# Impact of structure on grazing collisions of black holes

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# Overview

- Motivation
- Black-hole collisions in 3+1 dimensions
- Black-hole collisions in higher dimensional spacetimes
- Further topics
- Conclusions and outlook

# 1. Motivation

# 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 Planck mass is much lower?

  I.e. Gravity much stronger at small length scales?
- Gravity not measured below $0.16\ mm$! Diluted due to...
  - Large extra dimensions
  - Extra dimension with warp factor

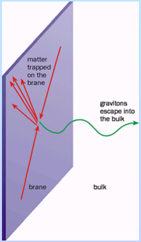
# TeV Gravity

## Large extra dimensions

Arkani-Hamed, Dimopoulos & Dvali '98

- SM confined to "3+1" brane
- Gravity lives in bulk

  $\Rightarrow$ Gravity diluted



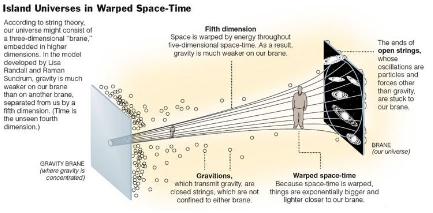

## Warped geometry

Randall & Sundrum '99

- 5D AdS Universe with 2 branes:

  "our" 3+1 world, gravity brane
- $5^{th}$ dimension warped

  $\Rightarrow$ Gravity weakened

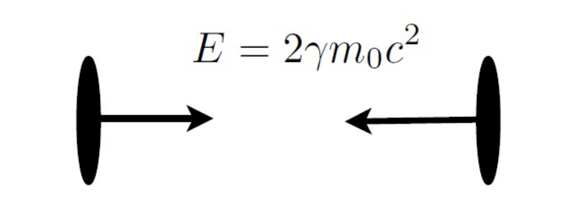



**Either way: Gravity strong at $\gtrsim$ *TeV***

# BH formation and hoop conjecture

- Hoop conjecture

  Thorne '72



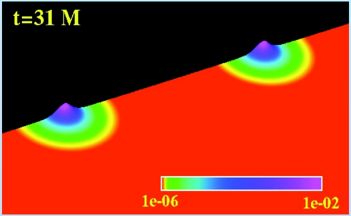

- de Broglie wavelength: $\lambda = \frac{hc}{E}$
- Schwarzschild radius: $r = \frac{2GE}{c^4}$
- BH will form if $\lambda < r \quad \Leftrightarrow \quad E \gtrsim \sqrt{\frac{hc^5}{G}} \equiv E_{\text{Planck}}$

# BH formation in boson field collisions

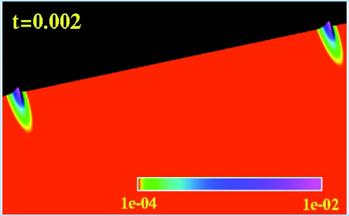
Pretorius & Choptuik ’09

- Einstein plus minimally coupled, massive, complex scalar filed

  “Boson stars”



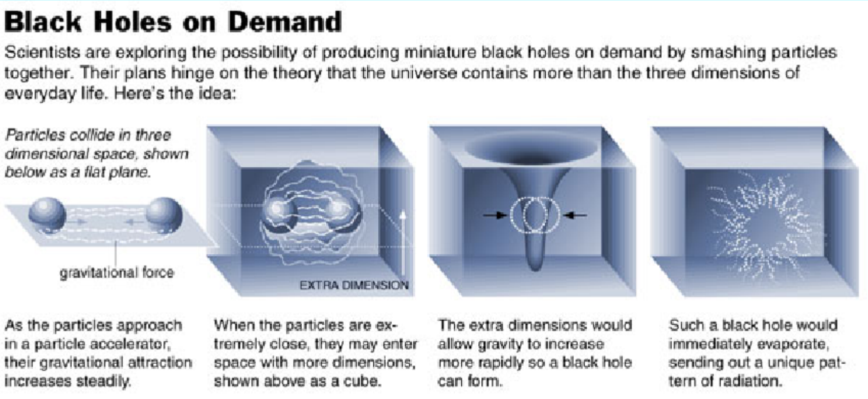

$\gamma = 1$




$\gamma = 4$

- BH formation threshold: $\gamma_{\text{thr}} = 2.9 \pm 10\ \%$
- About $1/3$ of hoop conjecture prediction

