Searches for Galactic White Dwarf Binary Systems

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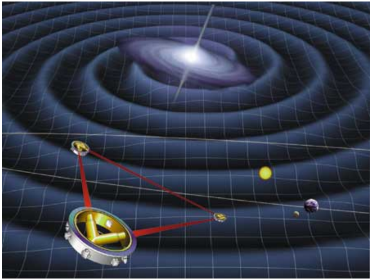
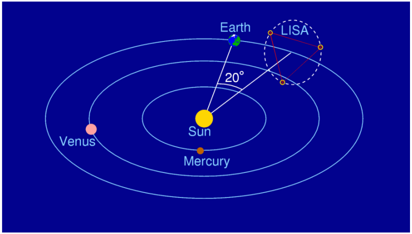
SFB/TR7 Meeting (C6)
2008 February 26
G080049-00-Z

Outline

LISA: Interferometry in Space

- Planned Joint NASA-ESA Mission: to launch 2018 or later
- 3 spacecraft will orbit sun in 5 mio km ▽
  & 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

Outline

1. LISA Searches at AEI
   - Search Programs
   - Mock LISA Data Challenges
2. White Dwarf Binary Search
   - $\mathcal{F}$-Statistic Search for Periodic Gravitational Waves
   - MLDC Pipeline and Results

LISA Search Programs at AEI

- Search for white-dwarf binaries (Prix, JTW, Khurana)
  Long-lived, nearly periodic
- Searches for supermassive black-hole binaries (Babak, Porter) Chirping inspiral
- Searches for extreme mass ratio inspirals (EMRIs) (Babak, Porter, Gair)
  Stellar-mass BH spirals into supermassive BH

Galactic White-Dwarf Binaries (Prix, JTW, Khurana)

- Quasi-periodic signal; can apply methods from ground-based searches for spinning neutron stars
- Many sources present; have to distinguish fainter signals from secondary maxima in parameter space
- AEI search uses $\mathcal{F}$-stat code developed for LIGO; coïncidence condition used to identify true signals.
- See posters outside & second half of this talk

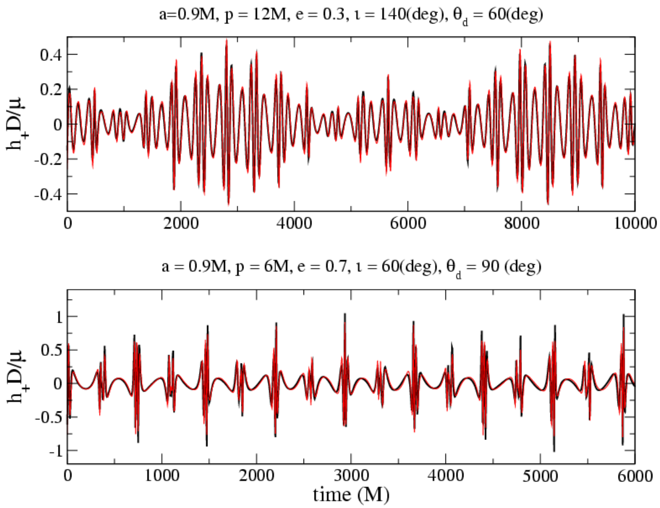
SMBH binaries (Babak, Porter)

- Group currently uses two independent search algorithms
- Can detect non-spinning binary in quasi-circular orbit
- Have started considering spins & eccentricities
- See posters outside & discussion this afternoon

Extreme Mass Ratio Inspirals (Babak, Porter, Gair)

- Stellar-mass compact object spirals into supermassive BH @ center of a galaxy
- Probe geometry near central BH – “spacetime mapping”
- Orbits typically eccentric & inclined
  waveforms depend on 14 different parameters
- Intricate waveforms (harmonics, precession)
  complicated likelihood structure in param space
- AEI: multi-stage Metropolis-Hastings stochastic search
  Seems to find loud EMRI signals

EMRI Waveform



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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
- MLDC1 ran from June-December 2006; results announced at GWDAW 11, Dec 2006, Potsdam
- MLDC2 ran from January-June 2007; results announced at GR 18 / Amaldi 7, Jul 2007, Sydney, Australia
- MLDC1B ran from July-December 2007; results announced at GWDAW 12, Dec 2007, Boston, Mass.
- MLDC3 runs from January-December 2008; results to be announced at GWDAW 13

First Mock LISA Data Challenge

- MLDC1 Results submitted December 2006
- MLDC1B Results submitted December 2007
- Data sets:
  - Challenge 1.1: White Dwarf Binaries: Periodic Sources
  - Challenge 1.2: Super-Massive Black Hole Inspirals
  - Challenge 1.3: Extreme Mass Ratio Inspirals (deadline postponed until MLDC2)
- Entries submitted by Prix/JTW (1.1), Cornish/Porter (1.2), Babak/Barack/Gair/Porter (1.3)

Second Mock LISA Data Challenge

- Results submitted June 2007
- Data sets:
  - Challenge 1.3: Extreme Mass Ratio Inspirals
  - Challenge 2.1: Galactic Binaries (30 Million)
  - Challenge 2.2: “Whole Enchilada”: Galaxy + EMRIs + BHB
- Entries submitted by Prix/JTW (WDB), Babak/Porter (SMBH), Cornish/Porter (SMBH), Babak/Barack/Gair/Porter (EMRI)

Third Mock LISA Data Challenge

- Results due December 2008
- Data sets:
  - Challenge 3.1: Galactic WDB w/frequency evolution
  - Challenge 3.2: SMBH binary + galaxy
  - Challenge 3.3: EMRIs
  - Challenge 3.4: Bursts
  - Challenge 3.5: Stochastic Background

Outline

Periodic GW Sources

- 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 changes projection $\overleftrightarrow{h} : \overleftrightarrow{d}$
- 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

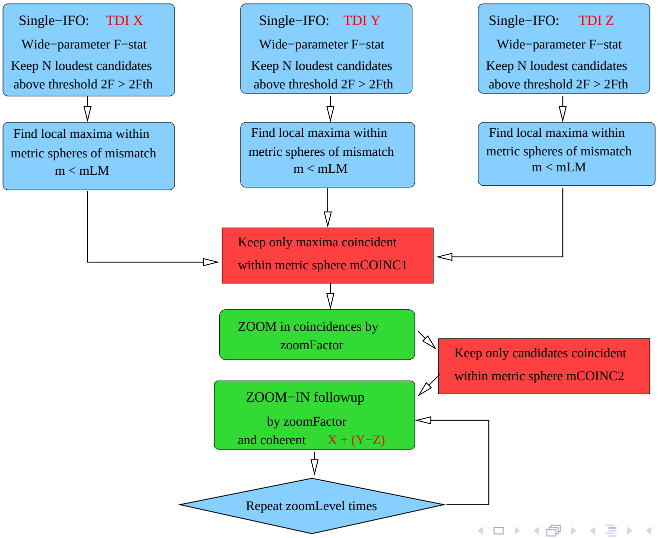
$$-\int \frac{|\widetilde{x}(f) - \mathcal{A}^\mu \widetilde{h}_\mu(f)|^2}{S_n(f)} df + \int \frac{|\widetilde{x}(f)|^2}{S_n(f)} df = -\mathcal{A}^\mu \mathcal{M}_{\mu\nu} \mathcal{A}^\nu + 2\mathcal{A}^\mu x_\mu$$

  quadratic in $\mathcal{A}$; maximize analytically
- log-likelihood maximized by amplitude parameters
  $\mathcal{A}^\mu_{\text{MLE}} = \mathcal{M}^{\mu\nu} x_\nu$; 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 $\mathcal{A}_{\text{MLE}}$

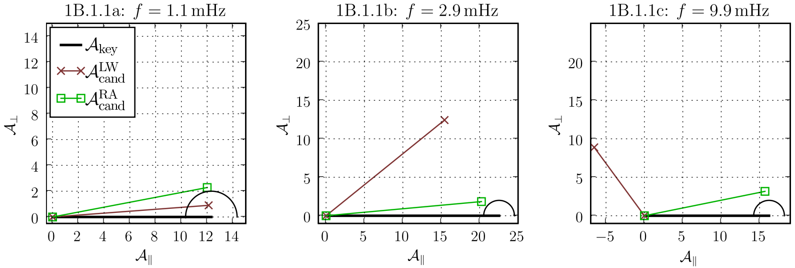
Currently the basis of LIGO searches for spinning neutron stars

Outline

Pipeline for Prix/Whelan/Khurana MLDC Searches



Challenge 1(B).1.1: Isolated Binaries

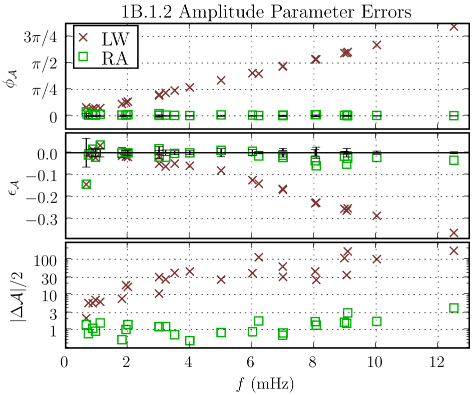


	f (mHz)	Δf(nHz) LW	Δf(nHz) RA	ϕ_{sky}(mrad) LW	ϕ_{sky}(mrad) RA	ϵ_θ LW	ϵ_θ RA
a	1.1	−2.4	−2.4	104.5	104.5	1.3	1.3
b	2.9	0.9	0.9	56.0	56.5	0.5	0.7
c	9.9	1.8	1.8	30.8	26.6	1.5	1.2

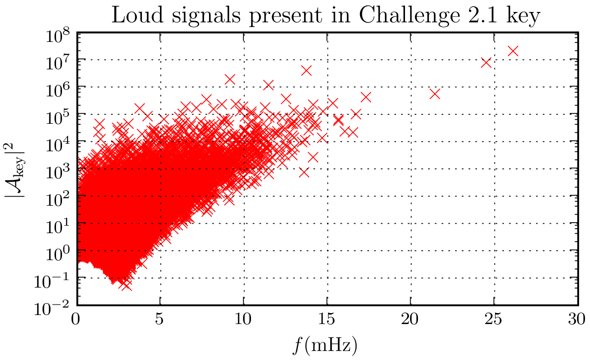
Good sky position even w/long-wavelength response
Rigid adiabatic response needed to get amp params

Challenge 1(B).1.2: Verification Binaries

20 verification binaries w/known dop params; amp params well fit if RA response used.

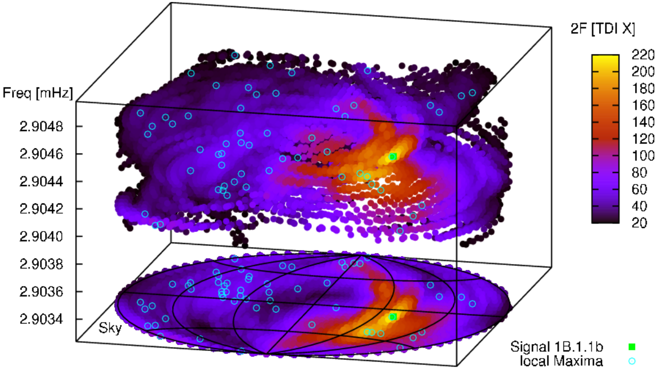


Galactic Binaries Injected in MLDC2



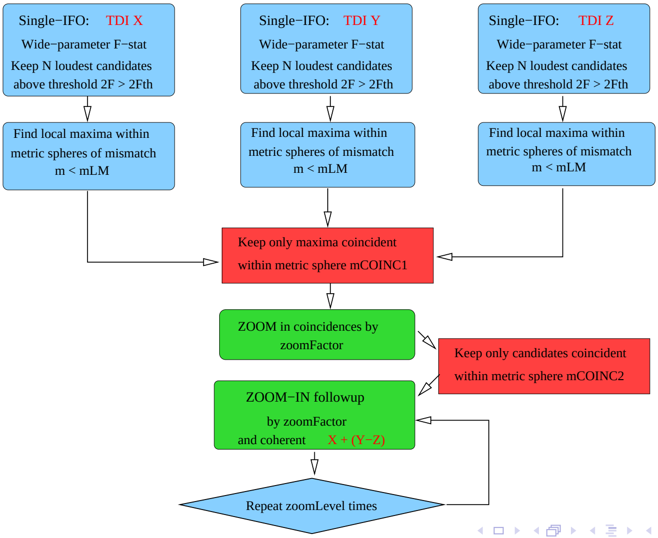
Challenge 2.1 has 26 million galactic WD binaries, of which 59401 designated as “bright” sources

Secondary Maxima in Doppler Parameter Space

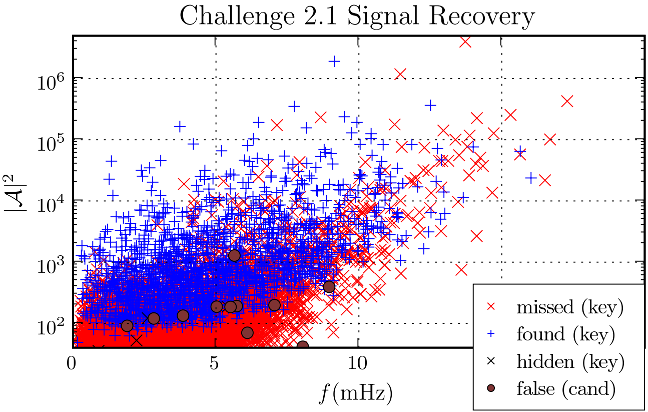


True signals identified by coïncidence btwn TDI vars

Pipeline for Prix/Whelan/Khurana MLDC Searches



Overview of Galactic Signals Recovered



Found many signals, but still missed some bright ones (especially at higher f)

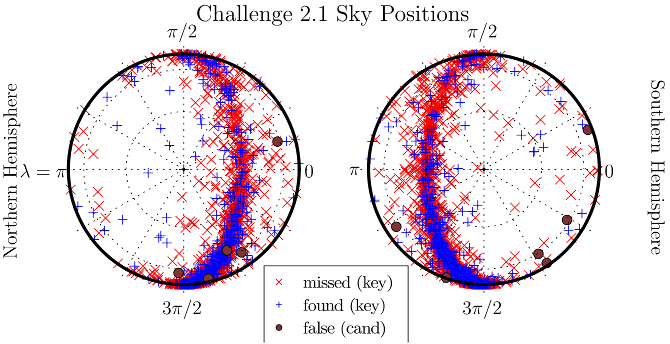
Statistics of Galactic Signals Recovered

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

Freqs	Found	Missed	Hidden	False
0–5 mHz	1012	3642	2	3
5–10 mHz	679	1363	1	8
10–15 mHz	73	90	0	0
15–20 mHz	2	5	0	0
20–27 mHz	0	3	0	0

Future searches will subtract found bright signals & iterate

Sky Map of Found & Missed Binaries



Galaxy clearly visible

Conclusions

- $\mathcal{F}$-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
- Weaker signals can be mistaken for secondary maxima
  partially overcome by coïncidence condition
  Probably need signal subtraction to go further
- MLDC3 adds $\dot{f}$ dim to param space
  may need to use semi-coherent methods