MLDC: Mock (e)LISA Data Challenges.

Stas Babak (with input from J. Gair and E. Porter)

AEI, (Max-Planck-Institute für Gravitationsphysik), Golm

22 October, 2012

Outline

What are MLDCs?

- Goal #1: Demonstrate that we can meet LISA's scientific requirements
- Goal #2: Develop common framework which allows comparison of various data analysis (DA) methods
- Goal #3: Push for development and improvement of DA techniques.
- Coordinated and organized by a small group (MLDC taskforce). Software for generating the data is public (Google code).
- MLDCs were produced (roughly) once a year and increasing in complexity.
- Results are collected after the deadline and assessed: article in a refereed journal.

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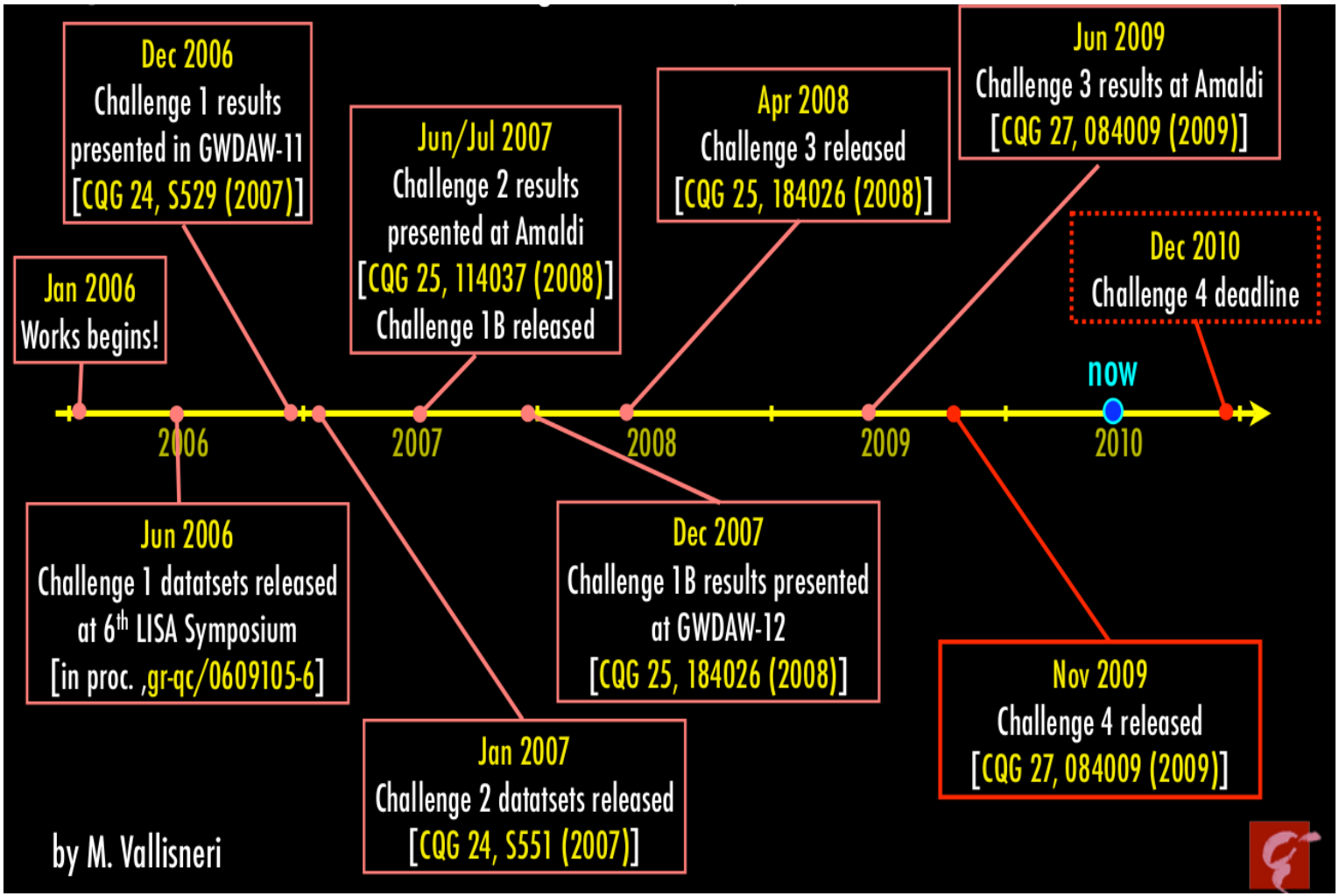
Timeline


Dec 2006
Challenge 1 results presented in GWDAW-11
[CQG 24, S529 (2007)]
Jun/Jul 2007
Challenge 2 results presented at Amaldi
[CQG 25, 114037 (2008)]
Challenge 1B released
Apr 2008
Challenge 3 released
[CQG 25, 184026 (2008)]
Jun 2009
Challenge 3 results at Amaldi
[CQG 27, 084009 (2009)]
Jan 2006
Works begins!
Dec 2010
Challenge 4 deadline
now
2006
2007
2008
2009
2010
Jun 2006
Challenge 1 datatsets released at 6th LISA Symposium
[in proc. ,gr-qc/0609105-6]
Dec 2007
Challenge 1B results presented at GWDAW-12
[CQG 25, 184026 (2008)]
Nov 2009
Challenge 4 released
[CQG 27, 084009 (2009)]
Jan 2007
Challenge 2 datatsets released
[CQG 24, S551 (2007)]
by M. Vallisneri

