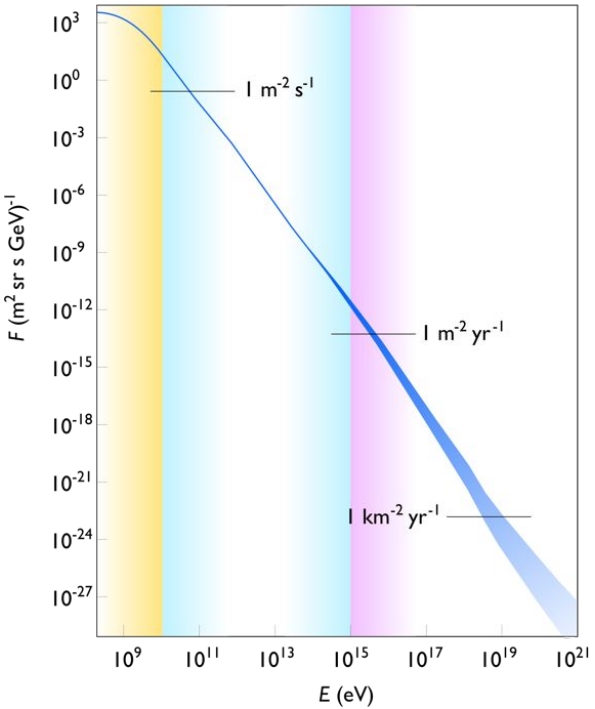
Searching for neutrinos from Microquasar flares

Sébastien Le Stum
lestum@cppm.in2p3.fr

IRN Neutrino Meeting, Nantes, 20/06/2023

Motivations for neutrino astronomy

Main question: what is the origin and the role of the cosmic rays in the Universe ?

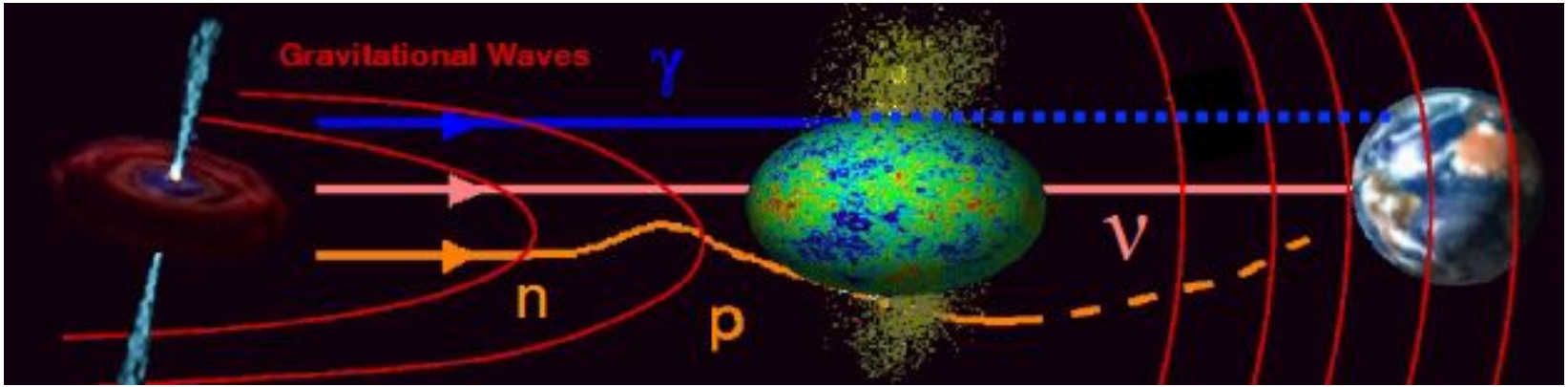


- Discover 100 years ago but still unknown origin
- Spectrum over 32 orders of magnitude

- Mysteries at the ultra high energies > 10^{20} eV,
  which acceleration mechanism ?
  Which sources ?
  Which cosmic evolution ?

- Connection to the other messengers (ν, γ, GW)
- At the heart of the non-thermal astronomy

Neutrinos: cosmic messengers



- Neutrinos: neutral, stable, weakly interacting
  - not absorbed by background light/CMB ➔ access to cosmological distances
  - not absorbed by matter ➔ access to dense environments
  - not deviated by magnetic fields ➔ astronomy over full energy range
- ‘Smoking gun’ signature for hadronic processes
- Correlated in time/direction with electromagnetic and gravitational waves
- New window of observation on the Universe

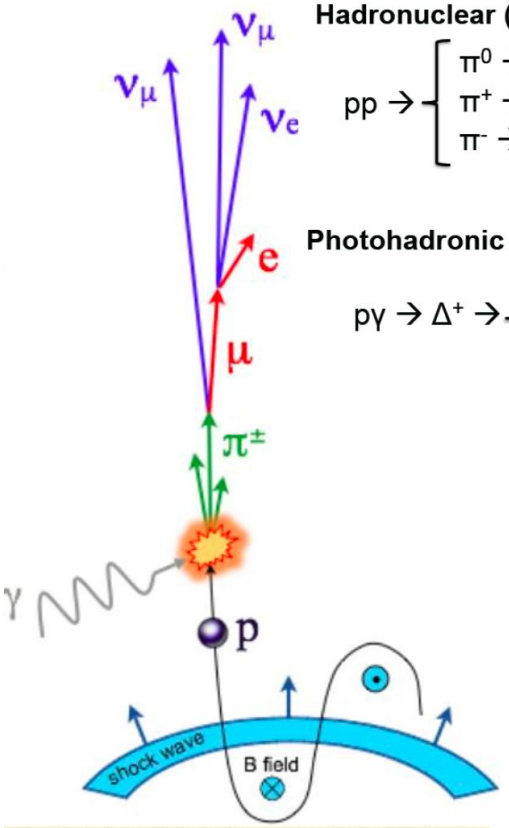
Link between Cosmic Rays/Neutrinos/Gamma

- Analytical relation from gamma to neutrino:

$$\frac{N_{\gamma/\nu}}{E_{\gamma/\nu}} \approx k_{\gamma/\nu} \left(\frac{E_{\gamma/\nu}}{1\,\mathrm{TeV}}\right)^{-\Gamma_{\gamma/\nu}} \exp\left(-\sqrt{\frac{E_{\gamma/\nu}}{\epsilon_{\gamma/\nu}}}\right)$$

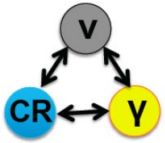
$$\begin{aligned} k_\nu &\approx (0.71 - 0.16\alpha)\, k_\gamma \\ \Gamma_\nu &\approx \Gamma_\gamma \approx \alpha - 0.1 \\ \epsilon_\nu &\approx 0.59\,\epsilon_\gamma \approx \epsilon_p/40\ . \end{aligned}$$

Kappes *et al*, 2007



Hadronuclear (e.g. star burst galaxies and galaxy clusters)

$$pp \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\,\gamma \\ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \bar{\nu}_\mu \\ \pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \bar{\nu}_\mu \nu_\mu \end{cases}$$



Photohadronic (e.g. gamma-ray bursts, active galactic nuclei)

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\,\pi^0 \rightarrow p\,\gamma\,\gamma \\ n\,\pi^+ \rightarrow n\,\mu^+ \nu_\mu \rightarrow n\,e^+ \nu_e \bar{\nu}_\mu \nu_\mu \end{cases}$$

cosmic ray + gamma

cosmic ray + neutrinos

Neutrino flavour ratio at source:

pion-muon decay

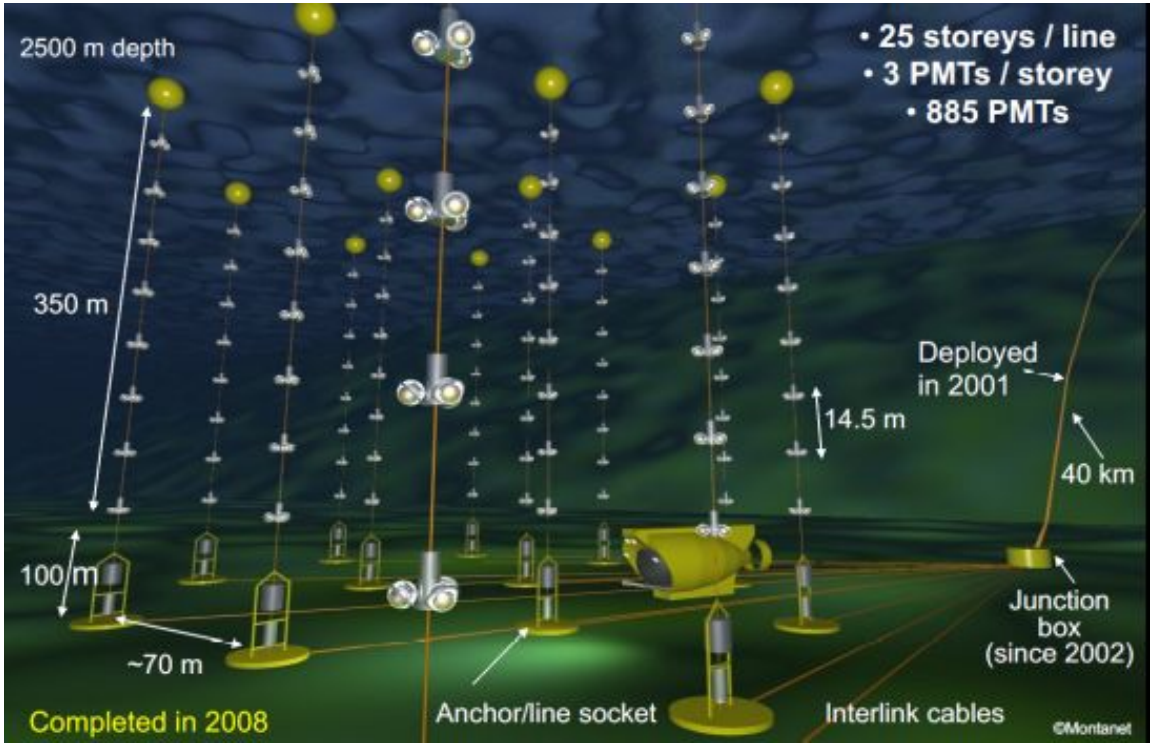
$$\nu_e : \nu_\mu : \nu_\tau \sim 1 : 2 : 0$$

Oscillations average out over cosmic baselines

$$\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$$

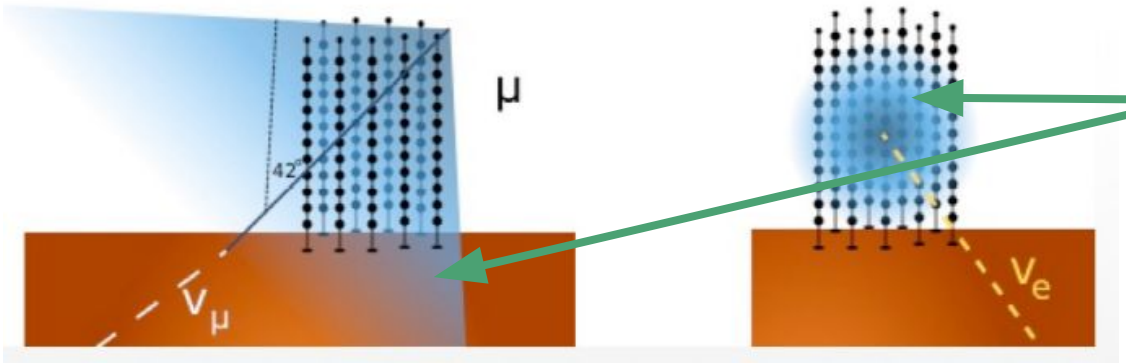
The ANTARES detector

- First undersea neutrino telescope
- Took data from 2008 to 2022
- 12 lines
- Located in the Mediterranean Sea near Toulon, France



Detection principle

2 event topologies:



Cherenkov light from **secondary particles** after neutrino interaction

Track-like event

⇒ ν_μ (+ ν_τ) Charged Current interaction

⇒ Better angular resolution

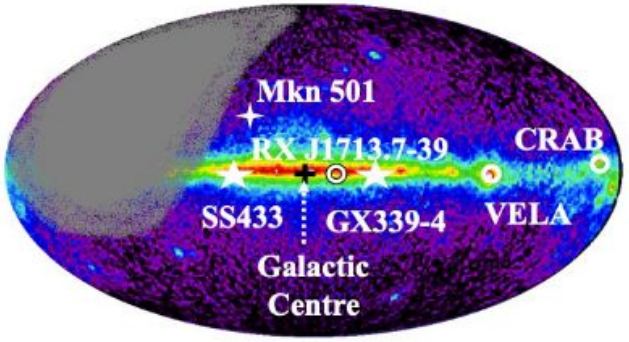
Shower-like event

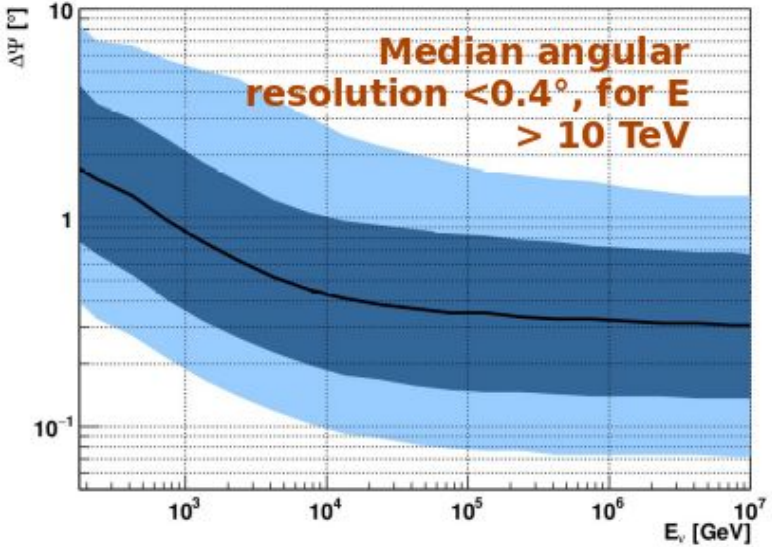
⇒ ν_e, most ν_τ Charged current + Neutral Current interactions

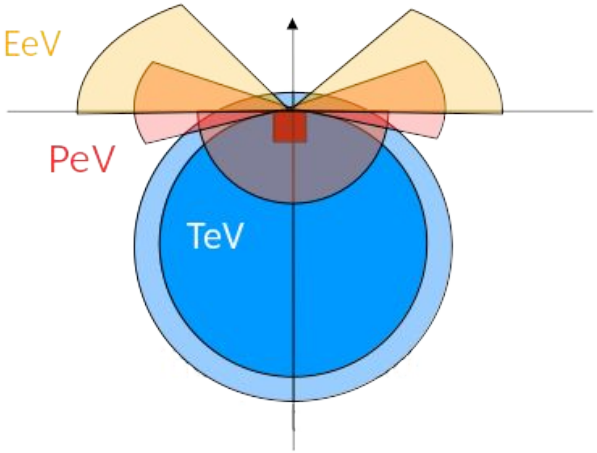
⇒ Better energy resolution

ANTARES Detector performances

- Visibility of galactic center
- 95% duty cycle

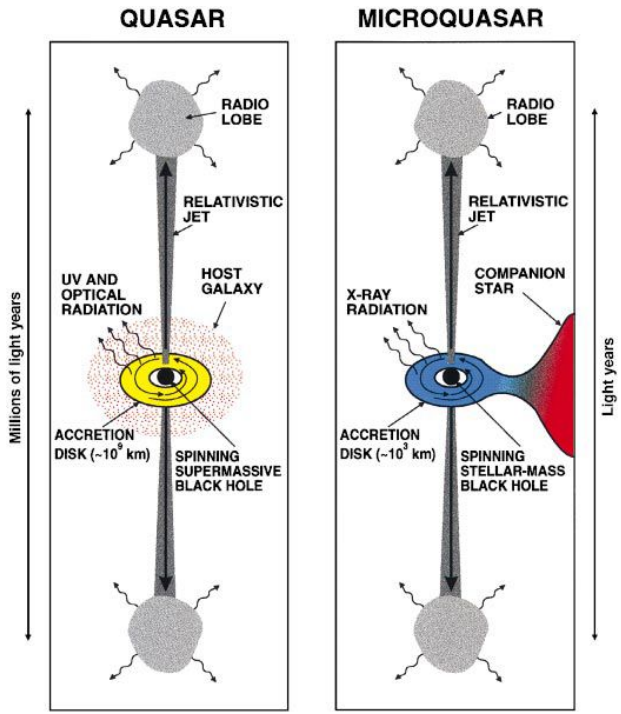




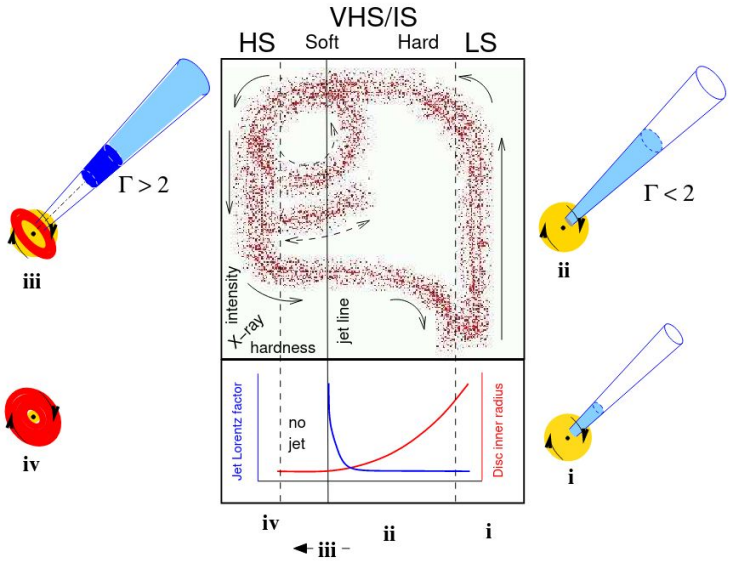


What are microquasars?

