Gravitational Waves and Galaxy Mergers

RAJESH KUMAR DUBEY

LOVELY PROFESSIONAL UNIVERSITY, PUNJAB, INDIA

YITP-2019, KYOTO UNIVERSITY, JAPAN. FEB 12, 2019

Motivation

- **What are the ways and possibilities for detecting GWs emerging from SMBHs in the cosmological time durations**

- The **first direct observation of gravitational waves** was made on

  14 September 2015 and was announced by
the LIGO and Virgo collaborations on 11 February 2016.

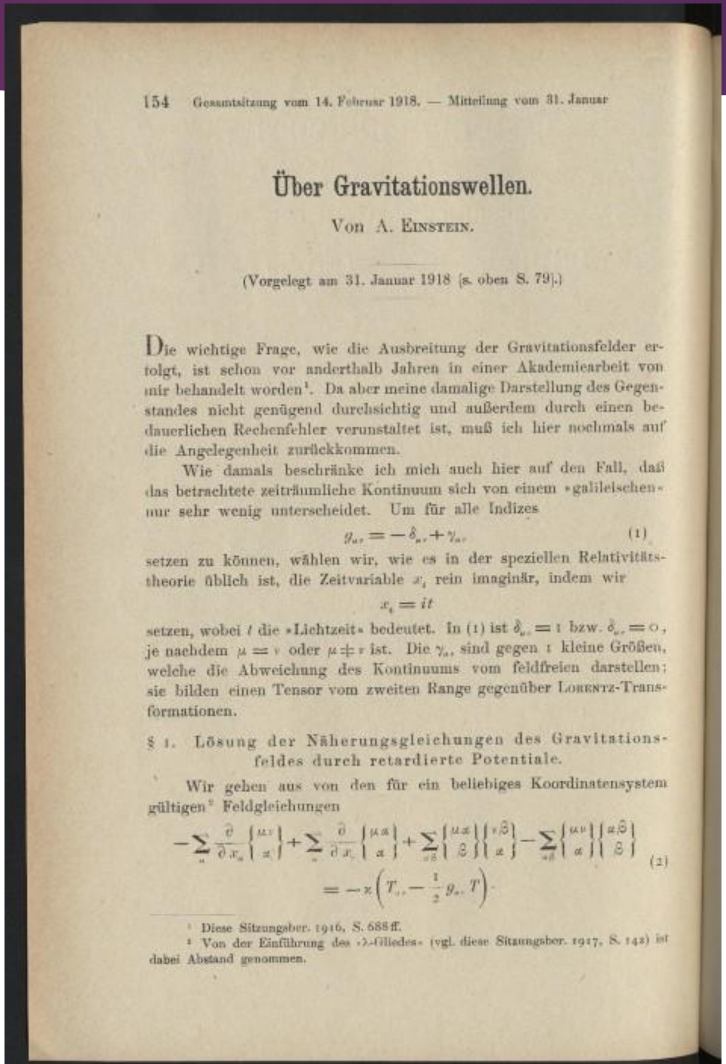
- We at YITP {11 Feb-15 Feb, 2019} unknowingly celebrating the third anniversary.

What is in the next 20 minutes !

- GW-First Indirect Evidence PSR B1913+16
- Simulations for BH mergers
- Galaxy Mergers
- Supermassive Black Holes in Mergers of Galaxies
- Scope of GW from Galaxy Mergers

GW- in General Relativity

Rajesh K Dubey, YITP, 12/02/2019



154 Gesamtsitzung vom 14. Februar 1918. — Mitteilung vom 31. Januar

Über Gravitationswellen.

Von A. Einstein.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden[1]. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.

Wie damals beschränke ich mich auch hier auf den Fall, daß das betrachtete zeiträumliche Kontinuum sich von einem »galileischen« nur sehr wenig unterscheidet. Um für alle Indizes

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \quad (1)$$

setzen zu können, wählen wir, wie es in der speziellen Relativitätstheorie üblich ist, die Zeitvariable x_4 rein imaginär, indem wir

$$x_4 = it$$

setzen, wobei t die »Lichtzeit« bedeutet. In (1) ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu} = 0$, je nachdem $\mu = \nu$ oder $\mu \neq \nu$ ist. Die $\gamma_{\mu\nu}$ sind gegen 1 kleine Größen, welche die Abweichung des Kontinuums vom feldfreien darstellen; sie bilden einen Tensor vom zweiten Range gegenüber Lorentz-Transformationen.

§ 1. Lösung der Näherungsgleichungen des Gravitationsfeldes durch retardierte Potentiale.

Wir gehen aus von den für ein beliebiges Koordinatensystem gültigen[2] Feldgleichungen

$$-\sum_{\alpha} \frac{\partial}{\partial x_\alpha} \begin{Bmatrix} \mu\nu \\ \alpha \end{Bmatrix} + \sum_{\alpha} \frac{\partial}{\partial x_\nu} \begin{Bmatrix} \mu\alpha \\ \alpha \end{Bmatrix} + \sum_{\alpha\beta} \begin{Bmatrix} \mu\alpha \\ \beta \end{Bmatrix} \begin{Bmatrix} \nu\beta \\ \alpha \end{Bmatrix} - \sum_{\alpha\beta} \begin{Bmatrix} \mu\nu \\ \alpha \end{Bmatrix} \begin{Bmatrix} \alpha\beta \\ \beta \end{Bmatrix} = -\varkappa \left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T \right) \quad (2)$$

[1] Diese Sitzungsber. 1916, S. 688 ff.

[2] Von der Einführung des »λ-Gliedes« (vgl. diese Sitzungsber. 1917, S. 142) ist dabei Abstand genommen.

$$g_{ij} = d_{ij} + h_{ij}$$

h_{ij}: transverse, traceless and propagates at v=c

Einstein in (1916, 1918)

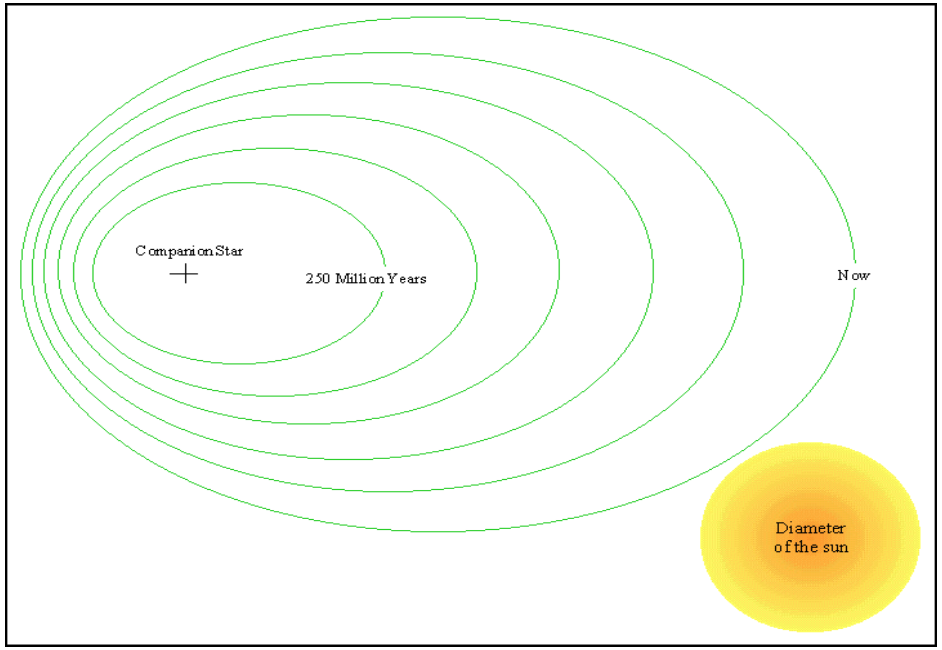
Consequences of Einstein's theory

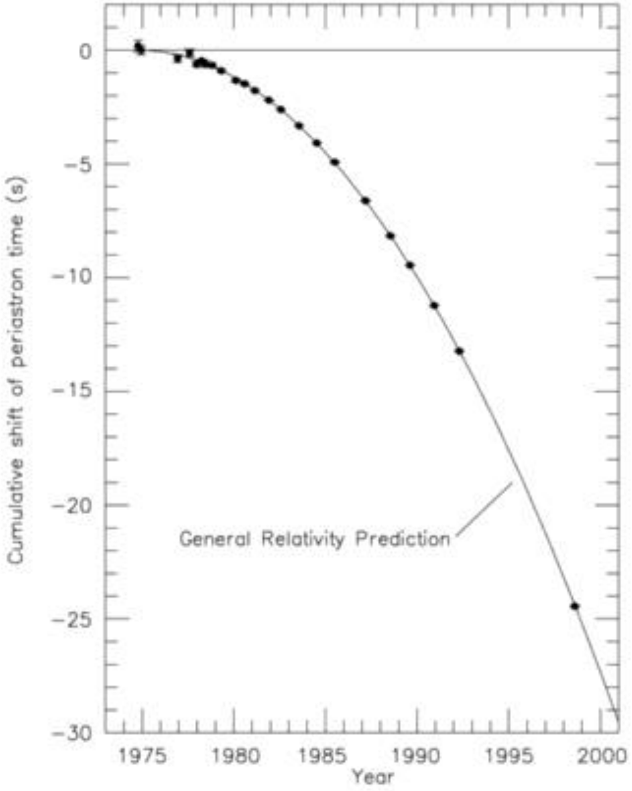
- Gravitational time dilation and frequency shift
- Orbital effects and the relativity of direction
- Gravitational waves
- Gravitational lensing
- Orbital decay

GW-First Indirect Evidence

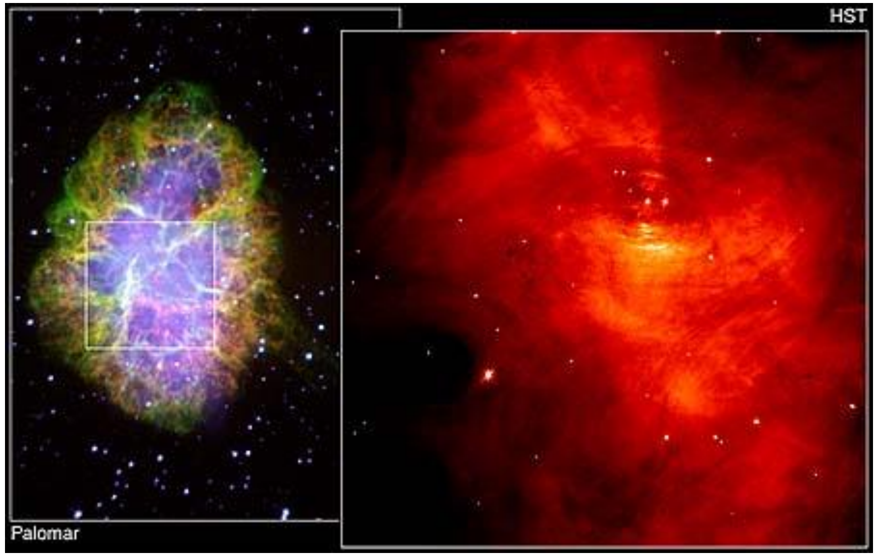
- Steady decrease in orbital separation due to loss of energy through GWs.

