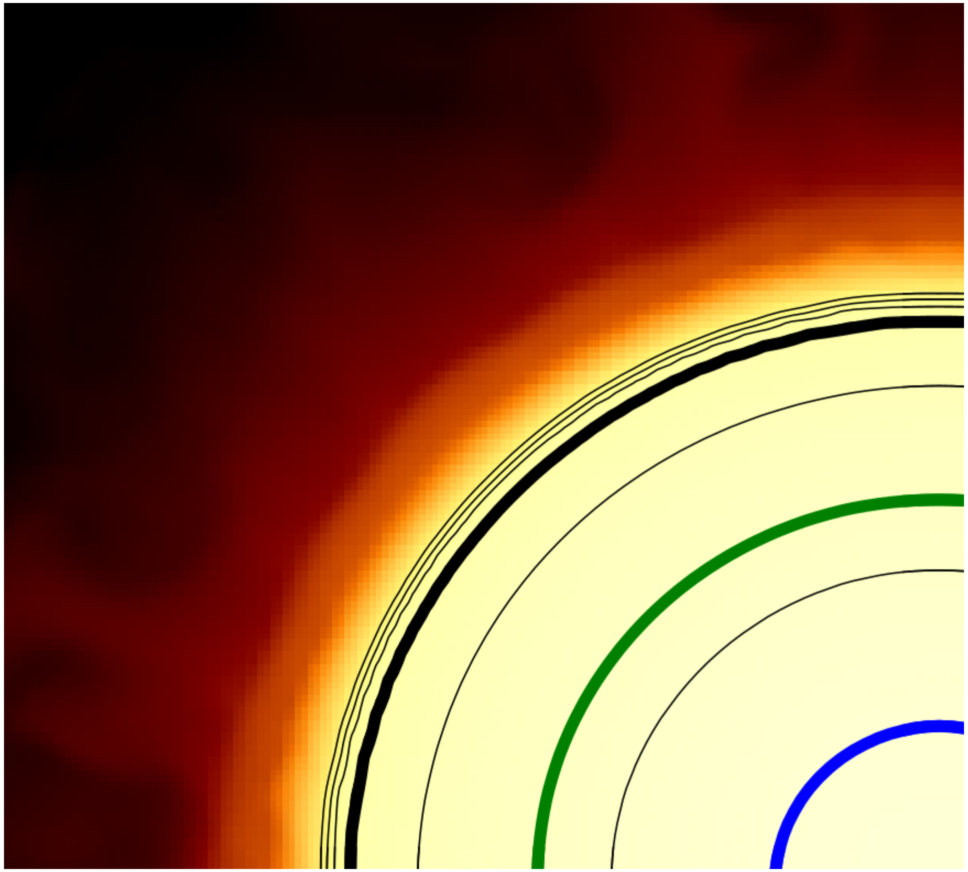


GR on the Computer

Vorlesung vertreten durch Michael T. Rattay,
Goethe University Frankfurt
15. June 2018

Compact object zoo

- End products of stellar evolution (**compact stars**)
  - White dwarfs (**$\sim r_{Earth}$, $\sim M_\odot$**) remnants of stellar collapse (**$<8M_\odot$**)
  - **Neutron stars** (**$r_{NS}\sim 10km$, $\lesssim 2.17\ M_\odot \equiv M_{TOV}$, $\rho_c \geqq \rho_0$**); produced by supernovae (**$8M_\odot$** to **$\sim 25M_\odot$**), upheld by neutron degeneracy pressure
  - Stellar **black holes**, equilibrium of degeneracy pressure against gravity breaks down, escape velocity reaches **c**; created by stars **$\geqq 25M_\odot$**
- Other compact objects
  - Intermediate and supermassive black holes
  - Exotic stars (Quark stars, Boson stars, etc.)

Solving General Relativity

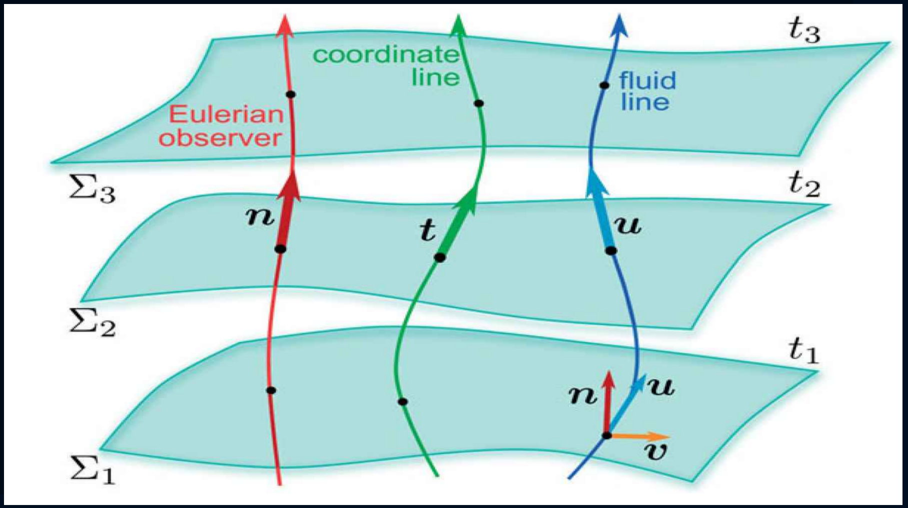
- **GR** solutions depend on the considered system
  - with enough symmetries → **analytical** solutions
  - with small parameters → **pertubative** solutions
  - If no symmetries, strong fields and dynamic system → solutions by **numerical relativity**
  - Evolution of the system → **relativistic hydrodynamics**
- **Equation of state** determines solutions: **P(ρ)**
- Exact **EOS** for dense matter is not known → different models in use
- **Mass radius relation**, causality and (future) observations constraint **EOS**

Numerical Relativity and Relativistic Hydrodynamics of Binary Neutron Star Mergers

A realistic numerical simulation of a twin star collapse, a merger of two compact stars or a collapse to a black hole needs to go beyond a static, spherically symmetric TOV-solution of the Einstein- and hydrodynamical equations.

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

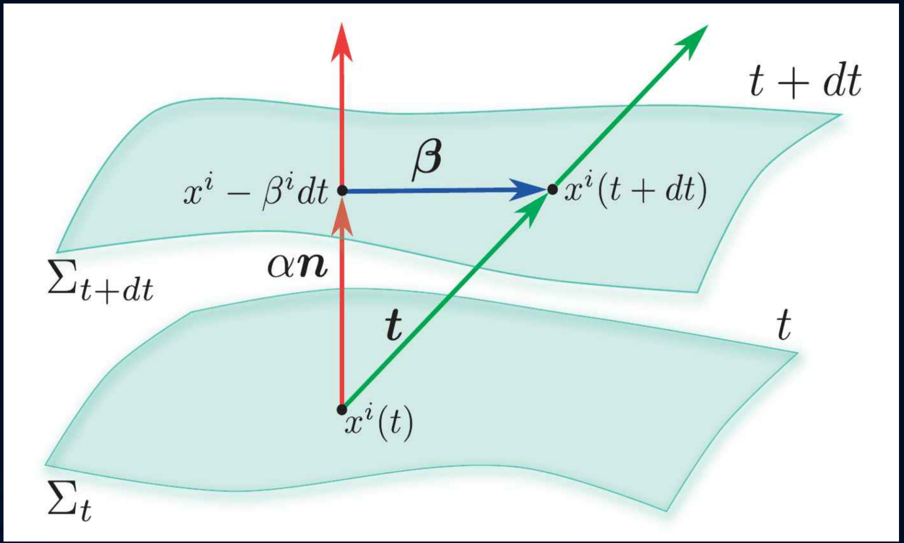
$$\nabla_\mu (\rho u^\mu) = 0 \,, \qquad \nabla_\nu T^{\mu\nu} = 0 \,.$$



(3+1) decomposition of spacetime

$$g_{\mu\nu} = \begin{pmatrix} -\alpha^2 + \beta_i \beta^i & \beta_i \\ \beta_i & \gamma_{ij} \end{pmatrix}$$

$$d\tau^2 = \alpha^2(t, x^j) dt^2 \qquad x^i_{t+dt} = x^i_t - \beta^i(t, x^j) dt$$



All figures and equations from: Luciano Rezzolla, Olindo Zanotti: Relativistic Hydrodynamics, Oxford Univ. Press, Oxford (2013)

