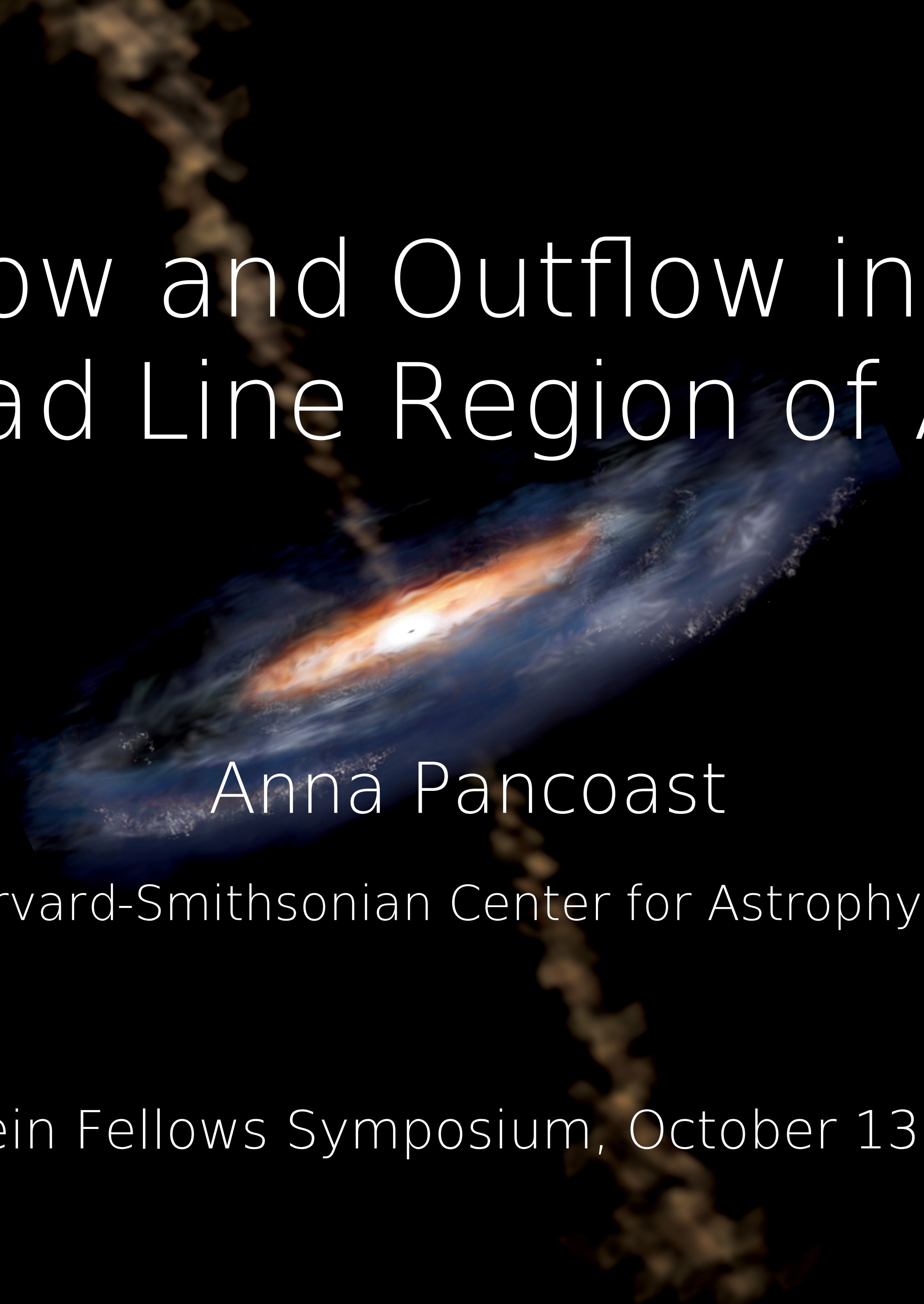
Inflow and Outflow in the Broad Line Region of AGN



Anna Pancoast

(Harvard-Smithsonian Center for Astrophysics)

Einstein Fellows Symposium, October 13, 2017

Collaborators:

Catherine Grier (PSU)
Michael Fausnaugh (OSU)
Peter Williams (UCLA)
Brendon Brewer (U. Auckland)
Tommaso Treu (UCLA)
Aaron Barth (UCI)
Keith Horne (St. Andrews)

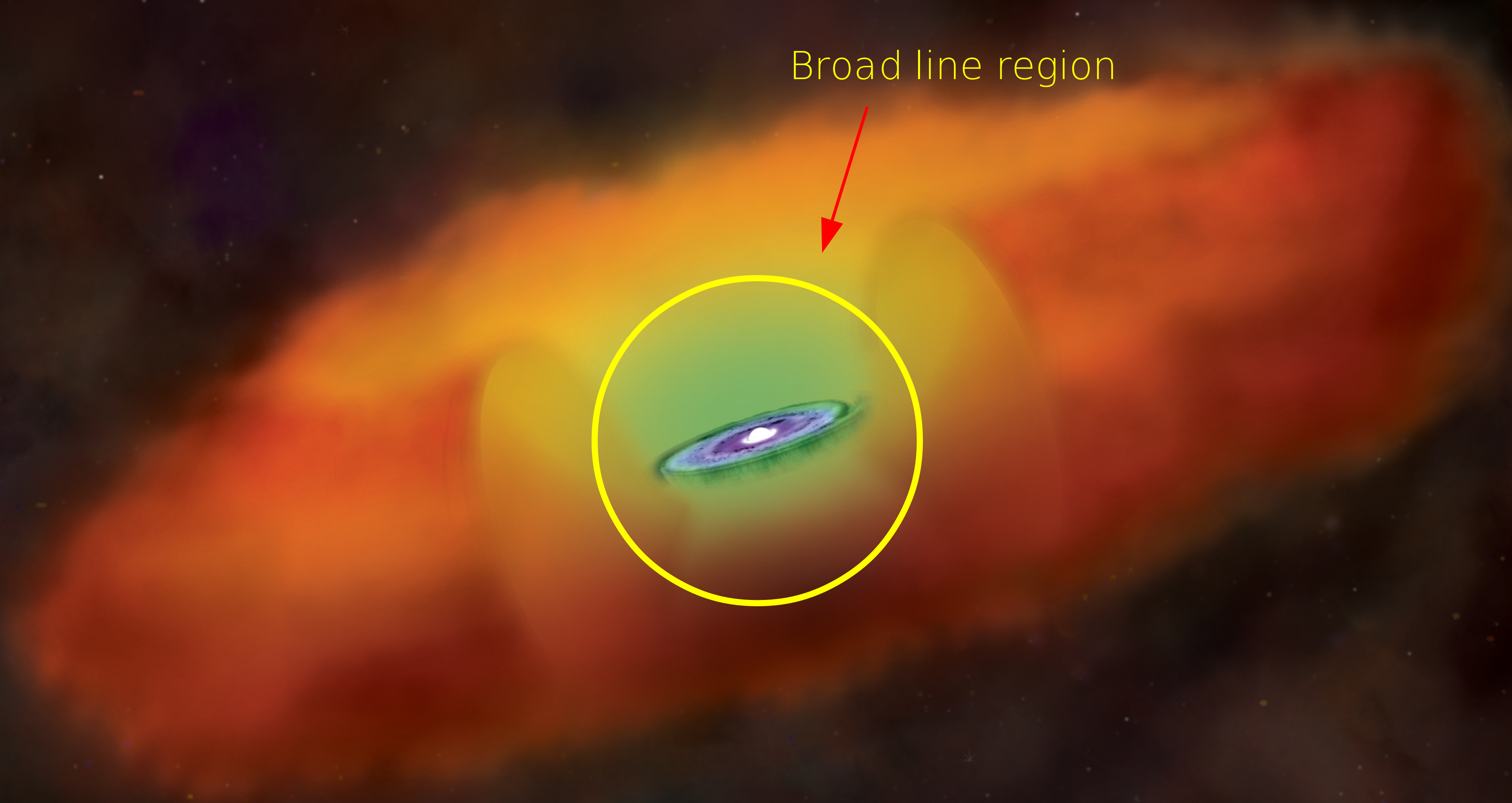
Lick AGN Monitoring Project (LAMP) 2008, 2011, and 2016 reverberation mapping campaigns

OSU 2010, 2014 reverberation mapping collaboration

AGN STORM collaboration

LCO AGN Key Project collaboration

Measuring black hole masses in AGN



Credit: NASA/CXC/M.Weiss

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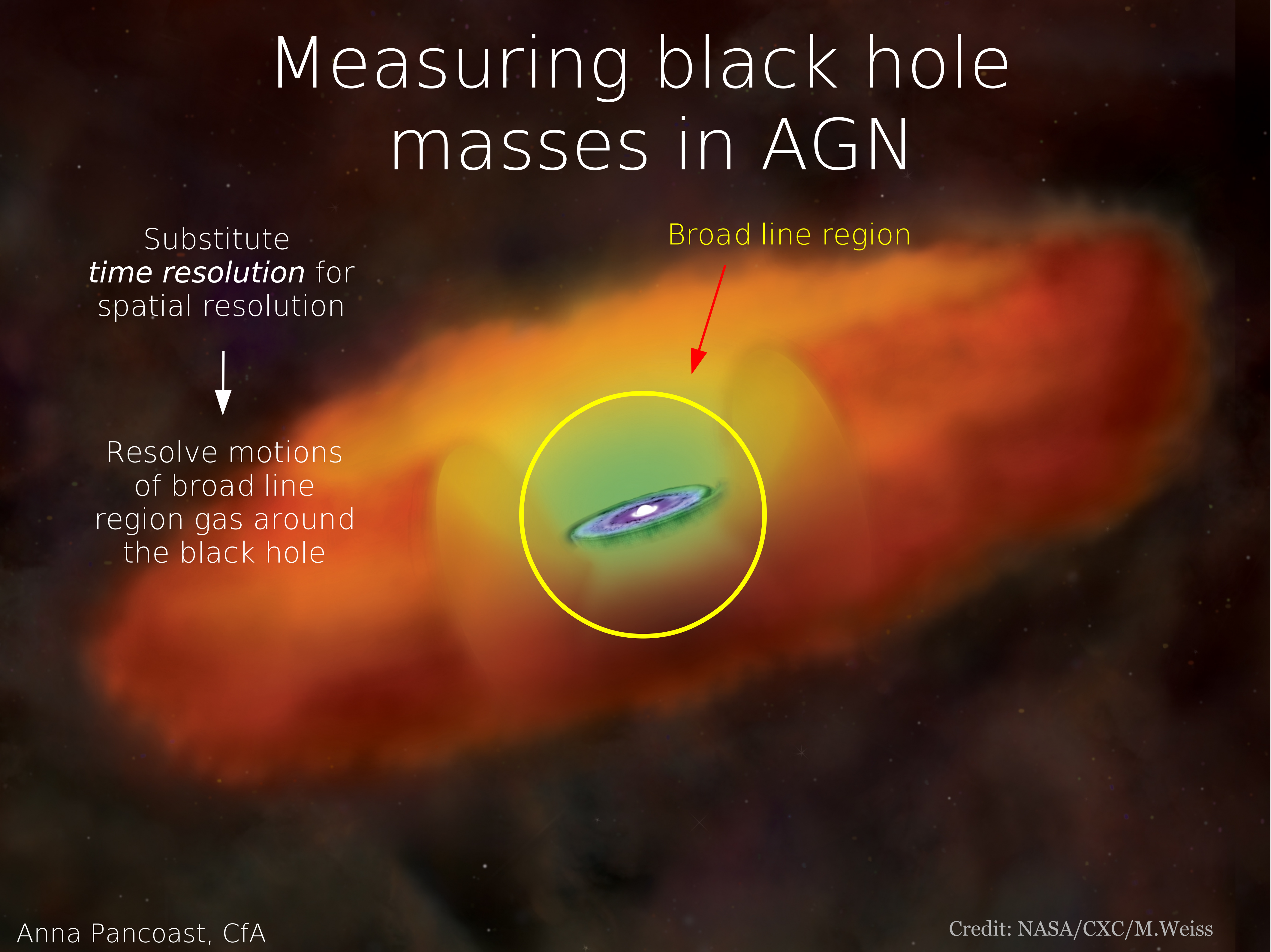
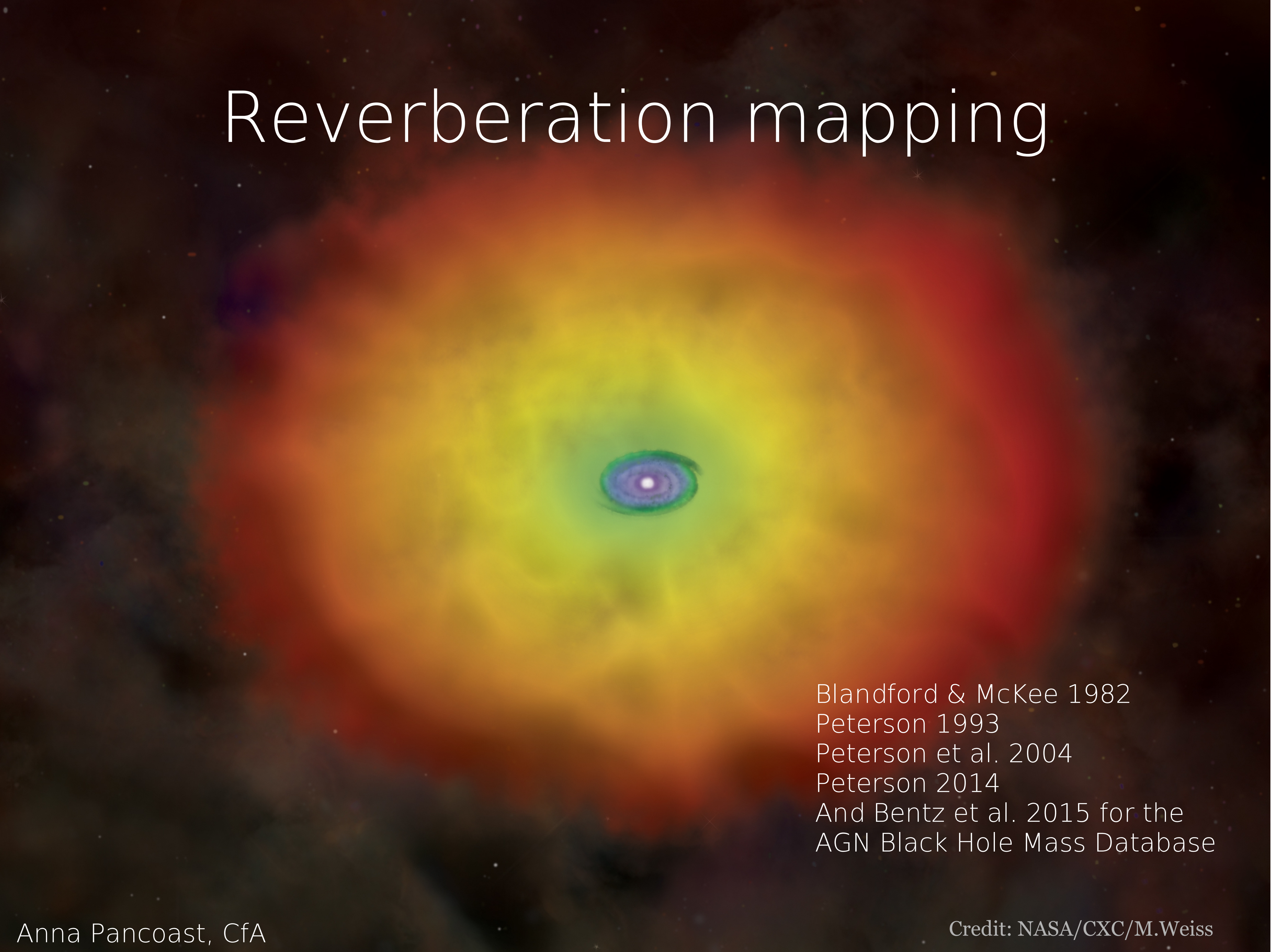

