Continuous Gravitational Waves from Spinning Neutron Stars

~~Status and Outlook~~

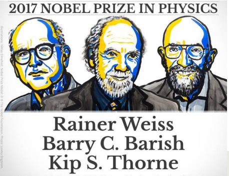
WHEN? and WHAT can we learn?

Reinhard Prix

Continuous-waves group
Albert-Einstein-Institute Hannover

Advances in Astroparticle Physics and Cosmology
AAPCOS @ SINP
Jan 2023

14 Sept 2015: GW Astronomy Begins



2017 NOBEL PRIZE IN PHYSICS

Rainer Weiss
Barry C. Barish
Kip S. Thorne

"for decisive contributions to the LIGO detector and the observation of gravitational waves"

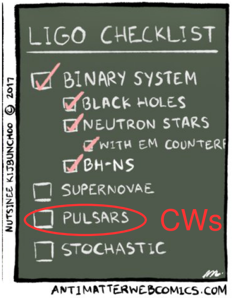
PHYSICAL REVIEW LETTERS

Member Subscription Copy
Library or Other Institutional Use Prohibited Until 2017

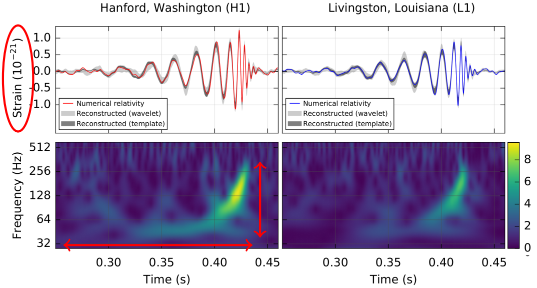
Articles published week ending 12 FEBRUARY 2016

Published by American Physical Society
APS physics
Volume 116, Number 6

[LVC, PRL116,061102(2016)]



CWs



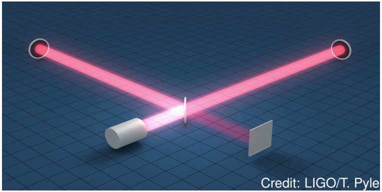
☞ "strong", short-duration, chirping

Part I

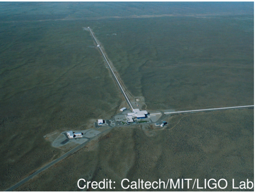
What are Continuous Gravitational Waves (CWs)?
What can we learn from them?

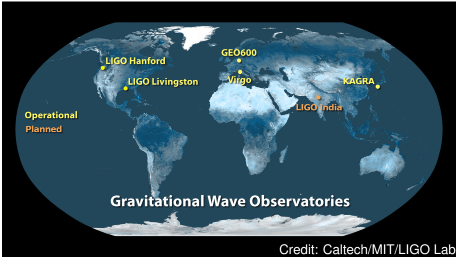
CONTINUOUS
GRAVITATIONAL
WAVES

Global Gravitational-Wave Detector Network


Credit: LIGO/T. Pyle


Credit: H. LÃ¼ck/AEI


Credit: Caltech/MIT/LIGO Lab



Credit: Caltech/MIT/LIGO Lab

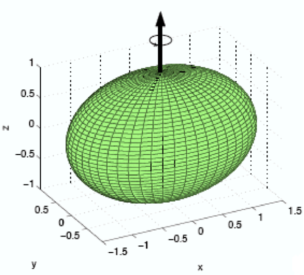

Credit: KAGRA

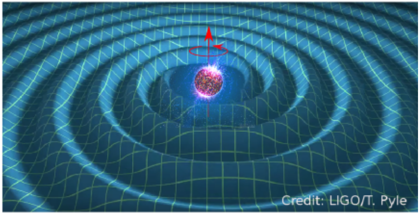

Credit: Caltech/MIT/LIGO Lab


Credit: The Virgo collaboration

Continuous Gravitational Waves

From Spinning Deformed Neutron Stars




Credit: LIGO/T. Pyle

deformed (ϵ) spinning NS ☞ periodic GWs at $f = 2f_{\text{spin}}$

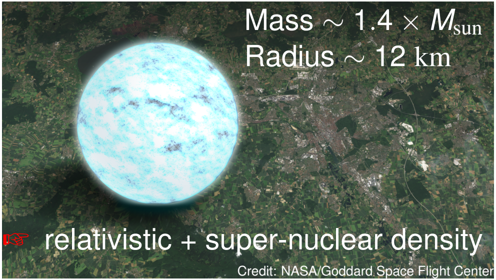
Strain amplitude h_0 on Earth

$$h_0 \approx 10^{-25} \left(\frac{\epsilon}{10^{-6}}\right) \left(\frac{I_{zz}}{10^{38}\,\mathrm{kg\,m^2}}\right) \left(\frac{f_{\text{spin}}}{50\,\mathrm{Hz}}\right)^2 \left(\frac{100\,\mathrm{pc}}{\text{distance}}\right)$$

