# Temperature and reverberation delay of circumnuclear hot dust in NGC 4151

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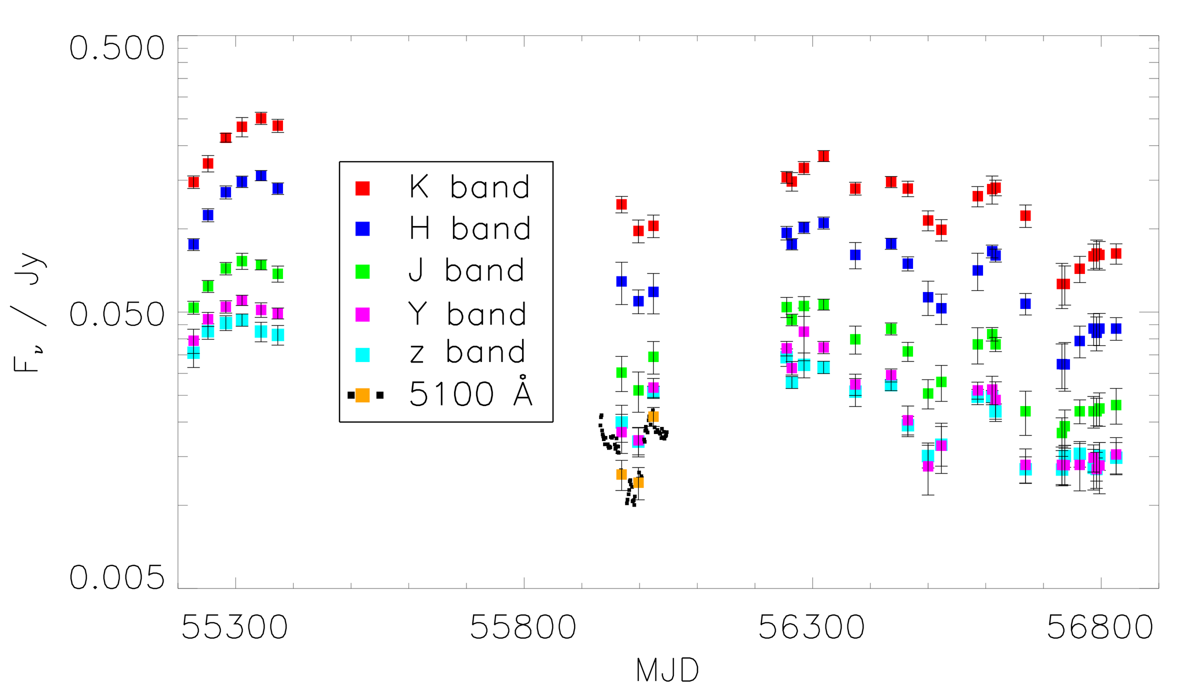
## Abstract

We would like to present our work on optical-nir-broad band dust reverberation of a sample of nearby AGN, with exciting first results on NGC4151, as published in Schnuelle et al. A&A 2013 and recently in Schnuelle et al., A&A 2015, where we discuss that precise ($\leq$ 5% level) photometric monitoring of the AGN dust can be used to trace morphological changes in a given target even without resolving the detailed geometry, i.e. without using interferometry and kilometric baselines. Eventually the combination of NIR-reverberation, interferometry and spectroscopy gives a unique tool to study dynamics of the circumnuclear dust confining the BLR, and our work focusses on working out timescales for torus dust formation, evolution and morphology changes.

