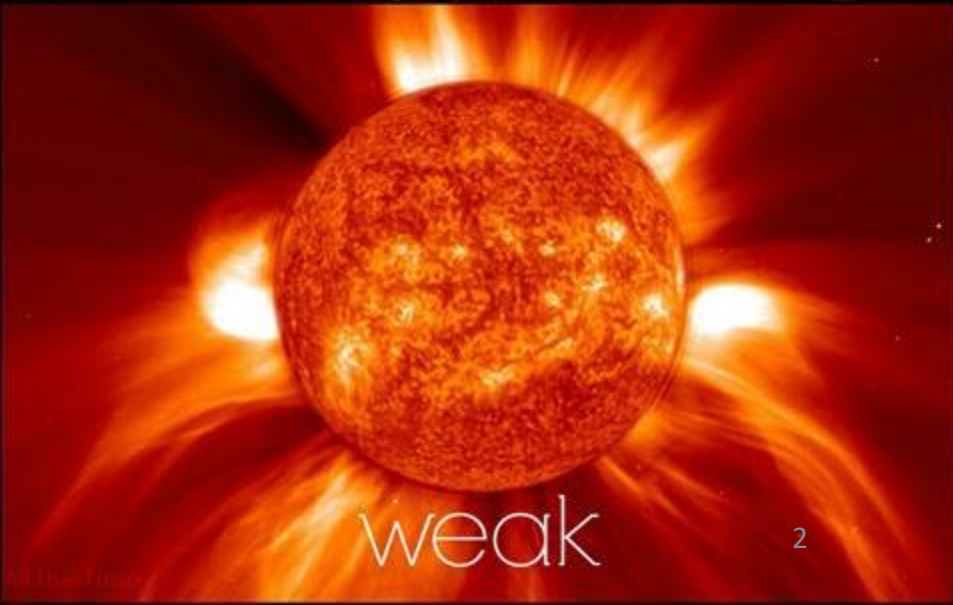
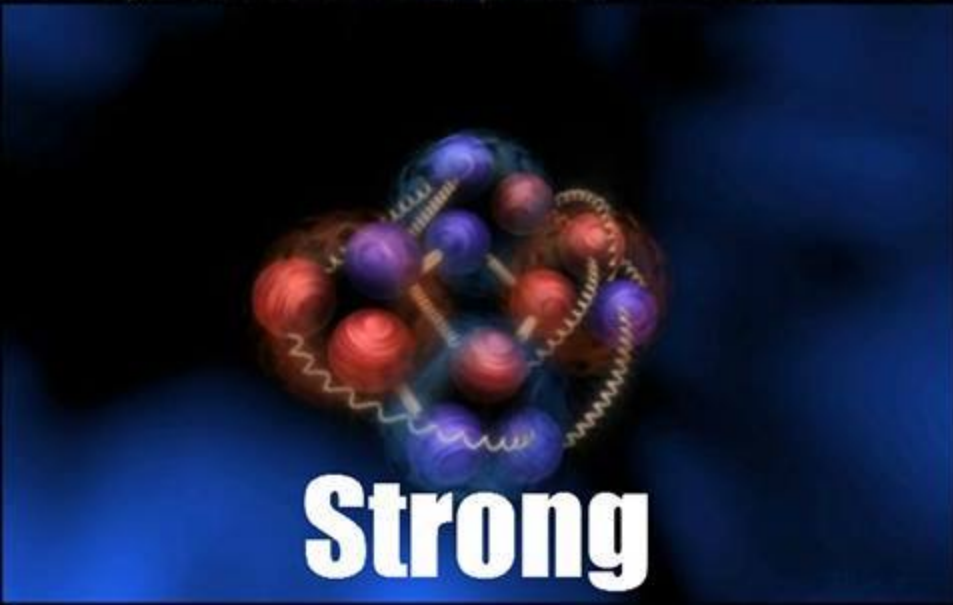
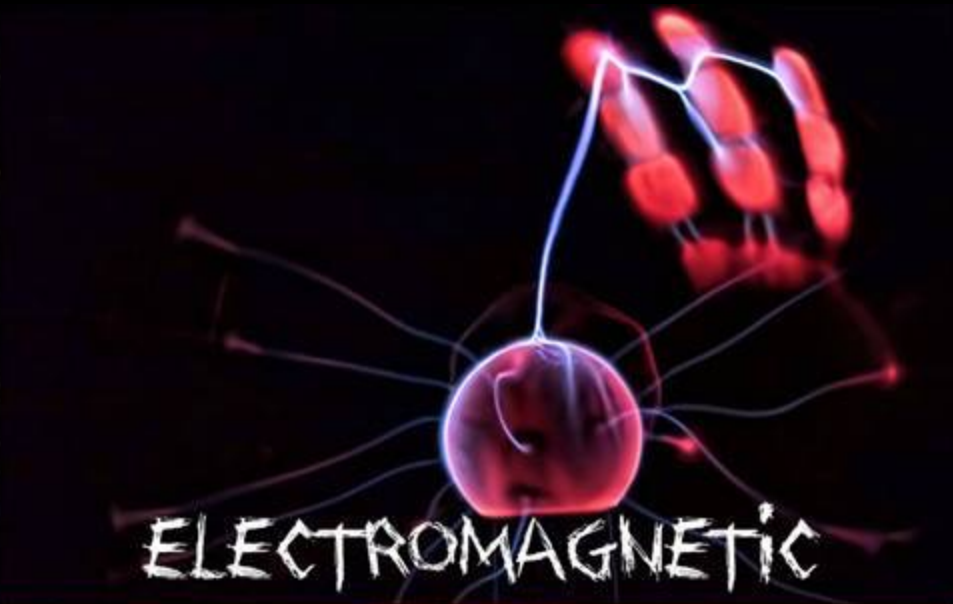




Astroparticle physics and Gravitational Waves

Gwenhael de Wasseige
on behalf of the teams

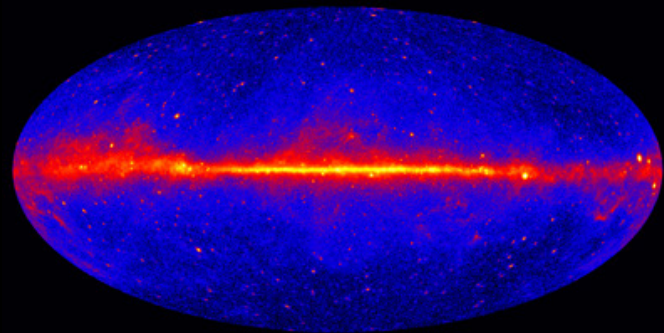
Essence of research in physics at IRMP



The new twist

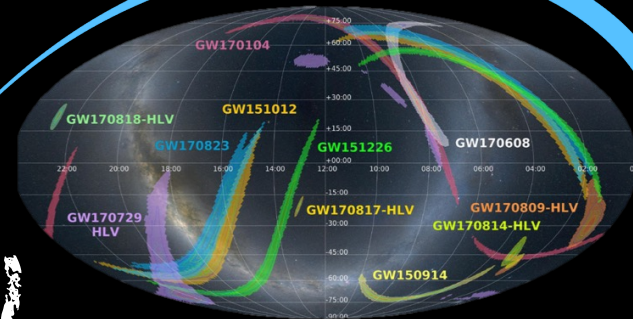


The new twist



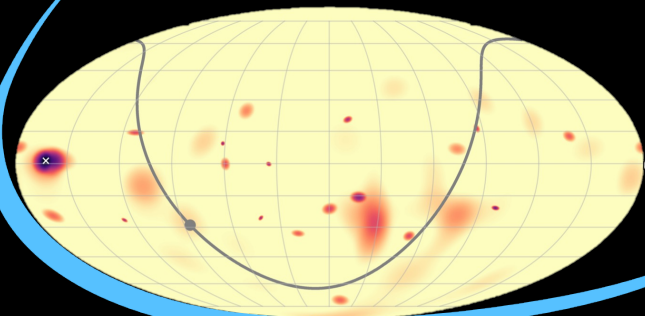
Electromagnetic waves

γ



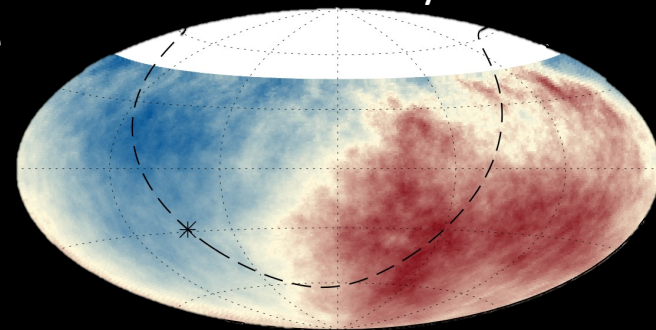
GW

Gravitational waves



Neutrinos

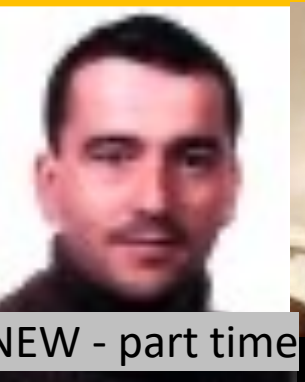
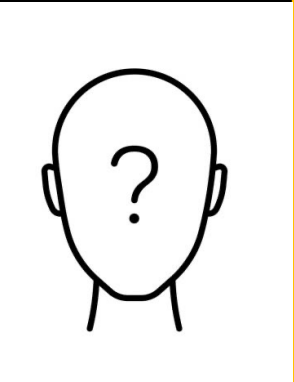
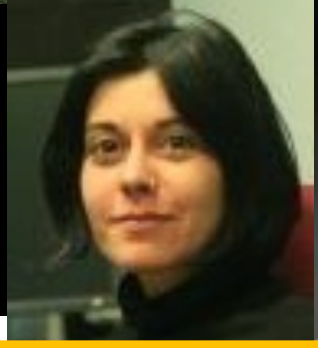
ν



Cosmic Rays

CR

IRMP



NEW - part time

NEW

Gravitational waves (GW)

Neutrinos (ν)

5 PhD students

3 postdocs

0.5 PAT/LR FTE
(0.2 from EU fundings)

1 academics
(+ 1 in 2024)

4 PhD students

4 postdocs

<0.1 PAT/LR FTE

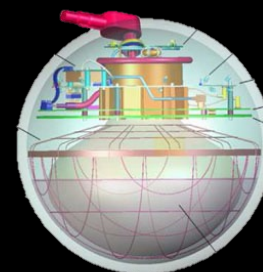
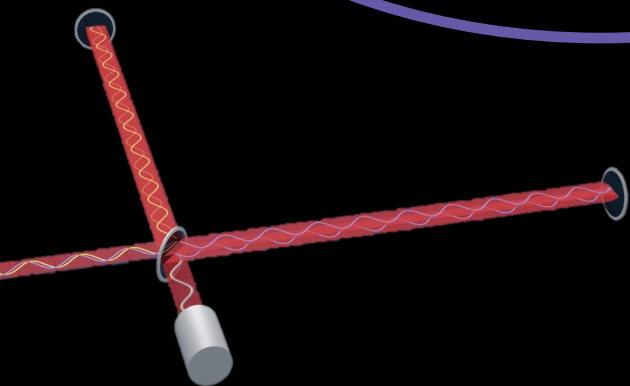
1 academics
(+ VL part time)

1 PhD student in
2024

1 postdoc



Members of:
one collaboration 'GW'
+ one collaboration 'Neutrinos'