Actual deformations ϵ highly uncertain: $10^{-12} < \epsilon \lesssim 10^{-4}(?)$

☞ weak, long-duration, near-monochromatic, (galactic!)

Neutron Stars: Remnants of Stellar Explosions

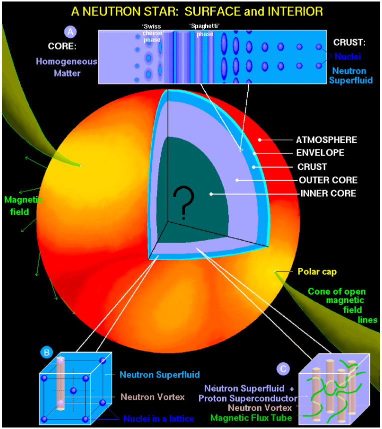


Mass $\sim 1.4 \times M_{\rm sun}$

Radius ~ 12 km

☞ relativistic + super-nuclear density

Credit: NASA/Goddard Space Flight Center



Credit: J.M. Lattimer/Stony Brook U.

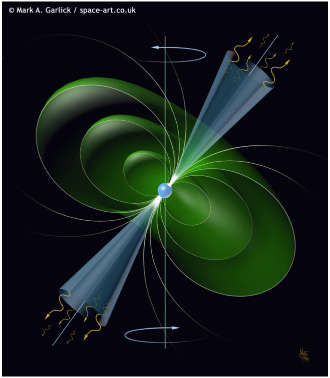
Rich laboratory for nuclear physics:

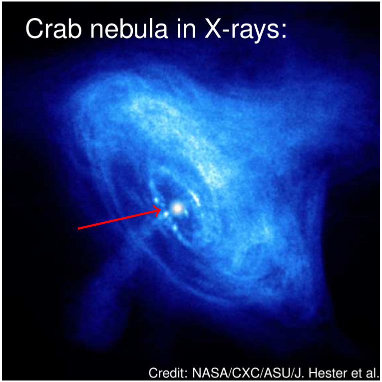
- equation of state (EOS)?
- structure and composition: superfluids, exotic matter, . . . ?
- maximal / actual deformation ϵ?
- population: $\mathcal{O}\left(10^8\right)$ unobserved NSs in our galaxy!
  ☞ “Gravitars”?

ALL-SKY SEARCH: search “whole” parameter space (sky, frequency, ...)

Some Neutron Stars Observed as Pulsars

Rotating Magnetic Field ☞ EM pulses (radio, optical, X-ray, γ-ray)





Credit: NASA/CXC/ASU/J. Hester et al.

$\sim$ 3400 pulsars currently known (SKA $\rightarrow$ 20 000)

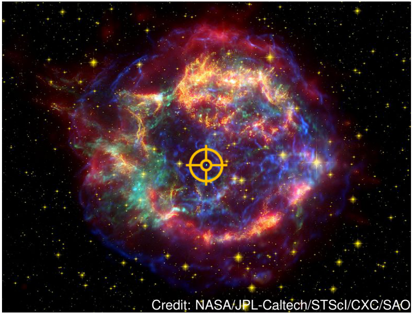
$0.1\,\mathrm{Hz} \lesssim f_{\mathrm{spin}} \lesssim 716\,\mathrm{Hz}$ ($\sim$ 700 in LIGO/Virgo band $\geq 10\mathrm{Hz}$)

TARGETED SEARCH: all parameters known (sky, frequency, binary)

NARROW-BAND SEARCH: + allow small uncertainty in frequency

Some Neutron Stars Seen in Supernova Remnants

About $\sim 10 - 20$ feasible targets currently known
☞ non-pulsing X-rays from a central compact object (CCO) in a supernova remnant (SNR) or pulsar-wind nebula (PWN)


