Spring 5-9-2016

Tools For Gravitational Wave Astronomy

Maria Babiuc-Hamilton
Marshall University, babiuc@marshall.edu

Recommended Citation

Babiuc-Hamilton MC, (2016, November). Tools for gravitational wave astronomy. Slides presented at JSI Workshop on Astrophysics in the Era of Gravitational Wave and Multimessenger Observations, Annapolis, MD.

Maria C. Babiuc-Hamilton

Marshall University, Huntington, WV

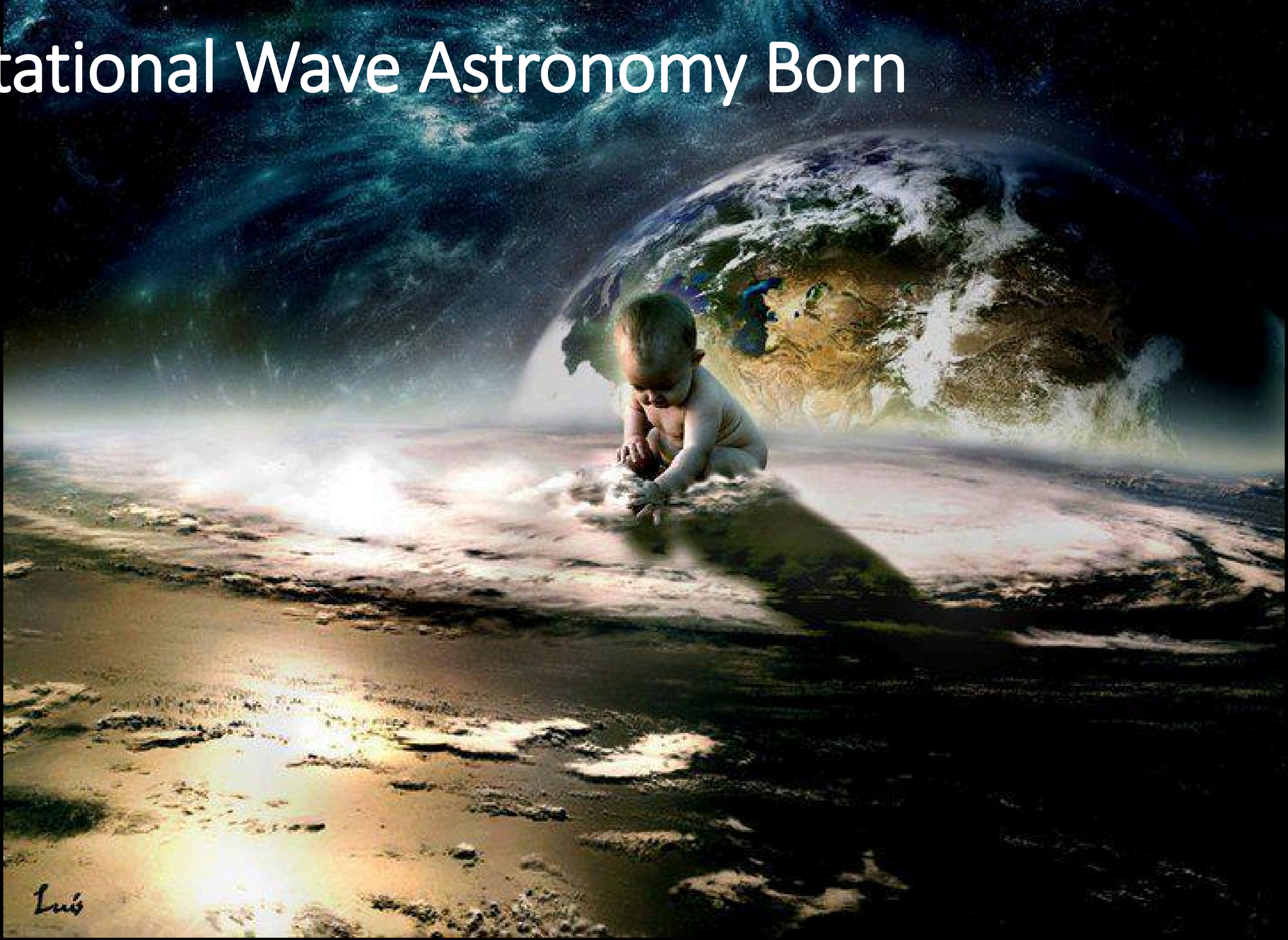
Tools for Gravitational Wave Astronomy