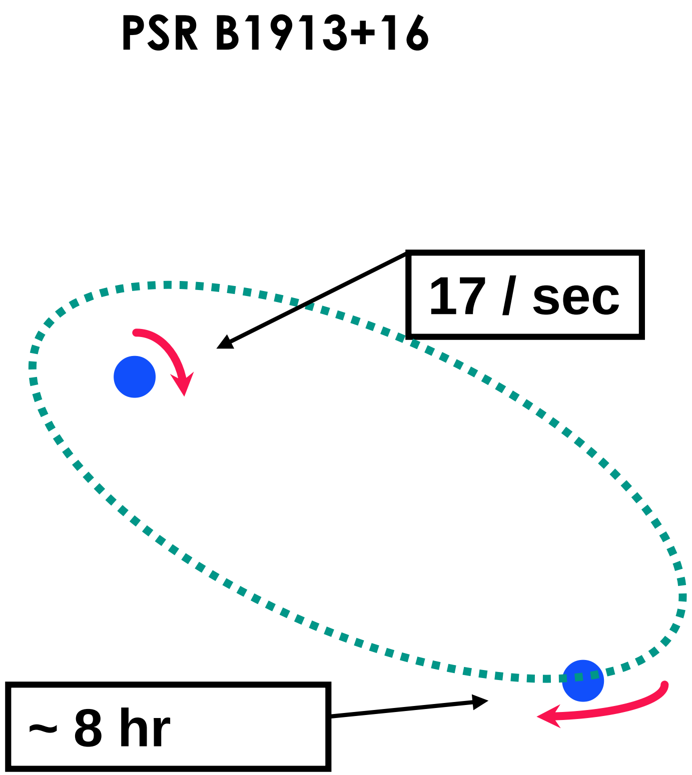

Hulse & Taylor
Nobel Prize Physics-1993



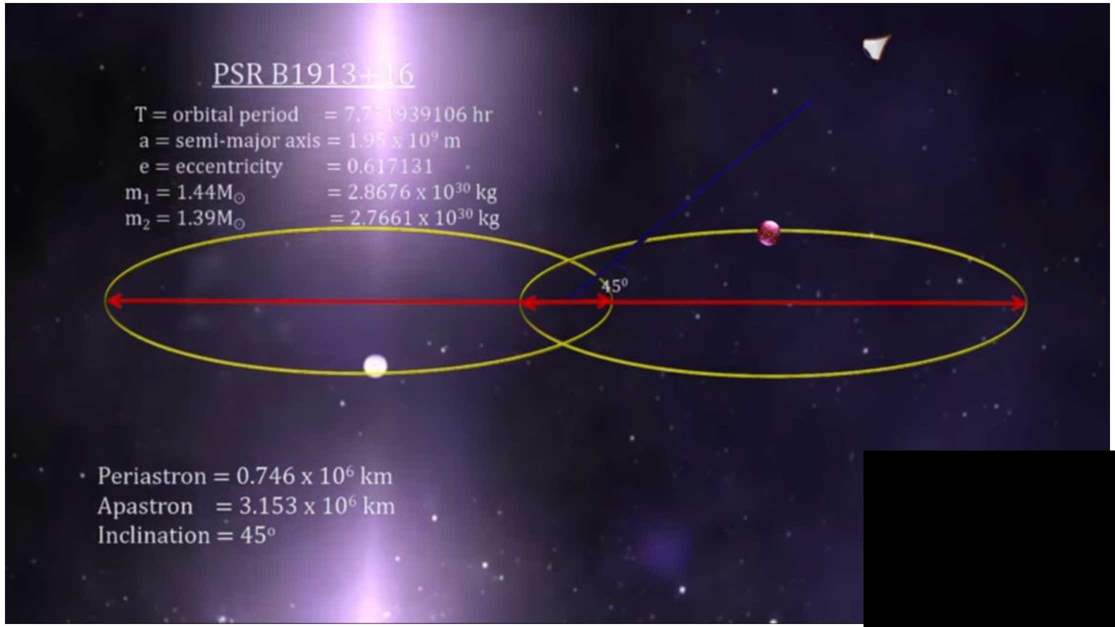


Hulse- Taylor Binary pulsars



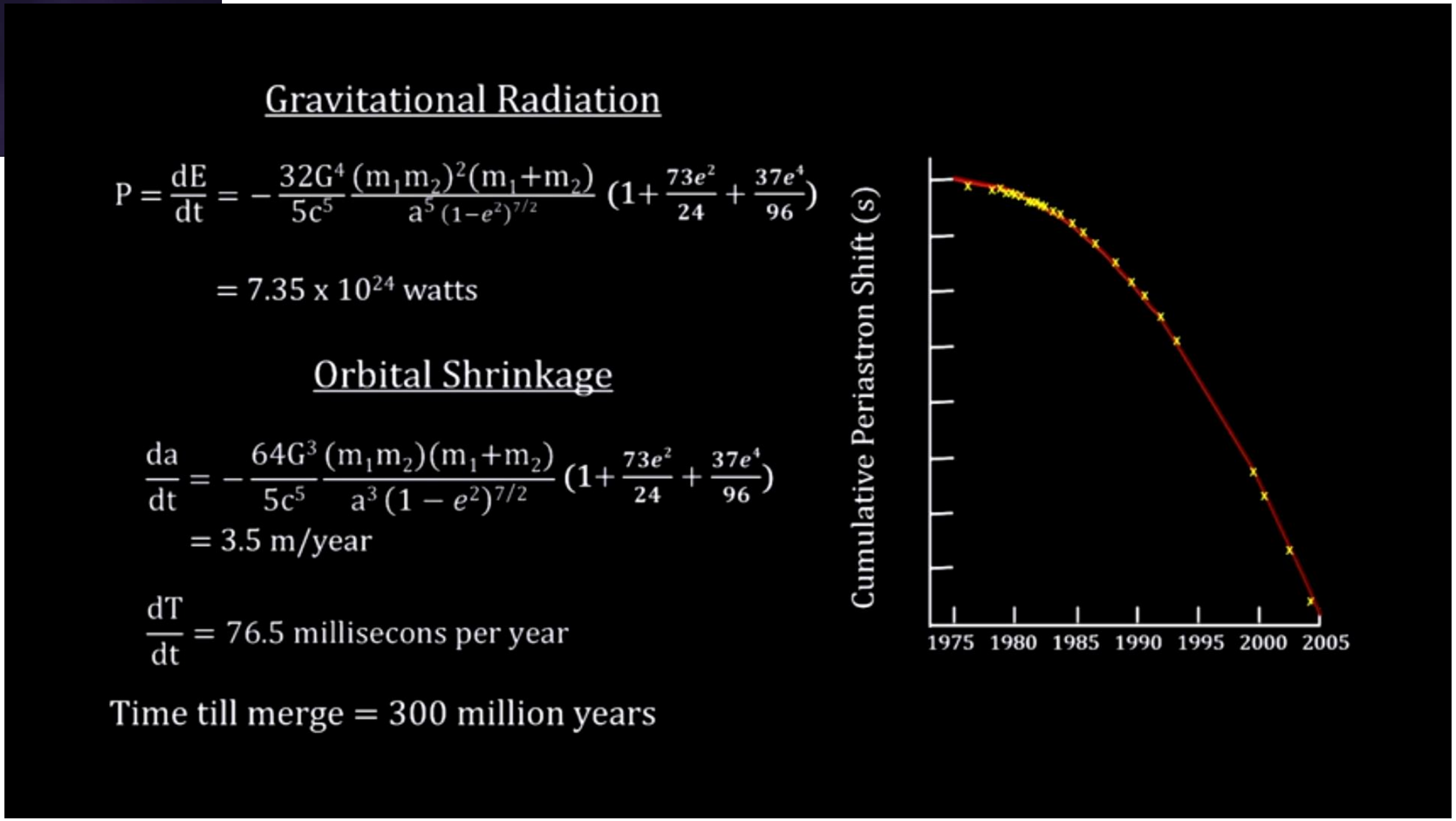


- A rapidly spinning pulsar (neutron star beaming EM radiation at us 17 x / sec)
- Orbiting around an ordinary star with 8 hour period
- Only 7 kpc away
- Discovered in 1975, orbital parameters measured
- Continuously measured over 25 years!



PSR B1913+16
Hulse-Taylor Binary

- Steady decrease in orbital separation due to loss of energy through GWs.



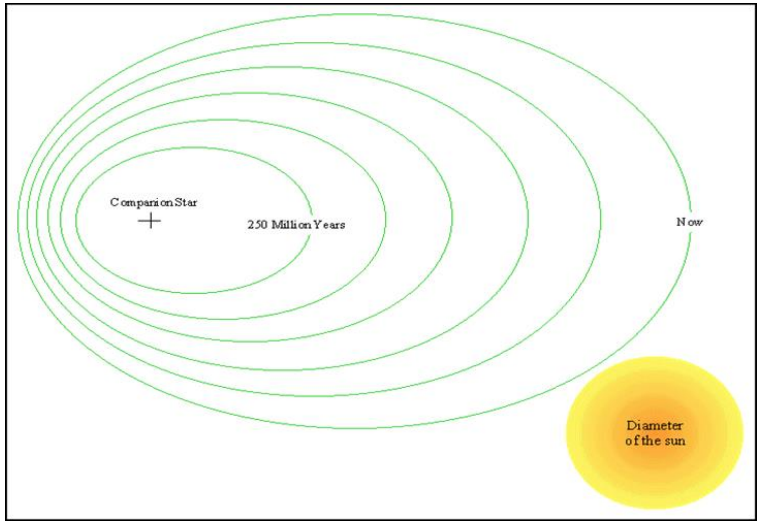
- **Emission of GWs.**
- **Separated by ~2×10^6 km**
- **Spiral in by 3 mm/orbit**
- **Time till merge= 300 million years**

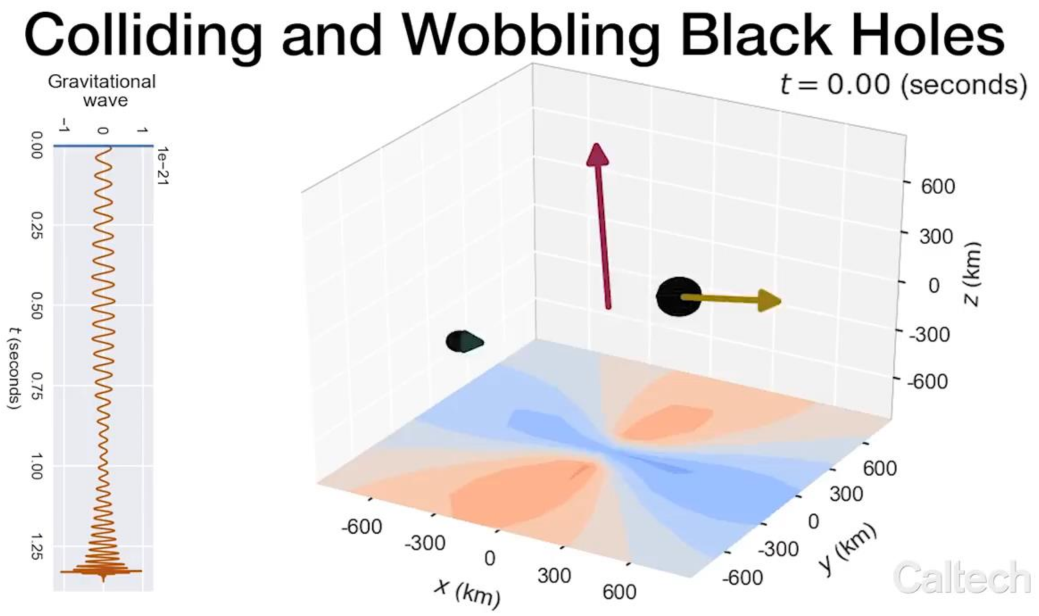
Weisberg & Taylor, 2004

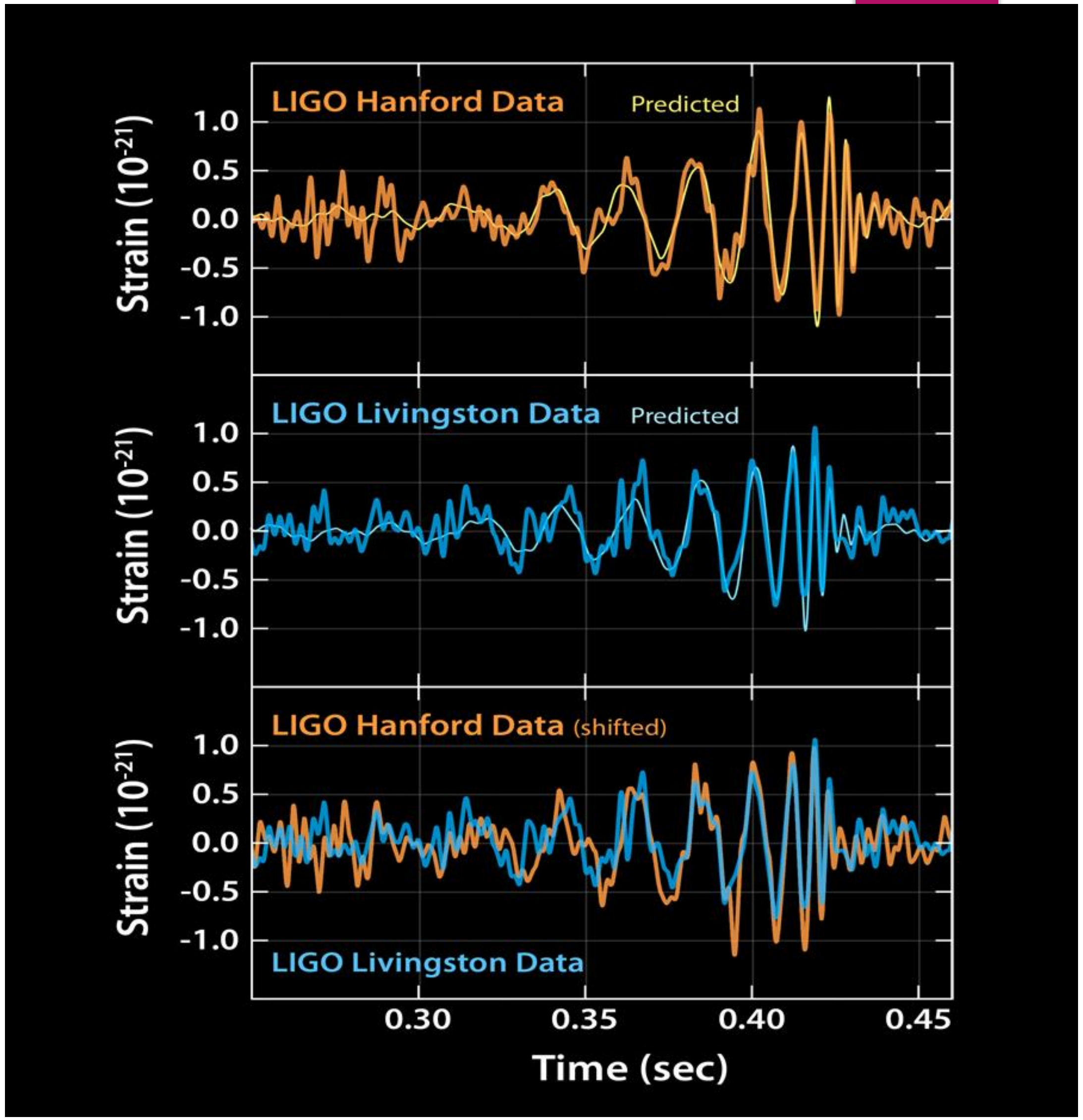
Future of PSR B1913+16 (Hulse-Taylor Binary)

Can we detect the GW from 1913+16 today ?

