Reverberation Measurements of the Inner Radius of the Dust Torus in 17 Seyfert Galaxies

New Result of the MAGNUM Project

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- MAGNUM Project
  - Light curves
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- Lag-Luminosity relation
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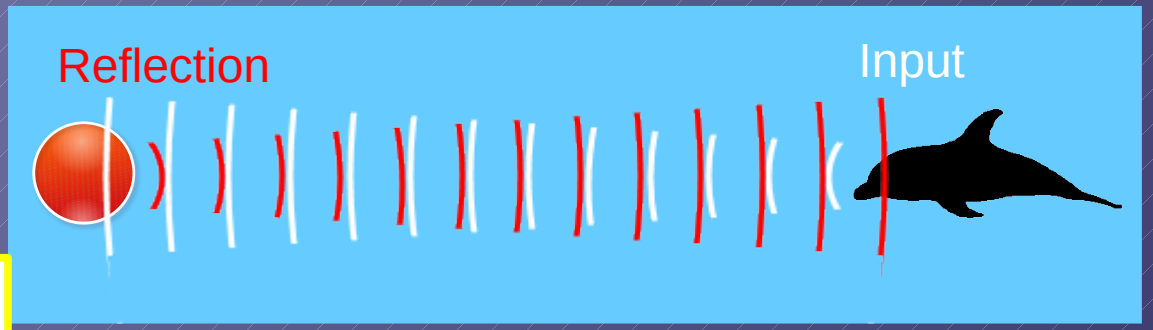
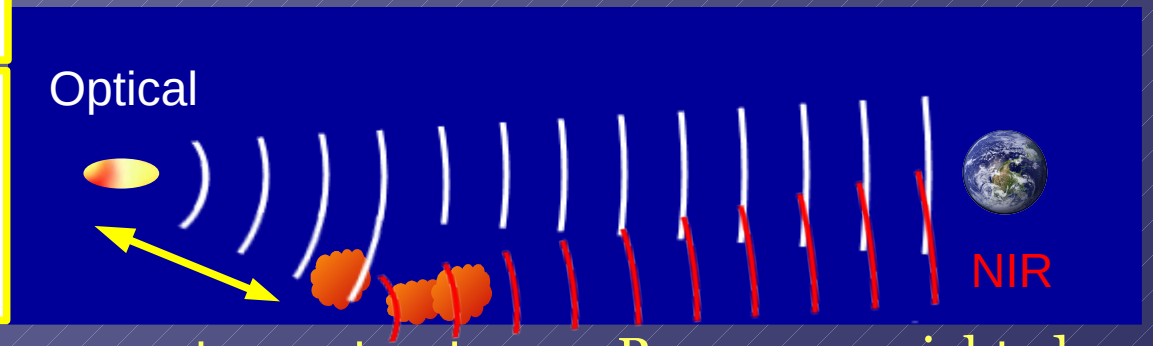
Dust Reverberation Mapping

- Method similar to “Echo Ranging”
  - Difference 1: The position of the source and receiver is different
  - Difference 2: Not reflection but thermal reprocess by dust
  - Difference 3: signal for detecting the time lag is variation feature on source and response light curve.



Torus inner radius
(e.g. Barvainis87, Kishimoto+07)

$$R_{\rm sub} = 1.3 \left(\frac{L_{UV}}{10^{46}\ {\rm erg\ s^{-1}}} \right)^{0.5} \left(\frac{T_{\rm sub}}{1500\ {\rm K}} \right)^{-2.8} \times \left(\frac{a}{0.05\ \mu{\rm m}} \right)^{-0.5} {\rm pc},$$

