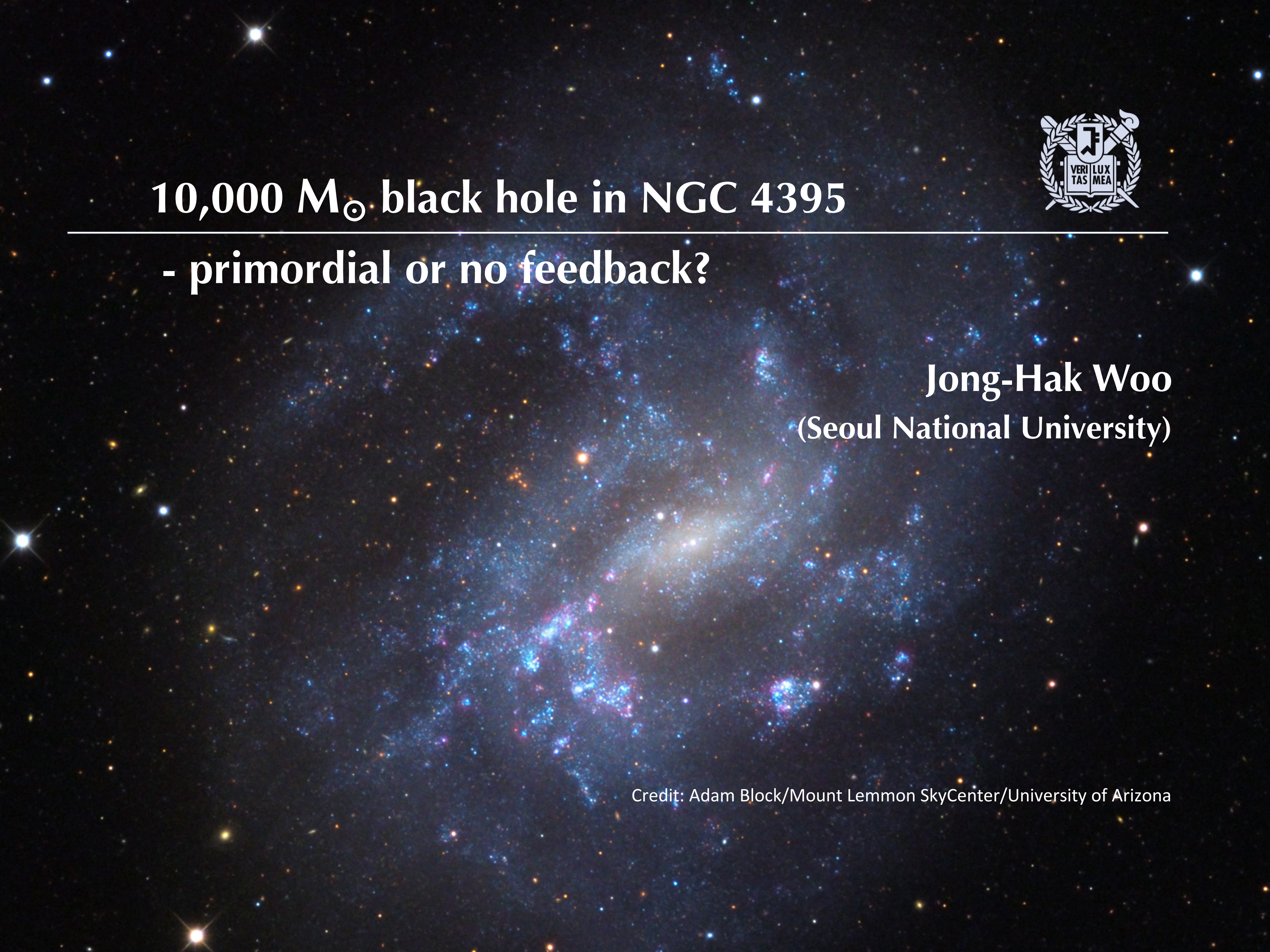
10,000 $M_\odot$ black hole in NGC 4395

- primordial or no feedback?

Jong-Hak Woo

(Seoul National University)

