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http://www.einsteintoolkit.org

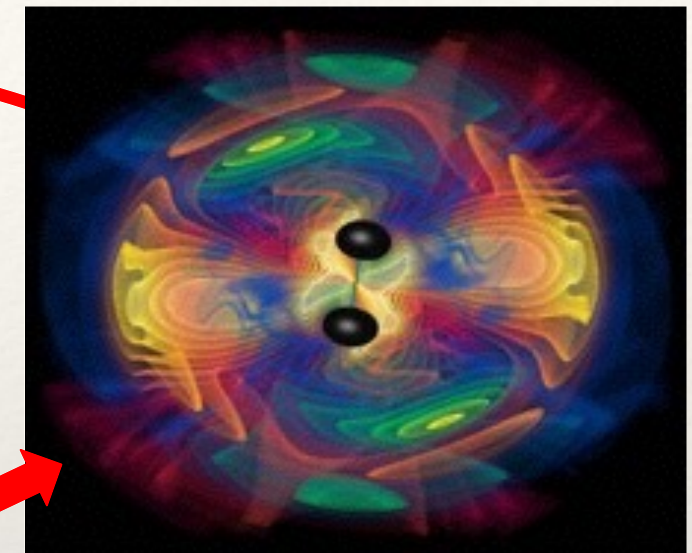
The Einstein Toolkit: an open framework for Numerical General Relativistic Astrophysics.

The Einstein Toolkit (ET) is an open-source computational infrastructure for that allows to solve the Einstein's Equations coupled to Matter on a three-dimensional grid.

I will discuss the implemented numerical methods and its scaling on modern HPC environment. Moreover, I will give details on its usage to model the merger of Neutron Stars and to computed the Gravitational Waves signal emitted in the process.

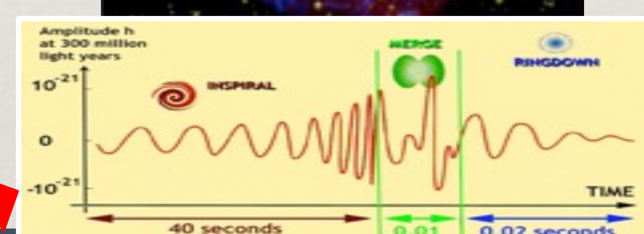
Main target: Gravitational Wave Physics

Models & Simulation



Observations

Scientific Discovery!



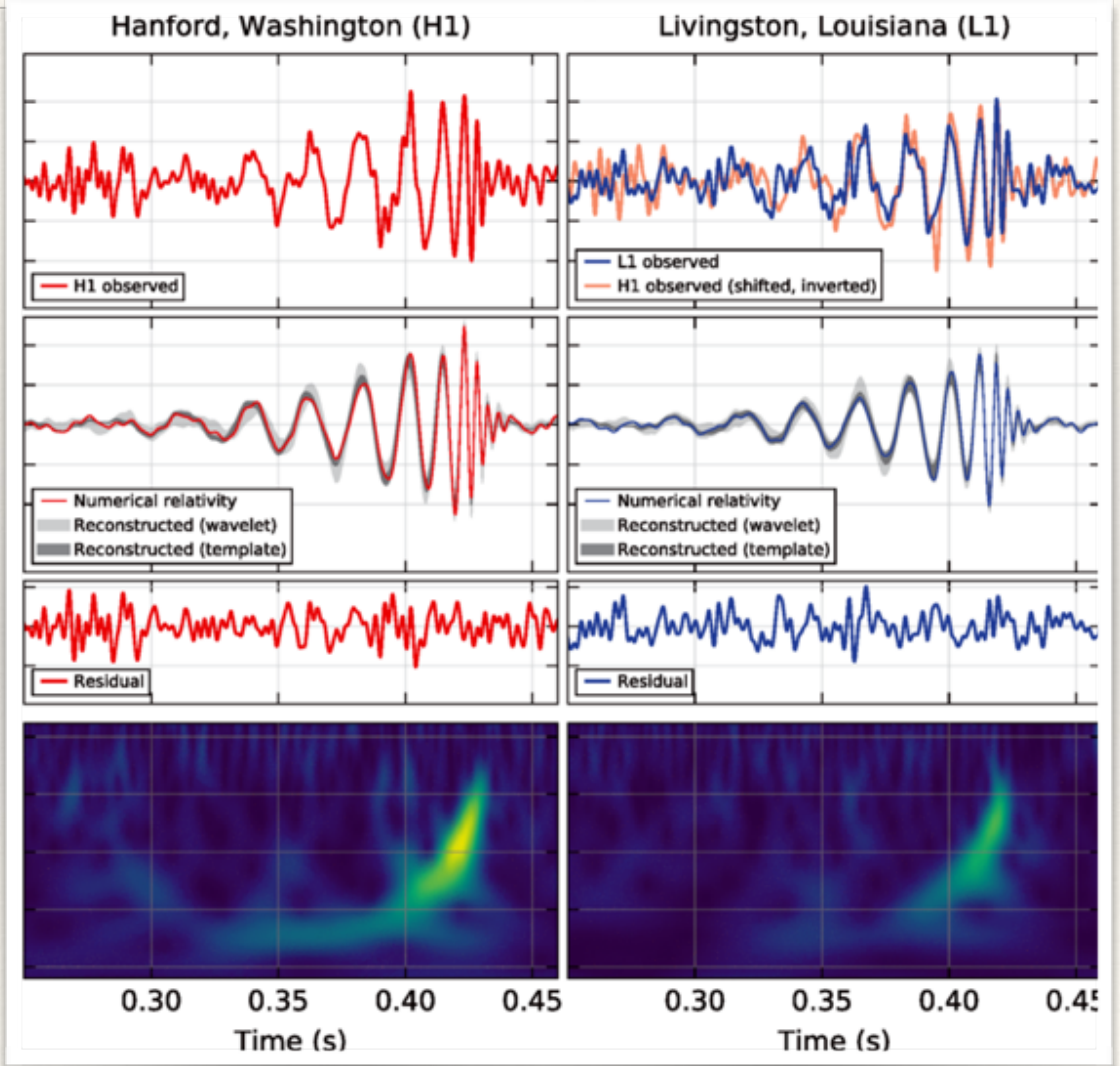
Theory

$G_{\mu\nu} = 8\pi T_{\mu\nu}$

Compact binaries, supernovae collapse, gamma-ray bursts, oscillating NSs, gravitational waves, …

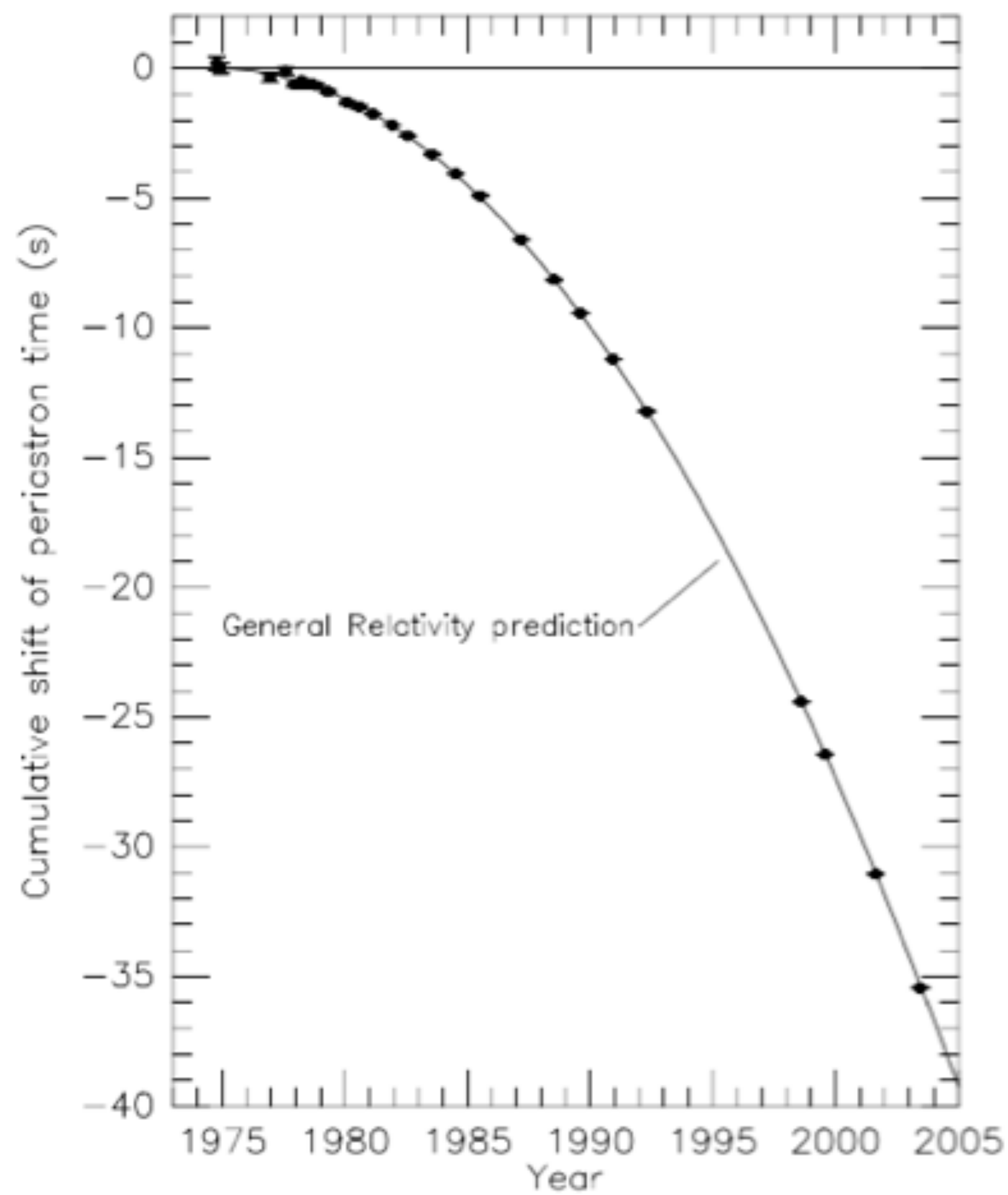
Need to model source: GW has been detected

- **The gravitational waves were detected on September 14, 2015 at 5:51 a.m. Eastern Daylight Time (09:51 UTC)** by both of the twin Laser Interferometer Gravitational-wave Observatory (LIGO) detectors, located in Livingston, Louisiana, and Hanford, Washington, USA.
- The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than **5.1σ**. The source lies at a luminosity distance of **410**(18) **Mpc** corresponding to a redshift z=0.09(4). In the source frame, the initial black hole masses are **36**(5)$\mathbf{M_\odot}$ and **29**(4)$\mathbf{M_\odot}$, and the final black hole mass is **62**(4)$\mathbf{M_\odot}$, with 3.0(5) $\mathbf{M_\odot c^2}$ radiated in gravitational waves. ***All uncertainties define 90% credible intervals.***



We already knew they (GW) exists!

- PSR B1913+16 (also known as J1915+1606) is a pulsar in a binary star system, in orbit with another star around a common center of mass. In 1974 it was discovered by Russell **Alan Hulse and Joseph Hooton Taylor, Jr., of Princeton University, a discovery for which they were awarded the 1993 Nobel Prize in Physics**
- Nature 277, 437 - 440 (08 February **1979**), J. H. TAYLOR, L. A. FOWLER & P. M. McCULLOCH: Measurements of second- and third-order relativistic effects in the orbit of binary pulsar PSR1913 + 16 have yielded self-consistent estimates of the masses of the pulsar and its companion, **quantitative confirmation of the existence of gravitational radiation at the level predicted by general relativity**, and detection of geodetic precession of the pulsar spin axis.



Main Target:NS-NS mergers

- MAIN TARGET LIGO/Virgo coll.:
  NS-NS merger sensitive frequency band approx. (40-2000) Hz
  Expected to rate ≈ 0.2 – 200 events per year events between 2016 – 19
  [J. Abadie et al. (VIRGO, LIGO Scientific), Class. Quant. Grav. 27, 173001 (2010)]