Astrophysics in the Era of Gravitational Wave and Multimessenger Observations

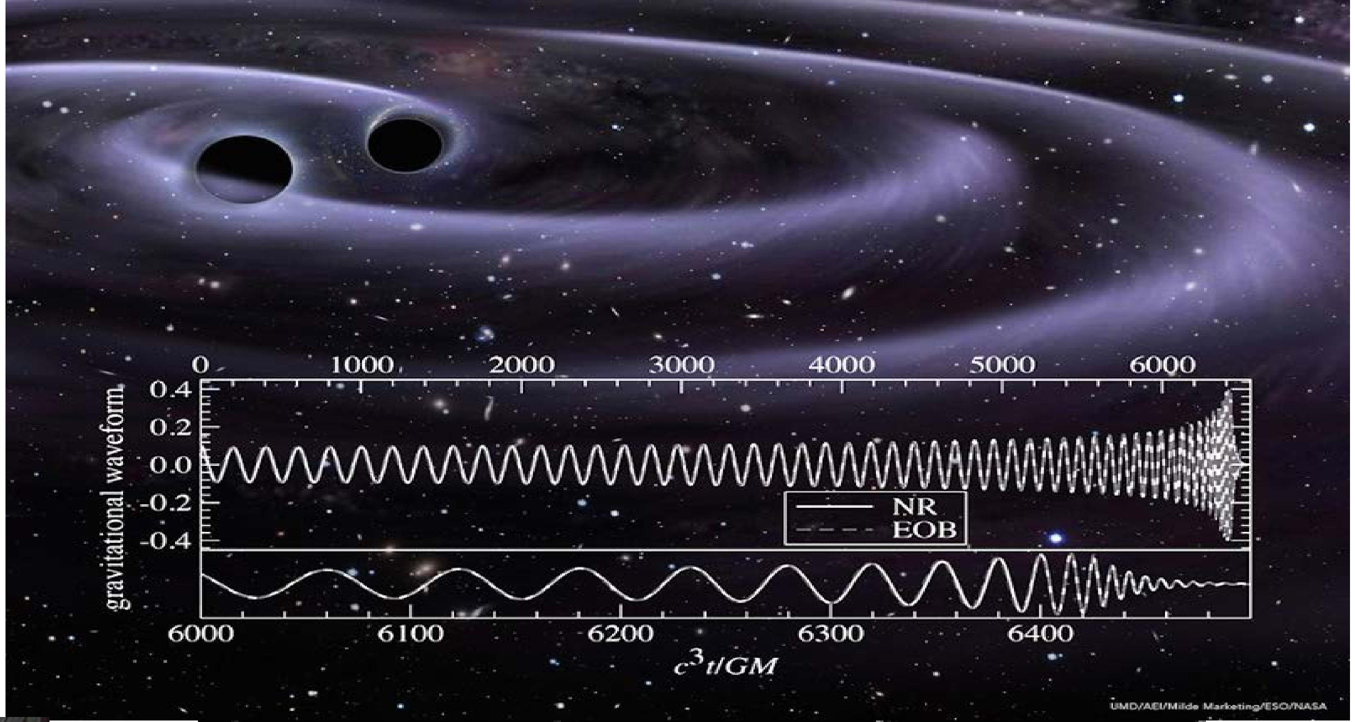
Wednesday, Nov. 9 Annapolis, 2016

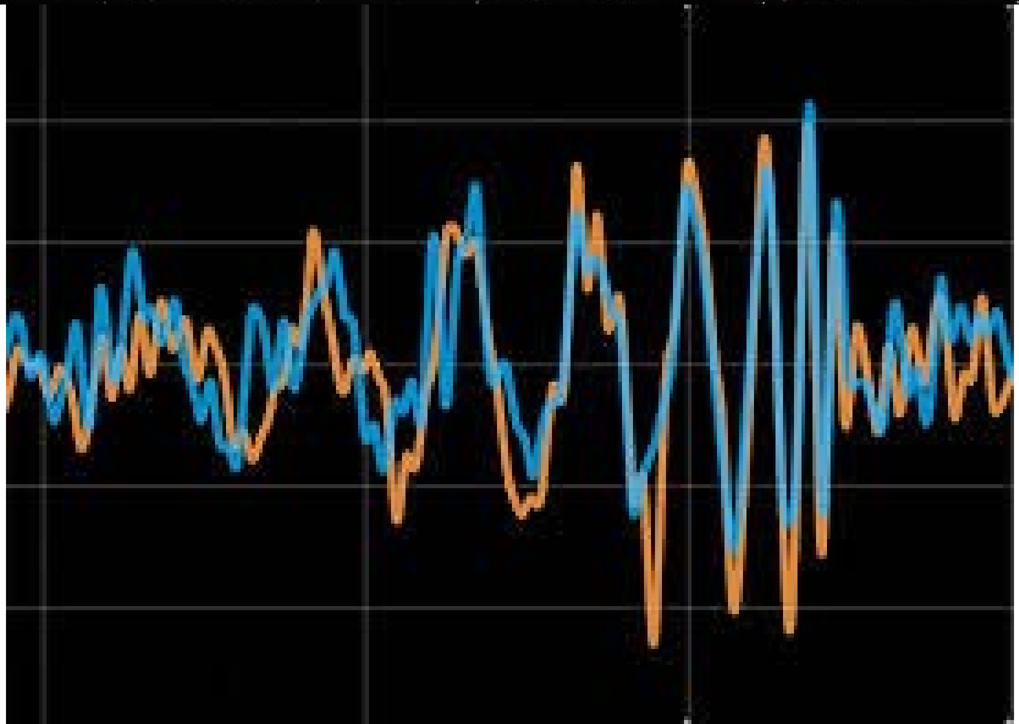
Gravitational Wave Detected Twice

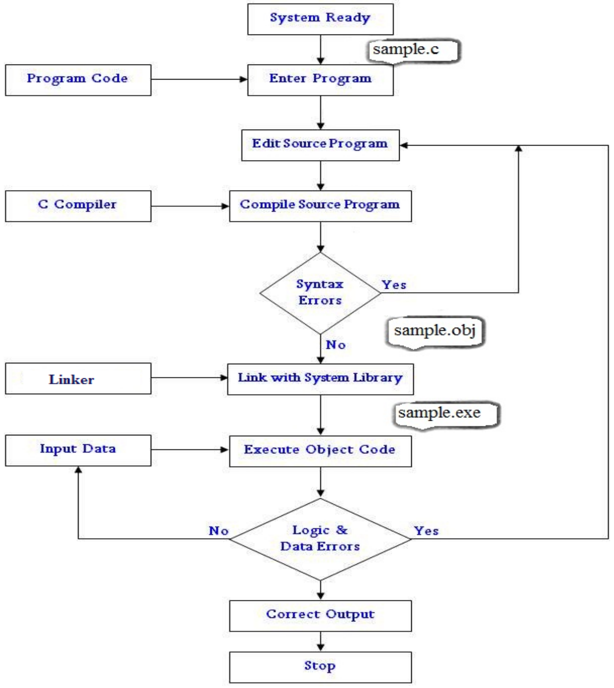
Gravitational Wave Astronomy Born




GENIUS







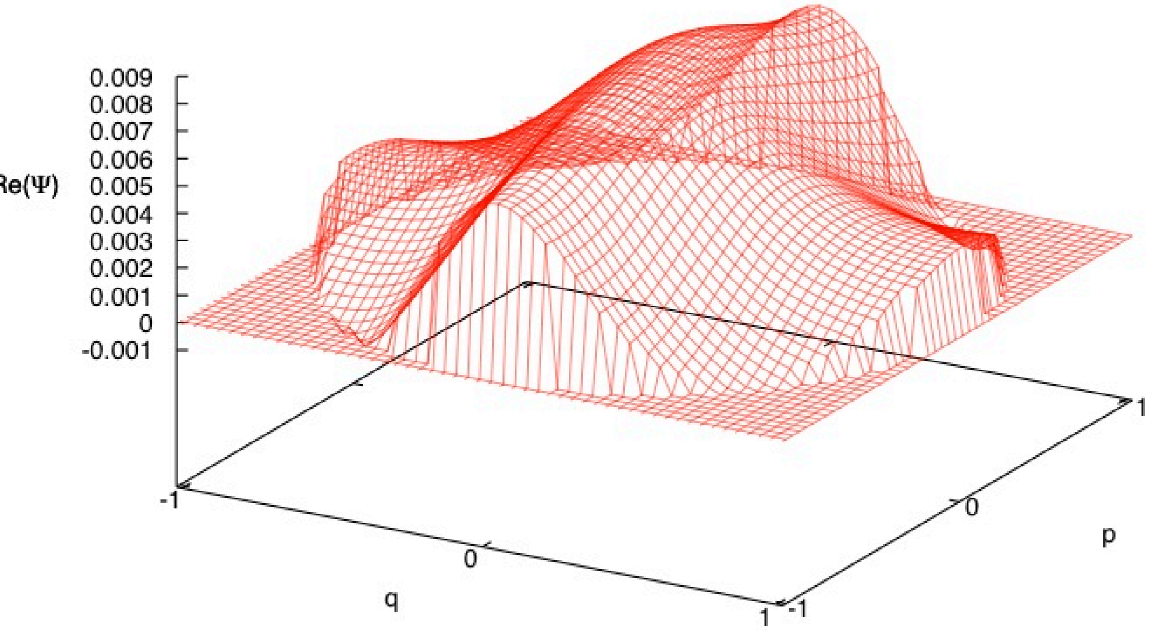
Process of compiling and running a C program.

Goldilocks Condition

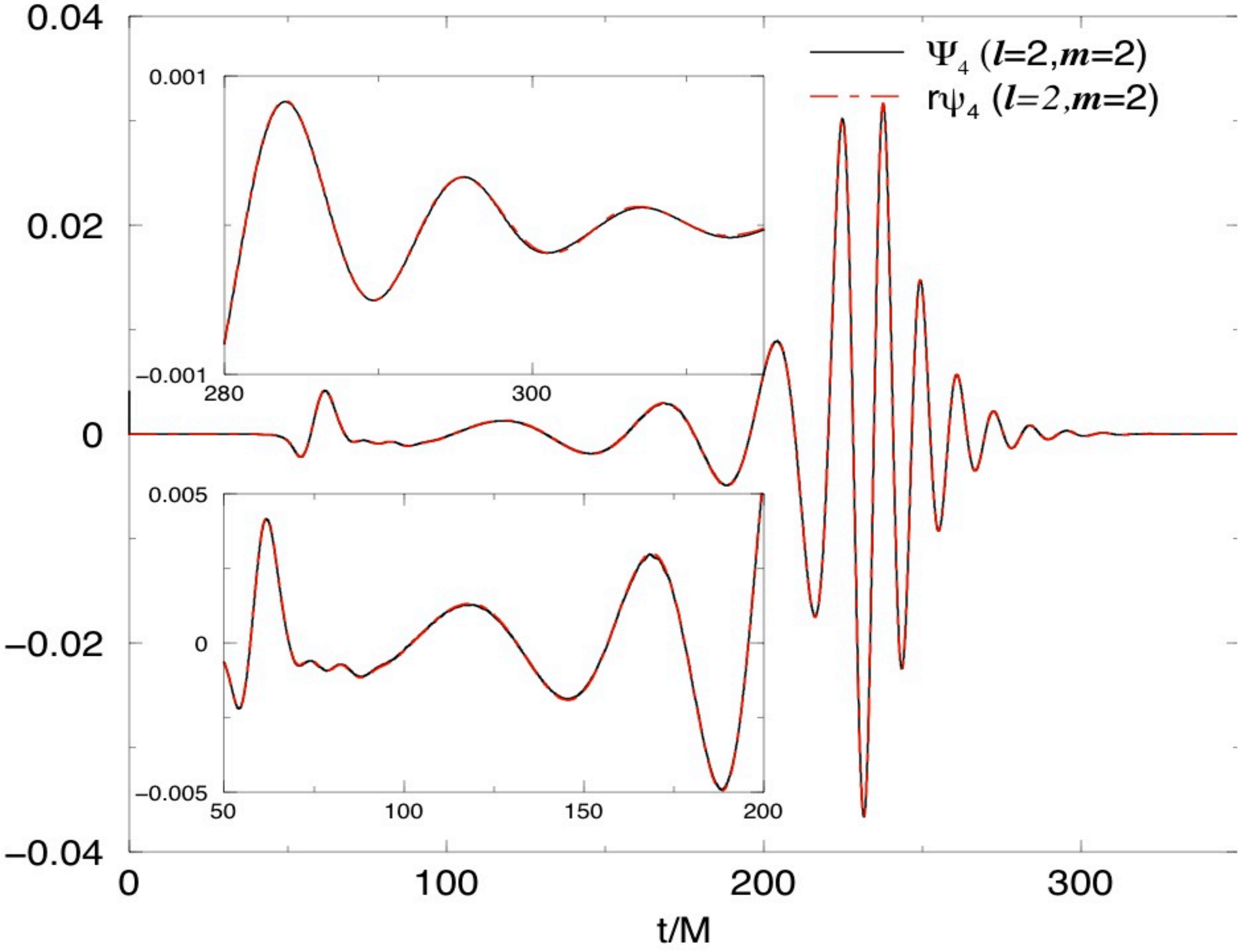
- "circumstances must be right for any type of complexity to form or continue to exist"