- Binary systems with a compact object (Black Hole or Neutron Star) and a companion star
- Matter transfer from the companion to the compact object
- Process of Accretion - Ejection:
  - Accretion through a **disk**
  - Ejection of matter through a **jet** (which can be relativistic)
- Emit mostly in X-Ray ⇒ XRB
- 2 Types:
  - LMXB - Low Mass companion: mass transfer via Roche Lobe overflow
  - HMXB - High Mass companion (type O and B): Mass transfer via winds
- Transient with periods of **outburst**

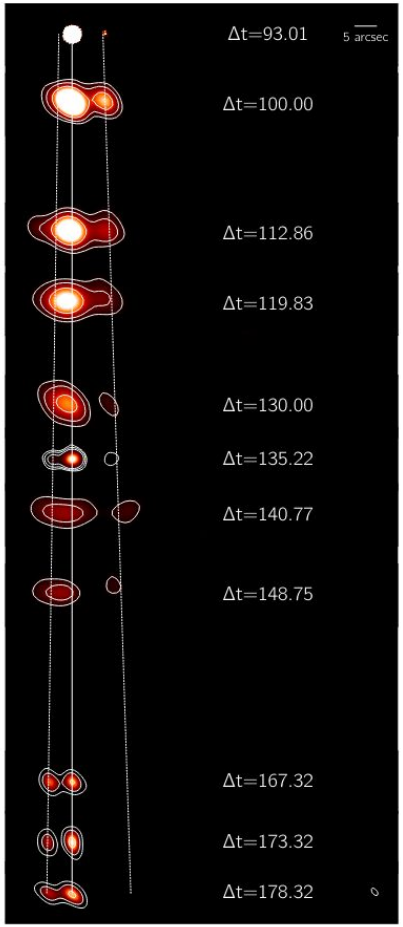


Microquasars: Ideal candidates for multi-messenger, time domain astronomy



XRay behaviour during a flare for our sources

⇒Sources that show this hysteresis pattern during flares associated with relativistic ejecta



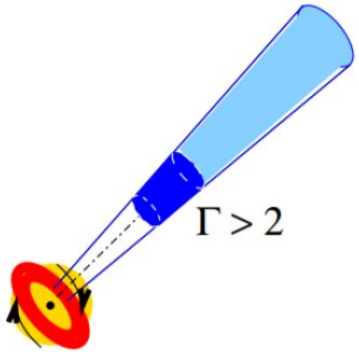
Radio resolved Discrete ejecta from MAXI J1820+070 during a state transition

Neutrino emission

During outbursts/state transitions, matter ejection with relativistic bulk speed

⇒ **Shock** formation with previously ejected mater

⇒ Possible acceleration of charged particle to very high energy



Those accelerated particles may produce

- Gamma photons
- **Neutrinos** (if contribution of hadronic processes)

Leptonic process

$$Inverse\,Compton:\ e^-_{accelerated} + \gamma_{LE} \rightarrow e^- + \gamma_{HE}$$

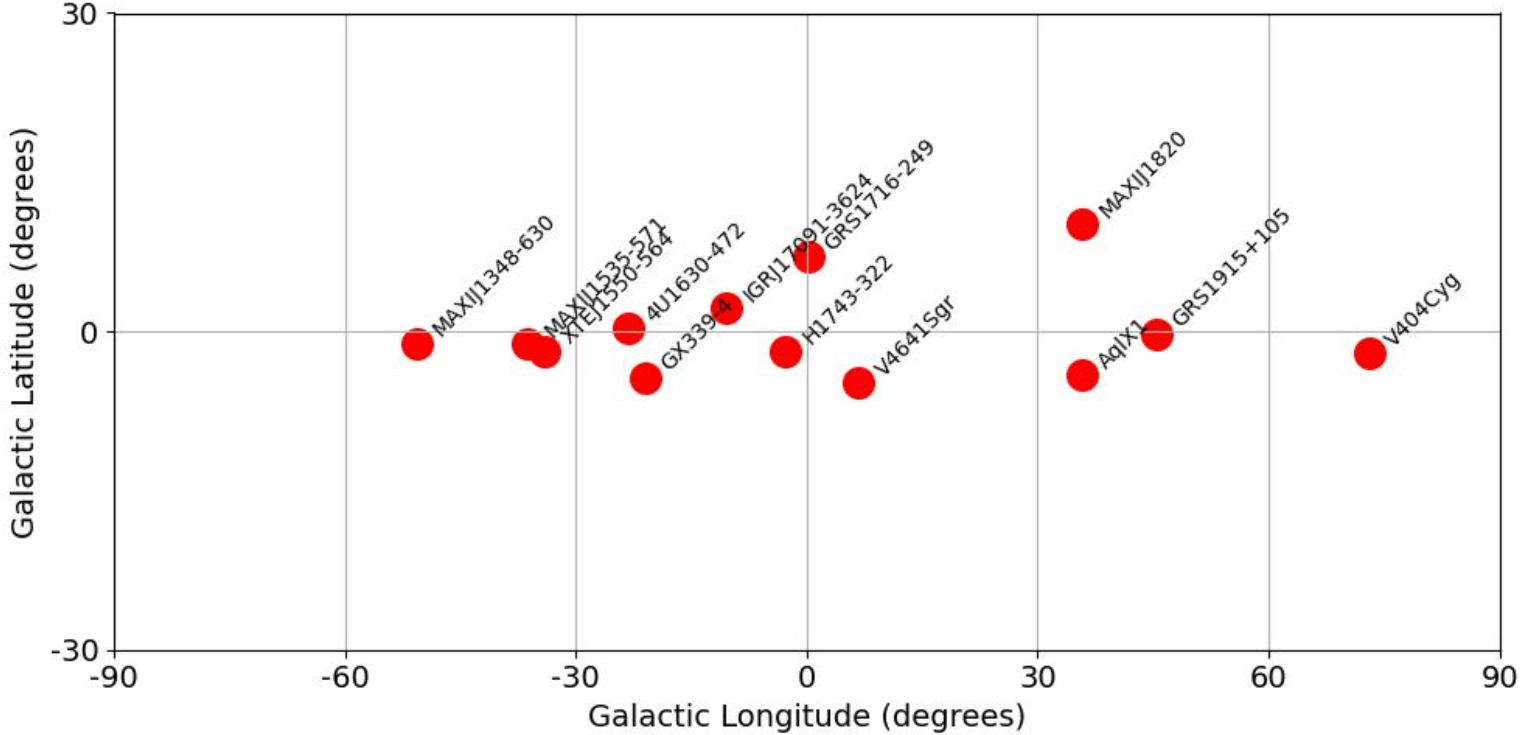
Hadronic process

$$\left.\begin{array}{l} p_{accelerated} + p \longrightarrow X + \left\{\pi^0, \pi^-, \pi^+\right\} \\ p_{accelerated} + \gamma_{LE} \rightarrow \Delta^+ \rightarrow p\pi^0 \ or \ n\pi^+ \end{array}\right| \rightsquigarrow \gamma_{\mathrm{HE}} \text{ and } \nu$$

What can we learn from the study of neutrino emission ?

