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Advanced Virgo Plus: Future Perspectives

F Acernese[1,2], M Agathos[3], A Ain[4], S Albanesi[5,6], C Alléné[7], A Allocca[8,2], A Amato[9,10], M Andia[11], T Andrade[12], N Andres[7], M Andrés-Carcasona[13], T Andrić[14], S Ansoldi[15,16], S Antier[17], T Apostolatos[18], E Z Appavuravther[19,20], M Arène[21], N Arnaud[11,22], M Assiduo[23,24], S Assis de Souza Melo[22], P Astone[25], F Aubin[24], S Babak[21], F Badaracco[26], S Bagnasco[6], J Baird[21], T Baka[27], G Ballardin[22], G Baltus[28], B Banerjee[14], P Barneo[12,29], F Barone[30,2], M Barsuglia[21], D Barta[31], A Basti[32,4], M Bawaj[33,19], M Bazzan[34,35], F Beirnaert[36], M Bejger[37], V Benedetto[38], M Berbel[39], S Bernuzzi[3], D Bersanetti[40], A Bertolini[10], U Bhardwaj[41,10], A Bianchi[10,42], M Bilicki[43], S Bini[44,45], M Bischi[23,24], M Bitossi[22,4], M-A Bizouard[17], F Bobba[46,47], M Boër[17], G Bogaert[17], G . Boileau[48,17], M Boldrini[49,25], L D Bonavena[34], R Bondarescu[12], F Bondu[50], R Bonnand[7], V Boschi[4], V Boudart[28], Y Bouffanais[34,35], A Bozzi[22], C Bradaschia[4], M Braglia[51], M Branchesi[14,52], M Breschi[3], T Briant[53], A Brillet[17], J Brooks[22], G Bruno[26], F Bucci[24], O Bulashenko[12,29], T Bulik[54], H J Bulten[10], R Buscicchio[55,56], D Buskulic[7], C Buy[57], G Cabras[15,16], R Cabrita[26], G Cagnoli[58], E Calloni[8,2], M Canepa[59,40], G Caneva[13], M Cannavacciuolo[46], E Capocasa[21], G Carapella[46,47], F Carbognani[22], M Carpinelli[55,60,22], G Carullo[32,4], J Casanueva Diaz[22], C Casentini[61,62], S Caudill[10,27], R Cavalieri[22], G Cella[4], P Cerdá-Durán[63], E Cesarini[62], W Chaibi[17], P Chanial[22,21], E Chassande-Mottin[21], S Chaty[21], P Chessa[32,4], F Chiadini[64,47], G Chiarini[35], R Chierici[65], A Chincarini[40], M L Chiofalo[32,4], A Chiummo[22], N Christensen[17], G Ciani[34,35], P Ciecielag[37], M Cieślar[37], M Cifaldi[61,62], R Ciolfi[66,35], S Clesse[67], F Cleva[17], E Coccia[14,52], E Codazzo[14], P-F Cohadon[53], A Colombo[55,56], M Colpi[55,56], L Conti[35], I Cordero-Carrión[68], S Corezzi[33,19], S Cortese[22], J-P Coulon[17], J-F Coupechoux[65], M Croquette[53], J R Cudell[28], E Cuoco[22,69,4], M Curyło[54], P Dabadie[58], T Dal Canton[11], S Dall'Osso[25], G Dálya[36], B D'Angelo[59,40], S Danilishin[9,10], S D'Antonio[62], V Dattilo[22], M Davier[11], J Degallaix[73], M De Laurentis[8,2], S Deléglise[53], F De Lillo[26], D Dell'Aquila[70,60], W Del Pozzo[32,4], F De Matteis[61,62], A Depasse[26], R De Pietri[71,72], R De Rosa[8,2], C De Rossi[22], R De Simone[64], L Di Fiore[2], C Di Giorgio[46,47], F Di Giovanni[63], M Di Giovanni[14], T Di Girolamo[8,2], D Diksha[10,9], A Di Lieto[32,4], A Di Michele[33], S Di Pace[49,25], I Di Palma[49,25], F Di Renzo[22,4],

