Exploring Dust Reverberation Mapping in AGN: Future Prospects with LSST+SPHEREx Data

Amit Kumar Mandal

Center for Theoretical Physics of the Polish Academy of Sciences

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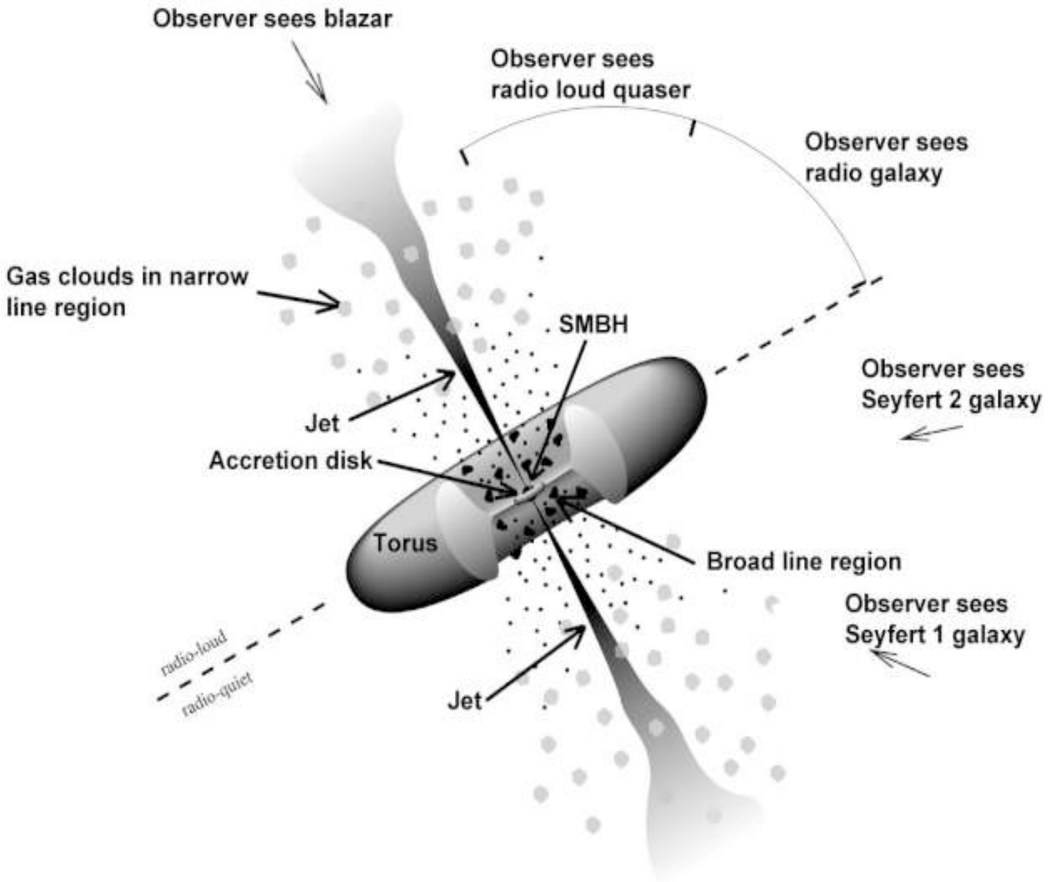
Collaborators: Prof. Bozena Czerny

Vikram Jaiswal, Raj Prince, Swayamtrupta Panda, Francisco Pozo Nunez, Ashwani Pandey, Mahammad Naddaf, Shulei Cao, Michal Zajacek, Bharat Ratra

Typical sizes of different components in AGN

Luminosity L ~ 10^{42} - 10^{46} erg s^{-1}

- **Accretion disk (R_{AC} ~ 0.001 pc)**
- **Broad Emission line Region (BLR) (R_{BLR} ~ 0.01 - 0.1 pc)**
- **Dust torus (R_{Torus} ~ 0.01 - 1 pc)**
- **Narrow Line Region (NLR) (R_{NLR} ~ 1 - few 10 pc)**
- **Relativistic Jets (Can extend upto Mpc scales)**



Urry and Padovani+1995

The central regions of AGN are very compact

The Way

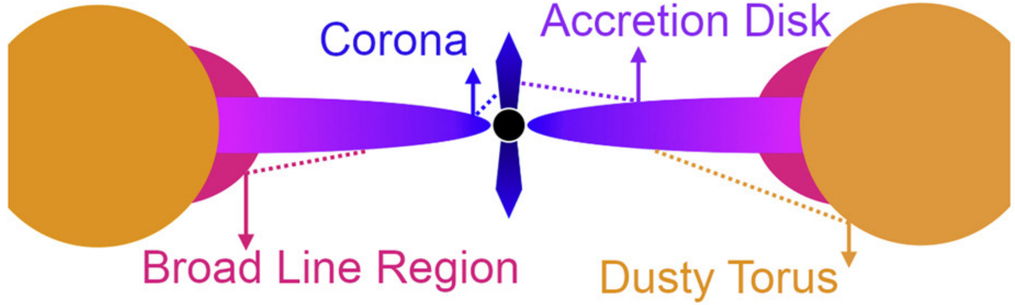
Indirect method: Reverberation mapping / Echo mapping technique (Blandford and Mackee 1982, Peterson 1993, 2014).

