The death of a star

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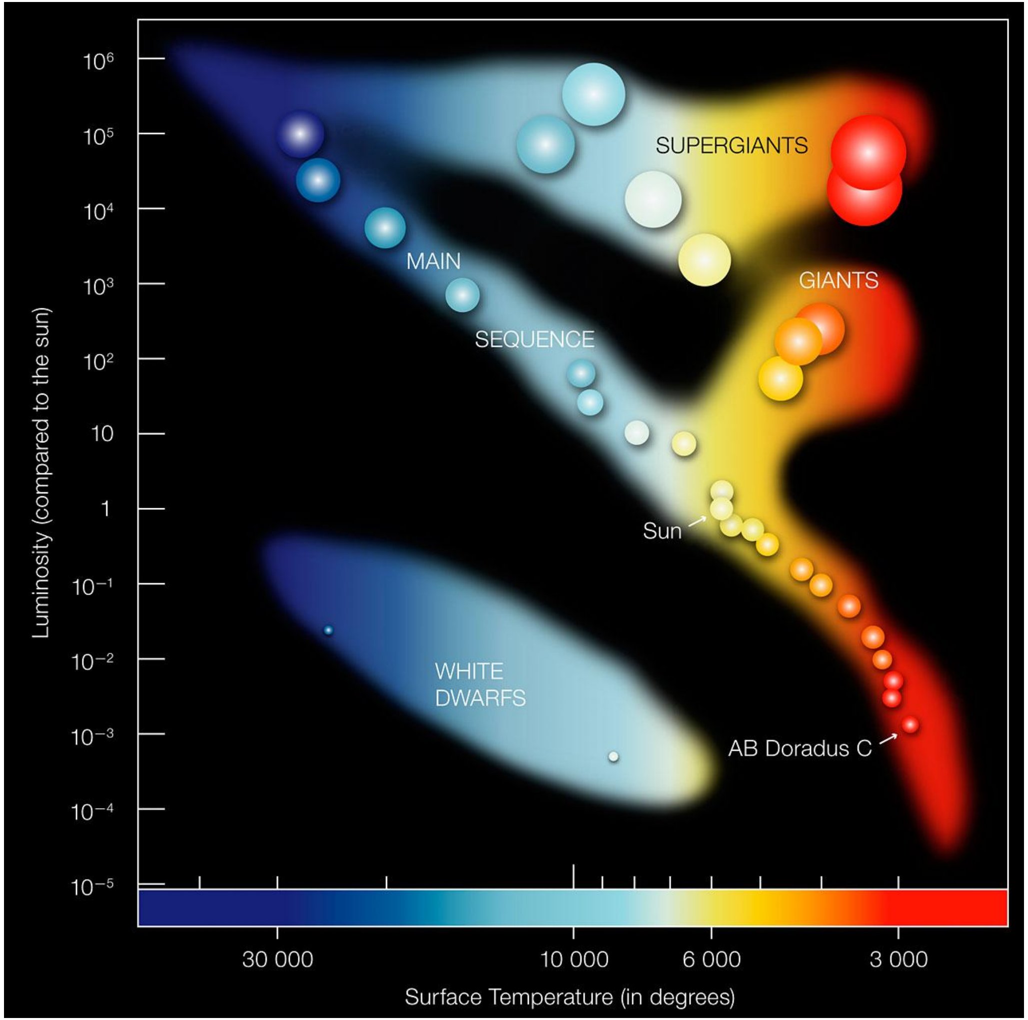
Outline

- Natural and unnatural deaths of stars
- Theory and observation
- Theory meets observations : Kerr black holes
- Summary

Pritam Banerjee
Shaswata Chowdhury
Debojyoti Garain
Parth Pandya
Aryabrat Mahapatra
Adarsh Pandey

Based on (+ references)

- ArXiv : 2401.17031 [astro-ph.HE]
- ArXiv : 2310.03539 [astro-ph.HE]
- JCAP 11 (2023) 062
- ApJ 929 (2022) 117
- ApJ 924 (2022) 20
- ApJ 910 (2021) 23
- ApJ 884 (2019) 95



Hertzsprung Russell Diagram
(Image Credit : ESO)

Due to internal mechanisms, stars of the main sequence will climb up the HR diagram, reach a giant phase and ultimately a red giant sheds much of its mass and becomes a white dwarf

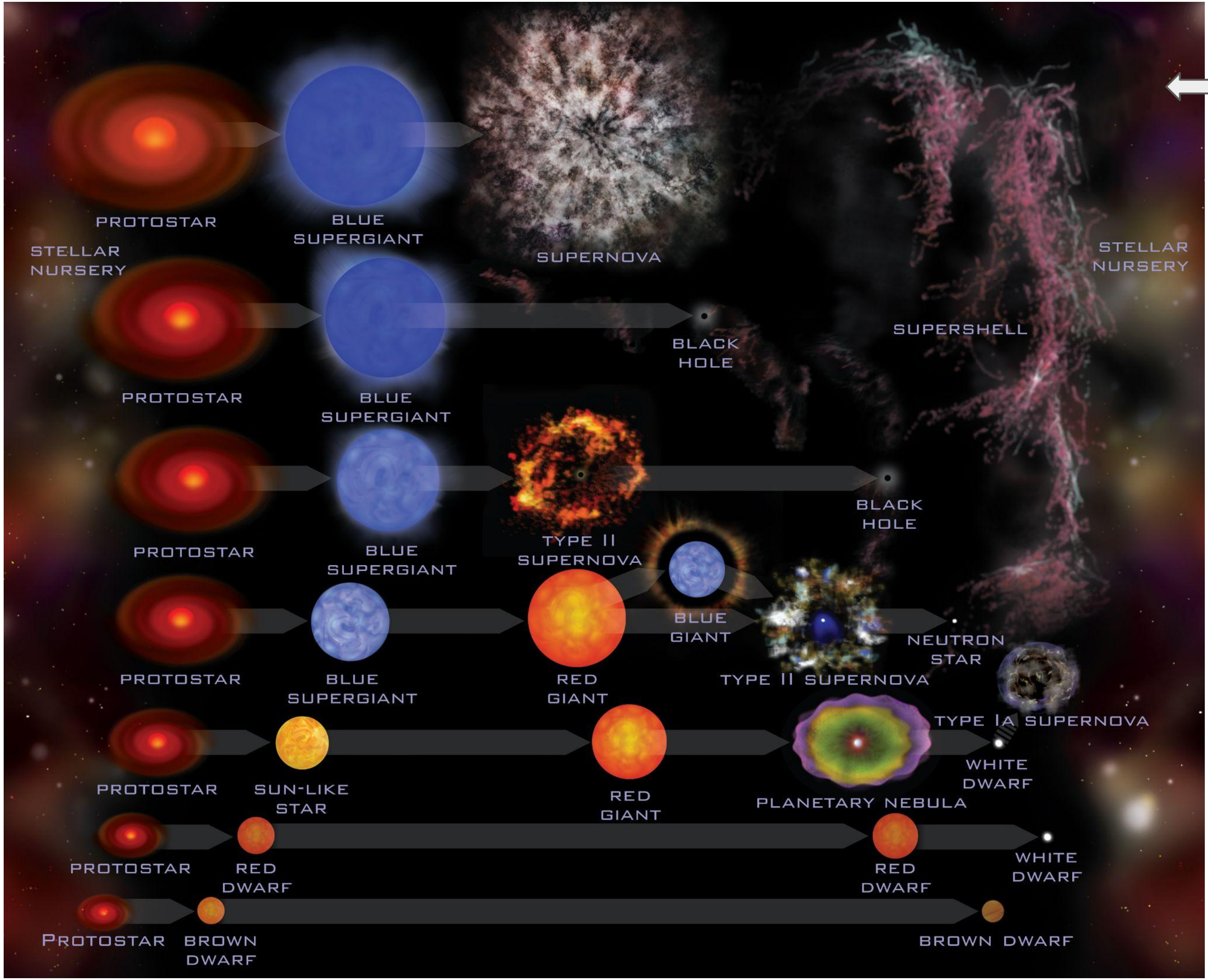


Image Credit : JPL

These are natural outcomes

A more dramatic situation might arise if a star meets a likely predator !

Sufficiently ferocious predators like black holes can eat up a star or rip it apart causing its unnatural death

This can happen due to non-local gravity : tides. Dramatic astrophysical phenomena.

The importance of tidal effects

Tidal effects are one of the most dramatic features of non-local gravity → can tear apart a massive object when non local forces exceed self gravity → can produce observable luminous flares → one of the main physical processes in accretion disc formation.

The comet Shoemaker Levy 9 broke into 21 pieces in July 1992 due to the tidal force of Jupiter and collided with it in July 1994 causing huge impacts on the surface of Jupiter.