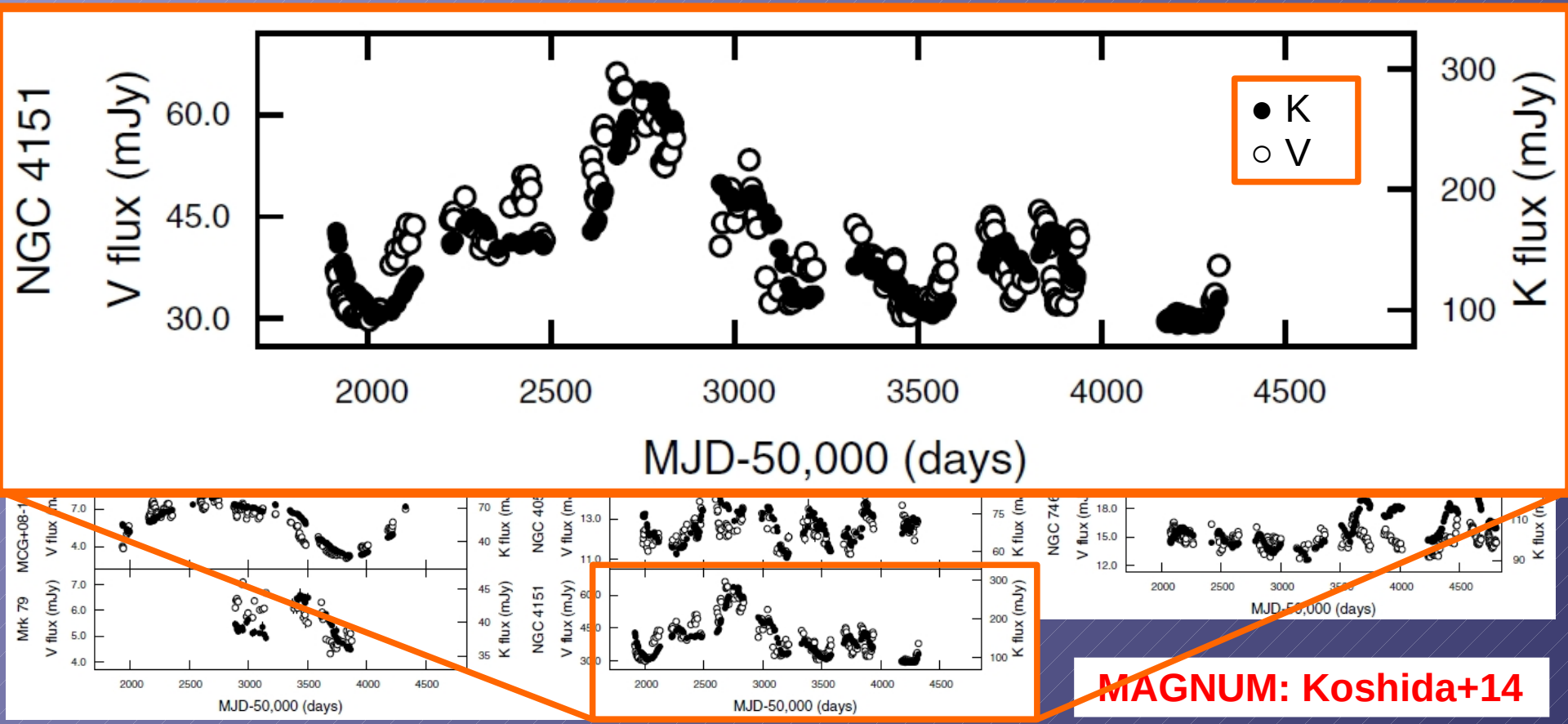


Received signal is the integration over torus structure →Response weighted

MAGNUM Project

- **MAGNUM Project (Yoshii 02)**
  - PI: Prof. Yoshii (the University of Tokyo)
  - Started in 1995, observed in 2000-2008
- **MAGNUM telescope**
  - Maui island, Hawaii
  - 2m Ritchey-Chretien, robotic operation
  - Dedicated to this project
- **Multicolor Imaging Photometer** (Kobayashi+98)
  - Optical/Near infra-red (NIR) simultaneous observation using dichroic mirror and two detectors (CCD/InSb)
- Main results
  - Minezaki+04, 06; Suganuma+04, 06; Tomita+06; Koshida+09, 14; Sakata +10; Yoshii+14
  - Collaborations: Breedt+09, Grier+12, Peterson+14, etc.

Light Curves

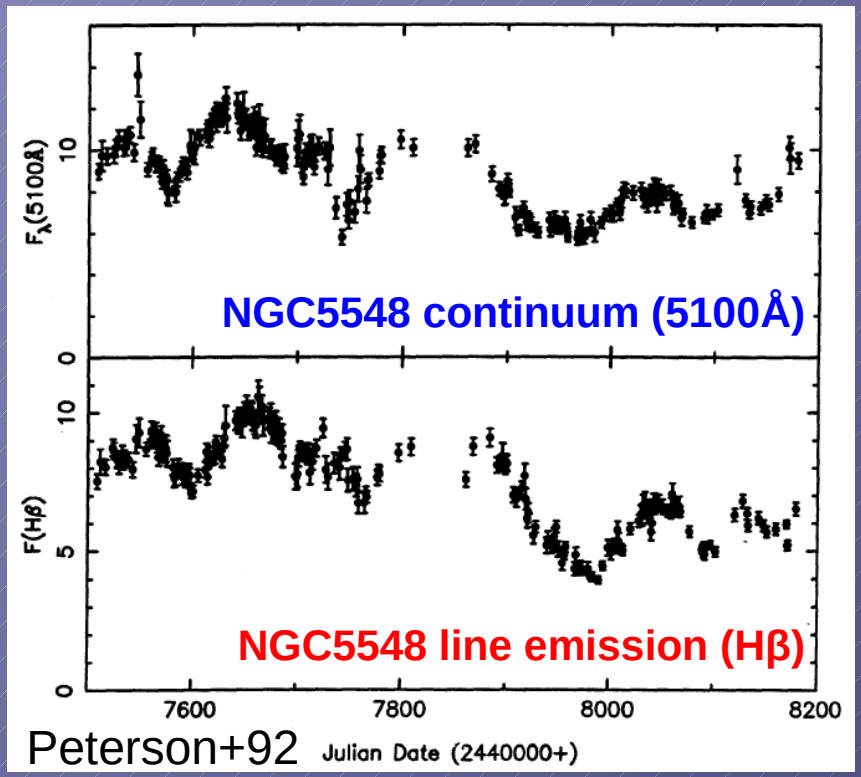


MAGNUM: Koshida+14

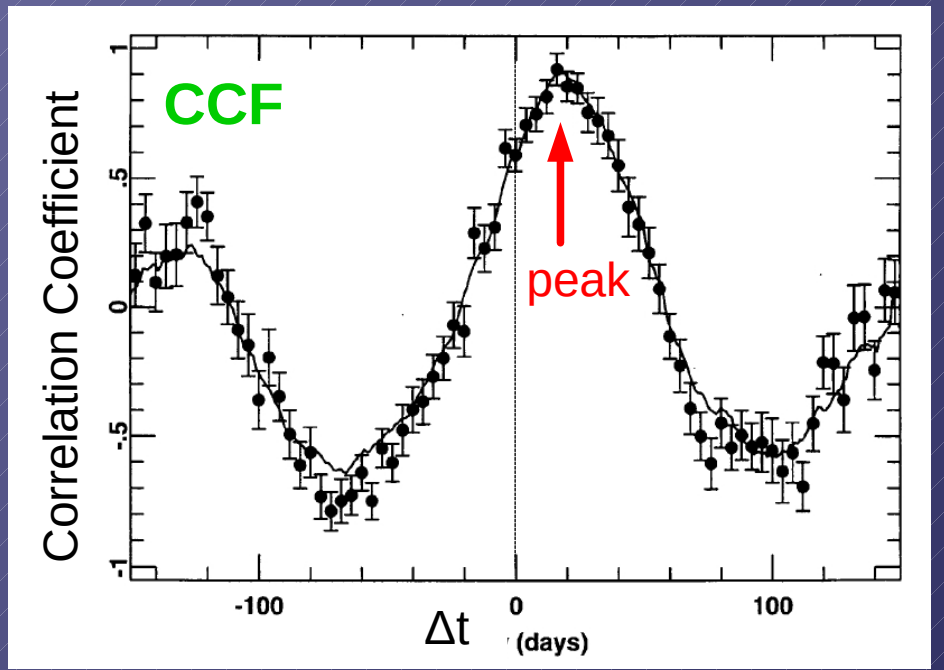
- Photometric accuracy: ~1%
- Sampling interval: 3-16 days (in season)
- 17 Seyfert galaxies in this paper, over ~60 targets in total for MAGNUM

