Numerical relativity: The role of black holes in gravitational wave physics, astrophysics and high-energy physics

U. Sperhake

DAMTP, University of Cambridge

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Overview

- Introduction, Numerical relativity
- BHs in GW physics
- BHs in astrophysics
- High-energy collisions of BHs
- BH holography
- Fundamental properties of BHs

1. Introduction, motivation

Evidence for astrophysical black holes

- X-ray binaries

  e. g. Cygnus X-1 (1964)

  MS star + compact star

  $\Rightarrow$ Stellar Mass BHs
  $\sim 5 \ldots 50\ M_\odot$

- Stellar dynamics

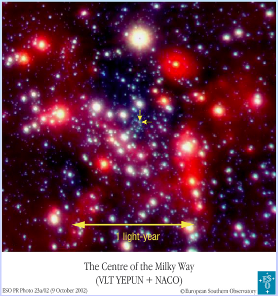
  near galactic centers,

  iron emission line profiles

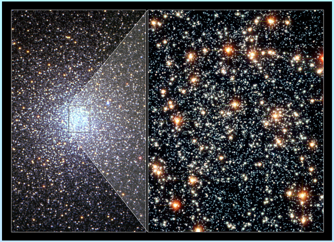
  $\Rightarrow$ Supermassive BHs

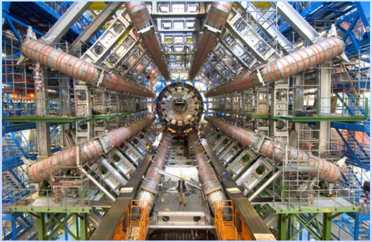
  $\sim 10^6 \ldots 10^9\ M_\odot$

  AGN engines



Conjectured BHs





- Intermediate mass BHs

  $\sim 10^2 \ldots 10^5\ M_\odot$

- Primordial BHs

  $\leq M_{Earth}$

- Mini BHs, LHC

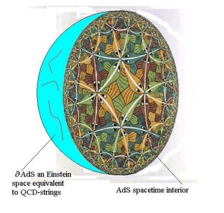
  $\sim TeV$

Note: BH solution is scale invariant!

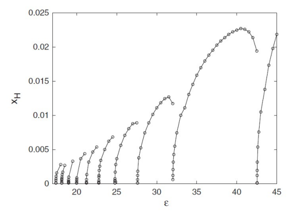
Research areas: Black holes have come a long way!

Astrophysics

Gauge-gravity duality

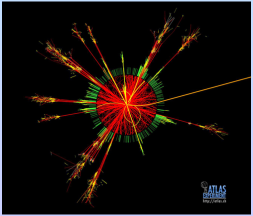


Fundamental studies

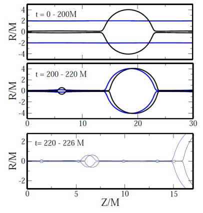


GW physics

High-energy physics



Fluid analogies



How to get the metric?

Train cemetery
Uyuni, Bolivia

- Solve for the metric $g_{\alpha\beta}$

Solving Einstein's equations: Different methods

- Analytic solutions
  - Symmetry assumptions
  - Schwarzschild, Kerr, FLRW, Myers-Perry, Emparan-Reall,...
- Perturbation theory
  - Assume solution is close to known solution $g_{\alpha\beta}$
  - Expand $\hat{g}_{\alpha\beta} = g_{\alpha\beta} + \epsilon h^{(1)}_{\alpha\beta} + \epsilon^2 h^{(2)}_{\alpha\beta} + \ldots \quad \Rightarrow$ linear system
  - Regge-Wheeler-Zerilli-Moncrief, Teukolsky, QNMs, EOB,...
- Post-Newtonian Theory
  - Assume small velocities $\Rightarrow$ expansion in $\frac{v}{c}$
  - N^{th} order expressions for GWs, momenta, orbits,...
  - Blanchet, Buonanno, Damour, Kidder, Will,...
- Numerical Relativity

A list of tasks

- Target: Predict time evolution of BBH in GR
- Einstein equations: 1) Cast as evolution system
  2) Choose specific formulation
  3) Discretize for computer
- Choose coordinate conditions: Gauge
- Fix technical aspects: 1) Mesh refinement / spectral domains
  2) Singularity handling / excision
  3) Parallelization

- Construct realistic initial data
- Start evolution...
- Extract physics from the data

A brief history of BH simulations

- Pioneers: Hahn & Lindquist '60s, Eppley, Smarr *et al.* '70s
- Grand Challenge: First $3D$ Code Anninos *et al.* '90s
- Further attempts: Bona & Massó, Pitt-PSU-Texas
  AEI-Potsdam, Alcubierre *et al.*
  PSU: first orbit Brügmann *et al.* '04

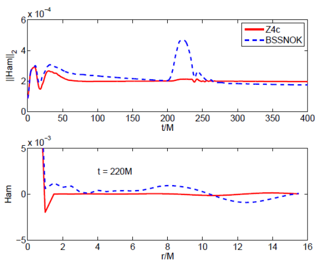
  Codes unstable!

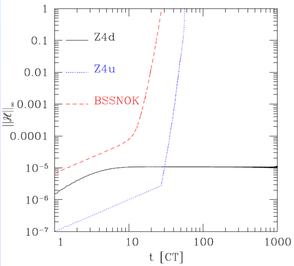
- Breakthrough: Pretorius '05 GHG
  UTB, Goddard'05 Moving Punctures
- ∼10 codes world wide

Formulations

- Formulations mostly used: GHG, BSSN
- Combine advantages from both through conformal Z4 formulation
  - Z4 system   Bona et al, PRD 67 104005, PRD 69 104003
  - Conformal decomposition $\Rightarrow$ Z4c, CCZ4
    Alic et al, PRD **85** 064040,   Cao et al, PRD **85** 124032

    Hilditch et al, arXiv:1212.2901   Weyhausen et al, PRD **85** 024038
- Advantages: constraint damping, constraint preserving BCs

