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Understanding Exoplanet Clouds Using Video Games Technologies

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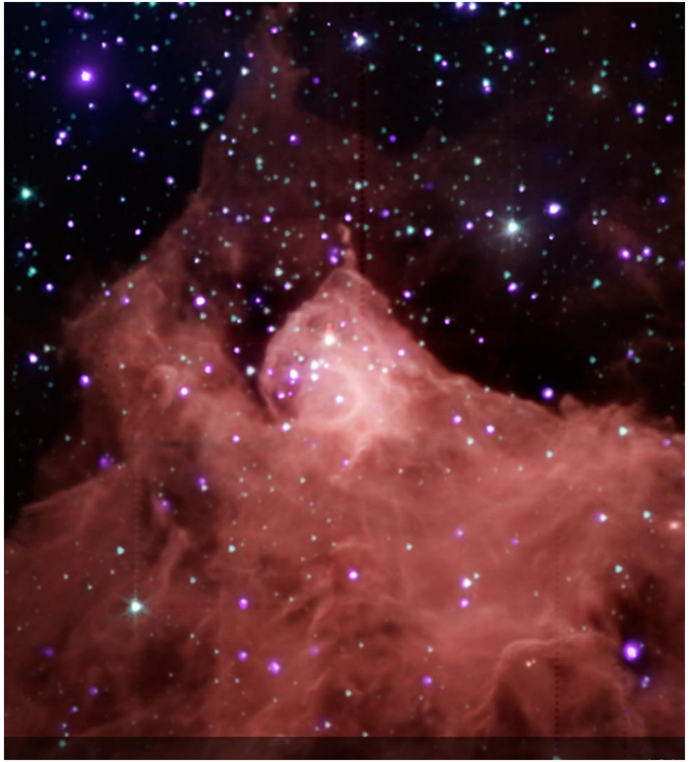
Background

Background / Star Formation

- Molecular clouds collapse due to self gravity;
- Pressure and friction lead to increased temperatures;
- Nuclear fusion then prevents further collapse (hydrostatic equilibrium).