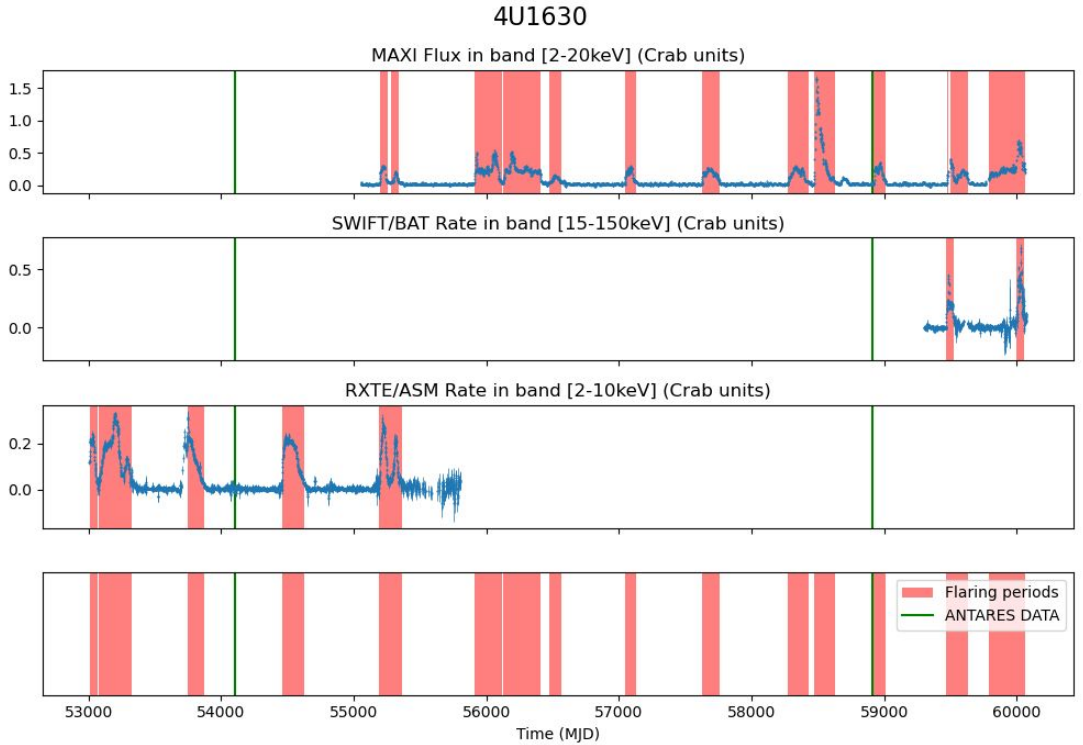
- Jet composition/formation ?
- Microquasars as cosmic ray engines ?

Studied sources: 13 LMXBs



XRay flares results

Source	Time flare (d)
IGRJ17091-3624	**45**
XTEJ1550-564	**18**
V4641 Sgr	**95.5**
AqlX1	**664**
4U1630-472	**1437**
GRS1915+105	**3873**
V404 Cyg	**13**
H1743-322	**737**
GX339-4	**1277**
MAXIJ1820+070	**226**
MAXIJ1535-571	**206**
MAXIJ1348-630	**171**
GRS1716-249	**296.5**



XRay flares definition

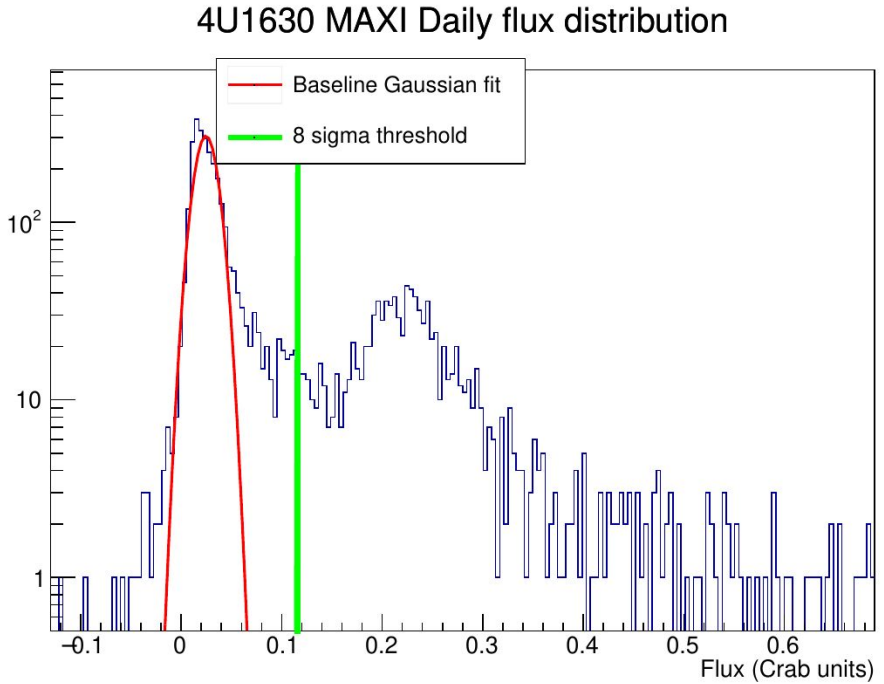
- Using **RXTE/ASM**, **MAXI/GSC** and **Swift/BAT** public data
- **Baseline** characterisation with a **gaussian fit** ⇒ μ_{BL} σ_{BL}
- Flares defined **from** data points that verify:

$$F - \Delta F > \mu_{\mathrm{BL}} + 8\,\sigma_{\mathrm{BL}}$$

- To data points that verify:

$$F - \Delta F < \mu_{\mathrm{BL}} + 2\,\sigma_{\mathrm{BL}}$$

to obtain start/end of flare

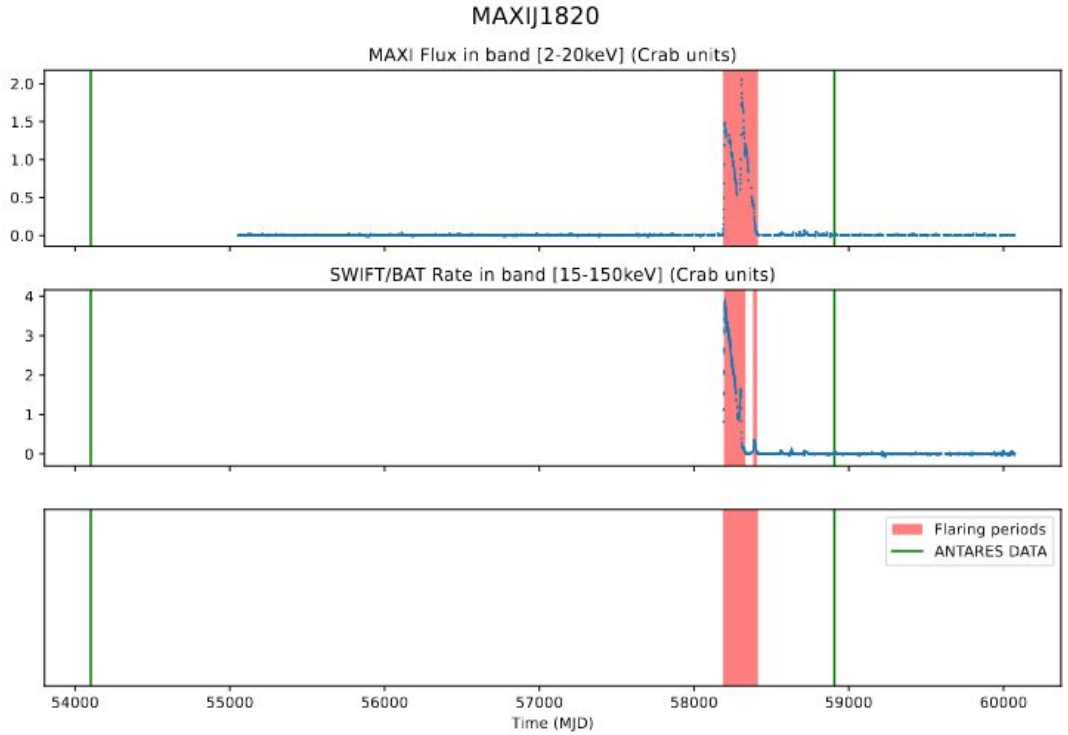


⇒ Neutrino search on time windows if flare in **any** band
⇒ Stacked search of every flare window for each source