L D'Onofrio[8,2], T Dooney[27], O Dorosh[74], M Drago[49,25], J-G Ducoin[75,21], U Dupletsa[14], O Durante[46,47], D D'Urso[70,60], P-A Duverne[11], L Errico[8,2], D Estevez[76], F Fabrizi[23,24], F Faedi[24], V Fafone[61,62,14], G Favaro[34], M Fays[28], E Fenyvesi[31,77], I Ferrante[32,4], F Fidecaro[32,4], P Figura[54], A Fiori[4,32], I Fiori[22], R Fittipaldi[78,47], V Fiumara[79,47], R Flaminio[7,80], J A Font[63,81], S Frasca[49,25], F Frasconi[4], A Freise[10,42], O Freitas[82], G G Fronzé[6], B Gadre[27], R Gamba[3], B Garaventa[40,59], J Garcia-Bellido[51], J Gargiulo [22], F Garufi[8,2], C Gasbarra[61,62], G Gemme[40], A Gennai[4], Archisman Ghosh[36], L Giacoppo[49,25], P Giri[4,32], F Gissi[38], S Gkaitatzis[22], F Glotin[11], B Goncharov[14], M Gosselin[22], R Gouaty[7], A Grado[83,2], M Granata[73], V Granata[46], G Greco[19], G Grignani[33,19], A Grimaldi[44,45], D Guerra[63], D Guetta[25], G M Guidi[23,24], F Gulminelli[84,85], Y Guo[10], P Gupta[10,27], N Gutierrez[73], L Haegel[21], O Halim[16], O Hannuksela[27,10], T Harder[17], K Haris[10,27], T Harmark[86], J Harms[14,52], B Haskell[37], A Heidmann[53], H Heitmann[17], P Hello[11], G Hemming[22], E Hennes[10], J-S Hennig[9,10], M Hennig[9,10], S Hild[9,10], D Hofman[73], N A Holland[10,42], V Hui[7], G A Iandolo[9], B Idzkowski[54], A Iess[69,4], G Iorio[34], P Iosif[87], T Jacqmin[53], P-E Jacquet[53], J Janquart[27,10], K Janssens[48,17], S Jaraba[51], P Jaranowski[88], P Jasal[12], V Juste[76], C Kalaghatgi[27,10,89], C Karathanasis[13], S Katsanevas[22], F Kéfélian[17], G Koekoek[10,9], S Koley[14], M Kolstein[13], S L Kranzhoff[9,10], A Królak[90,74], P Kuijer[10], S Kuroyanagi[51], P Lagabbe[7], D Laghi[57], M Lalleman[48], A Lamberts[17,91], A La Rana[25], I La Rosa[7], A Lartaux-Vollard[11], C Lazzaro[34,35], P Leaci[49,25], A Lemaître[92], M Lenti[24,93], E Leonova[41], N Leroy[11], N Letendre[7], M Lethuillier[65], K Leyde[21], F Linde[89,10], L London[41], A Longo[94], M Lopez Portilla[27], M Lorenzini[61,62], V Loriette[95], G Losurdo[4], D Lumaca[61,62], A Macquet[13,17], C Magazzù[4], R Maggiore[10,42], M Magnozzi[40,59], E Majorana[49,25], N Man[17], V Mangano[49,25], M Mantovani[22], M Mapelli[34,35], F Marchesoni[20,19,96], D Marín Pina[12,29,97], F Marion[7], A Marquina[68], S Marsat[57], F Martelli[23,24], M Martinez[13], V Martinez[58], A Masserot[7], M Mastrodicasa[25], S Mastrogiovanni[17], Q Meijer[27], A Menendez-Vazquez[13], L Mereni[73], M Merzougui[17], A Miani[44,45], C Michel[73], A Miller[26], B Miller[41,10], E Milotti[98,16], Y Minenkov[62], Ll. M Mir[13], M Miravet-Tenés[63], A L Mitchell[10,42], C Mondal[84], M Montani[23,24], F Morawski[37], G Morras[51], B Mours[76], C M Mow-Lowry[10,42], F Muciaccia[49,25], Suvodip Mukherjee[41], A Nagar[6,99], V Napolano[22], I Nardecchia[61,62], H Narola[27], L Naticchioni[25], J Neilson[38,47], S Nesseris[51], C Nguyen[21], G Nieradka[37], S Nissanke[41,10], E Nitoglia[65], F Nocera[22], J Novak[100,101,102,103], J F Nuño Siles[51], M Oertel[100,101,102,104,103], G Oganesyan[14,52], R Oliveri[100,101,102], M Orselli[19,33], C Palomba[25], P T H Pang[10,27], F Pannarale[49,25], F Paoletti[4], A Paoli[22], A Paolone[25,105], G Pappas[87], A Parisi[4,69], D Pascucci[36], A Pasqualetti[22], R Passaquieti[32,4], D Passuello[4], B Patricelli[32,4], R Pedurand[47], R Pegna[4,32], M Pegoraro[35], A Perego[44,45], A Pereira[58], C Périgois[66], A Perreca[44,45], S Perriès[65],