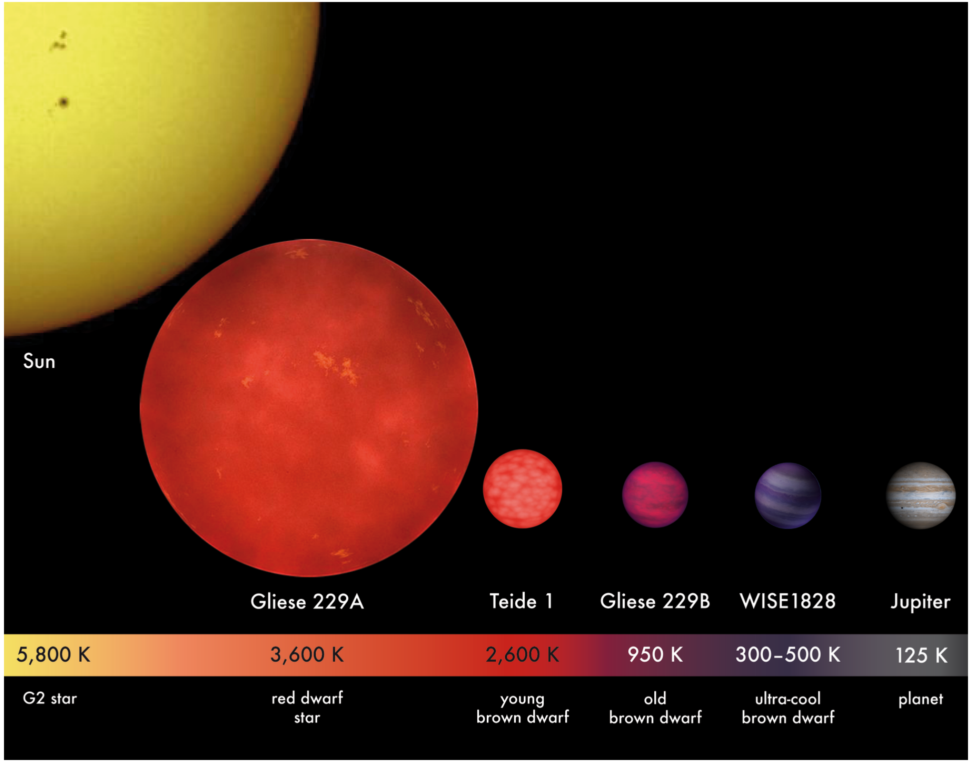


Cepheus-B molecular cloud and star formation region
- X-Ray NASA/CXC/PSU/K. Getman et al.
- IRL NASA/JPL-Caltech/CfA/J. Wang et al

Background / Brown Dwarfs I

- Cooler ($2500\text{K} < T < 500\text{K}$),
- Lighter ($90M_\text{J} < m < 10M_\text{J}$),
- Smaller ($R \approx R_\text{J}$)

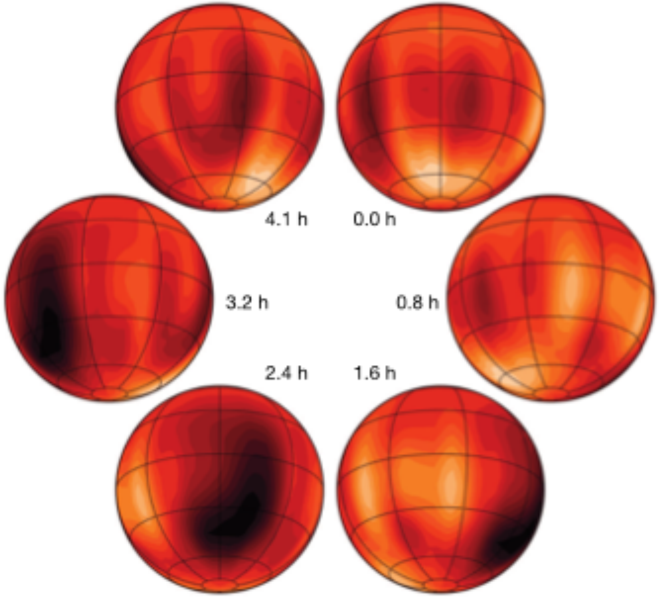
than stars ($1M_J \approx 10^{-3}M_\odot$).



PIA/V. Joergens. Joergens, Viki, "50 Years of Brown Dwarfs". Astrophysics and Space Science Library 401, Springer, ISBN 978-3-319-01162-2."

Background / Brown Dwarfs II

- Dust clouds are theorised and recently observed in warmer brown dwarfs.
- Clouds are formed in part of magnetically susceptible dust (TiO_2, SiO_2...)
- Existing models provide information on dust evolution (nucleation and mantle growth.)



- Surface map of Luhman 16B.
  Crossfield et al. 2014, Nature, 505, 654.
- Helling et al. 2008, Mon. Not. RAS. 391, 1854

Background / Problem

- Understanding why clouds disappear as brown dwarfs cool down makes it important to understand cloud coverage in brown dwarfs.
- Understanding interaction of atmospheric gas flows and magnetic fields on dust grains will drive better brown dwarf cloud coverage models.
- Faster fluid and atmospheric models could have application both for Earth sciences, and physics and game engines.

