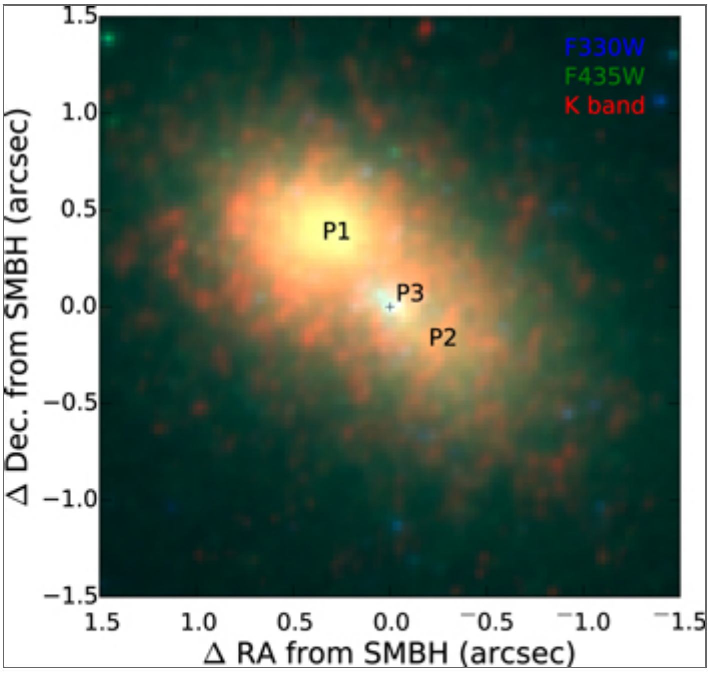
The eccentric disc of M31



[Image from Lockhart et al (2018)]

John Magorrian, 18 May 2021

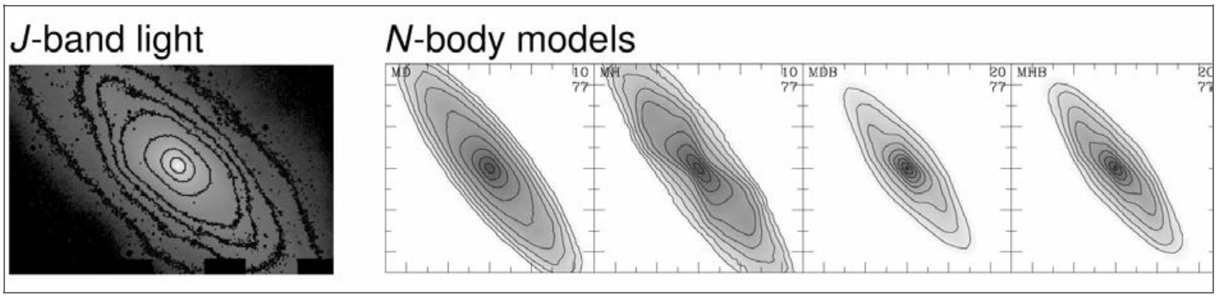
Outline

- Overview of observations of the centre of M31
- Interpretation using Tremaine's (1995) eccentric disc picture
- Observations → internal state of disc
    - assuming eccentric disc picture,
    - but with wilful ignorance of formation scenarios

Observations → eccentric disc picture

What's around M31's nucleus?

$D \sim 800$ kpc, meaning $1'' \simeq 4$ pc.
N-body/hydro models can match broad photometry/kinematics
Here's Athanassoula & Beaton (2006, see also Blaña et al 2017, Opitsch et al):

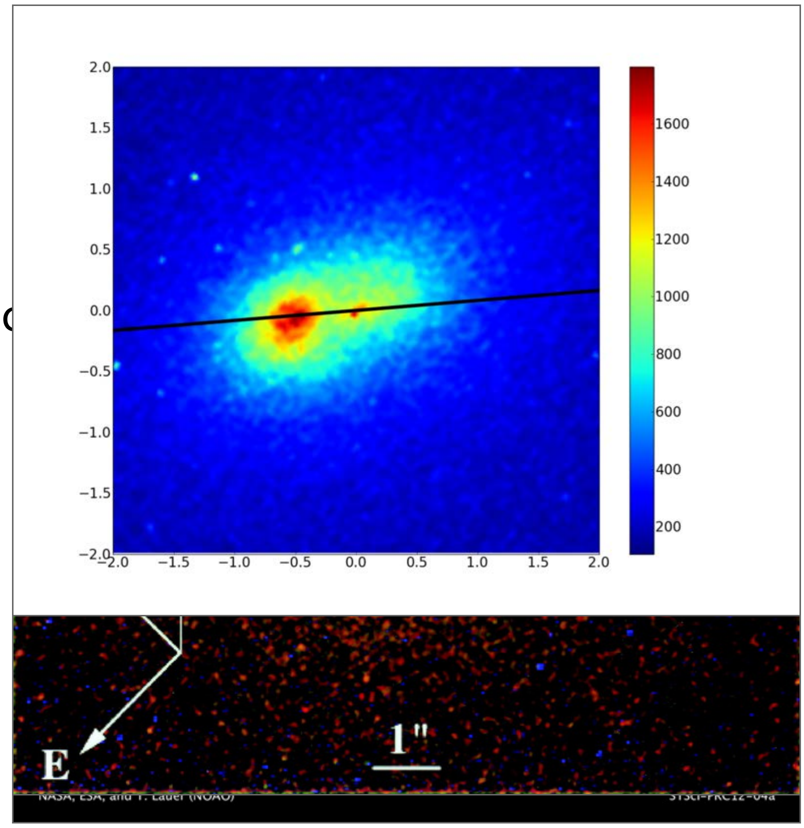


Best-fit mix "classical" with boxy/peanut bulge + bar.
Stellar disc inclination angle $i = 77^\circ$
with bar inclined $10^\circ - 20^\circ$ wrt major axis.

The view from HST

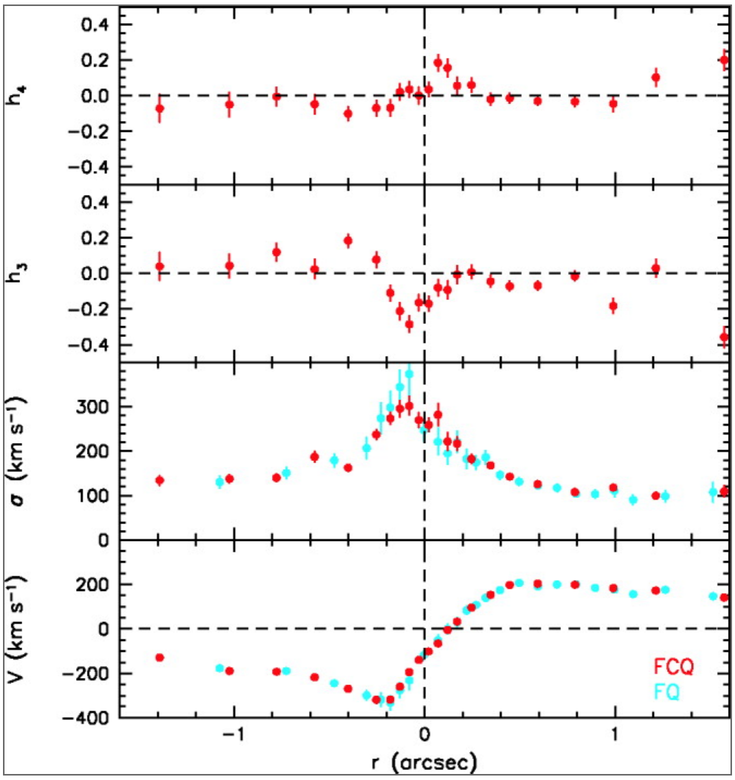
Images from WFPC and ACS (Lauer et al 98, 2012)

- P1: bright peak
- P2: fainter peak
    - photometric centre



HST spectroscopy

STIS CaT long-slit kinematics
(Bender et al 2005)
NB: peak in σ closer to P2 than P1!