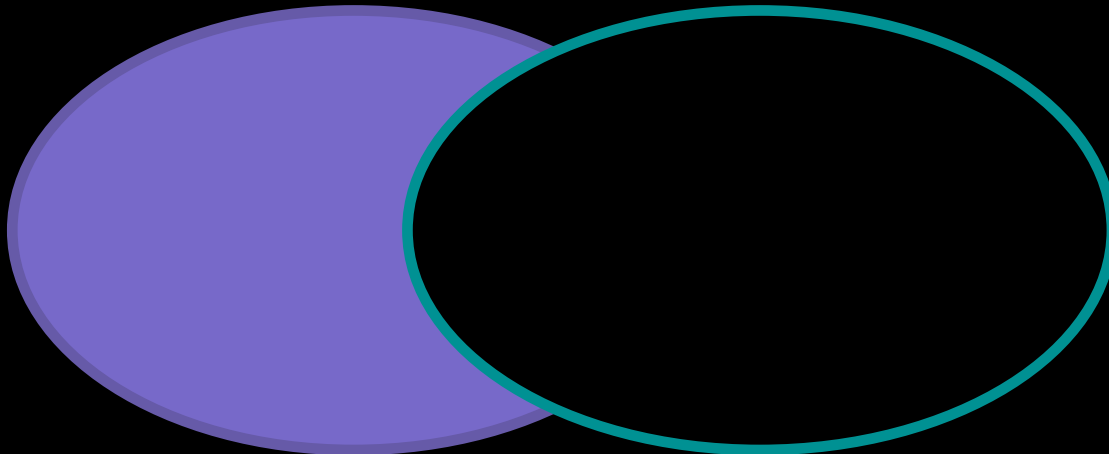
Members of Virgo and/or Einstein Telescope

Members of IceCube and/or KM3NeT

Gravitational waves

Gravitational waves (GW)

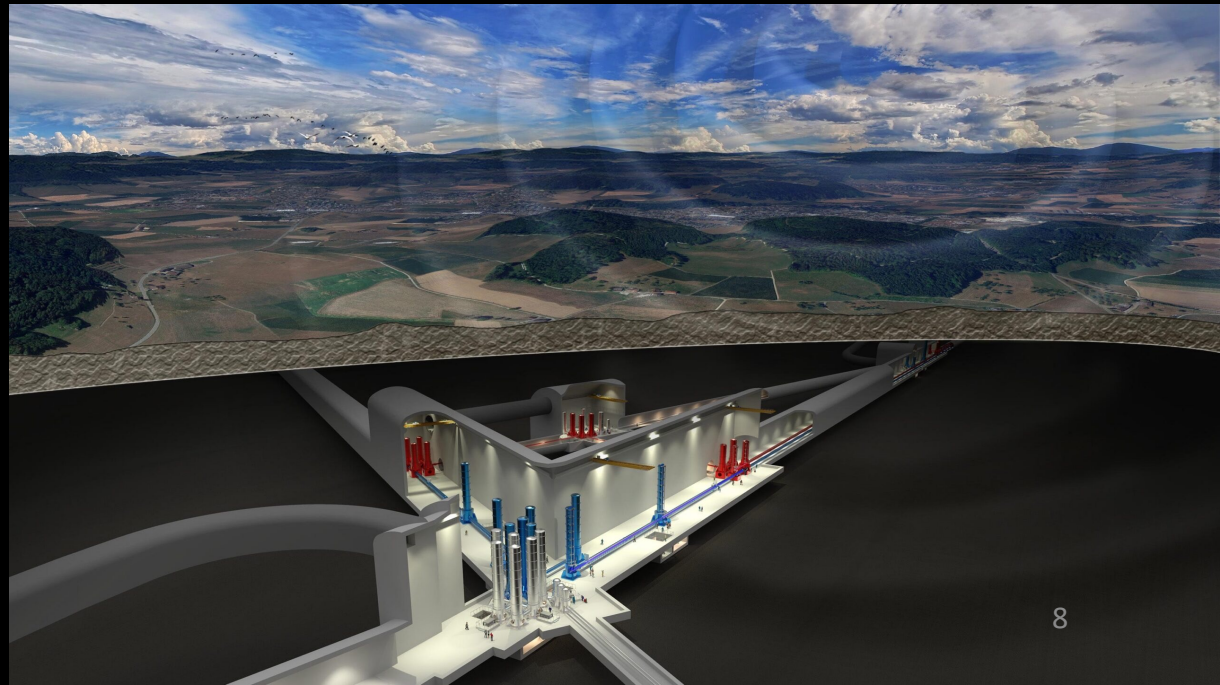
Neutrinos (ν)





Virgo, Italy
Currently taking data

Einstein Telescope
Future interferometer



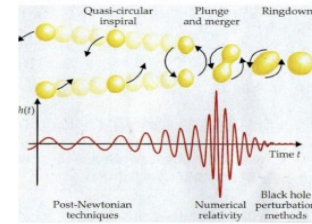
GW group - started in mid 2018

- **Permanent staff full-time on GW science:**
 - **G. Bruno**
 - From Sept 2024 : Justin Janquart (50% UCLouvain, 50% Royal Observatory of Belgium) specializing in GW physics data analysis.
 - From Sept 2024 : new “Logisticien de recherche” (not yet known; selection ongoing)
 - To replace Dr J. van Heijningen, who moved to Amsterdam (VUA) for a professorship in Oct 2023
 - To collaborate mostly with G. Bruno and C. Lauzin (NAPS) on instrumentation.
- **Postdocs:** D. Agarwal, J. Suresh and M. Vereecken (shared with the neutrino group)
Former: F. Badaracco, E. Ferreira, A. Miller, M. Sieniawska
- **PhD students:** R. Cabrita, F. De Lillo, A. Depasse, S. Venikoudis, M. Zeoli
- **Permanent staff at UCLouvain (or ROB) collaborating part-time on GW-related projects:**
 - Prof. C. Lauzin (IMCN institute - lasers and optics)
 - Dr A. Tanasijczuk (IRMP - computing, chair of the ET software and framework division)
 - Dr C. Arina (IRMP - research project coordination; EU InfraDev “ET-PP” chair of “Financial architecture” WP)
 - Prof. G. de Wasseige (IRMP - neutrino astronomy IceCube and KM3NeT; joint project on GW-neutrino coincident search)
 - Prof L. Jacques (ICTM institute - signal treatment, machine learning, signal deconvolution) – New
 - Dr B. Bertrand and Dr P. Defraigne (Royal Observatory of Belgium - atomic clocks on Earth and on satellites for tests of fundamental physics) – New

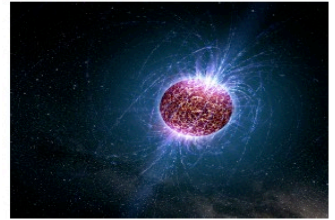
GW - Data analysis

- **Continuous Waves**
- **Stochastic background**
- **Multi-Messenger**

Merging neutron stars or black holes



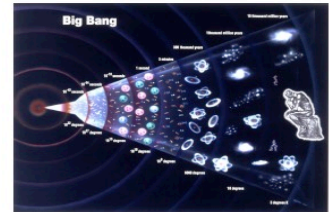
Asymmetric, fast-spinning neutron stars



Supernovae



Primordial gravitational waves



GW - Data analysis

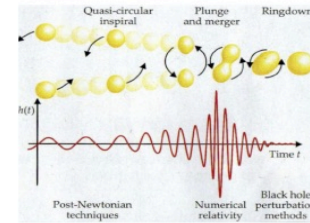
- **Continuous Waves**

- Several flagship analyses, Ultra-light DM, galactic center excess, extreme-ratio binaries , parallax for BNS, planetary-mass PBH
- **People:** A. Miller, M. Sieniawska, A. Depasse

- **Stochastic background**

- **Multi-Messenger**

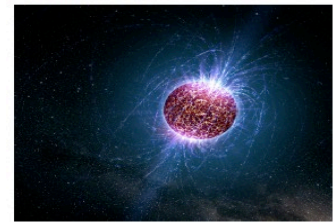
Merging neutron stars or black holes



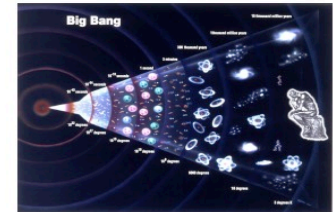
Supernovae



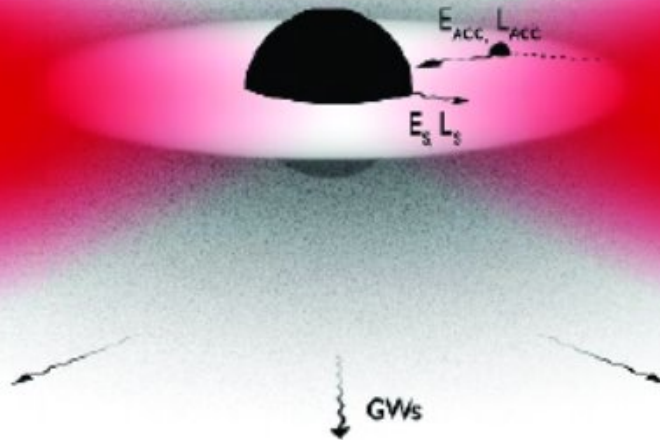
Asymmetric, fast-spinning neutron stars



Primordial gravitational waves



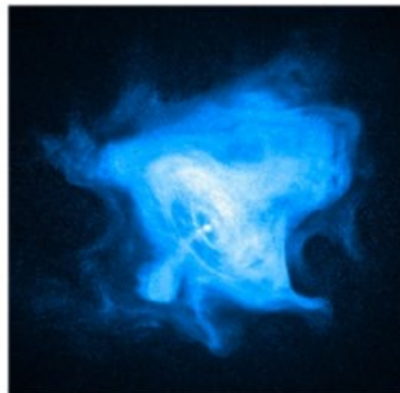
Searching for new physics



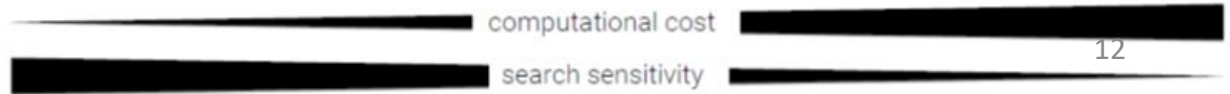
targeted search
known pulsars

directed search
known neutron stars

all-sky search
minimal assumptions



∩_(ツ)_∩



GW - Data analysis

• Continuous Waves

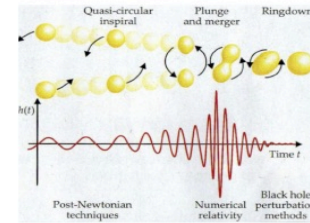
- Several flagship analyses, Ultra-light DM, galactic center excess, extreme-ratio binaries, parallax for BNS, planetary-mass PBH
- **People:** A. Miller, M. Sieniawska, A. Depasse

• Stochastic background

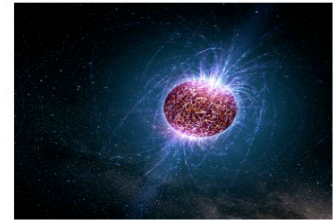
- Flagship anisotropic search, correlations with EM tracers, multiple SGWB components, MDC, pulsar glitches, SGWB from PBH (with CBC)
- **People:** D. Agarwal, F. De Lillo, J. Suresh [*anisotropic searches chair*], S. Venikoudis

