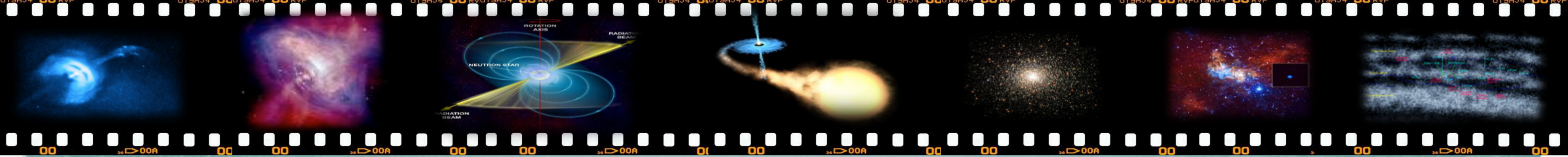


The detection of Continuous Gravitational Waves in the Advanced Detector Era

Paola Leaci

on behalf of the LIGO Scientific Collaboration and the Virgo Collaboration

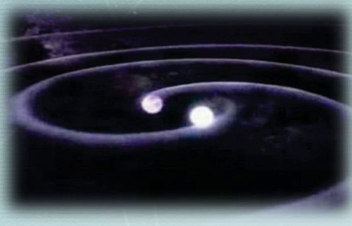
GWPAW 2017, Annecy (France)

G1700974

OUTLINE

- Gravitational-wave (GW) sources
- GW detector sensitivity progression
- Continuous Waves (CWs)
- Types of CW searches and methodologies
- CW search highlights
- Multi-messenger astronomy
- Other CW searches and Future Plans

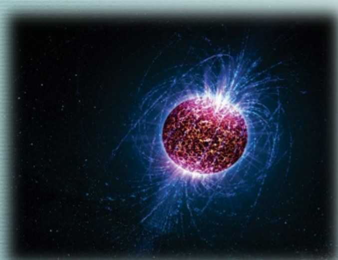
GW sources

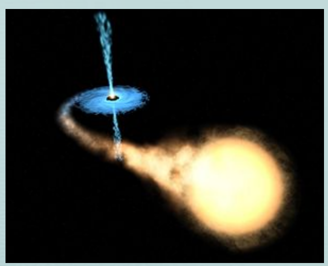


◆ **Compact Binary Coalescing systems *(CBC)*, well modeled waveforms.**
The inspiral, merger and ring-down of binary Neutron Stars (NSs) and Black Holes

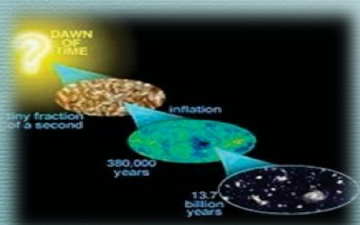
◆ **Supernovae, GRBs (*bursts*), unmodeled waveforms**
Short-duration GW events in coincidence (ideally) with signals in electromagnetic (EM) radiation/neutrinos

TRANSIENT SIGNALS





◆ **Fast-spinning NSs in our galaxy (CWs)**
e.g. non-axisymmetric spinning NSs; monochromatic waves; known waveform

