Tidal Disruption Events with SPH-EXA

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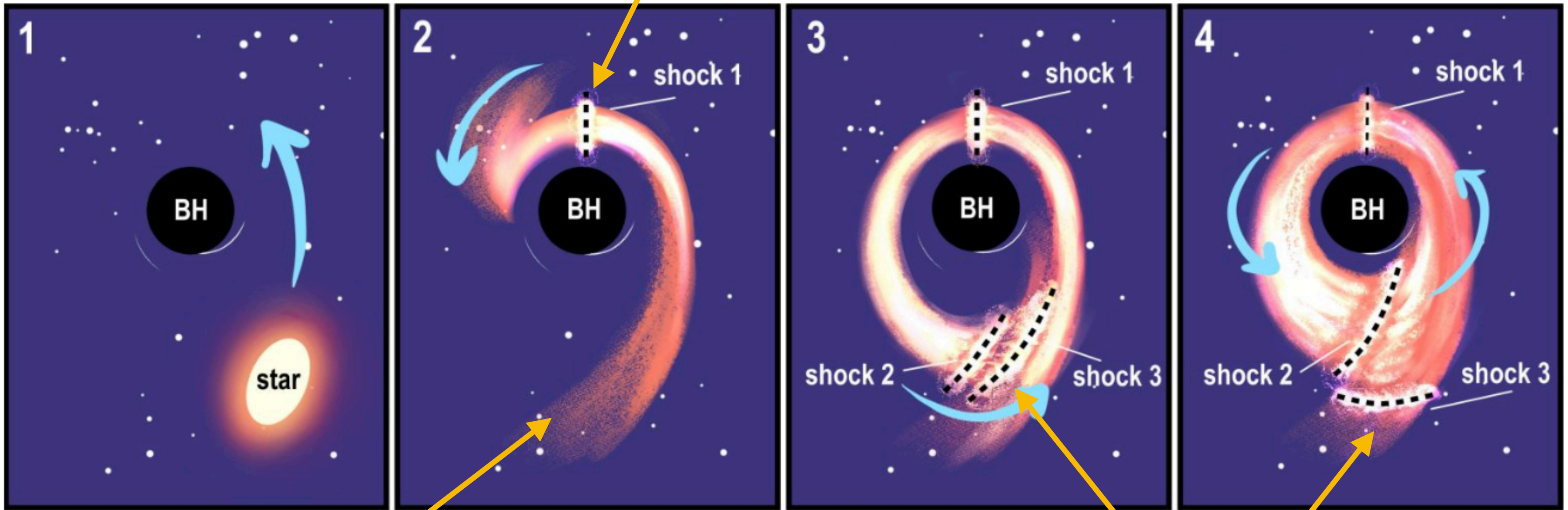
Tidal disruption events

stellar stream is compressed (Nozzle shock)

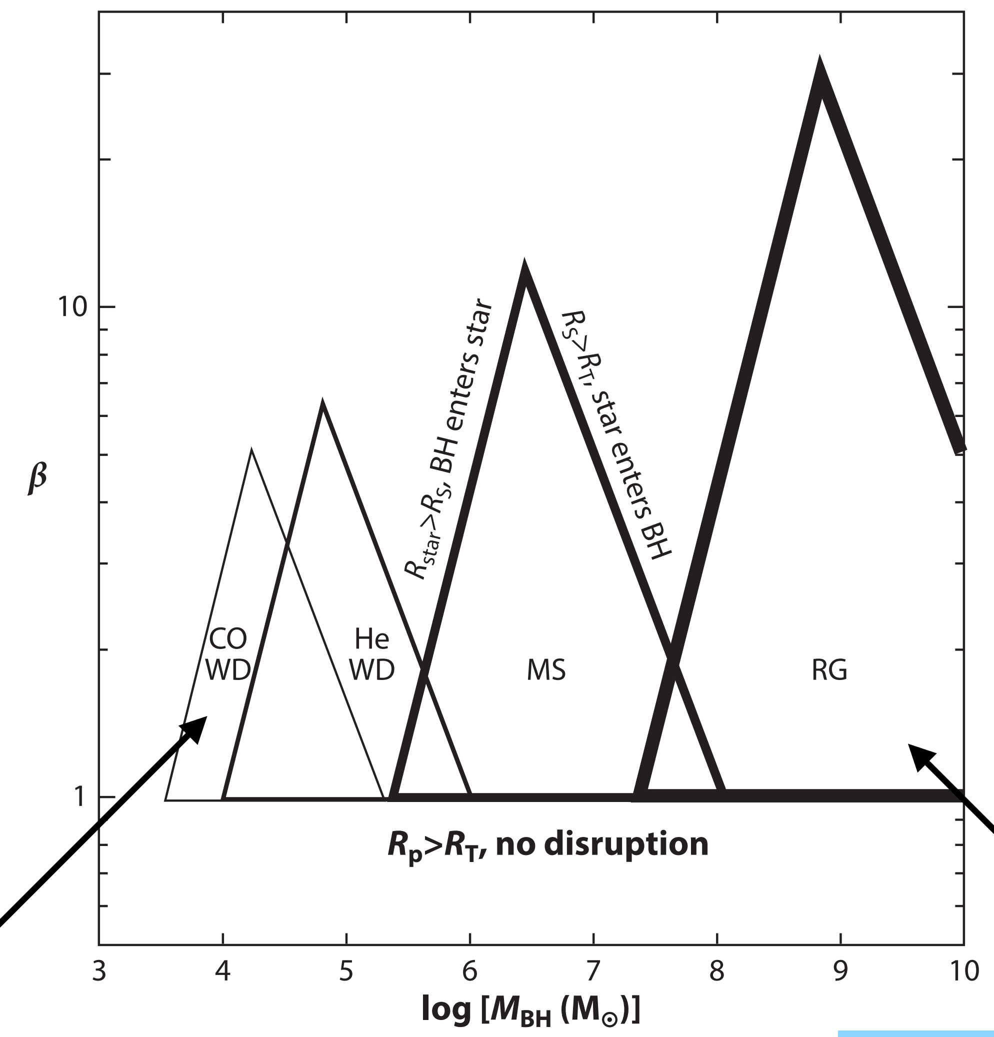


Credit: Jenni Jormanainen

tidal forces disrupt the star

flow collides with itself

Stellar sources

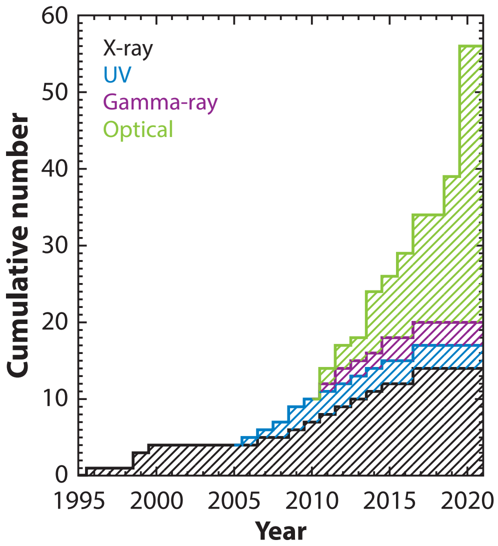


Credits: Gezari (2021)