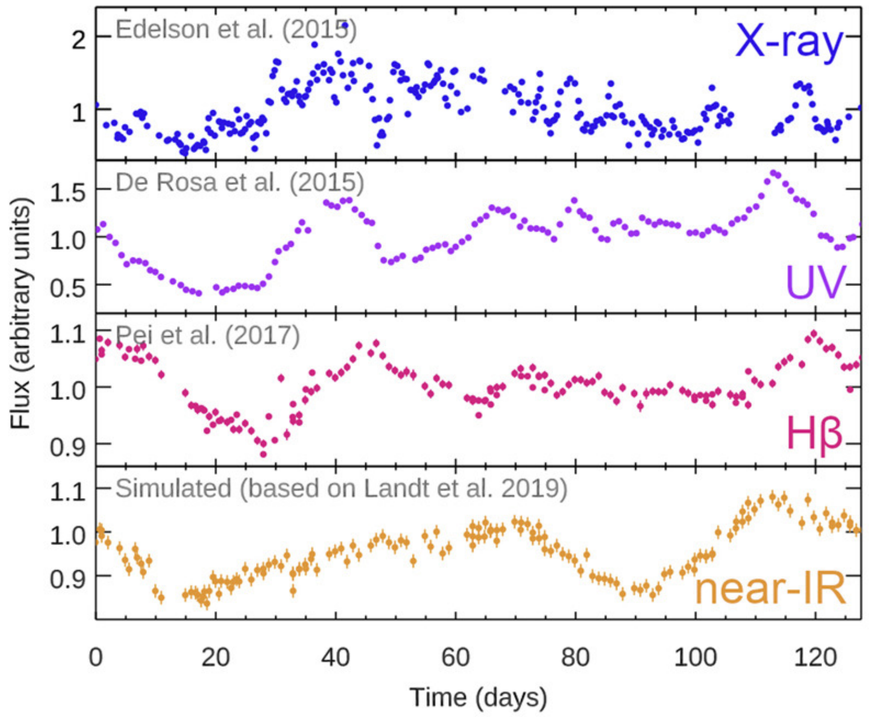
$$R < c\,\Delta t$$

Time resolution can be swapped for spatial resolution: Reverberation mapping

(Blandford and Mackee,1982; Peterson 1993, 2014).

This method uses an intrinsic property of AGN, i.e., flux variability.





Cackett et al., 2021

Dust Reverberation Mapping (DRM): Current status

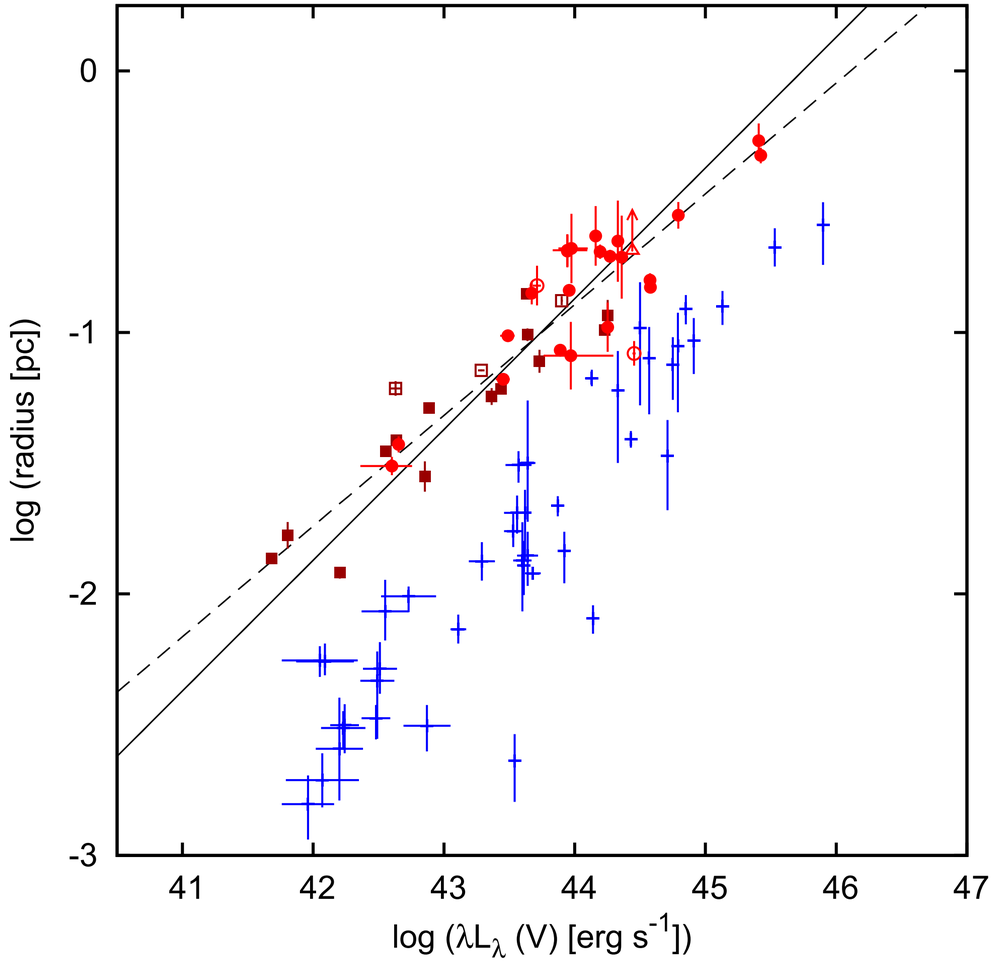
DRM is based on the delayed response of the IR continuum from torus to the optical/UV continuum from accretion disk.

$R_{dust,K} \sim L_V^{0.424}$ (based on K-band lags)

Limitations

- DRM (based on K-band) applied on ~ 40 AGNs
- Limited to AGNs: $10^{42.5} < L_V < 10^{45}$ erg/s

- **Need to expand R_{dust} – L relation for both high (> 10^{45} erg/s) and low luminosity (< $10^{42.5}$ erg/s) ends**



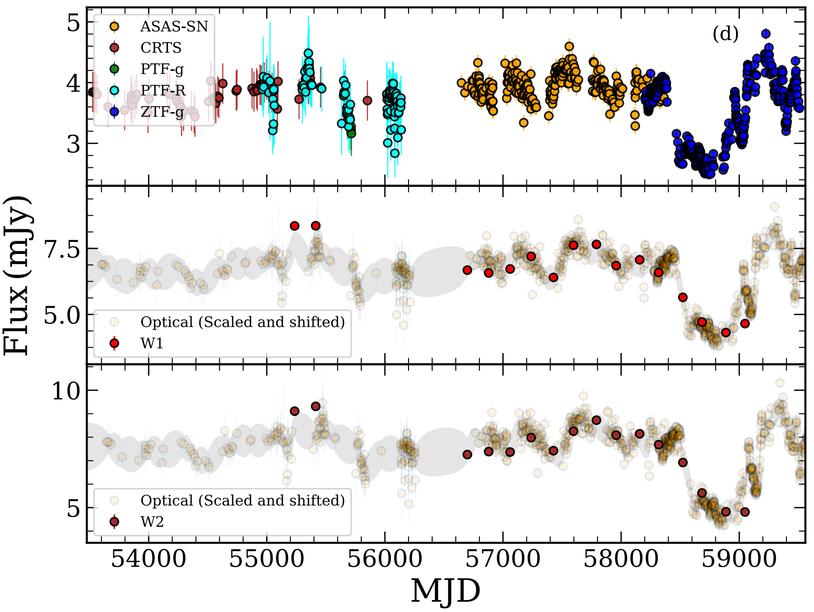
Minezaki et al. (2019)

