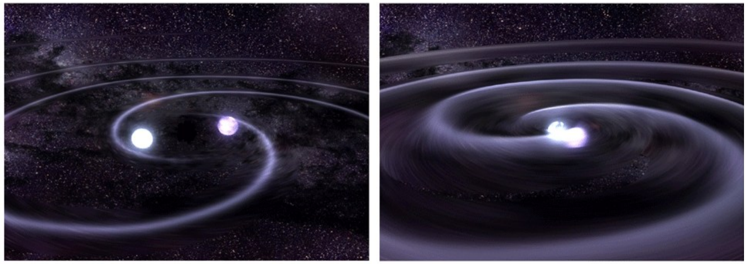
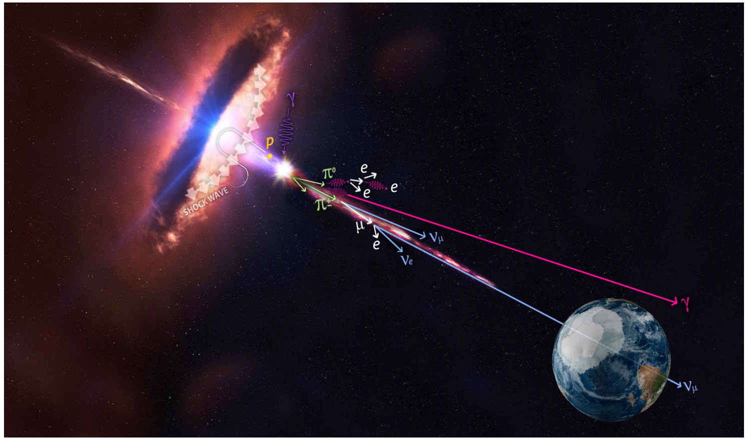
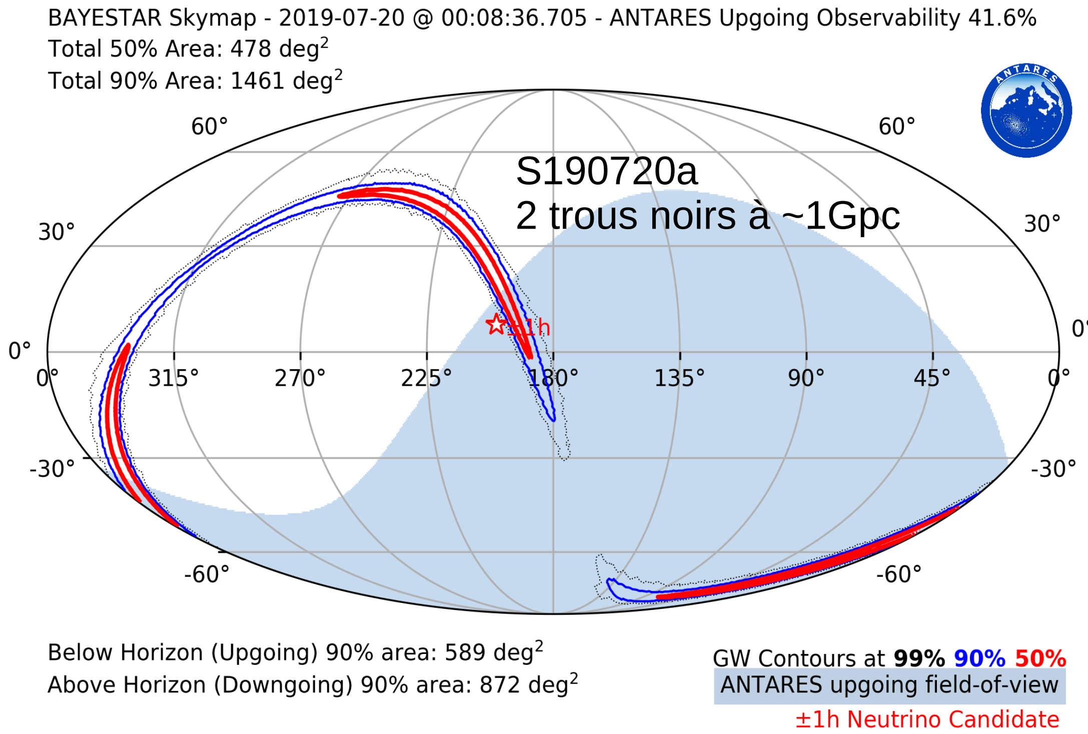
Création et développement d’une équipe « Astroparticules » à l’IPHC

Conseil Scientifique de l’IPHC, 25 août 2020







Création et développement d'une équipe « Astroparticules » à l'IPHC

Conseil Scientifique de l'IPHC, 25 août 2020

- **Introduction :** Neutrinos (*HEN ou NHE*) & Ondes Gravitationnelles (*GW* ou *OG*)

- **Partie I – La Science « Astroparticules » à l'IPHC**
  - Neutrinos / ANTARES & KM3NeT - GWHEN
  - Ondes Gravitationnelles / Virgo : recherche de coalescences de binaires compactes

- **Partie II – La Technique « Astroparticules » à l'IPHC**
  - KM3NeT / Modules Optiques Digitaux
  - Calibration des détecteurs d'OG : Calibrateur Newtonien

- **Conclusions**

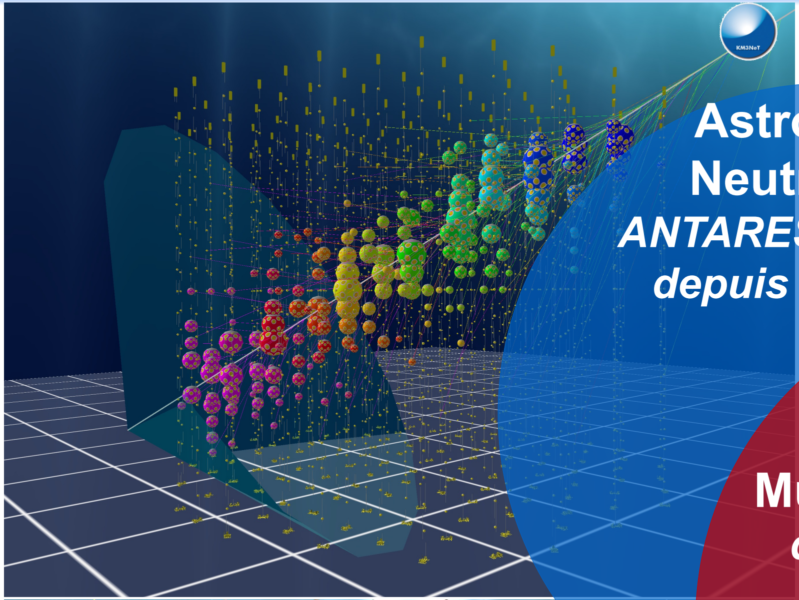
Création et développement d'une équipe « Astroparticules » à l'IPHC

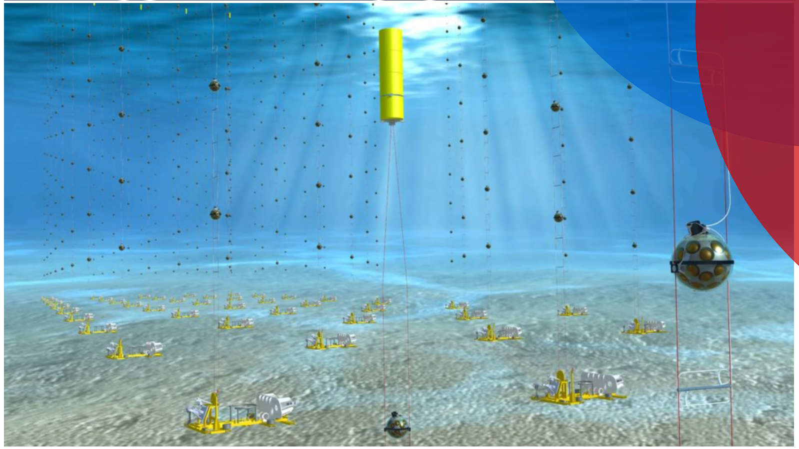
Conseil Scientifique de l'IPHC, 25 août 2020

L'équipe « **Astro** » aujourd'hui :

A. Albert	Enseignant-Chercheur UHA	KM3NeT	*temps partiel*
D. Drouhin	Enseignant-Chercheur UHA	KM3NeT	*temps partiel*
F. Huang	Postdoc	KM3NeT	100 %
T. Pradier	Enseignant-Chercheur Unistra	KM3Net/Virgo	50 % / 50 %
V. Juste	Etudiant M2 → Doctorant	ANTARES → Virgo	100 %
D. Estevez	Postdoc	Virgo	100%
B. Mours	Chercheur	Virgo	100%

« Astronomie Multi-Messagers » à l'IPHC

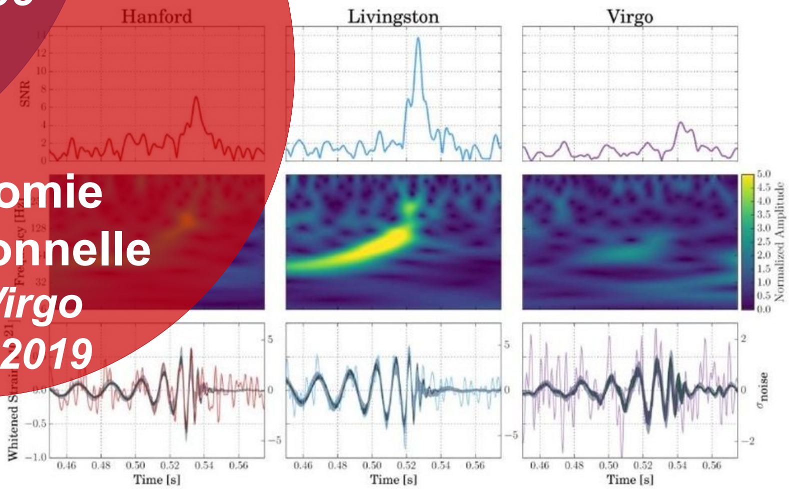




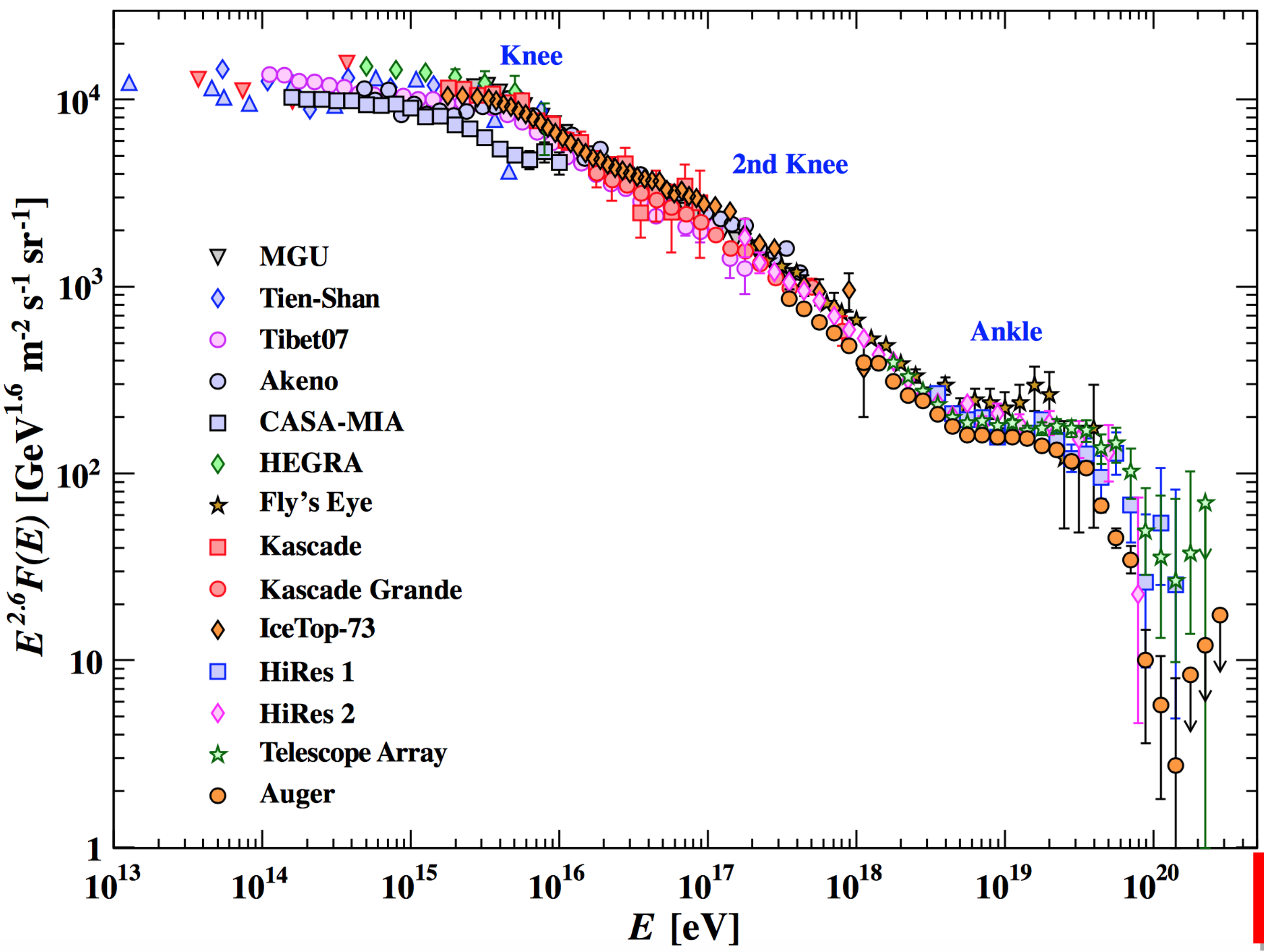
Astronomie Neutrino HE
ANTARES / KM3NeT
depuis 1999-2002

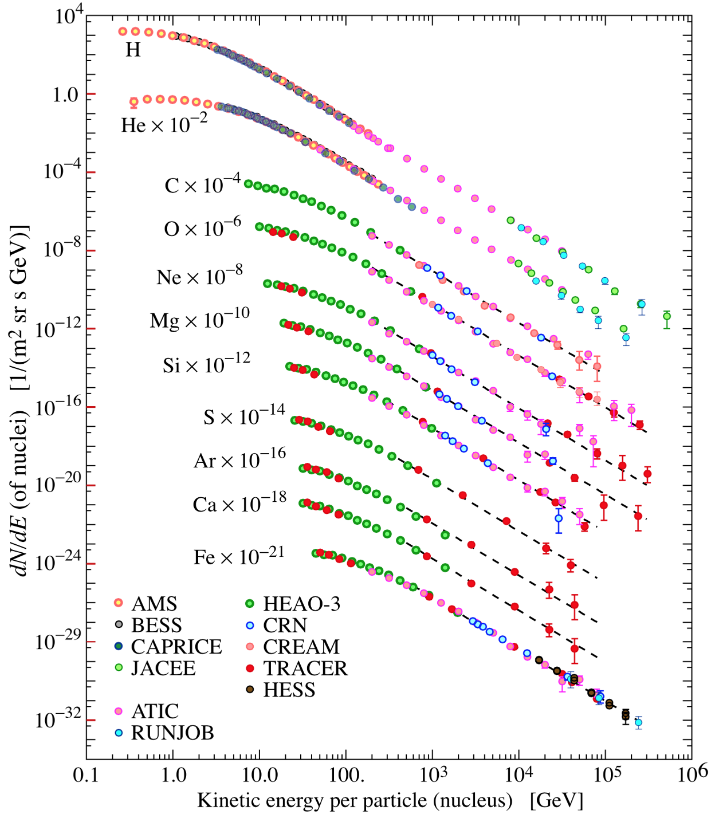
Astronomie Multi-Messagers
depuis 2006-08

Astronomie Gravitationnelle
LIGO-Virgo
depuis 2019



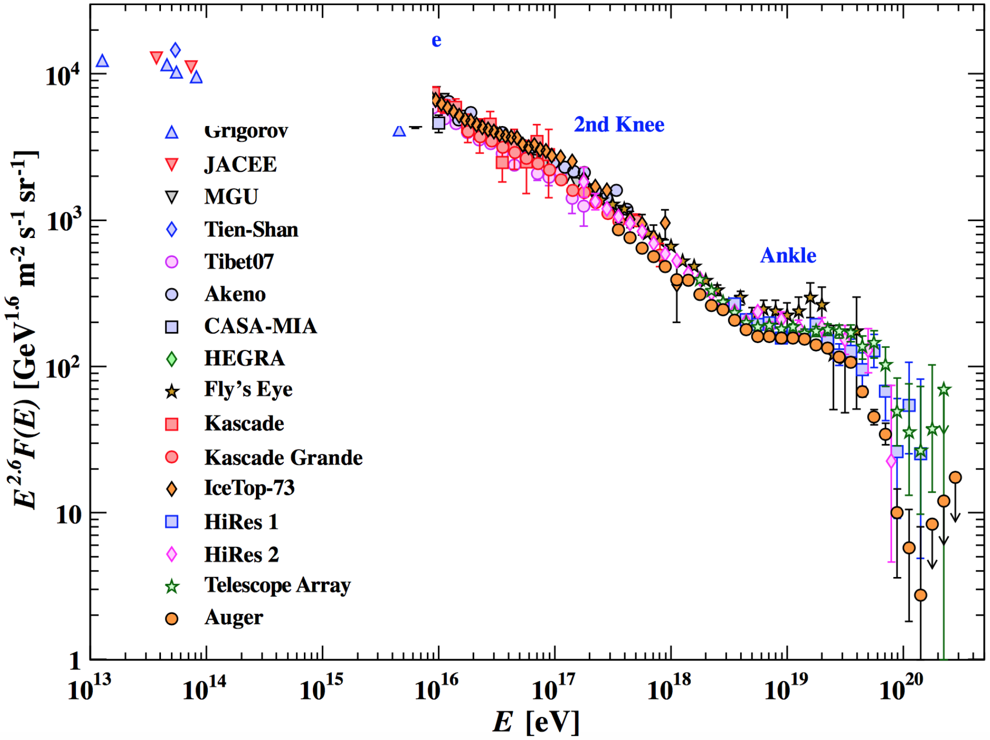
Des Rayonnements Cosmiques (RC)...

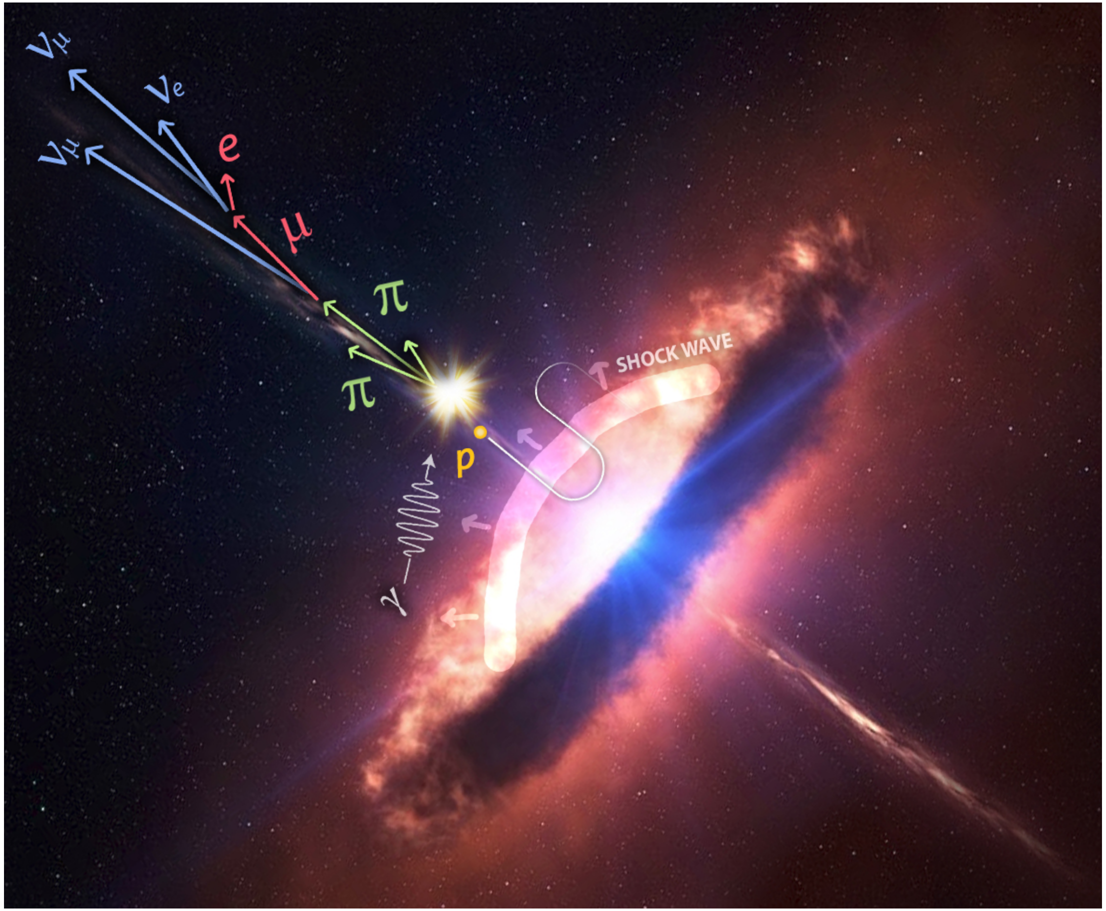




Des Rayons Cosmiques hadroniques

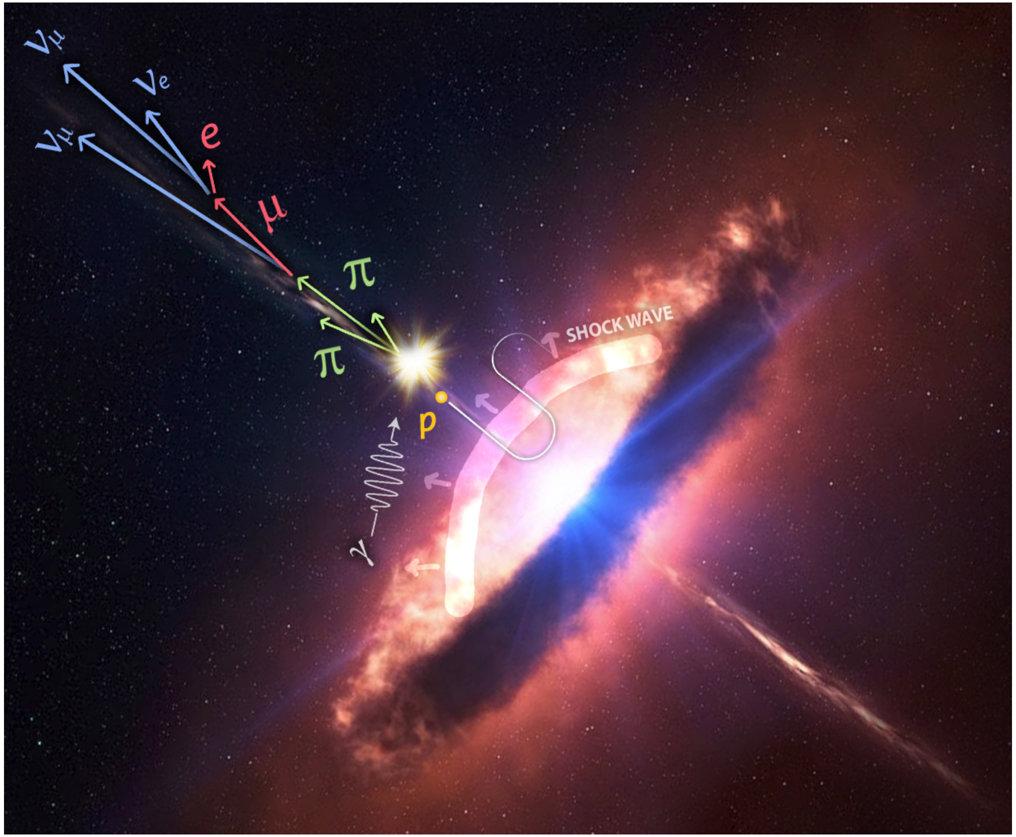
...aux Neutrinos (HEN)...