J W Perry[10,42], D Pesios[87], C Petrillo[33], K S Phukon[10,89], O J Piccinni[25,13], M Pichot[17], M Piendibene[32,4], F Piergiovanni[23,24], L Pierini[49,25], G Pierra[65], V Pierro[38,47], G Pillant[22], M Pillas[11], F Pilo[4], L Pinard[73], I M Pinto[38,47,106,8], M Pinto[22], K Piotrzkowski[26], A Placidi[19,33], E Placidi[49,25], W Plastino[107,94], R Poggiani[32,4], E Polini[7], E Porcelli[10], J Portell[12,29,97], E K Porter[21], R Poulton[22], M Pracchia[7], T Pradier[76], M Principe[38,106,47], G A Prodi[108,45], P Prosposito[61,62], A Puecher[10,27], M Punturo[19], F Puosi[4,32], P Puppo[25], G Raaijmakers[41,10], N Radulesco[17], P Rapagnani[49,25], M Razzano[32,4], T Regimbau[7], L Rei[40], P Rettegno[5,6], B Revenu[21,109], A Reza[10], A S Rezaei[25,49], F Ricci[49,25], S Rinaldi[32,4], F Robinet[11], A Rocchi[62], L Rolland[7], M Romanelli[50], R Romano[1,2], A Romero[13], S Ronchini[14,52], L Rosa[2,8], D Rosińska[54], S Roy[27], D Rozza[70,60], P Ruggi[22], E Ruiz Morales[51], P Saffarieh[10,42], O S Salafia[55,56,110], L Salconi[22], F Salemi[44,45], M Sallé[10], A Samajdar[56], N Sanchis-Gual[111,63], A Sanuy[12], A Sasli[87], P Sassi[19,33], B Sassolas[73], S Sayah[73], S Schmidt[27], M Seglar-Arroyo[7], D Sentenac[22], V Sequino[8,2], G Servignat[101], Y Setyawati[27], N S Shcheblanov[112,92], M Sieniawska[26], L Silenzi[19,20], N Singh[54], A Singha[9,10], V Sipala[70,60], J Soldateschi[93,113,24], V Sordini[65], F Sorrentino[40], N Sorrentino[32,4], R Soulard[17], V Spagnuolo[9,10], M Spera[34,35], P Spinicelli[22], C Stachie[17], D A Steer[21], J Steinlechner[9,10], S Steinlechner[9,10], N Stergioulas[87], G Stratta[114,25], M Suchenek[37], A Sur[37], J Suresh[26], B L Swinkels[10], A Syx[76], P Szewczyk[54], M Tacca[10], N Tamanini[57], A J Tanasijczuk[26], E N Tapia San Martín[10], C Taranto[61], M Tonelli[32,4], A Torres-Forné[63], I Tosta e Melo[60], E Tournefier[7], A Trapananti[20,19], F Travasso[20,19], J Trenado[12], M C Tringali[22], L Troiano[115,47], A Trovato[16,98], L Trozzo[2], K W Tsang[10,116,27], K Turbang[117,48], M Turconi[17], C Turski[36], H Ubach[12,29], A Utina[9,10], M Valentini[44,45], S Vallero[6], N van Bakel[10], M van Beuzekom[10], M van Dael[10,118], J F J van den Brand[9,42,10], C Van Den Broeck[27,10], M van der Sluys[10,27], A Van de Walle[11], J van Dongen[10,42], H van Haevermaet[48], J V van Heijningen[26], Z van Ranst[9], N van Remortel[48], M Vardaro[89,10], M Vasúth[31], G Vedovato[35], P Verdier[65], D Verkindt[7], P Verma[74], F Vetrano[23], A Viceré[23,24], J-Y Vinet[17], S Viret[65], A Virtuoso[98,16], H Vocca[33,19], R C Walet[10], M Was[7], N Yadav[37], A Zadrożny[74], T Zelenova[22], and J-P Zendri[35] (The Virgo Collaboration)

[1]Dipartimento di Farmacia, Università di Salerno, I-84084 Fisciano, Salerno, Italy
[2]INFN, Sezione di Napoli, I-80126 Napoli, Italy
[3]Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena, D-07743 Jena, Germany
[4]INFN, Sezione di Pisa, I-56127 Pisa, Italy
[5]Dipartimento di Fisica, Università degli Studi di Torino, I-10125 Torino, Italy
[6]INFN Sezione di Torino, I-10125 Torino, Italy
[7]Univ. Savoie Mont Blanc, CNRS, Laboratoire d'Annecy de Physique des Particules - IN2P3, F-74000 Annecy, France
[8]Università di Napoli "Federico II", I-80126 Napoli, Italy
[9]Maastricht University, 6200 MD Maastricht, Netherlands
[10]Nikhef, 1098 XG Amsterdam, Netherlands

