The role of dust in AGN

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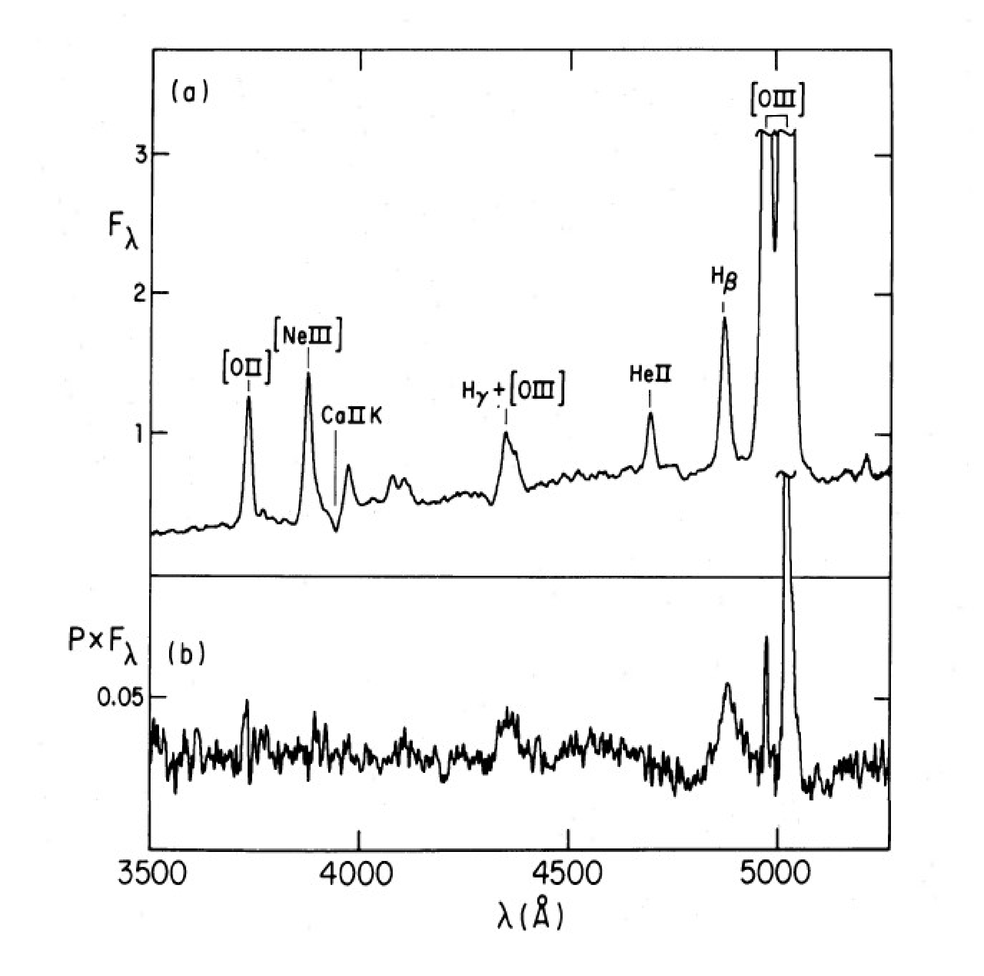
Basic facts

Dust is present in all galaxies, for example in the Milky Ways it obscures the view towards the nucleus (AV ~ 25 mag). This dust is contained mostly in the spiral arms.

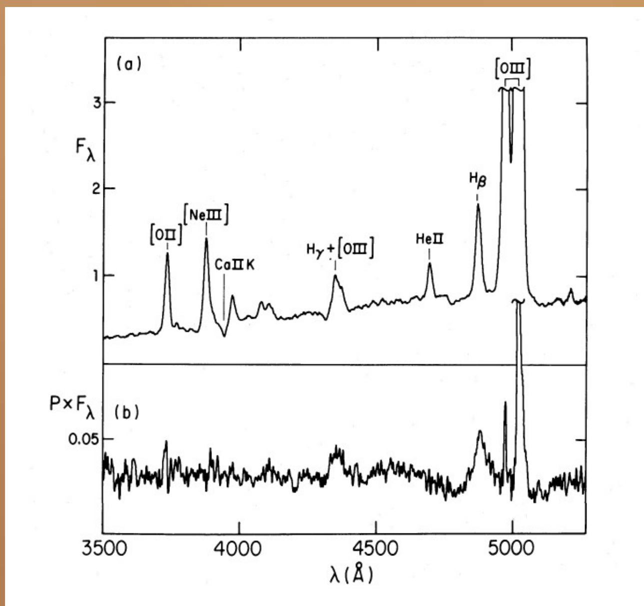
Basic facts about bright AGN



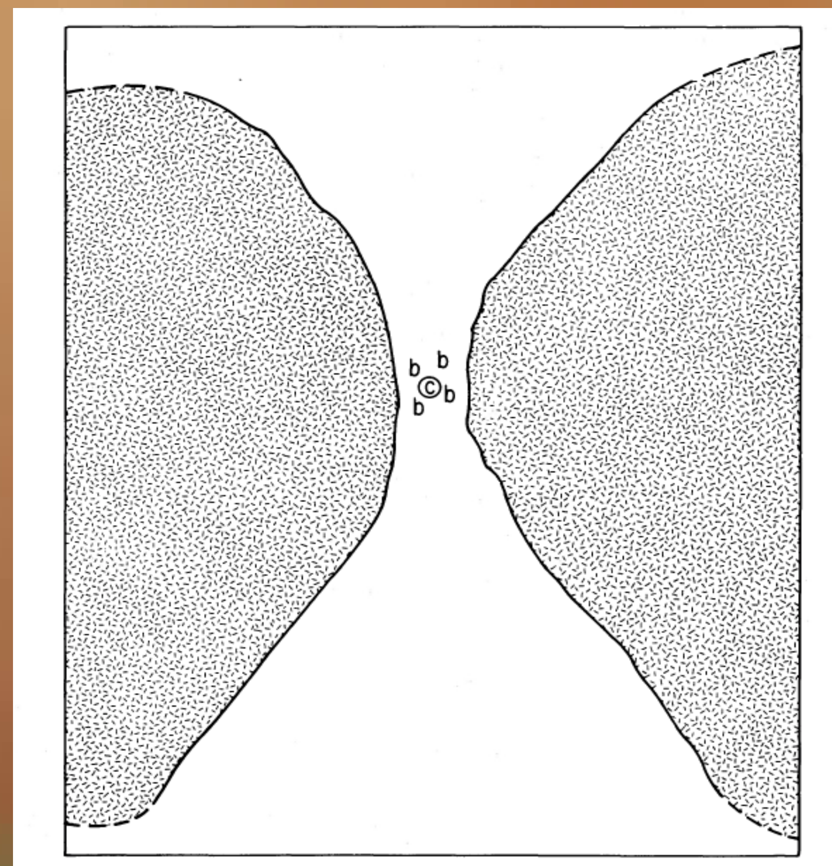
Antonucci & Miller (1985) took spectra of a well known Seyfert 2 galaxy NGC 1068 and showed that unpolarized light contains only narrow Hbeta line while polarized light revealed the presence of the weak polarized component.

Basic facts about bright AGN

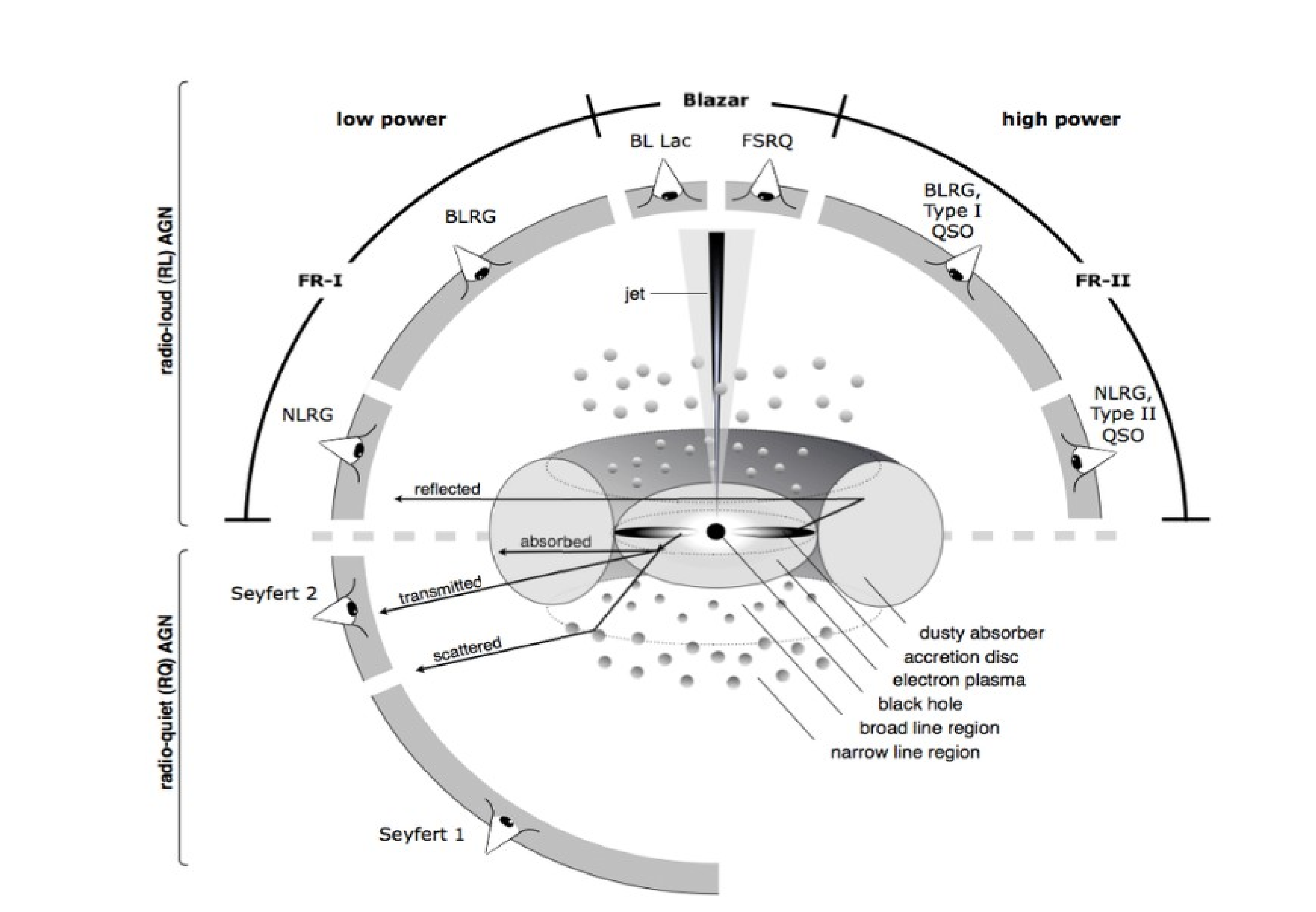
They proposed a torus as obscuring medium, and in this way the standard universal picture of an AGN was born.



