Dark Matter “Dominated” Galaxy Segue 1

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and collaborators

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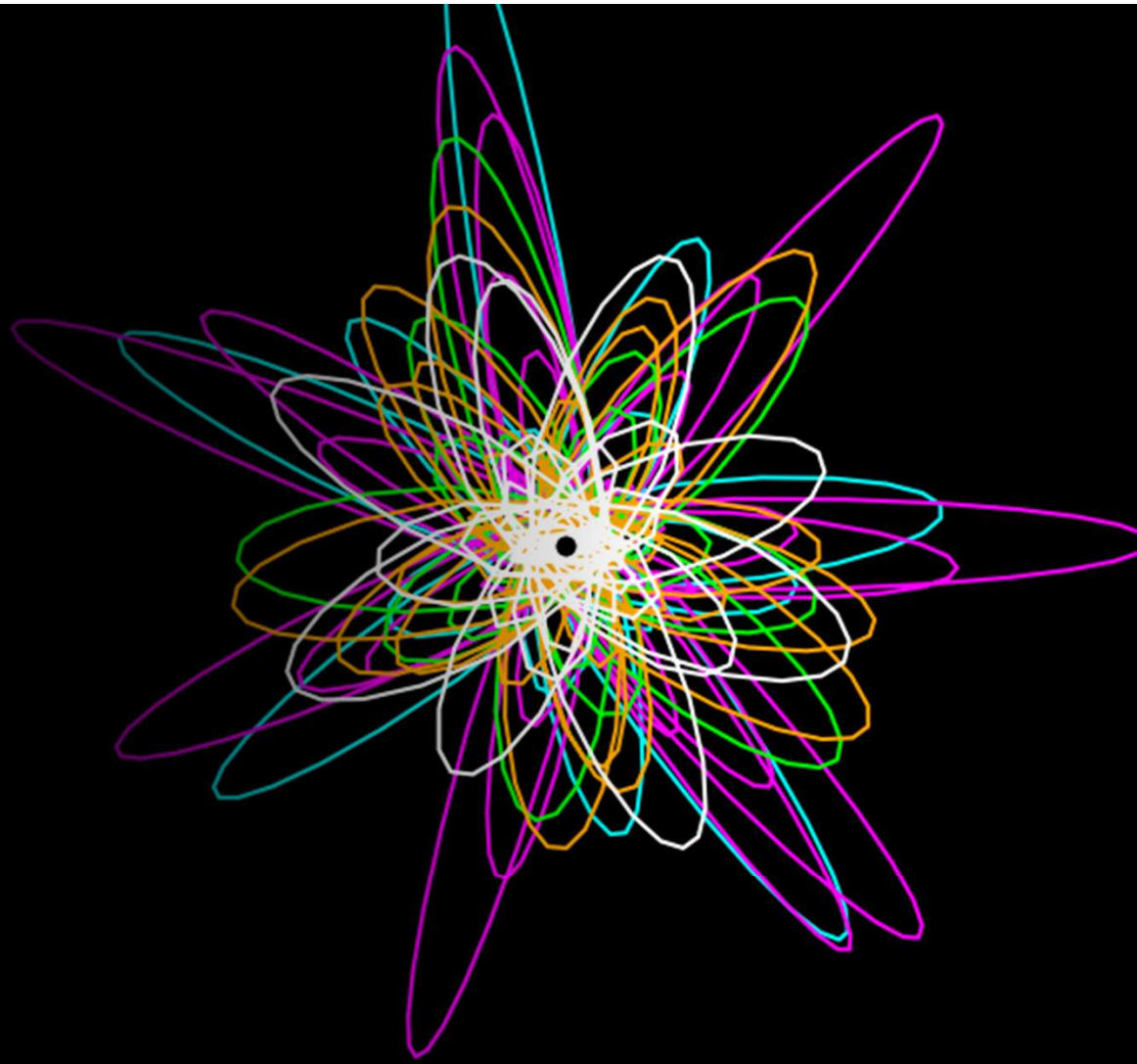
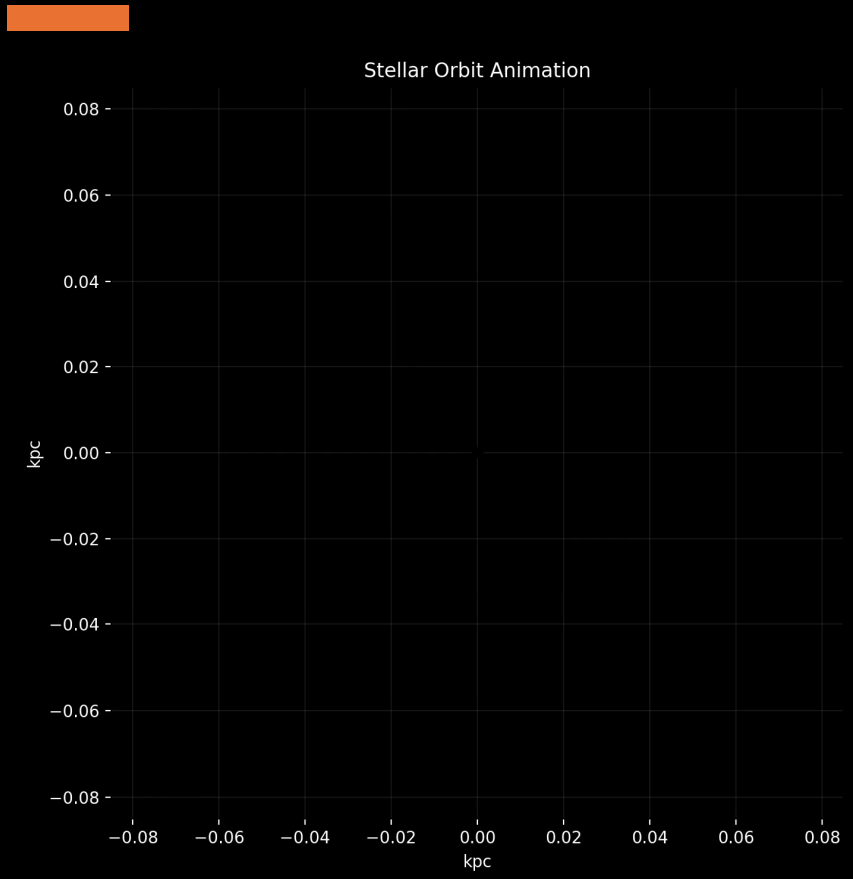


