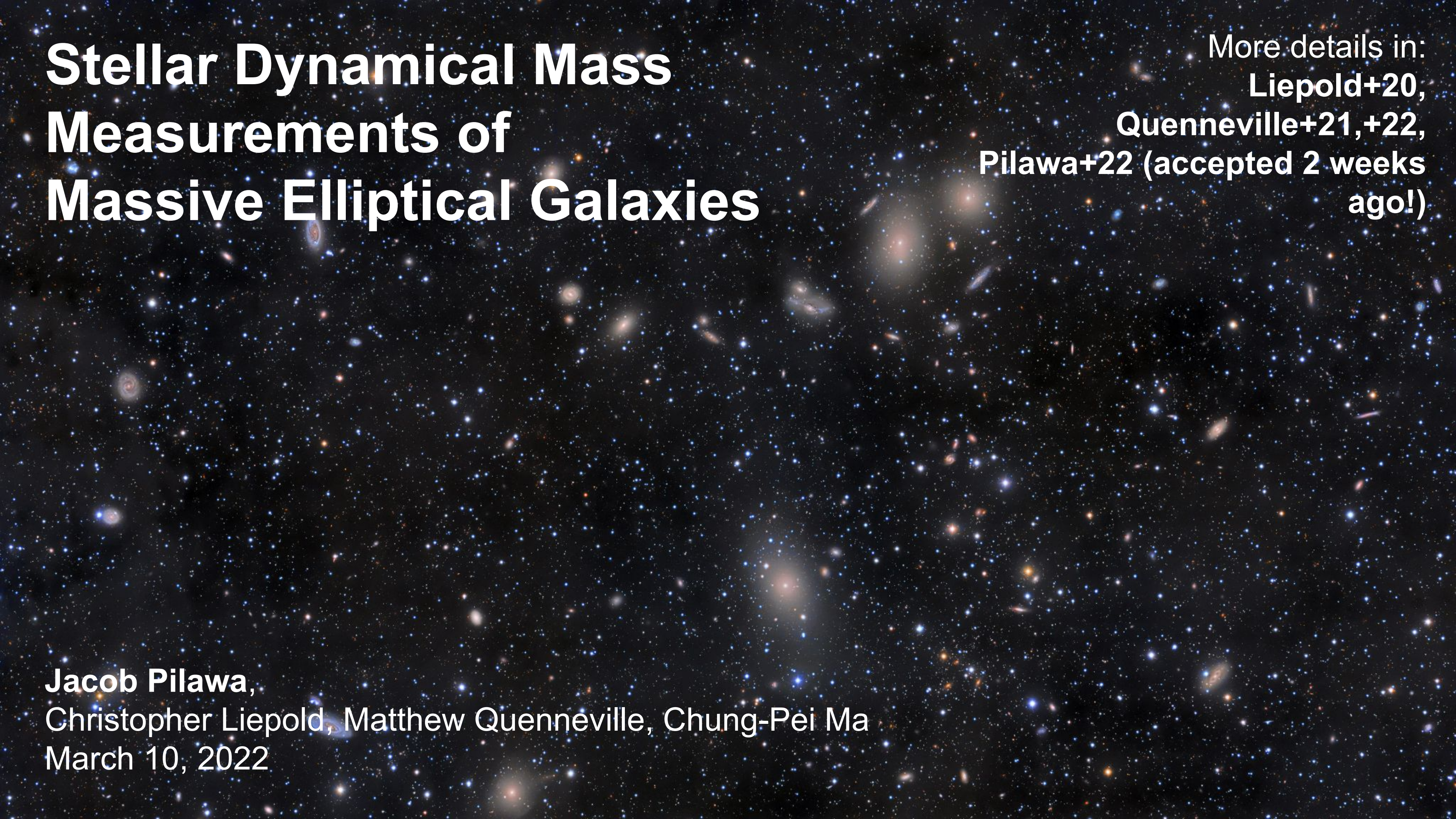


# Stellar Dynamical Mass Measurements of Massive Elliptical Galaxies

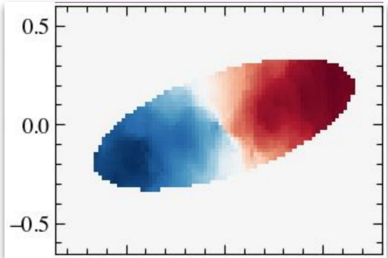
More details in:
**Liepold+20, Quenneville+21,+22, Pilawa+22 (accepted 2 weeks ago!)**

**Jacob Pilawa**,
Christopher Liepold, Matthew Quenneville, Chung-Pei Ma

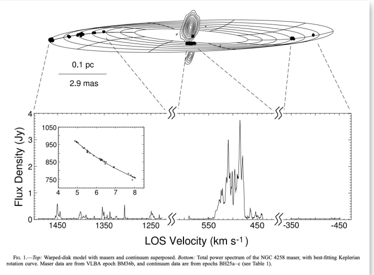
March 10, 2022

# ***main techniques for BH discovery:***

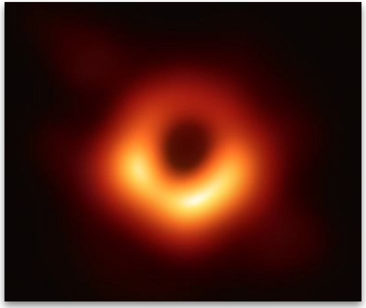
## gas disk dynamics



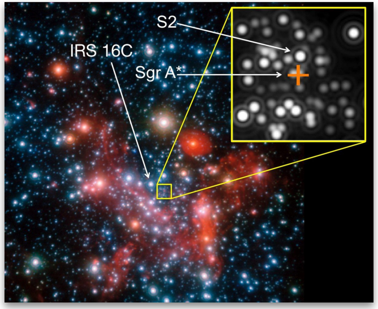

## maser disks




## EHT

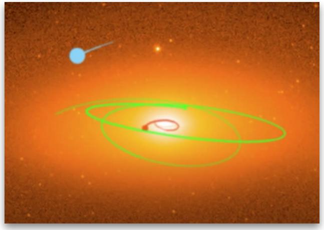


## galactic center




integrated light

## stellar dynamics



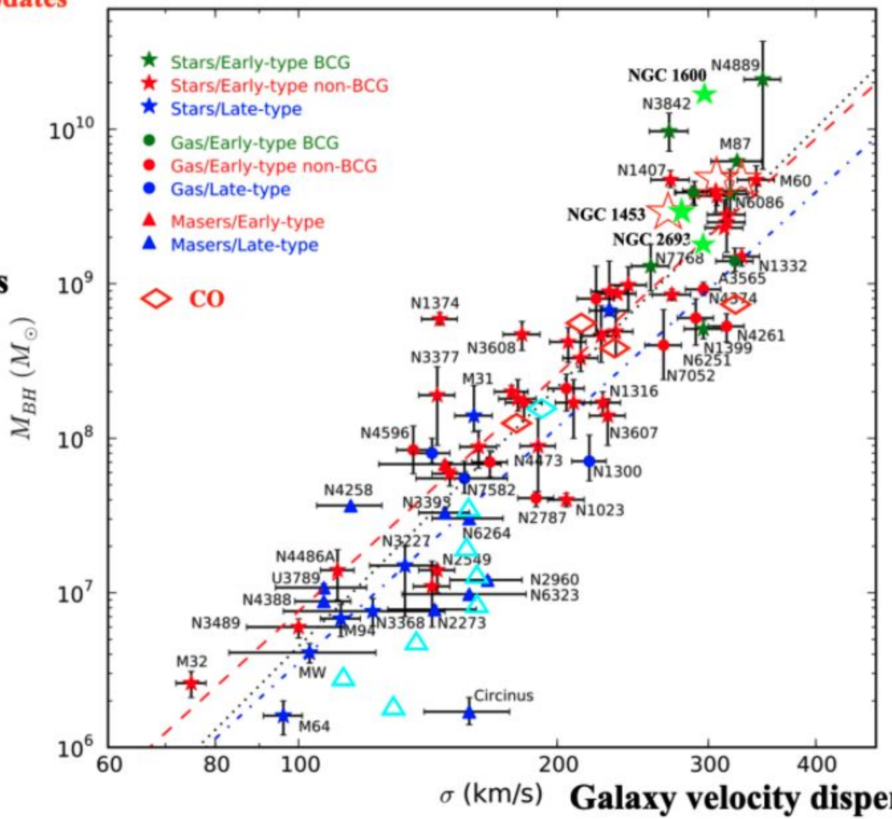
...

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

# *BLACK HOLES + GALAXIES*

McConnell & Ma (2013)
+ some updates

**4.5 dex**
**BH mass**




**Galaxy velocity dispersion**

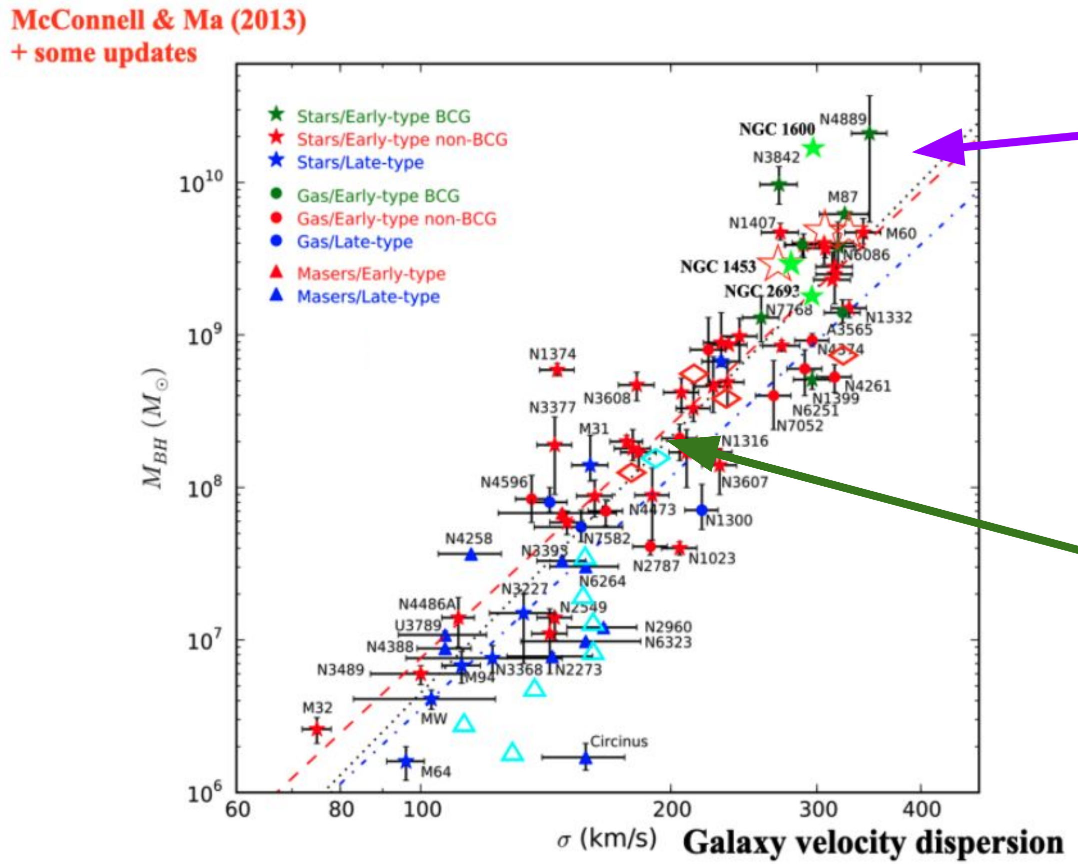
$$r_{\rm SOI} \approx \frac{GM}{\sigma^2} \sim 10\text{'s of pc}$$

$$r_{\rm galaxy} \sim 10\text{'s of kpc}$$

## *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 dry mergers**

→ BH increases
→ σ saturates
→ triaxial intrinsic shapes with slow rotation (V/σ < 0.2)

