Overall, informal outline

- SMBH mass measurements and the various techniques → why do we care about mass measurements in the first place?
    - Help inform assembly history and timeline of galaxy formation, understand star formation through feedback with the central black hole and quenching, understand current population of SMBHs and their demographics, understand and predict the gravitational wave signal from binary SMBHs, etc
    - Trace build up of mass in SMBHs over cosmic time/growth channels of galaxies over time
    - These are tough questions - MASSIVE survey was designed to mitigate these challenges and understand massive galaxy formation and the supermassive black holes at the centers of these large ellipticals
- Data Processing – what data do we use? How do we go from photometry and spectra to inputs?
    - Need to mention: exquisite IFU and photometry needed; IFU data used for full spectrum fitting for the velocity profiles of these galaxies expressed as Gauss-Hermite moments
    - Photometry needed to model the mass distribution of the stars
    - Show some typical velocity profiles, and maybe some unique ones that make the modeling challengings
- Modeling
    - Intro to axisymmetric and triaxial Schwarzschild models; TriOS code; give a sense of how complex these models are
    - Superposition of orbits is constructed to mimic the input light profile and kinematics from densely sampeld orbits in phase space
- Turning galaxy models into parameters
    - Briefly run through nested sampling routine and how we extract posterior information on these parameters
    - Maybe introduce here that for axisymmetric models, more often than not our models prefer edge-on inclinations and this was a sign that maybe these models are too flexible for their own good, leading to potential biases in the parameters
- Model Flexiblity and Mock Recovery
    - We've been testing this idea at Berkeley on the more complicated triaxial models.
    - Axisymmetric: does seem that edge-on is preferred when the models are good enough, the covariance with the other parameters doesn't seem to be too strong
    - Triaxial: model flexibility is a less strong and less obvious effect, and in our tests, we don't seem to see a need to penalize our models by their intrinsic flexibilities; our models seem to do a decent job at recovering the inputs, especially at the level our measurement uncertainties limit us to
- Where we are now and what's to come

Stellar Dynamical Mass Measurements of MASSIVE Elliptical Galaxies

More details in:
Liepold+20,
Quenneville+21,+22,
Pilawa+22,
Pilawa+23 (coming soon!)

Jacob Pilawa (UCB),
February 24, 2023 @ TAMU
Emily Liepold (UCB), Matthew Quenneville (UCB), Chung-Pei Ma (UCB)
+ Silvana Delgado Andrade (TAMU), Jonelle Walsh (TAMU)
+ Jenny Greene (Princeton), John Blakeslee (NOIRLab)

A roadmap for the talk:

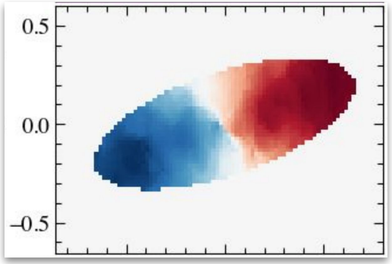
1. **Supermassive black holes in the largest galaxies**

2. Triaxial Schwarzschild modeling of massive ellipticals

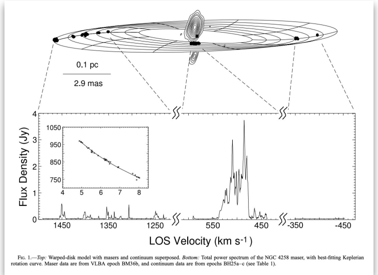
3. Robustness and Recovery Tests of Dynamical Modeling Techniques

main techniques for z~0 "direct" BH discovery:

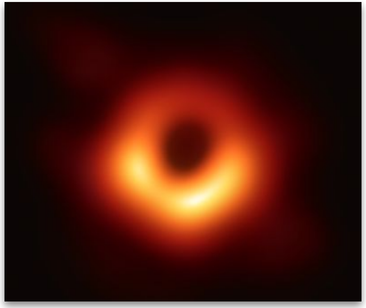
gas disk dynamics



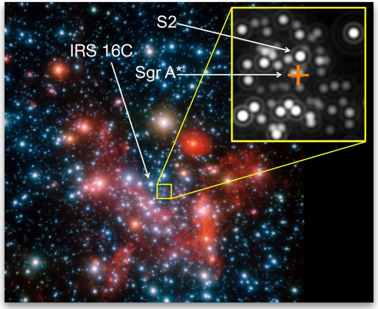
maser disks



EHT

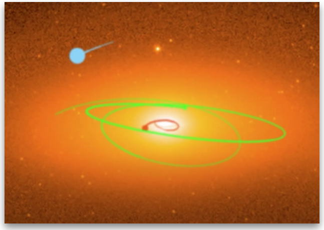


galactic center



integrated light →

stellar dynamics



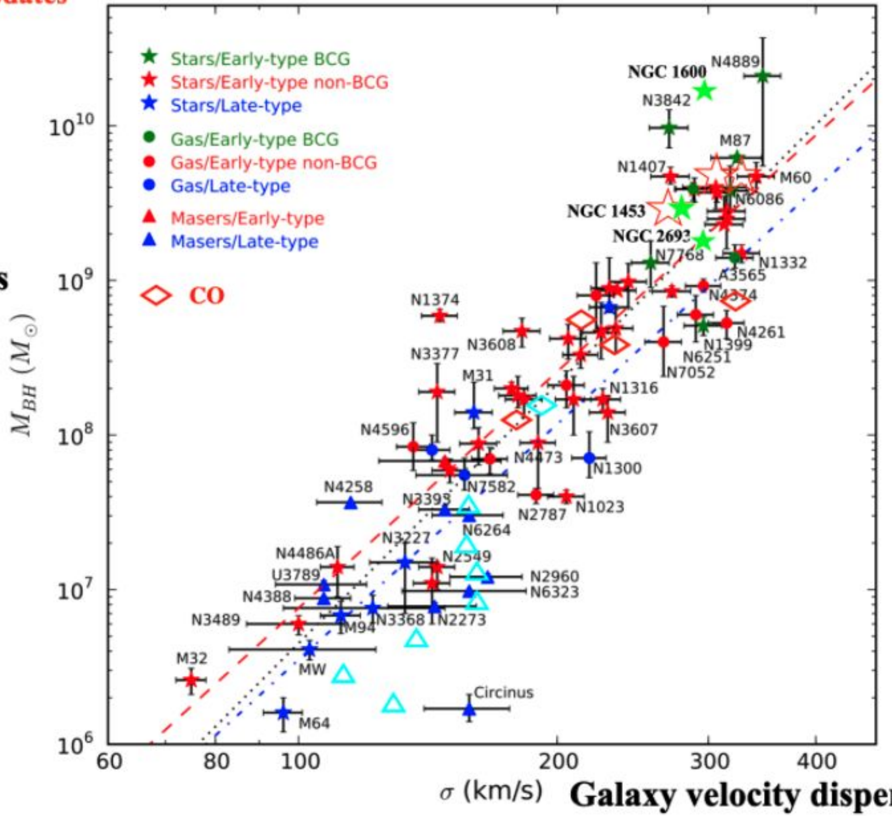
...

see: van den Bosch+08 (stellar), Barth+01, Walsh+10 (gas dynamics), Miyoshi+95, Herrnstein+99 (masers). slide inspiration: J. Walsh (TAMU)

BLACK HOLES + GALAXY EVOLUTION

McConnell & Ma (2013)
+ some updates

4.5 dex
BH mass



Galaxy velocity dispersion

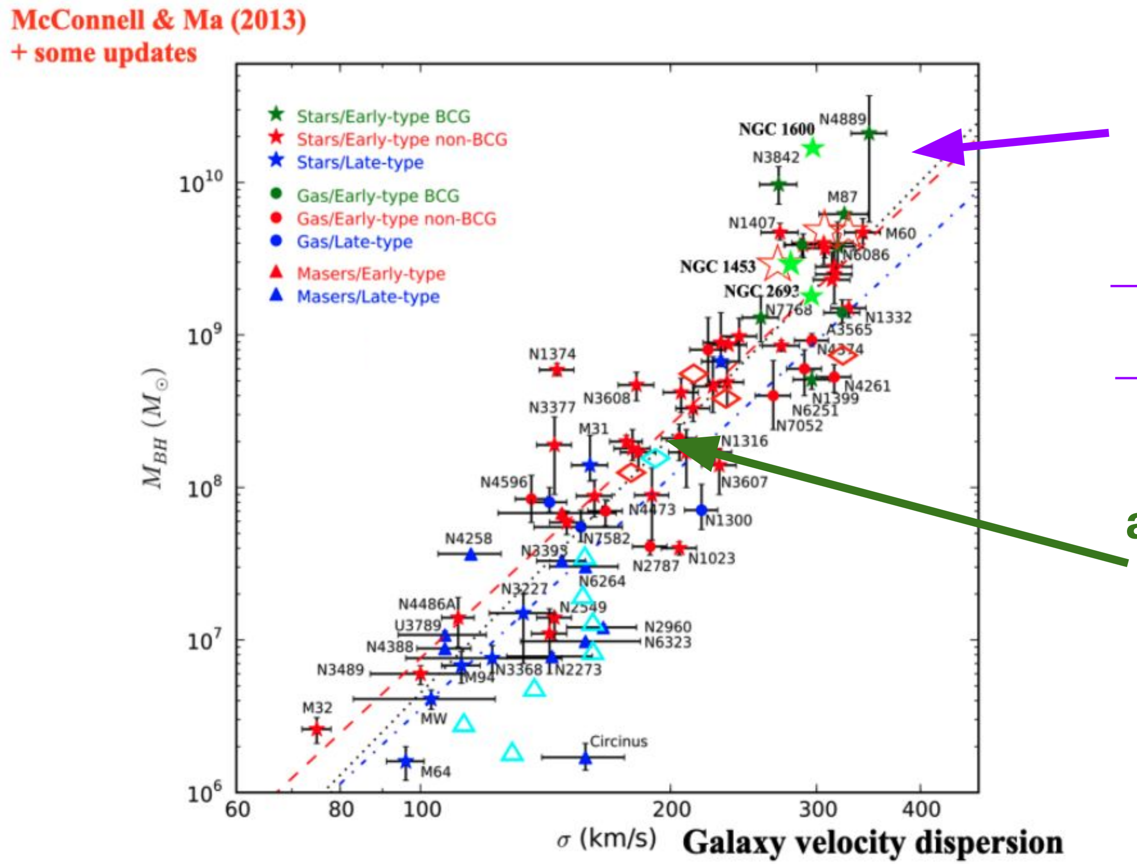
$$r_{\mathrm{SOI}} \approx \frac{GM}{\sigma^2} \approx 10\text{'s to } 100\text{'s of pc}$$

$$r_{\mathrm{galaxy}} \approx 10\text{'s of kpc}$$

how do galaxies and SMBHs evolve together?

McConnell & Ma (2013); Kormendy & Ho (2013); Saglia (2016), Thomas (2016)

A CLUE: the most MASSIVE galaxies



growth by gas-poor mergers

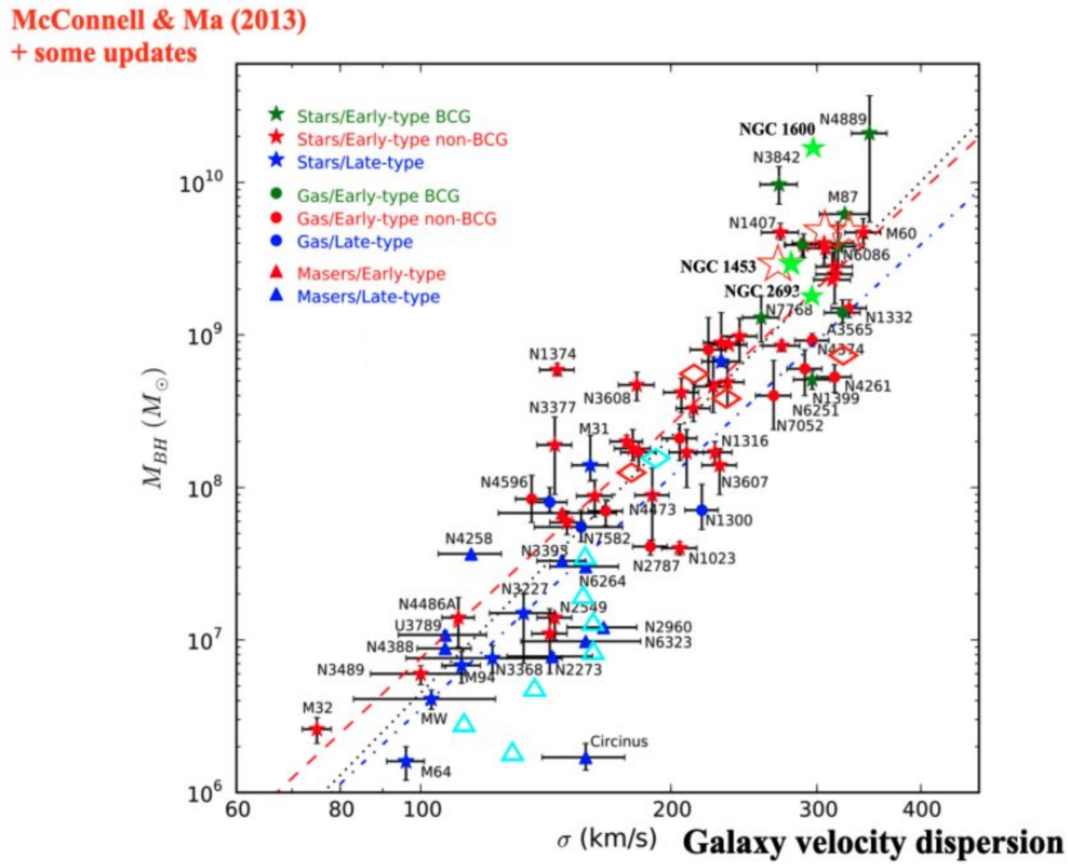
→ BH increases
→ σ saturates
→ kinematically misaligned, slow rotation (V/σ ~< 0.2)
→ **indicative of triaxiality?**

growth by gas accretion/gas-rich mergers

→ BH increases
→ fast rotators (V/σ >~ 0.3)
→ kinematically aligned
→ **axisymmetric shapes**

McConnell & Ma (2013)

A CLUE: the most MASSIVE galaxies



[i.e., Yu+2019 (reverberation mapping), Thater+21 (gas dynamics)],
[i.e.,Shannon+2015,Arzoumanian+2019],[i.e.,Li+2019, Habouzit+2020]

our interpretation depends on M_{BH}'s at the most massive end

1. Estimating BH Masses

2. Cross-checking of methods (e.g., ALMA gas dynamics [e.g., Cohn+2021, Kabasares+2022])

3. Calibration of reverberation mapped AGN

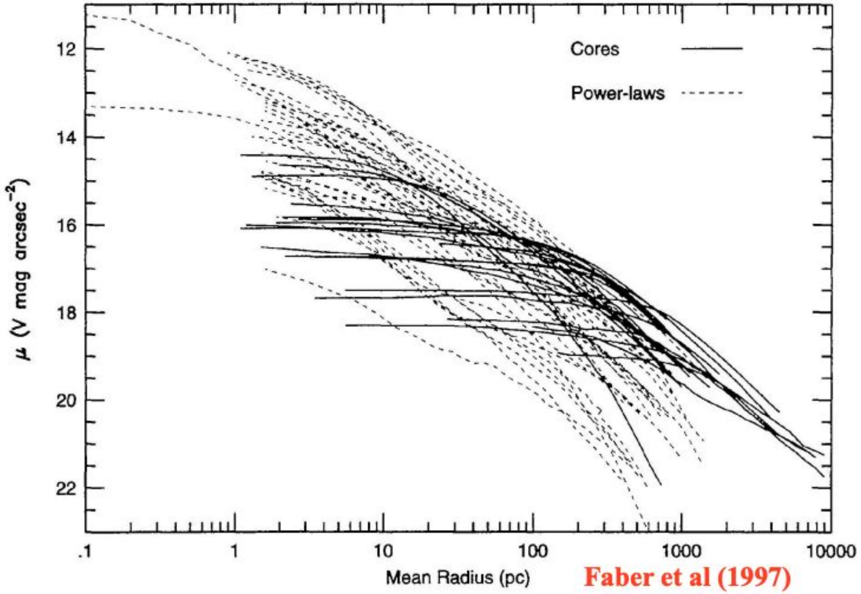
4. z~0 mass function → BBH merger rates

5. Comparison to simulations of AGN feedback modes and mechanisms

… but it's challenging…

why are massive ellipticals a challenge?

they're both rare, and have **extremely** faint/flat cores



sphere of influence is **tiny**

$$r = \frac{GM_{BH}}{\sigma^2} \approx 50\text{pc}\frac{M_{BH}}{10^9 M_\odot}\left(\frac{300\ \text{km s}^{-1}}{\sigma}\right)^2$$

a few 0.1's arcsec at ~100Mpc

→ **long exposures on 8-10m telescopes!**

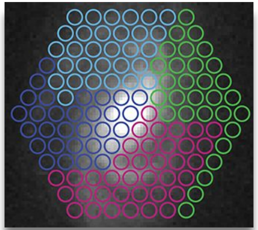
The MASSIVE Survey

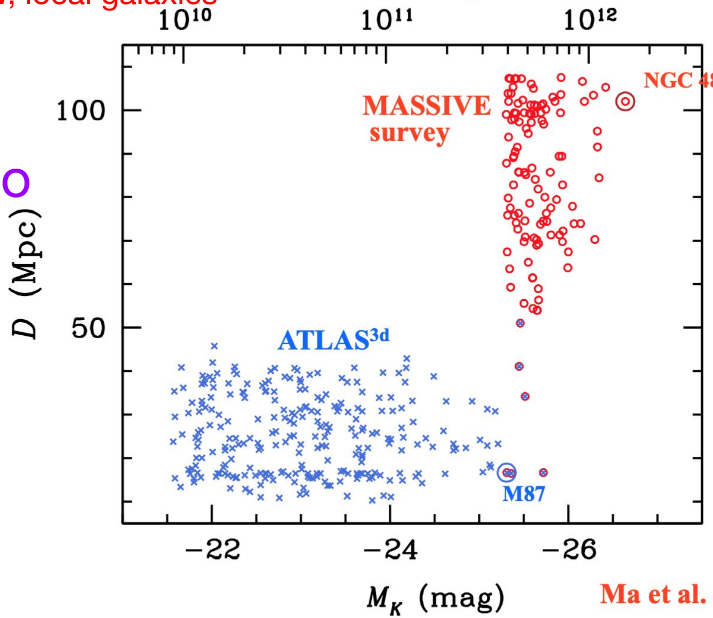
a **volume-limited** survey of the ~100 most ***MASSIVE***, local galaxies

$M_* > 10^{11.5} M_{sun}$

McDonald Observatory

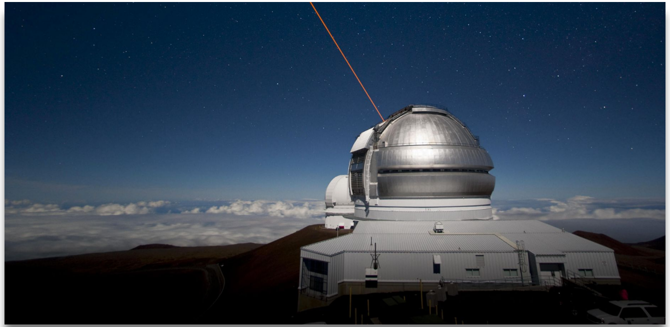
Wide-field IFU (107"x107", out to ~2 R_{eff})





Ma et al. (2014)

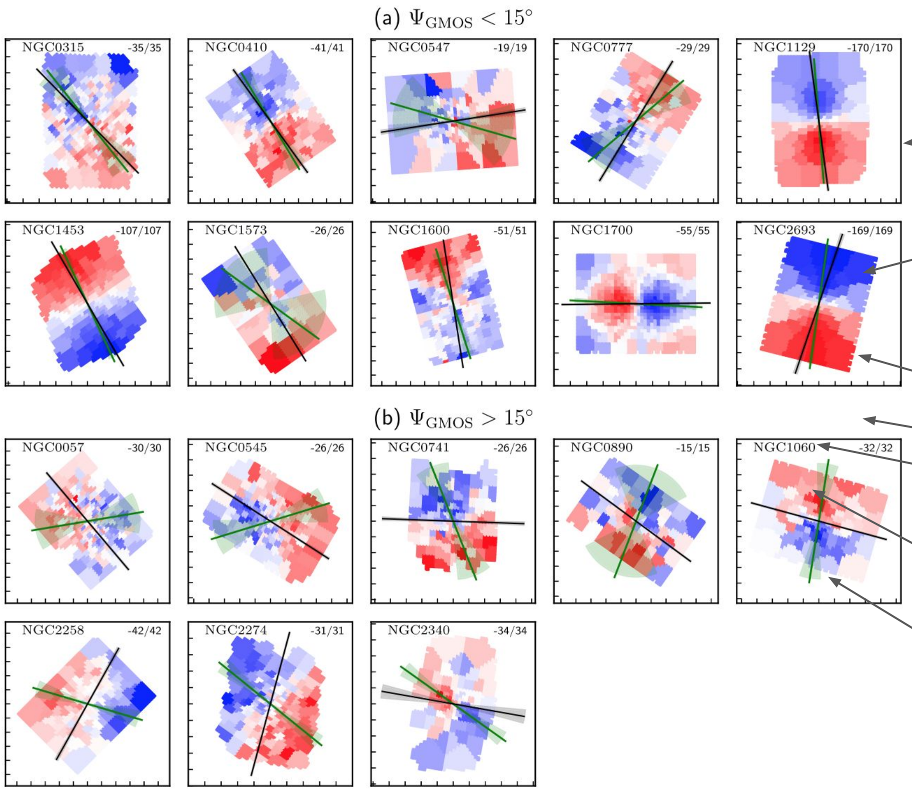
Gemini North



High-resolution, **high SNR** IFU (~0.3" to ~5'' at SNR~125)

Photometry: CFHT, HST, UKIRT, PanSTARRS

The MASSIVE Survey:
Stellar Kinematics

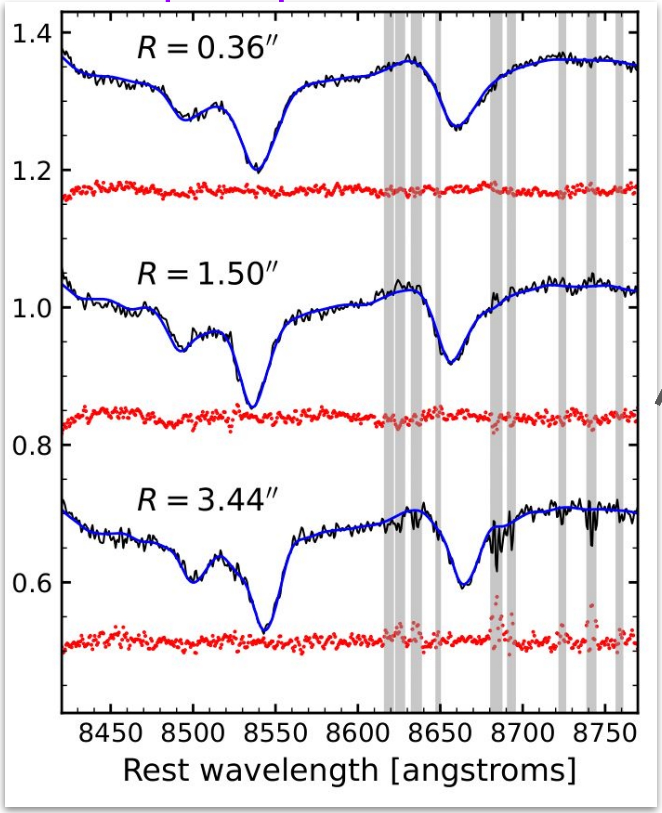


MASSIVE Survey Related Papers

I	Survey paper	Ma +	(2014) ApJ
II	Stellar pop gradient	Greene +	(2015) ApJ
III	Molecular gas #1	Davis +	(2016) MNRAS
IV	X-ray properties	Goulding +	(2016) ApJ
	NGC1600 black hole	Thomas +	(2016) Nature
V	Stellar kinematics	Veale +	(2017) MNRAS
VI	Ionized gas	Pandya +	(2017) ApJ
VII	λ & environment	Veale +	(2017) MNRAS
VIII	σ radial profile	Veale +	(2018) MNRAS
IX	WFC3 photometry	Goullaud +	(2018) ApJ
X	Kinematic alignment	Ene +	(2018) MNRAS
XI	Molecular gas #2	Davis +	(2019) MNRAS
XII	Stellar pop vs env	Greene +	(2019) ApJ
XIII	Core kinematics #1	Ene +	(2019) ApJ
XIV	Core kinematics #2	Ene +	(2020) ApJ
XV	NGC1453 black hole	Liepold +	(2020) ApJ
	SBF distances	Jensen +	(2021) ApJ
	SBF H_0	Blakeslee +	(2021) ApJ
	Axisymmetric orbit code	Quenneville +	(2021) ApJ
	Triaxial orbit code	Quenneville +	(2022) ApJ
XVI	Stellar pop & IMF	Gu +	(2022) ApJ
XVII	NGC2693 black hole	Pilawa+	(2022) ApJ
XVIII	CFHT imaging	Quenneville +	(2022) submitted
	Globular clusters	Hartmann +	(2023) submitted

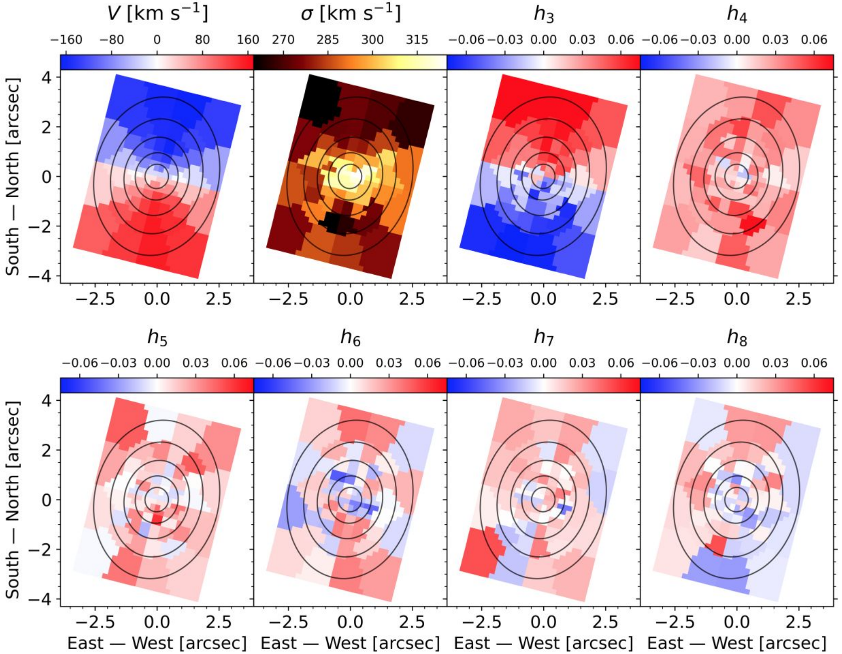
The MASSIVE Survey: Stellar Kinematics

Observables:
3 sample spectra from GMOS



measure **spatially resolved** line-of-sight velocity distributions of stars

$$f(v) \propto \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(v-V)^2}{\sigma^2}} \left[1 + \sum_{m=3}^{n} h_m H_m \left(\frac{v-V}{\sigma} \right) \right]$$



A roadmap for the talk:

1. Supermassive black holes in the largest galaxies

2. **Triaxial Schwarzschild modeling of massive ellipticals**

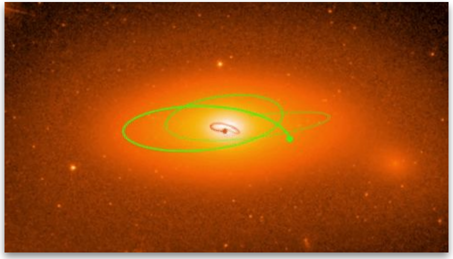
3. Robustness and Recovery Tests of Dynamical Modeling Techniques

dynamical modeling

a new code for
Schwarzschild modeling:

***TriOS*:**
Triaxial Orbit
Superposition
(van den Bosch+08,
Quenneville+21 updates)

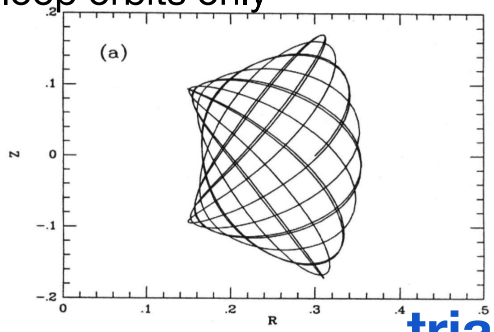
inputs: stellar kinematics, surface brightness; galaxy model parameters

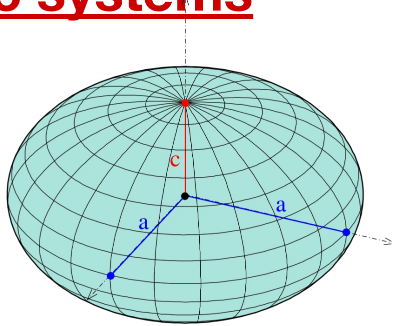


outputs: set of stellar orbits which best reproduces the input kinematics

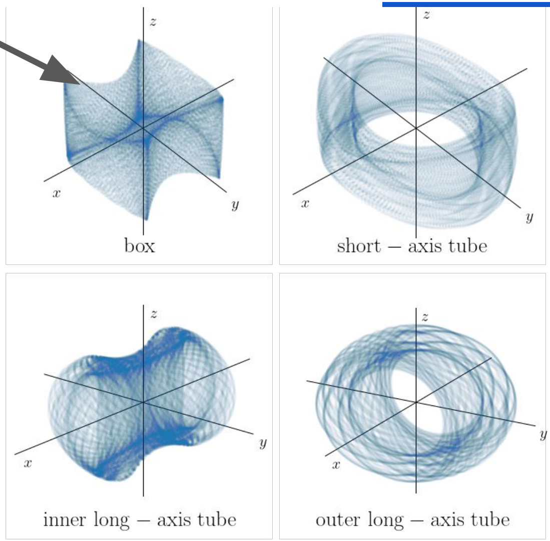
axisymmetric systems

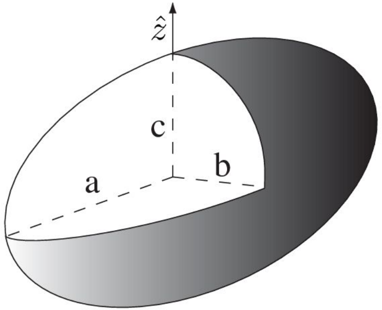
loop orbits only





triaxial systems





dynamical modeling

1. Choose a trial potential:

`Galaxy =(DM)+(STARS)+(BH)+...`

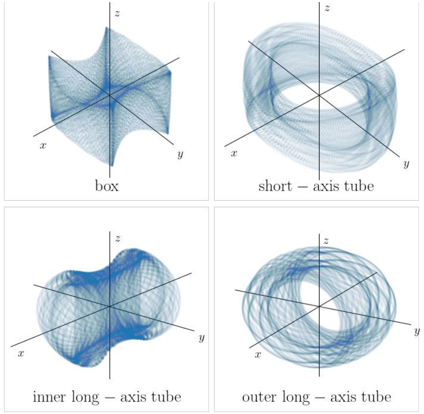
2. Generate stellar orbits in trial potential

