

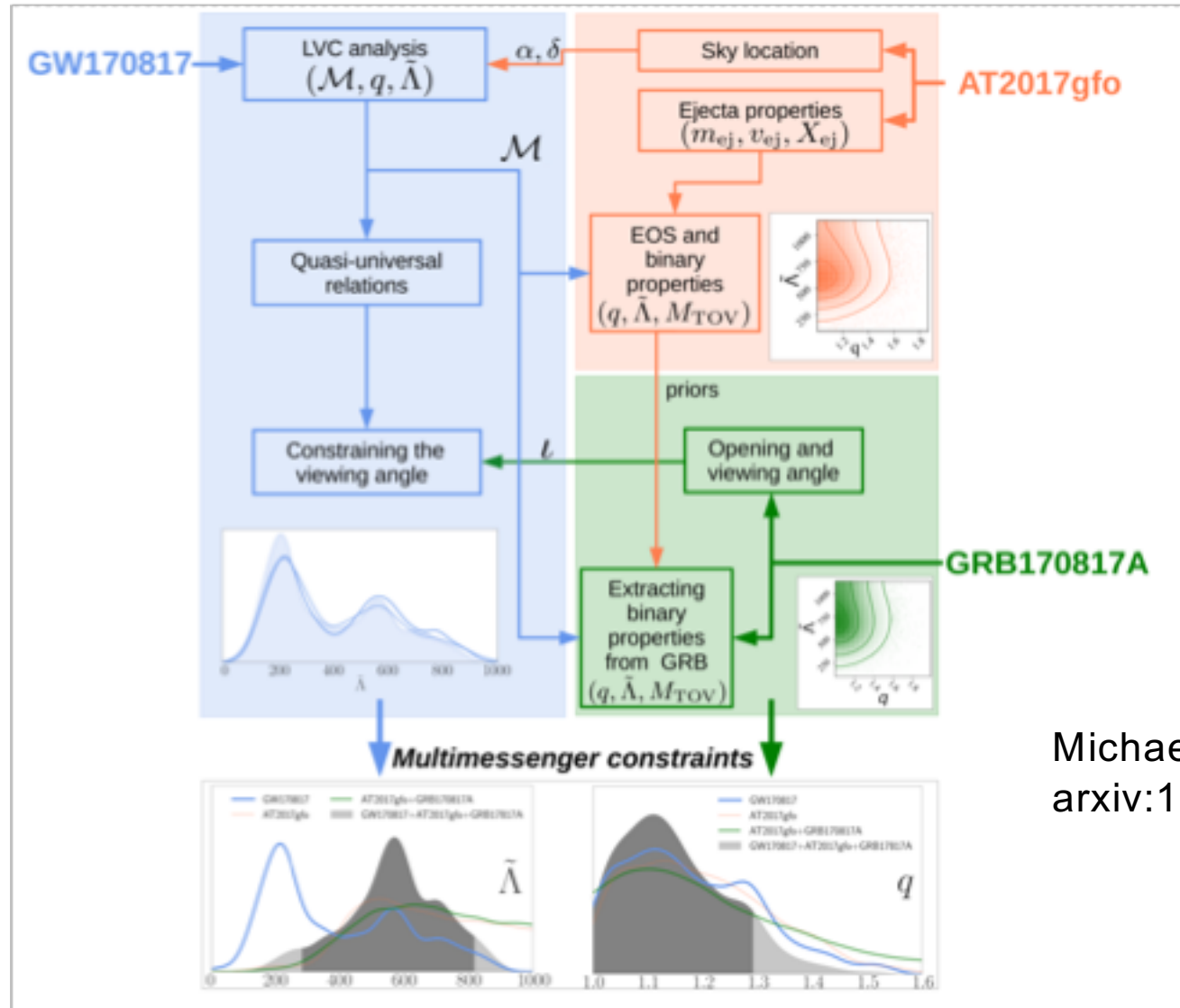
# Introduction to BNS merger simulation via Einsteintoolkit

