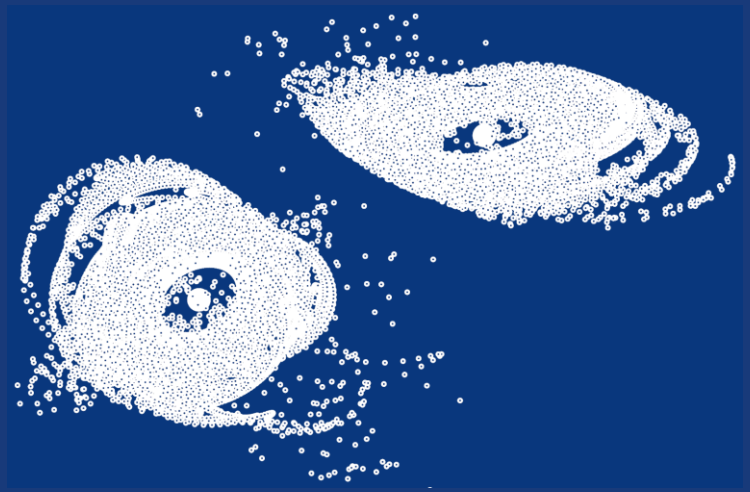
Haus der Astronomie



Simulating Interacting Galaxies

The results of a high school internship project

Michael Thiel

Manuel Brea-Carreras

Acknowledgements

Markus Pössel
Haus der Astronomie
MPIA

International Summer Internship at HdA 2017

Galaxy Evolution - applied to our project

Main reference and inspiration

GALACTIC BRIDGES AND TAILS

ALAR TOOMRE
Department of Mathematics, Massachusetts Institute of Technology
AND
JURI TOOMRE*
Department of Mathematics, New York University, and
Goddard Institute for Space Studies, New York

Received 1972 May 19

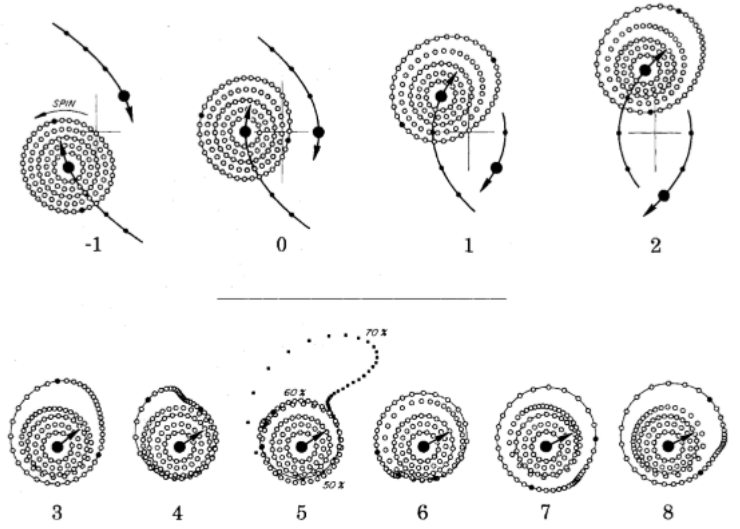


FIG. 1.—A flat retrograde ($i = 180°$) parabolic passage of a companion of equal mass. The two small filled circles denote test particles from the $0.6R_{min}$ ring which, in the absence of the encounter, would have reached positions exactly to the right and left of the victim mass at $t = 0$. The filled squares at $t = 5$ depict additional test particles from $0.7R_{min}$. (Note the partial interpenetrations of the outermost rings at $t = 4$, 5, and 6, and their continuing oscillations thereafter.)

