Multi-messenger analysis in ANTARES/KM3NeT

D. Dornic (CPPM)

MANTs - Mainz 2016

ANTARES: multi-messenger program

Time-dependent searches:

- GRB [Swift, Fermi, IPN]
- Micro-quasar and X-ray binaries [Fermi/LAT, Swift, RXTE]
- Gamma-ray binaries [Fermi/LAT, IACT]
- Blazars [Fermi/LAT, IACT, TANAMI…]
- Crab [Fermi/LAT]
- Supernovae Ib,c [Optical telescopes]
- Fast radio burst [radio telescopes]

Multi-messenger correlation:

- Correlation with the UHE events [Auger]
- Correlation with the gravitational wave [Virgo/Ligo]
- 2pt-correlation with 2FGL catalogue, loc. galaxies, BH…

Real-time analysis:

- TAToO: follow-up of the neutrino alerts with optical telescopes [TAROT, ROTSE, ZADKO, MASTER], X-ray telescope [Swift/XRT], GeV-TeV γ-ray telescopes [HESS] and radio telescope [MWA]
- Online search of fast transient sources [GCN, Parkes]

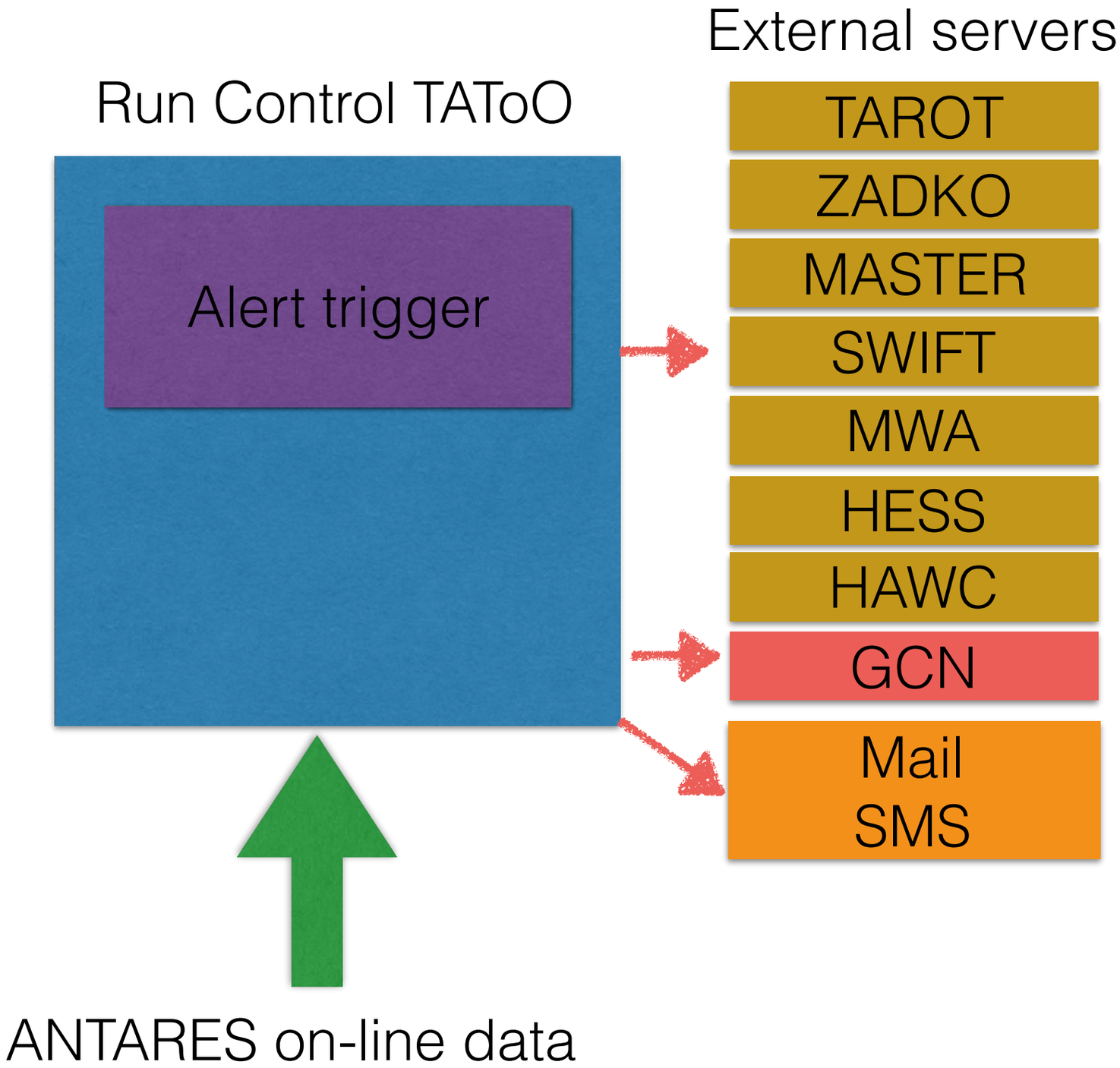
Plan

1. Real-time physics analysis
    * EM follow-up of ANTARES alerts
    * On-line analysis of external alerts

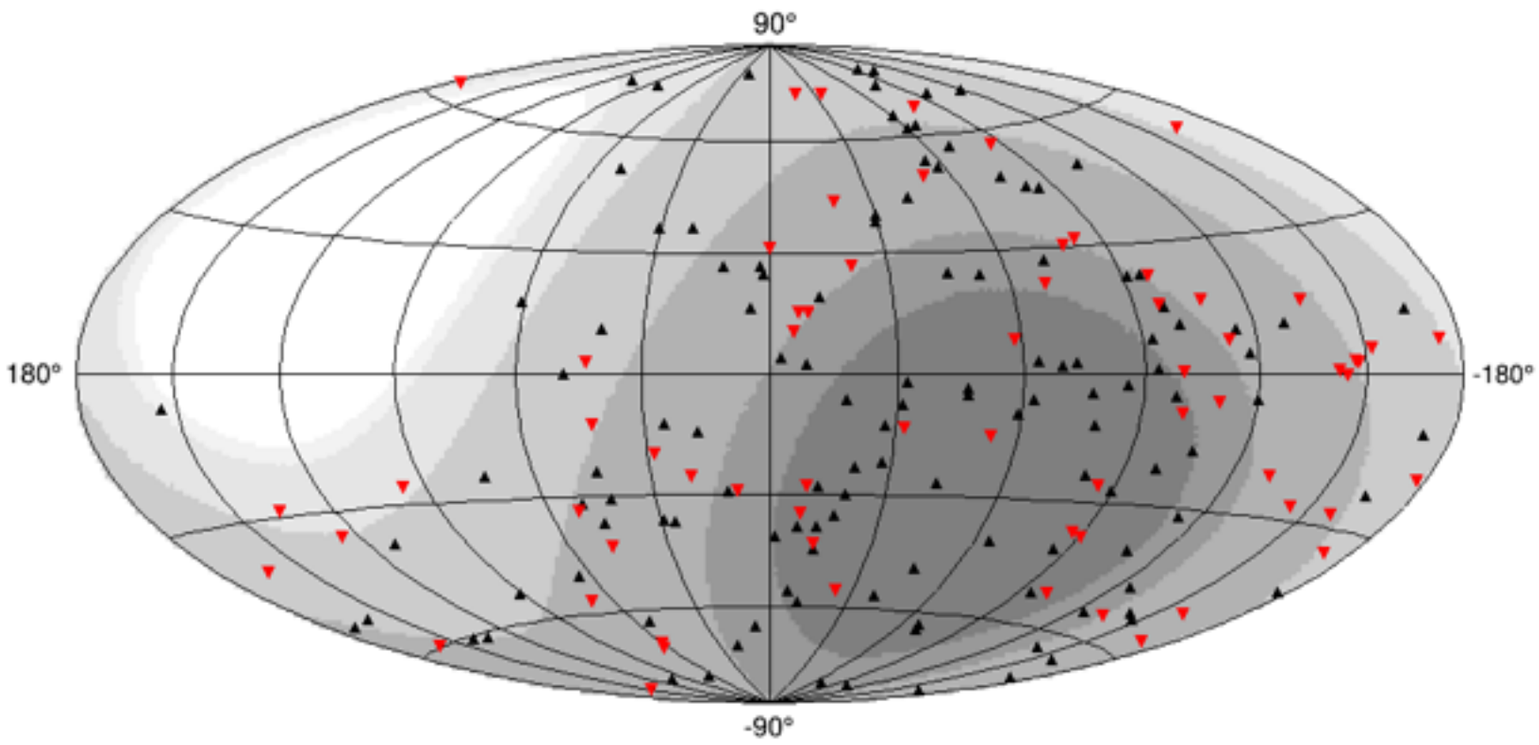
2. Gravitational wave - Neutrino correlation

3. Time-dependent analysis

TAToO alert system



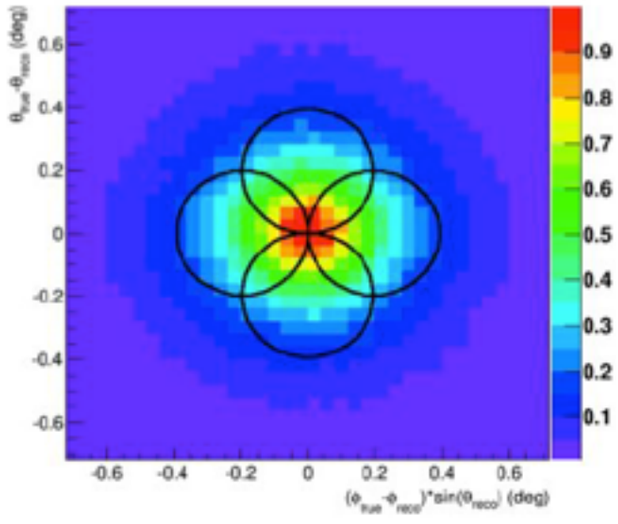
TAToO alert triggers



Triggers: Single HE neutrinos (~10 TeV), single neutrino with direction close to local galaxies (~1 TeV), doublet of neutrinos

Performances:

* Time to send an alert: ~5s
* First image of the follow-up: <20s (with TAROT few alerts in 15s)
* Median angular resolution: 0.3-0.4°
* Dedicated optical image analysis pipeline



TAToO: early follow-up

Visible:

93 alerts analyzed 01/2010-01/2016 from TAROT, ROTSE, MASTER

=>13 alerts with delay <1min (best: 17s)

=> no transient candidate associated to neutrinos

X-ray:

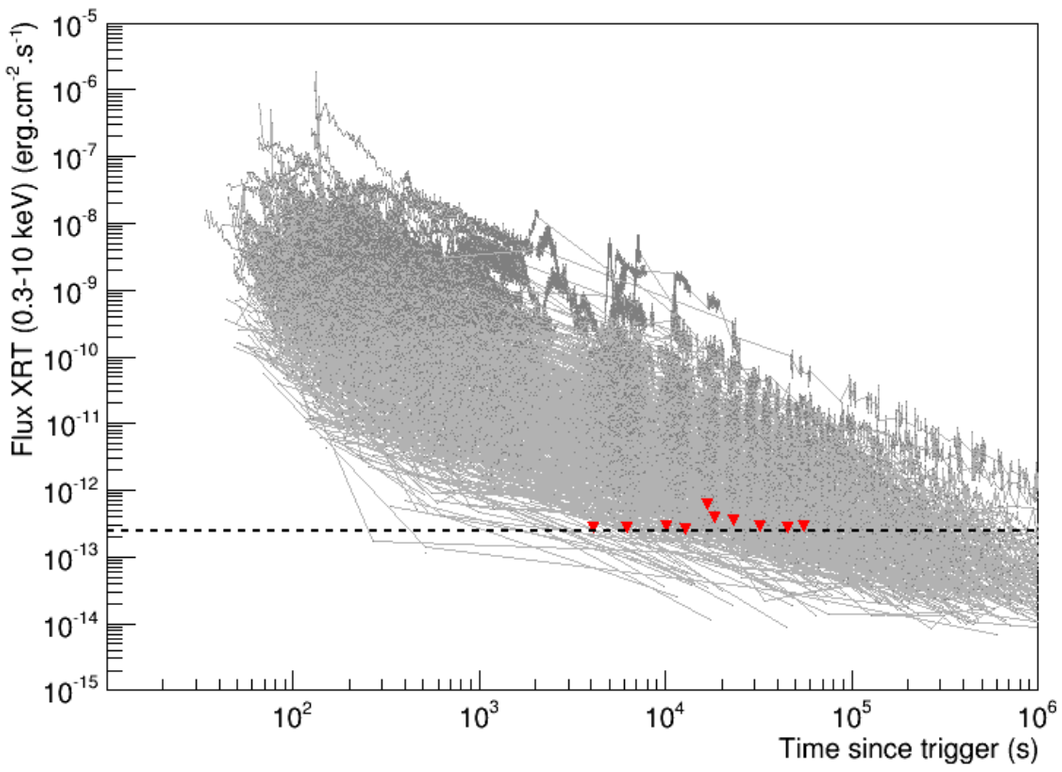
12 alerts analyzed 06/2013-01/2016

=> average delay ~5-6 hours

=> no transient candidate associated to neutrinos

=> Constrains on origin of individual neutrinos

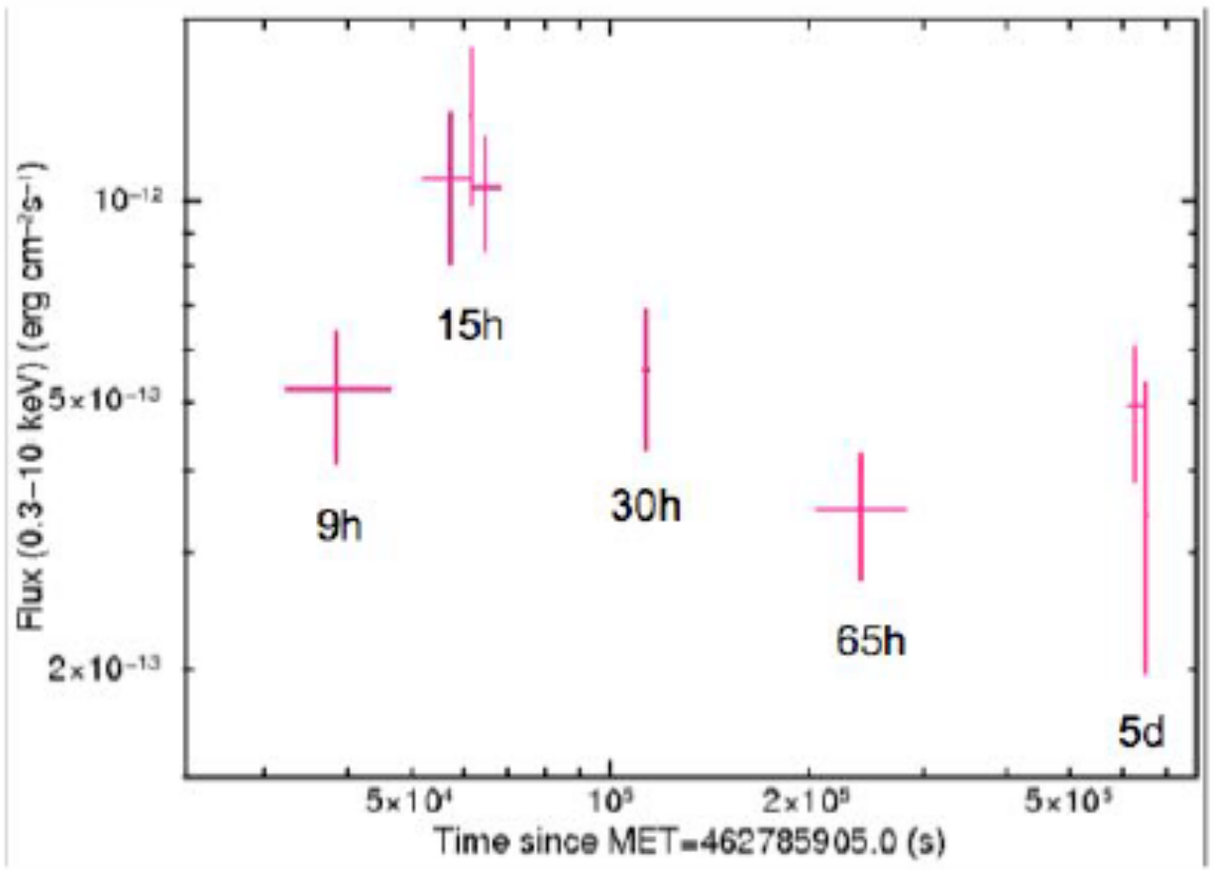
=> Interpretation of the UL in the case of GRB afterglow

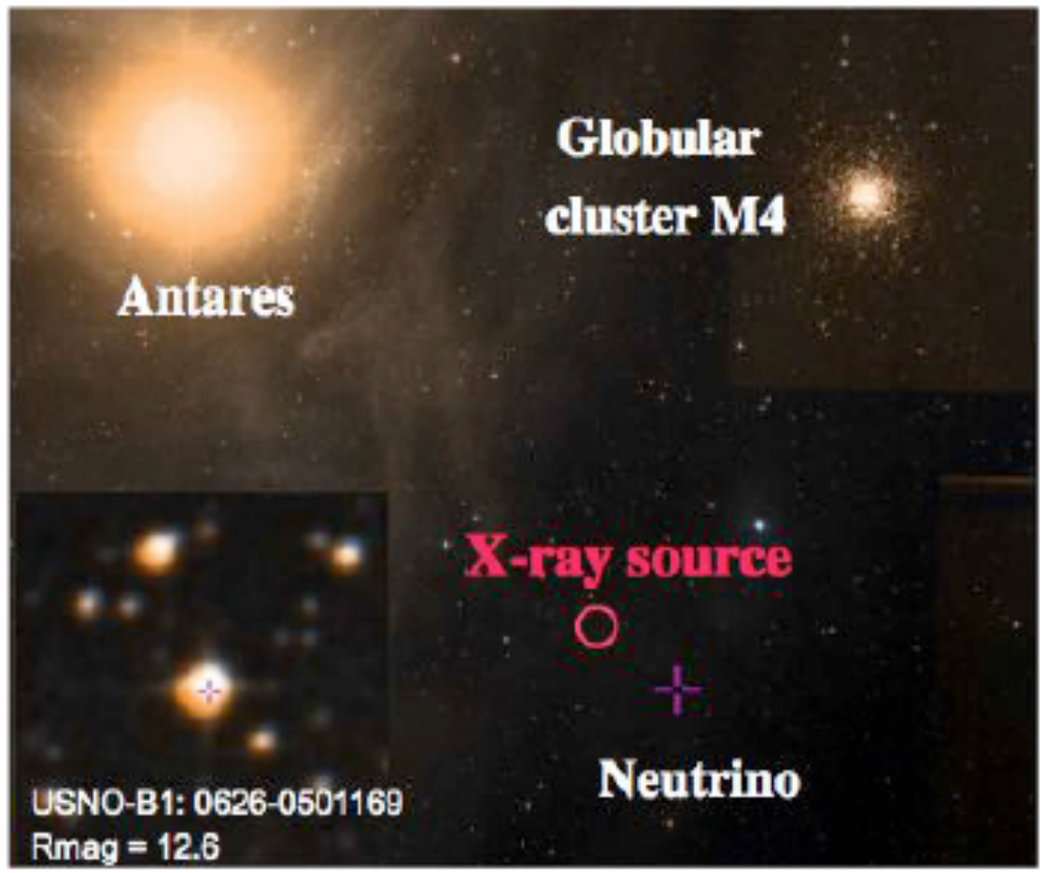


TAToO: ANT150901

➜ Alert **VHE (Sept. 1, 2015)**
E ~ 50-100 TeV
RA=246.306°; dec=-27.468°
Uncertainty: ~18 arcmin (radius, 50%)

Sent after 10 s to MASTER, Swift-XRT
Follow-up with **Swift-XRT after 9h**
Follow-up with **MASTER after 10h**





GCN #18231
ATEL #7987

➜ 16 ATEL + 6 GCN: multi-λ observations
+ few non-reported results

GCN 18236: optical/NIR spectroscopy from NOT
*"All this points to USNO-B1.0 0626-0501169 being a **young accreting G-K star,** undergoing a **flaring episode** that produced the X-ray emission."*
Confirmed by Jansky VLA radio observation (Atel 7999) + X-Shooter observations

TAToO: ANT150901

- Neutrinos
  - IceCube: ATel 8097
- Optical
  - Pan-STARRS: ATel 7992, 8027
  - SALT: ATel 7993
  - NOT: ATel 7994 GCN18236
  - WiFeS: ATel 7996
  - CAHA: ATel 7998, GCN18241
  - MASTER: ATel 8000 GCN18240
  - LSGT: ATel 8002
  - NIC: ATel 8006
  - ANU: GCN18242
  - GCM: GCN18239
  - VLT/X-shooter
- X-rays
  - Integral: ATel 7995
  - MAXI: ATel 8003
  - Swift: ATel 8124, GCN18231
- Radio
  - Jansky VLA: ATel 7999, 8034
- Gamma-rays
  - MAGIC: ATel 8203
  - Fermi-GBM: GCN18352
  - HAWC
  - HESS

Great interest by astro-community

TAToO results

<u>Nb alerts</u>: 221 alerts sent to optical telescopes since mid 2009 +12 to the X-ray telescopes since mid 2013 +14 to M.W.A since 2016 + 2 to HESS in the last year

<u>Result papers</u>:

* Optical and X-ray early follow-up of ANTARES neutrino alerts (JCAP 2016)
* Search for core-collapse supernovae in optical follow-up observations of ANTARES neutrino alerts (JCAP 2016)
* Murchison Widefield Array Limits on Radio Emission from ANTARES Neutrino Events (PRL 2016)
* Multi-wavelength of the neutrino alert ANT150901 (end 2016)