Yongjia Huang

RIKEN

*RIKEN - RESCEU Joint Seminar*

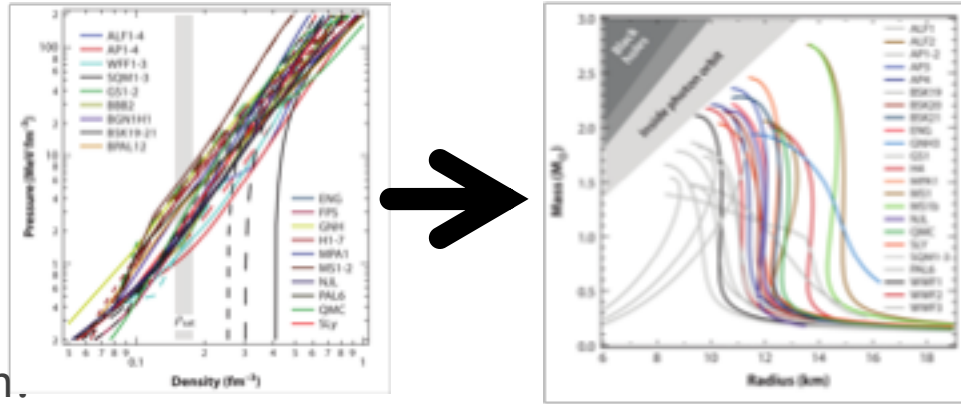
# Why to do simulation?



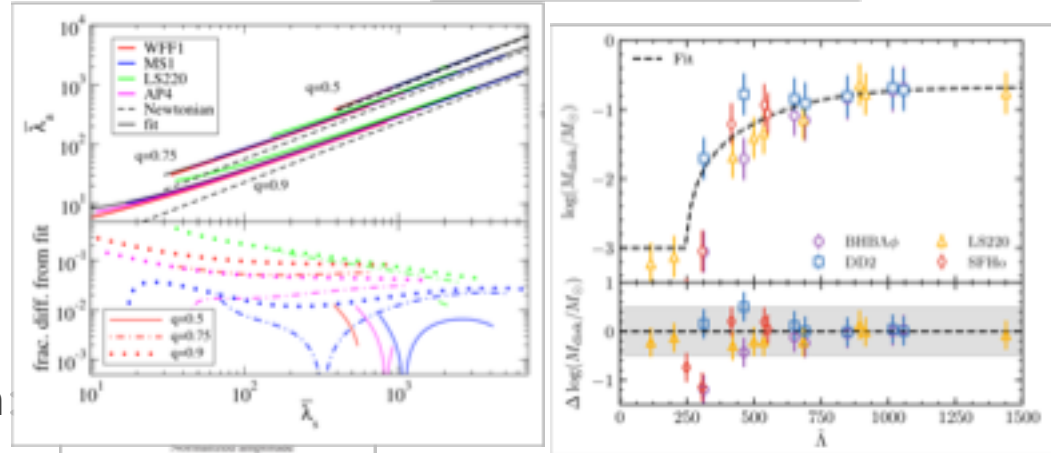
Michael W. Coughlin  
arxiv:1812.04803

# Theory , Simulation and Observation

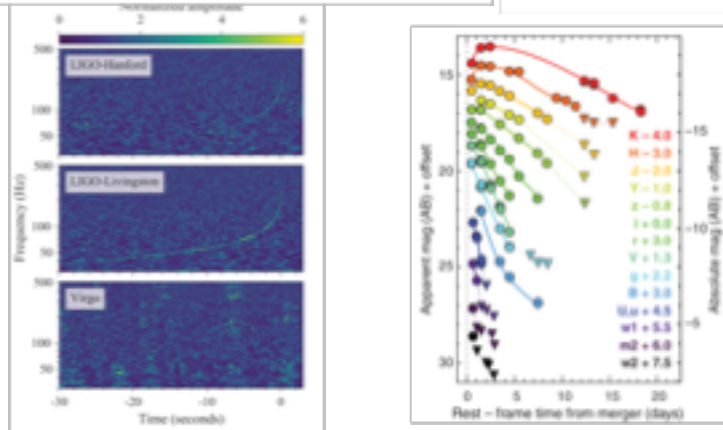
Theory:



Quasi-universal relation.



