BLR Dynamical Modeling in Reverberation Mapping

Yan-Rong Li
Institute of High Energy Physics

SEMAMBH collaboration
MAHA collaboration

"Mapping Central Regions of Active Galactic Nuclei"
Guilin China, 2019-09-20

Outline

I. An introduction to BLR dynamical modeling
II. Application to Mrk 142
III. Application to NGC 3227
IV. Future improvements

All efforts of RM analysis

To obtain the transfer function/velocity-delay map from the integral eqaution

$$L(v,t) = \int \Psi(v,\tau) C^{1+\gamma}(t-\tau) d\tau$$

For small continuum variations, the linearized equation is

$$\Delta L(v,t) = \int \Psi(v,\tau) \Delta C(t-\tau) d\tau$$

$$\Delta L(v,t) = L(v,t) - L_0$$
$$\Delta C(t) = C(t) - C_0$$

All efforts of RM analysis

To obtain the transfer function/velocity-delay map from the integral equation

$$L(v,t) = \int \Psi(v,\tau) C^{1+\gamma}(t-\tau) d\tau$$

Methods:

- ✓ Fourier transformation: Blandford & McKee 1982
- ✓ Regularized linear inversion: Krolik & Done 1995; Skielboe+2015
- ✓ Maximum entropy technique: Horne 1994
- ✓ BLR dynamical modeling: Pancoast et al. 2011, 2014; Li et al. 2013, 2018

All efforts of RM analysis

Dynamical modeling approach explores the best solution with input BLR models

$$L(v,t) = \int \Psi(v,\tau) C^{1+\gamma}(t-\tau) d\tau$$

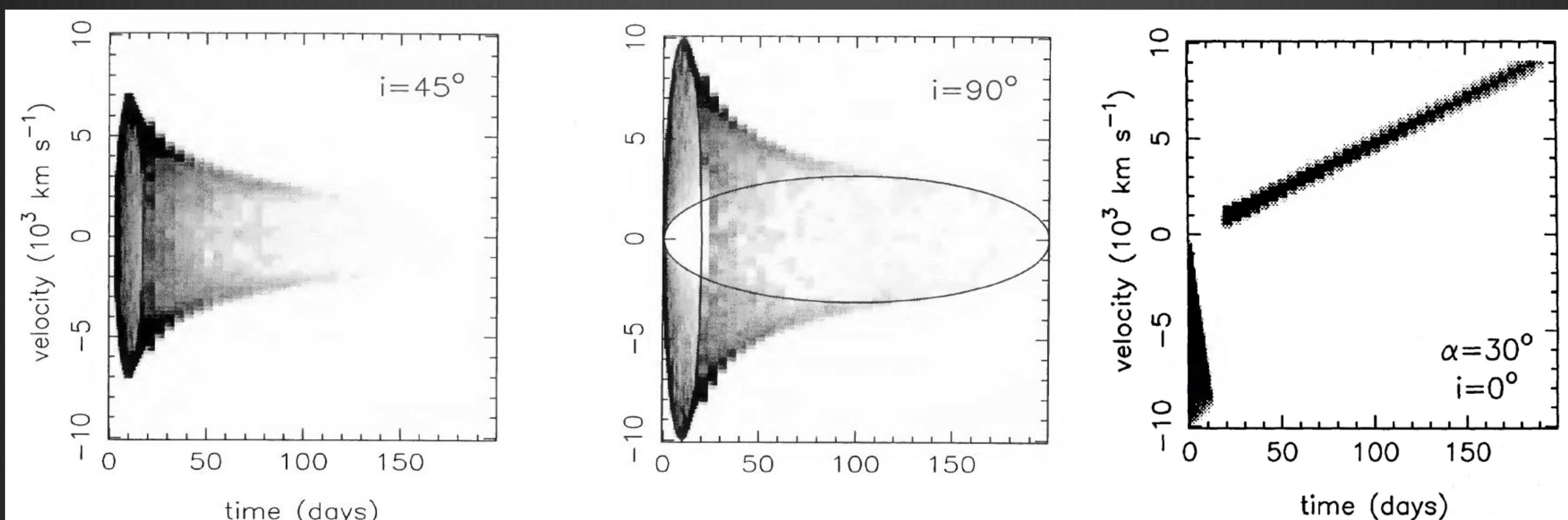
BLR dynamical model

Early attempts: computing $\boldsymbol{\Psi}(\boldsymbol{v}, \boldsymbol{\tau})$

The response of the broad emission line region to ionizing continuum variations – III. An atlas of transfer functions

E. Pérez,[1] A. Robinson[2] and L. de la Fuente[1]
[1] *Instituto de Astrofísica de Canarias, 38200 La Laguna, Tenerife*
[2] *Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA*

Perez et al. 1992, MNRAS, 256, 103



inclined disk

edge-on disk

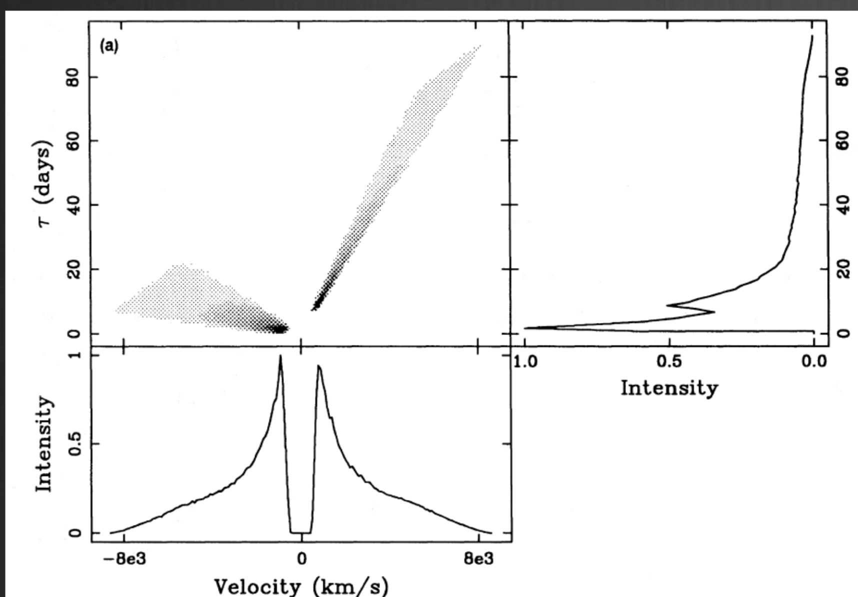
bi-conical outflow

Early attempts: computing $\boldsymbol{\Psi}(\boldsymbol{v}, \boldsymbol{\tau})$

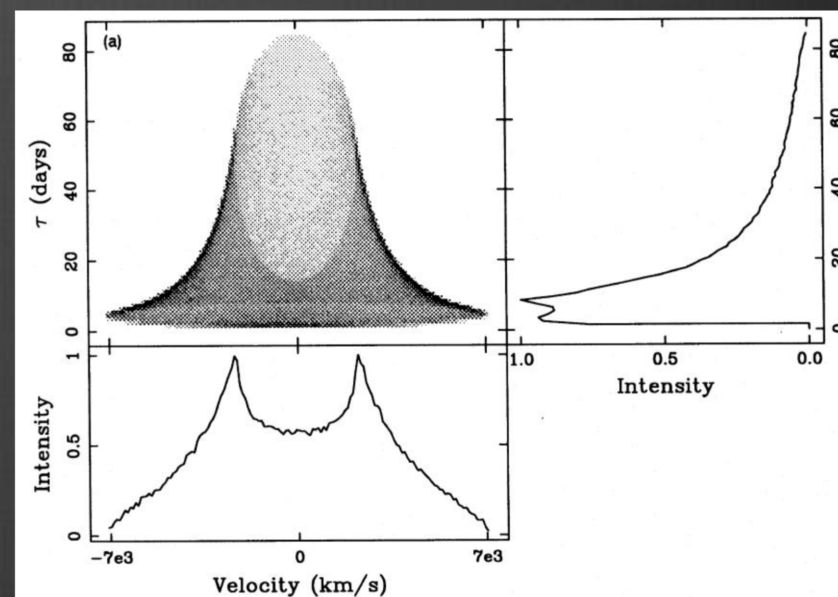
Response functions as diagnostics of the broad-line region in active galactic nuclei – II. Anisotropic line emission

P. T. O'Brien,[1,2] M. R. Goad[1] and P. M. Gondhalekar[3]
[1]*Department of Physics & Astronomy, University College London, Gower Street, London WC1E 6BT*
[2]*Astrophysics, Department of Physics, Oxford University, Keble Road, Oxford OX1 3RH*
[3]*Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX*

O'Brien et al. 1994, MNRAS, 268, 845



outflow



inclined disk

Bottorff et al. (1997): hydromagnetic wind model

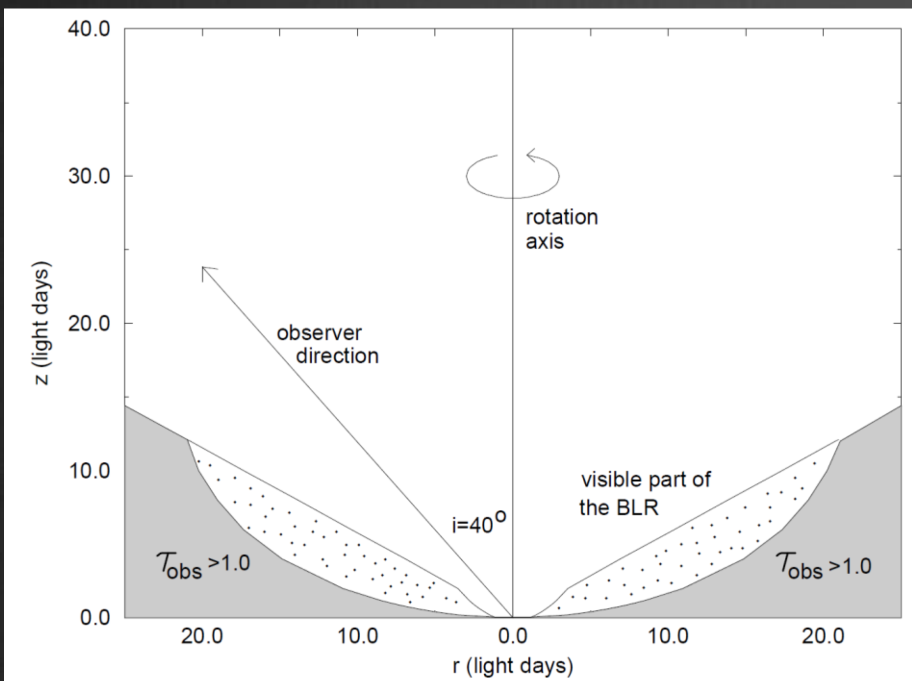
DYNAMICS OF BROAD EMISSION-LINE REGION IN NGC 5548: HYDROMAGNETIC WIND MODEL VERSUS OBSERVATIONS