RII: Waves of the Future: Capacity Building for the Rising Tide of STEM in WV

Numerical Binary-Black Hole Waveforms



The gravitational wave at the peak of the signal



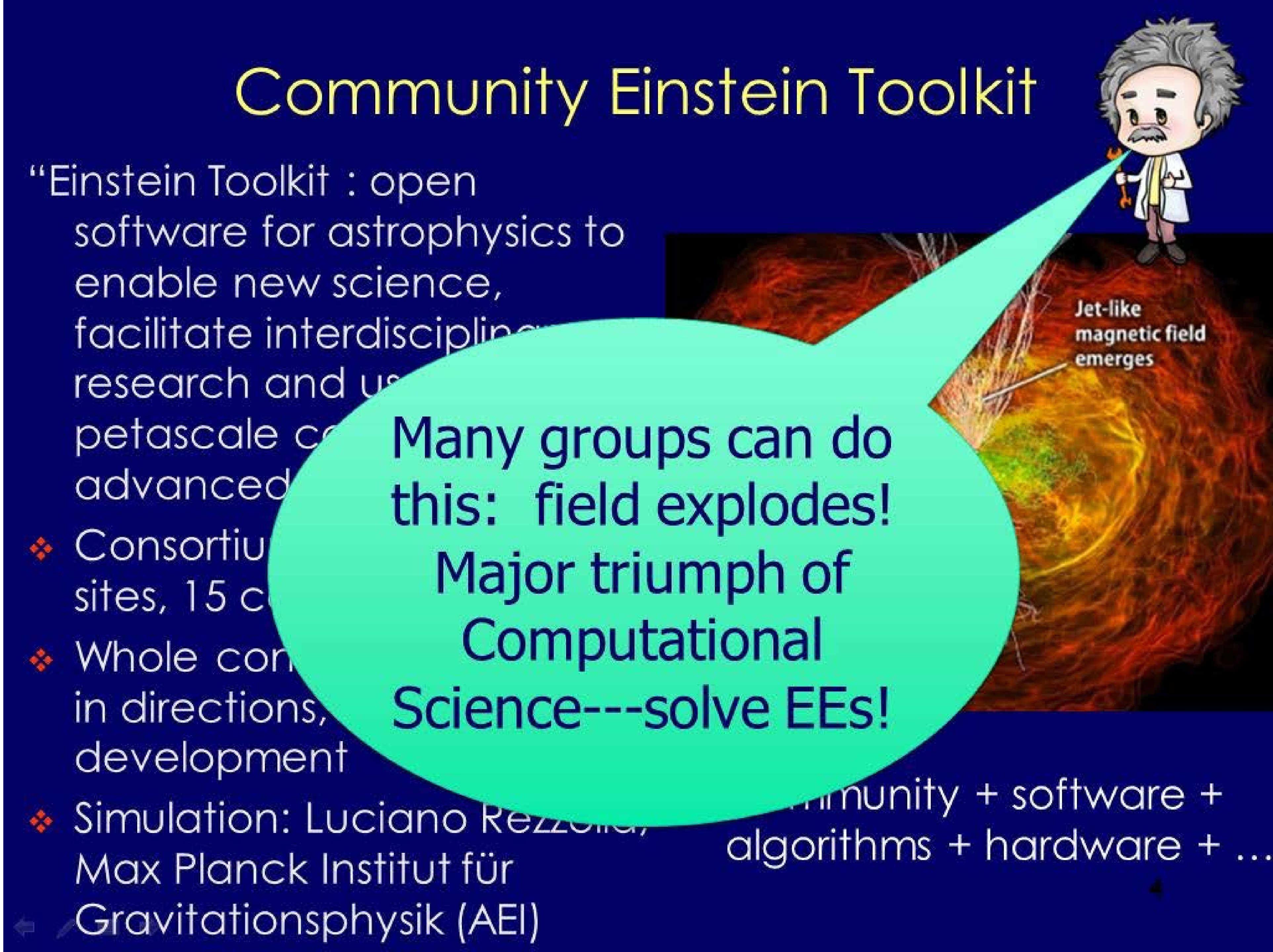
The principal mode of the wave in time

Hardware

Software

Excel

Wolfram Mathematica



Data

LIGO Open Science Center

LIGO is operated by California Institute of Technology and Massachusetts Institute of Technology and supported by the U.S. National Science Foundation.

Data Releases for Events

This page shows data for validated gravitational wave data surrounding confirmed discoveries, as well as data corresponding to important non-detections where detectable gravitational waves might plausibly have been expected, e.g., the data surrounding one or more gamma-ray bursts, supplying evidence for or against a scientific model.

- GW150914
- GW151226
- LVT151012
- Blind Injection of September 16, 2010
- GRB 051103 (non-detection)

Rapid Triggers from LIGO Data

The LIGO Scientific Collaboration (LSC) and the Virgo Collaboration currently started taking data in 2015, and we expect the sensitivity of the network to improve over time. Gravitational-wave transient candidates will be identified promptly upon acquisition of the data; we aim for distributing information with an initial latency of a few tens of minutes initially, possibly improving later.

einstein toolkit

Compile and run binary black hole GW150914

Download

Download the Cactus tree using the GW150914 thornlist:

```
curl -O -L https://raw.githubusercontent.com/gridaphobe/CRL/ET_2016_05/GetComponents

chmod a+x GetComponents

./GetComponents --parallel http://einsteintoolkit.org/about/gallery/gw150914/GW150914.th

cd GW150914
```

Download the parameter file:

```
curl -Lf http://einsteintoolkit.org/about/gallery/gw150914/GW150914.rpar -o par/GW150914.rpar
```

Compile

Configure SimFactory for your machine:

- If you are on a cluster that SimFactory supports, run

  ```
  simfactory/bin/sim setup
  ```

  Hit enter for each question if the default is OK. If you intend to run on a cluster that requires an allocation, make sure to configure this during setup.
- If you are not using a cluster supported by SimFactory, see Compiling the Einstein Toolkit for instructions.