Characteristic scales

M31 has a distinct nucleus $L_V \simeq 6 \times 10^6 L_\odot$.
Stars in central ~ 5” are old (7–13 Gyr) and extremely metal-rich ([Z/H]=0.3–0.5) – more so than the surrounding bulge (**Saglia+2010**).

Peaks P1 and P2 have identical colours.
Fainter P2 is photometric centre of galaxy (to $\sim 0.1''$).

- P1-P2 separation $r = 0.5$ arcsec = 2 parsec
- $\Delta v \sim 200$ km/s
- Dynamical time $r/\Delta v \sim 10^4$ yr.

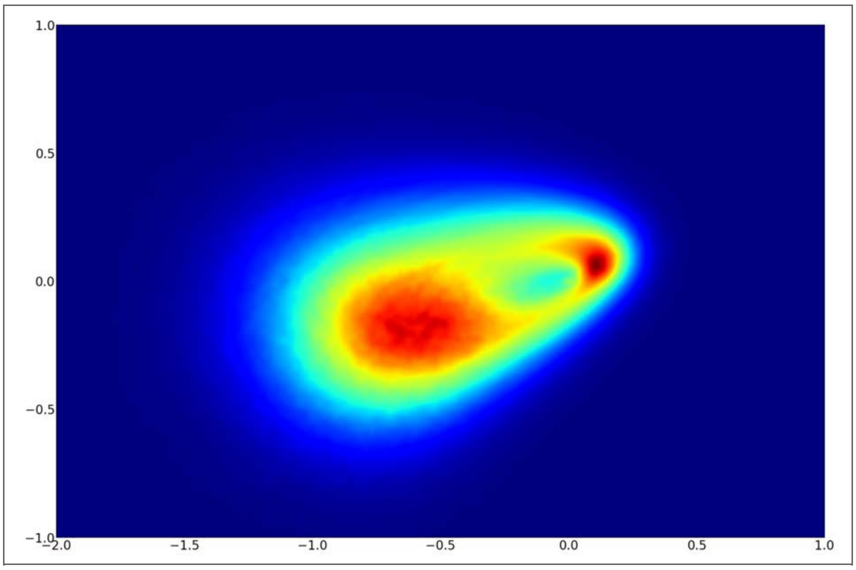
Dust extinction? Two distinct clusters? …

Eccentric disc model (Tremaine 1995)

Consider a clump of orbits in $\Phi = -\frac{GM_\bullet}{r}$ with similar $(a, \mathbf{e}, i)$:

Stars linger at apocentre.

In projection can appear as two peaks, with one slightly offset from BH.

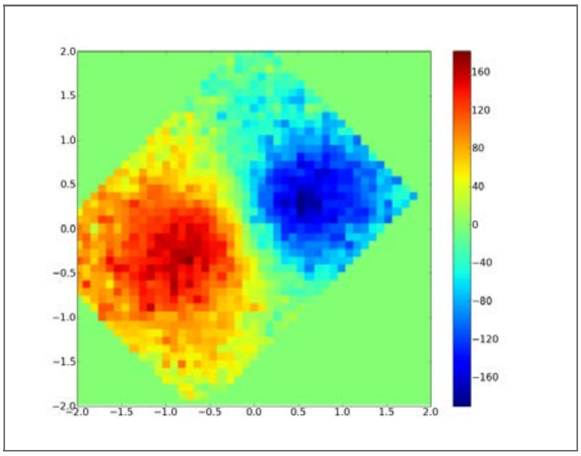


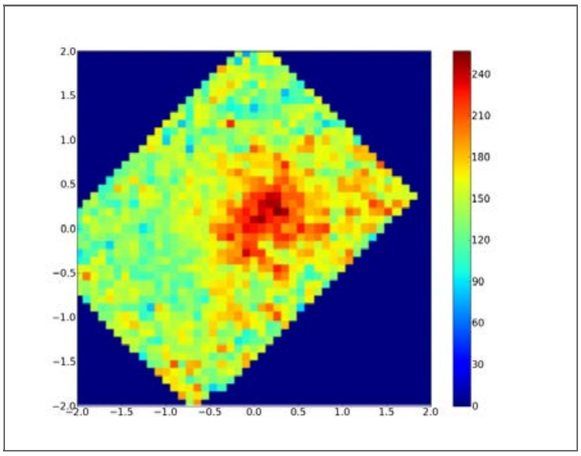
Open questions:

- How to maintain?
- How to form?

Integral field kinematics of nucleus

V (left) and σ (right) fields measured by OASIS IFU (Bacon et al 2001):

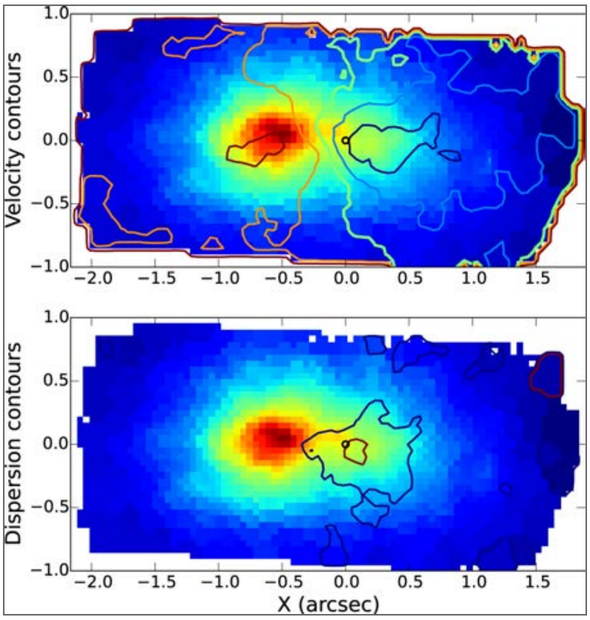




Ca T again. PSF FHWM: 0.4 to 0.8 arcsec.
Location, alignment of peaks consistent with T95 eccentric disc picture.

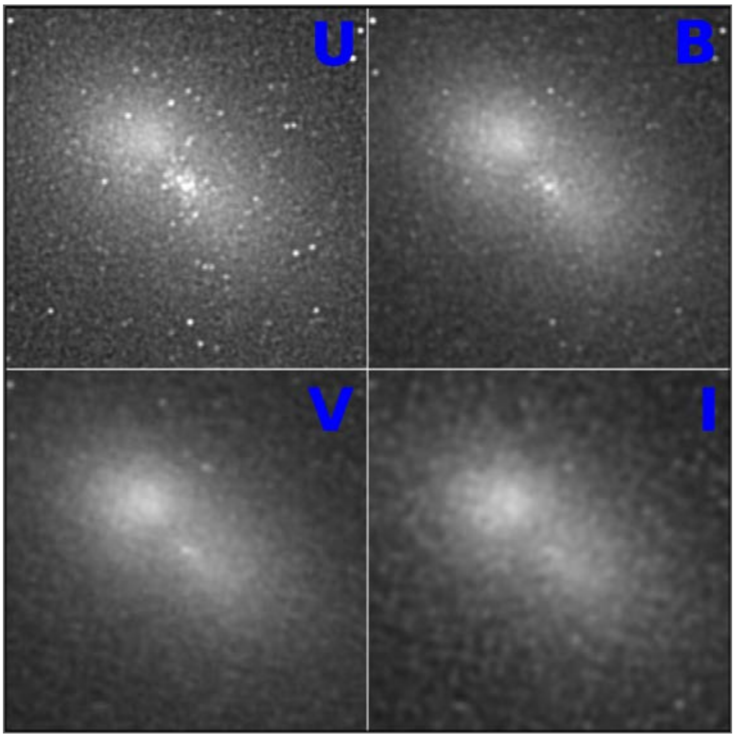
Integral field kinematics of nucleus

Keck observations from Lockhart et al (2018)
FWHM: $0\farcs12/0.45$ pc
Image:
NIRC2 K-band
Contours:
OSIRIS 2.2µm
Consistent with T95.