• Multi-Messenger

Merging neutron stars or black holes



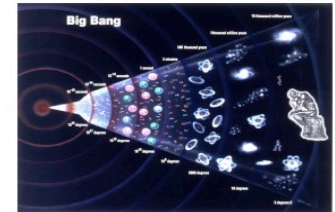
Asymmetric, fast-spinning neutron stars



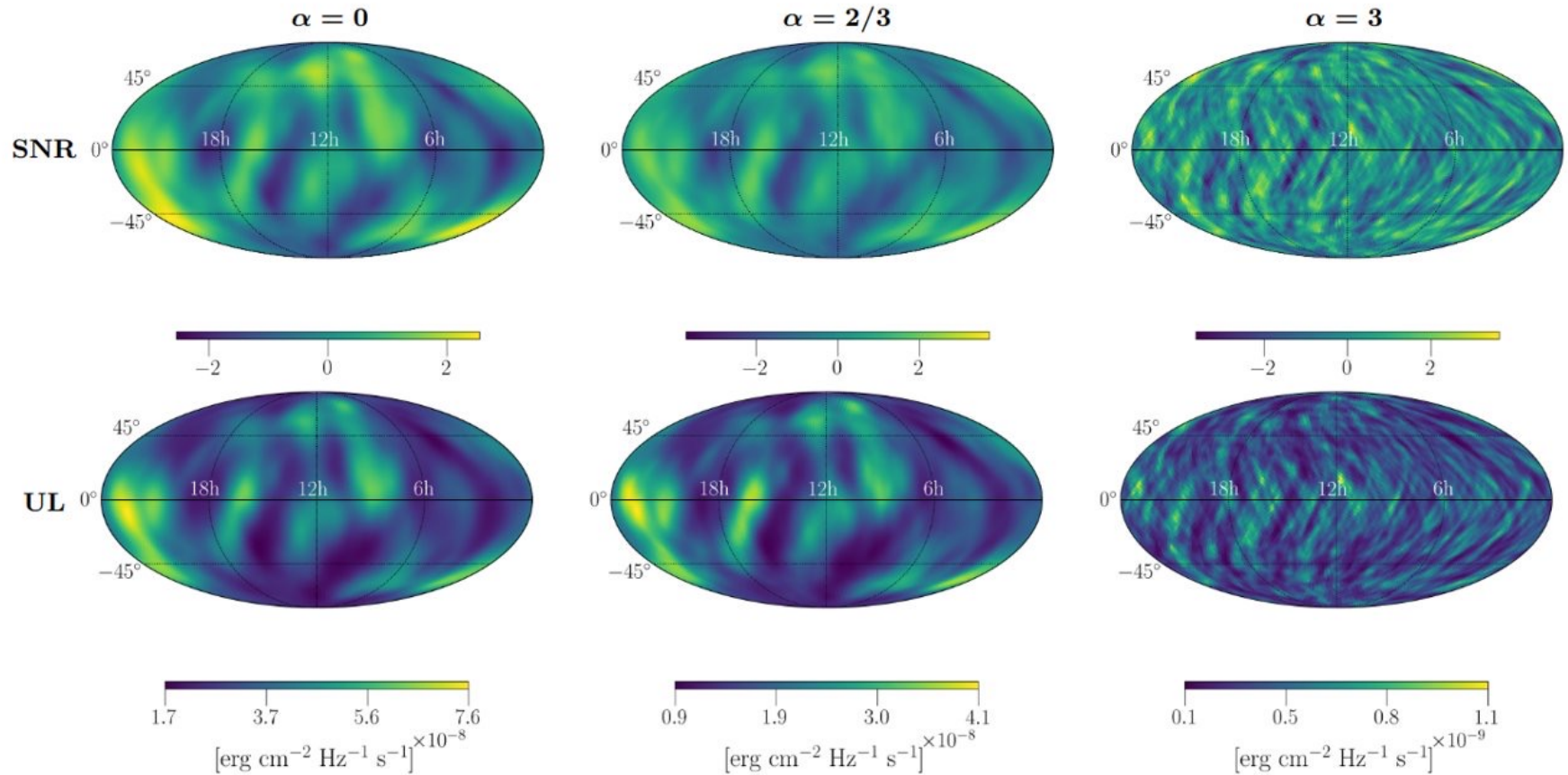
Supernovae



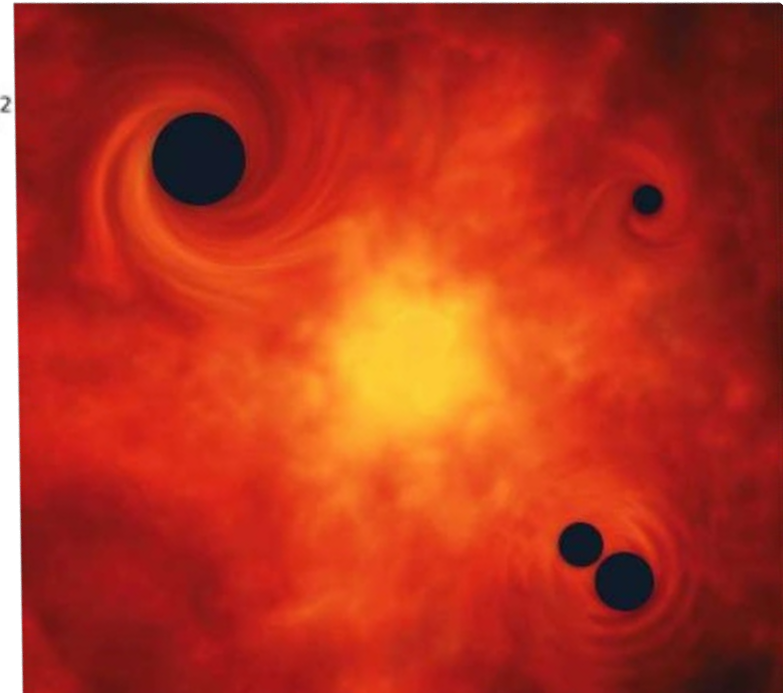
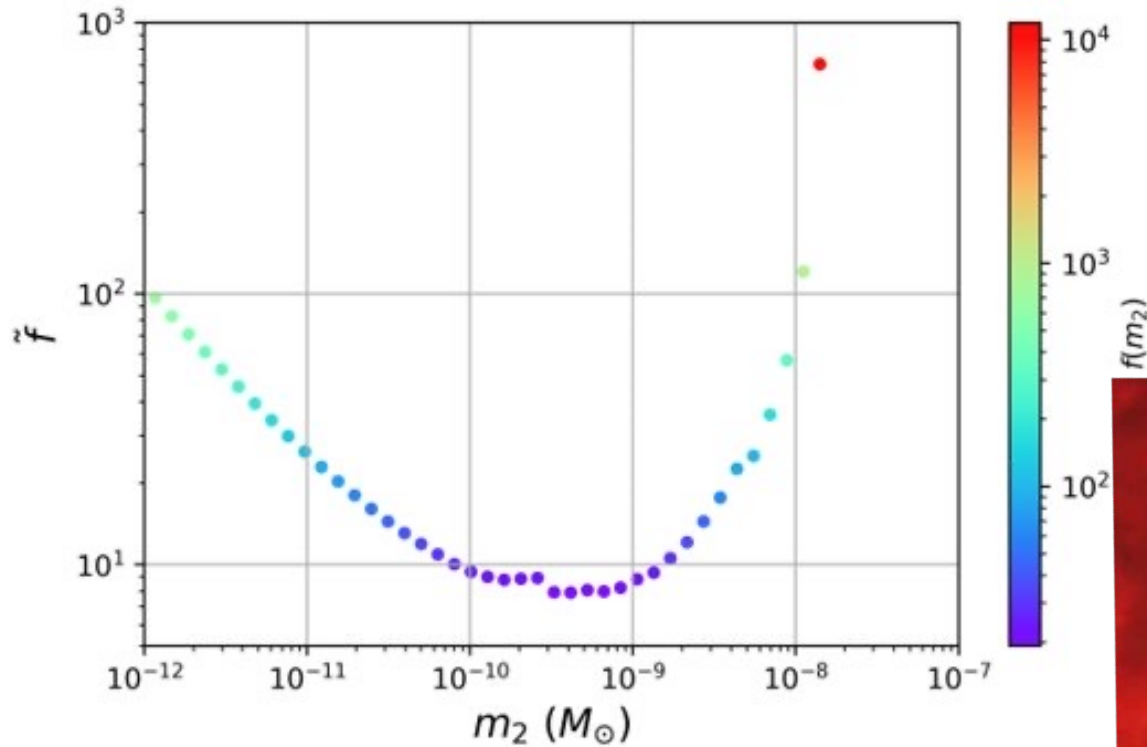
Primordial gravitational waves



Search for anisotropies in the stochastic GW background



Searching for signatures of primordial black holes



GW - Data analysis

- **Continuous Waves**

- Several flagship analyses, Ultra-light DM, galactic center excess, extreme-ratio binaries, parallax for BNS, planetary-mass PBH
- **People:** A. Miller, M. Sieniawska, A. Depasse

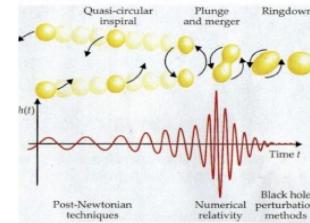
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- **Multi-Messenger**

- Search for coincident GW-neutrinos from AGN
- **People:** M. Vereecken [*IceCube liaison officer*]

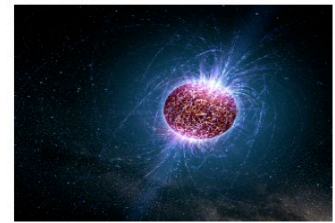
Merging neutron stars or black holes



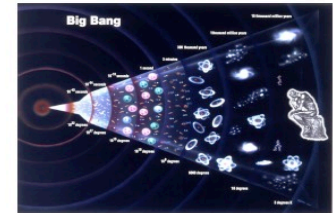
Supernovae



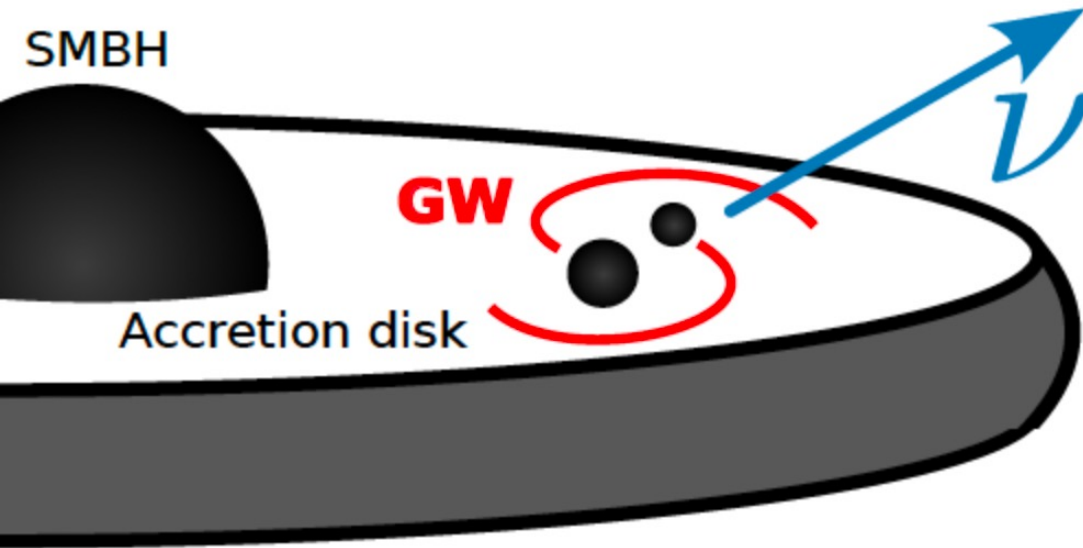
Asymmetric, fast-spinning neutron stars



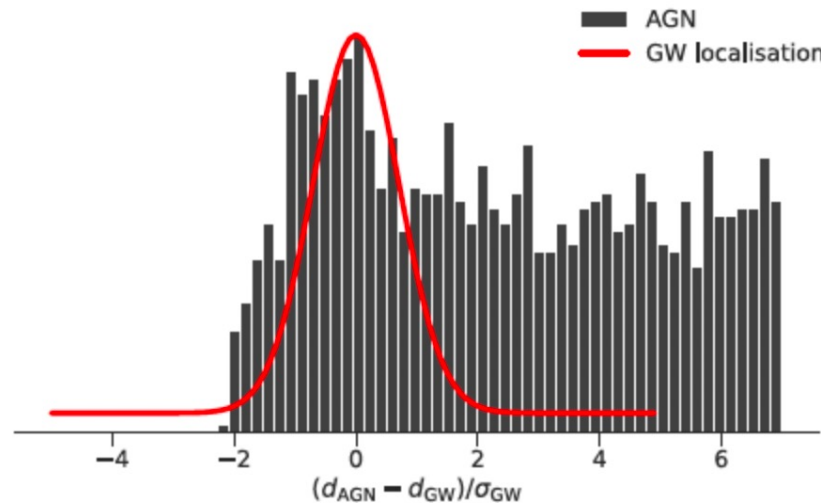
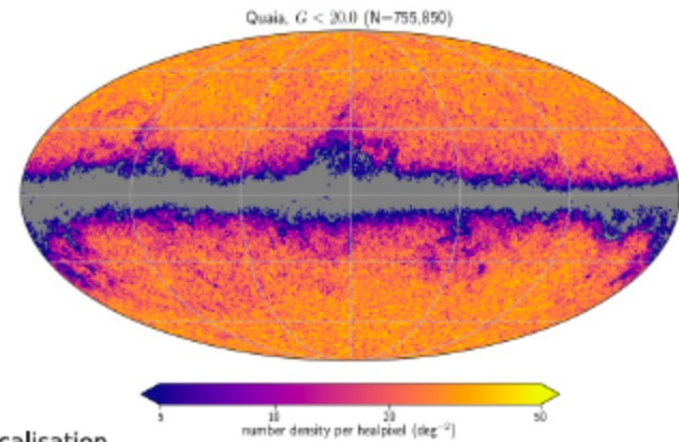
Primordial gravitational waves