Cross Correlation method

- Find a time lags Δt at cross correlation function (CCF) “maximum”
- High accuracy measurement of Δt requires…
  - High accuracy photometry
  - Frequent sampling monitor

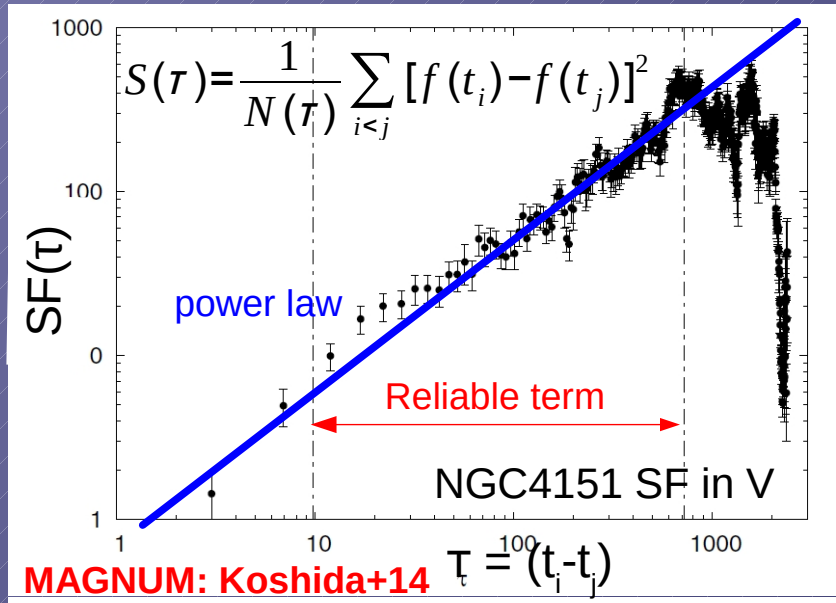


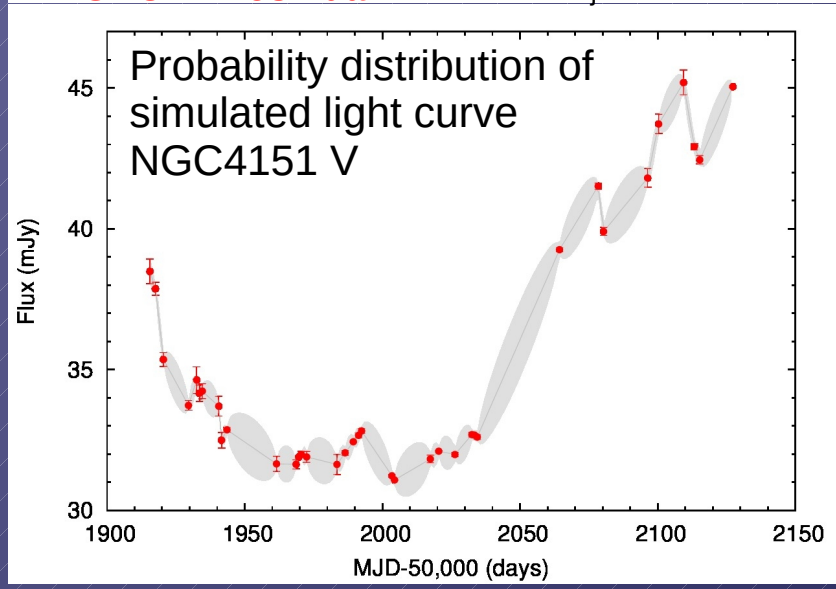
$$F_{CCF}(\tau)=\frac{1}{N}\sum_{i=1}^{N}\frac{[L(t_i)-\bar{L}][C(t_i-\tau)-\bar{C}]}{\sigma_C\sigma_L}$$



CCF method in MAGNUM

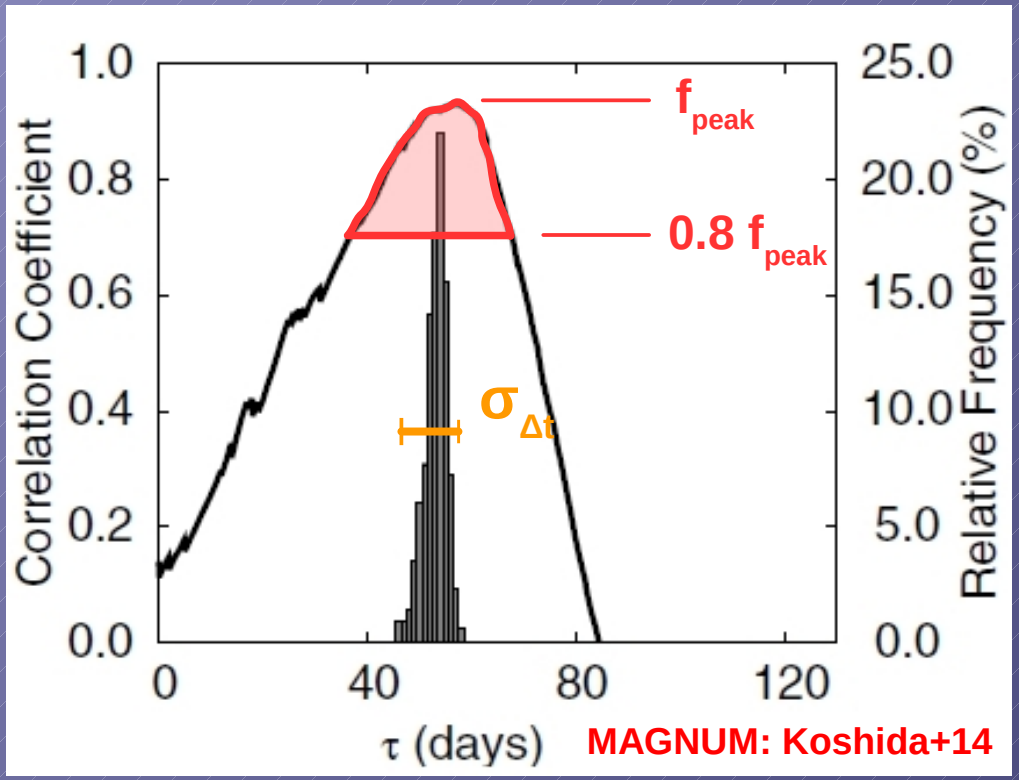
- Interpolation of light curves
  - Stochastic simulation using Structure Functions (Collier and Peterson 01)
  - Provability distribution of variation based on the observational light curve
  - Fit a power law function on reliable term
- Monte Carlo Simulation
  - To simulate the sampling effect and photometric error
  - Interpolate “pair” flux points for observed flux point on both light curves.