Numerical relativity 1/4

- Evolve spacetime: 3+1 split → back to space+time
- Define spacelike hyper surfaces $\boldsymbol{\Sigma_t}$ with:
  - Normal one form $\boldsymbol{\Omega_\mu = \nabla_\mu t}$ and…
  - Unit normals: $\boldsymbol{n_\mu = - \alpha\, \Omega_\mu}$ (future pointing)
- Spatial tensor contractions vanish: $\boldsymbol{v^\mu n_\mu = 0}$
- Differential geometry in $\boldsymbol{\Sigma_t}$ (metric, derivative …):
  - Metric: $\boldsymbol{\gamma_{\rho\sigma} = g_{\alpha\beta}\gamma^\alpha{}_\sigma \gamma^\beta{}_\rho = g_{\alpha\beta} + n_\alpha n_\beta}$
  - Derivative: $\boldsymbol{D_\alpha f = \gamma_\alpha{}^\beta \nabla_\beta f}$ and $\boldsymbol{D_\alpha v^\beta = \gamma_\alpha{}^\sigma \gamma^\beta{}_\rho \nabla_\sigma v^\rho}$
  - Spatial Riemann tensor: $\boldsymbol{{}^{(3)}R^\rho{}_{\sigma\alpha\beta} v_\rho = 2 D_{[\beta} D_{\alpha]} v_\rho}$

Numerical relativity 2/4

- Embed Σ_t in the manifold with extrinsic curvature:

$$K_{\sigma\rho} = \gamma^{\alpha}{}_{\sigma}\gamma^{\beta}{}_{\rho}\nabla_{(\alpha}n_{\beta)} = -1/2\mathcal{L}_n\gamma_{\sigma\rho}$$

- Relate 4D and 3D curvature: Gauss, Cadazzi and Ricci equations (plenty calculations!)
- Adopt coordinates $x^{\alpha} = [t, x^i]$ and time vector $t^{\sigma} = \alpha\, n^{\sigma} + \beta^{\sigma}$
- Decompose Einstein to 3+1 equations $(S_{\sigma\rho} = \gamma^{\alpha}{}_{\sigma}\gamma^{\beta}{}_{\rho}T_{\alpha\beta})$:
  - nn: ${}^{(3)}R + K^2 - K_{ij}K^{ij} = 16\pi\rho$ $(\rho = T_{\alpha\beta}n^{\alpha}n^{\beta})$ Hamiltonian constraint (H)
  - nγ: $D_j(K^{ij} - \gamma^{ij}K) = 8\pi S^i$ Momentum constraint (M)
  - γγ: $\partial_t K_{ij} = \alpha({}^{(3)}R_{ij} - 2K_{ik}K^k{}_j + KK_{ij} - D_iD_j\alpha - 8\pi\alpha(S_{ij} - 1/2\gamma_{ij}(S-\rho))$

    $+ \beta^k\partial_k K_{ij} + K_{ik}\partial_j\beta^k + K_{kj}\partial_i\beta^k$
  - Definition of K_{ij}: $\partial_t \gamma_{ij} = -2\alpha K_{ij} + D_i\beta_j + D_j\beta_i$ i,j=1,2,3

Numerical relativity 3/4

- Coordinate freedom by **α, β:**
  - $ds^2 = -\alpha\, dt^2 + \gamma_{ij}\, (dx_i + \beta_i dt)\, (dx^j + \beta^j dt)$
- So far so good... but...
  - Solve constraints for γ_{ij}, K_{ij} — (H) and (M) are of no known math type
  - Choose gauge **α, β** — Singularities have to be avoided, have to be chosen before solution
  - Evolve $\partial_t \gamma_{ij}$, $\partial_t K_{ij}$ — Not well posed equations! Numerics will fail.
- Solution: conformal transformation: $\gamma_{ij}(x^i) = \phi^4(x^i)\tilde{\gamma}_{ij}(x^i)$
  - **$\phi(x^i) > 0$; induces conformal geometry ($\tilde{R}$, $\tilde{D}_i$, ...)**

Numerical relativity 4/4: conclusion

- Further steps:
  - Conformal trafo yields elliptic equation for (H')
  - Transverse (divergence free), traceless decomposition of $\mathbf{K^{ij}=A^{ij}+{}^{1/3}\gamma^{ij}K}$ yields elliptic operator for $\mathbf{A^{ij}=\phi^{-10}\tilde{A}_{ij}}$
  - Trafo of equations yields **4 coupled, elliptic 2nd order PDEs**, can be solved numerically!
  - Solvable with boundary conditions (problematic for BH with spin >0.9)
- Evolution of initial data: e.g. BSSNOK equations
  - $\mathbf{\partial_t \gamma^*_{ij} = \ldots;\ \partial_t \tilde{A}_{ij} = \ldots;\ \partial_t \phi = \ldots;\ \partial_t K = \ldots;\ \partial_t \tilde{\Gamma}_i = \ldots}$ **(see [1])**
- Alternative formulations: CCZ4, generalized harmonic formulation

The ADM equations

The ADM (Arnowitt, Deser, Misner) equations come from a reformulation of the Einstein equation using the (3+1) decomposition of spacetime.

$$\partial_t \gamma_{ij} = -2\alpha K_{ij} + \mathscr{L}_{\boldsymbol{\beta}} \gamma_{ij} = -2\alpha K_{ij} + D_i\beta_j + D_j\beta_i$$

$$\partial_t K_{ij} = -D_i D_j \alpha + \beta^k \partial_k K_{ij} + K_{ik}\partial_j \beta^k + K_{kj}\partial_i\beta^k + \alpha\left({}^{(3)}R_{ij} + KK_{ij} - 2K_{ik}K^k{}_j\right) + 4\pi\alpha\left[\gamma_{ij}(S-E) - 2S_{ij}\right]$$

Time evolving part of ADM

$$D_j(K^{ij} - \gamma^{ij}K) = 8\pi S^i$$

$${}^{(3)}R + K^2 - K_{ij}K^{ij} = 16\pi E$$

Constraints on each hypersurface

Three dimensional covariant derivative

$$D_\nu := \gamma^\mu{}_\nu \nabla_\mu = (\delta^\mu_\nu + n_\nu n^\mu)\nabla_\mu$$

Spatial and normal projections of the energy-momentum tensor:

$$S_{\mu\nu} := \gamma^\alpha{}_\mu \gamma^\beta{}_\nu T_{\alpha\beta},$$
$$S_\mu := -\gamma^\alpha{}_\mu n^\beta T_{\alpha\beta},$$
$$S := S^\mu{}_\mu,$$
$$E := n^\alpha n^\beta T_{\alpha\beta},$$

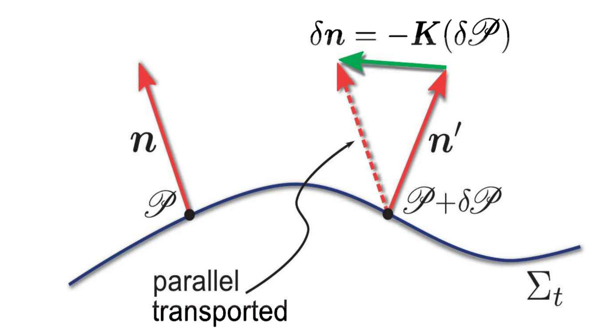
Extrinsic Curvature:

$$K_{\mu\nu} := -\gamma^\lambda{}_\mu \nabla_\lambda n_\nu$$

Three dimensional Riemann tensor

$${}^{(3)}R^\mu{}_{\nu\kappa\sigma} = \partial_\kappa {}^{(3)}\Gamma^\mu_{\nu\sigma} - \partial_\sigma {}^{(3)}\Gamma^\mu_{\nu\kappa} + {}^{(3)}\Gamma^\mu_{\lambda\kappa}{}^{(3)}\Gamma^\lambda_{\nu\sigma} - {}^{(3)}\Gamma^\mu_{\lambda\sigma}{}^{(3)}\Gamma^\lambda_{\nu\kappa}$$

$${}^{(3)}\Gamma^\alpha_{\beta\gamma} = \frac{1}{2}\gamma^{\alpha\delta}\left(\partial_\beta\gamma_{\gamma\delta} + \partial_\gamma\gamma_{\delta\beta} - \partial_\delta\gamma_{\beta\gamma}\right)$$



All figures and equations from: Luciano Rezzolla, Olindo Zanotti: Relativistic Hydrodynamics, Oxford Univ. Press, Oxford (2013)

From ADM to BSSNOK

Unfortunately the ADM equations are only weakly hyperbolic (mixed derivatives in the three dimensional Ricci tensor) and therefore not "well posed". It can be shown that by using a conformal traceless transformation, the ADM equations can be written in a hyperbolic form. This reformulation of the ADM equations is known as the BSSNOK (Baumgarte, Shapiro, Shibata, Nakamuro, Oohara, Kojima) formulation of the Einstein equation. Most of the numerical codes use this (or even better the CCZ4) formulation.

