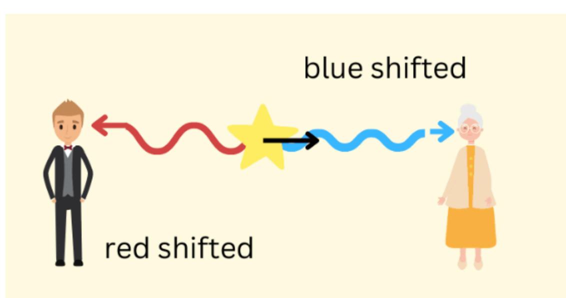
Big Science with Small Data: Improving Galaxy Mass Estimates on Sparse Data Sets

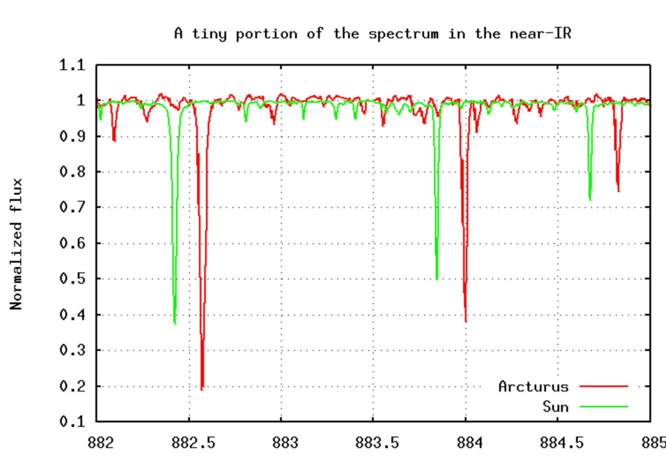
Researcher: Andrew Hicks | PI: Marla Geha | Post-Doc: Farnik Nikakhtar

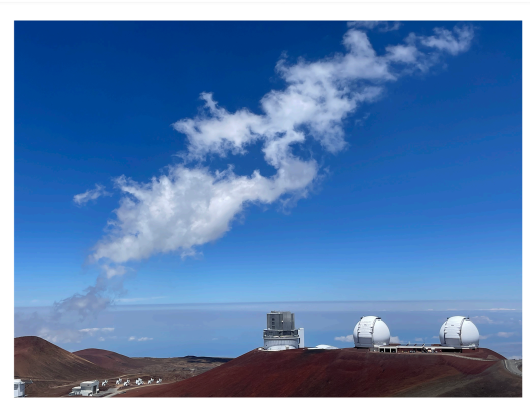
Abstract: The Sun is one of $N_{stars} \approx 10^{11}$ that make up the Milky Way Galaxy. The observable universe is home to $N_{galaxies} \approx 10^{11}$ similar to our own Milky Way. Orbiting each of these galaxies are smaller galaxies known as dwarf galaxies with $10^3 \lesssim N_{stars} \lesssim 10^9$. To estimate the masses of these galaxies we look to the motion of their stars and apply the classical laws of gravitation. Using this method, the amount of gravitational matter present far exceeds the amount of ordinary matter, even when accounting for the gas and dust. Thus, some other source of gravitational mass must be present, typically dubbed "dark-matter". Being able to precisely estimate the mass of these galaxies provides an important constraint for the nature of this substance. However, time scales associated with the orbits of these stars are on the order of 10^8 yrs making it quite difficult to accurately measure the motions of individual stars. Further, the techniques that are available are often costly and time-consuming meaning that astronomers must occasionally work with incomplete data sets to perform their analysis. We use mock data sampled from a plummer sphere potential to investigate the effects that this non-idealized sampling has on our mass-estimates. We then suggest a protocol for correcting for errors introduced by non-idealized sampling and demonstrate its effectiveness.

How do we weigh galaxies*?