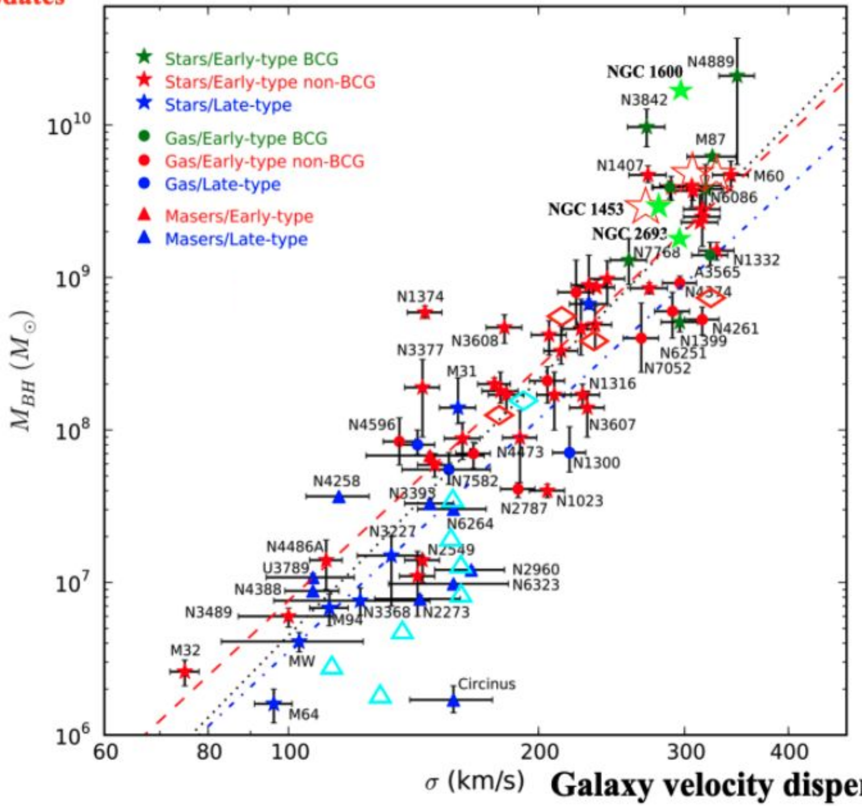
**growth by gas accretion/gas-rich mergers**

→ BH increases
→ fast rotators (V/σ ~ 0.3)
→ axisymmetric shapes

McConnell & Ma (2013)

# A CLUE: the most MASSIVE galaxies

McConnell & Ma (2013)
+ some updates




**Galaxy velocity dispersion**

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

1. Estimating BH Masses

2. Cross-checking of methods/calibrate reverberation mapping masses

3. z~0 mass function → BBH merger rates

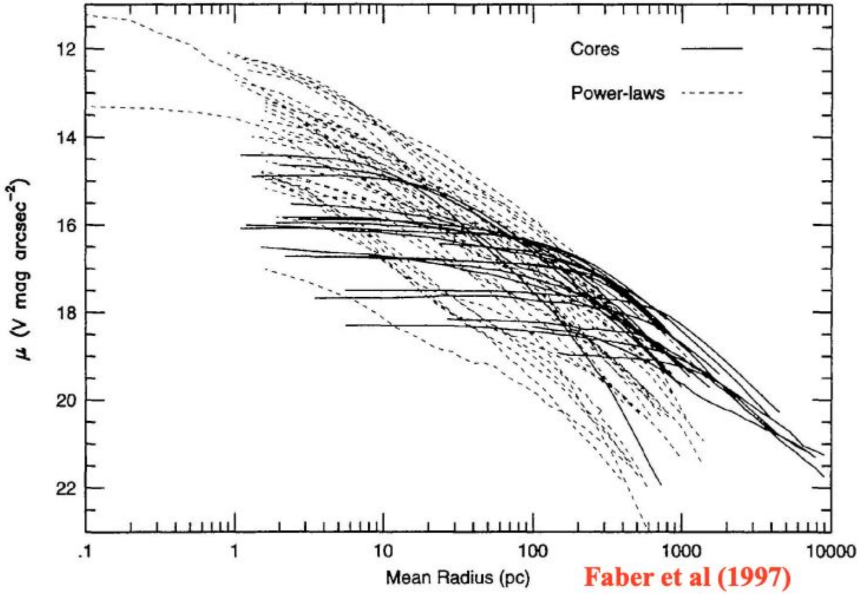
4. Comparison to simulations of AGN feedback modes and mechanisms

… but it's challenging…

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

# why are massive ellipticals a challenge?

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




Faber et al (1997)

sphere of influence
is **tiny**

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

0.1 arcsec at 100 Mpc

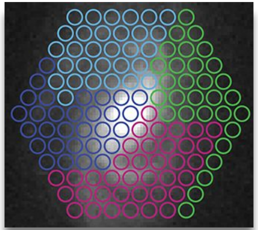
**→ long exposures on 8-10m telescopes!**

# *The MASSIVE Survey*

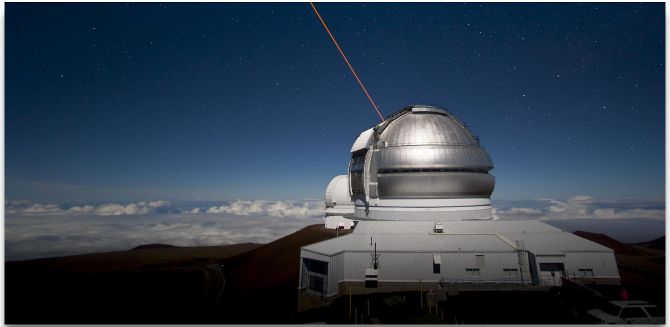
a **volume-complete** survey of the ~100 most ***MASSIVE***, local galaxies

## McDonald Observatory

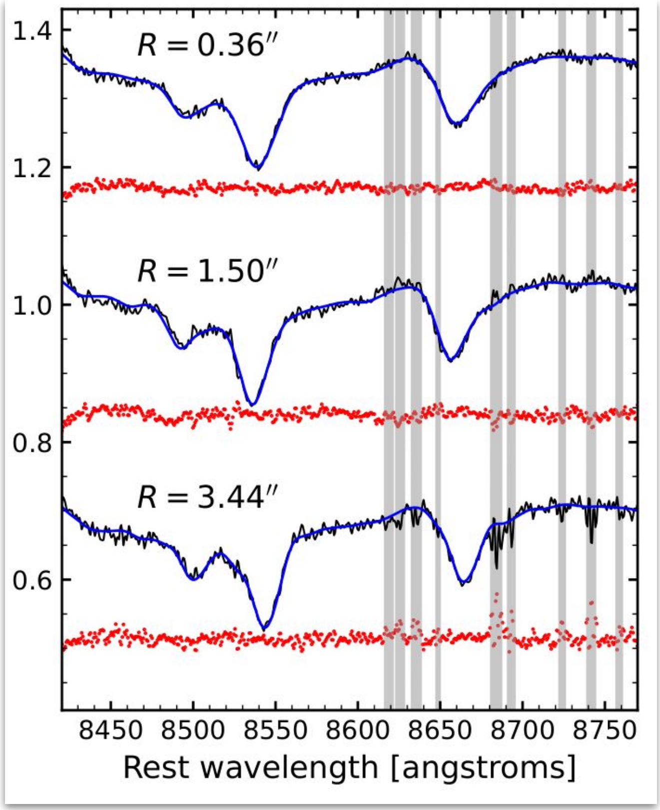
Wide-field IFU (out to ~2 $R_{eff}$)



## Gemini North



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



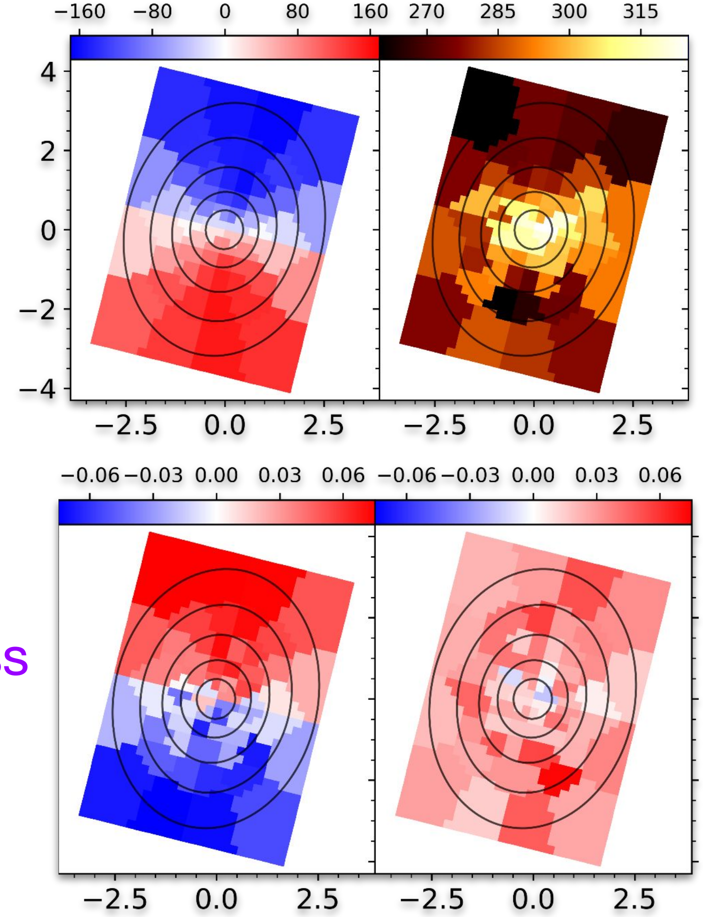

*Spectra from Gemini North/GMOS (Pilawa+22)*

MASSIVE I: Ma+2014,
MASSIVE II-XVI: Awesome science + other MASSIVE results!
MASSIVE XVII: Pilawa+22

