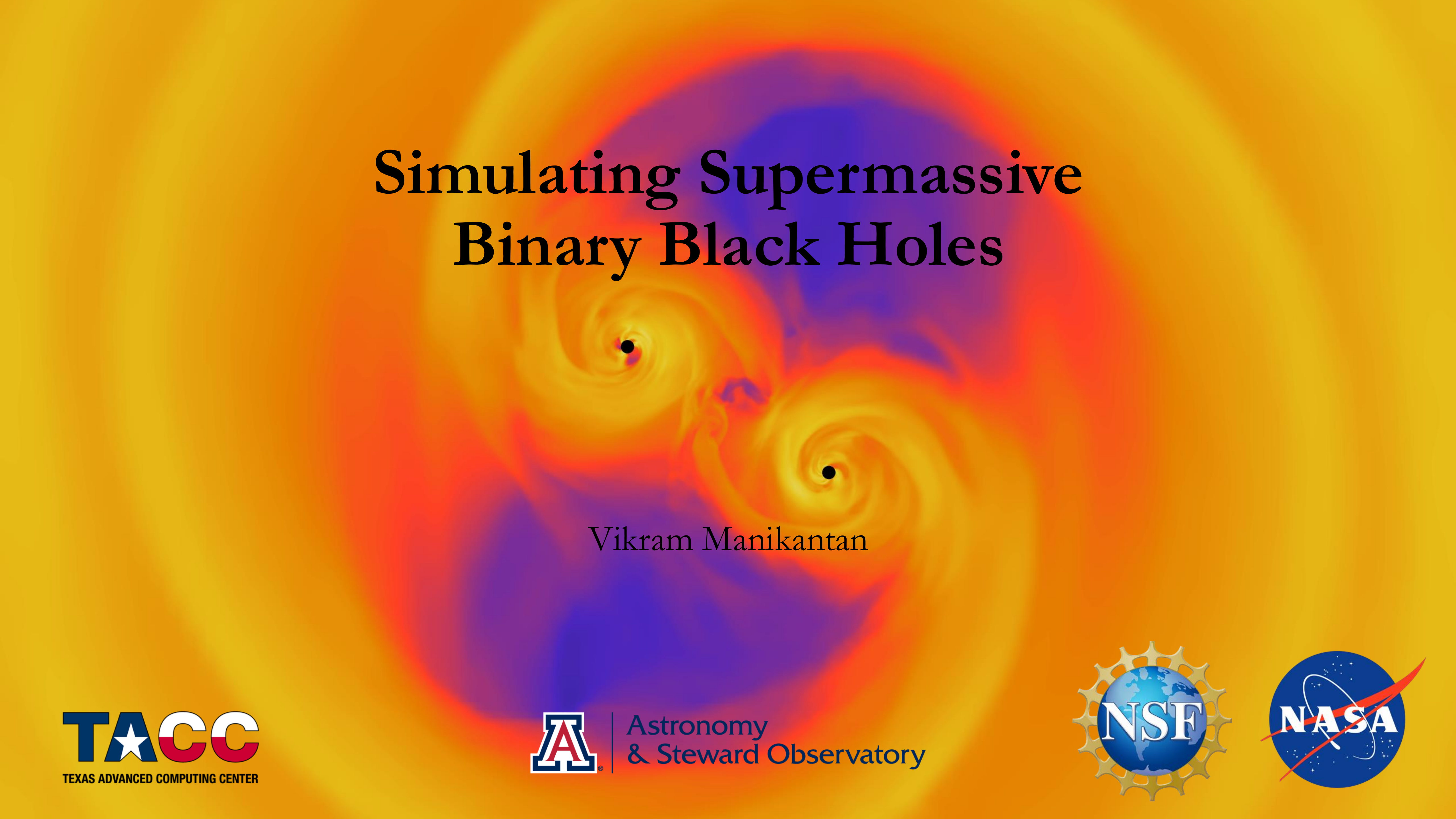

Simulating Supermassive Binary Black Holes

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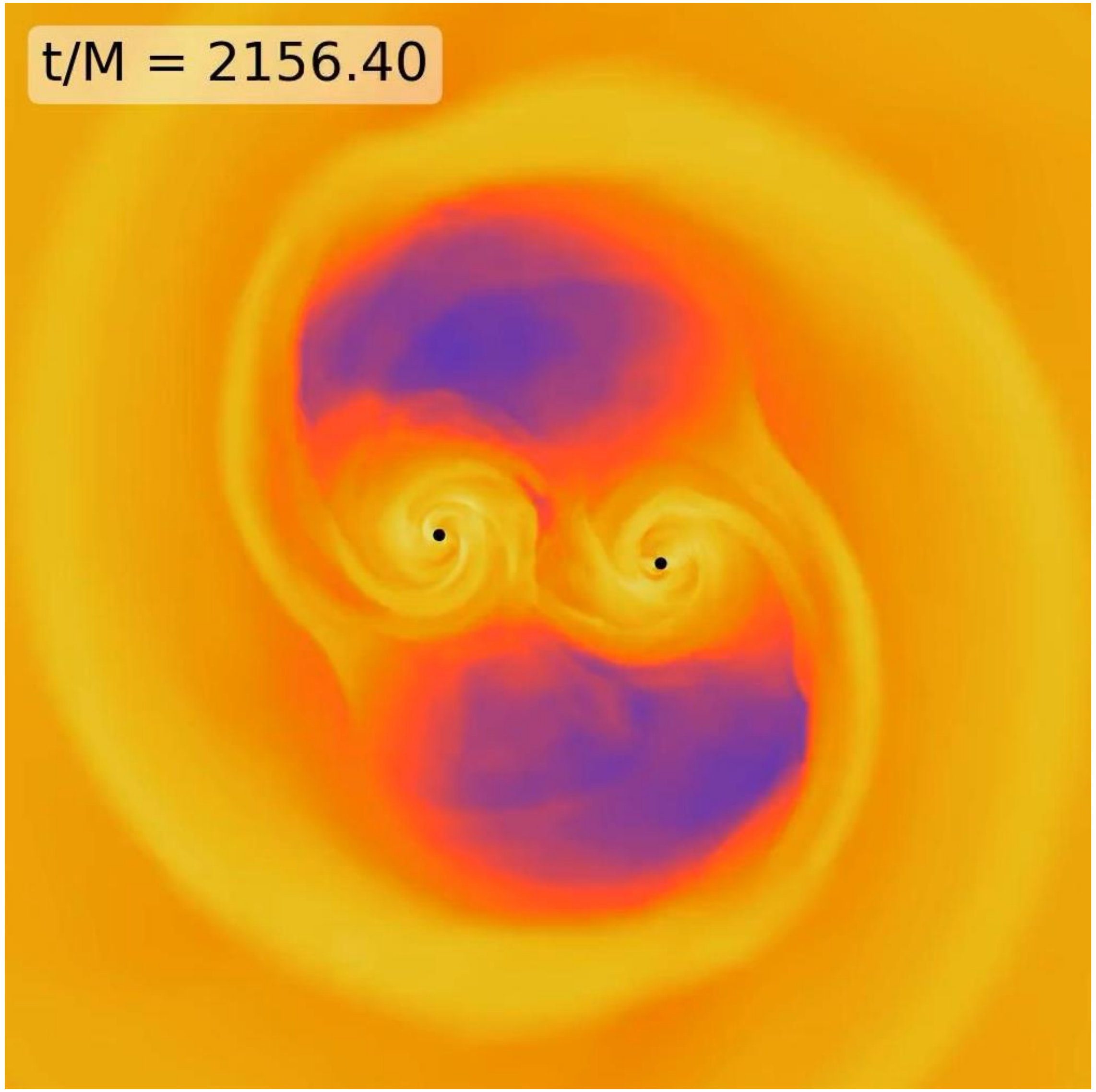
Astronomy
& Steward Observatory