Participation

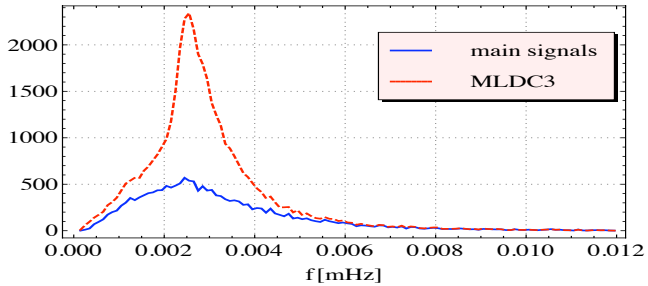
Albert-Einstein-Institut Golm
Albert-Einstein-Institut Hannover
Caltech/NASA JPL
Cardiff U.
Carleton College
Chinese Academy of Sci., Beijing
CNRS APC Paris
CNRS Nice
Indian Inst. of Tech., Kharagpur
Montana State U.
Nanjing U.
NASA Ames
NASA Goddard
Northwestern U.
Polish Academy of Sciences
Rochester Institute of Technology
U. Auckland
U. Birmingham
U. Cambridge
U. Glasgow
U. Illes Balears
U. Maryland
U. Southampton
U. Wroclaw
U. Texas Brownsville

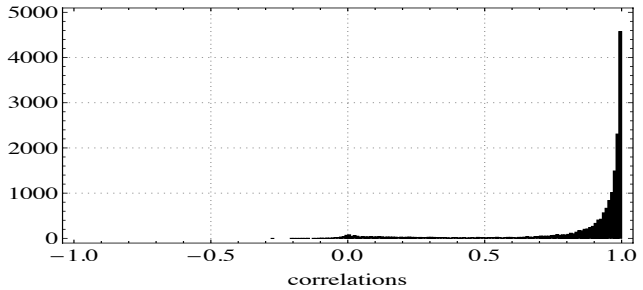
Overall:
70 participants from
25 institutions

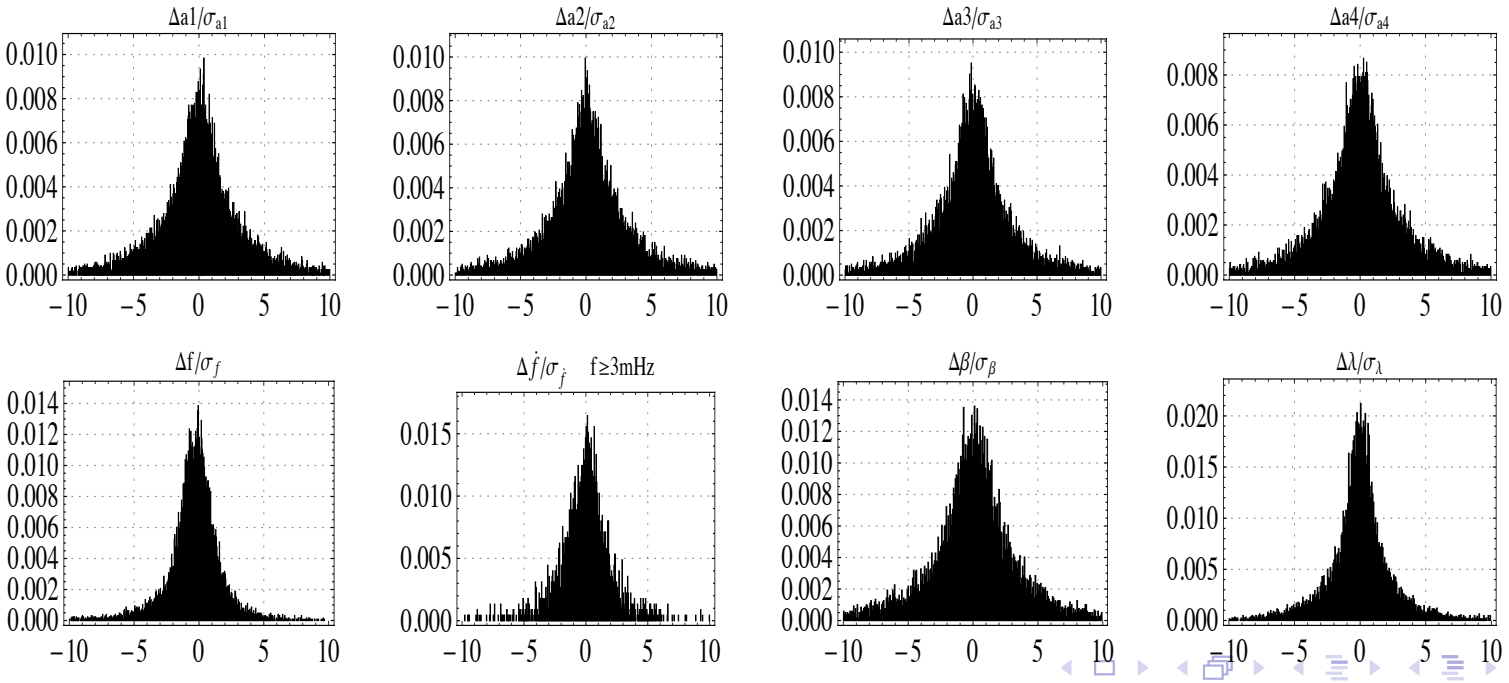
Content

	MLDC 1	MLDC 2	MLDC 1B	MLDC 3	MLDC 4
Galactic binaries	• Verification • Unknown isolated • Unknown interfering	• Galaxy $3x10^6$	• Verification • Unknown isolated • Unknown interfering	• Galaxy $6x10^7$ chirping	• Galaxy $6x10^7$ chirping
Massive BH binaries	• Isolated	• 4-6x, over "Galaxy" & EMRIs	• Isolated	• 4-6x spinning & precessing over "Galaxy"	• 4-6x spinning & precessing, extended to low-mass
EMRI		• Isolated • 4-6x, over "Galaxy" & MBHs	• Isolated	• 5 together, weaker	• 3 x Poisson(2)
Bursts				• Cosmic string cusp	• Poisson(20) cosmic string cusp
Stochastic background				• Isotropic	• Isotropic