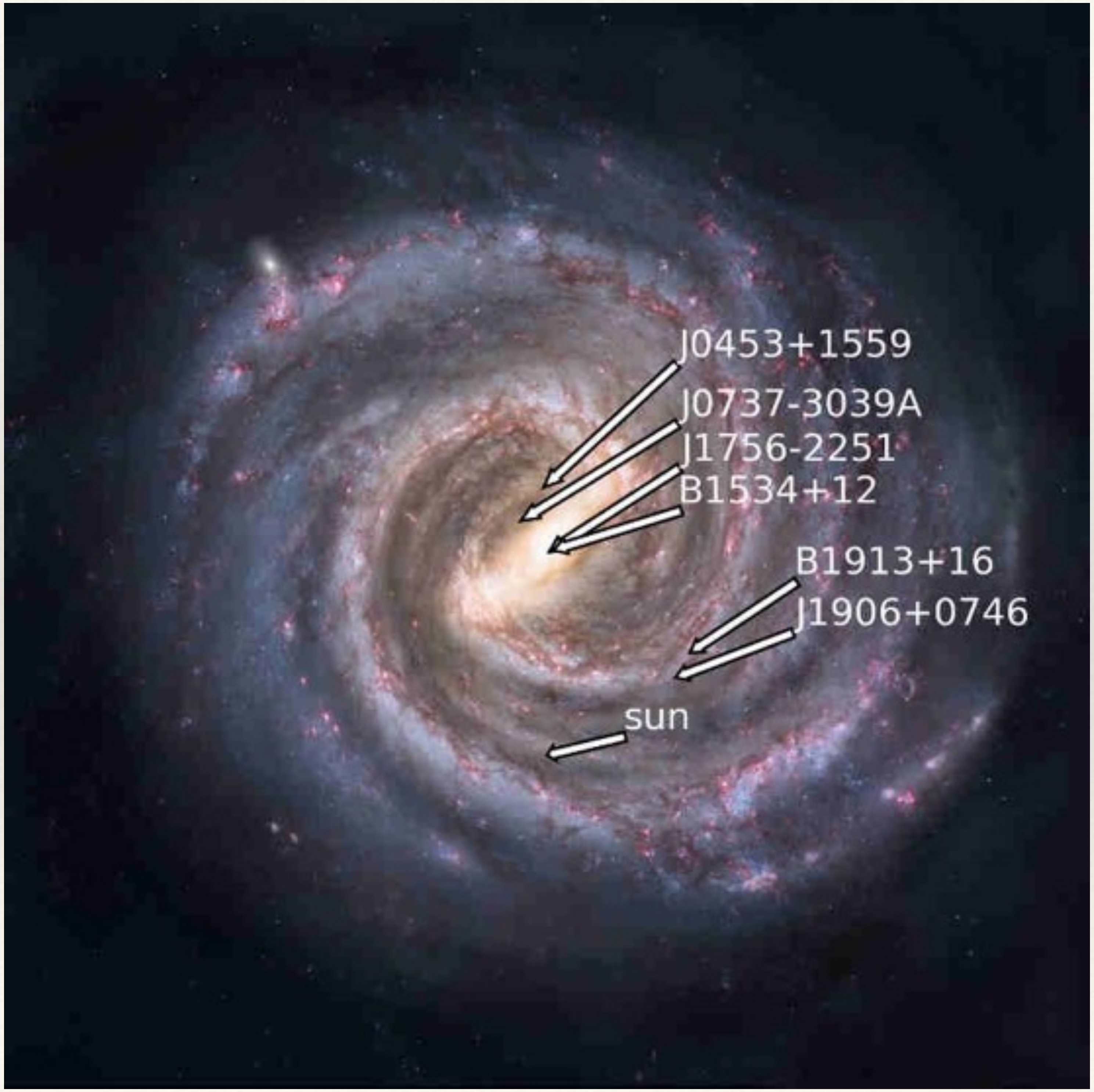
- **Core collapse in supernova**
- **BH-BH merger** —— (FOUND!)
- **BH-NS merger**
- **"*Mountains*" (deformation) on the crust of Neutron Stars**
- **Secular instability of Neutron stars**
- **Dynamical instability of Neutron star**

Table 1: Double neutron star systems known in the Galaxy

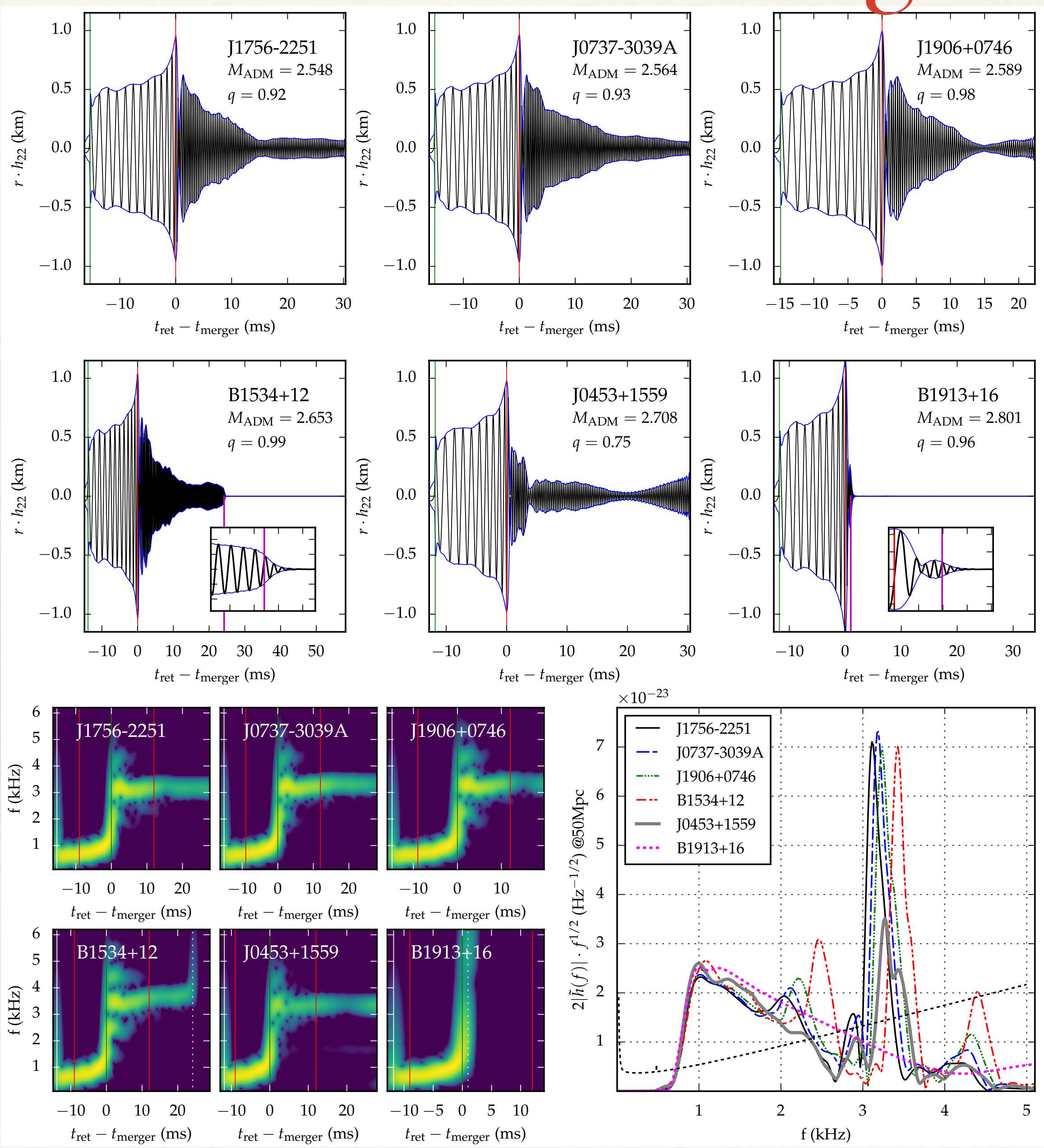
Pulsar	Period (ms)	P_b (days)	x (lt-sec)	e	M ($M_\odot$)	M_p ($M_\odot$)	M_c ($M_\odot$)	References
J0737−3039A	22.699	0.102	1.415	0.0877775(9)	2.58708(16)	1.3381(7)	1.2489(7)	1
J0737−3039B	2773.461		1.516					
J1518+4904	40.935	8.634	20.044	0.24948451(3)	2.7183(7)	-	-	2
B1534+12	37.904	0.421	3.729	0.27367740(4)	2.678463(4)	1.3330(2)	1.3454(2)	3
J1753−2240	95.138	13.638	18.115	0.303582(10)	-	-	-	4
J1756−2251	28.462	0.320	2.756	0.1805694(2)	2.56999(6)	1.341(7)	1.230(7)	5
J1811−1736	104.1	18.779	34.783	0.82802(2)	2.57(10)	-	-	6
J1829+2456	41.009	1.760	7.236	0.13914(4)	2.59(2)	-	-	7
J1906+0746*	144.073	0.166	1.420	0.0852996(6)	2.6134(3)	1.291(11)	1.322(11)	8
B1913+16	59.031	0.323	2.342	0.6171334(5)	2.8284(1)	1.4398(2)	1.3886(2)	9
J1930−1852	185.520	45.060	86.890	0.39886340(17)	2.59(4)	-	-	10
J0453+1559	45.782	4.072	14.467	0.11251832(4)	2.734(3)	1.559(5)	1.174(4)	This Letter
Globular cluster systems								
J1807−2500B*	4.186	9.957	28.920	0.747033198(40)	2.57190(73)	1.3655(21)	1.2064(20)	12
B2127+11C	30.529	0.335	2.518	0.681395(2)	2.71279(13)	1.358(10)	1.354(10)	13

Table from: Martinez et al.: "Pulsar J0453+1559: A Double Neutron Star System with a Large Mass Asymmetry" arXiv:1509.08805v1

Artistic view of the location of the six galactic system.