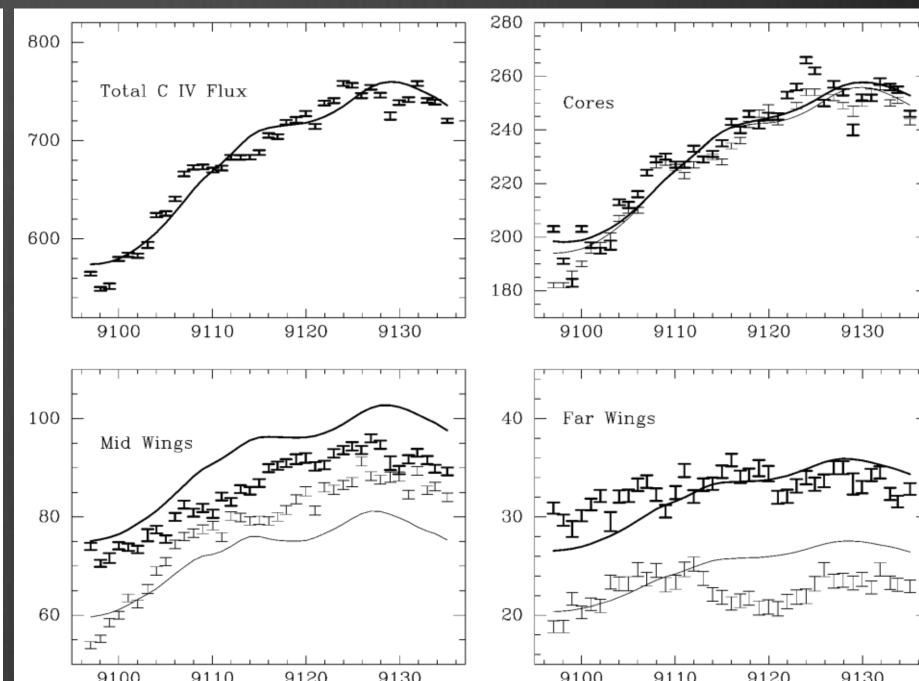
MARK BOTTORFF, KIRK T. KORISTA, AND ISAAC SHLOSMAN
Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506-0055; bottorff@pa.uky.edu, korista@pa.uky.edu, shlosman@pa.uky.edu

AND

ROGER D. BLANDFORD
Theoretical Astrophysics 130-33, California Institute of Technology, Pasadena, CA 91125; rdb@tapir.caltech.edu

BH mass estimated:
$\sim 3 \times 10^7 M_\odot$

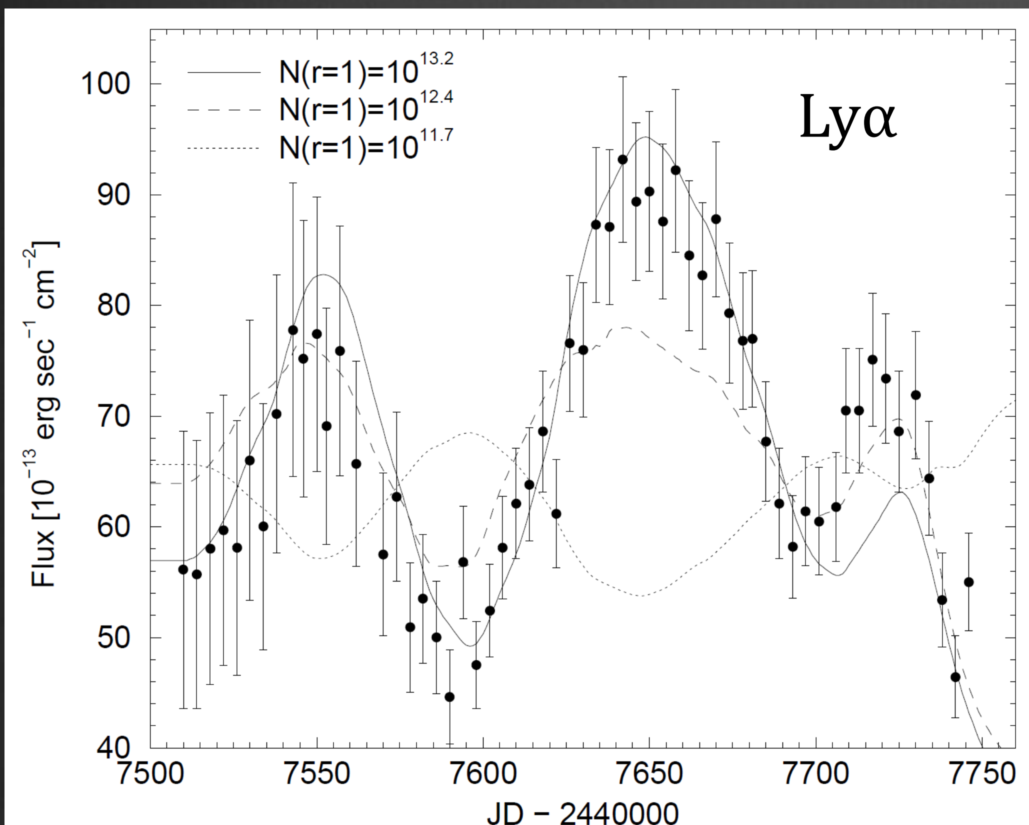




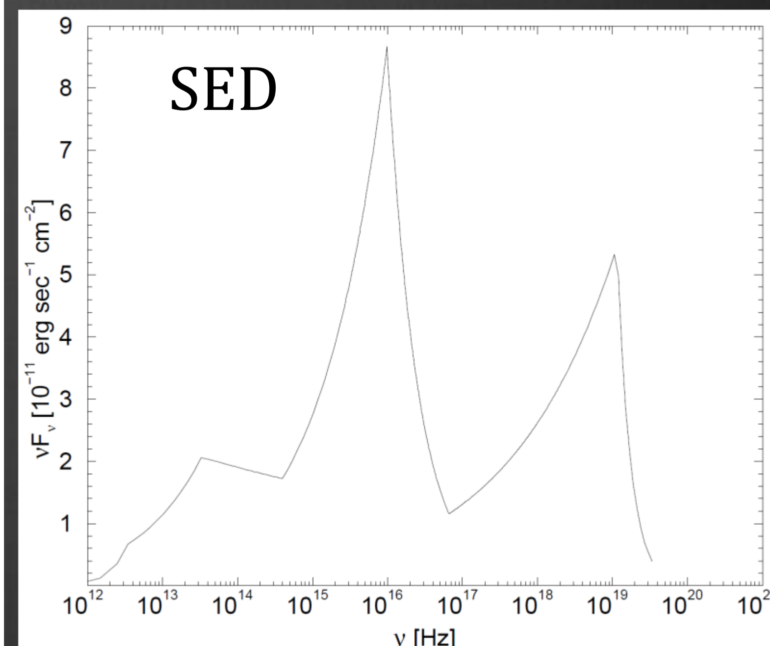
Kaspi & Netzer (1999): spherical BLRs

MODELING VARIABLE EMISSION LINES IN ACTIVE GALACTIC NUCLEI: METHOD AND APPLICATION TO NGC 5548

SHAI KASPI AND HAGAI NETZER
School of Physics and Astronomy and the Wise Observatory, The Raymond and Beverly Sackler Faculty of Exact Sciences, Tel-Aviv University, Tel-Aviv 69978, Israel; shai@wise.tau.ac.il, netzer@wise.tau.ac.il



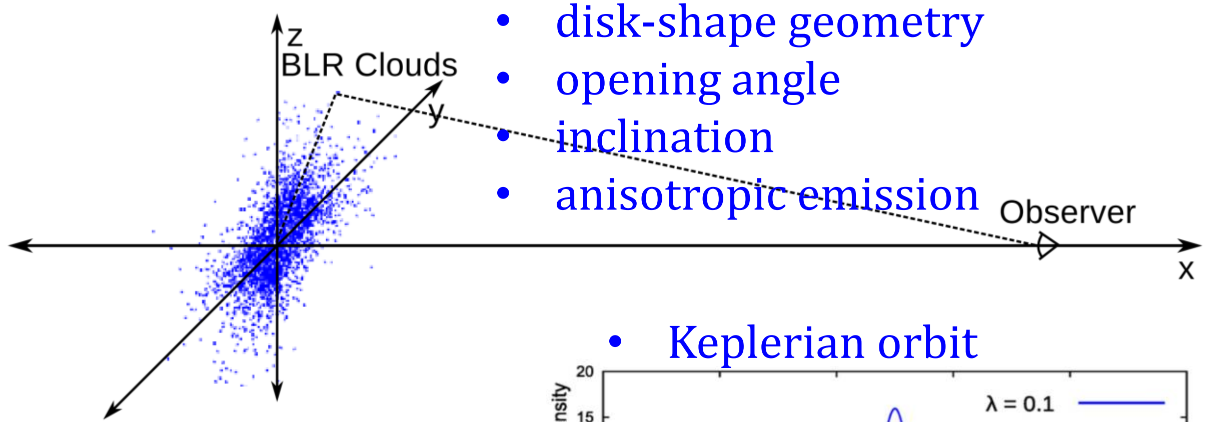
Photoionization included, but velocity-unresolved



Pancoast et al. (2011): modern version

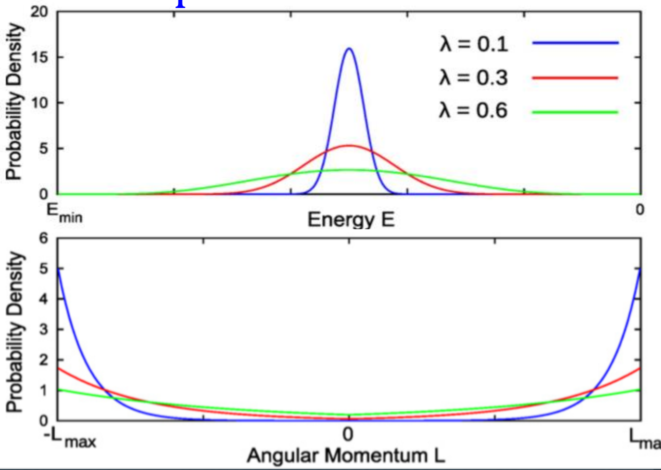
GEOMETRIC AND DYNAMICAL MODELS OF REVERBERATION MAPPING DATA

ANNA PANCOAST, BRENDON J. BREWER, AND TOMMASO TREU[1]
Department of Physics, University of California, Santa Barbara, CA 93106-9530, USA; pancoast@physics.ucsb.edu