THE NUCLEUS ISN'T COMPLETELY RED AND DEAD

Inner $3'' \times 3''$ in *U*, *B*, *V*, *I* (Lauer et al 2012);
U-band light peaks just inside P2
– call it P3!

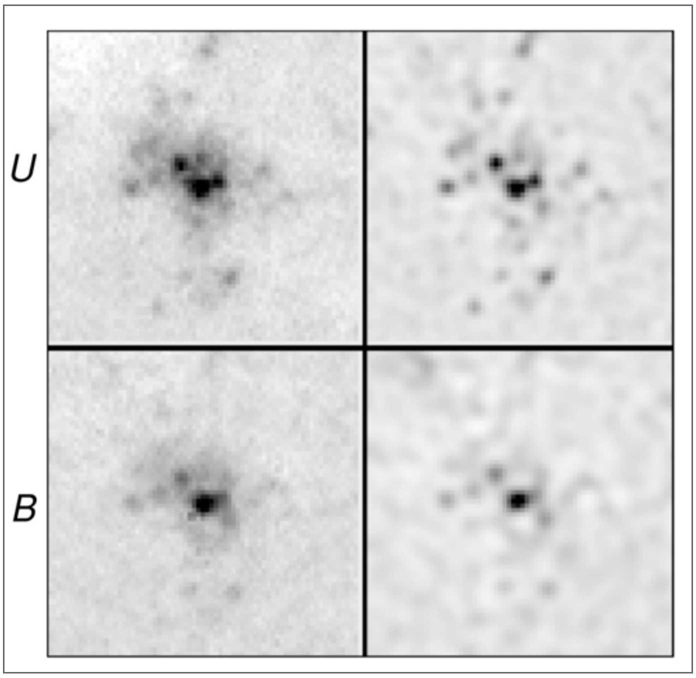


P3

Zoom to $0\rlap{.}''81 \times 0\rlap{.}''81$:
L: Nyquist-sampled
R: deconvolved
Starburst 100-200 Myr:

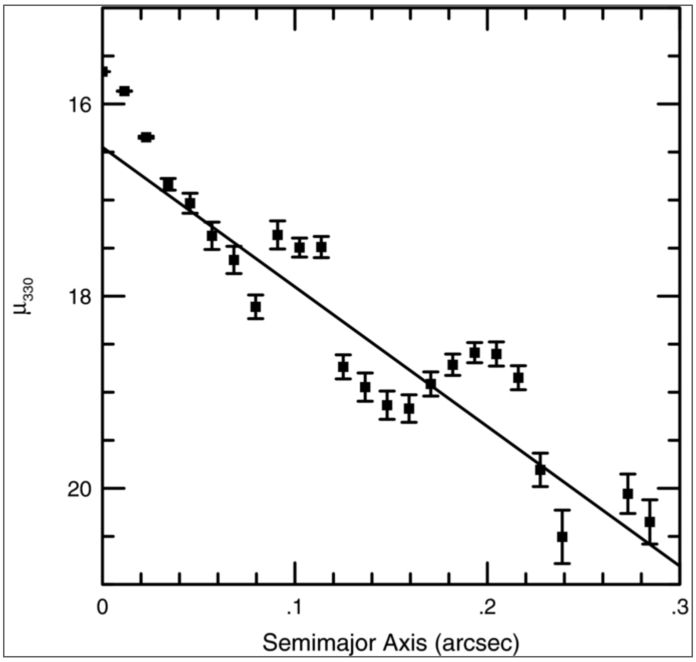
- A0-type spectrum
- colours
- SBF

(Lauer et al 2012)



P3

Zoom to $0\farcs81 \times 0\farcs81$: P3 has scalelength $0\farcs075 = 0.3$ pc (0.3 mas/yr) (Lauer et al 2012)



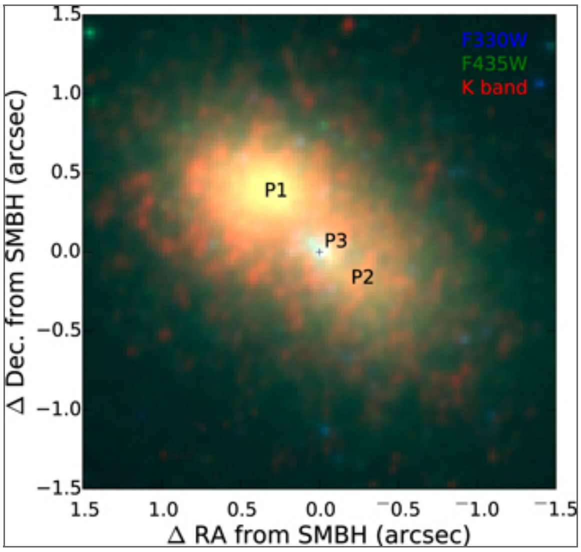
Summary of observations

Double nucleus P1–P2, separated by 2 pc.
Consistent with T95 eccentric disc picture:

- velocity fields plausible
- young stellar population P3 coincident with where we'd expect the BH to be.

But

- does it agree in detail?
- can we learn anything about internal structure?
- clues to formation?



[Image: Lockhart et al 2018]

More detailed modelling

Focus on details of M31:

- Statler (1999), Salow & Statler (2001, 2004)
- Bacon et al (2001)
- Sambhus & Sridhar (2002)
- Peiris & Tremaine (2003)
- …

Eccentric stellar discs in general:

- Hopkins & Quataert (2010)
- Gualandris et al (2012)
- Kazandjian & Touma (2013)
- Arca–Sedda & Capuzzo–Dolcetta (2017)
- Davydenkova & Rafikov (2018)
- Gruzinov, Levin & Zhu (2020)
- …
- Following pair of speakers (Madigan, Tremaine)

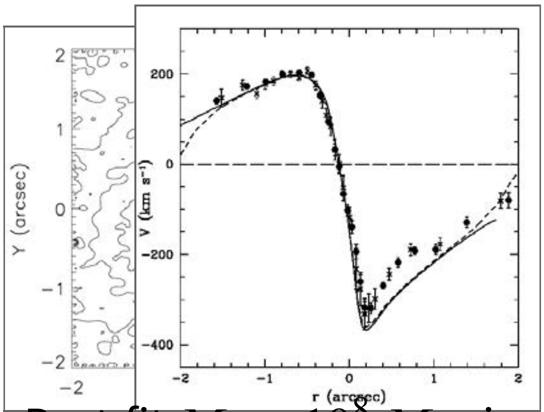
Dynamical sophistication = Kepler (1620)

Peiris & Tremaine (2003)

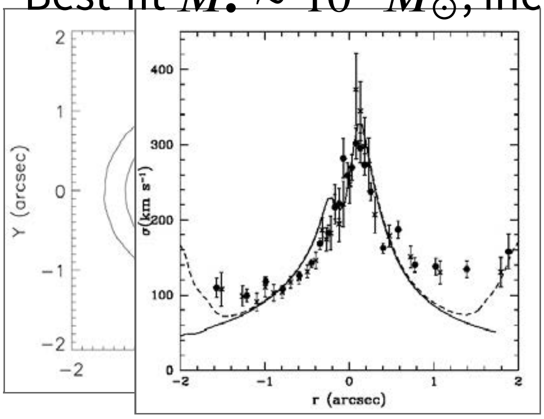
Take $\Phi = -\frac{GM_\bullet}{r}$. Assume phase space DF (biaxial symmetry in y, z planes)

$$f(a, \mathbf{e}, I) = g(a) e \exp\left[-\frac{1}{2}\left(\frac{\mathbf{e} - \mathbf{e}_m(a)}{\sigma_\mathrm{e}}\right)^2\right] \sin I \exp\left[-\frac{1}{2}\left(\frac{I}{\sigma_I(a)}\right)^2\right]$$

with parametrized $g(a)$, $\mathbf{e}_m(a)$, $\sigma_I(a)$. Adjust parameters to fit:



Best-fit $M_\bullet \sim 10^8\ M_\odot$, inclination $i = 54^\circ$ (vs 77° of main disc)



Brown & JM (2013)

Relax PT03 DF, but keep biaxial symmetry in y and z planes.
Assume that stellar orbit distn is

$$f = \sum_k w_k \exp\left[-\frac{(a-a_k)^2}{2\sigma_a^2}\right] e \exp\left[-\frac{(\mathbf{e}-\mathbf{e}_k)^2}{2\sigma_e^2}\right] \sin I \exp\left[-\frac{I^2}{2{\sigma_{I,k}}^2}\right]$$

a sum of blobs centred on fixed knots in (a, e) plane, plus
$\sigma_{I,i} = \{15^\circ, 30^\circ, 45^\circ\}$.