[11]Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France
[12]Institut de Ciències del Cosmos (ICCUB), Universitat de Barcelona (UB), c. Martí i Franquès, 1, 08028 Barcelona, Spain
[13]Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, and ICREA, E-08193 Barcelona, Spain
[14]Gran Sasso Science Institute (GSSI), I-67100 L'Aquila, Italy
[15]Dipartimento di Scienze Matematiche, Informatiche e Fisiche, Università di Udine, I-33100 Udine, Italy
[16]INFN, Sezione di Trieste, I-34127 Trieste, Italy
[17]Université Côte d'Azur, Observatoire Côte d'Azur, CNRS, Artemis, F-06304 Nice, France
[18]Department of Physics, National and Kapodistrian University of Athens, 15771 Ilissia, Greece
[19]INFN, Sezione di Perugia, I-06123 Perugia, Italy
[20]Università di Camerino, I-62032 Camerino, Italy
[21]Université Paris Cité, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France
[22]European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy
[23]Università degli Studi di Urbino "Carlo Bo", I-61029 Urbino, Italy
[24]INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Firenze, Italy
[25]INFN, Sezione di Roma, I-00185 Roma, Italy
[26]Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium
[27]Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University, 3584 CC Utrecht, Netherlands
[28]Université de Liège, B-4000 Liège, Belgium
[29]Departament de Física Quàntica i Astrofísica (FQA), Universitat de Barcelona (UB), c. Martí i Franqués, 1, 08028 Barcelona, Spain
[30]Dipartimento di Medicina, Chirurgia e Odontoiatria "Scuola Medica Salernitana", Università di Salerno, I-84081 Baronissi, Salerno, Italy
[31]Wigner RCP, RMKI, H-1121 Budapest, Hungary
[32]Università di Pisa, I-56127 Pisa, Italy
[33]Università di Perugia, I-06123 Perugia, Italy
[34]Università di Padova, Dipartimento di Fisica e Astronomia, I-35131 Padova, Italy
[35]INFN, Sezione di Padova, I-35131 Padova, Italy
[36]Universiteit Gent, B-9000 Gent, Belgium
[37]Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, 00-716, Warsaw, Poland
[38]Dipartimento di Ingegneria, Università del Sannio, I-82100 Benevento, Italy
[39]Departamento de Matemáticas, Universitat Autònoma de Barcelona, 08193 Bellaterra (Barcelona), Spain
[40]INFN, Sezione di Genova, I-16146 Genova, Italy
[41]GRAPPA, Anton Pannekoek Institute for Astronomy and Institute for High-Energy Physics, University of Amsterdam, 1098 XH Amsterdam, Netherlands
[42]Department of Physics and Astronomy, Vrije Universiteit Amsterdam, 1081 HV Amsterdam, Netherlands
[43]Center for Theoretical Physics, Polish Academy of Sciences, 02-668, Warsaw, Poland
[44]Università di Trento, Dipartimento di Fisica, I-38123 Povo, Trento, Italy
[45]INFN, Trento Institute for Fundamental Physics and Applications, I-38123 Povo, Trento, Italy
[46]Dipartimento di Fisica "E.R. Caianiello", Università di Salerno, I-84084 Fisciano, Salerno, Italy
[47]INFN, Sezione di Napoli, Gruppo Collegato di Salerno, I-80126 Napoli, Italy
[48]Universiteit Antwerpen, 2000 Antwerpen, Belgium
[49]Università di Roma "La Sapienza", I-00185 Roma, Italy
[50]Univ Rennes, CNRS, Institut FOTON - UMR 6082, F-35000 Rennes, France
[51]Instituto de Fisica Teorica UAM-CSIC, Universidad Autonoma de Madrid, 28049 Madrid, Spain
[52]INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi, Italy
[53]Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, F-75005 Paris, France
[54]Astronomical Observatory Warsaw University, 00-478 Warsaw, Poland

[55]Università degli Studi di Milano-Bicocca, I-20126 Milano, Italy
[56]INFN, Sezione di Milano-Bicocca, I-20126 Milano, Italy
[57]L2IT, Laboratoire des 2 Infinis - Toulouse, Université de Toulouse, CNRS/IN2P3, UPS, F-31062 Toulouse Cedex 9, France
[58]Université de Lyon, Université Claude Bernard Lyon 1, CNRS, Institut Lumière Matière, F-69622 Villeurbanne, France
[59]Dipartimento di Fisica, Università degli Studi di Genova, I-16146 Genova, Italy
[60]INFN, Laboratori Nazionali del Sud, I-95125 Catania, Italy
[61]Università di Roma Tor Vergata, I-00133 Roma, Italy
[62]INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy
[63]Departamento de Astronomía y Astrofísica, Universitat de València, E-46100 Burjassot, València, Spain
[64]Dipartimento di Ingegneria Industriale (DIIN), Università di Salerno, I-84084 Fisciano, Salerno, Italy
[65]Université Lyon, Université Claude Bernard Lyon 1, CNRS, IP2I Lyon / IN2P3, UMR 5822, F-69622 Villeurbanne, France
[66]INAF, Osservatorio Astronomico di Padova, I-35122 Padova, Italy
[67]Université libre de Bruxelles, 1050 Bruxelles, Belgium
[68]Departamento de Matemáticas, Universitat de València, E-46100 Burjassot, València, Spain
[69]Scuola Normale Superiore, I-56126 Pisa, Italy
[70]Università degli Studi di Sassari, I-07100 Sassari, Italy
[71]Dipartimento di Scienze Matematiche, Fisiche e Informatiche, Università di Parma, I-43124 Parma, Italy
[72]INFN, Sezione di Milano Bicocca, Gruppo Collegato di Parma, I-43124 Parma, Italy
[73]Université Lyon, Université Claude Bernard Lyon 1, CNRS, Laboratoire des Matériaux Avancés (LMA), IP2I Lyon / IN2P3, UMR 5822, F-69622 Villeurbanne, France
[74]National Center for Nuclear Research, 05-400 Świerk-Otwock, Poland
[75]Institut d'Astrophysique de Paris, Sorbonne Université, CNRS, UMR 7095, 75014 Paris, France
[76]Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
[77]Institute for Nuclear Research, H-4026 Debrecen, Hungary
[78]CNR-SPIN, I-84084 Fisciano, Salerno, Italy
[79]Scuola di Ingegneria, Università della Basilicata, I-85100 Potenza, Italy
[80]Gravitational Wave Science Project, National Astronomical Observatory of Japan (NAOJ), Mitaka City, Tokyo 181-8588, Japan
[81]Observatori Astronòmic, Universitat de València, E-46980 Paterna, València, Spain
[82]Centro de Física das Universidades do Minho e do Porto, Universidade do Minho, PT-4710-057 Braga, Portugal
[83]INAF, Osservatorio Astronomico di Capodimonte, I-80131 Napoli, Italy
[84]Université de Normandie, ENSICAEN, UNICAEN, CNRS/IN2P3, LPC Caen, F-14000 Caen, France
[85]Laboratoire de Physique Corpusculaire Caen, 6 boulevard du maréchal Juin, F-14050 Caen, France
[86]Niels Bohr Institute, Copenhagen University, 2100 København, Denmark
[87]Department of Physics, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece
[88]University of Białystok, 15-424 Białystok, Poland
[89]Institute for High-Energy Physics, University of Amsterdam, 1098 XH Amsterdam, Netherlands
[90]Institute of Mathematics, Polish Academy of Sciences, 00656 Warsaw, Poland
[91]Université Côte d'Azur, Observatoire Côte d'Azur, CNRS, Lagrange, F-06304 Nice, France
[92]NAVIER, École des Ponts, Univ Gustave Eiffel, CNRS, Marne-la-Vallée, France
[93]Università di Firenze, Sesto Fiorentino I-50019, Italy
[94]INFN, Sezione di Roma Tre, I-00146 Roma, Italy
[95]ESPCI, CNRS, F-75005 Paris, France
[96]School of Physics Science and Engineering, Tongji University, Shanghai 200092, China
[97]Institut d'Estudis Espacials de Catalunya, c. Gran Capità, 2-4, 08034 Barcelona, Spain
[98]Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy
[99]Institut des Hautes Etudes Scientifiques, F-91440 Bures-sur-Yvette, France
[100]Centre national de la recherche scientifique, 75016 Paris, France