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Three Main Studies

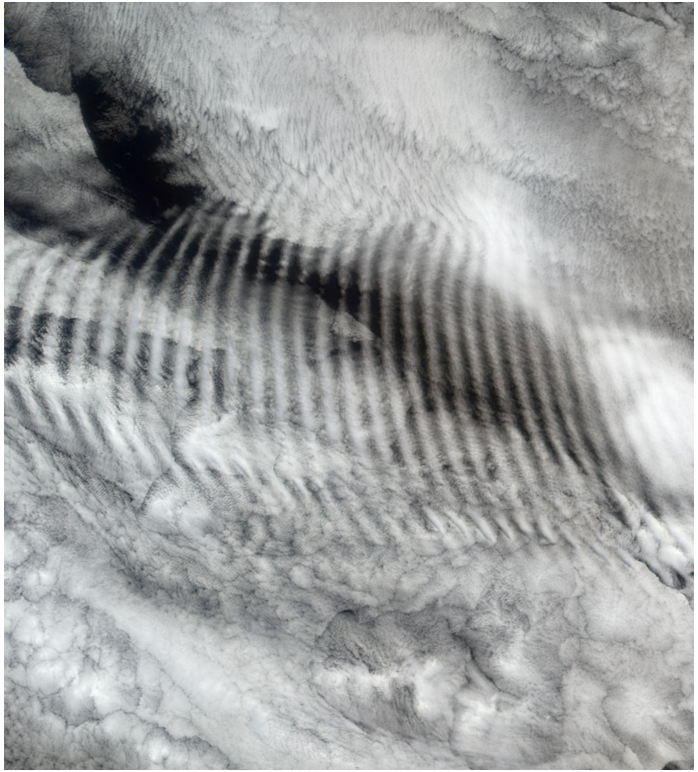
- Analysing the impact of internal gravity waves on the formation of dust clouds in Brown Dwarfs.
- Investigating the applicability of scientific numerical integration methods to video game engine applications.
- Investigating the interaction of dust clouds with weather and magnetic fields using GPGPU methods, and applying fluid solvers to video game engines.

Study 1

Impact of Internal Gravity Waves on Dust Cloud Formation

Study 1 / Internal Gravity Waves

- Density or velocity perturbations create atmospheric oscillations;
- IGW have been observed on Earth and solar system Gas Giants;
- on Earth, IGW lead to banded structures in clouds.



Gravity Waves Ripple over Marine Stratocumulus Clouds
NASA/GSFC/LaRC/JPL, MISR Team

Study 1 / Hypothesis & Aims

Internal gravity waves in brown dwarf atmospheres lead to similar banded clouds and could inform atmospheric models

- Establish a relationship between observable wave structure (distance between bands, time periodicity) and atmospheric profile (density, pressure and temperaturel;
- simulate internal gravity waves and investigate their impact on dust cloud formation numerically.

Gravity Waves' Dispersion Relation

ANGULAR FREQUENCY

WAVE NUMBER, X

$$\omega^2 = \frac{N^2 k_x^2}{k_x^2 + k_y^2}$$

WAVE NUMBER, Y

$$N^2 = -\frac{g}{\rho_0}\frac{\partial \rho_0}{\partial y}$$

BUOYANCY FREQUENCY
(BRÜNT-VÄISÄLÄ)

ATMOSPHERIC DENSITY

Study 1 / Methods II

$$\frac{\partial \zeta}{\partial t} = -\frac{g}{\rho_0}\frac{\partial \rho}{\partial x}$$

$$\frac{\partial \rho}{\partial t} = \frac{\partial \rho_0}{\partial y}\frac{\partial \psi}{\partial x}$$

$$\zeta = -\frac{\partial^2 \psi}{\partial x^2} - \frac{\partial^2 \psi}{\partial y^2}$$

