$\mathcal{F}$-Statistic Searches for White Dwarf Binaries in the Mock LISA Data Challenges

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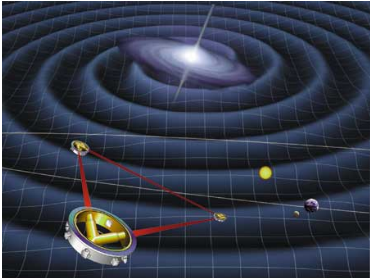
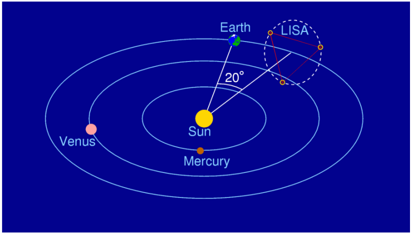
Outline

1. LISA Data Analysis
   - The LISA Mission
   - Mock LISA Data Challenges
2. White Dwarf Binary Search
   - $\mathcal{F}$-Statistic Search for Periodic Gravitational Waves
   - MLDC Pipeline and Results

LISA: Gravitational Wave Detection in Space

- Planned Joint NASA-ESA Mission: to launch 2018 or later
- 3 spacecraft will orbit sun in 5 mio km $\bigtriangledown$
  & track each other w/lasers
- Laser phase data combined to simulate 3 IFOs (2 indep):
  "Time-Delay Interferometry" (TDI): $X(t)$, $Y(t)$, $Z(t)$





Credits: NASA/JPL; MPI for Gravitational Physics (AEI)/Einstein Online

Mosk LISA Data Challenges?

Mock LISA Data Challenges

- LISA data analysis presents unusual challenges;
  Need to coördinate searches for different types of signals
  Need plan worked out before LISA flies
- LISA International Science Team (LIST) has organized MLDCs to build community expertise
  Extract simulated signals from simulated LISA noise

Challenge	Dates	Results Presented
MLDC1	2006 Jun-Dec	GWDAW 11, Potsdam
MLDC2	2007 Jan-Jun	GR 18 / Amaldi 7, Sydney
MLDC1B	2007 Jul-Dec	GWDAW 12, Boston
MLDC3	2008 Jan-Dec	GWDAW 13, Arecibo

- Search for periodic signal from white-dwarf binaries
  by AEI team of Reinhard Prix, JTW & Deepak Khurana

Periodic GW Signals

Oscillating mass quadrupole generates periodic grav waves

- Searching for sinusoidal signals is easy:
  Fourier transform $\widetilde{x}(f)$ & look for peaks
- But signal won't be sinusoidal:
  - Motion of detector doppler-shifts signal
  - Change in orientation produces amplitude modulation
- Signal parameters:
  - 4 Amplitude params: GW amp, initial phase, inclination & orientation of WD orbit (or NS spin); Combine into $\{\mathcal{A}^\mu\}$
  - 3+ Doppler params: intrinsic f, ecliptic lat & lon of source (also spindown if appropriate); represent by θ

$\mathcal{F}$-Stat Search for Periodic GWs (JKS 1998)

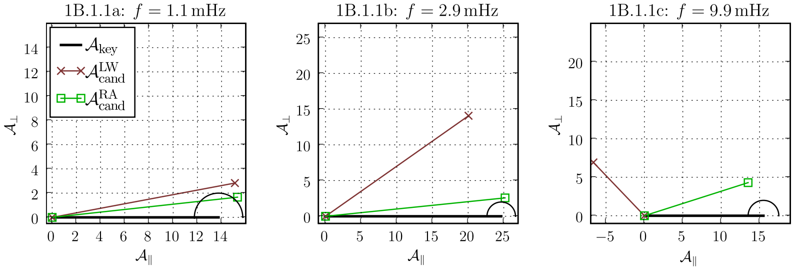
- Measured strain (= noise + signal) is (implicit $\sum_{\mu=1}^{4}$)
  $x(t;\mathcal{A},\theta) = n(t) + \mathcal{A}^{\mu} h_{\mu}(t;\theta)$
  $n(t)$ & $h_{\mu}(t;\theta)$ depend on detector, $\mathcal{A}$ does not
- Jaranowski, Królak, Schutz 1998: Log-likelihood

  $$-\int \frac{|\widetilde{x}(f) - \mathcal{A}^{\mu}\widetilde{h}_{\mu}(f)|^2}{S_n(f)} df + \int \frac{|\widetilde{x}(f)|^2}{S_n(f)} df = -\mathcal{A}^{\mu}\mathcal{M}_{\mu\nu}\mathcal{A}^{\nu} + 2\mathcal{A}^{\mu}x_{\mu}$$

  quadratic in $\mathcal{A}$; maximize analytically
- log-likelihood maximized by amplitude parameters
  $\mathcal{A}^{\mu}_{\mathrm{MLE}} = \mathcal{M}^{\mu\nu}x_{\nu}$; max value is $2\mathcal{F} = x_{\mu}\mathcal{M}^{\mu\nu}x_{\nu}$
- $\mathcal{F}$-stat search technique:
  - Make a grid of doppler params θ (freq & sky pos)
  - For each choice of θ, calculate $2\mathcal{F}$ from data
  - High values are candidate sources w/amp params $\mathcal{A}_{\mathrm{MLE}}$

Currently the basis of LIGO searches for spinning neutron stars

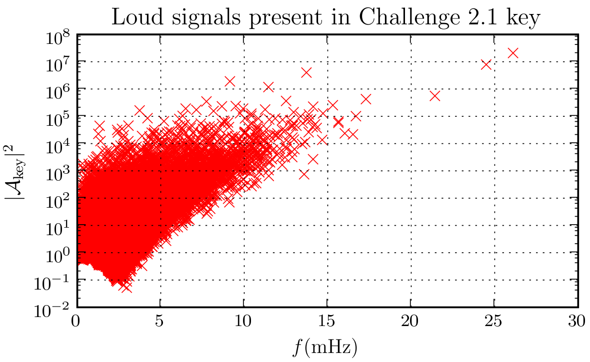
Challenge 1(B).1.1: Isolated Binaries



	f (mHz)	Δf(nHz) LW	Δf(nHz) RA	ϕ_{sky}(mrad) LW	ϕ_{sky}(mrad) RA	ϵ_θ LW	ϵ_θ RA
a	1.1	−0.7	−0.7	61.9	46.1	0.5	0.3
b	2.9	0.9	0.9	12.3	7.7	1.1	0.9
c	9.9	1.8	1.8	5.1	7.5	0.4	0.5

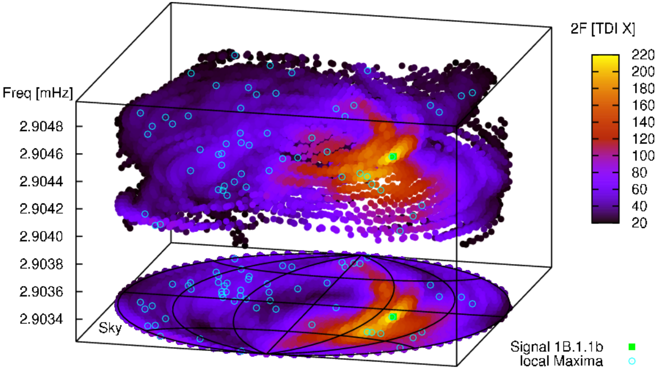
Good sky position even w/approx long-wavelength response
More accurate Rigid adiabatic resp needed for amp params

Galactic Binaries Injected in MLDC2



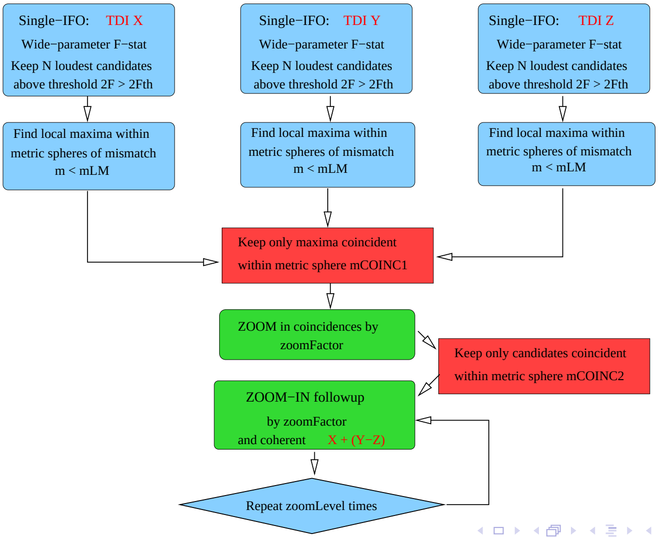
Challenge 2.1 has 26 million galactic WD binaries, of which 59401 designated as “bright” sources

Secondary Maxima in Doppler Parameter Space

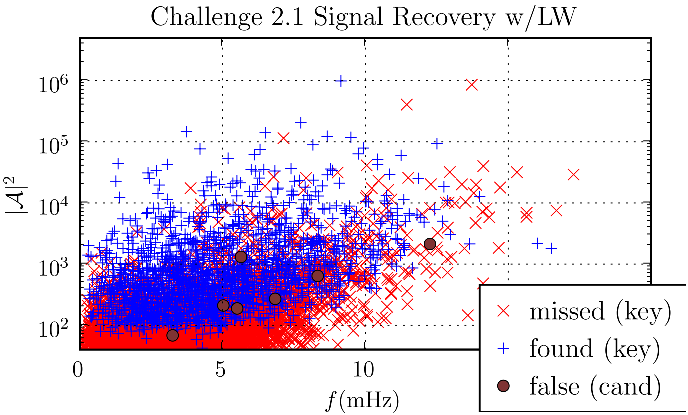


True signals identified by coïncidence btwn TDI vars

Pipeline for Prix/Whelan/Khurana MLDC Searches

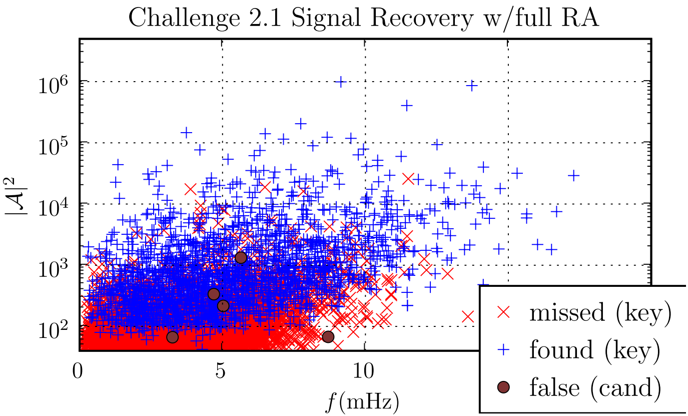


Overview of Galactic Signals Recovered (LW)



Found many signals, but still missed some bright ones (especially at higher f), using long-wavelength response

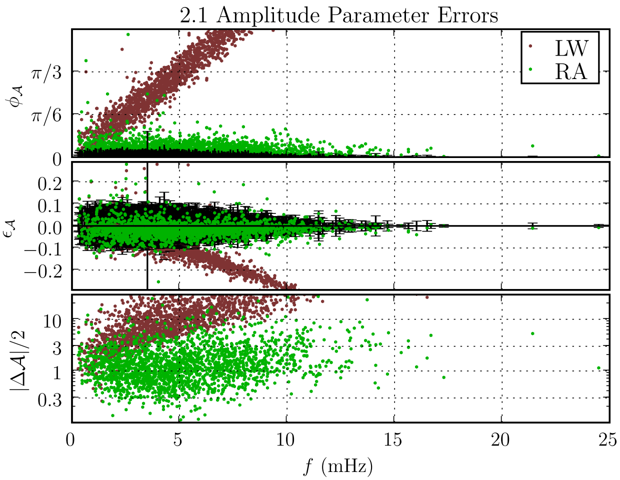
Overview of Galactic Signals Recovered (RA)



Rigid adiabatic response improves signal recovery

Loudest "misses" now found

Amplitude Accuracy w/RA



Amp param errors comp to statistical expectations

Statistics of Galactic Signals Recovered

Focus on sources w/expected $2\mathcal{F} > 40$

Freqs	Signals ($\lvert\mathcal{A}\rvert^2 > 40$)	Found LW	Found RA	False LW	False RA
0–5 mHz	4443	982	1025	1	2
5–10 mHz	1966	652	822	5	3
10–15 mHz	163	68	133	1	0
15–20 mHz	7	2	7	0	0
20–27 mHz	3	0	2	2	0
Total	6582	1704	1989	9	5

Improved response improves efficiency
Future searches may subtract found bright signals & iterate

Conclusions

- Mock LISA Data Challenge Searches
  (Prix, JTW, Khurana):
  $\mathcal{F}$-statistic method to find doppler-shifted periodic signals
  applied to mock LISA data
- Had to model LISA response beyond long-λ limit
  to get accurate amplitude param recovery
  & find higher-frequency signals
- Weaker signals can be mistaken for secondary maxima
  partially overcome by coïncidence condition
  Probably need signal subtraction to go further

Stay tuned for future MLDCs!