Modeling the Reverberation Response of the Broad Line Region in Active Galactic Nuclei

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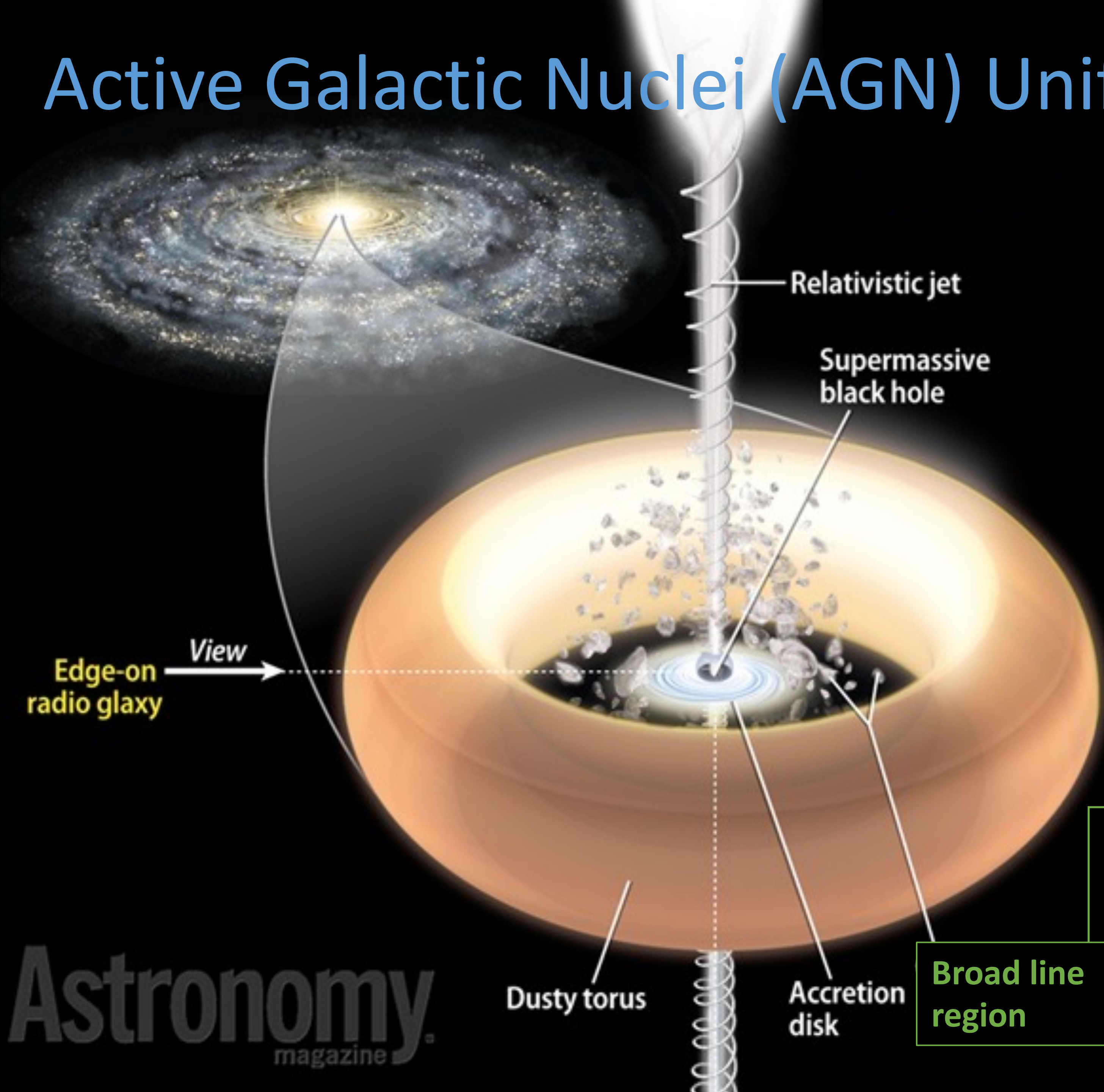
RIT AGN &
Galactic Environments

Active Galactic Nuclei (AGN) Unification Model



Broad line region

Center of an active galaxy is an active galactic nucleus (AGN)

The accretion disk is the UV continuum source which photoionizes the surrounding the BLR, which is deep within

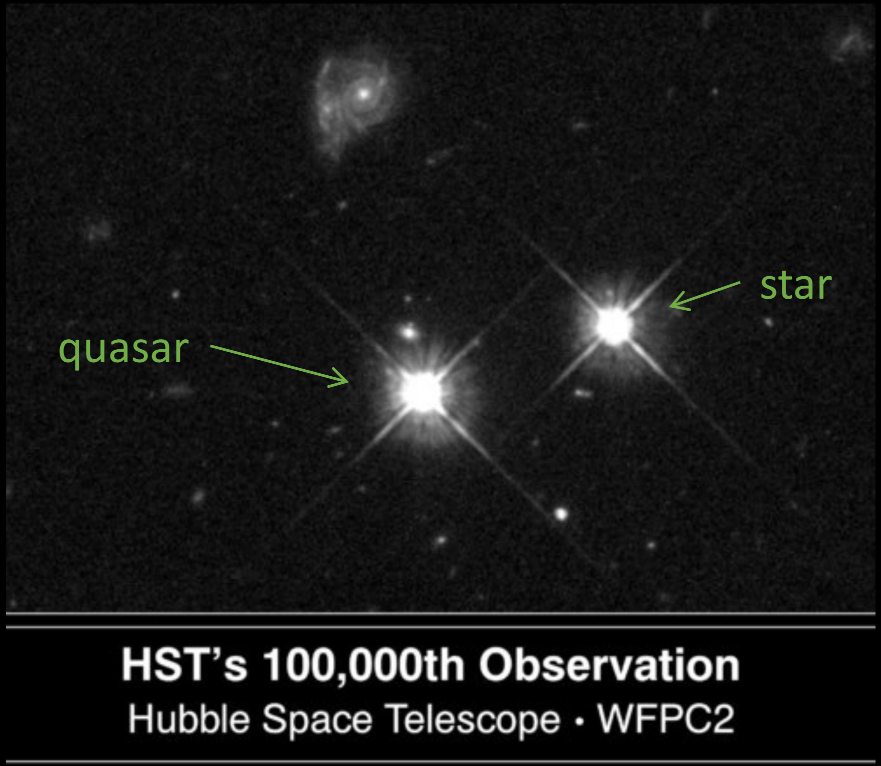
the gravitational potential well of SMBH