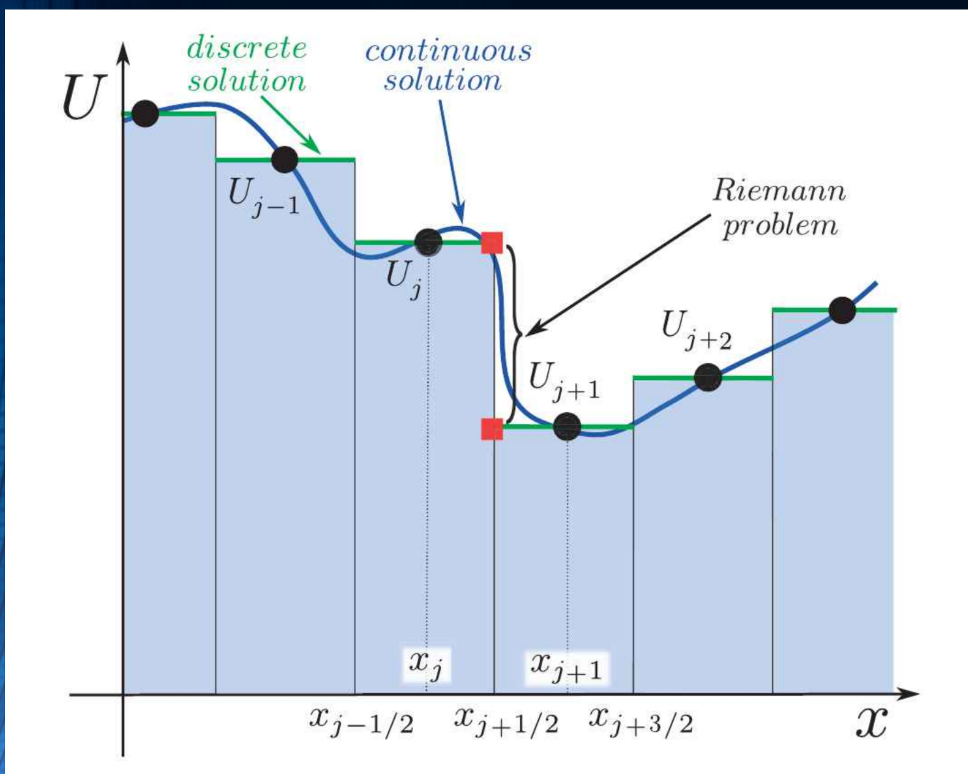
The 3+1 Valencia Formulation of the Relativistic Hydrodynamic Equations

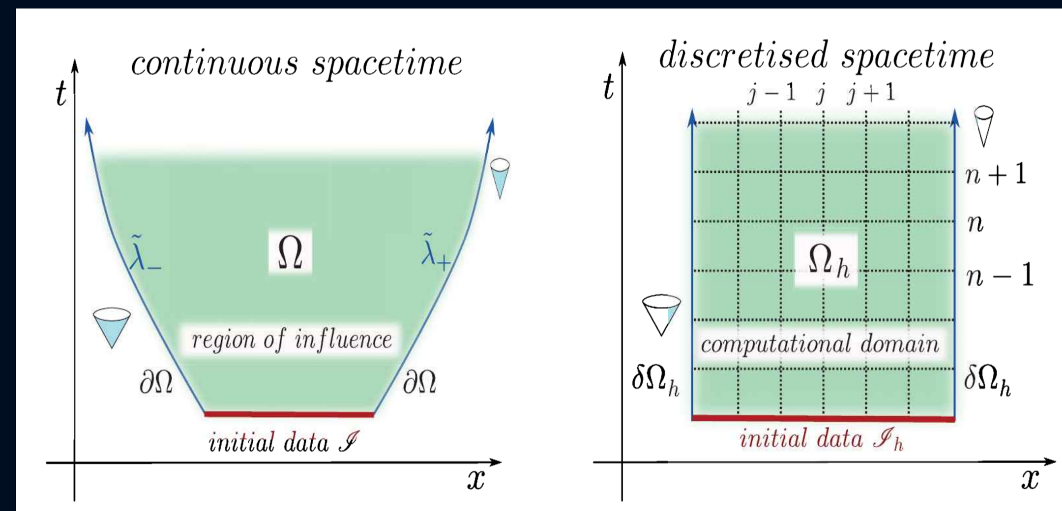
$$\nabla_\mu(\rho u^\mu) = 0\,, \\ \nabla_\nu T^{\mu\nu} = 0\,.$$

To guarantee that the numerical solution of the hydrodynamical equations (the conservation of rest mass and energy-momentum) converge to the right solution, they need to be reformulated into a conservative formulation. Most of the numerical “hydro codes” use the 3+1 Valencia formulation.

Finite difference methods

Discretisation of a hyperbolic initial value boundary problem.





High resolution shock capturing methods (HRSC methods are needed, when Riemann problems of discontinuous properties and shocks needs to be evolved accurately.)

All figures from: Luciano Rezzolla, Olindo Zanotti: Relativistic Hydrodynamics, Oxford Univ. Press, Oxford (2013)

Gauge Conditions

On each spatial hypersurface, four additional degrees of freedom need to be specified: A slicing condition for the lapse function and a spatial shift condition for the shift vector need to be formulated to close the system. In an optimal gauge condition, singularities should be avoided and numerical calculations should be less time consuming.

na-Massó family of slicing conditions: $$\partial_t \alpha - \beta^k \partial_k \alpha = -f(\alpha)\, \alpha^2 (K - K_0)$$

“1+log” slicing condition: $f = 2/\alpha$ where $f(\alpha) > 0$ and $K_0 \coloneqq K(t=0)$

“Gamma-Driver” shift condition:

$$\partial_t \beta^i - \beta^j \partial_j \beta^i = \frac{3}{4} B^i,$$
$$\partial_t B^i - \beta^j \partial_j B^i = \partial_t \tilde{\Gamma}^i - \beta^j \partial_j \tilde{\Gamma}^i - \eta B^i$$

