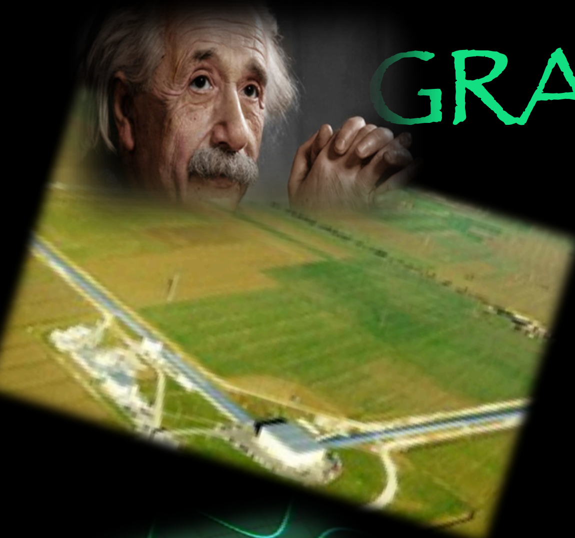
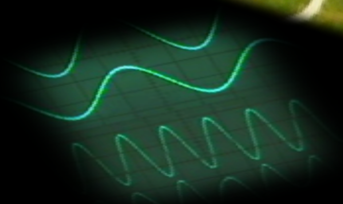
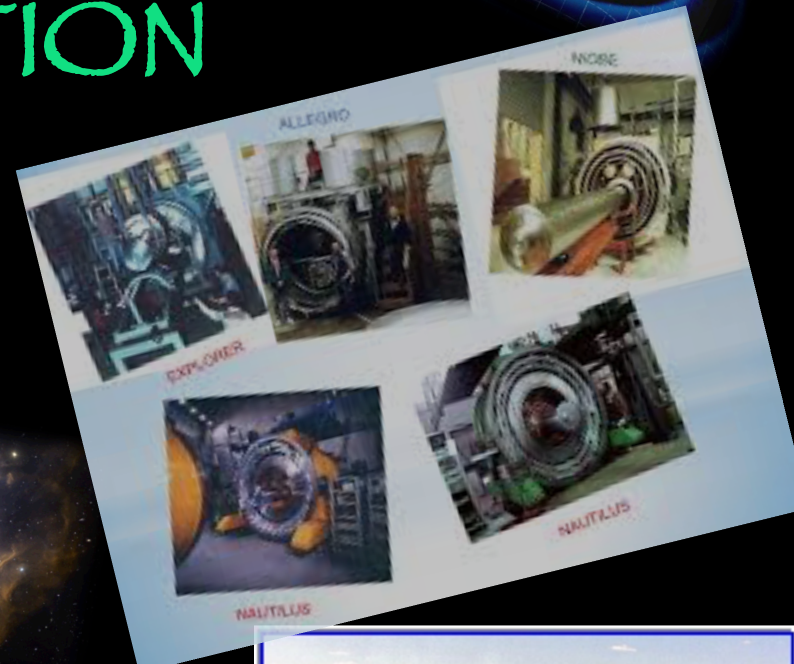
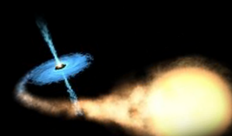




GRAVITATIONAL WAVES DETECTION



Sabrina D'Antonio

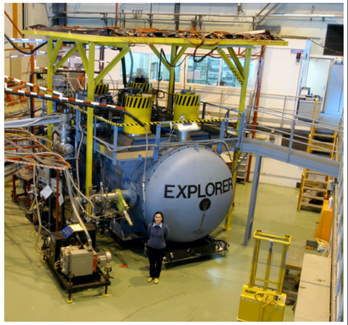


Roma Tor Vergata Dec 2018

NAUTILUS
LNF - FRASCATI

Bar Al 5056 M = 2270 kg
L = 2.91 m Ø = 0.6 m
ν_A=935Hz @ T = 3 K
Cosmic ray detector

EXPLORER
CERN - GENEVA



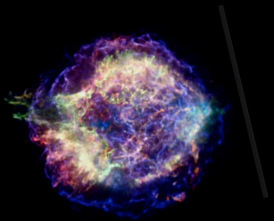
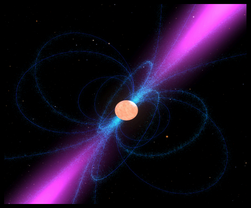
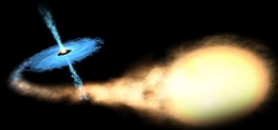
Bar Al 5056 M = 2270 kg
L = 2.97 m Ø = 0.6 m
ν_A= 915 Hz @ T = 3 K
Cosmic ray detector

ROG
ricerca onde gravitazionali
gravitational wave research

1999 - 2016

03/1999: Thesis Physics:" Ricerca di coincidenze con I dati dei rivelatori di onde gravitazionai Explorer e Nautilus"; supervisors: G.Pizzella G.Vittorio Pallottino

07/1999: fellowship INFN at the LNF in the Informatic-Electronic
09/2001 sector with the title: "Acquisition systems and data processing for gravitational wave detectors".
development of algorithms and data analysis for the search of bursts and continuous GW signals;

ROG
ricerca onde gravitazionali
gravitational wave research

1999 - 2016

09/2001: research grant in the University of Rome Tor Vergata

- ✓ development of algorithms and data analysis for the search of bursts and continuous GW signals;
- ✓ Study of the correlation between GW detectors data and gamma ray bursts (BATSE e Beppo Sax);
- ✓ IGEC: International Gravitational Event Collaboration
  ALLEGRO (USA), AURIGA (Padova) e NIOBE (Australia),
  EXPLORER (since 1991 at 2.6K) e NAUTILUS (0.14K);
- ✓ Cosmic rays detection telescope (streamer tubes);
- ✓ study of the correlation of the data of the gravitational detectors with cosmic rays;

09/2002 – 09/2007: first contract (art. 23) INFN Tor Vergata:

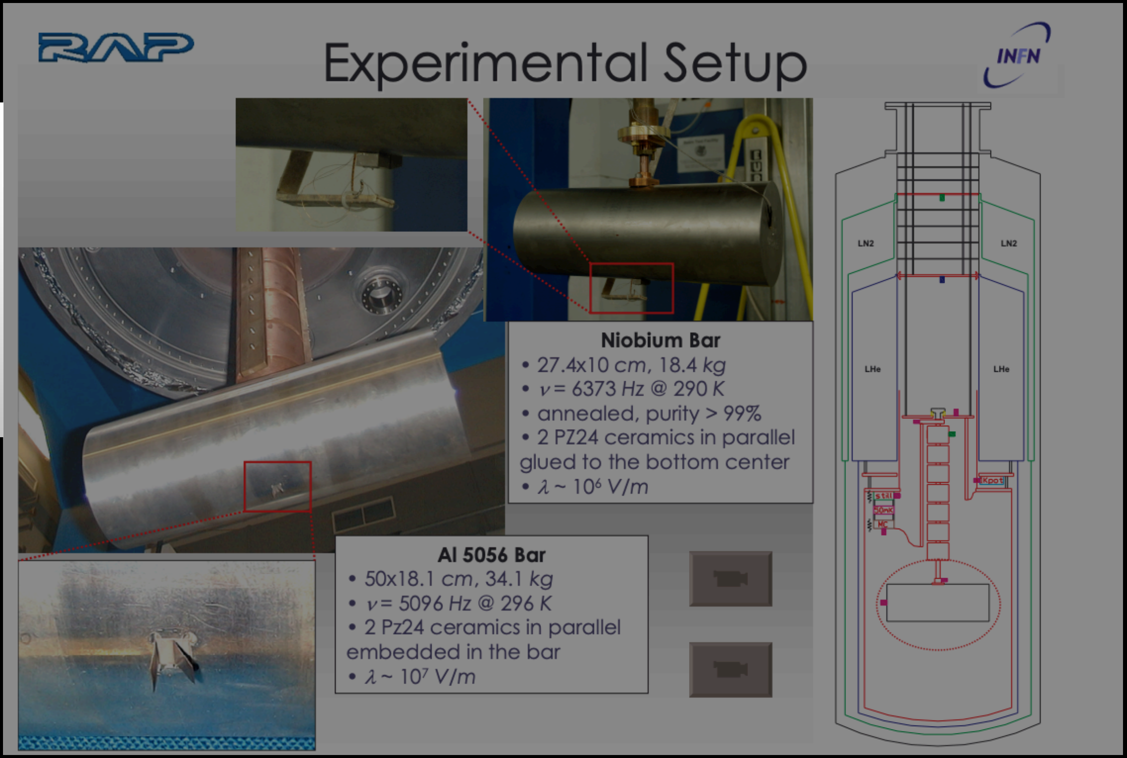
- ✓ My research work goes on with the previous activities
- ✓ 2004-2009: RAP experiment: Rivelazione Acustica di Particelle

Rivelazione Acustica di Particelle

DAΦNE BTF Runs

All the measurements have been done in the *DAΦNE Beam Test Facility*, using pulses of electrons

- pulse duration = 1 ÷ 10 *ns*
- $n_e = 10^8 \div 10^9\ e^-$
- *E* = 510 MeV
- spot size ≈ 2 cm
- Beam Current Monitor sensitivity ≈ $1.4\ 10^7\ e^-$



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Europhys.Lett., 76, pp.987 993 ISSN: 0295-5075, 2006 (Impact Factor