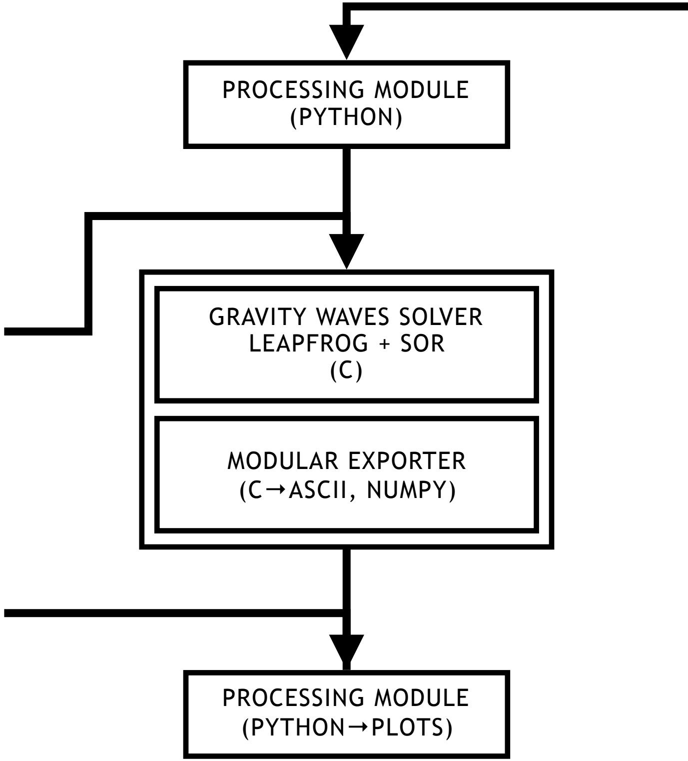
LINEAR FLUID EQUATIONS

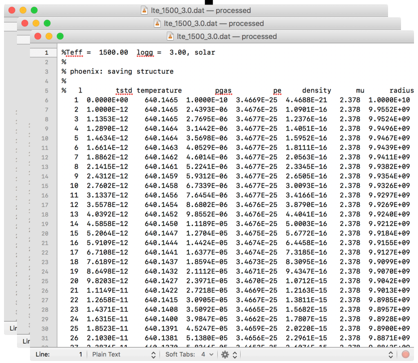
$$J_* = f\left(p_{gas}, \rho_{gas}, T_{gas}, n_{TiO_2}\right)$$