Twin stars

- Solutions for **NS** with two equilibria

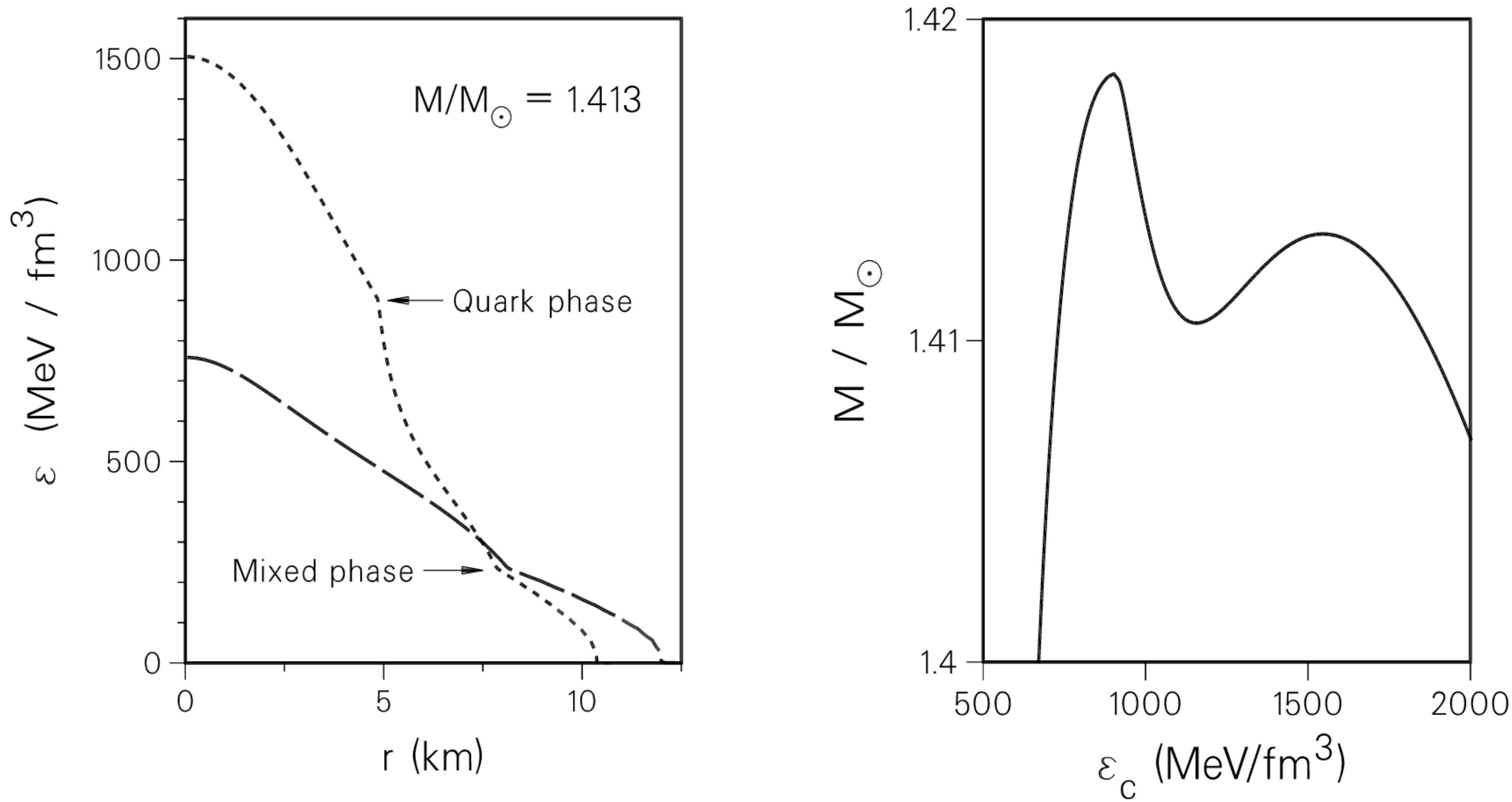
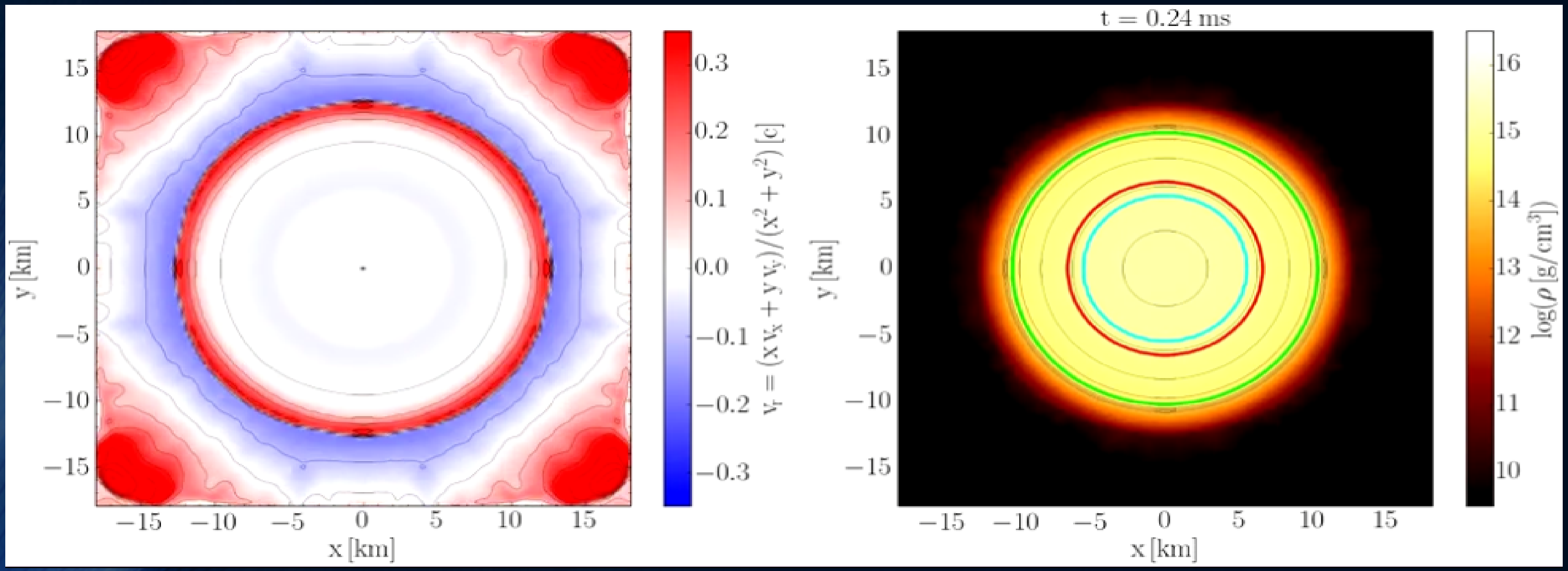


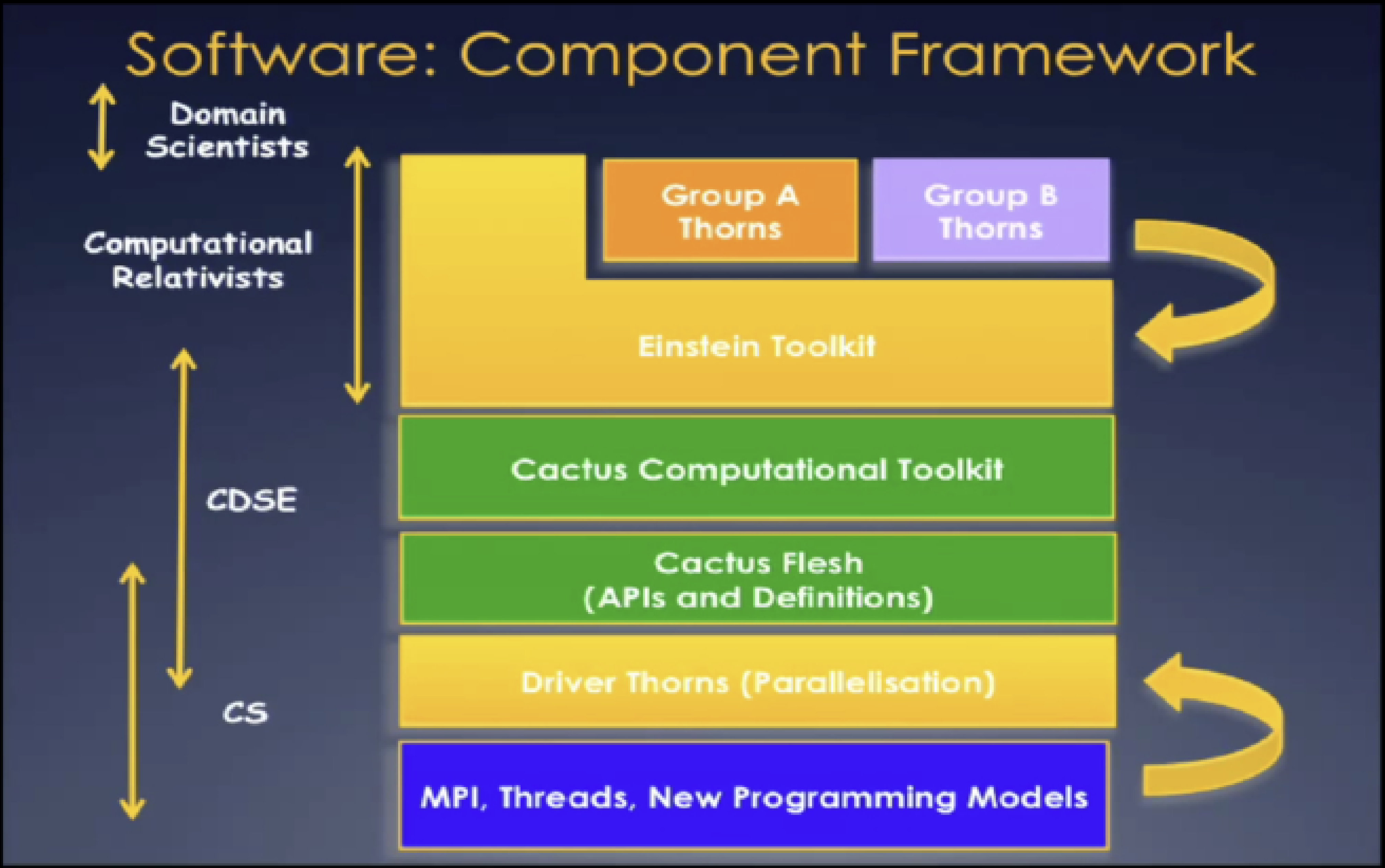
FIG. 2. Stellar sequence of neutron stars and their twins as a function of central density. Both segments with positive slope correspond to stable configurations since their normal modes of vibration are found to be stable.