Free parameters: **(only 814 of them)**

- $M_\bullet$;
- orientation of disc on sky $(\theta_l, \theta_i, \theta_a)$.
- $n_a \times n_e \times n_I = 30 \times 9 \times 3$ blob weights, w_k.

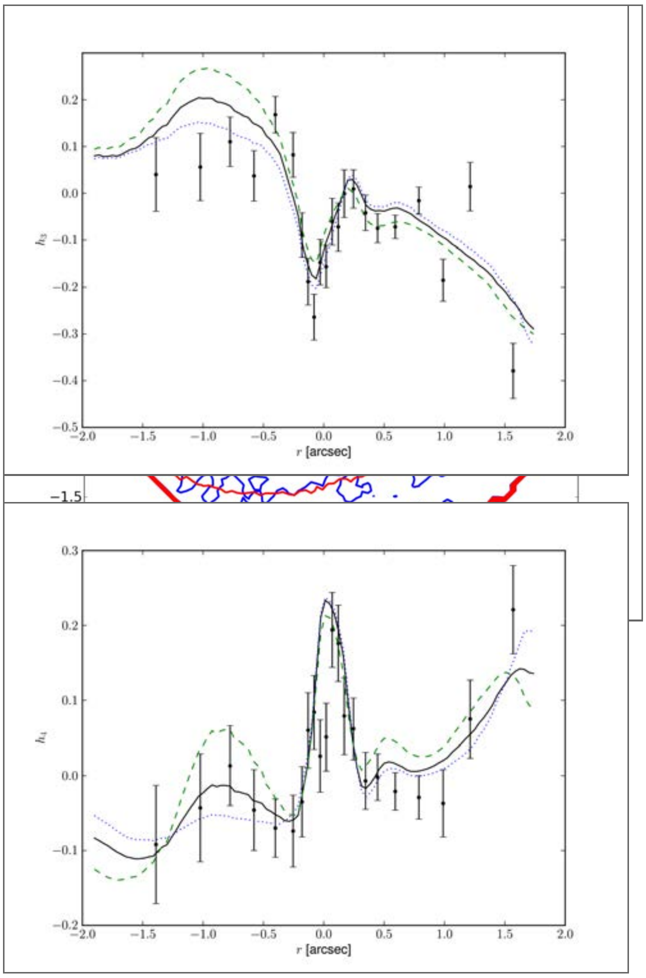
Calculate contribution of each blob to WFPC photometry + STIS kinematics.

Infer w_k by fitting to observations for each choice of $M_\bullet$, angles.

Find best fit when $M_\bullet \sim 10^8 M_\odot, i \simeq 57^\circ$.

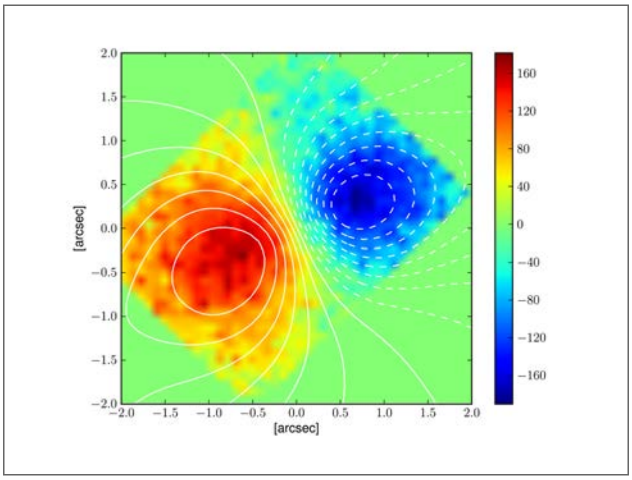
NAIVE 3D MODELS OF MASSLESS DISCS

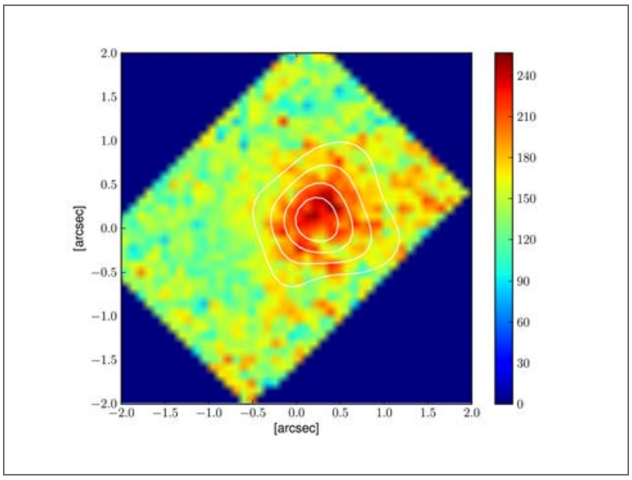
How well does it fit? Photometry and kinematics



NAIVE 3D MODELS OF MASSLESS DISCS

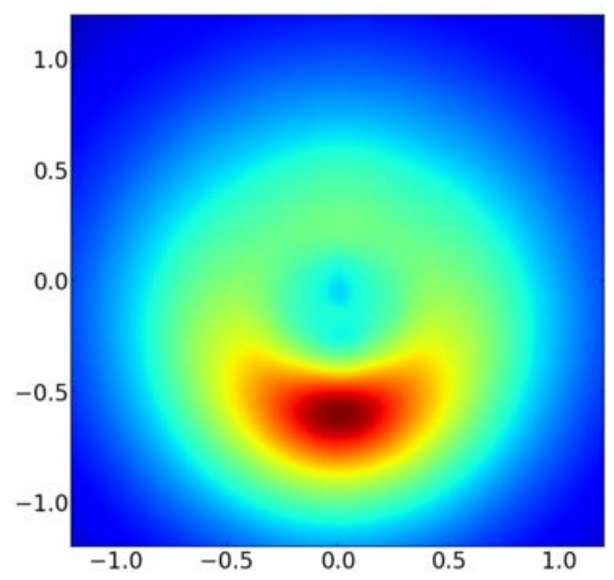
Bacon et al (2001) measured kinematics with OASIS IFU.
Our model **predictions** agree well. Here's V and σ:



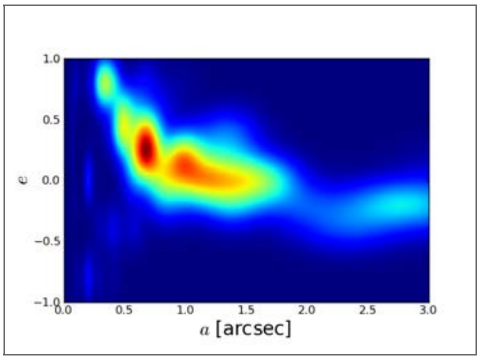


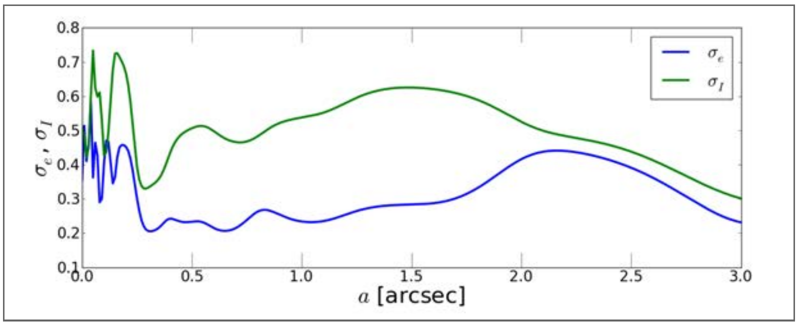
NAIVE 3D MODELS OF MASSLESS DISCS

What does the disc look like?