Searching for GW and neutrinos in disks of Active Galactic Nuclei

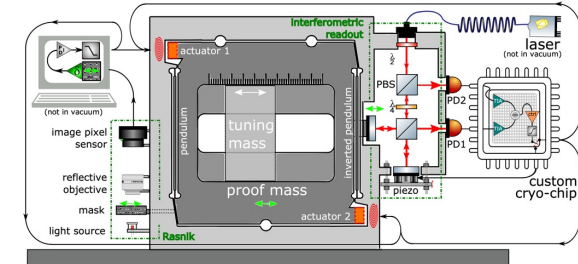


Quaia catalog



GW - instrumentation and computing

- Instrumentation



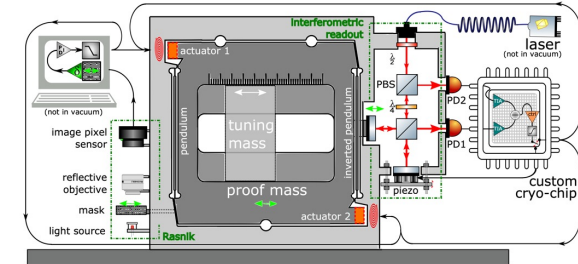
- Computing

- Organizational aspects

GW - instrumentation and computing

- **Instrumentation**

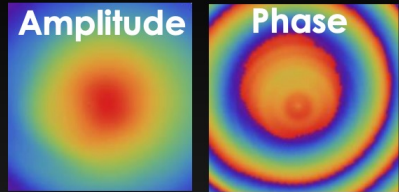
- **Virgo:** phase cameras for mode mismatch mitigation (optical setup in Laser & Optics technological platform), optical simulations, commissioning (on site)
- **ET:** superconducting cryogenic inertial sensors (E-TEST R&D facility) and construction of parts of mirror suspension system for the ETpathfinder facility,
- **People:** J. van Heijningen (chair of ET auxiliary optics suspensions WG), C. Lauzin, F. Badaracco, E. Ferreira, R. Cabrita, M. Zeoli



- **Computing**

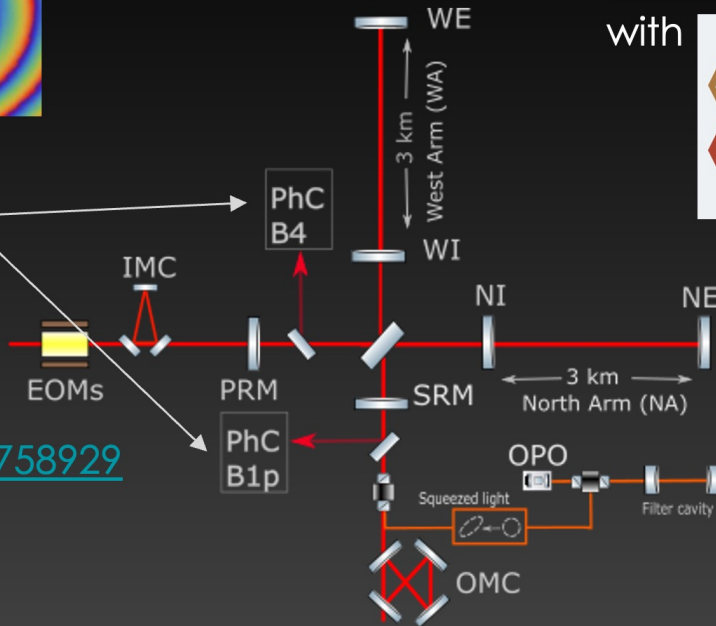
- **Organizational aspects**

Wavefront sensing and mode-mismatch

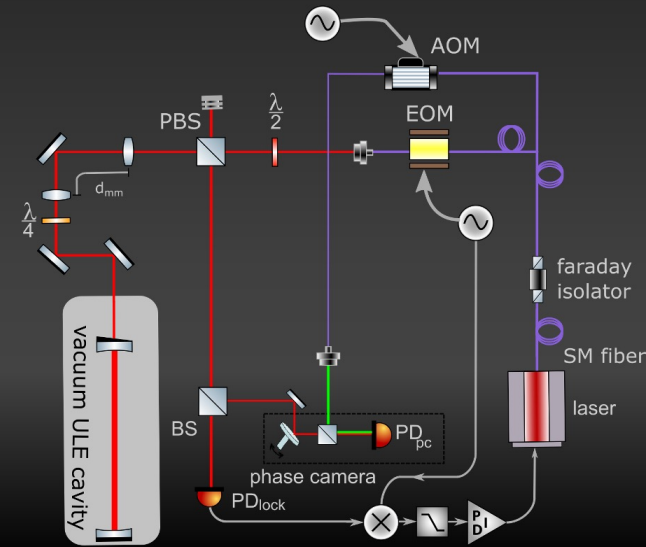
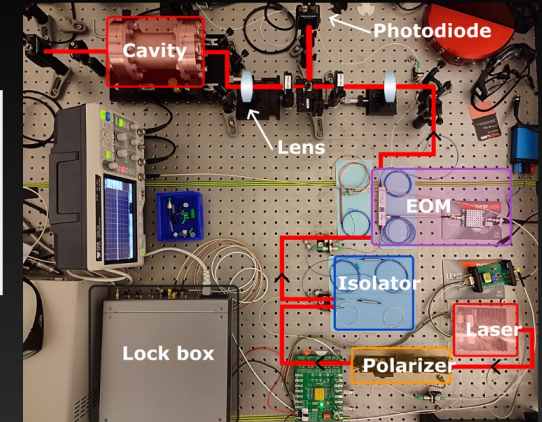
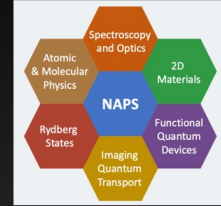


Phase Camera (PhC) measures the beam wavefront

[10.5281/zenodo.6758929](https://zenodo.org/record/6758929)

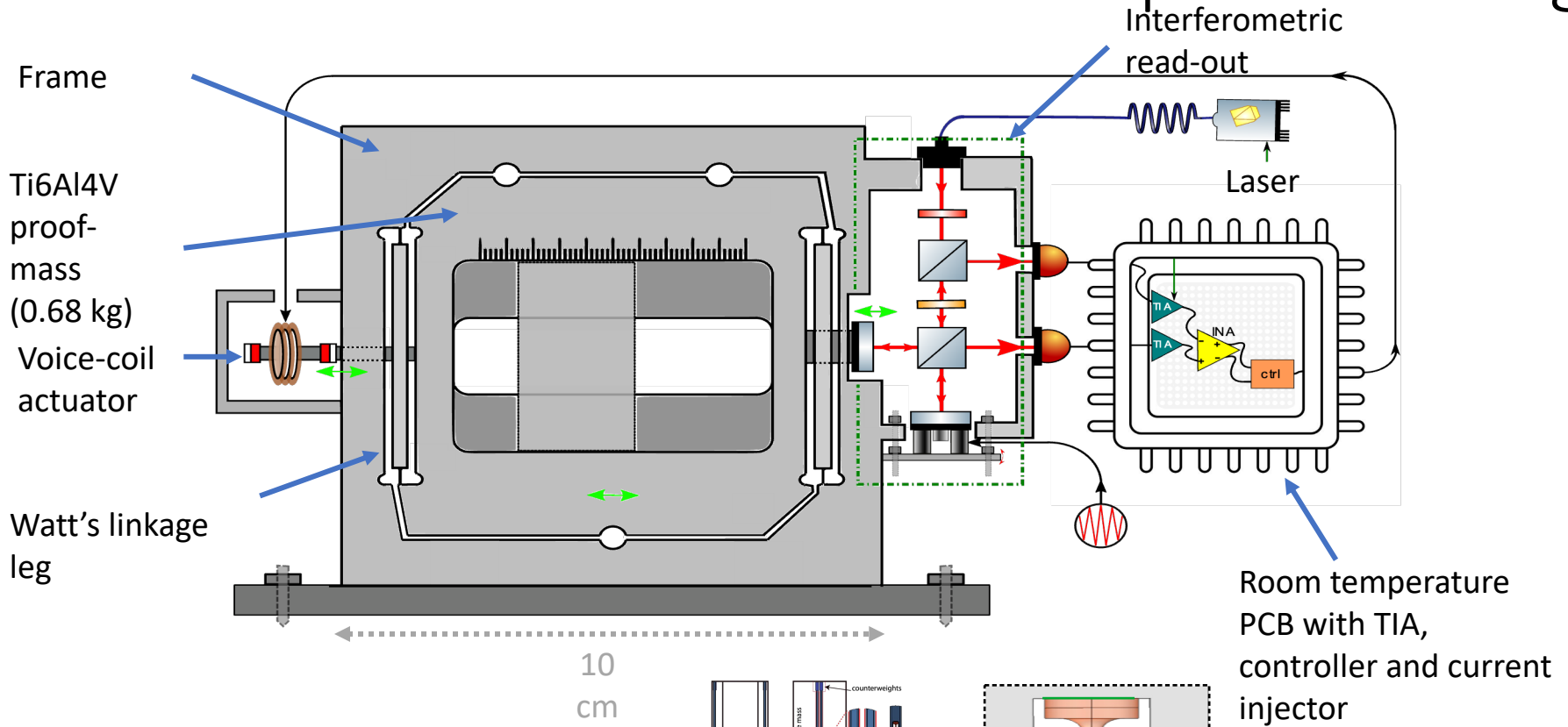


Collaboration with



Active collaboration with colleagues from Nanoscopic physics

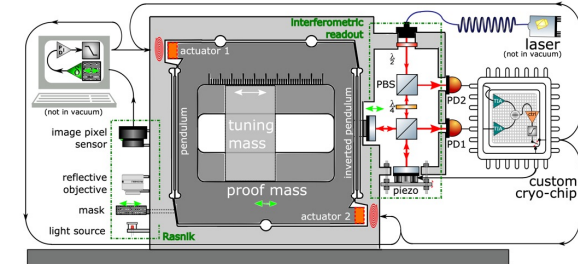
Cryogenic interferometric inertial sensor and suspension design



GW - instrumentation and computing

• Instrumentation

- **Virgo:** phase cameras for mode mismatch mitigation (optical setup in Laser & Optics technological platform), optical simulations, commissioning (on site)
- **ET:** superconducting cryogenic inertial sensors (E-TEST R&D facility) and construction of parts of mirror suspension system for the ETpathfinder facility,
- **People:** J. van Heijningen (chair of ET auxiliary optics suspensions WG), C. Lauzin, F. Badaracco, E. Ferreira, R. Cabrita, M. Zeoli



• Computing

WLCG cluster at UCLouvain integrated in LVK computing system since 2019
3000 cores (37 kHEPscore) and 2400 TB - 10% are Virgo specific resources

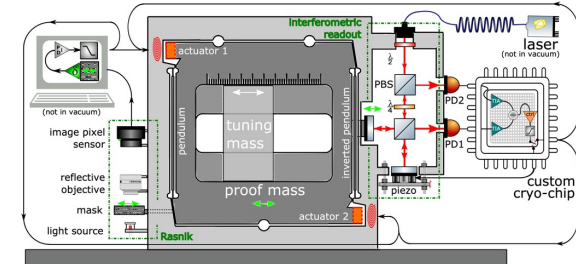
- **Virgo:** LVK computing center and providing “OSDF origin server” service
- **ET:** computing center for mock data challenges.
- **People:** A. Tanasijczuk (chair of ET division “software, framework and data challenges”)

