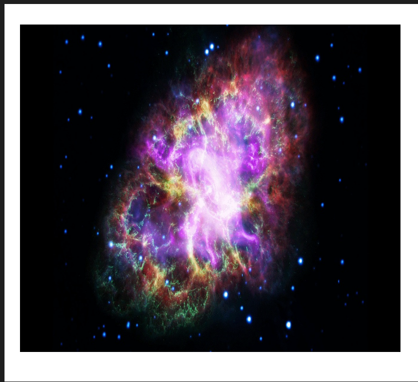
CUTTING-EDGE STRATEGIES TO IDENTIFY NEW GEMS
-GRAVITATIONAL AND ELECTROMAGNETIC WAVE SOURCES-
IN THE UNIVERSE WITH CURRENT AND NEXT-GENERATION DETECTORS



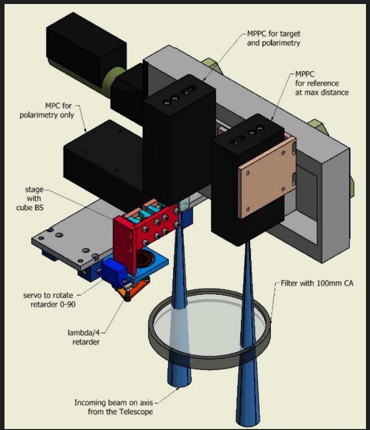
Pia Astone

for the NEW-GEMS PRIN2020 group

INFN Sezione di Roma

Virgo, Cascina

2022, March 7^{th} Seminario INFN



SIFAP2

Silicon Fast Astronomical Photometer

INFN CNAF

CNAF

Progetto: Cutting-edge strategies to identify new GEMS (Gravitational- and ElectroMagnetic-wave Sources) in the Universe with current and next-generation detectors

PI: Pia Astone, INFN Roma

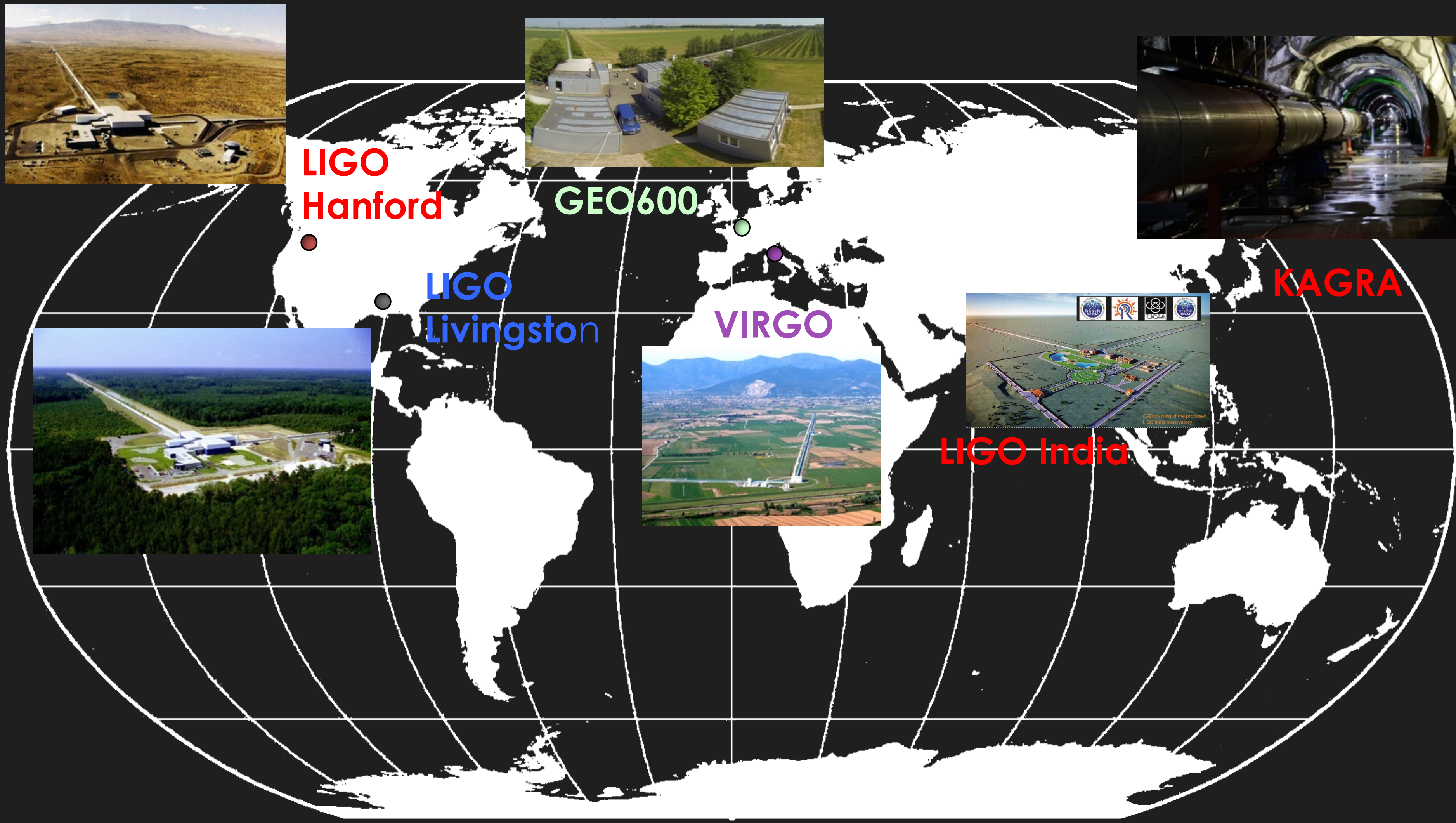
PRIN 2020

INAF: Luigi Stella (local coordinator), Alessandro Papitto

INFN: Stefano Dal Pra (CNAF), Sabrina D’Antonio (RM2), Cristiano Palomba

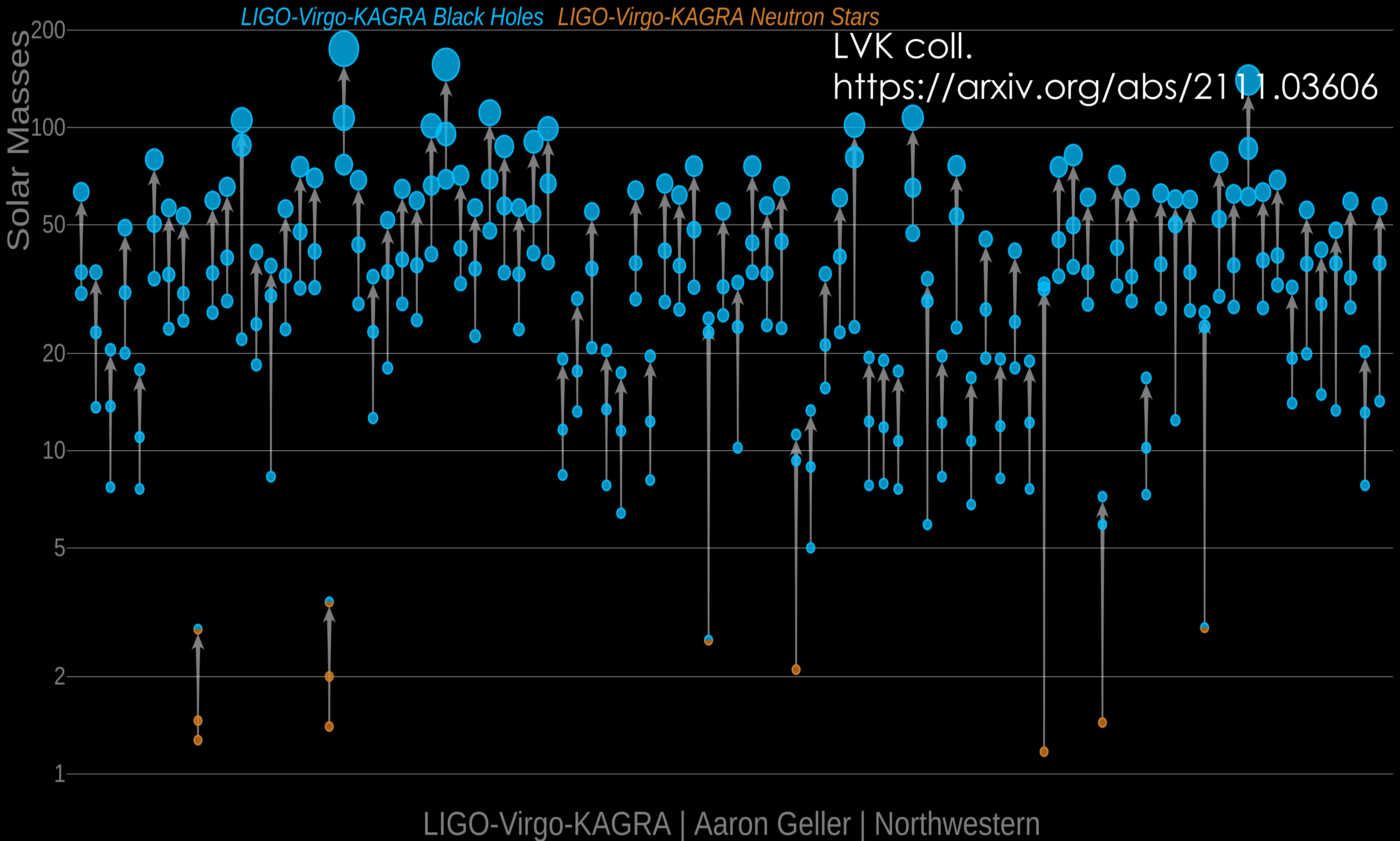
Sapienza : Paola Leaci (local coordinator)

THE CURRENT-NEAR FUTURE TERRESTRIAL NETWORK OF GW DETECTORS



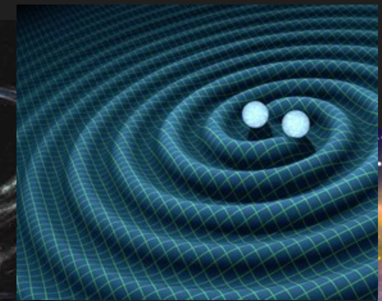
VIRGO ha iniziato la presa dati nel 2003
E ha rivelato il primo segnale nel 2017

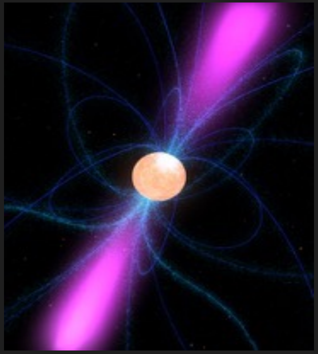
2021: the third catalog of GW sources

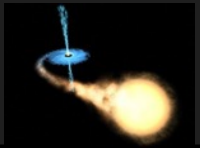


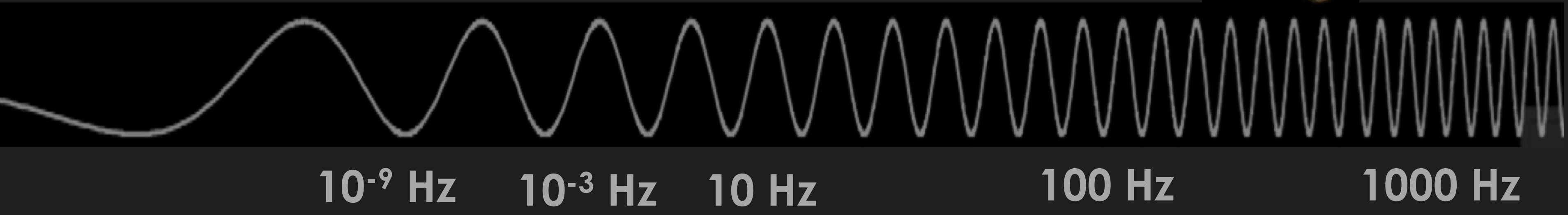
LVK coll.
https://arxiv.org/abs/2111.03606

