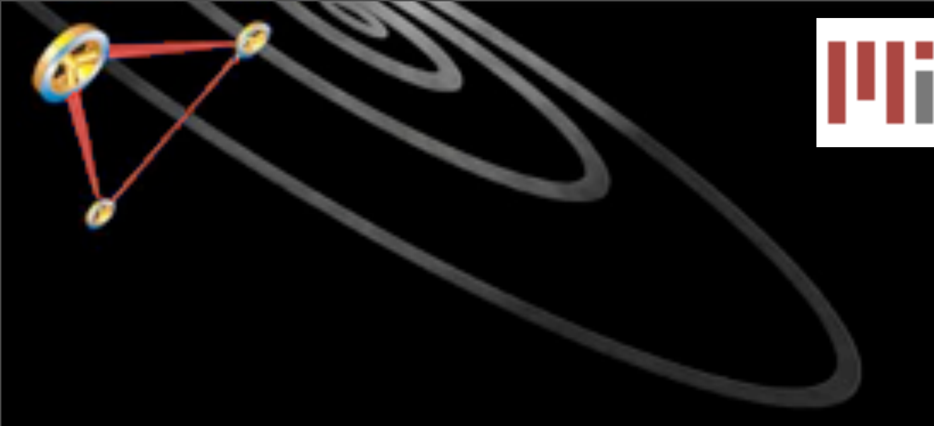


The Mock LISA Data Challenges

I. Mandel

CIERA@Northwestern / MIT

for the MLDC Taskforce :

S. Babak, J. Baker, M. Benacquista, N. Cornish, S. Larson, I. Mandel, S. T. McWilliams, A. Petiteau, E. Porter, E. Robinson, M. Vallisneri (co-chair), A. Vecchio (co-chair)

GR-19 , July 5 2010 , Mexico City

What are the MLDCs ?

Goals :

- Demonstrate that we can meet the LISA science and data analysis requirements
- Develop common frameworks to measure the performance of analysis algorithms
- Understand data analysis quantitatively to translate requirements into design decisions
- Encourage and track development of LISA data-analysis infrastructure

MLDCs:

- Coordinated, voluntary effort of the gravitational wave (GW) community
- Periodically issue data sets with GW signals embedded in noise
- Data sets : Training (injection parameters are known) & Challenge (blind).

Develop a plan for increasing-complexity challenges (generation & analysis):

- Phase 1 (MLDC 1, 1B, 2, 3) : establish common standards for LISA orbits, noise & response; test recovery and parameter estimation of significant astrophysical sources.
- Phase 3 (MLDC 4, 5) : face global-fit problem; analyze real-world data.

MLDC Timeline

Formulated at the LIST meeting in Pasadena, 2005.

Jan 2006
Works begins!

Jun 2006
Challenge 1 datatsets released at 6th LISA Symposium
[in proc. ,gr-qc/0609105-6]

Dec 2006
Challenge 1 results presented in GWDAW-11
[CQG 24, S529 (2007)]

Jan 2007
Challenge 2 datatsets released
[CQG 24, S551 (2007)]

Jun/Jul 2007
Challenge 2 results presented at Amaldi
[CQG 25, 114037 (2008)]
Challenge 1B released

Dec 2007
Challenge 1B results presented at GWDAW-12
[CQG 25, 184026 (2008)]

Apr 2008
Challenge 3 released
[CQG 25, 184026 (2008)]

Jun 2009
Challenge 3 results at Amaldi
[CQG 27, 084009 (2009)]

Nov 2009
Challenge 4 released
[CQG 27, 084009 (2009)]

now

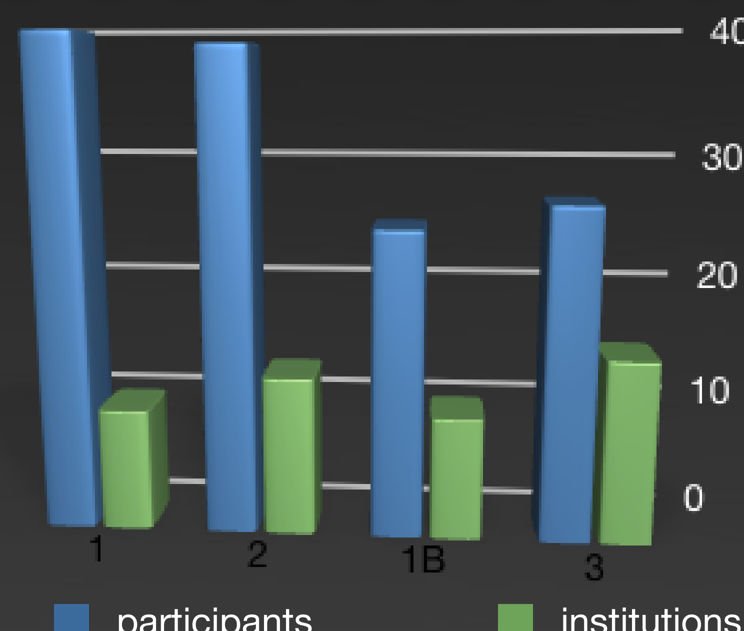
Dec 2010
Challenge 4 deadline

2006 2007 2008 2009 2010

by M. Vallisneri

70 Participants from 25 institutions

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



	participants	institutions
MLDC 1	40	10
MLDC 2	39	13
MLDC 1B	25	10
MLDC 3	27	15

MLDC progression

	MLDC 1	MLDC 2	MLDC 1B	MLDC 3	MLDC 4
Galactic binaries	• Verification • Unknown isolated • Unknown interfering	• Galaxy 3×10^6	• Verification • Unknown isolated • Unknown interfering	• Galaxy 6×10^7 chirping	• Galaxy 6×10^7 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

Challenge 3

The Mock LISA Data Challenges: from challenge 3 to challenge 4

Stanislav Babak[1], John G Baker[2], Matthew J Benacquista[3], Neil J Cornish[4], Shane L Larson[5], Ilya Mandel[6], Sean T McWilliams[2], Antoine Petiteau[1], Edward K Porter[7], Emma L Robinson[1], Michele Vallisneri[8,9], Alberto Vecchio[10] (the Mock LISA Data Challenge Task Force), Matt Adams[4], Keith A Arnaud[2], Arkadiusz Błaut[11], Michael Bridges[12], Michael Cohen[9], Curt Cutler[8,9], Farhan Feroz[12], Jonathan R. Gair[13], Philip Graff[12], Mike Hobson[12], Joey Shapiro Key[4], Andrzej Królak[14], Anthony Lasenby[12,15], Reinhard Prix[16], Yu Shang[1], Miquel Trias[17], John Veitch[10] and John T Whelan[18] (the Challenge 3 participants)

CQG 27, 084009 (2009)

- MLDC 3.1 : 60 million chirping Galactic binaries,
- MLDC 3.2 : 4 - 6 spinning MBH binaries,
- MLDC 3.3 : 5 EMRIs,
- MLDC 3.4 : Poisson(5) cosmic string cusp bursts,
- MLDC 3.5 : Stochastic background.