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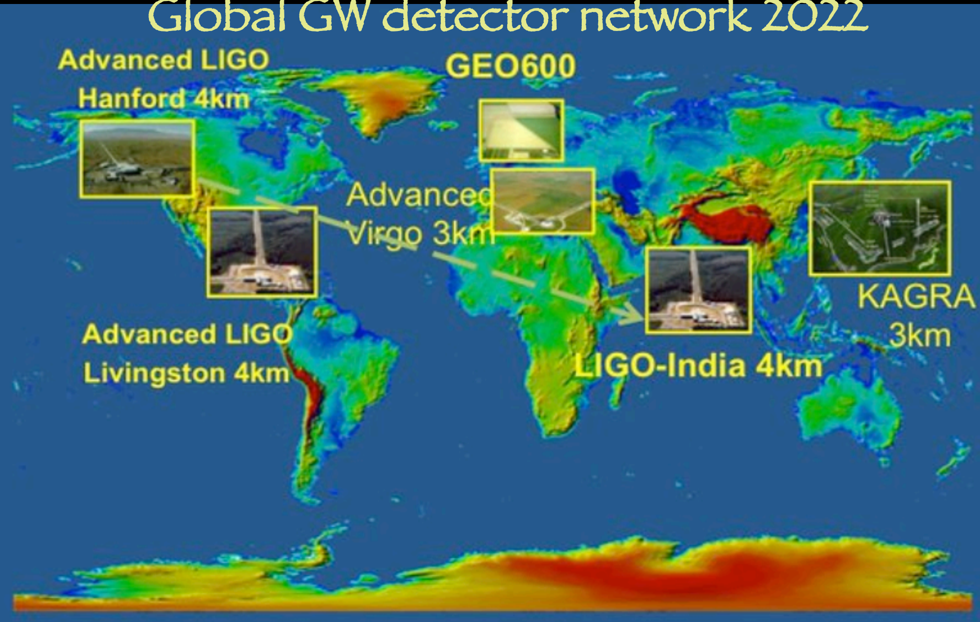
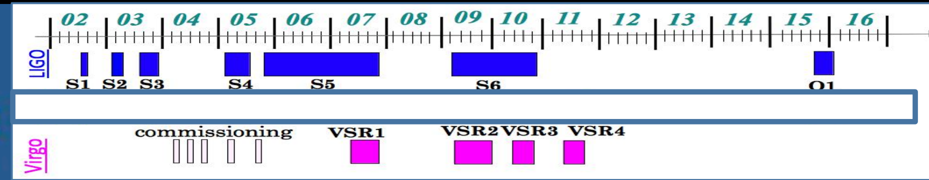
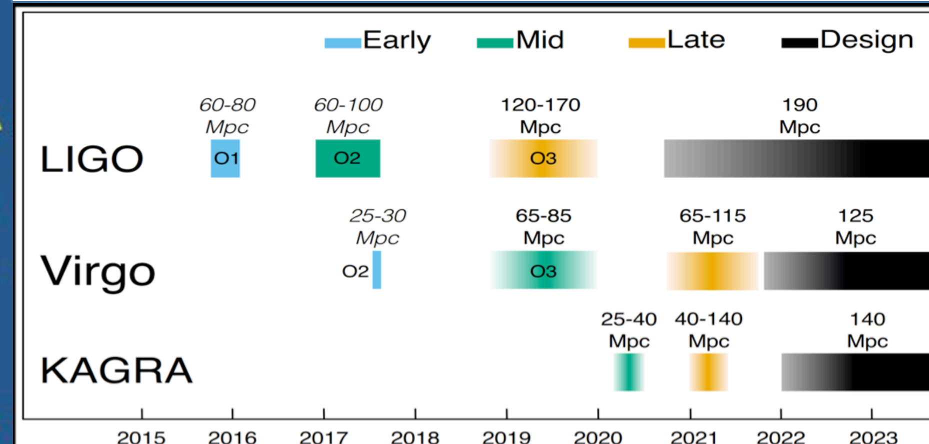
Results of the IGEC-2 search for gravitational wave bursts during 2005.
Phys.Rev.D 76:102001,2007 (Impact Factor 4.922).

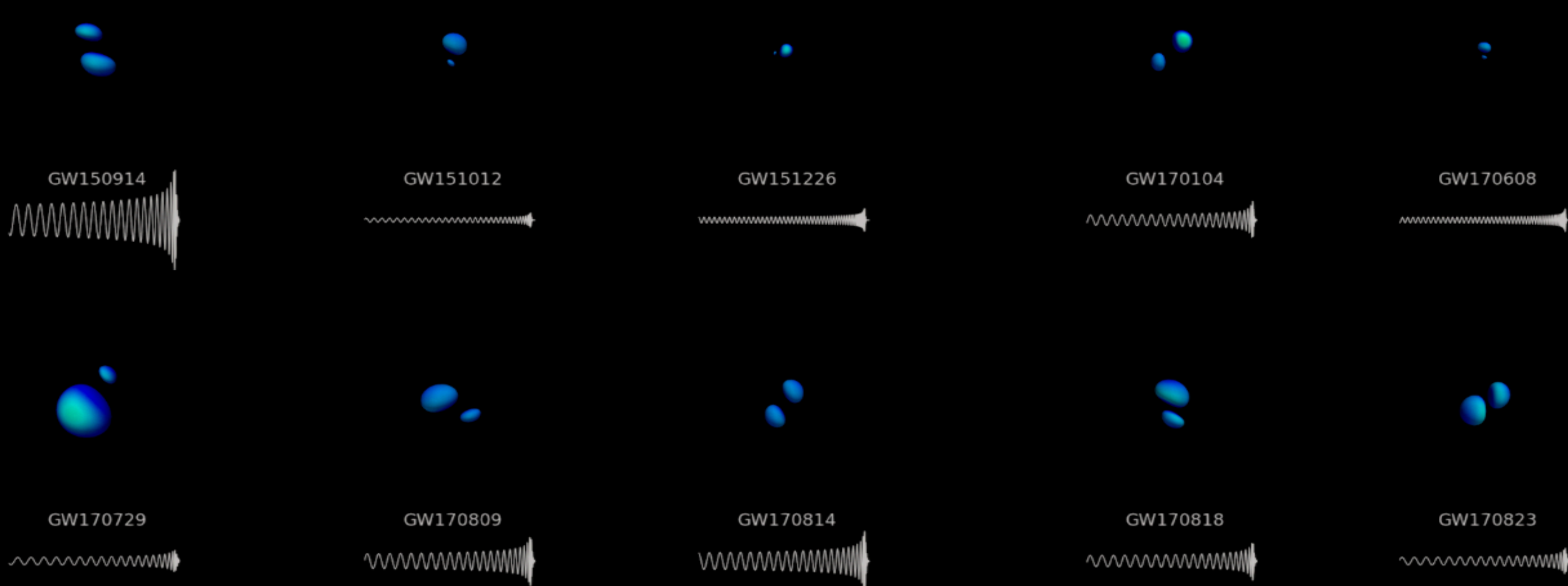
P. Astone et al.
IGEC2: A 17-month search for gravitational wave bursts in 2005-2007.
Phys.Rev. D82 022003 2010.

From 2006

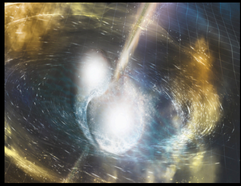




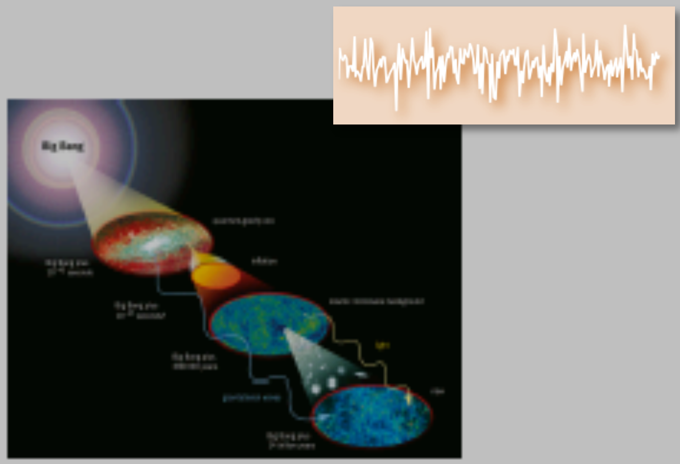
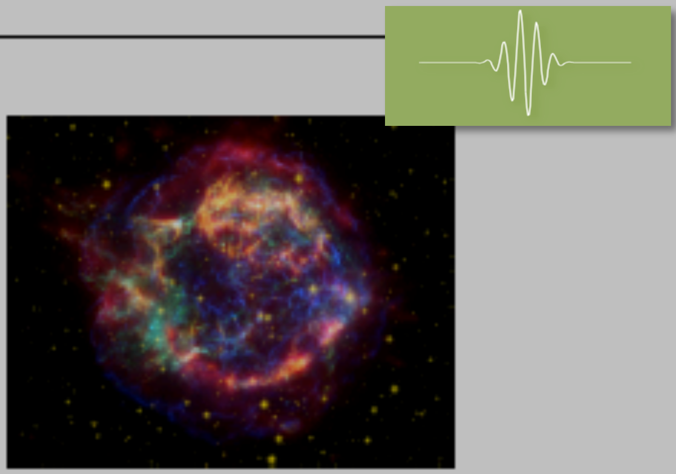




GW170817



Gravitational waves sources and GW signals

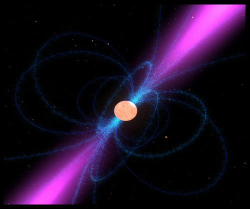
	◆ Modeled waveforms.	◆ Unknown waveforms.
Long-lived		
Transients	 ✓ detected	

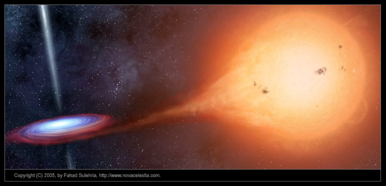
My main topic: CW signals

- Long-lived (persistent in time) signals emitted in presence of a mass quadrupole variable moment in a (almost)-periodic way.
- Expected sources in LIGO-Virgo band involve compact objects like neutron stars.
- The signal amplitude is orders of magnitude weaker than transient events from black hole and neutron star mergers strain : $O(10^{-26})$ vs $O(10^{-21})$.

- Signal time duration is longer than the typical observational times.