- Orbital period of 8h corresponds to a GW frequency $f_{GW} \sim 10^{-4}$ Hz
- Interferometers on the Earth can not be sensitive enough due to seismic noise.
- However, due to gravitational radiation reaction, the binary spirals-in with increasing velocity and frequency (and also increasing amplitude due to the stronger gravitational field).
- In 300 million years the GW frequency rises to $f_{GW} \sim 10$ Hz and fifteen minutes later to $f_{GW} \sim 1000$ Hz leading to 16,000 cycles in the last three minutes before coalescence.
- All this brings the system in the sensitivity bandwidths of Earth-bound detectors. The orbital eccentricity would reduce from $e = 0.617$ to $e \to 0$.




Colliding and Wobbling Black Holes
Gravitational wave
t = 0.00 (seconds)
t (seconds)
x (km)
y (km)
z (km)
Caltech


LIGO Hanford Data
Predicted
LIGO Livingston Data
Predicted
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10^{-21})
Time (sec)

GW 150914

Brief Summary of Detection Capabilities of Mature LIGO Interferometers

• **Inspiral of NS/NS, NS/BH and BH/BH Binaries:** The table below [15] shows estimated rates $\mathcal{R}_{\rm gal}$ in our galaxy (with masses $\sim 1.4 M_\odot$ for NS and $\sim 10 M_\odot$ for BH), the distances $\mathcal{D}_{\rm I}$ and $\mathcal{D}_{\rm WB}$ to which initial IFOs and mature WB IFOs can detect them, and corresponding estimates of detection rates $\mathcal{R}_{\rm I}$ and $\mathcal{R}_{\rm WB}$; Secs. 1.1 and 1.2.

		NS/NS	NS/BH	BH/BH in field	BH/BH in globulars
	$\mathcal{R}_{\rm gal}$, yr^{-1}	10^{-6}–10^{-4}	$\lesssim 10^{-7}$–10^{-4}	$\lesssim 10^{-7}$–10^{-5}	10^{-6}–10^{-5}
	$D_{\rm I}$	20 Mpc	43 Mpc	100	100
LIGO-1	$\mathcal{R}_{\rm I}$, yr^{-1}	$1 \times 10^{-4} - 0.03$	$\lesssim 1 \times 10^{-4} - 0.3$	$\lesssim 3 \times 10^{-3} - 0.5$	$0.03 - 0.5$
	$D_{\rm WB}$	300 Mpc	650 Mpc	$z = 0.4$	$z = 0.4$
LIGO-2	$\mathcal{R}_{\rm WB}$, yr^{-1}	$0.5 - 100$	$\lesssim 0.5 - 1000$	$\lesssim 10 - 2000$	$100 - 2000$

Estimated detection rates for compact binary inspiral events

V. Kalogera (population synthesis)

A catalog of 171 high-quality binary black-hole simulations for gravitational-wave astronomy

[arXiv: 1304.6077]

Abdul H. Mroué,[1] Mark A. Scheel,[2] Béla Szilágyi,[2] Harald P. Pfeiffer,[1] Michael Boyle,[3] Daniel A. Hemberger,[3] Lawrence E. Kidder,[3] Geoffrey Lovelace,[4,2] Sergei Ossokine,[1,5] Nicholas W. Taylor,[2] Anıl Zenginoğlu,[2] Luisa T. Buchman,[2] Tony Chu,[1] Evan Foley,[4] Matthew Giesler,[4] Robert Owen,[6] and Saul A. Teukolsky[3]

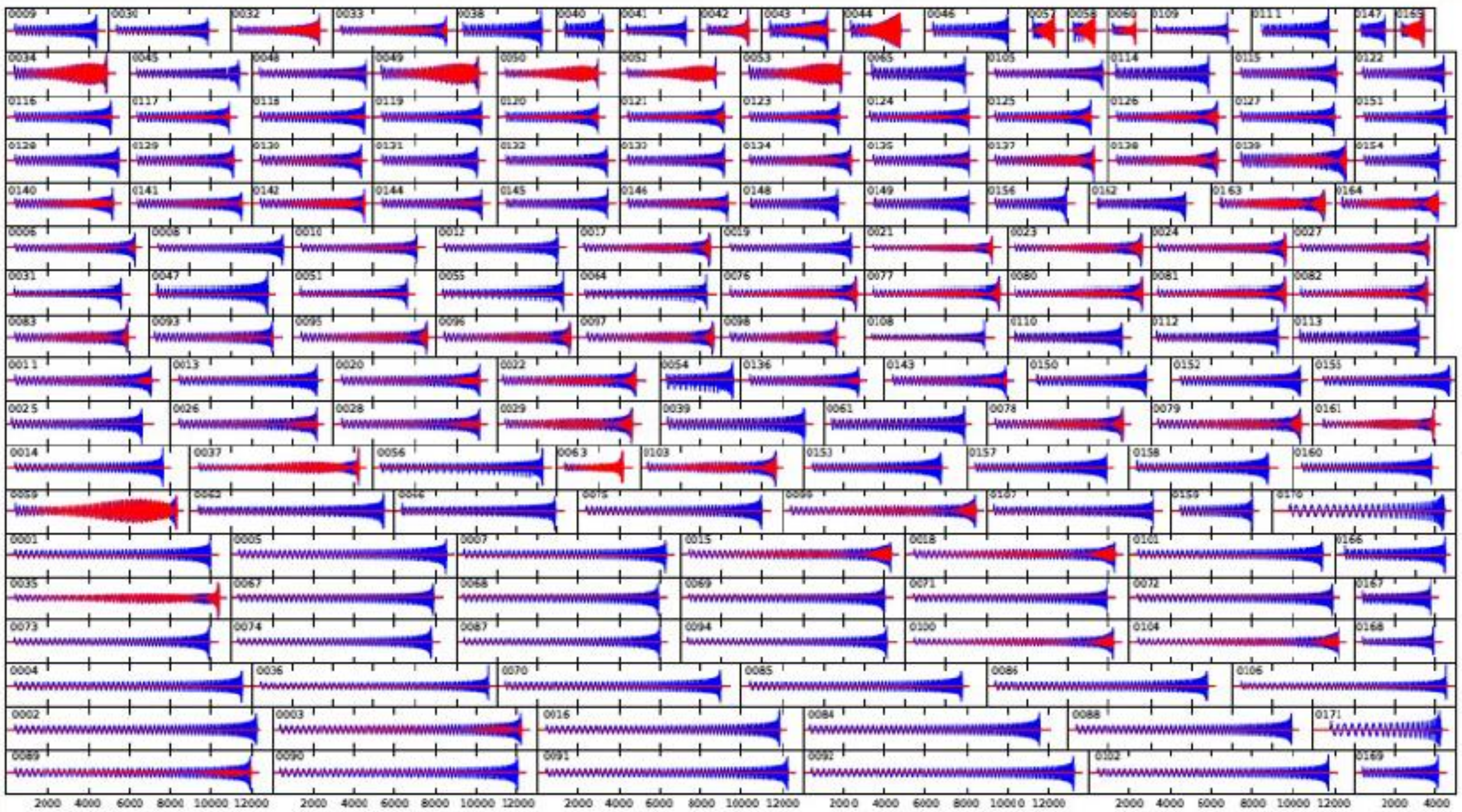
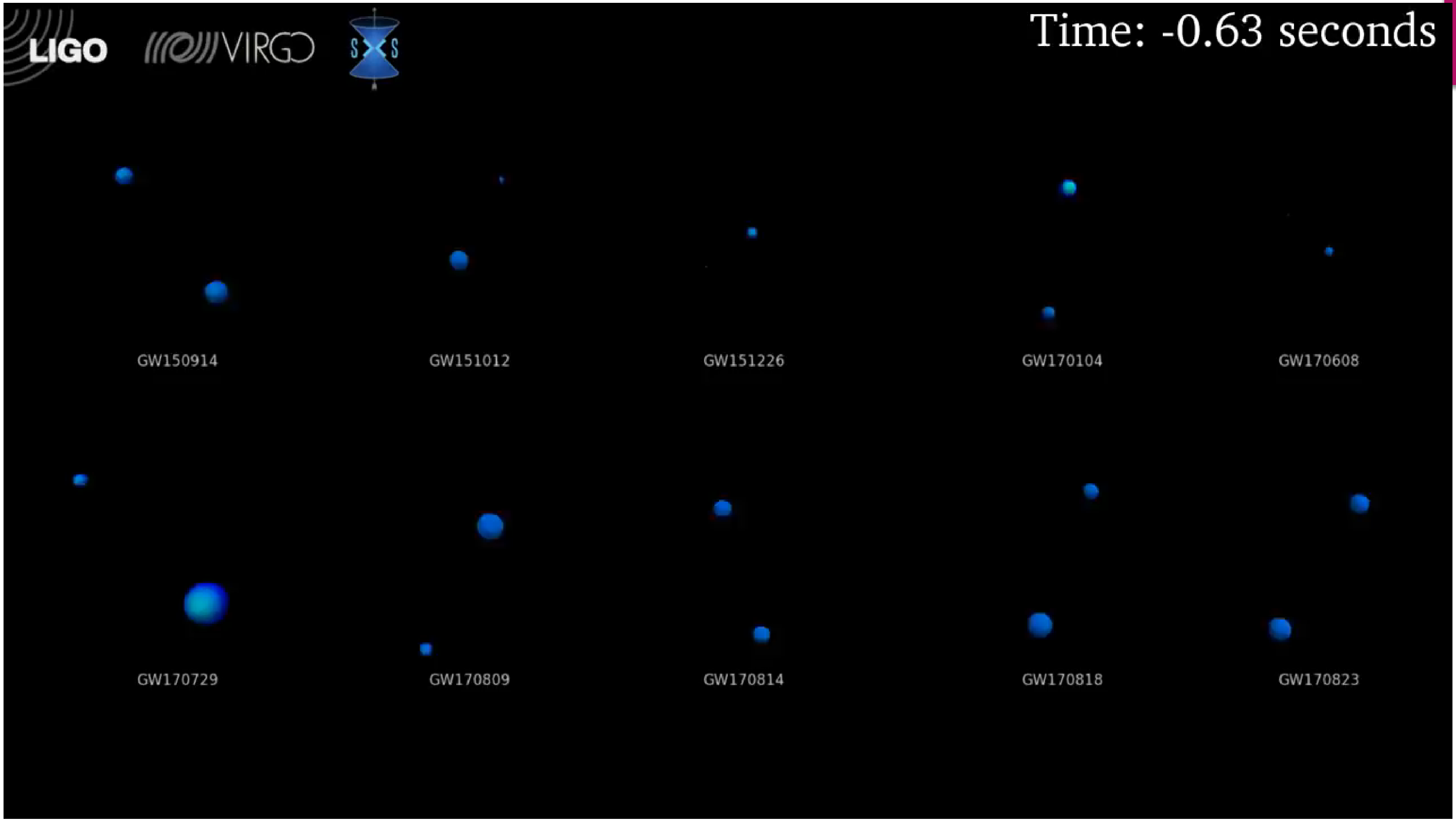


FIG. 3: Waveforms from all simulations in the catalog. Shown here are h_+ (blue) and h_x (red) in a sky direction parallel to the initial orbital plane of each simulation. All plots have the same horizontal scale, with each tick representing a time interval of $2000M$, where M is the total mass.


LIGO
VIRGO
SXS
Time: -0.63 seconds
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823

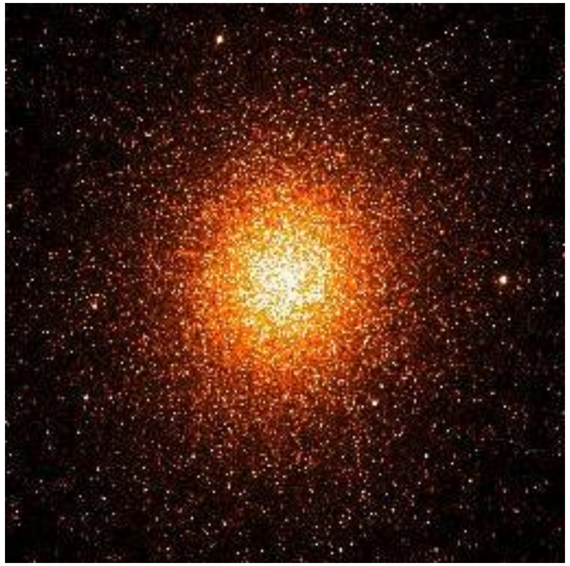
How Improbable are Stellar Collisions?

Most fascinating aspects

1. Most of the matter involved doesn't collide with anything.

2. Most of the mass in a typical galaxy consists of collisionless dark matter. Thus, dark matter from the companion galaxy passes through that of the target with no effects except for those due to their collective gravitational forces.

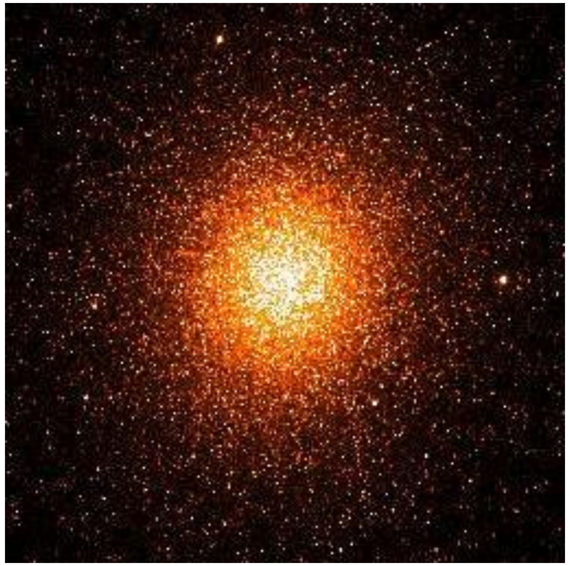
3. There is only a very small probability for direct star-star collisions.



