SRGWmb2025 – Storage Rings & Gravitational Waves – mini-brainstorm

Future GW Observations:
Spectral Coverage, Old/New Directions, Critical Technologies

Stefania Petracca [University of Sannio, INFN]
Innocenzo M. Pinto [Retired Professor, LVK Member, OSA Fellow]

10 Feb 2025, 08:30 → 11 Feb 2025, 18:00 Europe/Zurich
6/R-012 - conference room (CERN)

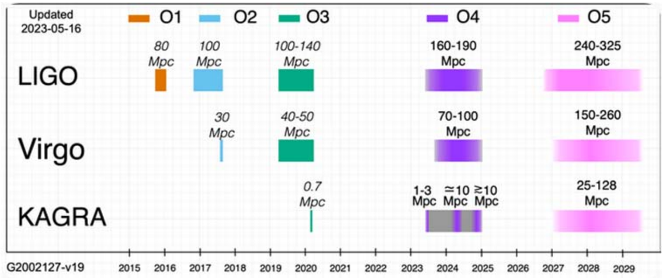
Outline

- The LVK Observatory
- Noise Budget – Optical Coatings R&D etc.
- Mass Gaps, Missing CWs, Eccentric Orbits, etc. – Data Analysis R&D
- Spaceborne Detectors & Pulsar Timing Arrays – Spectral Coverage
- HF GW Sources and Detectors (?)
- Possible PA / GW Technology Cross-Breeding Benefits
- Storage Rings as GW Detectors and Sources
- Gertsen’shtein effect : EM GW Detectors – Dual-Use ALP Detectors/Experiments
- Toward a GW Hertz Experiment ?
- Critical Technologies

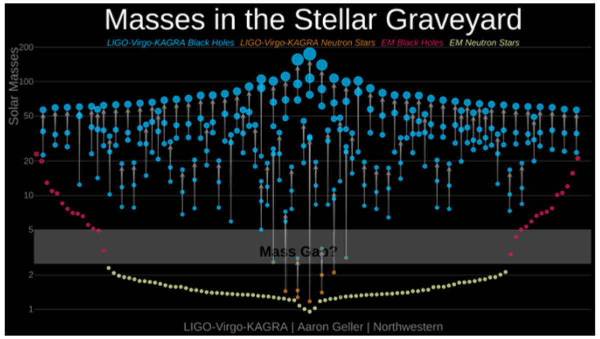
Running/Planned GW Observatories

- The 2nd generation LIGOs [Aasi et al., CQG 32 (2015) 074001], Virgo [Acernese et al., CQG 32 (2015) 024001] and (1st underground and cryogenic) KAGRA [Akutsu et al., Progr. Th. Exp. Phys. 2021 (2021) 05A101] are the four "legs" of the LIGO-Virgo-Kagra (LVK) GW Observatory, featuring good (albeit limited) direction-of-arrival and source-reconstruction capabilities. Addition of a LIGO-clone in India [www.gw-indigo.org/tiki-index.php] is envisaged*.

- As of today, *many* GW *chirps* have been observed across five observational runs spanning several months; mostly from BH-BH, but also from NS-NS and (recently) NS-BH binaries, including *multi-messenger* (GW, EM and neutrino) observations [Meszaros et al., Nature Rev. Phys. 1 (2019) 585]



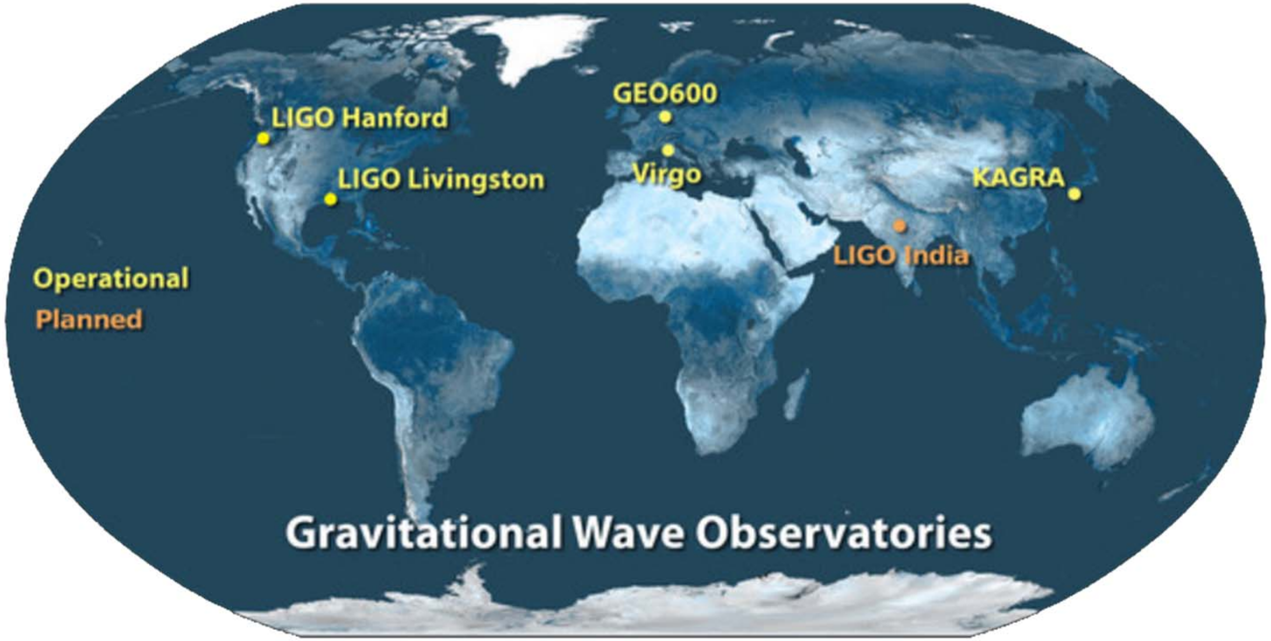
[Shoemaker et al., LIGO-G2002127]

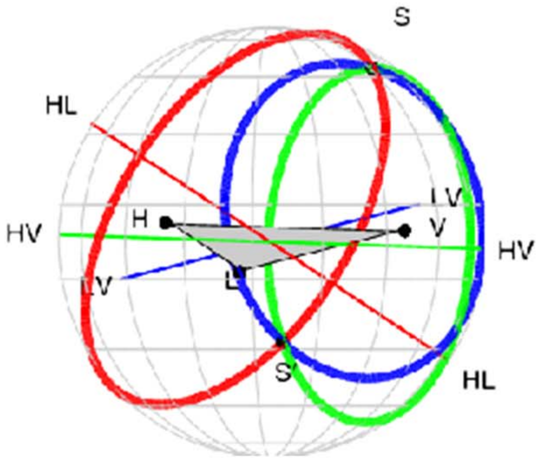


[https://media.ligo.northwestern.edu/gallery/masses-in-the-stellar-graveyard]

*Smaller scale interferometric detectors, including GEO-600, TAMA-300, the Caltech-40m, and the 100m-cryogenic CLIO, are mainly used as technology test-beds for the bigger instruments .

3+ Detectors


LIGO Hanford
LIGO Livingston
GEO600
Virgo
KAGRA
LIGO India
Operational
Planned
Gravitational Wave Observatories


S
HL
HV
H
LV
V
HV
L
S'
HL

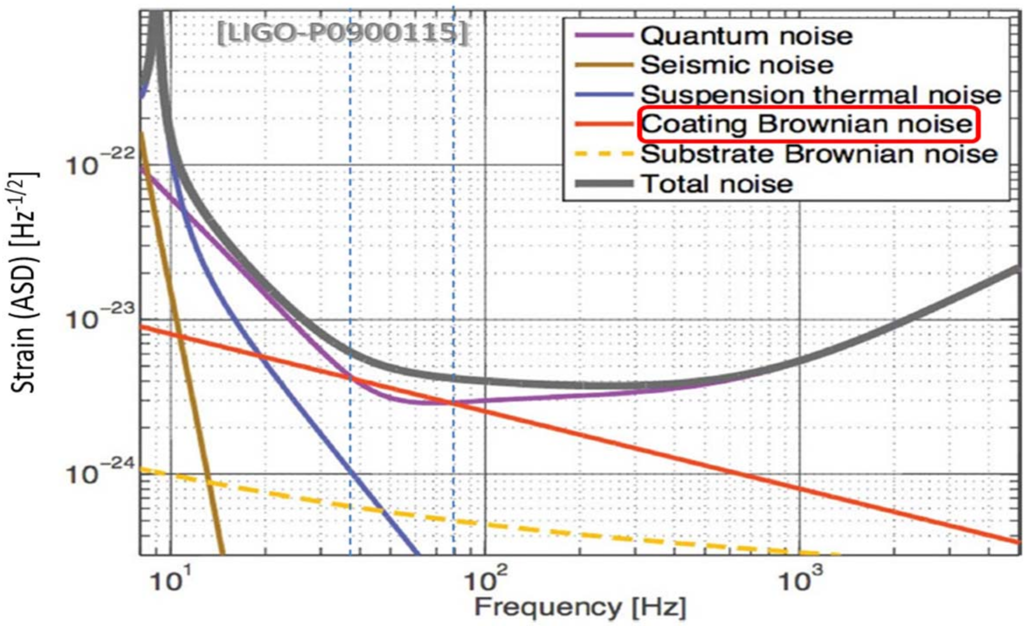

LIGO Hanford
4Km FP-arms

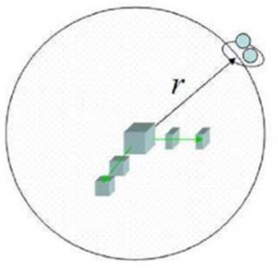

LIGO Livingston


Virgo

Earthbound GW Detectors Noise Budget

- Seismic noise (at low frequencies), and laser (shot) noise (at high frequencies) limit the observational window of Earth-bound interferometric detectors to (20 - 200 Hz), where the noise floor is dominated by thermal noise in the mirrors terminating the interferometer arms. Next - gen Earth - bound detectors, such as the Einstein Telescope (ET) [https://www.et-gw.eu], and the Cosmic Explorer [https://cosmicexplorer.org/], with reduced noises and improved source-localization / reconstruction capabilities, will be *similarly limited* by the same main types of noise in terms of spectral coverage.



