AGN Reverberation Mapping: the pc Scale Garden of Massive Black Holes
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Dust Reverberation of AGNs and Its Cosmological application

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Outline

- AGN distance based on the dust reverberation (torus RM)
  - Dust sublimation
  - An old dust lag-luminosity relation
- Recent results from the MAGNUM project
  - A torus RM survey for nearby 17 Seyfert galaxies
  - The dust lag-luminosity relation
  - The Hubble diagram based on the torus-RM distances
- Future progress on the torus-RM cosmology
  - Uncertainties in the torus-RM distance and possible solutions
  - Extension to higher redshifts

Dust in the innermost region of the torus

- The sublimation of the dust grains
  - The dust is directly illuminated by the radiation from the accretion disk.
  - As the dust is closer to the accretion disk, its temperature becomes higher.
  - The dust sublimates when it locates too close to the accretion disk. $T_{\mathrm{sub}} \approx 1800$ K for graphite grain, 1500K for silicate grain

(Salpeter 77, Huffman 77)

- Inner radius of the dust torus (r_{in})
  - The dust grain is heated up to the sublimation temperature (T_{sub}).
  - The equilibrium of the incident and emitted radiation energy is:

$$\boxed{\pi a^2 \int Q_\nu \frac{L_\nu^{\mathrm{AD}}}{4\pi r_{\mathrm{in}}^2} \mathrm{d}\nu = 4\pi a^2 \int Q_\nu \pi B_\nu(T_{\mathrm{sub}}) \mathrm{d}\nu}$$

where *a* : dust grain size, *Q* : absorption coefficient of dust,
B: Planck function

(see Barvainis 87)

Distance based on the torus RM

- The radius – luminosity relation for the $r_{\rm in}$ of the dust torus
  - Theoretical expectation :

$$\boxed{r_{\rm in} = A(L_\nu^{\rm AD})^{0.5}}$$

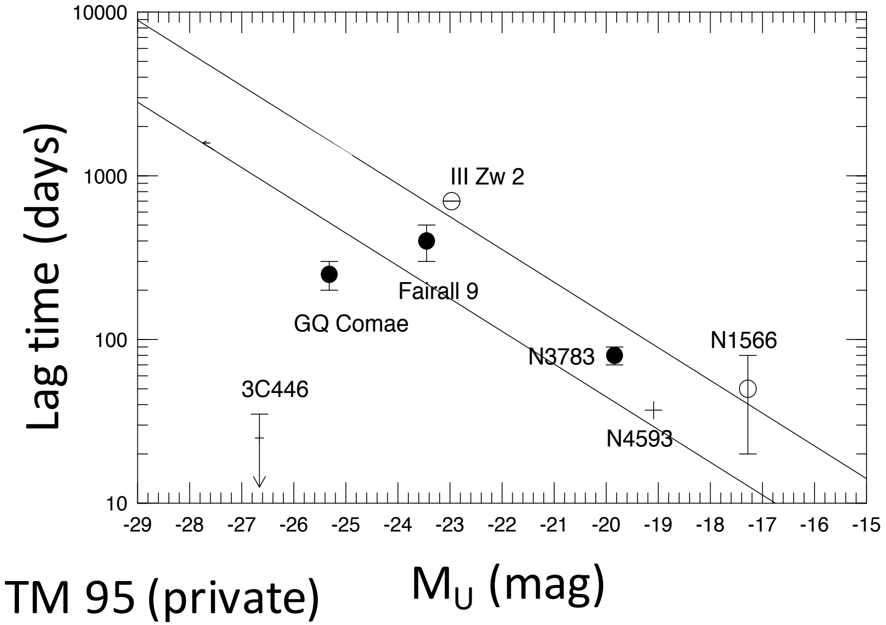
  - The proportional constant A can be determined by the dust sublimation model with the parameters of Q_ν, L_ν, and $T_{\rm sub}$.
    - L_ν : little systematic variation in AGN spectra of different luminosities
    - Q_ν, $T_{\rm sub}$: determined by the properties of dust grain, which will be common in AGNs
- The luminosity distance

$\boxed{c\Delta t}$ determined by torus RM

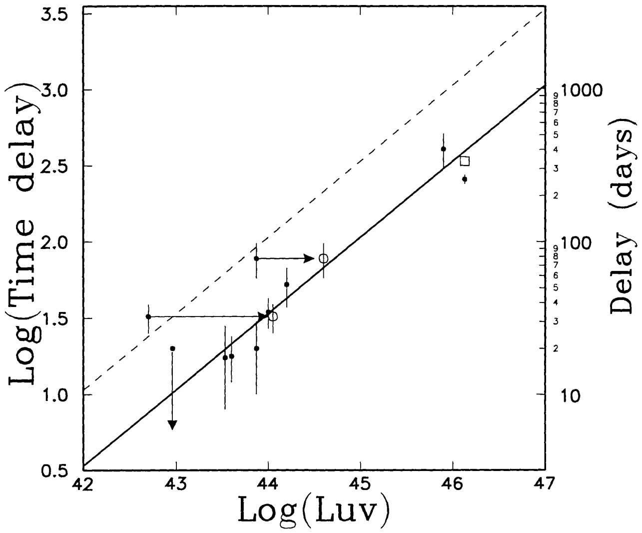
$$d_{\rm L} = \left(\frac{L^{\rm AD}}{4\pi f^{\rm AD}}\right)^{0.5} \propto \boxed{r_{\rm in}} \times (f^{\rm AD})^{-0.5}$$

Torus RM (-1990s)

- The dust lag-luminosity relation for the torus-RM distance
  - There were limited number of the torus RM observations.
    NGC 4151 (Penston+ 74); III Zw 2 (Lebofsky & Rieke 80);
    Fairall 9 (Clavel, Wamsteker, & Glass 89); NGC 3783 (Glass 92);
    GQ Comae (Sitko+ 93); NGC 4151 (Oknyanskij 93, 99); Mrk 744 (Nelson 96)
  - The correlation was suggested as theoretically expected.
    Although the number and quality of the dust lag are somewhat limited.



TM 95 (private)