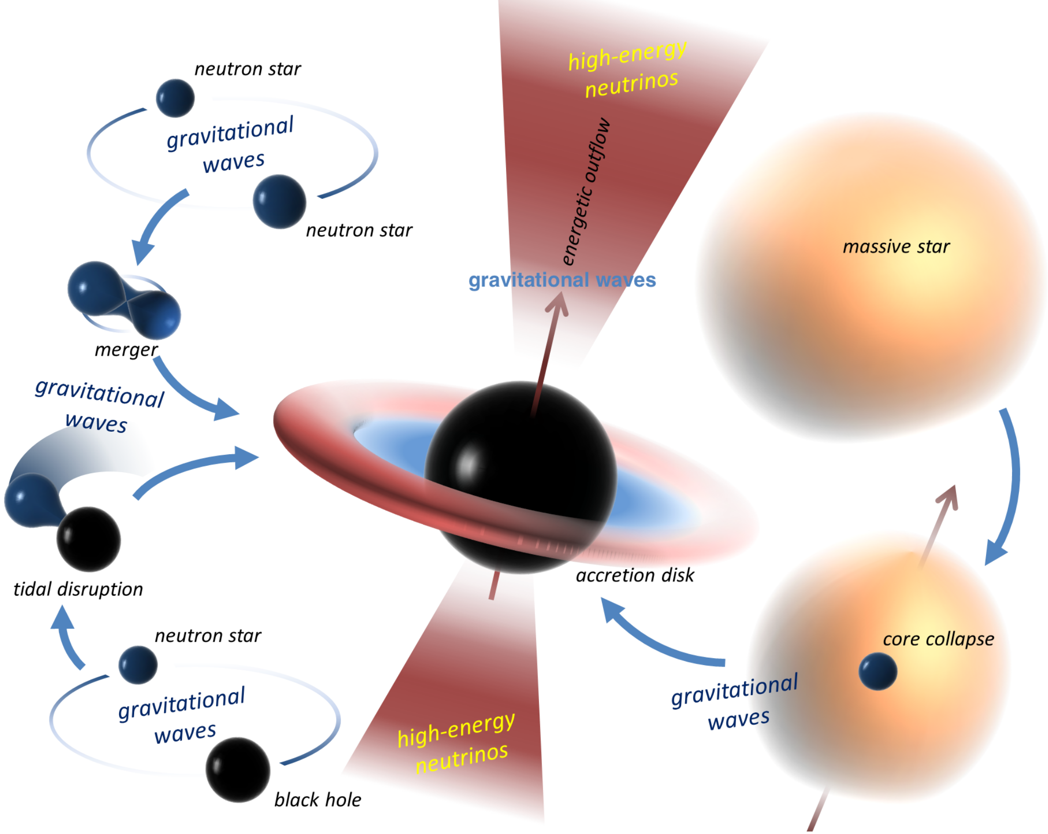




Le neutrino comme *sonde* des sources de RC

...et aux Ondes Gravitationnelles : des sources similaires



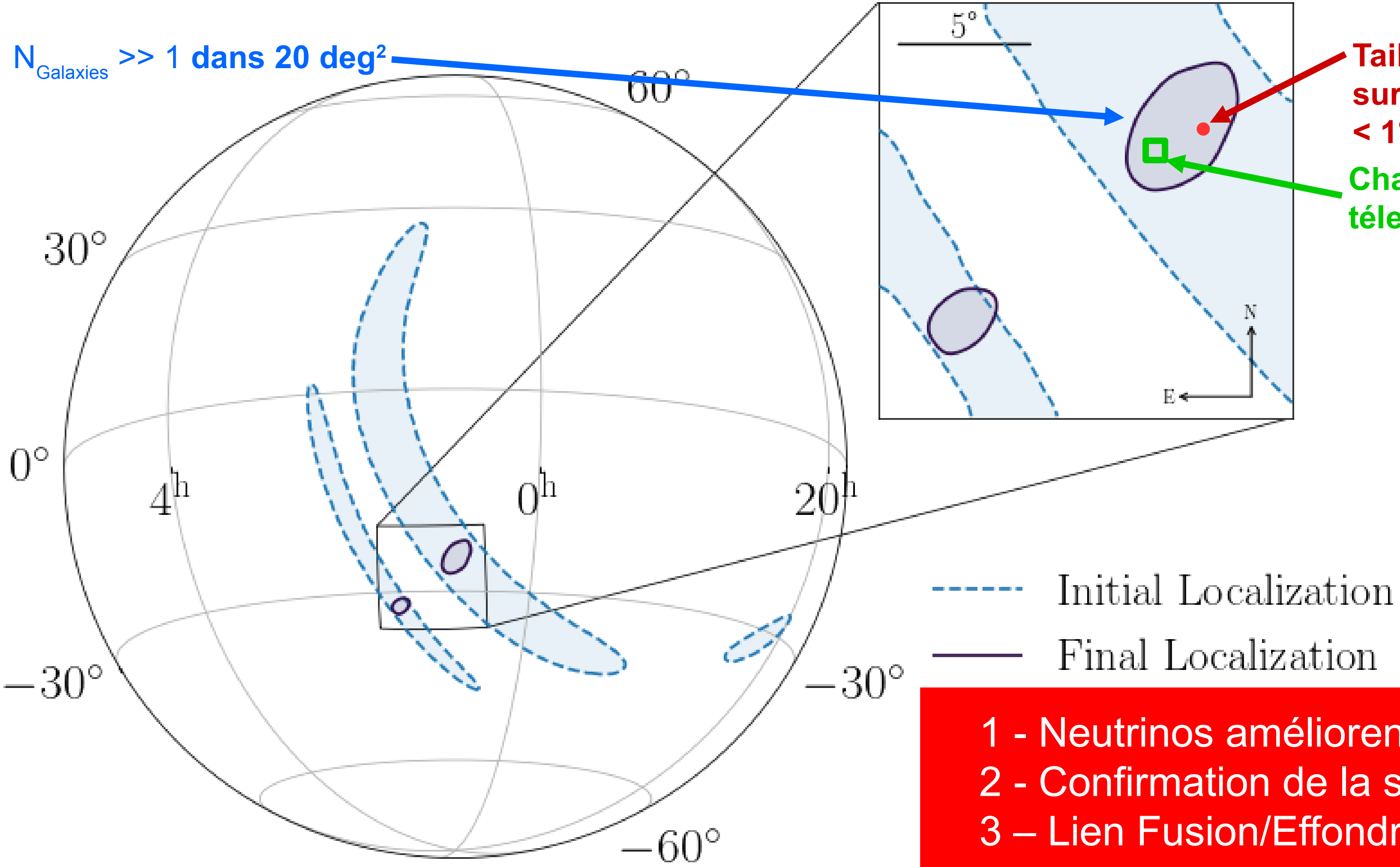


Sources HEN

Sources GW → HEN

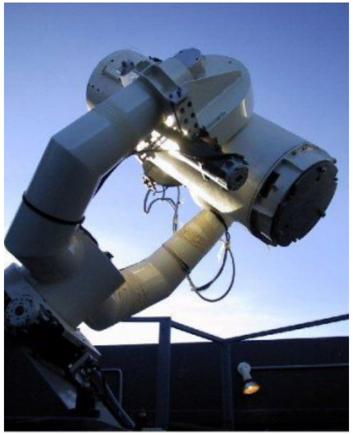
Neutrinos & Ondes Gravitationnelles : intérêt conjoint

$N_{Galaxies}$ >> 1 dans 20 deg²



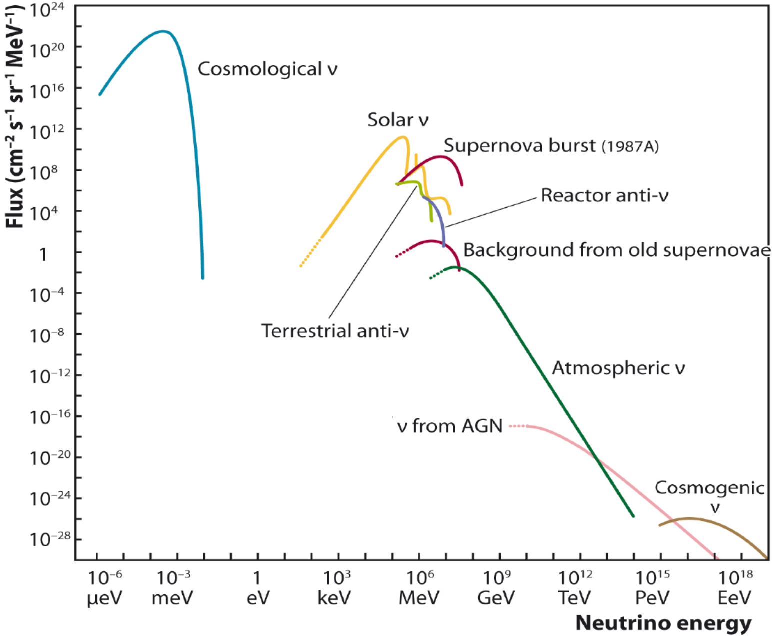
Taille typique de l'erreur sur la direction d'un neutrino < 1° x 1°

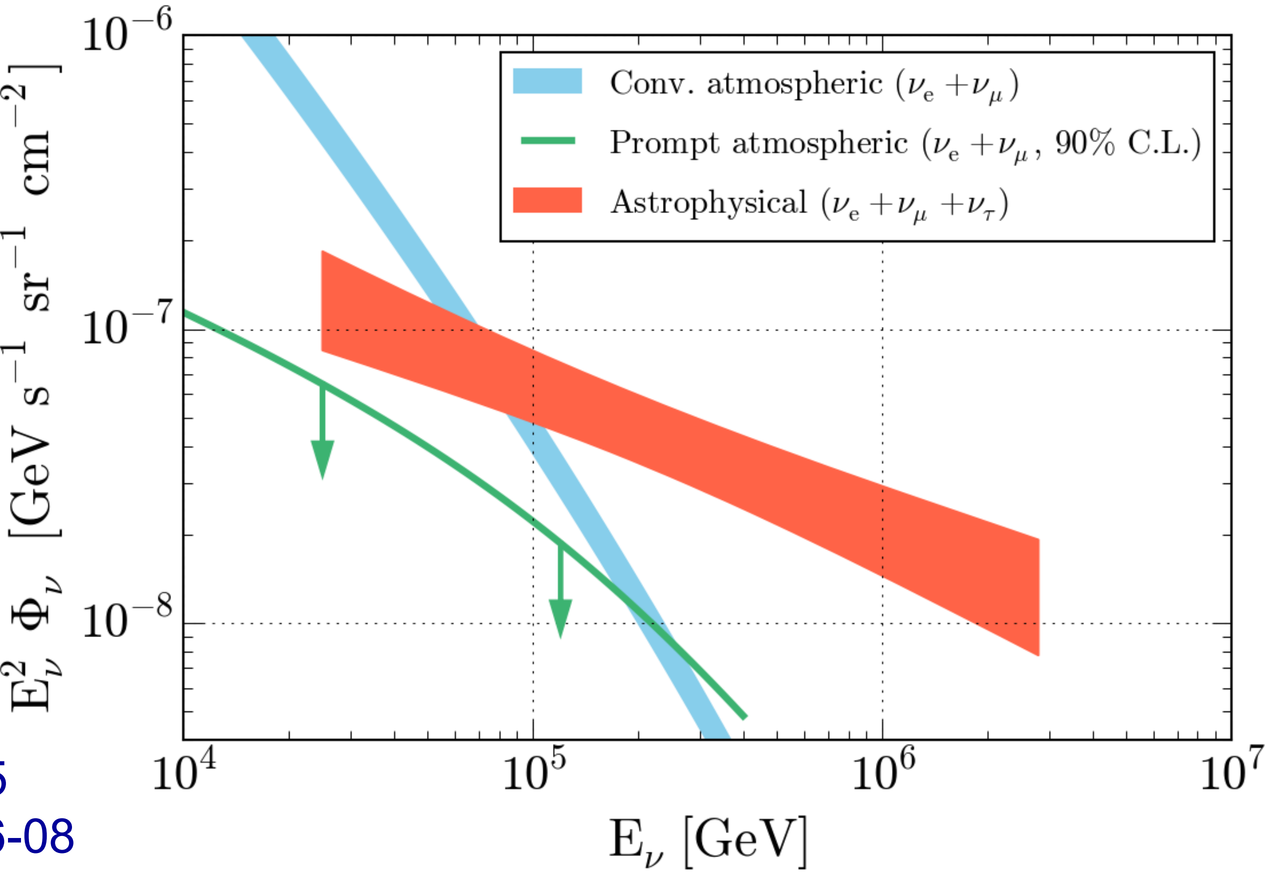
Champ de vue typique d'un télescope optique ~1° x 1°



1 - Neutrinos améliorent la *localisation*
2 - Confirmation de la source Neutrinos
3 – Lien Fusion/Effondrement → Ejection

Une science récente, pour les observations



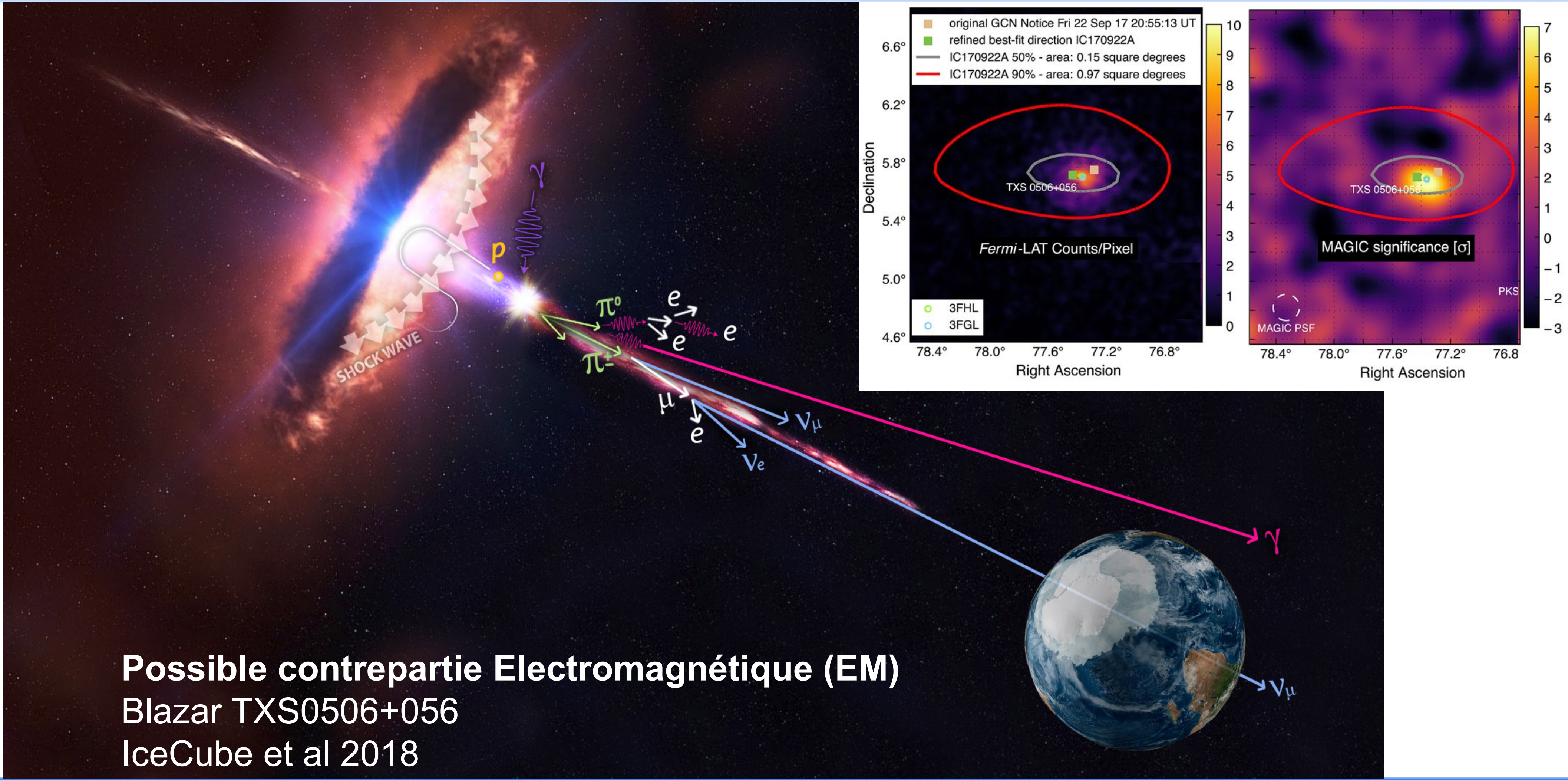


- DUMAND/AMANDA – 1976 → 1995
- ANTARES – Proposal 1999 → 2006-08

- IceCube – 2005 → fin de construction 2010

Observation d'un flux diffus de neutrinos astrophysiques : IceCube 2013

Une science récente, pour les observations



Possible contrepartie Electromagnétique (EM)

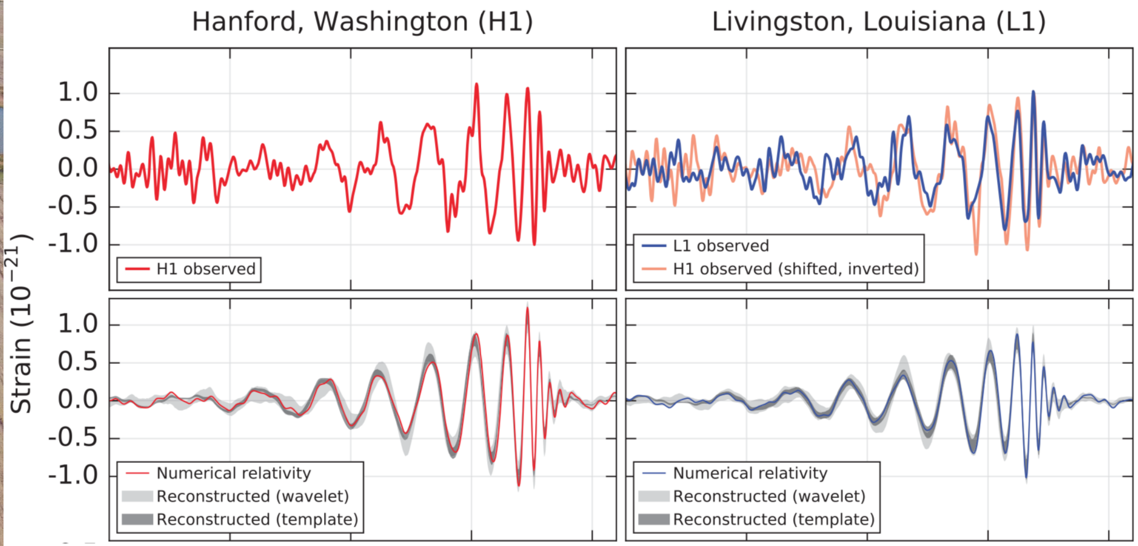
Blazar TXS0506+056

IceCube et al 2018

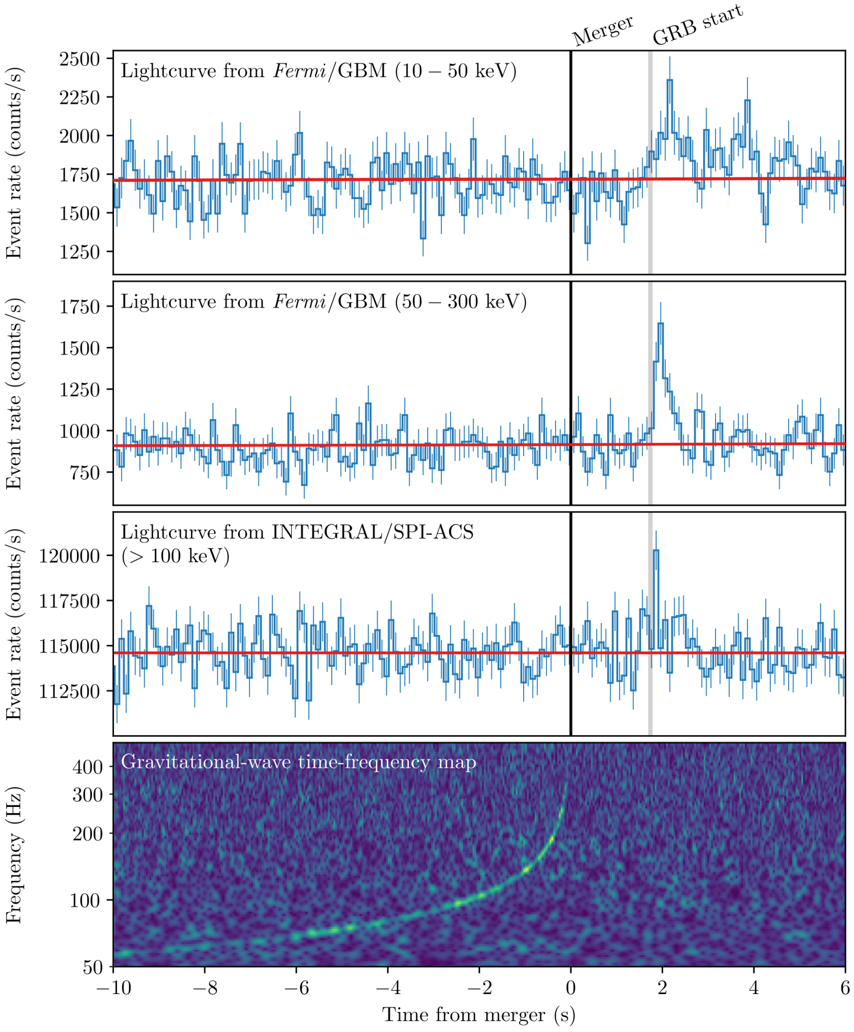
Une science récente, pour les observations

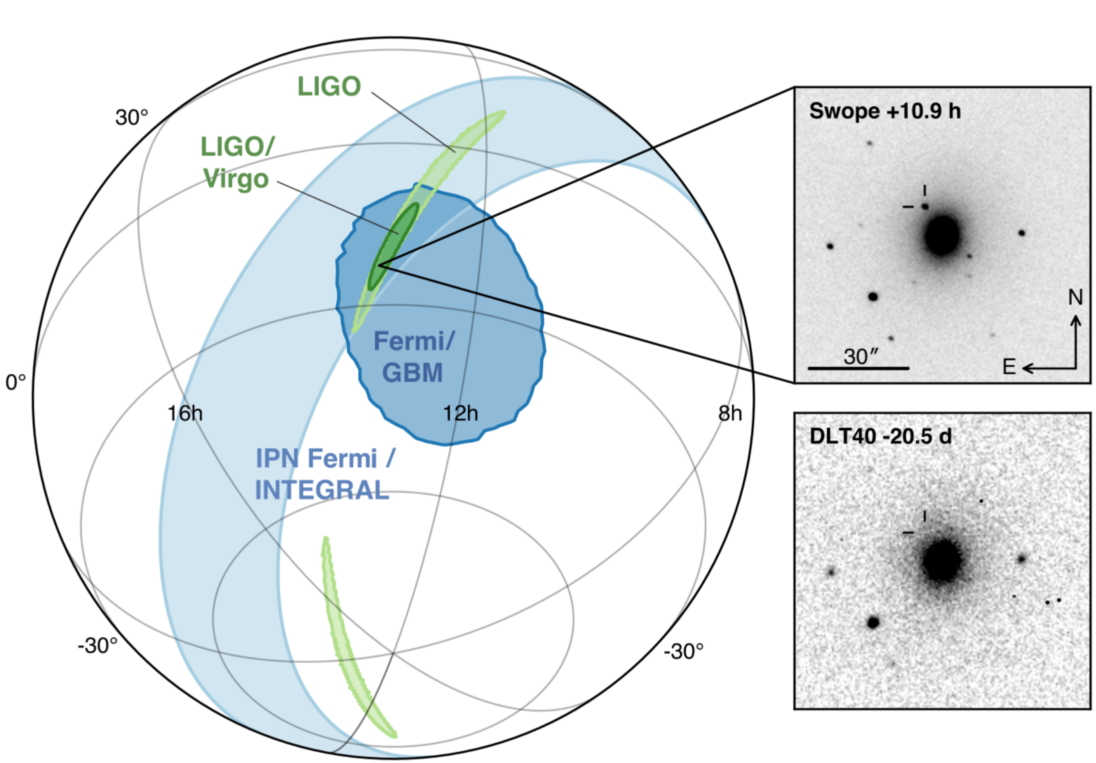
- 1960s : barres de « Weber »
- 1990 : Approbation de LIGO (US)
- 1993-4 : Approbation de Virgo (Fr-It)

1er signal GW observé : 2015
GW150914



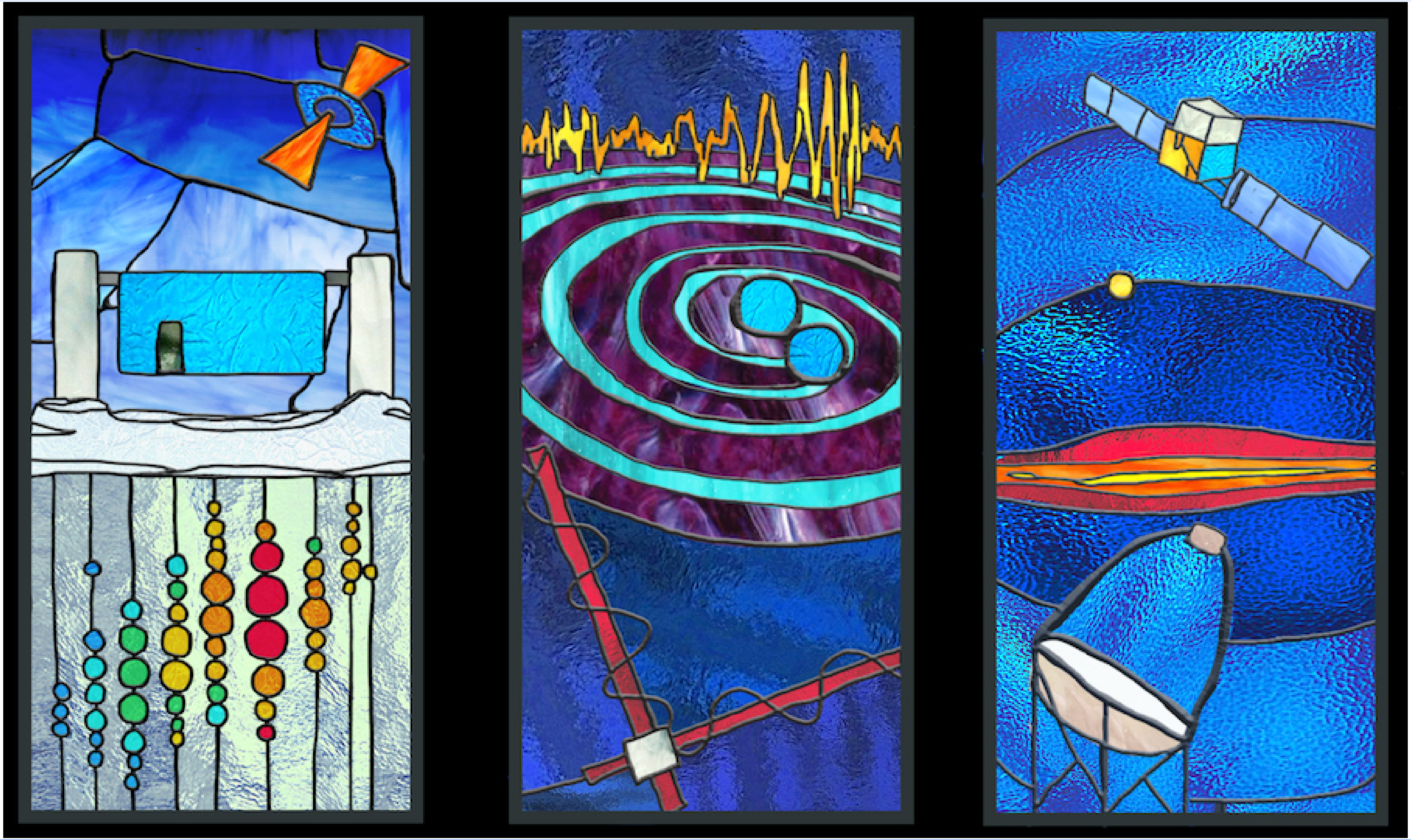
Une science récente, pour les observations



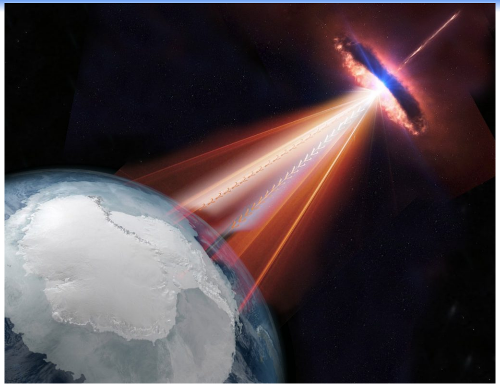


1ère contrepartie EM : 2017
GW170817

Des connexions EM-GW-HEN établies, à confirmer ou établir...



Des connexions EM-GW-HEN établies, à confirmer ou établir...



HEN Astronomy
GeV-EeV
ANTARES, KM3NeT/ARCA, IceCube

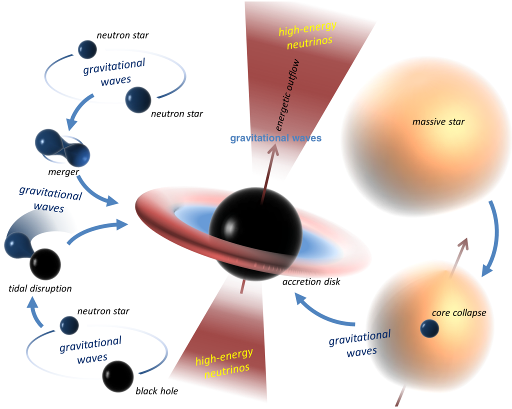
γ-ray Astronomy
Fermi, HESS, CTA...