Measuring black hole masses in AGN
Substitute *time resolution* for spatial resolution
Resolve motions of broad line region gas around the black hole
Broad line region
Anna Pancoast, CfA
Credit: NASA/CXC/M.Weiss

Reverberation mapping

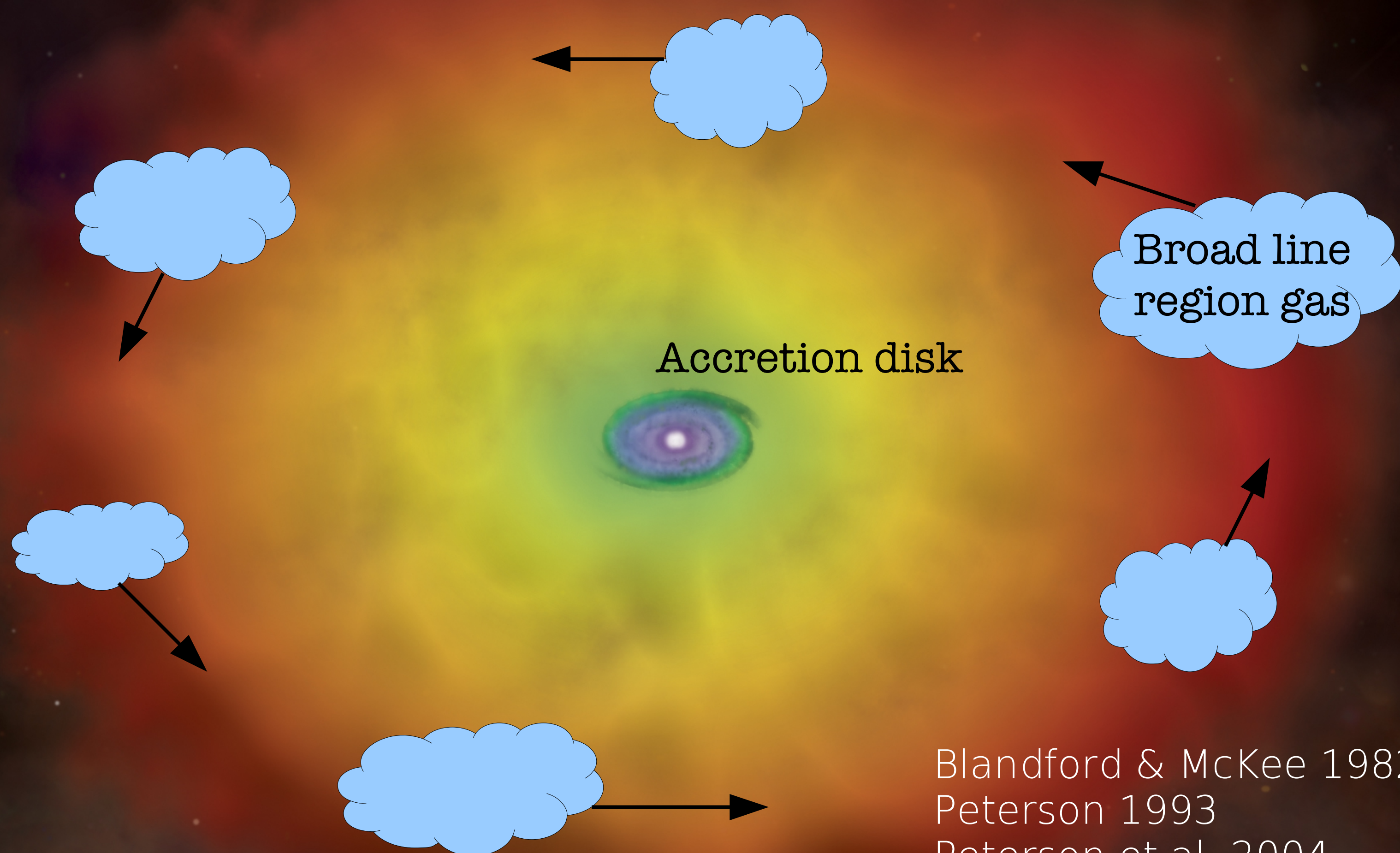


Blandford & McKee 1982
Peterson 1993
Peterson et al. 2004
Peterson 2014
And Bentz et al. 2015 for the AGN Black Hole Mass Database

Anna Pancoast, CfA

Credit: NASA/CXC/M.Weiss

Reverberation mapping



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Anna Pancoast, CfA

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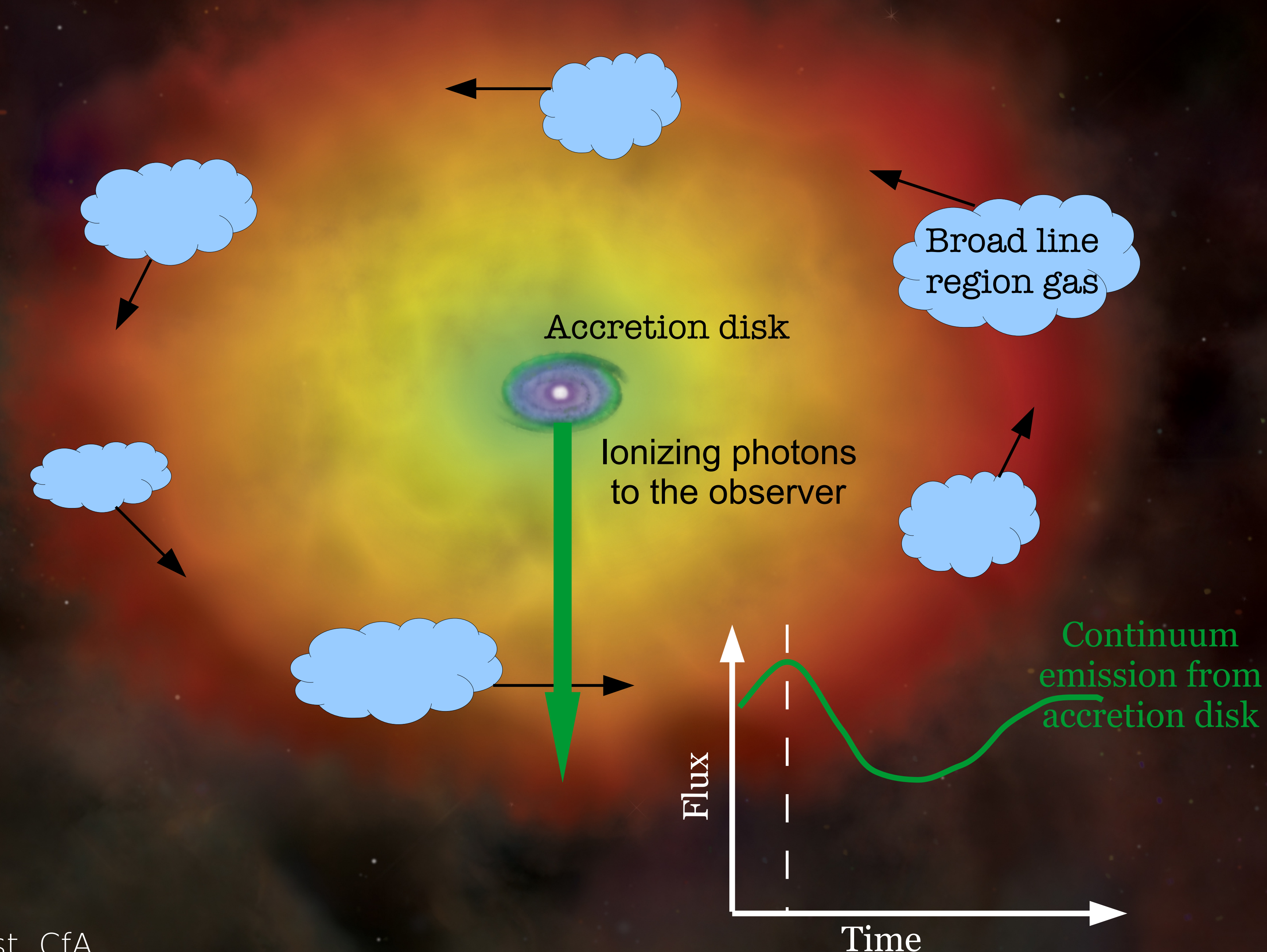

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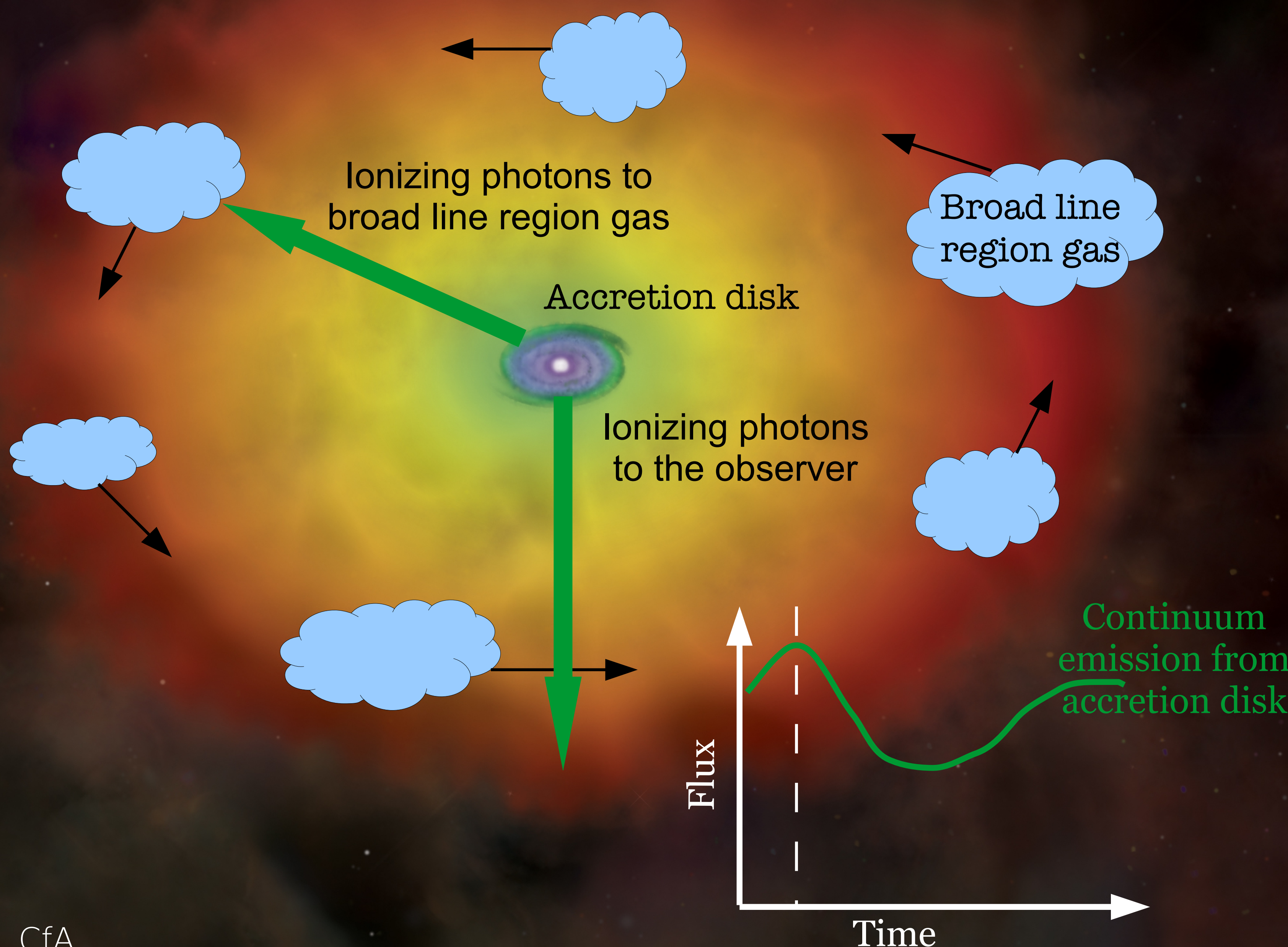