# Motivation (High-energy physics)




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

  $\Rightarrow$ Model particle collisions by black-hole collisions

  Banks & Fischler '99; Giddings & Thomas '01

# Black-hole formation in high-energy collisions

- Cosmic-rays hitting the earth's atmosphere
- Parton-parton collisions above TeV energies, LHC


→ Talk by Colon, Sec. R9

# Proton collisions at the LHC

Energy stored in a single beam:

$360\ MJ = 90\ kg$ of TNT

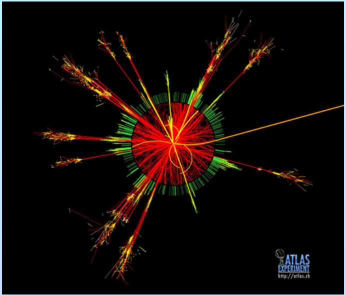
$= 15\ kg$ of chocolate

Landsberg '11 talk at NRHEP Madeira


# 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

# Further motivation

BH collisions and dynamics of interest beyond TeV gravity:

- Test Cosmic Censorship
- Probe GR in the most violent regime
- Zoom-whirl behaviour; “critical” phenomena
- Super-Planckian physics?
- Collisions in alternative theories of gravity

# 2. Computational framework dimensions

# Black-hole collisions in $D = 4$

- Numerical relativity breakthroughs carry over

  Pretorius '05, Goddard '05, Brownsville-RIT '05
- "Moving puncture" technique
- BSSN formulation; Shibata & Nakamura '95, Baumgarte & Shapiro '98
- $1 + \log$ slicing, $\Gamma$-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

# Black-hole collisions in $D = 4$

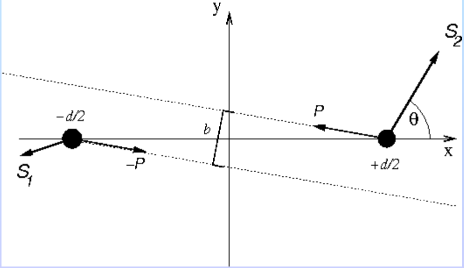
- Take two black holes

  Total rest mass: $M_0 = M_{\mathrm{A},\,0} + M_{\mathrm{B},\,0}$

  Initial position: $\pm x_0$

  Linear momentum: $\mp P[\cos\alpha,\ \sin\alpha,\ 0]$

- Impact parameter: $b \equiv \frac{L}{P}$

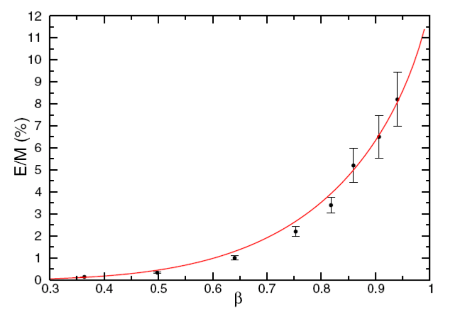


# 3. The non-spinning case

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

- Total radiated energy: $14 \pm 3$ % 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

# $b \neq 0$: Zoom whirl orbits

Pretorius & Khurana '07

- 1-parameter family of initial data: impact parameter
  - Fine tune parameter

    $\Rightarrow$ "Threshold of

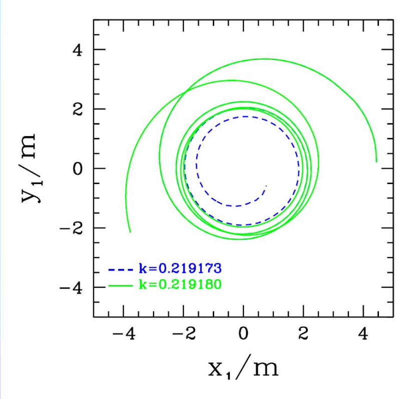
    immediate merger"
  - Analogue in geodesics
  - Remniscent of

