Searching for Periodic Gravitational Waves from Spinning Neutron Stars

Reinhard Prix

Albert-Einstein-Institut Hannover

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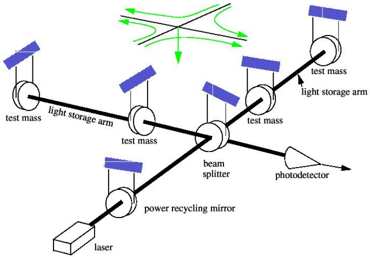
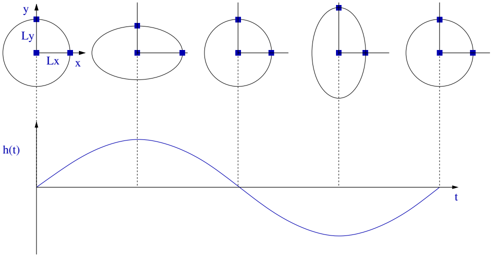
Outline

Detection of gravitational waves

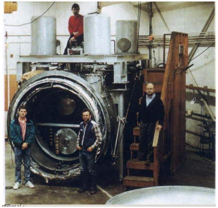




Measure scalar Strain $h(t) \equiv \frac{L_x(t) - L_y(t)}{2L} \overset{LWL}{\approx} \frac{1}{2} d^{ij} \, h^{TT}_{ij}$

☞ *"listening"* to the Universe

Worldwide Network of Detectors



Continuous GWs from Spinning Neutron Stars

Rotating neutron star:

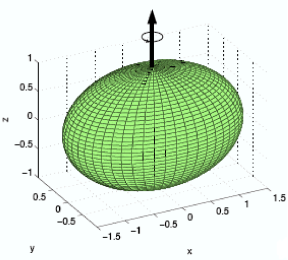
- non-axisymmetric $\epsilon = \frac{|I_{xx} - I_{yy}|}{I_{zz}}$
- rotation rate ν

☞ GW with frequency $f = 2\,\nu$

Strain-amplitude h_0 on earth:

$$h_0 = \left(\frac{16\pi^2\,G}{c^4}\right)\,\frac{\epsilon\,I_{zz}\,\nu^2}{d}$$

$$= 4 \times 10^{-25}\left(\frac{\epsilon}{10^{-6}}\right)\left(\frac{I_{zz}}{10^{45}\,\mathrm{g\,cm}^2}\right)\left(\frac{\nu}{100\ \mathrm{Hz}}\right)^2\left(\frac{100\,\mathrm{pc}}{d}\right)$$



1st generation sensitivity (S5/S6): $\sqrt{S_\mathrm{n}} \sim 2 \times 10^{-23}\,\mathrm{Hz}^{-1/2}$

☞ CW signals buried in the noise $\Longrightarrow$ need "matched filtering"

$\mathrm{SNR} \propto \frac{h_0}{\sqrt{S_n}}\sqrt{T}$ observation time $T \sim (\mathrm{days} - \mathrm{months})$

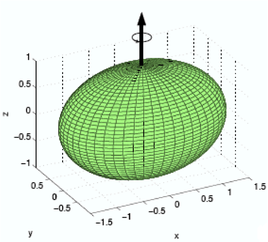
Different CW emission mechanisms

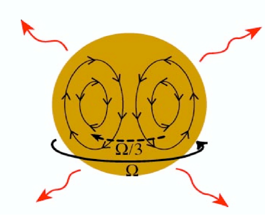
Continuous waves:

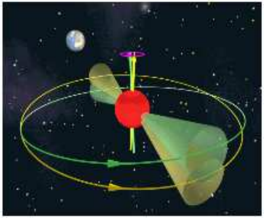
- CW lifetime $\gtrsim T_{\rm obs}$
- quasi-monochromatic sinusoid $f \sim \mathcal{O}(\nu)$

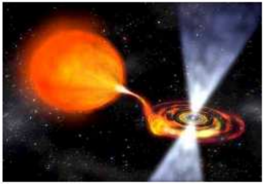
Emission mechanisms:

- "Mountains" ($f = 2\nu$)
- Oscillations (r-modes: $f \sim 4\nu/3$)
- Free precession ($f \sim \nu, 2\nu$)
- Accretion (driver)









Statistics as applied Probability Theory

Probability Theory: an extension of the framework of deductive logic to work with *incomplete information* (“Inference”)

[Jaynes, Cox]

A ... logical proposition, e.g.

A = “There is a (detectable) GW signal in this data”

$A(h_0, f)$ = “The GW signal has amplitude h_0, frequency f”

$P(A|I) \equiv$ 'plausibility' of A being true *given* I

'I' ... set of relevant 'knowledge' and model assumptions

$P(A|I)$ quantifies an observer's state of knowledge about A

☞ not an intrinsic property of the observed system!

(Jaynes “Mind projection fallacy”)

The Three Laws

(Cox 1946, 1961, Jaynes) Requiring 3 conditions for $P(A|I)$:
(i) $P \in \mathbb{R}$, (ii) consistency, (iii) agreement with "common sense"
one can *derive* unique laws of probability (up to gauge):

1. $P(A|I) \in [0,1]$ $\quad \begin{cases} P(A|I) = 1 & \Leftrightarrow (A|I) \text{ certainly true} \\ P(A|I) = 0 & \Leftrightarrow (A|I) \text{ certainly false} \end{cases}$
2. $P(A|I) + P(\text{not } A|I) = 1$
3. $P(A \text{ and } B|I) = P(A|B,\, I)\; P(B|I)$

☞ $P(A|B,I) = P(B|A,I)\,\frac{P(A|I)}{P(B|I)}$ ("Bayes' theorem")
☞ $P(A \text{ or } B|I) = P(A|I) + P(B|I) - P(A \text{ and } B|I)$

We observe data 'x', what can we learn from it?

