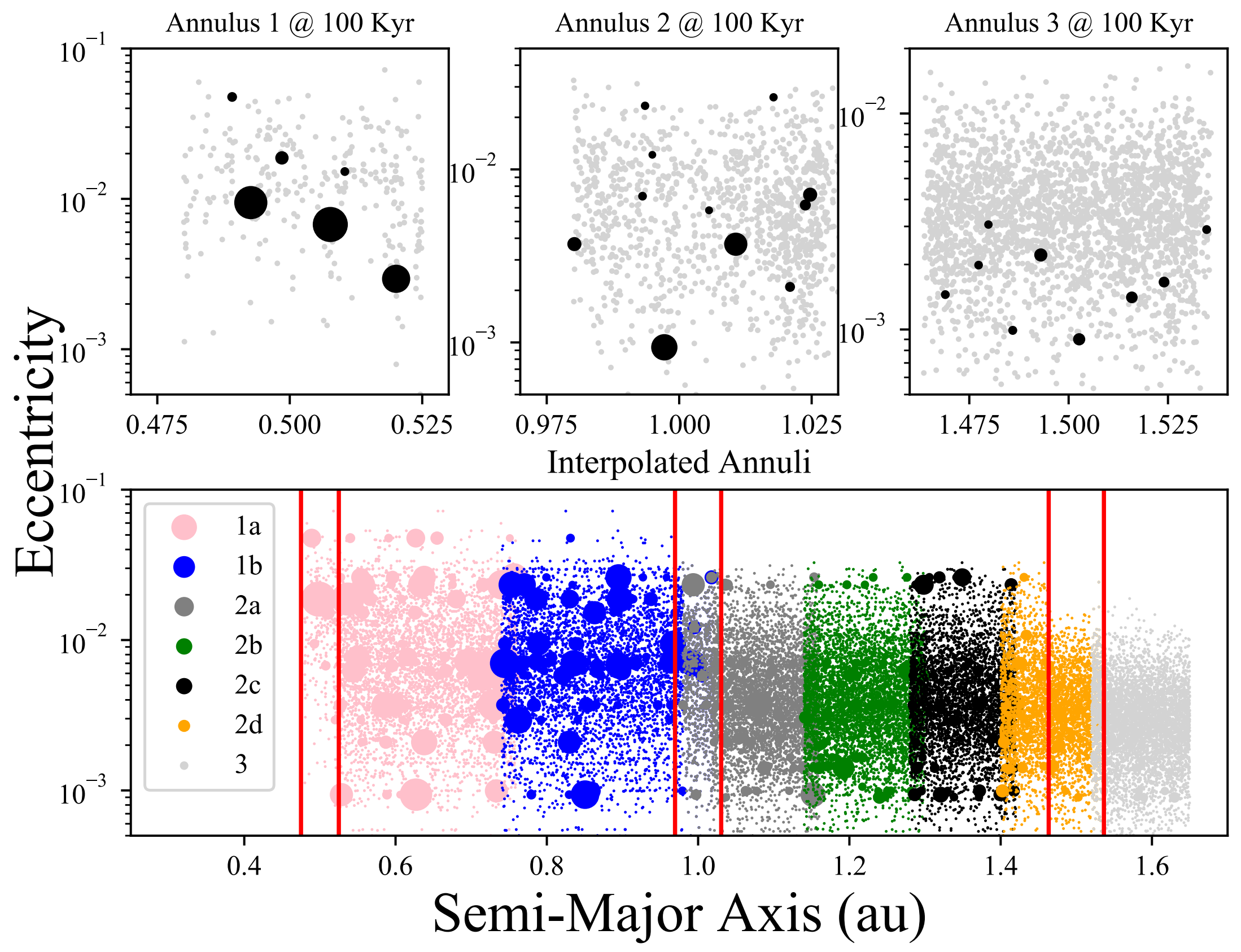
New initial conditions for terrestrial planet formation derived from high resolution simulations of planetesimal accretion

Matt Clement (Carnegie EPL), Nate Kaib (OU), John Chambers (Carnegie EPL)