Antonucci & Miller (1985)

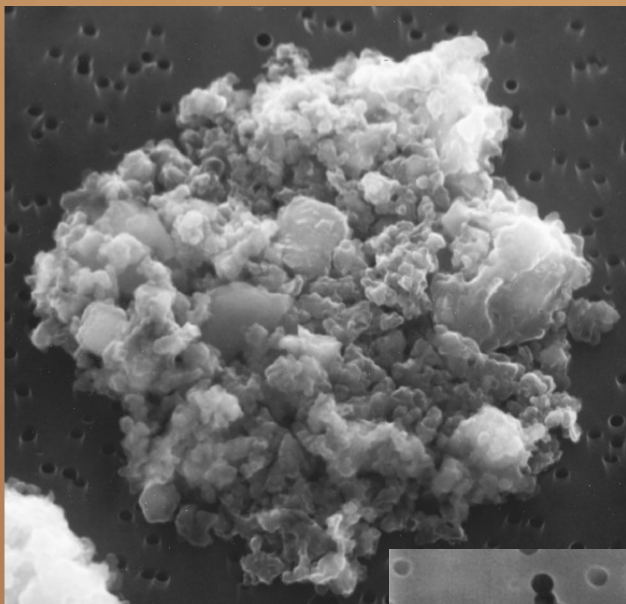


Basic facts about bright AGN



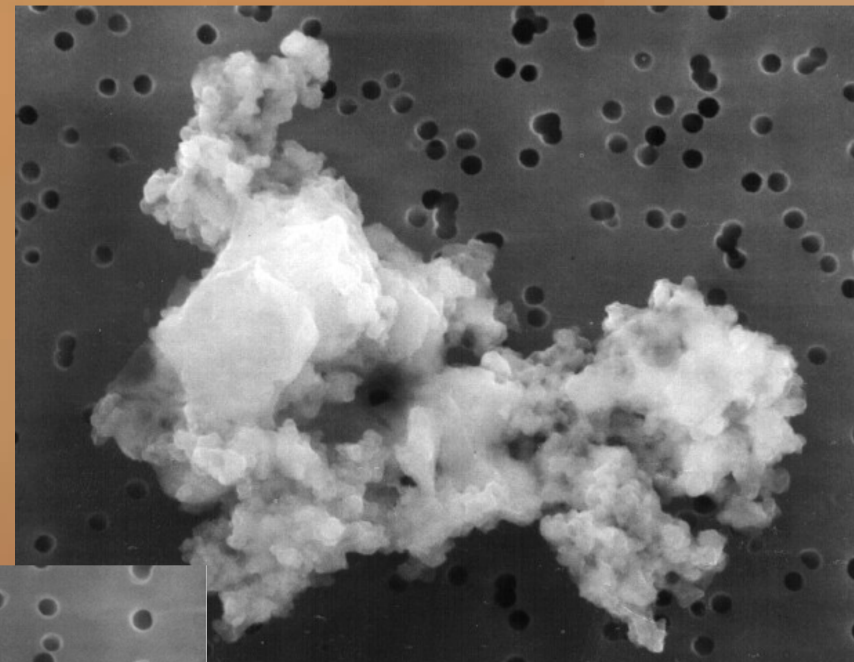
From Beckman & Schroeder (2012)

Dust properties: dust in nature



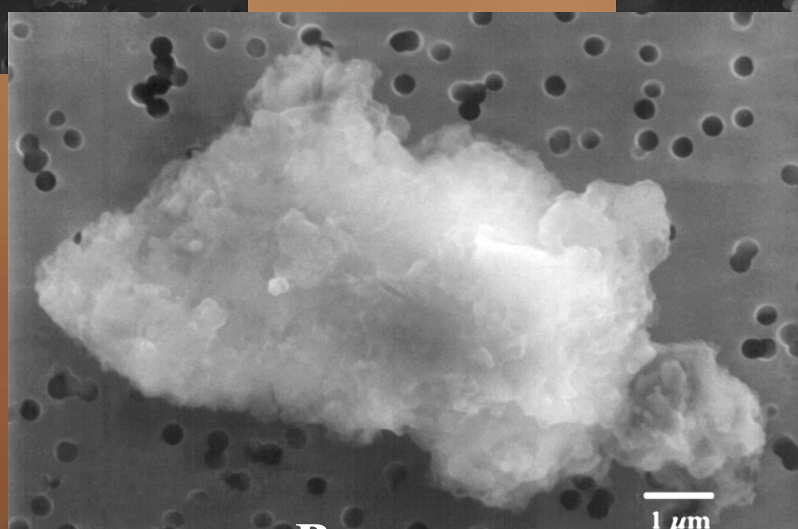
interplanetary
dust particle

D. Brownlee, University of Washington, and E. Jessberger, Institut für Planetologie, Münster, Germany, wikipedia



Dust particle in laboratory,

Volten et al., 2007



10 micron interplanetary dust collected in the stratosphere,
stardust.jpl.nasa.gov/science/sdparticle.htm

l

0.001 – 10 000 μm

Dust chemistry

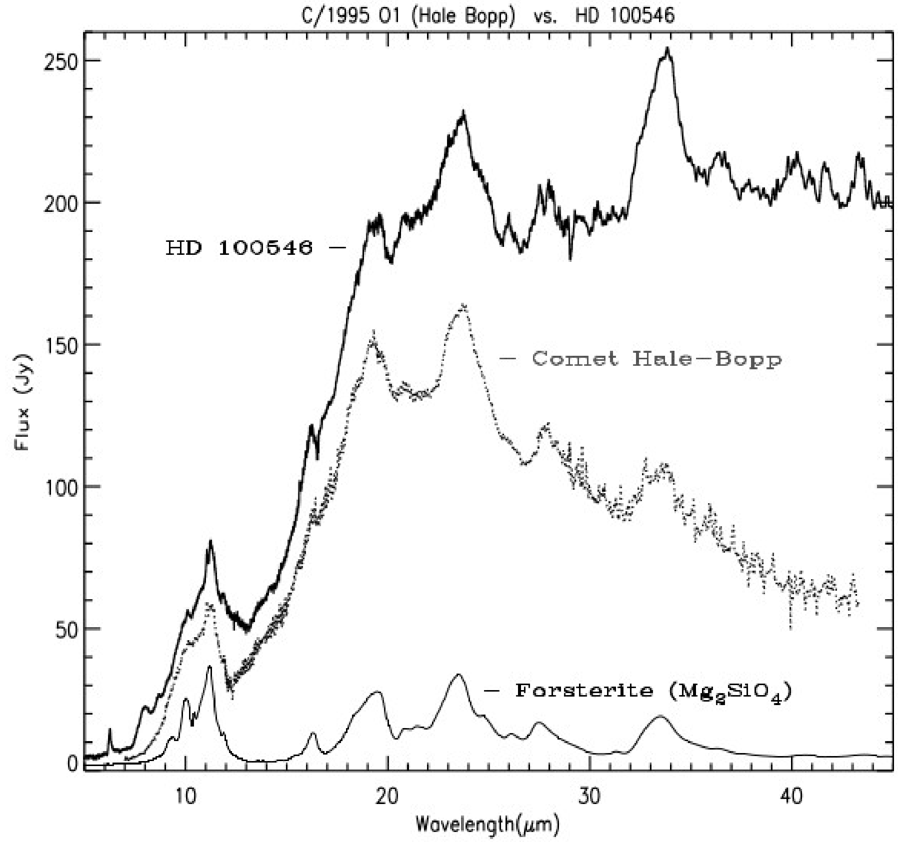
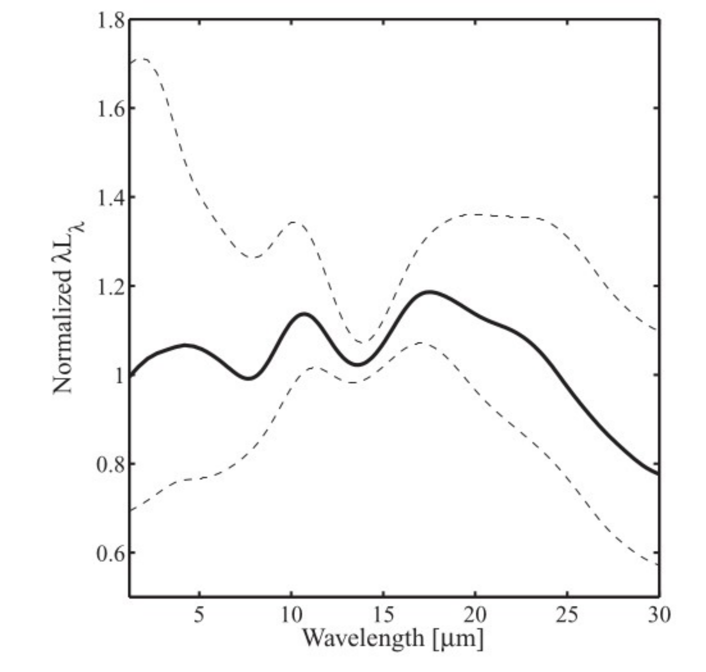


Fig. 5 Infrared spectra of the Young Stellar Object HD 100546 (top curve) compared to those of comet Hale-Bopp (middle), both taken with the Infrared Space Observatory (ISO). The bottom curve shows a laboratory spectrum of forsterite (van den Ancker 1999)

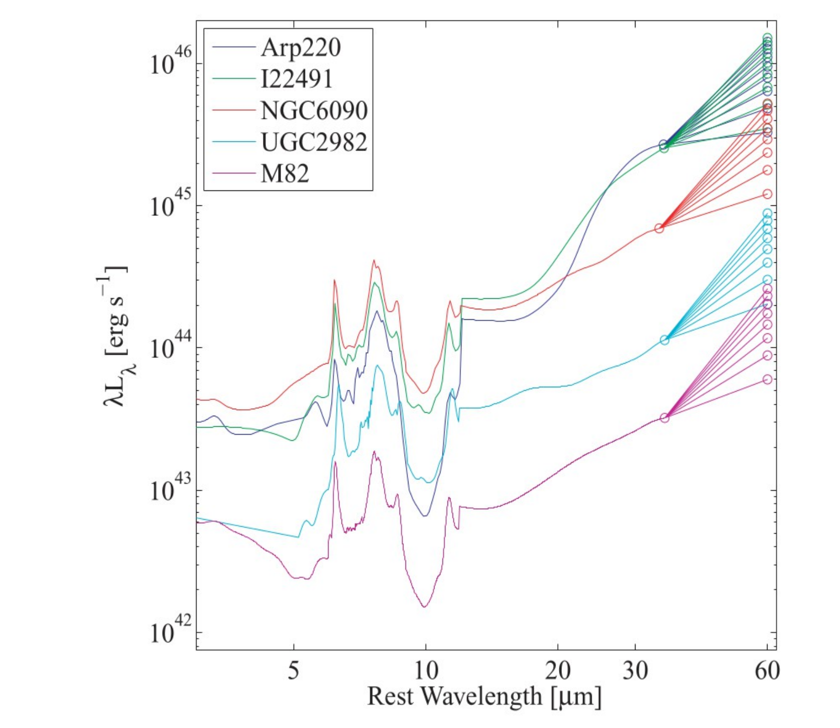
Dust chemistry is very complex. It is by now very carefully studies in meterorites, coments, stars and in the laboratory which allows to identify the dust molecules.

From Gruen et al. (2019)

Dust 'location' in AGN spectrum



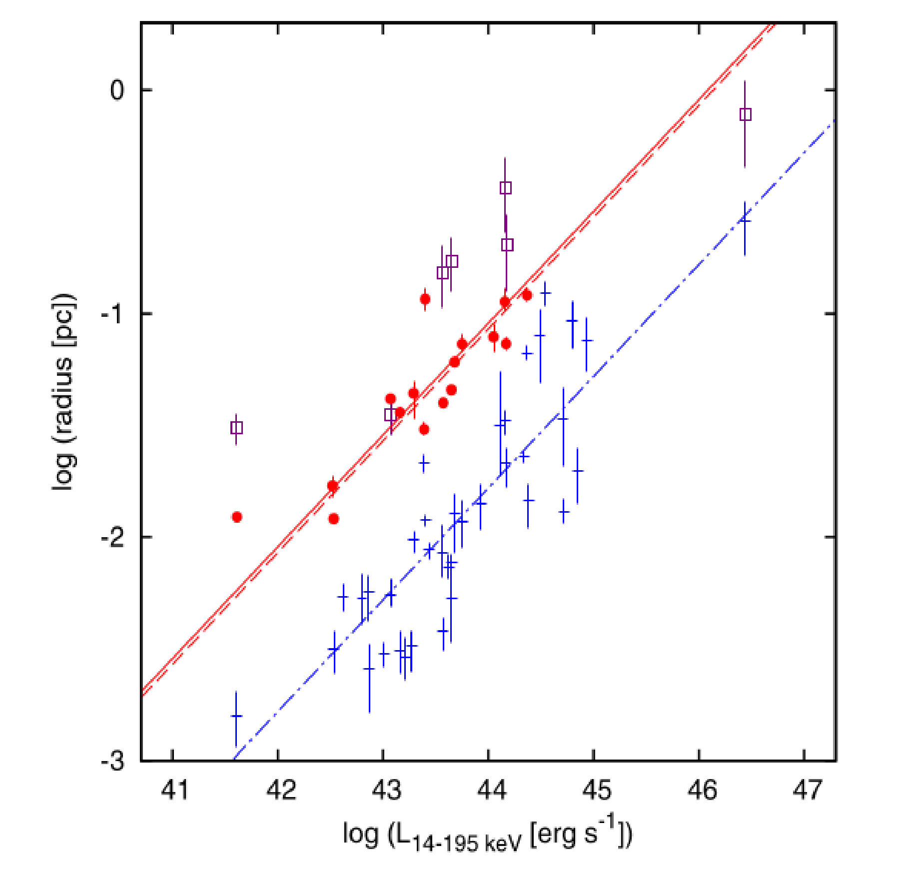
From Mor & Netzer (2012)



Dust is seen roughly as the (multicolor) black body emission with temperure below ~ 1500 K (sublimation) but features in absorption and emission, mostly from silicates, are clearly visible in many sources.