Galactic binaries







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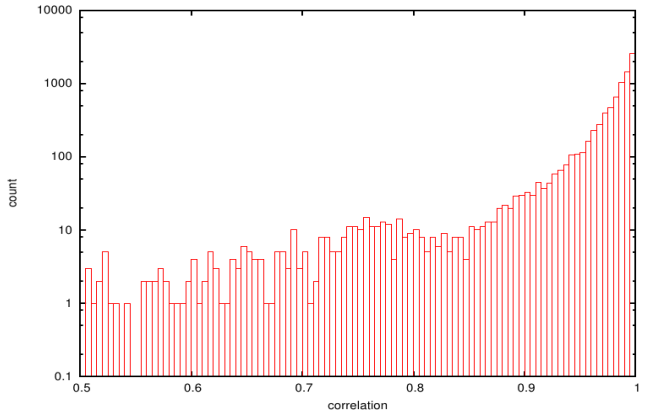

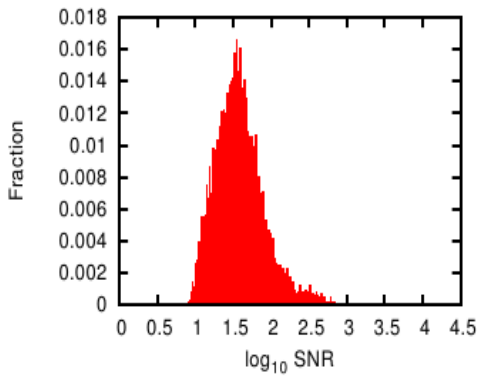

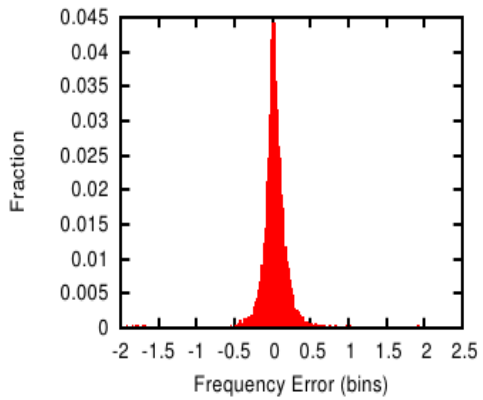

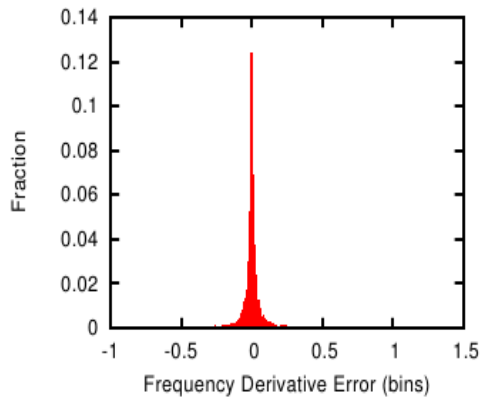

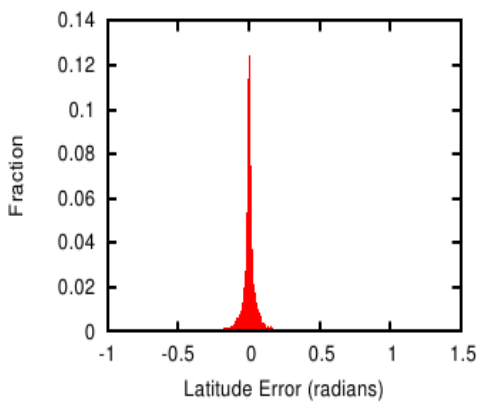

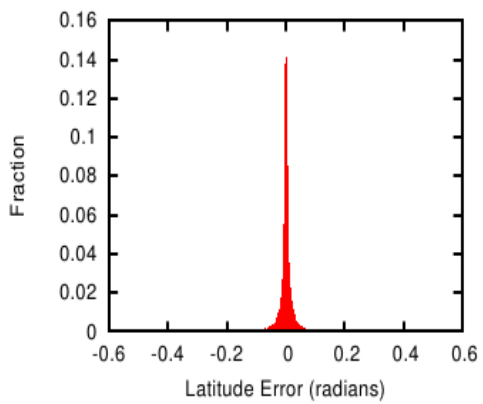

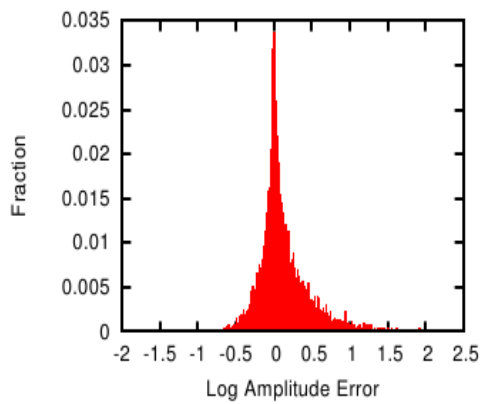

MLDC3: Spinning BBHs

source (SNR_{true})	group	$\Delta M_c/M_c$ $\times 10^{-5}$	$\Delta\eta/\eta$ $\times 10^{-4}$	Δt_c (sec)	Δsky (deg)	Δa_1 $\times 10^{-3}$	Δa_2 $\times 10^{-3}$	$\Delta D/D$ $\times 10^{-2}$	FF
MBH-1	AEI	2.4	6.1	62.9	11.6	7.6	47.4	8.0	0.9936
(1670.58)	CambAEI	3.4	40.7	24.8	2.0	8.5	79.6	0.7	0.9925
	MTAPC	24.8	41.2	619.2	171.0	13.3	28.7	4.0	0.9996
	JPL	40.5	186.6	23.0	26.9	39.4	66.1	6.9	0.9981
	GSFC	1904.0	593.2	183.9	82.5	5.7	124.3	94.9	0.1827
MBH-3	AEI	9.0	5.2	100.8	175.9	6.2	18.6	2.7	0.9995
(847.61)	CambAEI	13.5	57.4	138.9	179.0	21.3	7.2	1.5	0.9993
	MTAPC	333.0	234.1	615.7	80.2	71.6	177.2	16.1	0.9945
	JPL	153.0	51.4	356.8	11.2	187.7	414.9	2.7	0.9898
	GSFC	8168.4	2489.9	3276.9	77.9	316.3	69.9	95.6	0.2815
MBH-4	AEI	4.5	75.2	31.4	0.1	47.1	173.6	9.1	0.9994
(160.05)	CambAEI	3.2	171.9	30.7	0.2	52.9	346.1	21.6	0.9991
	MTAPC	48.6	2861.0	5.8	7.3	33.1	321.1	33.0	0.9352
	JPL	302.6	262.0	289.3	4.0	47.6	184.5	28.3	0.9925
	GSFC	831.3	1589.2	1597.6	94.4	59.8	566.7	95.4	−0.1725
MBH-2	AEI	1114.1	952.2	38160.8	171.1	331.7	409.0	15.3	0.9469
(18.95)	CambAEI	88.7	386.6	6139.7	172.4	210.8	130.7	24.4	0.9697
	MTAPC	128.6	45.8	16612.0	8.9	321.4	242.4	13.1	0.9260
	JPL	287.0	597.7	11015.7	11.8	375.3	146.3	9.9	0.9709
MBH-6	AEI	1042.3	1235.6	82343.2	2.1	258.2	191.6	26.0	0.9293
(12.82)	CambAEI	5253.2	1598.8	953108.0	158.3	350.8	215.4	29.4	0.4399