Determining Black Hole (BH) Mass

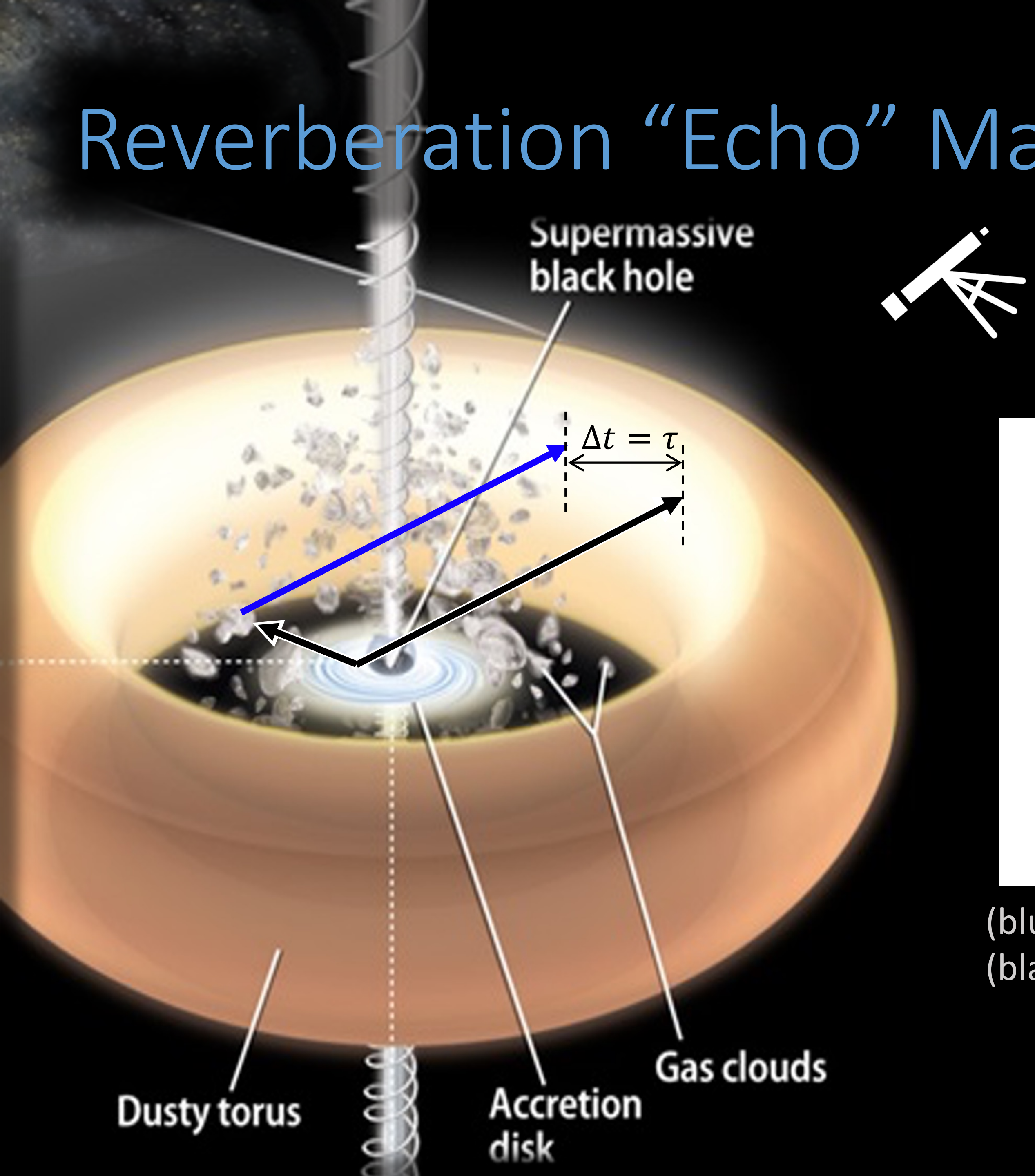
Virial theorem for an ensemble of gas clouds:

$$(\Delta v)^2 = f \frac{G M_{BH}}{R_{BLR}}$$

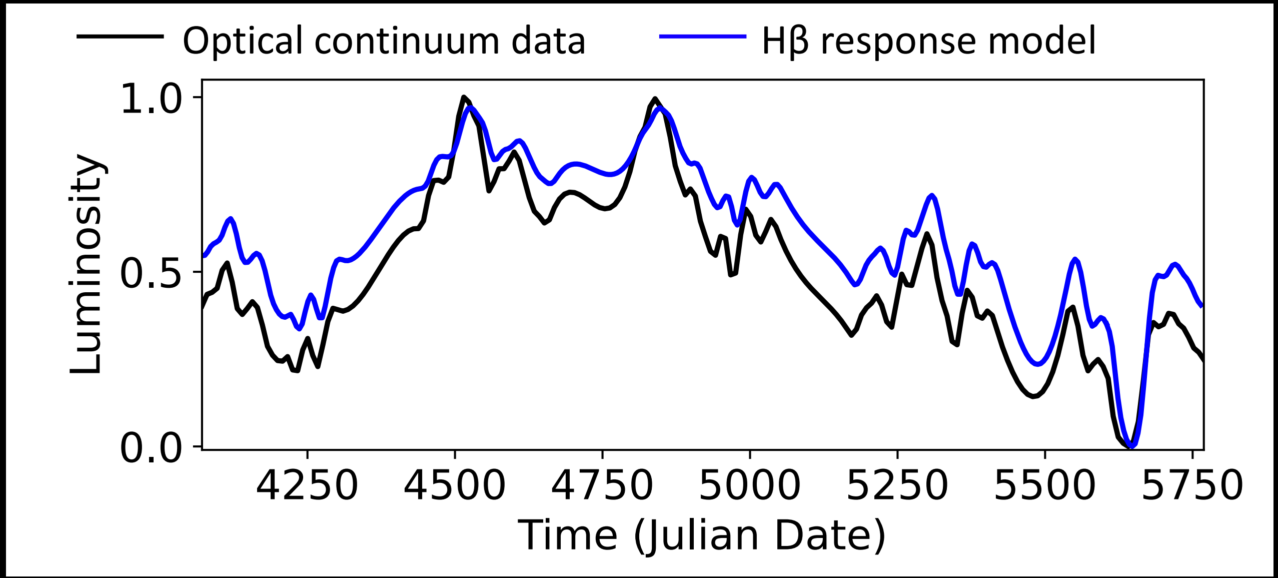
G – *gravitational constant*
M_{BH} – *BH mass*
Δv – *velocity dispersion*
R_{BLR} – *BLR size*
f – *(virial factor)*
unknown geometry and kinematics



Reverberation "Echo" Mapping



$R_{BLR} \propto c\tau$

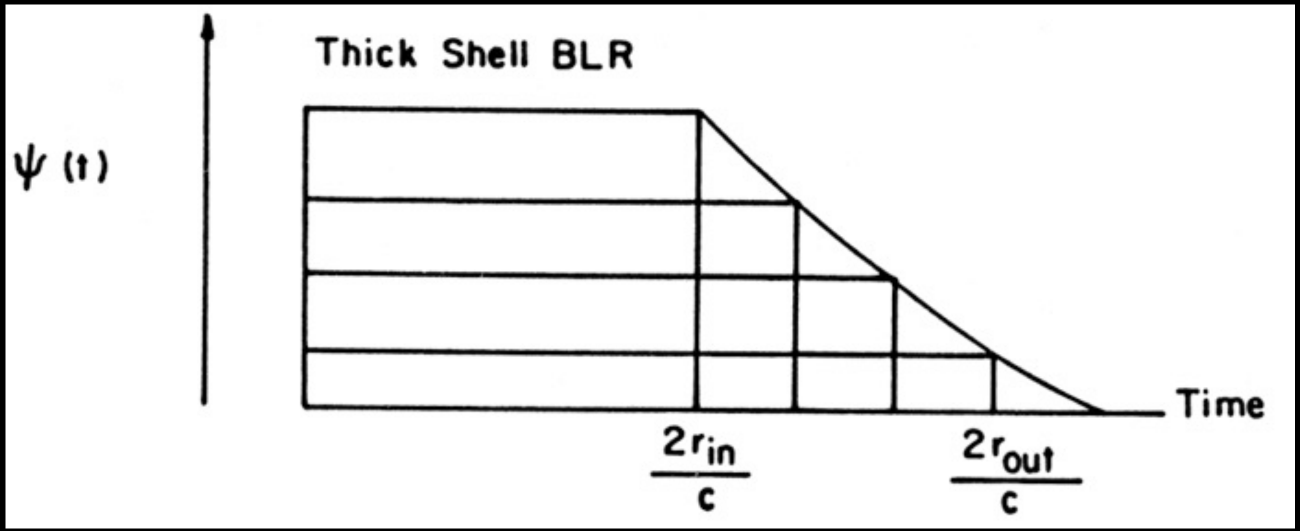


(blue) Optical continuum light-curve of NGC 3783 (Lira et al. 2011)
(black) Simulated broad Hβ light-curve