Compile Cactus:

```
simfactory/bin/sim build --thornlist=thornlists/GW150914.th
```

Run

Note that the simulation requires about 82 GB of RAM, so most likely you will need to use a cluster. Submit the simulation:

```
simfactory/bin/sim create-submit GW150914_28 --define N 28 --parfile par/GW150914.rpar --procs 128 --walltime
24:00:00
```

You can choose a different number of cores than 128; if it is too small, the simulation will run out of memory.

When the simulation starts running, it will write its output data into GW150914_28 in your simulations directory. You can find the directory containing the output with:

```
simfactory/bin/sim get-output-dir GW150914_28
```

You can see the status of the simulation with

```
simfactory/bin/sim list-simulations GW150914_28
```

for example

```
GW150914_28            [ACTIVE (RUNNING), restart 0000, job id 363502]
```

Output

You can see the console output of the simulation in

```
/path/to/GW150914_28/output-0000/GW150914_28.out
```

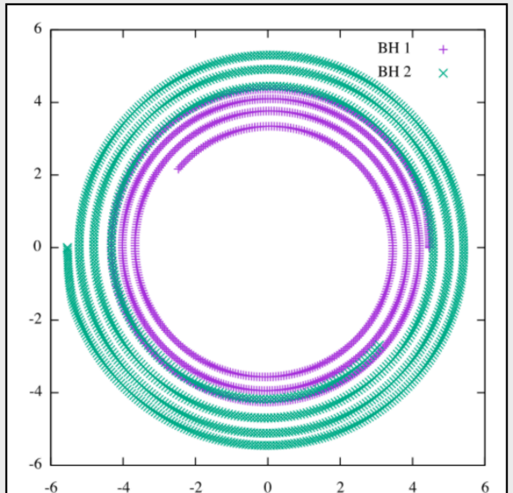
for example:

```
Simulation name: GW150914_28
Running simulation GW150914_28

       10
  1   0101       ************************
  01  1010 10      The Cactus Code V4.3.0
 1010 1101 011      www.cactuscode.org
  1001 100101    ************************
    00010101
     100011     (c) Copyright The Authors
      0100      GNU Licensed. No Warranty
      0101
--------------------------------------------------------------------------------

Cactus version:    4.3.0
...
--------------------------------------------------------------------------------------------------------
Iteration      Time | *me_per_hour |          ML_BSSN::phi | *TISTICS::maxrss_mb | *TICS::swap_used_mb
                    |              |   minimum     maximum |   minimum   maximum |   minimum   maximum
--------------------------------------------------------------------------------------------------------
        0     0.000 |    0.0000000 | 0.0005741   0.9995490 |      2580      3510 |         0         0
        4     0.009 |    3.0212222 | 0.0005853   0.9995490 |      2781      3811 |         0         0
        8     0.017 |    5.5436288 | 0.0005960   0.9995490 |      2781      3811 |         0         0
       12     0.026 |    7.4708510 | 0.0006063   0.9995490 |      2781      3811 |         0         0
       16     0.034 |    9.2093008 | 0.0006161   0.9995490 |      2781      3811 |         0         0
...
```

Visualise

You can do a quick-and-dirty visualisation of the coordinate tracks of the black holes with gnuplot:

```
cd /path/to/GW150914_28/output-0000/GW150914_28
gnuplot

set size square 0.75,0.75
set key
plot 'puncturetracker-pt_loc..asc' u 23:33 title "BH 1", 'puncturetracker-pt_loc..asc' u 24:34 title "BH 2"
```



Eloisa Bentivegna

SimulationTools

for Mathematica

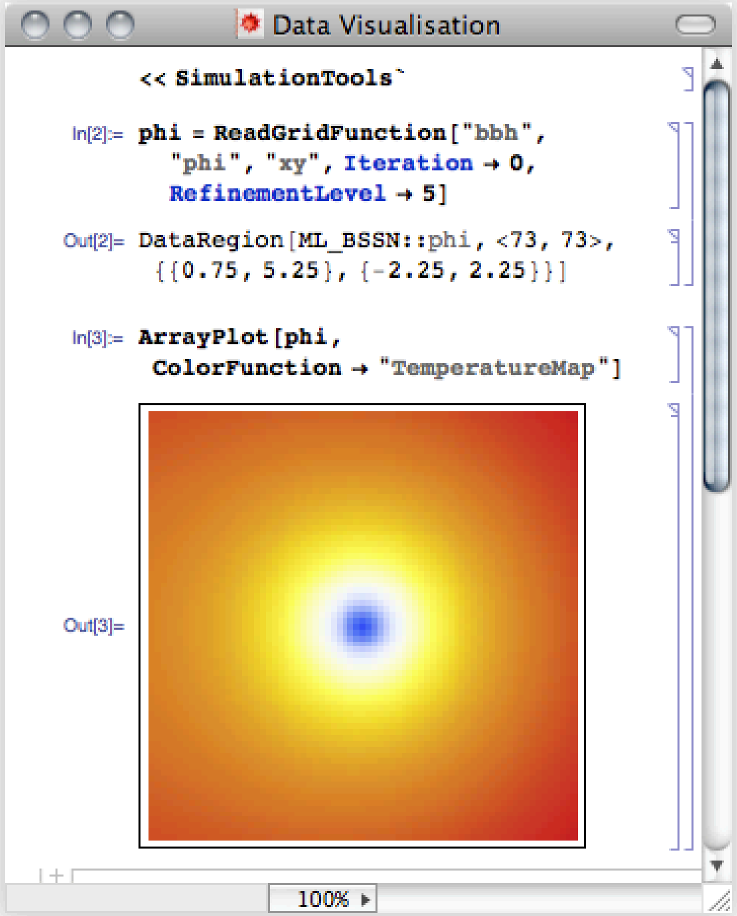
About | Features | Documentation | Codes | Download | Support | Development

SimulationTools is a free software package for the analysis of numerical simulation data in Mathematica.

Features

- Programmatic Interface to Simulation Data
- Hide low-level simulation details
- Enhanced List and Array Data Types
- Useful for all simulation data, but explicitly supports the Cactus code
- Numerical Relativity and the Einstein Toolkit

Download



Please report any issues (bugs or feature requests) on the Issues Page.

SimulationTools was written by Ian Hinder and Barry Wardell, with contributions from Kyriaki Dionysopoulou and Aaryn Tonita. It is provided as free software under the GNU GPL (v3). Please see the Documentation Introduction for an example of how this software can be acknowledged and cited in publications.

Ian Hinder

Best Case Scenario

```
#!/usr/bin/env python

from math import *
import sys
import re
from string import Template

##########################################################################
# Binary black hole configuration
##########################################################################

# BHs labeled as '+' and '-' ('p' and 'm') for their initial position
# on the x axis.  The more massive BH is '+'.

D = ...                 # Separation
q = .../...             # Mass ratio: q = mp/mm >= 1
M = ...                 # Total mass
chip = [0, 0, ...] # Dimensionless spin of + BH (x0 > 0, more massive)
chim = [0, 0, ...] # Dimensionless spin of - BH (x0 < 0, less massive)
Pr = -...;              # Radial linear momentum
Pphi = ...;             # Azimuthal linear momentum

##########################################################################
# Initial data
##########################################################################
```

Free Variables:

1. Separation
2. Mass ratio
3. Total Mass
4. Spins

PN Variables:

- momenta

Caveat:

- *Only one solution for a circular orbit*
- *Fully GR problem, PN can only guess*