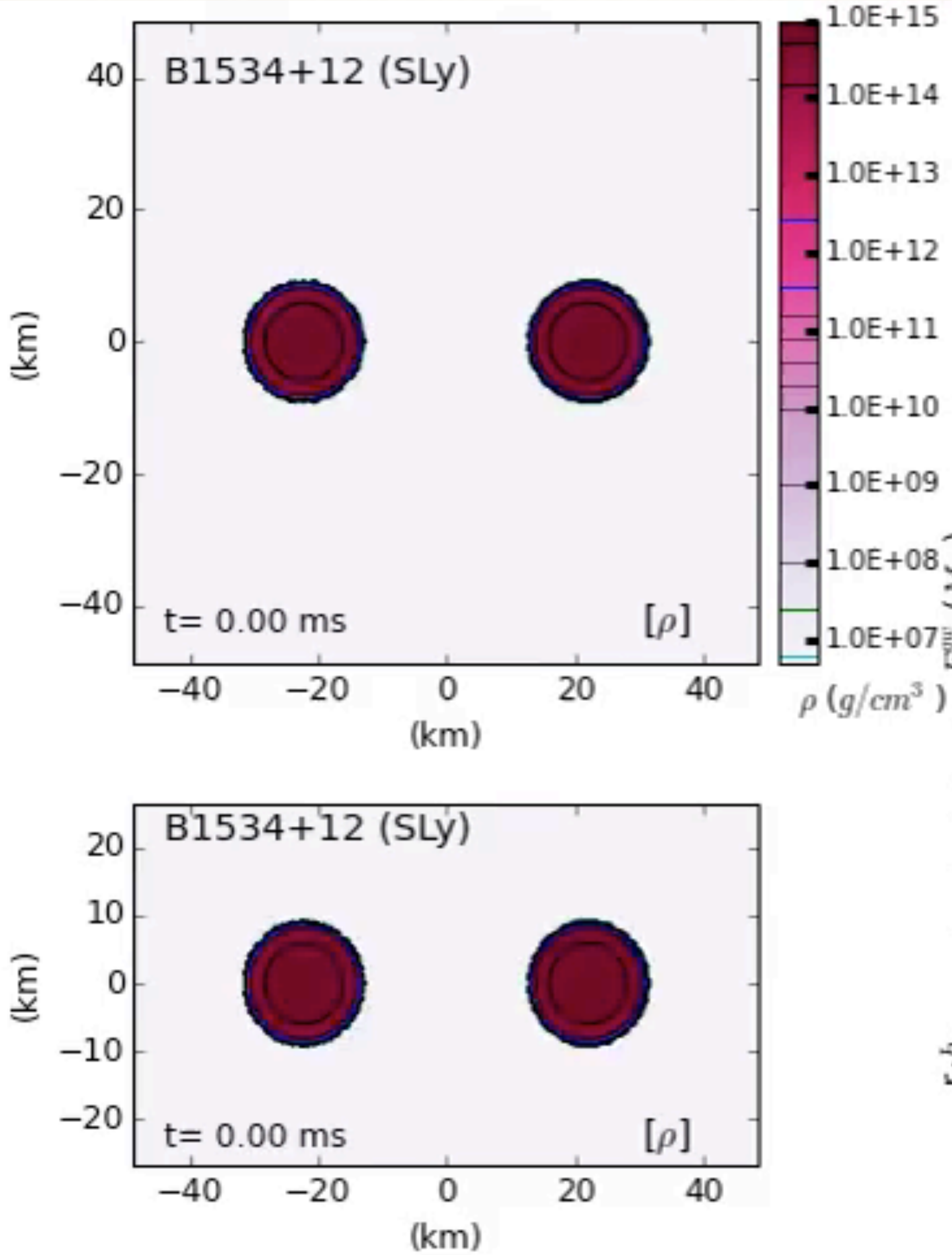


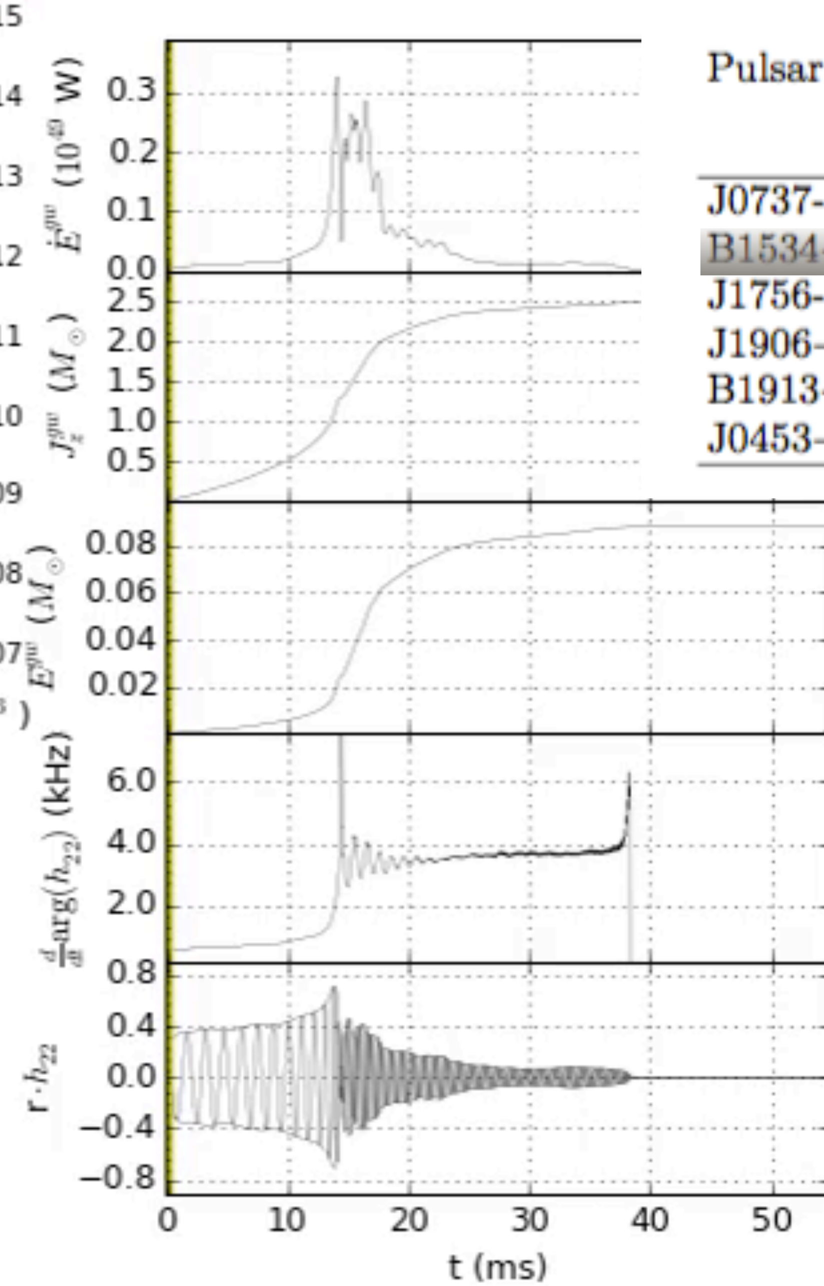
The simulated GW signal



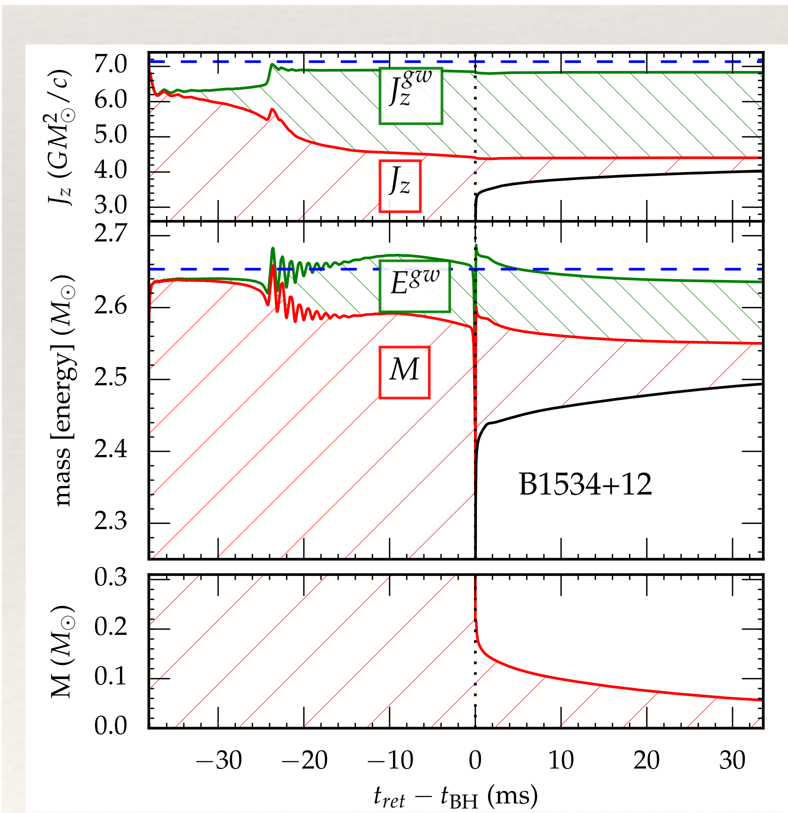
Modeling Mergers of known Galactic Binary Neutron Stars,
A. Feo, R. De Pietri, F. Maione and F. Loeffler, arXiv 1608.02810(2016)

The evolution of the B1534+12 system.



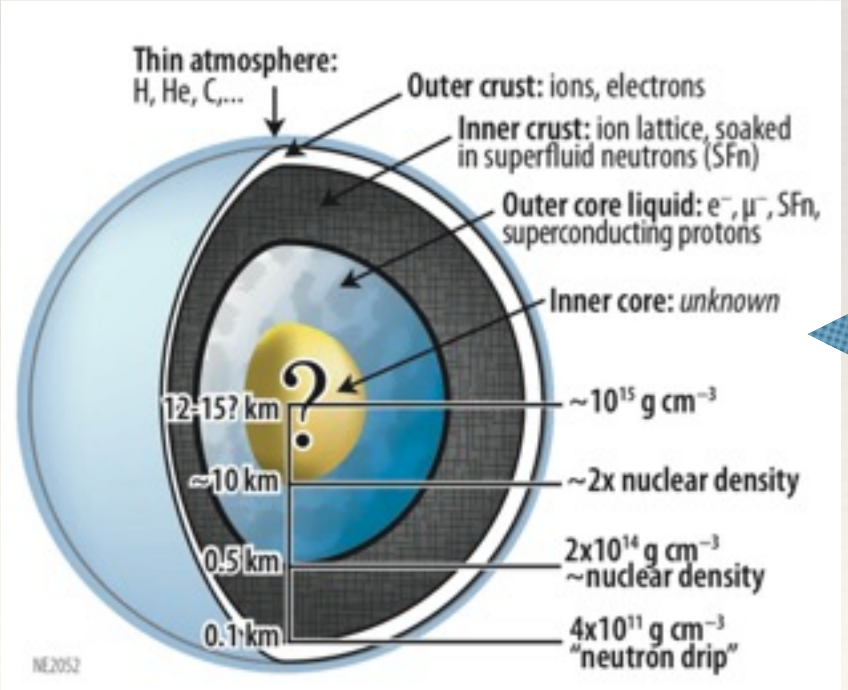


Pulsar	M_p $[M_\odot]$	M_c $[M_\odot]$	q	$M^{(1)}$ $[M_\odot]$	$M^{(1)}$ $[M_\odot]$
J0737-3039A	1.3381(7)	1.2489(7)	0.93	1.36	1.47
B1534+12	1.3330(2)	1.3454(2)	0.99	1.46	1.47
J1756-2251	1.341(7)	1.230(7)	0.92	1.33	1.47
J1906+0746*	1.291(11)	1.322(11)	0.98	1.41	1.45
B1913+16	1.4398(2)	1.3886(2)	0.96	1.53	1.59
J0453+1559	1.559(5)	1.174(4)	0.75	1.27	1.74

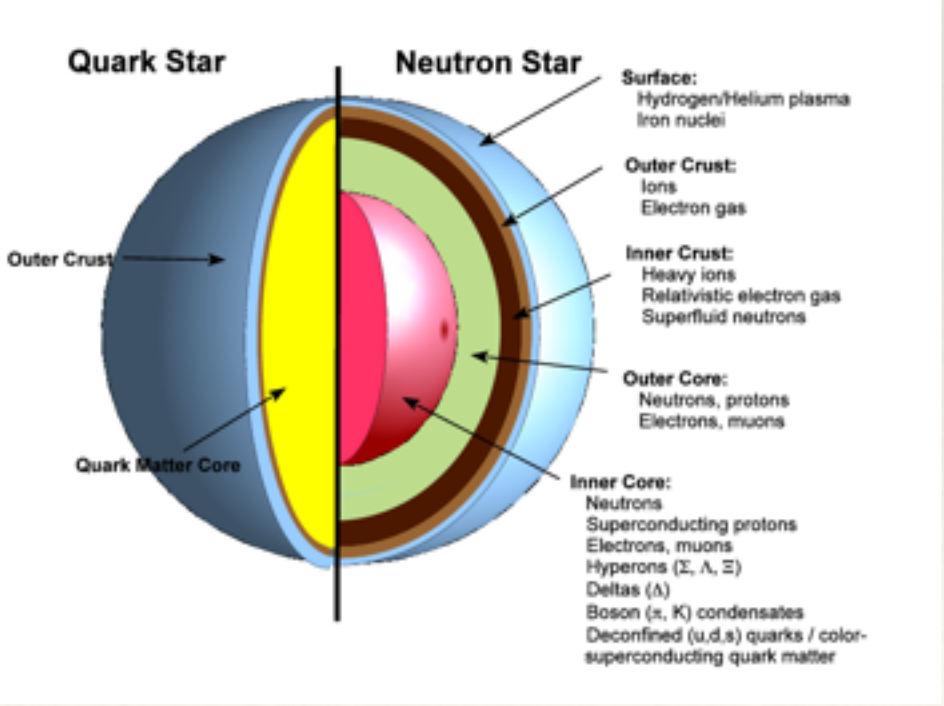


BNS as a probe for Nuclear Matter EOS

- Neutron Stars are a degenerate state of matter that is formed after the core collapse in a supernova event (where the electrons fall into nuclear matter and get captured by protons forming neutrons).
- Excellent laboratory to study high-density nuclear physics and EOS.
- Neutron star composition still unknown (neutron, resonance, hyperons,…)
- The extreme condition inside a NS cannot be reproduced in a laboratory.
- Typical properties of NS:



$$R \simeq 10Km$$
$$M \simeq 1.4M_{\odot}$$
$$T \in [1.4ms, 8.5s]$$
$$B \in [10^8, 10^{14}]Gauss$$



Need to be modeled by Numerical Simulations

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G\, T_{\mu\nu}$$ **Einstein Equations**

$$\nabla_\mu T^{\mu\nu} = 0$$ **Conservation of energy momentum**

$$\nabla_\mu (\rho\, u^\mu) = 0$$ **Conservation of baryon density**

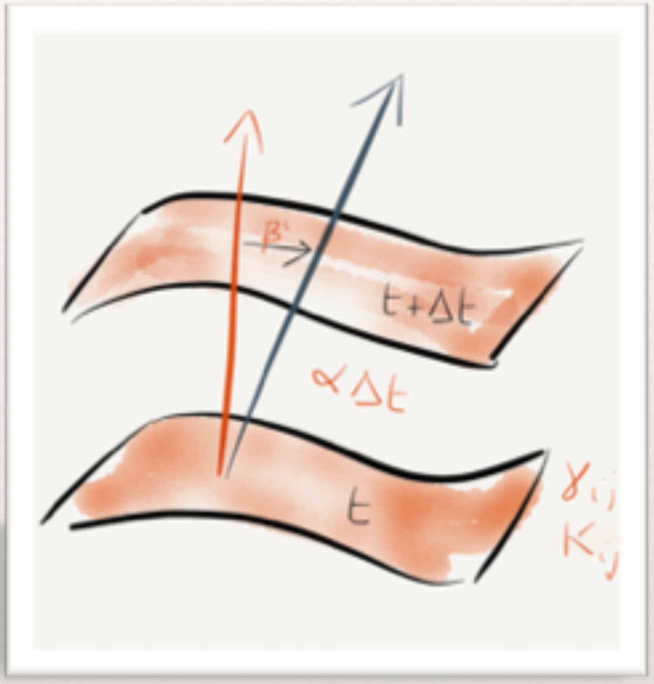
$$p = p(\rho, \epsilon)$$ **Equation of state**

Ideal Fluid Matter

$$T^{\mu\nu} = (\rho(1+\epsilon) + p) u^\mu u^\nu + p g^{\mu\nu}$$

- But these are 4D equations! Need to write as 3+1 evolution equations.
- Spacetime get foliated into 3D spacelike surfaces, in which we define our variables. We evolve them along a time direction normal to those surfaces.
- (Magneto)Hydrodynamics is written in terms of conservative form and special numerical techniques are used for the fluxes calculations.
- All physical variables and equations are discretized on a 3D Cartesian mesh and solved by a computer. Uses finite differences for derivative computations and standard Runge-Kutta method for time integrations.
- Different formulation of the Einstein Eqs have been developed in the last 20 years. BSSN-NOK version of the Einstein's Eqs.

The base formalism (ADM)



1. **Choose initial spacelike surface and provide initial data (3-metric, extrinsic curvature)**
2. **Choose coordinates:**
   - Construct timelike unit normal to surface, choose lapse function
   - Choose time axis at each point on next surface (shift vector)
   - Evolve 3-metric, extrinsic curvature

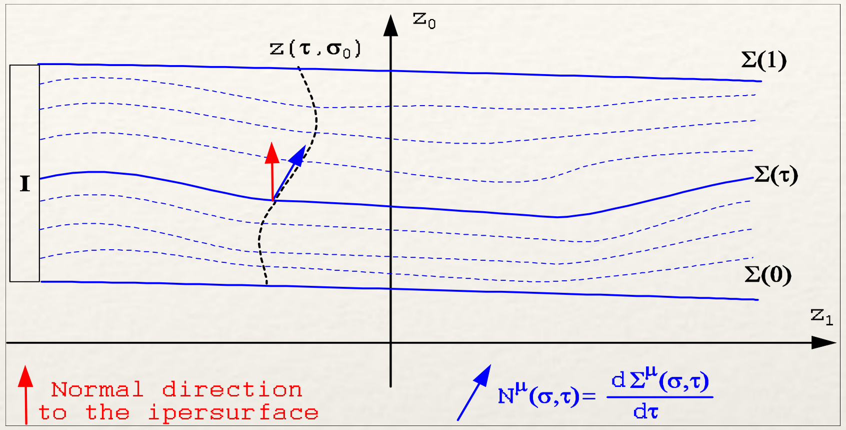
Use usual numerical methods:

1. **Structured meshes (including multi-patch), finite differences (finite volumes for matter), adaptive mesh refinement (since ~2003). High order methods.**
2. **Some groups use high accuracy spectral methods for vacuum space times**

Unfortunately Einstein Equation must be rewritten !