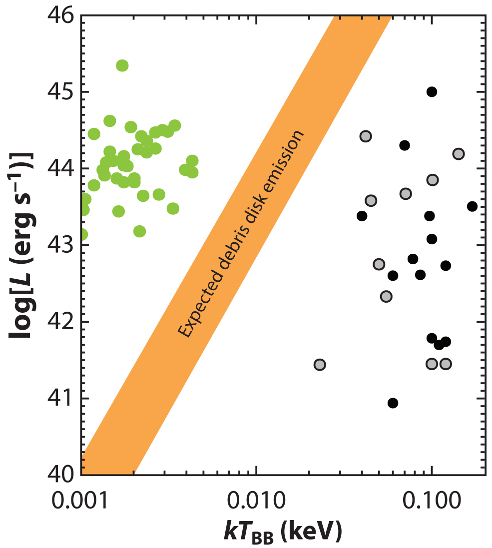
intermediate-mass black holes disrupt white dwarfs

red giants can only be disrupted by supermassive black holes

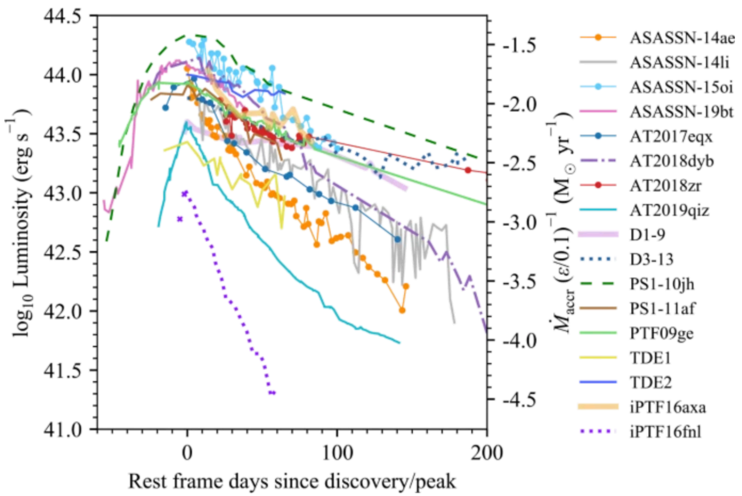
Properties



Detections of TDEs



Luminosity vs Temperature for UV / optical (green) and X-ray-detected (black) TDEs



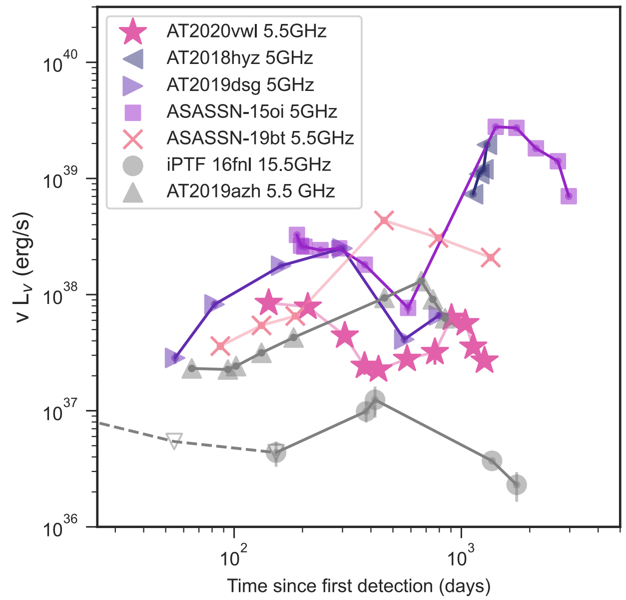
Light curves and corresponding mass accretion rates (van Velzen et al. 2020)

- ~100 TDEs have been detected
- LSST will greatly improve this
- bimodal distribution of spectrum
- emission mechanism not fully clear
- probably UV and optical through shocks, X-rays through accretion disk

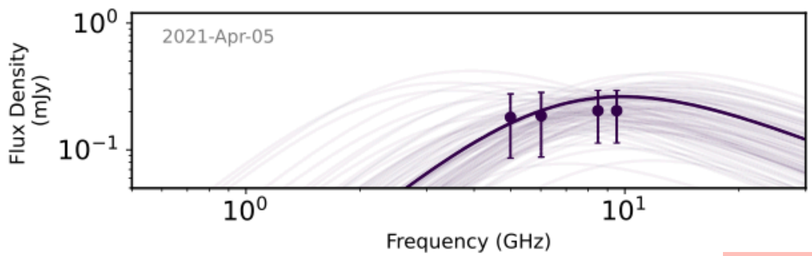
Sources: Gezari (2021)

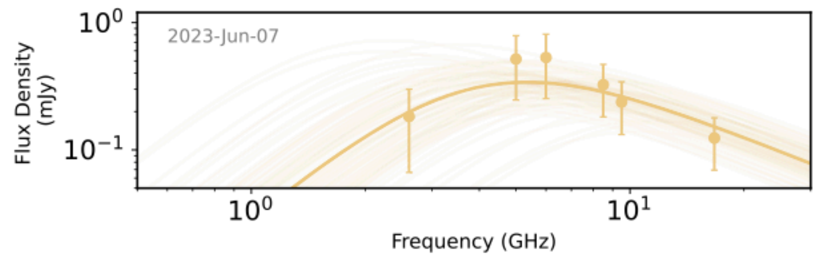
Radio emission

- Peaked synchrotron spectrum that evolves to lower frequency with time
- Visible for years (much longer than optical/X-ray emission)
- Half of TDEs show a radio follow-up
- Synchrotron emission (from outflows and jets)
- origin not well understood
- very rarely relativistic jet



Credits to Goodwin et al. 2024





shift to lower frequencies

Credits to Goodwin et al. 2024

What can they be used for?