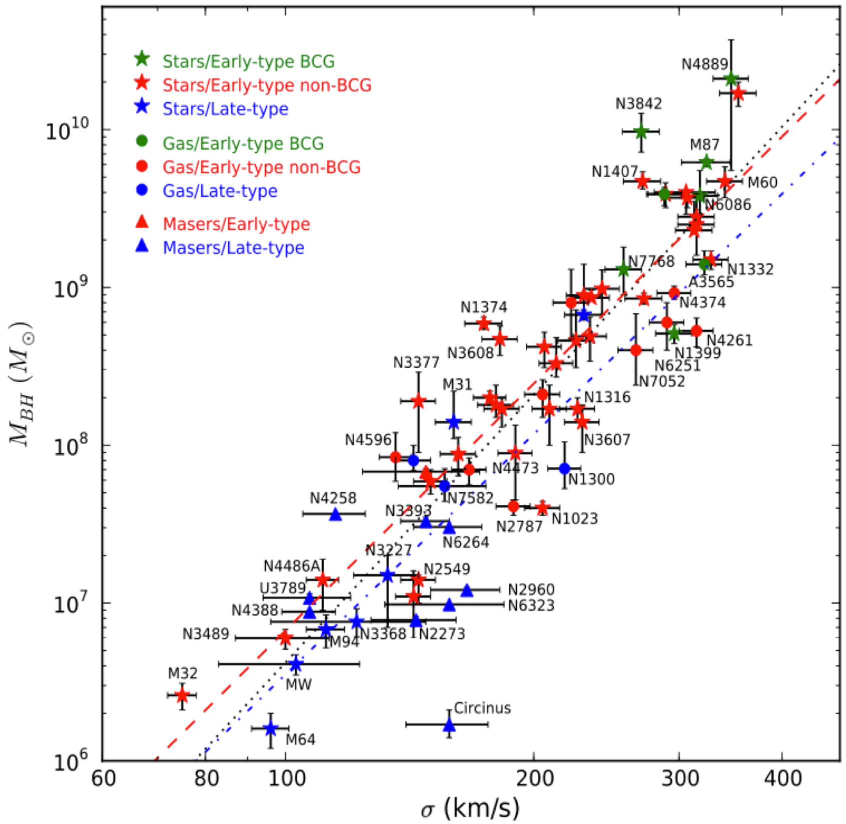


Credit: Adam Block/Mount Lemmon SkyCenter/University of Arizona

Black hole population in the local universe

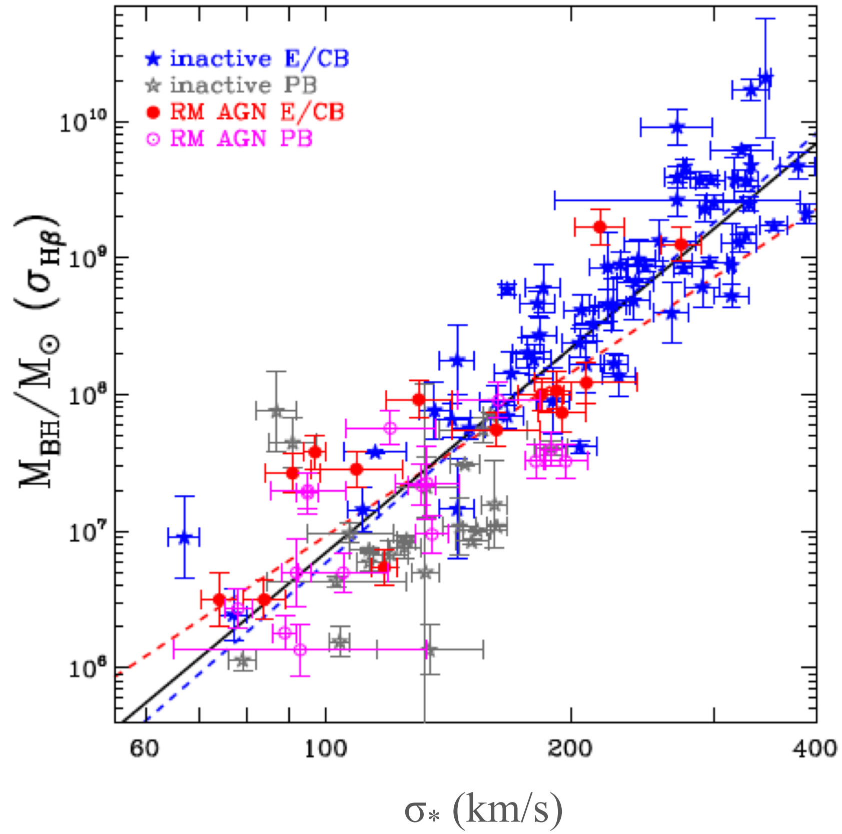
- AGN feedback derives the M-sigma relation?
- lower limit of mass of giant black holes?

dynamical mass (Non-AGN)



McConnell & Ma 2013

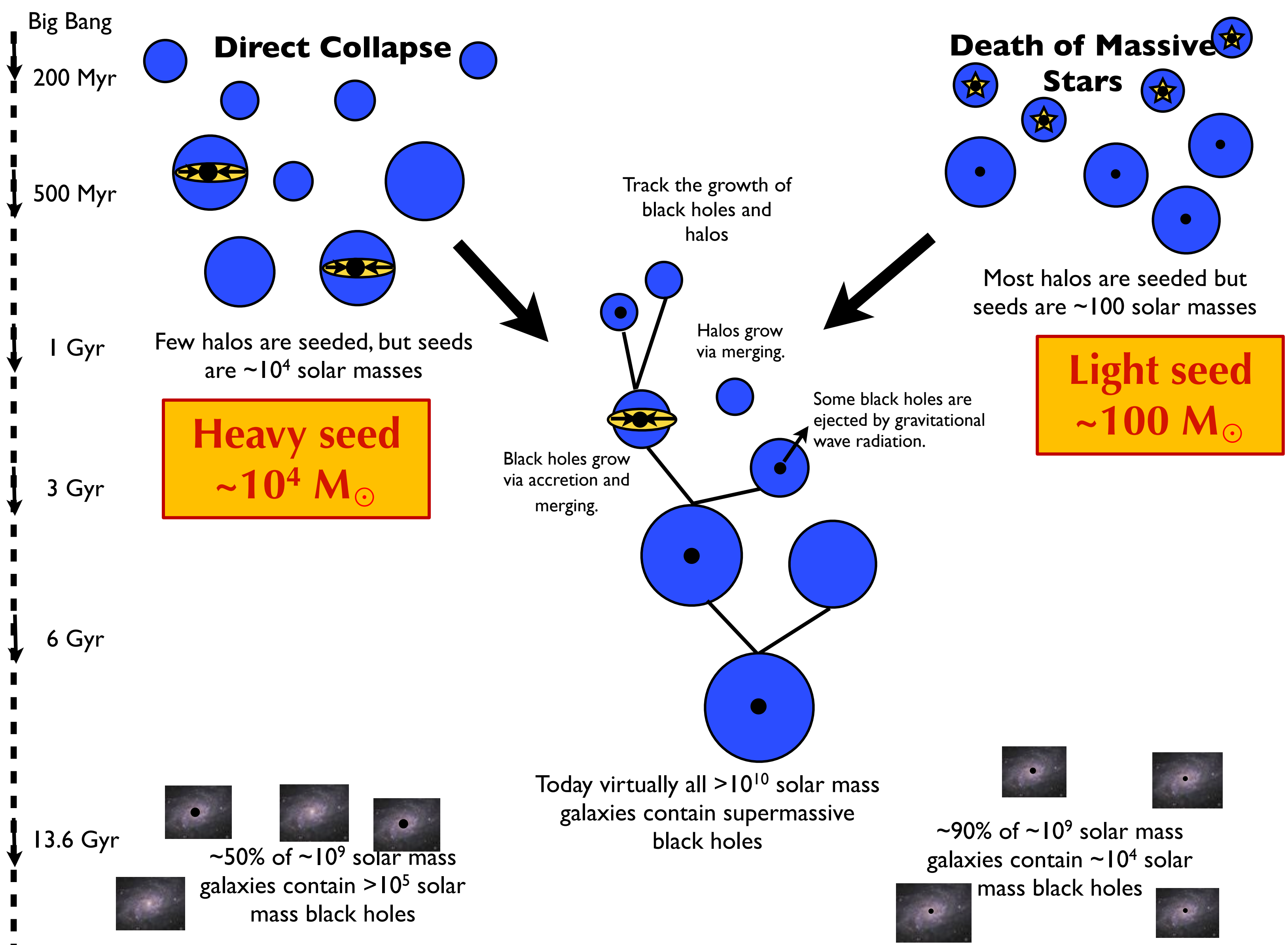
+ reverberation mass (AGN)