$$ds^2 = -\alpha^2 dt^2 + g_{ij}(dx^i + \beta^i dt)(dx^j + \beta^j dt)$$

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 0$$



- BSSN version of the Einstein's equations that introduce additional conformal variables:

$$R_{ij} = -\tfrac{1}{2}\tilde{g}^{lm}\tilde{g}_{ij,lm} - \tilde{g}_{k(i}\partial_{j)}\tilde{\Gamma}^k + \tilde{\Gamma}^k\tilde{\Gamma}_{(ij)k} + \tilde{g}^{lm}(2\tilde{\Gamma}^k_{l(i}\tilde{\Gamma}_{j)km} + \tilde{\Gamma}^k_{im}\tilde{\Gamma}_{klj})$$

$$R^{TF}_{ij} = R_{ij} - \tfrac{1}{3} g_{ij} R$$

$$\partial_t \varphi = -\tfrac{1}{6}\alpha K + \beta^i \partial_i \varphi + \tfrac{1}{6}\partial_i \beta^i$$

$$\partial_t K = -g^{ij}\nabla_i\nabla_j\alpha + \alpha(\tilde{A}_{ij}\tilde{A}^{ij} + \tfrac{1}{3}K) + \beta^i\partial_i K$$

$$\partial_t \tilde{g}_{ij} = -2\alpha K_{ij} + \tilde{g}_{jk}\partial_i\beta^k + \tilde{g}_{ik}\partial_j\beta^k - \tfrac{2}{3}\tilde{g}_{ij}\partial_k\beta^k$$

$$\partial_t \tilde{\Gamma}^i = -2\tilde{A}^{ij}\partial_j\alpha + 2\alpha(\Gamma^i_{jk}\tilde{A}^{jk} - \tfrac{2}{3}\tilde{g}^{ij}\partial_j K + 6\tilde{A}^{ij}\partial_j\varphi) + \\ + \beta^k\partial_k\tilde{\Gamma}^i - \tilde{\Gamma}^k\partial_k\beta^i + \tfrac{2}{3}\tilde{\Gamma}^i\partial_k\beta^k + \tfrac{1}{3}\tilde{g}^{ij}\partial_j\partial_k\beta^k + \tilde{g}^{jk}\partial_j\partial_k\beta^i$$

$$\partial_t \tilde{A}_{ij} = e^{-4\varphi}(-(\nabla_i\nabla_j\alpha)^{TF} + \alpha R^{TF}_{ij}) + \alpha\left(\tilde{A}_{ij}K - 2\tilde{A}_{ik}\tilde{A}^k{}_j\right) - \partial_i\partial_j\alpha + \\ + \beta^k\partial_k\tilde{A}_{ij} + \left(\tilde{A}_{ik}\partial_j + \tilde{A}_{jk}\partial_i\right)\beta^\kappa - \tfrac{2}{3}\tilde{A}_{ij}\partial_k\beta^k$$

- Matter evolution (B set to zero) using shock capturing methods based on the GRHydro code

[4] M. Shibata, T. Nakamura: "**Evolution of three dimensional gravitational ..**", **Phys. Rev. D52(1995)5429**
[5] T.W. Baumgarte, S.L. Shapiro: "**On the numerical integration of Einstein..**", **Phys. Rev. D59(1999)024007**

Matter evolution need HRSC Methods

$$\nabla_\mu T^{\mu\nu} = 0 \qquad p = p(\rho, \epsilon)$$

Ideal Fluid Matter

$$T^{\mu\nu} = (\rho(1+\epsilon) + p)u^\mu u^\nu + p g^{\mu\nu}$$

$$\frac{\partial \vec{u}}{\partial t} + \frac{\partial \vec{f^i}}{\partial x^i} = \vec{s}(\vec{u})$$

- **The equation of a perfect fluid are a non linear hyperbolic system.**
- **Wilson (1972) wrote the system as a set of advection equation within the 3+1 formalism.**
- **Non-conservative. Conservative formulations well-adapted to numerical methodology:**
    - Martí, Ibáñez & Miralles (1991): 1+1, general EOS
    - Eulderink & Mellema (1995): covariant, perfect fluid • Banyuls et al (1997): 3+1, general EOS
    - Papadopoulos & Font (2000): covariant, general EOS

Numerical Methods in Astrophysical Fluid Dynamics

- **Finite difference methods.** Require numerical viscosity to stabilize the solution in regions where discontinuities develop.
- **Finite volume methods. Conservation form**. Use Riemann solvers to solve the equations in the presence of discontinuities (Godunov 1959). HRSC schemes.
- **Symmetric methods**. Conservation form. Centred finite differences and high spatial order.
- **Particle methods.** Smoothed Particle Hydrodynamics (Monaghan 1992). Integrate movement of discrete particles to describe the flow. Diffusive.
- **For hyperbolic systems of conservation laws, schemes written in conservation form guarantee that the convergence (if it exists) is to one of the weak solutions of the system of equations (Lax-Wendroff theorem 1960).**

Task to complex for a single group

- We are not all Computer Scientists.
- We need help and infrastructure to efficiently run codes on different machines and to distribuite the workload
- We need an easy way to build on the shoulder of other people works.
- …..

Cactus was developed for

- **Solving computational problems which:**
    - are too large for single machine
    - require parallelization (MPI, OpenMP, GPU?)
    - involve multi-physics
    - use eclectic/legacy code
    - use code written in different programming languages
- **Taking advantage of distributed development.**

Cactus: 1997-today

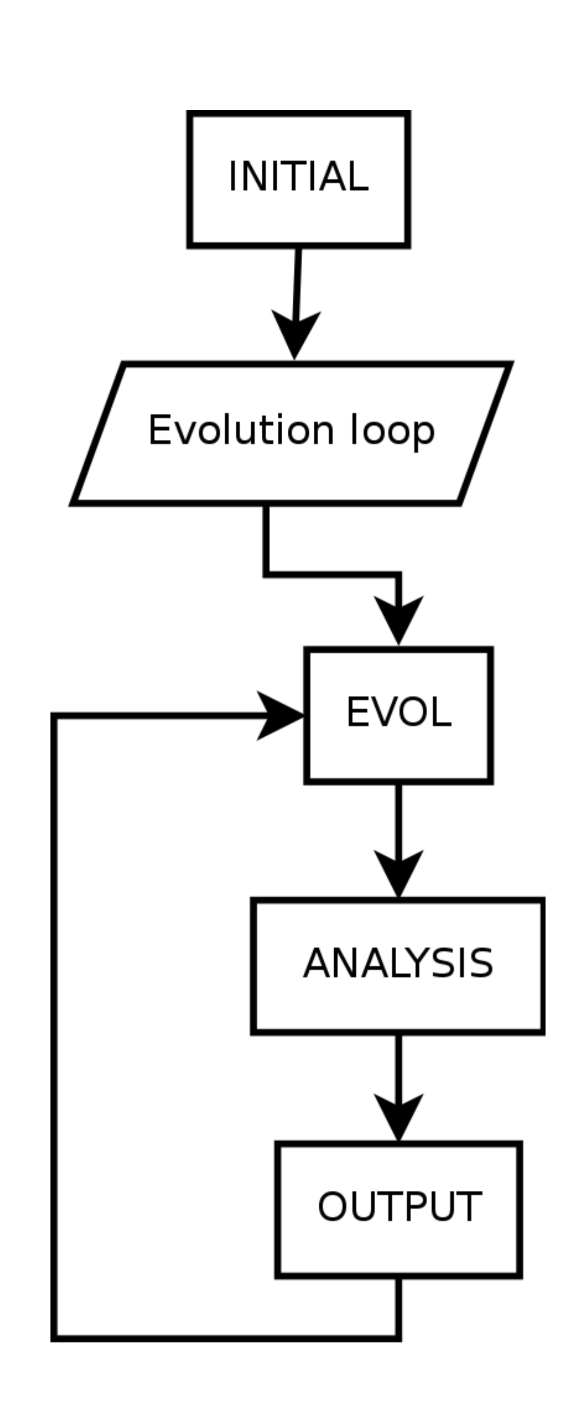
- **History:**
  - Black Hole Grand Challenge ('94-'98): multiple codes, groups trying to collaborate, tech/social challenges, NCSA (USA) group moves to AEI (Germany).
- **New software needed!**
- **Vision …**
  - Modular for easy code reuse, community sharing and development of code
  - Highly portable and flexible to take advantage of new architectures and technologies (grid computing, networks)
  - Higher level programming than "MPI": abstractions
  - Emerging: general to support other applications, better general code, shared infrastructure

Cactus is the base infrastructure at the base of ET

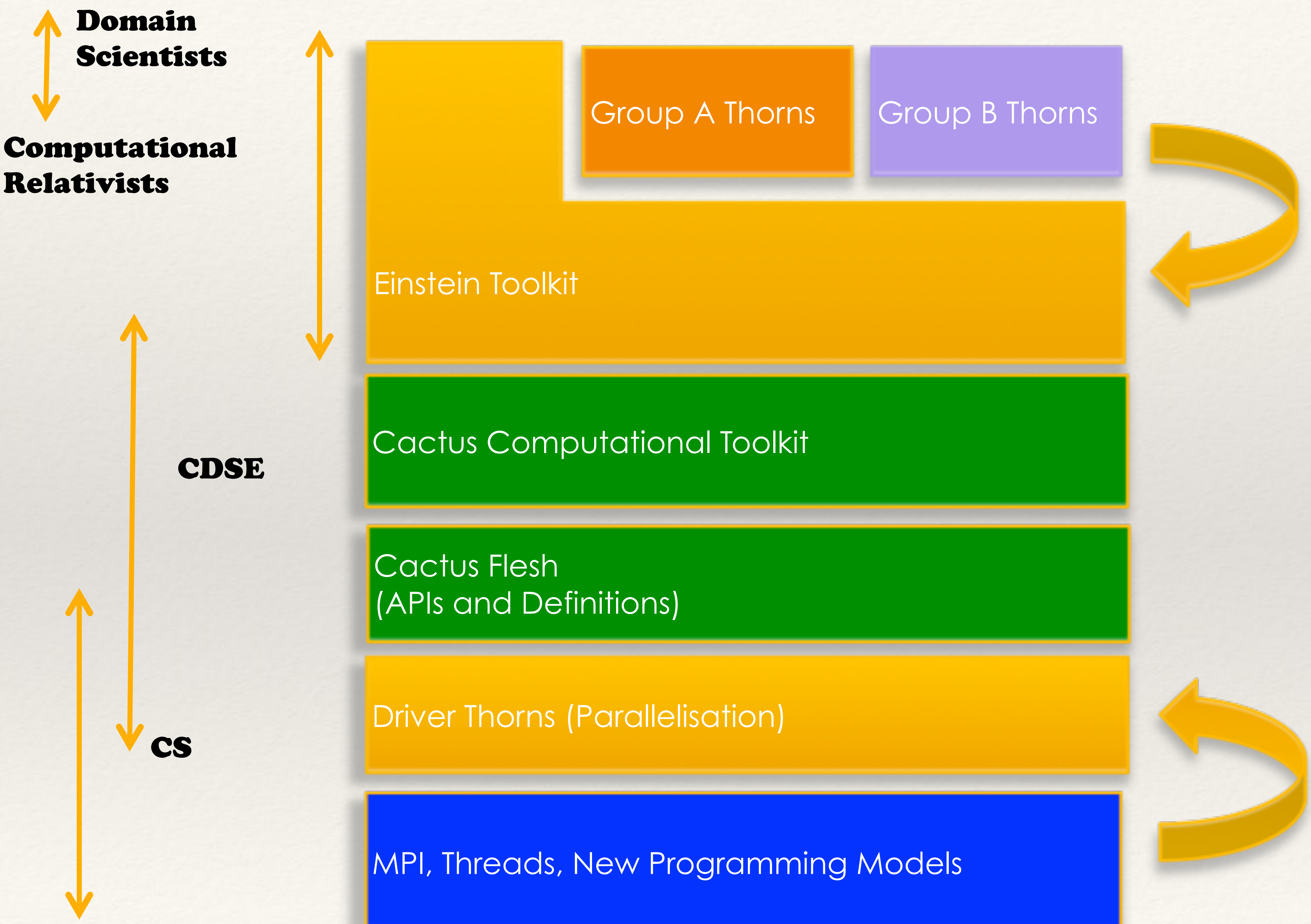
- **Cactus is:**
  - a framework for developing portable, modular applications
  - focusing on high-performance simulation codes
  - designed to allow experts in different fields to develop modules based upon their experience and to use modules developed by experts in other fields with minimal knowledge of the internals or operation of the other modules
- **Cactus:**
  - does not provide executable files
  - provides infrastructure to create executables
- **Why?**
  - Problem specific code not part of Cactus
  - System libraries different on different systems
  - Cactus is free software, but often problem specific codes are not (non-distributable binary)

Structure Overview

- **Two fundamental parts**
- **The Flesh**
  - The core part of Cactus
  - Independent of other parts of Cactus
  - Acts as utility and service library
- **The Thorns**
  - Separate libraries (modules) which encapsulate the implementation of some functionality
  - Can specify dependencies on other implementations

