

Title: PSI 2018/2019 - Strong Field Gravity - Lecture 15

Speakers: William East

Collection: PSI 2018/2019 - Strong Field Gravity (East)

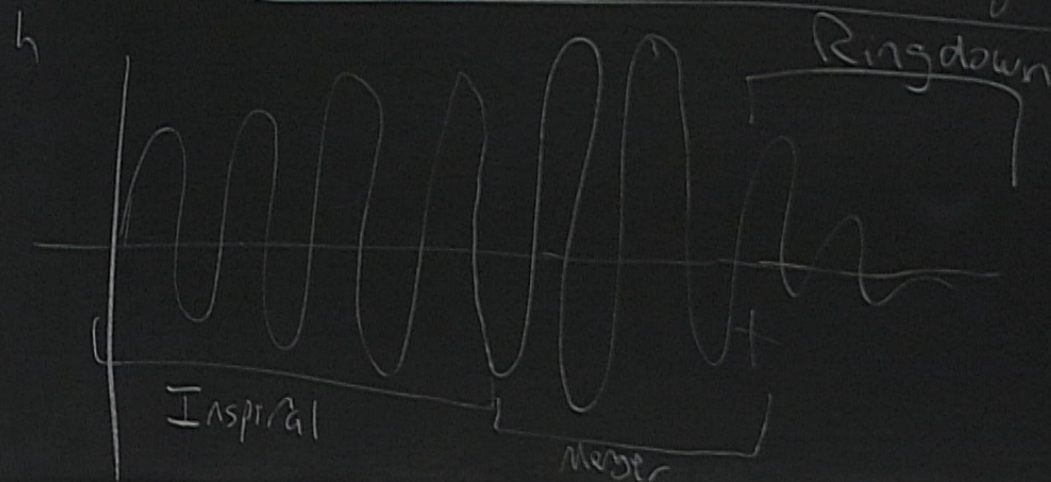
Date: March 22, 2019 - 9:00 AM

URL: <http://pirsa.org/19030022>

Binary black hole mergers

$$R_{\text{as}} = 0$$

Combine different techniques



Inspiral : Post-Newtonian expansion

Merger : Numerical Relativity

Ringdown : black hole perturb.

on Post Newtonian

Expand Ein. Eq.

From Vir. Theor: $\left(\frac{v}{c}\right)^2 \sim \frac{M}{r} \sim \epsilon$

#PN means up to $\epsilon^{\#}$

For 2-body motion

$$\frac{d\vec{v}}{dt} = \frac{GM}{r^2} \left[-\hat{n} + \frac{1}{c^2} \vec{A}_{1PN} + \frac{1}{c^4} \vec{A}_{2PN} + \frac{1}{c^5} \vec{A}_{2.5PN} + \dots \right]$$

leading order radiation reaction

$$\vec{A}_{1PN} = \left[(4+2\mu) \frac{GM}{r} - (1+3\mu)v^2 + \frac{3}{2} \mu \dot{r}^2 \right] \hat{n} + (4-2\mu) \dot{r} \vec{v}$$

$$\mu = \frac{m_1 m_2}{M}$$

Leading order : $\dot{f} = \frac{192\pi}{5} f^2 \left(\frac{2\pi G M f}{c^3} \right)^{5/3} M = \mu^{3/5} M$

Merger : Need full solutions - compute numerical

- Well posed formulation of EFEs (Gen)
- Control constraint violating modes (constraint
- Good ID
- Resolution of disparate length scales