Abstract

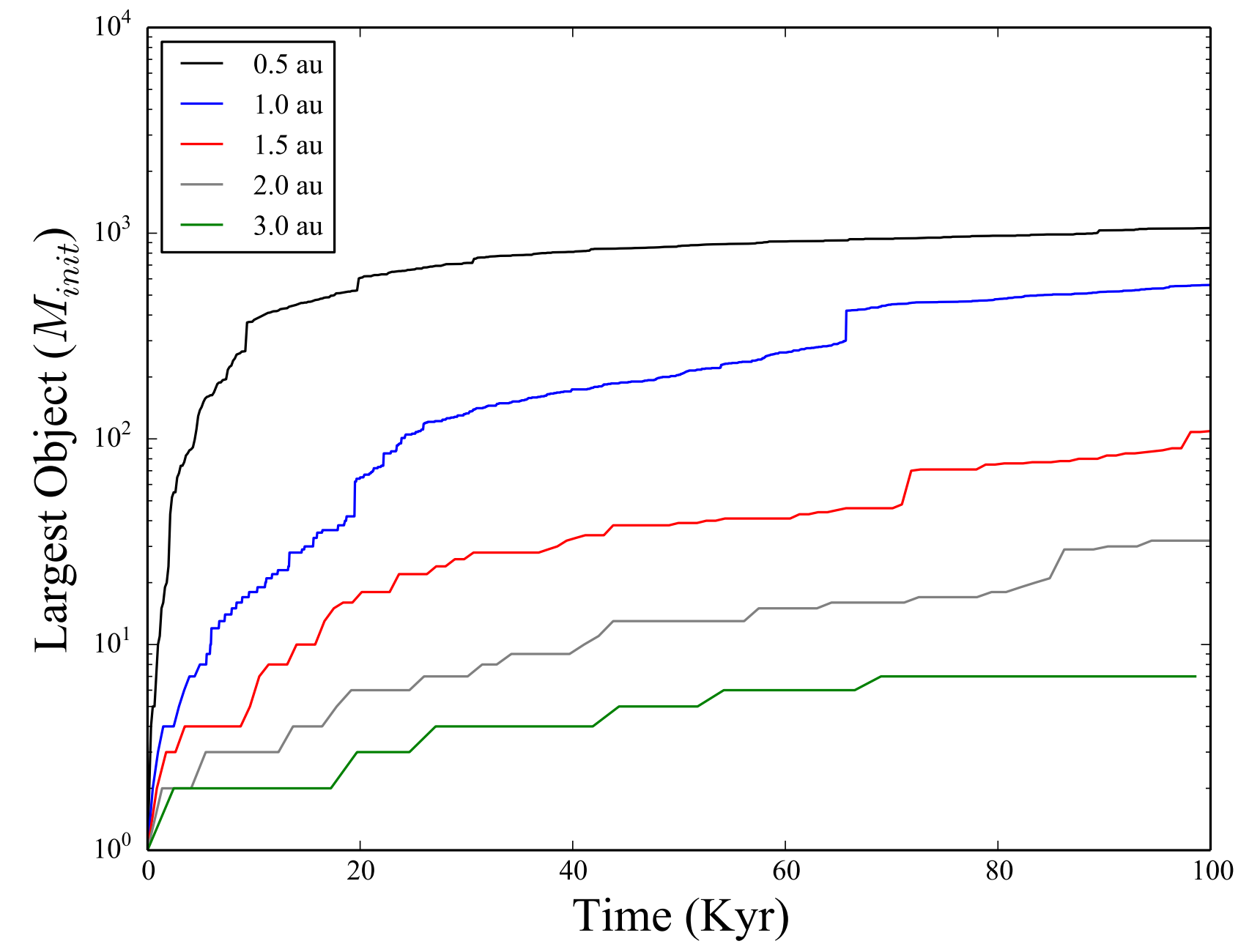
The solar system's terrestrial planets are thought to have accreted over millions of years out of a sea of smaller embryos and planetesimals. Because it is impossible to know the surface density profile for solids and size frequency distribution in the primordial solar nebula, distinguishing between the various proposed evolutionary schemes has historically been difficult. Nearly all previous simulations of terrestrial planet formation assume that Moon- to Mars-massed embryos formed throughout the inner solar system during the primordial gas-disk phase. However, validating this assumption through models of embryo accretion is computationally challenging because of the large number of bodies required. Here, we reevaluate this problem with **GPU-accelerated, direct N-body simulations of embryo growth starting from r ~ 100 km planetesimals**. We find that embryos emerging from the primordial gas phase at a given radial distance already have masses similar to the largest objects at the same semimajor axis in the modern solar system. Thus, Earth and Venus attain ~50% of their modern mass, Mars-massed embryos form in the Mars region, and Ceres-massed objects are prevalent throughout asteroid belt. Consistent with other recent work, our new initial conditions for terrestrial accretion models produce markedly improved solar system analogs when evolved through the giant impact phase of planet formation. However, we still conclude that an additional dynamical mechanism such as giant planet migration is required to prevent Earth-massed Mars analogs from growing.