Teil III

<u>Inhalte des Teil III:</u>

- How to download and build (compile) the Einstein Toolkit
- How to run a test simulation (static_tov.par)
- Run and visualize (Mathematica or Python) one of the following problems
    - Migration of an unstable neutron star to a stable configuration
    - Collapse of an unstable neutron star to a black hole
    - Collapse of a neutron star to a quark star (twin star collapse)




Software: Component Framework
Domain Scientists
Computational Relativists
CDSE
CS
Group A Thorns
Group B Thorns
Einstein Toolkit
Cactus Computational Toolkit
Cactus Flesh
(APIs and Definitions)
Driver Thorns (Parallelisation)
MPI, Threads, New Programming Models

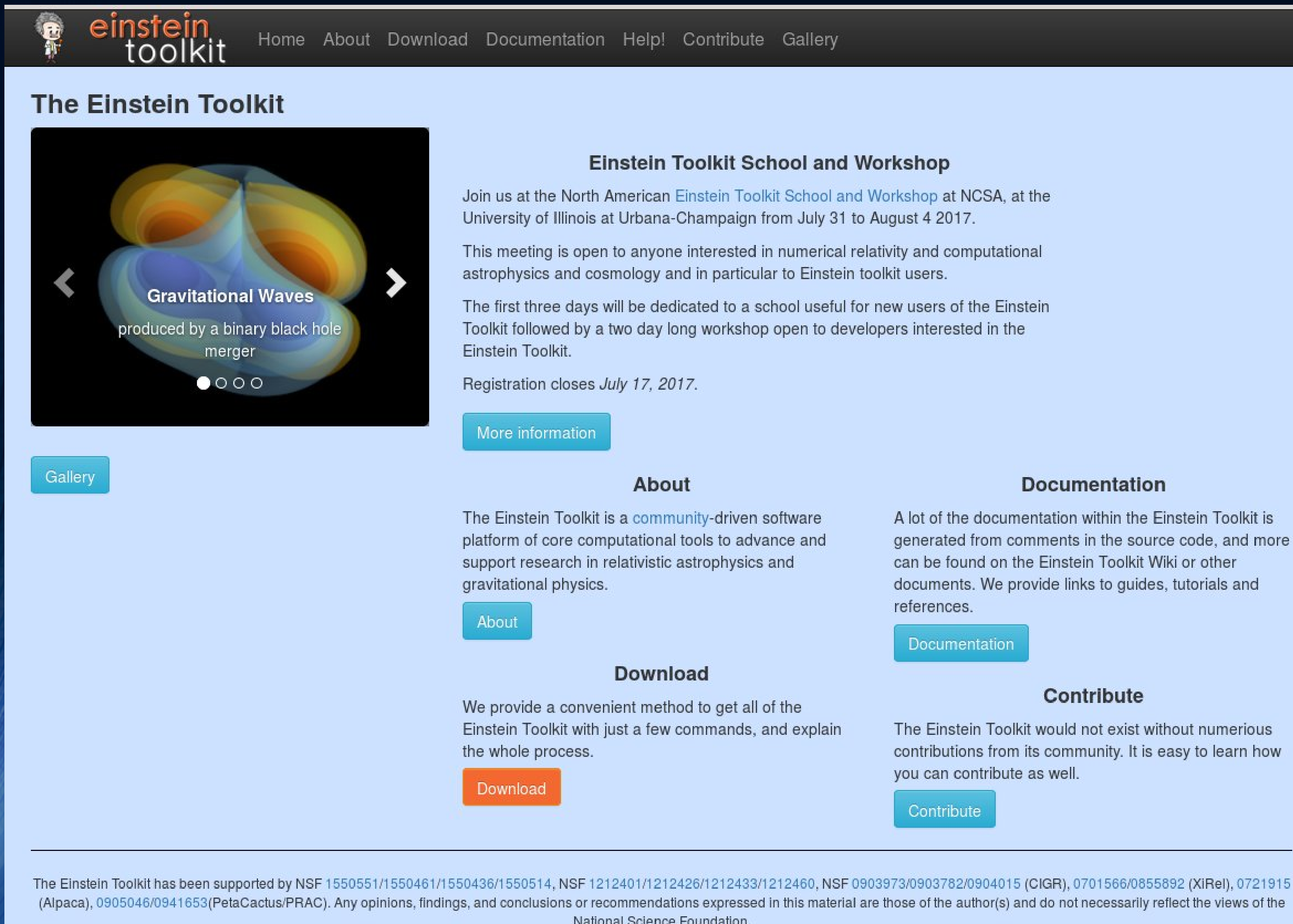
Einstein Toolkit

"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."

* 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)

HTTP://WWW.EINSTEINTOOLKIT.ORG

Das Einstein Toolkit



Das Einstein Toolkit: Download

einstein toolkit Home About Download Documentation Help! Contribute Gallery

Download & Requirements

The Einstein Toolkit is hosted on many different machines around the world. We provide a script called GetComponents to simplify downloading the toolkit. This page just describes how to download the toolkit - you may also be interested in the Tutorial for New Users which leads you through these steps and more on the Queen Bee supercomputer, or in a simpler tutorial for setup on a typical Linux box.

Users of the Einstein Toolkit are encouraged to register which also signs up for the users mailing list.

Main Toolkit

Citations

The development of production level scientific software, such as the components of the Einstein Toolkit, represents the academic output of researchers. These scientific contributions should be acknowledged and respected on par with those solely based in theory or experiment. Please review our Citation Policy.

Current release: Payne-Gaposchkin (released on December 16th, 2016)

This is the recommended version of the toolkit for most users. See the release notes for more information.

Note: OSX users cannot use the 'subversion' client shipped by Apple. In that case install subversion either from homebrew or macports.

Enter the directory on your machine in which you would like to download the ET (for example, your home directory), and type the commands listed below. This will create a directory called Cactus in which the components of the Einstein Toolkit are downloaded.

```
curl -kLO https://raw.githubusercontent.com/gridaphobe/CRL/ET_2016_11/GetComponents
chmod a+x GetComponents
./GetComponents --parallel https://bitbucket.org/einsteintoolkit/manifest/raw/ET_2016_11/einsteintoolkit.th
```

A tarball of the release is also available here, but using GetComponents is the preferred method to obtain the code. Use the tarball only if there is no way to use GetComponents (which should almost never be the case).

ET-Download auf dem Fuchs-Cluster

```
[prakti1@login02.csc ~]$ cd ET-2016-11/
[prakti1@login02.csc ET-2016-11]$ curl -kLO https://raw.githubusercontent.com/gridaphobe/CRL/ET_2016_11/GetComponents
  % Total    % Received % Xferd  Average Speed   Time    Time     Time  Current
                                 Dload  Upload   Total   Spent    Left  Speed
100 99330  100 99330    0     0   486k      0 --:--:-- --:--:-- --:--:-- 30.9M
[prakti1@login02.csc ET-2016-11]$ chmod a+x GetComponents
[prakti1@login02.csc ET-2016-11]$ ./GetComponents --parallel https://bitbucket.org/einsteintoolkit/manifest/raw/ET_2016_11/einsteintoolkit.th
-----------------------------------------------------------------
  Checking out module: par
      from repository: https://bitbucket.org/einsteintoolkit/einsteinexamples.git
                 into: Cactus
```

```
[prakti1@login02.csc ET-2016-11]$ curl -kLO https://raw.githubuse
  % Total    % Received % Xferd  Average Speed   Time    Time
                                 Dload  Upload   Total   Spent
100 99330  100 99330    0     0   486k      0 --:--:-- --:--:-- -
[prakti1@login02.csc ET-2016-11]$ chmod a+x GetComponents
[prakti1@login02.csc ET-2016-11]$ ./GetComponents --parallel http
-----------------------------------------------------------------
  Checking out module: par
      from repository: https://bitbucket.org/einsteintoolkit/eins
                 into: Cactus
-----------------------------------------------------------------
  Checking out module: .clang-format
      from repository: https://bitbucket.org/cactuscode/cactus.gi
                 into: Cactus
                   as: flesh
-----------------------------------------------------------------
  Checking out module: CONTRIBUTORS
      from repository: https://bitbucket.org/cactuscode/cactus.gi
                 into: Cactus
                   as: flesh
-----------------------------------------------------------------
  Checking out module: COPYRIGHT
      from repository: https://bitbucket.org/cactuscode/cactus.gi
                 into: Cactus
                   as: flesh
-----------------------------------------------------------------
  Checking out module: doc
      from repository: https://bitbucket.org/cactuscode/cactus.gi
                 into: Cactus
                   as: flesh
-----------------------------------------------------------------
  Checking out module: lib
      from repository: https://bitbucket.org/cactuscode/cactus.gi
                 into: Cactus
                   as: flesh
-----------------------------------------------------------------
```

```
-----------------------
nDependencies1
/cactuscode/cactustest.git

-----------------------
  Checking out module: CactusTest/TestFortranDependencies2
      from repository: https://bitbucket.org/cactuscode/cactustest.git
                 into: Cactus/arrangements
-----------------------------------------------------------------
  Checking out module: EinsteinAnalysis/QuasiLocalMeasures
      from repository: https://bitbucket.org/einsteintoolkit/einsteinanalysis.git
                 into: Cactus/arrangements
-----------------------------------------------------------------
  Checking out module: EinsteinInitialData/IDAxiOddBrillBH
      from repository: https://bitbucket.org/einsteintoolkit/einsteininitialdata.git
                 into: Cactus/arrangements
-----------------------------------------------------------------
  Checking out module: PITTNullCode/SphericalHarmonicRecon
      from repository: https://bitbucket.org/einsteintoolkit/pittnullcode.git
                 into: Cactus/arrangements
-----------------------------------------------------------------
  Checking out module: PITTNullCode/SphericalHarmonicDecomp
      from repository: https://bitbucket.org/einsteintoolkit/pittnullcode.git
                 into: Cactus/arrangements
-----------------------------------------------------------------
  Checking out module: EinsteinExact/ModifiedSchwarzschildBL
      from repository: https://github.com/barrywardell/EinsteinExact.git
                 into: Cactus/arrangements
-----------------------------------------------------------------
  Checking out module: EinsteinInitialData/Hydro_InitExcision
      from repository: https://bitbucket.org/einsteintoolkit/einsteininitialdata.git
                 into: Cactus/arrangements
-----------------------------------------------------------------
  Checking out module: EinsteinUtils/SetMask_SphericalSurface
      from repository: https://bitbucket.org/einsteintoolkit/einsteinutils.git
                 into: Cactus/arrangements
-----------------------------------------------------------------
  Checking out module: PITTNullCode/SphericalHarmonicReconGen
      from repository: https://bitbucket.org/einsteintoolkit/pittnullcode.git
                 into: Cactus/arrangements
-----------------------------------------------------------------
  Checking out module: EinsteinInitialData/IDConstraintViolate
      from repository: https://bitbucket.org/einsteintoolkit/einsteininitialdata.git
```

