The Mock LISA Data Challenges : From challenge 3 to 4.

Ed Porter

APC – Paris

For the MLDC Taskforce

What are the MLDCs?

- Formulated at the LIST meeting in Pasadena, 2005, with co-chairs Neil Cornish (MSU, US) and Bernard Schutz (AEI, Germany)
- Validate proposed algorithms and ensure they meet the requirements of a LISA data analysis sytem
- Develop a plan for increasingly difficult challenges
- Also develop a plan for analysis of challenges
- Release training and blind data sets

The MLDC Taskforce

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M. Benacquista,
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E. Robinson
I Thorpe

MLDC Timeline

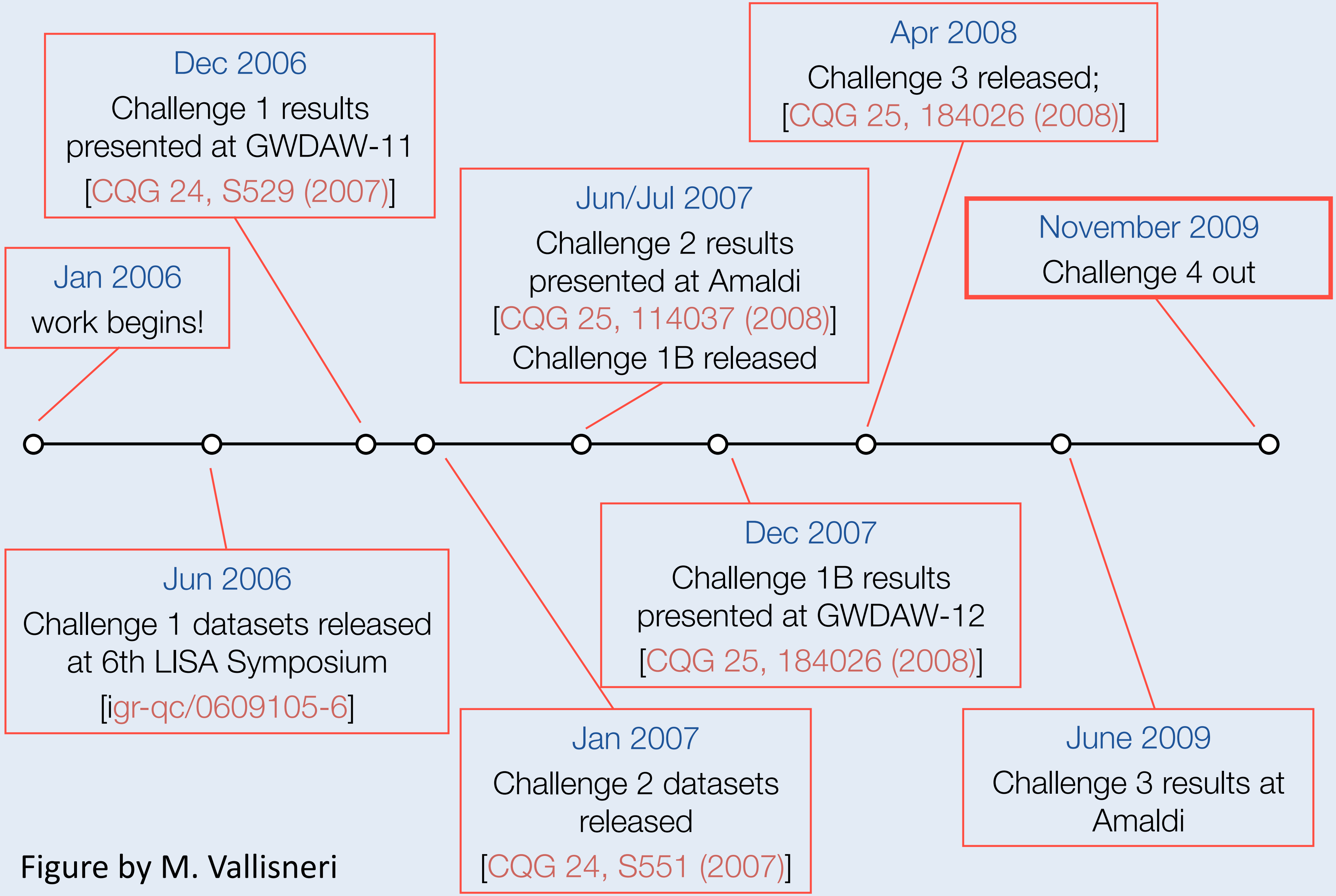

Figure by M. Vallisneri

What has already been accomplished?

	MLDC 1	MLDC 2	MLCD 1B	MLDC 3
GB	• Verification ✓ • Unknown, isolated ✓ • Unknown, interfering ✓	• Galaxy of $3x10^6$ ✓	• Verification ✓ • Unknown, isolated ✓ • Unknown, confused ✓	• Galaxy of $6x10^7$ chirping ✓
MBH	• Isolated ✓	• 4–6x, over Galaxy and EMRIs ✓	• Isolated ✓	• Over Galaxy spinning, precessing ✓
EMRI		• Isolated ✓ • 4–6x, over Galaxy and SMBHs	• Isolated ✓	• 5 together, weaker ✓
New				• Cosmic string cusp bursts ✓ • Cosmological background ✓

Table by M. Vallisneri

Previous challenges

	participants	institutions
MLDC 1	40	10
MLDC 2	39	13
MLDC 1B	25	10

Also, 26 related publications

Challenge 3

- 29 participants from from 18 institutions

AEI, Potsdam AEI, Hannover APC, Paris Caltech, Pasadena Cavendish Lab., Cambridge IOA, Cambrige Inst. Of Mathematics, Warsaw JPL, Pasadena Kavli Institute, Cambridge	Montana State Univ., Bozeman NASA Goddard, Greenbelt Northwestern Univ., Evanston RIT, Rochester Univ. de les Illes Belears, Majorca Univ. Of Birmingham, Birmingham Univ. Of Texas, Brownsville Univ. Of Wroclaw, Wroclaw Utah State Univ., Logan