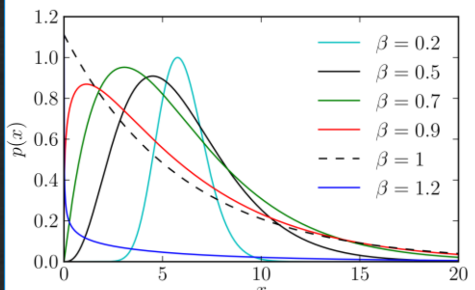


- disk-shape geometry
- opening angle
- inclination
- anisotropic emission

- Keplerian orbit



- position: Gamma distribution

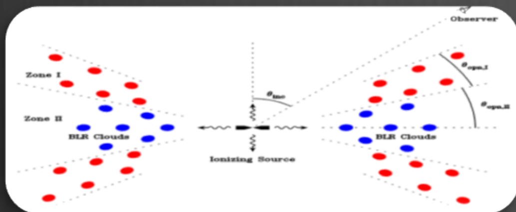


$$p(\boldsymbol{\theta}|\boldsymbol{D}, I) \propto p(\boldsymbol{\theta}|I)\, p(\boldsymbol{D}|\boldsymbol{\theta}, I)$$

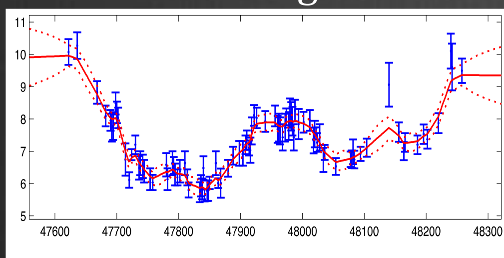
- Bayesian inference
- Sophisticated sampling algorithm
- Fully explore parameter space

BLR dynamical modeling: generic flowchart

BLR model



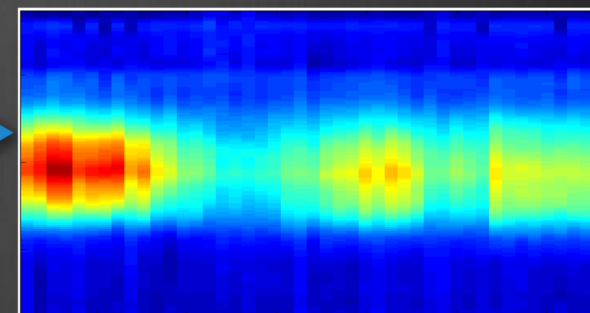
Continuum light curve



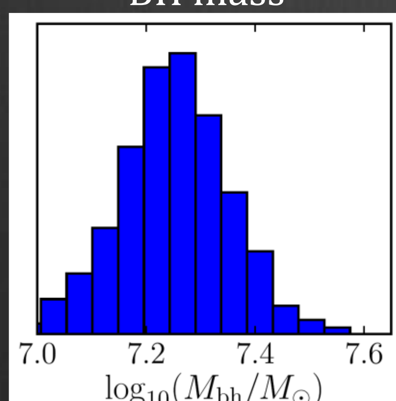
posterior probability

Markov-Chain Monte Carlo

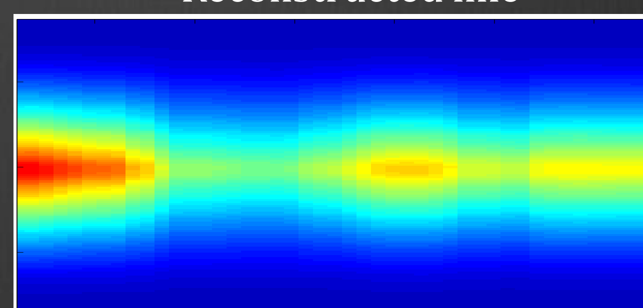
Broad-line data



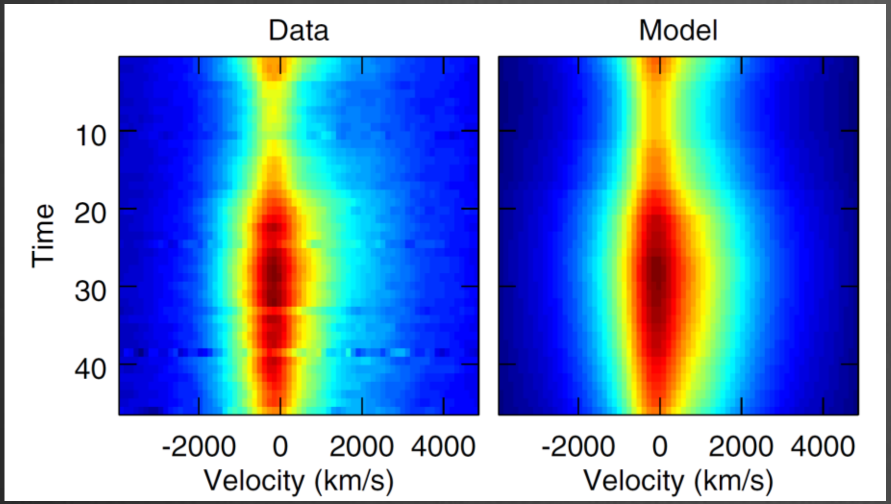
BH mass

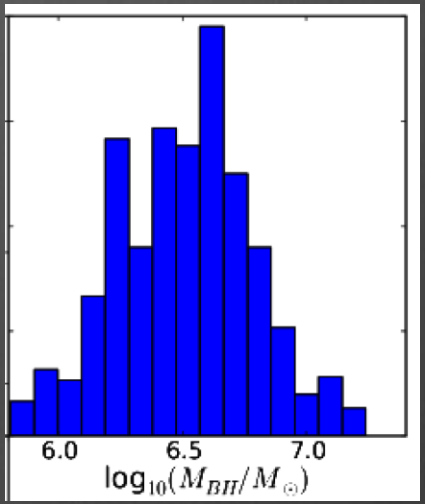


Reconstructed line

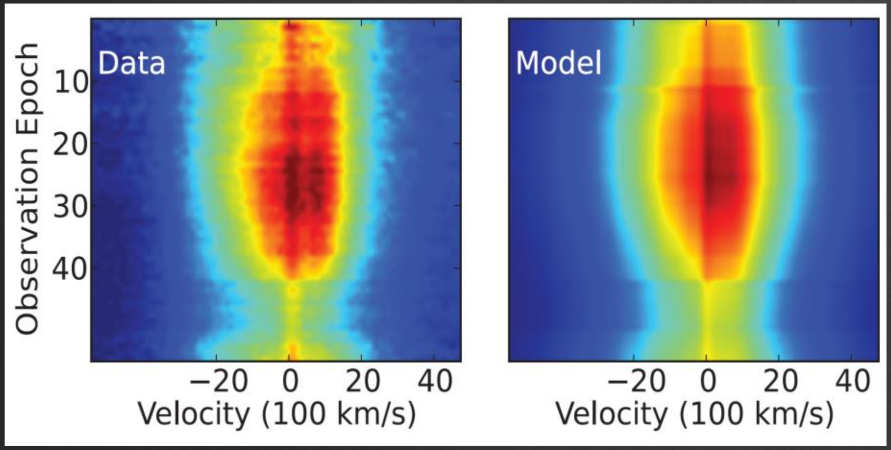


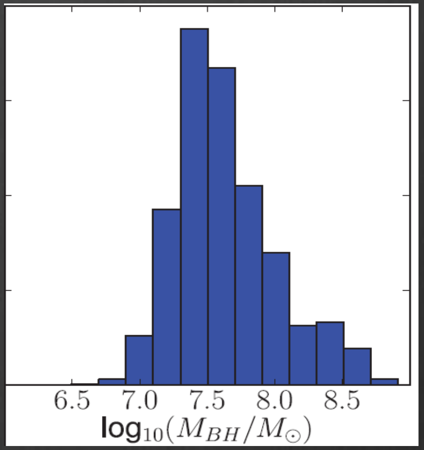
Arp 151 (Brewer et al. 2011)





Mrk 50 (Pancoast et al. 2012)



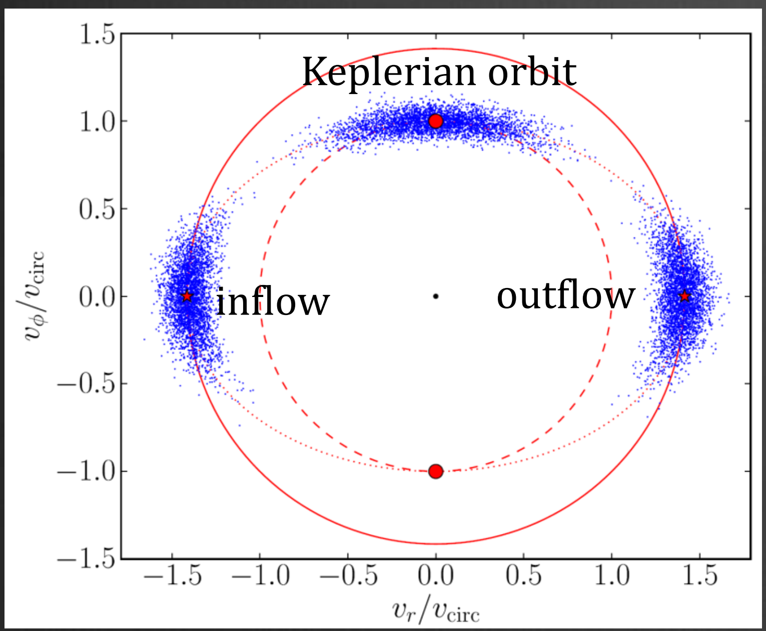


Pancoast et al. (2014): further improvements

Modelling reverberation mapping data – I. Improved geometric and dynamical models and comparison with cross-correlation results

Anna Pancoast,[1★] Brendon J. Brewer[2] and Tommaso Treu[1†]