What about its orbit distribution?



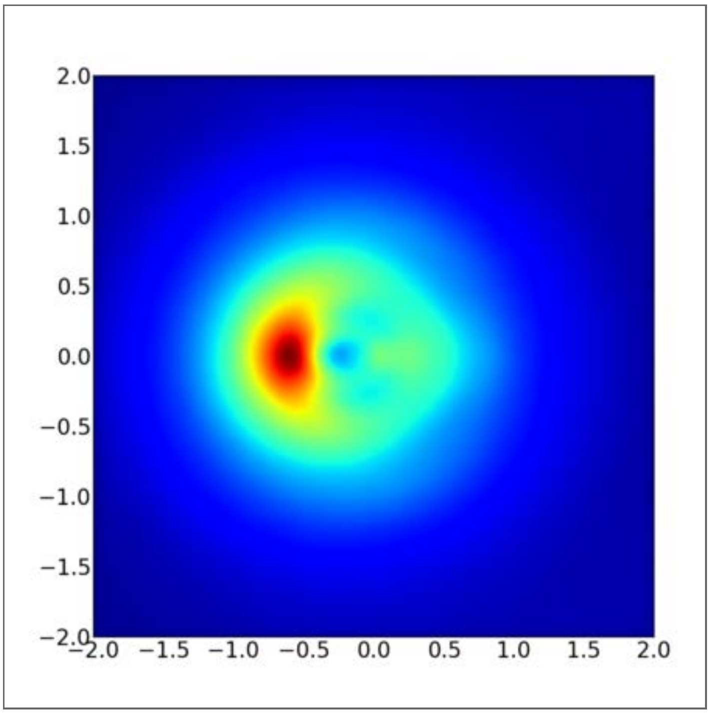


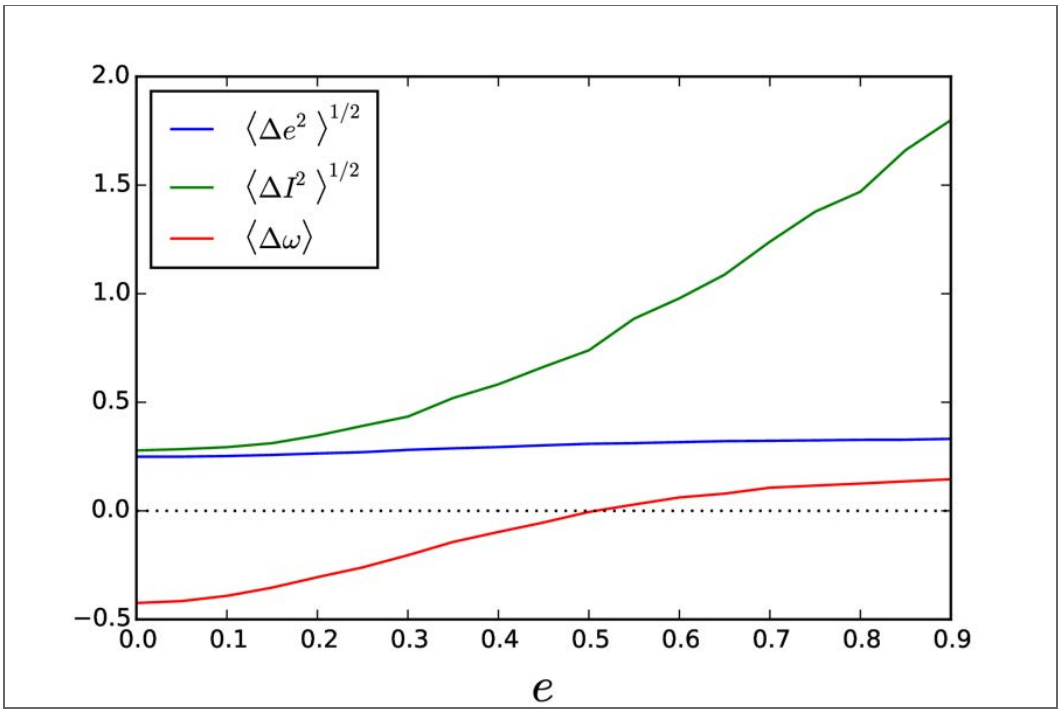
Notice that $\sigma_I/\sigma_e \simeq 2$!
Compare $\sigma_I/\sigma_e \simeq \frac{1}{2}$ produced by two-body interactions *in an axisymmetric disc*
(Ida, Kokubo, Makino 1993).

Dynamical sophistication = Gauss (1818)

Resonant relaxation (Rauch & Tremaine 1996)

Adding weak peturbation $\Phi_\star$ to $\Phi = -\frac{GM_\bullet}{r}$ makes stars' $(a, e, \omega, I, \Omega)$ change slowly.
Calculate $\dot{\mathbf{L}}$, $\dot{\mathbf{e}}$ by averaging $\Phi_\star$ over orbit: smear orbit into ring.
Diffusion coeffs within rings of varying e:





So, we **expect** $\sigma_I/\sigma_e > 1$ in eccentric discs with $\Phi \simeq -GM_\bullet/r$.

[Vector vs scalar RR.]

The end of the road for Kepler

We've assumed that $\Phi = -\frac{GM_\bullet}{r}$ and find $M_\bullet \sim 10^8\ M_\odot$
Using $L_V = 6 \times 10^6\ L_\odot$ means disc mass $M_\star \sim \frac{1}{10} M_\bullet$.
$\Rightarrow$ Keplerian $\Phi = -\frac{GM_\bullet}{r}$ is questionable.

> *A mechanism is needed to maintain apsidal alignment against differential precession…*
> *A … promising possibility is that the alignment is maintained by the self-gravity of the disk.* ***(T95)***

Suppose that:
in some rotating frame BH+disc system is stationary.
Then,

- Does such an equilibrium exist?
- What's the pattern speed Ω_p ?
- How does disc perturbation $\Phi_\star$ affect orbit distn?

Dynamical sophistication = Sridhar & Touma (1999)

Orbits in axsiymmetric potentials

Almost Keplerian → osculating elements: $(\mathbf{x}, \mathbf{v}) \to (a, e, w, \omega)$.
Surface of section: J_ϕ versus ϕ at apocentre for $E = \Phi(5\,\mathrm{pc})$:

Averaging over mean anomaly w gives $J_{\mathrm{fast}} = \sqrt{GMa} \simeq$ const.
$H \to \bar{H}(J_\phi | J_{\mathrm{fast}})$: $J_\phi =$ const; steady precession in $\omega = \phi_{\mathrm{apo}} + \pi$.

Orbits in eccentric disc potentials ($\Omega_{\mathrm{P}} = 0$)

Breaking axisymmetry means $H \simeq \bar{H}(\omega, J_\phi | J_{\mathrm{fast}})$: new orbit families!