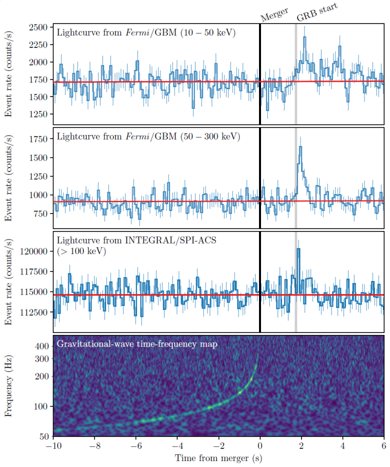
GW Astronomy
LIGO, Virgo, KAGRA

Connexion GW-HEN
→ à établir

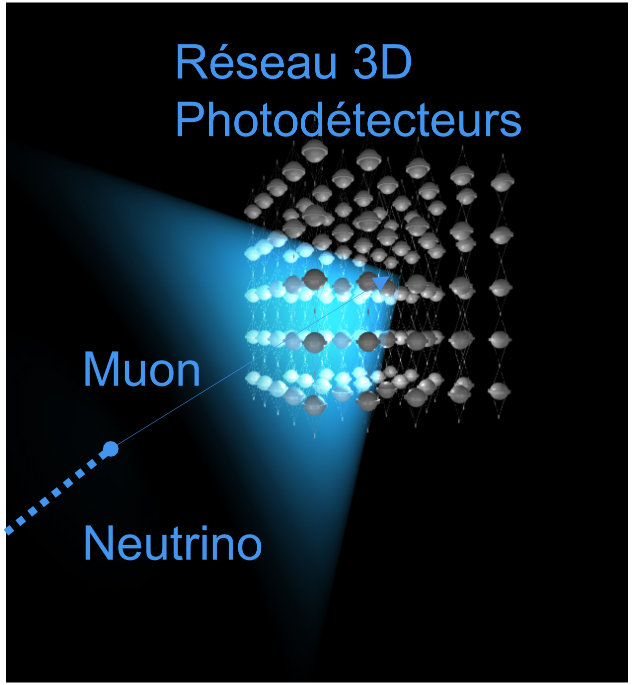
Connexion EM-HEN
TXS0506+056
→ 2018 - à confirmer

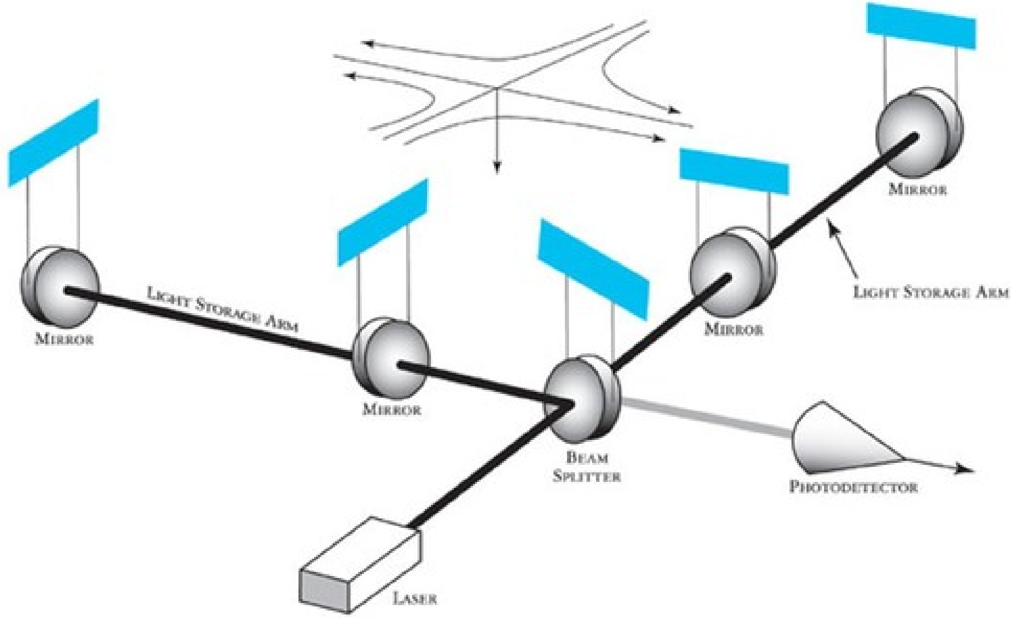
Connexion EM-GW
GW170817
→ établie 2017

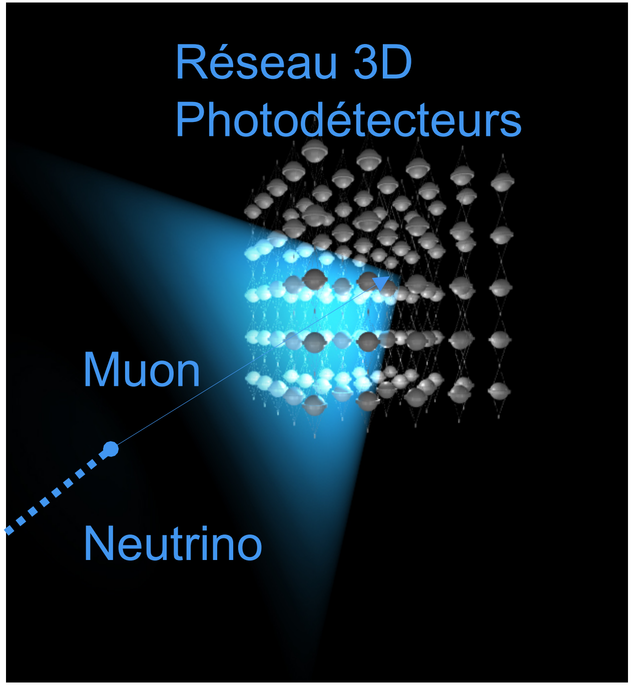


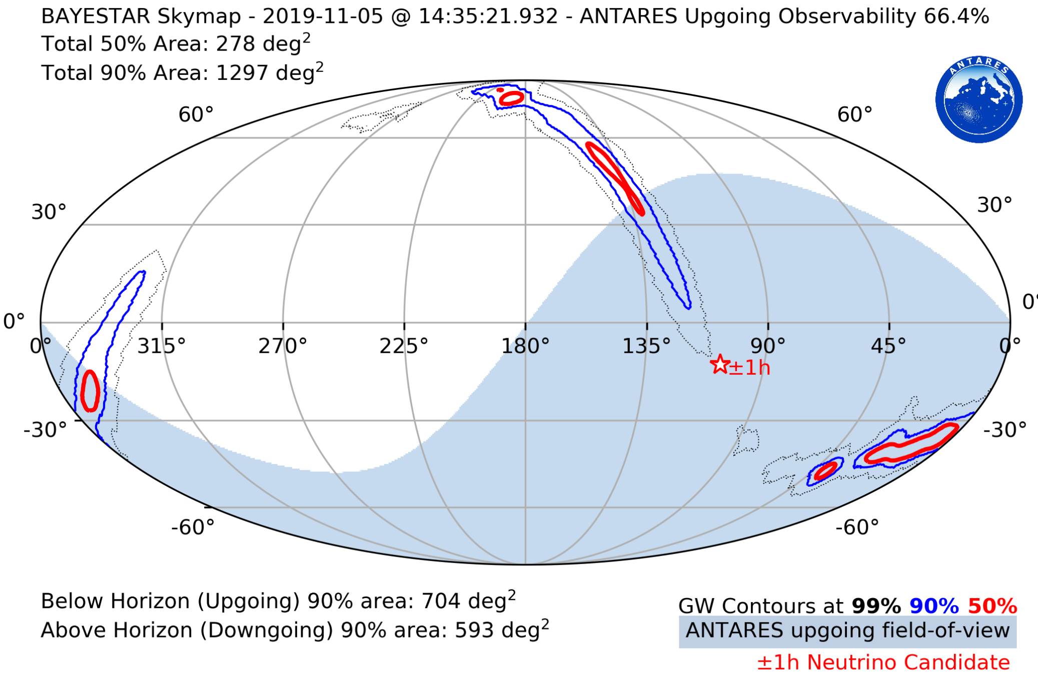


Partie I – La Science « Astroparticules » à l'IPHC





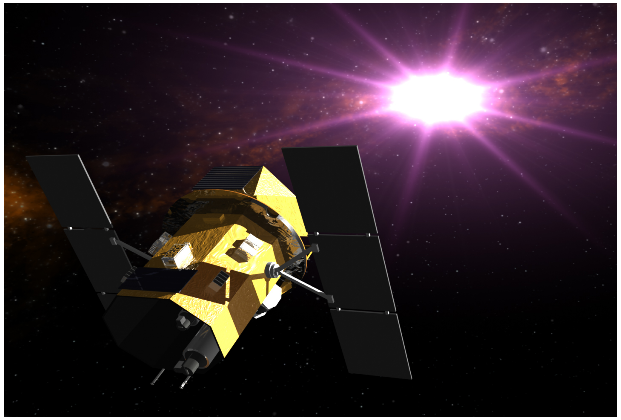


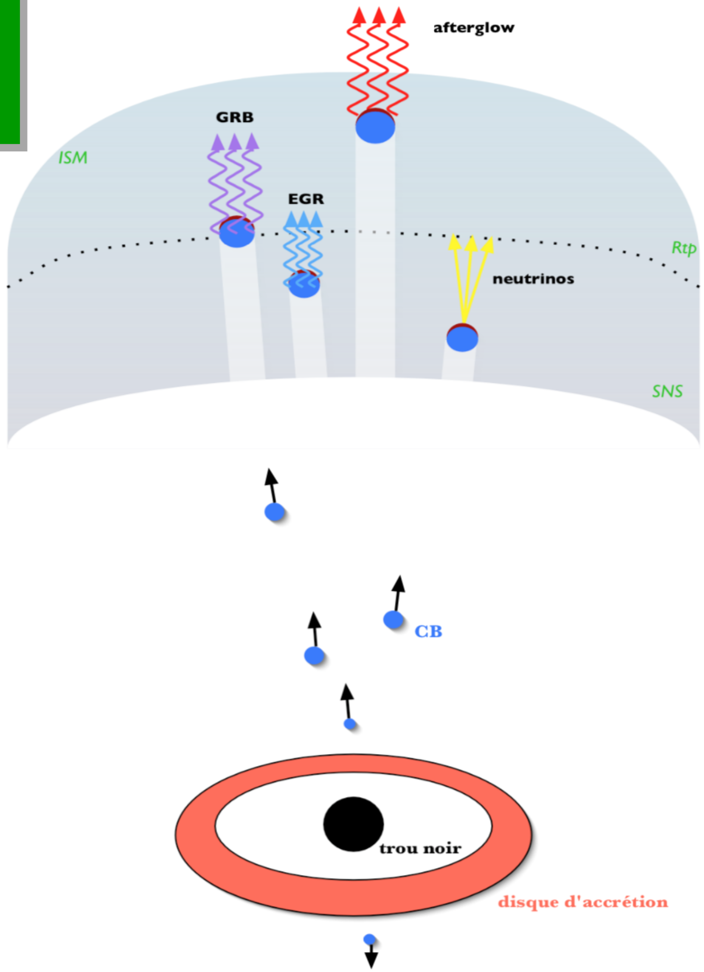


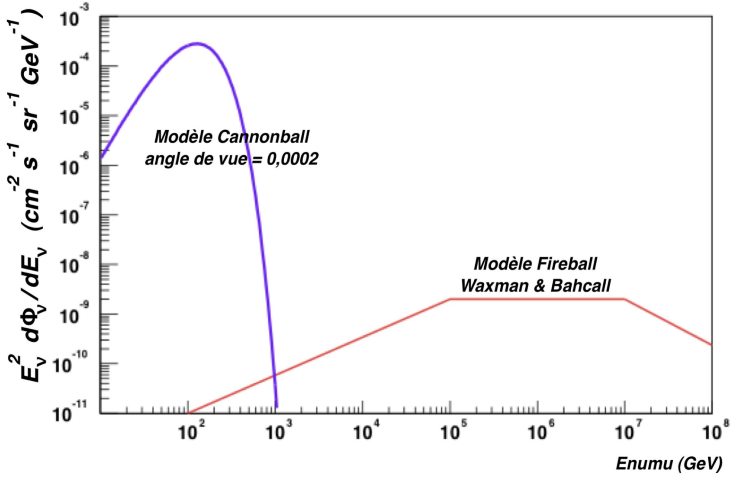
I.1 – Science Neutrinos HE
Activités Analyse/ANTARES-KM3NeT @ IPHC

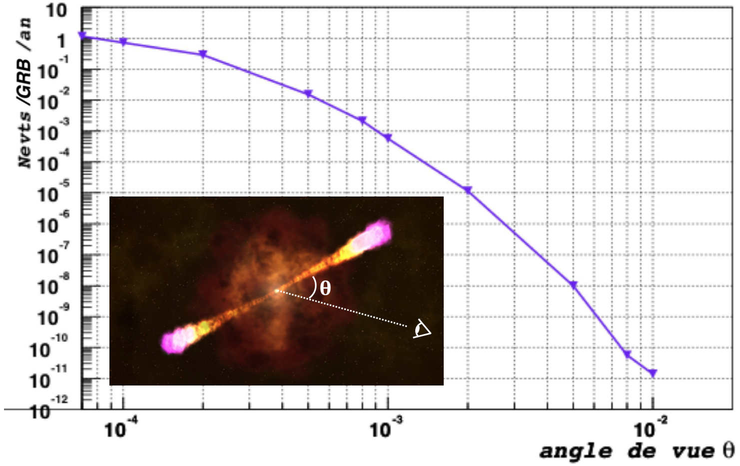
Des Analyses Neutrinos Multi-Messagers

Avant le déploiement d'ANTARES
Sursauts gammas: des γ aux HEN
Prédictions pour ANTARES





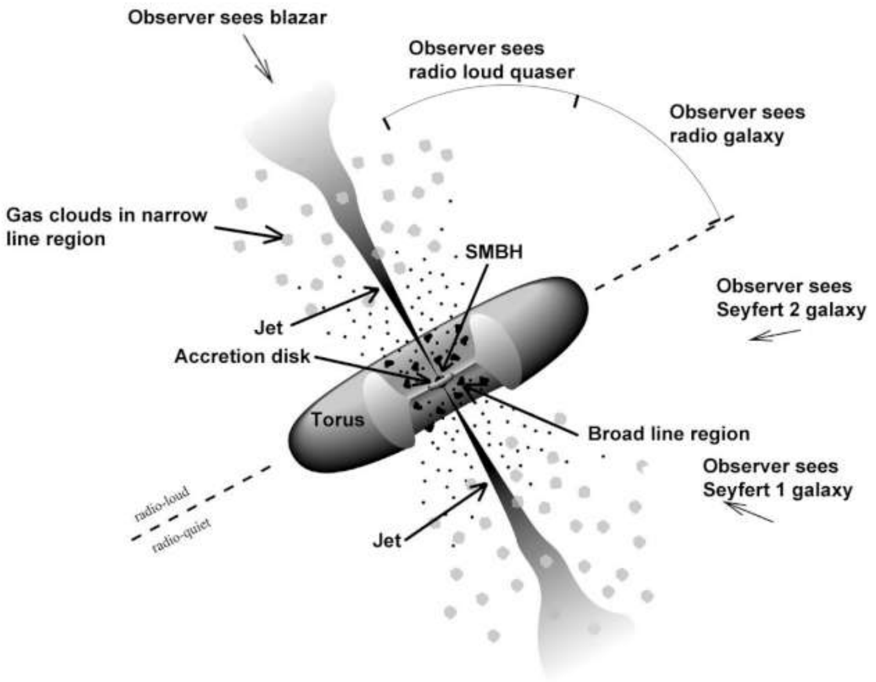


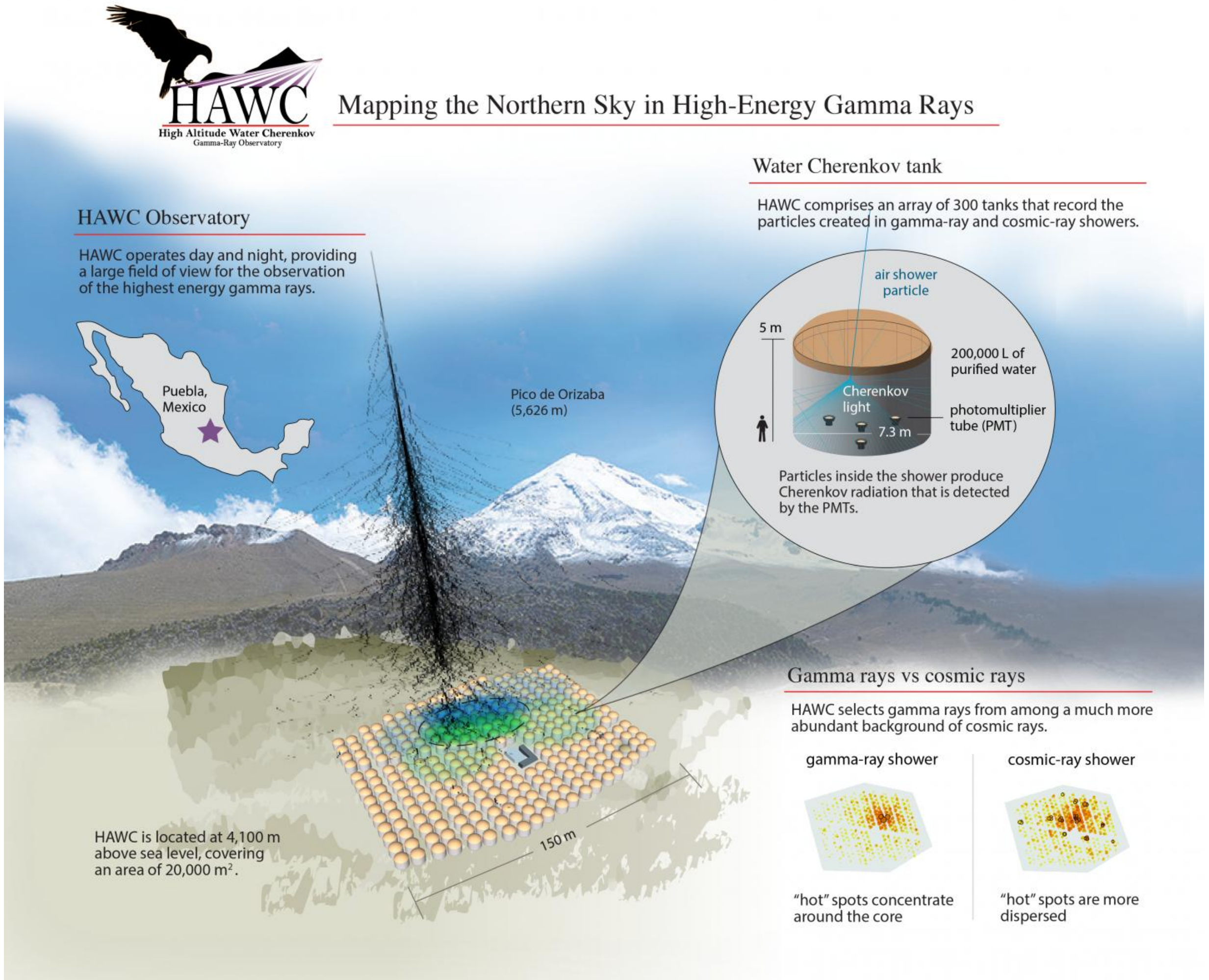


1ère thèse 2001-04
S. Ferry

Des Analyses Neutrinos Multi-Messagers

Depuis le déploiement d'ANTARES
AGN : des γ aux HEN
Observations avec ANTARES

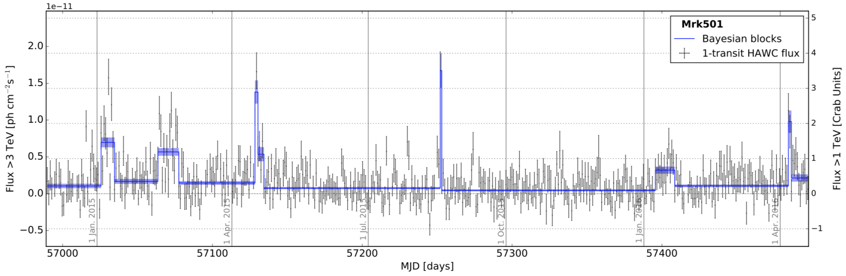


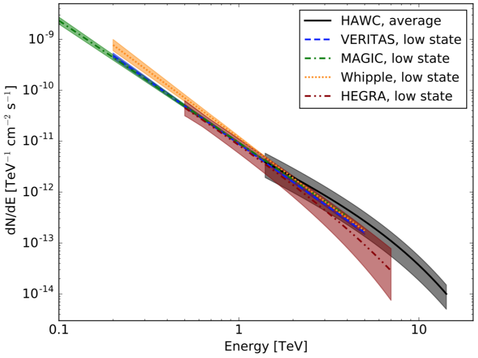


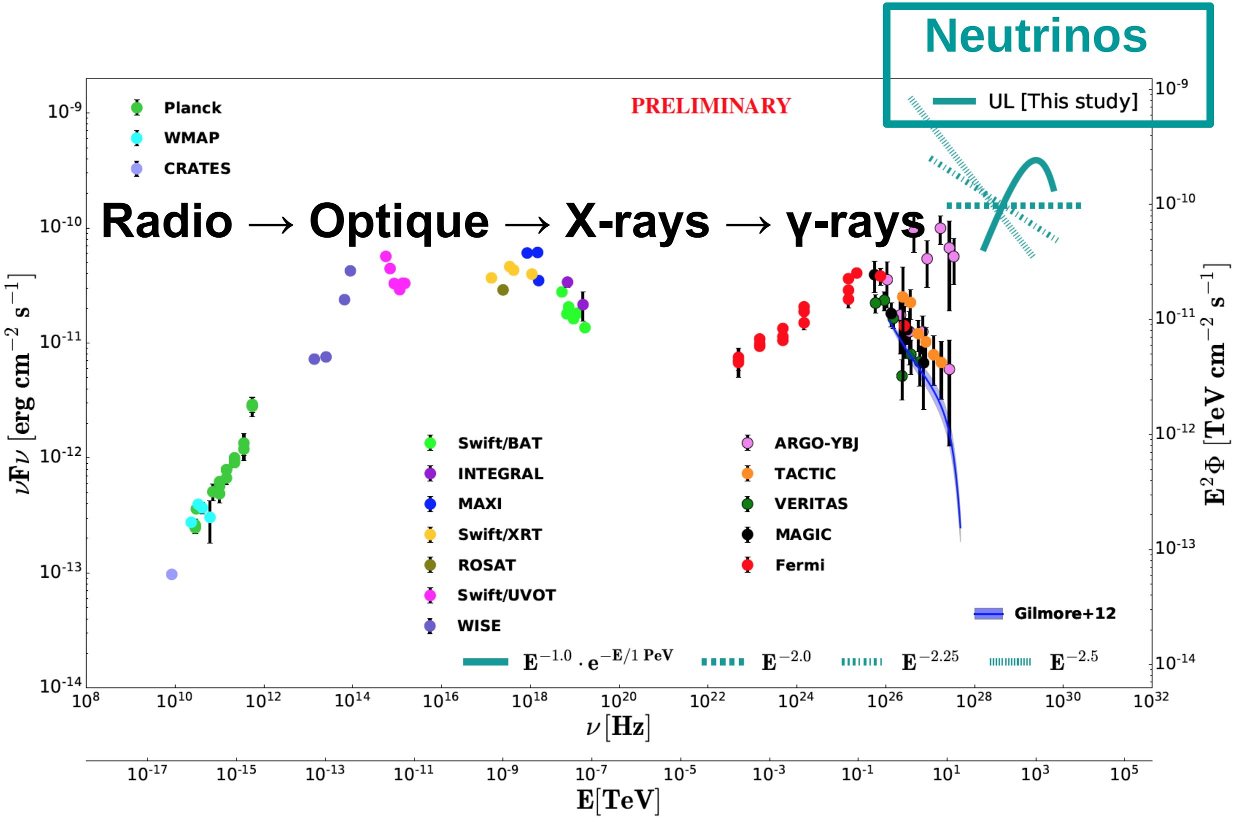
Dernière thèse 2016-19
M. Organokov

Des Analyses Neutrinos Multi-Messagers

Depuis le déploiement d'ANTARES
AGN : des γ aux HEN
Observations avec ANTARES



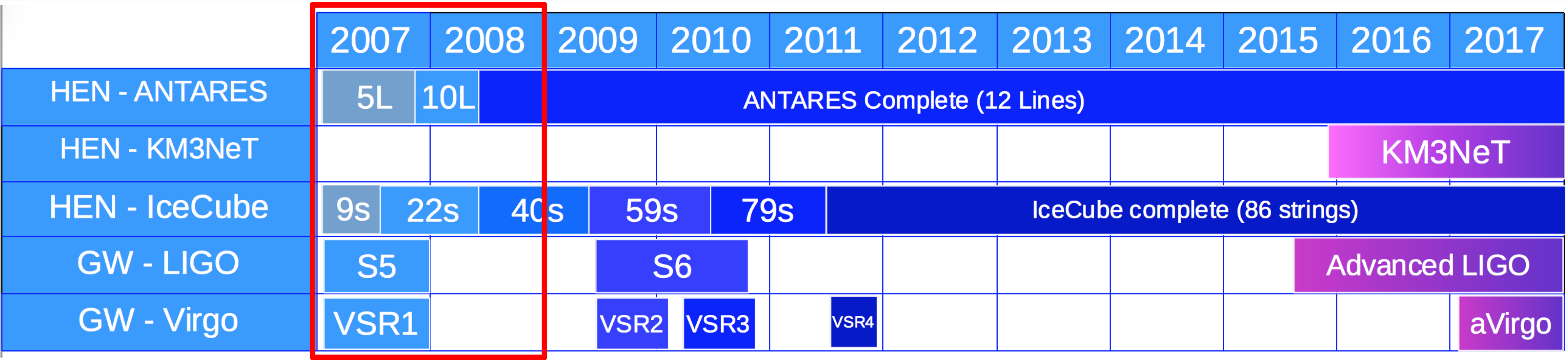




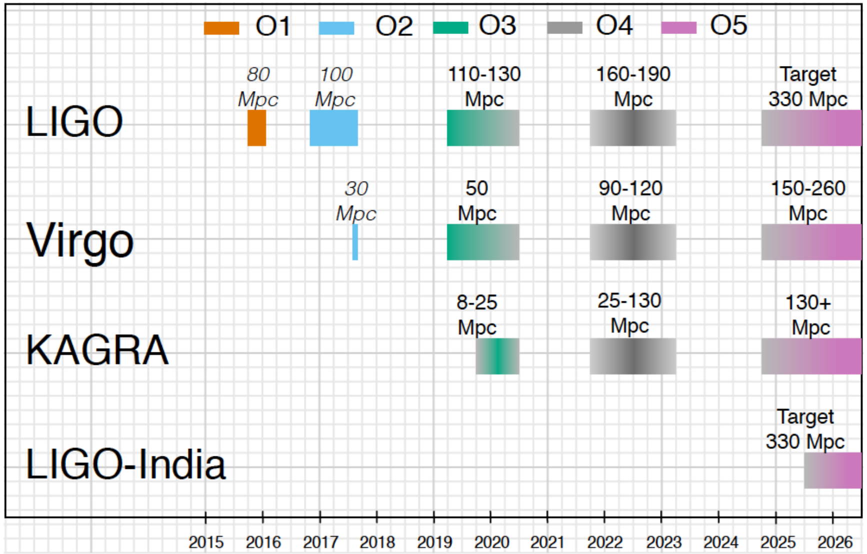
Dernière thèse 2016-19
M. Organokov

Mrk 501 – Données 2014-2017

GW+HEN – GWHEN dans le temps



Proposition des coïncidences



- Phase « initiale » : 2007-2011
- Phase « avancée » : depuis 2015
  → O1 → O5

GWHEN : de la faisabilité...