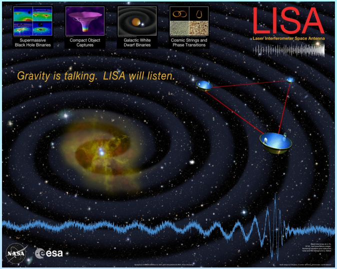


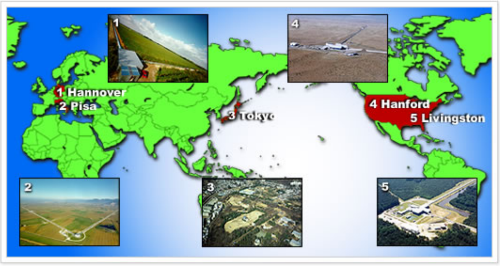


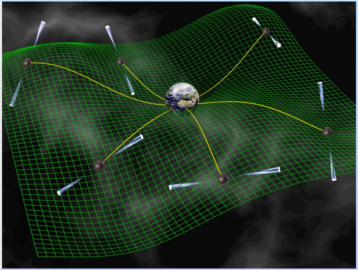
2. BHs in GW physics

Gravitational wave detectors

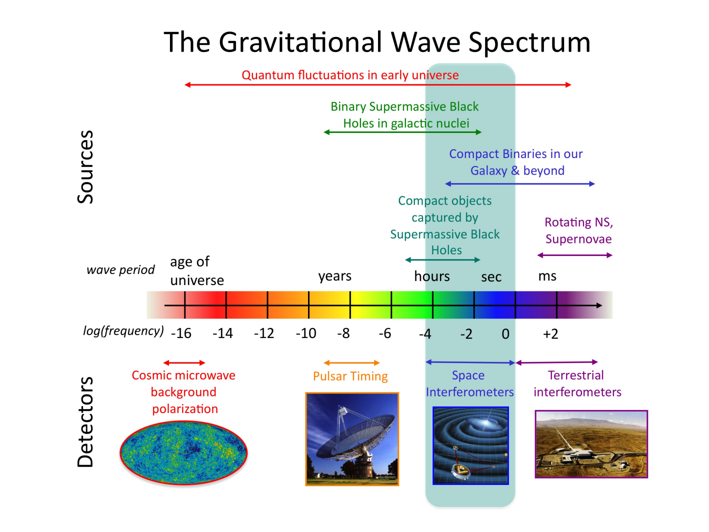
- Accelerated masses $\Rightarrow$ GWs
- Weak interaction!
- Laser interferometric detectors







The gravitational wave spectrum



Free parameters of BH binaries

- Total mass M

  Relevant for GW detection: Frequencies scale with M

  Not relevant for source modeling: trivial rescaling

- Mass ratio $q \equiv \frac{M_1}{M_2}$, $\qquad \eta \equiv \frac{M_1 M_2}{(M_1 + M_2)^2}$

- Spin: $\vec{S}_1$, $\vec{S}_2$ (6 parameters)

- Initial parameters

  Binding energy E_{b} — Separation

  Orbital ang. momentum L — Eccentricity

  Alternatively: frequency, eccentricity

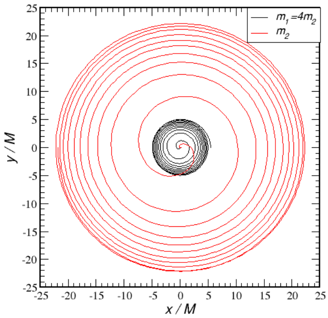
BBH trajectory and waveform

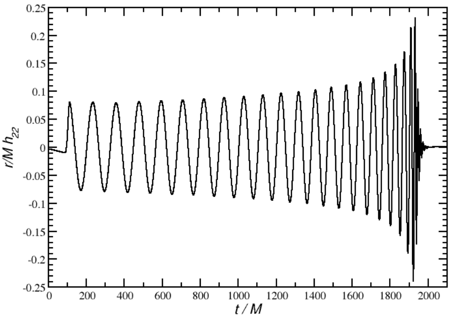
- $q = 4$, non-spinning binary; ~ 11 orbits

  US et al, CQG **28** 134004

Trajectory

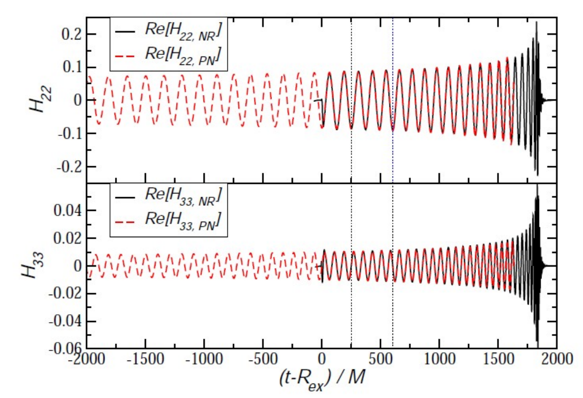
Quadrupole mode





Template construction

- Stitch together PN and NR waveforms
- EOB or phenomenological templates for $\geq$ 7-dim. par. space



Template construction

- Phenomenological waveform models
  - Model phase, amplitude with simple functions $\to$ Model parameters
  - Create map between physical and model parameters
  - Time or frequency domain

    Ajith et al, CQG **24** S689, PRD **77** 104017, CQG **25** 114033, PRL **106** 241101; Santamaria et al, PRD **82** 064016, Sturani et al, arXiv:1012.5172 [gr-qc]

- Effective-one-body (EOB) models
  - Particle in effective metric, PN, ringdown model
    Buonanno & Damour PRD **59** 084006, PRD **62** 064015
  - Resum PN, calibrate pseudo PN parameters using NR
    Buonanno et al, PRD **77** 026004, Pan et al, PRD **81** 084041, PRD **84** 124052; Damour et al, PRD **77** 084017, PRD **78** 044039, PRD **83** 024006