Formulate "question" as a proposition A and *compute* $P(A|\mathbf{x}, I)$

Hypothesis Testing

The usual GW hypotheses

$\mathcal{H}_\mathrm{G}$: data is pure Gaussian noise: $\mathbf{x}(t) = \mathbf{n}(t)$

$\mathcal{H}_\mathrm{S}$: data is *signal* + GN: $\mathbf{x}(t) = \mathbf{n}(t) + \mathbf{h}(t; \mathcal{A}, \lambda)$

Data from several detectors: $\mathbf{x} = \{x^1, x^2, \ldots\}$
Gaussian noise: $P(\mathbf{n}|\mathbf{S}_\mathrm{n}) = \kappa\, e^{-\frac{1}{2}(\mathbf{n}|\mathbf{n})}$

Signal amplitude parameters $\mathcal{A} = \{h_0, \cos\iota, \psi, \phi_0\}$
CW Signal phase parameters $\lambda = \{\text{sky-position}, f, \dot{f}, \ldots\}$

☞ Given $\mathbf{x}$, how can we decide between $\mathcal{H}_\mathrm{G}$ and $\mathcal{H}_\mathrm{S}$?

Bayes factor

Directly *compute* $P\left(\mathcal{H}_\mathrm{S}|\mathbf{x}, I\right)$, or equivalently compute "odds":

$$O_\mathrm{SG}(\mathbf{x}) \equiv \underbrace{\frac{P\left(\mathcal{H}_\mathrm{S}|\mathbf{x}, I\right)}{P\left(\mathcal{H}_\mathrm{G}|\mathbf{x}, I\right)}}_{\text{"Posterior odds"}} = \underbrace{\frac{P\left(\mathbf{x}|\mathcal{H}_\mathrm{S}, I\right)}{P\left(\mathbf{x}|\mathcal{H}_\mathrm{G}, I\right)}}_{\text{"Bayes factor"}} \times \underbrace{\frac{P\left(\mathcal{H}_\mathrm{S}|I\right)}{P\left(\mathcal{H}_\mathrm{G}|I\right)}}_{\text{"prior odds"}},$$

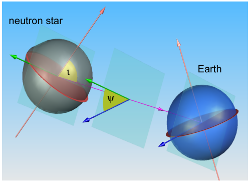
Assume *given* phase parameters λ, *unknown* $\mathcal{A}$

Bayes factor $B_\mathrm{SG}(\mathbf{x})$ "updates" our knowledge about $\mathcal{H}_\mathrm{S}$:

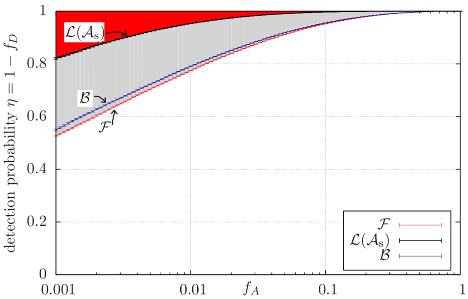
$$B_\mathrm{SG}(\mathbf{x}) = \int \mathcal{L}(\mathbf{x}; \mathcal{A})\, P\left(\mathcal{A}|\mathcal{H}_\mathrm{S}, I\right) d^4\mathcal{A}$$

- $\mathcal{A}$-prior $P\left(\mathcal{A}|\mathcal{H}_\mathrm{S}, I\right)$
- Likelihood ratio $\mathcal{L}(\mathbf{x}; \mathcal{A}) \propto \exp[-\frac{1}{2}\mathcal{A}^\mu \mathcal{M}_{\mu\nu}\mathcal{A}^\nu + \mathcal{A}^\mu\, x_\mu]$

What $\mathcal{A}$-prior to use? Beating the $\mathcal{F}$-statistic ...



- simple prior: $P\left(\mathcal{A}^\mu|\mathcal{H}_S\right) = \text{const}$
  ☞ $\mathcal{B}_\mathcal{F}(\mathbf{x}) = \int \mathcal{L}(\mathbf{x};\mathcal{A})\, d^4\mathcal{A}^\mu \propto e^{\mathcal{F}(\mathbf{x})}$
- *correct* prior $P\left(\mathcal{A}|\mathcal{H}\right)$: isotropic NS axis
  ☞ $\mathcal{B}(\mathbf{x}) \equiv \int \mathcal{L}(\mathbf{x};\mathcal{A})\, dh_0\, d\cos\iota\, d\psi\, d\phi_0$



- $\mathcal{F}$-statistic historically derived as $\max_\mathcal{A} \mathcal{L}(\mathbf{x};\mathcal{A}) \propto e^{\mathcal{F}(\mathbf{x})}$ [JKS(1998)]
- $\mathcal{B}(x)$ is *more powerful* than $\mathcal{F}(x)$
  R Prix, B Krishnan, CQG 26 (2009)
- $\mathcal{B}(x)$ is Neyman-Pearson *optimal*
  A Searle, arXiv:0804.1161 (2008)

Can we make $\mathcal{F}$ more robust vs “line” artifacts?