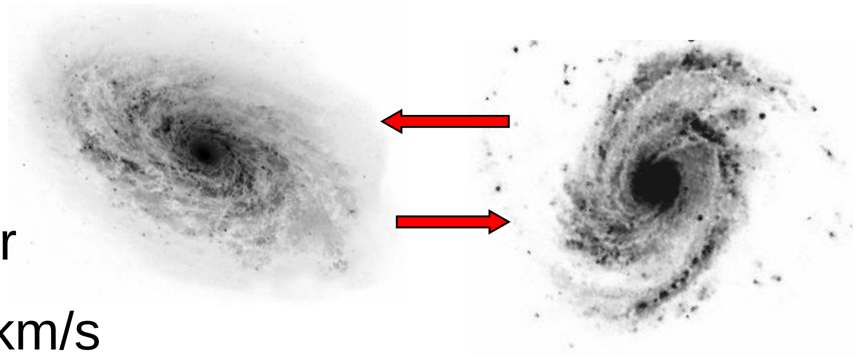
How Improbable are Stellar Collisions?

Most fascinating aspects

1. The cross section of a star like the Sun is about 10^{17} m^2,while the surface density of stars near the Sun is of order 10 per light year squared (10^{-32} m^{-2}).
2. This implies that the collision probability is of order 10^{-15} for a typical star.
3. The stellar density is much greater in the centers of galaxies, but the basic point is not changed.



What happens when galaxies merge

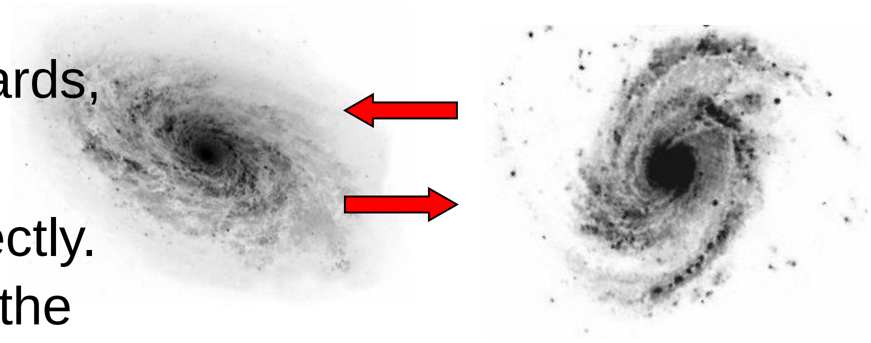


1. Galaxy collisions involve a tremendous amount of energy.

2. Two objects with masses of the order of 10^{12} solar masses or
   2×10^{42} kg meet with typical relative velocities of about 300 km/s

3. Collision energy is of order 10^{53} J. This is energy is equivalent to about $10^{8\sim9}$ supernovae, e.g., a number of supernovae that ultimately can be produced in the merger of the two galaxies

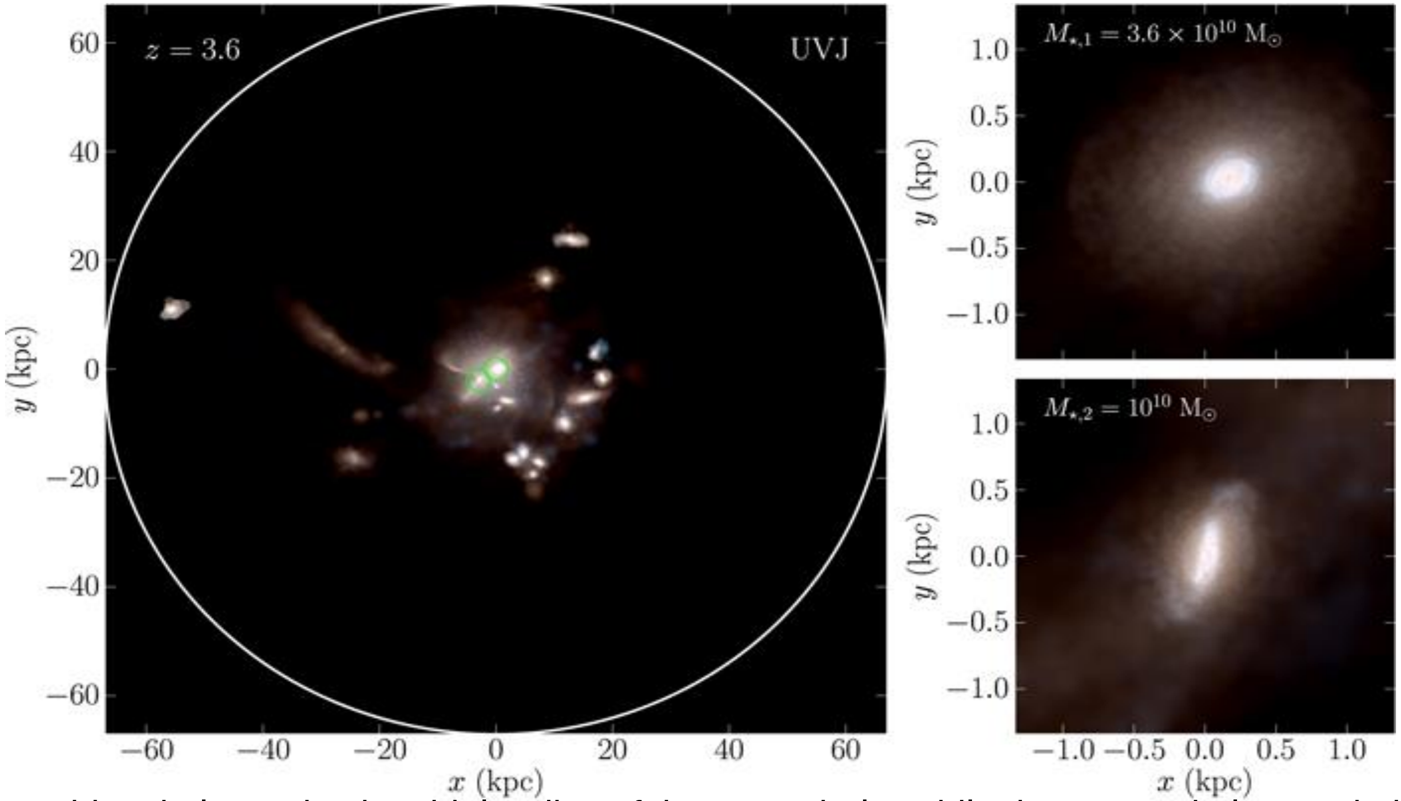
The Problem for GWs Detection



1. Galaxy collisions are extremely slow by terrestrial standards, with typical timescales of order 3 x 10^8 yrs., or 10^{16} sec.
2. There is little hope of observing any of the dynamics directly. Moreover, these systems are caught at random times in the interaction.
3. Main reasons why it is so difficult to interpret the observations, and arrange the systems in a physical classification scheme

Swift Coalescence of Supermassive Black Holes in Cosmological Mergers of Massive Galaxies

The merger of two massive galaxies at Z~ 3.5



The white circle marks the virial radius of the group halo, while the green circles mark the merging galaxies. The upper-right and lower-right panels show a zoom-in on the central galaxy of the group and the interacting companion, respectively. Lengths are in physical coordinates.

Two disk-like galaxies in a nearly parabolic (slightly hyperbolic) orbit, with their stellar spins misaligned by ≈ 67^0

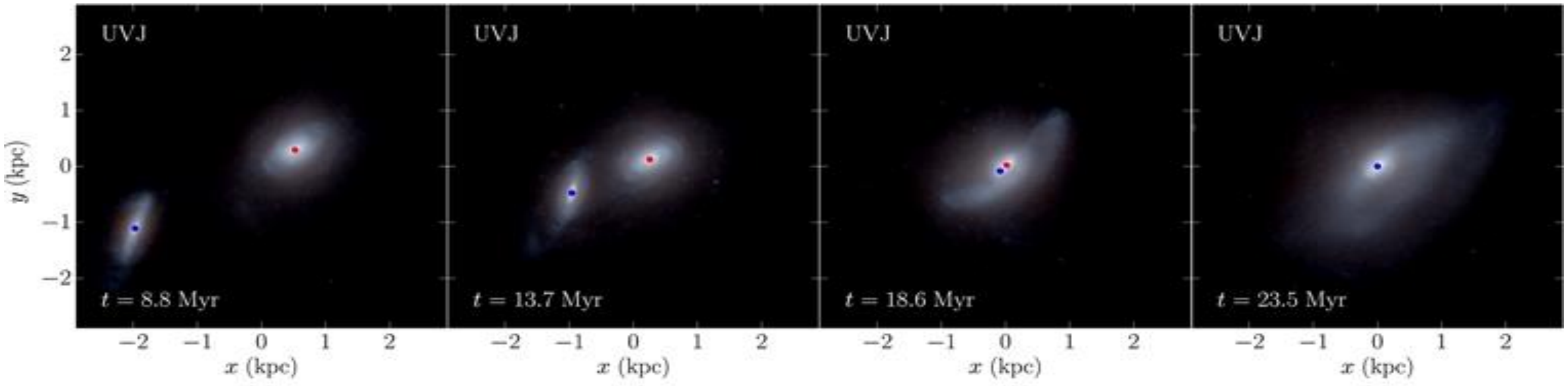
The two galaxies have stellar masses M_1 and M_2 with gas fractions f ≈7.7% and f ≈ 11.5% , respectively.

The cores of the two galaxies are at a separation of ≈ 4 kpc

Introduced two SMBHs at the local minima of the gravitational potential of the galactic cores.

Khan et al.

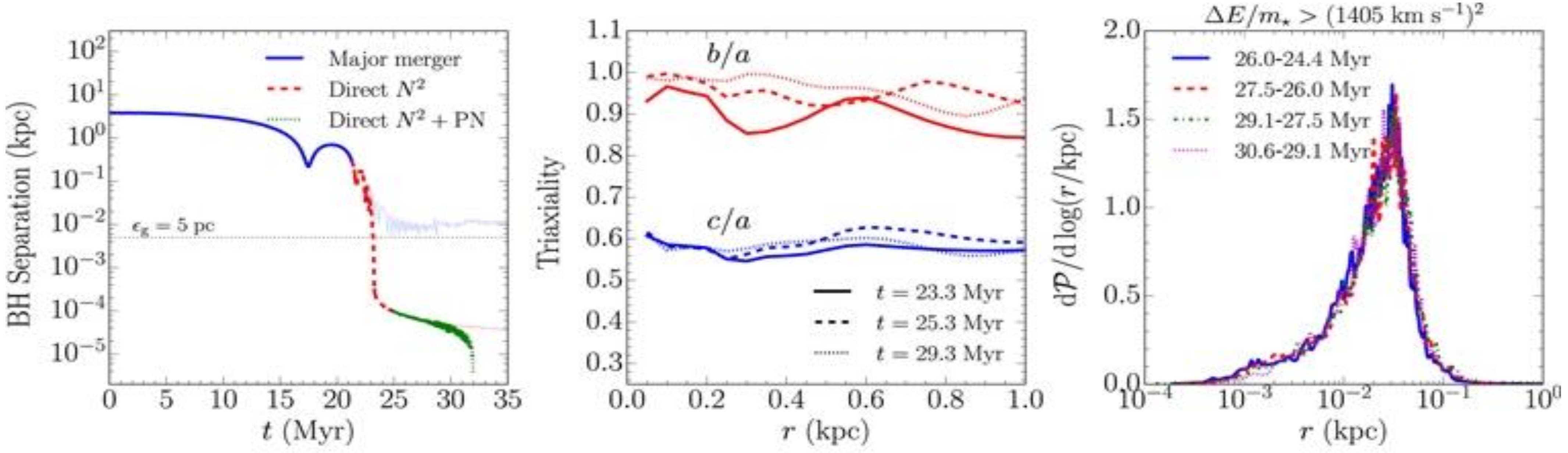
Swift Coalescence of Supermassive Black Holes in Cosmological Mergers of Massive Galaxies



From left to right: time evolution of the galaxy merger after the beginning of the resampled, higher-resolution simulation
Each panel shows a mock UVJ photometric image of the merger, and the red and blue dots mark the position of the primary and secondary BH, respectively. Lengths are in physical coordinates.