- finding dormant supermassive black holes
- characterizing intermediate-mass black holes (via white dwarf TDEs)
- improve the knowledge of occupation fractions of supermassive black holes and intermediate-mass black holes in galaxies
- Multimessenger astronomy (High-energy neutrinos and gravitational waves)

SPH-EXA

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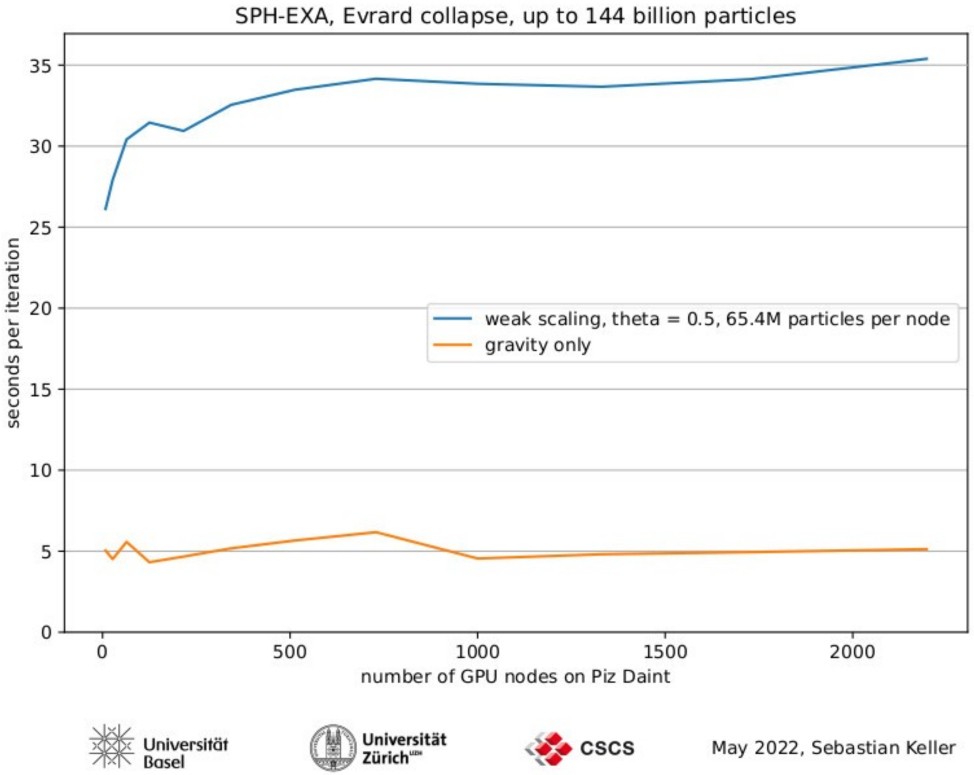
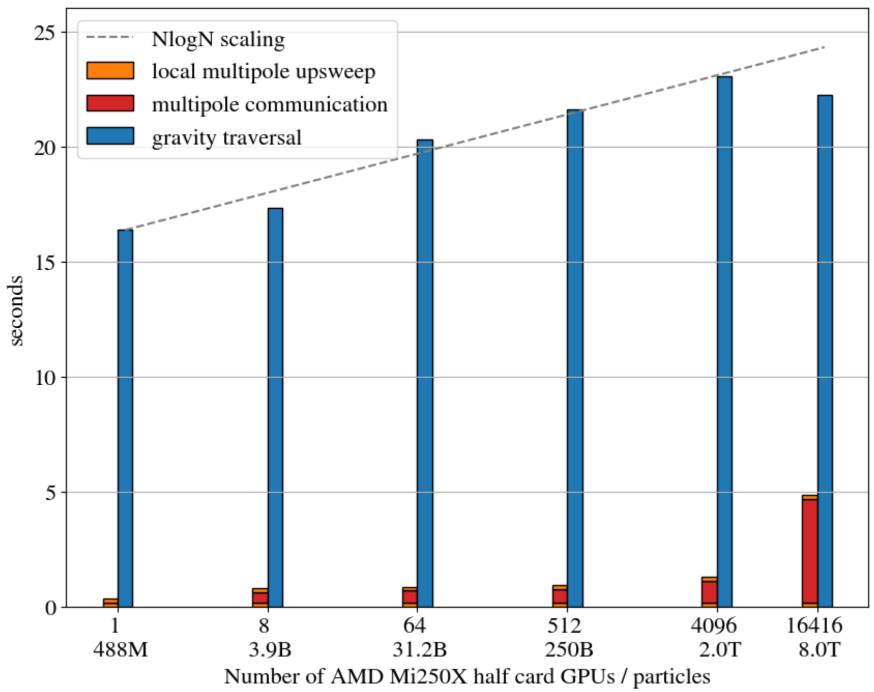
Jonathan Coles
Jean Favre

- modern SPH implementation (generalized volume elements, integral approach to derivatives, AV cleaner)
- coupled with N-body solver
- subgrid physics
- Fully on GPUs
- Scalability for exa-scale computing