Das Einstein Toolkit: Setup mit SimFactory

```
[prakti1@login02.csc Cactus]$ ./simfactory/bin/sim setup --machine fuchs


Here we will define some necessary Simulation Factory defaults.


Determining local machine name: login02.cm.cluster
Creating machine login02.cm.cluster from generic: machine login02.cm.cluster [/home/agmisc/prakti1/ET-2016-11/Cactus/repos/simfactory2/mdb/mach
enter value for key user [prakti1]:
enter value for key email [prakti1]:
enter value for key allocation []:
enter value for key sourcebasedir (the parent directory containing the Cactus sourcetree) [/home/agmisc/prakti1/ET-2016-11]:
enter value for key basedir (the location of simfactory simulations) [/home/agmisc/prakti1/simulations]:


would you like to enter key/value pairs for a specific machine? [Y/N*]:

--------------------SUMMARY--------------------:


[default]
user            = prakti1
email           = prakti1
allocation      =
sourcebasedir   = /home/agmisc/prakti1/ET-2016-11
basedir         = /home/agmisc/prakti1/simulations


------------------END SUMMARY------------------:

Save contents [Y*/N]:
Contents successfully written to /home/agmisc/prakti1/ET-2016-11/Cactus/repos/simfactory2/etc/defs.local.ini
[prakti1@login02.csc Cactus]$
```

Das Einstein Toolkit: Kompilierung

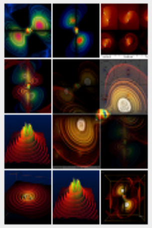
```
[praktil@login02.csc Cactus]$ ./simfactory/bin/sim build et --thornlist ./manifest/einsteintoolkit.th --machine fuchs
Using configuration: et
Reconfiguring et
Writing configuration to: /home/agmisc/praktil/ET-2016-11/Cactus/configs/et/OptionList
Cactus - version: 4.2.3
Reconfiguring et.
Using configuration options from configure line
  Setting fds to '4,5 -j --'
End of options from configure line
Adding configuration options from '/home/agmisc/praktil/ET-2016-11/Cactus/configs/et/OptionList'...
  Setting VERSION to '2015-05-16'
  Setting CPP to 'cpp'
  Setting FPP to 'cpp'
  Setting CC to '/cm/shared/apps/intel/composer_xe/2013_sp1.3.174/composer_xe_2013_sp1.3.174/bin/intel64/icc'
  Setting CXX to '/cm/shared/apps/intel/composer_xe/2013_sp1.3.174/composer_xe_2013_sp1.3.174/bin/intel64/icpc'
  Setting F77 to '/cm/shared/apps/intel/composer_xe/2013_sp1.3.174/composer_xe_2013_sp1.3.174/bin/intel64/ifort'
  Setting F90 to '/cm/shared/apps/intel/composer_xe/2013_sp1.3.174/composer_xe_2013_sp1.3.174/bin/intel64/ifort'
  Setting CPPFLAGS to '-DCCTK_DISABLE_OMP_COLLAPSE -DCCTK_DISABLE_RESTRICT'
  Setting FPPFLAGS to '-DCCTK_DISABLE_OMP_COLLAPSE -traditional -DCCTK_DISABLE_RESTRICT'
  Setting CFLAGS to '-g -traceback -msse3 -align -std=c99 -U__STRICT_ANSI__'
  Setting CXXFLAGS to '-g -traceback -msse3 -align -std=c++11 -D__builtin_fmaxf=fmaxf -D__builtin_fmaxl=fmaxl -D__builtin_fmin
  Setting F77FLAGS to '-g -traceback -msse3 -align -pad -safe-cray-ptr'
  Setting F90FLAGS to '-g -traceback -msse3 -align -pad -safe-cray-ptr'
  Setting C_LINE_DIRECTIVES to 'yes'
  Setting F_LINE_DIRECTIVES to 'yes'
  Setting LDFLAGS to '-Wl,--export-dynamic -Wl,-rpath,/cm/shared/apps/intel/composer_xe/2013_sp1.3.174/composer_xe_2013_sp1.3.1
th,/cm/shared/apps/intel/composer_xe/2013_sp1.3.174/composer_xe_2013_sp1.3.174/ipp/lib/intel64 -Wl,-rpath,/cm/shared/apps/inte
_xe_2013_sp1.3.174/tbb/lib/intel64/gcc4.4'
  Setting BEGIN_WHOLE_ARCHIVE_FLAGS to '-Wl,--whole-archive'
  Setting END_WHOLE_ARCHIVE_FLAGS to '-Wl,--no-whole-archive'
  Setting VECTORISE to 'yes'
  Setting VECTORISE_ALIGNED_ARRAYS to 'no'
  Setting VECTORISE_INLINE to 'no'
  Setting VECTORISE_STREAMING_STORES to 'no'
  Setting DEBUG to 'no'
  Setting CPP_DEBUG_FLAGS to '-DCARPET_DEBUG'
  Setting FPP_DEBUG_FLAGS to '-DCARPET_DEBUG'
  Setting C_DEBUG_FLAGS to '-O0 -debug all'
  Setting CXX_DEBUG_FLAGS to '-O0 -debug all'
```

Das Einstein Toolkit: Weitere Informationen

einstein toolkit

- Welcome
- About the Toolkit
  - Members
  - Maintainers
  - Governance
  - Capabilities
  - Gallery
  - Releases
  - Tools
- Download
- Community Services
  - Wiki
  - Blog
  - Support
  - Seminars
  - Issue Tracker
- Documentation
  - Tutorial for New Users
  - Citing

Welcome



EinsteinToolkit@Flickr

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.

Please read our pages about the Einstein Toolkit, its governance, and how to get started with the toolkit for more information.

