Quasars for cosmology

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Bad Old Days

In 1998 I attended a conference on "Galaxy Dynamics", Rutgers University. I showed a poster on intermittent activity of AGN, and my poster did not qualify for prceedings since „AGN are irrelevant for galaxy dynamics and evolution”...

With Roman we planned to meet one day at the same conference...

But it's really now that studies of active galaxies and galaxy evolution/cosmology really starts to meet.

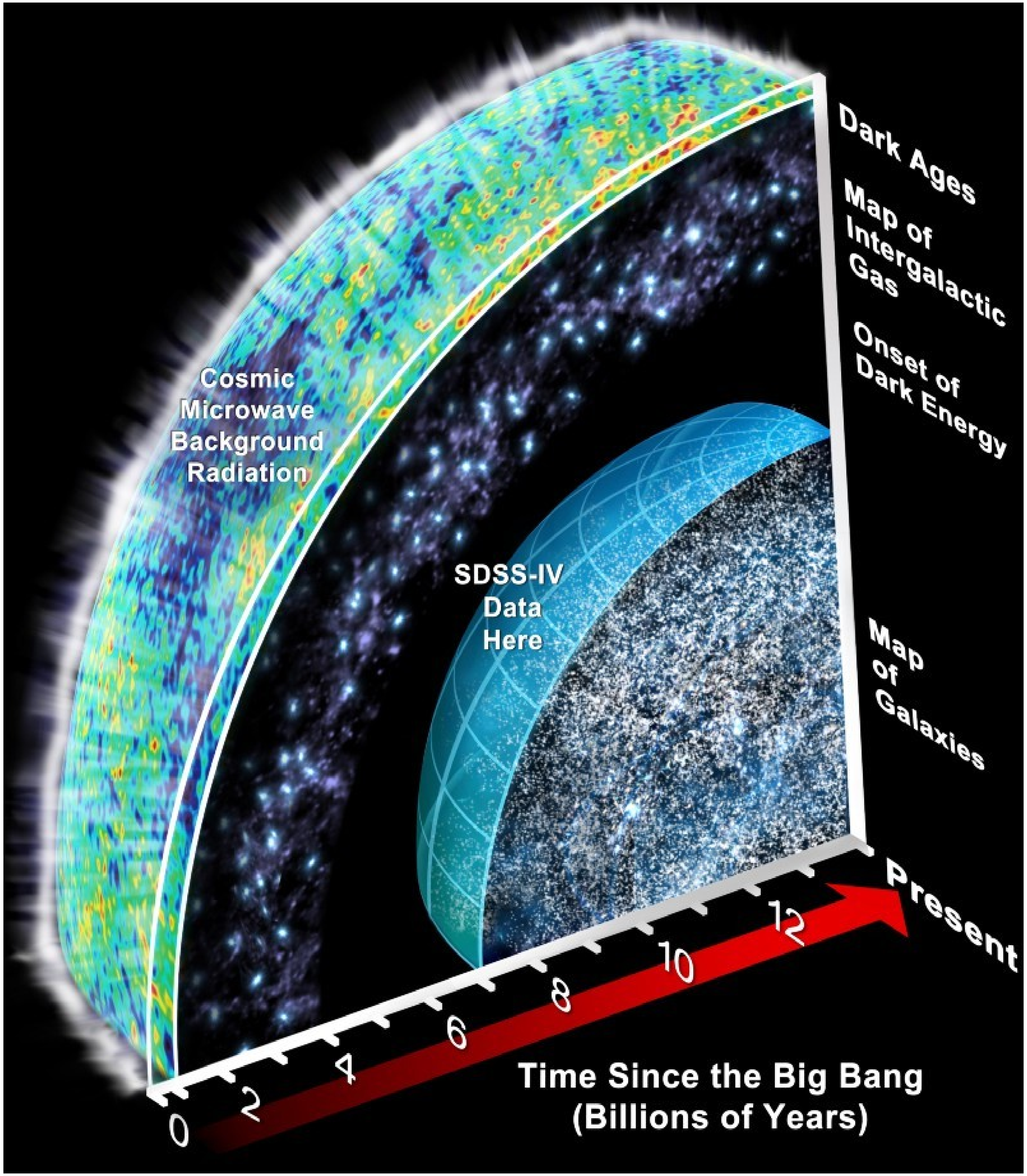
Quasars are rare but important

- Quasars are seen up to redshift 7; the record holder: ULAS J1120+0641 ($z = 7.085$) discovered in 2010

- Quasars are bright, hard to specify the record holder but some have luminosities above 10^{48} erg/s (e.g. HS 1946+7658 ($z = 3.02$)

- Quasars do not show significant evolution with redshift in their properties

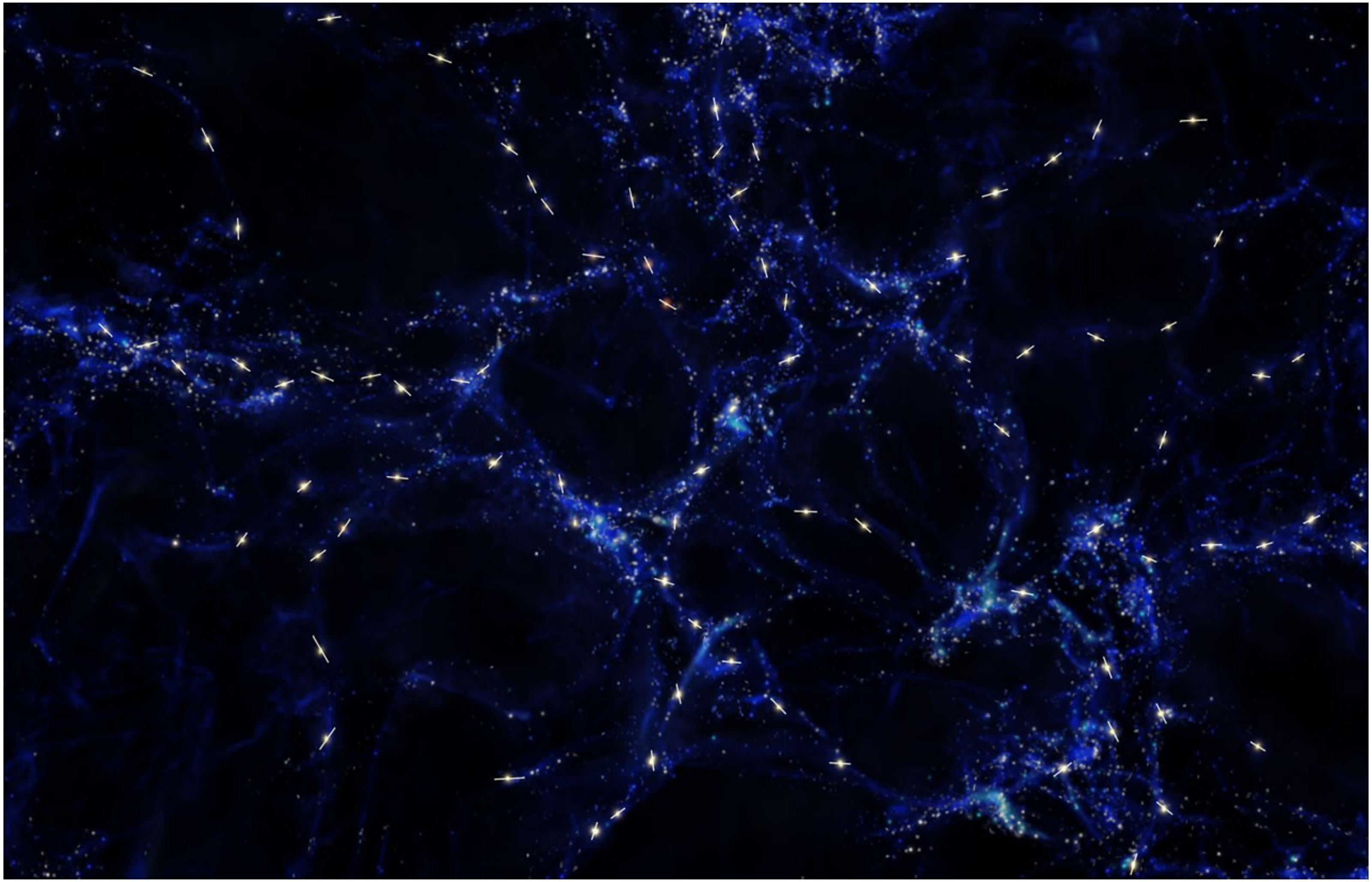
- Quasars are numerous: we know now 187 000 spectroscopically studied objects (Schneider et al. 2010; Paris et al. 2012). More is comming from SDSS and Gaia. XD QSO contains **1.6 mln** quasar candidates from SDSS DR8.