An Ultra-dim "Fossil" Galaxy

- Mass-to-light ratio > 1000
  - M_Sun / L_Sun (Solar mass over Solar luminosity)
  - Central stars have rapid orbital velocities, implying invisible mass
- Comes very close to the Milky Way
  - ~23kpc, close enough for strong tidal interactions
- Stars have widely varying metallicities
  - Likely due to Milky Way Tidal forces

https://aasnova.org/2018/08/08/the-origin-of-the-satellite-segue-1/

(Geha et al. 2009; Fritz et al. 2018; Frebel et al. 2014)



Orbit Superposition Modeling (OSPM)

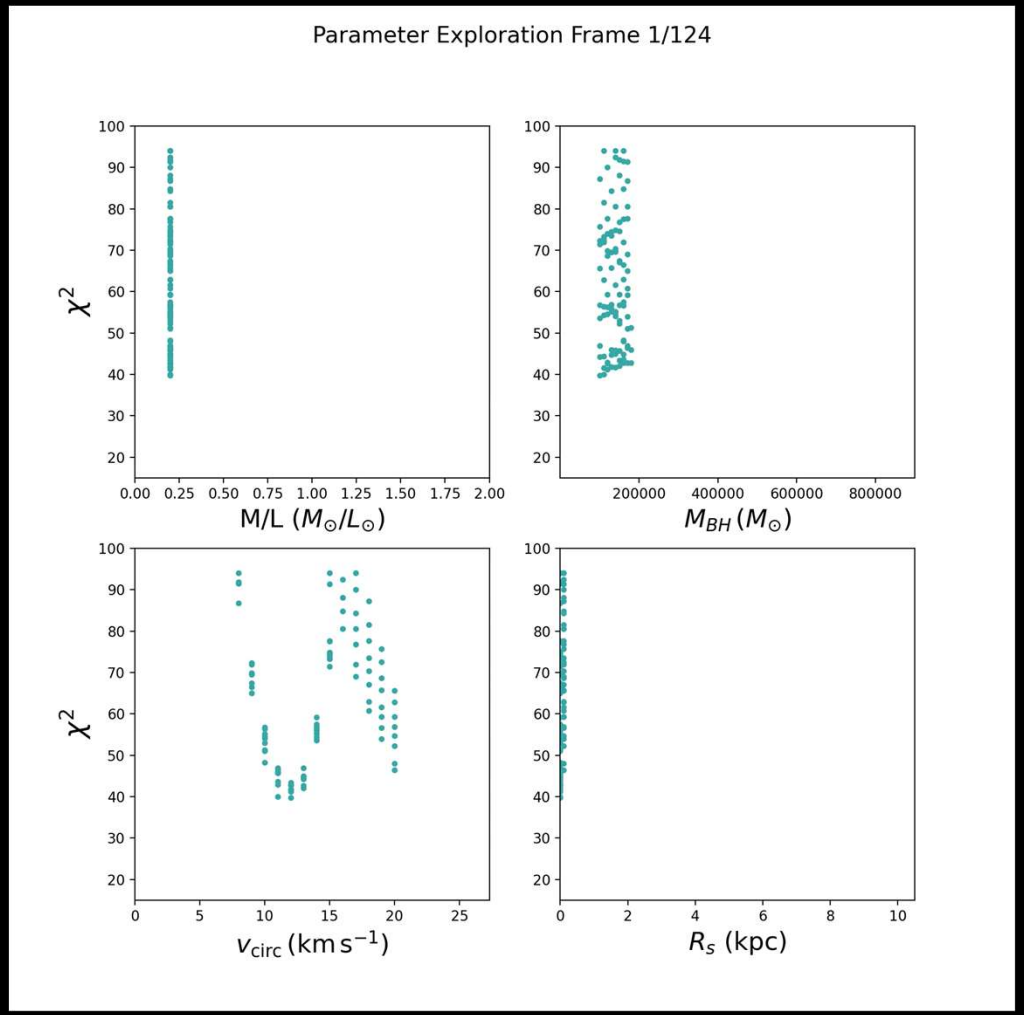
- Simulates stellar orbits in a fixed gravitational potential
- Assigns weights to orbits to match surface brightness and kinematics
- Applied to nearby galaxies with detailed imaging and line-of-sight velocity data
- Finds best-fit model by minimizing:

$$\chi^2 = \sum_i \left(\frac{\sum_j w_j A_{ij} - D_i}{\sigma_i} \right)^2$$

(Schwarzschild 1979; Gebhardt et al. 2003; Gebhardt et al. 2000)

Testing Every Possibility:

- We have a 4-parameter model:
  - M/L, M_BH, V_circ, and R_s
- 100,000+ Runs
  - Red = no dark matter => terrible fit
  - Blue = no black hole => less terrible fit
- Radius tends to the model's lowest radial limit
- Manual exploration of Parmeter space.