[101]Laboratoire Univers et Théories, Observatoire de Paris, 92190 Meudon, France
[102]Observatoire de Paris, 75014 Paris, France
[103]Université PSL, 75006 Paris, France
[104]Université de Paris, 75006 Paris, France
[105]Consiglio Nazionale delle Ricerche - Istituto dei Sistemi Complessi, I-00185 Roma, Italy
[106]Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", I-00184 Roma, Italy
[107]Dipartimento di Matematica e Fisica, Università degli Studi Roma Tre, I-00146 Roma, Italy
[108]Università di Trento, Dipartimento di Matematica, I-38123 Povo, Trento, Italy
[109]Subatech, CNRS/IN2P3 - Institut Mines-Telecom Atlantique - Université de Nantes, 4 rue Alfred Kastler BP 20722 44307 Nantes C'EDEX 03, France
[110]INAF, Osservatorio Astronomico di Brera sede di Merate, I-23807 Merate, Lecco, Italy
[111]Departamento de Matemática da Universidade de Aveiro and Centre for Research and Development in Mathematics and Applications, 3810-183 Aveiro, Portugal
[112]Laboratoire MSME, Cité Descartes, 5 Boulevard Descartes, Champs-sur-Marne, 77454 Marne-la-Vallée Cedex 2, France
[113]INAF, Osservatorio Astrofisico di Arcetri, I-50125 Firenze, Italy
[114]Istituto di Astrofisica e Planetologia Spaziali di Roma, 00133 Roma, Italy
[115]Dipartimento di Scienze Aziendali - Management and Innovation Systems (DISA-MIS), Università di Salerno, I-84084 Fisciano, Salerno, Italy
[116]Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, 9747 AG Groningen, Netherlands
[117]Vrije Universiteit Brussel, 1050 Brussel, Belgium
[118]Eindhoven University of Technology, 5600 MB Eindhoven, Netherlands

E-mail: `antonino.chiummo@ego-gw.it`

Abstract. While completing the commissioning phase to prepare the Virgo interferometer for the next joint Observation Run (O4), the Virgo collaboration is also finalizing the design of the next upgrades to the detector to be employed in the following Observation Run (O5). The major upgrade will concern decreasing the thermal noise limit, which will imply using very large test masses and increased laser beam size. But this will not be the only upgrade to be implemented in the break between the O4 and O5 observation runs to increase the Virgo detector strain sensitivity. The paper will cover the challenges linked to this upgrade and implications on the detector's reach and observational potential, reflecting the talk given at 12th Cosmic Ray International Seminar - CRIS 2022 held in September 2022 in Napoli.

1. Introduction

The Advanced Virgo Gravitational Wave Antenna is a kilometer-scale, Fabry-Perot-enhanced, dual recycled Michelson interferometer located in Italy, close to Pisa [1]. The Advanced Virgo interferometer has detected, together with the two LIGO interferometers located in the USA [2], an impressive collection of Gravitational Wave (GW) emissions from Astronomical sources in the last observation runs O2 and O3. Indeed, during the O2 observation run, just after the joining of the Advanced Virgo detector to the GW-antenna network, a triple coincidence signal was observed by the three detectors. Such a signal triggered the observations of an Electromagnetic counterpart which was the first Multi-messenger event (GW170817,[3]). Furthermore, during the last observation run (O3), which lasted about one year of data taking from April 2019 to March 2020, about 80 gravitational waves were also detected by the joint GW detector network LIGO-Virgo.