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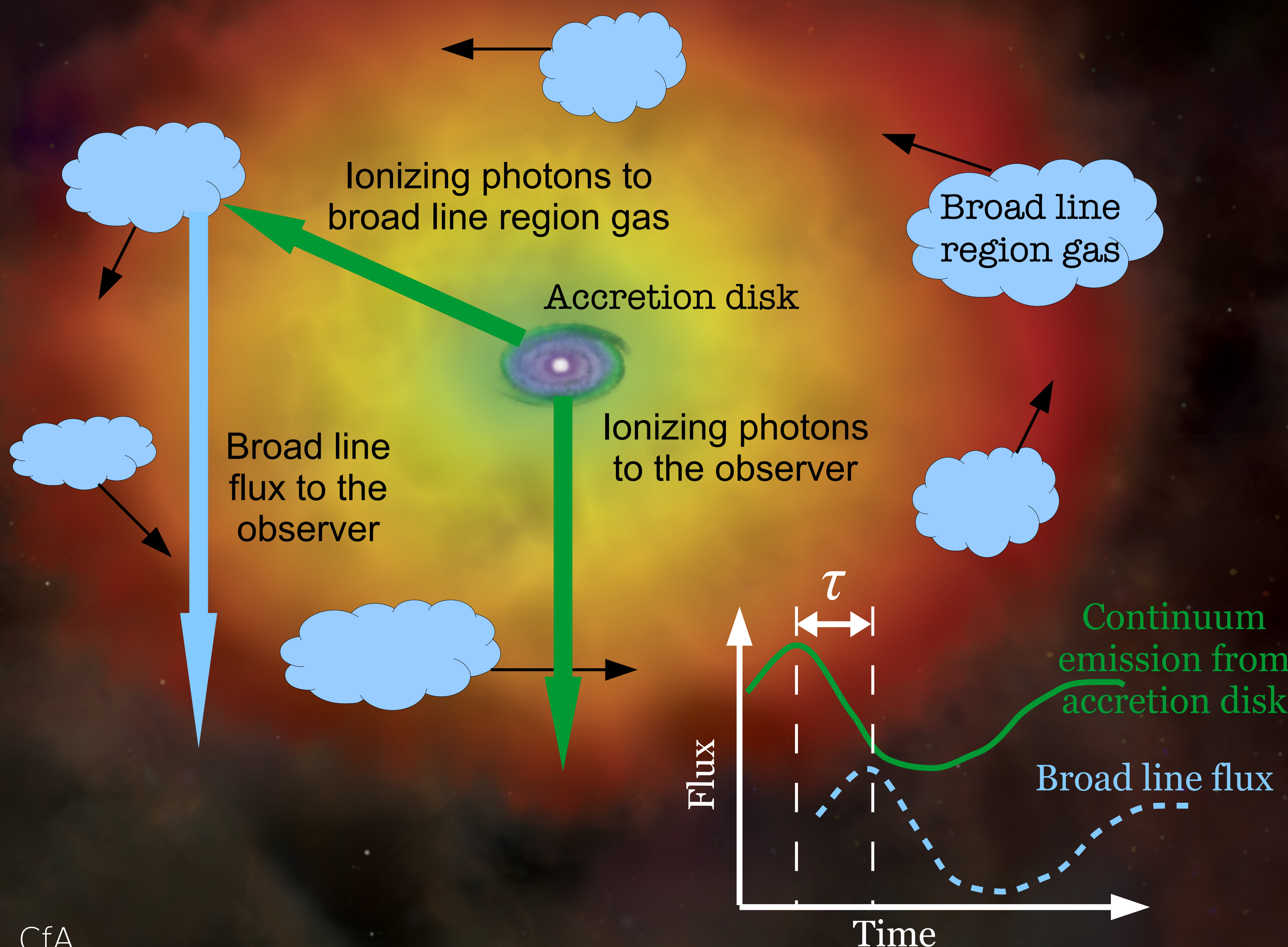

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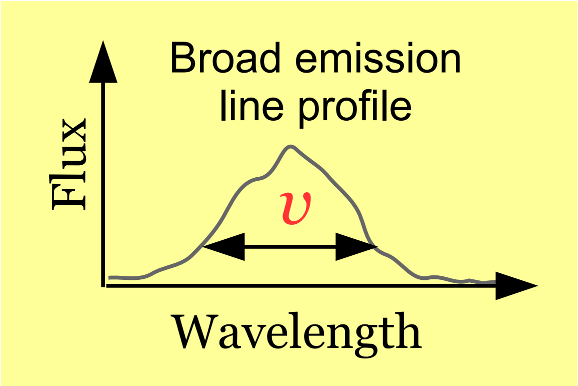
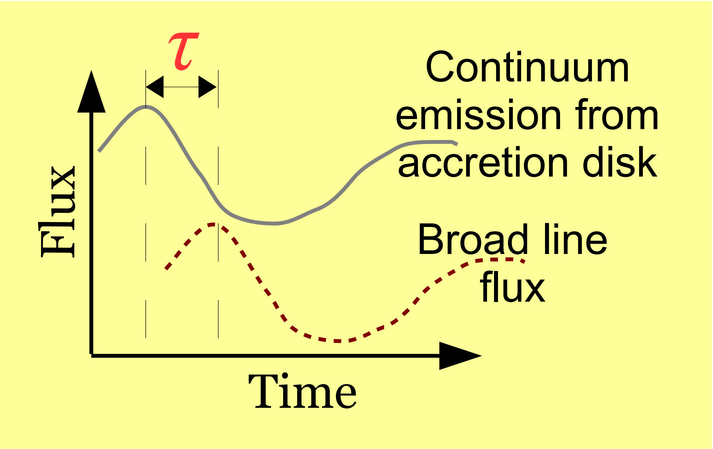
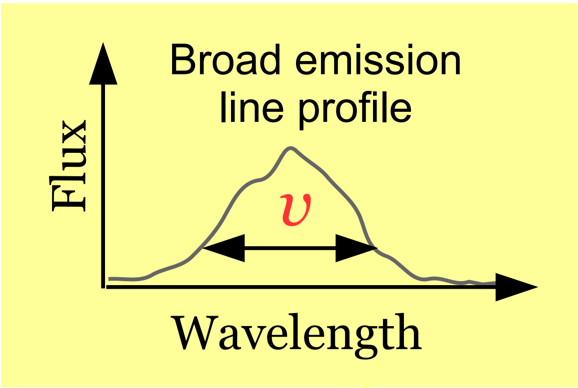
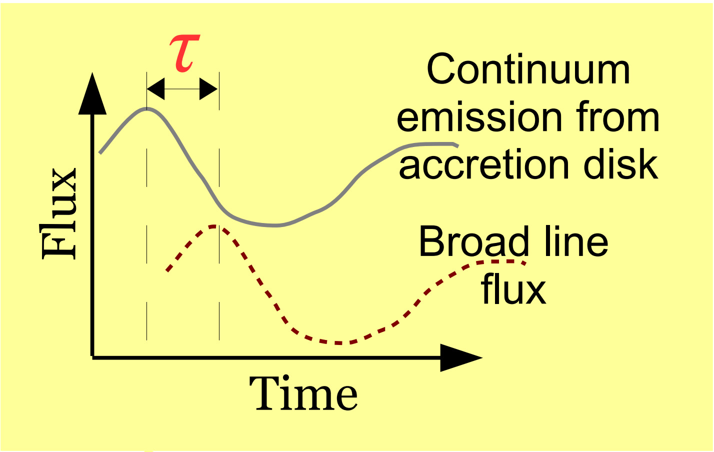
Reverberation mapping black hole masses





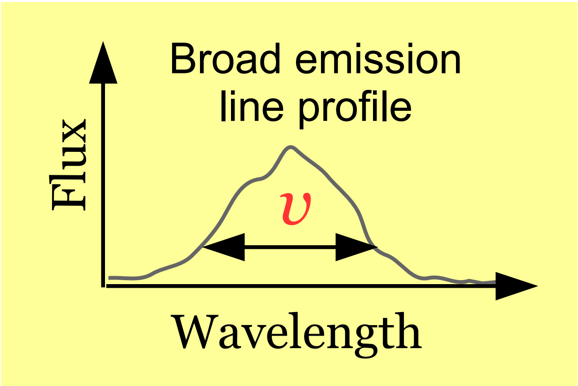
Reverberation mapping black hole masses

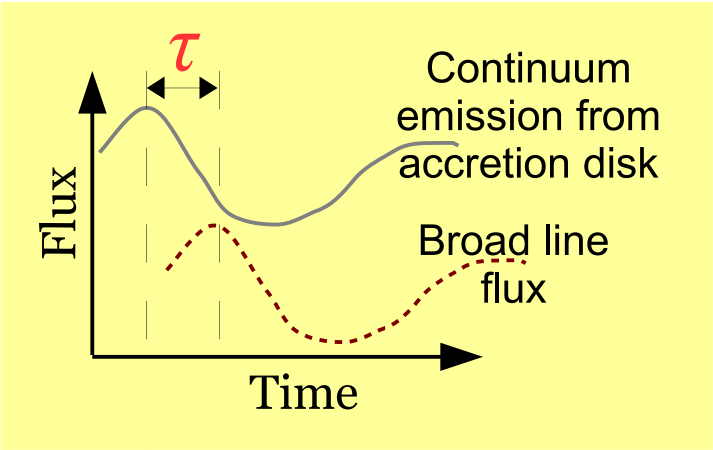




$$M_{\mathrm{vir}} = f\, v^2\, c\, \tau / G$$

Reverberation mapping black hole masses





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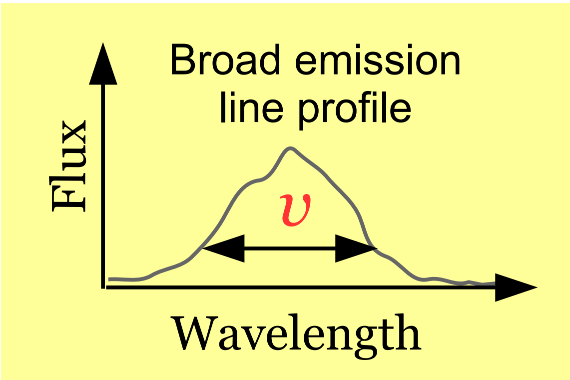
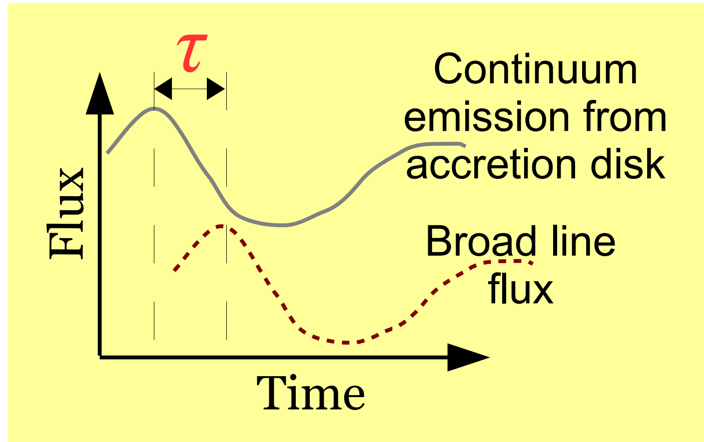
Reverberation mapping black hole masses





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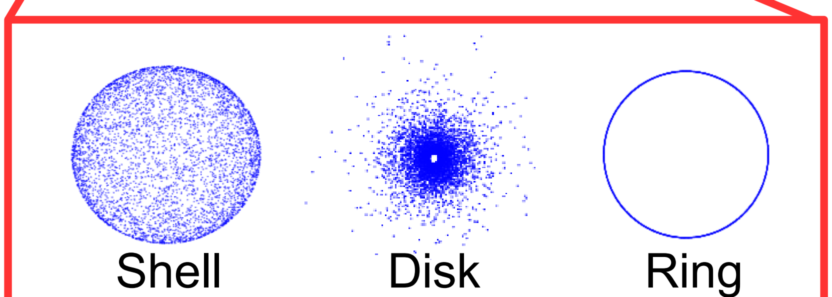

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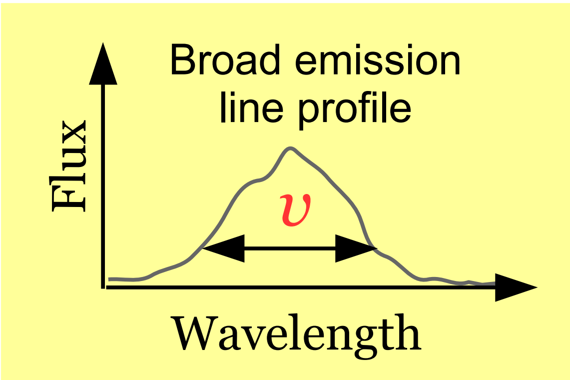
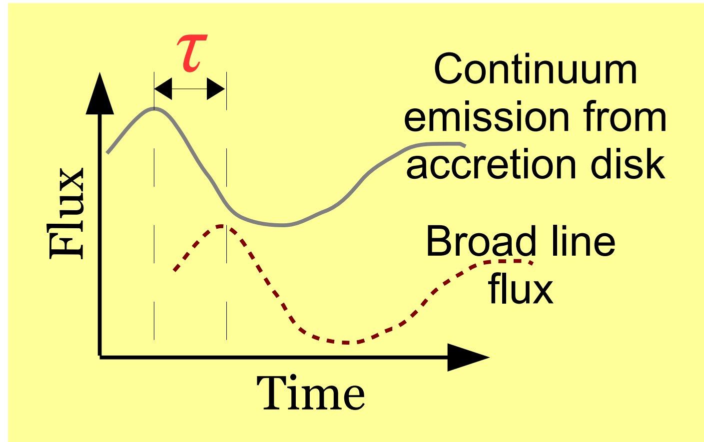
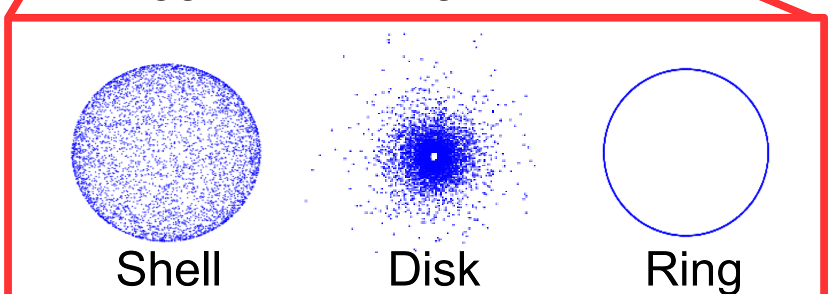
Reverberation mapping black hole masses





$$M_{\text{vir}} = f\, v^2\, c\, \tau / G$$

Determining *f* is our biggest challenge!