[1] *Department of Physics, University of California, Santa Barbara, CA 93106, USA*
[2] *Department of Statistics, The University of Auckland, Private Bag 92019, Auckland 1142, New Zealand*



velocity sampling

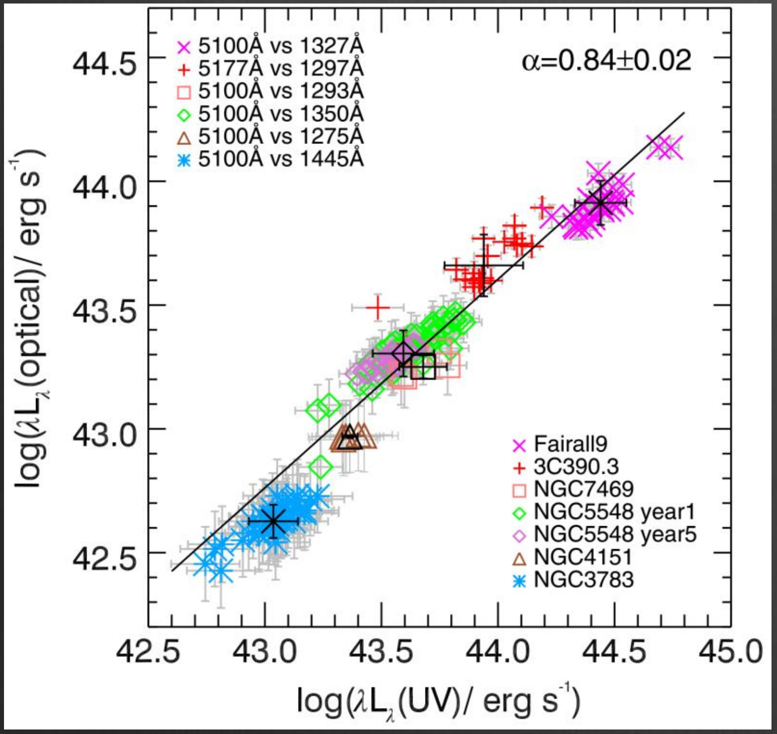
- Better velocity sampling of BLR clouds
- Inflow/outflows
- Improved anisotropic treatments

see Peter Williams' talk

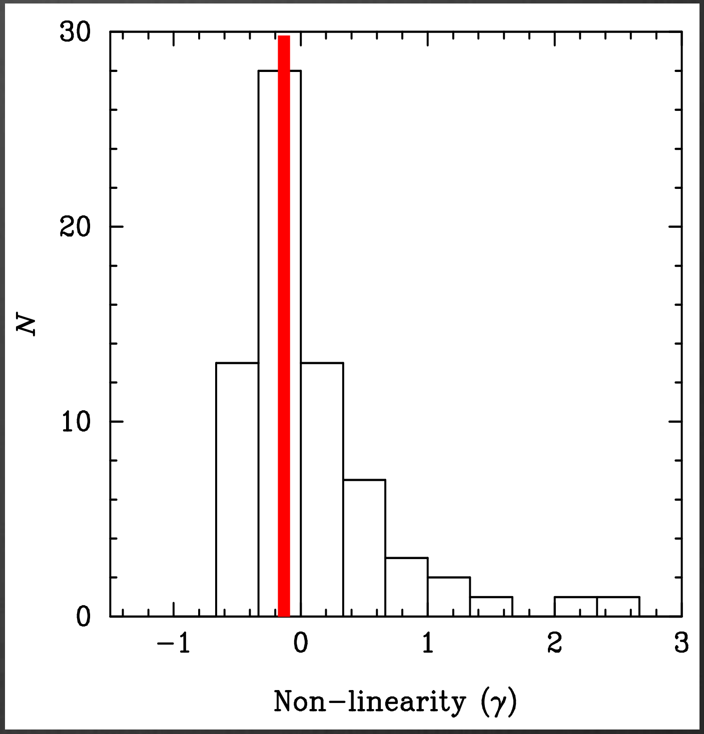
Li et al. (2013, 2018): independent approach

Following Pancoast et al.'s work, but include two additional points:

✓ Includes non-linear response of broad lines: $L(v,t) \propto C^{1+\gamma}(t-\tau)$



Kilerci Eser et al. 2015



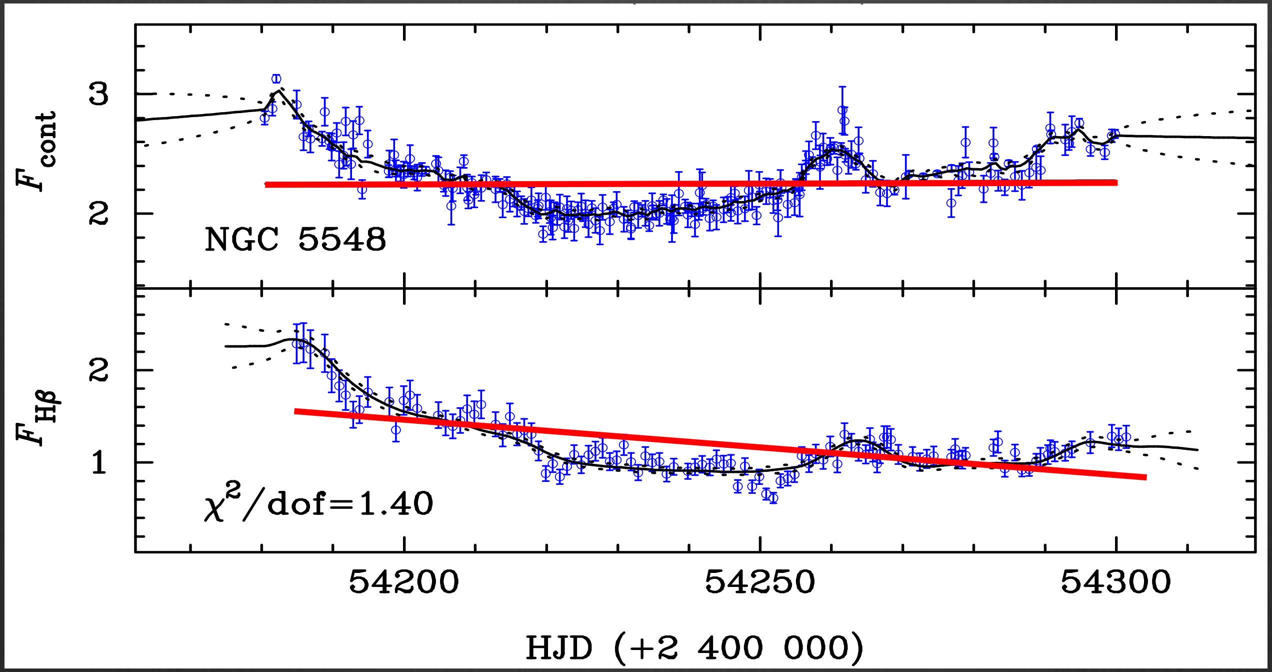
Li et al. 2013

Li et al. (2013, 2018): independent approach

Following Pancoast et al.'s work, but include two additional points:

✓ Includes non-linear response of broad lines: $L(v,t) \propto C^{1+\gamma}(t-\tau)$

✓ Long-term detrending



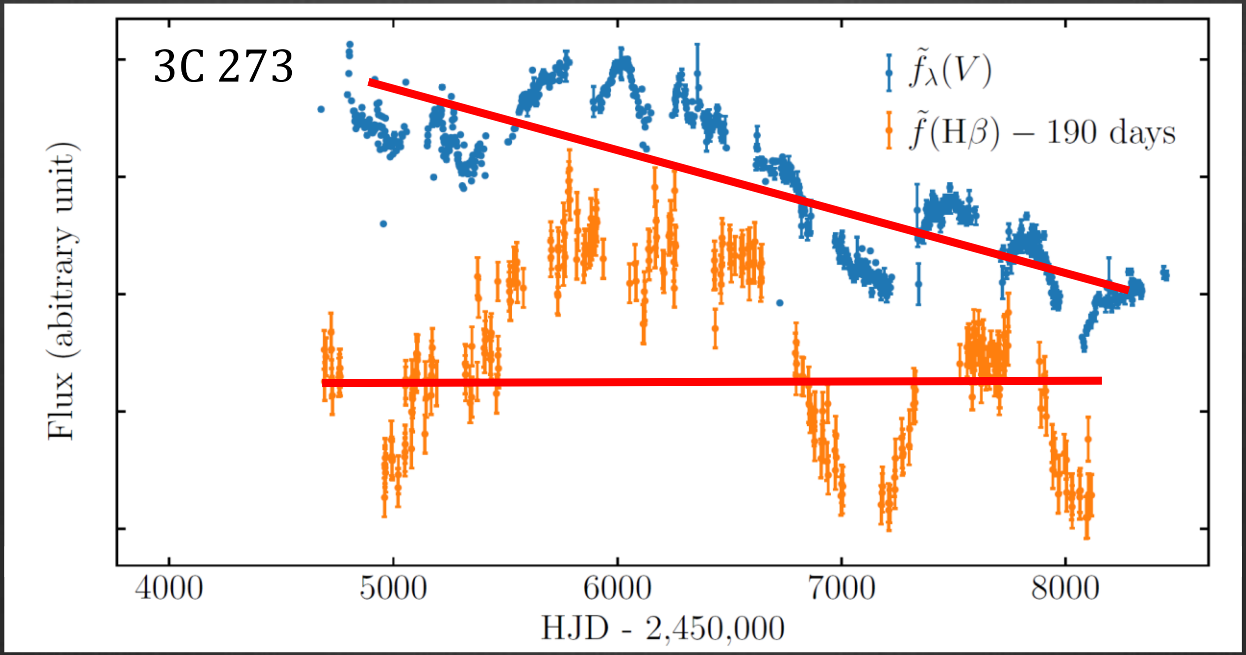
Denney et al. 2010

Li et al. (2013, 2018): independent approach

Following Pancoast et al.'s work, but include two additional points:

✓ Includes non-linear response of broad lines: $L(v, t) \propto C^{1+\gamma}(t - \tau)$

✓ Long-term detrending



Zhang et al. 2019

Software： BRAINS

BLR Reverberation-mapping Analysis Integrated with Nested Sampling

- C Language, MPI parallel interface
- Diffusive nested sampling
- Publicly available at https://github.com/LiyrAstroph/BRAINS

BRAINS

Bayesian Reverberation-mapping Analysis Integrated with Nested Sampling

A package for dynamically modeling broad-line regions and analyzing reverberation mapping data, and measuring the black hole mass.