GRAVITATIONAL WAVE SPECTRUM

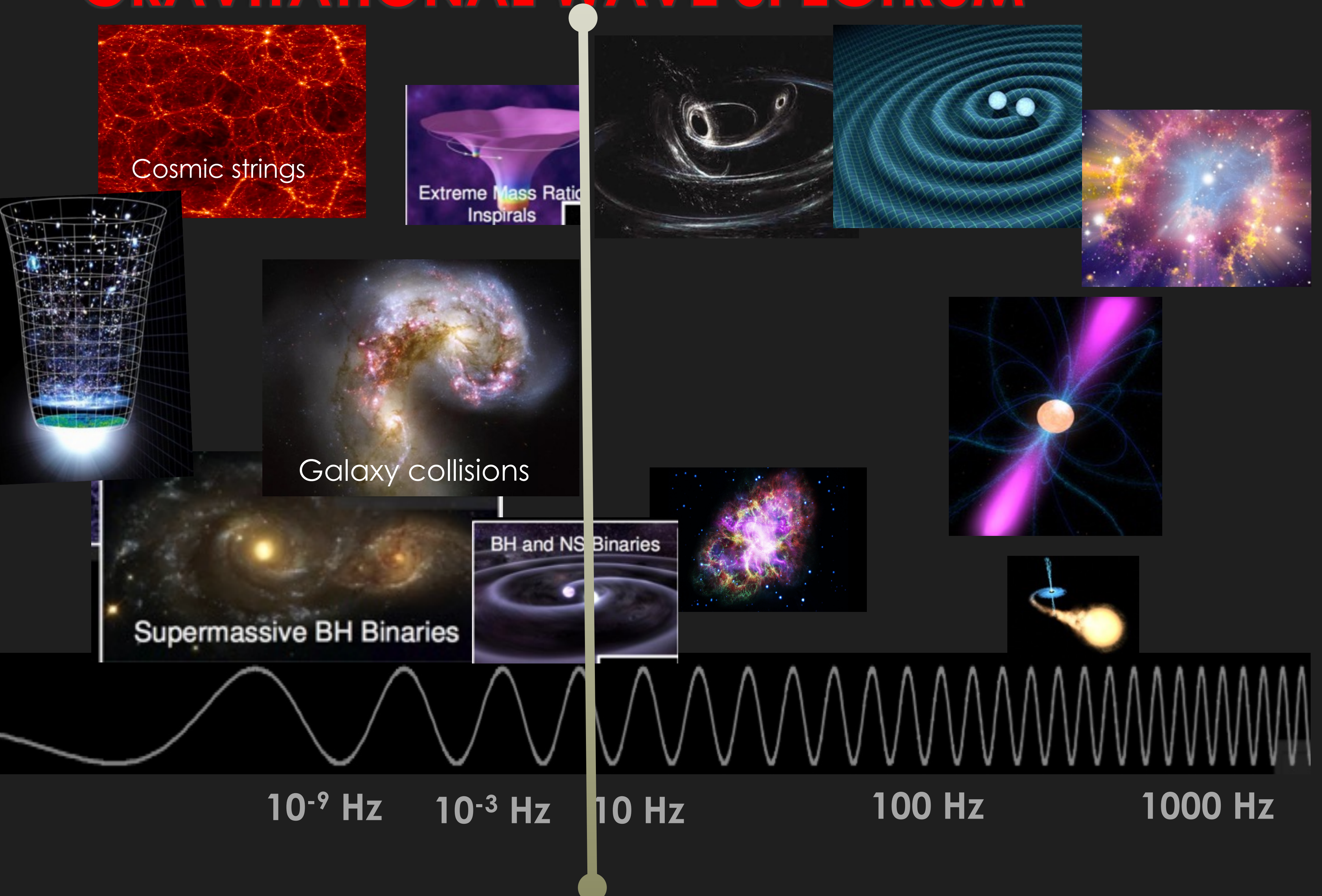




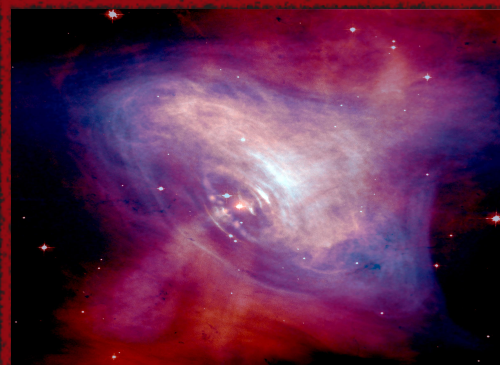
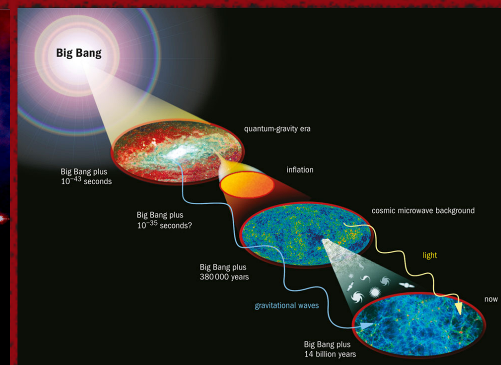
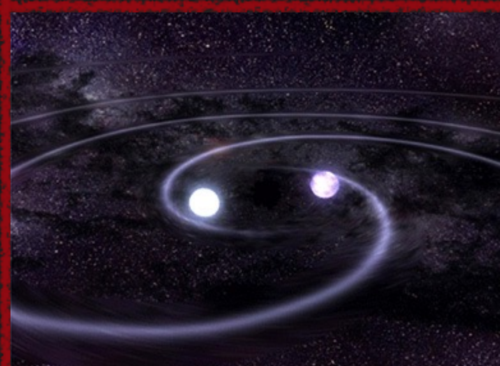
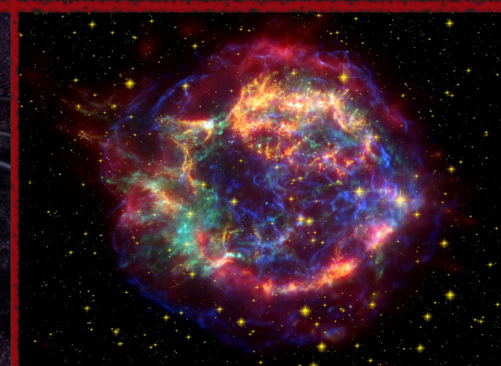




GRAVITATIONAL WAVE SPECTRUM

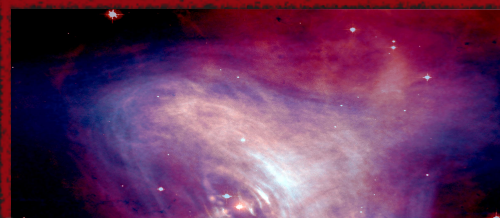
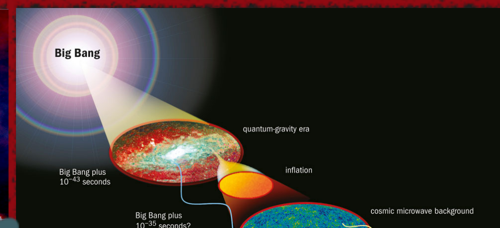
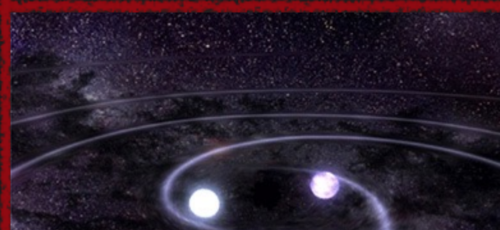
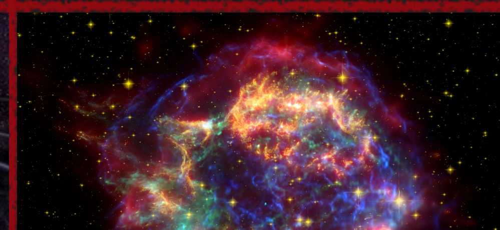


A CLASSIFICATION BASED ON SIGNAL CHARACTERISTICS

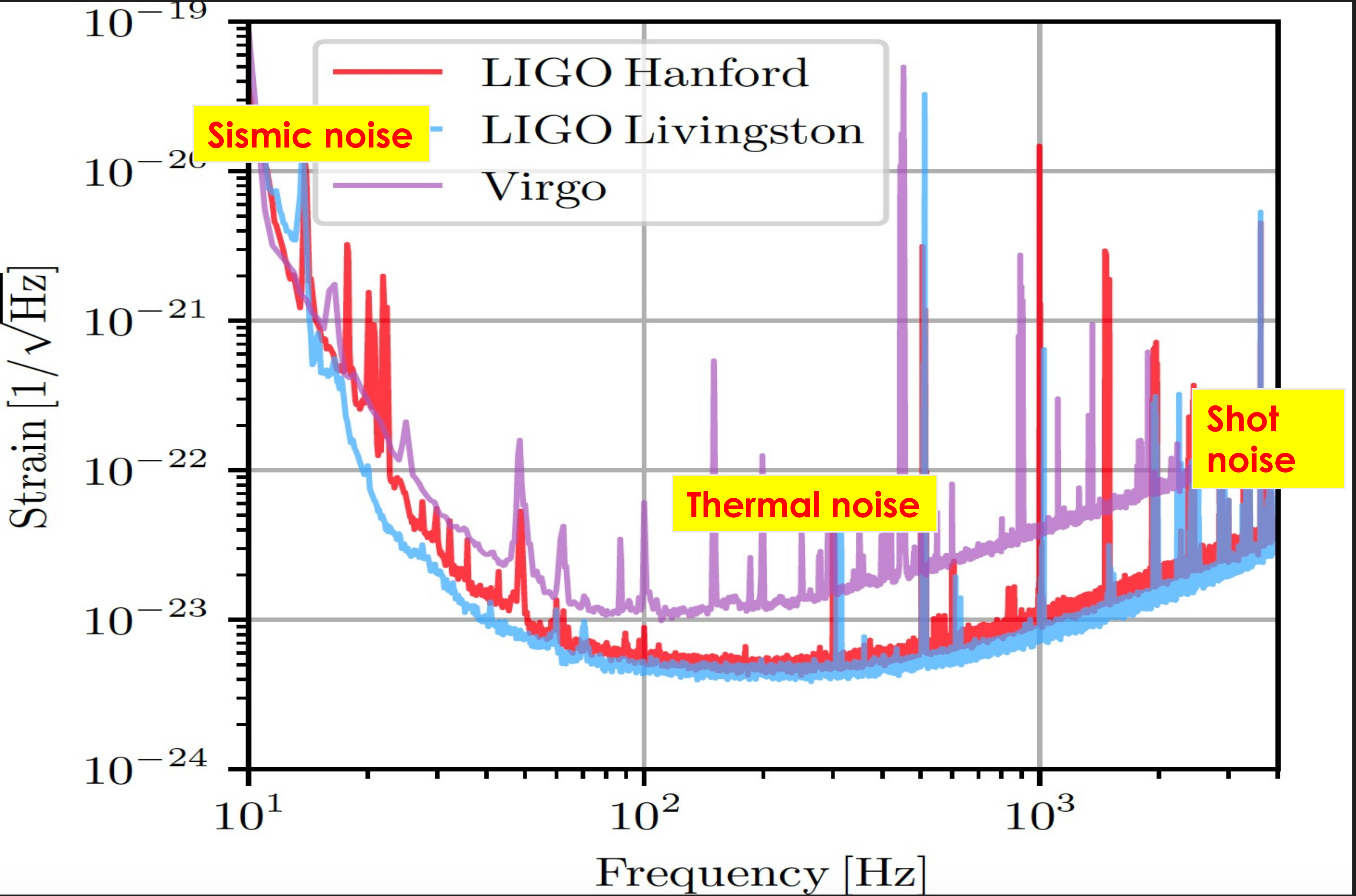
<table>
<tr><th></th><th>Modeled waveform</th><th>Unmodeled waveform</th></tr>
<tr><td>Long-lived
T ~months or years</td><td></td><td>
</td></tr>
<tr><td>Transients
T ~up to minutes</td><td></td><td></td></tr>
</table>

The sources represented in the pictures do not cover all the possibilities

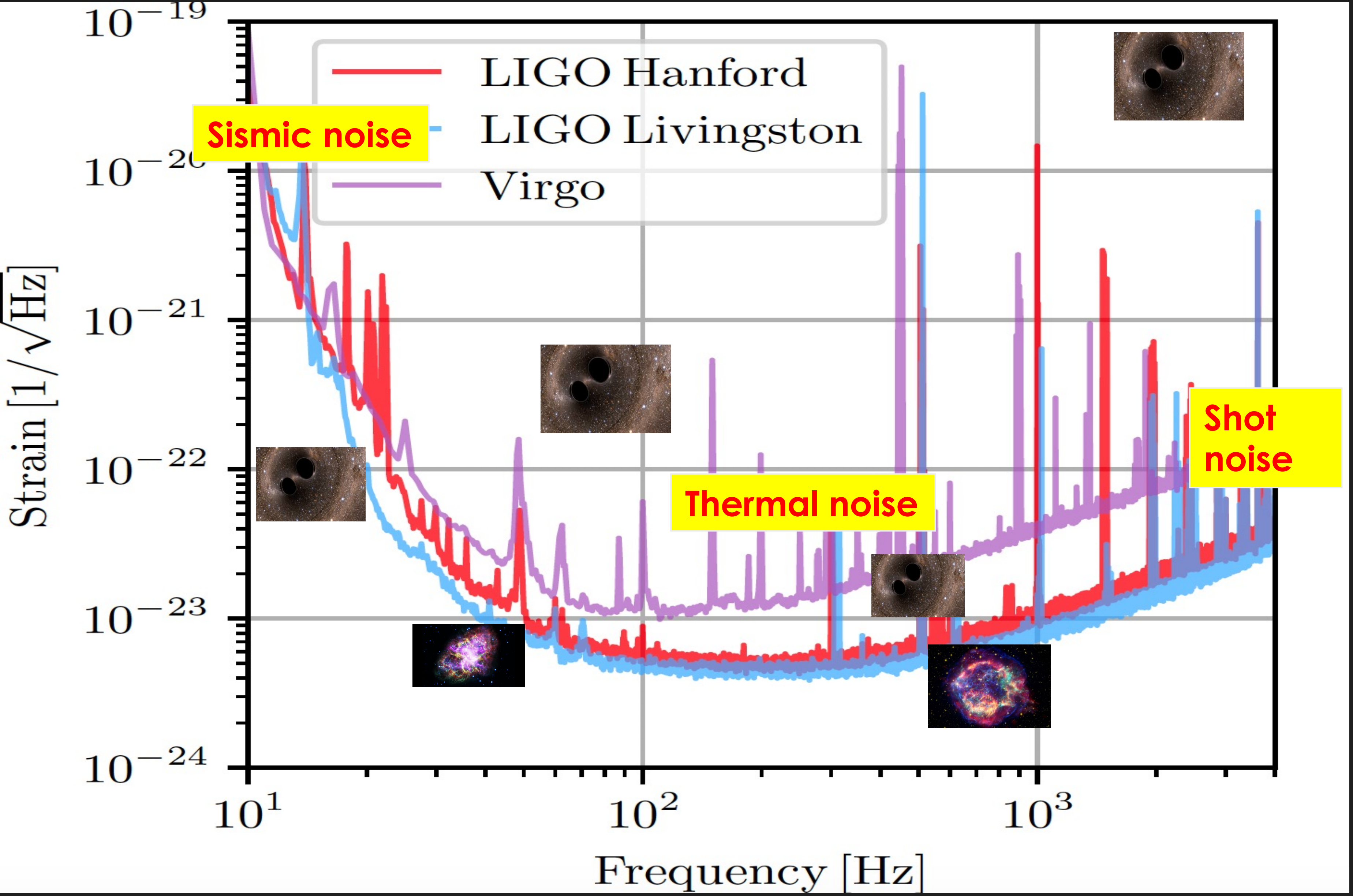
A CLASSIFICATION BASED ON SIGNAL CHARACTERISTICS

	Modeled waveform	Unmodeled waveform
Long-lived T ~months or years	 **Continuous waves** h_0 <~10^{-26}	 **Stochastic background** $h_0 \sim 10^{-28}$
Transients T ~up to minutes	 **Compact binary coalescence** $h_0 \sim 10^{-21}$	 **Bursts** $h_0 \sim 10^{-21}$