Computed on archival data and in real time

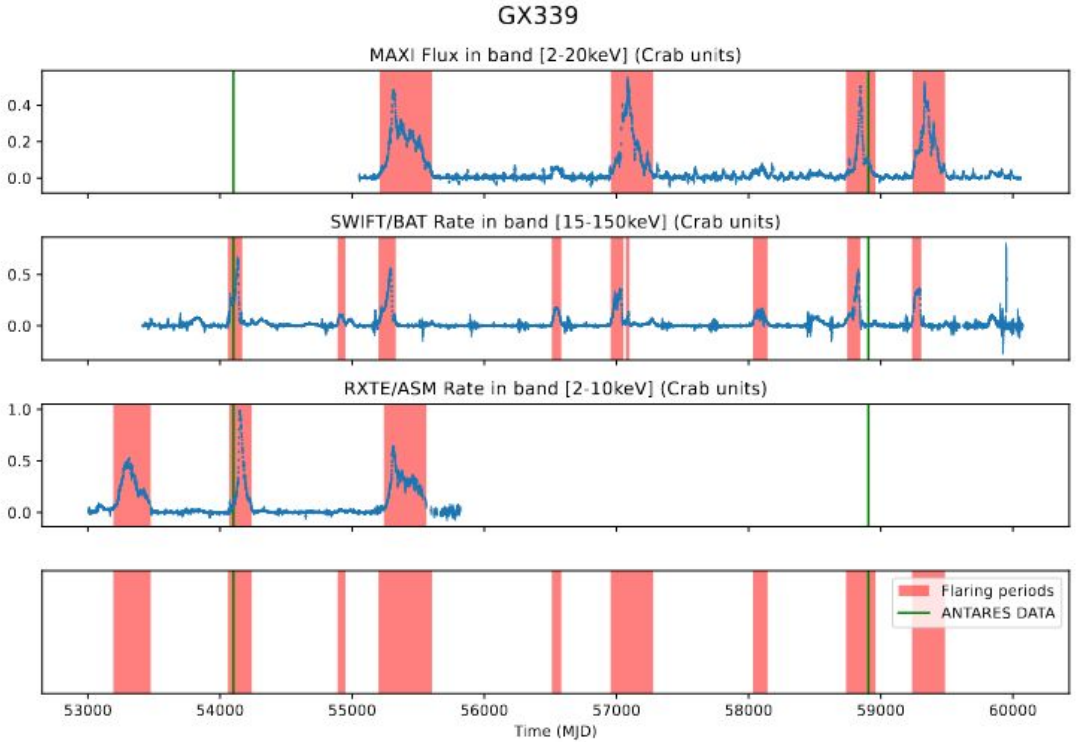
XRay flares results

Source	Time flare (d)
IGRJ17091-3624	**45**
XTEJ1550-564	**18**
V4641 Sgr	**95.5**
AqlX1	**664**
4U1630-472	**1437**
GRS1915+105	**3873**
V404 Cyg	**13**
H1743-322	**737**
GX339-4	**1277**
MAXIJ1820+070	**226**
MAXIJ1535-571	**206**
MAXIJ1348-630	**171**
GRS1716-249	**296.5**



XRay flares results

Source	Time flare (d)
IGRJ17091-3624	**45**
XTEJ1550-564	**18**
V4641 Sgr	**95.5**
AqlX1	**664**
4U1630-472	**1437**
GRS1915+105	**3873**
V404 Cyg	**13**
H1743-322	**737**
GX339-4	**1277**
MAXIJ1820+070	**226**
MAXIJ1535-571	**206**
MAXIJ1348-630	**171**
GRS1716-249	**296.5**



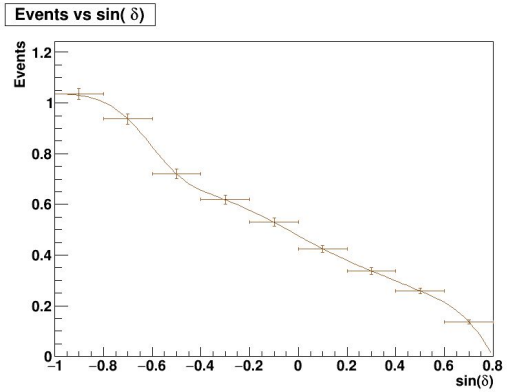
ANTARES Analysis method

Unbinned likelihood

$$\mathcal{L}(n_s) = \sum_{i=1}^{N_T} \{ \frac{n_s}{N_T} P(\Psi, \beta) P_{sg}(E, \beta) P_{sg}(t) + (1 - \frac{n_s}{N_T}) P(\delta) P_{bg}(E, \beta) P_{bg}(t) \}$$

PSF | Energy | Time — **SIGNAL**

Declination | Energy | Time — **BACKGROUND**



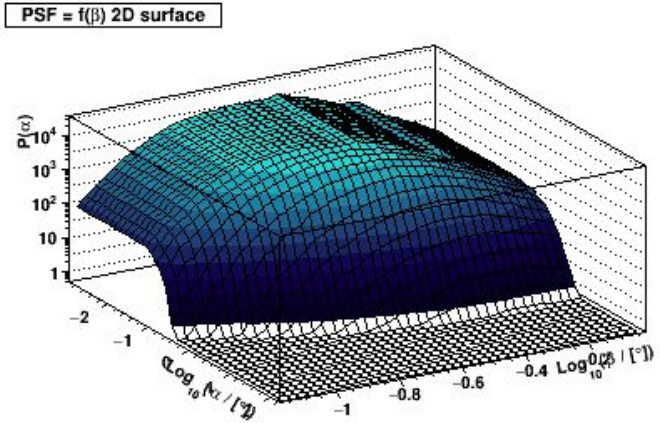
Background event declination PDF

Likelihood ratio Test Statistic:

$$TS = -2 \times \log(\frac{\mathcal{L}(n_s{=}0)}{\mathcal{L}(n_s{=}n_{max})})$$

Sensitivity:

$$Sen = \sum_{i=0}^{N} P(TS^i > TS^{n=0}_{median}) Poiss(i|n_s)$$



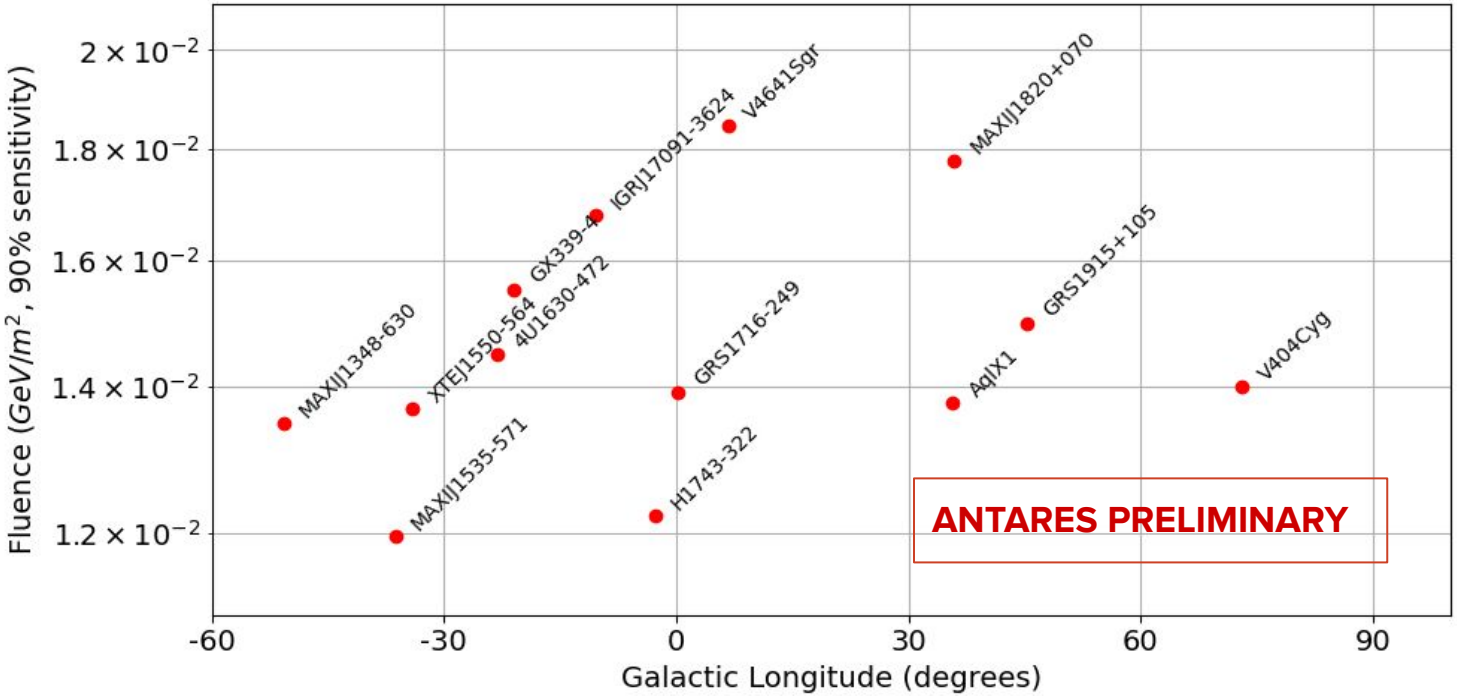
Signal event PSF PDF

Computed with pseudo-experiments

Fluence sensitivities

$$\mathcal{F} = \Delta T \int_{100\mathrm{GeV}}^{100\mathrm{PeV}} E \frac{\mathrm{d}N}{\mathrm{d}E} \mathrm{d}E$$ assuming $$\frac{\mathrm{d}N}{\mathrm{d}E} = \phi_0 E^{-2}$$