Even an ideal interferometer will encounter limits to its strain sensitivity which are dictated by Physics laws or by the fact that it is ground-based. For instance, even with ideal isolation from seismic noise, the low-frequency region of the strain sensitivity will be limited by the displacement noise of the mass distribution around the interferometer test-masses: the Newtonian Noise [4]. At some frequencies (around 40 Hz for current technologies and configuration) the Newtonian

Noise is overcome by another fundamental noise: the thermal vibration noise of the test-mass mirror surfaces. This noise is due to the coating mechanical friction and is sensed by the laser beam wave front reflected off the test masses [5]. At higher frequencies, it is the Quantum nature of the light which eventually sets a limit to the faintest possible signal an interferometer is able to detect [6].

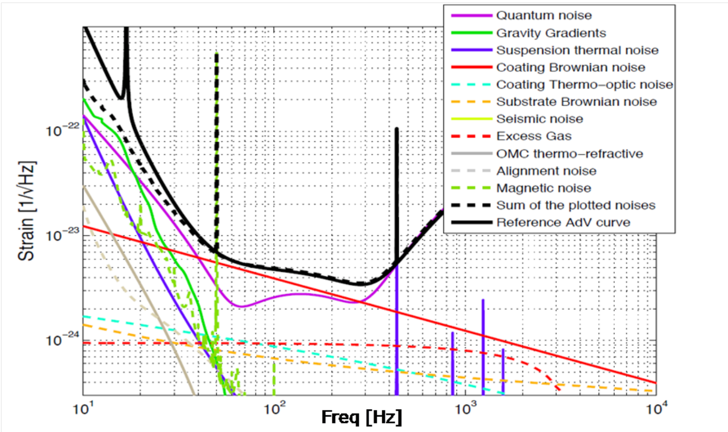

Figure 1. An example of the limiting noises in a dual recycled GW interferometer. The cumulative power spectral density for the residual strain noise is plotted against frequency for the detection bandwidth. The breakdown of the noise budget is computed via GWINC. From the Advanced Virgo Technical Design Report [7]

After the O3 observation run, the Advanced Virgo detector started its upgrade to the Advanced Virgo Plus (AdV+) configuration to further improve the sensitivity [8]. These improvements concerned both the residual technical noises and the impact of fundamental noises. It is staged in two phases: the phase 1 aims to reduce the quantum noise affecting the interferometer and make the thermal noise the ultimate limit of the Virgo sensitivity. This phase will be completed before the foreseen O4 run, together with the LIGO and Kagra detectors, which is currently due to start in March 2023 [9].
A second phase will then start after the completion of the Observation Run 4 (O4) and will be aimed to reduce the impact of the thermal noise on the AdV+ strain sensitivity. It will be completed by the beginning of the Observation Run 5 (O5), currently foreseen at the beginning of 2026.

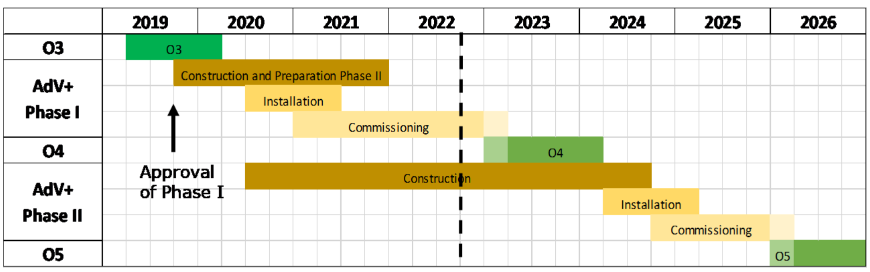

Figure 2. The schedule for the two-staged Advanced Virgo Plus project. In the first phase the aim is to reduce the quantum noise and hit the thermal noise wall, while in the second phase the thermal noise impact on the interferometers gets reduced.

2. The second phase of the Advanced Virgo Plus Project

In order to push down the limit imposed by the thermal noise to the sensitivity, a combination of approaches can be used: 1) reduce the thermal noise source by a) going to cryogenic temperatures, b) reducing the mechanical friction inside the coating; and 2) improve the optical design so that the interferometer is less sensitive to the thermal noise, as described in [5]:

$$S_x(f) \propto \frac{Td}{w^2}\left(\frac{Y_C}{Y_S}+\frac{Y_S}{Y_C}\right)\phi_C \tag{1}$$

where $S_x(f)$ is the power spectral density of the strain noise due to the displacement noise of the mirror surface, T the equilibrium temperature, d the coating thickness, w the Gaussian beam radius on the mirror, Y_S and Y_C the Young moduli of the substrate and coating materials, and ϕ_C the mechanical loss angle of the coating stack. While the solution 1a) is enticing, its deployment means a very invasive hardware change and it is not mature enough in terms of technology for the GW interferometers. The chosen approach for AdV+ phase II is then to improve the coating loss angle ϕ_C and enlarge the beam size. The beam size will be significantly enlarged only on the end test masses (ETMs) where the reflectivity requirements imply a large number of coating layers [10].

2.1. *Implication of a larger beam: a tighter control for less stable resonators*

The design of a larger beam on the ETMs has a large impact on the whole detector. The most obvious is that also the diameters of the ETM mirrors have to be proportionally enlarged. In the design of the arm Fabry-Perot resonator to obtain the large beam on the ETMs, the proven substrate production capabilities, the vacuum link apertures and the interferometer sensing and control were into account. The size of the ETMs was decided to be 55 cm diameter (from the current 35 cm), equal in size as the currently used beam-splitter mirror in Advanced Virgo, while keeping the current thickness of 20 cm, so resulting in a mass of roughly 100 Kg from the current 42 Kg. The size of the beam which can be allocated on the new ETMs was therefore increased to 96 mm from the current 58 mm.
The radii of curvature (RoC) for both the ETMs and the Input Test Mass (ITM) mirrors were adjusted to provide such an eigenmode for the arm Fabry-Perot: the ETM RoC is 1683 m for AdV+ phase I and will be 1969 m for phase II, while the ITM RoC will change from the current 1420 m to a shorter 1067 m. Also the RoC of the recycling mirrors will have to adapt to these values, and in turn all the mode-matching telescopes at the ports of the interferometers will have to be modified. A consequence of this revised design is that arm Fabry-Perot resonator will have a cavity g-factor closer to the 1 [11], so closer to optical instability region, requiring not only more stringent control of the optical aberrations and figure errors of the core optics, but also a more demanding angular control during the interferometer operations.
The Thermal Compensation System (TCS) will also play a major role in controlling the aberrations induced by the high power circulating in the interferometer [12]. Indeed the foreseen injected power will be of the order of 80 W, a factor two larger than what expected for phase I. In order to cope with the more delicate inteferometer, a large upgrade of the TCS is foreseen both in terms of actuators (thermal projectors, CO_2 lasers, ring heater for correcting core-optics RoC) and sensors (Phase cameras and Hartman Wavefront sensors).

2.2. *Mirrors and coatings*

The larger beam will be accommodated on larger ETMs. The substrates for producing such mirrors have already been procured and the polishing started in December 2021. This is a very delicate and long process to ensure that the surface error is within the tight requirements. Several upgrades at the Laboratoire des Matériaux Avancés are then needed to properly coat these substrates, including the tools for handling the substrates, the upgrades of the Grand Coater machine, the improvements for the cleaning tools. Also the metrology needs to be largely upgraded, in order to provide increased accuracy for the scattering, absorption, and geometry measurements.

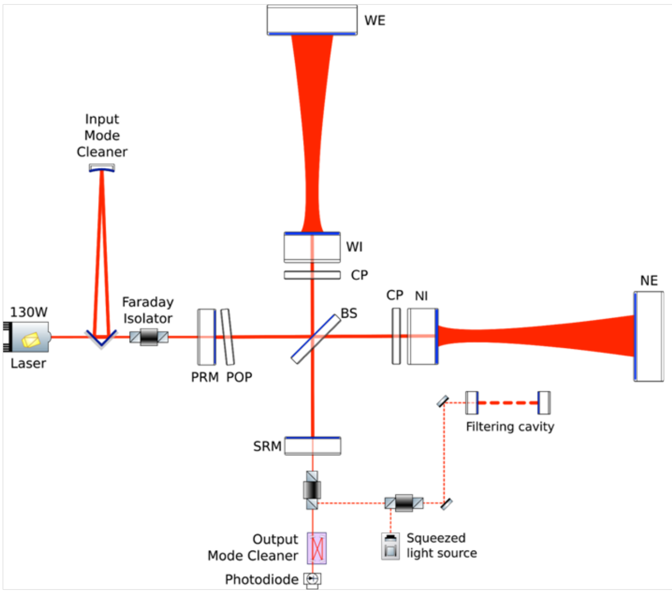

Figure 3. Simplified optical scheme for the second phase of AdV+. With respect to the first phase of the project, the main modification will be the enlargement of the End Mirrors of the Fabry-Perot resonators and the related implications [9, 8].

The coating material development is one of the other pillar activity to reduce the thermal noise impact on the interferometer sensitivity. Indeed the research and development for the coating has eventually become a joint activity between LIGO and Virgo collaborations, in the common interest of reaching a better sensitivity for the whole network. Promising results in terms of optical and mechanical properties have been achieved by studying $TiO_2 : GeO_2/SiO_2$ stacks: first monolayer and multi-layers coating were produced at the LMA Grand Coater and the final choice of the coating design will be taken jointly by LIGO and Virgo collaborations in a few months.

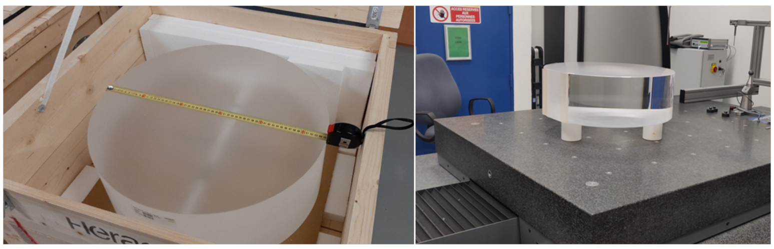

Figure 4. The large substrates for the phase II test masses. The Fused Silica substrates will be used to made the 55cm-large End Mirrors needed in the phase two.