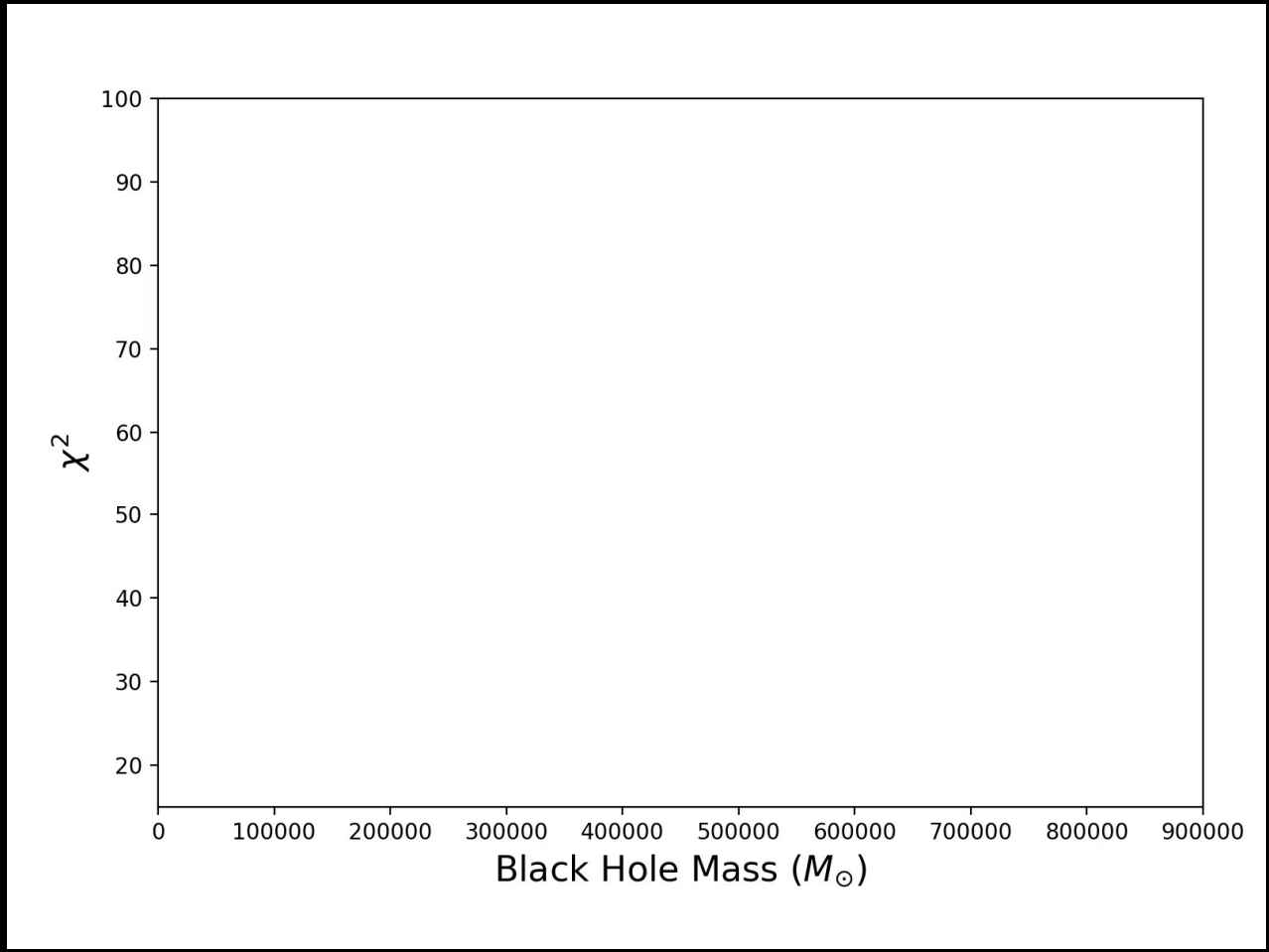


SMBH Mass

- Best fit comes from fits with black hole mass:

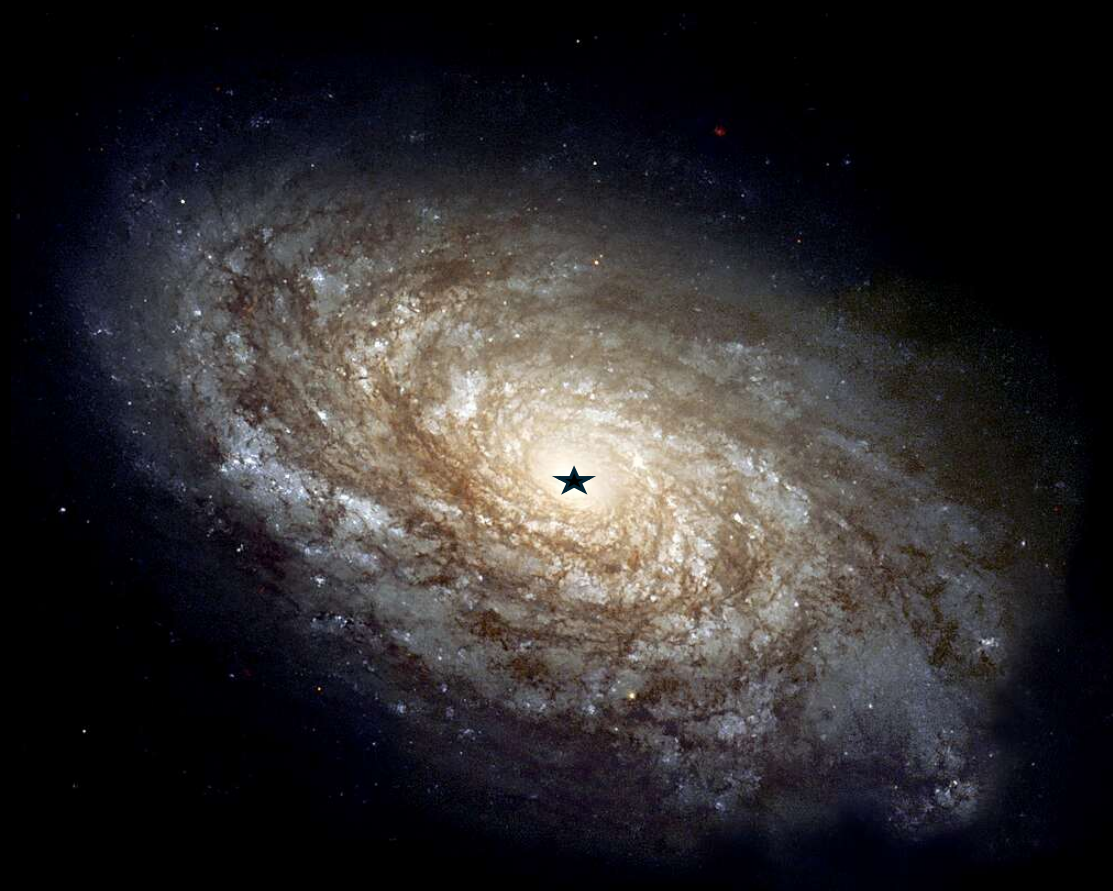
$$4 \pm 1.5 \times 10^5 M\odot$$

- Dark matter halo type (Core vs. NFW)
  - No significant impact on the black hole's mass



Impact

- Challenges assumptions on:
  - Dark matter abundancies
  - Dark matter composition in dark matter "dominated" regions
  - Galaxy Formation and evolution
  - “Rarity” of SMBH



https://science.nasa.gov/asset/hubble/dusty-spiral-galaxy-ngc-4414/

Future Works

- Apply model to other galaxies, such as Draco
- Explore "little red dot" parallels in other dark matter dominated regions
- Expand OSPM with modern techniques
  - AI to efficiently explore parameter space
  - Python & Julia for high-performance modeling

https://science.nasa.gov/asset/hubble/draco-dwarf-spheroidal/

(Kocevski et al. 2024; Mateo 1998; Walker et al. 2009)

