Multi-messenger follow-up of GW150914 with the ANTARES neutrino telescope

Alexis Coleiro (APC / Université Paris Diderot)
on behalf of the ANTARES collaboration

6th Roma International Conference on Astroparticle Physics
June 23, 2016

Outline

1) ANTARES multi-messenger program
2) Astrophysical context and sources of interest
3) Neutrino follow-up of GW150914

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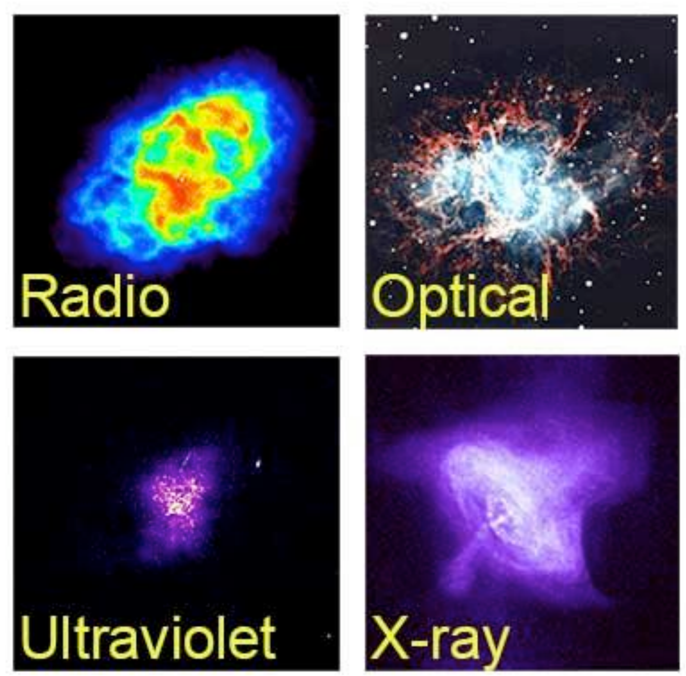
ANTARES multi-messenger program

From multi-wavelength to multi-messenger astronomy



- HE neutrinos
- HE cosmic rays
- Gravitational Waves

Connection between astrophysics and particle physics
Synergies between different collaborations

Multi-messenger and time-dependent analysis:
- increase discovery potential
- improve statistical significance

ANTARES multi-messenger program

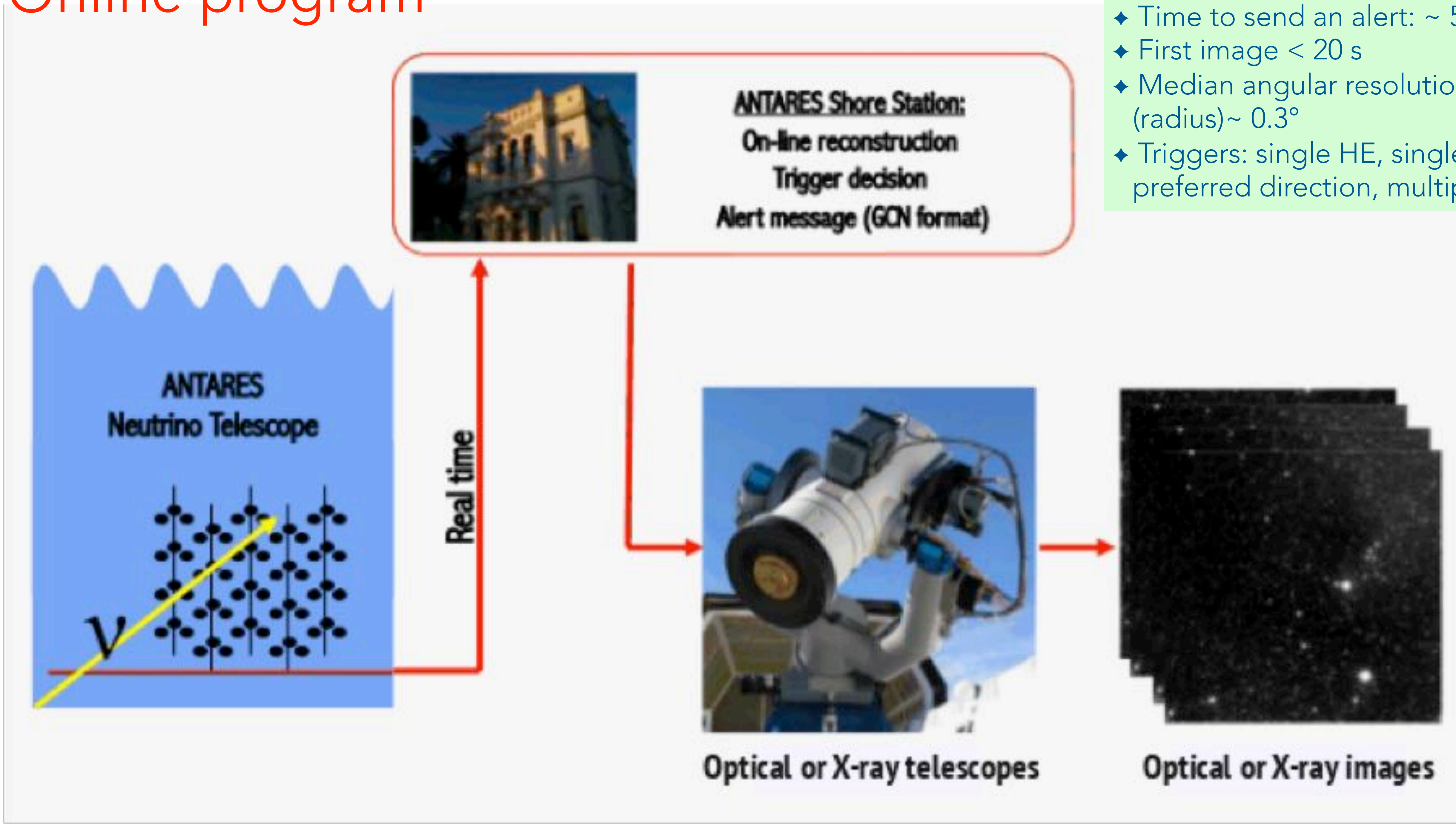
- **Online**: ANTARES triggers follow-up observations