Quasars reach the Dark Ages epoch.

They trace the evolution of the Universe since that epoch.

Image credit: Sloan Digital Sky Survey (SDSS).



The new VLT results indicate that the rotation axes of the quasars tend to be parallel to the large-scale structures in which they find themselves.

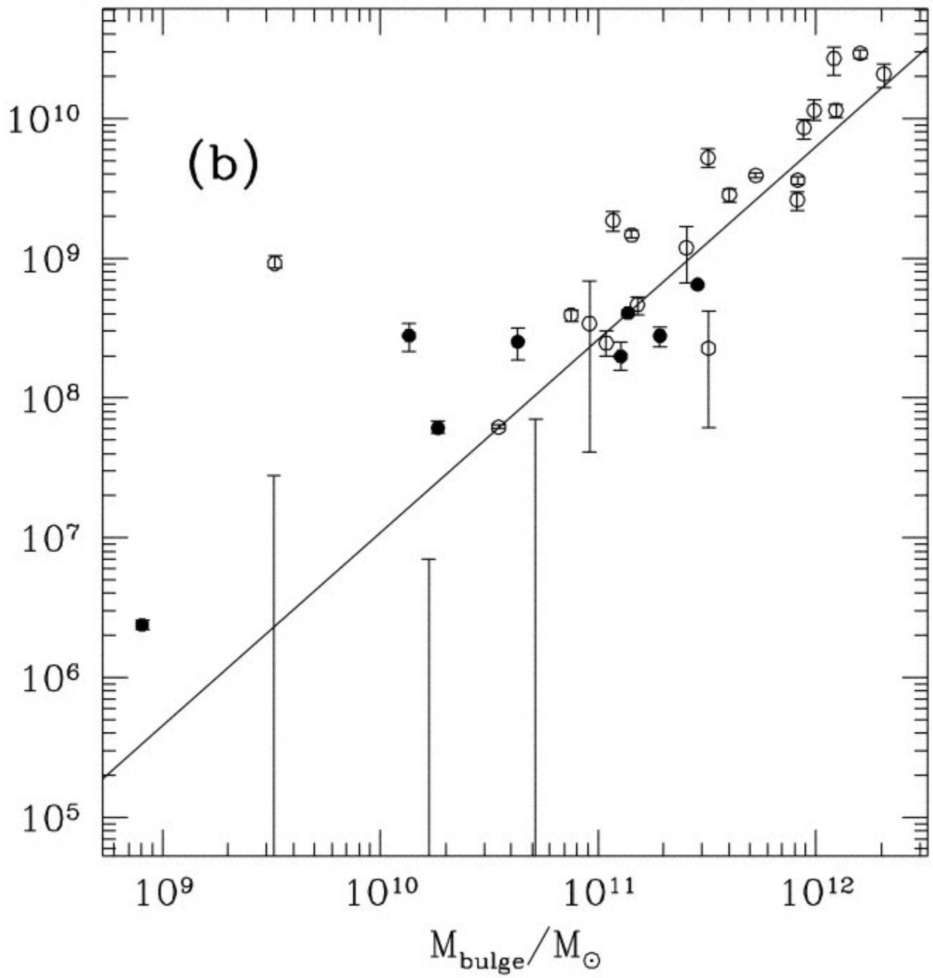
Image credit: ESO/M. Kornmesser, Artistic outline to show schematically the mysterious alignments between the spin axes of quasars and the large-scale structures that they inhabit. These alignments are over billions of light-years and are the largest known in the Universe. The large-scale structure is shown in blue and quasars are marked in white with the rotation axes of their black holes indicated with a line. This picture is for illustration only and does not depict the real distribution of galaxies and quasars. of quasar alignment silhouetted against the large-scale structure of the Universe.

Two major break-points in 1998:

1. M-sigma relation

2. Star formation history vs. quasar activity

M-sigma relation



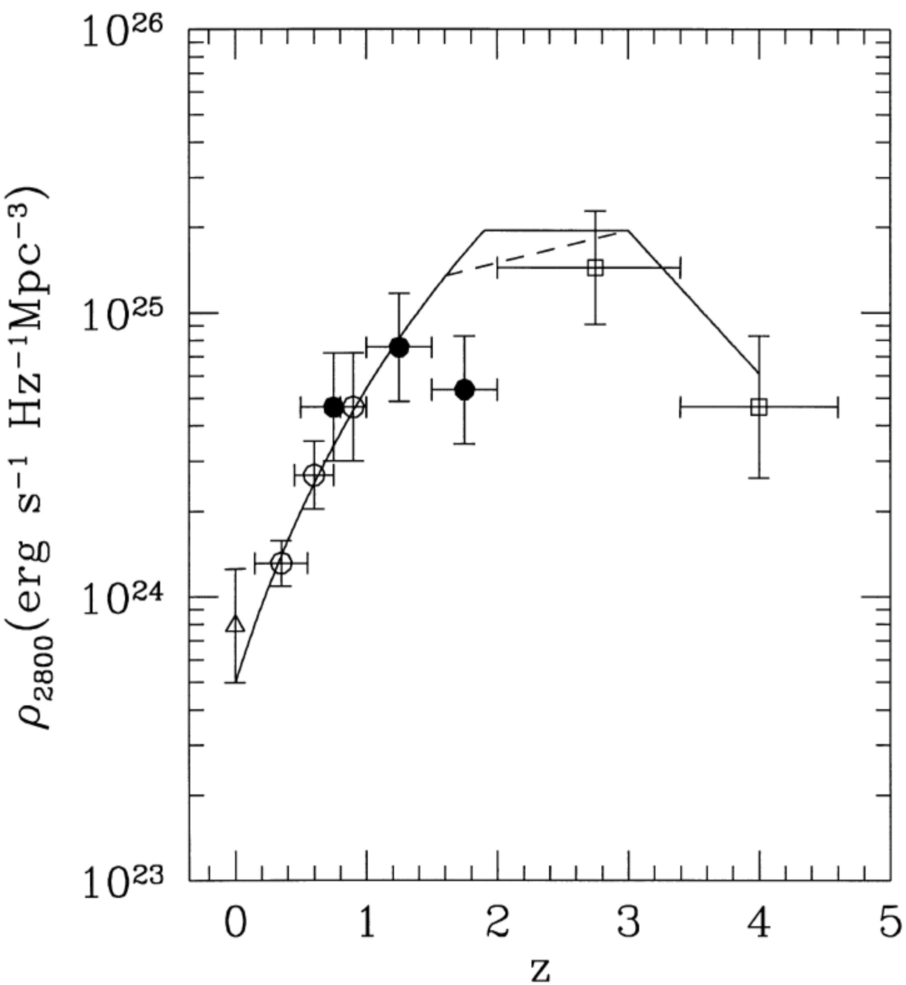
Magorrian et al. :

Mbh = 0.0052 Mbulge

It implies the existence of the mechanism regulating the common growth of a galaxy and a central black hole.