IOP Publishing — Classical and Quantum Gravity

Class. Quantum Grav. 25 (2008) 114039 (9pp) doi:10.1088/0264-9381/25/11/114039

Search method for coincident events from LIGO and IceCube detectors

Yoichi Aso[1], Zsuzsa Márka[1], Chad Finley[2], John Dwyer[1], Kei Kotake[3] and Szabolcs Márka[1]

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[2] Department of Physics, University of Wisconsin, Madison, WI 53706, USA
[3] Division of Theoretical Astronomy, National Astronomical Observatory of Japan, Mitaka, Tokyo, Japan

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Received 1 November 2007, in final form 31 January 2008
Published 15 May 2008
Online at stacks.iop.org/CQG/25/114039

Abstract

We present a coincidence search method for astronomical events using gravitational wave detectors in conjunction with other astronomical observations. We illustrate our method for the specific case of the LIGO gravitational wave detector and the IceCube neutrino detector. LIGO trigger events and IceCube events which occur within a given time window are selected as time-coincident events. Then the spatial overlap of the reconstructed event directions is evaluated using an unbinned maximum likelihood method. Our method was tested with Monte Carlo simulations based on realistic LIGO and IceCube event distributions. We estimated a typical false alarm rate for the analysis to be 1 event per 435 years. This is significantly smaller than the false alarm rates of the individual detectors.

Contents lists available at ScienceDirect

ELSEVIER — Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Coincidences between gravitational wave interferometers and high energy neutrino telescopes

Thierry Pradier *

Institut Pluridisciplinaire Hubert Curien (IPHC/DRS), University Louis-Pasteur, Strasbourg, France

A R T I C L E I N F O

Available online 24 December 2008

Keywords:
Neutrino telescopes
Gravitational wave interferometers
X-ray binaries
Soft gamma repeaters

A B S T R A C T

Sources of gravitational waves (GW) and emitters of high energy neutrinos (HE ν) both involve compact objects and matter moving at relativistic speeds. GW emission requires a departure from spherical symmetry, which is the case if clumps of matter are accreted around black holes or neutron stars, and ejected in relativistic jets, where neutrinos are believed to be produced. Both messengers interact weakly with the surrounding matter, hence point directly to the heart of the engines that power these emissions. Coincidences between GW interferometers (e.g. VIRGO) and HE ν telescopes (e.g. ANTARES) would then give a unique insight on the physics of the most powerful objects in the Universe. The possibility, observability and detectability for such GW/HE ν coincidences are analysed.

Deux études indépendantes en 2007-2008
→ groupe de travail conjoint GWHEN

...à la réalisation : interféromètres initiaux (2007-2011)

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

A first search for coincident gravitational waves and high energy neutrinos using LIGO, Virgo and ANTARES data from 2007

The ANTARES collaboration, the LIGO scientific collaboration and the Virgo collaboration

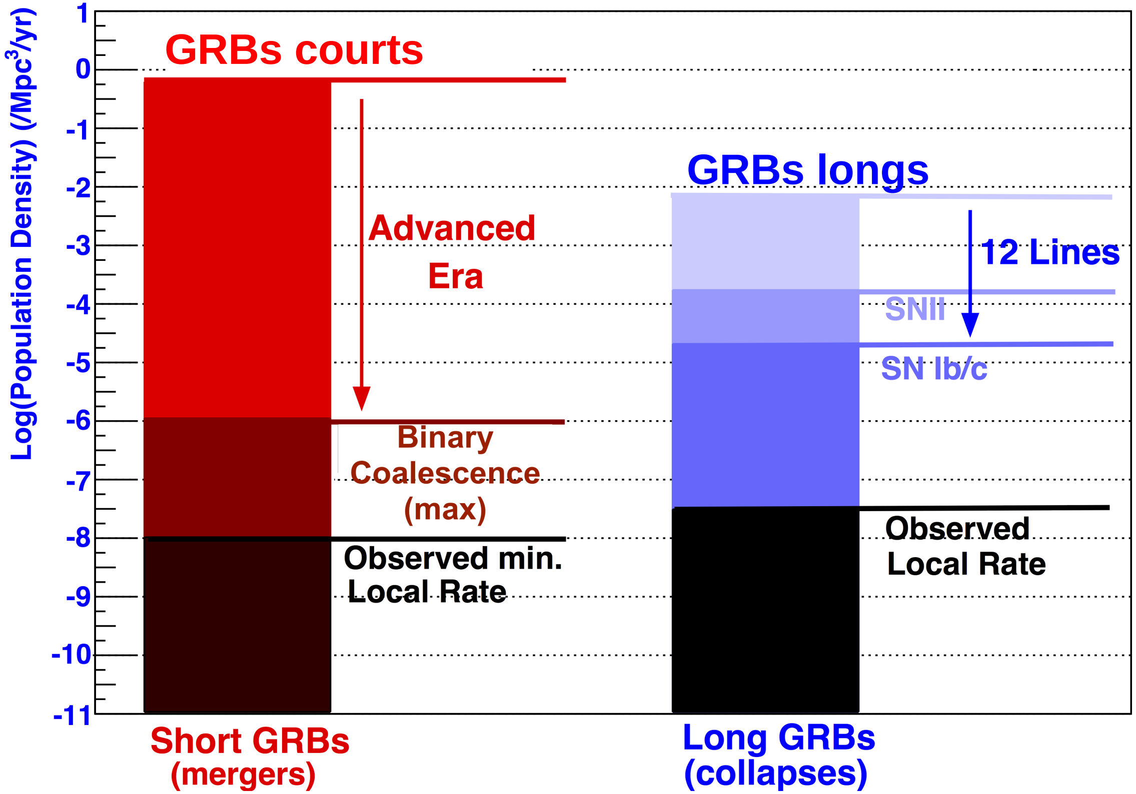
E-mail: antares.spokesperson@in2p3.fr, lsc-spokesperson@ligo.org, virgo-spokesperson@ego-gw.it, Irene.DiPalma@aei.mpg.de, thierry.pradier@iphc.cnrs.fr

Received April 8, 2013
Accepted April 22, 2013
Published June 7, 2013

3 Collaborations
~1000 auteurs

Abstract. We present the results of the first search for gravitational wave bursts associated with high energy neutrinos. Together, these messengers could reveal new, hidden sources that are not observed by conventional photon astronomy, particularly at high energy. Our search uses neutrinos detected by the underwater neutrino telescope ANTARES in its 5 line configuration during the period January - September 2007, which coincided with the fifth and first science runs of LIGO and Virgo, respectively. The LIGO-Virgo data were analysed for candidate gravitational-wave signals coincident in time and direction with the neutrino events. No significant coincident events were observed. We place limits on the density of joint high energy neutrino - gravitational wave emission events in the local universe, and compare them with densities of merger and core-collapse events.

JCAP06(2013)008



Limites sur les densités de sources conjointes GW+HEN (/volume/temps)

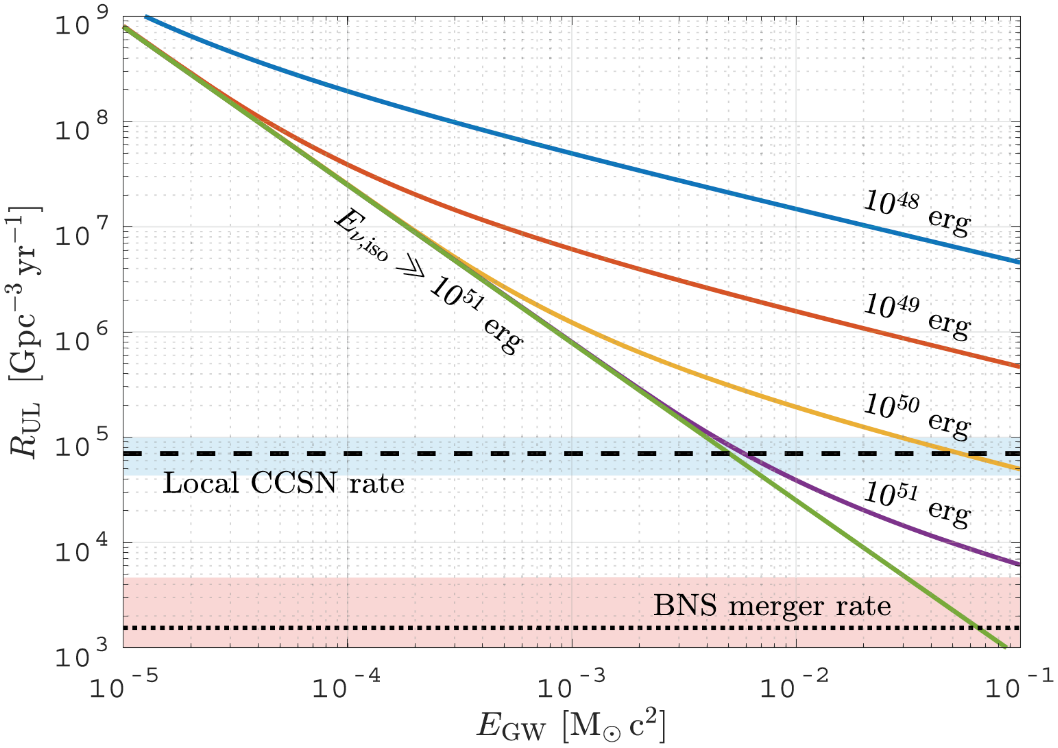
...à la réalisation : interféromètres avancés (depuis 2015)

THE ASTROPHYSICAL JOURNAL, 870:134 (16pp), 2019 January 10
https://doi.org/10.3847/1538-4357/aaf21d

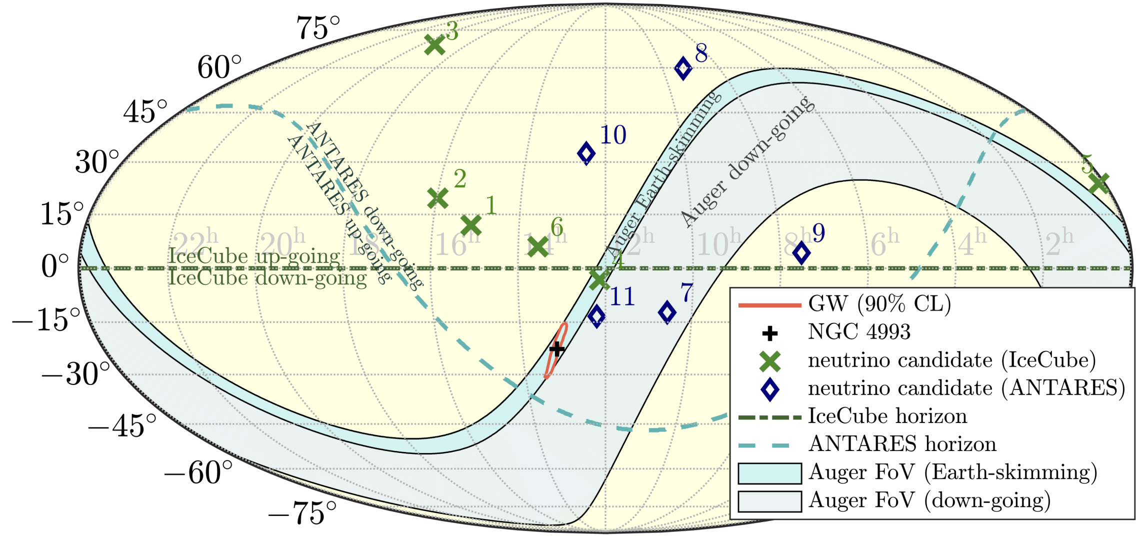
Search for Multimessenger Sources of Gravitational Waves and High-energy Neutrinos with Advanced LIGO during Its First Observing Run, ANTARES, and IceCube

A. Albert[1], M. André[2], M. Anghinolfi[3], M. Ardid[4], J.-J. Auber
B. Belhorma[9], V. Bertin[5], S. Biagi[10], R. Bormuth[11,12], J. Boum
J. Brunner[5], J. Busto[5], A. Capone[16,17], L. Caramete[14], J. C
T. Chiarusi[20], M. Circella[21], J. A. B. Coelho[6], A. Coleiro[6,7], M.
A. F. Díaz[22], A. Deschamps[23], C. Distefano[10], I. Di Palma[16,17],
T. Eberl[26], I. El Bojaddaini[27], N. El Khayati[13], D. Elsässer[28], A
G. Ferrara[10], L. Fusco[6,29], P. Gay[6,30], H. Glotin[31], T. Grégoir
A. J. Heijboer[11], Y. Hello[23], J. J. Hernández-Rey[7], J. Hößl
M. Kadler[28], O. Kalekin[26], U. Katz[26], N. R. Khan-
V. Kulikovskiy[3,35], C. Lachaud[6], R. Lahmann[26], D. Lefèvre
G. Maggi[5], M. Marcelin[8], A. Margiotta[20,29], A. Marinelli
P. Migliozzi[42], A. Moussa[27], S. Navas[44], E. Nezri[8], A.
P. Piattelli[10], V. Popa[14], T. Pradier[1], L. Quinn[5], C. Racca[45],
I. Salvadori[5], D. F. E. Samtleben[11,12], M. Sanguineti[3,24], P.
M. Taiuti[3,24], Y. Tayalati[13], A. Trovato[10], B. Vallage[6,39], V.
D. Zaborov[5], J. D
(ANTARES

4 Collaborations
~1500 auteurs

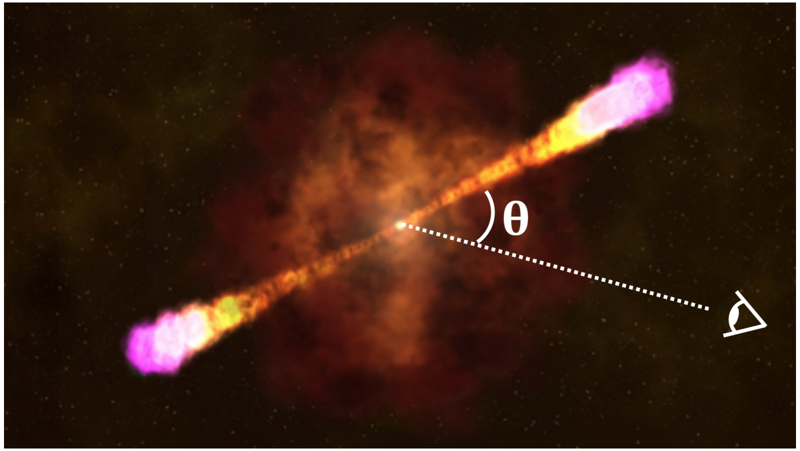


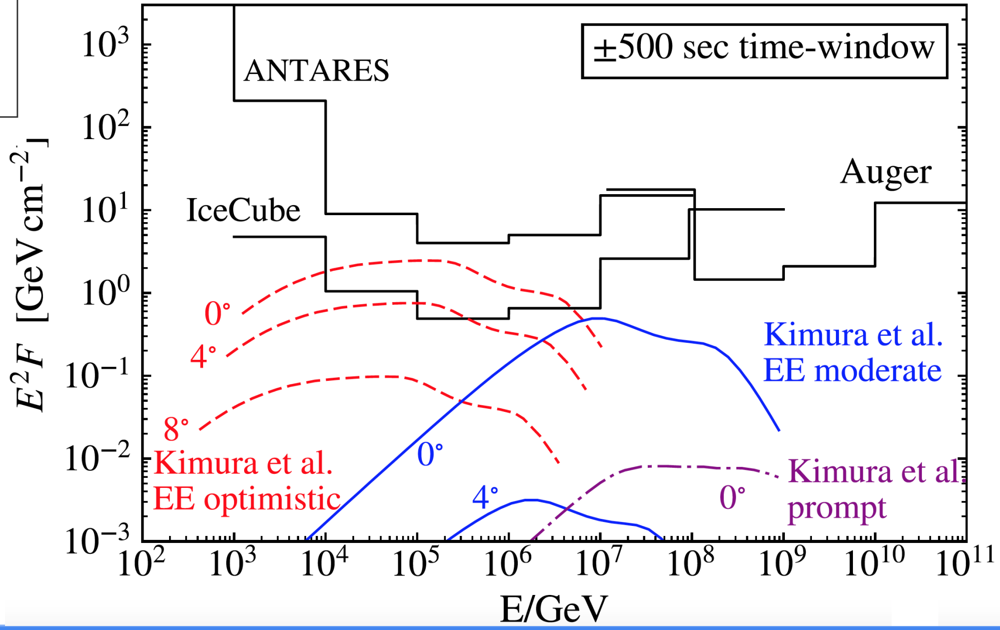
...à la réalisation : interféromètres avancés (depuis 2015)



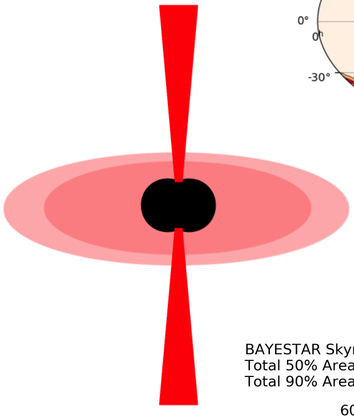
GW170817 : 1ère recherche de neutrinos en provenance d'une fusion de 2 étoiles à neutrons

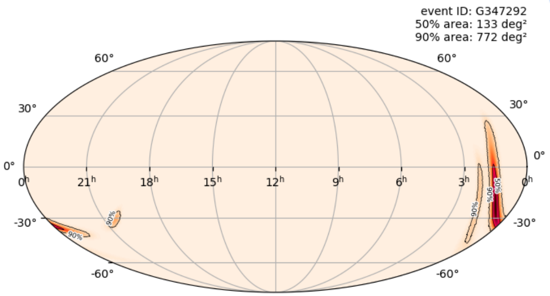
5 Collaborations
~2000 auteurs

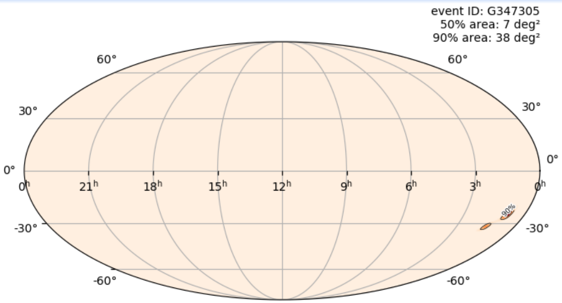




D'O2 à O3 : traitement automatisé des alertes LIGO/Virgo

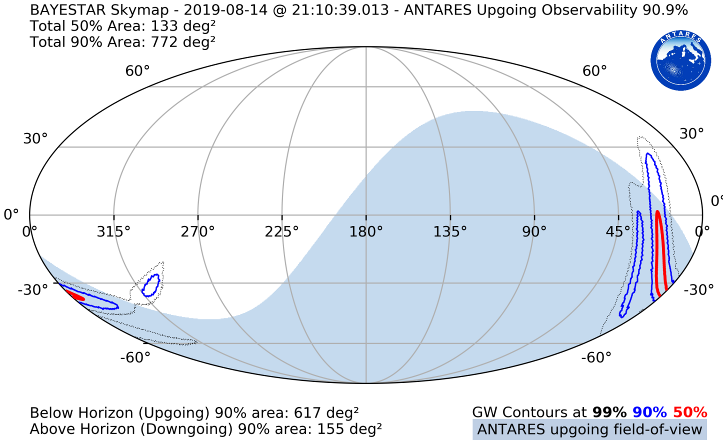


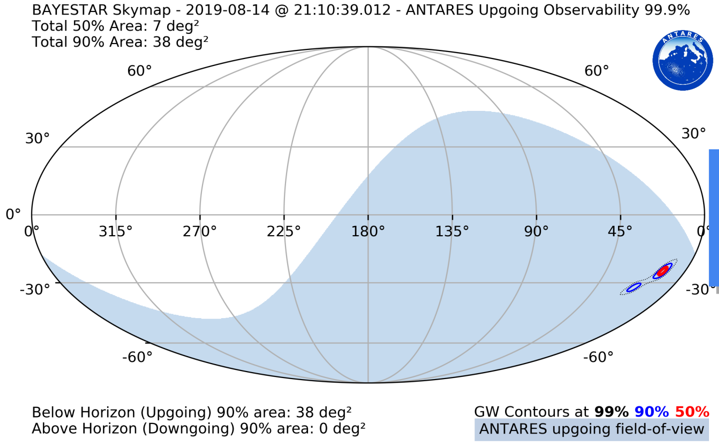




Virgo/LIGO

t_{alert} + 21min — t_{alert} +2h





ANTARES

Traitement + Résultats dès réception → GCN dès la vérification humaine effectuée...

D'O2 à O3 : traitement automatisé des alertes LIGO/Virgo

```
////////////////////////////////////////////////////////////////////////
TITLE:   GCN CIRCULAR
NUMBER:  25324
SUBJECT: LIGO/Virgo S190814bv: Identification of a GW compact binary merger candidate
DATE:    19/08/14 23:39:31 GMT
FROM:    Geoffrey Mo at LIGO  <geoffrey.mo@ligo.org>

The LIGO Scientific Collaboration and the Virgo Collaboration report:

We identified the compact binary merger candidate S190814bv during
real-time processing of data from LIGO Hanford Observatory (H1), LIGO
Livingston Observatory (L1), and Virgo Observatory (V1) at 2019-08-14
21:10:39.013 UTC (GPS time: 1249852257.013).
The candidate was found by the GstLAL [1], pycbc [2],
MBTAOnline [3], and CWB [4] analysis pipelines.

S190814bv is an event of interest because its false alarm rate, as
estimated by the online analysis, is 2e-33 Hz, or about one in 1e25
years. The event's properties can be found at this URL:

https://gracedb.ligo.org/superevents/S190814bv

The classification of the GW signal, in order of descending
probability, is MassGap (>99%), Terrestrial (<1%), BNS (<1%), BBH
(<1%), or NSBH (<1%). These values are based on
point mass estimates which assigns an estimate of 100% to a single
astrophysical class when the Terrestrial probability is very small.
We will provide updates based on parameter estimation as soon
as they become available.

Assuming the candidate is astrophysical in origin, there is strong
evidence against the lighter compact object having a mass < 3 solar
masses (HasNS: <1%). Using the masses and spins inferred from the
signal, there is strong evidence against matter outside the final
compact object (HasRemnant: <1%).

Two sky maps are available at this time and can be retrieved from the
GraceDB event page:
 * a sky map generated by BAYESTAR [5] using data from the
   Livingston and Virgo detectors, distributed via GCN notice about
   21 minutes after the candidate.
 * bayestar.fits.gz, an updated sky map generated by BAYESTAR using
   data from the Livingston, Hanford, and Virgo detectors, distributed
   about 2 hours after the candidate. This is the preferred skymap.
   The 90% credible region is 38 deg2. Marginalized over the whole sky,
   the a posteriori luminosity distance estimate is 276 +/- 56 Mpc
   (a posteriori mean +/- standard deviation).
```

