Impact of structure on grazing collisions of black holes

U. Sperhake

CSIC-IEEC Barcelona

NRHEP Network First Meeting, Aveiro 12st July 2012



IEEC

< ロ > < 同 > < 回 > < 回 >

U. Sperhake (CSIC-IEEC)

Impact of structure on grazing collisions of black holes

2/07/2012 1 / 3

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

U. Sperhake (CSIC-IEEC)

Impact of structure on grazing collisions of black holes 12/

< ロ > < 同 > < 回 > < 回 > = 回 > = 回

1. Motivation

U. Sperhake (CSIC-IEEC)

Impact of structure on grazing collisions of black holes

/07/2012 3 / 3

The Hierarchy Problem of Physics

- Gravity $\approx 10^{-39} \times$ other forces
- Higgs field $\approx \mu_{obs} \approx 250 \text{ GeV} = \sqrt{\mu^2 \Lambda^2}$ where $\Lambda \approx 10^{16} \text{ GeV}$ 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

U. Sperhake (CSIC-IEEC)

Impact of structure on grazing collisions of black holes

/07/2012 4 / 3

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

< ロ > < 同 > < 三 > < 三 >

• 5th dimension warped

\Rightarrow Gravity weakened

Island Universes in Warped Space-Time



Either way: Gravity strong at $\gtrsim TeV$

Impact of structure on grazing collisions of black holes

BH formation and hoop conjecture

- Hoop conjecture
 - Thorne '72

$$E = 2\gamma m_0 c^2$$

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

U. Sperhake (CSIC-IEEC)

Impact of structure on grazing collisions of black holes

12/07/2012 6 / 33

(日)

BH formation in boson field collisions

Pretorius & Choptuik '09

• Einstein plus minimally coupled, massive, complex scalar filed

"Boson stars"



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

U. Sperhake (CSIC-IEEC

Impact of structure on grazing collisions of black holes

2/07/2012 7 / 33

Motivation (High-energy physics)

Black Holes on Demand

Scientists are exploring the possibility of producing miniature black holes on demand by smashing particles together. Their plans hinge on the theory that the universe contains more than the three dimensions of everyday life. Here's the idea:



As the particles approach in a particle accelerator, their gravitational attraction increases steadily. When the particles are extremely close, they may enter space with more dimensions, shown above as a cube. The extra dimensions would allow gravity to increase more rapidly so a black hole can form.

Such a black hole would immediately evaporate, sending out a unique pattern of radiation.

Matter does not matter at energies well above the Planck scale
 ⇒ Model particle collisions by black-hole collisions
 Banks & Fischler '99: Giddings & Thomas '01

U. Sperhake (CSIC-IEEC

Impact of structure on grazing collisions of black holes

/07/2012 8 / 3

Black-hole formation in high-energy collisions

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



 \rightarrow Talk by Colon, Sec. R9

U. Sperhake (CSIC-IEEC)

Impact of structure on grazing collisions of black holes 12/07/

< □ > < 同 > < 三 > <

9 / 33

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





U. Sperhake (CSIC-IEEC

Impact of structure on grazing collisions of black holes

07/2012 10/3

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

U. Sperhake (CSIC-IEEC)

Impact of structure on grazing collisions of black holes

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

12/33

2. Computational framework dimensions

U. Sperhake (CSIC-IEEC)

Impact of structure on grazing collisions of black holes 12

7/2012 13/3

< ロ > < 同 > < 回 > < 回 > = 通

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, 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

U. Sperhake (CSIC-IEEC

12 14/3

Black-hole collisions in D = 4

- Take two black holes
 - Total rest mass: $M_0 = M_{A, 0} + M_{B, 0}$ Initial position: $\pm x_0$ Linear momentum: $\mp P[\cos \alpha, \sin \alpha, 0]$
- Impact parameter: $b \equiv \frac{L}{P}$