Nowadays mostly in M-sigma relation form, where sigma stands for stellar dispersion.

SFR/quasar activity



Boyle and Trelevich (1998) - the plot of the cosmic evolution of quasars and Star Formation Rate (SFR).

Also Richstone et al.1998

Implies that quasar activity and star formation proceed together!

Quasar application to cosmology

- **Active role**

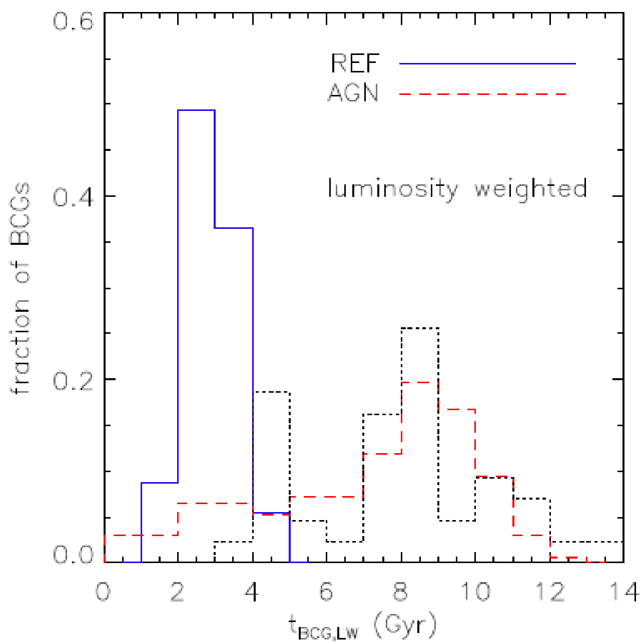
Quasars are very bright, the brightest quasars reach more than 1048 erg/s, other active galaxies are less numerous but they shape their surrounding

- **Passive role**

Quasars shine like lanters and they can be used as tracers of other material, they can be used to determine cvarious cosmological parameters

Active role - feedback

Galaxy formation needs quasars. They must produce the energy input at the level of a few per cent of the energy produced by the accretion onto black hole.



Simulations by McCarthy et al. based on OverWhelmingly Large Simulations project. Without (REF) and with AGN input.

Black histogram: data from Loubser et al. 2009

GENERAL ASPECTS

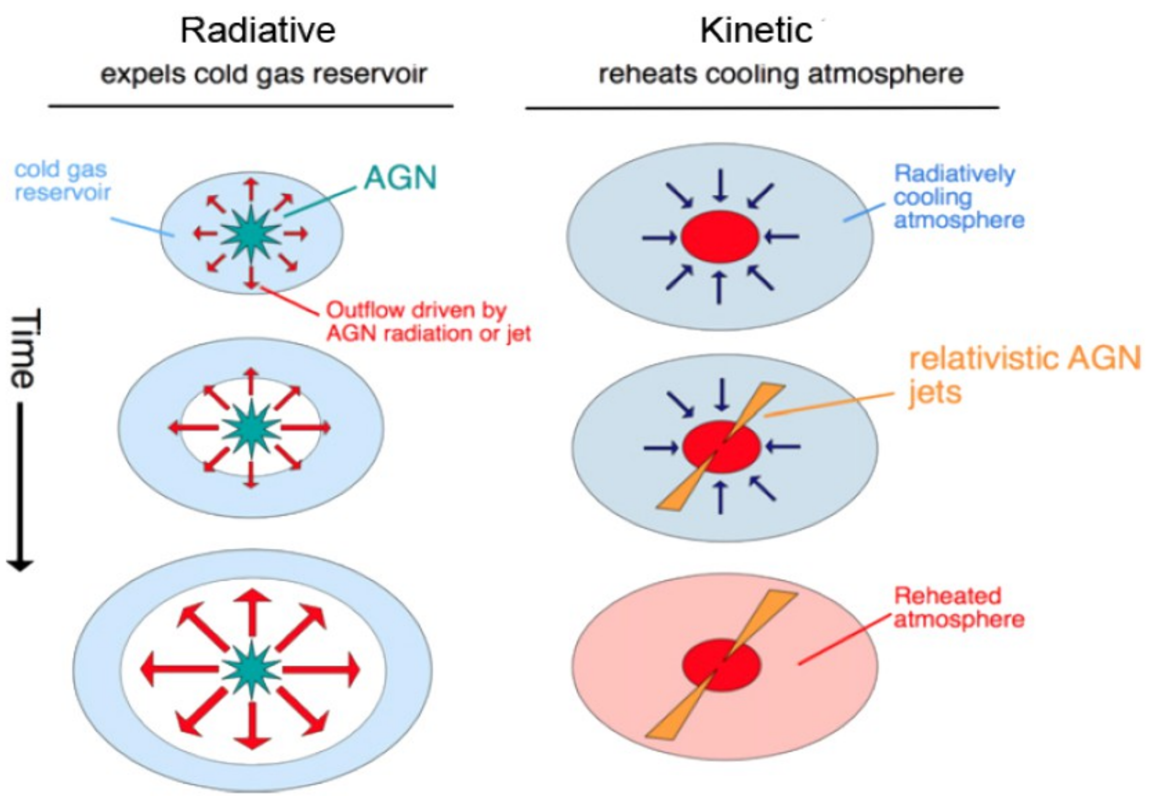
- **galaxies increase in size with time but their masses do not grow – AGN induced puffs up (Ishibashi et al.**
- **Too many stars, too soon**
- **Wrong shape of luminosity function**
- **CD galaxies too massive.**
- **by the control of the star formation rate AGN must provide the M-sigma relation**

- **In groups of galaxies (to control the group structure through regulation of gas mass fraction)**

