есть форма.

(Возможно, это может быть проект Евроазиатского Астрономического Общества?)

OUTLINE

Look at some of the progress made in AGN research in the almost six decades since the pioneering work of Eric Dibai.

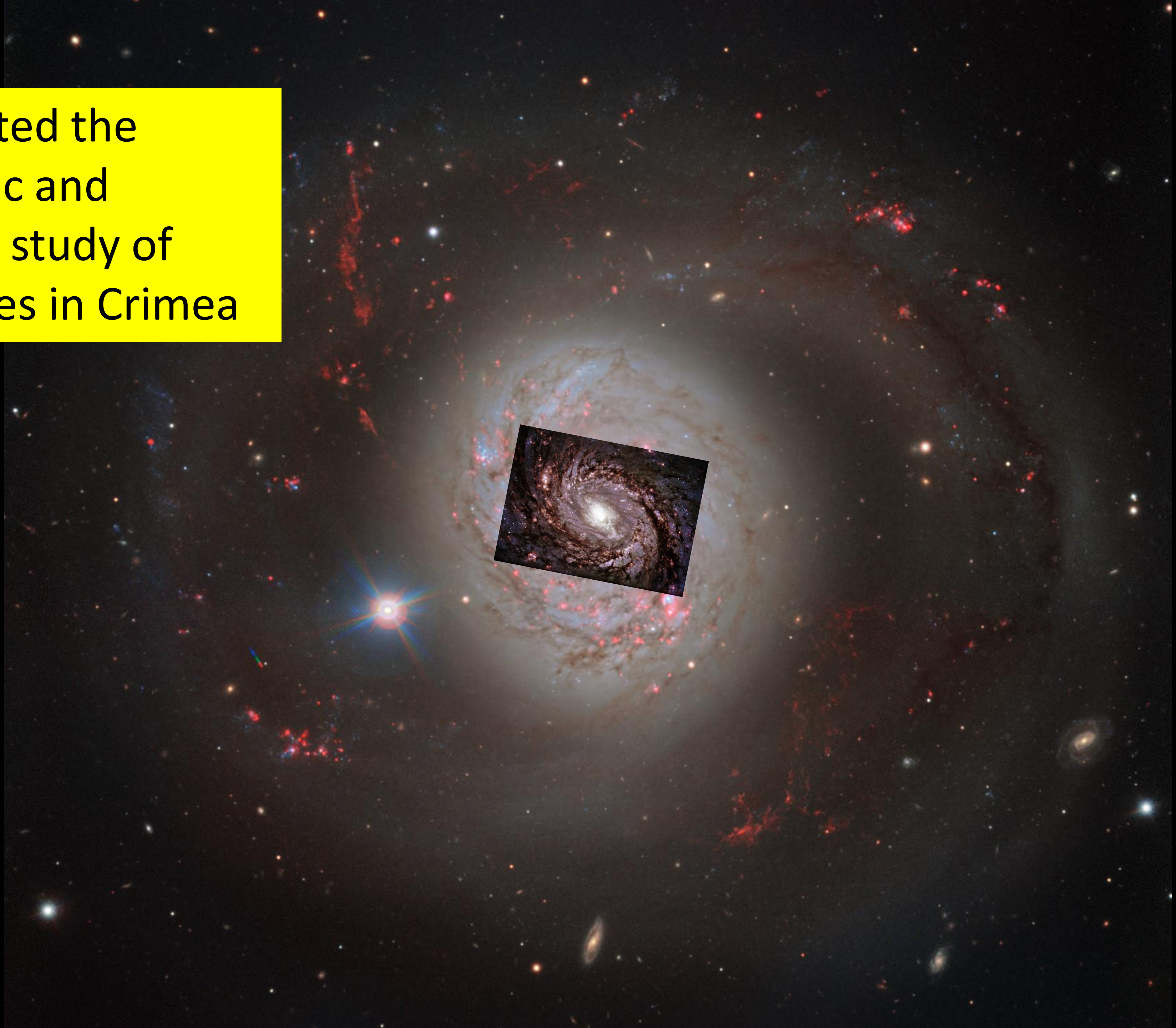
- The narrow-line region (NLR) – Dibai & Pronik (1965)
- The broad-line region (BLR) – Dibai & Pronik (1967)
- Variability of the broad lines and continuum
- Polarization – Dibai & Shakhovskoi (1966)
- The connection between galaxy mass and AGN luminosity – Zasov & Dibai (1970).
- Reverberation mapping and our modern view of the BLR
- The Dibai method of determining black hole masses – Dibai (1977)
- Eddington ratios – Dibai (1977, 1980)
- Variability timescales, black hole mass and BLR size – Dibai & Lyutyi (1976)
- The connection between black hole mass and host galaxy mass – Zasov & Dibai (1970), Dibai (1980)
- Concluding remarks

NGC 1068

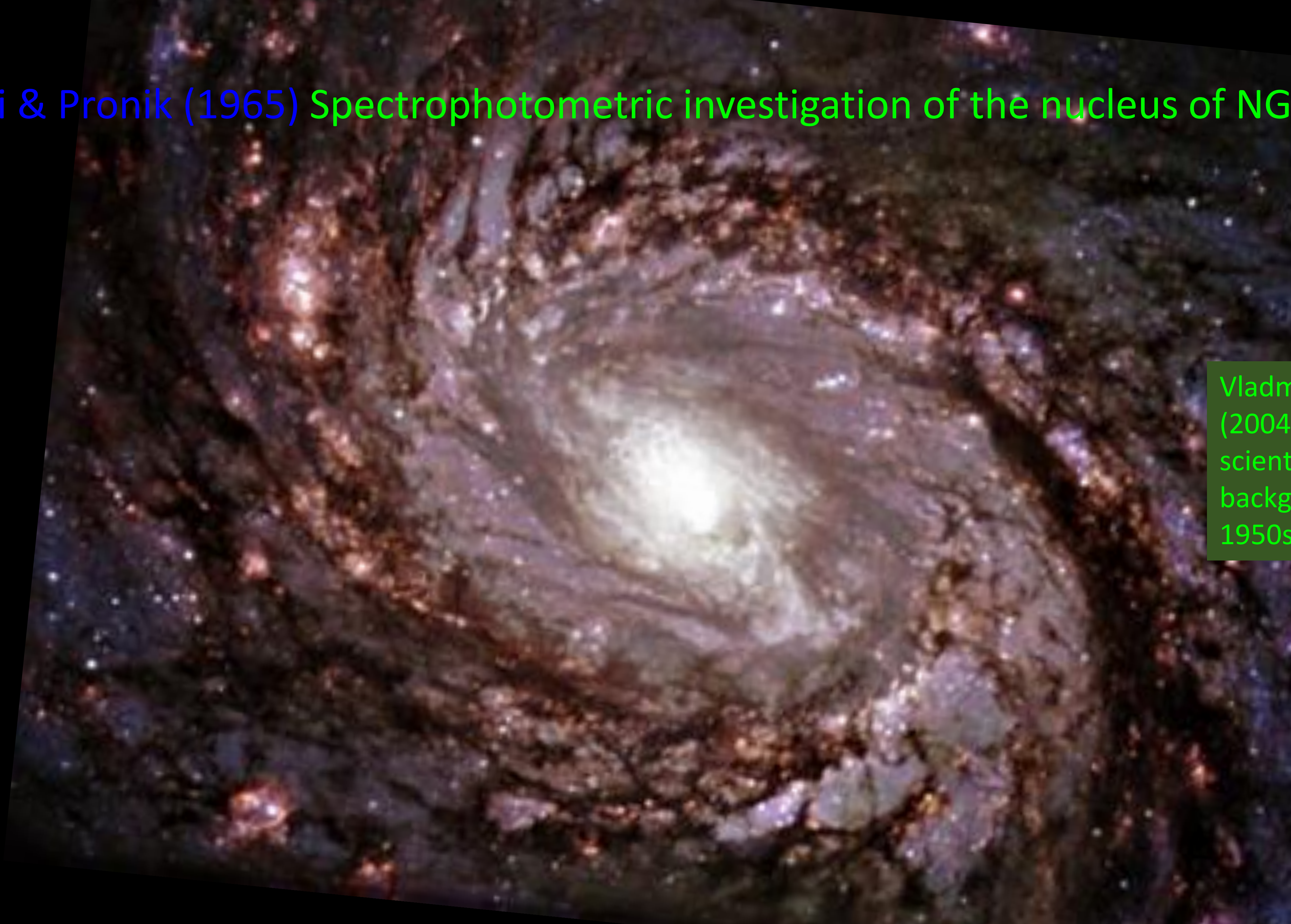
NGC 1068

Dibai’s early work (late 1950s) was on gas/shocks in space. Early ideas (still cited) of sequential star formation. (shocks and star formation)

Dibai instigated the spectroscopic and photometric study of active galaxies in Crimea



Dibai & Pronik (1965) Spectrophotometric investigation of the nucleus of NGC 1068



Vladmir I. Pronik (2004). Similar scientific background in late 1950s to Dibai.

The narrow-line region (NLR)

(Called the "nebular zone" by Dibai & Pronik)

Dibai & Pronik (1965) "Spectrophotometric investigation of the nucleus of NGC 1068" [submitted on 1964 December 15.]