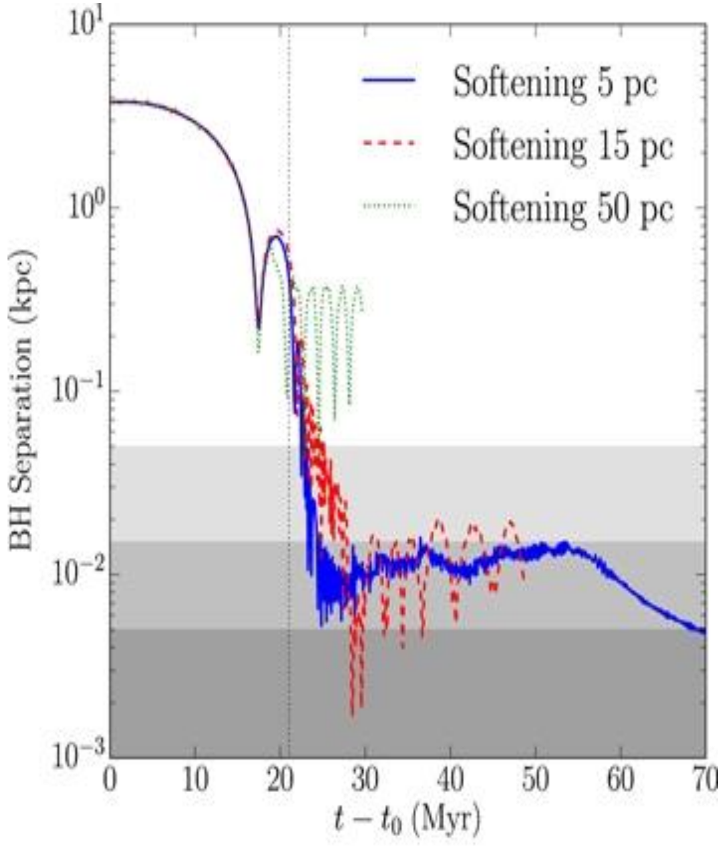
Khan et al.

Swift Coalescence of Supermassive Black Holes in Cosmological Mergers of Massive Galaxies



Left panel: time evolution of the separation between the SMBHs. Blue-solid, red-dashed, and green-dotted lines show the evolution during the hydrodynamical, re-sampled simulation of the merger, the direct N-body calculation, and after having introduced post-Newtonian corrections, respectively. Thin and light versions of the same lines refer to the continuation of the respective simulations. The horizontal dotted line marks the gravitational softening of the hydrodynamical simulation.
Center panel: radial profiles of the ratio b/a (red line) and c/a (blue line) between the principal axes of the moment of inertia tensor (c≤b≤a) at different times: 23.3 Myr (solid line), 25.3 Myr (dashed line), and 29.3 Myr (dotted line).
Right panel: probability density function of the radial distance from the center of the merger remnant for the stellar particles that have interacted with the central binary across 26–24.4 Myr (blue, solid), 27.5–26 Myr (red dashed line), 29.1–27.5 Myr (green dotted–dashed line), and 30.6–29.1 Myr (magenta dotted line).

Khan et al.



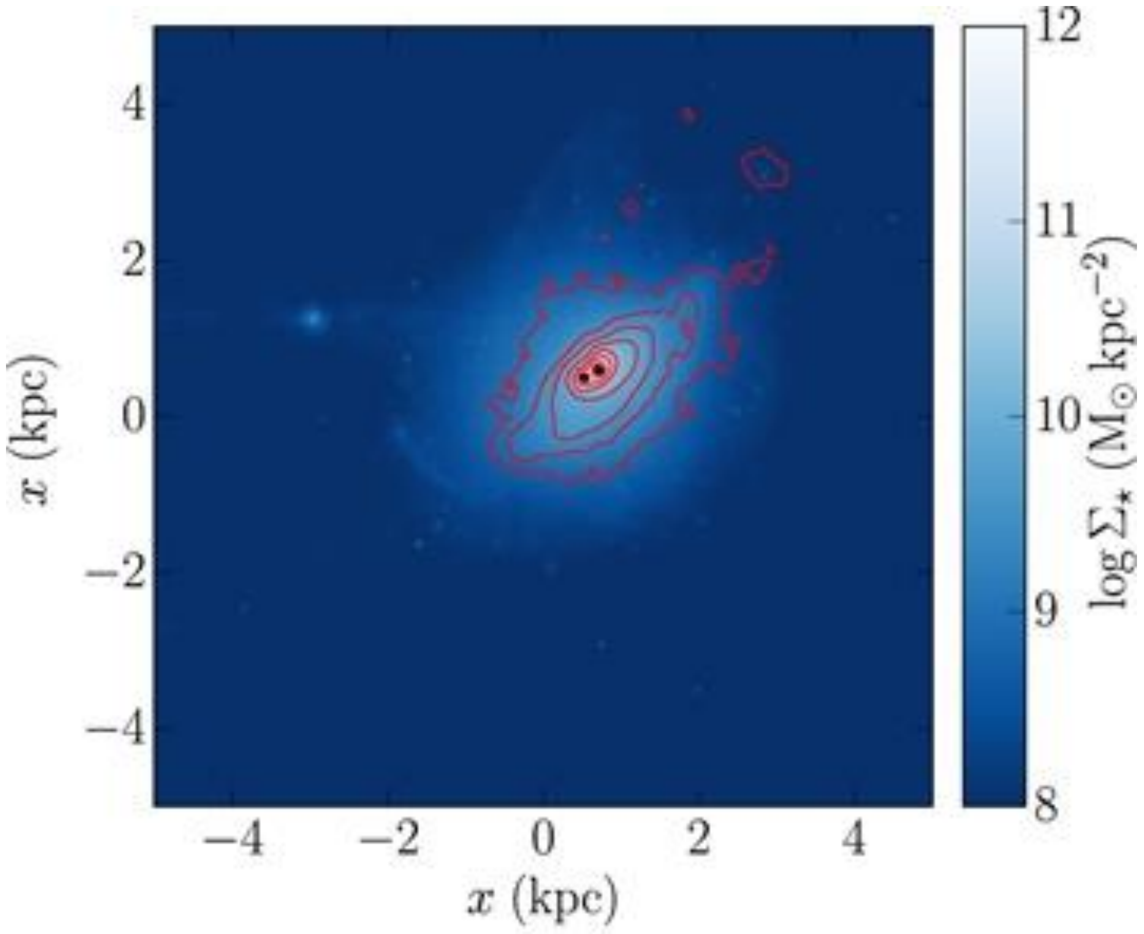
Khan et al.

Swift Coalescence of Supermassive Black Holes in Cosmological Mergers of Massive Galaxies

- Evolution with time of the separation between the two black holes at different spatial resolution in the re-sampled hydrodynamical simulations of the merger. Blue-solid, red dashed, and green dotted lines refer to softening
- ϵ = 5, 15 and 50 pc, respectively. The same separations are also marked by the gray shaded bands, while the vertical line indicates the moment at which the direct N-body simulation is initialized.

Swift Coalescence of Supermassive Black Holes in Cosmological Mergers of Massive Galaxies

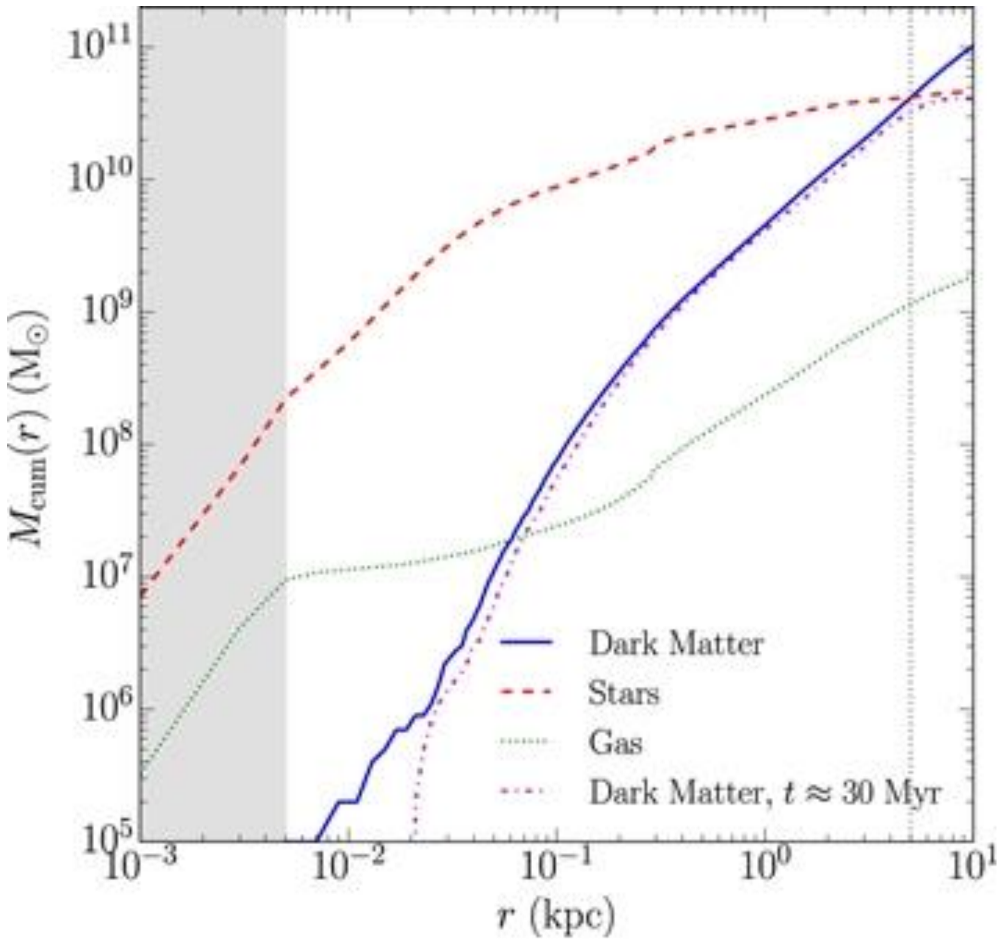
Surface density map of the stellar component at the time of the beginning of the N-body simulation. Red continuous lines represent isocontours of stars younger than ~22.5 Myr (i.e., formed from the beginning of the resampled merger simulation). The black dots denote the positions of the two black holes..



Khan et al.

Swift Coalescence of Supermassive Black Holes in Cosmological Mergers of Massive Galaxies

Mass profile of dark matter (blue continuous line), stars (red dashed line) and gas (green dotted line) at t≈ 21.5 Myr when selected the inner 5 kpc (vertical dotted line) for the direct N-body simulation. The gray area marks ϵ = 5 pc. The magenta dotted-dashed line shows the dark matter profile at t≈ 30 Myr



Khan et al.

Observable Parameters

Minkowski spacetime as $h_{\mu\nu}$, and taking the transverse-traceless (TT) gauge, the spatial components of $h_{\mu\nu}^{TT}$ are given by the quadrupole formula as

$$h_{ij}^{TT} = \frac{2G}{c^4 r}\ddot{I}_{ij}(t - r/c), \quad (1)$$

where G is the gravitational constant and r is the distance from the observer to the merging galaxies. Here I_{ij} is the components of the traceless internal tensor given by

$$I_{ij} = \sum_k m^{(k)} \left(x_i^{(k)} x_j^{(k)} - \frac{1}{3}\delta_{ij} {x^{(k)}}^2 \right) \quad (2)$$

where $x_i^{(k)}$ represents the position of k-th particle. Later we will set the initial separation of two galaxies in the direction of x.

The luminosity of gravitational waves is given by

$$L_{\rm GW} = \left(\frac{dE}{dt}\right)_{\rm GW} = \frac{G}{5c^5}\sum_{ij} \dddot{I}_{ij}\dddot{I}_{ij} \quad [\mathrm{erg\ s^{-1}}]. \quad (3)$$

Merging process of two galaxies using the parallel N-body solver Gadge

TABLE I: Models used in this subsection. Column(1):model name. Column(2):total mass. Column(3):mass of halo. Column(4):mass of disk. Column(5):mass of bulge. Column(6):disk scale radius. Column(7):tidal radius.

model	$M_{\rm tot}$ (10^{10} $M_\odot$)	$M_{\rm h}$	$M_{\rm d}$	$M_{\rm b}$	$r_{\rm d}$ (kpc)	$r_{\rm t}$ (kpc)
model-0	31.1	26.5	3.9	0.7	4.5	56.5
model-A	31.9	25.0	4.4	2.2	4.5	98.9
model-D	195.6	188.9	4.5	2.2	4.5	330.7

T. Inagaki et. al.

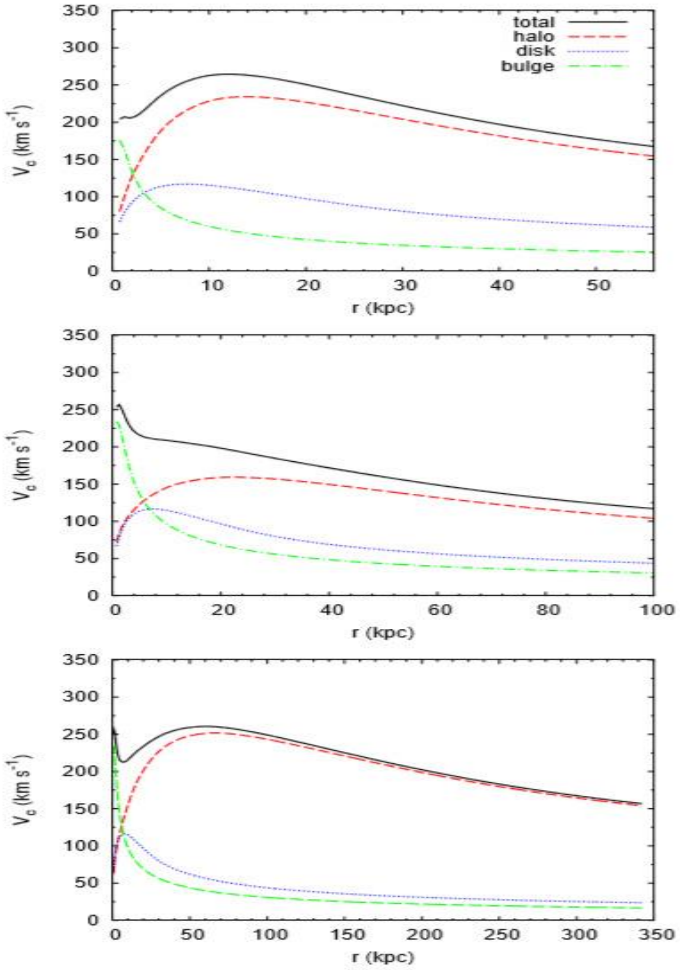


FIG. 1: Rotation curve, $V_c(r) = \sqrt{GM(r)/r}$, for halo+disk+bulge (solid), halo (dashed), disk (dotted), and bulge (dash-dotted) for a range from galactic center to r_t. Top: model-0. Middle: model-A. Bottom: model-D.