SCIENCE RUN O3 DETECTOR'S STRAIN

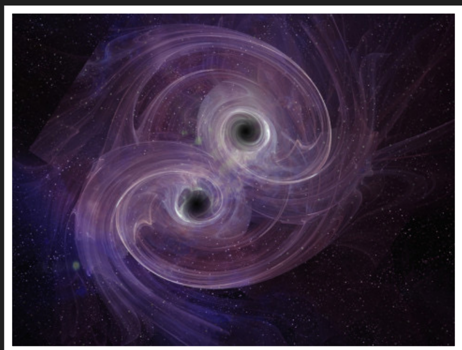


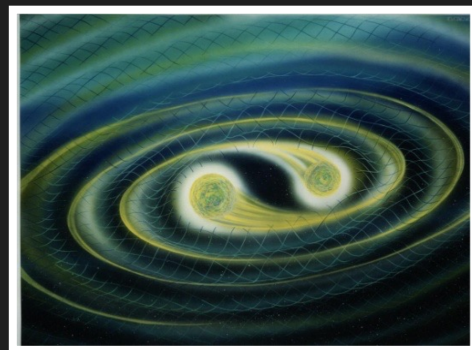
SCIENCE RUN O3 DETECTOR'S STRAIN



SOURCES, SIGNALS and SEARCH METHODS

CBC: Coalescence of binary system of neutron stars and/or stellar-mass black-holes



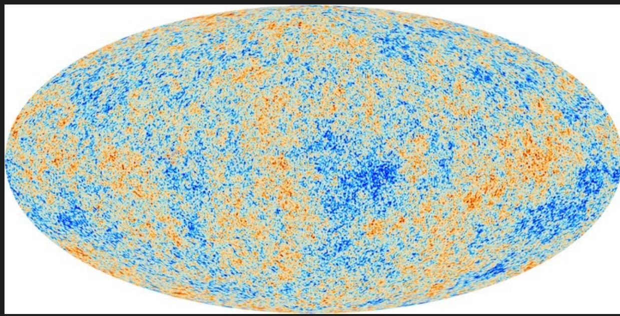


Matched-filter Modeled searches

Burst: Core-collapse of massive stars

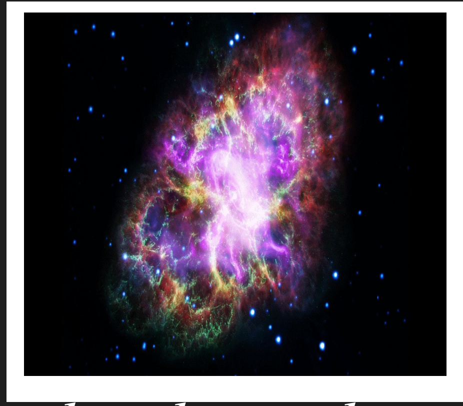
Unmodeled searches

Stochastic Background



Cross-correlations

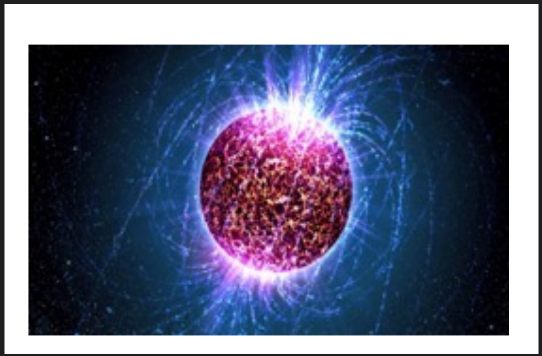
CW: Isolated or binary neutron stars



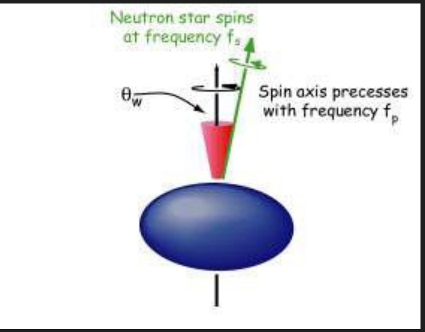
FFT based and hierarchical searches

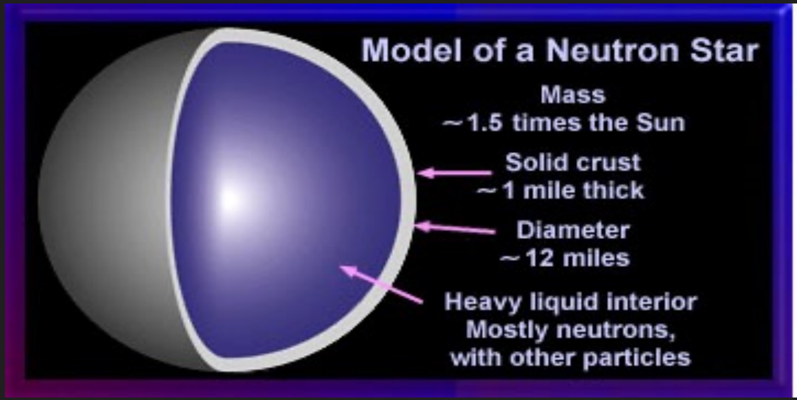
THE BASIC PROBLEM OF DETECTING CW SOURCES

- **Cbc** signals are of limited duration, well modeled and visible given the actual sensitivities , even if "far" from us. Gw170817 distance was ~ 40 Mpc from Earth.
- **Continuous signals**, like those emitted by compact object isolated or in binary systems, typically have long duration but strain amplitudes are much weaker , $O(10^{-26})$ compared to $O(10^{-21})$



CONTINUOUS WAVES EMITTED BY NEUTRON STARS





$$h_0 \cong 10^{-26} \left(\frac{I_{zz}}{10^{38} kg \cdot m^2} \right) \left(\frac{10kpc}{d} \right) \left(\frac{f}{300 \ Hz} \right)^2 \left(\frac{\varepsilon}{10^{-6}} \right)$$

deformation due to elastic or magnetic stresses: $\mathbf{f_{GW} = 2 f_{spin}}$
deformation due to (anisotropic)matter accretion (e.g., LMXB);
excitation of long-lived oscillations (e.g., r-modes): $\mathbf{f_{GW} = 4/3 f_{spin}}$

Expected signals are not monochromatic at the detector. Frequency (and phase) are modified by various effects:

- Doppler effect due to the detector motion;
- orbital motion for sources in binary systems;
- source spin-down (rotation frequency decreases due to energy loss; relativistic effects; antenna pattern).

For isolated NS the maximum foreseen **ellipticity** depends on the star crust physics, the matter equation of state at supra-nuclear density and on the deformation mechanism.

$\varepsilon_{max} \sim 10^{-5}$ for a 'standard' NS (fluid core, normal nuclear matter)

$\varepsilon_{max} \sim 10^{-3}$ for 'hybrid' stars (hadron-quark core)

$\varepsilon_{max} \sim 10^{-3} (B/10^{16}\,G)^2$ deformation from the volume averaged magnetic field.

$\varepsilon_{max} \sim 10^{-1}$ for quark star.

Lasky, Glampedakis, MNRAS 458 2016
N. Jonhson-McDaniel, B. Owen
PRD 86 063600 , PRD 87 129903

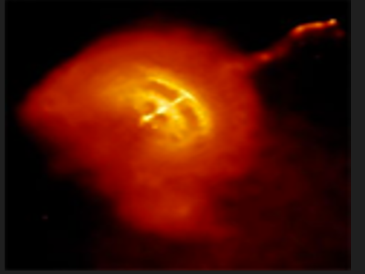
10^{-5} corresponds to a 'mountain' ~10 cm high!

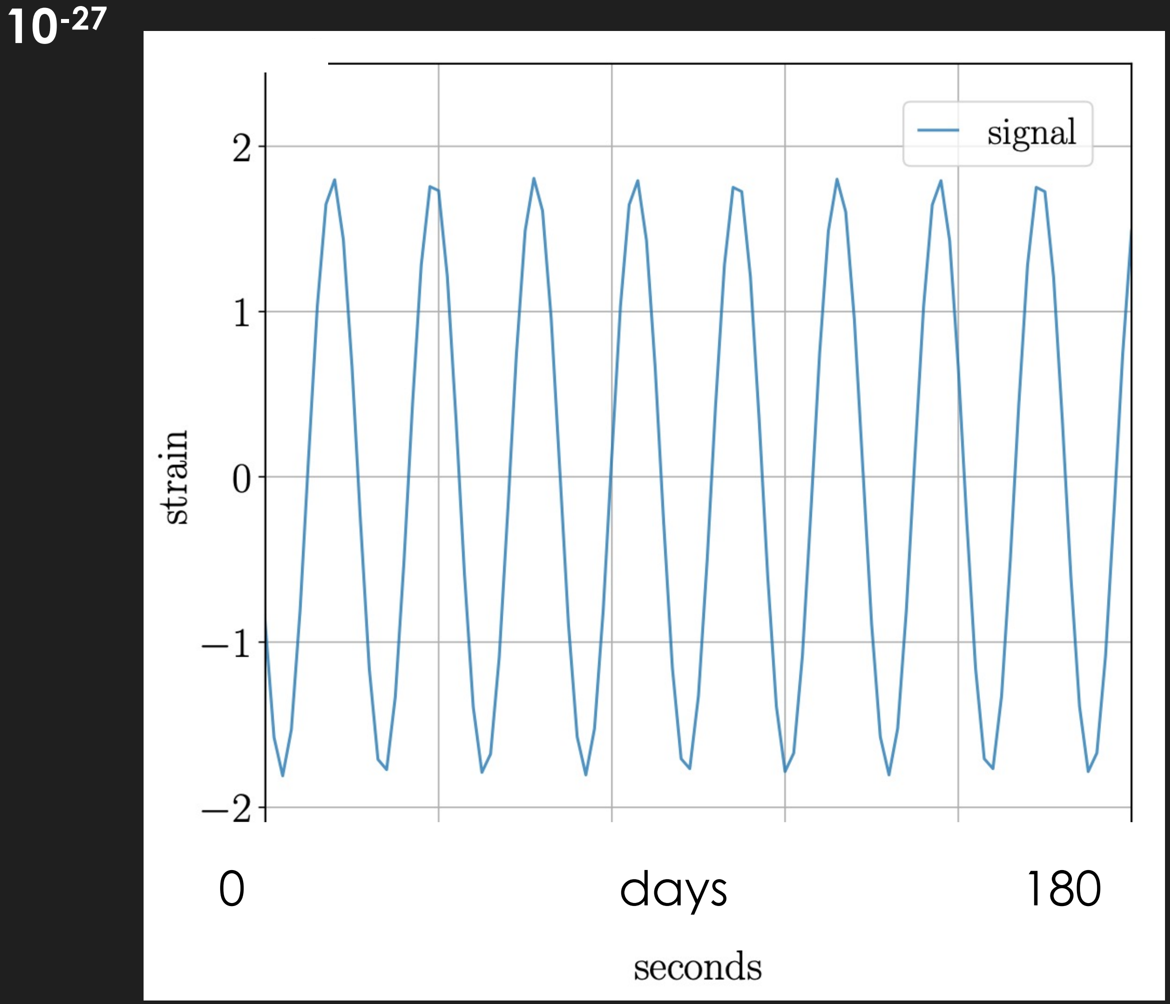
CW signals: What will a detections tell us?

- NS internal structure (EOS, viscosity, superfluidity)
- Maximum spin allowed for a NS
- Intensity and geometry of interior magnetic field
- Accretion physics
- NS demography (including a possible population of ``exotic" stars) and implications for a stochastic background.
- Testing GR

➢ Even a null result can be used to constrain NS parameters, like ellipticity or the internal magnetic field, and at least some of the EOS's.

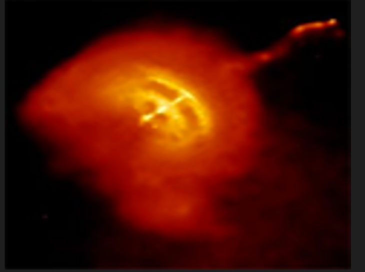
The continuous wave signal at the detector

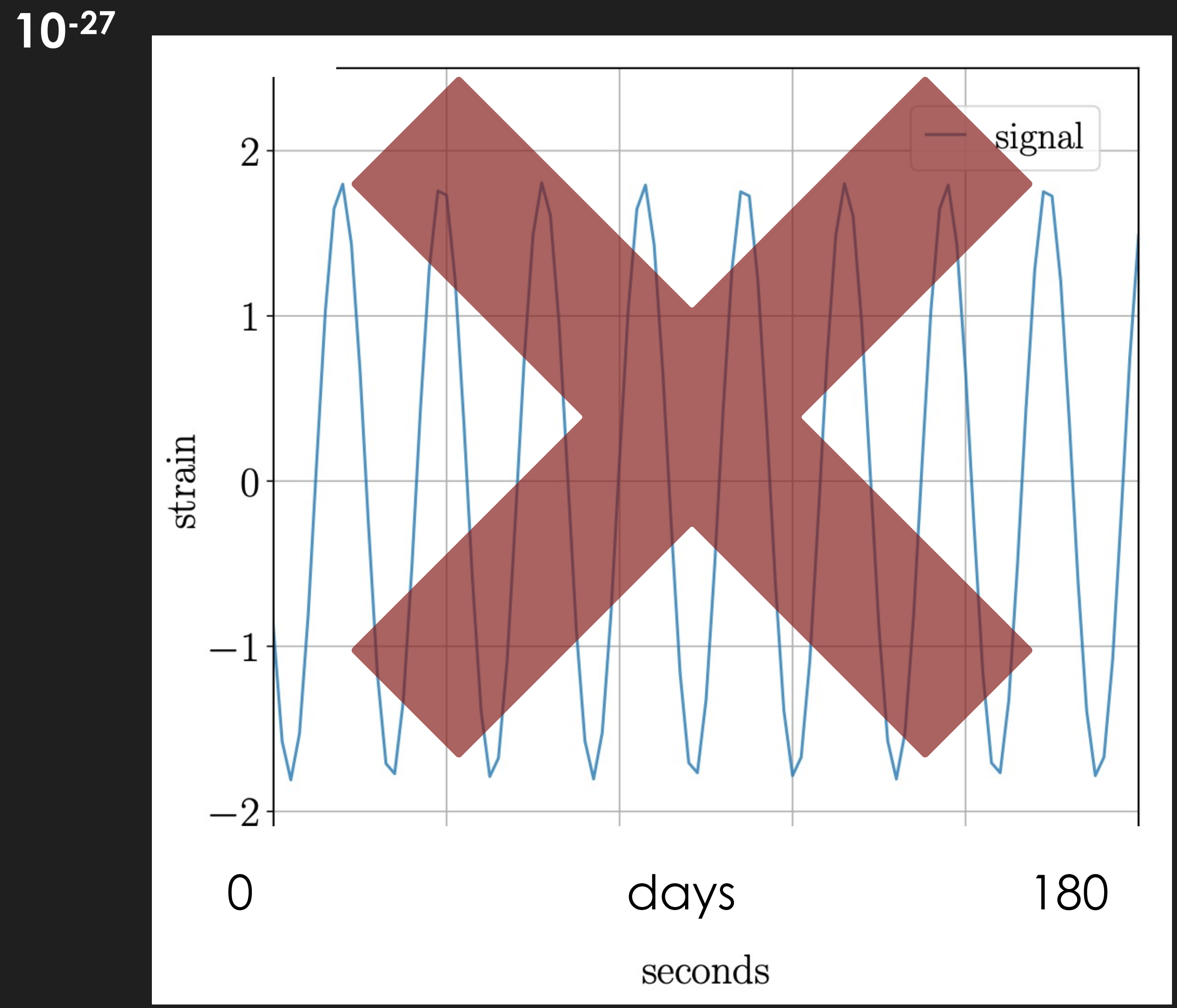




Values here are just to mark order of magnitues of the effects

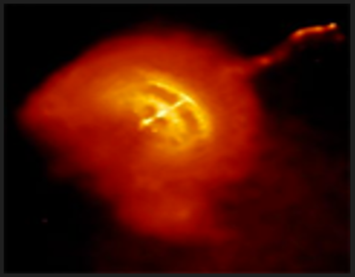
The continuous wave signal at the detector