The Ninja project

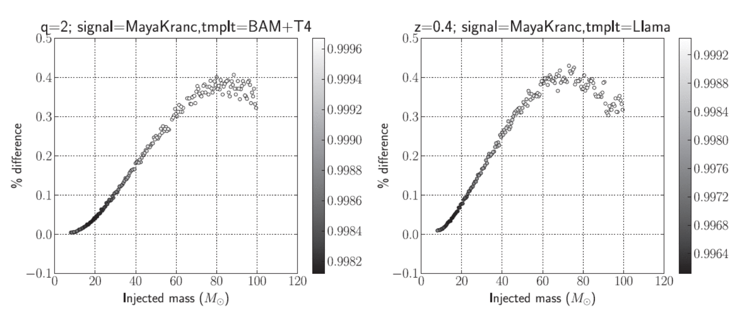
https://www.ninja-project.org/

Aylott et al, CQG **26** 165008, CQG **26** 114008

Ajith et al, CQG **29** 124001

- Use PN/NR hybrid waveforms in GW data analysis
- Ninja2: 56 hybrid waveforms from 8 NR groups
- Details on hybridization procedures
- Overlap and mass bias study:
  - Take one waveform as signal, fixing M_{tot}
  - Search with other waveform (same config.) varying $t_0,\ \phi_0,\ M_{tot}$

The Ninja project



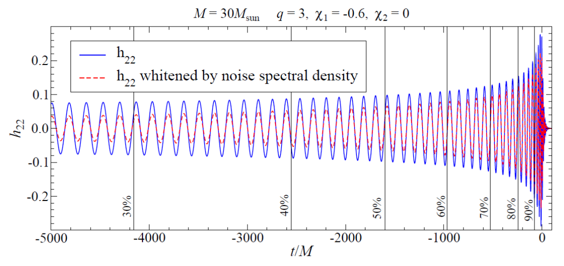
- Left: $q = 2$, non-spinning waveforms, MAYAKRANC, BAM + T4
- Right: $q = 1$, $\chi_1 = \chi_2 = 0.4$ waveform, MAYAKRANC, LLAMA + T4
- Mass bias < 0.5 %

The NRAR project

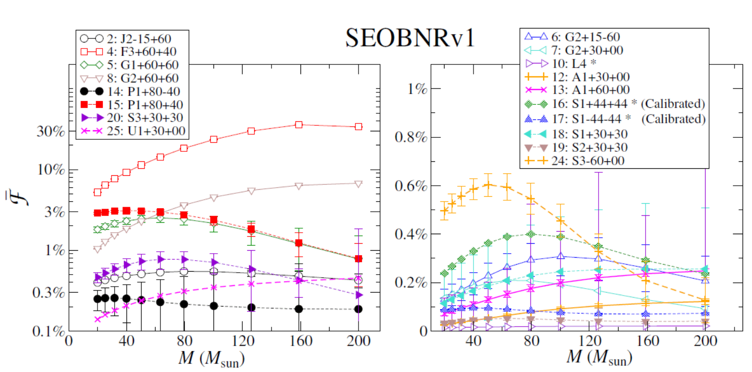
`https://www.ninja-project.org/doku.php?id=nrar:home`

Hinder, Buonanno et al, under LSC review

- Pool efforts from 9 NR groups
- 11M core hours on XSEDE Kraken
- $22+3$ waveforms, including precessing runs
- Standardize analysis, comparison with analytic models



The NRAR project

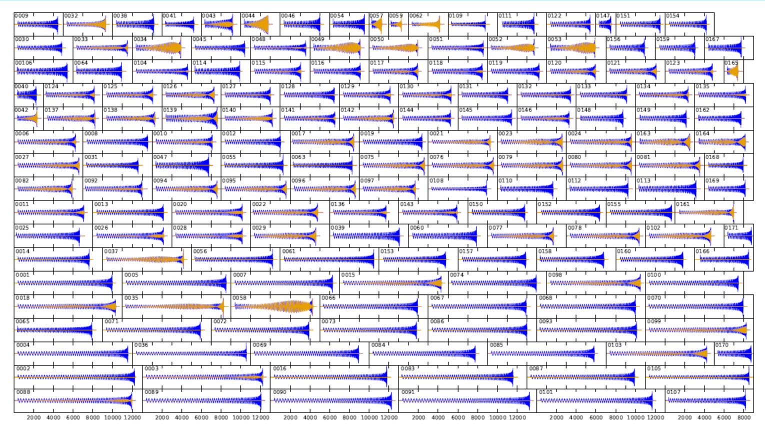


- Unfaithfulness $\bar{\mathcal{F}} = 1 -$ best overlap varying t_0, ϕ_0
- $\bar{\mathcal{F}}$ between SEOBNRv1 and NR waveforms

Tools of mass production

- SpEC catalog: 171 waveforms: $q \le 8$, 90 precessing, ≤ 34 orbits

  Mroué et al, arXiv:1304.6077 [gr-qc] $\rightarrow$ Talk H.Pfeiffer



Strategies in parameter space

- SpEC: 16 orbits in 40 hours
- Still, 7-dimensional parameter space $\rightarrow$ $N \sim 10^7$ waveforms?
- Probably too many... Accuracy needed... $\rightarrow$ Talk S.Husa
- Reduce $\#$ of parameters describing dominant spin effects

  Ajith et al, PRL **106** 241101, PRD **84** 084037,

  Pürrer et al, arXiv:1306.2320 [gr-qc] $\rightarrow$ Talk M.Pürrer
- Spin-robit resonances $\Rightarrow$ preferred regions in parameter space?

  Gerosa et al, arXiv:1302.4442 [gr-qc]
- Trade-off: Quantity or quality of waveforms?

  Both affects parameter estimation!