# *The MASSIVE Survey*

Velocity
V [km/s]

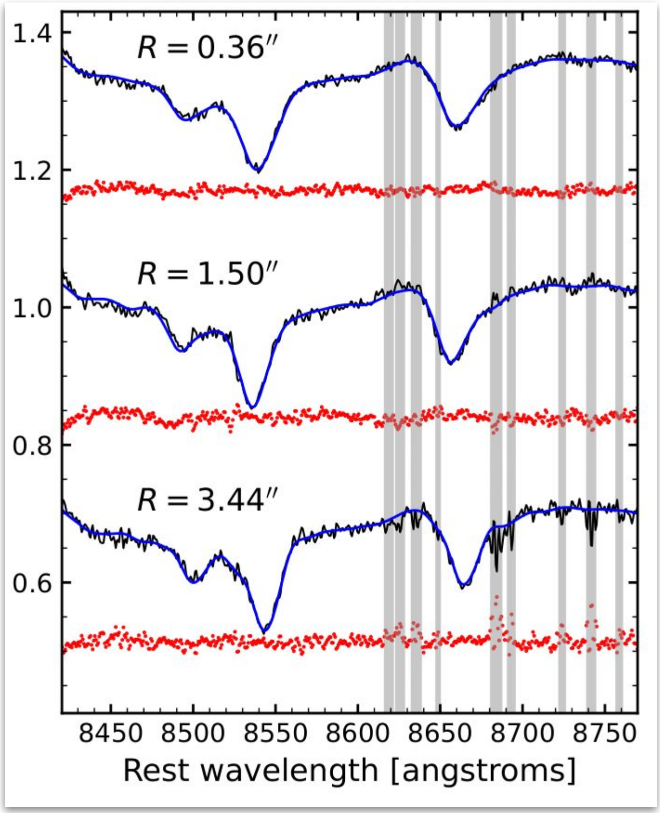
Dispersion
σ [km/s]




Skewness
$h_3$

Kurtosis
$h_4$

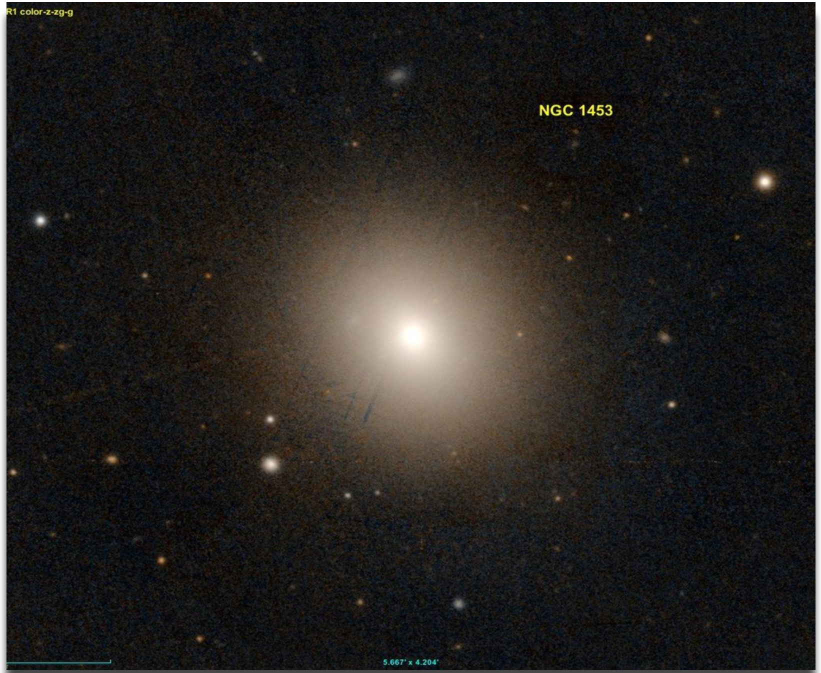
* rarely determined by others

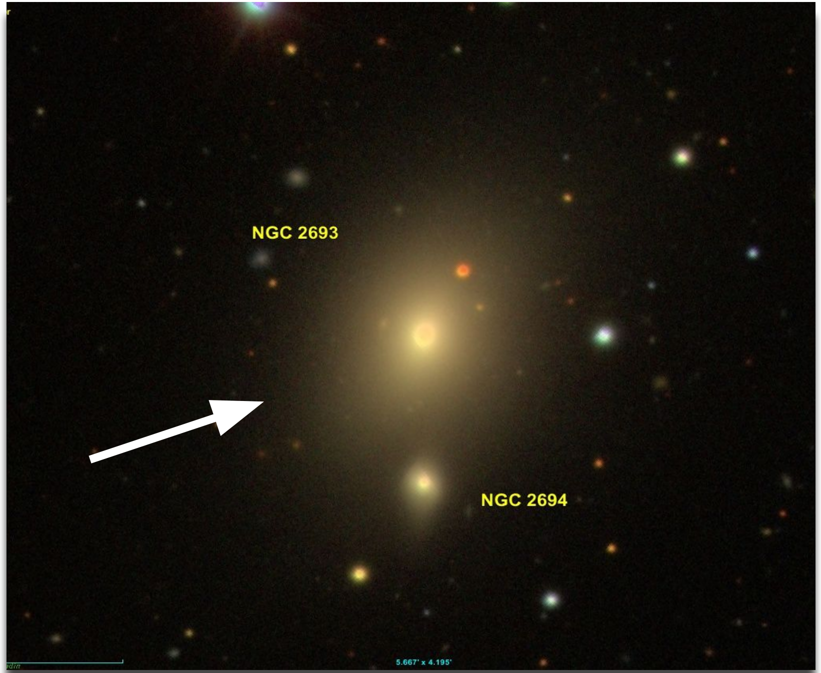



*Spectra from Gemini North/GMOS*
*(Pilawa+22)*

# stellar kinematics of NGC 1453 and 2693

Liepold+20
Quenneville+21
Pilawa+22



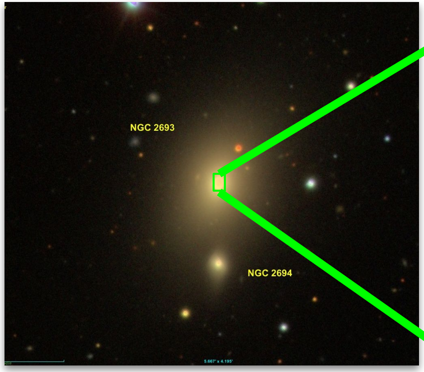



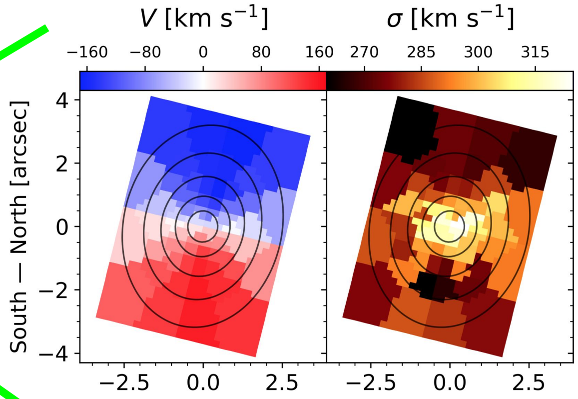

SDSS DR9 Images

# stellar kinematics of NGC 1453 and 2693

*Liepold+20*
*Quenneville+21*
*Pilawa+22*

## *NGC 2693*

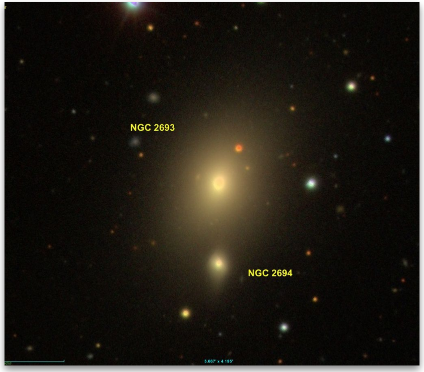


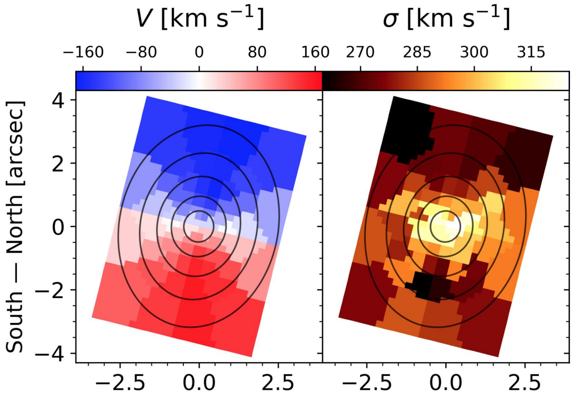




- regular, fast rotator (V~150 km/s, σ~320 km/s)

# stellar kinematics of NGC 1453 and 2693

*NGC 2693*



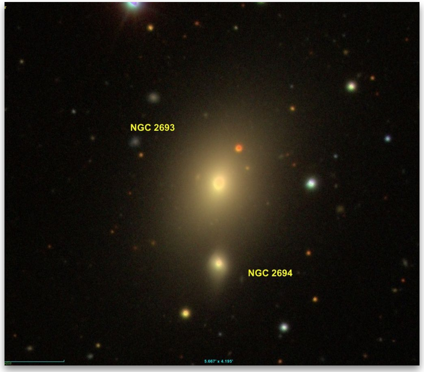



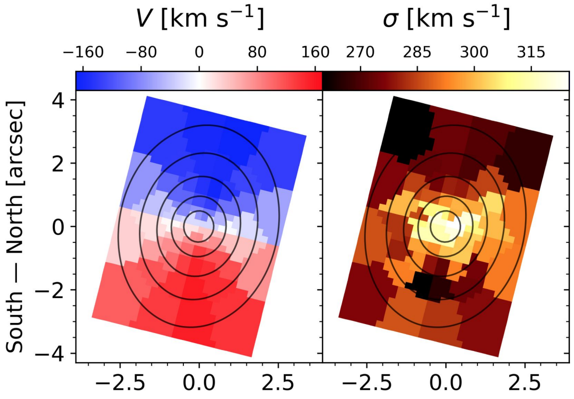

- regular, fast rotator (V~150 km/s, σ~320 km/s)
- mostly regular, elliptical isophotes