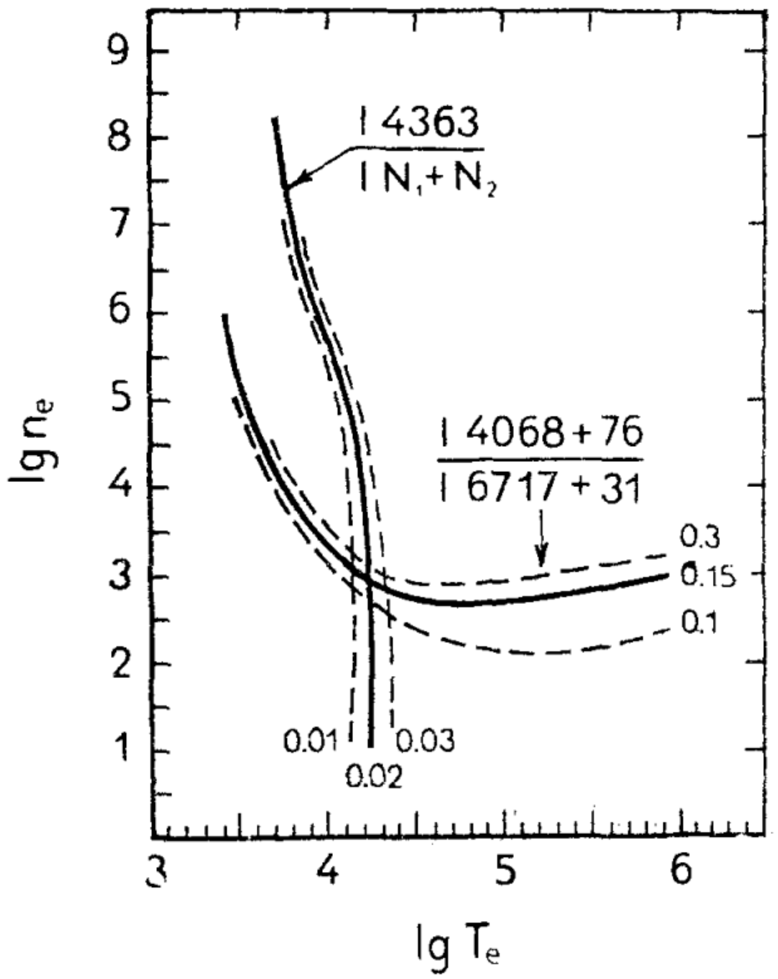
[On 1964 November 24th Osterbrock and Parker had submitted a very similar paper on NGC 1068.]

Earliest applications of nebular astrophysics to an AGN.

NGC 1068 known from Burbidge, Burbidge & Prendergast (1959) to have gas being expelled from the nucleus at three times the escape velocity.

Dibai & Pronik:

- **Estimated the electron density** as $n_e \approx 10\ \mathrm{cm}^{-3}$ from [O III] and [S II] line ratios.
- **Mass of gas** in NLR estimated as $\approx 10^5$ solar masses.
- **Filling factor** of $\approx 10^{-3}$.



Problem: neither Dibai & Pronik, nor Osterbrock & Parker, could explain the strengths of the lines. Not enough ionizing photons.

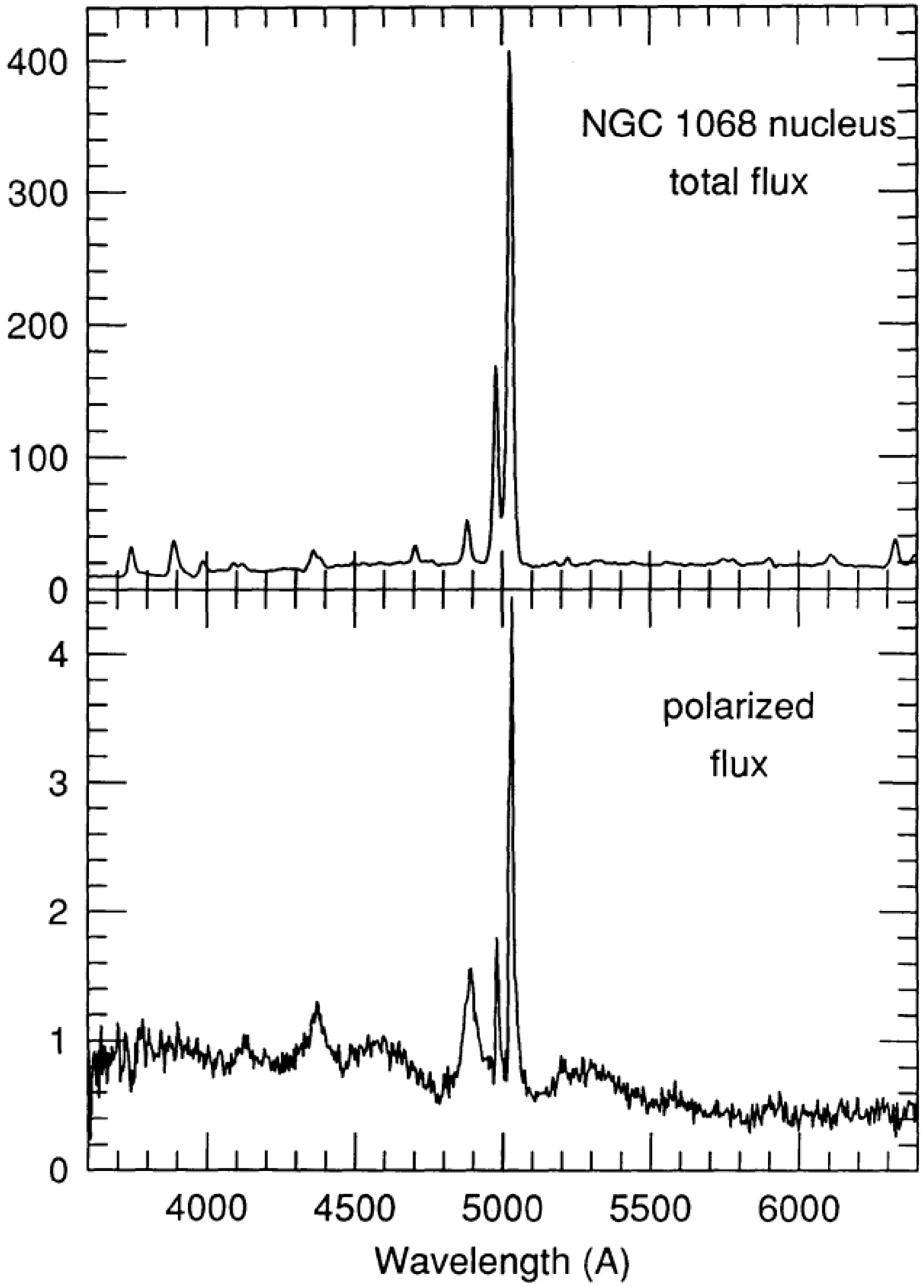
Solution:

(A) There are two types of AGN, type 1, where we see the BLR and type 2 where we don't (Khachikian and Weedman 1972)

(B) Keel (1980): We view Seyfert 2s off-axis. *The ionizing continuum and broad-line region of Seyfert 2s like NGC 1068 are hidden from our direct view by dust.*

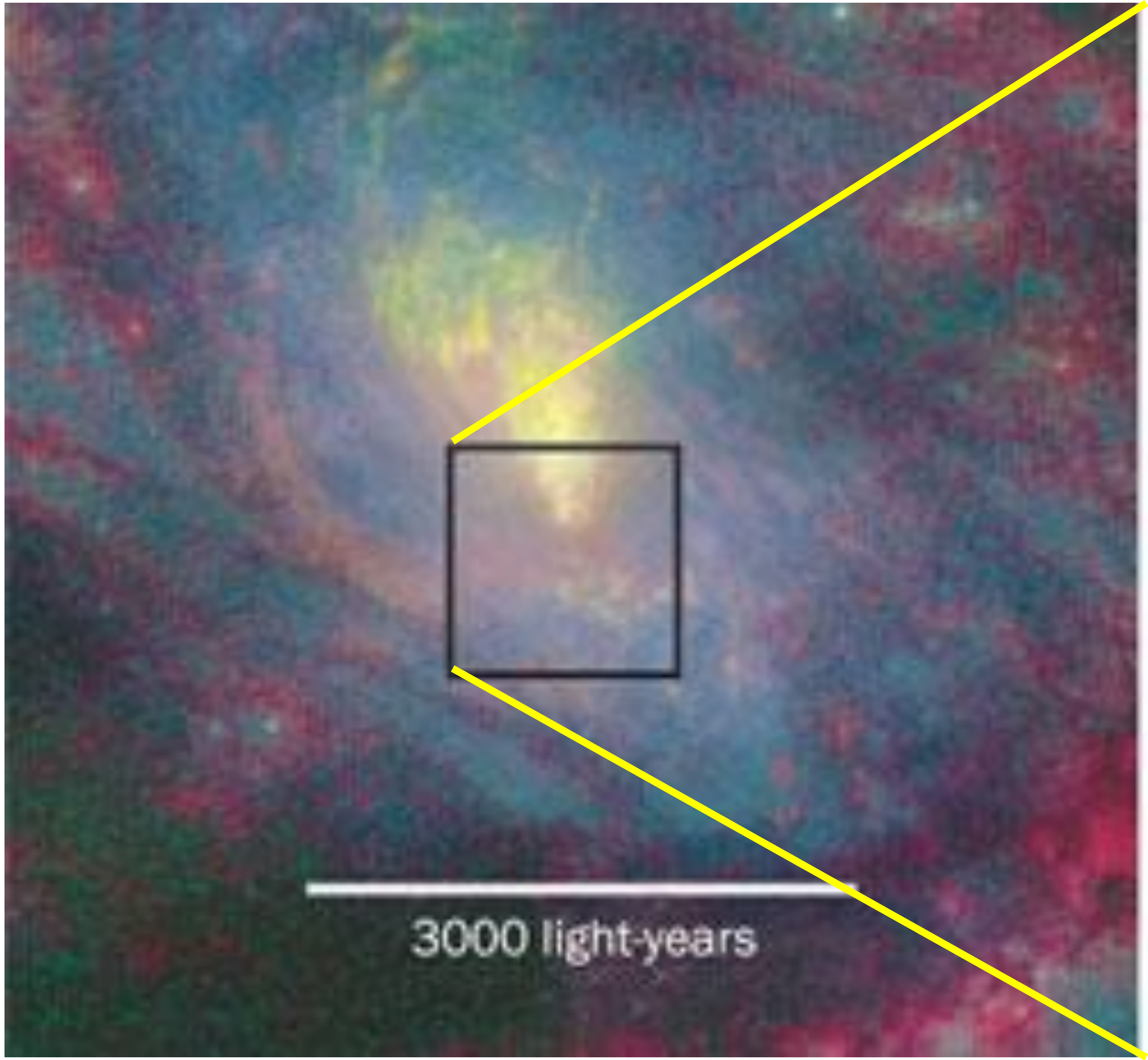
Spectacularly confirmed by Antonucci & Miller (1984) – "hidden BLR" revealed in polarized reflected light.