CCF method in MAGNUM

- Time lag definition: Centroid of a part of CCF with 80% and more efficiency against the peak
  - For Avoiding to count a local peak on CCF
  - Adopt the centroid of CCF Centroid Distribution (CCCD) as the lag

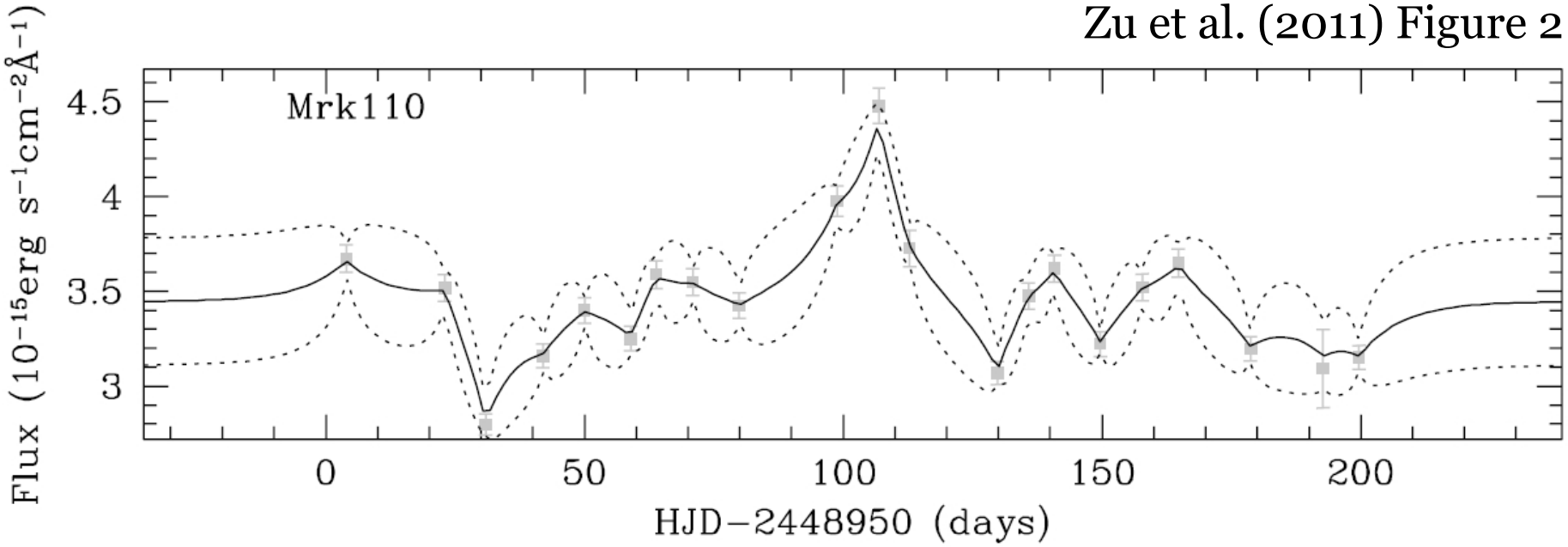


- Time lag: Median of centroid distribution
- Error: ± 34.1 percentile point

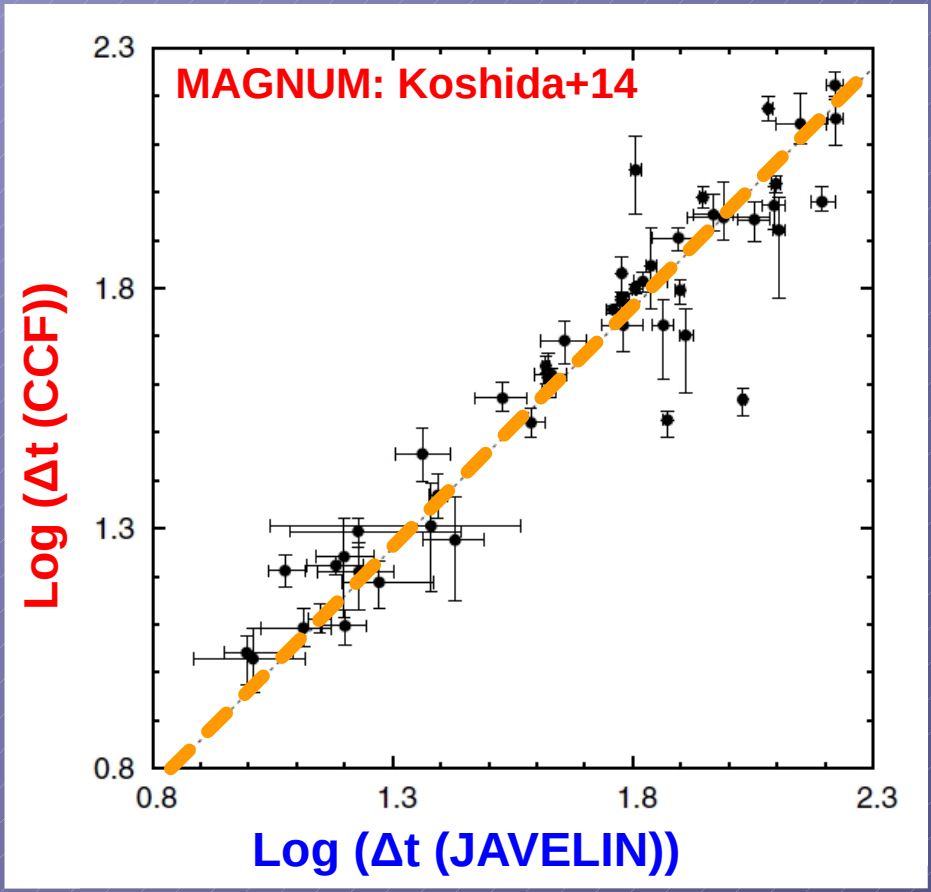
JAVELIN

- Zu et al. (2011)
- Adopting Dumped Random Walk (DRW) for AGN variation model
- Assuming a top hat shape transfer function (TF)
- Calculate likelihood distribution using Markov Chain Monte Carlo (MCMC) method.
  - Δt, Two parameters for DRW model, Width of the TF