*Liepold+20*
*Quenneville+21*
*Pilawa+22*

# **stellar kinematics of NGC 1453** and **2693**

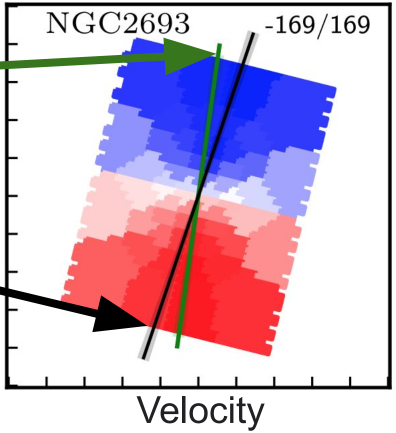
***NGC 2693***




**average orientation of stellar motion**

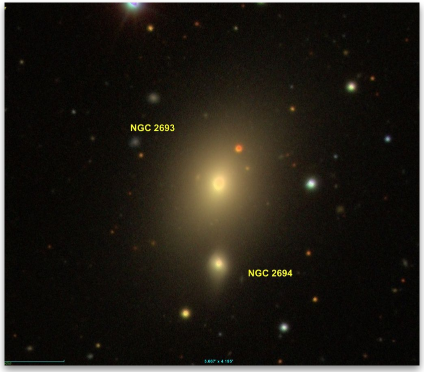
**photometric major axis**

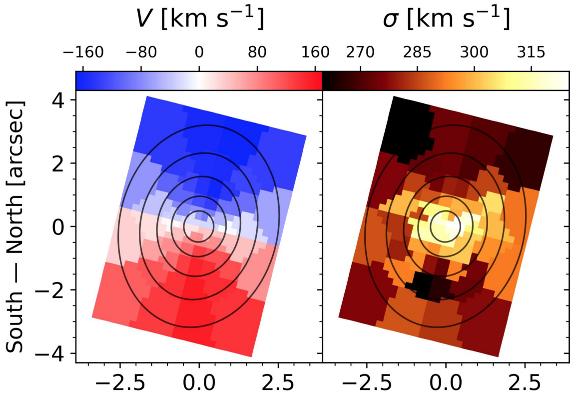



- regular, fast rotator (V~150 km/s, σ~320 km/s)
- mostly regular, elliptical isophotes
- **kinematic** and **photometric** major axes are ***nearly*** aligned (ΔΨ~5°)

# stellar kinematics of NGC 1453 and 2693

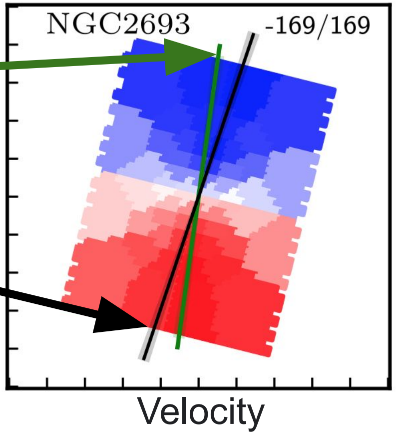
### *NGC 2693*




**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°)

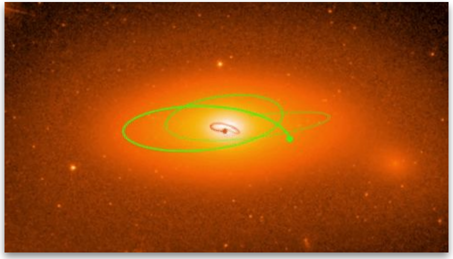
properties consistent with **axisymmetric** intrinsic shapes, so let's test!

# triaxial dynamical modeling

a new code for
Schwarzschild modeling:

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

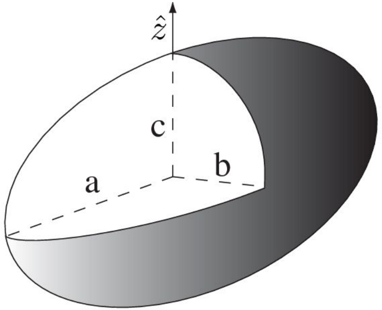
**inputs:** stellar kinematics, surface brightness; galaxy model parameters

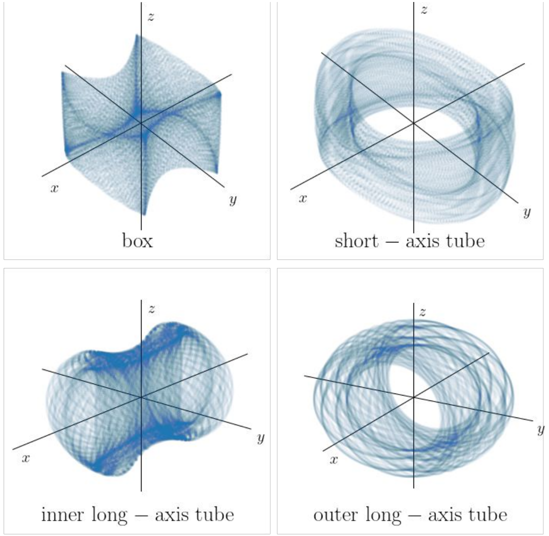


**outputs:** set of stellar orbits which best reproduces the input kinematics

## <u>triaxial systems</u>

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



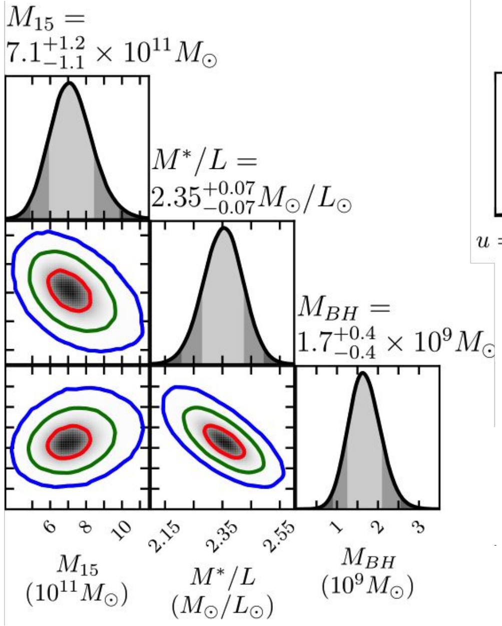
# stellar dynamical modeling: applications to NGC 2693

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

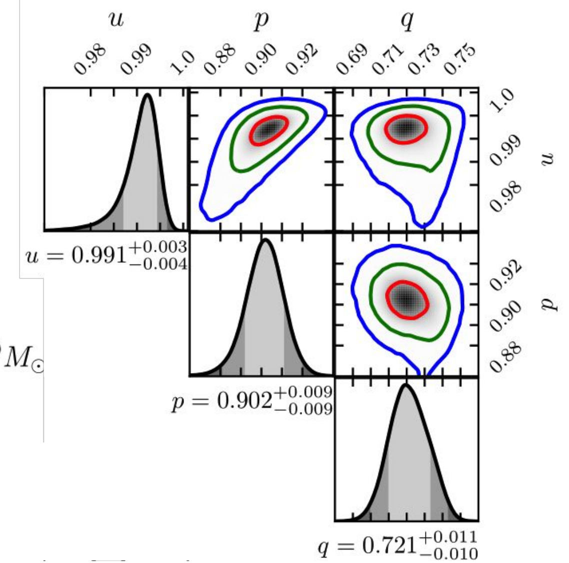
- **neither galaxy is axisymmetric (p = 1)**
  - Intermediate-to-major axis ratio: **p = b/a ~ 0.9**
  - Minor-to-major axis ratio: **q= c/a ~ 0.7**

- **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*

# Summary

**discovery** of two new **supermassive black holes**:

**NGC 1453**: $(2.9\pm0.4) \times 10^9 M_{Sun}$
**NGC 2693**: $(1.7\pm0.4) \times 10^9 M_{Sun}$

→ first simultaneous measurements of **BH + DM halo + galaxy shape**

both NGC 1453 *and* NGC 2693 are **mildly triaxial** despite appearing axisymmetric

→ axisymmetric NGC 2693 models prefer a ~25% larger BH, but **more examples are needed**

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

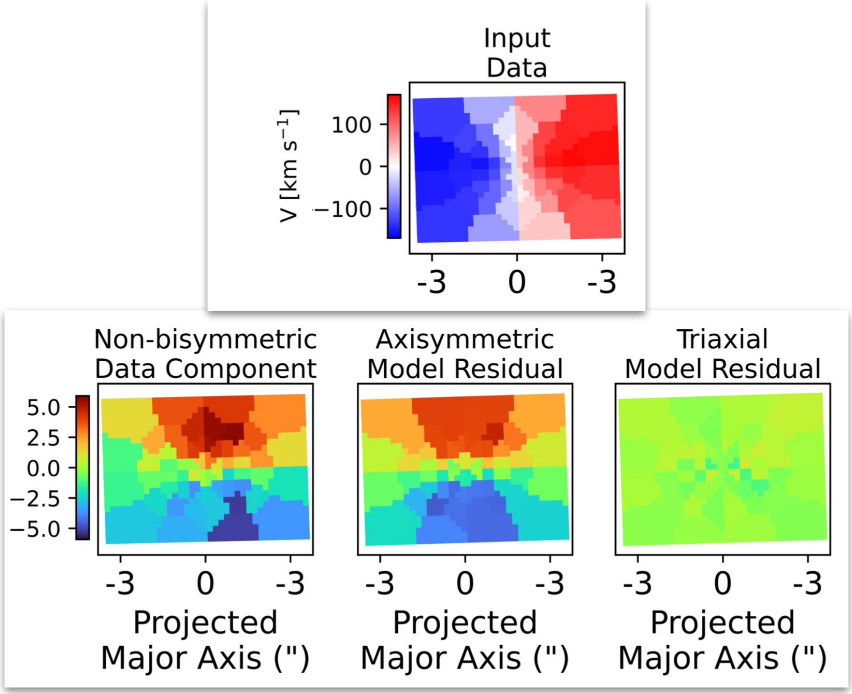
→ **~20 MASSIVE** galaxies are ready for modeling, none of which are simple fast rotators