GENGA: a GPU accelerated N-body package

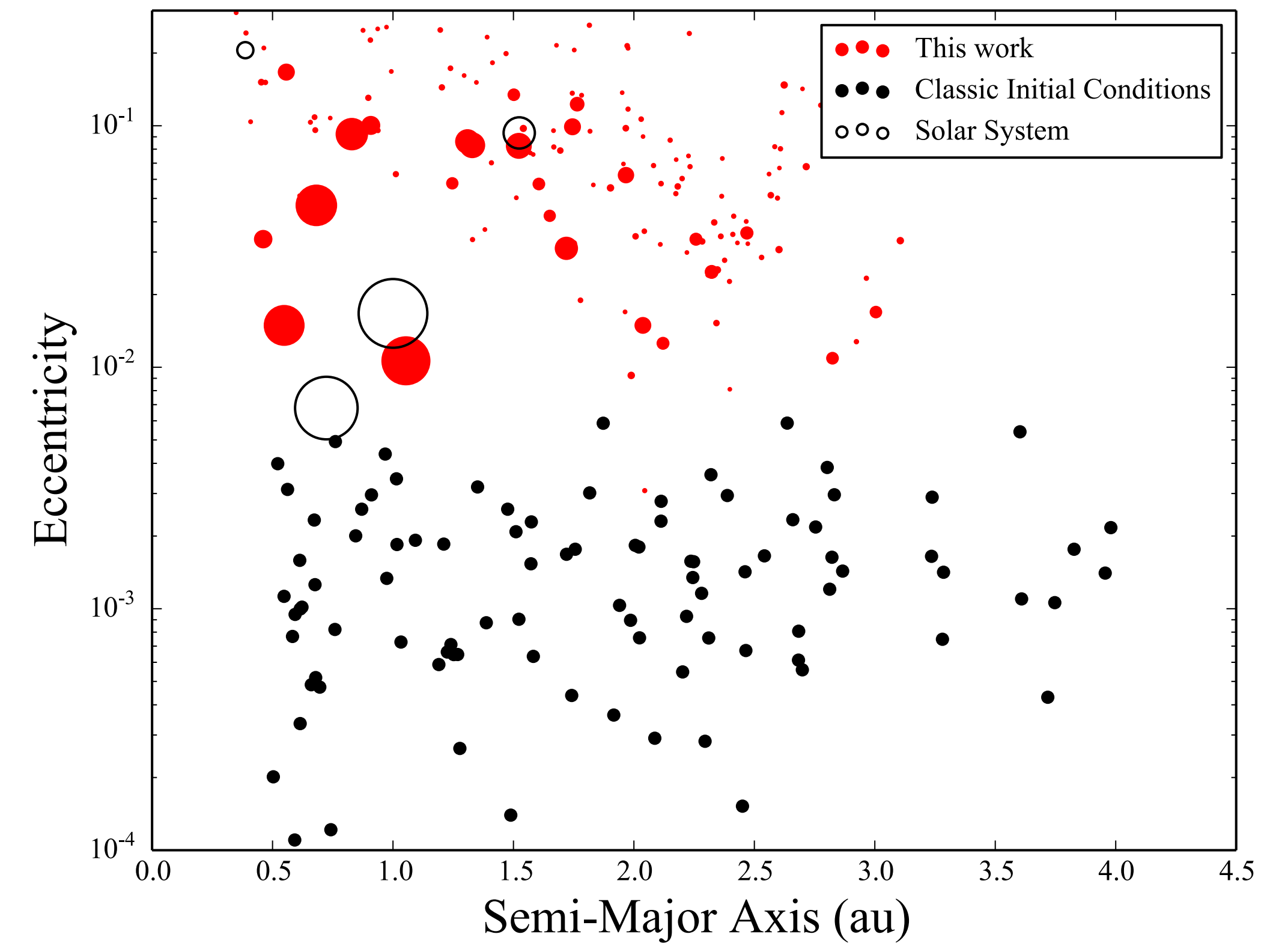


- GENGA: parallelized version of Mercury's hybrid integrator (Grimm et al. 2014: available at: https://bitbucket.org/sigrimm/genga/src/default/)
- We use a **multi-annular approach** (above) and combine and interpolate between different radial annuli of ~5,000, fully-interacting, ~100 km planetesimals until the full terrestrial disk is assembled in one simulation with ~45,000 particles.
- Our project took almost 2 years on Kepler K20 GPUs to follow the terrestrial disk through the gas disk phase for 3 Myr,

