Designing an All-Sky Search on Einstein@Home

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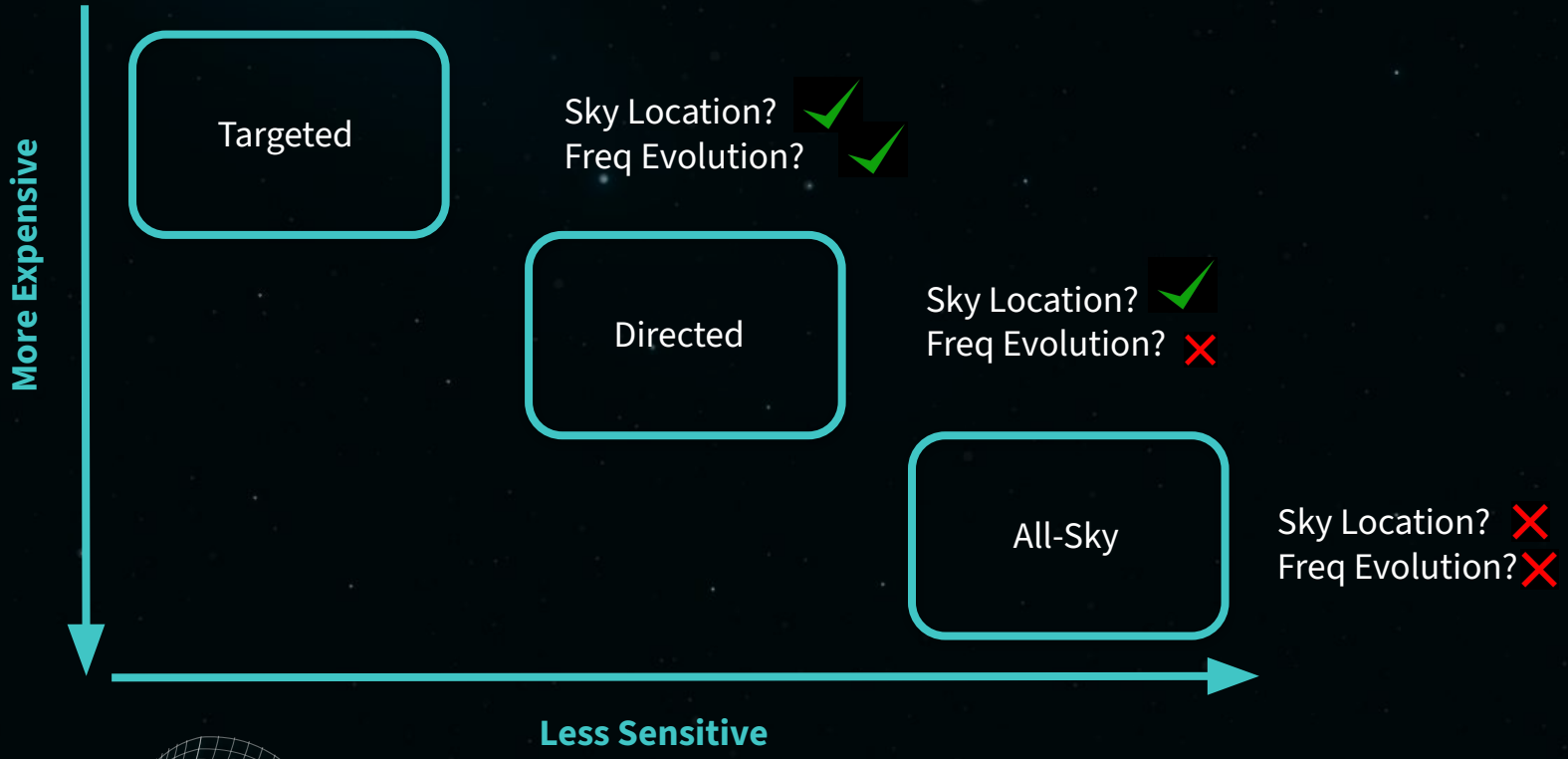
The 2024 BNU Continuous Gravitational Waves Workshop

17	Suzhou	Jiangsu	5,892,892
18	Jinan*	Shandong	5,648,162
19	Changsha*	Hunan	5,630,256
20	Kunming*	Yunnan	5,273,144
21	Harbin*	Heilongjiang	5,242,897
22	Shijiazhuang*	Hebei	5,090,440
23	Hefei*	Anhui	5,055,978
24	Dalian~	Liaoning	4,913,879
25	Xiamen†	Fujian	4,617,251

Outline

- Introduction
- Timing Einstein@Home Searches
- Choosing a Search Setup
- Sensitivity Estimates
- Outlook

Types of Searches



The Signal at Detector

8 Parameters

Amplitude
- GW amplitude: h_0
- Inclination angle: ι
- Polarization angle: ψ
- Initial phase: Φ_0

Phase Evolution
- Freq evolution: f $f^{(k)}$
- Sky position: α δ

$$h(t;\mathcal{A},\lambda) = \sum_{\mu=1}^{4} \mathcal{A}^{\mu} h_{\mu}(t;\lambda)$$

$$h(t) = F_{+}(\alpha,\delta,\psi;t)h_{+}(t) + F_{\times}(\alpha,\delta,\psi;t)h_{\times}(t)$$

