The centre of M31
vs the Milky Way

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Bologna, 17 Jan 2017

Outline

Both M31 and MW have:

- central supermassive black hole (BH)
- surrounded by a dense cluster of stars
  - MW's cluster is typical
  - M31's is unusual

Outline:

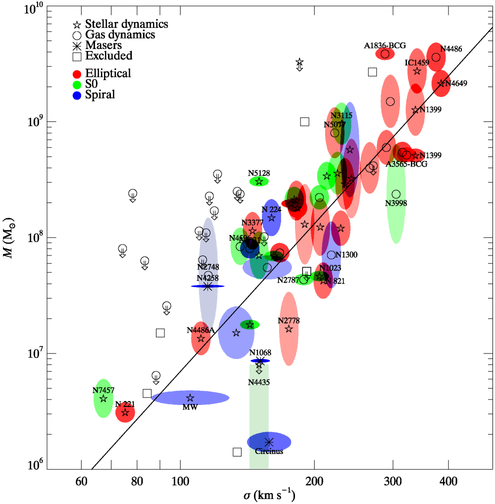
1. Motivation/context
2. MW
3. M31

Motivation

HST and friends: black holes (BHs)

(Gültekin et al 2009)

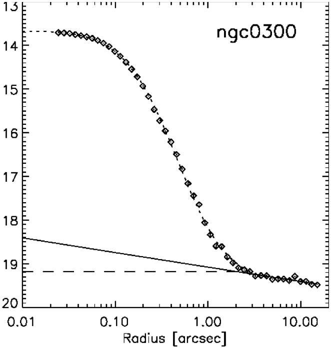
Black holes: standard equipment



$$M_\bullet \sim 3 \times 10^8 \left(\frac{\sigma_{\mathrm{bulge}}}{200\ \mathrm{km/s}} \right)^4$$

$$\sim 2 \times 10^{-3} M_{\mathrm{bulge}}$$

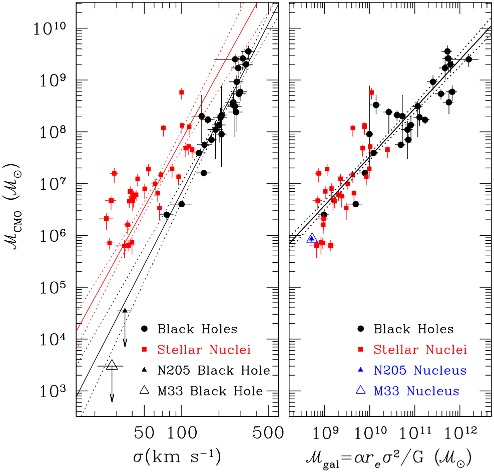
Nuclear stellar clusters (NCs)
(e.g., van der Marel et al. 2007)



Only “hot” component in late-type spirals. Best studied there.
Present in $> \frac{1}{2}$ of early- and late-type spirals, dEs, low-L Es.

Bursty star formation, detectable within last 10^8 yr.

Scaling – NSCs in early-type Virgo galaxies
(e.g., Wehner & Harris 2006; Côté et al 2006)



$L \sim 10^6 L_\odot$, $r \propto L^{0.5}$

- *Photometric* masses! (For all but $\sim$ 10)
- Low-mass extension of $M_\bullet$-$M_{\rm bulge}$?
- But NSCs bigger by 3.3x?
- Common formation mechanism?
- Do NSCs harbour BHs? Yes! (NGC 4395, MW)

Open questions

Three problems:

1. How do BH and surrounding bulge form? How do they “know” about one another?
   - bulge characteristic radius ($\sim$ kpc) vs
   - BH “sphere of influence” radius ($\sim$ pc)

2. Connection between BH and NSC?

3. Dynamics of dense stellar systems ($10^6\ M_\odot\ \mathrm{pc}^{-3}$)
   - Dynamical processes around BH? (Mass segregation, resonant relaxation...)
   - Collisions of stars?
   - Tidal disruption of stars by BH?
   - Gravitational wave emission from neutron stars/white dwarfs? (EMRI)

Solution to 3: focus on nearby galaxies! (MW, M31)

What would we like to know?

We (usually) only have a snapshot of present state of galaxy.

Two things we'd like to extract from snapshot

1. 6d phase space DF $f(\mathbf{x}, \mathbf{v})$ of each stellar pop
2. gravitational potential $\Phi(\mathbf{x})$
   - ideally split into contributions from stars, BH, "dark" matter etc.

Observed snapshot = projection of $f(\mathbf{x}, \mathbf{v})$.
Usually need **Jeans' theorem** to constrain $\Phi(\mathbf{x})$.

Test scenarios for galaxy formation and evolution against resulting Φ, f.

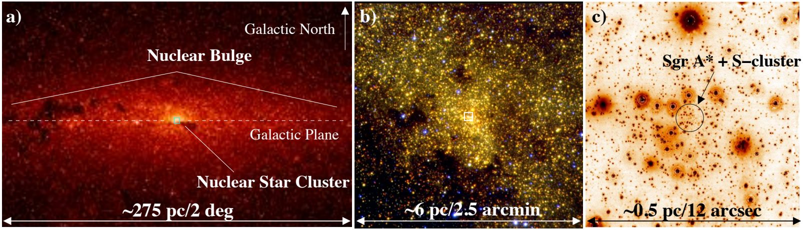
The Milky Way

(massive failure)

Stellar pops at Galactic centre (scale $\sim$ 10 pc)

(Genzel et al., Ghez et al.)

NSC emerges clearly in MIR:



Schödel+2014 (L: 4.5μm; M: 1.2 — 2.2μm; R: K)

Detect giants, supergiants, MS $> 3\ M_\odot$ (not *identify*: crowding, extinction)

Populations:

- dominant old population depleted in inner 10 arcsec
- B stars (“S” stars) in inner arcsec
- O stars further out, some in disc-like configuration.