Runaway growth is highly efficient in the inner disk



New initial conditions for the giant impact phase



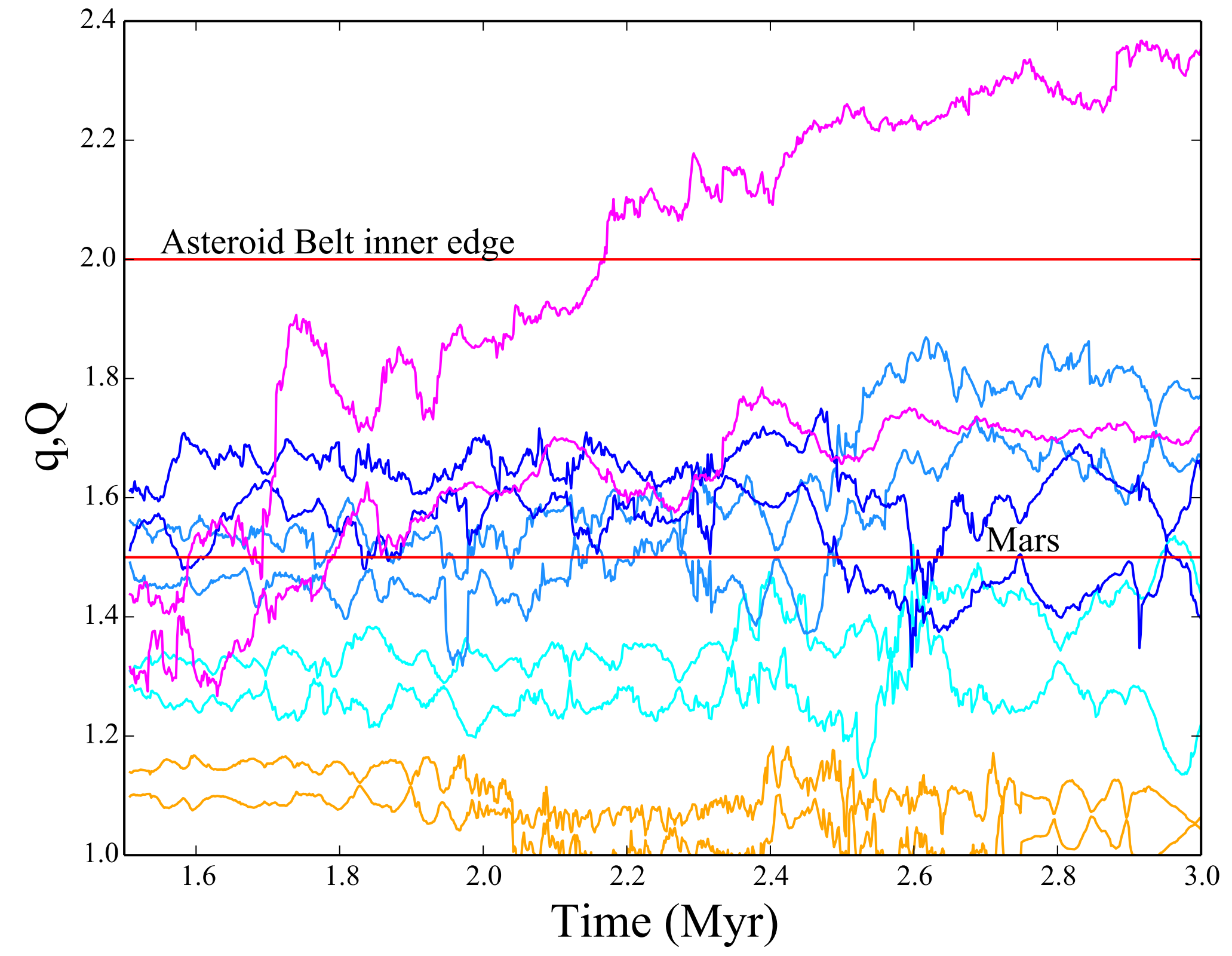
Bi-modal makeup depends on radial location

- R = total mass in embryos / total mass in planetesimals.