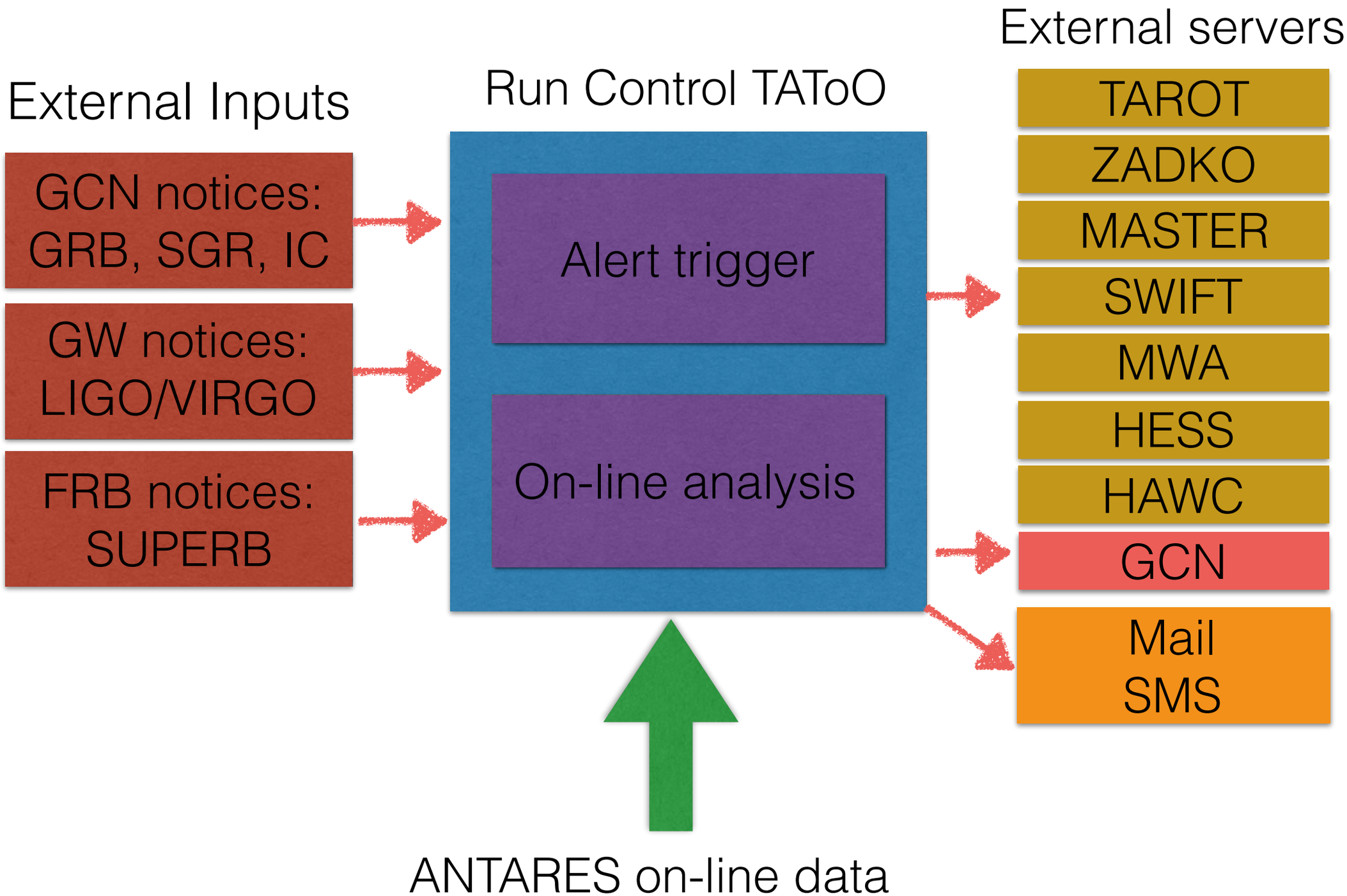
TAToO

* **TAToO:** multi wavelength follow-up of neutrinos

Radio	Visible	X-ray	GeV-ray	TeV-ray	TeV-ray
MWA	TAROT	Swift	Fermi	HESS	HAWC
(12/yr)	ZADKO	(6 alerts/yr)	(Offline)	(1+1 alert/yr)	(10 alerts/yr)
	MASTER				
	GWAC				
	(30 alerts/yr)				

Private MoU with all the observatories
Different transfert protocoles (mail, GCN socket, VO Event…)

On-Line set-up



* alerts also from SNEWS

GCN notices

- Receive the notices from the GCN in real-time (anttatoo.in2p3.fr)
- Notices from Swift, Fermi GBM+LAT, IPN
- Tag: GRB or SGR
- Real-time analysis: search in a cone of 2 deg* and 15 min time window around the alert.
- **System working since September 2013 with an efficiency >99%**
- **> 600 alerts treated**

Trigger number 496473540
Ra 347.55 Dec -19.91
Error 7.19
T0 2016-9-25 5:18:56
Last comment 86% GRB
========== NOTICE LIST ==========
PKT INFO: Received: LT Sun Sep 25 05:19:03 2016
Type= 110 SN= 1 FERMI-GBM Alert
Hop_cnt= 0
PKT_SOD= 0.00 [sec] delta=19143.00 [sec]
RECORD_NUM= 1
TRIGGER_NUM= 496473540
TJD= 17656
SOD= 19136.45 [sec] delta=6.55 [sec]
TRIGGER_DUR= 2.048 [sec]
E_RANGE= 3-4 [chan] 47-291 [keV]
ALGORITHM= 14
DETECTORS= 0,0,0, 0,0,0, 1,0,1, 0,0,1, 0,0,
SC_LONG= 293.58 [deg]
SC_LAT= 5.28 [deg]
PKT INFO: Received: LT Sun Sep 25 05:19:21 2016
Type= 111 SN= 1 FERMI-GBM Flt Position
Hop_cnt= 0
PKT_SOD= 0.00 [sec] delta=19161.00 [sec]
RECORD_NUM= 47
TRIGGER_NUM= 496473540
TJD= 17656
SOD= 19136.45 [sec] delta=24.55 [sec]
RA= 255.7000 [deg] (J2000)
Dec= 45.3833 [deg] (J2000)
ERROR= 14.5333 [deg radius, statistical only]

expert@anttatoo.in2p3.fr 25 septembre 2016 07:31
To: Damien Dornic
New-matching-notice-496473540

NOTICE trigger id: 496473540
Nb de signal : 0
Bruit de fond : 27
Stabilite : [22 25 33 26 18]
==========
Window low time limit : 250
Window high time limit: 750
Lamda limit : -5.4
Cos theta limit : 0
Angle limit : 2

* For Fermi, use error on direction

IceCube alerts

- **IceCube is sending since March 2016 for HESE + EHE neutrinos, alerts through AMON to the public community (GCN network)**.

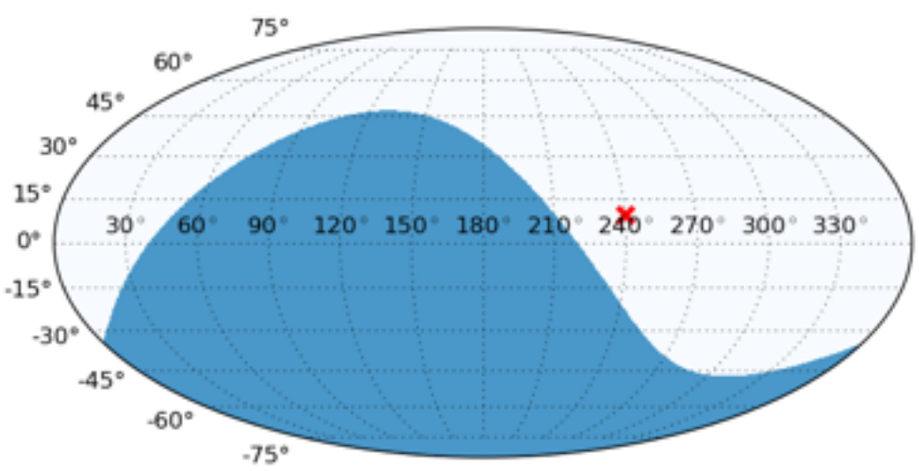
TYPE	POS_ERROR [radius]	TIME SINCE TRIGGER	COMMENTS	
AMON_ICECUBE_HESE	2-9deg	0.5-3 min	Direction of a single hi-energy neutrino	ACTIVE
AMON_ICECUBE_EHE	0.2-0.8deg	0.5-3 min	Direction of a single extremely hi-energy neutrino	ACTIVE
AMON_ICECUBE_COINC	1-2	0.5-3 min	Temporal/spatial coinc between IceCube neutrinos	NOT YET PUBLIC

- Rate: 0.5-1 time per month for each type of alerts
- 4 alerts have been sent up to now
- Implement the same analysis as for the GRB: search in a Max(2^{o},error pos) cone and +/- 1000 s, +/-1 h, +/-1d around the time of the alert
- If zero result, compute upper limits