	MTAPC	56608.7	296.7	180458.8	119.7	369.2	297.6	25.1	0.0016

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MBH-6	AEI	1042.3	1235.6	82343.2	2.1	258.2	191.6	26.0	0.9293
(12.82)	CambAEI	5253.2	1598.8	953108.0	158.3	350.8	215.4	29.4	0.4399
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	MTAPC	56608.7	296.7	180458.8	119.7	369.2	297.6	25.1	0.0016

MLDC3: Spinning BBHs

source (SNR_{true})	group	$\Delta M_c/M_c$ $\times 10^{-5}$	$\Delta\eta/\eta$ $\times 10^{-4}$	Δt_c (sec)	Δsky (deg)	Δa_1 $\times 10^{-3}$	Δa_2 $\times 10^{-3}$	$\Delta D/D$ $\times 10^{-2}$	FF
MBH-1	AEI	2.4	6.1	62.9	11.6	7.6	47.4	8.0	0.9936
(1670.58)	CambAEI	3.4	40.7	24.8	2.0	8.5	79.6	0.7	0.9925
	MTAPC	24.8	41.2	619.2	171.0	13.3	28.7	4.0	0.9996
	JPL	40.5	186.6	23.0	26.9	39.4	66.1	6.9	0.9981
	GSFC	1904.0	593.2	183.9	82.5	5.7	124.3	94.9	0.1827
MBH-3	AEI	9.0	5.2	100.8	175.9	6.2	18.6	2.7	0.9995
(847.61)	CambAEI	13.5	57.4	138.9	179.0	21.3	7.2	1.5	0.9993
	MTAPC	333.0	234.1	615.7	80.2	71.6	177.2	16.1	0.9945
	JPL	153.0	51.4	356.8	11.2	187.7	414.9	2.7	0.9898
	GSFC	8168.4	2489.9	3276.9	77.9	316.3	69.9	95.6	0.2815
MBH-4	AEI	4.5	75.2	31.4	0.1	47.1	173.6	9.1	0.9994
(160.05)	CambAEI	3.2	171.9	30.7	0.2	52.9	346.1	21.6	0.9991
	MTAPC	48.6	2861.0	5.8	7.3	33.1	321.1	33.0	0.9352
	JPL	302.6	262.0	289.3	4.0	47.6	184.5	28.3	0.9925
	GSFC	831.3	1589.2	1597.6	94.4	59.8	566.7	95.4	−0.1725
MBH-2	AEI	1114.1	952.2	38160.8	171.1	331.7	409.0	15.3	0.9469
(18.95)	CambAEI	88.7	386.6	6139.7	172.4	210.8	130.7	24.4	0.9697
	MTAPC	128.6	45.8	16612.0	8.9	321.4	242.4	13.1	0.9260
	JPL	287.0	597.7	11015.7	11.8	375.3	146.3	9.9	0.9709
MBH-6	AEI	1042.3	1235.6	82343.2	2.1	258.2	191.6	26.0	0.9293
(12.82)	CambAEI	5253.2	1598.8	953108.0	158.3	350.8	215.4	29.4	0.4399
	MTAPC	56608.7	296.7	180458.8	119.7	369.2	297.6	25.1	0.0016