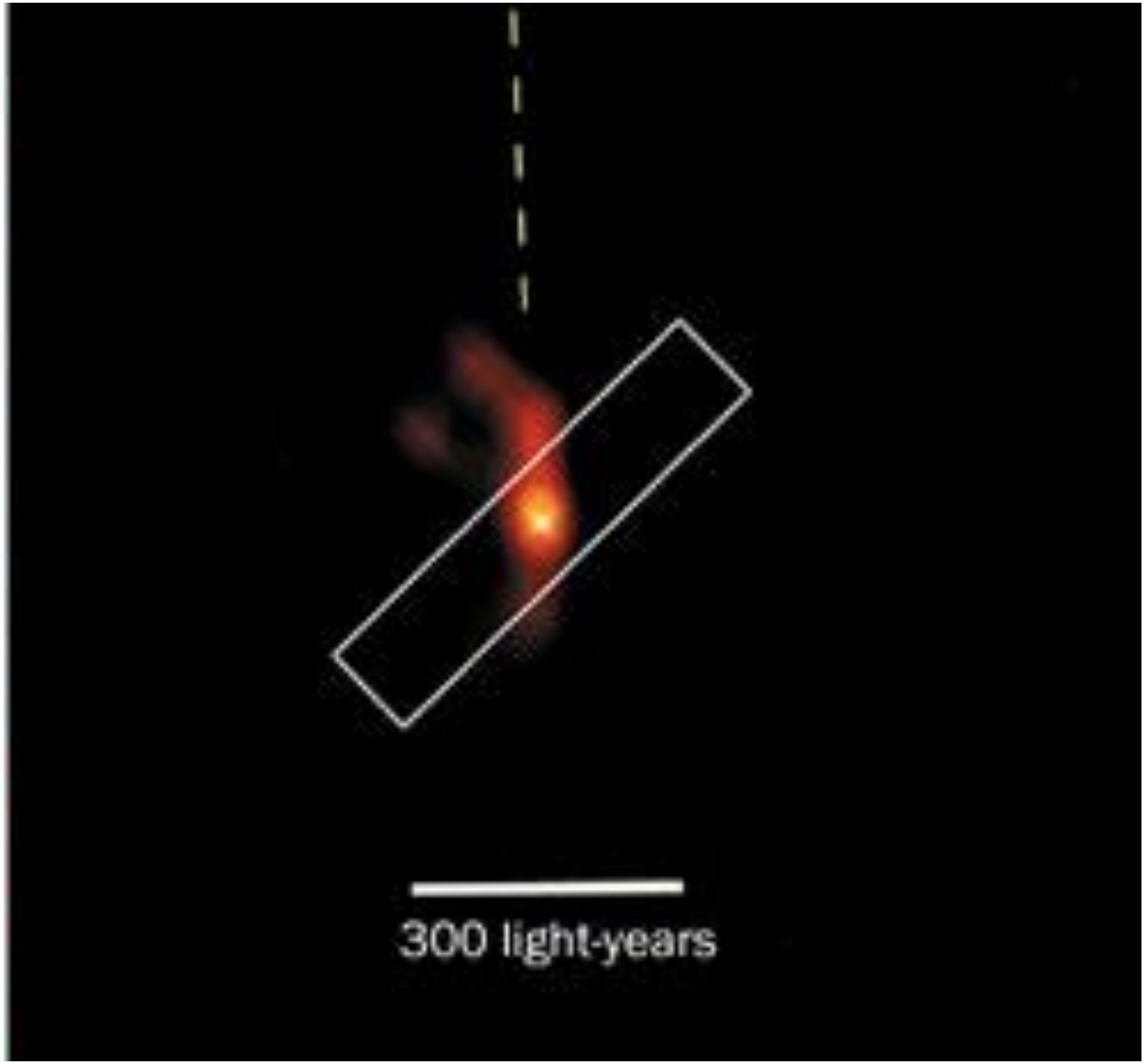
Hidden nucleus can now be seen directly in the mid-IR.



Hubble Space Telescope (optical)

VLT (mid-IR)

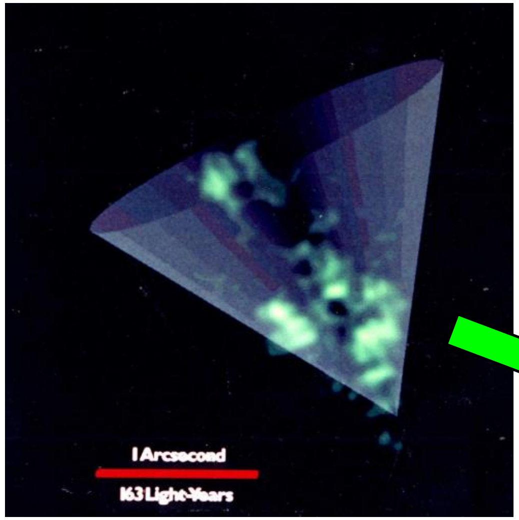




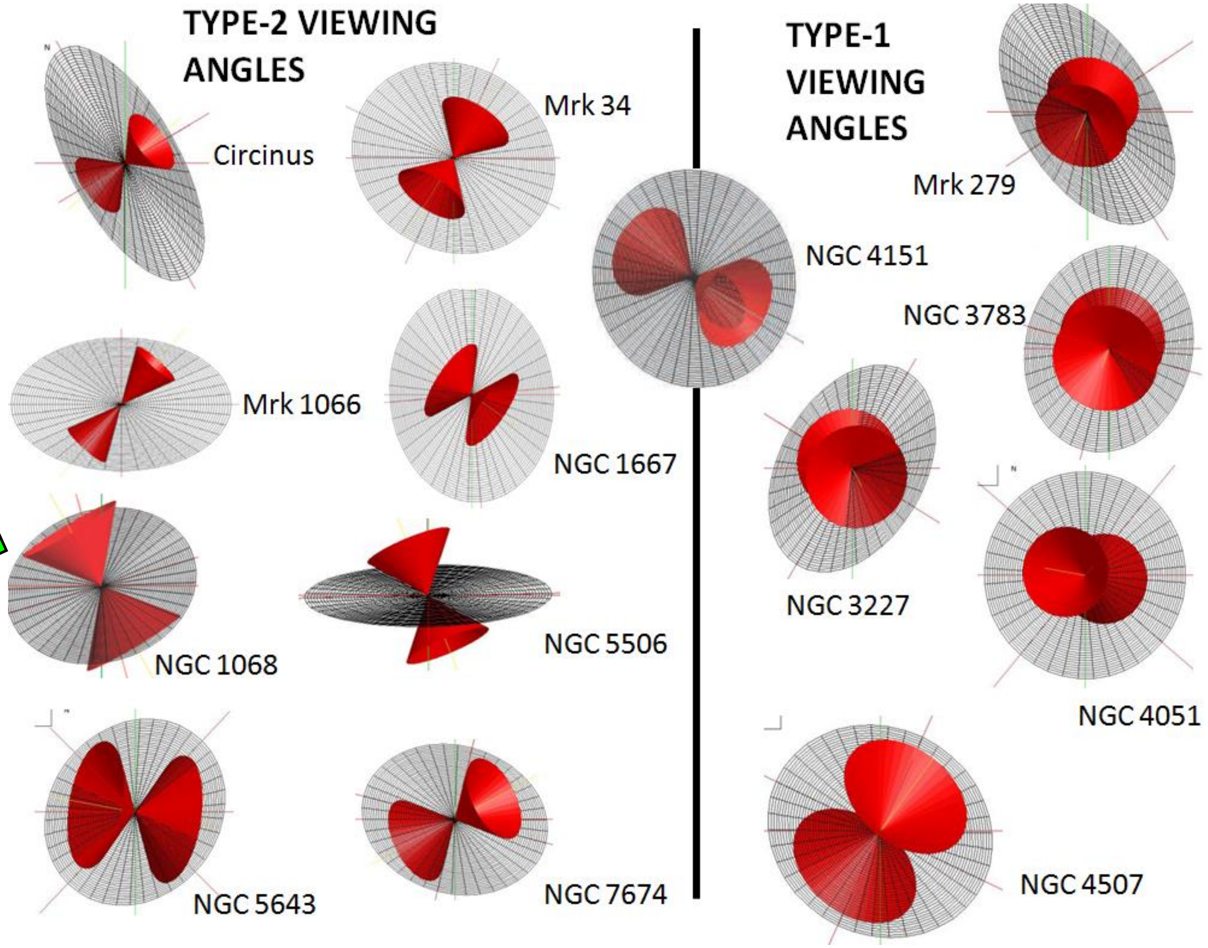
Current understanding of the NLR

- In Trinidad-Falcão *et al*. (2021) we get similar NLR masses from *HST* observations.
- Noting the high mass of the NLR and that the mass was comparable to the mass of interstellar gas near the nucleus, Dibai & Pronik proposed that **the NLR is predominantly gas that has been "raked up" from the interstellar medium**.
- Walker (1966), high-spatial-resolution Lick Observatory coudé spectroscopy of NGC 1068 $\Rightarrow$ outflow close in transitioning to pure rotation beyond 1500 pc. *I.e*., consistent with the Dibai & Pronik picture.
- In Fischer *et al*. (2018) we show from *HST* observations of 12 nearby AGNs that this is generally true. ". . . we report an average maximum outflow radius of $\sim$ 600 pc, with gas continuing to be kinematically influenced by the central AGN out to an average radius of $\sim$ 1130 pc."