numerically

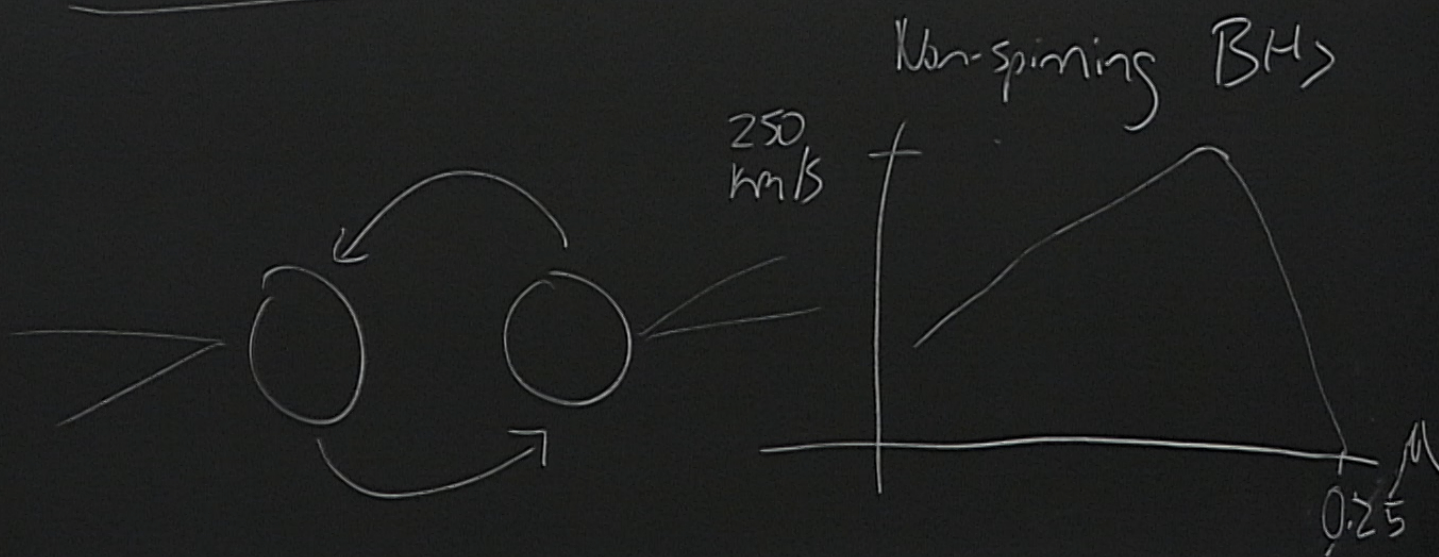
- Handling black hole singularities
(excision, punctures)

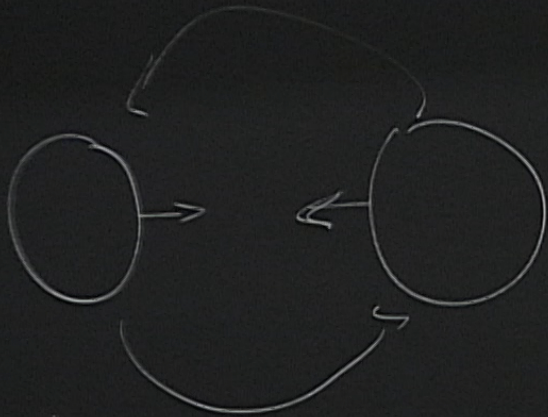
(Gen. harmonic, Z4, BSSN, ...)

(constraint damping, ...)

$$r_{\text{BH}} \ll R_{\text{orig}} \ll r_{\text{obs}}$$

- Handling black hole singularities
(excision, punctures)





"Super-kick"

$$v_{\text{recoil}} \sim 4000 \text{ km/s}$$

Frameworks to Combine/interpolate:

- Effective One Body (EOB)
- Phen Waveforms
- Machine Learning

Binary NS mergers

Relativistic Euler Eqs:

$$\nabla_a(\rho_0 u^a) = 0$$

$$\nabla_a T^{ab} = 0$$

$$T_{ab} = (\rho + p) u_a u_b + p g_{ab}$$

$$\rho = \rho_0 (1 + \epsilon)$$

Euler Eqns: $\nabla_a(\rho_0 u^a) = 0$ $T_{ab} = (\rho + P)u_a u_b + P g_{ab}$

$\nabla_a T^{ab} = 0$ $\rho = \rho_0(1 + \epsilon)$

6 vars: ρ_0, ϵ, P, v^i

5 Eqns.

$$(\rho + P)u_a u_b + P g_{ab}$$

$$\rho = \rho_0 (1 + \epsilon)$$

Equation of State:

$$P(\rho_0, \epsilon)$$

$$\rho \sim 10^{15} \text{ g/cm}^3$$

Phase $\Psi(f) = \frac{3}{128(\pi M f)^{5/2}} \left[1 + \alpha_{1PN} X + \dots + (\alpha_{5PN} + \alpha_{tidal}) X^5 \right]$

$X = (\pi M f)^{2/3}$

$$Q_{ab} = -\Lambda M^5 \epsilon_{ab}$$

$$\alpha_{tidal} = -24 \left[\left(1 + 12 \frac{m_1}{m_2} \right) \Lambda_1 + (1 \leftrightarrow 2) \right]$$