MLDC3: Spinning BBHs

source (SNR_{true})	group	$\Delta M_c/M_c$ $\times 10^{-5}$	$\Delta\eta/\eta$ $\times 10^{-4}$	Δt_c (sec)	Δsky (deg)	Δa_1 $\times 10^{-3}$	Δa_2 $\times 10^{-3}$	$\Delta D/D$ $\times 10^{-2}$	FF
MBH-1	AEI	2.4	6.1	62.9	11.6	7.6	47.4	8.0	0.9936
(1670.58)	CambAEI	3.4	40.7	24.8	2.0	8.5	79.6	0.7	0.9925
	MTAPC	24.8	41.2	619.2	171.0	13.3	28.7	4.0	0.9996
	JPL	40.5	186.6	23.0	26.9	39.4	66.1	6.9	0.9981
	GSFC	1904.0	593.2	183.9	82.5	5.7	124.3	94.9	0.1827
MBH-3	AEI	9.0	5.2	100.8	175.9	6.2	18.6	2.7	0.9995
(847.61)	CambAEI	13.5	57.4	138.9	179.0	21.3	7.2	1.5	0.9993
	MTAPC	333.0	234.1	615.7	80.2	71.6	177.2	16.1	0.9945
	JPL	153.0	51.4	356.8	11.2	187.7	414.9	2.7	0.9898
	GSFC	8168.4	2489.9	3276.9	77.9	316.3	69.9	95.6	0.2815
MBH-4	AEI	4.5	75.2	31.4	0.1	47.1	173.6	9.1	0.9994
(160.05)	CambAEI	3.2	171.9	30.7	0.2	52.9	346.1	21.6	0.9991
	MTAPC	48.6	2861.0	5.8	7.3	33.1	321.1	33.0	0.9352
	JPL	302.6	262.0	289.3	4.0	47.6	184.5	28.3	0.9925
	GSFC	831.3	1589.2	1597.6	94.4	59.8	566.7	95.4	−0.1725
MBH-2	AEI	1114.1	952.2	38160.8	171.1	331.7	409.0	15.3	0.9469
(18.95)	CambAEI	88.7	386.6	6139.7	172.4	210.8	130.7	24.4	0.9697
	MTAPC	128.6	45.8	16612.0	8.9	321.4	242.4	13.1	0.9260
	JPL	287.0	597.7	11015.7	11.8	375.3	146.3	9.9	0.9709
MBH-6	AEI	1042.3	1235.6	82343.2	2.1	258.2	191.6	26.0	0.9293
(12.82)	CambAEI	5253.2	1598.8	953108.0	158.3	350.8	215.4	29.4	0.4399
	MTAPC	56608.7	296.7	180458.8	119.7	369.2	297.6	25.1	0.0016

MLDC3: EMRis

Source (SNR_{true})	Group	SNR	$\frac{\Delta M}{M}$ $\times 10^{-3}$	$\frac{\Delta \mu}{\mu}$ $\times 10^{-3}$	$\frac{\Delta \nu_0}{\nu_0}$ $\times 10^{-5}$	Δe_0 $\times 10^{-3}$	$\Delta \lvert S \rvert$ $\times 10^{-3}$	$\frac{\Delta \lambda_{SL}}{\lambda_{SL}}$ $\times 10^{-3}$	Δspin (deg)	Δsky (deg)	$\frac{\Delta D}{D}$
EMRI-1	MTAPCIOA	21.794	5.05	3.29	1.61	−5.1	−1.4	−19	23	2.0	0.07
(21.673)	MTAPCIOA	21.804	−0.06	−0.01	−0.08	−0.05	0.02	0.54	3.5	1.0	0.13
EMRI-2	MTAPCIOA	32.387	−3.64	−2.61	−3.09	3.8	0.87	12	11	3.7	3×10^{-3}
(32.935)	BabakGair	22.790	33.1	−19.7	10.1	−33	−7.3	25	47	3.5	−0.25
	BabakGair	22.850	32.7	−20.0	9.94	−32	−7.2	25	58	3.5	−0.24
	BabakGair	22.801	33.5	−19.5	10.5	−33	−7.4	240	40	3.5	−0.25
EMRI-3	MTAPCIOA	19.598	1.62	0.38	−0.10	−0.35	−0.94	−3.0	5.0	3.0	−0.04
(19.507)	BabakGair	21.392	1.77	1.01	1.95	−1.2	−0.68	−2.3	116	4.5	0.13
	BabakGair	21.364	2.26	1.88	2.71	−2.0	−0.69	−2.5	65	6.1	0.14
	BabakGair	21.362	1.51	1.01	2.09	−1.3	−0.50	−1.7	7.6	6.2	0.14
	EtfAG	—	54.0	4.88	−7375	26	17	—	—	32	0.83
EMRI-4	MTAPCIOA	−0.441	−8.77	−10.1	−6.03	−3.7	144	950	99	13	−2.3
(26.650)											
EMRI-5	MTAPCIOA	17.480	−3.32	5.00	−1.80	0.22	55	62	43	1.8	−1.3
(36.173)											

MLDC3: EMRis

Source ($\mathrm{SNR}_{\mathrm{true}}$)	Group	SNR	$\frac{\Delta M}{M}$ $\times 10^{-3}$	$\frac{\Delta \mu}{\mu}$ $\times 10^{-3}$	$\frac{\Delta \nu_0}{\nu_0}$ $\times 10^{-5}$	Δe_0 $\times 10^{-3}$	$\Delta \lvert S \rvert$ $\times 10^{-3}$	$\frac{\Delta \lambda_{\mathrm{SL}}}{\lambda_{\mathrm{SL}}}$ $\times 10^{-3}$	Δspin (deg)	Δsky (deg)	$\frac{\Delta D}{D}$
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(36.173)											