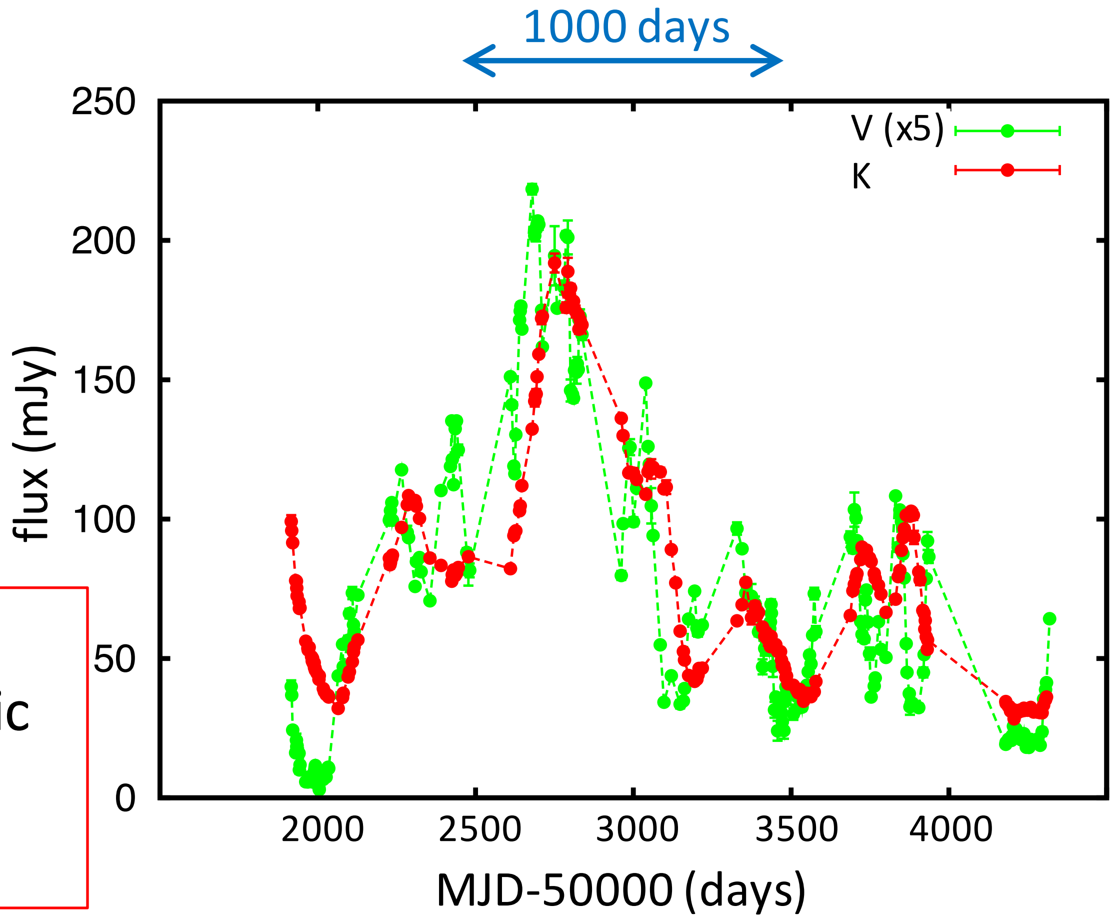
Oknyanskij 99; Oknyanskij & Horne 01

New torus RM project

- The MAGNUM project (Yoshii+ 1995-)
  - A large systematic torus RM survey program was conducted (Yoshii 02; Yoshii, Kobayashi, & TM 03), which aims to
    - Establish the radius-luminosity relation for the dust torus
    - Measure the luminosity distance of AGNs to constrain the cosmological parameters
  - A robotic 2-m telescope dedicated for the optical and near-infrared monitoring observation was built at the Haleakala observatory (Kobayashi, TM+98).
    - The observation was carried out during 2000-2008.

Light curves

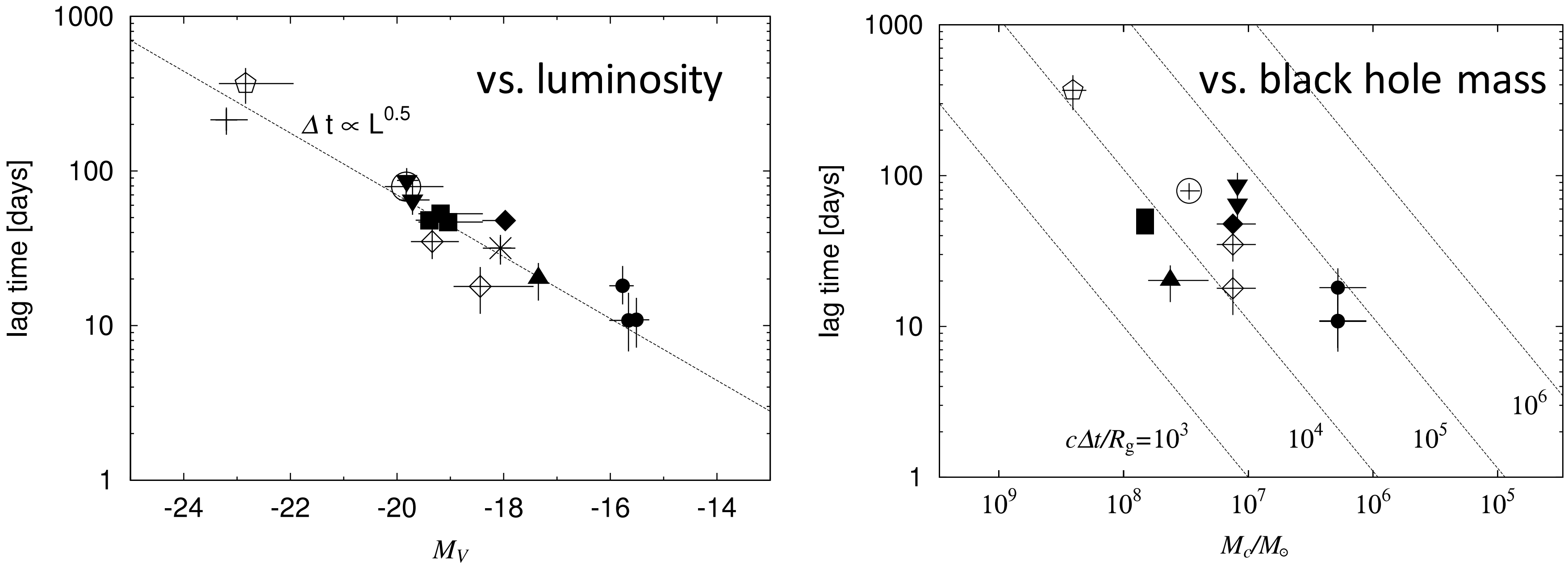
- The MAGNUM project (Yoshii+ 1995-)
  - The V- and K-band light curves (NGC 4151 as an example)



Both the sample size, and
the cadence and the photometric
accuracy of the light curve
were much improved.

The radius-luminosity relation for the dust torus

- Initial result from the MAGNUM project
  - The dust lag is well correlated with the luminosity as expected, while it is only weakly correlated with the black hole mass (TM+04; Suganuma, TM+ 06).