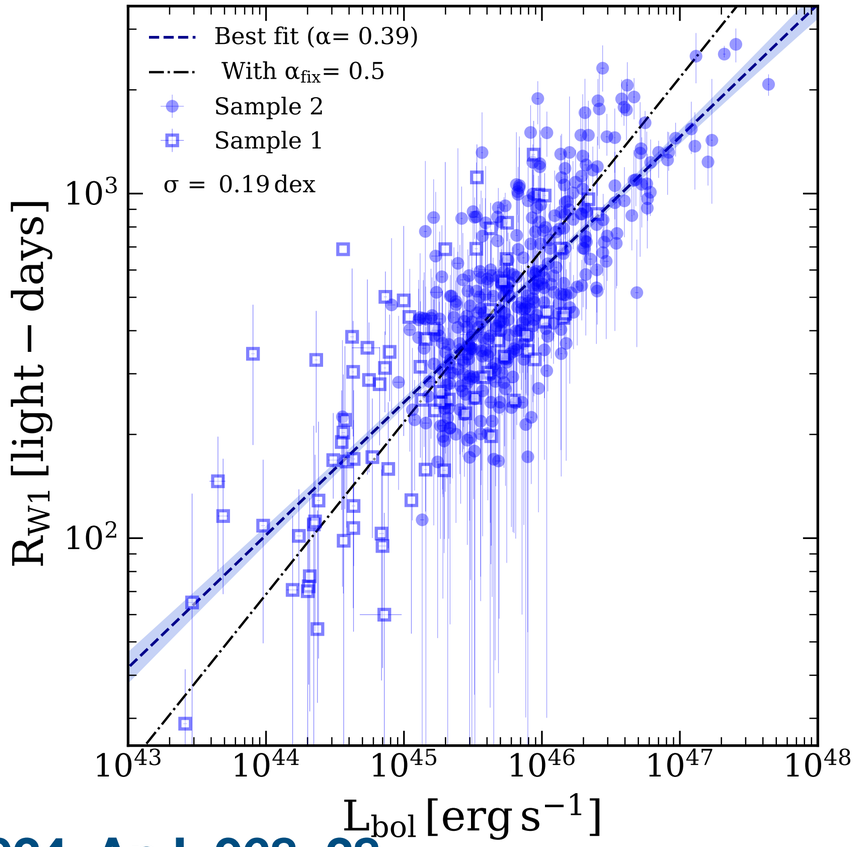
DRM based on WISE bands (high luminosity AGNs): Current status

DRM based on WISE W1 and W2 lags relative to optical band; used to constrain torus size in AGN

$R_{dust,W1} \sim L_{bol}^{0.39}$, σ = 0.19 dex (R_{W1}-L_{bol})

$R_{dust,W2} \sim L_{bol}^{0.33}$, σ = 0.18 dex (R_{W2}-L_{bol})





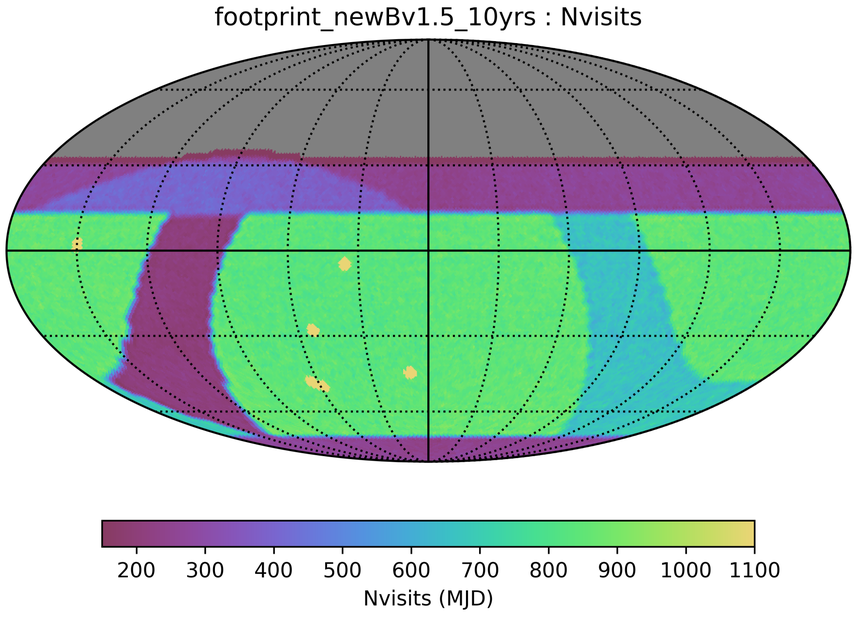
Limitations:

1. **R_{dust} v/s Luminosity correlation is different among studies**
2. **Poor sampling in IR-W1 and W2 band light curves data (cadence~180 days)**
3. **Optical light curves constructed from different surveys have different SNR**
4. **The lags (below 200 days) are not well constrained, have large uncertainties**

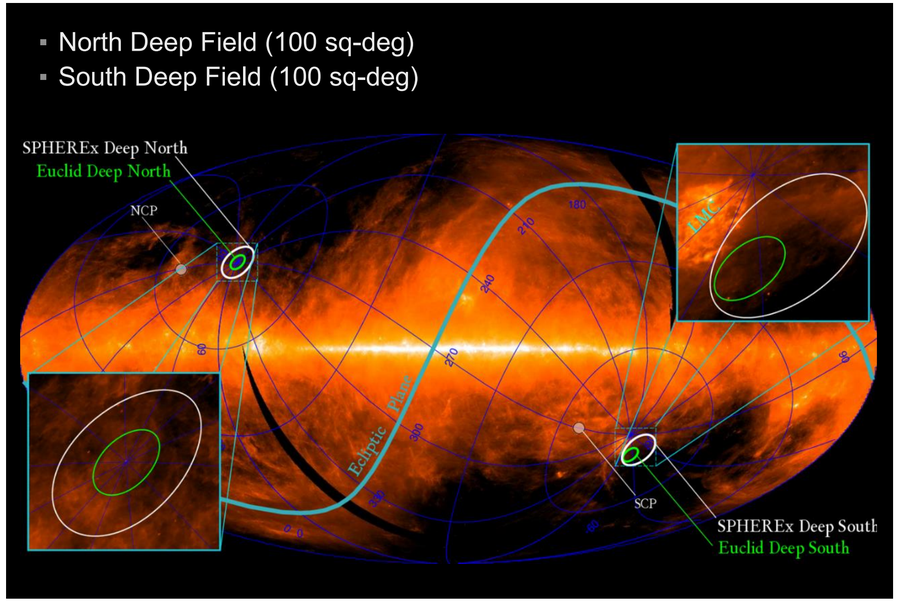
Mandal et al., 2024, ApJ, 968, 28

Dust reverberation mapping: Future possibilites

LSST: Large Synoptic Survey Telescope
SPHEREx: Spectro-Photometer for the History of the Universe, Epoch of Reionization and Ices Explorer