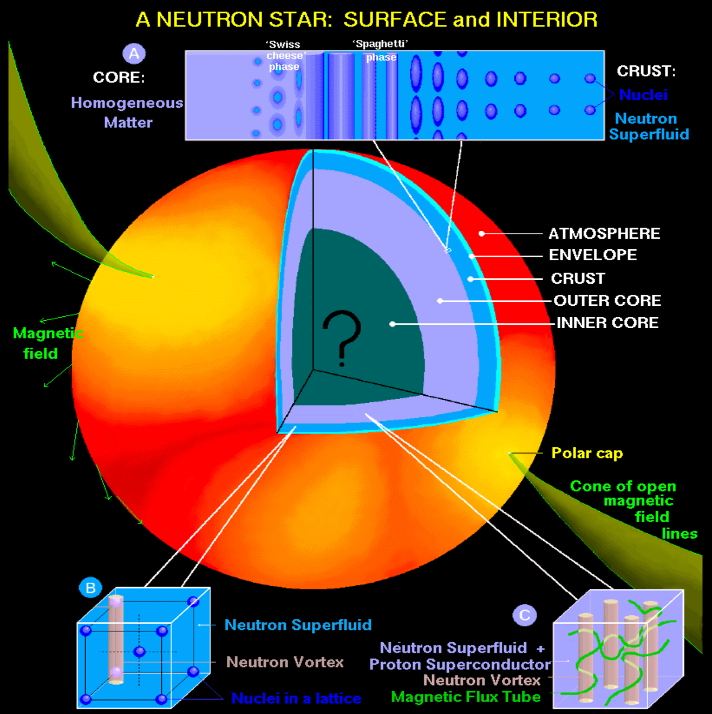
The persistent nature of CW will allow to make very accurate measures of the source parameters and to study tiny effects over long times





What can we learn from a CW signal?

- Great interest in detecting GW radiation: physics of such stars is poorly understood.
  Interior properties not understood: equation of state, superfluidity, superconductivity, solid core, source of magnetic field.



- Constraints on:
  - NS EOS
  - NS ellipticity
  - NS mass

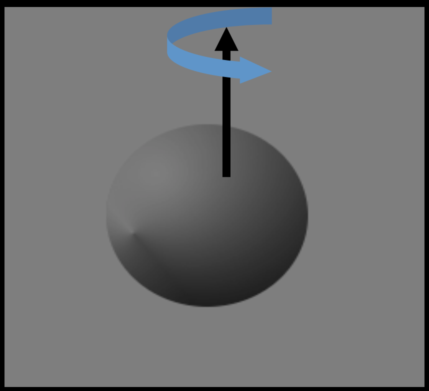
If accompanied by EM observation either from a known pulsar search or through follow-up of unknown sources

$f_{GW} = 2f_{rot}$ star is probably a triaxial ellipsoid
$f_{GW} \approx 2f_{rot}$ components producing EM and GW emission are not completely coupled (information on crust and core coupling of star)
$f_{GW} \approx (4/3)\, f_{rot}$ emission from r-modes is favoured information on interior fluid motion

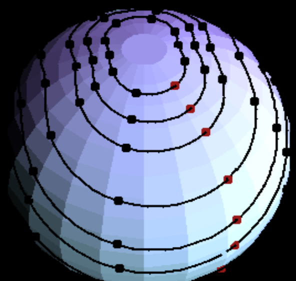
Emission mechanisms for CW from spinning NS in the LIGO-VIRGO frequency band

To emit CWs a NS must have some degree of non-axisymmetry originating from:

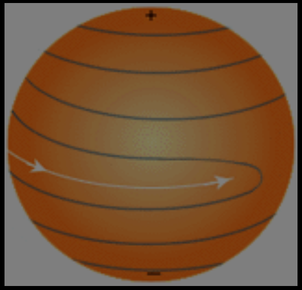
- ✓ deformation due to elastic stresses or magnetic field;
- ✓ deformation due to matter accretion (e.g. LMXB);
- ✓ free precession around rotation axis;
- ✓ excitation of long-lasting oscillations
- ✓ (e.g. r-modes);



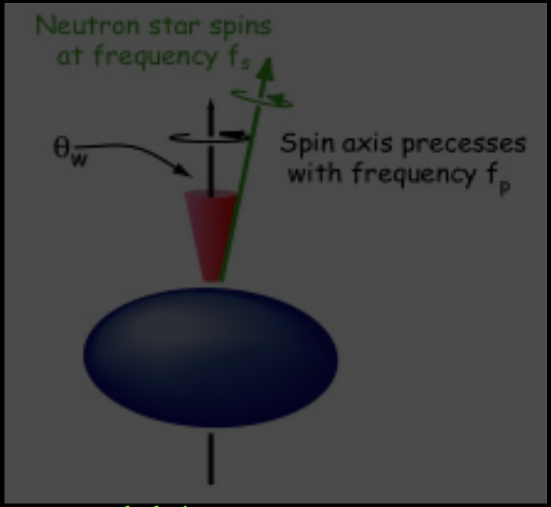
Bumpy Neutron Star



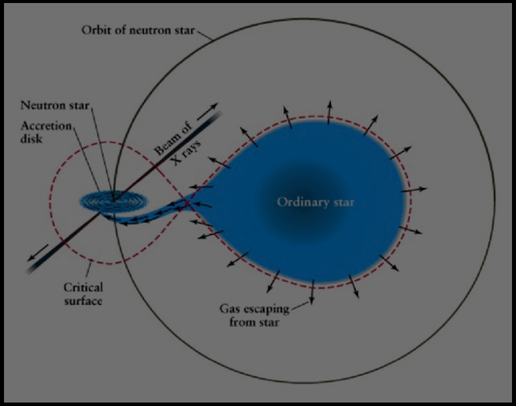
R-modes in accreting stars



Magnetic mountains



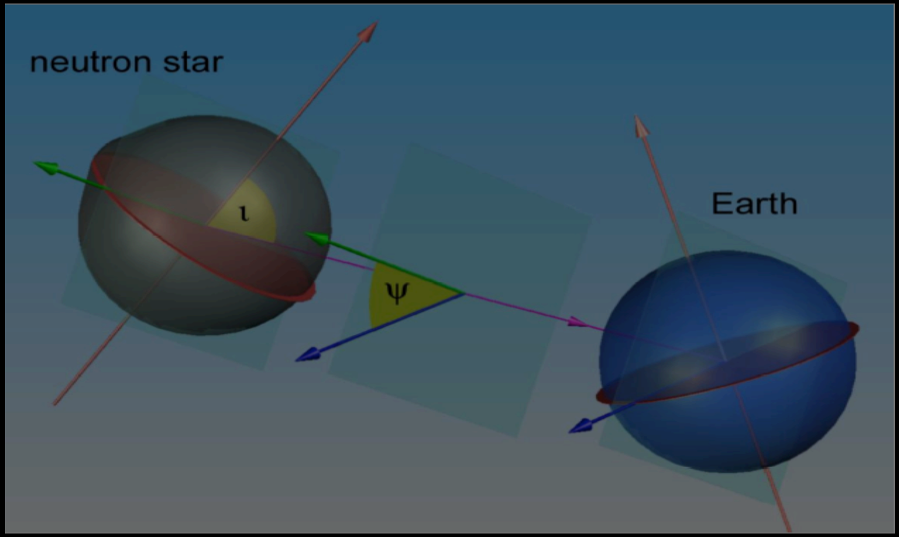
Wobbling Neutron Star



Low Mass X-Ray Binaries

Expected Signal on Earth

For an isolated tri-axial *non-precessing* neutron star emitting at twice its rotational frequency:



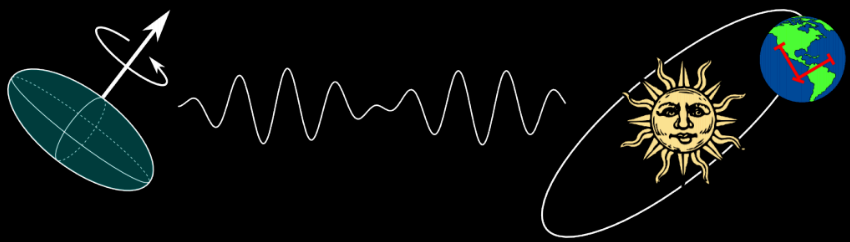
$$h_0 \cong 10^{-27}\left(\frac{I_{zz}}{10^{38}\,kg\cdot m^2}\right)\left(\frac{10kpc}{d}\right)\left(\frac{f}{100Hz}\right)^2\left(\frac{\varepsilon}{10^{-6}}\right)$$

→ ε : fractional difference among the moments of inertia in the rotation plane.

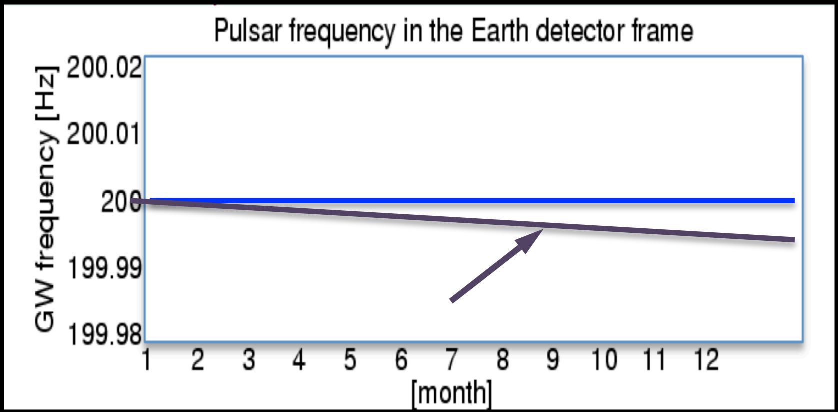
ε=10^{-5} corresponds to a 'mountain' ~10 cm high!