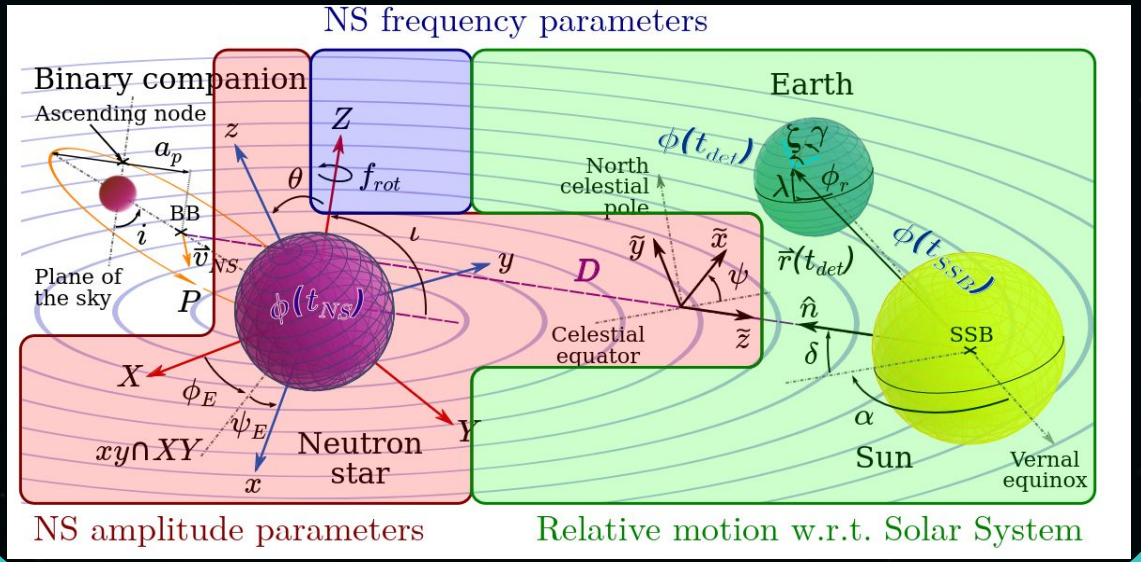
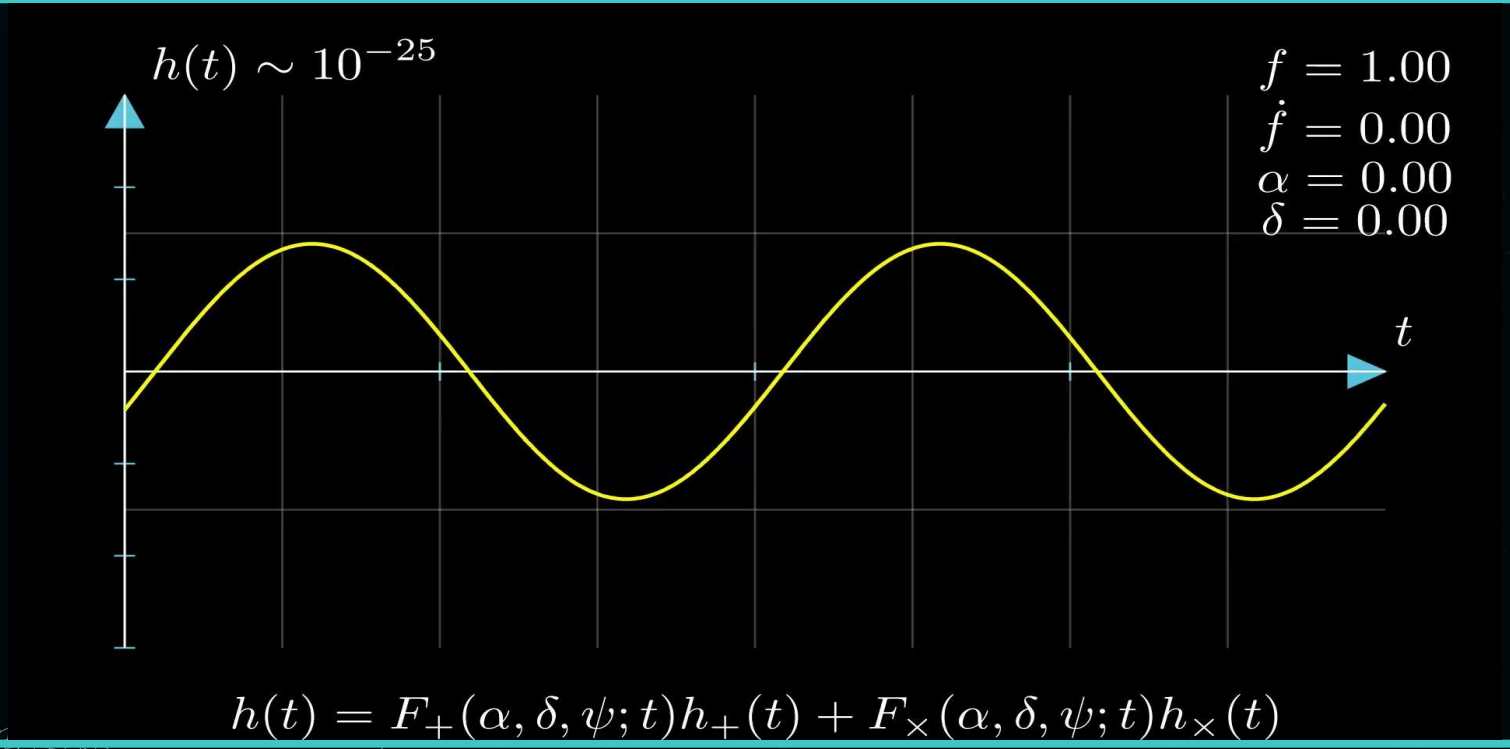


Image credits: K. Wette, Astroparticle Physics 153, 102880 (2023)