References:

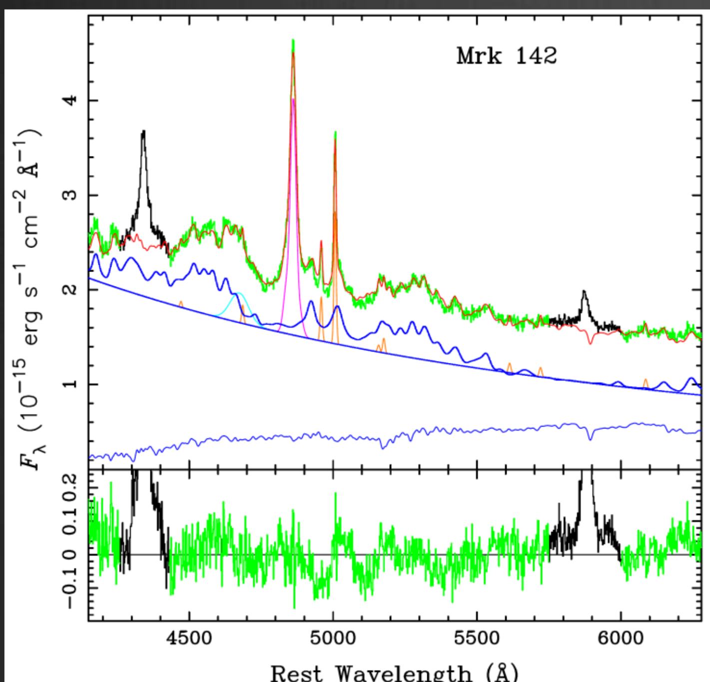
- Li, Y.-R., Songshen, Y.-Y., Qiu, J., et al. 2018, ApJ, 869, 137.
- Li, Y.-R., Wang, J.-M., Ho, L. C. et al. 2013, ApJ, 779, 110.

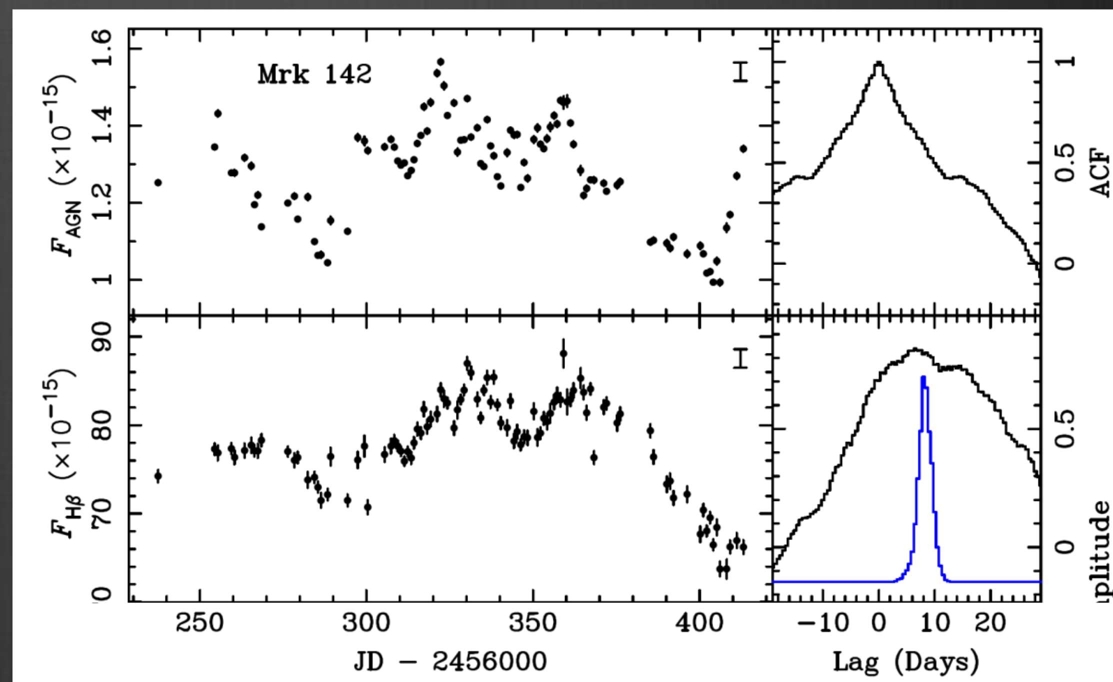
docs passing

Read the documentation.

Our application to Mrk 142

- Mrk 142 is a narrow-line Seyfert I galaxy
- Monitored by SEAMBH project (Lijiang 2.4m Telescope) between 2012-2013
- Dimensionless accretion rate $\dot{\mathscr{M}} = \dot{M}c^2/L_{Edd} \approx 45$

