SENR/NRPy+:
Black Hole Binaries on the Desktop

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In collaboration with
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Thomas W. Baumgarte

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http://tinyurl.com/SENRcode

Toward Black Hole Binaries on the Desktop

1. Extend BSSN-in-spherical-coordinates technique to broader class of static, singular coordinates
   - Implement this technique in new SENR/NRPy+ code
2. Singular coordinates that comove with binary
   - First moving puncture BHB evolutions in singular curvilinear coords
   - First BHB evolutions in corotating frame, without excision
3. BHBs in dynamical, bispherical-like coordinates

Previous talk

This talk

Stay tuned!

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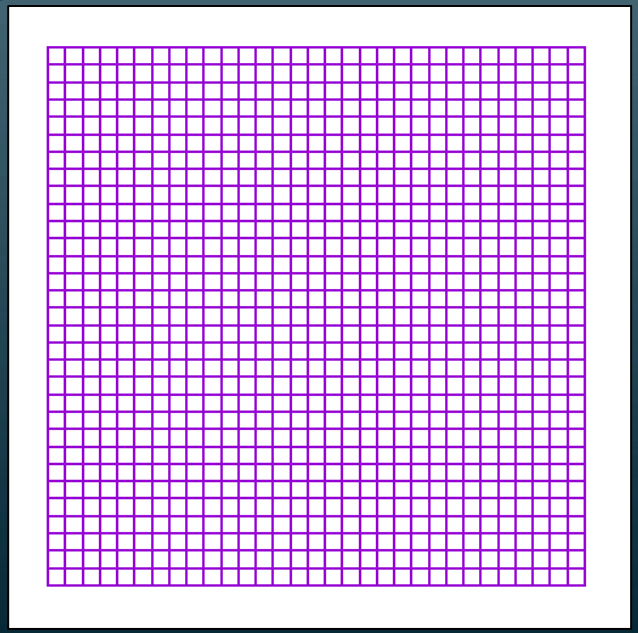
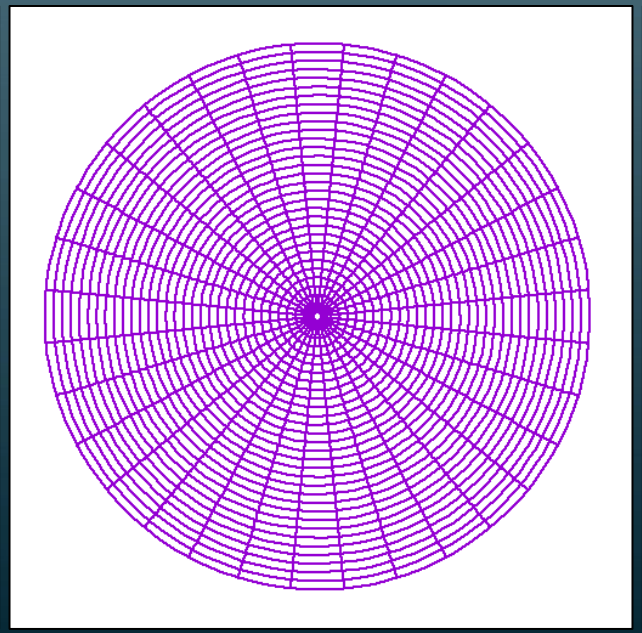
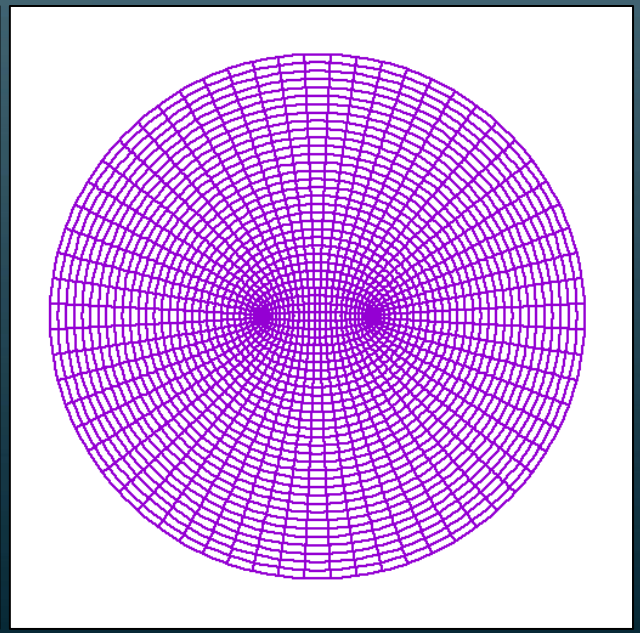
Coordinate Choices in NRPy+