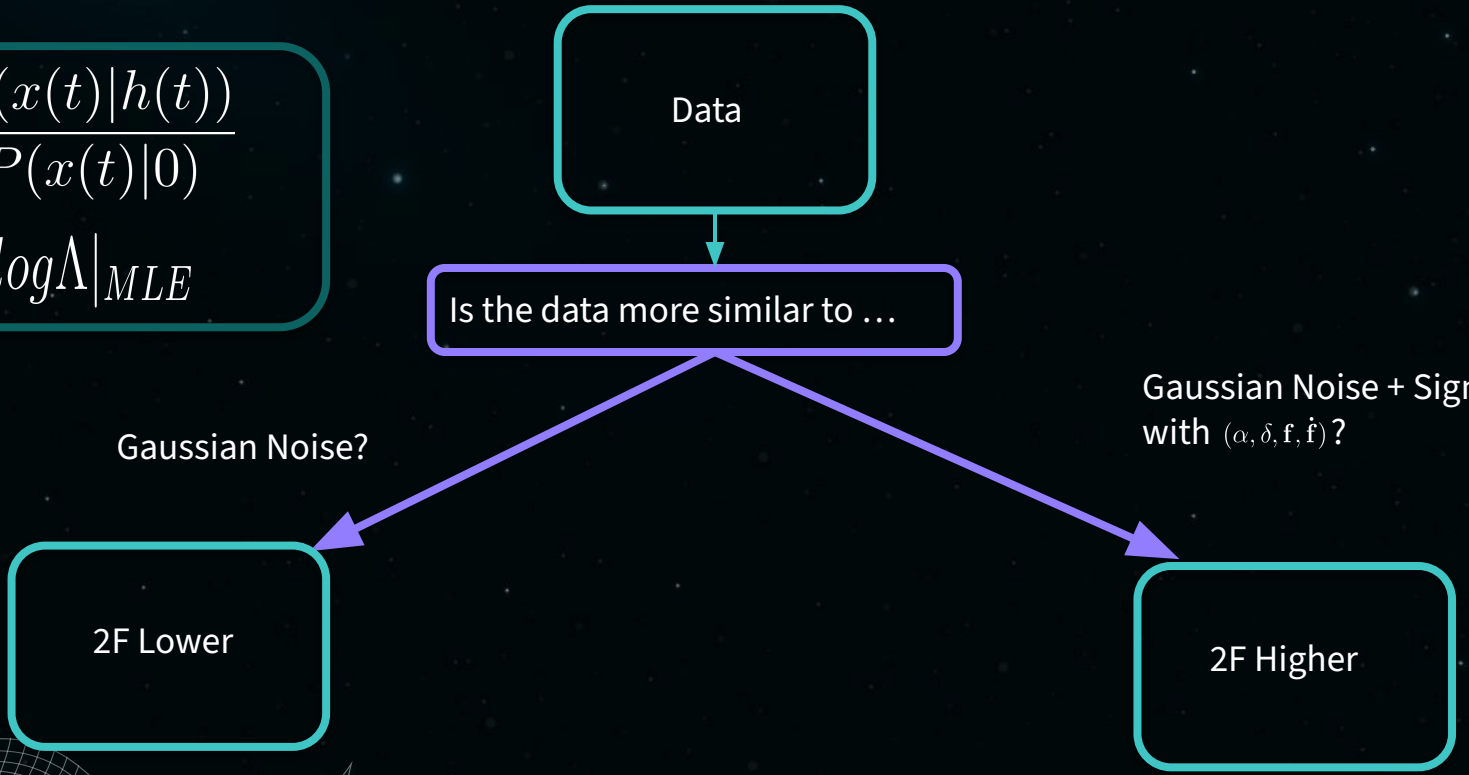
Example: Signal at Hanford



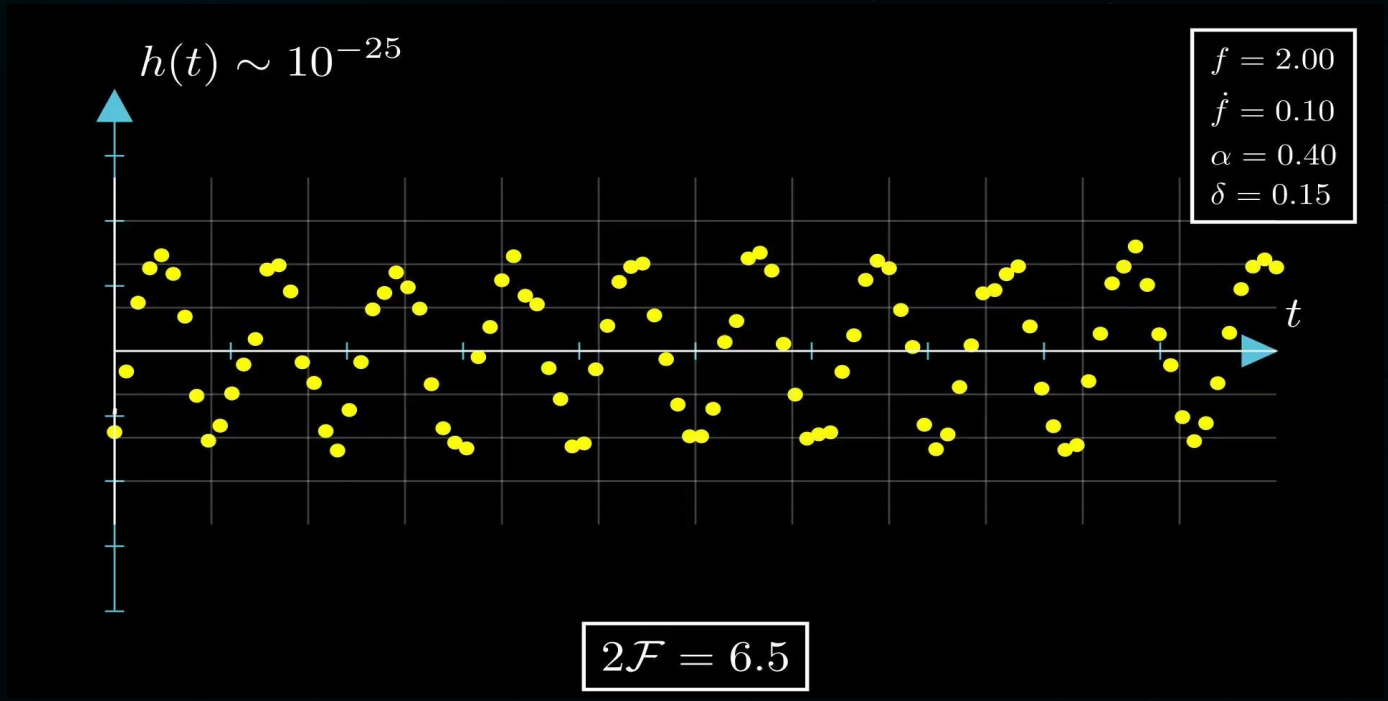
Detection Statistic

$$\Lambda = \frac{P(x(t)|h(t))}{P(x(t)|0)}$$

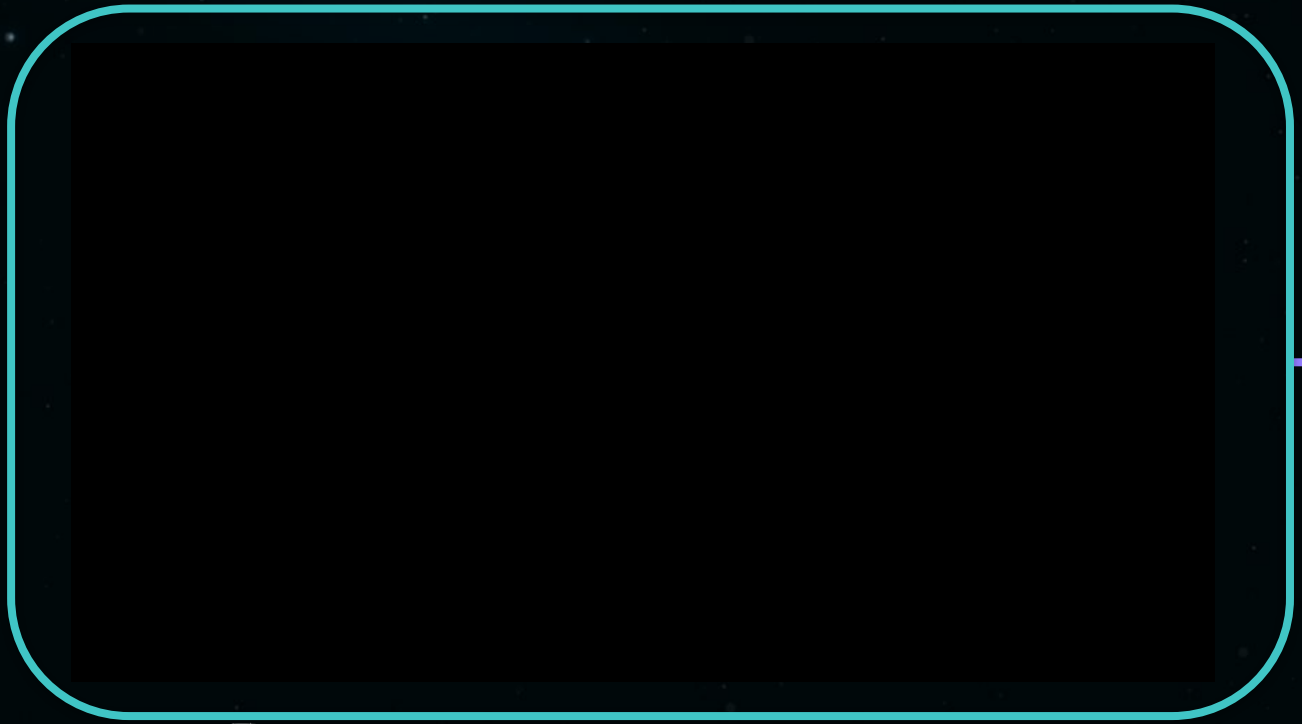
$$\mathcal{F} \equiv log\Lambda|_{MLE}$$



Detection Statistic

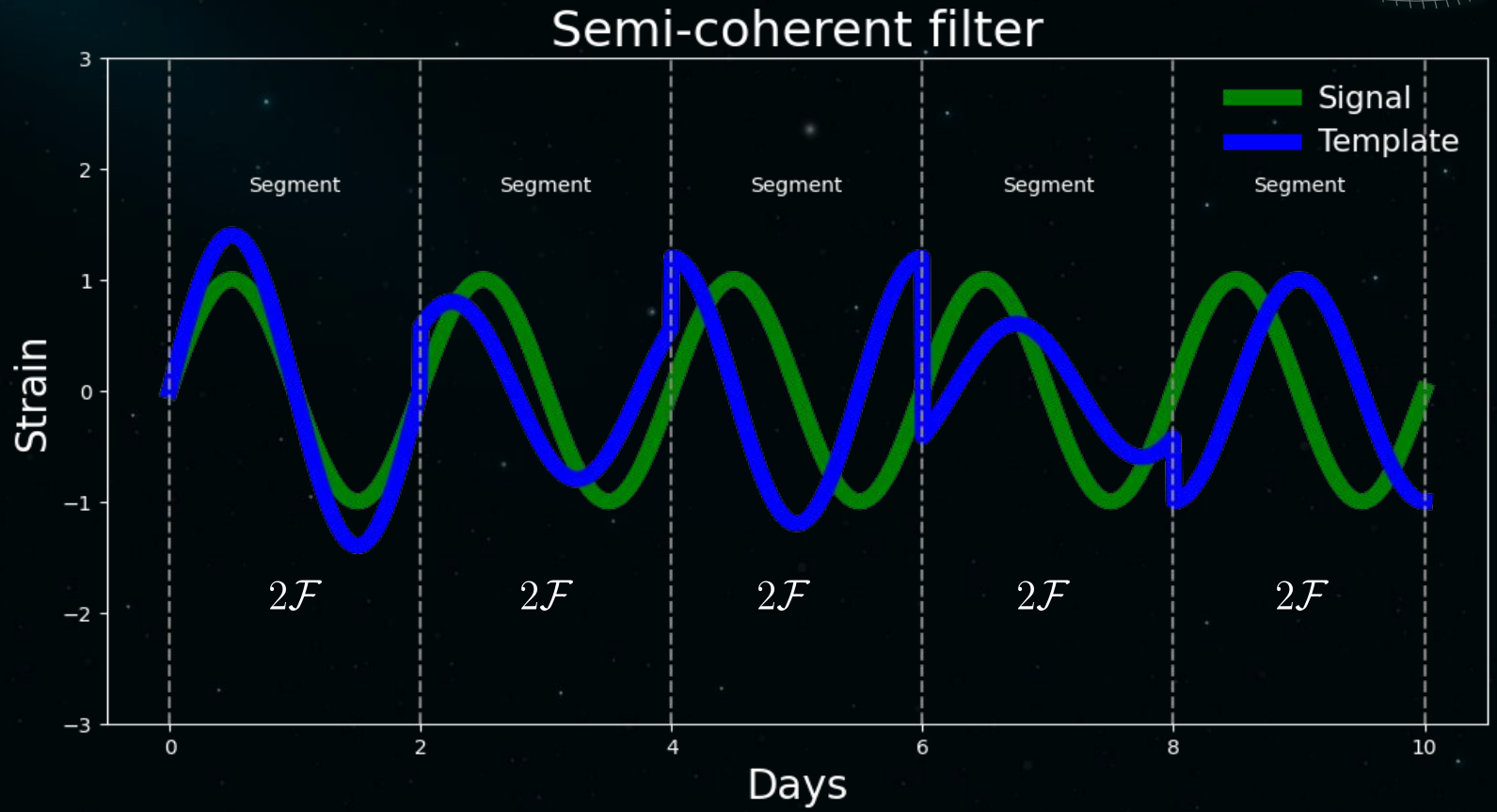


Mismatch



$$\frac{2\mathcal{F}^{PM} - 2\mathcal{F}^{MM}}{2\mathcal{F}^{PM} - 4}$$

Denser grid ⇒
Lower Mismatch ⇒
Higher Runtime


Semi-coherent filter
Signal
Template
Segment
Segment
Segment
Segment
Segment
$2\mathcal{F}$
$2\mathcal{F}$
$2\mathcal{F}$
$2\mathcal{F}$
$2\mathcal{F}$
Strain
Days
3
2
1
0
−1
−2
−3
0
2
4
6
8
10

Computational Cost

Cost of search ∝ # of templates * log likelihood calc time

Example: Previous all sky search on O3a data on E@H:

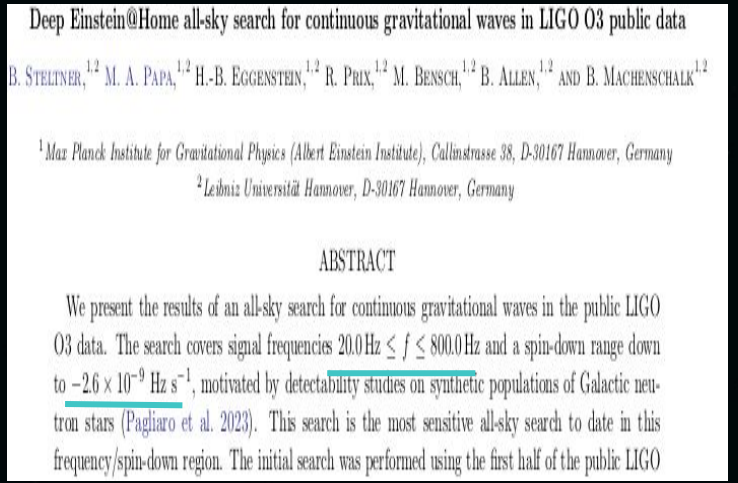
Coherent	Semi-Coherent
Freq ~ 32 billion choices	Freq ~ 2.5 million choices
Sky ~ 9.9 trillion choices	Sky ~ 547 million choices
f1 ~ 670 thousand choices	f1 ~ 5 thousand choices
~ 728 octillion templates	~ 6.8 quintillion templates
~ 2.14 * 10^14 years	~ 2000 years of compute time
~ Age of universe * 15000	

Fully coherent

- Sensitivity $\propto T_{obs}^{\frac{1}{2}}$
- Cost $\propto T_{obs}^{m}$

Semi Coherent

- Sensitivity $\propto N_{seg}^{\frac{1}{4}} T_{seg}^{\frac{1}{2}}$
- Cost $\propto N_{seg}^{n} T_{seg}^{m}$ (n << m)



Deep Einstein@Home all-sky search for continuous gravitational waves in LIGO O3 public data

B. Steltner,[1,2] M. A. Papa,[1,2] H.-B. Eggenstein,[1,2] R. Prix,[1,2] M. Bensch,[1,2] B. Allen,[1,2] and B. Machenschalk[1,2]

[1] Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Callinstrasse 38, D-30167 Hannover, Germany
[2] Leibniz Universität Hannover, D-30167 Hannover, Germany

ABSTRACT

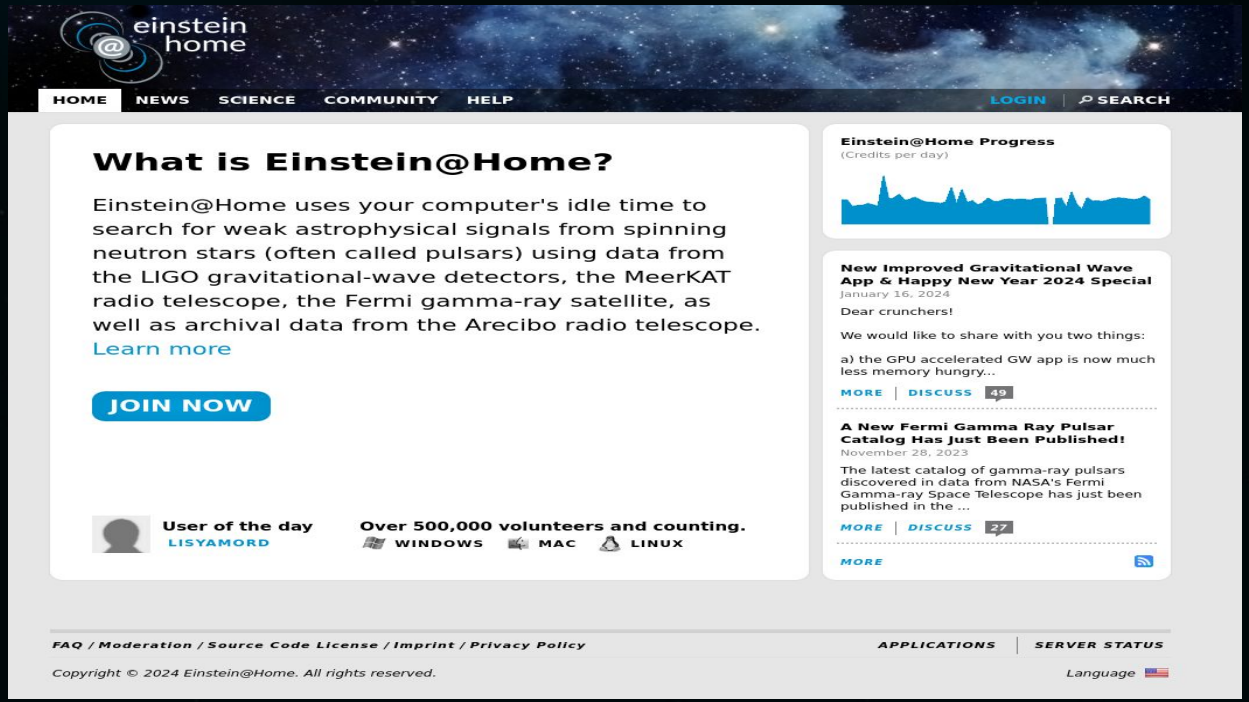
We present the results of an all-sky search for continuous gravitational waves in the public LIGO O3 data. The search covers signal frequencies 20.0 Hz $\leq f \leq$ 800.0 Hz and a spin-down range down to -2.6×10^{-9} Hz s^{-1}, motivated by detectability studies on synthetic populations of Galactic neutron stars (Pagliaro et al. 2023). This search is the most sensitive all-sky search to date in this frequency/spin-down region. The initial search was performed using the first half of the public LIGO