Zu et al. (2011) Figure 2



Comparison of Two RM methods

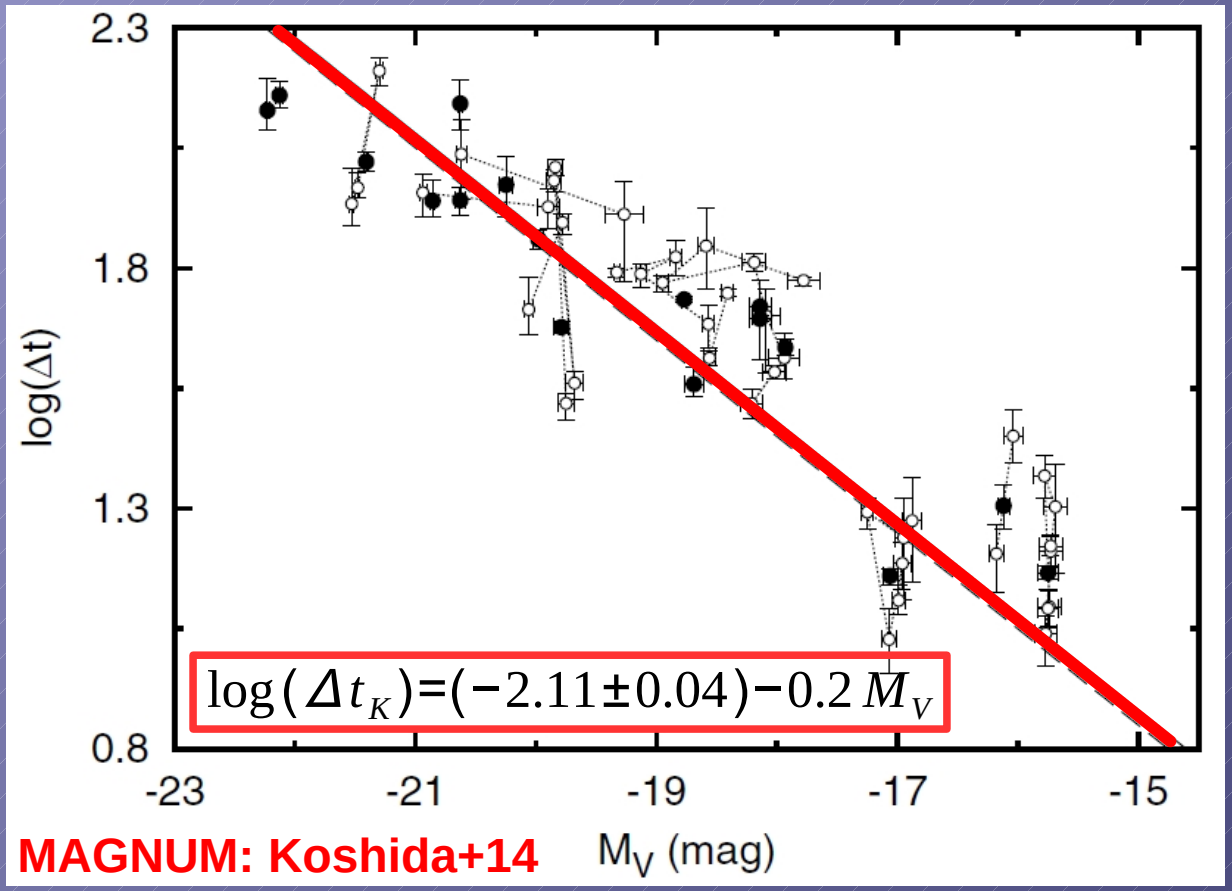


- The time lags are derived using CCF and JAVELIN for each of 49 peaks or valleys on the light curves of 17 Seyfert galaxies,

The results of two method agree within 10% systematic difference.

Lag Luminosity Relation

- Strong correlation with intrinsic scatter 0.13 dex in Δt

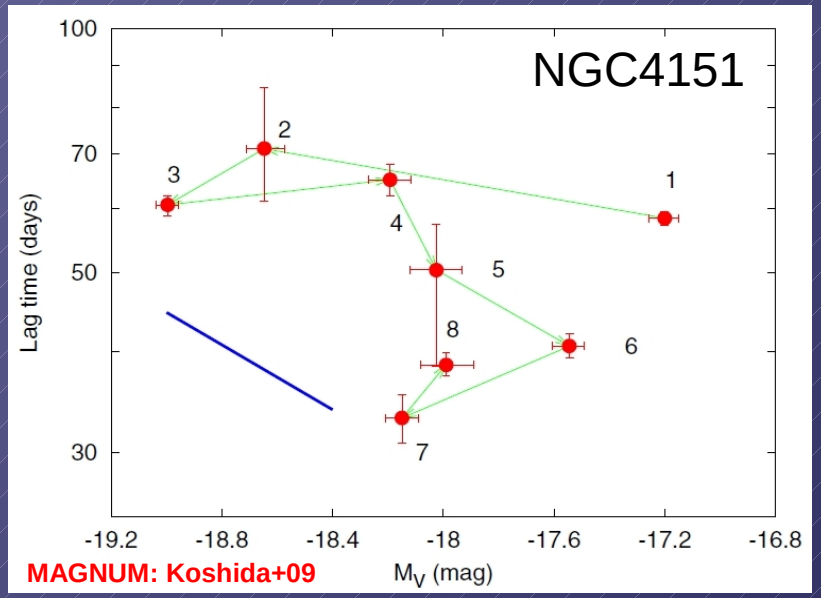


- **observed flux (V)** subtraction of non-variable component: Host galaxy (GALFIT, Peng et al. 2002), Narrow emission lines (Hβ and [O III])
- **luminosity distance** based on HI line recession velocity assuming h_o=0.73, Ω_M=0.3, Ω_Λ=0.7