- (Perturbed) circulating loops (both prograde and retrograde)
- librating loops (trapped around $\phi_{\mathrm{apo}} = \pi$, both prograde and retrograde)
    - These produce an "aligned" overdensity towards P2
- lenses (next slide)

ORBITS IN ECCENTRIC DISC POTENTIALS ($\Omega_P = 0$)

Slightly more bound orbits:

- The centrophilic lens orbits have no net sense of rotation
    - This one is parented by the (anti-aligned) $\phi_{apo} = 0$ radial orbit.
- In contrast loop orbits are centrophobic and have definite sense of rotation
- There is another lens family…

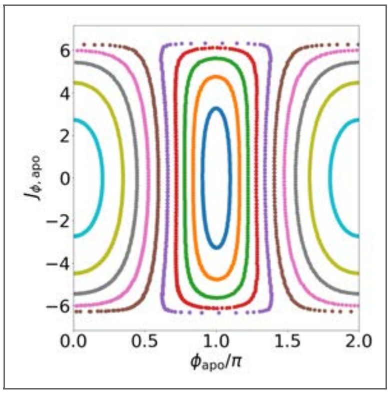
Orbits in eccentric disc potentials ($\Omega_{\mathrm{P}} = 0$)

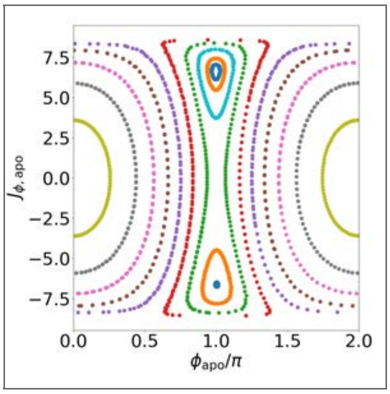
For deeper E the loops disappear completely:

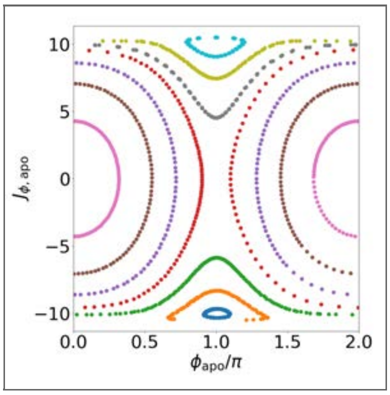
Loops replaced by epicycles on the $\phi_{\mathrm{apo}} = \pi$ (aligned) radial orbit.

Orbit families for $\Omega_{\mathrm{P}} = 0$

(Symmetric about $J_\phi = 0$!)





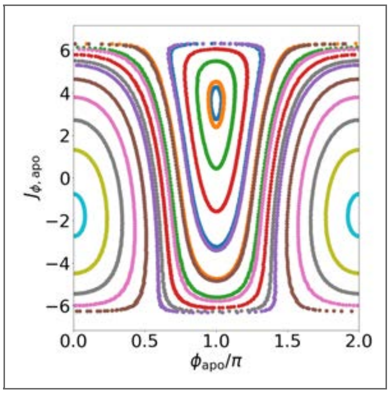


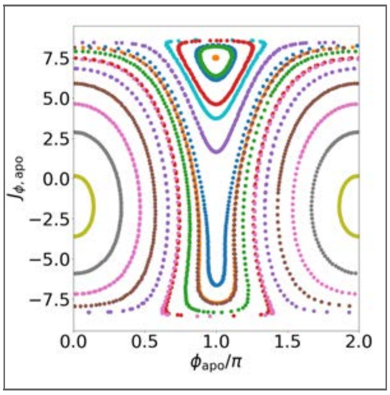
Close to BH: aligned/anti-aligned radial orbits
Further out: loops emerge in aligned area.
NB: Phase-space volume $\mathrm{d}^2\mathbf{r}\,\mathrm{d}^2\mathbf{p} = T_r\,\mathrm{d}\phi_{\mathrm{apo}}\,\mathrm{d}J_\phi\,\mathrm{d}H$.

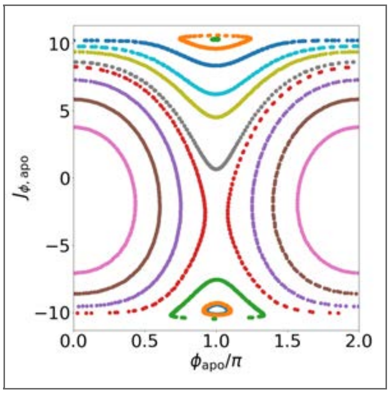
What if we add figure rotation?

BH+disc system rotates about CofM with pattern $\Omega_{\rm p} = 1$ km/s/pc.

$H = H_{\rm Kep} - \Omega_{\rm p} \cdot \mathbf{J}_\phi + \Phi_\star$.







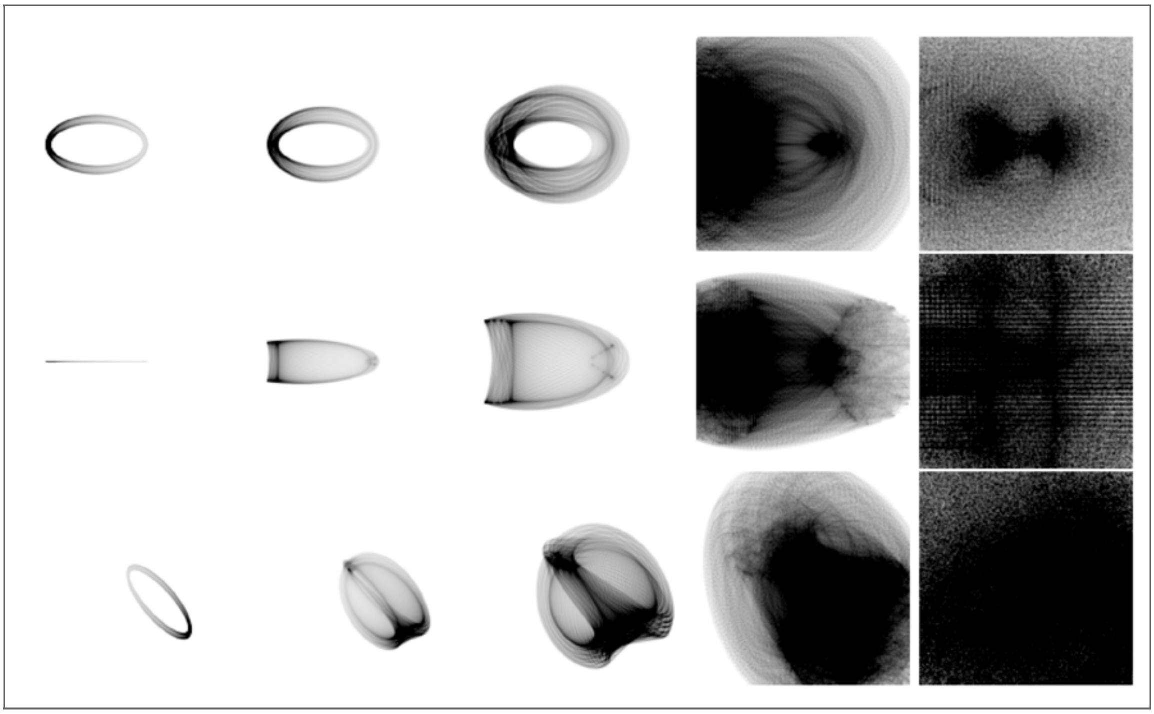
Parent orbit of lenses become loops, $J_\phi \neq 0$!

This $J_\phi > 0$ for aligned orbits ($\phi_{\rm apo} = \pi$) when $\Omega_{\rm p} > 0$.

What if we add figure rotation?

