Universität Zürich UZH

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New developments in GENGA - more functions for more physics

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Carving through the Codes, Davos 2017

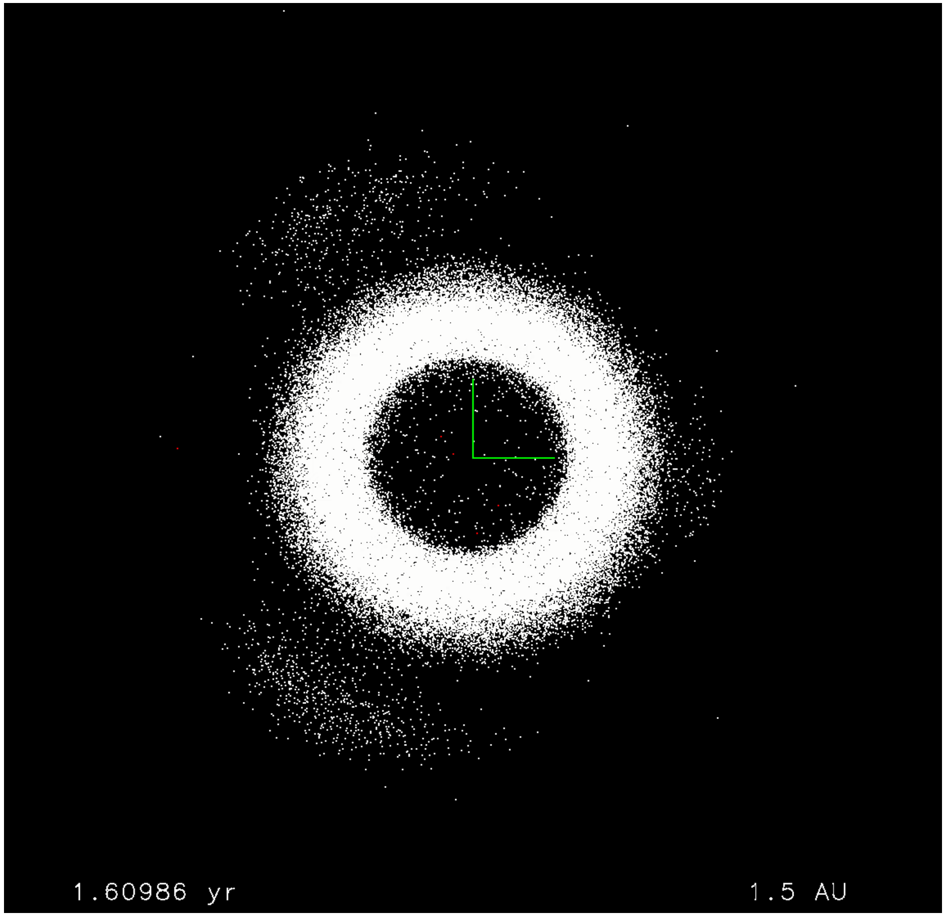
GENGA

GENGA is a hybrid symplectic N-body integrator, optimized to simulate planet formation and planetary system evolution.

It can simulate:

- up to **32768** massive bodies
- up to **1** million test particles
- up to **100000** parallel small simulations

The code runs fully on GPUs.



Outline

- Theory non-Newtonian forces
- Application I: Asteroid breakup
- Application II: Planetesimal accretion

Theory: the hybrid symplectic integrator

$$H = H_A + H_B + H_C,$$

Using democratic coordinates

$$H_A = \sum_{i=1}^{N} \left(\frac{p_i^2}{2m_i} - \frac{G m_i m_\odot}{r_{i\odot}} \right)$$

Keplerian drift, analytical

$$- \sum_{i=1}^{N} \sum_{j=i+1}^{N} \frac{G m_i m_j}{r_{ij}} [1 - K(r_{ij})],$$

Bulirsh-Stoer direct integration

$$H_B = - \sum_{i=1}^{N} \sum_{j=i+1}^{N} \frac{G m_i m_j}{r_{ij}} K(r_{ij})$$

Kick, order N^2

$$H_C = \frac{1}{2m_\odot} \left(\sum_{i=1}^{N} \mathbf{p}_i \right)^2 .$$

Sun Kick

Theory: GR corrections

$$\mathbf{f_{GR}} = -\frac{G(M_\odot + m_p)}{r^2 c^2} \cdot$$

$$\left(-2(2-\eta)\dot{r}\dot{\mathbf{r}} + \left[(1+3\eta)\dot{\mathbf{r}}\cdot\dot{\mathbf{r}} - \frac{3}{2}\eta\dot{r}^2 \right.\right.$$

$$\left.\left. - 2(2+\eta)\frac{G(M_\odot + m_p)}{r}\right]\hat{\mathbf{r}}\right)$$

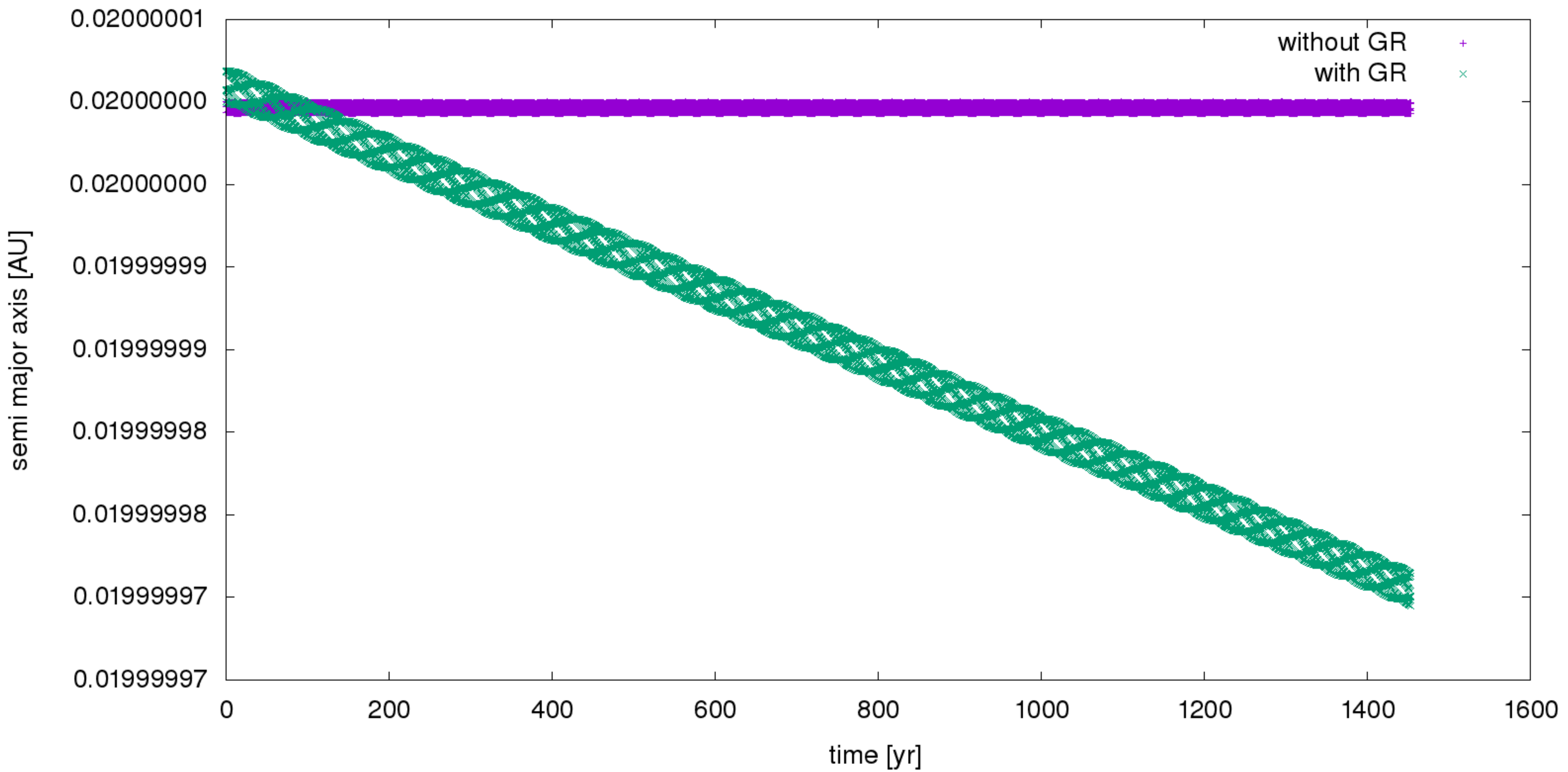
$$\eta = \frac{M_\odot m_p}{(M_\odot + m_p)^2}$$