Credit: NASA/JPL-Caltech/STScI/CXC/SAO

Example: Cassiopeia-A (Cas-A)
supernova remnant containing CCO
~ 300 years old
$\sim 3.4\,\mathrm{kpc}$ distance

DIRECTED SEARCH: known sky-position, unknown frequency

Some Neutron Stars in Accreting Binaries

Fastest pulsar $f_{\mathrm{spin}} \approx 716\,\mathrm{Hz}$, breakup-limit $f_{\mathrm{spin}}^{\mathrm{max}} \lesssim 1.5$ kHz

What limits the NS-spin?

$$\text{Accretion-torque} = \text{GW torque } (\propto f^5)$$

☞ most promising target: Scorpius X-1 (Sco X-1)

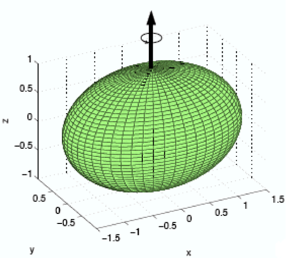
DIRECTED BINARY SEARCH: known sky-position, unknown spin

\+ uncertainties in orbital parameters {period, semi-major axis, phase, eccentricity}

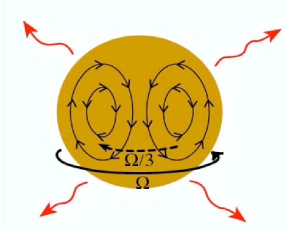
\+ uncertain accretion-induced spin-wandering

CW Emission Mechanisms

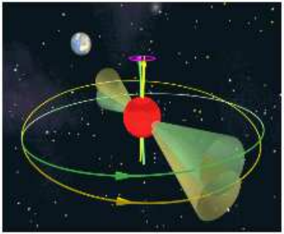
"Mountains" $f = 2f_{\mathrm{spin}}$



r-modes $f \approx \frac{4}{3} f_{\mathrm{spin}}$ (EOS-dependent)

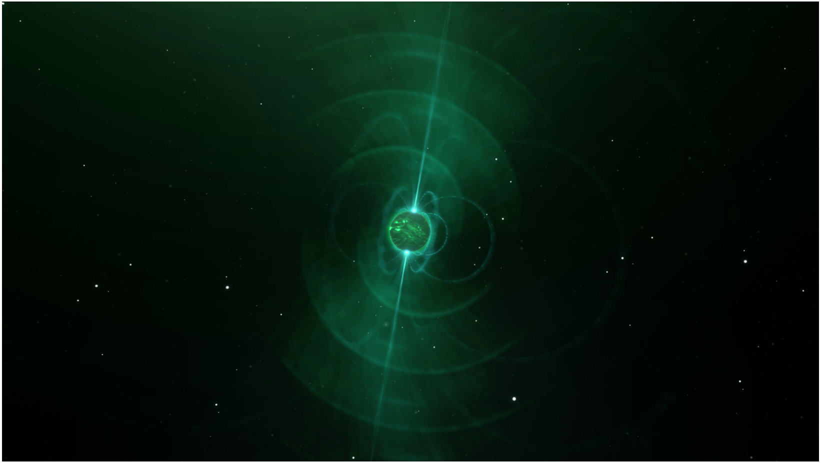


Precession $f \sim f_{\mathrm{spin}}$ and $2f_{\mathrm{spin}}$



(Accretion $f \sim 2f_{\mathrm{spin}}$ or $\frac{4}{3} f_{\mathrm{spin}}$)

Short movie summary



[CW-group@AEI, youtu.be/mV4-DUalJ5I]

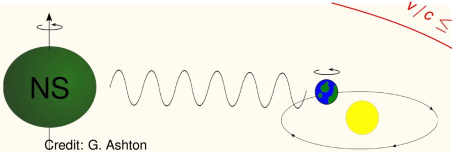
Part II

How do we Search for Continuous Gravitational Waves?
Why is it so hard?