• Organizational aspects

GW - instrumentation and computing

• Instrumentation

- **Virgo:** phase cameras for mode mismatch mitigation (optical setup in Laser & Optics technological platform), optical simulations, commissioning (on site)
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• Computing

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- **Virgo:** LVK computing center and providing “OSDF origin server” service
- **ET:** computing center for mock data challenges.
- **People:** A. Tanasijczuk (chair of ET division “software, framework and data challenges”)

• Organizational aspects

- **ET:** coordination of Work Package “financial architecture” in the EU “ET Preparatory Phase” project
- **People:** C. Arina

Preparatory projects for ET

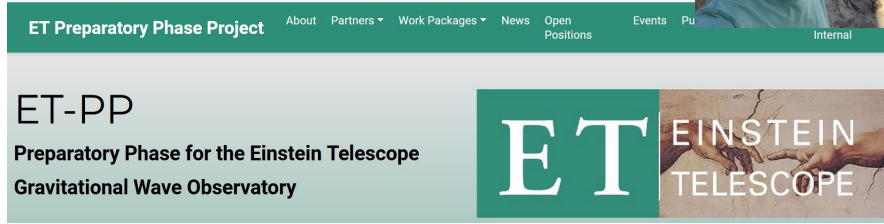
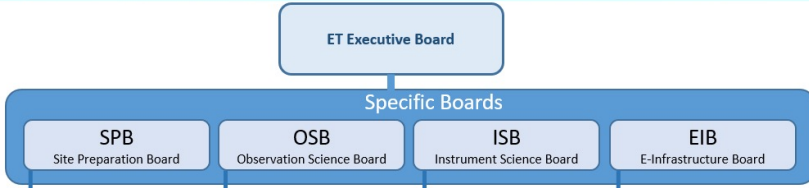
ESFRI

ET COLLABORATION

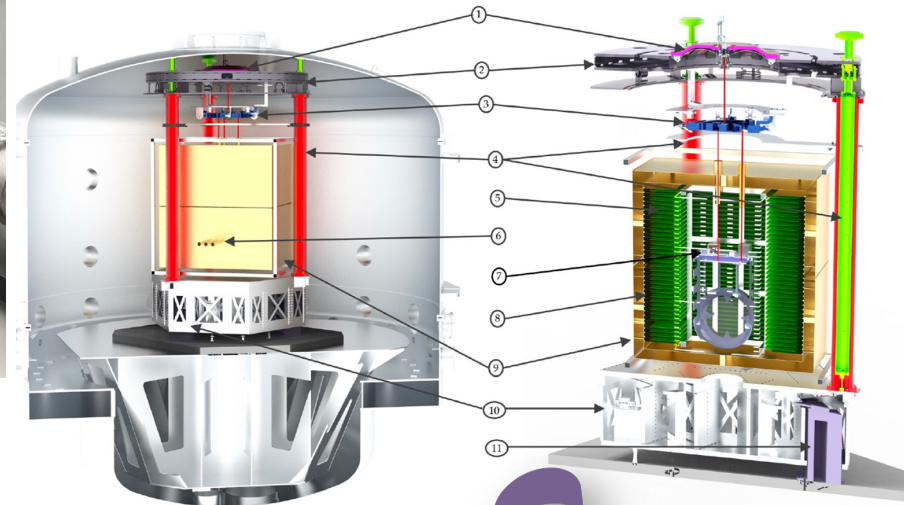


J. Van Heijningen
Chair of DIVISION
AUXILIARY OPTICS

A. Tanasijczuk
Chair of DIVISION
SOFTWARE &
FRAMEWORKS



C. Arina
Chair of WP3: FINANCIAL
ARCHITECTURE



GW - Publications

• Continuous waves

- A. Miller et al., arXiv: 2301.10239 [astro-ph.HE].
- M. Sieniawska et al., arXiv:2212.07506
- T. S. Yamamoto et al., Phys. Rev. D 106 (2 July 2022), p. 024025.
- A. Miller et al., Phys. Rev. D 103, 103002
- LVK Collaborations, Phys.Rev.D 105 (2022) 6, 063030
- A. Miller et al., Phys. Rev. D 105.10 (2022), p. 103035.
- H Guo et al., arXiv: 2205.10359 [astro-ph.IM].
- LVK Collaborations, Phys.Rev.D 105 (2022) 102001.
- A. Miller et al., Phys.Rev.D 105 (2022) 6, 062008.
- A. Miller et al., Phys. Dark Univ. Volume 32, May 2021, 100836
- LVK Collaborations, Phys. Rev. D 100 (2019): 024004

• Stochastic background

- F. De Lillo and J. Suresh, arxiv:2310.05823, submitted to Phys.Rev.D.
- LVK Collaborations, Phys.Rev.D 104 (2021) 2, 022005.
- D. Agarwal et al., arXiv: 2302.12516 [gr-qc]
- K. Z. Yang et al., arXiv: 2304.07621 [gr-qc] (submitted to Phy.Rev.D).
- F. De Lillo et al., Phys. Rev. D 107, 102001.
- A. Renzini et al. wave, Astrophys.J. 952 (2023) 1, 25.
- D. Agarwal et al., Phys. Rev. D. 106 (2022) 4, 043019.
- LVK Collaborations; Phys.Rev.D 105 (2022) 12, 122001.
- F. D. Lillo et al., Mon.Not.Roy.Astron.Soc. 513 (2022) 1, 1105-1114.

• Instrumentation

- A Goodwin et al. Optica — Vol. 11, no.2, p. 273-290 (2024)
- R. Cabrita, on behalf of the Virgo collaboration, Proceedings of the GRavitational-waves Science&technology Symposium (GRASS), June 2022.
- E. Ferreira et al.; Jour. of Phy. Conf. Ser. — Vol. 2156, no.1, p. 012080 (2021)
- J. van Heijningen et al.; 2020 JINST 15 P06034
- J. van Heijningen et al.; 2023 Journ. Sound and Vibr. 552 P117614.
- C. Arina et al.; Class.Quant.Grav. 39 (2022) 21, 215008
- J. van Heijningen et al.; 2022 NIM 1041 P167231
- H. Van der Graaf et al.; 2023 NIM 1050 P168160
- J. van Heijningen et al.; J. Appl. Phys. 133, 244501 (2023)
- J. Harms et al; 2021 ApJ 910 1

Funding for Virgo and Einstein Telescope (1)

Projects

- 2019- 2025: G. Bruno (main promoter), C. Lauzin, J. van Heijningen, S. Clesse (ULB), J.R. Cudell (Uliege), M. Fays (Uliege)

Inter-university FNRS IISN research convention “Virgo” (1.2 M€ in total so far; **700 k€** for UCLouvain for personnel, computing, instrumentation, travel and M&O).

- 2019-2025: G. Bruno (main promoter), C. Ringeval, J.-R. Cudell (Uliege) and C. Collette (Uliege);

Belgian inter-university ARC grant “Gravitational WAVE Science” (950 k€ in total – 520 k€ for UCLouvain for personnel, computing and instrumentation)

- 2020-2022: J. van Heijningen (main promoter) and G. Bruno,

Walloon Region "BEWARE" grant (**240 k€** for a 2-year postdoctoral position and instrumentation on R&D in collaboration with the industry.

- 2021-2025: G. Bruno, J. van Heijningen, M. Fays (Uliege, main promoter) and C. Collette (Uliege)

Inter-university FNRS IISN research convention “Einstein Telescope” (300 k€ in total; **150 k€** for UCLouvain for personnel and travel).

- 2021-2025: G. Bruno (main promoter), J. van Heijningen and C. Collette (Uliege):

FNRS PDR project “STELLAR” (**400 k€** for personnel and instrumentation)

- 2024-2028: G. Bruno (main promoter) and C. Lauzin;

Walloon Region Win4Project grant “ETOPT” (**2.3 M€** for instrumentation and personnel)

Funding for Virgo and Einstein Telescope (2)

Individual grants

- 2019-2024 **UCLouvain assistantship** A. Depasse (supervisor G. Bruno)
- 2020-2023 **FNRS FRIA PhD grant** F. De Lillo (supervisor G. Bruno)
- 2021-2022 **UCLouvain FSR grant** A. Miller (supervisor G. Bruno)
- 2022-2025 **FNRS CR postdoc grant** A. Miller (supervisor G. Bruno) - postponed.
- 2023-2026 **FNRS FRIA PhD grant** S. Venikoudis (supervisor G. Bruno)
- 2024-2026 **UCLouvain FSR grant** D. Agarwal (supervisor G. Bruno)

Large consortia

- 2019- 2023: **EU interreg project “E-TEST”** grant (15 M€ in total; **300 k€** for UCLouvain).
- 2019- 2023: **EU interreg project “ETpathfinder”** grant (15 M€ in total; UCLouvain not eligible for geographical reasons, but invited as external partner).
- 2021- 2025: **EU infradev project “ET-PP”** grant (**4 M€** in total; **part of salary of C. Arina** coordinator of “ET financial architecture” WP).

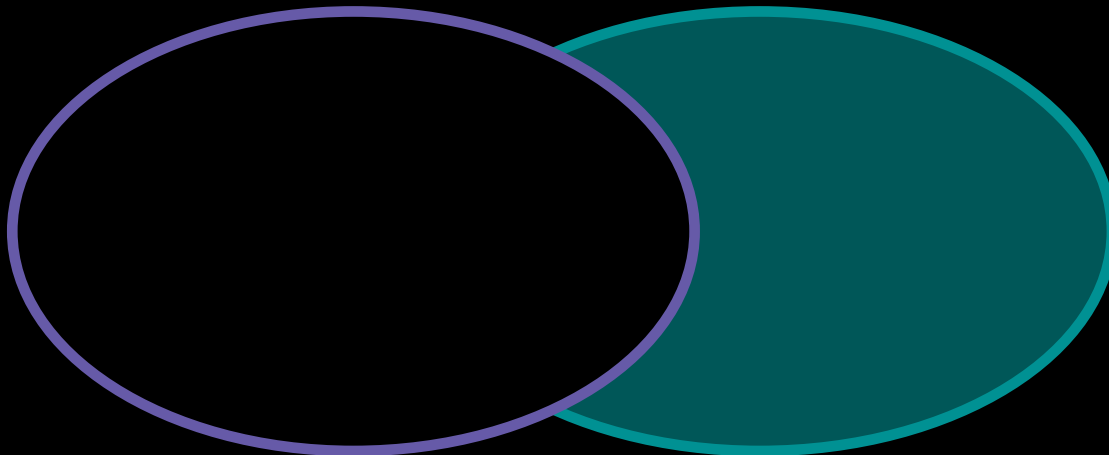
Other smaller projects

- 2020-2023 J. van Heijningen and G. Bruno "MIT SeedFund" (**30 k€** of travel budget for extended stays of UCLouvain researchers at MIT and vice-versa)
- 2021 –2023 UCLouvain member of the EU H2020 MSCA-RISE "NEWS" program funding long-term exchanges of researchers with the US and Japan (**40 k€** for UCLouvain)