$$\gamma = f\left(p_{gas}, \rho_{gas}, T_{gas}, n_{TiO_2}\right)$$

DUST FORMATION MODEL

- Gail et al. 1984
- Helling et al. 2001



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% phoenix: saving structure
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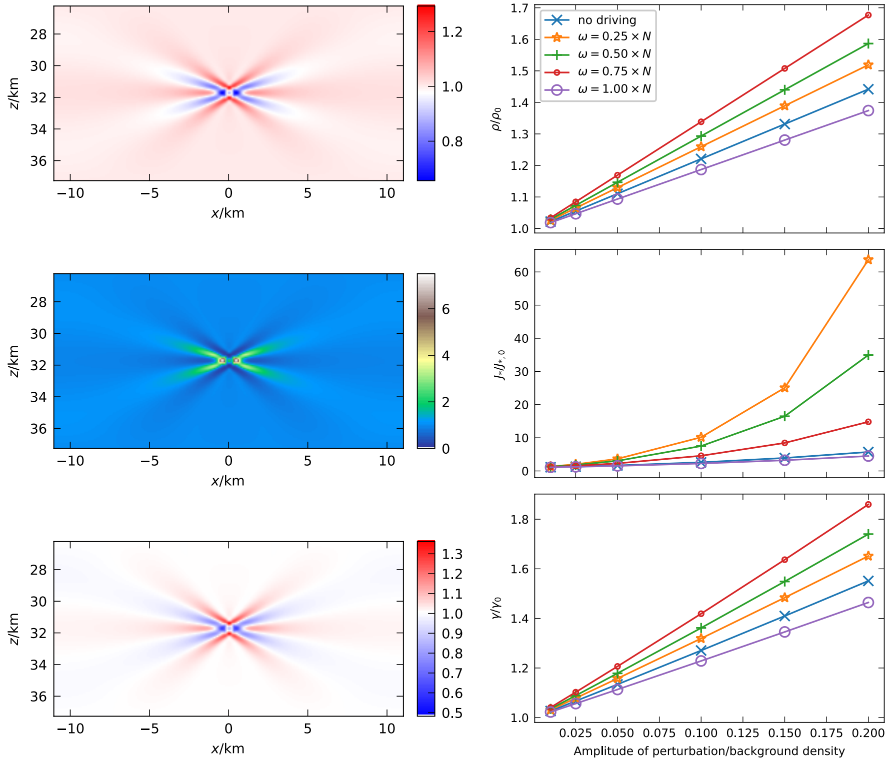
  26  2.1030E-11    640.1381  5.1380E-05  3.4656E-25  2.2961E-15   2.378  9.8871E+09
```


DRIFT-PHOENIX MODEL DATA

- Hauschildt and Baron. 1999
- Helling et al. 2004
- Helling and Woitke. 2006
- Witte et al. 2009
- Witte et al. 2011
- Stark et al. 2018

Study 1 / Results I

- Internal gravity waves cause density, temperature and pressure variations;
- Strong increase in nucleation (up to 60x).
- Mild increase in mantle growth (up to 1.8x).



Study 1 / Results II

- Model fluid equations require iterative method (SOR), which is hard to parallelise and poorly suited for GPGPU implementation;