Limits in the parameter space

- Mass ratio $q = 100$

  Lousto & Zlochower, PRL **106** 041101

  Head-on case: US et al, PRD **84** 084038

- Spin magnitude $\chi = 0.97$

  Superposed Kerr-Schild data (non-conformally flat)

  Lovelace et al, CQG **29** 045003 $\rightarrow$ Talk G.Lovelace

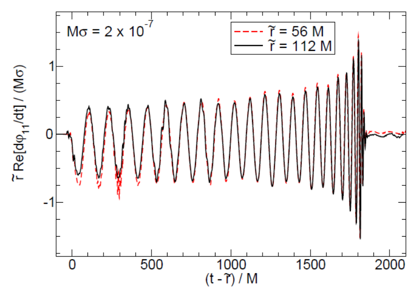
- Separations $D = 100\ M$; few orbits

  Lousto & Zlochower, arXiv:1304.3937 [gr-qc]

Going beyond GR: Scalar-tensor theory of gravity

- Brans-Dicke theory: 1 parameter ω_{BD}; well constrained
- Bergmann-Wagoner theories: Generalize $\omega = \omega(\phi),\ V = V(\phi)$
- No-hair theorem: BHs solutions same as in GR
  e.g. Hawking, Comm.Math.Phys. **25** 167
  Sotiriou & Faraoni, PRL **108** 081103
- Circumvent no-hair theorem: Scalar bubble
  Healey et al, arXiv:1112.3928 [gr-qc]
- Circumvent no-hair theorem: Scalar gradient
  Horbatsch & Burgess, JCAP **1205** 010,
  Berti et al, arXiv:1304.2836 [gr-qc]

  → Talk L.Gualtieri



3. BHs in Astrophysics

Gravitational recoil

- Anisotropic GW emission $\Rightarrow$ recoil of remnant BH

  Bonnor & Rotenburg, Proc.Roy.Soc. **265** 109 Peres, PR **128** 2471,
  Bekenstein, ApJ **183** 657

- Escape velocities:

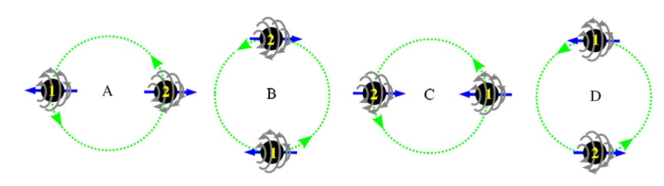
Globular clusters	30 $\mathrm{km/s}$
dSph	20 $-$ 100 $\mathrm{km/s}$
dE	100 $-$ 300 $\mathrm{km/s}$
Giant galaxies	$\sim$ 1000 $\mathrm{km/s}$

Ejection / displacement of BH $\Rightarrow$

- Growth history of SMBHs
- BH populations, IMBHs
- Structure of galaxies

Spinning BHs: Superkicks

- Superkick configuration:



- Kicks up to $v_{\rm max} \approx 4\,000\ \rm km/s$

  Campanelli *et al.*, PRL **98** 231102

  González *et al.* PRL **98** 231101

- Suppression via spin alignment and Resonance effects in inspiral
  Schnittman, PRD **70** 124020

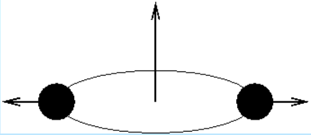
  Bogdanovicź et al, ApJ **661** L147

  Kesden et al, PRD **81** 084054, ApJ **715** 1006

Even larger kicks: superkick and hang-up

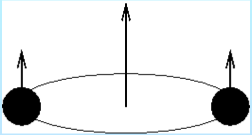
Lousto & Zlochower, PRL **107** 231102

Superkicks

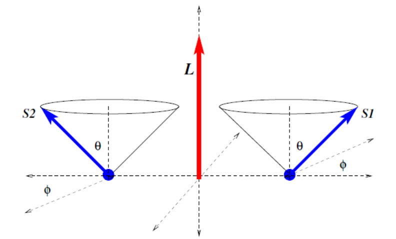


- Moderate GW generation
- Large kicks

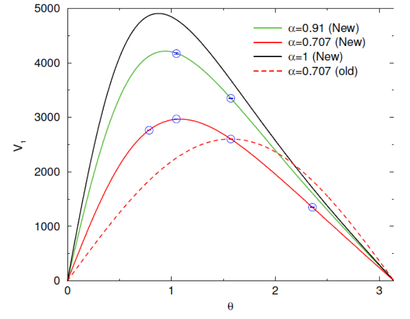
Hangup



- Strong GW generation
- No kicks



Superkicks and orbital hang-up



- Maximum kick about 25 % larger: $v_{\rm max} \approx 5\,000$ km/s
- Distribution asymmetric in θ; v_{max} for partial alignment
- Supression through resonances still works

Berti et al, PRD **85** 124049

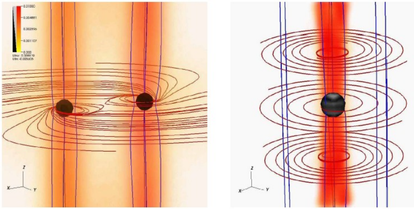
EM counterparts generated by binary BHs

- EM signatures through shocks, accretion, rel. beaming
  Bode et al, ApJ **715** 1117, ApJ **744** 45   Bogdanovic et al, CQG **28** 094020
- Accretion, luminosity enhanced relative to single BH of same M
  Farris et al, PRD **81** 084008
- Circumbinary disks may not produce detectable EM counterparts
  Bode et al, ApJ **744** 45   Moesta et al, PRD **81** 064017   Alic et al, ApJ **754** 36
- Blandford-Znajek like effect due to magnetic field generated by disk could be observable
  Palenzuela et al

EM counterparts generated by binary BHs

Palenzuela et al, PRL **103** 081101, Science **329** 927
PRD **81** 084007, PRD **82**, 044045

- Non-spinning BH binary
- Einstein-Maxwell equtions with “force free” plasma
- Electromagnetic field extracts energy from **L** $\Rightarrow$ jets
- Optical signature: double jets