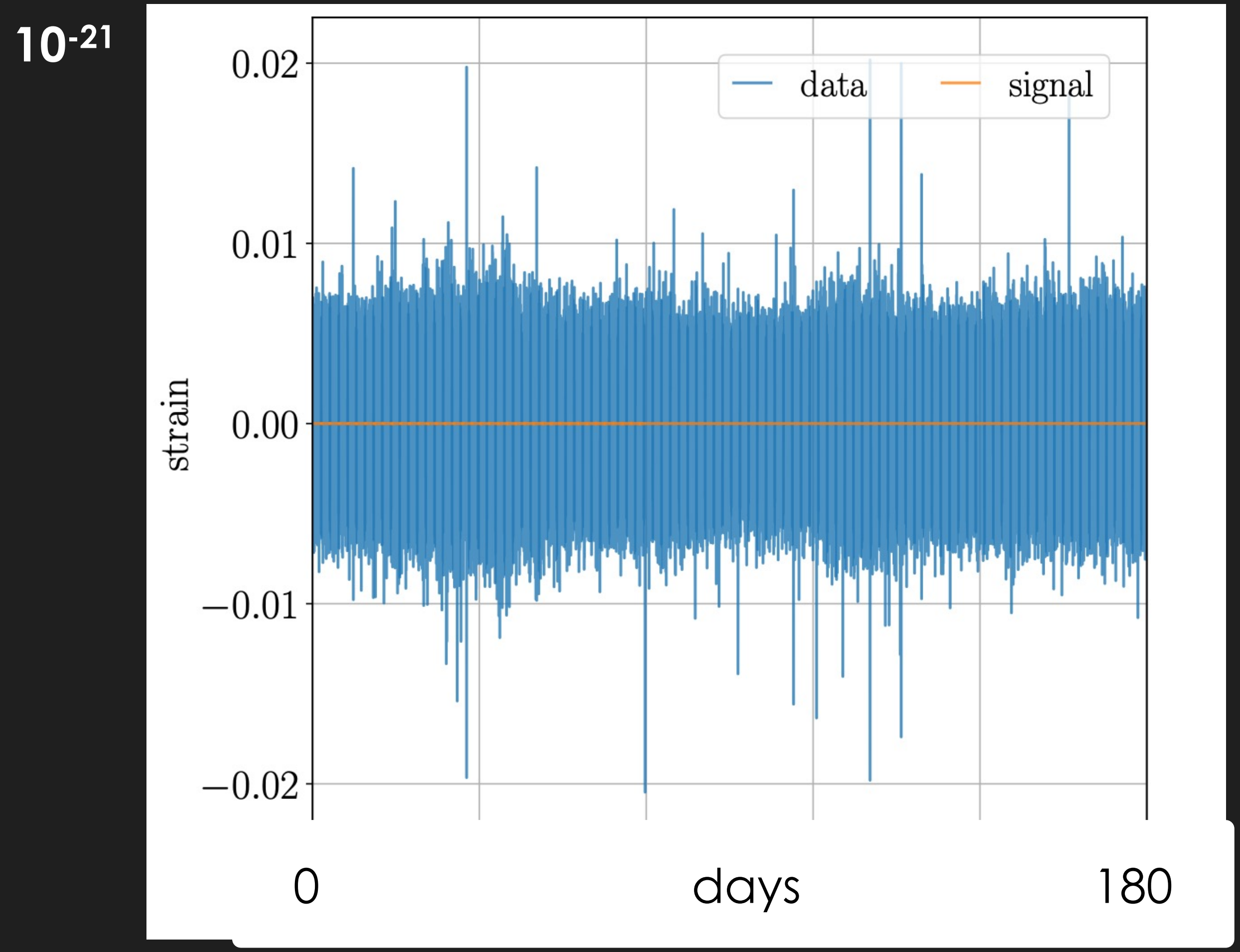




Values here are just to mark order of magnitues of the effects

The continuous wave signal in the detector noise





Values here are just to mark order of magnitues of the effects

NEUTRON STARS SIGNAL MODEL

A CW received at the detector is NOT exactly monochromatic

- SPIN-DOWN due to the loss of energy of the star

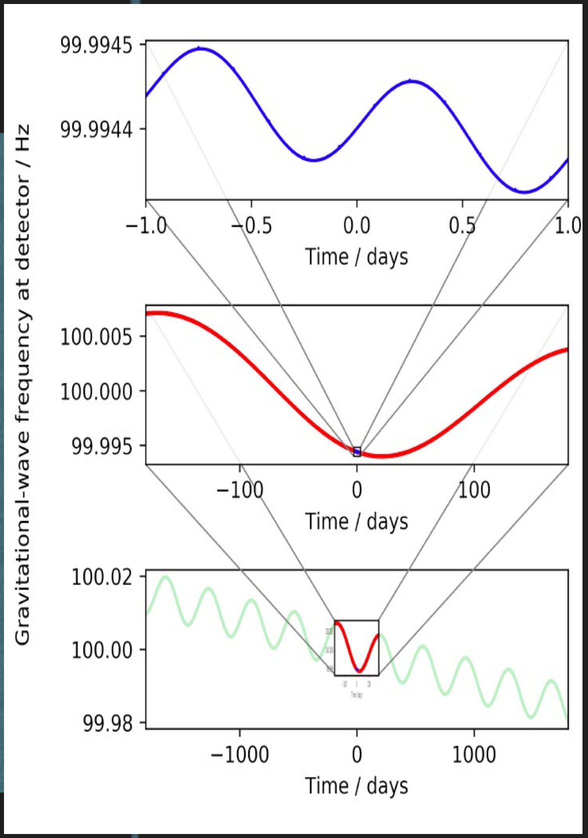
$$f_0(t) = f_0 + \dot{f}_0(t - t_0) + \frac{\ddot{f}_0}{2}(t - t_0)^2 + \cdots$$

- DOPPLER shift due to the motion of the Earth

$$f(t) = \frac{1}{2\pi}\frac{d\Phi(t)}{dt} = f_0(t)\left(1 + \frac{\vec{v} \cdot \hat{n}}{c}\right)$$

- SIDEREAL VARIATION of the amplitude

Astone et al,
Phys. Rev. D 90, 042002



Courtesy: O. J. Piccinni

In some cases, hierarchical procedures are needed

(compromise between sensitivity and computational problems)

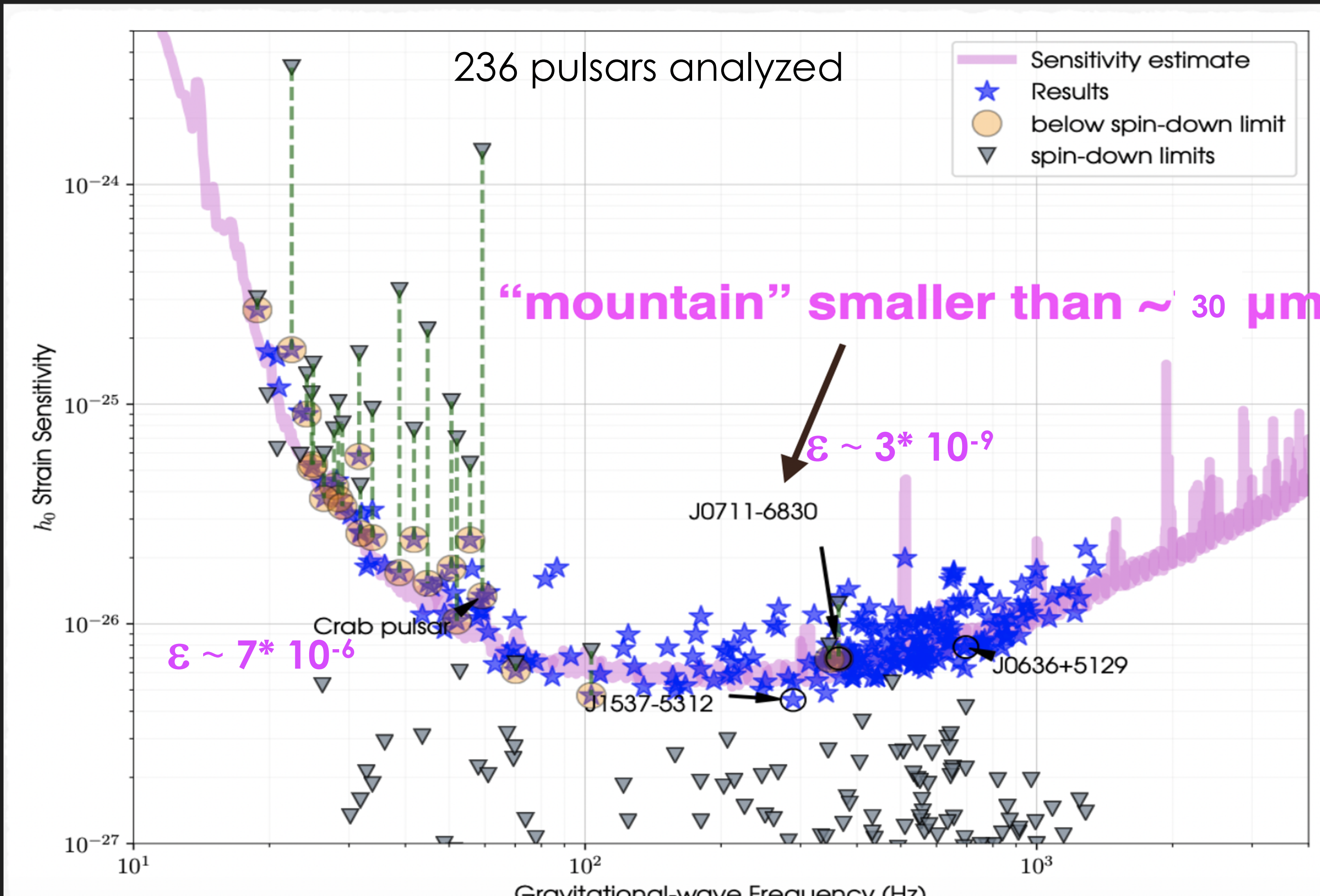
THE BASIC PROBLEM OF DETECTING CW SOURCES

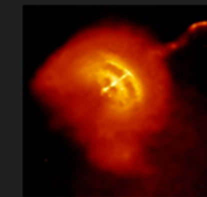
To detect these signals, we need to integrate over long times.

At the actual sensitivities our main target for continuous searches are galactic non-axisymmetric spinning NS, isolated or in binary systems, such that the frequency of the emitted GW, is in the band of our detectors ~[20-2000] Hz.

We know that potential sources of CW exist: **2500+ NS** are observed (mostly pulsars) and **O(10^8 - 10^9)** are expected to exist in the Galaxy.

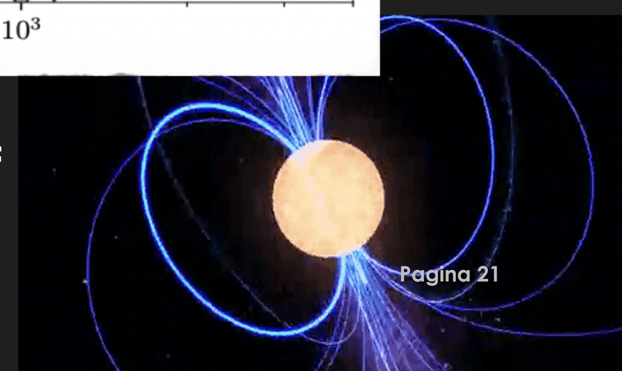
Multimessenger astronomy plays a very important role