NSF

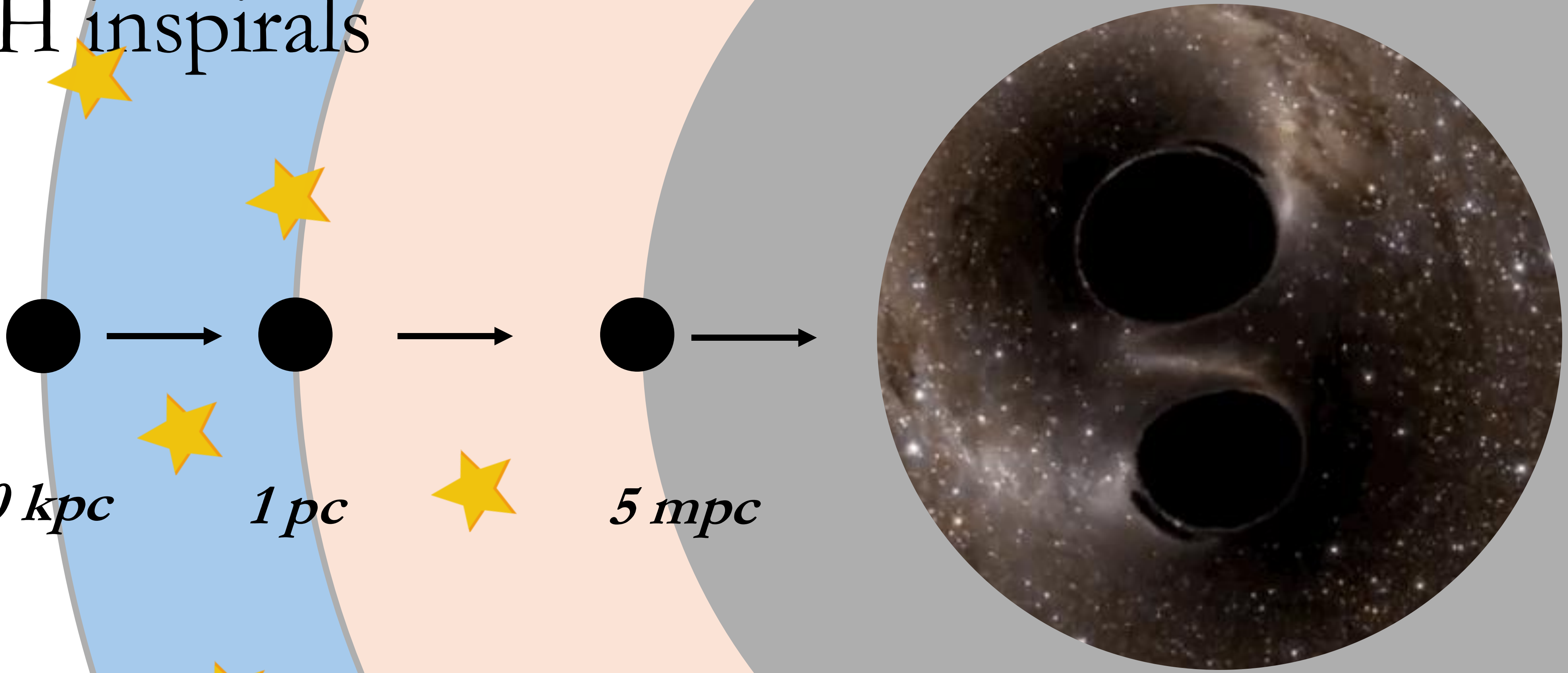
NASA

Today

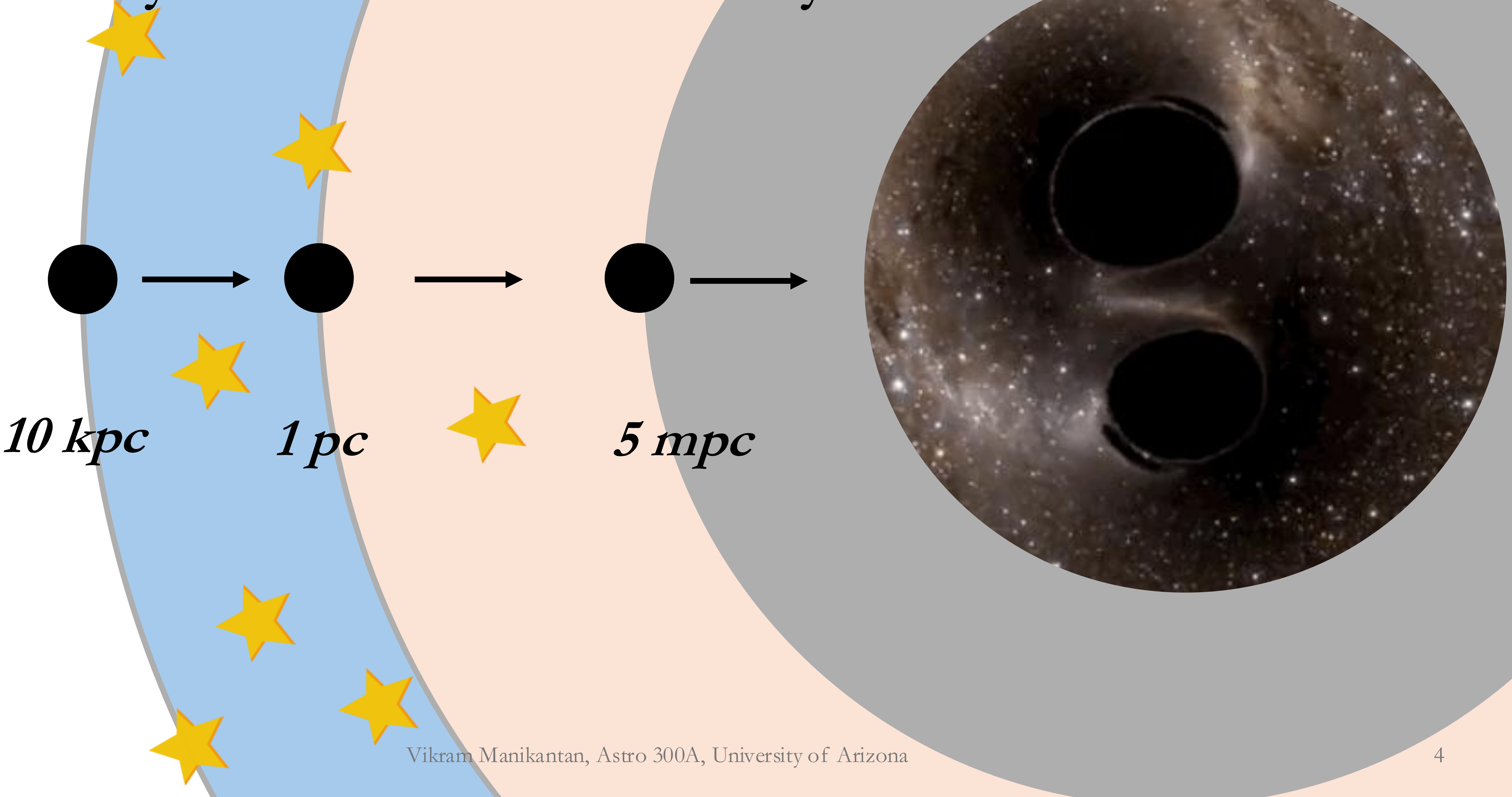
1. Tell you about my research!
2. In-class activity: working with simulated gravitational waveforms



Multiple stages and processes to SMBH inspirals

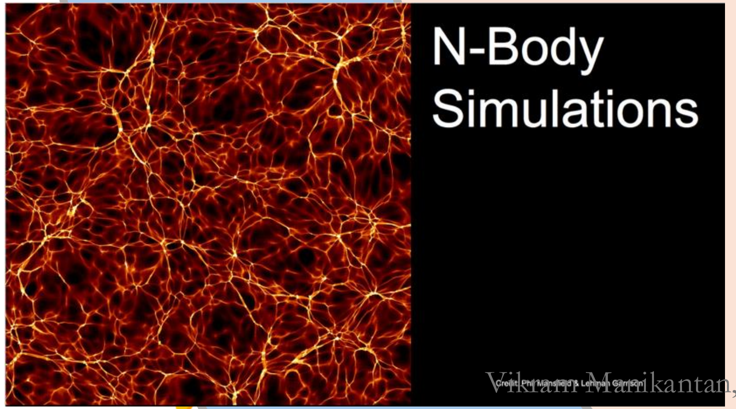


Equations we derived were nice, but how do you simulate these systems?