Cartesian-like

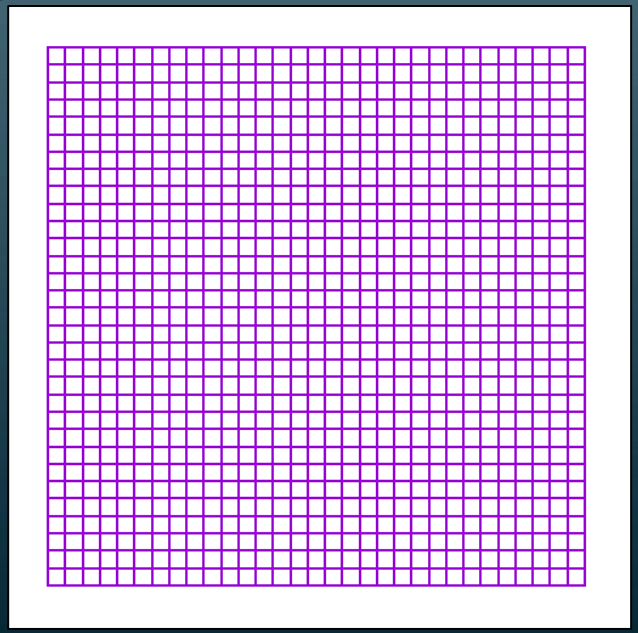


Spherical-like
Cylindrical-like

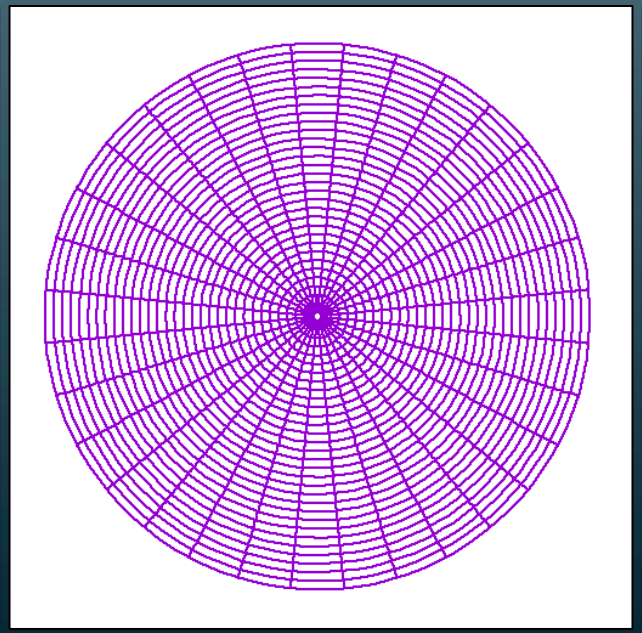


Bispherical-like

Coordinate Choices in NRPy+



Cartesian-like



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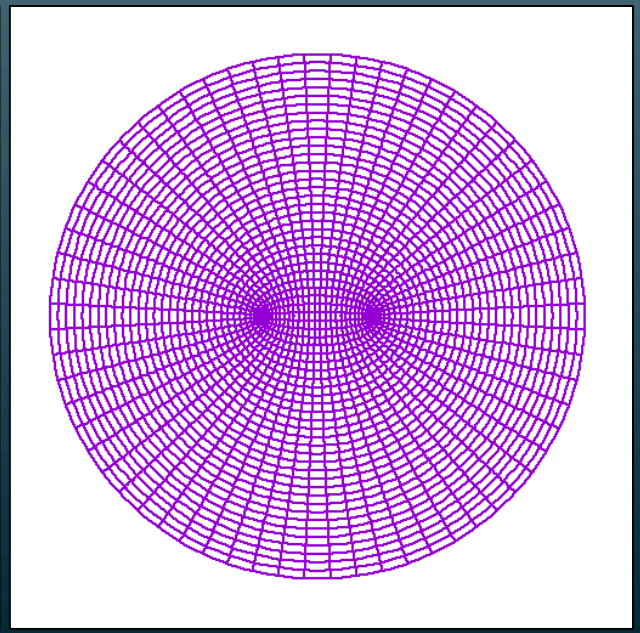
Cylindrical-like



Bispherical-like

Previous Work: Dual Frame Approach

- Used by SXS Collaboration in SpEC code (PRD 74 104006)
  - Generalized harmonic formalism (GHF)
    - Wish to keep (excised) BHs stationary
  - Cannot directly & easily modify shift, so...
    - Promote spatial coordinates to explicit functions of time:
      - $x^i \rightarrow x^i(t)$
    - Add a control system to dynamically adjust coordinates to maintain corotation
  - Net result: A dual frame
    - Harmonic gauge controls spatial slice
    - $x^i(t)$ controls numerical grid sampling

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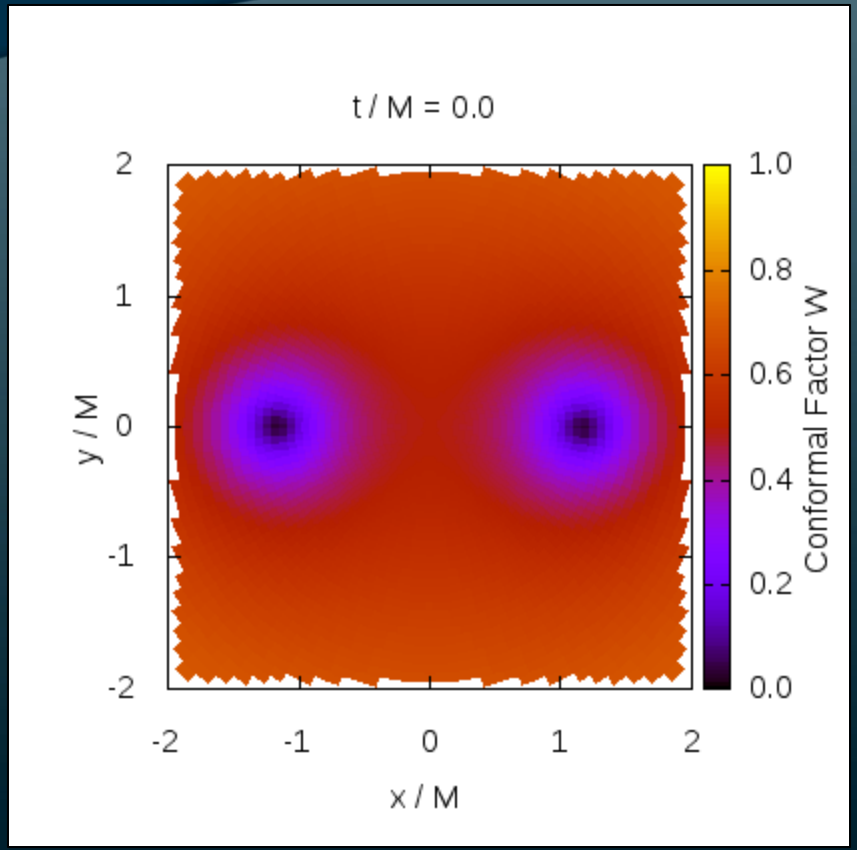
Our Approach: Adjust Shift Vector Directly!

- Moving puncture formalism:
  - Reference-metric formulation of BSSN, advective 1+log lapse, and modified advective gamma-driver shift evolution
  - Unlike GHF, shift = free param
- Based on puncture position, **adjust the shift vector** to maintain corotation about CoM
- Net result: A single frame
  - Shift vector controls both numerical grid sampling and spatial slice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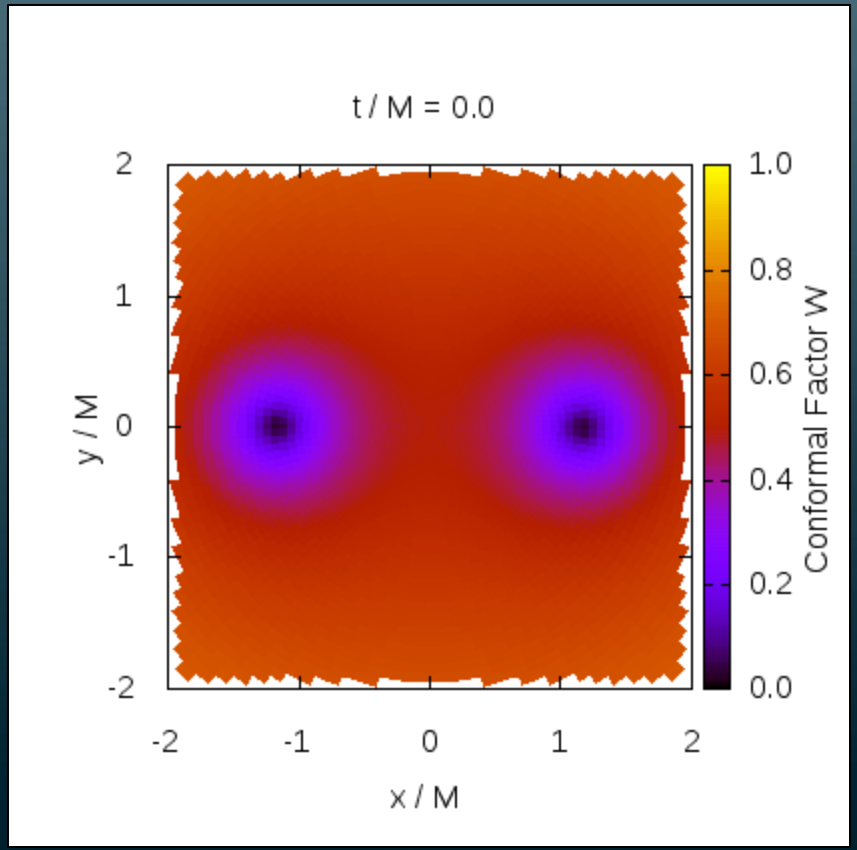
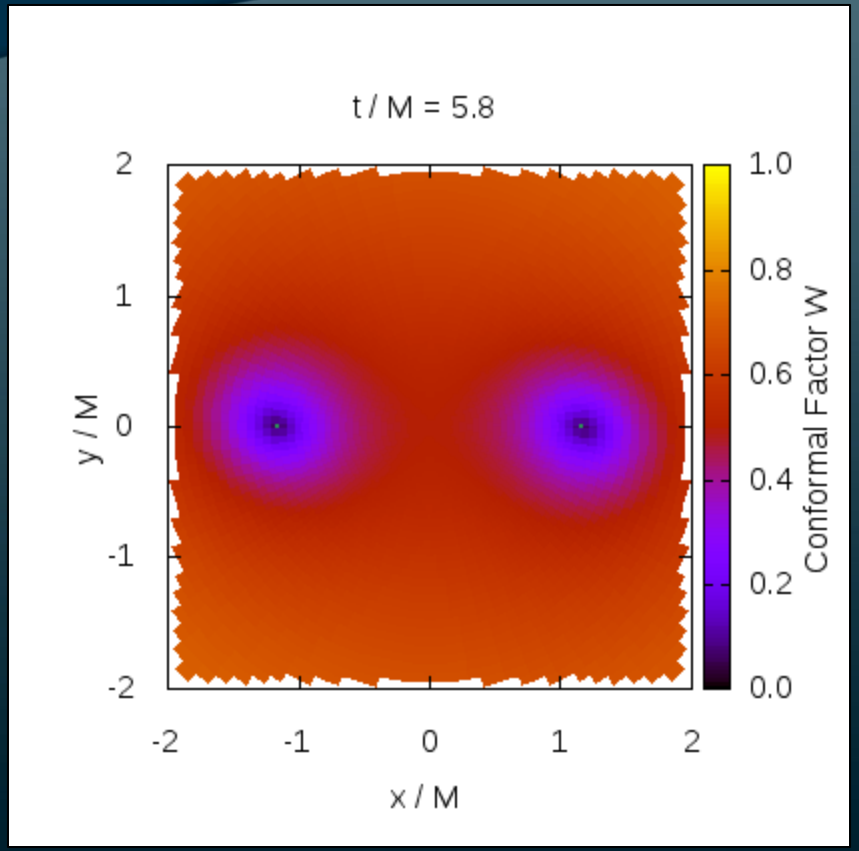
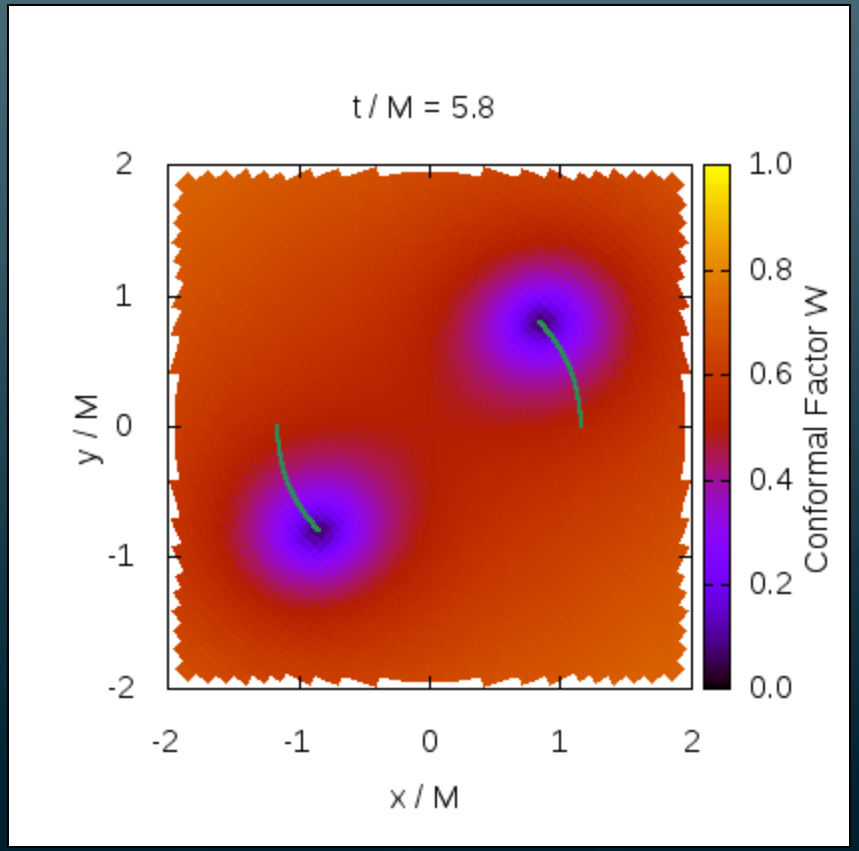
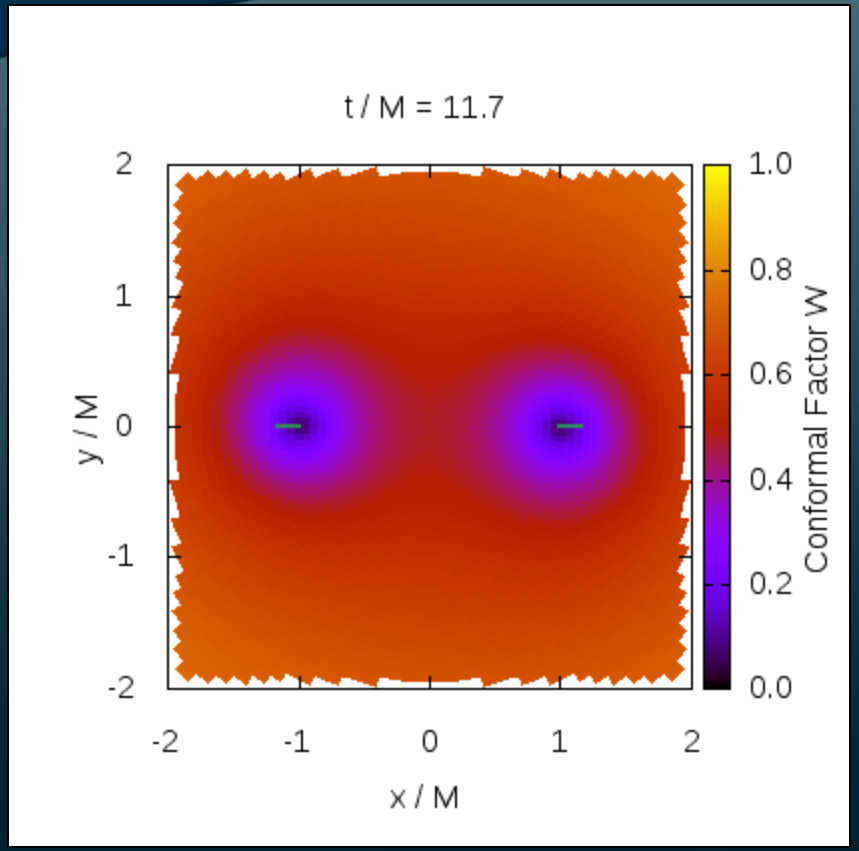
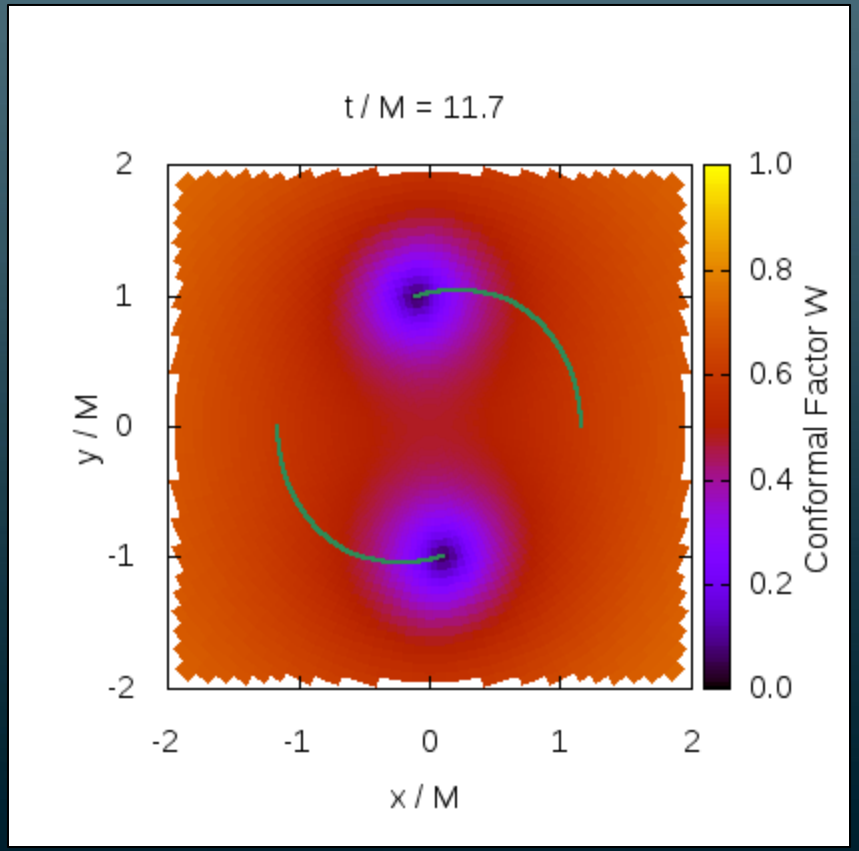
2
1
0
-1
-2
y / M
-2
-1
0
1
2
x / M
1.0
0.8
0.6
0.4
0.2
0.0
Conformal Factor W

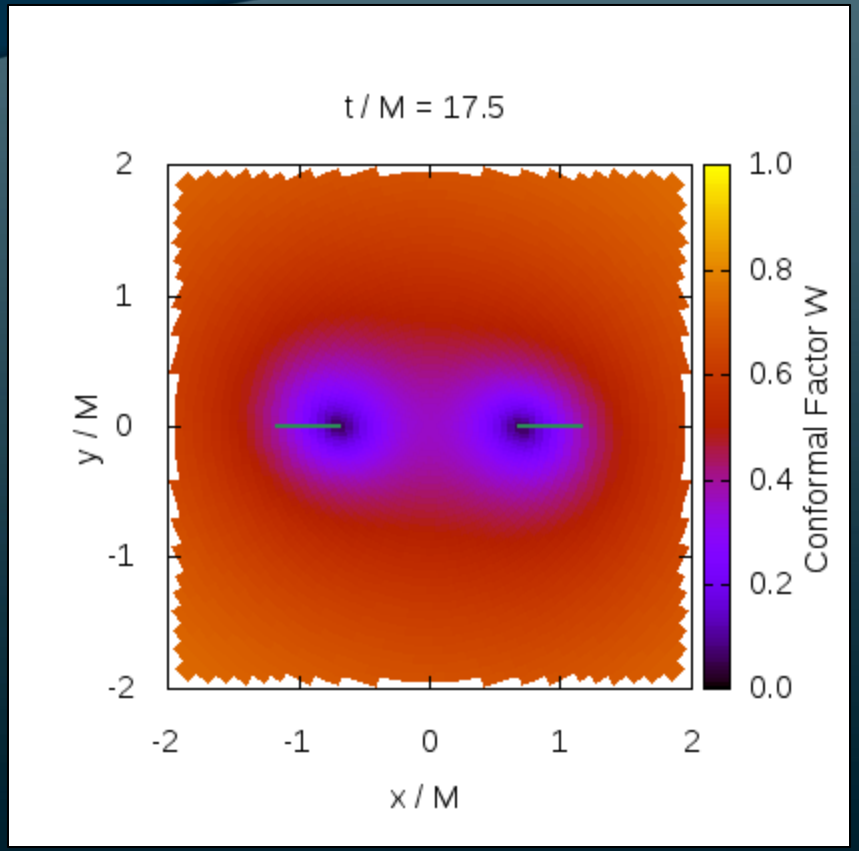

t / M = 0.0
2
1
0
-1
-2
y / M
-2
-1
0
1
2
x / M
1.0
0.8
0.6
0.4
0.2
0.0
Conformal Factor W

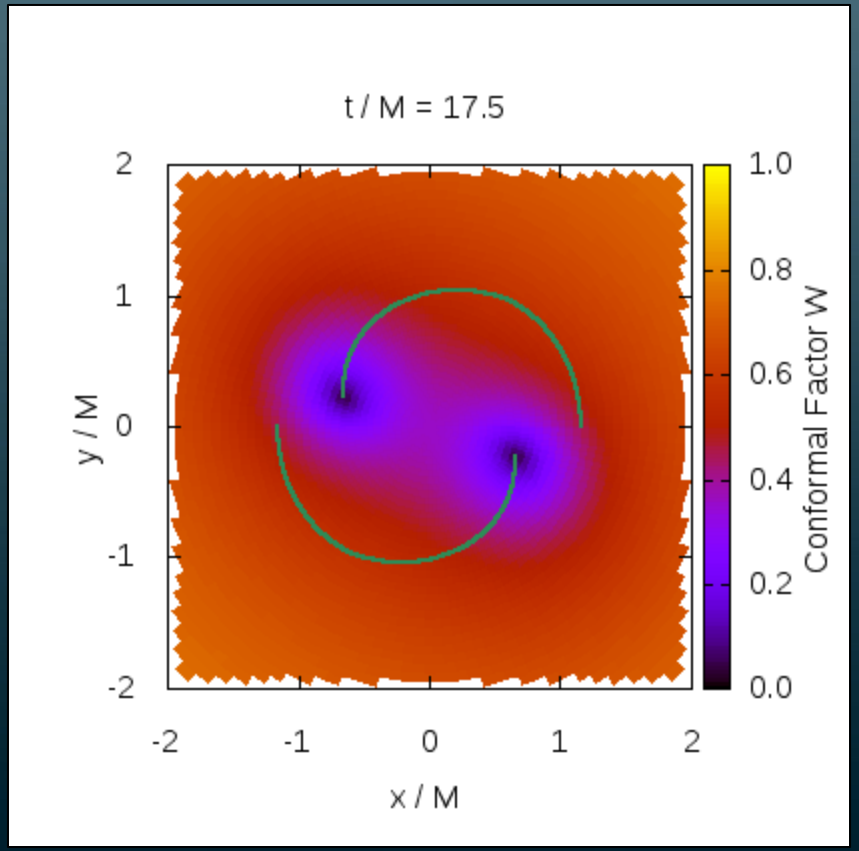

t / M = 5.8
2
1
0
-1
-2
y / M
-2
-1
0
1
2
x / M
1.0
0.8
0.6
0.4
0.2
0.0
Conformal Factor W


t / M = 5.8
2
1
0
-1
-2
y / M
-2
-1
0
1
2
x / M
1.0
0.8
0.6
0.4
0.2
0.0
Conformal Factor W