Challenge 3.1: Galactic binaries

- Injection : 60 million chirping galactic binaries of which 20,000 - 30,000 should be resolvable.

- Participants and methods :

  - **AEIRIT** (AEI Hannover & Rochester Inst. of Tech) :

    LIGO-style hierarchical search based on the F-statistic and on frequency-domain rigid-adiabatic templates.

  - **BhamUIB** (U. Birmingham & Balearic islands) :

    Delayed rejection MCMC algorithm to search in 3 frequency windows: 0.3 mHz $< f <$ 0.4 mHz, 0.9 mHz $< f <$ 1 mHz and 1.6 mHz $< f <$ 1.7 mHz.

  - **PoWrWa** (AEI Golm, U. of Wroclaw & Polish Acad. of Sc.):

    Iterative matched-filtering search that uses the F-statistic and rigid-adiabatic templates.

Challenge 3.1: Galactic binaries

- Results :

  Used a correlation criterion, C >0.9 : for each recovered signal, C is computed using the closest injected signal with SNR > 3.

- AEIRIT :

  1940 sources (95 % of recovered sources).

- BhamUIB :

  494 sources (30 % of recovered sources but used just 3 narrow-bands).

- PoWrWa :

  14,838 sources (33 % of recovered sources). However when correcting for a bug at f > 3 mHz, PoWrWa achieve 58 % for 6,955 sources at f < 3 mHz.

- MTJPL entry for MLDC 2 (non-chirping) returned 20,000 sources with 99 % having C > 0.9

Challenge 3.2: Spinning MBH binaries

- Injection :
  - 5 ("unknown" number : 4 -6) spinning Massive Black Hole binaries with :
    - 3 coalescing within the 2 years period,
    - and 2 outside of 2 years.
  - MBH binaries embedded in instrumental noise and a partially resolved galaxy.

Condition on injected population :

4–6 *MBH binaries*	for each: $m_1 = 1$–$5 \times 10^6\, M_\odot$, $m_1/m_2 = 1$–4, $a_1/m_1 = 0$–1, $a_2/m_2 = 0$–1
...including	MBH$_1$: $t_c = 90 \pm 30$ days, SNR ~ 2000
	MBH$_2$: $t_c = 765 \pm 15$ days, SNR ~ 20
...and 2–4 chosen from	MBH$_3$: $t_c = 450 \pm 270$ days, SNR ~ 1000
	MBH$_4$: $t_c = 450 \pm 270$ days, SNR ~ 200
	MBH$_5$: $t_c = 540 \pm 45$ days, SNR ~ 100
	MBH$_6$: $t_c = 825 \pm 15$ days, SNR ~ 10
plus *Galactic confusion*	randomized population with approx. SNR < 5 $\sim 26 \times 10^6$ binaries; no verification

SNR of sources in blind dataset :

- 1670.58
- 12.82
- 847.61
- 160.05
- 18.95

Challenge 3.2: Spinning MBH binaries

- Participants and methods :
  - AEI (AEI Golm) :
    Multimodal genetic algorithm with A-statistic [Petiteau et al., PRD 81 104016 , 2010].
  - CamAIE (U. Cambridge & AEI) :
    MultiNest with A-statisitc [Bridges et al., MNRAS 398 1601, 2009].
  - GSFC (NASA Goddard):
    Tempered Metropolis-Hastings MCMC algorithm found in Xspec [Arnaud et al., web].
  - JPLCITNWU (JPL/CalTech & Northwestern U.):
    Two stages search using a non-spinning MBH search & MultiNest [Brown et al., CQG 24 S595, 2007].
  - MTGWAGAPC (Montana State U. & APC,CNRS):
    Parallel tempered MHMC algorithm using thermostated/frequency annealing [Cornish & Porter, 2006].

Challenge 3.2: Spinning MBH binaries

Results :

Coalescence during the observation : $t_c < T_{obs}$

Coalescence after the observation : $t_c > T_{obs}$

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 (1670.58)	AEI	2.4	6.1	62.9	11.6	7.6	47.4	8.0	1657.71	0.9936	0.9914
	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 (847.61)	AEI	9.0	5.2	100.8	175.9	6.2	18.6	2.7	846.96	0.9995	0.9989
	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 (160.05)	AEI	4.5	75.2	31.4	0.1	47.1	173.6	9.1	160.05	0.9989	0.9994
	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 (18.95)	AEI	1114.1	952.2	38160.8	171.1	331.7	409.0	15.3	20.54	0.9399	0.9469
	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 (12.82)	AEI	1042.3	1235.6	82343.2	2.1	258.2	191.6	26.0	13.69	0.9288	0.9293
	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: Spinning MBH binaries

Results : SNR and Fitting Factor

Coalescence during the observation : $t_c < T_{obs}$

Coalescence after the observation : $t_c > T_{obs}$

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 (1670.58)	AEI	2.4	6.1	62.9	11.6	7.6	47.4	8.0	1657.71	0.9936	0.9914
	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
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1664.87	0.9972	0.9981
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	267.04	0.1827	0.1426
MBH-3 (847.61)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	846.96	0.9995	0.9989
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	847.04	0.9993	0.9993
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	842.96	0.9943	0.9945
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	835.73	0.9826	0.9898
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	218.05	0.2815	0.2314
MBH-4 (160.05)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	160.05	0.9989	0.9994
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	160.02	0.9991	0.9992
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	149.98	0.8766	0.9352
	JPL	[illegible]	[illegible]	[illegible]	4.0	[illegible]	[illegible]	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 (18.95)	AEI	1114.1	952.2	38160.8	171.1	331.7	409.0	15.3	20.54	0.9399	0.9469
	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 (12.82)	AEI	1042.3	1235.6	82343.2	2.1	258.2	191.6	26.0	13.69	0.9288	0.9293
	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

- All signals were recovered
- When $t_c < T_{obs}$, the fitting factor is higher than 0.99 for most of the results
- When $t_c > T_{obs}$, the fitting factor is higher than 0.92 for most of the results