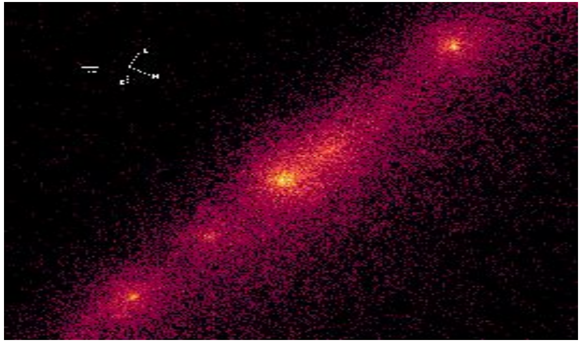
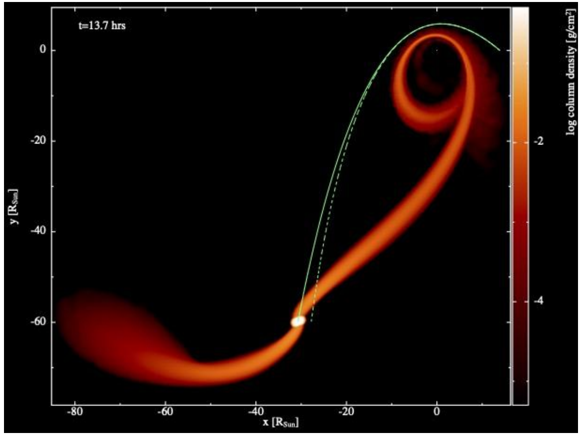


Image Credit : Wikimedia

When a star gets ripped apart due to tidal forces, one can get a fascinating view of its “interior” which is crucial to understanding stellar composition and stellar evolution : fallback rates are observable.

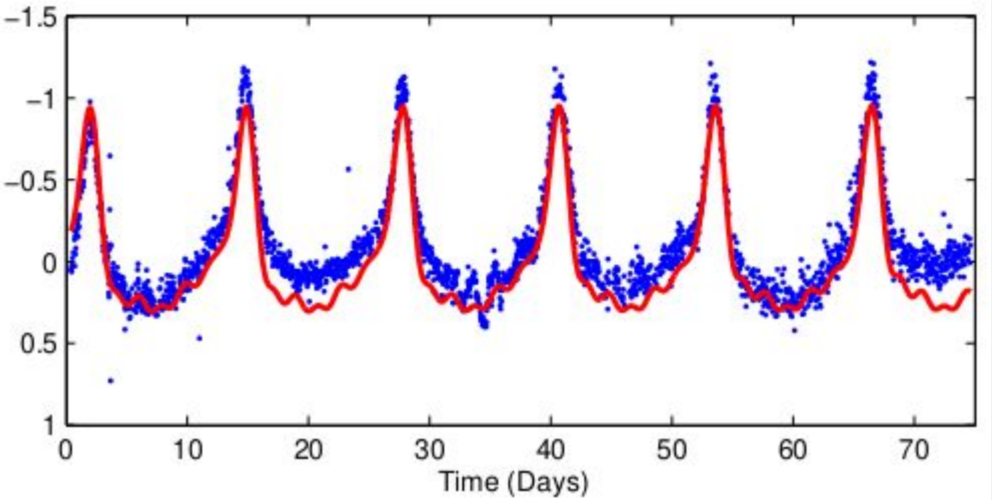
Provide astrophysical tests of gravity beyond GR.

Analytical computations not possible : this is a sample of how a tidal disruption event of a star looks like :



Tides not only cause disruptions, it can cause love too ! Called Heartbeat stars or stars in love

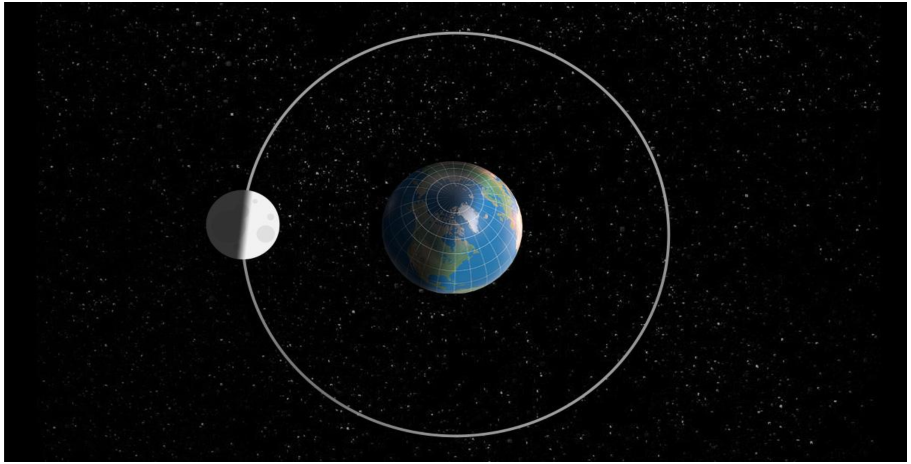
Image Credit : DST, GOI



Tidal torques play a major role in planetary systems

Can give rise to phenomena in planet-satellite systems like tidal locking

Image Credit : NASA



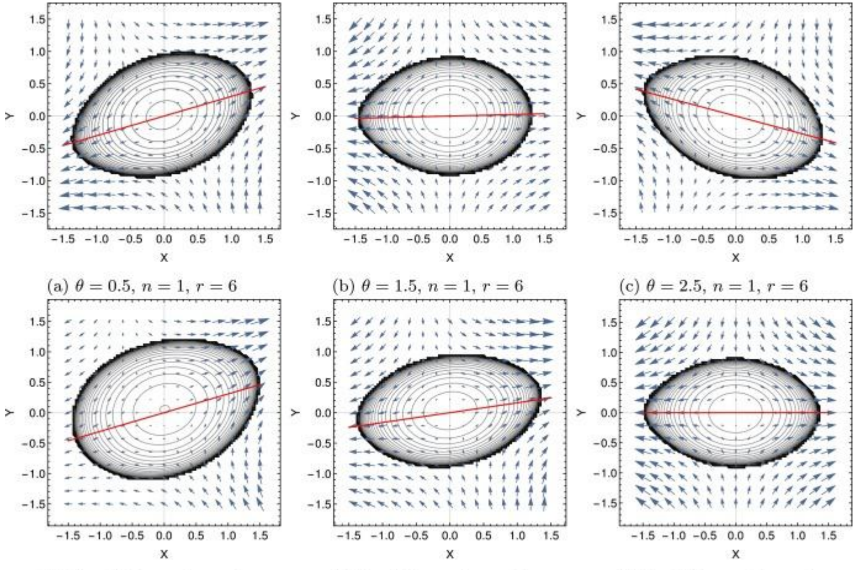
Familiar examples

- Earth tides. Can quantify tidal effects in simple scenarios :

$$a_T(A) = \left[\frac{GM_m}{(r-\Delta R)^2} - \frac{GM_m}{r^2}\right]\hat{i} \simeq \frac{2GM_m\Delta R}{r^3}\hat{i}$$

$$a_T(C) \simeq -\frac{GM_m\Delta R}{r^3}\hat{j}$$

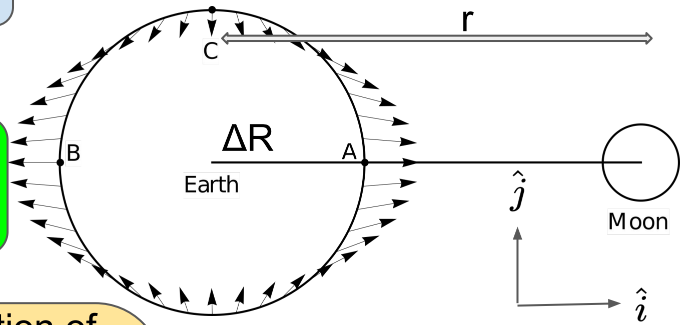
$$a_T(B) = \left[\frac{GM_m}{(r+\Delta R)^2} - \frac{GM_m}{r^2}\right]\hat{i} \simeq -\frac{2GM_m\Delta R}{r^3}\hat{i}$$



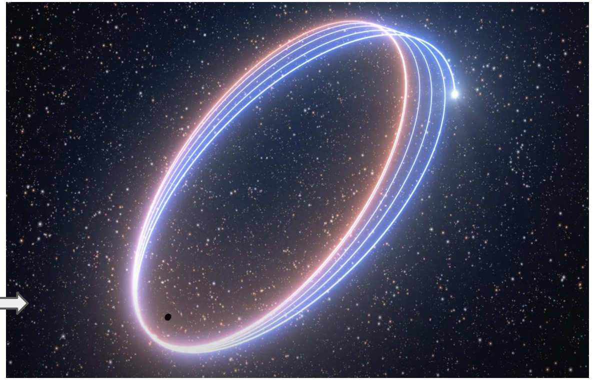
(a) $\theta = 0.5,\ n = 1,\ r = 6$ (b) $\theta = 1.5,\ n = 1,\ r = 6$ (c) $\theta = 2.5,\ n = 1,\ r = 6$

(d) $\theta = 1.05,\ n = 1,\ r = 3$ (e) $\theta = 1.3,\ n = 1,\ r = 3$ (f) $\theta = 1.57,\ n = 1,\ r = 3$

Stellar Tides



The deformation of the star gives rise to very interesting effects like tidal torques that maximise at periapsis and couples with tidal oscillations. Image Courtesy : Science



First take : Fermi Normal frame

- We need a frame of reference that is locally flat all along a timelike geodesic : Fermi normal frame.
- So we take a star in this local tetrad basis which moves with the star along its timelike geodesic $\mathcal{G}$.

- Local Flatness : An observer on $\mathcal{G}$ sees the flat Minkowski metric :

$$g_{\mu'\nu'}\hat{e}^{\mu'}_{\mu}\hat{e}^{\nu'}_{\nu} = \eta_{\mu\nu} \quad ; \qquad \Gamma^{\mu}_{\alpha\beta}\Big|_{\mathcal{G}} = 0$$

- Riemann Tensor remains non-zero.