t / M = 11.7
y / M
x / M
Conformal Factor W
2
1
0
-1
-2
1.0
0.8
0.6
0.4
0.2
0.0


t / M = 11.7
y / M
x / M
Conformal Factor W
2
1
0
-1
-2
1.0
0.8
0.6
0.4
0.2
0.0


t / M = 17.5
y / M
x / M
Conformal Factor W
2
1
0
-1
-2
1.0
0.8
0.6
0.4
0.2
0.0


t / M = 17.5
y / M
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2
1
0
-1
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1.0
0.8
0.6
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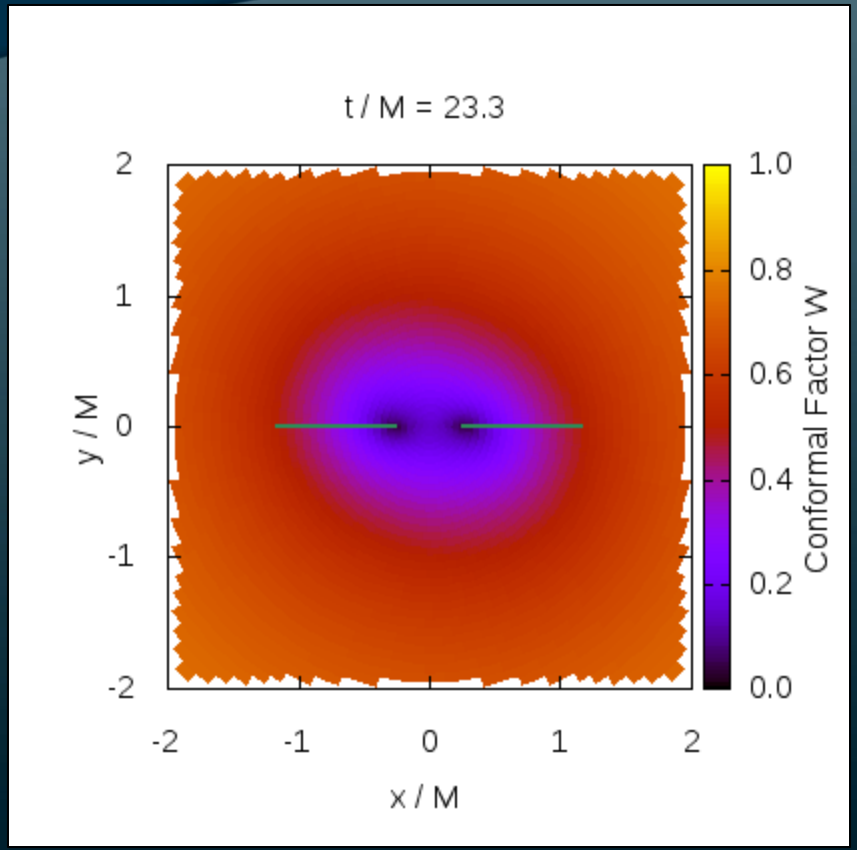
0.2
0.0


t / M = 23.3
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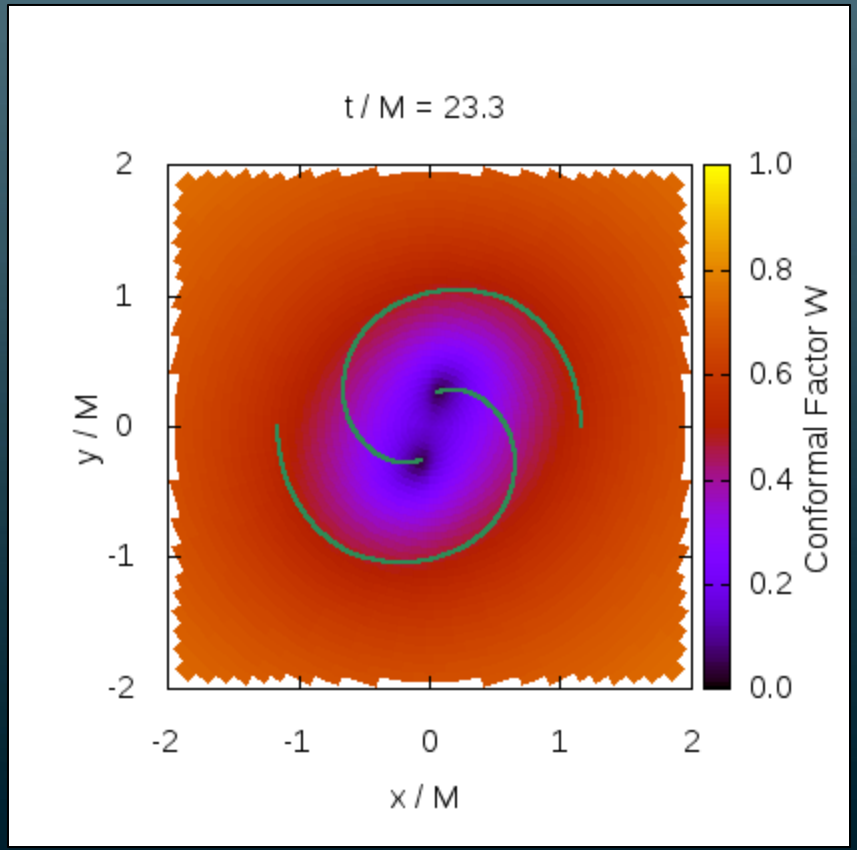
1
0
-1
-2
y / M
-2
-1
0
1
2
x / M
1.0
0.8
0.6
0.4
0.2
0.0
Conformal Factor W