- each simulation steps requires > 10 minutes, making such methods unsuitable for game applications;
- equations requiring leapfrog integration represent an insignificant fraction of the required processing power by comparison.

Study 1 / Conclusions & Further Work

Conclusions

- Internal gravity waves contribute to increase dust cloud formation;
- cloud structures are too small to be observable using current telescopes, but time variability could help.

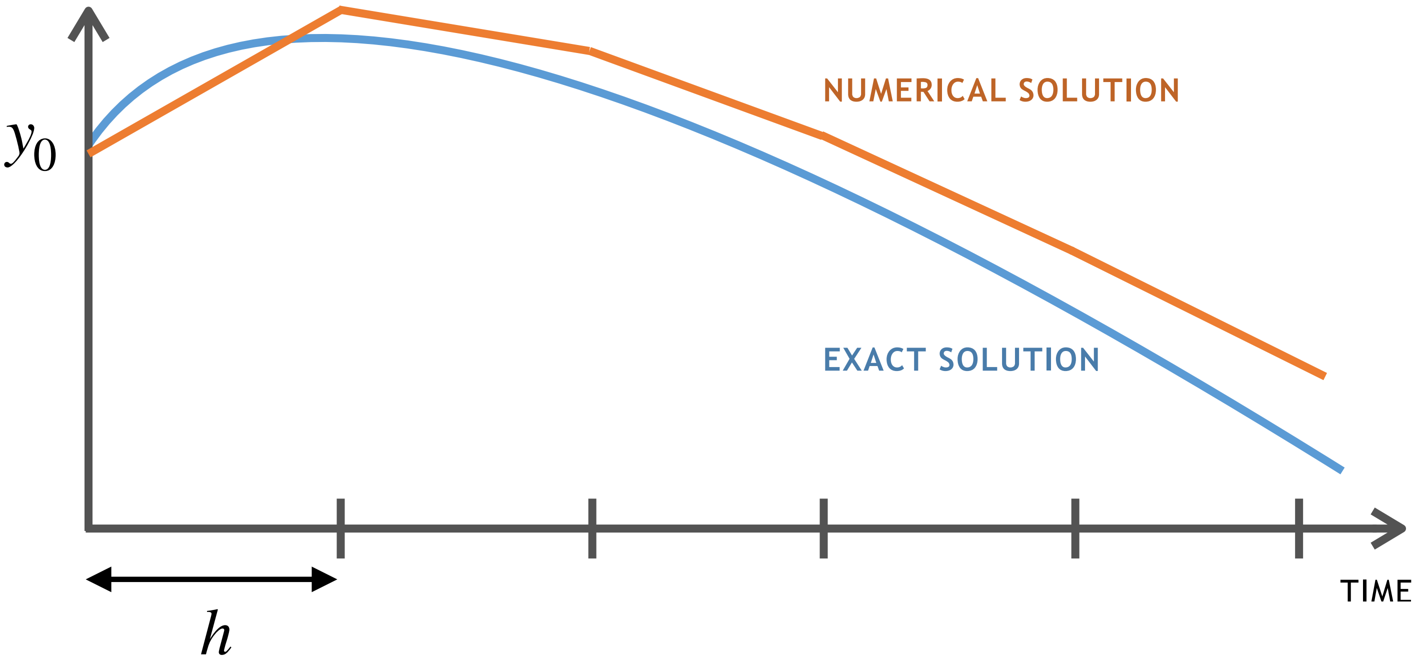
Further Work

- Test of observation & recovery method using published data.
- Paper publication (Astronomy & Astrophysics)
  Poster Presentation (Extreme Solar Systems Conference

Study 2

Numerical methods for physics engines

$$y' = f(t, y(t))$$



Study 2 / Numerical Methods

Explicit Euler
Semi-Implicit Euler
Velocity Verlet

Runge-Kutta 4
Leapfrog
Midpoint

Predictor-Corrector
