High Energy Collisions of Black Holes Revisited

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Outline

- Previous Results
- Bowen York ID/Lorentz Boosted ID
- Numerical Infrastructure
- Initial configurations
- Results and Error analysis

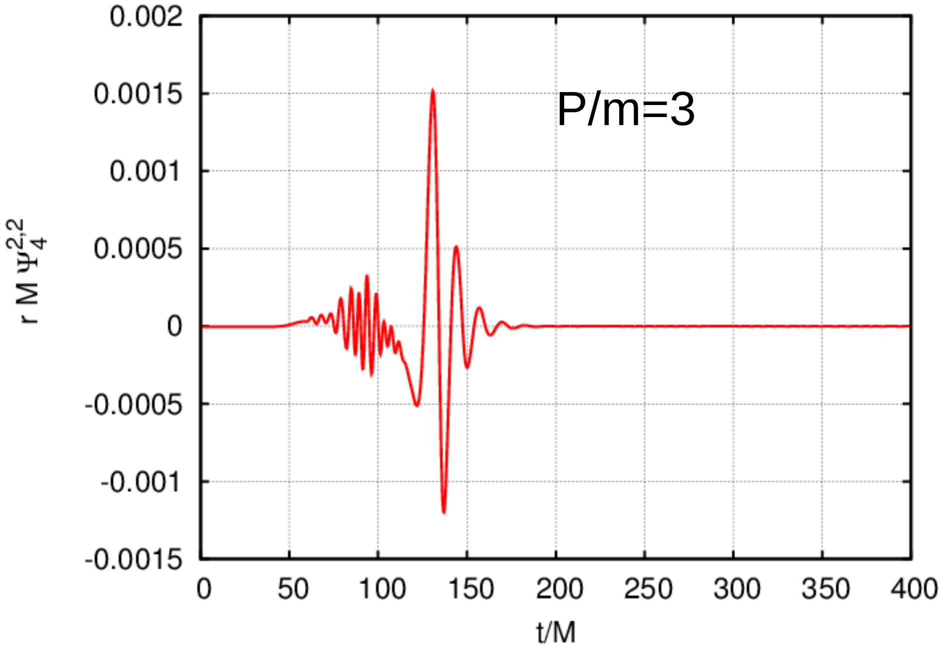
Previous Studies

- Maximum E_{rad} from Area Theorems by Hawking and Penrose is 29%
- By applying perturbation theory to the collision of shock waves, the maximum E_{rad} is 25% and 16.4% for 1st and 2nd order corrections, respectively (D'Eath and Payne, 1992)
- First numerical relativity study by Sperhake et al. (2008) found E_{rad}= 14 +/- 3%
- Latest theoretical work:
  - Black hole thermodynamics: E_{rad}=13.4% (Siino 2013)
  - Multipolar analysis of the ZFL: E_{rad}=17% (Berti et al. 2010)

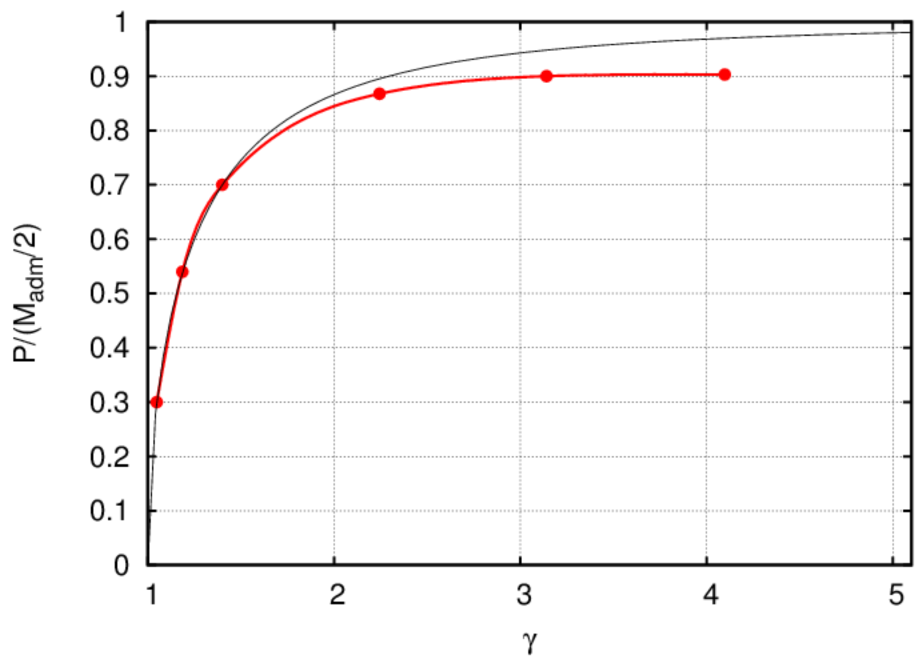
Bowen York Initial Data

- Analytic solution for the momentum constraint by assuming conformal flatness
- Uses punctures to solve Hamiltonian constraint

Spurious Radiation



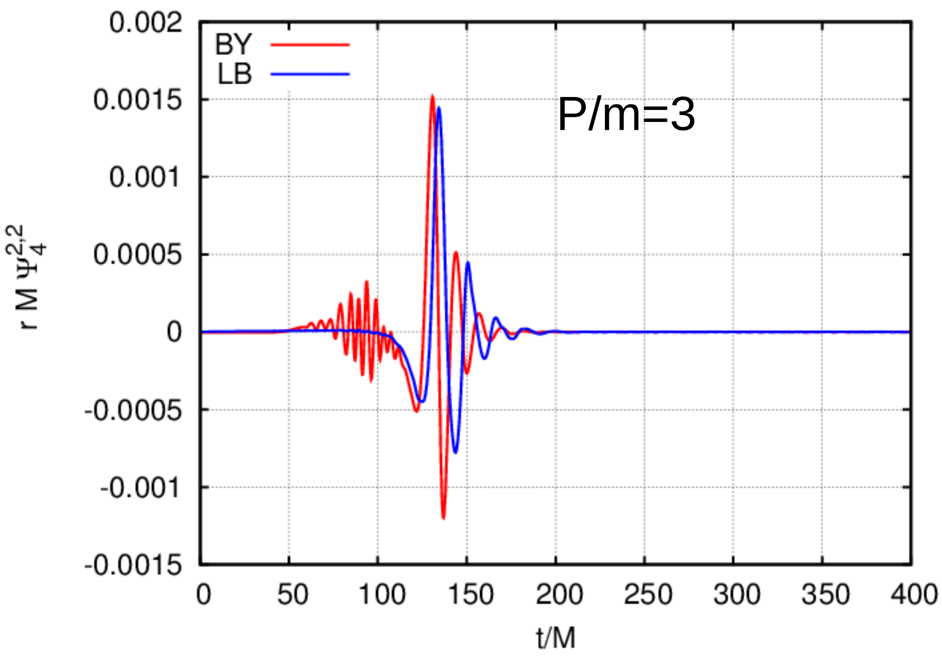
Limit to v/c at infinity



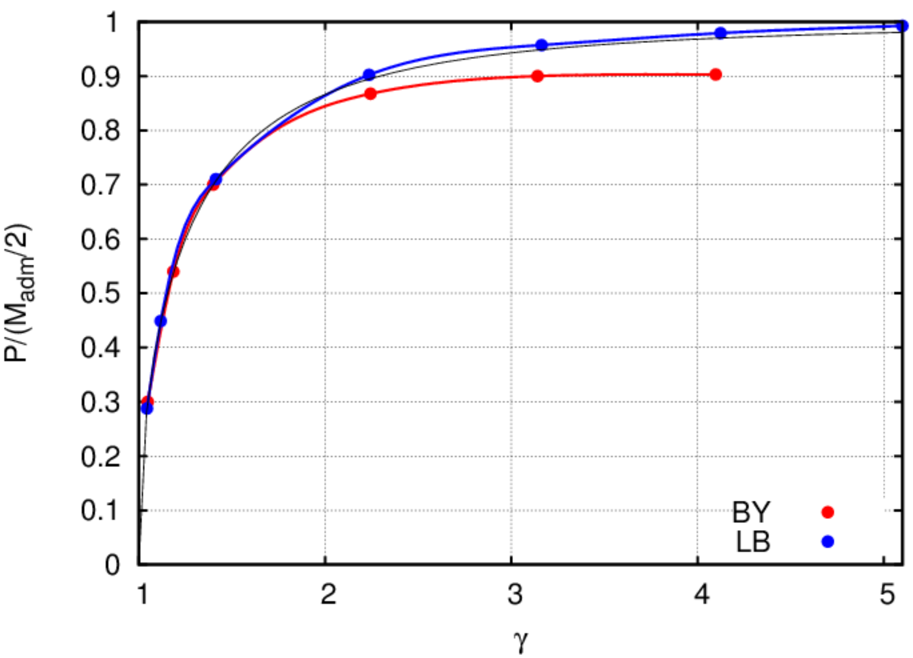
Lorentz Boosted Initial Data

- Solves both Hamiltonian and Momentum constraints using the puncture approach
- Superposes two LB spacetimes with attenuation

Spurious Radiation



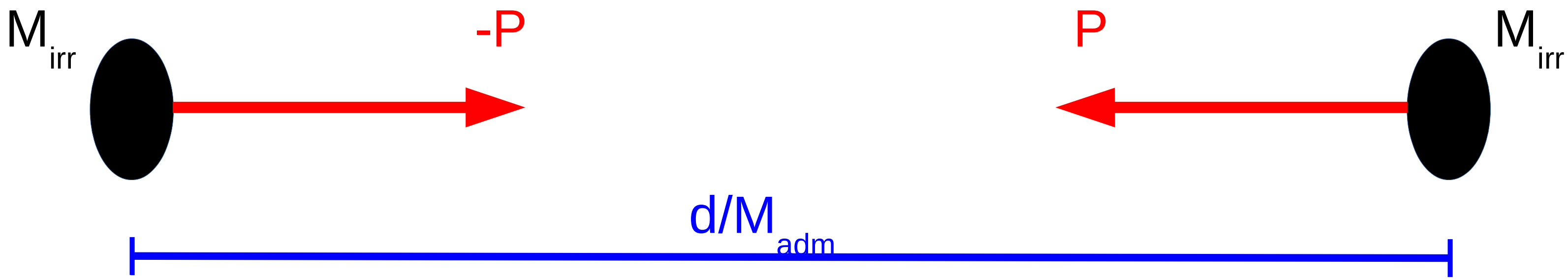
Limit to v/c at infinity



Numerical Infrastructure

- RIT's LazEv Numerical Relativity code
- Modified TwoPunctures initial data for superposed Lorentz Boosted Schwarzschild black holes
- To have stronger damping of the constraint violations we use the CCZ4 (Conformal and Covariant Z4) formulation of Einstein's Equations instead of BSSN
- To damp lapse gauge waves, we use a shock-avoiding gauge evolution and start at larger initial separations
- Accurate analytical calculations of the energy radiated at infinity