Spatially-resolved spectroscopy shows that the **NLR lies on a thin, hollow bi-cone** with a ≈ 40° half-opening angle (Crenshaw & Kraemer 2000, Das *et al*. 2005, 2006, Fischer *et al*. 2013). Can get orientation.



NGC 1068 (HST)



Wampler (1968): **NLR is *dusty*.** ∴ **Outflow driven by radiation pressure on dust.**

The Broad-Line Region (BLR)

- Dibai & Pronik (1967) “A spectrophotometric study of Seyfert-”galaxy nuclei. [Dibai’s most-cited paper.]

Recognition of what we now call the “broad-line region”(BLR) as having very different properties from the NLR (two different “subsystems”)

- BLR density three orders of magnitude greater than NLR (now recognized to be even more)
- Size of the BLR of the order of a parsec or less (versus 100s of pc for NLR)
- Mass of BLR up to a few 10s of solar masses (as opposed to 10^4 for NLR)
- A “sharp distinction in properties.” “No smooth transition is observed from one class of subsystems to the other.”

Now recognized that there is indeed no “intermediate-line region” (ILR). (There is gas of intermediate velocity, but it is the outer regions of the BLR and has a very different density, kinematics, and location from the NLR.)

Dibai & Pronik (1967) (Continued):

- "The main source of ionization is the radiation coming from the central regions of the nucleus."
- **Quasi-stellar objects, radio galaxies, and Seyferts similar.** *"The physical conditions responsible for the emission by the gas are the same in all the objects*." Cautiously assert that there is "a similarity of the radiation field of the gas in all classes of active extragalactic objects (quasi-stellar sources, radio galaxies , and Seyfert galaxies)."

Note: the sizes of BLRs now believed to somewhat smaller and the densities larger. (See later.)

A discovery missed! – broad-line variability

Burbidge & Burbidge (1966) had discovered variations the broad Mg II λ2798 line *profile* of 3C 345 in 1965 (Lick Observatory photographic spectra.) Displaced emission line peaks. Changed in intensity and wavelength over a few week!

Wampler (1966) The *red wing* of Mg II in 3C 345 varies the most. (Lick Observatory scanner spectrophotometry.)

Dibai & Pronik (1967). **What they missed**: making a comparison with Seyfert (1943).

Ratio of Hβ fluxes Dibai & Pronik (1967) / Seyfert (1943) **[compared with [O III] λ4959]**

NGC 1068	0.89 ± 0.14	NGC 3516	0.3	$\Rightarrow$ **Hβ 3 times fainter!**
NGC 1275	1.14 ± 0.14	NGC 4051	1.8	$\Rightarrow$ Hβ twice as bright
NGC 7469	1.17 ± 0.14			

Andrillat & Souffrin (1968) – discovered a *huge* change in Hβ – [O III] region of NGC 3516 since Seyfert (1943).

But they decided it was [O III] that was varying!! (Because there was a strong stellar continuum in 1967 and starlight doesn't vary.)

A & S referred to Dibai & Pronik for NLR/BLR properties, *but didn't look at their observations*:

EW(Hβ) = 20 Å in 1964/65 (Dibai & Pronik)

EW(Hβ) < 0.4 Å in 1967 (Andrillat & Souffrin)

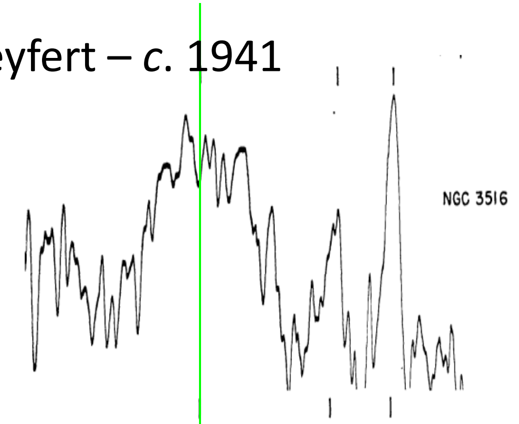
If they had, **A&S would have discovered that *both* the BLR *and* the continuum had varied!**

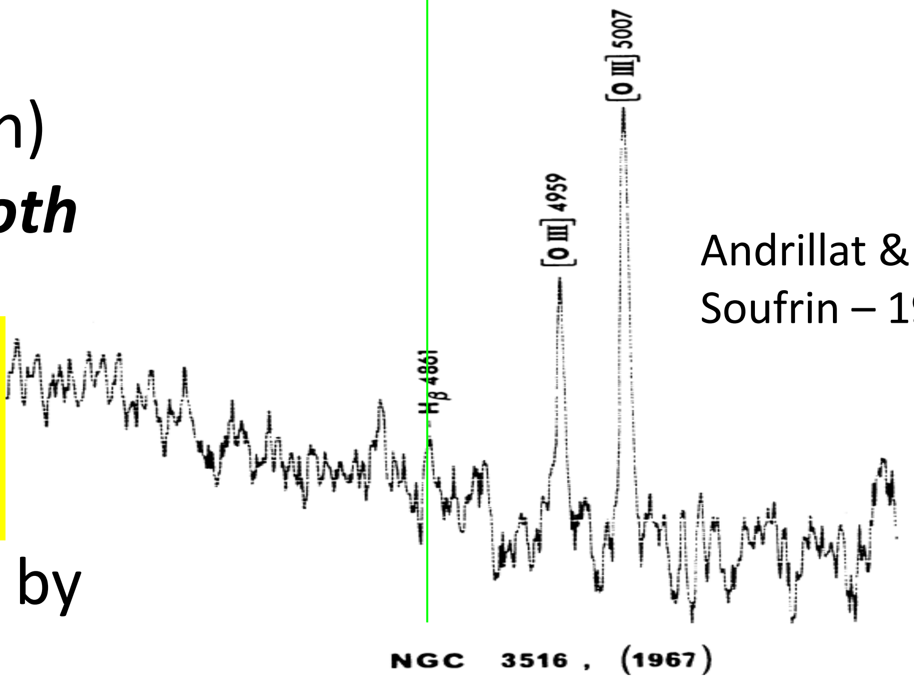
NGC 3516 had gone from a type 1 to a type 2!

What A&S had actually discovered was **the first changing look AGN!** ("CL AGN")

(CL AGN phenomenon recognized for NGC 4151 by Lyutyi & Oknyanski & Chuvaev (1984)]

Seyfert – *c.* 1941





Andrillat & Soufrin – 1967

Continuum variability

A. N. Deutsch (1958 – unpublished until 1966 Byurakan IAU Symposium) NGC 5548 varied.

Antoinette de Vaucouleurs (1958 – working on the 1964 *Reference Catalogue of Bright Galaxies*) – UBV colors of Seyferts vary from month to month.

[Lesson to be learnt: believe your error bars!]

Smith & Hoffleit (1963) 3C 273 highly variable on timescales of a week to decades.

Fitch, Pacholczyk & Weymann (1967) – *U*, *B*, *V* & *K* band variability of NGC 4151.

Dibai, Zaitseva & Lyutyi (1968, 1969) "Clearly a systematic monitoring of Seyfert-galaxy nuclei will be absolutely necessary. This task is within the capability of moderate –sized telescopes; one need only pay close attention to the accuracy of the measurements."

Also asked about the surface brightness and colours *of the host galaxies* [more later].

Polarization

Dibai & Shakhovskoi (1966) Polarization observations of Seyferts

- NGC 1068 and NGC 1275 polarized; upper limits on polarization of other Seyferts.
- Dombrovskii & Gagen-Torn (1968) different results but confirmed polarization of Seyferts.

Resolution of discrepancy: *polarization varies!* (Gagen-Torn & Babadzhanyants 1969; Kruszewski 1971)

Optical polarization taken as evidence of non-thermal emission in the optical.