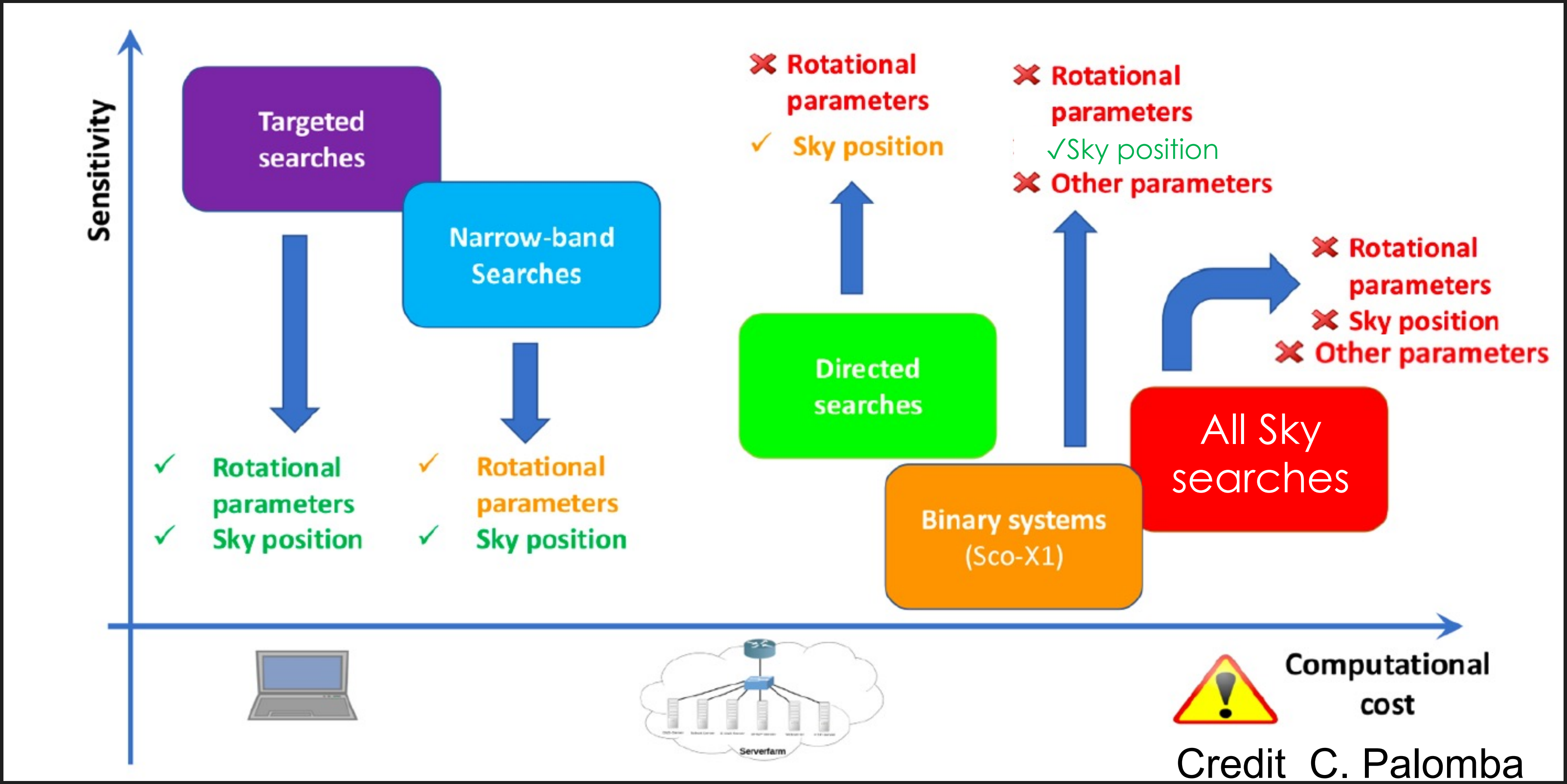


LIGO/Virgo coll: https://arxiv.org/pdf/2111.13106.pdf

For the Crab and Vela pulsars limits are factors of
~ 100 and ~ 20 more constraining than spin-down limits

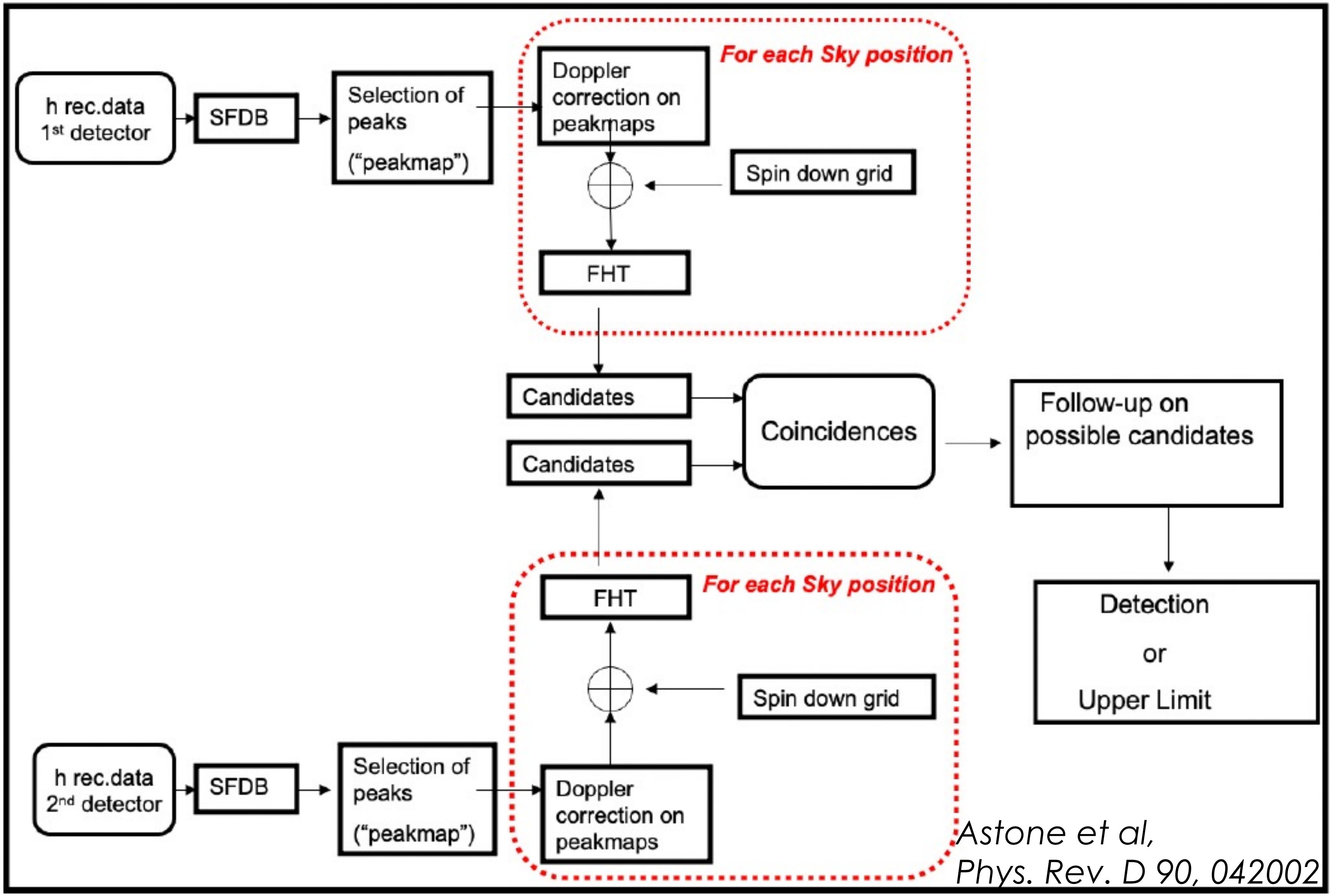


THE COMPUTATIONAL PROBLEM



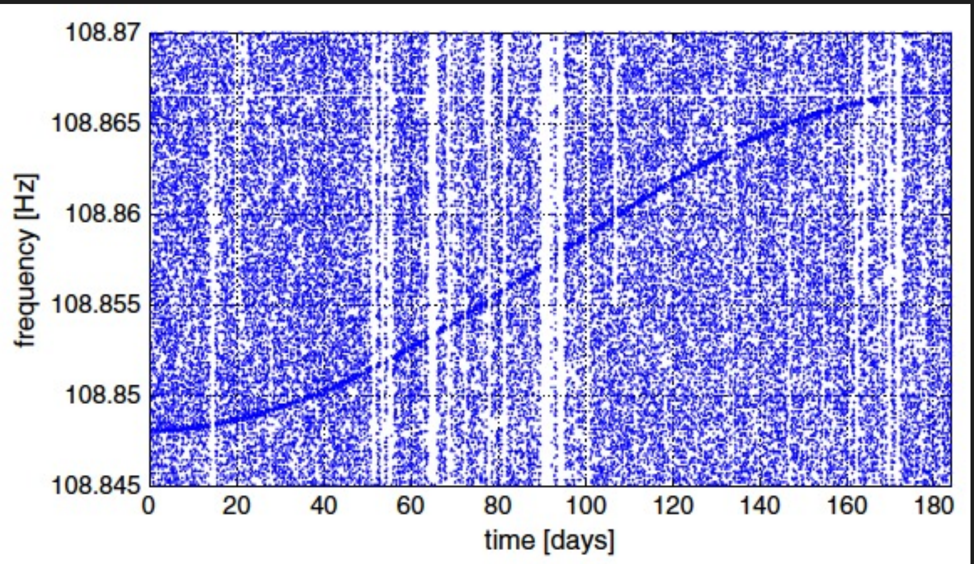
Order of magnitude estimation for hierarchical All Sky searches (isolated NS !) is: 1 year, 3 detectors. ~ 80 million core-hours

The “Frequency Hough” search procedure



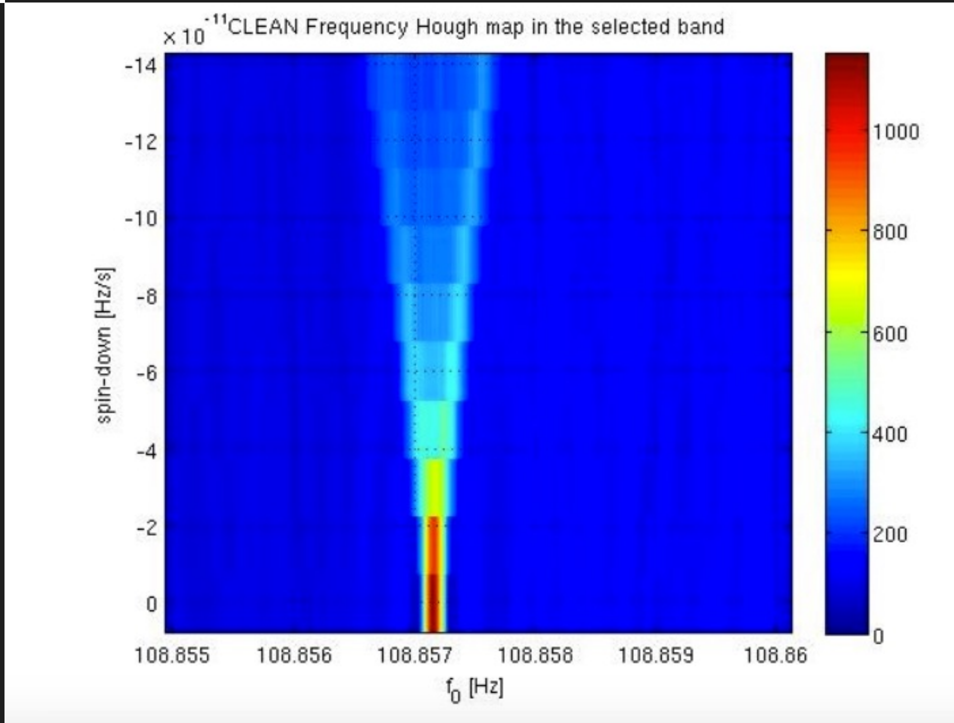
Astone et al, Phys. Rev. D 90, 042002

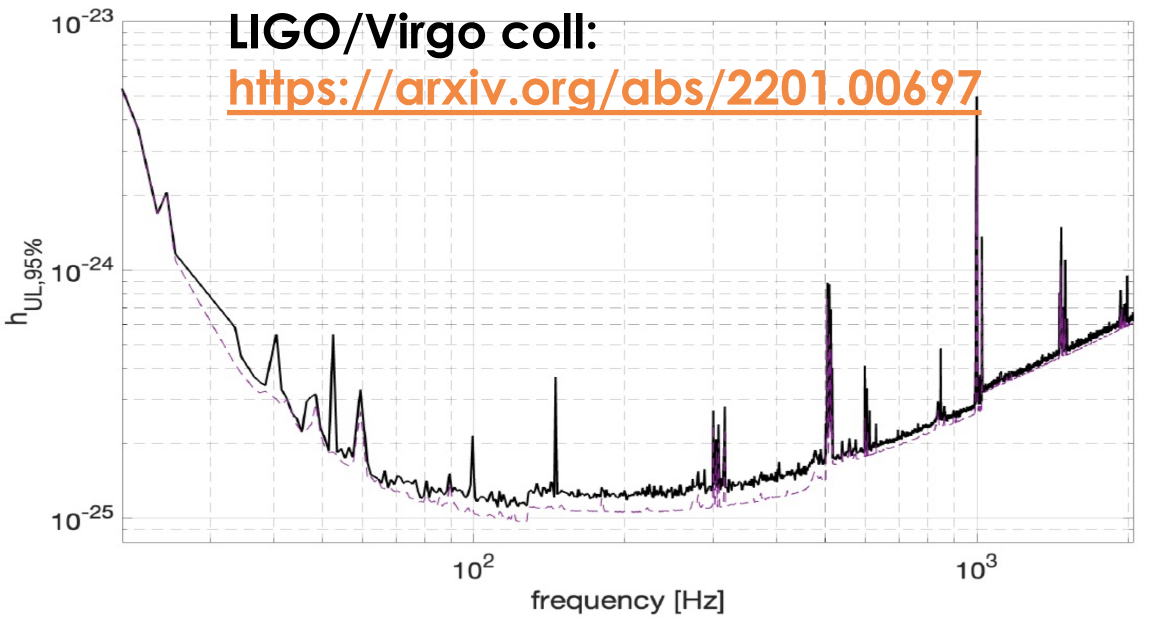
The "Frequency Hough" search procedure



An example of hierarchical procedure used in All-Sky searches

Typically executed @CNAF, which gives important support

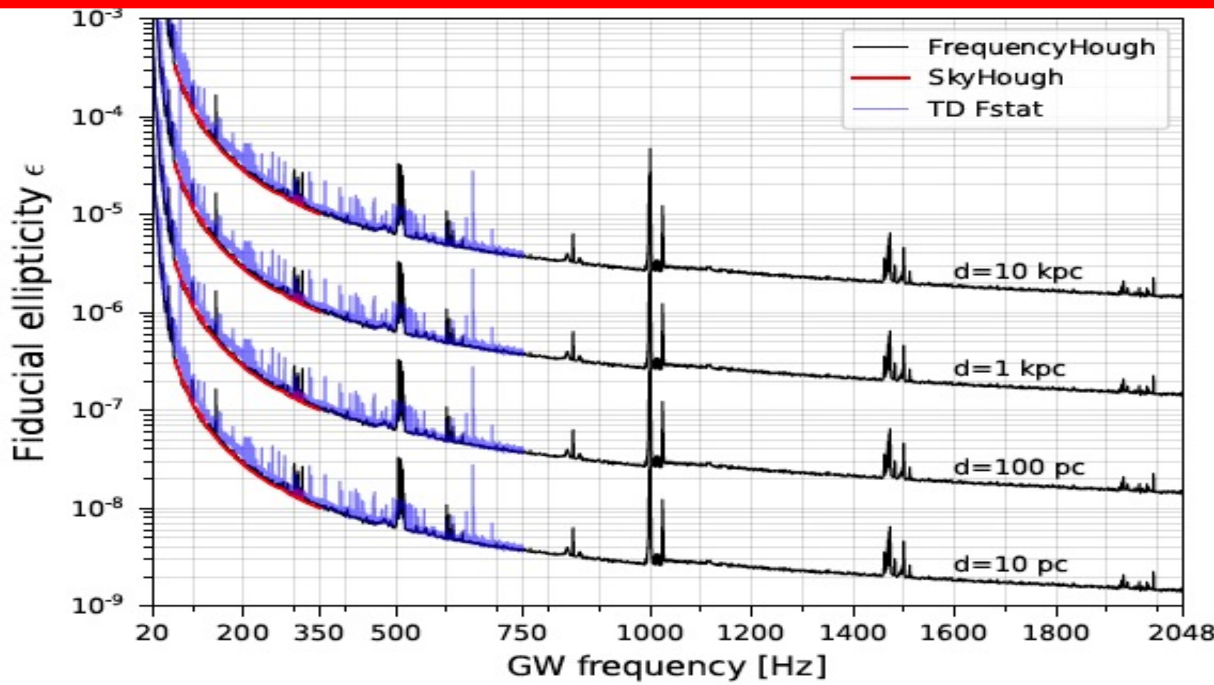




Results of O3 analysis for CW

All-Sky searches

$$\epsilon = \frac{c^4}{4\pi^2 G} \frac{h_0 d}{I_{zz} f^2}.$$



Assuming all rotational energy goes into GW

WHAT ARE MAGNETARS?