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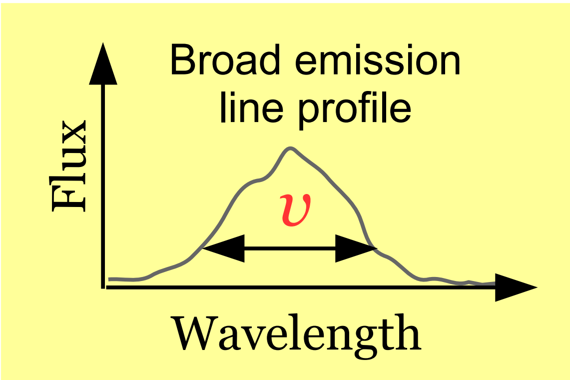
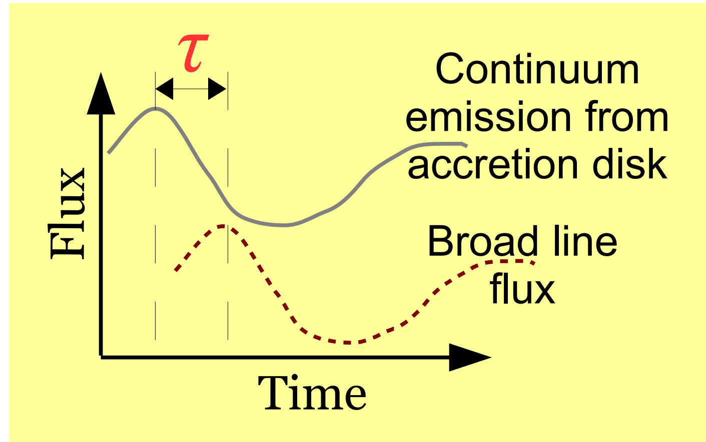
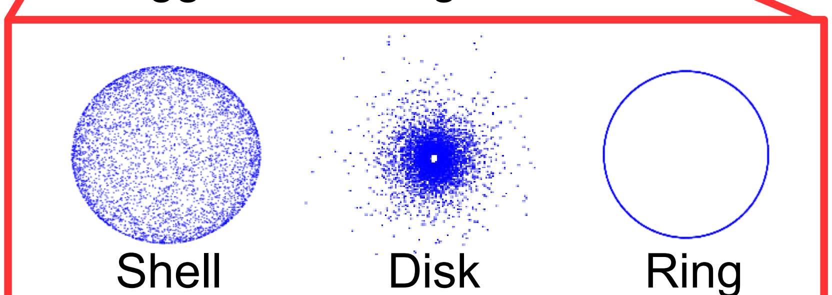
Reverberation mapping black hole masses



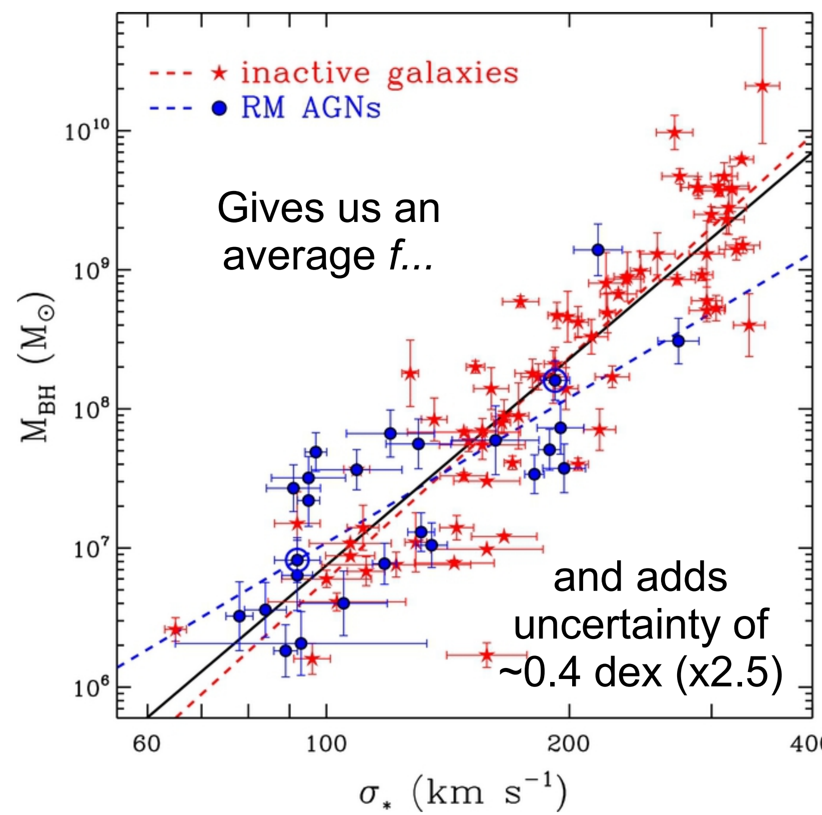


$$M_{\mathrm{vir}} = f\, v^2\, c\, \tau / G$$

Determining f is our biggest challenge!



Woo et al. 2013



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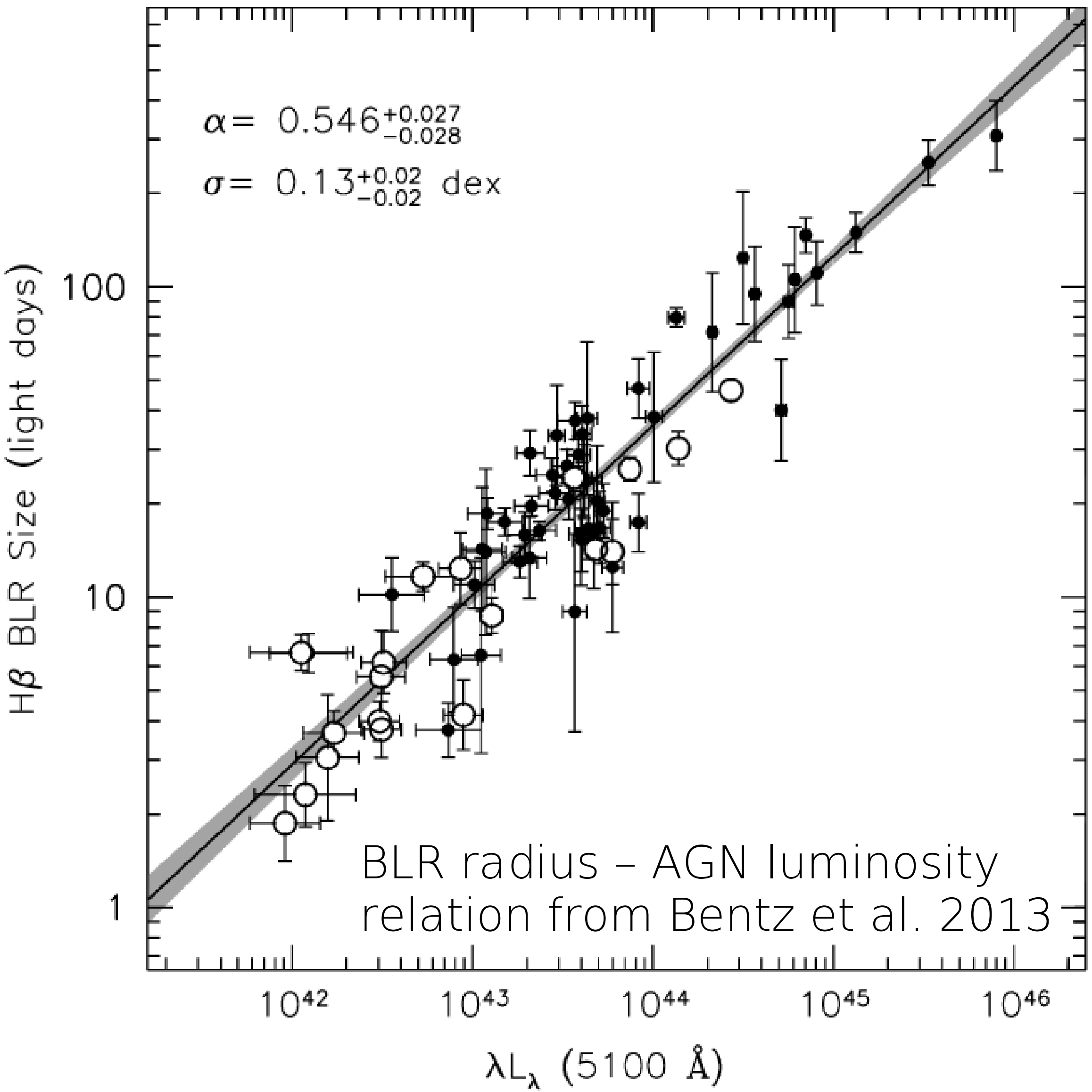
Measuring M_{BH} at higher *z*



Allows for single-epoch AGN black hole mass estimates:

- Use line width to get ***v***
- Use L_{AGN} to get r_{BLR}

Apply to any AGN with a broad emission line spectrum

→ large source of uncertainty is unknown structure and evolution of the BLR

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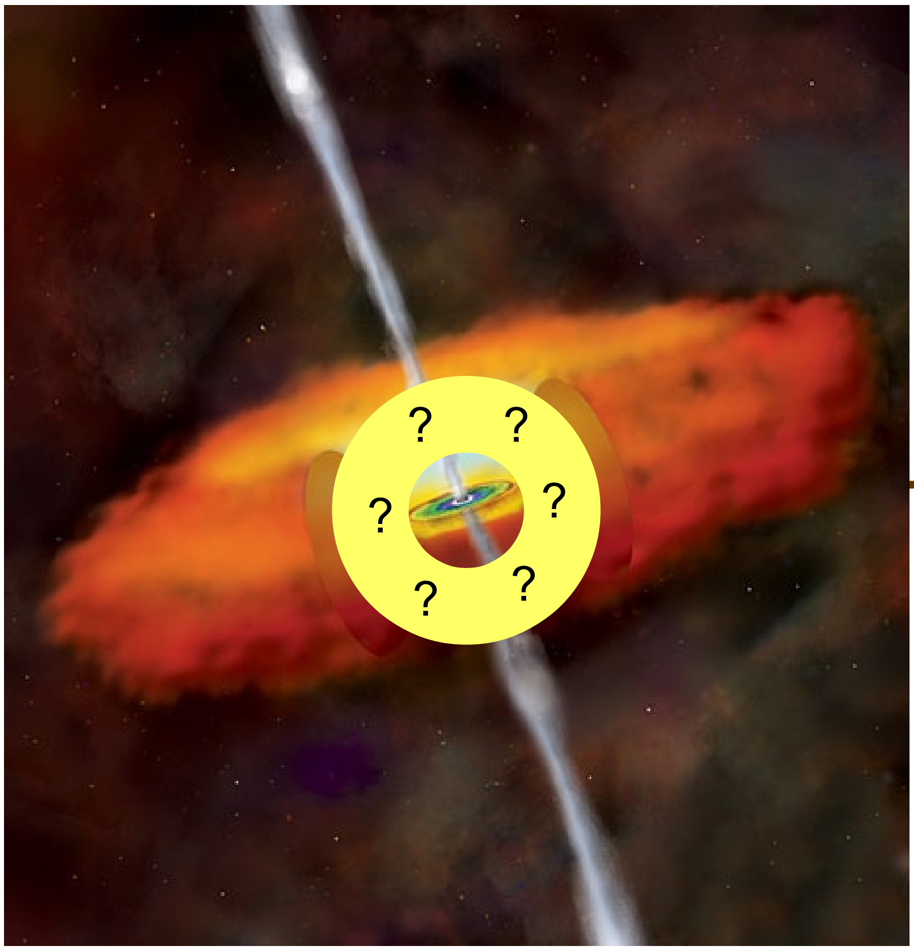
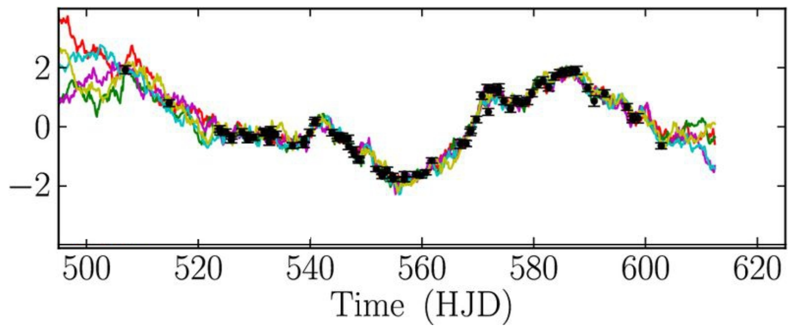
How can we measure the properties of the broad line region?