GCN LIGO/Virgo 14/08 23h40
GCN ANTARES 15/08 8h21

***NB** – Pas d'urgence ici à publier la circulaire :*
→ pas de neutrino observé...

```
////////////////////////////////////////////////////////////////////////
TITLE:   GCN CIRCULAR
NUMBER:  25330
SUBJECT: LIGO/Virgo S190814bv : no neutrino counterpart candidate in ANTARES search
DATE:    19/08/15 08:21:11 GMT
FROM:    Antoine Kouchner at ANTARES Collaboration  <kouchner@apc.in2p3.fr>

M. Ageron (CPPM/CNRS), B. Baret (APC/CNRS), A. Coleiro (APC/Universite de Paris), M. Colomer (APC/Universite de
Paris), D. Dornic (CPPM/CNRS), A. Kouchner (APC/Universite de Paris), T. Pradier (IPHC/Universite de Strasbourg)
report on behalf of the ANTARES Collaboration:

Using on-line data from the ANTARES detector, we have performed a follow-up analysis of the
recently reported LIGO/Virgo S190814bv event using the 90% contour of the updated bayestar probability
map provided by the GW interferometers about two hours after the candidate (GCN#25324
<https://gcn.gsfc.nasa.gov/gcn3/25324.gcn3>).
The ANTARES visibility at the time of the alert, together with the 50% and 90% contours of the probability map
are shown at http://antares.in2p3.fr/GW/S190814bv.png <http://antares.in2p3.fr/GW/S190814bv.png>.
Considering the location probability provided by the LIGO/Virgo collaborations, there is a
99.9% chance that the GW emitter was in the ANTARES **upgoing** field of view at the time of the alert.

No up-going muon neutrino candidate events were recorded in the ANTARES sky during a
+/-500s time-window centered on the time 2019-08-14 21:10:39 and in the 90% contour of the S190814bv
event. The expected number of atmospheric background events in the region visible by ANTARES is
4.04e-05 in the +/- 500s time window. An extended search during +/- 1 hour gives no
up-going muon neutrino coincidence. The expected number of atmospheric background events in the
region visible by ANTARES is 2.91e-04 in this larger time window.

ANTARES is the largest undersea neutrino detector, installed in the Mediterranean Sea, and it is
primarily sensitive to neutrinos in the TeV-PeV  energy range. At 10 TeV, the median angular
resolution for muon neutrinos is about 0.5 degrees. In the range 1-100 TeV ANTARES has a
competitive sensitivity to this position in the sky.
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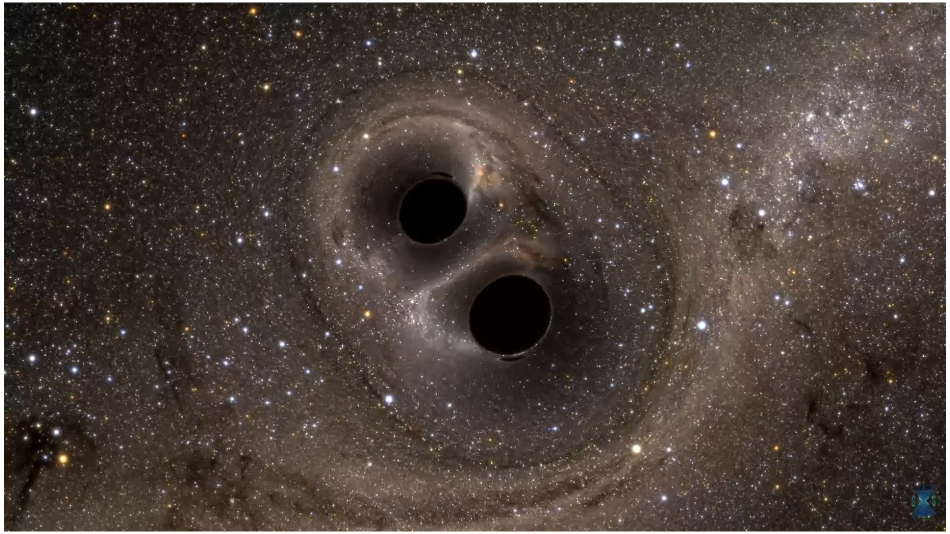
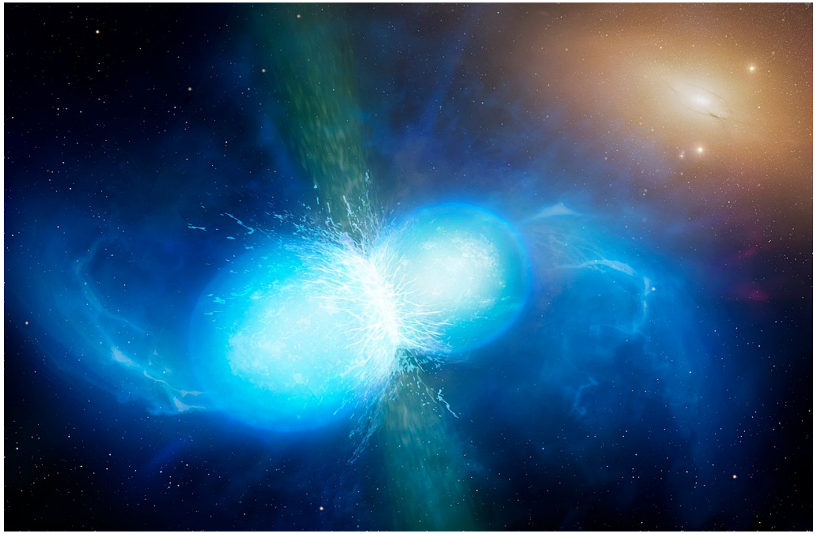
D'O3 à O4-O5 : un traitement individualisé des alertes GW ?

Binary Black Hole (BBH)

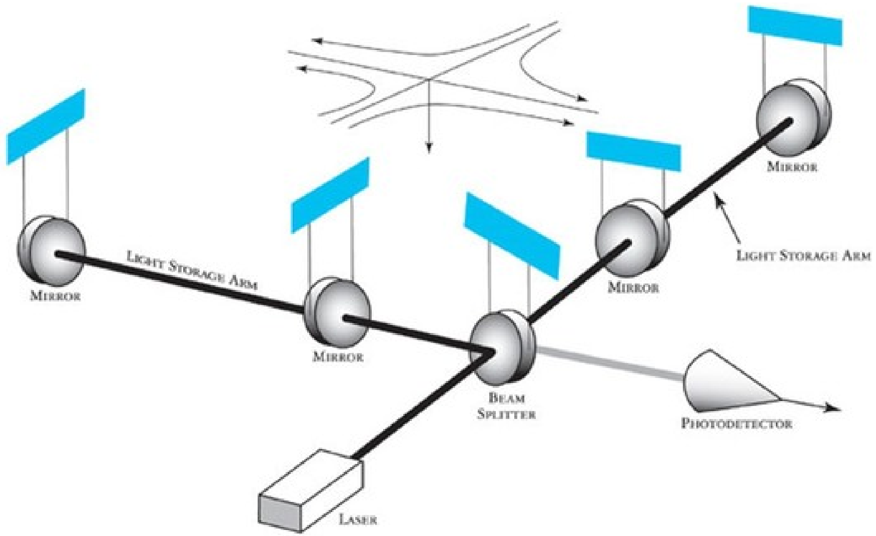


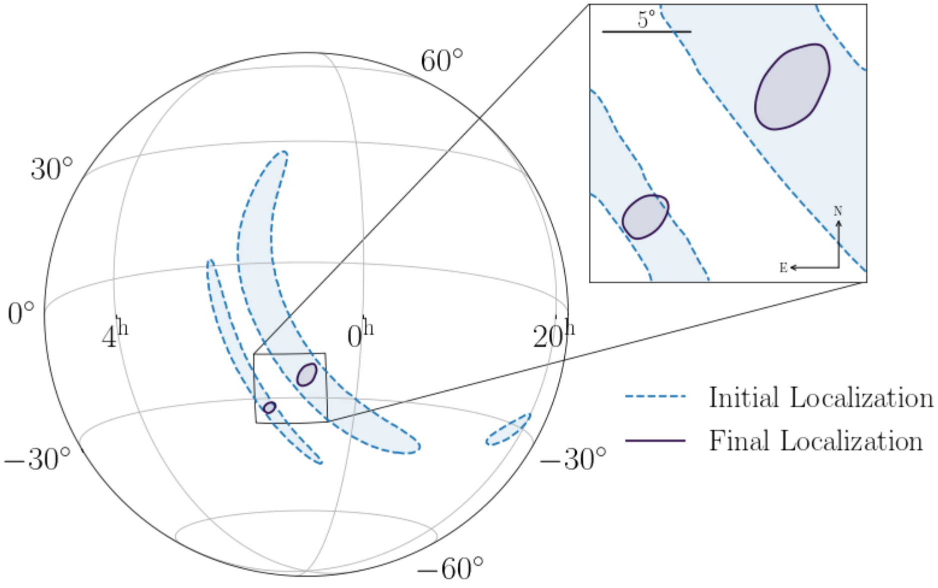
Binary Neutron Stars (BNS)



- Donner la priorité aux BNS par rapport aux BBHs dans les analyses Neutrinos
  → *Relâcher les contraintes* sur les analyses Neutrinos BNS
- Prise en compte de la masse totale finale dans l'analyse
- Détections à un seul interféromètre (zones à 90% très grandes)

Evolutions facilitées par KM3NeT+Virgo dans le même laboratoire





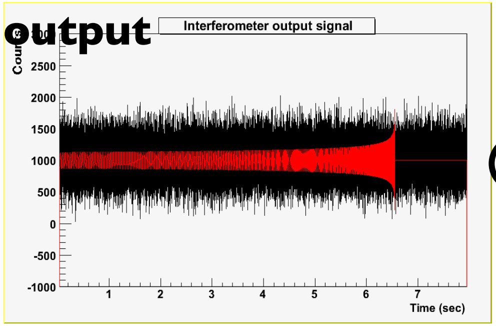
I.2 – Science Ondes Gravitationnelles
Activités Analyse/Virgo @ IPHC

Recherche de coalescence de binaires avec MBTA

- Le contexte: analyse des données LIGO Virgo commune depuis 2007
  - Partage complet des données, publications communes, groupes d'analyse communs
  - Plusieurs chaine d'analyse utilisée en parallèle (*online* et *offline*)
    - Redondance/émulation
- MBTA: Multi Band Template Analysis
  - Un pipeline développé depuis de nombreuse année, initialement au LAPP
  - Premier pipeline utilisé pour les recherches en ligne (2009)
  - Groupes Virgo actuellement impliqués: LAPP, Urbino, IP2I (Lyon), IPHC
  - La spécificité: filtrage adapté par bandes de fréquence pour optimiser le calcul
    - Utilise 3 à 10 fois moins de CPU que les deux autres principaux pipelines

Filtrage adapté

Calibrated detector output



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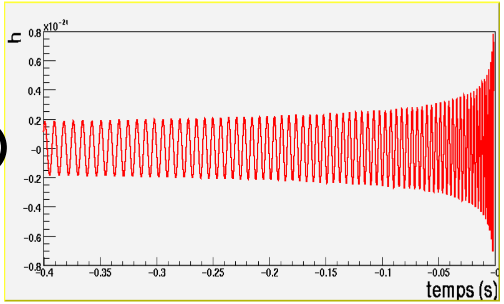
Template



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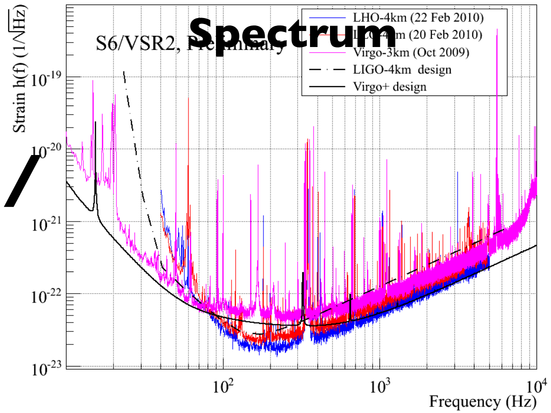
Noise Power Spectrum



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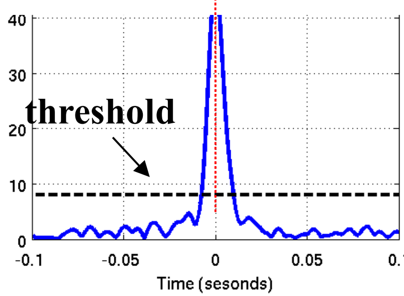
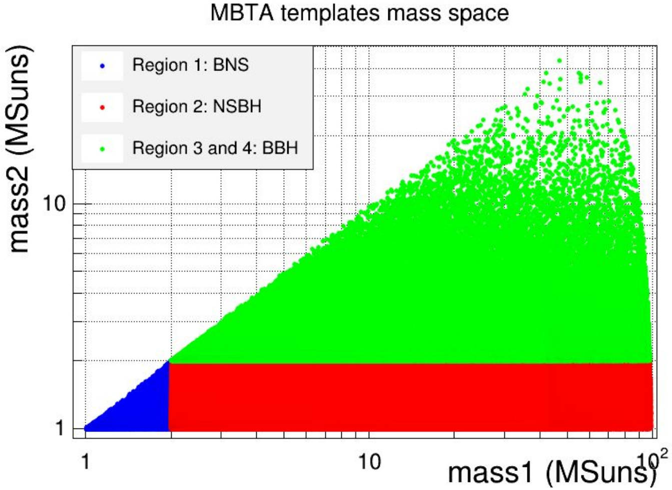
Signal To Noise Ratio



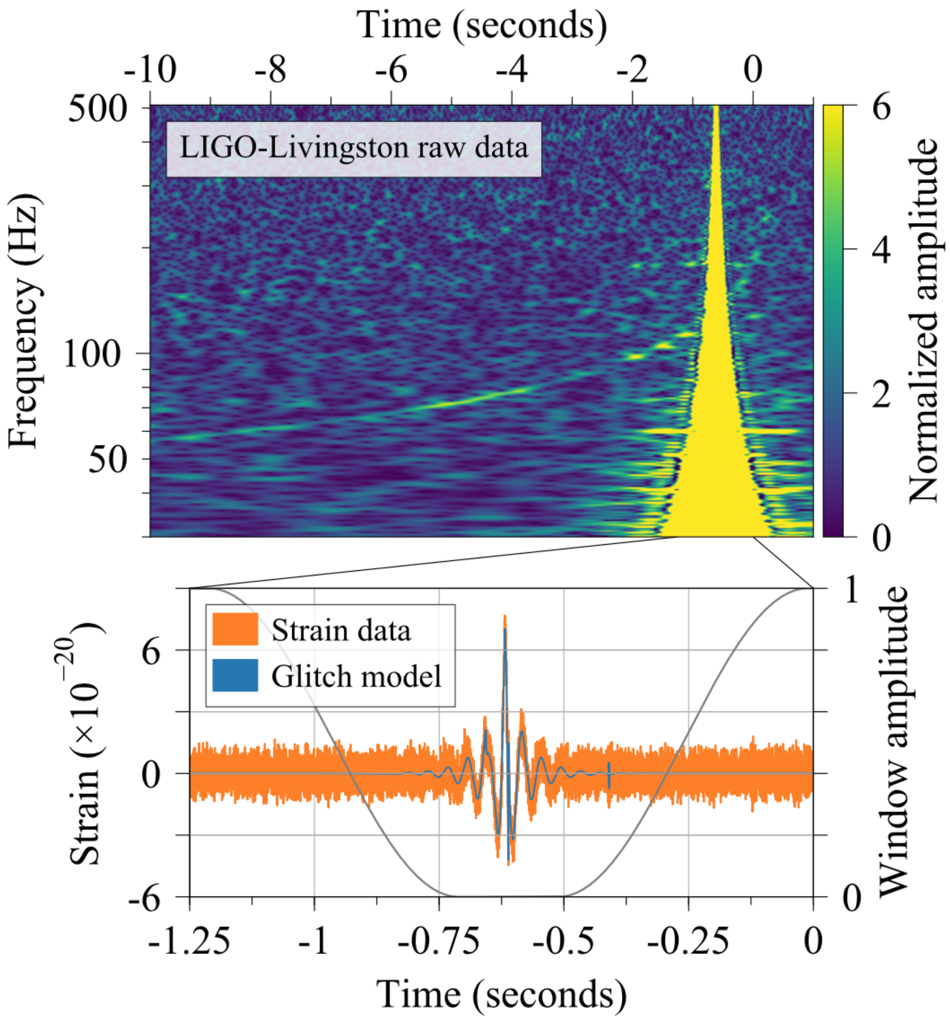
- Filtrage adapté: convolution du signal + bruit avec la forme attendu = SNR
  - Utilisation de FFTs pour avoir le SNR en continu
- CBC*: le *template* dépend des paramètres de la source
  - Environ 700 k template utilisés pendant O3
    - Espace des paramètres investigué: de 1 à 100 masses solaires + spin
  - Paramètres de la source: ceux du template avec le SNR maximum



* *CBC = Compact Binary Coalescence*

Les défis de la recherche de CBC

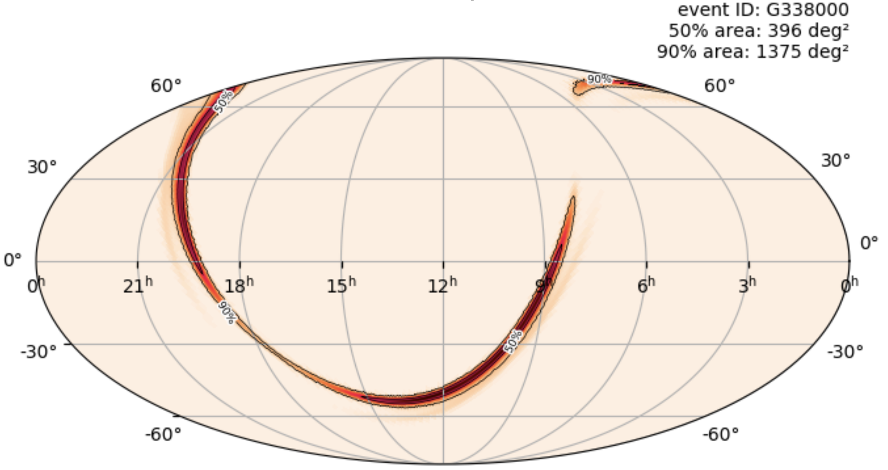
- Les données sont parfois bruitées
  - Des « parasites » plus ou moins forts
    - Exemple emblématique: GW170817