Multi-messenger observation



# How to do the simulation?

Lorene + Einteintoolkit **Public!**

Lorene: To calculate the initial data for simulation.

Einteintoolkit: Read the initial data and solve the evolution problem of by Whisky code.

# Lorene

Download: <https://lorene.obspm.fr>

A very useful document:

[https://docs.einsteintoolkit.org/etdocs/images/2/29/GT\\_2018\\_WG\\_Initial\\_Data\\_with\\_Instructions\\_for\\_Lorene.docx.pdf](https://docs.einsteintoolkit.org/etdocs/images/2/29/GT_2018_WG_Initial_Data_with_Instructions_for_Lorene.docx.pdf)

|                  |               |              |
|------------------|---------------|--------------|
| Alternatives     | BosonStar     | Kerr2        |
| App_hor          | CVS           | Mag_eos_star |
| Bin_BH           | Einstein      | Magnetstar   |
| Bin_BH_mass_diff | Ernst         | Magstar      |
| Bin_hor          | Ernstbbh      | Nrotstar     |
| Bin_ns_bh        | Evol_BH       | Rot_star     |
| Bin_star         | GraVaStar     | Sfluide      |
| Bin_star_ncp     | HiggsMonopole | Spectral     |
| Bin_star_xcts    | Isol_hor      | Test         |
| Binary_star      | Kerr          | Tutorial     |