U. Sperhake (CSIC-IEEC)

Impact of structure on grazing collisions of black holes

2/07/2012 15 / 33

3. The non-spinning case

U. Sperhake (CSIC-IEEC

Impact of structure on grazing collisions of black holes 12/0

7/2012 16 / 3

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

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

About half of Penrose '74



Agreement with approximative methods

Flat spectrum, multipolar GW structure

Berti et al. '10

U. Sperhake (CSIC-IEEC

Impact of structure on grazing collisions of black holes

2/07/2012 17 / 3

$b \neq 0$: Zoom whirl orbits

Pretorius & Khurana '07

- 1-parameter family of initial data: impact parameter
 - Fine tune parameter
 - ⇒ "Threshold of immediate merger"
 - Analogue in geodesics
 - Remniscent of
 "Critical Phenomena"
 - Similar observations by Healy *et al.* '09

larger q

Zoom-whirl more likely for



Impact of structure on grazing collisions of black holes 12/07/20

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

Immediate vs. Delayed vs. No merger

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



U. Sperhake (CSIC-IEEC

Impact of structure on grazing collisions of black holes

2/07/2012 19 / 33

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



U. Sperhake (CSIC-IEEC)

Impact of structure on grazing collisions of black holes 12

(重▶ 重 ∽)Q /07/2012 20/3

Critical impact parameter

- $b < b_{crit} \Rightarrow Merger$
 - $b > b_{crit} \Rightarrow Scattering$
- Numerical study: $b_{crit} = \frac{2.5 \pm 0.05}{v} M$ Shibata. Okawa & Yamamoto '08
- Independent study by US, Pretorius, Cardoso, Berti *et al.* '09, '12 $\gamma = 1.23...2.93$:
 - $\chi = -0.6, 0, +0.6$ (anti-aligned, nonspinning, aligned)
- Limit from Penrose construction: $b_{crit} = 1.685 M$ Yoshino & Rychkov '05

U. Sperhake (CSIC-IEEC

2 21/33

◆□ ▶ ◆□ ▶ ◆ □ ▶ ◆ □ ▶ ● ● ● ● ●

Critical impact parameter

Preliminary results



- Effect of spin reduced for large γ
- b_{scat} for $v \rightarrow 1$ not quite certain

Impact of structure on grazing collisions of black holes

2/07/2012 22 / 33

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 , Cardoso, Pretorius, Berti, Hinderer & Yune

U. Sperhake (CSIC-IEEC)

Impact of structure on grazing collisions of black holes

7/2012 23 / 33

Gravitational radiation: Delayed merger



U. Sperhake (CSIC-IEEC)

Impact of structure on grazing collisions of black holes

▲ E → E → Q Q Q 2/07/2012 24 / 33

4. Collisions of spinning holes

U. Sperhake (CSIC-IEEC

Impact of structure on grazing collisions of black holes

07/2012 25 / 3

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



U. Sperhake (CSIC-IEEC)

Impact of structure on grazing collisions of black holes 12/07

/2012 26 / 33

Diminishing impact of structure as $v \rightarrow 1$



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

U. Sperhake (CSIC-IEEC)

Impact of structure on grazing collisions of black holes

12/07/2012 27 / 33

Radiated GW energy: $\gamma = 1.23$

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



U. Sperhake (CSIC-IEEC)

Impact of structure on grazing collisions of black holes

12/07/2012 28 / 33

Radiated GW energy: $\gamma = 1.96$

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



U. Sperhake (CSIC-IEEC)

Impact of structure on grazing collisions of black holes

2/07/2012 29 / 33

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

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



U. Sperhake (CSIC-IEEC

Impact of structure on grazing collisions of black holes

2/07/2012 30 / 3

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

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



U. Sperhake (CSIC-IEEC

Impact of structure on grazing collisions of black holes

2/07/2012 31 / 3

5. Conclusions

U. Sperhake (CSIC-IEEC)

Impact of structure on grazing collisions of black holes 12

7/2012 32/3

< □> < □> < □> < □>
 < □> < □> < □>

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: $b_{crit} \approx \frac{2.5 M}{V}$
- Cosmic Censorship holds
- Zoom-whirl behaviour in 4D
- Impact of spin diminishes as γ increases
- Maximal GW energy little affected by spin
- Delay $\rightarrow \infty$ as $b \rightarrow b_{scat}$; Universal scaling?

2012 33/3

<ロ> < 同 > < 同 > < 三 > < 三 > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > < □ > <