Gravitational Wave Searches w/LIGO & Virgo: Continuous Waves & Stochastic Backgrounds

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on behalf of the LIGO Scientific Collaboration
and the Virgo Collaboration
19th Int'l Conference on General Relativity & Gravitation
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Outline

1. Gravitational Waves Searches w/LIGO & Virgo
    - Observations
    - Data Analysis
2. Searches for Stochastic Backgrounds
    - Search Method
    - Isotropic Background Searches
    - Directional Searches
3. Searches for Periodic Signals
    - Targeted Searches
    - Directed Searches
    - All-Sky Searches

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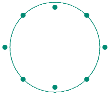
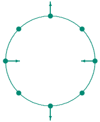
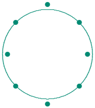
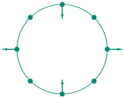
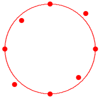
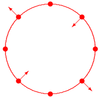
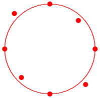
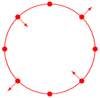
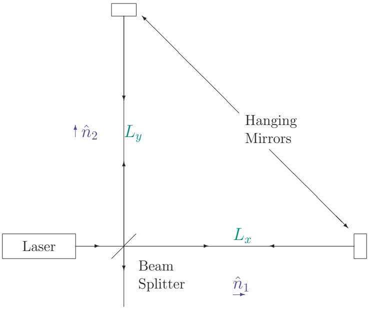
Gravitational Waves

- Generated by moving/oscillating mass distribution
- Lowest multipole is quadrupole

Plus (+) Polarization				
Cross (×) Polarization				

Measuring GWs w/Laser Interferometry

Interferometry: Measure GW-induced distance changes



- Measure small change in

$$L_x - L_y = \sqrt{g_{11} L_0^2} - \sqrt{g_{22} L_0^2}$$

$$= \sqrt{(1+h_{11}) L_0^2} - \sqrt{(1+h_{22}) L_0^2}$$

$$\approx L_0 \frac{h_{11} - h_{22}}{2} \sim L_0 h_+$$

- More gen,

$$(L_1 - L_2)/L_0 = \overset{\leftrightarrow}{h} : \overset{\leftrightarrow}{d}$$

with “response tensor”

$$\overset{\leftrightarrow}{d} = \frac{\hat{n}_1 \otimes \hat{n}_1 - \hat{n}_2 \otimes \hat{n}_2}{2}$$

(also when $\hat{n}_1$ & $\hat{n}_2$ not $\perp$)

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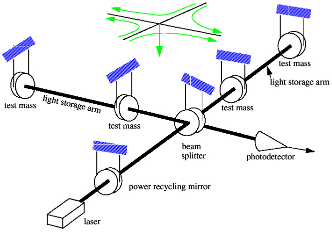

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$$L_x - L_y = \sqrt{g_{11} L_0^2} - \sqrt{g_{22} L_0^2}$$
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$$\approx L_0 \frac{h_{11} - h_{22}}{2} \sim L_0 h_+$$

- More gen, $(L_1 - L_2)/L_0 = \overleftrightarrow{h} : \overleftrightarrow{d}$ with "response tensor"

$$\overleftrightarrow{d} = \frac{\hat{n}_1 \otimes \hat{n}_1 - \hat{n}_2 \otimes \hat{n}_2}{2}$$

(also when $\hat{n}_1$ & $\hat{n}_2$ not $\perp$)