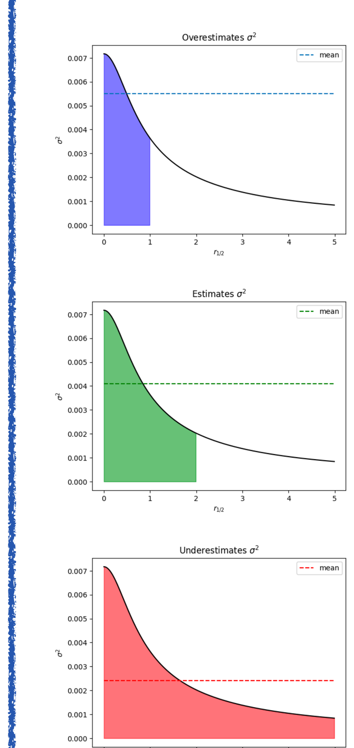


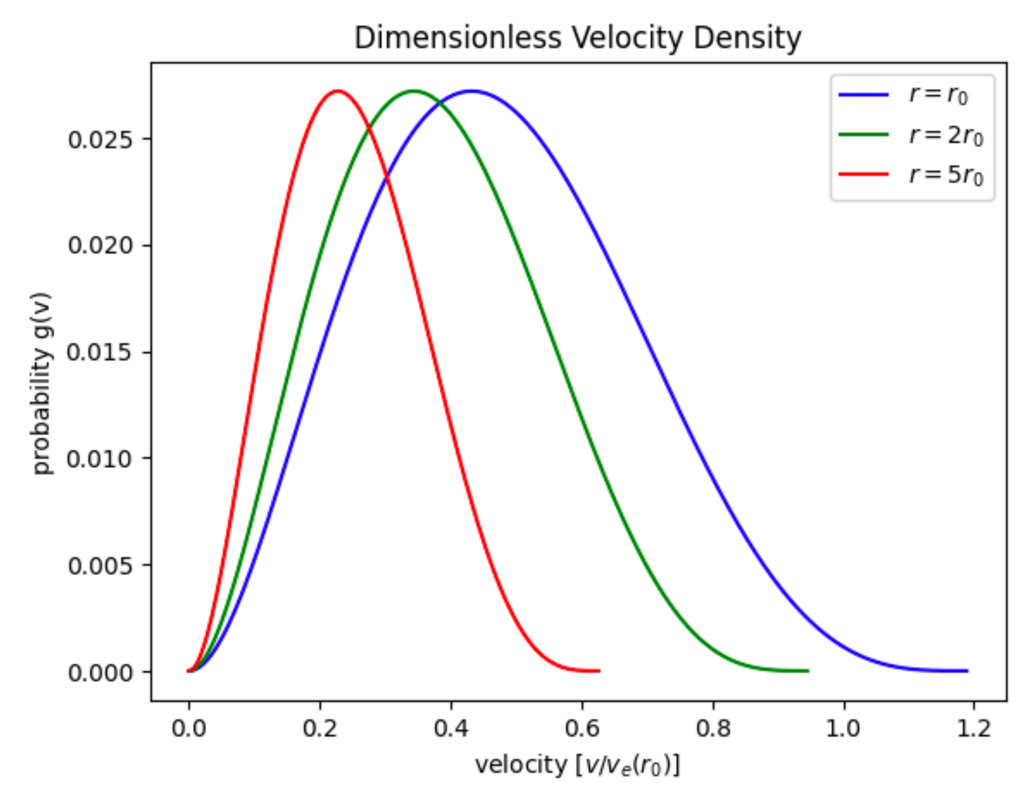
Obtain line-of-sight velocities from high-resolution spectral data





Keck Telescopes





Conditional Probability: $P(v \mid r) \propto v^2 \left[\left(1 + r^2\right)^{-\frac{1}{2}} + \frac{1}{2} v^2 \right]^{\frac{7}{2}}$

Estimate amount of mass ($M_{1/2}$) contained within the half-light radius ($r_{1/2}$) using wolf-mass estimate.

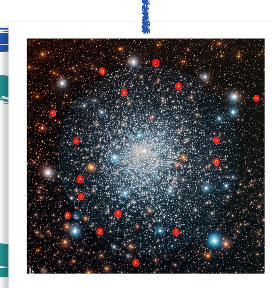
$$M_{1/2} = 3G^{-1} \left\langle \sigma_{los}^2 \right\rangle r_{1/2}$$

