



## II Workshop on Black Holes

21-22 December 2009 | Instituto Superior Técnico, Lisboa



## High-energy collisions of black holes

Vitor Cardoso for Ulrich Sperhake (Caltech)

*Phys. Rev. Lett.*101,161101 (2008); *arXiv:0806.1738*

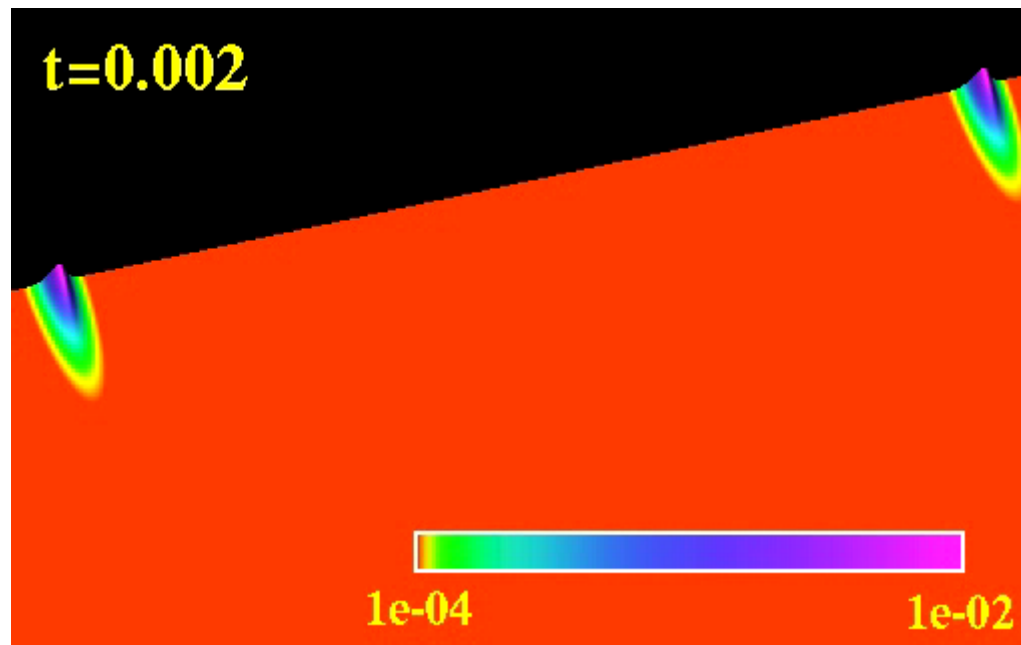
*Phys. Rev. Lett.*103,131102 (2009); *arXiv:0907.1252*

# High energy collisions

## The Hoop Conjecture

•Two boson stars

$$2M/R = 1/20, \quad \gamma > 3$$



*Courtesy of Pretorius*

*K. Thorne, 1972; Choptuik and Pretorius, arXiv:0908.1780*

# High energy collisions

- **Black holes do form in high energy collisions**
- **Trans-Planckian scattering is well described by BH collisions!**

# High energy collisions

- **Black holes do form in high energy collisions**
- **Trans-Planckian scattering is well described by BH collisions!**
- **Test Cosmic Censorship**
- **TeV-scale gravity** (see M. Sampaio, C. Espírito Santo)
- **Holography and HIC** (P. Pani's talk)
- **Universal Dyson Limit**  $dE/dt < c^5/G = 10^{59}$  erg/s
- **Test analytical techniques, etc**

# Numerical Results

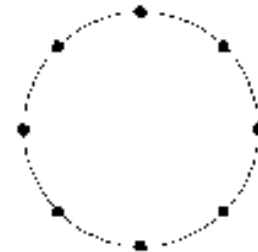
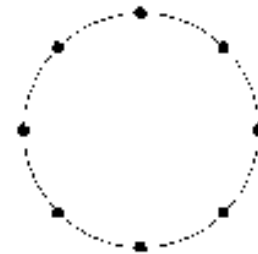
(For Numerical procedure see Zilhão and Witek's talk)