Model reverberation mapping data using a model for the broad line region

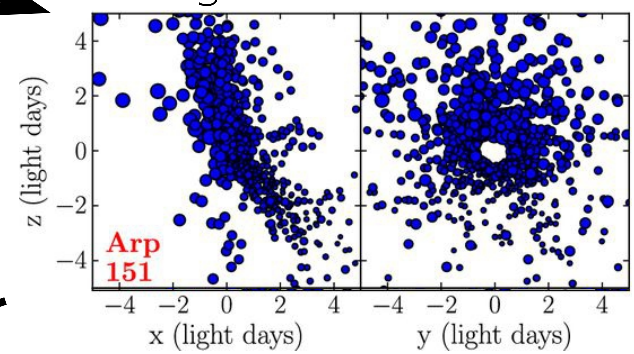
- *Quantitatively* constrain the structure of the broad line region
- Measure ***f*** for individual AGN
- Measure the black hole mass with <0.4 dex uncertainty

A simply parameterized phenomenological model for the broad line region

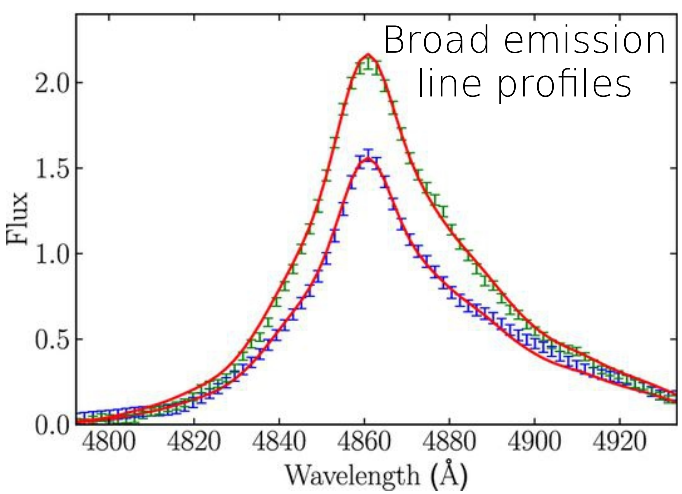


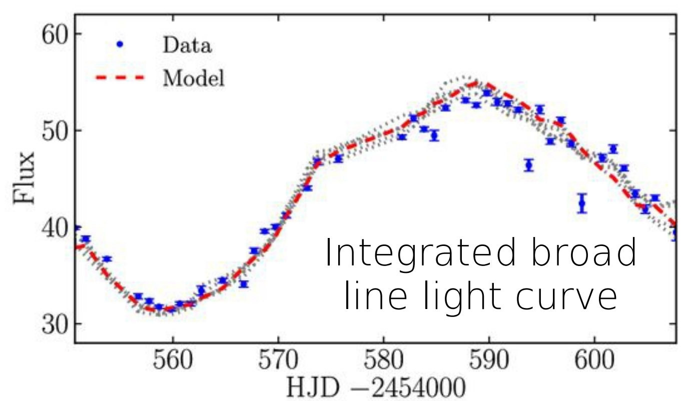
1. Model the AGN continuum light curve using Gaussian processes to evaluate the continuum flux at arbitrary times

Edge-on Face-on



2. Model the geometry and dynamics of the broad line region in order to assign positions and velocities to the point particles





3. Make model broad emission line profiles to compare with the data

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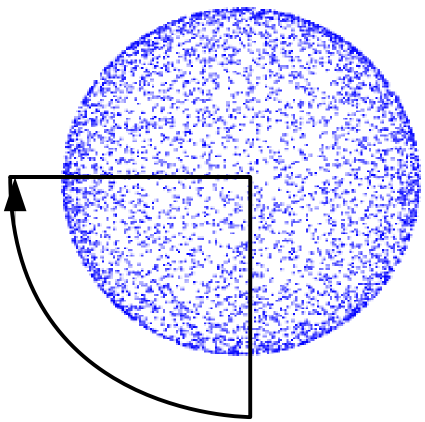
A simply parameterized phenomenological model for the broad line region

- Geometry



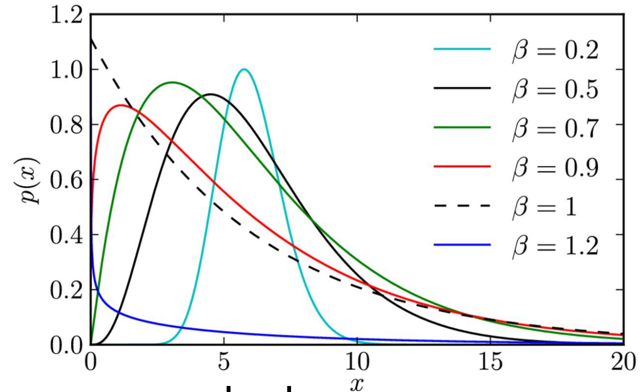
Opening angle
(sphere → disk)

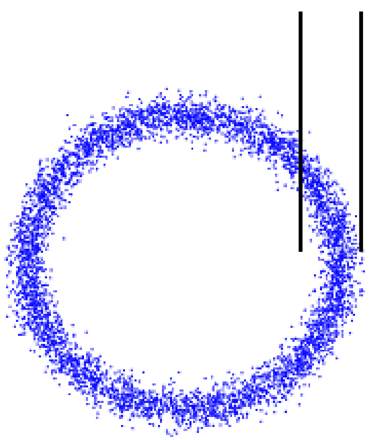
Transparent →
opaque mid-plane

More emission from
near or far side

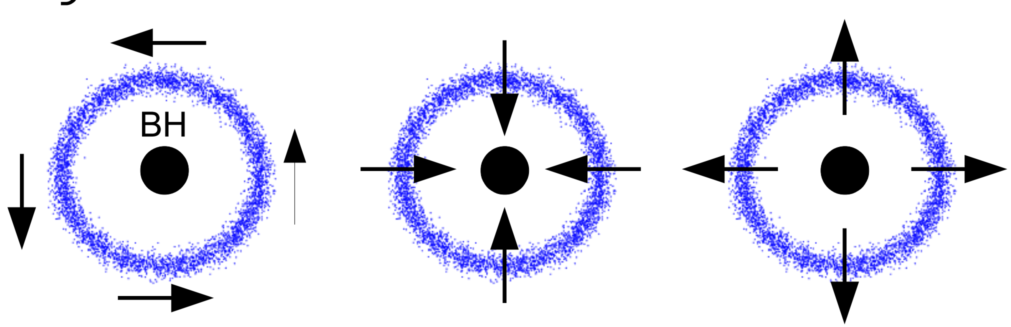
Disk → cone

Radial profile of emission:
Gamma distribution





- Dynamics



Near-circular   Inflowing   Outflowing

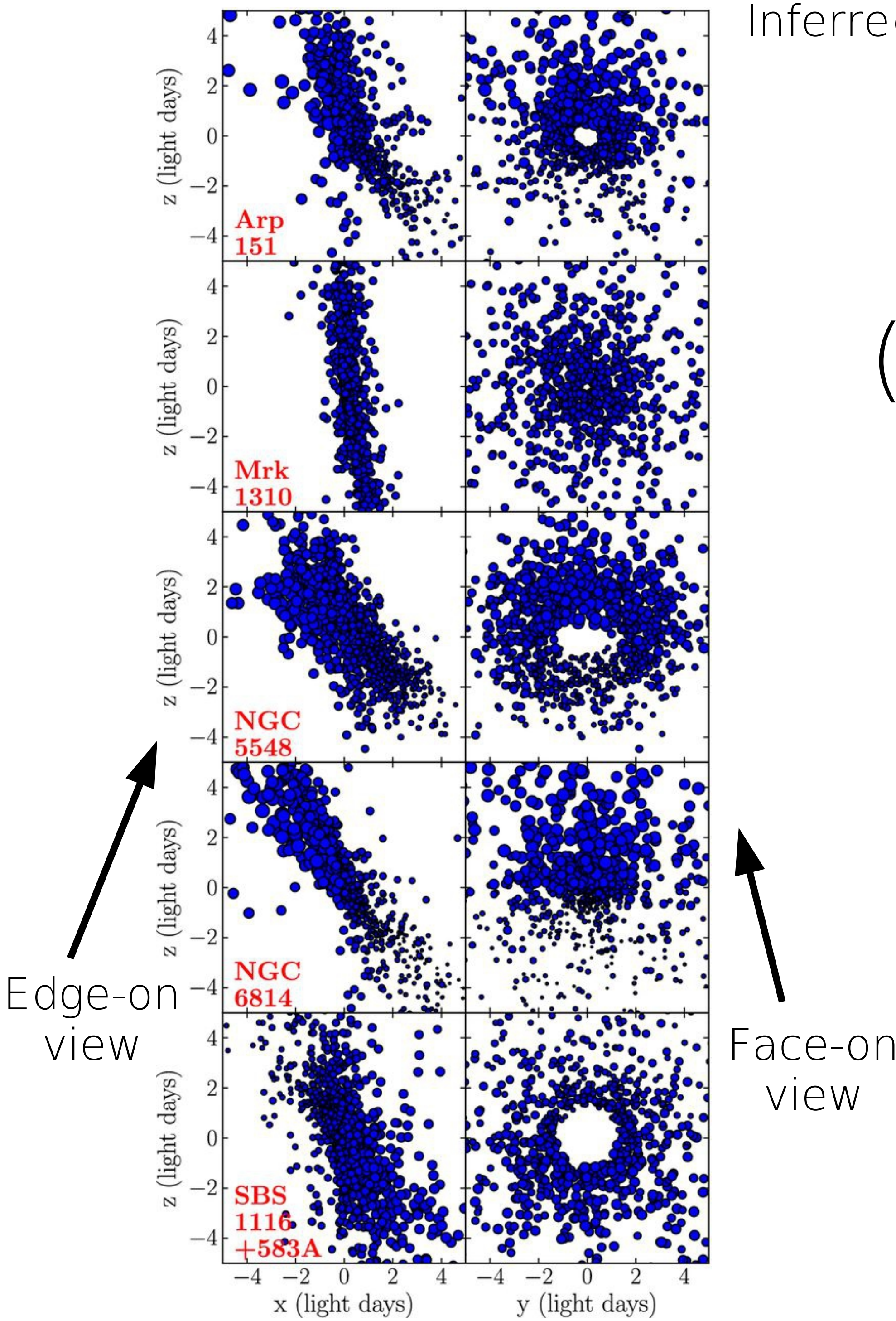
Pancoast, Brewer, & Treu 2014

What is the *structure* of the Hβ-emitting broad line region?

Inferred broad line region geometry

The Lick AGN Monitoring Project (LAMP) 2008 results

(Pancoast, Brewer, Treu et al. 2014)



- Hβ-emitting geometry: close to face-on thick disks
- Consistent with preferential emission back towards central ionizing source
- Dynamics: inflow and/or elliptical orbits
- Black hole mass constrained with 0.15 – 0.3 dex uncertainty

Data from: Bentz et al. 2009, Walsh et al. 2009
Spectral decomposition from: Park et al. 2012a

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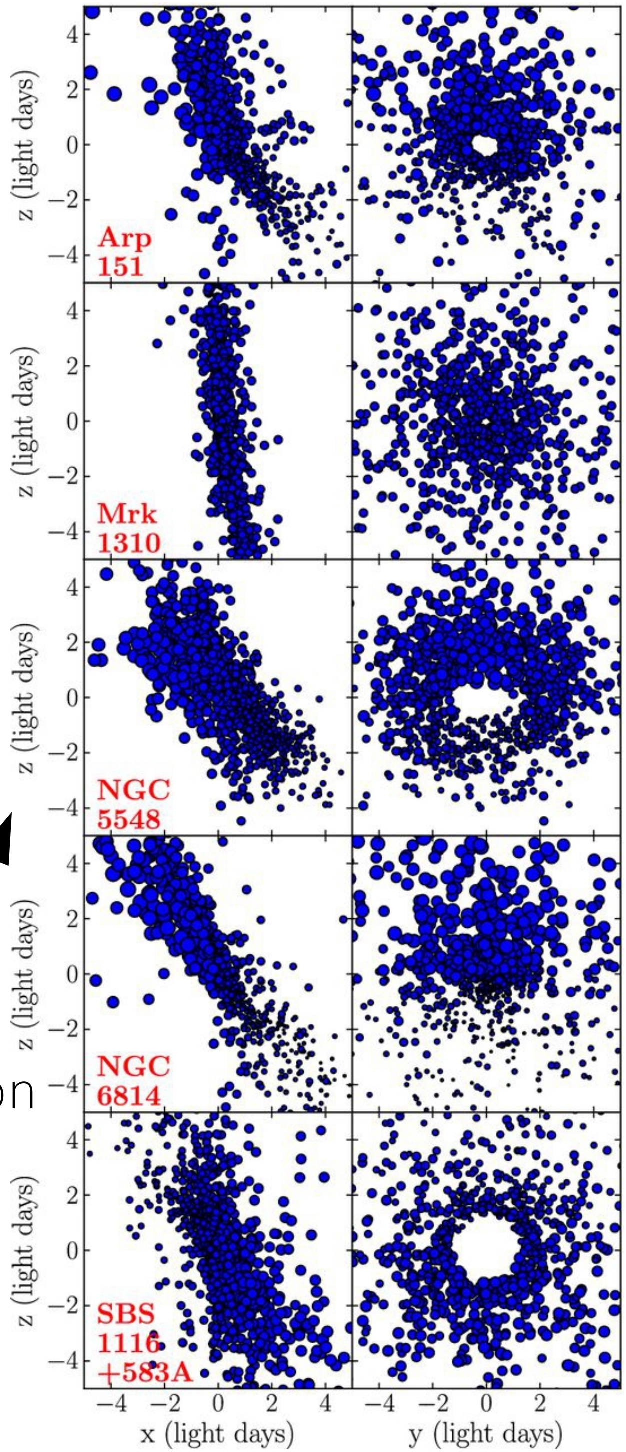
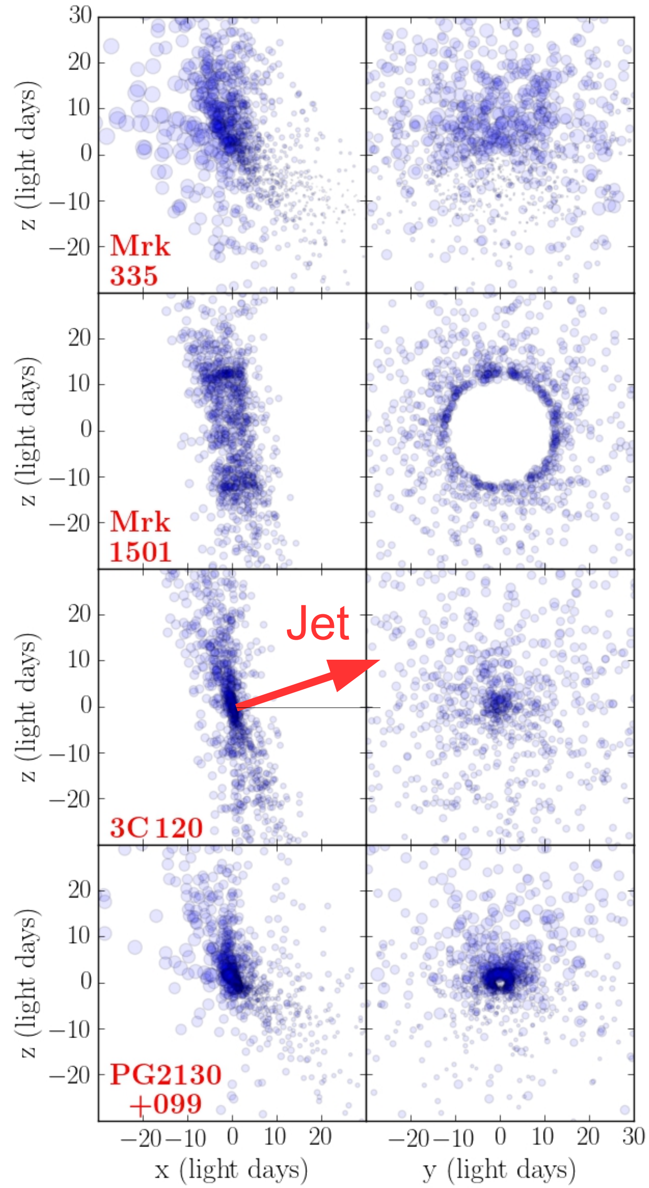