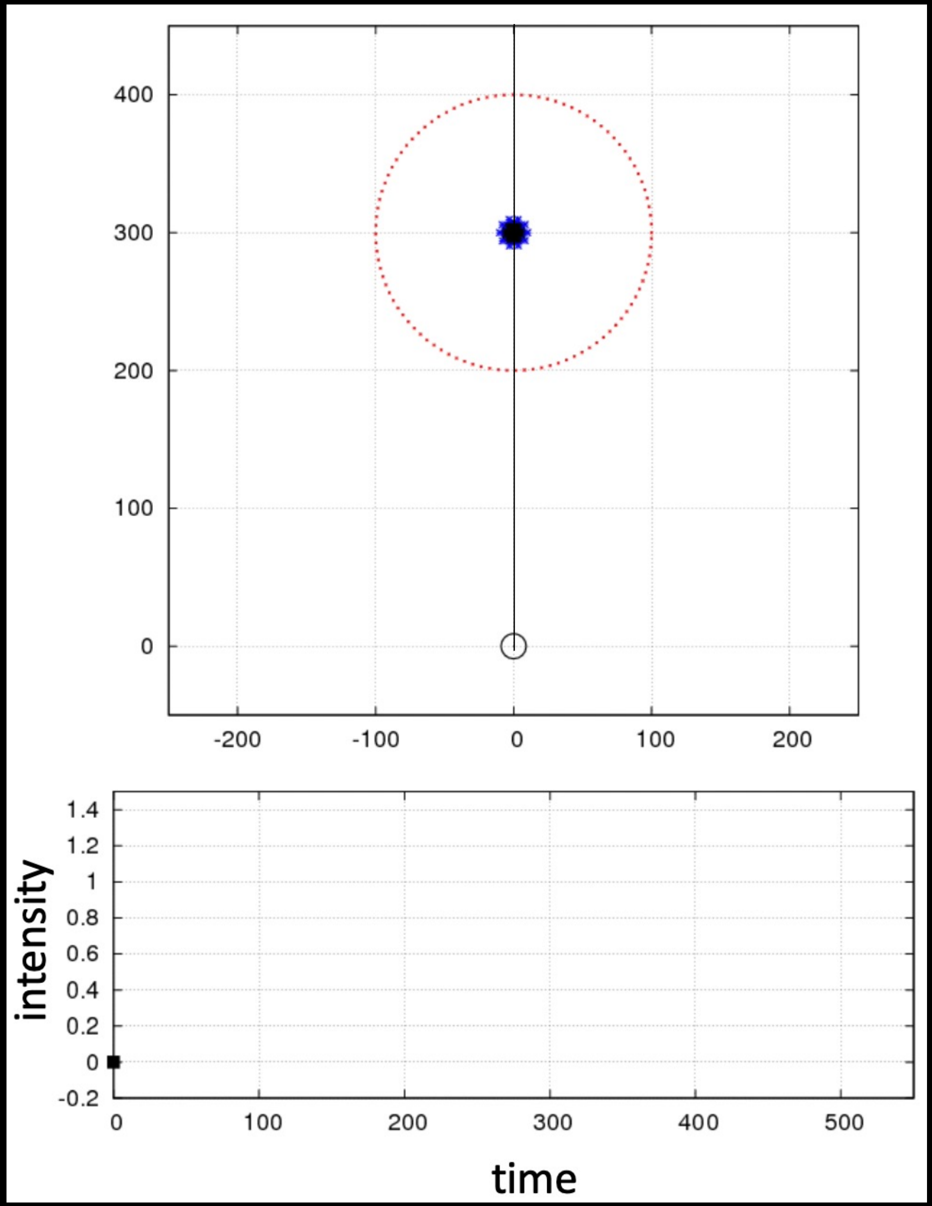
Reverberation Mapping

- Pulse/flash from accretion disk (blue dots)
- Clouds respond and the photons (red dots) are detected
- Observer measures the "Top Hat" Transfer Function

the response light-curve is the convolution of the transfer function with the "driving" light-curve



Blandford & McKee, 1982; Almeyda et al., 2017



Gif Credit: Dr. Michael Richmond, RIT

Modeling Code: BELMAC

Torus Reverberation MApping Code (TORMAC) - Created by Almeyda et al. 2017

TORMAC takes an input light curve to simulate the IR dust emission response from clouds in the dusty torus (Almeyda et al. 2017, Almeyda 2017)

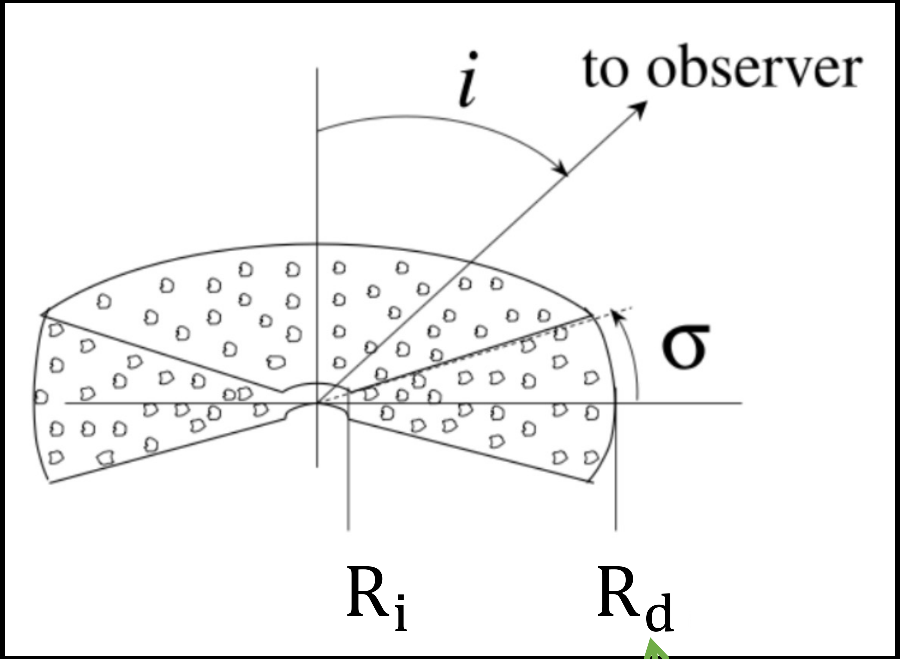
BELMAC (Broad Emission Line MApping Code) takes an input light curve to simulate the velocity-resolved response from clouds in the BLR for multiple broad emission lines (Rosborough et al., *in prep)*