Neutrino astronomy

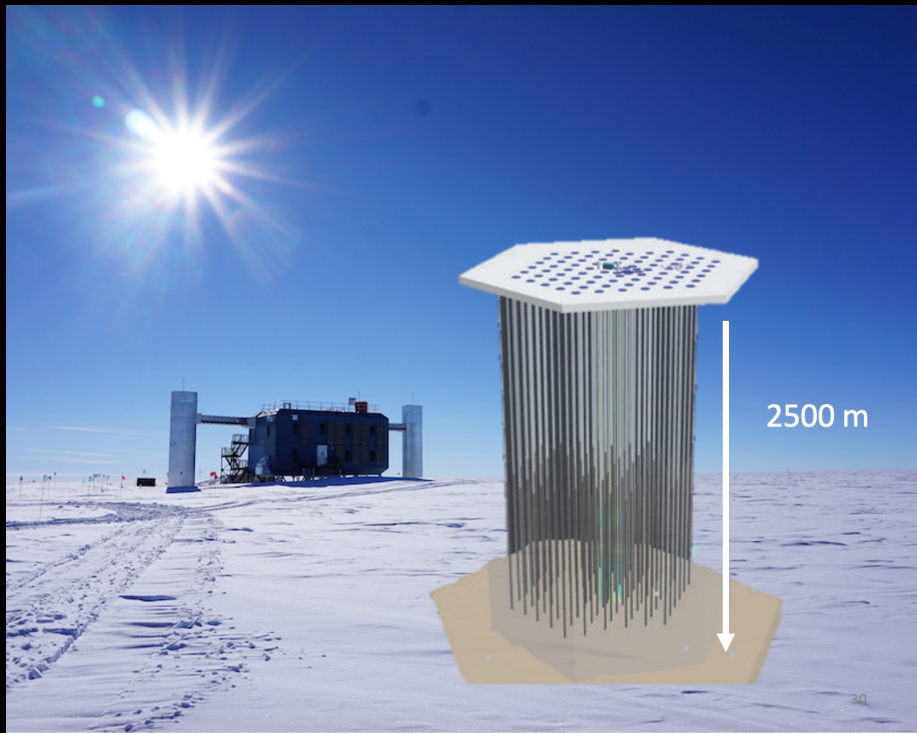
Gravitational waves (GW)

Neutrinos (ν)



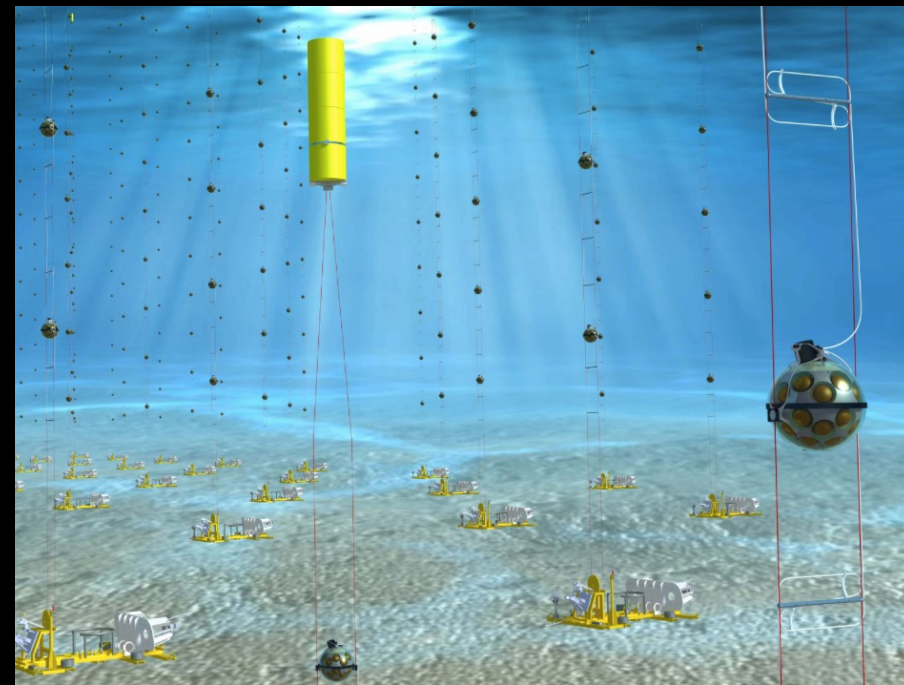
Neutrino group - started in Sept 2021

- **Permanent staff full-time on neutrino science:**
 - **G. de Wasseige**
 - V. Lemaître
- **Postdocs:** M. Lamoureux, C. Raab, J. Lazar, and M. Vereecken (shared with the GW group)
- **PhD students:** K. Kruiswijk, J. Mauro, P. A. Sevlé, E. Genton
- **Permanent staff at UCLouvain collaborating part-time on neutrino-related projects:**
 - Prof. G. Bruno (IRMP - GW; joint project on GW-neutrino coincident search)



IceCube, South Pole
Taking data since 2011
Full member since October 2021

KM3NeT, Mediterranean Sea
In construction
Full member since February 2024



Neutrinos - Data analysis

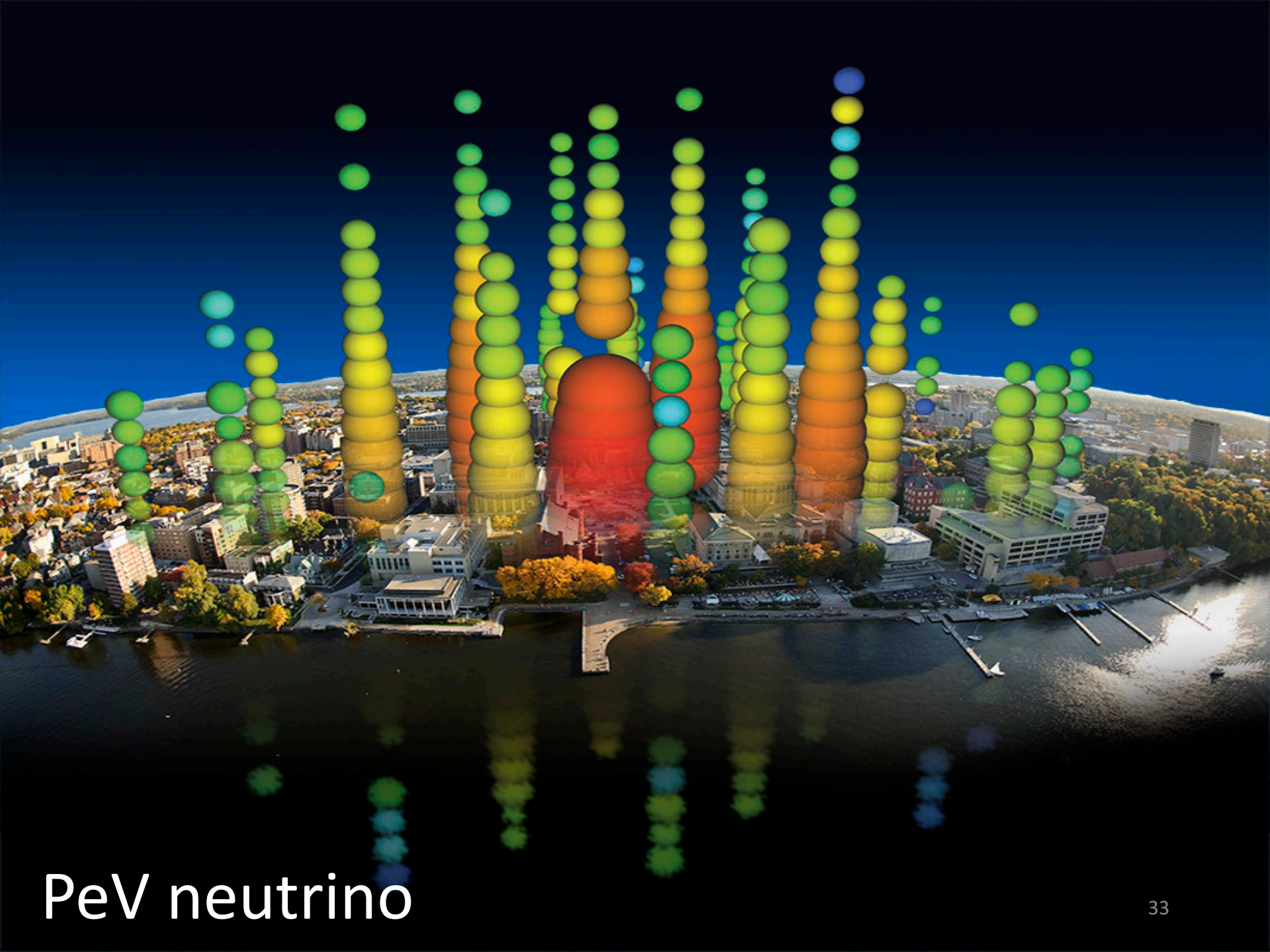
- **Enlarging the detection limits of large neutrino telescopes**

- **Searching for astrophysical neutrinos**

- **Multi-detector + Multi-Energy + Multi-Messenger**

Neutrinos - Data analysis

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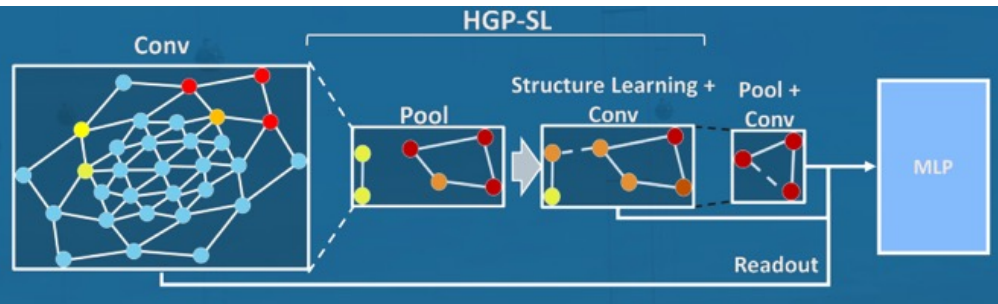
PeV neutrino

970
MeV
 ν_e

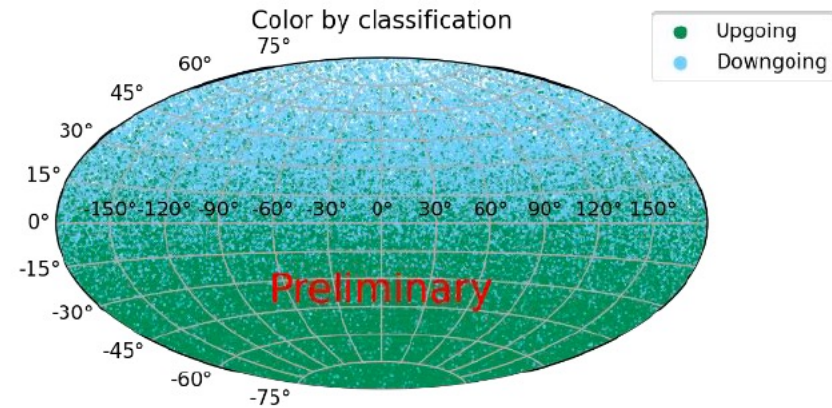


ICECUBE

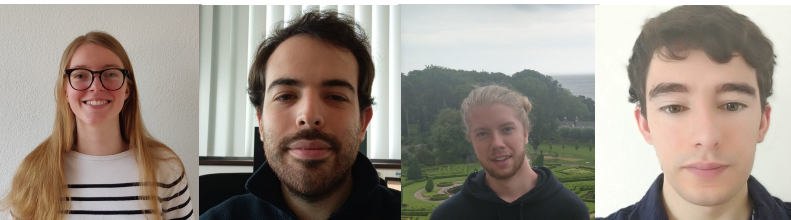
Enlarging the detection limits of large neutrino telescopes