SPH-EXA: Excellent scalability

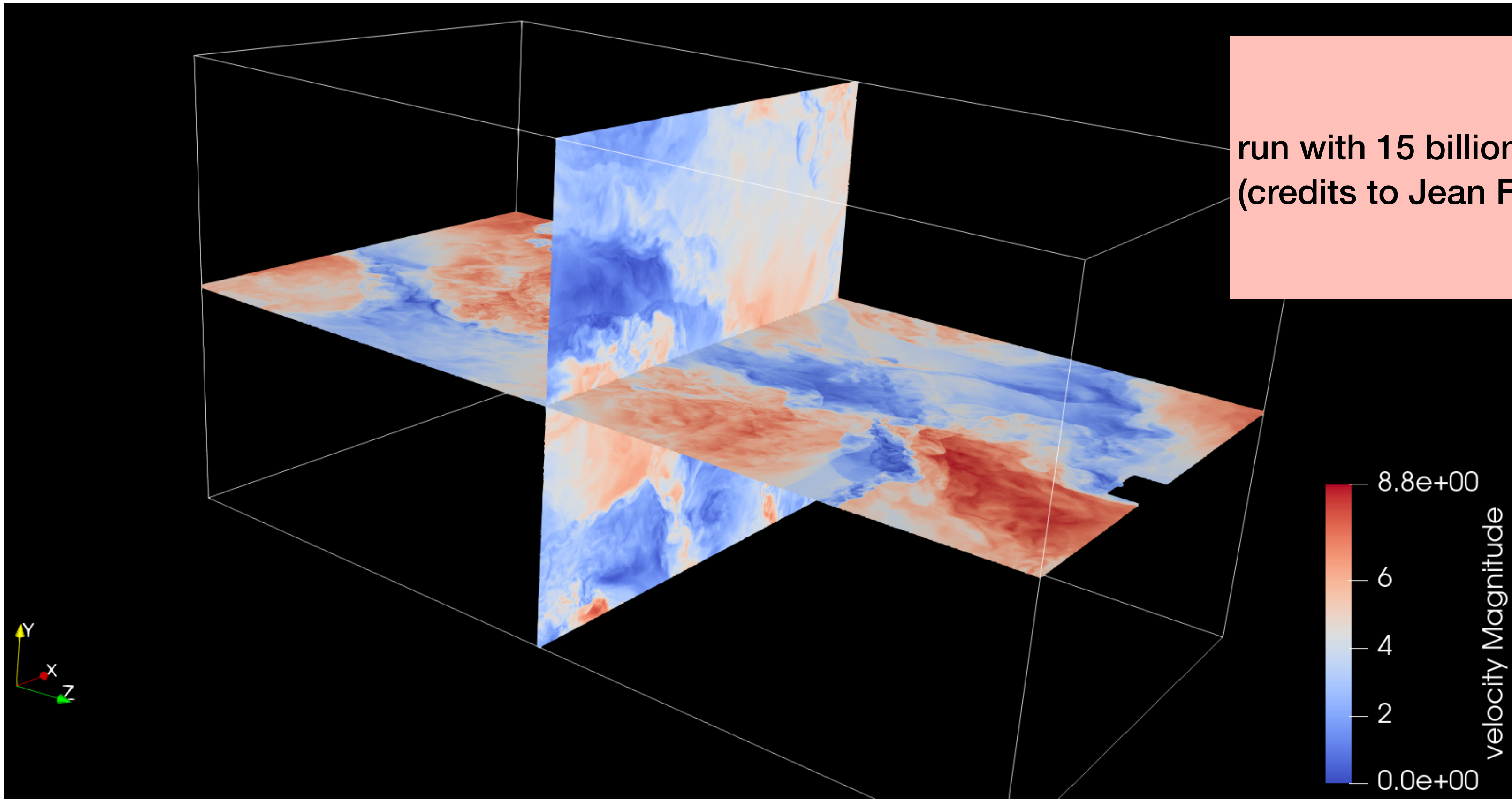




Weak scaling of SPH-EXA. Left: Evrard collapse, right: gravity-only (N-body) test up to 8 T particles

Credits to S. Keller

Turbulence and gravity in star-formation (TGSF) simulations with SPH-EXA



run with 15 billion particles (credits to Jean Favre)

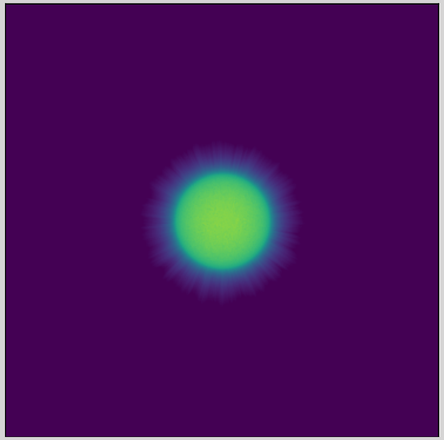
- will be the largest turbulence simulation for star formation (1 trillion particles)
- 2000 nodes on LUMI-G

Numerical simulations (Collaboration with Christopher Nixon (Leeds, UK), Eric Coughlin (Syracuse University, USA)

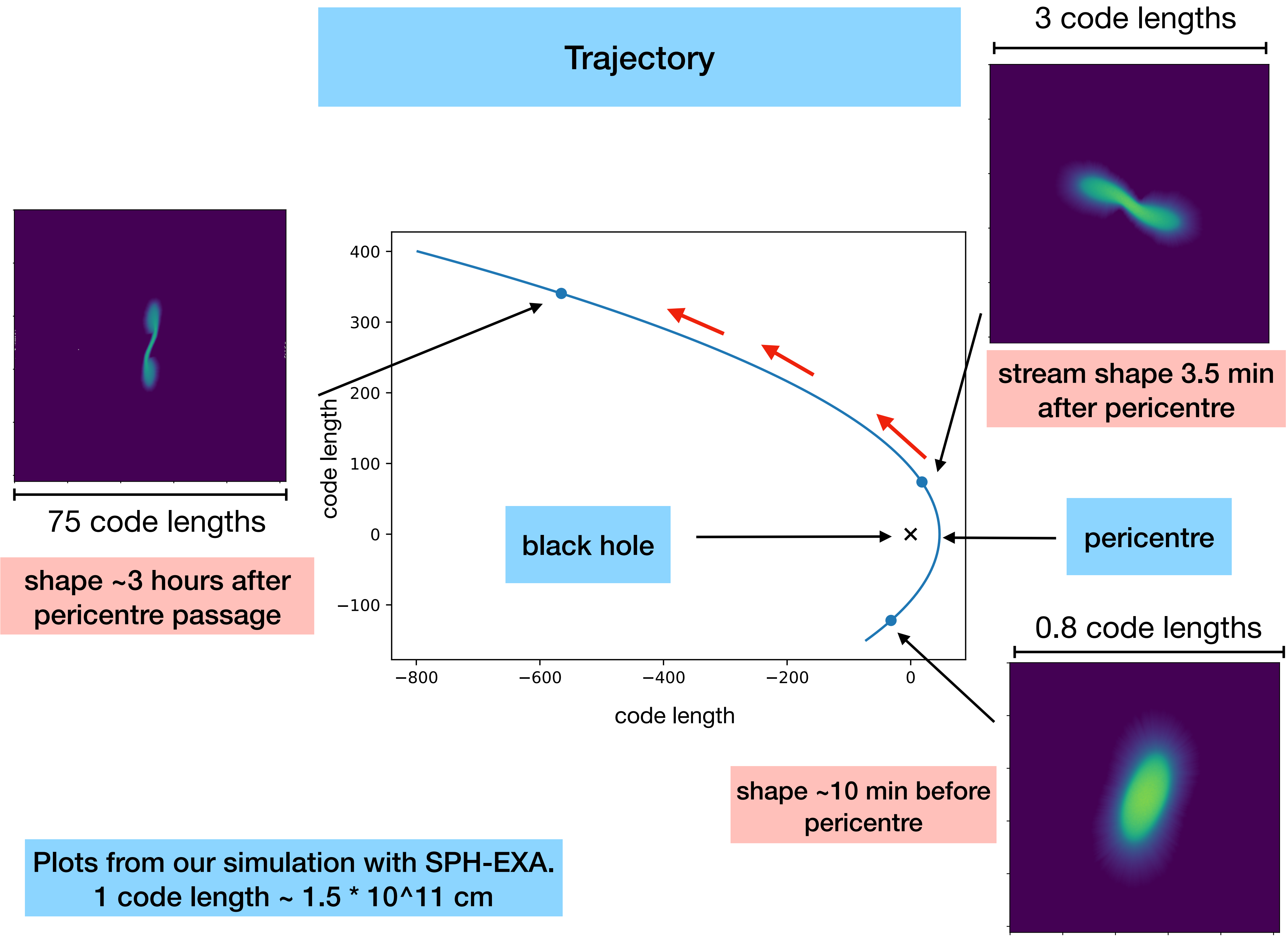
- SPH-EXA has all the required capabilities
- Recreate the results from Fancher et al. 2023 using SPH-EXA (done)
- Then continue with higher-resolution problems (ongoing). This is important to correctly catch the emission mechanism.