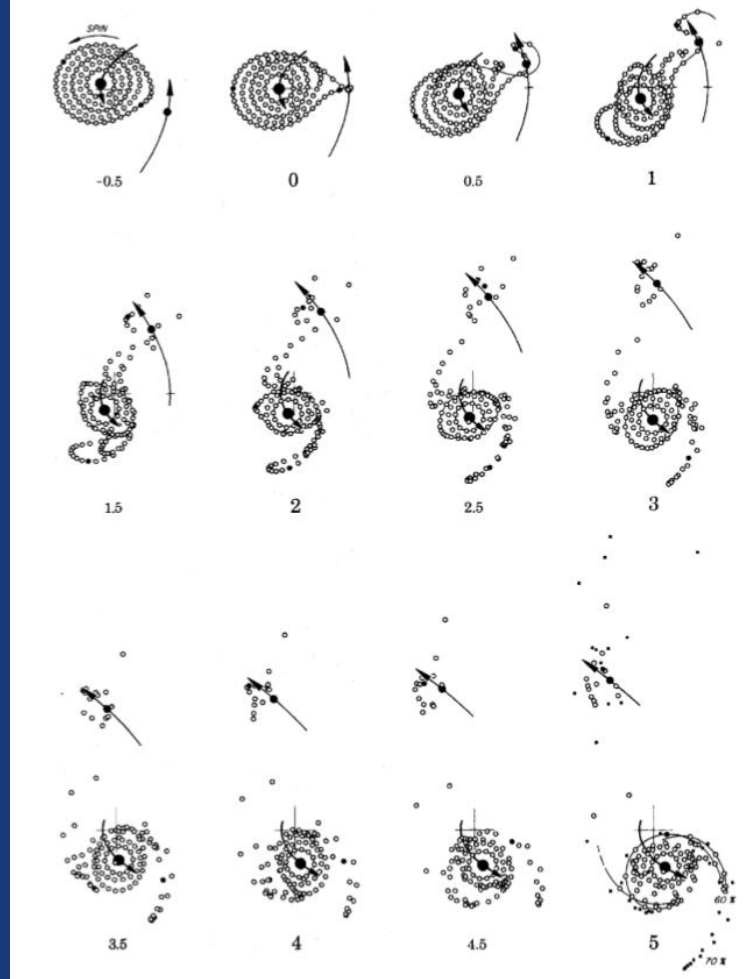
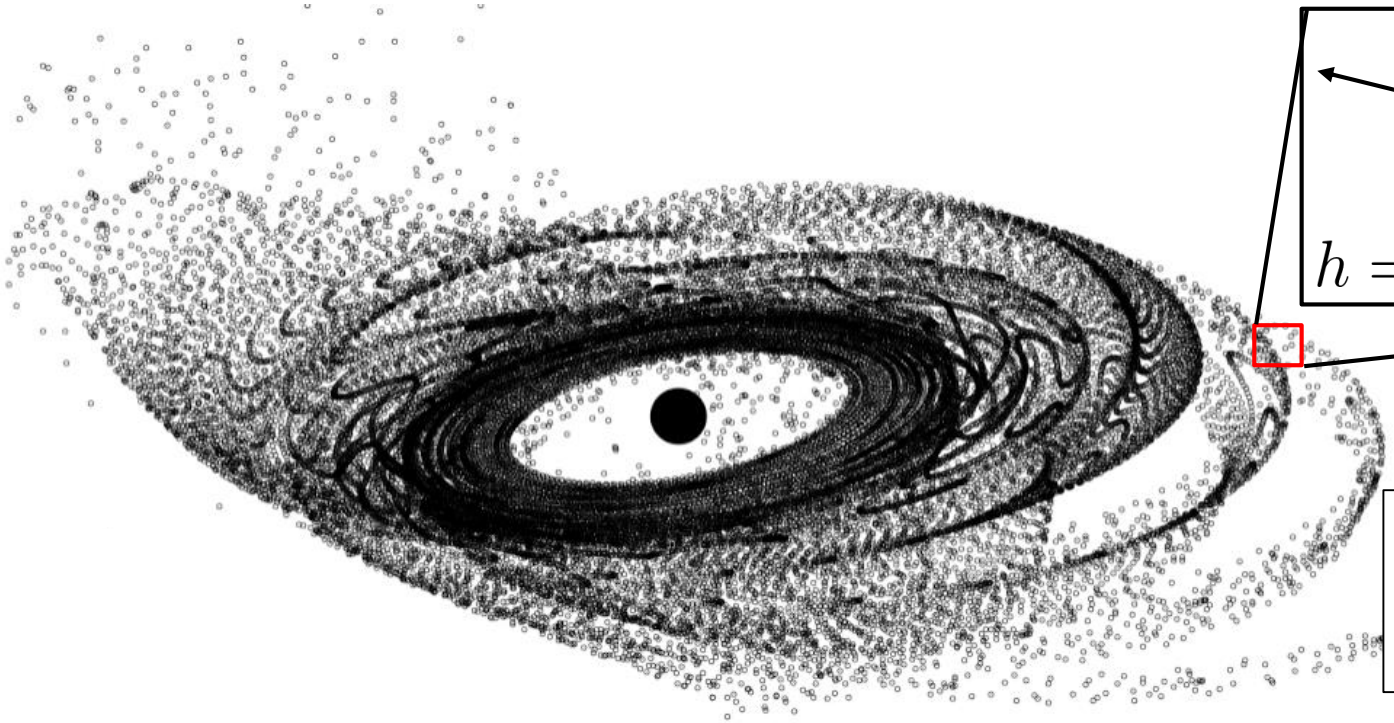
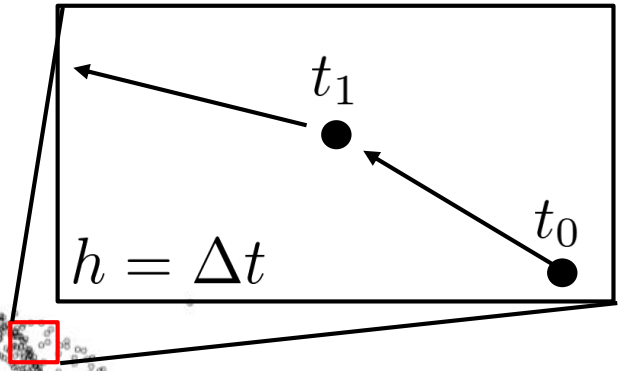


