Introduction to BNS merger simulation via Einsteintoolkit

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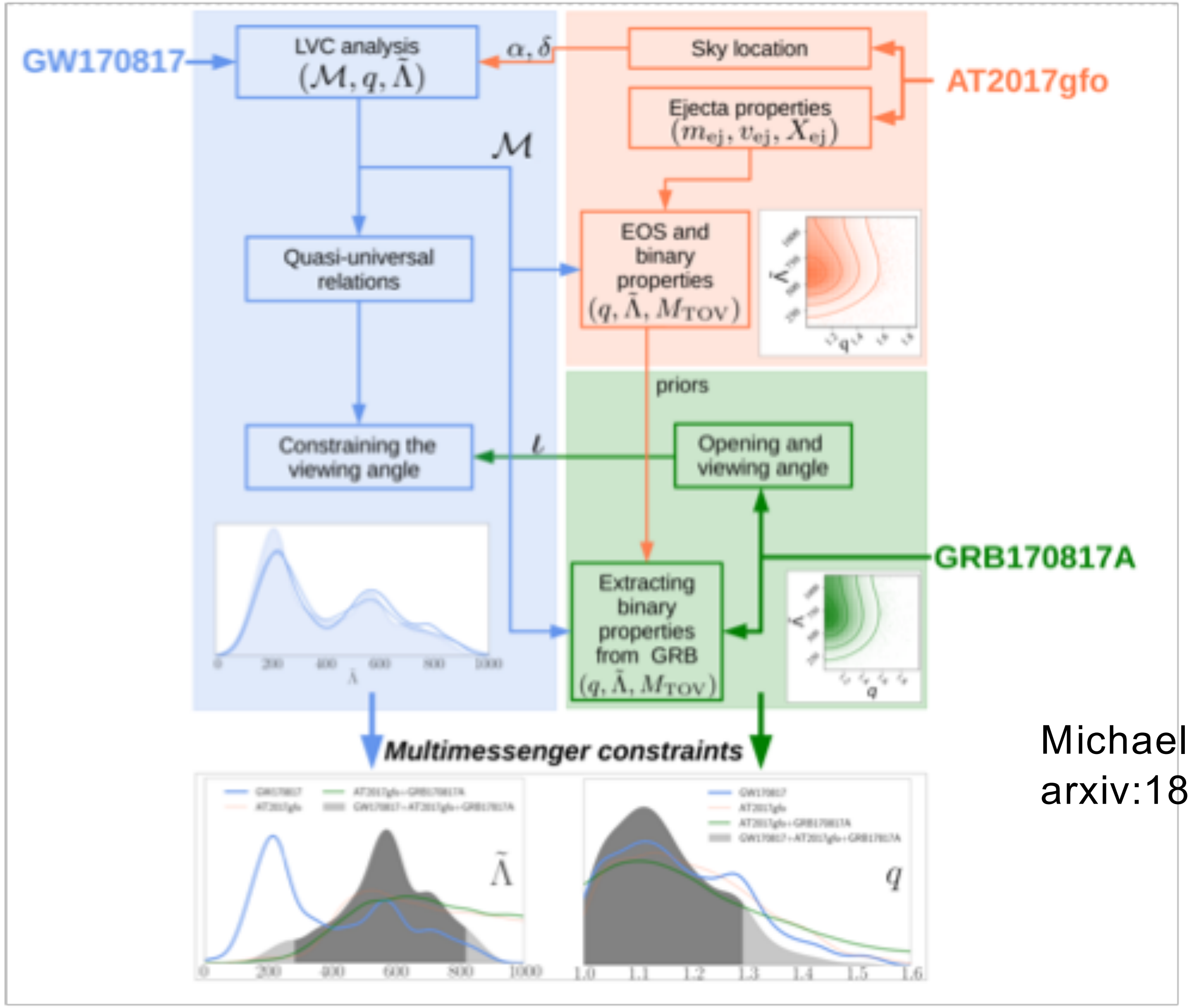
RIKEN

RIKEN - RESCEU Joint Seminar

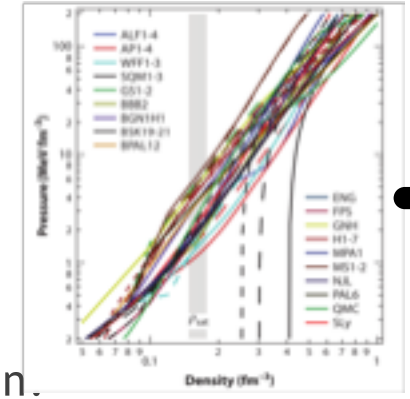
Why to do simulation?