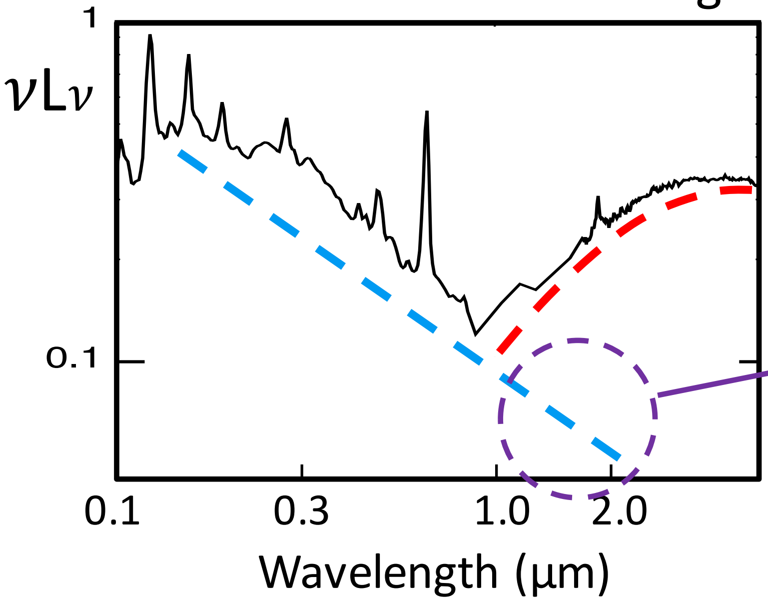


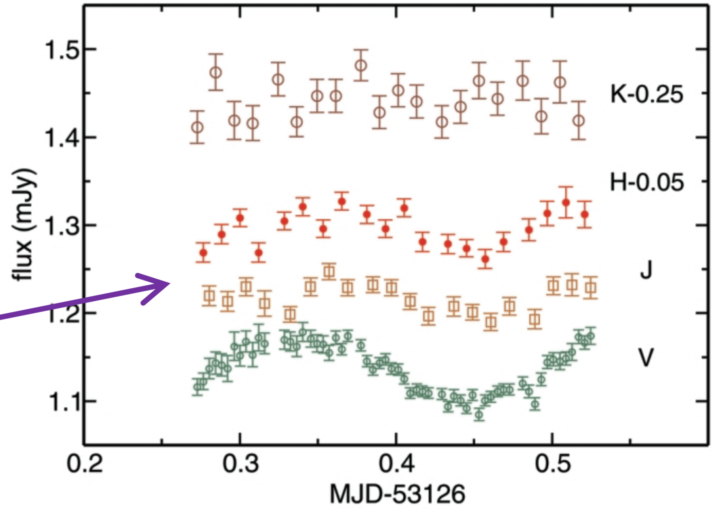
Suganuma, TM+ 06

The filled symbols represent the data from the MAGNUM, the others from the literature.

The radius-luminosity relation for the dust torus

- The torus RM survey for 17 nearby Seyferts (Koshida, TM+ 14)
  - Dust lag :
    The data of whole sample were analyzed systematically.
    - The accretion disk component in the K-band flux was subtracted prior to the lag analysis to estimate the dust lag correctly.
      - It was estimated by extrapolating the simultaneously obtained V-band flux assuming the power-law continuum SED.





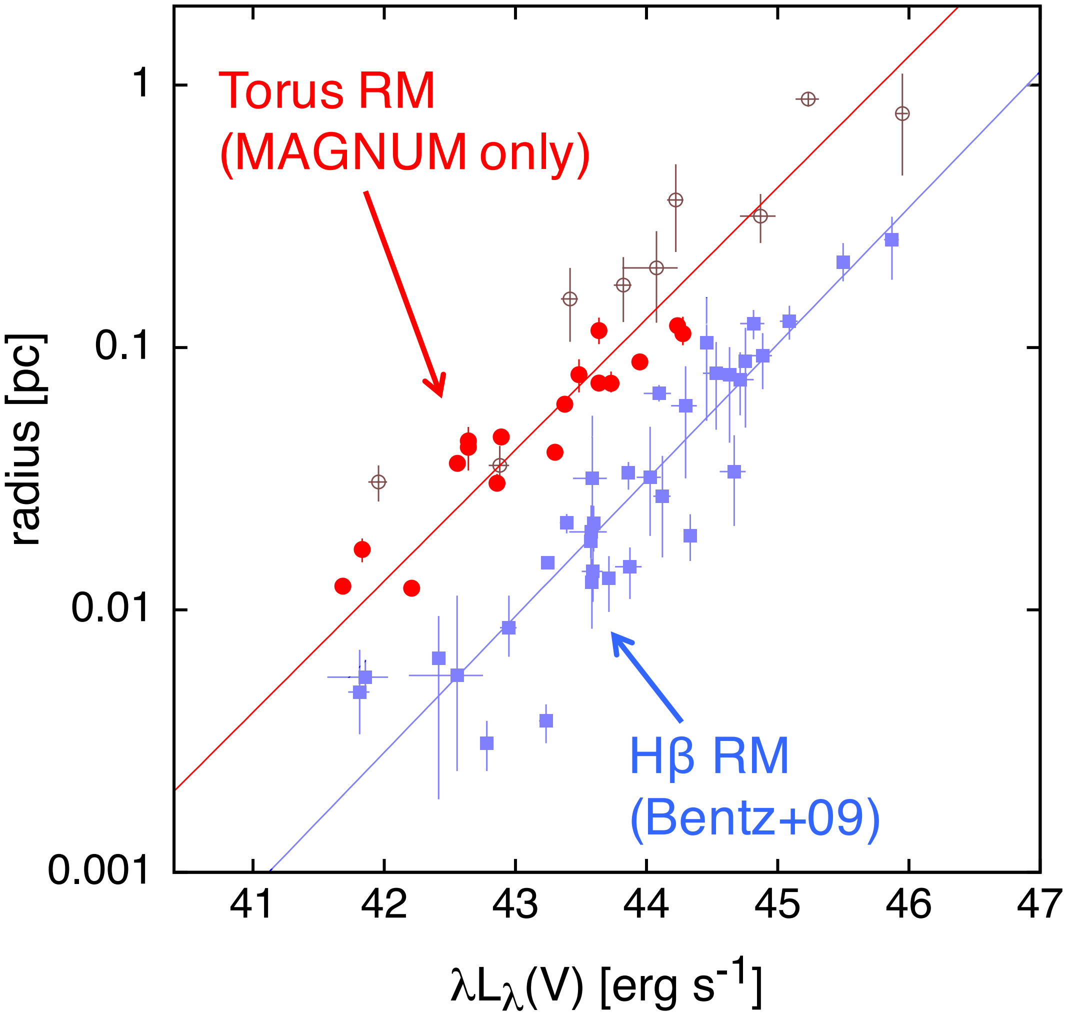
Intraday variation of NGC 4395 (TM+ 06)

The radius-luminosity relation for the dust torus

- The torus RM survey for 17 nearby Seyferts (Koshida, TM+ 14)
  - Dust lag :
    The data of whole sample were analyzed systematically
    - The accretion disk component in the K-band flux was subtracted prior to the lag analysis.
    - A conventional CCF+CCCD method and Javelin (Zu+ 11) were used to obtain the dust lag: They showed consistent results.
    - When different good features in the light curves of a target were found in different epochs, dust lag was obtained respectively.
      → 49 dust lags were obtained in total:
      This was the largest homogeneous data collection of the torus RM.
  - Luminosity :
    The host-galaxy component in the V-band flux was carefully estimated with high angular resolution images obtained by the HST, and subtracted (Sakata, TM+ 10; see Bentz+ 09,13).

The radius-luminosity relation for the dust torus

- The torus RM survey for 17 nearby Seyferts (Koshida, TM+ 14)



– The observed dust lag clearly correlates with the optical luminosity as expected :

$$\boxed{r_{\mathrm{in}} \propto (L_{\mathrm{opt}})^{0.5}}$$

– The dust lag place an upper boundary of the broad emission-line lags (presented by Suganuma, TM+06).