Woo + 2015

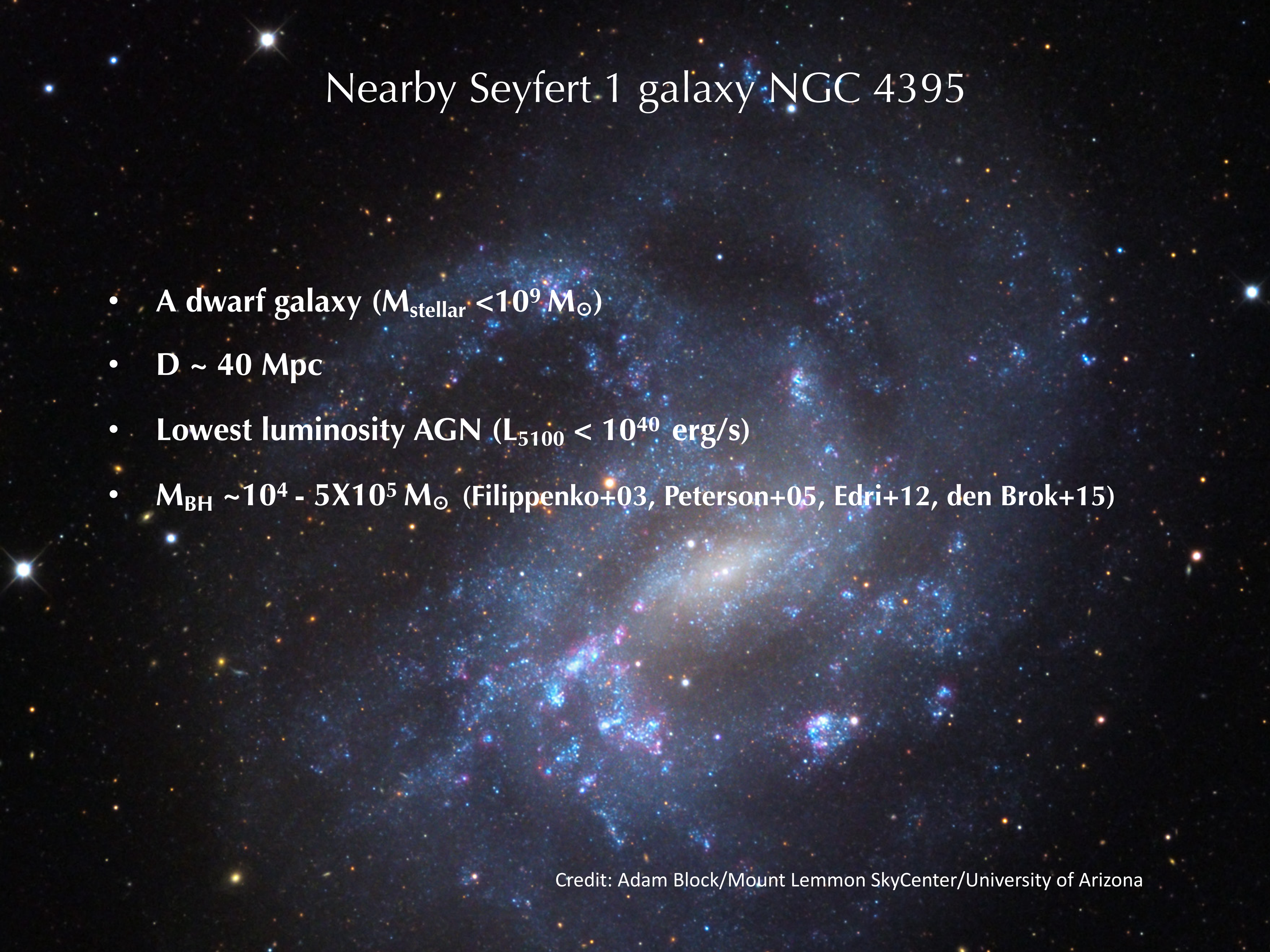
Formation of giant black holes

Greene+12



Nearby Seyfert 1 galaxy NGC 4395

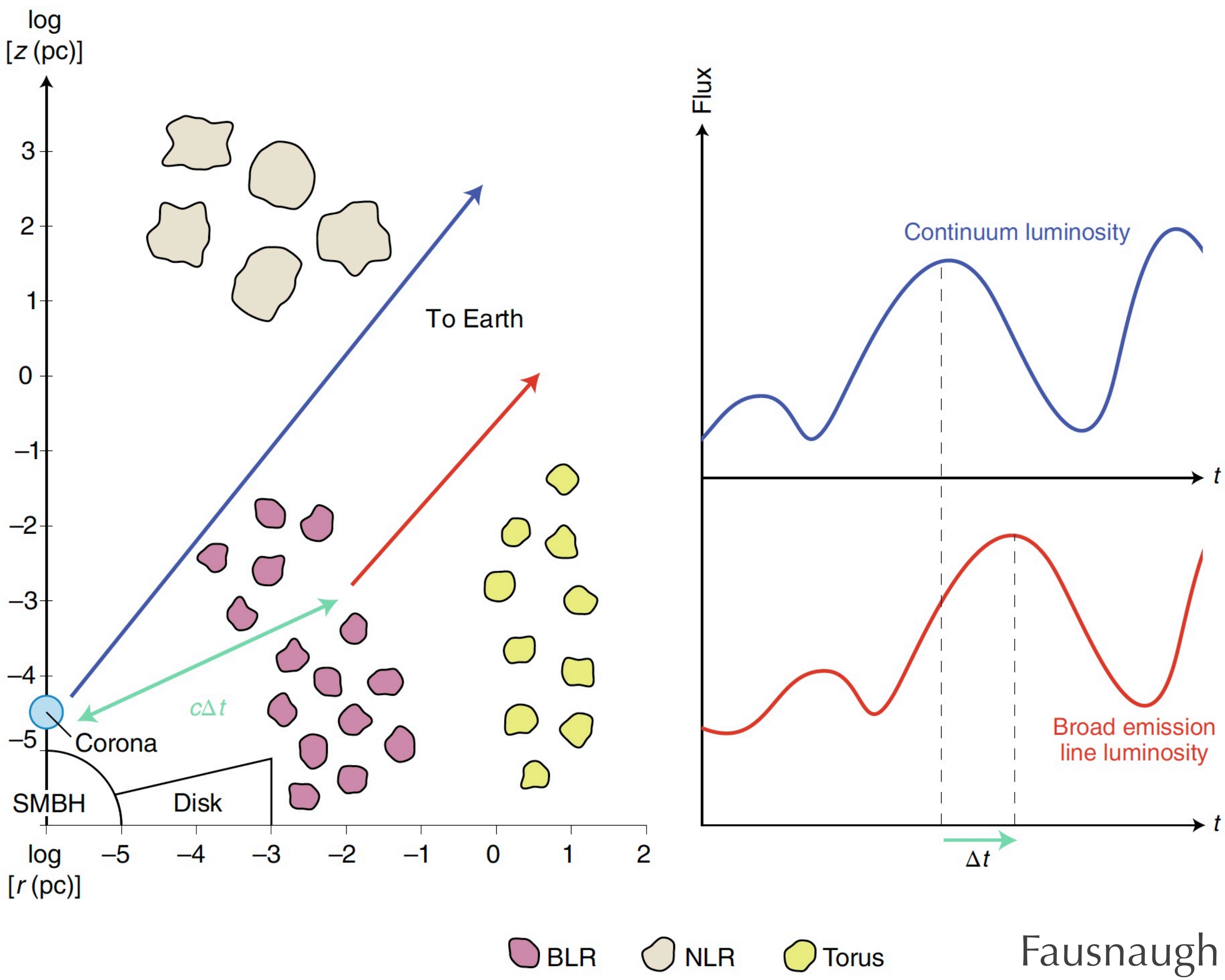
- **A dwarf galaxy ($M_{stellar} < 10^9\ M_\odot$)**
- **D ~ 40 Mpc**
- **Lowest luminosity AGN ($L_{5100} < 10^{40}$ erg/s)**
- **$M_{BH} \sim 10^4$ - $5X10^5\ M_\odot$ (Filippenko+03, Peterson+05, Edri+12, den Brok+15)**