To detect these signals we need to integrate over long times

The Signal from a NS

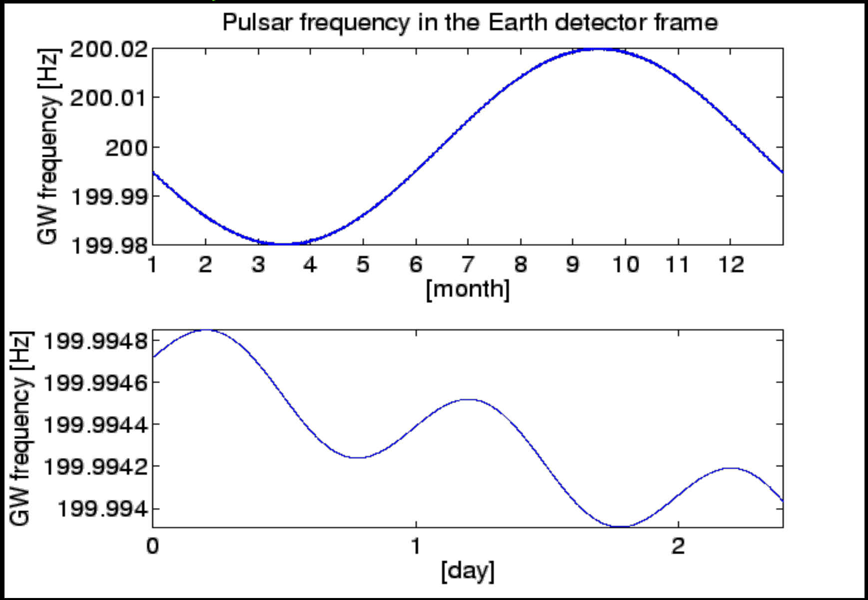


(frequency almost constant)



Spin-down:
due to the loss of energy (in some cases a spin-up could be present) ⇒ **phase evolution**

GW frequency at the detector

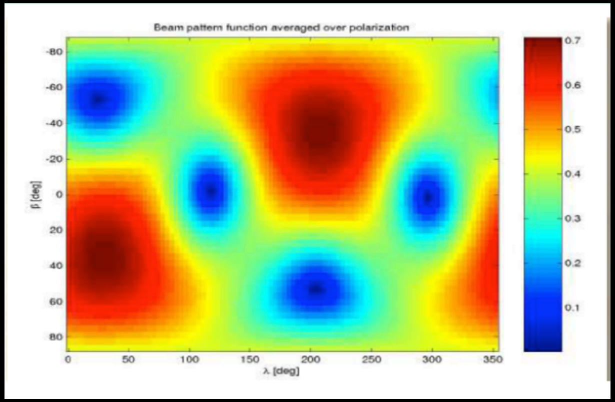


Frequency (and phase) are modified by the Doppler Effect due to the orbital and rotational motion of Earth
(depend on the source position).

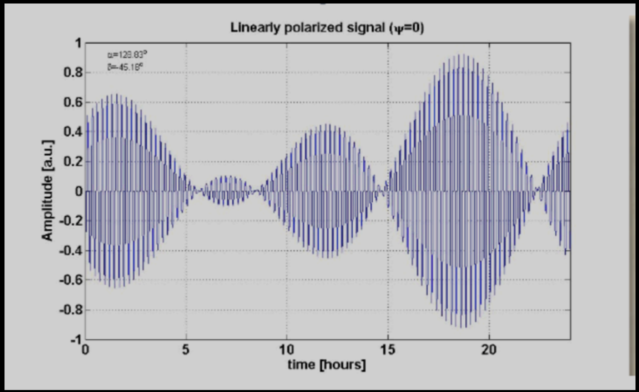
- Annual variation: up to $\sim 10^{-4}$
- Daily variation: up to $\sim 10^{-6}$

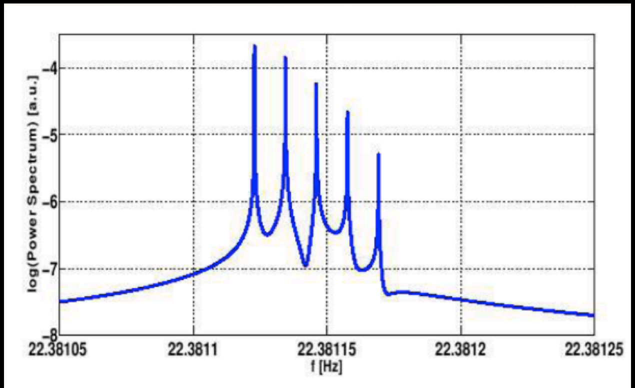
The Signal from a NS

The detector response produce a splitting of the signal power among the five angular frequencies ω, $\omega \pm \Omega$ and $\omega \pm 2\Omega$, Ω is the Earth sidereal angular frequency.

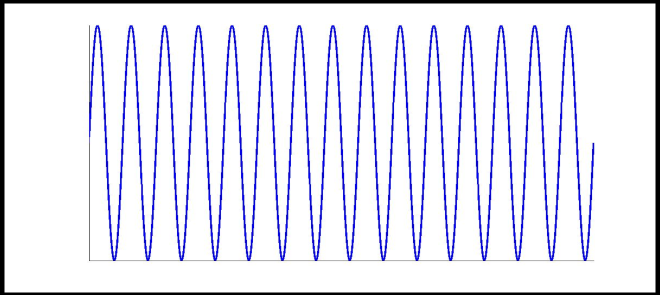


GW signal at the detector





GW signal at the source:



Continuous Waves Searches

Depending on our knowledge of the source parameters the impact on the needed computing resources is relevant and limits the sensitivity of the search and/or the parameter search we can exploit.

- position
- frequency,
- Frequency derivatives
- orbital parameters

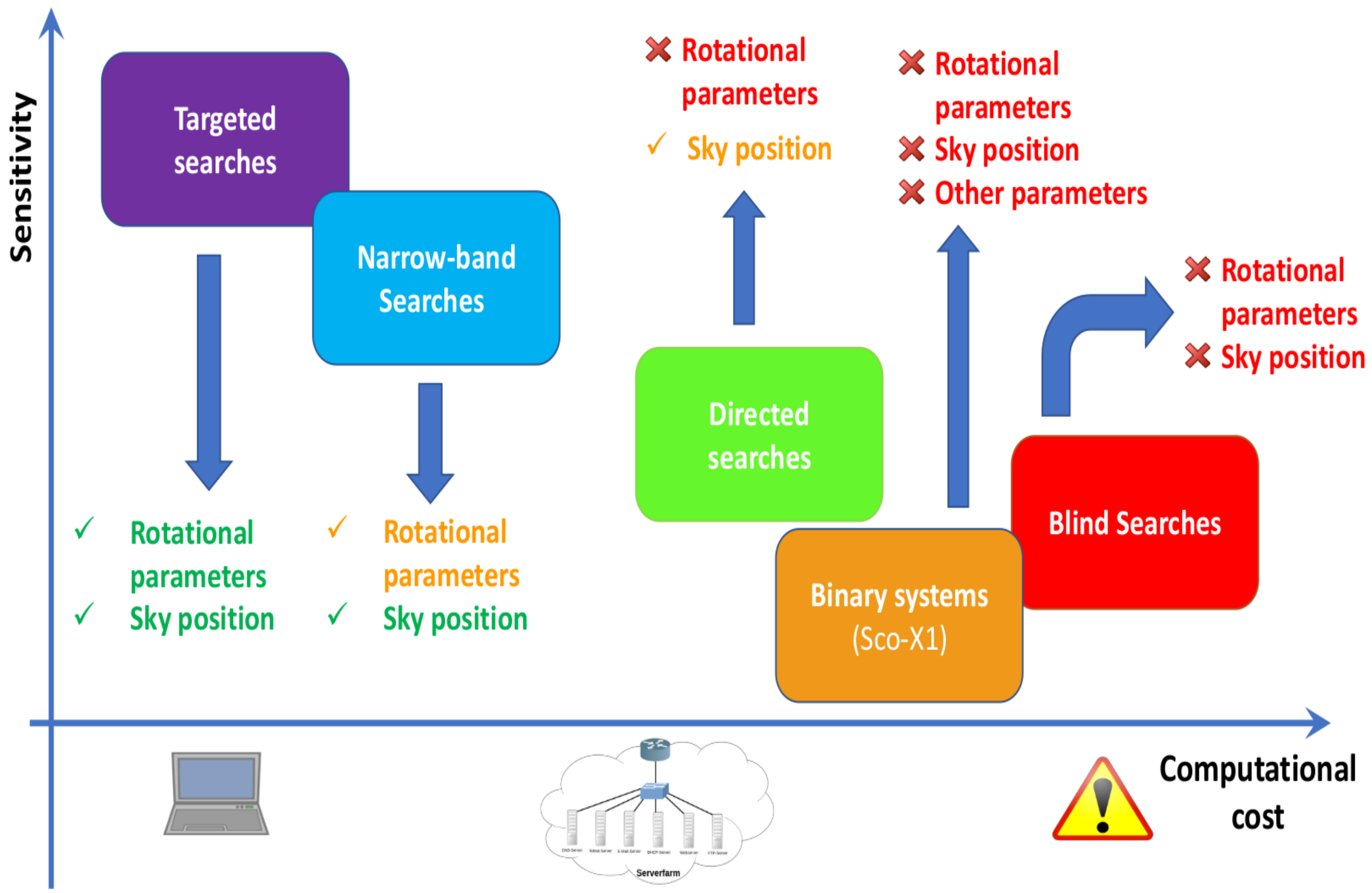
Different algorithms have been developed, depending on what we know about the source

What drives the choice is the computational expense of the search!