Fabrycky 2010, Kidder 1995

Force depends on both, positions and velocities.

Including this force in the kick kernel is not symplectic.

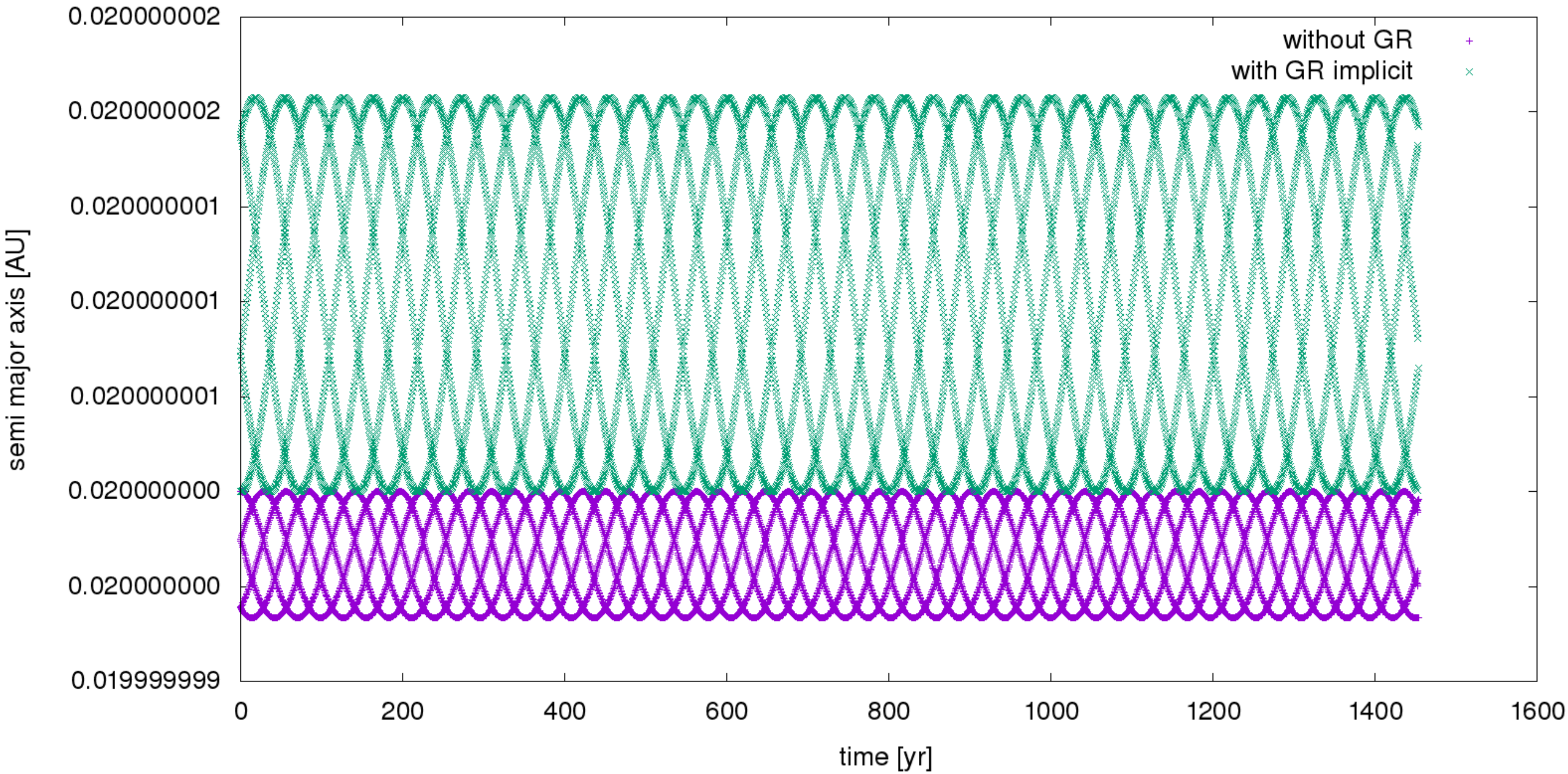
Hot Jupiter test case



Theory: Implicit midpoint method

$$v_{n+1} = v_n + dt * a(t + dt/2, 1/2(v_n + v_{n+1}))$$

```
for(int k = 0; k < 30; ++k){
        a = a(x,vt,t)
        vt = v + 0.5 * dt * a
}
```