- **Offline**: ANTARES analysis based on electromagnetic/ multi-messenger observations

Real time alert sending

Online program

- Time to send an alert: ~ 5 s
- First image < 20 s
- Median angular resolution (radius)~ 0.3°
- Triggers: single HE, single with preferred direction, multiplet



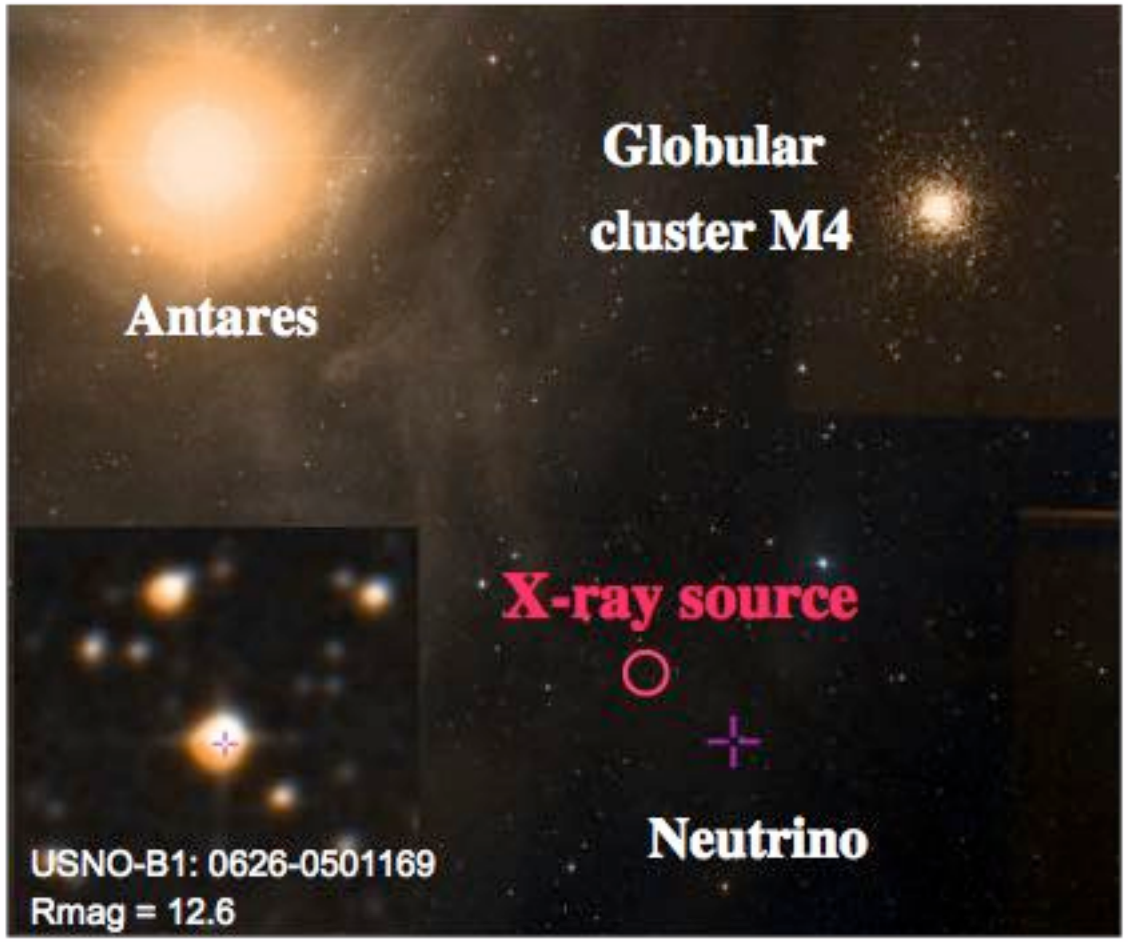
205 alerts sent to optical telescopes since mid 2009
+12 to Swift since mid 2013

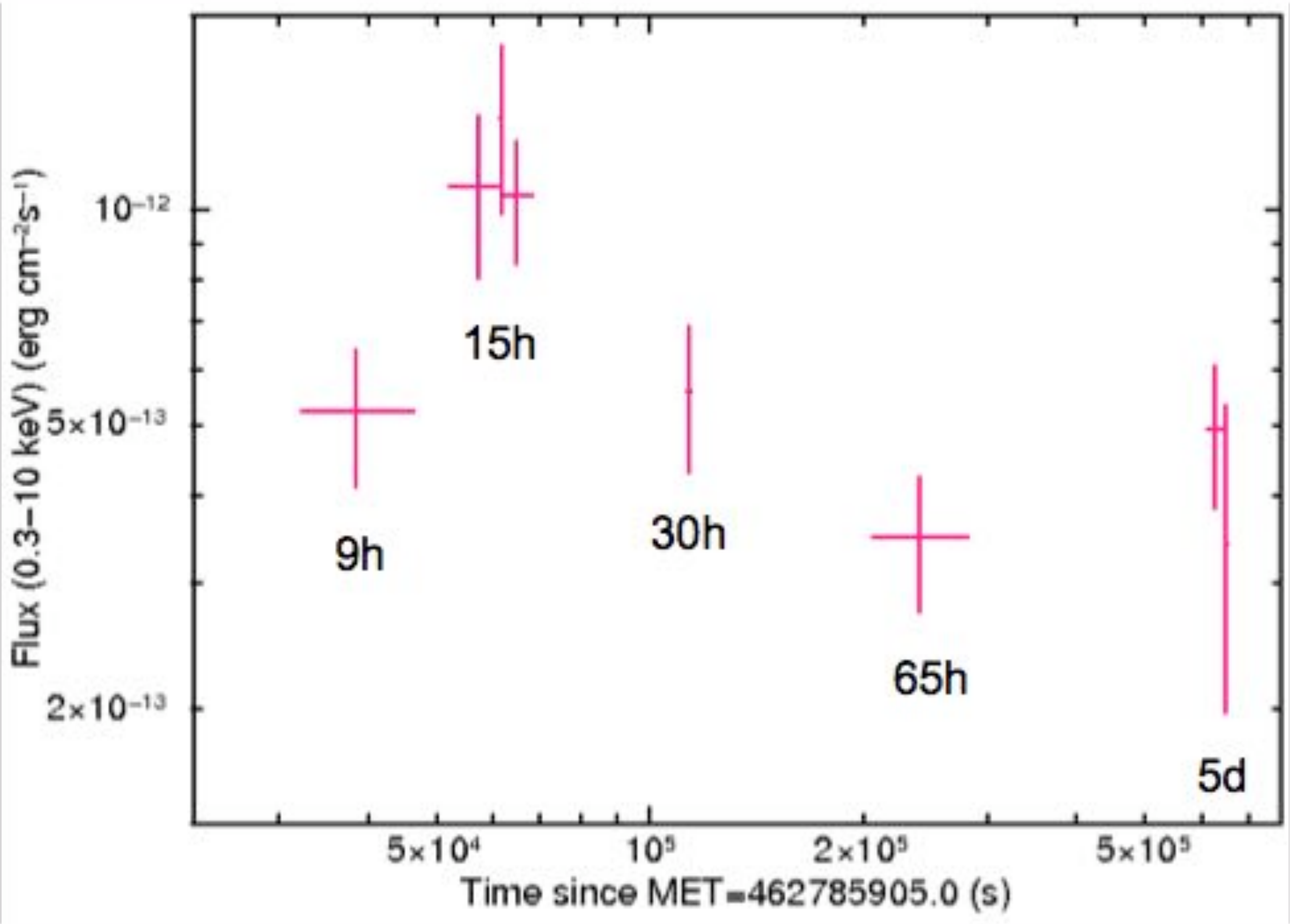
Ageron et al, Astropart. Phys. 35 (2012) 530-536