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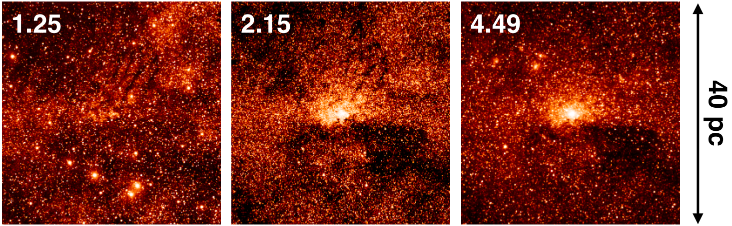

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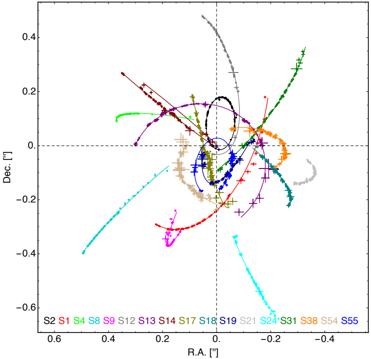
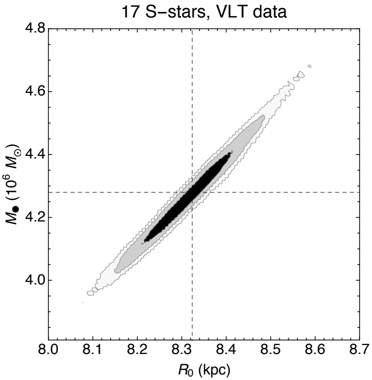
S stars (scale $\sim 10^{-2}$ pc.)
(Most recent: Gillessen et al 2017)

Simultaneous $7 + 6N = 109$-parameter fit to $N = 17$ stars:





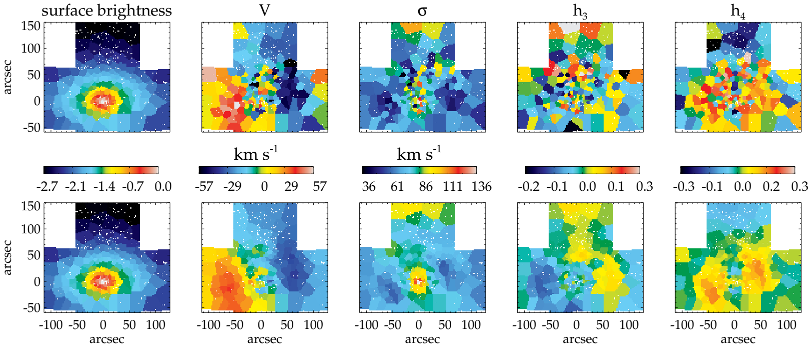
$$\frac{M_\bullet}{10^6\,M_\odot} = 4.28 \pm 0.10\,\big|_{\rm stat} \pm 0.21\,\big|_{\rm sys}\,.$$

Good handle on $M_\bullet$: sets inner BC on dyn. models.
But what can we say about the surrounding star cluster?

Cluster at centre of Milky Way (pc scales)

Binned kinematics from Feldmeier+2014,17

Top: **Integrated kinematics**, cleaned to remove bright stars.

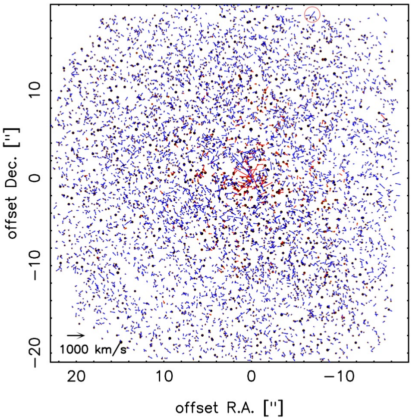


Bottom: model fit to these data, $M_\bullet/10^6\,M_\odot = 1.7 - 4.1$.

But: what lurks beneath? Is V twist real?

Cluster at centre of Milky Way (inner 1 pc)

Alternative: Schoedel et al (2009) provide (x, y, v_x, v_y) for sample of 6000 stars within 1pc of Galactic centre: (z, v_z) missing



Q: What's the mass distribution $\rho(r)$? BH vs cluster?
What does the cluster look like in 3d? in 6d? Mini Gaia!

Results from dynamical modelling of 6000 PMs
(JM, in prep)

Use orbit-superposition (Schwarzschild) method:

- assume spherical symmetry (for now)
- no assumption about anisotropy
- no assumption about number density profile
- simultaneous fit to (x, y, v_x, v_y) of all 6000 stars (w/ errors)

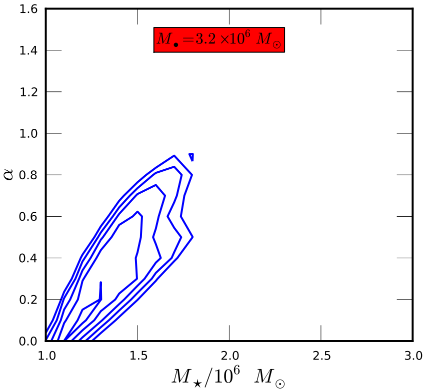
Procedure:

1. Potential Φ: BH $M_\bullet$ plus stars $\rho_\star \propto r^{-\alpha}$, with $M_\star$ within 1 pc.
2. Split phase space into blocks of orbits
3. Find orbit dist in this Φ that best matches observed distn

This yields likelihood of $(M_\bullet, M_\star, \alpha)$.

Results from dynamical modelling
(JM, in prep)

Contours of log-likelihood
spaced at $\Delta \log \mathrm{p}(D|\Phi) = 1$ (i.e., "$\Delta\chi^2 = 2$").