Theory: Symplectic GR correction

$$H_{GR} = \alpha H_{Kep}^2 + \frac{\beta}{r^2} + \gamma p^4$$

Saha, Tremaine 1994

$$\alpha = \frac{3}{2mc^2}$$

scale drift: $dt' = \left(1 - \frac{3\mu}{2c^2 a}\right) dt$

$$\beta = \frac{-\mu^2 m}{c^2}$$

Add to kick

$$\gamma = -\frac{1}{2m^3 c^2}$$

Add to sun kick

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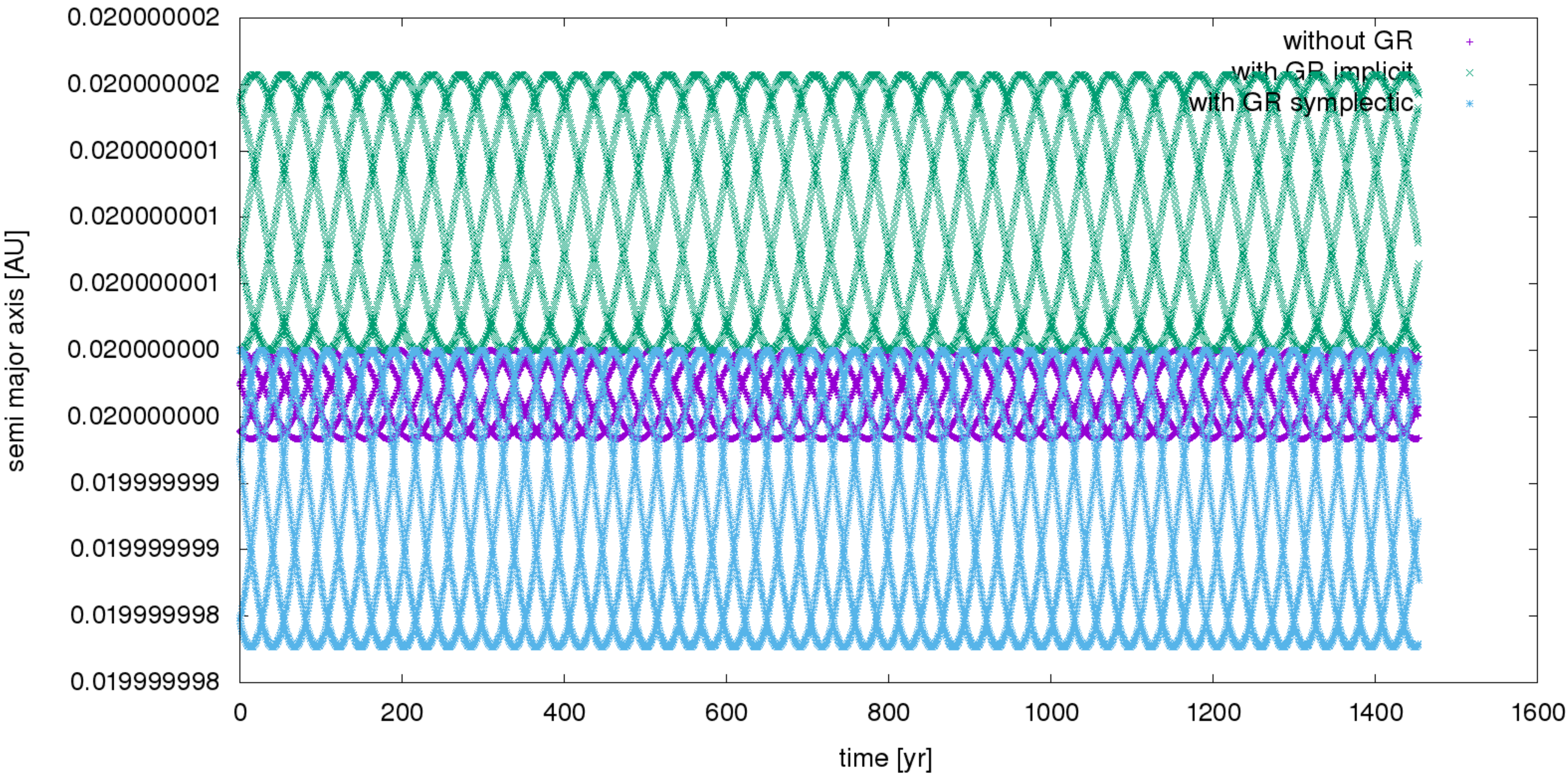
Add to sun kick

$$H_A = \sum_{i=1}^{N} \left(\frac{p_i^2}{2m_i} - \frac{Gm_i m_\odot}{r_{i\odot}} \right)$$
$$- \sum_{i=1}^{N} \sum_{j=i+1}^{N} \frac{Gm_i m_j}{r_{ij}} [1 - K(r_{ij})],$$

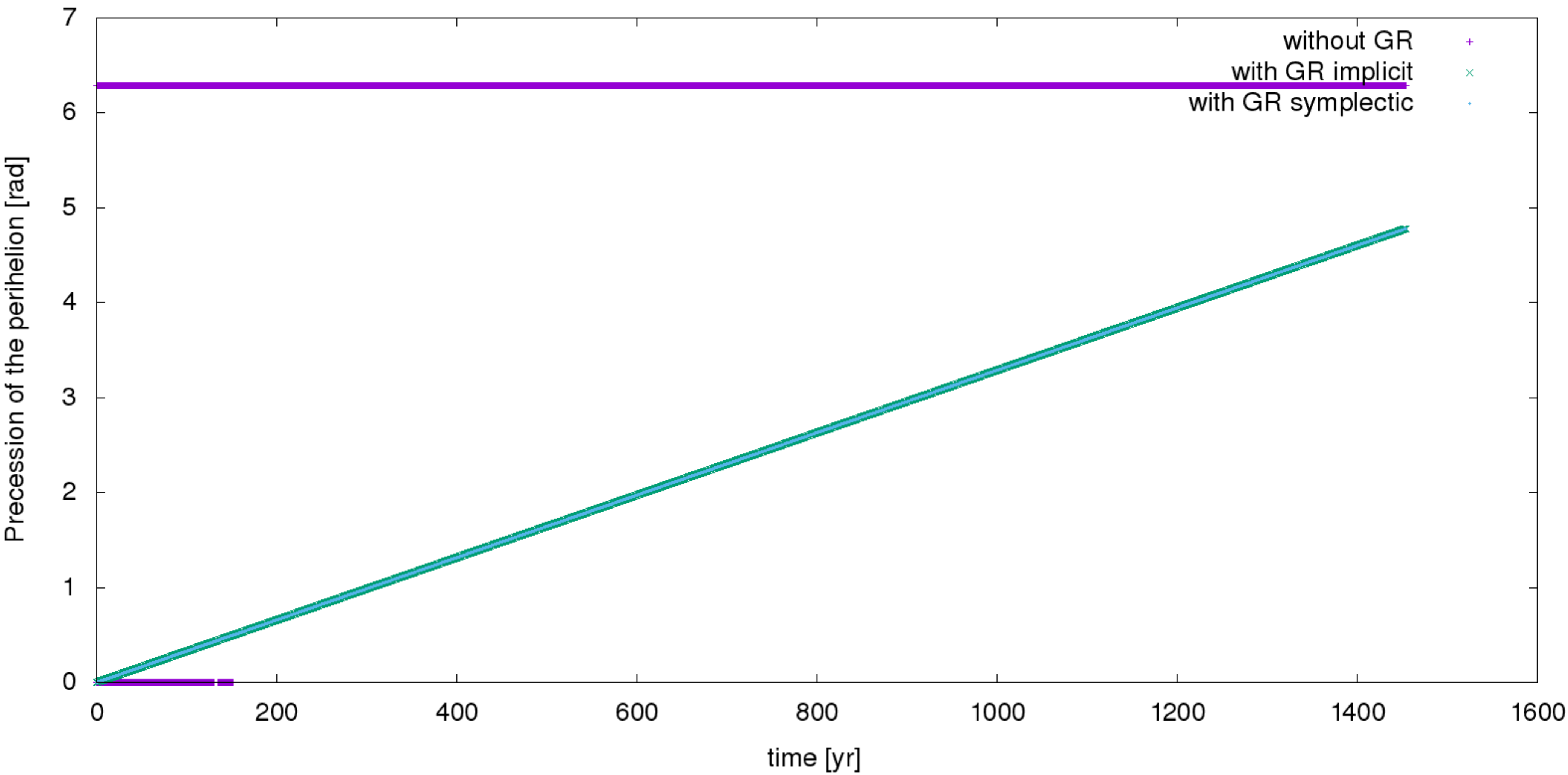
Problem in close encounters:
scale only time for sun acceleration