FIG. 4.—A flat direct ($i = 0°$) parabolic passage of a quarter-mass companion

Structure of the Simulation





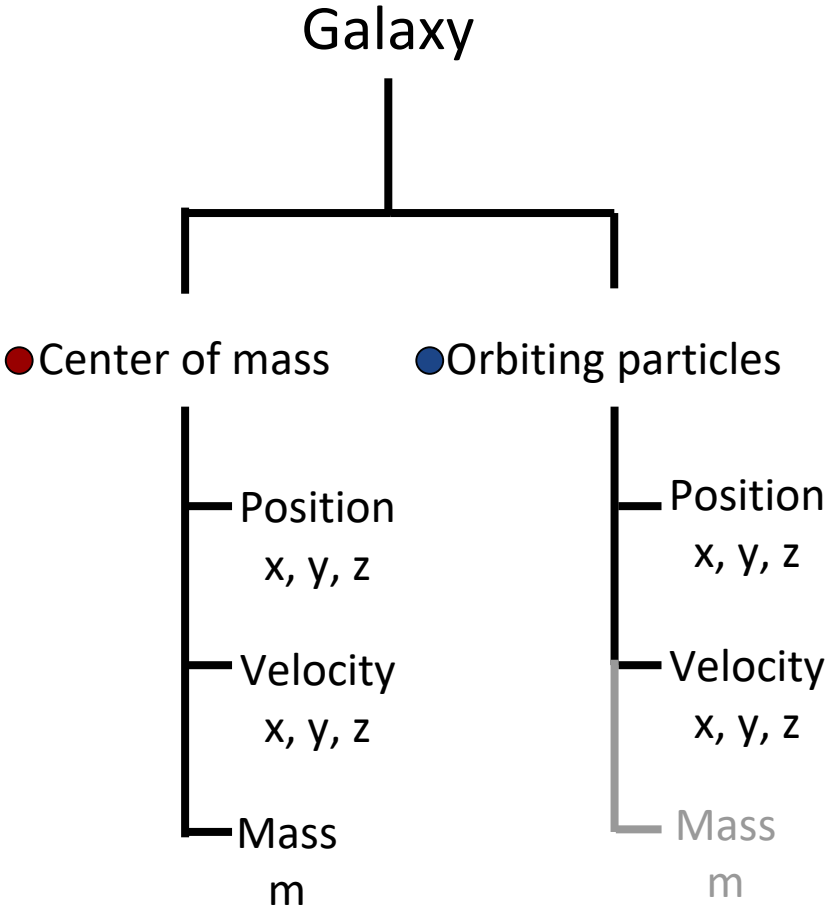
Matplotlib output

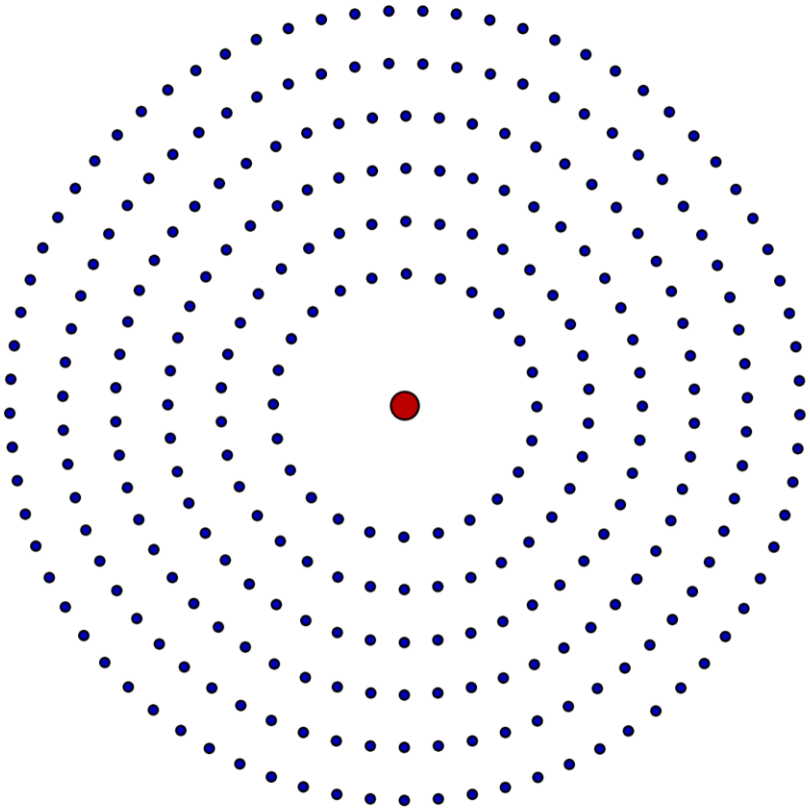
$t_n = nh$

Update function

$t_{n+1} = (n+1)h$

Structure of the Simulation





Structure of the Simulation

Update function

- Analytical solution
  - Two bodies
- Numerical solution
  - Any number of bodies

$$\ddot{\vec{x}}_n^{(j)} = \vec{g}_n^{(j)} = G \sum_{i=1}^{B} \frac{m_i}{|\vec{x}_n^{(i)} - \vec{x}_n^{(j)}|^3} (\vec{x}_n^{(i)} - \vec{x}_n^{(j)})$$