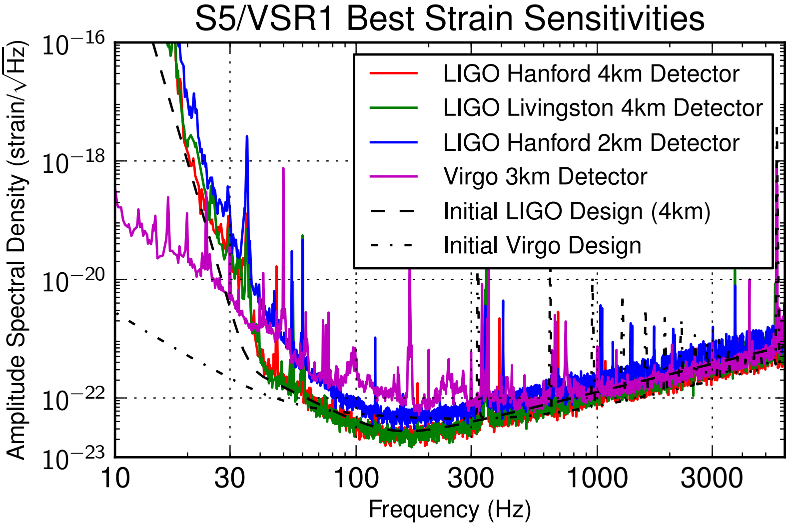
Rogues' Gallery of Ground-Based Interferometers

LIGO Hanford (Wash.)

LIGO Livingston (La.)

GEO-600 (Germany)

Virgo (Italy)


S5/VSR1 Best Strain Sensitivities
Amplitude Spectral Density (strain/√Hz)
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-23}
10
30
100
300
1000
3000
Frequency (Hz)
LIGO Hanford 4km Detector
LIGO Livingston 4km Detector
LIGO Hanford 2km Detector
Virgo 3km Detector
Initial LIGO Design (4km)
Initial Virgo Design

GW Observatory Network

- LSC detectors conducting science runs since 2002
  - LIGO Hanford (4km H1 & 2km H2)
  - LIGO Livingston (4km L1)
  - GEO-600 (600m G1)
- Virgo (3km V1) started science runs in 2007
- Recent long runs:
  - LIGO/GEO S5: Nov 2005-Sep 2007: LIGO @ design sens
  - Virgo VSR1: May-Sep 2007: Begin joint LSC-Virgo analysis
- Current/Ongoing joint runs:
  - LIGO (H1 & L1) S6: Jul 2009-Oct 2010
  - Virgo VSR2 Jul 2009-Jan 2010 & VSR3 about to start
- LIGO & Virgo will go offline in 2010/2011 to begin upgrade to Advanced Detectors

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Classification of GW Signals

In LIGO/Virgo band (10s-1000s of Hz),
natural division of sources:

	modelled	unmodelled
long	Periodic Sources (e.g., Rotating Neutron Star)	Stochastic Background (Cosmological or Astrophysical)
short	Binary Coalescence (Black Holes and/or Neutron Stars)	Bursts (Supernova, messy merger, etc.)

- This talk: long-lived sources (Stochastic and Periodic)
- Talk by D. Brown: Binary Coalescence
- Talk by J. Smith: Bursts

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Stochastic Background Search Method

- Noisy data from GW Detector:
  $x(t) = n(t) + h(t) = n(t) + \overleftrightarrow{h}(t) : \overleftrightarrow{d}$
- Look for correlations between detectors

$$\langle x_1 x_2 \rangle = \overbrace{\cancel{\langle n_1 n_2 \rangle}}^{\text{avgto0}} + \overbrace{\cancel{\langle n_1 h_2 \rangle}}^{\text{avgto0}} + \overbrace{\cancel{\langle h_1 n_2 \rangle}}^{\text{avgto0}} + \langle h_1 h_2 \rangle$$

- Expected cross-correlation (frequency domain)

$$\langle \tilde{x}_1^*(f) \tilde{x}_2(f') \rangle = \langle \tilde{h}_1^*(f) \tilde{h}_2(f') \rangle = \overleftrightarrow{d}_1 : \langle \overleftrightarrow{\tilde{h}}{}_1^*(f) \otimes \overleftrightarrow{\tilde{h}}_2(f') \rangle : \overleftrightarrow{d}_2$$

- For stochastic backgrounds

$$\langle \tilde{h}_1^*(f) \tilde{h}_2(f') \rangle = \delta(f - f') \gamma_{12}(f) \frac{S_{\text{gw}}(f)}{2}$$

$S_{\text{gw}}(f)$ encodes spectrum; $\gamma_{12}(f)$ encodes geometry

Detection Statistic

- Expected cross-correlation (frequency domain)

$$\langle \tilde{x}_1^*(f)\tilde{x}_2(f')\rangle = \langle \tilde{h}_1^*(f)\tilde{h}_2(f')\rangle = \delta(f-f')\gamma_{12}(f)\frac{S_{\text{gw}}(f)}{2}$$

- Optimally filtered cross-correlation statistic

$$Y = \int df\, \tilde{x}_1^*(f)\, Q(f)\, \tilde{x}_2(f)$$

- Filter encodes expected spectrum & spatial distribution (isotropic, pointlike, spherical harmonics . . .)

$$Q(f) \propto \frac{\gamma_{12}^*(f) S_{\text{gw}}^{\text{exp}}(f)}{S_{n1}(f) S_{n2}(f)}$$

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Searching for an Isotropic Background

- Simplest background would be isotropic & unpolarized
- Overlap reduction function from integral over sky

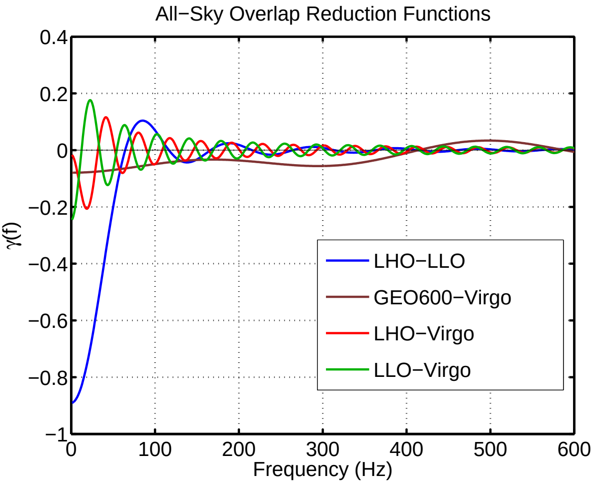
$$\gamma_{12}(f) = d_{1ab} d_2^{cd} \frac{5}{4\pi} \iint_{S^2} d^2\Omega_{\hat{k}}\, P^{\mathrm{TT}ab}{}_{cd}(\hat{k})\, e^{i2\pi f \hat{k}\cdot\Delta\vec{r}/c}$$

- Express spectrum in terms of contribution to $\Omega = \rho/\rho_{\mathrm{crit}}$:

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

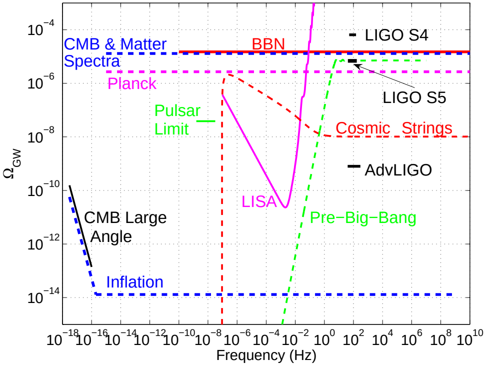
so

$$S_{\mathrm{gw}}(f) = \frac{3H_0^2}{10\pi^2} f^{-3}\, \Omega_{\mathrm{gw}}(f)$$



For flat spectrum, most sensitivity from LLO-LHO low freq

Stochastic Models and Limits



S5 limit $\Omega_{\mathrm{gw}}(f) < 6.9 \times 10^{-6} \left(\frac{72\,\mathrm{km}/\mathrm{s}/\mathrm{Mpc}}{H_0}\right)^2$

[Abbott et al (LSC & Virgo) *Nature* **460**, 990 (2009)]

surpasses indirect limit from Big-Bang Nucleosynthesis

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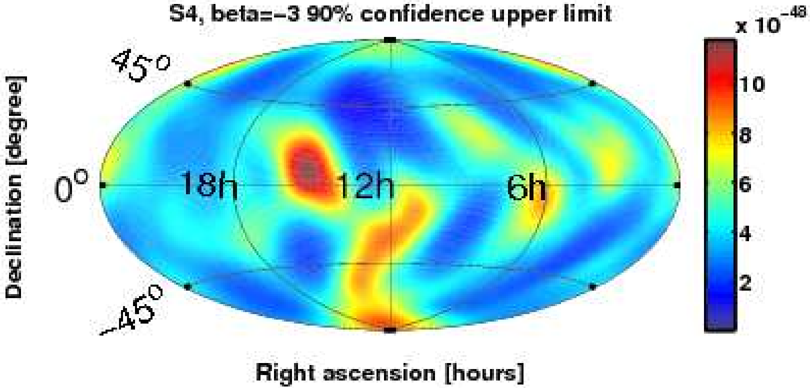
“Radiometer” Search for a Pointlike Background

- Adjust phases to optimally filter for random (unpolarized) signal propagating along $\hat{k}$:

$$\gamma_{12}(f) \propto d_{1ab} d_2^{cd} P^{\mathrm{TT}ab}{}_{cd}(\hat{k}) e^{i2\pi f \hat{k}\cdot\Delta\vec{r}/c}$$

- Provides unmodelled search for long-lived GWs from interesting direction (e.g., Scorpius X-1); note that true signal w/unknown polarization not same as unpolarized signal assumed by search.
- Can also look at all directions at once to produce maps; “dirty” map is anisotropic bg convolved w/pt spread fcn.
- S4 results in Abbott et al (LSC) *PRD* **76**, 082003 (2007); S5 results forthcoming

S4 Stochastic Upper Limit Map



Note: 10^{-48} in these units $\cong$

$\Omega_{\mathrm{gw}}(100\,\mathrm{Hz}) \sim 4 \times 10^{-7} \left(\frac{72\,\mathrm{km/s/Mpc}}{H_0}\right)^2$

(all from one point)

Other Search Methods

- Expand unknown stochastic BG in spherical harmonics & measure or set limits on coefficients (Thrane et al *PRD* **80**, 122002 (2009))
- Exploit sensitivity of LIGO-Virgo network to isotropic bg above 200 Hz (Cella et all *CQG* **24**, S639 (2007))

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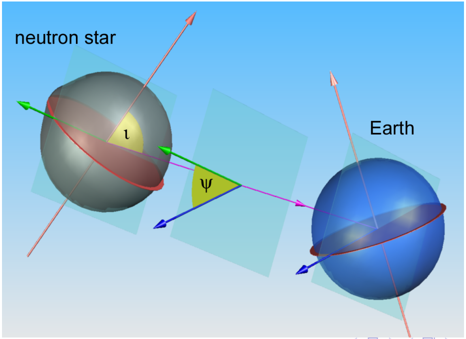
Continuous Wave Signals

- Rotating NS w/deformation or long-lived oscillation emits nearly sinusoidal signal

$$\overleftrightarrow{h}(t) = h_0 \left[\frac{1+\cos^2\iota}{2} \cos\Phi(\tau(t)) \overleftrightarrow{e}_+ + \cos\iota \sin\Phi(\tau(t)) \overleftrightarrow{e}_\times \right]$$



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  - $\Phi(\tau)$: phase evolution in rest frame f, $\dot{f}$, …
  - $\tau(t)$: Doppler mod from detector motion (& binary orbit)
- Templates parameterized by phase params (intrinsic) f, $\dot{f}$, sky pos (α, δ), orbital params (if NS in binary)
- Don’t need to search over amplitude params (extrinsic) h_0, spin orientation (ι, ψ), ϕ_0 (can analytically maximize likelihood over them)

Computing Cost and Search Strategies

All-sky coherent search of full phase param space infeasible:
# of templates skyrockets w/increasing integration time
E.g, for all-sky search with one spindown,

$$N_{\text{tmplts}} \sim \frac{1}{\Delta f}\frac{1}{\Delta \dot{f}}\frac{1}{\Delta \text{sky}} \sim T \cdot T^2 \cdot (fT)^2 \propto T^5$$

Different strategies depending on knowledge of object:

- Known pulsars: all phase parameters known,
  can do fully coherent **Targeted Search**
  Note $f_{\text{gw}} = 2f_{\text{rot}}$ for triaxial ellipsoid rotating about principal axis
- Unknown objects: need to use semi-coherent methods for **All-Sky Search**
- Known objects not seen as pulsars
  (e.g., SN remnants, LMXBs): can do **Directed Search**
  but need to cope w/uncertain remaining phase parameters