Challenge 3

- *60 million chirping GBs* of which 20-30,000 should be resolvable
- *5 spinning MBHs* with 3 coalescing within the 2 year period, and 2 outside of 2 years. MBHs embedded in instrumental noise and a partially resolved galaxy. (*13 < SNR < 1700*)
- *5 EMRIs* embedded in instrumental noise. Low SNRs (*20 < SNR < 36*)
- *3 Cosmic-string–cusp bursts* in instrument noise with slightly randomised noise sources. One month data set. (*33 < SNR < 43*)
- *Stochastic background*. Isotropic signal in instrument noise with randomised noise levels. 192x2 linearly polarised stochastic sources at uniform distribution across the sky. Groups to return value for quantity

$$\Omega_{\mathrm{gw}}(f) = \frac{1}{\rho_{\mathrm{crit}}} \frac{\mathrm{d}\rho_{\mathrm{gw}}(f)}{\mathrm{d}\log f}$$

Challenge 3.1 : Galactic Binaries

- **BhamUIB** : delayed rejection MCMC algorithm to search in the 3 windows $0.3mHz < f < 0.4$ mHz, 0.9 $mHz < f < 1$ mHz, 1.6 $mHz < f < 1.7$ mHz
- **AEIRIT** : LIGO style hierarchical F-Statistic search using rigid adiabatic templates
- **PoWrWa** : Sequential F-Statistic matched filtering search using rigid adiabatic templates

Challenge 3.1 : Galactic Binaries

- Used a correlation criterion of $C > 0.9$
- BhamUIB : 494 sources (30%)
- AEIRIT : 1940 sources (95%)
- PoWrWa : 14,838 sources (33%. However when correcting for a bug at $f > 3$mHz, PoWrWa achieve 58% for 6,955 sources at $f < 3$ mHz)
- MTJPL entry for Challenge 2 returned ~20,000 sources with 99% having $C > 0.9$

Challenge 3.2 : Spinning Massive Black Holes

- **AEI** : Genetic algorithm with A-Statistic
- **CambAEI** : MultiNest with A-Statistic
- **GSFC** : MCMC algorithm found in Xspec
- **JPLCITNWU** : Two stage search using a non-spinning MBH search with MultiNest
- **MTGWAGAPC** : Parallel tempered MHMC algorithm using thermostated/frequency annealing

Challenge 3.2 : Massive Black Holes

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 $\times 10^{-3}$	$\Delta D/D$ $\times 10^{-2}$	SNR	FF_A	FF_E
MBH-1	AEI	2.4	6.1	62.9	11.6	7.6	47.4	8.0	1657.71	0.9936	0.9914
(1670.58)	CambAEI	3.4	40.7	24.8	2.0	8.5	79.6	0.7	1657.19	0.9925	0.9917
	MTAPC	24.8	41.2	619.2	171.0	13.3	28.7	4.0	1669.97	0.9996	0.9997
	JPL	40.5	186.6	23.0	26.9	39.4	66.1	6.9	1664.87	0.9972	0.9981
	GSFC	1904.0	593.2	183.9	82.5	5.7	124.3	94.9	267.04	0.1827	0.1426
MBH-3	AEI	9.0	5.2	100.8	175.9	6.2	18.6	2.7	846.96	0.9995	0.9989
(847.61)	CambAEI	13.5	57.4	138.9	179.0	21.3	7.2	1.5	847.04	0.9993	0.9993
	MTAPC	333.0	234.1	615.7	80.2	71.6	177.2	16.1	842.96	0.9943	0.9945
	JPL	153.0	51.4	356.8	11.2	187.7	414.9	2.7	835.73	0.9826	0.9898
	GSFC	8168.4	2489.9	3276.9	77.9	316.3	69.9	95.6	218.05	0.2815	0.2314
MBH-4	AEI	4.5	75.2	31.4	0.1	47.1	173.6	9.1	160.05	0.9989	0.9994
(160.05)	CambAEI	3.2	171.9	30.7	0.2	52.9	346.1	21.6	160.02	0.9991	0.9992
	MTAPC	48.6	2861.0	5.8	7.3	33.1	321.1	33.0	149.98	0.8766	0.9352
	JPL	302.6	262.0	289.3	4.0	47.6	184.5	28.3	158.34	0.8895	0.9925
	GSFC	831.3	1589.2	1597.6	94.4	59.8	566.7	95.4	−45.53	−0.1725	−0.2937
MBH-2	AEI	1114.1	952.2	38160.8	171.1	331.7	409.0	15.3	20.54	0.9399	0.9469
(18.95)	CambAEI	88.7	386.6	6139.7	172.4	210.8	130.7	24.4	20.36	0.9592	0.9697
	MTAPC	128.6	45.8	16612.0	8.9	321.4	242.4	13.1	20.27	0.9228	0.9260
	JPL	287.0	597.7	11015.7	11.8	375.3	146.3	9.9	18.69	0.9661	0.9709
MBH-6	AEI	1042.3	1235.6	82343.2	2.1	258.2	191.6	26.0	13.69	0.9288	0.9293
(12.82)	CambAEI	5253.2	1598.8	953108.0	158.3	350.8	215.4	29.4	10.17	0.4018	0.4399
	MTAPC	56608.7	296.7	180458.8	119.7	369.2	297.6	25.1	11.34	-0.0004	0.0016