Dust location from the time delays

Nowadays the reverberation measurements (i.e. light echo studies) are the key method to get an insight into unresolved sources.

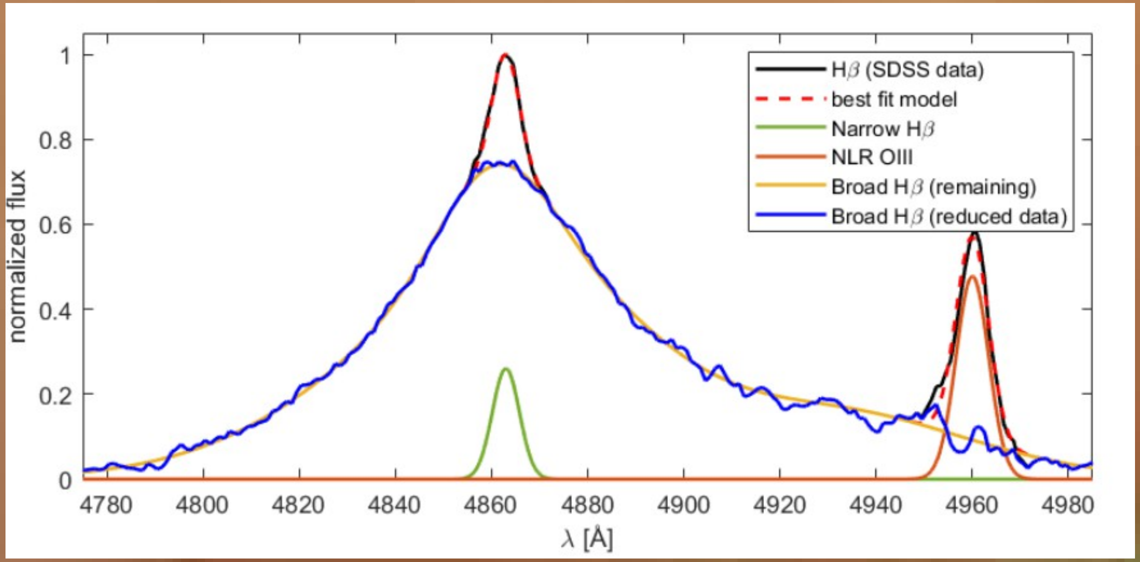


Time delays imply that the hottest dust is located by a factor 5 further away from the black hole than the BLR (Hbeta).

Koshida et al. 2014

Dust as a separator between the BLR and NLR

Mean quasar spectrum from SDSS shows clearly shows a two-component character of the Hbeta line. This implies a gap in distance (this in velocity) between BLR and NLR. It was explained by Netzer & Laor (1993) as due to the onset of dust, efficiently competing with ionized plasma for photons.



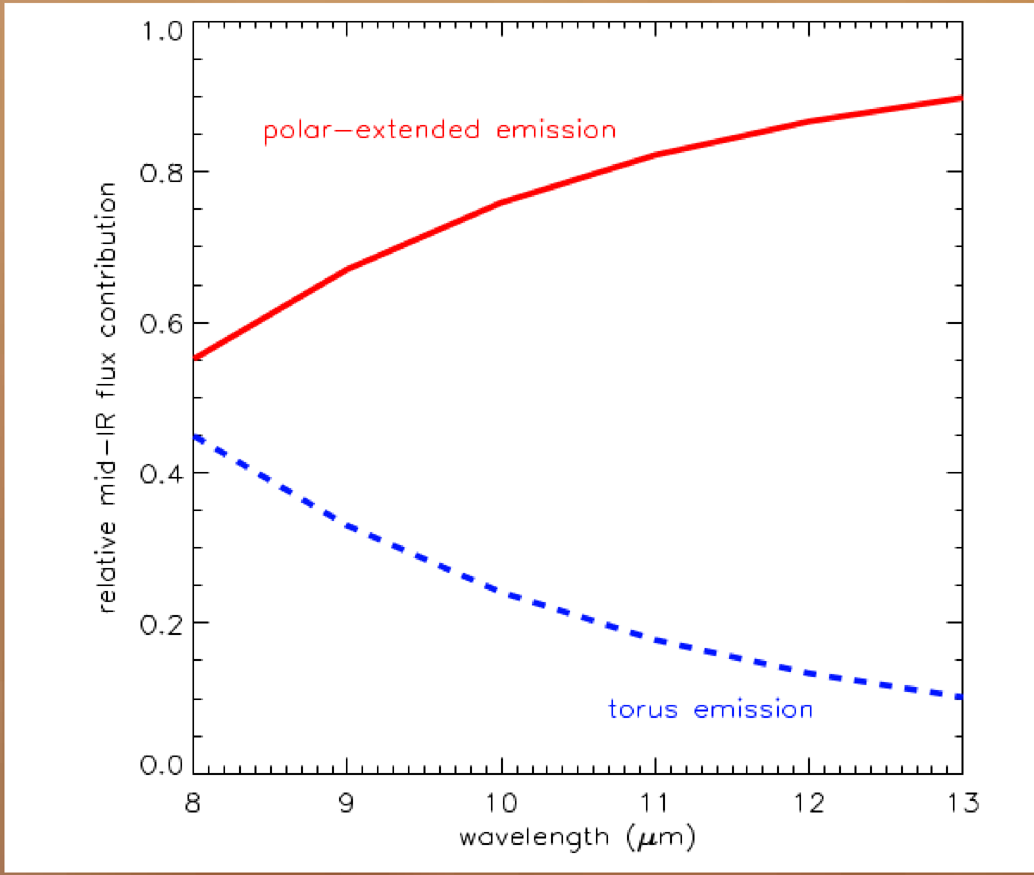
But this is the end of good news for the standard torus.

Naddaf et al. 2022

List of problems for the standard torus:

- 'static' torus shape cannot be supported by the thermal motion, so it should be some sort of the dynamical structure (inflow or outflow)
- the torus must be clumpy, otherwise the broad band spectrum and the absorption/emission features cannot be explained
- mapped IR emission is dominated by the polar emission, NOT equatorial from the torus:

List of problems for the standard torus:



Hoenig et al. (2013) performed interferometric mapping of of the unobscured (type 1) AGN in NGC 3783. Fitting the visibility plane they have got the following result: most of the (mid-IR) emission comes from the polar direction

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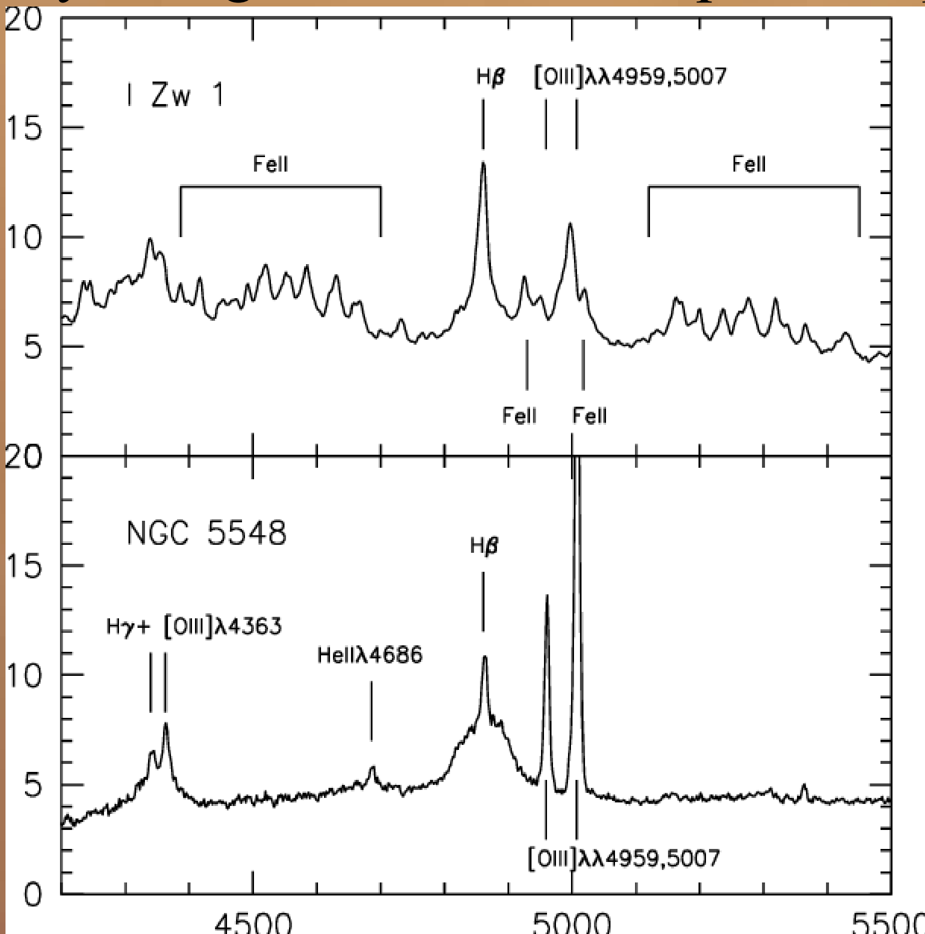
List of problems for the standard torus:

High Eddington ratio objects have Hbeta line frequently well modeled by a single Lorentzian shape, no separate NLR component is needed.



In Adkirari et al. (2016) we showed that if the local density is high the dust is not intecepting the radiation more efficiently than partially ionized hydrogen.

Thus the BLR can be mixed with dust.

From Sulentic et al. (2007)

List of problems for the standard torus:

- 'static' torus shape cannot be supported by the thermal motion, so it should be some sort of the dynamical structure (inflow or outflow)
- the torus must be clumpy, otherwise the broad band spectrum and the absorption/emission features cannot be explained
- mapped IR emission is dominated by the polar emission, NOT equatorial from the torus
- in high Eddington ratio sources (Narrow Line Seyfert 1 galaxies, type A quasars) there is no gap between BLR and NLR, and the dust can be mixed with BLR medium
- dust can exist in the accrtion disk much closer than the dusty torus, and can actually be the driver of the BLR

Our idea – BLR as failed wind

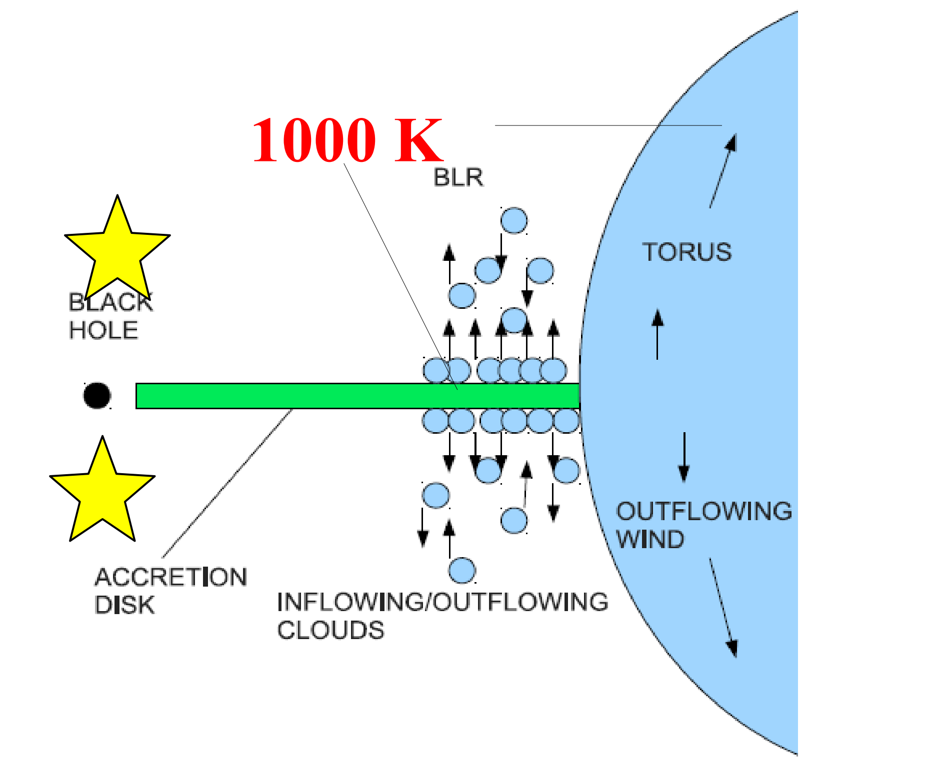


Fig. 1. The BLR region covers the range of the disk with an effective temperature lower than 1000 K: the dusty wind rises and then breaks down when exposed to the radiation from the central source. The dusty torus is the disk range where the irradiation does not destroy the dust and the wind flows out.

Dust leads to outflow but dust cannot survive in the temperature much higher than 1000 K!

Strong radiation field kills the dust (evaporation process)

Wind, which is not a wind, is what we need!

We call it FRADO – Failed Radiatively Accelerated Dusty Outflow.

Our simple idea

$$R \propto L_{300nm}^{1/2}$$

Observations

$$L_{300nm} \propto (M\dot{M})^{2/3}$$

Accretion disk theory

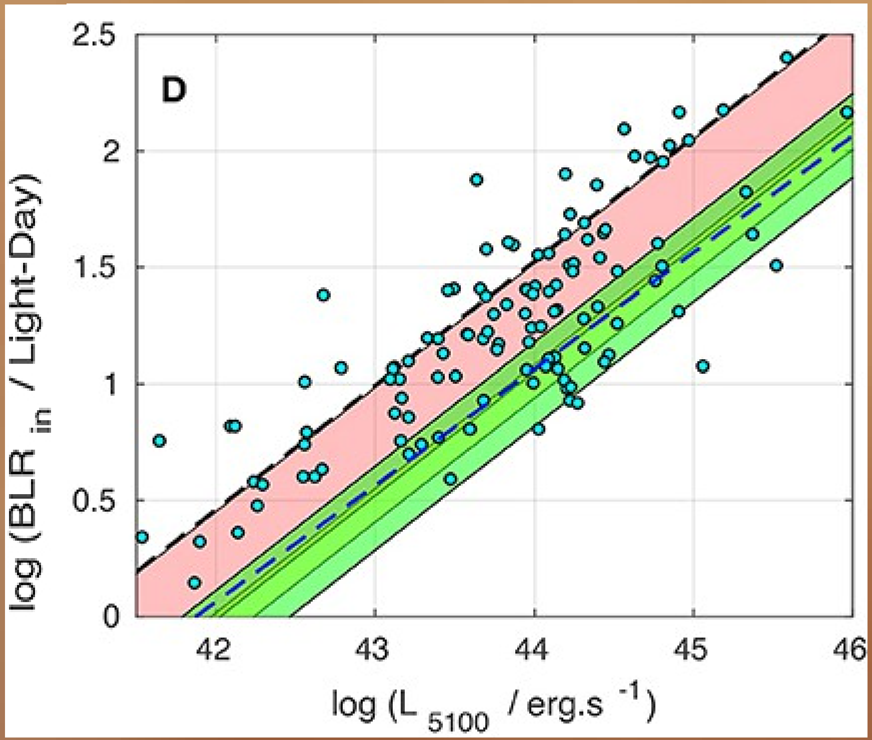
$$T_{eff} \propto (\frac{M\dot{M}}{R^3})^{1/4}$$

Czerny & Hryniewicz 2011

$$T_{\rm eff} = 995 \pm 74 \text{ K},$$

Disk temperature at location where Hbeta forms is always 1000 K, for every object!

Dust in FRADO setting the inner radius of the BLR

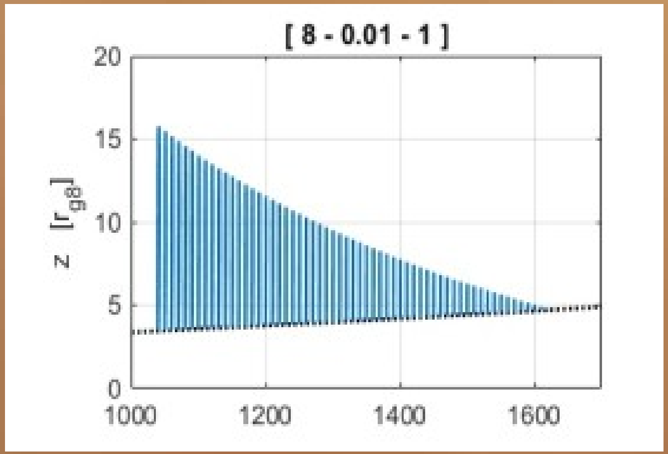


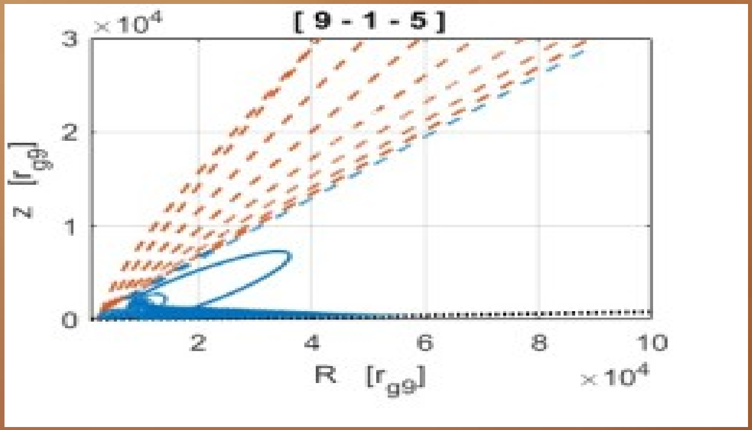
The onsert of the BLR in our model depends basically only on the dust sublimation temperature, and the monochromatic luminosity of the source. Some dispersion is introduced by the effect of the shielding which we now include in computations.

Naddaf et al. 2020

2.5-D picture of dusty region from FRADO

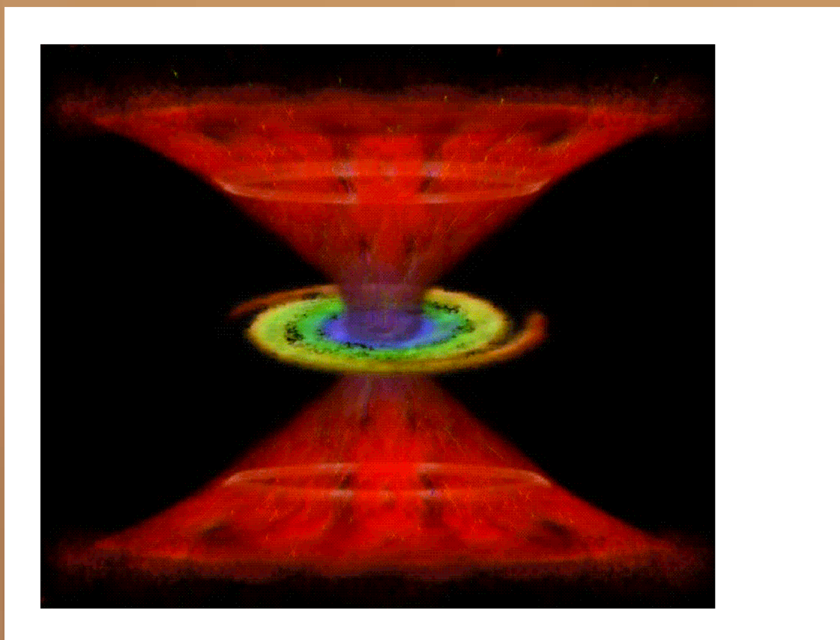
In Naddaf et al. (2022) we performed computations of the motion of dusty clouds under careful description of the radiative force, and including dust sublimation, for a broad range of parameters.

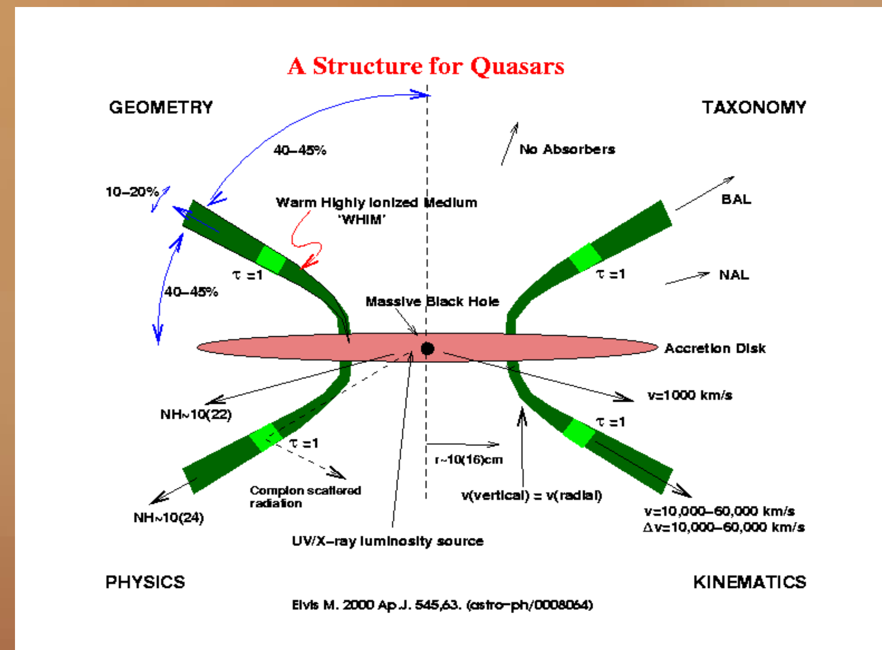




At lower accretion rates, lower masses and solar metallicity we indeed see a failed wind while for larges masses, larger accretion rates and supersolar metallicity we see actually also an outflow.

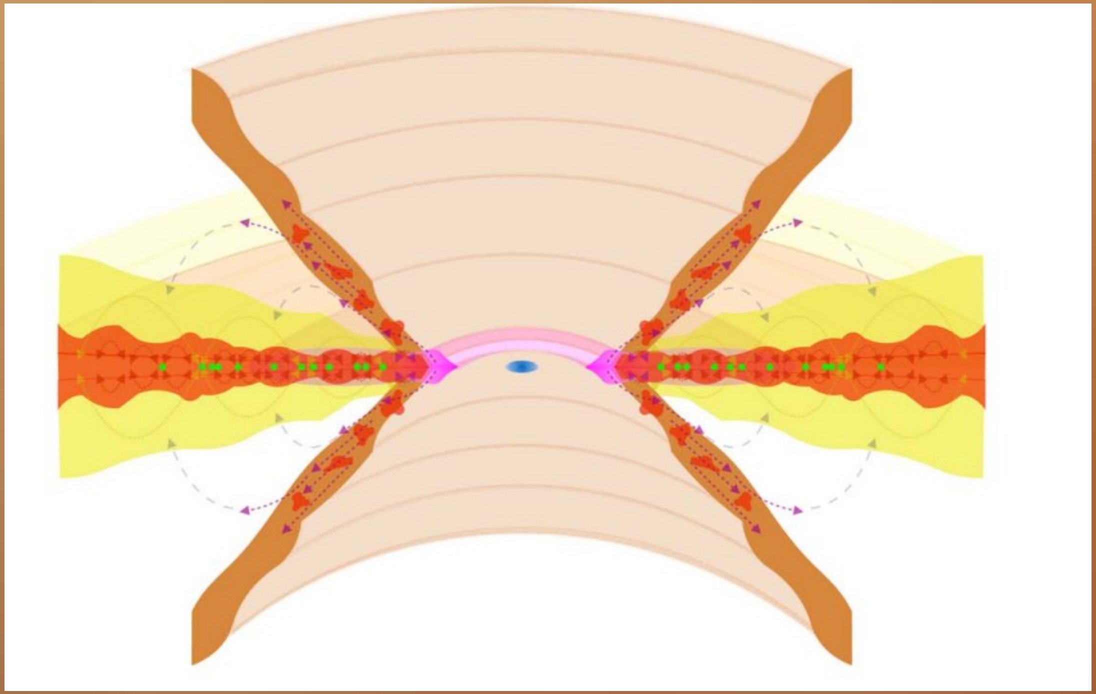
Dusty BLR vs. observationally based ideas on dust/outflow geometry





These pictures illustrate the scenario for quasars developed by Elvis (2000).