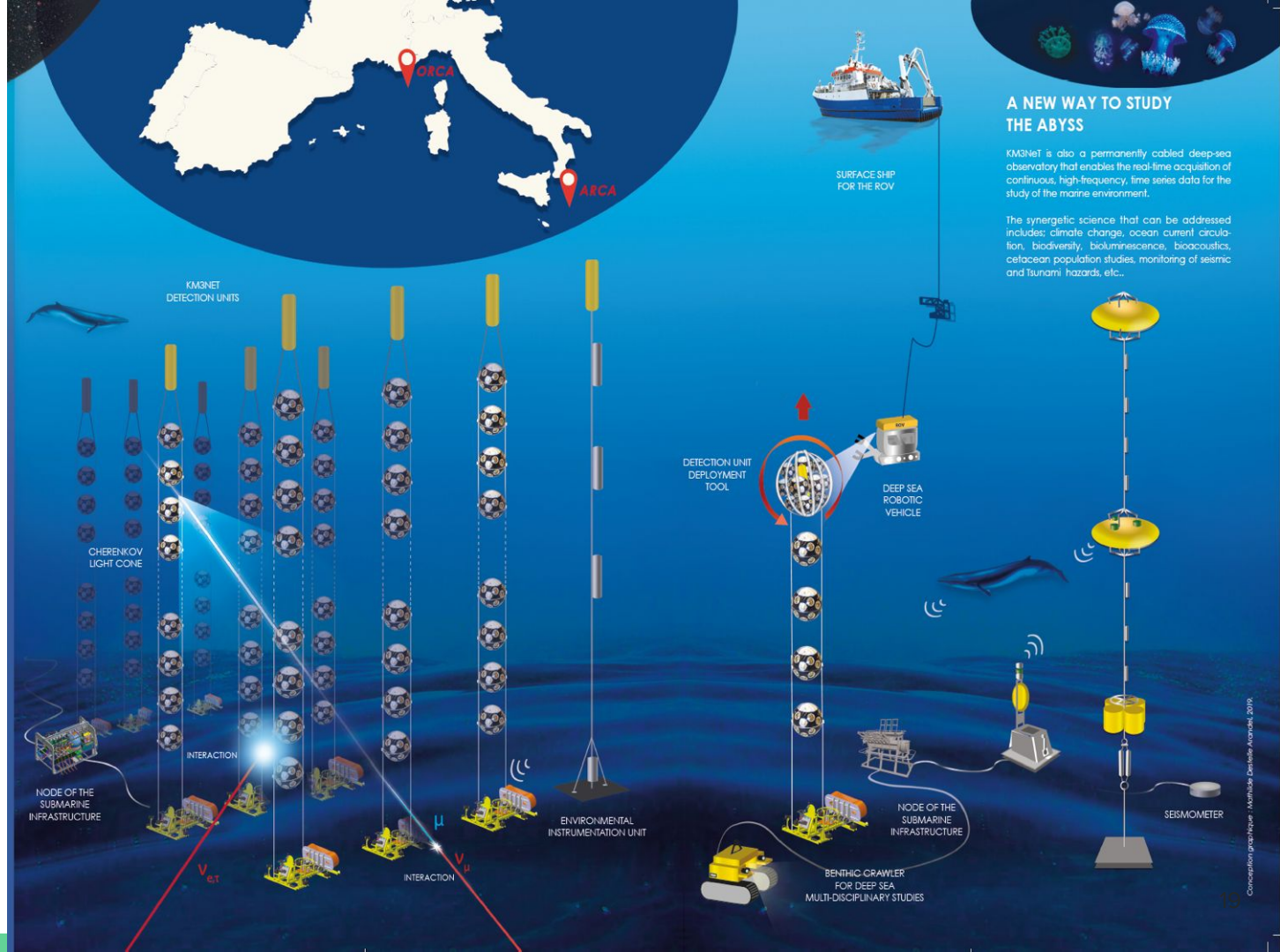
All-flavor incoming flux



⇒ Sensitivities on the **total energy** emitted in neutrino during flares

ANTARES Dismantled in June 2022

Successor: **KM3NeT**



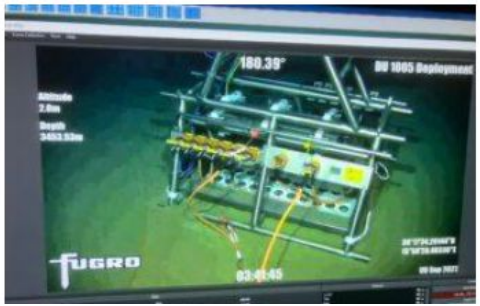
Infrastructure

⇒ 2 sites:

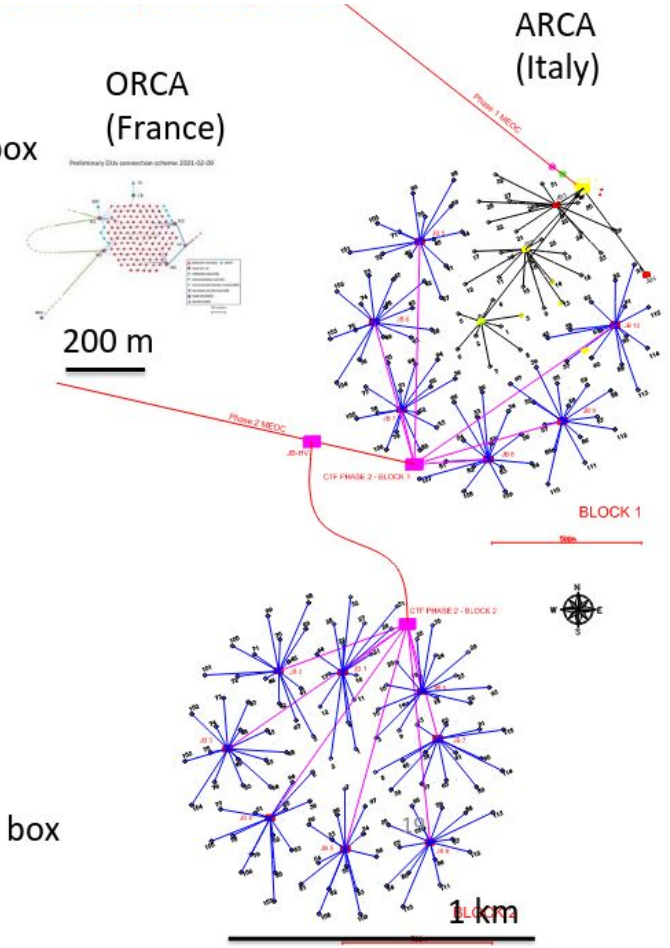
- ORCA (France): optimised for GeV to TeV
- ARCA (Italy): optimised for TeV to PeV

ORCA
2nd junction box
Oct 2020

ARCA
2nd Cable
Nov 2020



ARCA
3rd junction box
Sept 2022



Real-time Microquasar flares detection

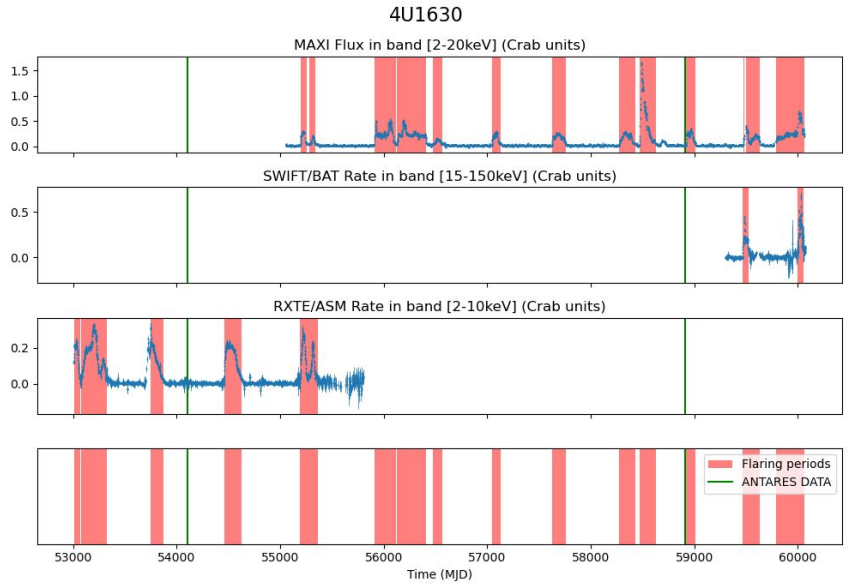
If an X-Ray flare is detected, an alert is sent and follow-up analysis are automatically performed:

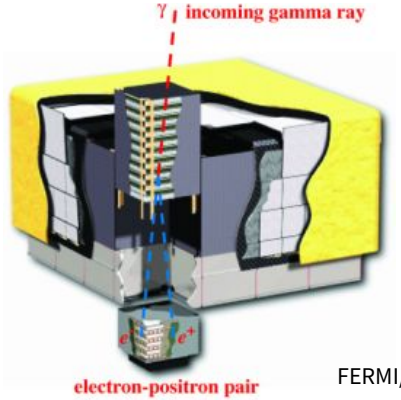
⇒ Follow-up with **FERMI/LAT** Analysis (HE gamma)

- Binned Likelihood Analysis
- Search for new, uncatalogued, source at the alert position
- Time window: 24h before alert time up to last available data

⇒ **KM3NeT** follow-up analysis

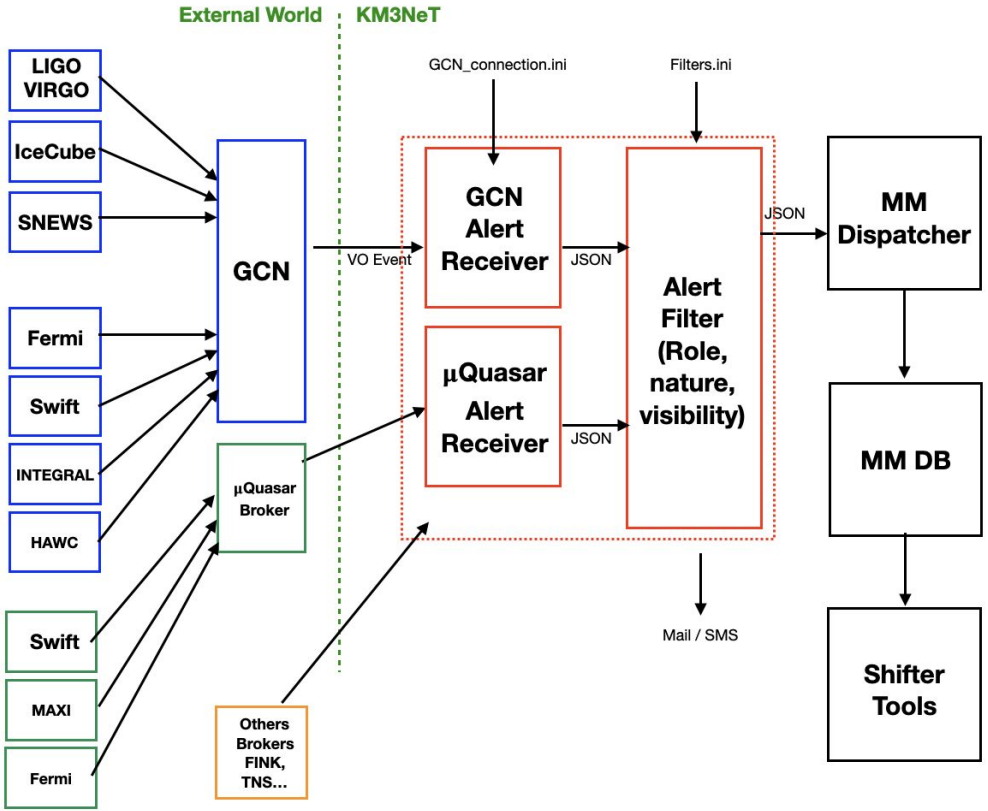
⇒ **HESS** (gamma VHE) observations to be triggered if a signal is found





FERMI/LAT Telescope

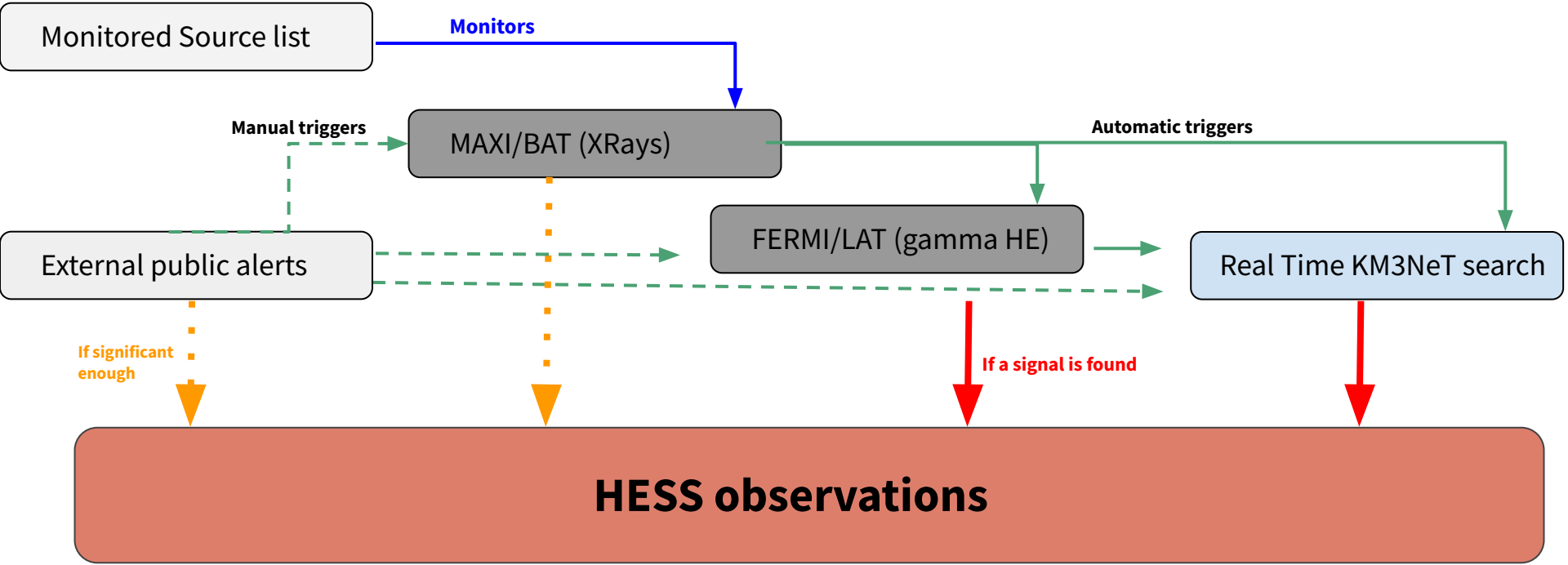
KM3NeT Real-Time analysis framework



Goal: Simultaneous MWL/MM follow-up

Automated analysis follow-ups from external alerts

Microquasar Real-Time monitoring



Conclusion

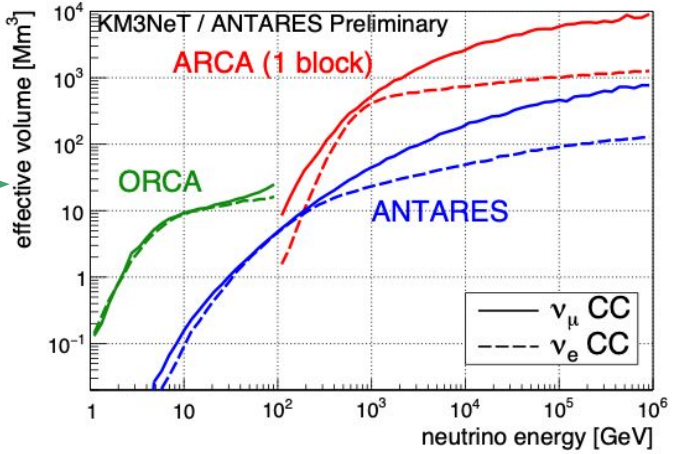
- Fluence sensitivities to neutrino emission obtained for a list of microquasars in flaring states
- Analysis performed on ANTARES data from 2008 to 2020
- Final results with full ANTARES data set to be made public in the next months
- Similar analysis performed with HESS observations
- Next: Interpretations of neutrino/gamma relations

- ANTARES operations concluded
- Successor KM3NeT in construction

⇒ Better sensitivities and lower energy threshold for future flares

⇒ Real-time analysis framework in development

⇒ Relationship between Neutrinos and MWL

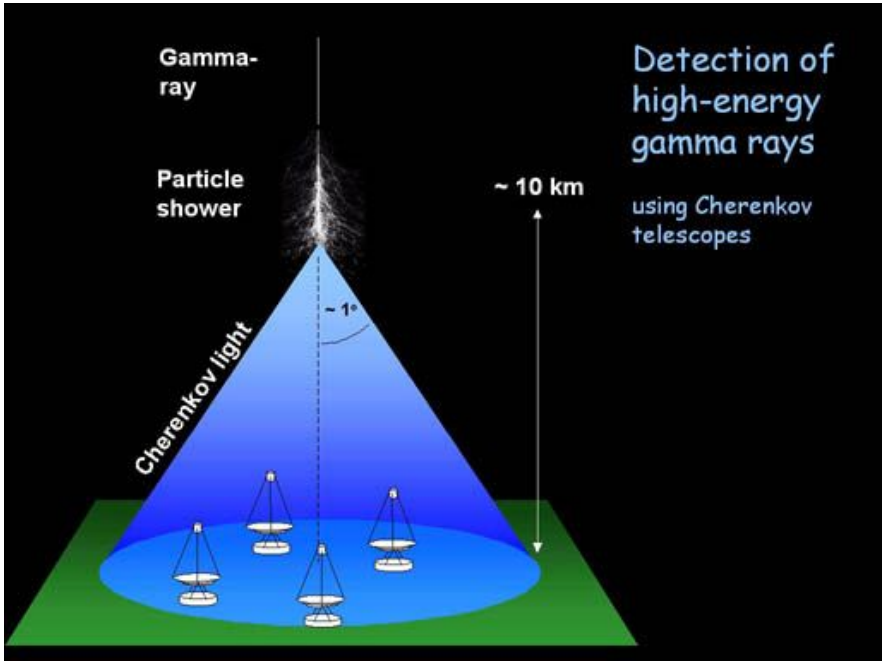


Thank you for your attention!