- Fancher et al. 2023:
- investigates the stellar stream after first pericentre passage; using multiple resolutions up to 128M
- finds important role for self-gravity
- evidence for gravitational collapse

- The numerical problem is conceptually easy:
- Black hole (10^6 M_star) modeled by Newtonian potential
- Star is forced to be a polytrope with tidal radius = pericentre distance
- The star starts on a parabolic orbit with pericentre distance >> Schwarzschild radius

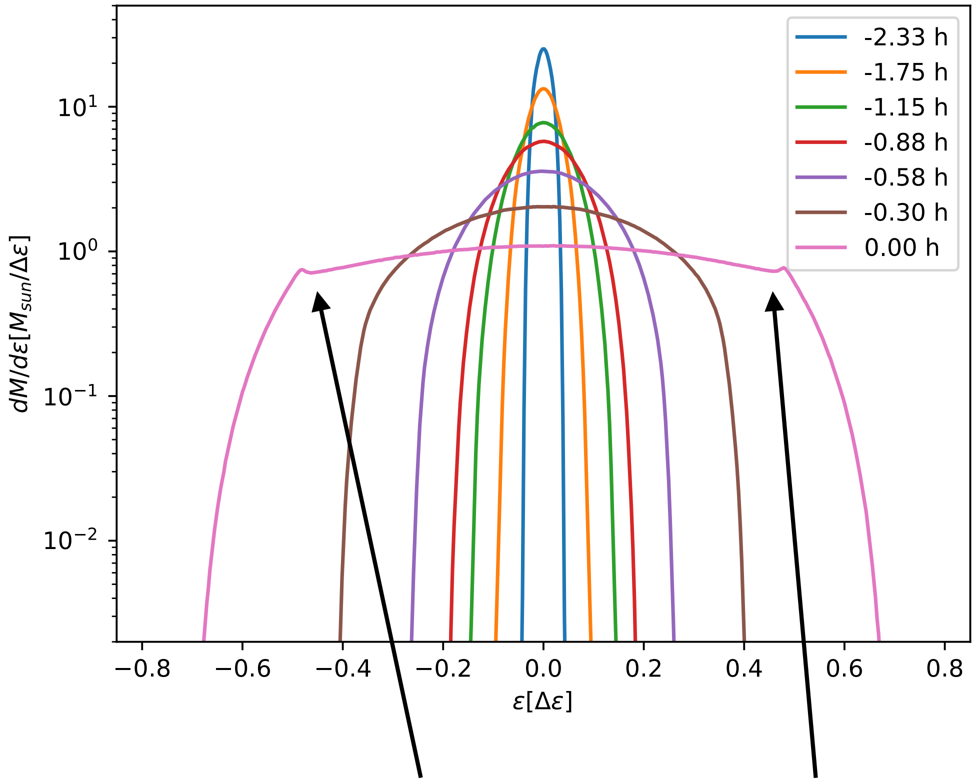


initial shape of the star



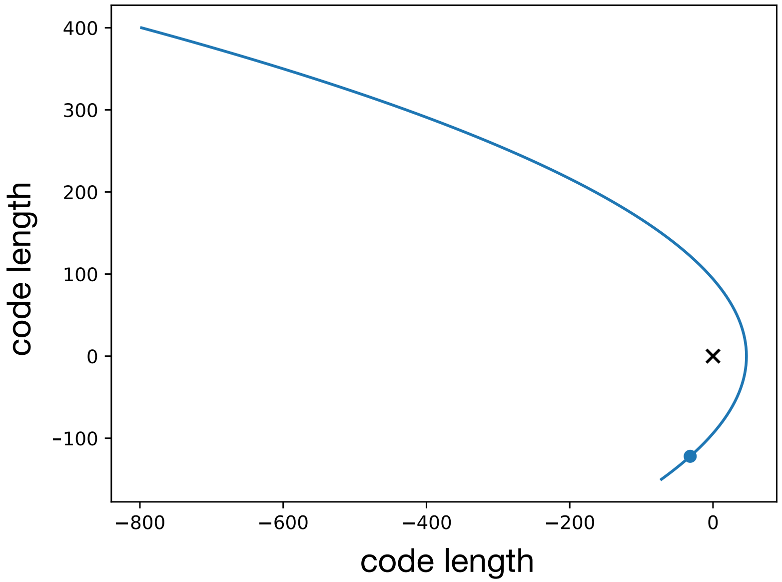
Trajectory
3 code lengths
stream shape 3.5 min after pericentre
75 code lengths
shape ~3 hours after pericentre passage
400
300
200
100
0
−100
code length
−800
−600
−400
−200
0
code length
black hole
pericentre
0.8 code lengths
shape ~10 min before pericentre
Plots from our simulation with SPH-EXA.
1 code length ~ 1.5 * 10^11 cm

Before pericentre

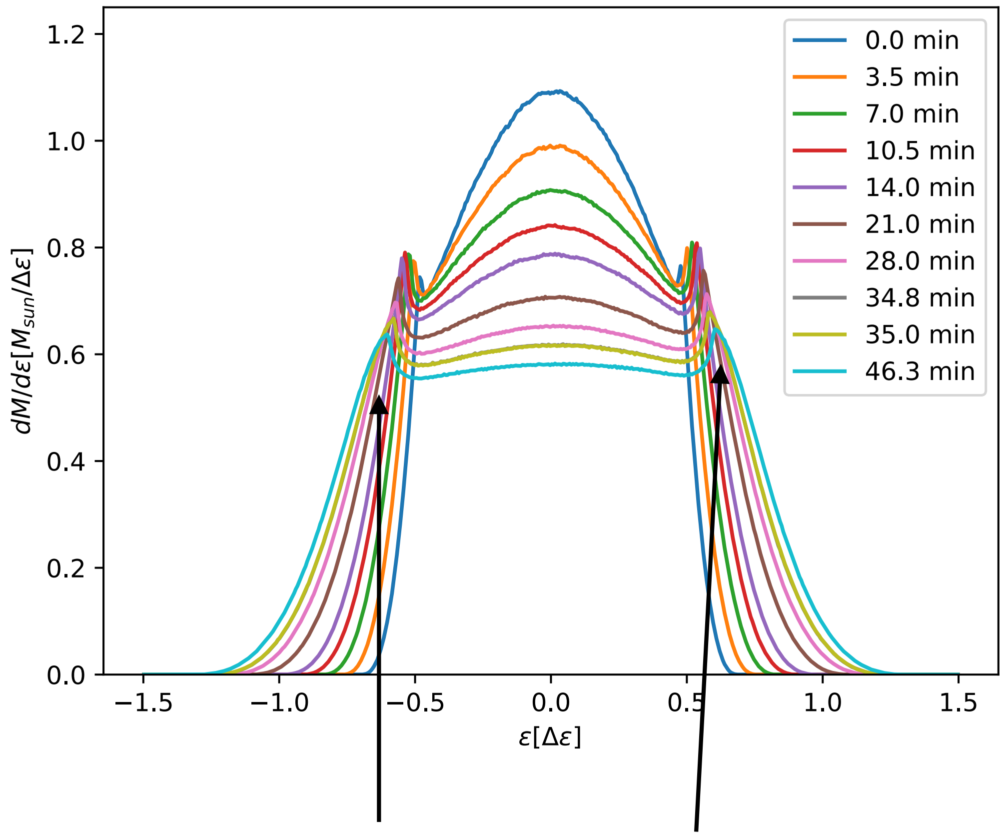


Mass distribution function of binding energy (SPH-EXA 128M)