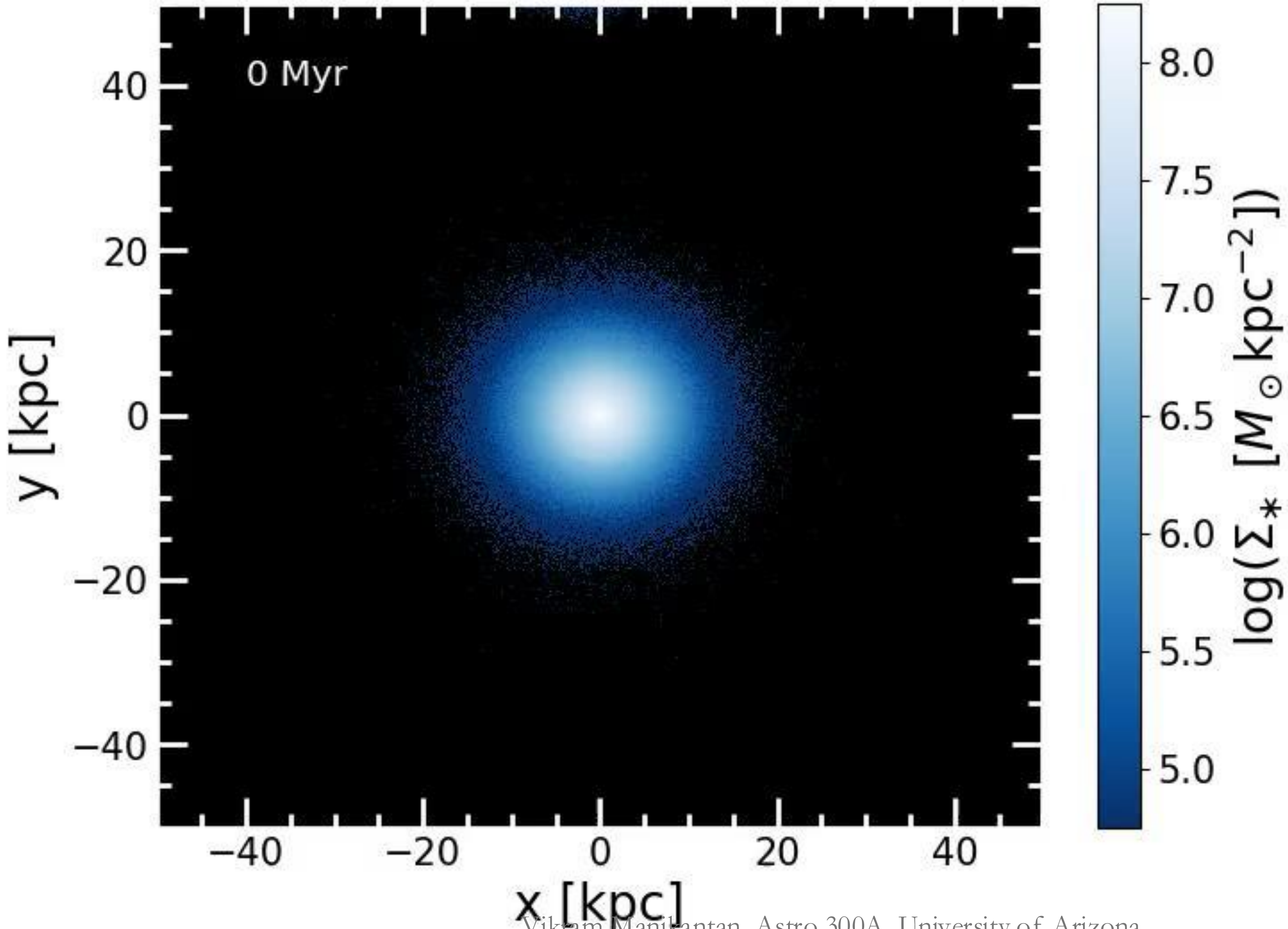


Depends on your length-scale

10 kpc ***1 pc*** ***5 mpc***



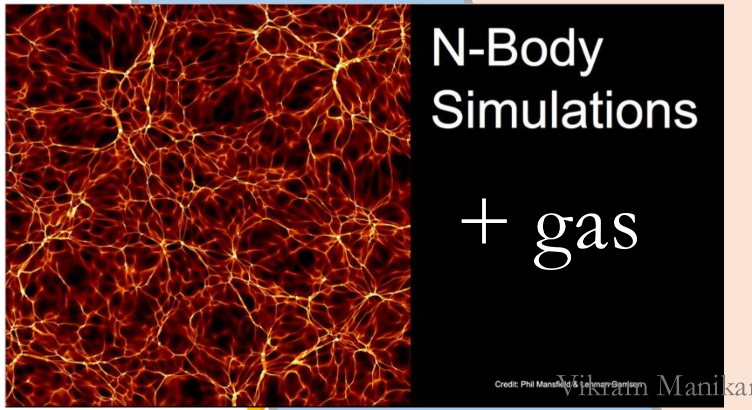
N-body galaxy merger simulations



From Himansh Rathore, 3rd year graduate student working with Prof. Gurtina Besla

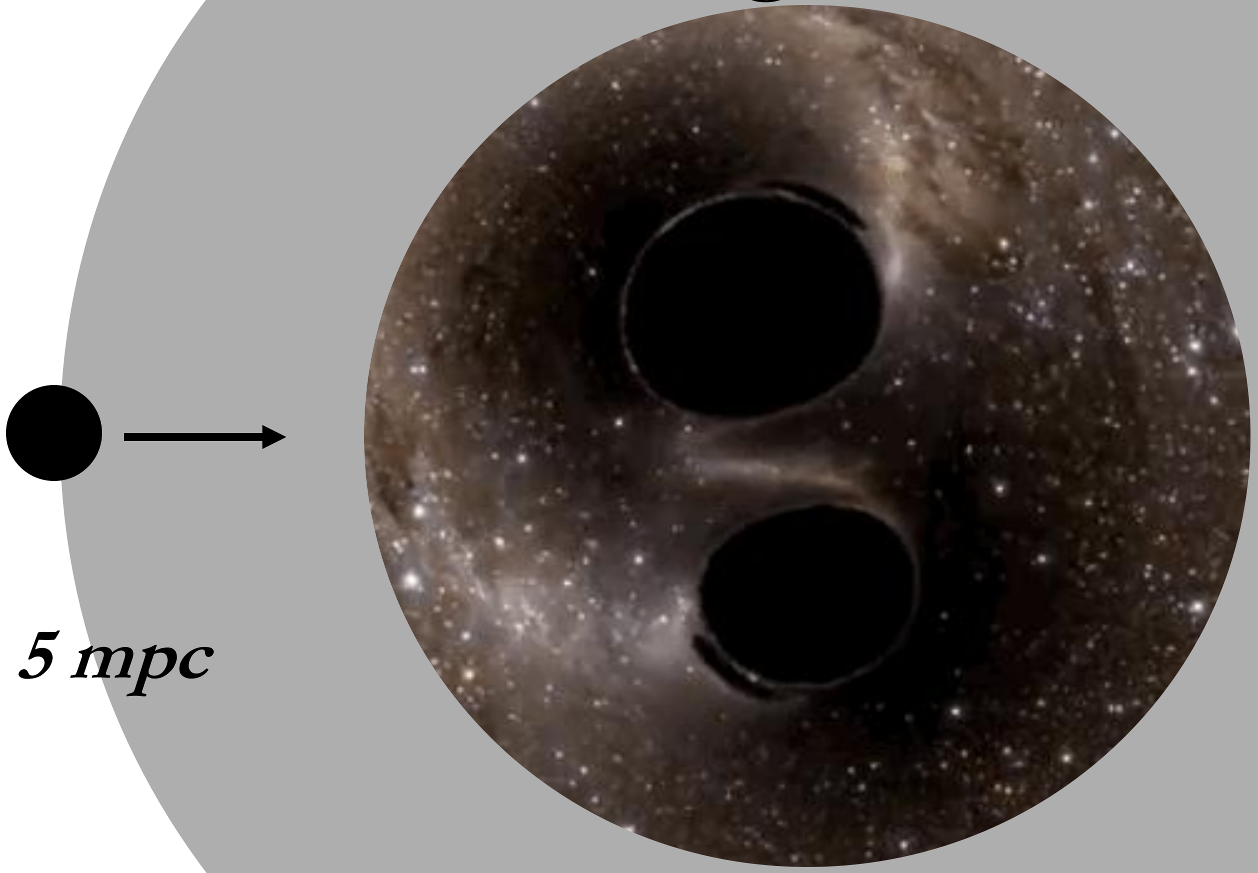
Depends on your length-scale and physics

10 kpc   *1 pc*   *5 mpc*



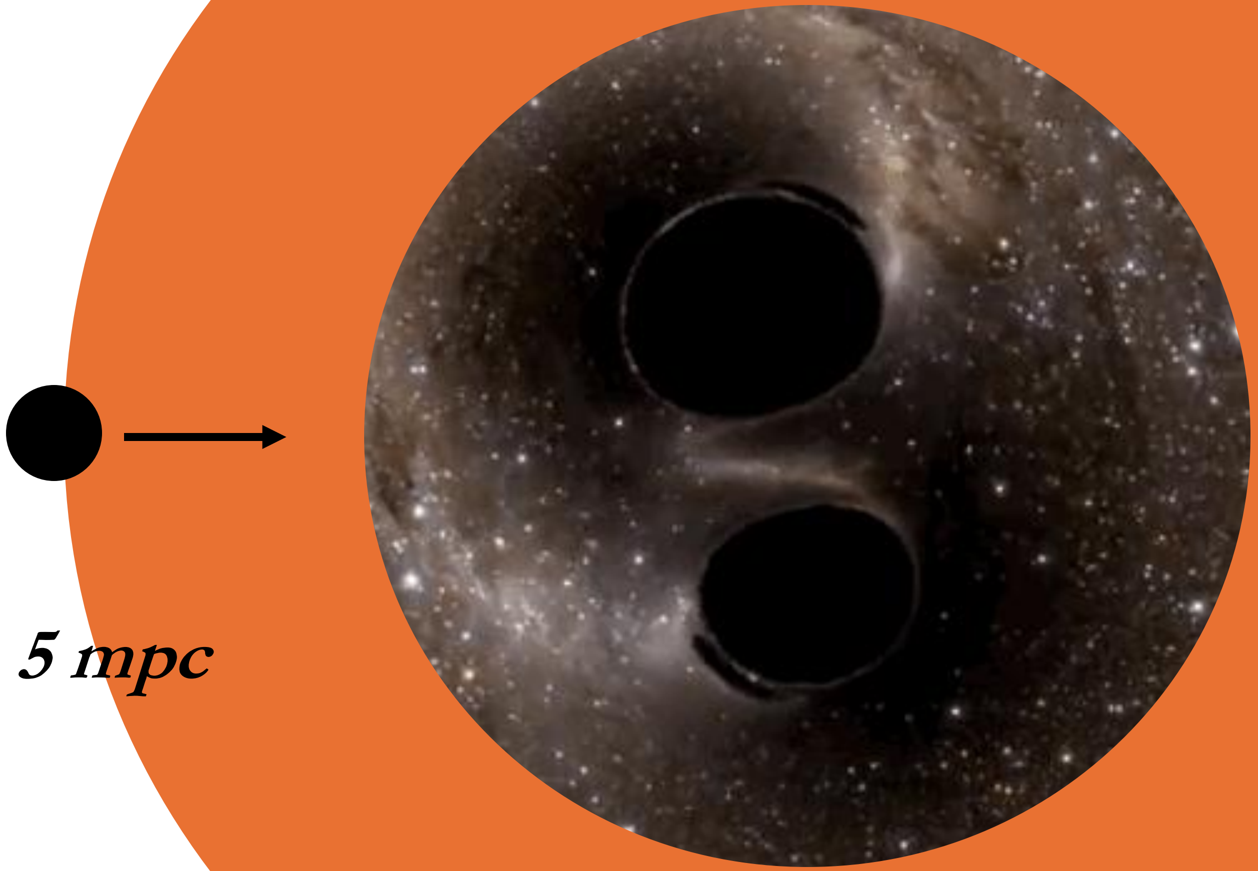
Sub 5mpc, we called the GW-driven regime