Torus RM for cosmology

- Distance based on the torus RM (Yoshii, TM+ 14)
  - The dust sublimation model at the innermost dust torus was built.
    - L_ν : a power-law SED with $\alpha_\nu = -0.5 \pm 0.2$ (e.g., Vanden Berk+01)
    - Q_ν : the absorption coefficient of graphite (Draine & Lee 84,93) with the grain size distribution intermediate between the standard MRN and that for radio-quiet quasars by Gaskell+ 04.
    - $T_{\rm sub}$: $T_{\rm d}$ = 1700±50 K from the near-infrared SED of the time-variable flux component (Tomita 05; Tomita, TM+06)
  - The luminosity distances d_L is expressed using the dust lag as follows :

$$d_{\rm L} = (\Delta t/{\rm days}) \times 10^{0.2(m_V - A_V - k_V - 14.4)} \ \ [{\rm Mpc}]$$

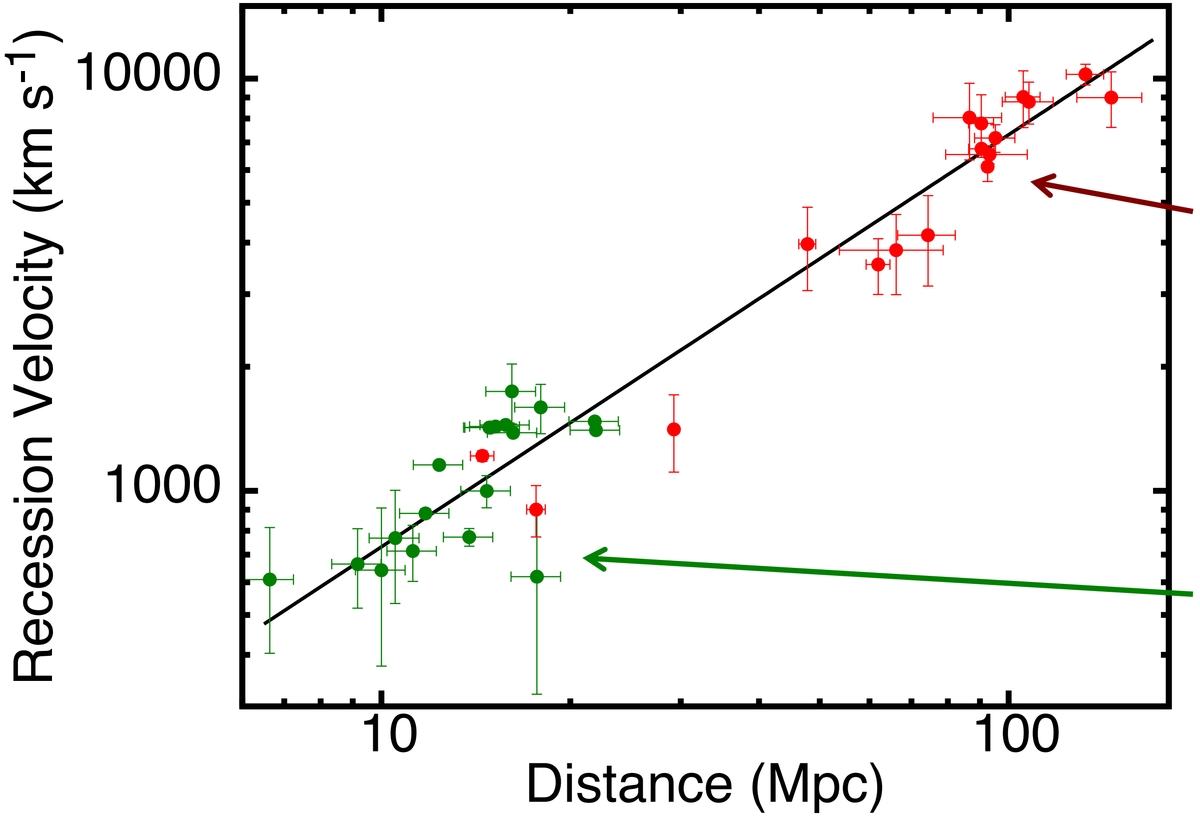
or equivalently,

$$\boxed{d_{\rm L} = 2.5 \times \left(\frac{\Delta t}{\rm days}\right)\left(\frac{f_V}{\rm mJy}\right)^{-0.5} \quad [{\rm Mpc}]}$$

(when A_V=0, k_V=0)

Torus RM for cosmology

- The Hubble diagram (Yoshii, TM+ 14)
  - The luminosity distances of 17 Seyfert galaxies at z<0.04 were estimated based on the dust sublimation model using the dust lag (Koshida+14) to make a Hubble diagram.



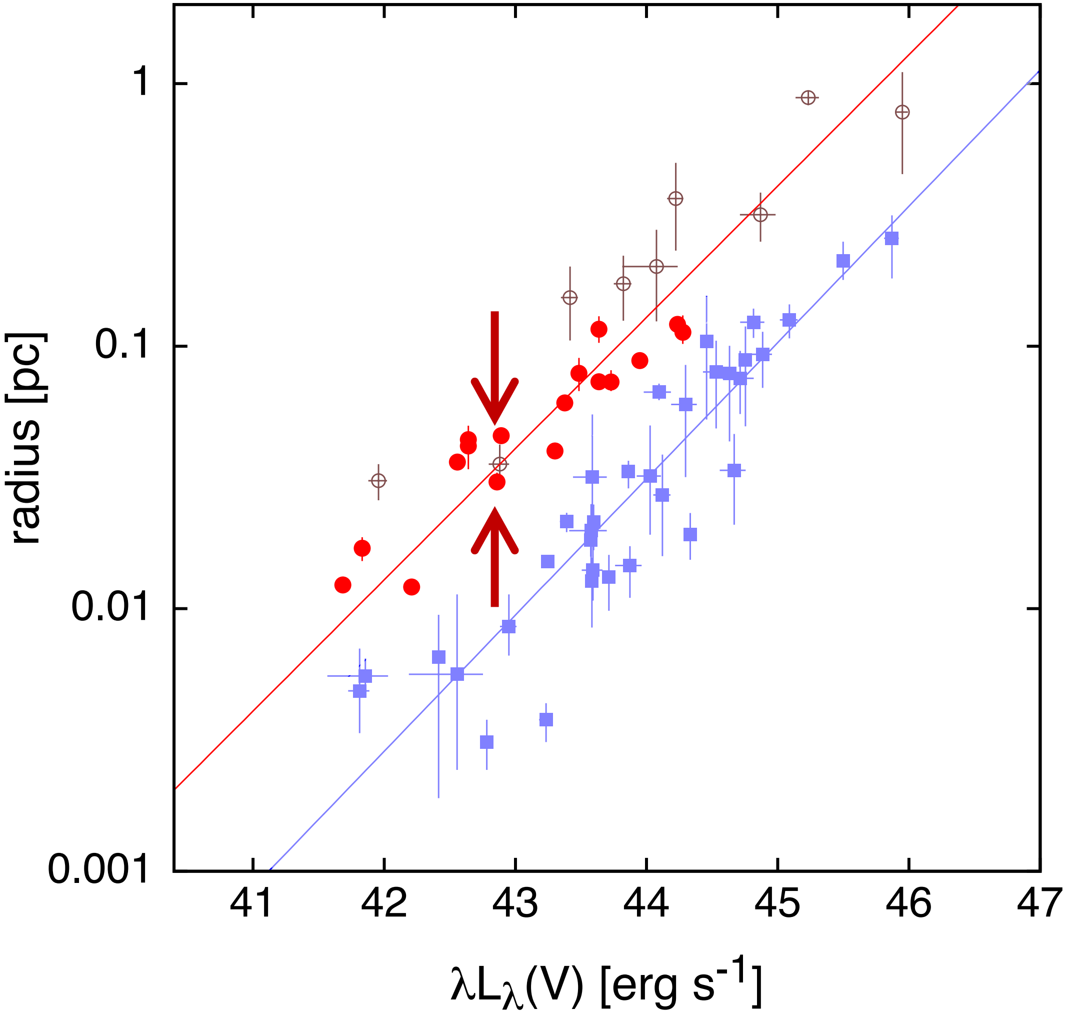
The best-fit Hubble constant based on the torus-RM distance:

$H_0 = 73 \pm 3$ (random) km/s/Mpc

Consistent with the Cepheid distance scale (Freeman+ 01)