Comparison



0.020000002
0.020000002
0.020000001
0.020000001
0.020000001
0.020000000
0.020000000
0.019999999
0.019999999
0.019999998
0.019999998
semi major axis [AU]
0
200
400
600
800
1000
1200
1400
1600
time [yr]
without GR
with GR implicit
with GR symplectic

Comparison



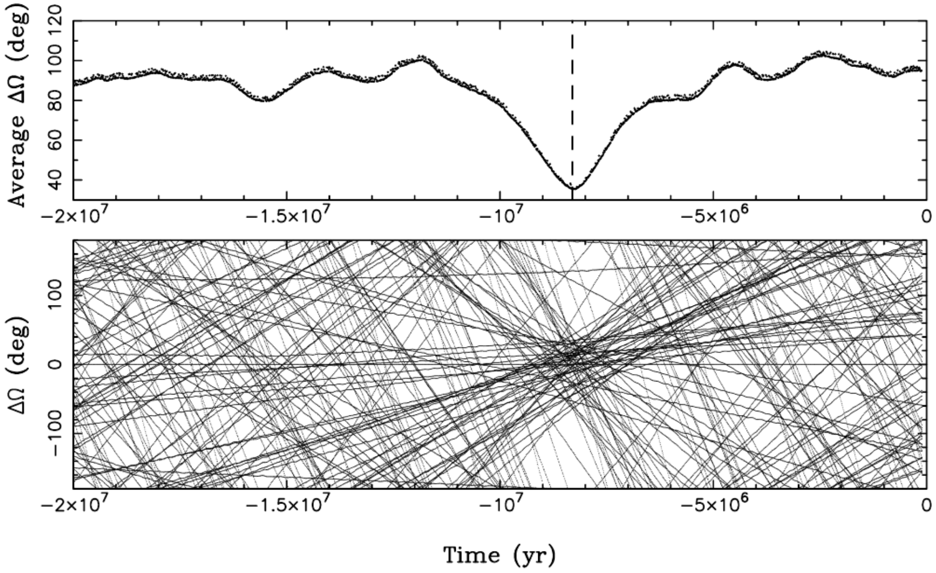
without GR
with GR implicit
with GR symplectic
Precession of the perihelion [rad]
time [yr]
0
1
2
3
4
5
6
7
0
200
400
600
800
1000
1200
1400
1600

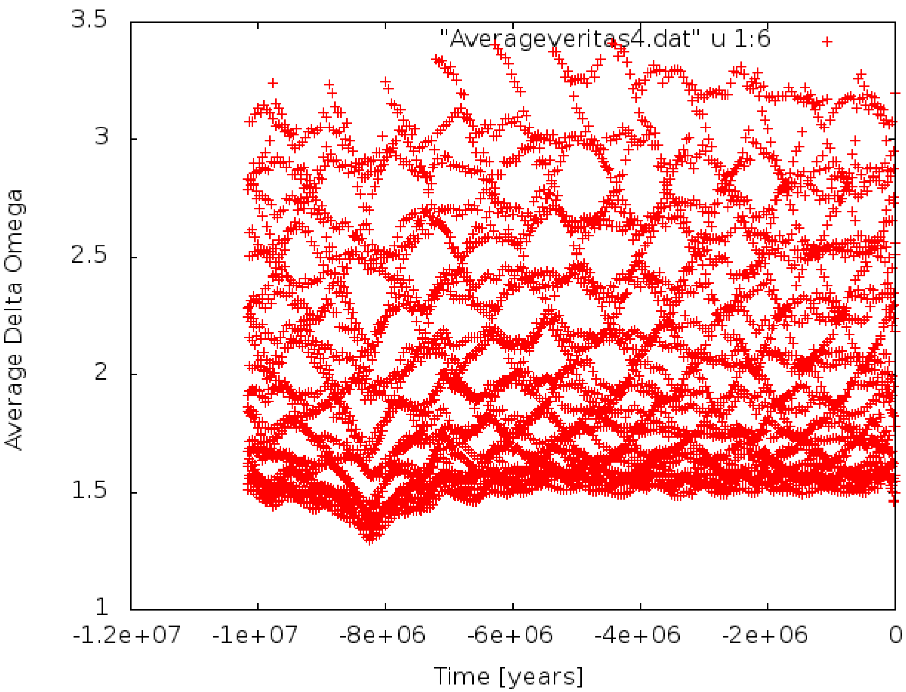
Non-Newtonian forces in GENGA

• GR correction	symplectic
• Tidal forces	implicit
• Rotational deformation	implicit
• Gas drag	force
• Yarkovsky	force
• Poynting-Robertson	force