- This is where t_0 was less than the Hubble time
- In other words, the effects of gravitational waves were <u>**significant**</u>
- So, we need to consider general relativity (rather than Newtonian gravity)



More than GR, there are also fluids

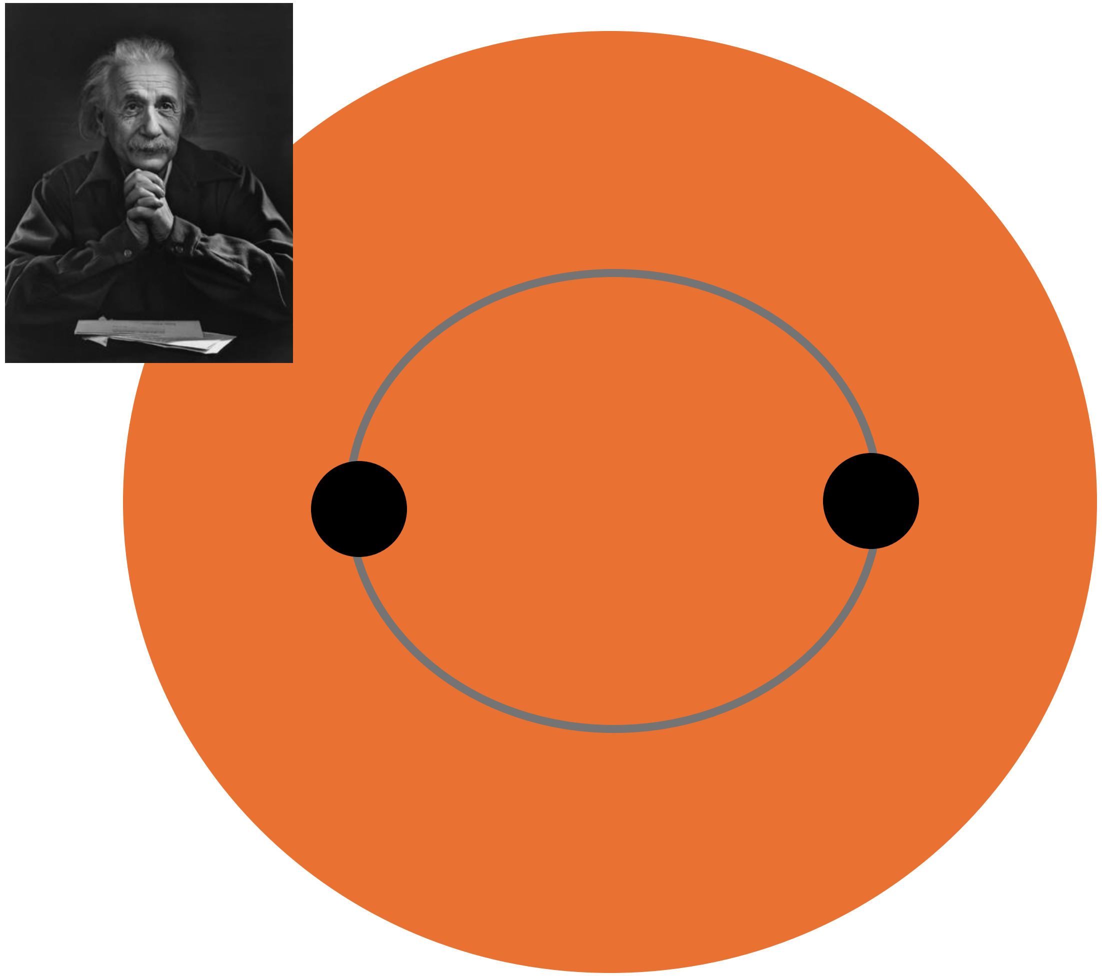
- This is where t_0 was less than the Hubble time
- In other words, the effects of gravitational waves were **<u>significant</u>**
- So, we need to consider general relativity
- But, there is also lots of material hanging around we have to model



Suddenly, it is more complex

- We need general relativity:

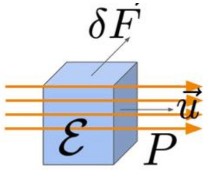
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$



- And, we also need fluid dynamics!

ρ – density
$\vec{u}$ – bulk motion
P – pressure
ε – internal energy density (n, T)

Fluid dynamics



$$\frac{\partial \rho}{\partial t} = -\vec{\nabla} \cdot (\rho \vec{u})$$

$$\frac{\partial \tilde{E}}{\partial t} = -\vec{\nabla} \cdot \left[\vec{u}\left(\tilde{E} + P\right)\right] + \rho \vec{u} \cdot \vec{g} + \Gamma - \Lambda$$

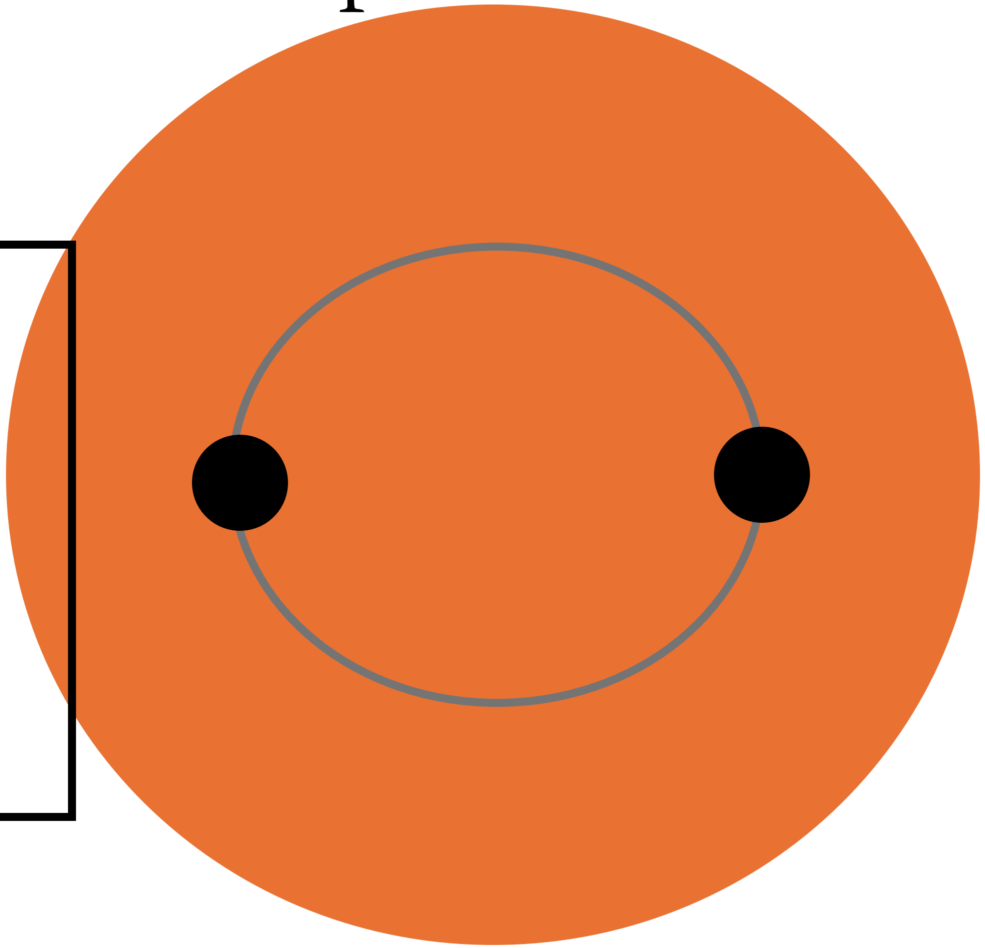
$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \vec{\nabla} \vec{u} = -\frac{\vec{\nabla} P}{\rho} - \vec{\nabla} \Phi$$

$$\mathcal{E} = \frac{3}{2} P \qquad \tilde{E} = \frac{1}{2} \rho u^2 + \mathcal{E}$$

Navier-Stokes Equations
Continuity
Momentum
Energy

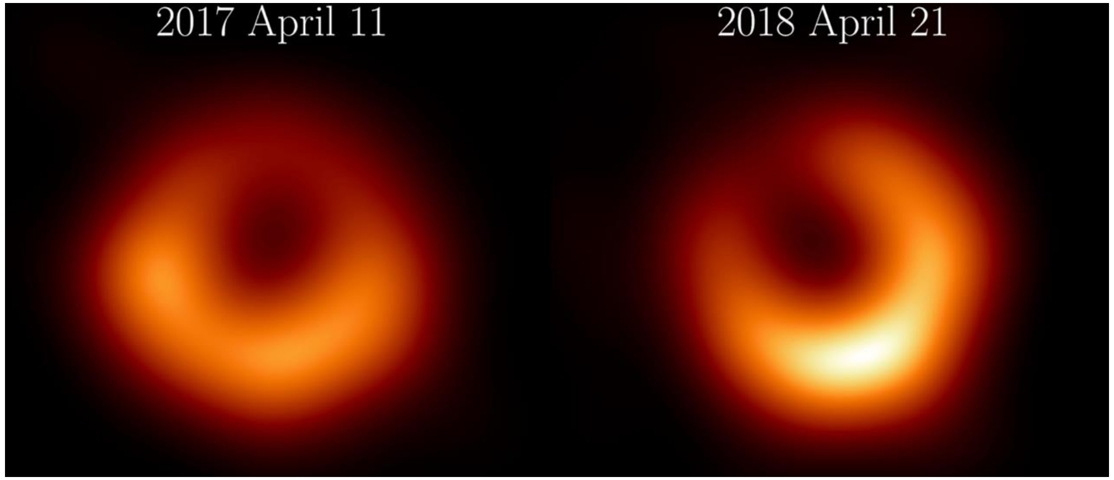
In fact, the picture is so much more complicated!