t / M = 23.3
2
1
0
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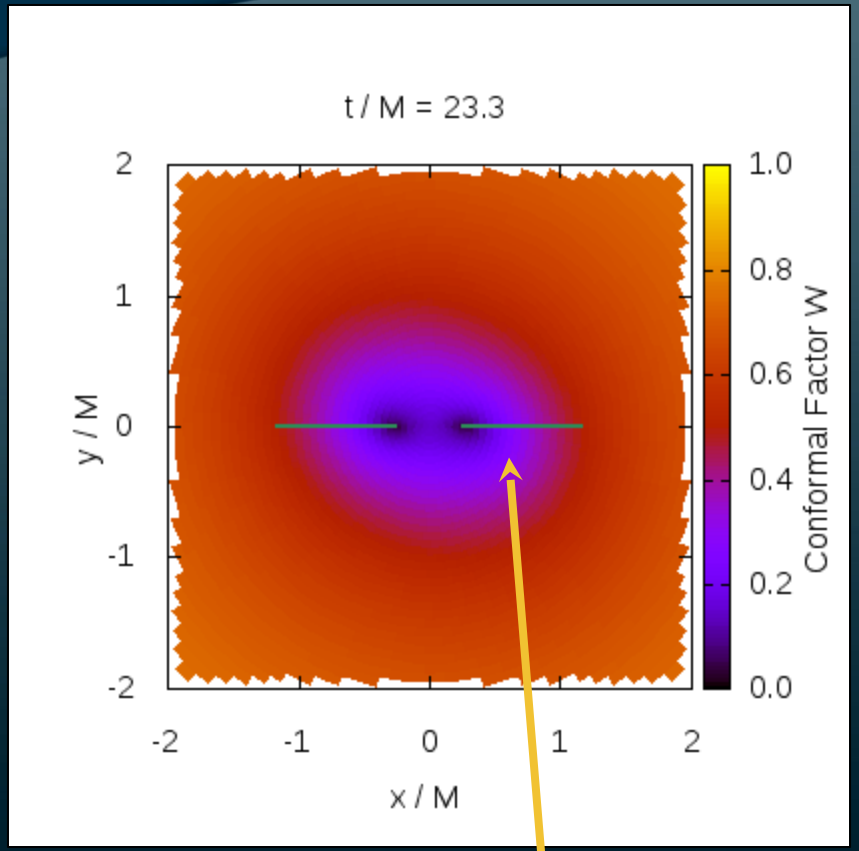
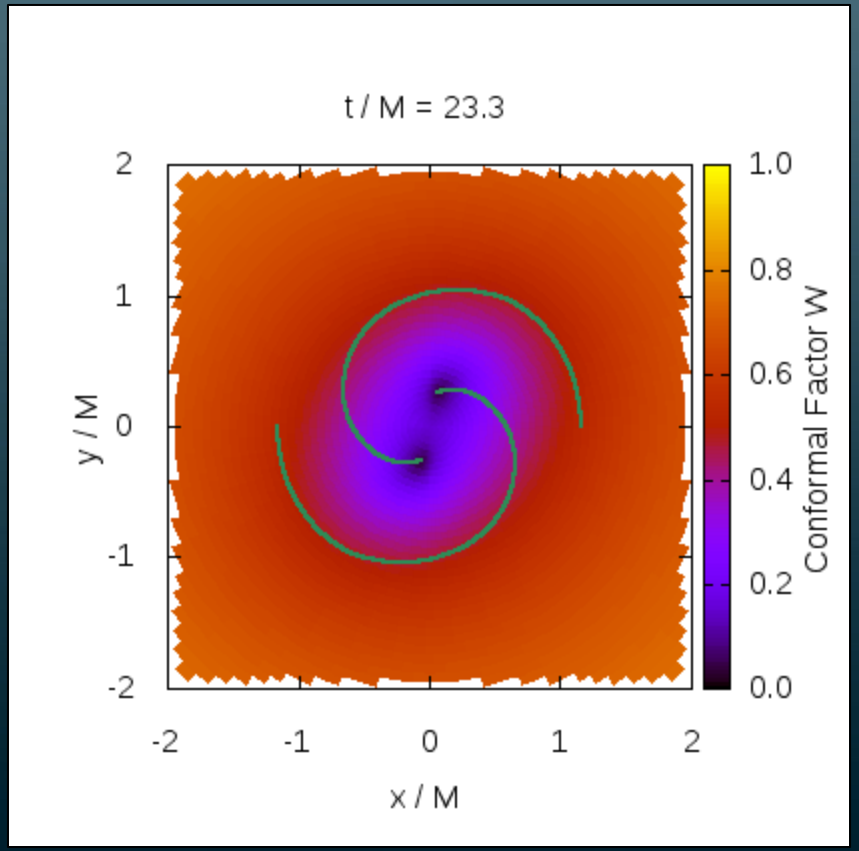
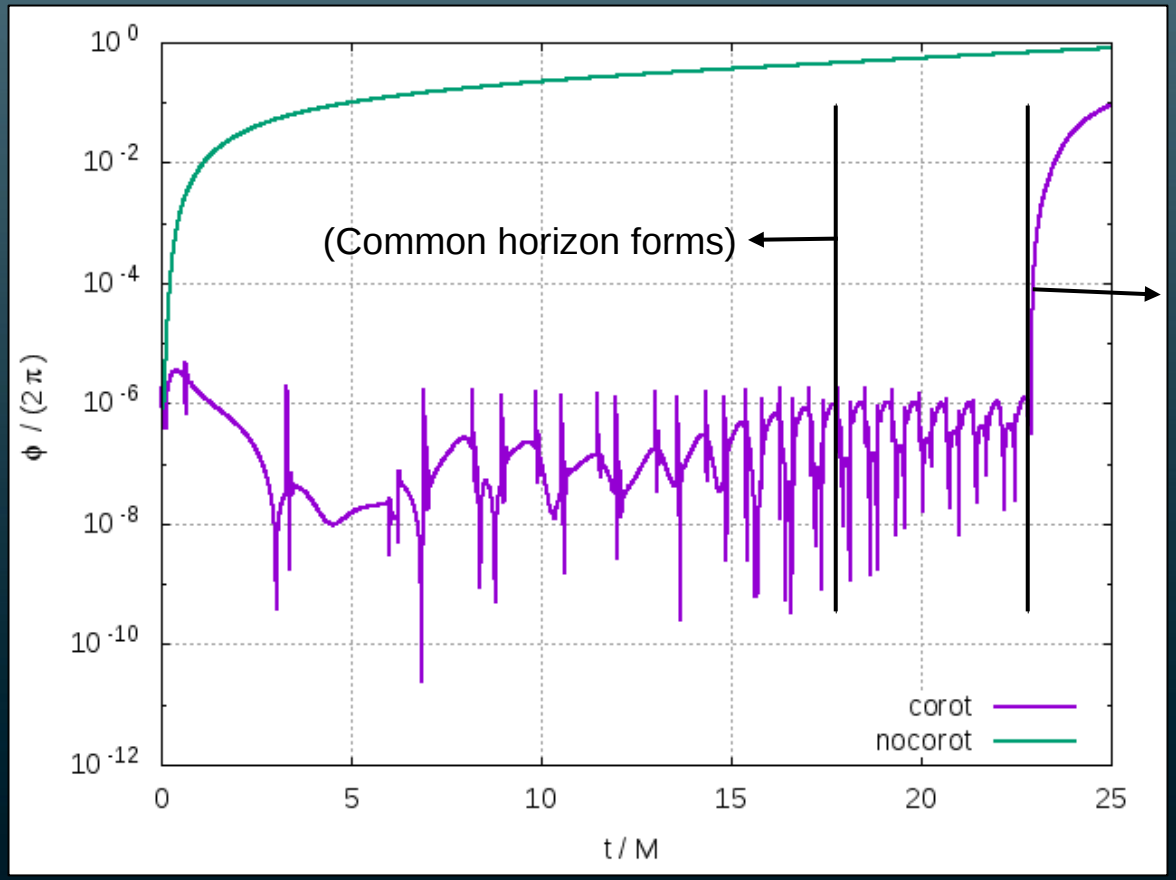


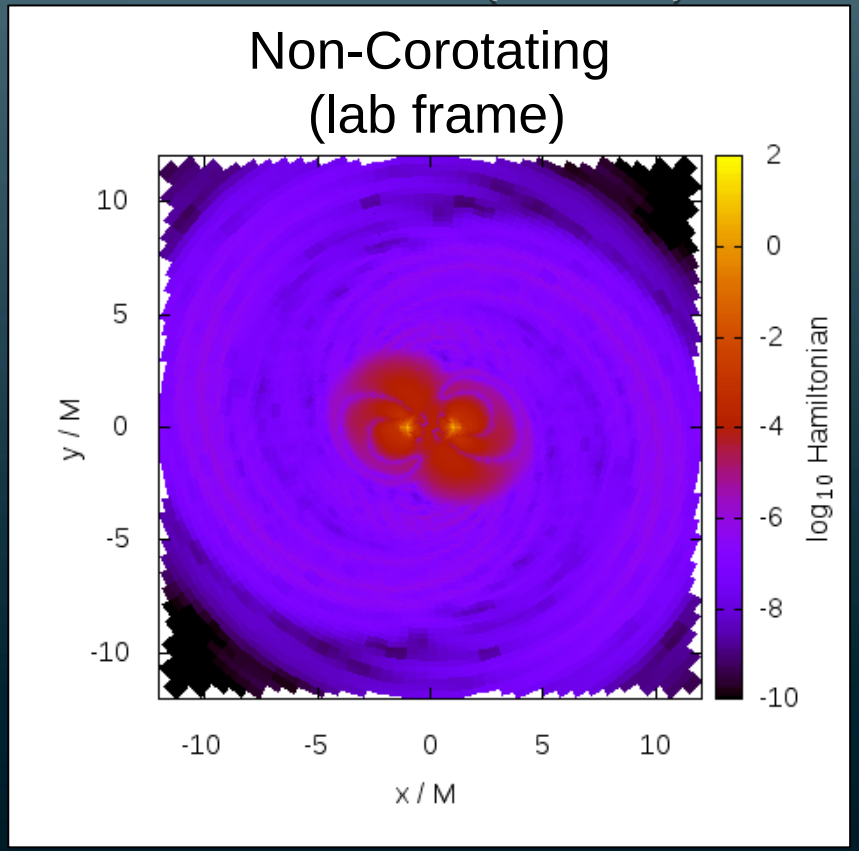


How well is corotation maintained?