Veritas breakup

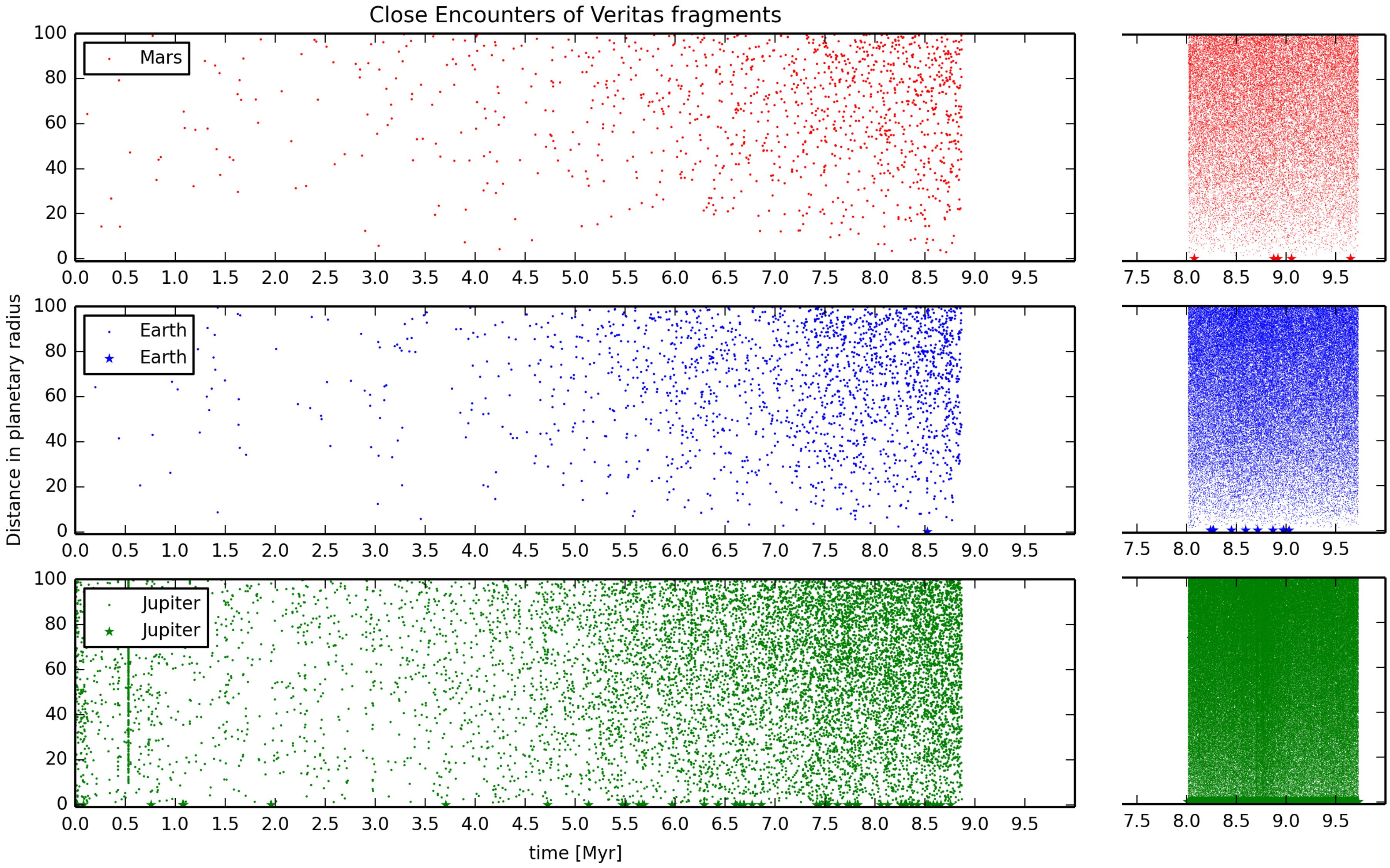
Nesvorny et al. 2013



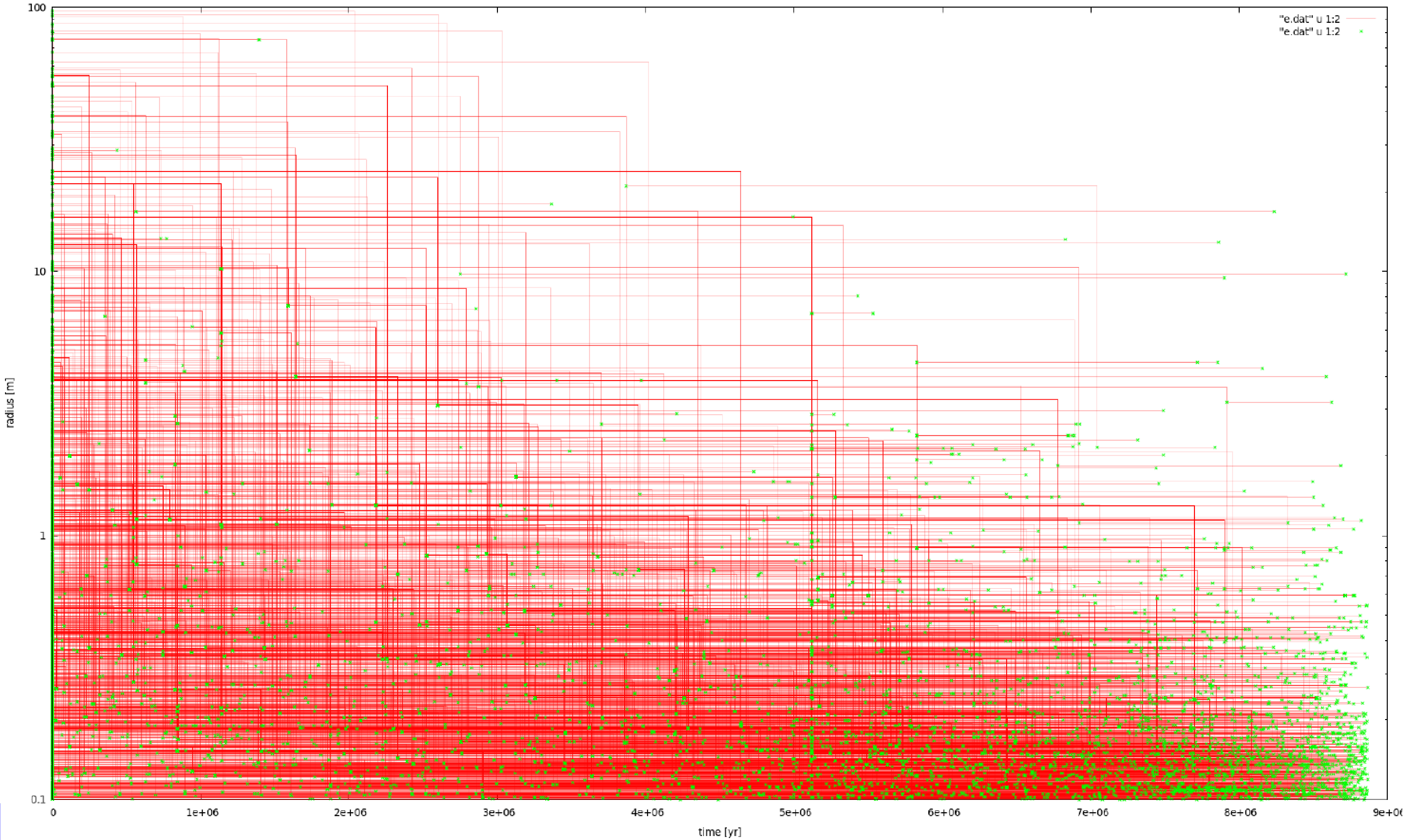


Yarkovsky effect
Poyting Robertson drag
Collision model