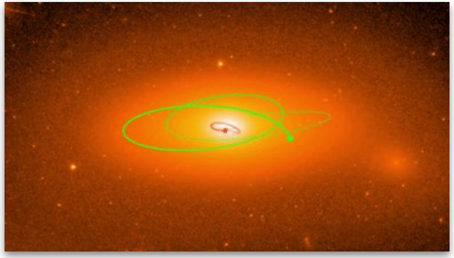
3. Determine which orbits most accurately reproduce **kinematics** + **photometry** for a *single* trial potential

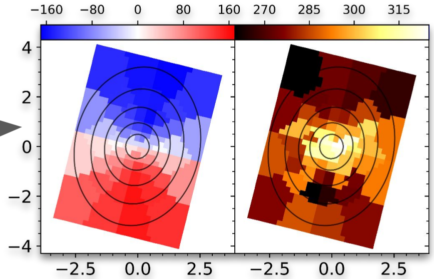
4. Find which assumed potential fits **kinematics** + **photometry** best **across trial potentials (BH, ML, Shapes)**

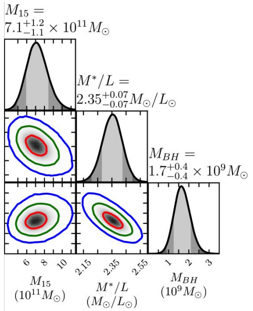
triaxial: BH, M/L, DM Halo, 3 shape parameters

axisymmetric: BH, M/L, DM Halo, inclination





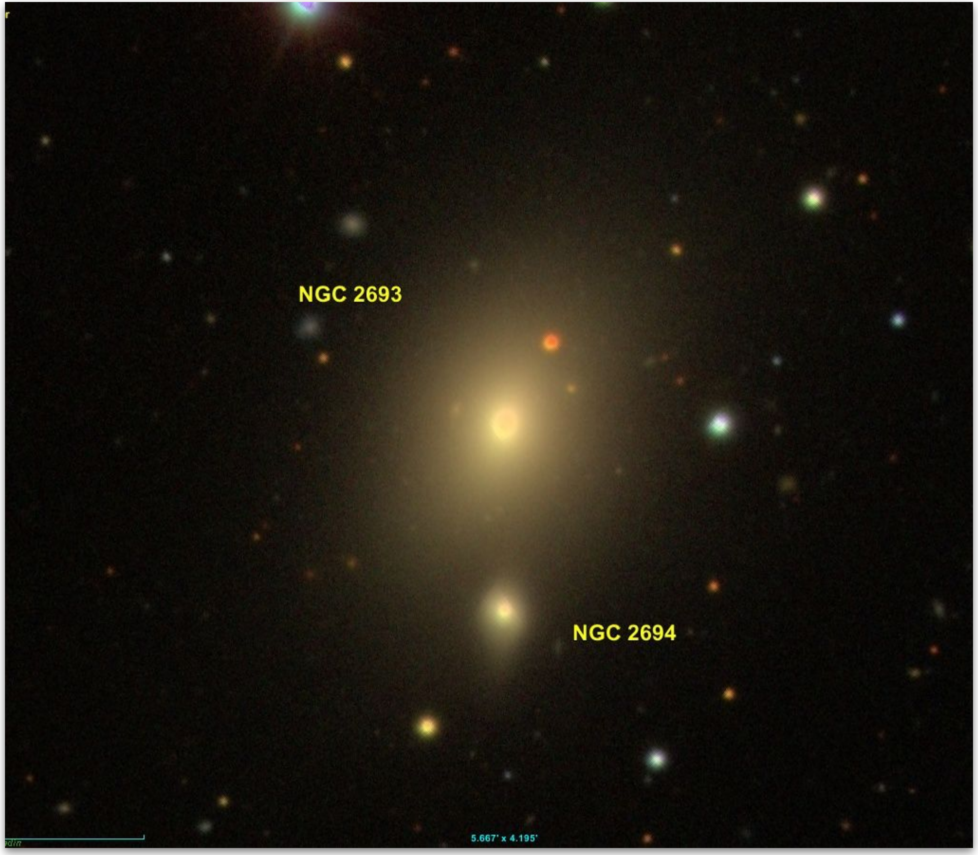




stellar kinematics of NGC 2693

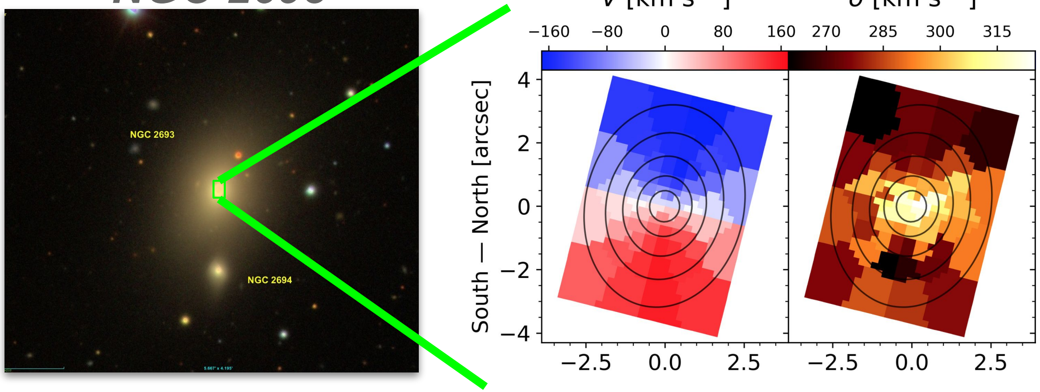
Liepold+20
Quenneville+21
Pilawa+22

NGC 2693



stellar kinematics of NGC 2693

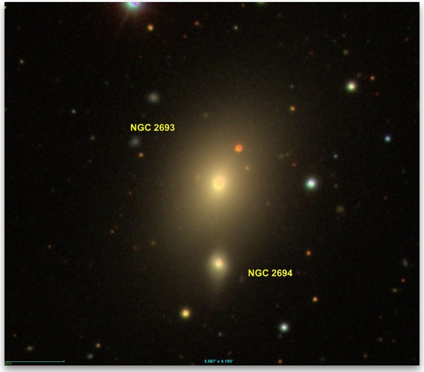
NGC 2693

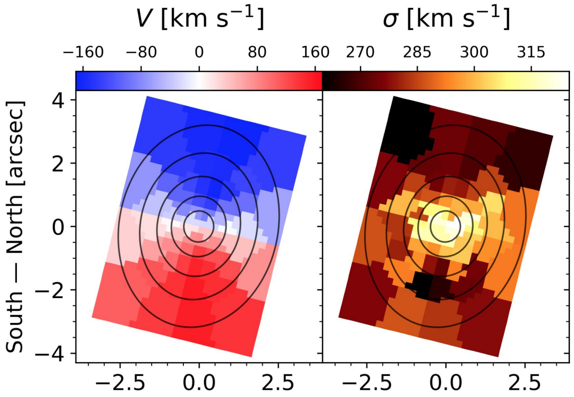


- regular, fast rotator (V~150 km/s, σ~320 km/s)

stellar kinematics of NGC 2693

NGC 2693

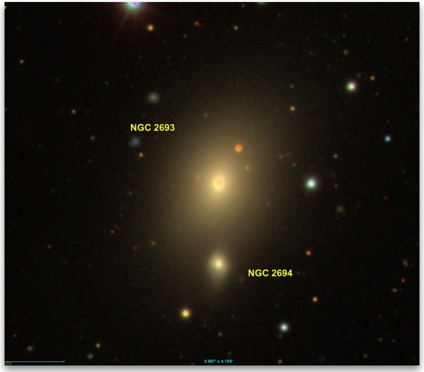


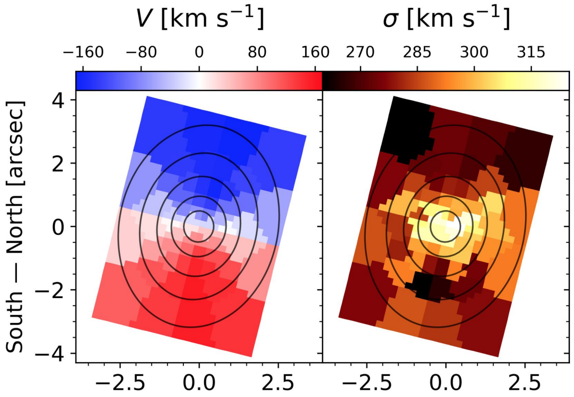


- regular, fast rotator (V~150 km/s, σ~320 km/s)
- mostly regular, elliptical isophotes

stellar kinematics of NGC 2693

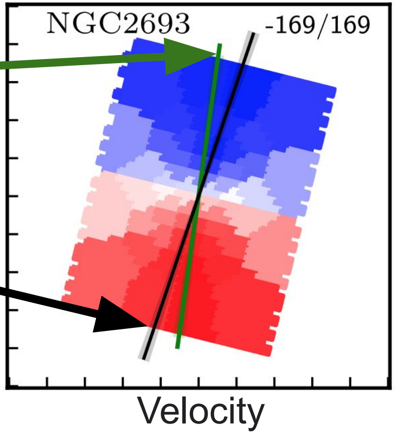
NGC 2693





average orientation of stellar motion

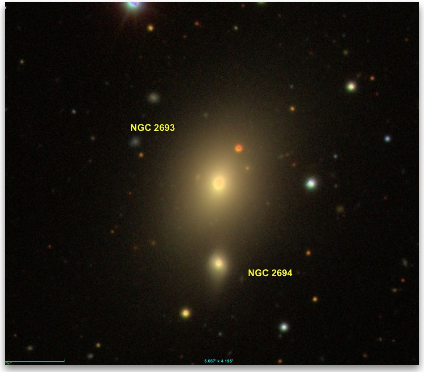
photometric major axis

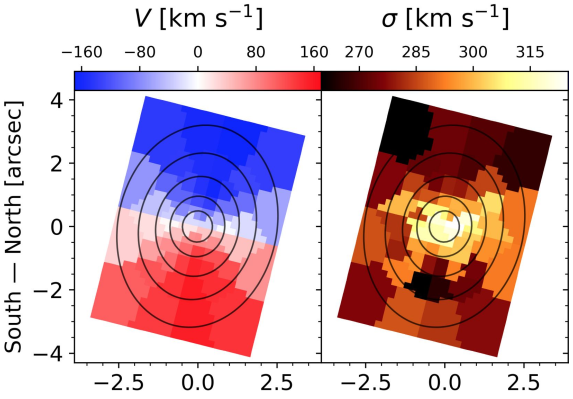


- regular, fast rotator (V~150 km/s, σ~320 km/s)
- mostly regular, elliptical isophotes
- **kinematic** and **photometric** major axes are ***nearly*** aligned (ΔΨ~5°)

stellar kinematics of NGC 2693

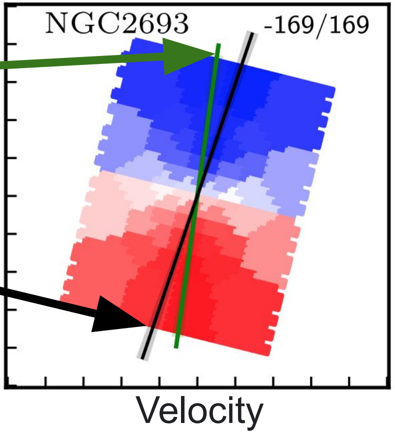
NGC 2693





average orientation of stellar motion

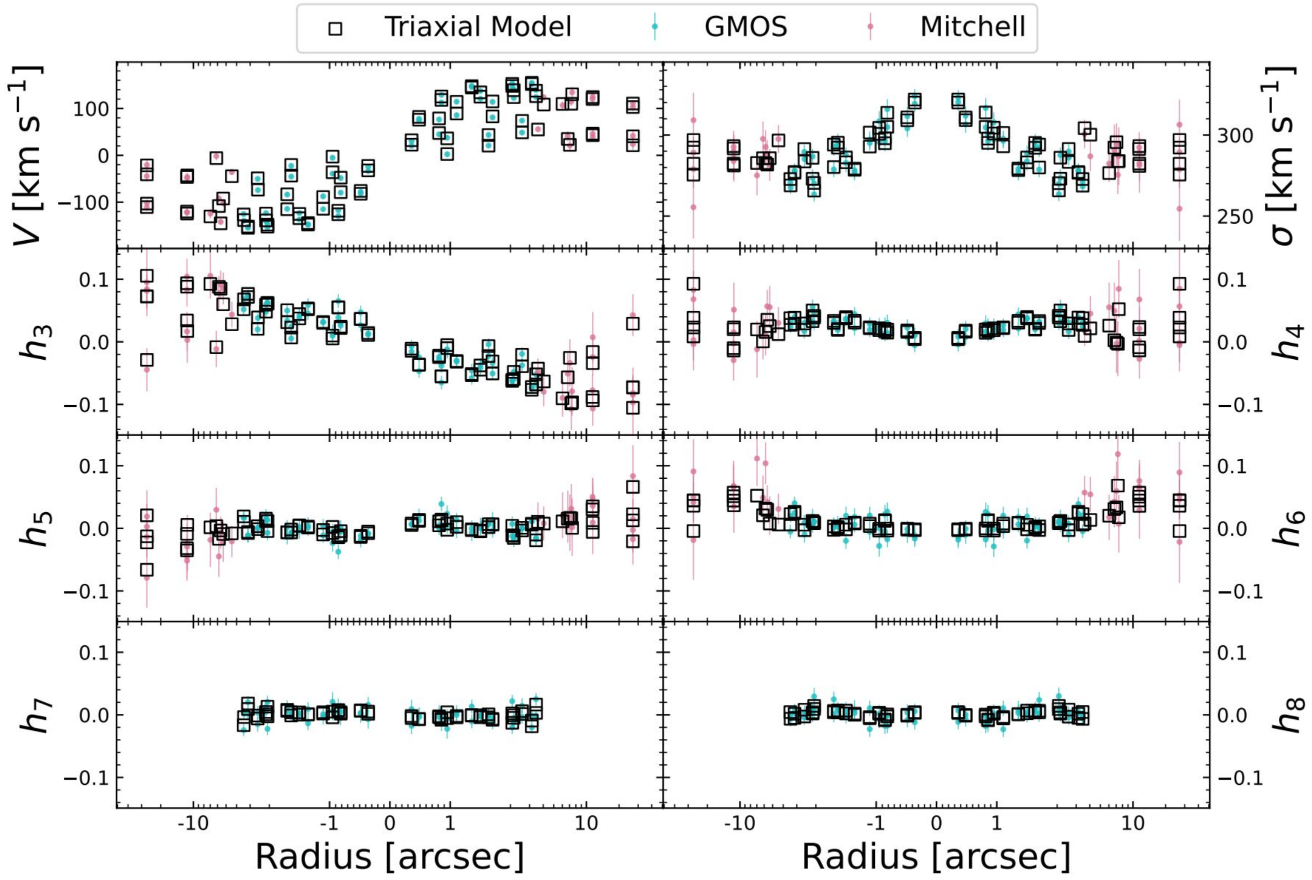
photometric major axis

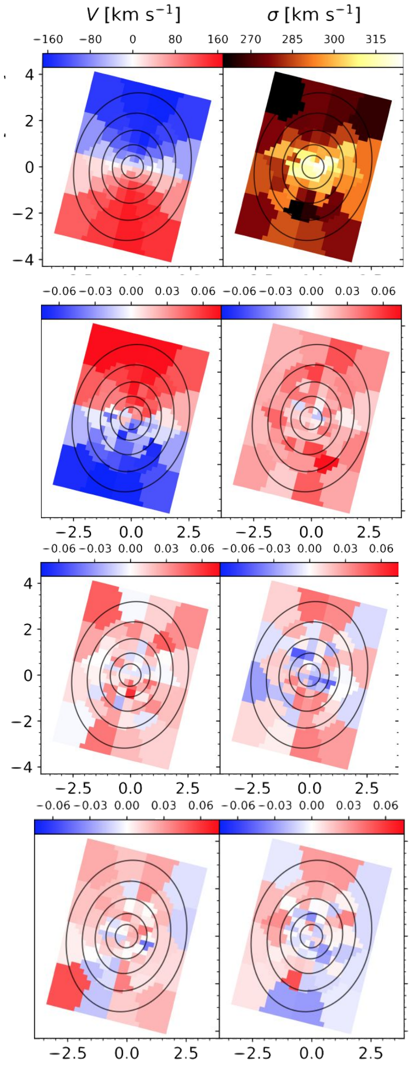


- regular, fast rotator (V~150 km/s, σ~320 km/s)
- mostly regular, elliptical isophotes
- **kinematic** and **photometric** major axes are ***nearly*** aligned (ΔΨ~5°)

properties ***nearly*** consistent with **axisymmetric** intrinsic shapes, so let's test!

stellar dynamical modeling: applications to **NGC 2693**



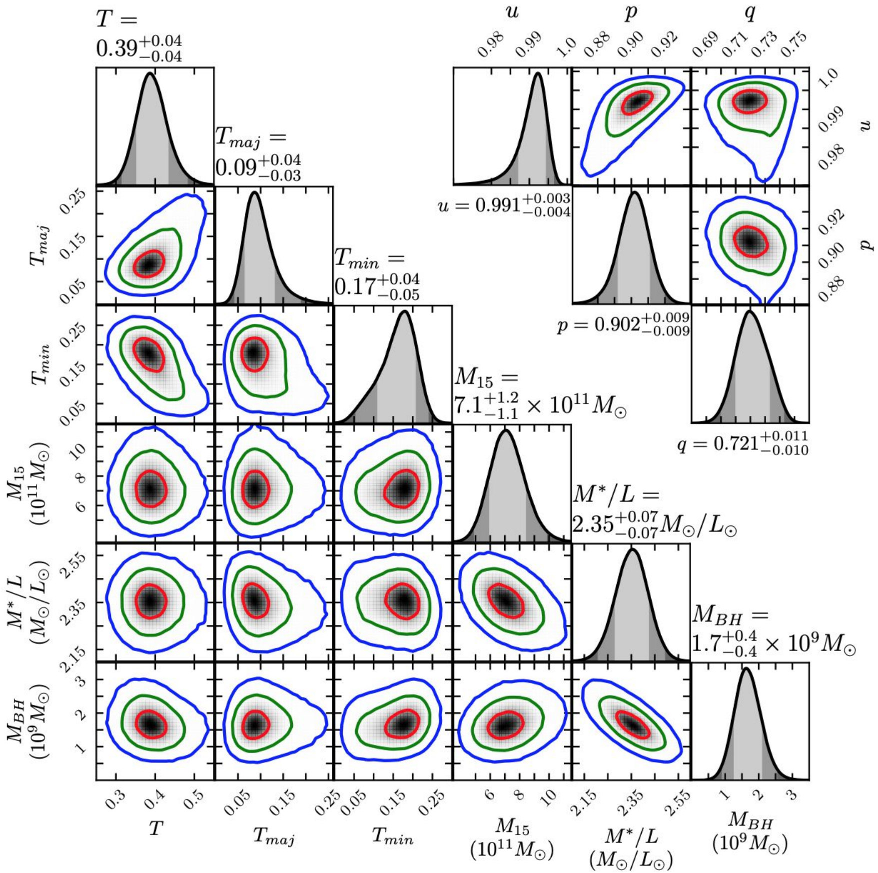


stellar dynamical modeling: applications to **NGC 2693**

- first simultaneous measurements of DM mass, BH mass, **and intrinsic shapes**

- **N2693 has a moderately triaxial intrinsic shape,**
  - Intermediate-to-major axis ratio: **p = b/a ~ 0.9**
  - Minor-to-major axis ratio: **q= c/a ~ 0.7**

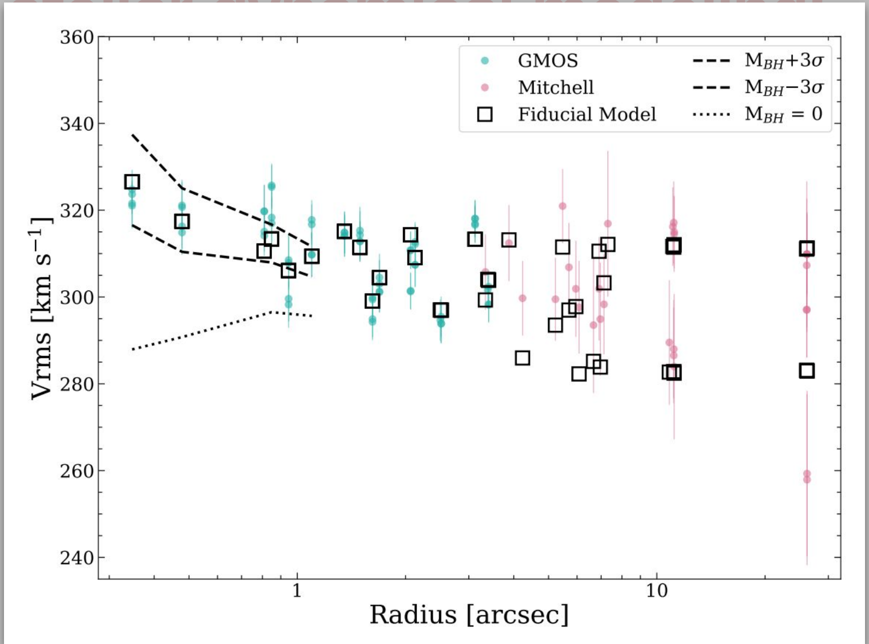
- **NGC 2693 M_{BH} = (1.7±0.4) x 10^9 M_{sun}**

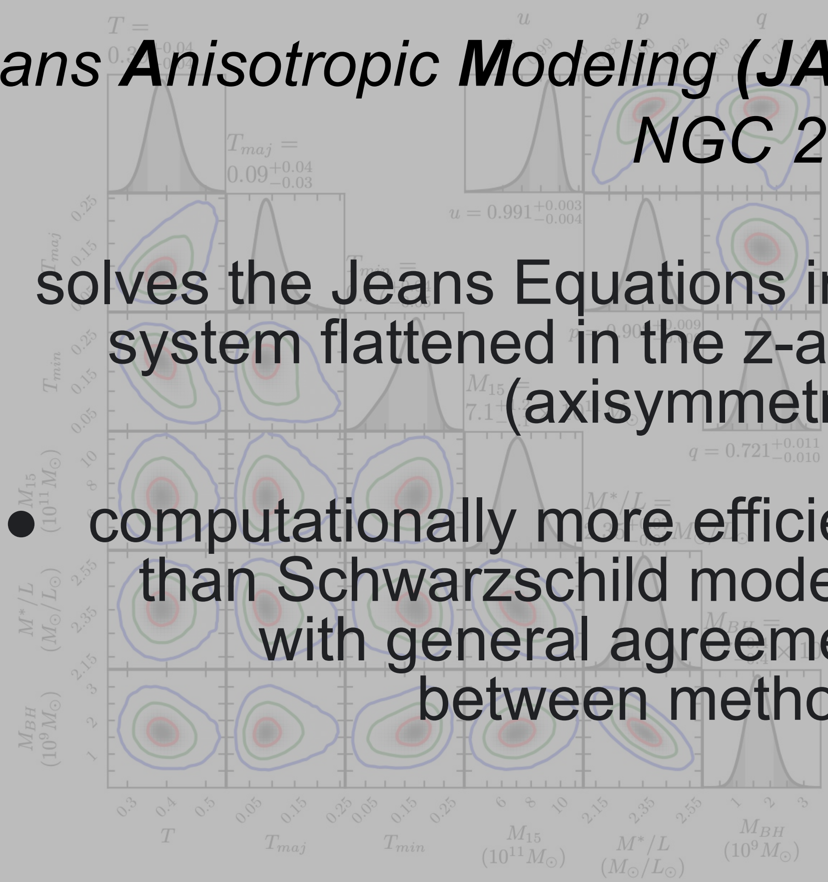


TRIAXIAL	AXISYMMETRIC
NGC 2693 BH: (1.7±0.4) x 10^9 M_{sun} →	(2.4 ± 0.6) x 10^9 M_{sun}

Pilawa+22

*Jeans **A**nisotropic **M**odeling **(JAM)**: NGC 2693*





- solves the Jeans Equations in a system flattened in the z-axis (axisymmetric)
- computationally more efficient than Schwarzschild models, with general agreement between methods

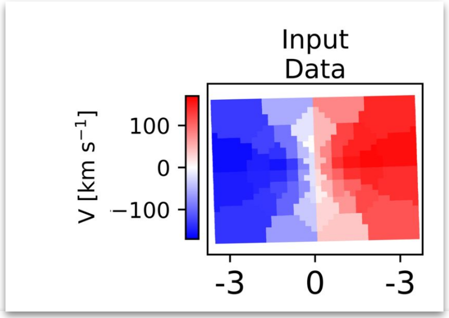
- NGC 2693 M_{BH} = (1.7±0.4) x 10^9 M_{sun}

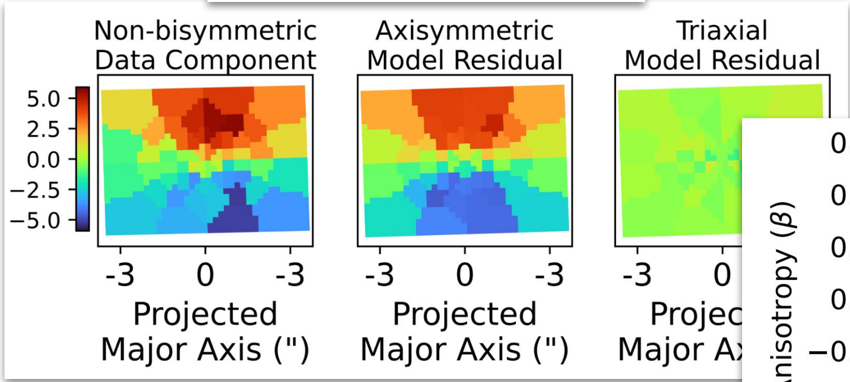
JAM	**AXISYMMETRIC Schwarzschild**
(2.9 ± 0.3) x 10^9 M_{sun} →	(2.4 ± 0.6) x 10^9 M_{sun}

Pilawa+22

what happened to the axisymmetric models?