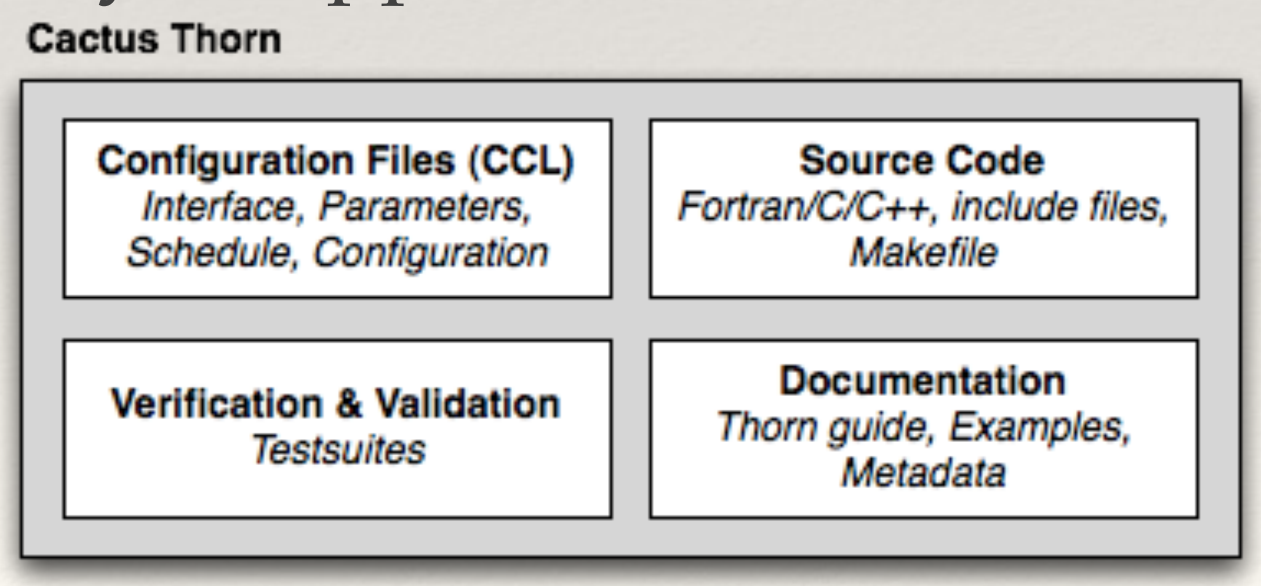


Software: Component Framework



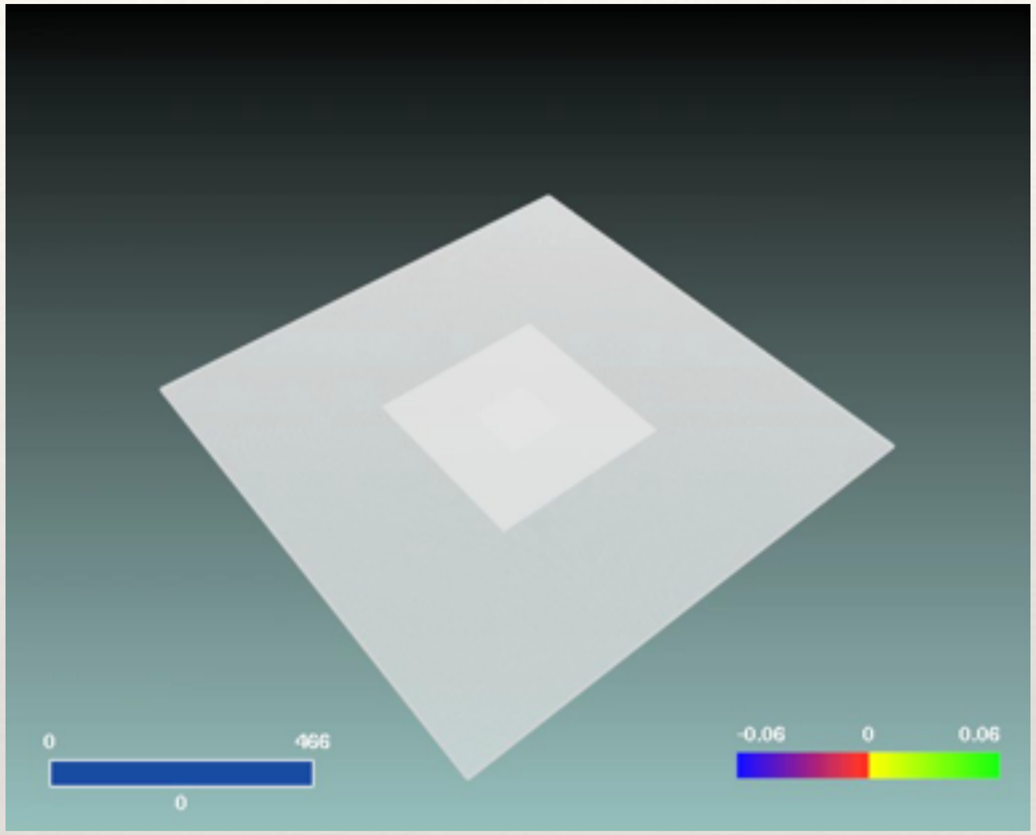
Key Features

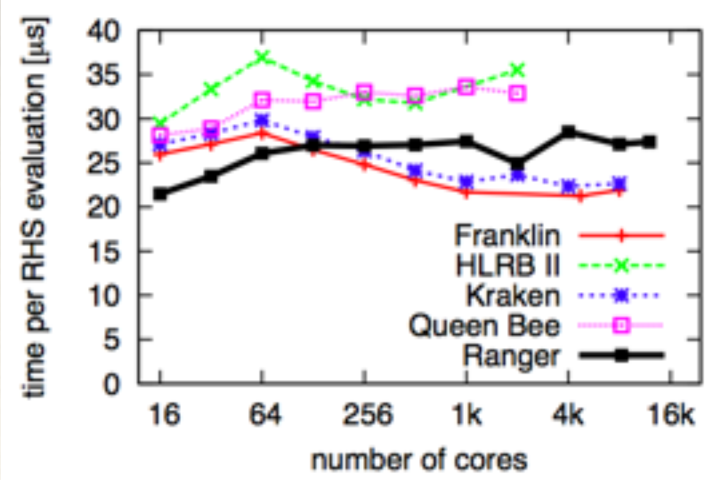
- Driver thorn provides scheduling, load balancing, parallelization
- Application thorns deal only with local part of parallel mesh
- Different thorns can be used to provide the same functionality, easily swapped.



AMR: Carpet

- **Set of Cactus thorns**
  - Developed by Erik Schnetter
- **Berger-Oliger style adaptive mesh refinement with sub-cycling in time**
  - High order differencing (4,6,8)
  - Domain decomposition
  - Hybrid MPI-OpenMP
- 2002-03: **Design of Cactus** gave the opportunity to many groups, even competing ones, to have AMR at work with little code change





Numerical Relativity with Cactus

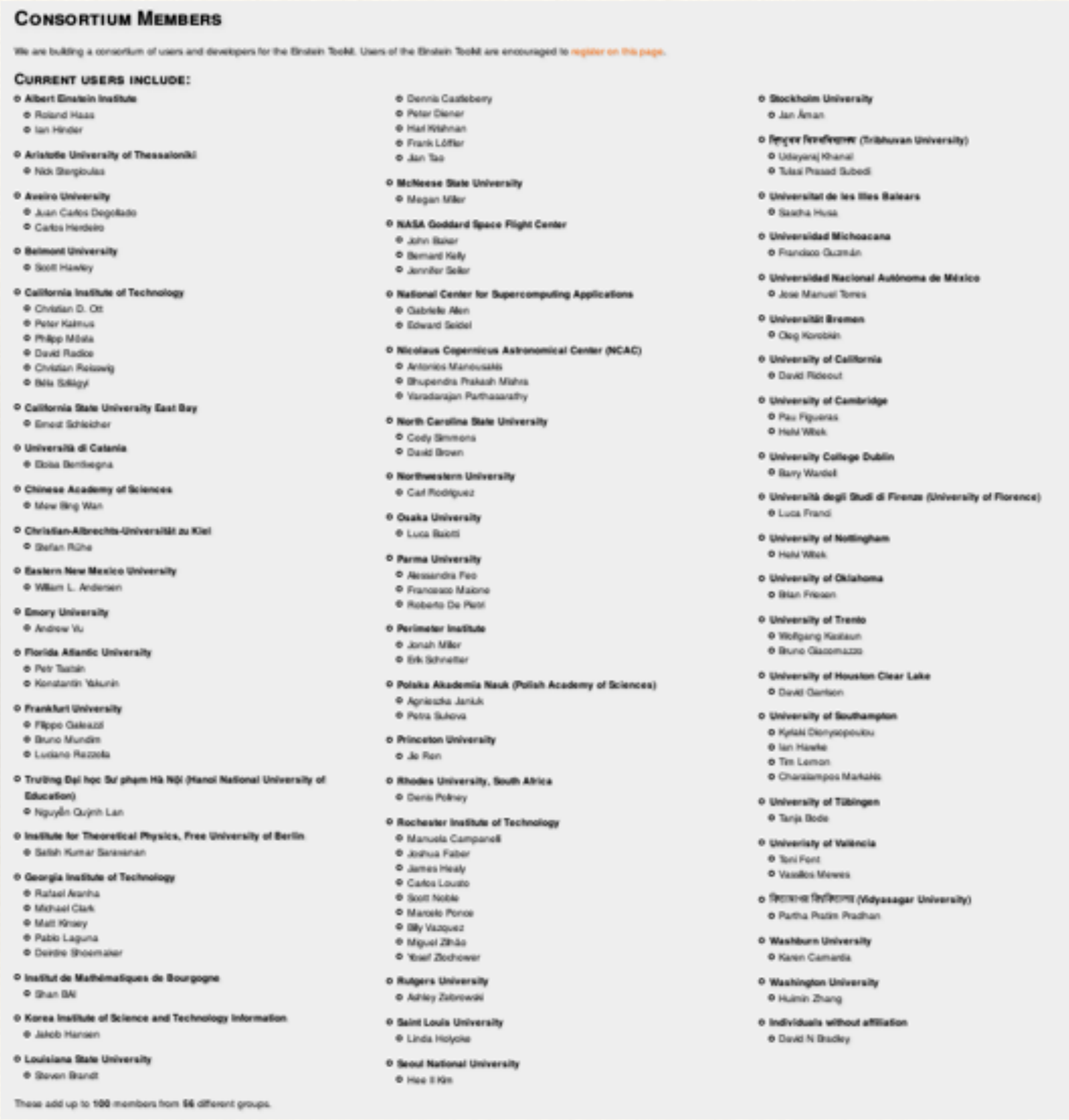
- 1997: 1st version of Cactus just for relativity (Funding from MPG/NCSA)
- 1999: Cactus 4.0: "Cactus Einstein" thorns
- 1999-2002: EU Network "Sources of Gravitational Waves"
  - Led to Whisky Code for GR Hydro in Cactus
- Groups develop codes based on Cactus Einstein
- 2007: LSU/RIT/PennState/GeorgiaTech: NSF XiRel
  - Improve scaling for multiple codes using Cactus
- 2009-: LSU/RIT/GeorgiaTech/Caltech/AEI: NSF CIGR
  - Shared cyberinfrastructure including matter
  - Einstein Toolkit from community contributions
  - Sustainable, community supported model

Einstein Toolkit

- "The Einstein Toolkit Consortium is developing and supporting open software for relativistic astrophysics. Our aim is to provide the core computational tools that can enable new science, broaden our community, facilitate interdisciplinary research and take advantage of emerging petascale computers and advanced cyberinfrastructure."
- WEB SITE: http://einsteintoolkit.org
- TO DOWNLOAD (Compile an almost any computer system)
  - curl -kLO https://raw.githubusercontent.com/gridaphobe/CRL/ET_2016_05/GetComponents
  - chmod a+x GetComponents
  - ./GetComponents --parallel https://bitbucket.org/einsteintoolkit/manifest/raw/ET_2016_05/einsteintoolkit.th

Einstein Toolkit

- Consortium: 94 members, 49 sites, 14 countries
- **Sustainable community model:**
- 9 Maintainers from 6 sites:
  - oversee technical developments,
  - quality control, verification and validation, distributions and releases
- Whole consortium engaged in directions, support, development
- Open development meetings
- Governance model: still being discussed (looking at CIG, iPlant)



Consortium Members

We are building a consortium of users and developers for the Einstein Toolkit. Users of the Einstein Toolkit are encouraged to register on this page.

Current users include:

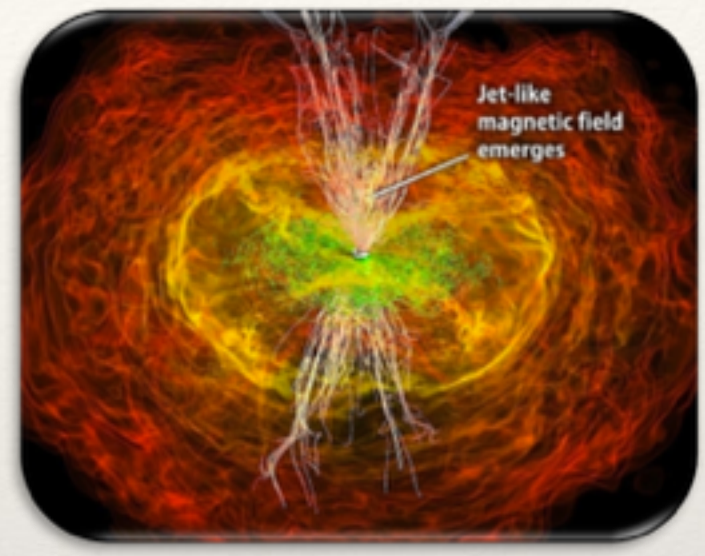
- Albert Einstein Institute
- Aristotle University of Thessaloniki
- Aveiro University
- Belmont University
- California Institute of Technology
- California State University East Bay
- Università di Catania
- Chinese Academy of Sciences
- Christian-Albrechts-Universität zu Kiel
- Eastern New Mexico University
- Emory University
- Florida Atlantic University
- Frankfurt University
- Trường Đại học Sư phạm Hà Nội (Hanoi National University of Education)
- Institute for Theoretical Physics, Free University of Berlin
- Georgia Institute of Technology
- Institut de Mathématiques de Bourgogne
- Korea Institute of Science and Technology Information
- Louisiana State University
- McNeese State University
- NASA Goddard Space Flight Center
- National Center for Supercomputing Applications
- Nicolaus Copernicus Astronomical Center (NCAC)
- North Carolina State University
- Northwestern University
- Osaka University
- Parma University
- Perimeter Institute
- Polska Akademia Nauk (Polish Academy of Sciences)
- Princeton University
- Rhodes University, South Africa
- Rochester Institute of Technology
- Rutgers University
- Saint Louis University
- Seoul National University
- Stockholm University
- (Tribhuvan University)
- Universitat de les Illes Balears
- Universidad Michoacana
- Universidad Nacional Autónoma de México
- Universität Bremen
- University of California
- University of Cambridge
- University College Dublin
- Università degli Studi di Firenze (University of Florence)
- University of Nottingham
- University of Oklahoma
- University of Trento
- University of Houston Clear Lake
- University of Southampton
- University of Tübingen
- University of València
- (Vidyasagar University)
- Washburn University
- Washington University
- Individuals without affiliation