Compromise! : Semi-Coherent Searches

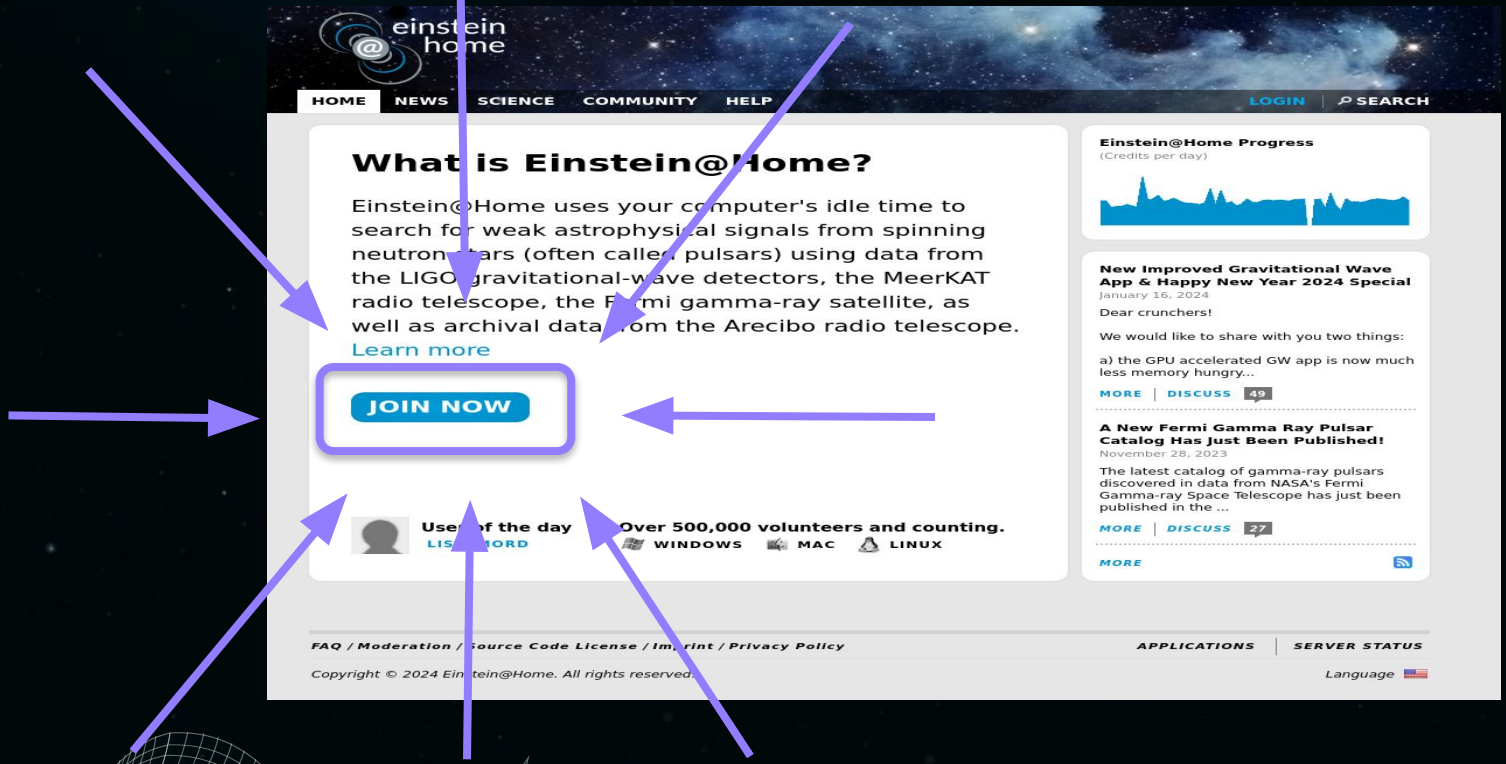
ATLAS and Einstein@Home

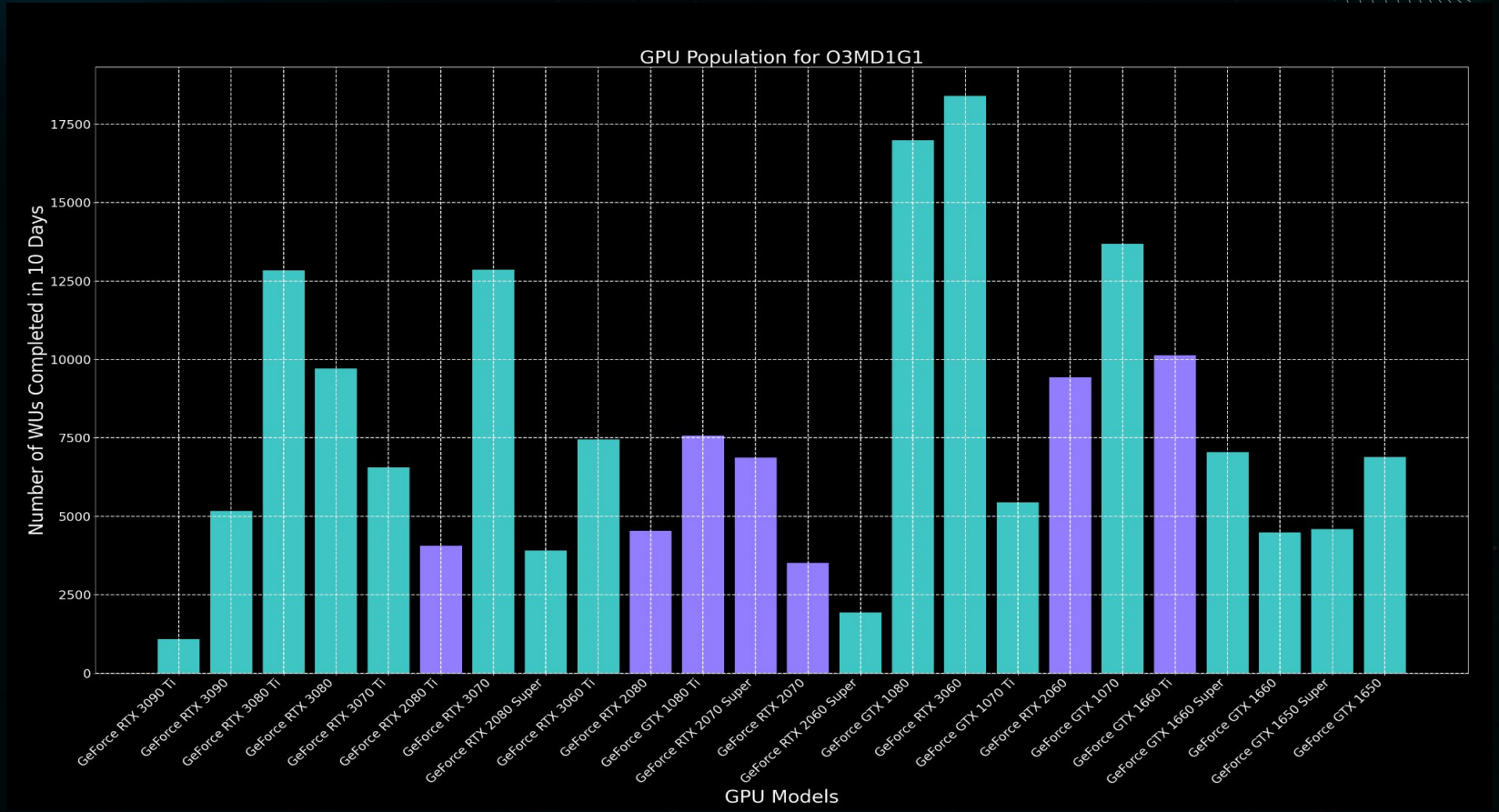
Credit: M. Fiorito/Max Planck Institute for Gravitational Physics