Structure of the Simulation

Euler Integration

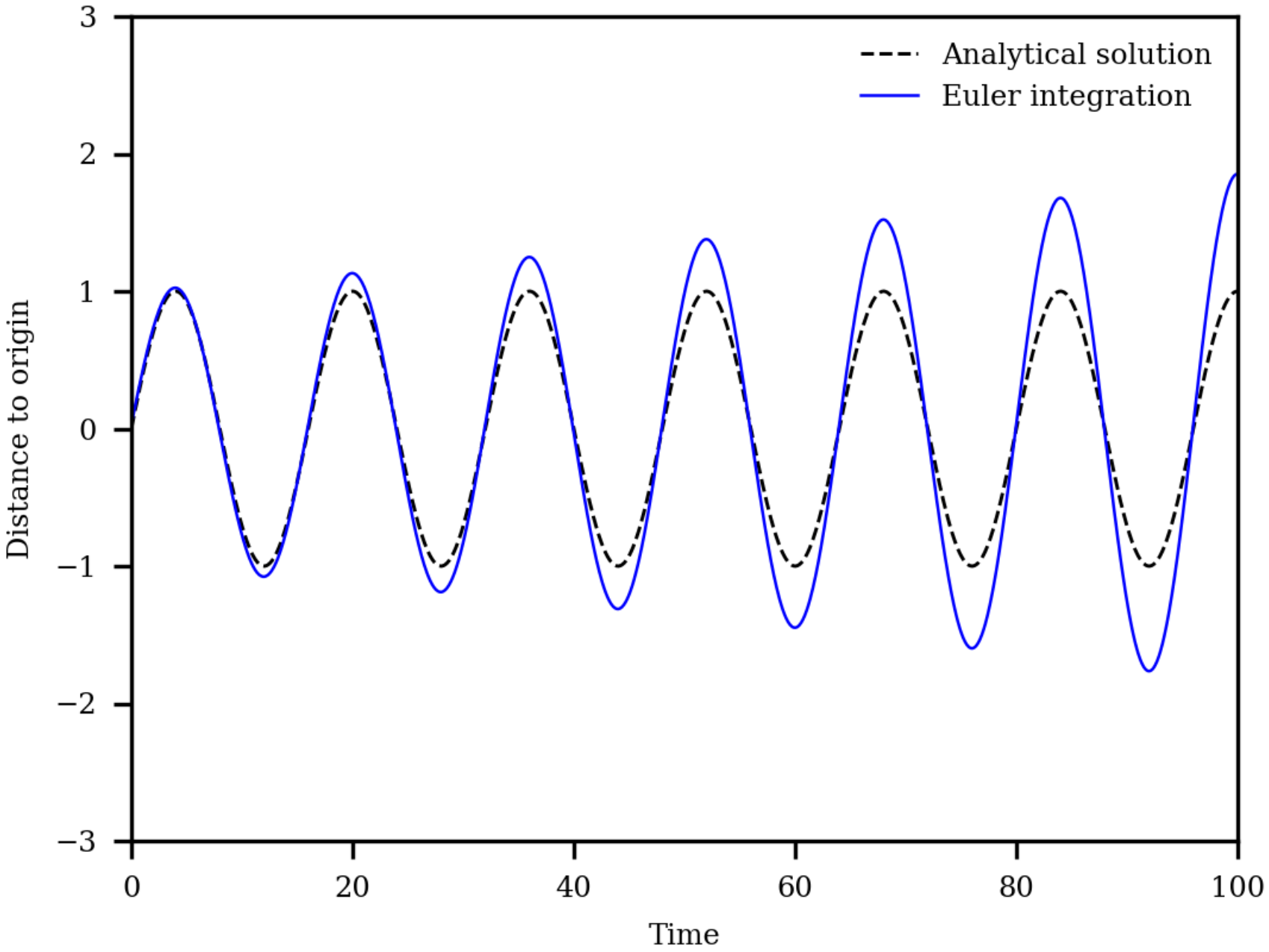
- Time update
$$t_n = t_0 + nh$$
- Velocity update
$$\dot{\vec{x}}_{n+1} = \dot{\vec{x}}_n + h\ddot{\vec{x}}_n$$
- Position update
$$\vec{x}_{n+1} = \vec{x}_n + h\dot{\vec{x}}_n$$