Lorene/Codes

# Nrotstar

par\_eos.d: EOS table

par\_rot.d: configuration for various parameters(physical, computational, multi-grid)

```
1 Date: 4 september 2000
2 ...Name(P): Akmal et al. 1998 A33rdv+GXX (Open)...
3 ...BP0+HP0 outer crust, Sly4 inner crust...
4 # 5.448,1.296e14
5 #
6 172 *** Number of lines
7 #
8 #      n, B [1e^0-11]  rho [g/cm^3]  mu [MeV/c^2]
9 #
10 1 0.7924807018670800-14  0.131039285744713e+02  0.3802547893366890e+02
11 12 0.7924807018670800-13  0.4379448774428280e+02  0.1477218179470440e+02
12 12 0.7924807018670800-13  0.1310394029983310e+02  0.1220802126816070e+07
13 4 0.2985887666671725-12  0.4359442873642870e+02  0.7899527994031400e+17
14 6 0.7924807018670800-12  0.1310394757545120e+04  0.4796147821786360e+08
15 6 0.2985887666671725-12  0.4359442814392250e+04  0.3185787284709130e+09
16 7 0.7924807018670800-12  0.1310397524912940e+02  0.2821382056763880e+09
17 0 0.2985887666671725-18  0.435944188893500e+00  0.1378277844105000e+02
18 9 0.7924807018670800-18  0.1310388889097610e+00  0.8258787941050000e+02
19 1 0.2985887666671725-09  0.4359736431159070e+00  0.634888888888888e+02
20 2 0.4374182348092880-09  0.1844843258512510e+07  0.231888888888888e+02
21 3 0.1581848478845440-09  0.2624734784643440e+07  0.875888888888888e+02
22 4 0.397168995848200-09  0.4073623419548870e+07  0.391188888888888e+04
23 0 0.479388316712130-09  0.6388887178388930e+07  0.623488888888888e+04
24 0 0.977364838543870-09  0.1255844941819820e+08  0.145888888888888e+05
25 7 0.4798385191158480-07  0.3384712896741810e+08  0.383388888888888e+06
26 8 0.39739648758480-07  0.4676138438827440e+08  0.188488888888888e+06
27 9 0.792418846526630-07  0.131087982847950e+09  0.268488888888888e+06
28 18 0.158181486297650-06  0.2626263965273790e+09  0.667888888888888e+06
29 13 0.179833286849120-06  0.3388412388587190e+09  0.873888888888888e+06
30 12 0.315479495463282-06  0.431784787777170e+09  0.161788888888888e+07
31 13 0.479934888488852-06  0.6387742762346450e+09  0.382788888888888e+07
32 14 0.4374188589312480-06  0.184415848889290e+10  0.412788888888888e+07
33 16 0.729727674876420-06  0.131283618464790e+10  0.583488888888888e+07
34 16 0.946971348844110-06  0.148864936888816e+10  0.684888888888888e+07
35 17 0.1831878884017480-06  0.2644437888871920e+10  0.117388888888888e+08
36 18 0.268626459317230-06  0.431728875993240e+10  0.235488888888888e+08
37 19 0.397141379778440-05  0.648787616783811e+10  0.434388888888888e+08
38 20 0.482727428453880-05  0.882232795558410e+10  0.564388888888888e+08
39 21 0.4877382848825470-05  0.181148634342580e+11  0.778388888888888e+08
40 22 0.792426458878220-05  0.131948429171420e+11  0.184888888888888e+09
41 23 0.947783888574370-05  0.144112818774821e+11  0.142888888888888e+09
42 24 0.125489953358270-04  0.187188888247993e+11  0.175888888888888e+09
43 25 0.182143638848840-04  0.254212738748340e+11  0.258388888888888e+09
44 26 0.1798419383179330-04  0.331438402473470e+11  0.348488888888888e+09
45 27 0.268588898905820-04  0.417888672823470e+11  0.482888888888888e+09
46 28 0.3824372644583890-04  0.586171458881450e+11  0.594788888888888e+09
47 29 0.397148931294250-04  0.642299842883321e+11  0.888888888888888e+09
48 30 0.58888738518774320-04  0.8341284387897080e+11  0.113888888888888e+10
49 31 0.8151158195827370-04  0.182644588488841e+12  0.145888888888888e+10
50 32 0.654548324644200-04  0.189233889328801e+12  0.147888888888888e+10
51 33 0.8485432988979790-04  0.141667888459721e+12  0.283388888888888e+10
52 34 0.1827819482347280-03  0.178234571707929e+12  0.294788888888888e+10
53 35 0.118616834242430-03  0.184293815683888e+12  0.289238888888888e+10
54 36 0.1235844187872880-03  0.289887284885238e+12  0.327888888888888e+10
```