    "Critical Phenomena"
  - Similar observations by

    Healy *et al.* '09

    Zoom-whirl more likely for

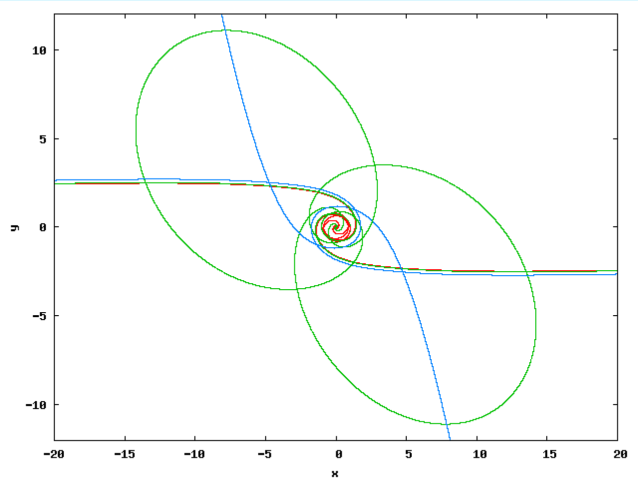
    larger $q$



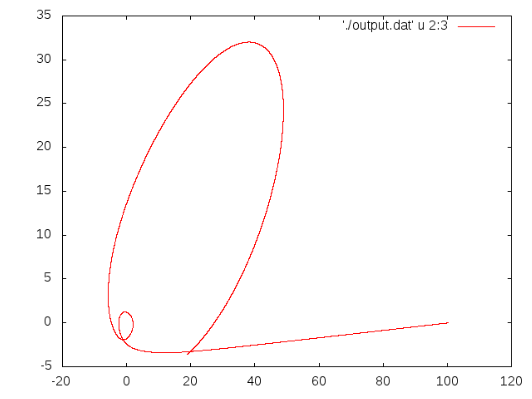
# Grazing collisions: $b \neq 0, \quad \vec{S} = 0, \quad \gamma = 1.52$

Immediate vs. Delayed vs. No merger

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



# Grazing collisions: $b = 2.55\ M, \quad \vec{S} = 0, \quad \gamma = 2.68$



# Critical impact parameter

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

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

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

  Shibata, Okawa & Yamamoto '08

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

  $\gamma = 1.23 \ldots 2.93$:

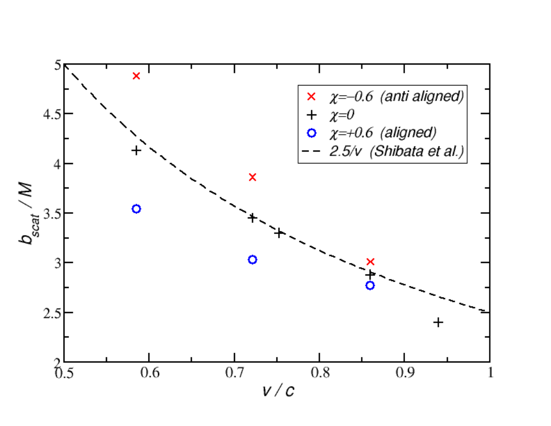
  $\chi = -0.6,\ 0,\ +0.6$ (anti-aligned, nonspinning, aligned)

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

  Yoshino & Rychkov '05

# Critical impact parameter

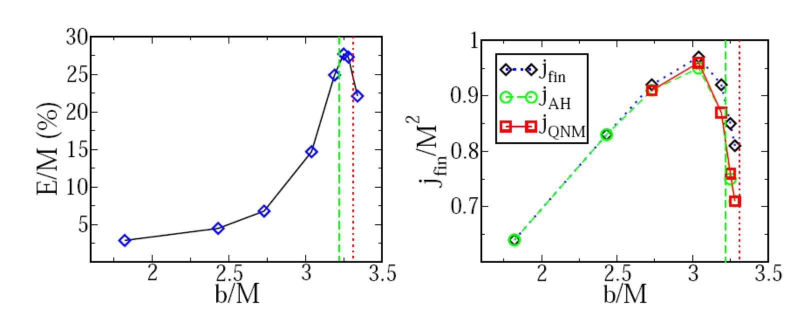
## Preliminary results




- Effect of spin reduced for large $\gamma$
- $b_{\rm scat}$ for $v \to 1$ not quite certain