Challenge 3.2 : Massive Black Holes

source (SNR_{true})	group	$\Delta M_c/M_c$ $\times10^{-5}$	$\Delta\eta/\eta$ $\times10^{-4}$	Δt_c (sec)	Δsky (deg)	Δa_1 $\times10^{-3}$	Δa_2 $\times10^{-3}$	$\Delta D/D$ $\times10^{-2}$	SNR	FF_A	FF_E
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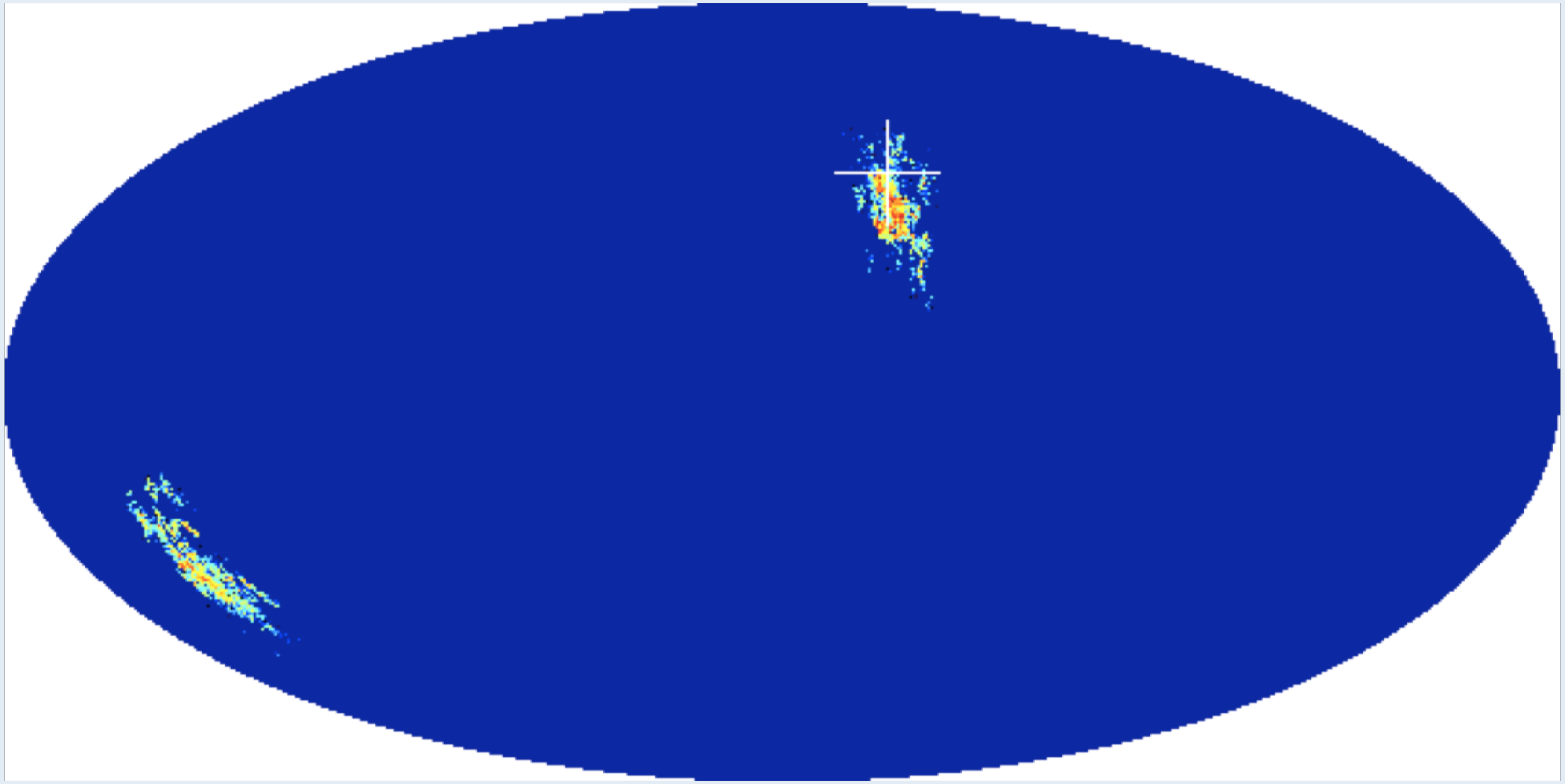
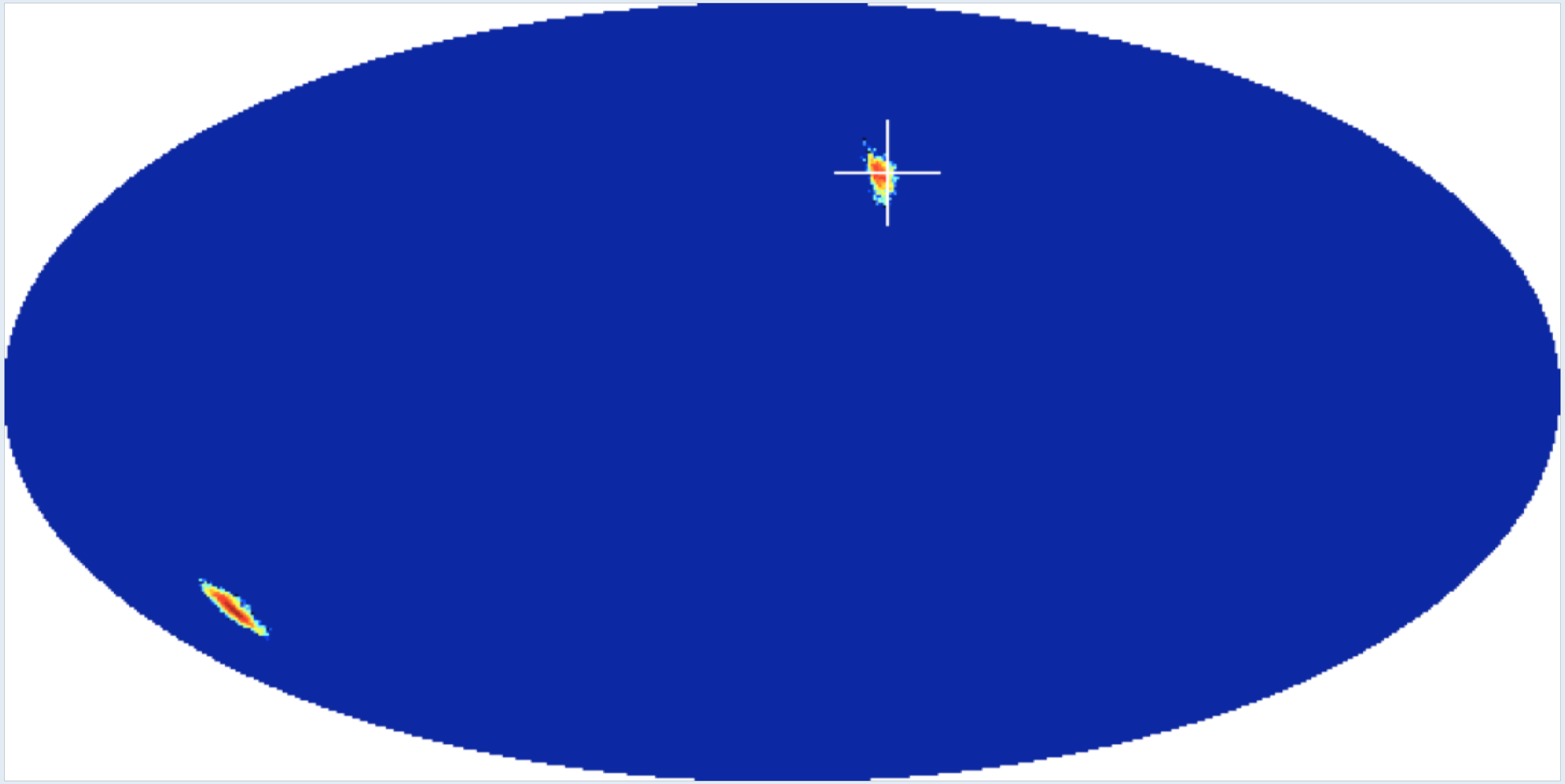
Challenge 3.2 : Massive Black Holes



30 days before merger

Monte Carlo by Neil Cornish

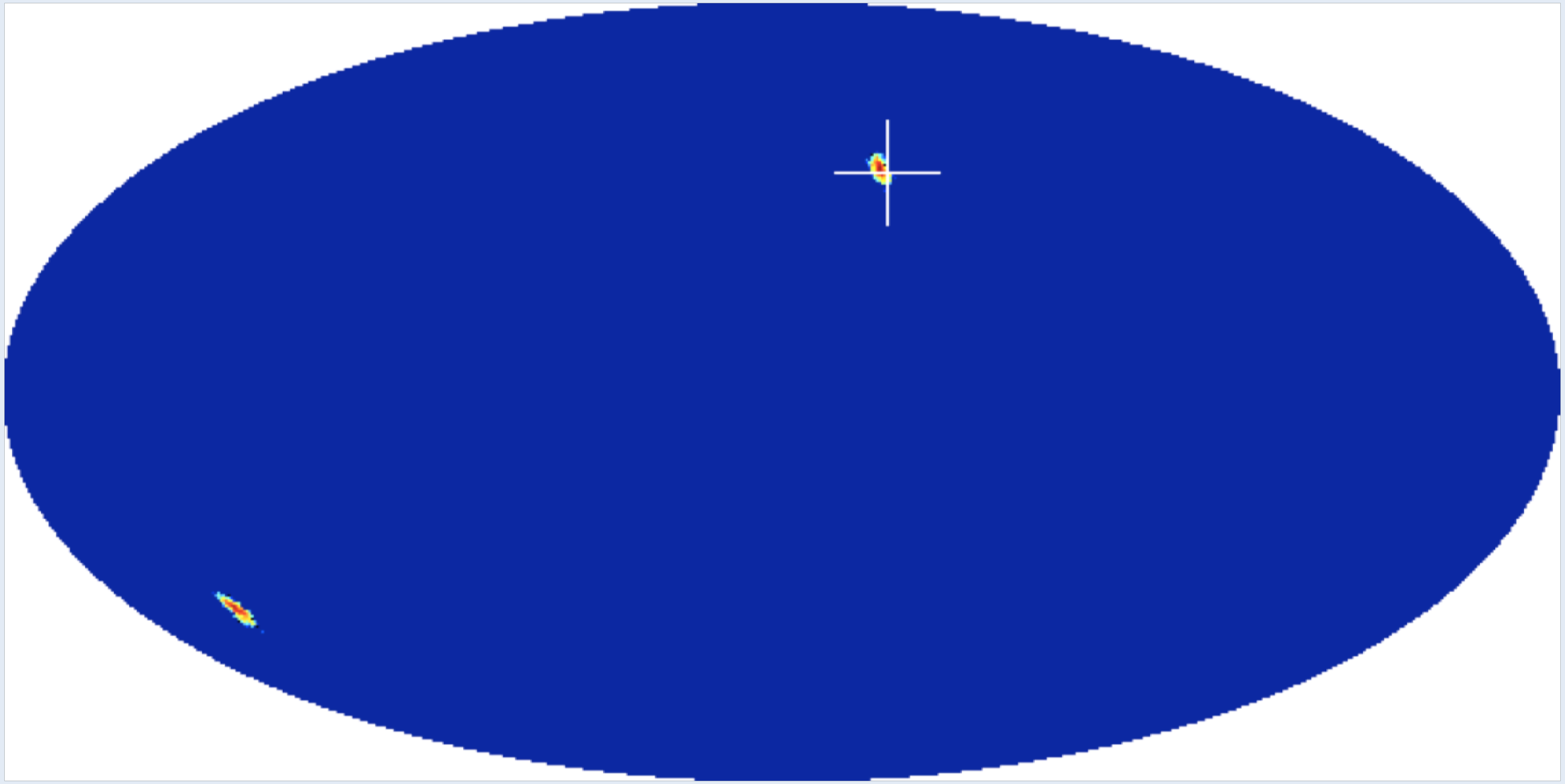
Challenge 3.2 : Massive Black Holes



7 days before merger

Monte Carlo by Neil Cornish

Challenge 3.2 : Massive Black Holes

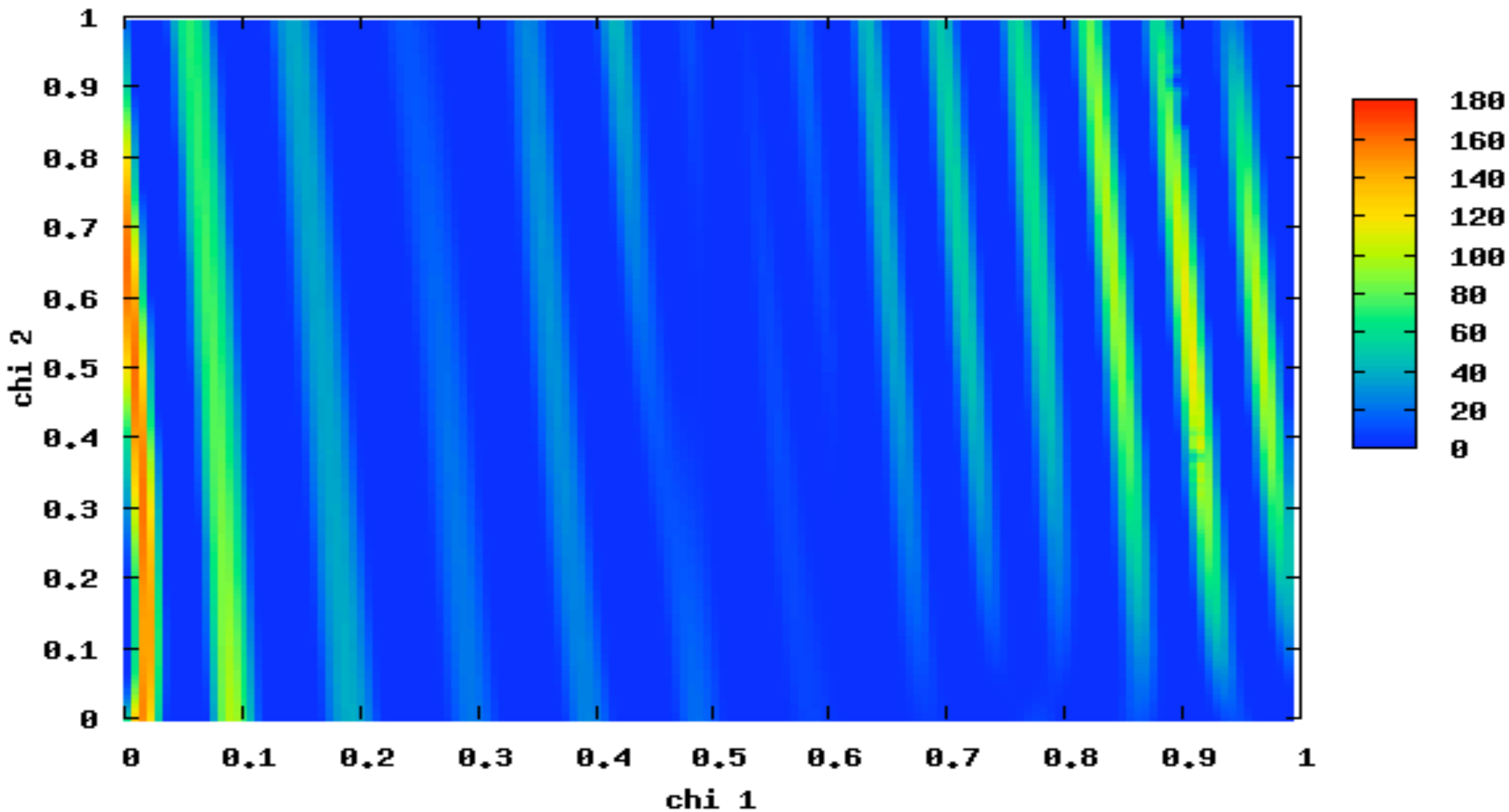


1 day before merger

Monte Carlo by Neil Cornish