Fragmentation model

Impacts and close encounters



Radius evolution of fragments



Comparison to observed meteors

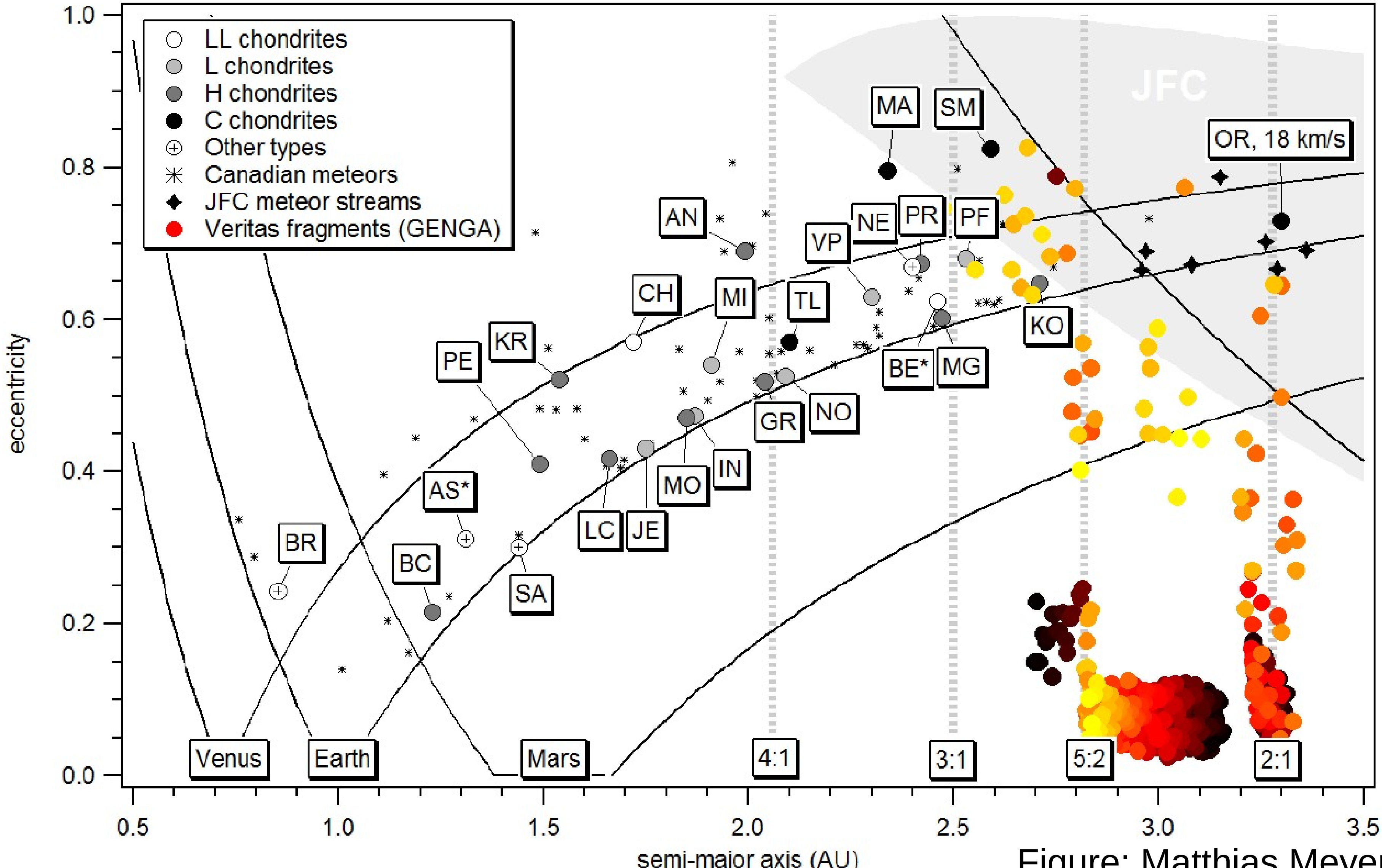
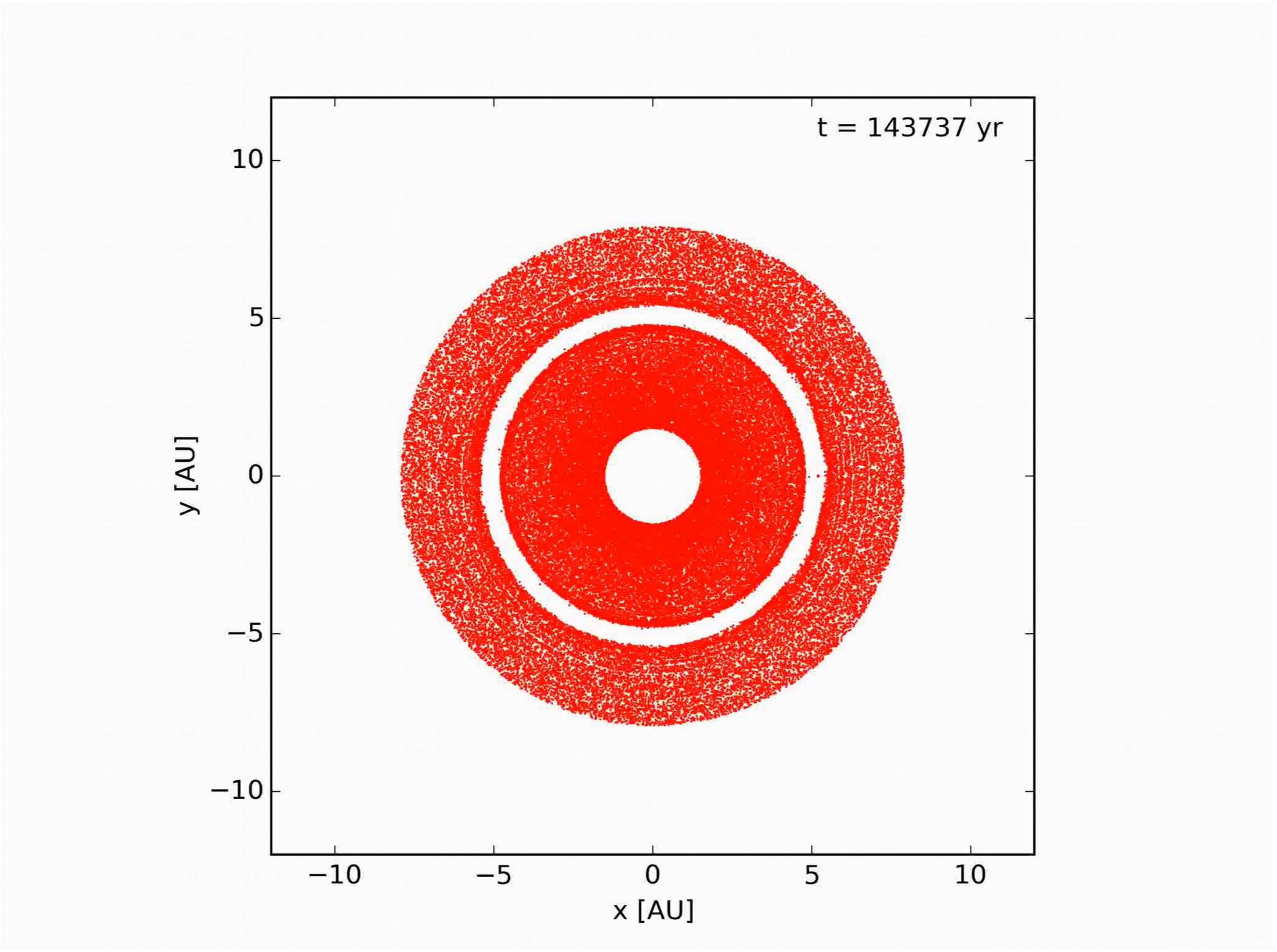