Dusty BLR vs. observationally based ideas on dust/outflow geometry



This picture comes from Hoenig (2019), it is based IR and sub-mm data, and offers a geometry for the dusty torus. Similar geometry to ours but outflow located at much larger radius.

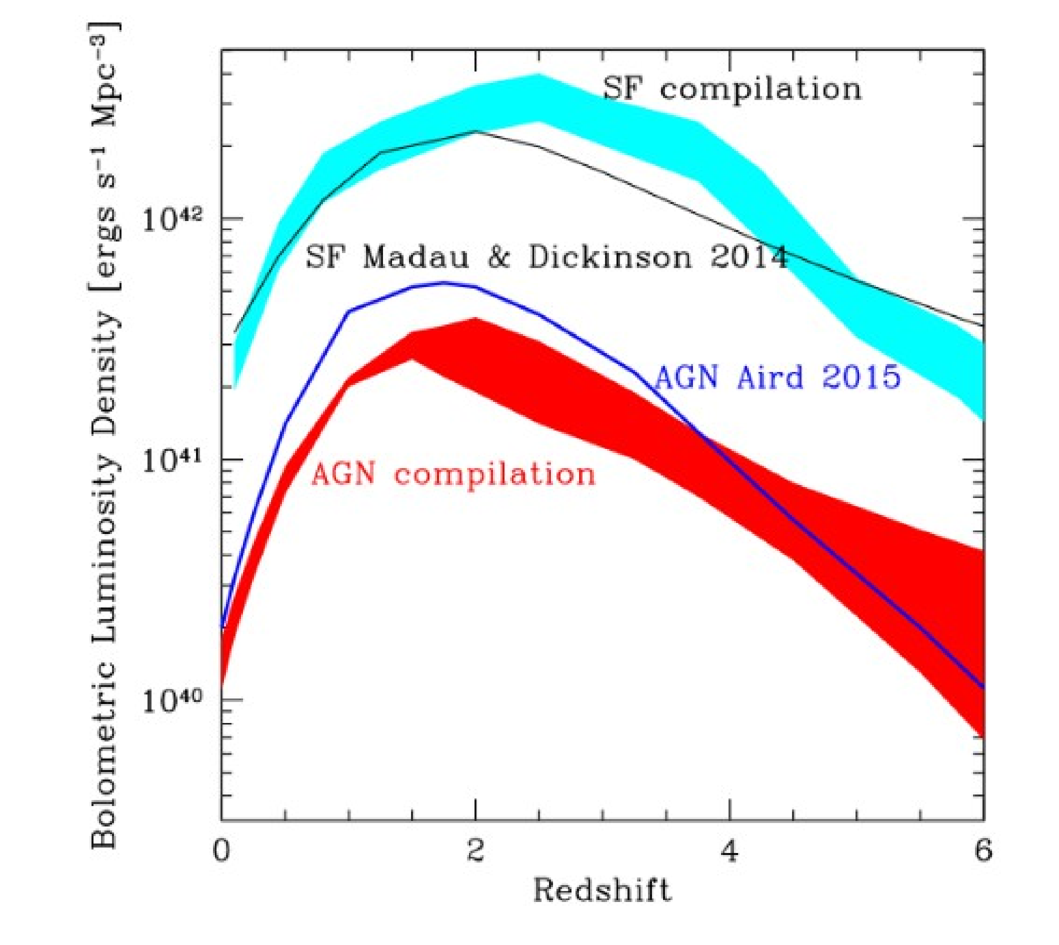
Dust origin in AGN

Dust in the torus and in the outer part of accretion disk can come:

- From outside
- Produced in situ

The answer is not clear. Always solar or supersolar metallicity of even high redshift quasars may seem inconsistent with low initial metallicity of the host but statistical studies clearly show strong star formation, at least in the inner part.

Quasar and star formation



Śniegowska, PhD Thesis, adapted from Fiore et al. (2017).

Both quasars and SFR peak roughly at z=2, actually SFR seems to proceede the quasar stage. So there may be enough metals even at the early stage for powering AGN with metal enriched material.

Dust origin in AGN

Dust in the torus and in the outer part of accretion disk can come:

- From outside
- Produced in situ

Option in situ is also interesting. Outer parts of the disk can be gravitationally unstable, leading to vigous star forming, with predominantly fast evolving massive stars (e.g. Jermyn et al. 2021, Cantiello et al. 2021).
However, the standard disk in the region of the effective temperature ~ 1500 K allows to form dust directly in the disk atmosphere, as in stars (Elvis et al. 2002).

Dust production in BLR of AGN:

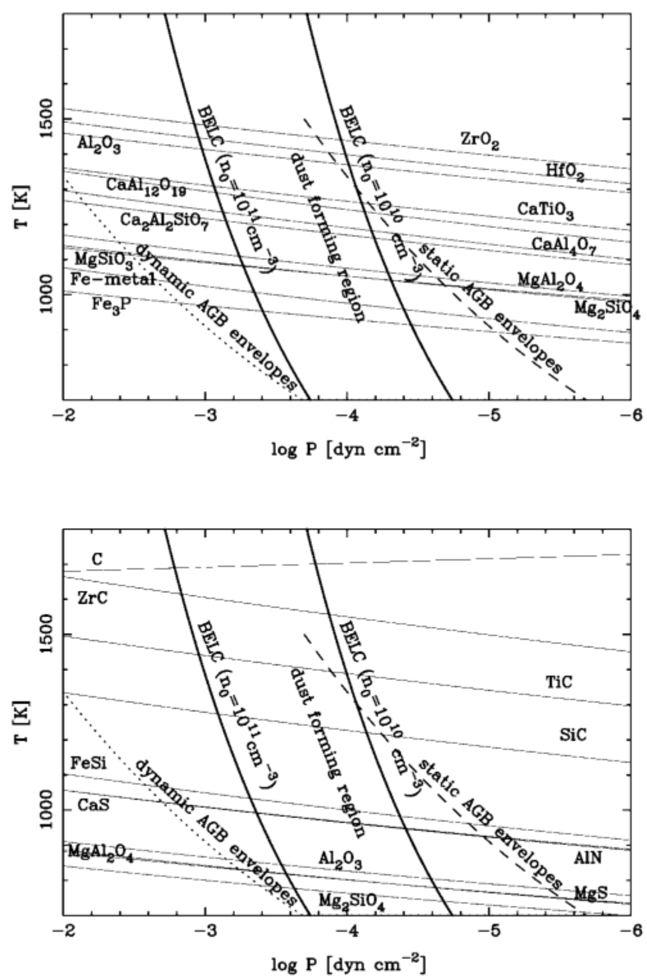


FIG. 1.—Phase transition lines for O-rich (*top panel*) and C-rich (*bottom panel*) dust precursor molecules (adapted from Lodders & Fegley 1999). The hatched area is the dust formation region in the circumstellar envelopes of evolved cool giant stars, delimited by the two cases of static and dynamic (pulsating) AGB atmospheres. The thick solid line is the path of BELCs as they expand, for two different values of their initial density.

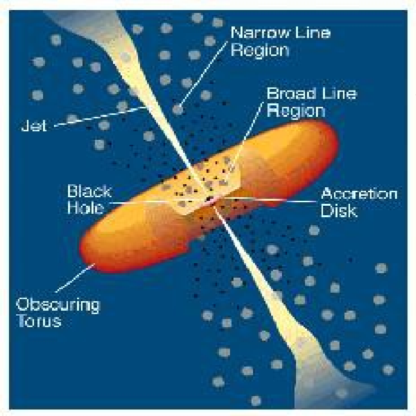
A picure from Elvis et al. (2002) showing the parameter range (temperature, density – here give through pressure) for prodution of O-rich and C-rich molecules in AGB stars.

Conditions in the AGN disk at the BLR distance are just the same, in Naddaf et al. papers we actually use a dust radiation pressure code developed for AGB stars.

One caveat: pulsating stars are more efficient dust producers. But AGN disk could be doing that also!

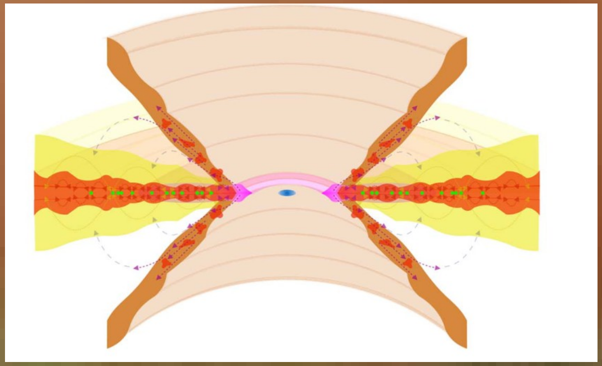
Summary:

- 'static' torus cannot offer a description consistent with the theory and with the data
- the BLR and the dusty outflow must be clumpy
- it is not clear if actually BLR ouflow can replace the 'torus', so we would have just one structure
- observational constraints (mapping vs. time delays) may not be probing the same region; time delays probes more the inner radius, maps are more flux-weigthed), but tests are clearly possible



OLD

NEW



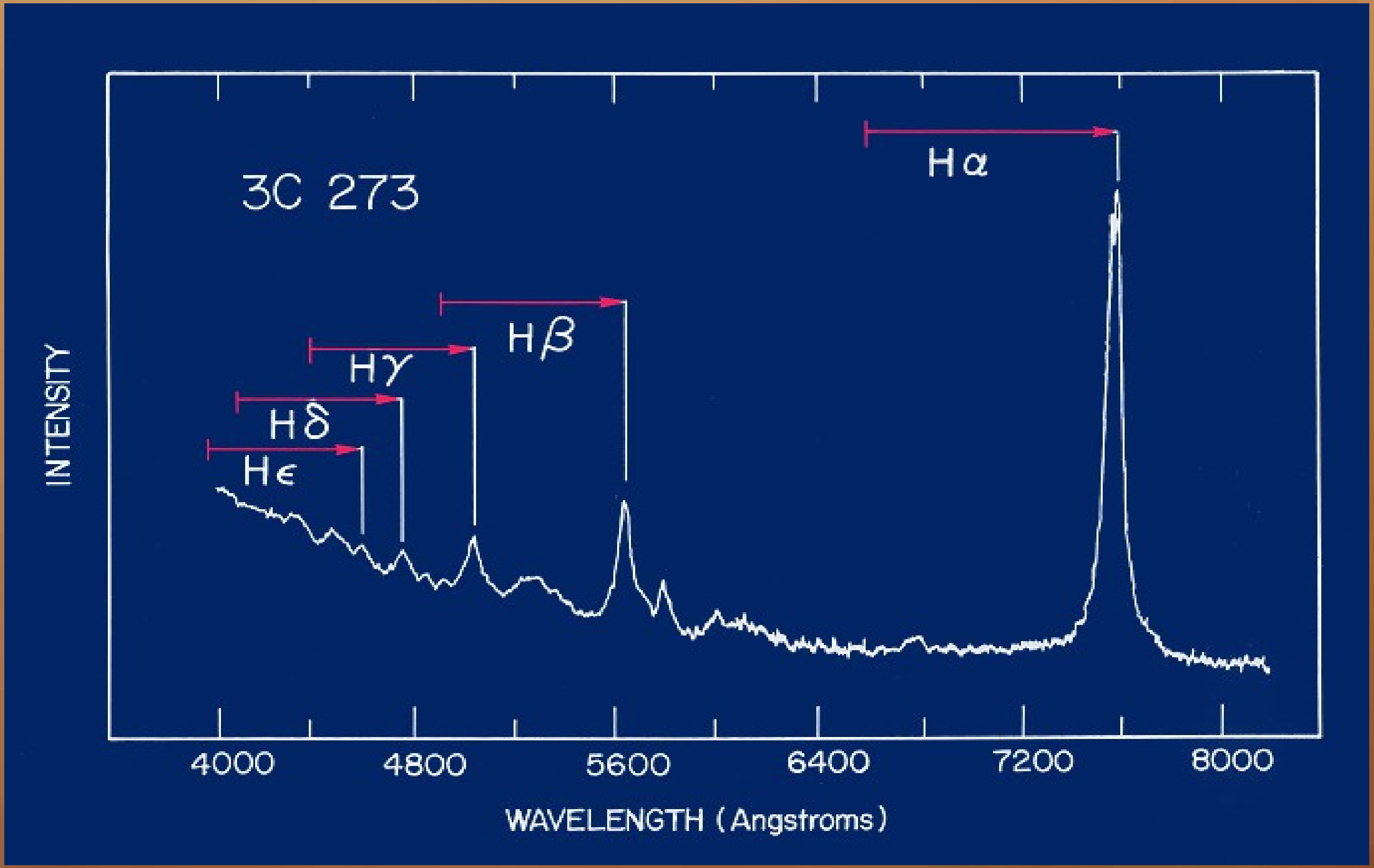
Thank you!