Development of novel event selection techniques



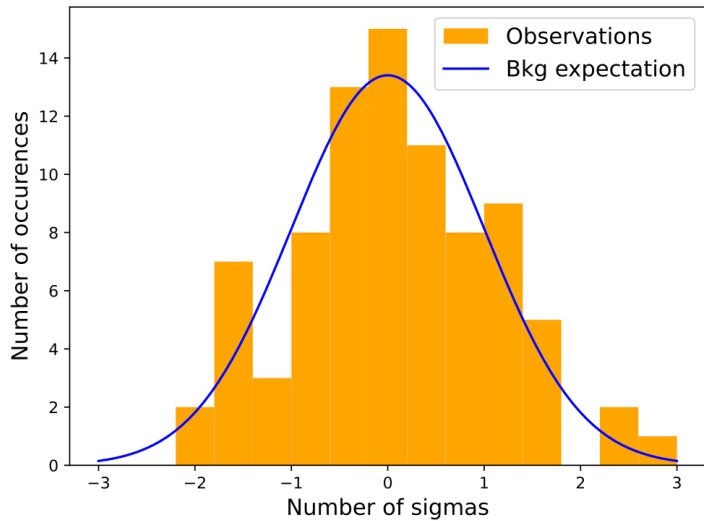
Direction reconstruction of the event



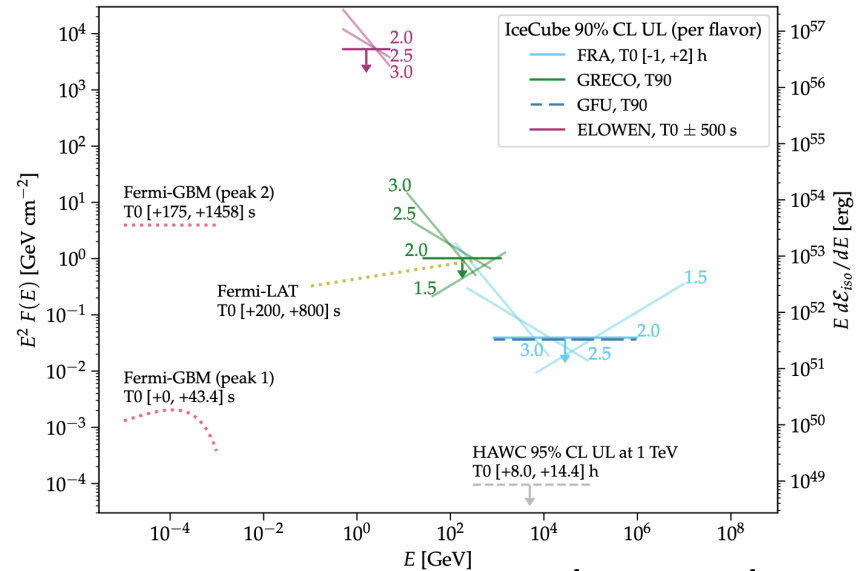
Neutrinos - Data analysis

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Searching for astrophysical neutrinos



GW follow-ups with neutrinos



GRB221009A IceCube results

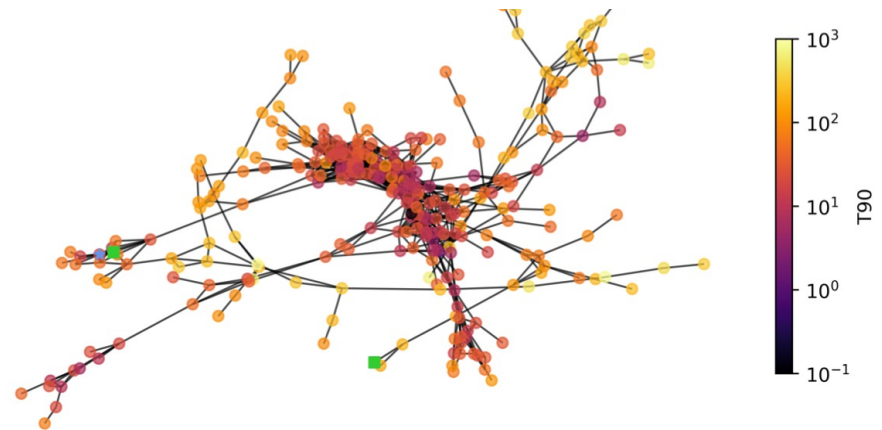
KM3Net Shifter Tools

ORCA - ARCA - MM - CCSN - Alerts - Tools - Gwenhärt de Wasseige

KM3Net Shifter Tools home page

- ORCA high-level monitoring
- ORCA RTA dashboard
- ARCA high-level monitoring
- ARCA RTA dashboard
- MM dashboard
- Analysis dashboard
- CCSN monitoring
- External triggers **3174 new**
- KM3Net alerts
- Manual search
- Shifter manual
- Rocket chat
- GCN writer
- Current shift report
- All shift reports
- Shifters calendar

Development of analyses and tools for real-time astronomy



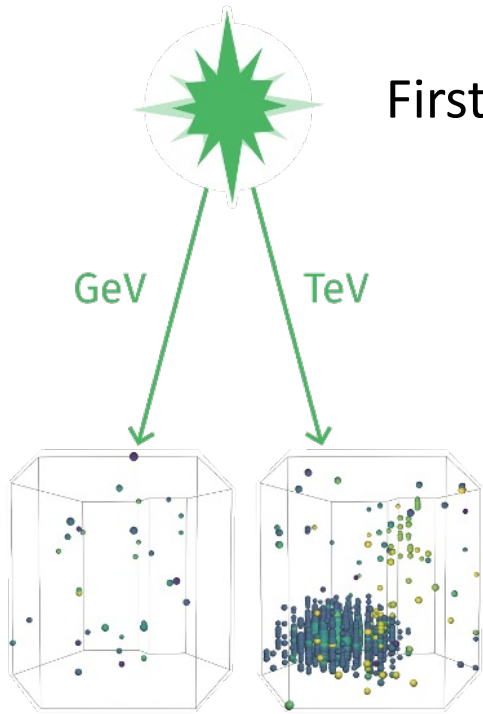
Use of graphs to identify sub-populations of astrophysical events

Neutrinos - Data analysis

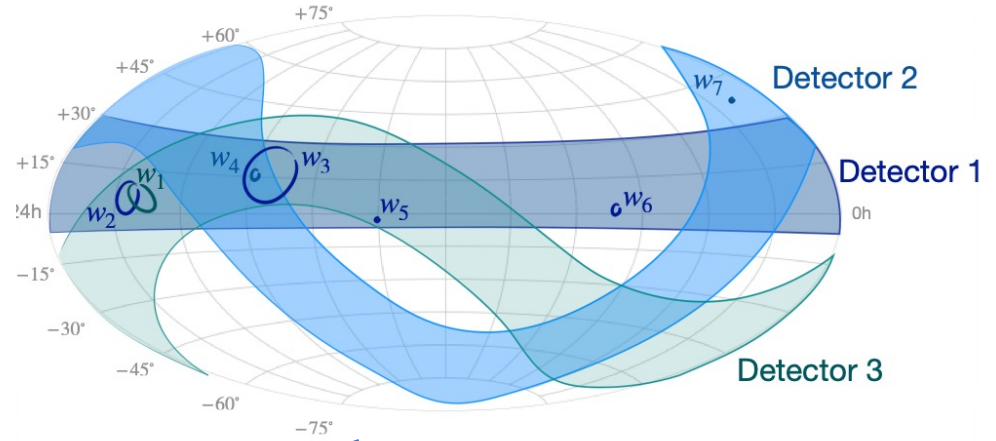
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- **Multi-detector + Multi-Energy + Multi-Messenger**
 - The 'UCLouvain' way forward
 - **People:** K. Kruiswijk, E. Genton, J. Lazar, J. Mauro, M. Lamoureux, C. Raab, P. A. Sevle, M. Vereecken

Our 'way forward'