Run	$R(a<1$ au$)$	$R(1<a<2$ au$)$	$R(2<a<3$ au$)$
NOJS	3.33	1.76	0.28
8JS	3.81	1.56	0.22
GROW	2.95	2.16	0.25

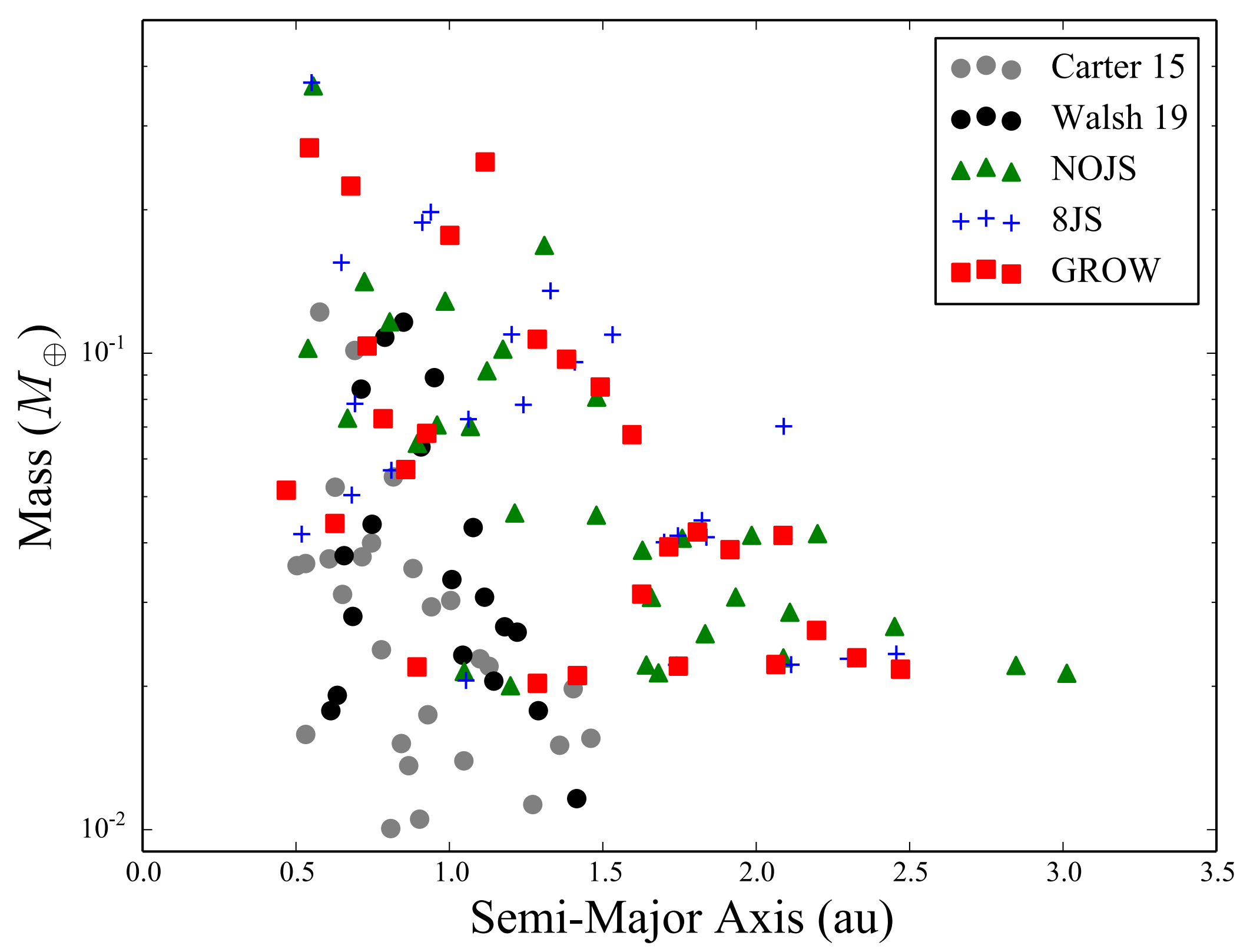
- NOJS = no Jupiter and Saturn.
- 8JS = Jupiter and Saturn as 8 Earth-mass seeds.
- GROW = Jupiter and Saturn grow logarithmically from Earth-mass seeds in 3 Myr.
- High R in Earth/Venus-forming region:
  - **Advantageous for delaying the Moon-forming impact** (Jacobson & Morbidelli 2014) and matching the total mass accreted in the late veneer (Lykawka & Ito 2019).
- Moderate R in the Mars-forming region:
  - **Advantageous for limiting Mars' mass** in an early instability scenario (Clement et al. 2018,2019).
- Low R in the asteroid belt:
  - The asteroid belt is highly unprocessed with its **initial SFD largely preserved** around the time of gas disk dissipation. Some material is implanted in the belt from the inner disk.