Initial Setup



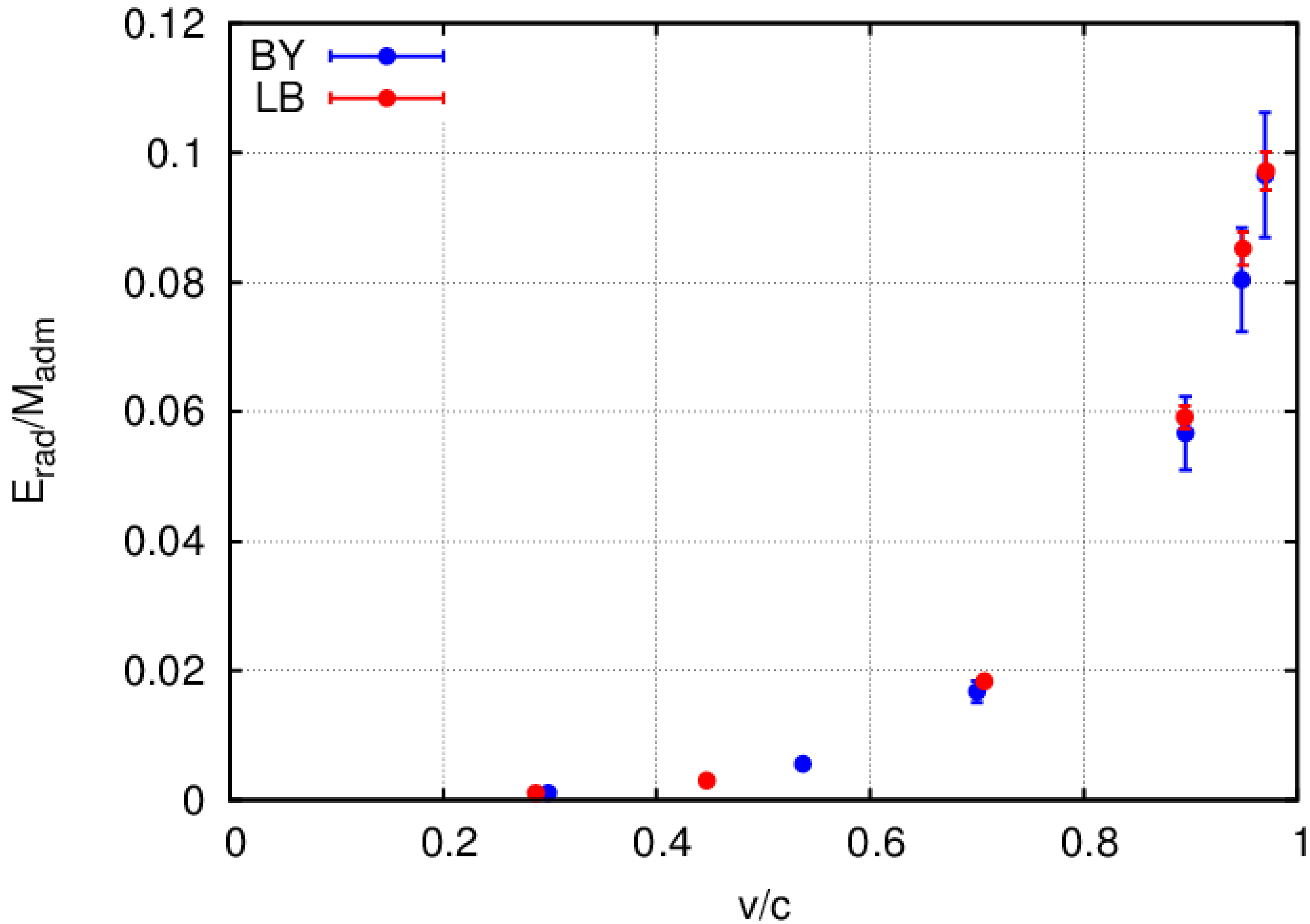
- Simple 1-parameter study
- ADM mass normalized to 1
- 6 simulations of each BY, LB BSSN, and LB CCZ4
- For LB CCZ4, d/M chosen sufficiently large that the binding energy between the BHs is small and gauge waves have time to dissipate