Continuous-Wave Signal at the Detector

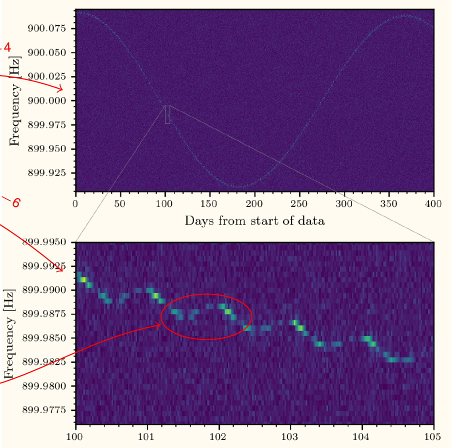
CW signals are not pure sinusoids:

- intrinsic spindown
  small: $\dot{f}, \ddot{f}, \ldots \lesssim 0.1\,\mathrm{Hz/yr}$
- Earth orbital + diurnal motion



Credit: G. Ashton

- rotating antenna-pattern
- if NS in a binary: additional orbital Doppler modulation



Credit: G. Ashton

☞ template: signal waveform, depends on:

sky-position, $f, \dot{f}, \ldots +$ binary-orbital parameters

How to Search for CWs: Coherent Matched Filtering

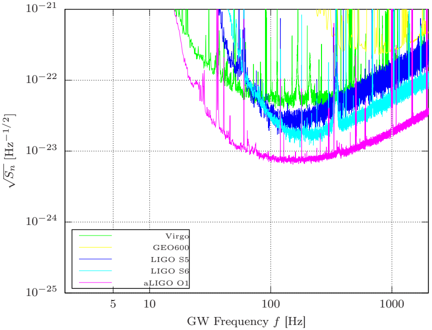
Optimal matched filtering

☞ Signal-to-Noise ratio

$$\rho \propto \frac{h_0}{\boxed{\sqrt{S_n}}}\sqrt{T}$$

$h_0 \lesssim 10^{-25}$ ☞ $T \gtrsim \mathcal{O}\,(\text{days})$

Problem: Computing Cost



If parameter uncertainties $\Delta(\text{sky}, f, \ldots)$ ☞ need template bank

$$\left.\begin{aligned} \text{Cost}(\Delta f) &\propto T \\ \text{Cost}(\Delta\{f, \dot{f}\}) &\propto T^3 \\ \text{Cost}(\Delta\{\text{sky}, f, \dot{f}\}) &\propto T^5 \\ &\vdots \end{aligned}\right\}$$

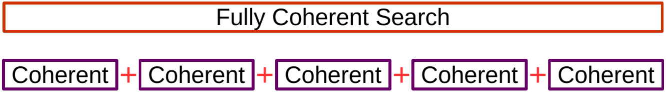
☞ limits coherence time $T \lesssim \mathcal{O}\,(\text{days})$

☞ limits sensitivity

☞ "optimal" in principle, but suboptimal at finite computing cost

How to Search for CWs: Semi-Coherent Methods

☞ Semi-coherent methods:
split data T into N_{seg} shorter segments T_{seg}
+ combine coherent results by summing:



Fully Coherent Search

Coherent + Coherent + Coherent + Coherent + Coherent

Sum = Semicoherent Search

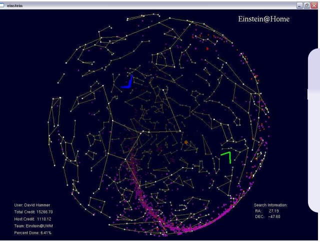
less sensitive for same amount of data, but much faster!

☞ allows analysing all the data

☞ more sensitive at fixed computing cost if $\Delta(\mathrm{sky}, f, \dot{f}, \ldots) > 0$

[+] maximize sensitivity (template banks, N_{seg}, T_{seg}) at fixed cost

[+] maximize computing power: clusters, GPUs, Einstein@Home



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

Maximize available computing power

- Split parameter-space into small “workunits”
- Send workunits to participating hosts
- Hosts return finished work and request next

- Public distributed computing project
- launched @AEI in “Einstein Year” 2005 ☞ 17 years!
- $\sim$48 000 participating hosts, $\sim$ 12 PFlop/s (24x7)
- Fully leveraging hosts’ GPU power
- Most sensitive all-sky and directed CW searches

☞ You can sign up and participate! `https://einsteinathome.org`

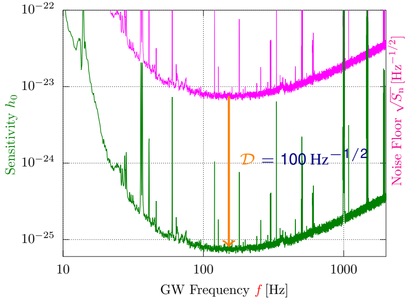
Sensitivity Depth $\mathcal{D}$ of a CW search

Sensitivity / Upper Limit $\equiv$ Smallest detectable $h_0\big|^{\text{confidence}=90\%}_{\text{p-value}=1\%}$