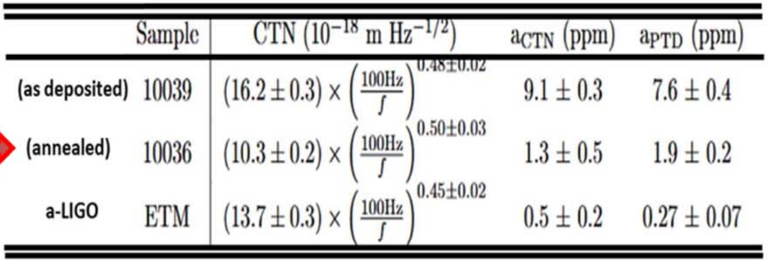


Visibility volume & event rate $\Bigg\} \propto PSD_{floor}^{-3/2}$

... a $\mathbf{5}\boldsymbol{\mu m}$ thick film sets the performance of a $\mathbf{5}\boldsymbol{Km}$ size detector !!

Multimaterial Coatings

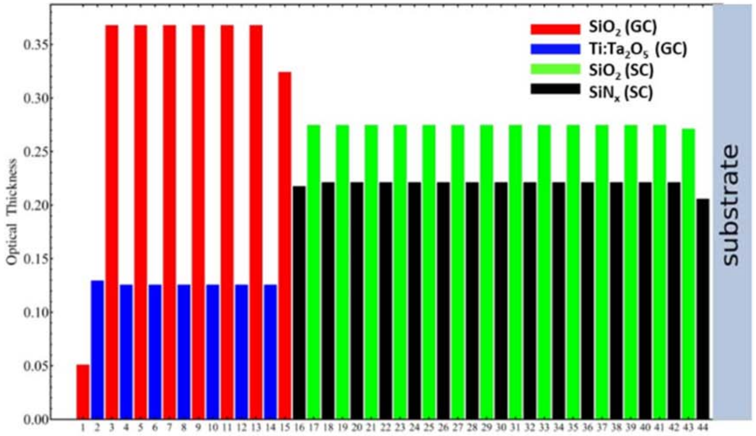
- Prototype design by V. Pierro @USannio.
  Material params provided by LMA (SC & GC).
  - Design goals: $\alpha_P = 1.5ppm; \tau_P = 5.6ppm.$
- Made/tested @LMA (M. Granata et al) ,
  - *Small Coater* (SC) for bottom (SiO_2/SiN_x) stack
  - *Grand Coater* (GC) for top (SiO_2/Ta_2O_5) stack.
- CTN measurements @MIT (N. Demos et al).
- Results [Granata et al., PRD 111 (2025) 042003]



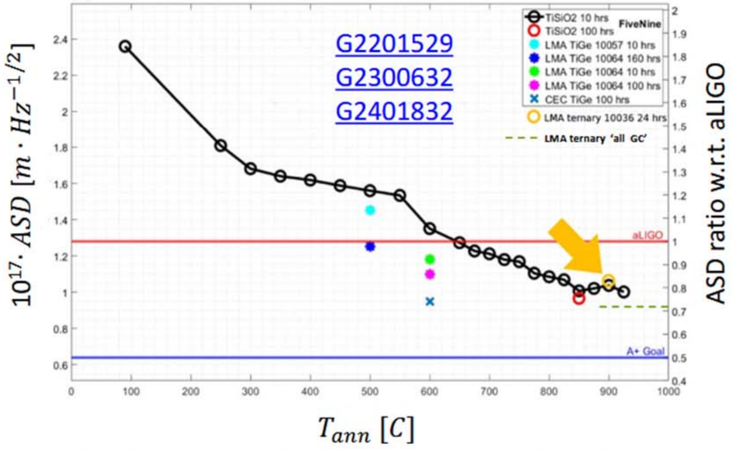
	Sample	CTN (10^{-18} m $Hz^{-1/2}$)	a_{CTN} (ppm)	a_{PTD} (ppm)
(as deposited)	10039	$(16.2 \pm 0.3) \times \left(\frac{100Hz}{f}\right)^{0.48 \pm 0.02}$	9.1 ± 0.3	7.6 ± 0.4
(annealed)	10036	$(10.3 \pm 0.2) \times \left(\frac{100Hz}{f}\right)^{0.50 \pm 0.03}$	1.3 ± 0.5	1.9 ± 0.2
a-LIGO	ETM	$(13.7 \pm 0.3) \times \left(\frac{100Hz}{f}\right)^{0.45 \pm 0.02}$	0.5 ± 0.2	0.27 ± 0.07

in excellent agreement with design.

- Noise ASD @100Hz 25% lower than aLIGO.
  Reflectance & absorption fit the design values.
- Point scatterers & other defects (excess diffraction) under investigation.



[Pierro et al., PRR 3 (2021) 023172]

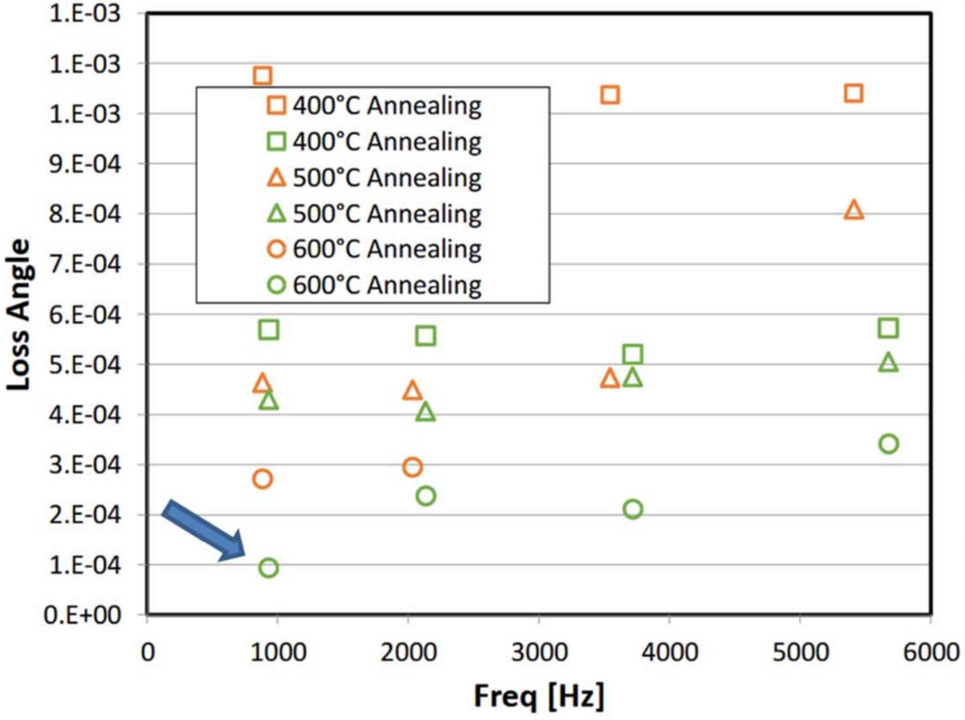


G2201529
G2300632
G2401832

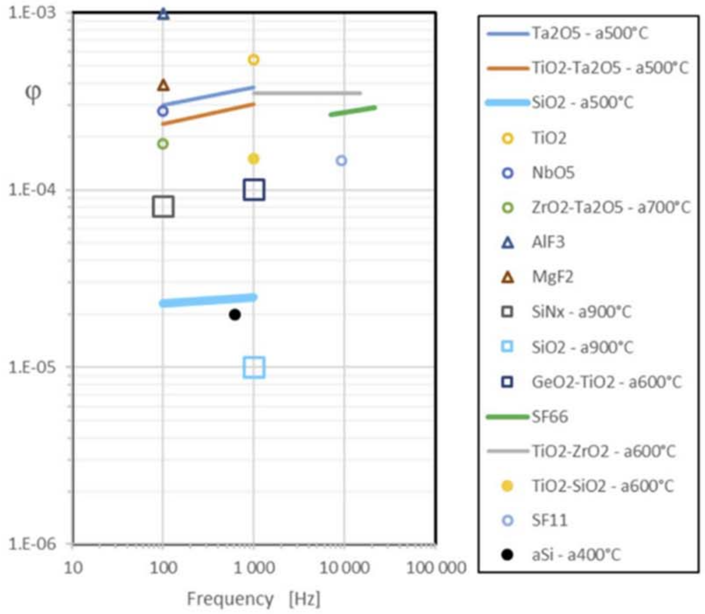
- SC-deposited SiO_2 has *larger* (twofold) mechanical losses compared to GC-deposited one. *Lower* CTN expected if *both* stacks are deposited in the GC.

Nanolayered Optical Films

- Materials: QWL films with $n_{eff} = 2.07$ designed & deposited @USannio/UniSA
- GeNS measurements @LMA by L. Mereni



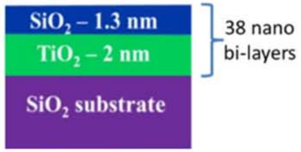
Quest of the
Coating Holy Grail
(Amorphous materials only)



Red markers: *fast* deposition (1Å/s both materials)

Green markers: *slow* deposition (0.2Å/s TiO_2, 0.4Å/s SiO_2)

⟹ **slower deposition yields lower CTN**



SiO_2 – 1.3 nm

TiO_2 – 2 nm

SiO_2 substrate

38 nano bi-layers

QWL film @ 1064nm

$n_{eff} = 2.07$

(calculated & measured)

- L. Mereni et al., LIGO - G2401236 , G2401199

Mass Gaps, Missing (CW)-GWs, Eccentric BCS etc.

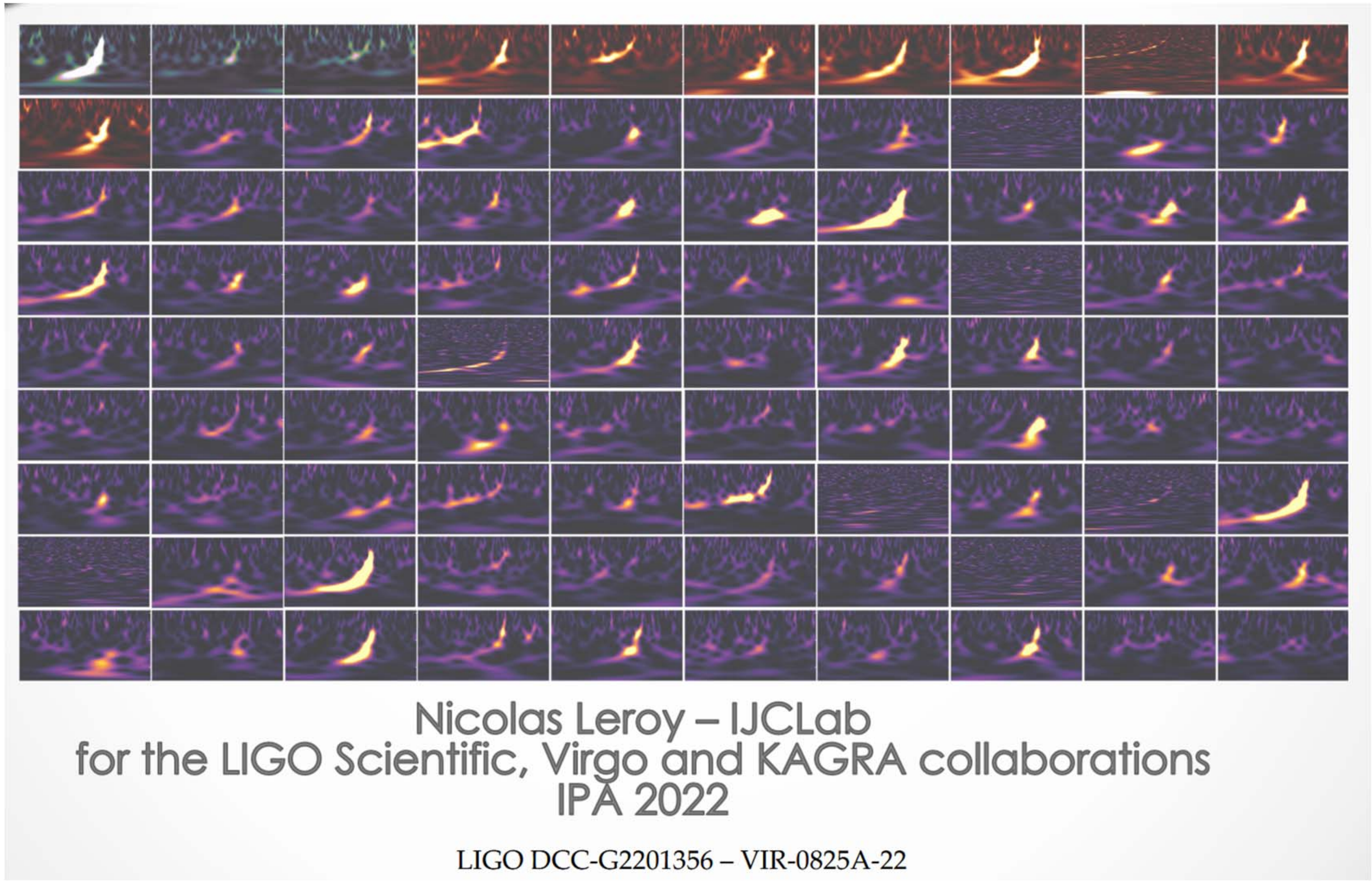
(Chirp-)Mass *gaps* in the observed CBS population [Edelman et al., Ap.J. Lett. L23 (2021) 913] exist.

So far (2024) only a handful of events have been vetted where the compa-panion masses are in the NS-BH gap (2 to 5 $M_{\odot}$) – the most relevant being perhaps GW230529 (likely a NS-BH binary with $M_{BH} \cong 2.5 - 4.5 M_{\odot}$. [Abac et al., Ap. J. Lett. L34 (2024) 970]

So far, despite the develop[ment of elegant and powerful dedicated data analysis pipelines, including the world-scale Einstein@Home computing farm, no almost-continuous GW from spinning NS has been detected. See [Abac et al., arXiv:2501. 01495 (2025)] and [Ming et al., Ap. J. 977 (2024) 154] for up-to-date accts.

BCS with *eccentric orbits* may form as an effect of several mechanis, and remain *fairly* eccentric until the very last phases of coalescence (in contrast to previous belief) [Wagner & O'Shaughnessy, PRD 110 (2024) 124024].
As of today, detection and orbital parameter estimation algorithms appropriate for eccentric orbits are still under development. The search for eccentric orbits in observed coalescence events has remained elusive so far [Abbot et al., Ap.J. 883 (2019) 149; Abac et al. Ap. J, 973 (2024) 132].

Clever Representations : Time-Frequency Tracks

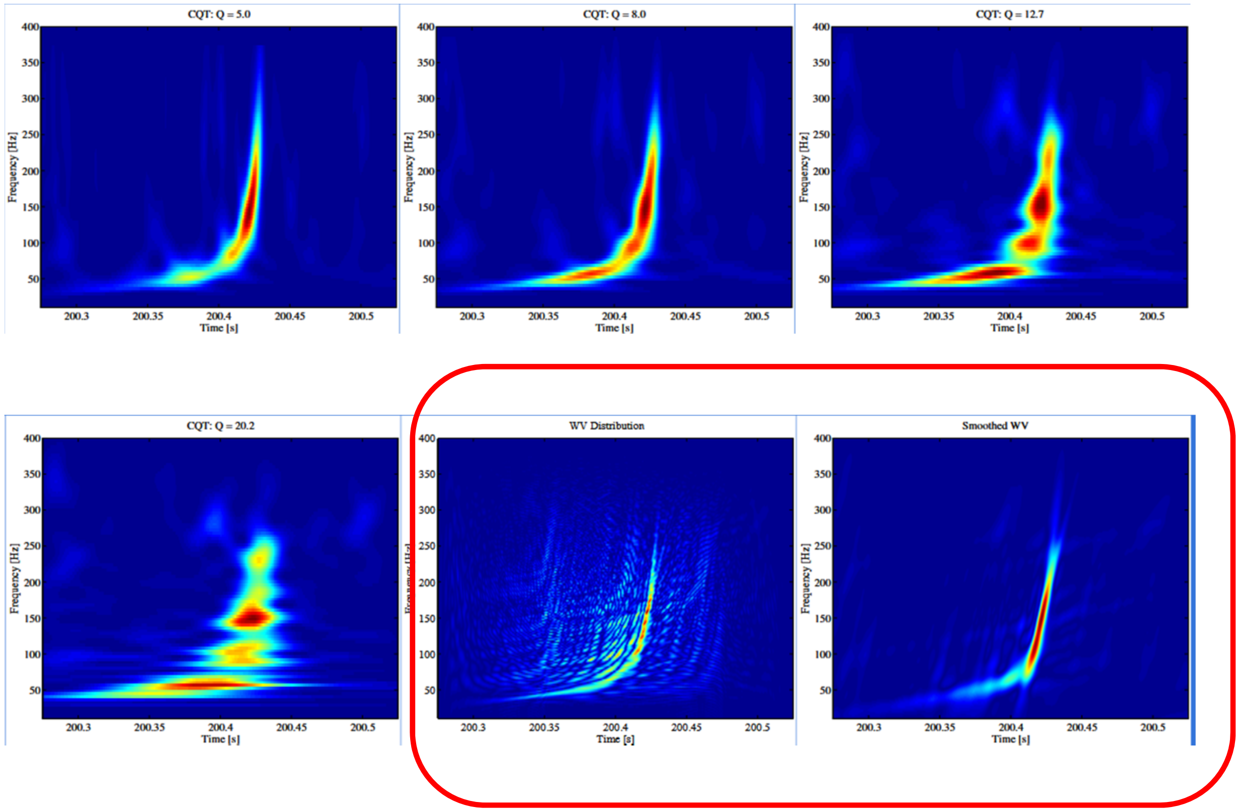


Nicolas Leroy – IJCLab
for the LIGO Scientific, Virgo and KAGRA collaborations
IPA 2022

LIGO DCC-G2201356 – VIR-0825A-22

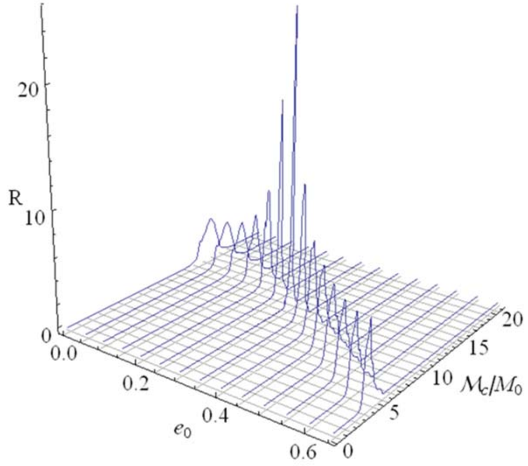
(More) Clever TF Representations

Goal: achieve largest resolution in *both* time and frequency ...

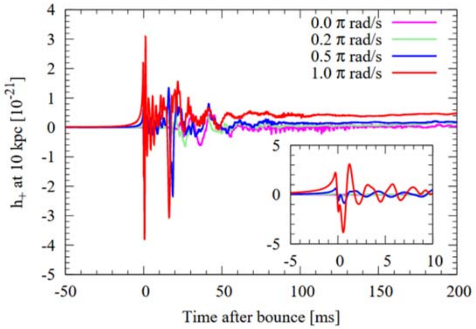


... while suppressing intermodulation artifacts.
Best solution so far: *smoothed* & *sparsified* Wigner-Ville.
[Flandrin & Borgnat, IEEE Trans SP-58 (2010) 2974]

In particular, sharp(er) TF representations based on compressed coding can be used to build efficient estimators of chirp mass *and* orbital eccentricity at some reference time **[Pinto, J. Phys. Conf. Ser. 2081 (2021) 012008]**...



Unmodeled Signals



- A wide class of expected GW signals are basically *un-modeled* (collapsing binaries and rotating neutron stars are *exceptions* !) These include, e.g., GW bursts from *supernovas*, GRBs, etc. [Anderson and Kokkotas, Lect.Notes Phys. 653 (2005) 255].

- Supernova outburst waveforms have been extensively studied by numerical simulations, but no simple physically *parameterized* model is available [Dimmelmaier et al., Phys. Rev. D78 (2008) 064056; Yokozawa et al., Ap. J. 811 (2015) 86].

- An observatory made of $D > 2$ (non-colocated, non-aligned) detectors allows to write *any* $S_d(t)$ as a linear combination of the *other* $S_k(t)$, $k \neq d$, with coefficients depending uniquely on the ${F_d}^{+,\times}(\Omega_s)$. This is known as *multiple-detector redundancy* [Gürsel and Tinto, Phys. Rev. D40 (1989) 3884].

<u>Example</u> : $D = 3$. Three equations relating the (measurable) $S_k(t)$, k =1,2,3, to the two transverse-traceless GW components h^+ and $h^\times$

$$\det\begin{pmatrix} S_1 & {F_1}^+ & {F_1}^\times \\ S_2 & {F_2}^+ & {F_2}^\times \\ S_2 & {F_3}^+ & {F_3}^\times \end{pmatrix} = 0 = ({F_2}^+{F_3}^\times\text{-}{F_2}^\times{F_3}^+)\, S_1 - ({F_1}^+{F_3}^\times - {F_1}^\times{F_3}^+)\, S_2 + ({F_1}^+{F_2}^\times - {F_1}^\times{F_2}^+)\, S_3$$

Unmodeled Signals, contd.

- If *no noise* was there in the data, $V_d(t) = S_d(t)$ and we may construct $S_1(t)$ (a *template* for $V_1(t)$) as follows :

$$S_1 = \frac{(F_1{}^{+}F_3{}^{\times} - F_1{}^{\times}F_3{}^{+})}{(F_2{}^{+}F_3{}^{\times} - F_2{}^{\times}F_3{}^{+})} V_2 - \frac{(F_1{}^{+}F_2{}^{\times} - F_1{}^{\times}F_2{}^{+})}{(F_2{}^{+}F_3{}^{\times} - F_2{}^{\times}F_3{}^{+})} V_3 \qquad [*]$$

(similar formulas hold for S_2, S_3), even if the observed GW is *unmodeled/unknown*.

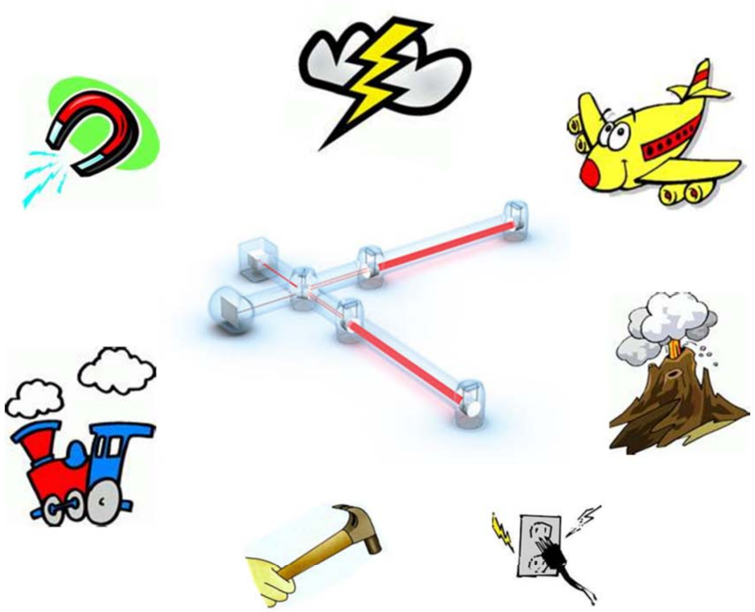
- This *appealing idea* for detecting (*and reconstructing*) *unmodeled* GWs by clever *data-fusion* using D>2 detectors was first suggested by Klimenko and Rakhmanov [Class. Quantum Gravity, 22 (2005) S131].

Sergey Klimenko (UFL) **Malik Rakhmanov (UTA)**

Problem I : for some DOAs, the matrix-inversion behind eq. [$*$] may be plagued by *ill-conditioning* , hence Tikhonov regularization may be needed, to obtain a *pseudo*-inverse [Rakhmanov, *Class. Quantum Grav.* **23** (2006) S673];

Problem II : we need to take into account that the individual detector noises are non-Gaussian, and that the (pseudo)-templates obtained as above are also affected by heavy-tailed noise. We shall accordingly filter *all* V_d data using the appropriate nonlinear $g(x)$ to implement a multi-sensor *locally-optimum* detection statistic .

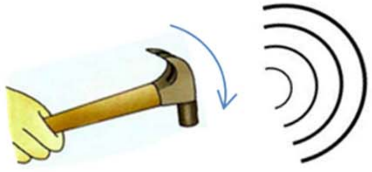
*Glitches**



… transient disturbances of environmental or instrumental origin leaking into the data channel via different linear (and nonlinear) paths …

… glitches appear in the data (and aux/monitoring) channels as linear combinations (with random amplitudes and delays) of a *small* number of (linear and nonlinear) *canonical responses* …

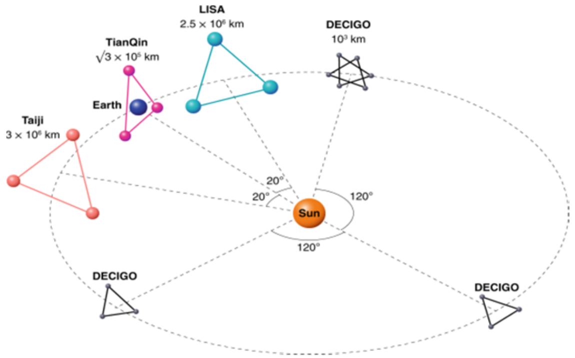
Glitches make the noise non-Gaussian (*locally* optimum detectors, noise subtraction, glitch dictionaries...)



*) … the word comes from Yiddish term ***glitsh*** (גליטש) aka slippery (dangerous) step …

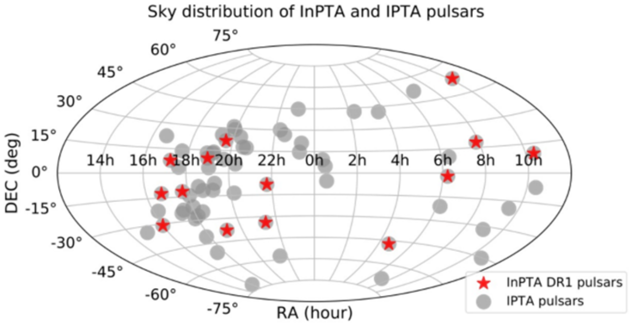
Running/Planned GW Observation Experiments

- Observing lower frequency GWs will be possible with LISA [https://lisamission.org/], a large scale ($2.5 \cdot 10^9$ m arm-length) space-borne interferometric detector, planned for launch in 2037, whose pathfinder mission was remarkably successful [Armano et al., PRL 116 (2016) 231101].
  - ♦ Two comparable Chinese project [Luo et al., CQG 33 (2016) 035010, W.-H. Ruan et al., arXiv: 1807.09495v2], and a smaller (Earth orbit-scale) Japanese project [http://decigo.jp/index_E] have been proposed; further developments of space-borne interferometers may be envisaged [Crowder and Cornish, PRD72 (2005) 083005].



[Y. Gong et al., Nature Astron. 5 (2021) 881]

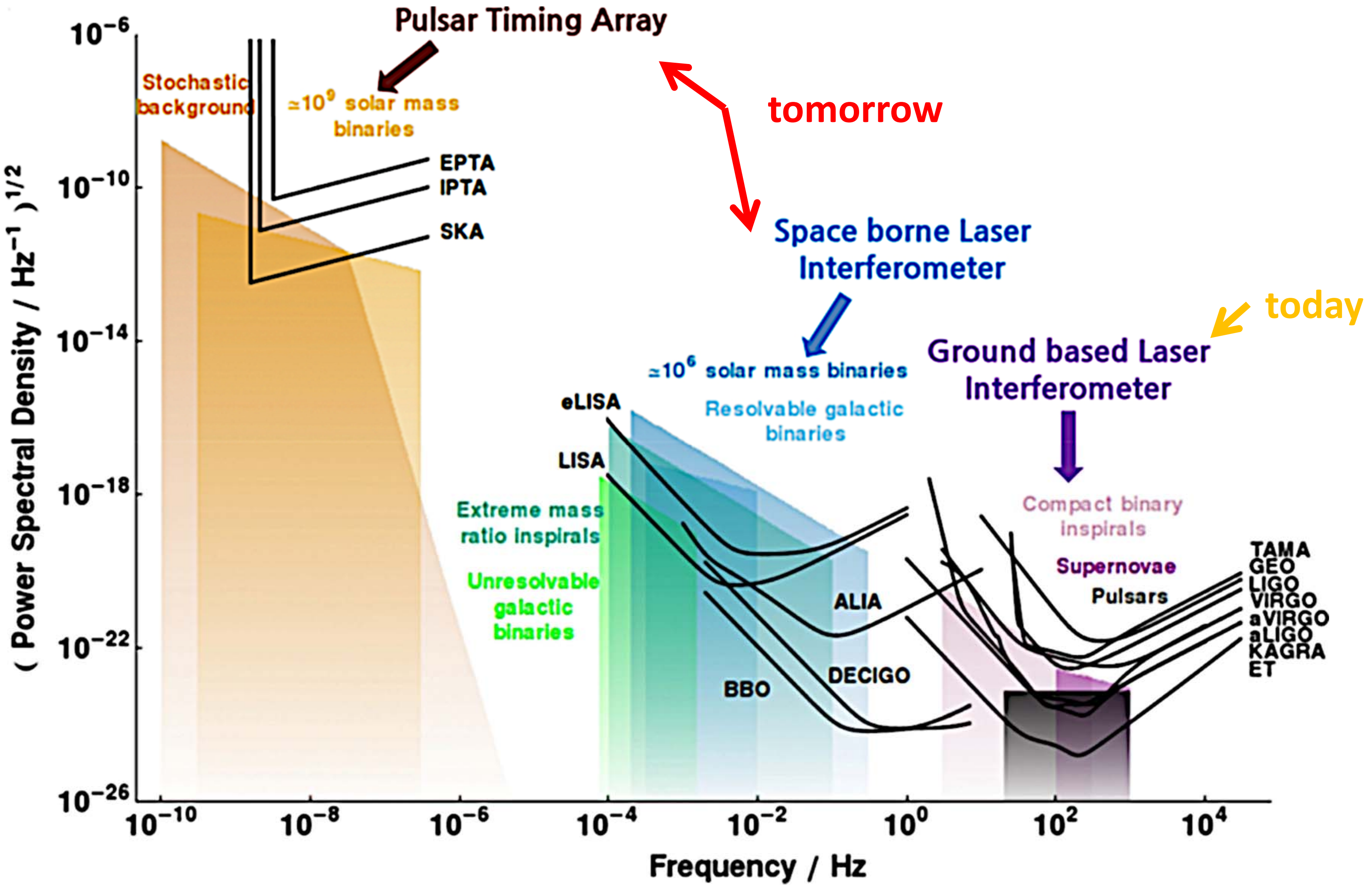
- Pulsar-timing [Hobbs and Dai, Nat.l Sci. Rev. 4 (2017) 707] will eventually open a window on the extreme low-frequency bands of the GW spectrum. Early results from the leading Labs [https://ipta4gw.org/, https: //nanograv.org/, www.epta.eu.org/, https://www.atnf.csiro.au/ research/pulsar/ppta/ , https://inpta.iitr.ac.in/, https://www.skao.int/, https://www.prao.ru/] look promising .



[https://inpta.iitr.ac.in/]

Spectral Coverage of Running/Planned GW Observatories

[I.H. Park, J. Korean Phys. Soc. 78 (2021) 886]



Back-of-an-Envelope Numbers

Source reduced quadrupole moment

$$Q_S \sim M_S R_S^2$$

Characteristic frequency

$$T_S \sim f_S^{-1} \sim \frac{r_S}{v_S} \sim \frac{c}{r_g}\left(\frac{v_S}{c}\right)\left(\frac{r_g}{r_S}\right) \sim 10^5 \left(\frac{v_S}{c}\right)\left(\frac{r_g}{r_S}\right)\left(\frac{M_\odot}{M_S}\right)$$

$3.63 \cdot 10^{59}$ erg/sec

$$L_{GW} \sim \frac{G}{c^5}(\dddot{Q}_S)^2 \sim \boxed{\frac{G}{c^5}} f_S^6 M_S^2 R_S^4 \sim \frac{c^5}{G}\left(\frac{r_g}{r_S}\right)^2 \left(\frac{v_S}{c}\right)^6 \quad \Longrightarrow$$

…for a SN in the Virgo cluster

$$L_{GW} \sim 3 \cdot 10^2 \; erg \; cm^{-2} \; sec^{-1}$$

compare with

$$L_{EM} \sim 10^{-9} \; erg \; cm^{-2} \; sec^{-1}$$

$$h \sim \frac{G}{c^4}\frac{\ddot{Q}_S}{r} \sim \frac{G}{c^4}\frac{f_S^2 M_S R_S^2}{r} \sim 10^{-19}\left(\frac{v_S}{c}\right)^2 \left(\frac{r_g}{r_S}\right)^{-1} \left(\frac{M_\odot}{M_S}\right)^{-1} \left(\frac{10\ Mpc}{r}\right)$$

…quite **small !!**

Radiation-damping timescale

$$\tau_S \sim \frac{K_S}{L_{GW}} \sim \frac{1}{4}\left(\frac{r_g}{c}\right)\left(\frac{v_S}{c}\right)^{-4}\left(\frac{r_S}{r_g}\right)^2 \sim 10^{-5}\left(\frac{v_S}{c}\right)^{-4}\left(\frac{r_S}{r_g}\right)^2\left(\frac{M_\odot}{M_S}\right)^{-1}$$

…quite **large !!**

HF-GW Sources (& Detectors) ?

- Potential natural HF GW sources have been recently reviewed in [Aggarwal et al., Living Revs. Relativ. 24 (2021) 4]. Present day event-rate estimates are **very* speculative*. In a pragmatic attitude [Cruise, CQG 29 (2012) 095003] it is suggested operating (and improving) available HF-GW detectors to obtain reliable *upper bounds* on HF-GWs of natural origin.

- Laser interferometers designed to detect GWs in the 10-100 MHz range, w. fractional bandwidth $\sim 10^{-3}$ were proposed in [Nishizawa et al., PRD77 (2008) 022002], and prototyped shortly after [Akutsu et al., PRL 101 (2008) 101101].
  Correlation between similar co-located instruments (w. 40m arm-length), originally aimed at probing quantum-geometry spacetime fluctuations [https://holometer.fnal.gov/], has been used to set upper limits on the stochastic GW energy density in the 1-10 MHz band [Chou et al., PRD 95 (2017) 063002], and to rule out harmonic sources above a GW-strain level $\sim 10^{-21}\mathrm{Hz}^{-1/2}$ in that band [Martinez and Kamai, CQG 37 (2020) 205006]. A similar improved prototype is in construction at Cardiff University [Vermeulen et al., CQG 38 (2021) 085008].

- Narrowband HF-GW detectors, based on HF phonon-trapping in bulk-acoustic wave resonators, tunable throughout the HF to UHF band have been prototyped at UWA [Goryachev et al., PRL 127 (2021) 071102; Lasky and Thrtane, **PRD 104 (2021) 103017],** and are (MEGA) under active development [Campbell et al., Sci. Rep.ts (2023) 13:10638] **.**

Rationale

- In a recent CERN (SRGW2021) workshop [https://indico.cern.ch/event/982987], storage-rings/colliders were (re)-considered as potential GW sources/detectors;
- Also, three recent meetings, hosted by the ICTP [https://indico.ictp.it/event/9006/] and CERN [htpps://indico.cern.ch/event/1074510/] focused on high frequency (HF) GWs [https:// indico.cern.ch/event/1257532/];
- These Meetings paved the way for a revived cooperations between Particle Accelerators and GW Physicists. This is *not* new: the intersection between these Communities has *never* been void !
- Indeed, after the 1st observation of the Higgs boson at the LHC (2012), and the 1st direct detection of GWs (2015), both Communities started thinking how to benefit from ideas and technologies developed by the other Party, in particular as regards covering the “blind-spots” of the GW spectrum, so far unexplored;
- A preliminary review of possible synergies and critical directions was attempted by these Authors in a poster presented at the 14th IPAC (2023).

Technology Cross-Breeding Benefits ?

- Is technology cross-breeding between PA and GW promising ?

- Gravitational wave detectors based on *matter* (ultracold Sr atom beams) rather than *light* interferometry may target the 0.01 to 1 Hz spectral range [Dimopoulos et al., Phys. Lett., vol. B678 (2009) 37], and could greatly benefit from existing advanced PA technologies . At least two such experiments are under active development [Badurina et al., J. Cosmol. Astropart. Phys. 5 (2020) 011; Y.A. El-Neaj et al., Eur. Phys. J. Quantum Technol. 7 (2020) 6].

- Housing of a prototype atom-beam interferometer in an LHC access tunnel at CERN is under consideration [Arduini et al., arXiv:2304.00614].

- On the other hand, it has been suggested that GW detector technology achievements, especially in *quantum - limited metrology* [Braginsky and Manukin, *Measurement of Weak Forces in Physics Experiments*, Chicago Univ. Press (1977)] and noise control [Harry et al. (Eds.), *Optical Coatings and Thermal Noise in Precision Measurement*, Cambridge Univ. Press (2012)], may offer new improvements to hadronic/nuclear cross-section measurements [Englert et al., Europhys. Lett. 123 (2018) 41001].

Particle Accelerators as GW Sources/Detectors ?

- ● Old and new ideas on this subject were reviewed at the CERN SRGW-21 (ARIES-WP6) Meeting [Berlin et al., arXiv:2105.00992].

- ● A first analysis of direct (*primary*) synchrotron GW radiation from a storage ring (at $\omega = \omega_{circ}$) was made in [Diambrini-Palazzi and Fargion, Phys. Lett. B197 (1987) 302]. Revised estimates, including *secondary* synchrotron GW radiation produced by photon-graviton) conversion (Gertsenshteyn effect) of the EM synchrotron radiation in a strong magnetic field (at $\omega = \gamma^3\omega_{circ}$) have been discussed by Jowett [https://indico.cern.ch/event/982987/contributions/4270745] and Chen [arXiv:2111.0455734] .

- ○ Betatron motion response to an incoming (high-frequency, plane) GW [Zer-Zion, Astropart. Phys., 14 (2000) 239], its enhancement by proper lattice design, and its possible tuning to a specific steady GW source (e.g., PSR B0531 + 21) have been discussed by Oide [https://indico.cern.ch/event/982987/contributions/4199474/] ;

- ○ A thorough analysis of the noise budget of a GW detector in the mHz band, based on accurate longitudinal orbit-timing has been presented by Rao [Phys. Rev. D102 (2020) 122005; ibid D110 (2024) 022007];

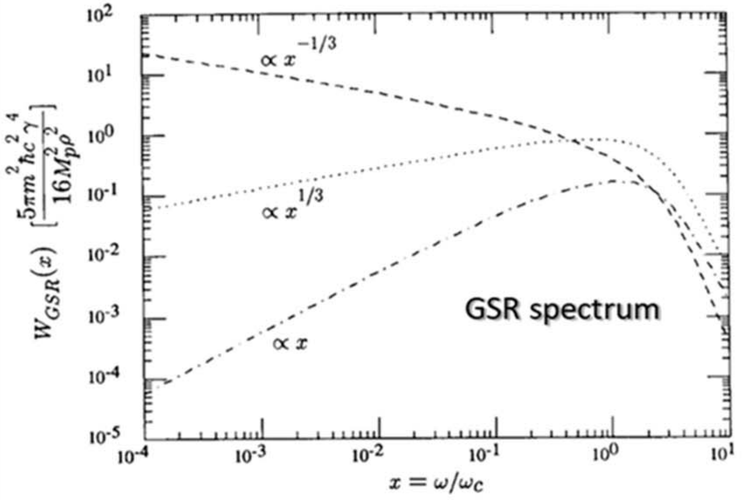
GSR – Orders of Magnitude

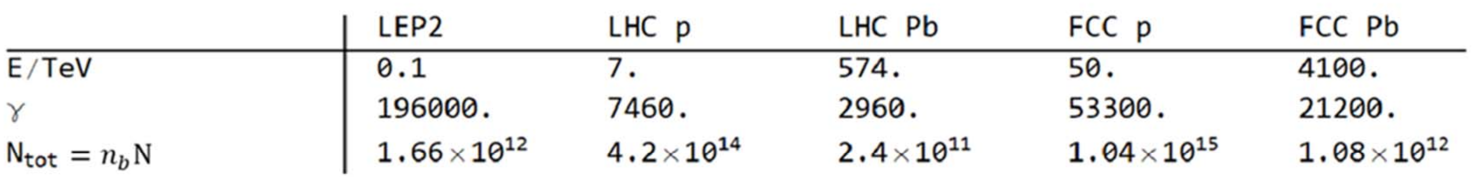
- All n_b particles in a bunch, ad all N bunches (assumed (distributed asymmetrically along the ring) radiate GSR *coherently.*
- Total GSR luminosity : $W_{GSR}^{(tot)} \sim \gamma^4 \left(\frac{m_p}{M_P}\right)^2 \frac{\hbar c^2}{R_{ring}^2}$

  ($M_P \approx 2.17 \cdot 10^{-5}\ g$ being the Planck mass)
- GSR graviton rate : $\dot{N} \sim \gamma^4 \left(n_b N \frac{m_p}{M_P}\right)^2 \frac{c}{R_{ring}}$
- Metric deviation : $h \sim n_b N \cdot \gamma^2 \left(\frac{m_p}{M_P}\right)^2 \frac{R_{ring}}{R}$

  (at distance R from ring)

[P. Chen, 2021]





	LEP2	LHC p	LHC Pb	FCC p	FCC Pb
E/TeV	0.1	7.	574.	50.	4100.
γ	196000.	7460.	2960.	53300.	21200.
$N_{tot} = n_b N$	1.66×10^{12}	4.2×10^{14}	2.4×10^{11}	1.04×10^{15}	1.08×10^{12}

- Jowett has shown that *protons* win vs heavy ions (*Pb*) in terms of P_{GSR} [W]
- *Secondary* GSR would be peaked at *much shorter* (a γ^{-3} factor) wavelengths (down to the IR), and would be fainter by a factor

$$\left(\frac{L_H}{\lambda_c}\frac{H}{H_C}\right)^2 \ll 1 \quad \text{, where} \begin{cases} \lambda_C = \frac{\hbar}{m_p} \text{ is the single-particle Compton wavelength} \\ L_H \text{ is the interaction-length with the mag field } H \\ H_C = \frac{m_p c^3}{e\,\hbar} \text{ is the Schwinger critical field} \end{cases}$$

Gertsen’shtein Effect

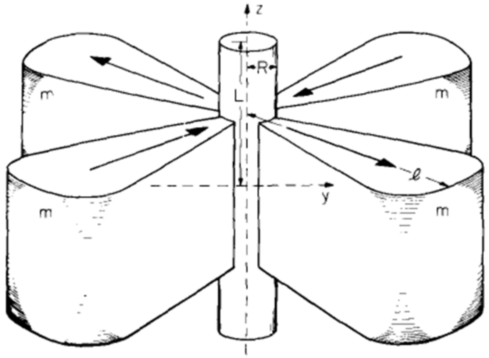
- GW detectors (and sources) based on the direct (and inverse) Gertsen’shtein effect (photon graviton conversion in a static magnetic field [Gertsenshtein, JETP 14 (1962) 84] have been studied in depth and extensively by the Russian School [Braginskii et al., JETP 38 (1974) 865; Гальцов и др., “Излучение гравитационных волн электродинамическими системами,” Издательство МГУ Москва (1984); Grishchuk, ArXiv: gr-qc/0306013 (2003); … ; Gorelik et al., Bull. Lebedev Phys. Inst. 45 (2018) 39; Pustovoit et al., J. Phys. Conf. Ser. 1557 (2020) 012034; Ibid. 2081 (2021) 012009, etc.].

- Different EM detectors of GWs have been proposed (see [A. Berlin et al., PRD 105, (2022) 116011] for a recent review), exploiting the interaction of a GW with the cavity shell, and/or with the vacuum equivalent displacement currents. Depending on the GW frequency, different gauges may be adopted to make the coupling description easier to manage [Rakhmanov, CQG 31 (2014) 085006].

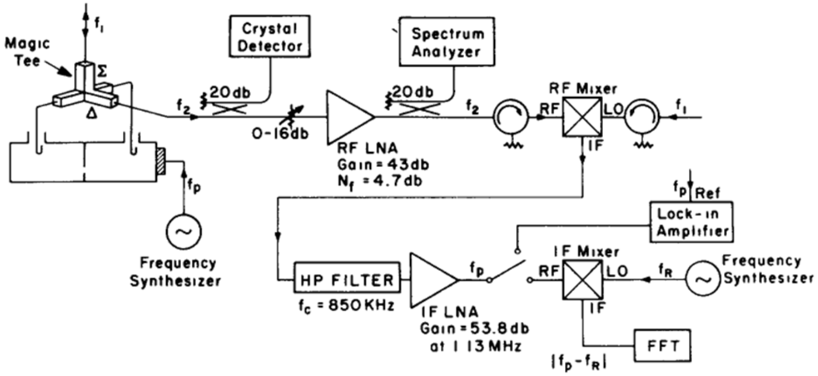
- Both HF and LF detectors based on EM resonators have been analyzed and prototyped [Iacopini et al., Phys. Lett. A73 (1979) 140; Pegoraro et al., Phys. Lett. A68 (1978) 165; Caves, Phys. Lett. B80 (1979) 323; Reece et al., Phys. Lett. A104 (1984) 341; Cruise, CQG 17 (2000) 2525; Ballantini et al., ArXiv:gr-qc/0502054 (2005); Cruise and Ingley, CQG 22 (2005) S479, etc], and are worth renewed interest, in view of important advances in the relevant key technologies.

(see Domcke’s talk)

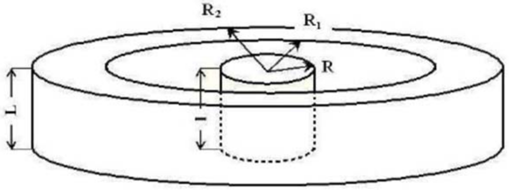
Electrogravitational Coupling Based GW Detectors



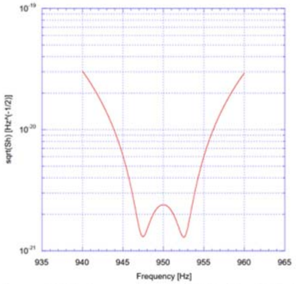
Caves design (1980)



Reece's prototype circuitry (1984)



Grishchuk toroidal design (2003)

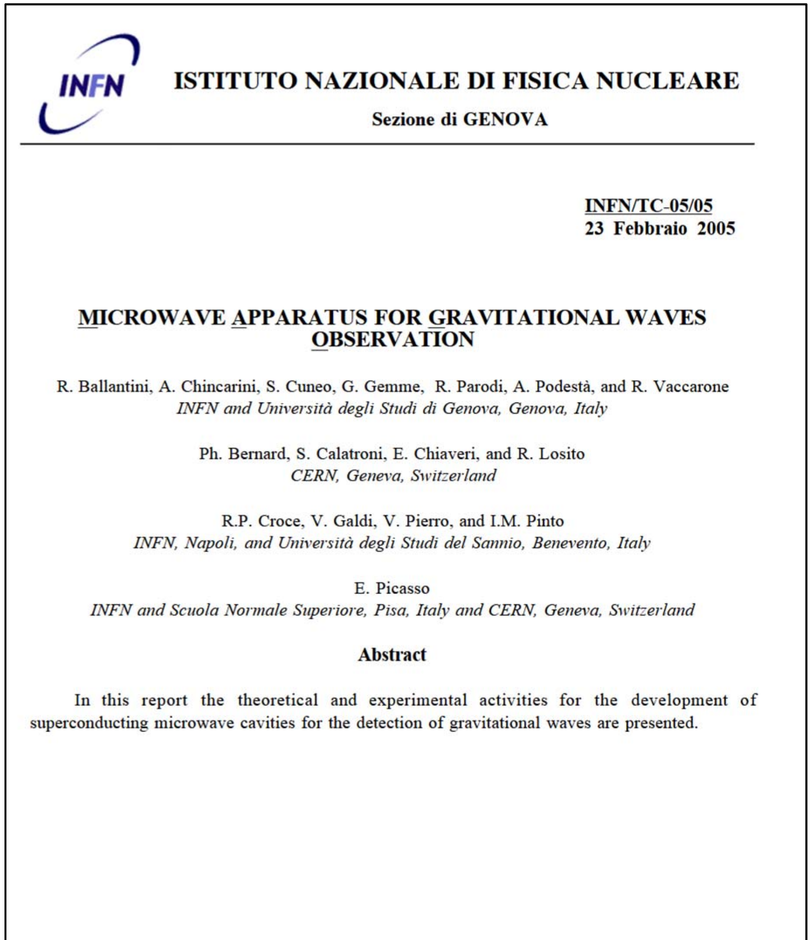


system sensitivity ($\omega_m \approx \omega_2 - \omega_1 \approx 1$ kHz, $Q = 10^{10}$, $Q_m = 10^6$, $T = 1.8$ K, $T_{eq} = 1$ K, stored energy $U \approx 1$ J per cavity)

Ballantini et al. "MAGO" prototype (2005)

- tunable } adjustable (iris) coupler
- bandwidth adjustable
- single or *xylophone* operation
- detailed noise budget analysis

MAGO (2005 ... 2025)



ISTITUTO NAZIONALE DI FISICA NUCLEARE
Sezione di GENOVA

INFN/TC-05/05
23 Febbraio 2005

MICROWAVE APPARATUS FOR GRAVITATIONAL WAVES OBSERVATION

R. Ballantini, A. Chincarini, S. Cuneo, G. Gemme, R. Parodi, A. Podestà, and R. Vaccarone
INFN and Università degli Studi di Genova, Genova, Italy

Ph. Bernard, S. Calatroni, E. Chiaveri, and R. Losito
CERN, Geneva, Switzerland

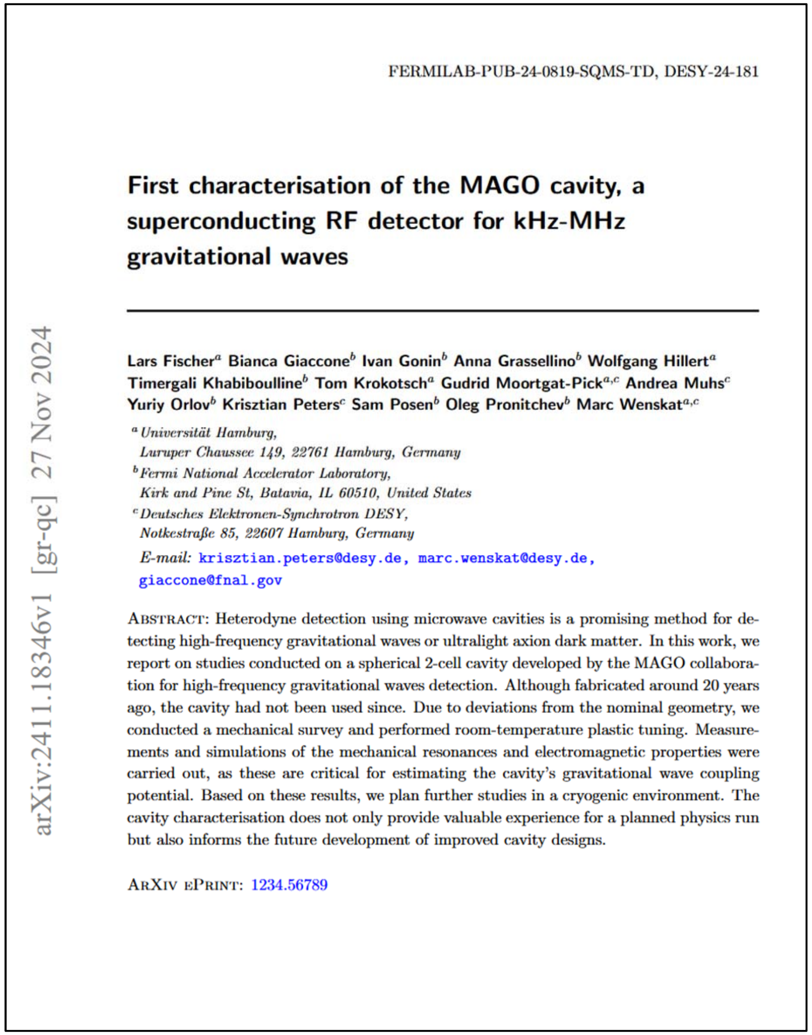
R.P. Croce, V. Galdi, V. Pierro, and I.M. Pinto
INFN, Napoli, and Università degli Studi del Sannio, Benevento, Italy

E. Picasso
INFN and Scuola Normale Superiore, Pisa, Italy and CERN, Geneva, Switzerland

Abstract

In this report the theoretical and experimental activities for the development of superconducting microwave cavities for the detection of gravitational waves are presented.

https://www.openaccessrepository.it/record/20935/files/INFN-TC-05-5.pdf



FERMILAB-PUB-24-0819-SQMS-TD, DESY-24-181

arXiv:2411.18346v1 [gr-qc] 27 Nov 2024

First characterisation of the MAGO cavity, a superconducting RF detector for kHz-MHz gravitational waves

Lars Fischer[a] Bianca Giaccone[b] Ivan Gonin[b] Anna Grassellino[b] Wolfgang Hillert[a] Timergali Khabiboulline[b] Tom Krokotsch[a] Gudrid Moortgat-Pick[a,c] Andrea Muhs[c] Yuriy Orlov[b] Krisztian Peters[c] Sam Posen[b] Oleg Pronitchev[b] Marc Wenskat[a,c]

[a] *Universität Hamburg,*
Luruper Chaussee 149, 22761 Hamburg, Germany
[b] *Fermi National Accelerator Laboratory,*
Kirk and Pine St, Batavia, IL 60510, United States
[c] *Deutsches Elektronen-Synchrotron DESY,*
Notkestraße 85, 22607 Hamburg, Germany

E-mail: `krisztian.peters@desy.de`, `marc.wenskat@desy.de`, `giaccone@fnal.gov`

ABSTRACT: Heterodyne detection using microwave cavities is a promising method for detecting high-frequency gravitational waves or ultralight axion dark matter. In this work, we report on studies conducted on a spherical 2-cell cavity developed by the MAGO collaboration for high-frequency gravitational waves detection. Although fabricated around 20 years ago, the cavity had not been used since. Due to deviations from the nominal geometry, we conducted a mechanical survey and performed room-temperature plastic tuning. Measurements and simulations of the mechanical resonances and electromagnetic properties were carried out, as these are critical for estimating the cavity's gravitational wave coupling potential. Based on these results, we plan further studies in a cryogenic environment. The cavity characterisation does not only provide valuable experience for a planned physics run but also informs the future development of improved cavity designs.

ARXIV EPRINT: 1234.56789

ALP-Experiments as HF-GW Detectors

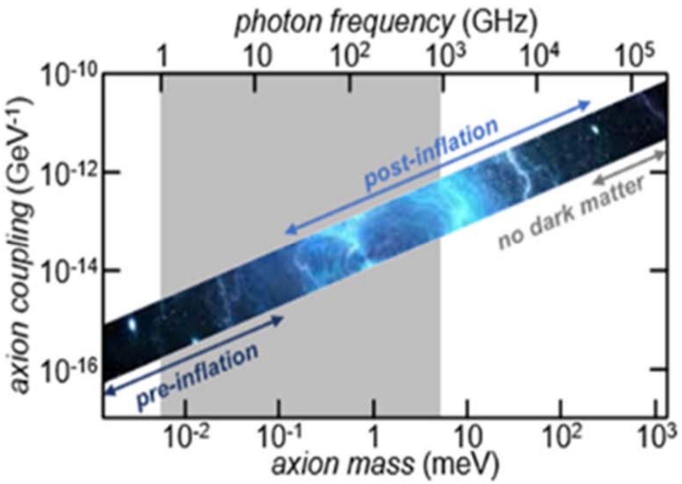
- Remarkably, several experiments aimed at exploring the spectrum of Axion-like particles (ALP) and other candidate dark matter constituents are also based on high-Q EM resonators [Berlin et al., arXiv:2203.12714 (2022)], e.g. in view of the analogy between Gertshensteyn (graviton-photon) and Primakoff (axion-photon) effects [Sikivie et al. PRL 98 (2007) 172002].

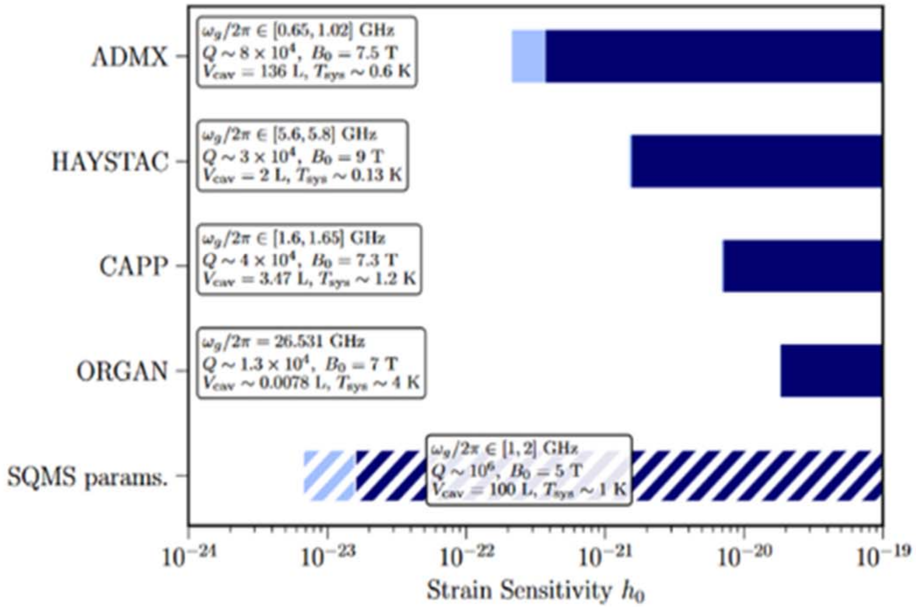
- Hence ALP like experiments may be used to place limits on natural GW radiation in various bands of the HF-GW spectrum, almost at *no added cost* [Domcke et al., PRL 129 (2022) 041101 ; Tobar et al., Symmetry, 14 (2002) 2165].

- Indeed, upper limits on (stochastic) GWs in the frequency bands (2.7 to 14) $\cdot 10^{14}$ Hz and (5 to 12) $\cdot 10^{18}$ Hz , have been already derived from data gathered by ALP detection experiments [Eijili et al. Eur. Phys. J. C79 (2019) 1032].

- The "buy – one – get - one – free" feature of ALP/HF-GW experiment is a strong arrow in the bow for their Proponents.

ALP/HF-GW Experiments (as of Today)





Left: Axion mass, coupling, and photon-frequency (Primakoff-conversion).

