THE DEMOGRAPHY OF MASSIVE DARK OBJECTS IN GALAXY CENTERS

By Magorrian et al. (1998)

As presented by Mike Berry
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What are Massive Dark Objects? (MDOs)

- Most likely supermassive black holes
- Star clusters of the required mass and size are difficult to construct and maintain
- Fit entire LOS v-dispersion for arbitrary axisymmetric galaxy models
- Crude models predict MDO mass fairly accurately (M87)
Data from 36 bulges from HST photometry and decent ground based long-slit spectroscopy

Fit two-integral axisymmetric dynamical models (not most general but computationally inexpensive)

Find a statistical distribution of MDOs as a function of galaxy luminosity

Not meant to unambiguously show that an MDO is present in any individual galaxy
Two-integral approach (cylindrical and axisymmetric about z-axis)

Assume constant mass to L ratio (Y)

Makes them flattened spherical isotropic models

No physics behind why galaxies must be like this
Procedure

- Use maximum likelihood to find smooth L-density that fits observed surface brightness
  - Large range in density but uncertainty is less than observed error
- Calculate $\Phi$ using $Y$ and MDO mass $M_\odot$, then find $v_r$ and $v_z$ using the inclination angle ($i$)
- Project luminosity weighted moments to LOS velocities and convolve with observations
- Least squares fit to obtain $M_\odot$ and $Y$ based on the likelihood that we see the observed data
Individual Galaxy Results

- 4 of 36 galaxies – not well fit by models
  - Known to have kinematically distinct cores
- By comparison 2 of the other 32 others are known to have kinematically distinct cores
- 3 of 32 are consistent to 1 sigma with $M_{\odot}=0$
- 4 of 32 are consistent to 2 sigma with $M_{\odot}=0$
- MDO – required to produce 2nd moment in galaxies
A few interesting galaxies

- HST data for M32, n3115, n3379, n4594
  - All are reasonably well fit
- 5 galaxies with nuclear activity or heavy dust (2 models to correct)
  - Assume all light comes from stars
  - Only use photometry > Rmin
- Galaxies with Rmin > 0 are subject to skepticism
Assume MDO depends on \( x (x = M_o / M_b) \) and other parameters \((w)\)

Seek most likely set of parameters given data (5 models)

**TABLE 4**

<table>
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<tr>
<th>( P )</th>
<th>( f )</th>
<th>( \log x_0 )</th>
<th>( x ) or ( \log \Delta )</th>
<th>( \log \langle x \rangle )</th>
<th>( \langle \log x \rangle )</th>
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<tr>
<td>( P_{PL1} )</td>
<td>1.000(^{+0.000}_{-0.057} )</td>
<td>(-0.633^{+0.125}_{-0.100} )</td>
<td>(-0.784^{+0.056}_{-0.037} )</td>
<td>(-1.347^{+0.115}_{-0.111} )</td>
<td>(-3.178^{+0.893}_{-0.893} )</td>
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<tr>
<td>( P_{PL2} )</td>
<td>0.950(^{+0.032}_{-0.062} )</td>
<td>(-2.790^{+0.031}_{-0.063} )</td>
<td>(-1.725^{+0.131}_{-0.173} )</td>
<td>(-2.268^{+0.097}_{-0.087} )</td>
<td>(-2.338^{+0.153}_{-0.188} )</td>
</tr>
<tr>
<td>( P_S )</td>
<td>1.000(^{+0.000}_{-0.067} )</td>
<td>(-1.705^{+0.204}_{-0.109} )</td>
<td>(-0.456^{+0.178}_{-0.122} )</td>
<td>(-1.880^{+0.117}_{-0.108} )</td>
<td>(-2.338^{+0.153}_{-0.188} )</td>
</tr>
<tr>
<td>( P_G )</td>
<td>0.940(^{+0.042}_{-0.067} )</td>
<td>(-2.930^{+0.325}_{-0.000} )</td>
<td>(-1.717^{+0.098}_{-0.082} )</td>
<td>(-1.808^{+0.105}_{-0.096} )</td>
<td>(-1.992^{+0.106}_{-0.091} )</td>
</tr>
<tr>
<td>( P_{LG} )</td>
<td>0.970(^{+0.030}_{-0.055} )</td>
<td>(-2.281^{+0.100}_{-0.100} )</td>
<td>(-0.289^{+0.060}_{-0.065} )</td>
<td>(-1.965^{+0.143}_{-0.119} )</td>
<td>(-2.282^{+0.103}_{-0.109} )</td>
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**NOTES.**—The best-fitting parameters \( \omega \) and their 68% confidence limits for each assumed distribution \( P(x \mid \omega, P) \). By definition, \( 0 \leq f \leq 1 \). The last two columns give the logarithm of the expectation value of \( x \equiv M_*/M_{\text{bulge}} \) and the expectation value of \( \log x \) for those galaxies with \( M_* \neq 0 \) [both calculated from \( P(x \mid \omega, P) \)]. The mean \( \langle x \rangle \) does not exist for \( P_{PL2} \).
Fig. 11.—(a) Probability distributions $Pr(x | \omega, P)$ for the best-fitting parameters $\omega$. The heavy solid and dashed curves show results for $P_{PLa}$ and $P_{LO}$, the two best-fitting cases. The light solid, dashed, and dotted curves are for $P_5$, $P_{PL1}$, and $P_6$, respectively. (b) “Nonparametric” probability distribution $Pr(x)$ (heavy solid curve) and its 68% confidence limits (heavy dashed curves) obtained using the Metropolis algorithm with $\lambda = 5$. The best-fitting parameterized distributions $P_{PL2}$ and $P_{LO}$ are overlaid as the light solid and dashed curves, respectively.
Conclusions

- 32/36 galaxies are well described by 2-integral axisymmetric models
- 28/32 require a substantial MDO
  - 97% of galaxies have $M_o/M_b \sim 0.05$
- Probably a different formation history for galaxies without a MDO
- 2-integral models are not the most generic but fits agree reasonably well with previous data