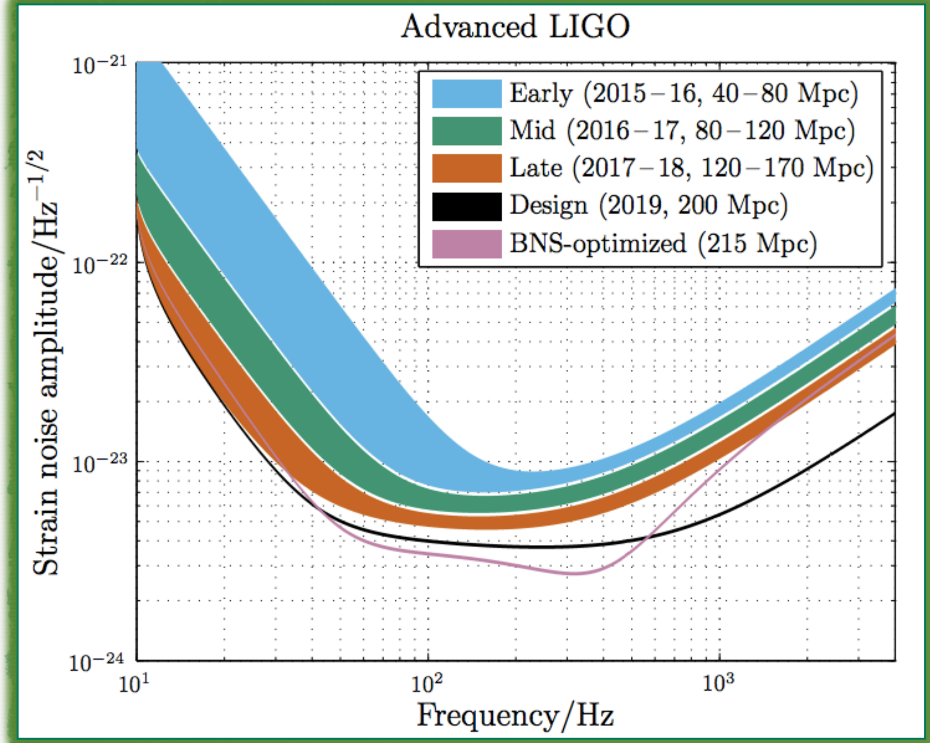


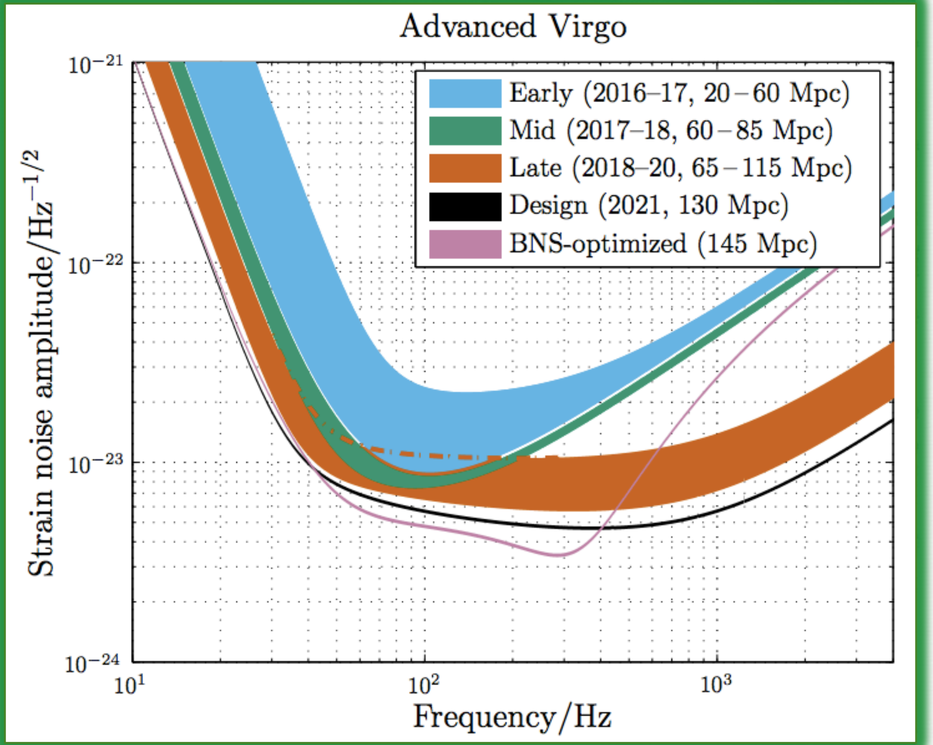
◆ **Cosmological GW (*stochastic background*)**
A background of primordial and/or astrophysical GWs; unknown waveform

CONTINUOUS SIGNALS

Advanced LIGO and Virgo expected sensitivity progression

LVC, LRR 19, 1 (2016); arxiv.org/abs/1304.0670v3





- **The second Advanced LIGO observing run (O2) began on November 30th, 2016 and is currently in progress**
- **Advanced Virgo has started the C8 commissioning run on May 5th, 2017**

Beyond Advanced LIGO & Virgo

- **2006-2010:** ***detectors took 2 years worth of data at unprecedented sensitivity levels***
- **2015-2022:** ***five large detectors will become operational***
- **Advanced LIGO detectors are operating, Advanced Virgo will come soon online**

- **Einstein Telescope (2020+):** 10 km arm length, triangular underground cryogenic detector
  CQG, 2010, 27, 084007
- **LIGO Voyager (2025-2030):** cryogenic (120 K) high power; x 3 improvement in aLIGO strain sensitivity
- **LIGO Cosmic Explorer (2030+):** new 40 km arm length interferometer

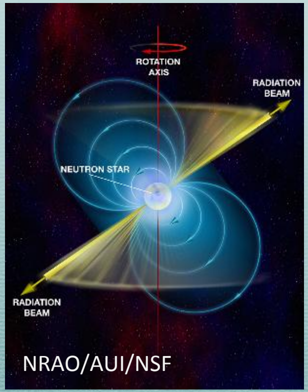
arXiv:1607.08697

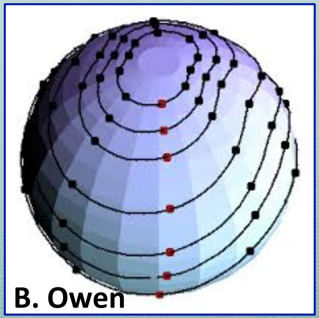
The CW SIGNAL

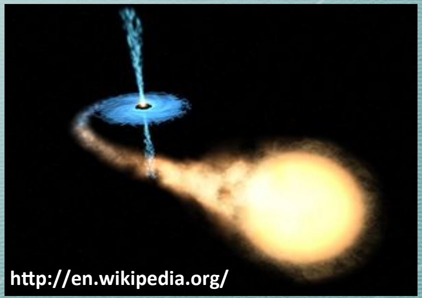
- More than 2500 observed NSs (mostly pulsars) and $O(10^8 – 10^9)$ expected to exist in the Galaxy

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

  - deformation due to elastic stresses or magnetic field not aligned to the rotation axis ($f_{GW} = 2\ f_r$)
  - free precession around rotation axis ($f_{GW} \sim f_r + f_{prec;}\ f_{GW} \sim 2f_r + 2\ f_{prec}$)
  - excitation of long-lasting oscillations (*e.g.* r-modes; $f_{GW} \sim 4/3\ f_r$)
  - deformation due to matter accretion (*e.g.* LMXB; $f_{GW} \sim 2\ f_r$)







CWs from rotating neutron stars

The measured strain amplitude h_0 on Earth is given by

$$h_0 = 4 \cdot 10^{-25} \left(\frac{\varepsilon}{10^{-5}}\right)\left(\frac{I_{zz}}{10^{45}\,\mathrm{g\,cm}^2}\right)\left(\frac{f_r}{100\ \mathrm{Hz}}\right)^2 \left(\frac{1\,\mathrm{kpc}}{d}\right)$$

with d distance to the source, with $\varepsilon = (I_{xx}-I_{yy})/I_{zz}$ being the equatorial non-axisymmetry and I_{ab} the moments of inertia.

