KU LEUVEN

TIME to Study Mass Transfer

The New 3D Horizon for Binary Evolution

Dr. Davey Dickson

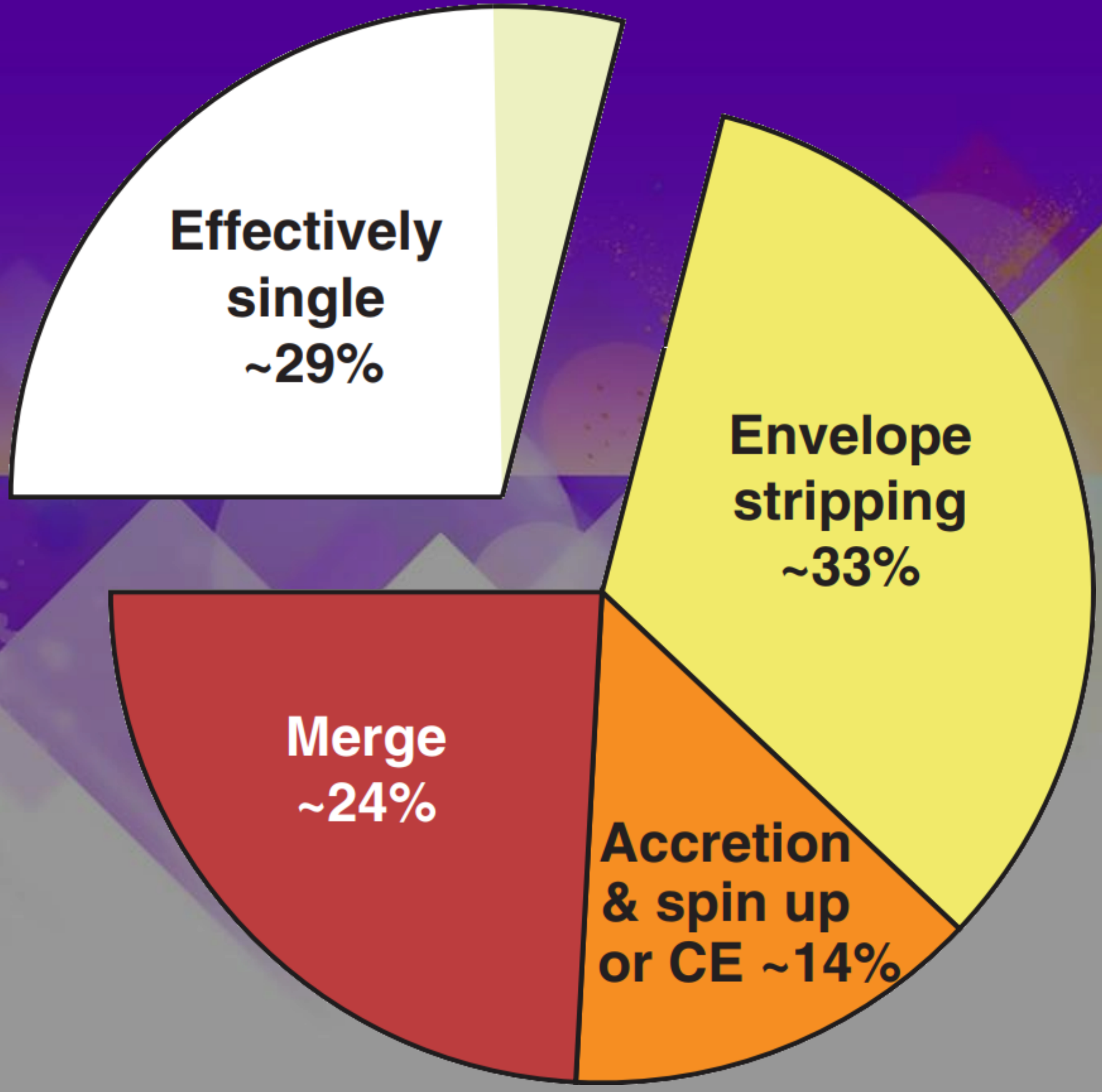
The Problem

Binary Evolution

Binary Stars

Binary System: 2+ stars or stellar-mass objects bound together

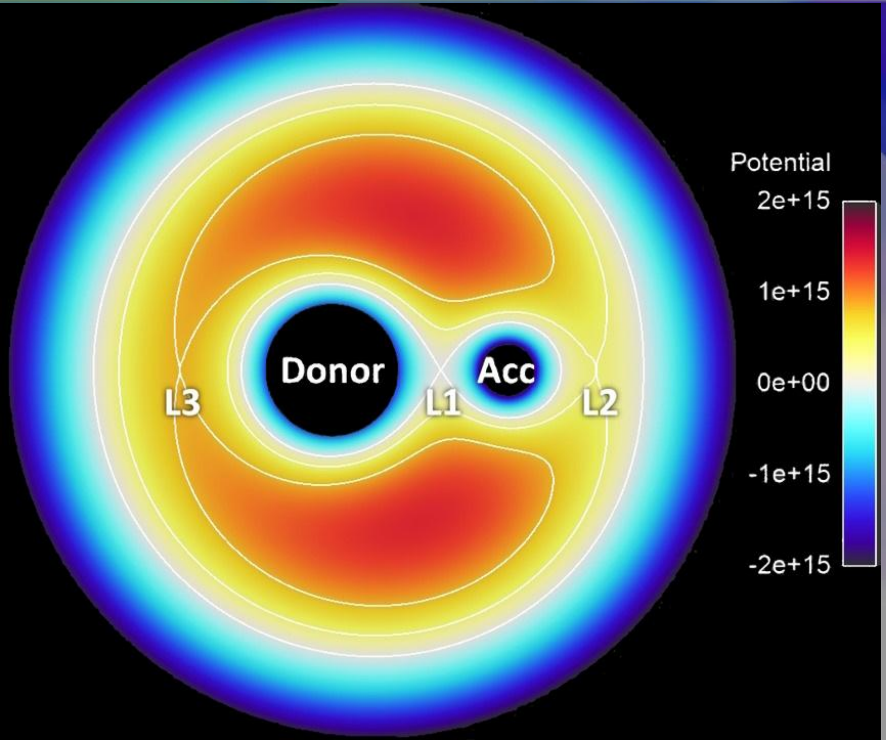
- Massive stars drive evolution (chemical & dynamical)
- Most shaped by close binary interactions
- Stripping, accretion, CEs, and mergers caused by...