Real time alert sending

➜ 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**





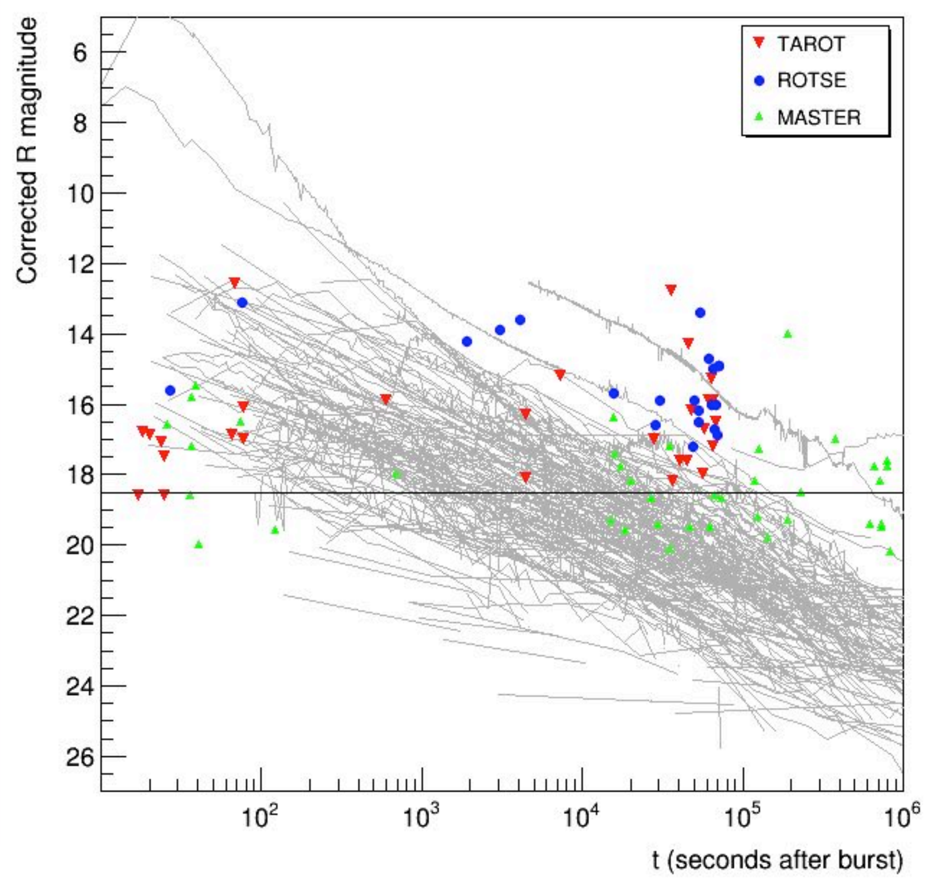
GCN #18231
ATEL #7987

➜ 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

Real time alert sending

Optical:
93 alerts with early follow-up analyzed (01/2010-01/2016)
from TAROT, ROTSE, MASTER
➜ 13 alerts with delay <1min (best: 17s)
➜ no transient candidate associated to neutrinos