PN is Inevitable

$$\Omega^2 = \frac{Gm}{r^3}\left\{1 + (-3+\nu)\gamma + \left(6 + \frac{41}{4}\nu + \nu^2\right)\gamma^2 + \left(-10 + \left[-\frac{75707}{840} + \frac{41}{64}\pi^2 + 22\ln\left(\frac{r}{r'_0}\right)\right]\nu + \frac{19}{2}\nu^2 + \nu^3\right)\gamma^3\right\} + \mathcal{O}\left(\frac{1}{c^8}\right)$$

$$\dot{r} = -\frac{64}{5}\frac{G^3m^3\nu}{r^3c^5}\left[1 + \gamma\left(-\frac{1751}{336} - \frac{7}{4}\nu\right)\right],$$

$$\dot{\Omega} = \frac{96}{5}\frac{Gm\nu}{r^3}\gamma^{5/2}\left[1 + \gamma\left(-\frac{2591}{336} - \frac{11}{12}\nu\right)\right]$$

$$\gamma \equiv \frac{Gm}{rc^2} = \mathcal{O}\left(\frac{1}{c^2}\right)$$

$$\Delta = (m_1 - m_2)/m$$

$$\boldsymbol{a} = -\Omega^2\boldsymbol{x} - \frac{32}{5}\frac{G^3m^3\nu}{c^5r^4}\left[1 + \gamma\left(-\frac{743}{336} - \frac{11}{4}\nu\right)\right]\boldsymbol{v} + \mathcal{O}\left(\frac{1}{c^8}\right)$$

$$X_1 = m_1/m, \; X_2 = m_2/m$$

$$\boldsymbol{y}_1 = \boldsymbol{x}\left[X_2 + 3\gamma^2\nu\Delta\right] - \frac{4}{5}\frac{G^2\nu m^2\Delta}{rc^5}\boldsymbol{v} + \mathcal{O}\left(\frac{1}{c^6}\right) \qquad \boldsymbol{y}_2 = \boldsymbol{x}\left[-X_1 + 3\gamma^2\nu\Delta\right] - \frac{4}{5}\frac{G^2\nu m^2\Delta}{rc^5}\boldsymbol{v} + \mathcal{O}\left(\frac{1}{c^6}\right)$$

http://www.livingreviews.org/lrr-2014-2

You Start with PN

$$h^{\ell m} = \frac{2G\,m\,\nu\,x}{R\,c^2}\sqrt{\frac{16\pi}{5}}\,\mathcal{H}^{\ell m}\,e^{-\mathrm{i}m\,\psi}$$

$$\begin{aligned}
\mathcal{H}^{22} = 1 &+ x\left(-\frac{107}{42}+\frac{55}{42}\nu\right) + 2\pi x^{3/2} + x^2\left(-\frac{2173}{1512}-\frac{1069}{216}\nu+\frac{2047}{1512}\nu^2\right) \\
&+ x^{5/2}\left(-\frac{107\pi}{21}-24\,\mathrm{i}\,\nu+\frac{34\pi}{21}\nu\right) + x^3\left(\frac{27027409}{646800}-\frac{856}{105}\,\gamma_\mathrm{E}+\frac{428\,\pi}{105}\mathrm{i}+\frac{2\pi^2}{3}\right. \\
&\left.+\left(-\frac{278185}{33264}+\frac{41\pi^2}{96}\right)\nu-\frac{20261}{2772}\nu^2+\frac{114635}{99792}\nu^3-\frac{428}{105}\ln(16x)\right) \\
&+ x^{7/2}\left(-\frac{2173\pi}{756}+\left(-\frac{2495\pi}{378}+\frac{14333}{162}\mathrm{i}\right)\nu+\left(\frac{40\pi}{27}-\frac{4066}{945}\mathrm{i}\right)\nu^2\right)+\mathcal{O}\left(\frac{1}{c^8}\right).
\end{aligned}$$

http://www.livingreviews.org/lrr-2014-2

Know Your PN

$$x = \frac{1}{4}\Theta^{-1/4}\left\{1 + \left(\frac{743}{4032} + \frac{11}{48}\nu\right)\Theta^{-1/4} - \frac{1}{5}\pi\Theta^{-3/8} + \left(\frac{19583}{254016} + \frac{24401}{193536}\nu + \frac{31}{288}\nu^2\right)\Theta^{-1/2} + \left(-\frac{11891}{53760} + \frac{109}{1920}\nu\right)\pi\Theta^{-5/8} + \left[-\frac{10052469856691}{6008596070400} + \frac{1}{6}\pi^2 + \frac{107}{420}\gamma_E - \frac{107}{3360}\ln\left(\frac{\Theta}{256}\right) + \left(\frac{3147553127}{780337152} - \frac{451}{3072}\pi^2\right)\nu - \frac{15211}{442368}\nu^2 + \frac{25565}{331776}\nu^3\right]\Theta^{-3/4} + \left(-\frac{113868647}{433520640} - \frac{31821}{143360}\nu + \frac{294941}{3870720}\nu^2\right)\pi\Theta^{-7/8} + \mathcal{O}\left(\frac{1}{c^8}\right)\right\}.$$

$$\Theta \equiv \frac{\nu c^3}{5Gm}(t_c - t)$$

$$\nu \equiv \frac{\mu}{m} \equiv \frac{m_1 m_2}{(m_1 + m_2)^2}.$$

Euler's constant $\gamma_E \simeq 0.577$

$$\phi = -\frac{x^{-5/2}}{32\nu}\left\{1 + \left(\frac{3715}{1008} + \frac{55}{12}\nu\right)x - 10\pi x^{3/2} + \left(\frac{15293365}{1016064} + \frac{27145}{1008}\nu + \frac{3085}{144}\nu^2\right)x^2 + \left(\frac{38645}{1344} - \frac{65}{16}\nu\right)\pi x^{5/2}\ln\left(\frac{x}{x_0}\right) + \left[\frac{12348611926451}{18776862720} - \frac{160}{3}\pi^2 - \frac{1712}{21}\gamma_E - \frac{856}{21}\ln(16\,x) + \left(-\frac{15737765635}{12192768} + \frac{2255}{48}\pi^2\right)\nu + \frac{76055}{6912}\nu^2 - \frac{127825}{5184}\nu^3\right]x^3 + \left(\frac{77096675}{2032128} + \frac{378515}{12096}\nu - \frac{74045}{6048}\nu^2\right)\pi x^{7/2} + \mathcal{O}\left(\frac{1}{c^8}\right)\right\},$$

$$x \equiv \left(\frac{G\,m\,\Omega}{c^3}\right)^{2/3}$$

$$\psi \equiv \phi - \frac{2GM\,\Omega}{c^3}\ln\left(\frac{\Omega}{\Omega_0}\right)$$

http://www.livingreviews.org/lrr-2014-2

Suffering is Optional

$$\dot{r} = -2.7069\left(1.21329 - \frac{1.5053}{\sqrt{r}} + \frac{2.60155}{r}\right) r^{-2.993}$$

$$p_r = -1.9188\left(1.76084 - \frac{5.3029}{\sqrt{r}} + \frac{9.06417}{r}\right) r^{-3.288}$$

$$p_t = \pm\left(P_{3PN}(r) - \frac{35.0988}{r^{5.36702}}\right)$$

$$\frac{p}{\mu} = \sqrt{\frac{M}{D}} + 2\epsilon\left(\frac{M}{D}\right)^{3/2} + \frac{1}{16}\epsilon^2(42 - 43\nu)\left(\frac{M}{D}\right)^{5/2}$$

$$+\frac{\epsilon^3}{128}\left[480 + (163\pi^2 - 4556)\nu + 104\nu^2\right]\left(\frac{M}{D}\right)^{7/2}.$$

The total mass is $M = M_1 + M_2$, the reduced mass is $\mu = M_1 M_2/M$, $\nu = \mu/M$, and the PN order of each term is indicated by ϵ. For equal-mass black holes with $M_1 = M_2 = 0.5$, we have $\mu = \nu = 0.25$.

separation/M	$-\dot{r}$ ($\times 10^{-3}$)	$-p_r/M$ ($\times 10^{-3}$)	p_t/M
8.0	5.3857	2.0906	0.112349
8.5	4.4944	1.7023	0.107614
9.0	3.7839	1.4019	0.103376
9.5	3.2133	1.1670	0.099561
10.0	2.7512	0.9813	0.096109
10.5	2.3736	0.8328	0.092968
11.0	2.0624	0.7128	0.090099
11.5	1.8039	0.6150	0.087464
12.0	1.5872	0.5343	0.085037
12.5	1.4042	0.4672	0.082791
13.0	1.2487	0.4110	0.080706
13.5	1.1156	0.3635	0.078765
14.0	1.0010	0.3231	0.076952
14.5	0.9018	0.2886	0.075255
15.0	0.8155	0.2589	0.073661
15.5	0.7398	0.2331	0.072161
16.0	0.6734	0.2106	0.070746
16.5	0.6150	0.1911	0.069409
17.0	0.5629	0.1738	0.068143
17.5	0.5169	0.1586	0.066942
18.0	0.4757	0.1452	0.065801
18.5	0.4386	0.1331	0.064715
19.0	0.4055	0.1224	0.063679
19.5	0.3757	0.1129	0.062691
20.0	0.3488	0.1043	0.061747

TABLE II: Radial velocity and radial (p_r) and tangential (p_t) components of the black hole momentum as a function of the separation in ADMTT coordinates for selected values of the separation. The numbers have been produced from a PN-inspiral from $D = 100M$.