***Thank you!***

# *Extra Slides*

# what about axisymmetric models?

Pilawa+22




**analogy:**

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

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

**triaxial** models

**axisymmetric** models

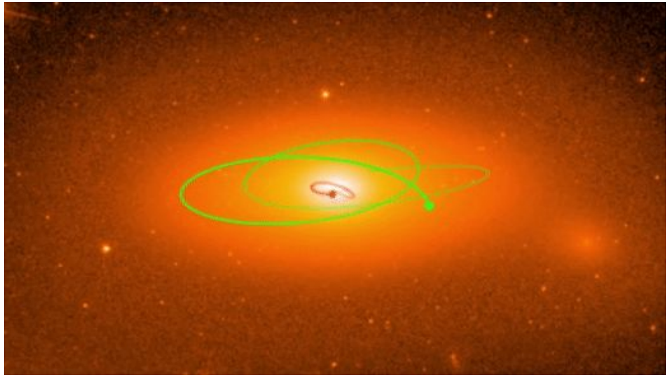
| | **TRIAXIAL** | **AXISYMMETRIC** |
|---|---|---|
| **NGC 2693 BH:** | **$(1.7\pm0.4) \times 10^9\ M_{sun}$ →** | **$(2.4 \pm 0.6) \times 10^9\ M_{sun}$** |

*van den Bosch+2008*

# stellar dynamics pt. 2

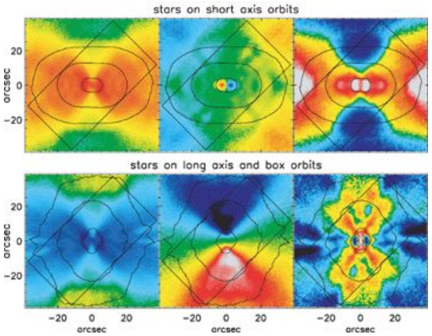
1. Choose a trial potential:

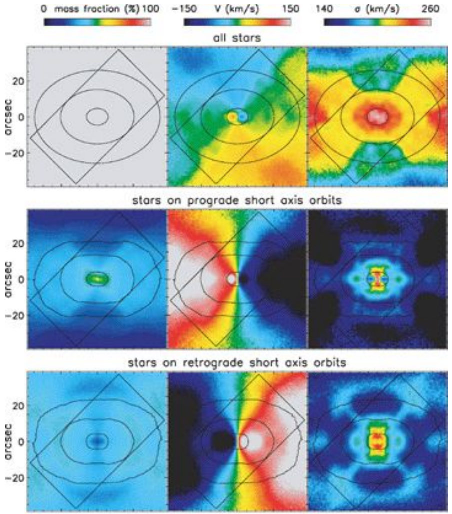
```
Galaxy =(DM)+(STARS)+(BH)+...
```



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

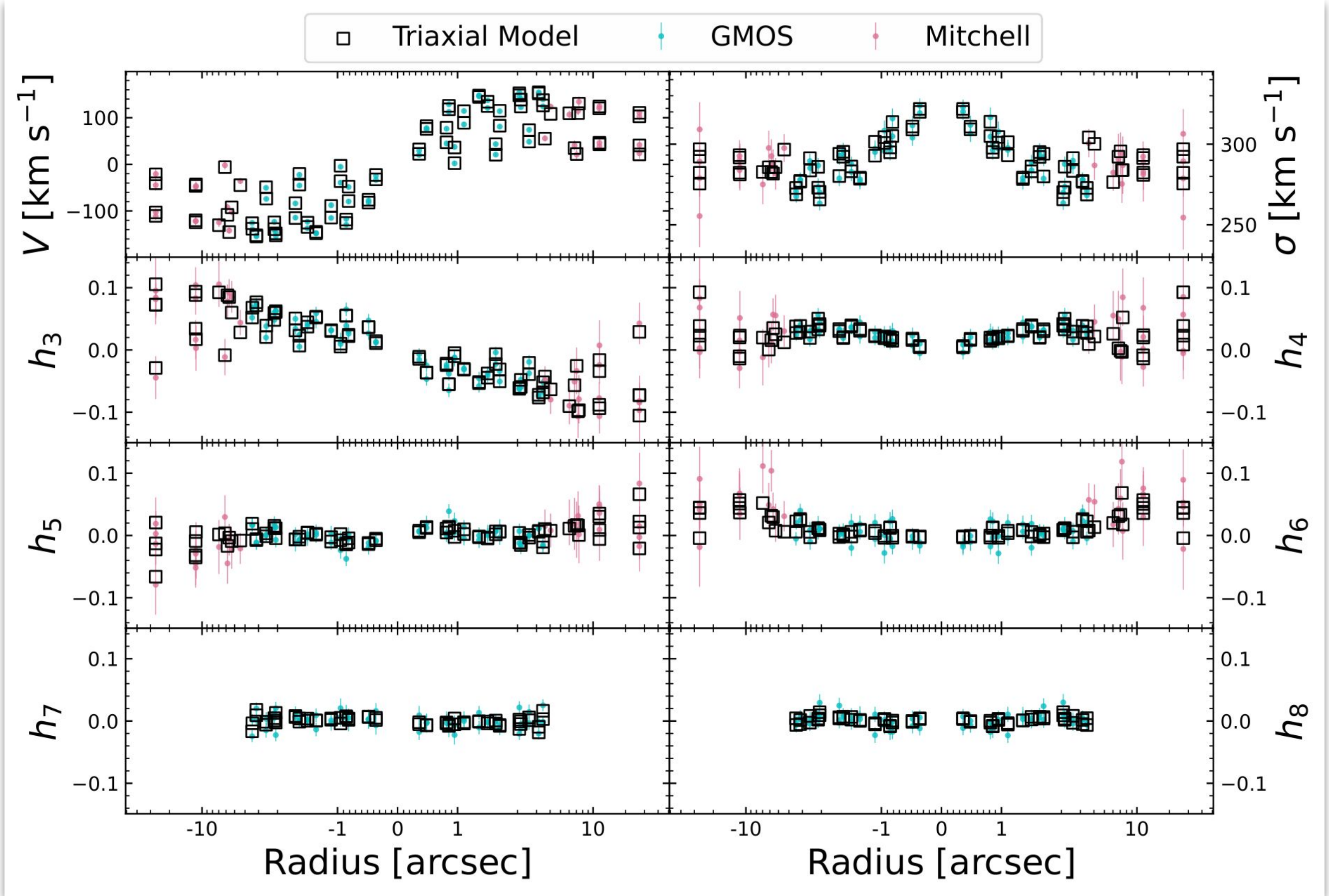
3. Assign weights to orbits → Reproduce kinematics