Adrián-Martinéz et al, JCAP 02(2016)062

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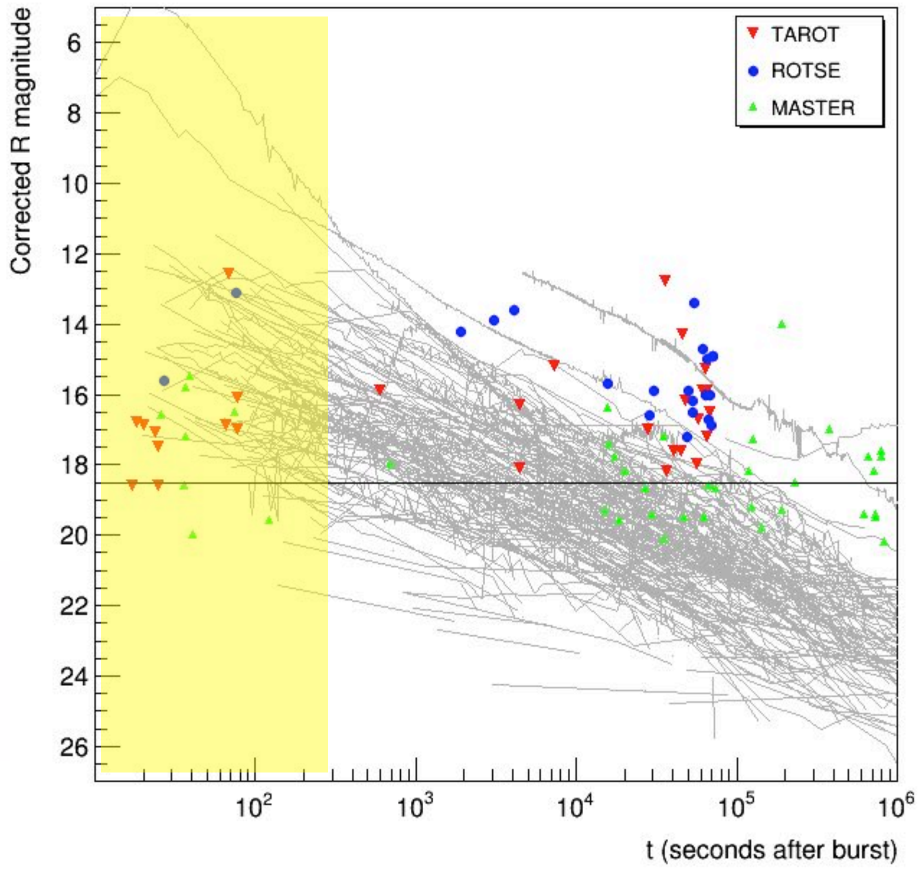
Exclude GRB at 80% C.L.
<u>if fast follow-up</u>



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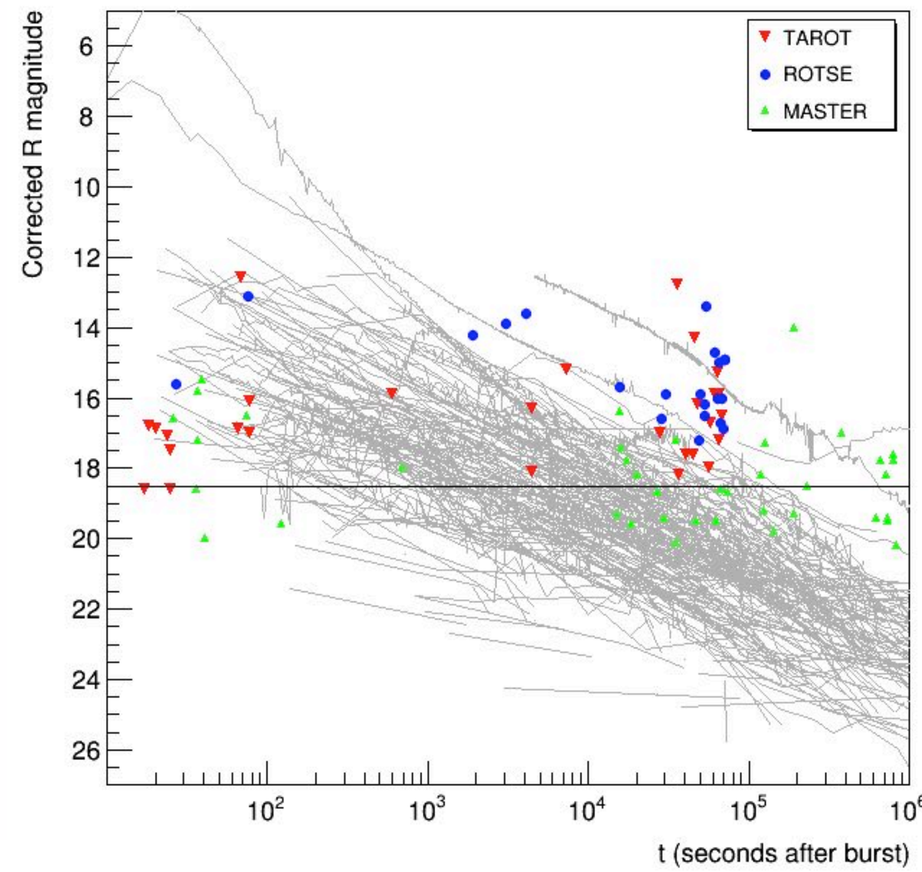
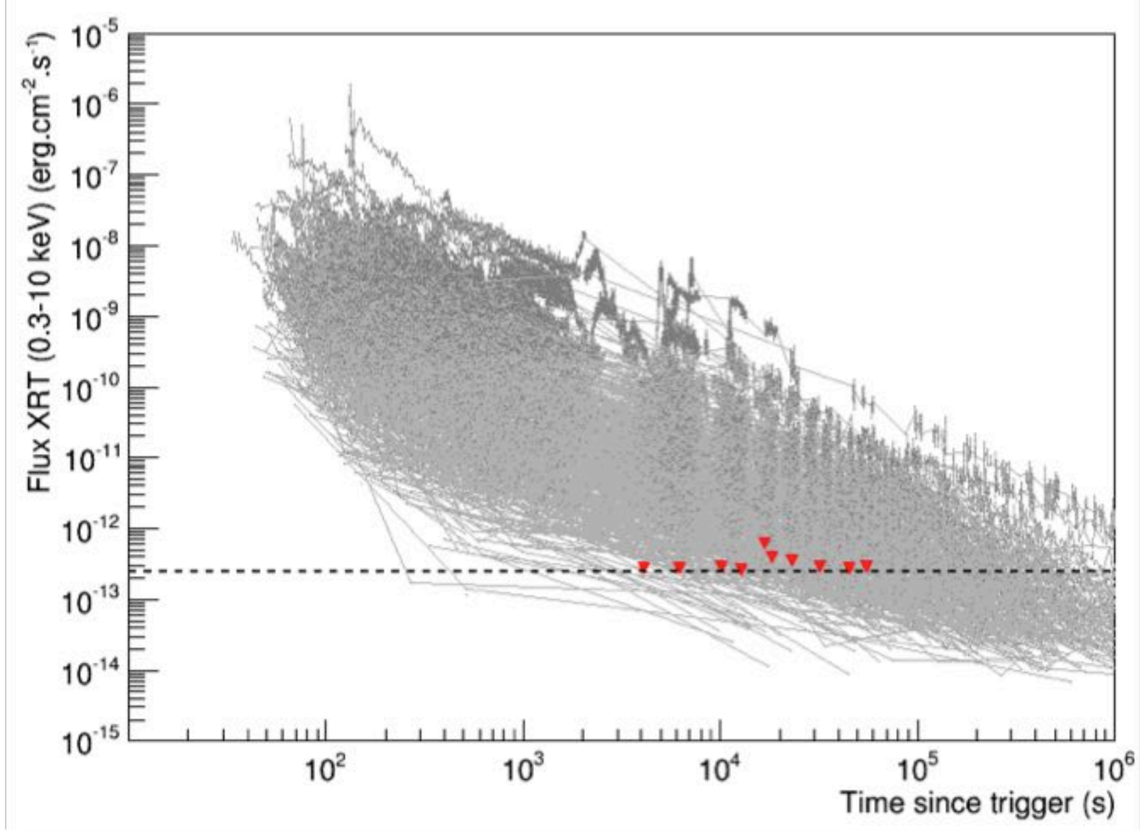
X-ray:
12 alerts analyzed (06/2013-01/2016)
➜ average delay ~5-6 hours
➜ no transient candidate associated to neutrinos