MLDC3: EMRis

Source ($\mathrm{SNR}_{\mathrm{true}}$)	Group	SNR	$\frac{\Delta M}{M}$ $\times 10^{-3}$	$\frac{\Delta \mu}{\mu}$ $\times 10^{-3}$	$\frac{\Delta \nu_0}{\nu_0}$ $\times 10^{-5}$	Δe_0 $\times 10^{-3}$	$\Delta \lvert S \rvert$ $\times 10^{-3}$	$\frac{\Delta \lambda_{\mathrm{SL}}}{\lambda_{\mathrm{SL}}}$ $\times 10^{-3}$	Δspin (deg)	Δsky (deg)	$\frac{\Delta D}{D}$
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(21.673)	MTAPCIOA	21.804	−0.06	−0.01	−0.08	−0.05	0.02	0.54	3.5	1.0	0.13
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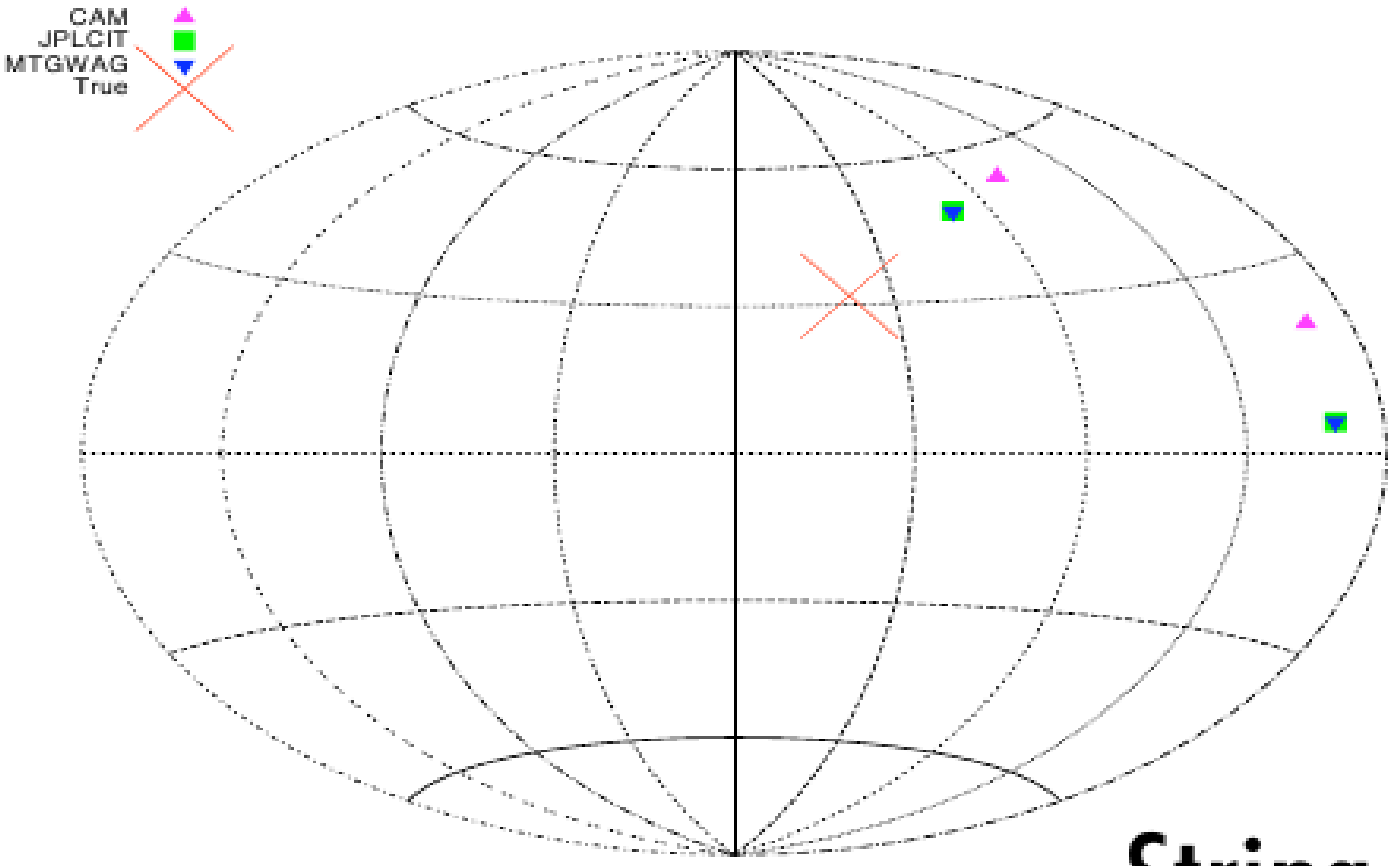
EMRI-3	MTAPCIOA	19.598	1.62	0.38	−0.10	−0.35	−0.94	−3.0	5.0	3.0	−0.04
(19.507)	BabakGair	21.392	1.77	1.01	1.95	−1.2	−0.68	−2.3	116	4.5	0.13
	BabakGair	21.364	2.26	1.88	2.71	−2.0	−0.69	−2.5	65	6.1	0.14
	BabakGair	21.362	1.51	1.01	2.09	−1.3	−0.50	−1.7	7.6	6.2	0.14
	EtfAG	—	54.0	4.88	−7375	26	17	—	—	32	0.83
EMRI-4	MTAPCIOA	−0.441	−8.77	−10.1	−6.03	−3.7	144	950	99	13	−2.3
(26.650)											
EMRI-5	MTAPCIOA	17.480	−3.32	5.00	−1.80	0.22	55	62	43	1.8	−1.3
(36.173)											