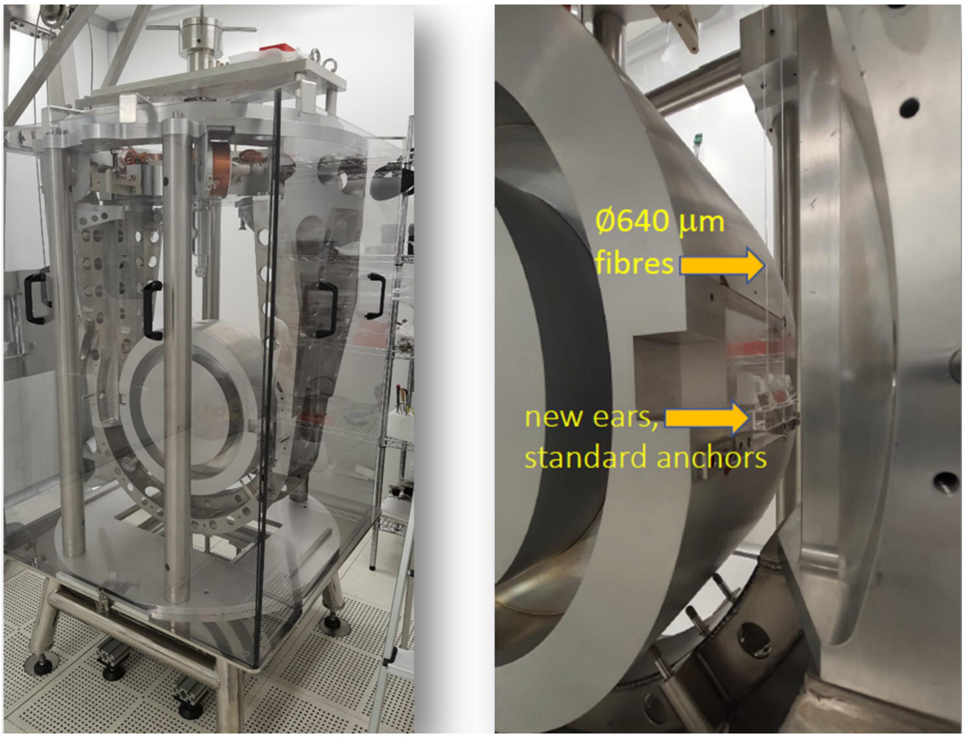

Figure 5. The prototype payload for phase II large masses has been assembled and it is under the test phase, including the 640 μm thick fused silica fibers which will hold the real mirror.

2.3. Large mirrors, large payloads, large super-attenuators

These mirrors will have anyway to be suspended and isolated from the external environment, so requiring a largely modified payload and super-attenuator [13] to host them. The payload for the ETMs has beam strongly modified with the goal of suspending a 100 kg mirror. The first prototype already demonstrated to be able to carry this kind of mirror, including the development and installation of prototype fused silica fibers of 640 μm diameter holding a dummy 100 kg cylinder. Also the super-attenuator design is roughly completed, and a prototype with revised elastic elements is under construction and validation.

3. Conclusions

While completing the commissioning to join the O4 run together with LIGO, the Virgo Collaboration is preparing the upgrade for the next observation run O5. This upgrade is designed to bring an increase of the inteferometer reach by almost a factor three with respect to the phase I (almost an order magnitude more in terms of explored volume). For this purpose, the main throttle will be to push down the thermal noise limiting the strain sensitivity at mid-band, where the detector has its peak sensitivity. This will be achieved with a two-fold approach: reduce the source of the thermal noise via engineering of the coating material and technique and with a new optical design, which will be less sensitive to this kind of noise.

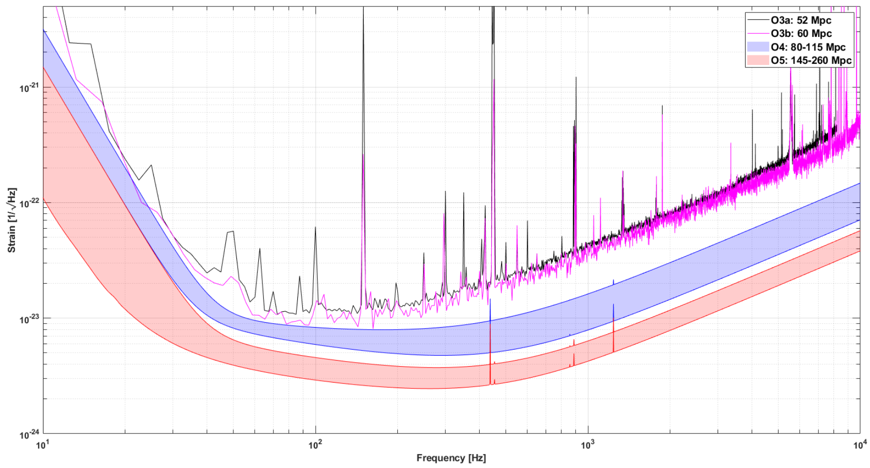

Figure 6. Expected evolution of Advanced Virgo sensitivity. The solid lines are the measured strain residual noise for O3 (range of 60Mpc) while the two bands identify the target for O4 (blue area, range 80-115Mpc), and O5 (pink area, range 145-260Mpc).

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