Velocity Verlet

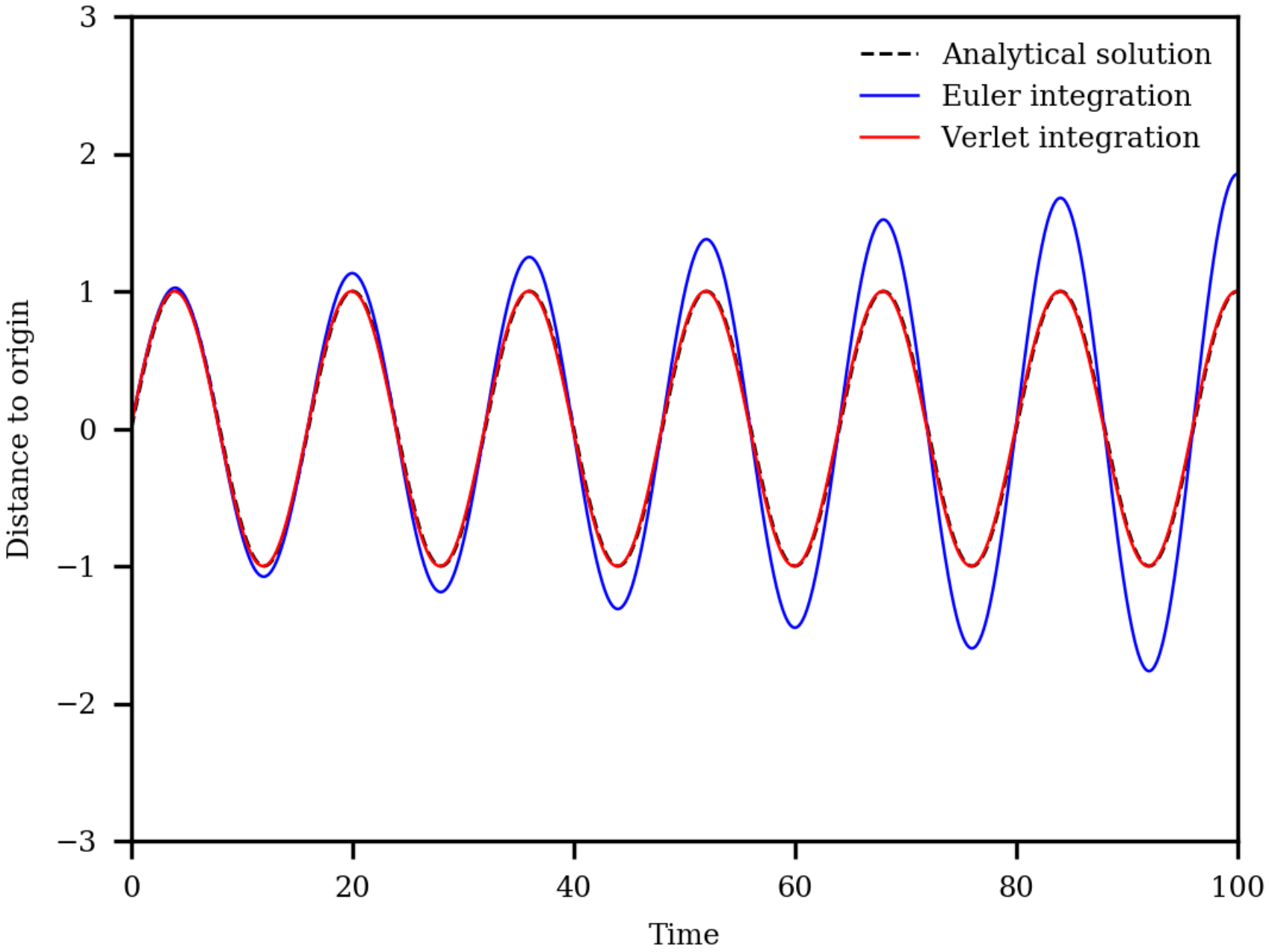
- Half velocity update
$$\dot{\vec{x}}_{n+\frac{1}{2}} = \dot{\vec{x}}_n + \frac{1}{2}\ddot{\vec{x}}_n h$$
- Position update
$$\vec{x}_{n+1} = \vec{x}_n + \dot{\vec{x}}_{n+\frac{1}{2}} h$$
- Velocity update
$$\dot{\vec{x}}_{n+1} = \dot{\vec{x}}_{n+\frac{1}{2}} + \frac{1}{2}\ddot{\vec{x}}_{n+1} h$$

For $n = 1, 2, 3...$

Structure of the Simulation



Structure of the Simulation



Structure of the Simulation

Why use numpy's linear algebra libraries?