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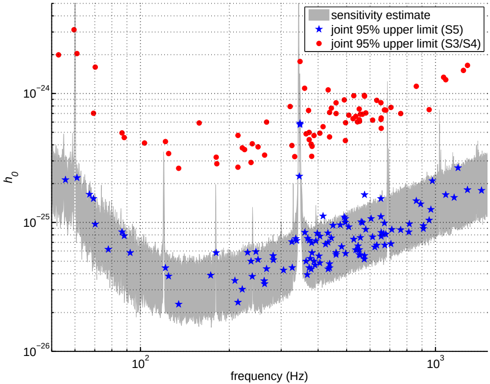
Searching for Known Pulsars

- Phase params (rotation, sky pos [& binary params]) known
- Can search over amplitude params (h_0, ι, ψ, ϕ_0); search cost NOT driven by observing time
- Use Markov-Chain Monte Carlo to obtain posterior probability distribution for amplitude parameters
- Posterior on h_0 gives upper limit on GW strength (if no detection)

Known Pulsar Upper Limits

Limits set on 116 pulsars w/rotation freq $> 20\,\mathrm{Hz}$ ($f_{\mathrm{gw}} > 40\,\mathrm{Hz}$)



Abbott et al (LSC & Virgo) + Bégin et al *ApJ* **713**, 671 (2010)

Crab Pulsar Upper Limit

- Isolated pulsars have indirect spindown upper limit
  GW emission above limit ⟶ more spindown than seen
- For the Crab Pulsar, LIGO upper limit beats spindown limit
  Abbott et al (LSC) *ApJL* **683**, L45 (2008)
  Abbott et al (LSC & Virgo) *ApJ* **713**, 671 (2010)
  No more than 2% of spindown energy loss can be in GW
- Thanks to its low-frequency sensitivity, Virgo should also be able to reach spindown limit for Vela ($f_{\mathrm{GW}} = 22.38\,\mathrm{Hz}$)

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Directed Search Methods

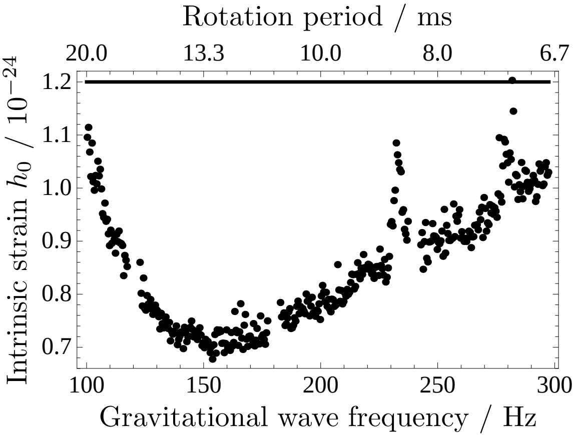
- Known or suspected neutron stars not seen as pulsars
- Knowledge of sky position reduces parameter space
- Can do fully coherent search on short stretch of data using $\mathcal{F}$-statistic method (Jaranowski, Królak, Schutz *PRD* **58**, 063001 (1998)):
  - Search over remaining phase params (freq & orbit)
  - Analytically maximize likelihood ratio over amp params
  - Use maximized likelihood as detection statistic
- To use all available data instead,
  need to combine coherent sub-searches incoherently

Cassiopeia A

- Supernova remnant $\sim 3\,\text{kpc}$ away, $\sim 300\,\text{yr}$ old; central compact object seen in x-rays, but spin period unknown
- Indirect limit on GW emission from age of neutron star
- Sky position known, can search over f, $\dot{f}$, $\ddot{f}$ param space using $\mathcal{F}$-stat on 12 days of LIGO S5 Data: Abadie et al (LSC & Virgo) arXiv:1006.2535