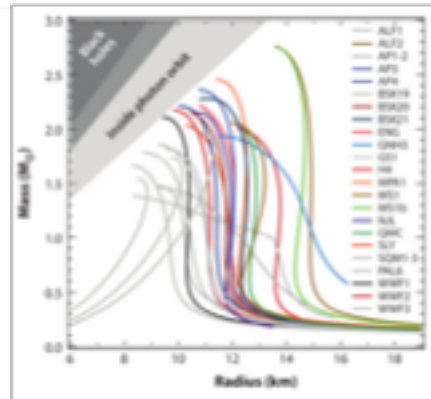
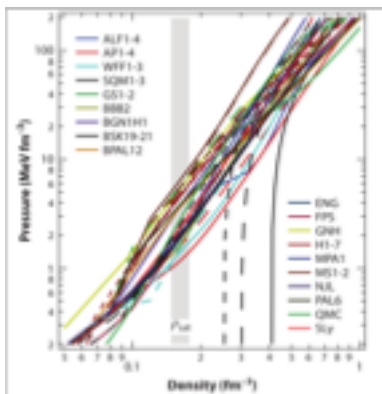
```
1 ***** PHYSICAL PARAMETERS *****
2 1 Relativity parameter: 1 = relativistic computation , 0 = Newtonian
3 0.226189 ent_c : central enthalpy [c^2]
4 716. freq_si : rotation frequency [Hz]
5 1. fact_omega : 1.01 = search for the Keplerian frequency, 1. = otherwise.
6 -1.48 Requested baryon mass [M_sol] (effective only if mer_mass > mer_max)
7 ***** COMPUTATIONAL PARAMETERS *****
8 100 mer_max : maximum number of steps
9 1.e-7 precis : threshold on the enthalpy relative change for ending the computation
10 10 mer_rot : step at which the rotation is switched on
11 716. freq_ini_si : initial rotation frequency [Hz] (switched on at mer = mer_rot)
12 10 mer_change_omega : step at which f is changed to reach freq_si
13 20 mer_fix_omega : step at which f must have reached freq_si
14 1 delta_mer_kep : number of steps after mer_fix_omega to search for Kepler.
15 0.3 thres_adapt : threshold on (dM/dr_eq)/dM/dr_pole for the mapping adaptation
16 1800 mer_triax : step at which the 3-D perturbation is switched on
17 1.e-3 ampli_triax : relative amplitude of the 3-D perturbation
18 2000 mer_mass : step from which the baryon mass is forced to converge (if negative, variation of Omega)
19 0.5 aexp_mass : exponent for the increase factor of the central enthalpy
20 0.5 relax : relaxation factor in the main iteration
21 4 mermax_poisson : maximum number of steps in Map_et::poisson
22 1.5 relax_poisson : relaxation factor in Map_et::poisson
23 1.e-14 precis_adapt : precision in Map_et::adapt
24 1 graph : 1 = graphical outputs during the computation
25 ***** MULTI-GRID PARAMETERS *****
26 3 nz : total number of domains
27 1 nzet : number of domains inside the star
28 1 nzadapt : number of domains of where the mapping adaptation will be done.
29 17 nt : number of points in theta (the same in each domain)
30 1 np : number of points in phi (the same in each domain)
31 # Number of points in r and (initial) inner boundary of each domain:
32 33 0. <- nr & min(r) in domain 0 (nucleus)
33 33 1. <- nr & min(r) in domain 1
34 33 2. <- nr & min(r) in domain 2
35 9 3. <- nr & min(r) in domain 2
36 0.1 enthalpy defining boundary between domains 0 and 1
```

# Result

Baryon mass : 1.542902951 M sol  
Gravitational mass : 1.399956857 M sol

Uniformly rotating star

-----  
Omega : 4498.76068 rad/s      f : 716 Hz  
Rotation period : 1.396648045 ms  
Relativistic star  
Compactness  $G M_g / (c^2 R_{\text{circ}})$  : 0.1711066882  
Central  $N^\phi / \Omega$  : 0.457732919  
Error on the virial identity GRV2 : 1.368957617e-05  
Star\_rot::grv3 : gravitational term : -0.6149101783  
Star\_rot::grv3 : matter term : 0.6149087475  
Error on the virial identity GRV3 : -2.326842438e-06  
Quadrupole moment Q : 0.07327583855  $10^{38}$  kg m<sup>2</sup>  
Q / (M R\_circ<sup>2</sup>) : 0.01803476394  
c<sup>4</sup> Q / (G<sup>2</sup> M<sup>3</sup>) : 0.615994013  
Angular momentum J : 0.7236749219 G M\_sol<sup>2</sup> / c  
c J / (G M<sup>2</sup>) : 0.369244656  
Moment of inertia: 1.415970833  $10^{38}$  kg m<sup>2</sup>  
Ratio T/W : 0.03483279983  
Circumferential equatorial radius R\_circ : 12.08106007 km  
Surface area : 1700.620525 km<sup>2</sup>  
Mean radius : 11.63318879 km