Bulirsch-Stoer

GAMES METHODS ⟷ SCIENTIFIC METHODS

Study 2 / Aims

- Test the accuracy and efficiency of typical games- and scientific- focused numerical methods using well-understood test cases (harmonic spring motion)
- Establish whether methods used in scientific contexts could benefit physics and game engine applications

Study 2 / Methods

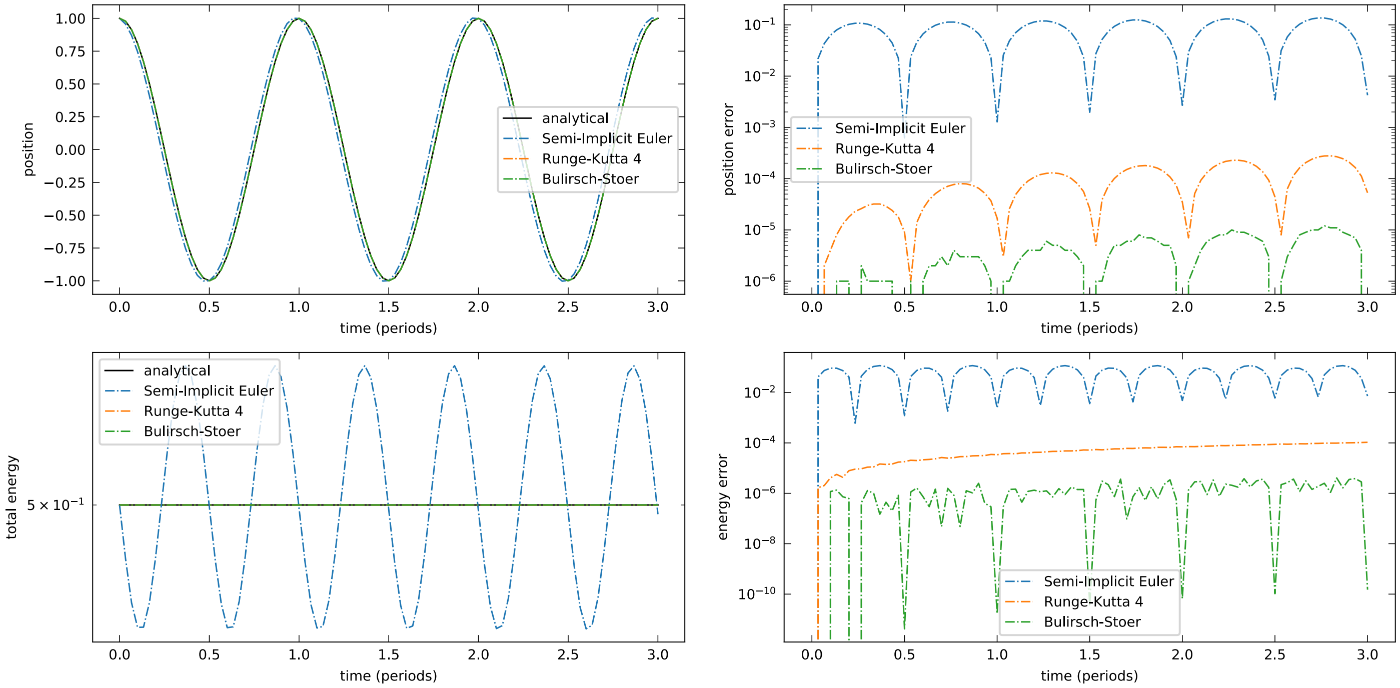
- Implement test framework and each method in C++
- Measure & compare accuracy of each method using known cases
- Measure brute-force speed of each method
- Evaluate Bulirsch-Stoer and Predictor-Corrector methods for games applications

Study 1 / Initial Tests

$$\ddot{x} = -\frac{k}{m}x$$

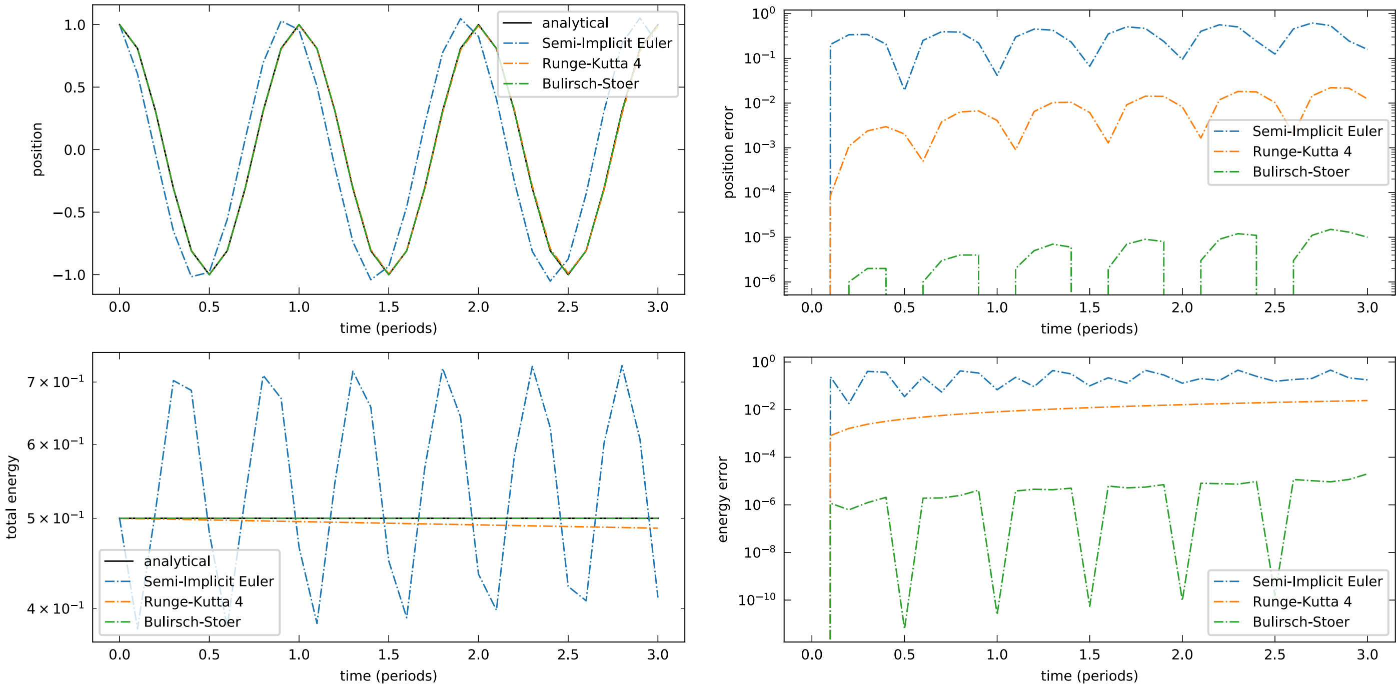
Harmonic Spring Motion

Study 1 / Initial Tests

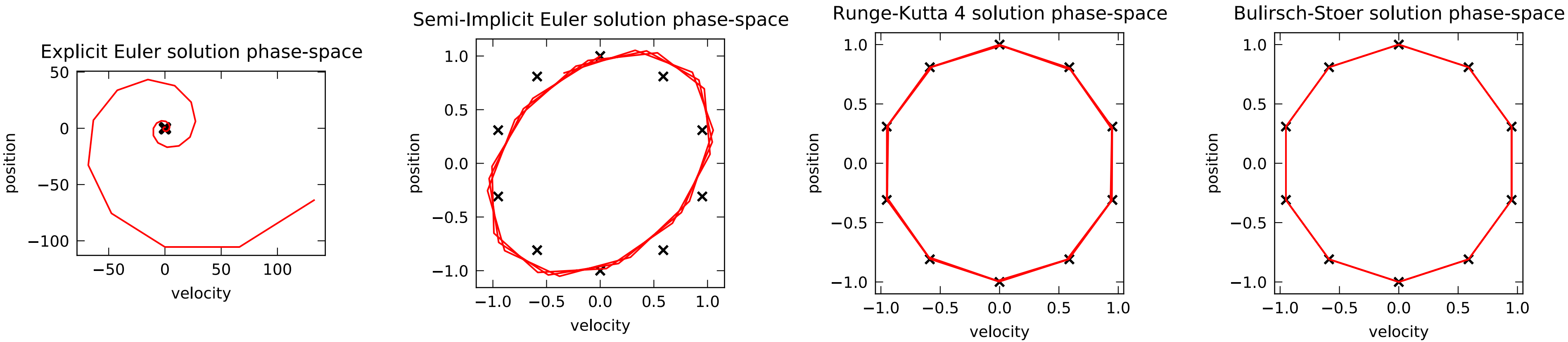


30 time steps per oscillation period

Study 1 / Initial Tests