Einstein@Home

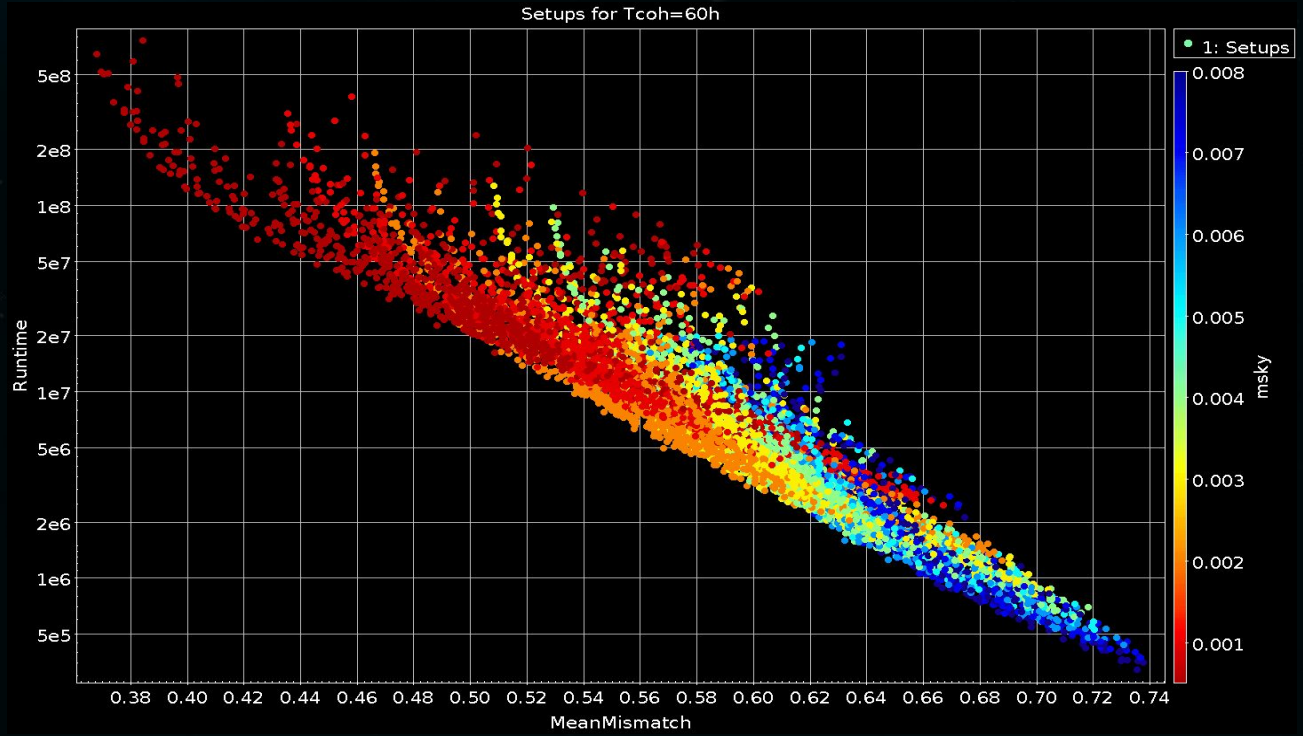


Einstein@Home




GPU Population for O3MD1G1
Number of WUs Completed in 10 Days
0
2500
5000
7500
10000
12500
15000
17500
GeForce RTX 3090 Ti
GeForce RTX 3090
GeForce RTX 3080 Ti
GeForce RTX 3080
GeForce RTX 3070 Ti
GeForce RTX 2080 Ti
GeForce RTX 3070
GeForce RTX 2080 Super
GeForce RTX 3060 Ti
GeForce RTX 2080
GeForce GTX 1080 Ti
GeForce RTX 2070 Super
GeForce RTX 2070
GeForce RTX 2060 Super
GeForce GTX 1080
GeForce RTX 3060
GeForce GTX 1070 Ti
GeForce RTX 2060
GeForce GTX 1070
GeForce GTX 1660 Ti
GeForce GTX 1660 Super
GeForce GTX 1660
GeForce GTX 1650 Super
GeForce GTX 1650
GPU Models

Mismatch V Computational Cost



Sensitivity Estimates

What does it mean to “recover” a signal?

- Choose the loudest candidate per x number of templates
- Would this candidate be louder than a signal with strength ρ?
- If not then the signal is recovered, else not.

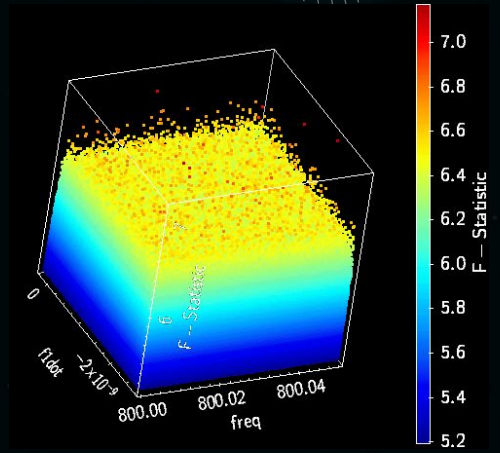
Do injection search and recovery multiple times? - EXPENSIVE ✕

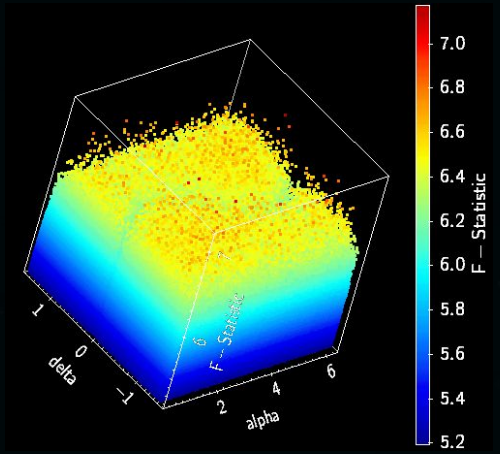
Instead: Our Method

- No MC simulations required!
- “Semi-Analytical”

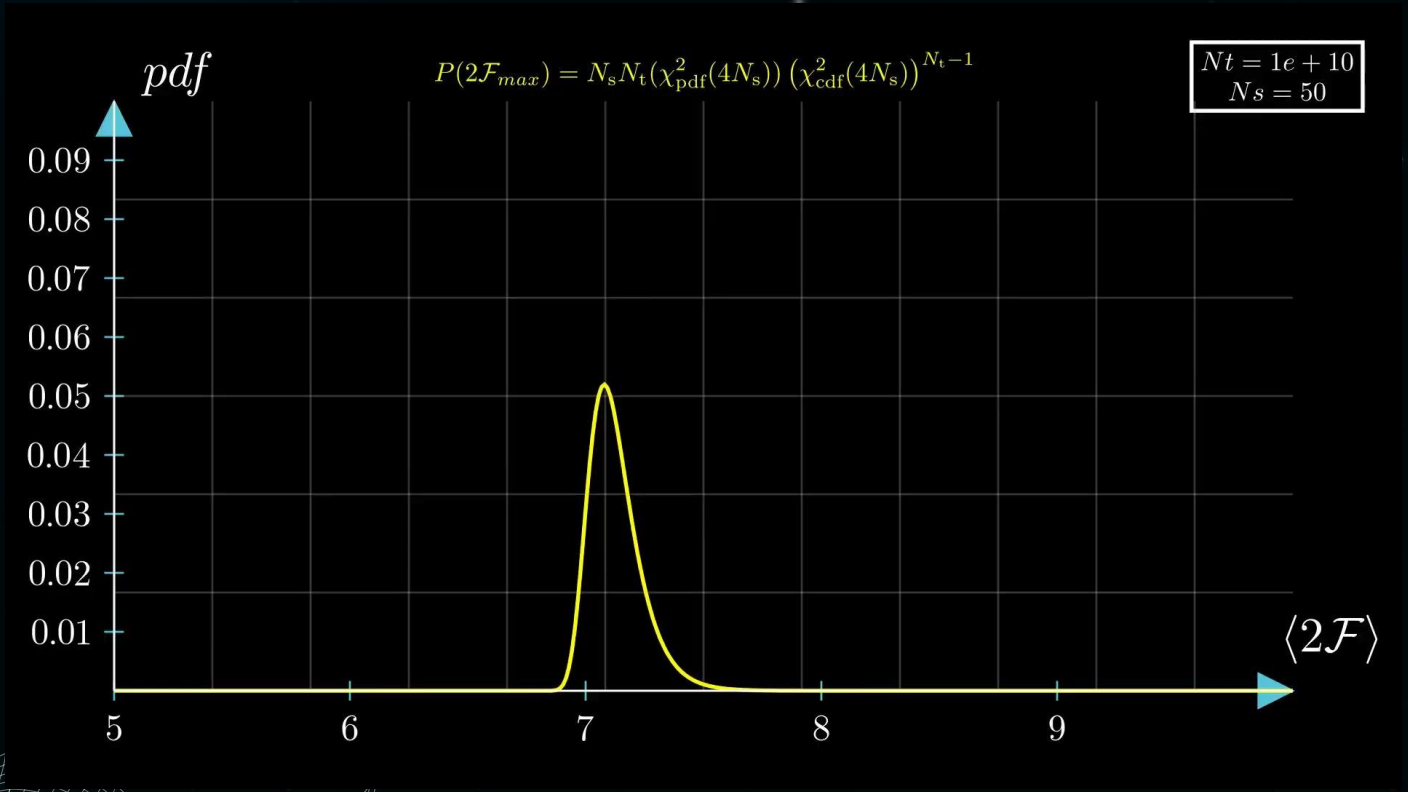
$$2\mathcal{F}^{max}_{Noise} \sim \text{Known}$$