- Emission approximated using recombination theory (Rosborough et al. 2023, *ApJ, submitted)*
  OR
- Emission calculated from photoionization model grids created with Cloudy (Ferland et al. 2017)

BELMAC

Sets-up a 3D ensemble of clouds arranged in spherical coordinates and described by,

- σ half-opening angle width of disk (90º = sphere)
- i inclination
- $Y_{BLR} = {R_d}/{R_i}$
- $dN \propto \left(\frac{r}{R_d}\right)^p dr$ Cloud distribution
- N number of clouds
- $n \propto r^s$ gas density



Dust sublimation radius for the BLR

Rosborough et al., 2023, *submitted;* Almeyda et al., 2017; Image: Adapted from Nenkova et al. 2008

BELMAC: the Velocity Field

(current implementation)

<u>Radial</u>

Assumptions: Equation of motion only includes gravity and radiation pressure terms

<u>Rotational</u>

Assumptions: Circular (Keplerian), $v \propto r^{-1/2}$

Orbits are randomly inclined between $\pm\sigma$

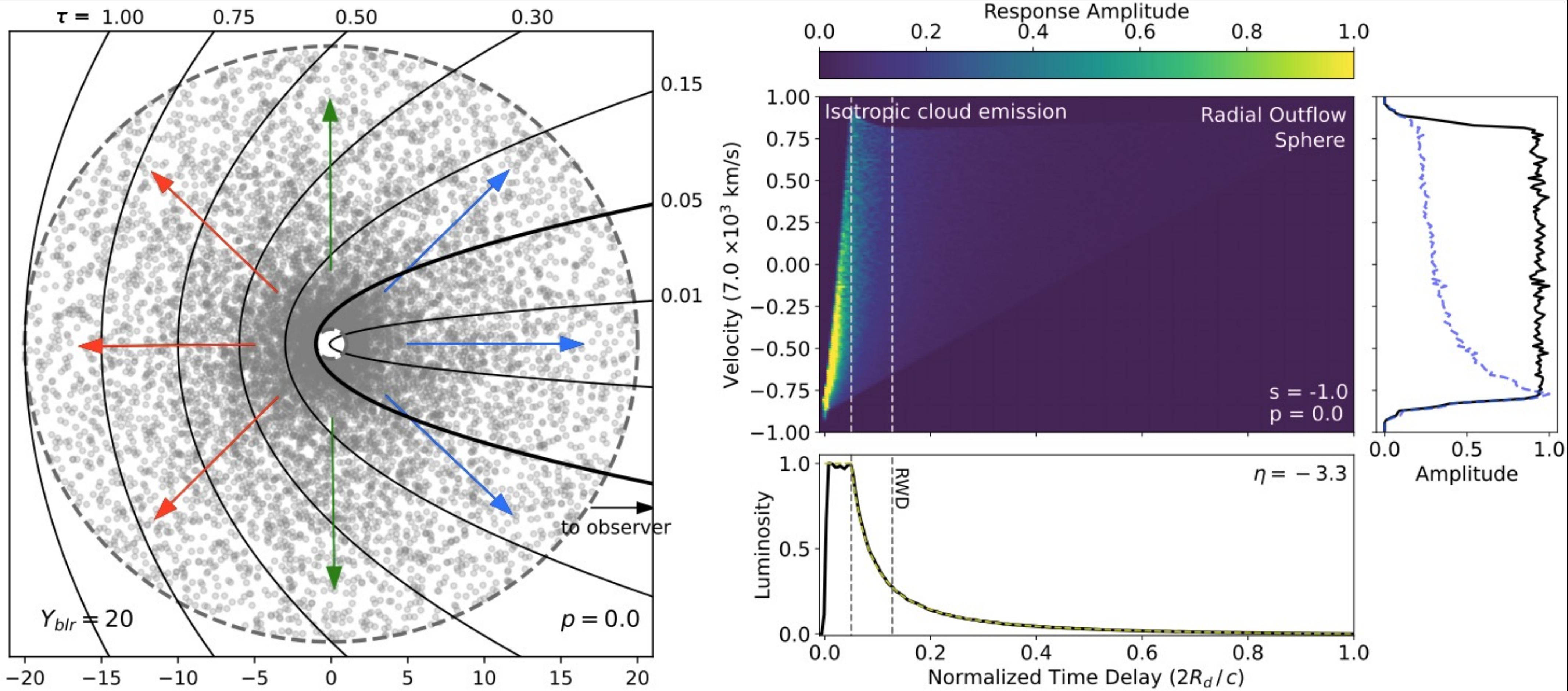
<u>Random</u>

Turbulent motion

Rosborough, et al., *2023, submitted*, Netzer, 2008

Spherical BLR: Velocity-Resolved Response

. . . to a single “pulse” from the accretion disk

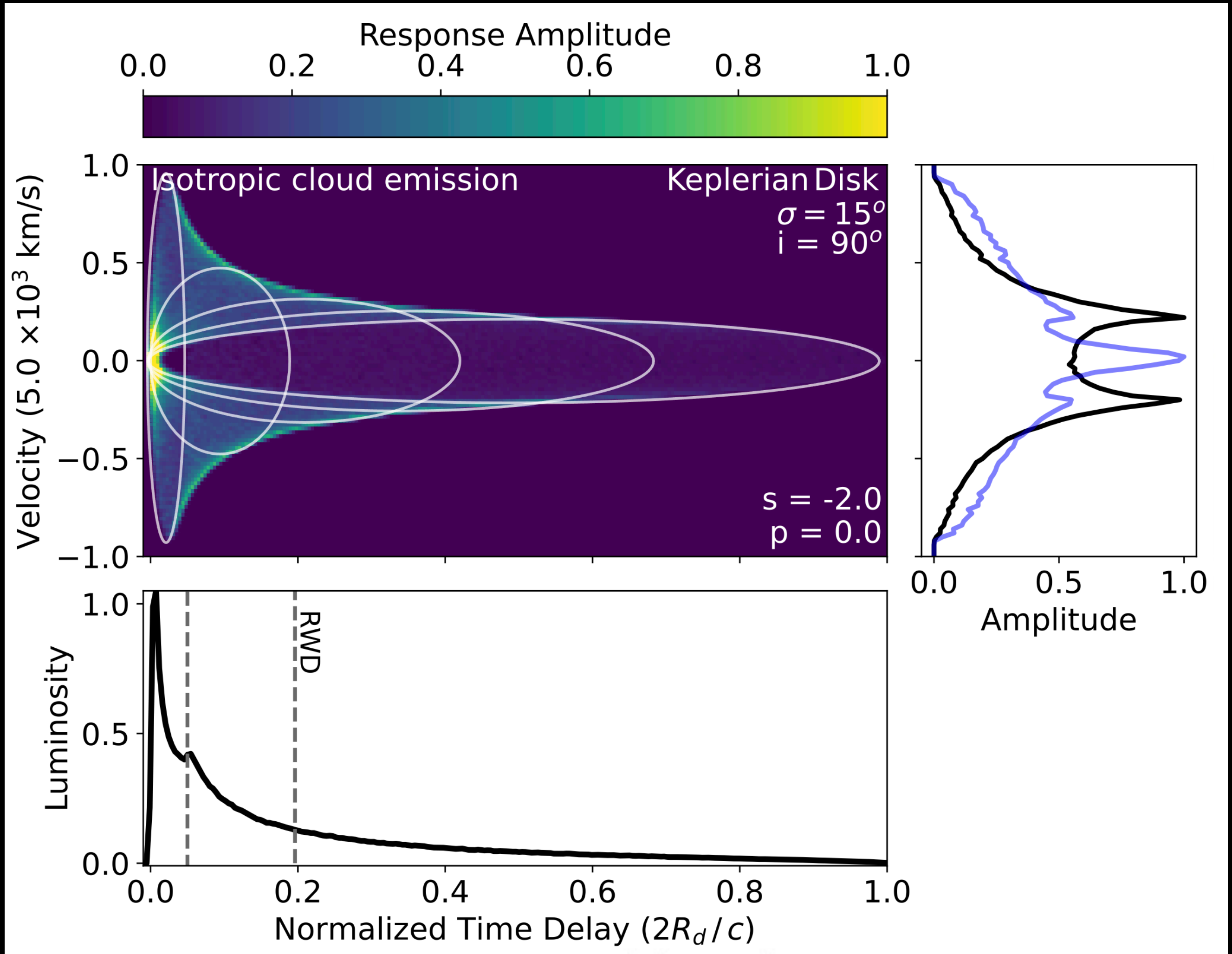


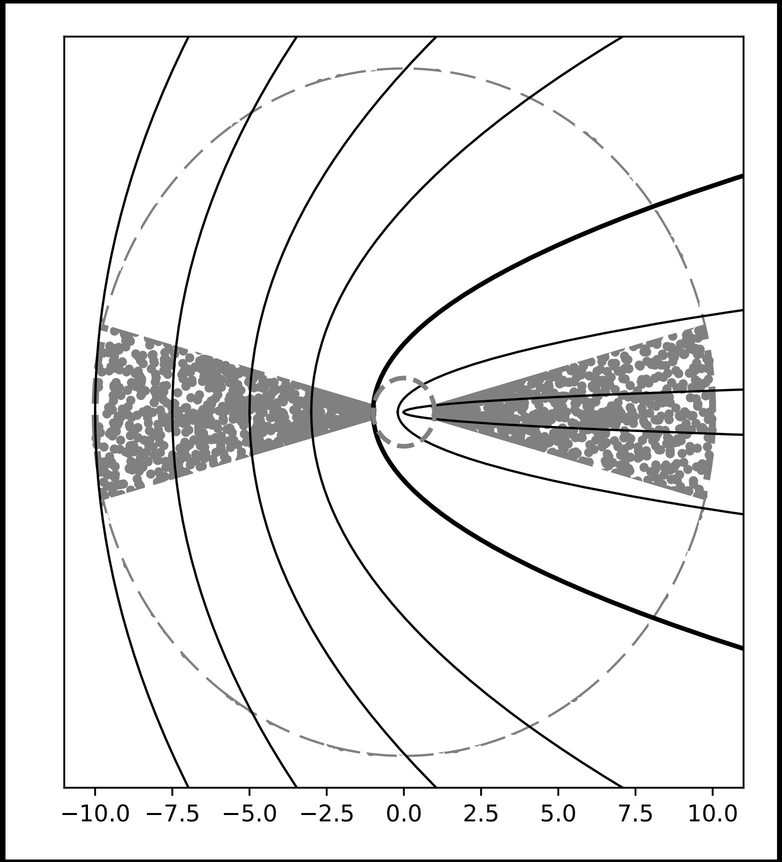
Velocity-resolved (2D) transfer function

Rosborough et al., 2023, *ApJ submitted*

Edge-on Thin Disk: Velocity-Resolved Response

. . . to a single "pulse" from the accretion disk





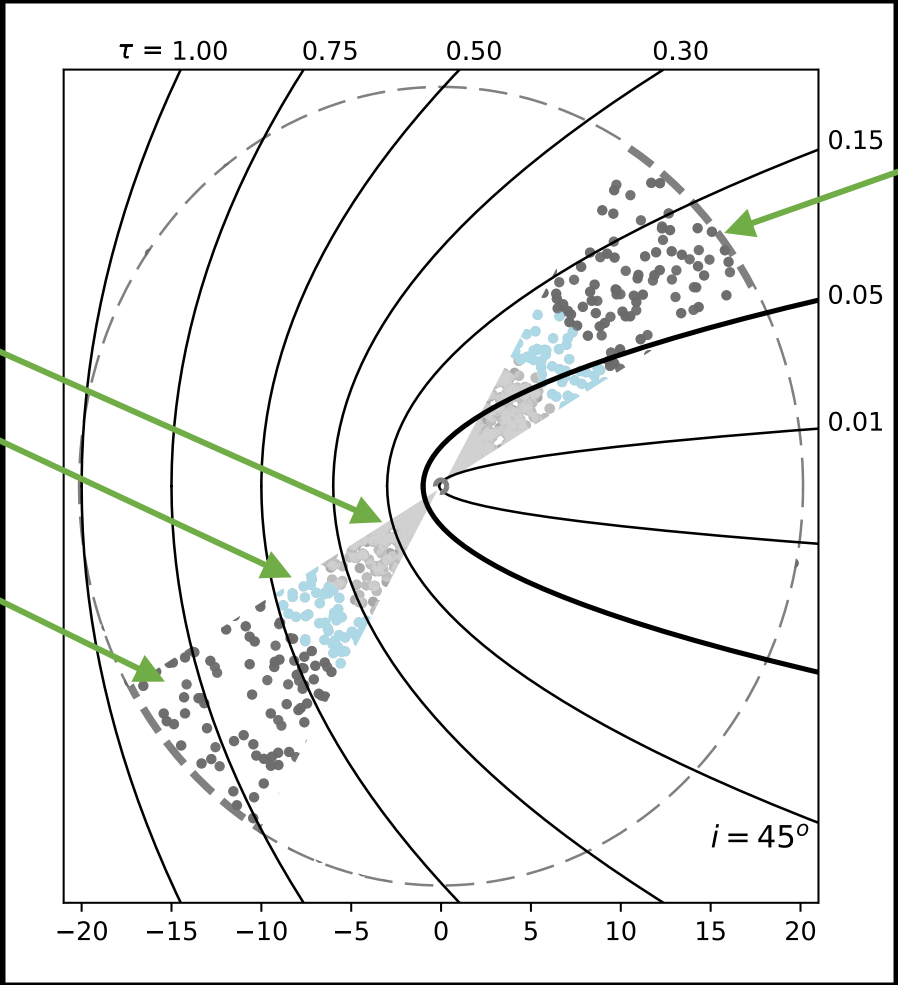
Rosborough et al., 2023, *ApJ submitted*

Matter-Bounded Clouds and Anisotropy

Matter-bounded clouds (fully ionized)