Credit: Adam Block/Mount Lemmon SkyCenter/University of Arizona

Reverberation (light-echo) mapping

$$M_{BH} \propto R_{BLR}\,(c\,\Delta t) \times V^2$$



Fausnaugh + 19

Reverberation-mapping campaign in 2017 & 2018

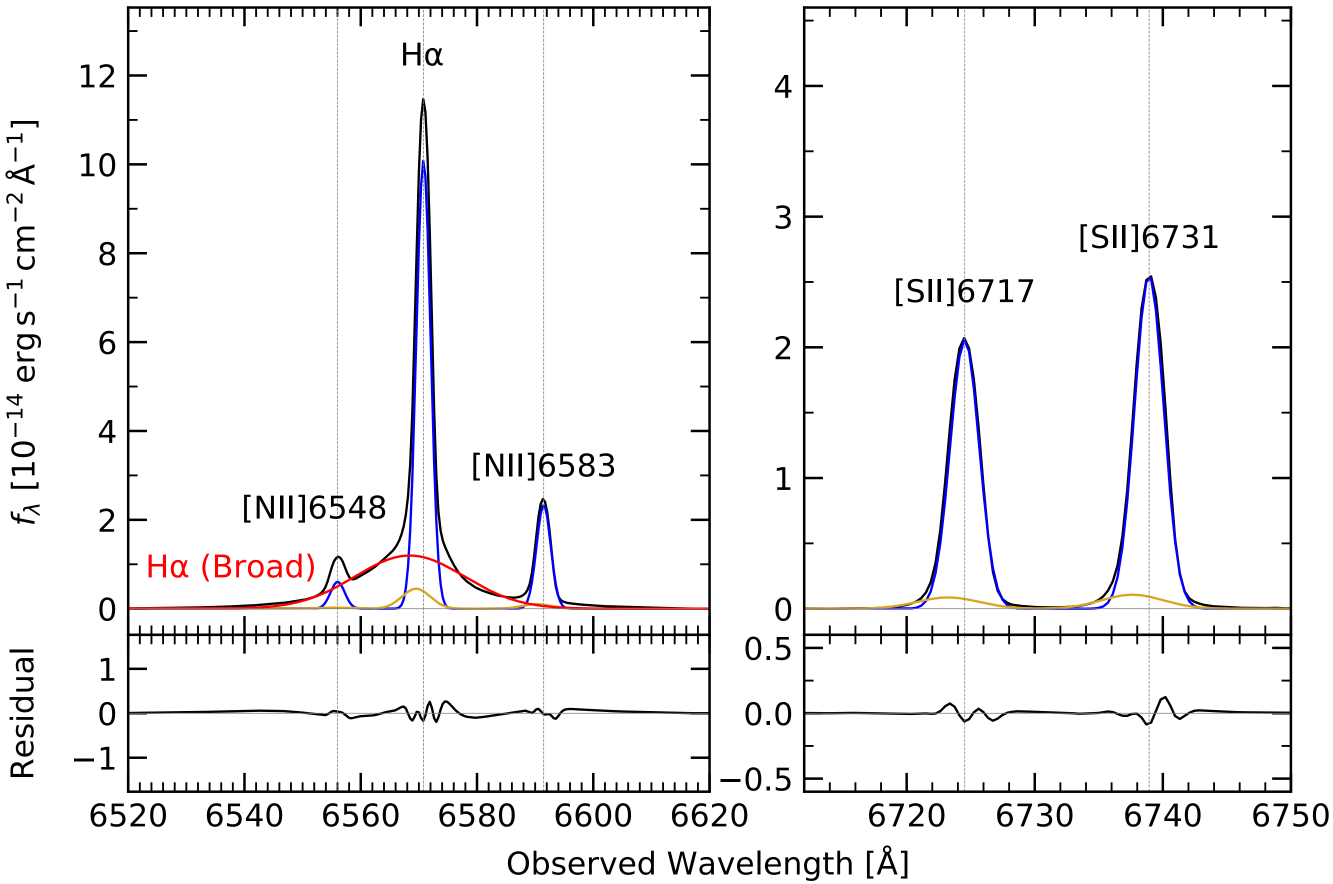
Hojin Cho (SNU),
Collaboration with UMichigan, KASI, + many

- Ha lag is expected to be **1-4 hours** (based on L_{Ha} &previous estimates)
- **5-10 min. time cadence** & > ~1 night base-line required
- Large aperture telescope is needed for spectroscopy monitoring

- Spectroscopy monitoring with Gemini GMOS:
  - 2 consecutive nights in 2017 and 2 consecutive nights in 2018
- Photometry monitoring:
  - V-band imaging with 1m-class telescopes
  - **narrow Hα band imaging** with 2-m class telescopes

NGC 4395 – Gemini GMOS spectroscopy

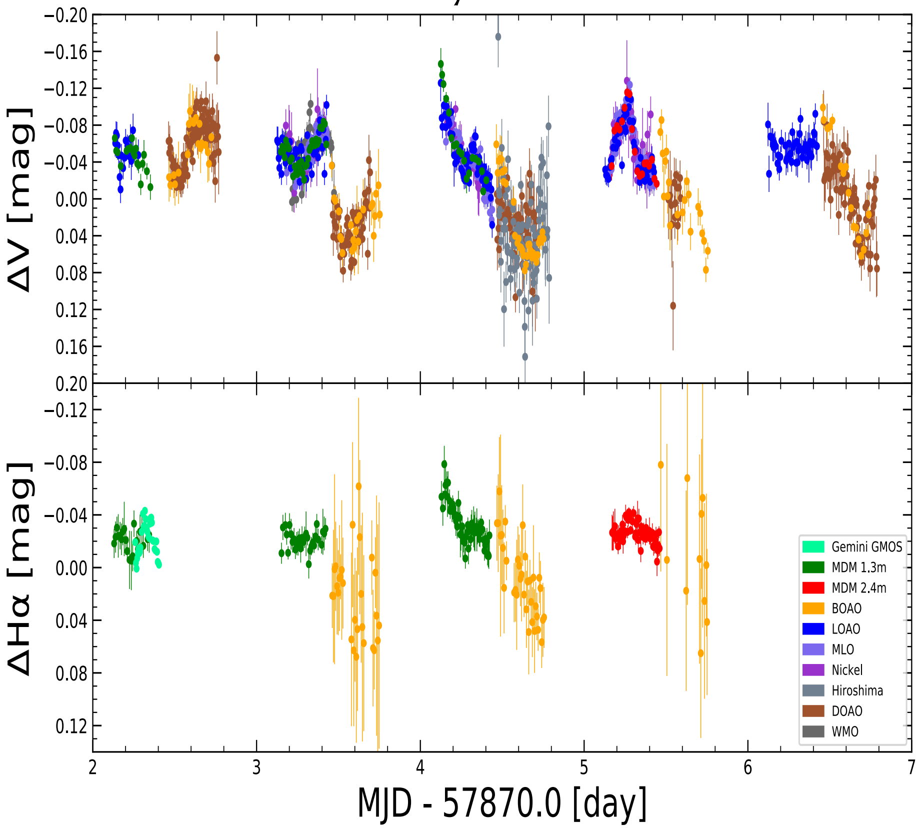
- Gemini spectroscopy monitoring in 2017 & 2018 failed due to storm
- ~3 hour observing provides high quality spectrum and velocity of Hα
- broad Hα line $\boldsymbol{\sigma_{H\alpha}}$ **= 426 km/s** (FWHM = ~1000 km/s)