Challenge 3.2 : Massive Black Holes

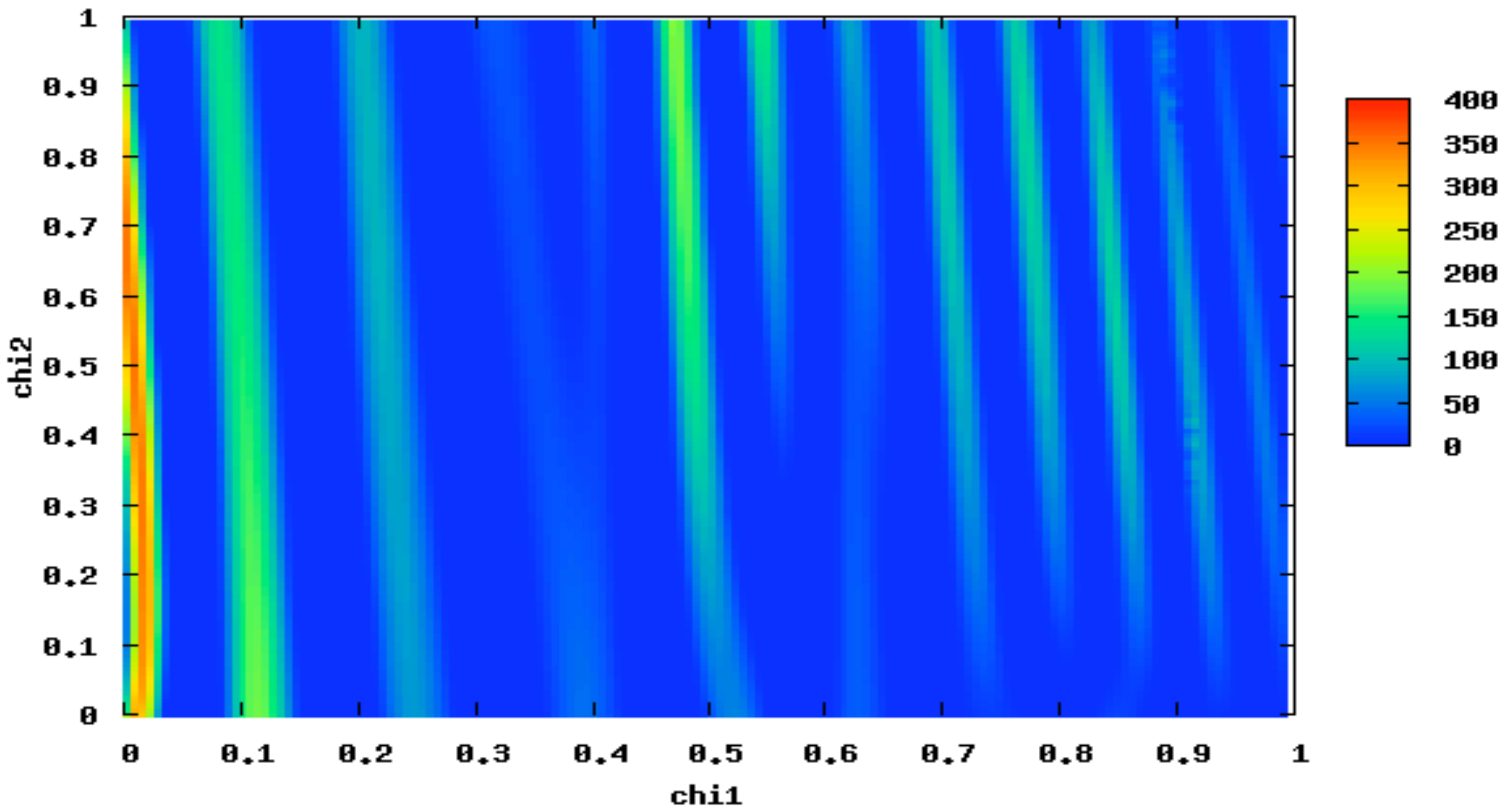
30 days before merger



Monte Carlo by Ed Porter

Challenge 3.2 : Massive Black Holes

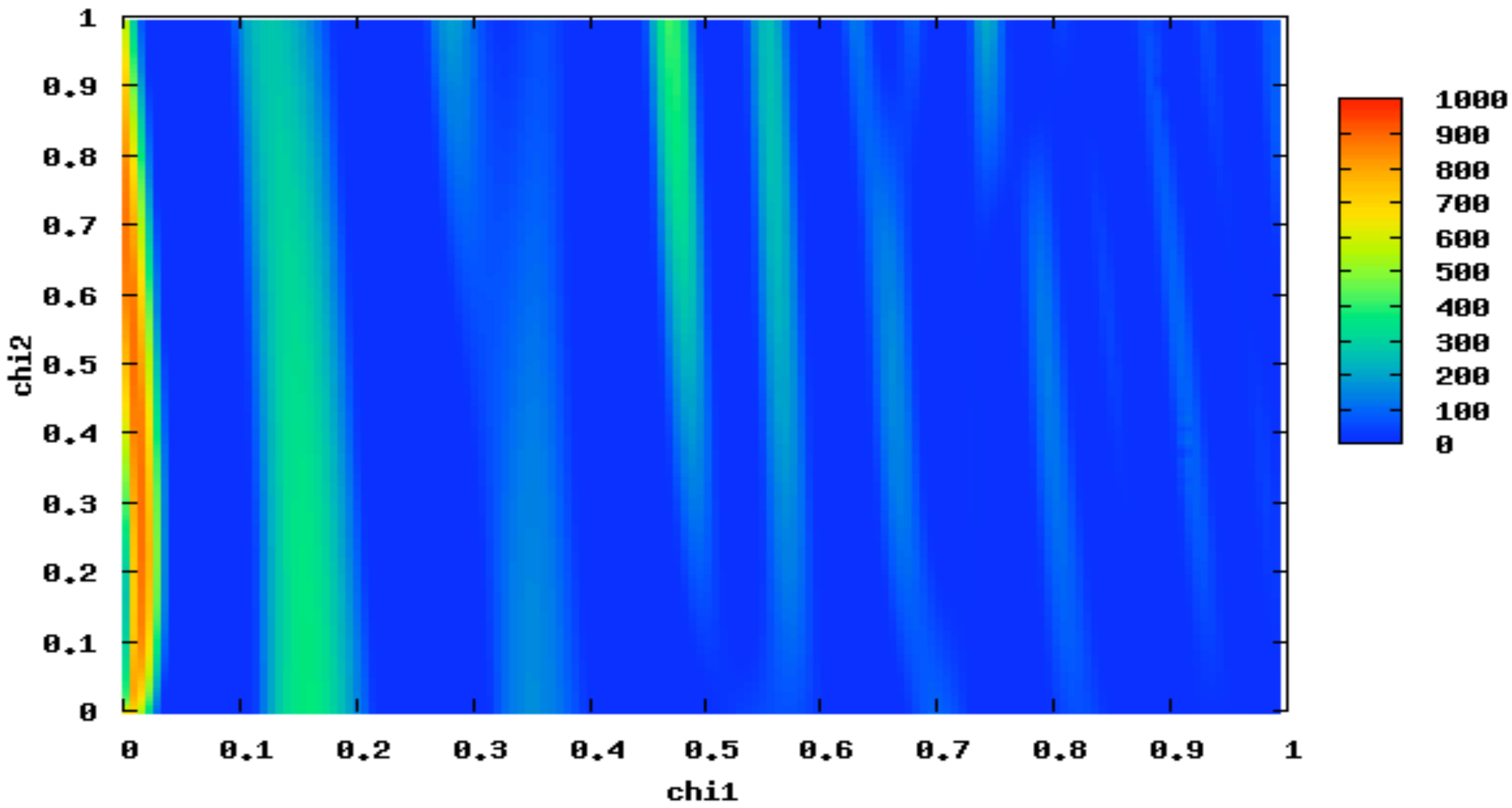
7 days before merger



Monte Carlo by Ed Porter

Challenge 3.2 : Massive Black Holes

1 day before merger



Monte Carlo by Ed Porter

Challenge 3.3 : EMRIs

- **BabakGair** : Stochastic sampling and MCMC for harmonic identification, F-Statistic in harmonic space + final MCMC
- **EtfAG** : Improved Time-Frequency method
- **MTAPCIOA** : Parallel tempered MHMC combined with harmonic jumps