10 time steps per oscillation period



10 time steps per oscillation period

Preliminary Results

Bulirsch-Stoer method stays accurate at larger time step, but “hides” complexity by creating sub-steps when required

Further Work

- Test selected methods for processing speed
- Integrate Bulirsch-Stoer method in simple game engine for testing

Study 3

Fast fluid-particle solver for dust cloud motion

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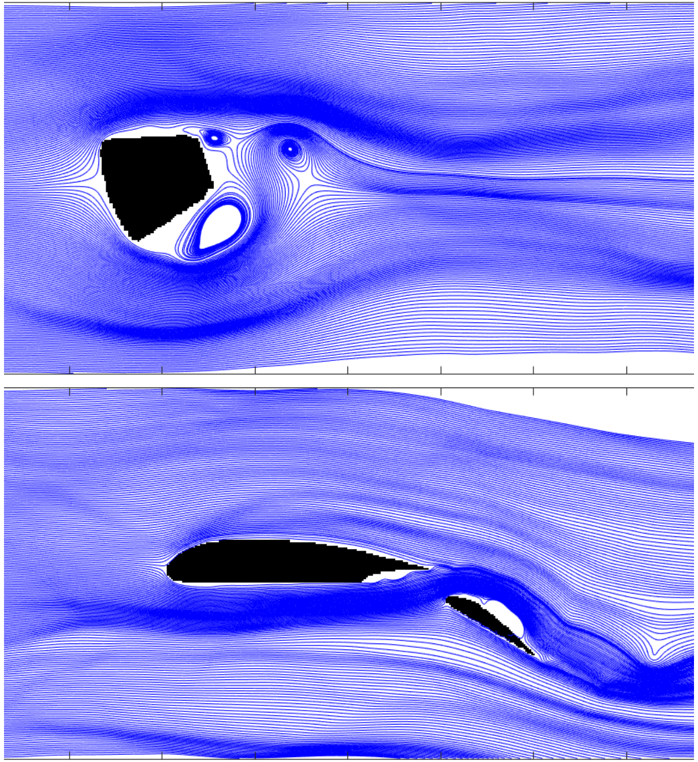
Study 3 / Preliminary Work

- Prototype implementation of a Lattice-Boltzmann fluid solver
- Able to load arbitrary boundaries (drawn as bitmap images)



Further Work

- Implement GPGU/parellel LB solver
- Couple fluid solver with magnetic dust particle solver (brown dwarf clouds)
- Investigate usability of LB for interactive fluid simulation in games

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