Outline:

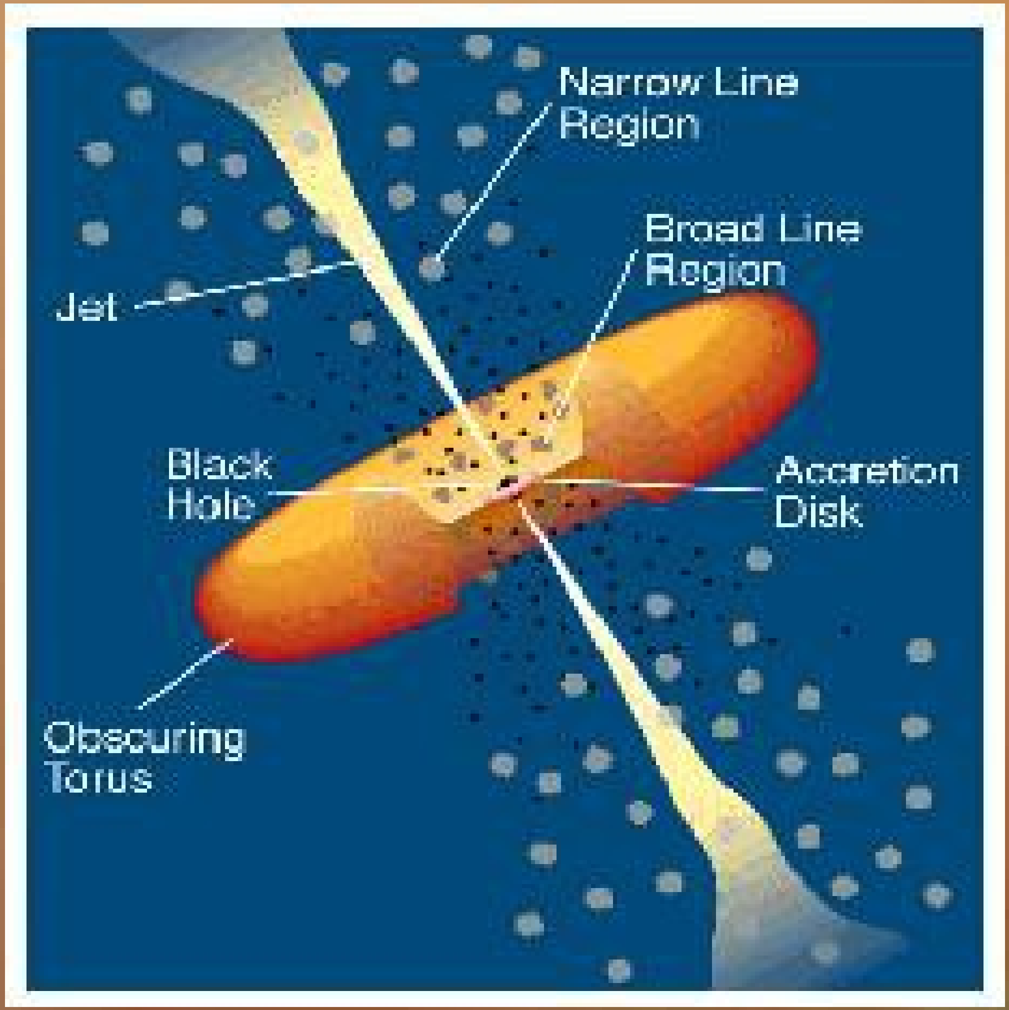
I. Well organized part

II. Loose ends

Standard view of BLR



Standard view of BLR



Current view of quasars/active galactic nuclei

Inner 100 pc of an active galaxy. Outer parts marginally resolved. Inner parts studied using spectroscopy.

from Urry & Padovani 1995

Summary of properties

- BLR clouds generally not seen in absorption (NAL cannot be due to BLR ?)
- cover about 30 % of the sky from the point of view of the central source (from luminosity)
- roughly in Keplerian motion
- occasionally with double-peak disk-like profiles
- there are separate LIL and HIL regions, with HIL blueshifted (e.g. CIV) and LIL not blue-shifted (Hbeta, MgII, FeII)
- Hbeta located 10 – 100 light days from the central region (from reverberation)
- modelling of LIL frequently face energy budget problem

Reverberation measurements

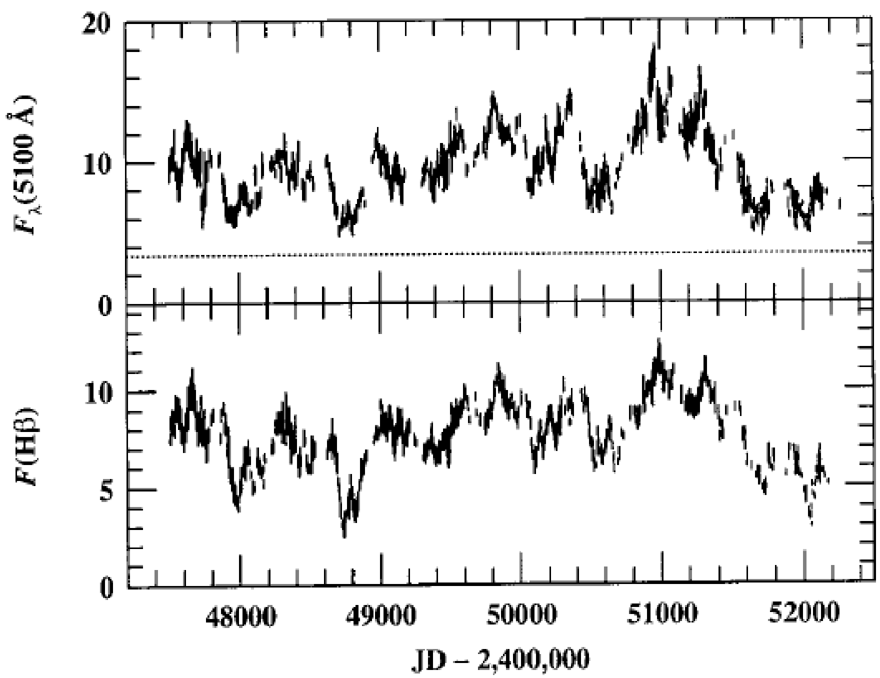


FIG. 1.—Optical continuum (*upper panel*) and Hβ (*lower panel*) light curves from 1989 December to 2001 December. The data are comprised of 1530 continuum measurements and 1248 emission-line measurements. The continuum fluxes are in units of 10^{-15} ergs s^{-1} cm^{-2} Å^{-1} and the line fluxes are in units of 10^{-13} ergs s^{-1} cm^{-2}. The horizontal dashed line is an estimate of the continuum contribution from the host galaxy (Romanishin et al. 1995) through the standard aperture used here (5″.0 × 7″.5). Flux measurements are in the observer's reference frame and are uncorrected for Galactic extinction.

Reverberation = time delay

Quasars and other active galaxies change their luminosity, and the luminosity of Hbeta line responds with a delay to the change of continuum.

Monitoring was aimed at explanation of the Broad Line Region geometry.

Reverberation results

Close to 40 sources were monitored, delays measured.
Motion of BLR clouds consist of Keplerian component and additional velocity component (neither outflow not inflow for Hbeta).

Statistical relation obtained from all these studies, with monochromatic flux from HST, starlight-subtracted:

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

Bentz et al. 2009

BLR radial size

Assumptions: T_eff = 1000 K gives the inner radius
T_irrad_spher = 1000 K gives the outer radius
(equal to the inner radius of the dusty)

$$\frac{r_{1000\,\mathrm{K}}}{R_{\mathrm{dust}}} = 0.03 \frac{M_8^{1/6}}{\dot{m}^{1/6}\eta_{0.1}^{1/2}},$$

Typically: Rdust/Rin = 30, but approaches 1 when the accretion rate drops AND the accretion efficiency drops as well (inner ADAF). Explanation of double profile of Hbeta line in a number of radio galaxies?

Other ideas of BLR location

(i) Transition from radiation pressure to gas pressure dominated disk (Nicastro 2000)

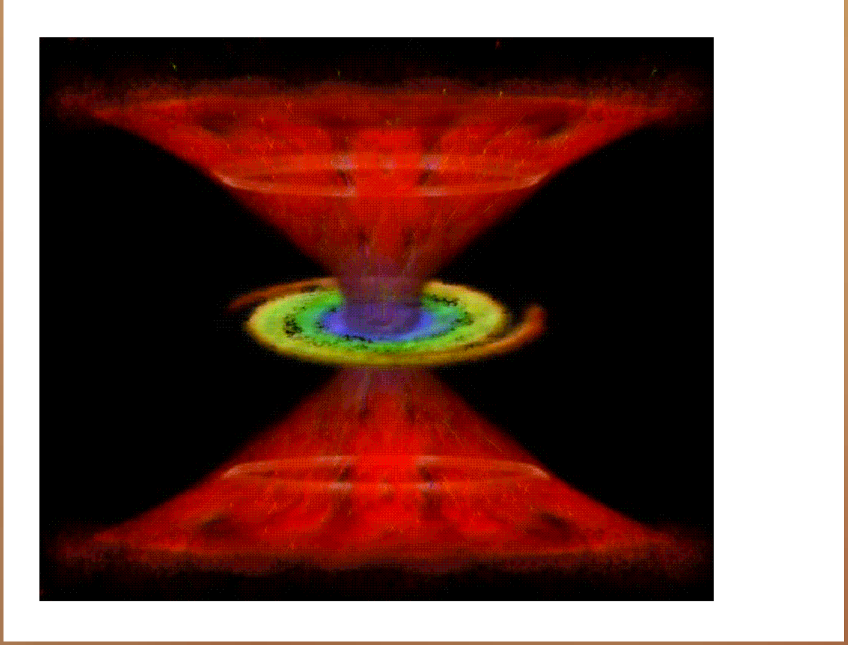
$$R_{\rm BLR}^{\rm radpres} \propto L_{5100}^{23/28} \dot{m}^{3/14},$$

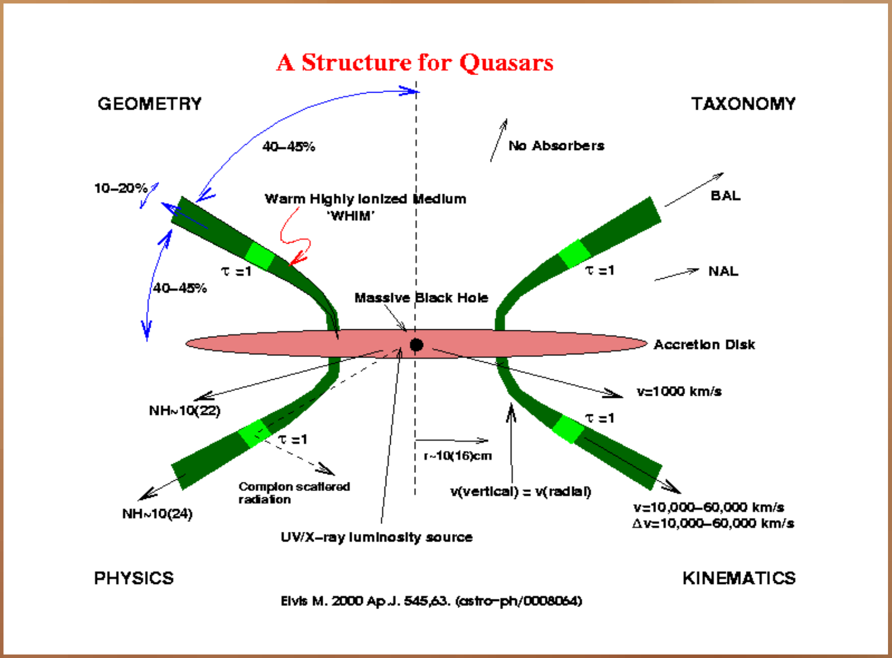
(ii) Onset of self-gravity (Collin & Hure 2001)

$$R_{\rm BLR}^{\rm sg} \propto L_{5100}^{1/36} \dot{m}^{-83/54} \quad \text{(region b)},$$
$$R_{\rm BLR}^{\rm sg} \propto L_{5100}^{-7/60} \dot{m}^{-37/90} \quad \text{(region c)},$$