MAXIMUM DEFORMATION

- **Normal NS** → $\varepsilon \leq 10^{-5}$
- **Hybrid (hadron-quark core)** → $\varepsilon \leq 10^{-3}$
- **Extreme quark stars** → $\varepsilon \leq 10^{-1}$

[Johnson-McDaniel & Owen, PRD 87, 129903 (2013)]

Types of CW searches

The way to search for CW signals depends on how much about the source is known. There are different types of searches:

- **TARGETED** searches for observed NSs. The source parameters (sky location, frequency & frequency derivatives) are assumed to be known with great accuracy (*e.g.* the Crab and Vela pulsars) => *O*(workstation)

- **NARROWBAND** searches for observed NSs with high uncertainties in rotational parameters. A small mismatch between the GW frequency (spindown) and the rotational star frequency (spindown) inferred from EM observations needs to be taken into account => *O*(workstation)

- **DIRECTED** searches, where sky location is known while frequency and frequency derivatives are unknown (*e.g.* Cassiopeia A, SN1987A, Scorpius X-1, galactic center, globular clusters) => *O*(cluster)

- **ALL-SKY** searches for unknown pulsars => computing challenge (Einstein@Home – Cloud – Grid Infrastructures)

Further types of CW searches

- **TRANSIENT** searches for short (days-weeks) CW signals useful to account for a non standard morphology :
  - Development of a machine learning-based method to search for long duration CW transients, starting with r-modes and generalizing to different transients. This ongoing project is based on neural networks and random forests.
  - Hierarchical follow-up of transient CW-like candidates (See Keitel's talk)
- Take into account NS glitches (Ashton et al., 1704.00742)

How to look for CW signals?

- In all-sky searches we need to search for unknown sources located everywhere in the sky, with signal frequency as high as ~ 2 KHz and with values of spin-down as large as possible =>

- COMPUTATIONALLY LIMITED!!

- Optimal coherent strategies (PRD 58, 063001, 1998) with long observations time T become computationally undoable

$$SNR \sim \frac{h_0}{\sqrt{S_n}} \sqrt{T}$$

Computing cost ~ T^{6+}

- Need to resort to SEMICOHERENT METHODS, where the entire data set is split into *N* shorter segments. Each segment is analyzed coherently, and afterwards the information from the different segments is combined incoherently:

$$SNR \sim \frac{h_0}{\sqrt{S_n}} \sqrt{T}\, N^{1/4}$$

- Fully coherent FOLLOW-UP happens only for the most promising candidates

Highlights from recent O1* searches

* O1: Advanced LIGO's first observing run occurred between Sep. 12, 2015 and Jan. 19, 2016

O1 All-sky searches

- Joint contribution from 4 CW pipelines to analyze [20-475] Hz and [-1, 0.1] x 10^{-8} Hz/s (see next two slides)

- Einstein@Home [20-100] Hz and [-26, 3.1] x 10^{-10} Hz/s search (see Walsh's talk):

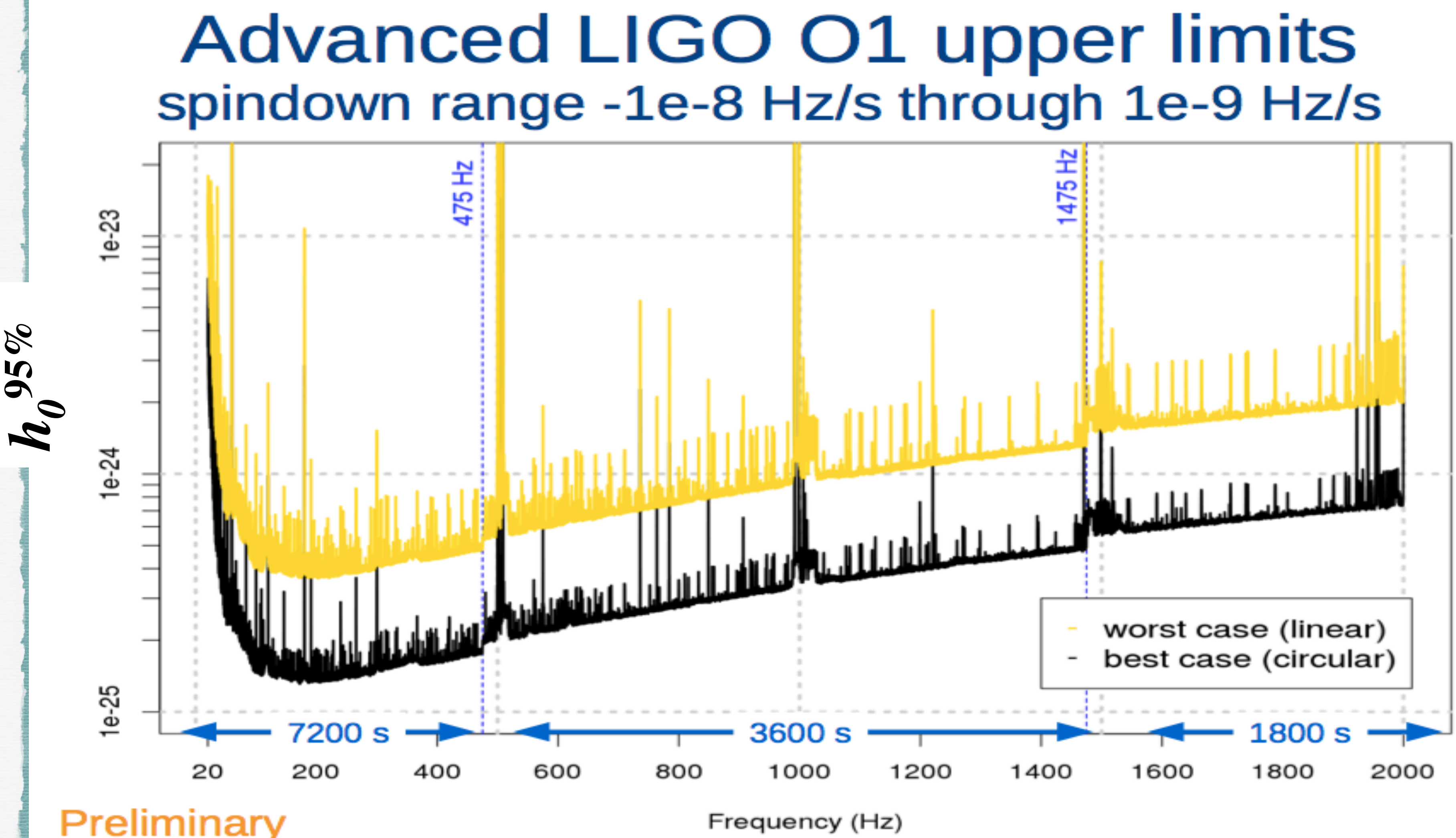
Above 55 Hz the ellipticity of sources within 100 pc is constrained to be smaller than 10^{-5} (preliminary results)