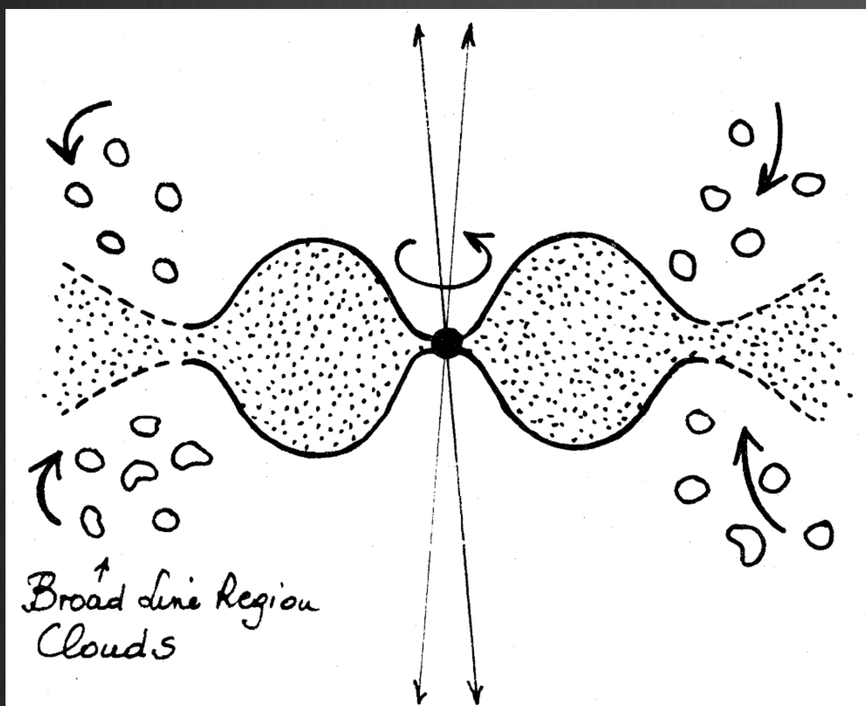


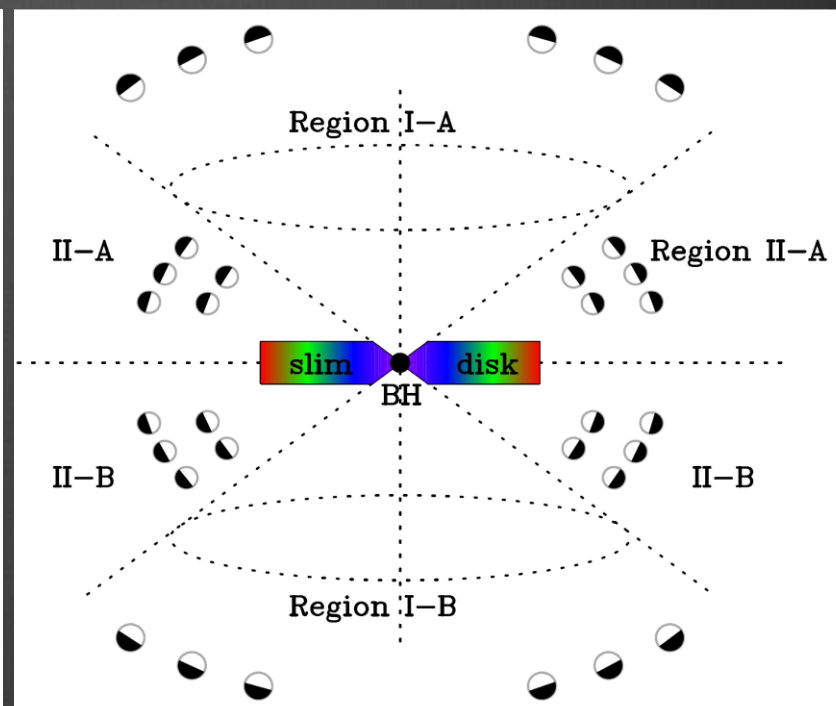


Hu et al. 2015

Our application to Mrk 142

- For super-Eddington accretion, self-shadowing effect is important



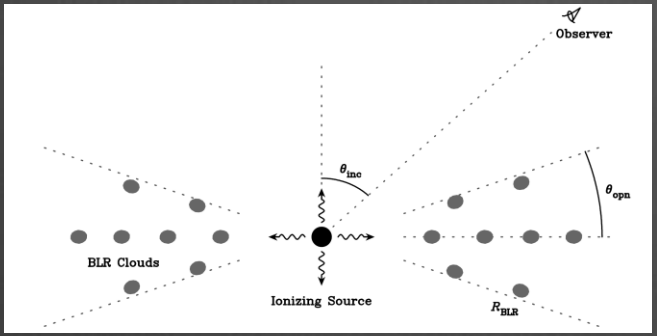


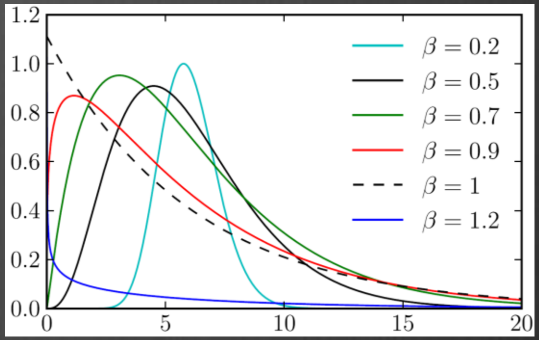
Wang et al. 2014

Our application to Mrk 142

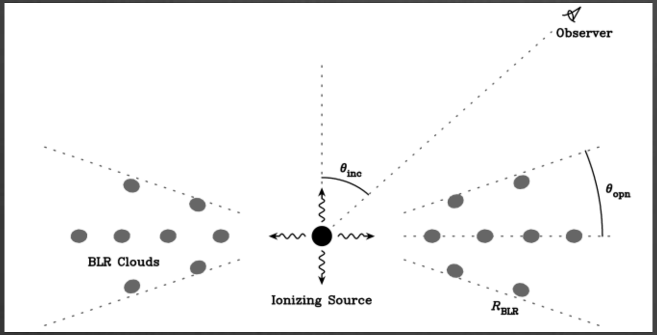
Three models

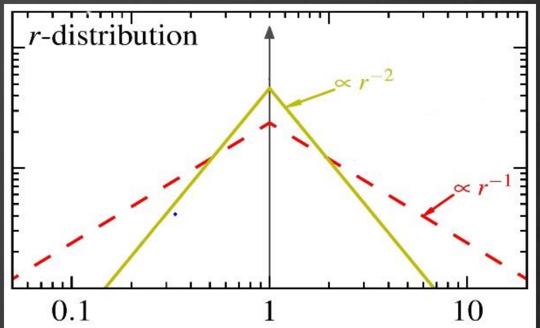
M1



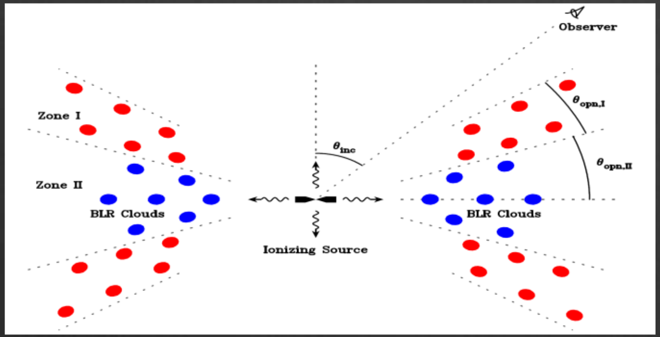


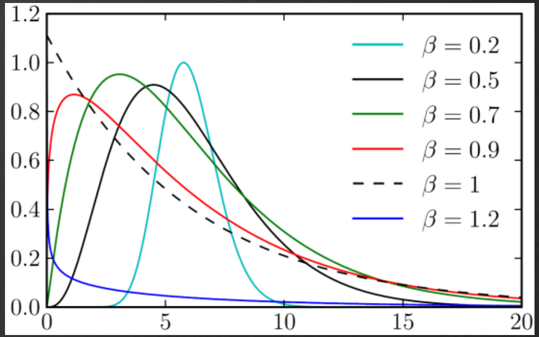
M2





M3



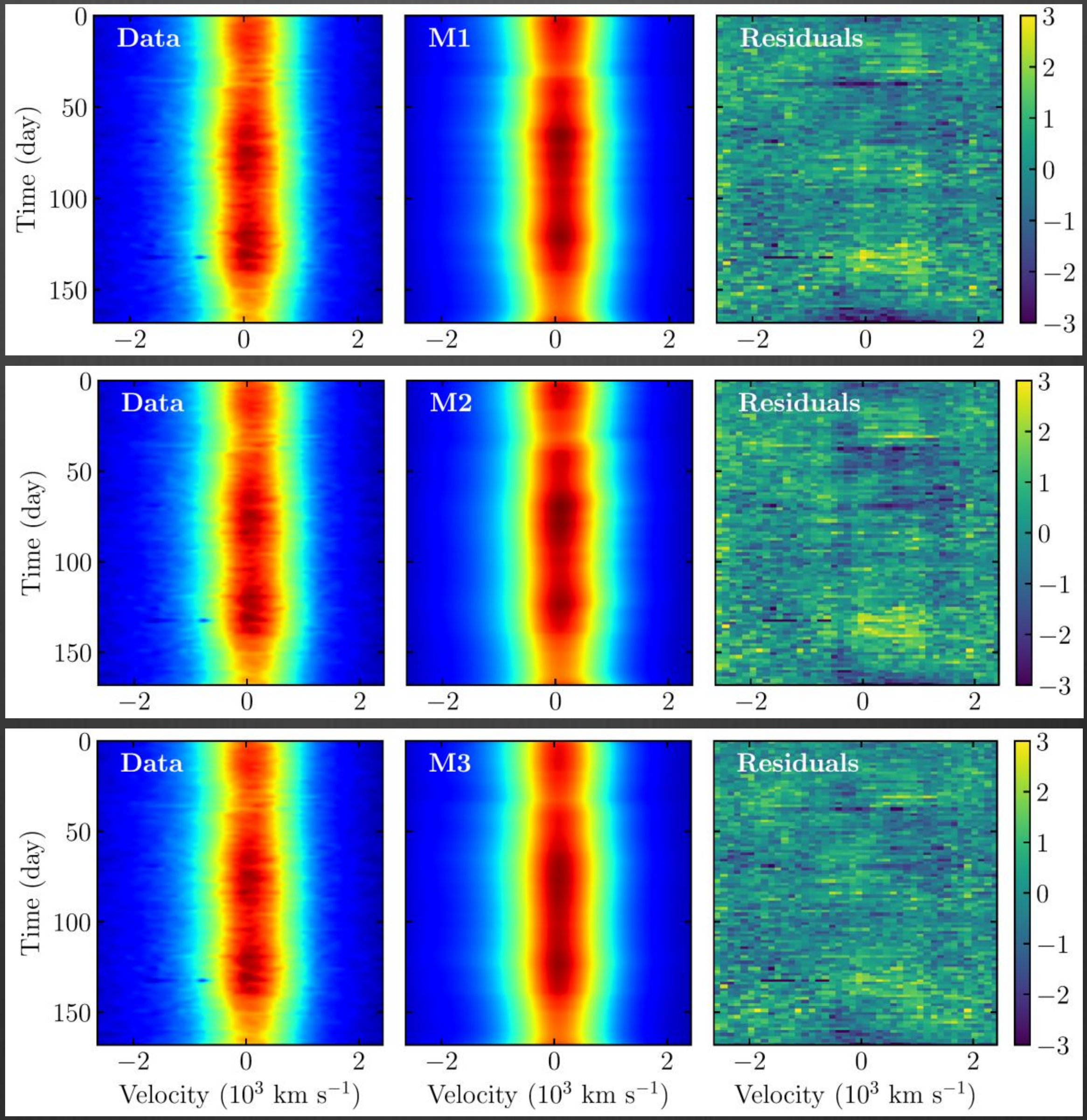


Our application to Mrk 142

M1

M2

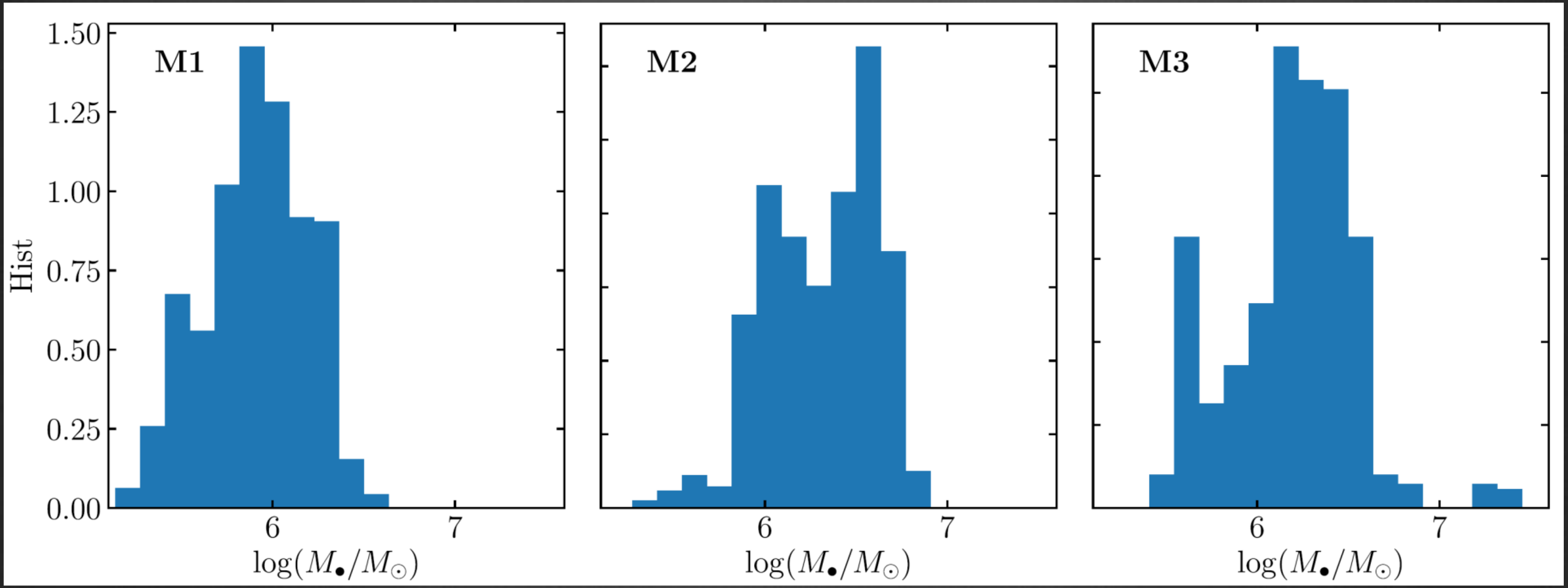
M3



Model comparison: M3 is the most probable

	$M1$	$M2$	$M3$
$\ln \mathcal{L}_{\max}$	0	−280	164
BIC	0	288	−105
AIC	0	562	−313
$\log K$	0	−118	68