Challenge 3.3 : 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 (21.673)	MTAPCIOA	21.794	5.05	3.29	1.61	−5.1	−1.4	−19	23	2.0	0.07
	MTAPCIOA	21.804	−0.06	−0.01	−0.08	−0.05	0.02	0.54	3.5	1.0	0.13
EMRI-2 (32.935)	MTAPCIOA	32.387	−3.64	−2.61	−3.09	3.8	0.87	12	11	3.7	3×10^{-3}
	BabakGair	22.790	33.1	−19.7	10.1	−33	−7.3	250	47	3.5	−0.25
	BabakGair	22.850	32.7	−20.0	9.94	−32	−7.2	250	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 (19.507)	MTAPCIOA	19.598	1.62	0.38	−0.10	−0.35	−0.94	−3.0	5.0	3.0	−0.04
	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 (26.650)	MTAPCIOA	−0.441	−8.77	−10.1	−6.03	−3.7	144	950	99	13	−2.3
EMRI-5 (36.173)	MTAPCIOA	17.480	−3.32	5.00	−1.80	0.22	55	62	43	1.8	−1.3

Challenge 3.3 : 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	250	47	3.5	−0.25
	BabakGair	22.850	32.7	−20.0	9.94	−32	−7.2	250	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 (26.650)	MTAPCIOA	−0.441	−8.77	−10.1	−6.03	−3.7	144	950	99	13	−2.3
EMRI-5 (36.173)	MTAPCIOA	17.480	−3.32	5.00	−1.80	0.22	55	62	43	1.8	−1.3

Challenge 3.3 : 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)	$\frac{\Delta D}{D}$
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Challenge 3.4 : Cosmic string-cusp bursts

- **CAM** : MultiNest
- **CaNoe** : Time-Frequency algorithm
- **JPLCIT** : MultiNest & MCMC
- **MTGWAG** : Parallel tempered MCMC

Challenge 3.4 : Cosmic string-cusp bursts

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

Challenge 3.4 : Cosmic string-cusp bursts

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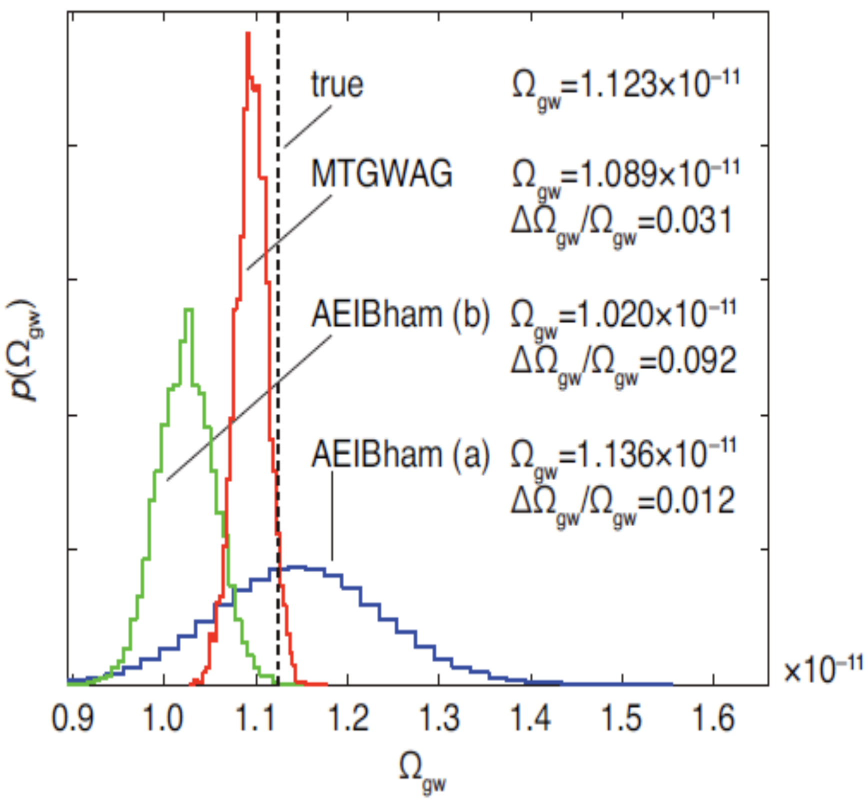
	MTGWAG	137.9	0.980	0.110	0.161	41.418	0.99327	0.99948

Challenge 3.5 : Stochastic background

- **AEIBham** : MCMC
- **MTGWAG** : Parallel tempered MCMC



noise	estimated/true	frac. error
$pm_1+pm_2^*$	$6.5/4.7 \times 10^{-48}$	0.385
$pm_1^*+pm_3$	$3.2/5.4 \times 10^{-48}$	0.397
$pm_2+pm_3^*$	$6.9/5.8 \times 10^{-48}$	0.197
$pd_1+pd_2^*$	$3.733/3.752 \times 10^{-37}$	5.0×10^{-3}
$pd_1^*+pd_3$	$3.568/3.547 \times 10^{-37}$	6.1×10^{-3}
$pd_2+pd_3^*$	$3.805/3.804 \times 10^{-37}$	3.6×10^{-4}