Highlights from all-sky searches: ISOLATED pulsars

1

- **Search parameter space: [20, 475] Hz; [-1, 0.1] x 10^{-8} Hz/s**
- **Four pipelines contributing:**
  - **Frequency Hough** [PRD 90, 042002 (2014)]
  - **Powerflux** [PRD 94, 042002 (2016)]
  - **Sky Hough** [CQG 31, 085014 (2014)]
  - **Time-Domain F-Statistic** [CQG 31, 165014 (2014)]
- Einstein@Home followup of interesting candidates (see Walsh's talk)
- Any potentially interesting candidate will be deeply scrutinized by employing methodologies that are being developed to search for CW signals deviating from our standard models
- ASTROPHYSICAL range: At 475Hz we are sensitive to NSs with equatorial ellipticity $\varepsilon \sim 8e\text{-}7$ and as far away as 1 kpc (preliminary results)

Highlights from all-sky searches: ISOLATED pulsars



Spindown LIMIT

- **Assuming that the measured spindown of the source is totally due to GW emission, we get an upper limit on the signal amplitude**

$$h_0^{\mathrm{sd}} = \left(\frac{5}{2}\frac{G I_{zz} \dot{f}_{\mathrm{rot}}}{c^3 d^2 f_{\mathrm{rot}}}\right)^{1/2} = 8.06 \times 10^{-19} \frac{I_{38}^{1/2}}{d_{\mathrm{kpc}}} \sqrt{\frac{|\dot{f}_{\mathrm{rot}}|}{f_{\mathrm{rot}}}}$$

Going below the spindown limit means we are putting a constraint on the fraction of spindown energy due to the emission of GWs.

- **The spindown limit on the signal amplitude corresponds to an upper limit on the star ellipticity given by**

$$\epsilon^{\mathrm{sd}} = 0.237 \left(\frac{h_0^{\mathrm{sd}}}{10^{-24}}\right) I_{38}^{-1} (f_{\mathrm{rot}}/\mathrm{Hz})^{-2}\, d_{\mathrm{kpc}}.$$

Highlights from targeted searches 1

LVC, ApJ 839 (2017)

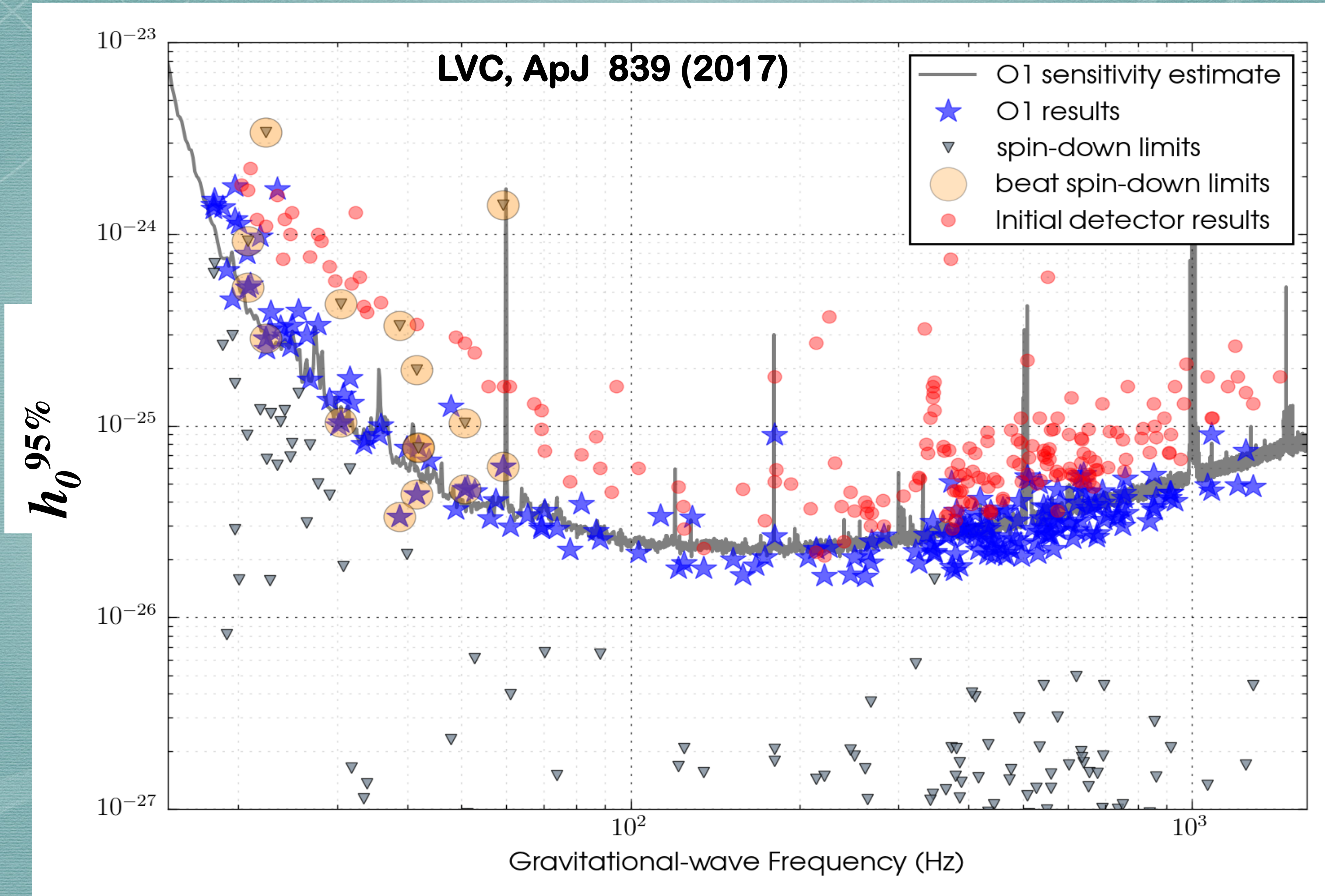
- **Analyzed 200 known pulsars (119 out of 200 are in binary systems)**

