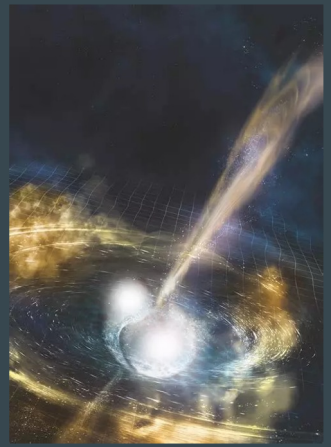
SVOM and the multimessengers (ToO-MM program)

...



Nicolas Leroy – IJCLab
Damien Dornic - CPPM

SVOM ToO program

ToO nominal

- 1/day
- Allocated time : 1 orbit (~45min)
- Max latency : 24-48h
- Instr: MXT and VT

ToO MM

- 1/week
- Allocated time : 1-14 orbits (24h max)
- Max latency : 12h (S-band) / <4h (BeiDou)
- Instr: MXT and VT
- react to GW and neutrinos

ToO Exceptional

- 1/month
- Allocated time : 7-14 orbits (24h max)
- Max latency : 12h (S-band) / <4h (BeiDou)
- Instr: MXT and VT

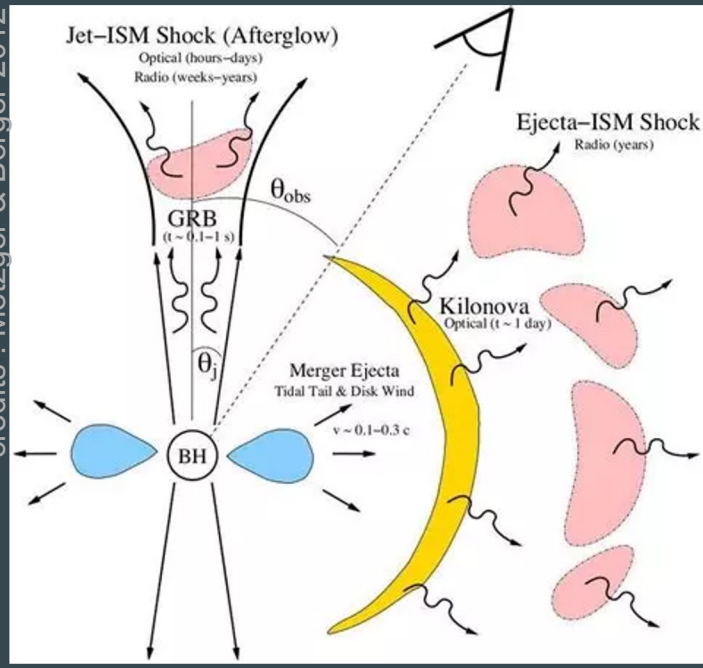
Open-access in most of the case 100% of the scientific products will be delivered to the scientific community as soon as they are available

100% of the informations that are needed to trigger external follow-ups will be publicly available as soon as possible (within few minutes)

Possible GW - EM emission

NS-NS and NS-BH mergers

- Short Gamma-Ray Bursts (GRBs):
  - Prompt γ-ray emission(< 2 s).
  - Multiwavelength afterglow emission: X-ray,o optical and radio (minutes, hours, days, months).
- Kilonova: optical and NIR (days-weeks).
- Late blast wave emission: radio (~ months, years).
- Tests of GR and measurement of Hubble constant will also be possible



credits : Metzger & Berger 2012

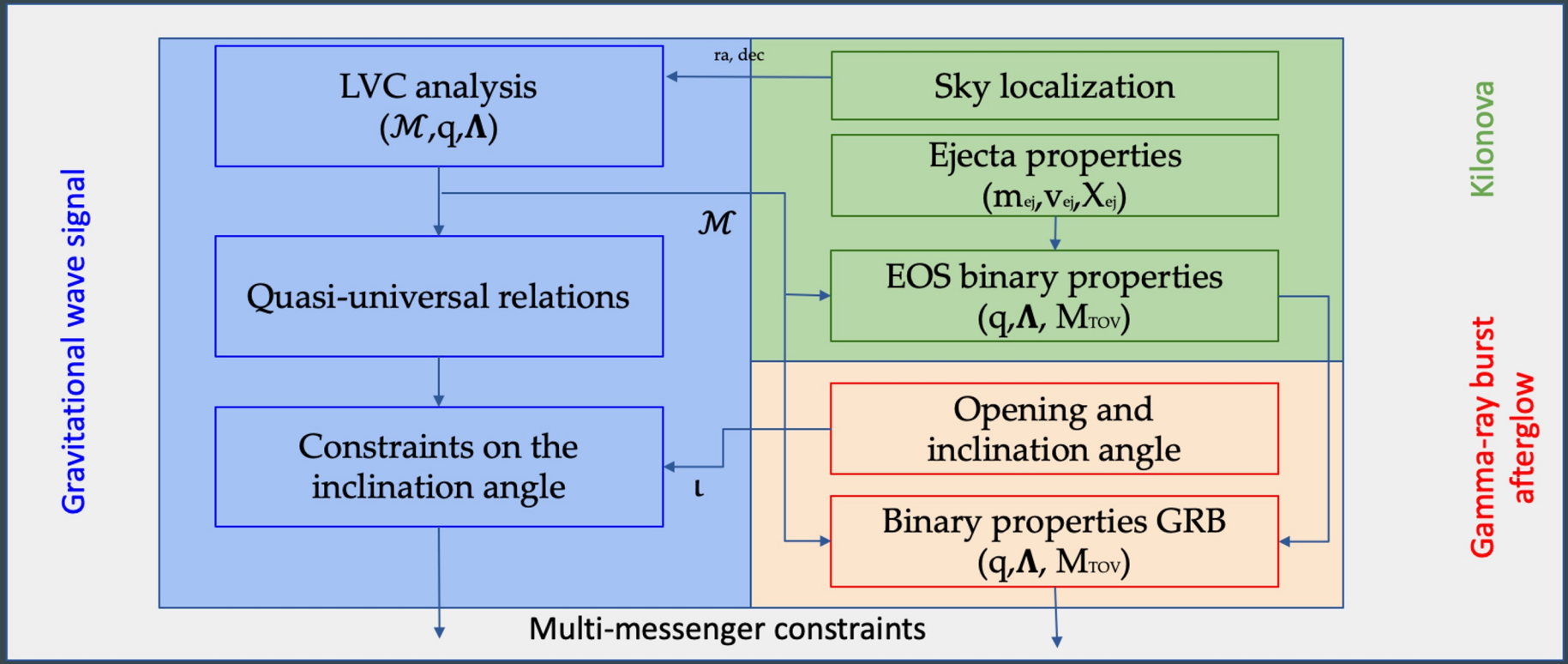
Long GRB or core collapse : GW sensitive only to closed-by galaxies