Tight enough correlation even for empirical distance measurement such as in BLR (Watson+11)

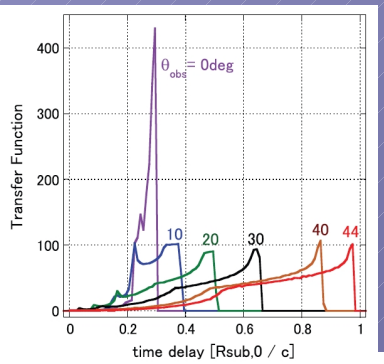
L-Δt relation; scatter

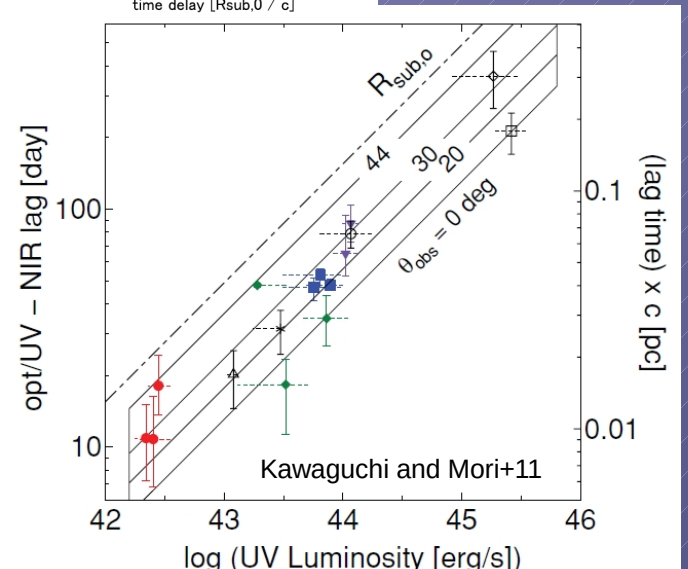
- The origin of scatter
  - Intrinsic extinction: 0.054 dex in Δt (Cacket et al. 2007)
  - Energy distribution of dust heating flux: 0.01 dex in Δt with $\sigma_{\alpha\nu}$=0.1 for (flux) $\propto \upsilon^{\alpha\upsilon}$
  - "Hysteresis" effect between Lopt and Δt: 0.11 dex
- … Still have room of ~0.1 dex
  → Viewing angle of torus?