Binary\_star

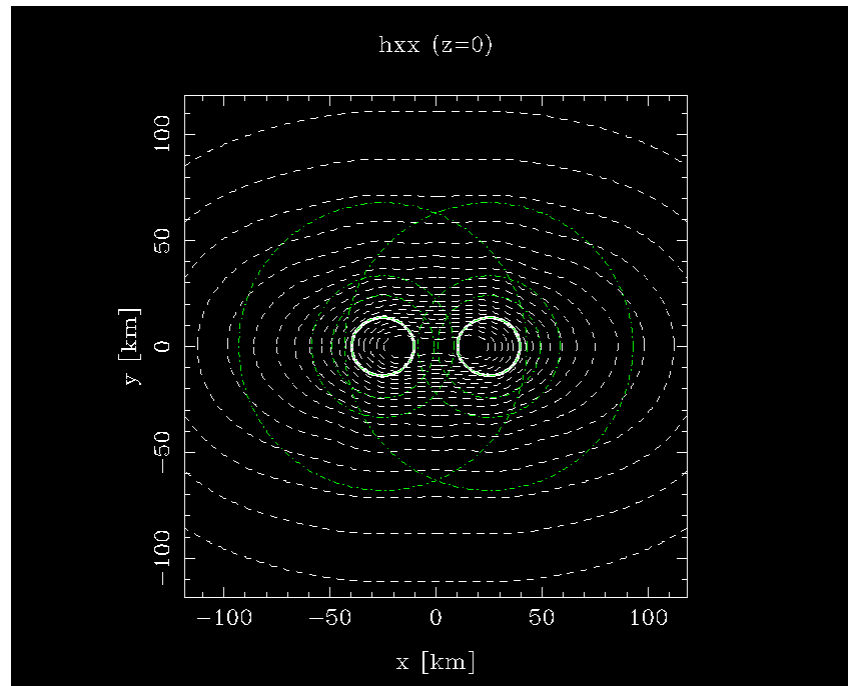
par\_eos1.d par\_eos2.d

par\_init.d, par\_grid1.d; par\_grid2.d (to set up individual stars in isolation)

```
1 # Physical parameters for the binary initial conditions
2 #####
3 100.    <- coordinate distance between the two stellar centers [km]
4 0.169125 <- initial central enthalpy of star 1
5 1    <- rotational state of star 1 : 1 = irrotational, 0 = corotating
6 0.169125 <- initial central enthalpy of star 2
7 1    <- rotational state of star 2 : 1 = irrotational, 0 = corotating
8 0 1 for conformally flat metric, 0 otherwise.
```

par\_coal.d (computational parameters)

-> resu.d

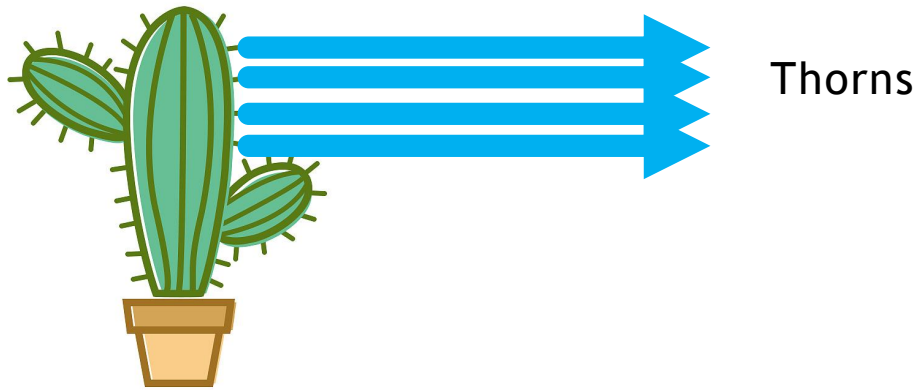




# Einstein toolkit

Download: <https://einsteintoolkit.org/download.html>

Cactus



```
ActiveThorns = "Time MoL"  
ActiveThorns = "Coordbase CartGrid3d Boundary StaticConformal"  
ActiveThorns = "SymBase ADMBase TmunuBase HydroBase InitBase ADMCoupling ADMMacros"  
ActiveThorns = "IOUtil Formaline"  
ActiveThorns = "SpaceMask CoordGauge Constants LocalReduce aeilocalinterp  
  LoopControl"  
ActiveThorns = "Carpet CarpetLib CarpetReduce CarpetRegrid2 CarpetInterp"  
ActiveThorns = "CarpetIOASCII CarpetIOScalar CarpetIOHDF5 CarpetIOBasic"  
  
ActiveThorns = "ML_ADMConstraints NaNChecker"
```

## About Thorns

Cactus/arrangements or Cactus/repos

interface.ccl : the Cactus interface, which defines the grid functions, variables, etc.

param.ccl : the parameters introduced by this thorn, and the parameters needed from other thorns.

schedule.ccl : scheduling information for routines called by the flesh.

configuration.ccl : configuration options for the thorn.