Problem with $O_{\mathrm{SG}}(\mathbf{x}) = \frac{P(\mathcal{H}_\mathrm{S}|\mathbf{x})}{P(\mathcal{H}_\mathrm{G}|\mathbf{x})} \propto e^{\mathcal{F}(\mathbf{x})}$

Anything that resembles $\mathcal{H}_\mathrm{S}$ more than Gaussian noise $\mathcal{H}_\mathrm{G}$ can trigger large O_{SG}, regardless of its “goodness-of-fit” to $\mathcal{H}_\mathrm{S}$!

e.g. quasi-monochromatic+stationary detector artifacts (“lines”)

☞ add an *alternative* hypothesis $\mathcal{H}_\mathrm{L}$ to capture “lines”

“Zeroth order line”: single-detector signal trigger

$\mathcal{H}_\mathrm{L}$ = "**x** looks like a signal in only one detector"

☞ $$\mathcal{H}_\mathrm{L} \equiv \left[\left(\mathcal{H}_\mathrm{S}^1 \text{ and } \mathcal{H}_\mathrm{G}^2 \right) \text{ or } \left(\mathcal{H}_\mathrm{G}^1 \text{ and } \mathcal{H}_\mathrm{S}^2 \right) \right]$$

Extended CW statistics

Using 'simple' $\mathcal{F}$-stat priors: $P(\mathcal{H}_\mathrm{L}|\mathbf{x}) \propto l_1\, e^{\mathcal{F}_1(x_1)} + l_2\, e^{\mathcal{F}_2(x_2)}$

with prior line odds $l_D \equiv \frac{P(\mathcal{H}_\mathrm{L}^D|I)}{P(\mathcal{H}_\mathrm{G}^D|I)}$ in detector D

Two ways to use $\mathcal{H}_\mathrm{L}$:

1. line "veto" statistic: $O_\mathrm{SL}(\mathbf{x}) \equiv \frac{P(\mathcal{H}_\mathrm{S}|\mathbf{x})}{P(\mathcal{H}_\mathrm{L}|\mathbf{x})}$

   e.g. for loud candidates with $\mathcal{F}(\mathbf{x}) > \mathcal{F}^*$

2. "line-robust" detection statistic: $O_\mathrm{SN}(\mathbf{x}) \equiv \frac{P(\mathcal{H}_\mathrm{S}|\mathbf{x})}{P(\mathcal{H}_\mathrm{N}|\mathbf{x})}$

   with extended noise hypothesis: $\mathcal{H}_\mathrm{N} \equiv (\mathcal{H}_\mathrm{G}$ or $\mathcal{H}_\mathrm{L})$

(used in E@H S6Bucket, S6LV1)

[Prix, Keitel, Papa, Leaci, Siddiqi, in preparation]

Line "veto" followup O_{SL}

☞ $$O_{\mathrm{SL}}(\mathbf{x}) \equiv \frac{P(\mathcal{H}_{\mathrm{S}}|\mathbf{x})}{P(\mathcal{H}_{\mathrm{L}}|\mathbf{x})} \propto \frac{e^{\mathcal{F}(\mathbf{x})}}{l_1\, e^{\mathcal{F}_1(x_1)} + l_2\, e^{\mathcal{F}_2(x_2)}}$$

Special case $l_1 = l_2$: $(\mathcal{F}_{\max} \equiv \max\{\mathcal{F}_1, \mathcal{F}_2\})$

$$\ln O_{\mathrm{SL}}(\mathbf{x}) = c_0 + [\mathcal{F}(\mathbf{x}) - \mathcal{F}_{\max}(x)] - \underbrace{\ln\left(1 + e^{(\mathcal{F}_{\min} - \mathcal{F}_{\max})}\right)}_{\in[0,\ln 2]}$$

Recover *ad-hoc* veto criterion as special case

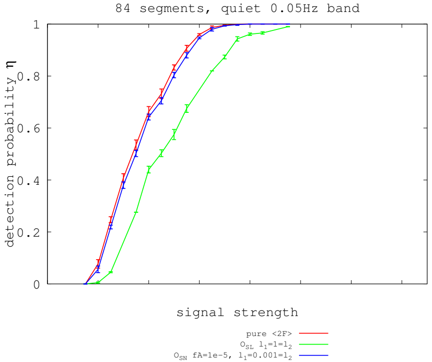
$$\ln O_{\mathrm{SL}}(\mathbf{x}) - c_0 \approx \mathcal{F}(\mathbf{x}) - \mathcal{F}_{\max}(x)$$

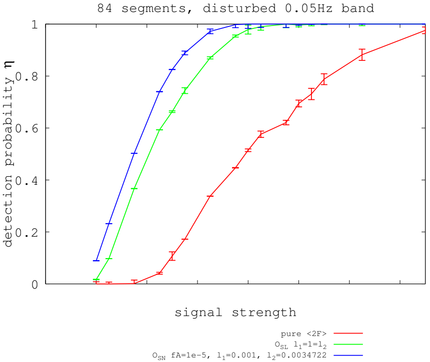
☞ veto if $\mathcal{F}_{\max}(x) > \mathcal{F}(\mathbf{x}) \iff$ special choice of threshold!

“Line-robust” detection statistic $O_{\mathrm{SN}}(\mathbf{x})$

$$O_{\mathrm{SN}}(\mathbf{x}) \equiv \frac{P(\mathcal{H}_{\mathrm{S}}|\mathbf{x})}{P(\mathcal{H}_{\mathrm{L}}|\mathbf{x}) + P(\mathcal{H}_{\mathrm{G}}|\mathbf{x})} \propto \frac{e^{\mathcal{F}(\mathbf{x})}}{e^{\mathcal{F}^*} + l_1\, e^{\mathcal{F}_1(x_1)} + l_2\, e^{\mathcal{F}_2(x_2)}}$$

- $\mathcal{F}^*$ is a prior constant (requires “tuning”)
- ☞ estimate prior line-odds l_D from detector data!