Corotation is maintained to ~2 parts in 10^6 (~10^{-3} $\Delta\phi$)!



Hamiltonian Constraint Violation Comparison at $t / M \sim 9.9$ (¼ Orbit)



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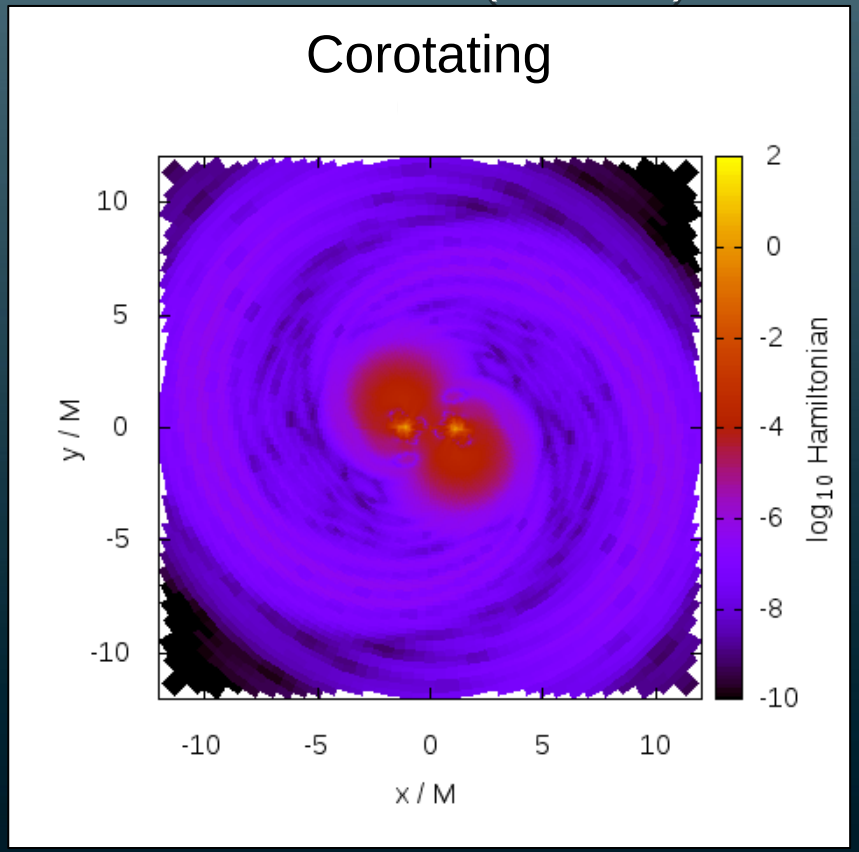
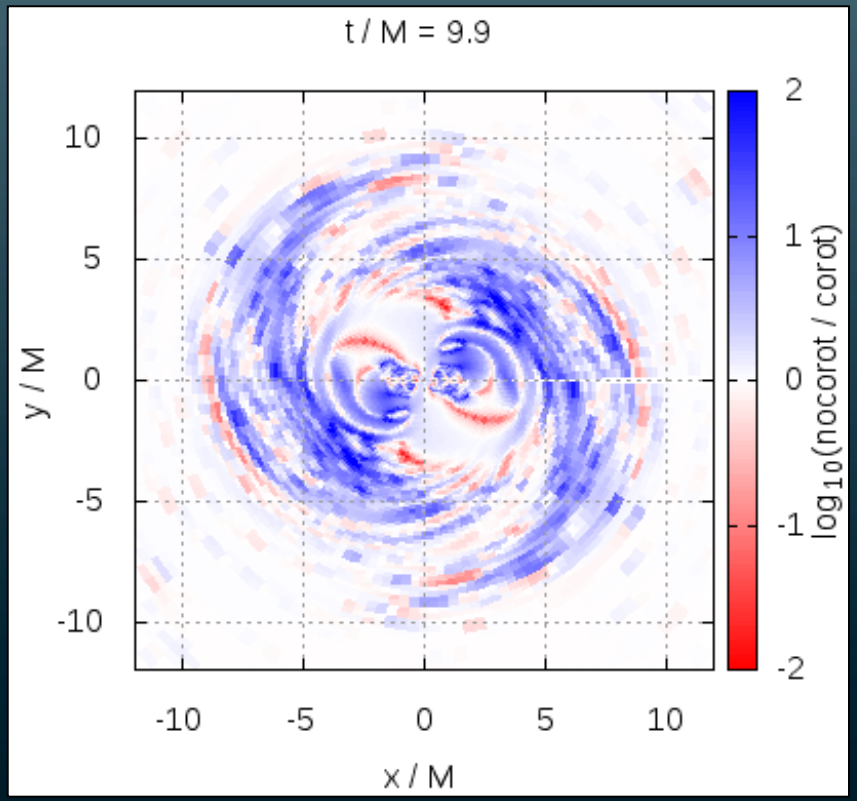


Corotating versus Non-corotating:
(Bluer points → corotation has lower error)



Needed Diagnostics for Black Hole Binaries? Use the Einstein Toolkit!

Basic Diagnostics in SENR

1. Puncture tracker
2. Constraint violation monitors

State-of-the-art Diagnostics in ETK

1. Gravitational wave extraction
   a. Ψ_4
   b. Mode-by-mode decomp.
2. Horizon diagnostics
   a. Apparent horizon finder
   b. Isolated horizon formalism
3. Global diags (surf & vol ints)
   a. ADM Mass & J

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Why reinvent the wheel?

Build a bridge instead!

Needed Diagnostics for Black Hole Binaries? Use the Einstein Toolkit!

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New SENR→ETK interpolation bridge