Depends on

- Noise floor: ASD $\sqrt{S_n}(f)$
- Search method ☞ constant *sensitivity depth* $\mathcal{D}$

$$h_0(f) = \frac{\sqrt{S_n(f)}}{\mathcal{D}}$$

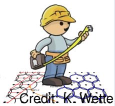


Examples:

- Fully-coherent search, 2 years of data from 2 detectors:
  ☞ $\mathcal{D} \sim 1000\,\mathrm{Hz}^{-1/2}$
- Semi-coherent all-sky search over $f, \dot{f}$:
  ☞ $\mathcal{D} \sim 20 - 60\,\mathrm{Hz}^{-1/2}$

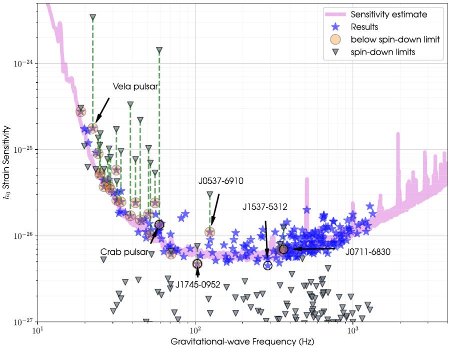
Part III

Status: Where do we stand right now?



Credit: K. Wette

Targeted Search for Known Pulsars

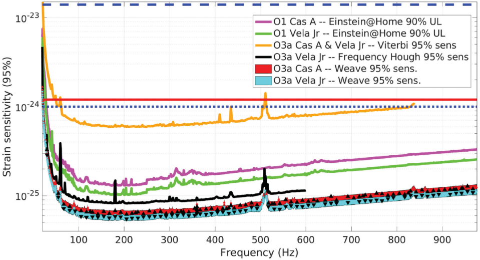


[LVK, ApJ935, 1 (2022)]

- O2+O3 LIGO+Virgo: $T_{\mathrm{data}} \sim 1100\,\mathrm{d}$
  ☞ $\mathcal{D} \sim 860\,/\sqrt{\mathrm{Hz}}$
- Targeted 236 pulsars
- Beat spindown-limit for 23 pulsars
  surpassed spindown-limit for Crab by $\sim 100\times$, Vela by $\sim 20\times$

Directed Search for CCOs in SNRs

WEAVE-based search for Cas-A and Vela-Jr

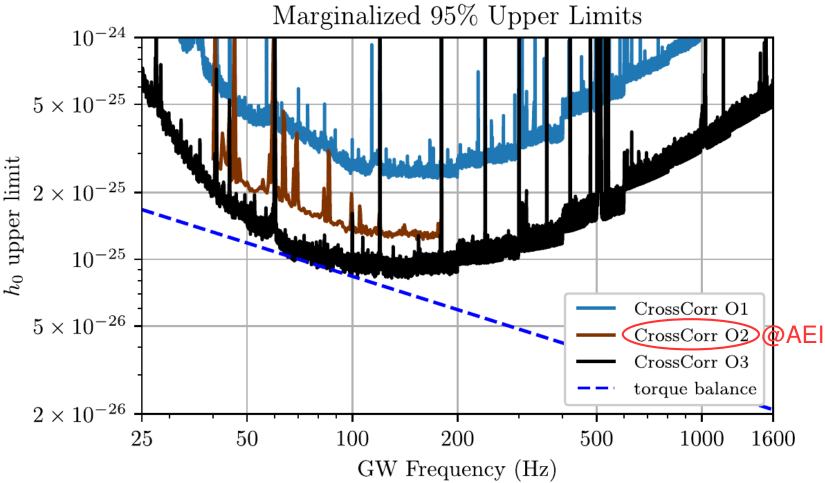


[LVC, PRD105 (2022)]

- O3a LIGO $\sim$ 6 months of data
- Directed at Cas-A and Vela-Jr SNRs in $f \in [20, 1000]$Hz
- Semi-coherent setup: $36 \times 5\,\text{d}$, $24 \times 7.5\,\text{d}$
- ☞ Sensitivity depths: $\mathcal{D} \sim 73 - 80\,/\sqrt{\text{Hz}}$