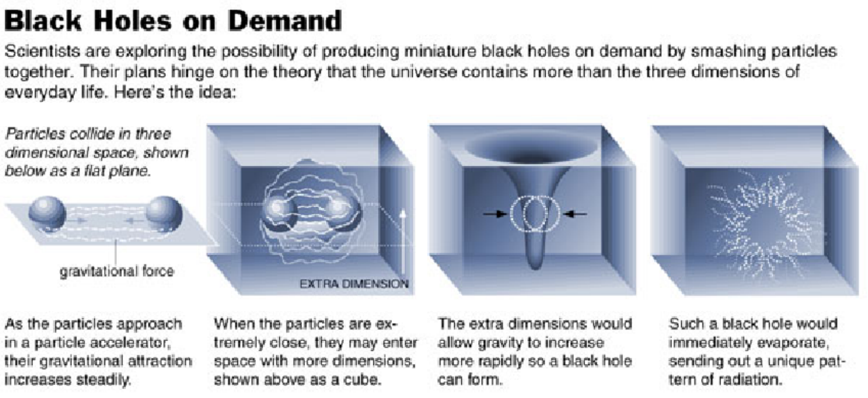
(a) $-8.2\,M_8$ hrs (b) $4.6\,M_8$ hrs

4. High-energy BH collisions

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

Stages of BH formation



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

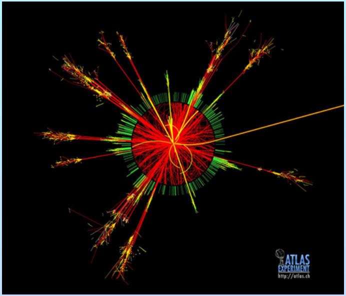
$\Rightarrow$ Model particle collisions by black-hole collisions

Banks & Fischler, gr-qc/9906038; Giddings & Thomas, PRD **65** 056010

Experimental signature at the LHC

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

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



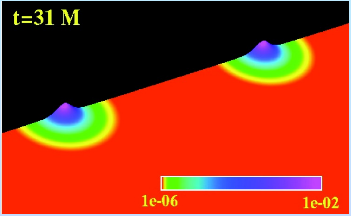
ToDo:

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

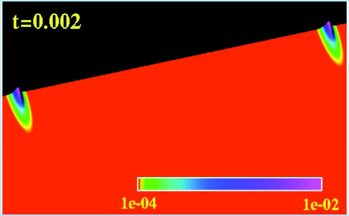
Does matter "matter"?

- Hoop conjecture $\Rightarrow$ kinetic energy triggers BH formation
- Einstein plus minimally coupled, massive, complex scalar filed

  "Boson stars" Pretorius & Choptuik, PRL **104** 111101



$\gamma = 1$



$\gamma = 4$

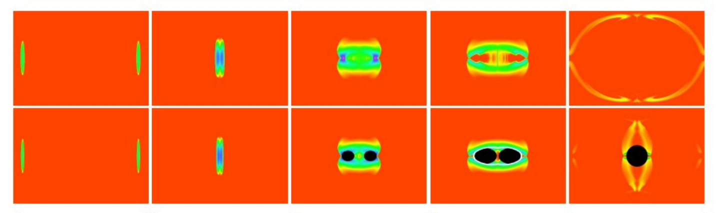
- BH formation threshold: $\gamma_{\rm thr} = 2.9 \pm 10\ \% \sim 1/3\ \gamma_{hoop}$
- Model particle collisions by BH collisions

Does matter "matter"?

- Perfect fluid "stars" model
- $\gamma = 8 \dots 12$; BH formation below Hoop prediction

East & Pretorius, PRL **110** 101101

- Gravitational focussing $\Rightarrow$ Formation of individual horizons



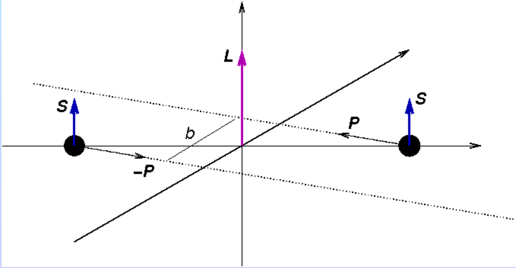
- Type-I critical behaviour
- Extrapolation by 60 orders would imply no BH formation at LHC

Rezzolla & Tanaki, CQG **30** 012001

$D = 4$: Initial setup: 1) Aligned spins

- Orbital hang-up   Campanelli et al, PRD **74** 041501
- 2 BHs: Total rest mass: $M_0 = M_{\mathrm{A},\,0} + M_{\mathrm{B},\,0}$

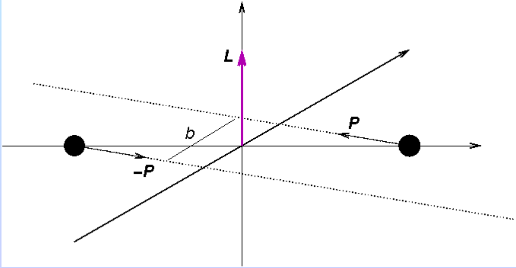
  Boost: $\gamma = 1/\sqrt{1-v^2}$, $M = \gamma M_0$
- Impact parameter: $b \equiv \frac{L}{P}$



$D = 4$: Initial setup: 2) No spins

- Orbital hang-up   Campanelli et al, PRD **74** 041501
- 2 BHs: Total rest mass: $M_0 = M_{\mathrm{A},\,0} + M_{\mathrm{B},\,0}$

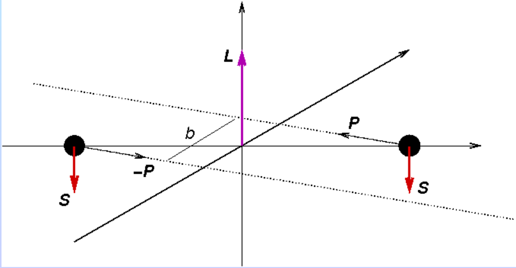
  Boost: $\gamma = 1/\sqrt{1 - v^2}$, $M = \gamma M_0$
- Impact parameter: $b \equiv \frac{L}{P}$



$D = 4$: Initial setup: 3) Anti-aligned spins

- Orbital hang-up   Campanelli et al, PRD **74** 041501
- 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: $b \equiv \frac{L}{P}$