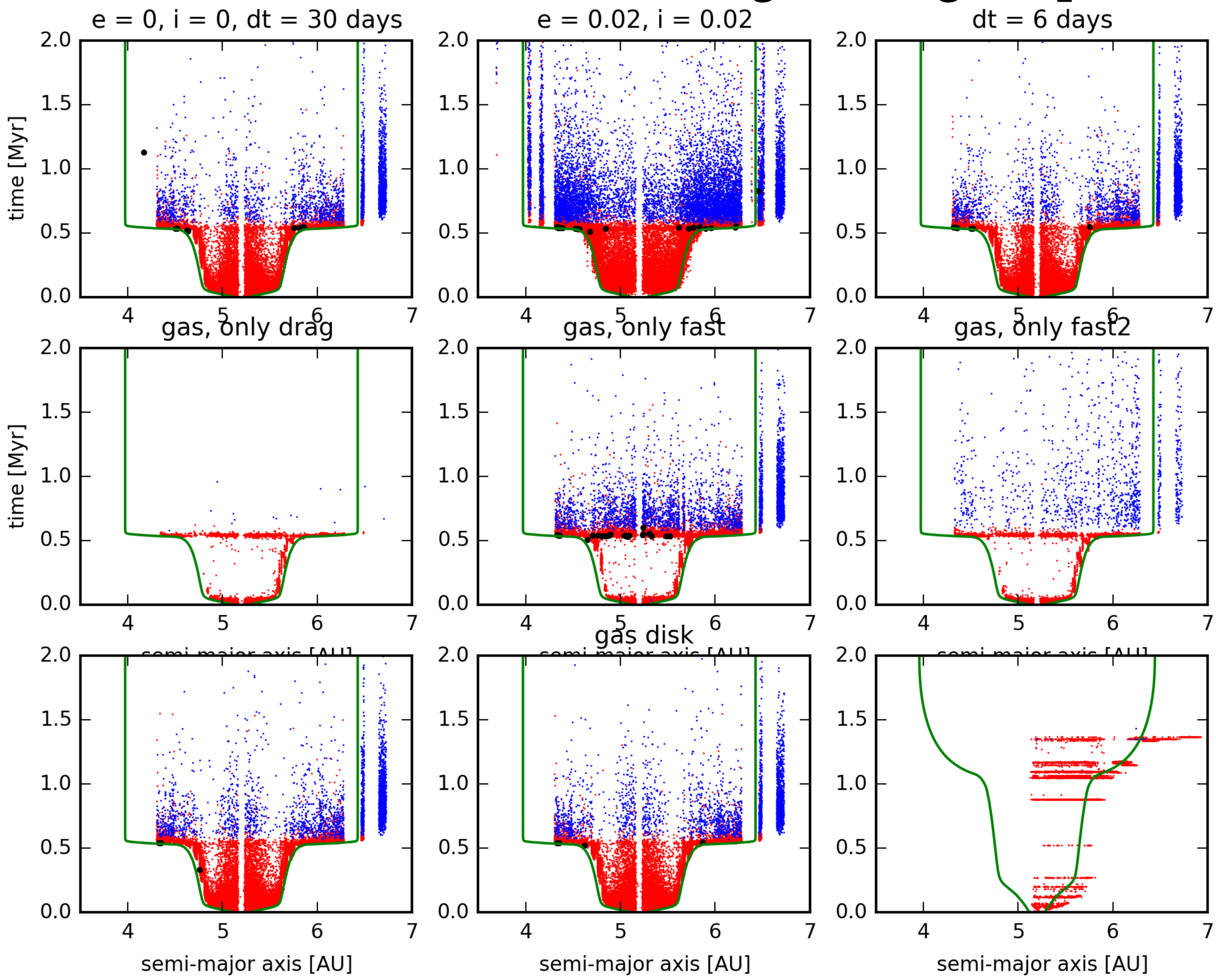
Figure: Matthias Meyer

Planetesimal accretion on growing Jupiter

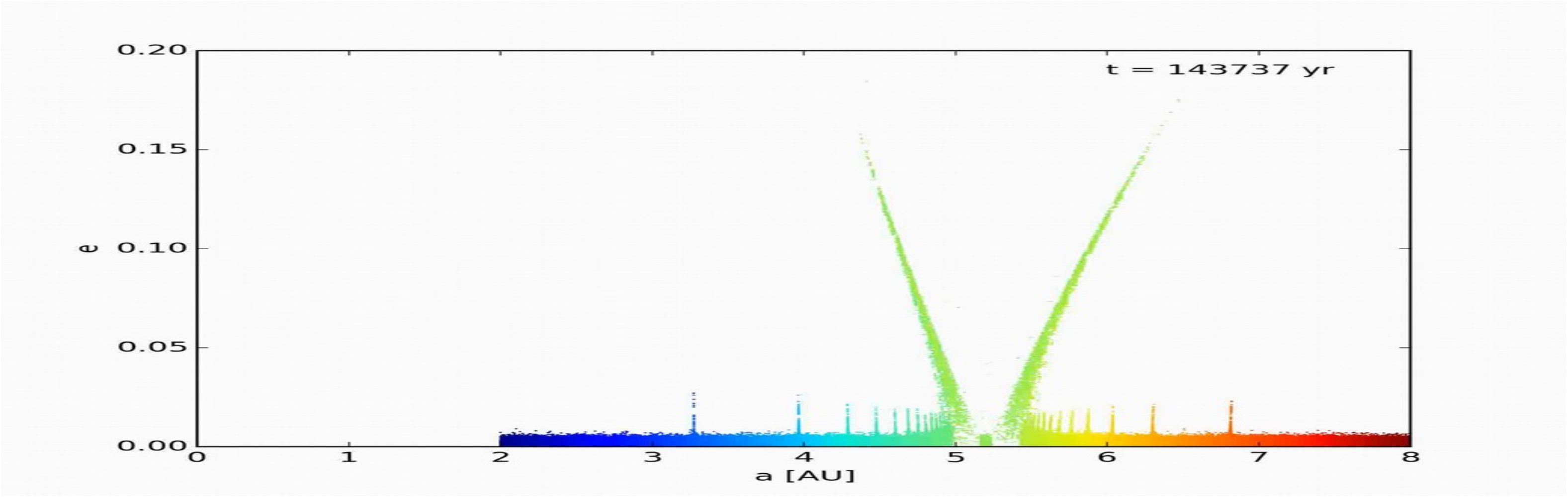
Simulate mass and radius evolution of giant planets with external code (Christoph Mordassini).
Affects final mass, radius and atmosphereic enrichement.