Lorentz Boosted CCZ4

d/M_{adm}	P/M_{irr}
100	0.3
100	0.5
200	1.0
200	2.0
300	3.0
400	4.0

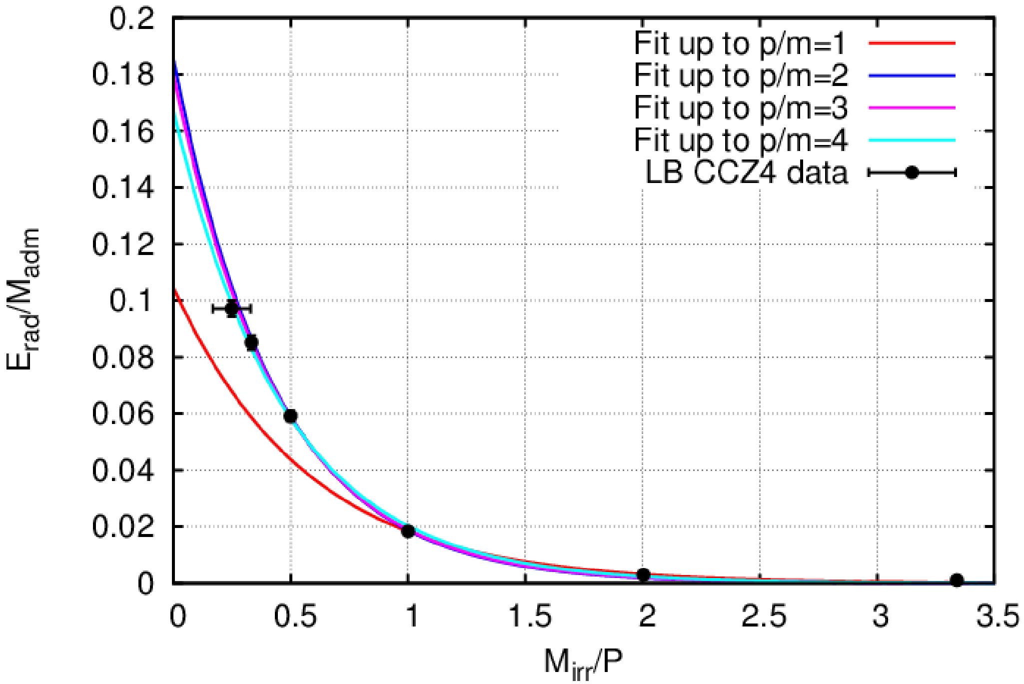
Results

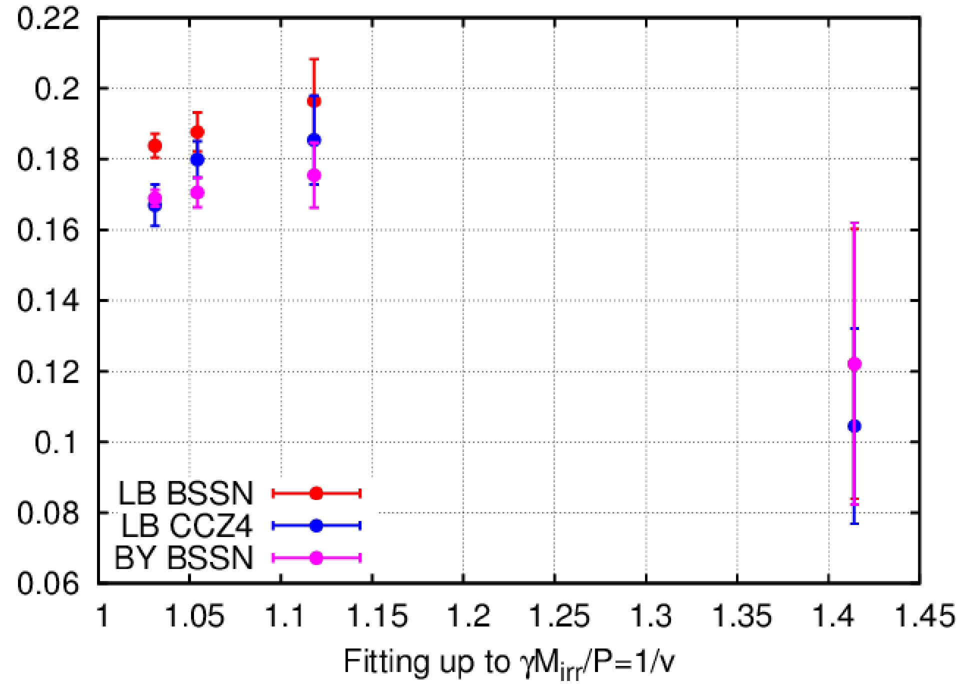
- Using BY ID, we reproduce the work of Sperhake et al. 2008
- Higher uncertainty for BY due to spurious burst
- Lorentz Boosted data agrees with BY data within error bars