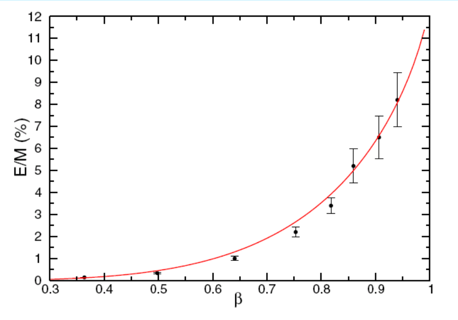


$D = 4$: Head-on: $b = 0, \quad \vec{S} = 0$

- Total radiated energy: 14 ± 3 % for $v \to 1$

  US et al, PRL **101** 161101

  About half of Penrose '74



- Agreement with approximative methods

  Flat spectrum, GW multipoles Berti et al, PRD **83** (2011) 084018

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

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

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

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

  Shibata et al, PRD **78** 101501(R)

- Independent study US et al, PRL **103** 131102, arXiv:1211.6114

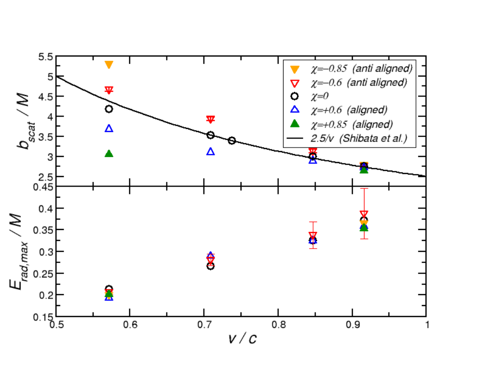
  $\gamma = 1.23 \ldots 2.93$:

  $\chi = \pm 0.85, \; \pm 0.6, \; 0$ (anti-aligned, nonspinning, aligned)

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

  Yoshino & Rychkov, PRD **74** 124022

$D = 4$: Scattering threshold and radiated energy $\vec{S} \neq 0$

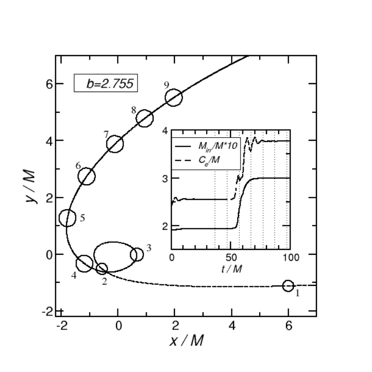


US et al, arXiv:1211.6114

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

$D = 4$: 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

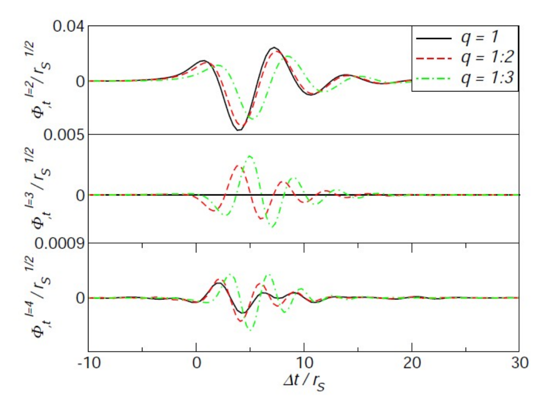


US et al, arXiv:1211.6114

$D = 5$: Unequal-mass head-on

Dimensional reduction: Zilhão et al, PRD **81** 084052

Wave extraction: Kodama & Ishibashi PTP **110** 701,   Witek et al, PRD **82** 104014

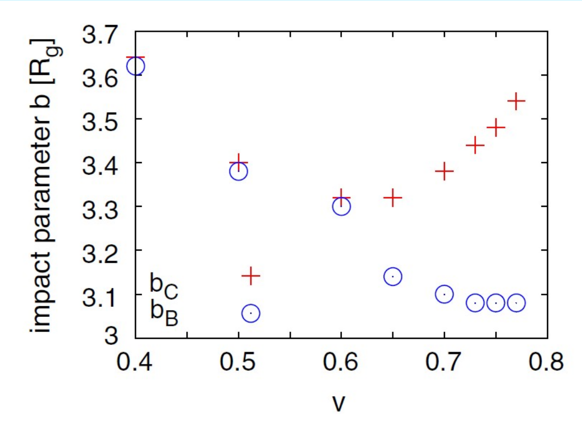


Witek *et al.*, PRD **83** 044017

$D = 5$: Scattering threshold

Modified Cartoon: Yoshino & Shibata, PRD **80** 084025

First boosted collisions in $D > 4$: Okawa et al, PRD **83** 121501



Numerical stability still an issue...

5. BH Holography

The AdS/CFT conjecture

Maldacena, Adv.Theor.Math.Phys. **2** 231

- "strong form": Type IIb string theory on $AdS_5 \times S^5$

  $\Leftrightarrow \mathcal{N} = 4$ super Yang-Mills in $D = 4$

  Hard to prove; non-perturbative Type IIb String Theory?

- "weak form": low-energy limit of string-theory side

  $\Rightarrow$ Type IIb Supergravity on $AdS_5 \times S^5$

- Some assumptions, factor out S^5

  $\Rightarrow$ General Relativity on AdS_5

- Corresponds to limit of large N, $g^2 N$ in the field theory

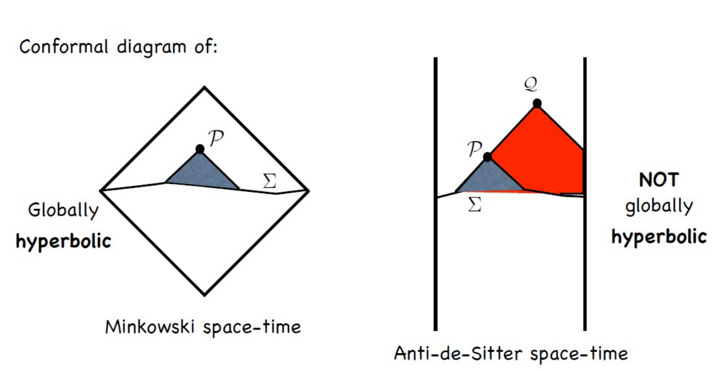
- E. g. Stationary AdS BH $\Leftrightarrow$ Thermal Equil. with T_{Haw} in dual FT

  Witten, Adv.Theor.Math.Phys. **2** 253

The boundary in AdS

- Dictionary between metric properties and vacuum expectation values of CFT operators.