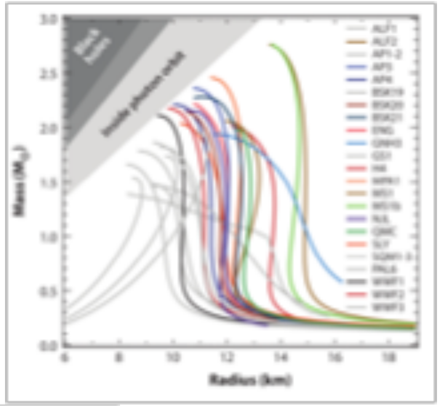


Michael W. Coughlin
arxiv:1812.04803

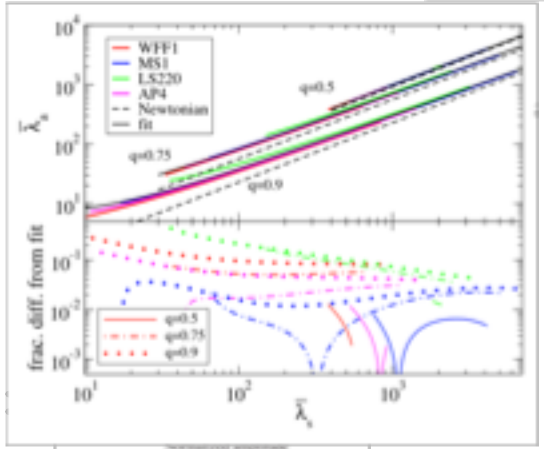
Theory , Simulation and Observation

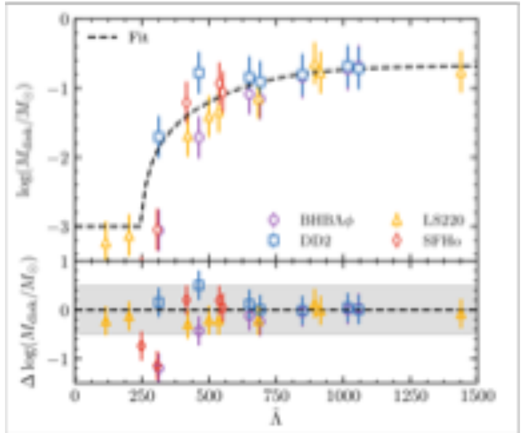
Theory:



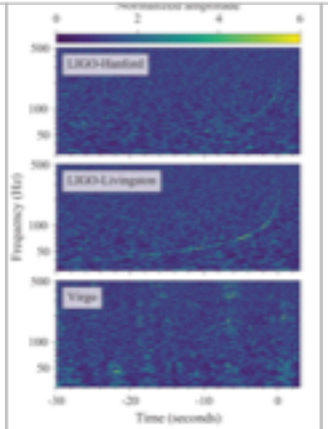


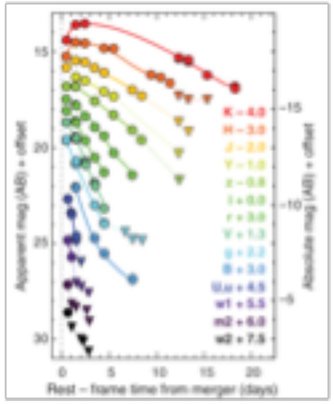
Quasi-universal relation:





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

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

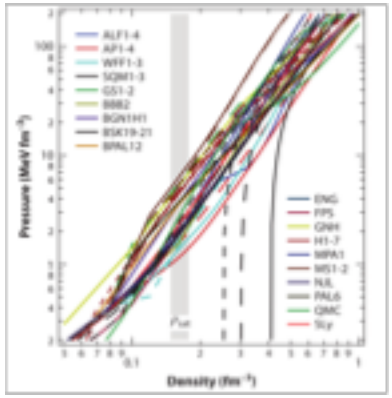
par_eos.d: EOS table

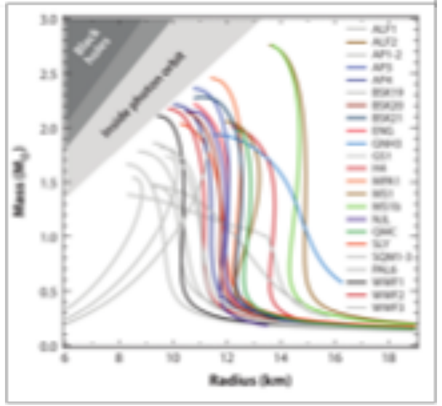
par_rot.d: configuration for various parameters(physical, computational, multi-grid)

```
##################### PHYSICAL PARAMETERS ########################################
1       Relativity parameter: 1 = relativistic computation , 0 = Newtonian
0.226189    ent_c : central enthalpy [c^2]
716.      freq_si : rotation frequency [Hz]
1.     fact_omega : 1.01 = search for the Keplerian frequency, 1. = otherwise.
-1.40     Requested baryon mass [M_sol] (effective only if mer_mass > mer_max)
##################### COMPUTATIONAL PARAMETERS ###################################
100       mer_max : maximum number of steps
1.e-7    precis : threshold on the enthalpy relative change for ending the computation
10       mer_rot : step at which the rotation is switched on
716.     freq_ini_si : initial rotation frequency [Hz] (switched on at mer = mer_rot)
10       mer_change_omega : step at which f is changed to reach freq_si
20       mer_fix_omega : step at which f must have reached freq_si
1       delta_mer_kep : number of steps after mer_fix_omega to search for Kepler.
0.3     thres_adapt : threhold on (dH/dr_eq)/dH/dr_pole) for the mapping adaptation
1000     mer_triax : step at which the 3-D perturbation is switched on
1.e-3    ampli_triax : relative amplitude of the 3-D perturbation
2000     mer_mass : step from which the baryon mass is forced to converge (if negative, variation of Omega)
0.5      aexp_mass : exponent for the increase factor of the central enthalpy
0.5      relax : relaxation factor in the main iteration
4        mermax_poisson : maximum number of steps in Map_et::poisson
1.5      relax_poisson :  relaxation factor in Map_et::poisson
1.e-14   precis_adapt : precision in Map_et::adapt
1        graph : 1 = graphical outputs during the computation
##################### MULTI-GRID PARAMETERS ######################################
3   nz : total number of domains
1   nzet : number of domains inside the star
1   nzadapt : number of domains of where the mapping adaptation will be done.
17  nt: number of points in theta (the same in each domain)
1   np: number of points in phi   (the same in each domain)
# Number of points in r and (initial) inner boundary of each domain:
33  0.  <-   nr   &   min(r)  in domain 0  (nucleus)
33  1.  <-   nr   &   min(r)  in domain 1
33  2.  <-   nr   &   min(r)  in domain 2
9   3.  <-   nr   &   min(r)  in domain 2
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_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^2
Q / (M R_circ^2) :          0.01803476394
c^4 Q / (G^2 M^3) :         0.615994013
Angular momentum J :          0.7236749219 G M_sol^2 / c
c J / (G M^2) :               0.369244656
Moment of inertia:          1.415970833 10^38 kg m^2
Ratio T/W :               0.03483279983
Circumferential equatorial radius R_circ :      12.08106007 km
Surface area :    1700.620525 km^2
Mean radius :     11.63318879 km
```