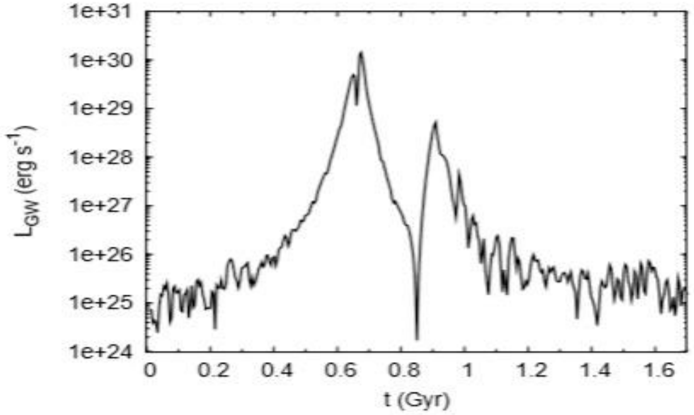


FIG. 2: Time evolution of luminosity of gravitational waves for model-0.

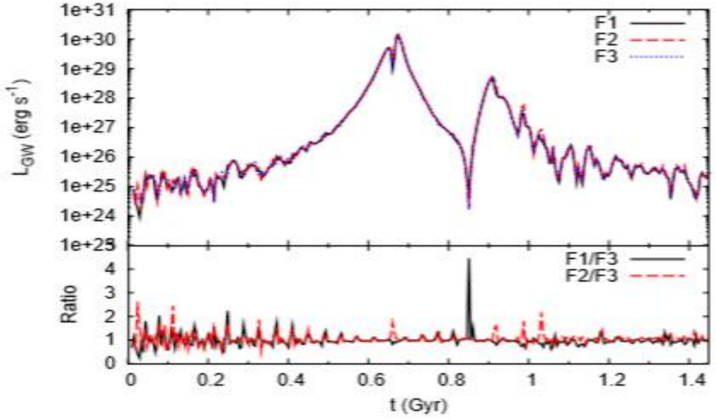


FIG. 3: Top: comparison of gravitational wave luminosities calculated with three different approaches for model-0. See text for detail. Bottom: ratios of luminosity, F1/F3 and F2/F3.

T. Inagaki et. al.

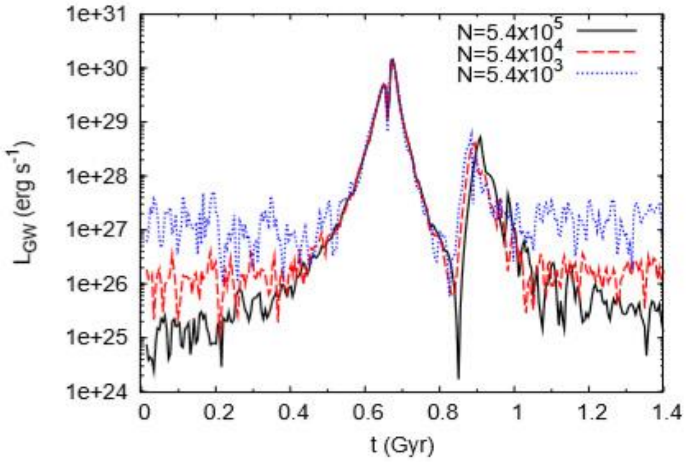


FIG. 4: Dependence on particle number (5.4×10^5: solid, 5.4×10^4: dashed, 5.4×10^3: dotted). Other parameters are the same as the model-0.

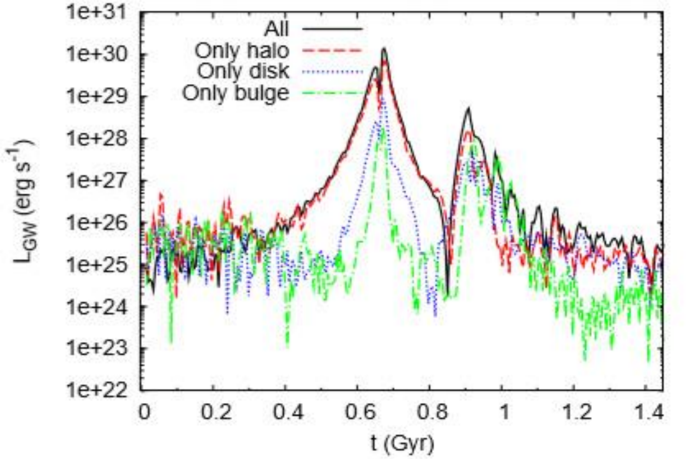


FIG. 5: Time evolution of luminosity of gravitational waves for model-0 with contribution from halo (dashed), disk (dotted), bulge (dash-dotted) only. Total luminosity is also shown (solid).

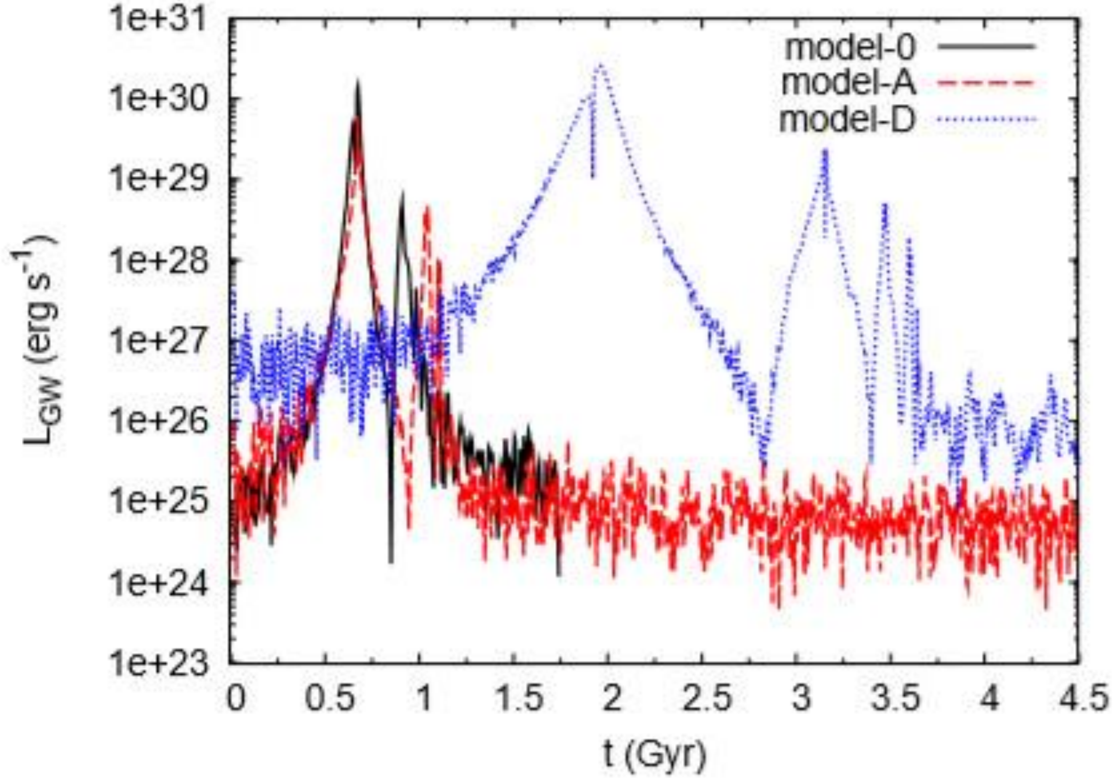


FIG. 6: Time evolution of luminosity of gravitational waves for model-0 (solid), model-A (dashed), and model-D (datted).

T. Inagaki et. al.

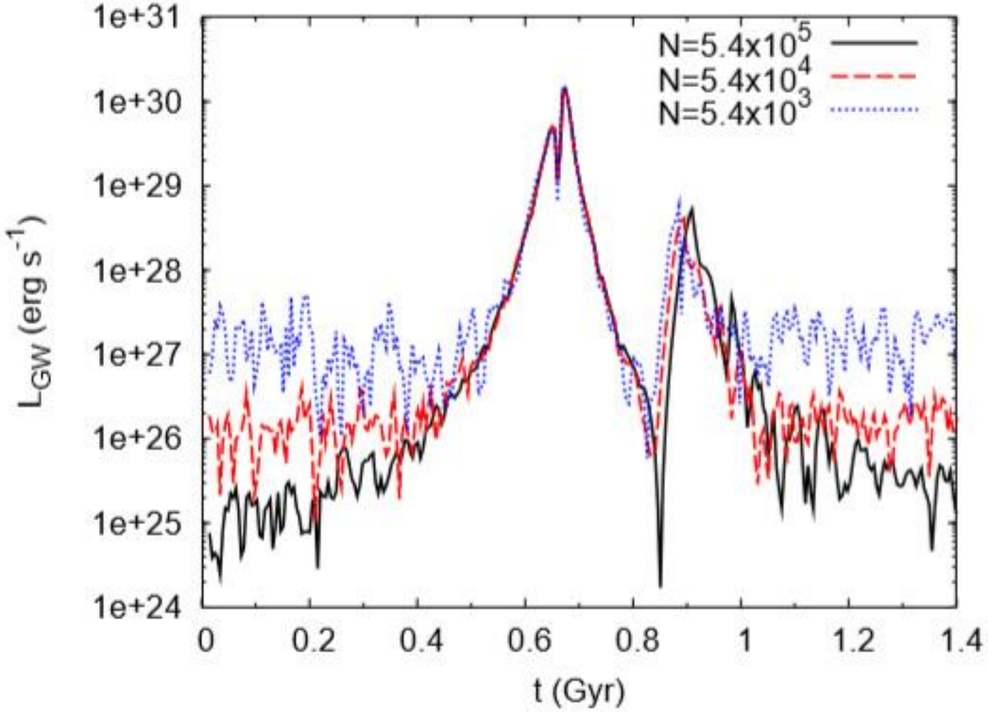


FIG. 4: Dependence on particle number (5.4×10^5: solid, 5.4×10^4: dashed, 5.4×10^3: dotted). Other parameters are the same as the model-0.

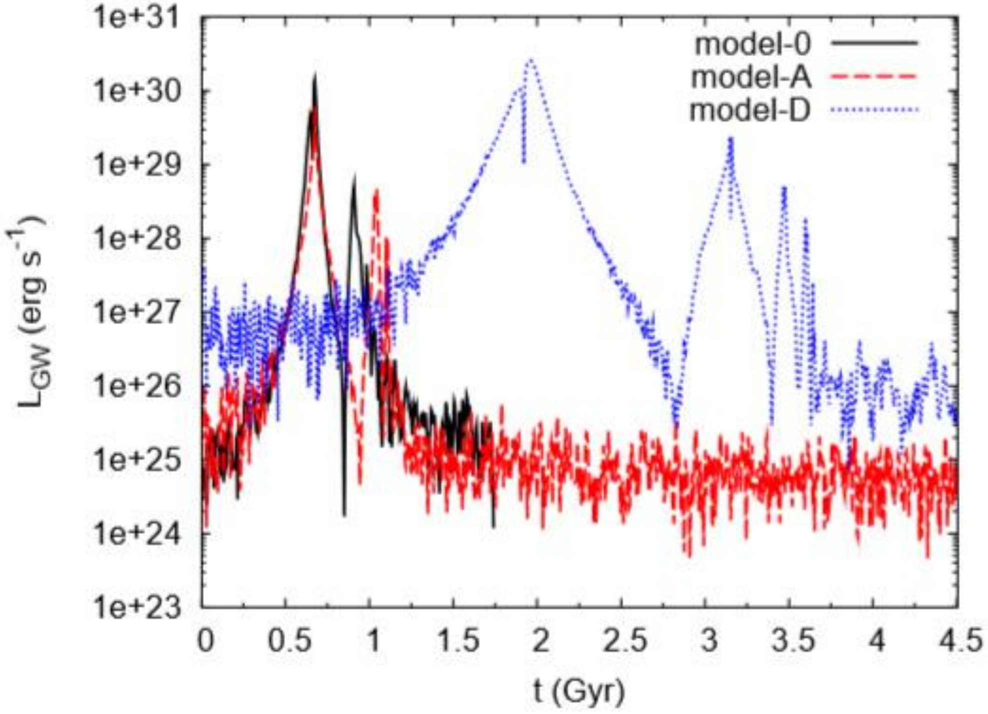


FIG. 6: Time evolution of luminosity of gravitational waves for model-0 (solid), model-A (dashed), and model-D (datted).