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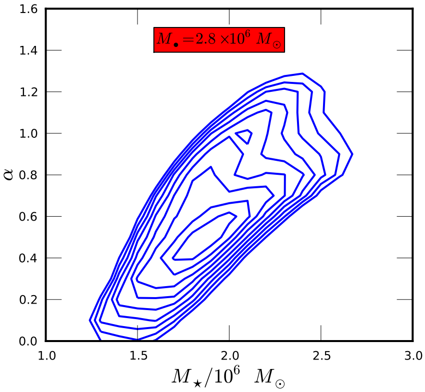

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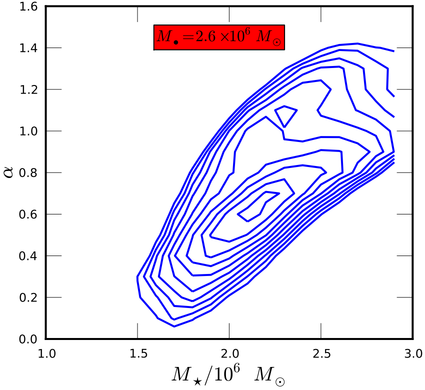

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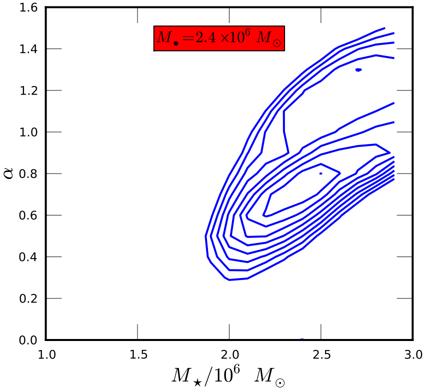
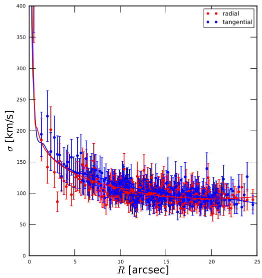


Summary of spherical models of MW

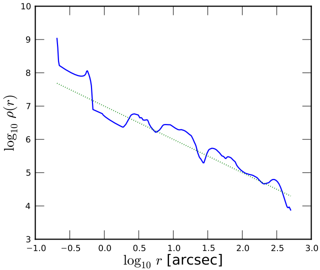
My best-fitting orbit-superposition model has:

- $M_\bullet = \underbrace{2.6}_{\pm 0.1\text{ish}} \times 10^6 M_\odot$, around which
- the stellar mass density $\rho_\star \sim r^{-0.6}$, having
- $M_\star = 2.1 \times 10^6 M_\odot$ within 1 pc.

Does it look plausible? Yes!



Binned-up velocity dispersions agree!

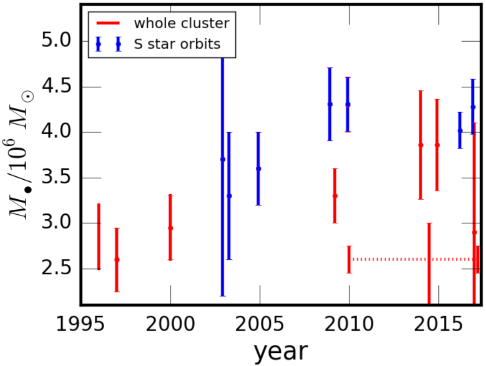


Mass (dotted) follows light (solid)!

Analysis based on Jeans equs gives consistent result.

Milky Way: BH growth in action

Evolution of MW's BH mass over time:



Puzzle: why do red and blue disagree? Not $\beta(r)$, binning. Maybe $j(r)$?

Assumption that cluster is spherical? Non-rotating? (No!)

Related to disc-like distn of young stars? Probably.

See also Fritz+2015, Chatzopoulos+2015, Feldmeier+2017.

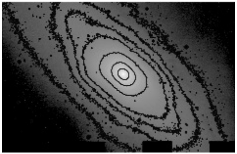
M31

(great success)

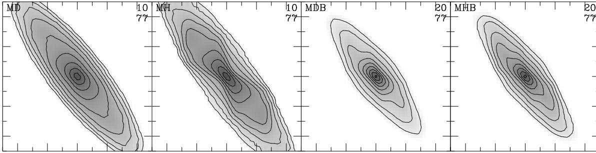
M31 overview

$D \sim 800$ kpc
N-body/hydro models (Athanassoula & Beaton 2006; Blaña et al 2017) can match broad photometry/kinematics
Examples: (A+B06)

J-band light



N-body models



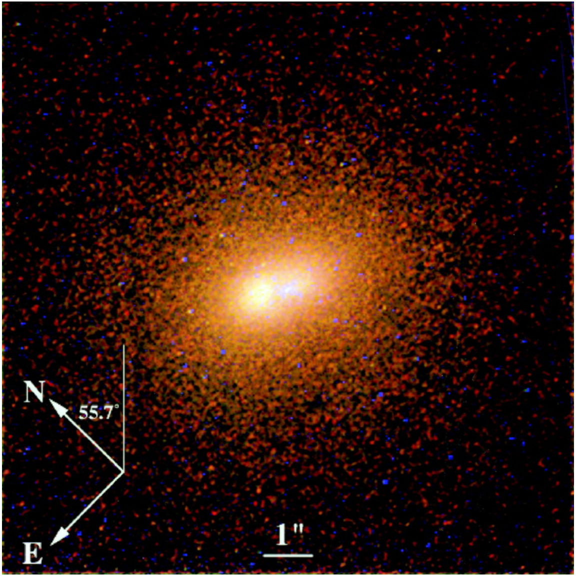
Best models mix "classical" with plus boxy/peanut bulge.
Suggest inclination angle $i = 77^\circ$,
bar inclined $10 - 20^\circ$ wrt major axis.

Nowadays many surveys of outer parts (PANDAS, HELGA, ...)