Λ tidal deform parameter

$$\sim \left(\frac{R}{M} \right)^5$$

$$\left[1 + \alpha_{\text{spN}} X + \dots + (\alpha_{\text{spN}} + \alpha_{\text{tide}}) X^5 + \dots \right]$$

$$X = (\pi M f)^{2/3}$$

$$\left[\left(1 + 12 \frac{M_1}{M_2} \right) \Lambda_1 + (1 \leftrightarrow 2) \right]$$

tidal deform parameter

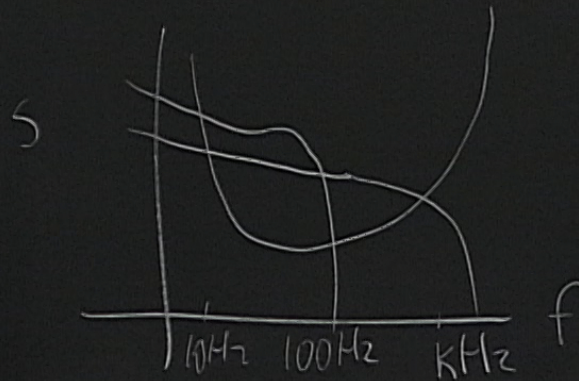
$$C = \frac{M}{R} \sim 0.15 - 0.2$$

$$\begin{aligned} \text{c.f. BH} &\sim 0.5 \\ &= 0.17 \left(\frac{M / 1.4 M_\odot}{R / 12 \text{ km}} \right) \end{aligned}$$

Phase $\Psi(f) = \frac{3}{128(\pi M F)^{5/2}} \left[1 + \alpha \right]$

$X =$

$$Q_{ab} = -\Lambda M^5 \epsilon_{ab}$$



$$\alpha_{\text{tide}} = -24 \left[\left(1 + 12 \frac{m_1}{m_2} \right) \right]$$

$\propto$ tidal deform
 $\sim \left(\frac{R}{m} \right)^5$

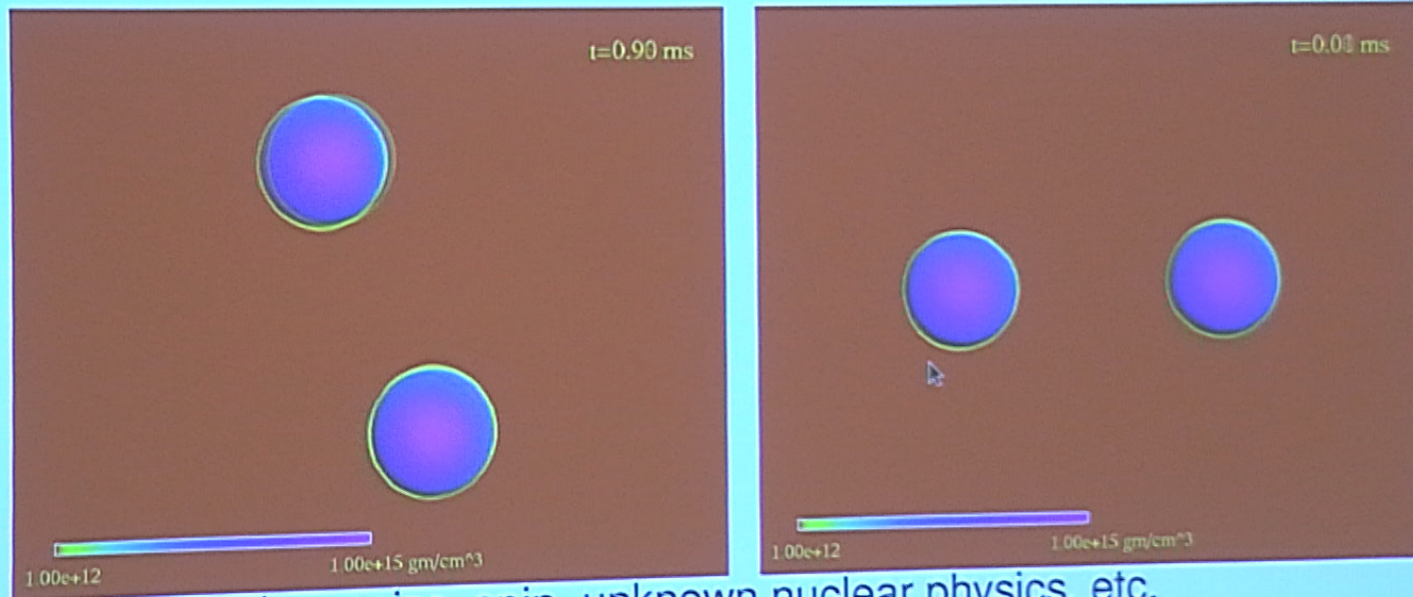
State:

- Magnetic fields
- Radian transport

ϵ)