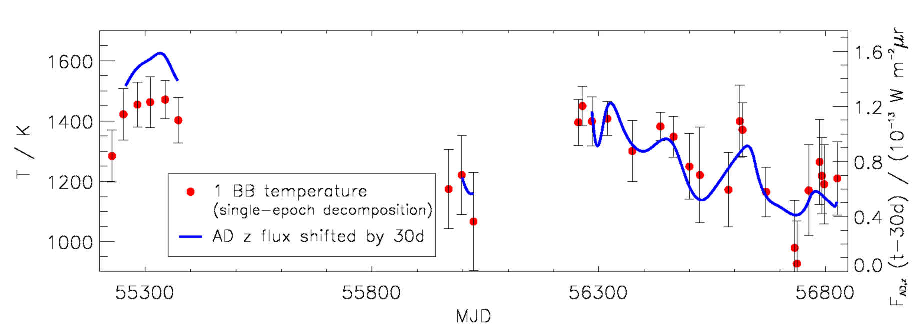
## 1 Observations

- 0.8-2.3$\mu$m photometry for 29 epochs in 2010 Jan - 2014 Jun ($zYJHK$ bands with Omega 2000 camera, Calar Alto, Spain)
- 5100 Å continuum for 76 epochs in 2012 Jan- Apr (Boller & Chivens CCDS spectrograph, MDM Observatory, Kitt Peak)




NGC4151: Calibrated 2010-2014 fluxes. Photometry of the NIR data performed with the `ISIS` image subtraction package (Alard 2000).

## 2 Methods




The circumnuclear hot dust at a radial distance $R_{dust}$ from the accretion disk (AD) re-emits the incident radiation in the NIR, and responds to variations in the AD flux with a characteristic lag time $\tau = R_{dust}/c$. For NGC 4151 in the observed time range, a pre-analysis of our data (see figure, and Schnülle et al. 2013, 2015 for details) shows that also the dust temperature closely tracks the time-shifted AD signal.

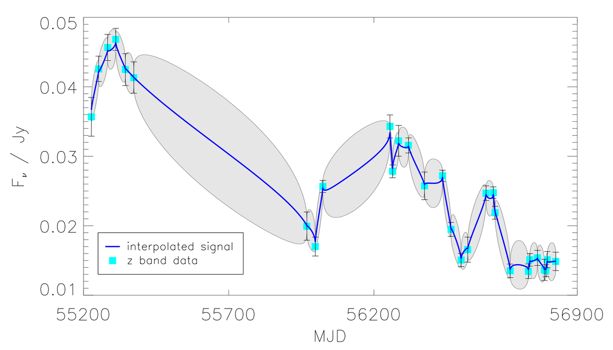
We thus **decompose** our measured total fluxes in each epoch **into power-law (AD) plus blackbody (dust)** component using a **multi-epoch, multiwavelength fit** of the form (with blackbody function $BB(.)$)

$$F_\lambda(\lambda, t, \mathbf{x}) = C_1 \cdot F_z(t) \cdot \lambda^{-\alpha} + BB(C_2, \lambda, T(\nu \cdot F_z(t-\tau)))\,.$$

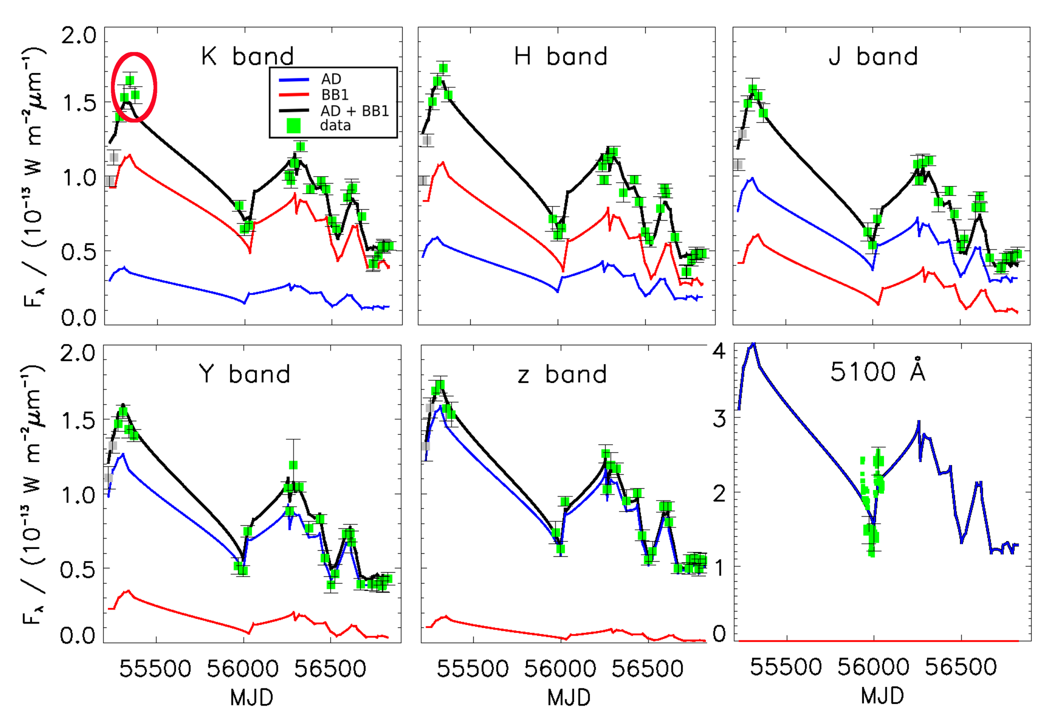
The vector $\mathbf{x}$ comprises all model parameters, e.g. the AD power-law index $\alpha$, hot dust temperature $T$, reverberation delay $\tau$, variability factor $\nu$. In our model, **$T$ evolves in response to AD** ($z$-band) **variations** as