star is deformed
and divided in a bound and
unbound part

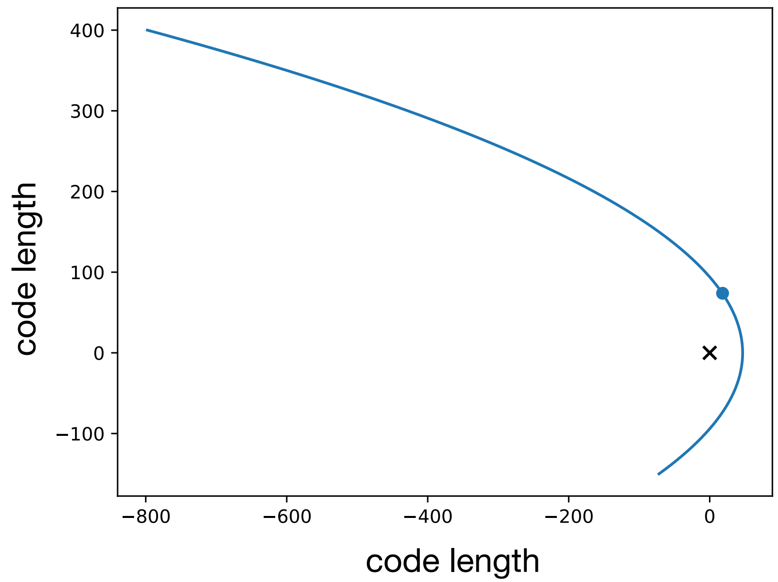


After pericentre passage

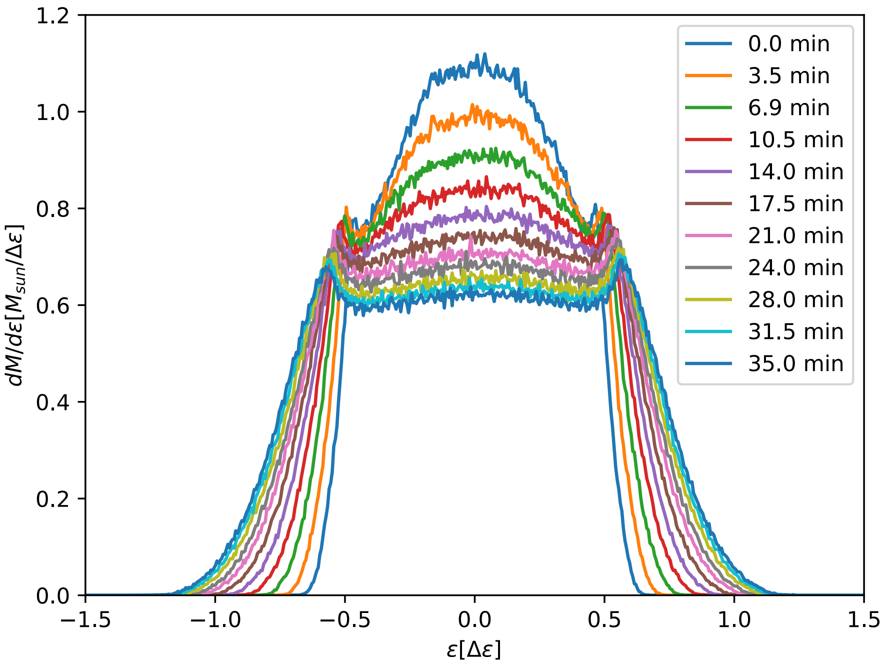


Mass distribution function of binding energy (SPH-EXA 128M)

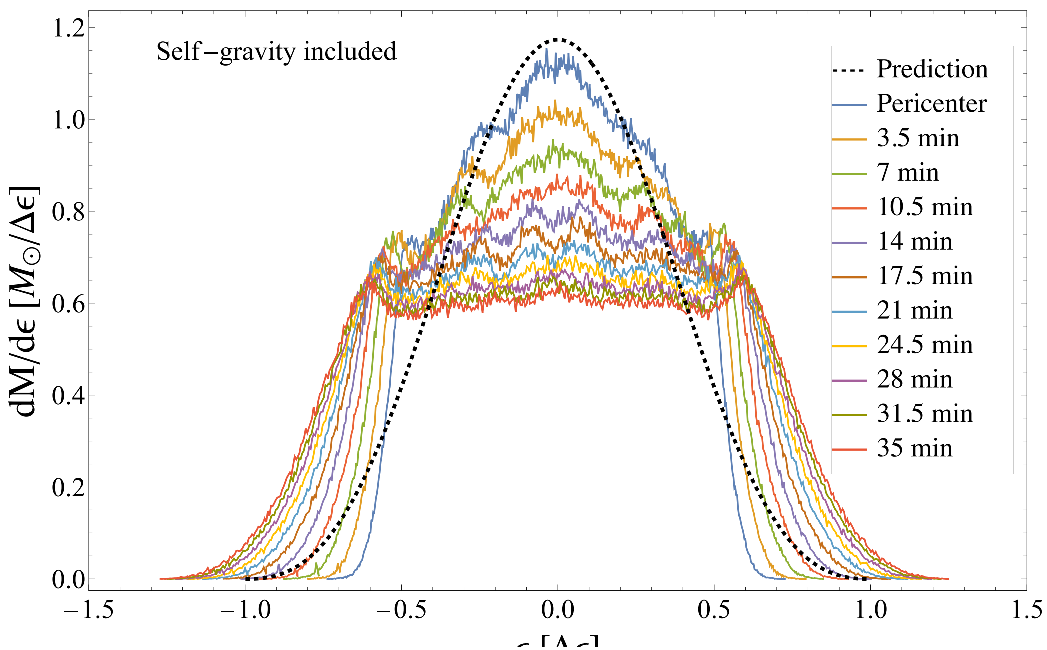
development of „wings“ through self-gravity (Fancher et al. 2023)