LSST footprint (image credit: LSST community forum)



SPHEREx footprint: NEP and SEP deep field (Image credit:Ja Hwan King)

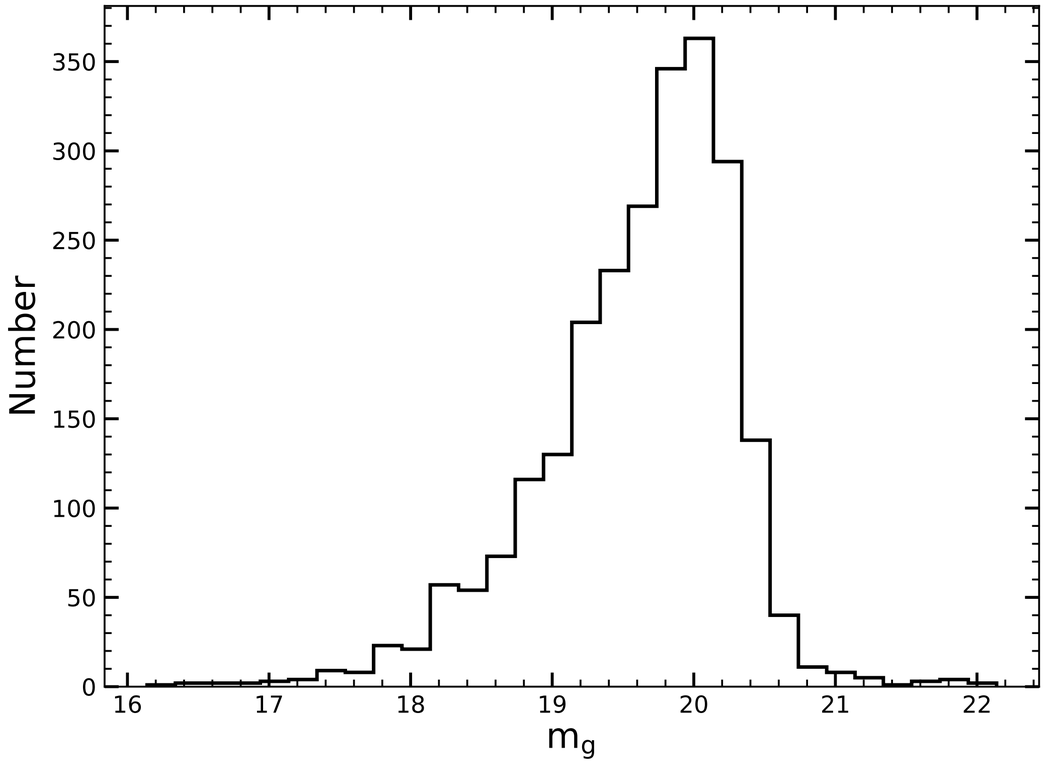
- LSST FOV: 18000 degrees^2
- Filters: u, g, r, i, z, y

- SPHEREx: NEP, SEP (~ each of 100 degrees^2)
- Cover 0.75 to 5 μm range with 96 different colour bands
- Cadence ~ 6 days (with ~6 months seasonal gap)

- Optical data from LSST (SEP field) + ZTF (NEP field)
- IR data from SPHEREx

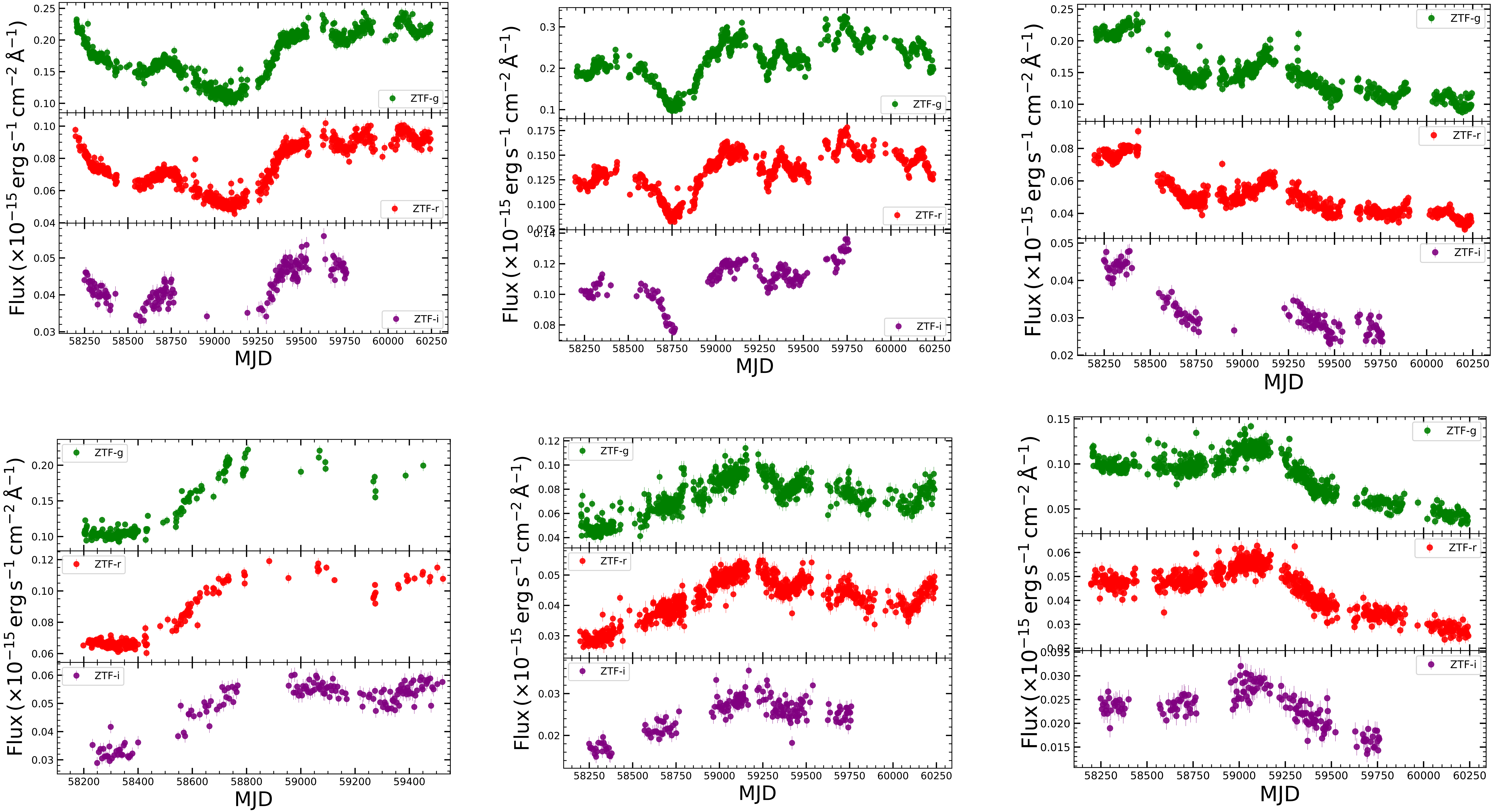
Test with available data: ZTF light curves in SPHEREx NEP field