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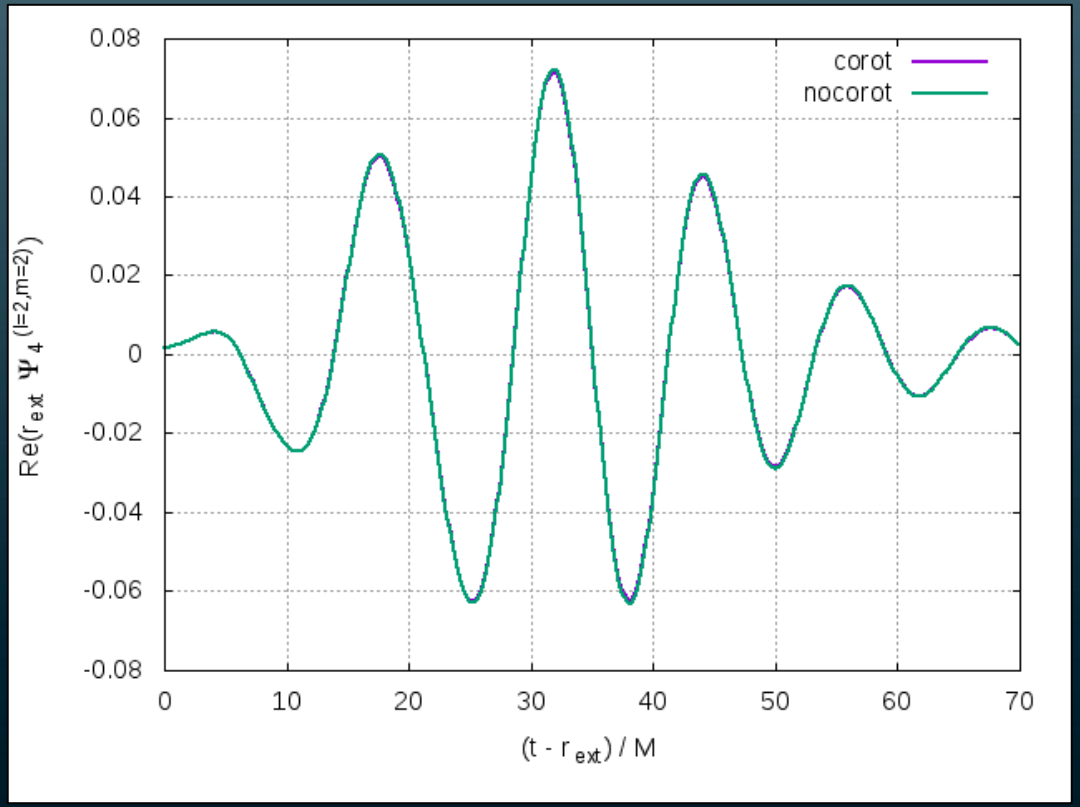
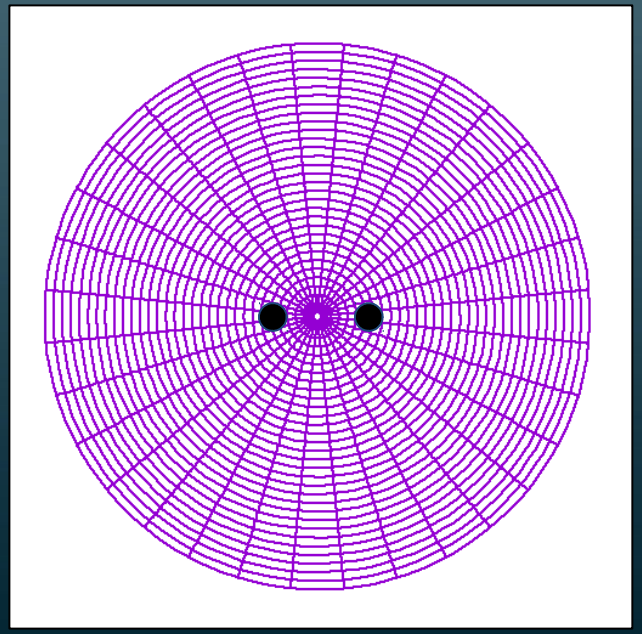
2-Step Interpolation Bridge

1. Interpolate rescaled spacetime quantities in curvilinear basis to Cartesian-sampled grid
2. Transform to Cartesian basis

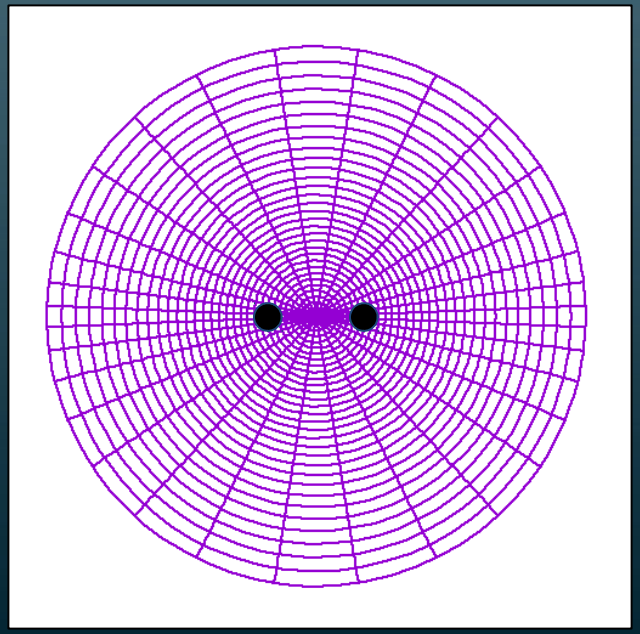
Waveform Extraction:
Corot & Nocorot Agree Well!
(Using SENR→ETK diagnostic bridge)



Corotation Works!
Optimizing Coordinates for Corotation

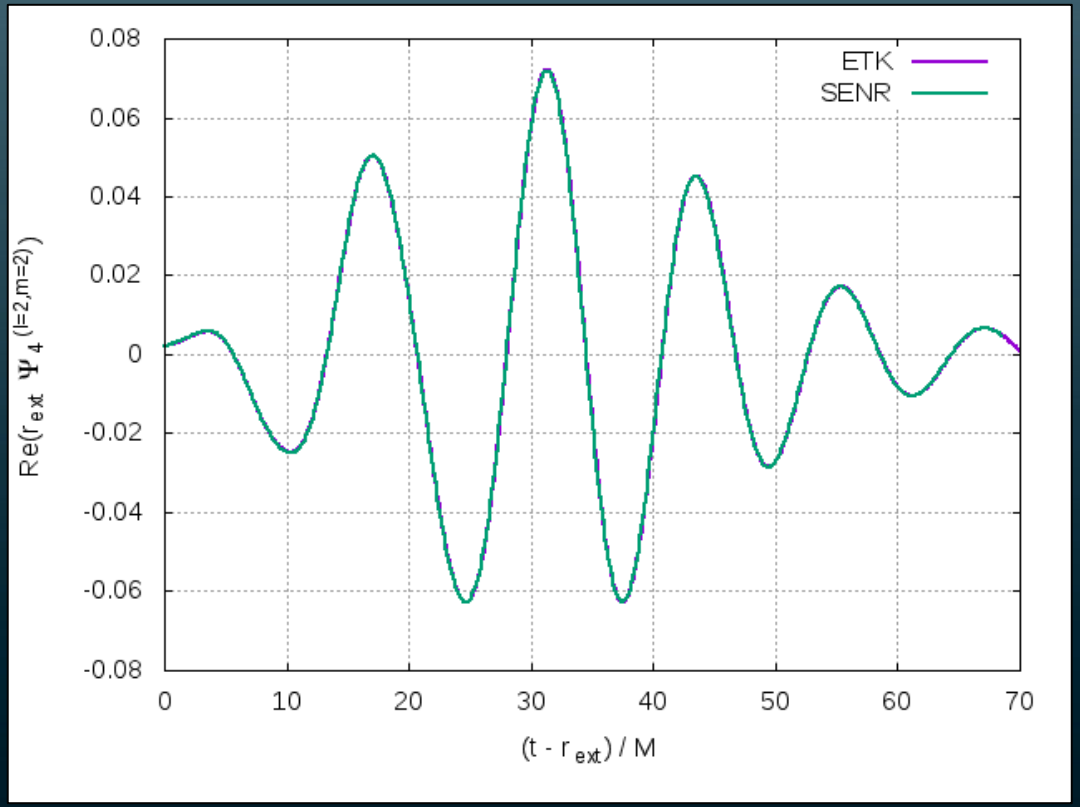


Sinh-ρ & Sinh-*z* Cylindrical



Same, but with Squeezed-ϕ

Waveform Extraction:
ETK (McLachlan) AMR vs SENR corot:
Excellent agreement!



Summary and Outlook

- For the first time
  - Moving-puncture black hole binary evolutions, without excision, in **singular coordinates** and a **corotating frame**
- Corotating frame
  - Minimal dynamics → smaller errors
  - BHB gravitational waveforms validated against
    - non-corotating frame simulation
    - Einstein Toolkit simulation

- **Next Step: Conquer the consumer-grade desktop!**
  - **Bispherical-like, dynamical coordinates**