➜ constraints on origin of individual neutrinos
➜ interpretation of the UL in the case of GRB afterglow
➜ GRB origin unlikely





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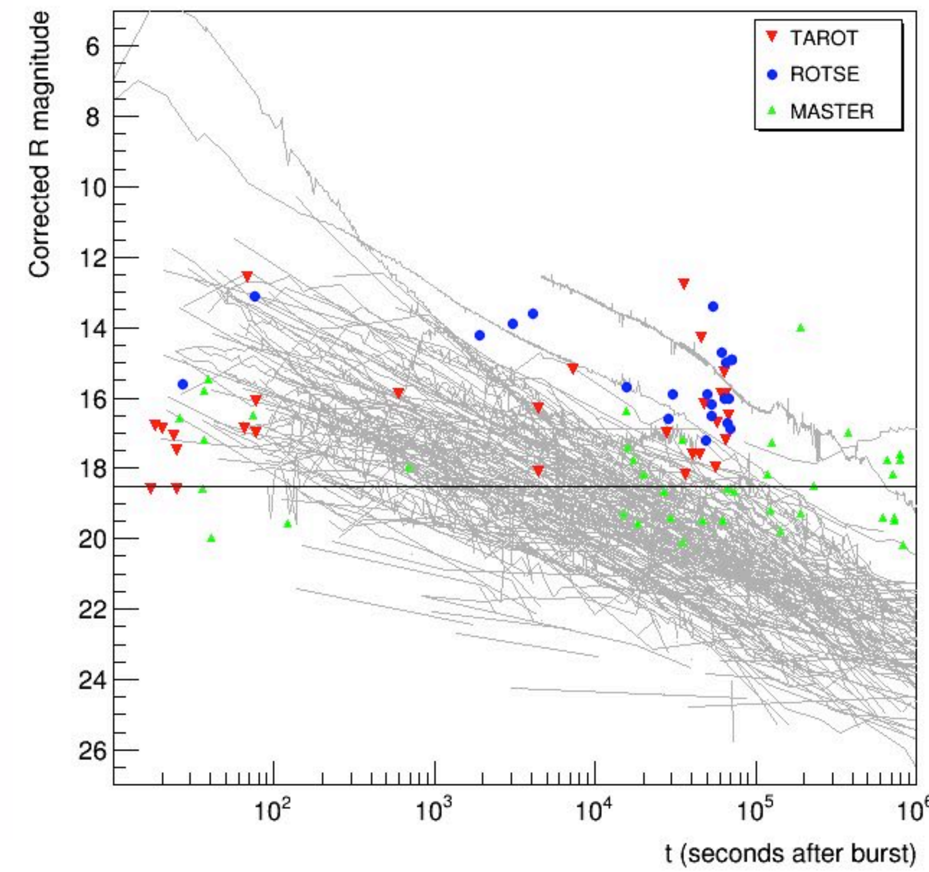
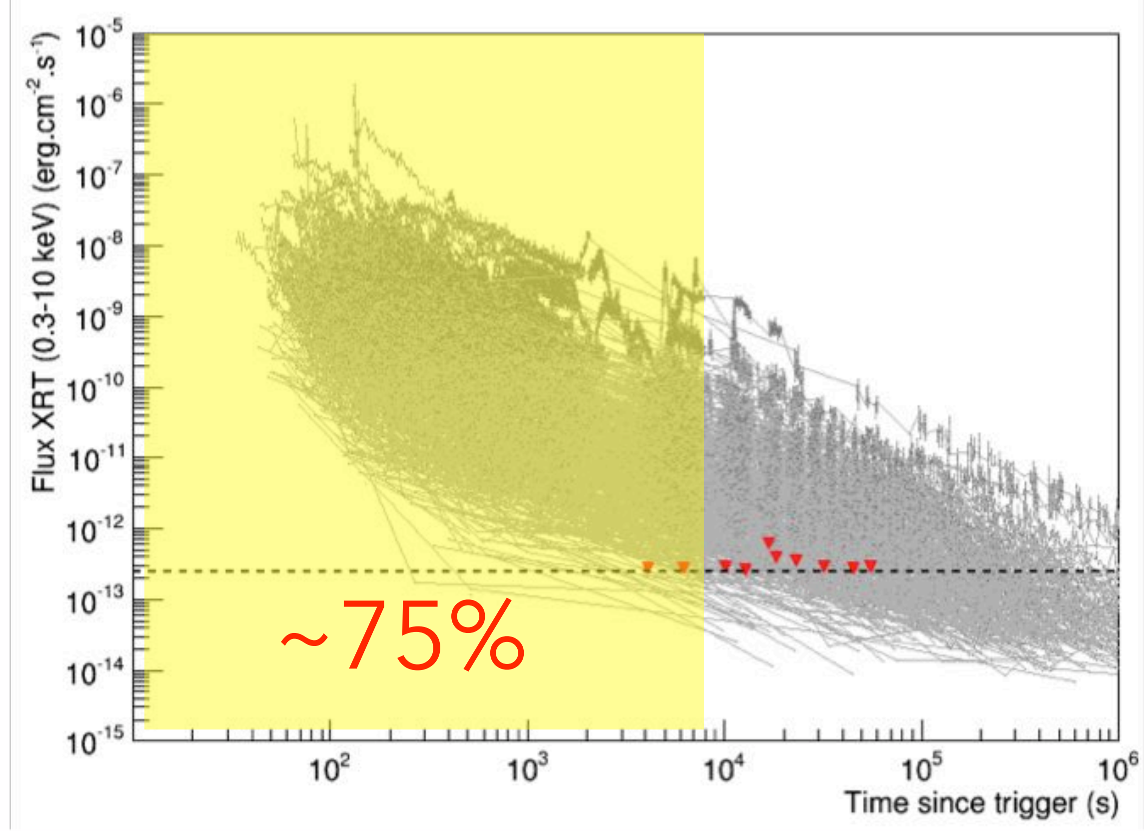