- X-rays and UV (minutes,days) - optical (weeks, months) - radio (years)

Isolated neutron stars : soft gamma rays repeaters or pulsar glitches (X and radio)

Common detection

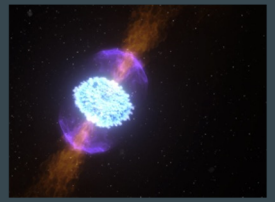
- Allow to have complementary information



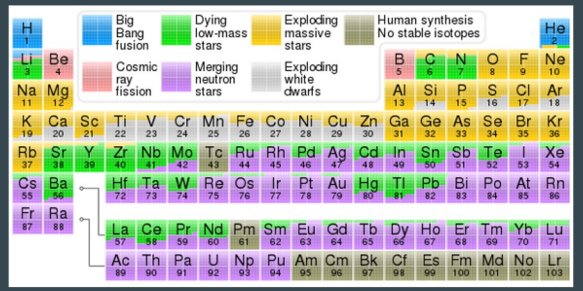
GW170817/GRB170817A

relativistic astrophysics

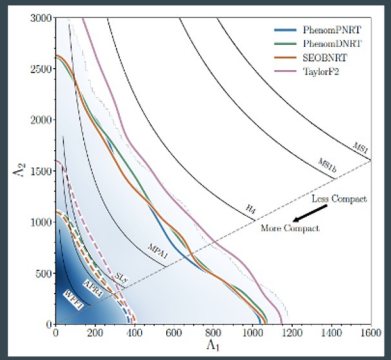
radioactive powered transients



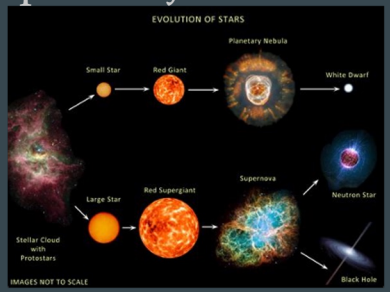
nucleosynthesis



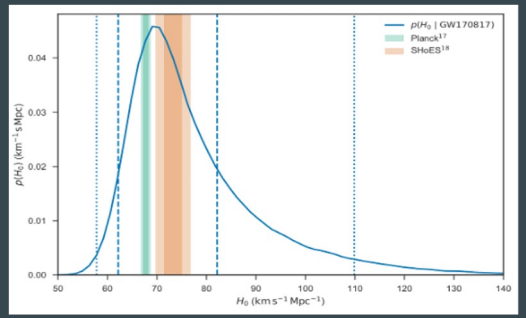
nuclear matter



compact object evolution



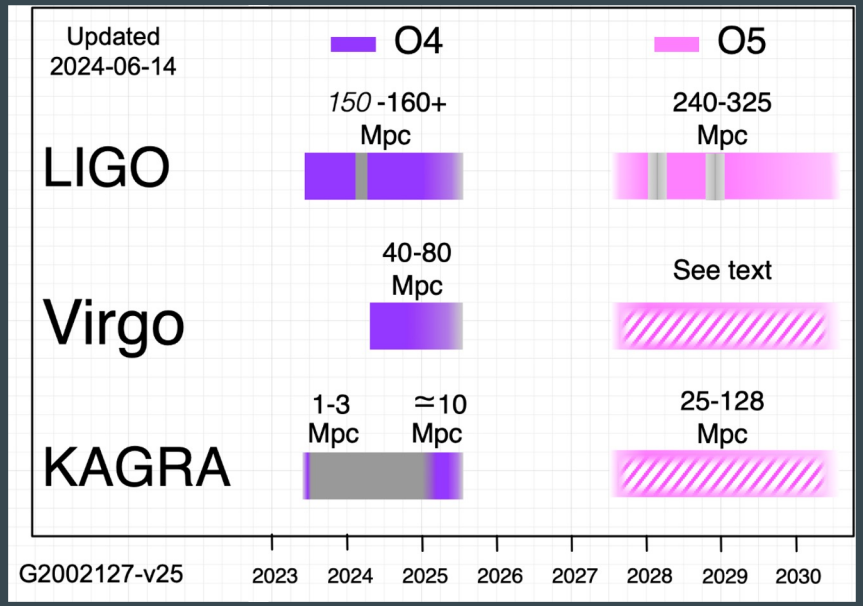
cosmology

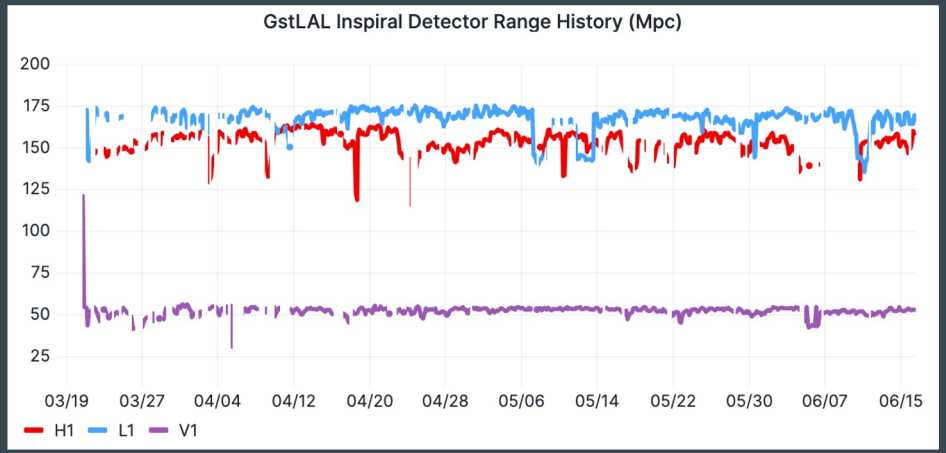


GW Network

The O4 run form LIGO-Virgo-KAGRA has been extended up to 9th of June

O5 will start during extended phase of SVOM





Distance averaged on all sky regions and inclination with SNR=8

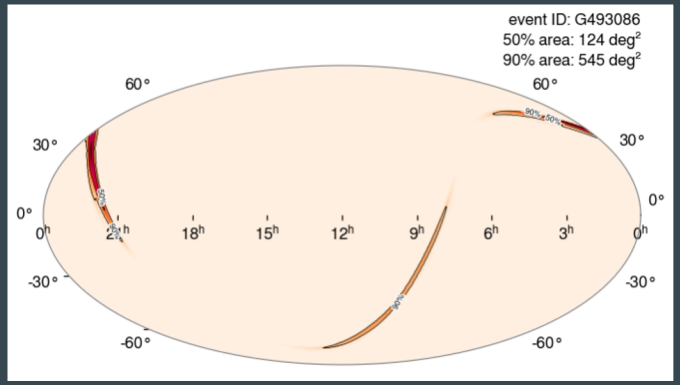
3-detector sky error region

O4b triggers are done with only 2 detectors

Virgo is then used to refine the parameter estimation, including sky map - even with low SNR