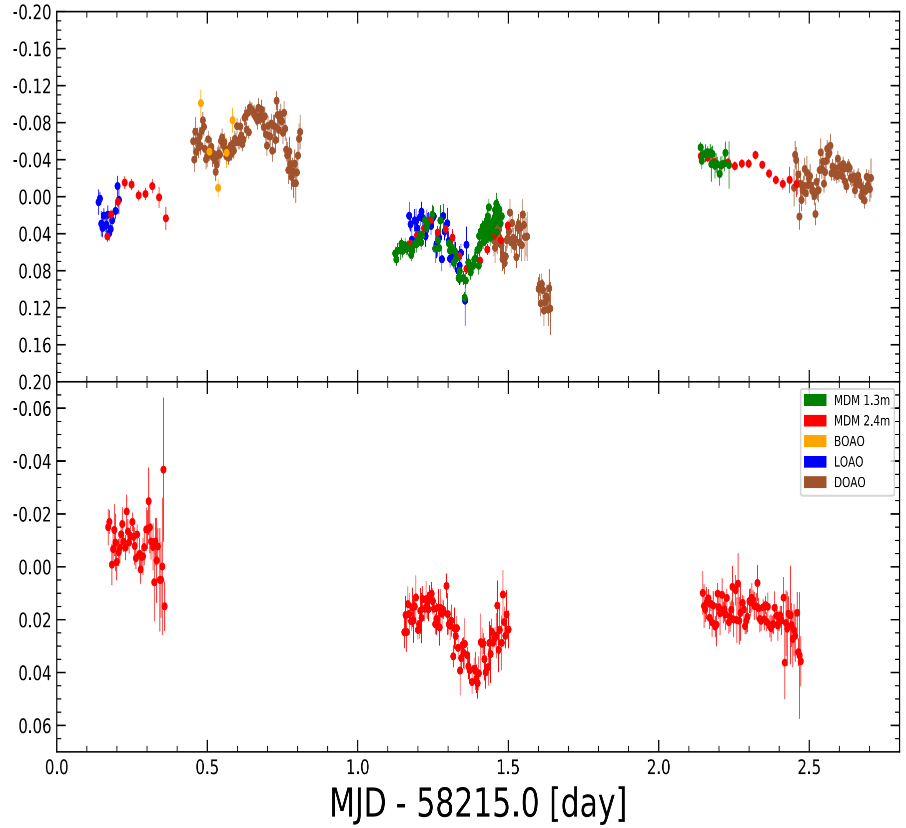
Photometry campaign

- **V-band monitoring** with multiple 1-m telescopes (continuum)
- **Narrow Hα-band monitoring** with 2-m telescopes (Hα line)