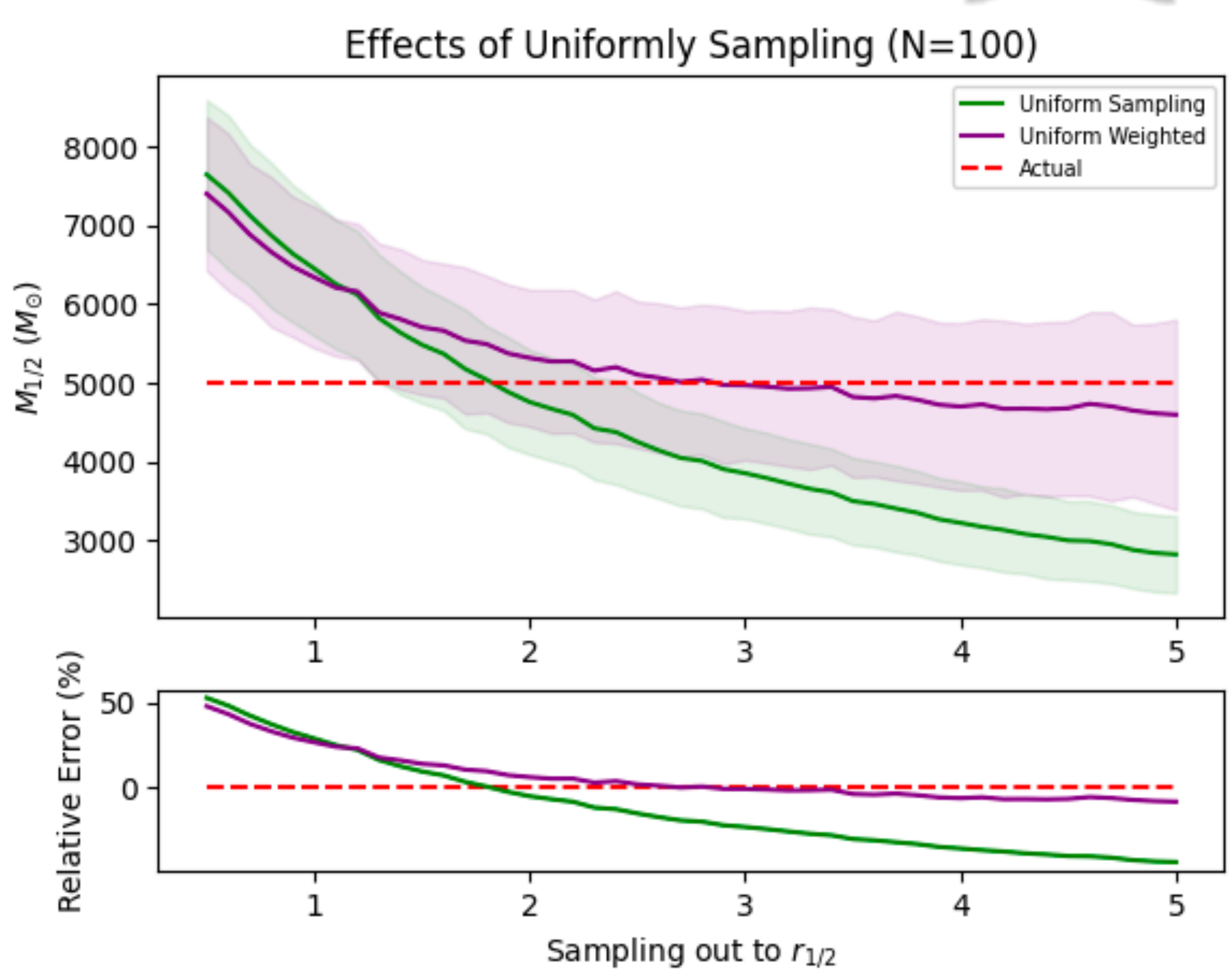
where,

$$\sigma^2 = \sum_{i=0}^{N} \frac{(v_i - \bar{v})^2}{N} = \left\langle v^2 \right\rangle - \left\langle v \right\rangle^2$$

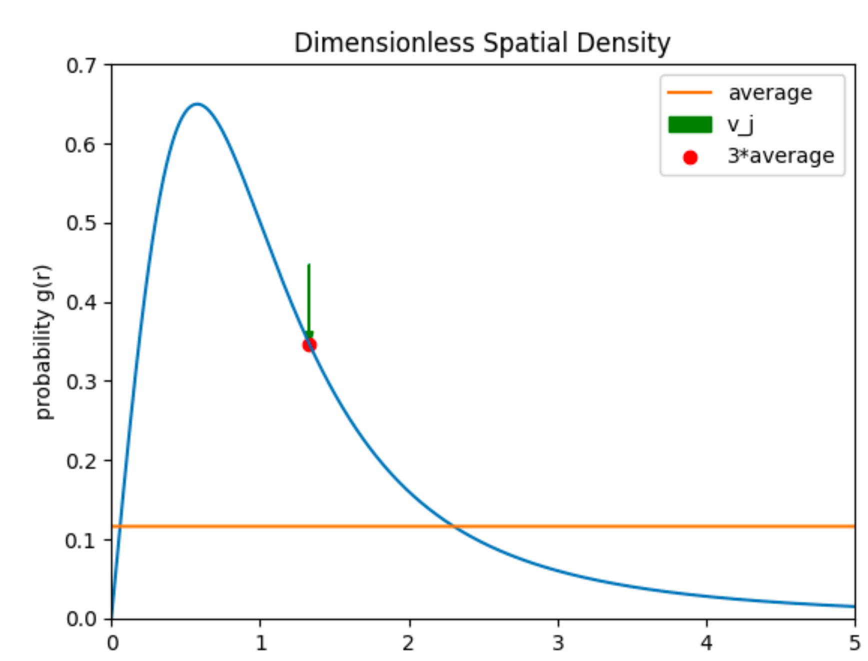
Note (*): This is just one of several ways astronomers use to compute the dynamical mass of galaxies.