Pilawa+22

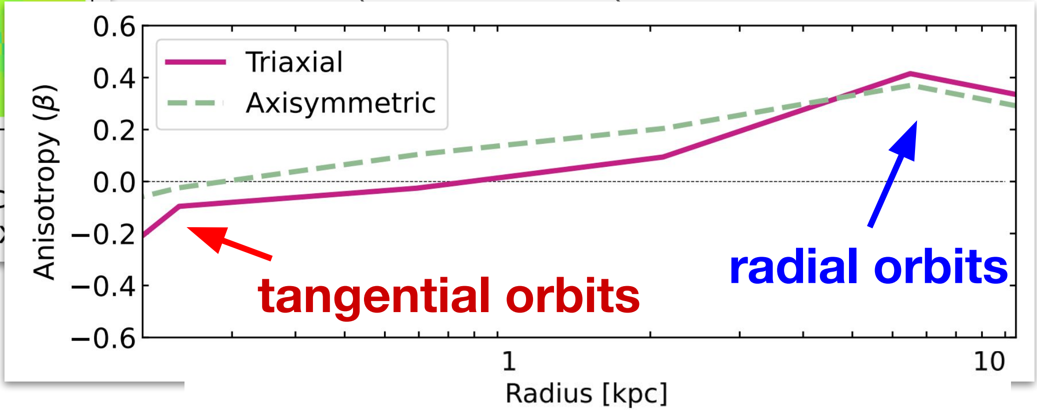




analogy:

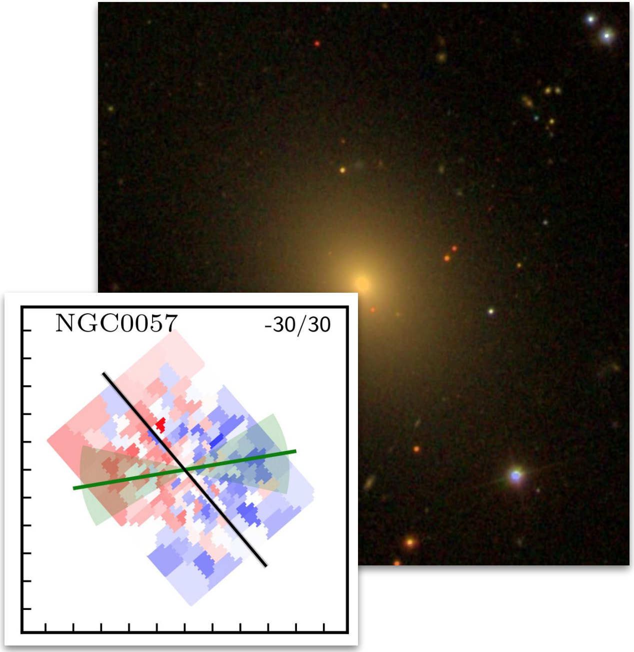
$$f(x) = f_{even}(x) + f_{odd}(x)$$

$$V(x) = V_{bisymmetric}(x) + V_{non\text{-}bisymmetric}(x)$$



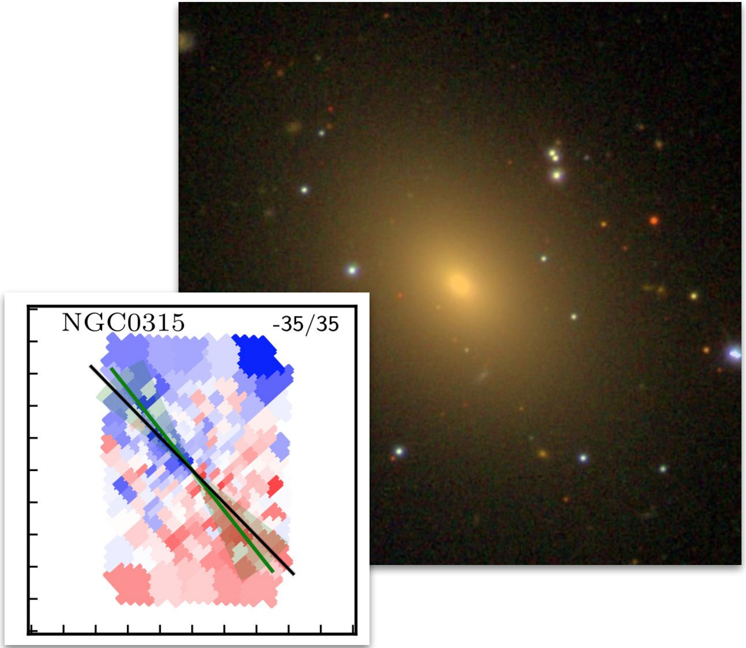
stellar dynamical modeling: ongoing work

NGC 57



- *Slow rotation (~25 km/s), **kinematically** and **photometrically** misaligned*
- *Most isolated MASSIVE galaxy*

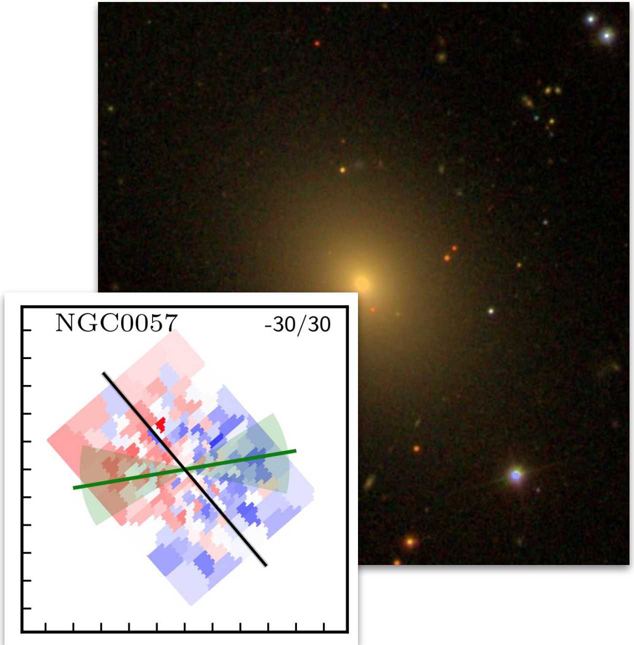
NGC 315



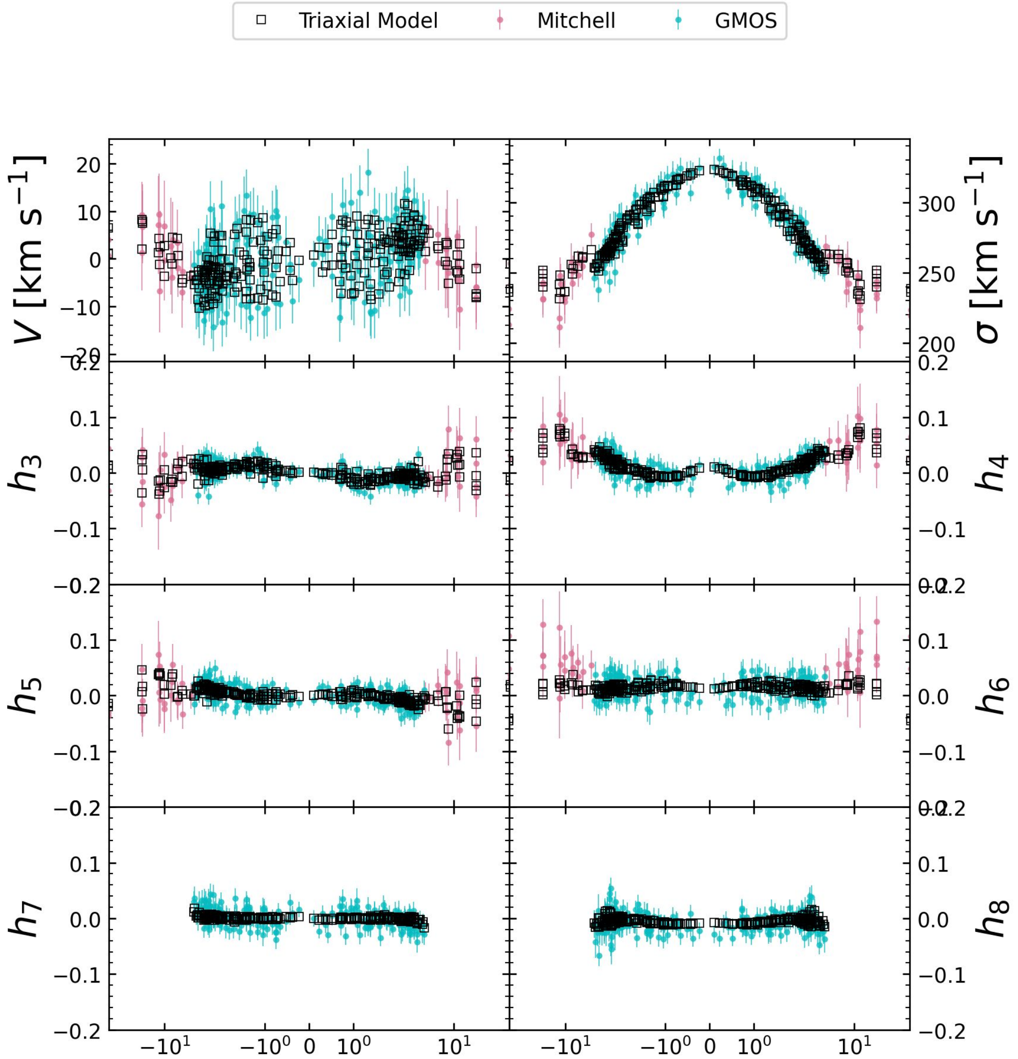
- *Slow rotation (~30 km/s), **kinematically** and **photometrically** aligned*
- *Has ALMA CO M_{BH} measurement [Boizelle, Walsh+2021]*

stellar dynamical modeling:
ongoing work

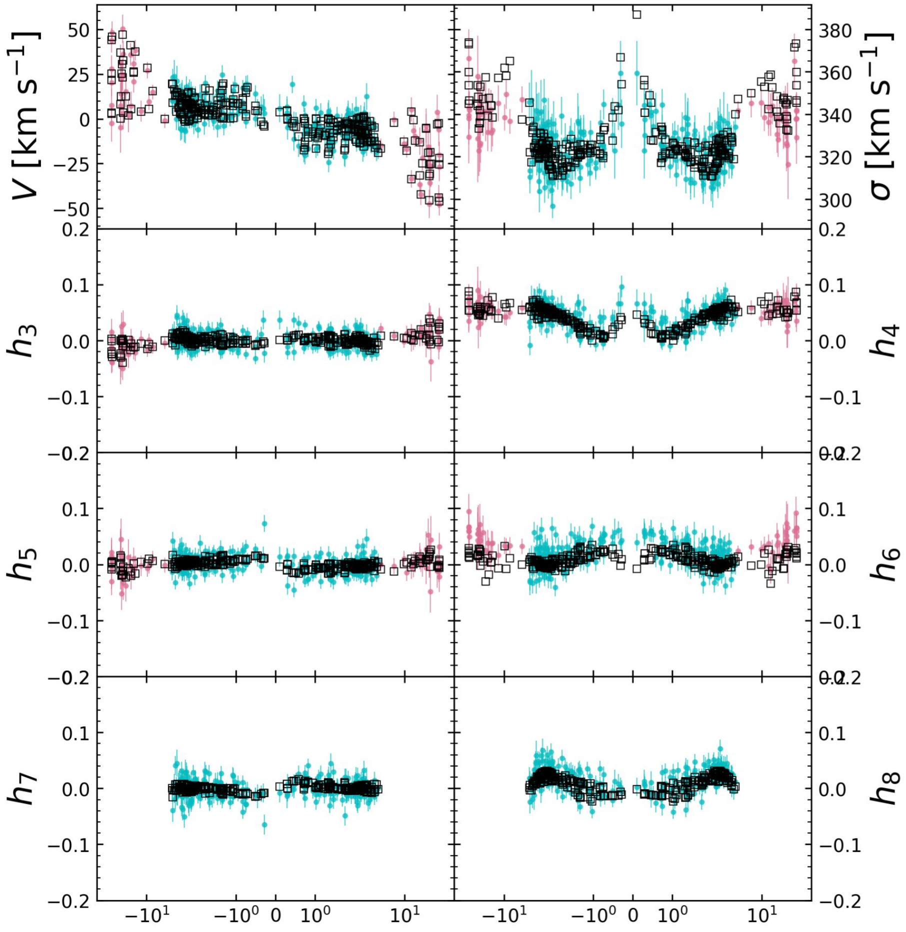
NGC 57



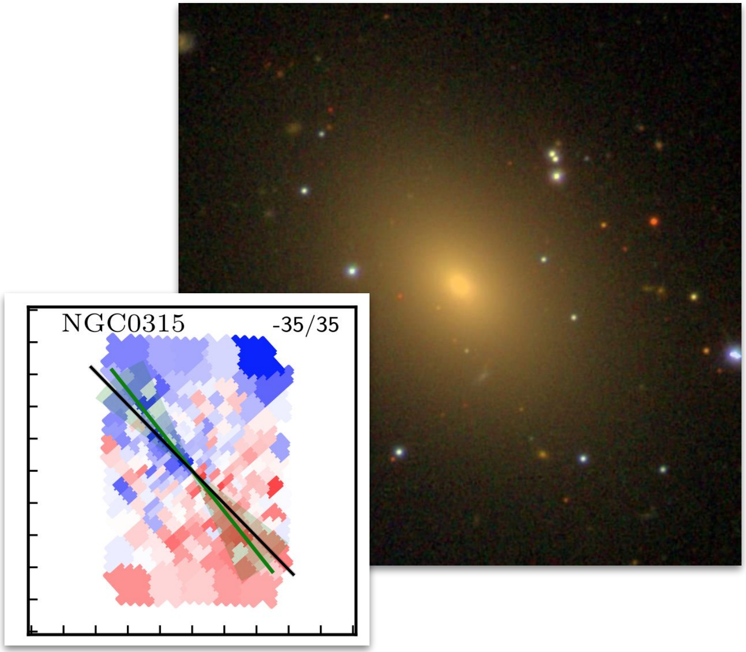
- *Slow rotation (~25 km/s), **kinematically** and **photometrically** misaligned*
- *Most isolated MASSIVE galaxy*



stellar dynamical modeling:
ongoing work



NGC 315



- *Slow rotation (~30 km/s), **kinematically** and **photometrically** aligned*
- *Has ALMA CO M_{BH} measurement*

A roadmap for the talk:

1. Supermassive black holes in the largest galaxies

2. Triaxial Schwarzschild modeling of massive ellipticals

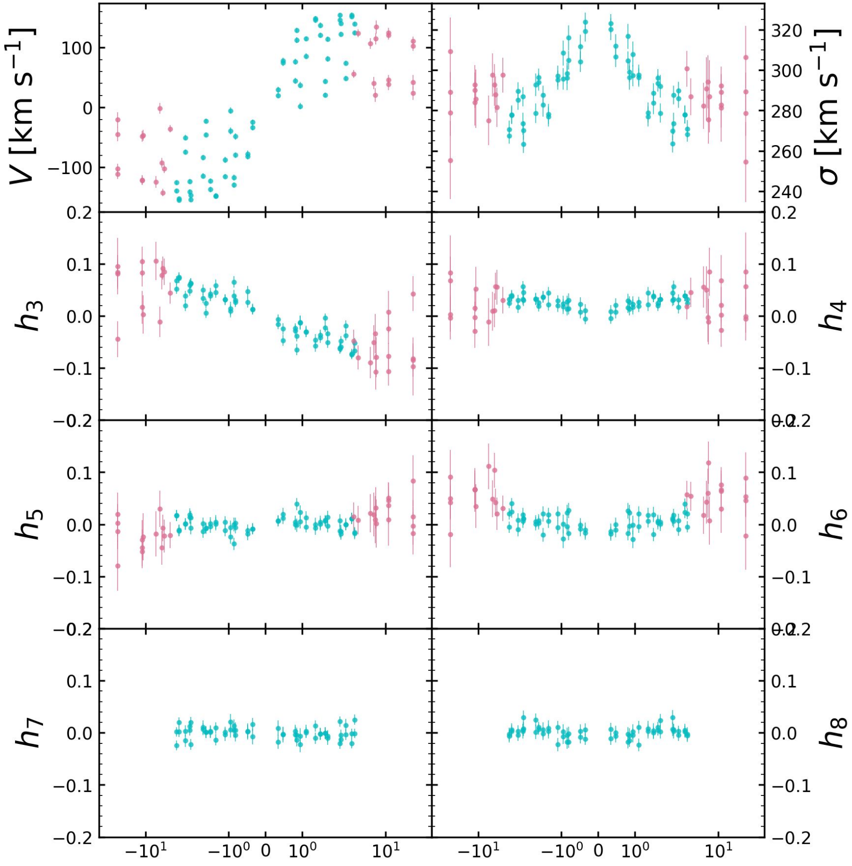
3. **Robustness and Recovery Tests of Dynamical Models**

Taking a step back…
how robust are Schwarzschild orbit models?

input: mock kinematics from a galaxy with known parameters

how well can we recover a series of **known** inputs?

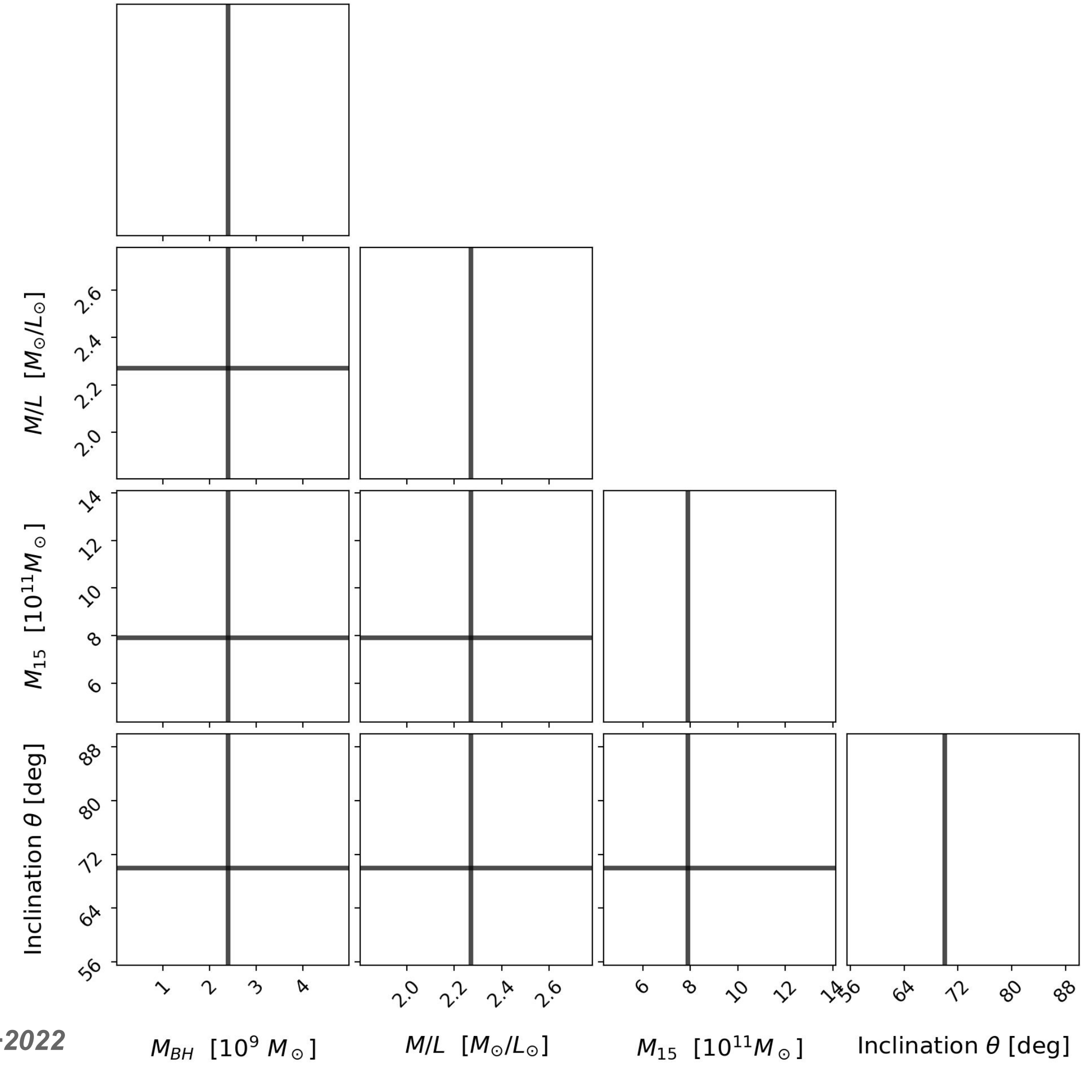
TriOS



Krajnovic+2006, Cappellari+2008, Liepold+2021 Lipka+2021,+2022

Schwarzschild Mock Recovery: Axisymmetric Models

black:
input model kinematics
(from an **i = 70° mock galaxy model**)

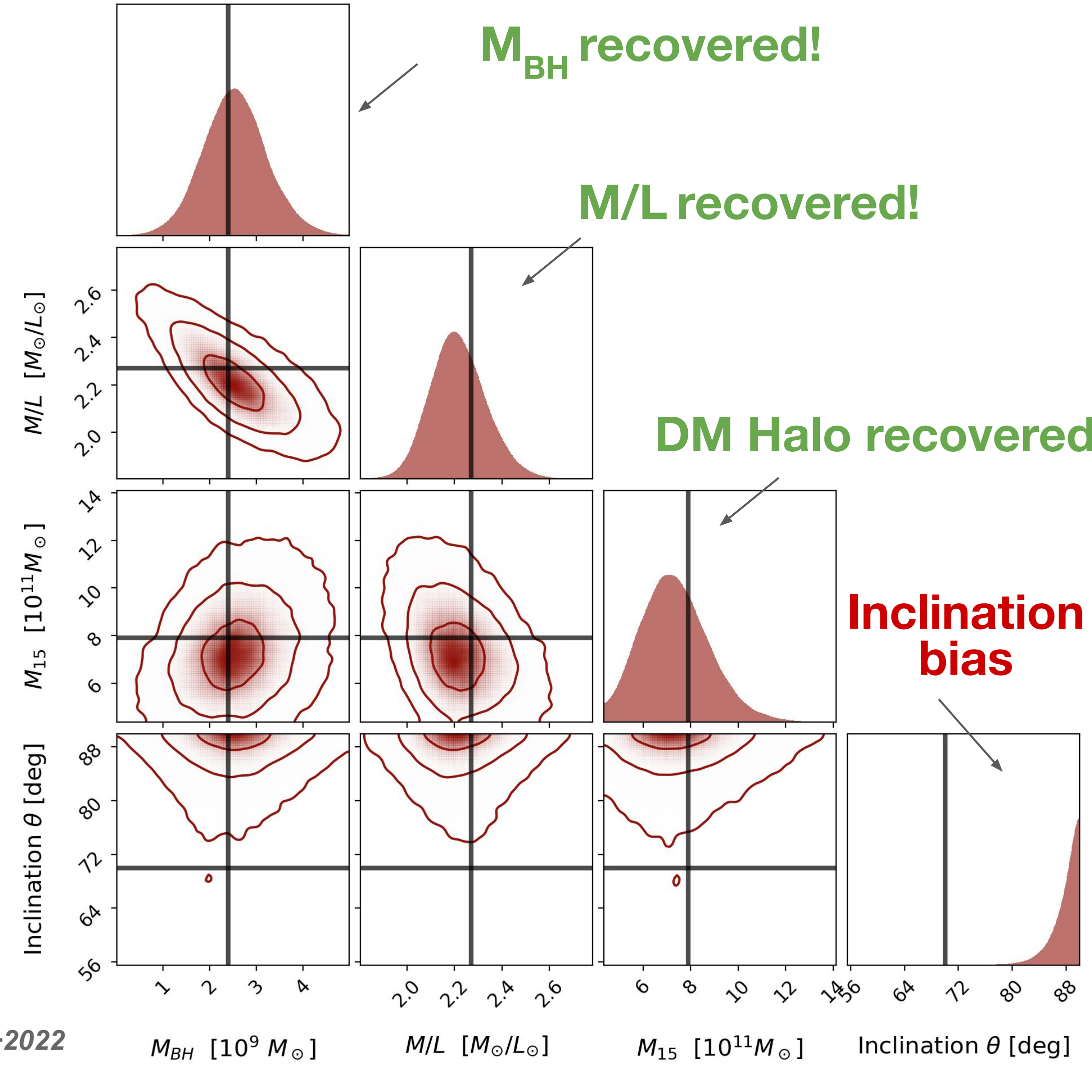


Krajnovic+2006, Cappellari+2008, Liepold+2021 Lipka+2021,+2022

Schwarzschild Mock Recovery: Axisymmetric Models

black:
input model kinematics (from an **i = 70° mock galaxy model**)

red: recovered posteriors on parameters from Schwarzschild models

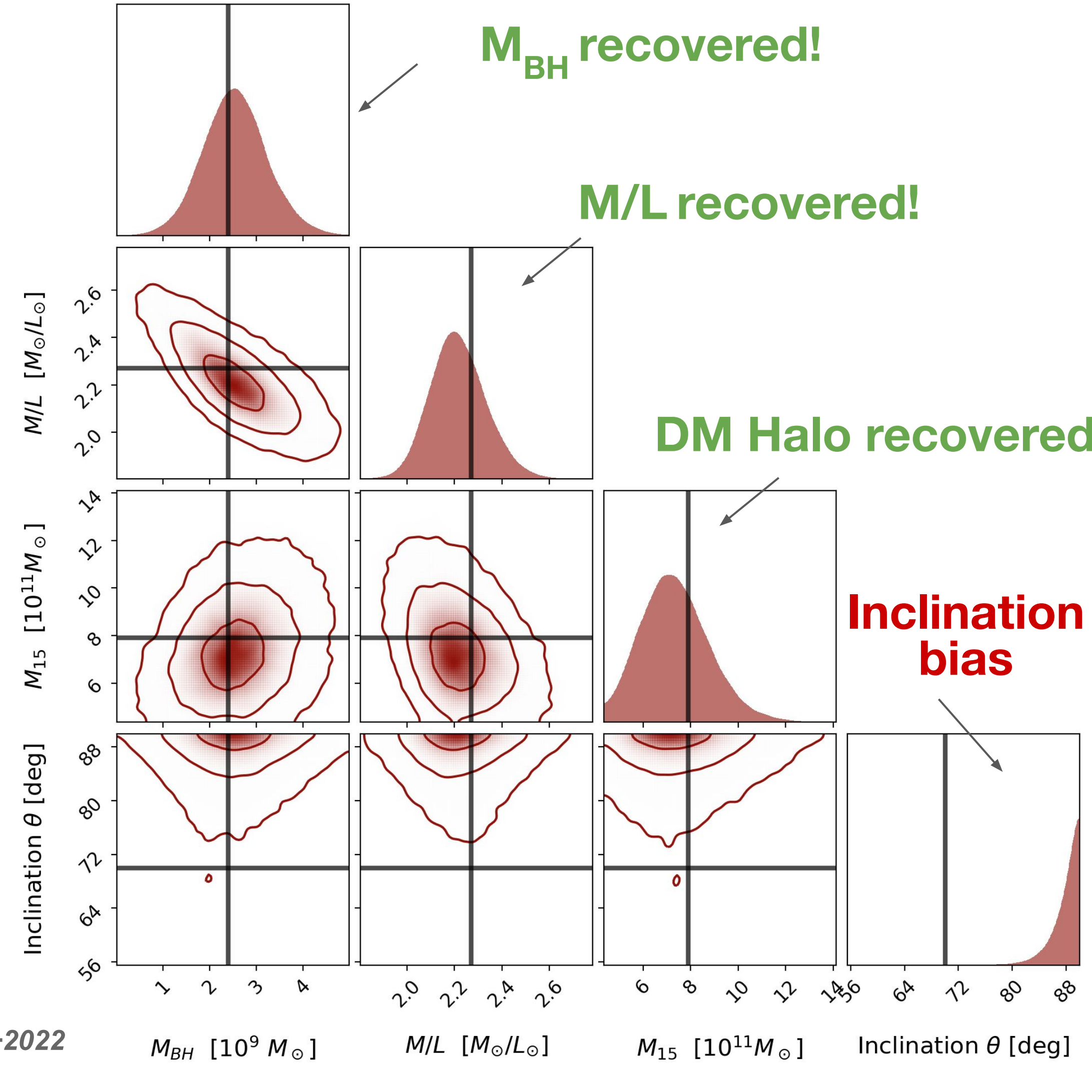


Krajnovic+2006, Cappellari+2008, Liepold+2021 Lipka+2021,+2022

Schwarzschild Mock Recovery:
Axisymmetric Models

best case scenario:
large range of inclinations
are consistent with the data

typical case:
axisymmetric
schwarzschild
models exhibit a
bias toward
edge-on
inclinations



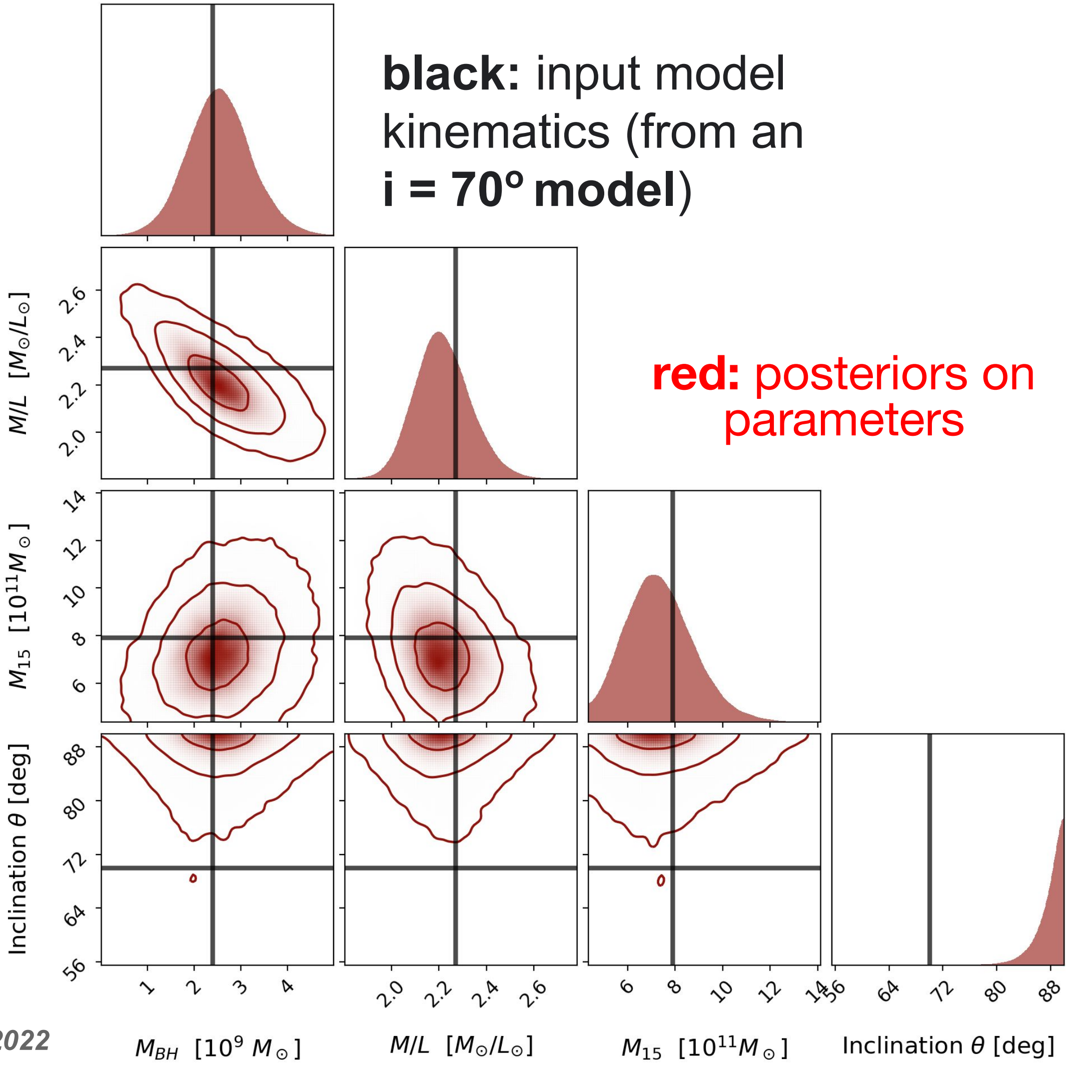
Krajnovic+2006, Cappellari+2008, Liepold+2021 Lipka+2021,+2022

Schwarzschild Model Flexibility:
Axisymmetric Models

edge on:
prograde and retrograde orbits are maximally different

face on:
prograde and retrograde orbits are identical

→ edge-on models have a larger set of unique **basis functions** for the superposition of orbits!
→ larger "**flexibility**" in these models



Krajnovic+2006, Cappellari+2008, Liepold+2021 Lipka+2021,+2022

Schwarzschild Mock Recovery:
Axisymmetric Models

best case
large range
are consisten

typica
axisym
schwa
models
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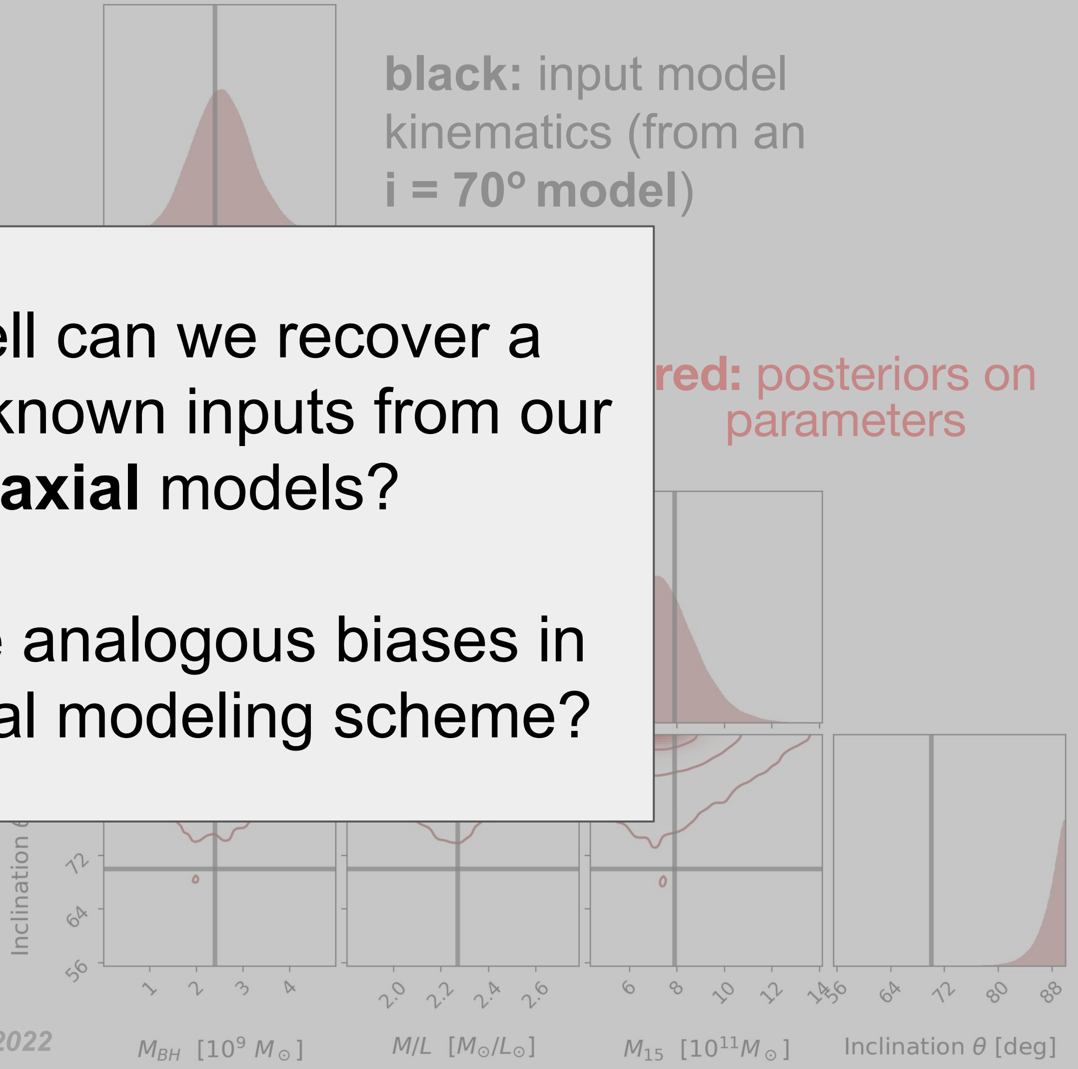
edge-on
inclinations

(a) how well can we recover a series of known inputs from our **triaxial** models?