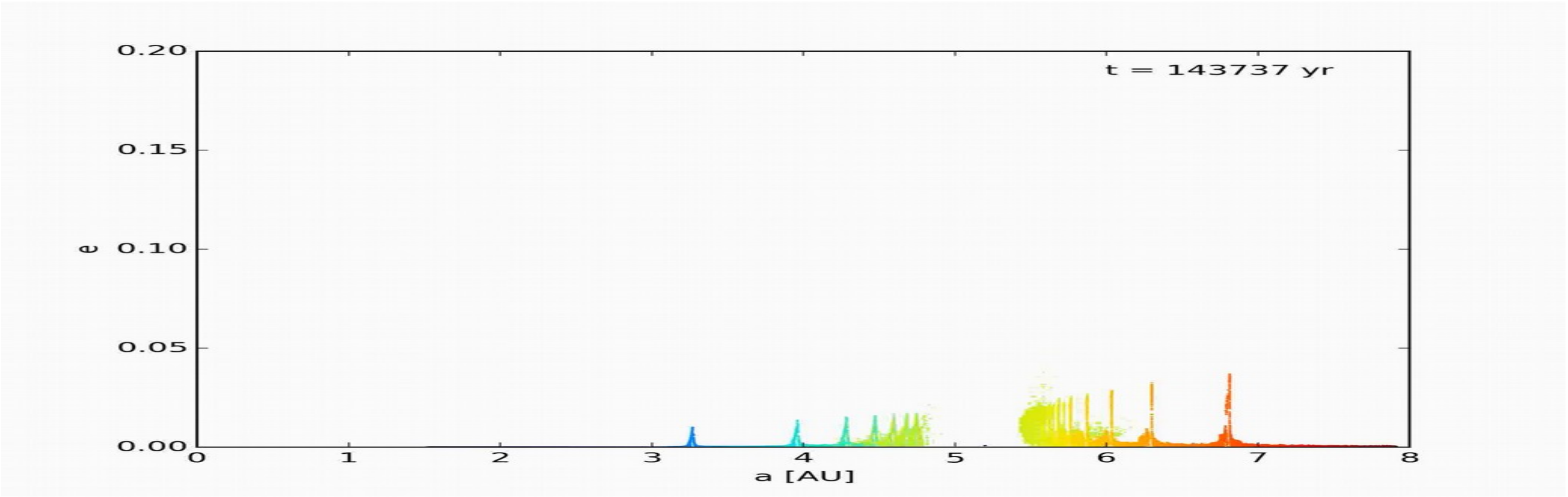


Planetesimal accretion on growing Jupiter



Planetesimal accretion with gas drag





GASOLENGA: GASOLINE meets GENGA

Resolve collisions with SPH
Include particle fragmentation

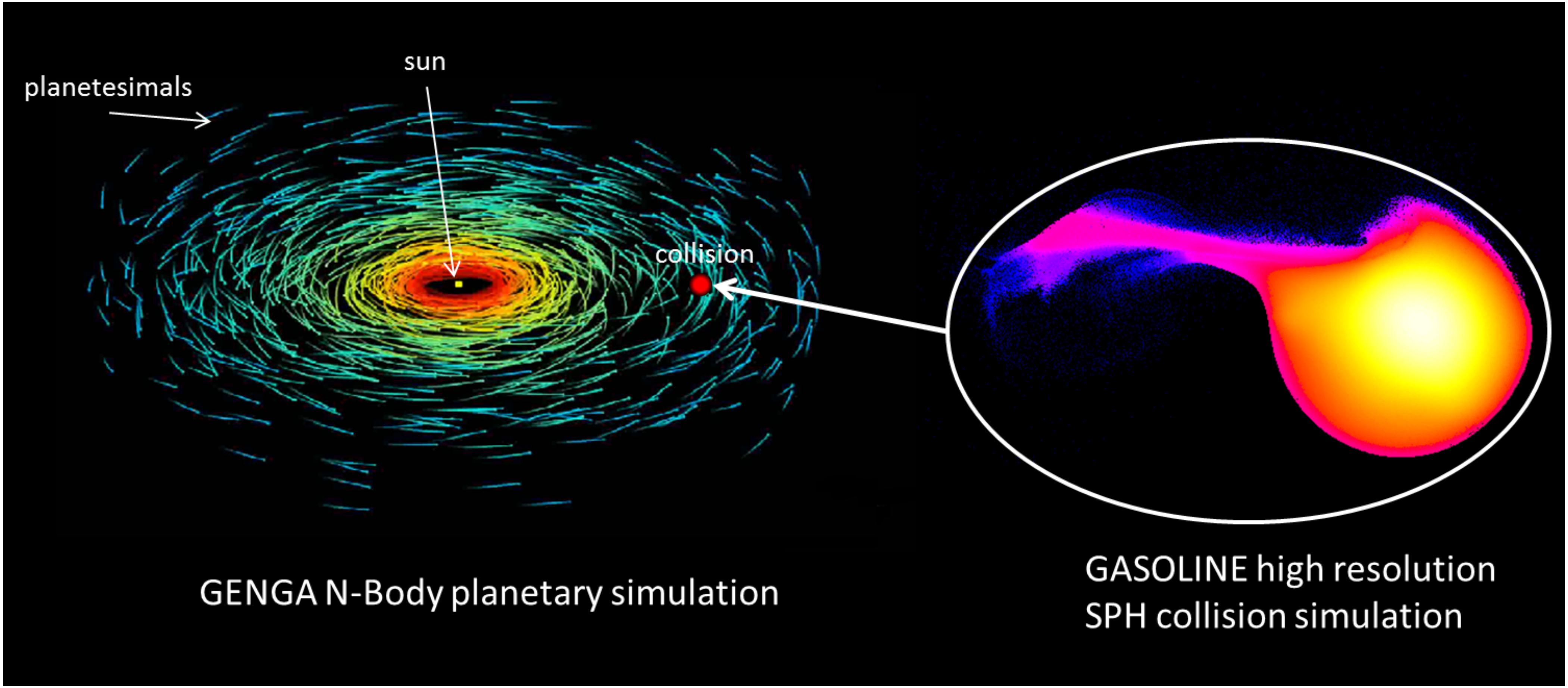


Figure: Matthäus Heer

Possible applications

- Stability analysis of exoplanetary systems
- Asteroid dynamics and meteroite delivery
- Planetesimal /Pebble accretion models
- Transit Timing Variation
- Planet formation with collision model

- Need better gas disk model
- Need better gas accretion model