- Valid throughout the geodesic : The basis vectors $\hat{e}^{\mu'}_{\nu}$ are to be parallel transported along the geodesic.

$$(\nabla_{\alpha'}\hat{e}^{\mu'}_{\nu})u^{\alpha'} = 0$$

Strategy :

For a generic stationary space-time, construct FNC.

⇩

Consider equatorial parabolic (or elliptical) orbits by suitably choosing energy and angular momentum.

⇩

Solve the hydrodynamic equation of the fluid star numerically in the presence of tidal potential.

⇩

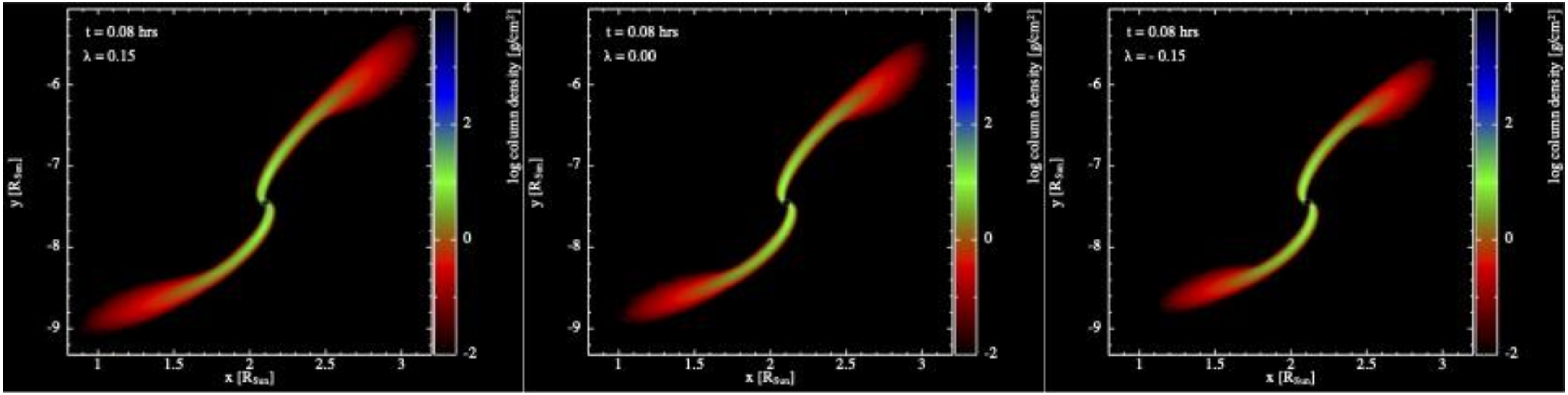
Obtain critical density below which star is disrupted. Gives other critical parameter values.

All this is great, but lacks dynamics : we always assumed hydrodynamic equilibrium.

Tidal disruption events can only be properly understood if we can follow an object in real (Newtonian) time as it approaches a central mass.

Stars are often partially disrupted : interesting physics that cannot be captured by equilibrium model.