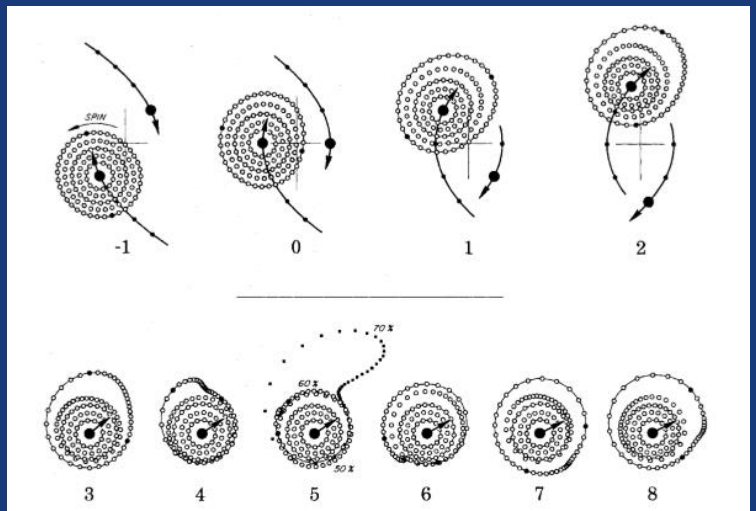
- Simulation times on "light" example:

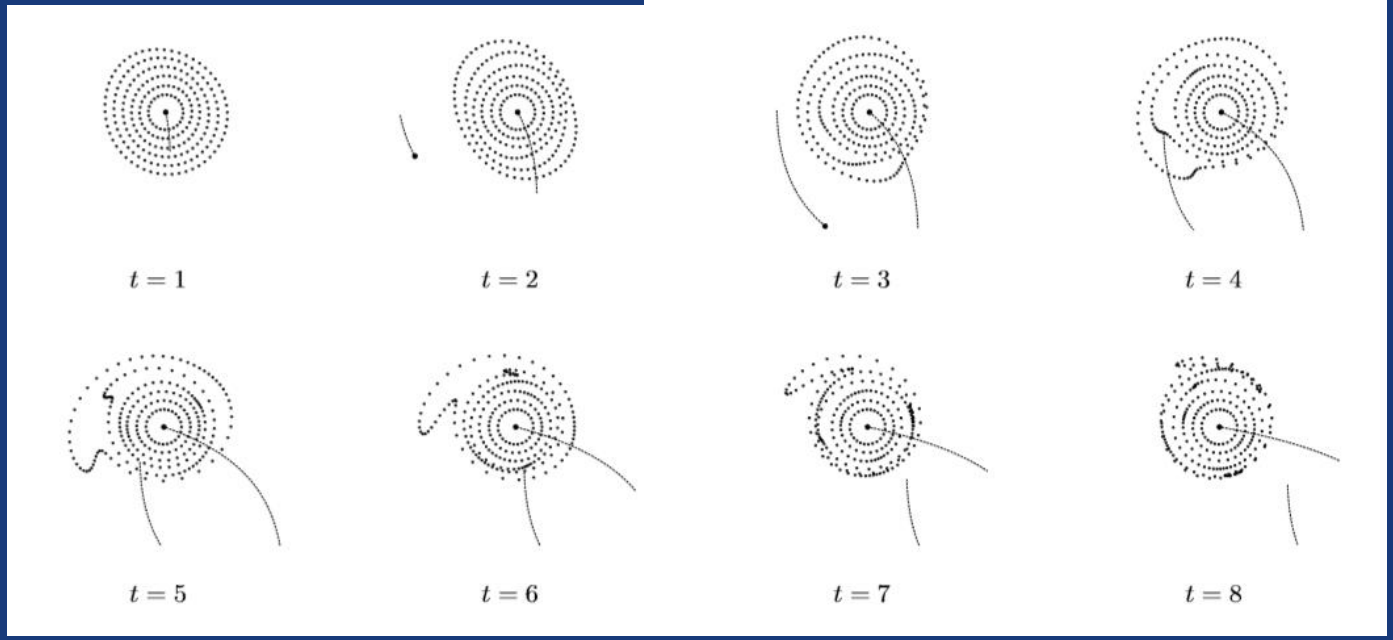
Vectorized algorithm	13.26 s
Iterative algorithm	2874.42 s