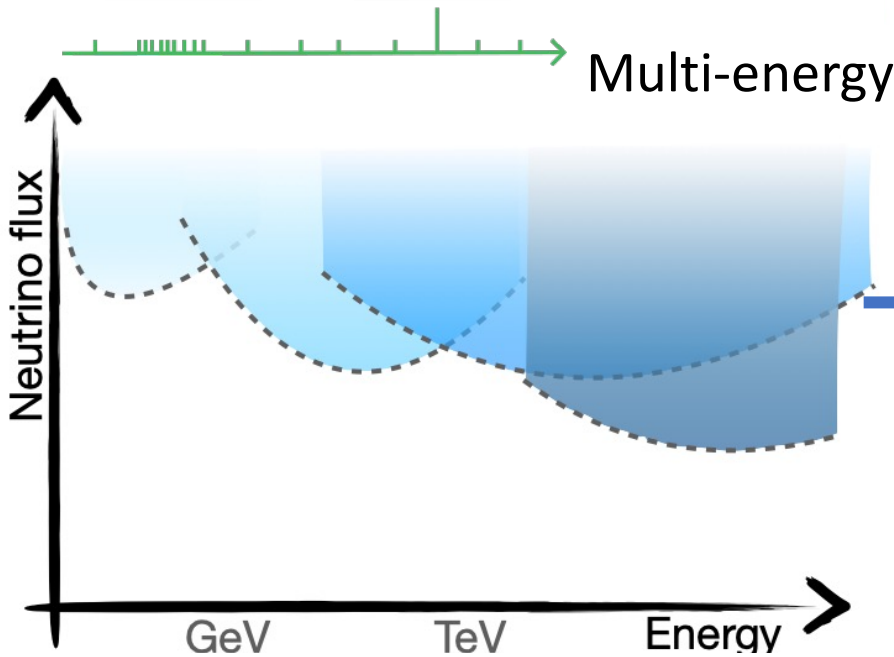
First step



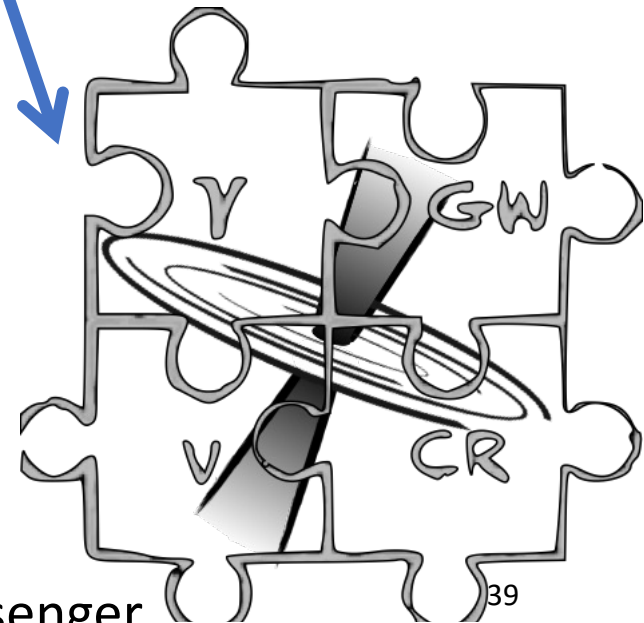
Multi-detector



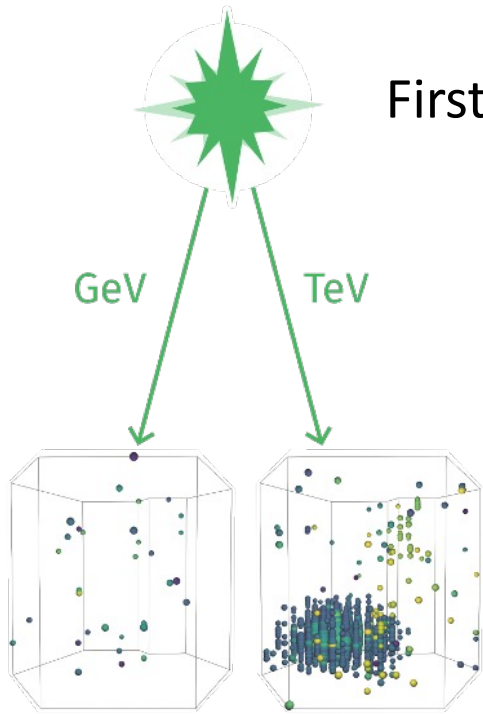
Multi-energy



Multi-messenger

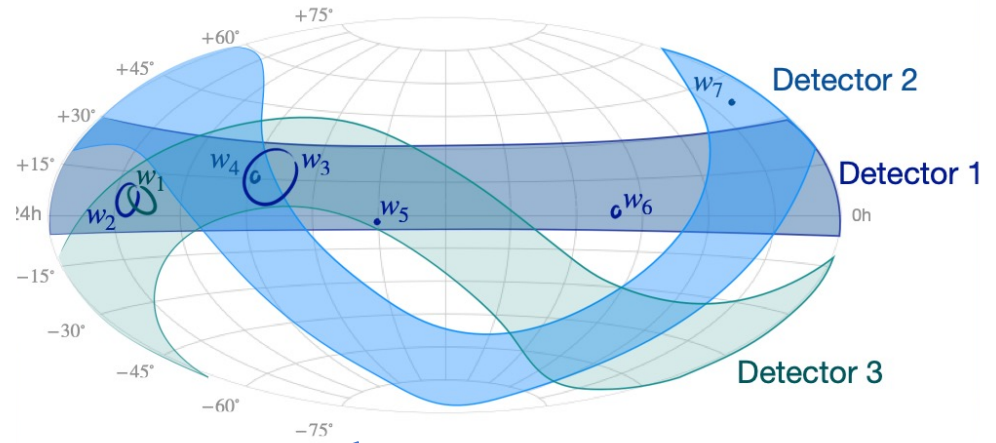


First step

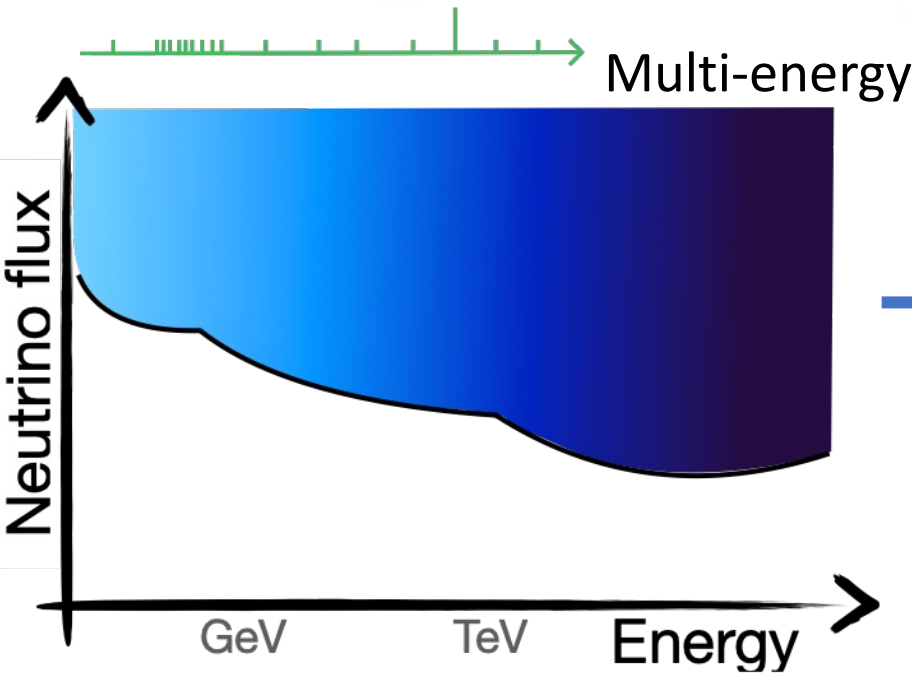


Our 'way forward'

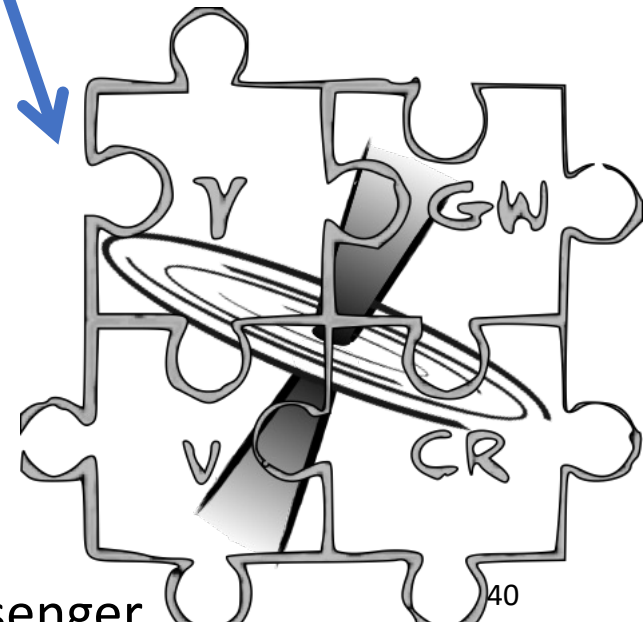
Multi-detector



Multi-energy



Multi-messenger



Neutrinos – Related activities

- **Neutrino oscillation studies in KM3NeT**
- **Development of a DOM integration site**
- **Interdisciplinary studies**
- **Art and Sciences**

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- **People:** V. Lemaître

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- **People:** J. Mauro, E. Genton



Collaboration with Donald Fortescue,
Marseille, Louvain-la-Neuve

Collaboration with Tim Otto Roth,
Arts et Métiers, Paris



Neutrinos - Publications

• **Searching for astrophysical neutrinos**

- The KM3NeT Collaboration, Searches for neutrino counterparts from gravitational waves from the LIGO/Virgo third observing run with KM3NeT, JCAP 04(2024)026, arXiv:2311.03804 [astro-ph.HE]
- The IceCube Collaboration, Limits on Neutrino Emission from GRB 221009A from MeV to PeV using the IceCube Neutrino Observatory, ApJL 946 L26 (2023), arXiv:2302.05459 [astro-ph.HE].
- The KM3NeT Collaboration, The Real-time Analysis Platform of KM3NeT and its first results, ICRC 2023, Nagoya, Japan, PoS(ICRC2023)1125.
- The ANTARES and KM3NeT Collaboration, Follow-up of O3 gravitational wave events with neutrinos in ANTARES and KM3NeT telescopes, ICRC 2023, Nagoya, Japan, PoS(ICRC2023)1506
- The KM3NeT Collaboration Follow-up of multi-messenger alerts with the KM3NeT ARCA and ORCA detectors, ICRC 2023, Nagoya, Japan, PoS(ICRC2023)1521.
- The IceCube Collaboration, IceCube search for neutrinos from GRB 221009A, ICRC 2023, Nagoya, Japan, PoS(ICRC2023)1511.
- G. Bruno, GDW, R. Gorski, M. Lamoureux, M. Vereecken, Searching for joint neutrino and gravitational wave emission from the environment of Active Galactic Nuclei, ICRC 2023, Nagoya, Japan, PoS(ICRC2023)1508
- M. Lamoureux and G. de Wasseige, Identification of time-correlated neutrino clusters in populations of astrophysical transient sources, ICRC 2023, Nagoya, Japan, PoS(ICRC2023)1514
- G. Bruno, G. de Wasseige, M. Lamoureux, R. Gorski, M. Vereecken, Searching for joint neutrino and gravitational wave emission from the environment of Active Galactic Nuclei, ICRC 2023, Nagoya, Japan, PoS(ICRC2023)1507
- K. Kruiswijk and G. de Wasseige, The classification and categorisation of gamma ray bursts with machine learning techniques for neutrino detection, ICRC 2023, Nagoya, Japan, PoS(ICRC2023)1508
- J. Mauro and G. de Wasseige, Searching for sub-populations within the gamma-ray solar flares catalog: a graph-based clustering analysis, ICRC 2023, Nagoya, Japan, PoS(ICRC2023)1292.

Enlarging the detection limits of large neutrino telescopes

- K. Kruiswijk and G. de Wasseige for the IceCube Collaboration, Probing neutrino emission at GeV energies from astrophysical transient events with the IceCube Neutrino Observatory, ICRC 2023, Nagoya, Japan, PoS(ICRC2023)1513.
- J. Mauro and G. de Wasseige, for the KM3NeT Collaboration, Improving the sensitivity of KM3NeT to MeV-GeV neutrinos from solar flares, ICRC 2023, Nagoya, Japan, PoS(ICRC2023)1294.

Art and Sciences

- D. Fortescue, J. Mauro and G. de Wasseige for the KM3NeT Collaboration, Art and Astrophysics in Conversation with KM3NeT Deep in the Mediterranean Sea, ICRC 2023, Nagoya, Japan, PoS(ICRC2023)1621.

Funding for IceCube and KM3NeT (1)

Projects

- 2021-2024: G. de Wasseige (promoter)

Francqui Startup Grant (200 k€ for UCLouvain for personnel, equipment, and travel).

- 2022- 2025: G. de Wasseige (UCLouvain promoter), J. Aguilar, S. Toscano, I. Maris (ULB)

Inter-university FNRS IISN research convention “IceCube” (**550 k€** for UCLouvain for personnel, M&O, and travel).

- 2023-2026: G. de Wasseige (main promoter)

BELSPO Polar grant “Low Energy Astrophysical Neutrinos in the Ice” (**240€** for personnel and travel).

- 2024-2026: G. de Wasseige (main promoter) and V. Lemaître

Inter-university FNRS IISN research convention “KM3NeT” (**220 k€** for UCLouvain for personnel, M&O, and travel).

Funding for IceCube and KM3NeT (2)

Individual grants

- 2022-2025 **FNRS ASP PhD grant** K. Kruiswijk (supervisor G. de Wasseige)
- 2022-2025 **FNRS CR postdoc grant** M. Lamoureux (supervisor G. de Wasseige)
- 2023-2026 **FNRS FRIA PhD grant** J. Mauro (supervisor G. de Wasseige)
- 2023-2024 **BAEF postdoc grant** J. Lazar (supervisor G. de Wasseige)

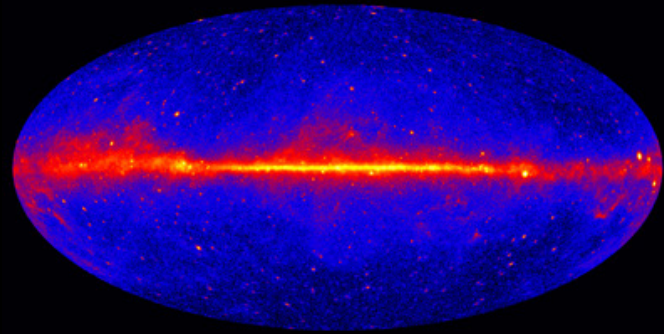
Large consortia

- 2021- 2022: **EU SwafS project** “**REINFORCE**” grant (**2 M€** in total; **20k€** for UCLouvain).
- 2021- 2025: **EU infraserv project** “**ACME**” grant (**14.5 M€** in total, **370k€** for UCLouvain, WP leader).

Other smaller projects

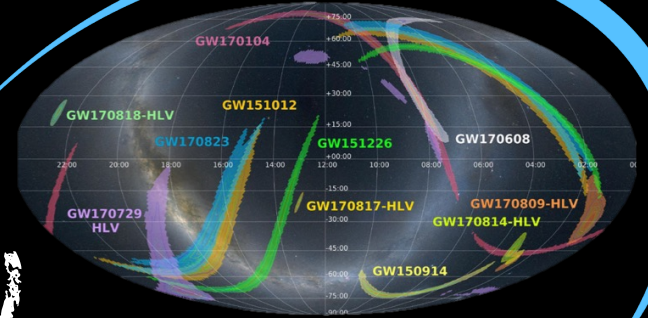
- 2020-2023 G. de Wasseige “Hoover SeedFund” (**30 k€** of travel budget for extended stays of UCLouvain researchers at Harvard University and vice-versa)
- 2024-2025 G. de Wasseige **FWB incitant** (**75k€** for UCLouvain for personnel, M&O, and travel).

Thanks!



Electromagnetic waves

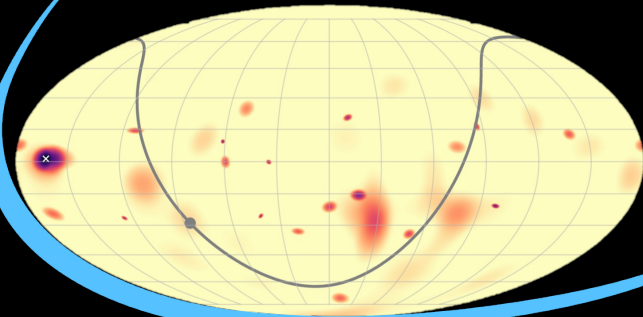
γ



Gravitational waves

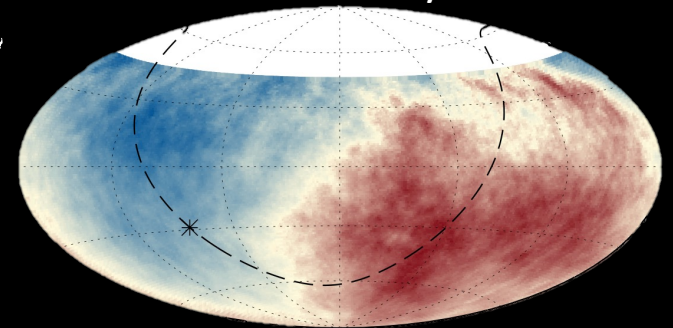
GW

+



Neutrinos

ν



Cosmic Rays

CR

IRMP