    - → Recherche de coïncidence lors des premier *runs*
- Le bruit d'un détecteur
  - n'est pas stationnaire
  - change d'une prise de données à l'autre
- Le résultat du pipeline n'est pas juste le SNR
  - il faut estimer le taux de fausses alarmes
  - Il faut fournir le résultat détaillé du filtrage adapté
    - Utilisé pour calculer les cartes de ciel
- Il y a la demande de fournir plus d'info en ligne
  - Comment traduire les chances d'observer une contrepartie?



MBTA et la prise de données O3

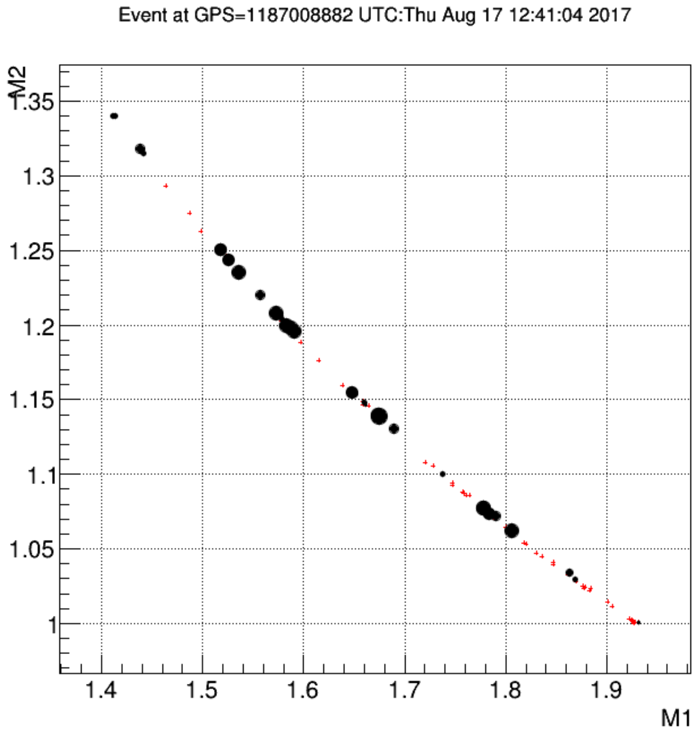
- Utilisé en ligne pendant toute la prise de données
  - Un des pipelines qui fournit les candidats officiels
  - Fonctionne sur des machines du site de Virgo
  - Latence typique:
    - Données LIGO et Virgo disponible: t_0+15 secondes
    - Candidats soumis dans GraceDB: t_0+35-50 secondes
- Analyse *offline*
  - Nouveau pour O3
  - But : inclure les résultats de MBTA dans le catalogue final LIGO/Virgo

S190707q

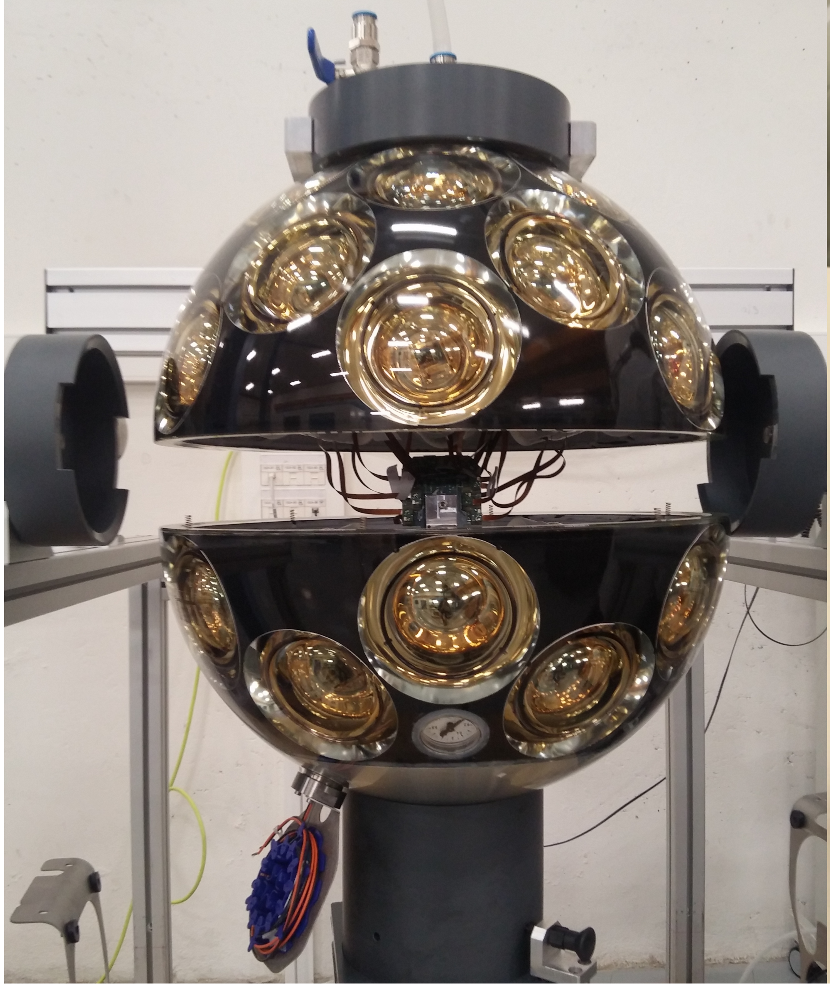


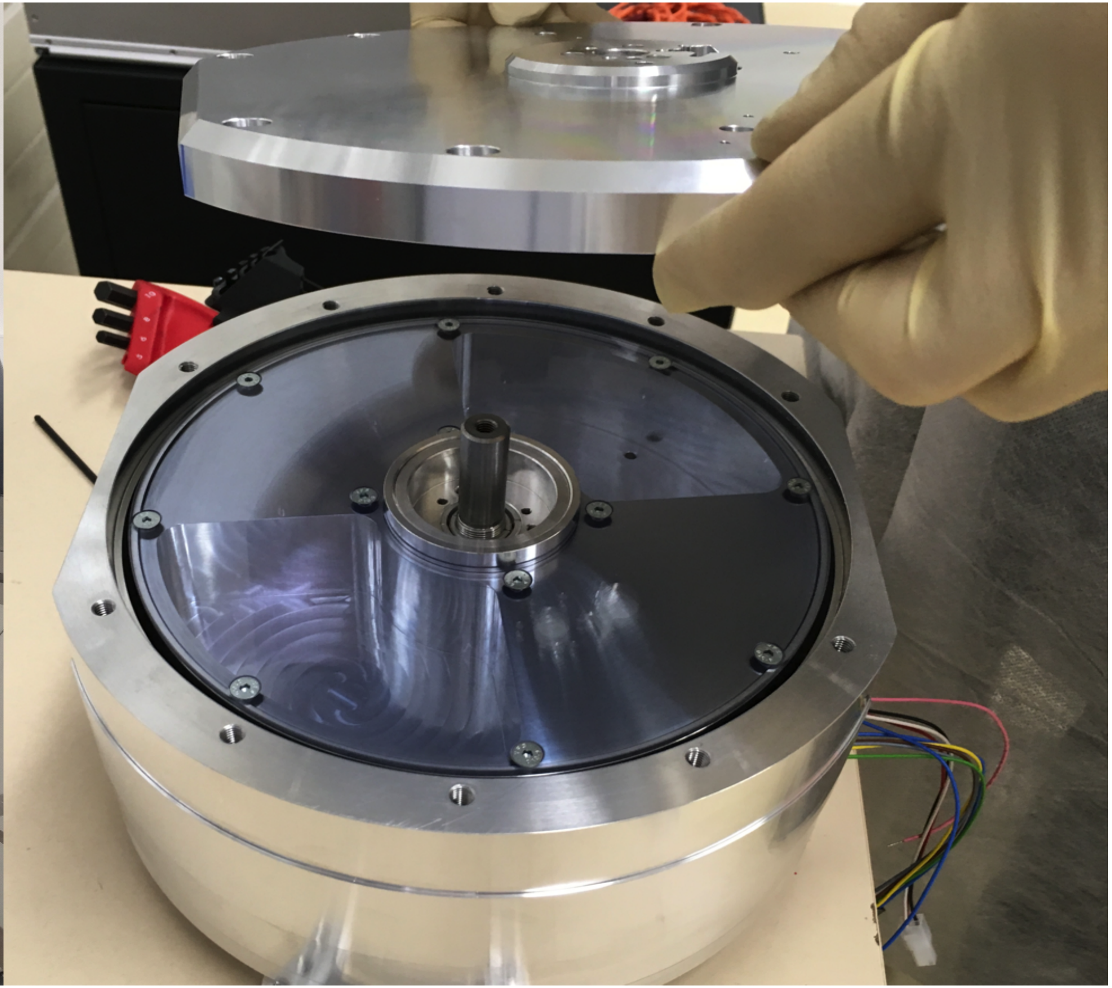
MBTA à l'IPHC : passé, présent et futur

- Développement du code, support, en collaboration avec les autres contributeurs
  - Exemple pendant la prise de données O3: recherche de signal « sous le seuil » rajouté en octobre 2019
- Déploiement de la chaine d'analyse en ligne
  - Configuration, maintenance, suivi pendant la prise de donnée
  - Connexion lors d'alertes pour valider ou pas l'alerte automatique
- Contribution à l'analyse *offline* des données O3
  - Ajustement du pipeline (code, configuration), production
    - Prétraitement des données réels et simulées, support pour la production au CC, production à Cascina (Virgo)
- Activité future: préparation pour O4:
  - Recherche d'événements observés dans un seul détecteur
    - Thèse de Vincent Juste qui va démarrer le 1ier octobre (financement CNRS-MITI)
  - Fournir plus d'information (Dimitri Estevez, post doc)
    - Exemple: calcul de la probabilité d'avoir une étoile à neutrons
  - Réduire la latence
  - Mise à jour du code/pipeline: arrivée de KAGRA, améliorations diverses
  - …

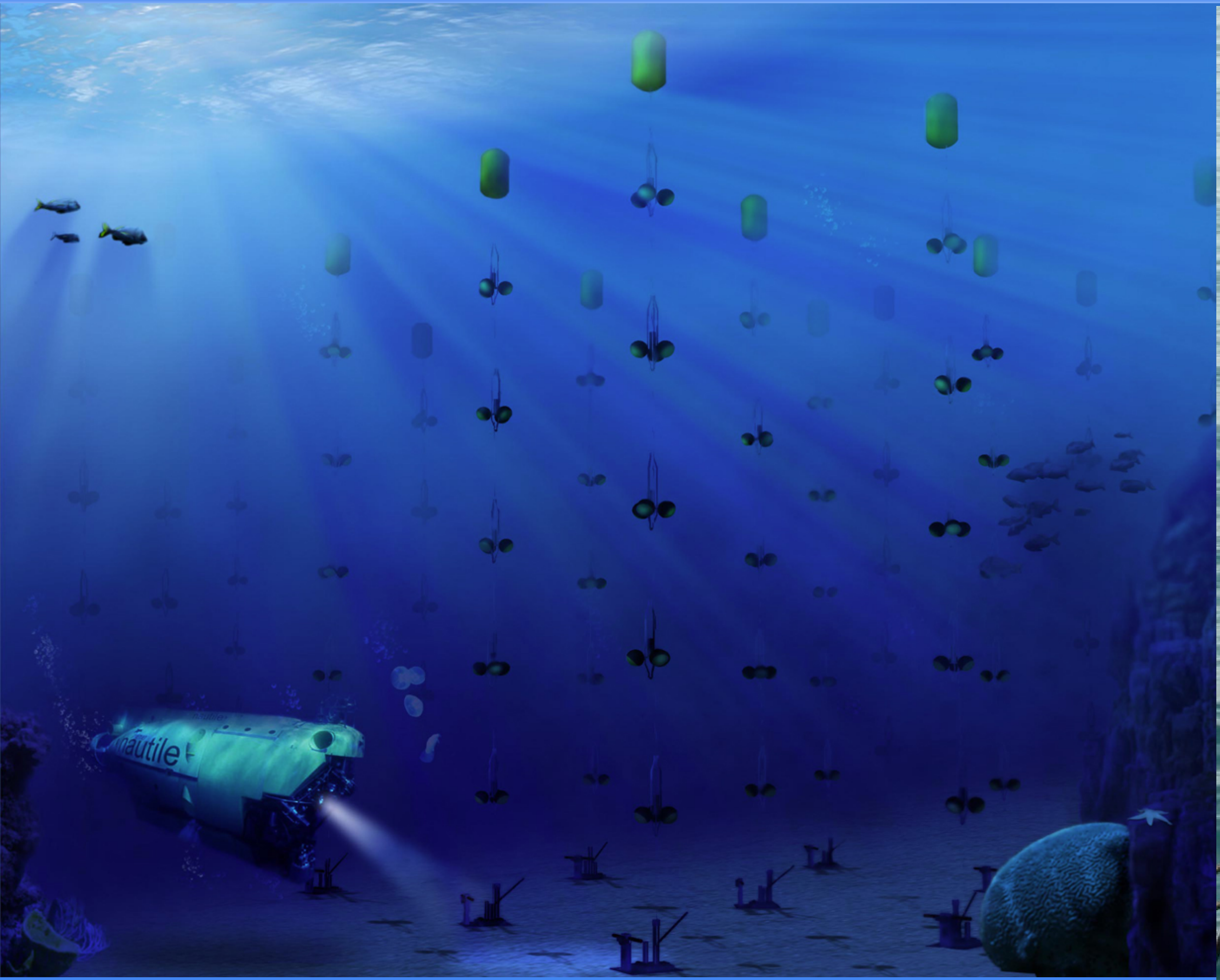


Partie II – Technique « Astroparticules » à l'IPHC



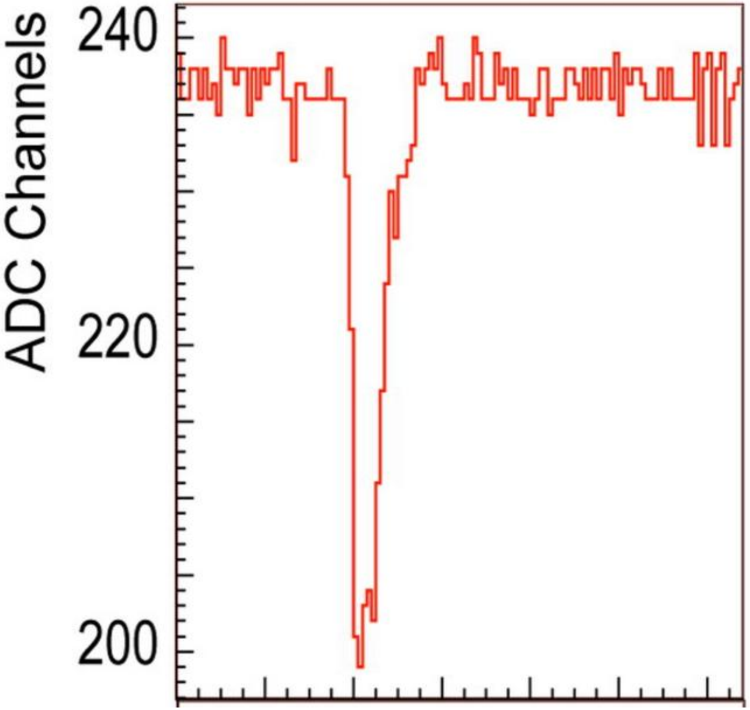


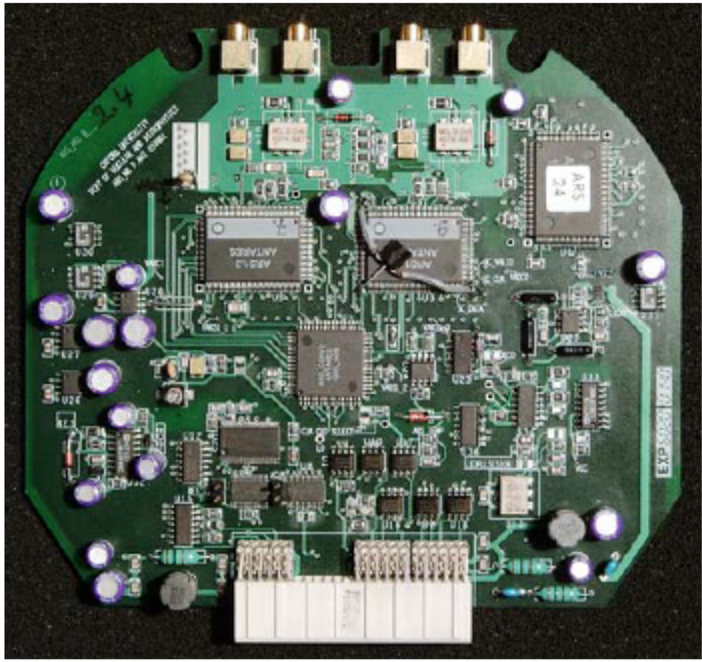
Une implication technique constante



Une implication technique constante

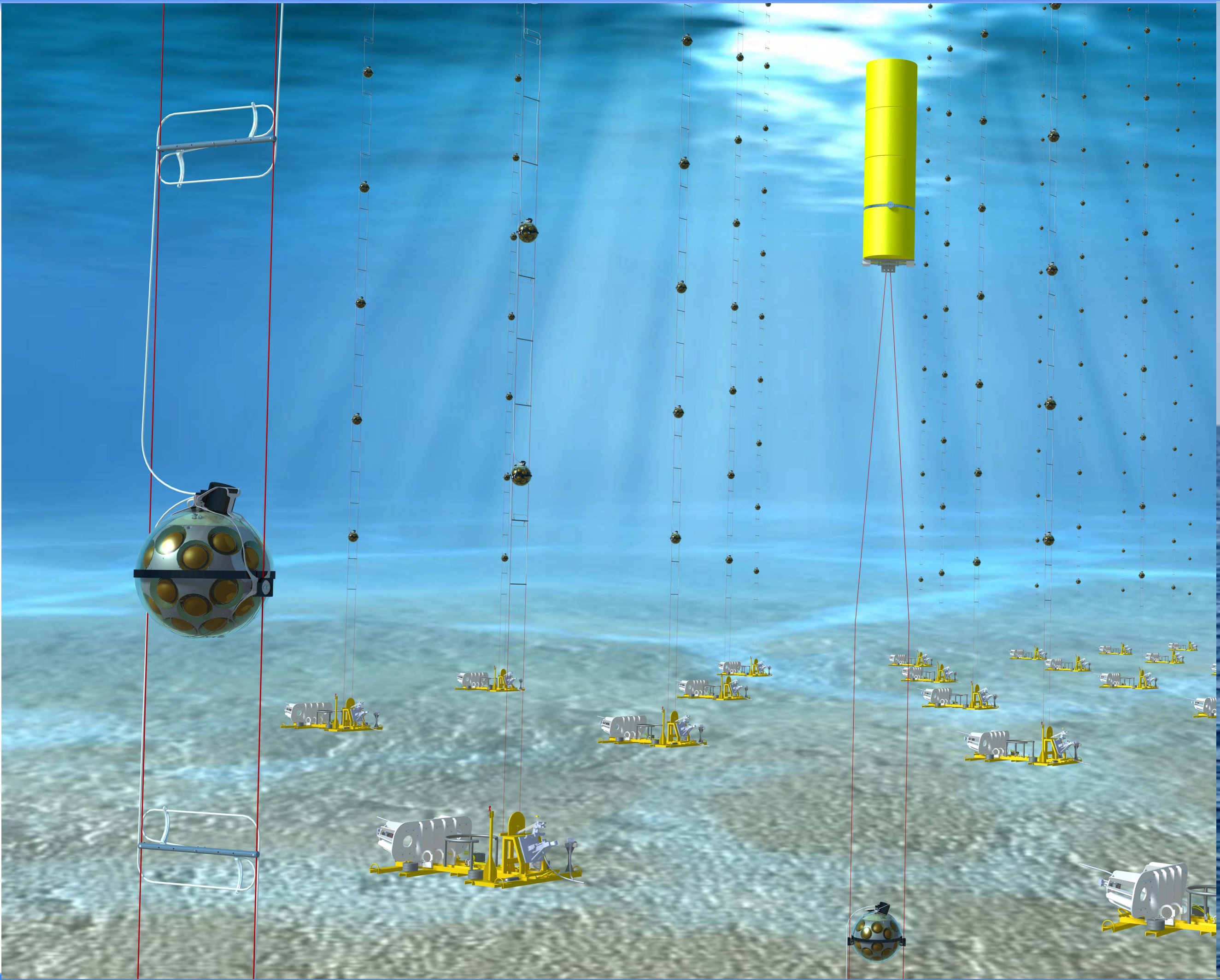
ANTARES :
Electronique frontale
1999 (2002) → 2010





Caractérisation de la carte
Tests des 900 cartes produites
Etalonnages *in situ*

Modules Optiques Digitaux de KM3NeT



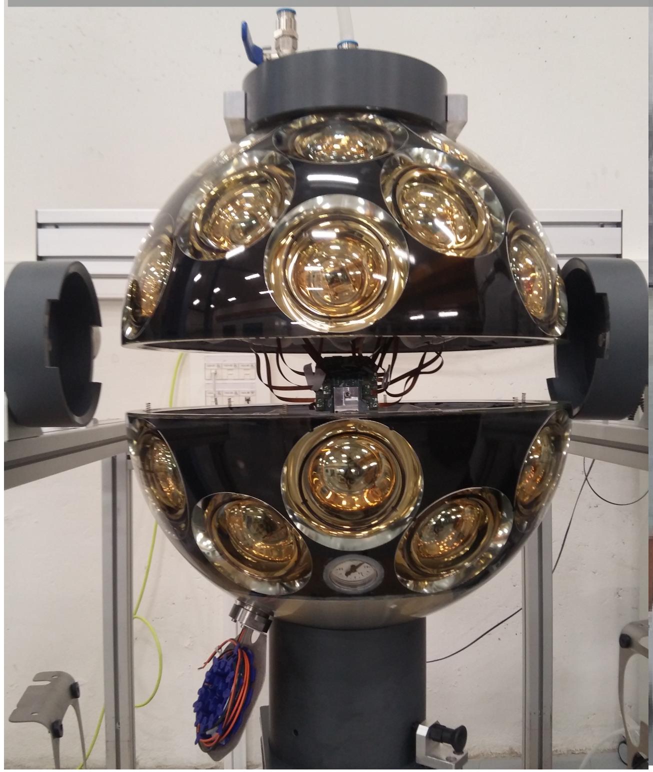
KM3NeT approuvé au
CS IPHC 06/2017

Une implication technique constante

KM3NeT
Production de DOM
(depuis 2016)
1er DOM 07/2018 → 9 DOMs

Une implication technique constante

KM3NeT
Production de DOM
(depuis 2016)
1er DOM 07/2018 → 9 DOMs

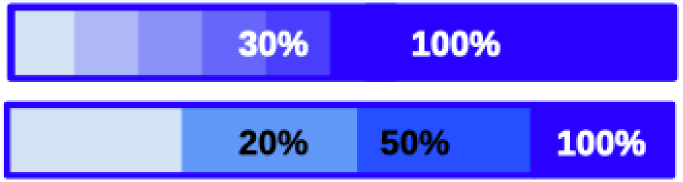


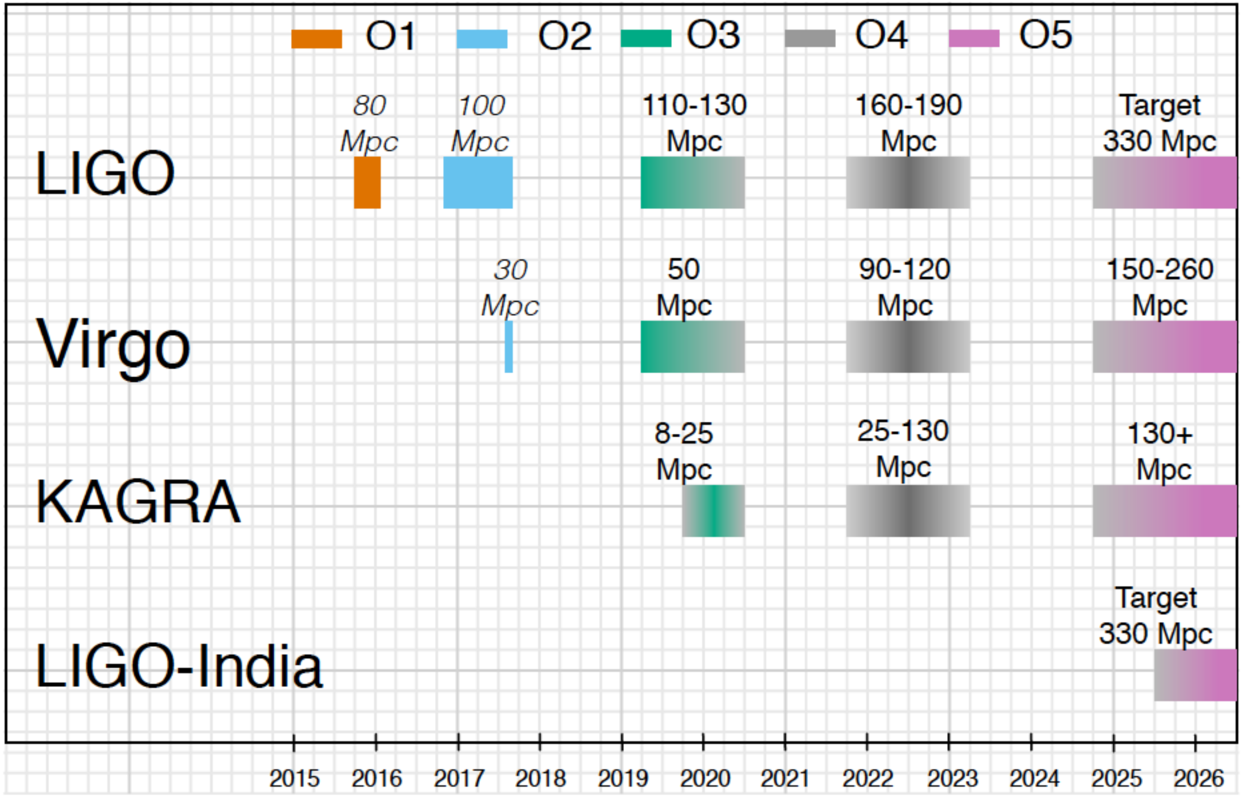
1 des 3 sites pour ORCA – Phase 2
Subatech (100%), NIKHEF (50%)
115 x 18 DOMs à produire au total

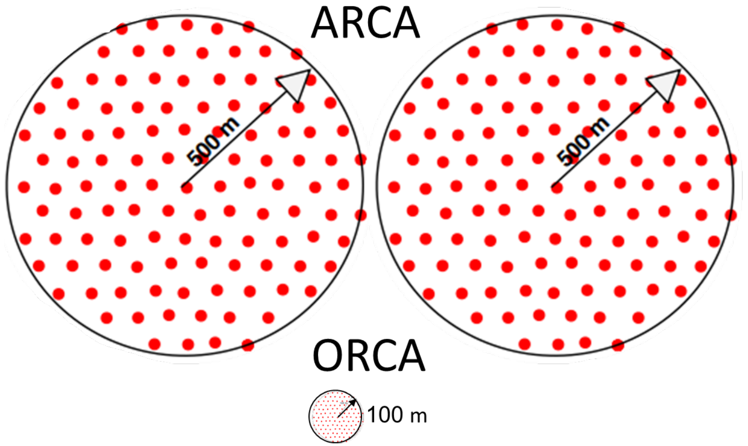
L'implication technique KM3NeT dans le temps

ORCA (E_{HEN} = 1-100 GeV)

ARCA (E_{HEN}>TeV)



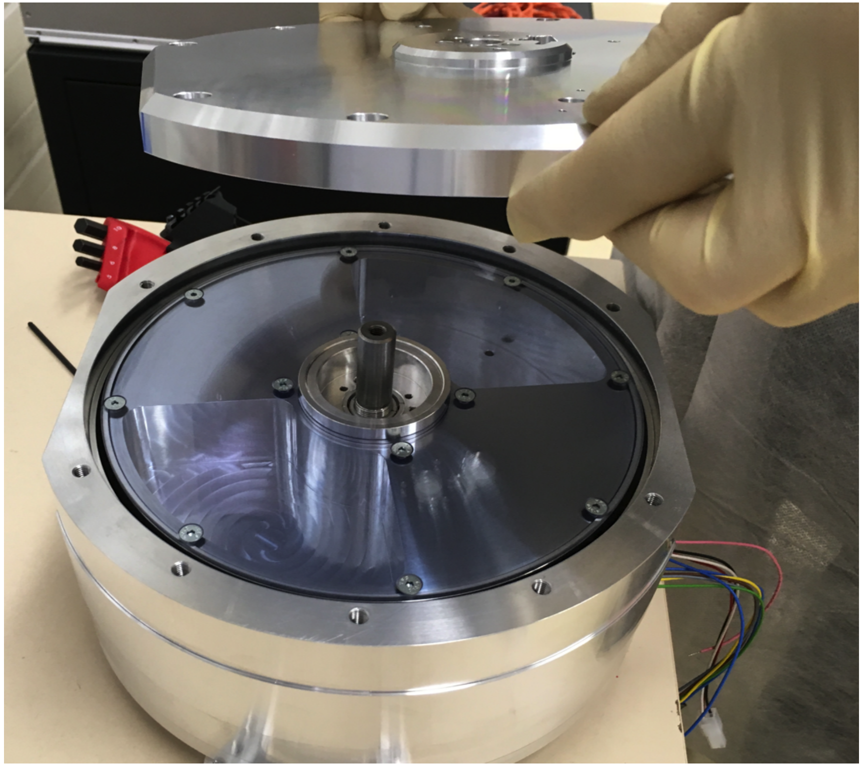




Intégration de DOMs KM3NeT :

ORCA – Phase 2
→ 33 lignes/115 fin 2022 ?
→ 33 x 18 DOMs sur 3 sites
→ 115 lignes d'ici 202X...

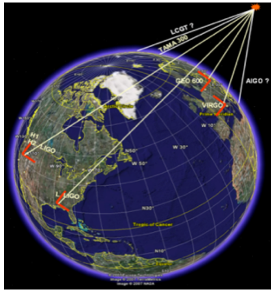
ARCA – Phase 1
→ 24 lignes/230 fin 2021 ?
→ Complétion 202X ?

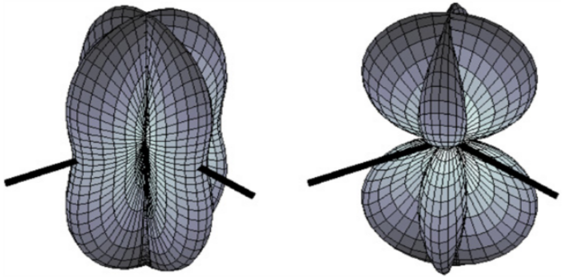


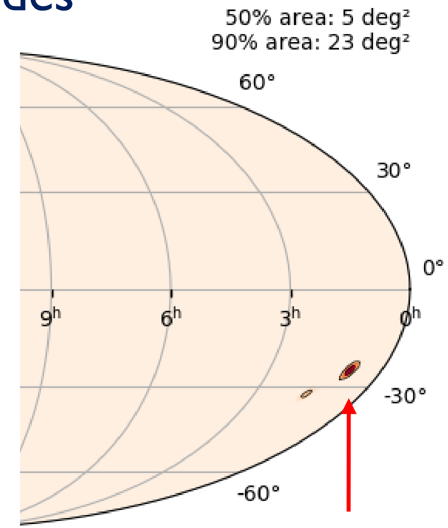
Partie II.2 – Technique « Ondes Gravitationnelles »
Virgo @ IPHC

Why an accurate calibration for GW : skymaps

- Sky maps built using times of flight and relative amplitudes







GW190814: 23+2.6 $M_\odot$

- Need a reconstructed h(t) accurately calibrated in:
  - Amplitude
    - Current SNR up to 20-30
    - Could expect SNR close to 100 within few years and much more with ET
      → Require sub-percent accuracy
  - Time/phase over the full frequency spectrum
    → Need to target less than 10 us (i.e. 0.3 mrad @ 50 Hz)
  - + Cross calibration between detectors
- A better calibration will be needed to find weak optical counterparts

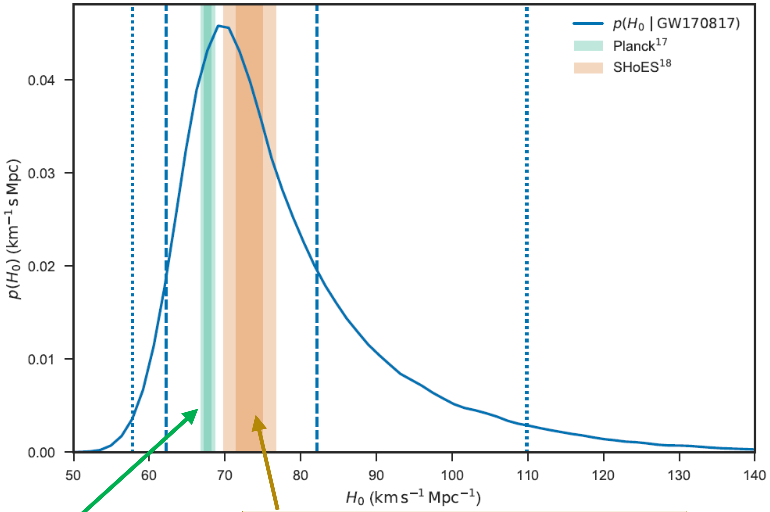
Why an accurate calibration for GW : Hubble constant

- Measuring the Hubble Constant with GW:
  - GW170817 – AT2017gfo
    - GW only; d =40^{+8}_{-14} Mpc (90% CL)
    - Using sky position of AT2017gfo: d = $43.8^{+2.9}_{-6.9}$ (68% CL)
      → H_O = 70.0 +12.0 -8.0 km/s/Mpc
    - Could be improved with radio counterpart info:
      - H_O = 72.4 +7.9 -7.3 km/s/Mpc
  - Statistical measurement with BBH possible

$$v_H = H_0 d$$

Hubble flow velocity from host galaxy NGC4993

Distance from GW



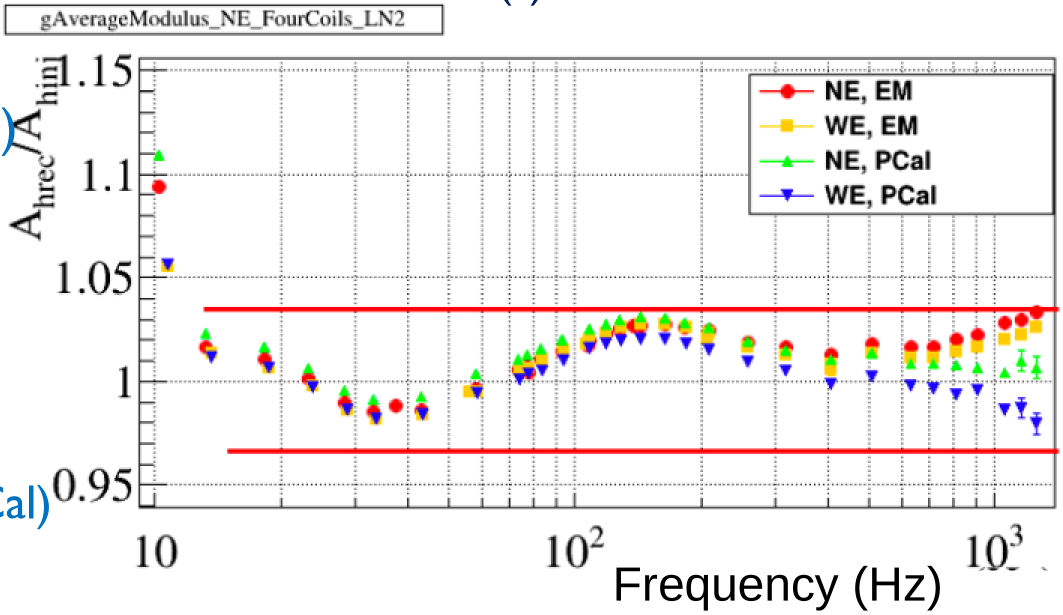
CMB/BAO measurements

Measurements with distance ladder

- Error on h(t) calibration translate to H_0 error
  - Will become dominant with the coming up runs