- **Catalog used for type 1 AGNs:** Byun at al., 2023
- **Number of type 1 AGNs in NEP:** 2427
- **Number of type 1 AGNs in SEP:** 2383
- **ZTF light curves (g,r,i-bands):** For NEP
- Used ZTF DR-20 which starts from 2018
- **Lightcurve available:** 2230 (about 90% targets in NEP)
- **No. of targets with m_g < 19:** 409

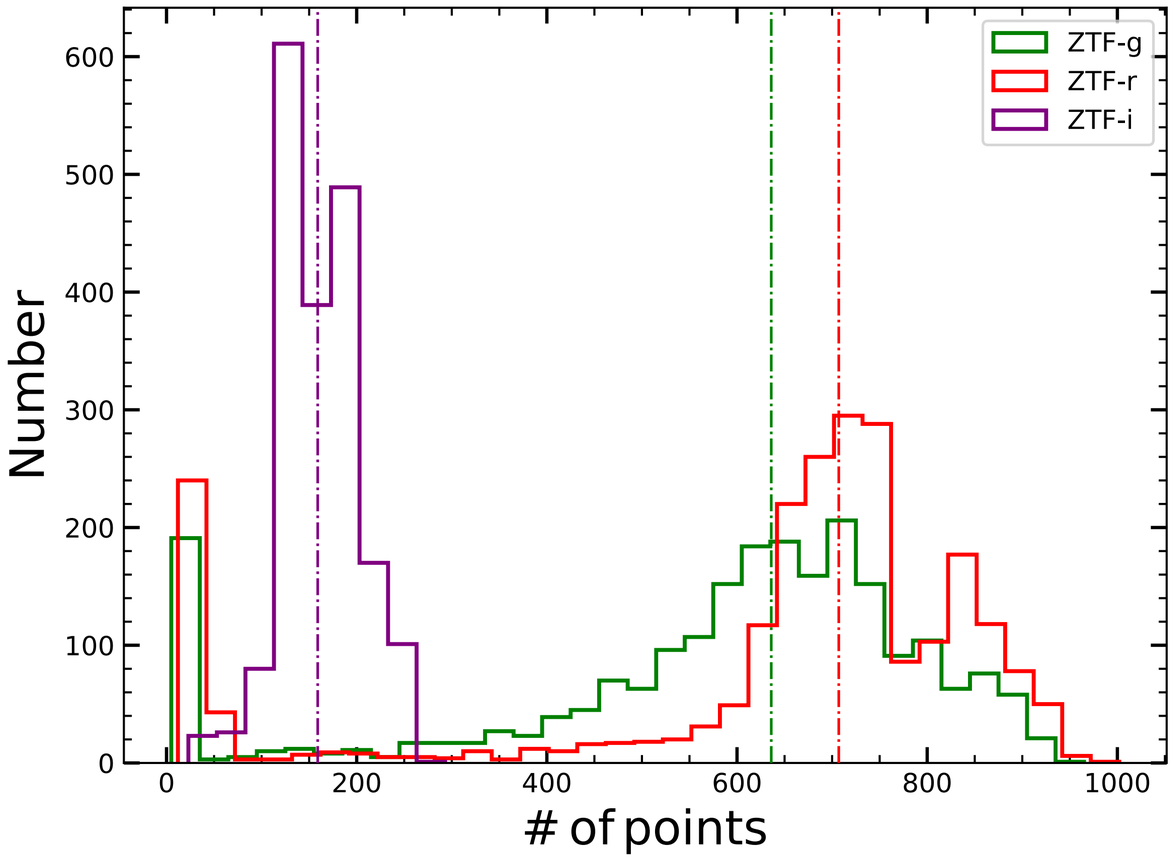


Distribution of g-band apparent magnitude for 2427 AGNs

Examples of optical light curves from ZTF



ZTF light curves in SPHEREx NEP field



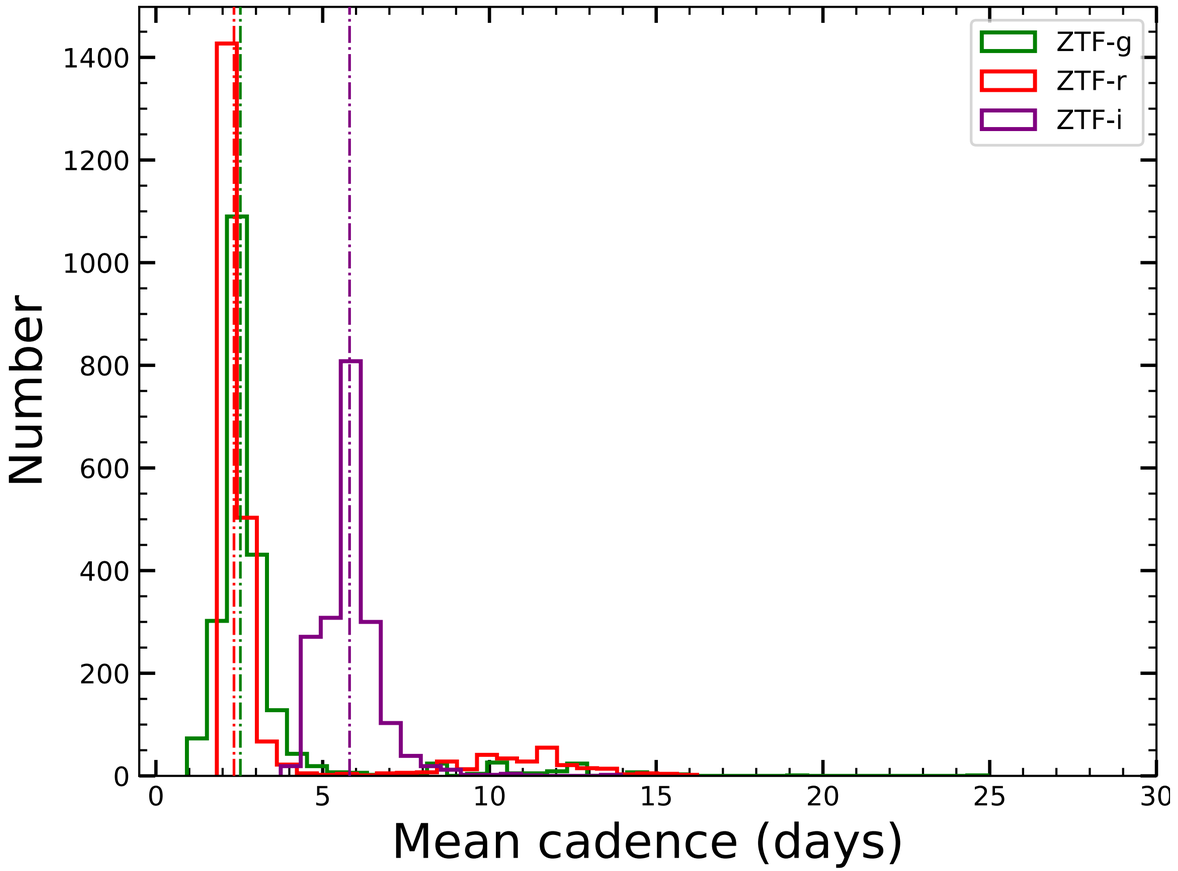
Distribution of the number of data points present in the light curves in ZTF-g,r,i-bands.