Adrián-Martinéz et al, JCAP 02(2016)062

Real time alert sending

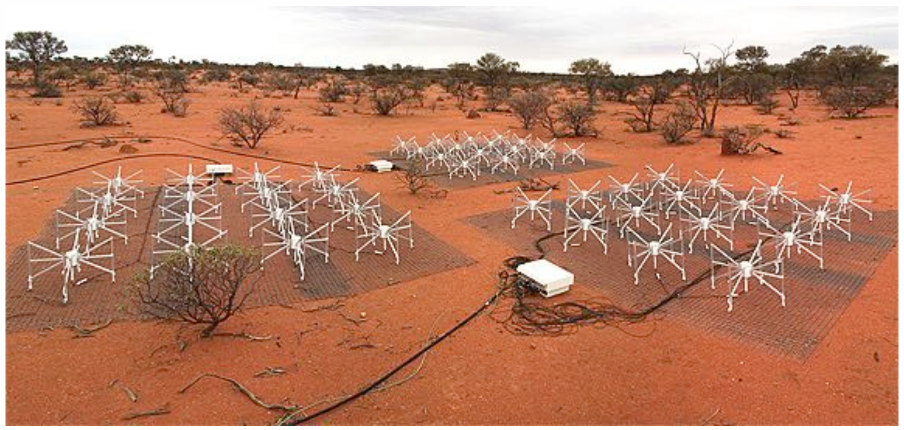
Radio	Optical	X-ray	GeV-ray	TeV-ray	TeV-ray
MWA	TAROT ROTSE ZADKO MASTER	Swift	Fermi	HESS	HAWC
(12/yr)	(30 alerts/yr)	(6 alerts/yr)	(Offline)	(2 alerts/yr)	(10 alerts/yr)

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

- + GW alerts from adv-LIGO/VIRGO
- + AMON

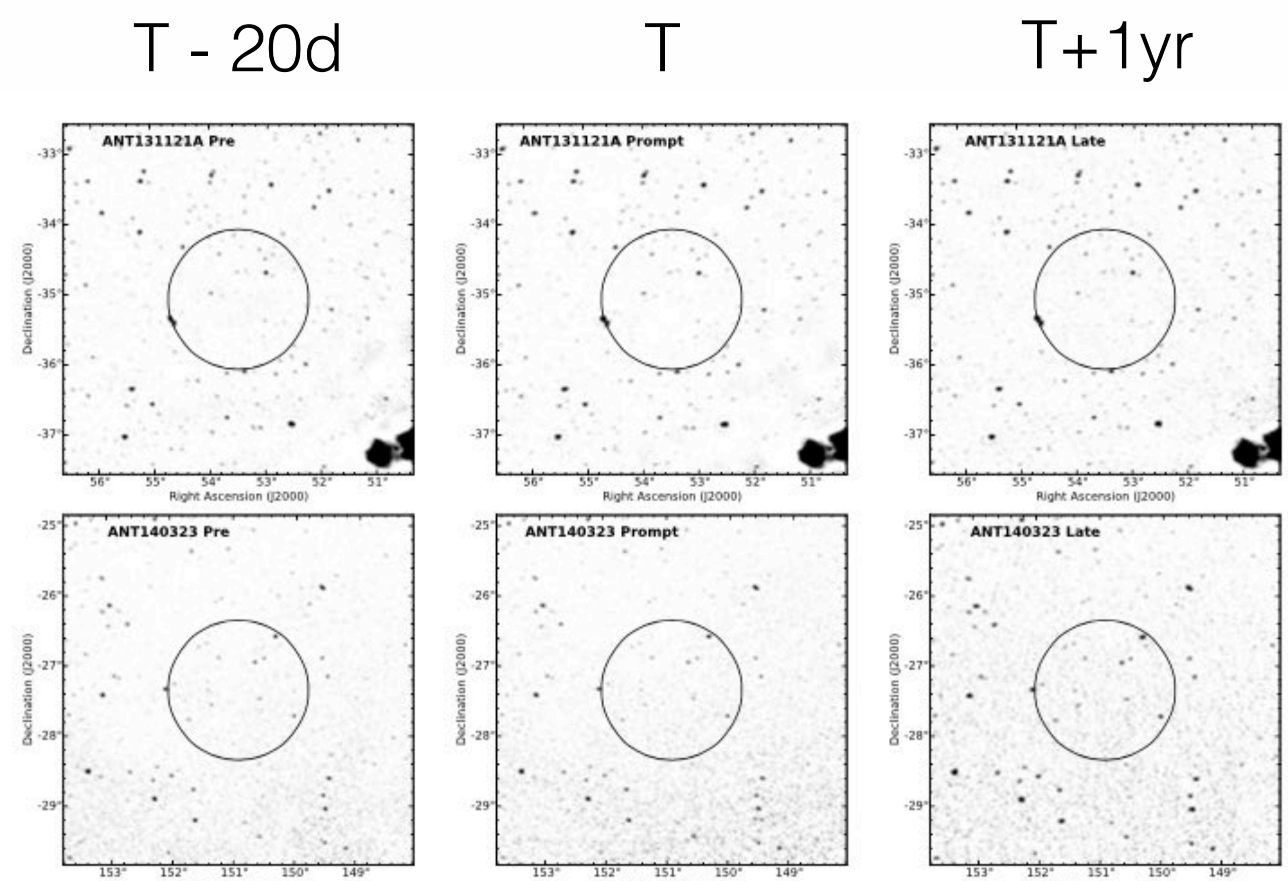
Real time alert sending

Murchidson Widefield Array: radio telescope (Australia, 80-300 MHz):
2 alerts (directional trigger, local galaxies <20 Mpc)