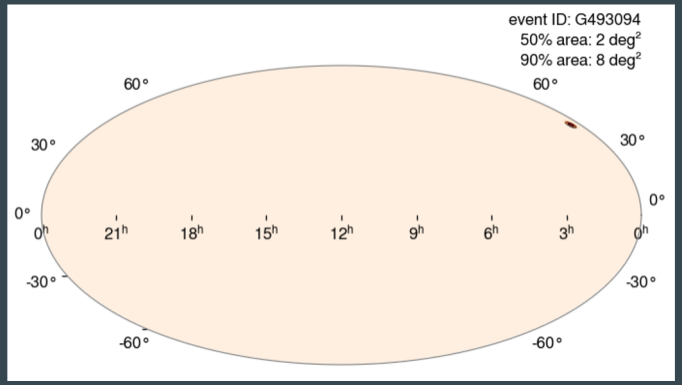
27 candidates since O4b (~90 days) - BBHs + 1 NSBH candidate

LIGO only



S240615dg - BBH event

LIGO + Virgo



Expected rate in O4 and O5

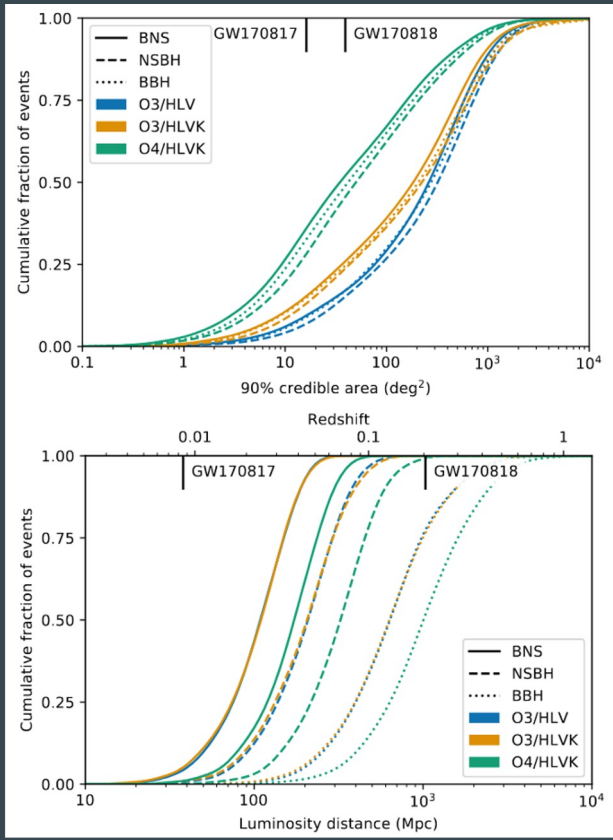
If we limit to 2 to 4 detectors alerts

We could expect up to 1 evt/day

Possibly one GRB event in common with GW emission (based on short GRBs in O3)

O5 will be 2 times more sensitive
-> 10 times more sources

Observation Run	Network	Expected BNS Detections	Expected NSBH Detections	Expected BBH Detections
O4	HLVK	10^{+52}_{-10}	1^{+91}_{-1}	79^{+89}_{-44}
		Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.
O4	HLVK	33^{+5}_{-5}	50^{+8}_{-8}	41^{+7}_{-6}



Possible GW counterpart - "standard" GRB case

- X-ray afterglow
  - fast decrease in flux
  - need fast reaction

- Visible afterglow
  - time-scale a bit longer for mag 23
  - need to use all the instrument to quickly scan and find bright optical counterpart
    - GWAC, GFT and F# instruments will be a plus