M31 Nucleus
Hubble Space Telescope • ACS/HRC
HST ACS/HRC
WIYN/KPNO 0.9m Mosaic I
NASA, ESA, and T. Lauer (NOAO)
STScI-PRC12-04a

Data

WFPC photometry (Lauer et al 98):



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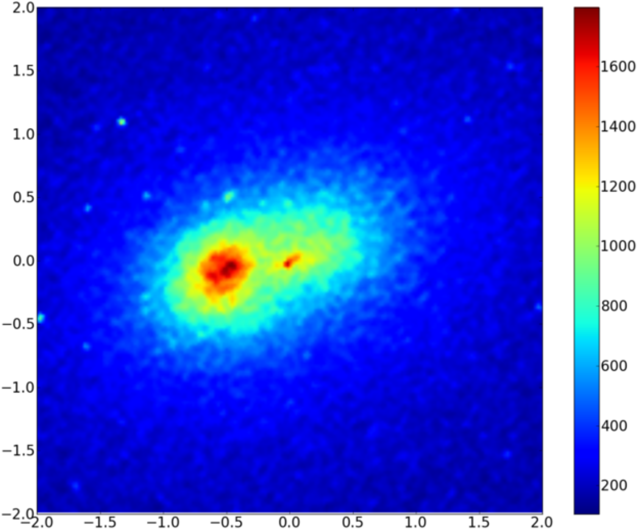
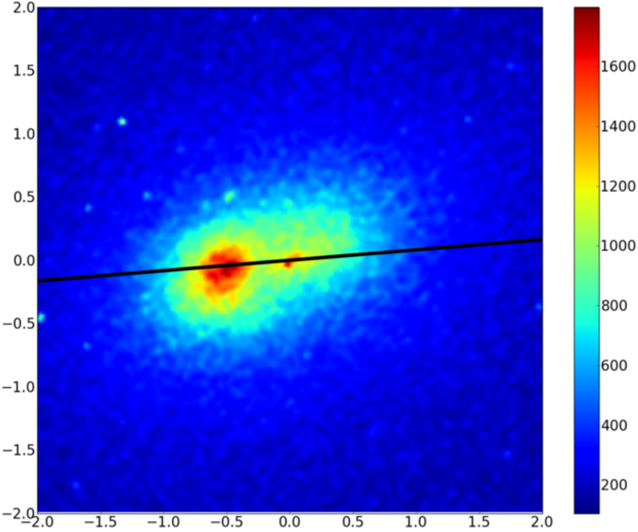


Data

STIS CaT long-slit kinematics (Bender et al 2005):



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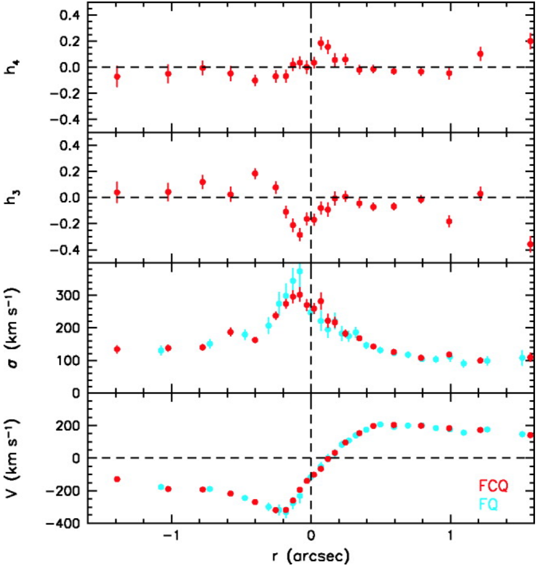


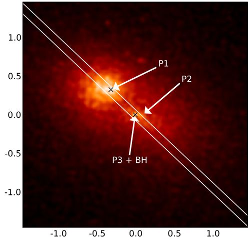
Characteristic numbers for M31 double nucleus

Distinct nucleus $L_V \simeq 6 \times 10^6 L_\odot$ with two peaks, P1 and P2.

P1 and P2 have identical colours: **old, red**.
Blue cluster within P2 is known as P3.

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 $2\pi r/v \sim 10^5$ yr.



Two distinct clusters?
Dynamical friction timescale only $\sim 10^8$ yr.

Tremaine's (1995) eccentric disc scenario

Double nucleus is eccentric disc of stars around BH

– applies to dominant **old, red** stellar population –

Subsequent dynamical modelling by

- Statler (1999), Salow & Statler (2001, 2004)
- Sambhus & Sridhar (2002)
- Peiris & Tremaine (2003)
- Bender et al (2005)

plus some ab initio simulation work.

3d models of massless discs
Peiris & Tremaine 2003

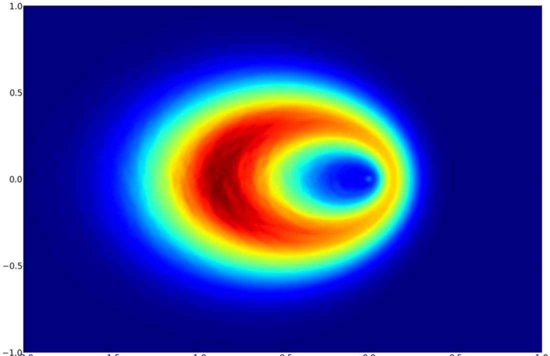
Forget about stellar mass, GR. Take $\Phi = -\frac{GM_\bullet}{r}$.

All stars are on elliptical orbits, characterised by

- size, shape (a, e)
- orientation (ω, I, Ω).

Stars linger at apocentre $\Rightarrow$ bright spot off BH.

Clump of stars around $a = 1$, $e = 0.7$ projected along z:



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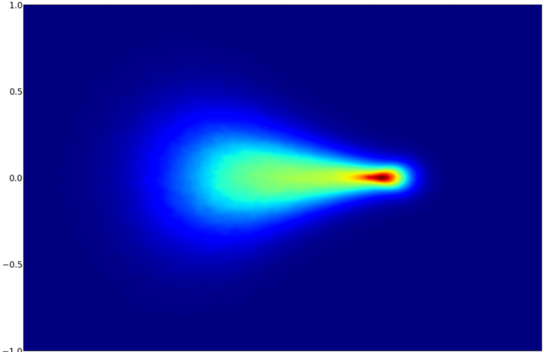
Clump of stars around $a = 1$, $e = 0.7$ projected along y:



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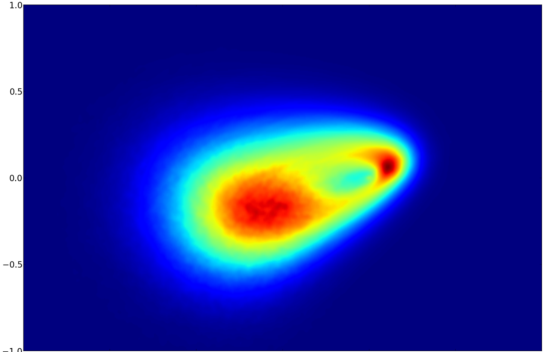
Clump of stars around $a = 1$, $e = 0.7$ projected along los:



Euler angles:
θ_l, θ_i, θ_a

Naive 3d models of massless discs
(Calum Brown & JM, MNRAS 2013)

Assume biaxial symmetry in y and z planes.
Assume that orbit distn can be written as

$$f = \sum_i w_i \exp\left[-\frac{(a-a_i)^2}{2\sigma_a^2}\right] e \exp\left[-\frac{(\mathbf{e}-\mathbf{e}_i)^2}{2\sigma_e^2}\right] \sin I \exp\left[-\frac{I^2}{2{\sigma_{I,i}}^2}\right].$$

Multiblob expansion

Blobs centred on fixed pts in (a, e) plane, plus
$\sigma_{I,i} = \{15°, 30°, 45°\}$.

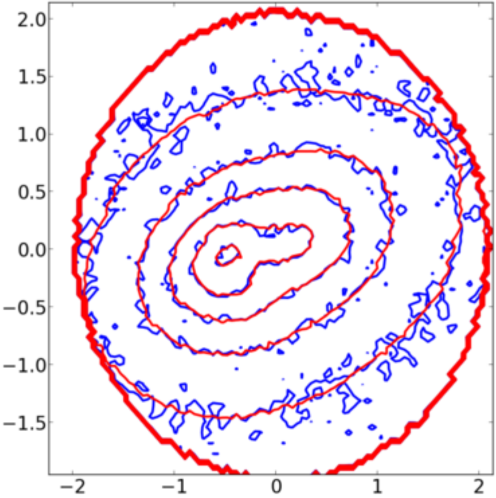
Free parameters:

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

Infer parameters from WFPC photometry + STIS kinematics.