- Most important result: Emitted gravitational waves (GWs)
- Newman-Penrose scalar (Nerozzi's talk)

$$\Psi_4 = C_{\alpha\beta\gamma\delta} n^\alpha m^\beta n^\gamma m^\delta$$

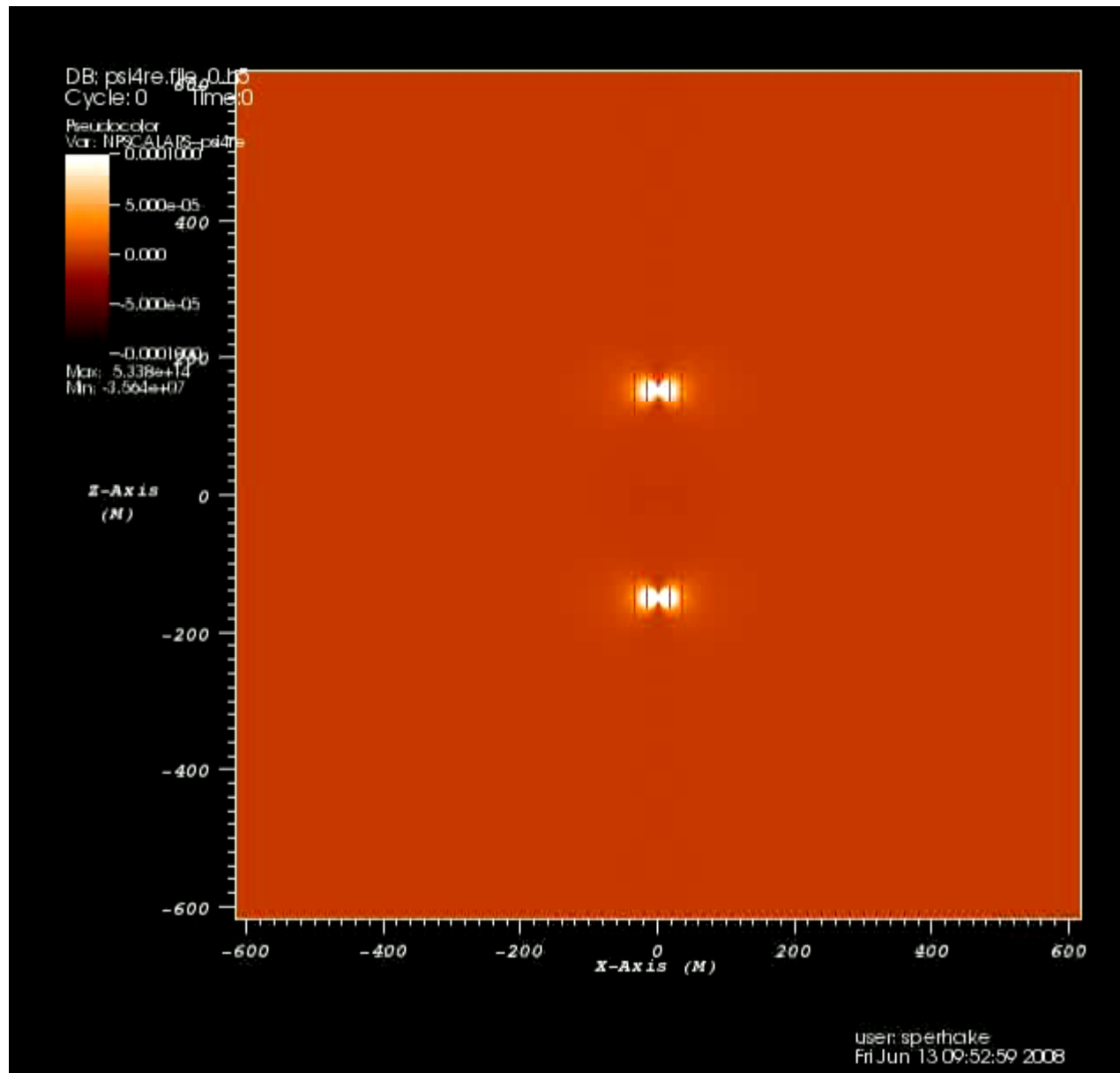
Complex  $\rightarrow$  2 free functions

- GWs allow us to measure
  - ✓ Radiated energy  $E_{\text{rad}}$
  - ✓ Radiated momenta  $P_{\text{rad}}, J_{\text{rad}}$