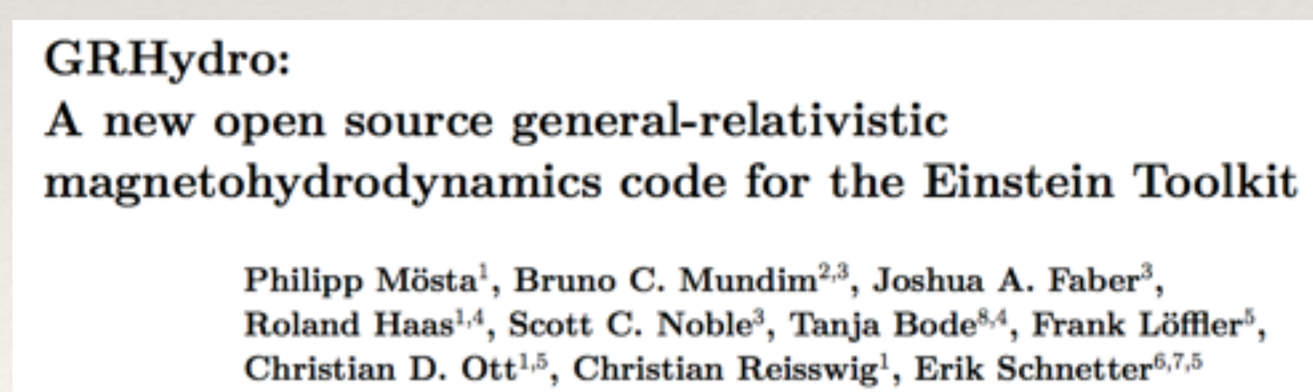
These add up to 100 members from 56 different groups.

Einstein Toolkit Members

The GRHydro ET Thorn

- Base: GRHD public version of Whisky code (EU 5th Framework)
- Much development plus new MHD
- Caltech, LSU, AEI, GATECH, Perimeter, RIT (NSF CIGR Award)
- Full 3D and dynamic general relativity
- Valencia formalism of GRMHD:
- Relativistic magnetized fluids in
- ideal MHD limit
- Published text results, convergence
- arXiv: 1304.5544 (Moesta et al, 2013)
- All code, input files etc part of
- Einstein Toolkit
- User support





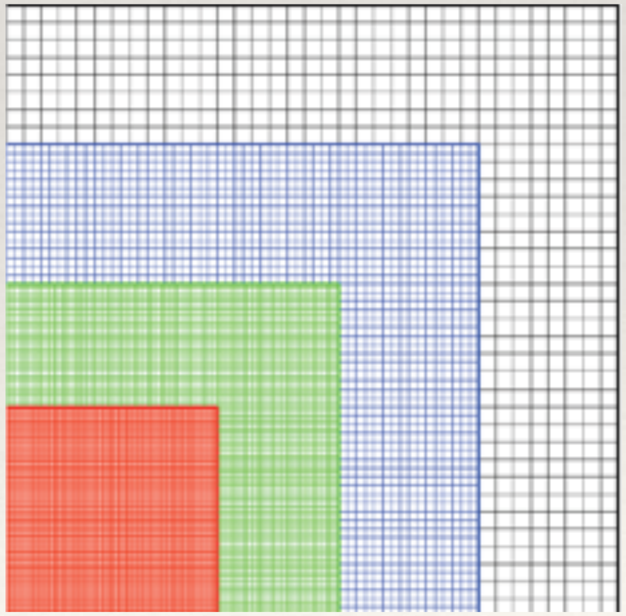
GRHydro:
A new open source general-relativistic magnetohydrodynamics code for the Einstein Toolkit

Philipp Mösta[1], Bruno C. Mundim[2,3], Joshua A. Faber[3], Roland Haas[1,4], Scott C. Noble[3], Tanja Bode[8,4], Frank Löffler[5], Christian D. Ott[1,5], Christian Reisswig[1], Erik Schnetter[6,7,5]

The code: Einstein TOOLKIT + LORENE

- **Cactus** framework for parallel high performance computing (Grid computing, parallel I/O)
- **Einstein Toolkit** open set of over 100 Cactus thorns for computational relativity along with associated tools for simulation management and visualization
- Mesh refinement with **Carpet**
- Matter Evolution with **GRHydro:**
  (Magnetic+**CT evolution** of Magnetic Field)
  HLLE Riemann Solver
  WENO Reconstruction methods (*)
  PPM Reconstruction methods
- Metric evolution MacClacan:
  BSSN gravitational evolutions (*)
  Z4 gravitational evolutions
- Initial data computed using di **LORENE CODE**

cactus code

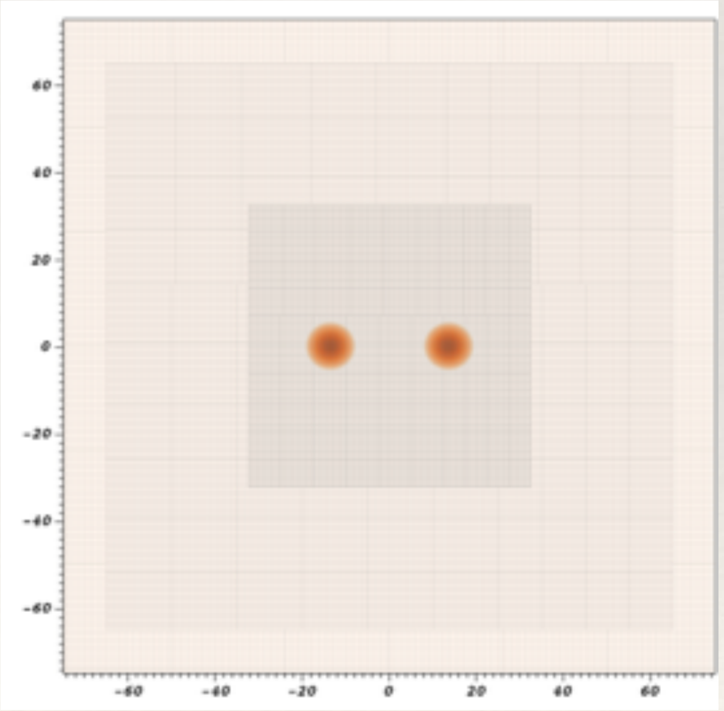


The computational challenge: minimal requirement.

- Cartesian grid with at-least 6 refinement levels.
- Standard Resolution in the finest grid **0.25** CU and up to 0.125 CU.
  => from 5,337,100 grid points and up to 42,696,800 for each refinement level.

Level	$\min(x/y)$ (CU)	$\max(x/y)$ (CU)	$\min(z)$ (CU)	$\max(z)$ (CU)	(N_x, N_y, N_z) $dx = 0.25$
1	-720	720	0	720	(185,185,96)
2	-360	360	0	360	(205,205,106)
3	-180	180	0	180	(205,205,106)
4	-90	90	0	90	(205,205,106)
5	-60	60	0	30	(265,265,76)
6	-30	30	0	15	(265,265,76)
(7	-15	15	0	7.5)	(265,265,76)

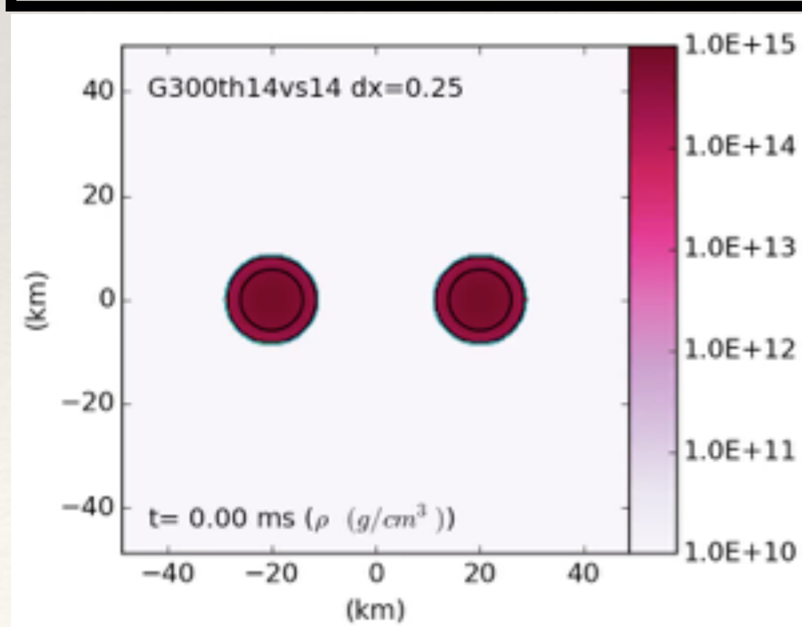
- Outer grid extends to 720M (1063Km) to extract gravitational waves far from the source.
- One extra refinement level added just before collapse to black hole.
- **17 spacetime variables + 4 gauge variables + 5** base variables evolved in each point + all the additional and derived variable needed to formulate the problem.
- **MPI+OpenMP code parallelization** already in place.