- More than a 200-fold improvement

Results - Two Elementary Examples

$$e \approx 1.21$$
$$R_{min} \approx 30.46 \text{ kpc}$$





Results - Two Elementary Examples

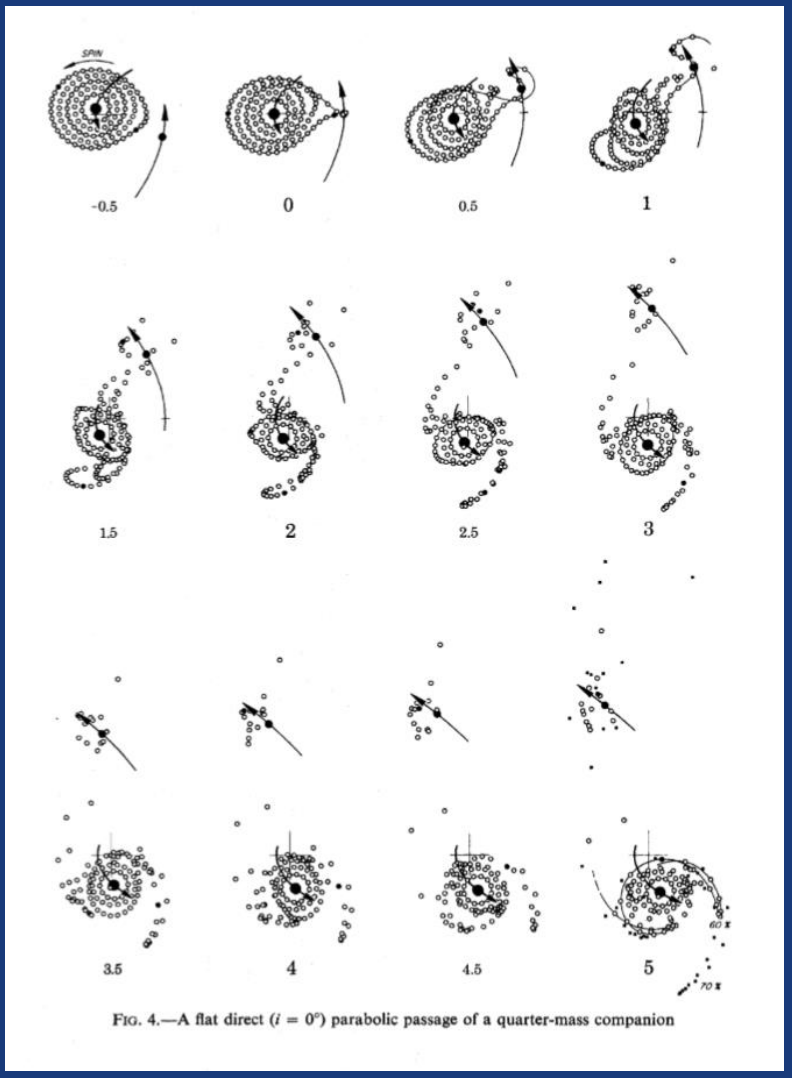
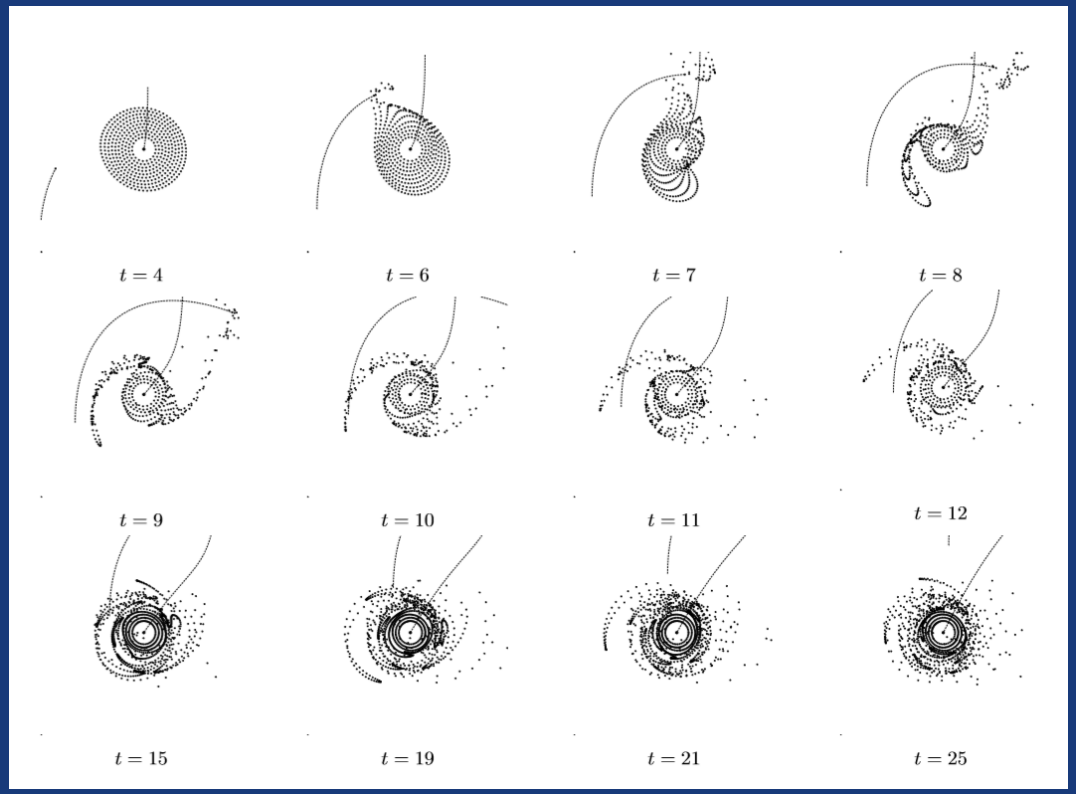