Download

November 2014: We are pleased to announce the tenth release (code name "Herschel") of the Einstein Toolkit, an open, community developed software infrastructure for relativistic astrophysics.

https://www.youtube.com/watch?v=EO4d32ch6OI
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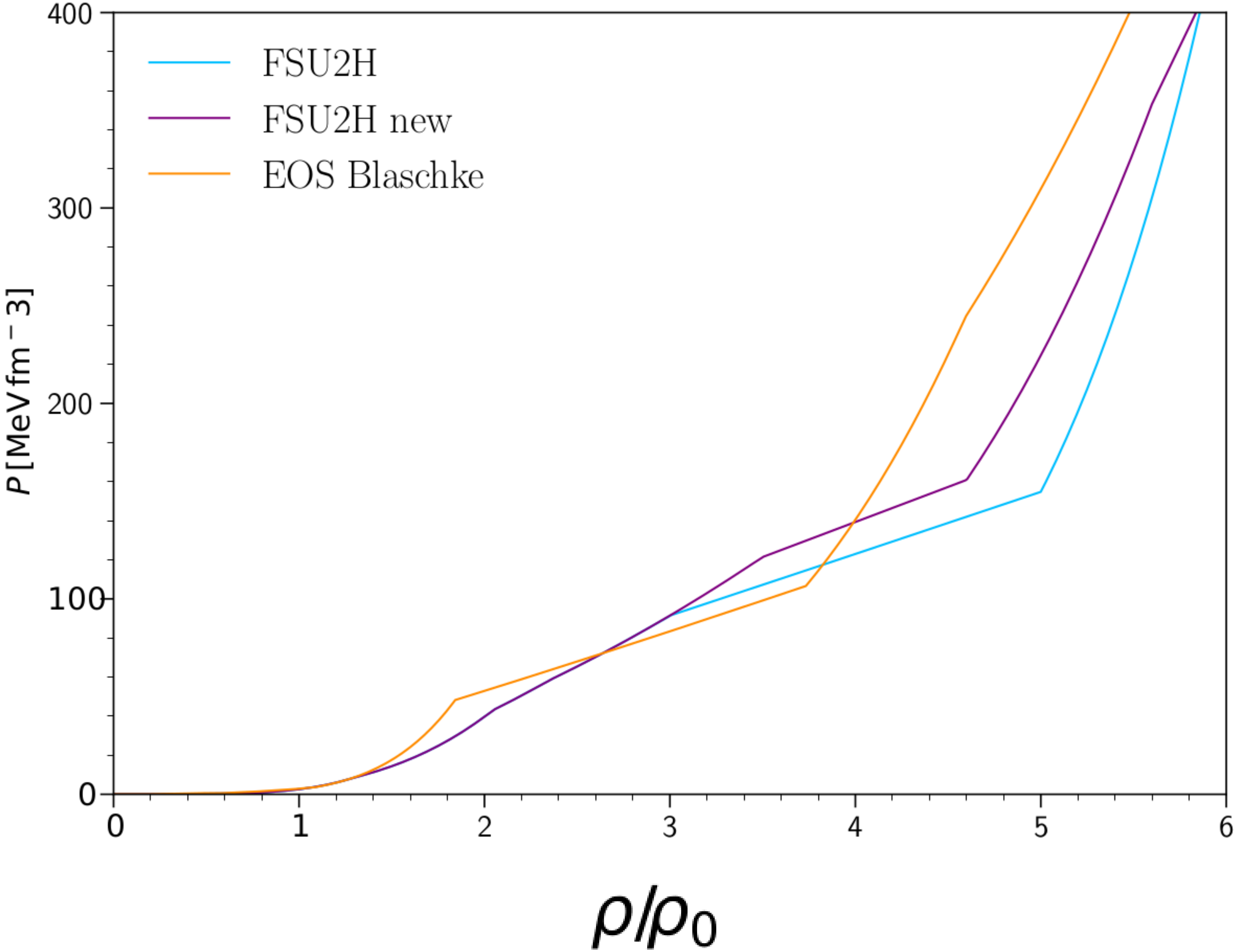
https://www.youtube.com/watch?v=Qg6PwRI2uS8
https://www.youtube.com/watch?v=ZW3aV7U-aik

Equation of State examples



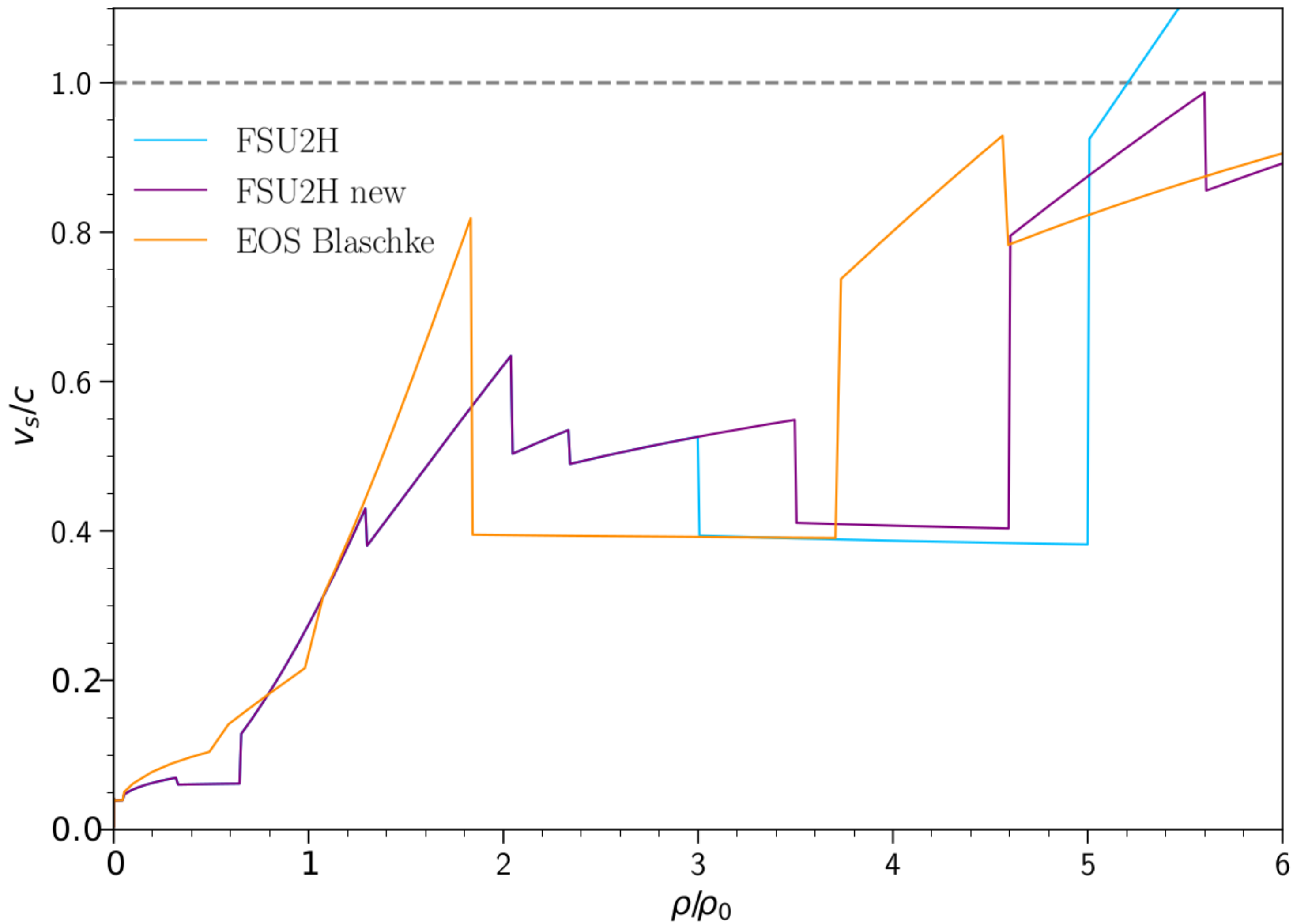


FIG. 6. FSU2Hnew and Blaschke equation of states density to pressure and speed of sound profile.