Connor et al arxiv 2406.05297

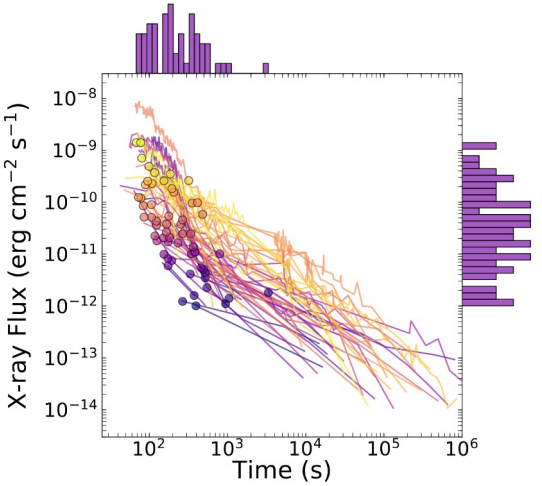
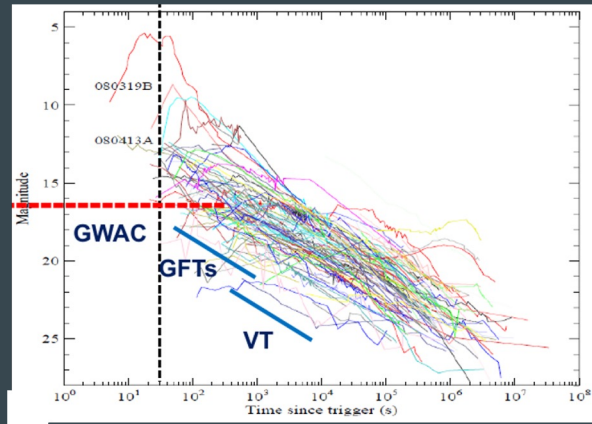


Figure 1. Observer-frame X-ray lightcurves (0.3 – 10 keV) for *Swift* sGRBs in our sample. The filled circles represent our constraints on the time t_o (upper limit) and flux F_o (lower limit), and the histograms on both axes track the distribution of these values for our sample. In general our sample has $t_o \lesssim 3600$ s and $F_o \gtrsim 10^{-12}$ erg cm^{-2} s^{-1}.

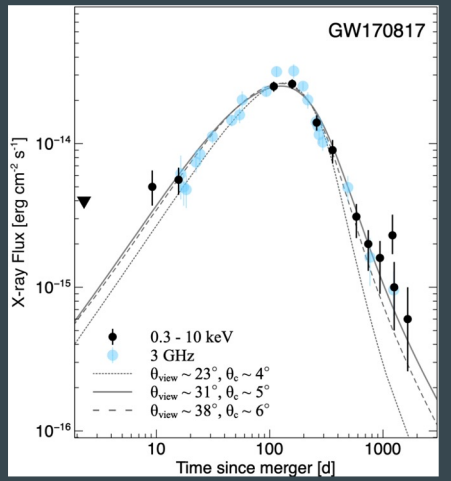
Wang 2013

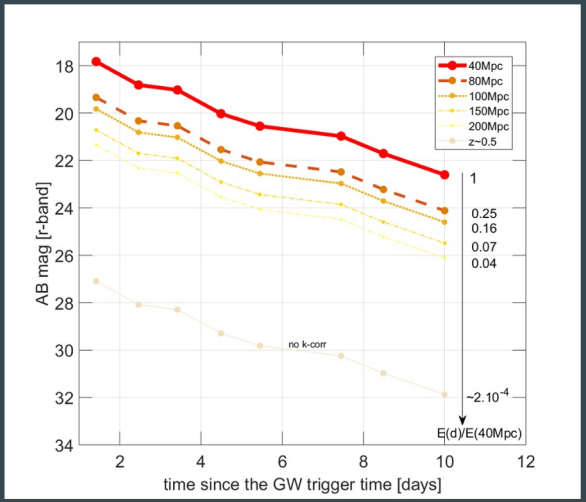


Possible GW counterpart - GW170817 case

- X-ray emission
  - with radio emission allow to define the geometry of the jet
  - peak after several days - time depending of the jet opening angle and the observation angle
  - possibly too faint for MXT

- UV to IR emission - kilonovae
  - During merger phase rich neutrons matter could produce heavy elements by neutron capture (r-process)
  - Quasi isotropic emission, heated by radioactivity, emission expected to shift from blue to red during cooling
  - Ejecta physics and nuclear equation of state
  - Need to reach large magnitude





Neutrino panorama

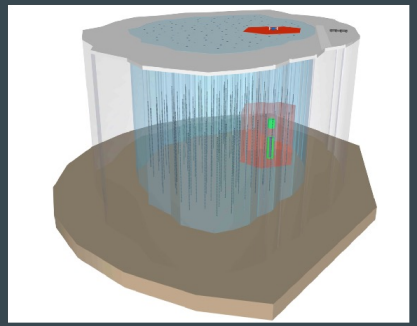
Precision Frontier

Intensity Frontier

Energy Frontier

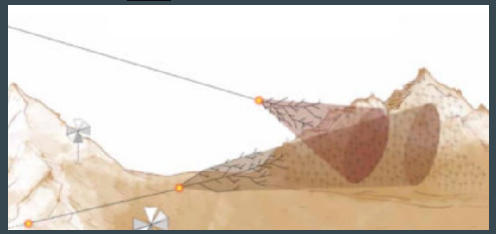
KM3NeT, GVD, P-ONE?

Having the best angular resolution with a reasonable instrumented volume



IceCube Gen2, TRIDENT?

Having the largest statistics with reasonable precision



GRAND, ARA, ARIANNA, POEMMA

Tracking cosmogenic ν at UHE

Neutrino Multi-messenger alerts

Given the current statistics-limited samples of astrophysical neutrinos, one of the most optimum analysis strategies is to:

- Alerts to community upon detection of likely « astrophysical » neutrinos for rapid follow-ups
- Real-time searches for neutrino signals in response to transient events observed in other messengers

These observations can:

- Strengthen or refine detections made in single messenger
- Probe source dynamics and populations, even in the absence of signal
- Identify the sources of the observed high-energy astrophysical neutrinos

Multi-messenger synergies with neutrinos

Optical telescopes: TAROT, COLIBRI, GRANDMA, MASTER, LCOGT, ZTF, LSST...
Easy access follow-up of large error box
Characterisation of the potential counterpart with spectroscopy (nature, redshift...)