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  - RICE University

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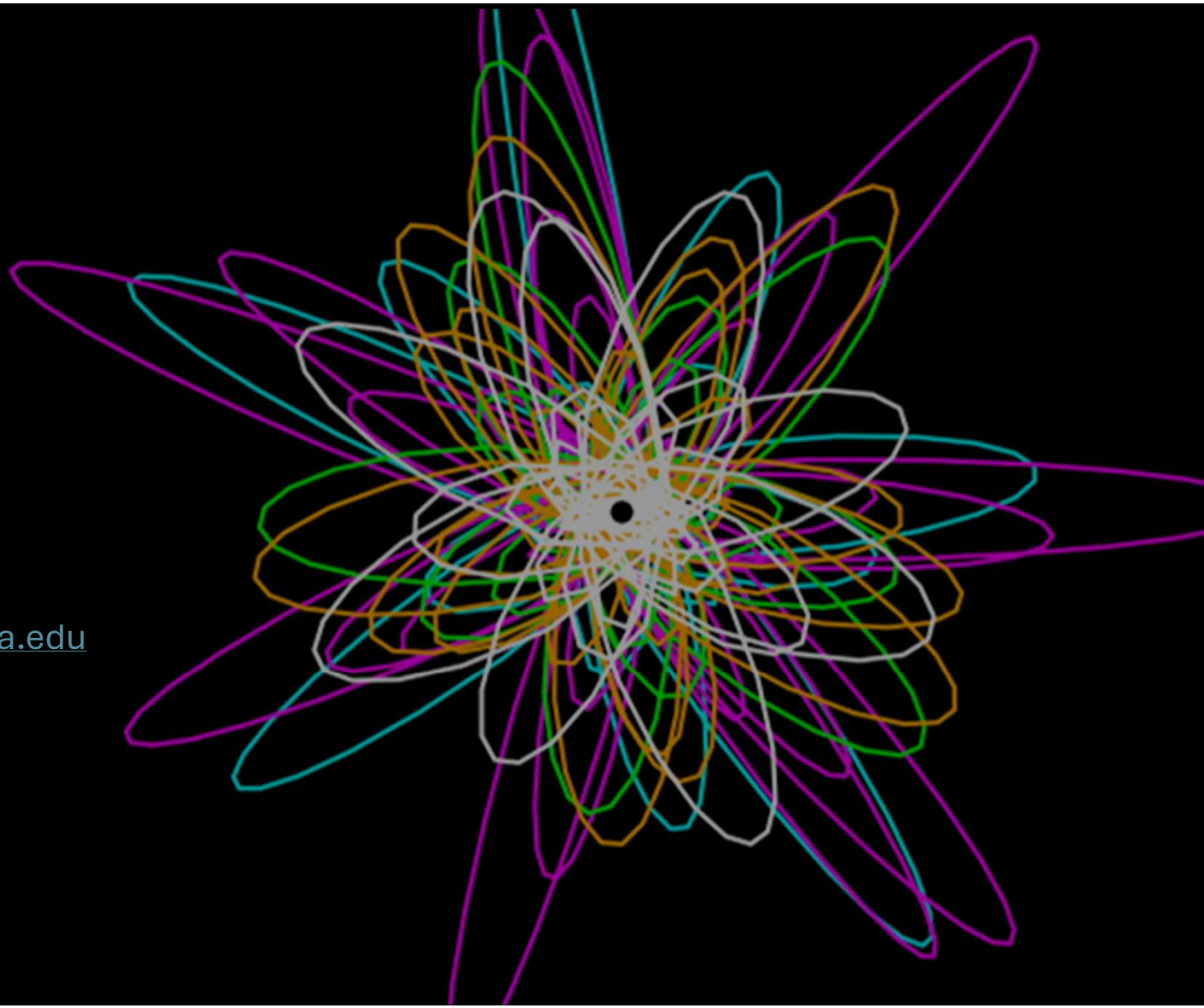
  - UT Austin