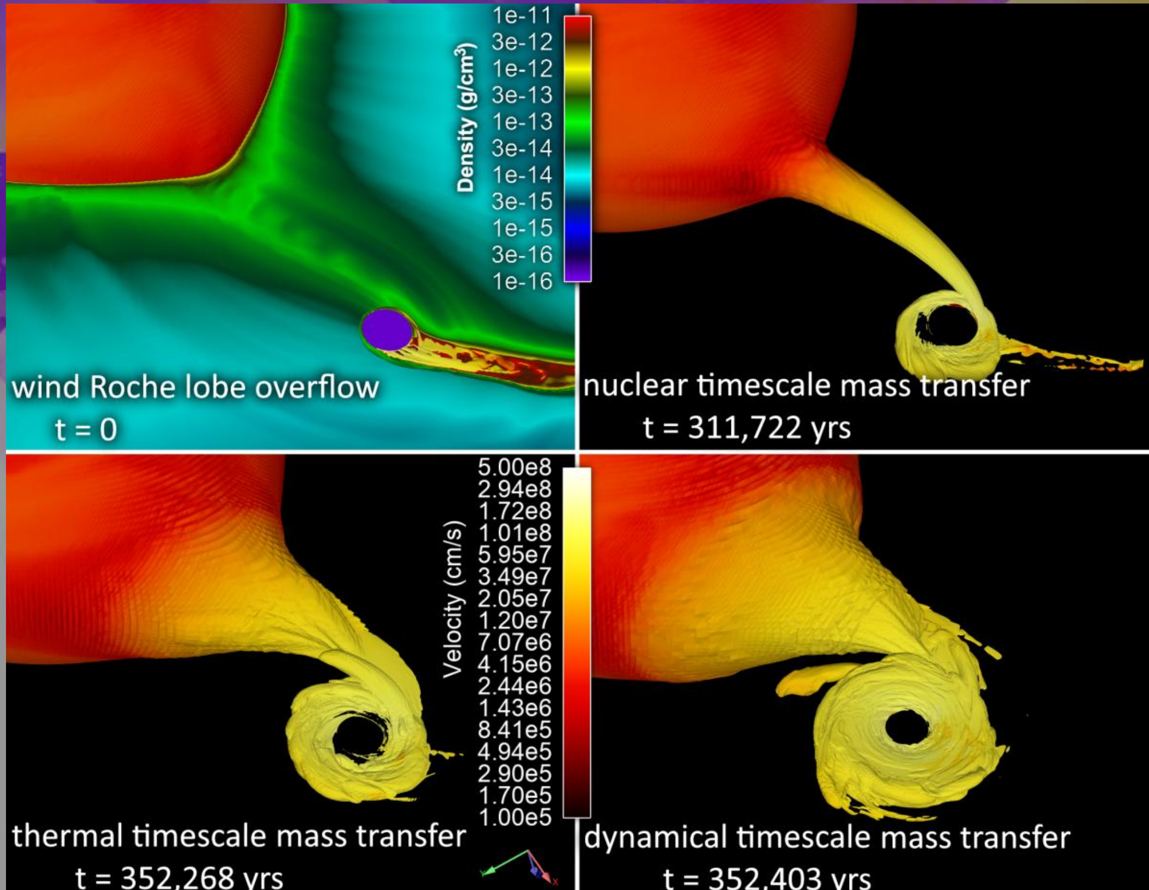


Sana et al. 2012

Roche Lobe Overflow

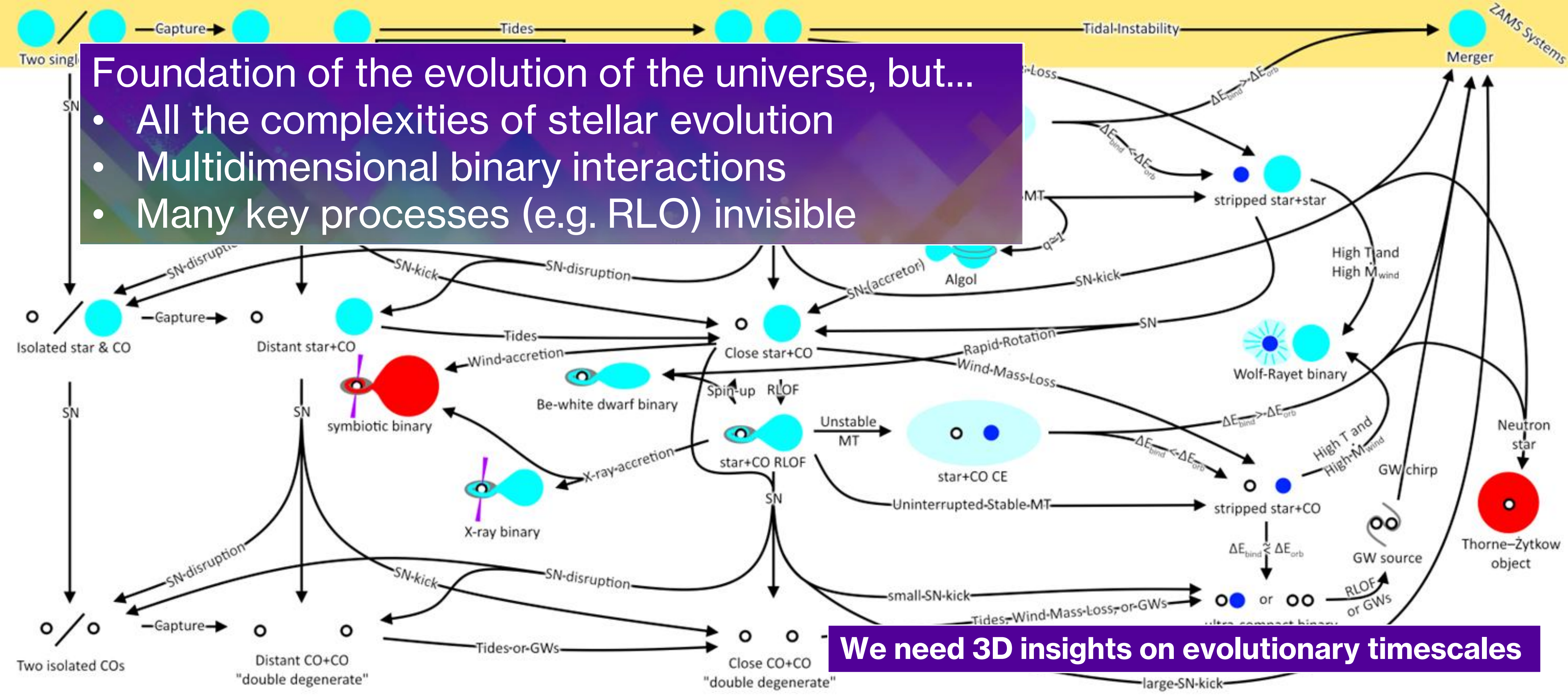
- Multiscale in length (1 km – 1 au)
- Multiscale in time (1 s – 1 Myr)
- Feedback is essential
- In some cases, unstable to perturbation





Binary Evolution

Foundation of the evolution of the universe, but…
- All the complexities of stellar evolution
- Multidimensional binary interactions
- Many key processes (e.g. RLO) invisible