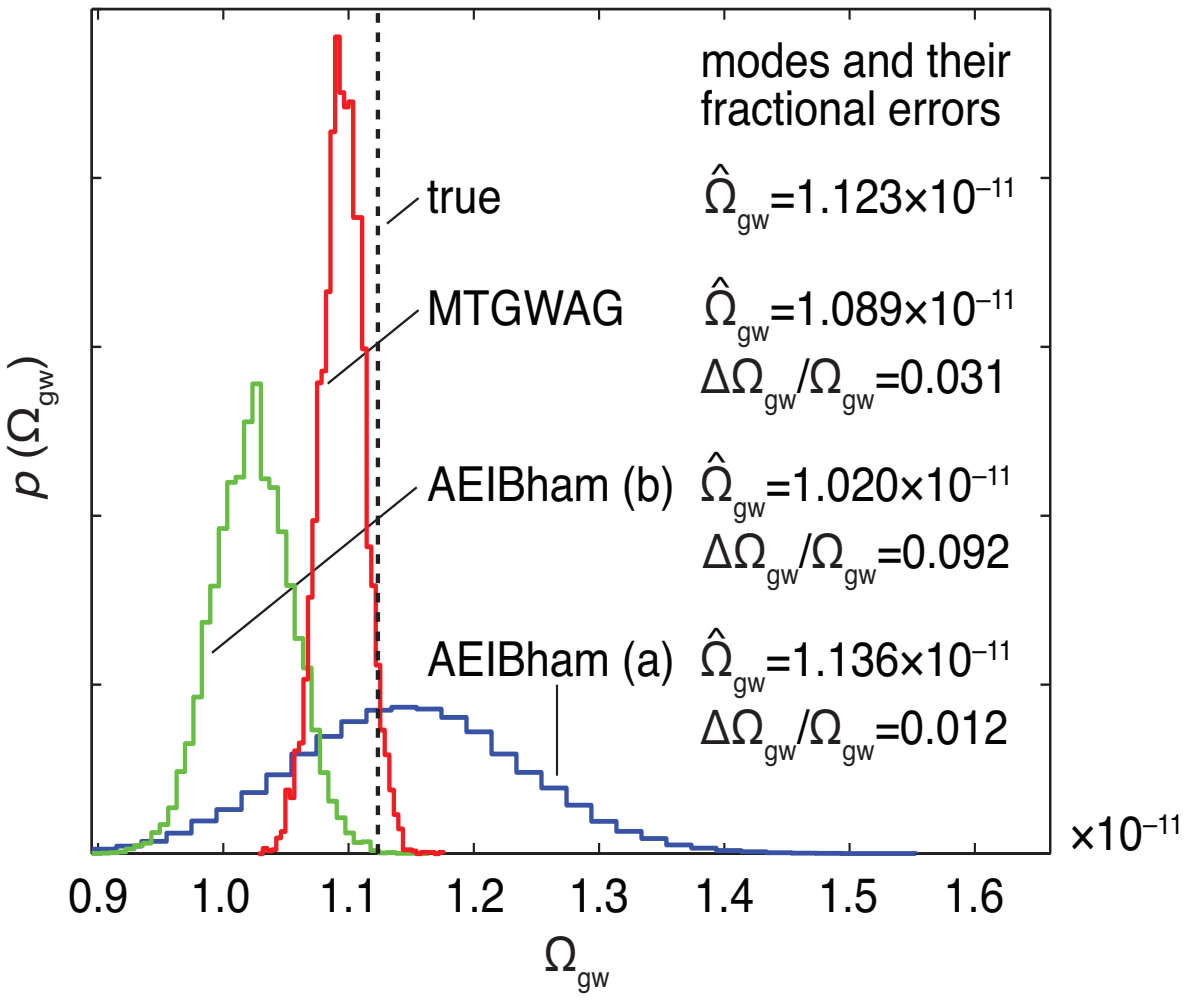
MLDC3: GW bursts from the cusps on the cosmic strings

source (SNR_{true})	group	Δsky (deg)	Δt_D (sec)	$\Delta\psi$ (rad)	$\Delta\mathcal{A}/\mathcal{A}$	SNR	FF_A	FF_E
String-1	CAM	106.9	1.462	0.501	0.904	43.706	0.99947	0.99797
(43.46)	CAM	49.4	2.331	1.065	1.128	43.520	0.99964	0.99591
	JPLCIT	34.2	1.585	3.726	0.413	43.506	0.99986	0.99844
	JPLCIT	113.7	1.574	3.739	0.431	43.497	0.99988	0.99847
	MTGWAG	106.6	2.071	2.600	0.745	43.287	0.99975	0.99565
String-2	CAM	82.0	3.683	4.846	0.062	33.690	0.99945	0.99986
(33.6)	JPLCIT	90.5	4.005	4.268	0.282	33.689	0.99949	0.99929
	JPLCIT	45.2	3.847	6.364	0.231	33.694	0.99939	0.99960
	MTGWAG	53.1	3.223	0.158	0.011	33.696	0.99926	0.99978
String-3	CAM	80.8	1.249	3.785	0.338	41.326	0.99073	0.99923
(41.42)	CAM	133.3	1.715	3.257	0.238	41.456	0.99388	0.99869
	CAM	44.5	0.763	3.202	0.066	41.142	0.99700	0.99883
	JPLCIT	59.0	1.546	3.129	0.317	41.315	0.99554	0.99848
	JPLCIT	157.7	1.226	5.614	0.220	41.316	0.99717	0.99864
	MTGWAG	137.9	0.980	0.110	0.161	41.418	0.99327	0.99948