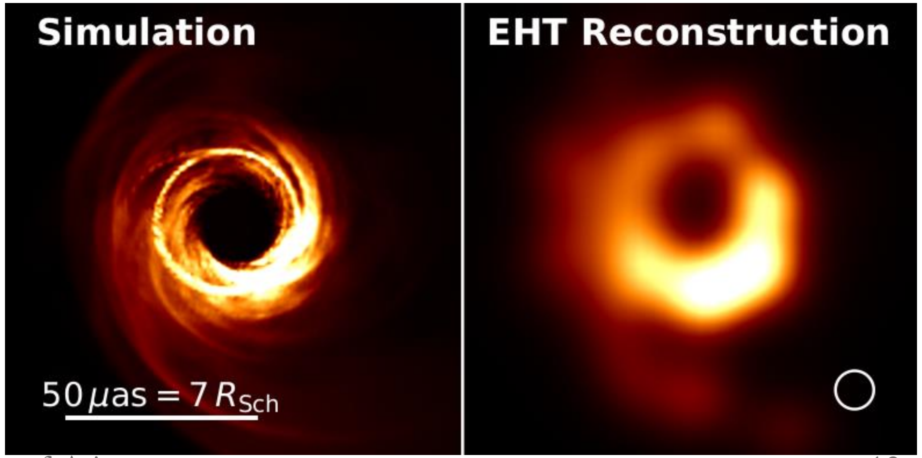
- Self-gravitating N-body simulations
  - Dynamical friction
- Fluid Dynamics
  - Accretion, viscosity, winds
- General relativity
  - Gravitational waves, jets
- Magnetic fields
  - Jets would come from here, viscosity, winds
- Radiation?
  - Photons everywhere! Accretion disks, jets, winds



Simulations can be confirmed and tested now

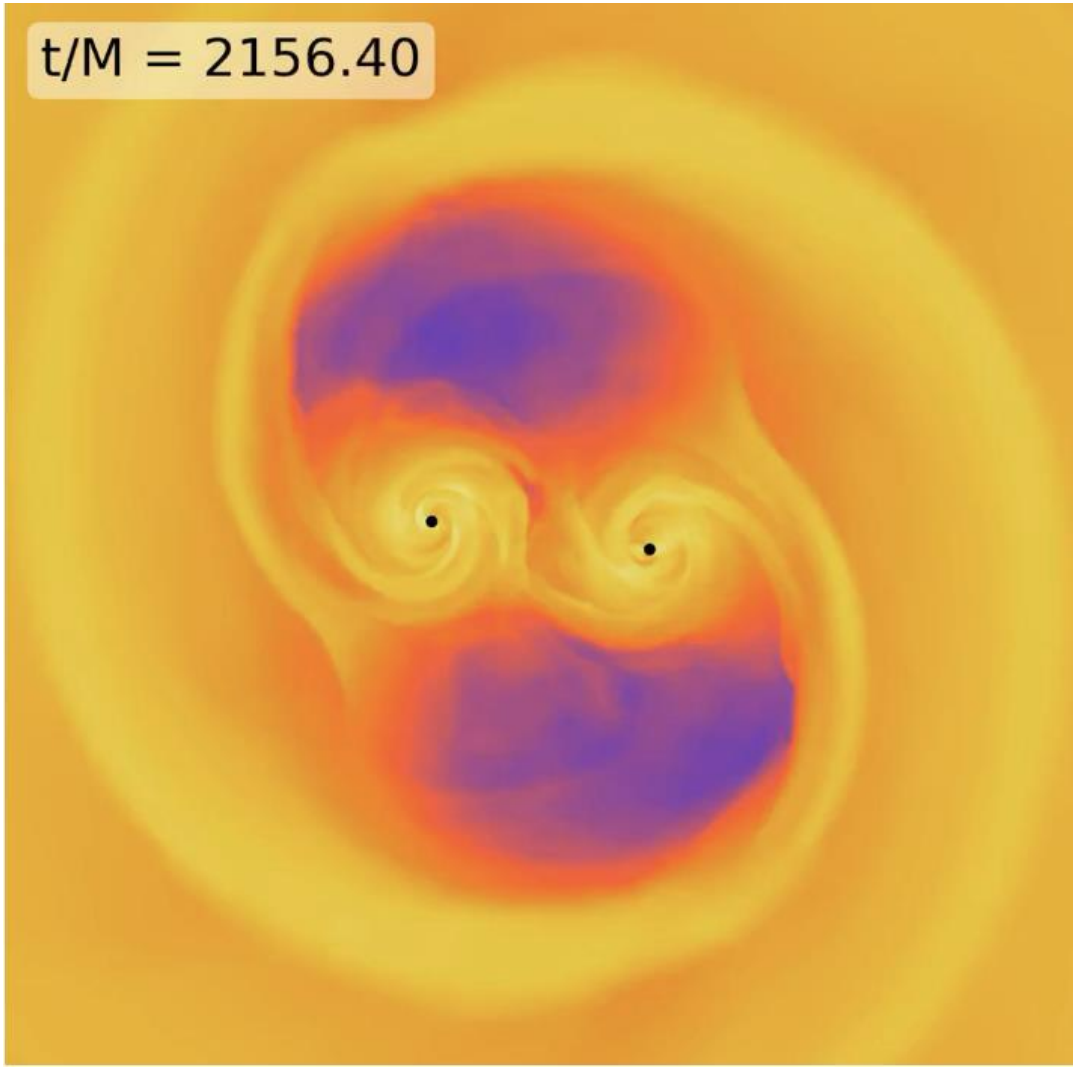
- By modeling GR and fluid dynamics around black holes, we can predict what they will look like
- Simulations reasonably predict the EHT images!
- We can test our simulations and understanding directly





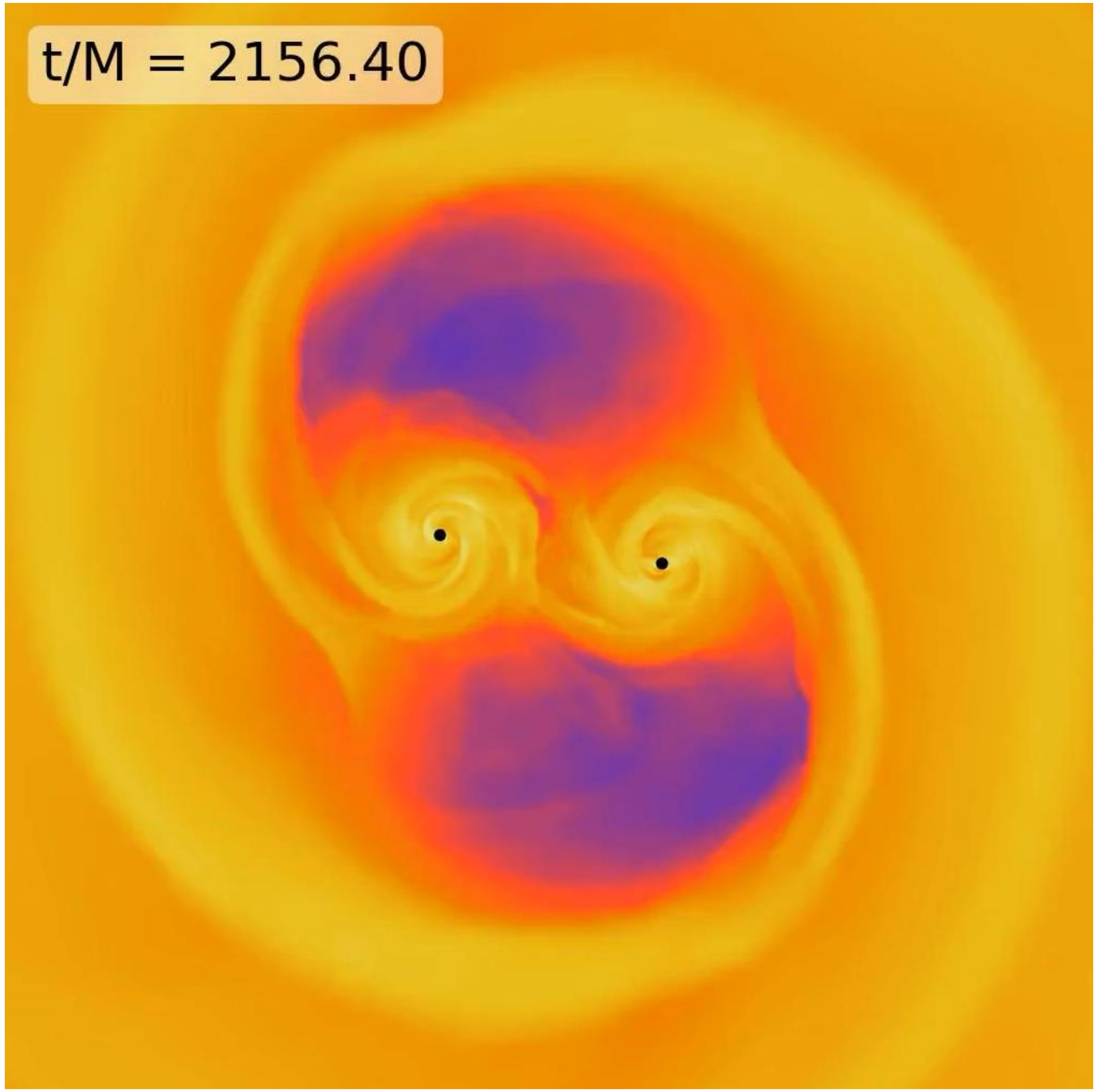
GRMHD Simulations

- We do general-relativistic (GR) magnetohydrodynamic (MHD) simulations of binary black holes
- Very expensive – these simulations take months to run on high-performance computing!