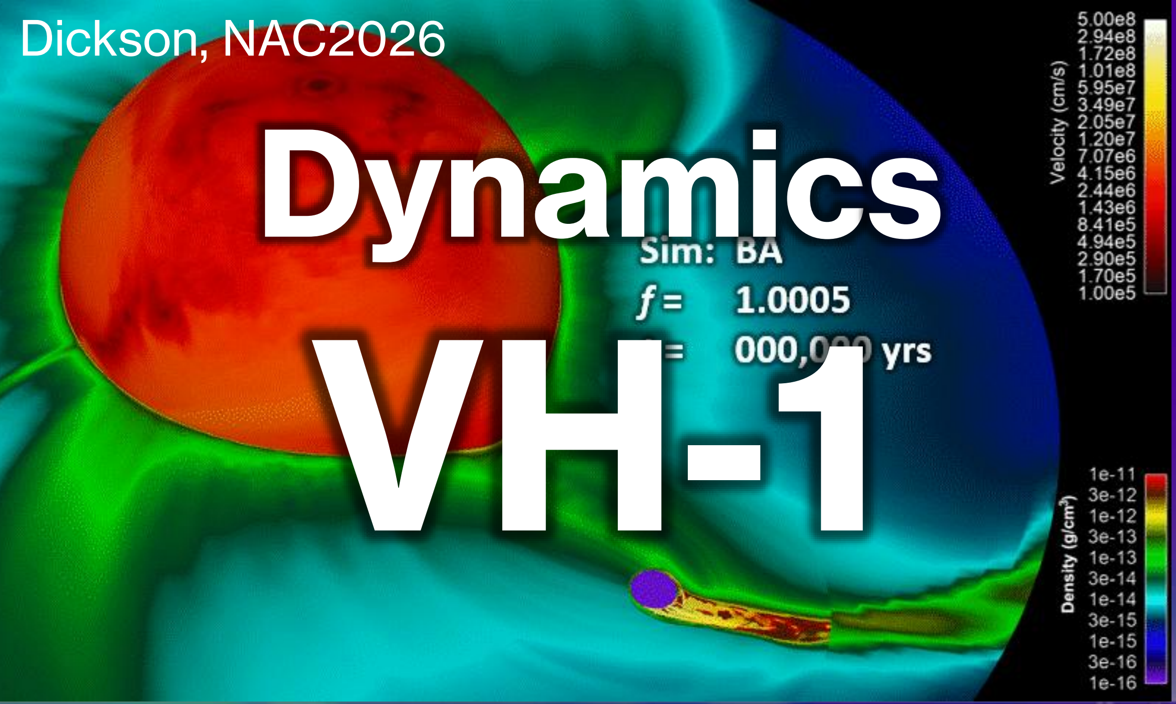


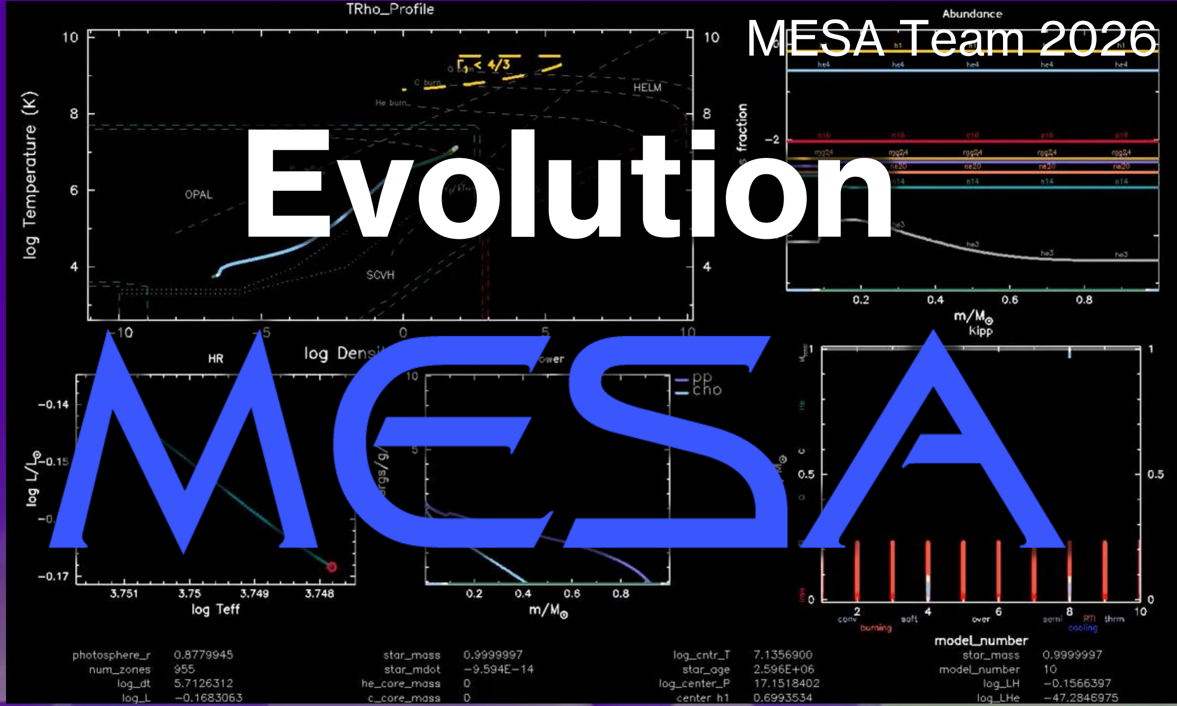
We need 3D insights on evolutionary timescales

The Solution

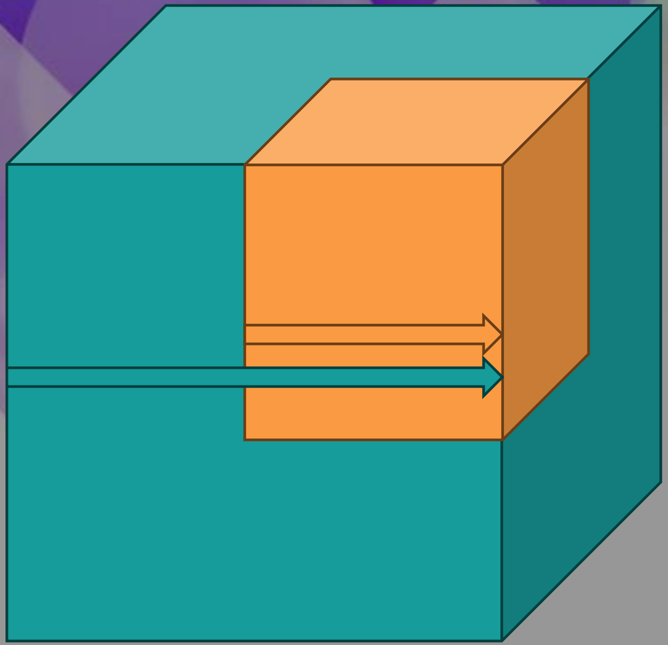
3D Evolution

Dynamics vs. Evolution





- Computational cost requires compromise
- Higher dimensions = exponential cost



Recent Developments

VH-1

Full-system binary simulations with

- donor envelope dynamics (2024)
- Star-Star binaries (2025)
- X-ray feedback (2025)
- Simulated lightcurves (2026)