1- Slow-spinning NS (P ~ 2-12 s) with super-critical dipole B

$$B_d > 4.4\times10^{13} G$$

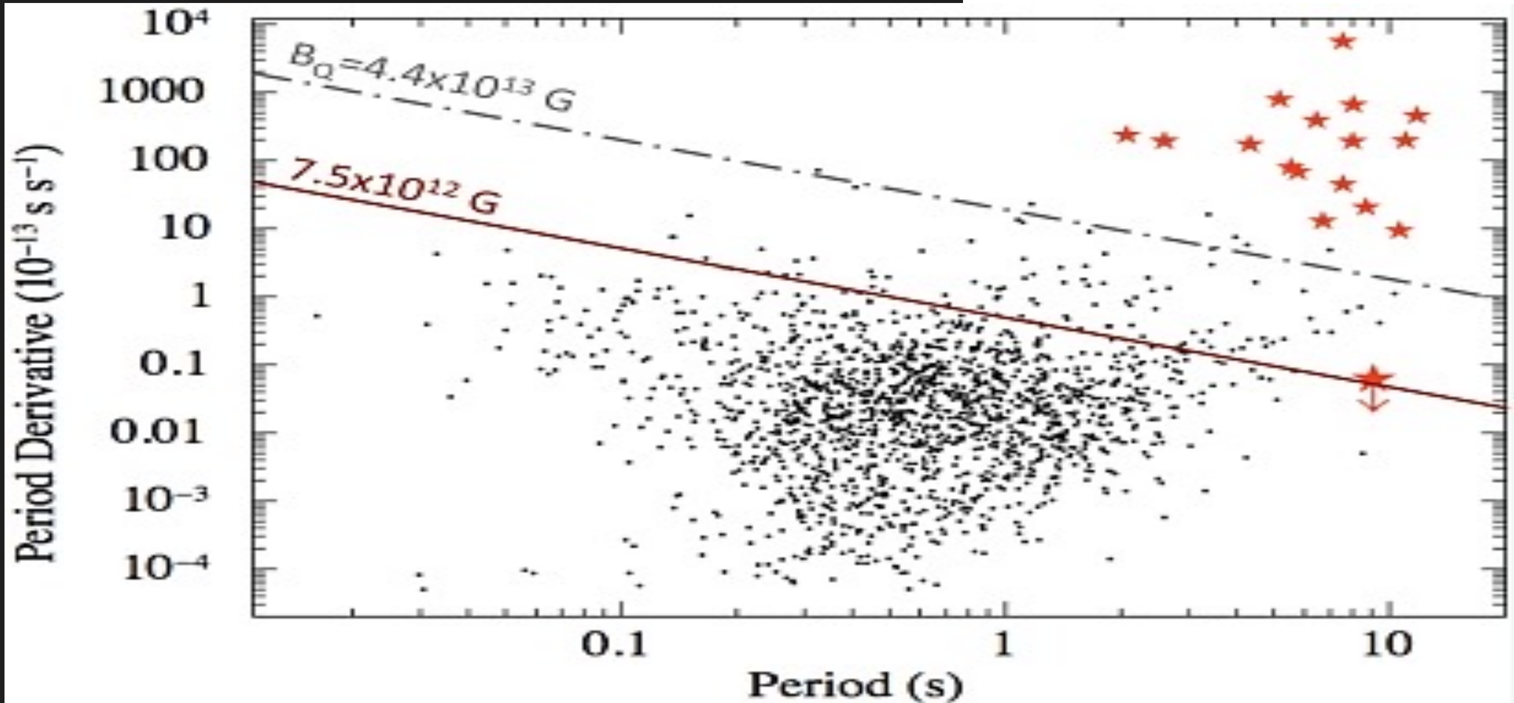
2- X-ray bright pulsators, powered by B

$$L_X \sim 10^{34} - 10^{36}\ ergs^{-1}$$

3- Giant flares (3 to date in our Galaxy)

$$\Delta E \sim 10^{45.5} - 10^{47}\ \mathrm{erg}$$

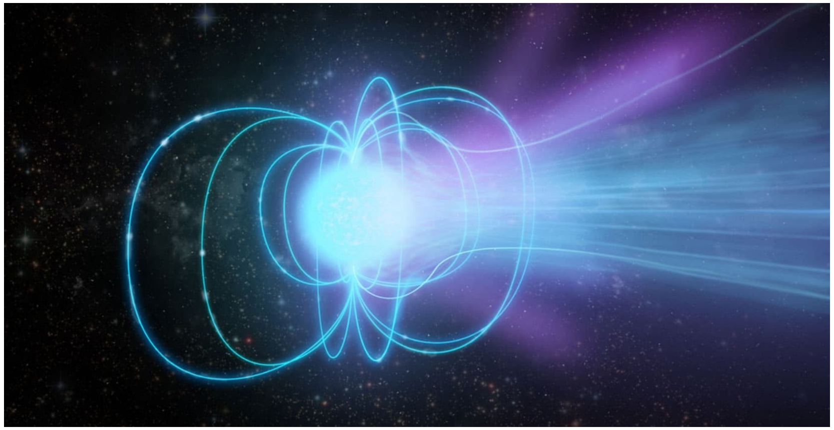
$$\Delta t \sim 0.1\ s \rightarrow 300\ s$$



Rea et al. 2010

WHAT ARE MAGNETARS?

Magnetic energy is the source of their emission



The exterior dipole is not sufficient.

An even stronger interior B-field must be present

(predicted by models then demonstrated by observations)

$$B_{\text{int}} > 3\times10^{15}\text{G}$$

What makes them so special ?

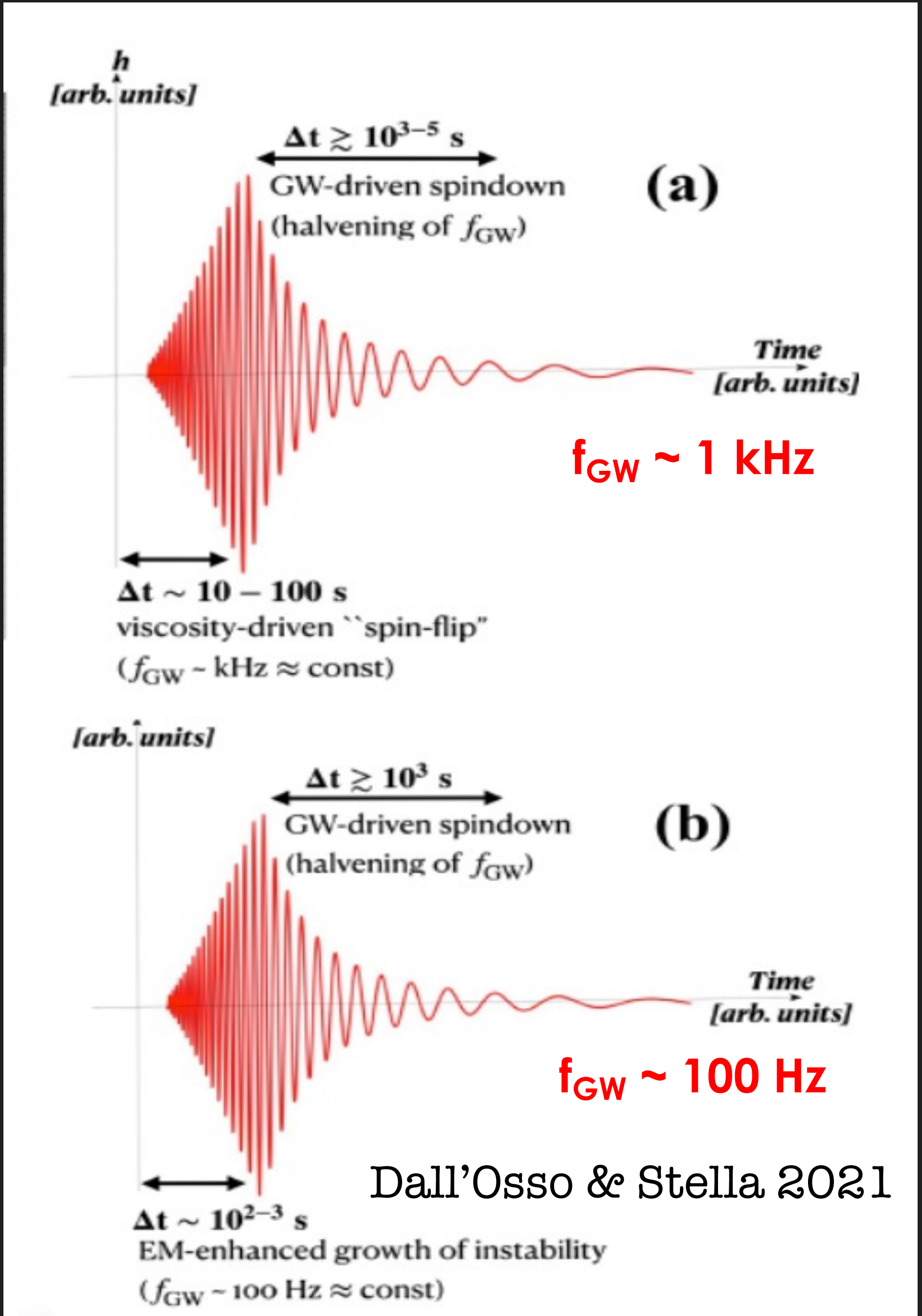
(a) How do magnetars acquire such strong B-fields?

(b) Which factors decide whether a nascent NS will become a magnetar?

GW ASTRONOMY AND THE KEY TO MAGNETAR FORMATION

Mechanism 1

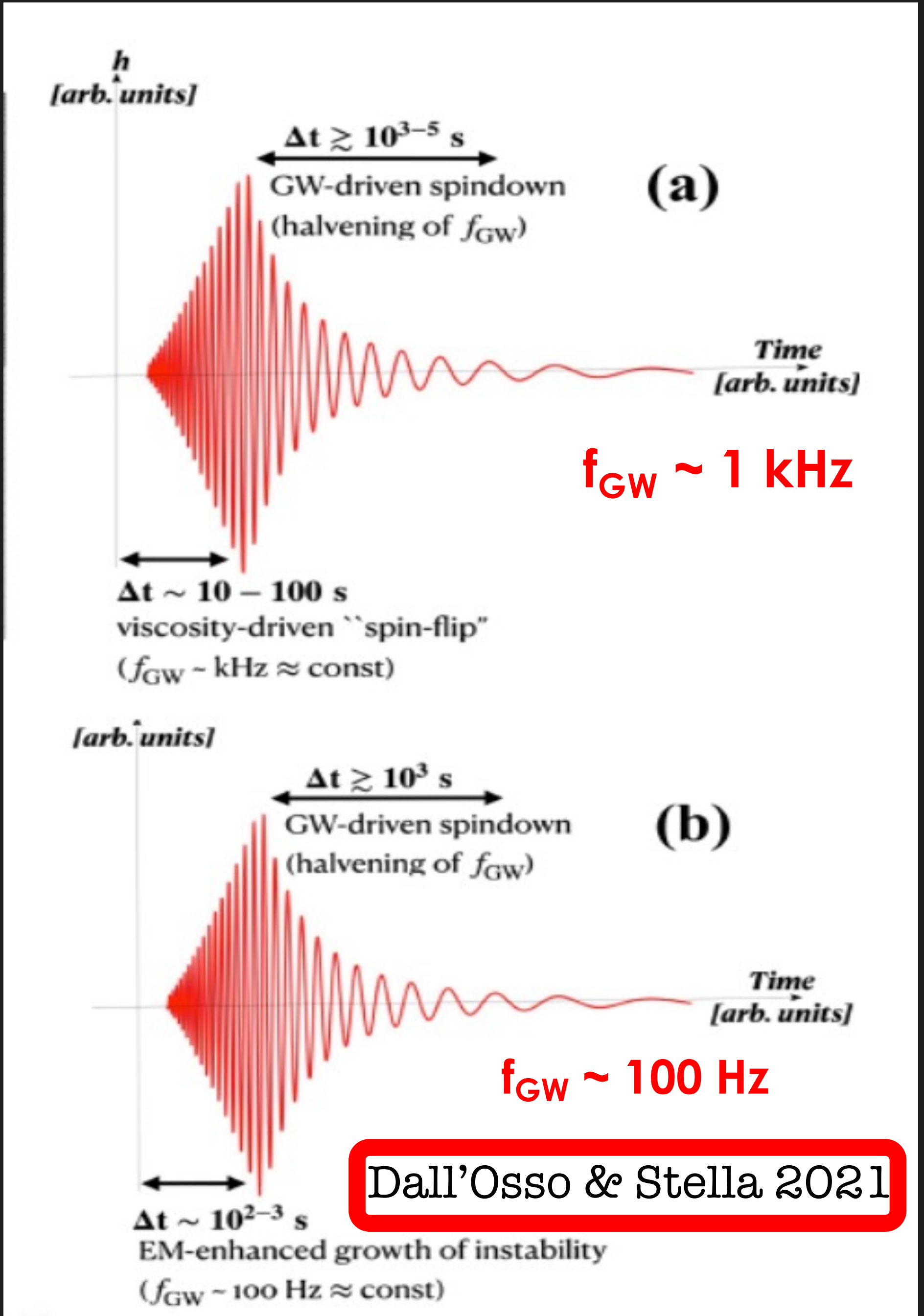
Mechanism 2



Dall'Osso & Stella 2021

GW ASTRONOMY AND THE KEY TO MAGNETAR FORMATION

Mechanism 1



f_{GW} ~ 1 kHz

KEY GOAL:

developing ad-hoc search strategies
with maximal sensitivity
(horizon of a few Mpc)