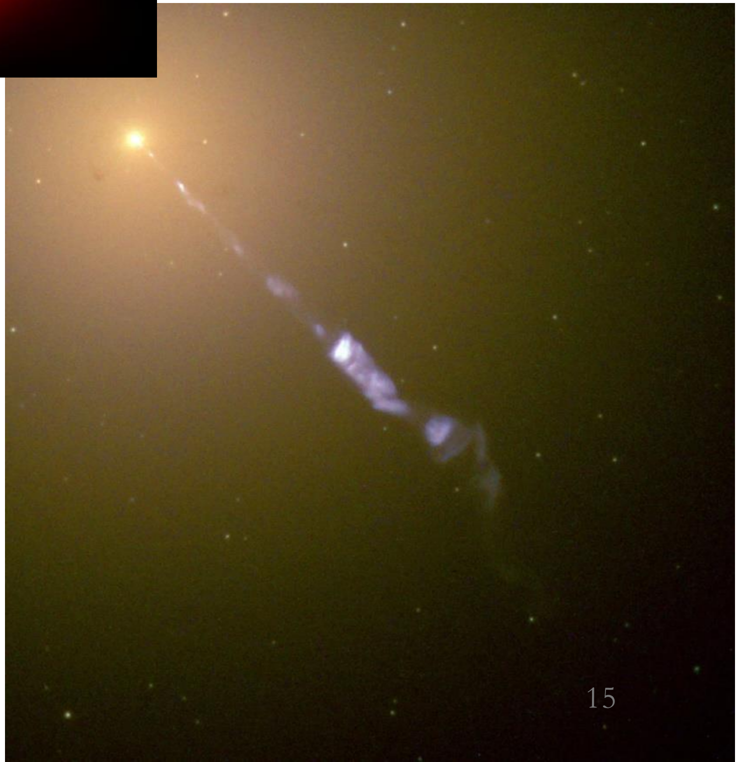
GRMHD Simulations

- We do general-relativistic (GR) magnetohydrodynamic (MHD) simulations of binary black holes
- Very expensive – these simulations take months to run on high-performance computing!
- These are from 'first-principles' (very few assumptions)



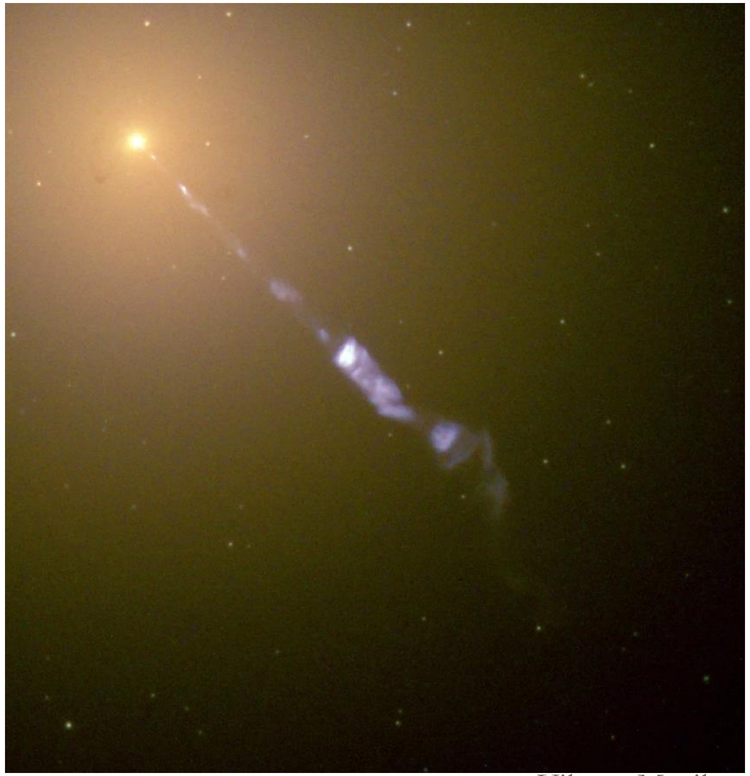
These BHs also launch jets

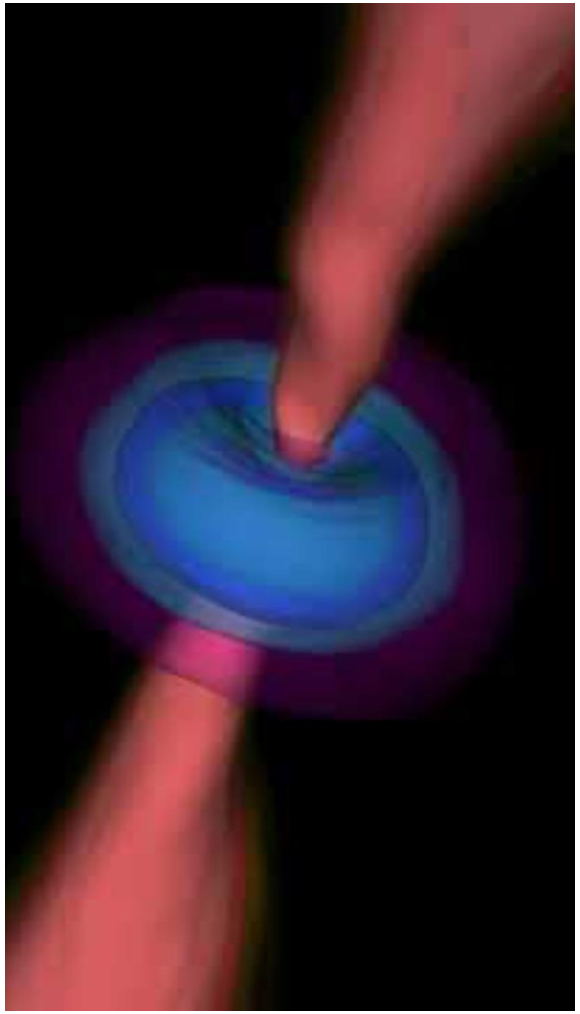
- Sometimes known as blazars, quasars, or active galactic nuclei
- These are galactic-scale jets (many kpc) that are powered by black holes (maybe few AU)
- How do they create these outflows?



BHs + magnetic fields launch jets!

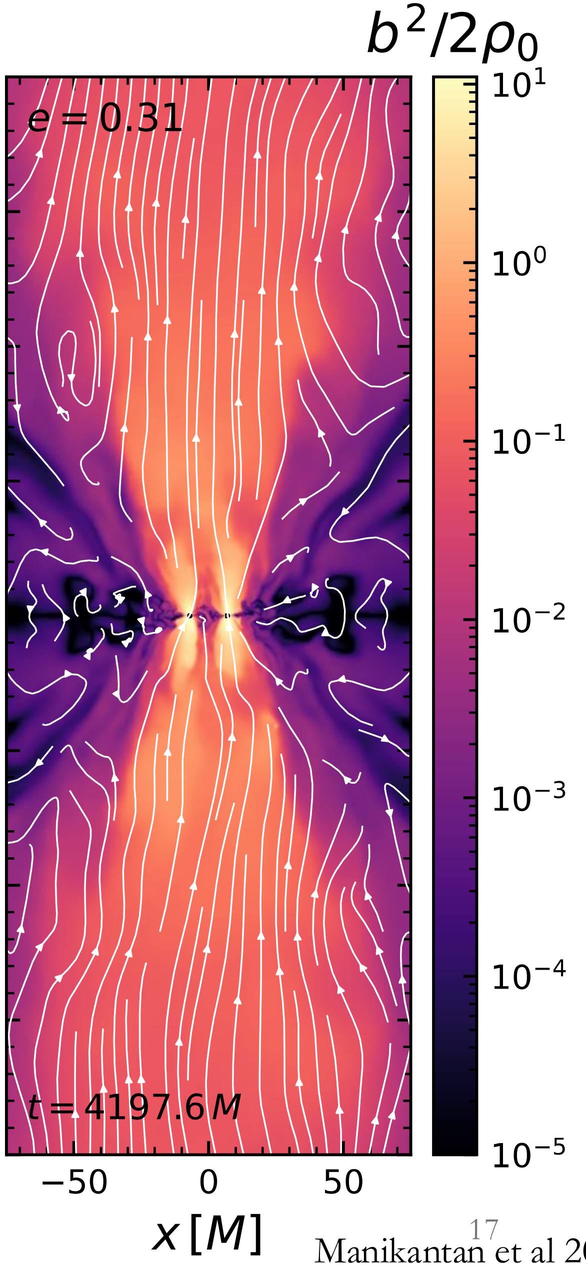
- When you combine BHs and magnetic fields, they launch jets!