MESA

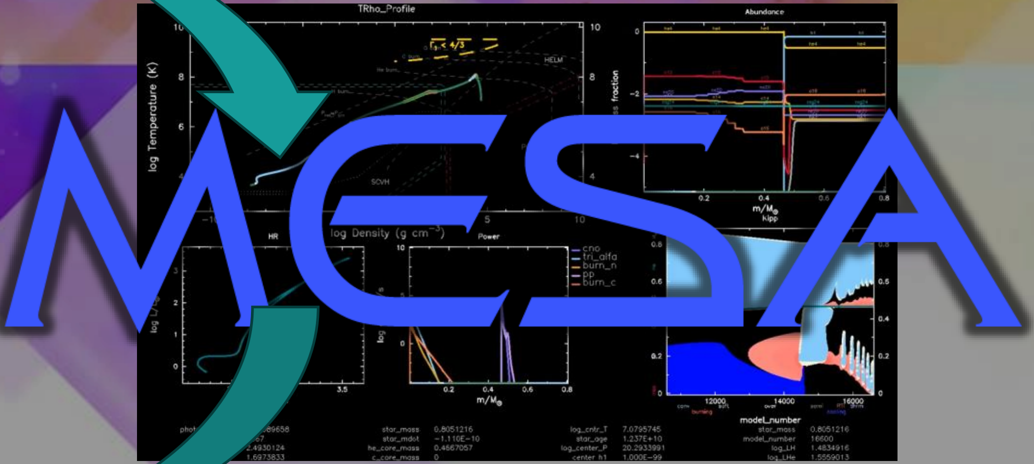
Full-system binary simulations with

- Angular momentum transfer (2019)
- Tidal deformations (2020s)
- Precise mass transfer (2021)
- True hydrostatic equilibrium (2025)

Time-Incremented Multiscale Evolution (TIME)

Extract fluxes from steady state

$$\frac{f_i}{|\dot{f}_i|} = \tau_i$$



Evolve by τ_i-scaled timestep

Time-Incremented Multiscale Evolution (TIME)

- Decouples duration from spatial resolution
- Variable time resolution
- Complete feedback