# Simfactory

Build and submit your simulation.

`--remote` an useful choice to build and run in supercomputer

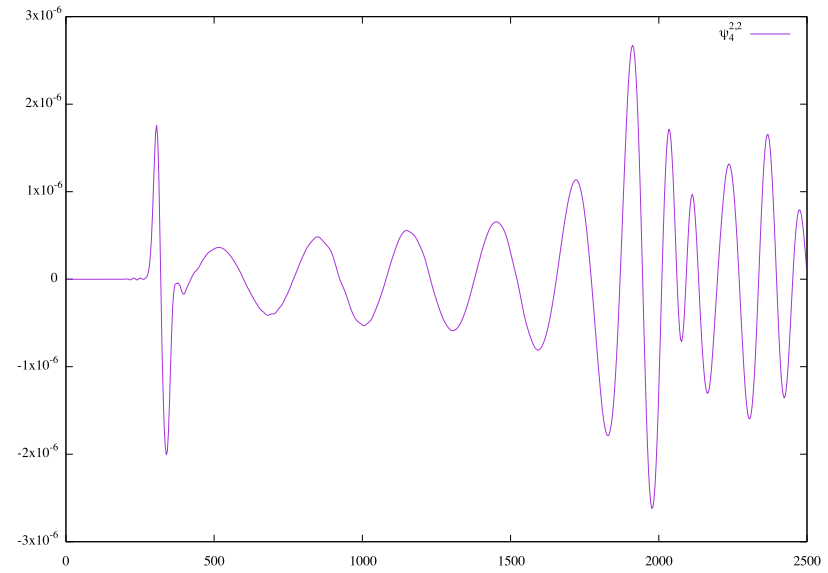
Initial data: `resu.d`

Parameter file: active the thrans and choose the paramters to do simulation  
(Cactus/par)

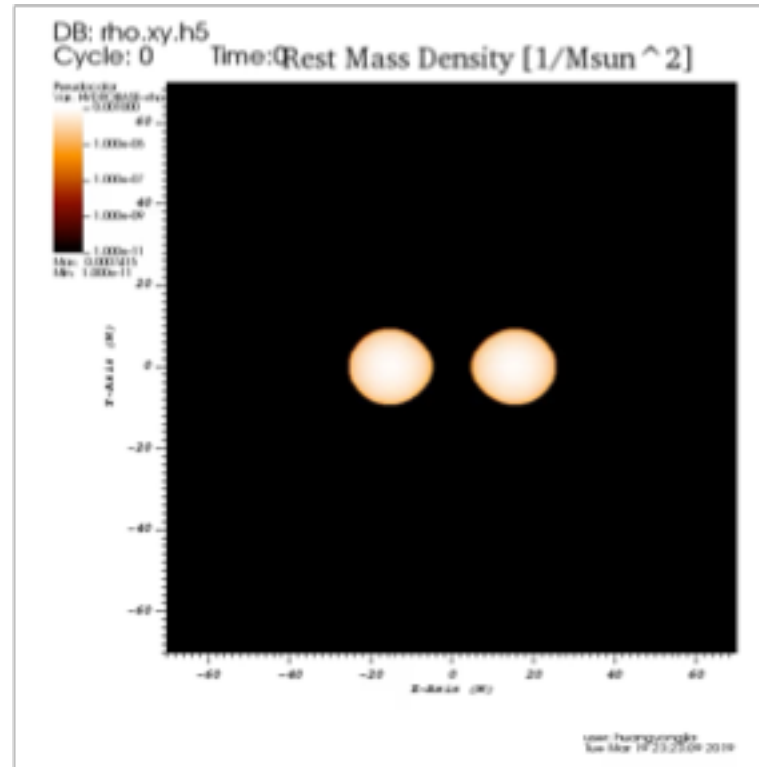
```
# =====  
# Grid  
# =====  
Grid::avoid_origin      = "no"  
Grid::domain            = "full"  
Grid::type               = "coordbase"  
  
ReflectionSymmetry::reflection_x      = "no"  
ReflectionSymmetry::reflection_y      = "no"  
ReflectionSymmetry::reflection_z      = "yes"  
ReflectionSymmetry::avoid_origin_x    = "yes"  
ReflectionSymmetry::avoid_origin_y    = "yes"  
ReflectionSymmetry::avoid_origin_z    = "yes"  
  
CoordBase::xmin         = -1024  
CoordBase::xmax         = 1024  
CoordBase::ymin         = -1024  
CoordBase::ymax         = 1024  
CoordBase::zmin         = 0  
CoordBase::zmax         = 1024  
  
CoordBase::spacing      = "numcells"  
CoordBase::ncells_x     = 128  
CoordBase::ncells_y     = 128  
CoordBase::ncells_z     = 64
```