Directed Search For Scorpius X-1

LIGO O3 data

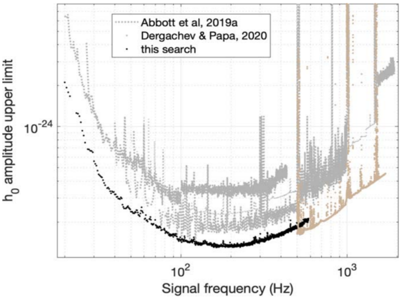


[LVK, ApJL 941 (2022)]

☞ Sensitivity Depth $\mathcal{D} \sim \mathcal{O}(50\,/\sqrt{\text{Hz}})$

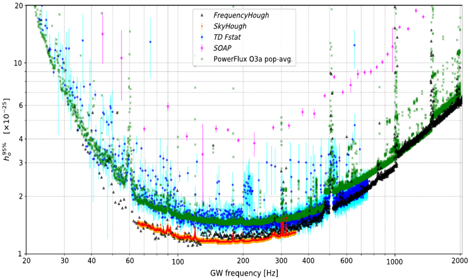
All-Sky Search for Isolated Neutron Stars

Einstein@Home: O2



[Steltner et al., ApJ 909 (2021)]

LVK: O3



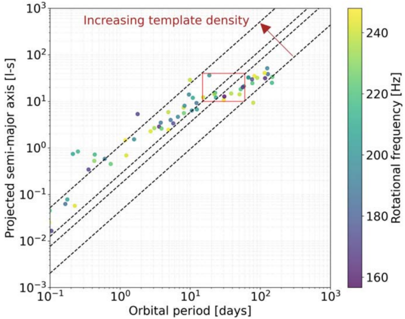
[LVK, PRD 106 (2022)]

Sensitivity Depth $\mathcal{D} \sim 53\,/\sqrt{\text{Hz}}$

Note: “Depth” $\mathcal{D}$ is not the only relevant measure!

- “Breadth” of parameter-space covered
- Robustness to signal-model deviations

All-Sky Search for Neutron Stars in Binary Systems



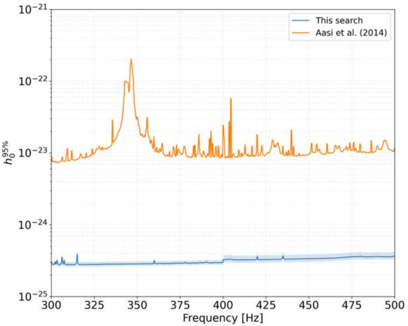


Table 1

Range of Values of the Signal Waveform Parameters Covered by the Search

Parameter	Range
f_0 : Frequency [Hz]	300–500
$\lvert\dot{f}_0\rvert$: Frequency deriv. [Hz/s]	$<4 \times 10^{-10}$
a_{p} : Projected semimajor axis [lt-s]	10–40
P : Orbital period [days]	15–60
t_{asc} : Time of ascension [s]	$t_m \pm P/2$
e : Orbital eccentricity	$<5.7 \times 10^{-3} \left[\frac{500\text{ Hz}}{\mathrm{f}_0}\right]$
α : Right ascension [rad]	0–2π
δ : decl. [rad]	$-\pi/2$–$\pi/2$

[Covas et al. ApJL 929 (2022)]

6D parameter space!

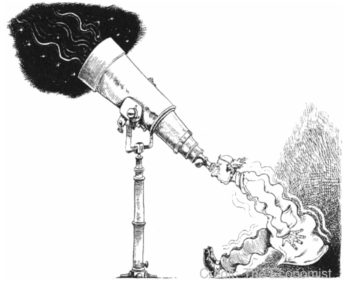
semi-coh: $\sim 17\,000 \times 900\,\mathrm{s}$!

Sensitivity Depth $\mathcal{D} \sim 17\,/\sqrt{\mathrm{Hz}}$

☞ ongoing: expanding ranges in a_p and P!