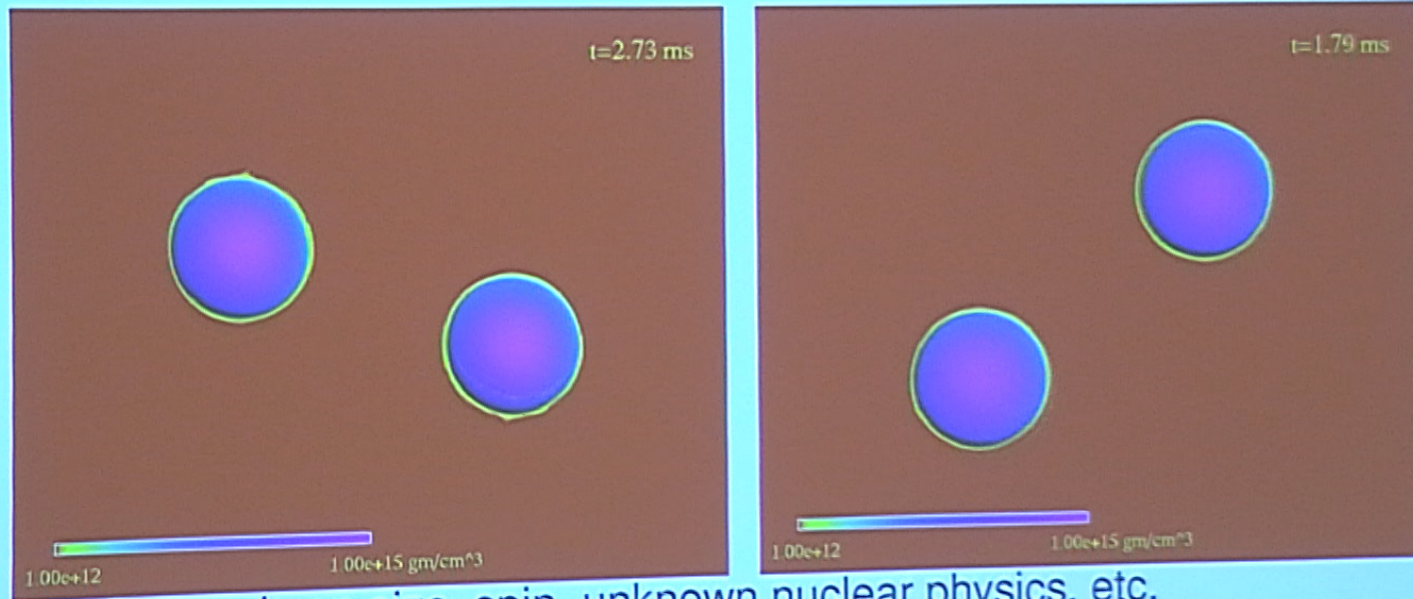
cm^3

Collapse to black hole versus forming a hypermassive neutron star



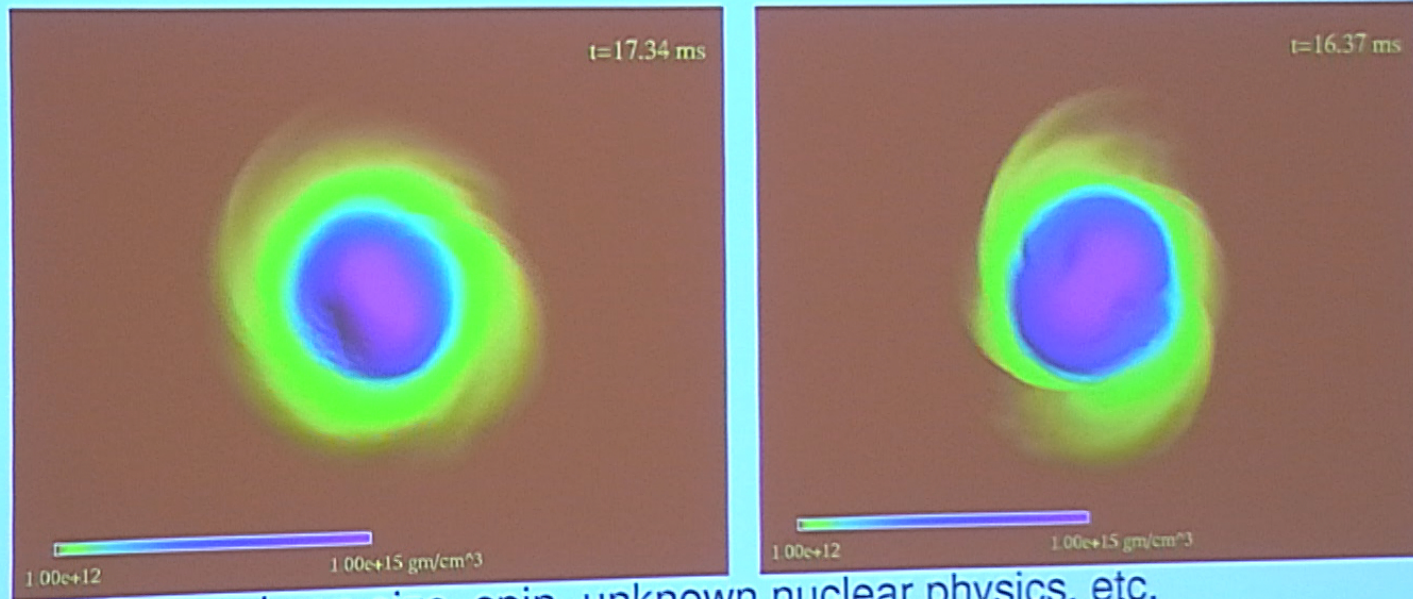
Depends on size, spin, unknown nuclear physics, etc.