Need high performance computing based on GR : SPH based parallel code

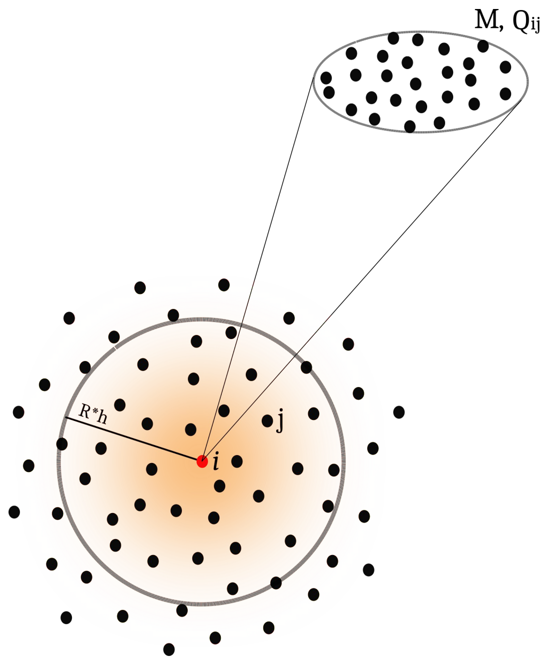


A few of words on SPH …

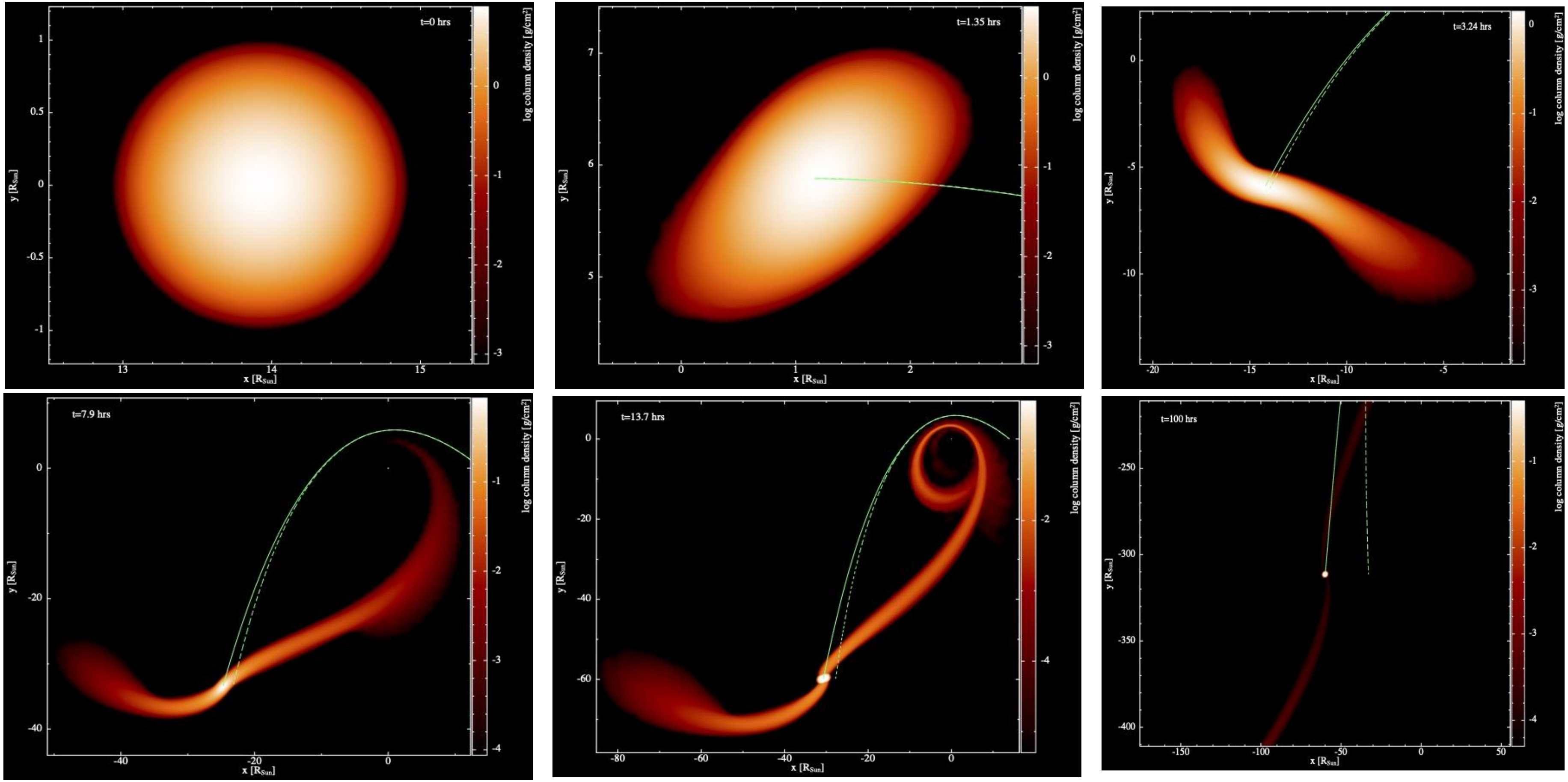
- An infinitesimal fluid element ≈ a smoothed particle
- Mesh-free Lagrangian method. No grids, no boundaries.
- Automatic conservation of energy, momentum (Ideally).

- Hydrodynamic properties and short range forces are evaluated from neighbours.
- Binary tree reduces interactions $\mathcal{O}(\mathcal{N}^2) \rightarrow \mathcal{O}(\mathcal{N}\log_2\mathcal{N})$
- Far field gravity is calculated using multipole moments of particle groups/ nodes.

- Temporal evolution is done using time reversal, symplectic leapfrog integrator.
- Individual time-stepping ensures that each particle evolves on its own time scale.
- Particle is “woken up” to react to its rapidly moving neighbours.