(b) are there analogous biases in our triaxial modeling scheme?

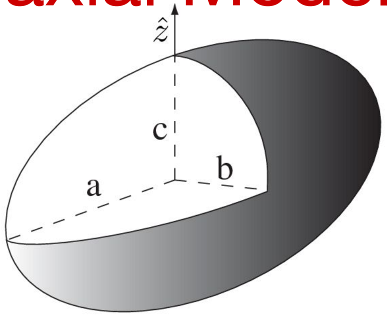
black: input model kinematics (from an **i = 70° model**)

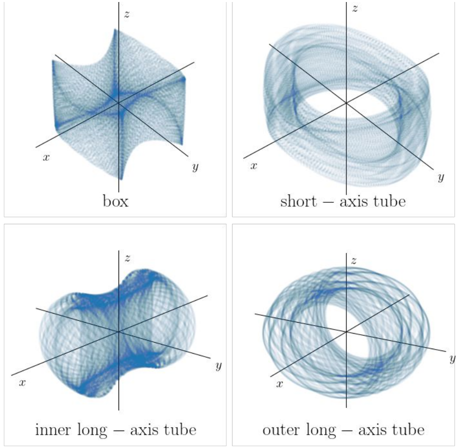
red: posteriors on parameters

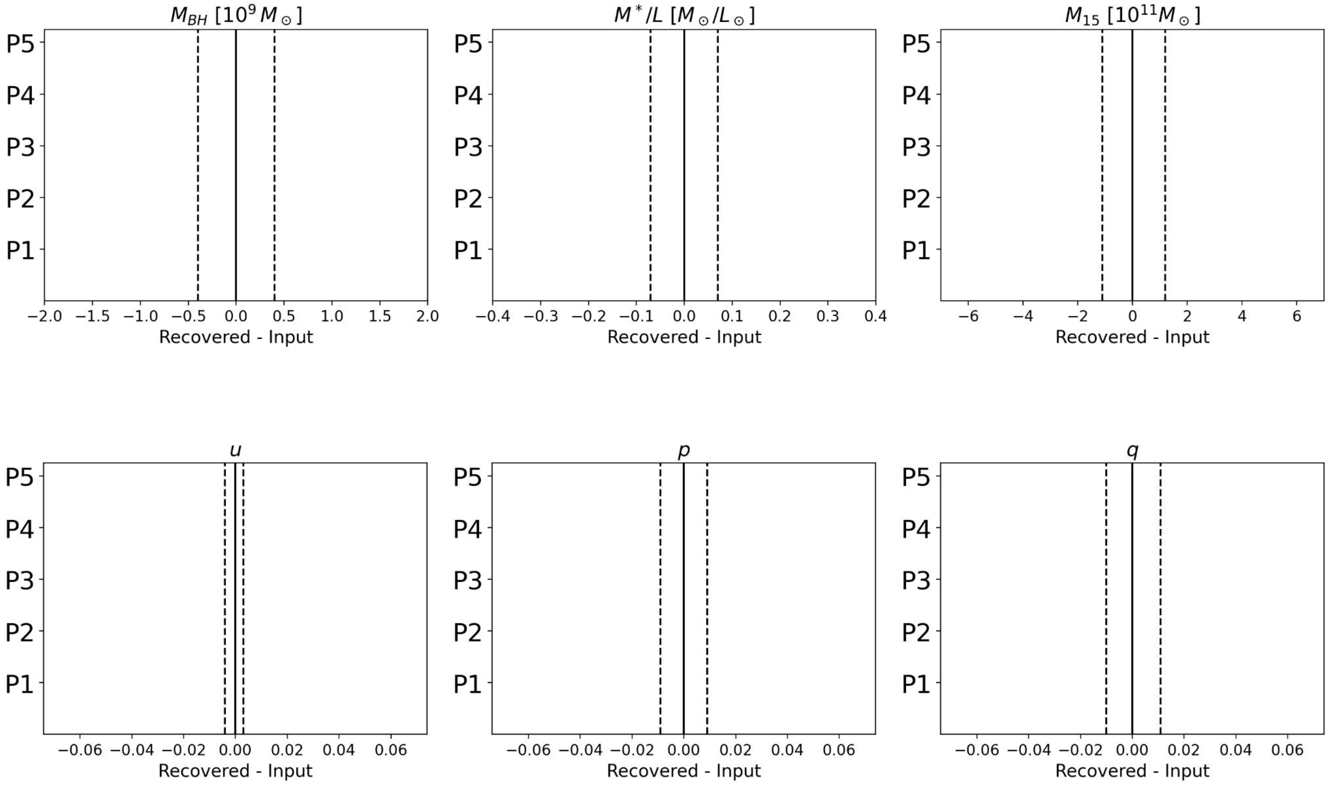


Krajnovic+2006, Cappellari+2008, Liepold+2021 Lipka+2021,+2022

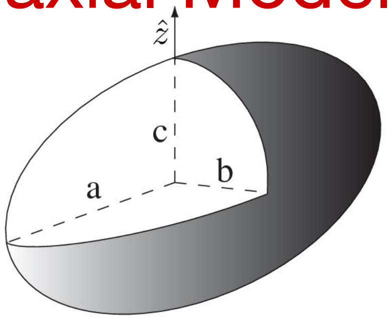
Schwarzschild Model Flexibility:
Triaxial Models

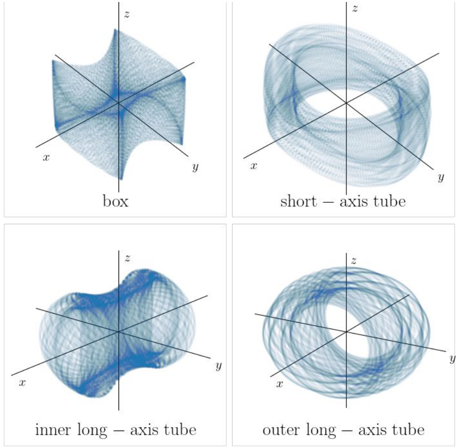


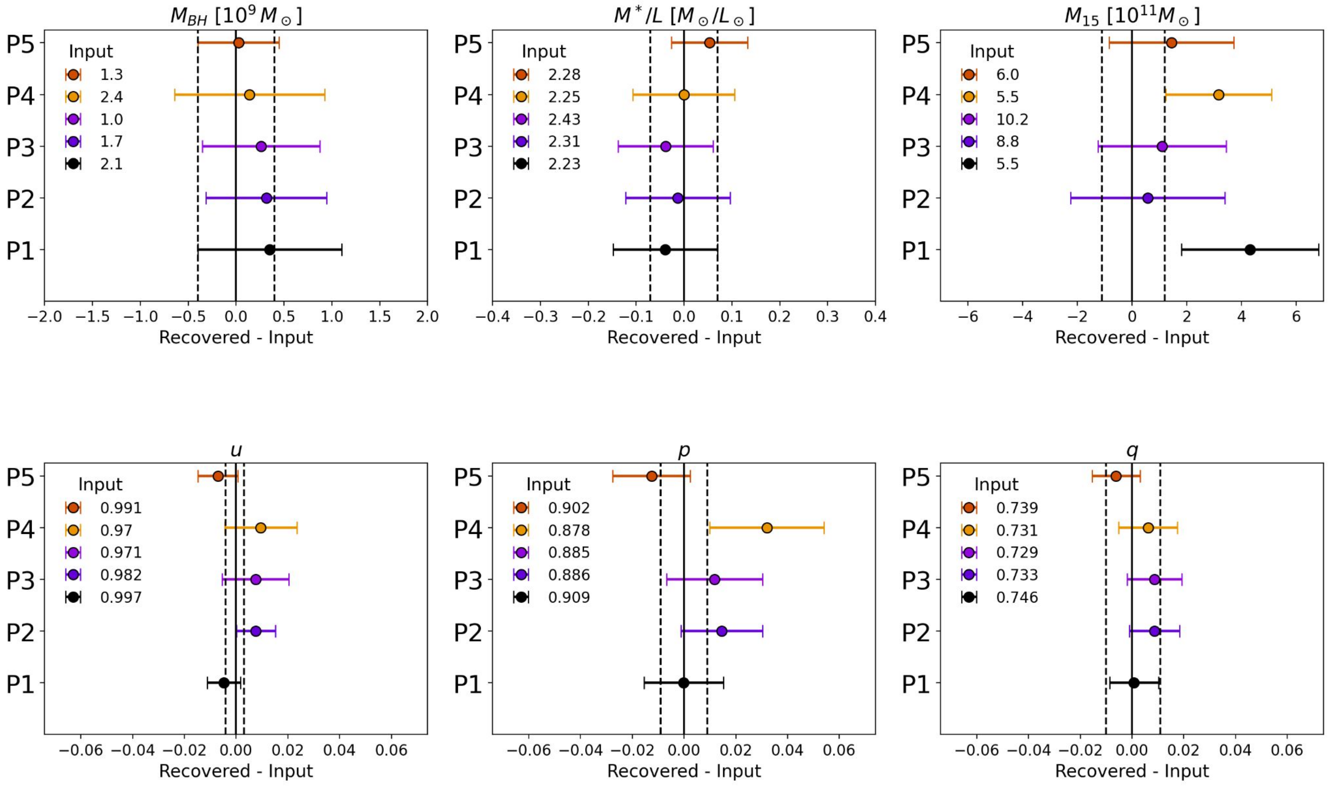




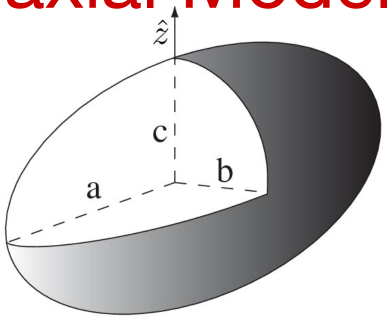
Schwarzschild Model Flexibility:
Triaxial Models

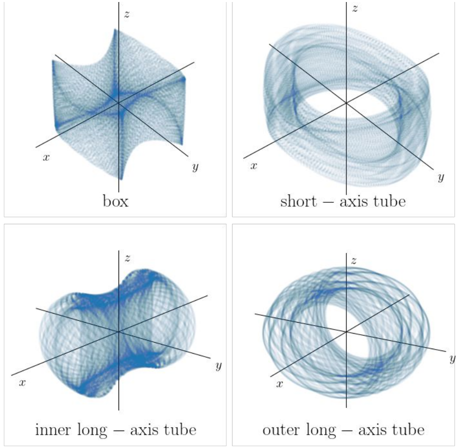


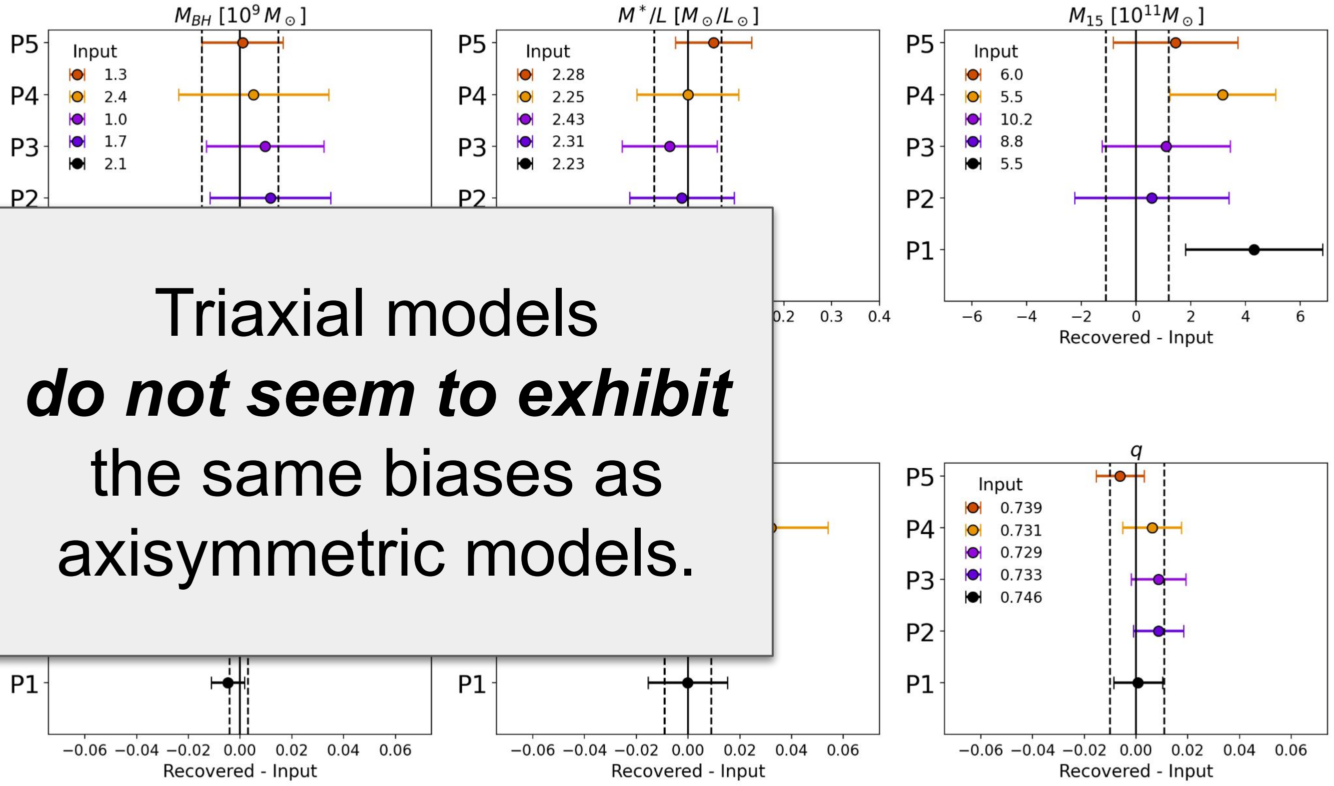




Schwarzschild Model Flexibility:
Triaxial Models



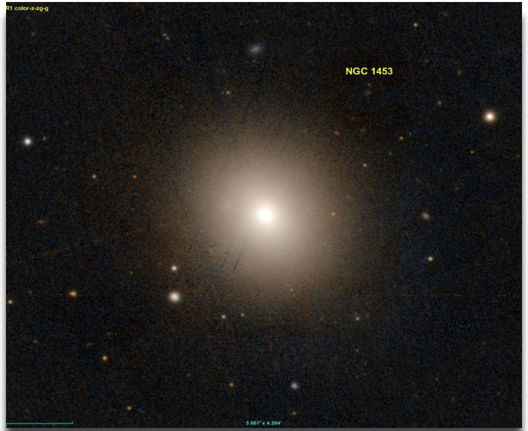




Triaxial models ***do not seem to exhibit*** the same biases as axisymmetric models.

<u>Summary:</u> *Recent Dynamical Modeling Efforts*

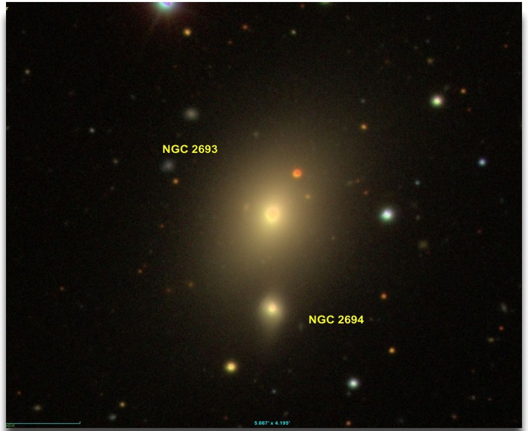
NGC 1453



Quenneville+2021

- M_{BH} = (2.9 ± 0.4) x 10^9 M_{sun}
- p = b/a = (0.933 ± 0.015)
- q = c/a = (0.779 ± 0.012)

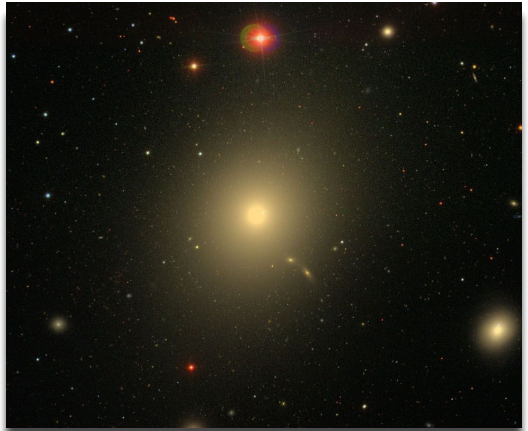
NGC 2693



Pilawa+2022

- M_{BH} = (1.7 ± 0.4) x 10^9 M_{sun}
- p = b/a = (0.902 ± 0.009)
- q = c/a = (0.721 ± 0.010)

M87



Liepold+2023

- $(5.37^{+0.37}_{-0.25} \pm 0.22) \times 10^9 M_\odot$
- p = b/a = (0.845 ± 0.004)
- q = c/a = (0.772 ± 0.004)

Thank you!

Summary:

discovery and **dynamical modeling** of new **supermassive black holes**:
NGC 2693: (1.7±0.4) x 10^9 M_{Sun}
NGC 1453: (1.7±0.4) x 10^9 M_{Sun}

→ first simultaneous measurements of **BH + DM halo + galaxy shape;** axisymmetric + triaxial + JAM

schwarzschild models are **extremely** powerful, and we can robustly recover known inputs

→ computationally cheap ways to estimate **model flexibility** and its effects (or lack thereof) on recovered parameters

we are ready for **more dynamical modeling** more **complicated kinematic structure**

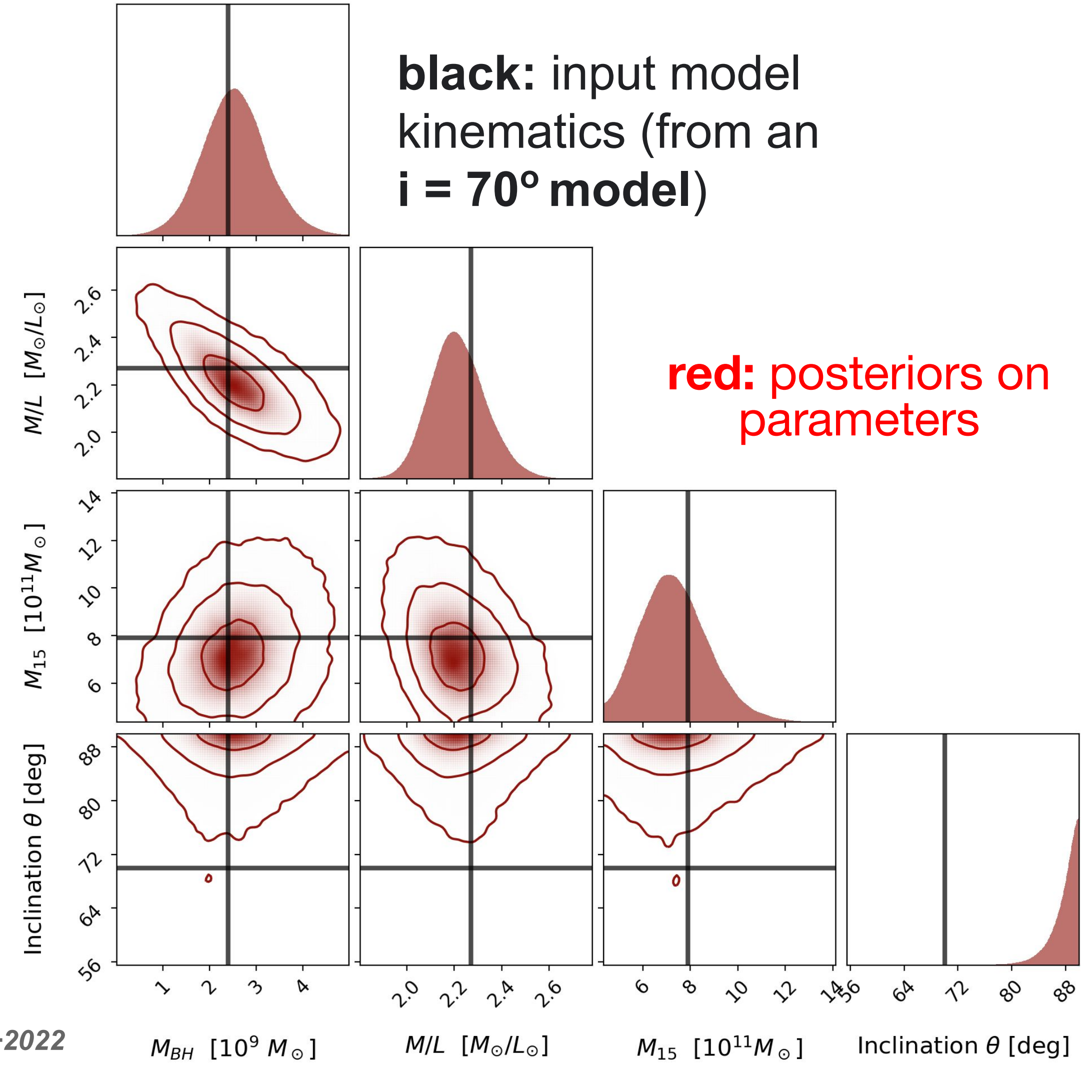
→ **~20 MASSIVE** galaxies are ready for modeling, none of which are simple fast rotators

Thank you!

Extra Slides

Schwarzschild Model Flexibility: Axisymmetric Models

can we fix this?



black: input model kinematics (from an **i = 70° model**)

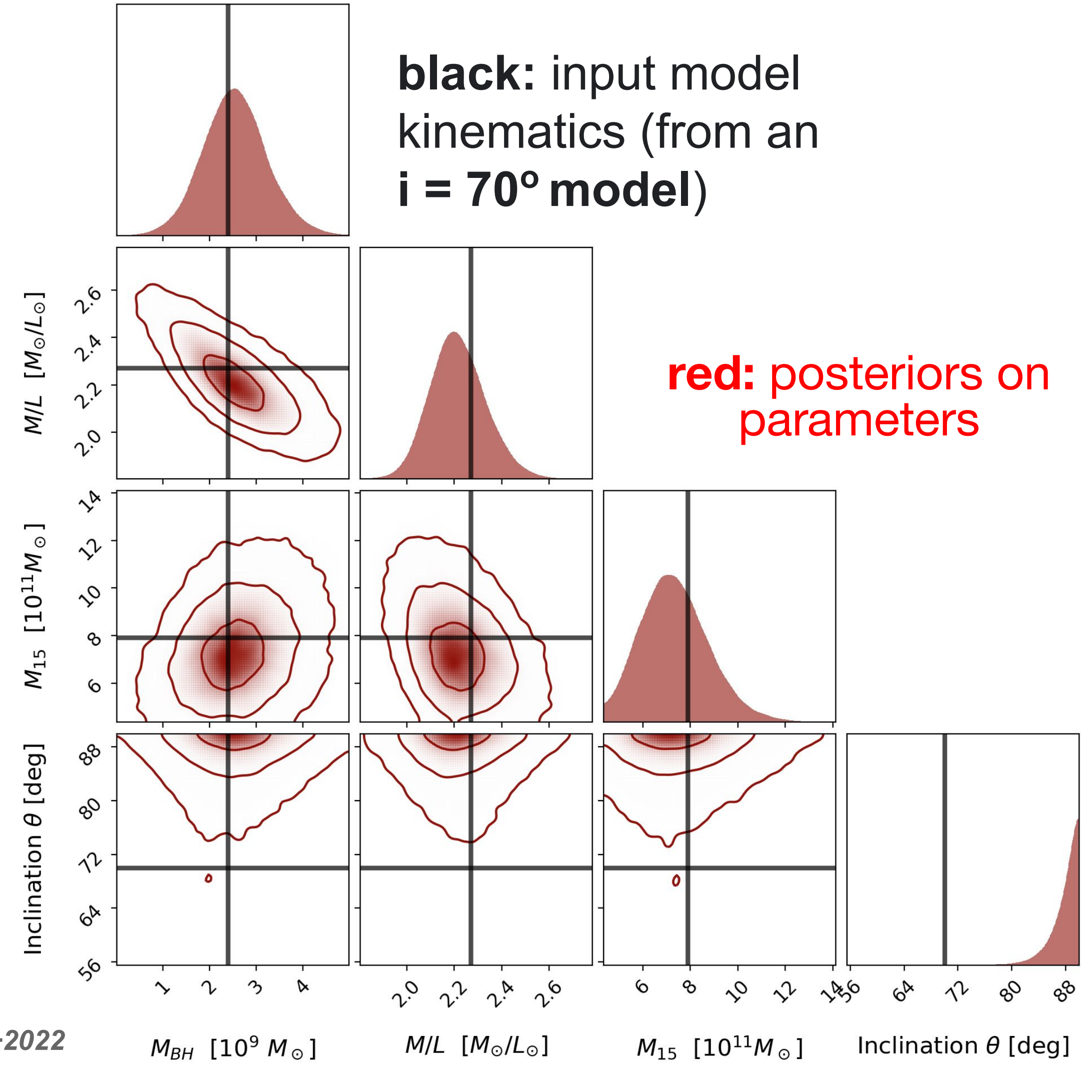
red: posteriors on parameters

Krajnovic+2006, Cappellari+2008, Liepold+2021 Lipka+2021,+2022

Schwarzschild Model Flexibility:
Axisymmetric Models

can we fix this?

- one approach (Ye 1998): **generalized d.o.f. m_{eff}**



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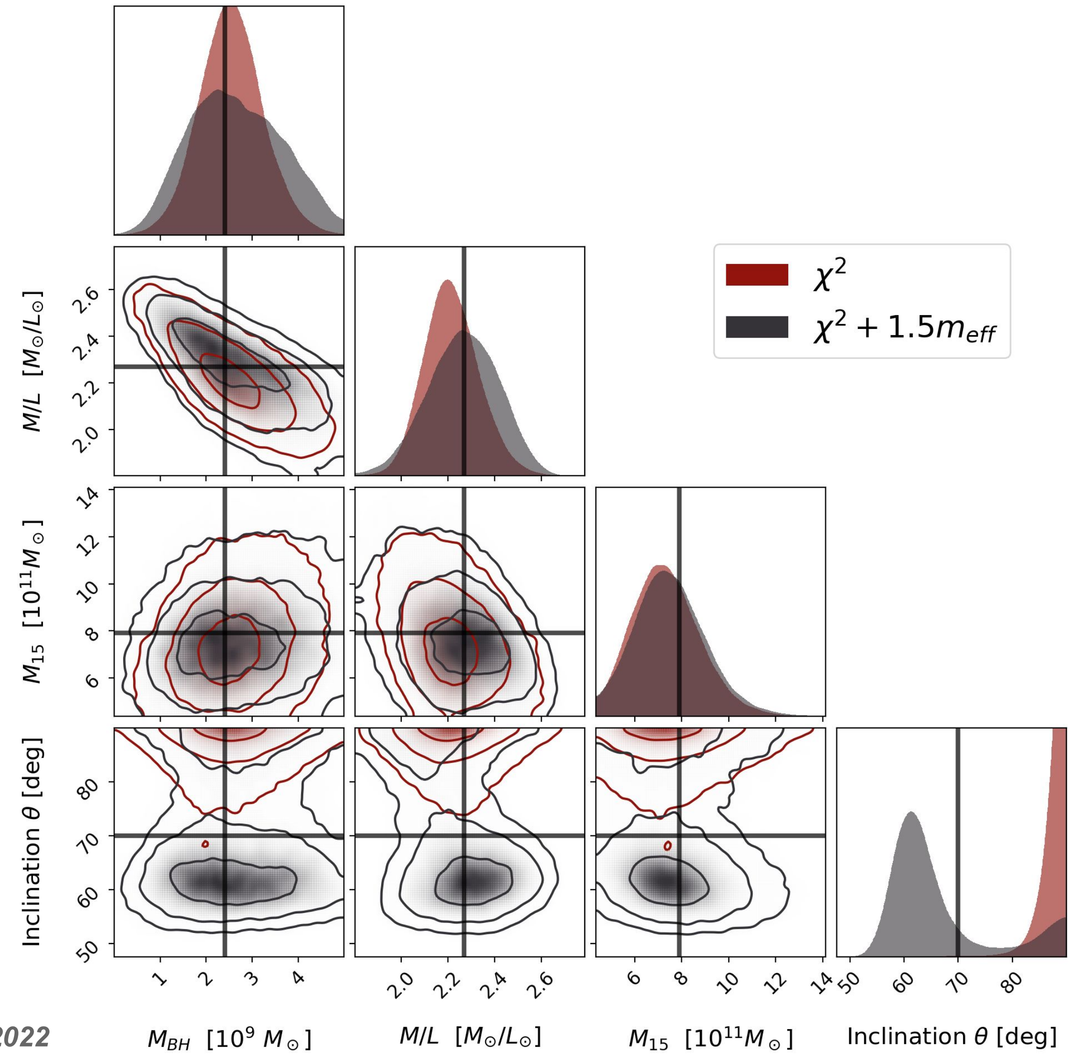
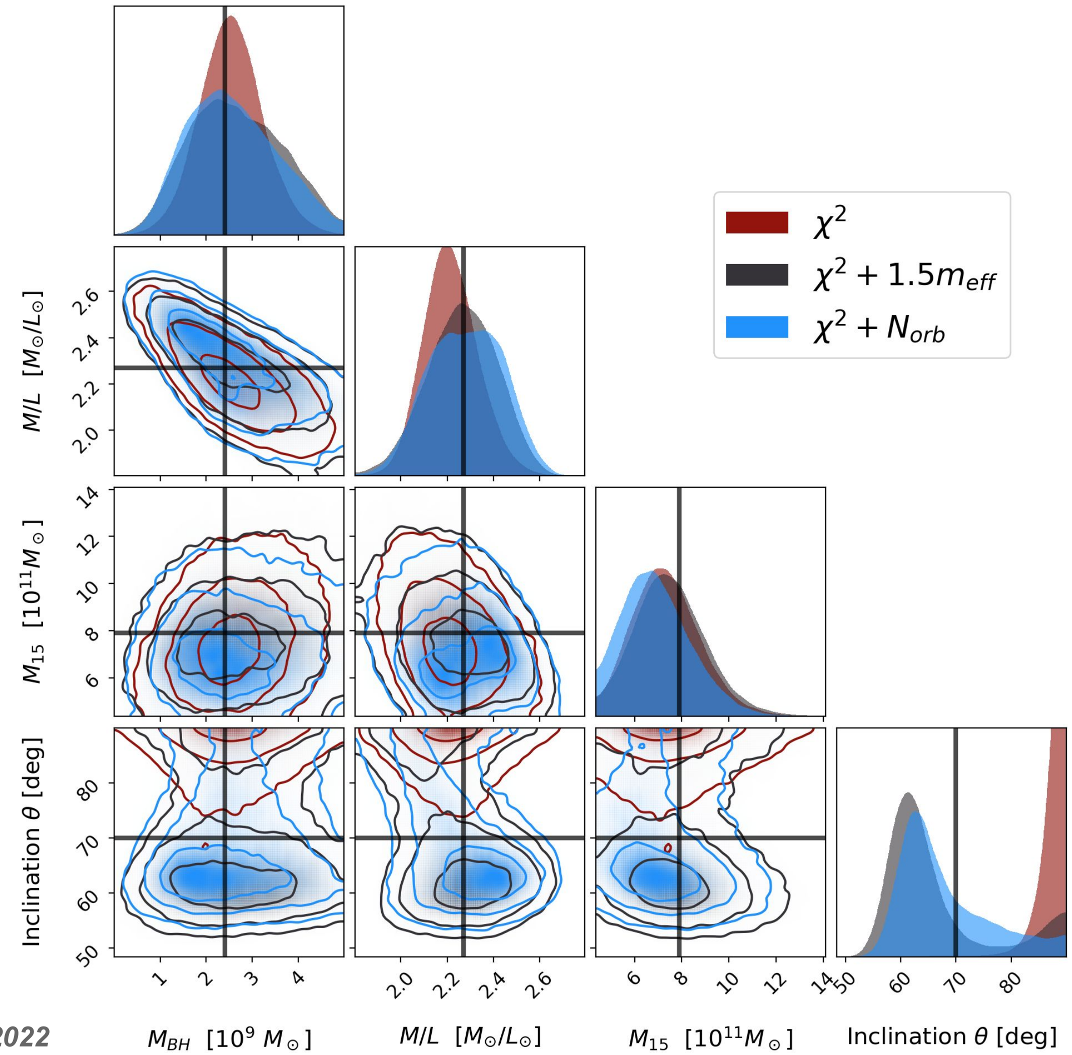


Krajnovic+2006, Cappellari+2008, Liepold+2021 Lipka+2021,+2022

Schwarzschild Model Flexibility: Axisymmetric Models

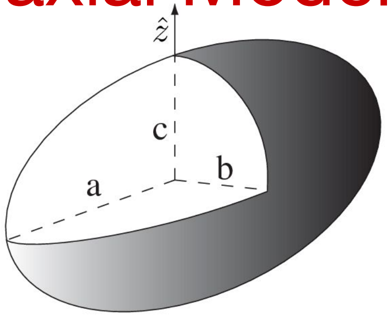
can we fix this?