- **In clusters of galaxies (to stop the efficient cooling flows)**

Active role - feedback

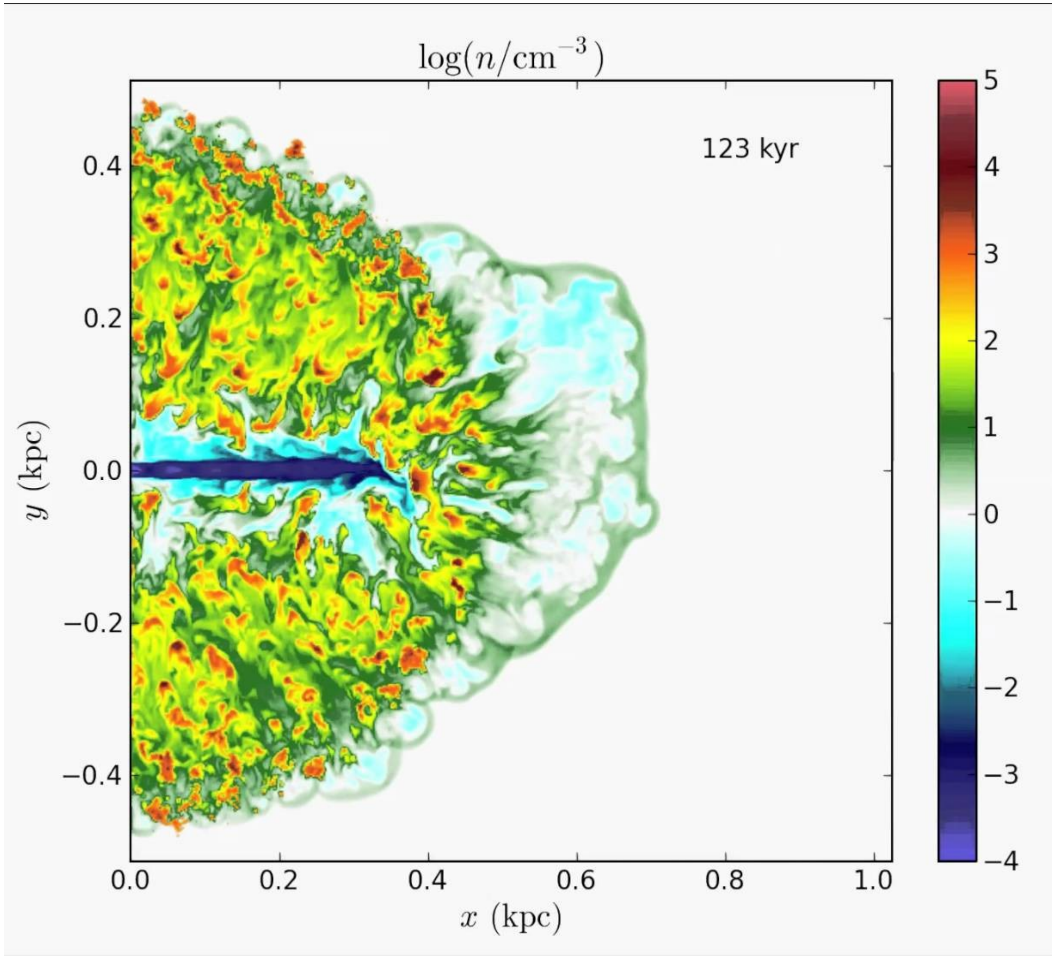
The question is whether quasars/AGN can provide that much energy, in the right time, and in the right form.
AGN can produce energy in the form of radiation, kinetic energy in the collimated flow (jet), and kinetic energy in the form of a colimated wind.



Schematic diagram to illustrate the radiative and kinetic mode of AGN feedback. The fleft sequence illustrates the wide-angle outows driven by radiation from the central quasar. The right sequence is characterized by small opening angle jets coming from the central radio source, which reheats the radiatively cooling atmosphere. Adapted by F. Becerra from Alexander & Hickox (2012).

Active role - feedback

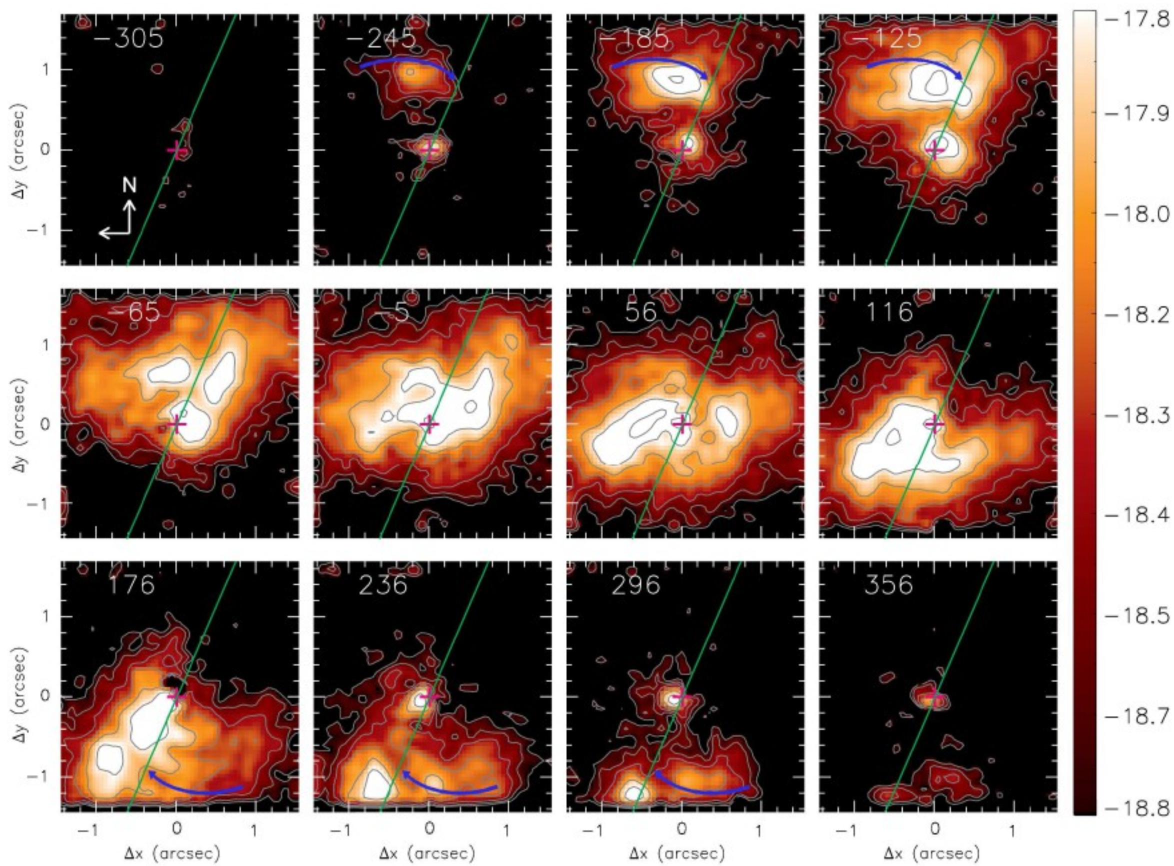
In cosmological simulations the feedback used to be a black box bringing energy. Recent simulations show incredible complexity of the interaction, taking into account the clumpy structure of the galaxy.



Example: jest propagation in a clumpy medium, Alexander Wagner (YouTube).

Feedback – observational data

Direct observations are only possible so far for the nearby AGN since high spatial resolution is required, and 3-D cube data must be obtained (image x spectrum)

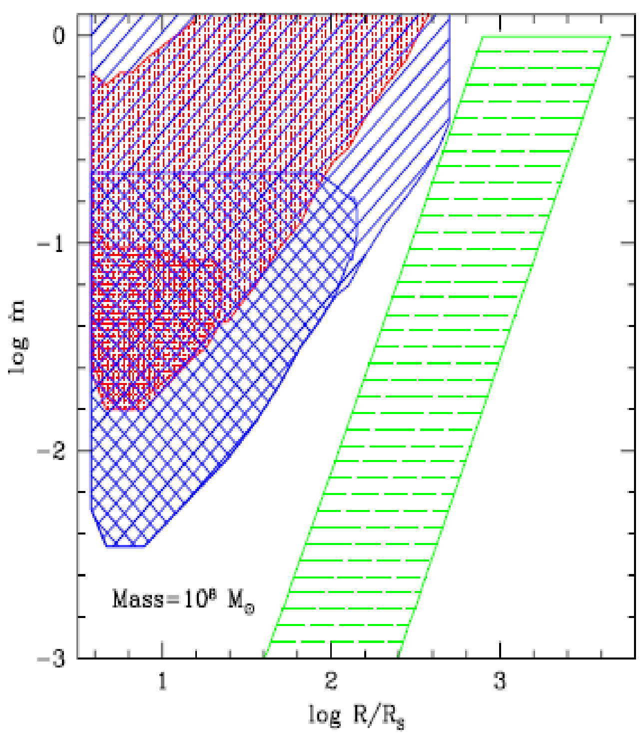


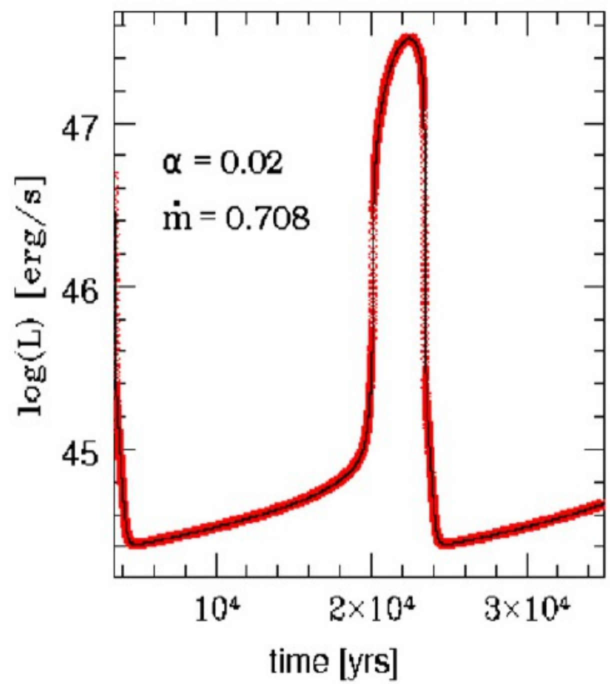
An example from recent Gemini North study of NGC 2110 with NIFS (Diniz et al. 2015)