X-ray telescopes: Swift, NUSTAR, SVOM...
Very clean sky
Provide transient triggers (GRB, AGN, Novae...)
ToO program (not so easy access)

γ-ray telescopes: Fermi-LAT
All-sky complete monitoring
Provide transient triggers (GRB, AGN...)

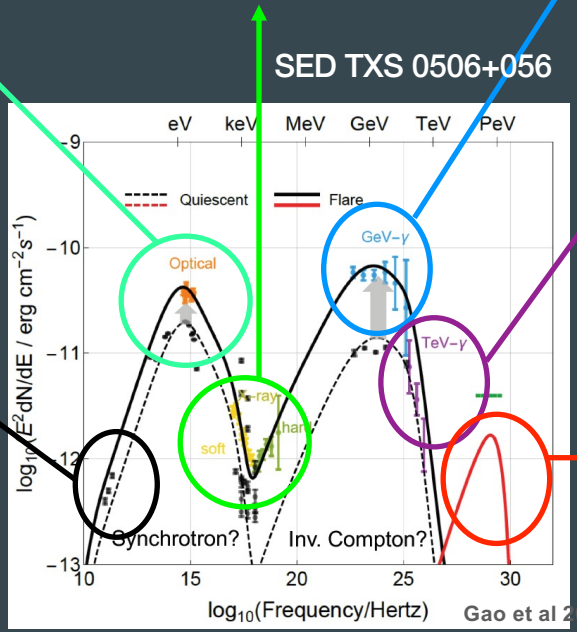
VHE γ-ray telescopes: HESS, MAGIC, LST, CTA...
Most natural common science case
Follow-up (not easy access)

VHE γ-ray telescopes: HAWC, LHAASO, SWGO...
All-sky monitoring
Provide triggers

Radio telescopes: OVRO, MWA, Lofar, Nenufar, ASKAP, SKA, VLBI...
Provide triggers (FRB...)
Follow-up

Neutrino telescopes: IceCube, KM3NeT, GVD...
Mutual follow-up
Confirmation of sources, improve significance

link with LIGO/VIRGO, SK, SNEWS



IceCube neutrino alerts

GOLD / BRONZE single track events

- Improved background rejections
- Added through-going track selections
- “Signalness” = NSignal / (NSignal + NBackground)
- 2 classifications:
  - GOLD : > 50% signalness. [Rate = 1 / month]
  - BRONZE : > 30% signalness [Rate = 1.33 / month]

- Good angular resolution: ~0.4-1.4 deg
- Selection based only on the properties of the neutrino, provide in the notice the list of 4FGL sources in the error region

Single cascade events

- Very low atmospheric background (>85% cosmic probability)
- Rate = 0.7 / month
- But, poor angular resolution (~10 deg radius)
- Selection based only on the properties of the neutrino

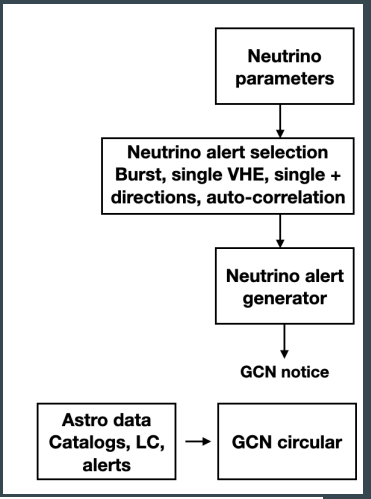
KM3NeT neutrino alert scheme

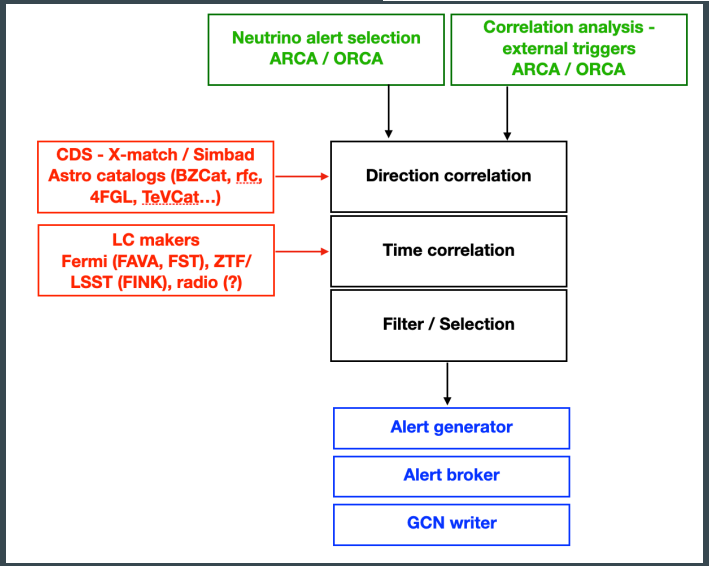
- Selecting only 1-2 neutrinos per month from 5-6000 atmospheric neutrinos is not an easy task and depending on the selection procedure, we can find a different sample.

- With the growing number of MM/MWL alerts in the future, it is important to increase the scientific content of the alert.
  We are trying to implement new type of alerts based on their astro content.