BBHs + magnetic fields launch jets

- And so do our binary black hole simulations!
- Magnetic fields are very strong near the black hole
- And these help launch relativistic outflows



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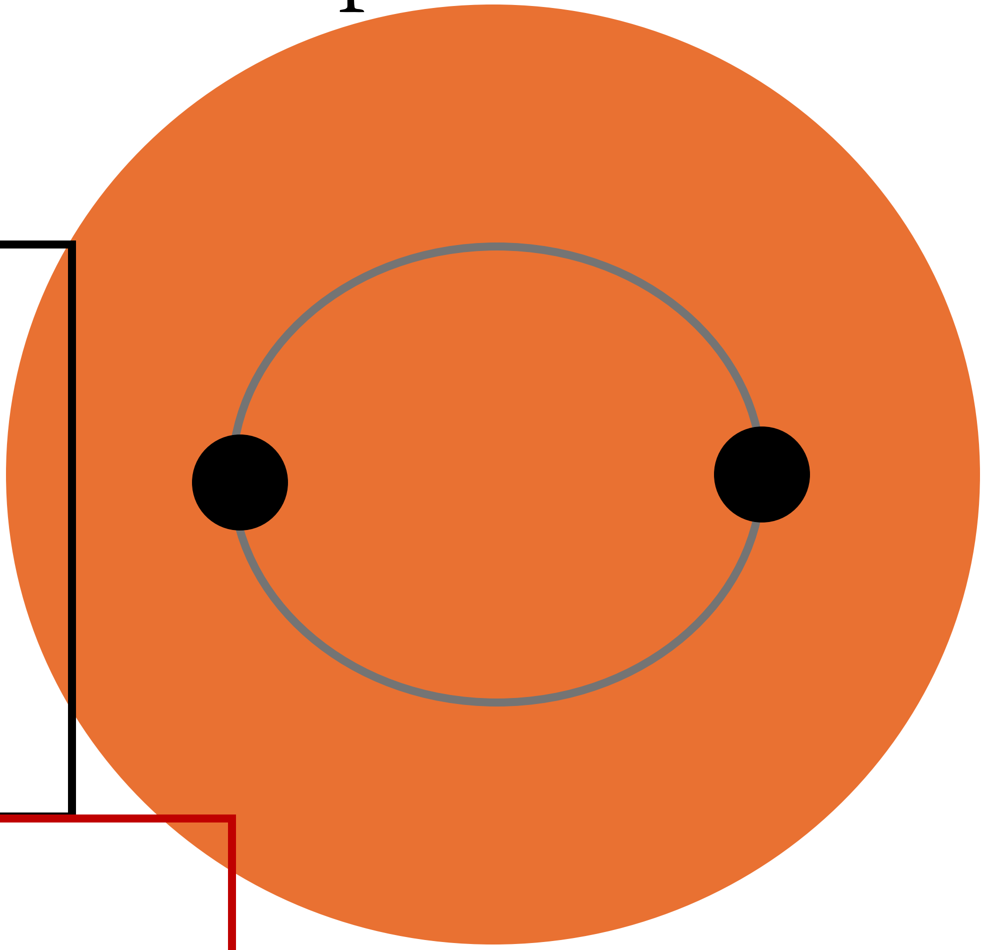

Predicting electromagnetic emission

- Using radiative transfer, I can predict what photons will be emitted and reabsorbed
- Calculate this for the entire simulation
- Predict how luminous our system is

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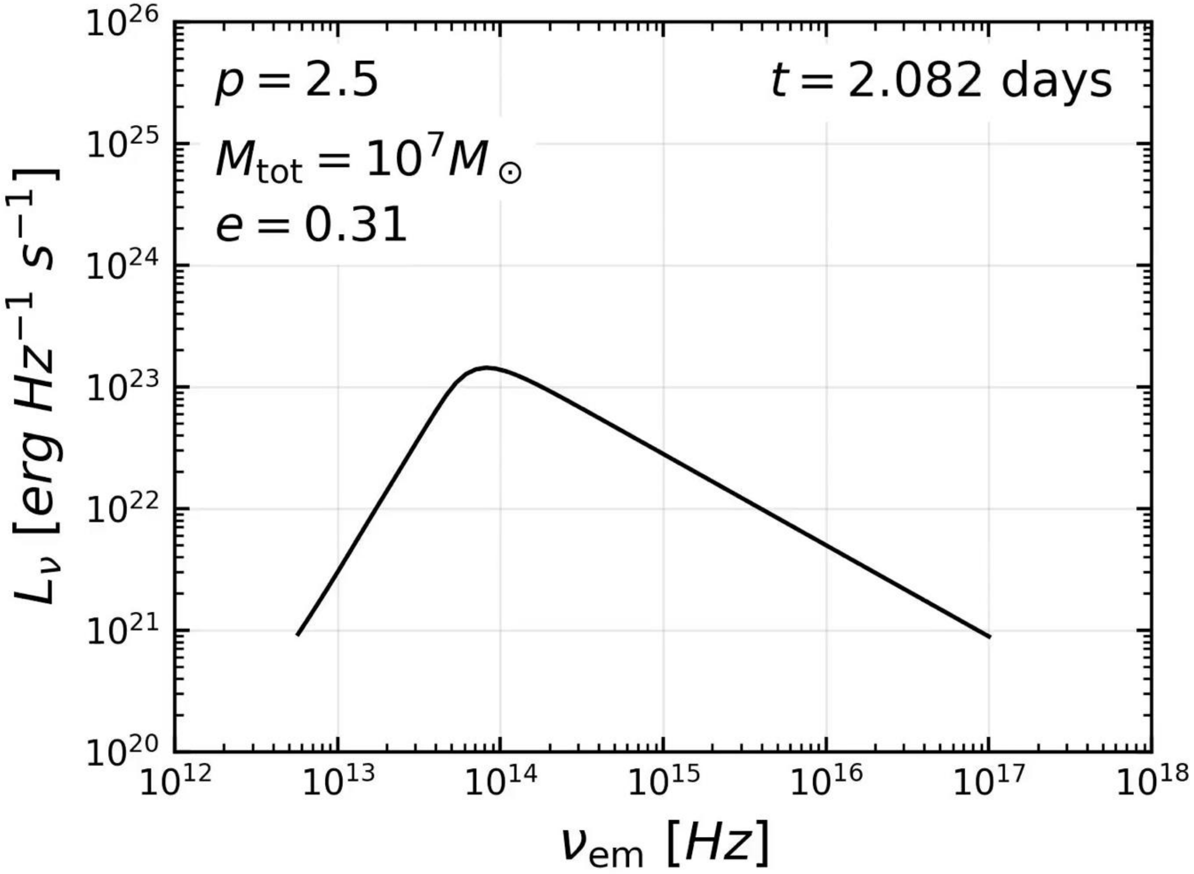
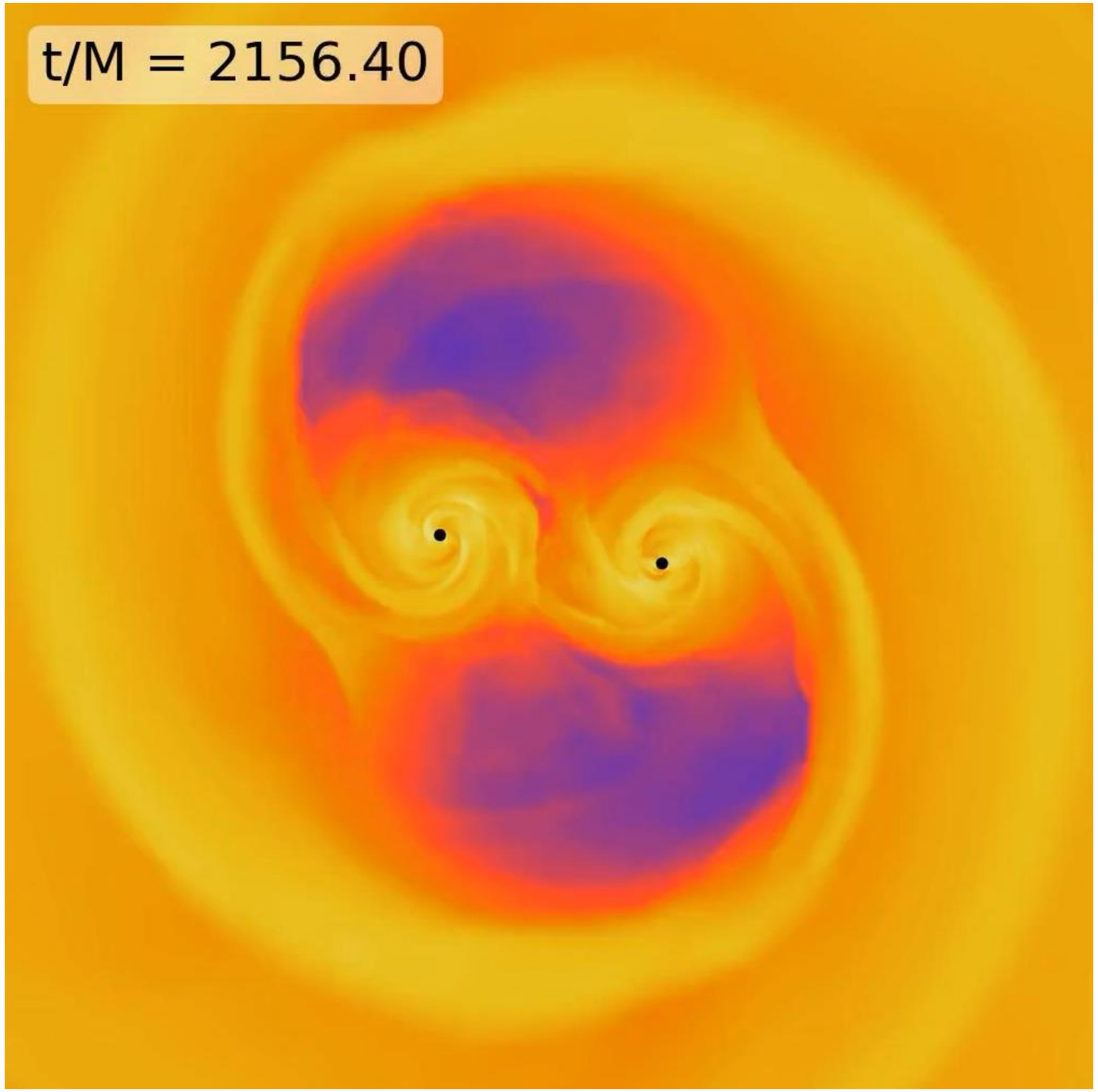


