Universality and wave absorption in high-energy collisions of spinning black holes

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Overview

- Motivation
- Setup
- Results
- Conclusions and outlook

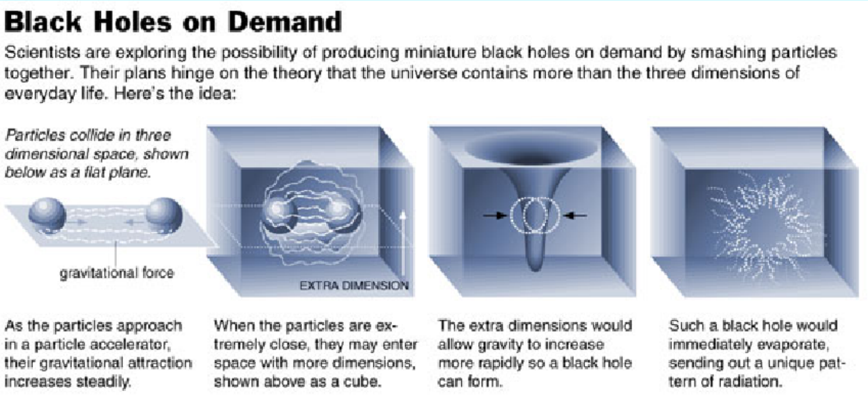
The Hierarchy Problem of Physics

- Gravity $\approx 10^{-39} \times$ other forces
- Higgs field $\approx \mu_{obs} \approx 250\ GeV = \sqrt{\mu^2 - \Lambda^2}$

  where $\Lambda \approx 10^{16}\ GeV$ is the grand unification energy
- Requires enormous finetuning!!!
- Finetuning exist: $\frac{987654321}{123456789} = 8.0000000729$
- Or E_{Planck} much lower? Gravity strong at small r?

  $\Rightarrow$ BH formation in high-energy collisions at LHC
- Gravity not measured below 0.16 mm! Diluted due to...
  - Large extra dimensions   Arkani-Hamed, Dimopoulos & Dvali '98
  - Extra dimension with warp factor   Randall & Sundrum '99

Motivation (High-energy physics)



- Matter does not matter at energies well above the Planck scale

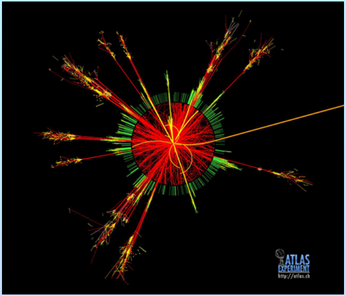
  ⇒ Model particle collisions by black-hole collisions

  Banks & Fischler ’99; Giddings & Thomas ’01

Experimental signature at the LHC

Black hole formation at the LHC could be detected by the properties of the jets resulting from Hawking radiation.

- Multiplicity of partons: Number of jets and leptons
- Large transverse energy
- Black-hole mass and spin are important for this!



ToDo:

- Exact cross section for BH formation
- Determine loss of energy in gravitational waves
- Determine spin of merged black hole

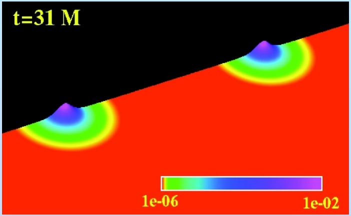
Does matter “matter”?

- Matter does not matter at energies $\ll E_{Planck}$

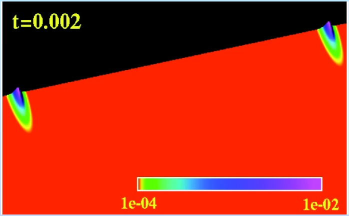
  Banks & Fischler ’99; Giddings & Thomas ’01

- Einstein plus minimally coupled, massive, complex scalar filed

  “Boson or fluid stars” Pretorius & Choptuik ’09, East & Pretorius ’12



$\gamma = 1$



$\gamma = 4$

- BH formation threshold: $\gamma_{\rm thr} = 2.9 \pm 10\ \% \sim 1/3\ \gamma_{hoop}$
- Model particle collisions by BH collisions