T. Inagaki et. al.

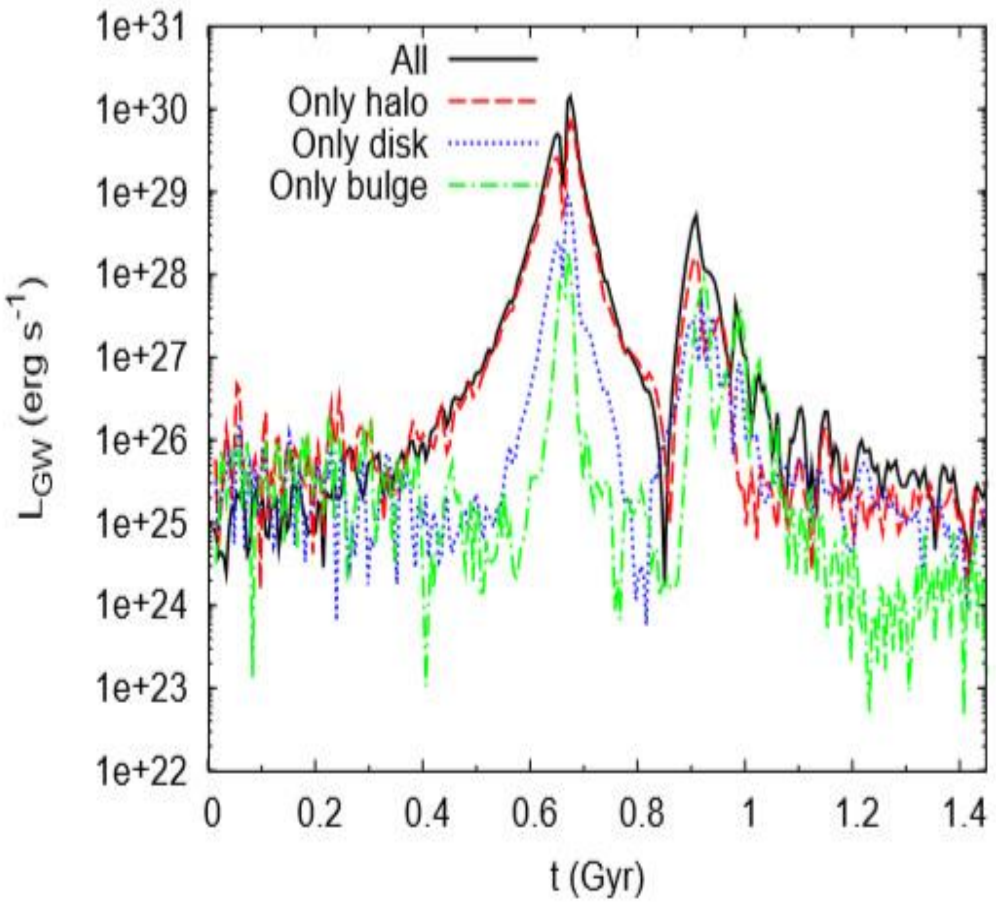


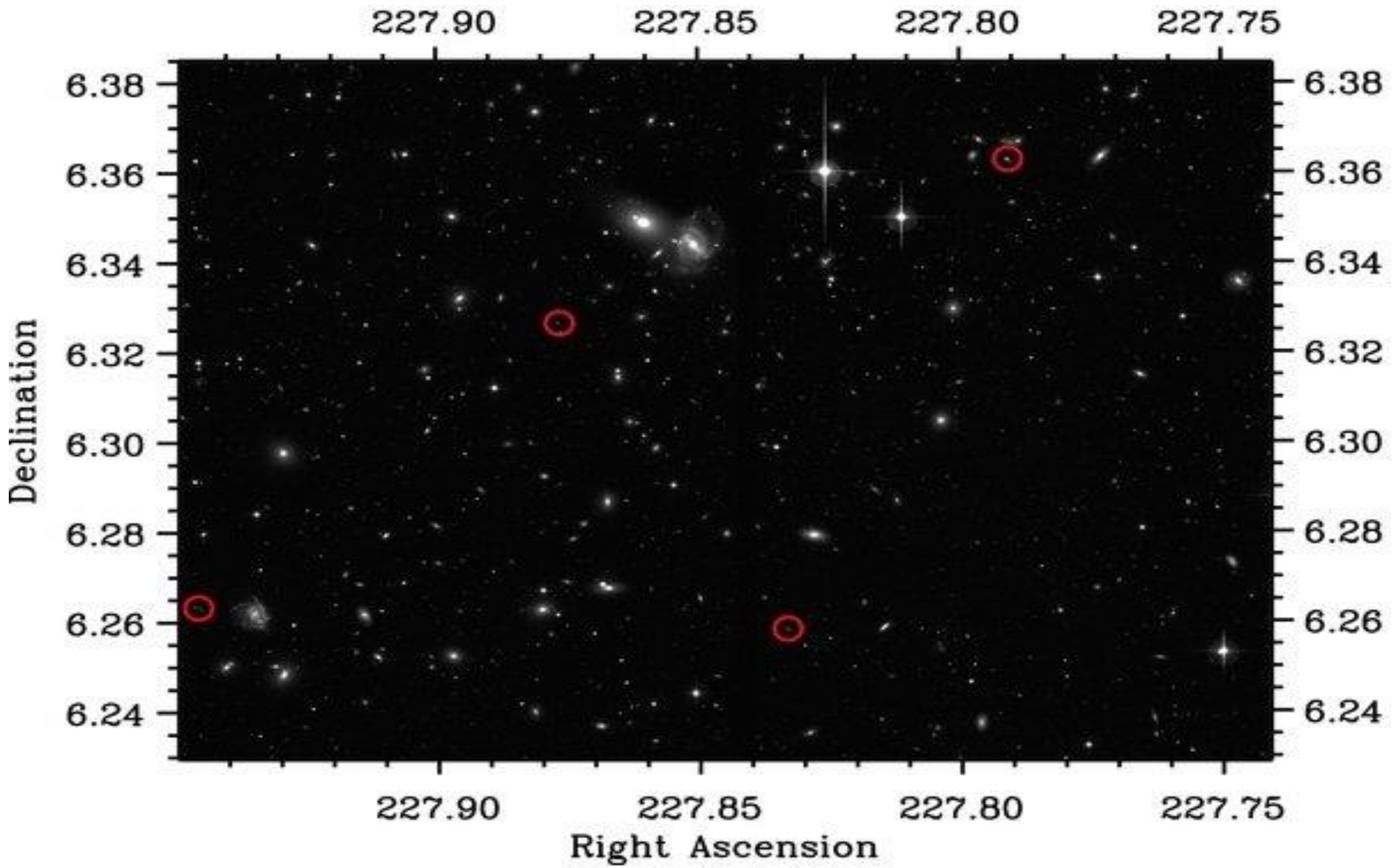
FIG. 5: Time evolution of luminosity of gravitational waves for model-0 with contribution from halo (dashed), disk (dotted), bulge (dash-dotted) only. Total luminosity is also shown (solid).

T. Inagaki et. al.

Scope of Gravitational Waves in Galaxy Mergers

Rajesh K Dubey, YITP, 12/02/2019

Abell Galaxy Cluster with 4 merging Galaxies



Center region of the galaxy cluster Abell 2033. The size of the image is ~0.2 × 0.15 deg^2. There are four merging galaxies detected in this region.

Chorng-Yuan Hwang and Ming-Yan Chang 2009 ApJS

39 Multi-mergers Systems

Table 1. Catalogue of multimergers. 'SDSS Objid' is the unique label for the primary object (chosen by Galaxy Zoo) for each system. 'Type' describes whether the multimerger is major, middle or minor (see text for definition). M_1, M_2, etc. give the stellar mass estimates of the galaxies (to 1DP) in descending order for the system, given in terms of log $M^*(M_\odot)$. Galaxies marked '*' are part of a *major* triple merger ($M_1/M_2 < 3$ and $M_2/M_3 < 3$) *and* are bright enough to be in the volume-limited analysis ($M_r < -20.55$) thereby contributing to the major triple-merger fraction (see Section 4).

	Type	SDSS Objid	Stellar mass					Mass ratio	
			M_1	M_2	M_3	M_4	M_5	M_1/M_2	M_2/M_3
1	Minor	587725491062571042	11.6	10.7	9.94			8.06	5.94
2	Major	587725816951865440	11.6*	11.5*	11.0*			1.20	2.65
3	Major	587726014546772187	11.7*	11.6*	11.5*	11.0		1.26	1.51
4	Minor	587726016157384716	11.0	10.4	10.3			4.21	1.10
5	Major	587726033303765102	11.7*	11.4*	10.9*			1.98	2.88
6	Middle	587726033846009923	11.7	11.4	10.5			2.17	7.38
7	Minor	587727865644974418	11.3	10.7	10.1			3.51	3.99
8	Minor	587729385547038748	12.0	11.1	10.9	10.2		7.56	1.58
9	Minor	587729772070633570	11.6	10.6	10.5			8.96	1.44
10	Minor	587731511544905794	11.9	10.9	!			8.42	NA
11	Major	587732050018107546	11.1*	10.7	10.6*			2.66	1.08
12	Major	587732483809345720	11.5*	11.4*	11.2*			1.31	1.84
13	Minor	587732483811770549	11.7	10.7	10.6	9.99		10.4	1.23
14	Minor	587733081346605098	10.9	10.0	9.18			8.47	6.71
15	Major	587734303805604056	11.7*	11.4*	11.3*			2.01	1.36
16	Minor	587735696979656747	10.7	10.2	9.62			3.18	4.58
17	Minor	587736477053681696	11.5	10.7	10.4			6.79	2.00
18	Major	587736807771078935	11.7*	11.3*	11.2*			2.28	1.26
19	Major	587736919972643151	11.9*	11.7*	11.2*	10.6*		1.93	2.60
20	Middle	587738952027734025	11.6	11.2	10.1			2.48	11.9
21	Major	587739096450727993	9.98	9.83	9.48			1.40	2.24
22	Middle	587739382058909818	11.5	11.2	10.5			2.14	4.57
23	Middle	587739607547904036	11.2	11.2	9.90			1.12	20.2
24	Minor	587739646203461677	11.8	10.8	10.0			9.95	6.71
25	Major	587739652645191695	10.4	10.2	10.2	9.38	8.58	1.62	1.02
26	Middle	587739811038101752	11.4	11.1	10.3			2.33	6.03
27	Minor	587739844321542224	11.4	10.8	10.8	10.6		3.62	1.03
28	Major	587742014603985009	11.3*	11.1*	11.1*			1.44	1.08
29	Middle	587742060517064897	11.9	11.4	10.9			2.59	3.16
30	Major	587742062126235884	11.1*	10.9	10.4			1.80	2.75
31	Minor	587744727686381602	11.3	10.8	10.2			3.54	3.68
32	Middle	587745244697329759	11.5	11.4	10.4			1.18	11.0
33	Major	588010359624826929	11.6*	11.3*	11.0*			2.15	2.01
34	Minor	588013382728221044	11.5	10.9	10.6			4.31	2.18
35	Middle	588013384351678489	11.1	11.0	10.3	10.0		1.14	5.60
36	Major	588016878292631762	11.4*	11.0*	10.6			2.39	2.65
37	Minor	588017705070100599	11.4	10.7	10.6			5.15	1.19
38	Major	588018090007003216	11.6*	11.3*	11.1			1.90	1.58
39	Major	588848898849439845	11.0*	10.7*	10.2*			1.74	2.98

The entry marked '!' has no photometric data and shows a rare failure of the SDSS deblending routine.

Drag D.W. et. al

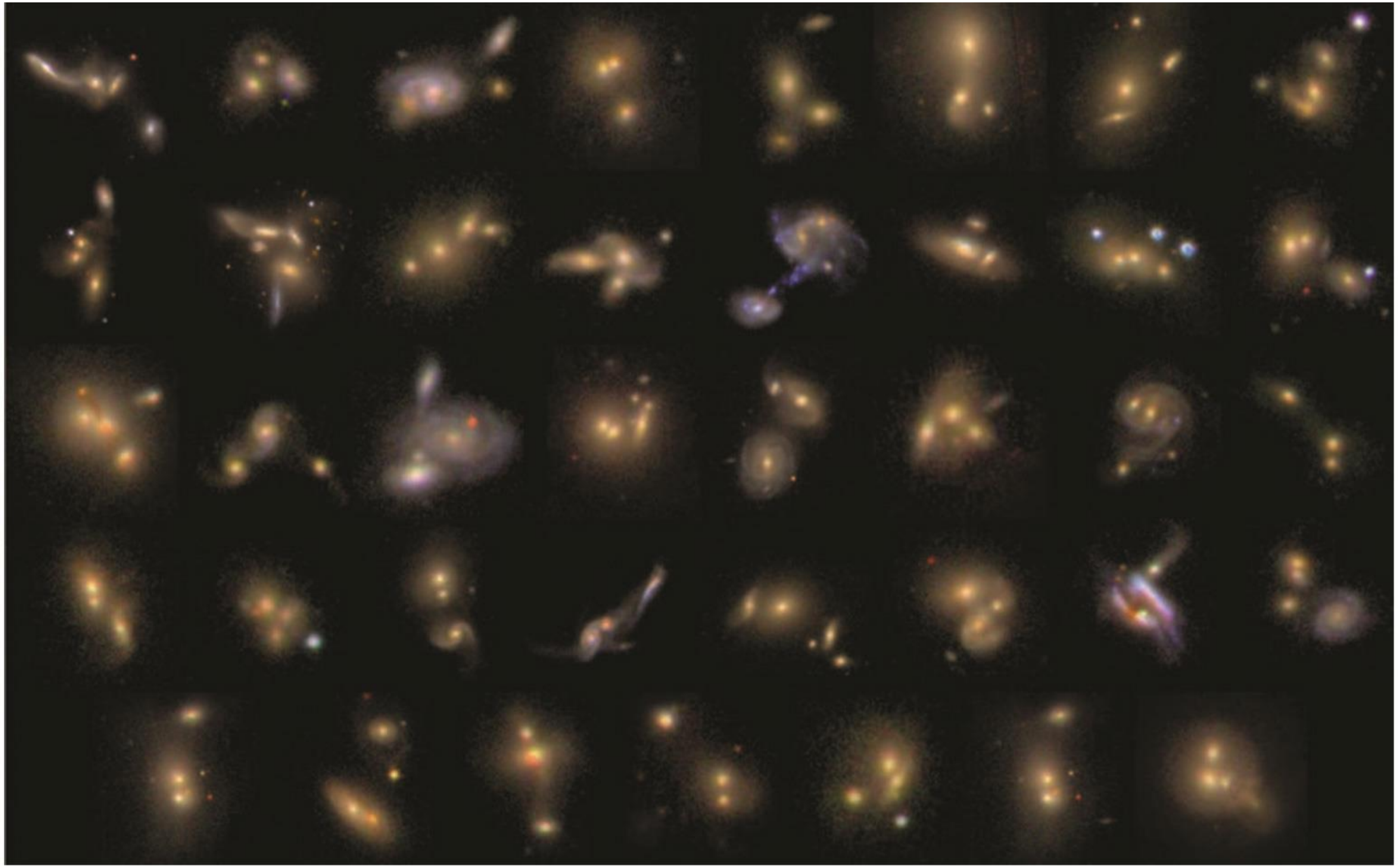


Figure 1. Images of the 39 multimerger systems obtained from GZM1. Each tile has been scaled for optimal viewing, typically with sides of ∼50 arcsec.