Neutron Star "Mountains": What do we know?

- *Maximal possible* deformations:
  - Conventional NS crustal shear:
    ☞ $\epsilon_{\max} \sim 10^{-7} - 10^{-6}$ [Ushomirsky, Cutler, Bildsten]
  - Exotic EOS: strange-quark solid cores
    ☞ $\epsilon_{\max} \sim 10^{-5} - 10^{-4}$ [B. Owen]
- Models predicting *actual* deformations:
  - large toroidal field $B_t \sim 10^{15}\,\mathrm{Gauss} \perp$ to rotation:
    ☞ $\epsilon \sim 10^{-6}$ [C. Cutler]
  - accretion along B-lines $\Longrightarrow$"bottled" mountains
    ☞ $\epsilon \sim 10^{-6} - 10^{-5}$ [Melatos, Payne]
- *Minimal* deformation from magnetic field:

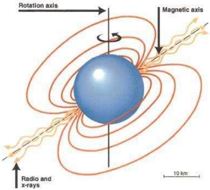
☞ $\epsilon_{\min} \sim 10^{-12} \left(\frac{B}{10^{12}\mathrm{Gauss}}\right)^2$ [Haskell et al.(2008)]

$\Longrightarrow$ Prior range: $\epsilon \in \left[10^{-12}, 10^{-4}\right]$

Spindown upper-limit for CWs from known pulsars

Rotational energy lost: $\dot{E}_{\mathrm{rot}} \propto I_{zz} \underbrace{\nu\,\dot{\nu}}_{\mathrm{observed}}$

Energy emitted in GWs: $\dot{E}_{\mathrm{GW}} \propto \nu^6\, I_{zz}^2\, \epsilon^2$



Spindown upper limit: Spindown fully due to GW emission

Assumed I_{zz} (from EOS) and known distance d:

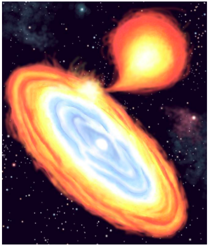
$\Longrightarrow$ Upper limit on deformation ϵ:

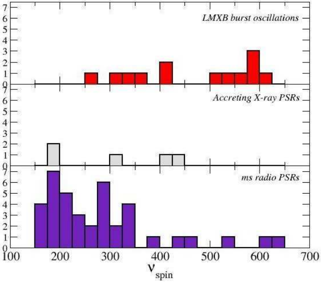
$$\epsilon_{\mathrm{sd}} \propto \sqrt{\frac{1}{I_{zz}} \frac{|\dot{\nu}|}{\nu^5}}$$

$\Longrightarrow$ Upper limit on amplitude h_0:

$$h_{\mathrm{sd}} \propto \frac{1}{d} \sqrt{I_{zz} \frac{|\dot{\nu}|}{\nu}}$$

Accretion





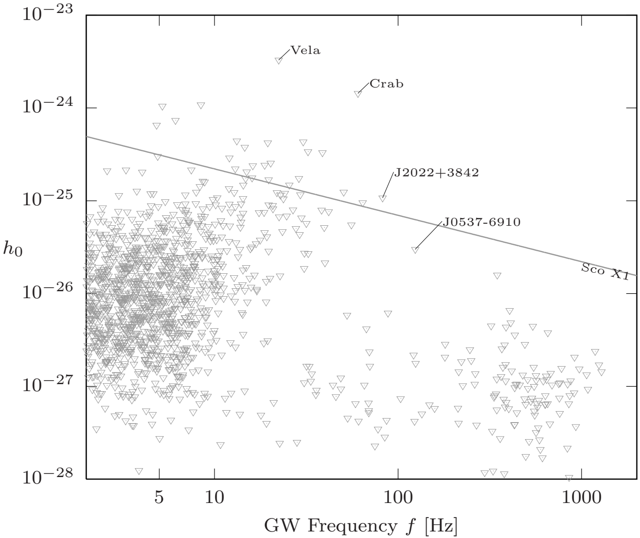
Breakup-limit $\nu_K \sim 1.5$ kHz ☞ What limits the NS-spin?

Bildsten, Wagoner: Accretion-torque = GW torque ($\propto \nu^5$)

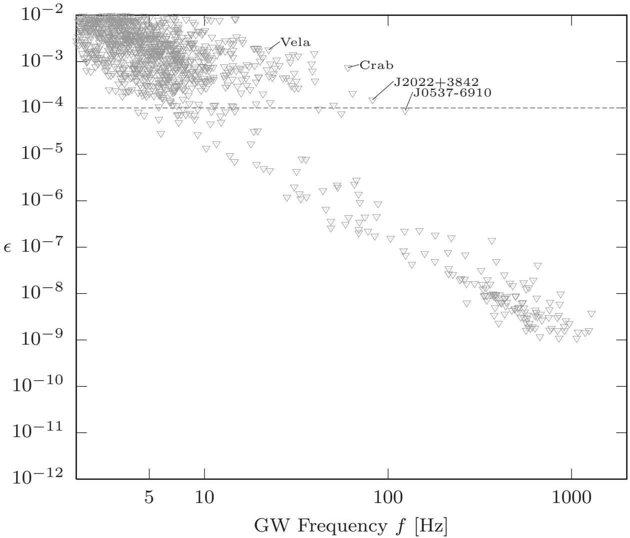
$$h_0 \approx 5 \times 10^{-27} \left(\frac{300\,\mathrm{Hz}}{\nu}\right)^{1/2} \left(\frac{F_\mathrm{x}}{10^{-8}\,\mathrm{erg\,cm^{-2}\,s^{-1}}}\right)^{1/2} .$$