Our application to Mrk 142

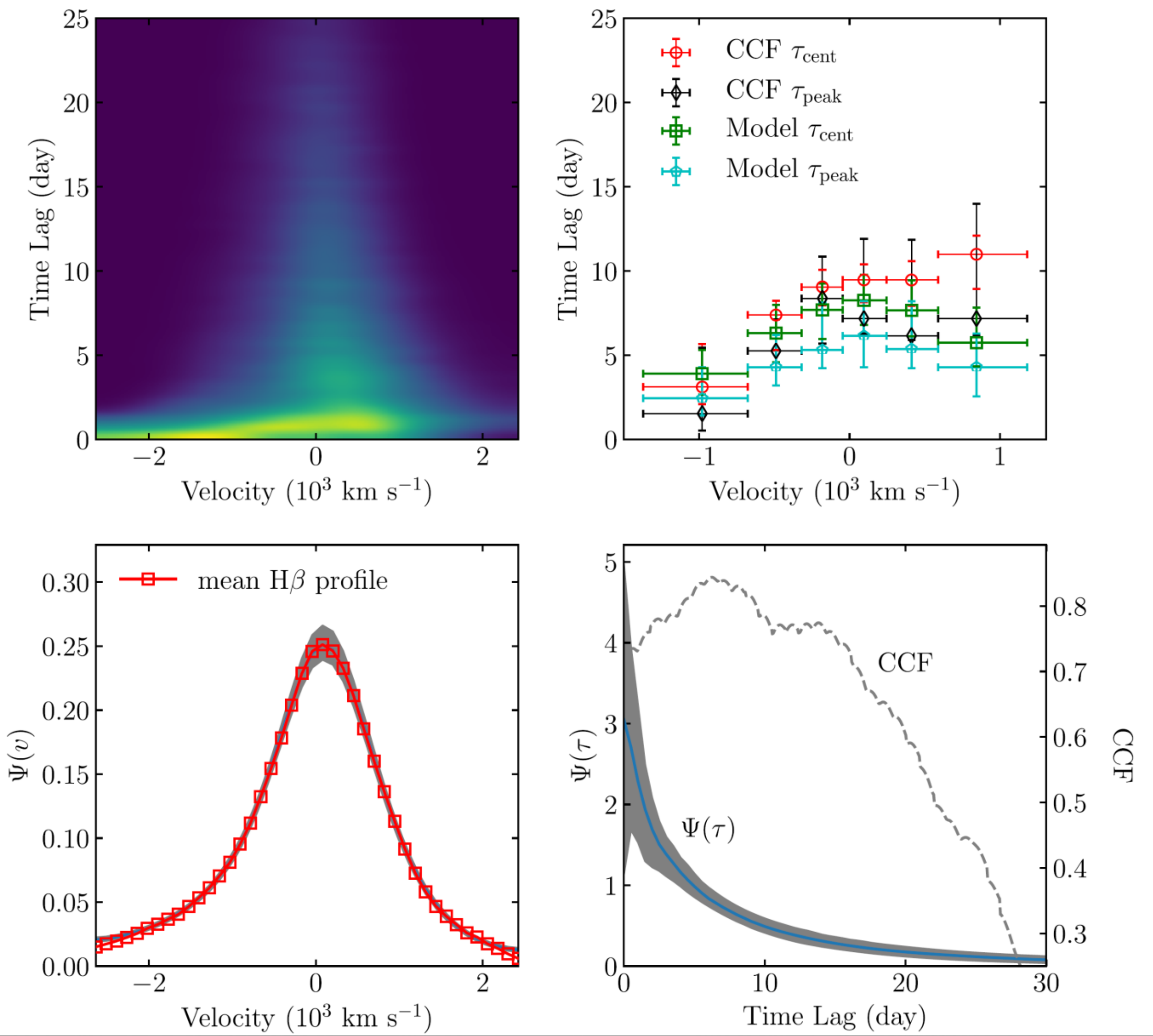


$$\log(M_{\bullet}/M_{\odot}) = 6.23^{+0.26}_{-0.45}$$

$$\log f = -0.36^{+0.33}_{-0.54}$$

FWHM of the mean spectrum
Consistent with the calibration of
Ho & Kim 2014 for pseudo-bulges

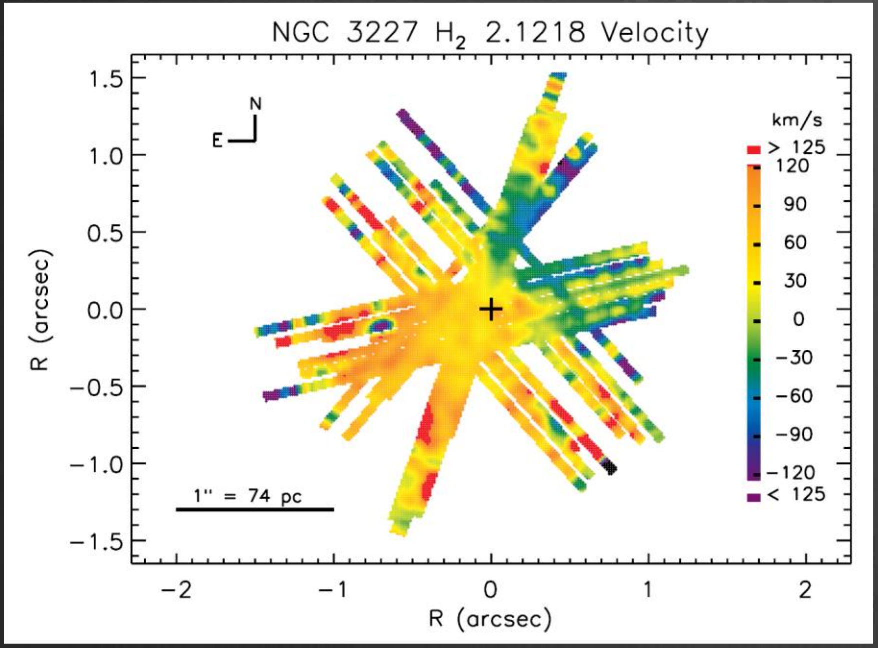
Our application to Mrk 142

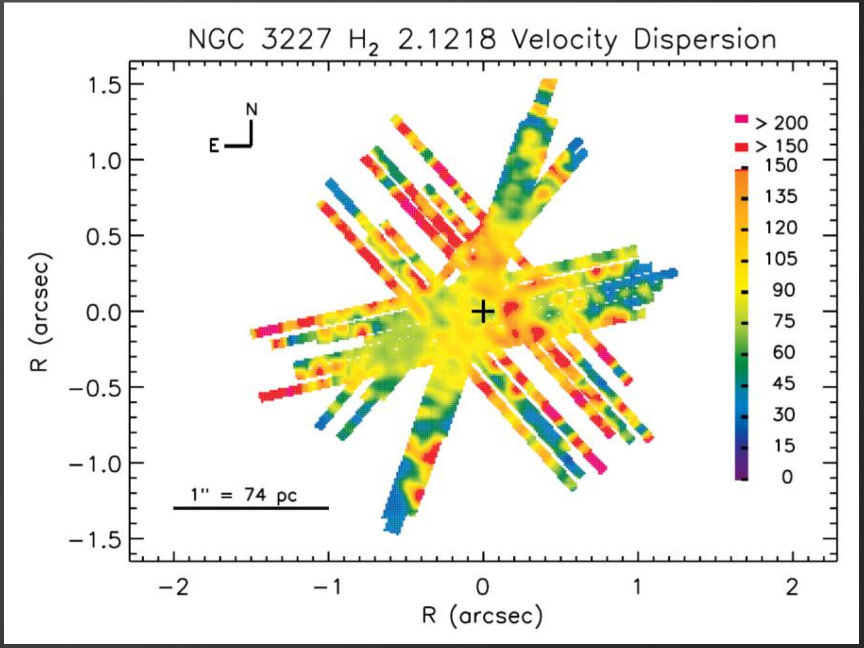


Our application to NGC 3227

CIRCUMNUCLEAR GAS IN SEYFERT 1 GALAXIES: MORPHOLOGY, KINEMATICS, AND DIRECT MEASUREMENT OF BLACK HOLE MASSES

Erin K. S. Hicks[1,2] and Matthew A. Malkan[1]



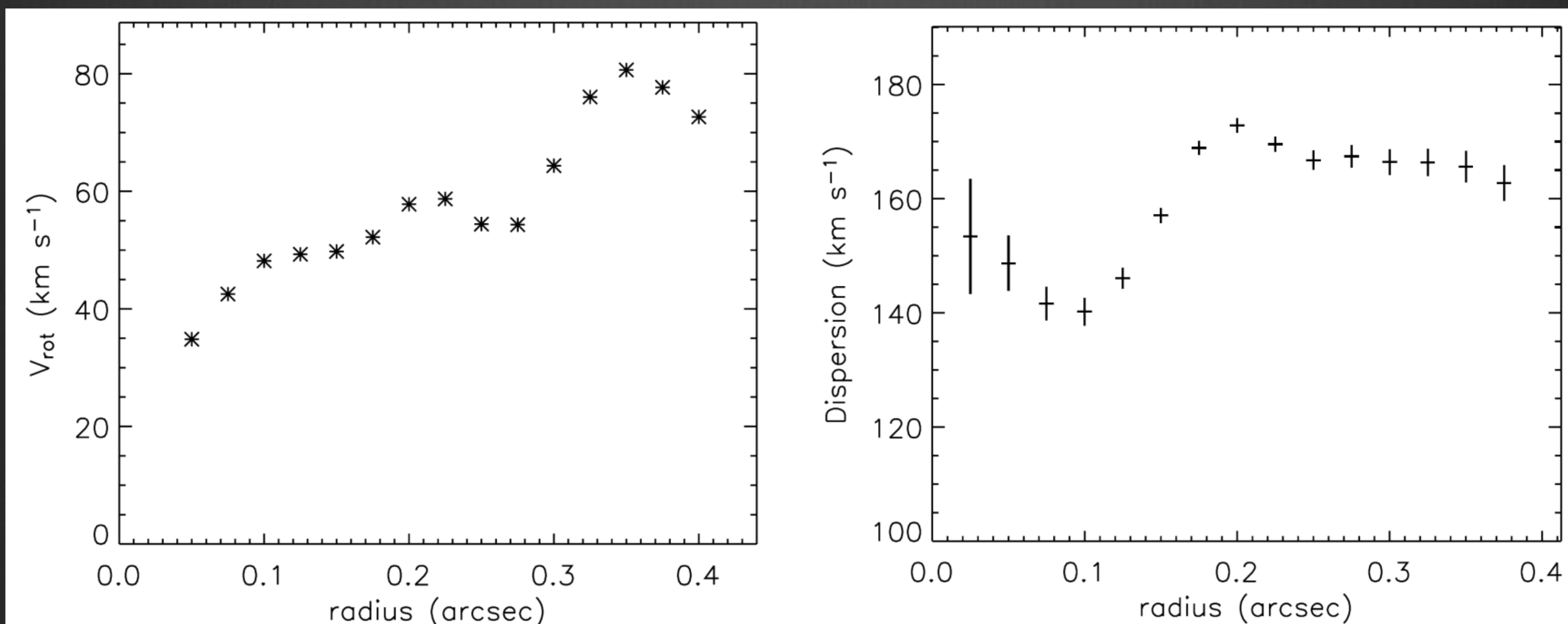


gas dynamics yields: $M_\bullet = 2.0^{+1.0}_{-0.4} \times 10^7 M_\odot$

Our application to NGC 3227

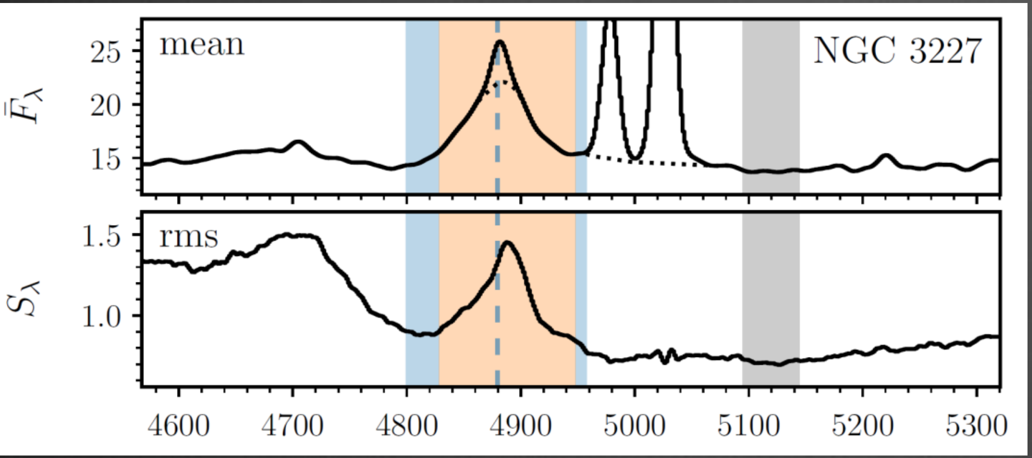
THE STAR-FORMING TORUS AND STELLAR DYNAMICAL BLACK HOLE MASS IN THE SEYFERT 1 NUCLEUS OF NGC 3227[1]