5 days in 2017

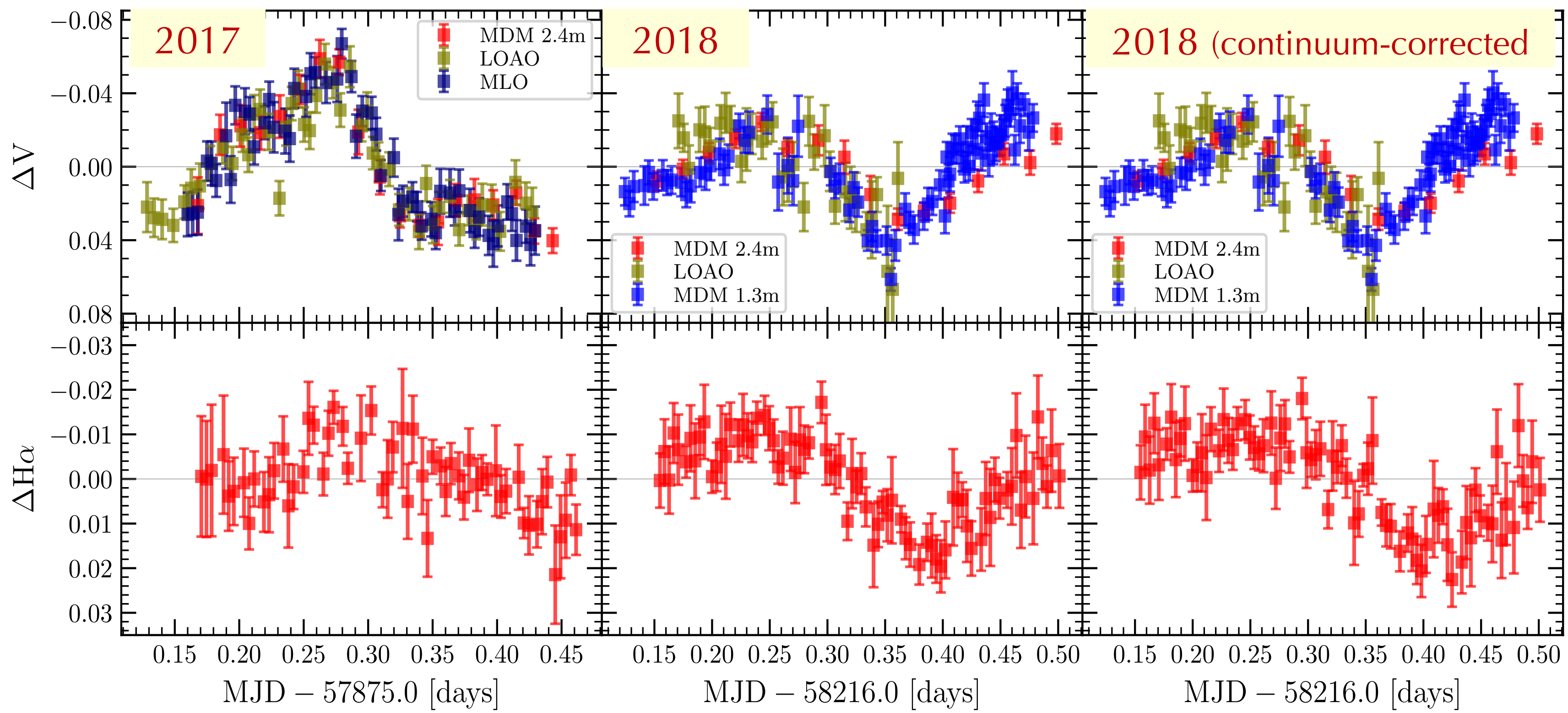


3 days in 2018



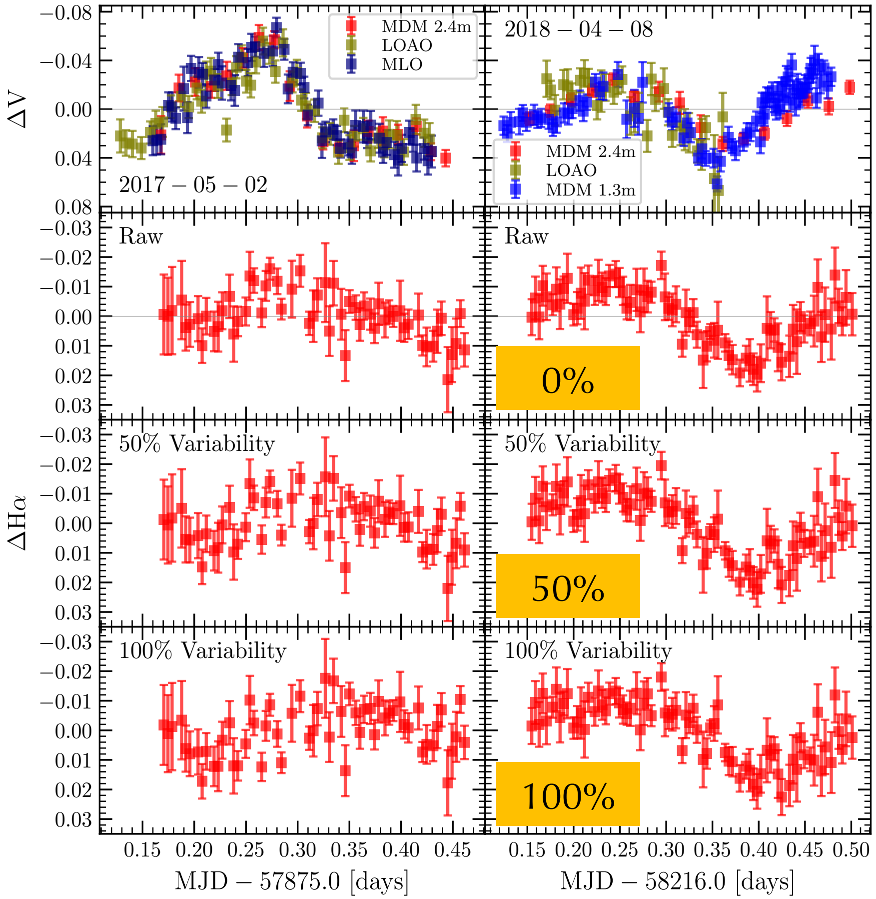
Photometry campaign

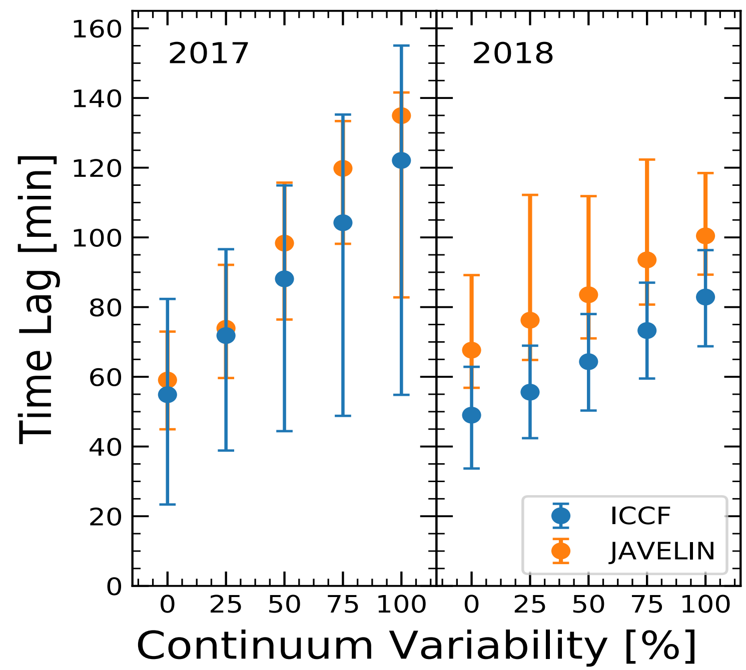
- Best light curves from May-02-2017 and Apr-08-2018
- Continuum flux in the Hα band decreases the time lag.
- Need to correct for the continuum contribution
- On average, **18.3% is continuum** in the Hα band.



Continuum correction for Hα line LC

- On average, **18.3% is continuum** in the Hα band imaging.
  (based on the spectral decomposition with GMOS mean spectrum)
- **Continuum variability is assumed to be 0, 50, 100%** of that in the V-band.
- Subtract continuum flux from each epoch

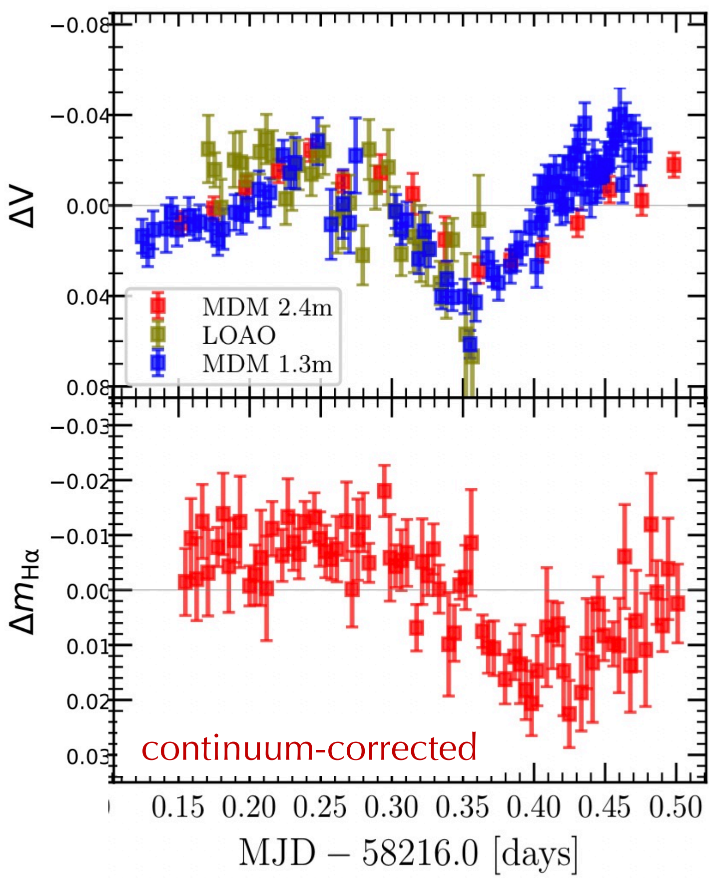




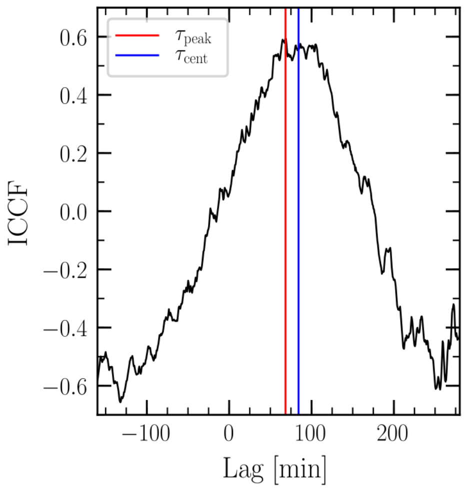
The light travel time to Hα line region is ~83 min.

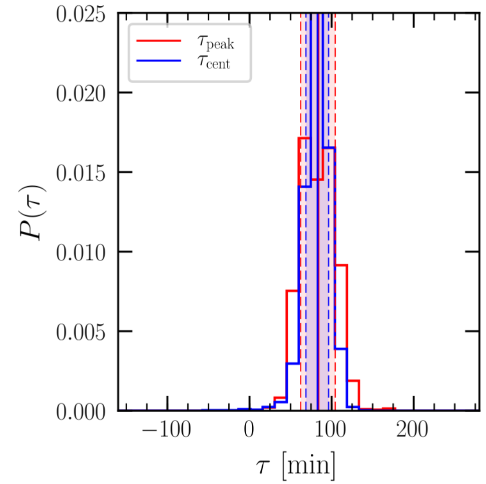
- After correcting for the continuum contribution (100% of V-band var.)
- Time lag measured between V- and Hα-band light curves.

UT 2018-04-08



- Hα lag ~ **83±14 min.** (~10 AU)
- The shortest light-echo with H





Smallest reverberation-based BH mass!

$M_{BH} = f\ R_{BLR}\ \sigma^2 / G$

- $\boldsymbol{\sigma}_{H\alpha} = 426$ km/s
- $R_{BLR} = 83 \pm 14$ minute
- $\mathbf{M_{BH} = 9.1^{+1.5}_{-1.6} \times 10^3\ M_\odot}$ (f =4.47)

From heavy seed?

- Mass is similar to the heavy seed (10^3 -10^4 $M_\odot$ e.g., Wise+ 2019)
- Relic of a primordial black hole?