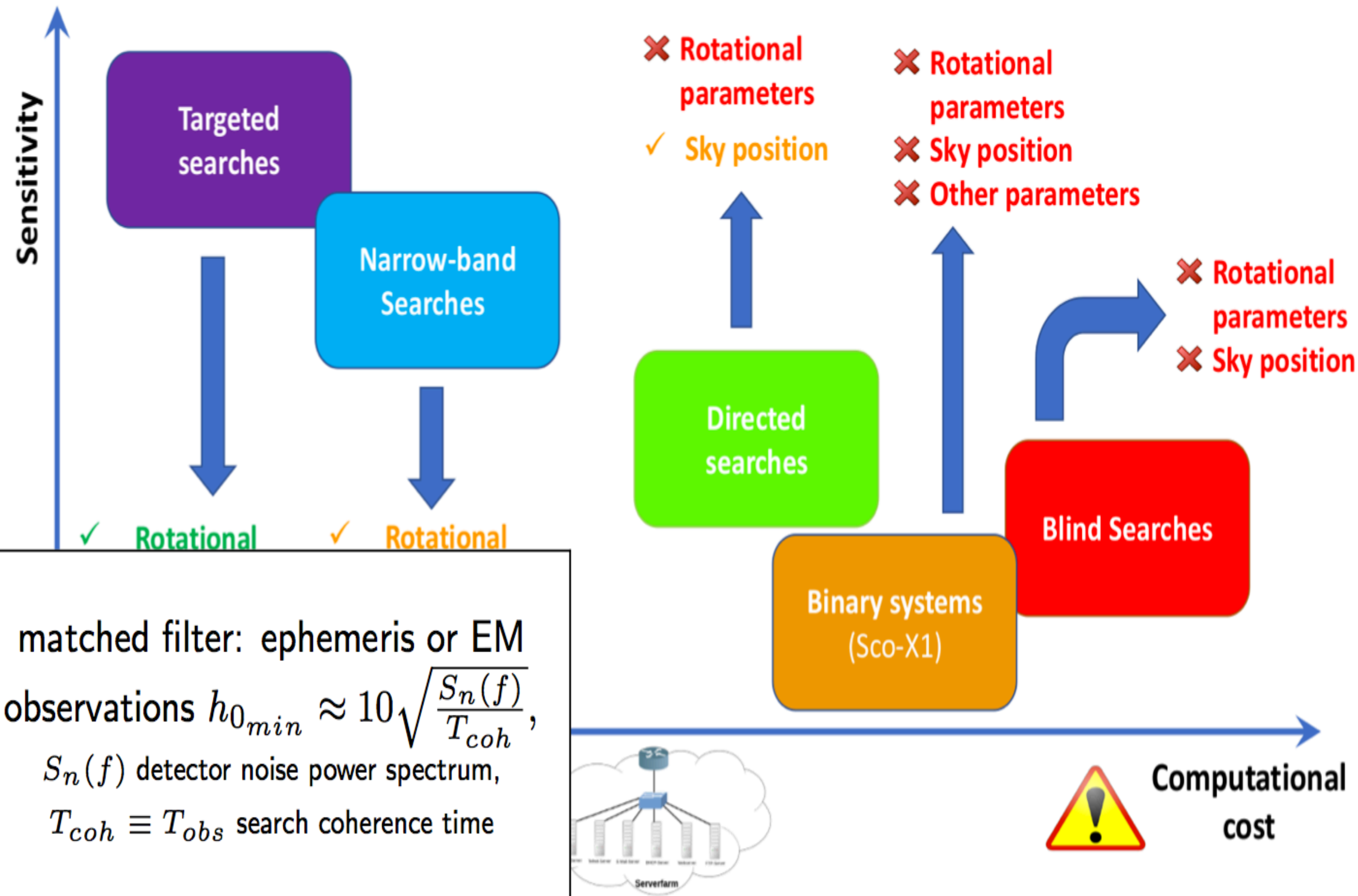
Multi-messenger collaboration is fundamental

The noise is our enemy- Noise data cleaning and characterization-> NOEMI
on-line Noise tool in LIGO VIRGO RUNs

- explore a $4+N$ dimensional space $(\alpha, \delta, f, \dot{f} + \text{derivatives})$



- explore a $4 + N$ dimensional space $(\alpha, \delta, f, \dot{f} + \text{derivatives})$



matched filter: ephemeris or EM observations $h_{0_{min}} \approx 10\sqrt{\frac{S_n(f)}{T_{coh}}}$,
$S_n(f)$ detector noise power spectrum,
$T_{coh} \equiv T_{obs}$ search coherence time

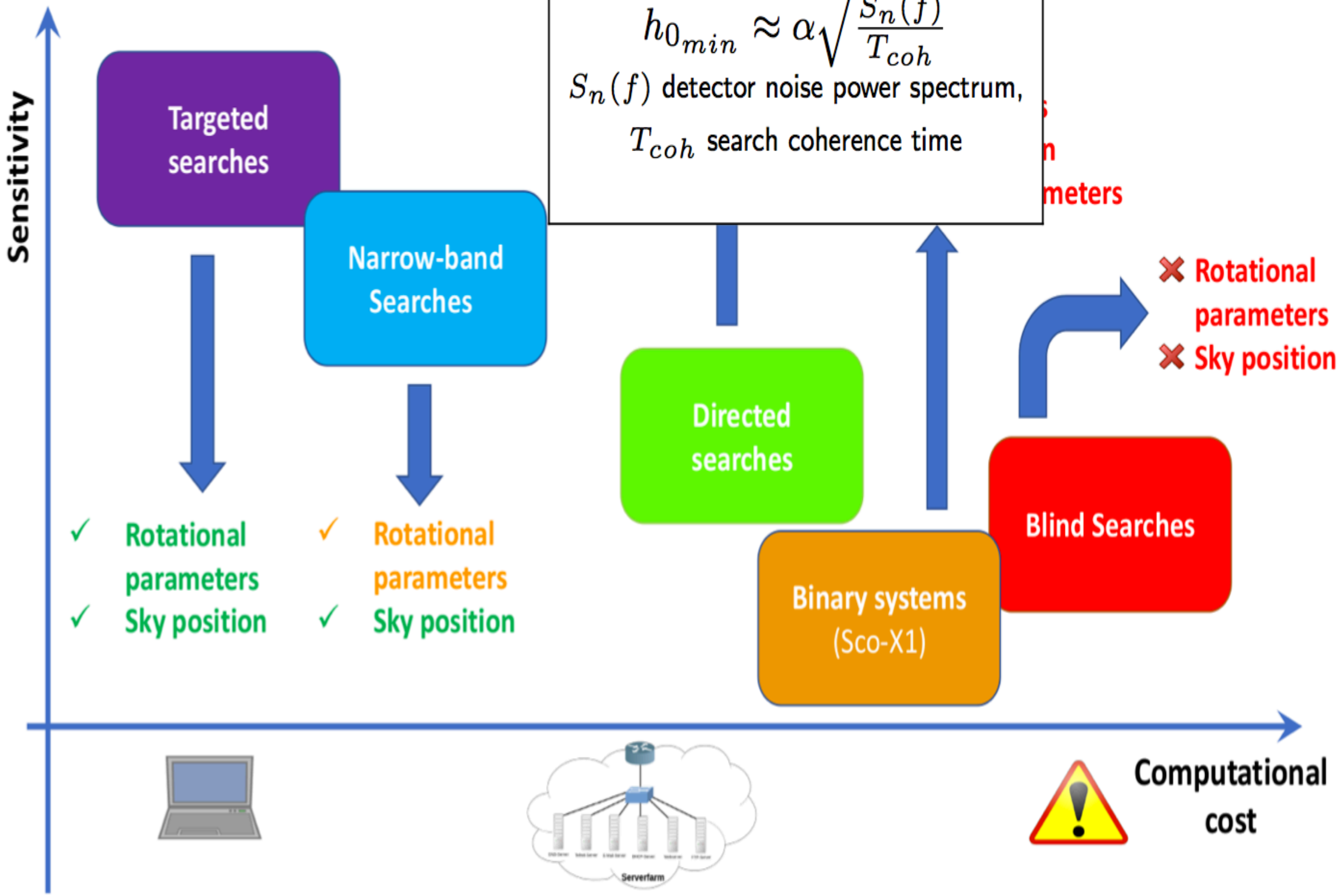
- explore a $4 + N$ dimens derivatives)

semi-coherent methods

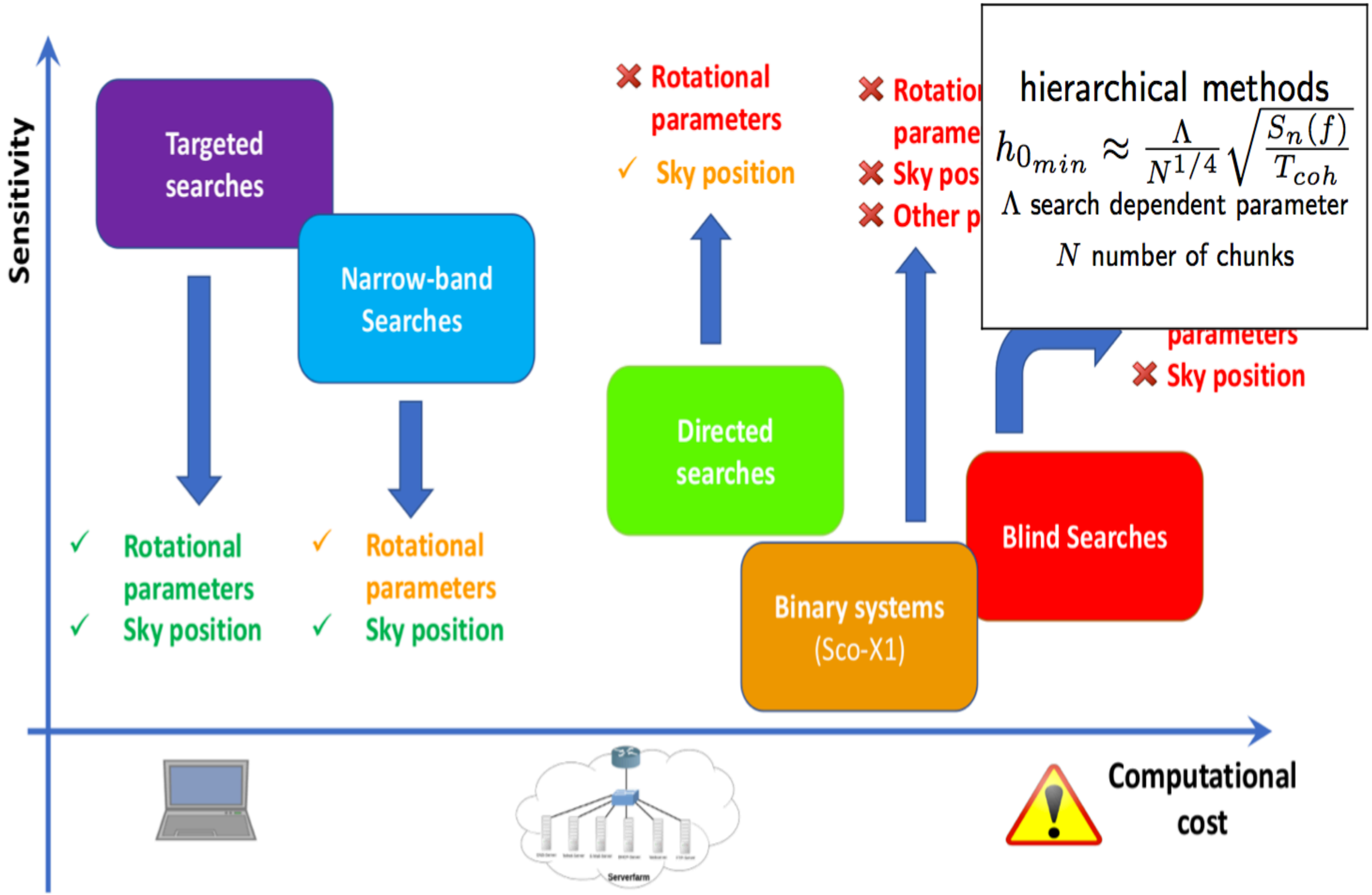
$$h_{0_{min}} \approx \alpha \sqrt{\frac{S_n(f)}{T_{coh}}}$$