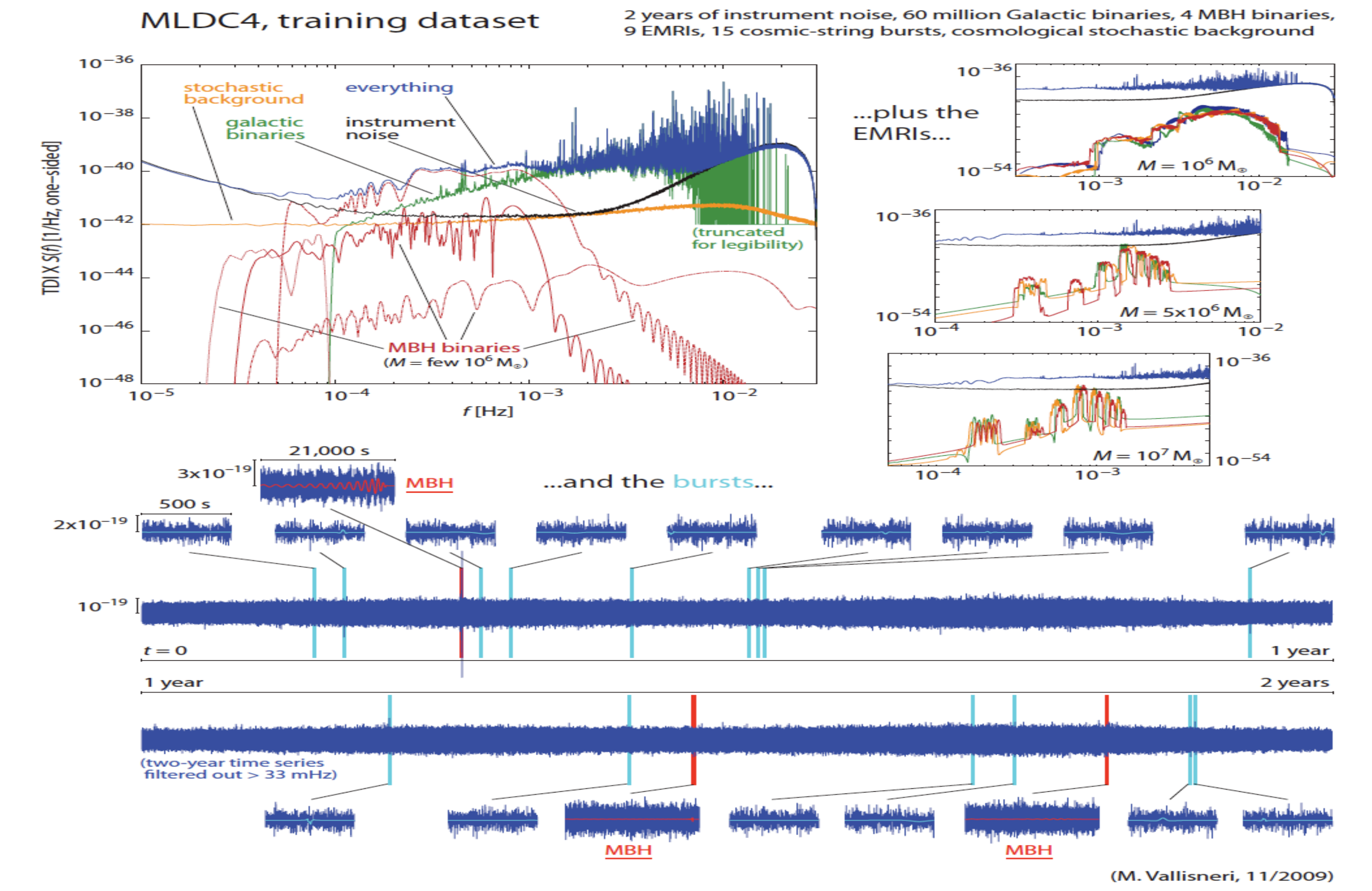
Challenge 4

- Was released in November 2009.
- Deadline : December 1st, 2010.
- Goal : global fit problem.
- Idea : groups either investigate subsets of sources, or form collaborations to go after the full global fit.
- Data sets are approximately 2 years long, with high (dt = 1.875 secs) and low (dt = 15 secs) cadence versions.
- 3 versions of each : two fractional-frequency and one strain.

Sources in Challenge 4

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*	$\mu = 9.5$–$10.5\, M_\odot$, $S = 0.5$–$0.7\, M^2$, $e_{\mathrm{plunge}} = \mathbf{0.05}$–$0.25$, $t_{\mathrm{plunge}} = 2^{21}$–$2^{22} \times 15$ 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*	$f_{\max} = 10^{-3-1}$ Hz, $t_C = \mathbf{0}$–$\mathbf{2^{22}} \times \mathbf{15}$ s, SNR = 10–100
isotropic stochastic background	$S_h^{\mathrm{tot}} = 0.7$–$1.3 \times 10^{-47} (f/\mathrm{Hz})^{-3}\, \mathrm{Hz}^{-1}$

Sources in Challenge 4



Challenge 5 & Beyond…

- Aim to simulate more realistic data, i.e. include data gaps, glitches etc

- Work closer with LISA and LPF experimentalists

- For MBHs, include merger-ringdown, hybrid/numerical relativity, eccentricity

- Non-GR sources, e.g. strange EMRIs

- Any other suggestions….

Conclusion

- GB resolution still falling short of theoretical predictions
- Detection of massive black holes is quite good. However, parameter estimation needs to be improved. Difficulties due to spins and other parameter degeneracies
- Detection of EMRIs is good. As with MBHs, the parameter space is highly degenerate producing multi-modal solutions. Resolution of the global maximum and hence estimation of parameters needs to be improved
- Cosmic string cusps detection is excellent. Parameter estimation is very poor due to the lack of Doppler information as LISA is effectively stationary and due to characteristics of the waveforms themselves
- Stochastic background estimation very good.

…join us for Challenge 4…

Challenge 4

For further information :

Wiki : www.tapir.caltech.edu/listwg1b

Data-sets : www.astrogravs.nasa.gov/docs/mldc

Lisatools repository : lisatools.googlecode.com