$$\mathrm{d}T(t)/T(t) = \nu \cdot \frac{1}{4} \cdot \mathrm{d}L_z(t-\tau)/L_z(t-\tau)\,.$$

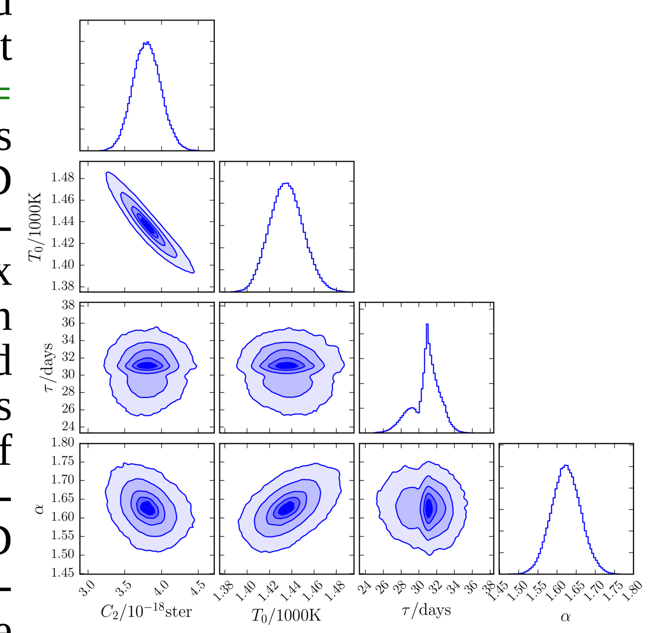
Prior to the fit, the **input AD signal is interpolated** for unmeasured times with the method of Rybicki and Press (Rybicki & Press 1992). The fit is then performed with an **MCMC** (Markov Chain Monte Carlo) type algorithm.