☞ Sco X-1: $h_0(f = 2\nu) \sim 3 \times 10^{-26}\,(540\,\mathrm{Hz}/f)^{1/2}$

Spindown Upper Limits: h_0



Spindown and Indirect Upper Limits: ϵ



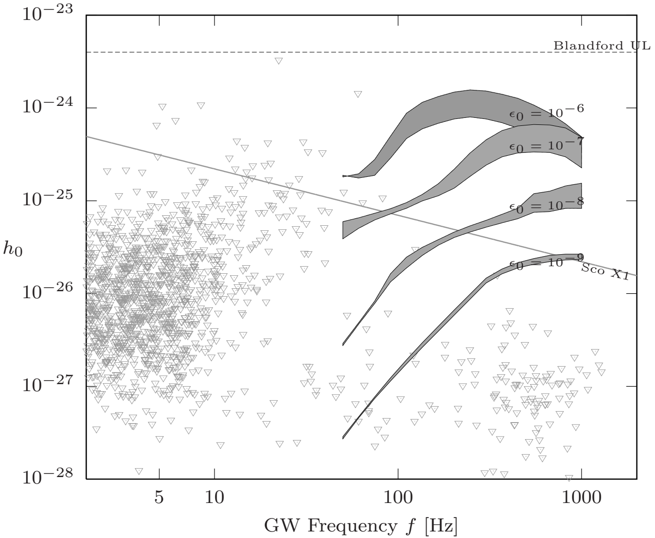
Unknown gravitar population?

"Gravitars" $\equiv$ {Population of unknown NSs, born spinning rapidly, spinning down purely due to GWs}

Blandford: If steady-state 2D uniform gravitar distribution in galactic disk, expected strongest signal is independent of $\{\epsilon_0, f\}$
$h_0 \sim 4 \times 10^{-24}$ (for birth-rate $\tau_B \sim 1/30\mathrm{y}$)

More detailed analysis by Knispel,Allen, PRD D78 (2008): distribution not 2D uniform, not steady-state: ☞ h_0 depends on f and (fixed) population ϵ_0

Unknown gravitar population?



Types of CW searches

- *Targeting* pulsars: sky-position and frequency $f(t)$ known
  - ☞ 1 template, computationally cheap $\sim \mathcal{O}$ (laptop)
  - ☞ use optimal method (Bayes factor, "matched filtering")
- *Directed*: sky-position known, frequency $f(t)$ unknown
- *Wide-parameter*: unknown sky-position and frequency $f(t)$
  $\mathrm{SNR} \propto \frac{h_0}{\sqrt{S_n}}\sqrt{T}$ BUT computing cost $\mathcal{C} \propto T^p$, $p \gtrsim 5$
  - ☞ optimal method computationally impossible
    - Semi-coherent methods: break data into N_{seg} shorter segments of length T_{seg}, combine incoherently
      $\mathrm{SNR} \underset{\sim}{\propto} \frac{h_0}{\sqrt{S_n}} N_{\mathrm{seg}}^{1/4} \sqrt{T_{\mathrm{seg}}}$, BUT cheaper!
      NOTE: Optimal method *at fixed computing-cost* unknown
    - maximize available computing power by using Einstein@Home, clusters + GPUs

Sensitivity estimate

"Sensitivity" $\equiv$ {weakest detectable signal amplitude h_0}

Depends on (i) detector noise $S_{\mathrm{n}}(f)$, (ii) search parameters θ:

- false-alarm p_{FA} (small) and detection $p_{\mathrm{det}}(\sim 90\%)$
- total amount of data used T_{data}
- "size" of the parameter-space $\mathbb{P}$
- Computing-cost: $\mathcal{C}_0$ = Computing-power $\times$ runtime
- internal pipeline parameters: $N_{\mathrm{seg}}, T_{\mathrm{seg}}, \mu, \ldots$

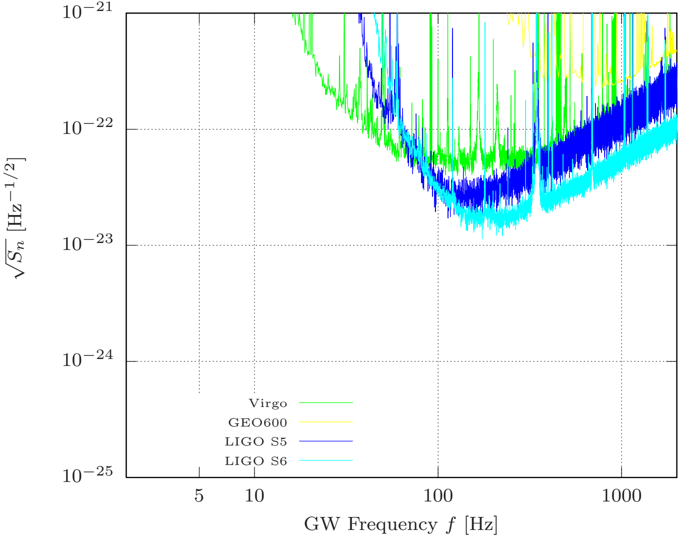
Define "characteristic sensitivity" $\sigma(\theta)$ of the method as