Uncertainties in the torus RM distance

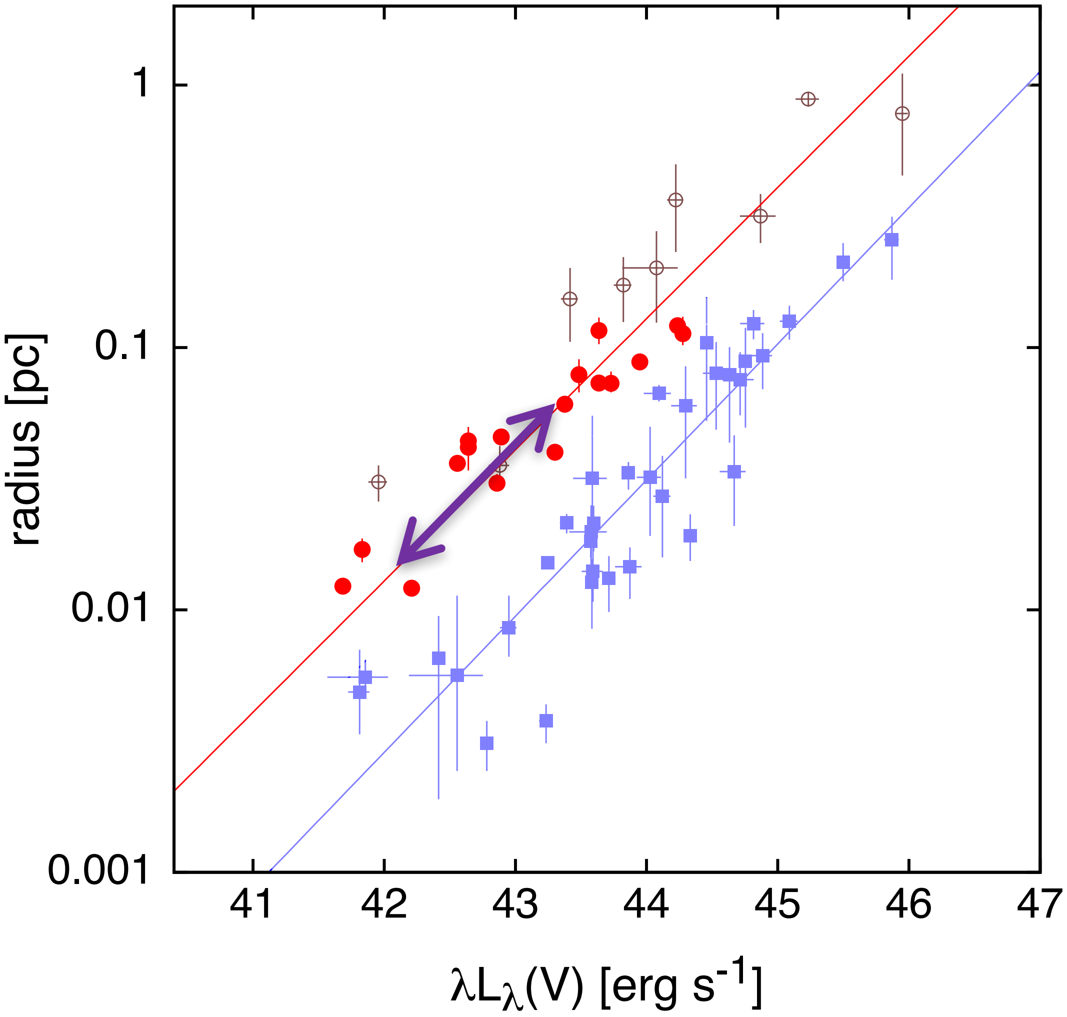
- Intrinsic scatter in the dust lag-luminosity relation



- Target to target variation around the best-fit dust lag-luminosity relation : $\sigma_{lag} \approx 0.13$ dex (Koshida, TM+ 14)
- Possible origins:
  - internal extinction
  - accretion disk SED
  - delayed response of the dust lag change
  - dust temperature
  - torus geometry
  - mass accretion rate

Time variation of the dust lag

- The dust lag becomes larger when the AGN becomes brighter?

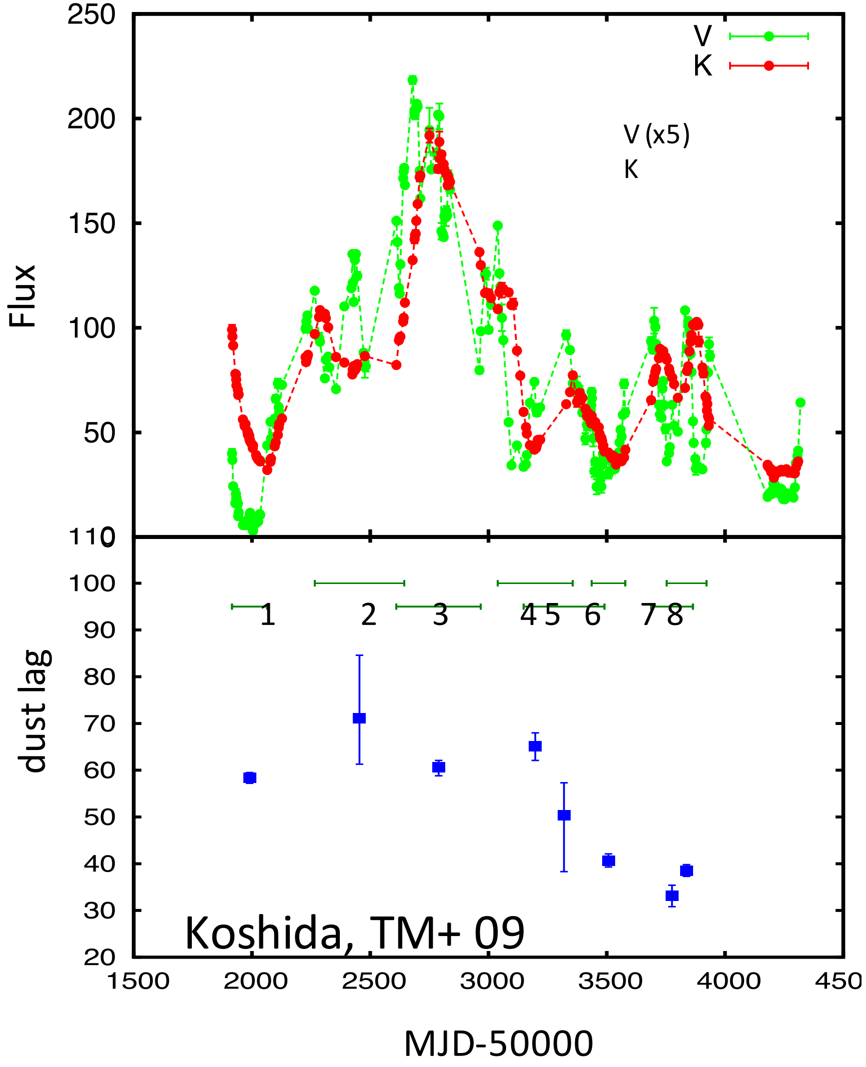


- If the inner radius of the dust torus strictly follows $r_{\text{in}} = A(L_\nu^{\text{AD}})^{0.5}$ at any time, the dust lag becomes larger when the AGN becomes brighter, tracking on the trend of the global dust lag-luminosity relation → would not lead to the intrinsic scatter of the relation.