Figure 6. Velocity channels along the H_2 emission line in $\approx$ 60 km s^{-1} bins (larger than velocity resolution of the data FWHM $\approx$ 44 km s^{-1}) centered on the velocities indicated in each panel. The central cross marks the position of the nucleus (peak of continuum emission), the intensities are represented in the color scale to the right in logarithmic units and the green line corresponds to the line of nodes. The spiral arms are delineated by the blue curves shown in the H_2 channel maps indicating the location of the inferred inflows discussed in Sec. 4.4.1.

Intermittent activity

AGN/quasar activity is possibly intermittent. This is caused by feeding process (minor mergers or just molecular clouds), but major mergers are also likely intermittent due to the accretion disk instability. This still remains to be studied.





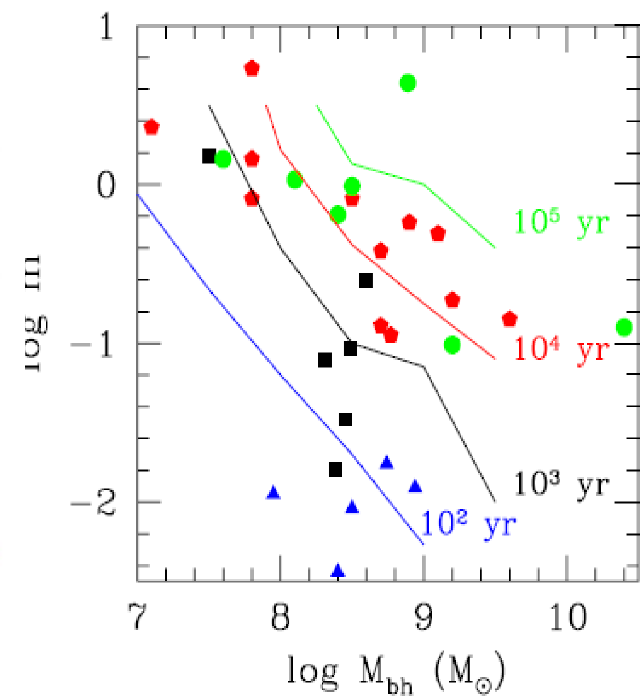
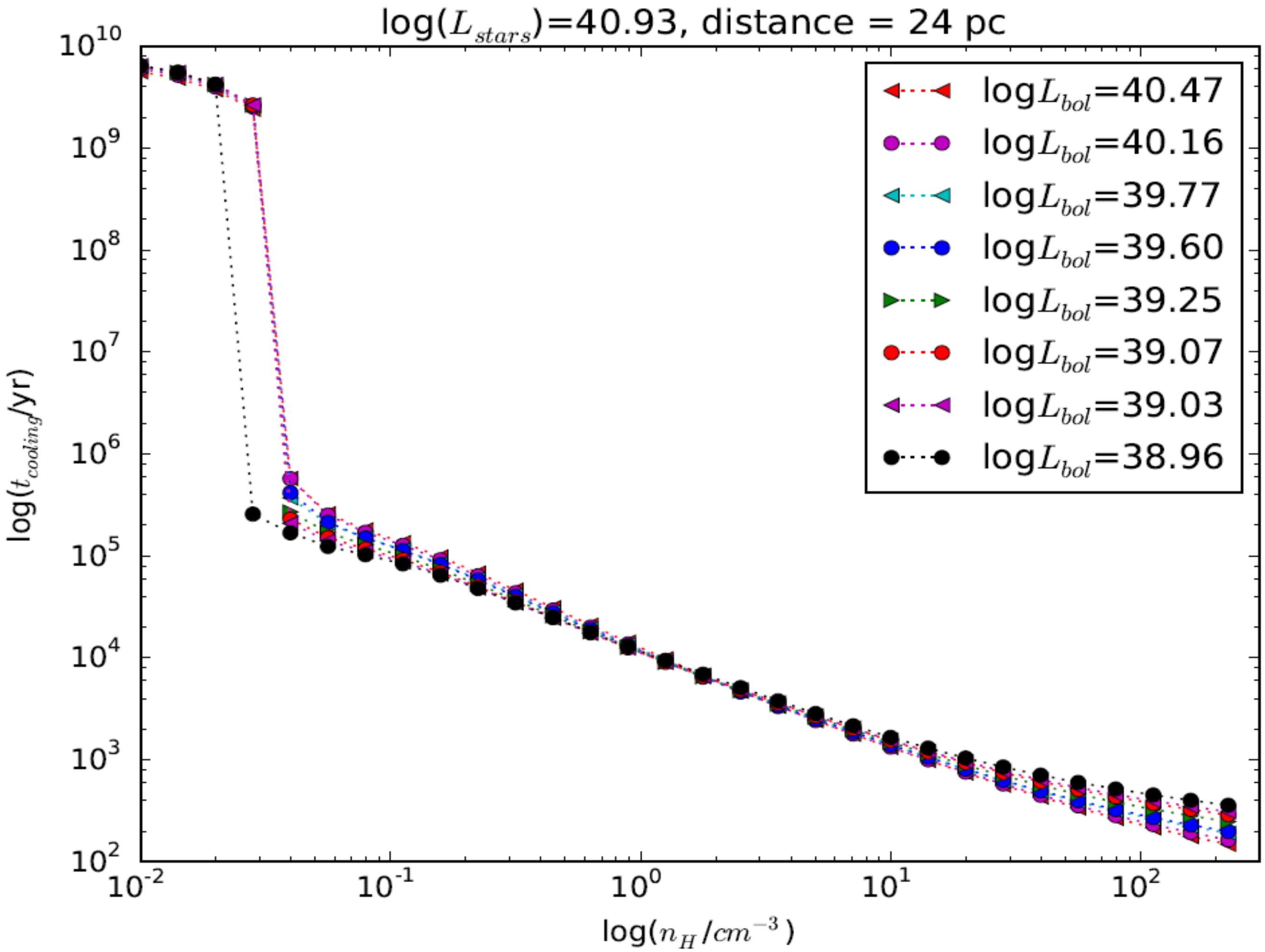


FIG. 3.— Comparison of the ages for young radio galaxies with the theoretical durations of outbursts triggered by disk instability in $M_{BH}-\dot{m}$ plane. The triangles, squares, pentagons, and circles correspond to the age in bins of $[0\text{-}5 \times 10^2]$, $[5 \times 10^2\text{-}5 \times 10^3]$, $[5 \times 10^3\text{-}5 \times 10^4]$, and $[5 \times 10^4\text{-}5 \times 10^5]$yrs respectively. The solid lines are the half of theoretical outburst durations predicted by the disk instability model with $\alpha = 0.1$, which are converted from the case of $\alpha = 0.2$ in Czerny et al. (2009, Fig. 5) using the scaling relation of Eq. (1).