  E. g. $T_{\alpha\beta}$ operator of CFT $\leftrightarrow$ transverse metric on *AdS* boundary.
- The boundary plays an active role in *AdS*! Metric singular!



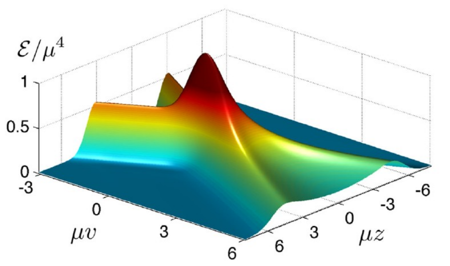
Collision of planar shockwaves in $\mathcal{N} = 4$ SYM

- Heavy-ion collisions (RHIC, LHC) $\Rightarrow$ Strongly coupled QGP
- Dual to colliding gravitational shock waves in AADS
- Characteristic study with translational invariance

  Chesler & Yaffe PRL **102** 211601, PRD **82** 026006, PRL **106** 021601

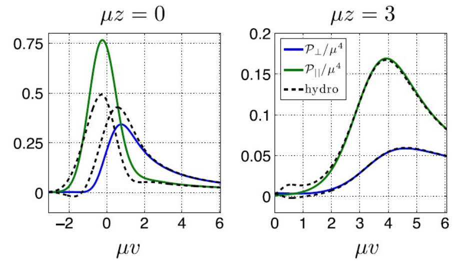
- Initial data: 2 superposed shockwaves

  $$ds^2 = r^2[-dx_+ dx_- + d\mathbf{x}_\perp] + \frac{1}{r^2}[dr^2 + h(x_\pm)dx_\pm^2]$$



Collision of planar shockwaves in $\mathcal{N} = 4$ SYM

- Initially system far from equilibrium
- Thermalization after $\Delta v \sim 4/\mu \sim 0.35\ fm/c$
- Confirms hydro sims. of QGP $\sim 1\ fm/c$ Heinz, nucl-th/0407067



- Non-linear vs. linear Einstein Eqs. agree within ~ 20 %
  Heller et al, PRL **108** (2012) 191601
- Thermalization in ADM formulation Heller et al, PRD **85** (2012) 126002

Cauchy ("4+1") evolutions in asymptotically AdS

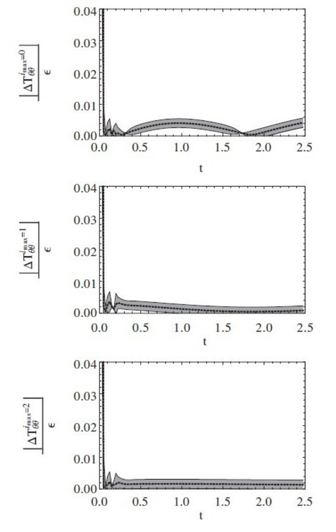
- Characteristic coordinates successful numerical tool in AdS/CFT
- But: restricted to symmetries, caustics problem...
- Cauchy evolution needed for general scenarios? Cf. BBH inspiral!!
- Cauchy scheme based on generalized harmonic formulation

  Bantilan & Pretorius, PRD **85** (2012) 084038

  - $SO(3)$ symmetry
  - Compactify "bulk radius"
  - Asymptotic symmetry of AdS_5: $SO(4,2)$
  - Decompose metric into AdS_5 piece and deviation
  - Gauge must preserve asymptotic fall-off

Cauchy (“4+1”) evolutions in asymptotically AdS

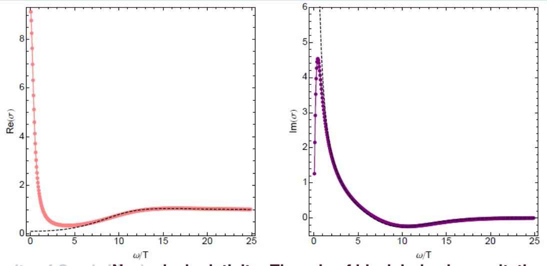
- Scalar field collapse
- BH formation and ringdown
- Low order QNMs $\sim$ perturbative studies, but mode coupling
- CFT stress-energy tensor consistent with thermalized $\mathcal{N} = 4$ SYM fluid
- Difference of CFT $T_{\theta\theta}$ and hydro ($+1^{st}$, 2^{nd} corrs.)



Conductivity and holography

Horowitz, Santos & Tong, arXiv:1204.0519, arXiv:1209.1098

- Goal: AC conductivity of cuprates (strange metals)
- Einstein-Maxwell in $D = 4$ with negative Λ plus scalar field
- Perturbed Reissner-Nordström AdS BH
- Conductivity in frequency space:
  - Drude's result at low ω, QFT plateau at high ω
  - Intermediate $\sim \omega^{-2/3}$ fall-off; cf. experiment!



6 Fundamental properties of BHs

Stability of AdS

- $m = 0$ scalar field in as. flat spacetimes Choptuik, PRL **70** 9

  $p > p^* \Rightarrow$ BH, $p < p^* \Rightarrow$ flat

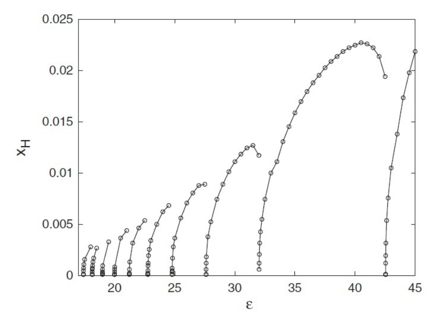
- $m = 0$ scalar field in as. AdS Bizoń & Rostworowski, PRL **107** 031102