Challenge 3.2: Spinning MBH binaries

Results : Sky position and distance

* Fisher Information Matrix

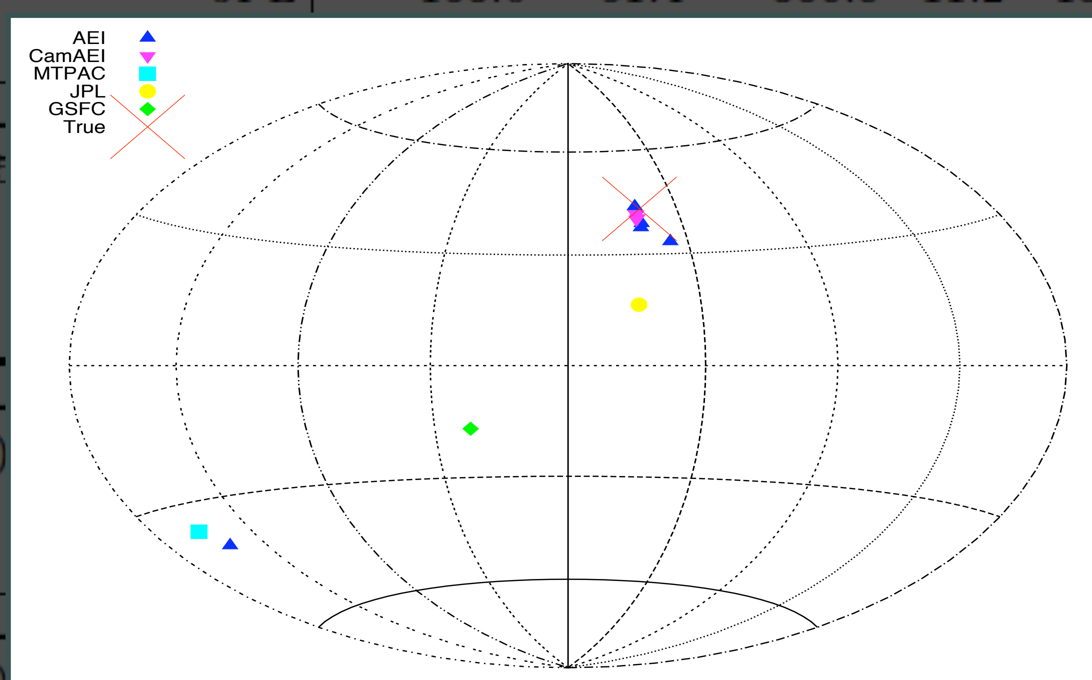
- Antipodal sky position degeneracy
- Results consistent with FIM* prediction
- Errors comparable, if not better, to those of the non-spinning binary searches (idem for masses and time at coalescence)

Coalescence during the observation : $t_c < T_{obs}$

Δsky (deg)	Error FIM*	$\Delta D/D$ $\times 10^{-2}$	Error FIM*
11.6		8.0	
2.0		0.7	
171.0	1.18	4.0	0.62
26.9		6.9	
82.5		94.9	
175.9		2.7	
179.0		1.5	
80.2	0.82	16.1	0.72
11.2		2.7	
77.9		95.6	
0.1		9.1	
0.2		21.6	
7.3	0.47	33.0	13.8
4.0		28.3	
94.4		95.4	

Coalescence after the observation : $t_c > T_{obs}$

Δsky (deg)	Error FIM*	$\Delta D/D$ $\times 10^{-2}$	Error FIM*
171.1		15.3	
172.4	10.37	24.4	16.8
8.9		13.1	
11.8		9.9	
2.1		26.0	
158.3	6.40	29.4	32.1
119.7		25.1	



Challenge 3.2: Spinning MBH binaries

Results : Spins

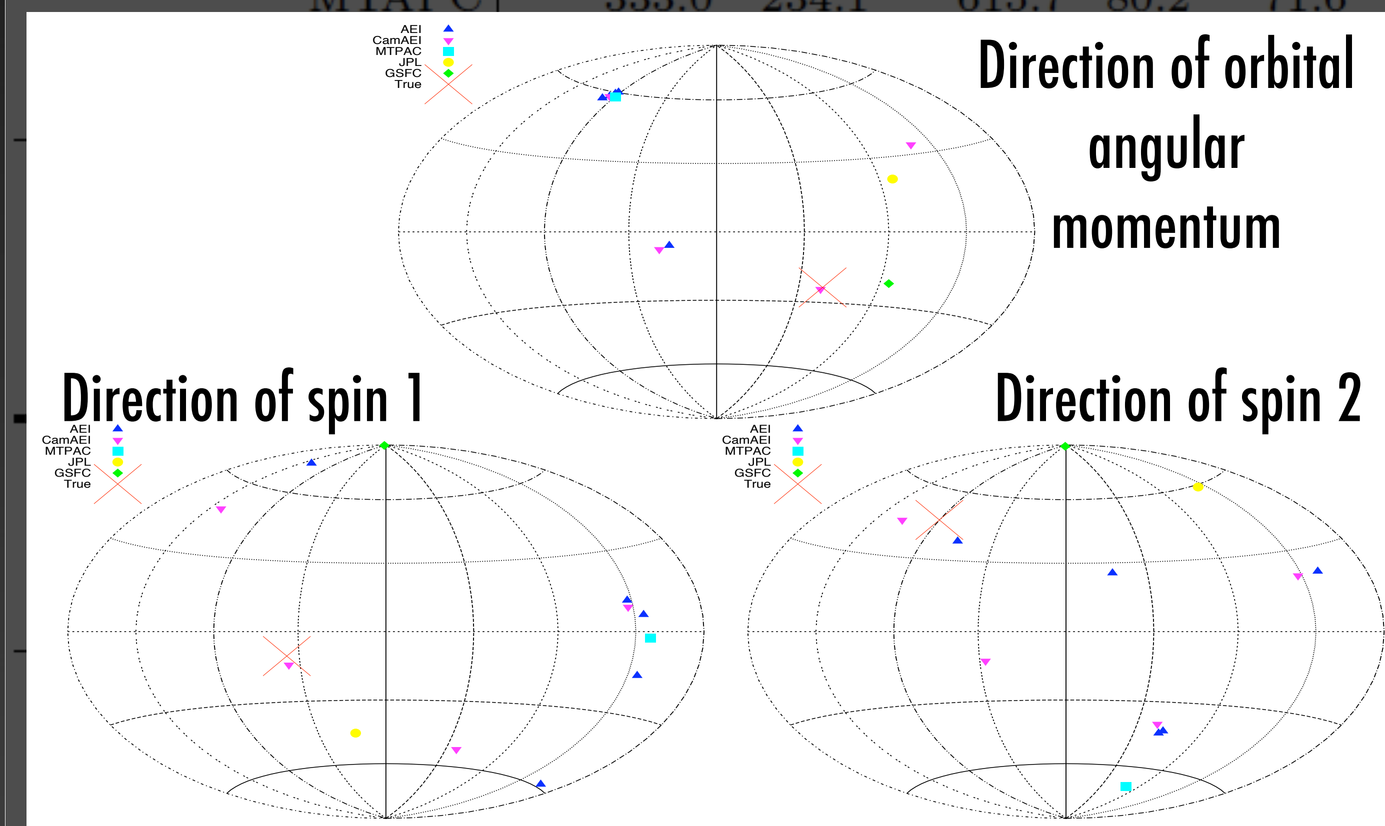
* Fisher Information Matrix

- Errors on amplitude close to FIM* prediction
- Degeneracies for initial directions of spins and orbital angular momentum : completely different directions give FF > 0.99 for $t_c < T_{obs}$.