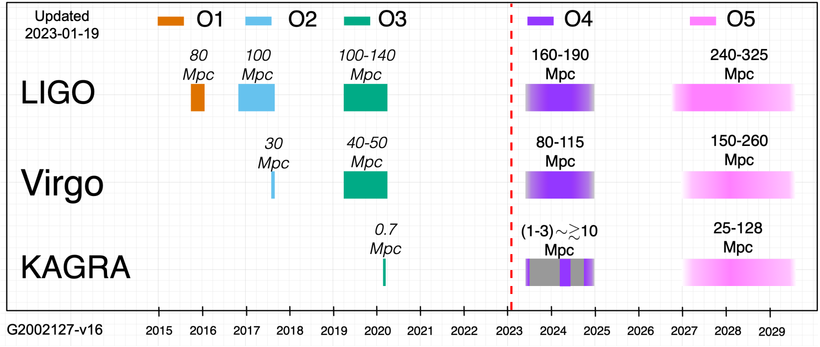
Part III

Outlook
Future Prospects for CW detection



Credit: The Economist

Roadmap of Observing Runs

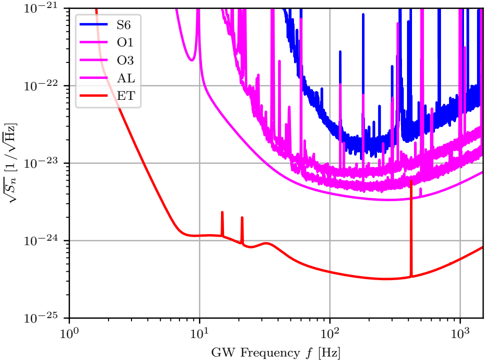


[Credit: LVK]

What Future Improvements Can We Expect?

Sensitivity gains in $h_0 = \frac{\sqrt{S_\mathrm{n}}}{\mathcal{D}}$ can come from

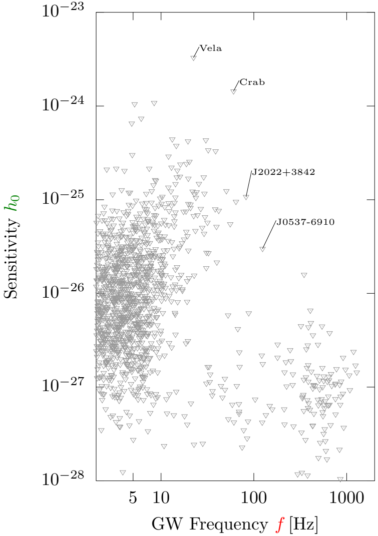
1. more sensitive detectors ☞ lower $\sqrt{S_\mathrm{n}}(f)$
2. greater search sensitivity depth $\mathcal{D}$
   - more computing power (Moore's law) ☞ $\mathcal{D} \sim \mathcal{C}_0^{1/10}$
   - more sensitive *search methods*: $30\% - 50\%$?



- 1st Gen: iLIGO S6
- 2nd Gen: aLIGO O1, O3, O5
- 3rd Gen: ET, CE, .. ∼ 2035(?)

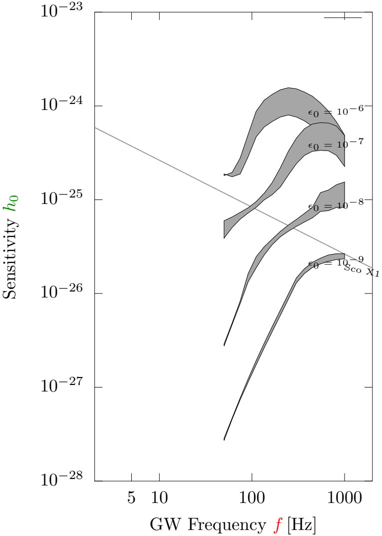
Outlook: The “CW Landscape”

Known pulsars [spindown limits]



[ATNF Pulsar Catalog]

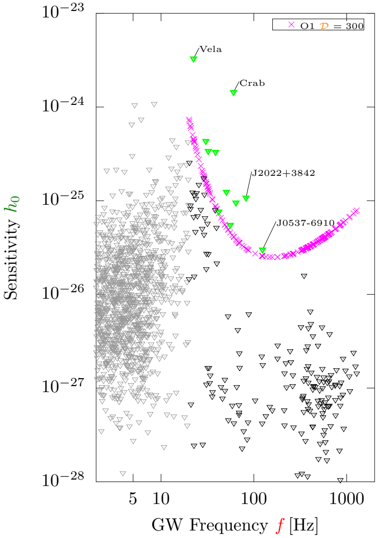
All-sky [gravitar population]



[Knispel&Allen, PRD D78(2008)]

