

Adaptive mesh numerical general relativity and critical phenomena in bubble collapse

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Plan for the talk

- Numerical General Relativity
 - Numerical GR is simple
 - Numerical GR is hard
- GRChombo Numerical GR with adaptive mesh refinement
- Scalar field bubble collapse
 - Critical phenomena in symmetric cases
 - Extension to asymmetric cases
- Future directions

Numerical General Relativity

Numerical General Relativity - what and why?

Foliation of 4D spacetime into 3D spatial hyper-surfaces evolved over a local time coordinate





"Exploring New Physics Frontiers Through Numerical Relativity" Cardoso, Gualtieri, Herdeiro, Sperhake arXiv 1409.0014

Numerical General Relativity is simple

• Evolution given by Einstein equation:

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi T_{\mu\nu}$$

- (More specifically) the 3+1 ADM decomposition of the Einstein equation which evolves the quantities:
 - The spatial metric $\gamma_{ij} = \begin{pmatrix} \gamma_{11} & \gamma_{12} & \gamma_{13} \\ \gamma_{21} & \gamma_{22} & \gamma_{23} \\ \gamma_{31} & \gamma_{32} & \gamma_{33} \end{pmatrix}$ (field values)
 - The extrinsic curvature
 (conjugate momenta of metric values)

$$K_{ij} = \left(\begin{array}{cccc} K_{11} & K_{12} & K_{13} \\ K_{21} & K_{22} & K_{23} \\ K_{31} & K_{32} & K_{33} \end{array}\right)$$

• Also evolve the energy momentum source: $\nabla_a \nabla^a \phi = 0$

Numerical General Relativity is hard

- Initial conditions/ solving the constraint equations
- Stability of numerical evolution
- freedom, singularities
 Finding horizons and

Gauge/coordinate

•

 Finding horizons and physical outputs



- Conformal thin sandwich, or transverse traceless decomposition, spectral methods (1980's)
- 1+log slicing/maximal slicing (1992) for lapse (time slicing), Gamma driver condition for the shift (spatial slicing)
- BSSN formulation (1998), plus
 CCZ4 constraint damping
- Efficient apparent horizon finders, gravitational wave outputs, ADM mass, angular and linear momenta - (2000 onwards)



Commercial break

GRChombo: a new resource for Numerical GR

 Built on Chombo - open source PDE solver with fully adaptive mesh

Chombo Lawrence Berkeley National Labs https://commons.lbl.gov/display/chombo/

- BSSN formulation, moving
 puncture gauge
- Very adaptable code
- Publicly available (soon!)

http://grchombo.github.io/



"GRChombo : Numerical Relativity with Adaptive Mesh Refinement (published in CQG)" arXiv 1503.03436

GRChombo in action... a binary black hole merger



Conformal factor of metric

Bubble Collapse

Bubble collapse - scalar fields

• Scalar field minimally coupled to gravity

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2} \partial^\mu \phi \partial_\mu \phi - U(\phi) - \frac{R}{16\pi G} \right]$$

- Potential with multiple minima
- Solutions exist which interpolate between two minima -> "bubbles"
- Motivation multiverse, inflaton, inflation...



Critical phenomena in scalar field collapse

 First observed by Choptuik in massless spherically symmetric case

Matthew W. Choptuik, Phys.Rev.Lett. 70 (1993) 9-12 "Universality and scaling in gravitational collapse of a massless scalar field"

 Critical threshold p* for black hole formation, mass scaling relation

 $M \propto (p-p*)^\gamma$

Universality, scale echoing



Review - Critical Phenomena in Gravitational Collapse Carsten Gundlach and José M. Martín-García <u>http://www.livingreviews.org/lrr-2007-5</u>

Asymmetric bubble collapse - same behaviour?



Katy Clough and Eugene Lim Critical Phenomena in Asymmetric Bubble Collapse (Forthcoming paper)

Asymmetric bubble collapse - same behaviour?

Field value ϕ



Conformal factor of metric



Katy Clough and Eugene Lim Critical Phenomena in Asymmetric Bubble Collapse (Forthcoming paper)

Future directions with GRChombo

- Further investigation of non spherically symmetric cases, e.g. deformed bubbles, multiple bubble collisions
- Multi minima potentials, transitions between minima during collisions
- Other topological defects, e.g. cosmic strings
- Conditions for inflation
- Modified gravity
- Cosmic censorship, including higher dimensional spacetimes - e.g. black rings

"The Endpoint of Black Ring Instabilities and the Weak Cosmic Censorship Conjecture" Figueras, Kunesch, Tunyasuvunakool arXiv 1512.04532



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Thank you for listening, any questions?

With thanks to our collaborators on the GRChombo code: Pau Figueras (QMU), Hal Finkel (Argonne National Laboratory), Markus Kunesch & Saran Tunyasuvunakool (DAMTP, Cambridge).