Janiuk & Czerny 2011; Czerny et al. 2009; Wu (2009)

Intermittent activity



The thermal equilibrium timescales of the interstellar medium are actually comparable to the expected timescales of the intermittency of an active nucleus;

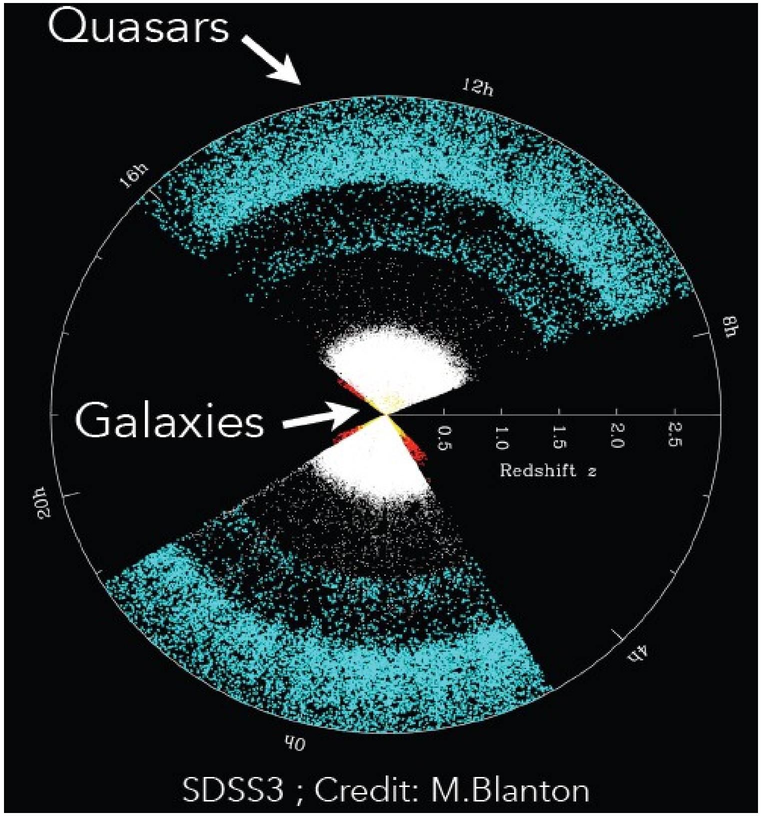
work in progress

Cooling timescales for a galaxy M60-UCD1; Rozanska, Kunneriath, Czerny et al., in preparation

Passive role

Quasars cover much larger volume of the Universe than galaxies. They can be used to probe its content and dynamics.

- Probing super-horizon large scale modes, including the Primordial Non-Gaussianity (PNG)
- Probing the intergalactic medium and faint intervening galaxies
- BAO from quasars – dark energy
- BAO for the intergalactic medium - dark energy
- Measurement of the deuterium content - nucleosynthesis
- Independent measurement of the Hubble constant and other cosmological parameters from multi-image (lensed) quasars
- Measurements of the black hole masses at high redshifts - constraints for the galaxy formation at high redshifts
- Measurements of the quasar orientation – constraints for the dynamics of the Large Scale Structure formation
- Tracing the expansion rate of the Universe - dark energy



Most of these projects have not reached yet the maturity (no firm results) but expectations are high.

Tracing the expansion rate of the Universe with quasars

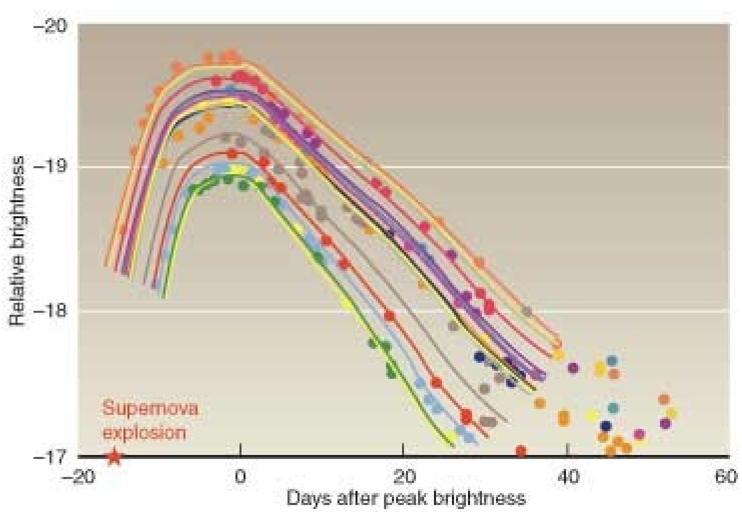
Quasars are not standard candles but the are ways to determine their absolute luminosity from their properties.

observed luminosity

absolute luminosity

redshift

Luminosity distance D(z)



But SN Ia are also not quite standard candles; they may have different progenitors and be of different sub-types; uncertainties acan be serious (Milne et al. 2015)

https://www.llnl.gov/str/SepOct08/hoffman.html

The advantage of use of quasars over the use of SN Ia:

- quasars at large redshifts have the same metallicity as closer objects
- the measurement is not entangled with the cosmology parameters (Melia 2015)

Determining quasar absolute luminosity

- **reverberation method**: measurement of the time delay of an emission line with respect to the continuum

  Needs many spectroscopic measurements for a single objects, although the use of multichannel photometry is also under discussion; theoretically well understood
- **selection method**: choice of quasars radiating at the Eddington luminosity for a give mass

  Needs a single spectroscopic measurement for an object; problematic ?
- **broad band index method**: determination of the absolute luminosity from the continuum shape

  Needs a single measurement in opt/UV and in X-rays; problematic ?

Broad band index method

This new method is based on the nonlinear relation between the UV and X-ray luminosity in quasars (Risaliti & Lusso 2015).

$$\log(L_X) = \beta + \alpha \log(L_{UV}). \quad (1)$$

om the we above equation we obtain

$$\text{g}(F_X) = \Phi(F_{UV}, D_L) = \beta' + \alpha \log(F_{UV}) + 2(\alpha - 1) \log(D_L), \quad (2)$$

here β' depends on the slope and intercept (i.e. $\beta' =$ $+ (\alpha - 1) \log(4\pi))$, and D_L is the luminosity distance,