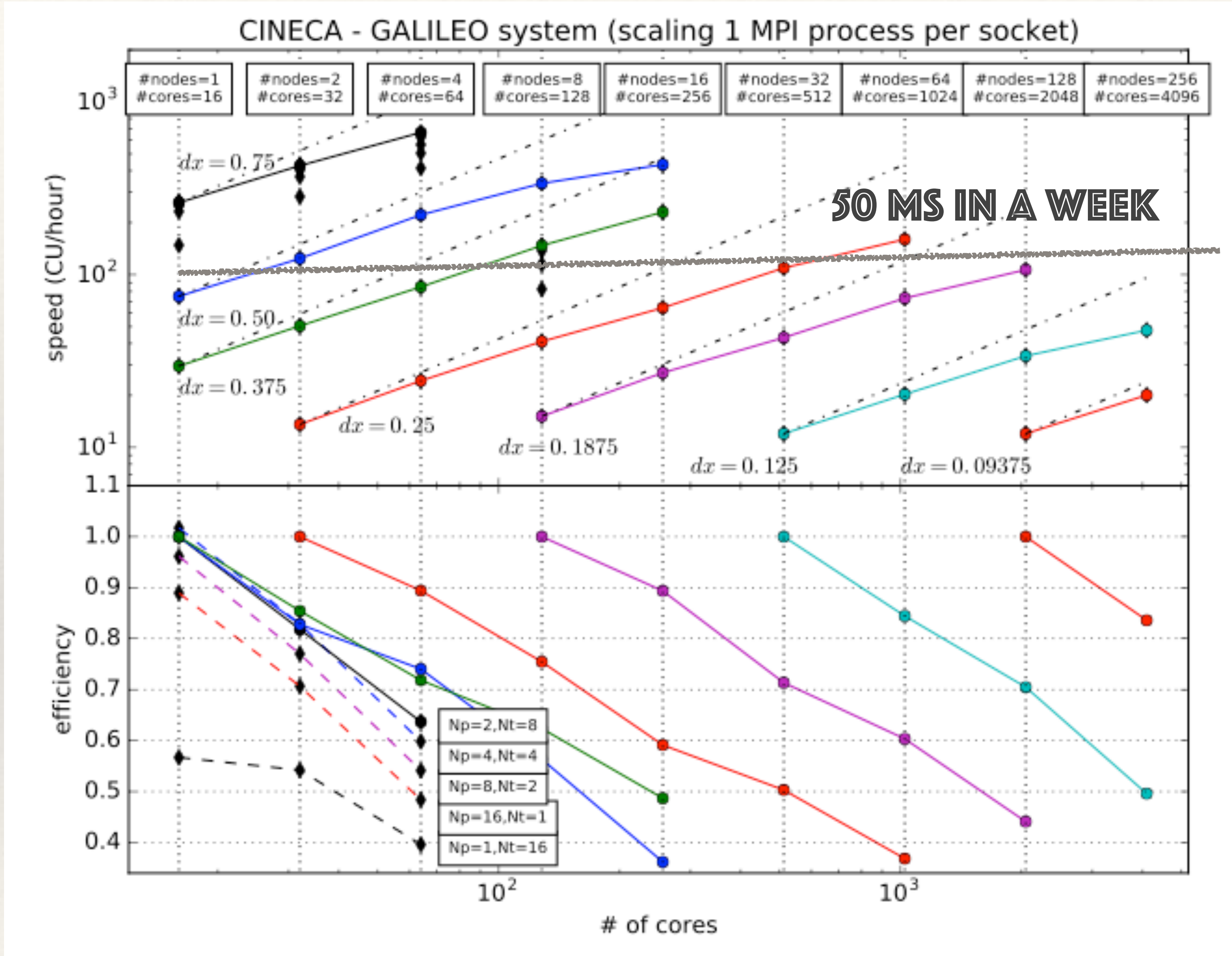


Scaling on real world simulations

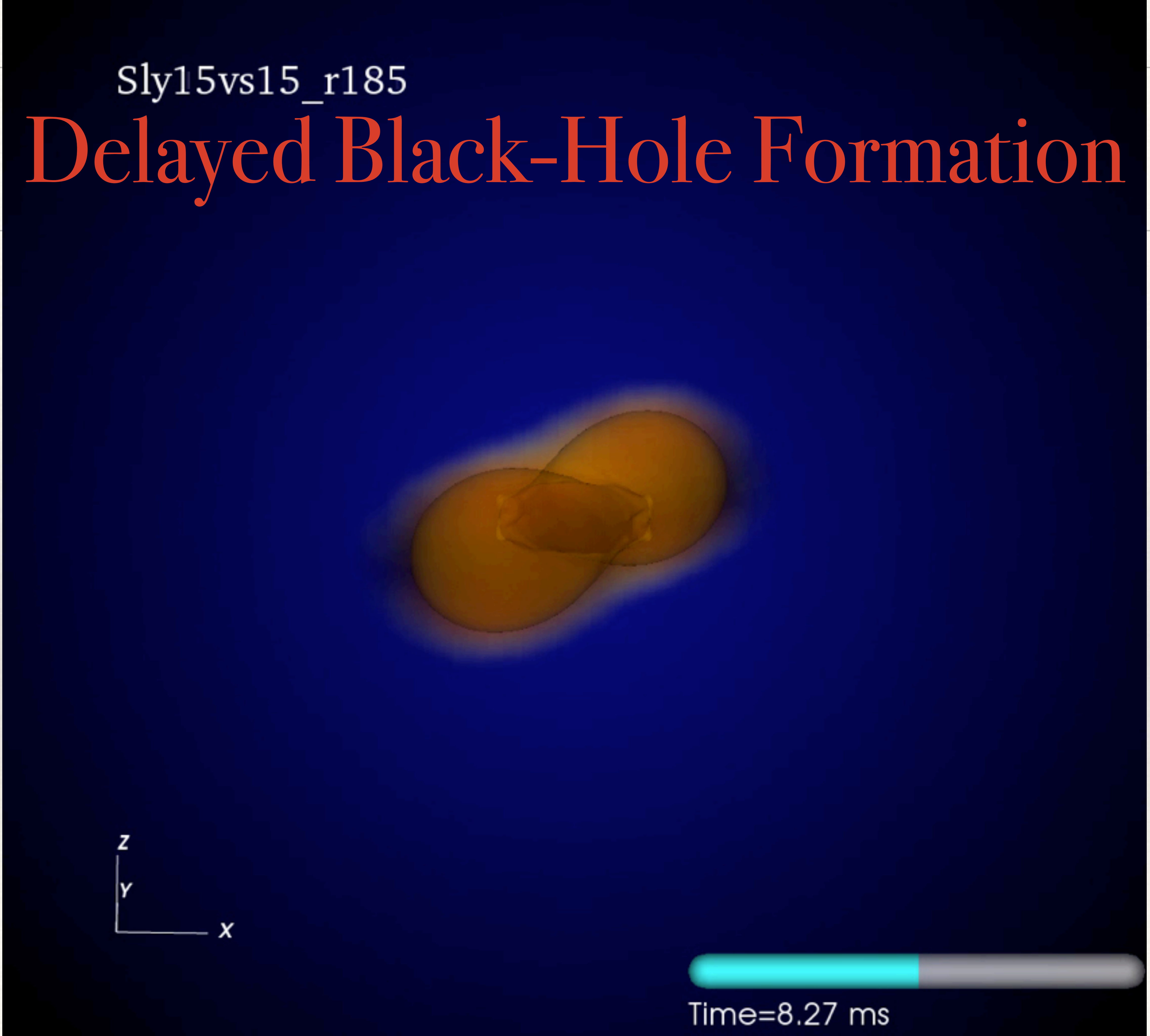
- Scaling of the the Einstein Toolkit on the CINECA "Galielo" system.
- Performance on a real world simulation!

Δx (CU)	0.75	0.50	0.375	0.25	0.185	0.125
# threads	16	64	128	256	512	2048
# MPI	2	8	16	32	64	256
Memory (GBytes)	3.8	19	40	108	237	768
speed (CU/h)	252	160	124	53	36	16
speed (ms/h)	1.24	0.78	0.61	0.26	0.18	0.08
cost (SU/ms)	13	81	209	974	2915	26053
total cost (kSU, 50 ms)	0.65	4	10.5	49	146	1300





Delayed Black-Hole Formation

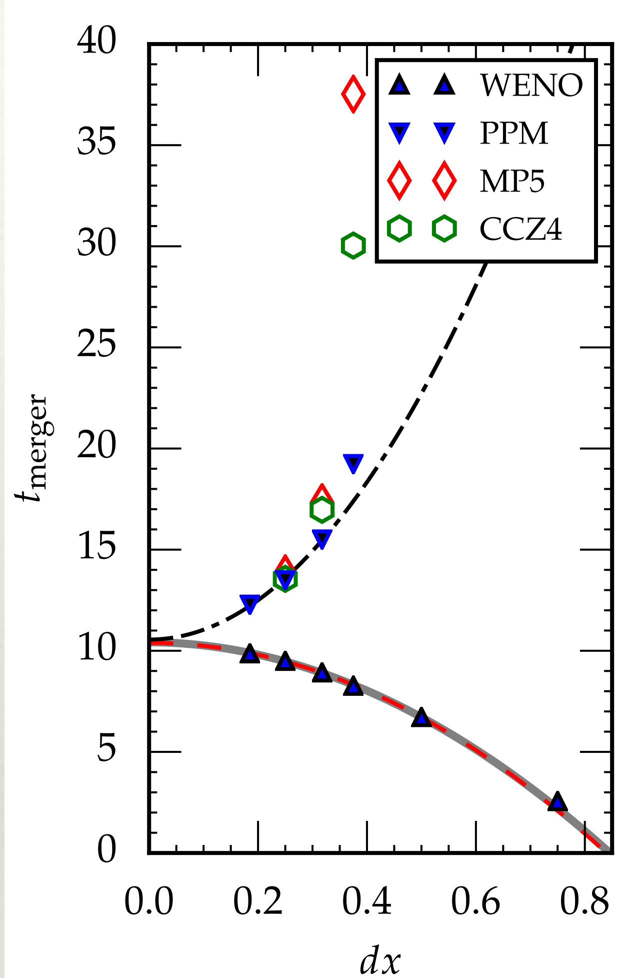


R. De Pietri, et all. Modeling Equal and Unequal Mass Binary Neutron Star Mergers Using Public Codes. Phys. Rev. D 93, 064047 arXiv:1509.08804

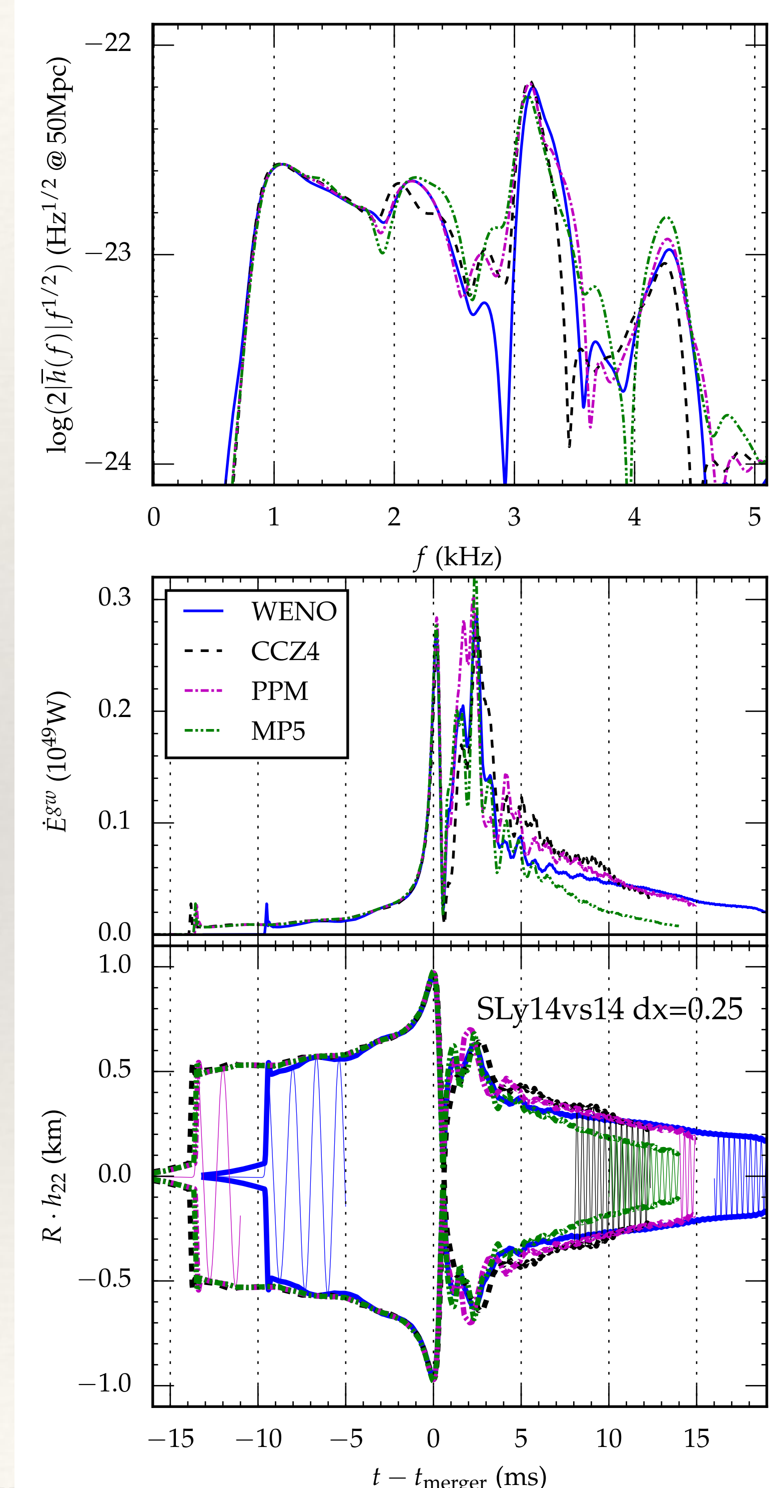
Modular structure: compare different methods!

Comparison between three different reconstruction methods (**WENO**,**PPM**,**MP5**)

and two gravity evolution schemes (**BSSN**,**CCZ4**).



	dx (CU)	t_{merger} (ms)
WENO	0.75	2.56
WENO	0.50	6.72
WENO	0.375	8.27
WENO	0.3125	8.93
WENO	0.25	9.50
WENO	0.185	9.87
PPM	0.375	19.23
PPM	0.3125	15.50
PPM	0.25	13.49
PPM	0.185	12.28
MP5	0.375	37.53
MP5	0.3125	17.34
MP5	0.25	13.81
CCZ4	0.375	30.03
CCZ4	0.3125	16.97
CCZ4	0.25	13.56



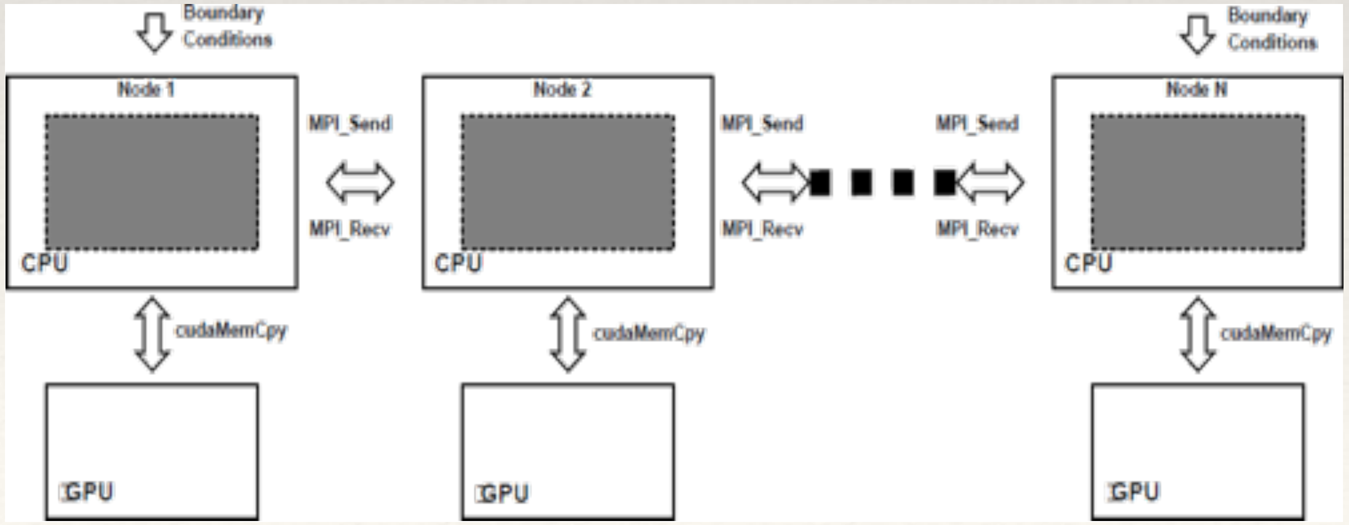
- The combination BSSN + WENO is the best for running sensible simulations at low resolution.
- With those methods you can run a qualitatively correct BNS simulation on your laptop!