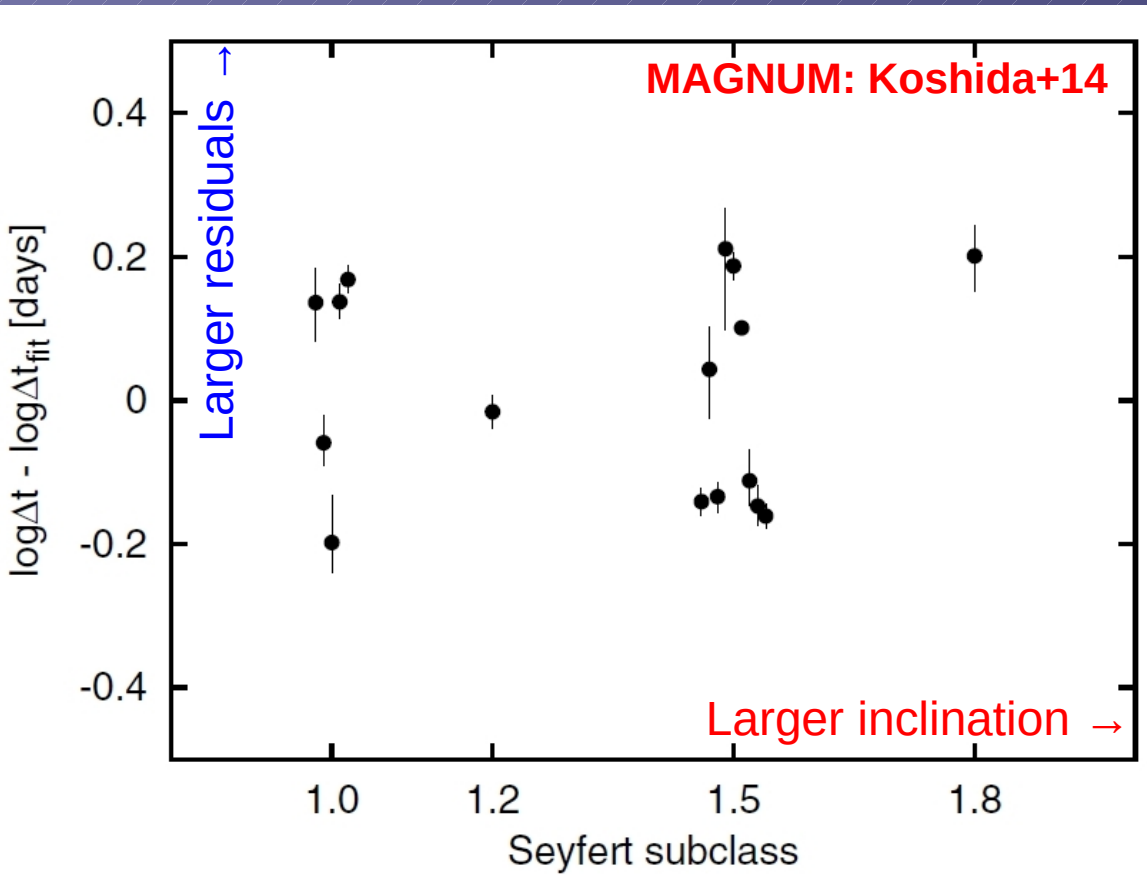


Dependency on Sy type

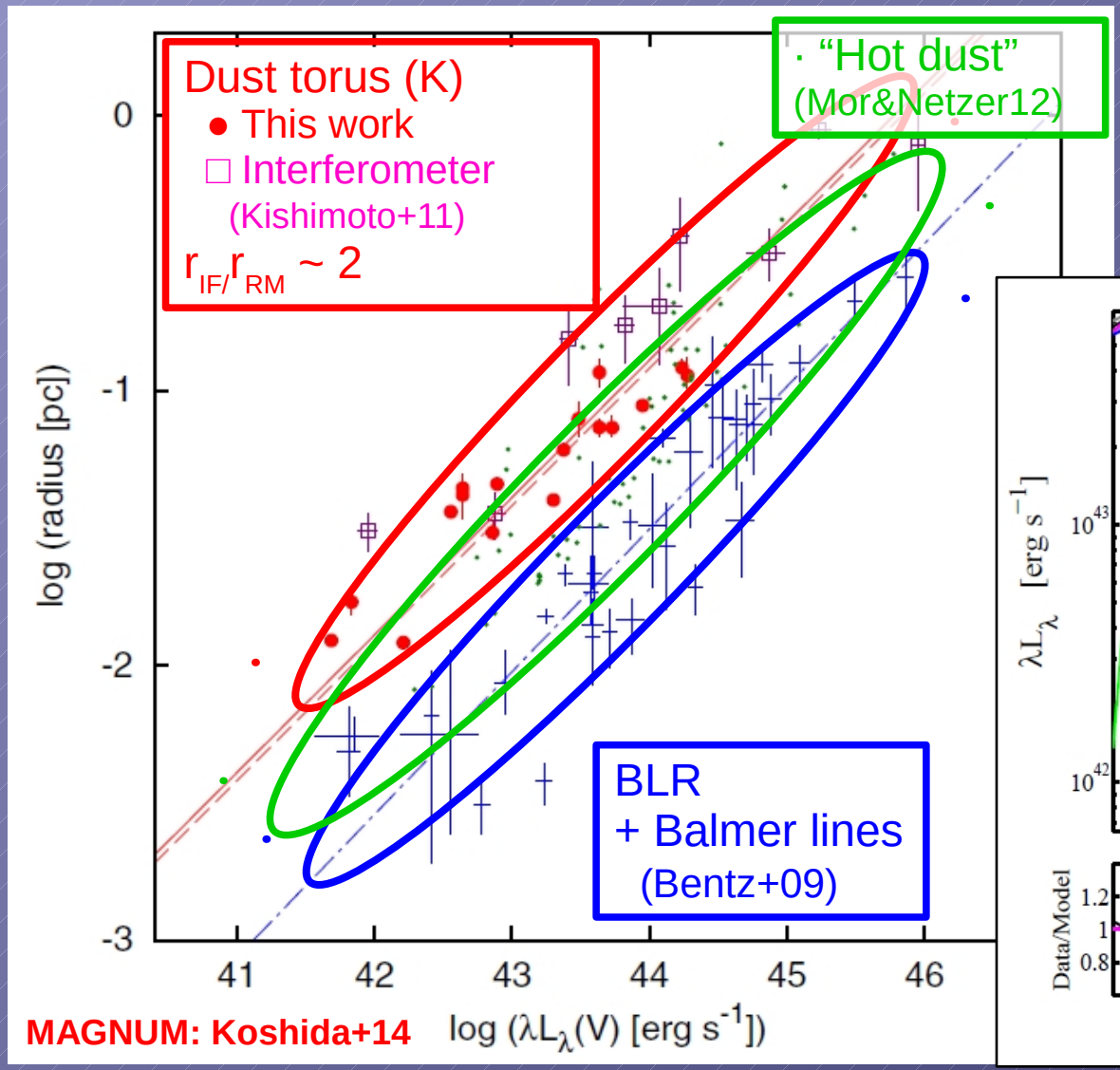
- Expected dependencies of Δt on torus inclination (Kawaguchi+2011, etc)
  - See the dependency of time lag against Seyfert type
- No significant correlation between time lag and Seyfert type