- **11 high-value targets (including Crab and Vela pulsars) analyzed with 3 pipelines: TD Bayesian [PRD 72, 102002, 2005], TD F/G-Stat [CQG 27, 194015, 2010] and FD 5-vector [CQG 27, 194016, 2010] method; the remaining 189 targets with only TD Bayesian algorithm;**

- **ULs improved by a factor 2.5 with respect to initial detector era:**
  - **Mainly due to detector sensitivity improvement**
  - **Further improvement by a factor 2.3 considering design sensitivity and one year of data**

- **Spindown limit beaten for 8 pulsars, including both Crab & Vela:**
  *** For the Crab and Vela pulsars less than ~ 2×10^{-3} and ~ 10^{-2} of the spindown luminosity is being lost via gravitational radiation, respectively**

Highlights from targeted searches 2



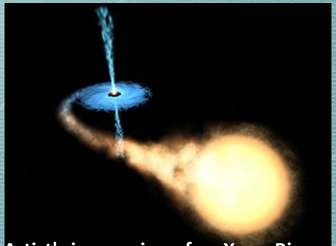
CWs from spinning NSs in binary systems

- More than half of the observed radio pulsars (with rotation rates that can plausibly emit CWs in the most sensitive band of the LIGO-Virgo detectors) are located in binary systems

- Accretion from a companion may cause an asymmetrical quadrupole moment of inertia of the spinning NS

- The CW signal from a source in a binary system is frequency-modulated by the source's orbital motion, which in general is described by five unknown *Keplerian parameters*

- Best candidate: Scorpius X-1 (the brightest low-mass X-ray binary), typically used as a *test bench* for all algorithms, as sky-position and binary orbital parameters are known with high accuracy



Artist's impression of an X-ray Binary

Accretion in LMXBs

- **Rapidly accreting NSs in LMXBs are interesting targets for CW searches**

- **The accretion is asymmetric due to the sporadic observation of x-ray pulsations**

- **This asymmetry can lead to GW emission through various mechanisms:**
  - **temperature-dependent electron capture onto nuclei in the crust [ApJ 501, L89 (1998)]**
  - **magnetic funneling of accreted material [ApJ 623, 1044 (2005)]**
  - **sustained instability of rotational *r*-modes [ApJ 516, 307 (1999)]**

- **The most rapidly observed accreting NSs do not spin at very high frequencies, and this seems to suggest that their accretion torques are balanced by GW emission torque [ApJ 501, L89 (1998)]**