Median number of data points (2018 - 2024,April):

ZTF-g band: 636

ZTF-r band: 707

ZTF-i band: 160



Distribution of the mean cadence values in ZTF-g, r and I-bands.

Median cadence values of the sample:

ZTF-g band: 2.5 days

ZTF-r band: 2.3 days

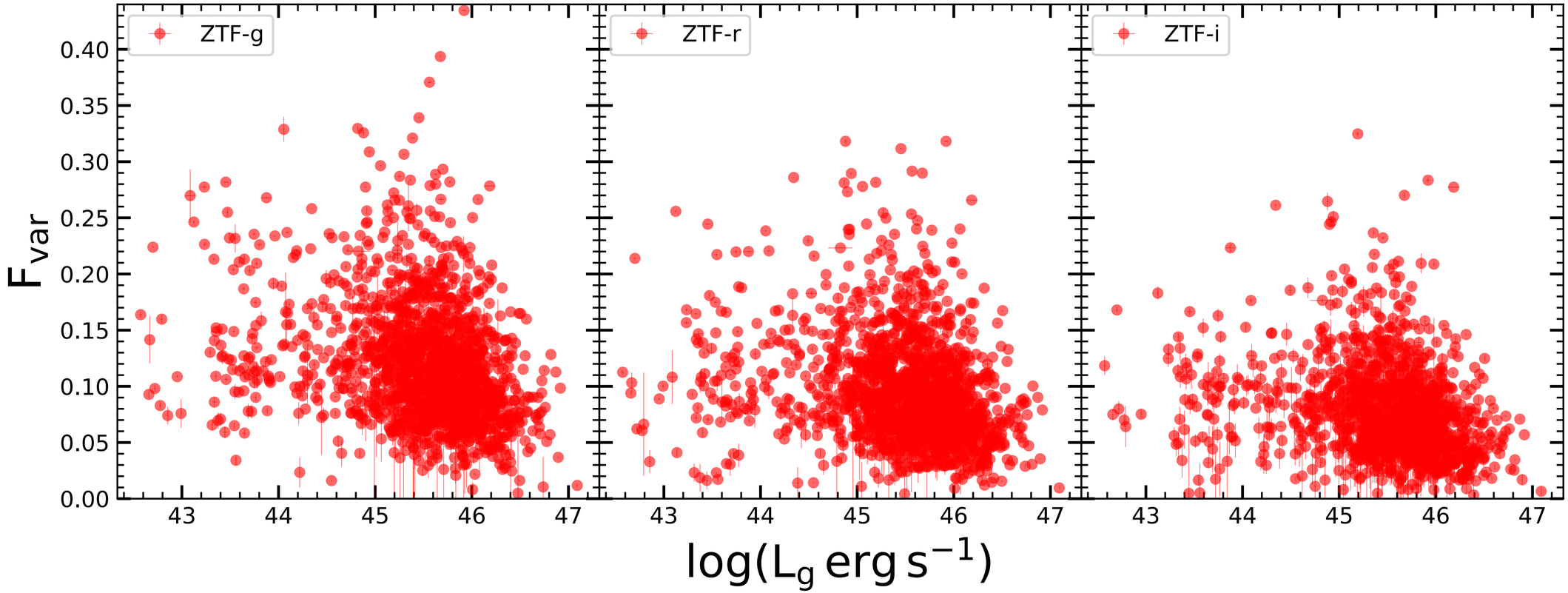
ZTF-i band: 5.8 days

F_{var} Vs luminosity

$$F_{var} = \sqrt{\frac{(\sigma^2 - \bar{\epsilon_{err}^2})}{\bar{x}^2}} \qquad \sigma^2 = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2$$

Where x is the flux value

- **Cover a wide range in luminosity:** $10^{42.3}$ erg/s < L_g < 10^{47} erg/s **(with F_{var} > 10%)**

