Computational Physics in both the Physics and Astronomy Curricula at the University of Arizona

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First: Some History

Prior to 2004: We had a sophomore level computational physics course, PHYS 205, taken by students in each degree program.

- Too much learning programming and not enough applications.
- Faculty treated it like a junior level course.
- Skills never used later in the curriculum.

Changes made in 2004

- Introduced a 1 credit programming course PHYS 105A.
  - Meets for two hours each week.
  - Approximately half “lecture” and half active programming.
  - Typically taught in C and/or Python.

- The computational physics course was now officially a junior level class, PHYS 305.

We recently surveyed our graduate students:

- “I had to teach myself everything I needed in grad school.”
- “It definitely would help to have had more background.”
- From PHYS 305 TA: “I didn’t understand why just using Euler’s method for all first order ODEs was a bad idea – until I was the TA.”
- No language consensus: Python, C, MatLab and even Fortran!

PHYS 105A Curriculum

- About half the semester devoted to learning programming skills (variables, conditional statements, loops, I/O, functions, pointers, arrays, structures, debugging strategies, random numbers, etc.)

- Simple physics examples that require these skills (basic numerical integration, linear squares fitting, etc.)

- Some time making plots using Python or locally developed C libraries.

PHYS 305 Curriculum

- 3/4 of the topics required. 1/4 left up to the instructor.
- Numerical Integration.
- Root finding.
- Solving First and Second Order ODEs.
- Solving time independent and time dependent PDEs.
- Data Analysis/statistics and Monte Carlo Methods.
- Other options: Computational linear algebra, Fourier analysis.
- Student project at the end: More advanced orbital dynamics or molecular dynamics, etc.

Example Homework

- Evaluate $\int_0^2 x \sin x \, dx$ using the midpoint version of the rectangular rule. Use 2, 4, 8, …. 2^{20} for the number of bins.

- Repeat using the trapezoidal rule and simpson's rule.

- Compare your results to the analytic solution. The error should scale as $\mathrm{error} \sim \mathrm{binsize}^{\mathrm{p}}$. Estimate p.

Another Homework Problem

- Two identical objects start from a height of 10 m. One starts at rest and falls straight down. The other has an initial horizontal velocity of 30 m/s. Use a terminal velocity of 10 m/s for both linear and quadratic drag. Determine the motion for three cases: no drag, linear drag and quadratic drag.

- For each case, which ball will hit the ground first and why?

How do students use this knowledge later?

- In Physics: Faculty are expected to have approximately 10% of the course grade based upon some computational assignments in PHYS 332, 426 and 472.

- In Astronomy: ASTR 302 and ASTR 400B and sometimes others.