$$h_0(f) = \frac{\sqrt{S_{\mathrm{n}}(f)}}{\sigma(\theta)}$$

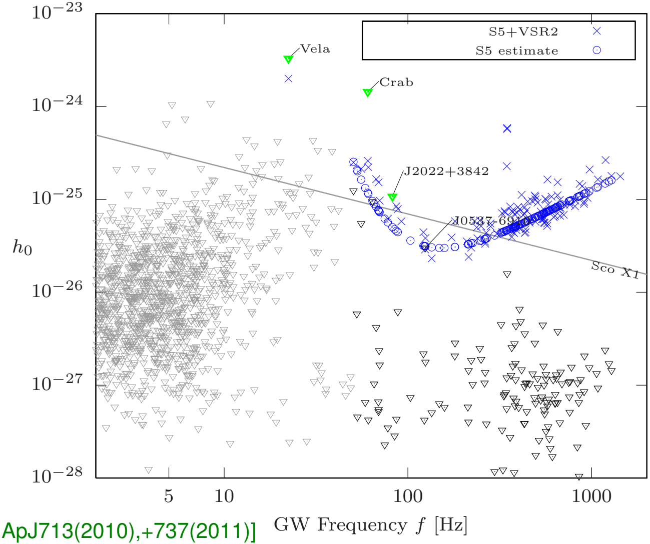
Examples of current Search Sensitivities

- Targeted searches (fully coherent): $h_0 = \frac{11.4}{\sqrt{T_{\rm data}}}\sqrt{S_n}$
  2 years of data from 2 detectors: $T_{\rm data} = 2 \times 2{\rm y} \approx 10^8{\rm s}$
  ☞ $\sigma \sim 1000\,{\rm Hz}^{-1/2}$
- Directed semi-coherent (e.g. Galactic-center, Cas-A,...)
  ☞ $\sigma \sim 70\,{\rm Hz}^{-1/2}$ $(N_{\rm seg} = 630,\, T_{\rm seg} = 2 \times 11.5{\rm h},\, \mu \sim 0.17)$
- All-sky searches for *isolated* NSs $(\mathcal{C}_0(E@H) \sim 10^{21}\,{\rm flop})$
  ☞ $\sigma \sim 30\,{\rm Hz}^{-1/2}$ $(N_{\rm seg} = 121,\, T_{\rm seg} = 2 \times 25{\rm h},\, \mu \sim 0.6)$
  [K. Wette, PRD85 (2012), Prix&Wette LIGO-T1200272]
- TwoSpect: First all-sky *binary* search
  ☞ $\sigma \lesssim 10\,{\rm Hz}^{-1/2}$ [E. Goetz, GWPAW12 talk]
  (huge parameter space, search ongoing)

Current Sensitivities: noise PSD $S_n(f)$

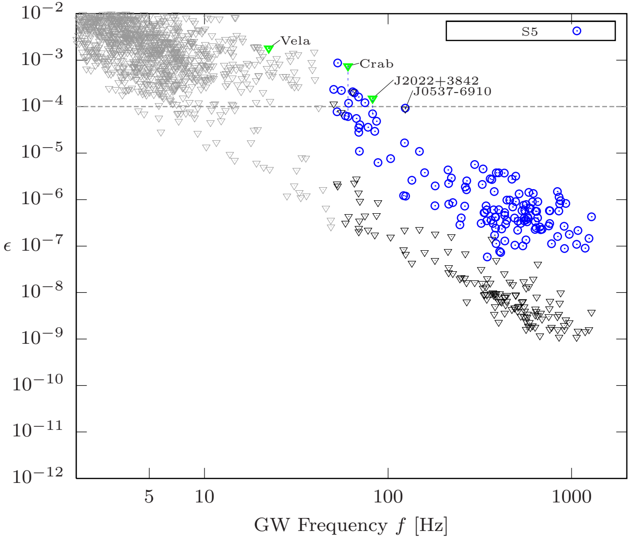


Current Sensitivity: Targeted searches ($\sigma \approx \frac{1000}{\sqrt{\mathrm{Hz}}}$)

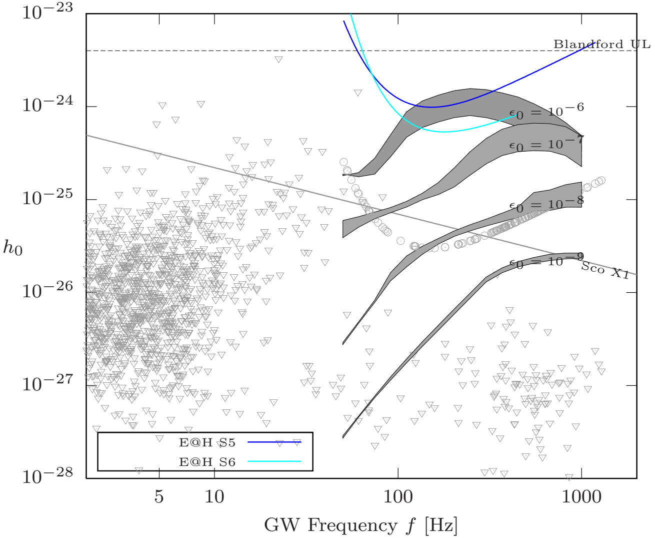


[LSC+Virgo,ApJ713(2010),+737(2011)]

Current Sensitivities: Targeted searches ($\sigma \approx \frac{1000}{\sqrt{\text{Hz}}}$)



Current Sensitivities: Einstein@Home ($\sigma \approx \frac{30}{\sqrt{\text{Hz}}}$)