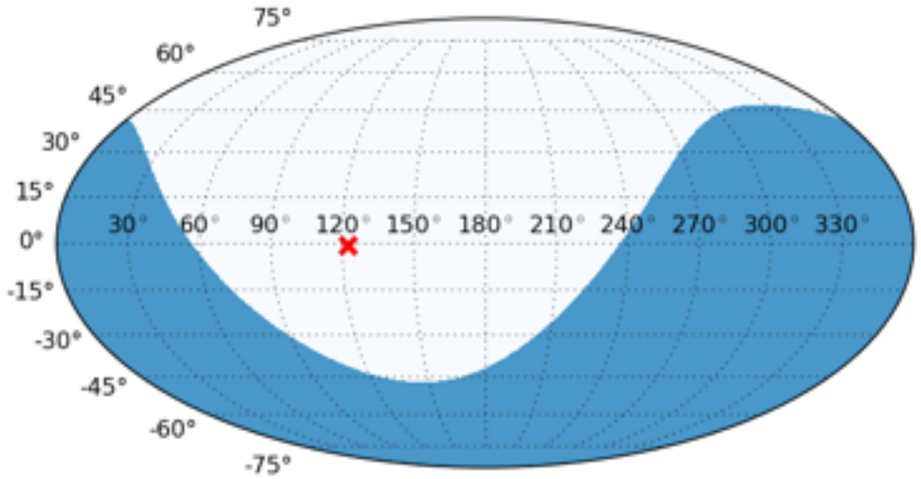
IceCube alerts

ANTARES sky visibility at the time of the alerts

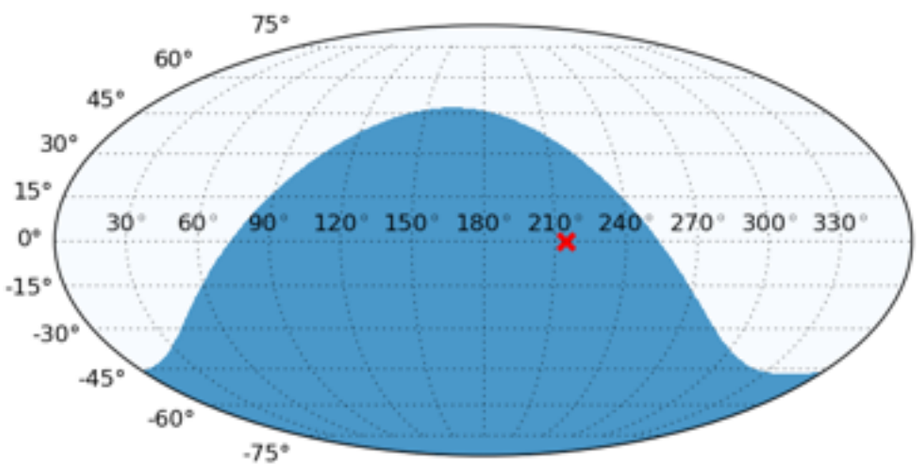
IC160427



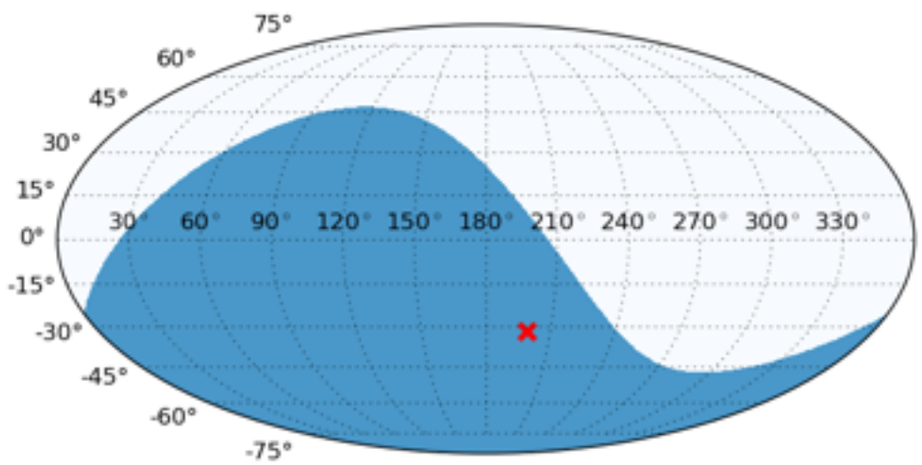
IC160806



IC160731



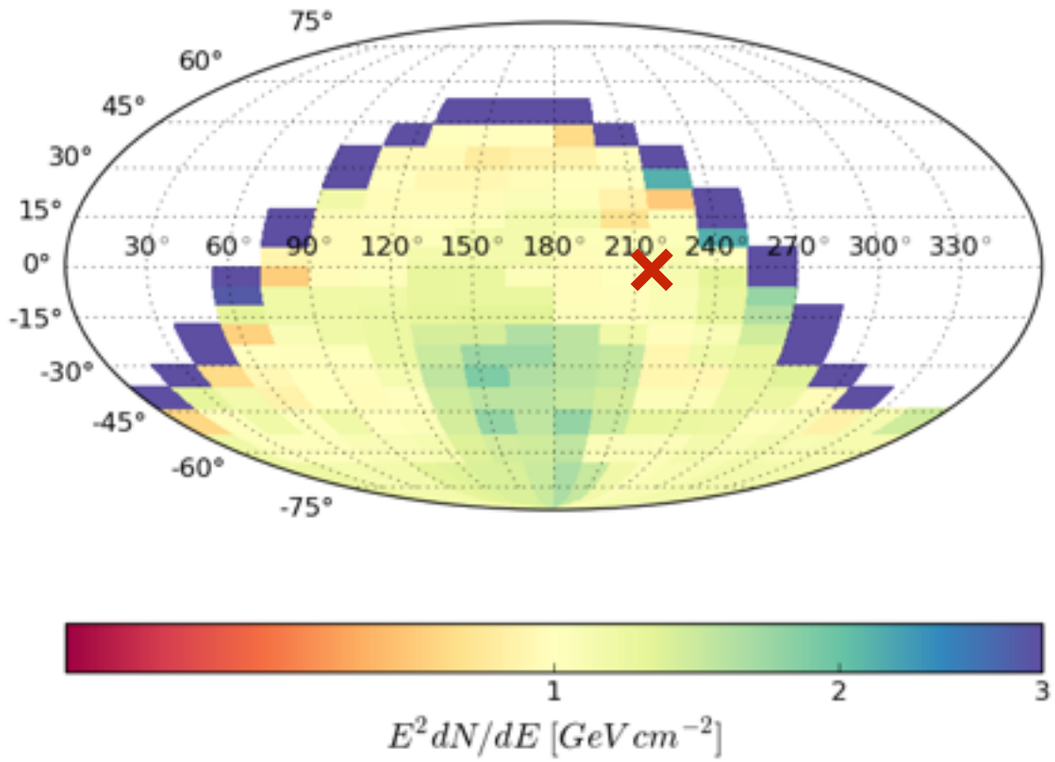
IC160814



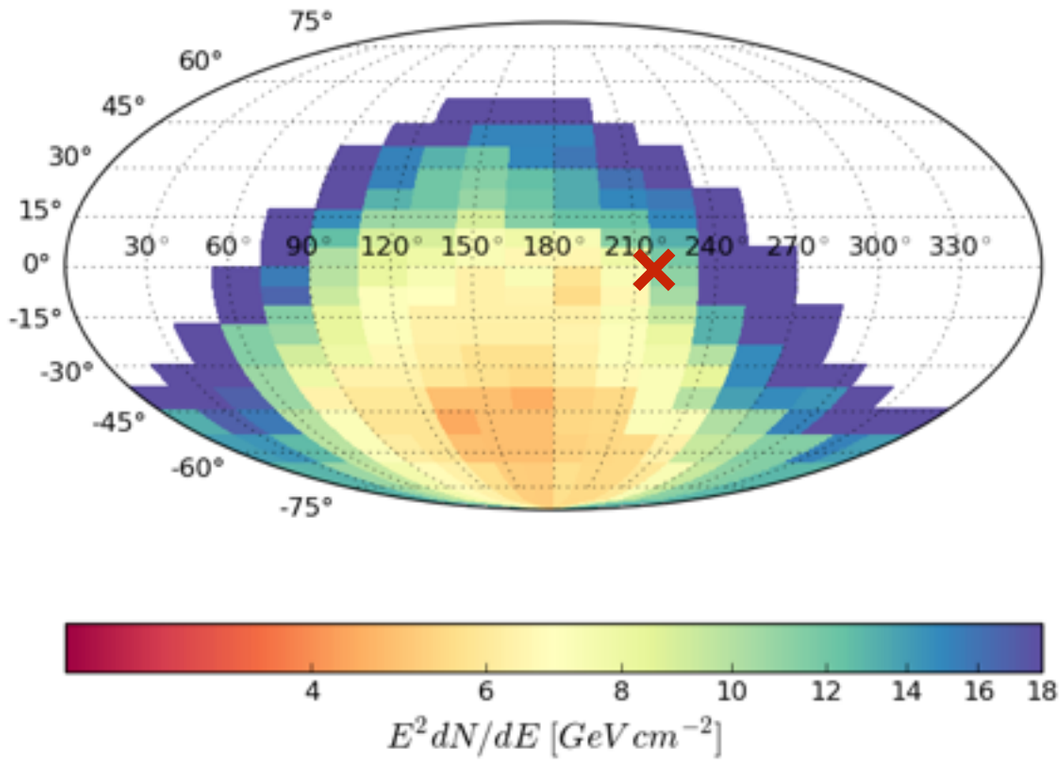
IC160731

Spectral fluence UL (90% C.L.):

E^{-2}



$E^{-2.5}$ Preliminary



Integrated fluence UL (90% C.L.):

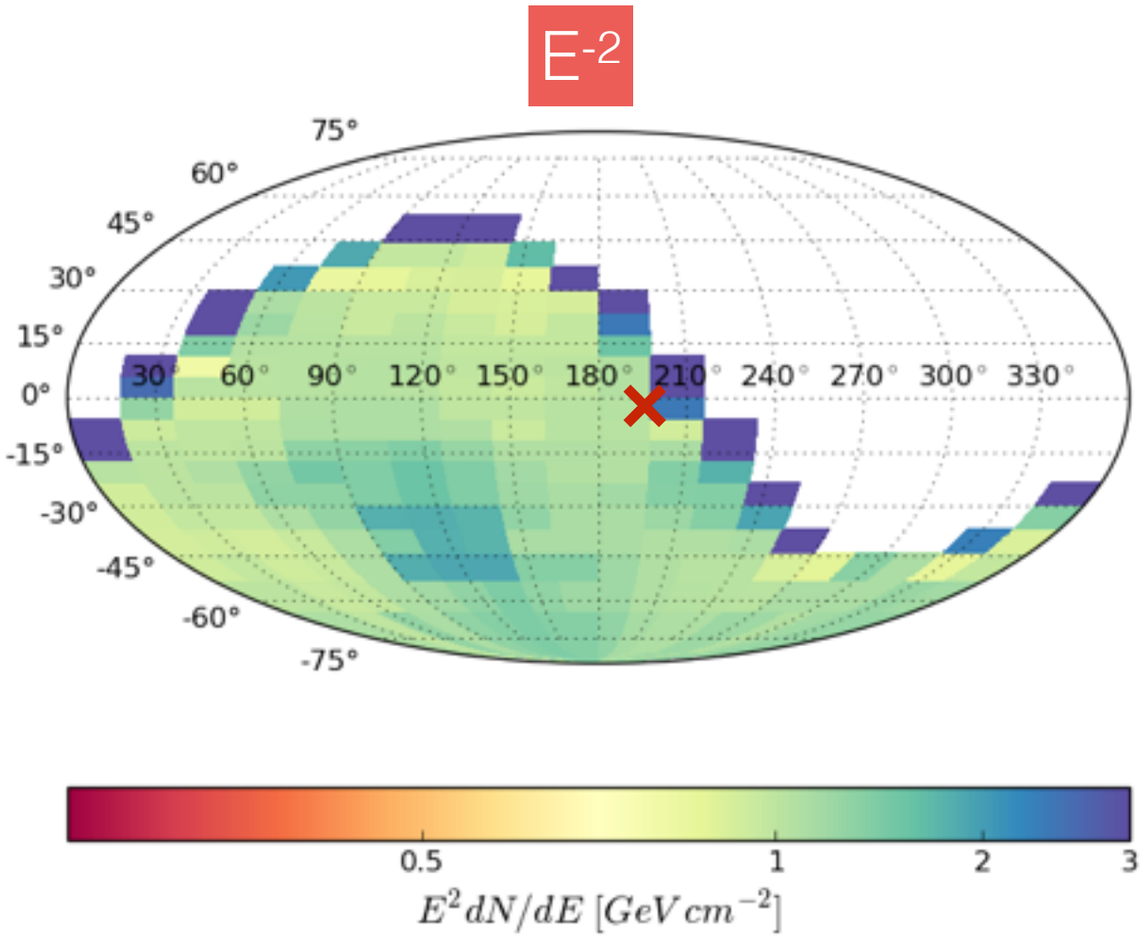
14.0 GeV/cm^2 in [2.8 TeV, 3.1 PeV] for E^{-2}

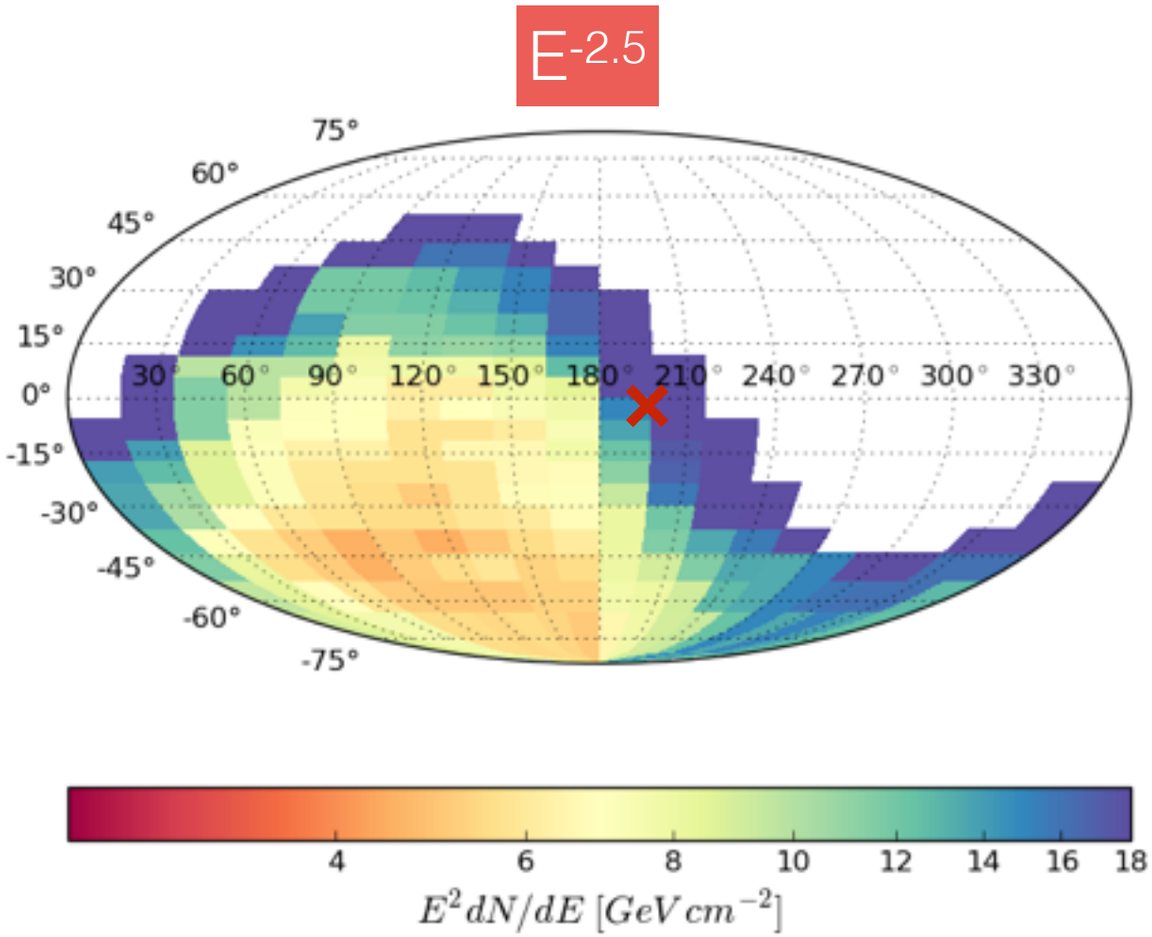
27.0 GeV/cm^2 in [0.4 TeV, 280 TeV] for $E^{-2.5}$

IC160814

Spectral fluence UL (90% C.L.):

Preliminary





Integrated fluence UL (90% C.L.):

15.7 GeV/cm^2 in [2.8 TeV, 3.3 PeV] for E^{-2}

43.0 GeV/cm^2 in [0.4 TeV, 280 TeV] for E$^{-2.5}$

GCN/Atel reports

After approval by the management and the PC (+ mail to the Collab.), we have submitted a GCN circular and an Atel telegram:

- IC160731: Atel #9324 & GCN #19772 (160805)
- IC160814: Atel #9440 & GCN #19885 (160831)

```
TITLE:   GCN CIRCULAR
NUMBER:  19772
SUBJECT: Search for counterpart to IceCube-160731A with ANTARES
DATE:    16/08/05 06:20:35 GMT
FROM:    Damien Dornic at CPPM,France  <dornic@cppm.in2p3.fr>

D. Dornic (CPPM/CNRS), A. Coleiro (APC/Universite Paris Diderot), report on behalf of the ANTARES
Collaboration:

Using data from the ANTARES detector, we have performed a follow-up analysis of the recently reported
single extremely high-energy (EHE) neutrino
+IceCube-160731A (AMON IceCube HESE 128290 6888376). Its position is -28.1 degrees below the horizon for
ANTARES which could yield to an up-going
+event at the time of the event.

ANTARES is the largest neutrino detector installed in the Mediterranean Sea primarily sensitive to
astrophysical neutrinos in the TeV-PeV energy
+range.  At 10 TeV, the median angular resolution for muon neutrinos is below 0.5 degrees. In the range
1-100 TeV, ANTARES has the best
+sensitivity to this position in the sky.

No up-going muon neutrino candidate events were recorded within three degrees of the IceCube event
coordinates during a +/- 1h time-window
+centered on the IceCube event time. A search on an extended time window of +/- 1 day has also yielded no
detection (50% visibility probability).

This yields a preliminary 90% upper limit on the fluence from a point source of  14 GeV.cm^-2 (2.8 TeV-
3.1PeV, energy range corresponding to
+5-95% of the energy distribution) and 27 GeV.cm^-2 (0.4-280 TeV) assuming a E^-2 and E^-2.5 power law
spectrum, respectively.
```

Search for counterpart to IceCube-160814A with ANTARES

ATel #9440; *D. Dornic (CPPM/CNRS), A. Coleiro (APC/Universite Paris Diderot), D. Turpin (CPPM/IRAP/CNRS) on behalf of the ANTARES Collaboration*
on 31 Aug 2016; 20:13 UT
Credential Certification: Damien Dornic (dornic@cppm.in2p3.fr)

Subjects: Neutrinos, Transient

Referred to by ATel #: 9456

Tweet Recommend 12

Using data from the ANTARES detector, we have performed a follow-up analysis of the recently reported single high-energy (HESE) neutrino IceCube-160814A (AMON IceCube HESE 58537957 128340). The reconstructed origin was 25.9 degrees below the horizon for ANTARES, with this position remaining below the horizon from -3.3h, +13h around the time of the alert. Thus ANTARES had a high sensitivity to any neutrinos from the same region. ANTARES is the largest neutrino detector installed in the Mediterranean Sea, and is primarily sensitive to astrophysical neutrinos in the TeV-PeV energy range. At 10 TeV, the median angular resolution for muon neutrinos is below 0.5 degrees. In the range 1-100 TeV, ANTARES has the best sensitivity to this position in the sky. No up-going muon neutrino candidate events were recorded within three degrees of the IceCube event coordinates during a +/- 1h time-window centered on the IceCube event time. A search on an extended time window of +/- 1 day has also yielded no detection (68% visibility probability). This yields a preliminary 90% upper limit on the muon-neutrino fluence from a point source of 15.7 GeV.cm^-2 over the energy range 2.8 TeV-3.1PeV (the range corresponding to 5-95% of the detectable flux) for an E^-2 power-law spectrum, and 43.0 GeV.cm^-2 (0.4-280 TeV) for an E^-2.5 spectrum. The ANTARES contact persons for this analysis are Damien Dornic (CPPM/CNRS, dornic@cppm.in2p3.fr), Alexis Coleiro (APC/Universite Paris Diderot, coleiro@apc.univ-paris7.fr) and Damien Turpin (CPPM/IRAP/CNRS, dturpin@irap.omp.eu) on behalf the ANTARES Collaboration.

Future: fully automatised processing of the IC alerts (receive and parse the notice, real-time analysis (+optimization), compute UL on-line.) => reduce the delay between the alert and the report (~1 day)

Plan

1. Real-time physic analysis
    * EM follow-up of ANTARES alerts
    * On-line analysis of external alerts

2. Gravitational wave - Neutrino correlation

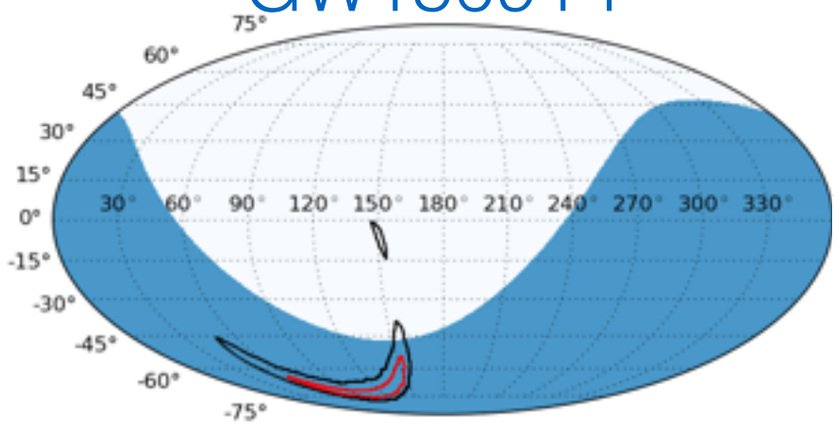
3. Time-dependent analysis

Gravitational events

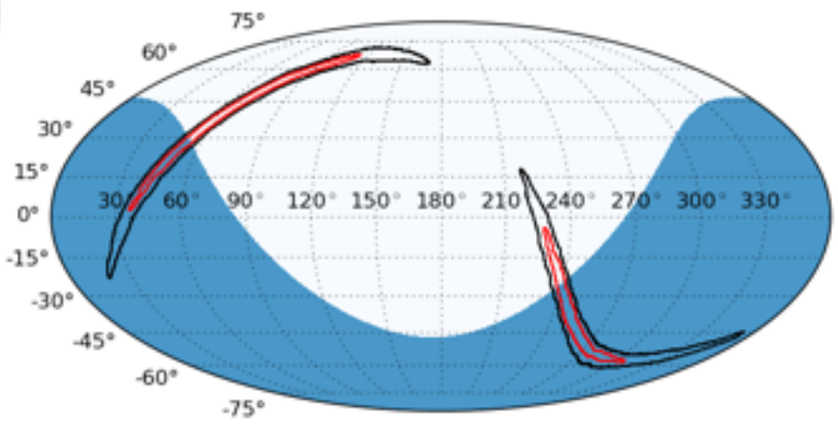
3 alerts sent by LIGO during the run 01 (2015/09->2016/01):

- GW150914: merging of 2 BHs (M= 36/29 Mo - 410 Mpc - 5.1 sigma)
- LVT151012: merging of 2 BHs (M= 23/13 Mo - 1000 Mpc - 1.7 sigma)
- GW151226: merging of 2 BHs (M= 14/7 Mo - 440 Mpc - >5 sigma)

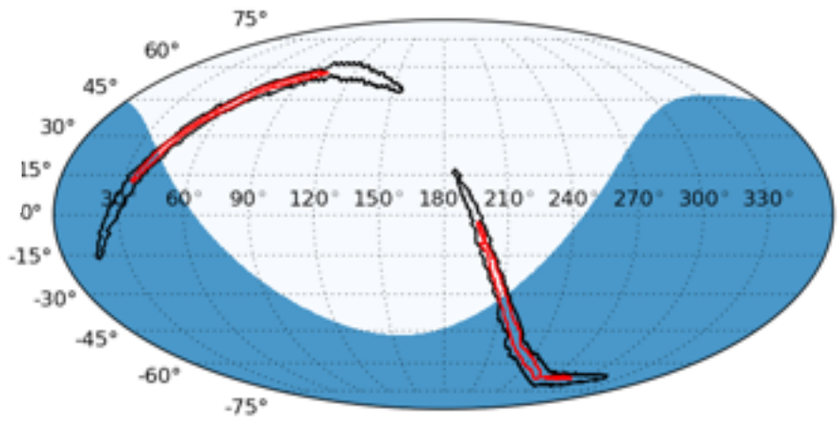
GW150914



LVT151012



GW151226



=> ANTARES + IceCube joint analysis
=> 2 joint papers

(Antares visibility)

GW150914

<u>In +/- 500s:</u>

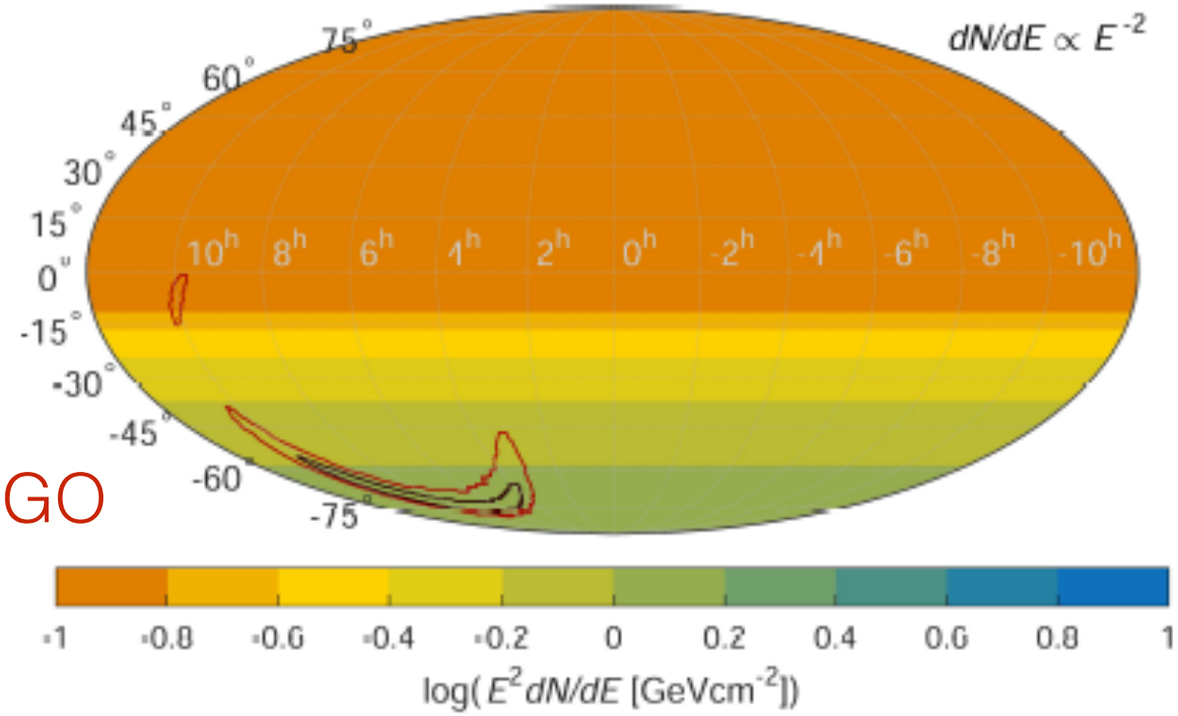
- ANTARES: 0 event
- IceCube : 3 events

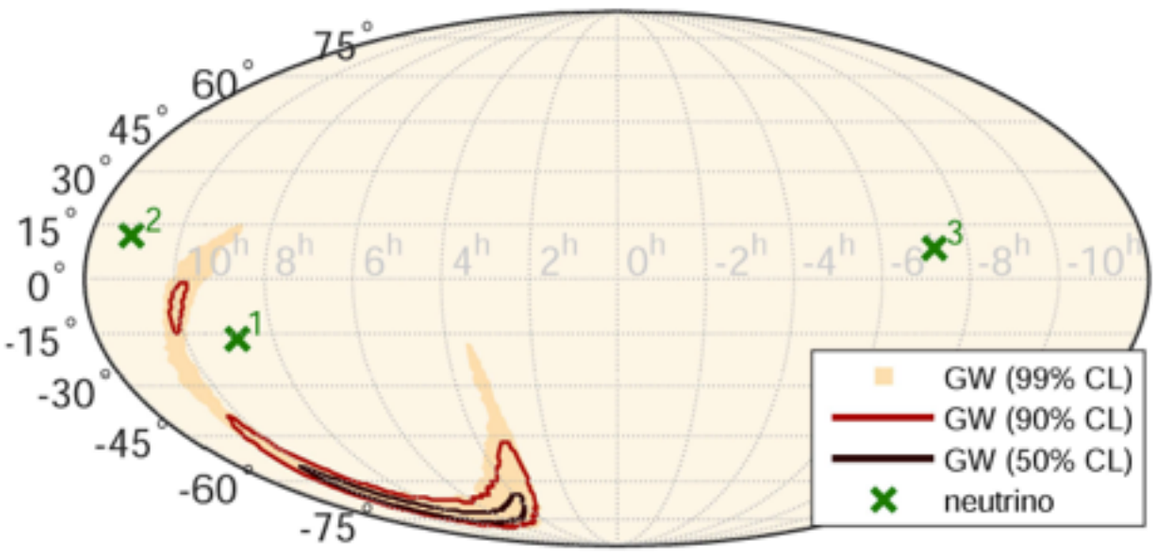
=> No correlation (<=> bkg)

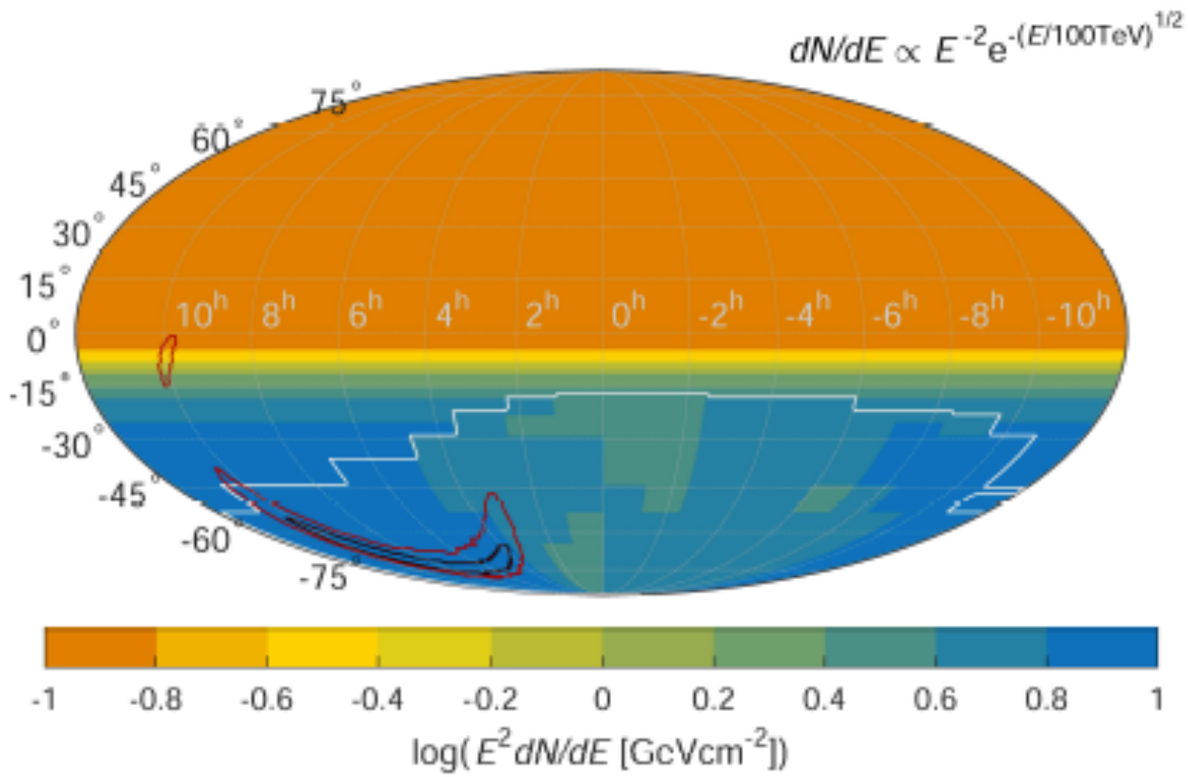
=> U.L.

=> 1st joint paper IC, ANT, LIGO/VIRGO

Phys. Rev. D 93 122010 (2016)







Work in progress
Still not public

GW151226 & LVT151012

In +/- 500s:

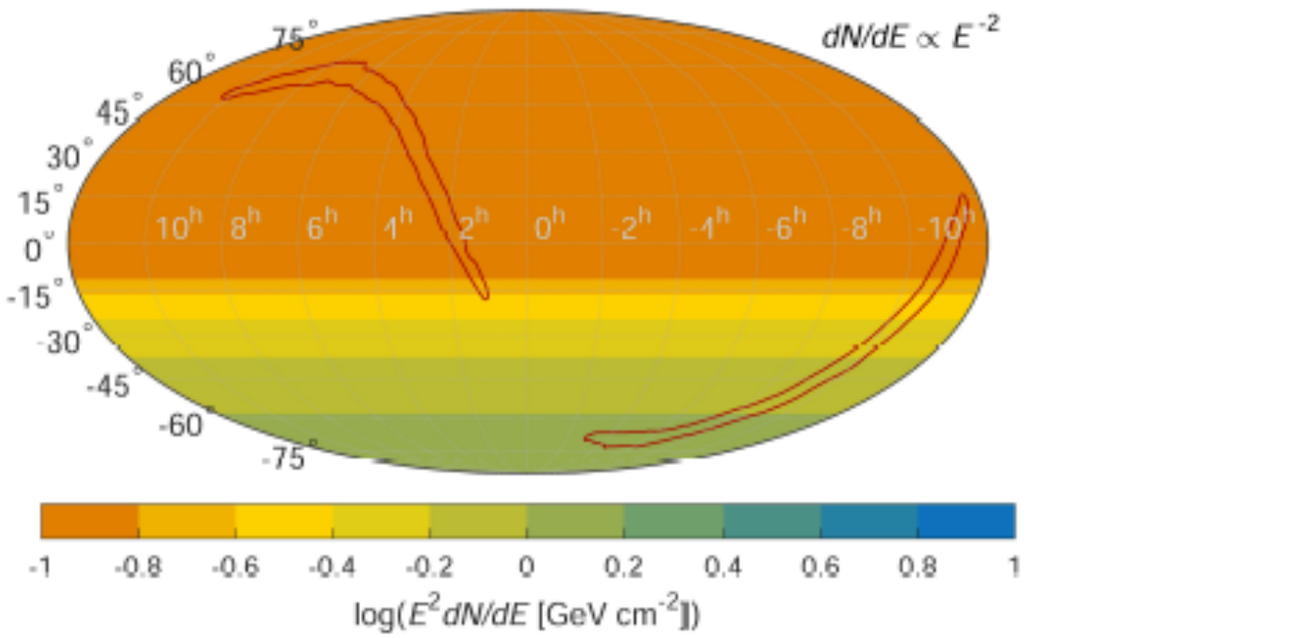
- ANTARES: 1/0 event
- IceCube : 3/4 events

=> No correlation (<=> bkg)

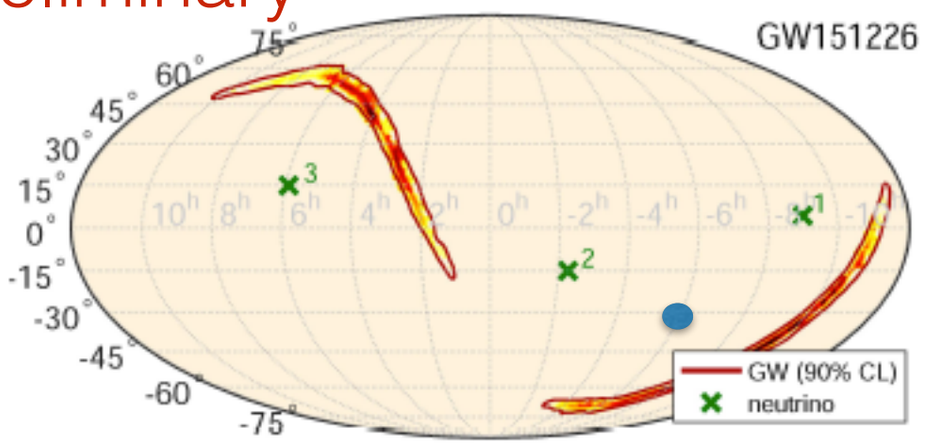
=> U.L.

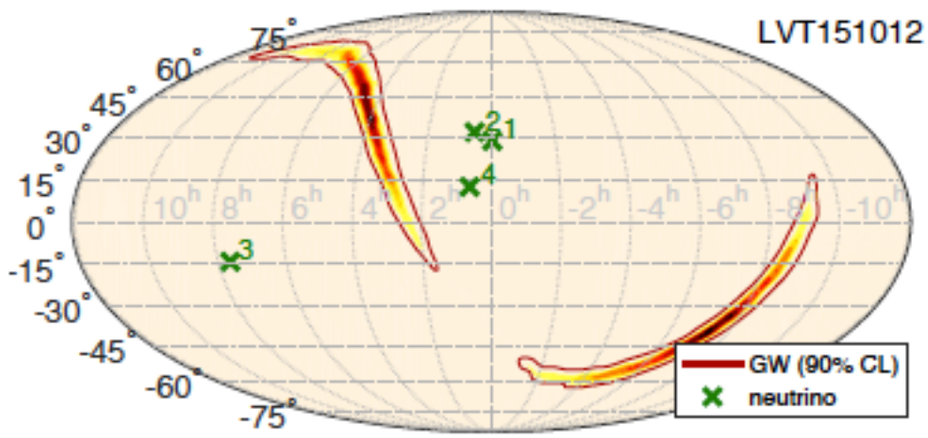
=> Joint paper in prep

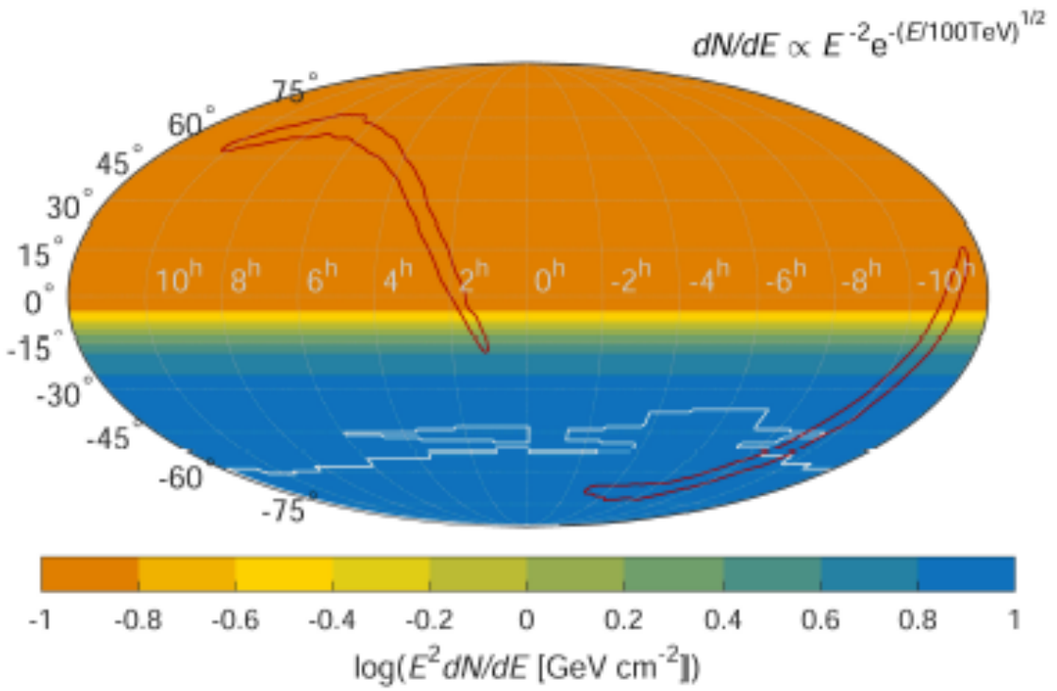
Preliminary



Preliminary







GW events: neutrino constrains

GW150914:

$$E^{ul}_{\nu,tot} = 5.4 \times 10^{51} - 1.3 \times 10^{54}\,erg$$
$$E^{ul(cutoff)}_{\nu,tot} = 6.6 \times 10^{51} - 3.7 \times 10^{54}\,erg$$

at $d=410^{+160}_{-180}$ Mpc

GW151226:

$$E^{ul}_{\nu,tot} = 2 \times 10^{51} - 3 \times 10^{53}\,erg$$
$$E^{ul(cutoff)}_{\nu,tot} = 2 \times 10^{51} - 2 \times 10^{54}\,erg$$

at d~440 Mpc

Preliminary

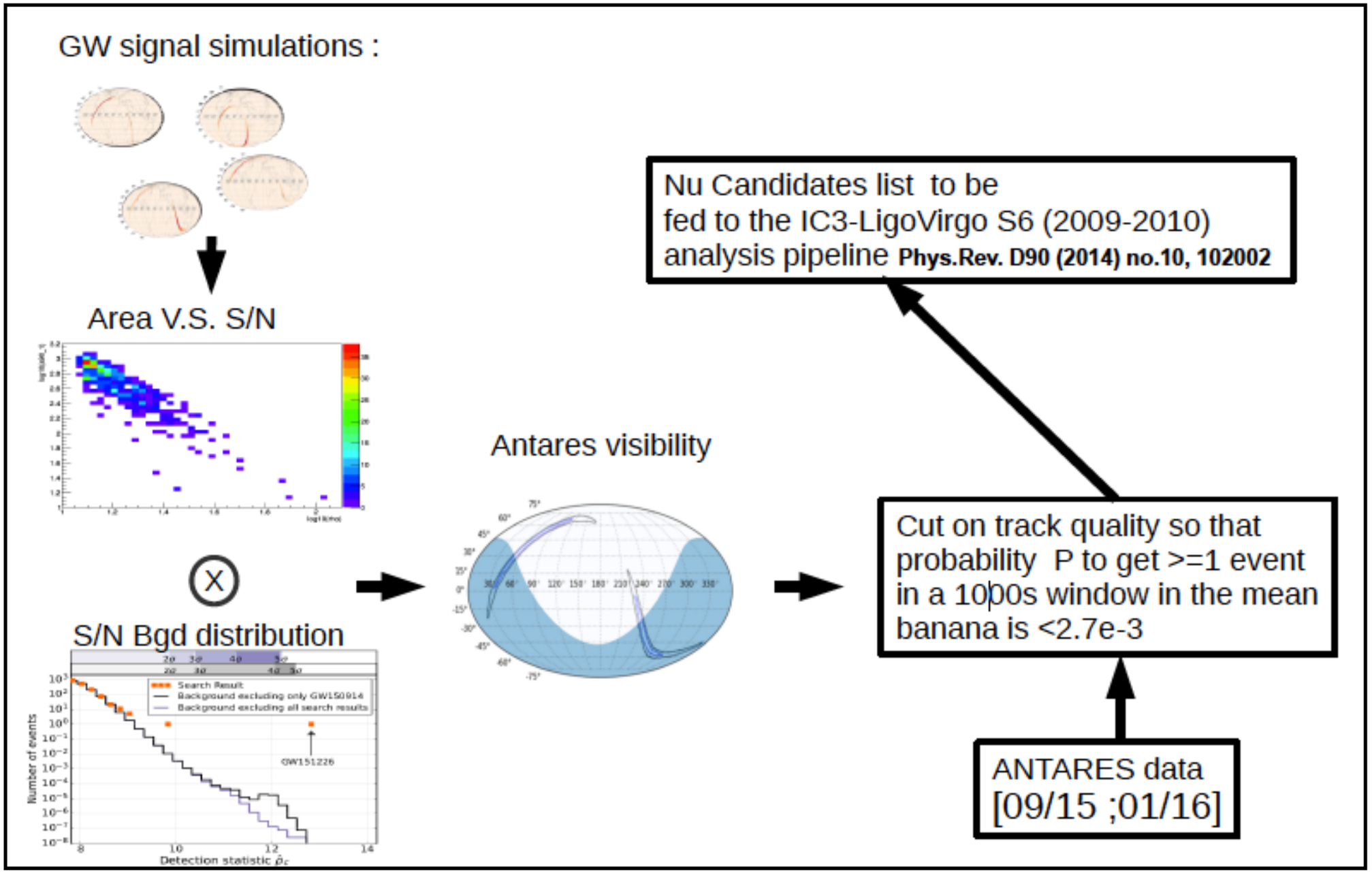
Constraints on the total energy emitted in neutrinos

- Energy radiated in GW: ~ 10^{54} erg
- Typical short GRB isotropic-equivalent energies are ~10^{49} erg
- May be similar to total energy radiated in neutrinos in GRBs

(Mészaros 2015, arXiV:1511.01396; Bartos et al., 2013, CQG 30, 12)

Work in progress - Still not public

GWHEN: sub-th events analysis in O1



=> Analysis in progress : LIGO/IC + LIGO/ANT

=> Joint paper LIGO/IC/ANT

Plan

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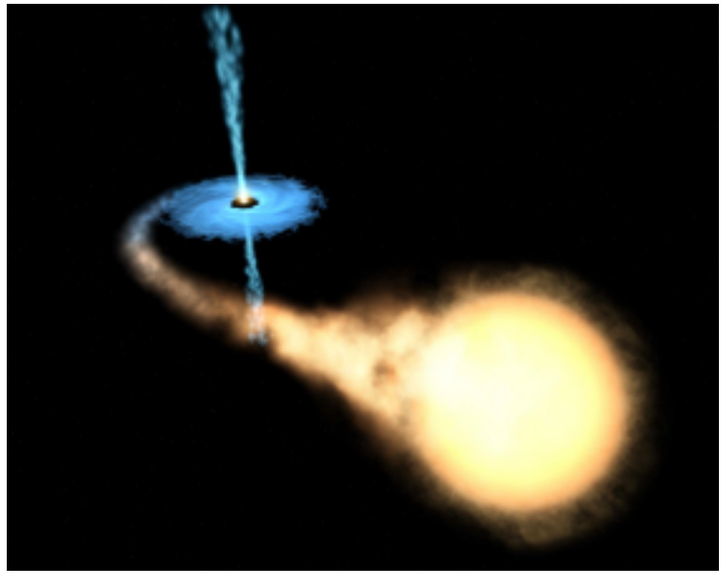
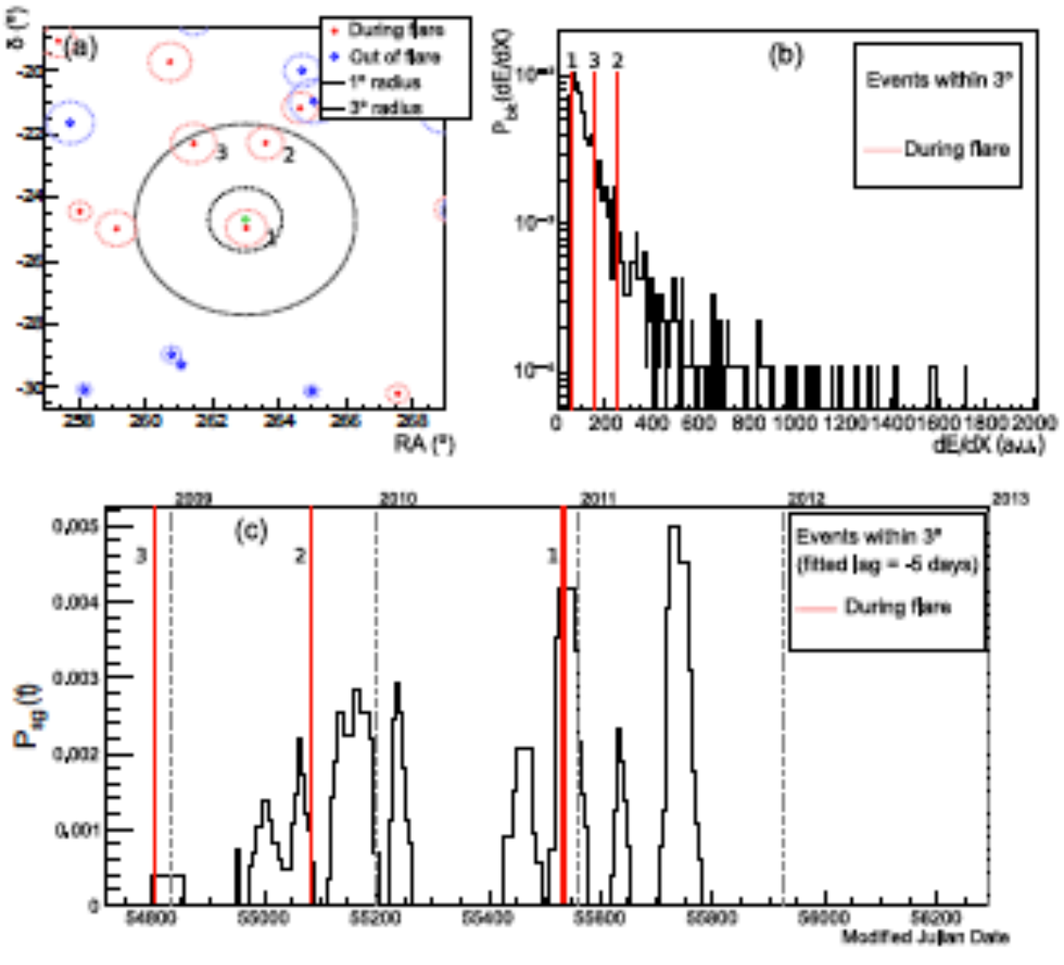
X-ray binaries

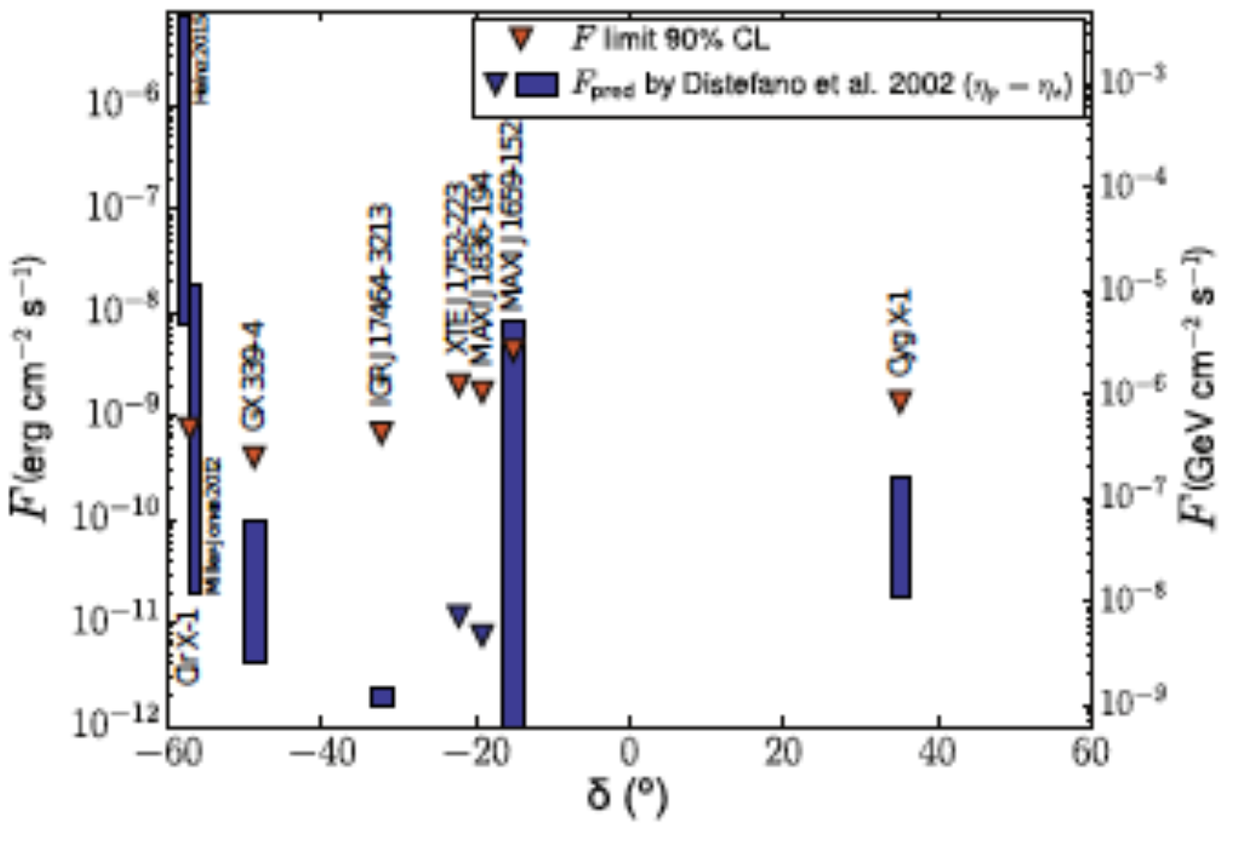


Analysis of 33 x-ray binaries: outburst + transition state periods (5yrs of data) => Paper submitted last week

GX 1+4



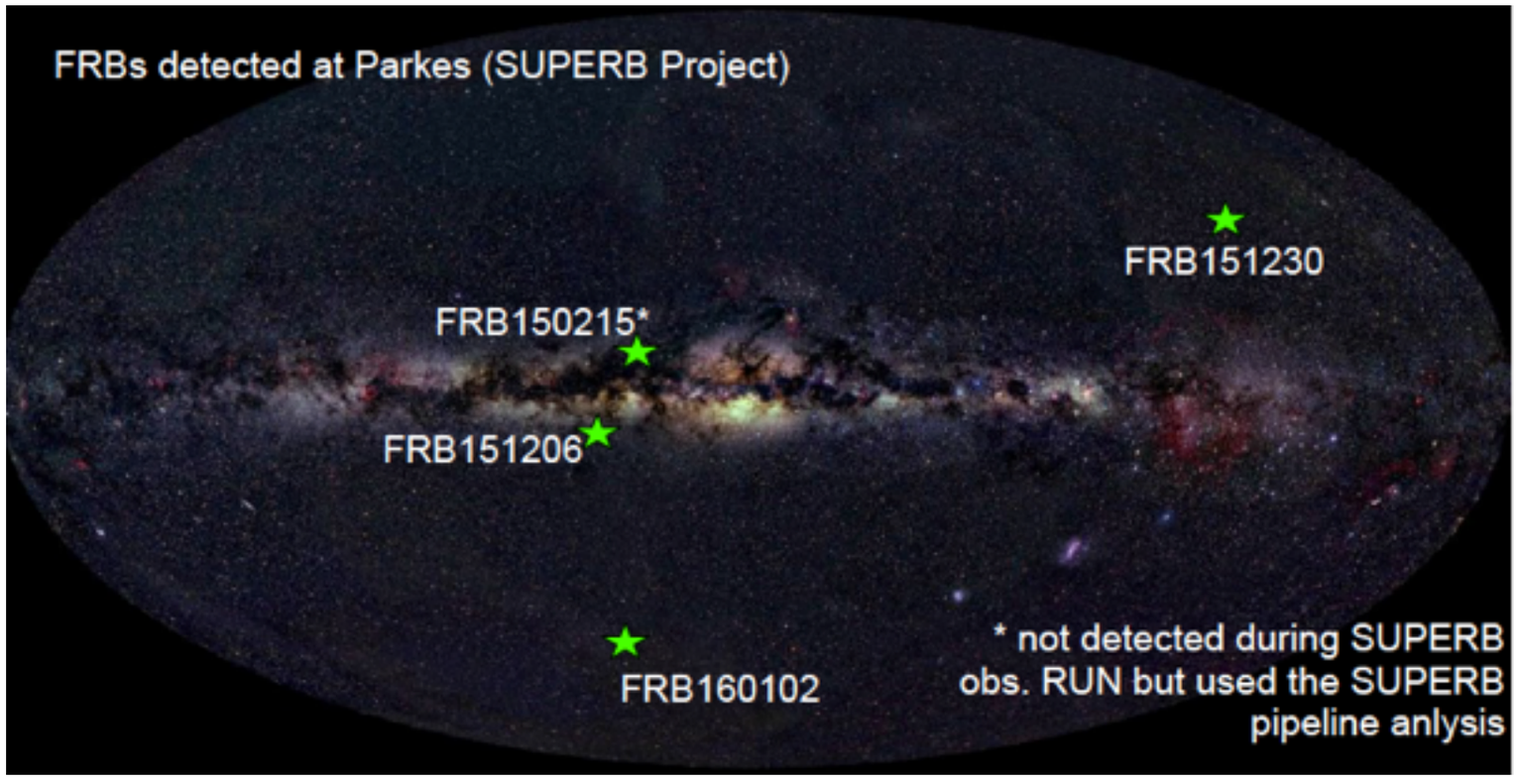
pre-trial: ~4%



C. Distefano, D. Guetta, E. Waxman, A. Levinson, 2002, ApJ, 575, 378.

Fast radio burst

ANTARES analysis of Parkes FRB events



ANTARES contribution
(validated by the ANTARES PC)

•No neutrino found in coincidence with FRB150215

• U.L on a E^{-2} and E^{-1} spectra

E^{-2} : $F_{\nu}^{90\%} < 0.014$ erg.cm^{-2} (8.65 GeV.cm^{-2})

E^{-1} : $F_{\nu}^{90\%} < 0.47$ erg.cm^{-2} (290.54 GeV.cm^{-2})

•U.L on Eiso released in neutrinos

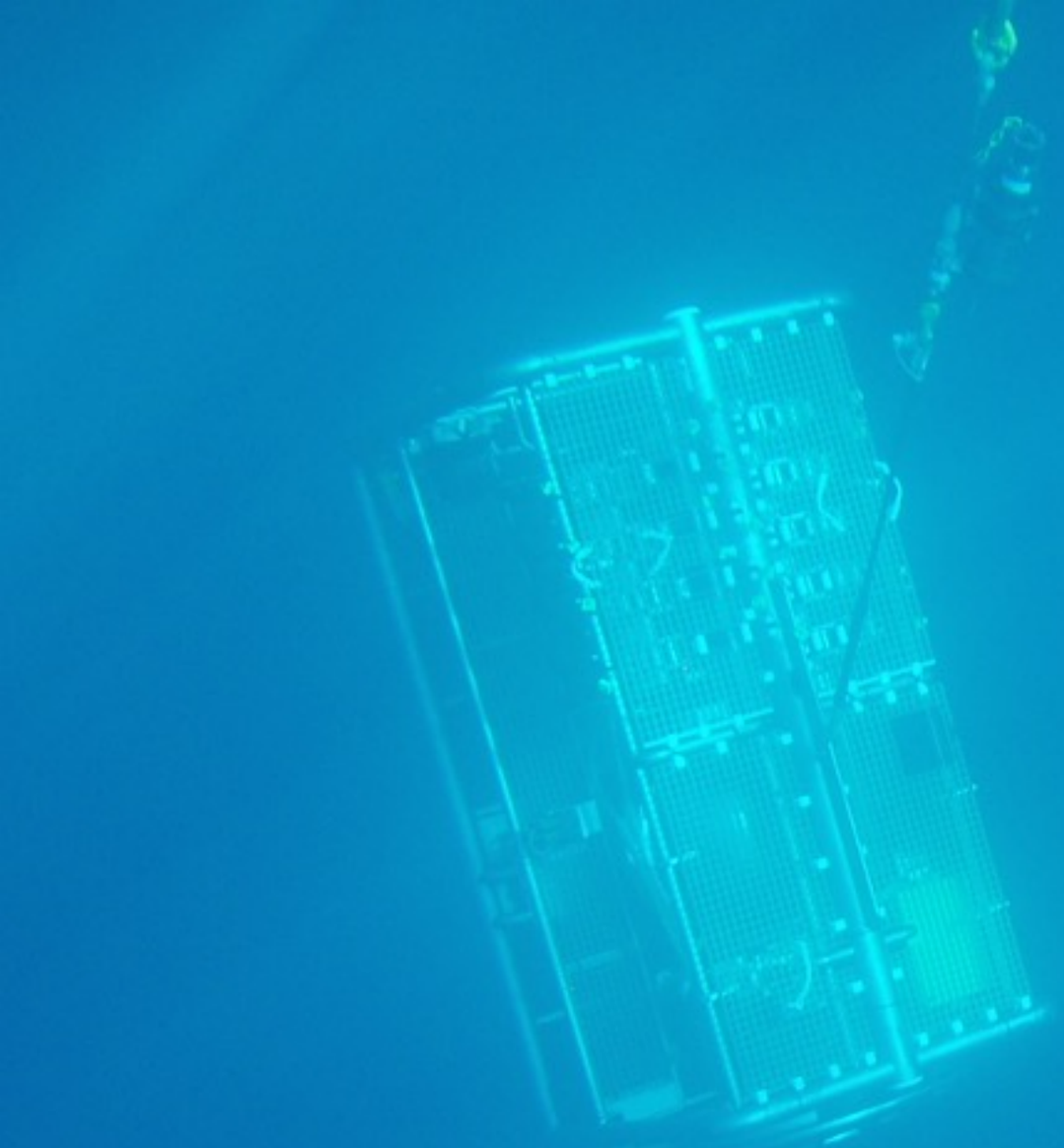
assuming $z = z_{DM} < 0.55$

E^{-2} : $E_{iso,\nu} < 1.40.10^{55}$ erg

E^{-1} : $E_{iso,\nu} < 3.10.10^{56}$ erg

=> 2 joint papers SUPERB/ANTARES (+others EM obs.) in prep

Still not public



Summary:

- Rich multi-messenger programs: more and more transient analysis are performed in real-time.
- Signature of MoUs has started between KM3Net and EM observatories.
- Computation of time-dependent sensitivities in progress in KM3NeT.

Last picture of the ORCA node in its way to the abyss


In the KM3NeT Fr site, few days ago…