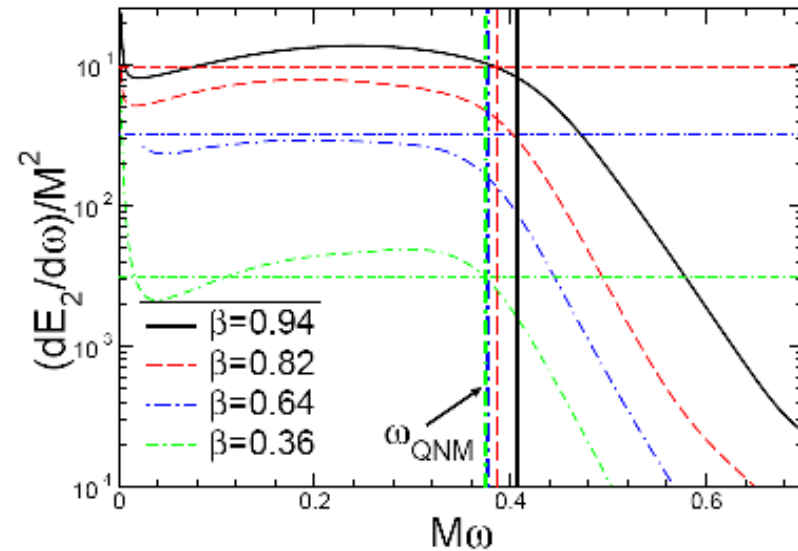
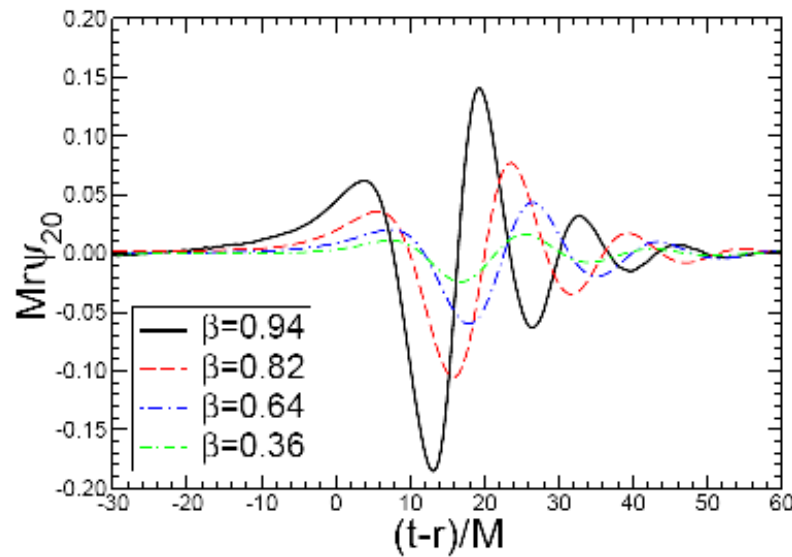


# Results

$$\beta = 0.93$$

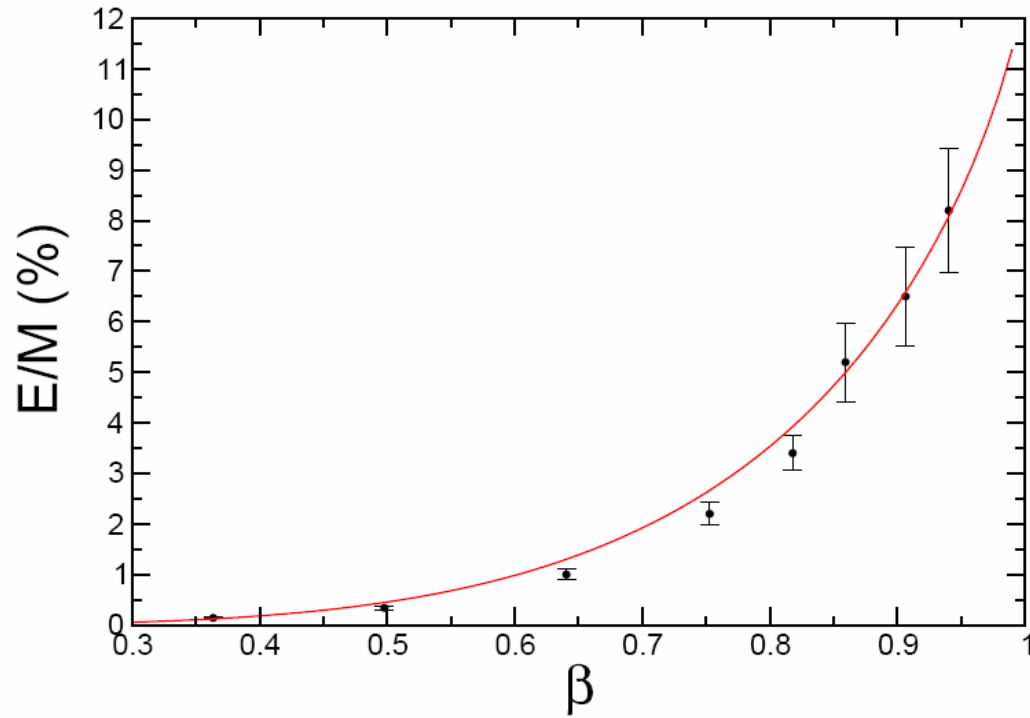


# Results



- **Waveform is almost just ringdown**
- **Spectrum is flat, in good agreement with ZFL (M. Lemos talk)**
- **Cutoff frequency at the lowest quasinormal frequency**