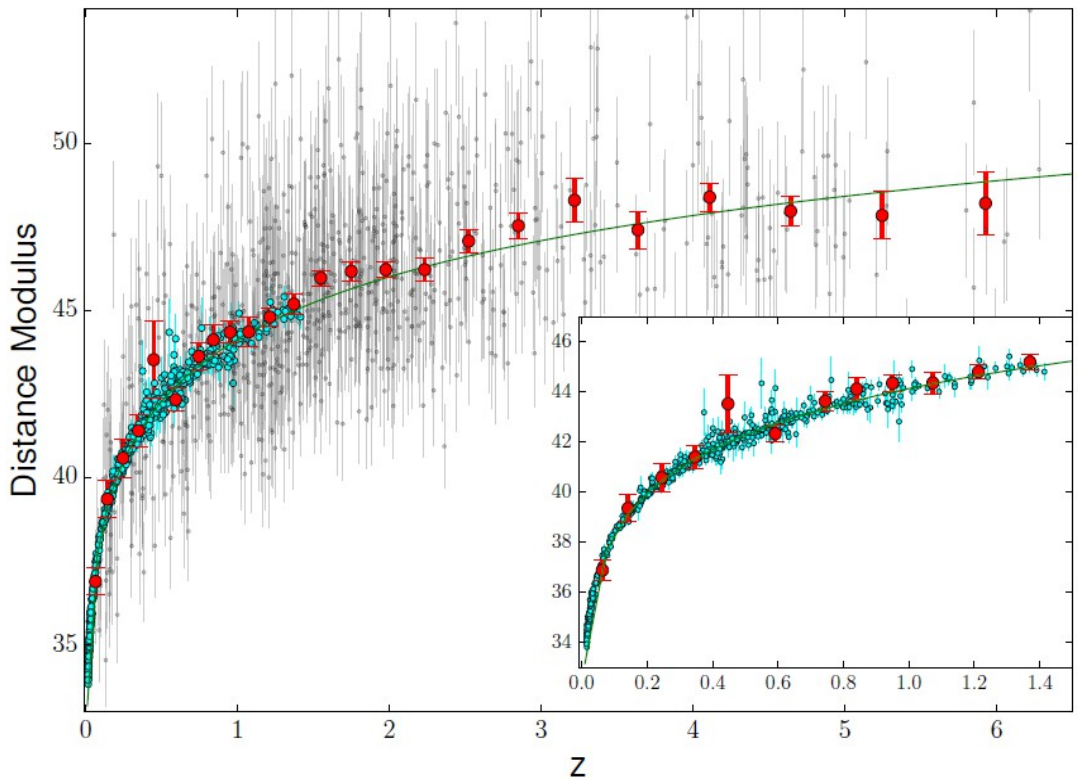


FIG. 5.— Hubble Diagram for the quasar sample (small gray points) and supernovae (cyan points) from the Union 2.1 sample (Suzuki et al. 2012). The large red points are quasar averages in small redshift bins. The inner box shows a zoom of the $z = 0 - 1.5$ range, in order to better visualize the match between the SNe and the quasar samples. The continuous line is obtained from a joint fit of the two samples assuming a standard ΛCDM cosmological model.

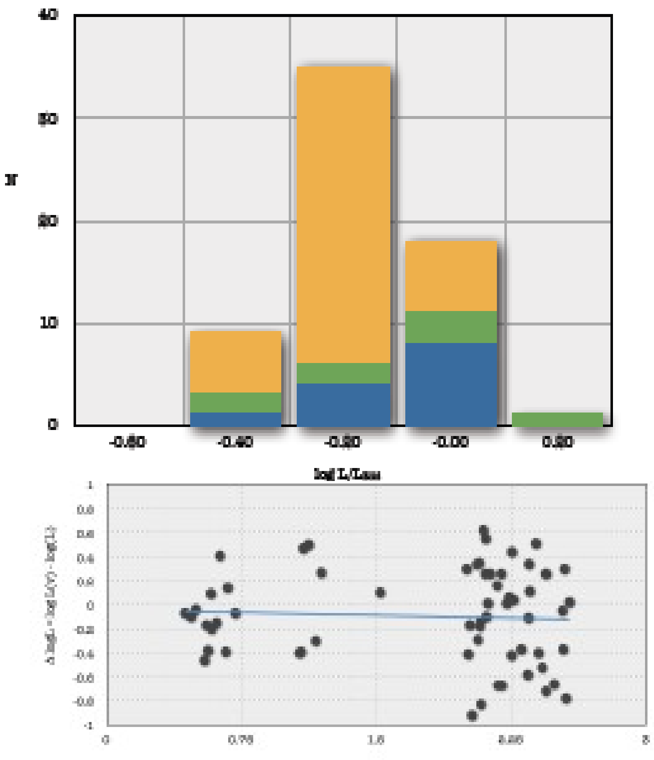
The procedure required pre-selection of objects; dust extinction was the major issue, so some iterative process was used when obtaining cosmological parameters.

Current result is fully consistent with supernovae but goes far up to the redshift 6.

assuming a ΛCDM model, we obtain $\Omega_M = 0.21^{+0.08}_{-0.10}$ and $\Omega_\Lambda = 0.95^{+0.30}_{-0.20}$

Selection method:

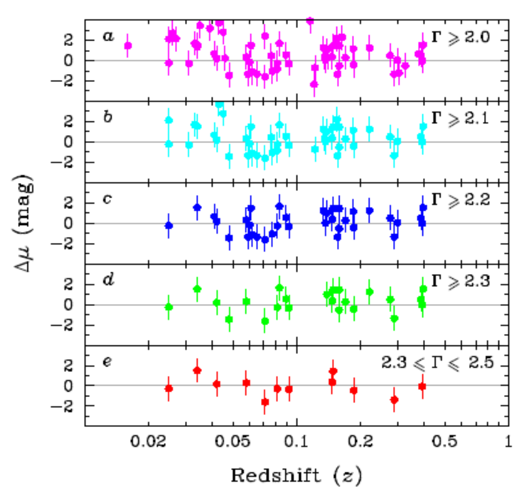
The mothod is being developed by Marziani-Sulentic group and J.-M. Wang group. Black hole mass in quasars is measured from the Broad Emission Line width, and absolute monochromatic luminosity. Black hole mass determines the Eddington luminosity. Marziani/Sulentic group requires selection of objects close to the Eddington luminosity and then some iterative procedure to use that in cosmology.



Selection and the tests of 63 quasars assuming concordance cosmology, Marziani et al. 2014

Wang et al. 2013 propose the selection of super-Eddington sources and to use the theoretical saturation limit

$$L_{\bullet} = \ell_0 \left(1 + a \ln \dot{m}_{15}\right) M_{\bullet}$$



Test of the method against concordance cosmology. Recent MHD give lower saturation limit ?

Reverberation method

Observations of nearby AGN lead to the discovery of the relation between the Hbeta line and the absolute monochromatic flux at 5100 Ang (Cherepashchuk & Lyutyi 1973; Wandel et al. 1999; Peterson et al. 2004). The most recent form reads (Bentz et al. 2009):

$$\log R_{BLR}[\mathrm{H}\beta] = 1.538 \pm 0.027 + 0.5 \log L_{44,5100},$$

THE ASTROPHYSICAL JOURNAL LETTERS, 740:L49 (5pp), 2011 October 20 WATSON ET AL.