Binary_star

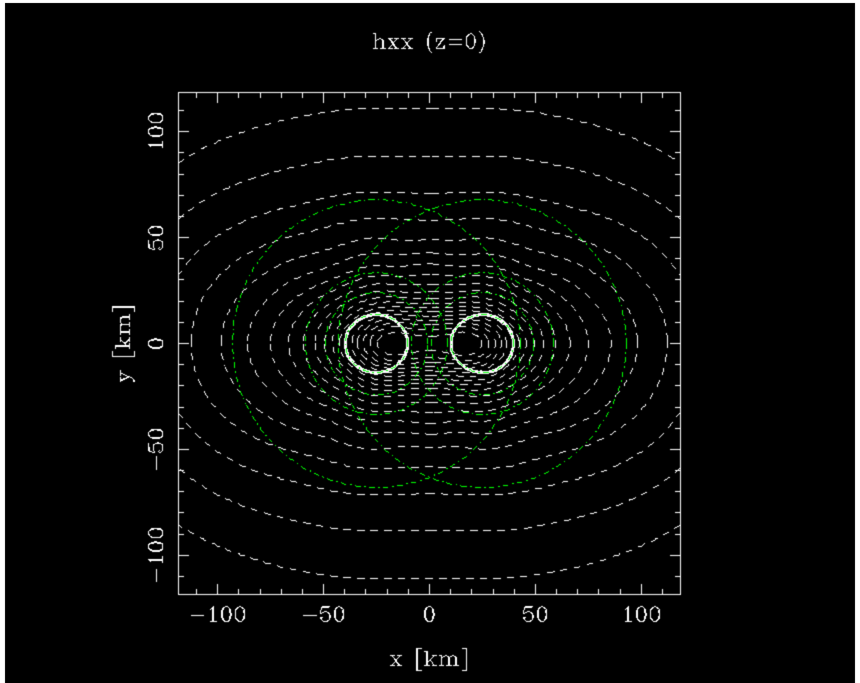
par_eos1.d par_eos2.d

par_init.d, par_grid1.d; par_grid2.d (to set up individual stars in isolation)

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

par_coal.d (computational parameters)