Some example orbits

Orbits in 3d (Calum Brown thesis)



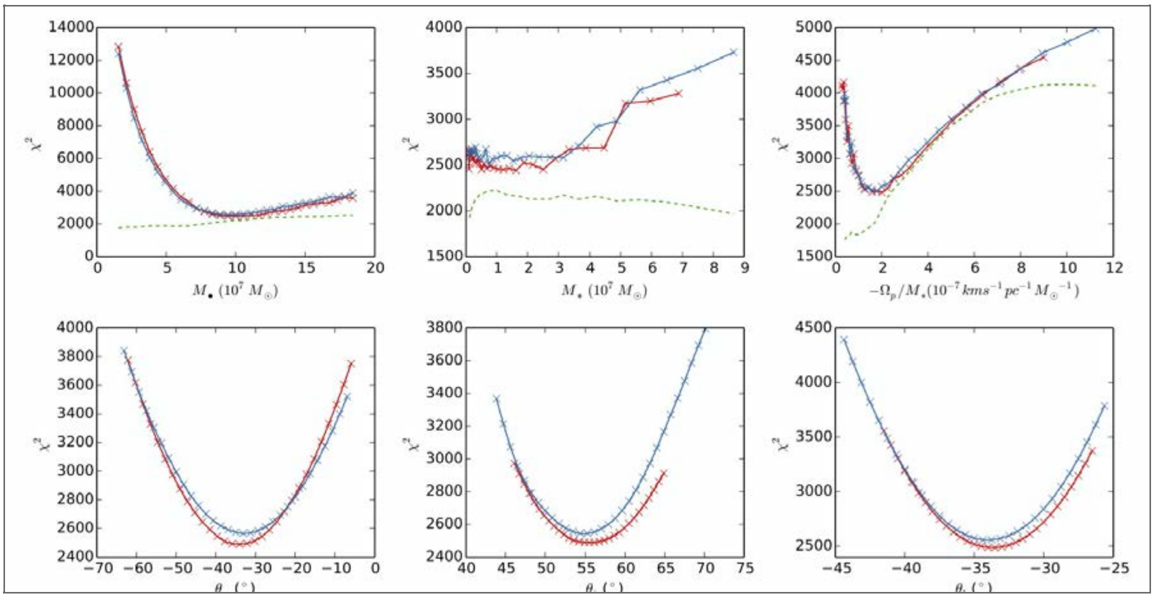
Putting this together (Calum Brown thesis)

How it works

BH plus disc rotate about centre of mass with pattern speed Ω_{p}
Steady-state DF $f = f(\mathbf{J})$
Projected on sky with some $(\theta_l, \theta_i, \theta_a)$ We want to know everything! (H, f)

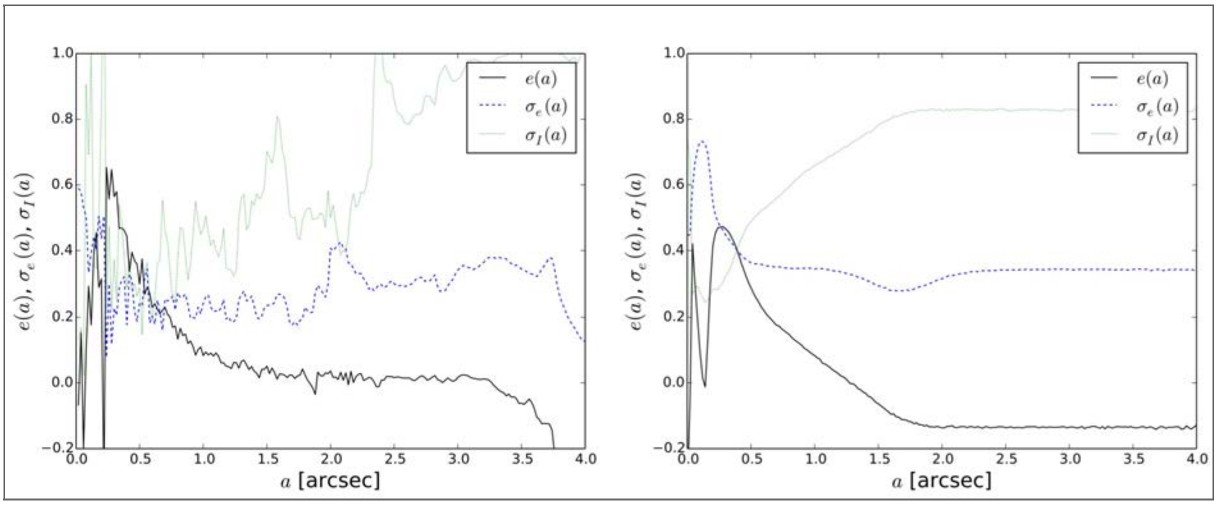
1. Assume $M_\bullet, \rho_\star, \Omega_{\mathrm{p}}$.
2. Follow orbits in this H
    - Sampling orbits well is *hard*
3. Project for $(\theta_l, \theta_i, \theta_a)$
4. Best linear combination of orbits that matches observations?
5. Adjust $(\theta_l, \theta_i, \theta_a)$, $M_\bullet$ and $\Omega_\bullet$ try again

CONSTRAINTS ON PARAMETERS

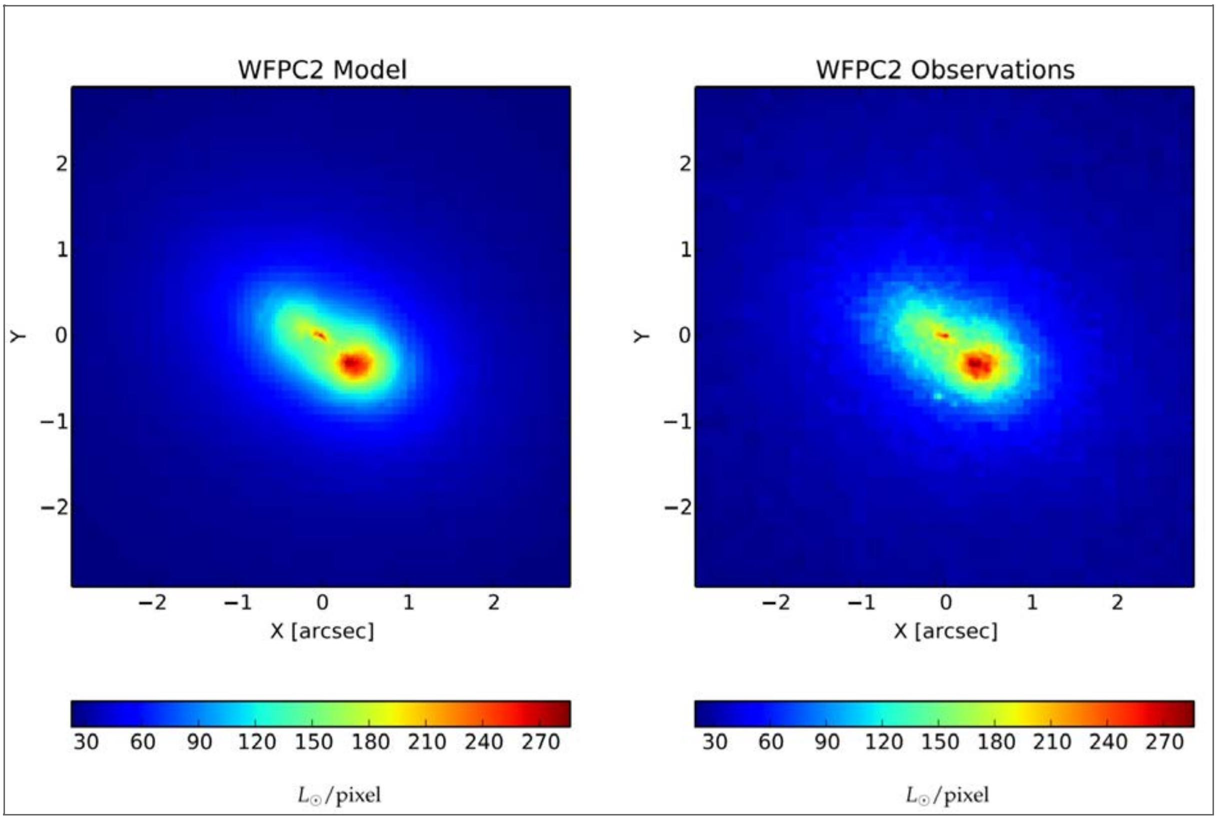


$$M_\bullet \sim 10^8\,M_\odot, \quad i \simeq 55^\circ, \quad \Omega_\mathrm{p} \sim 2\left(\frac{M_\star}{10^7\,M_\odot}\right)\,\text{km/s/pc}.$$