What if our data set is incomplete?





Sampling near the half-light radius is ideal but we can help correct for errors by applying weights for missing measurements



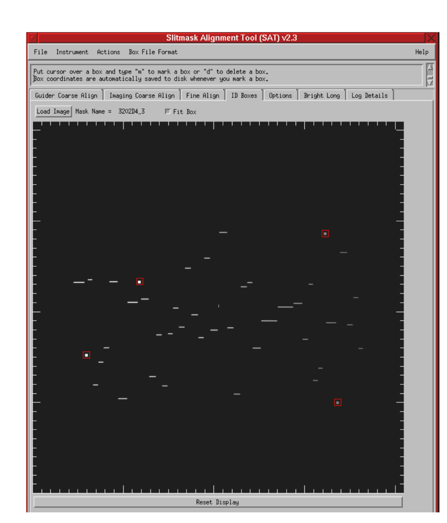
Measured Velocities:

$$v = [v_0, v_1, \ldots, v_j, \ldots, v_{N-1}, v_N]$$

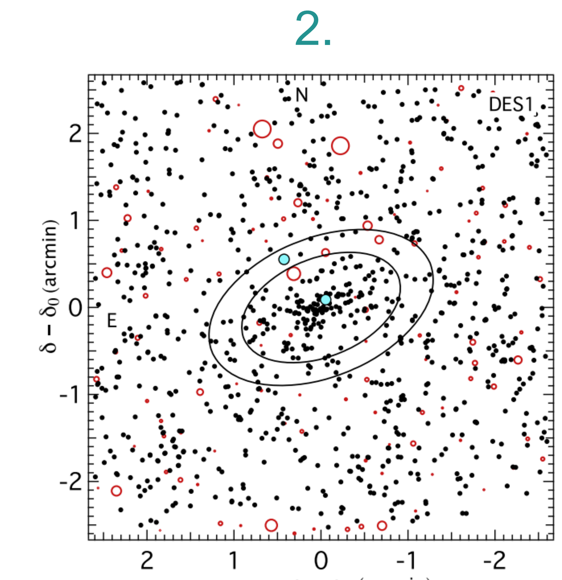
Weighted Velocities:

$$v = [v_0, v_1, \ldots, v_j, v_j, v_j \ldots, v_{N-1}, v_N]$$

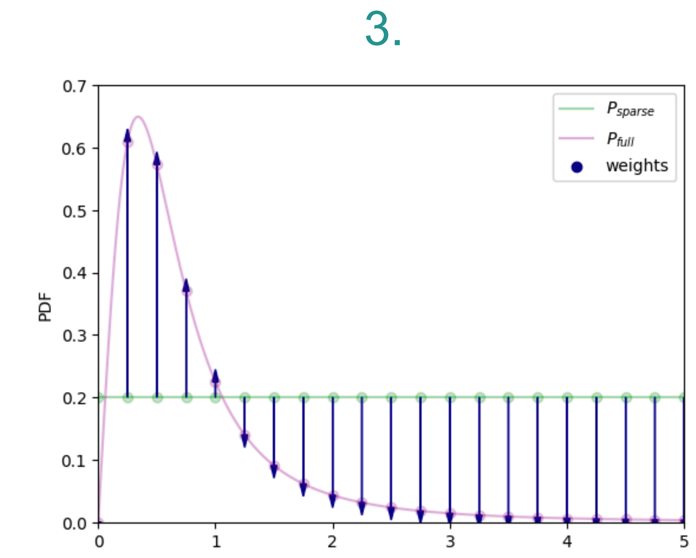
1.



2.