Test Case: Unstable RLO

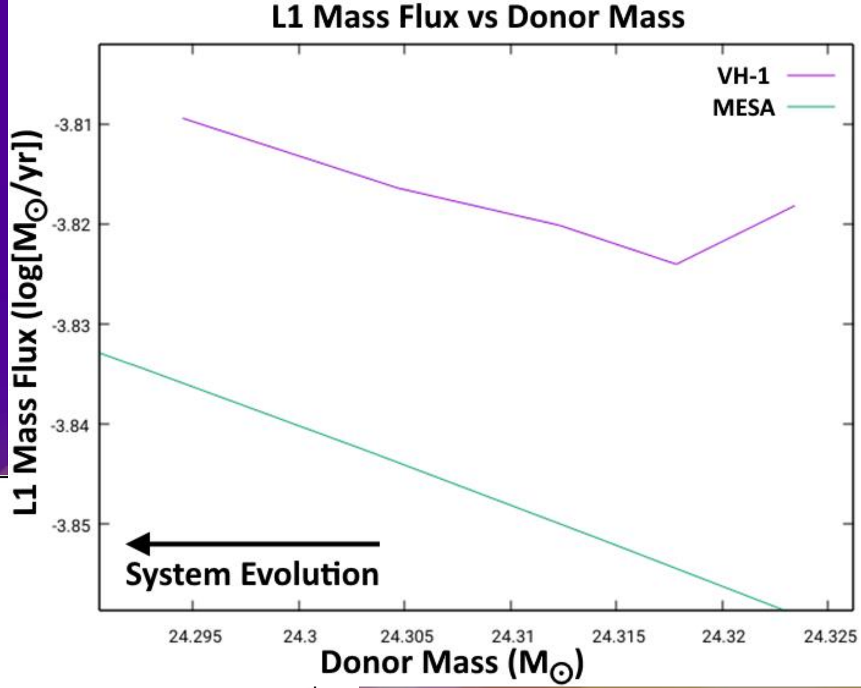
Running on 8 nodes of 128 cores

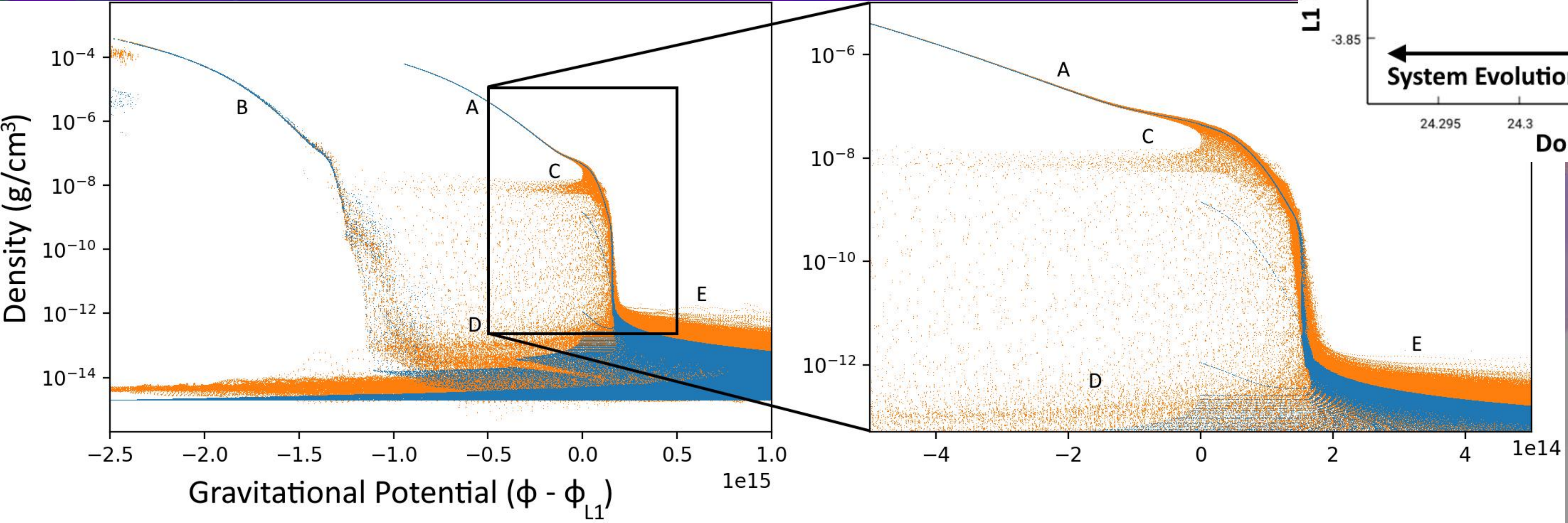
• Pure Evolutionary:	10^0-1 core-hours	~10 Seconds*
• TIME:	10^4-5 core-hours	~1 Day