Mechanism 2

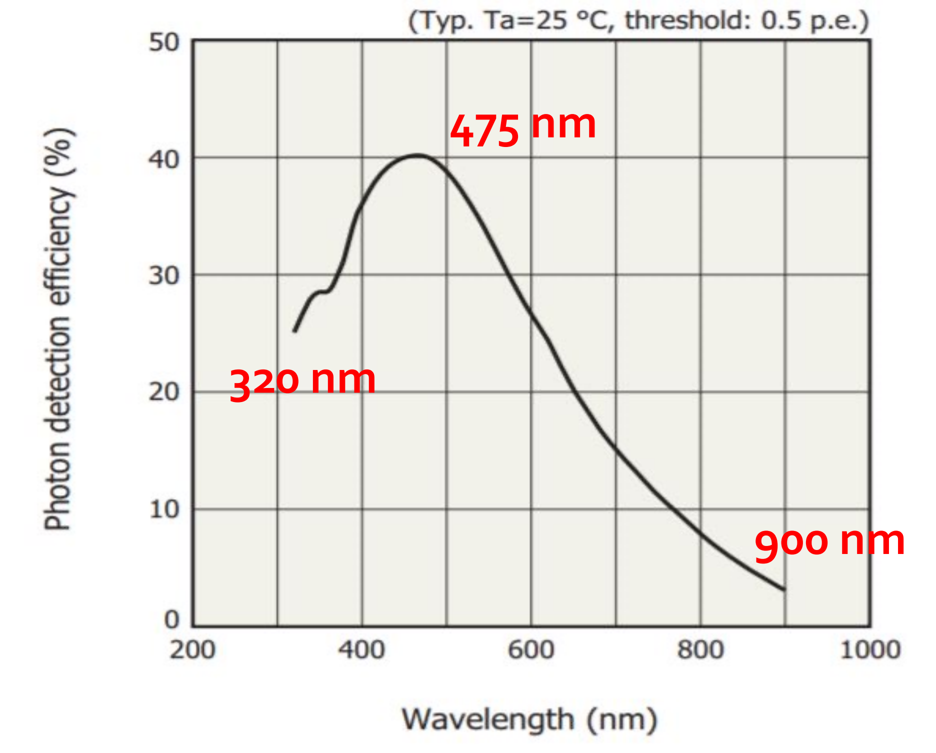
f_{GW} ~ 100 Hz

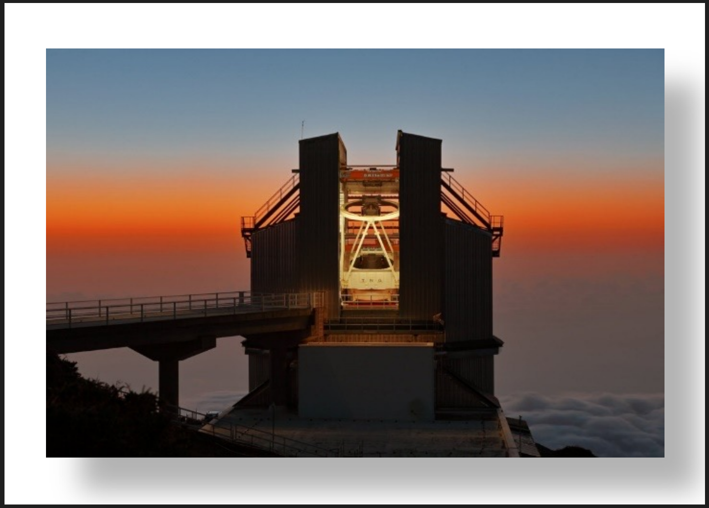
Dall'Osso & Stella 2021

The importance of an EM counterpart: SiFAP2

Mounted at the F/11 direct focus of the Nasymith A interface
Commercial Hamamatsu Silicon multipixel photon counters (SiPM)

→ **8 ns resolution** (60 μs absolute accuracy)
→ linear up to **V ≈ 10 mag**
→ **Polarimetric** capabilities (linear and circular)





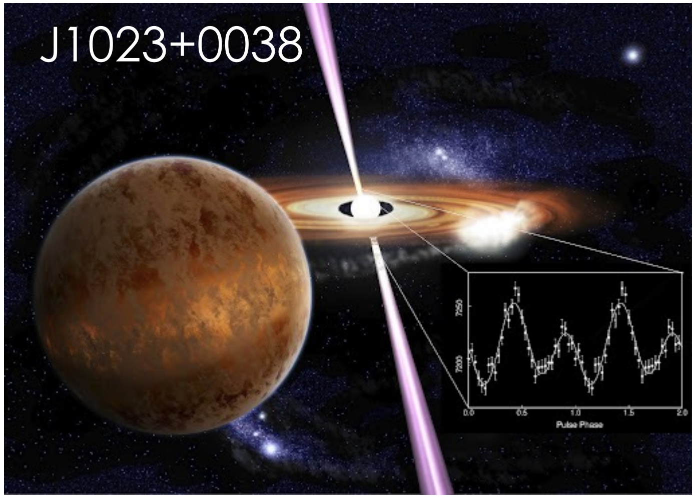
http://www.tng.iac.es/instruments/sifap2/
Ambrosino+ 2014,2018; Ghedina+ 2018

Optical ms pulsars: a challenge to the paradigm (1/2)

nature astronomy
LETTERS
DOI: 10.1038/s41550-017-0266-2

Optical pulsations from a transitional millisecond pulsar

F. Ambrosino[1,2], A. Papitto[3*], L. Stella[3], F. Meddi[1], P. Cretaro[4], L. Burderi[5], T. Di Salvo[6], G. L. Israel[3], A. Ghedina[7], L. Di Fabrizio[7] and L. Riverol[7]



Accretion vs Rotation power emission

➔ Can they coexist?

➔ Are they alternating with fast time scales?

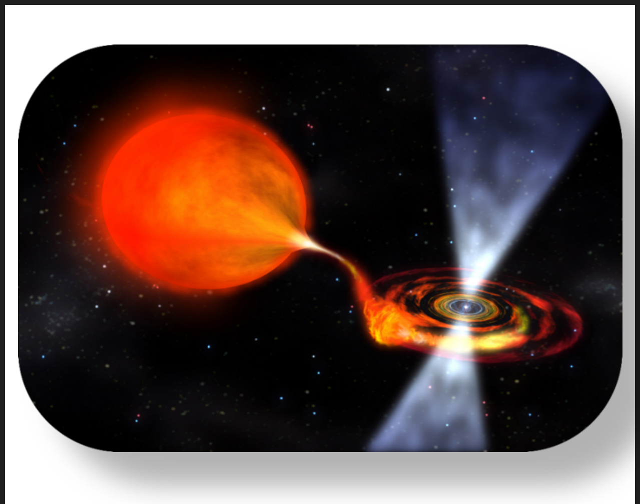
Ambrosino, Papitto et al. 2017, Nat. Astr.
Papitto et al. 2019, ApJ

Optical ms pulsars: a challenge to the paradigm (2/2)

nature astronomy
LETTERS
https://doi.org/10.1038/s41550-021-01308-0
Check for updates

Optical and ultraviolet pulsed emission from an accreting millisecond pulsar

F. Ambrosino[1,2,3,22] ✉, A. Miraval Zanon[4,5,22] ✉, A. Papitto[1], F. Coti Zelati[5,6,7], S. Campana[5], P. D'Avanzo[5], L. Stella[1], T. Di Salvo[8], L. Burderi[9], P. Casella[1], A. Sanna[9], D. de Martino[10], M. Cadelano[11,12], A. Ghedina[13], F. Leone[14], F. Meddi[3], P. Cretaro[15], M. C. Baglio[5,16], E. Poretti[5,13], R. P. Mignani[17,18], D. F. Torres[6,7,19], G. L. Israel[1], M. Cecconi[13], D. M. Russell[16], M. D. Gonzalez Gomez[13], A. L. Riverol Rodriguez[13], H. Perez Ventura[13], M. Hernandez Diaz[13], J. J. San Juan[13], D. M. Bramich[16] and F. Lewis[20,21]

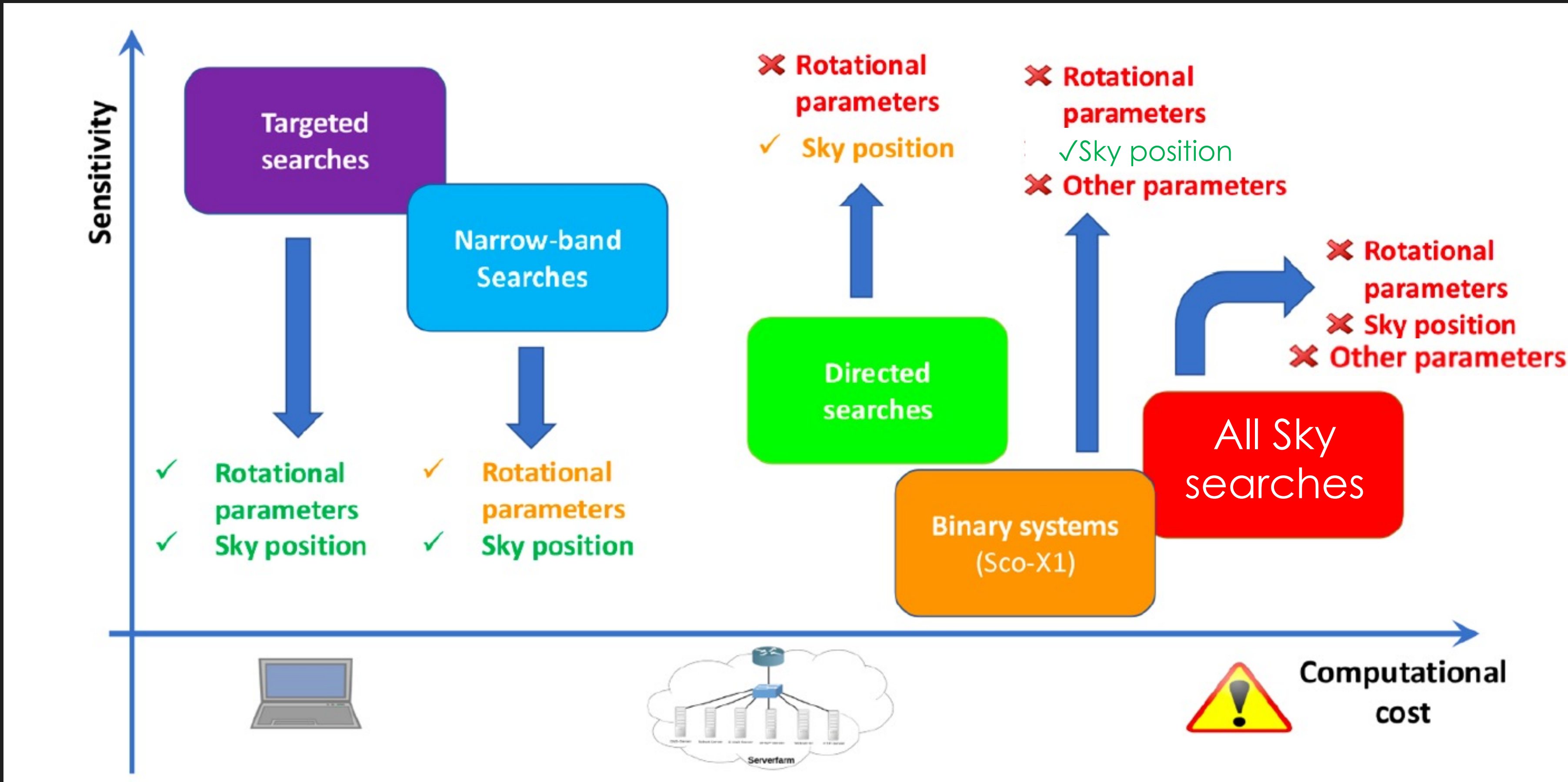


Ambrosino, Miraval Zanon et al. 2021, Nat. Astr.