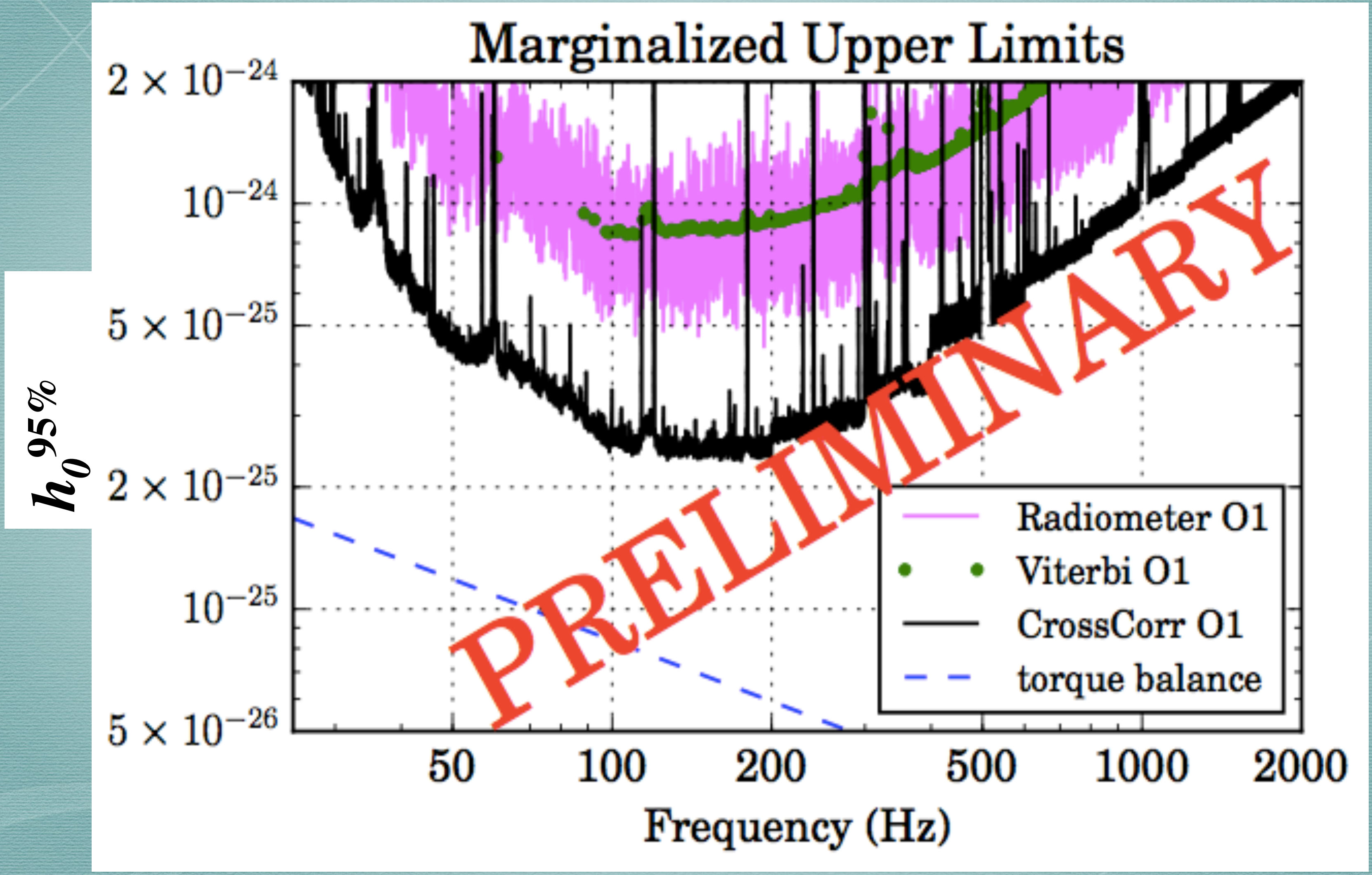
O1 Directed Scorpius X-1 searches 1

- The new Viterbi Sideband search combines a frequency domain matched filter (Bessel-weighted F-Stat) with a hidden Markov model to track wandering of the NS spin frequency, providing better sensitivity w.r.t previous Sideband pipeline by searching longer observation period [PRD 93, 123009 (2016); https://arxiv.org/abs/1704.03719].
- Computationally efficient: <~ 3000 CPU-hours
- No evidence for standard CW signals in the search frequency range [60 - 650] Hz

- The CrossCorr method [PRD 91, 102005 (2015)] is semicoherent with an adjustable coherence time to trade off sensitivity versus computing cost.
- Computationally intensive, but most sensitive [25 -2000] Hz search to date: preliminary results presented in Whelan's talk

- Radiometer search (including also other targets); LVC, PRL 118, 121102 (2017): $h_0^{90\%} \sim 6.5 \times 10^{-25}$ at 150 Hz

O1 Directed Scorpius X-1 searches 2



Multi-messenger Astronomy helps us a lot!

Multi-messenger Astronomy with GW searches

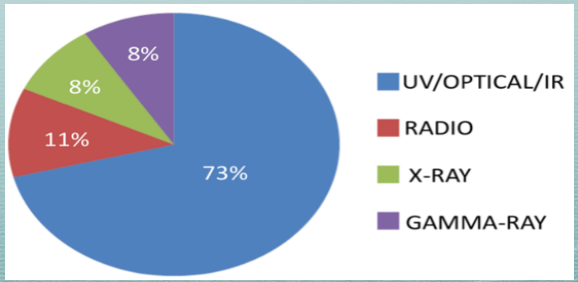
The GW-EM follow-up program

- **More than 70 Partners from 20 countries**
- **150 instruments, covering the full spectrum from radio to very high-energy gamma rays**

- **GW transient candidates are identified within tens of minutes and shared with EM partners**

- **Thanks to EM observations we can know (with high accuracy) the sky location and/or rotational parameters of several NSs, in particular radio pulsar (=> useful for DIRECTED and TARGETED searches)**

- **GW searches in coincidence with neutrinos (ANTARES, IceCub and future KM3NeT): useful to improve SOURCE SKY LOCALIZATION**



What can we learn about GWs from NSs?

Probing NS physics with GWs

- **NS Microphysics cannot be easily obtained via EM observations (composition of highly condensed matter, crystalline structure, viscosity)**
- **Information on NS quadrupolar deformation (ellipticity) will be useful to understand NS composition (only neutrons, quarks, exotic matter?)**
- **Other NS properties (masses, radii, sky locations)**
- **Detecting deviations from General Relativity:**
  - **speed of GWs**
  - **existence of other polarizations**
  - **First search for Non-Tensorial CWs in O1 LIGO data (in progress)**

What's needed to facilitate CW detection?