Comparison to Fancher et al. 2023



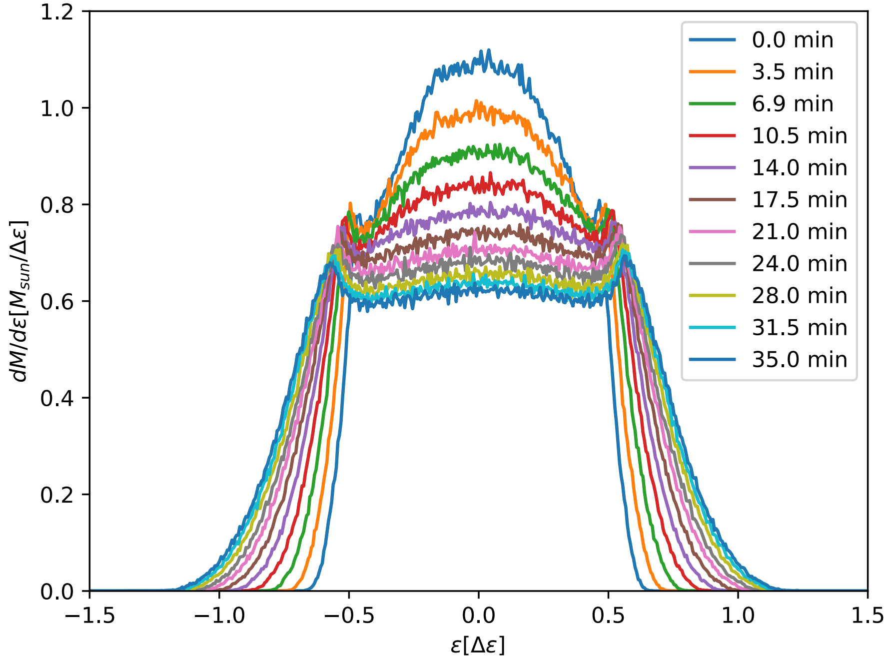
SPH-EXA (1M particles)

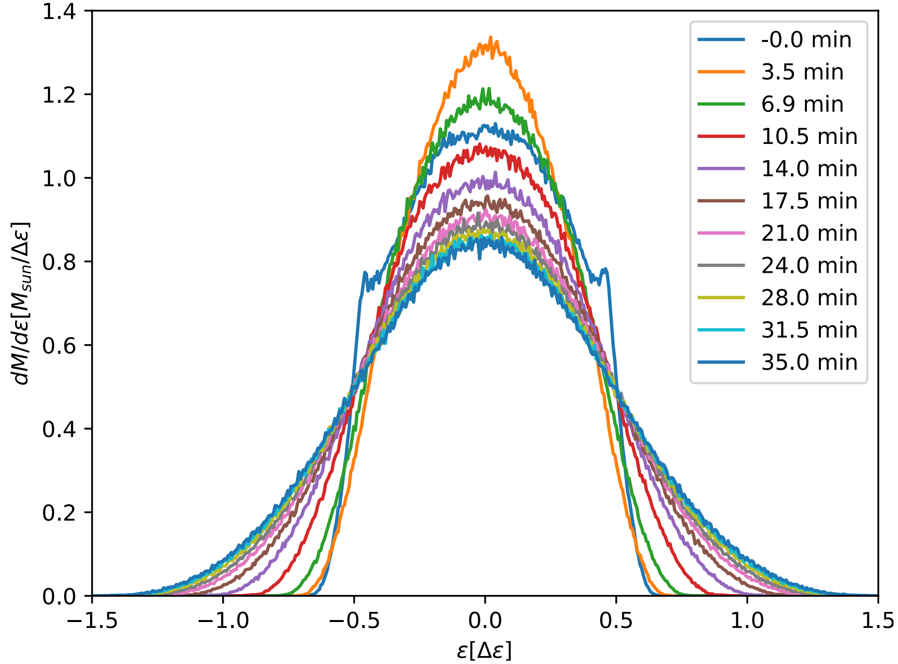


Fancher et al. 2023 (Phantom, 1M particles)

We find good agreement between the runs

self-gravity vs pressure forces





self-gravity + SPH

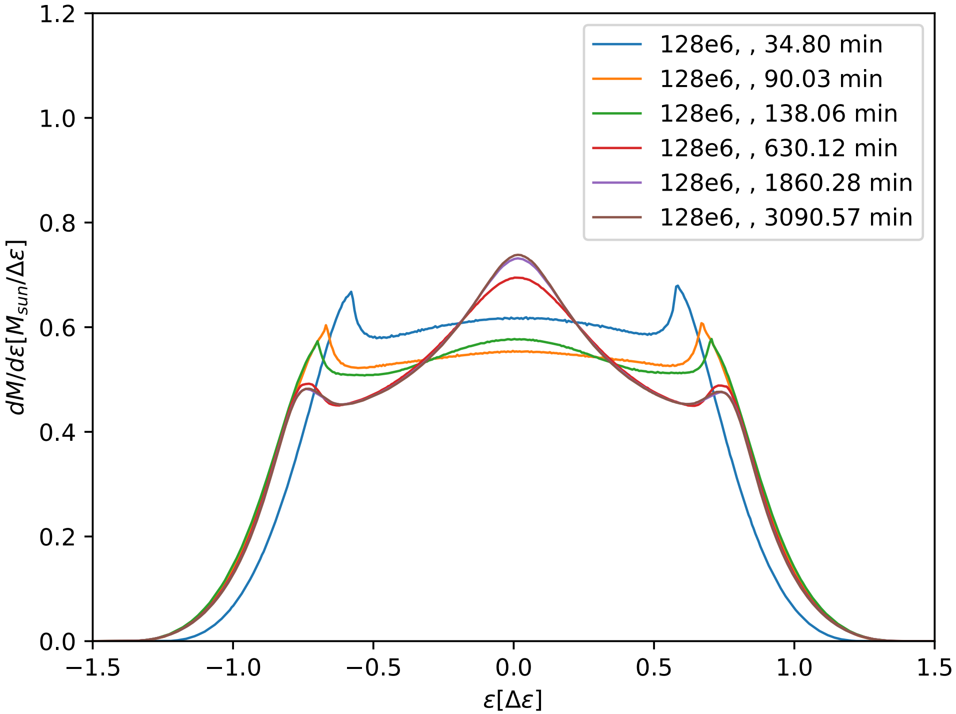
(SPH-EXA 1M)

self-gravity deactivated after pericentre

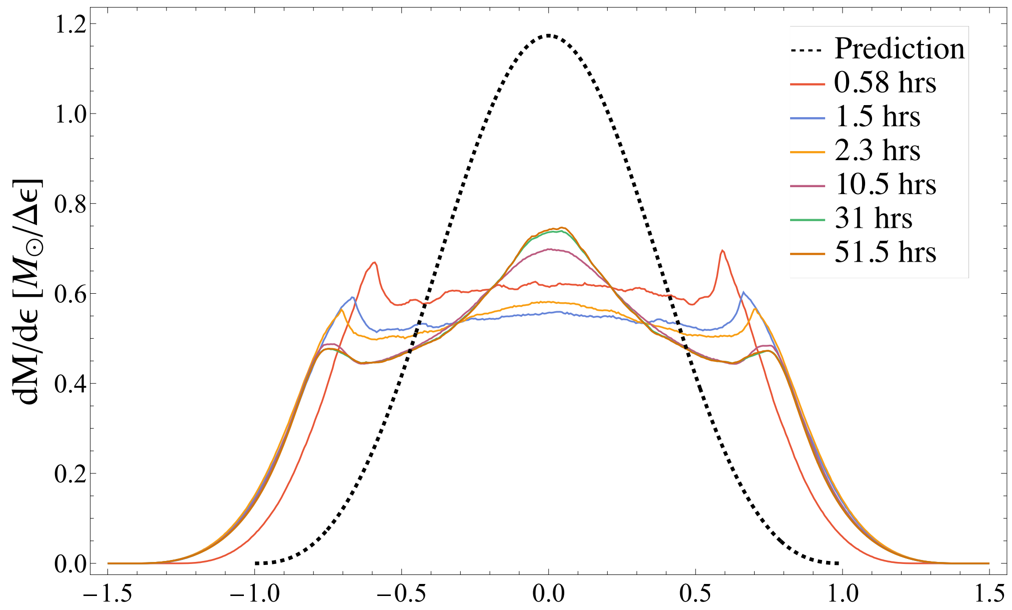
(SPH-EXA 1M)