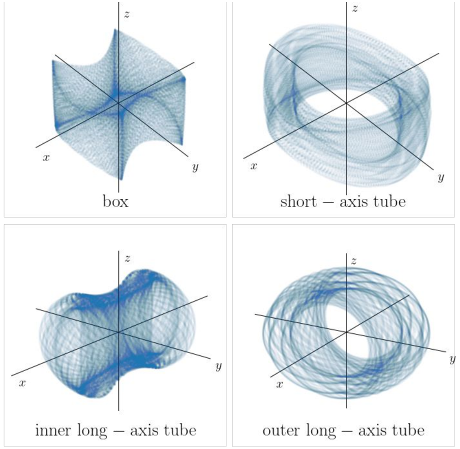
- one approach (Ye 1998): **generalized d.o.f. m_{eff}**
- alternative, ***faster*** approach:
  - penalize the model's χ^2 by "activated" orbits N_{orb} (orbits with non-zero weight in superposition)

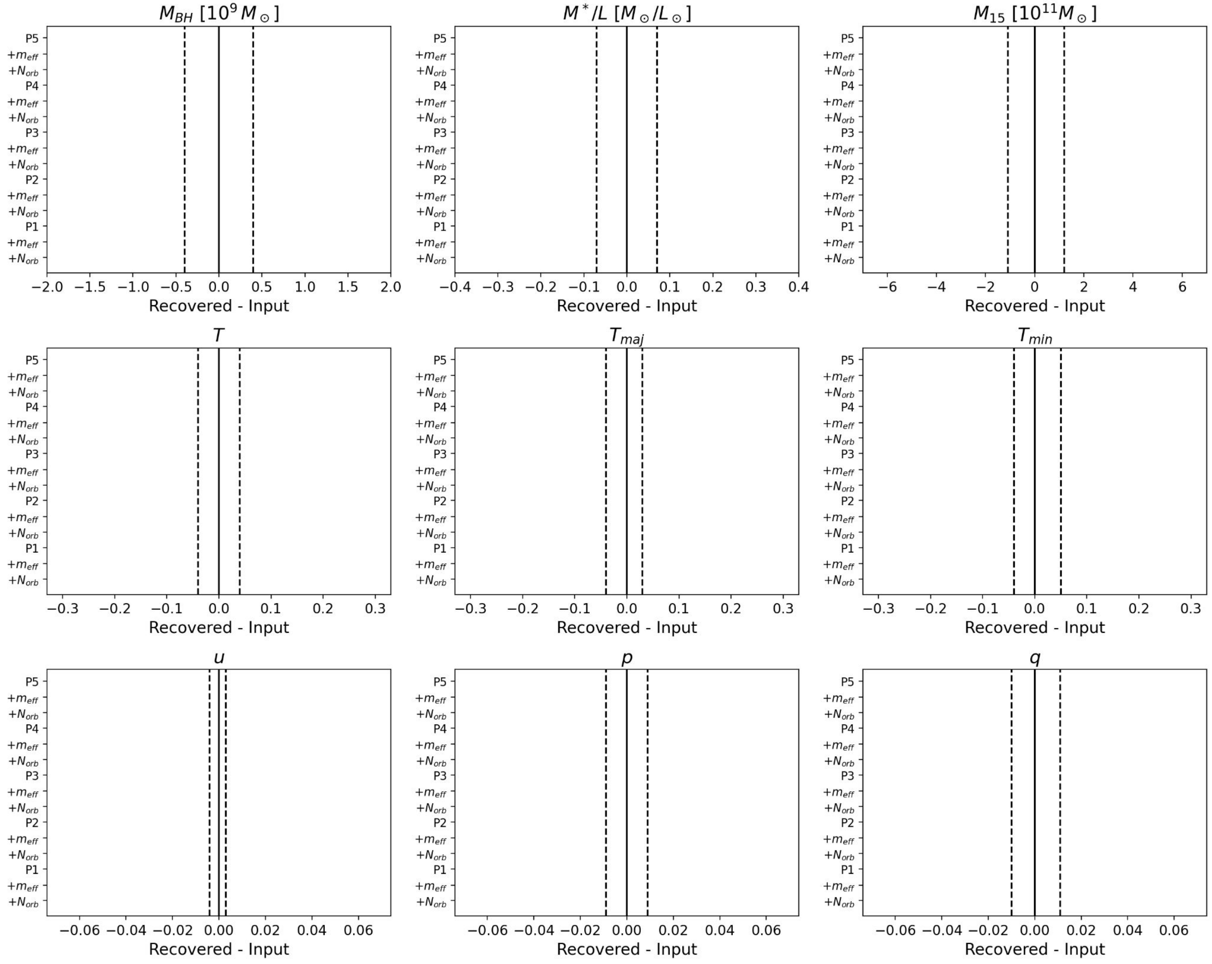


Krajnovic+2006, Cappellari+2008, Liepold+2021 Lipka+2021,+2022

Schwarzschild Model Flexibility:
Triaxial Models

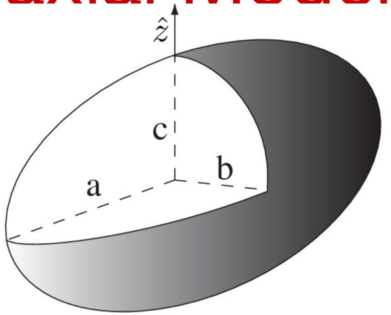


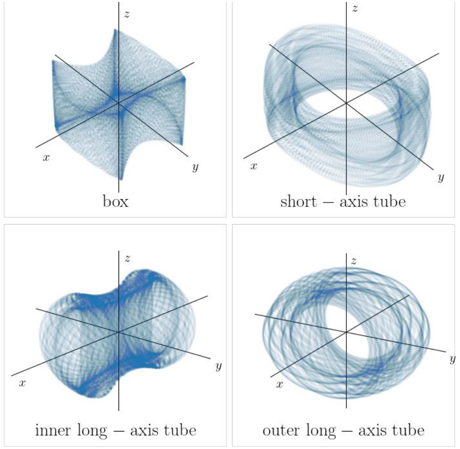


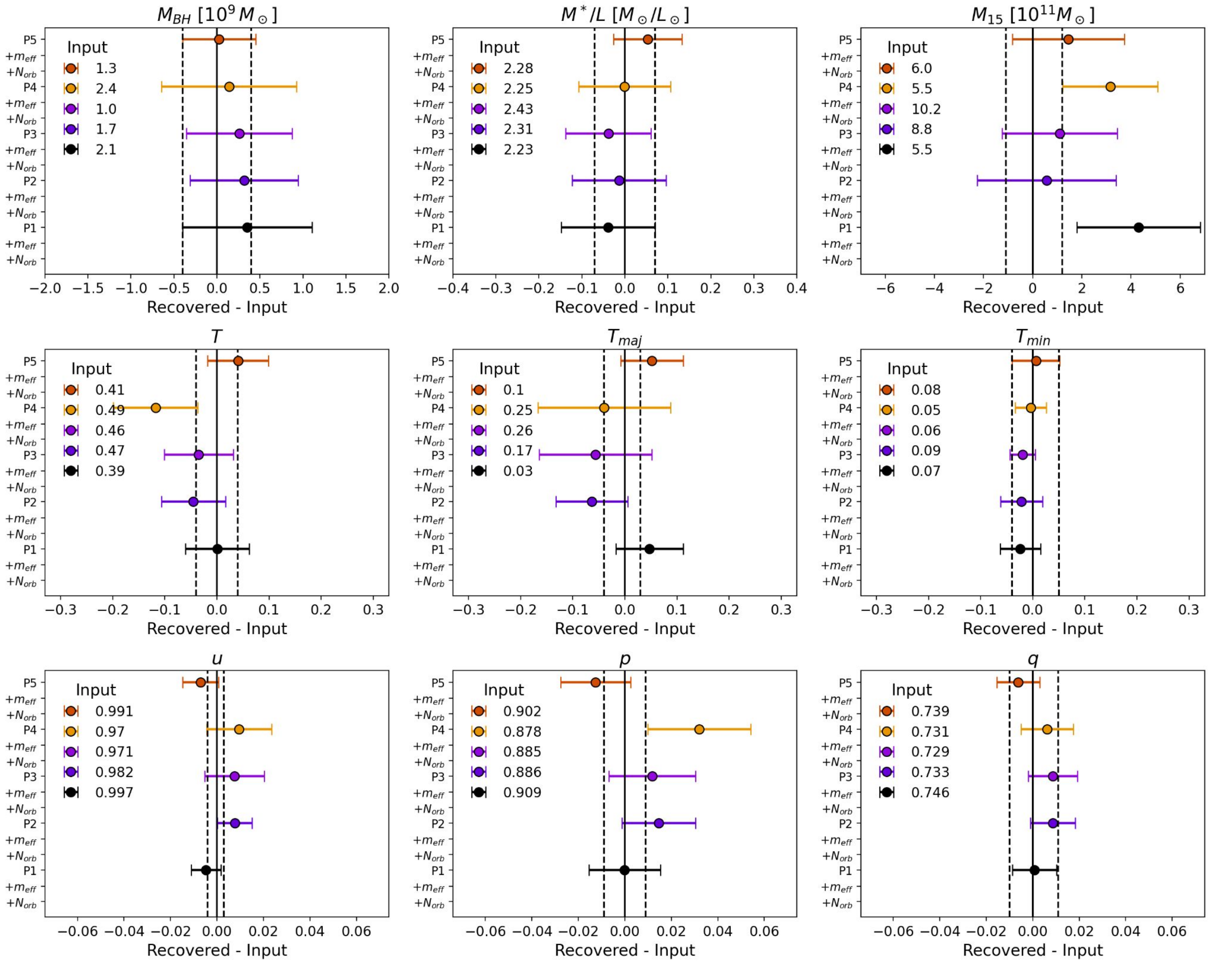


Schwarzschild Model Flexibility:

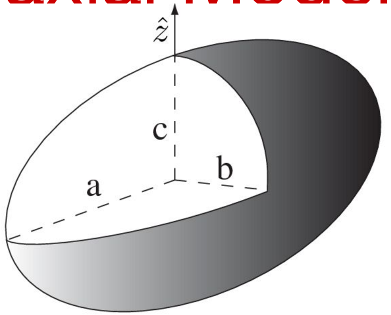
Triaxial Models

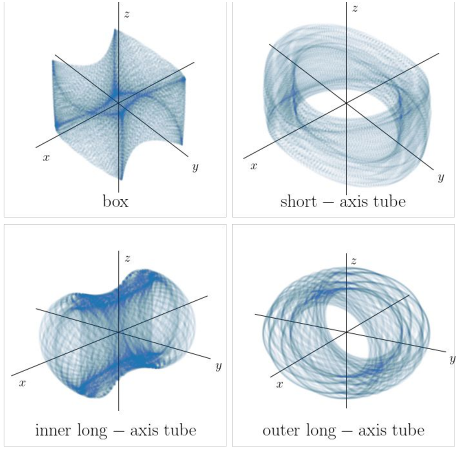


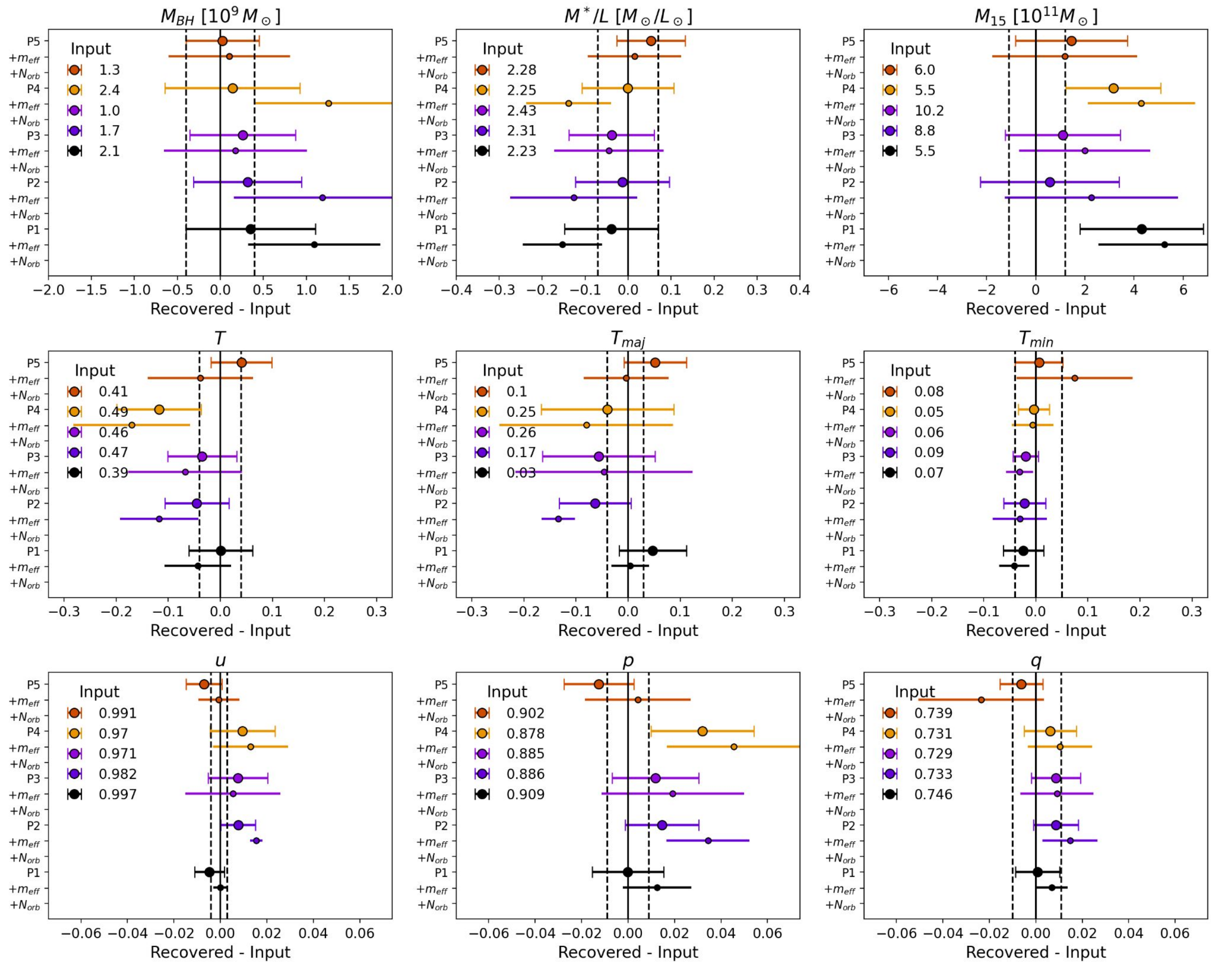




Schwarzschild Model Flexibility:
Triaxial Models

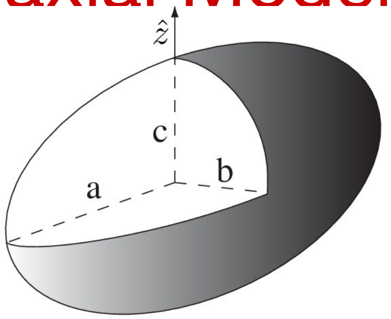


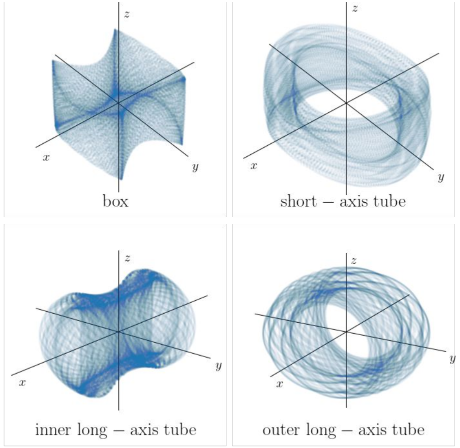


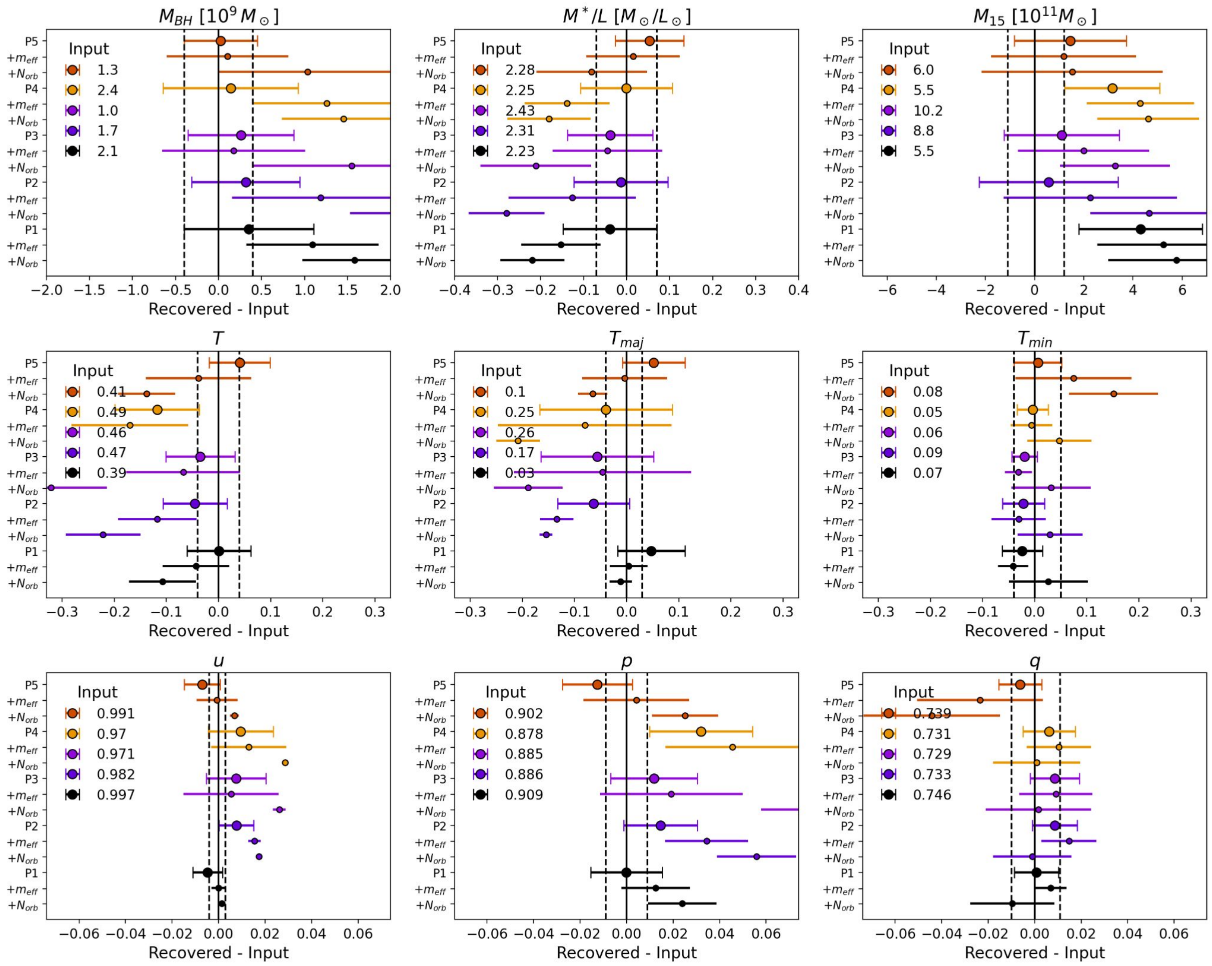


Schwarzschild Model Flexibility:

Triaxial Models







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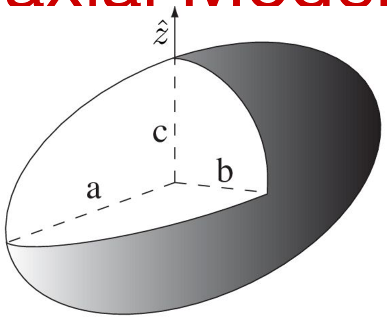
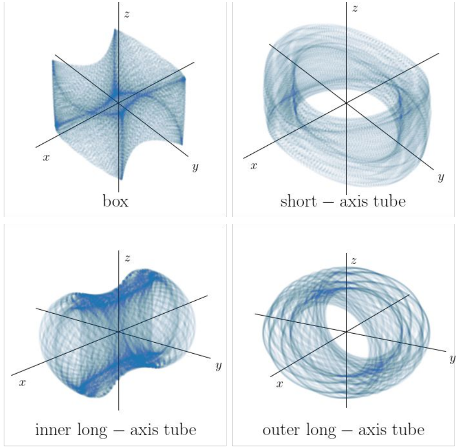
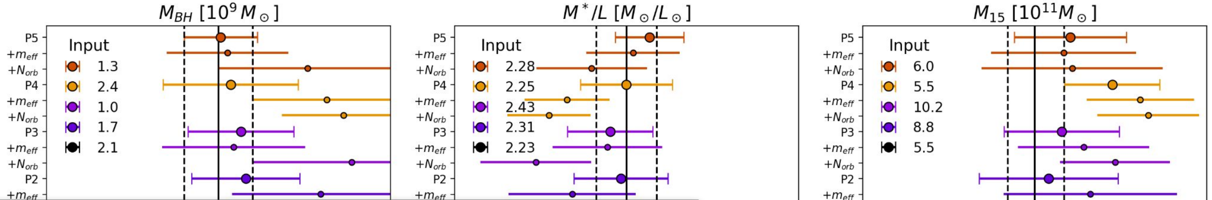
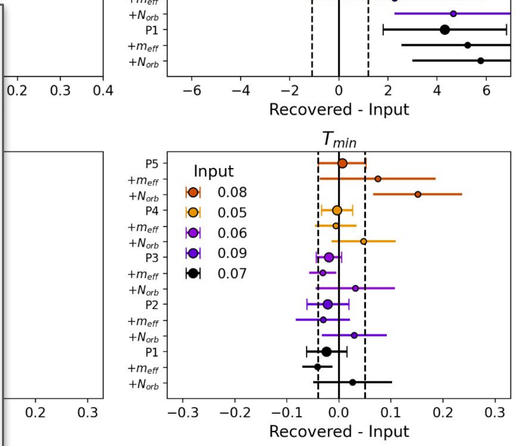
Triaxial Models

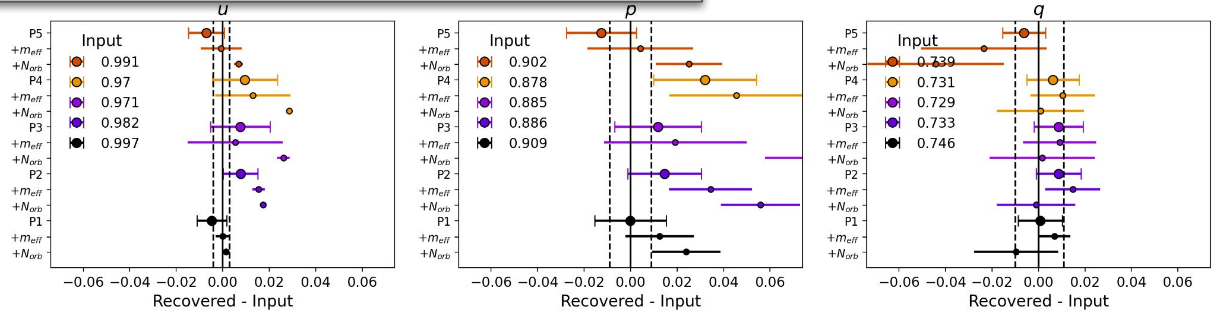






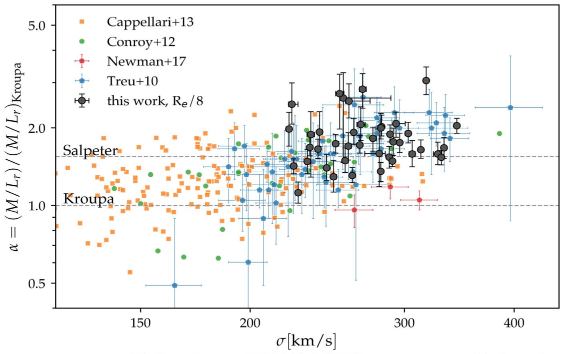
Triaxial models ***do not exhibit*** the same biases as axisymmetric models.