Coalescence during the observation : $t_c < T_{obs}$

Coalescence after the observation : $t_c > T_{obs}$

	Δa_1 $\times 10^{-3}$	Error FIM*	Δa_2 $\times 10^{-3}$	Error FIM*
$t_c < T_{obs}$	7.6	2.7	47.4	6.2
	8.5		79.6	
	13.3		28.7	
	39.4		66.1	
	5.7		124.3	
	6.2	2.9	18.6	5.3
	21.3		7.2	
	71.6		177.2	
	187.7		414.9	
	316.3		69.9	
	47.1	29.2	173.6	151.4
	52.9		346.1	
	33.1		321.1	
	47.6		184.5	
	59.8		566.7	
$t_c > T_{obs}$	331.7	725.6	409.0	902.6
	210.8		130.7	
	321.4		242.4	
	375.3		146.3	
	258.2	453.7	191.6	699.0
	350.8		215.4	
	369.2		297.6	



Challenge 3.3: EMRIs

- Injection : 5 EMRIs embedded in instrumental noise. Low SNRs (20< SNR<36)

5 *EMRIs*		for each: $\mu = 9.5$–$10.5\,M_\odot$, $S = 0.5$–$0.7\,M^2$,
		time at plunge $= 2^{21}$–$2^{22} \times 15$ s,
		ecc. at plunge $= 0.15$–0.25, SNR $= 10$–50
	…including	EMRI$_1$: $M = 0.95$–$1.05 \times 10^7 M_\odot$
		EMRI$_2$ and EMRI$_3$: $M = 4.75$–$5.25 \times 10^6 M_\odot$
		EMRI$_4$ and EMRI$_5$: $M = 0.95$–$1.05 \times 10^6 M_\odot$

3 high mass events ("low" frequency)

2 low mass events ("high" frequency)

- Participants and methods :
  - **BabakGair** (AEI Golm & Cambridge U.) :
    Stochastic sampling → MCMC to identify harmonics → F-statistic search in the space of harmonics → final MCMC (improved on [Babak et al., CQG 26 135004, 2009]).
  - **EtfAG** (Cambridge U. & Northwestern U.) :
    Improved Time-Frequency method CATS (Chirp-based Algorithm for Track Search, improved on [Gair, Mandel, Wen, CQG 25 184031, 2008]).
  - **MTAPCIOA** (Montana State U., APC & Cambridge U.):
    Parallel tempered MHMC combined with harmonic jump [Shapiro & Cornish, PRD 67 043014, 2009].

Challenge 3.3: EMRIs

Results :

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

Results : Detection and SNR

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	−2.6 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] $^{-3}$
	BabakGair	22.790	33.1	−19.7 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] .25
	BabakGair	22.850	32.7	−20.0 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] .24
	BabakGair	22.801	33.5	−19.5 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] .25
EMRI-3 (19.507)	MTAPCIOA	19.598	1.62	0.3 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] .04
	BabakGair	21.392	1.77	1. [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] .13
	BabakGair	21.364	2.26	1.8 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] .14
	BabakGair	21.362	1.51	1.0 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] .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

- For high mass events, most of the SNR was recovered.
- The low mass events were detected, but the SNR was not fully recovered.

C I E R A

Challenge 3.3: EMRIs

Results : Masses

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	−0.0[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.13
EMRI-2	MTAPCIOA	32.387	−3.64	−2.61	−3.0[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]10^{-3}
(32.935)	BabakGair	22.790	33.1	−19.7	10.1[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	−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

- Very good estimation for the masses in all the cases.

Challenge 3.3: EMRIs

Results : Spin and eccentricity

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-[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	−3.09	3.8	0.87	12	11	3.7	3×10^{-3}
(32.935)	[illegible]	[illegible]	[illegible]	[illegible]	10.1	−33	−7.3	250	47	3.5	−0.25
	[illegible]	[illegible]	[illegible]	[illegible]	9.94	−32	−7.2	250	58	3.5	−0.24
	[illegible]	[illegible]	[illegible]	[illegible]	10.5	−33	−7.4	240	40	3.5	−0.25
EMRI-[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	−0.10	−0.35	−0.94	−3.0	5.0	3.0	−0.04
(19.507)	[illegible]	[illegible]	[illegible]	[illegible]	1.95	−1.2	−0.68	−2.3	116	4.5	0.13
	[illegible]	[illegible]	[illegible]	[illegible]	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)											

- Good estimation of the spin for the high mass cases (1-2-3)
- Good estimation for the eccentricity

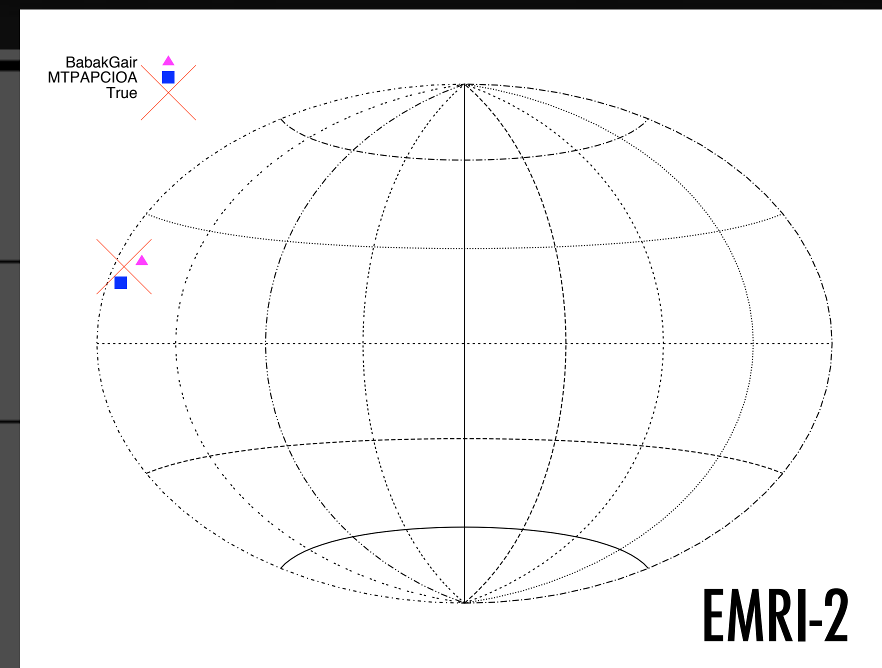
C I E R A

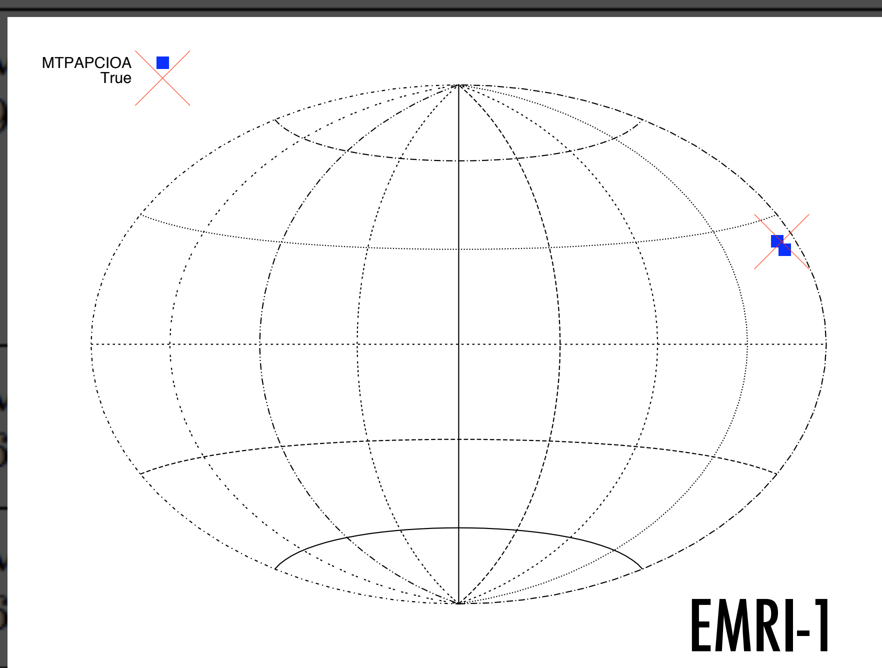
Challenge 3.3: EMRIs

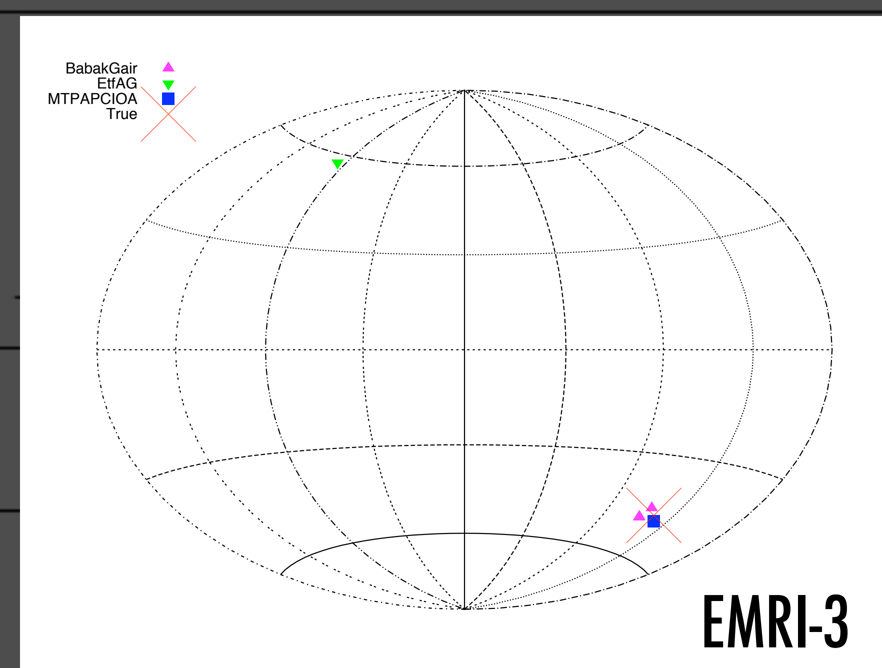
Results : Sky position and distance

- Error in sky position within few degrees

Source (S…	Group	SNR	$\frac{\Delta M}{M}$ …3	$\frac{\Delta\mu}{\mu}$ $\times 10^{-3}$	…pin …eg)	Δsky (deg)	$\frac{\Delta D}{D}$
E… (2…			…5	3.29	…23	2.0	0.07
			…6	−0.01	3.5	1.0	0.13
EMRI-2	MTAPCIOA	32.387	−3.64	−2.61	…11	3.7	3×10^{-3}
(32.935)	BabakGair	22.790	33.1	−19.7	…47	3.5	−0.25
	BabakGair	22.850	32.7	−20.0	…58	3.5	−0.24
	BabakGair	22.801	33.5	−19.5	…40	3.5	−0.25
EM…			…1.62	0.38	5.0	3.0	−0.04
(19…			…1.77	1.01	…16	4.5	0.13
			…2.26	1.88	…55	6.1	0.14
			…1.51	1.01	7.6	6.2	0.14
			…4.0	4.88	—	32	0.83
EM… (26…			…3.77	−10.1	…99	13	−2.3
EM… (36…			…3.32	5.00	…43	1.8	−1.3







Challenge 3.4: Cosmic string-cusp bursts

- Injection : 3 Cosmic string-cusp bursts in instrumental noise with slightly randomized noise sources. One-month data set. (33 < SNR < 36)

n Cosmic-string–cusp bursts	(with n Poisson-distributed with mean 5)
	$f_{\max} = 10^{-3-1}$ Hz, $t_C = 0$–2^{21} s, SNR = 10–100
	all instrument noise levels randomized ±20%

- Participants and methods :

$$|h_+(f)| = \mathcal{A} f^{-4/3}(1 + (f_{\rm low}/f)^2)^{-4}, \qquad h_\times = 0,$$

with $\exp(1 - f/f_{\max})$ suppression above $f_{\max}$

  - CAM (Cambridge U. & APC) :
    MultiNest [Feroz et al., CQG, 2010].
  - CaNoe (Cambridge U. & Northwestern U.) :
    Time-Frequency method CATS [Gair, Mandel, Wen, CQG 25 184031, 2008].
  - JPLCIT (JPL/CalTech) :
    MCMC and MultiNest. [Cohen, Cutler, Vallisneri, CQG, 2010]
  - MTGWAG (Montana State U.) :
    Parallel tempering MCMC [Shapiro & Cornish, PRD 67 043014, 2009].

Challenge 3.4: Cosmic string-cusp bursts

Results :

[CaNoe not included - no sky localization]

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

Results : SNR and Fitting Factor

- All groups successfully recovered all the 3 bursts
- Very good estimation of SNR and Fitting Factor > 0.99 BUT ...

source (SNR_{true})	group	Δsky (deg)	Δt_D (sec)	$\Delta\psi$ (rad)	$\Delta\mathcal{A}/\mathcal{A}$	SNR	FF_A	FF_E
String-1 (43.46)	CAM	106.9	1.462	0.501	0.904	43.706	0.99947	0.99797
	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 (33.6)	CAM	82.0	3.683	4.846	0.062	33.690	0.99945	0.99986
	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 (41.42)	CAM	80.8	1.249	3.785	0.338	41.326	0.99073	0.99923
	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

C I E R A

Challenge 3.4: Cosmic string-cusp bursts

Results : SNR, Fitting Factor and parameters

- All groups successfully recovered all the 3 bursts
- Very good estimation of SNR and Fitting Factor > 0.99 BUT ...
- ... poor accuracies on parameters due to the character of the waveform.

source (SNR_{true})	group	Δsky (deg)	Δt_D (sec)	$\Delta\psi$ (rad)	$\Delta\mathcal{A}/\mathcal{A}$	SNR	FF_A	FF_E
String-1 (43.46)	CAM	106.9	1.462	0.501	0.904	43.706	0.99947	0.99797
	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 (33.6)	CAM	82.0	3.683	4.846	0.062	33.690	0.99945	0.99986
	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 (41.42)	CAM	80.8	1.249	3.785	0.338	41.326	0.99073	0.99923
	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

Results : Sky

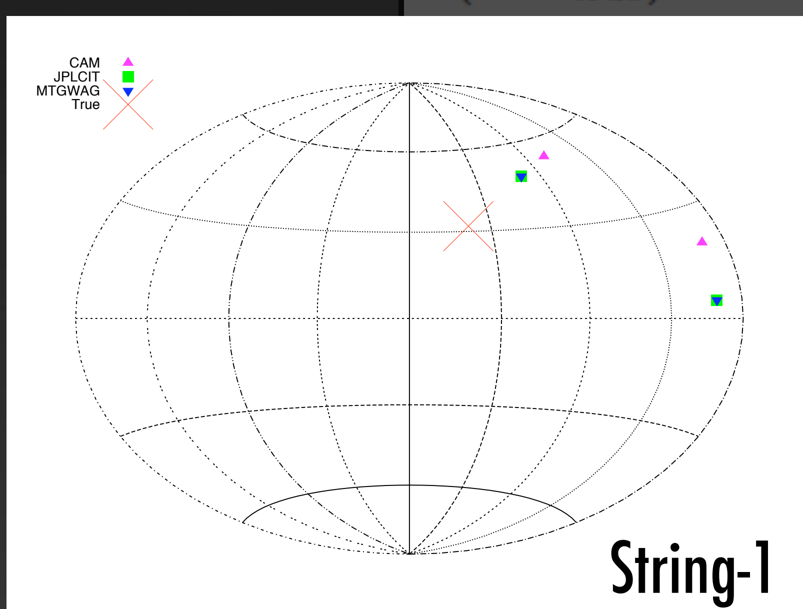
[See talk by C. Culter]

Short waveform

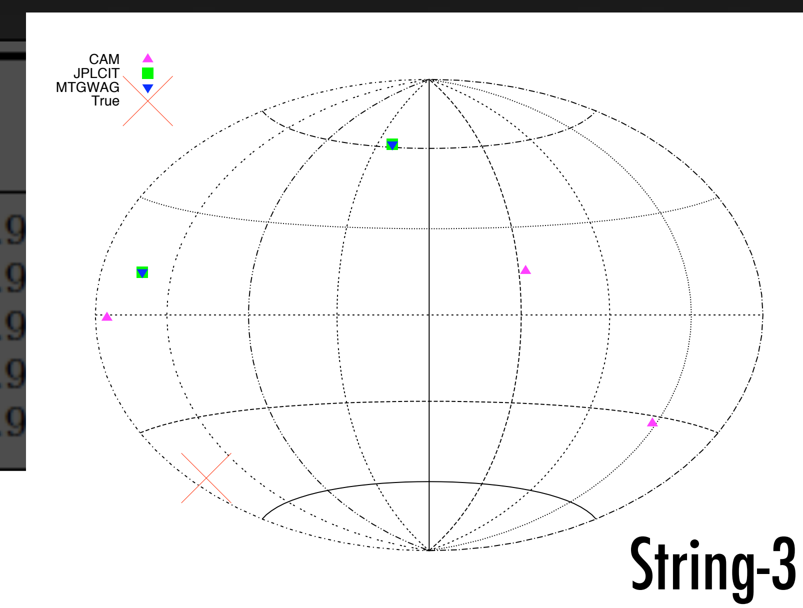
⇒ LISA is almost static during the duration of the waveform

⇒ No information on direction of the source from LISA motion

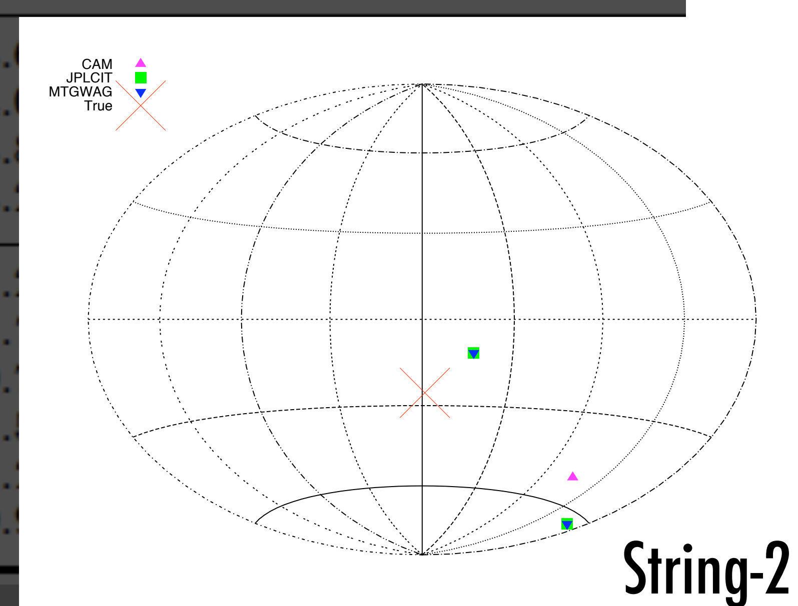
source (SNR_{true})	group	Δsky (deg)	Δt_D (sec)	$\Delta\psi$ (rad)	$\Delta\mathcal{A}/\mathcal{A}$	SNR	
	CAM	106.9	1.462	0.501	0.904	43.706	0.9
	CAM	49.4	2.331	1.065	1.128	43.520	0.9
	LCIT	34.2	1.585	3.726	0.413	43.506	0.9
	LCIT	113.7	1.574	3.739	0.431	43.497	0.9
	WAG	106.6	2.071	2.600	0.745	43.287	0.9
	CAM	82.0	3.				
	LCIT	90.5	4.				
	LCIT	45.2	3.				
	WAG	53.1	3.				0.99978
	CAM	80.8	1.				0.99923
(41.42)	CAM	133.3	1.				0.99869
	CAM	44.5	0.				0.99883
	JPLCIT	59.0	1.				0.99848
	JPLCIT	157.7	1.				0.99864
	MTGWAG	137.9	0.				0.99948