Citations

- **Schwarzschild, M. (1979).** *A numerical model for a triaxial stellar system in dynamical equilibrium.* Astrophysical Journal, **232**, 236–247. https://doi.org/10.1086/157282
- **Gebhardt, K., et al. (2000).**
  Axisymmetric Dynamical Models of the Central Regions of Galaxies.
  The Astronomical Journal, **119**(3), 1157–1171. https://doi.org/10.1086/301223
- **Geha, M., et al. (2009).**
  The Least Luminous Galaxy: Spectroscopy of the Milky Way Satellite Segue 1.
  The Astrophysical Journal, **692**(2), 1464–1475. https://doi.org/10.1088/0004-637X/692/2/1464
- **Frebel, A., Simon, J. D., & Kirby, E. N. (2014).**
  Segue 1: An Unevolved Fossil Galaxy from the Early Universe.
  The Astrophysical Journal, **786**(1), 74. https://doi.org/10.1088/0004-637X/786/1/74
- **Niederste-Ostholt, M., et al. (2009).**
  The Origin of Segue 1.
  Monthly Notices of the Royal Astronomical Society, **398**(4), 1771–1778. https://doi.org/10.1111/j.1365-2966.2009.15205.x
- **Fritz, T. K., et al. (2018).**
  The Orbit and Origin of the Ultra-faint Dwarf Galaxy Segue 1.
  Astronomy & Astrophysics, **619**, A103. https://doi.org/10.1051/0004-6361/201833343
- **Kocevski, D., et al. (2025).**
  Little Red Dots and the Rise of Obscured AGN in the Early Universe.
  Presentation at the 245th AAS Meeting.
- **Walker, M. G., Mateo, M., Olszewski, E. W., Peñarrubia, J., Wyn Evans, N., & Gilmore, G. (2009).**
  A Universal Mass Profile for Dwarf Spheroidal Galaxies?
  The Astrophysical Journal, 704(2), 1274–1287. https://doi.org/10.1088/0004-637X/704/2/1274
- **Mateo, M. (1998).**
  Dwarf Galaxies of the Local Group.
  Annual Review of Astronomy and Astrophysics, 36, 435–506. https://doi.org/10.1146/annurev.astro.36.1.435
- **Kocevski, D. D., Finkelstein, S. L., Barro, G., Taylor, A. J., Calabrò, A., Laloux, B., Buchner, J., Trump, J. R., Leung, G. C. K., Yang, G., Dickinson, M., Pérez-González, P. G., Pacucci, F., Inayoshi, K., Somerville, R. S., McGrath, E. J., Akins, H. B., Bagley, M. B., Bisigello, L., Bowler, R. A. A., Carnall, A., Casey, C. M., Cheng, Y., Cleri, N. J., Costantin, L., Cullen, F., Davis, K., Donnan, C. T., Dunlop, J. S., Ellis, R. S., Ferguson, H. C., Fujimoto, S., Fontana, A., Giavalisco, M., Grazian, A., Grogin, N. A., Hathi, N. P., Hirschmann, M., Huertas-Company, M., Holwerda, B. W., Illingworth, G., Juneau, S., Kartaltepe, J. S., Koekemoer, A. M., Li, W., Lucas, R. A., Magee, D., Mason, C., McLeod, D. J., McLure, R. J., Napolitano, L., Papovich, C., Pirzkal, N., Rodighiero, G., Santini, P., Wilkins, S. M., & Yung, L. Y. A. (2024).**
  The Rise of Faint, Red AGN at z > 4: A Sample of Little Red Dots in the JWST Extragalactic Legacy Fields.
  arXiv preprint arXiv:2404.03576. https://arxiv.org/abs/2404.03576

Questions???



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