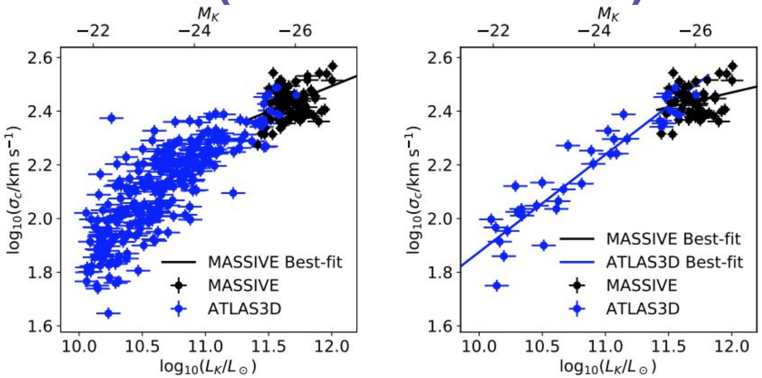


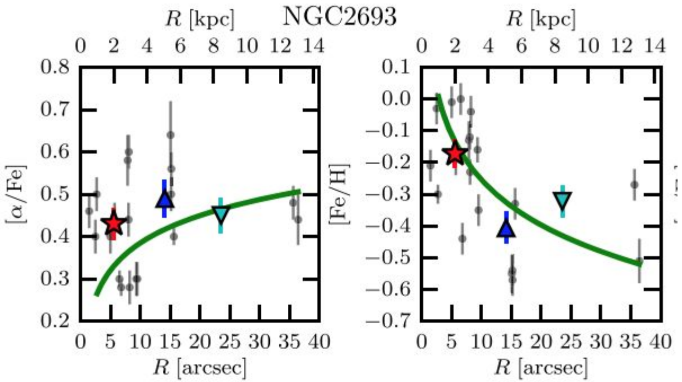
The MASSIVE Survey: Recent Studies

variations in the IMF in massive ellipticals (Gu+2022)

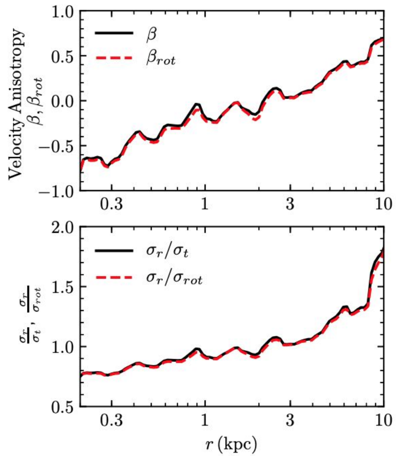


local scaling relations (Quenneville+2022)





chemical abundance gradients/formation history (Greene+2019)



dynamical modeling to constrain SMBH masses, shapes (Liepold+2020)

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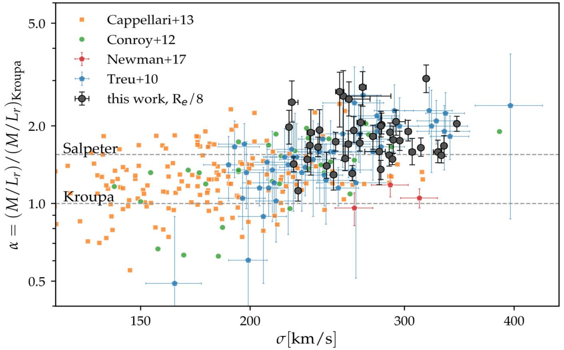

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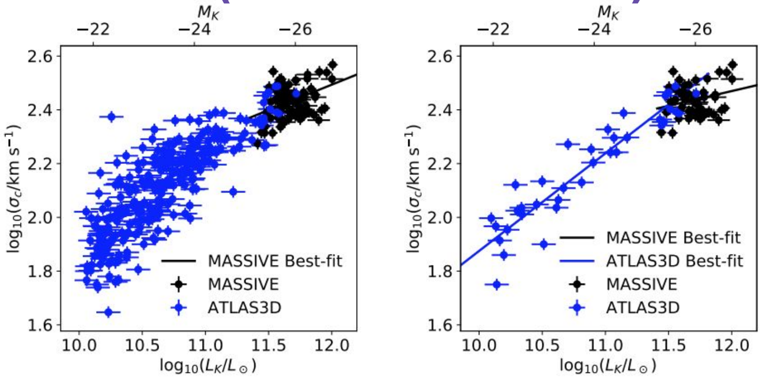

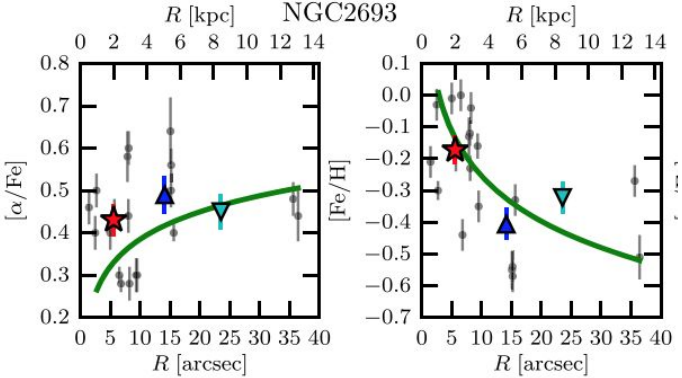

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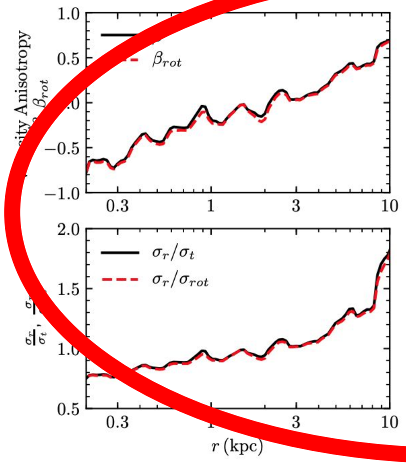
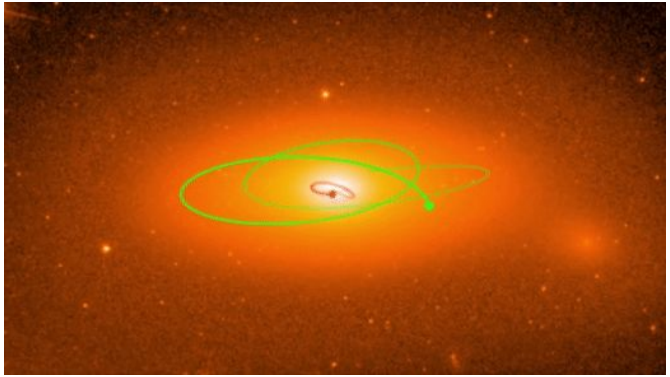


dynamical modeling to constrain SMBH masses, shapes (Liepold+2020)

stellar dynamics pt. 2

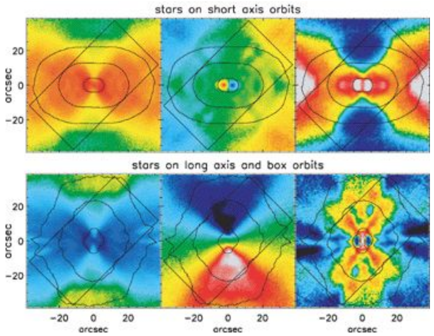
1. Choose a trial potential:

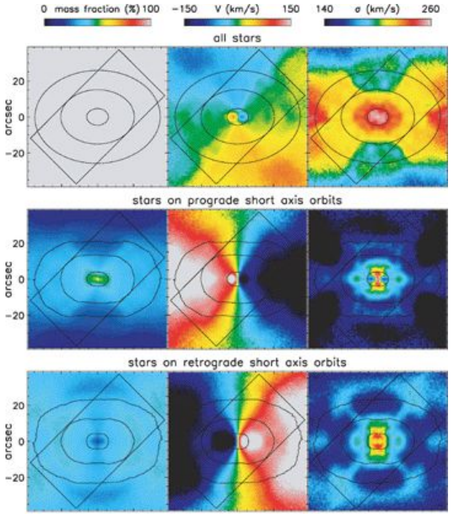
```
Galaxy =(DM)+(STARS)+(BH)+...
```



2. Integrate orbits in a given potential – store “observations” (i.e., positions, velocities of tracers)

3. Assign weights to orbits → Reproduce kinematics





4. Repeat for many potentials (BH, M/L, DM halo, galaxy shape, etc…) and find best fit to data.

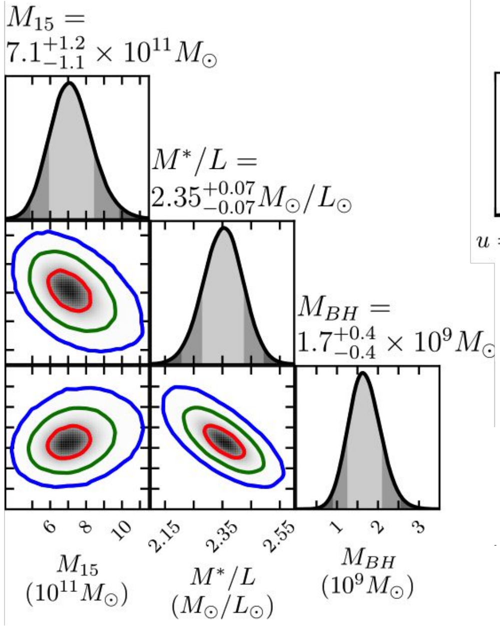
stellar dynamical modeling: applications to NGC 2693

- first simultaneous measurements of DM mass, BH mass, **and intrinsic shapes**

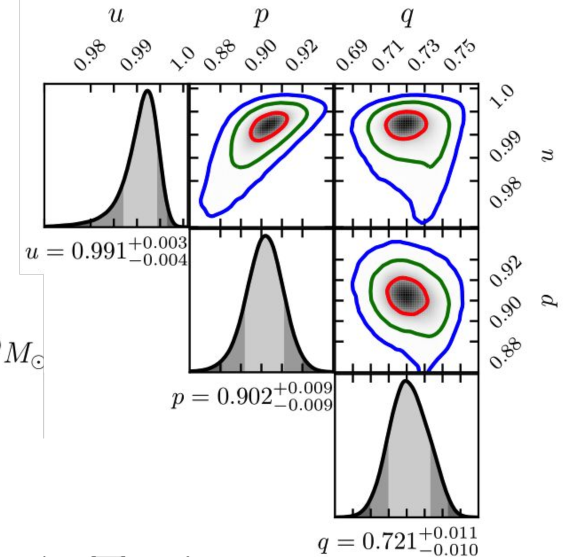
- **N2693 has a moderately triaxial intrinsic shape,**
  - Intermediate-to-major axis ratio: **p = b/a ~ 0.9**
  - Minor-to-major axis ratio: **q= c/a ~ 0.7**

- **NGC 2693 M_{BH} = (1.7±0.4) x 10^9 M_{sun}**

mass parameters



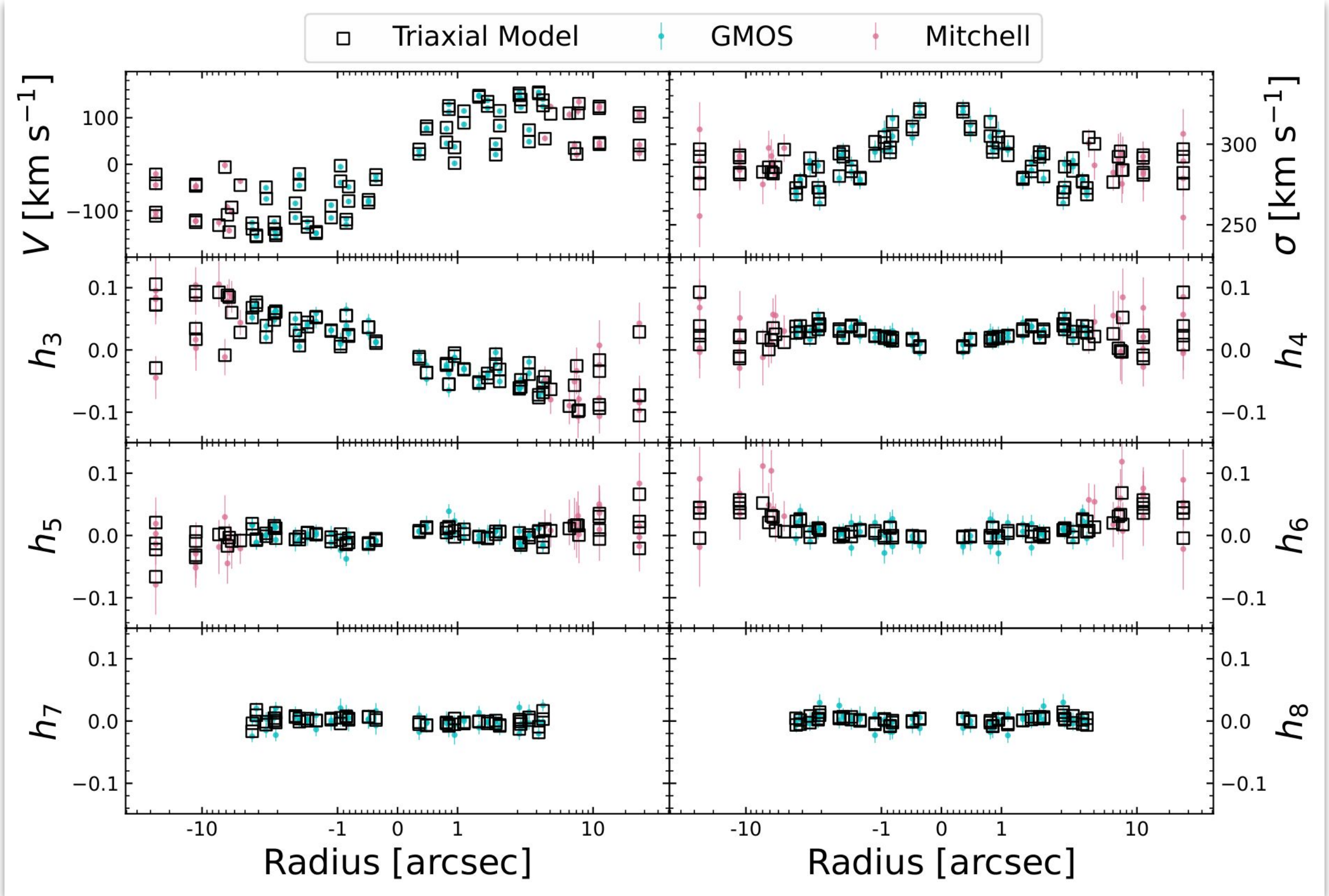
shape parameters



TRIAXIAL		AXISYMMETRIC
NGC 2693 BH: (1.7±0.4) x 10^9 M_{sun}	→	(2.4 ± 0.6) x 10^9 M_{sun}

Pilawa+22

modeling results:
applications to **NGC 2693**

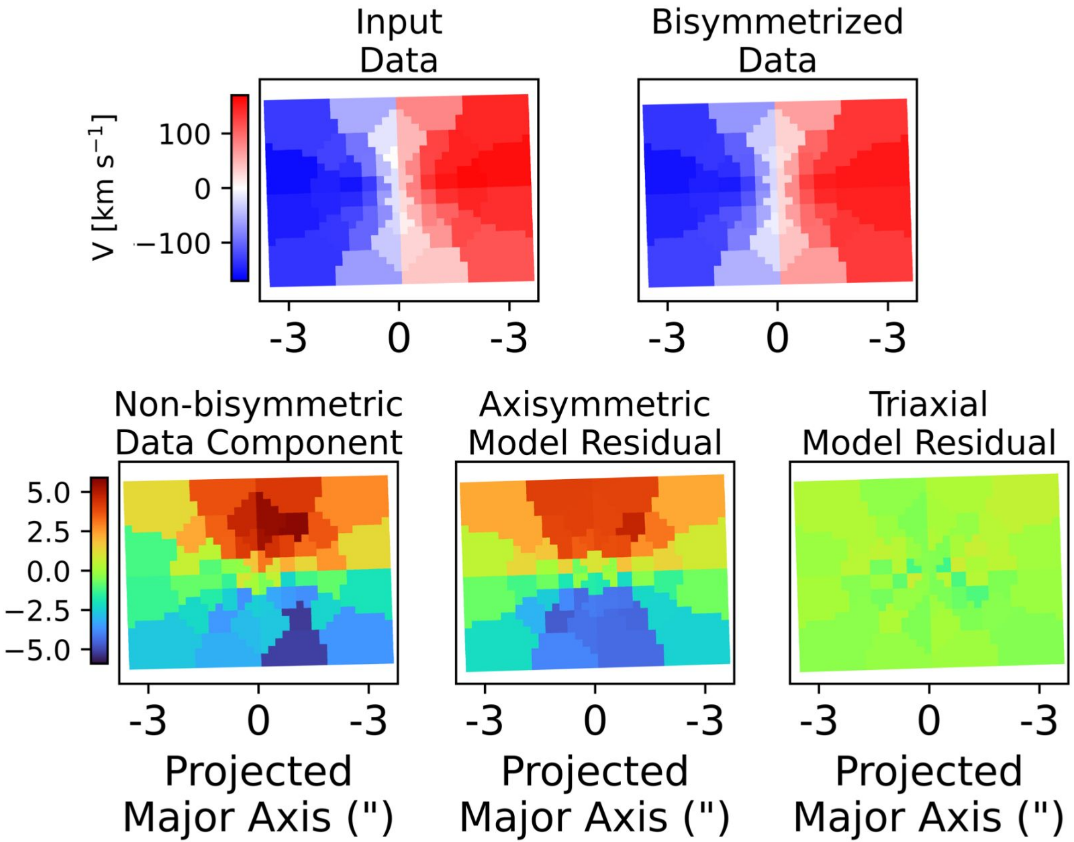


1”~350pc

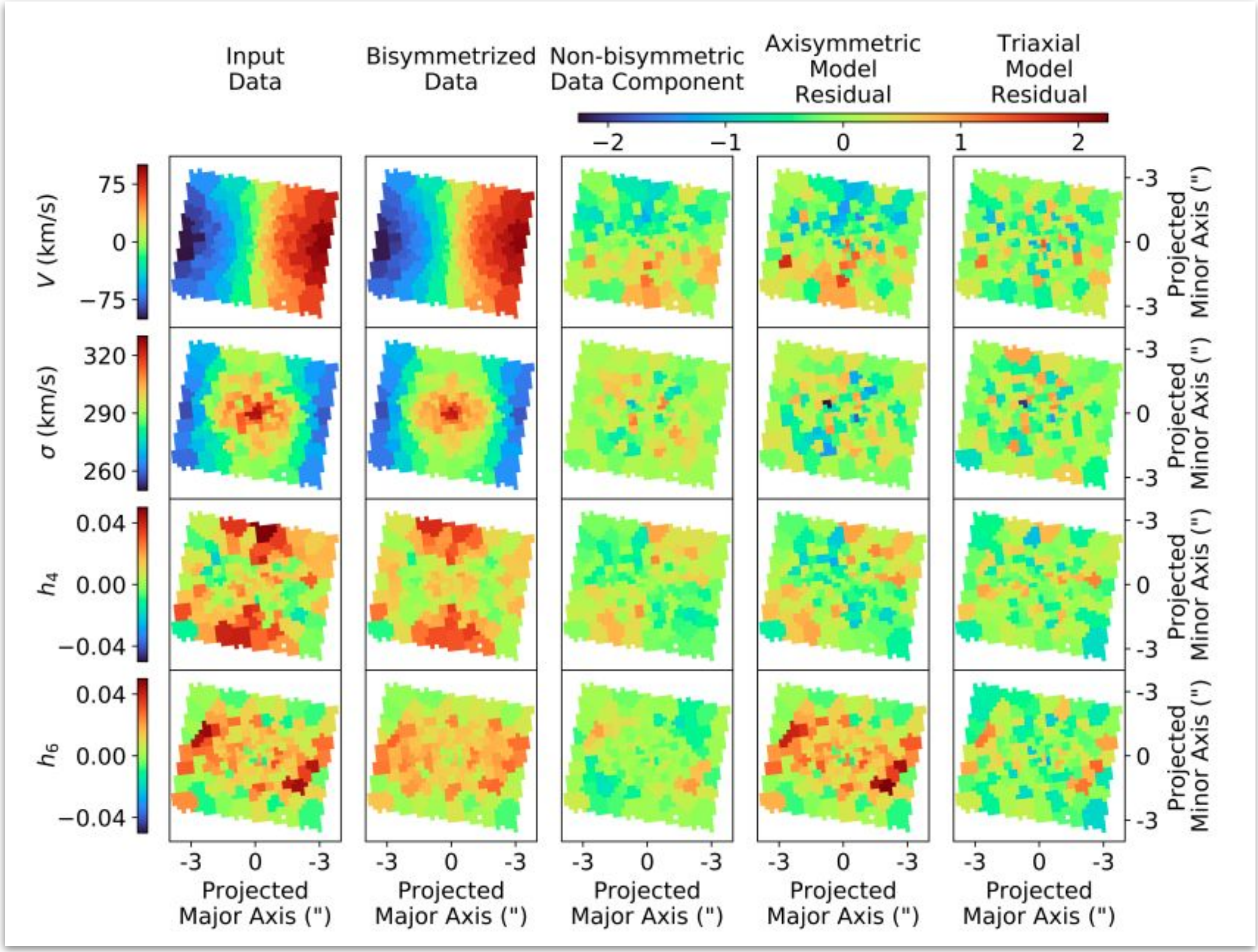
axisymmetric vs. triaxial models

- triaxial model fits data better
- triaxial model also reproduces more complicated velocity structure

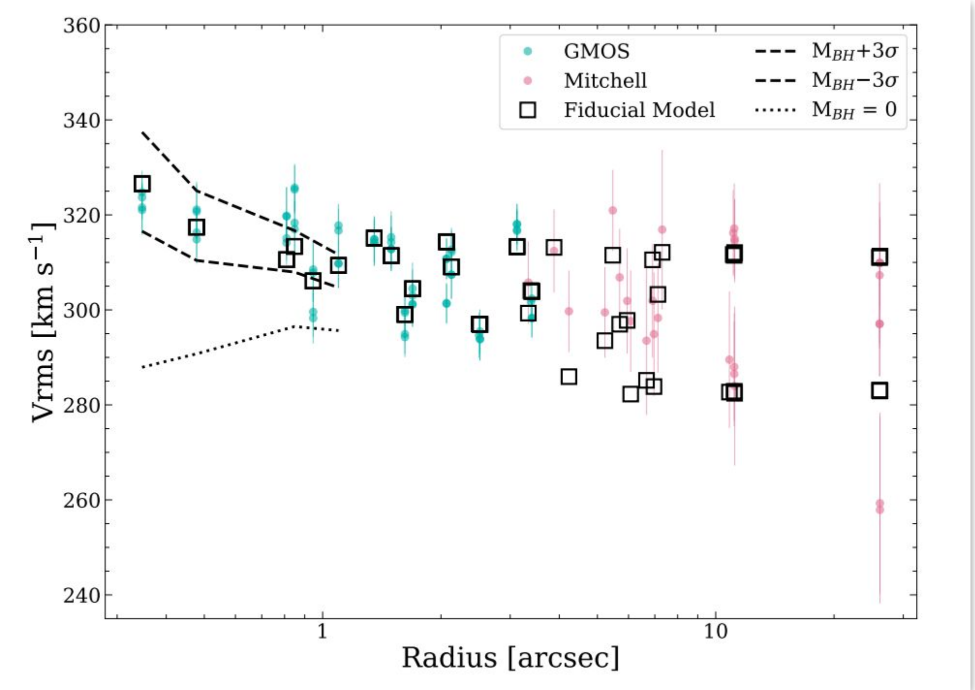
→ axisymmetric models cannot reproduce non-bisymmetric velocity components



axisymmetric vs. triaxial models



Jeans Modeling



Galaxy Parameter	Triaxial Orbit Model	Axisymmetric Orbit Model	JAM Model
$M_{\rm BH}$ $[10^9 M_\odot]$	1.7 ± 0.4	2.4 ± 0.6	2.9 ± 0.3
M^*/L $[M_\odot/L_\odot]$	2.35 ± 0.07	2.27 ± 0.1	2.17 ± 0.03
M_{15} $[10^{11} M_\odot]$	$7.1^{+1.2}_{-1.1}$	7.9 ± 1.3	4.7 ± 0.2
β_z	See caption.†	See caption.†	0.07 ± 0.01
T	0.39 ± 0.04		
$T_{\rm maj}$	$0.09^{+0.04}_{-0.03}$		
$T_{\rm min}$	$0.17^{+0.04}_{-0.05}$		
u	$0.991^{+0.003}_{-0.004}$		
p	0.902 ± 0.009		
q	$0.721^{+0.011}_{-0.010}$		
θ (°)	66^{+4}_{-3}		
ϕ (°)	72 ± 3		
ψ (°)	$93.0^{+0.7}_{-0.6}$		

Table 2. Summary of best-fit galaxy models for NGC 2693. For each parameter, we marginalize over the other dimensions and report the 1σ uncertainties. The axisymmetric orbit models and JAM models have fixed inclination of 70°. In orbit models, θ is the inclination angle in the oblate axisymmetric limit ($\psi = 90°$, or equivalenly $p = 1$), with $\theta = 90°$ being edge-on and $\theta = 0°$ being face-on. †We measure β_z in the orbit model as a function of radius, shown in the bottom panel of Figure 6. The best-fit JAM value of $\beta_z = 0.07 \pm 0.01$ is consistent with the range of β_z values measured from this best-fit model, with values ranging from $\beta_z = -0.27$ at small radii to $\beta_z = 0.28$ at large radii in both the triaxial and axisymmetric Schwarzschild models.

Cappellari+2014

Schwarzschild Modeling Power

our typical scenario:

- (~a few hun
kinematic a
* (~8 Gauss
moments pe
aperture)

**~ 10^3 kinem
constraints**

**typical schwar
model:**

- **≥ 10^4 orbits** with a
free weight
parameter

$\rightarrow 0$

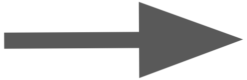
s) - (# params)

this were a
simple linear
model

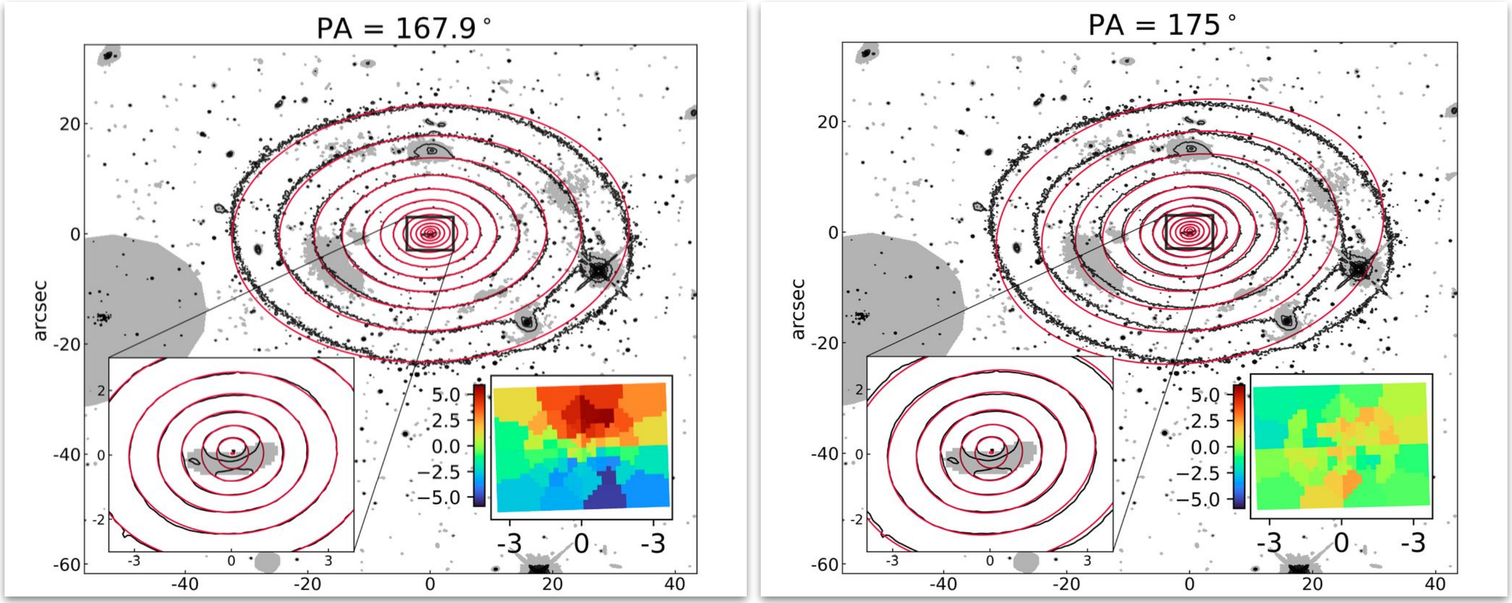
(a) how well can we recover a series of known inputs from our **triaxial** models?

(b) are there analogous biases in our triaxial modeling scheme?

axisymmetric vs. triaxial models

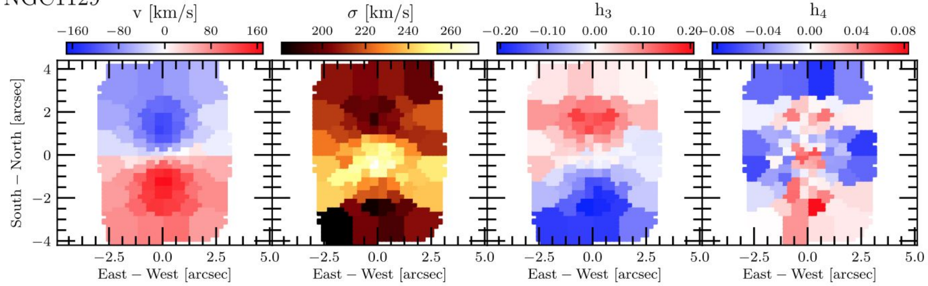


"rotating away" the non-bisymmetric component gives an inconsistent surface brightness profile