But NOT

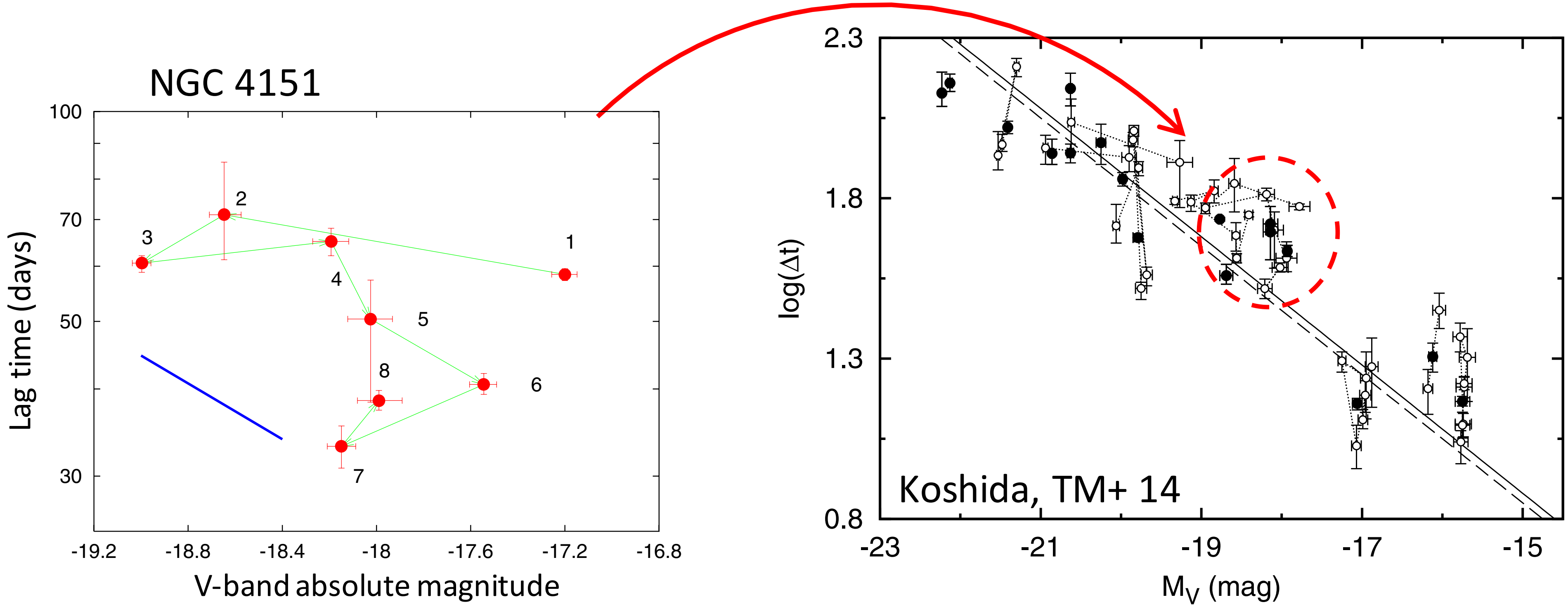
Time variation of the dust lag

- Delayed response of the dust lag change
  - The inner radius of the dust torus did NOT respond instantaneously according to the flux change of the accretion disk
    - torus RM : Koshida, TM+09; Oknyanskij+ 14; Schnulle+13, 15
    - Interferometry : Pott+ 10; Kishimoto+ 11, 13.



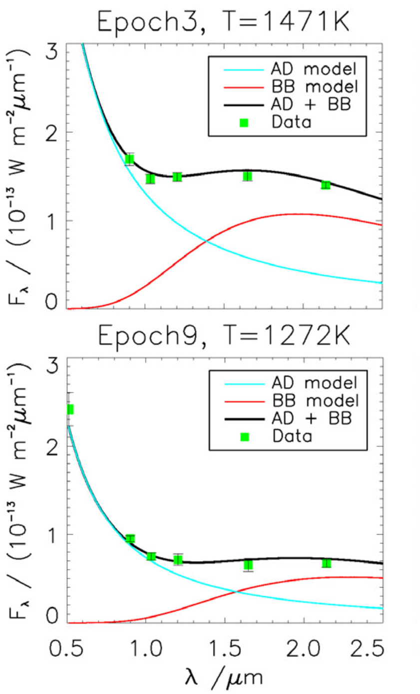
An origin of uncertainty in the torus RM distance

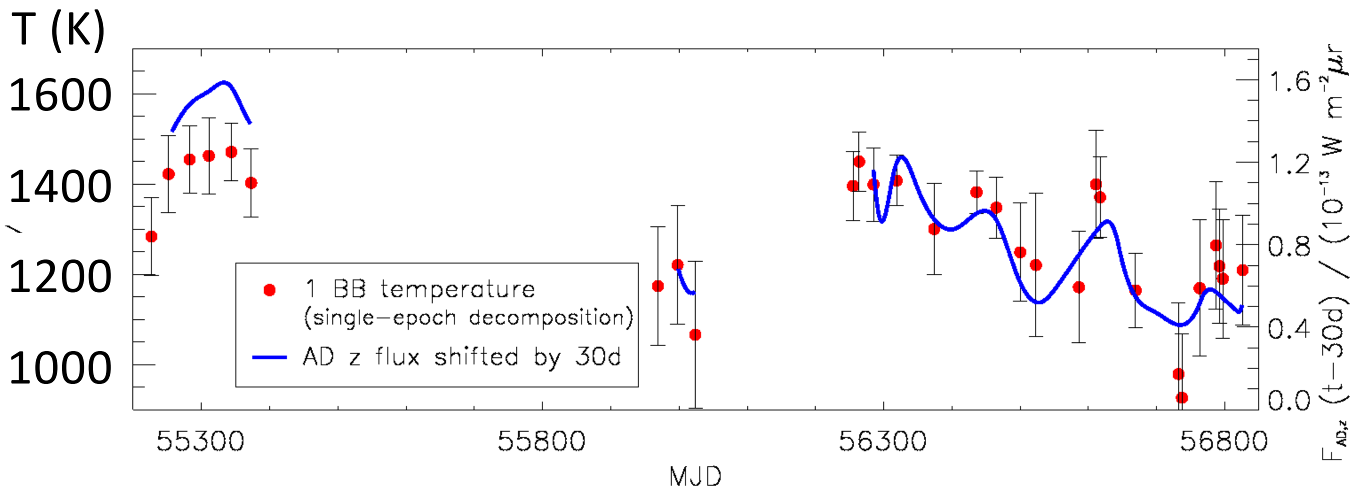
- Delayed response of the dust lag change
  - It will lead to a significant scatter for the dust lag-luminosity relation. (Koshida, TM+ 14; Schnulle+ 15)



Possible solution to reduce uncertainties in the torus RM distance

- Temperature variation of the dust emission in near-infrared
  - Schnulle+ 15 measured T_d for NGC 4151 in 2010-2014.
    - T_d < 1500 K, which is lower than the dust sublimation temperature → The hot dust located beyond the sublimation radius.
    - T_d changed in time time: It closely tracked the accretion disk flux variation in short timescales.