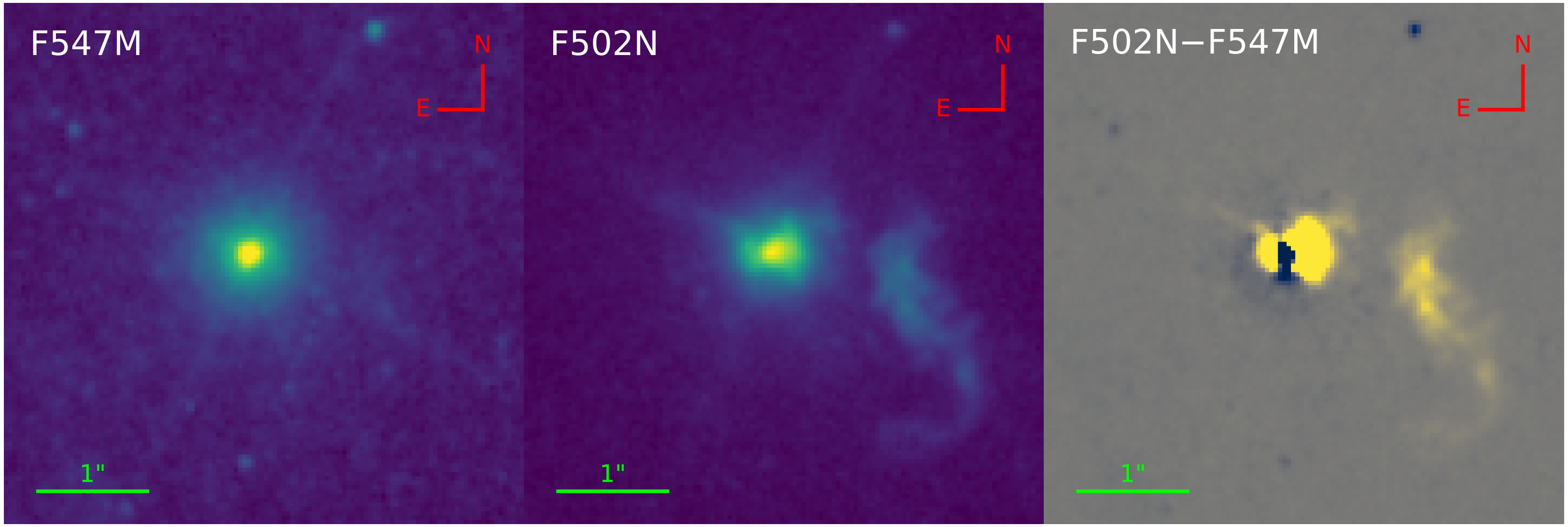
From light seed?

- How easy for a 100 $M_\odot$ BH to grow by a factor of 100?

Comparison with previous studies

- Dynamical mass reported as $\mathbf{4^{+8}_{-3}\times10^5\ M_\odot}$ (den Brok+15)
  - Based on **~1pc** resolution (required resolution is **0.1 pc**)
  - Mass modeling is complicated (AGN continuum +NSC + OIII)
  - an upper limit? - due to contamination by nuclear star cluster

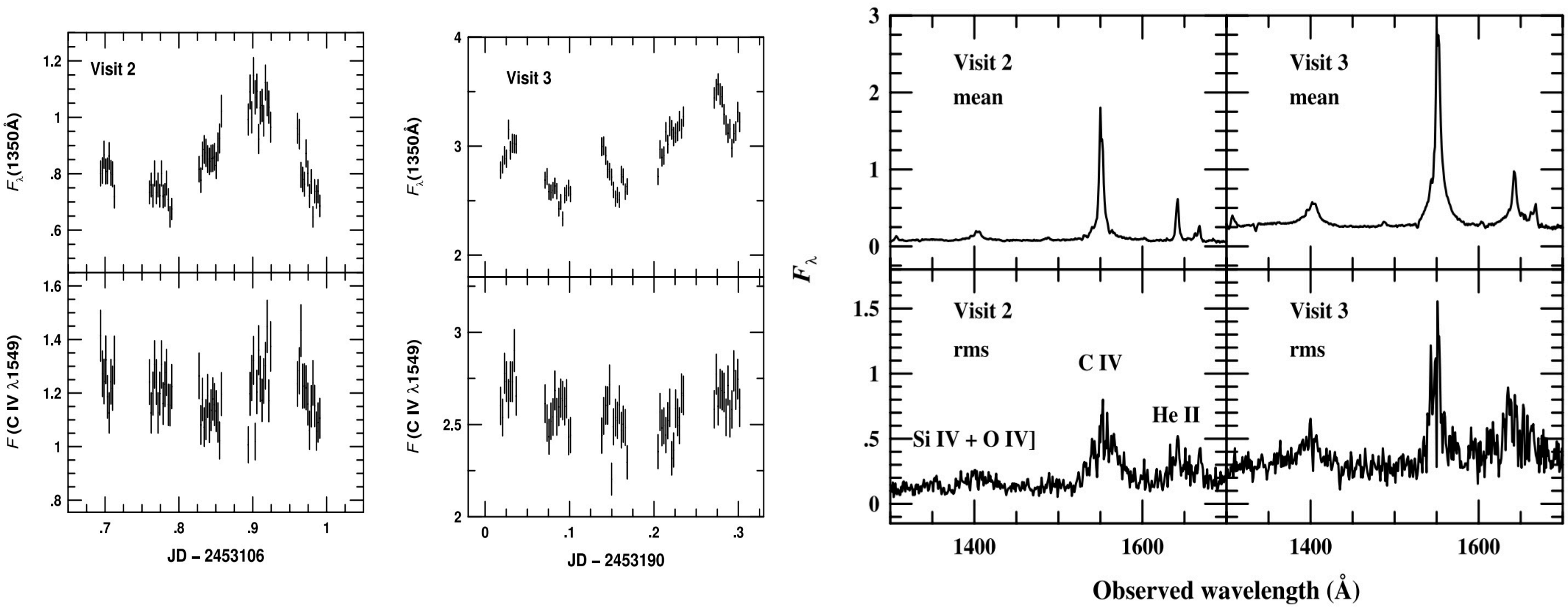
- Continuum-subtracted OIII image shows biconical, but asymmetric, outflow
- The axis of the [OIII] outflow is inclined relative to our line of sight.