BH collisions: Computational framework

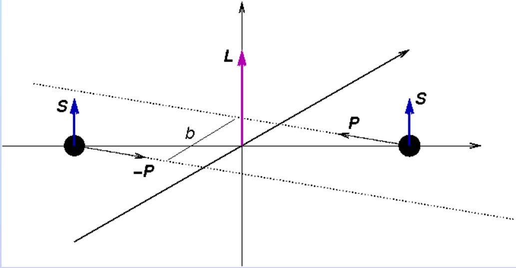
- Focus here: $D = 4$ dimensions
- "Moving puncture" technique

  Goddard '05, Brownsville-RIT '05
- BSSN formulation; Shibata & Nakamura '95, Baumgarte & Shapiro '98
- $1 + \log$ slicing, Γ-driver shift condition
- Puncture ini-data; Bowen-York '80; Brandt & Brügmann '97; Ansorg et al. '04
- Mesh refinement `Cactus, Carpet`
- Wave extraction using Newman-Penrose scalar
- Apparent Horizon finder; e.g. Thornburg '96

Initial setup: 1) Aligned spins

- Orbital hang-up   Campanelli et al. '06
- 2 BHs: Total rest mass: $M_0 = M_{\mathrm{A},\,0} + M_{\mathrm{B},\,0}$

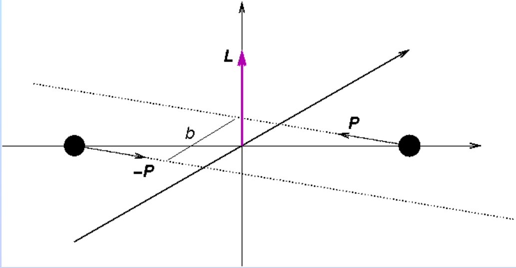
  Boost: $\gamma = 1/\sqrt{1 - v^2}$, $M = \gamma M_0$
- Impact parameter: $b \equiv \frac{L}{P}$



Initial setup: 2) No spins

- Orbital hang-up   Campanelli et al. '06
- 2 BHs: Total rest mass: $M_0 = M_{\mathrm{A},\,0} + M_{\mathrm{B},\,0}$

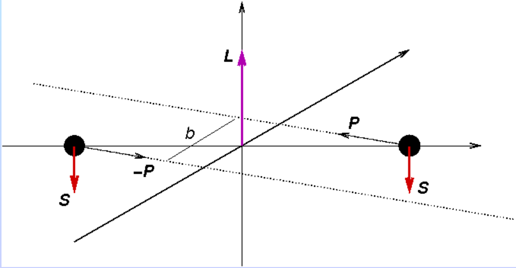
  Boost: $\gamma = 1/\sqrt{1 - v^2}$, $M = \gamma M_0$
- Impact parameter: $b \equiv \frac{L}{P}$



Initial setup: 3) Anti-aligned spins

- Orbital hang-up   Campanelli et al. '06
- 2 BHs: Total rest mass: $M_0 = M_{\mathrm{A},\,0} + M_{\mathrm{B},\,0}$

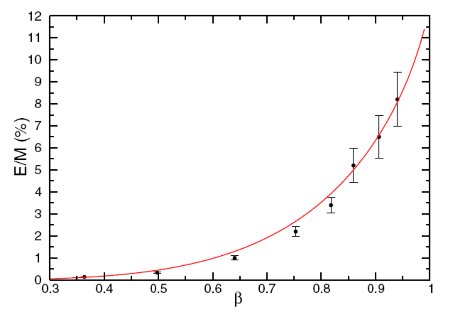
  Boost: $\gamma = 1/\sqrt{1-v^2}$, $M = \gamma M_0$
- Impact parameter: $b \equiv \frac{L}{P}$