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

# modeling results:
# applications to NGC 2693

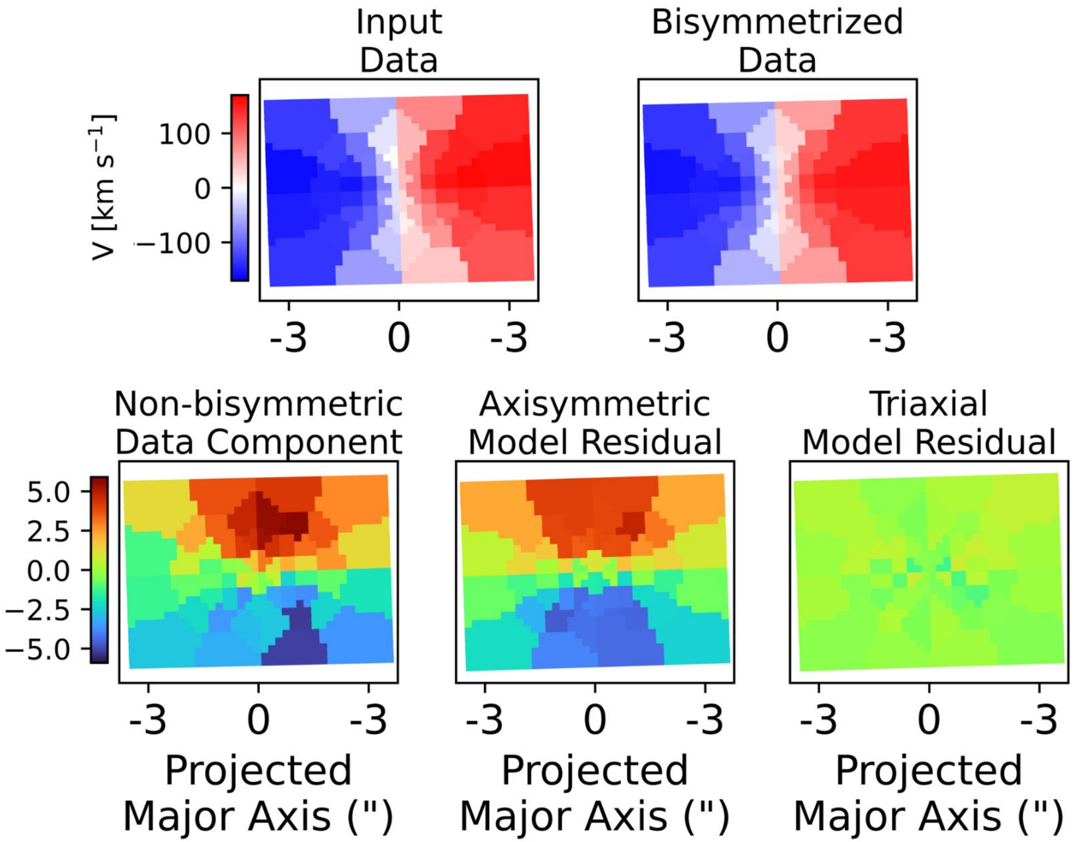



1”~350pc

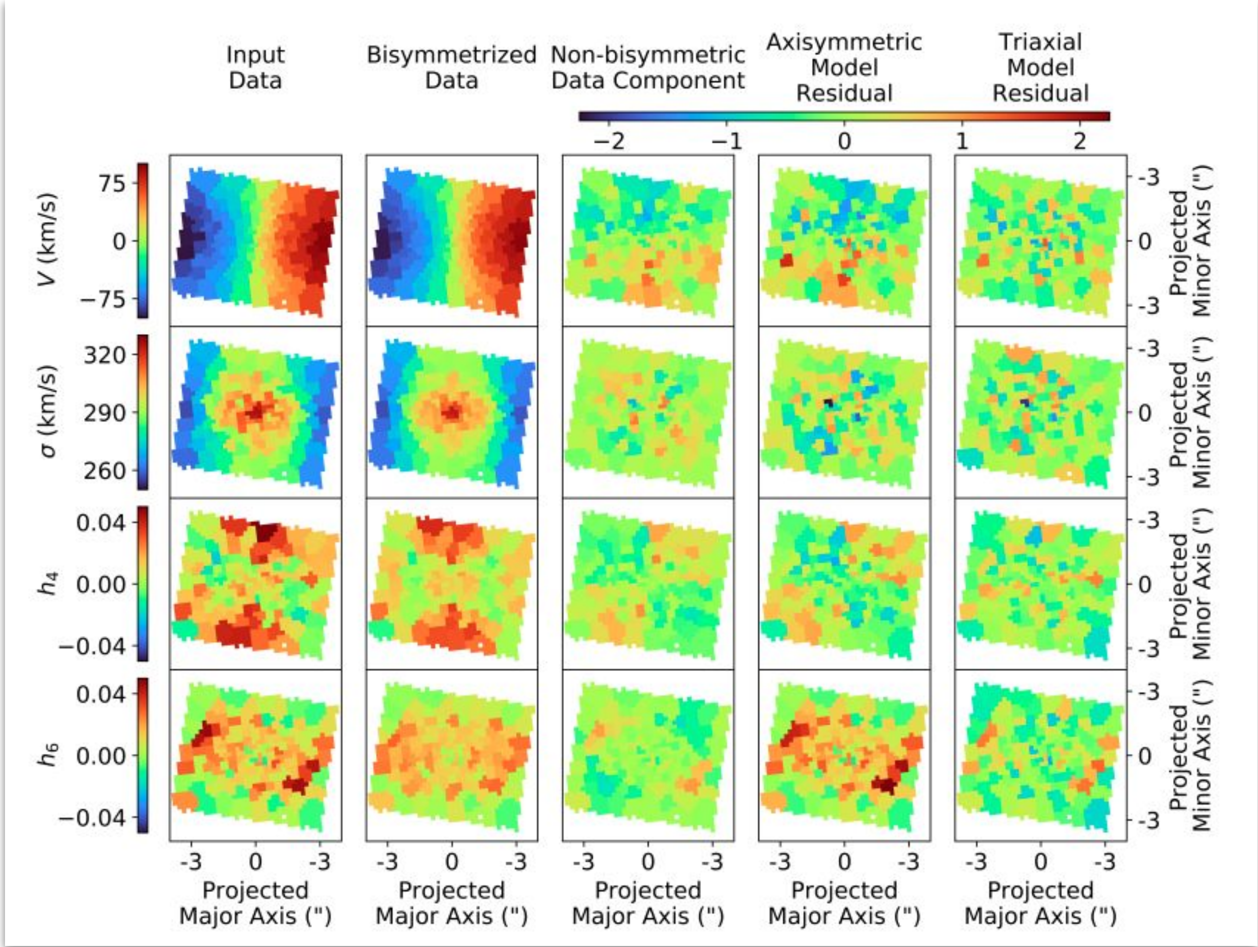
# axisymmetric vs. triaxial models

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

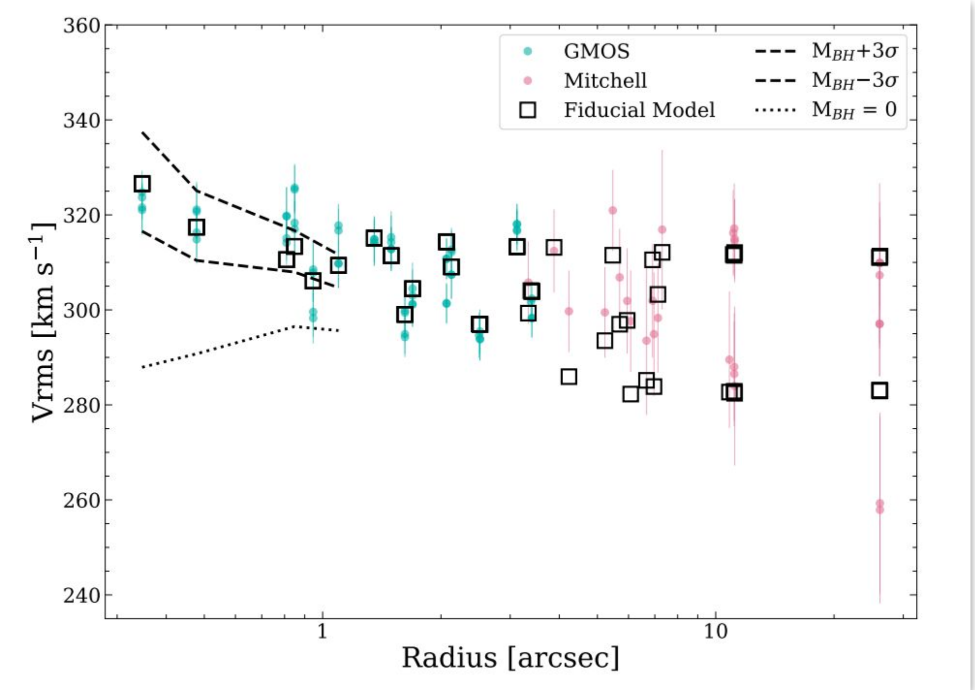
→ axisymmetric models cannot reproduce non-bisymmetric velocity components



# axisymmetric vs. triaxial models



# Jeans Modeling

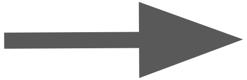



| Galaxy Parameter | Triaxial Orbit Model | Axisymmetric Orbit Model | JAM Model |
|---|---|---|---|
| $M_{\rm BH}$ [$10^9 M_\odot$] | $1.7 \pm 0.4$ | $2.4 \pm 0.6$ | $2.9 \pm 0.3$ |
| $M^*/L$ [$M_\odot/L_\odot$] | $2.35 \pm 0.07$ | $2.27 \pm 0.1$ | $2.17 \pm 0.03$ |
| $M_{15}$ [$10^{11} M_\odot$] |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

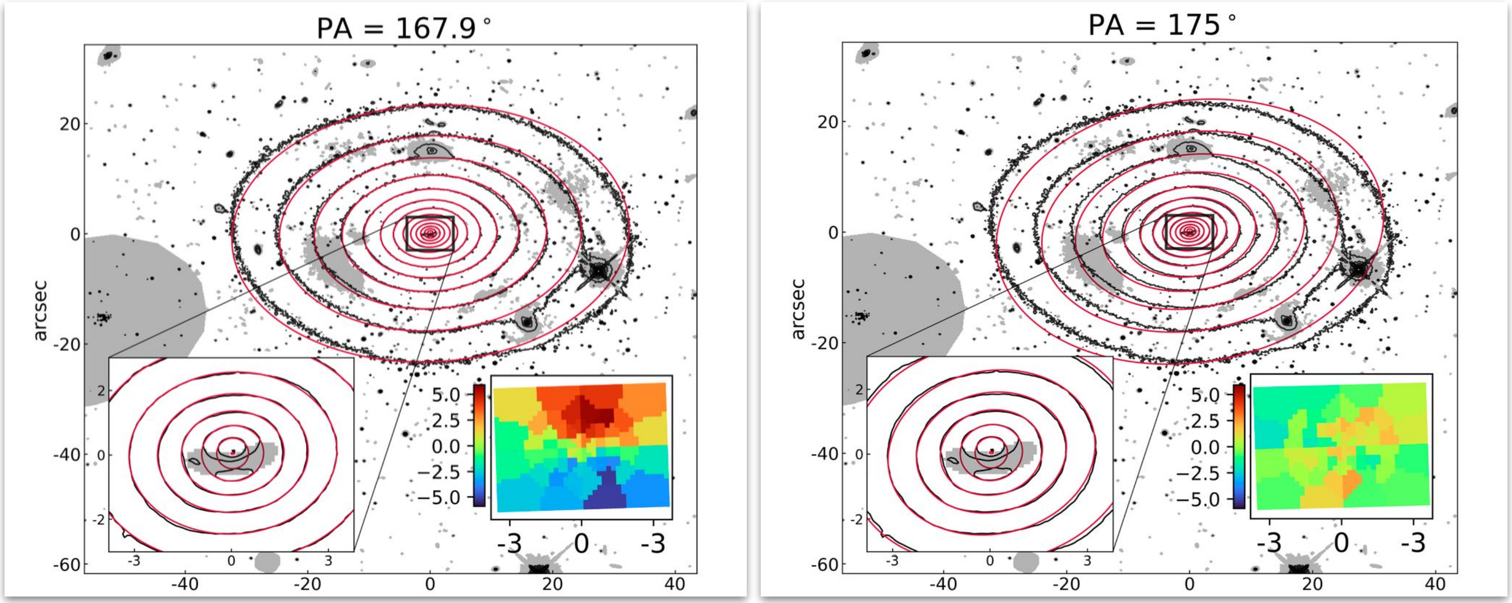
**Table 2.** Summary of best-fit galaxy models for NGC 2693. For each parameter, we marginalize over the other dimensions and report the $1\sigma$ uncertainties. The axisymmetric orbit models and JAM models have fixed inclination of 70°. In orbit models, $\theta$ is the inclination angle in the oblate axisymmetric limit ($\psi = 90°$, or equivalenly $p = 1$), with $\theta = 90°$ being edge-on and $\theta = 0°$ being face-on. †We measure $\beta_z$ 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 $\beta_z$ 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