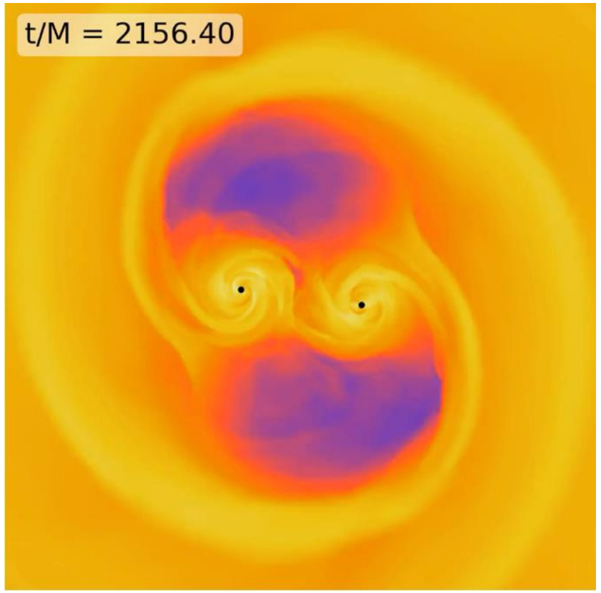
Research summary

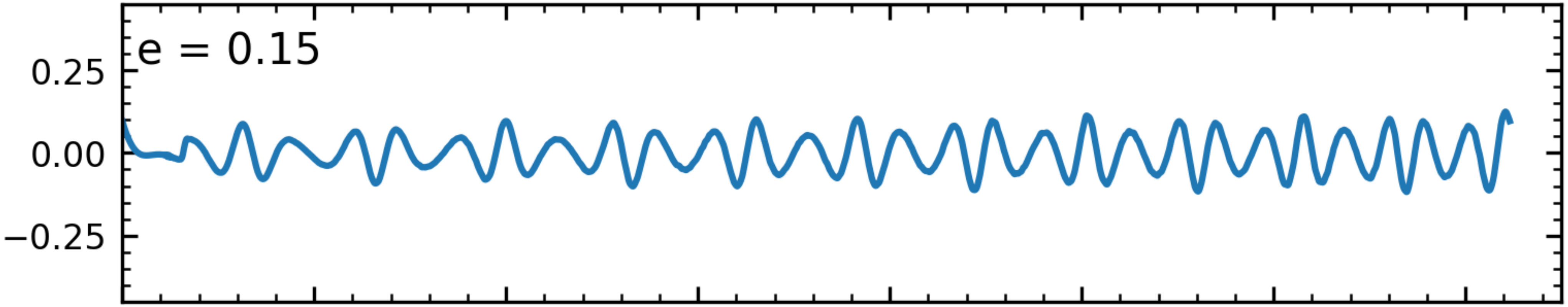
- Use GR and MHD simulations to predict the accretion flow around binary black holes
- Accretion produces emission in the X-ray and UV
- Jets can produce emission in radio, infrared, optical, X-ray and Gamma-ray

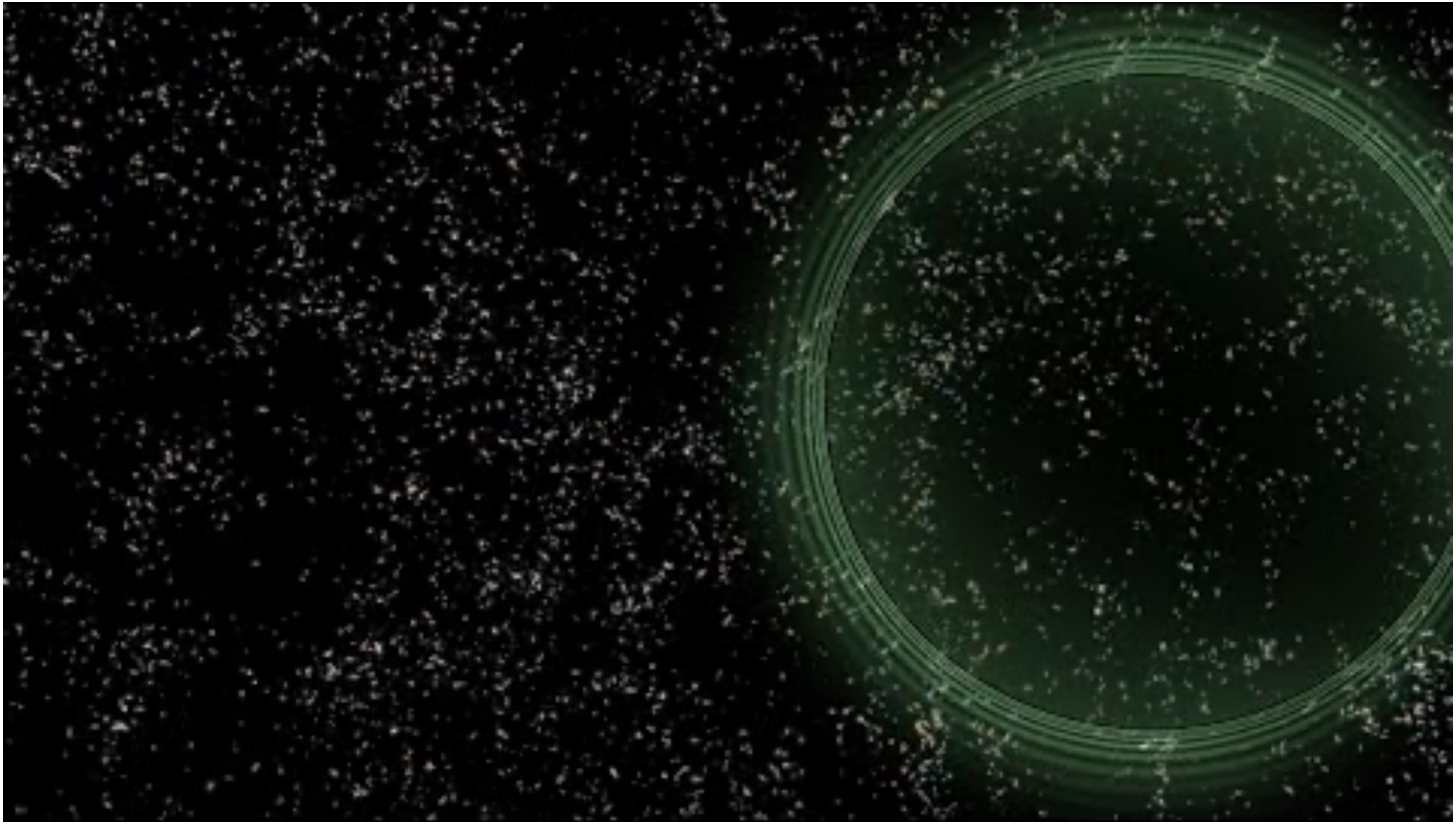


Gravitational Waves

- Our simulations also produce gravitational waves!
- Because we solve for Einstein's equations of general relativity



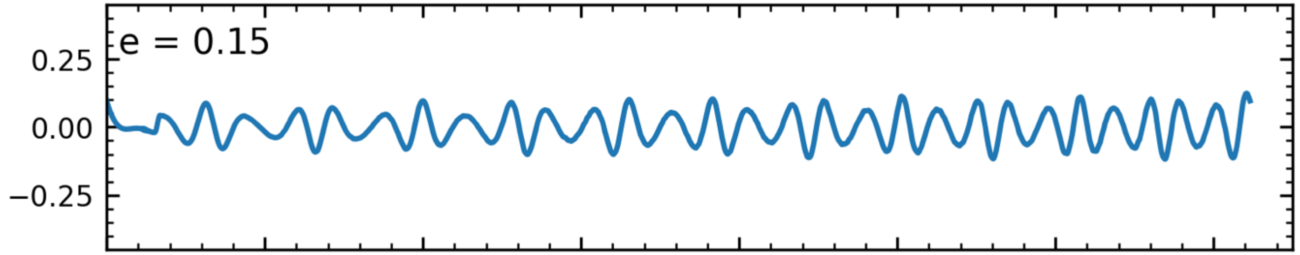




In-class Assignment: Gravitational Waves

- Let's play with some gravitational wave data!
- All the instructions should be in the d2L
- Let me show you the code we will be using…

$$t_0 = \frac{5}{256}\frac{c^5}{\mu M_1 M_2 G^3} a_0^4$$



Question: What is the actual merger timescale?