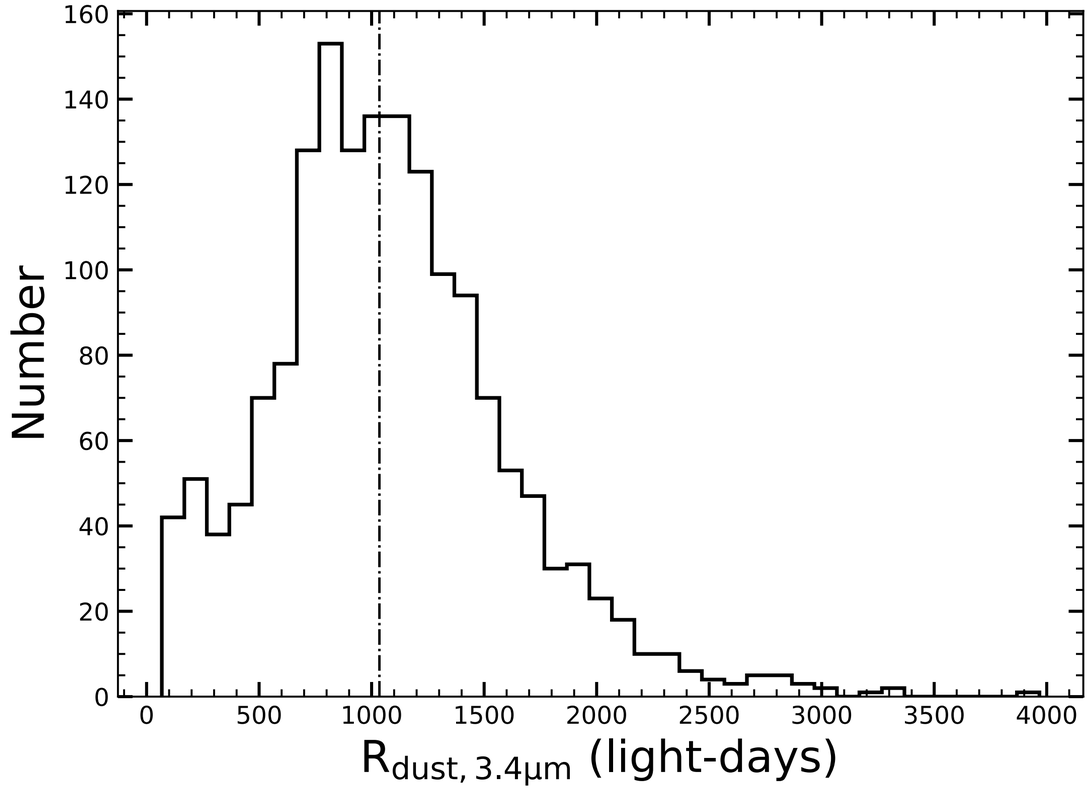


From left to right: Distribution of F_{var} as a function of luminosity in g-band in ZTF-g, r and i-bands

Expected dust torus size for the sample

- Expected torus size ($R_{dust,3.4\mu m}$) based on WISE W1-band (3.4 μm) lags are determined from R_{dust} - L_{bol} relation (Mandal et al., 2024)
- Sample size = 1650 (based on availability of redshift)
- 42.6 erg/s < log(L_g) < 47.1 erg/s
- L_{bol} = 10*L_g (is assumed)
- Median $R_{dust,3.4\mu m}$ = 1035 light-days

- **SPHEREx will continue observation for 2 years. To resolve larger dust lags (>1.5 years) previous complementary IR data from WISE can be used.**



Distribution of expected R_dust,3.4μm

Summary of Dust Reverberation Mapping

- Our preliminary variability tests with ZTF-light curves show that available AGNs in LSST+SPHEREx field are expected to show considerable flux variabilities suitable for RM analysis.

- Using optical data from LSST and IR data from SPHEREx, we can find the extent of dust torus with $R_{dust} < 600$ light-days

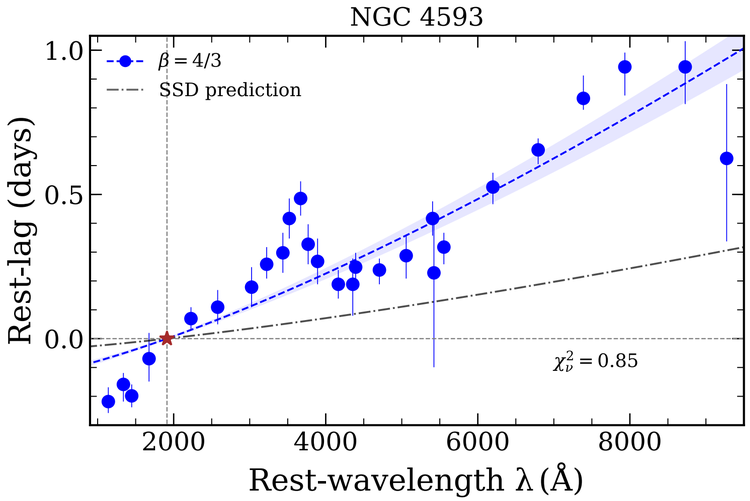
- To find torus size $R_{dust} > 600$ light-days, we can combine data from previous surveys (CRTS, ASAS-SN, ZTF, PTF for optical; and WISE for IR).

- Following the above two steps, we will be able to constrain the torus size - luminosity relationship over a large dynamic range of luminosity.

Accretion disk continuum Reverberation mapping with LSST

- A continuation of the previous talk by Prof. Bozena Czerny

Light curves in multiple optical bands can be used to constrain Size of the continuum emitting regions in AGN



Cackett+2018

$$r = r_0 \left[\left(\frac{\lambda}{\lambda_0} \right)^{\beta} - 1 \right] \; where \; \beta = 4/3$$