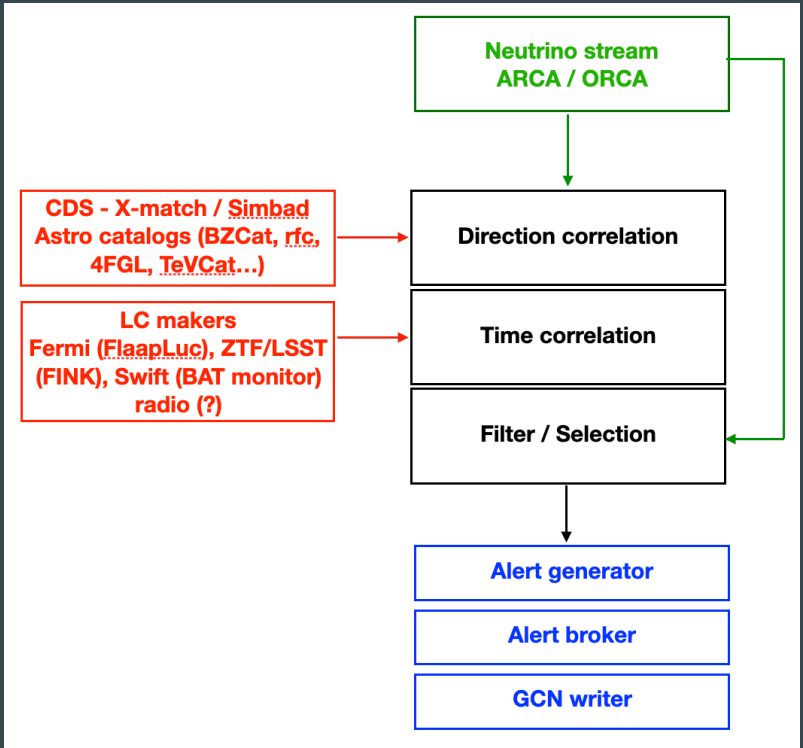
  - Reduce the threshold for the selection to a few per day and investigate the potential neutrino counterpart.
    If a potential interesting cosmic source is found, release an alert.

  - Keep the pure-based neutrino selection with a very high threshold (> gold)





KM3NeT Neutrino alert sending



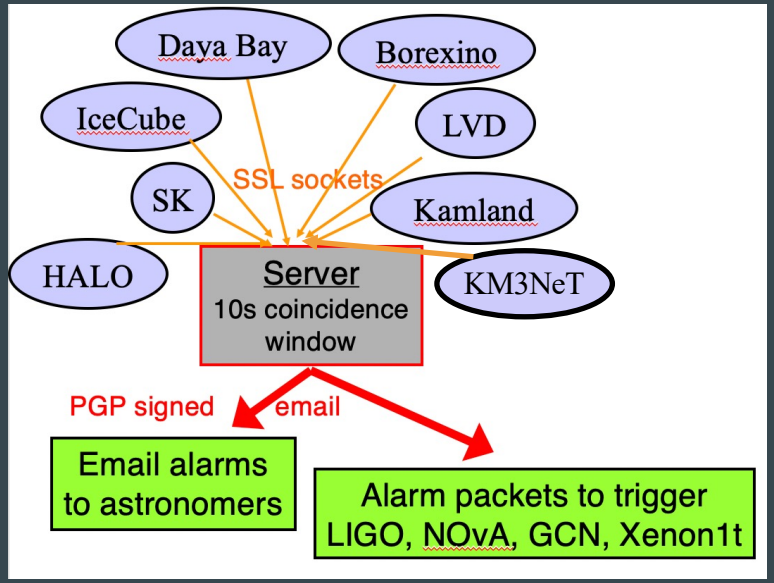
Work in progress (ETA: Sept 2024):

- New development of the neutrino alert selection by introducing time/space correlation of potential astro counterpart [« free » data]
- But, being as much as possible model/source type independent:
  - 1st step: look in HE catalogues (4FGL, TeVCat, BZCat, 3HSP, SGR, Swift-BAT...) to identify potential counterpart
  - 2nd step: Find real-time variability, flaring in radio (VLBI), optical (ZTF/LSST, ATLAS) and gamma-ray (Swift-BAT, Fermi-LAT)
- 3rd step: combined these information + neutrino properties to build the alert message
- Lower the complexity of the pure neutrino selection and increase interest
- Keep a pure neutrino criteria for exceptional characteristics

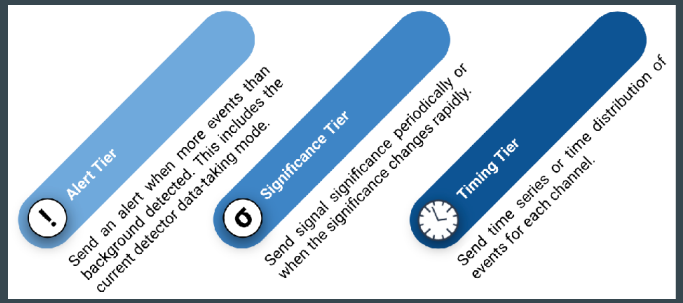
SNEWS

- SNEWS: Supernova Neutrino Early Warning System (started in 1998, fully operational in 2005)
- Neutrino detectors send alerts with FAR < 1 / week.
- 10 second coincidence time window.

=> A public alert is produced if coincidence is found. Prompt and positive alerts. Less than one false alert per century.

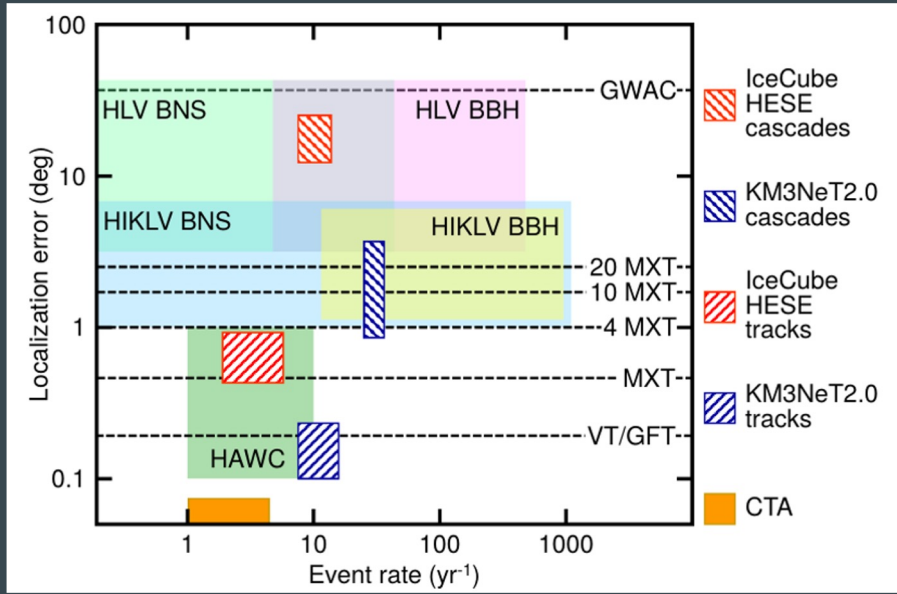


SNEWS 2.0 (in development)
Modern multi-messenger scenario, low-threshold alerts are common => Richer multi-messenger program.
3 level of alerts: Significance-based alerts, time-series sharing, real-time analysis capabilities (e.g. triangulation).