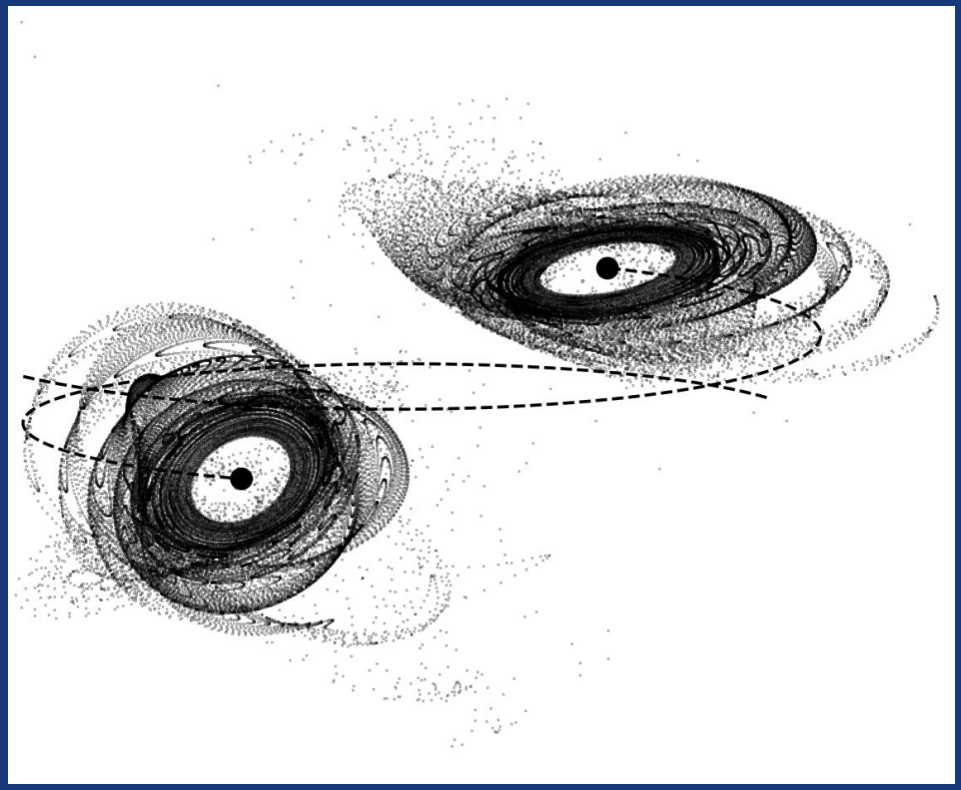
FIG. 4.—A flat direct ($i = 0°$) parabolic passage of a quarter-mass companion



$$e \approx 1.04$$

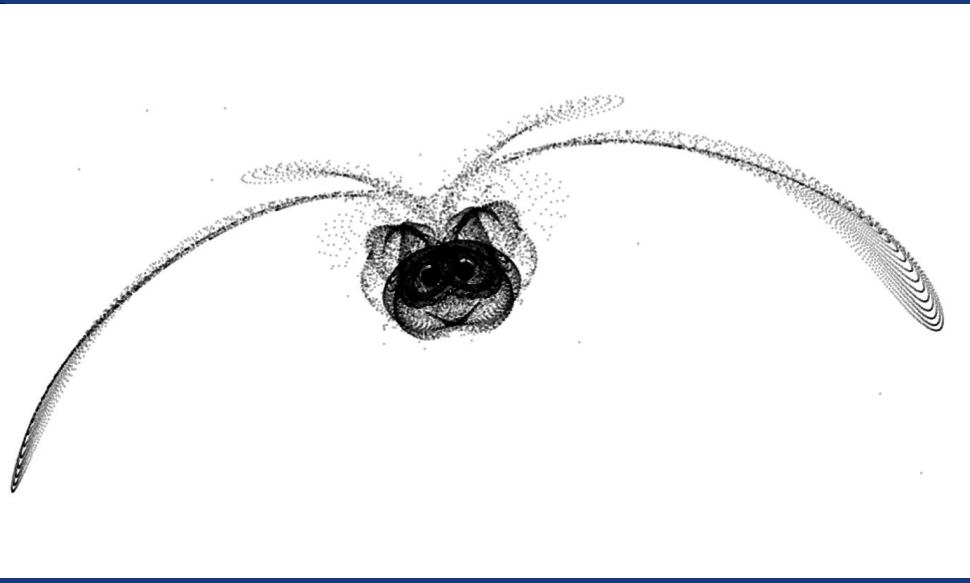
$$R_{min} \approx 27.02 \text{ kpc}$$

Results - Simulation of NGC 5426/7 pair



$e \approx 0.67$ $R_{min} \approx 28.16$ kpc

Results - Simulation of NGC 4038/9 pair



$e \approx 1.21$

$R_{min} \approx 30.46$ kpc

Our personal experience

- Obstacles we faced
- What kept us motivated?
- What we learned from the project

Application to Education

- Importance of the project
- Simplifications
- Pre-requirements for students

Bibliography

Toomre, A., and Toomre, J. 1972, in *Galactic Bridges and Tails*

https://apod.nasa.gov/apod/ap150212.html

https://apod.nasa.gov/apod/ap130825.html