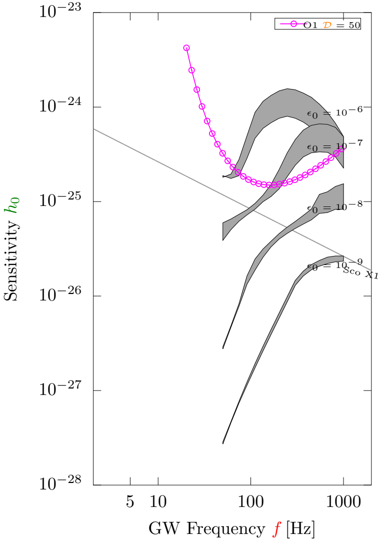
Outlook: Current (O1) sensitivity

Known pulsars [spindown limits]



[ATNF Pulsar Catalog]

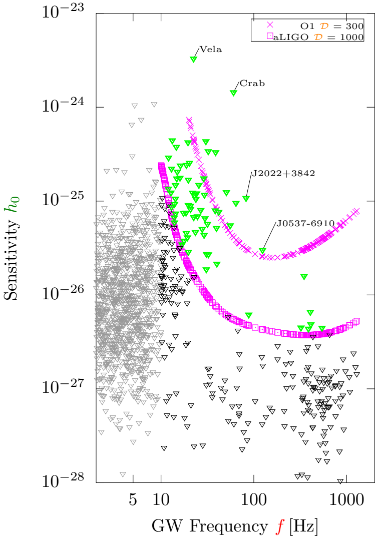
All-sky [gravitar population]



[Knispel&Allen, PRD D78(2008)]

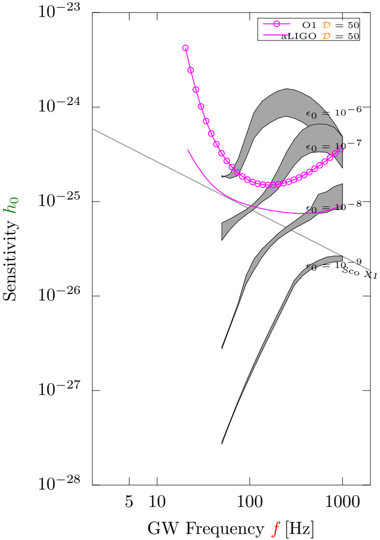
Outlook: Design LIGO sensitivity

Known pulsars [spindown limits]



[ATNF Pulsar Catalog]

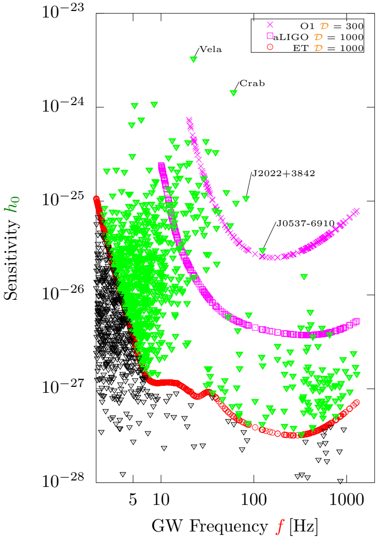
All-sky [gravitar population]



[Knispel&Allen, PRD D78(2008)]

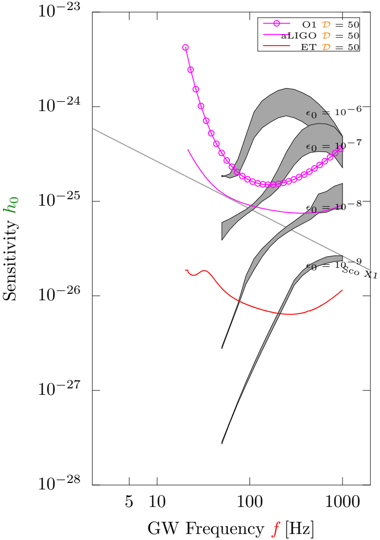
Outlook: (3rd-gen) EinsteinTelescope sensitivity

Known pulsars [spindown limits]



[ATNF Pulsar Catalog]

All-sky [gravitar population]



[Knispel&Allen, PRD D78(2008)]

Summary

- No guaranteed future CW detections, but . . .
- entering regime of “plausible” detectability since $\sim$O3 ...
- Even non-detection can be informative ☞ constraints
- Detections could be rich (astro-)physically: NS structure, population, dynamics, EOS, tests of GR . . .
- Continued effort to improve robustness, efficiency and sensitivity of our search methods
- CW searches strongly benefit from EM information: more information ☞ better sensitivity!
- First CW detection ☞ major milestone for NS physics!

☞ Einstein@Home `https://einsteinathome.org`

einstein
@
home

Thank You!