Collapse to black hole versus forming a hypermassive neutron star



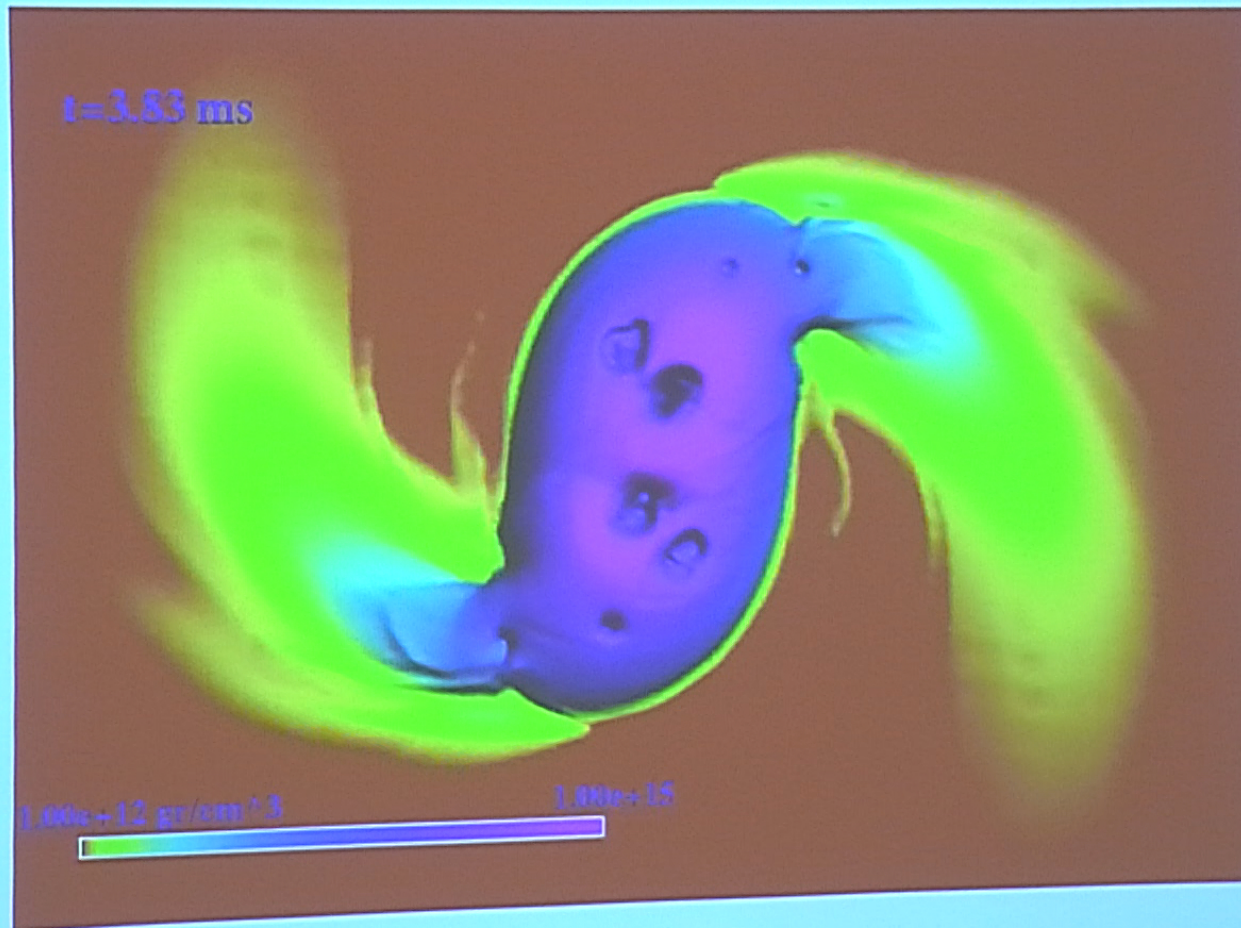
Depends on size, spin, unknown nuclear physics, etc.