Deviation in stellar trajectory due to asymmetric partial tidal disruption : first look : solid green : actual COM



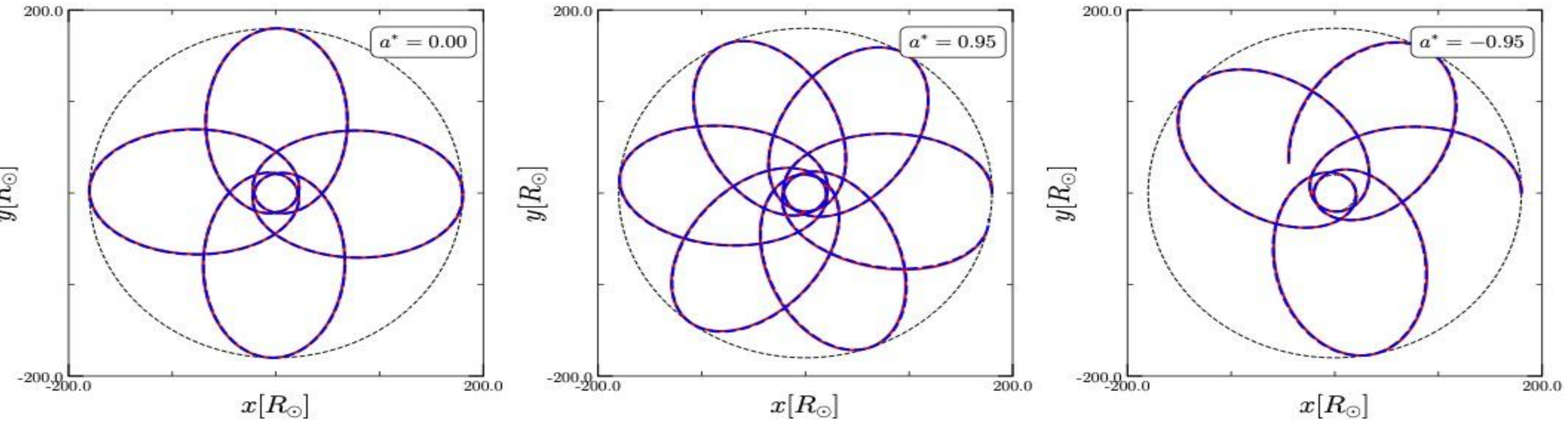
The situation becomes remarkably different if one includes stellar spin and Kerr black holes.

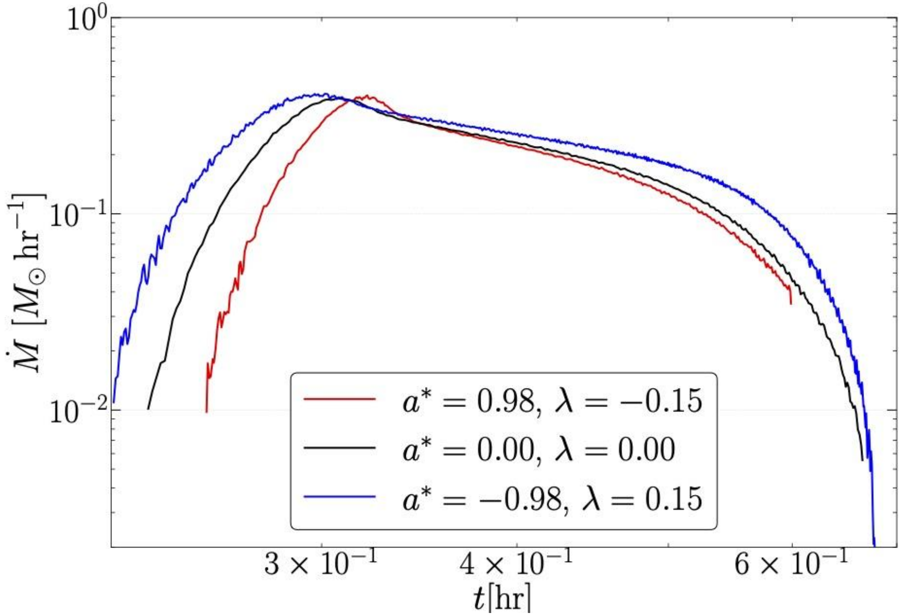
$$\frac{dU^\mu}{d\tau} = -\frac{1}{\rho\,\omega}\frac{\partial P}{\partial x^\mu}(U^\mu U^\nu + g^{\mu\nu}) - \Gamma^\nu_{\lambda\mu}U^\lambda U^\mu$$