Plantesimals scattered into the asteroid belt by growing Mars analogs



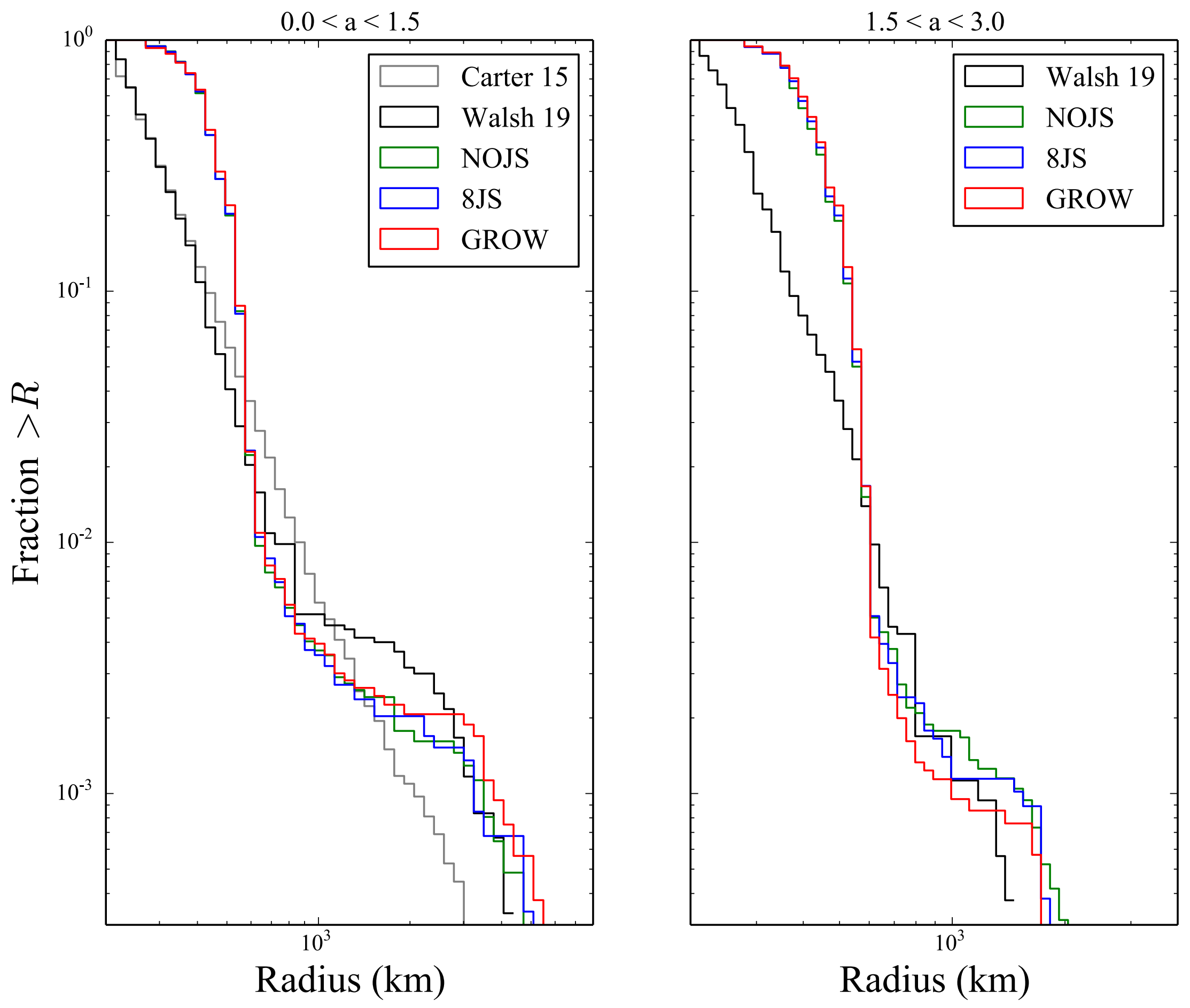
- Possible origin for Vesta (e.g.: Bottke et al., 2006, Mastrobuono-Battisti & Perets 2017).