(Nikolay Shakhovskoi continued polarization observations)

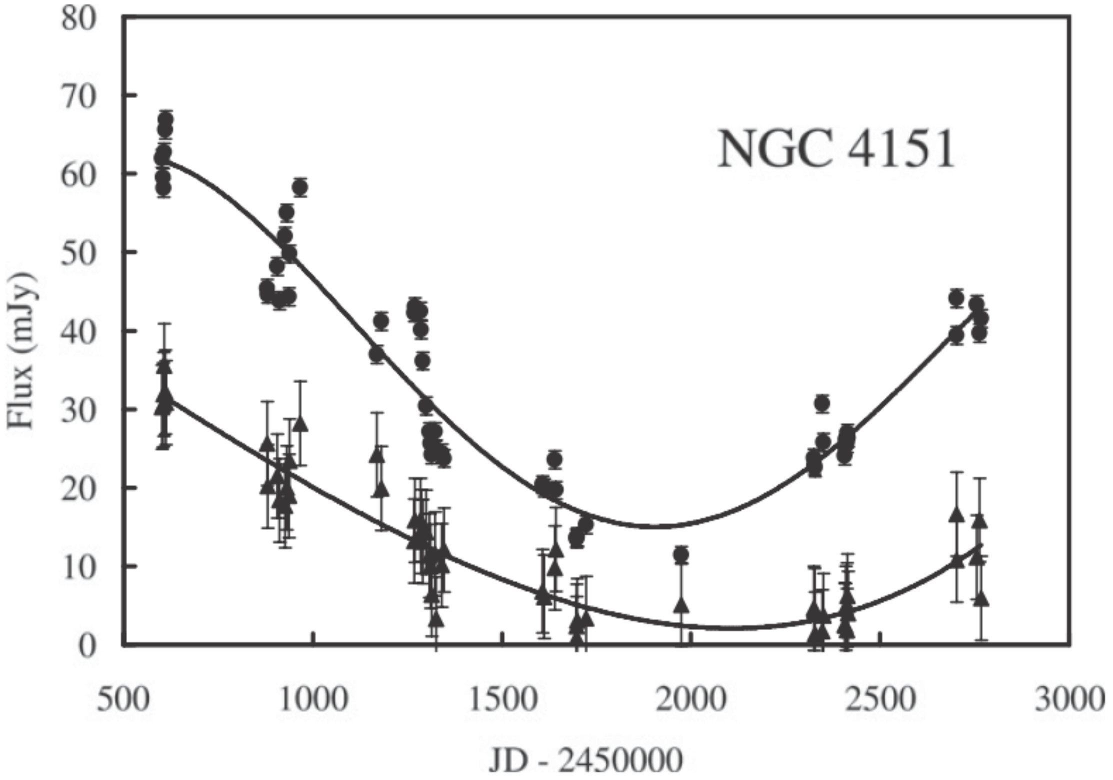
Merkulova & Shakhovskoi (2006) – 7 years of polarization variability in NGC 4151

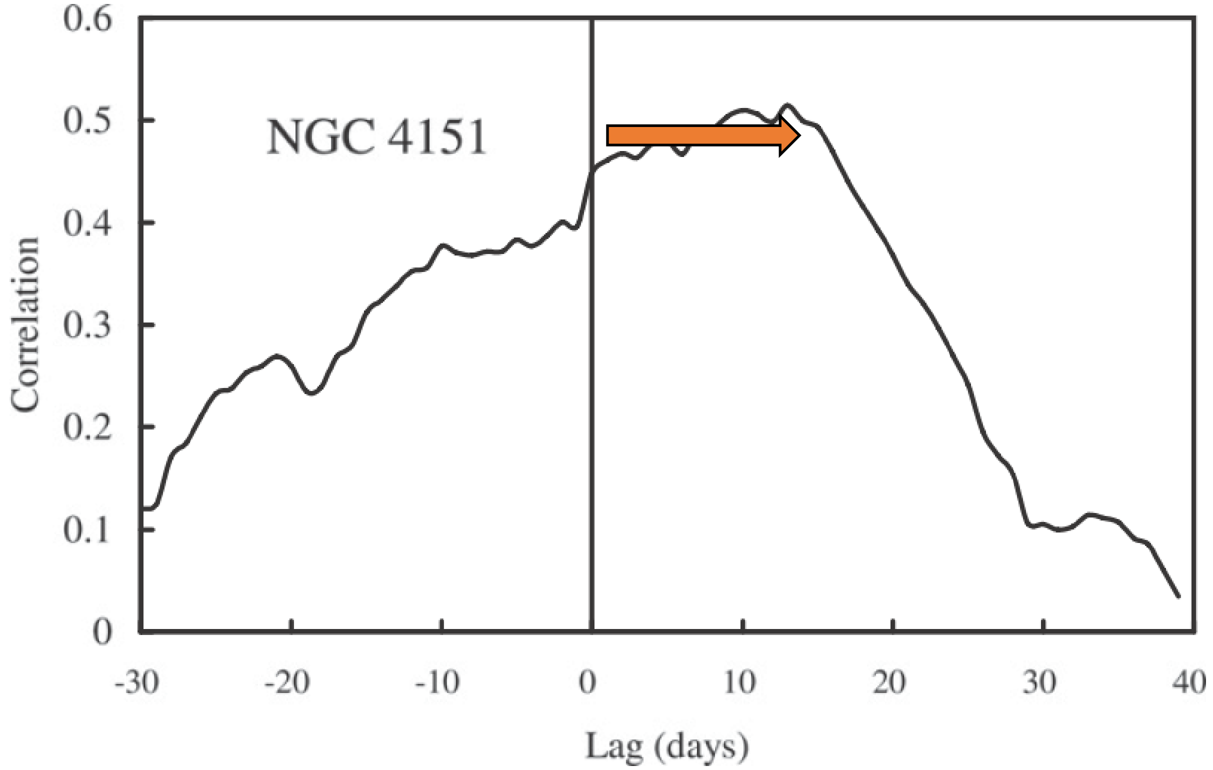
Gaskell, Goosmann, Merkulova, Shakhovskoy & Shoji (2012) – discovery of polarization reverberation (lag of about 2 weeks) ⇒

(a) Polarization is due to **scattering off dust** (*not* synchrotron radiation)

(b) **Dust is close to the broad-line region**

(c) Longer-term changes must be due to **dust clouds moving**





AGN luminosity correlated with galaxy mass!

Zasov & Dibai (1970) "Some Properties of Seyfert-Galaxy Nuclei and the Integrated Parameters of the Galaxies."

This was the first indication of co-evolution of black holes and galaxies!

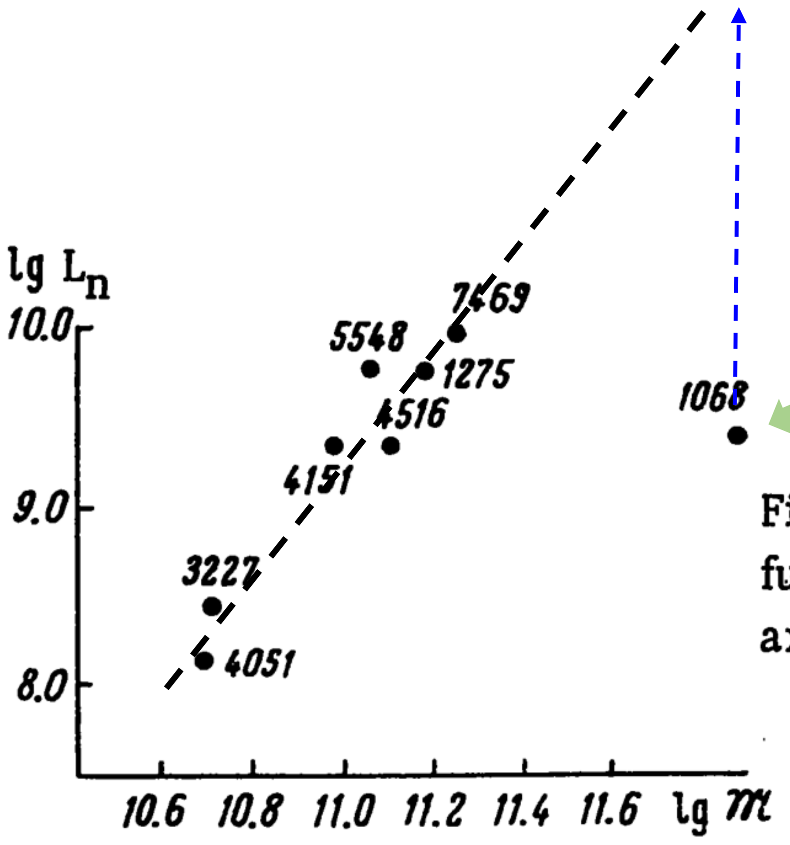


Fig. 2. Luminosity of nuclei as a function of the mass of the galaxy (in solar units).

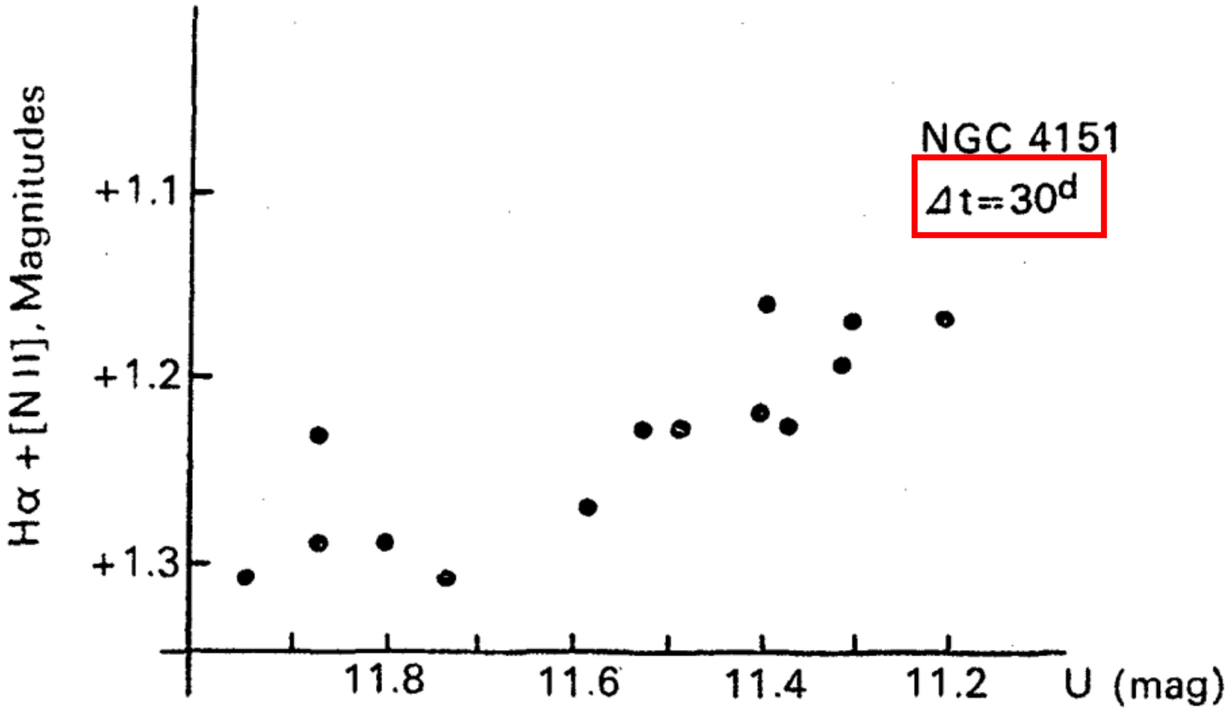
(Mostly the bulge mass)