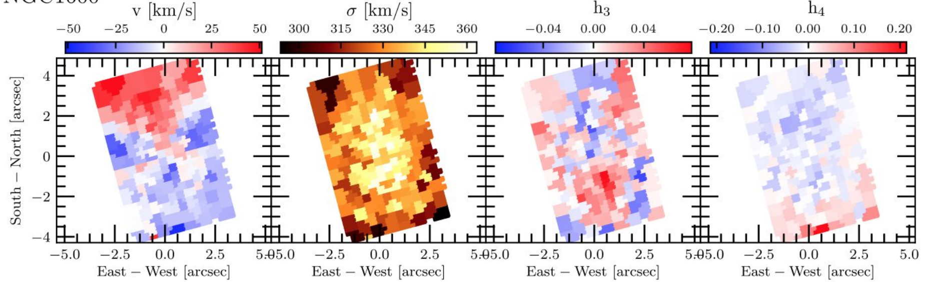


The MASSIVE Survey

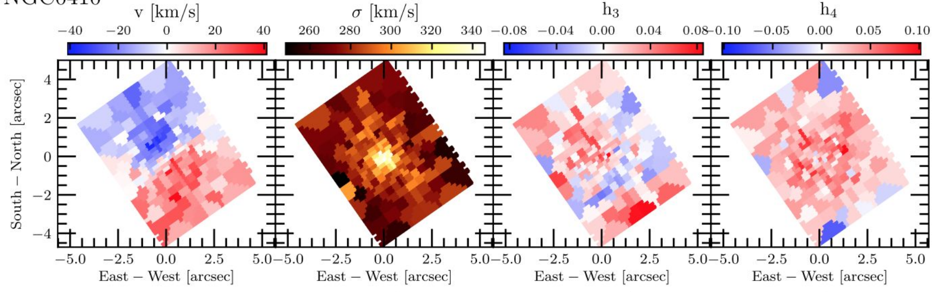
NGC1129



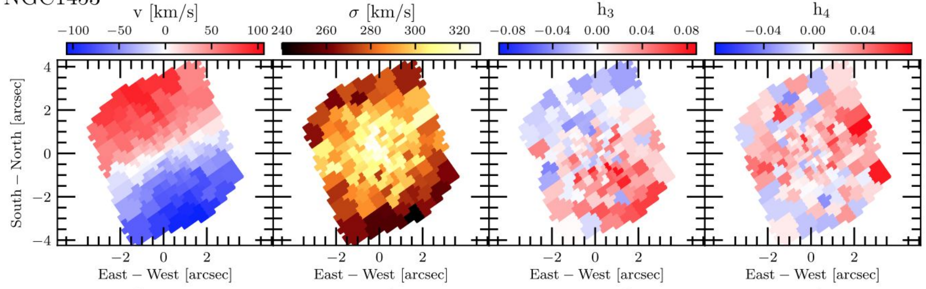
NGC1600



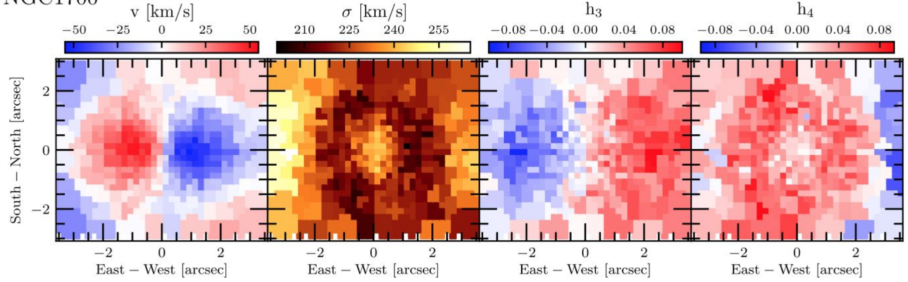
NGC0410



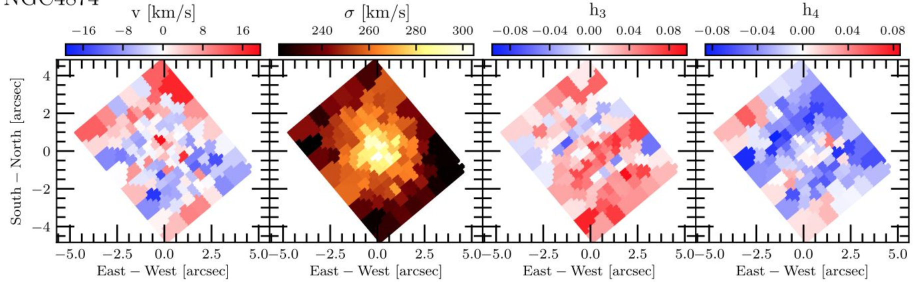
NGC1453



NGC1700

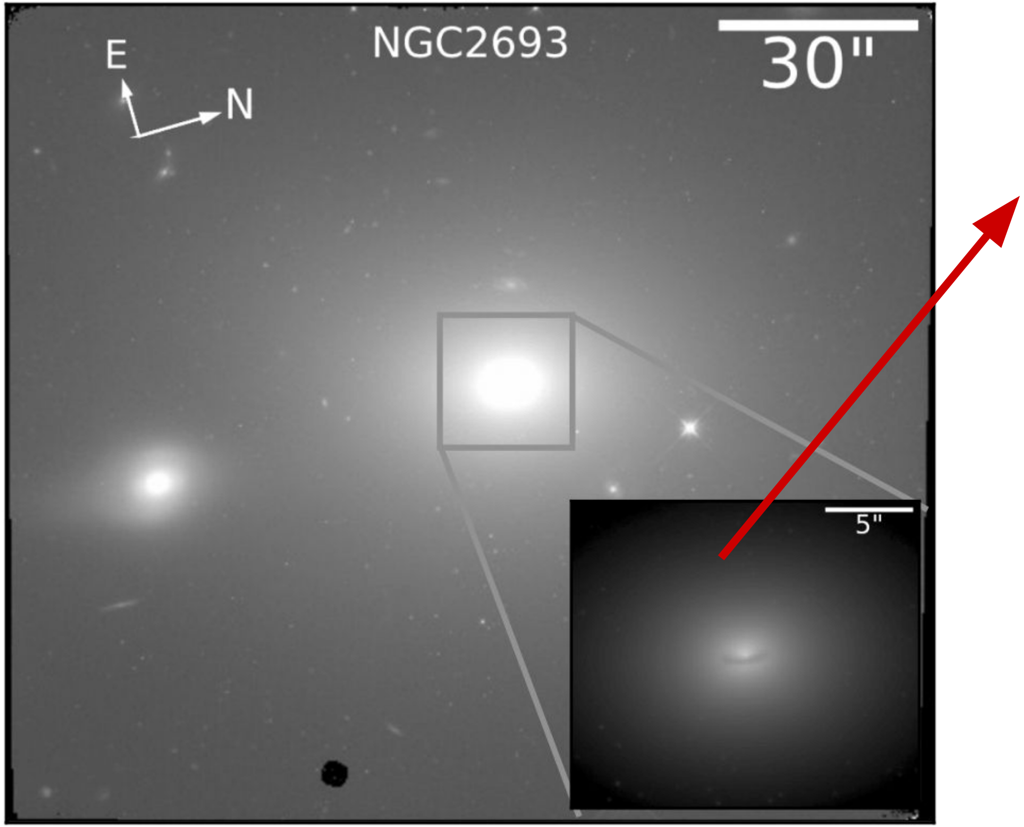


NGC4874



a nice surprise:

Pilawa+22



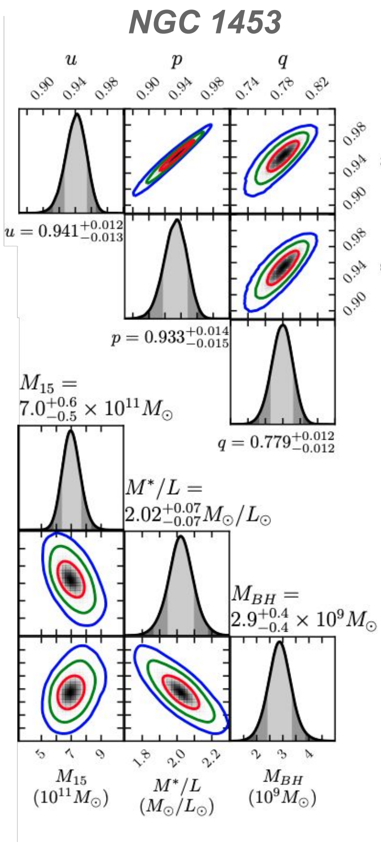
dust disk inclination:

θ~70 degrees

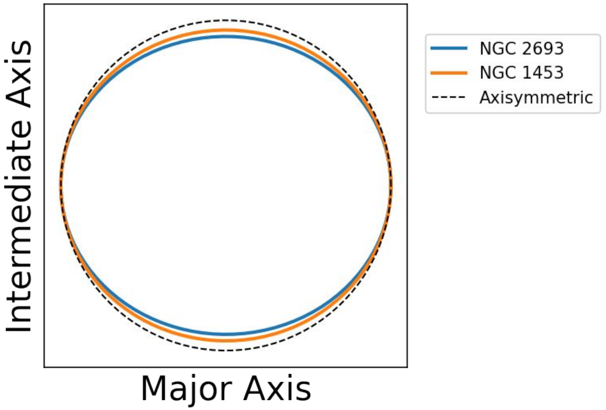
“inclination” from the triaxial model:

$\theta = 66^{+4}_{-3}$ degrees

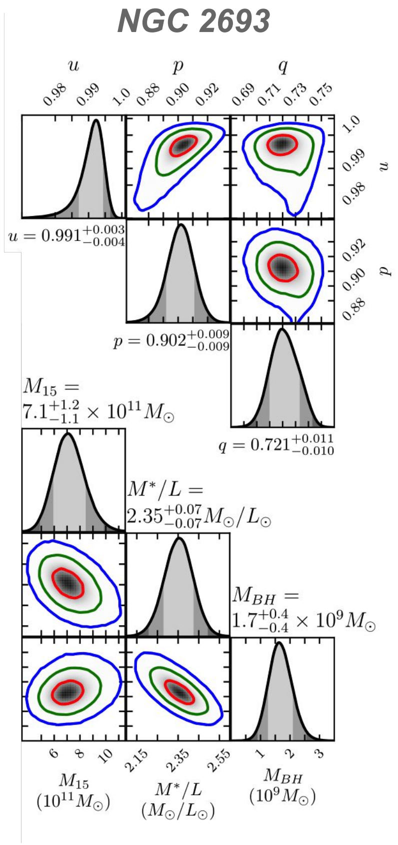
stellar dynamical modeling:
applications to **NGC 1453** and **2693**



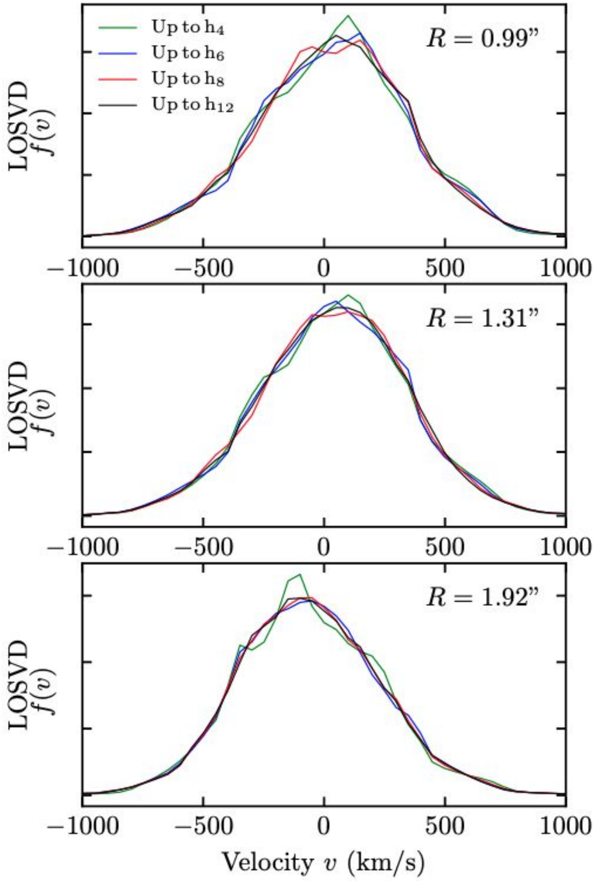
- first simultaneous measurements of DM halo, BH mass, **and intrinsic shapes**
- **neither galaxy is axisymmetric**, despite properties suggesting so



- NGC 1453 BH: 2.9 x 10^9 M_{sun}
- NGC 2693 BH: 1.7 x 10^9 M_{sun}



LOSVDs



Up to h_4
Up to h_6
Up to h_8
Up to h_{12}
$R = 0.99''$
$R = 1.31''$
$R = 1.92''$
LOSVD $f(v)$
−1000
−500
0
500
1000
Velocity v (km/s)

why *else* are SMBHs important?

Slide Inspiration: N. Sahu, Univ. Swinburne

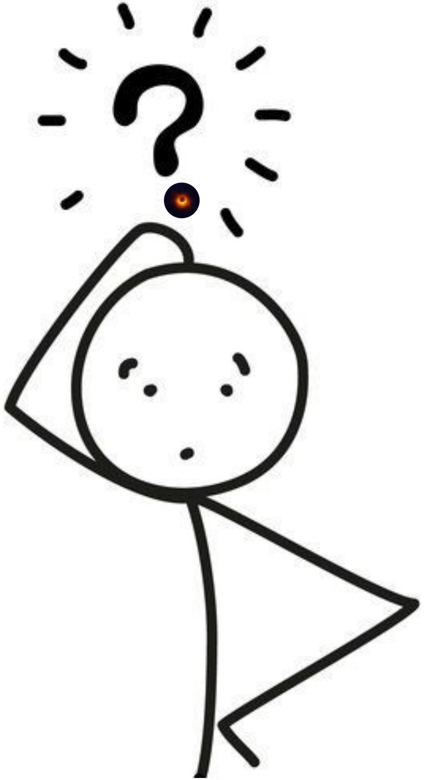
1. Estimate BH mass from galaxy properties where we can't resolve SOI

2. Cross-checking of gas dynamics, mega-maser disks, and reverberation mapping BH masses
[i.e., Yu+2019 (reverberation mapping), Thater+21 (gas dynamics)]

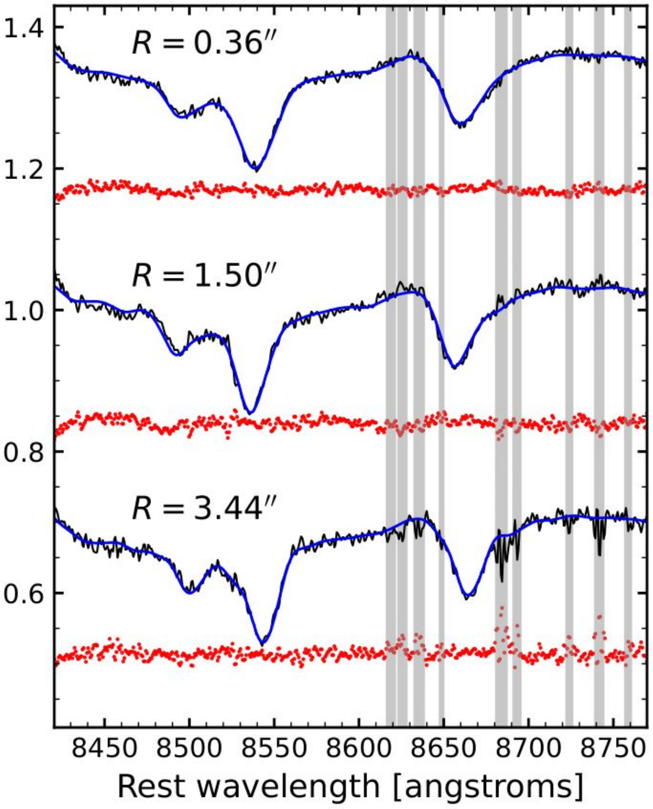
3. z~0 mass function/number density → predictions for long-λ gravitational wave signal from Pulsar Timing Arrays/LISA
[i.e., Shannon+2015, Arzoumanian+2019]

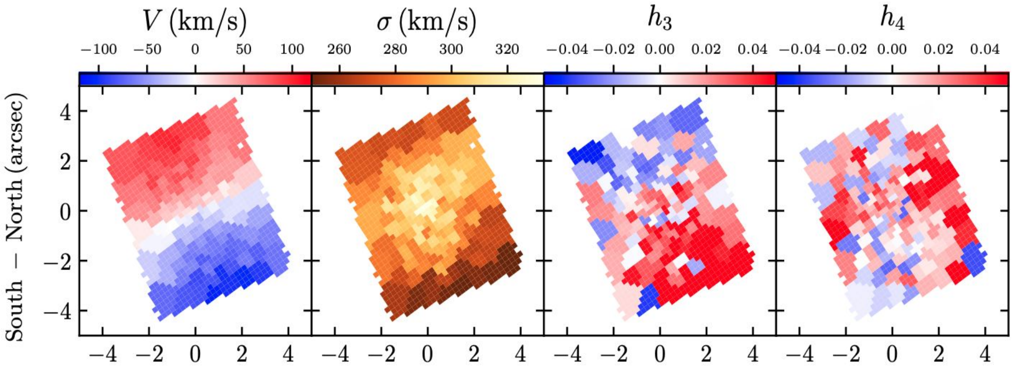
4. Comparison to simulations of AGN feedback modes and mechanisms
[i.e., Li+2019, Habouzit+2020]

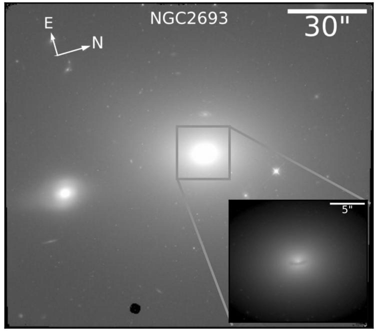
…

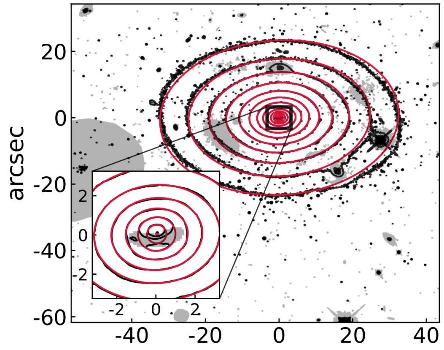


stellar dynamical modeling: applications to **NGC 1453** and **2693**









+ ~10,000 individual galaxy models

Nested Sampling in A Single Slide

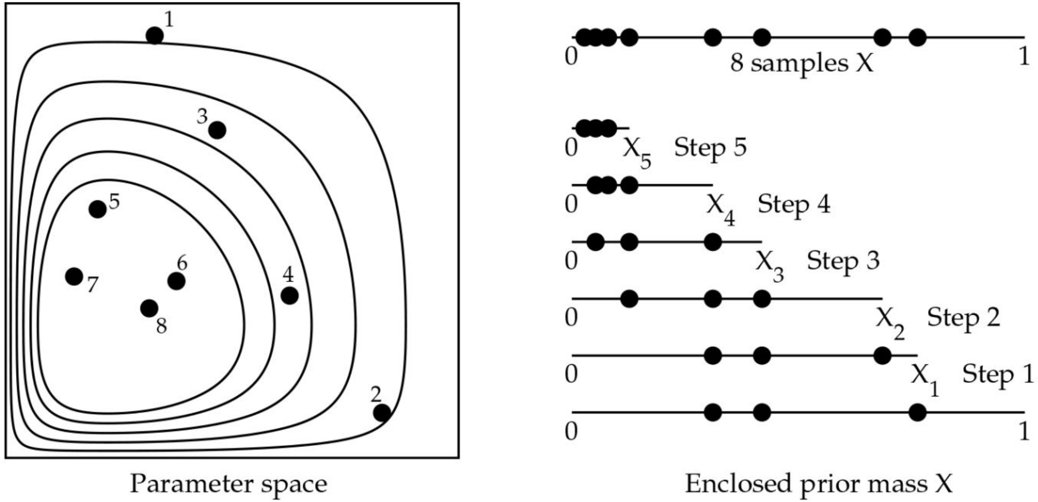


Figure 4: Nested sampling for five steps with a collection of three points. Likelihood contours shrink by factors exp(−1/3) in area and are roughly followed by successive sample points.

*J. Skilling 2006

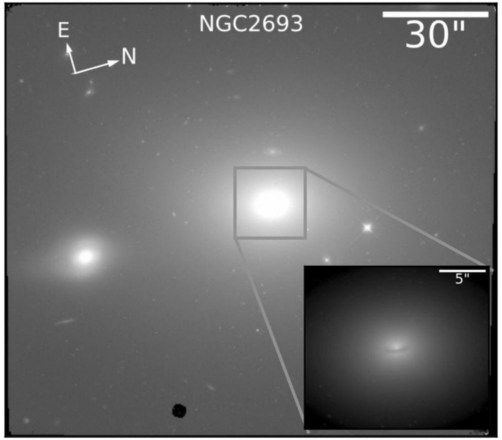
idea : iteratively sample points, getting rid of lowest likelihood at each step → volume shrinks to maxima of distributions

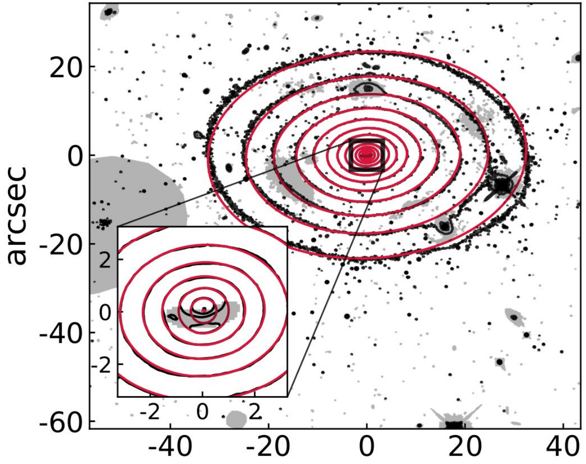
stellar dynamical models

CENTRAL IDEA:

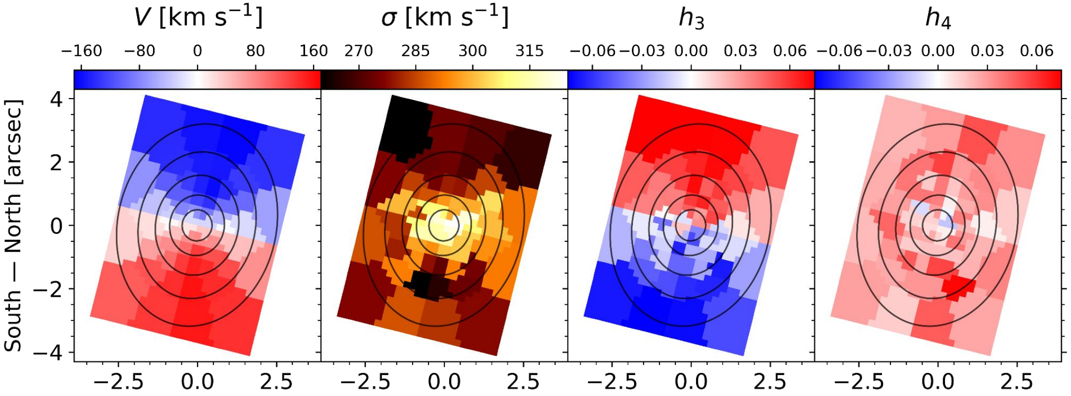
given **kinematics** + **surface brightness** of NGC 2693, can we determine the **galaxy's mass components** by integrating the orbits of stars in a gravitational potential?

surface brightness





line of sight velocity distribution

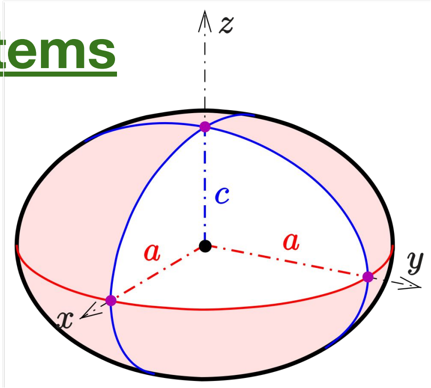


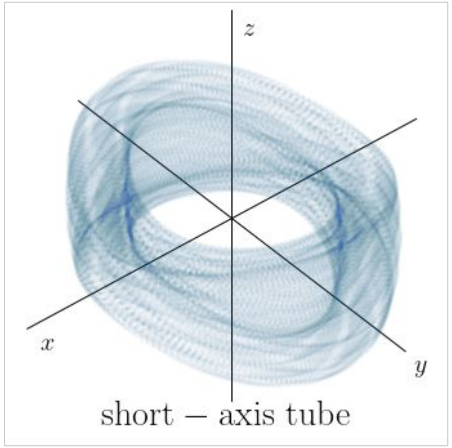
Pilawa+22

triaxial dynamical modeling

axisymmetric systems

- 4 parameters:
  - BH
  - M/L
  - DM Halo
  - Inclination



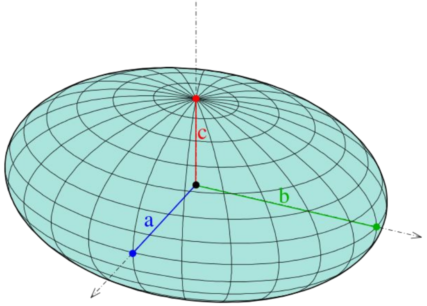


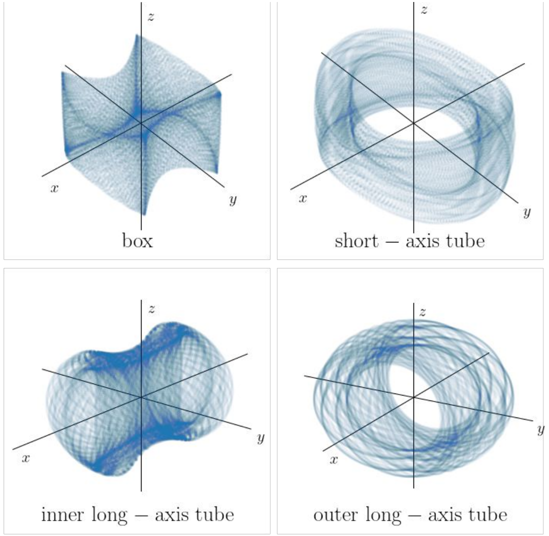
short — axis tube

important:
axisymmetric systems are, by construction, ***bisymmetric***

triaxial systems

- 6 parameters:
  - BH
  - M/L
  - DM Halo
  - 3 Shape Parameters



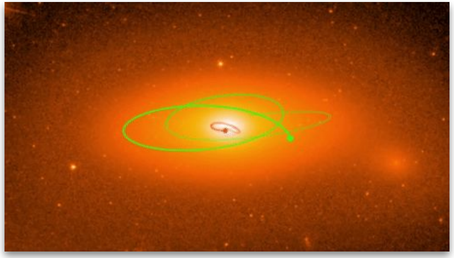


triaxial dynamical modeling

1. Choose a trial potential:

`Galaxy = (DM) + (STARS) + (BH) + ...`

2. Generate stellar orbits in trial potential

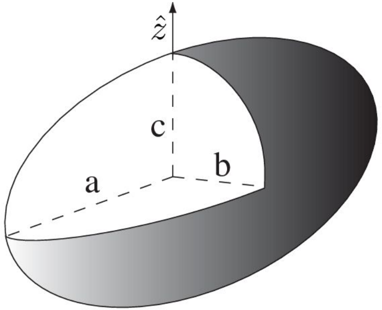


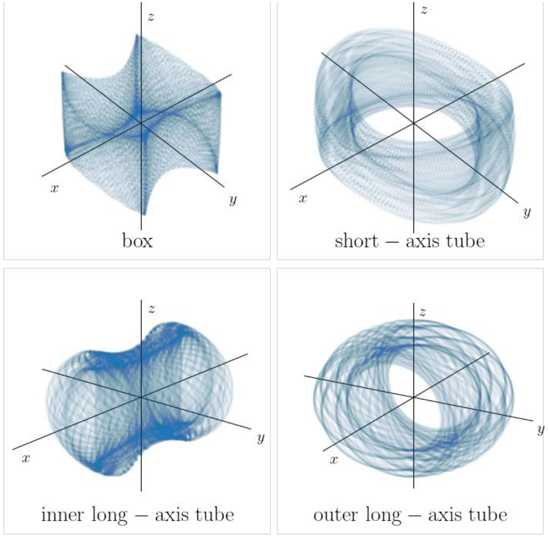
3. Determine which orbits most accurately reproduce **kinematics** + **photometry** for a *single* trial potential

4. Find which assumed potential fits **kinematics** + **photometry** best **across trial potentials (BH, ML, Shapes)**

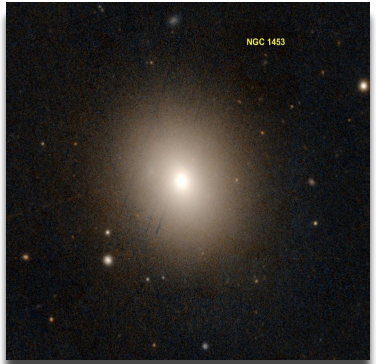
triaxial systems

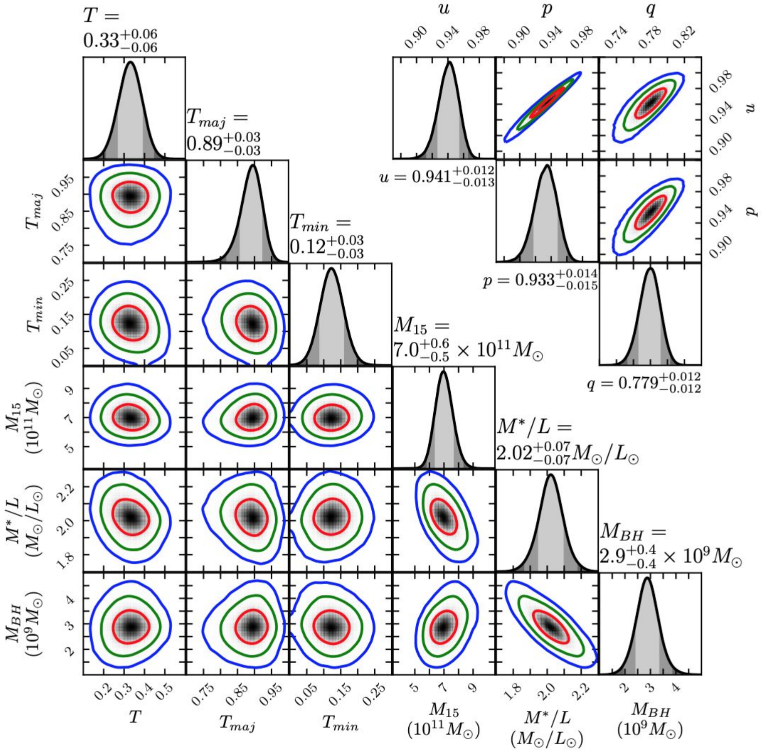
- 6 knobs to turn:
  - BH
  - M/L
  - DM Halo
  - 3 Shape Parameters





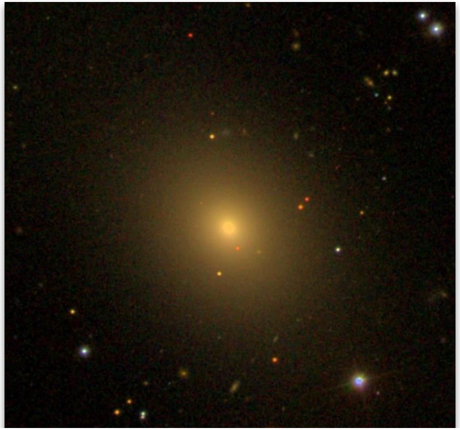
stellar dynamical modeling:
other applied cases

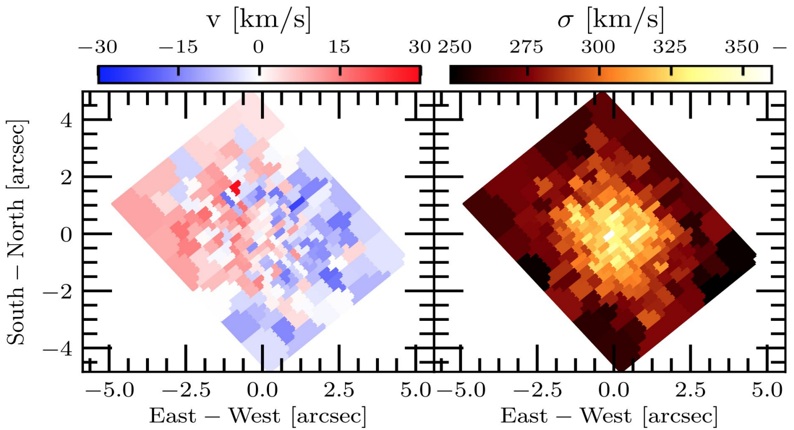


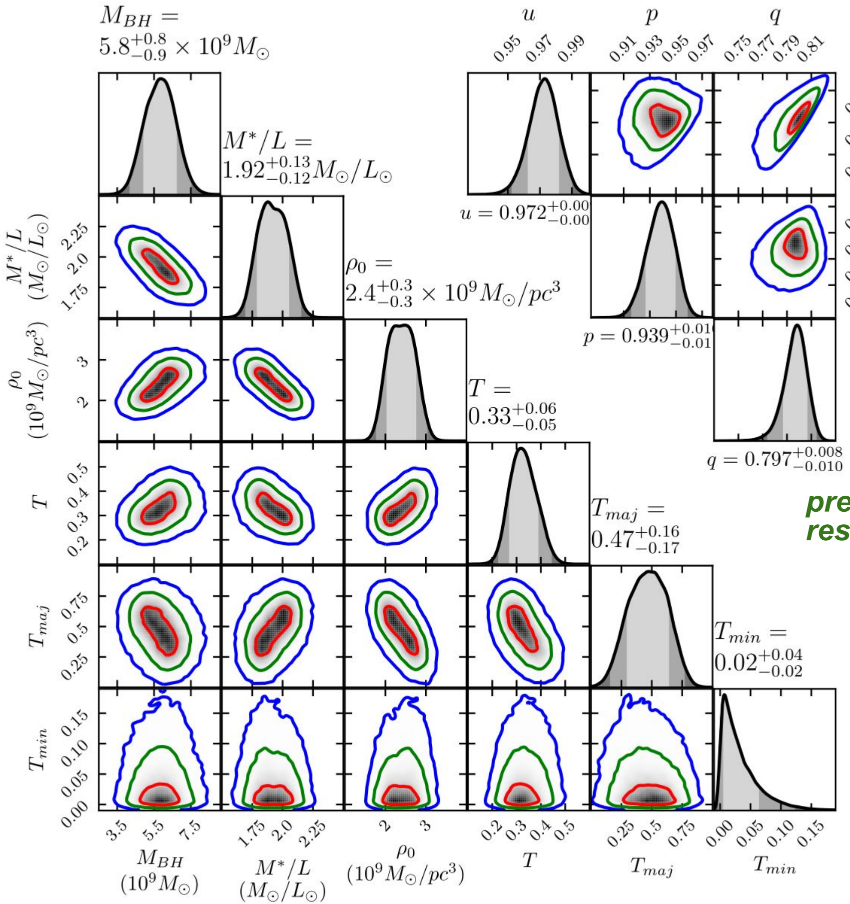


stellar dynamical modeling: ongoing work

NGC 57







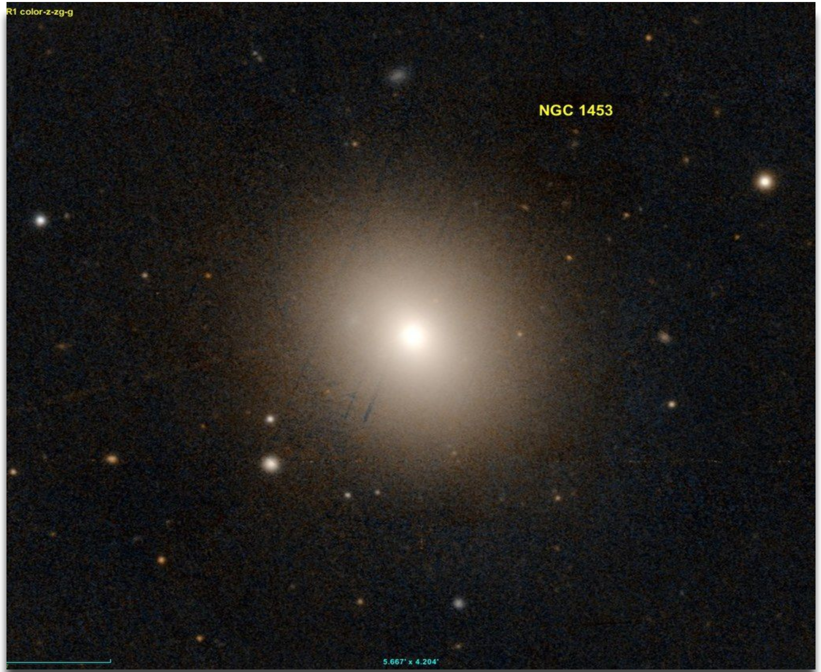
preliminary result!