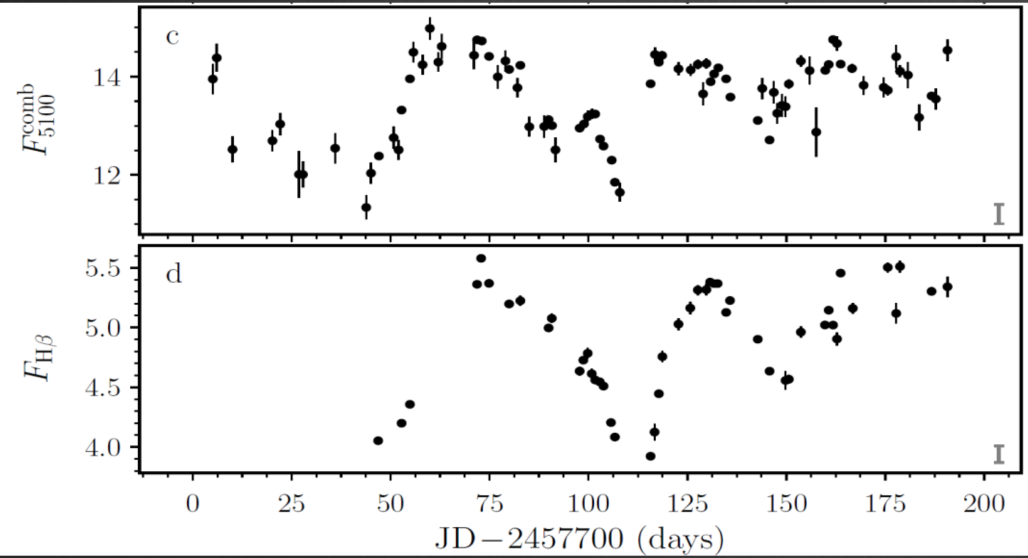
R. I. Davies,[2] J. Thomas,[2,3] R. Genzel,[2,4] F. Mueller Sánchez,[2] L. J. Tacconi,[2] A. Sternberg,[5] F. Eisenhauer,[2] R. Abuter,[2] R. Saglia,[2,3] and R. Bender[2,3]



stellar dynamics yields: $M_\bullet = (7\times10^6 - 2\times10^7)M_\odot$

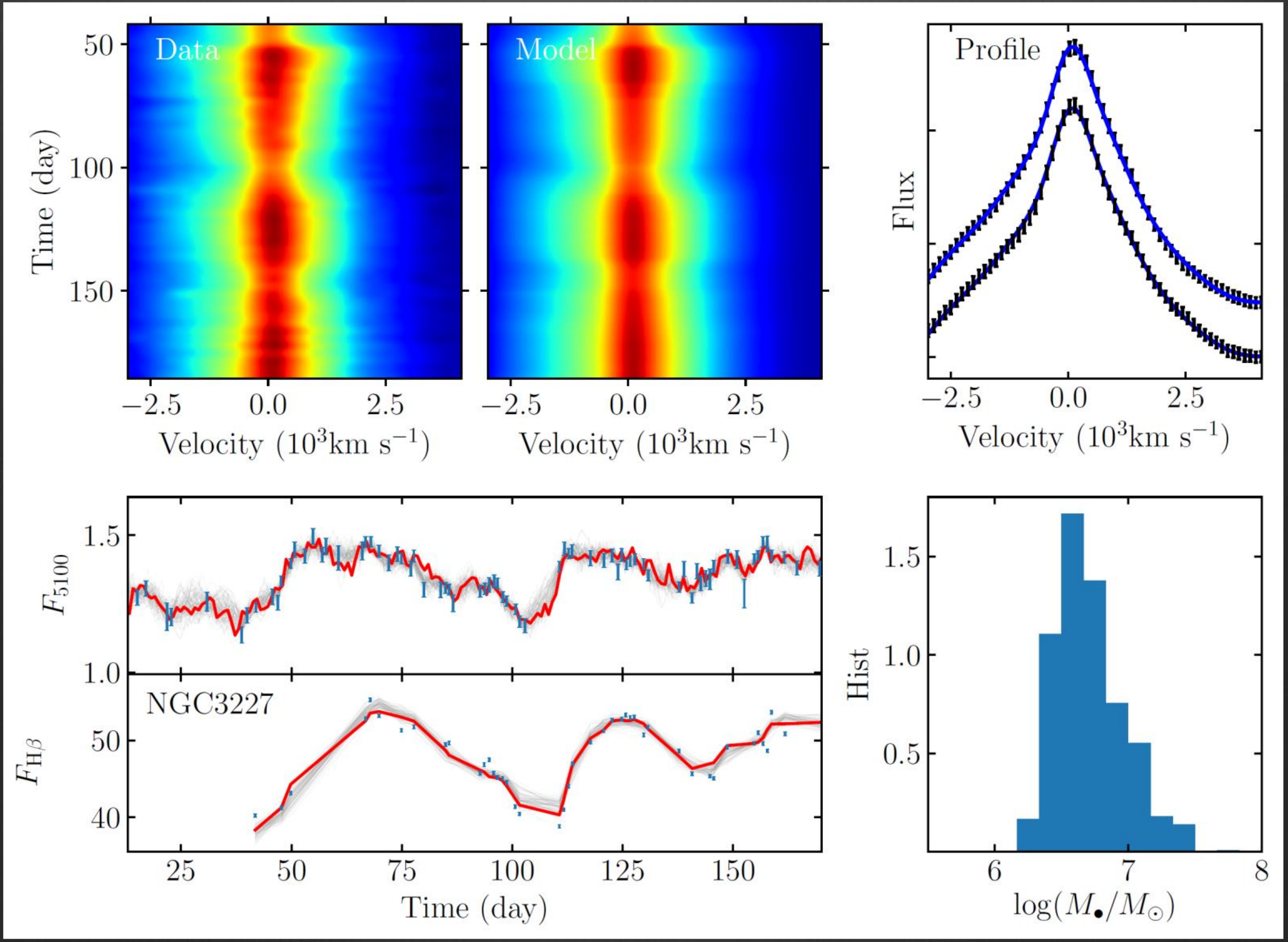
Our application to NGC 3227



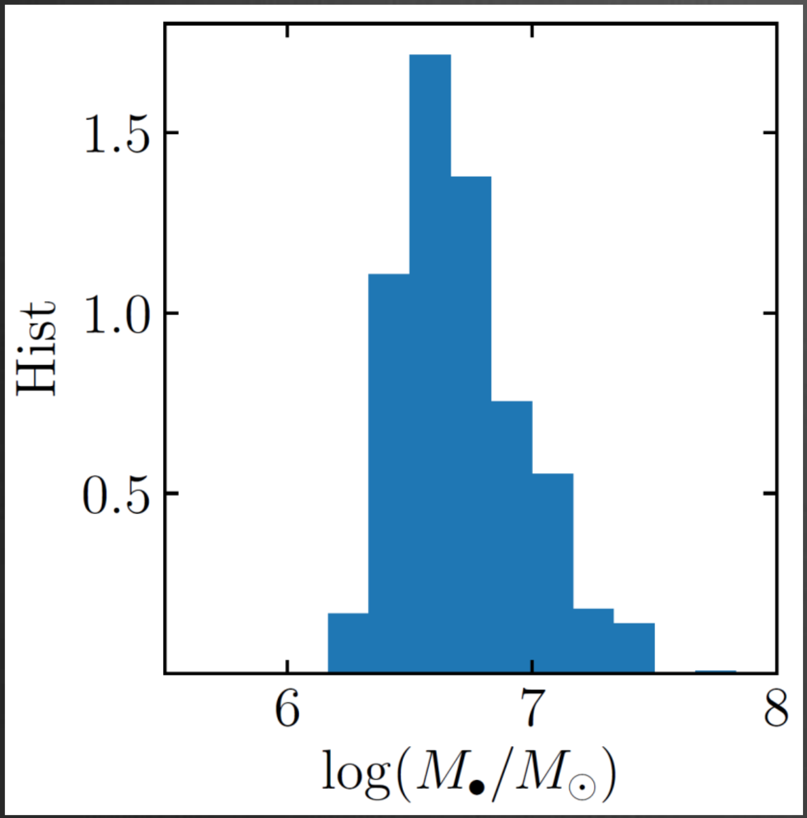


- monitored by MAHA project (WIRO 2.3m telescope) between 2016-2017
- see Mike Brotherton's talk and Jacob McLane's talk

Our application to NGC 3227



Our application to NGC 3227



Method	BH Mass ($10^6 M_\odot$)
Gas dynamics	20^{+10}_{-4}
Stellar dynamics	7-20
BLR dynamical modeling	$5.2^{+4.5}_{-2.2}$

Future improvements

- Systematic errors of BLR dynamical modeling

  comparison with other independent methods

  ✓ Stellar/gas dynamics (NGC 3227, NGC 4151)

  ✓ Spectro-interferometry (3C 273)

  see Yuyang Songsheng's talk

- Compare with other BLR models (e.g, disk wind)

- Include photoionization processes

Summary

- We developed BLR dynamical code "BRAINS", publicly available at https://github.com/LiyrAstroph/BRAINS
- Application to Mrk 142 shows a two-zone BLR
- Application to NGC 3227 shows a consistent BH mass measurement with other independent methods

Thank You