• Pure Dynamical:	10^11 core-hours	~10,000 Years

*Value averaged across a population, not parallelized

Dickson, NAC2026

Making MESA in Hydro





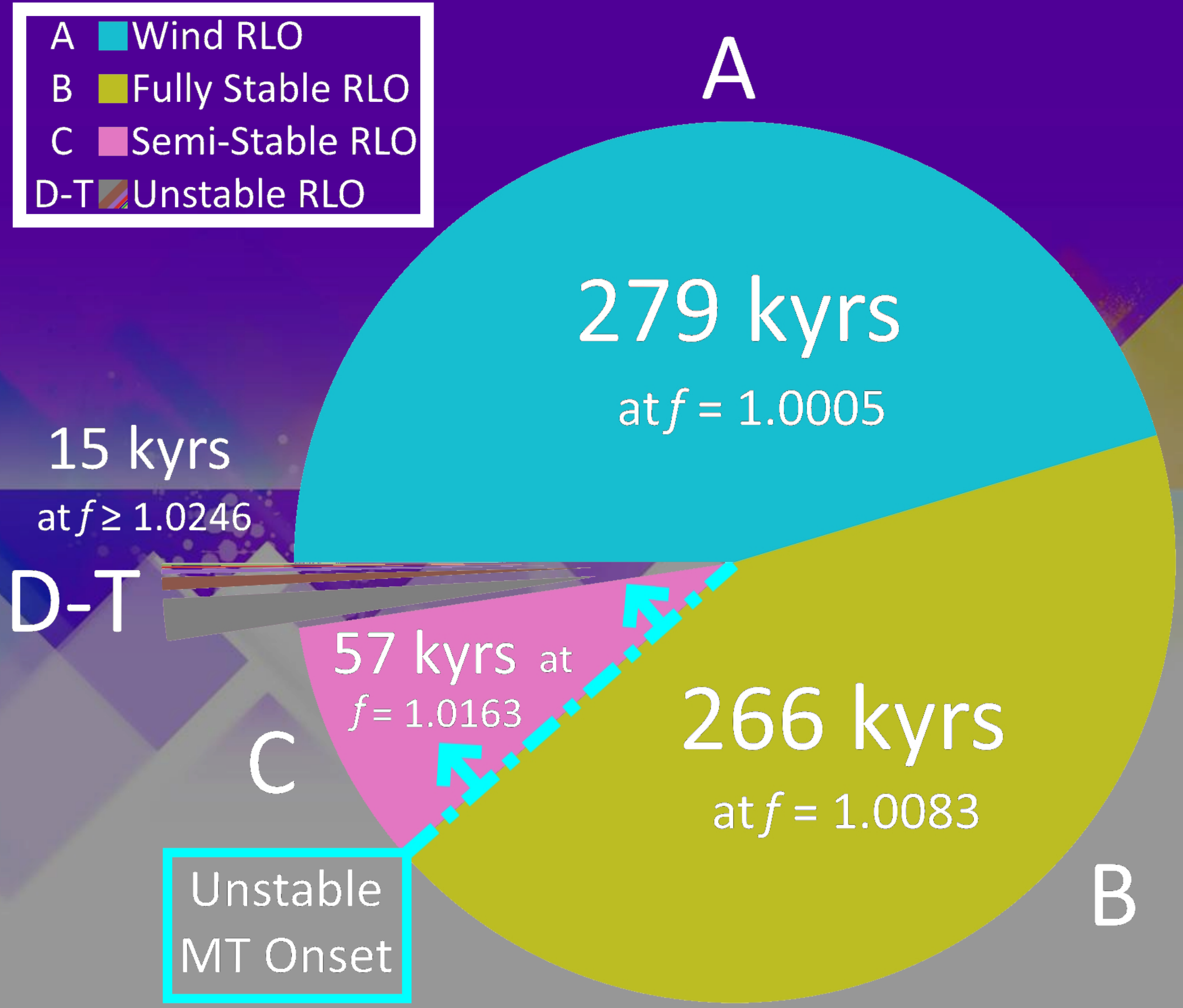
- Hydrostatic MESA initialization
- Steady state generated by VH-1