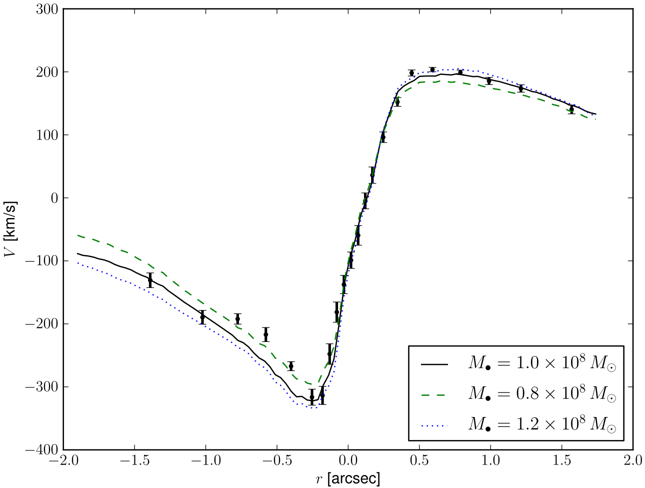
Naive 3d models of massless discs

Multiblob fit to WFPC



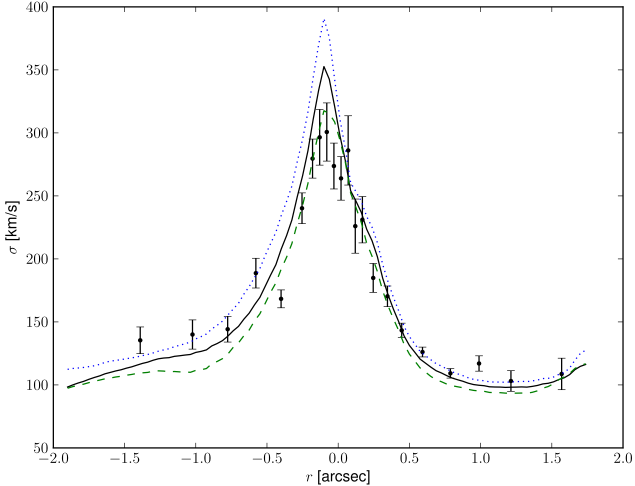
Naive 3d models of massless discs

Multiblob fit to STIS V for different $M_\bullet$



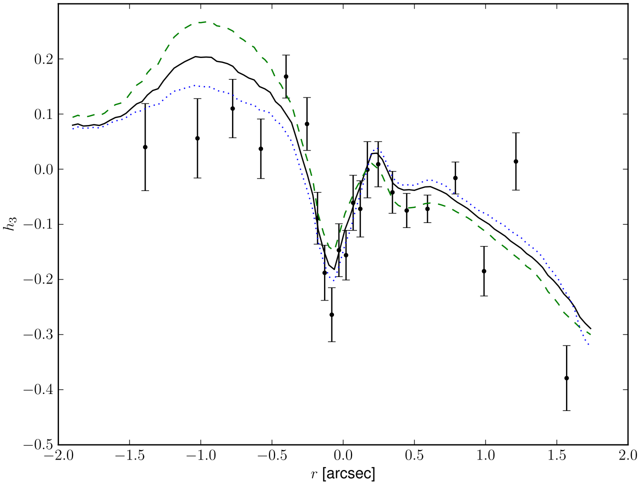
Naive 3d models of massless discs

Multiblob fit to STIS σ



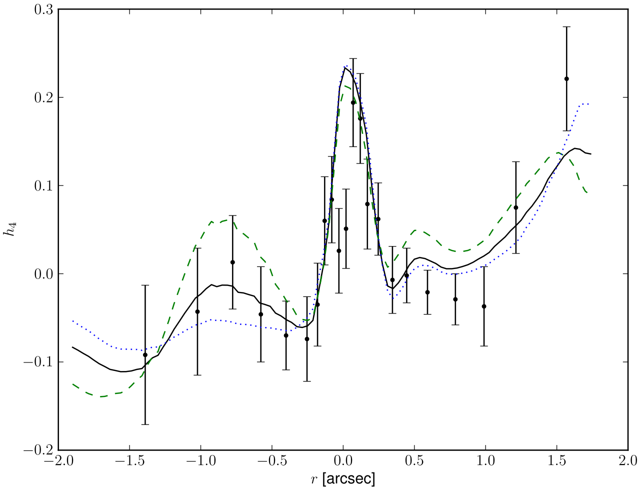
Naive 3d models of massless discs

Multiblob fit to STIS h_3



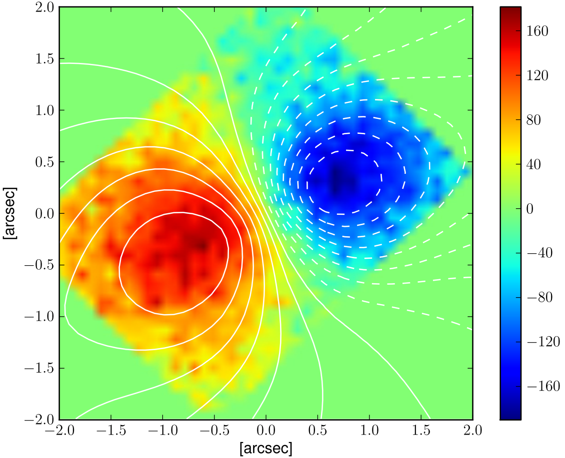
Naive 3d models of massless discs

Multiblob fit to STIS h_4



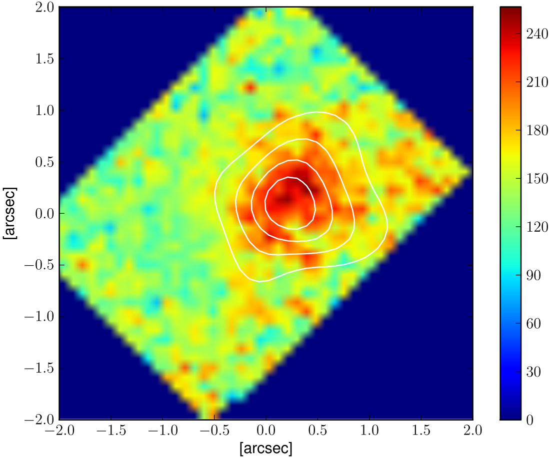
Naive 3d models of massless discs

Model *predictions* agree well with OASIS kinematic maps: V

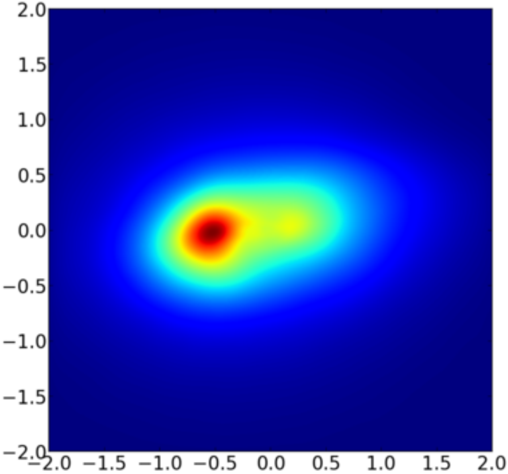


Naive 3d models of massless discs

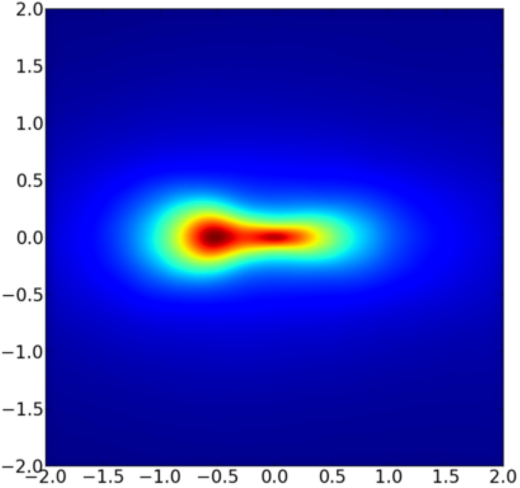
Model *predictions* agree well with OASIS kinematic maps: σ



What does the disc look like? LOS projection:

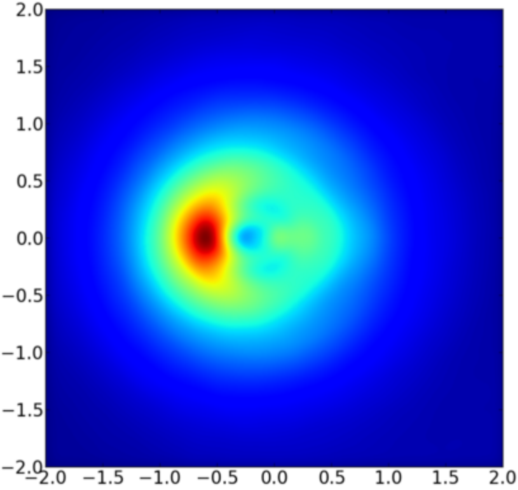


What does the disc look like? Edge-on:



Naive 3d models with massless discs
multiblob expansion results

What does the disc look like? Face-on:



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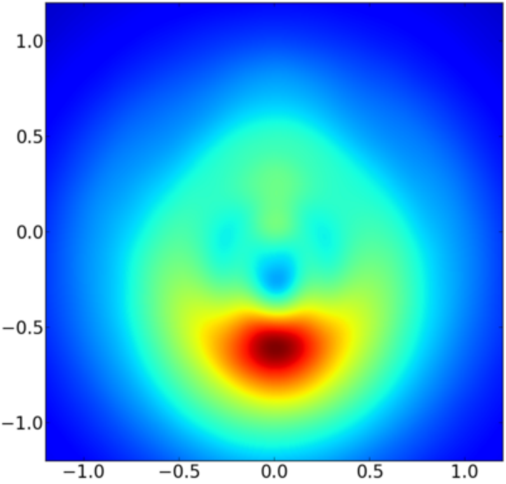