# axisymmetric vs. triaxial models

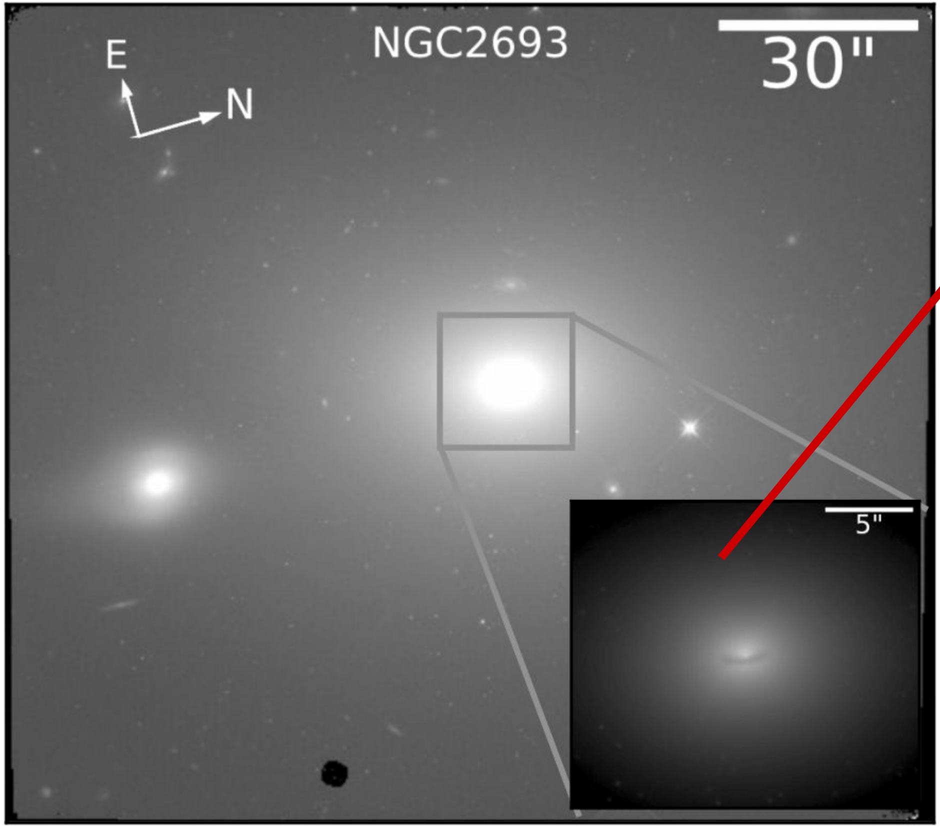


“rotating away” the non-bisymmetric component gives an inconsistent surface brightness profile



## a nice surprise:

*Pilawa+22*




**dust disk inclination:**

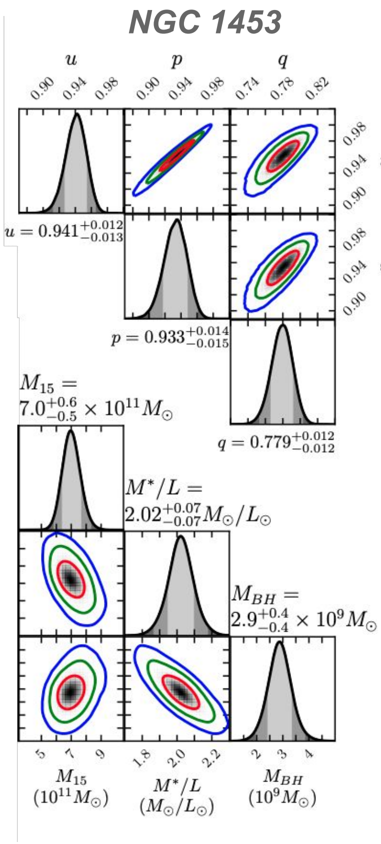
**θ~70 degrees**

**"inclination" from the triaxial model:**

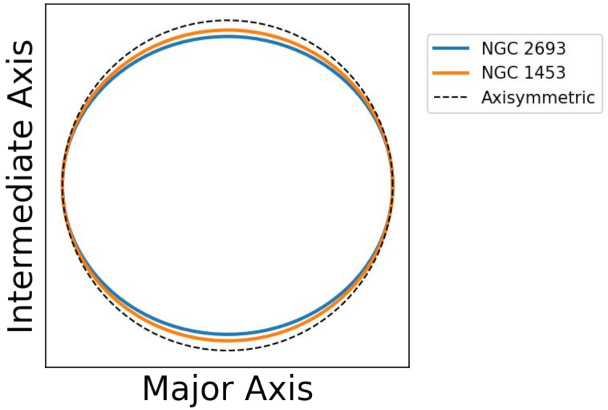
**$\theta = 66^{+4}_{-3}$ degrees**

# stellar dynamical modeling: applications to NGC 1453 and 2693

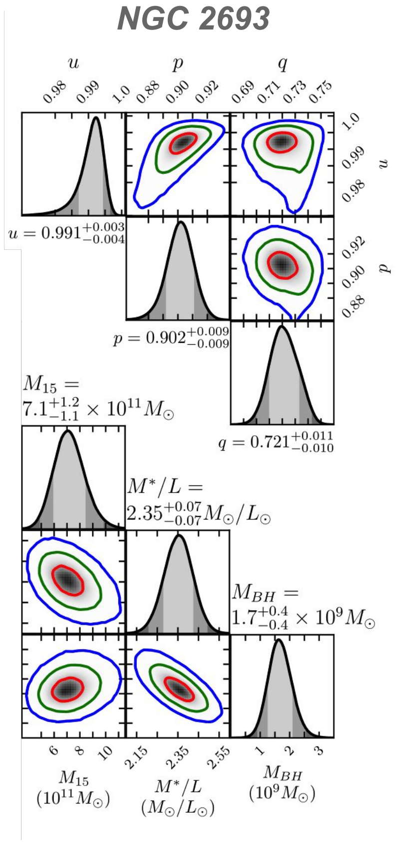
*Pilawa+22*



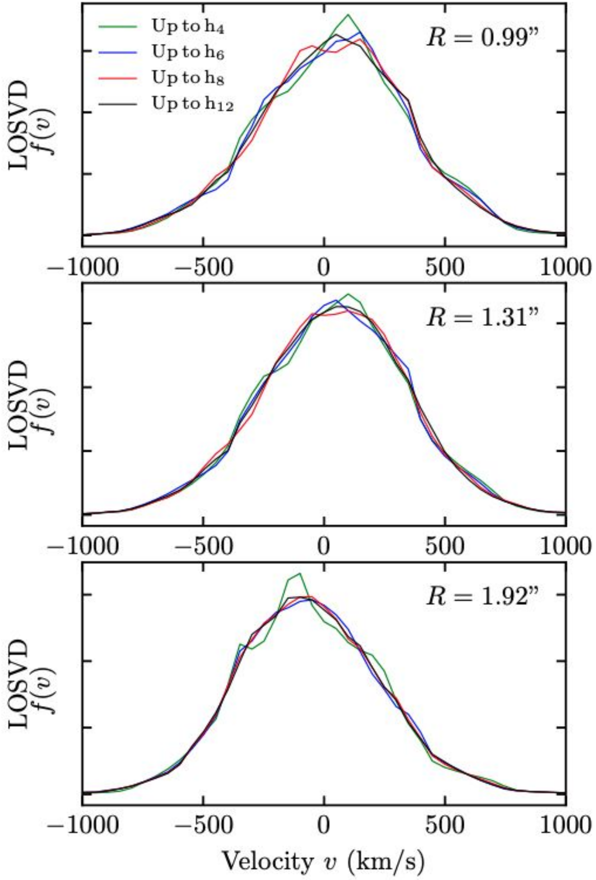

- first simultaneous measurements of DM halo, BH mass, **and intrinsic shapes**
- **neither galaxy is axisymmetric**, despite properties suggesting so




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



# LOSVDs



Up to h4
Up to h6
Up to h8
Up to h12
R = 0.99"
R = 1.31"
R = 1.92"
LOSVD f(v)
−1000 −500 0 500 1000
Velocity v (km/s)

Slide Inspiration: N. Sahu, Univ. Swinburne

# *why* ***else*** *are SMBHs important?*

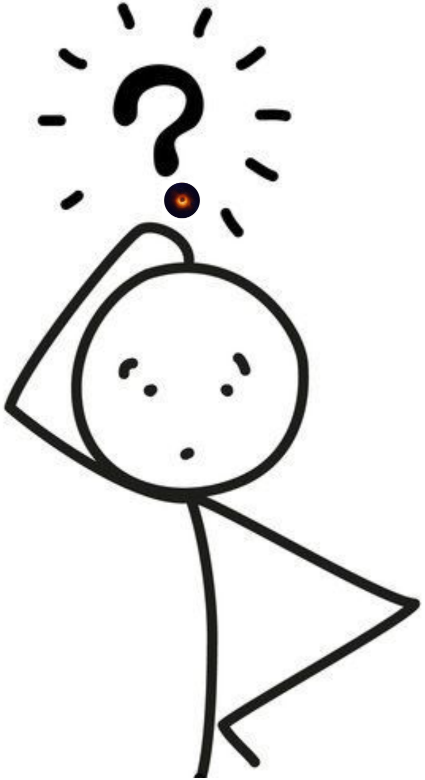
1. Estimate BH mass from galaxy properties where we can't resolve SOI

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]

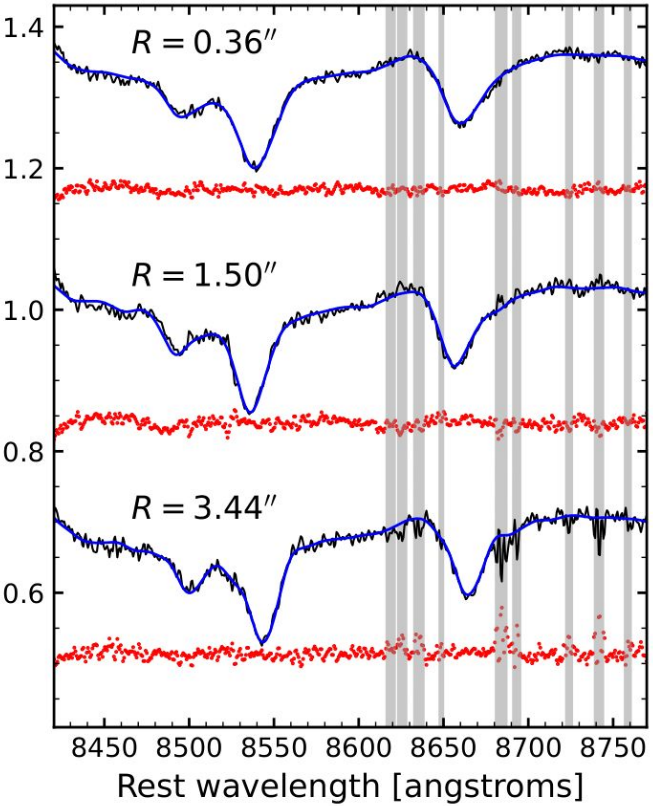
4. Comparison to simulations of AGN feedback modes and mechanisms
[i.e., Li+2019, Habouzit+2020]