Collapse to black hole versus forming a hypermassive neutron star



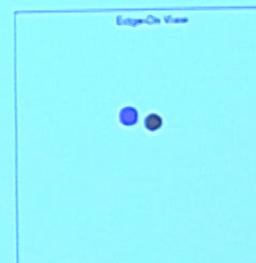
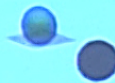
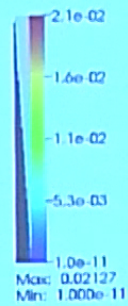
Depends on size, spin, unknown nuclear physics, etc.

Neutron stars merge



Black hole–neutron star merger

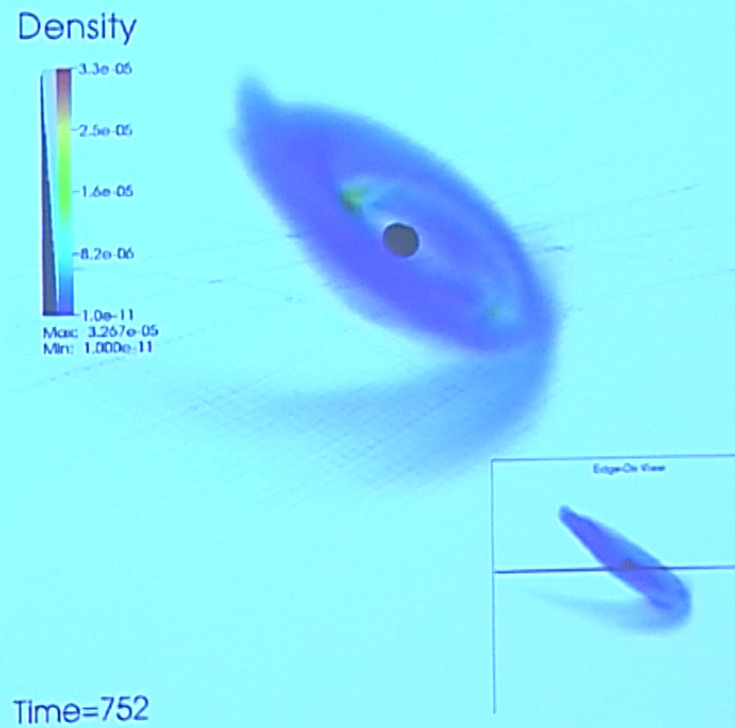
Density



Time=158

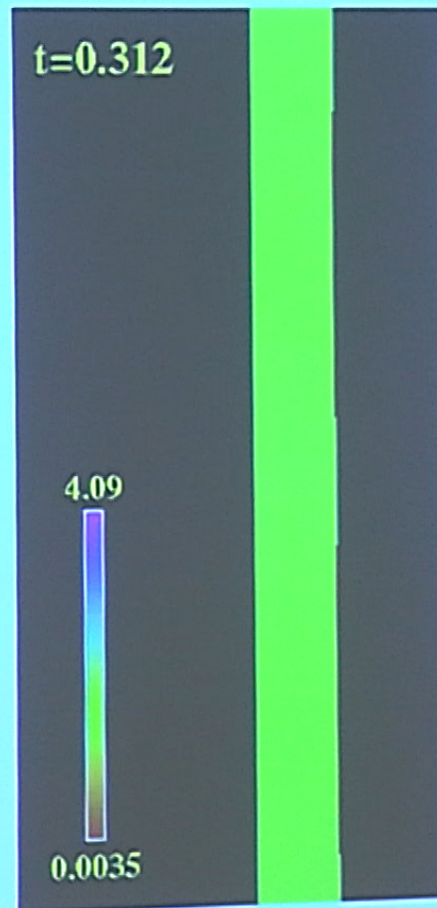
SXS Collaboration