Woo + 19, NA

Comparison with previous studies

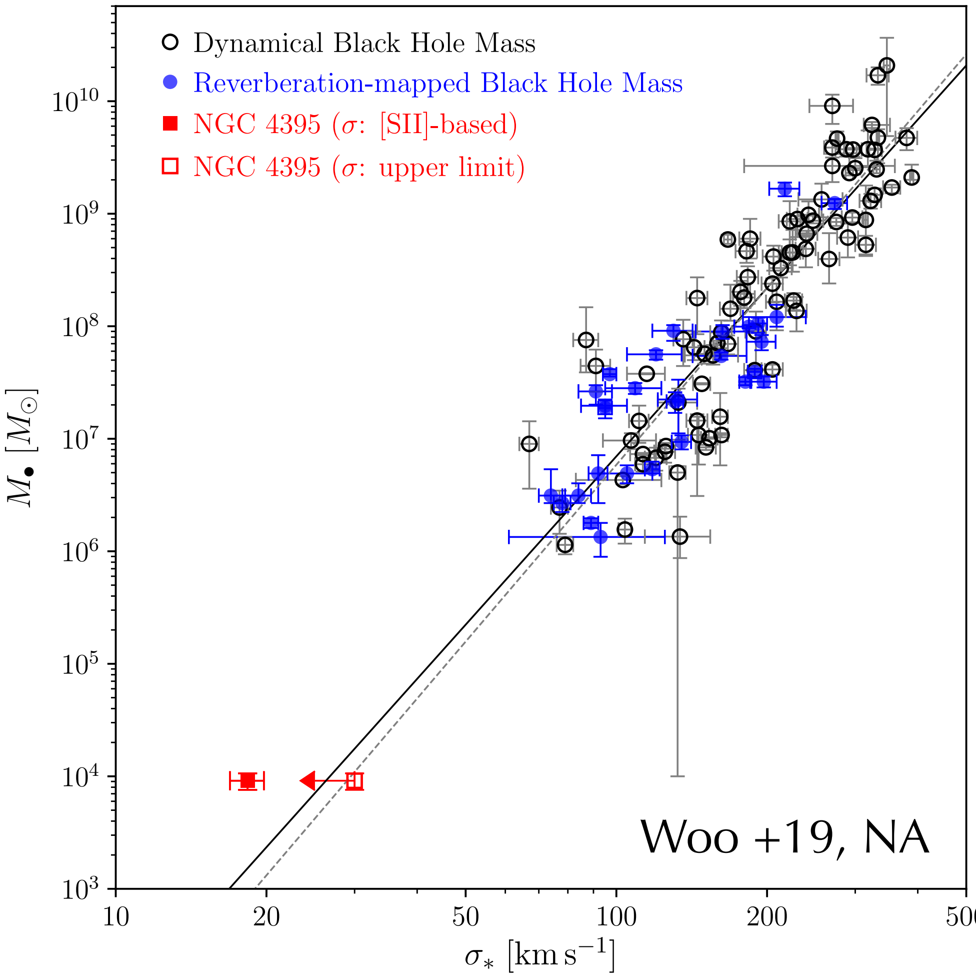
- CIV reverberation mass $\mathbf{3.6 \pm 1.1 \times 10^5\ M_\odot}$ (Peterson+05)
  - ➢ Time lag ~ $\boldsymbol{48^{+24}_{-19}\ min.}$ & $\boldsymbol{66^{+24}_{-29}\ min}$
  - ➢ CIV velocity **σ = ~3000 km/s** measured from rms spectra
  - ➢ With CIV FWHM from mean spectrum, **mass becomes ~2 ×10⁴** $\mathbf{M_\odot}$, consistent with our measurement
  - ➢ Difference in rms and mean spectra, low S/N in rms spectrum, etc



Peterson + 05

Intermediate-mass black hole follows M-sigma relation

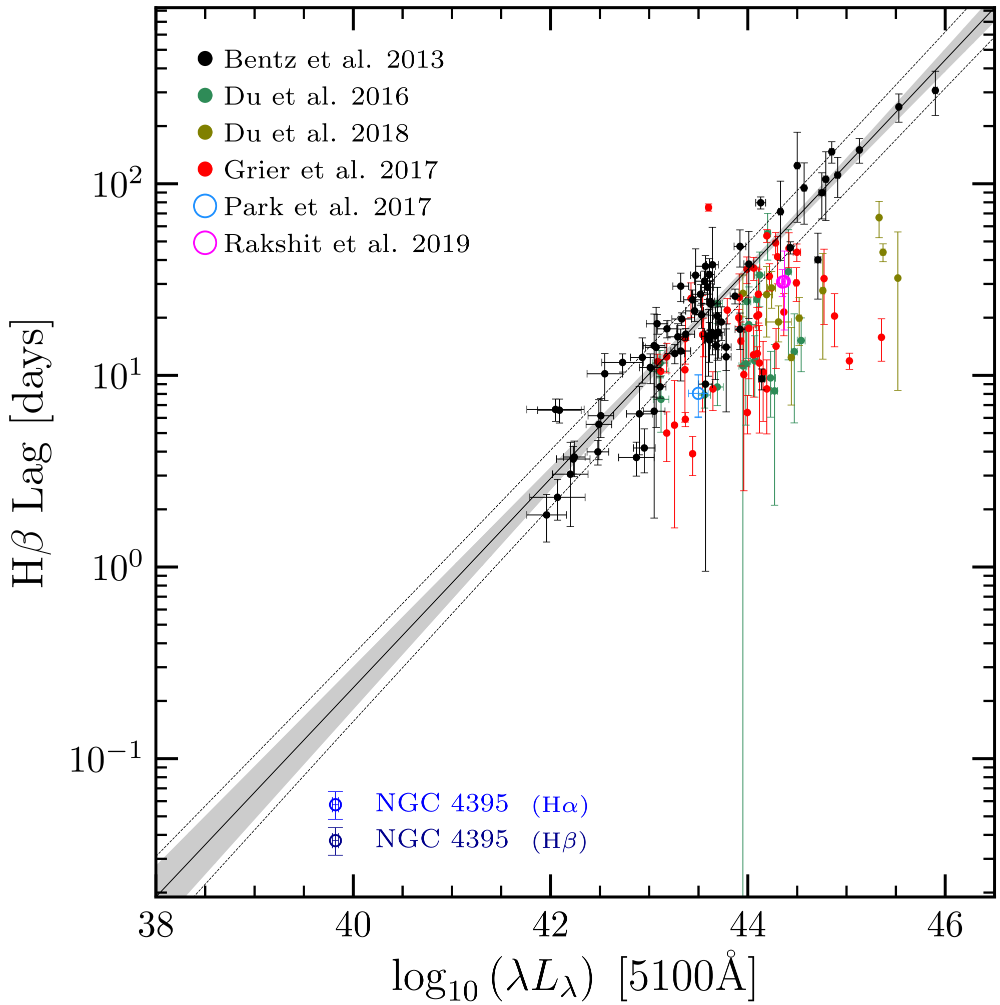
- NGC 4395, a dwarf galaxy hosts an IMBH.
- $\mathbf{M_{BH} = 9.1^{+1.5}_{-1.6} \times 10^{3}\ M_{\odot}}$ (f =4.47)
- $\boldsymbol{\sigma_*} \sim \boldsymbol{\sigma_{\rm SII}}$ = 18±1km/s (stellar lines undetected)
- $\boldsymbol{\sigma_*}$ < 30 km/s (Filippenko+03)
- **AGN feedback/self-regulation not required?**



Size (R_{BLR}) – luminosity relation

- Hα R_{BLR} = 83±14 min.
- Log L_{5100} = 39.8 (erg/s), after subtracting NSC ($4X10^{39}$ erg/s, den Brok+15)

- Uncertain slope?
- large scatter
- How reliable indirect BH mass estimates are ?



Cho +19 in prep.

Summary

- We report a ~10,000 $M_\odot$ BH in NGC 4395 based on the reverberation mapping study. This is the smallest reverberation mass, and a clear case for an IMBH.
- Reverberation mapping can be an effective method for searching for IMBHs, particularly when spatial resolution is not enough to probe the influence of BH's gravity.
- NGC 4395 follows the M-sigma relation of supermassive BHs, suggesting that AGN feedback is not required for the correlation, at least at this mass scale.