String-1



String-3



String-2

Challenge 3.5: Stochastic background

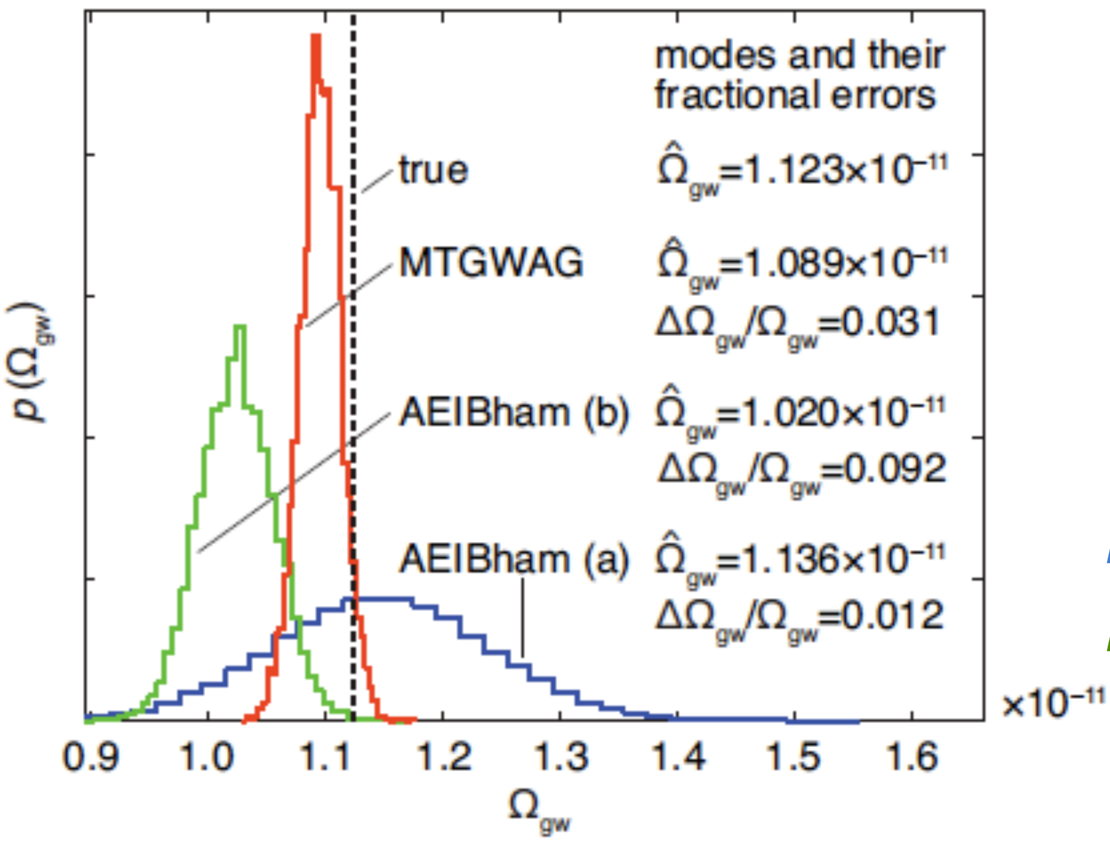
- Dataset :
  - Istropic signal in instrumental noise with randomized noise levels. 192x2 linearly polarized stochastic pseudo-sources at uniform distribution across the sky.
  - Characterized by a single dimensionless quantity : $\Omega_{\mathrm{gw}}(f) = \frac{1}{f} \frac{\mathrm{d}\,\rho_{\mathrm{gw}}(f)}{\mathrm{d}\,\log f}$, assumed to be uniform here.

- Participants and methods :
  - AEIBham (AEI Golm & U. of Birmingham) : MCMC for analyzing TDI A & E [Robinson & al, CQG 25 184019, 2008]. Run in two frequency bands : (a) 0.1 - 1 mHz , (b) 0.1 - 5 mHz.
  - MTGWAG (Montana State U.) : Parallel tempered MCMC for analyzing TDI A, E & T. Estimation of background and linear combinations of the individual LISA noises.

Challenge 3.5: Stochastic background

Results :

Posterior PDFs for Ω_{gw} :



LISA noise levels :

noise	MTGWAG/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}

AEIBham (a) : 0.1-1mHz
AEIBham (b) : 0.1-5mHz

pm : proof-mass noises
pd : photodetector noises

Both groups recovered the injected value by less than 10 % .

Challenge 4

- Goal : Global fit problem
- Data sets:
  - All the sources of challenge 3 in the same data set (same waveform with slightly modified priors)
  - 2 years with high (dt = 1.875 s) and low (dt = 15 s) cadence
  - 3 versions of each :
    - 2 fractional-frequency-fluctuation data sets simulated by SyntheticLISA & LISACode
    - 1 equivalent-strain data simulated by LISAsimulator.
- Idea : groups either investigate subsets of sources, or form collaboration to go after the full global fit.
- Dates : Released in November 2009 / Deadline 1st December 2010.