r_0: used to find the size of the continuum emitting region

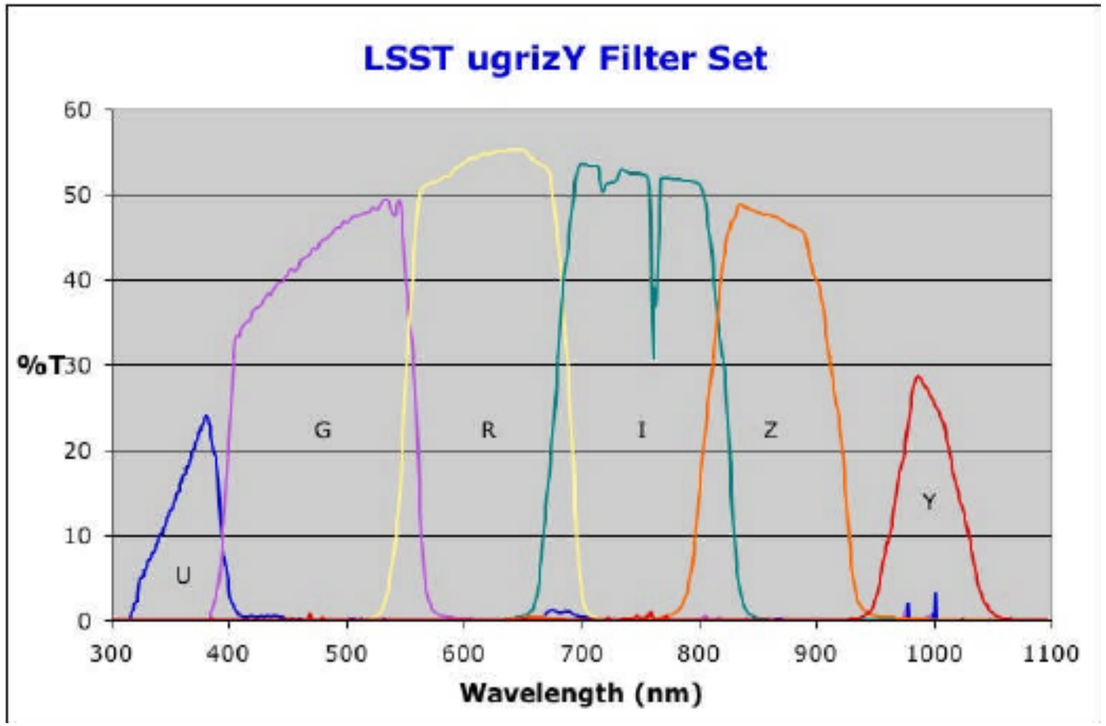
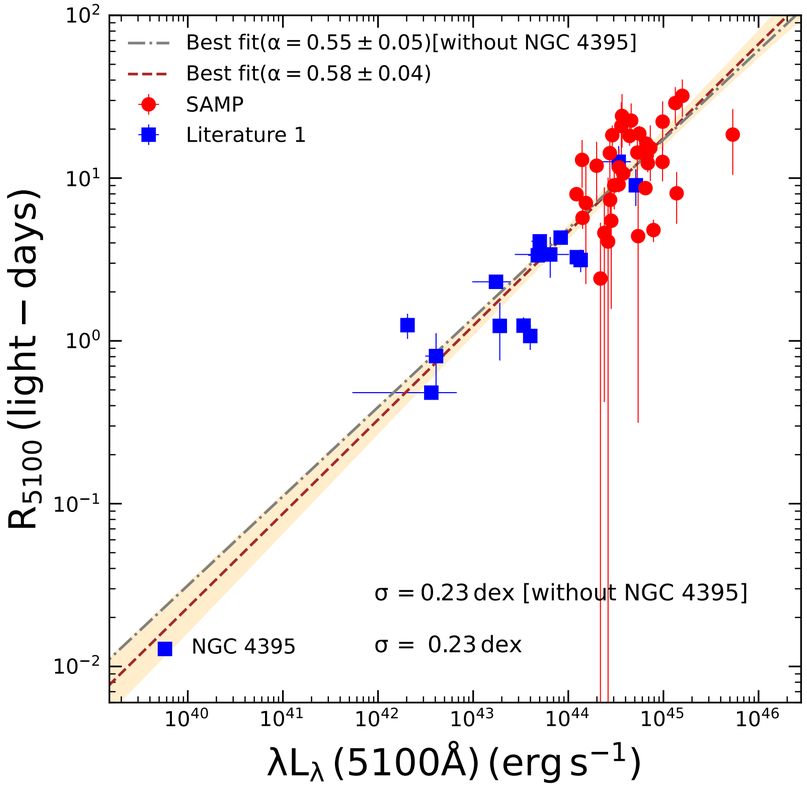
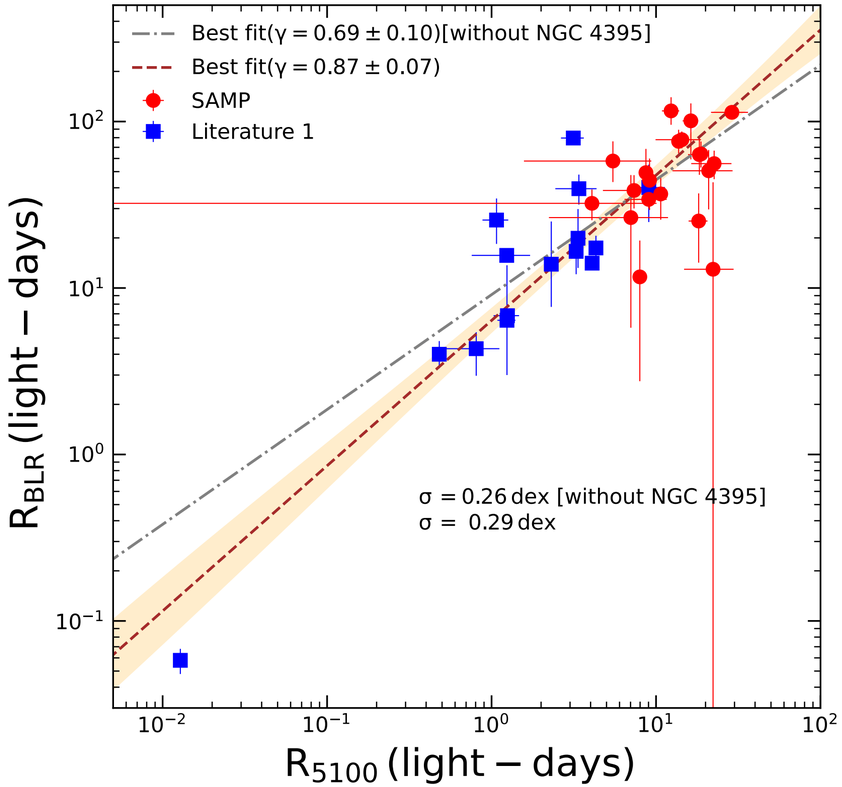


Image credit: Olivier+2006

Constrain disk size vs luminosity, BLR-size vs disk size relations with LSST data



Mandal et al., in preparation



Mandal et al., in preparation

- **Need to constrain R_{5100} - L_{5100} and R_{BLR} - R_{5100} relation over large dynamic range in luminosity: LSST can play an important role**

- **Once R_{BLR} - R_{5100} relationship is established over large dynamic range, can be used as single epoch BH mass estimator.**

Summary of continuum RM from LSST data

- Light curve data in u, g, r, i, z, y bands can be used to find size of the continuum emitting region in accretion disk

- Better constrain the disk size - luminosity and BLR size - disk size relations over large dynamic range using LSST data (specifically for the high luminosity AGNs)


thank you