A - Donor envelope
B - Accretor envelope
C - L1 tidal stream ($\phi = \phi_{L1}$)
D - Supplemental wind accretion
E - Non-accreting donor wind

Figure 2: Prototype model relaxation from hydrostatic MESA profile and its associated wind prescription. The donor (A) and accretor (B) envelopes are maintained in their hydrostatic profiles with minimal noise. Mass transfer (C) is initiated at the L1 Lagrange point as expected, and the accretor also sustains additional accretion (D) from the donor wind. The majority of the donor wind (E) is still lost from the system, in keeping with the hydrostatic solution. The dispersion in the VH-1 steady state arises from induced flow dynamics not accounted for in the MESA profile.

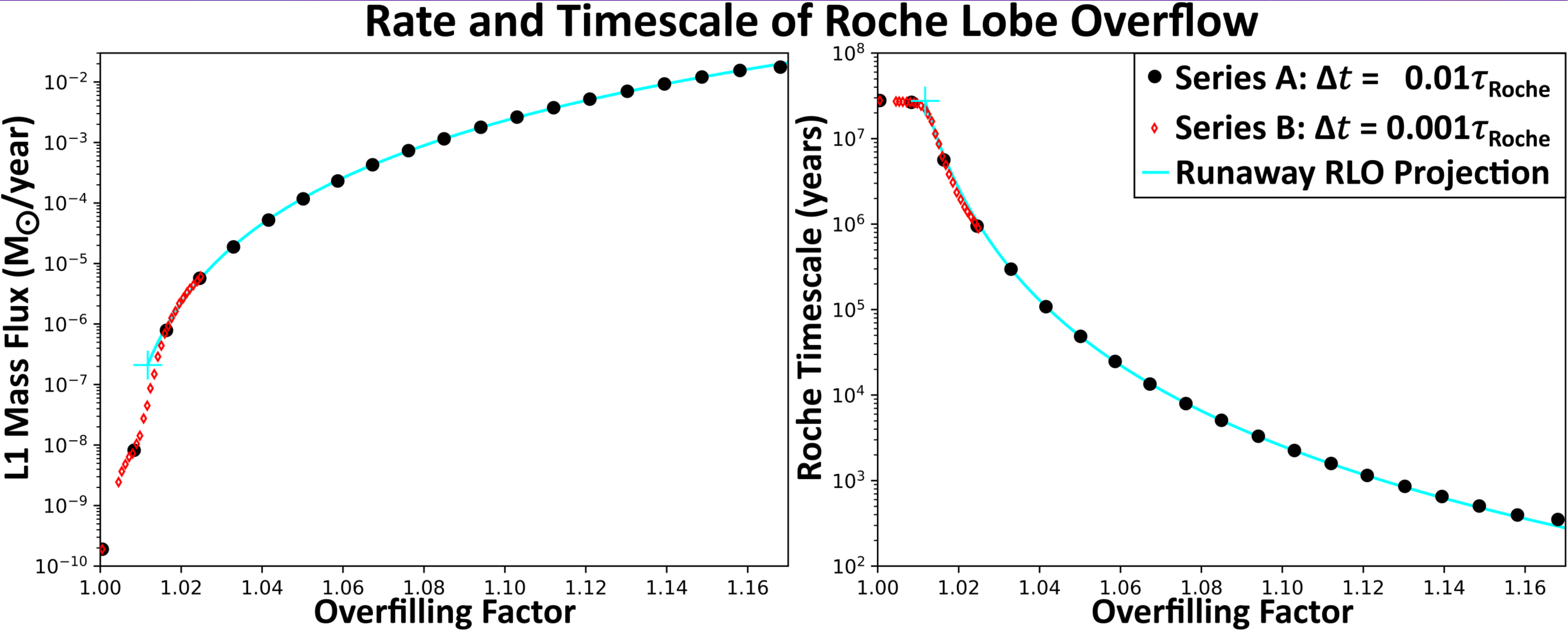
Results

Timescale

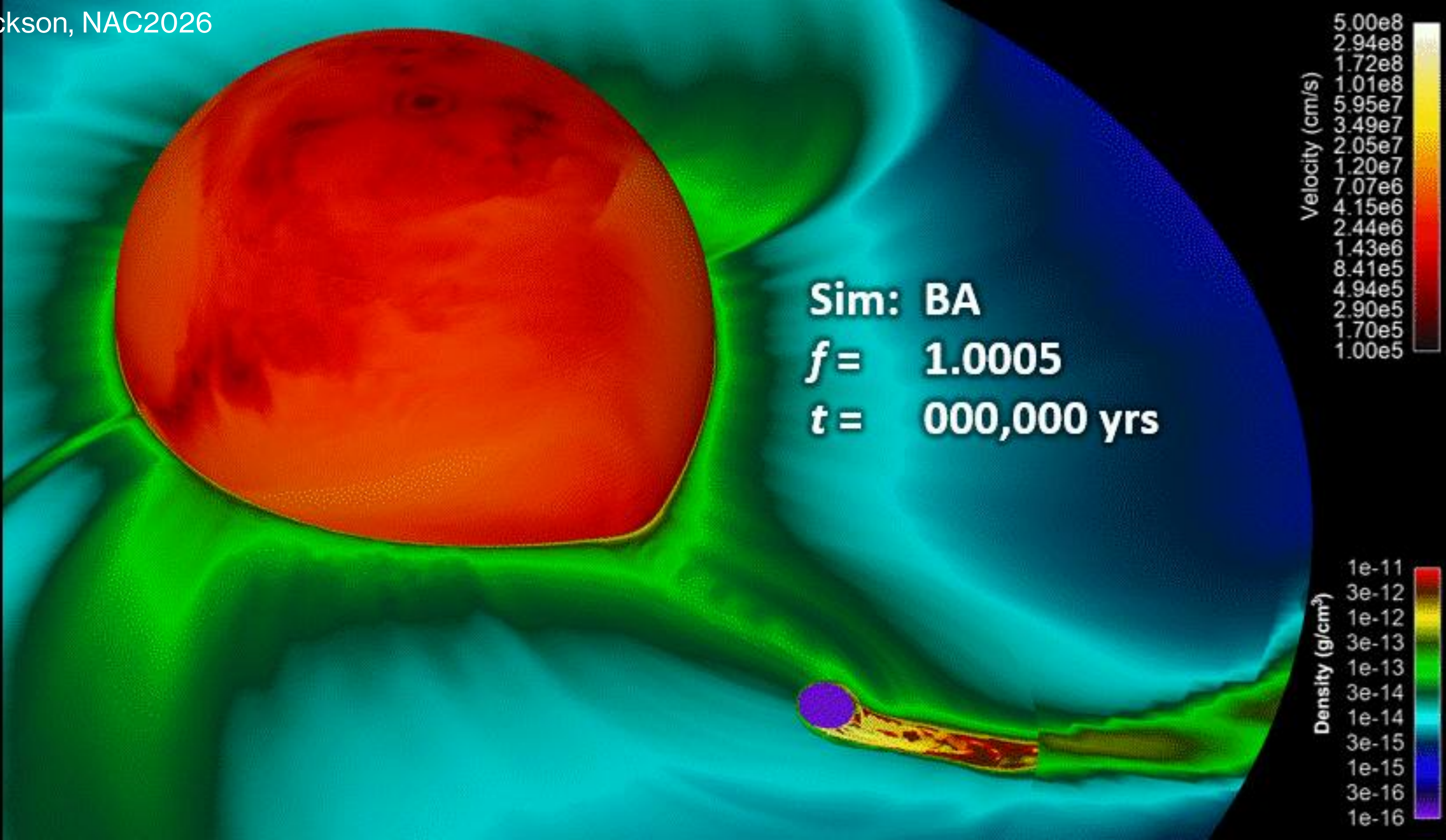


$$f = \frac{R_*}{R_{RL}}$$

Timescale


Rate and Timescale of Roche Lobe Overflow
L1 Mass Flux (M$_\odot$/year)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
1.00 1.02 1.04 1.06 1.08 1.10 1.12 1.14 1.16
Overfilling Factor