# Results



14%

$$\frac{E}{M} = E_{\infty} \left( \frac{1 + 2\gamma^2}{2\gamma^2} + \frac{(1 - 4\gamma^2) \log(\gamma + \sqrt{\gamma^2 - 1})}{2\gamma^3 \sqrt{\gamma^2 - 1}} \right)$$

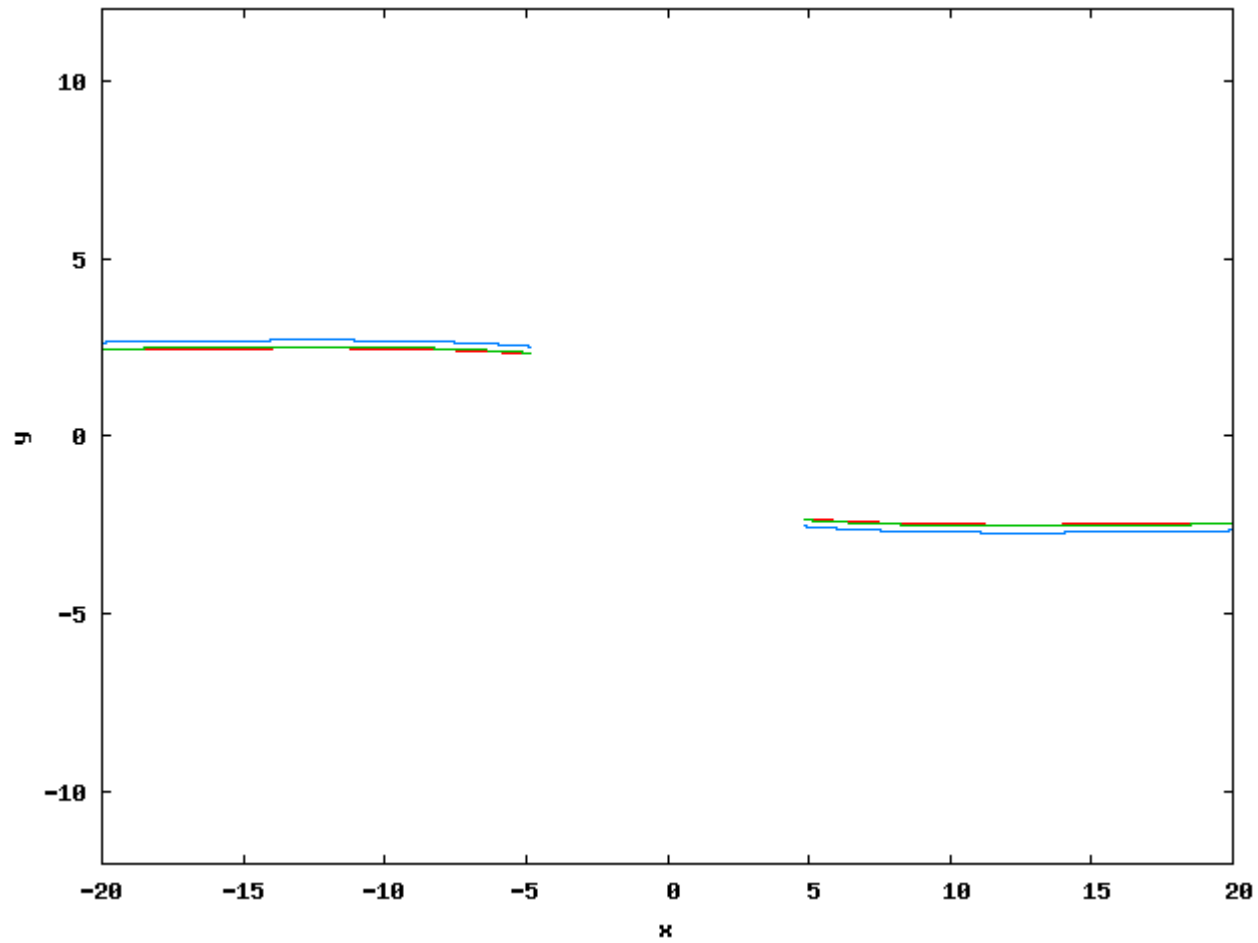


# Head-on Collisions

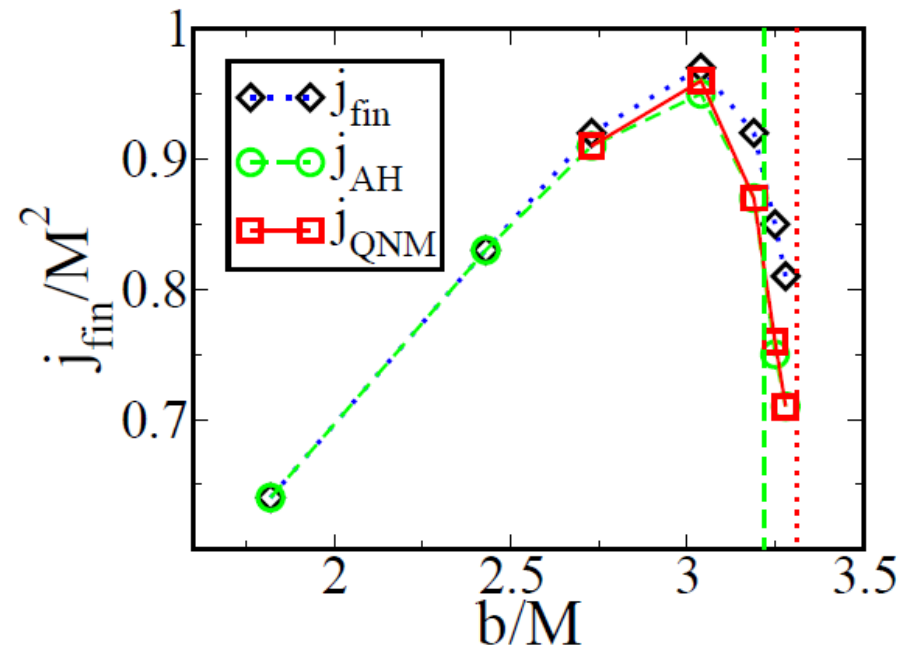
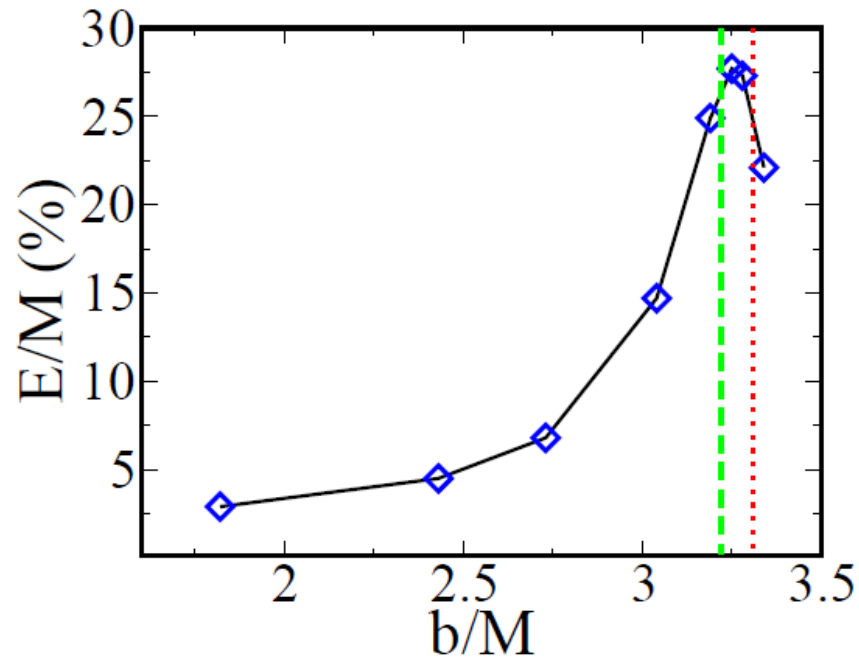
- Cosmic Censor as strong as ever
- About 14% is radiated away as  $v$  goes to the speed of light.
- Max. Luminosity:  $10^{-2}c^5/G$  factor 100 below Dyson
- (large amounts of junk: interesting topic for further study)

# Grazing Collisions

Plunge, zoom-whirl and scattering



# Grazing Collisions



More than 25% CM energy radiated for  $v=0.75 c!$

Final BH rapidly spinning

# Grazing Collisions

- Cosmic Censor as strong as ever
- Production cross-section:  $b/M=2.5/v$
- Max. Luminosity: close to Dyson limit (less than a factor 10)
- Maximum spin  $>0.95$
- Radiated energy  $>35\%CM$

## Future work

- Higher dimensions, other backgrounds (Witek, Zilhão)
- Can one see black ring formation? New phases?
- Spin, charge?
- Control de amount of junk radiation, increase boost, etc

**Thank you**