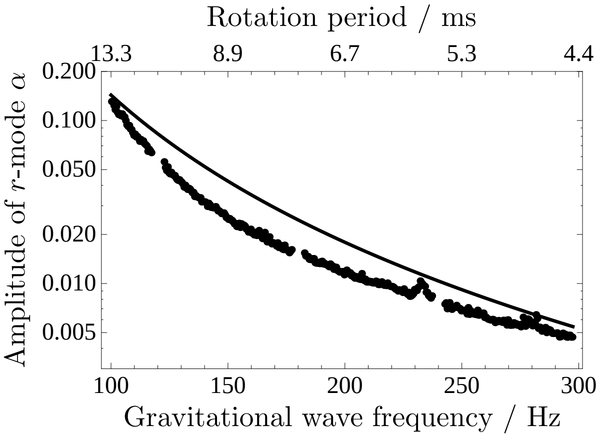
Cas A Upper Limits

LIGO upper limit surpasses indirect limit below 300 Hz

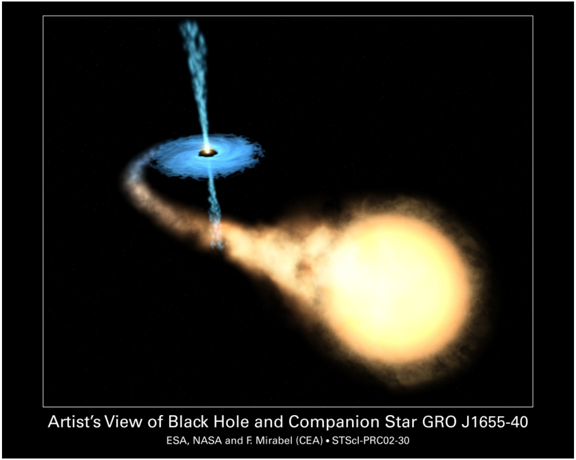


Cas A Upper Limits: r-Modes

Also set limit on strength of r-mode oscillation of Cas A CCO



Low-Mass X-Ray Binaries


Artist's View of Black Hole and Companion Star GRO J1655-40
ESA, NASA and F. Mirabel (CEA) • STScI-PRC02-30

Compact object accreting mass from companion star

Searching for Neutron Stars in LMXBs

- LMXB: BH/NS/WD accreting mass from companion star
- Accretion spinup may be balanced by GW spindown [Bildsten *ApJL* **501**, L89 (1998)] → no $\dot{f}$
- Scorpius X-1: $1.4M_\odot$ NS w/$0.4M_\odot$ companion unknown params are f_0, $a \sin i$, orbital phase
- LSC/Virgo searches for Sco X-1:
  - Coherent $\mathcal{F}$-stat search w/6 hr of S2 data Abbott et al (LSC) *PRD* **76**, 082001 (2007)
  - Directed stochastic ("radiometer") search (unmodelled)
  - Look for comb of lines produced by orbital modulation Messenger & Woan, *CQG* **24**, 469 (2007)
  - Cross-correlation specialized to periodic signal Dhurandhar et al *PRD* **77**, 082001 (2008)

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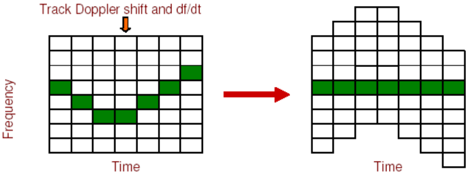
Semicoherent Searches

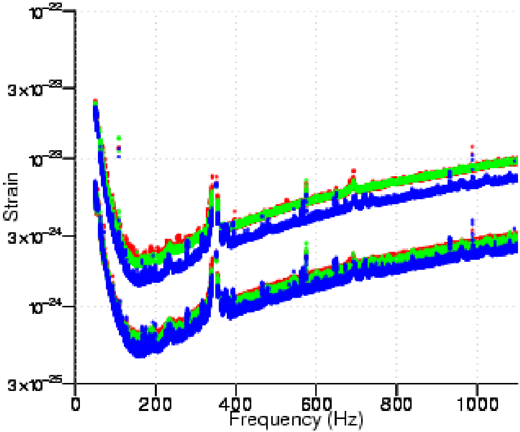
- Recall fully coherent searches limited by compute costs
- To probe full parameter space without restricting obs time, need to use semicoherent or incoherent methods
- E.g., shift Fourier bins by Doppler modulation & add power