They predict different scaling of the BLR

Fitting into global scheme – observational aspects





Elvis et al. 2000

Fitting into global scheme – theoretical aspects

Outflows were postulated before by many authors:

(i) Magnetically driven winds
(ii) Radiation driven winds

- radiation pressure wind (inner part)
- line driven wind (intermediate part)
- dust driven wind (outer part)
- **NEW**with failed wind region of LIL BLR

Theory **may** ? match the qualitative picture of Elvis 2000

Likely scheme:

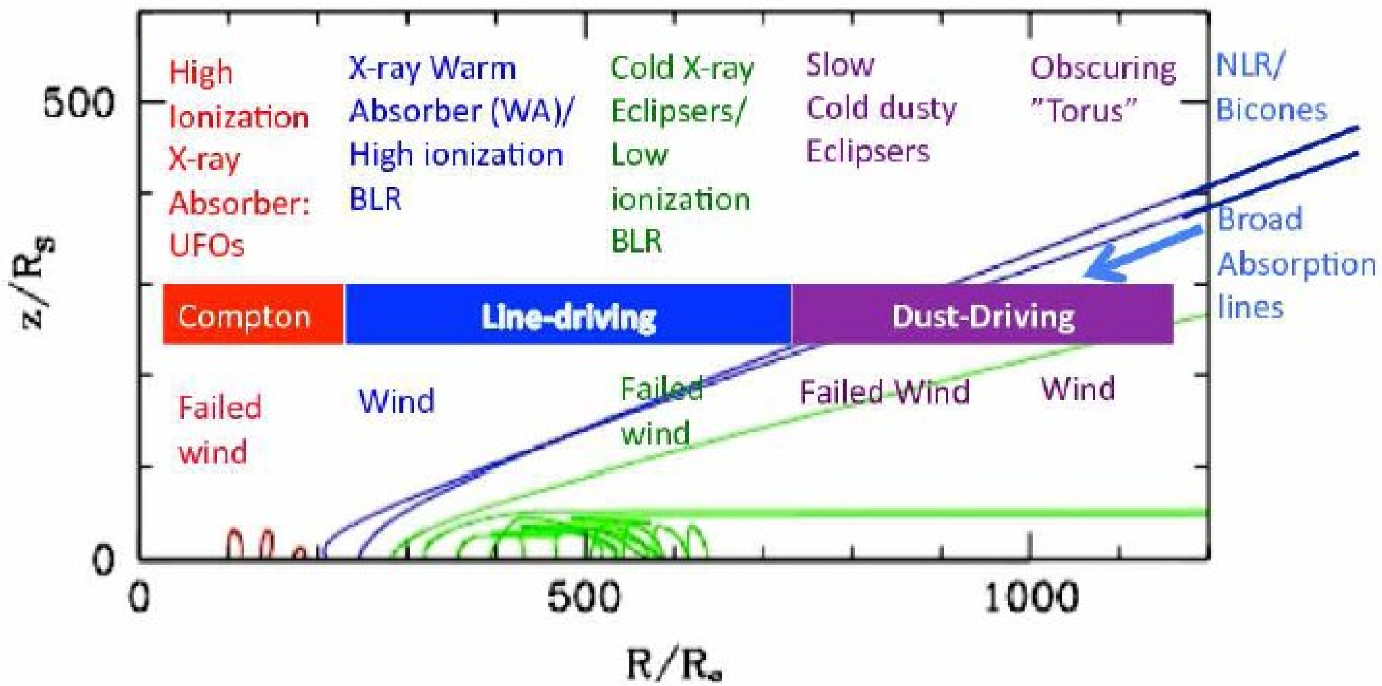
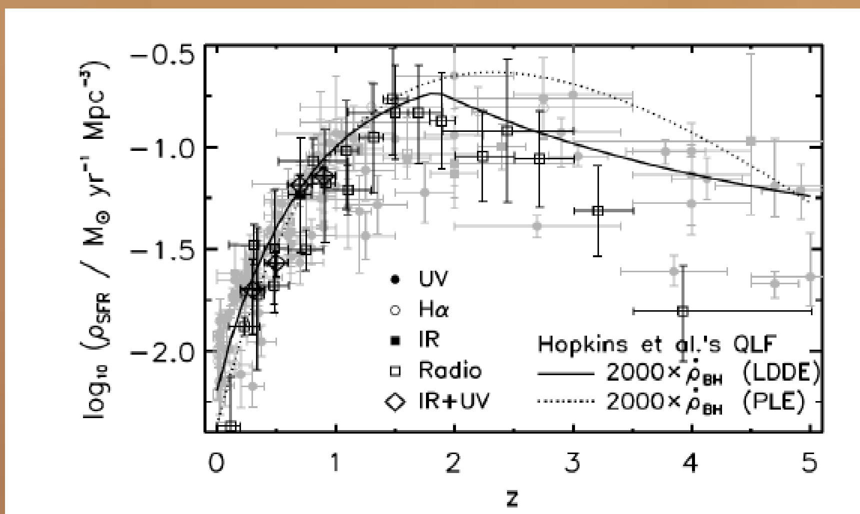


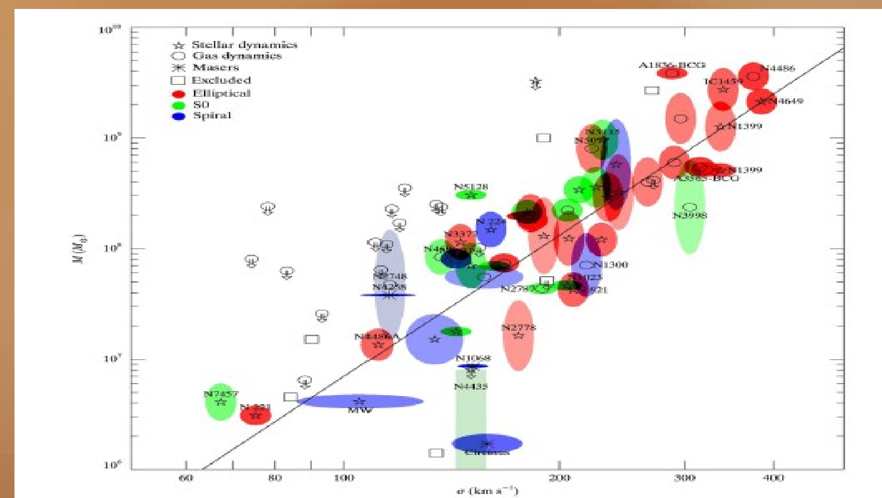
Figure 1: Flowlines of gas from a quasar accretion disk generated by QWIND (Elvis 2012). Compton- and Line-driving regions are already included in QWIND. The dust-driving region will be added by this proposal. Note the *linear* axes in units of R_S; angles are shown correctly.

Elvis 2012

Global importance of understanding of BLR nature and of AGN outflows



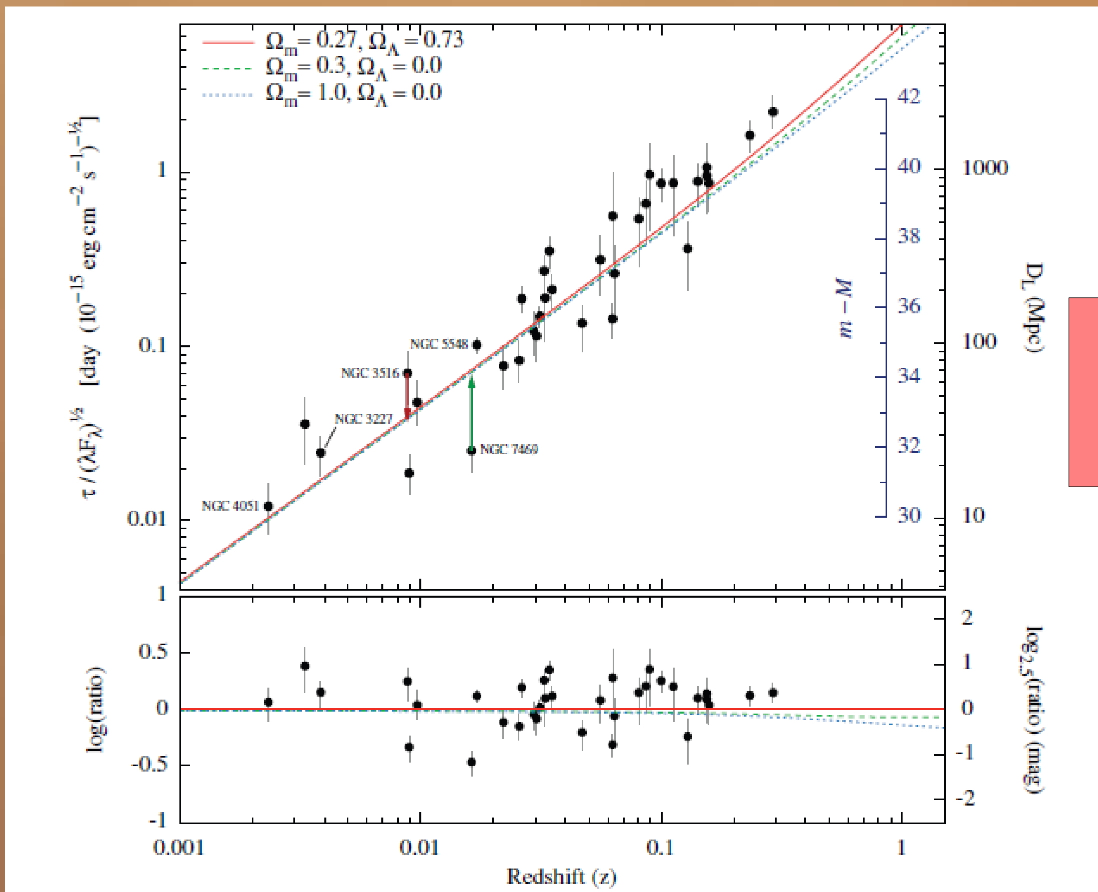
Zheng et al. 2009



Gultekin 2009

The coupling likely happens through mechanical **feedback** – outflow in radio-loud and radio-quiet AGN. Understanding of wind mechanisms opens a possibility to model the outflow from an accretion disk at all radii, and later to estimate its feedback on the whole galaxy.