Zach Etienne
Sasha Husa

SXS Gravitational Waveform

Completed Simulations

Important Information

Latest News and Updates

Help and Documentation

Click to subscribe (or unsubscribe) to the waveform announcement mailing list.
For general questions about the Catalog, please send an email to questions@black-holes.org.
For questions about a specific simulation, please click the email icon in the table below.

Filters	Filter Value
ID	string or regex SXS:BBH:0317
Select Filter	

Filter Reset

--Choose a field-- Add column

Download Table

Last updated: 2016-11-05

ID	Data	m_1/m_2	χ_1	χ_2	χ_{1x}	χ_{1y}	χ_{1z}	χ_{2x}
SXS:BBH:0317	Metadata DATA	3.327	0.5226	0.4482	0	0	0.5226	0

SXS Gravitational Waveform

Completed Simulations

Important Information

Latest News and Updates

Help and Documentation

Click to subscribe (or unsubscribe) to the waveform announcement mailing list.
For general questions about the Catalog, please send an email to questions@black-holes.org.
For questions about a specific simulation, please click the email icon in the table below.

Filters	Filter Value
ID	string or regex SXS:BBH:0305
Select Filter	

Filter Reset

--Choose a field-- Add column

Download Table

Last updated: 2016-11-05

ID	Data	m_1/m_2	χ_1	χ_2	χ_{1x}	χ_{1y}	χ_{1z}	χ_{2x}
SXS:BBH:0305	Metadata DATA	1.221	0.3300	0.4399	0	0	0.3300	0

SXS Gravitational Waveform Database

Help and Documentation

Data Columns

Column	Description
ID	A unique identification string for a simulation. It identifies the collaboration, type of binary, and number.
Data	Link to the metadata and downloadable data for a simulation.
m_1/m_2	Ratio of the Christodoulou masses at the relaxation time. We use $m_1 > m_2$.
$\chi_{1,2}$	Dimensionless spin magnitudes at the relaxation time.
$\chi_{\{1,2\}\{X,Y,Z\}}$	Dimensionless spin vector components at the relaxation time.
Ecc	Eccentricity estimated by fitting $d\omega_{orb}/dt$ for 2.5 orbits after the relaxation time.
$M\omega_{orb}$	Orbital frequency multiplied by the total Christodoulou mass at the relaxation time.
Orbits	Number of orbits from $t = 0$ until the region inside the common horizon is excised.
Email	Link to e-mail the SXS Collaboration about a particular simulation.

Columns that can be added by the dropdown menu are described in the Metadata file.

Command-line Downloads

If you would prefer to download data from the catalog using command-line tools instead of interactively in your browser, one available alternative is `wget`. To download an entire simulation (e.g. SXS:BBH:0001), you could use:

```
wget "http://www.black-holes.org/waveforms/data/Download.php?id=SXS:BBH:0001"
```

To download a subdirectory or individual file (e.g. Lev5/Horizons.h5 in SXS:BBH:0001), you could use:

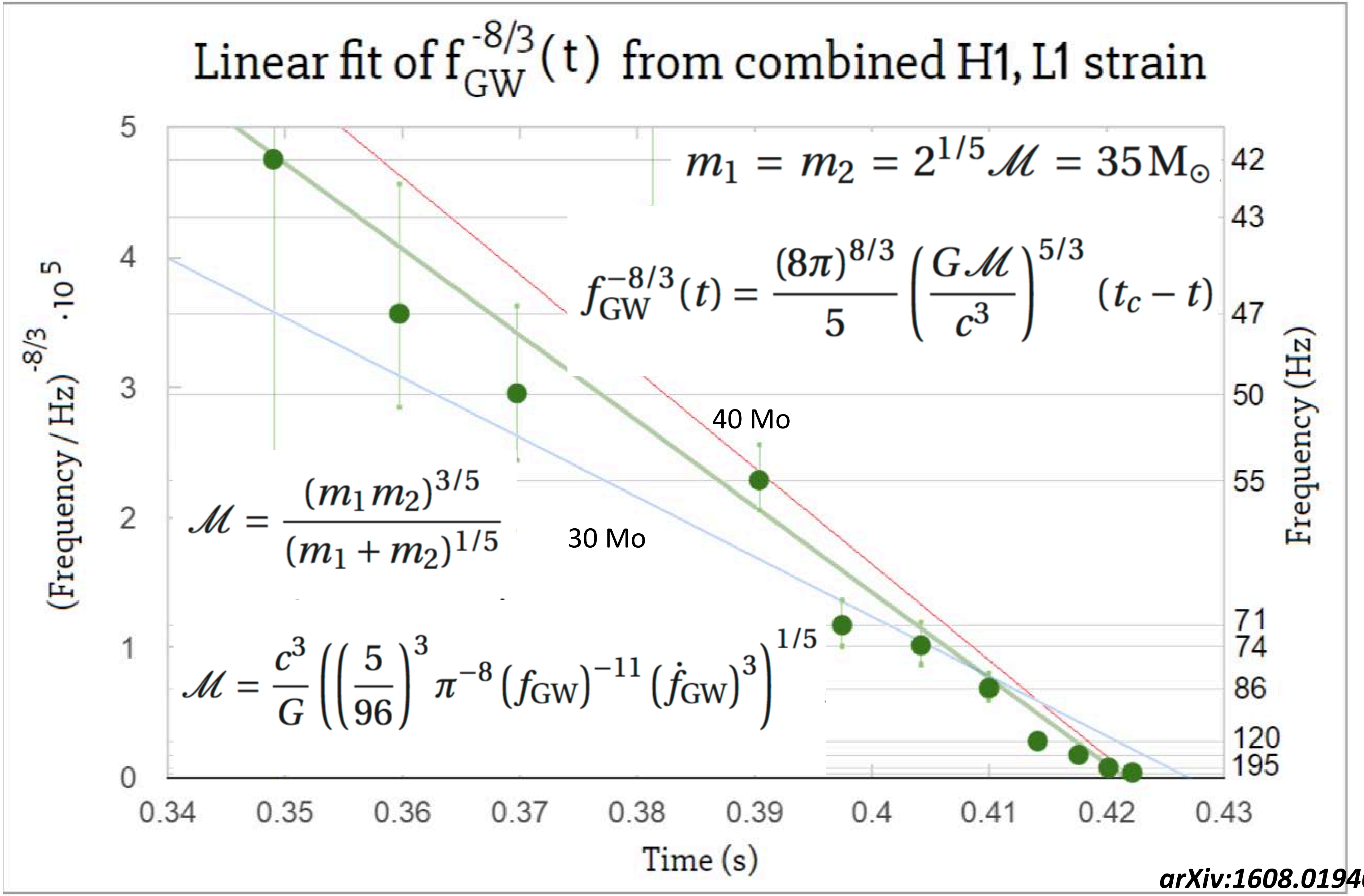
```
wget "http://www.black-holes.org/waveforms/data/Download.php?id=SXS:BBH:0001&file=Lev5/Horizons.h5"
```

If downloading a directory, the content is provided in the .tgz format.