$S_n(f)$ detector noise power spectrum,

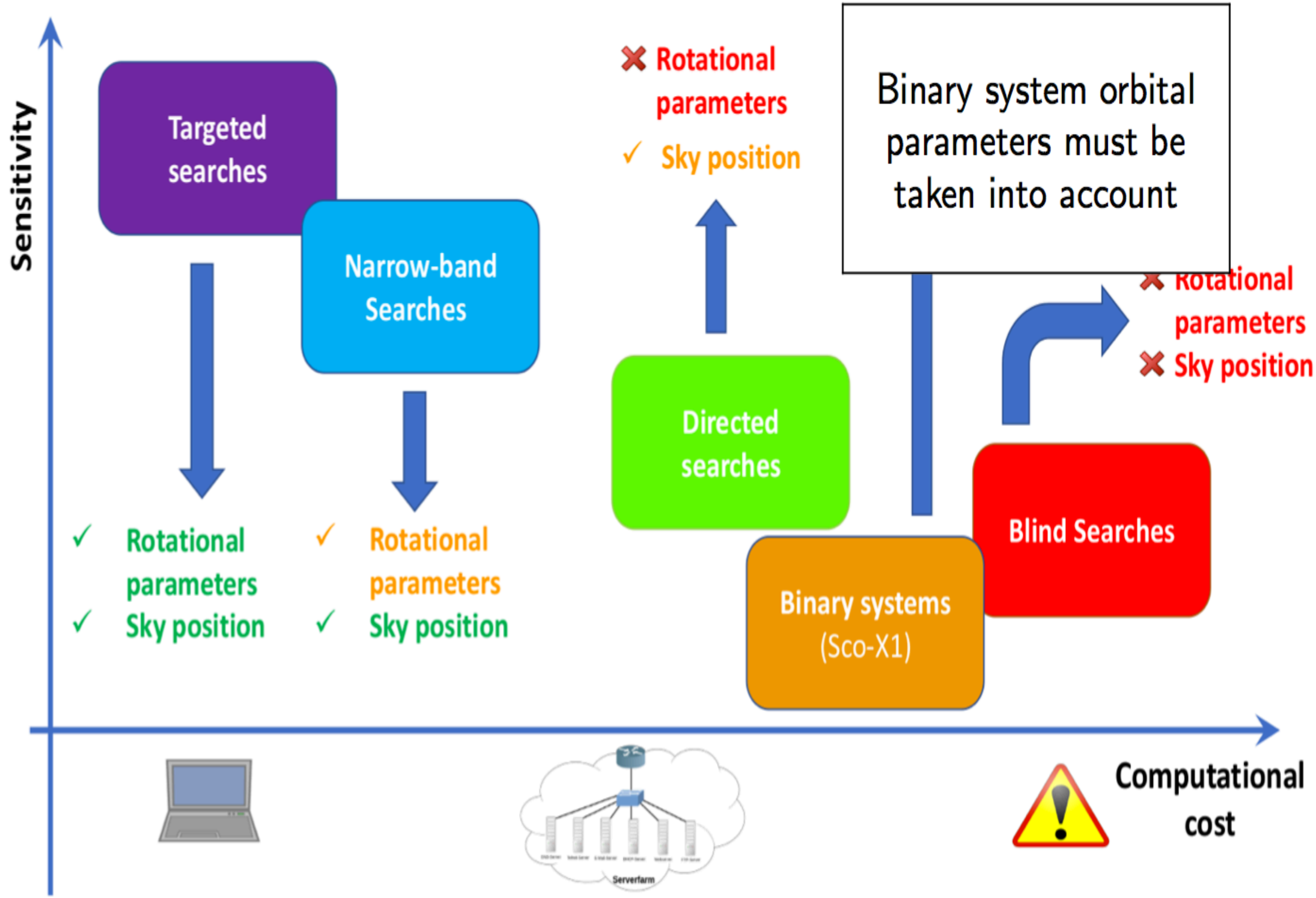
T_{coh} search coherence time



- explore a $4 + N$ dimensional space $(\alpha, \delta, f, \dot{f} + \text{derivatives})$



- explore a $4 + N$ dimensional space $(\alpha, \delta, f, \dot{f} + \text{derivatives})$



Sensitivity

Targeted search

Based on matched filter.
E.g. pulsars for which accurate ephemeris are available

$$h_{\min} \approx 10-25\sqrt{\frac{S_n(f)}{T_{obs}}}$$

Narrow-band search

Allows for a small mismatch between the GW and the EM signal

Wide-band ('directed') search

Based on semi-coherent methods.
E.g. CCOs, SNR, etc.

$$h_{\min} \approx 30\sqrt{\frac{S_n(f)}{T_{coh}}}$$

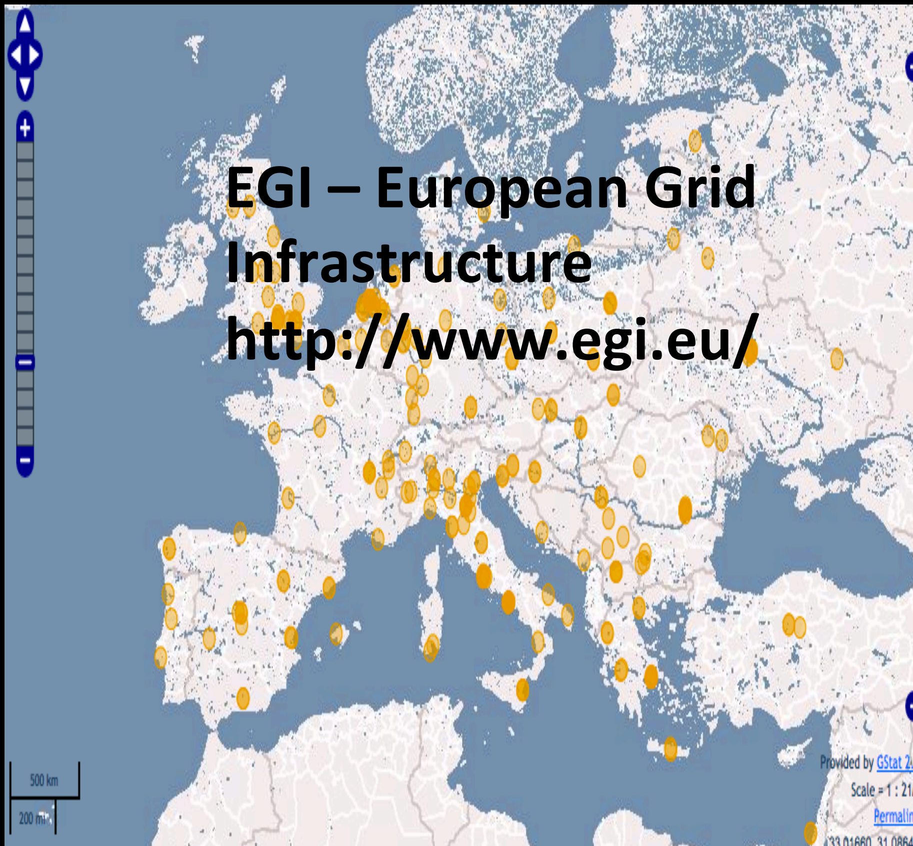
Blind search

Hierarchical methods.
Follow-up of the most interesting candidates.
Computationally bound

$$h_{\min} \approx \frac{\Lambda}{N^{1/4}}\sqrt{\frac{S_n(f)}{T_{coh}}}$$

Binary systems (e.g. Sco X-1)

Binary system orbital parameters must be taken into account.
Computationally bound



jobs submitted via **Grid**. In the analysis periods we work with ~ 2000 core committed 24 hours a day / 7 days a week.

Porting some parts of our GPU analysis software is a possibility we started working on.

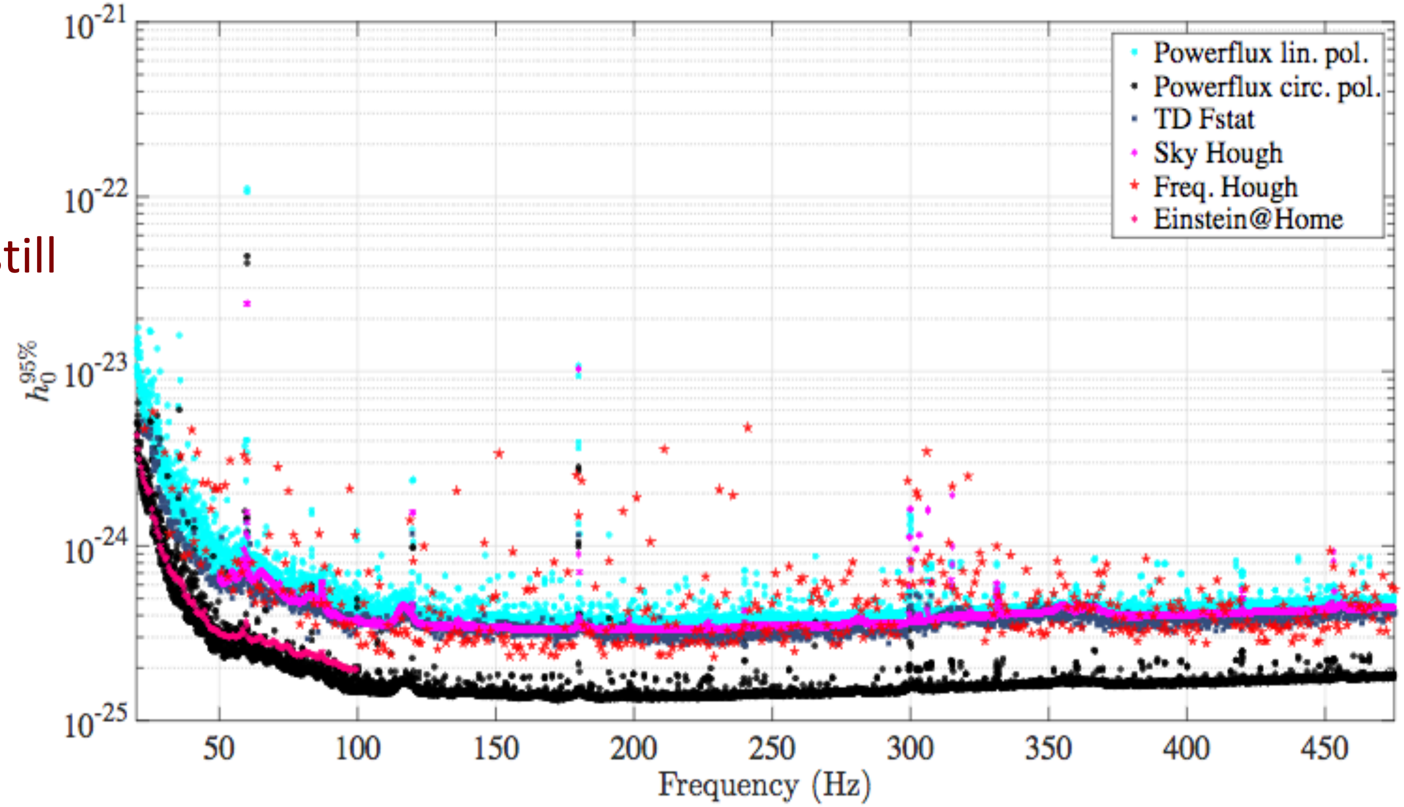
No continuous gravitational waves (CW) detected… yet!