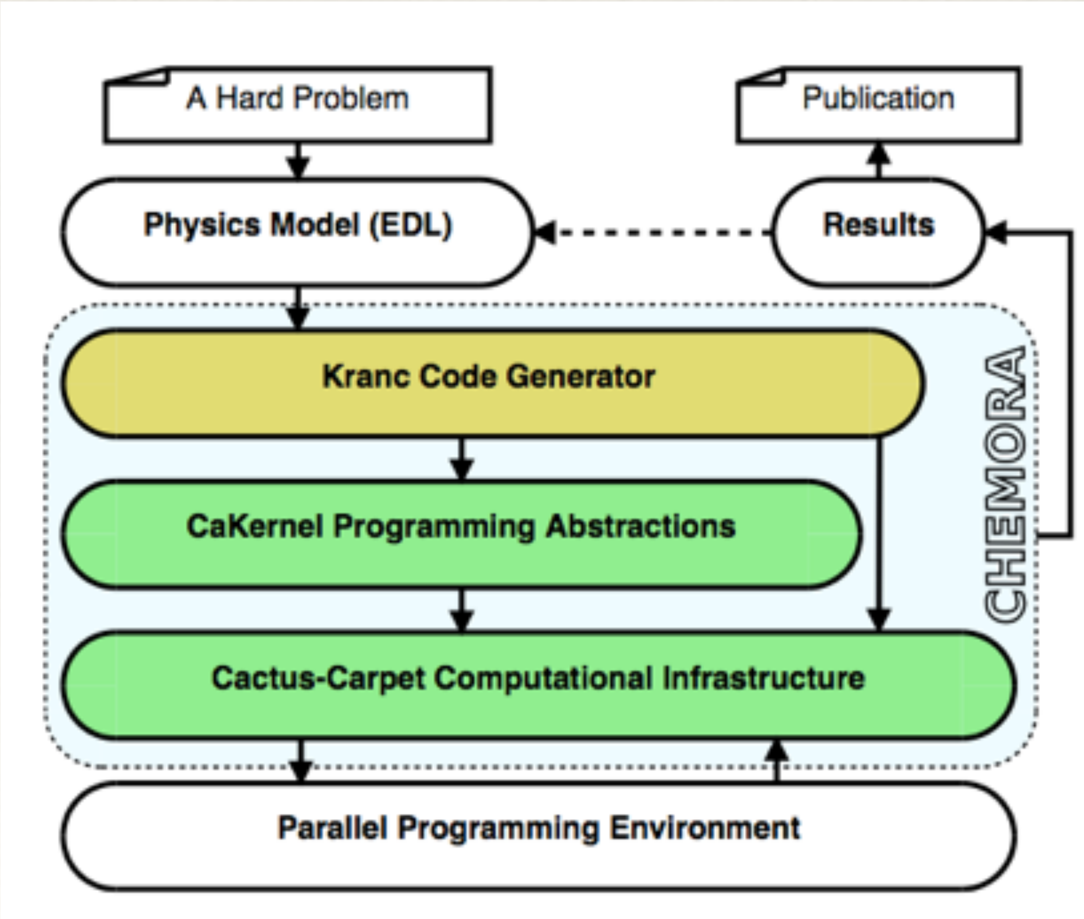
Challenge for the future

- **New physics: neutrino transport, photon radiation transport**
- **Massive scalability**
    - Local metadata, remove global operations
    - Extend Cactus abstractions for new programming models
    - Robust automatically generated code
    - Multithreading, accelerators
- **Tools: real time debuggers, profilers, more intelligent application-specific tools**
- **Data, visualization, profiling tools, debugging tools, tools to run codes, archive results, …**
- **Growing complexity of application, programming models, architectures.**
- **Social: how to develop sustainable software for astrophysics? CDSE and supporting career paths? Edcuation?**

"Chemora" PROJECT

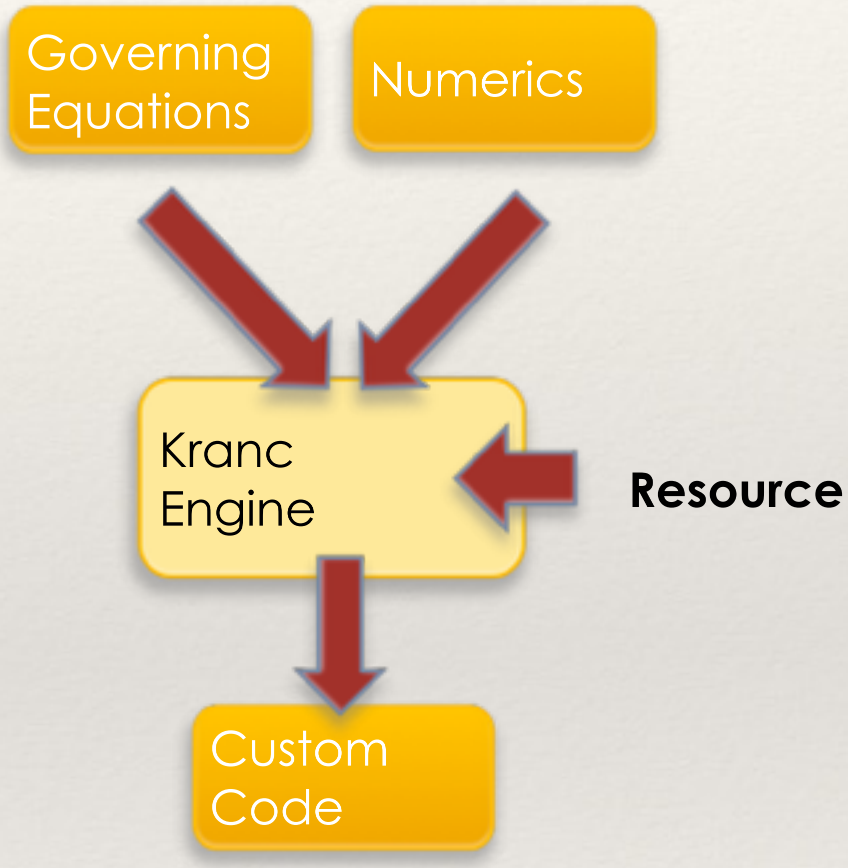
- Use large scale CPU/GPU systems efficiently for complex applications
- Reduce code rewrite, new programming paradigms
- Strategy uses:
- High level code transformations
- Loop traversal strategies
- Dynamically selected data/instruction cache
- JIT compiler tailored to application





Automatic code generation

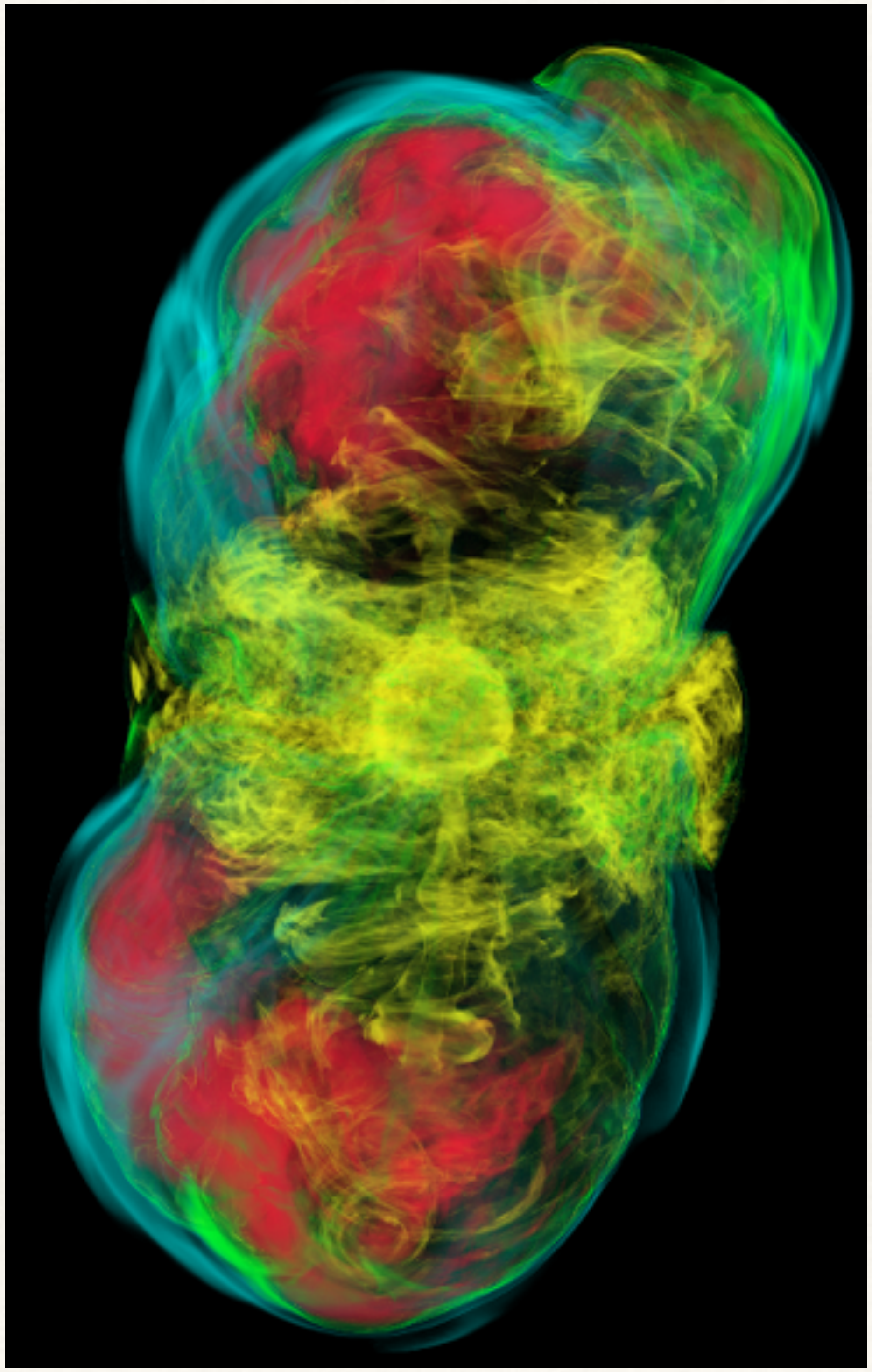
- Einstein equations very complex
  - Coding cumbersome, error prone
  - Deters experimentation
- Kranc: Mathematica tool to generate Cactus thorns from PDEs, specify differencing methods
- Vision: Generate entire codes from underlying equations/problem specification, optimize codes for target architectures
  - Revolutionize HPC
  - Opportunity to integrate verification/validation/data description



Kranc
Kranc Assembles Numerical Code

ET used for the study of core collapse !

- Not only used to simulate Binary Neutron Star Merger or Binary Black Hole Merger but also for studying CORE COLLAPSE.
- Philipp Mösta, Christian D. Ott, David Radice, Luke F. Roberts, Erik Schnetter, and Roland Haas. **Nature, Nov 30, 2015**



The "Physics" already implemented.

- **GR-evolutions** (McLachlan: BSSN and Z4)
- **Hydro/MHD-evolutions** (GRHydro, IllinoisGRMHD)
- **Exact/tabulated EOSs**
- **Initial data:** Trivial/exact/test ID, TOVSolver (nonrotating stars) TwoPunctures (single, binary BHs), Meudon (BBH/BHNS/BNS data)
- **Analysis:** AHFinderDirect, PunctureTracker, WeylScal4, Hydro Analysis, Outflow QuasiLocalMeasures, PITTNullCode

The future

- **Data-dependent task scheduling**
  reads/writes statements instead of before/after
- **Initial Data and Elliptic Solvers**
  concentrate on multi-grid solver and Lorene
- **Spherical Coordinates**
  reference metric to deal with coordinate singularity (Baumgarte et. al)
  partially implicit RK
- **Einstein Exploration Module**
  Examples, codes, tutorials not targeted at HPC, but education
- **IllinoisGRMHD**
  Full integration
- **New matter sources**
  complex scalar fields coupled to gauge vector fields, Maxwell fields, and collisionless particles
- **DataVault:** an easier way to share (large) data sets more metadata!
  collaboration with national data service (NCSA)
- **Your contribution!**

- **FUNDING:**
- historical
  EU network
  NSF (US): CIGR
  NSF (US): XiRel, Alpaca, PetaCactus
  NSF (US) PHY grants
  1212401/1212426/1212433/1212460
  (Caltech, GaTech, LSU, RIT)
- **NEW 4-year NSF (US) SSI grant (GaTech, LSU, RIT, UIUC, “external”)**
- **CODE SIZE:**
- **Repositories (53): bitbucket: 29 github: 3 cactuscode.org (svn): 21**
- **Code size: ≈230MB**
  Code size: ≈370MB (includes testsuites)
  Checkout size: ≈725MB (git + svn)
  Compiled footprint: ≈2.8GB
  (no external libraries, except Lorene)
  Executable size: 310MB
  (≈240MB without Formaline)
  Compilation time: ≈5min ... hours

Credits

- Frank Loeffler (Louisiana State University)
- Erik Schnetter (Perimeter Institute)
- Christian Ott (Caltech)
- Ian Hinder (Albert Einstein Institute)
- Roland Haas (Caltech)
- Tanja Bode (Tuebingen)
- Bruno Mundim (Albert Einstein Institute)
- Peter Diener (Louisiana State University)
- Christian Reisswig (Caltech)
- Joshua Faber (RIT)
- Philipp Moesta (Caltech)
- And many others

- WEB SITE:

  http://einsteintoolkit.org

- TUTORIAL:

  "Introduction to the Einstein Toolkit" from Oleg Korobkin at the 2015 Einstein Toolkit Workshop

  https://docs.einsteintoolkit.org/et-docs/images/9/95/Cactusintro.pdf

Example of simulation of BNS systems only using public codes. Means you can download the code and reproduce all the results on your system.
(http://www.fis.unipr.it/gravity/Research/BNS2015.html)
R. De Pietri, A. Feo, F. Maione and F. Loeffler,
Modeling Equal and Unequal Mass Binary Neutron Star Mergers Using Public Codes.
Phys. Rev. D 93, 064047 arXiv:1509.08804

Conclusions

- **Numerical relativity community generally now comfortable with sharing software**
  - Didn't happen overnight
  - Some fundamental issues resolved first (BH-BH evolutions)
  - Some trade-offs, flexibility / support
- **Einstein Toolkit approach**
  - Mechanism for injecting new science (e.g. GRHydro) and taking full benefit of new CS opportunities
  - Need to focus on implications for young researchers, motivation to contribute, scientific aims
  - Focus on modularity / abstractions reduces dependence on Cactus
- **Funding**
  - Need lightweight governance model to better target funding, help funding agencies make decisions, enable leveraging international funding
  - Target limited science funding where it will make a difference, leverage CS funding
  - Cactus: broader application base has potential to coordinate with other disciplines