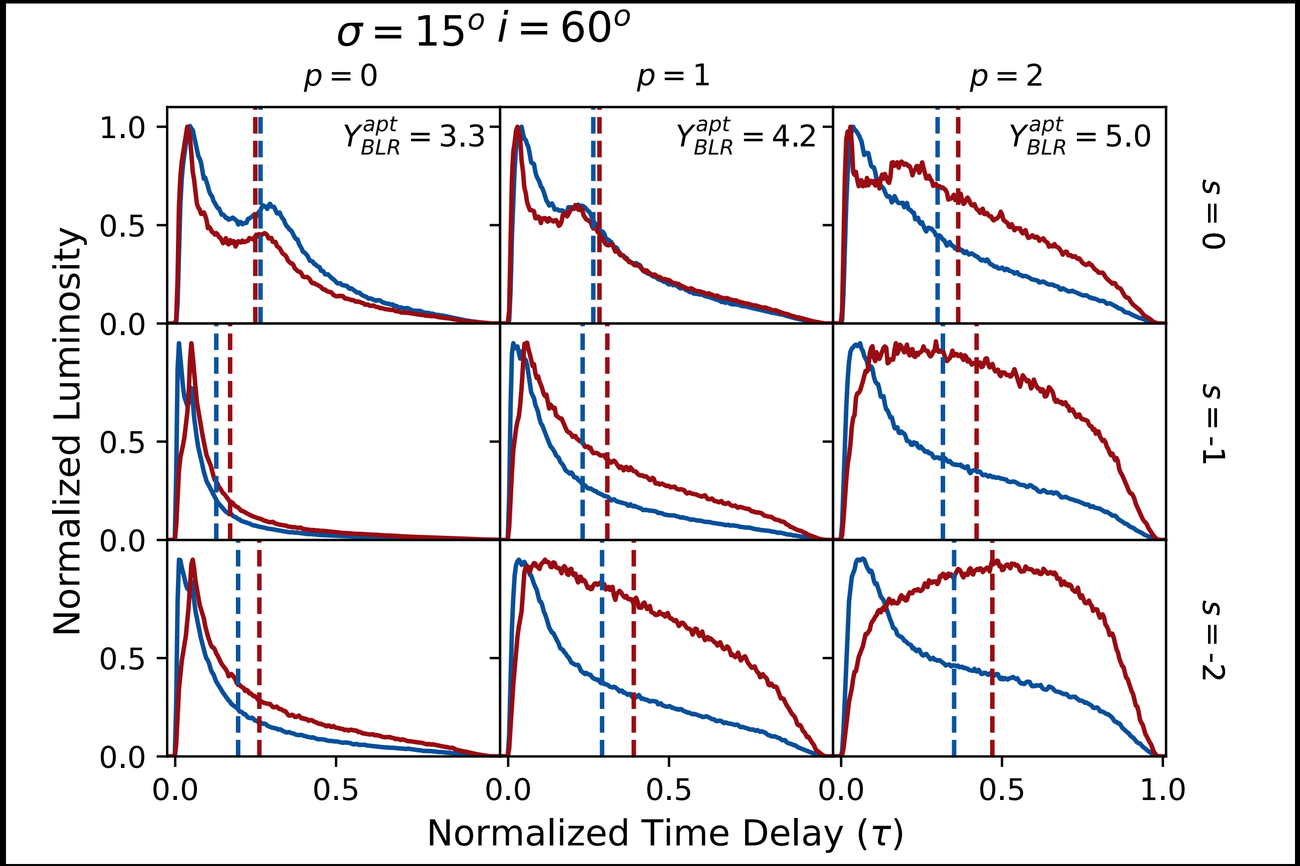
Transition clouds

Radiation-bounded clouds (partially ionized)



Anisotropic cloud emission (ACE) suppresses the response of near-sided clouds

Response Weighted Delay (RWD)



Isotropic cloud illumination (ICE)

Anisotropic cloud illumination (ACE)

$$Y_{BLR} = {}^{R_d}/_{R_{in}} = 20$$

$$n(r) = r^s$$

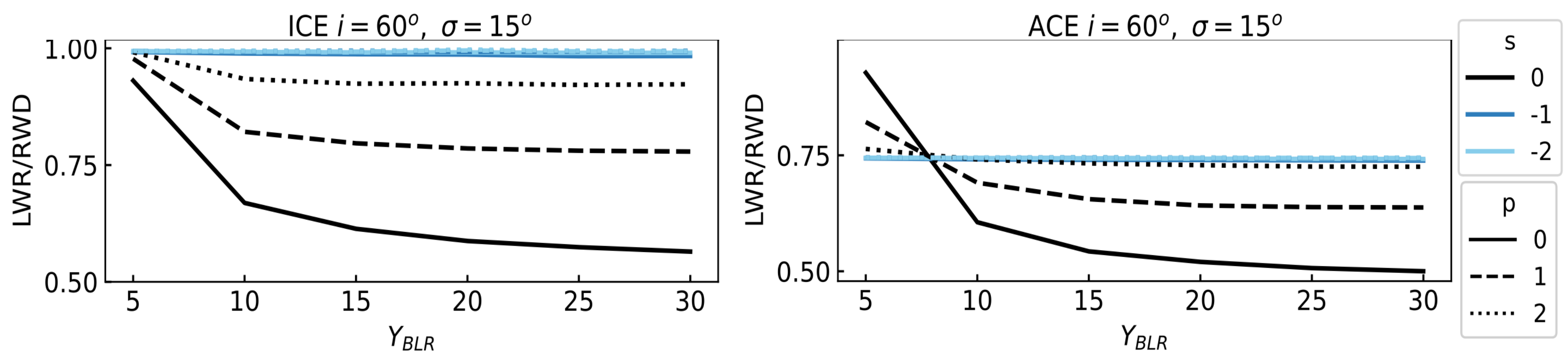
$$dN \propto r^p dr$$

} All radiation-bounded clouds

Dashed lines are the response weighted delays. In physical units, the observed lag is: $\tau = 2R_d RWD/c$

Rosborough et al., 2023, *ApJ submitted*

RWD vs Luminosity Weighted Radius (LWR)



In normalized units, theoretically, $LWR = RWD$ (recall $R_{BLR} \propto c\tau$)

Assuming $R_d LWR = R_{BLR}$, then the observed lag can overestimate R_{BLR} by a factor ~2

We find $RWD = LWR$ *only* when:

the BLR contained 100% radiation-bounded clouds and isotopically emitting clouds

$$f M_{BH} = \frac{(\Delta v)^2 R_{BLR}}{G}$$

Rosborough et al., 2023, *ApJ submitted*

Application to Data

Space Telescope and Optical Reverberation Mapping (STORM) Project 1

- NGC 5548
- X-ray, UV, optical, and IR monitoring

Super-Eddington AGN Mrk 142

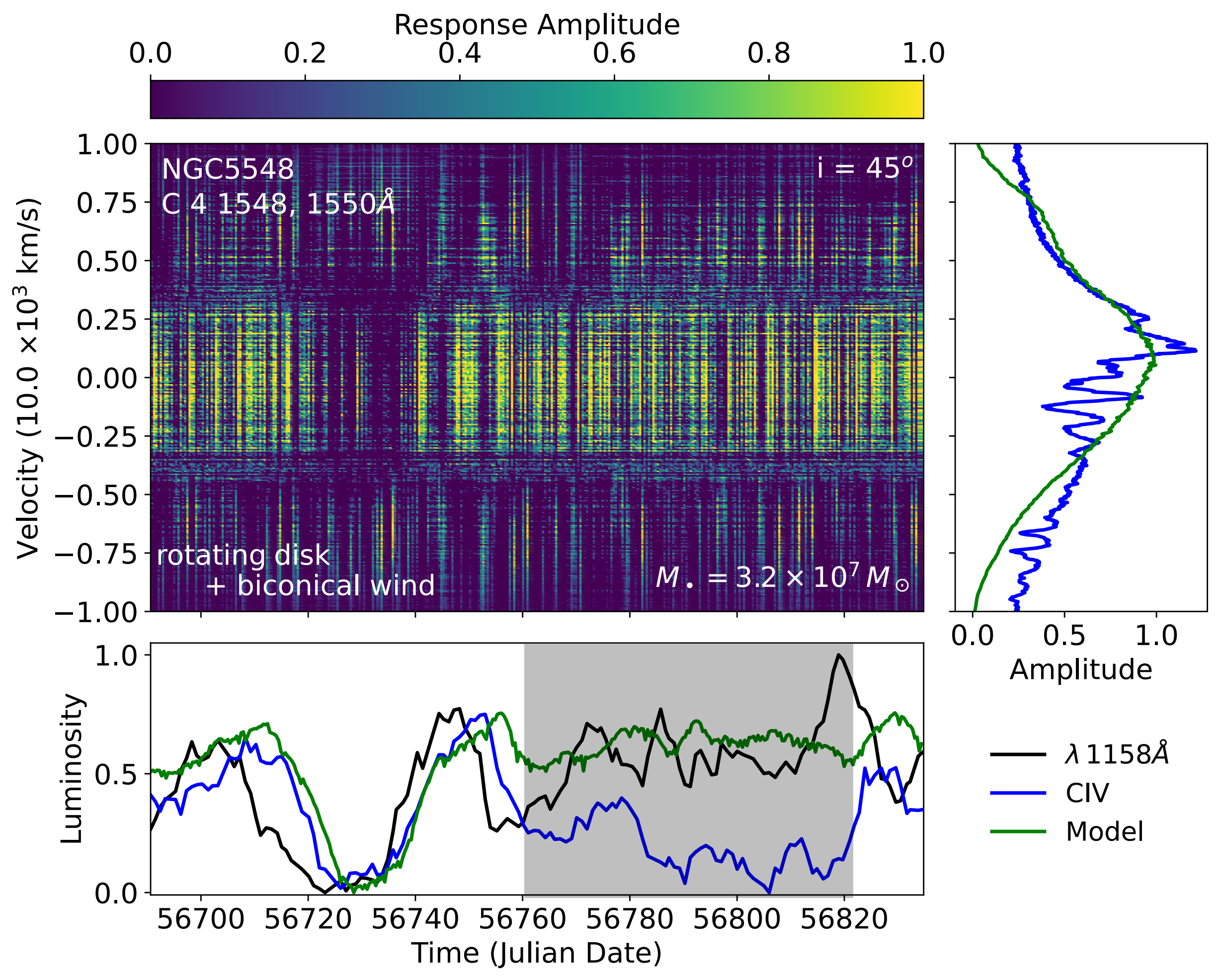
- Collaboration with Viraja Khatu and Sarah Gallagher at Western-Ontario University
- UV (*Swift*) and optical (Gemini-N and Lijiang) monitoring (Khatu 2022)

Preliminary Results: NGC 5548

- UV continuum (1158Å) data from HST
- CIV light-curve data from HST
- Delay time:
  - 3.3+1.1-0.7 days (median; Williams et al. 2019)
  - ~3-4 days (BELMAC model)
- Model parameters agree with previous work (by the AGN STORM 1 paper series)

"BLR Holiday"

- Dust-free obscurer?
- Change in L_{bol} ?
  (Dehghanian et al. 2019)



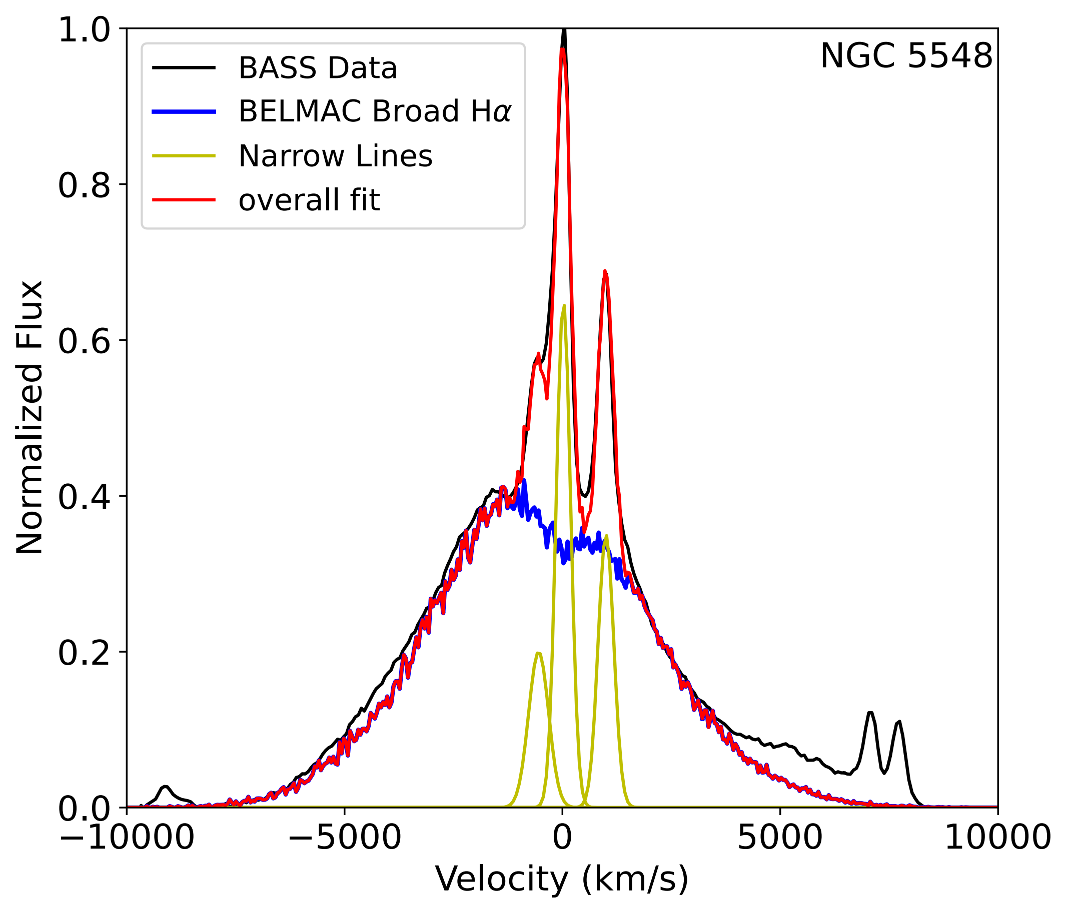
Data: Kriss et al. 2019

Summary and Conclusion

- BELMAC is a new BLR reverberation mapping modeling code
  - Velocity-resolved response
  - Multiple broad emission lines (e.g., Lyα, CIV, MgII, Hβ, NV, HeII…)
  - Response weighted delay can overestimate R_{BLR} by a factor ~2
- Ongoing Work:
  - Compile a library of 2D transfer functions (response to a “flash”)
  - Add parameter estimation procedure (Bayesian stat. with MCMC procedure)
  - Apply to data
    - upcoming SDSS-V and LSST (with 4MOST/TiDES spectroscopy)
    - Collaboration with Western-Ontario University: Mrk 142
    - Constrain the virial factor, and determine SMBH masses