- All-sky search results from first 8 months of LIGO S5 in Abbott et al (LSC) *PRL* **102**, 111102 (2009)

Early S5 All-Sky (PowerFlux) Result

ULs as a fcn of freq for different sky locations & orientations

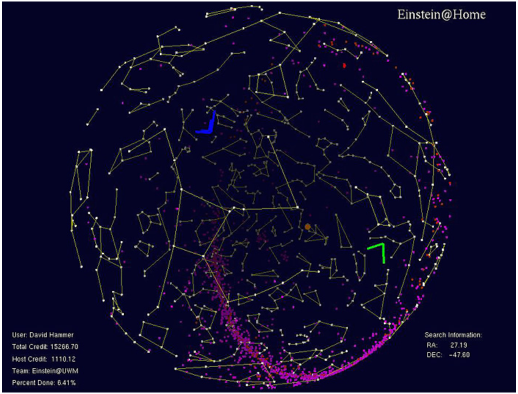


Abbott et al (LSC) *PRL* **102**, 111102 (2009)

Einstein@Home

Increase computing resources by enlisting volunteers

Distributed using BOINC & run as screensaver



User: David Hammer
Total Credit: 15266.70
Host Credit: 1110.12
Team: Einstein@UWM
Percent Done: 6.41%

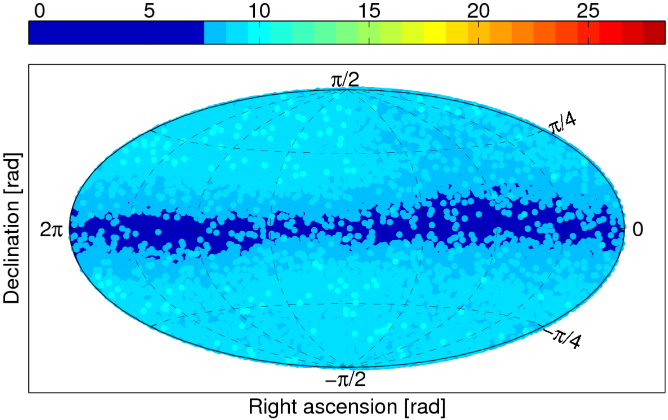
Search Information:
RA: 27.19
DEC: -47.60

http://www.einsteinathome.org/

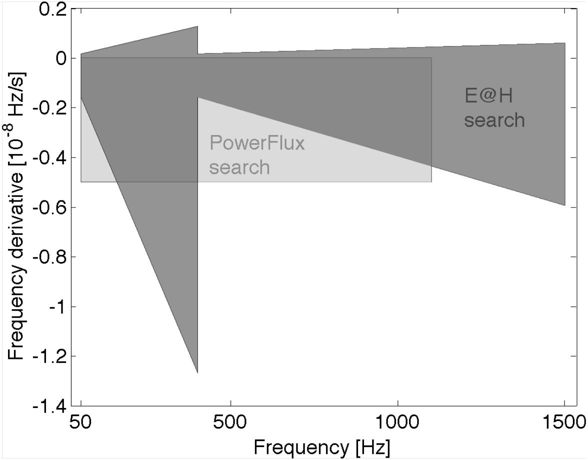
Einstein@Home Method

$\mathcal{F}$-stat calc on shorter segments; look for candidates in coinc

Early S5 results: Abbott et al (LSC) *PRD* **80**, 042003 (2009)



Comparison of All-Sky Searches



E@H and PowerFlux: complementary parts of param space

Summary

- Variety of searches for long-lived signals in LIGO/Virgo data
- Stochastic (unmodelled) searches w/cross-correlation
  - Isotropic
  - Directional
- CW (periodic, modelled) searches w/coherent & semicoherent methods
  - Targeted
  - All-Sky
  - Directed
- Direct observations starting to surpass indirect limits
  - Isotropic Stochastic BG beats BBN limit
  - Crab Pulsar beats spindown limit
  - Cas A beats spindown age limit
- Gearing up for advanced detector data