Edge-on view



Data from: Grier et al. 2012b

- Higher black hole mass, redshift, and AGN luminosity
- Dynamics mostly inflow
- 3C 120 has a measured radio jet inclination angle ~16 deg (Agudo+12)

(Grier, Pancoast et al. In press,arXiv:1705.02346)

The OSU 2010 reverberation mapping results

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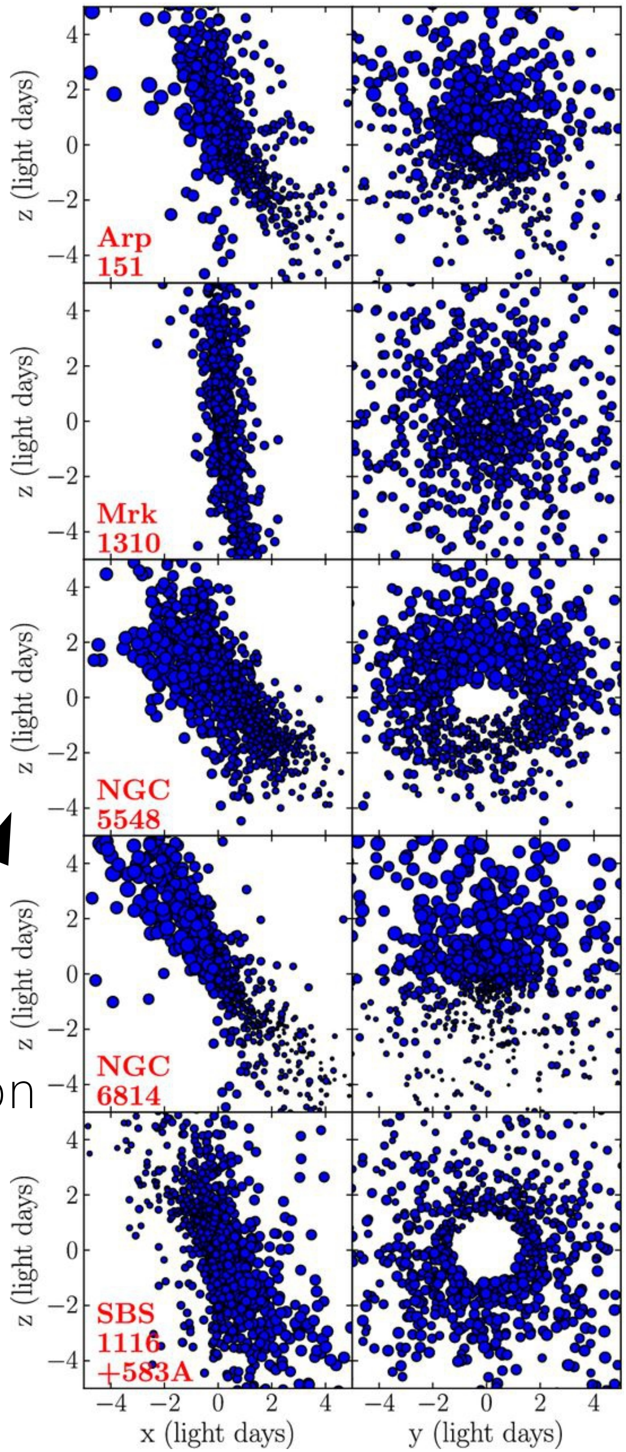
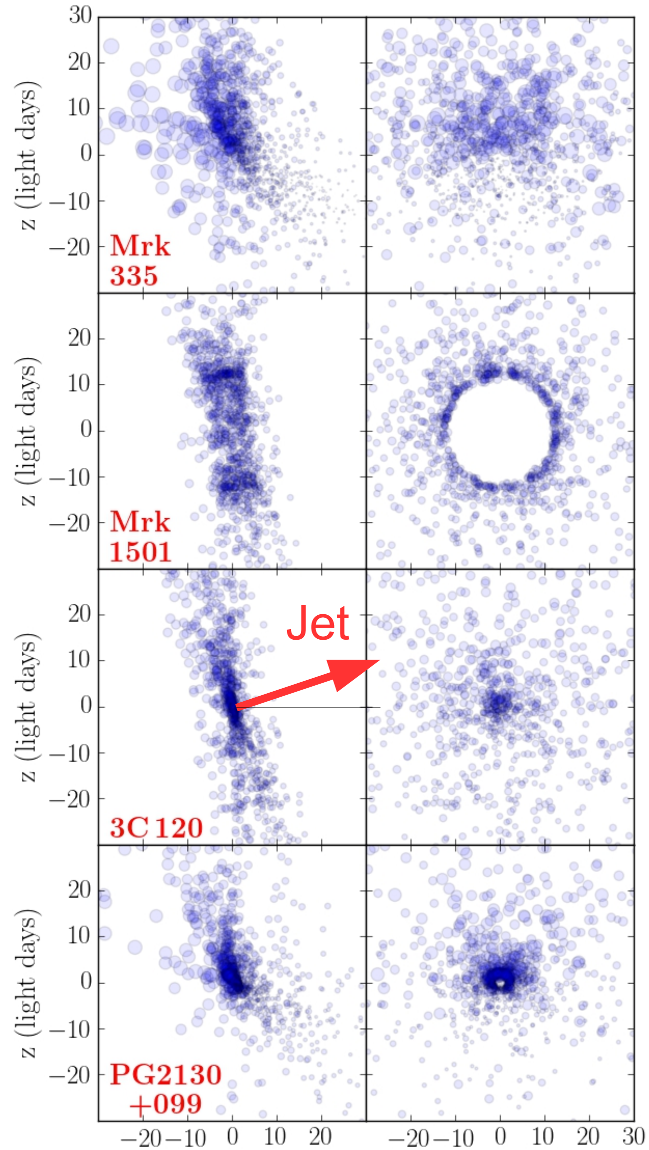
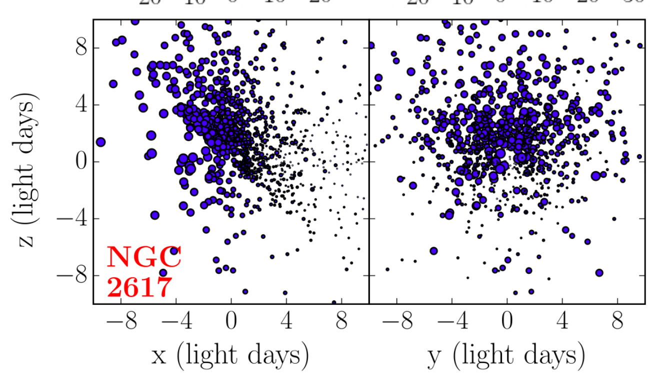
Data from:
Fausnaugh et al. 2017b

The OSU 2014 reverberation mapping *preliminary* results



Edge-on view





- 2+ AGNs with data quality sufficient for BLR modeling
- NGC 2617 is a "changing-look" AGN and new reverberation mapping target

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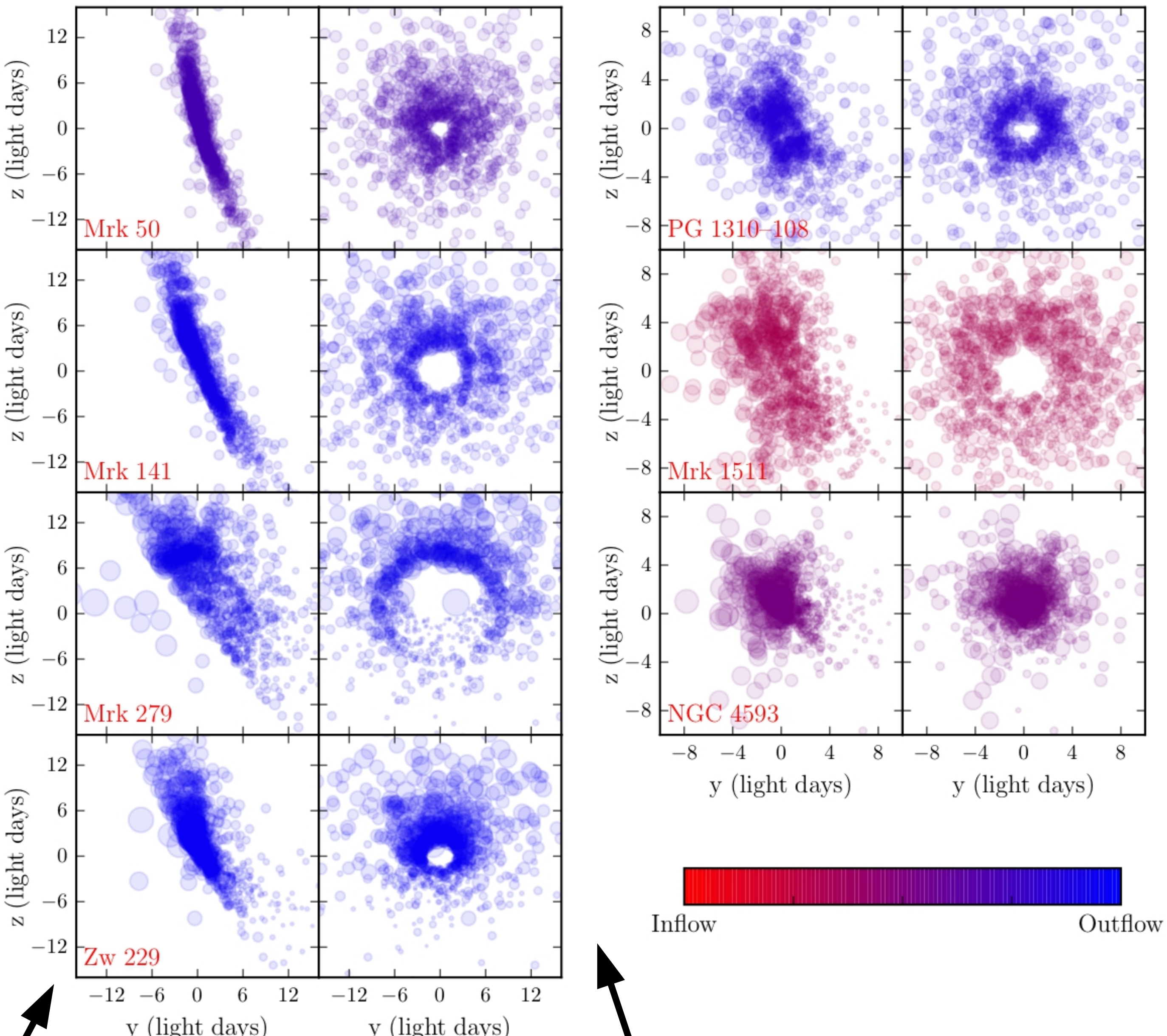
Data from: Barth et al. 2015



Edge-on view

Face-on view

The Lick AGN Monitoring Project 2011

- Campaign designed with BLR modeling in mind
- First 4 AGN with preference for outflowing dynamics
- Second dataset for Arp 151

(Williams, Pancoast et al. in preparation)

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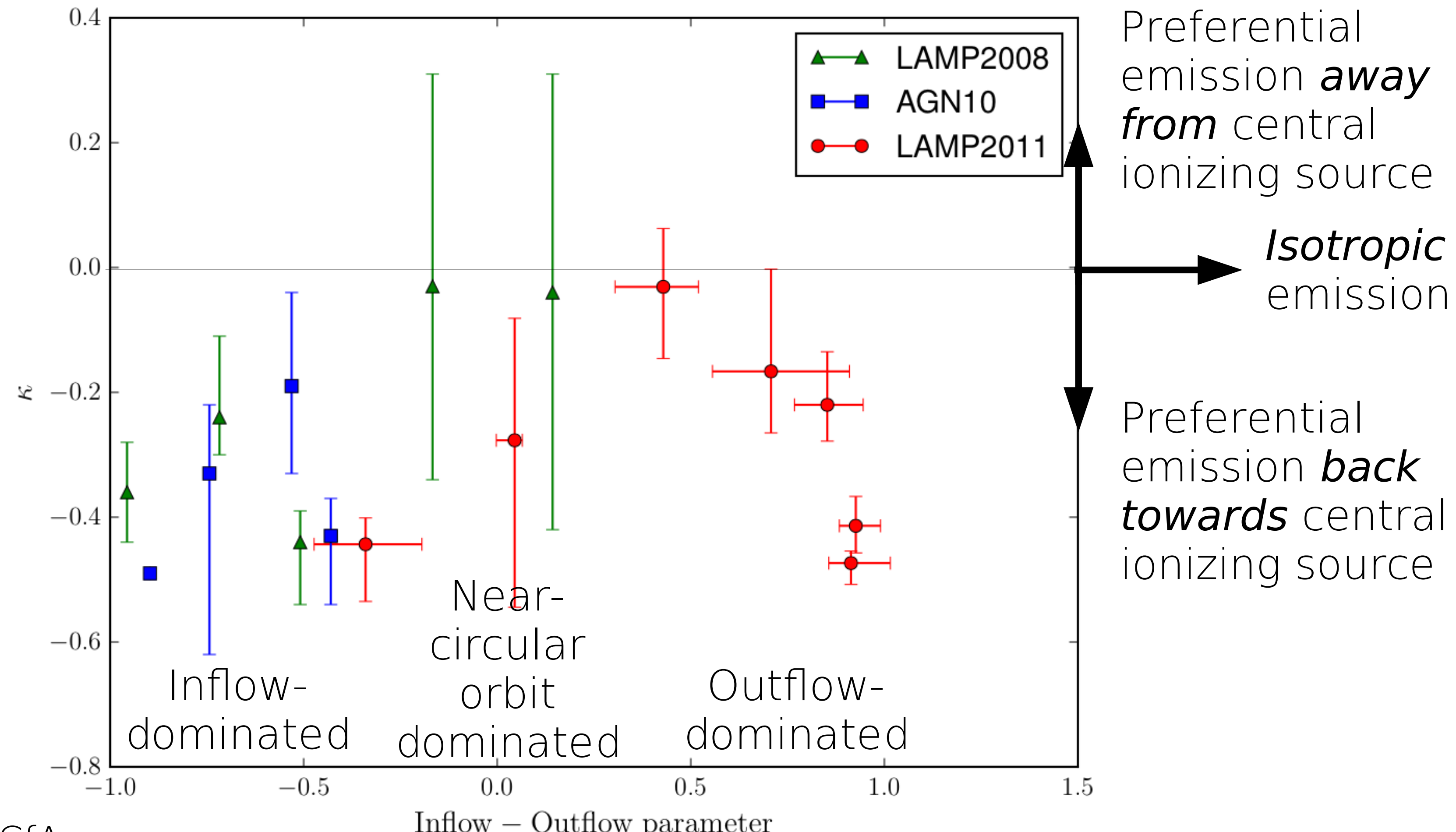
What is the *structure* of the Hβ-emitting broad line region?