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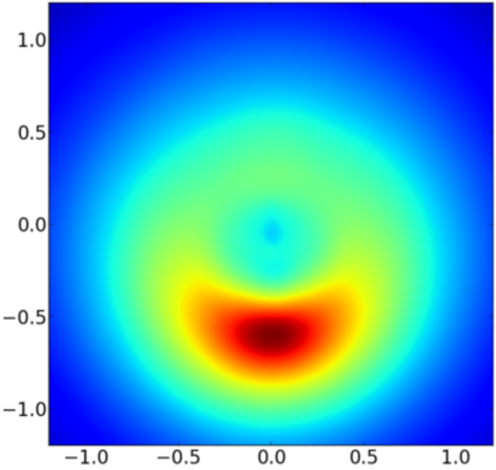
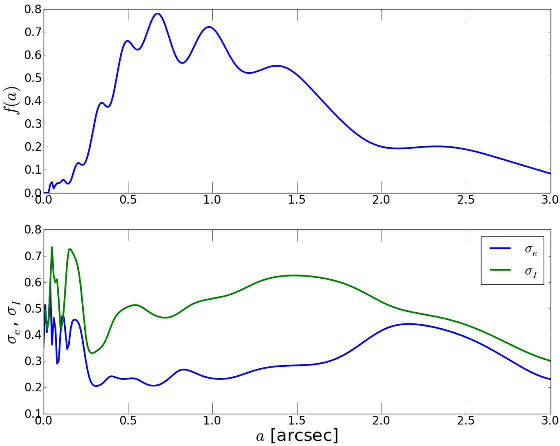


Naive models: loose end #1

Dispersion of I and e as function of a: NB: $\sigma_I \not\simeq 0.5\sigma_e$!



Naive models: loose end #2

We've assumed that $\Phi = -\frac{GM_\bullet}{r}$ and find $M_\bullet \sim 10^8\,M_\odot$.

But disc mass $M_\star \sim \frac{1}{10} M_\bullet$ (for $L_V = 6 \times 10^6\,L_\odot$).
$\Rightarrow$ Keplerian Φ zeroth-order approximation only!

Tremaine (1995)

Massive disc makes orbits precess at different rates.
Coherent eccentric disc won't last long.

It is reasonable to assume that:
BH-plus-disc system stationary in some rotating frame.

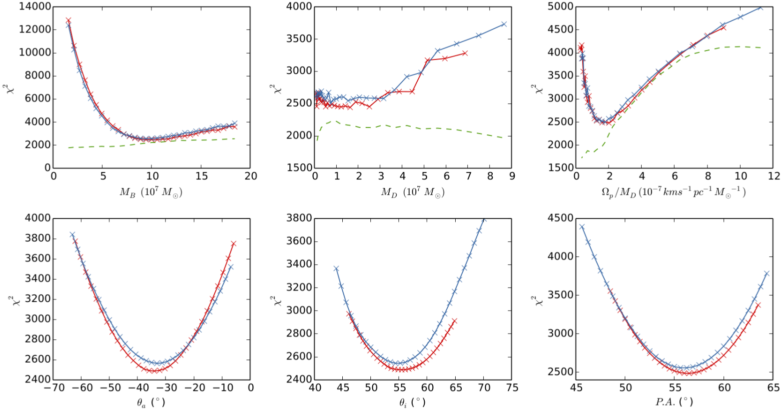
- What's the pattern speed Ω_p?
- How does non-Kepler Φ affect inferences about orbit distn?

Annoying: don't know $M_\bullet$, $\rho_\star$ or Ω_p.
Painful: orbits aren't simple ellipses:
numerical orbit integration; some precess excruciatingly slowly.

Less naive models
(Calum Brown thesis)

Potential = BH + disc:
New parameters $M_\star, \Omega_\mathrm{p}$ plus $\rho_\star(\mathbf{x})$.

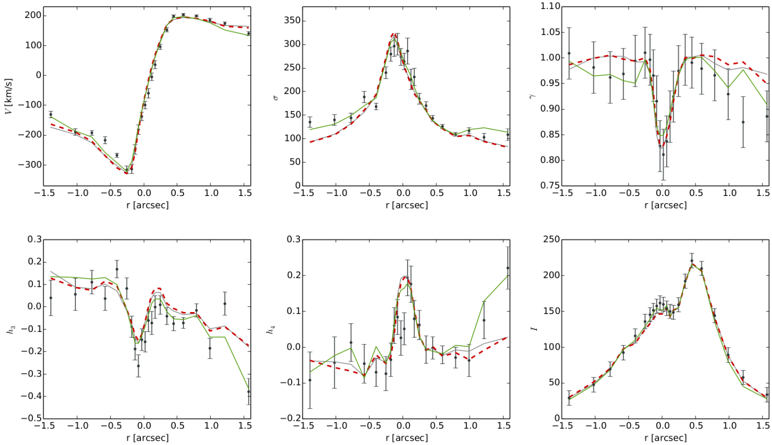
Scans over parameter space: (heroic work)



Less naive models
(Calum Brown thesis)

Iterating $\rho_\star(\mathbf{x})$ to self-consistency improves the fit!

Here are the STIS kinematics: initial model $\rightarrow$ final model.



Summary of M31 dynamical modelling
(Calum Brown thesis)

$$\text{inclination } \theta_i \simeq 57^\circ \text{ (vs } 77^\circ \text{ for main body)}$$

$$M_\bullet + M_\star \sim 10^8\, M_\odot$$

$$M_\star \lesssim 0.2 M_\bullet$$

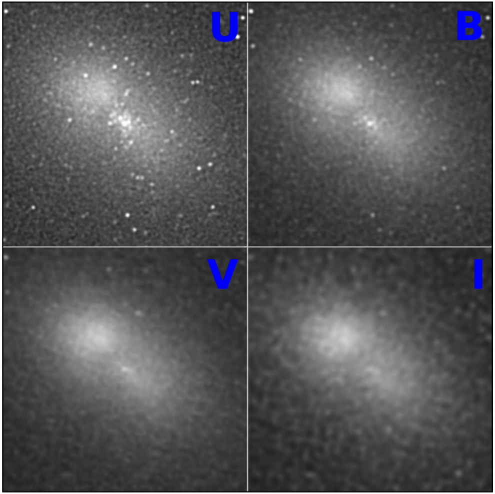
$$\text{Pattern speed } \Omega_\mathrm{p} \lesssim 10\,\text{km/s/pc}.$$

...from self-consistent biaxial models with figure rotation.