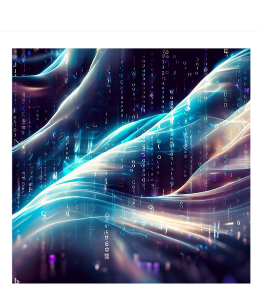


3.



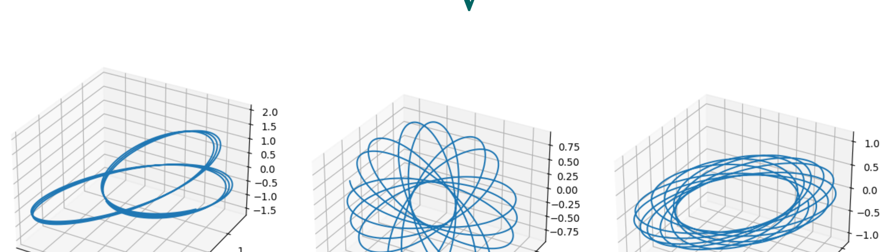
1. Use measured member to create probability distribution function (PDF) from the sparse data set: annotated $P_{sparse}(r)$
2. Use all member data to reconstruct the PDF from the full data set: annotated $P_{full}(r)$
3. Apply weights W such that $W \cdot P_{sparse} = P_{full}$ which is given by $w_i = \frac{P_{full}(r_i)}{P_{sparse}(r_i)}$

What's Next?



Our analysis was limited to the plummer potential $\Phi(r)$ given by:

$$\Phi(r) = -\frac{GM}{\sqrt{b^2 + r^2}}$$

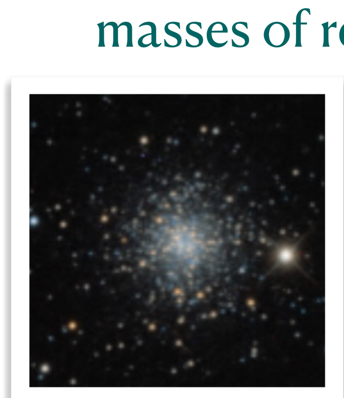


Analyze other model potentials, eg:

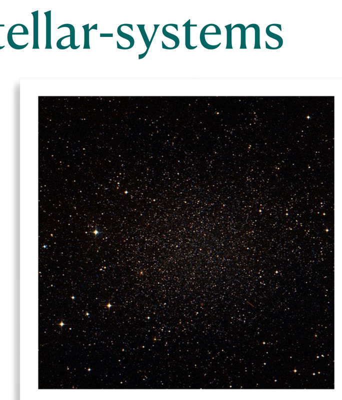
Hernquist: $\Phi(r) = -\frac{GM}{b + r}$

Isochrone: $\Phi(r) = -\frac{GM}{b + \sqrt{b^2 + r^2}}$

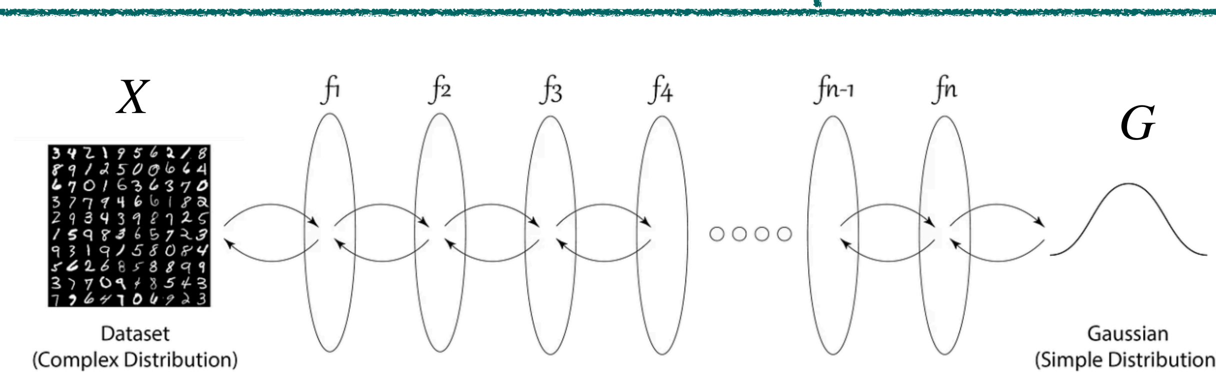
Implement protocol to estimate the masses of real stellar-systems



GC: NGC 6924



dSph: Sculptor



Use generative AI (OT Flow) to generate the missing measurements

Howard Hughes Medical Institute

Email: Andrew.Hicks-1@colorado.edu