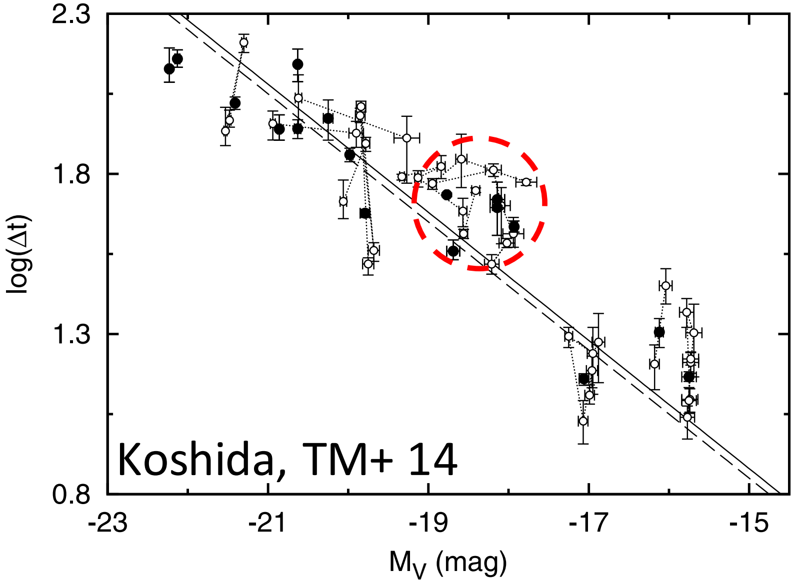


Schnulle+ 15

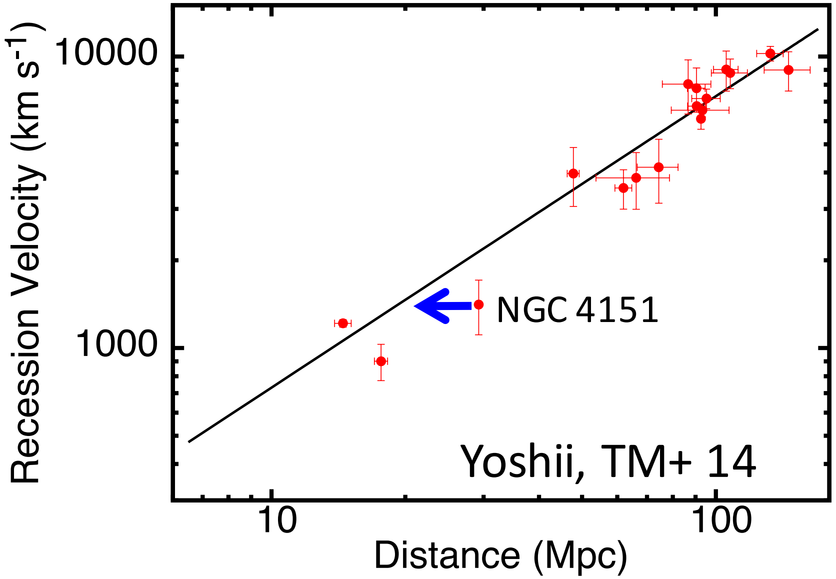
Possible solution to reduce uncertainties in the torus RM distance

- Temperature variation of the dust emission in near-infrared
  - The dust lags were larger than the global dust lag-luminosity relation for NGC 4151 in 2000-2008 →T_d might be lower than the ensemble value.
  - If the model parameters for an individual target can be determined observationally (the SED shape of L_ν^{AD}, T_d, a, etc.), the uncertainties in the torus-RM distance will be reduced (Yoshii, TM+ 14).

→ The torus RM distance becomes smaller for lower T_d



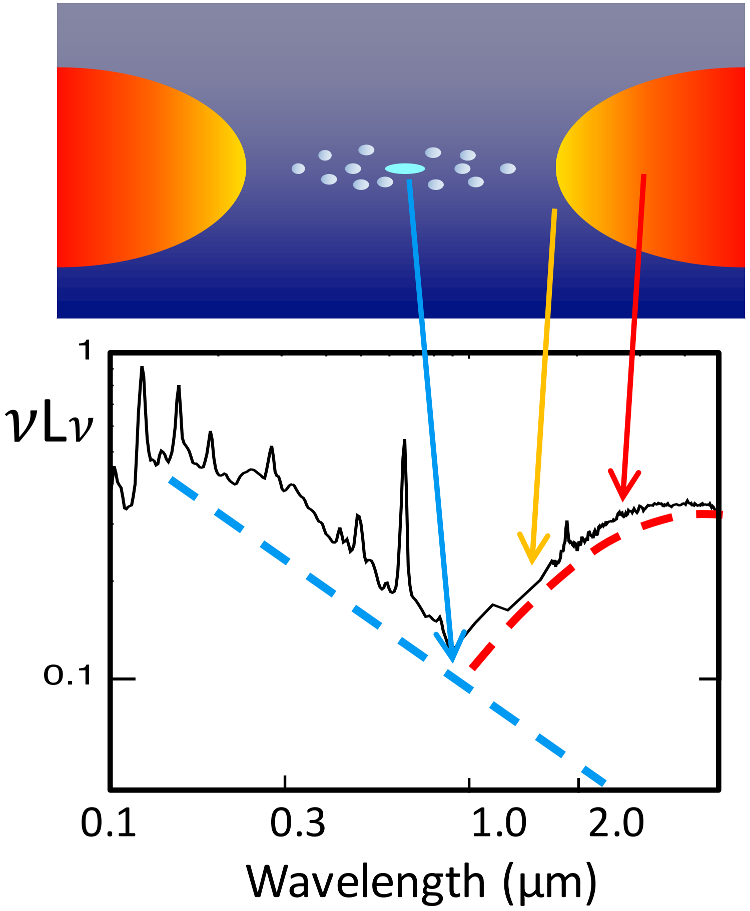
Koshida, TM+ 14



Yoshii, TM+ 14

Extension to higher redshifts

- Observations of higher-redshift targets
  - The emission in shorter wavelengths would be more contributed by higher temperature of dust, closer to the accretion disk, which would lead to the inter-band time lags in the dust torus emission.
  - For the target at higher redshift,
    - The dust lag should be corrected for the inter-band time lags according to the target redshift.
    - The accretion disk emission contributes larger for shorter wavelengths, and it also should be subtracted properly.

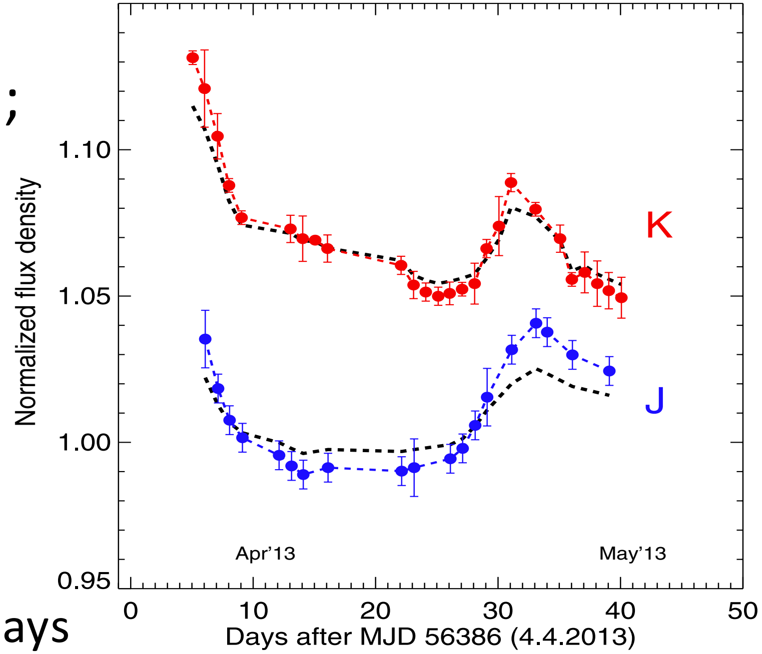


Extension to higher redshifts

- Inter-band time lag in the dust torus emission
  - According to the dust sublimation radius by Barvainis 87,

$$r_1 = 1.3 L_{\mathrm{uv},46}^{1/2} T_{1500}^{-2.8} \ \mathrm{pc}$$

    - Δt (J) / Δt (K) = 0.2 and Δt (H) / Δt (K) = 0.45, if $T \propto \lambda^{-1}$
  - Fortunately, the inter-band dust lag would be not so large based on the multi-band torus RM.
    (Tomita, TM+ 06; Pozo-Nunez+ 14, 15; Oknyanskij+ 15; Schnulle+ 15).
  - But some AGNs show relatively large inter-band dust lag (Oknyanskij+ 15 and references therein)
  - Further study is needed.