Sources in challenge 4

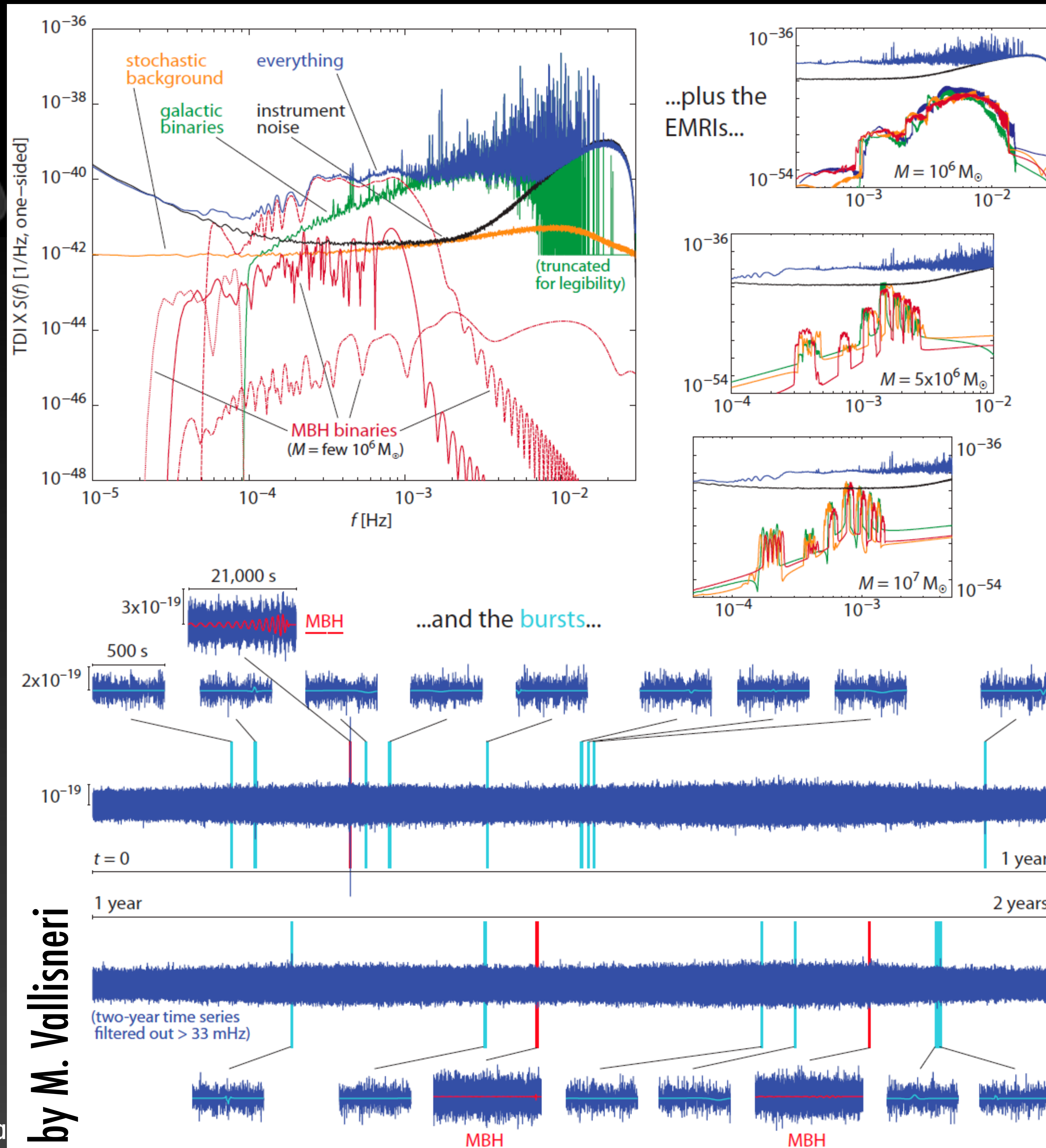
- Galactic binaries
- MBH binaries
  - extension to low-mass cases (higher frequency)
- EMRIs :
  - unknown number of sources
- Cosmic string-cusp bursts :
  - increase the number of sources with the duration of the data sets
- Isotropic stochastic background

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 six *EMRIs*	$\mu = 9.5$–$10.5\, M_\odot$, $S = 0.5$–$0.7\, M^2$, $e_{\text{plunge}} = \mathbf{0.05}$–$0.25$, $t_{\text{plunge}} = 2^{21}$–$2^{22} \times 15$ s, SNR $= \mathbf{25}$–$\mathbf{50}$
. . . 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*	$f_{\text{max}} = 10^{-3-1}$ Hz, $t_C = \mathbf{0}$–$\mathbf{2^{22}} \times \mathbf{15}$ s, SNR $= 10$–100
Isotropic stochastic background	$S_h^{\text{tot}} = 0.7$–$1.3 \times 10^{-47} (f/\text{Hz})^{-3}\ \text{Hz}^{-1}$

C I E R A

Sources in challenge 4

- One example (2 years) :
  - instrument noise,
  - 60 million Galactic binaries,
  - 4 MBH binaries,
  - 9 EMRIs,
  - 15 cosmic-string bursts,
  - cosmological stochastic background.



MLDC 5 & Beyond ...

- Include more realistic noise :
  - Non-stationary/Gaussian noises based on laboratory experiments and/or LISAPathfinder models/measurments,
  - Gaps, glitches, etc.
- Waveforms :
  - MBH binaries:
    - Full inspiral-merger-ringdown waveforms
    - Higher harmonics, eccentricity, ...
  - EMRIs:
    - Others models, event rates ...
- Extend variety of signals :
  - Other kind of bursts
  - Non-isotropic backgrounds and/or a variety of frequency spectra

Any other suggestions ...

Conclusions

- Results of challenge 3 : kind of “current status of LISA data analysis” :
  - Galactic binaries resolution is approaching theoretical predictions.
  - Detection of MBH binaries is good. Non-spinning parameters and spin amplitudes are quite well estimated. However, estimation of the other parameters is hard due to degeneracies.
  - Detection of EMRIs is good (without any other sources). In general, parameters are estimated well for high-mass, low-frequency sources. More work is needed for low-mass, rapidly-chirping sources, especially in cases of potential source confusion.
  - Cosmic string cusps detection is excellent. But parameter estimation is very poor due to characteristics of the waveforms themselves, in particular the short duration.
  - Stochastic background estimation is good.
- Ongoing step : the global fit with the challenge 4.
- Future : more realistic noises and waveforms ...

Resources / Further information :

- MLDC official website :
  - astrogravs.nasa.gov/docs/mldc
- MLDC taskforce wiki :
  - www.tapir.caltech.edu/dokuwiki/listwg1b:home
- Mailing lists :
  - formulation : lisatools-MLDC@gravity.psu.edu
  - participants : lisatools-challenge@gravity.psu.edu
- LISAtools software (including MLDC pipelines) :
  - lisatools.googlecode.com

Extra material

What are the MLDCs ?

- Goals :
  - Demonstrate that we can meet the LISA science and data analysis requirements,
  - Common frameworks to measure the performance of analysis algorithms,
  - Understand data analysis quantitatively to translate requirements into design decision.
- MLDCs:
  - Coordinated, voluntary effort of GW community,
  - Periodically issue data sets with noises and GW signals,
  - Codes :
    - Generation codes are public,
    - Analysis codes are not shared.

What are the MLDCs ?

- Data sets :
  - Training data sets : injection parameters are known,
  - Challenge data sets : blind.
- Develop a plan for increasing challenges:
  - Phase 1 (MLDC 1, 1B) : establish common standard for the LISA orbits, noises and response.
  - Phase 2 (MLDC 2, 3) : test recovery and parameter estimation of significant astrophysical sources.
  - Phase 3 (MLDC 4, 5) : face global-fit problem; analyze real-world data.
- Also develop a plan for analysis of challenges.