Exponential Fit

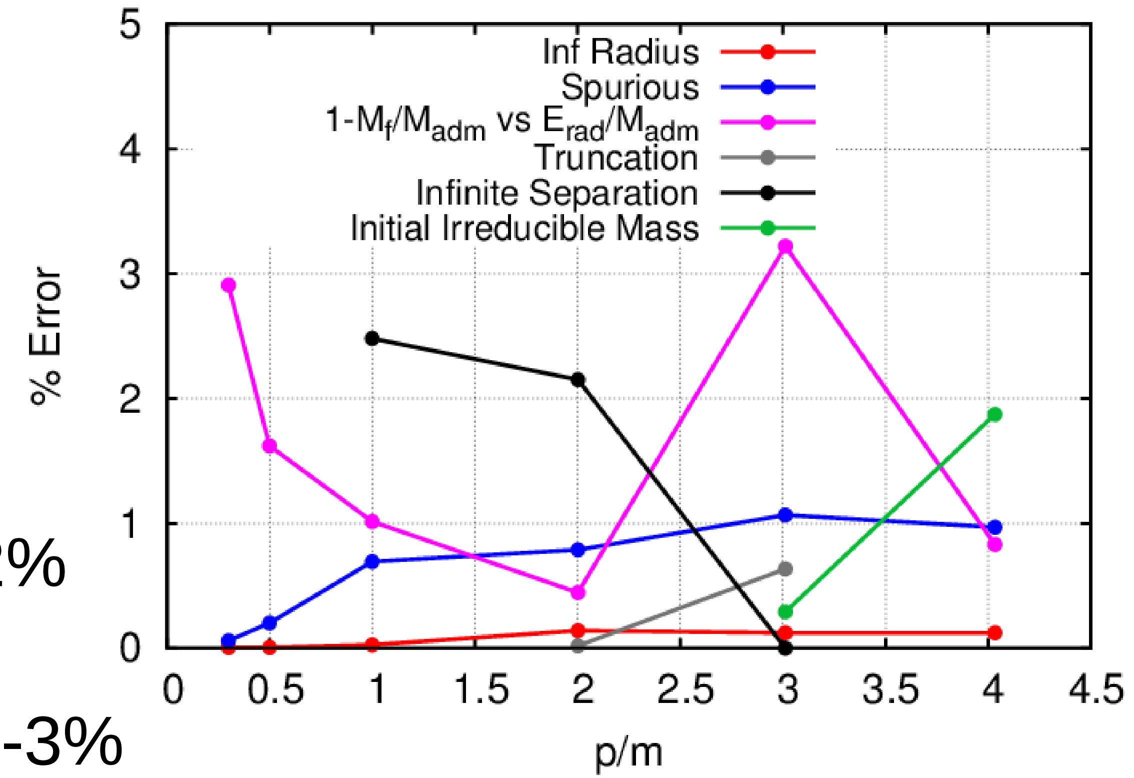
- Extrapolation to infinite P/M_{irr} using $E=A \exp(-b*M_{irr}/P)$
- To test robustness, we perform a series of exponential fits
- Using all data up to $P/M_{irr}=4$, we find between 16 and 19% energy radiated