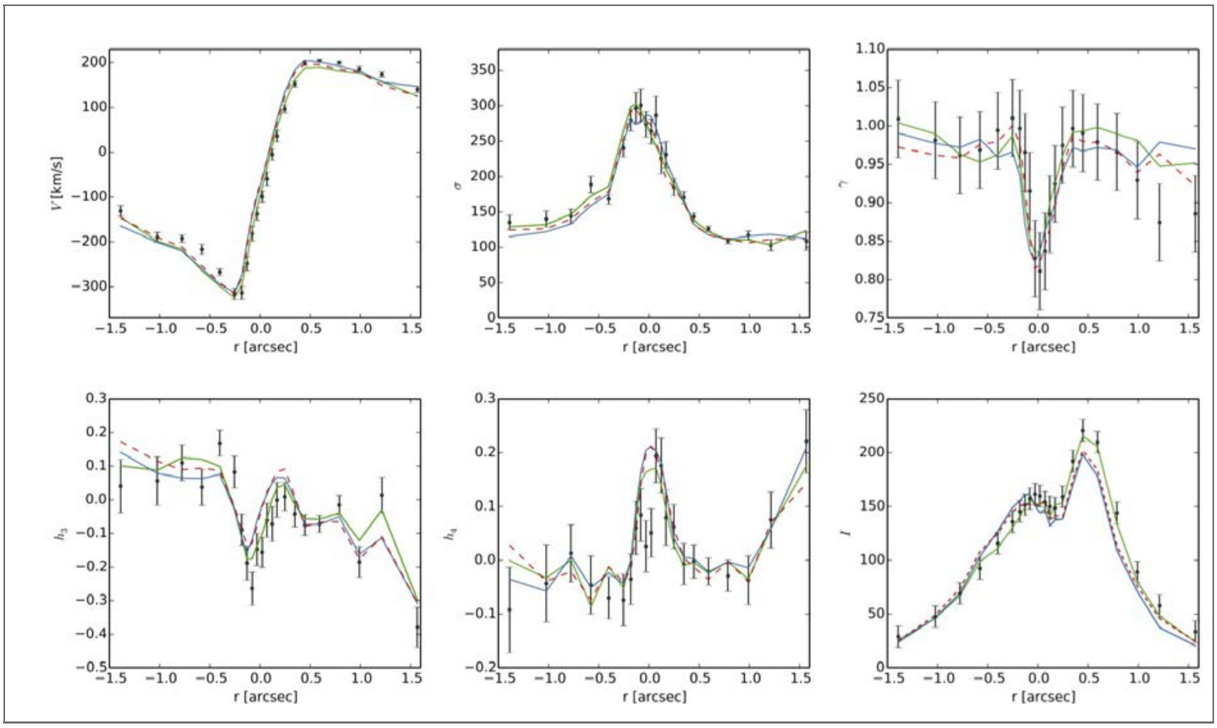
Calum's self-consistent DF versus the BM13 Kepler DF



How well does it fit? WFPC

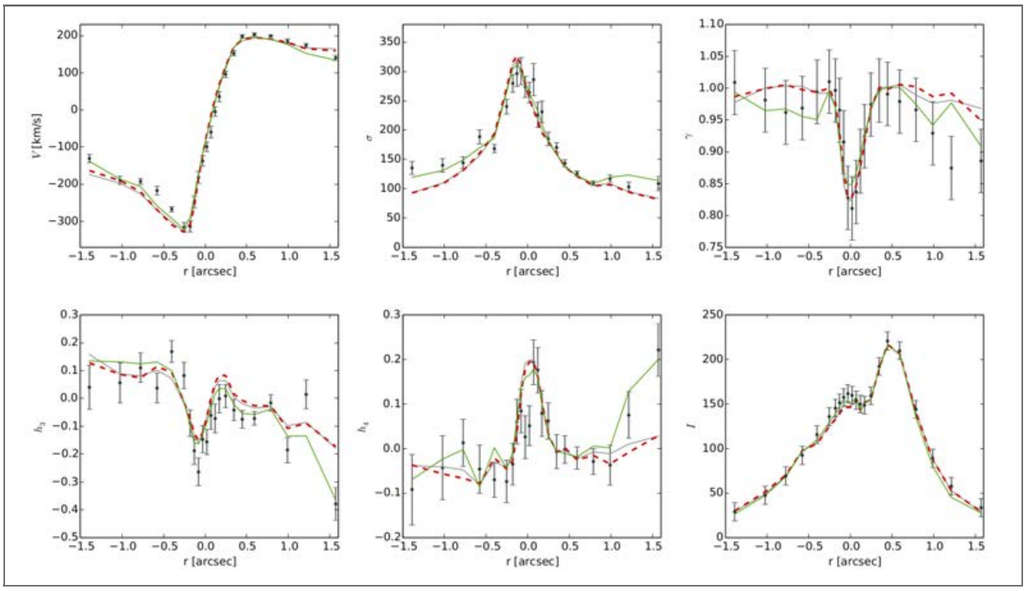


How well does it fit? STIS

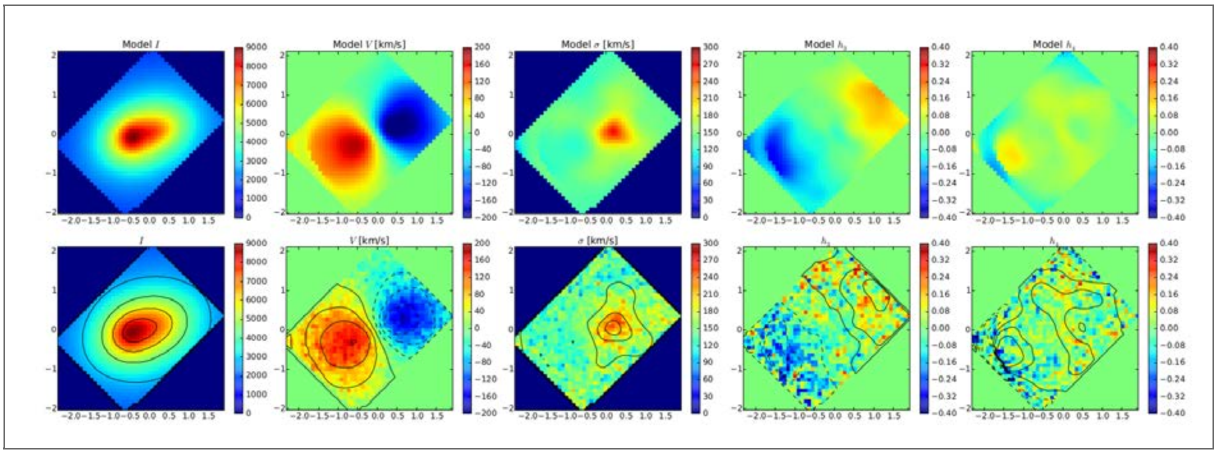


How well does it fit? STIS

Iterating $\rho_\star(\mathbf{x})$ to self-consistency improves the fit! (A bit)
Here are the STIS kinematics: initial guess to final models



How well does it fit? OASIS



But does it blend?

N-body realization viewed from frame corotating with $\Omega_{\mathrm{p}} = 1.65$ km/s/pc:

Summary

SUMMARY

- M31 has a double nucleus
    - distinct, old stellar population, save for P3
- Tremaine's (1995) eccentric disc picture is compelling
- $M_\bullet \sim 10^8 M_\odot, \quad i \simeq 55^\circ, \quad \Omega_{\rm p} \sim 2\left(\frac{M_\star}{10^7\ M_\odot}\right)$ km/s/pc, $\sigma_I > \sigma_e$

Models can't explain all details of kinematics, because…

- vertical sampling an unsolved problem
- we've imposed biaxial symmetry, plus
- steady state (in rotating frame): no warps or wobbles
- we assume BH+disc is isolated.

Open questions

Caveats:

- vertical sampling unsolved problem
- we've imposed biaxial symmetry, plus
- steady state (in rotating frame): no warps or wobbles
- we assume BH+disc is isolated.

Open questions:

- Why is the eccentric disc misaligned with its host?
- What sort of wobbles is an eccentric disc susceptible to?
- How do they form?
- What role do centrophilic orbits play? (e.g., lenses)
    - are they occupied?
    - do they enhance TDE rates?
- Where are the other eccentric stellar discs?