Result

Gravitational waves

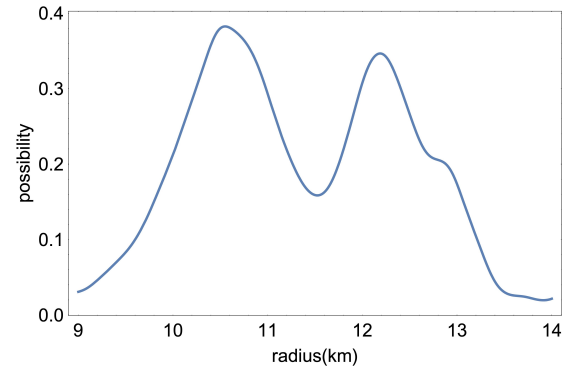
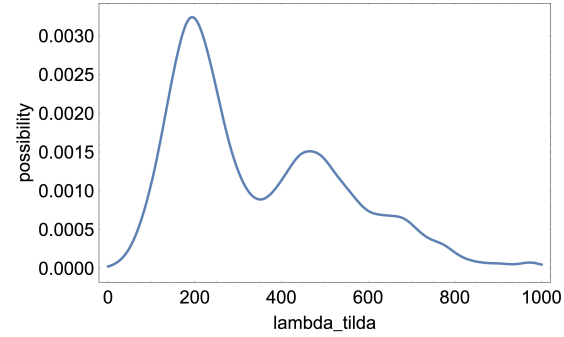
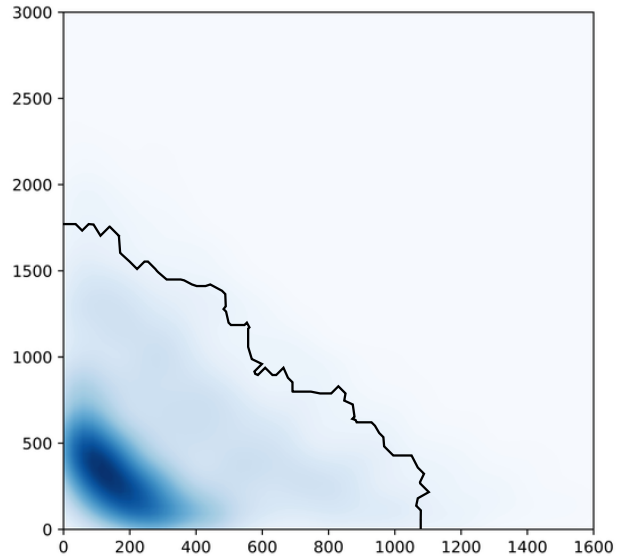


Mass Density evolution



# Future

Combined with Pycbc code to do parameter estimation



Tidal deformability,  
Post-merger signal

...

Construct more relations to connect observable quantities with microphysics

Thank you!