Global importance of understanding of BLR nature and of AGN outflows



Watson et al. 2011

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

Since even the high redshift quasars have the same metallicity and dust properties, there should not be a strong evolutionary effect involved

II. Loose ends

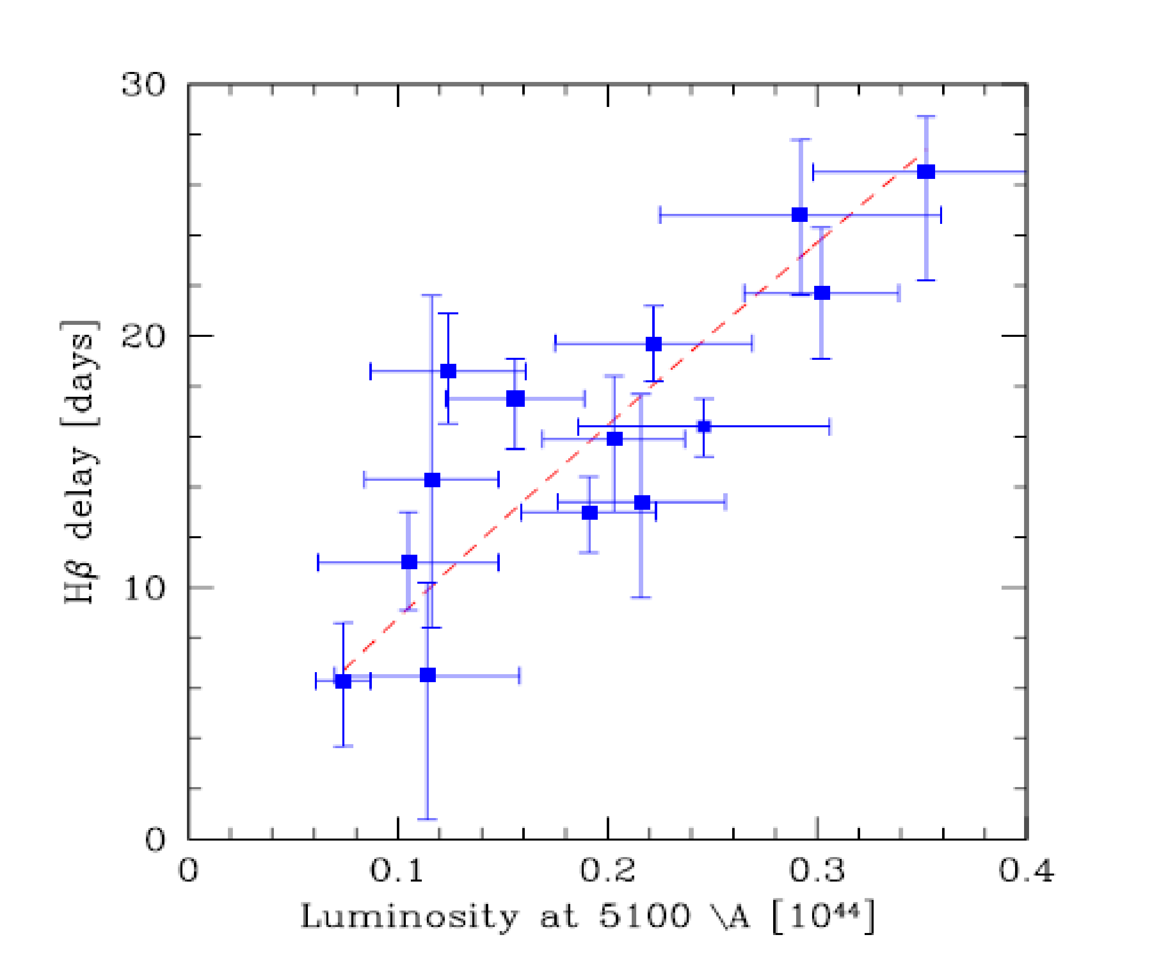
First complications

- in theory, the expression for a monochromatic flux contains **cos i** which must result in additional dispersion in BLR location between the sources

In our derivation of disk effective temperature we assumed 39.2 deg for all sources after Lawrence & Elvis 2010)

- in theory, the location of T=1000 K radius (i.e. BLR) in stationary disk cannot depend on time but the measurement is possible due to non-stationarity

NGC 5548



14 yrs of monitoring (Peterson et al), fluxes from Bents et al.

Best fit slope in log space
0.90 +/- 0.22

Not consistent with 0.5 as in statistical sample

Disk irradiation

The timescales within the outer accretion disks are thousands of years (thermal timescale) and millions of years (viscous timescale) but the reprocessing timescale is of order of a day.

However, I do not see how to reproduce **linear** reaction of BLR to the change of the irradiation flux.

Dusty wind computation requirements

Radiation pressure acting on dust on dust particle

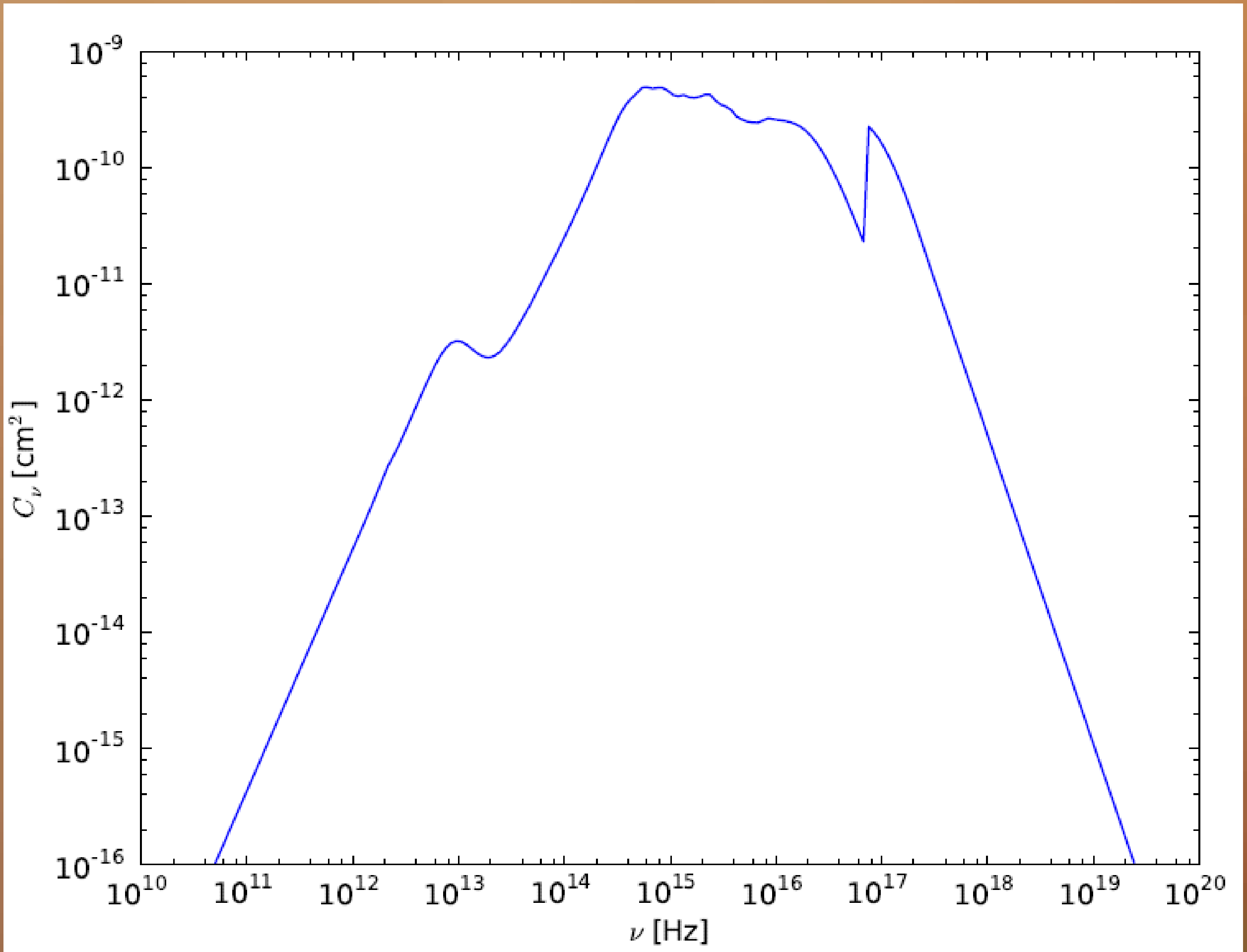
Global radiation field

Dust formation

Dust destruction

Wind dynamics (density and velocity field)

Radiation pressure



Example of dust crossection for an amorphous carbon grain, size 0.1 μm

Dust formation and destruction

Basic things are simple:

Dust particles (and graphen!) are hold together by intermolecular forces, and the binding energy is of order of 0.1 eV

This is why dust particles do not survive at higher temperatures than 1000 K.

Basic cross-section in dust formation σ is 10^{-15} cm^2, corresponding to a π D^2, where D is distance between atoms in sand or ice.

Dust formation

The mean free path and the timescale from a simple consideration

$\lambda = 1/(n\sigma)\ ;\ \ \tau = \lambda/v_s$

High (but not too high) temperature and high density needed for efficient process. For T=1000 K and n = 10^{10} the actual numbers are: λ = 1 km, τ = 1 s. Of course we need many collisions to form a dust particle consisting of 10^{10} molecules but the process speeds up for larger grains.

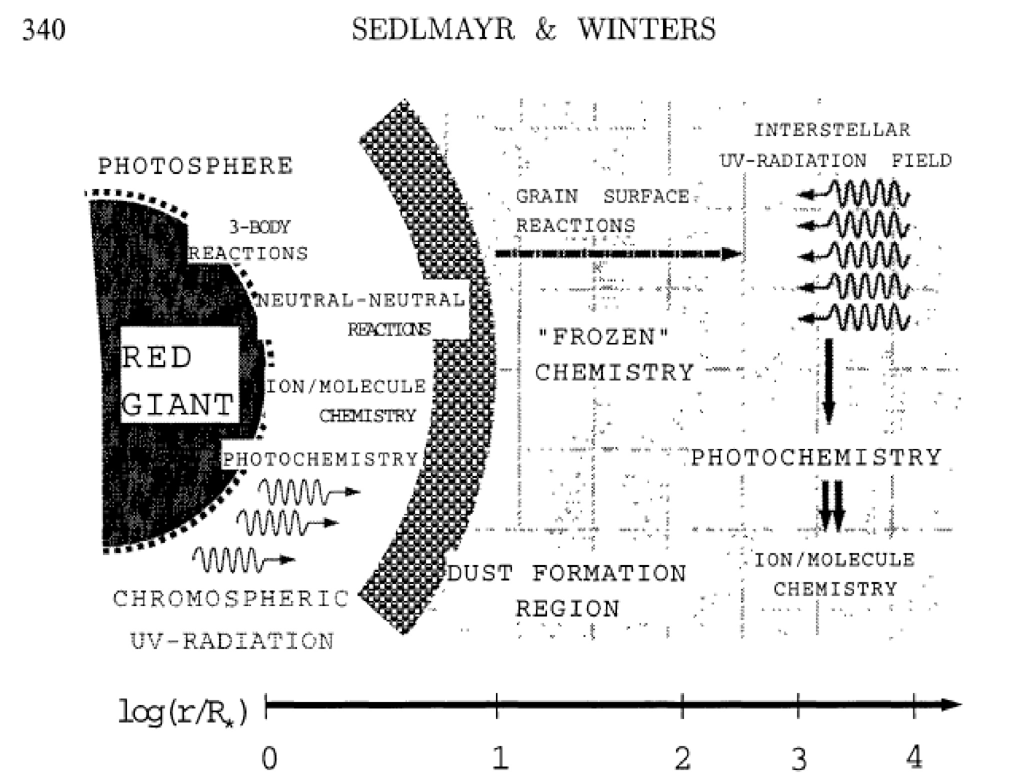


Figure 2. Chemical processes in different regions of the circumstellar shells around red giants (from Patzer 1998).

AGB vs. AGN

Similarities: effective temperature, density in the atmosphere
Differencies: gravity increasing/decreasing with hight
Temperature: increasing/decreasing due to extrenal irradiation in AGN

Local process of dust formation should be the same, trends with hight might be different

Important points in understanding of the stellar dust formation:
- two-step process (coagulation and grain rise)
- many phenomenological assumptions and complex chemisty needed to determine the grain composition

Dust destruction

Strong UV/X-ray irradiation brings the dust back to gasous phase. The dust particle size is decreasing

$$\dot{a} = \frac{-\int F_{nu}\sigma_{nu}d\nu + \sigma_B T^4_{dust}}{4\pi a^2 c_p (T_{gas} - T_{dust})}$$

And the timescale is short if the particle is not shielded from the strong irradiation (about 1 s in the innermost part of BLR).

Wind dynamics

Fully self-consistent computations of wind launching are difficult if not impossible. Wind becomes transonic very fast. High above the disk wind changes into a failed wind due to irradiation, and cannot be stationary.

Far into the dusty torus, the wind outflow cannot be launched by the disk radiation pressure acting on dust. Force balance between gravity and radiation flux acting on dust gives

$$z_{max} = \frac{3\dot{M}\sigma_{dust}}{8\pi c m_{dust}}$$

Conclusions

BLR is quite likely related to the formation of the dust in the accretion disk atmosphere

This simple mechanism has important implications for using AGN as cosmological probes

However, specific computing of the accretion disk outflows is rather complicated and should be done step by step