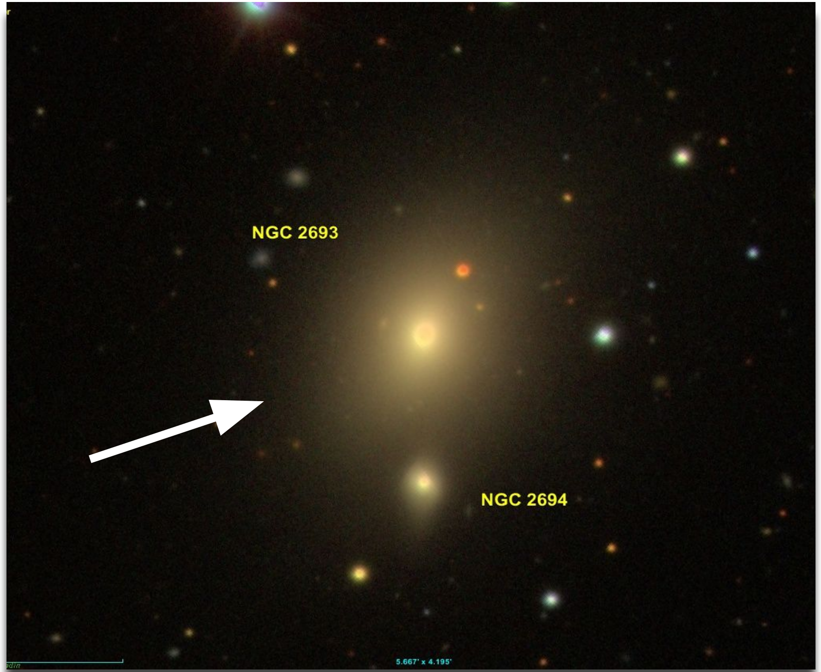
Triaxial Result: M_{BH} **~ 6 x 10^9 M_{sun},**

- **Another simultaneous measurement of mass components + intrinsic shape of a massive elliptical**

stellar kinematics of NGC 1453 and 2693

Liepold+20
Quenneville+21
Pilawa+22

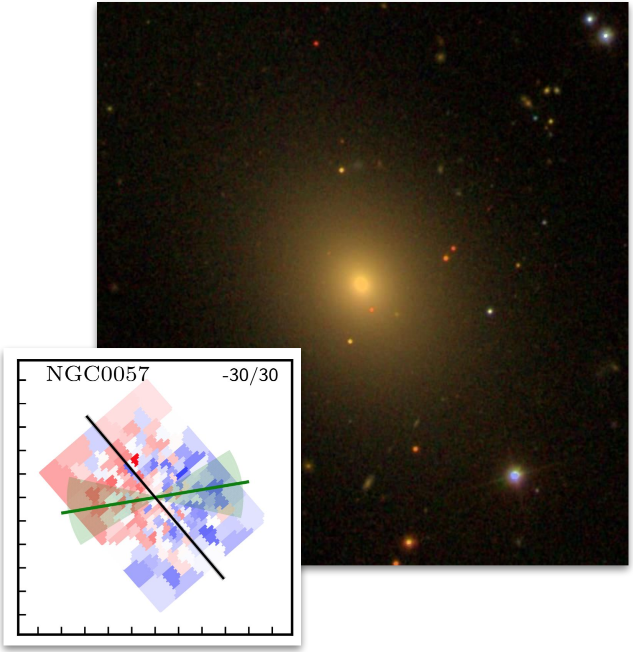


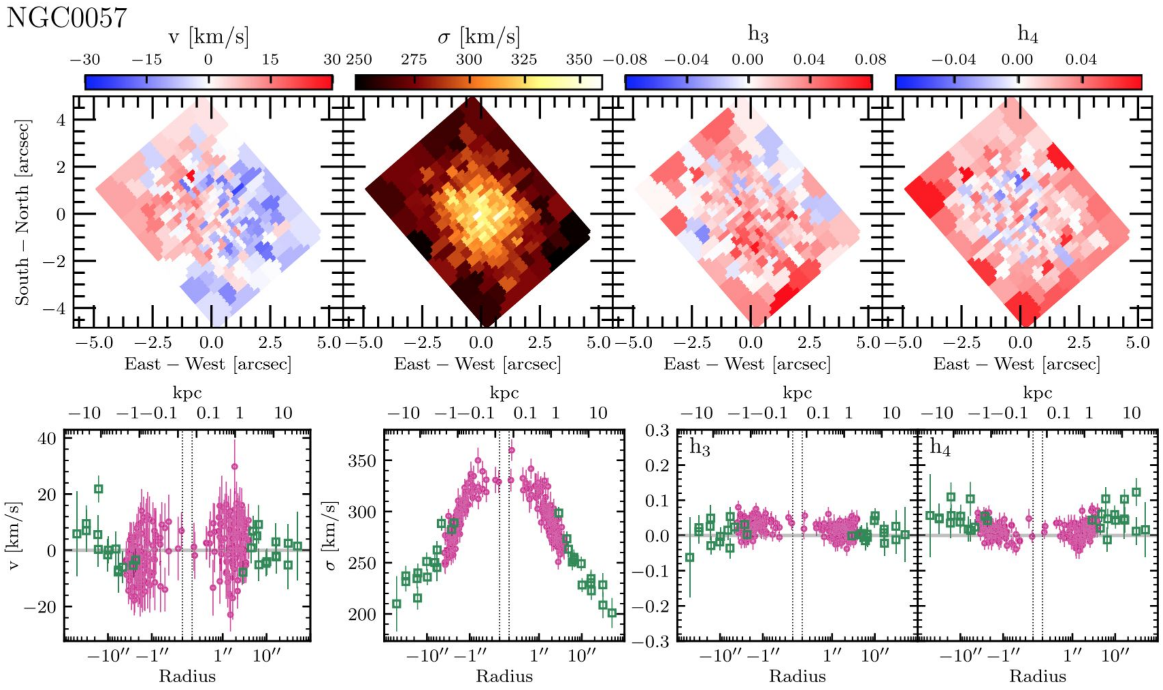


SDSS DR9 Images

stellar dynamical modeling:
ongoing work

NGC 57

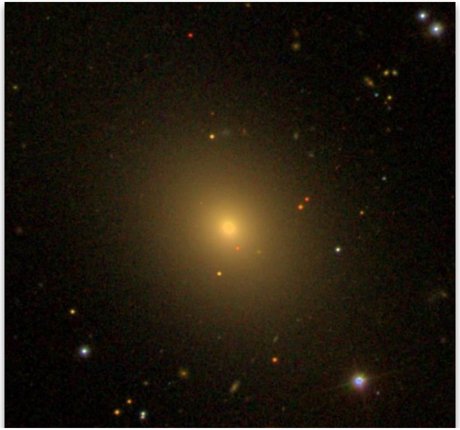


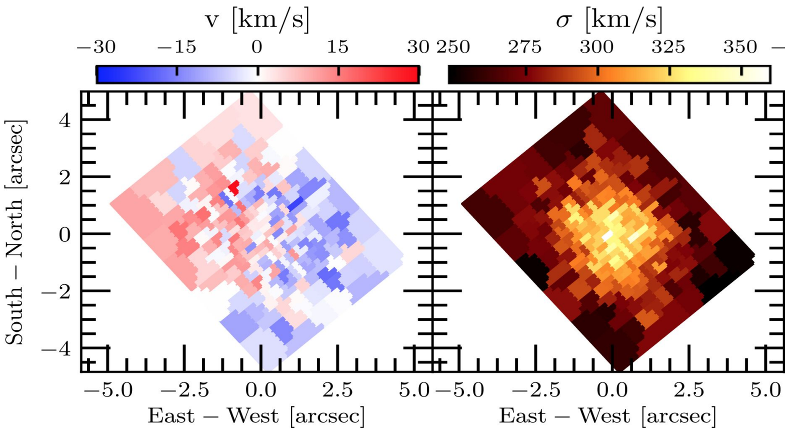


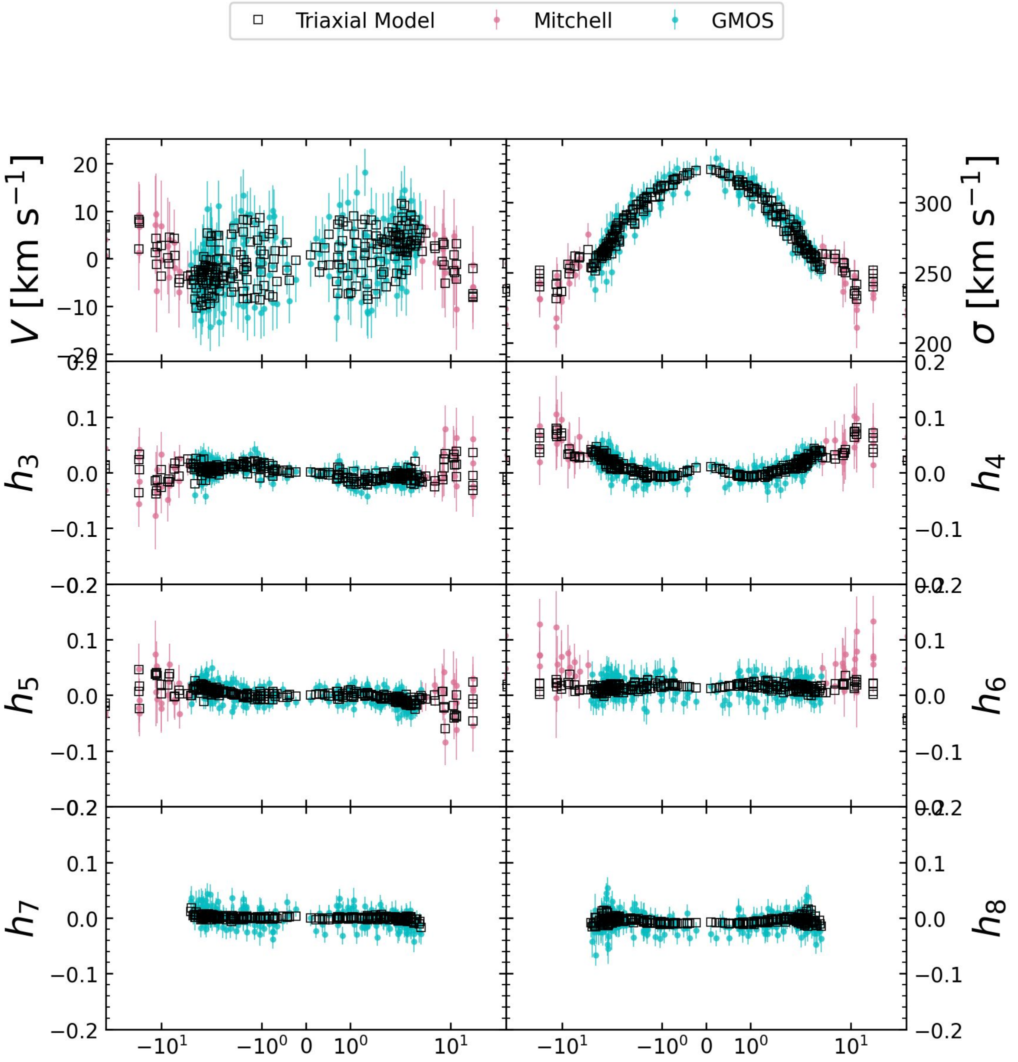
- *Slow rotation (~25 km/s),* ***kinematically*** *and* ***photometrically*** *aligned*

stellar dynamical modeling: ongoing work

NGC 57





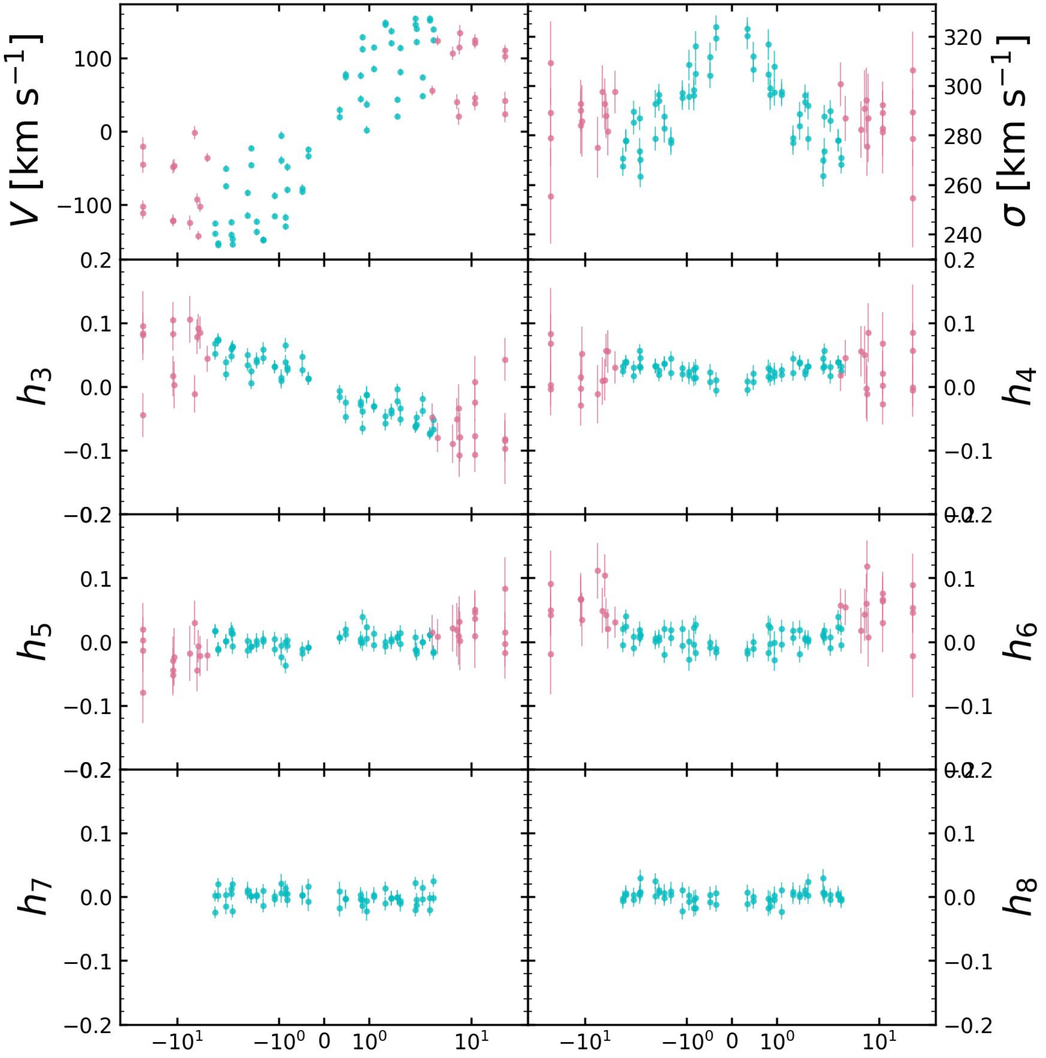


Transition to Mock Results

- Mention contrasting axisymmetric Mbh/difference with triaxial might be because of modeling differences, with inclination as the example case of parameter bias – could this be the underlying difference between recovered mass parameters?
    - Need to be a bit more elaborative on axisymmetric modeling if this is the case. Currently only describe triaxial modeling
- Motivate this with an example of fits with different numbers of d.o.f to show the difference (something simple), and a primer on m_eff
- Our machinery seems to reliably recover the inputs, and that our parameter recovery are not strongly dependent on the degrees of freedom in our models
- Additionally have started to investigate more interpretable measurements of model flexibility for schwarzschild models,

Schwarzschild Model Flexibility: Axisymmetric Models

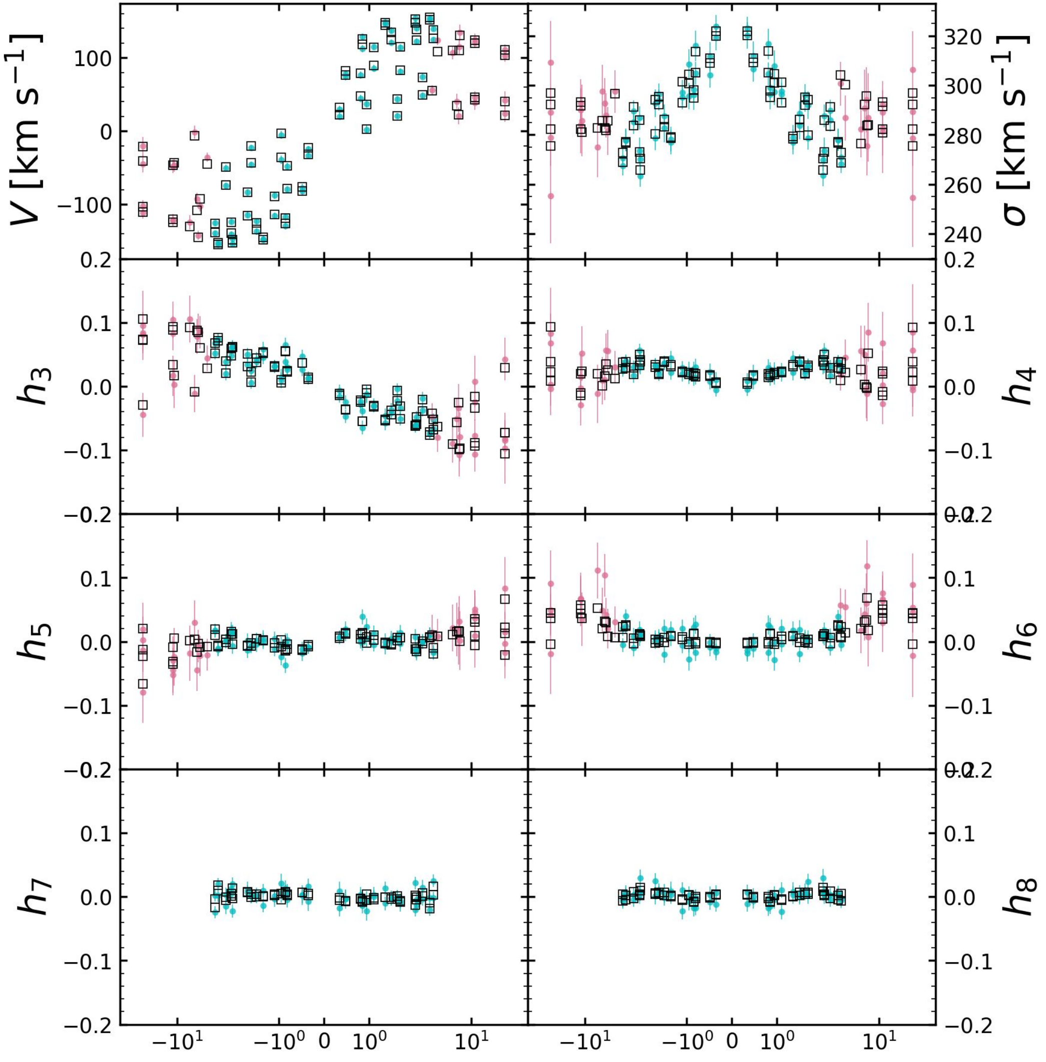
consider the following scenario:



Schwarzschild Model Flexibility:
Axisymmetric Models

consider the following scenario:

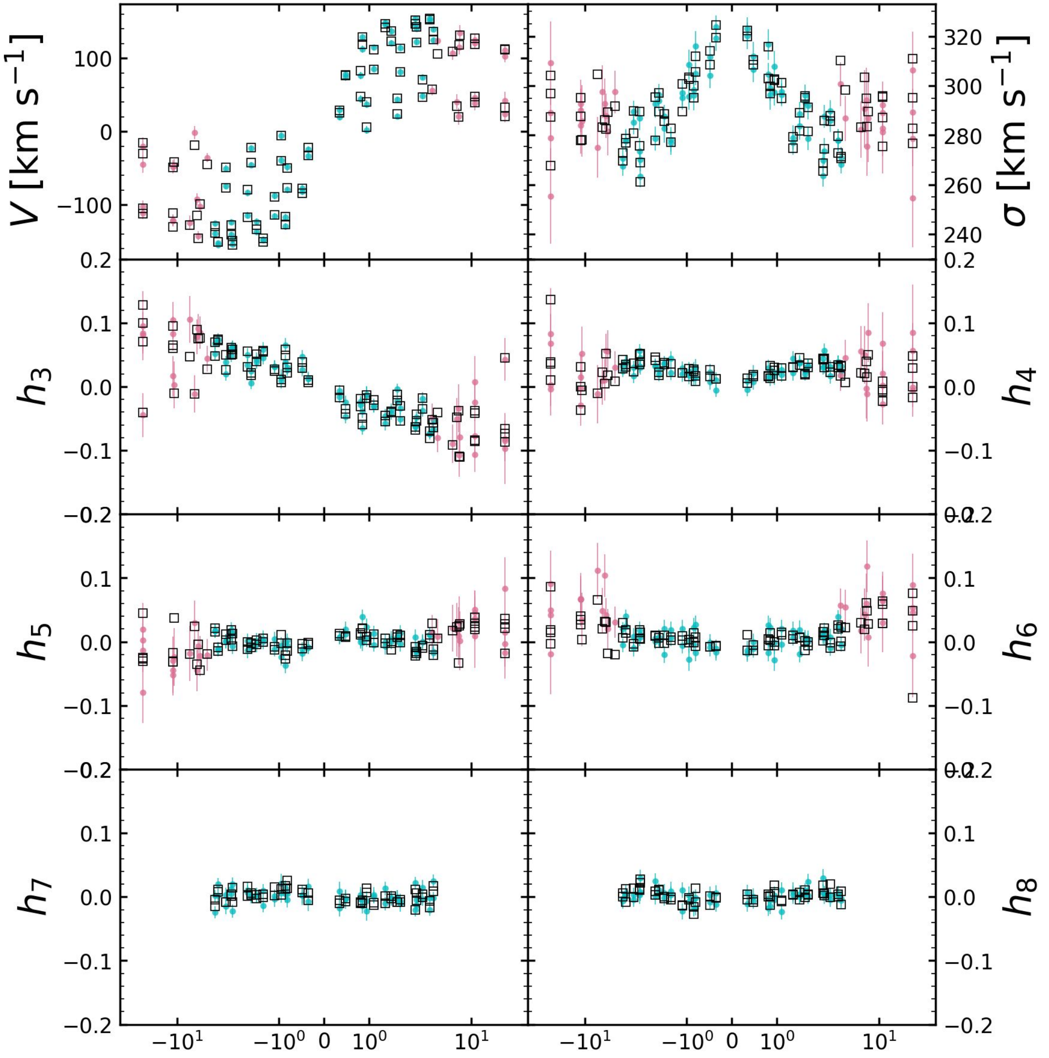
- We fit a Schwarzschild model to NGC 2693's data with the measured M_{BH}, M/L, DM halo, and i = 70°



Schwarzschild Model Flexibility: Axisymmetric Models

consider the following scenario:

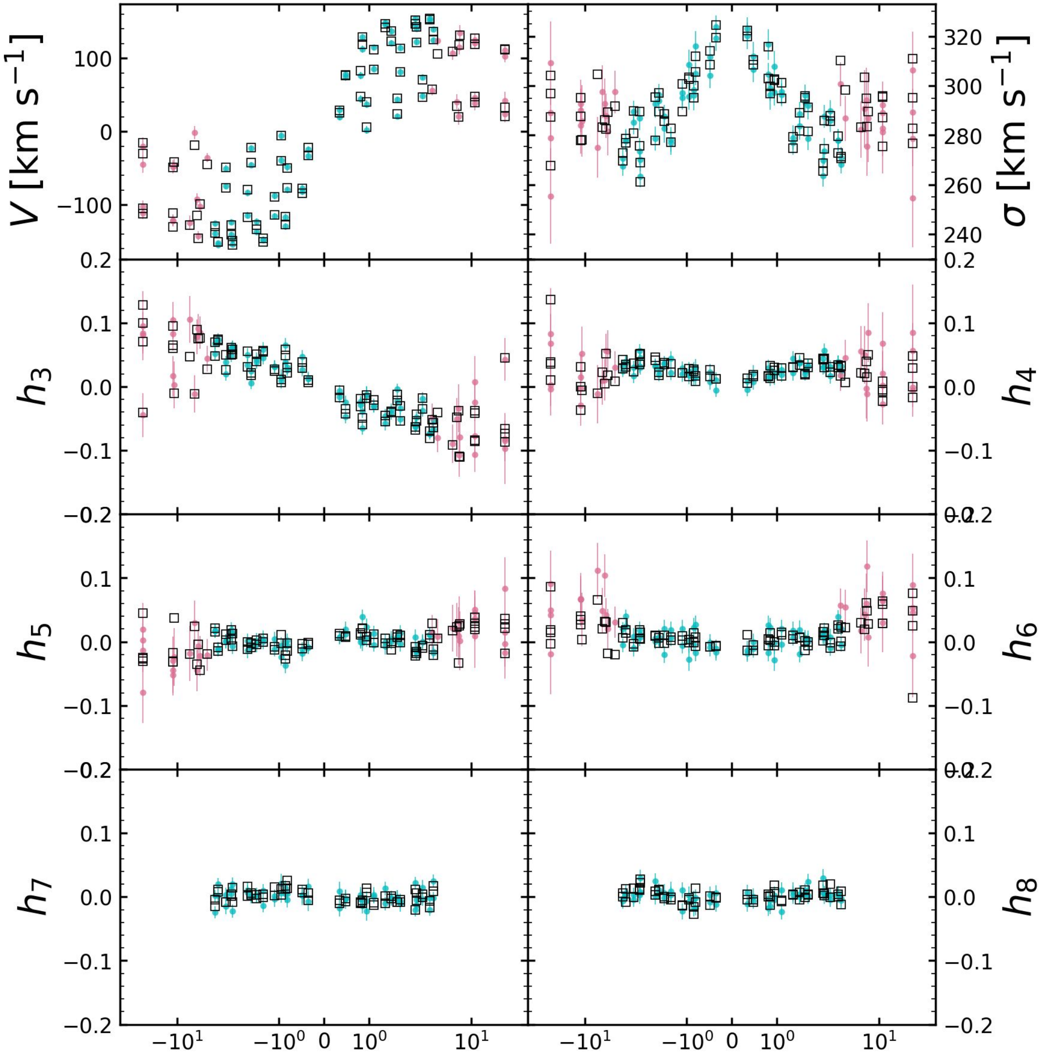
- We fit a Schwarzschild model to NGC 2693's data with the measured M_{BH}, M/L, DM halo, and i = 70°
- Perturb the model fit by the measurement uncertainty



Schwarzschild Model Flexibility: Axisymmetric Models

consider the following scenario:

- We fit a Schwarzschild model to NGC 2693's data with the measured M_{BH}, M/L, DM halo, and i = 70°
- Perturb the model fit by the measurement uncertainty
- Feed this as "input" to our code architecture and try to recover the correct inputs



Schwarzschild Modeling Power

our typical scenario:

- (~a few hundred kinematic apertures) * (~8 Gauss-Hermite moments per aperture)

  ~ 10^3 kinematic constraints

typical schwarzschild model:

- **≥ 10^4 orbits** with a free weight parameter

$$\chi_k^2 \to 0$$

k (degrees of freedom)
= (# data points) - (# params)
= negative

if this were a simple linear model

Schwarzschild Model Flexibility (pt 2)

motivating why we might expect this in axisymmetric models:

- both prograde and retrograde orbits are included in our orbits libraries, which have opposite signs and contribute maximally to the LOSVD in edge-on orientations; this in turn gives a higher effective degrees of freedom in these high i models
- In other words, they're more **flexible** as you move toward $i \rightarrow 90^{\circ}$
- Solution: apply a penalty which quantifies the flexibility of these models (have a slide motivating a penalty like m_eff/Norb, show results of penalizing the models as such)

Schwarzschild Model Flexibility (pt 3)

Triaxial models and current work:

- Currently evaluating if there is a similar bias in triaxial models which don't have the same symmetries in the orbits, plus have different families of orbits entirely
- Initial results seems to suggest that we don't need a penalty term for our triaxial models, and that we can accurately recover the parameters associated with a set of input kinematics