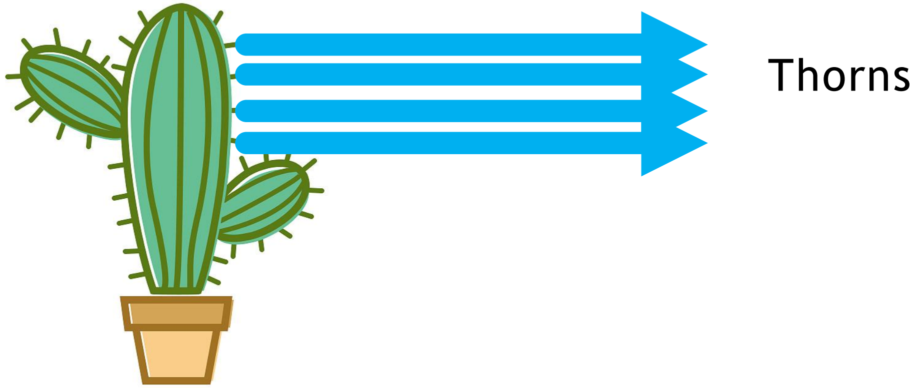
-> resu.d



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

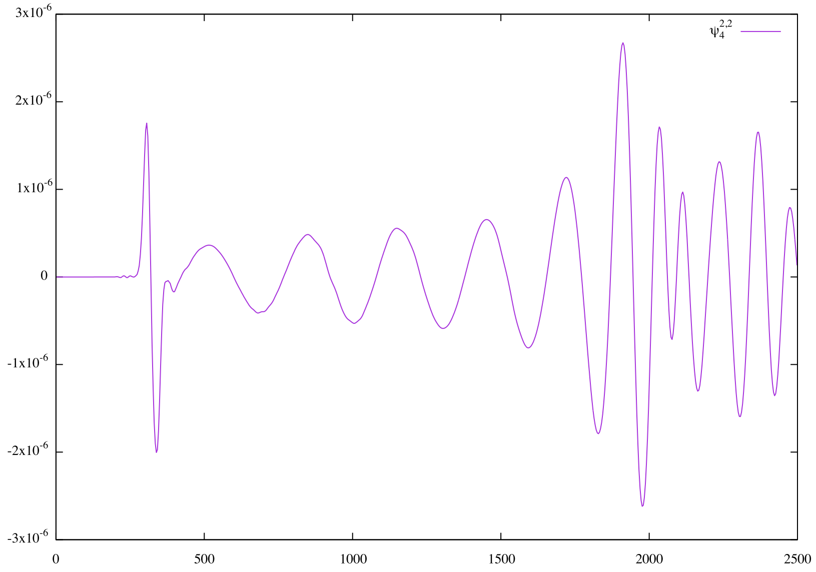
Initial data: resu.d

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

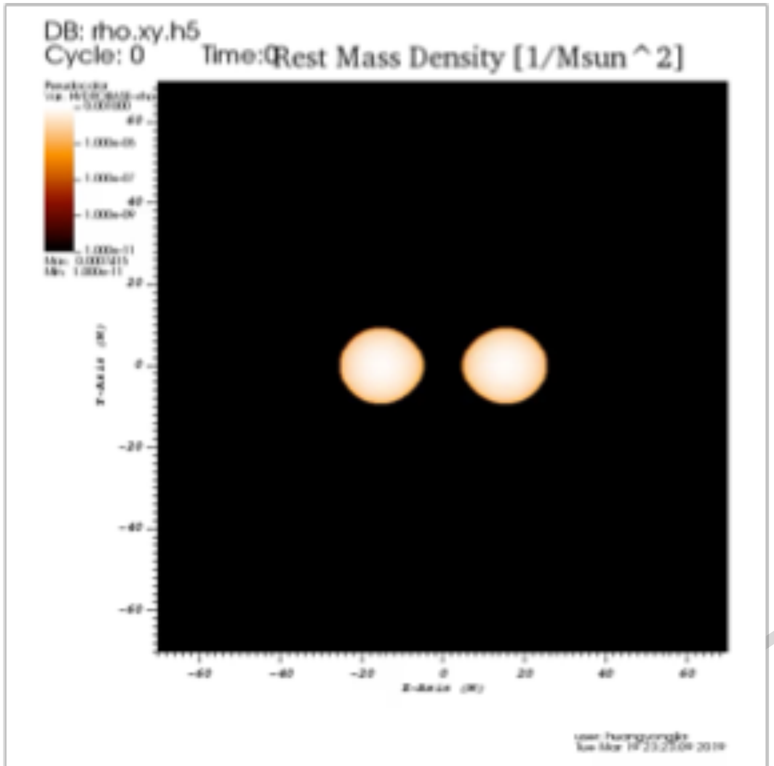
```
# ============================================================================
# Grid
# ============================================================================
Grid::avoid_origin            = "no"
Grid::domain              = "full"
Grid::type            = "coordbase"

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

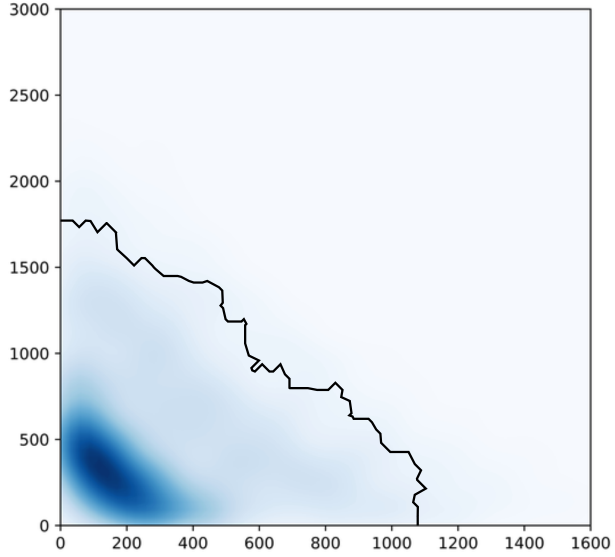


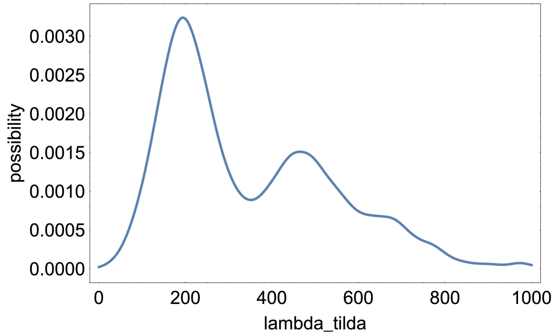
Mass Density evolution

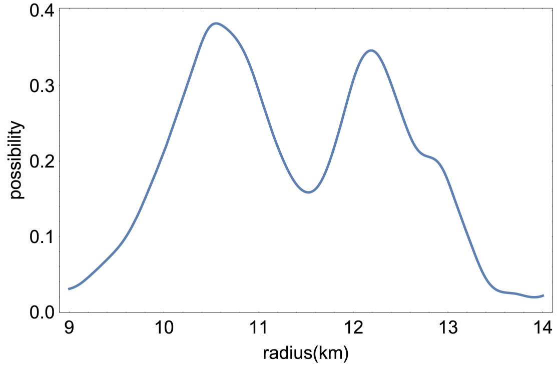


Future

Combined with Pycbc code to do parameter estimation







Tidal deformability,
Post-merger signal
…

Construct more relations to connect observable quantities with microphysics

Thank you!