File Descriptions

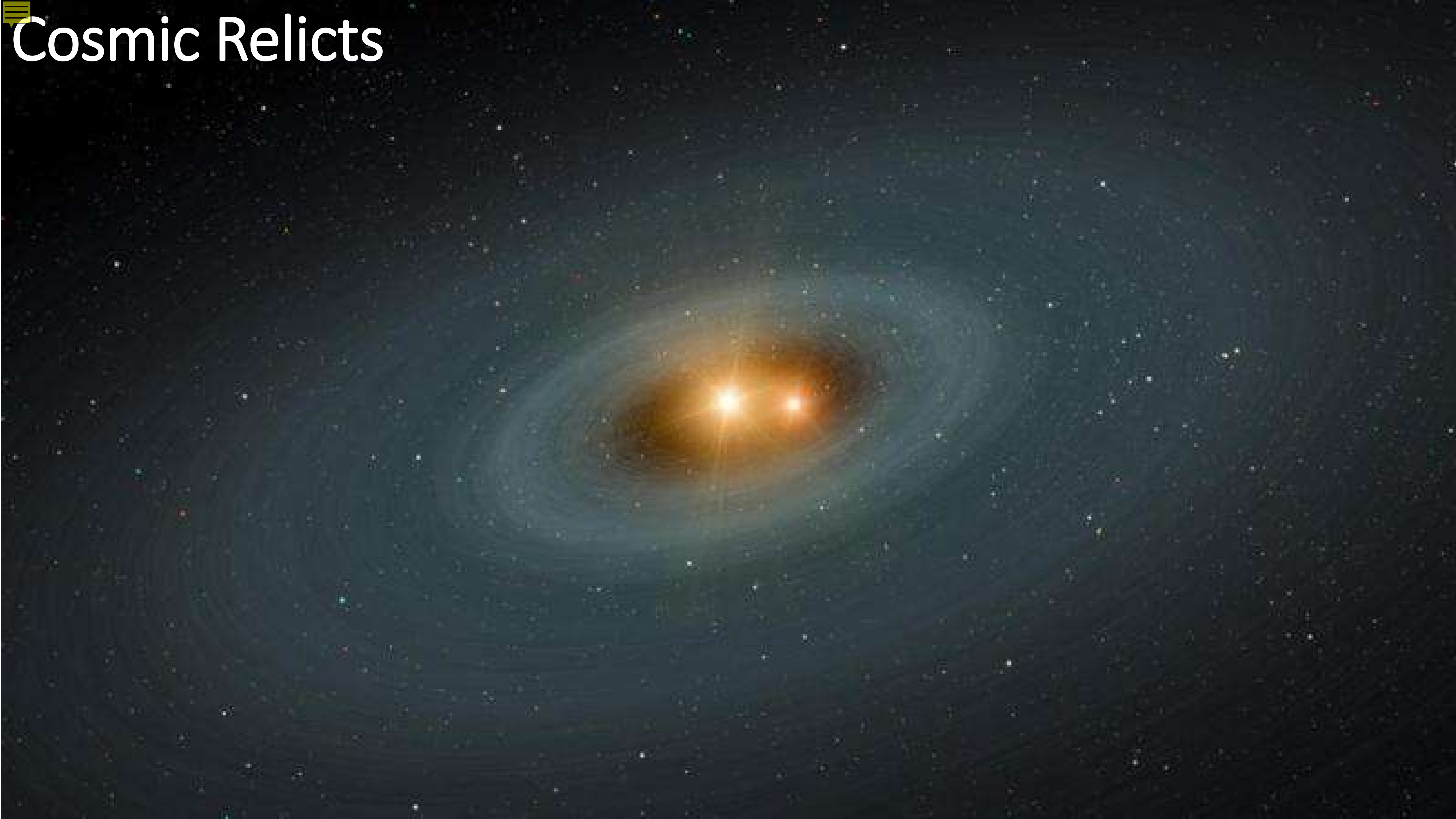
rhOverM_Asymptotic_GeometricUnits.h5, rMPsi4_Asymptotic_GeometricUnits.h5

Serguei Ossokine

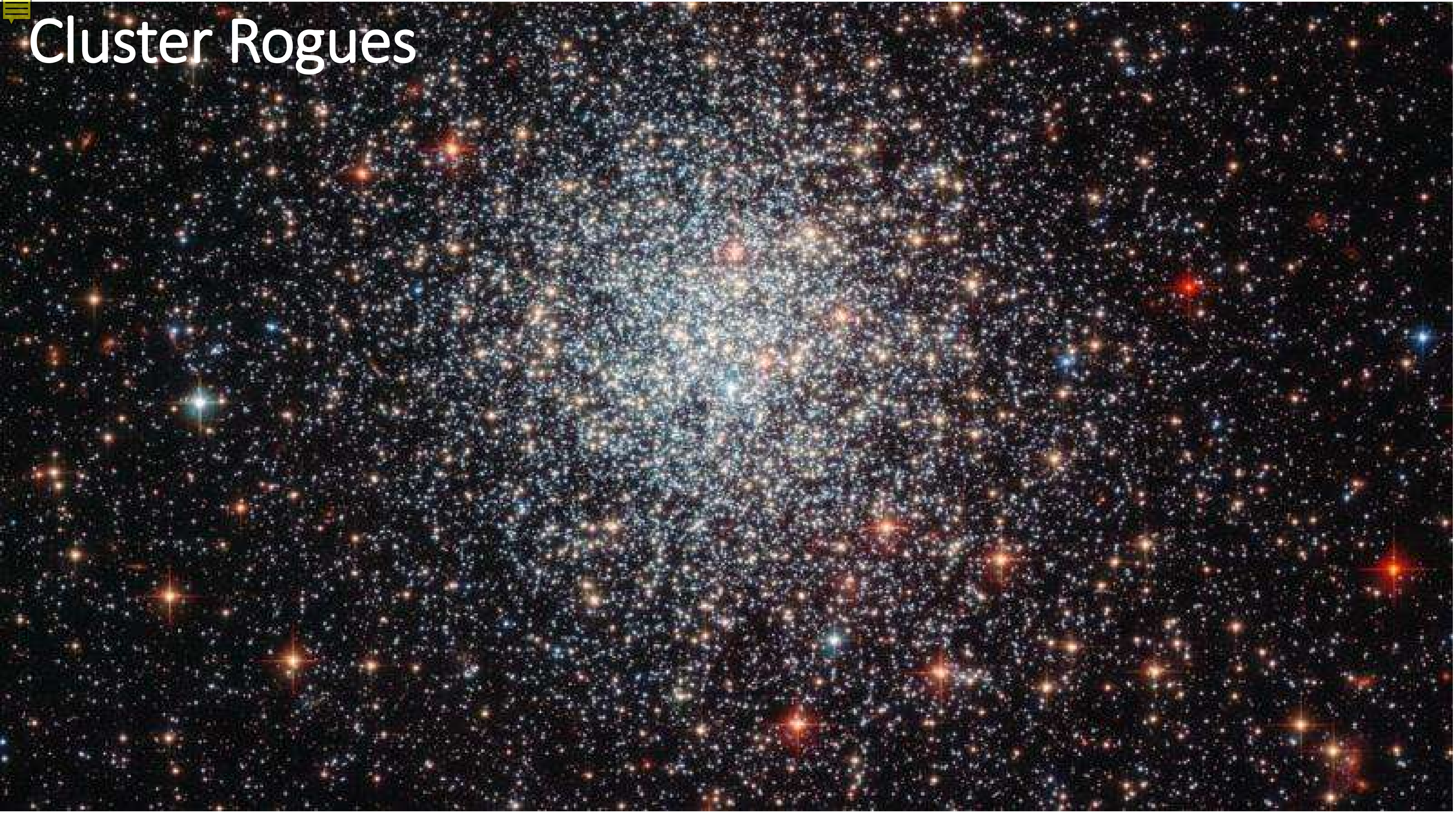


arXiv:1608.01940 [gr-qc]