Sources of Uncertainty

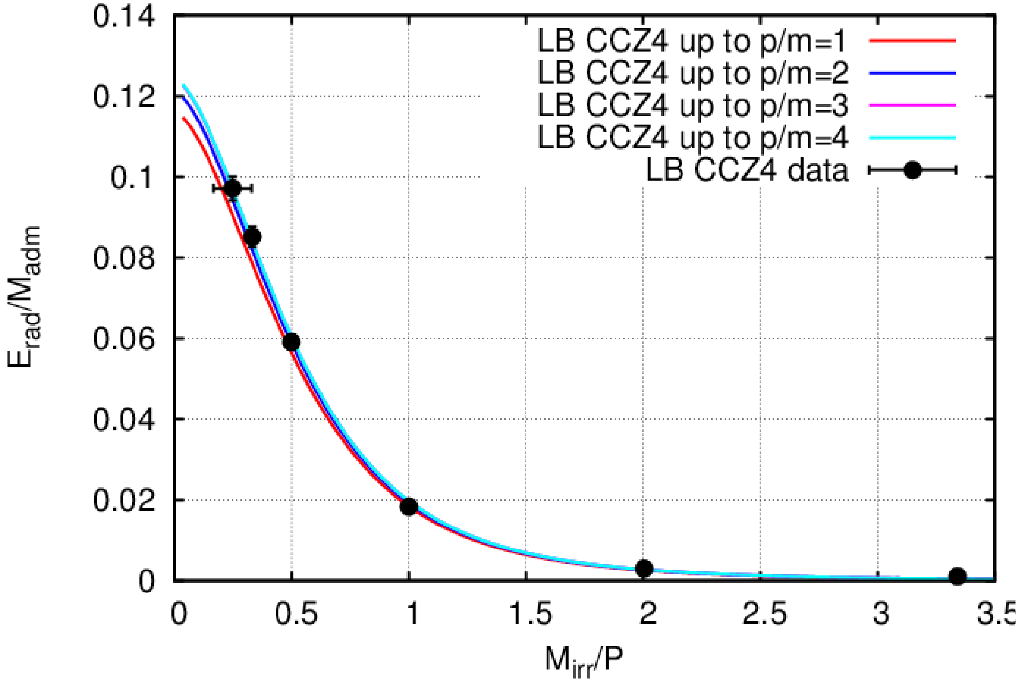
- Spurious Radiation ~ 1%
- Infinite Radius ~ 0.2%
- Truncation Error ~ 1%
- Infinite initial separation ~ 2%
- Difference in final mass ~ 1-3%

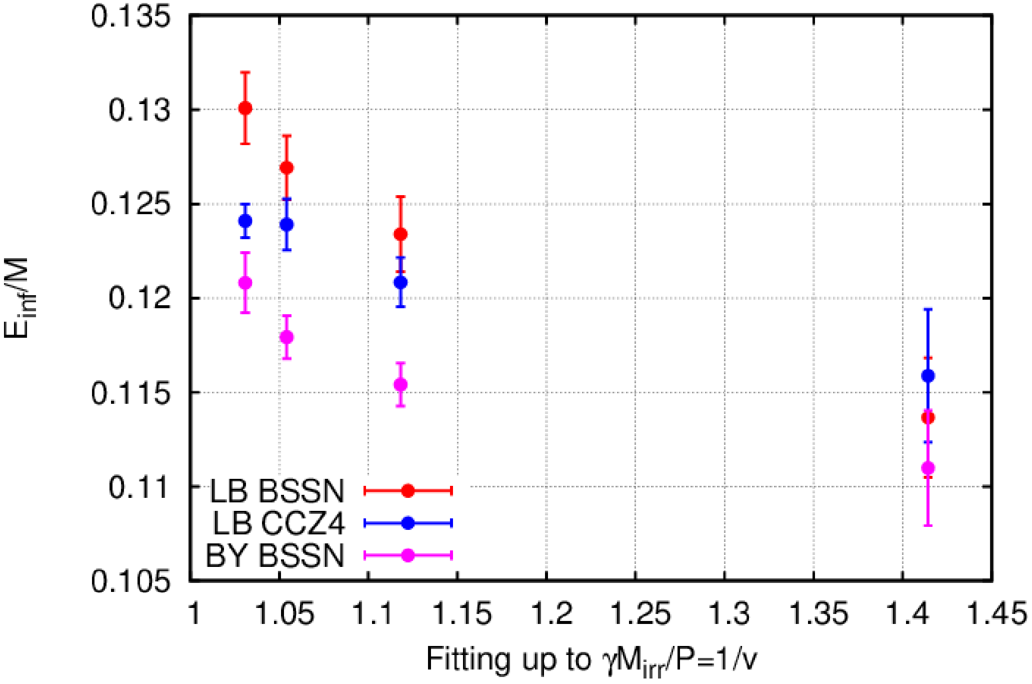


- Uncertainty in initial irreducible mass ~ 2% for P/Mirr=4

ZFL Fitting

- Extrapolation to infinite P/M_{irr} using ZFL as in Sperhake et al. 2008
- 12-13% energy radiated





Conclusions

- We produced a series of accurate BHB head-on collisions and calculated the energy radiated
- Despite the low uncertainty in the energy, both fittings work well, but yield different results
- To determine the fitting, we need to go to higher momentum – which will be very costly computationally