Comparison with previous works: embryo mass distributions



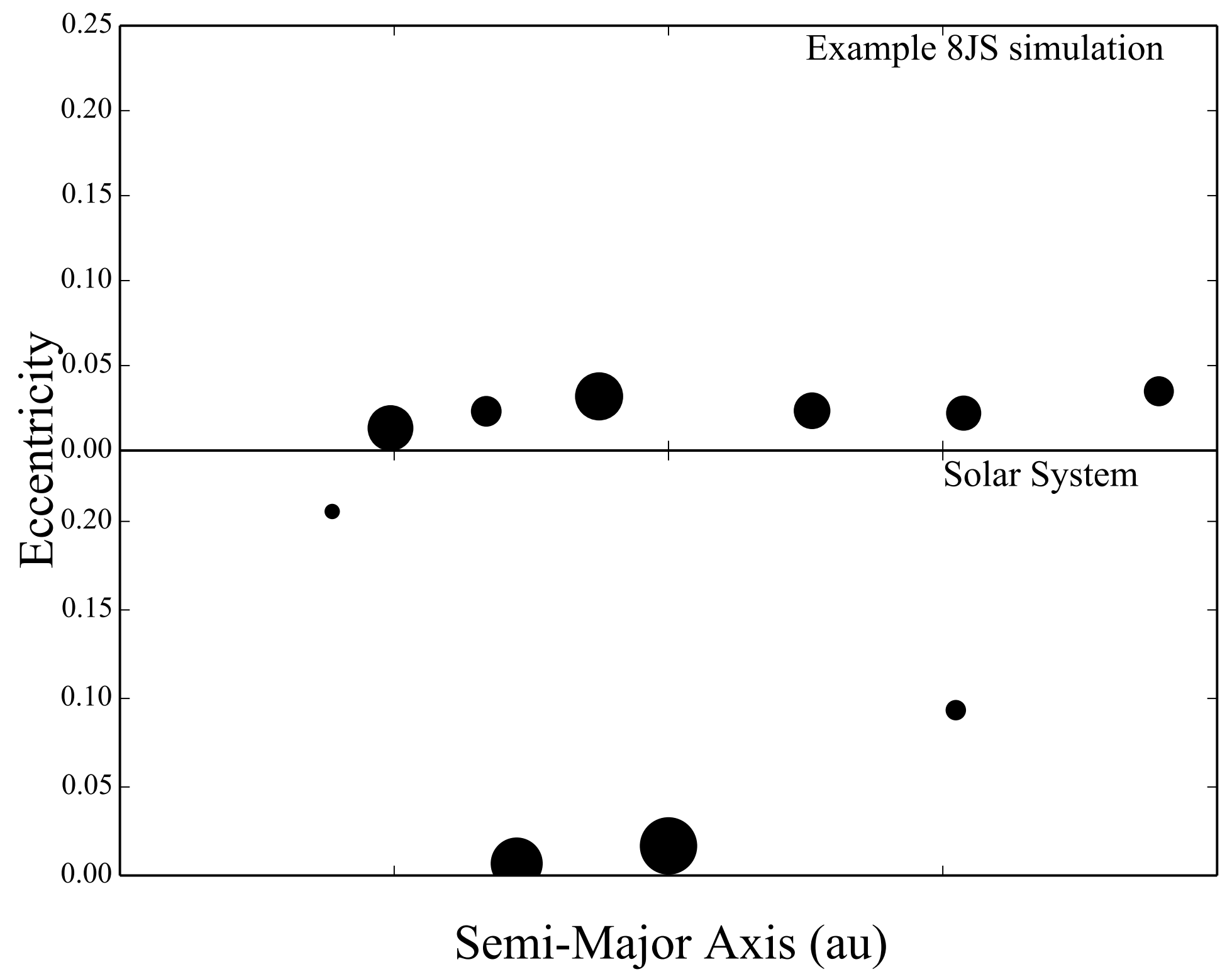
- Considering differences in assumptions, our results of a highly evolved inner disk and unprocessed primordial asteroid belt after nebular gas dispersal **are broadly consistent with other recent high-resolution studies:**
  - Walsh & Levison 2019 (LIPAD)
  - Carter et al. 2015 (PKDGRAV)
- We assess that the minor differences are mainly due to the different initial SFDs of planetesimals assumed in each study.
- The major conclusion of these different high-resolution investigations is that the **giant impact phase unfolds as a "delayed instability"** between a small population (10-15) of large proto-planets (1-5 times Mars' mass):
  - The last giant impact on Earth often involves equal-mass objects (e.g.: Canup 2012).
  - The innermost regions of the disk are highly depleted of planetesimals as runaway growth proceeds outward like a wave.
- We find that future studies attempting to follow a similar interpolation scheme should interpolate logarithmically between annuli, rather than linearly.