- **Geometry:** close to face-on thick disk, preferential emission back towards ionizing source, partly opaque disk mid-plane
- **Dynamics:** a range of near-circular elliptical orbits, inflow, and outflow



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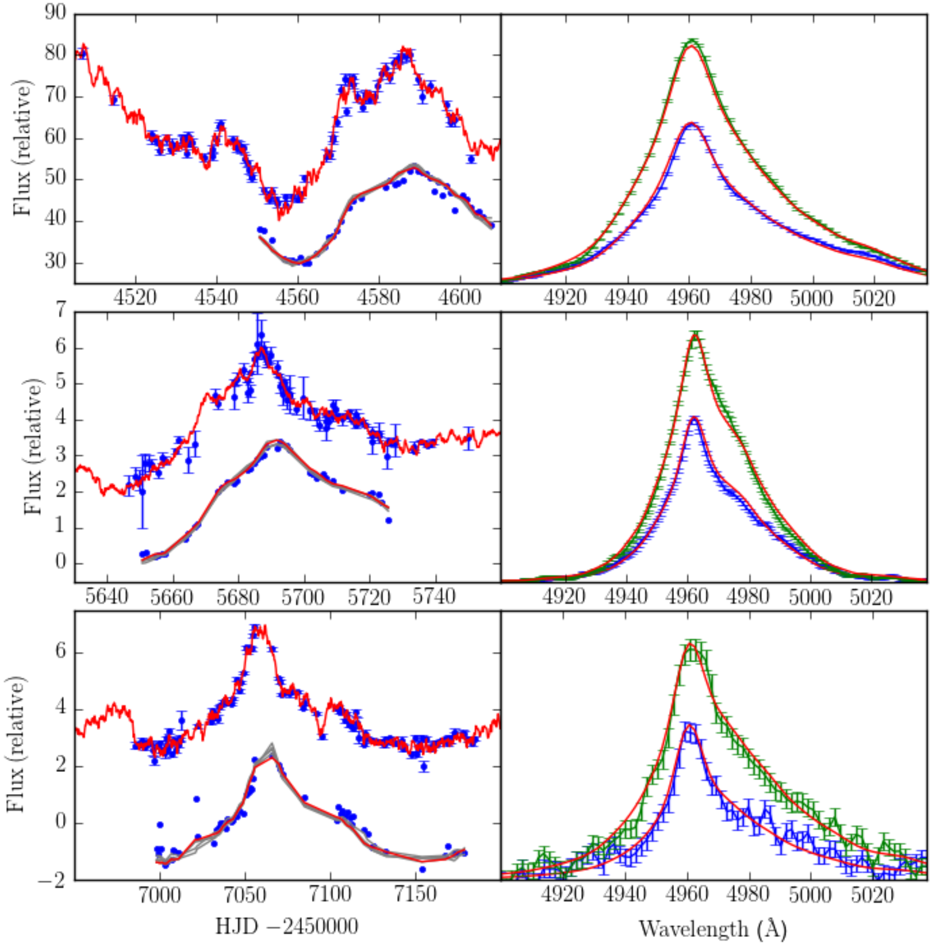
How *robust* are these constraints?

Data from:
Bentz et al. 2009 (LAMP 2008)
Barth et al. 2015 (LAMP 2011)
Valenti et al. 2015 (LCO AGN Key Project 2015)



(Pancoast et al. in preparation)

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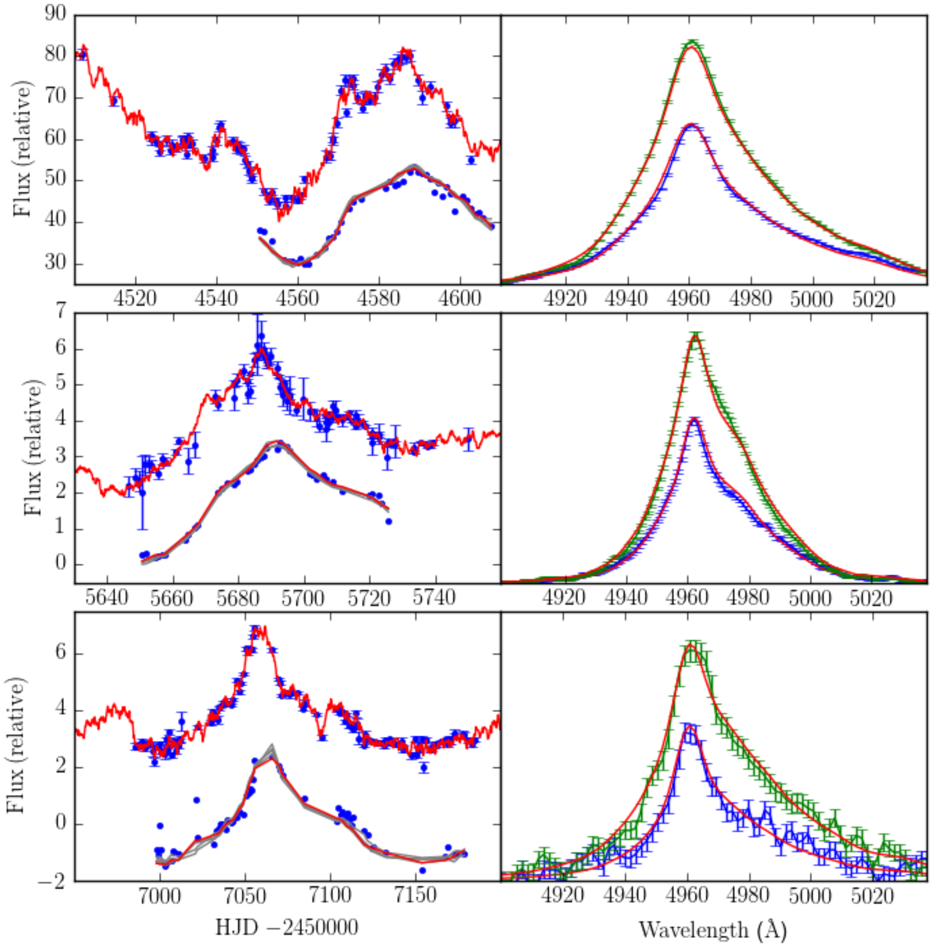
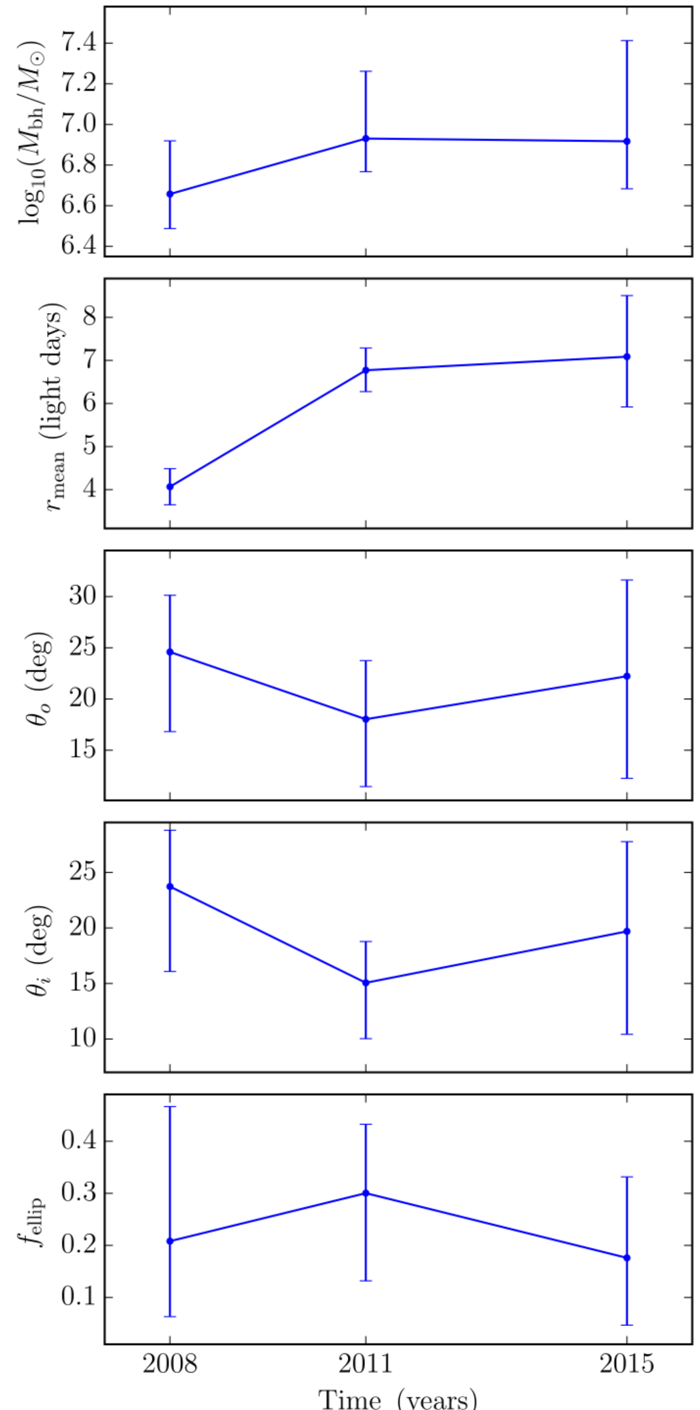


Evolution in the BLR?



(Pancoast et al. in preparation)

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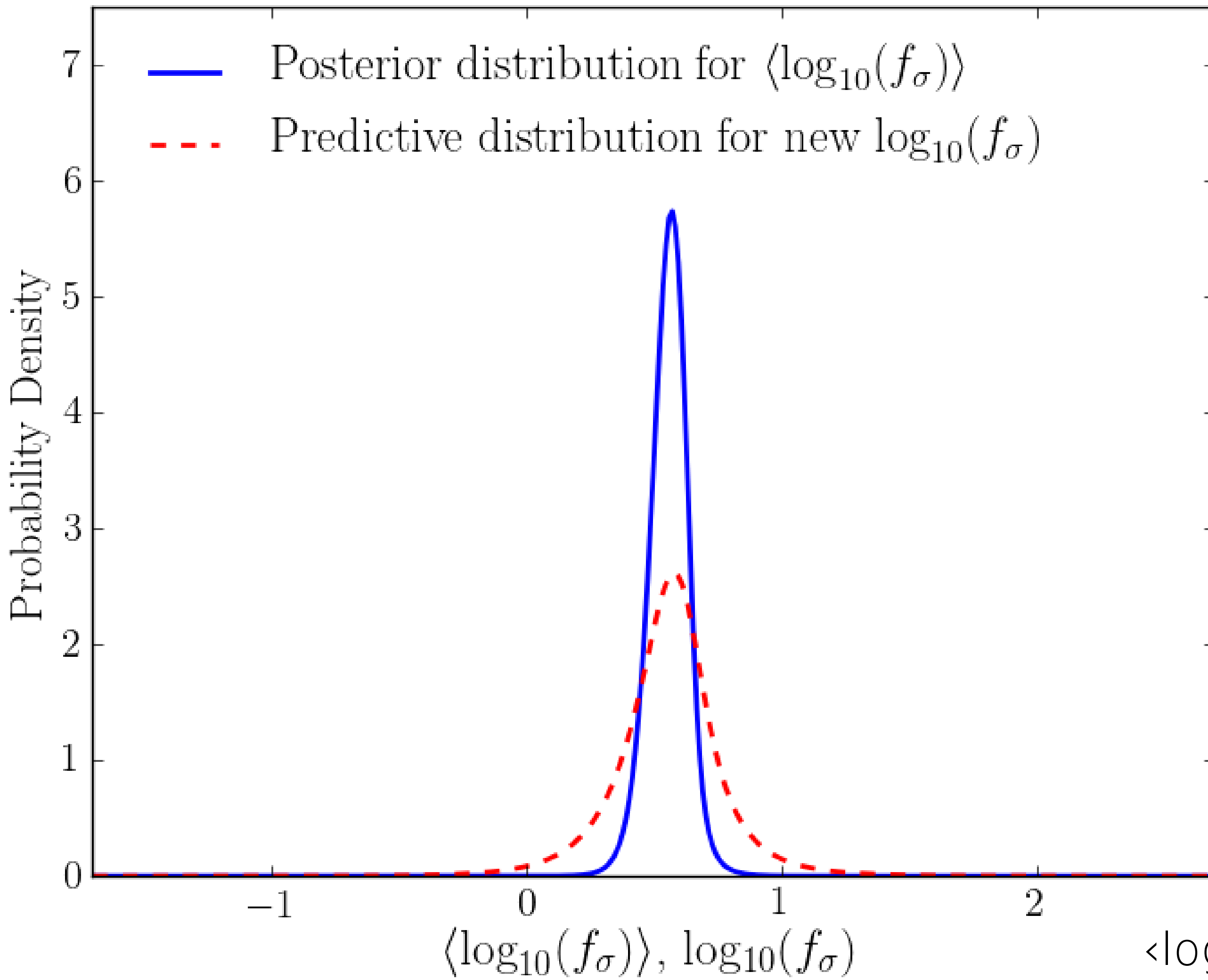
What about the big picture?