## 3 Results 1: Delay and temperature

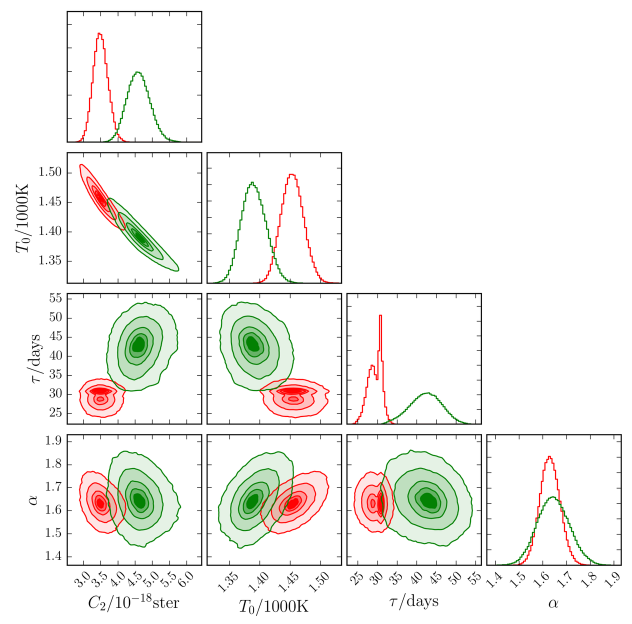



Best fit parameters for delay and initial temperature of the hot dust are **$\tau$ = 31.0 ± 1.6 days and $T_0$ = 1436±15 K**. The model parameters only marginally depend on the AD power-law index (we also considered the case of a changing index $\alpha \propto L_{AD}$). A mismatch between model and data in $JHK$ around MJD 56700 (see upper panel) is caused by insufficient sampling of the input signal. However, the mismatch in the $K$ band around MJD 55350 (red ellipse), seems to indicate that the lag around that date might still be higher than in later epochs. In the right panel, we show the marginalized posterior probability distributions for four model parameters. Contours mark the 10%, 25%, 50%, 85% and 99% confidence intervals. The multimodality of $\tau$ is discussed in boxes 4 + 5.



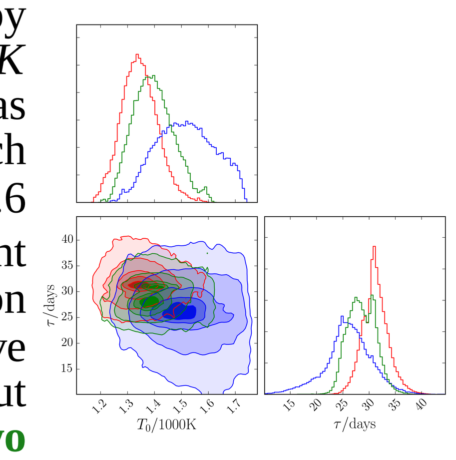
## 4 Results 2: Decrease of the reverberation delay

Splitting the data set into two subsets (set 1: epoch 1-9 (2010 - beginning of 2012 data), set 2: epochs 7-29 (2012 - 2014 data), the fit is improved and we see a **significant decrease in the reverberation lag from $\tau^{2010}$ = 42.5±4.0** in 2010 **to $\tau^{2013}$ = 29.6±1.7** in 2012-2014, as shown by the marginalized posterior probability distributions in the right panel. Moreover, $\tau$ appears multimodal in the 2012-2014 period (cause by different sampling and photometric accuracy excluded), which might point to a **changed dust distribution** between 2010 and 2012-2014.



## 5 Results 3: Detected morphology change / sub-structure?

The resolved bimodality in $\tau^{2013}$ is caused by slightly different delays for the bands $JHK$ (constituting the blackbody emission), as confirmed by performing separate fits for each band , i.e. $\tau_J^{2013}$ = 26.1 ± 4.8, $\tau_H^{2013}$ = 28.9 ± 2.6 and $\tau_K^{2013}$ = 31.4 ± 2.4, pointing to a slight radial extent of the dust within a narrow region around $\tau^{2013}$. Interestingly, what we observe is not just a smoothly extended structure, but at least **two separate blackbodies at two discrete, nearby, but different radii.** This feature is visible in the right panel, especially in the $H$ band ("inflection point" of the two different reverberation delays around $\tau \approx$ 30 days).



On a larger scale, however, we see no sub-structure, but a fairly compact distribution (see Schnülle el a. 2015 for details). Our observations rule out that a second, larger dust component within a 100-light-day radius from the source contributes significantly to the observed near-infrared flux in NGC 4151.

## 6 Conclusions

- **Dust temperature closely tracks AD variations** (delay of ≈ 30 days)
- **No** signatures of any **dust sublimation** (i.e., no increase in the hot dust reverberation delay) traced by our data → hot dust in this galaxy currently located beyond its sublimation radius
- **Hot dust reverberation delay change of ≈13 days (30%) in 2 years**
- **Morphology change** (→ small-scale structure) detected?
- **Compact hot dust distribution, no emission on larger (100d) scales**