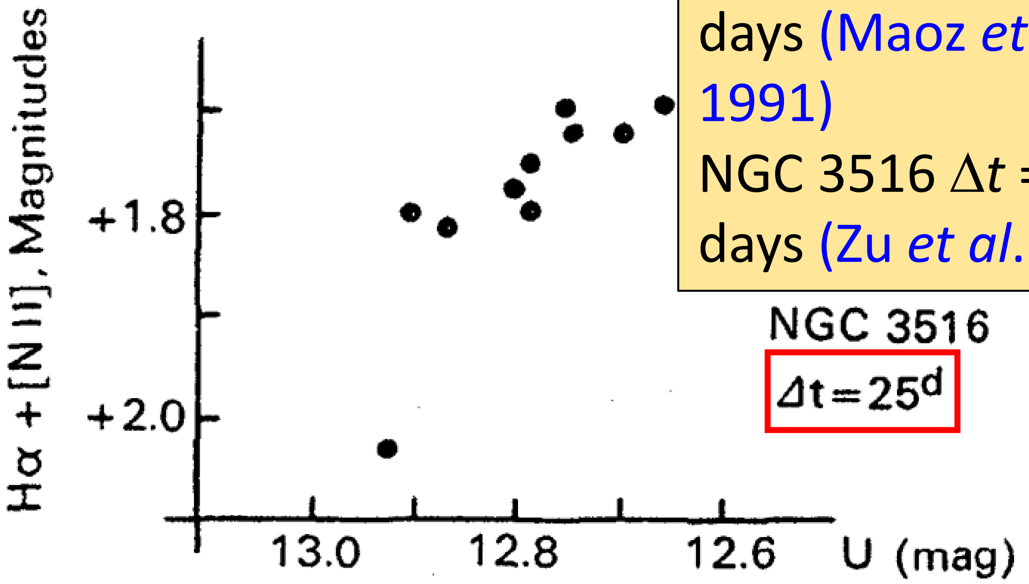
This was before the Keel (1980) discovery that the nuclei of Seyfert 2s were hidden by dust

Follow-on study Dibai & Zasov (1985) "This effect evidently is not attributable simply to observational selection but reflects a true interdependence between the nuclear activity and the properties of the system as a whole."

INVENTION OF REVERBERATION MAPPING (1972)

- Lyutyi & Cherepashchuk (1972) "Narrow-band photoelectric observations of Hα-line variability in the nuclei of Seyfert galaxies NGC 4151, NGC 3516 and NGC 1068" [Dibai was Victor Lyuti's thesis advisor] – **DISCOVERY OF SHORT TIME LAGS FOR Hα!!**





Modern values:
NGC 4151 Δt = 11 ± 4 days (Maoz *et al*. 1991)
NGC 3516 Δt = 15 days (Zu *et al*. 2011)

***Huge* impact! . . . BUT . . .**

Lyutyi & Cherepashchuk (1972) not *cited* at all until Gaskell & Sparke (1986)!

Nevertheless:

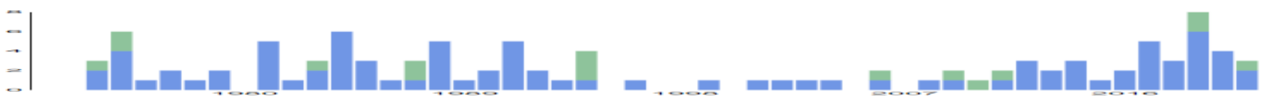
Cherepashchuk & Lyutyi (1973) [In English] – inspiration for Antonucci & Cohen (1983) and Gaskell & Sparke (1986).

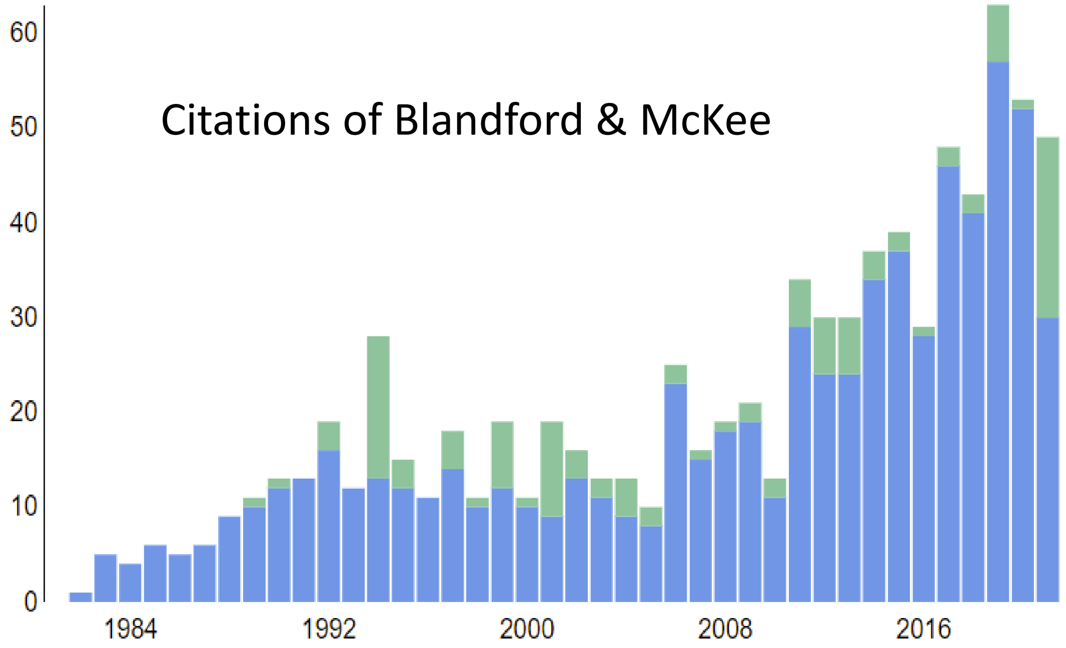
Two major setbacks:

(1) Unfortunately, *not* cited in Blandford & McKee (1982) who were unaware that the “reverberation mapping” they were proposing had been already been carried out in Crimea a decade earlier!!

Also: (2) Citations on the ADS show that Cherepashchuk & Lyutyi was deliberately ignored by a prolific astronomer!

Citations of Cherepashchuk & Lyutyi





Current understanding of the BLR

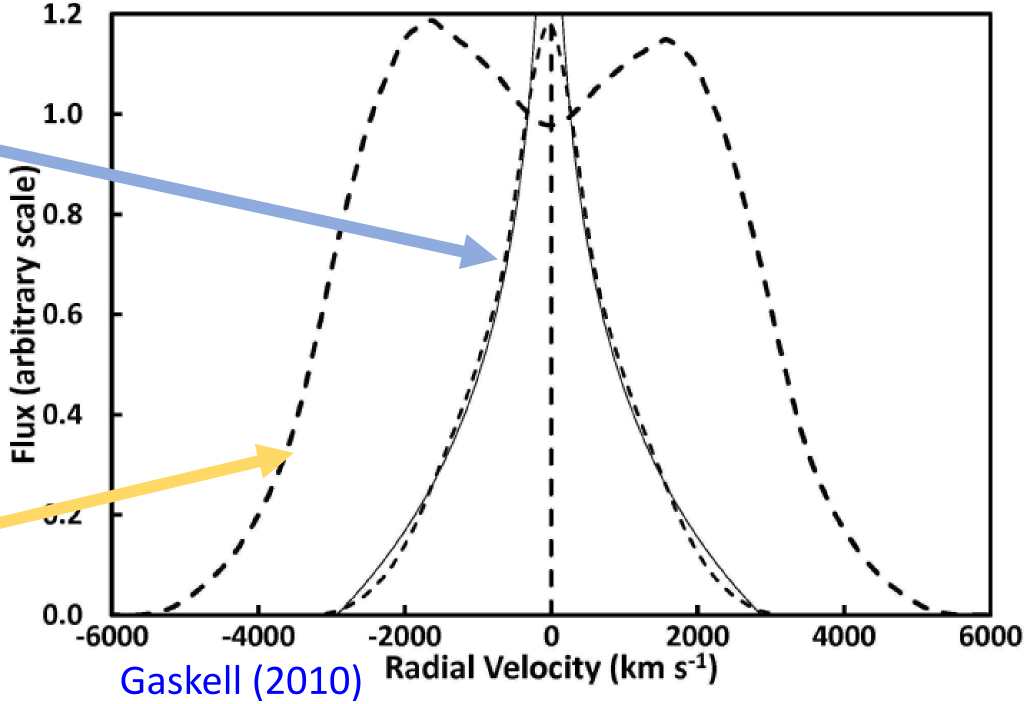
See Gaskell (2009) review.

BLR is *turbulent* dense gas in a flattened distribution (*height/radius* ~ 0.1 in the outer parts) located above the accretion disc and *co-rotating with it*.

Observed line profiles depend on the *orientation*. A "logarithmic" profile when the AGN is seen face-on and a double-peaked (disc-like) profile when seen off-axis (Gaskell 2010, 2011).

Viewed face-on.

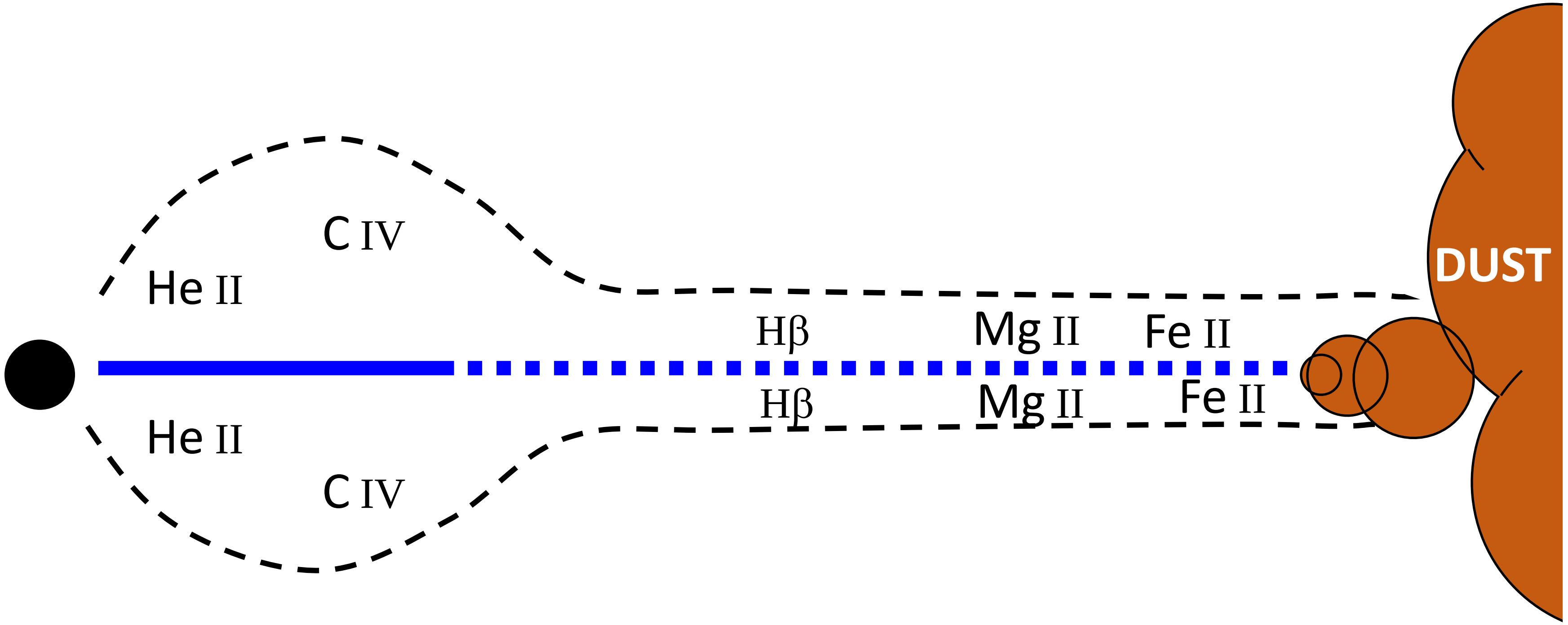
Same gas viewed 30° off-axis.



Gaskell (2010)

In addition, there is a *small* amount of outflowing, high-ionization gas, seen as a blueshifted component of C IV λ1549 because our view of the far side of outflow is blocked by the accretion disc (Gaskell 1982).

A modern idea of the BLR



(Edge-on view. Blue line is the plane of the accretion disc.)

After Gaskell, Klimek & Nazarova (2007)

Masses of supermassive black holes

Dibai (1977) "Masses of the central bodies of active galactic nuclei"

Dibai's most influential idea – led to work by > 1000 astronomers!

Introduced the "Dibai method" of getting black hole masses (also called the "photionization method" or the "single-epoch spectrum method".)

Important point: **only need a single spectrum** $\therefore$ now used for over 100,000 AGNs!

Mass from virial theorem: $M \propto v^2 R$.

v from *FWHM* (easy); R from photoionization considerations from L.

$$R \propto L^{\alpha}.$$

(Dibai inferred $\alpha = 0.33$)

Scaled masses to Lyutyi & Cherepashchuk (1972) reverberation mapping.

Problem: back then BLR thought not to be virialized (*e.g.*, radiatively accelerated Blumenthal & Mathews 1975)

Velocity-resolved reverberation mapping ruled out outflow (Gaskell 1988; Koratkar & Gaskell 1989) $\Rightarrow$ reverberation mapping could be used to get masses. (Now a major industry.)

Slope α of $R - L$ relationship? ($R \propto L^{\alpha}$)

Dibai inferred: $\alpha = 0.33$;

Now determined empirically from reverberation mapping:

Koratkar & Gaskell (1991): α "consistent with 0.5"

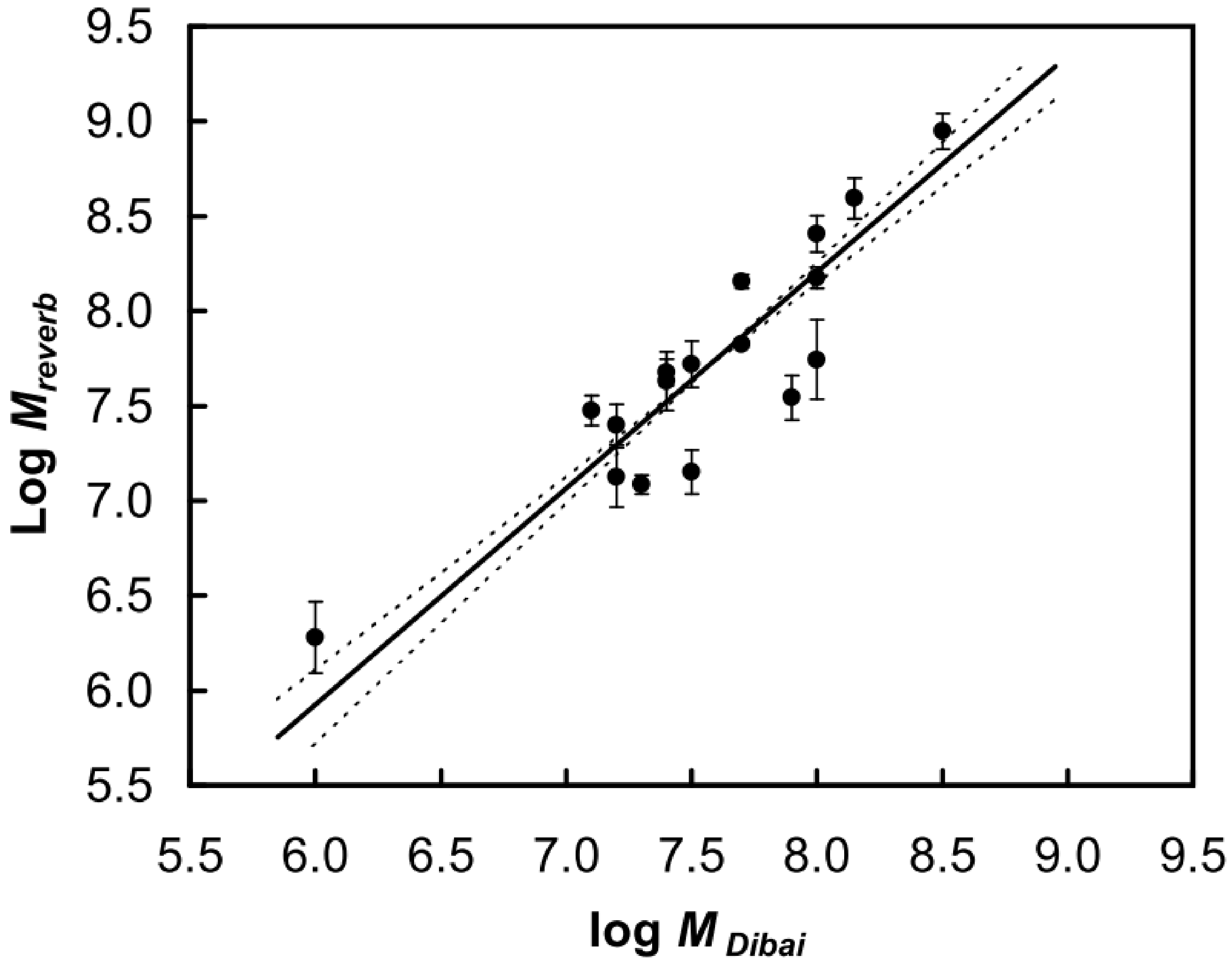
Kaspi *et al.* (2000): $\alpha = 0.70 \pm 0.03$

Bentz *et al.* (2013): $\alpha = 0.53 \pm 0.03$

A *vast* amount of work! Major international collaborations (including Crimea).

Also gives the zero point for R—L relationship.

Bochkarev & Gaskell (2009) compared Dibai's masses from the 1970s with subsequent reverberation mapping results. Excellent agreement! Consistent with experimental errors ⇒ AGNs are very similar.



Eddington ratio

Dibai (1977) had good masses.

Also had luminosities, $\therefore \Rightarrow$ **Eddington ratios** $\equiv L \,/\, L_{\mathrm{Edd}}$

"Evidently the luminosity of active nuclei of galaxies does not exceed the Eddington limit corresponding to their mass"

From his numbers, median ratio = 13%.

Dibai (1980) "The mass-luminosity relation for active galaxy nuclei"

$$L \propto M$$

$L \propto M \Rightarrow L \,/\, L_{\mathrm{Edd}} \approx$ constant on average (L fluctuates in an individual AGN, of course)

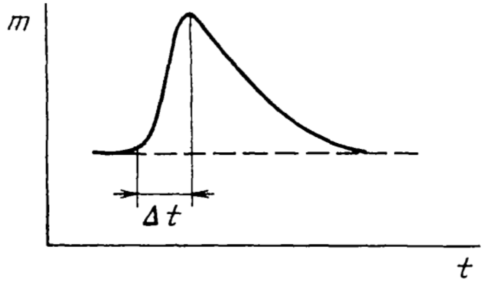
Confirmed by reverberation mapping (Koratkar & Gaskell 1991)

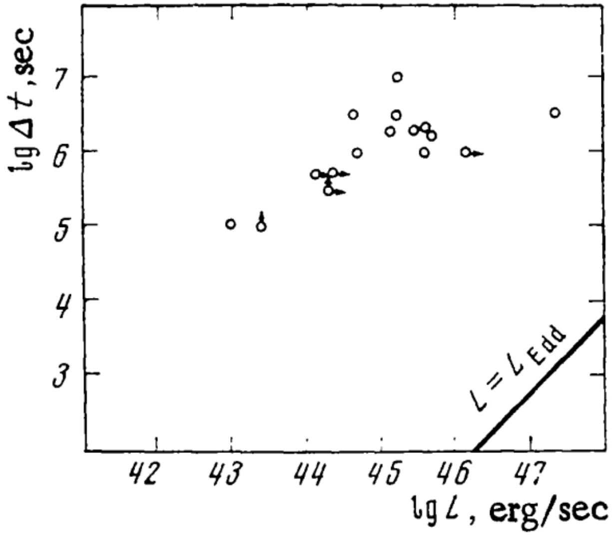
1-σ scatter is $\pm$ 0.3 dex.

Kollmeier *et al*. (2006) $L \,/\, L_{\mathrm{Edd}}$ has a lognormal distribution with $\pm$ 0.3 dex scatter.

Optical variability timescale – black hole mass and BLR size

Dibai & Lyutyi (1976) "Timescale of optical variability of galactic nuclei as a function of their luminosity and mass"

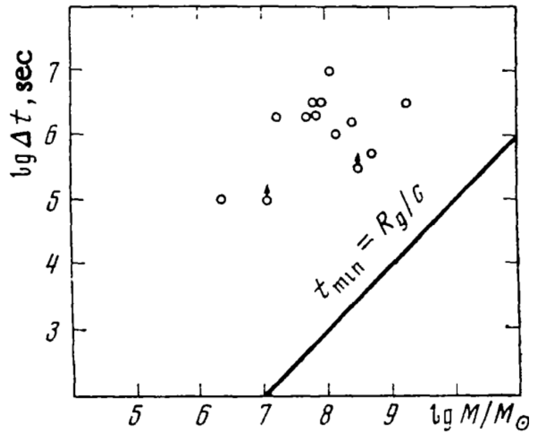




Defining the characteristics of AGN variability is tricky (ongoing area of research). Dibai & Lyutyi estimated a (shortest) characteristic timescale of variability as the flare rise time. Found that this timescale:

(a) increases with luminosity

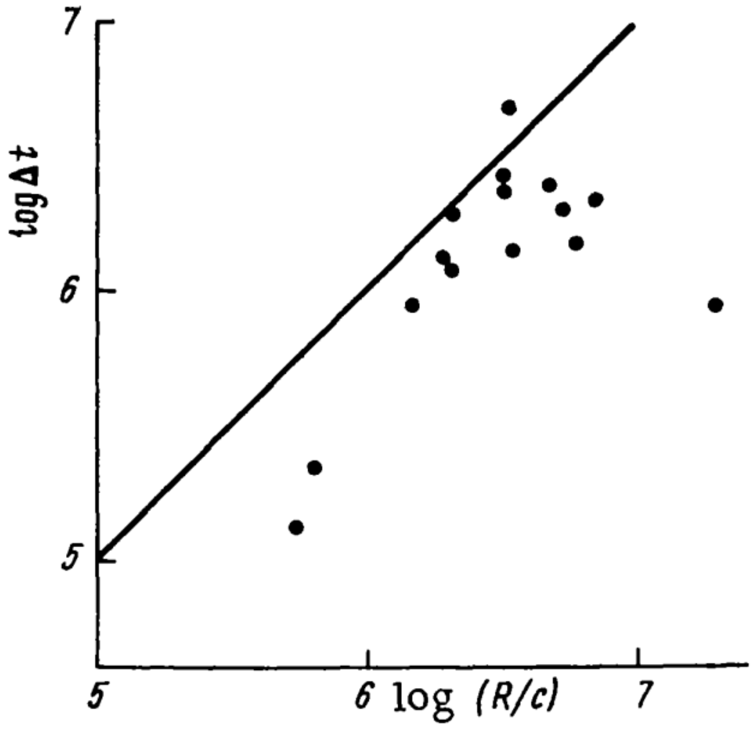
(b) was ~ light-crossing time at 100 Schwarzschild radii.



Dibai & Lyutyi (1984) “Optical variability parameters of active galactic nuclei”

[Published posthumously. Submitted only 5 months before Dibai died of cancer]

The light-crossing time of the BLR is only ≈ 3 times the flare optical variability timescale of flares.



Black hole masses and bulge masses

Since the luminosity of an AGN was proportional to the mass of the host galaxy (Zasov & Dibai 1970) *and* to the mass of the black hole (Dibai 1980), together these results ⇒ **the mass of the black hole is proportional to the mass of the bulge of the host galaxy!** **[Now one of the biggest areas of research in astronomy – thousands of papers!]**

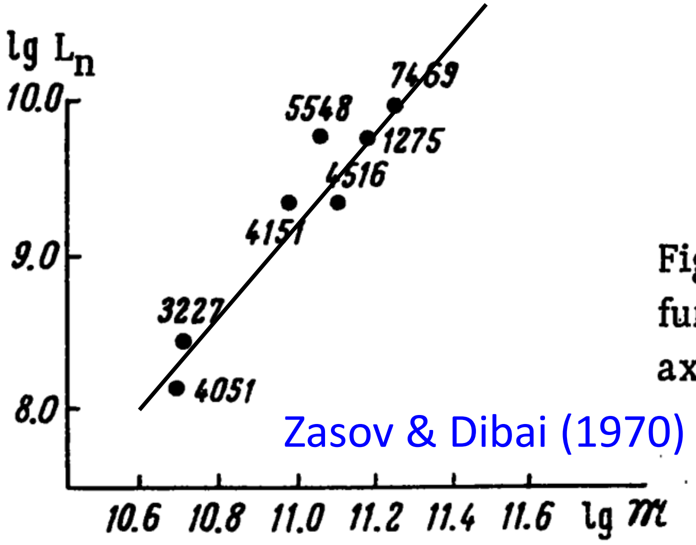


Fig. 2. Luminosity of nuclei as a function of the mass of the galaxy (in solar units).

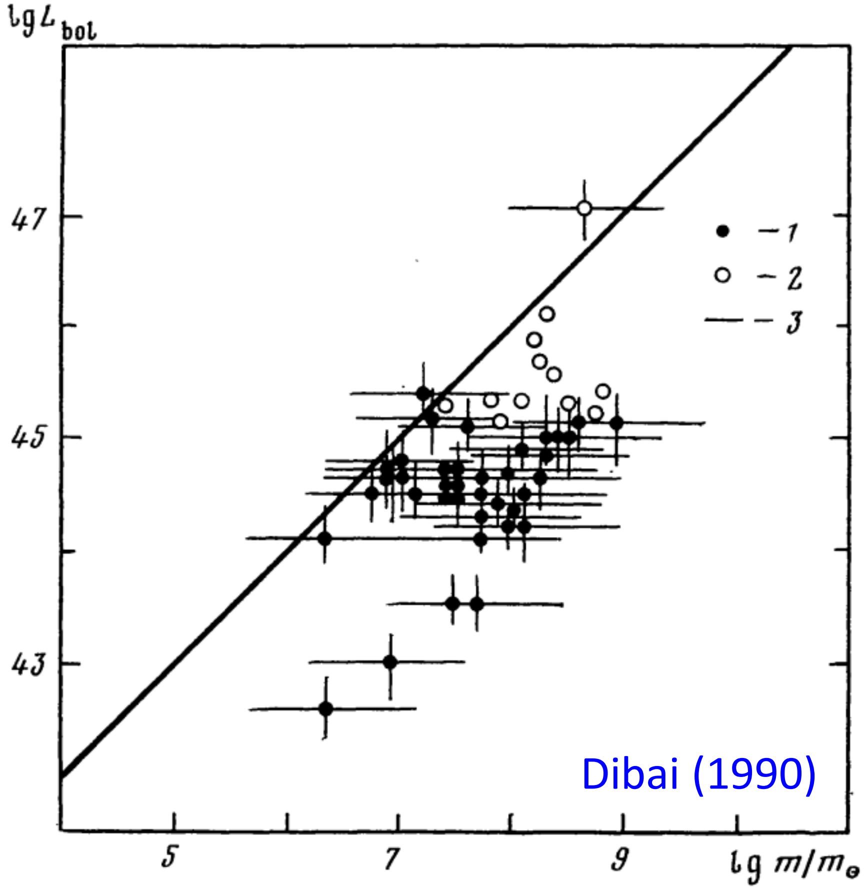


FIG. 1. The mass—luminosity relation for active galaxy nuclei. 1) Seyfert galaxies; 2) quasars. The line 3 represents the Eddington critical luminosity.

CONCLUSIONS

- Through his research, through his students and collaborators, and though his leadership and example, Dibai laid a foundation for understanding AGNs and for research which continues down to the present day.
- Much of our present day understanding of AGNs traces back to the pioneering work of Dibai and others at SAI/CrAO.
- I’m pleased to see this legacy continuing down to the present day and to be have been a small part of it.
- This conference and what we are going to hear in the next days is a testimonial to the legacy of the Crimean pioneers.

Спасибо!