An average value of the ***f*** factor



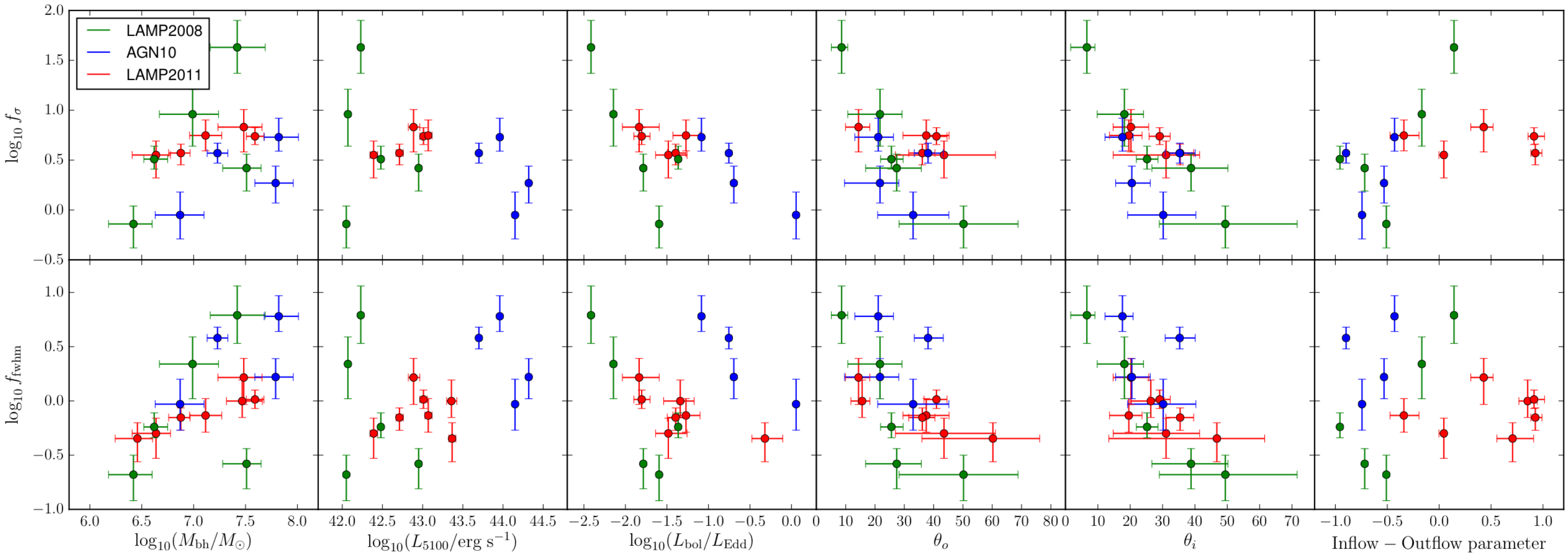
Using the full posterior PDFs for black hole mass for LAMP 2008, 2011, and the OSU 2010 datasets

(Williams, Pancoast et al. in preparation)

$\langle \log_{10}(f) \rangle = 0.56 \pm 0.08$

$\sigma(\log_{10}(f)) = 0.18 \pm 0.10$

Dependence of ***f*** on AGN/BLR properties



The f factor is most strongly correlated with inclination angle and opening angle of the disk

(Williams, Pancoast et al. in preparation)

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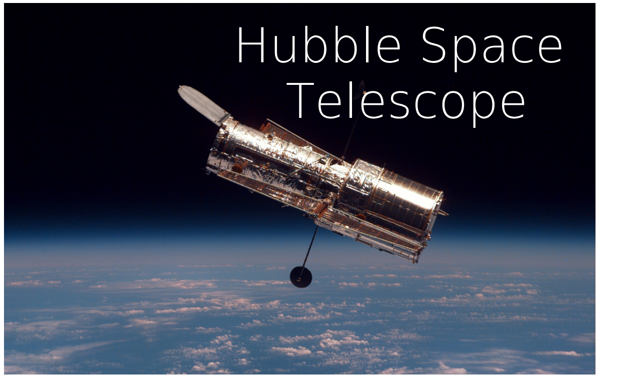
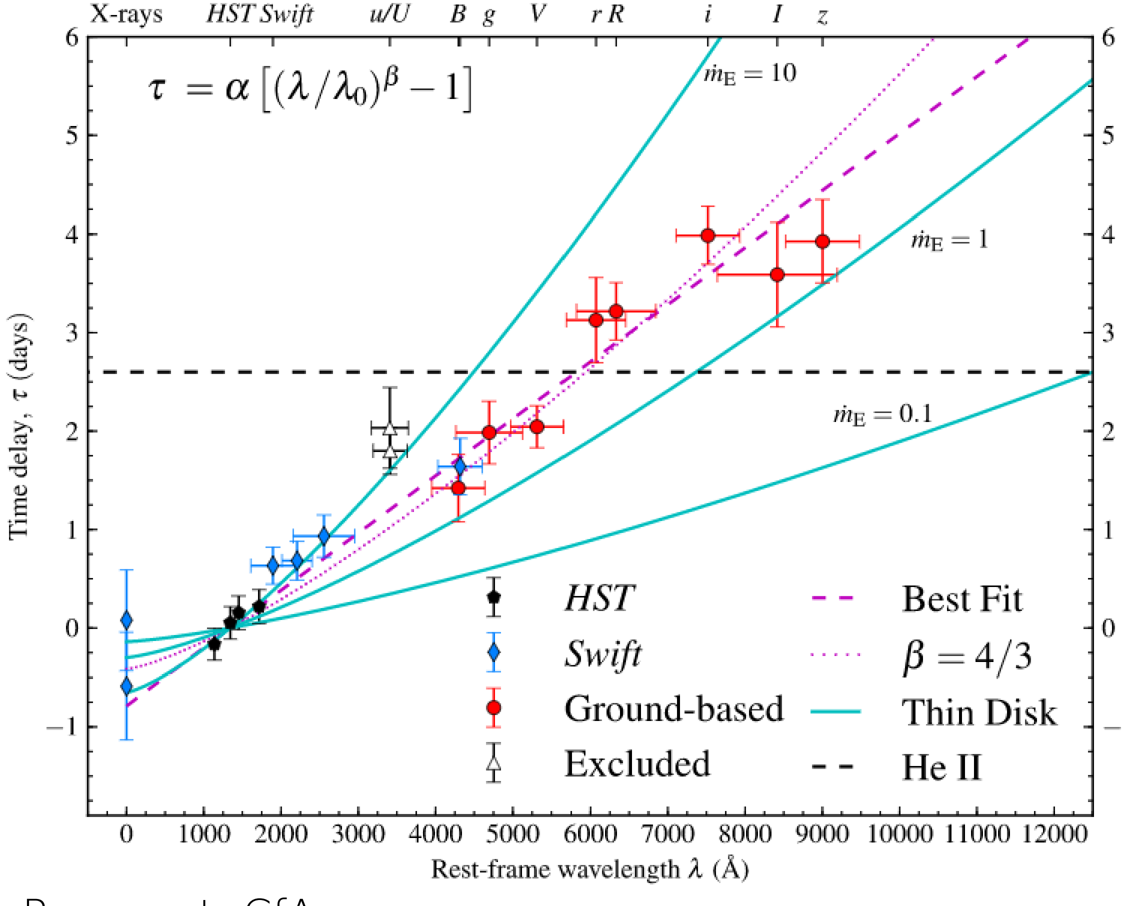
Where do we go from here?

The new generation of reverberation mapping experiments

The AGN Space Telescope and Optical Reverberation Mapping Program (AGN STORM)

Monitored NGC 5548 using HST + optical ground-based telescopes covering Lyα, CIV, and Hβ simultaneously





From Fausnaugh et al. 2016

Reverberation mapping of the AGN continuum:

- The accretion disk is larger than anticipated
- There is a measurable time lag between the UV and optical
- Inner broad line region overlaps with accretion disk

The new generation of reverberation mapping experiments

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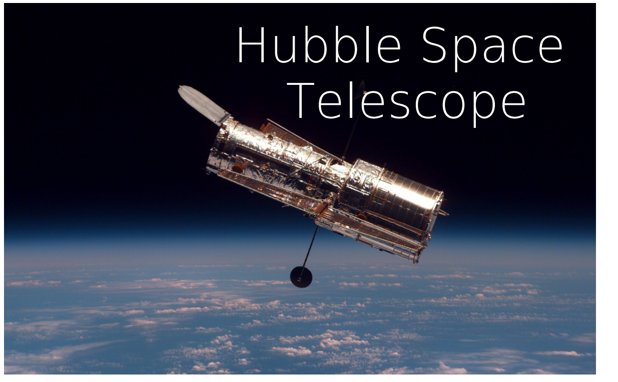

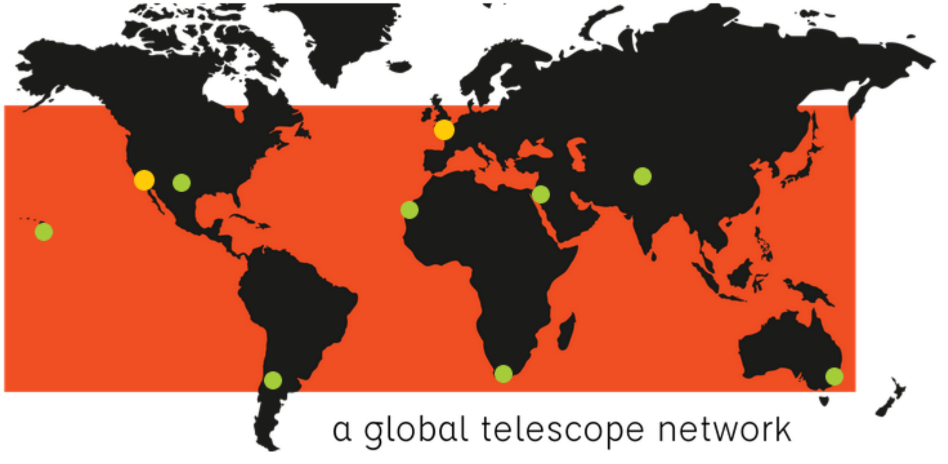

The Las Cumbres Observatory (LCO) AGN Key Project

Fully robotic monitoring of low-z AGNs, follow-up to explore evolution in the broad line region

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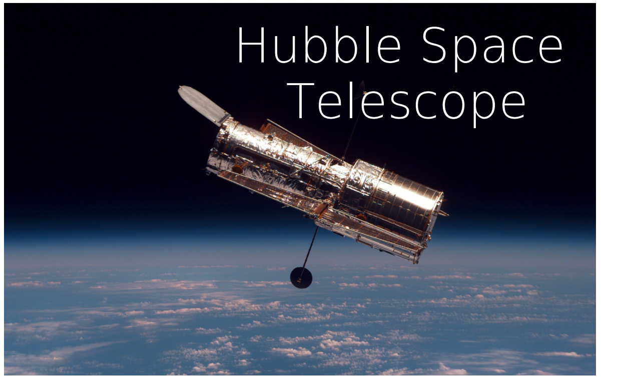

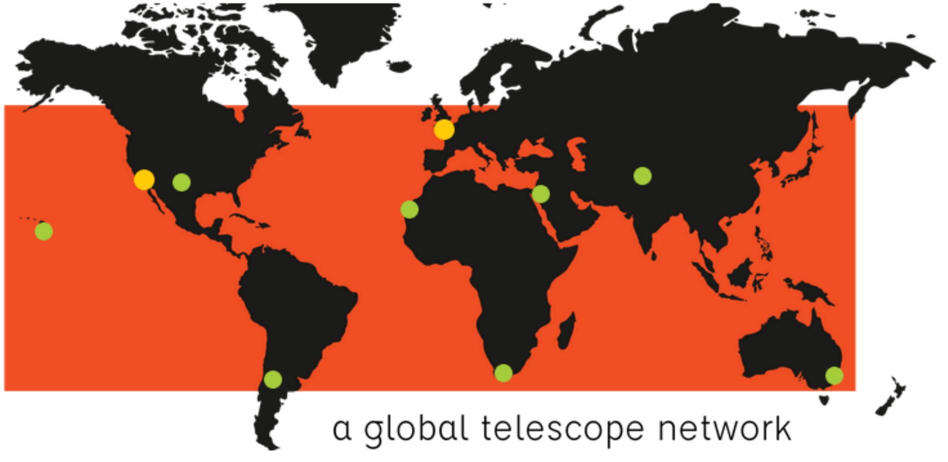

The Las Cumbres Observatory (LCO) AGN Key Project

Fully robotic monitoring of low-z AGNs, follow-up to explore evolution in the broad line region

The Lick AGN Monitoring Project 2016

Monitoring ~20 AGNs with higher luminosities, larger masses, and bigger broad line regions.

How does broad line region structure scale with AGN luminosity? Do we find more outflows?

Anna Pancoast, CfA

Conclusions

- Broad line region modeling of reverberation mapping allows us to:
  - Measure AGN black hole masses more precisely (0.1 – 0.3 dex uncertainty vs. ~0.4 dex)
  - Make first measurements of ***f*** for individual AGN
  - Constrain the detailed geometry and dynamics of the broad line region
- In progress: increasing the sample from 10 to 15+ AGN with broad line region modeling
- Flexible framework to test broad line region models (e.g. AGN outflow models, photoionization physics)

Image credit: NASA/CXC/M.Weiss