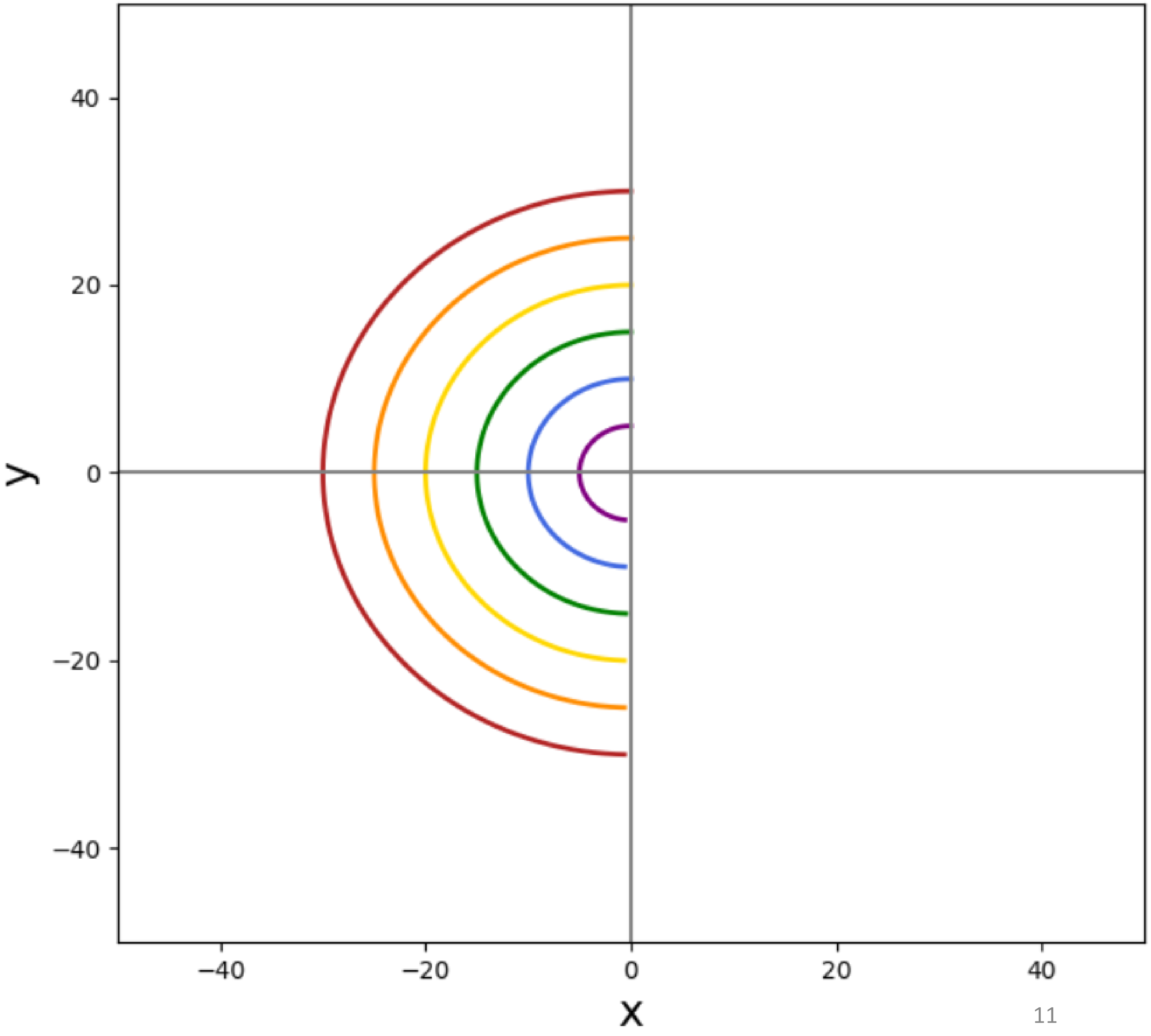
- All students must do a minimum of one semester of research. These projects often involve using their computational skills.

Sample Electromagnetism Problem

- Based upon a Griffiths' homework problem.
- A point charge q is released from rest in the equatorial plane of a fixed point dipole.

- Step 1: Explain qualitatively what the motion of the charge will be.
- Step 2: Numerically solve for the trajectory of the charge.
- Step 3: Determine the net force on a simple pendulum released from a horizontal position and interpret the result.

Trajectories for charges with different starting locations. The dipole moment points in $\hat{x}$.



Courtesy of Sammie Mackie

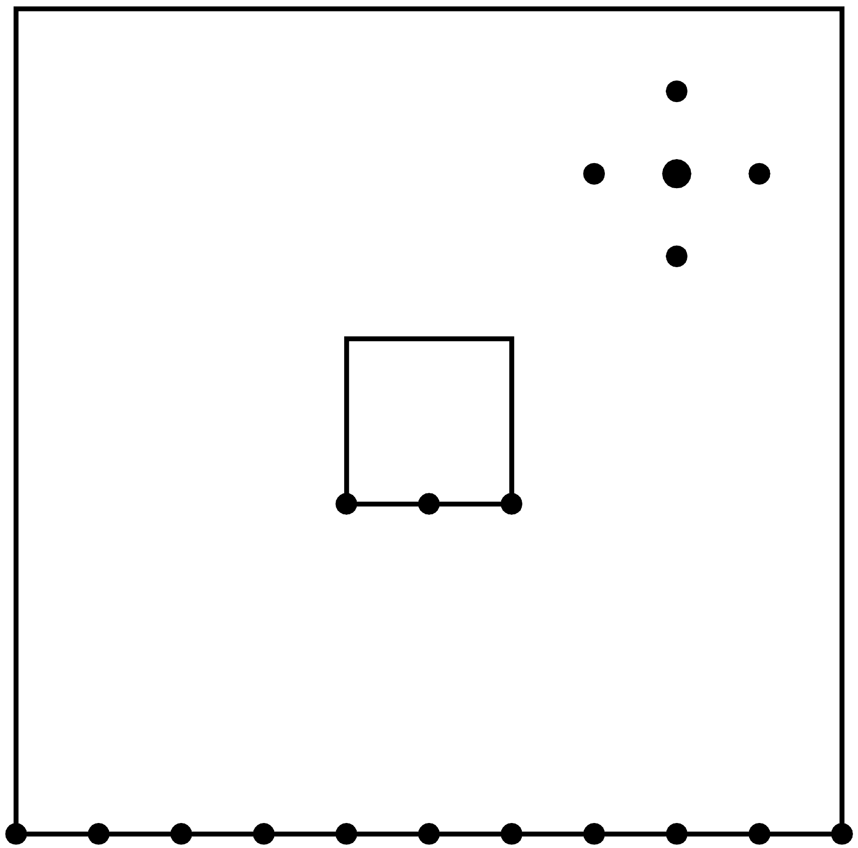
Table 1. Initial point and number of steps to complete one semicircle for each trajectory

Color	Initial Point	p_0 steps (for 1/2 circle)	$10p_0$ steps (for 1/2 circle)
Red	(0, 30)	3334	1052
Orange	(0, 25)	2314	732
Yellow	(0, 20)	1480	468
Green	(0, 15)	830	260
Blue	(0, 10)	368	114
Purple	(0, 5)	90	26

Courtesy of Sammie Mackie

Another Electromagnetism Problem

- A relaxation solution of Laplace's equation.
  V = Average of V for its neighbors.



- Compare with analytic solution.

- Compare results for low and high resolution grids.

- How does the number of steps to converge depend upon the initial guess?

Other Physics Examples

- Statistical mechanics: Simulate Brownian motion. Verify that the mean square displacement equals the number of steps times the step-length squared: $\overline{R^2} = Nl^2$.

- Determine $v(t)$ for an electron initially at rest in a uniform electric field E_0. The relativistic equation of motion is:

$$\frac{eE_0}{m} - \frac{\tau}{m}\frac{d}{dt}\left(\gamma^4 \frac{d^2v}{dt^2} + 3\gamma^6 \left(\frac{dv}{dt}\right)^2 \frac{v}{c^2}\right) = \frac{d}{dt}(\gamma v)$$

where τ is a constant.

ASTR 400B – Galaxy Evolution

- Given: Position/velocity data for stars in the Milky Way, M31 and M33.

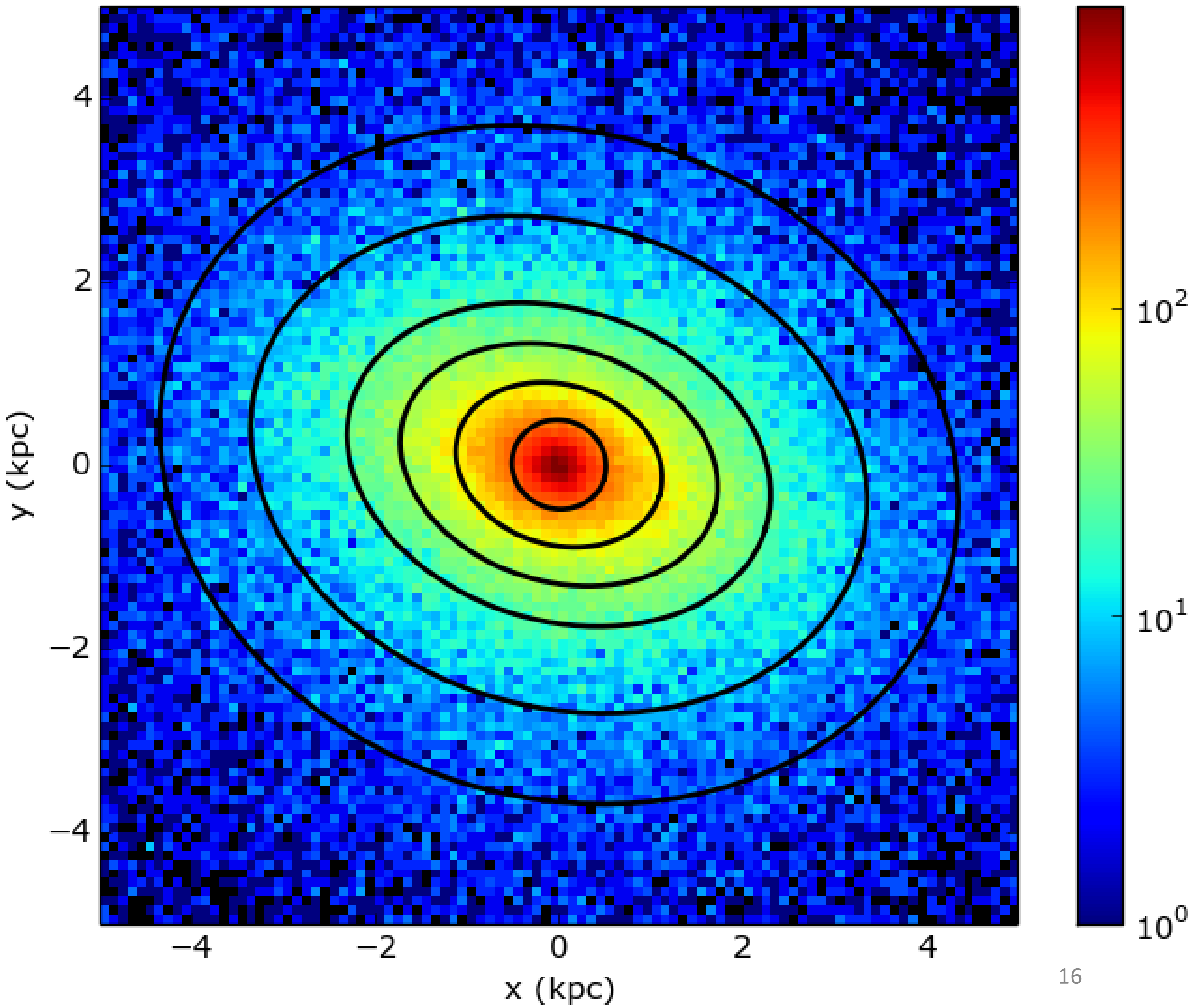
- Analyze the initial data:
  - What does the density distribution look like?
  - Are the stars really orbiting the galactic center?