Future Goals for BELMAC

- Make it public
- Combine with TORMAC for gas and dust reverberation mapping
- Expand geometry and kinematics for TDEs, black hole binaries, and black hole recoils

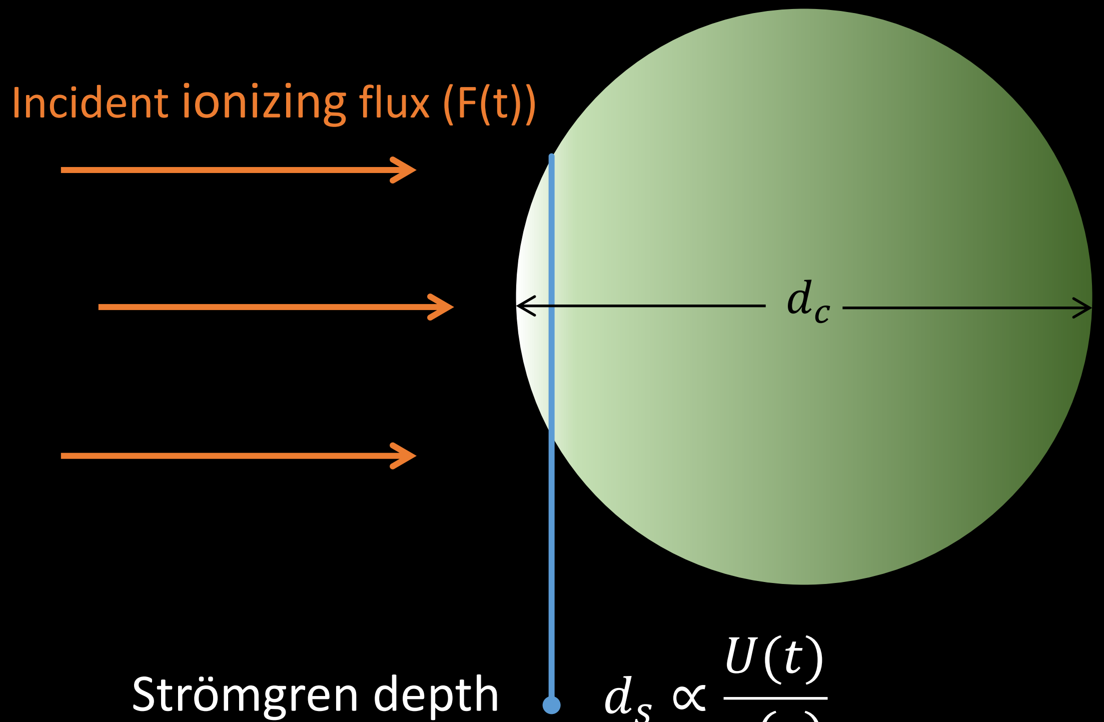


Cloud Emission

Assume spherical clouds and $m_{cl}(r) = constant \implies$

$$U(t) = \frac{F(t)}{cn}$$ Ionization parameter

$$n \propto r^{s} \qquad R_{cl} \propto r^{-s/3} \qquad d_s \propto r^{-2s-2}$$



$$d_s \propto \frac{U(t)}{n(r)}$$

Two modes:

Simple Recombination Theory

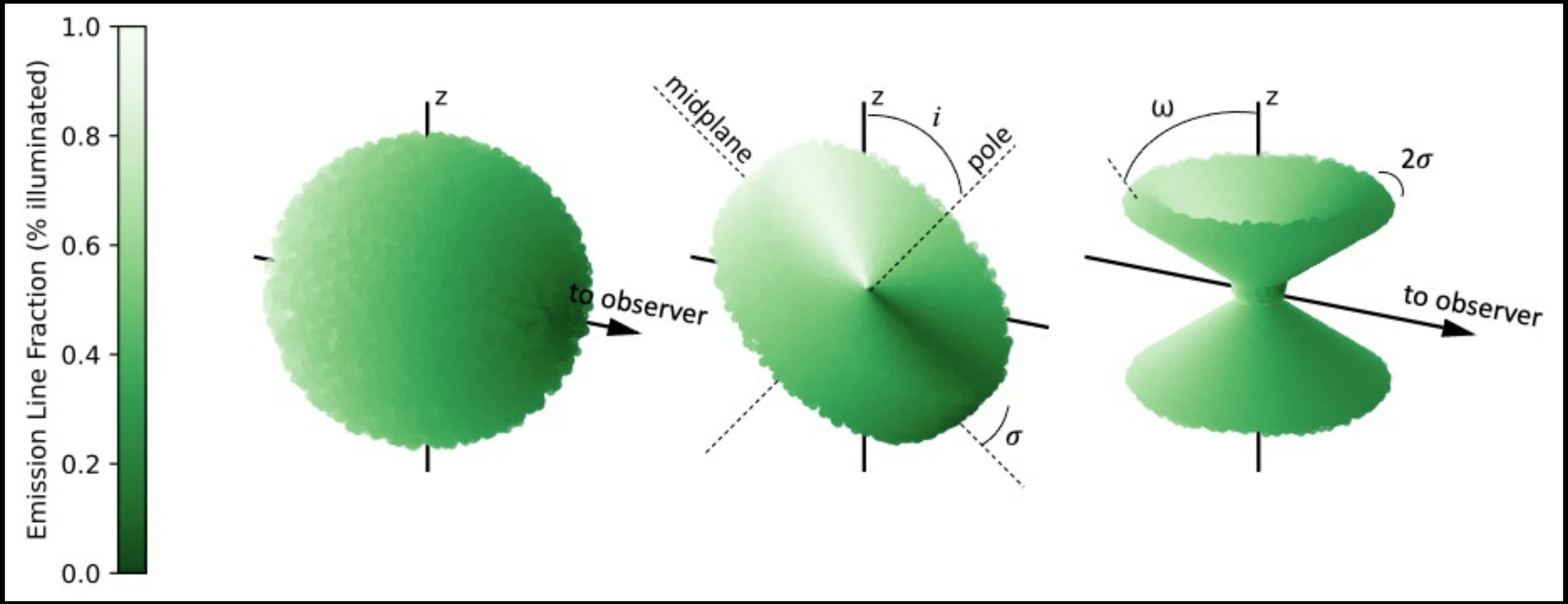
$$L_{cl} \propto n^2 R_{cl}^2 d_s$$

Photoionization Model Grids

- Code reads flux for multiple/desired broad lines given U(t), n, and column density

Rosborough, et al., *in prep*, Netzer, 2008

TORMAC+BLR



1.0
0.8
0.6
0.4
0.2
0.0
Emission Line Fraction (% illuminated)
z
to observer
midplane
z
i
pole
σ
ω
z
2σ
to observer

Example BLR Models

A biconical wind with or without a disk can also be modeled

Rotational and radial velocity components can be combined for rotating in/outflows

Radial and rotational components
Angular momentum conserved