- Most searches begin *after* an observing run has ended, and all the data is in
- Still analysing LIGO O1 & O2 data
- Strict emission limits have already been set from initial detector era data on signals from known and unknown neutron star sources.

- Non-detections (i.e. upper limits) **cannot** be used to exclude some EOS
- But even with a null result we can constrain other parameters, like ellipticity and the internal magnetic field .

All-sky (LVC, PRD 96, 062002, 2017)

O2 All-sky search is still ongoing



Frequency range: [20 , 475] Hz, Spin-down range: $[-10^{-8}, +10^{-9}]$ Hz/s. Significant improvement in the ULs with respect to past analyses (x3). Best limits on h_0 of 1.5×10^{-25} near 170 Hz. At 475 Hz sensitive to NS with ellipticity $\epsilon > 8 \times 10^{-7}$ as far as 1 kpc, for optimal spin orientation.

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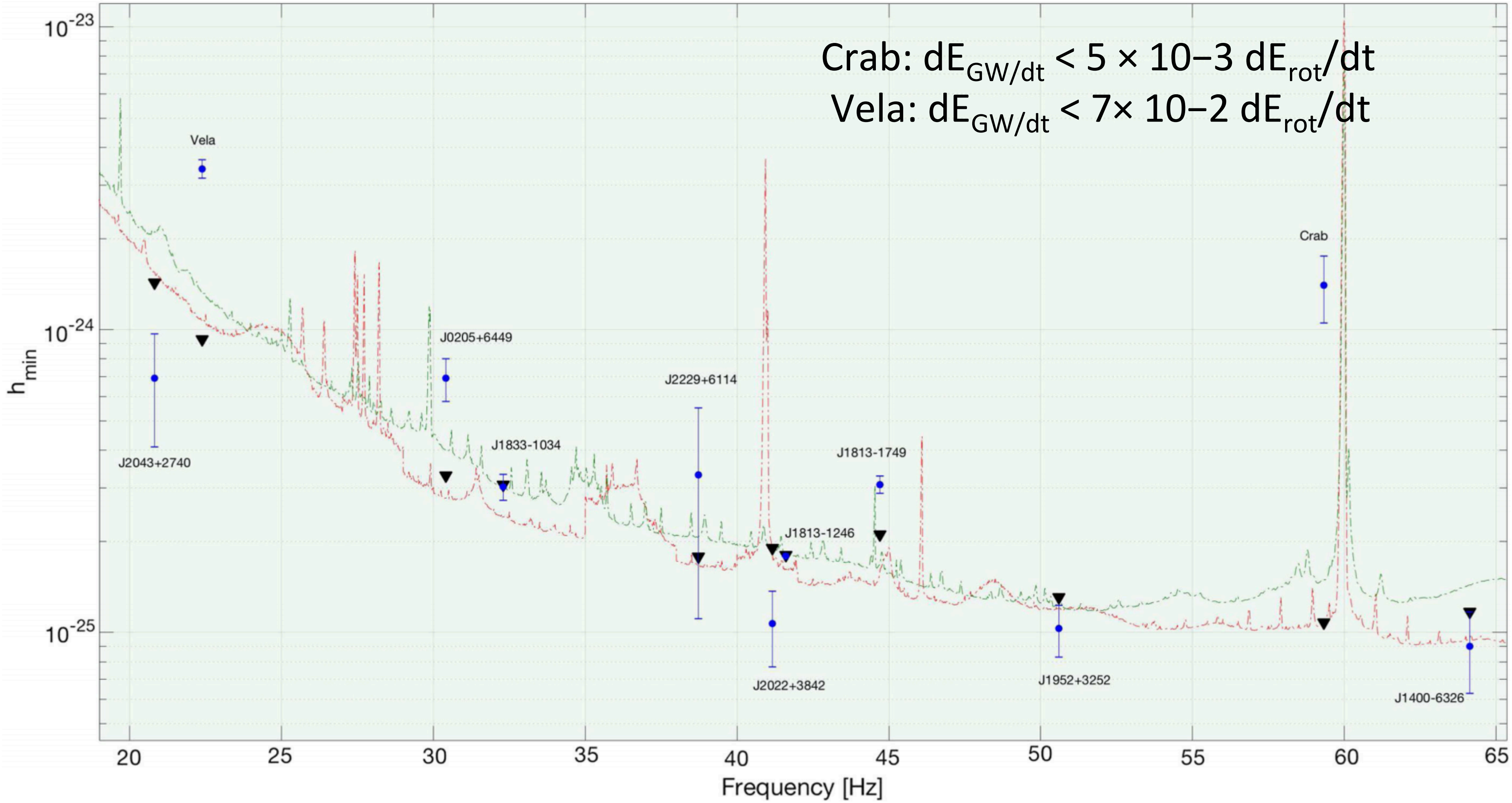
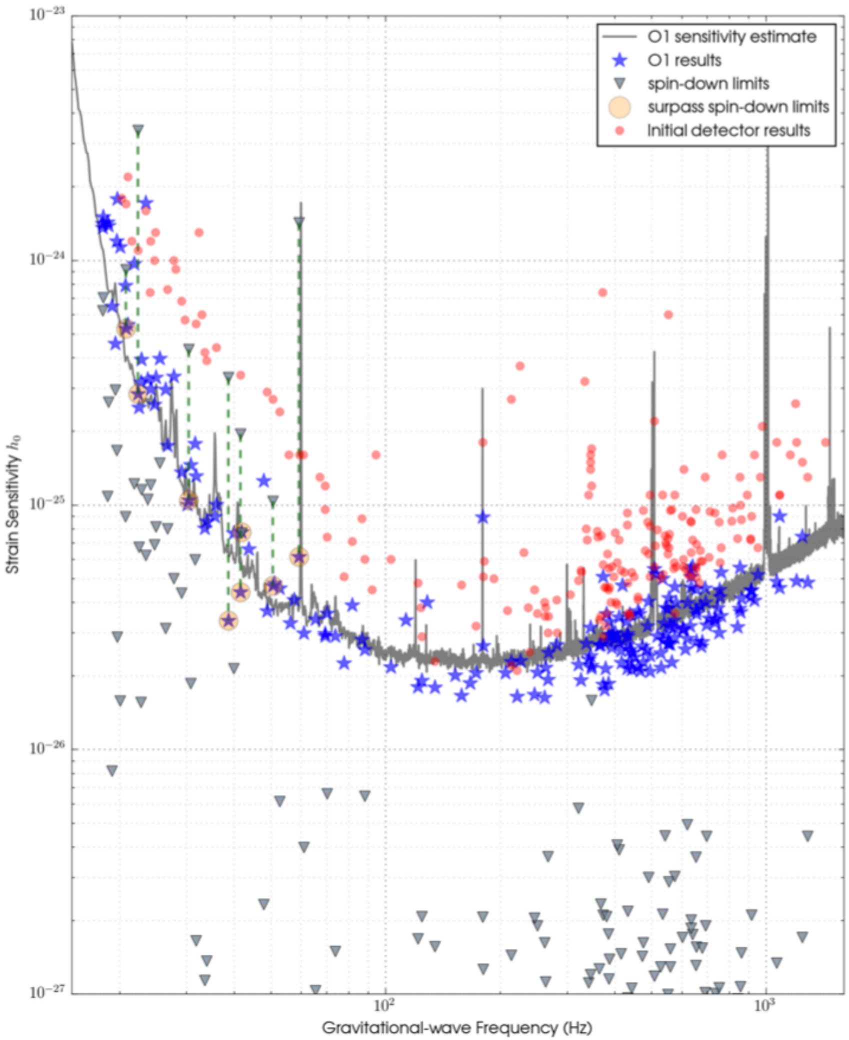


FIG. 2. Blue points: Value of the theoretical spin-down limit computed for the 11 known pulsars in our analysis, corresponding to Table II; error bars correspond to the 1σ confidence level. Black triangles: Median over the analyzed frequency band of the upper limits on the GW amplitude, corresponding to Table VI. Red dashed line: Estimated sensitivity at 95% confidence level of a narrow-band search using data from LIGO H. Green dashed line: Estimated sensitivity at 95% confidence level of a narrow-band search using data from LIGO L.