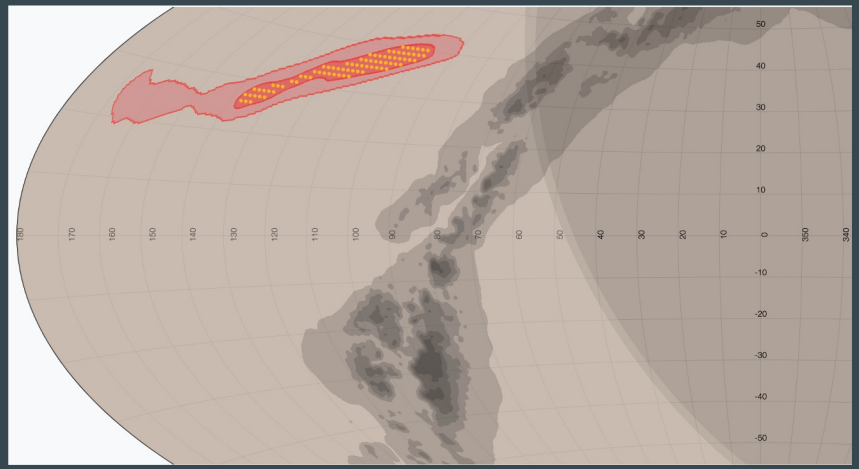
Scenario for MM follow-up with SVOM

- We will consider MXT, VT and ground telescopes to perform follow-up
- First automatic selection done at reception
  - different conditions depending of the instruments
  - will focus on event with possible electromagnetic counterpart
- Could use different strategies depending of the different instruments
  - include distance and galaxy catalogs to speed-up the scan



Observation strategy - tiling

- Cover the sky localisation map of GW
- Look for new object that are related to the GW
- Best suited for large FoV (>1deg²) instruments
- Widely used by current survey (PAN-STARRS, ZTF, TAROT,...)



Observation strategy - galaxy targeting

- Observed the galaxy compatible with the spatial information provided by GW

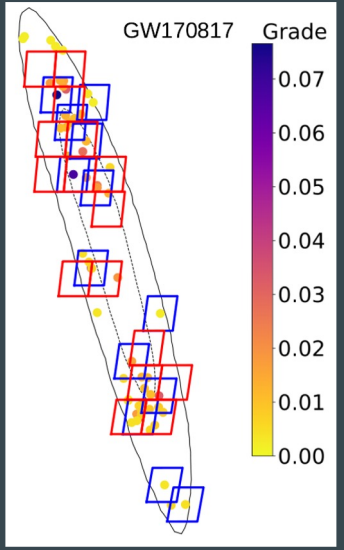
$$P_{\text{pos}} = P_{dV} = \frac{P_{\text{pixel}}}{\text{Pixel area}} N_{\text{pixel}} \, e^{-\frac{1}{2}\left(\frac{D_{\text{galaxy}} - \mu_{\text{pixel}}}{\sigma_{\text{pixel}}}\right)^2}$$

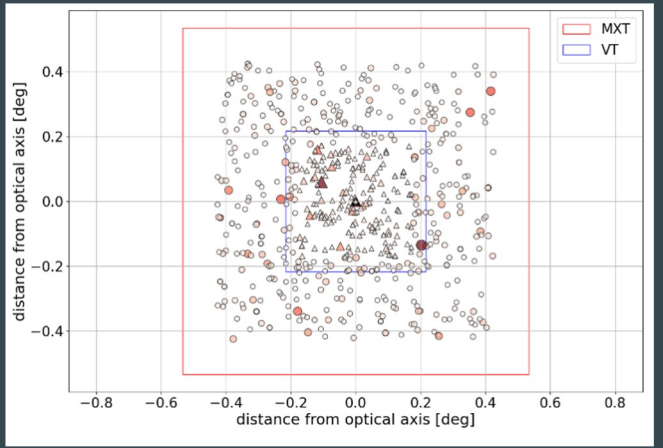
- Galaxies classified with
  - Spatial information
  - Stellar mass estimation

$$G_{\text{mass}} = \frac{M_{*,\text{galaxy}}}{\sum M_{*,\text{galaxy}}}$$

$$G_{\text{tot}} = P_{\text{pos}} \left(1 + \alpha\beta G_{\text{mass}}\right)$$

- MANGROVE catalog used to determine galaxy masses
- Best suited for small FoV instruments
- Take into account constraint of observations
- Technique used for 170817





Automatic pipeline within SVOM

Receive and digest alerts from GW, neutrinos and HE observatories and start automatically observation plan

Automatic selection based on physical information (flux, masses, ...), human validation if pass the cut