Cosmic Relicts



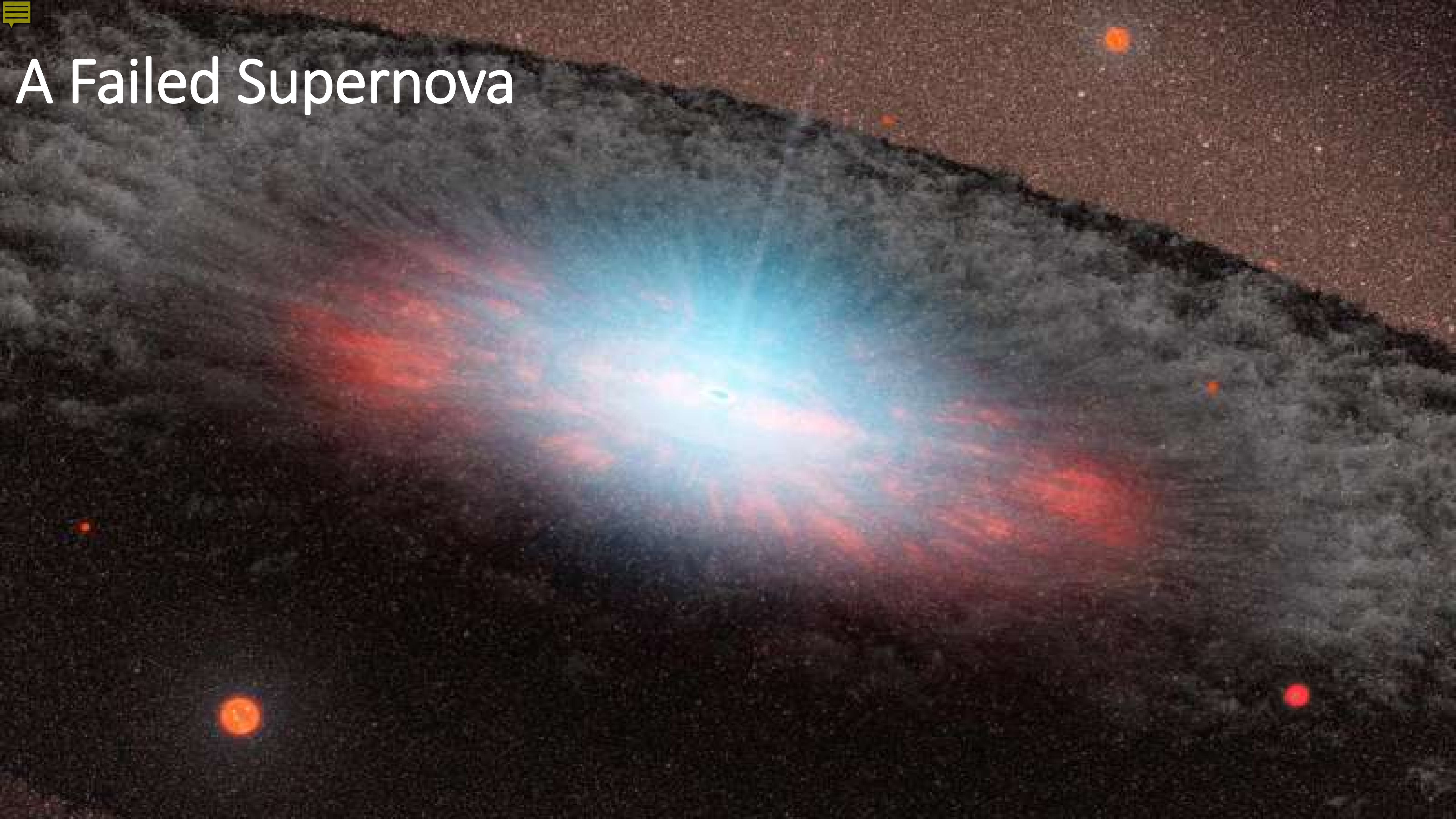
Cluster Rogues

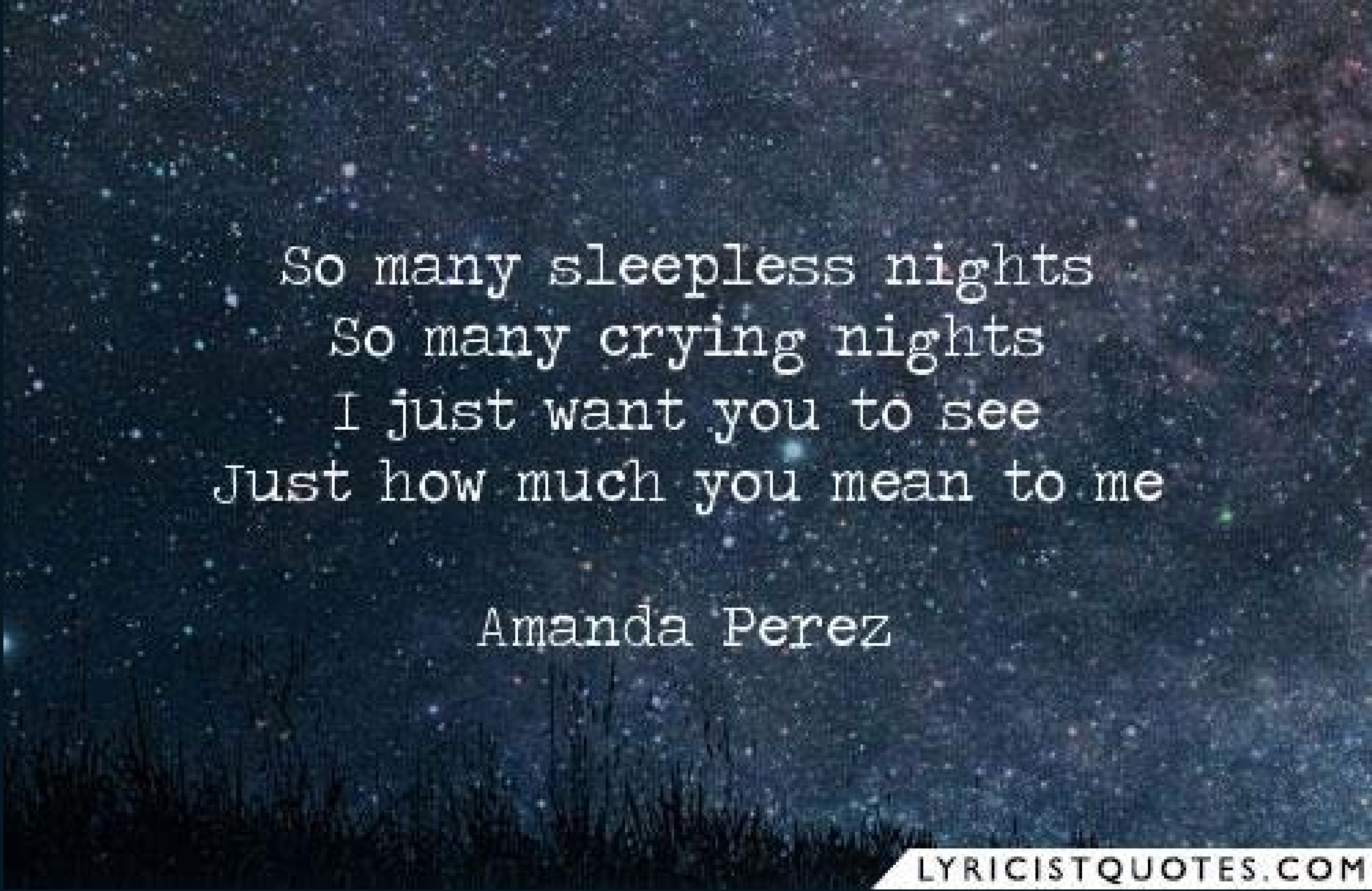


Galactic Captives

Seeds in the Early Universe

A Failed Supernova




So many sleepless nights
So many crying nights
I just want you to see
Just how much you mean to me
Amanda Perez
LYRICISTQUOTES.COM