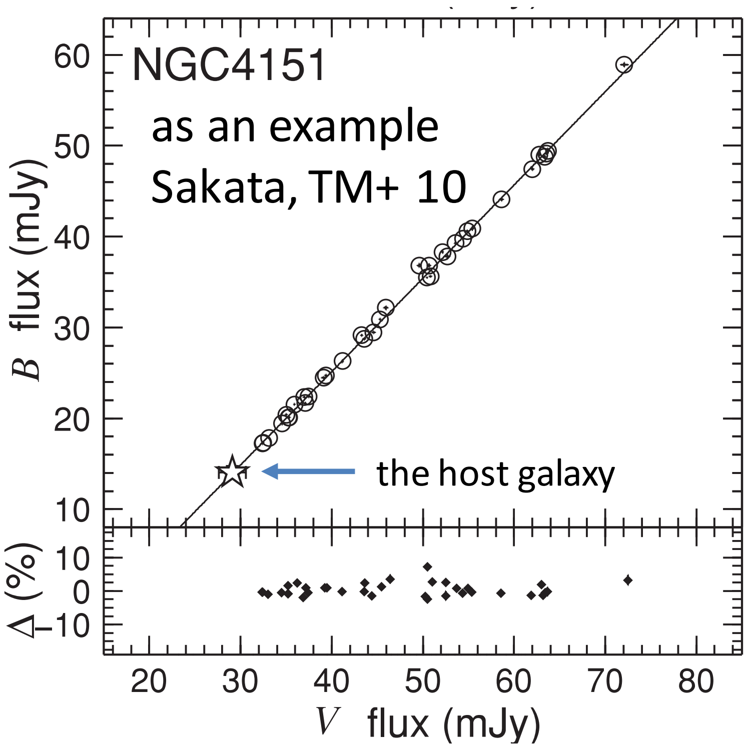


Pozo-Nunez+14 WPVS48

Δt (B-K)=71 days, Δt (B-J)=64 days

Extension to higher redshifts

- Estimation of the host galaxy flux
  - The host-galaxy flux should be subtracted for the torus-RM distance.
- Spectral variability of the optical continuum emission
  - Sakata, TM+ 10 presented that the multi-epoch flux in any 2 different bands showed a very tight linear correlation (the data come from the MAGNUM monitor).
  - They also estimated the host galaxy flux using the HST images, and found that the host-galaxy flux located on the fainter extension of the straight line.



NGC4151

as an example

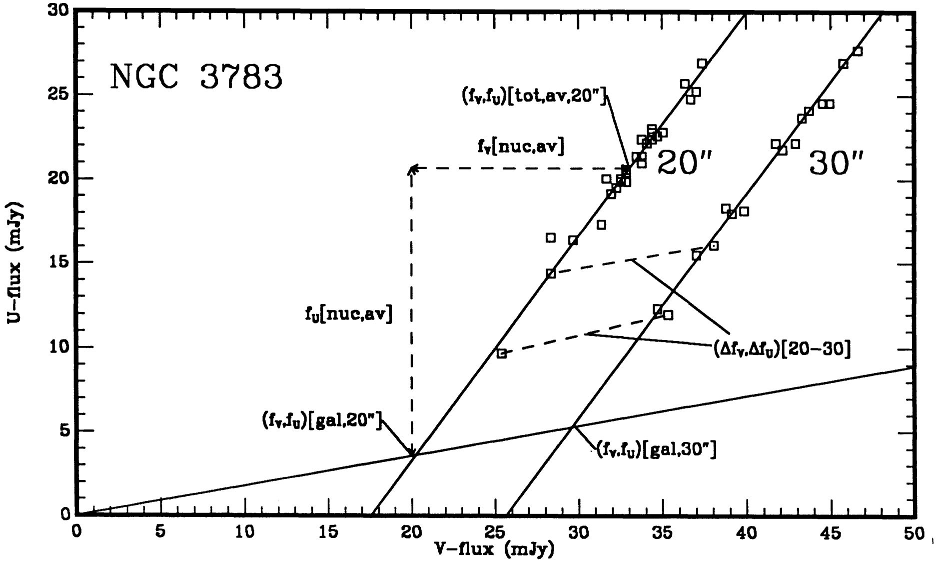
Sakata, TM+ 10

the host galaxy

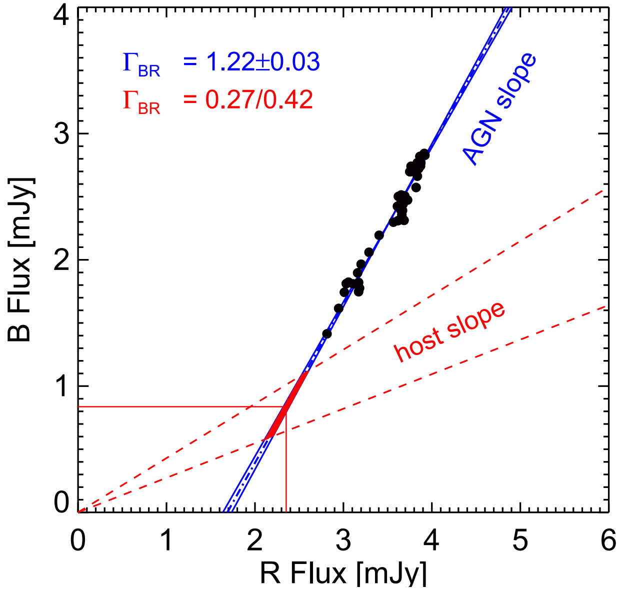
Extension to higher redshifts

- Estimation of the host galaxy flux from the monitoring data
  - The intersection of the regression line fitted to the flux data and the line represents the host galaxy color in the flux-flux diagram indicates the host galaxy fluxes (Choloniewski+ 81; Winkler+ 92; Winkler 97; Sakata, TM+ 10; Pozo-Nunez+ 14, 15).

Winkler+ 92



Pozo-Nunez+15 PGC50427



Summary

- Sublimation of dust : a key for the torus-RM distance.
- Results from the MAGNUM project
  - The best dust lag-luminosity relation to date
  - H_0=73 km/s/Mpc based on the torus-RM distance
- Future progress in the torus-RM cosmology
  - Refinement of the torus RM distance
    - The delayed response of the dust-lag change to the flux variation of the accretion disk is a significant source of intrinsic scatter of the dust lag-luminosity relation.
    - Measuring T_d and other observational parameter may help.
    - (Calibration of the torus-RM distance: coming soon)
  - Extension to higher redshift
    - Inter-band time lag in the torus emission should be corrected.
    - Estimation of the host-galaxy flux from the monitoring data.