Drag D.W. et.al.

100 Merging Galaxies from >15,000

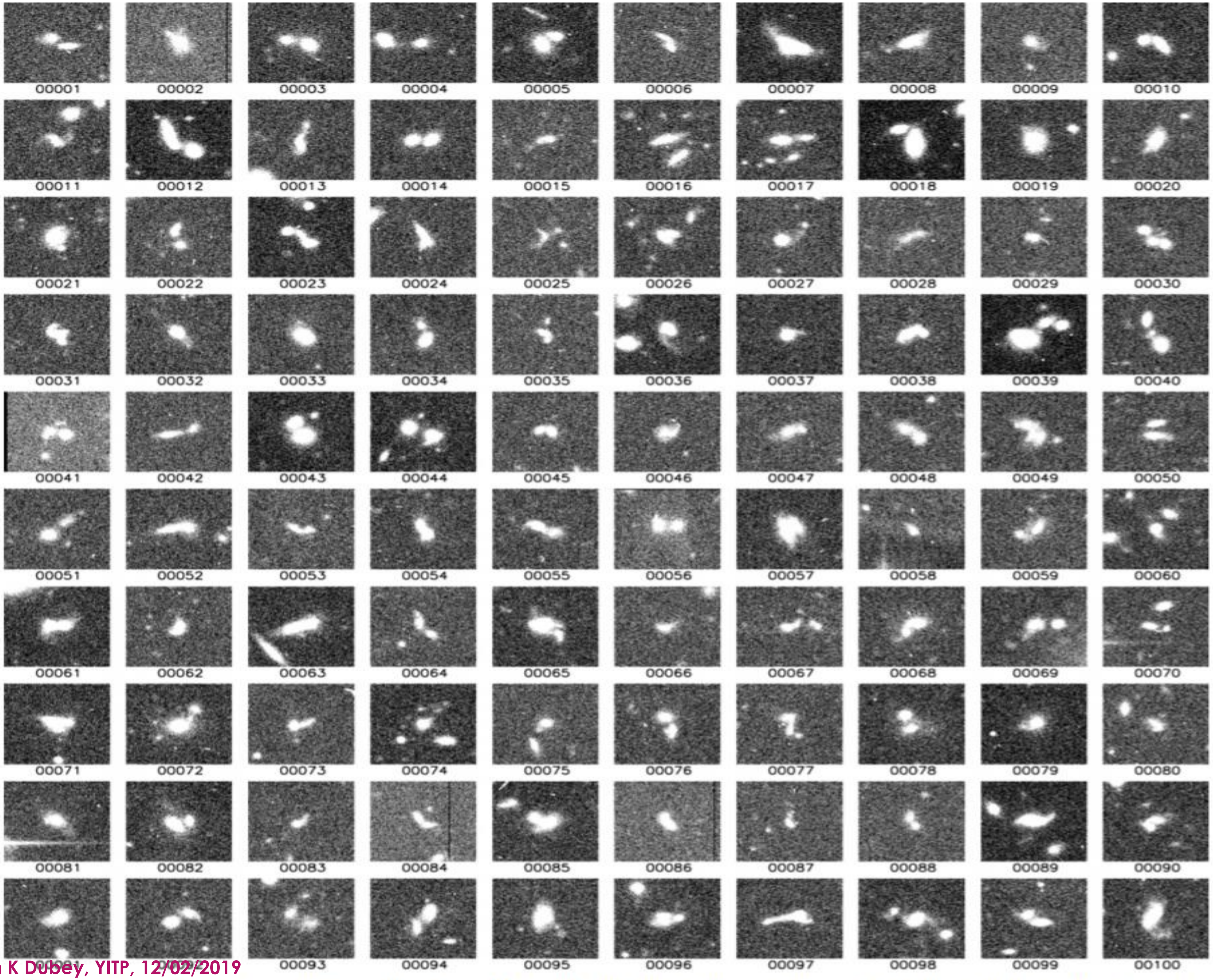
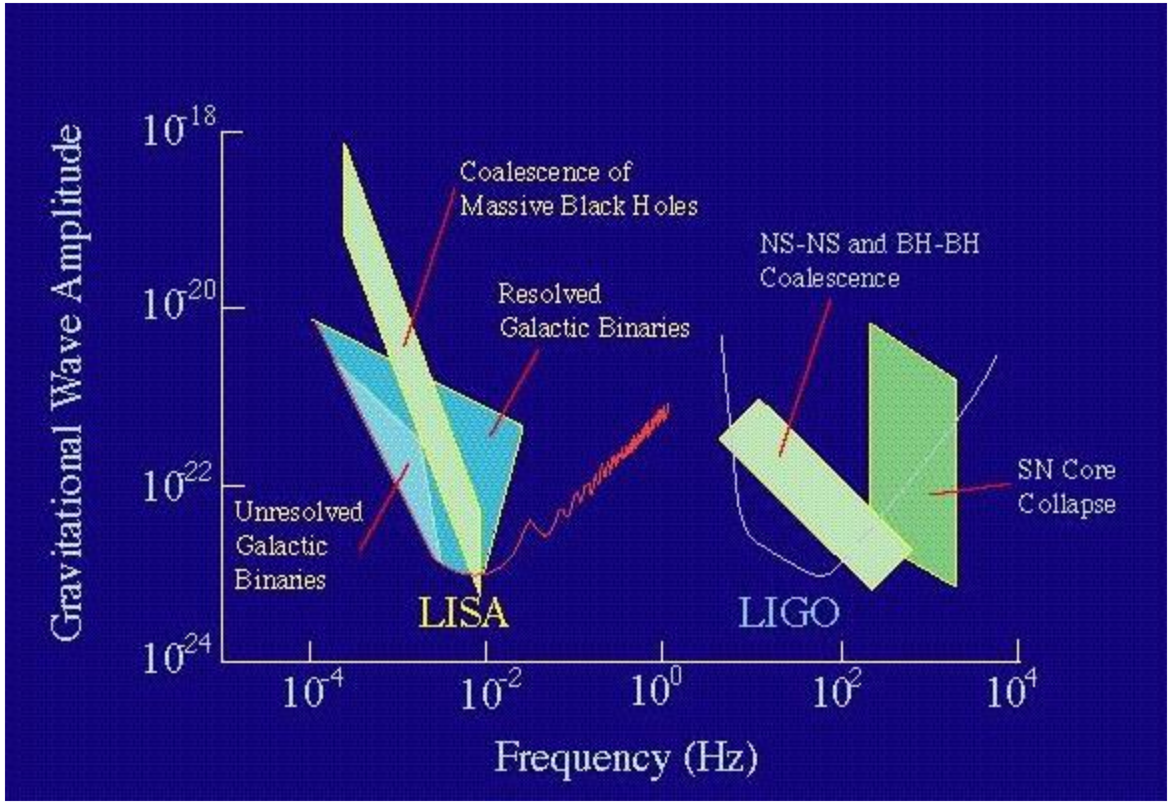


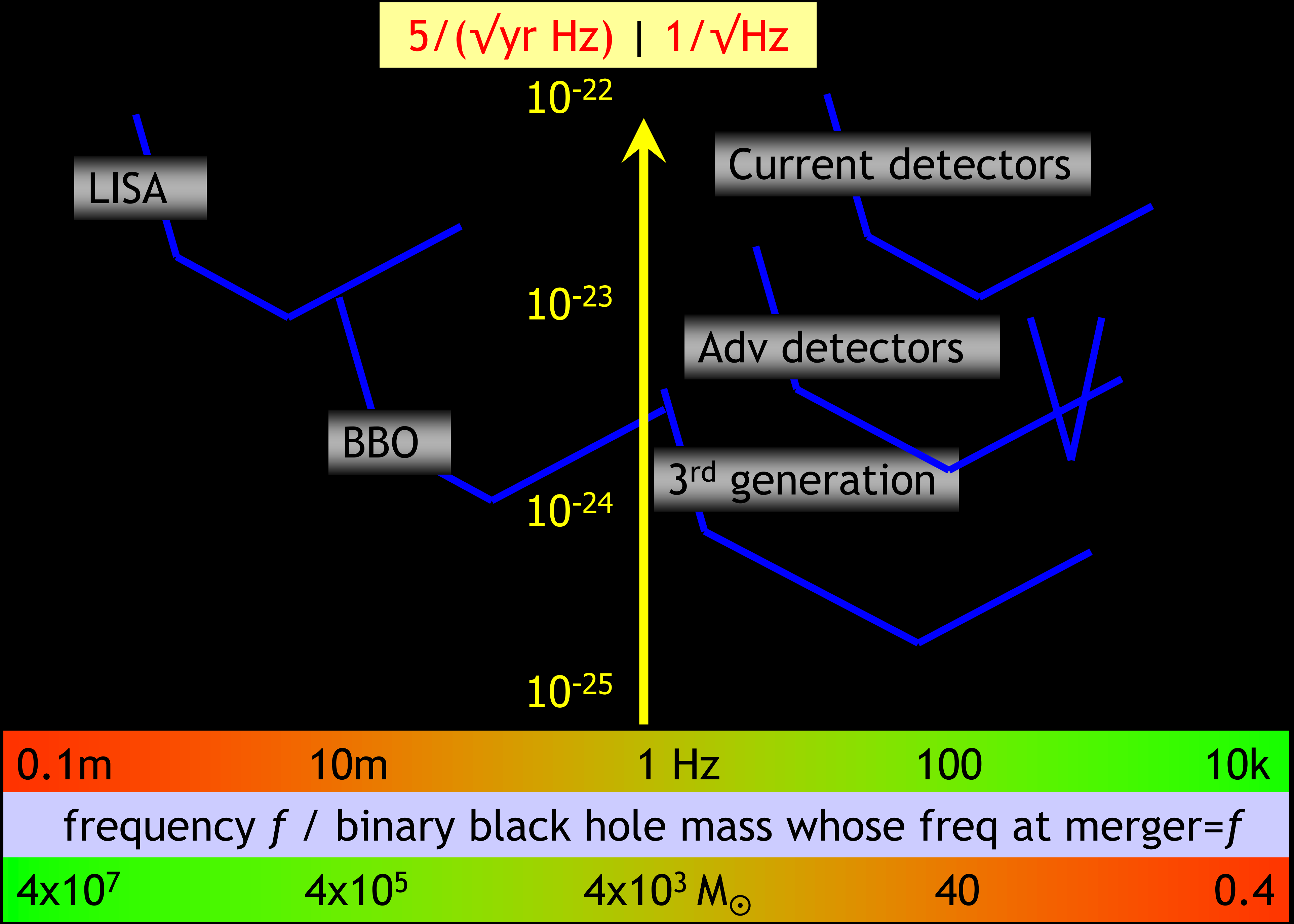
Figure 2. Examples of merging galaxy images in our catalog. From left to right and up to bottom are the merging galaxies in the catalog from id number 00001 to 00100. See the electronic edition of the Journal for the completed 15,147 images.

Hwang and Chang 2009

New eyes for physics and astronomy: opening a new window



http://www.srl.caltech.edu/lisa/graphics/master.html



5/(√yr Hz) | 1/√Hz
10-22
10-23
10-24
10-25
LISA
BBO
Current detectors
Adv detectors
3rd generation
0.1m
10m
1 Hz
100
10k
frequency f / binary black hole mass whose freq at merger=f
4x107
4x105
4x103 M⊙
40
0.4

Summary

- Experimentally, gravitational wave astronomy is about to start. The ground-based network of detectors (LIGO/Virgo/GEO/…) is being updated (ten-fold gain in sensitivity in 2015), and extended (KAGRA, LIGO-India)

- There exists a complementarity between Numerical Relativity and Analytical Relativity, especially when using the particular resummation of perturbative results defined by the Effective One Body formalism.

Every where galaxies are interacting and increasing possibilities of GWs detection by massive bodies inside them and BHs mergers

Thanks for Your Attention