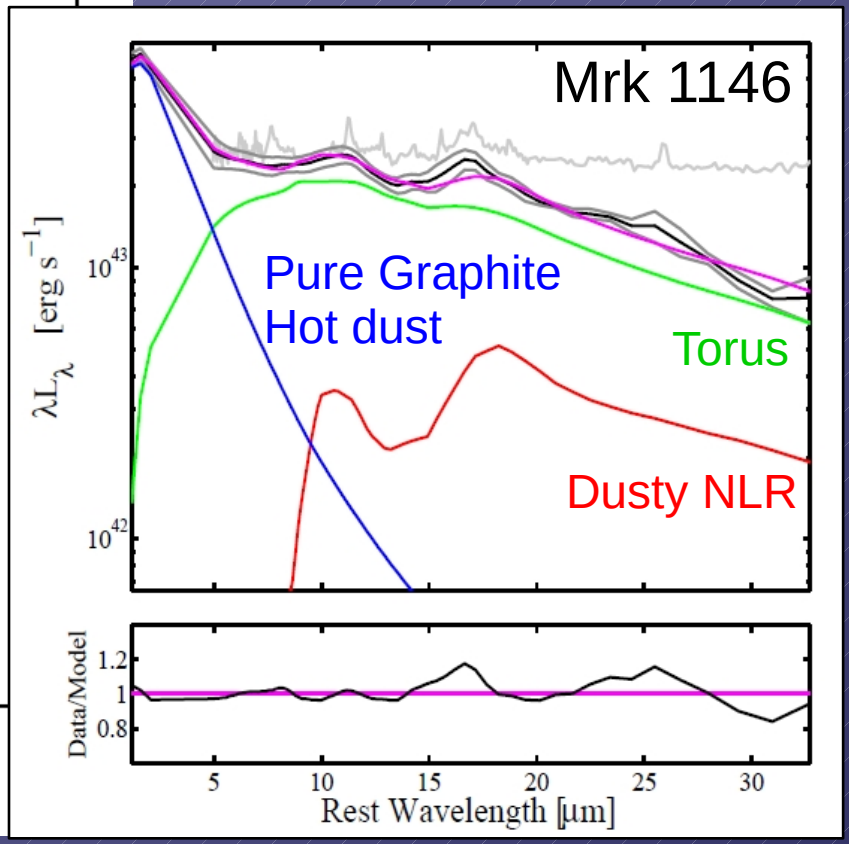






Inner Region Structure

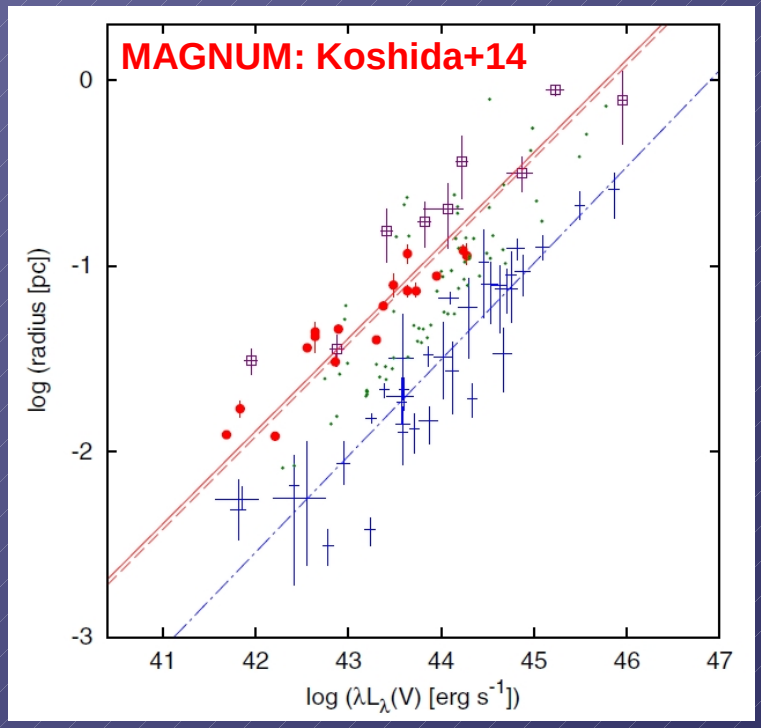




Innermost Region of Dust Torus

- BLR radius: r_{BLR}=-1.51+(0.52±0.06) log L_V
- Gap between K-band reverberation radii
  - Temperature structure of dust torus ($\Delta t_{,VH}$ is 7% smaller than $\Delta t_{,VK}$)
  - Ionization level structure of BLR
    - Lag for [Si IV]+[O IV], [C III], Mg II is larger in factor two than the lag for Hβ (Peterson et al. 2004)
  - Hot dust (Mor and Netzer 2012)
  - Rapid lag variation
    → existence of dense gas cloud even in the sublimation regions

Continuity between dust torus and BLR

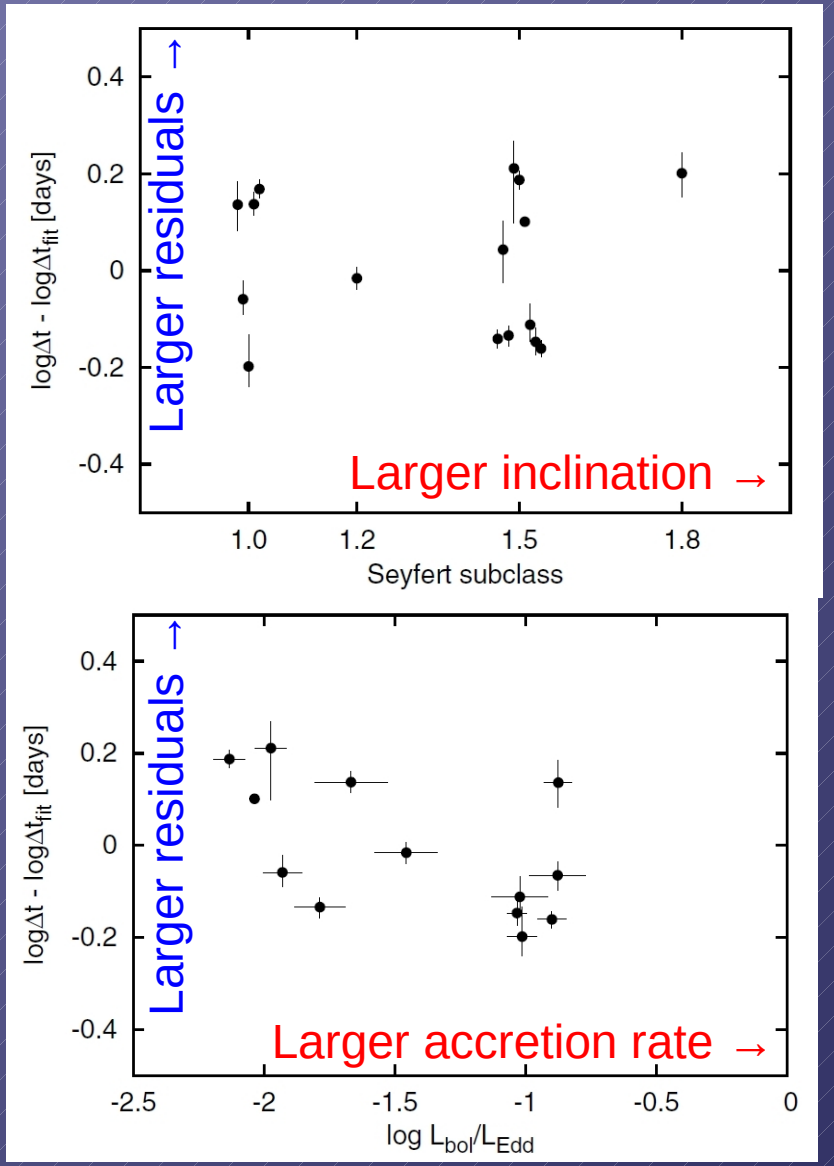


Summary

- 49 measurement of the inner radii of dust tori over 17 neaby Seyfert galaxies have been done through reverberation mapping method using MAGNUM project data.
- The inner radii showed strong correlation against accretion disk luminosity with 0.13 dex scatter.
- Comparing the other component of the inner region of AGNs, the RM radii of dust tori are consistent to the concept of the recent unified model.

Dependency on Sy type, L/L_{Edd}

- Expected dependencies on torus inclination or Eddington ratio (Kawaguchi+2011, etc)
  - Plot against Seyfert type
- No significant correlation between time lag and Seyfert type, or Eddington ratio
- Necessity of investigation in wider range of parameters



Kawaguchi and Mori+11 Fig. 5