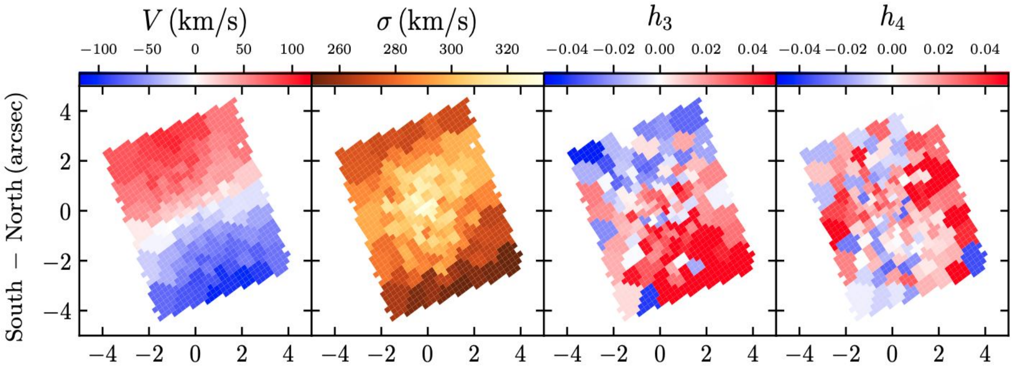
…

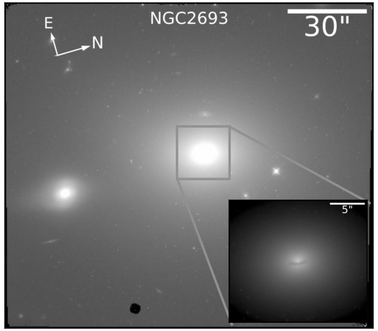


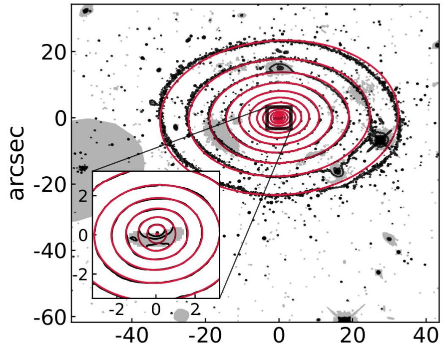
Liepold+20
Quenneville+21
Pilawa+22

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




**+ ~10,000 individual galaxy models**

Skilling+06

# Nested Sampling in A Single Slide

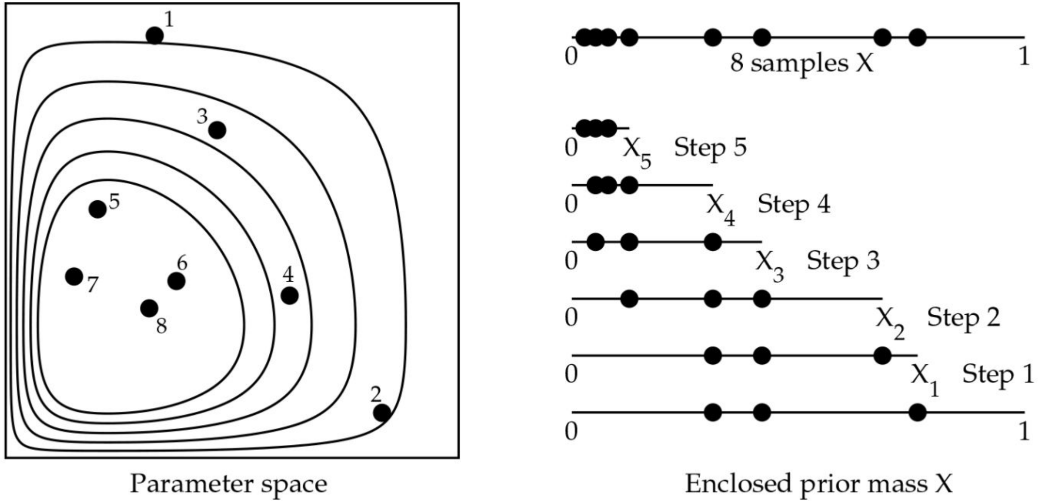



Figure 4: Nested sampling for five steps with a collection of three points. Likelihood contours shrink by factors exp(−1/3) in area and are roughly followed by successive sample points.

*J. Skilling 2006

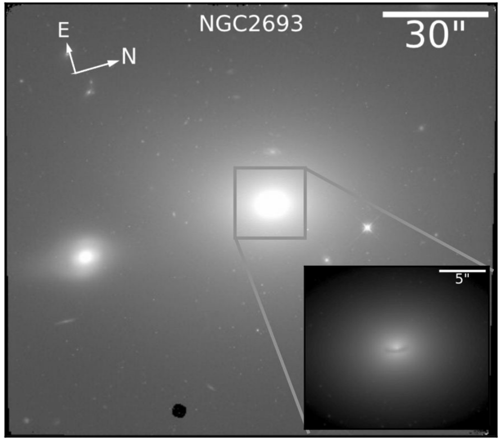
**idea : iteratively sample points, getting rid of lowest likelihood at each step → volume shrinks to maxima of distributions**

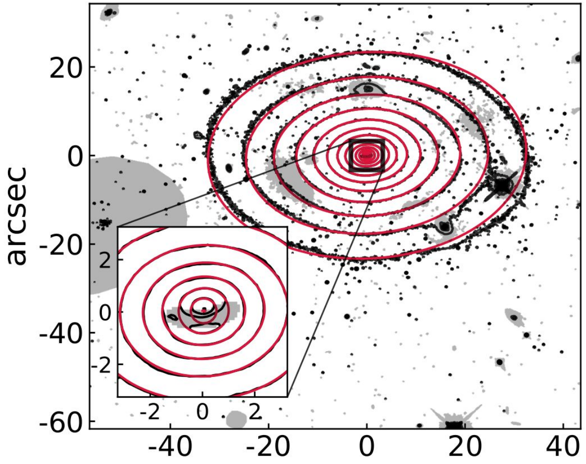
# stellar dynamical models

**CENTRAL IDEA:**

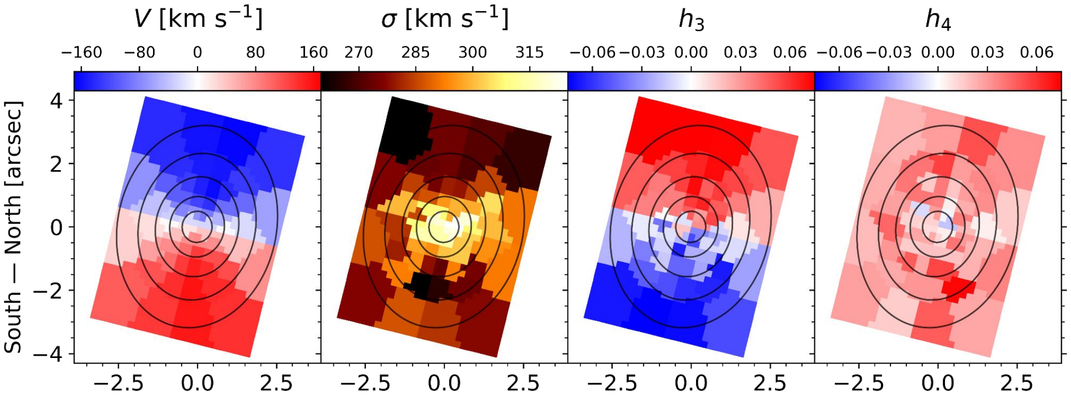
given **kinematics** + **surface brightness** of NGC 2693, can we determine the **galaxy's mass components** by integrating the orbits of stars in a gravitational potential?

## surface brightness




## line of sight velocity distribution

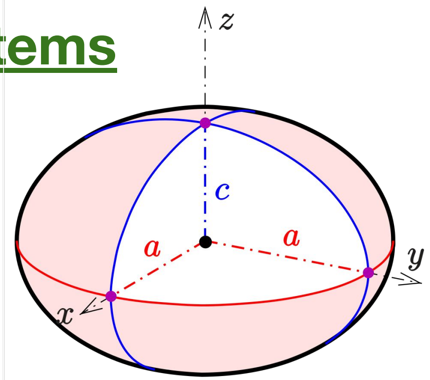


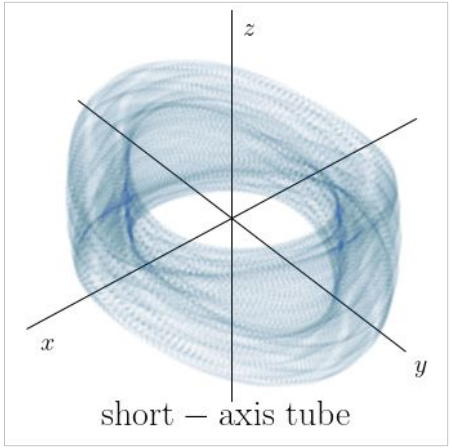

Pilawa+22

# triaxial dynamical modeling

## axisymmetric systems

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

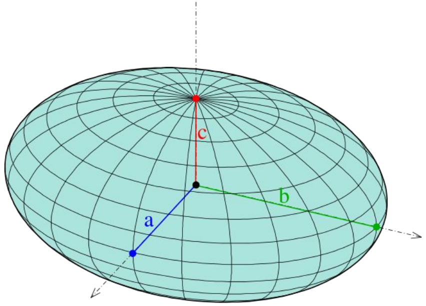


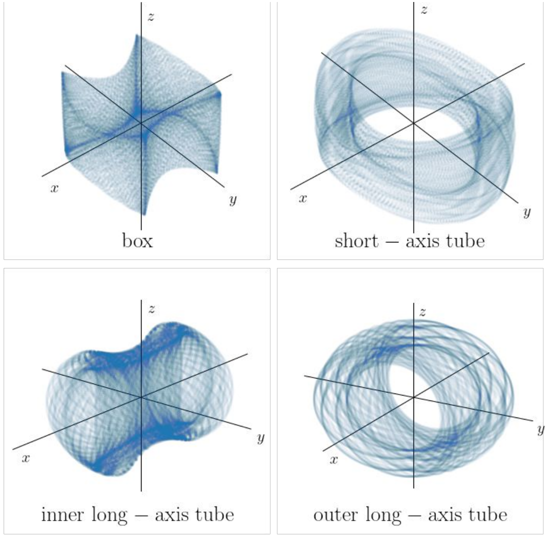




**important:**
axisymmetric systems are, by construction, ***bisymmetric***

## triaxial systems

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



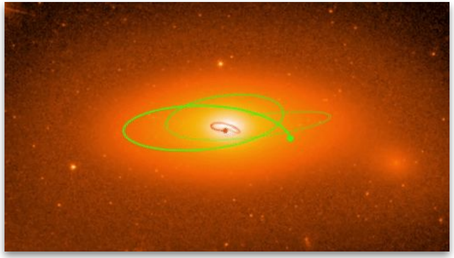



# triaxial dynamical modeling

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