- **UPDATED EPHEMERIS as fully coherent searches for CWs from known pulsars rely on coherent phase models and wrong ephemeris can introduce phase errors, which would result in a loss of signal-to-noise ratio**
- **RADIO OBSERVATORIES able to monitor the vast majority of radio pulsars, mainly those with high spindown, which translates into a strong CW emission (e.g. PSRs J1952+3252 and J1913+1011)**
- **GAMMA/X-RAY observations**
- **DISCOVER NEW PULSARS (in all EM bands) for directed/targeted/narrowband searches, which are more sensitive than all-sky searches**
- **ROBUST ALGORITHMS able to detect both our standard signal models and the unexpected!**
- **… and of course (more) SENSITIVE GW DETECTORS**

Ongoing Efforts: other CW searhes/activities 1

- Plethora of ongoing searches for CWs from both isolated NSs and NSs in binary systems:
  - Improvement of veteran pipelines
  - Development of new methodologies/algorithms
    - Leaci *et al.*, Novel directed search strategy to detect CWs from NSs in low- and high-eccentricity binary systems, https://arxiv.org/abs/1607.08751, PRD (in press)
    - Mastrogiovanni *et al.*, An improved algorithm for narrowband searches of continuous gravitational waves, CQG (in press)
    - Suvorova *et al.*, Hidden Markov model tracking of continuous gravitational waves from a neutron star with wandering spin, https://arxiv.org/abs/1606.02412, PRD 93, 123009 (2016)
    - Computationally efficient follow-up methodology (see D'Antonio poster and Piccinni's poster)
    - Generalized 5-vector method for NSs in binary systems (see Singhal's poster)
    - Candidate veto procedure (see Zhu's poster)
    - …
  - Mock-Data-Challenge (pipeline comparison for Scorpius X-1 searches)

Ongoing Efforts: other CW searhes/activities 2

- **Search for *r*-mode frequencies (Crab pulsar, CasA, …)**
- **Search for long transient CWs (machine-learning based algorithms)**
- **Search for Non-Tensorial continuous GWs (Isi *et al.* https://arxiv.org/abs/1703.07530)**
- **Finalizing O1 results (all-sky and narrowband searches) and getting ready for O2 data (three-detector-network as Virgo will join the run)**

A list of LIGO-Virgo CW papers can be found at https://galaxy.ligo.caltech.edu/svn/cw/public/index.html

TRANSIENT GWs have been already detected…

We are now looking forward to detecting <u>CONTINUOUS GW SIGNALs</u>

STAY TUNED!