- Evolve in time until the galaxies coalesce.

M31 Stellar densities fit by ellipses.

Ellipticities: 0.06, 0.24, 0.28, 0.28, 0.23, 0.18

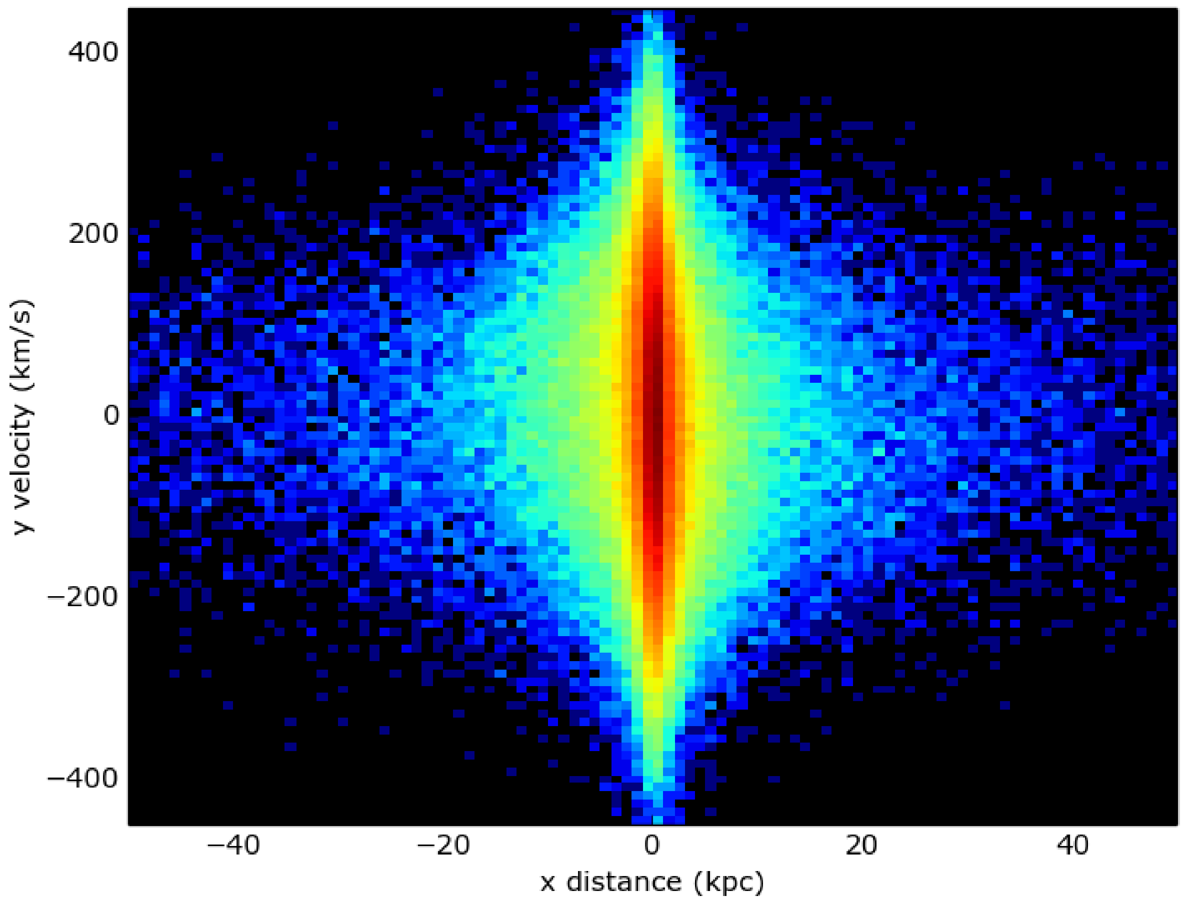
Courtesy: Ryan Hofmann



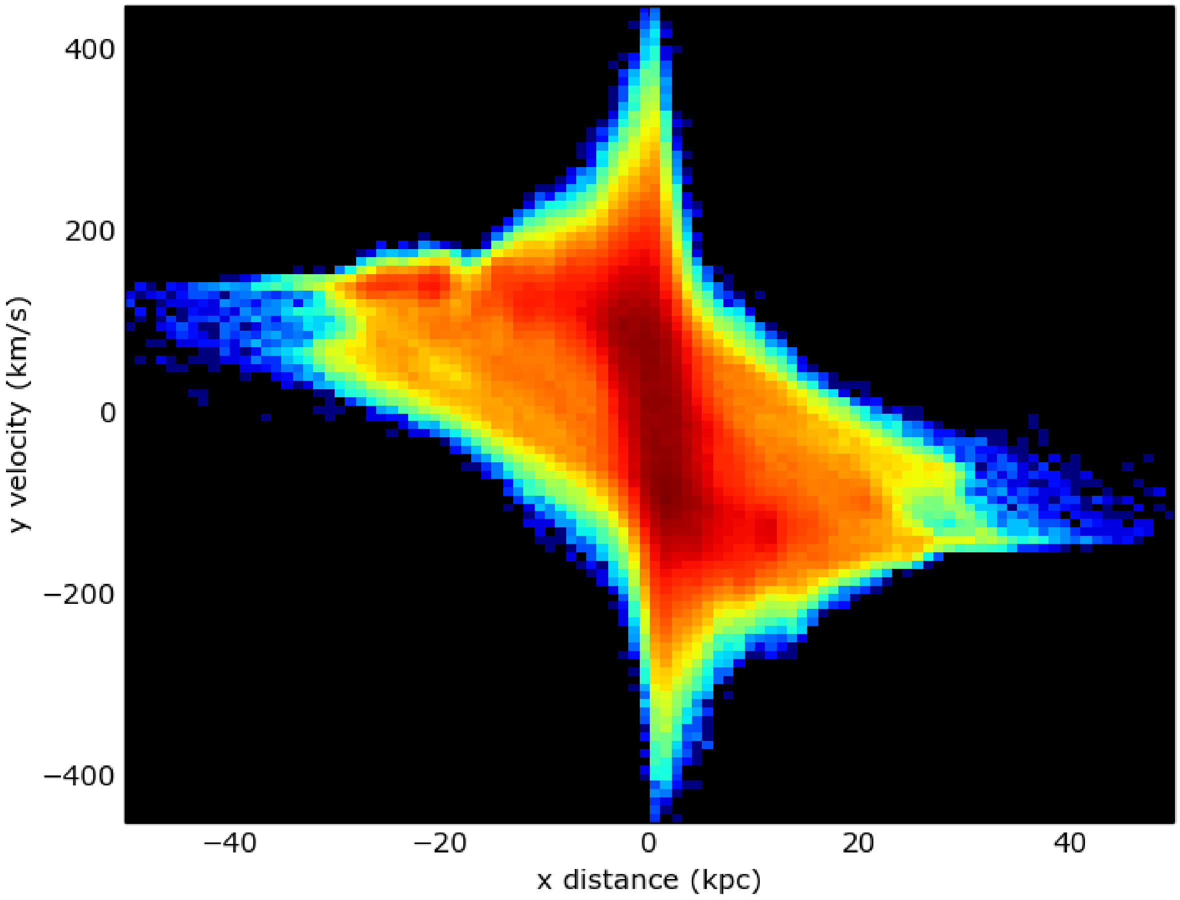
M31 Phase space plots for detecting rotation.

Courtesy: Ryan Hofmann

Galactic Bulge



Galactic disk



Things to improve in the future:

- Students in 105A start with an enormous range of abilities – very hard to manage.
- Faculty making computational upper division assignments with minimal educational value.
- Better coordination with astronomy.
- How to assess how well this is working.

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Questions?