$$2\mathcal{F}_{sig} \sim \chi^2(4N_s, \rho^2)$$

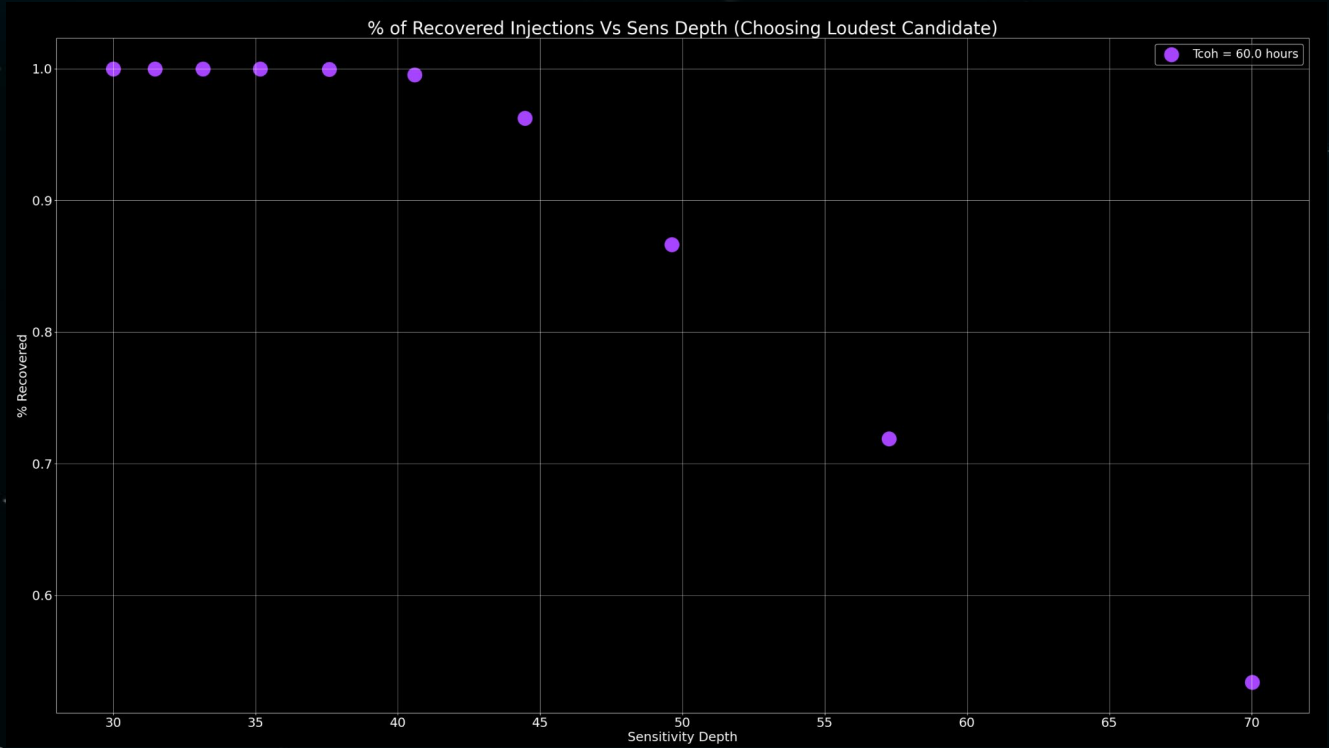




Semi Analytic Sensitivity



Detection Probability



Outlook - O4

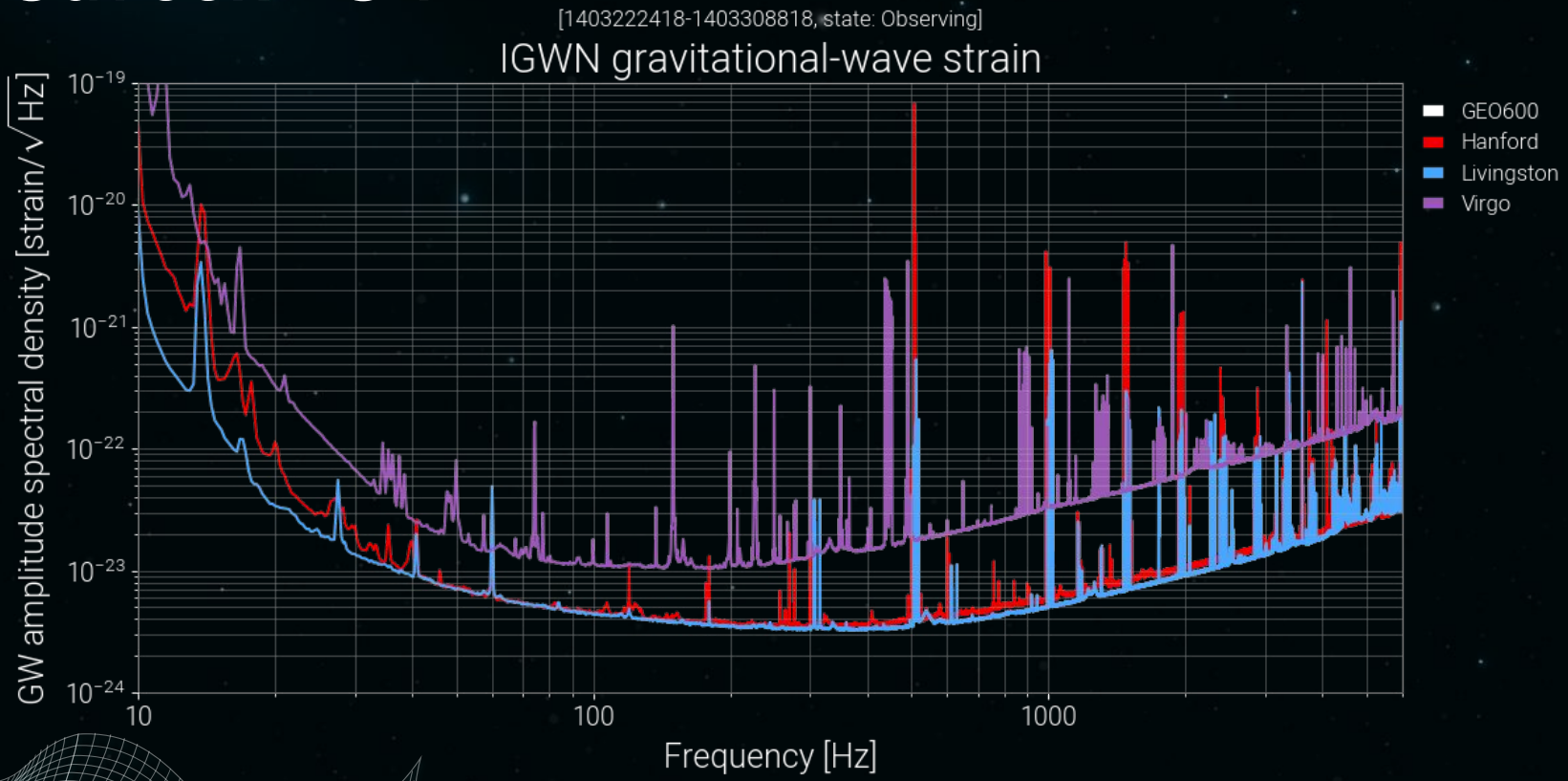


Image credits: GW Open Science Center

Thank you!