<u>Future</u>: search for **optical pulses** from **candidate steady gravitational wave** sources (e.g. **Sco X-1**) thanks to optical telescopes

➔ larger statistics wrt X-ray telescopes

THE COMPUTATIONAL PROBLEM

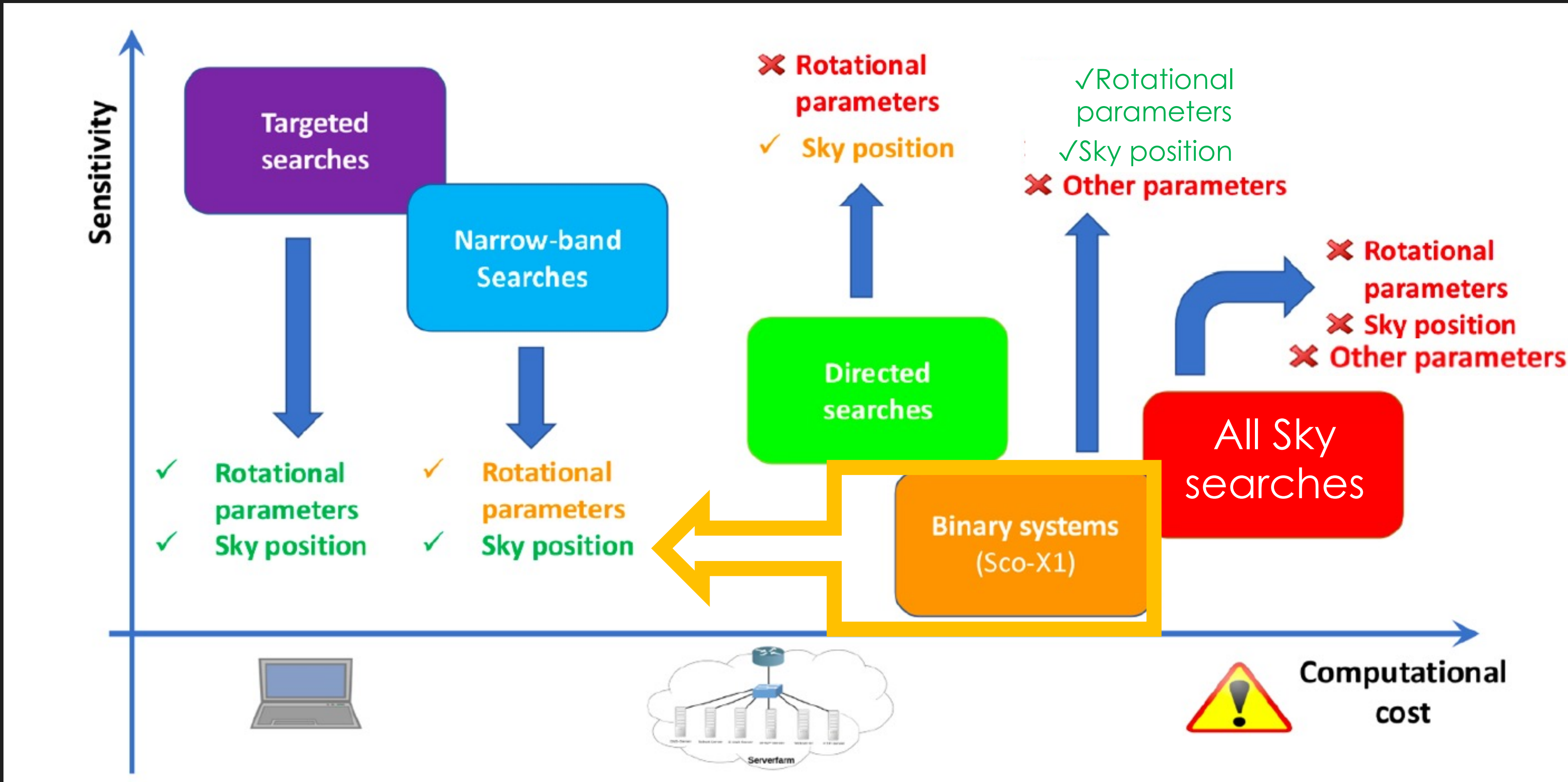


INFN CNAF

VIRGO

Sifap²

THE COMPUTATIONAL PROBLEM



- **Progetto:** Cutting-edge strategies to identify new GEMS (Gravitational- and ElectroMagnetic-wave Sources) in the Universe with current and next-generation detectors

PRIN 2020

PRIN 2020

Programmi di Ricerca Scientifica di Rilevante Interesse Nazionale

COFINANZIATO

Ruolo	**Coordinatore Scientifico del Programma di ricerca**
Dati sul progetto:	
Coordinatore scientifico	ASTONE Pia
Ateneo/Ente	Istituto Nazionale di Fisica Nucleare
Protocollo	2020BRP57Z
Settore ERC	PE9
Durata	36 mesi
Titolo del progetto	Cutting-edge strategies to identify new GEMS (Gravitational- and ElectroMagnetic-wave Sources) in the Universe with current and next-generation detectors
Contributo MUR	591.400 Euro
Cofinanziamento di Ateneo/Ente	129.000 Euro
Costo totale	720.400 Euro

Progetto: Cutting-edge strategies to identify new GEMS

PRIN 2020

CW detection

WP1: Data Analysis for CWs

- **WP1.1: All-sky searches (INFN, Sapienza)**
- **WP1.2: Directed searches (INFN, Sapienza, INAF)**
- **WP1.3: Searches for long-transient signals (INFN, Sapienza, INAF)**

WP2: EM sources

- **WP2.1: SiFAP photometer and optical millisecond pulsars**
  - WP2.1.1: SiFAP Development (INAF)
  - WP2.1.2: Observational results from SiFAP (INFN, Sapienza, INAF)
- **WP2.2: The study of magnetars (INFN, Sapienza, INAF)**

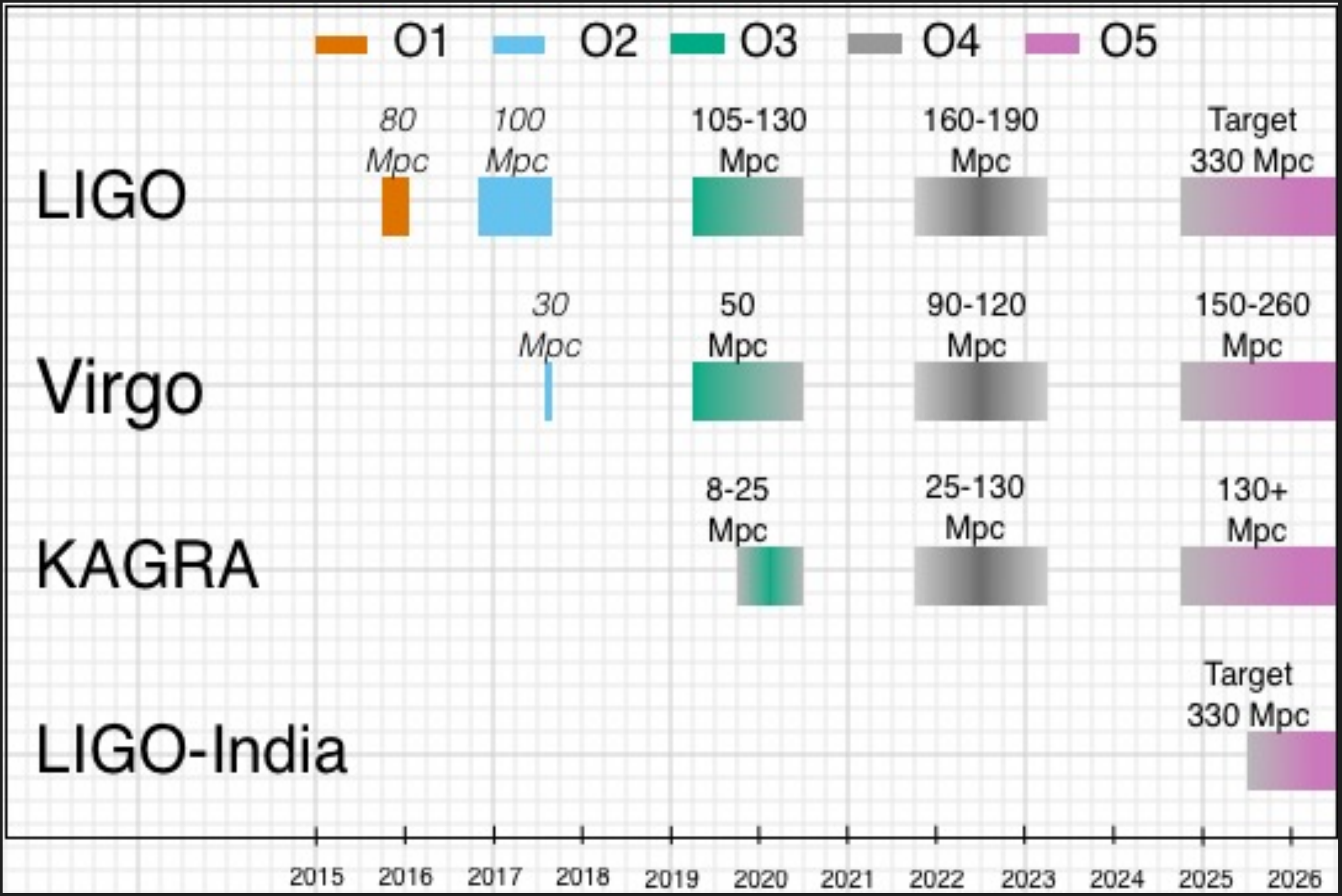
WP3: Advanced Computing

- **WP3.1: CPUs and GPUs**
  - WP3.1.1: Optimization for hierarchical searches (INFN, Sapienza)
  - WP3.1.2: Data Analysis for EM observations (INAF)
- **WP3.2: Machine Learning (INFN, Sapienza)**

Progetto: Cutting-edge strategies to identify new GEMS

	Year 1				Year 2				Year 3			
	1-3	4-6	7-9	10-12	1-3	4-6	7-9	10-12	1-3	4-6	7-9	10-12
WP1.1	*Sidereal filtering added to the FHT (D1)*				*GPU code testing, tuning and pilot studies (D3)*				*Analysis of the most recent GW detector data for all-sky searches and delivery of observational papers (D4)*			*Study of an ensemble of CW signals (D5)*
	Candidate vetoes (D2)											
WP1.2			*Sensitivity boost of searches for isolated NSs (D1)*		*Improved Resampling for binary NSs (D2)*		*Extension of the BSD-FHT pipeline to binary NSs (D3)*		*Analysis of the most recent GW detector data for directed searches and delivery of observational papers (D4)*			
WP1.3	*Parameter space reduction via EM observations, NS modeling and data analysis (D1)*				*RGB technique (D2)*		*2D-filtering and pattern recognition (D3)*				*Method comparison and Analysis of the most recent GW detector data (D4)*	
WP2.1	*SiFAP detectors improvement (D1)*											
	SiFAP timing accuracy enhancement (D2)											
	Feasibility study for the extension of SiFAP capabilities to nIR domain (D3)								*Searching for pulsars in absorbed regions with SiFAP nIR (D5)*			
	Searching for optical millisecond pulsations from LMXB systems with SiFAP (D4)											
WP2.2	*Modeling newborn NSs and magnetars (D1)*					*Constraints from SBOs (D3)*				*Templates; final performances assessment and parameter estimation (D2)*		
			Templates first studies and performance test (D2)									
WP3.1	*Optimization of data analysis routines (D3)*		*GPU code porting and optimization (D1, D2, D4)*									
WP3.2			*ML for CW long transients and binary systems (D1)*							*Studies on Quantum computing (D2)*		

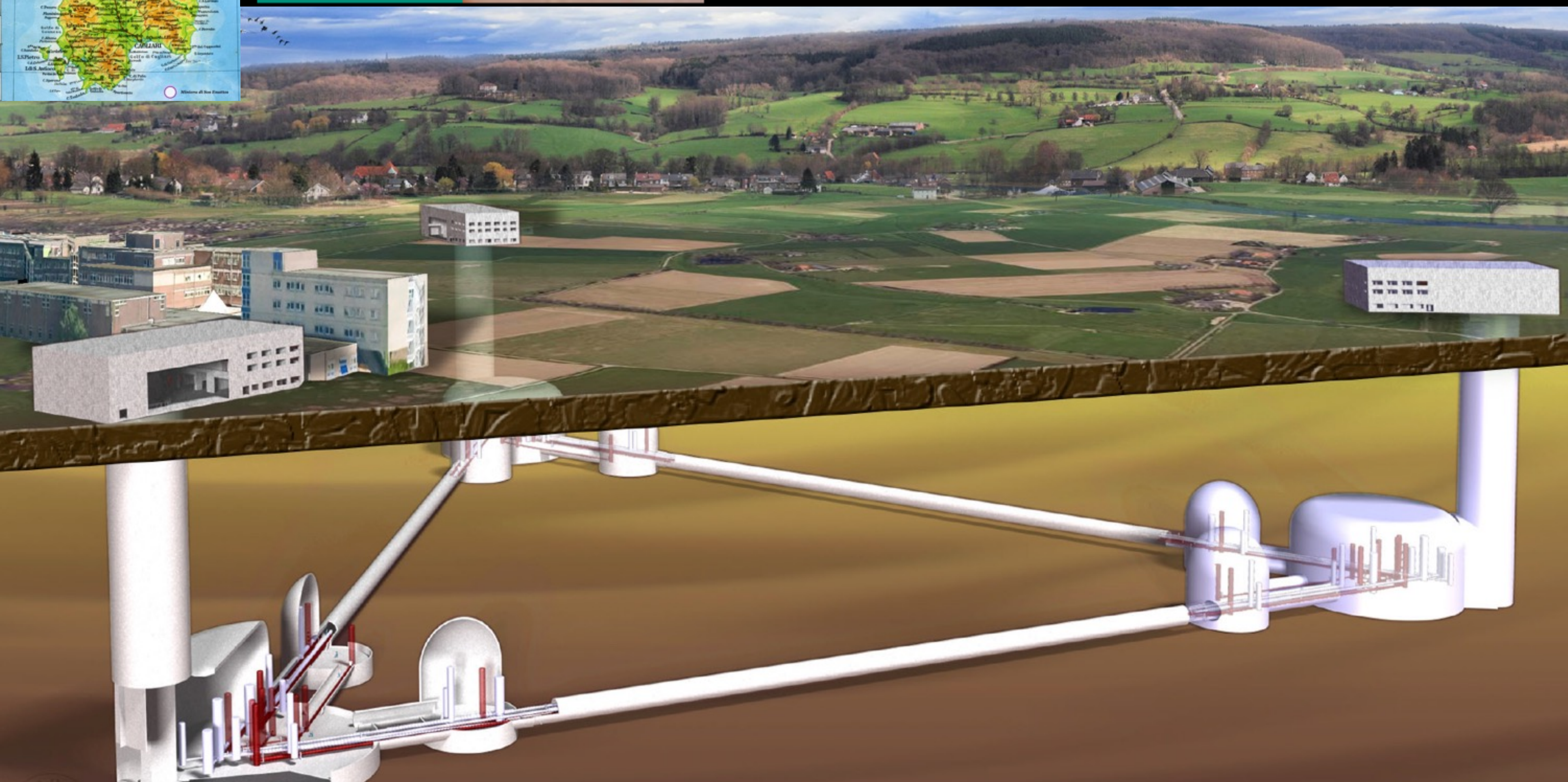
(NEAR) FUTURE OF GW DETECTORS:
PROGRESSES IN SENSITIVITY



Einstein telescope

ET EINSTEIN TELESCOPE

Our work is clearly fundamental in particular to be ready with robust and sensitive procedures in view of 3rd generation detectors



> ~ 2030

Next science run will begin at the end of 2022
Will last 1 year.
Our analysis will be prepared and tested in the period 2022-2023 and done during 2024.

Some analysis might run after 6 months, producing results during the second part of 2023

Credit NASA

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