    - More events, at larger distances
      → Systematic take over statistical errors
    - Need to target sub-percent accuracy

Calibration basics

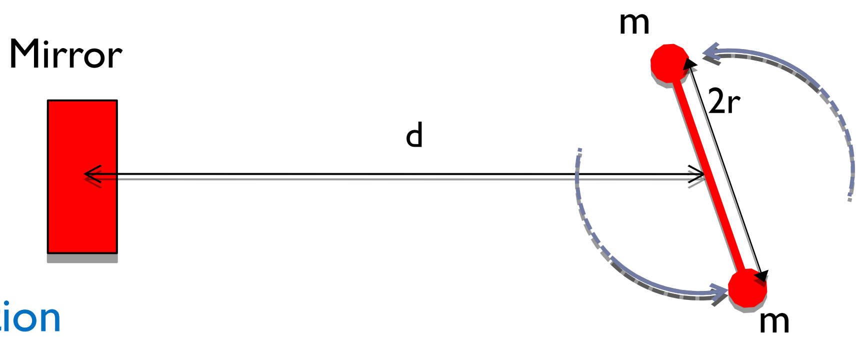
- Principle: inject a know mirror displacement and validate/correct h(t).
  - Checks with a set of frequencies (runs)
    or large frequency band (dedicated studies)

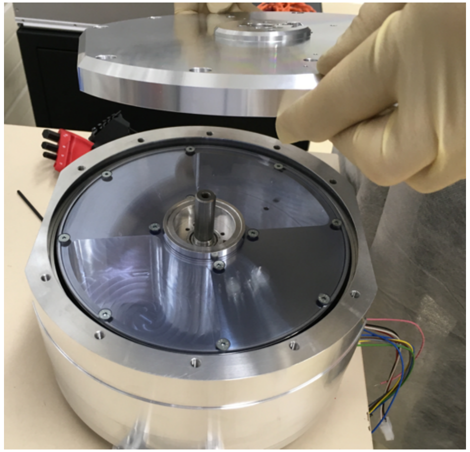


- Three techniques to move the mirrors:
  - Radiation pressure using an auxiliary laser (PCal)
  - Newtonian force using moving masses (Ncal)
  - Electromagnetic actuators (not the most accurate in the long run)
- Common challenges:
  - Do not introduce additional noise beside the injected calibration signals
  - Cross-calibration with LIGO and KAGRA
  - Stricter requirements as the sensitivity improves

Newtonian Calibrator (NCal)

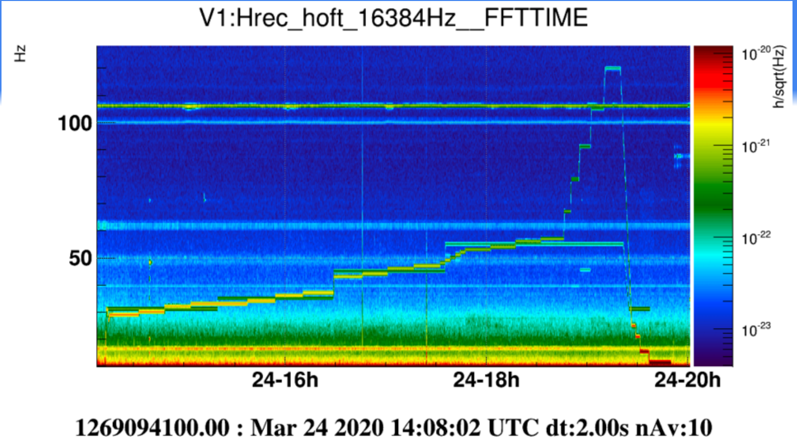
- Basic model: rotor made of two masses
  - The non linear Newtonian force creates the signal
  - Signal at twice the rotor frequency; 1/d^4 effect
- Expected benefits
  - Signal depends mostly on the rotor geometry and position
    - Mirror mass cancels out
  - No aging effect of the signal
  - Simple interface with the interferometer:
    - Could be moved from one site to another one
- Challenges
  - Able to rotate at few hundred Hz (10k-20k RPM), for years
    - "Without" mechanical vibration or electromagnetic noise
  - Well known geometry and mass
  - Able to be installed at different location with different orientation → support
  - Safety: no dislocation + protection in case of dislocation

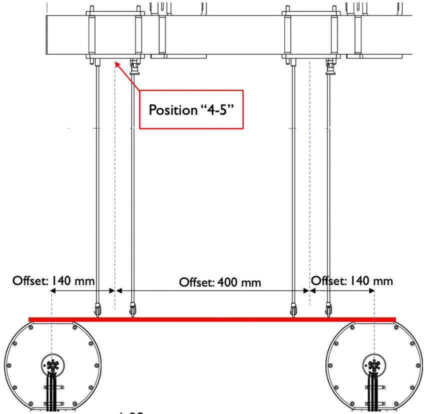


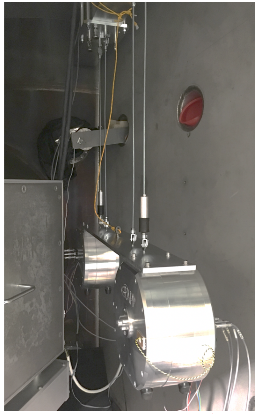


NCal prototype build at LAPP

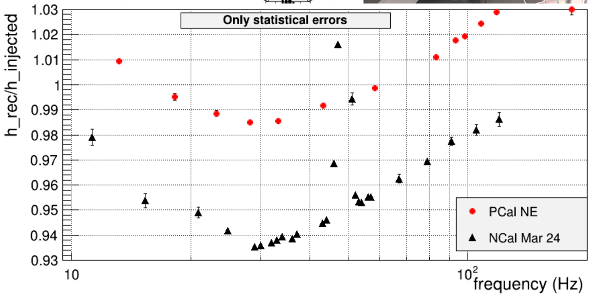
NCal calibration : last months activity

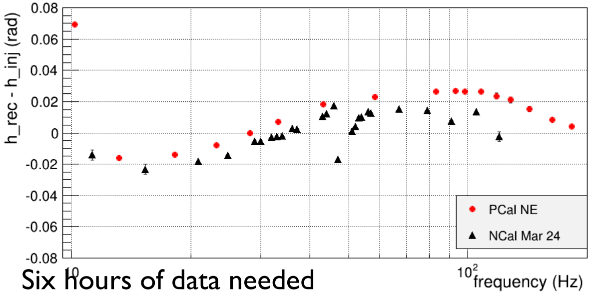






- Collect 6 data sets for for NCal investigations during O3
- Improve NCal support to reduce position uncertainties
  - Rigid connection of the 2 NCals
- Results achieved so far
  - Check of the overall amplitude
    - 4-5% discrepancy, not incompatible with systematic errors
  - Confirmation of the frequency/phase dependent shape
  - Discover an h(t) reconstruction issue around 50 Hz
  - Confirmation of the phase response





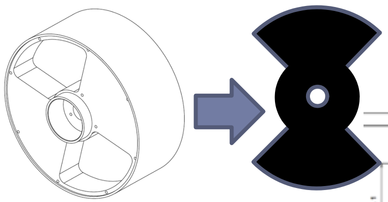
Six hours of data needed

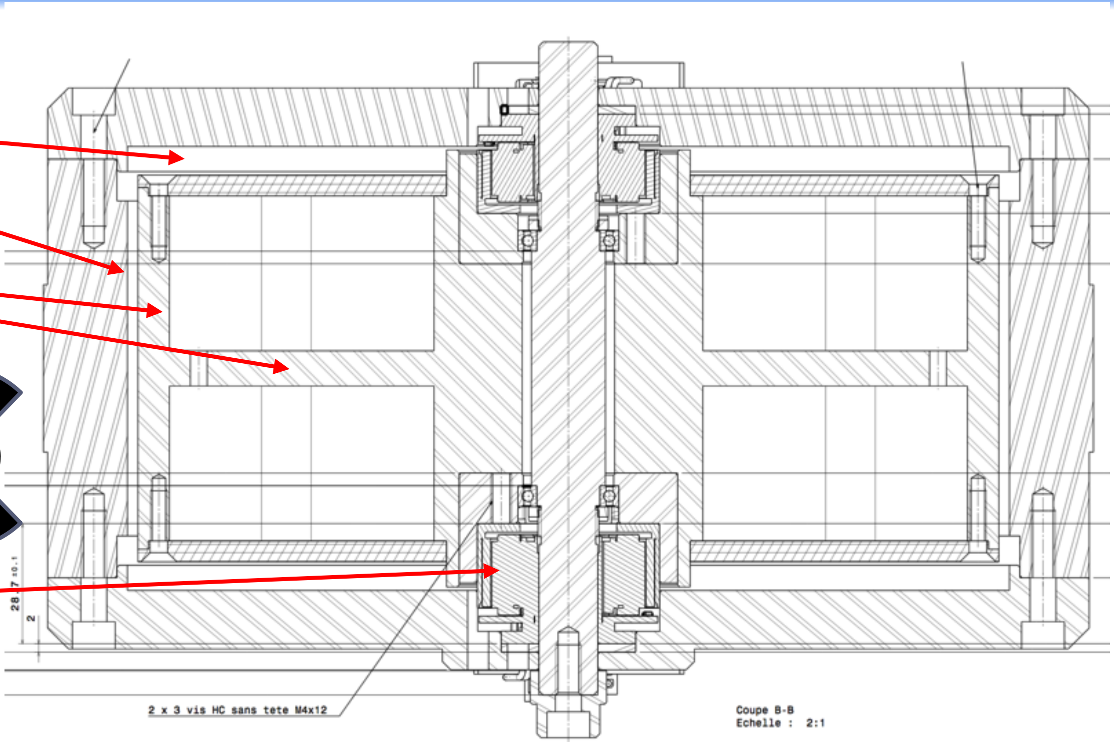
Goals/needed actions for forthcoming Observing Runs

- O4 run (2022)
  - Validate h(t) within 1% in the 10-200 Hz frequency range
    - Requires:
      - A better knowledge of the rotor geometry
      - More NCals around the mirror for better mirror position estimation
      - A better support for more stable NCal positioning
      - A better use of the motor: less friction/vibrations at the bearing level
      - Improved modelling and analysis
  - Faster measurement when doing a frequency scan
    - Requires a stronger NCal signal: rotor optimization
  - Add a permanent NCal monitoring line
    - Requires a reliable/better controlled NCal device for 24/7 operations at moderate rotation
  - Build expertise to better define O5 goals
- O5 run (2024-25) tentative goals:
  - Systematic uncertainty below 1% in the 10-200 Hz range
  - Go above 200 Hz; goal: 500 Hz?
  - Gain more expertise for O6 and Einstein Telescope

Work plan for O4 : new optimized NCal

- Simpler rotor optimization
  - Remove the top and side gaps
  - Amplitude gain: 31%
- Remove the “air sector”
  - Amplitude gain: a factor 2.
  - A more aggressive solution
    - Issue : noise/friction: vacuum?
- Replace aluminum by steel
  - Amplitude gain: 8/2.8 = 2.9

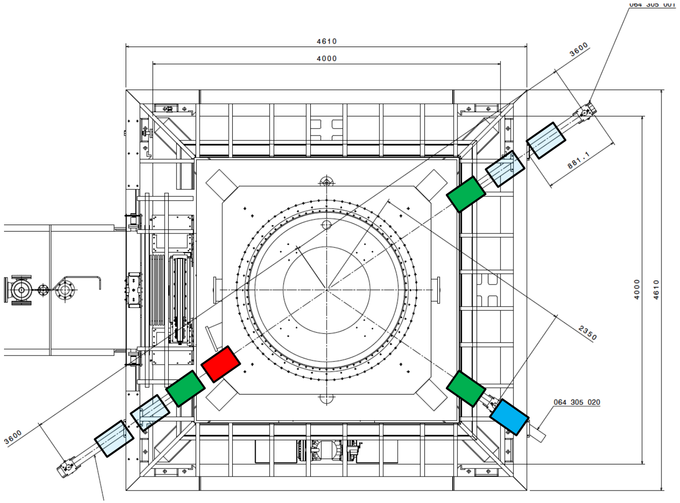




- Remove unneeded parts
- Use new bearings: less friction and vibrations
- Better balancing for reduced vibrations
- Need to redo the safety study
- Rotation slaved on the Virgo timing system: improved control system
- Activity involved: mostly mechanical design, studies, prototyping, tests
  - Limited production: 6 parts needed

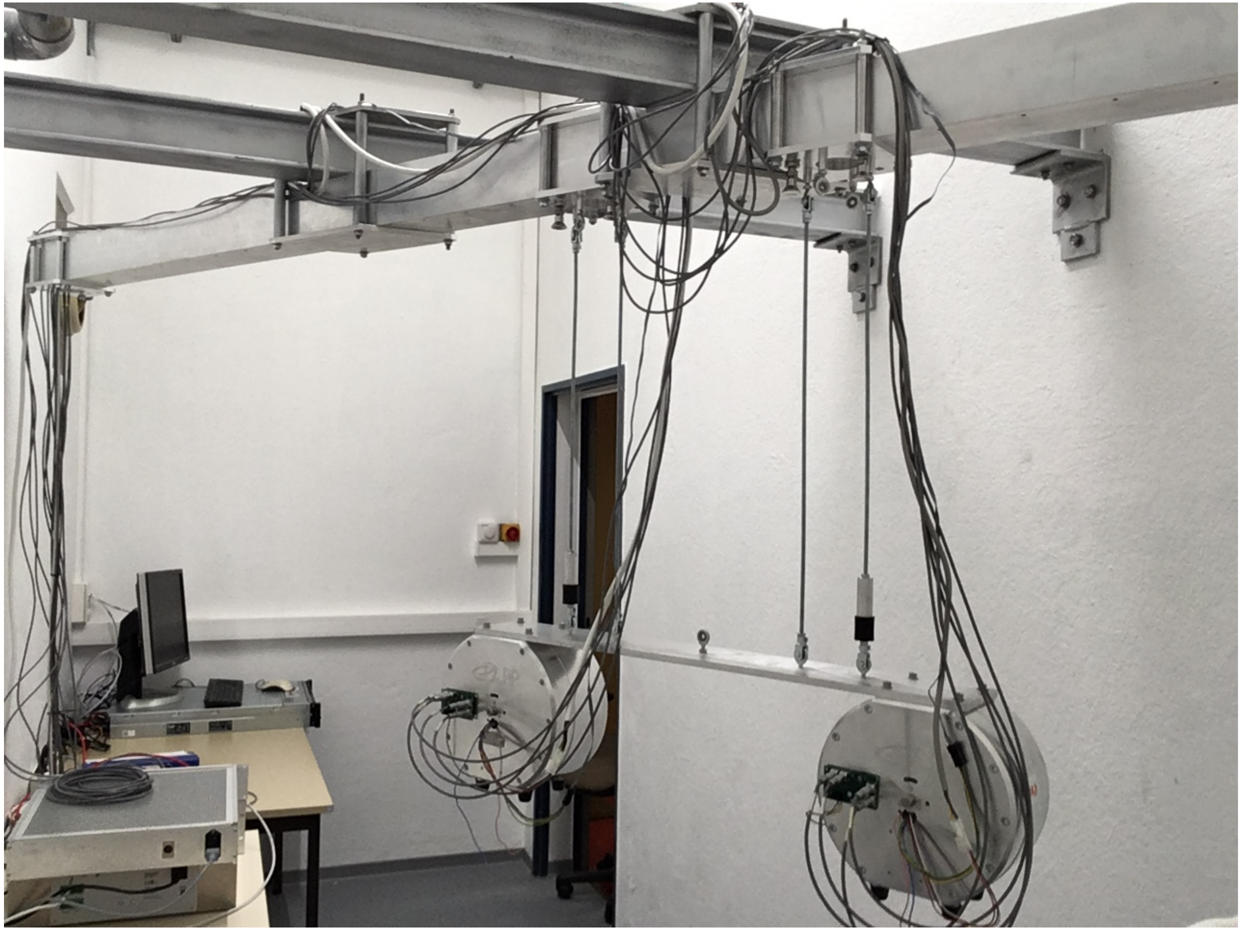
Work plan for O4 : improved NCal support

- Tentative layout for O4:
  - 1 close NCal for high frequency check (red)
  - 3 NCal for mirror position control (green)
  - 1 Far NCal for permanent line (blue)
- Requirements
  - Know the relative NCal positions within:
    - 0.1 mm within a "group" (same corner)
      - Easy if on the same rigid support
    - 0.5 mm from one group to another
  - Attenuate residual NCal vibrations
- Options
  - Stiffer hanging system for a NCal group
    - Could be a support for bottom
  - Softer system with position monitoring
  - Need to study and be ready for both options



NCal : test facility at IPHC

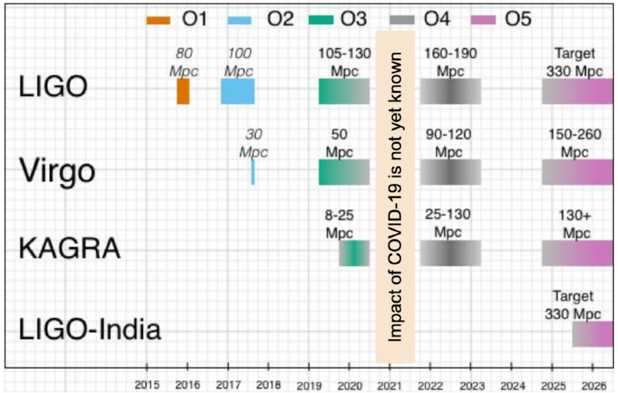
- The Virgo NCal system moved to Strasbourg in July/August
  - Replicate the hanging system
  - Install a Virgo DAQ system
  - Installed in build 02 room 100
- Purpose: test facility to study
  - New NCals
  - Support system vibrations
  - Control system
  - Reliability

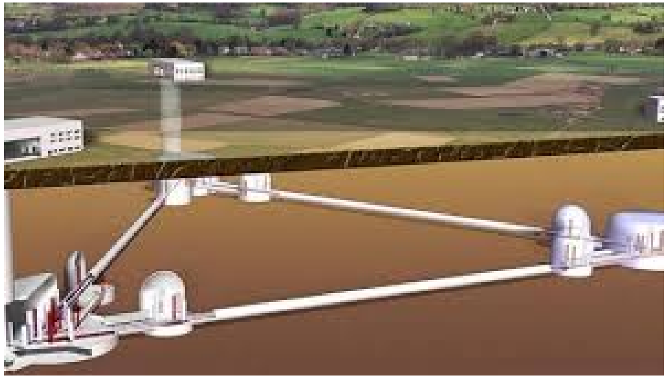


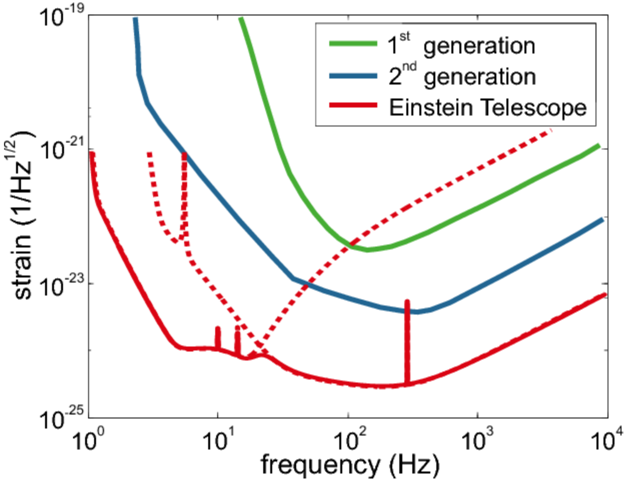
NCal Summary

- A detector contribution with direct connection to the science
- A moderate investment with high visibility
  - A moderate technical support needed
    - Mostly mechanics + physicist
- Not a one-shot activity but a long term project
  - NCal requirement will evolve with GW detectors sensitivity
  - A cycle of NCal version and upgrade
  - The workload is spread over many years
  - The know-how is as critical as the cost of the project

Coming up : AdV+ and the Einstein Telescope

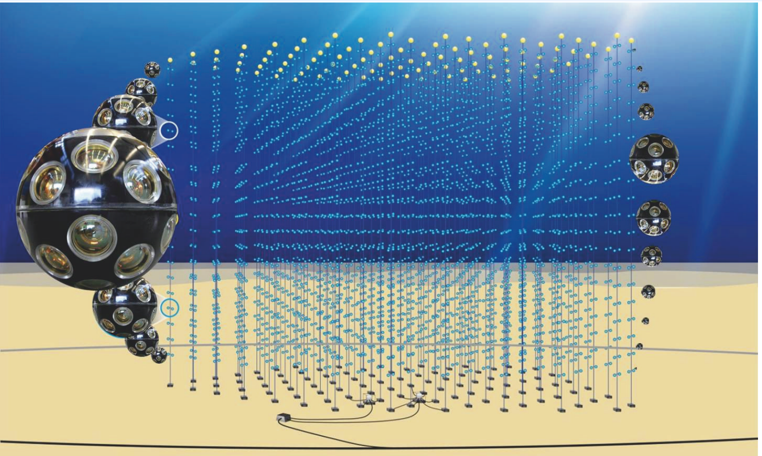


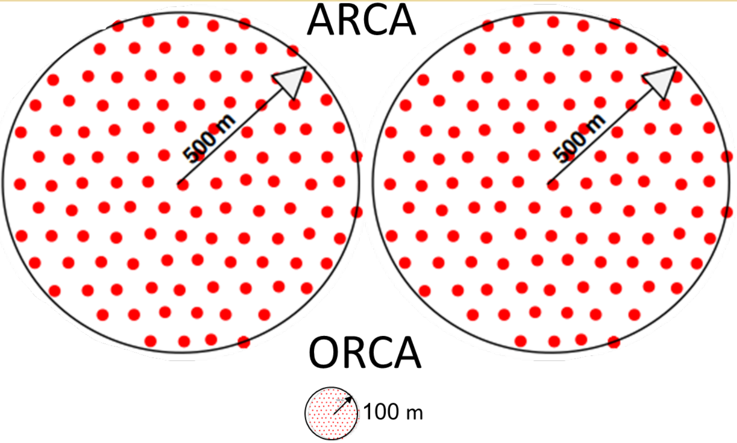




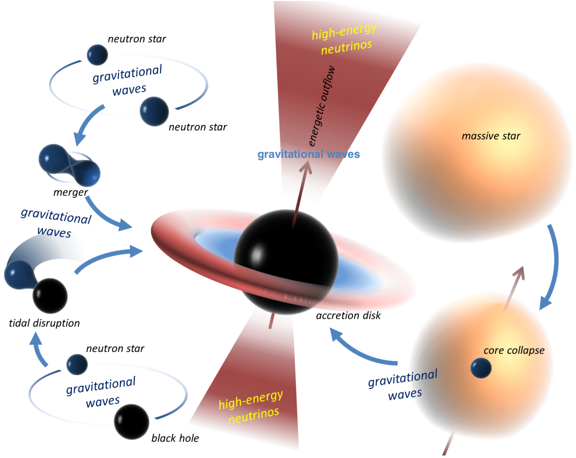
- 2022+: New data takings of Advanced Virgo+ and aLigo 'A+':
  - Volume of space searched increases by up to a factor 50
- 2030+: 3rd Generation: the Einstein Telescope: A new larger facility in Europe
  - Volume of space searched: x1000 → enable a large science program, e.g.:
    - Sense all stellar-mass BH mergers in the visible Universe: the seed for massive BH at center of galaxies?
    - Precision tests of General Relativity in extreme condition (BH): is GR right or do we need new physics?
    - Insight into how the Universe is expanding and evolving: is dark energy just a cosmological constant?
    - Explore the ultra dense matter: how neutron stars tear each other apart before smashing together?

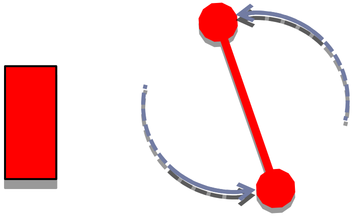
Conclusions : le futur « Astronomie Multi-Messagers » à l'IPHC

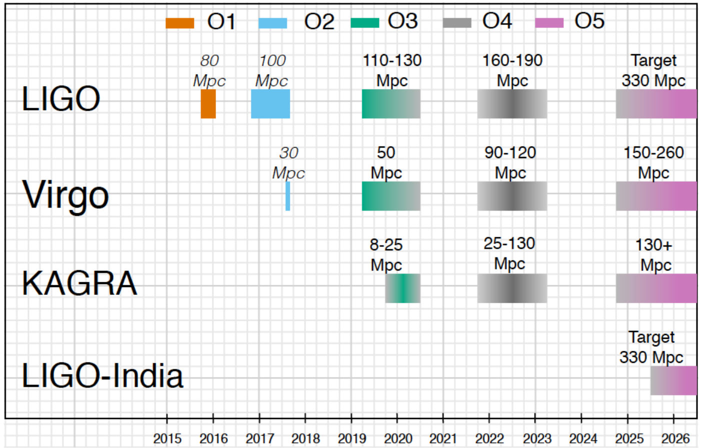


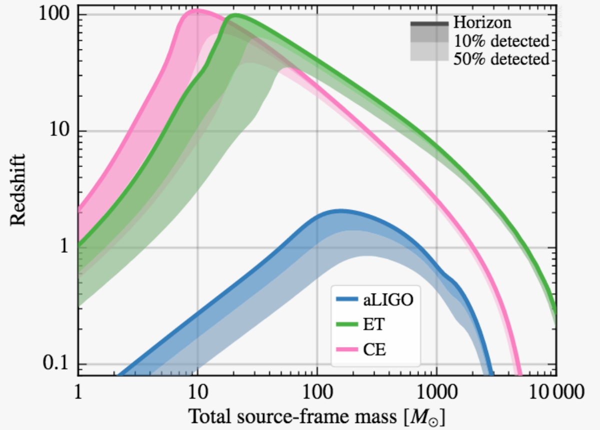


Neutrinos GeV – TeV – PeV
KM3NeT – ORCA & ARCA









Ondes Gravitationnelles
Virgo → Einstein Telescope

Conclusions

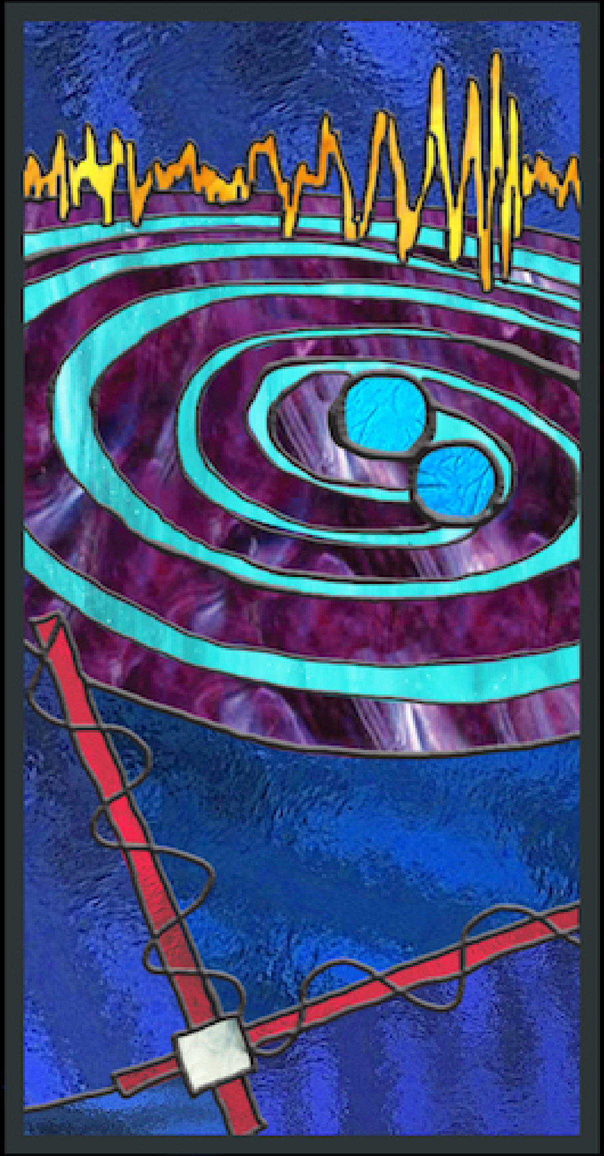
Domaine des **Astroparticules / Astronomie Multi-Messagers** en plein développement et avec un futur prometteur

Nous proposons la création et le développement d'un équipe « **Astroparticules** » à l'IPHC avec le programme de travail suivant :

- **Analyse des données**
  - Recherche de coalescences de binaires compactes dans les données LIGO-Virgo-KAGRA
  - Continuer le programme GWHEN au sein de KM3NeT et Virgo
- **Partie Technique**
  - Mener à bien la production de Modules Optiques Digitaux de KM3NeT
  - Développer les calibrateurs « Newtoniens » pour Virgo et les détecteurs futurs (E.T.)

Remarque: développement = renforcement de l'équipe de physiciens + support technique

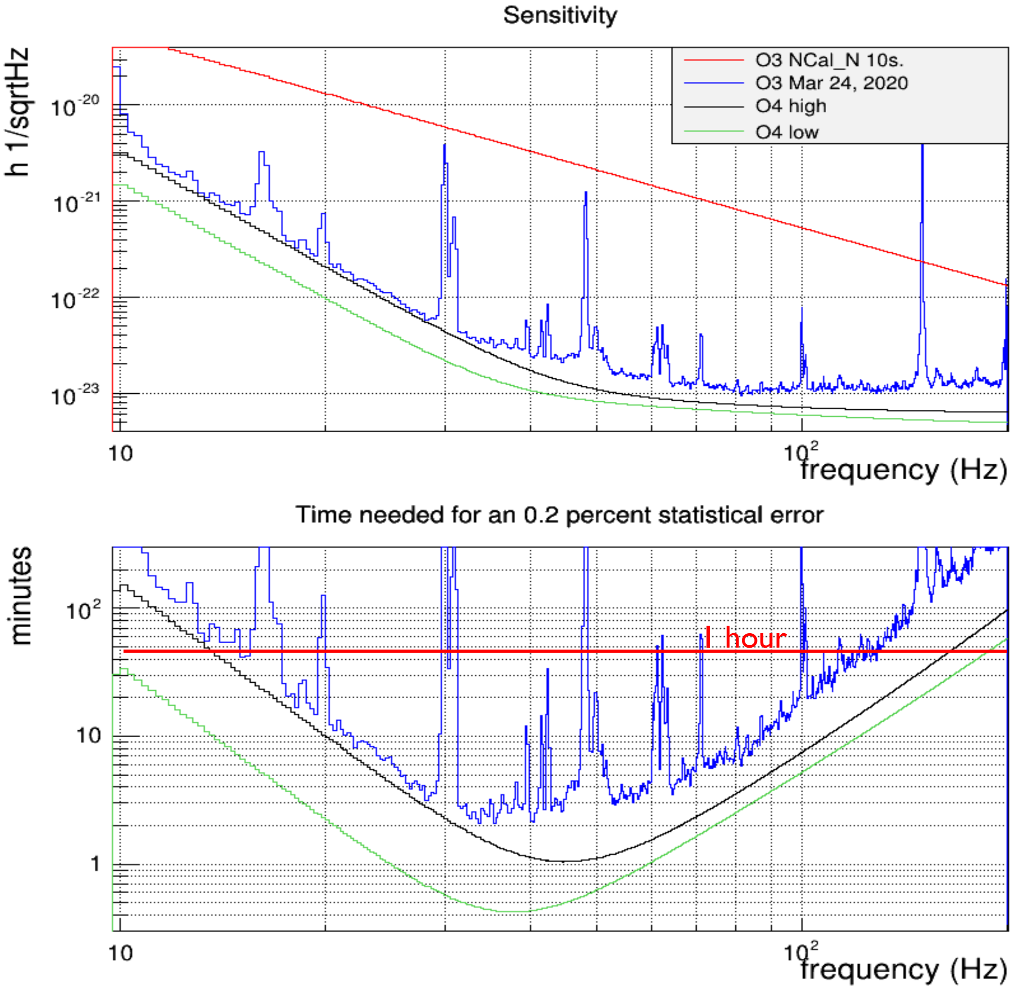
BACK UP



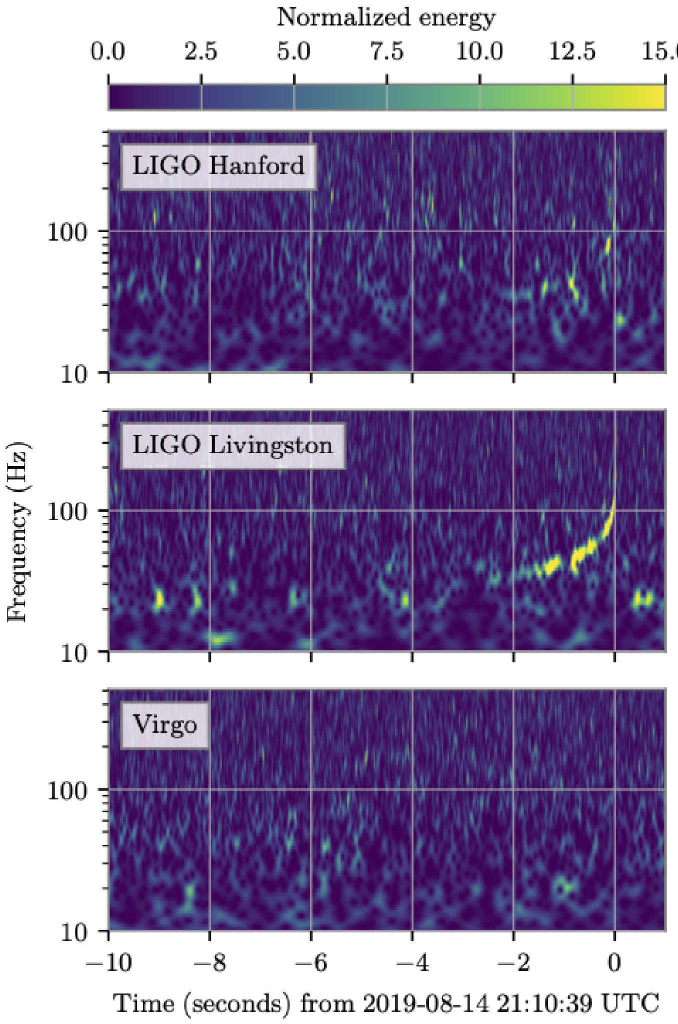
NCal : Time needed to get a result

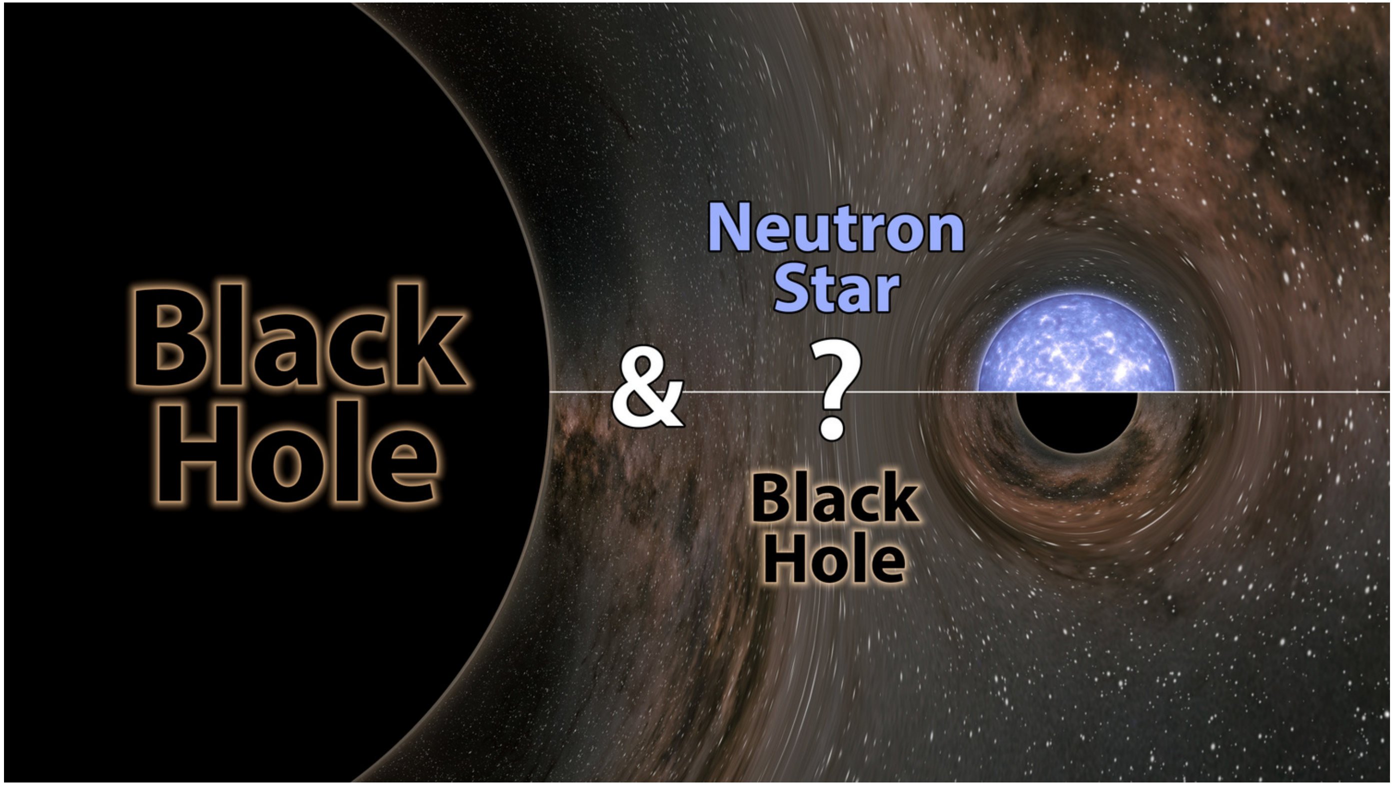
- O3 data with North NCal
  - 1. 27 m from mirror
  - Check at 200 Hz require 6 hours
    - For a 0.2% error
    - Just for one frequency point
- Need a stronger signal to speed up checks
- If NCal signal 2 times stronger

  → same result 4 times faster



GW190814, fusion de 2 objets compacts





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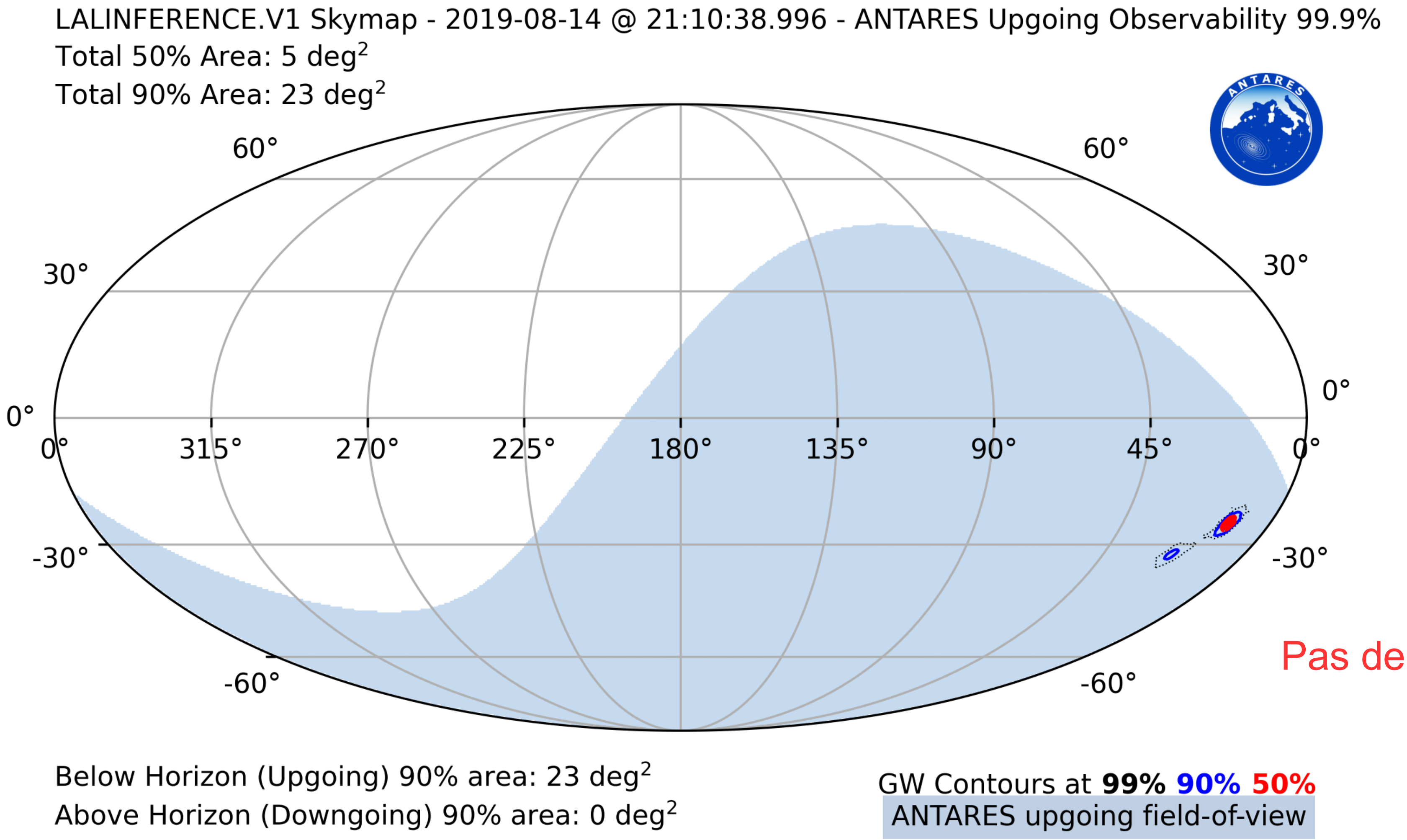
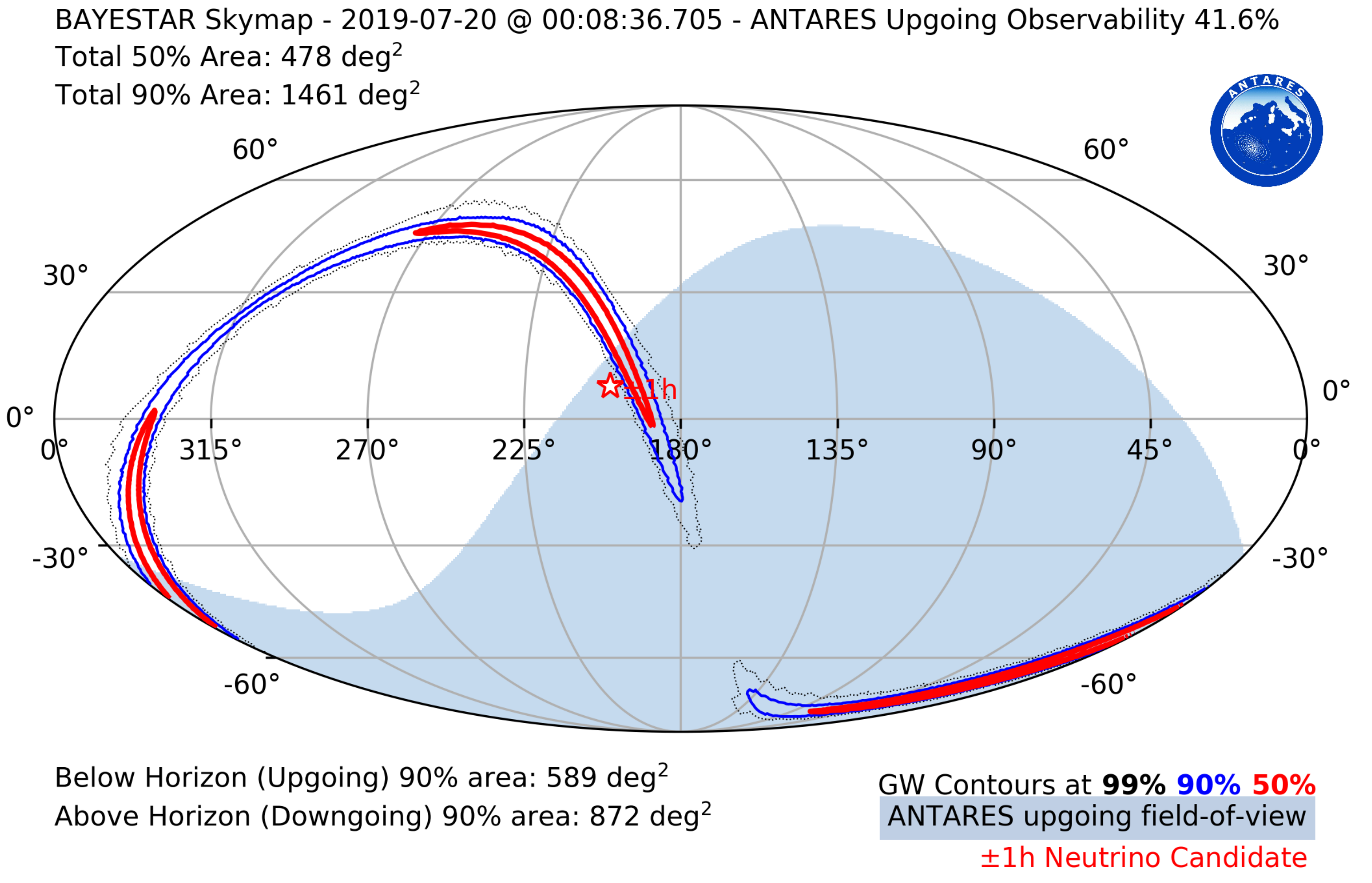


Pas de neutrino ?

Un autre exemple : S190720a, fusion de 2 trous noirs



1 neutrino dans ±1h
mais
pas dans la direction
de la source...

GW triggers : types of signals

Since April 2019 = 56 non-retracted alerts [52 followed by ANTARES]

BBH : 37 including S190412 (paper Apr. 2020)

NSNS : 6, including S190425z [Paper GW – **ANTARES offline**]

NSBH : 5 including S190814bv (**soon published**)

MassGap : 4

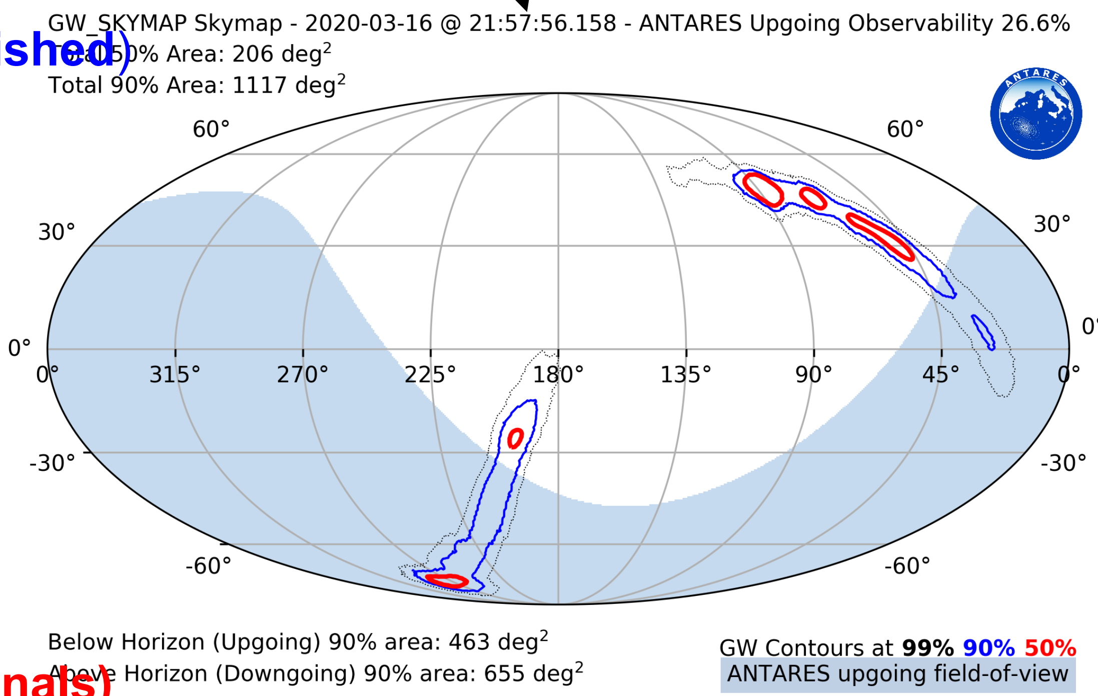
Burst : 1 (S200114f)

O3a : Apr 2019 → Sep. 2019
33 events

O3b : Nov 2019 → 27/03/2020 (Covid-19)
23 events

Catalog of O3a signals out soon (~40 signals)

Last event followed : MassGap S200316bg



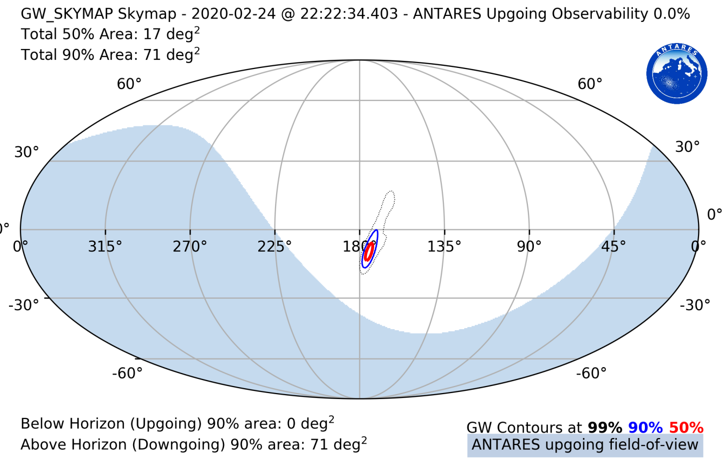
GW triggers : types of signals

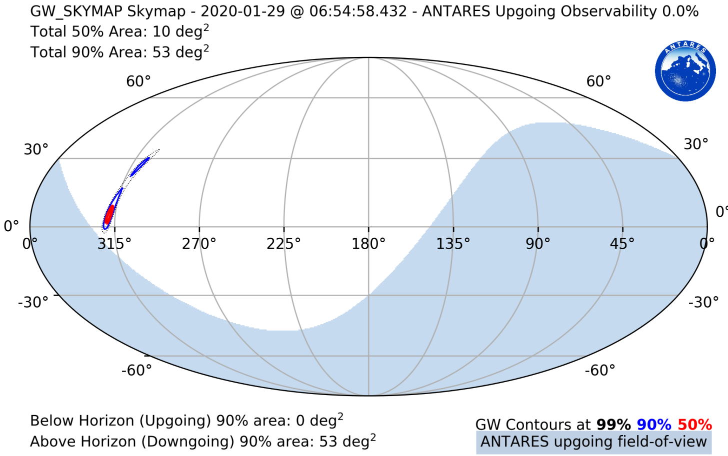
Since April 2019 = 56 non-retracted alerts

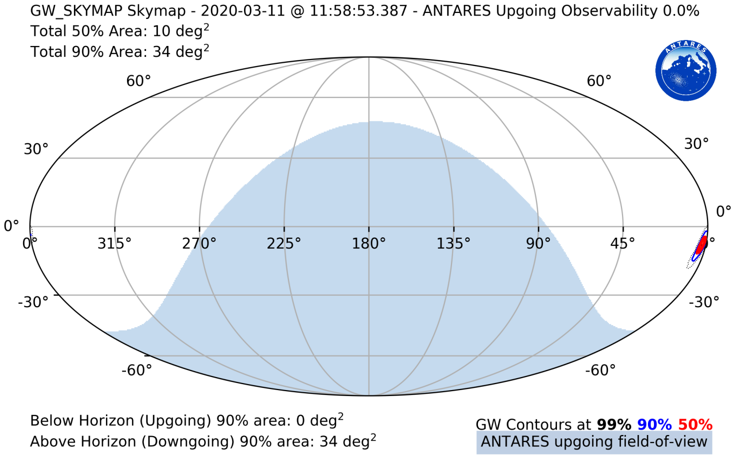
[52 followed by ANTARES]

Not followed :

- **BNS S1902425 ANTARES Offline**
- **3 BBH not in (upgoing) field of view :**
  - S200129m
  - S200224ca
  - S200311bg







GW triggers : types of signals

Since April 2019 = 56 non-retracted alerts [52 followed by ANTARES]

BBH : 37 including S190412 (paper Apr. 2020)

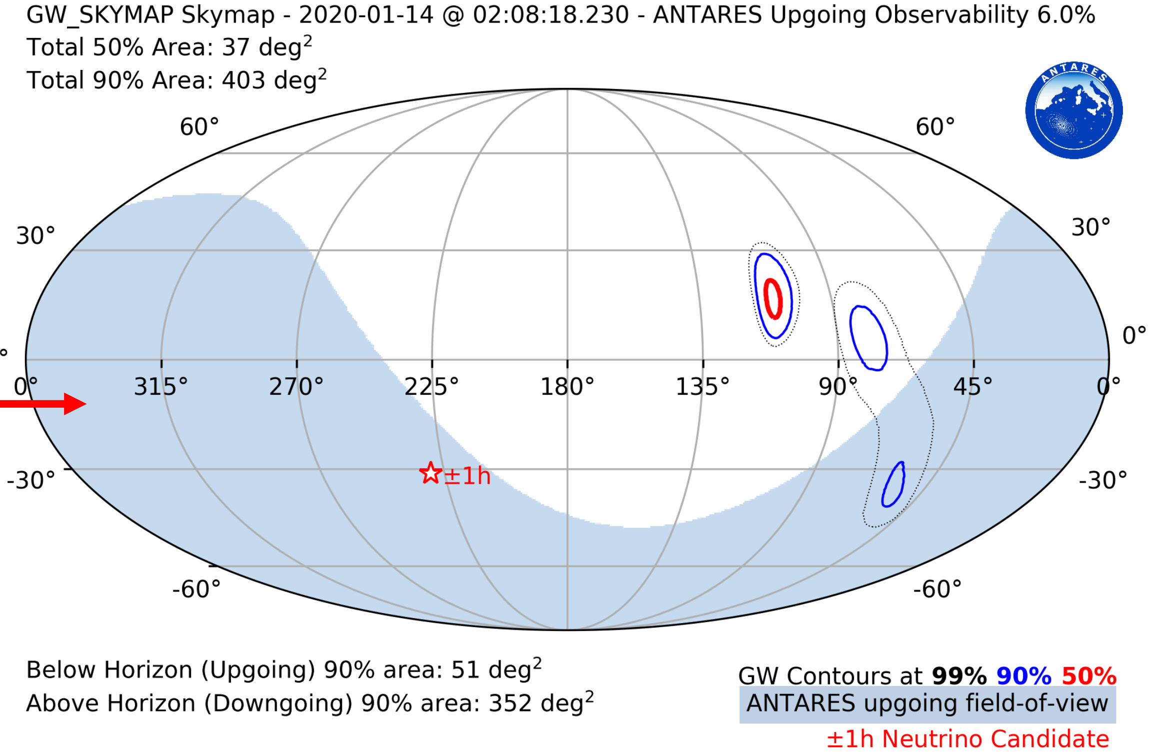
NSNS : 6, including S190425z

NSBH : 5 including S190814bv

MassGap : 4

Burst : 1 (S200114f)

1 neutrino in ± 1h but outside 90 % region

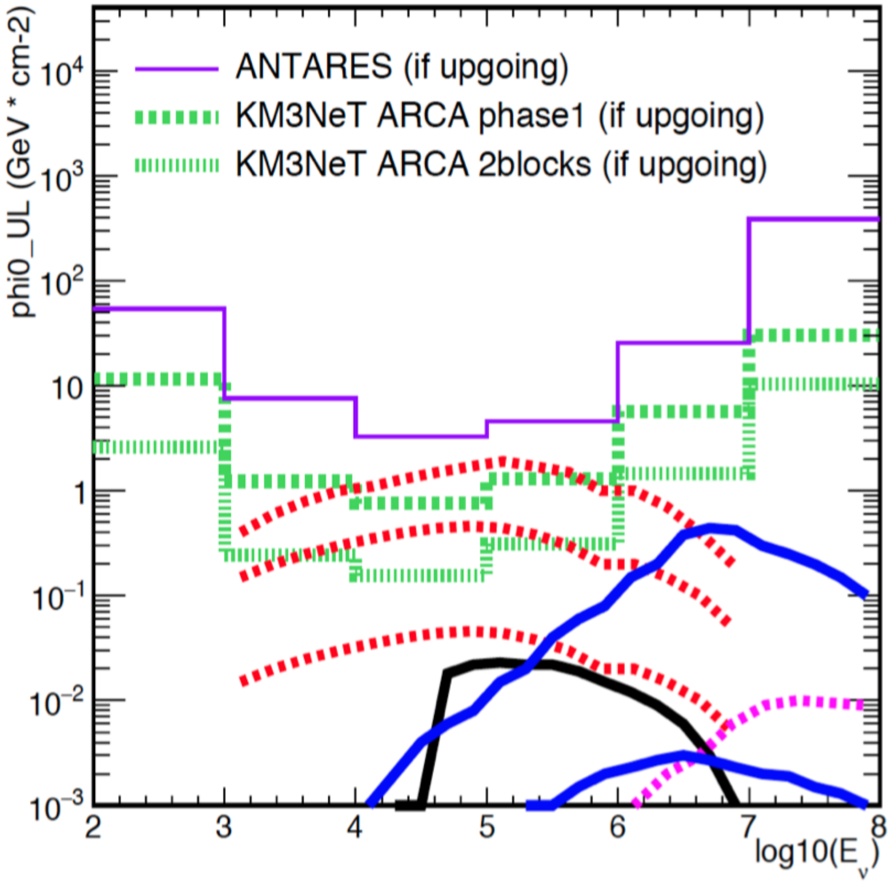


O3a : Apr 2019 → Sep. 2019
33 events

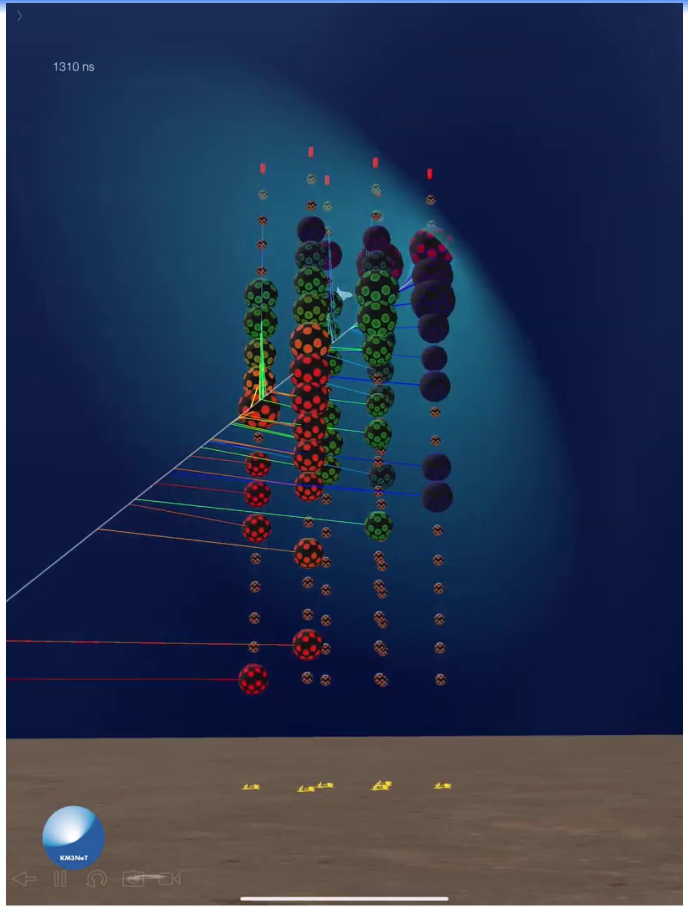
O3b : Nov 2019 → 27/03/2020 (Covid-19)
23 events

Catalog of O3a signals out soon (~40 signals)

Pour le futur : MM avec KM3NeT / ORCA + ARCA



Prédiction des performances (ici GW170817)



Reconstruction /Sélection en ligne de neutrinos « intéressants »