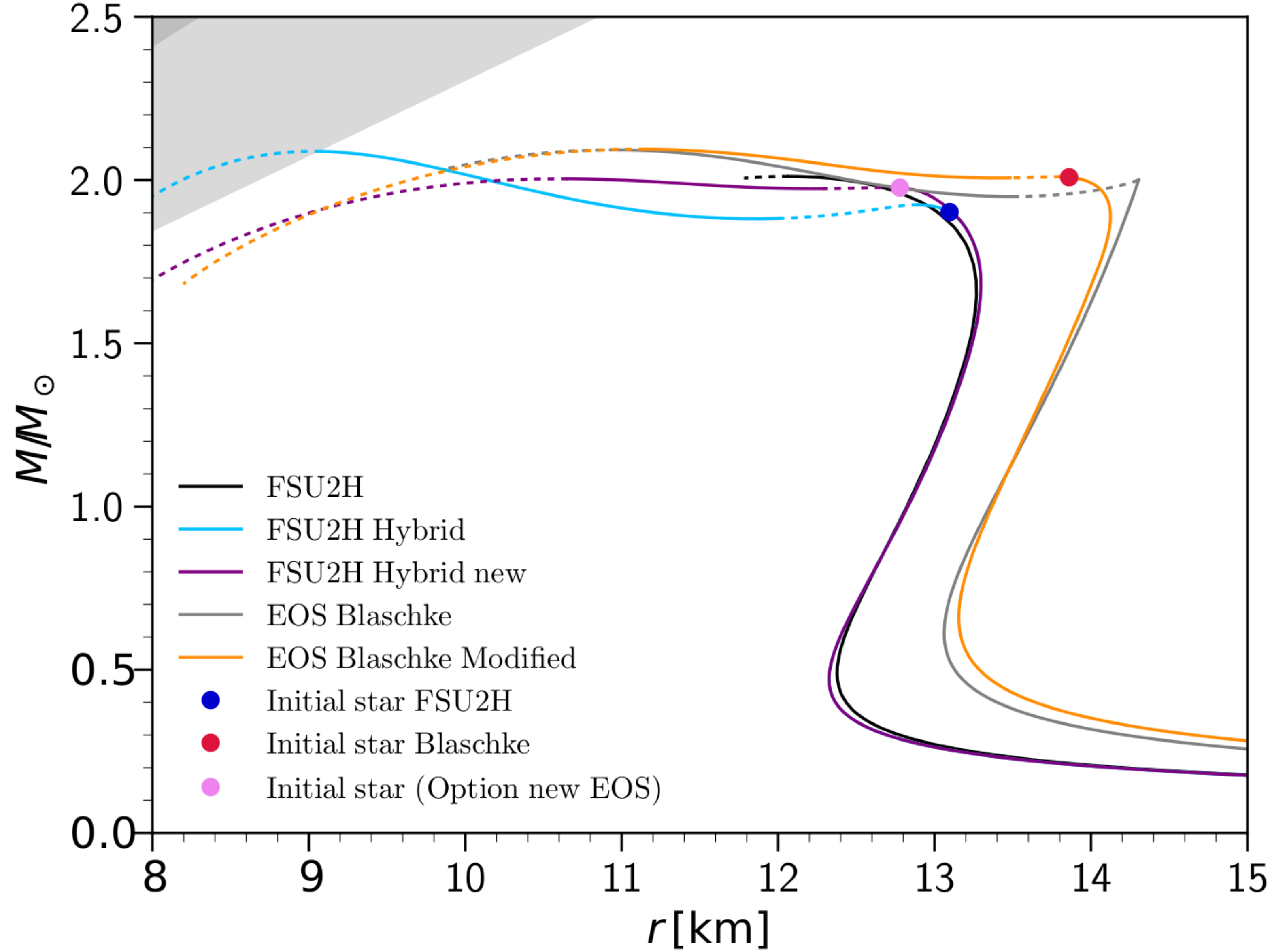
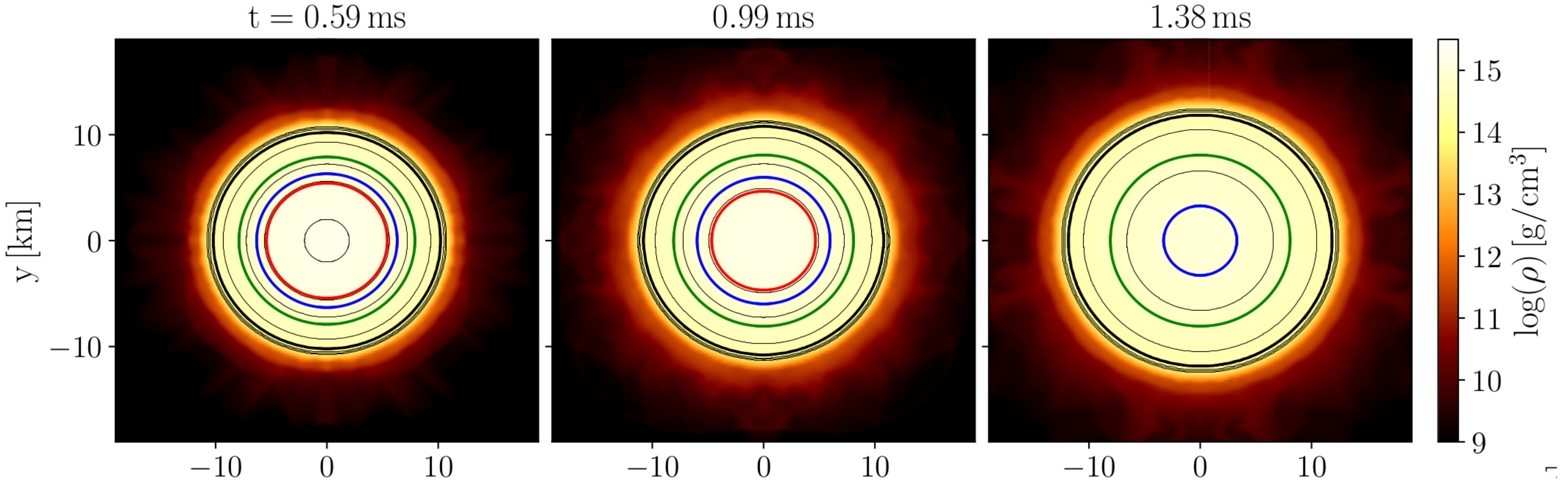
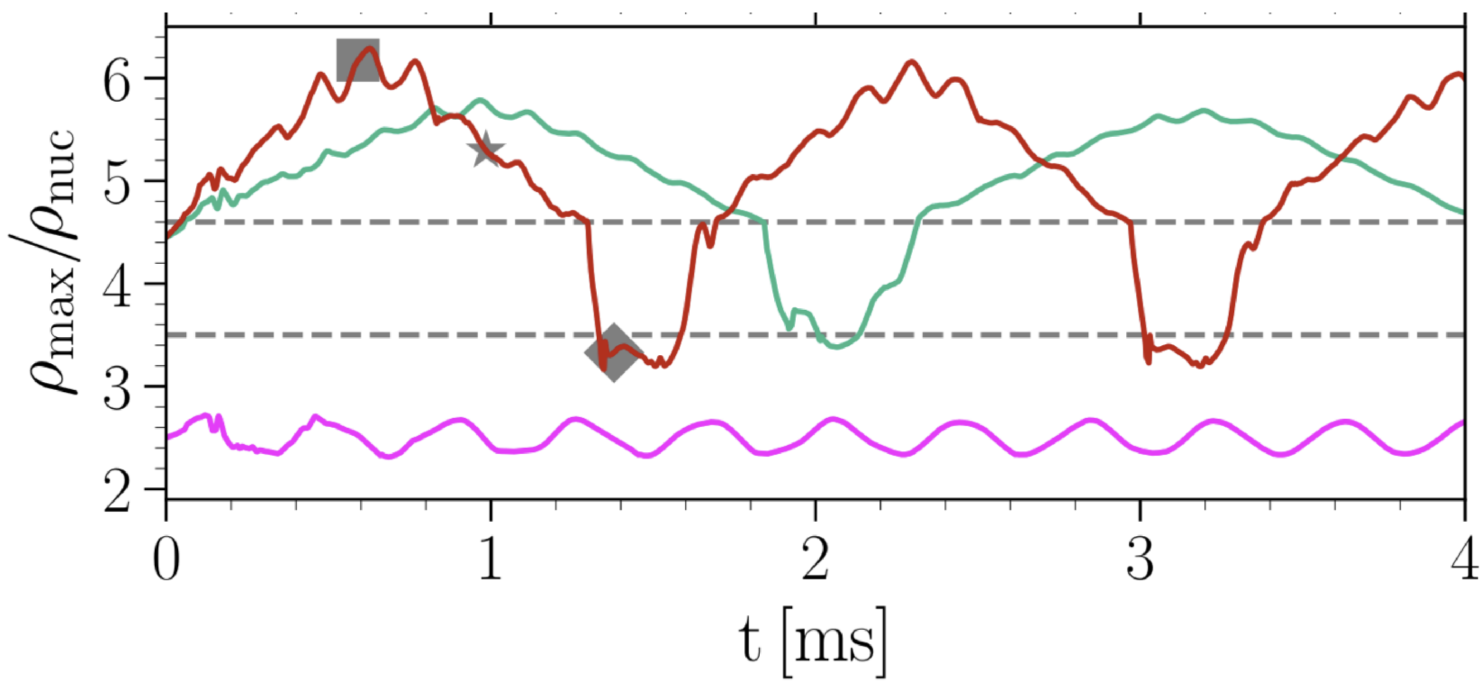


FIG. 7. Comparison of mass to radius relation of different equations of state.

FSU2H Twin star oscillations





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