Comparison with previous works: Size Frequency Distributions (SFDs)



Systems struggle to accrete in the giant impact phase

- We follow our GPU-formed systems of embryos and planetesimals through the giant impact phase with an additional suite of simplified, CPU-only simulations.
- Our embryo systems tend to be highly stable as a result of forming on well-separated orbits.
- The final systems tend to be poor solar system analogs (e.g.: below):
  - Too many terrestrial planets
  - Mars analogs are too massive and too numerous
  - Accretion timescales are too long
- **We speculate that a dynamical trigger such as an early giant planet instability (t<100 Myr;** Nesvorny et al. 2018, Morbidelli et al. 2018, Clement et al. 2018) is required to:
  - Destabilize the initial generation of protoplanets.
  - Remove additional, unnecessary Mars analogs.
  - Form the Moon.



Acknowledgements

M.S.C. and N.A.K. thank the National Science Foundation for support under award AST-1615975. N.A.K. also acknowledges support under NSF CAREER award 1846388. This research is part of the Blue Waters sustained-petascale computing project, which is supported by the National Science Foundation (awards OCI-0725070 and ACI-1238993) and the state of Illinois. Blue Waters is a joint effort of the University of Illinois at Urbana-Champaign and its National Center for Supercomputing Applications (Bode et al. 2013; Kramer et al. 2015). Further computing for this project was performed at the OU Supercomputing Center for Education and Research (OSCER) at the University of Oklahoma (OU). This work used the Extreme Science and Engineering Discovery Environment (XSEDE), which is supported by National Science Foundation grant number ACI-1548562. Specifically, it used the Bridges system, which is supported by NSF award number ACI-1445606, at the Pittsburgh Supercomputing Center (PSC: Nystrom et al. 2015). Additional computation for the work described in this paper was supported by Carnegie Science's Scientific Computing Committee for High-Performance Computing (hpc.carnegiescience.edu).

References

- Bottke, W. F., Nesvorný, D., Grimm, R. E., Morbidelli, A., & O'Brien, D. P. 2006, Natur, 439, 821
- Canup, R. M. 2012, Sci, 338, 1052
- Carter, P. J., Leinhardt, Z. M., Elliott, T., Walter, M. J., & Stewart, S. T. 2015, ApJ, 813, 72
- Clement, M. S., Kaib, N. A., Raymond, S. N., Chambers, J. E., & Walsh, K. J. 2019, Icar, 321, 778
  Clement, M. S., Kaib, N. A., Raymond, S. N., & Walsh, K. J. 2018, Icar,
- 311, 340
- Clement, M. S., Kaib, N. A., & Chambers, J. E. 2019, PSJ, 1, 1:18
- Grimm, S. L., & Stadel, J. G. 2014, ApJ, 796, 23
- Jacobson, S. A., & Morbidelli, A. 2014, RSPTA, 372, 0174
- Lykawka, P. S., & Ito, T. 2019, ApJ, 883, 130
- Mastrobuono-Battisti, A., & Perets, H. B. 2017, MNRAS, 469, 3597
- Morbidelli, A., Nesvorny, D., Laurenz, V., et al. 2018, Icar, 305, 262
- Nesvorný, D., Vokrouhlický, D., Bottke, W. F., & Levison, H. F. 2018, NatAs, 2, 878
- Walsh, K. J., & Levison, H. F. 2019, Icar, 329, 88

Check out our new paper: *"Embryo formation with GPU acceleration: re-evaluating the initial conditions for terrestrial accretion"* in PSJ: 10.3847/PSJ/ab91aa https://arxiv.org/abs/2005.03668