Head-on: $b = 0, \quad \vec{S} = 0$

- Total radiated energy: 14 ± 3 % for $v \to 1$ US *et al.* '08

  About half of Penrose '74



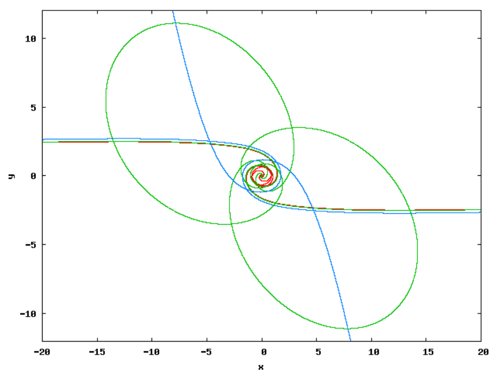
- Agreement with approximative methods

  Flat spectrum, multipolar GW structure Berti *et al.* '10

Grazing: $b \neq 0, \quad \vec{S} = 0, \quad \gamma = 1.52$

- Radiated energy up to at least 35 % M
- Immediate vs. Delayed vs. No merger

US, Cardoso, Pretorius, Berti, Hinderer & Yunes '09



Scattering threshold b_{scat} for $D = 4$, $\vec{S} = 0$

- $b < b_{\rm scat} \quad \Rightarrow \quad$ Merger

  $b > b_{\rm scat} \quad \Rightarrow \quad$ Scattering

- Numerical study: $\quad b_{\rm scat} = \frac{2.5 \pm 0.05}{v} M$

  Shibata, Okawa & Yamamoto '08

- Independent study by US, Pretorius, Cardoso, Berti *et al.* '09, '12

  $\gamma = 1.23 \ldots 2.93$:

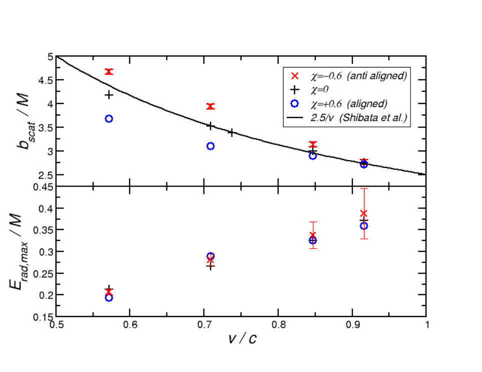
  $\chi = -0.6,\ 0,\ +0.6$ (anti-aligned, nonspinning, aligned)

- Limit from Penrose construction: $b_{\rm crit} = 1.685\ M$

  Yoshino & Rychkov '05

Scattering threshold and radiated energy

US, Berti, Cardoso & Pretorius ’12

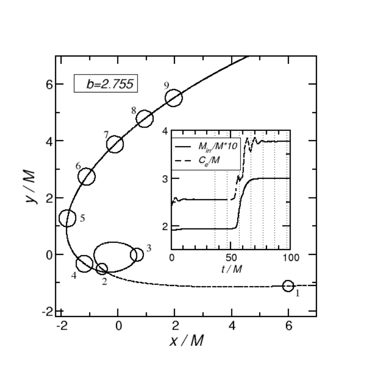


- At speeds $v \gtrsim 0.9$ spin effects washed out
- E_{rad} always below $\lesssim 50\ \%\ M$

Absorption

- For large γ: $E_{kin} \approx M$
- If E_{kin} is not radiated, where does it go?
- Answer: ~ 50 % into E_{rad}, ~ 50 % is absorbed

US, Berti, Cardoso & Pretorius '12



Conclusions and outlook

- Strong gravity $\Rightarrow$ particle collisions well modeled by BH collisions
- Numerical simulations of BH collisions with spins in $D = 4$
- Spin effects washed out at large boosts
- E_{rad} saturates near $\sim 50\ \%\ M$
- Rest of E_{kin} absorbed
- Structure of colliding particles negligible
- Assumption $M_{BH} = \mathcal{O}(1)M$ is good!
- TODO: $D > 4$, electric charge