Black hole–neutron star merger



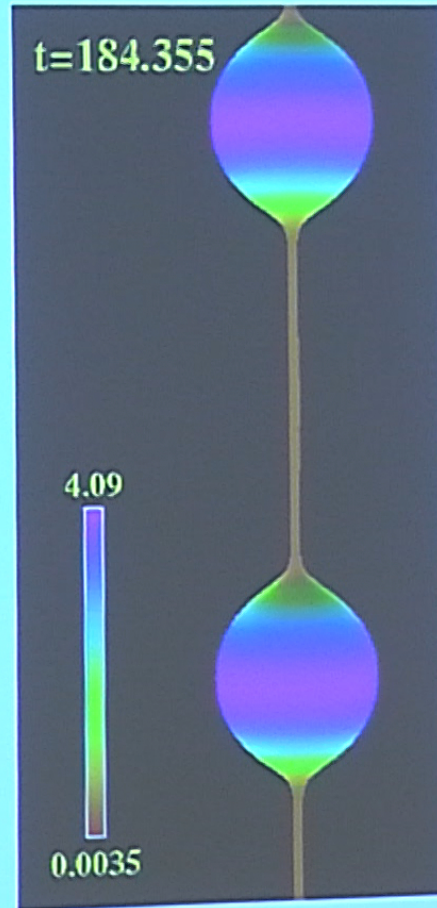
SXS Collaboration

Instability of black string



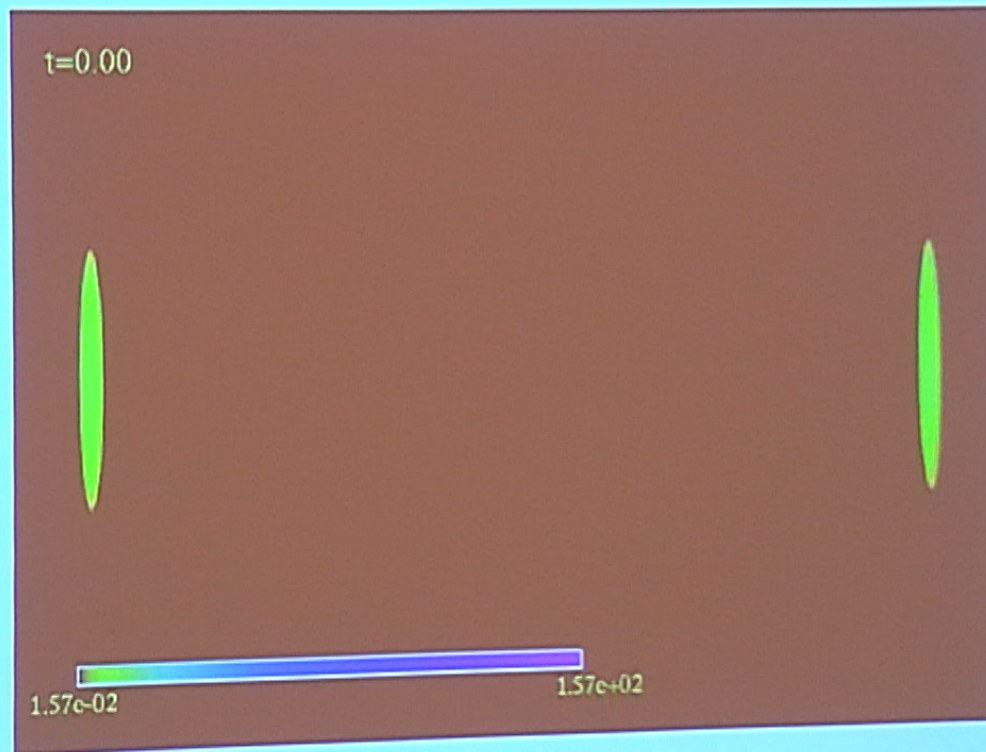
Lehner & Pretorius (2010)

Instability of black string

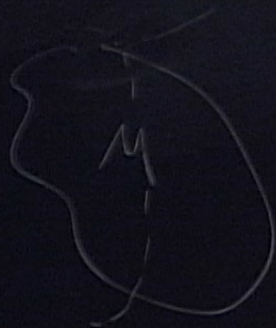


Lehner & Pretorius (2010)

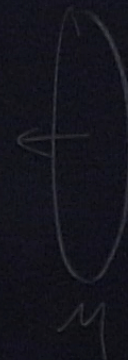
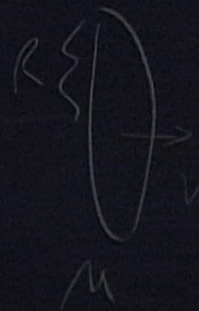
When do black holes form from ultrarelativistic collisions?