The grey zone corresponds to active experiments; the diagonal band to possible QCD generation mechanisms [Paolucci and Giazotto, Instruments 5 (2021) 14].

Right: Extrapolated GW strain sensitivity for some axion experiments [Berlin et al., PRD 105, (2022) 116011]

GW Hertz Experiment ?

- The feasibility of a HF-GW-based Hertz experiment based on direct/inverse Gertsen'-shtein effect has been discussed in [Kolosnitsin and Rudenko, Phys. Scrip. 90 (2015) 074059], including order of magnitude estimates.

(see I. Fomin's talk)

- Back in 1991, in a mantic discussion about the possibility of GW-based Communications (!), John D. Kraus (a father of Radioastronomy) suggested that a key to succeed in such a dream would be *matching* the extremely *low* GW free-space impedance [Kraus, IEEE Antennas Propag. Mag., 33 (1991) 21].

- Twenty years later, Ray W. Chiao suggested that *superconductors* may act as *GW mirrors*, as an effect of WEP violation by Cooper-pairs [Mintner et al., Physica E42 (2010) 234]. Albeit controversial – see Ref. [Bahamonde et al. Int. J. Mod. Phys. D29 (2020) 2043024] for a review and an alternative recent derivation of Chiao's argument .
  If experimentally substantiated, that would be a real game-changer [Chiao et al., ArXiv: 1712.08680 (2017)].

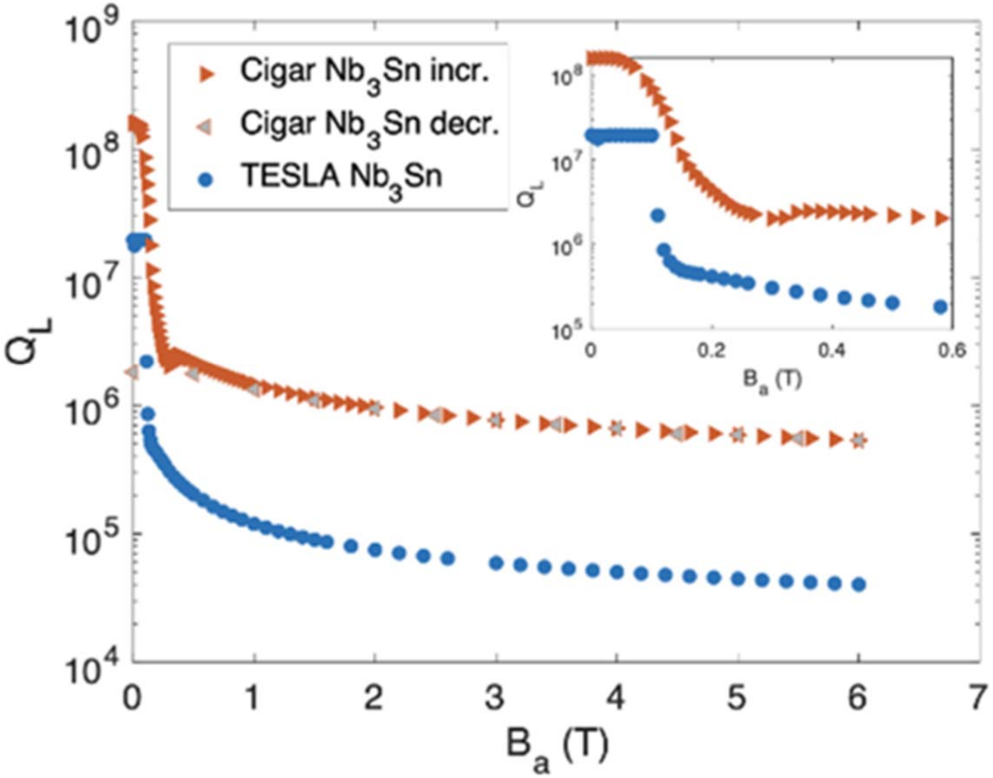
Progress in Critical Technologies for HF-GW

- Superconducting RF Technologies have been crucial for the development of colliders [S. Belomestnykh, Frontiers in Phys., 10 (2022) 933479], and will be a key component for present/future GW/ALP detectors [A. Berlin et al., arXiv:2203.12714 (2022)].
  GHz -SC resonators with $Q > 10^{10}$ are currently manufactured [A. Romanenko et al., Appl. Phys. Lett., 105 (2014) 234103], but cannot operate in strong magnetic fields, as required for GW/ALP experiments. Nb_3Sn or NbTi cavities (in a vortex state) may sustain *large* magnetic fields ($\sim 10T$), with $Q > 10^5$ [S. Posen et al., ArXiv: 2201.10733 (2022)].

- Single Photon Detectors (SPD) are developing along several directions (SNSPD, SPAD, TES). SPDs for THz [O. Astafiev et al., Appl. Phys. Lett. 80 (2002) 4250] and GHz [F. Paolucci, F. Giazotto, Instruments, 5 (2021) 14] operation are now available.

- Large Magnetic Fields. *Steady* operation of *hybrid* (SC/resistive) DC magnets at $\sim$ 45 T has been achieved [S. Hahn et al., Nature 570 (2019), 496, 2019].
  Pulsed fields (15 msec at $\sim 100\ T$) are now routinely produced [https://nationalmaglab.org/]. Localized giant pulsed field ($\sim 10^3\ T$) obtained by (destructive) magnetically-driven implosion have been demonstrated [D. Nakamura et al., Rev. Sci. Instrum. 89 (2018) 095106].

Backup Stuff - Nb_3Sn Cavity in a Strong Magnetic Field



Measured quality factor of Nb_3Sn cigar-shaped resonator vs (increasing or decreasing) magnetic field; measurements on the TESLA cavity are shown for comparison. Close-up in the inset [S. Posen et al., arXiv:2201.10733 (2022)]

Conclusions

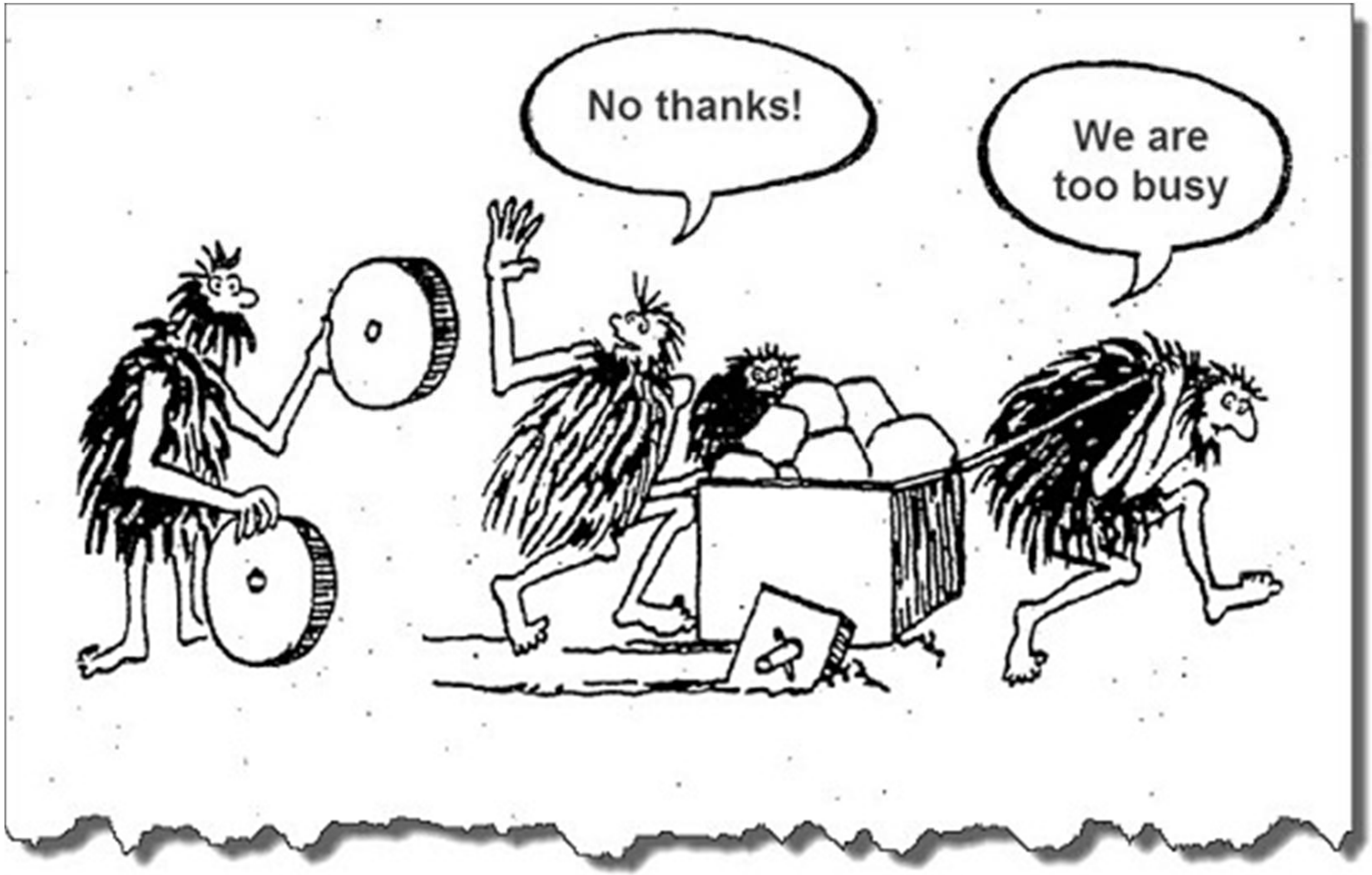
- We are likely facing a revival of mutual interest between the Particle Accelerators and Gravitational Wave Communities;

- This is not surprising : the fathers of LIGO, Virgo and KAGRA came from the world of high-energy/high luminosity colliders;

- Mutual knowledge and Technology breeding may boost both fields;

- The timescale for productive cooperation, and its potential will depend on our courage and good will (as usual !).

New Paradigms May be Hard to Receive …



… but be Worth a Try! …