MLDC3: GW bursts from the cusps on the cosmic strings

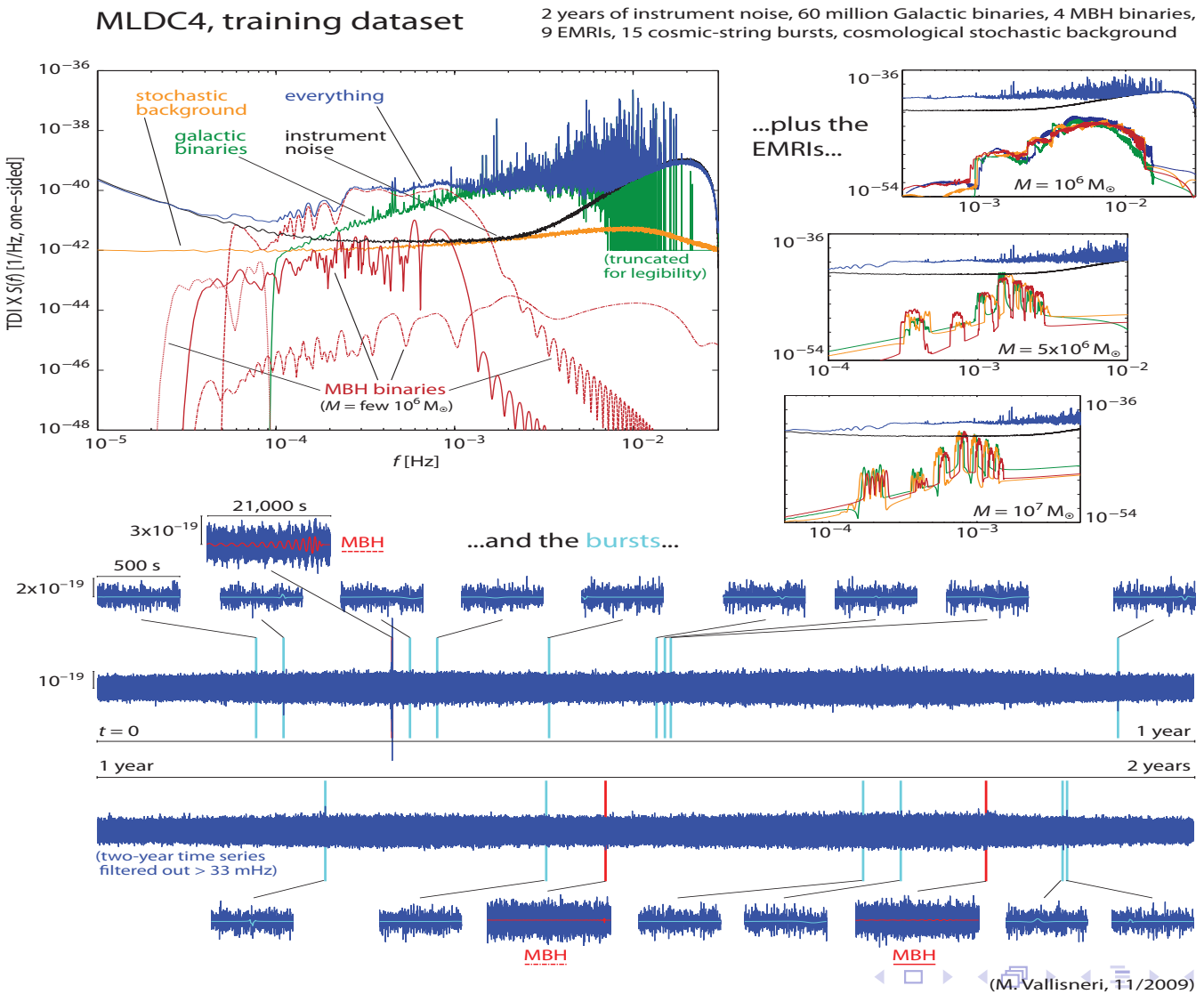


MLDC3: Stochastic GW background



MLDC4: was not finished

Galactic-binary background	$\sim 34 \times 10^6$ interacting, $\sim 26 \times 10^6$ detached systems
4–6 *MBH binaries*	$m_1 = \mathbf{0.5}$–$5 \times 10^6\, M_\odot$, $m_1/m_2 = 1$–$\mathbf{10}$, $a_1/m_1 = 0$–1, $a_2/m_2 = 0$–1, with t_c and SNRs as in MLDC 3.2
an average of 6 *EMRIs*	$\mu = 9.5$–$10.5\, M_\odot$, $S = 0.5$–$0.7\, M^2$, $e_{\rm plunge} = \mathbf{0.05}$–$0.25$, $t_{\rm plunge} = 2^{21}$–$2^{22} \times 15$ s, SNR = **25–50**
. . . including	**Poisson(2)** systems with $M = 0.95$–$1.05 \times 10^7\, M_\odot$
	Poisson(2) systems with $M = 4.75$–$5.25 \times 10^6\, M_\odot$
	Poisson(2) systems with $M = 0.95$–$1.05 \times 10^6\, M_\odot$
Poisson(20) *cosmic-string bursts*	$f_{\rm max} = 10^{-3-1}$ Hz, $t_C = \mathbf{0}$–$\mathbf{2^{22}} \times \mathbf{15}$ s, SNR = 10–100
isotropic stochastic background	$S_h^{\rm tot} = 0.7$–$1.3 \times 10^{-47} (f/{\rm Hz})^{-3}\, {\rm Hz}^{-1}$


MLDC4, training dataset
2 years of instrument noise, 60 million Galactic binaries, 4 MBH binaries, 9 EMRIs, 15 cosmic-string bursts, cosmological stochastic background
stochastic background
everything
galactic binaries
instrument noise
(truncated for legibility)
MBH binaries
(M = few 10^6 M⊙)
TDI X S(f) [1/Hz, one-sided]
f [Hz]
...plus the EMRIs...
M = 10^6 M⊙
M = 5x10^6 M⊙
M = 10^7 M⊙
21,000 s
3x10^-19
MBH
...and the bursts...
500 s
2x10^-19
10^-19
t = 0
1 year
1 year
2 years
(two-year time series filtered out > 33 mHz)
MBH
MBH

Future directions

- Split Mock data challenge in two directions;
- “Astrophysical” MDC (2 & 3 arms?)
  - We should redo MLDC3 for eLISA and MLDC1 (to attract new groups/students) Results could be compared to classic LISA.
  - We need to finish challenge # 4, but for new, eLISA coniguration.
  - ....
- “Instrumental” MDC
  - Need to move away from the Gaussian noise
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Future directions

- Split Mock data challenge in two directions;
- “Astrophysical” MDC (2 & 3 arms?)
  - We should redo MLDC3 for eLISA and MLDC1 (to attract new groups/students) Results could be compared to classic LISA.
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Astrophysical MDC

- Take astrophysical priors on the event rates, best current knowledge on parameters distribution functions: this will lead to higher event rate, wider (but non-homogeneous) parameter space
- Use the results of MDC for the inverse problem: constraining astrophysical models, statements about the mechanisms of source' formation.
- Set up MDC for testing fundamental physics: cosmology (partially done: GWs from strings and GWB), "no hair" theorem, GR in strong dynamic gravity via mergers of MBHs, ...
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- Lab. experiments and future data from LPF will provide us with information about expected non-Gaussian features in the instrumental noise.
- We work with idealized TDI: assuming prefect laser noise cancellation.
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Tools and People

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