While self-gravity is responsible for producing the wings, fluid pressure forces lead to a general broadening of the distribution

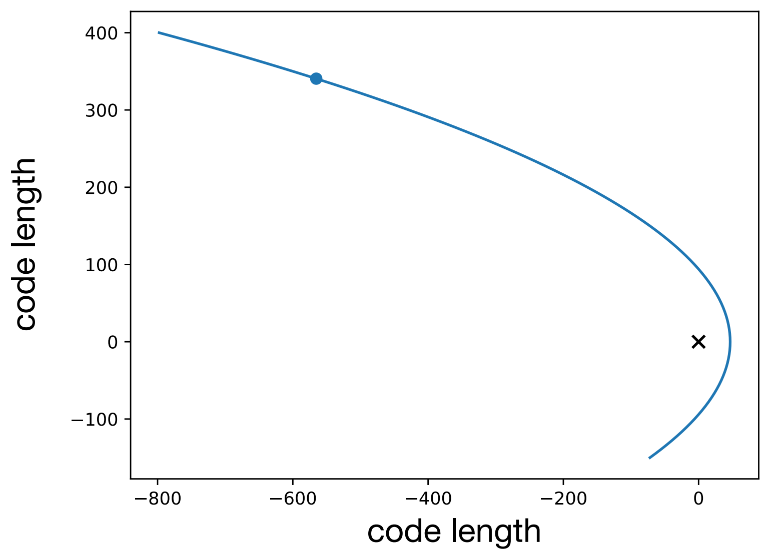
Longer term evolution



SPH-EXA (128M particles)

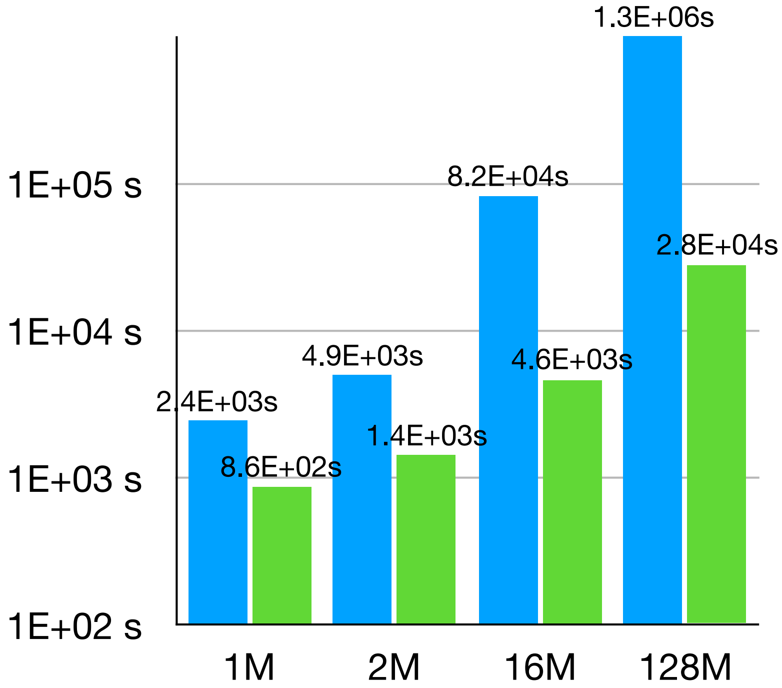


Fancher et al. 2023 (Phantom, 128M particles)



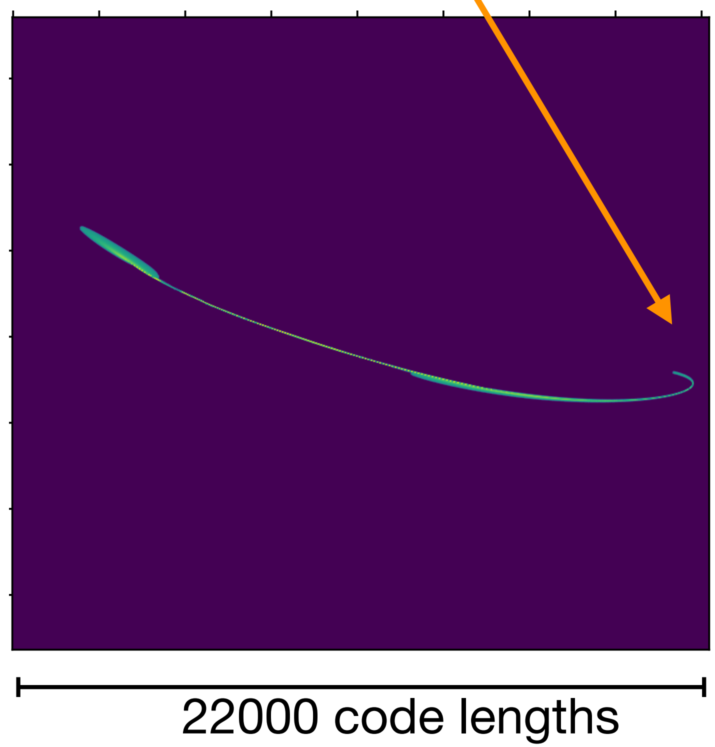
- Also good agreement on longer evolution
- question of GI remains (see wiggles at 0.58 h)

Current work



Time needed for simulations.
Blue: Fencher et al. 2023;
Green: our runs with SPH-EXA

The bound part is coming back; soon the stream will collide with itself



longer term evolution after second pericentre passage (SPH-EXA)

- **investigate gravitational collapse of the stream; should have a crucial dependence on gamma**
- **modify gamma (needs new initial conditions)**
- **go to much higher resolutions (~100b particles, GPU and efficient node-parallelism greatly beneficiary, ideal for SPH-EXA).**
- **simulate long-term evolution (multiple physical months)**

Outlook

High-resolution and long simulation timescales will allow to:

- show convergence in nozzle shock properties
- show convergence in debris structure and dynamics
- late-phase dynamics (low-energy emission in radio spectrum)
- investigate clumping of the stellar stream through self-gravity

After the long-time high-resolution simulations the next step will be to add additional physics:

- Radiation transport
- GR corrections
- Magnetic fields
- ISM envelope model