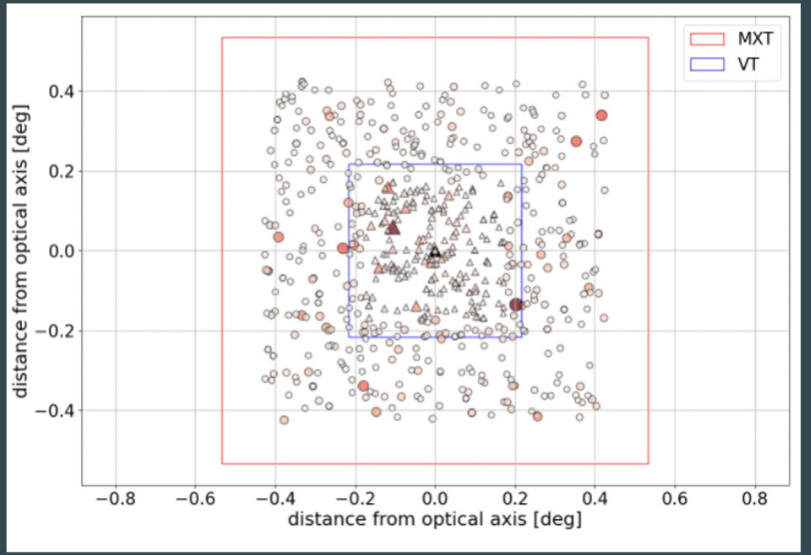
Need positions/maps and then pave the sky based on all instruments FoV - when possible used distance information to only select interesting galaxies

Proposed observation plans to the different observatories within the SVOM perimeter (VO or json file)

Satellite strategy

Observation plans now :

- Ensures that the VT is observing a galaxy of interest
- Take into account the sun constraint
- Takes into account edges bias
- Limit slew to fit with the system requirement
- Further optimize the galaxy targeting while
- Repositioning around the galaxies of interest



Ducoin et al, MNRAS 524, 2023

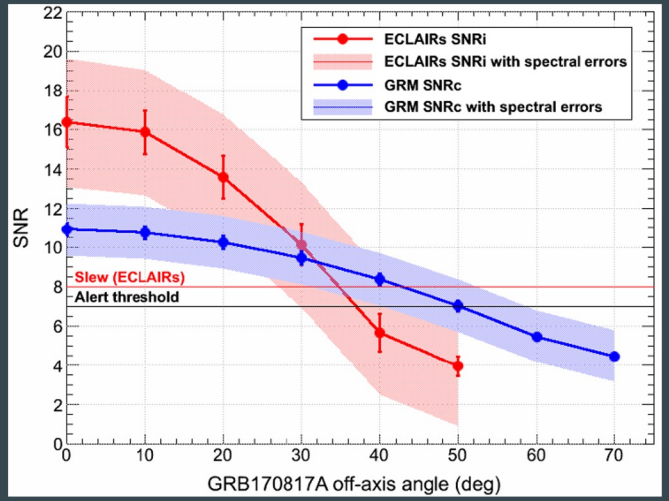
A GW170817 like event in SVOM

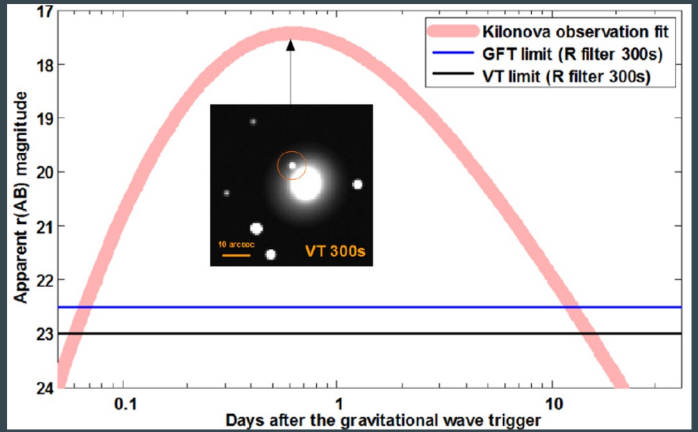
It the GRB appeared in ECLAIRs or GRM field of view

- ECLAIRs & GRM detection with high probability → slew request sent by ECLAIRs
- MXT and VT follow-up observations → kilonova easily detected by the VT

If not in ECLAIRs and GRM field of view

- LIGO-Virgo alert received at the French scientific center → GFT observations triggered, nearby galaxy targeting within the GW error contour (several observation cycles)
- Thanks to its NIR channel, Colibri would certainly have detected the kilonova





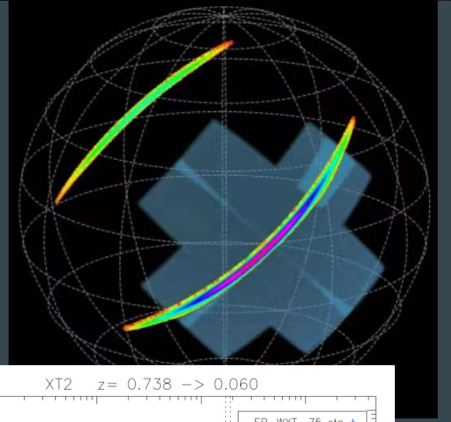
Links with Einstein Probe

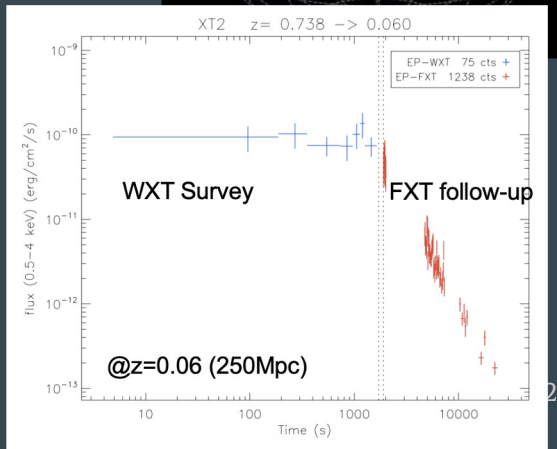
The two missions are well complementary

if combined we can obtain :

- multiband with large coverage
- allow deep and fast tiling strategy

Both missions share the same mission and data centers





Conclusions

- SVOM will be a key player in the multi-messenger studies in the next years
  - O4 has been extended up to June 2025 -> 8 months, hope for BNS !
  - KM3NET will start to send alerts as IceCube
- A specific tiling strategy has been setup to use both space and ground segments
- Possible synergies are possible with Einstein Probe and SVOM
- Join Tuesday afternoon session for hands-on