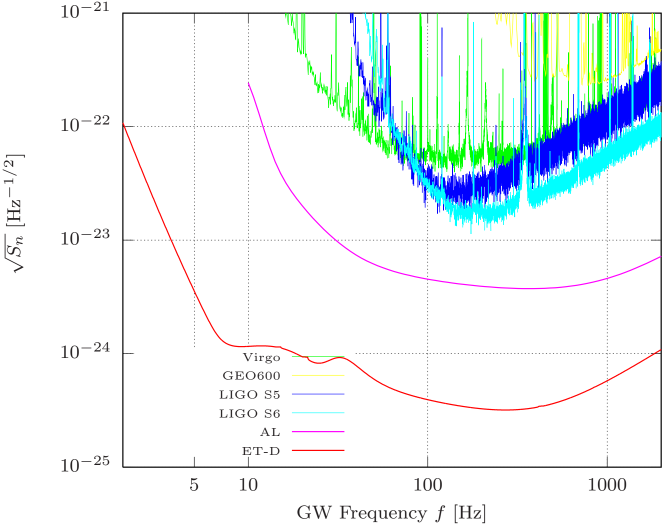


What future sensitivity improvements can we expect?

Generally, sensitivity gains can come from 3 factors:

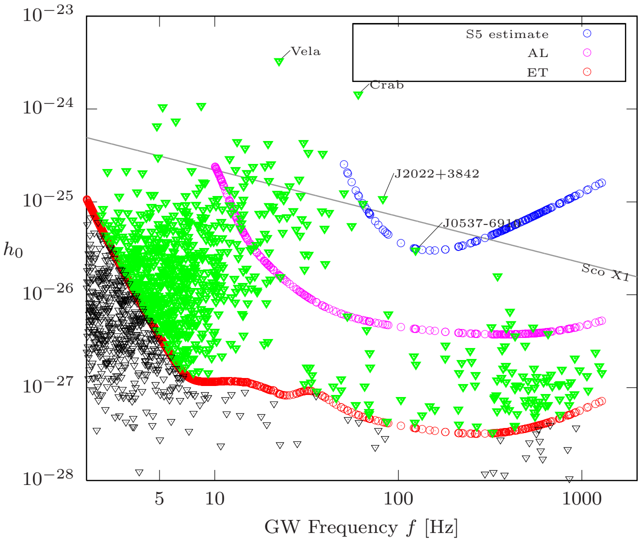
1. better (more sensitive) detectors $\sqrt{S_n}$
2. more computing power (Moore's law)
3. better *search methods*

1. How much can we gain from future detectors?

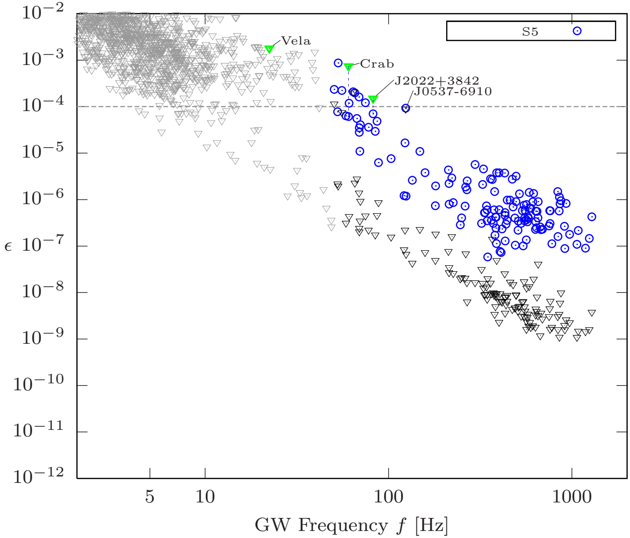


- Now
- $\sim$ 2018/2019
- $\sim$ 2025 – 2030

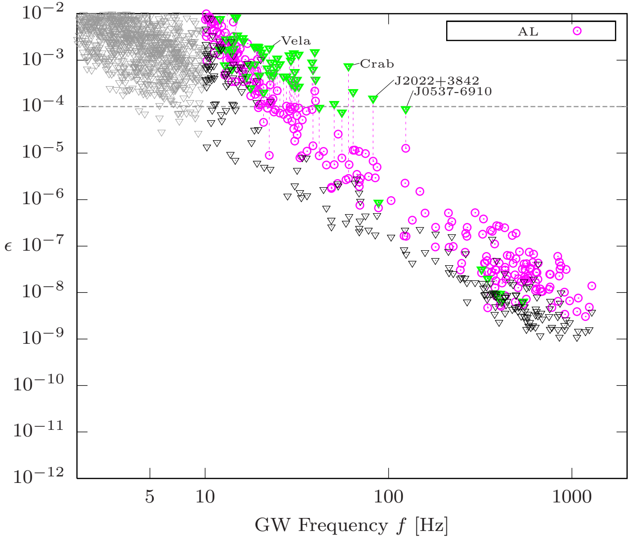
Future sensitivity: Targeted Searches h_0 ($\sigma \approx \frac{1000}{\sqrt{\mathrm{Hz}}}$)



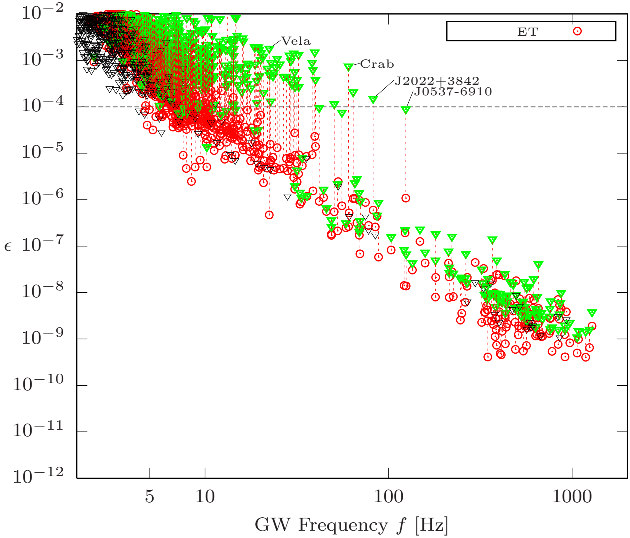
Future sensitivity: Targeted Searches ϵ ($\sigma \approx \frac{1000}{\sqrt{\mathrm{Hz}}}$)