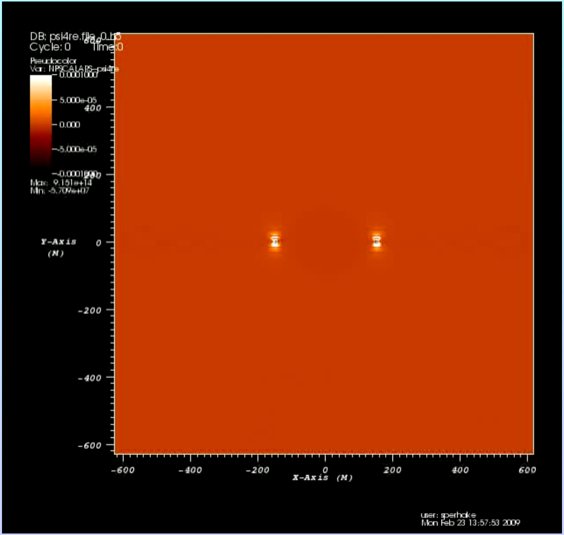
# Radiated quantities

- $b-$sequence with $\gamma = 1.52$
- Final spin close to Kerr limit
- $E_{\rm rad} \sim 35$ % for $\gamma = 2.93$; about 10 % of Dyson luminosity




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

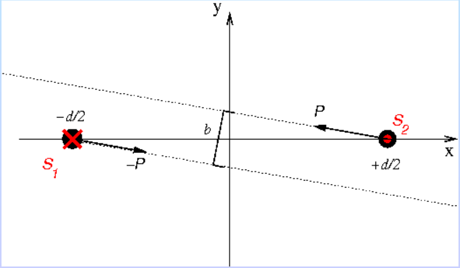
# Gravitational radiation: Delayed merger



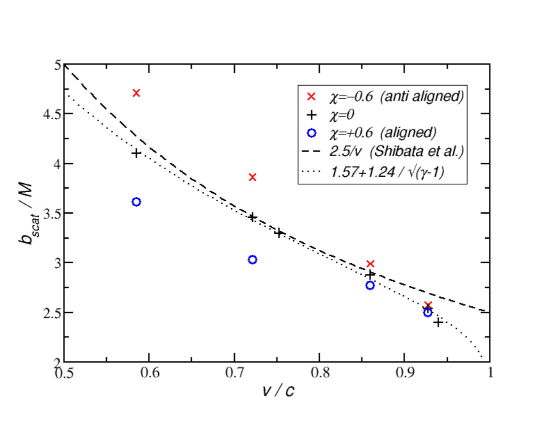
# 4. Collisions of spinning holes

# Initial configurations

- Mass ratio $q = 1$
- Impact parameter: $b \equiv \frac{L}{P}$
- Equal spins $\vec{S}_1 = \vec{S}_2$ aligned or anti-aligned with $\vec{L}$
- Spin magnitude $\chi_i = |\vec{S}_i|/M_i^2 = 0.63$
- Three sequences 'a', 'n', 'aa' for $\gamma = 1.233,\ 1.444,\ 1.958,\ 2.679$



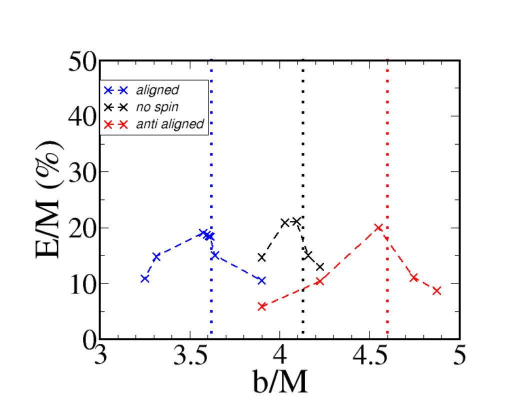
# Diminishing impact of structure as $v \to 1$