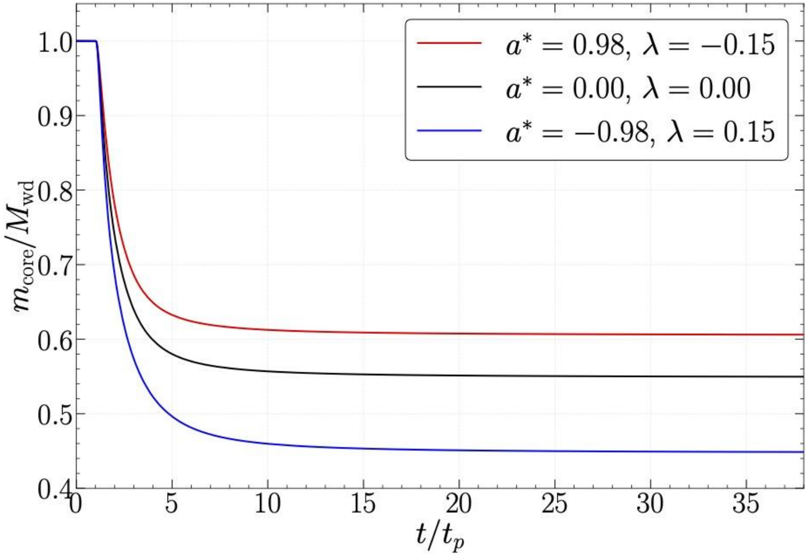
$$\frac{d^2x^i}{dt^2} = -(g^{i\lambda} - \dot{x}g^{0\lambda})\left[\frac{1}{\Gamma^2\rho\omega}\frac{\partial P}{\partial x^\lambda} + \left(\frac{\partial g_{\mu\lambda}}{\partial x^\sigma} - \frac{1}{2}\frac{\partial g_{\mu\sigma}}{\partial x^\lambda}\right)\dot{x}^\mu\dot{x}^\sigma\right]$$

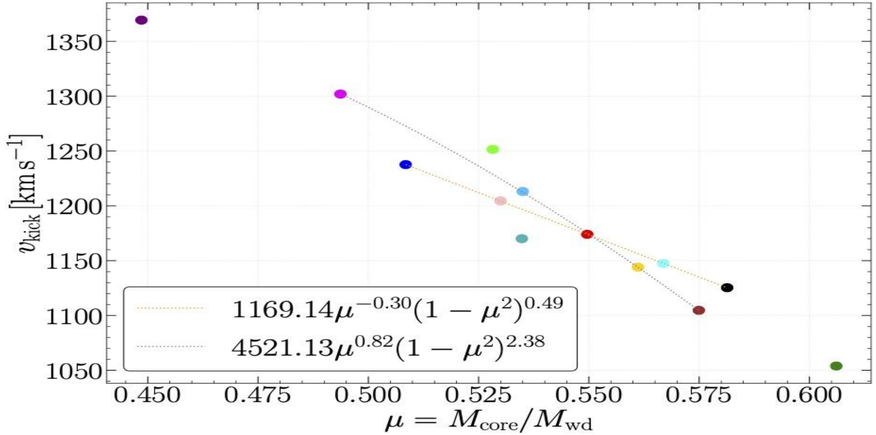
$$ds^2 = -\left(1 - \frac{2GMr}{c^2\,\Sigma}\right)dt^2 - \frac{4GMra\sin^2\theta}{c\,\Sigma}dtd\phi + \frac{\Sigma}{\Delta}dr^2 + \Sigma d\theta^2 + \left(r^2 + a^2 + \frac{2GMra^2\sin^2\theta}{c^2\,\Sigma}\right)\sin^2\theta d\phi^2$$

$$\Sigma = r^2 + a^2\cos^2\theta,\ \Delta = r^2 + a^2 - 2GMr/c^2,\ a = J/Mc$$



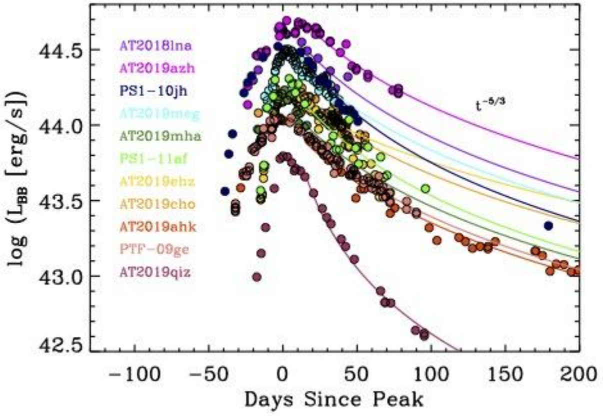






0.3 solar mass White Dwarf
Stellar spin period 5 minutes
10000 solar mass Kerr Black Hole
Minimum (periapsis) distance 39
Schwarzschild radii.

Significant amount of data over next 5-6 years



Taken from Gazeri, arXiv:2104.14580 [astro-ph.HE]

For the future :

What happens to phenomena like resonance locking for near extremal Kerr black holes ?

How do disruptions happen near wormhole throats ?

What happens when a star is disrupted very close to the event horizon ? Particularly important for White Dwarfs with Quantum Mechanics at play.