BACKUP

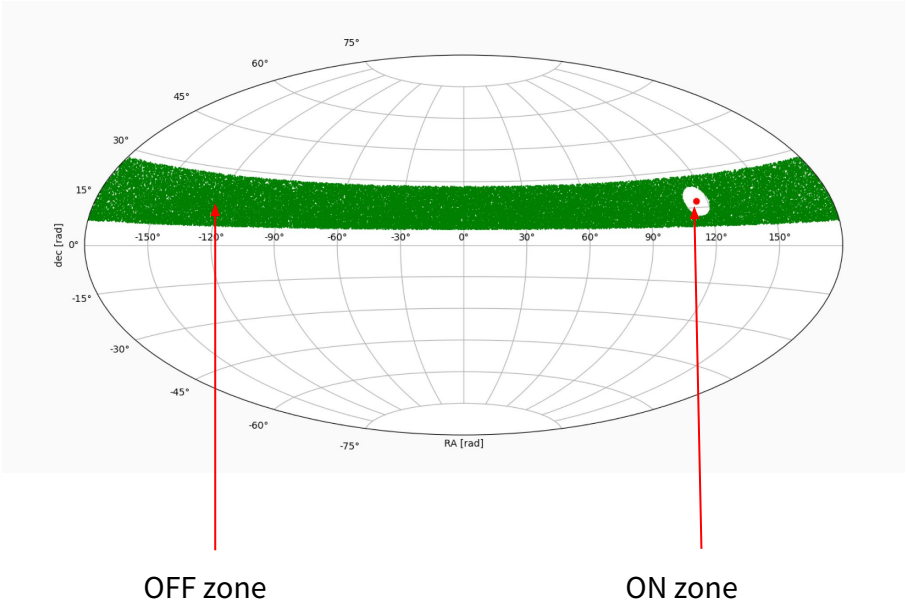
HESS Telescopes array

- High Energy Stereoscopic System
- Imaging Atmospheric Cherenkov Telescope array
- 4x12m + 1x28 m telescopes
- Very High energy gamma (10s of GeV to 10s of TeV) ⇒ Ideal joint observations with ORCA

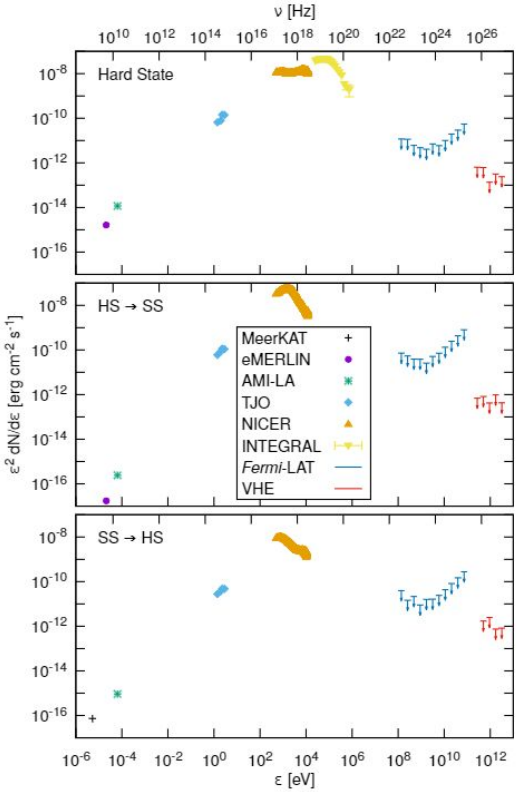


KM3NeT Analysis method

- Signal search in a ROI around the source
- Binned analysis with an ON/OFF method
- OFF region to evaluate the background rate in the ROI
- Regions definition:
  - ON : Cone around the source
  - OFF: Declination band around the source's declination
- Event selection
  - Optimisation: Model Rejection Factor, Model Discovery Potential
  - Parameters:
    - Angle from the source (ON region size)
    - Neutrino purity: simple cuts, BDT score

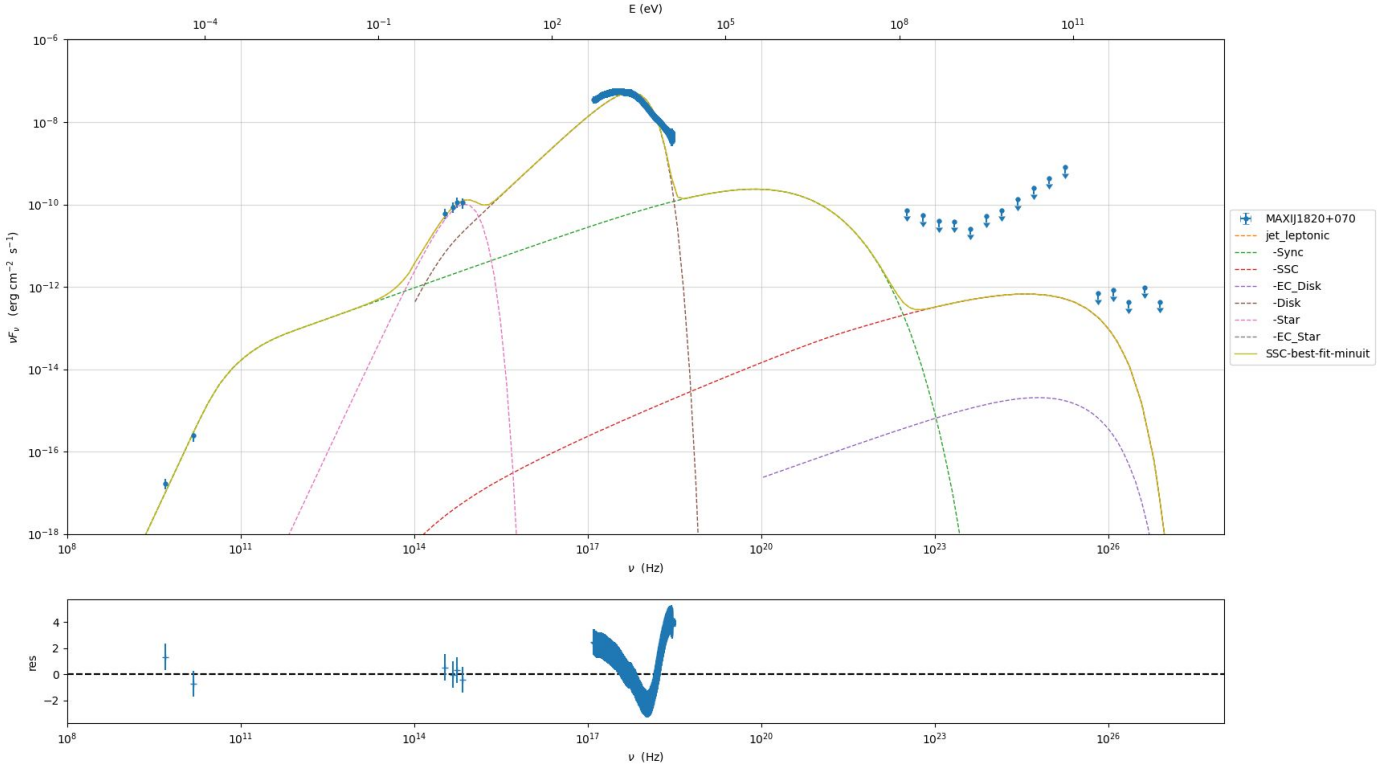


Search for VHE in a microquasar outburst



- MAXIJ1820+070 during 2018 outburst
- Joint observations with HESS/MAGIC/VERITAS
- No significant signal was detected, but limits on the emission location were drawn
- Common paper accepted in MNRAS (arXiv:2209.09785)

MAXIJ1820+070 SED Fitting



ANTARES Pseudo-experiments