East & Pretorius (2013)

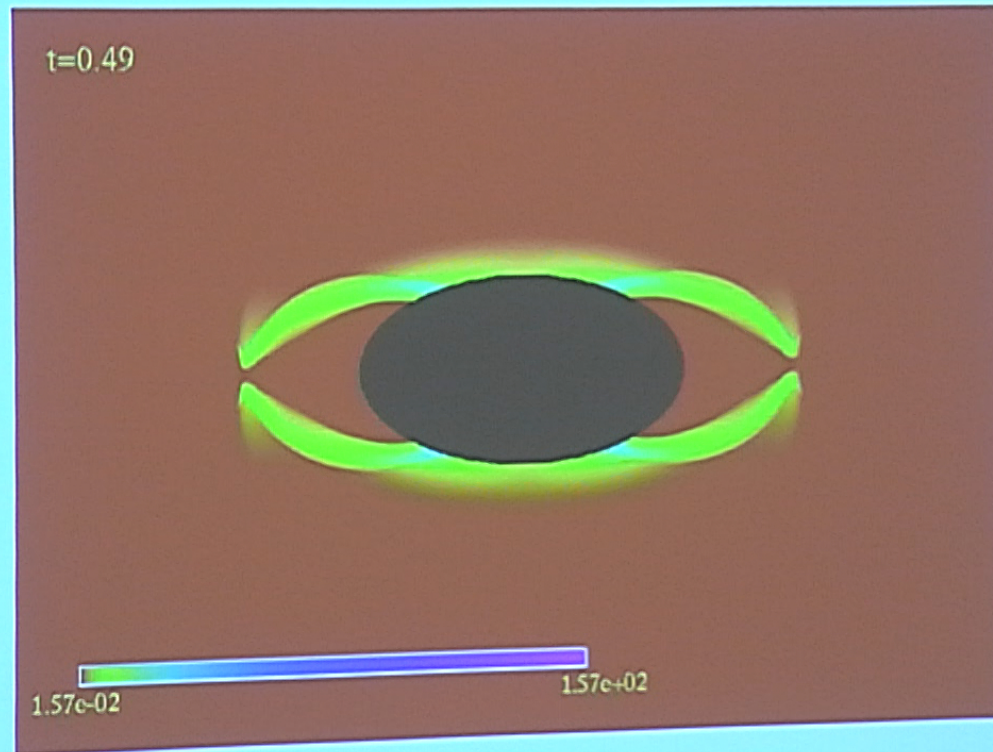


$$C_{\text{hor}} \leq 4\pi M$$



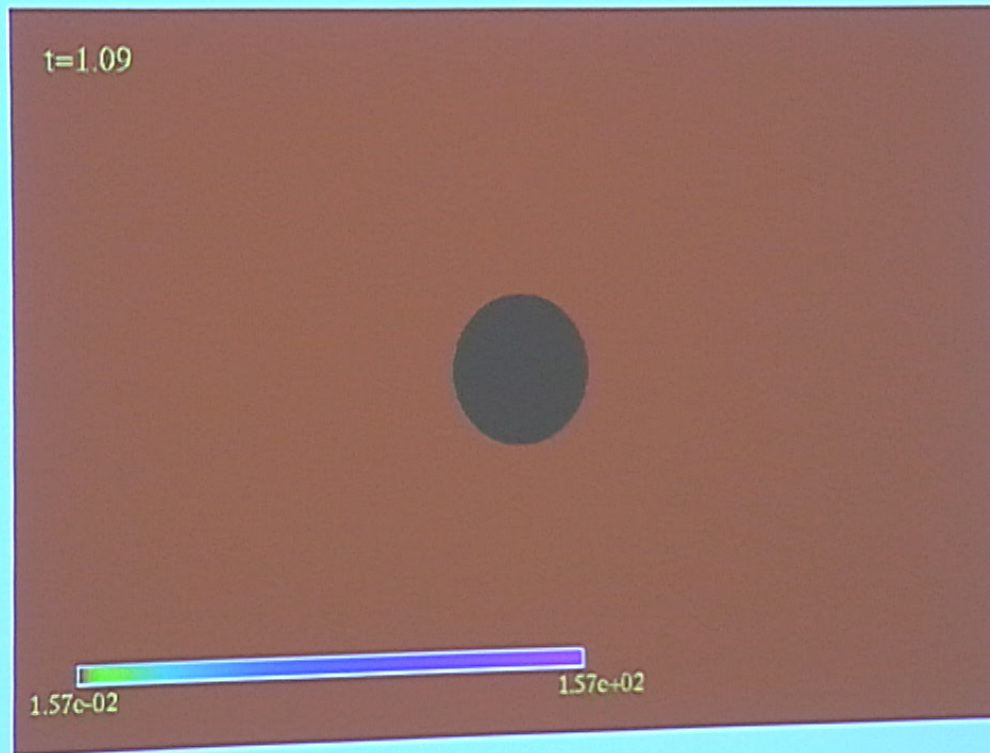
$$\frac{E}{R} = \frac{28M}{R} \sim \frac{1}{2}$$

When do black holes form from ultrarelativistic collisions?



East & Pretorius (2013)

When do black holes form from ultrarelativistic collisions?



East & Pretorius (2013)