- Similar behaviour for “Geons”
  Dias et al, CQG **29** 194002

- $D > 4$ dimensions
  Jałmużna et al, PRD **84** 085021

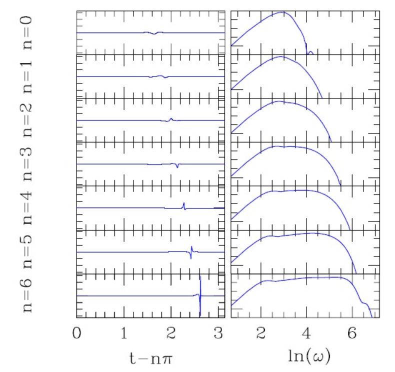
- $D = 3$: Mass gap: smooth solutions
  Bizoń & Jałmużna, arXiv:1306.0317

$\rightarrow$ Talk P.Bizoń



Stability of AdS

- Pulses narrow under successive reflections
  Buchel et al, PRD **86** 123011



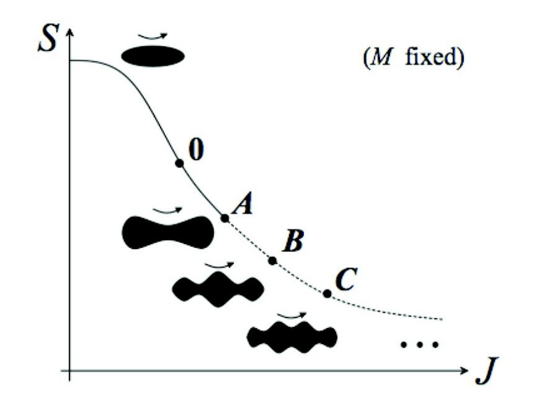
- ∃ Non-linearly stable solutions in AdS
  Dias et al, CQG **29** 235019, Buchel et al, arXiv:1304.4166,
  Maliborski & Rostworowski arXiv:1303.3186

Ray tracing for Choptuik type collapse

Thanks to Rob Hocking, DAMTP Cambridge

Bar mode instability of Myers-Perry BH

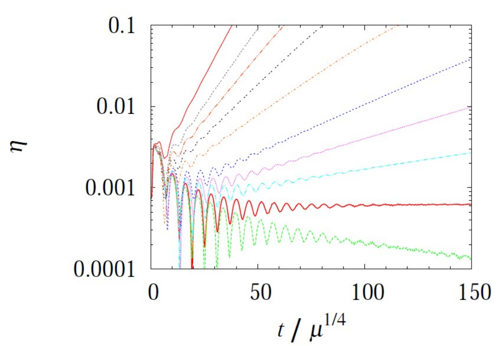
- MP BHs (with single ang.mom.) should be unstable.
- Linearized analysis Dias et al, PRD **80** 111701(R)



Non-linear analysis of MP instability

Shibata & Yoshino, PRD **81** 104035

- Myers-Perry metric; transformed to Puncture like coordinate
- Add small bar-mode perturbation
- Deformation $\eta := \frac{2\sqrt{(l_0 - l_{\pi/2})^2 + (l_{\pi/4} - l_{3\pi/4})^2}}{l_0 + l_{\pi/2}}$



Superradiant instability

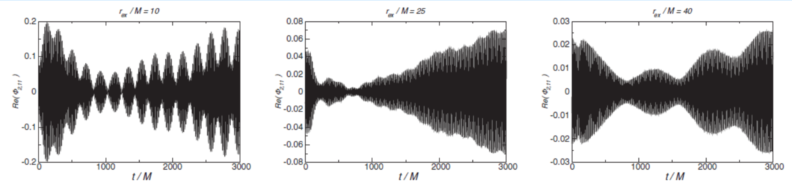
- Scattering of waves with $\text{Re}[\omega]$ off BH with ang. horizon velocity Ω_H

  $\Rightarrow$ amplification $\Leftrightarrow$ $\text{Re}[\omega] < m\Omega_H$

- Measure photon mass? Pani et al, PRL **109** (2012) 131102

- Numerical simulations Dolan, arXiv:1212.1477 Witek et al

- Instability of spinning BHs, Beating effects



Witek et al, PRD **87** (2013) 043513

More $\rightarrow$ Talks H.Okawa, H.Witek

Cosmic Censorship in $D = 5$

Pretorius & Lehner, PRL **105** 101102

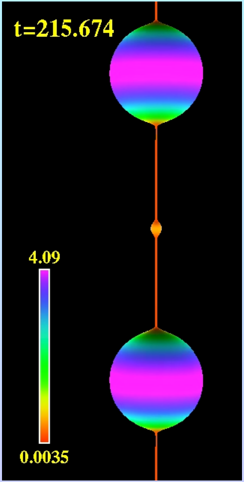
- Axisymmetric code
- Evolution of black string...
- Gregory-Laflamme instability

  cascades down

  in finite time

  until string has zero width

  $\Rightarrow$ naked singularity

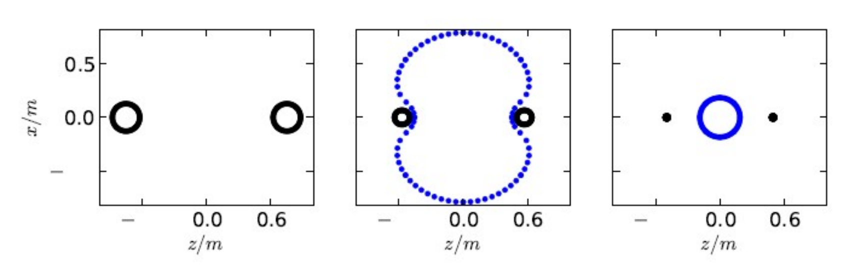


Cosmic Censorship in $D = 4$ de Sitter

Zilhão et al, PRD **85** (2012) 124062

- Two parameters: MH, d
- Initial data: McVittie type binaries McVittie, MNRAS **93** (1933) 325
- "Small BHs": $d < d_{crit} \Rightarrow$ merger

  $d > d_{crit} \Rightarrow$ no common AH
- "Large" holes at small d: Cosmic Censorship holds



Conclusions

- Nearly 10 years after breakthroughs, codes matured
- GW template bank within reach
- Kicks still getting bigger
- High-energy collisions understood in $D = 4$, higher $D \rightarrow$ stability
- Applications to AdS/CFT exploding...
- NR reveals new insight into BH stability