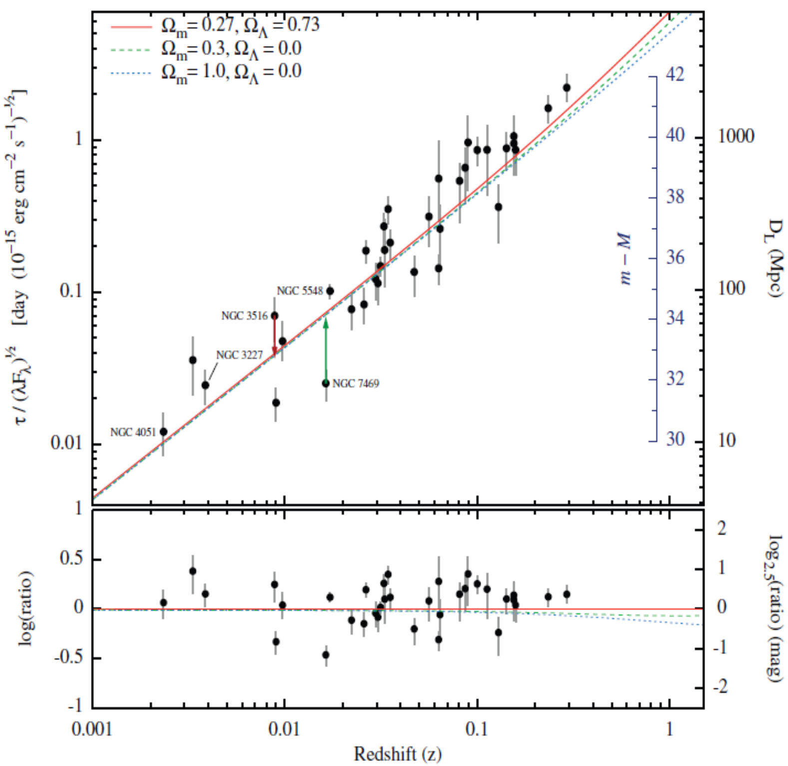


Figure 2. AGN Hubble diagram. The luminosity distance indicator $\tau/\sqrt{F}$ is plotted as a function of redshift for 38 AGNs with Hβ lag measurements. On the right axis the luminosity distance and distance modulus $(m - M)$ are shown using the SBF distance to NGC 3227 as a calibrator. The current best cosmology (Komatsu et al. 2011) is plotted as a solid line. The line is not fit to the data but clearly follows the data well. Cosmologies with no dark energy components are plotted as dashed and dotted lines. The lower panel shows the logarithm of the ratio of the data compared to the current cosmology on the left axis, with the same values but in magnitudes on the right. The red arrow indicates the correction for internal extinction for NGC 3516. The green arrow shows where NGC 7469 would lie using the revised lag estimate from Zu et al. (2011). NGC 7469 is our largest outlier and is believed to be an example of an object with a misidentified lag (Peterson 2010).

(A color version of this figure is available in the online journal.)

This relation was proposed to be used for measurement of the expansion rate of the Universe by Watson et al. (2011).

However, extension of the relation for nearby AGN to distant quasars seemed questionable.

Reverberation for more distant objects

In the paper Czerny & Hryniewicz (2011) we showed that the radius-luminosity relation can be explained as a combination of accretion disk theory and the onset of the dusty wind from the disk surface below 1000 K. Our FRADO (Failed Radiatively Accelerated Dusty Outflow) model solves the problem why **the distance scales with the monochromatic flux and NOT with the ionization flux** which was a puzzle since many years!

The relation can be safely extrapolated up to high redshifts.

But at that time there was no measurements for high redshift quasars. What is more, 7 objects at redshift about 2 were monitored but only one delay was tentatively measured (Kaspi et al. 2007). This was done using CIV line.

Observational programs for distant quasars

- In 2012 we started the program of monitoring 3 quasars at intermediate redshifts, using Mg II line (Justyna Modzelewska/Średzińska will talk more on that). The observation pattern was studied through simulations (Czerny et al. 2013). We do not have yet a delay measurement, expected delays are about 500 – 10000 days

- Gaia low resolution measurements will likely bring reverberation results for a small sample of quasars (Proft & Wambsgans 2015)

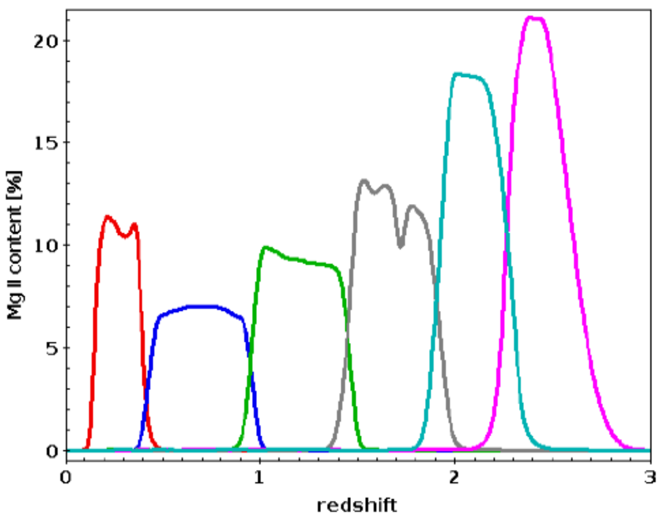
- LAMOST (Chinese facility close to Bejiging) initially planned to do spectroscopic monitoring of quasars as well, but at the moment they do only stars

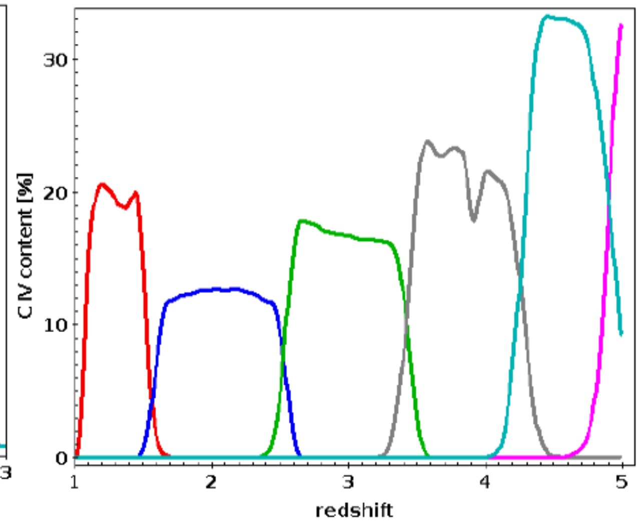
- SDSS Reverberation Mapping Project was performed (Shen et al. 2015), but only for 6 months; no delays reported so far, but they unlikely to be for distant quasars

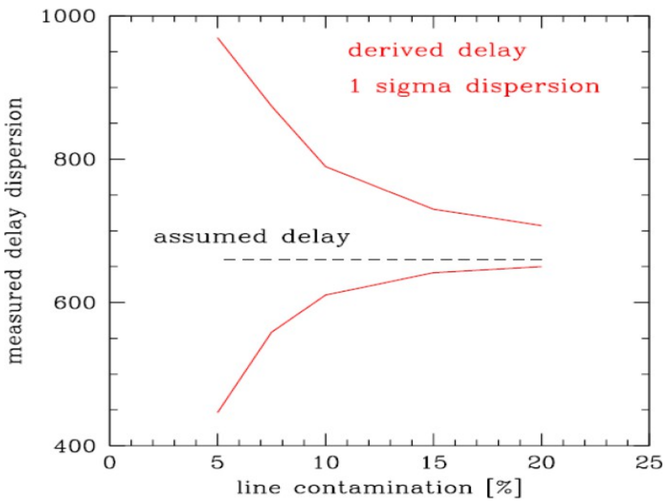
- OzDES spectroscopic survey is being performed since 2013 (King et al. 2015). This will cover 500 quasars for 5 years, with general setup as in Czerny et al. (2013), using the 30 deg^2 field of DES supernova.

Future possibilities

We analyse the possibility to have reverberation measurements from the Large Synoptic Sky Survey (LSST). This will be a 6-chanel photometric facility which will bring repeated observations (up to 100 per year) of numerous quasars. The problem is: this is photometry, not spectroscopy. Line contributes up to 20-30 percent to the continuum in a given chanel.







Kurcz et al., in preparation

We still work on various aspects of the spectral contamination and trends, to decrease the possible systematic error. Similar project is being done by the group of Chelouche.

The list of collaborators

Maciek Bilicki, Michał Chodorowski, Krzysztof Hryniewicz, Agnieszka Janiuk, Vladimir Karas, Agnieszka Kurcz, Magdalena Krupa, Devaki Kunneriath, Ishita Maity, Francesco Petrogalli, Wojtek Pych, Agata Różańska, Alex Schwarzenberg-Czerny, Justyna Średzińska/Modzelewska, Aneta Siemiginowska, Andrzej Udalski, Piotr Życki

Summary

- Quasars/AGN now have unquestionable role in cosmology

- It still remains to see whether they can play their active role as efficiently, as expected

- Their passive role is some aspects is already extremely useful (intervening absorption lines), and they are promising tools in many other aspects

- The seem to offer an independent tool for tracing the expansion of the Universe and determination of the properties of dark energy.