Targeted search (LVC, ApJ 839, 12, 2017)

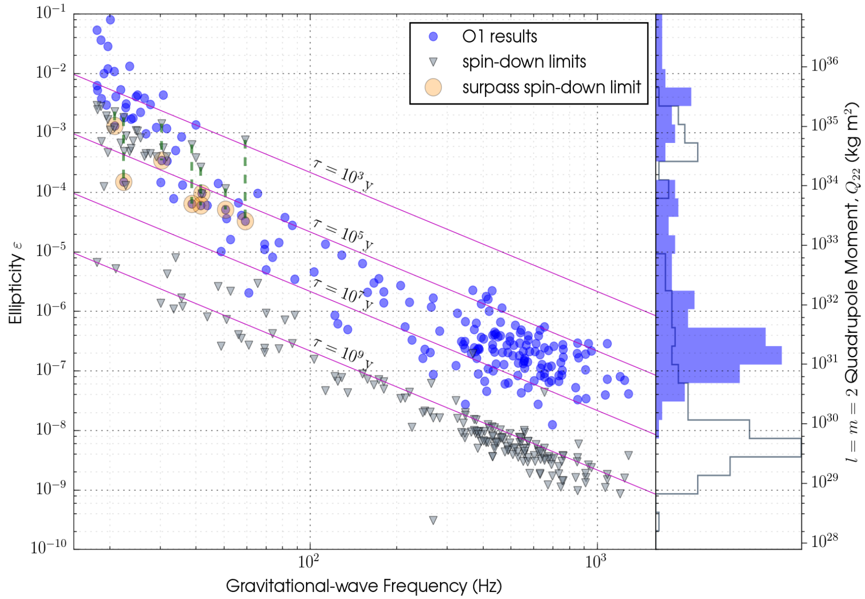


- About 430 known pulsars in Advanced LIGO band (20-2000Hz)
- 200 known pulsars analyzed,
- ULs improved by a factor 2.5 w.r.t the Initial LIGO/Virgo results,
- Spin-down limit beaten for 8 pulsars, including Crab & Vela
- PSR J1918-0642: smallest UL $h_0 = 1.6 \times 10^{26}$.

220 known Pulsars analysed for O2 data (Uls further improved by a factor 1.5-2)

Crab: $dE_{GW/dt} < 2 \times 10{-}3\ dE_{rot}/dt$
Vela: $dE_{GW/dt} < 2 \times 10{-}2\ dE_{rot}/dt$

Targeted search (LVC, ApJ 839, 12, 2017)



The ellipticity can roughly be converted to a "mountain' size using $25 \times (\epsilon/10^{-4})$ cm
Crab: $< 2 \cdot 10^{-3} \dot{E}_{rot}$ in GW, ~ 10 cm
Vela: $< 10^{-2} \dot{E}_{rot}$ in GW, ~ 50 cm

The diagonal lines show the ellipticities that would be required if a star had a particular characteristic age and was losing energy purely through gravitational radiation. Most constraining ellipticity is 1.3×10^{-8} for J0636+5129

✧ GW170817 : The outcome of the BNS coalescence can be:

- ✧ BH prompt formation. Favored by soft EOS.
- ✧ Hypermassive NS, that collapses to a BH in < 1s (burst-like signal)
- ✧ Supramassive NS, that collapses to a BH in 100-10000 s (long-transient signal
- ✧ Stable NS (continuous signal)

Which of these possibilities occurs depends on how much mass remains in the resulting object, as well as the composition and properties of matter inside neutron stars.

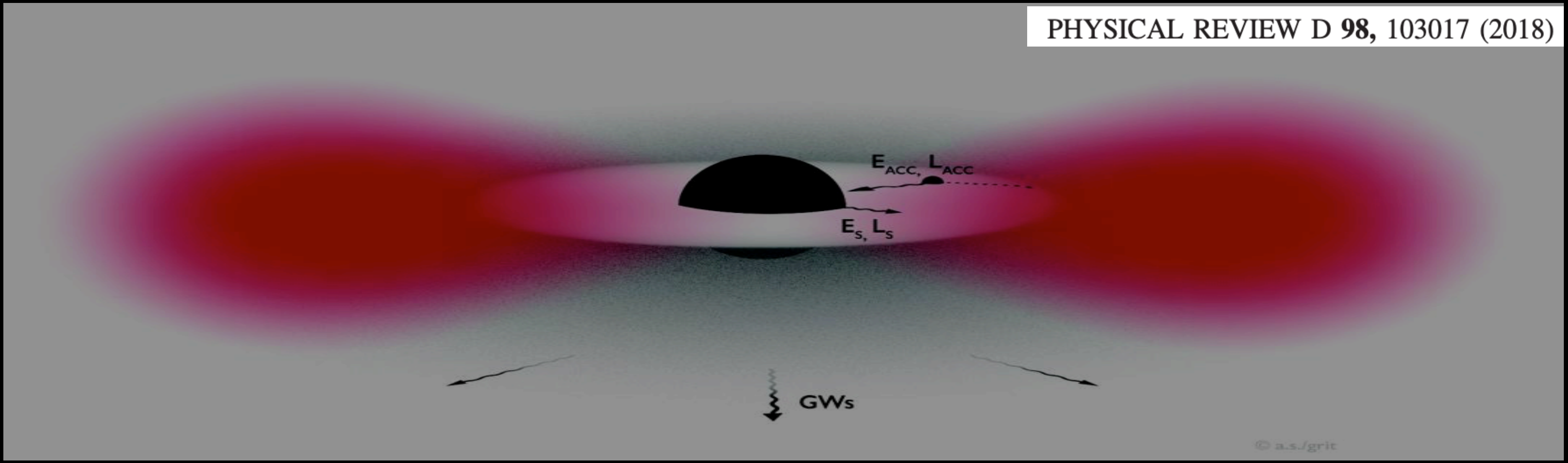
- Searches for short (<1 s) , medium (< 500 s) , long (hours, days) duration gw signals might be done.

Short transient post-merger emission: (Best Uls ~ 10^-22)
from a similar event may be detectable when advanced detectors reach design sensitivity or with next-generation detectors.)

Long transient post-merger emission: ongoing

PHYSICAL REVIEW D **98,** 102004 (2018) Method paper

CW signals from boson clouds around BHs: infer the boson mass via the GW detection



Light boson clouds around rotating black hole can activate a process of superradiant instability in which the bosonic field is amplified at the expense of the black hole rotational energy. When the boson field frequency is comparable to the black hole horizon angular frequency:

- ✓ the instability stops;
- ✓ the boson cloud, evolves by emitting long lasting gravitational waves;

$$f_{gw} = \frac{c^3}{\pi G}\mu\left(1-\frac{1}{8}(\mu M_{bh})^2\right)\ [Hz]$$

M_{bh} : BH mass,
m_b : boson mass

$$\mu = \frac{2G}{\hbar c^3} m_b$$

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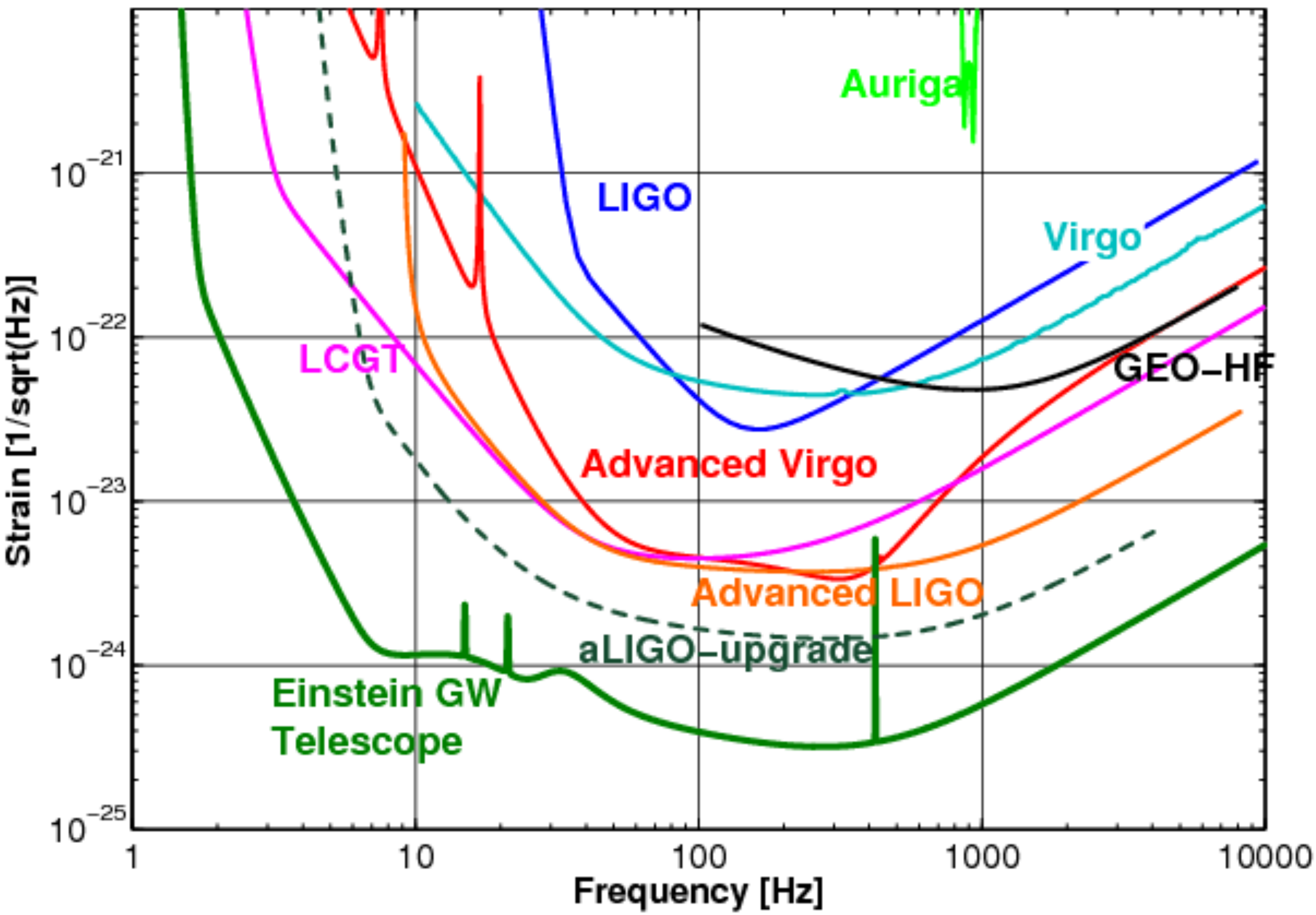
Grazie



Auriga
LIGO
Virgo
GEO-HF
LCGT
Advanced Virgo
Advanced LIGO
aLIGO-upgrade
Einstein GW Telescope
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
Strain [1/sqrt(Hz)]
1
10
100
1000
10000
Frequency [Hz]