Future sensitivity: Targeted Searches ϵ ($\sigma \approx \frac{1000}{\sqrt{\mathrm{Hz}}}$)



Future sensitivity: Targeted Searches ϵ $(\sigma \approx \frac{1000}{\sqrt{\text{Hz}}})$



2. How much can we gain from Moore's law?

"Computing power doubles every $\sim$ 2 years"

- 2nd generation: Advanced LIGO+Virgo, KAGRA,...
  $\sim 2018/2019$ ☞ ~ 3 doublings ☞ $\mathcal{C}_0[\mathrm{AL}] \sim 8 \times \mathcal{C}_0$
- 3rd generation, e.g. "Einstein Telescope" (ET):
  $\sim 2025 - 2030$ ☞ ~ 8 doublings ☞ $\mathcal{C}_0[\mathrm{ET}] \sim 256 \times \mathcal{C}_0$

How does h_0 sensitivity scale with $\mathcal{C}_0$?

- Targeted searches: no gain
- Wide parameter-space searches: [Prix,Shaltev,PRD85 (2012)]
  $h_0 \sim [\mathcal{C}_0^{-1/16}, \mathcal{C}_0^{-1/8}] \overset{\text{here}}{\approx} \mathcal{C}_0^{-1/10}$

Sensitivity increase due to Moore's law (e.g. for E@H)

$\sigma[\mathrm{AL}] \sim +25\%$ in Advanced-detector (AL) era
$\sigma[\mathrm{ET}] \sim +75\%$ in Einstein Telescope (ET) era

3. How much can we gain from *improved methods*?

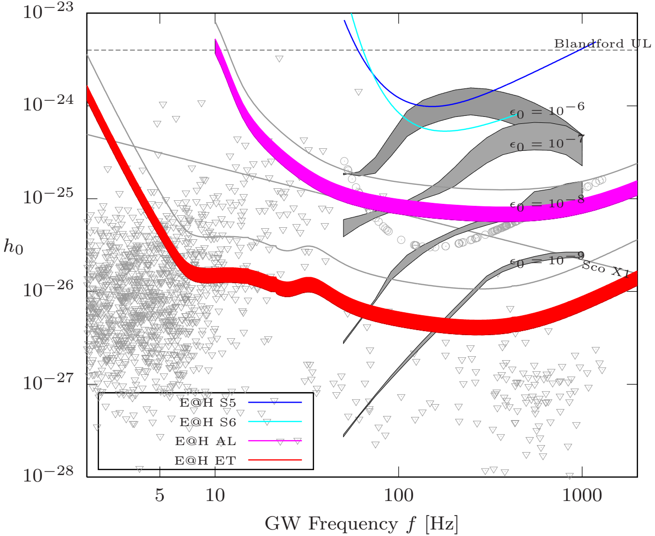
Wide parameter-space searches are computationally limited, optimal search method unknown.
How much improvement do we expect?

- *tuning* of semi-coherent method (StackSlide) can yield $+25\%$ wrt recent E@H searches [Prix,Shaltev,PRD85 (2012)]
- Coherent *follow-up* can yield up to $+80\%$ improvement, unclear if computing cost affordable [☞ Shaltev, PhD thesis]

Combined: Future all-sky sensitivities (e.g. E@H)

$$\sigma[S5, S6] \sim 30\,\mathrm{Hz}^{-1/2}$$
$$\sigma[\mathrm{AL}] \sim [47, 67]\,\mathrm{Hz}^{-1/2}$$
$$\sigma[\mathrm{ET}] \sim [65, 94]\,\mathrm{Hz}^{-1/2}$$

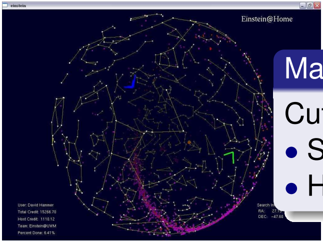
Future sensitivity of All-Sky Searches h_0



Conclusions

- No guaranteed future CW detections, but . . .
- . . . entering increasingly interesting territory!
- Future observations will definitely be informative (one way or the other), cutting substantially into the prior ranges
- Astrophysical conclusions will depend on exact nature of (non-)detection and assumed astrophysical models
- Lots of work remaining to improve our wide-parameter search *methods* (eg “Line-Veto”, Hierarchical, ...)
- Expand our searches to new *categories*: e.g. “transient CWs” (lifetime $\sim$ days) from NS glitches?

You can help by running Einstein@Home!



Maximize available computing power

Cut parameter-space λ in small pieces $\Delta\lambda$

- Send workunits $\Delta\lambda$ to participating hosts
- Hosts return finished work and request next

- Public distributed computing project, launched Feb. 2005
- Currently $\sim$100,000 participants, $\sim$ 1PFlop/s (24x7)
- All-sky search for GWs from unknown neutron stars
- Analyzed LIGO data from S3, S4, S5, S6
- March 2009: also search for binary radio pulsars in Arecibo+Parkes data ☞ First E@H discovery [Science 2010]
- Aug 2011: also search for γ-ray pulsars in Fermi-LAT data