Formation of P3?

What about P3?
(Lauer et al. 2012)

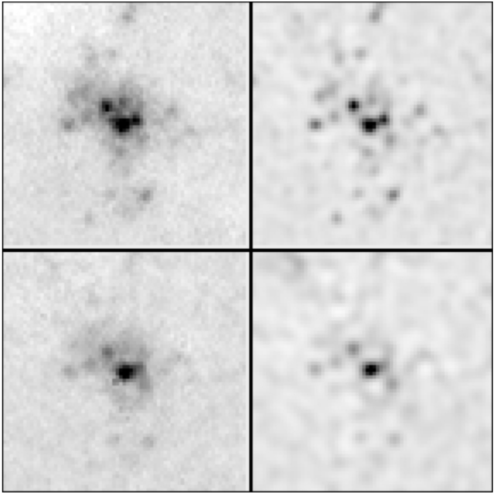
U, B, V, I images of inner $3'' \times 3''$:



U-band peak compact, within P2: call it P3!

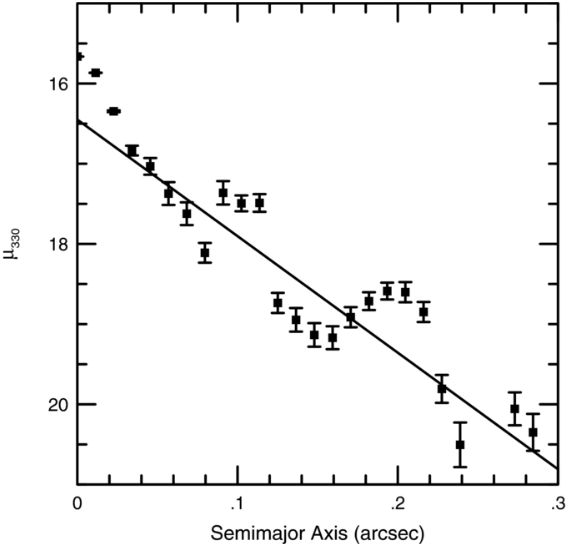
What about P3?
(Lauer et al. 2012)

Zoom to $0\farcs81 \times 0\farcs81$:
Nyquist-sampled (L) and deconvolved (R), *U* (top) *B* (bottom):



What about P3?
(Lauer et al. 2012)

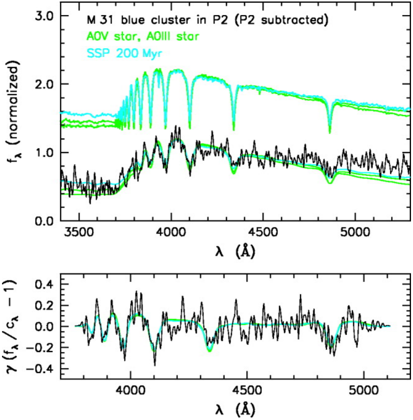
P3 has scalelength $\sim 0\farcs075 = 0.3$ pc in U:



What about P3?
(Bender et al. 2005, Lauer et al 2012)

P1, P2: typical old, red bulge stars.

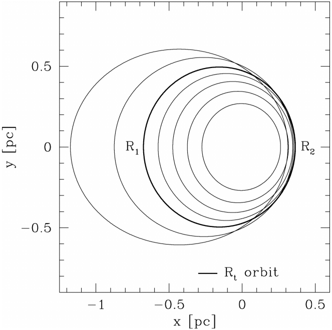
P3 has much younger spectrum (A0-type):



Spectra, colours, SBF $P(k)$: 100-200 Myr old starburst.

P3: a formation scenario
(Chang et al 2007)

Closed orbits in $M_\star / M_\bullet = 0.1$, Ω_p =3 km/s/pc potential:



1. Gas lost from old stars
2. settles onto ∼ closed orbits
3. which intersect at R_2:
   - shock, cool(?), starbust.

Requires low pattern speed Ω_p

P3: a formation scenario
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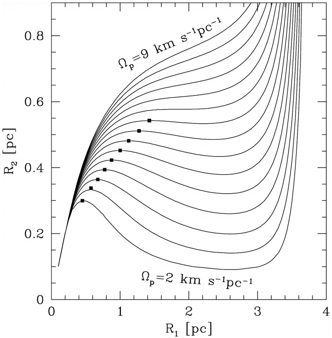
Closed orbits in $M_\star / M_\bullet = 0.1$, Ω_p =3 km/s/pc potential:



1. Gas lost from old stars
2. settles onto $\sim$ closed orbits
3. which intersect at R_2:
   - shock, cool(?), starbust.

Requires low pattern speed Ω_p

Conclusions

Summary: M31 vs MW

MW:

- Cluster looks broadly like those found in other galaxies
    - well-studied formation possibilities: e.g., infall of GCs
- Know BH mass very well: $4 \times 10^6\ M_\odot$ (S stars).
- Difficult to reproduce with “conventional” methods.
- Messy stellar distn
    - isotropic distribution of S stars
    - disc-like O/WR stars in inner pc
    - 3d/6d structure unclear
    - origin of young stars a mystery
    - extinction not well understood

M31:

- Unusual double nucleus (see also NGC 4486b)
- BH $\sim 10^8\ M_\odot$
- Confirm compelling T95 eccentric disc model for old stars
- distinct, old stellar population, save for P3
- Low $\Omega_{\rm p}$, but formation? DF against triaxial bulge? $m = 1$ mode? counter-rot instab?

How to form an eccentric disc?

Formation scenarios

How to form an eccentric disc?

- circular disc experiences dynamical friction from triaxial bulge? (Tremaine 1995)
- natural $m = 1$ mode? (Bacon et al 2001, Hopkins & Quataert 2010)
- instability of counter-rotating orbits? (Kazandjian & Touma 2012)