- Effect of spin reduced for large $\gamma$
- $b_{\rm scat}$ for $v \to 1$ not quite certain

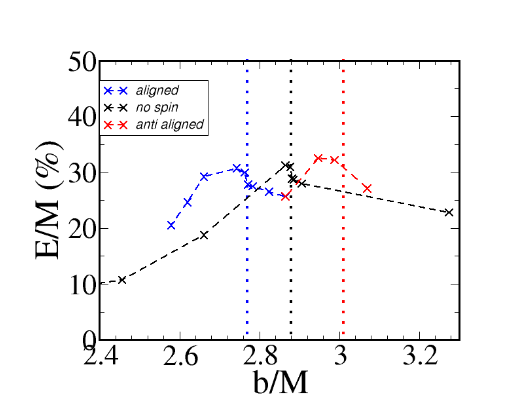
# Radiated GW energy: $\gamma = 1.23$

- $\chi_{1,2} = 0, \ \pm 0.6$
- Vary $b$
- “Hang-up” has little impact on radiation



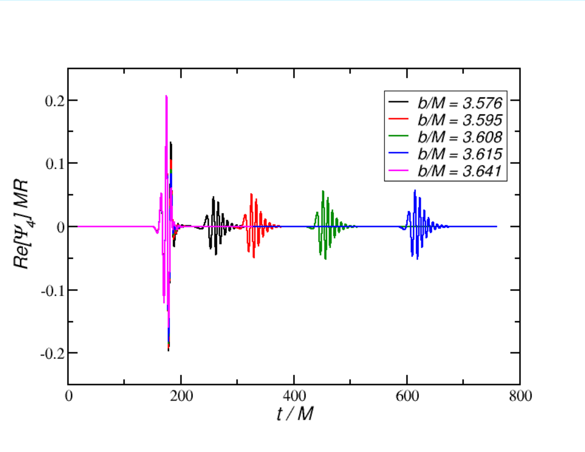
# Radiated GW energy: $\gamma = 1.96$

- $\chi_{1,2} = 0, \ \pm 0.6$
- Vary $b$
- Relatively minor increase in $E_{rad}$



# Delayed mergers: Aligned case, $\gamma = 1.52$

- Delayed merger $\Rightarrow$ Two wave bursts
- $b \rightarrow b_{scat} \Rightarrow$ Gap $\rightarrow \infty$



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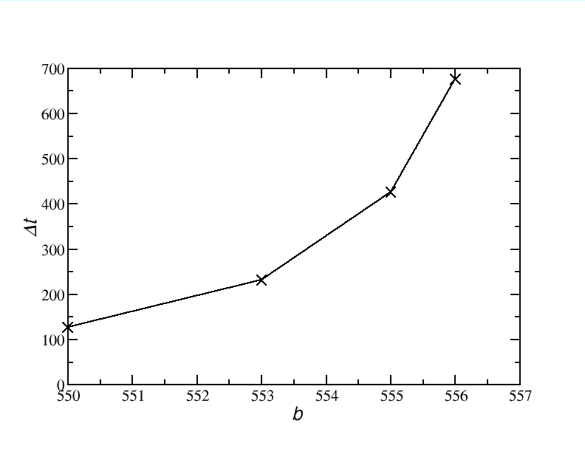

# 5. Conclusions

# Conlcusions

- “3+1” numerical framework can be modified for higher $D$
- Stability not yet as robust as in $D = 4$; gauge?
- Scattering threshold in 4D: $b_{\rm crit} \approx \frac{2.5\ M}{v}$
- Cosmic Censorship holds
- Zoom-whirl behaviour in 4D
- Impact of spin diminishes as $\gamma$ increases
- Maximal GW energy little affected by spin
- Delay $\to \infty$ as $b \to b_{scat}$; Universal scaling?