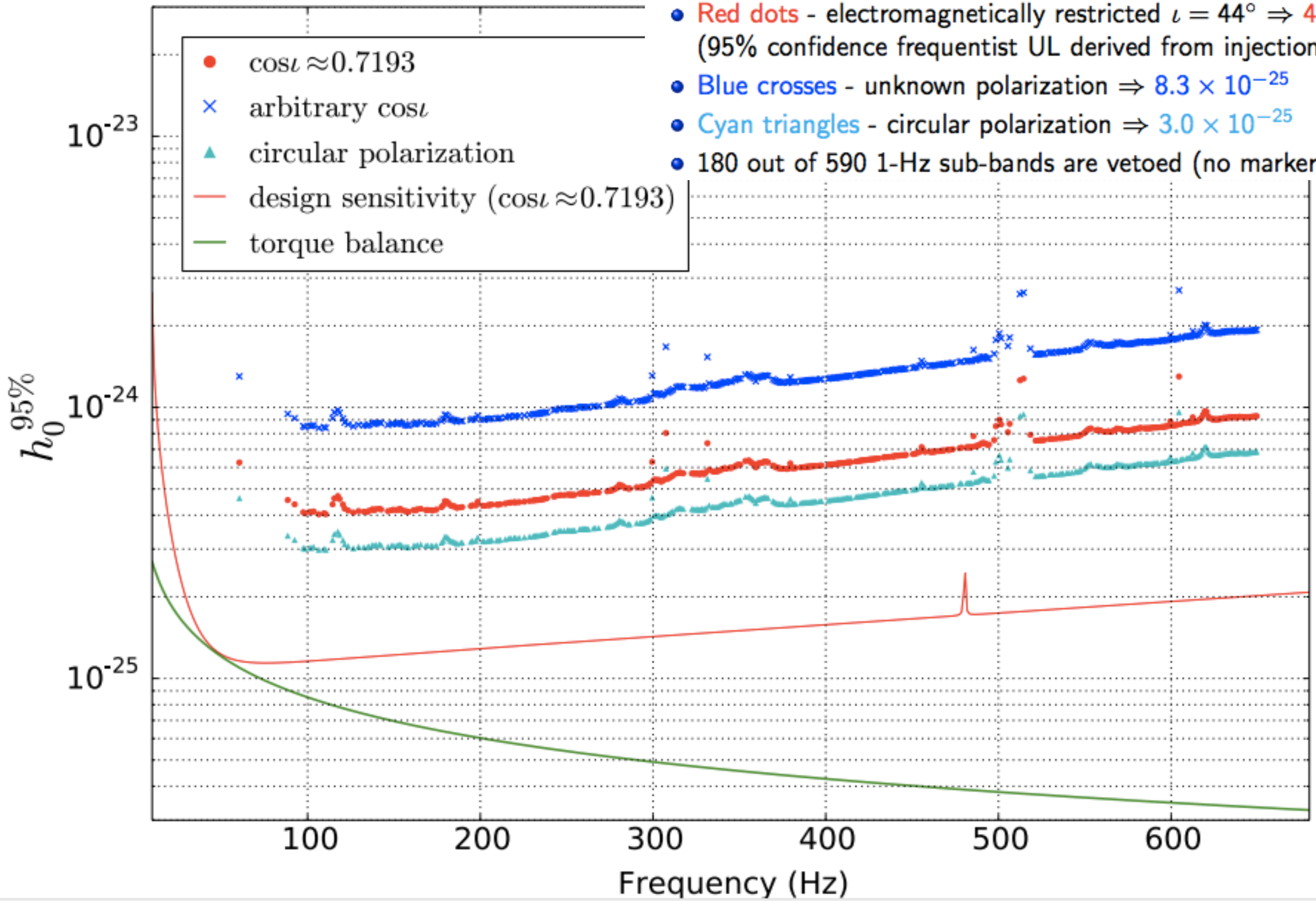
Thank you

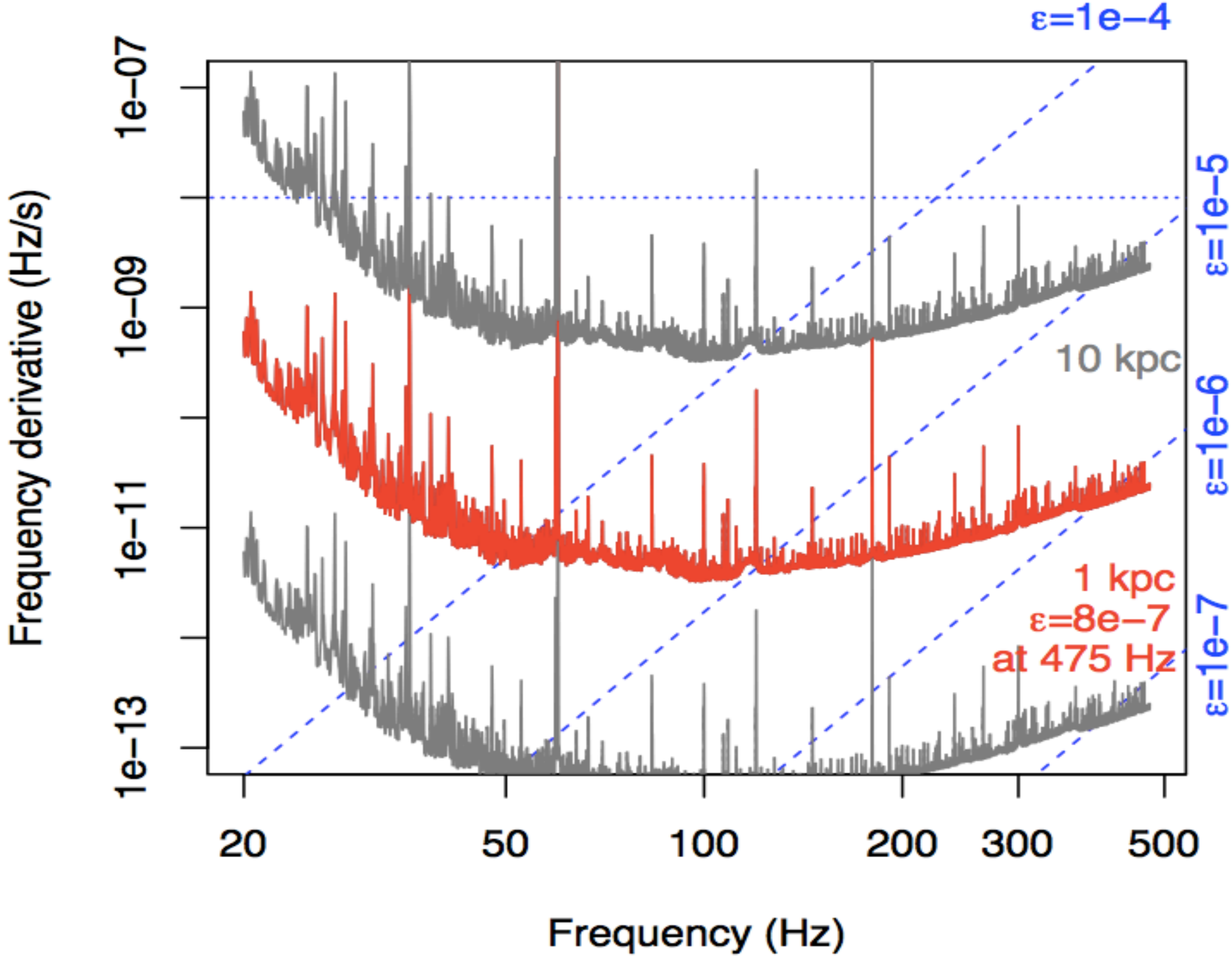
BACKUP slides

O1 Directed Scorpius X-1 Viterbi search

https://arxiv.org/abs/1704.03719

- Red dots - electromagnetically restricted $\iota = 44°$ $\Rightarrow$ 4.0×10^{-25} (95% confidence frequentist UL derived from injections)
- Blue crosses - unknown polarization $\Rightarrow$ 8.3×10^{-25}
- Cyan triangles - circular polarization $\Rightarrow$ 3.0×10^{-25}
- 180 out of 590 1-Hz sub-bands are vetoed (no marker)




ε=1e−4
ε=1e−5
ε=1e−6
ε=1e−7
10 kpc
1 kpc
ε=8e−7
at 475 Hz
1e−07
1e−09
1e−11
1e−13
Frequency derivative (Hz/s)
20
50
100
200
300
500
Frequency (Hz)

V. TORQUE-BALANCE UPPER LIMIT

In LMXBs the gravitational wave strain inferred from the torque-balance scenario can be expressed as a function of the spin frequency of the neutron star $f_\star$ and the the X-ray flux F_X according to [19, 27, 36]

$$h_0^{\rm eq} = 5.5 \times 10^{-27} \left(\frac{F_X}{10^{-8}\,{\rm erg\,cm^{-2}\,s^{-1}}}\right)^{1/2} \left(\frac{R_\star}{10\,{\rm km}}\right)^{3/4} \times \left(\frac{1.4 M_\odot}{M_\star}\right)^{1/4} \left(\frac{300\,{\rm Hz}}{f_\star}\right)^{1/2}, \quad (6)$$

where $R_\star$ is the stellar radius and $M_\star$ is the stellar mass.[2] We now ask how $h_0^{\rm eq}$ compares to the results of the analysis in Section IV.

Let us take the electromagnetically measured $F_X = 4 \times 10^{-7}\,{\rm erg\,cm^{-2}\,s^{-1}}$ [57] for Sco X-1 and the fiducial values $R_\star = 10\,{\rm km}$ and $M_\star = 1.4 M_\odot$. We plot $h_0^{\rm eq}$