Roche Timescale (years)
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
Series A: $\Delta t = 0.01\tau_{Roche}$
Series B: $\Delta t = 0.001\tau_{Roche}$
Runaway RLO Projection
1.00 1.02 1.04 1.06 1.08 1.10 1.12 1.14 1.16
Overfilling Factor

Dickson, NAC2026



Conclusions

Method
- MESA integration promising (7 orders faster than HD) and stable

MT Timescale
- $\gtrsim$300kyr – wind RLO
- $\gtrsim$300kyr – stable RLO
- $\lesssim$70kyr – unstable RLO (initially thermal, then dynamical)
- $f \geq 1.1$ transient – cannot be sustained for >100yrs

MT Efficiency
- Unstable MT conservative in mass and AM
- Stable MT conservative where $\dot{M}_{L1} \geq \dot{M}_{wind}$ in mass (but not AM)

Runaway RLO
- Began at $f{\sim}1.01$ and $\dot{M}_{L1}{\sim}10^{-6}M_{\odot}/yr$ (when wind becomes negligible)
- Occurs on a timescale $\sim 0.01\tau_{Roche,i}$

The 3D Evolution Horizon

Full MESA/VH-1
Hybridization

Modeling
Nuclear MT
(Myrs - Gyrs)

RLO Stability

Wind Efficiency

Progenitor Paths

Population Synthesis

Gravitational Waves

Galactic Evolution