Radio follow-up of 2 neutrino candidates:

Trigger ID	UT date	UT time	RA (deg)	Dec (deg)	Energy (TeV)
ANT 131121A	2013 Nov 21	14:58:28	53.5	−35.1	∼ 1
ANT 140323A	2014 Mar 23	15:31:01	150.9	−27.4	∼ 4



Croft et al, ApJ, 820 (2016) 65

Results: no radio transient/variable sources
➜ Limits on progenitors if we assume neutrinos are cosmic

If source at 20 Mpc, UL(5σ) = 90−340 mJy –> $L_{150\ MHz} < 10^{29}$ erg/s/Hz (<10^{37} erg/s)

If NS-NS coalescence ➜ limit on the distance z>0.2 (>1 Gpc)

ANTARES multi-messenger program

Time-dependent searches:

- GRB [Swift, Fermi, IPN] Talk by M. Sanguineti
- 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 , IceCube HESE

Talks by L. Fusco and A. Sanchez Losa

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]

TAToO

ANTARES multi-messenger program

Offline

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TAToO

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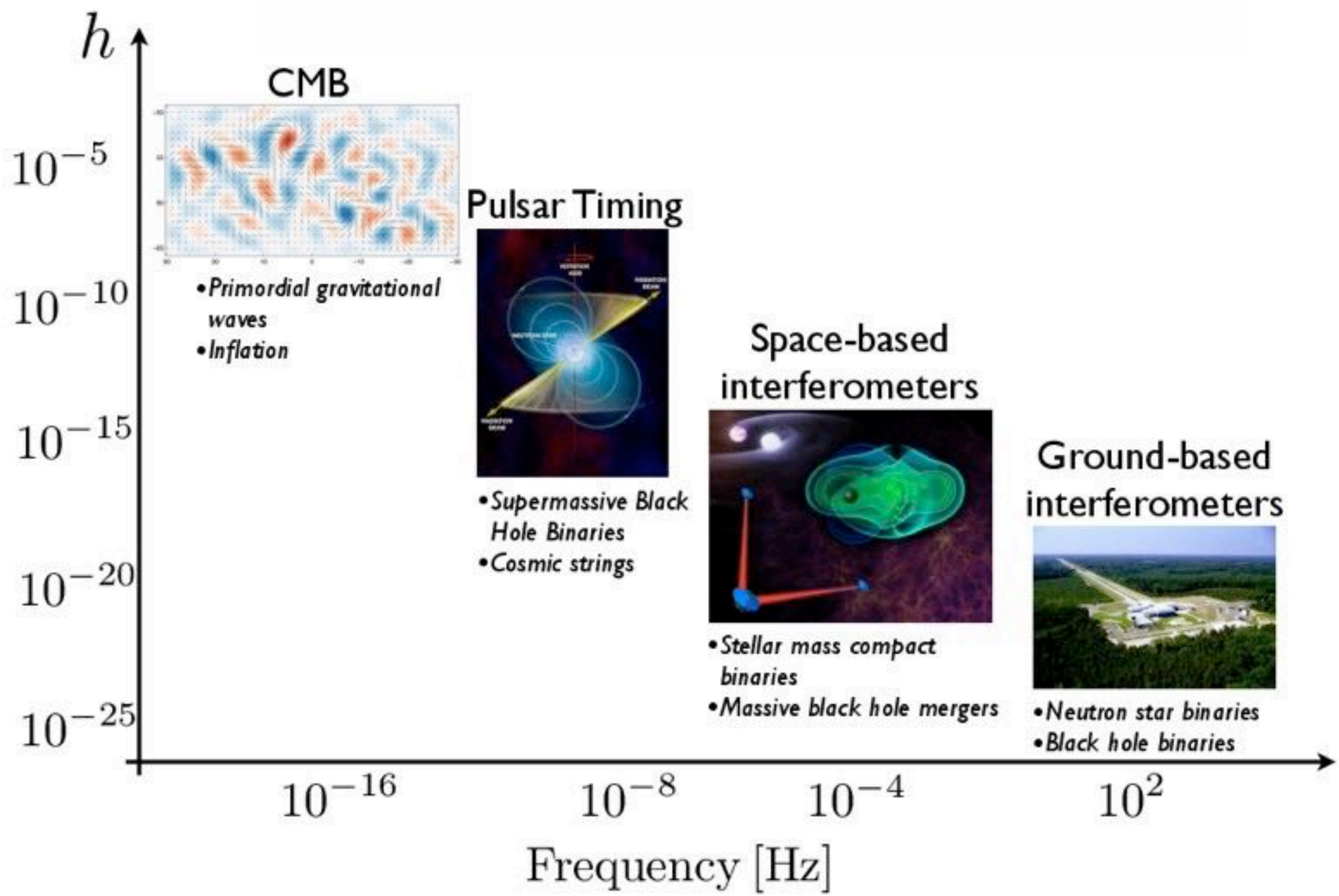
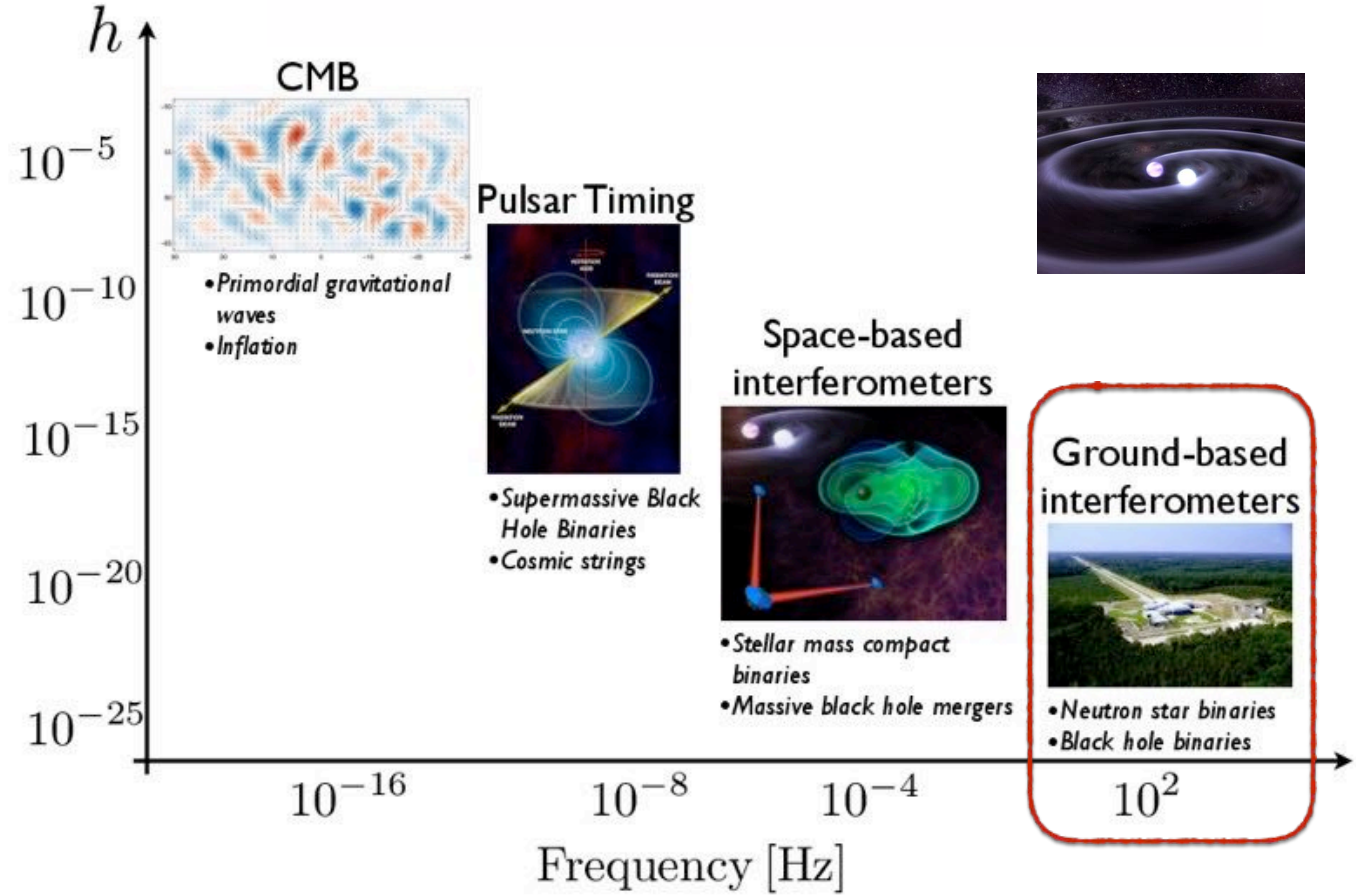
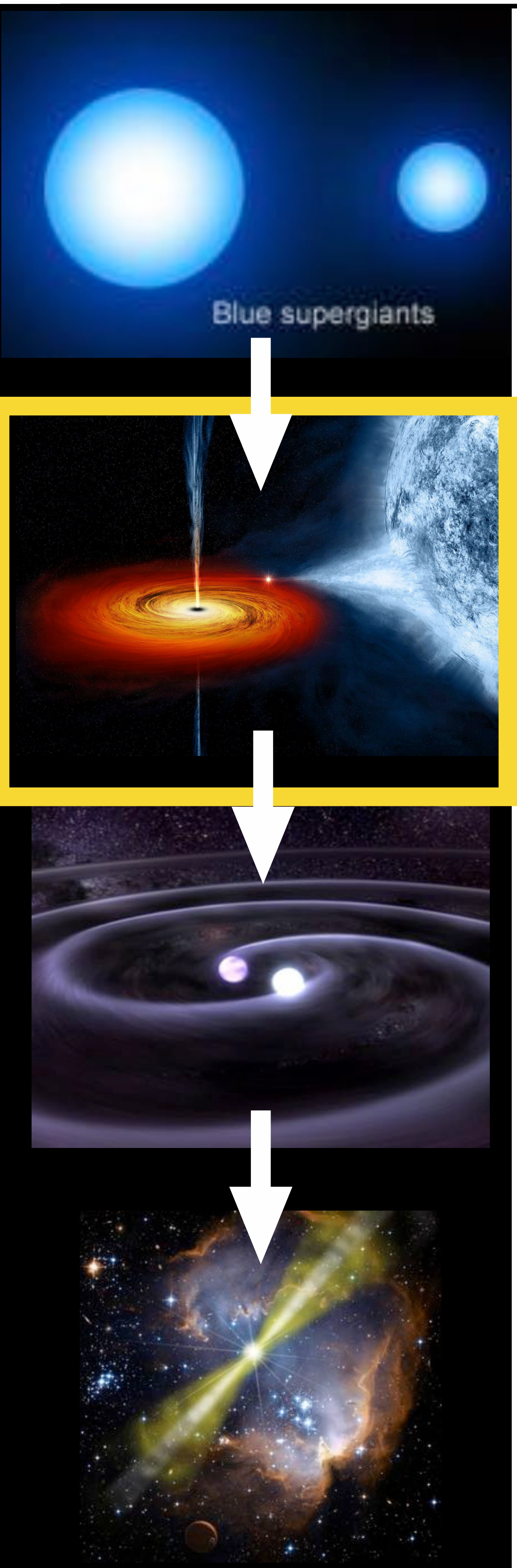
The big picture of gravitational wave astronomy



The big picture of gravitational wave astronomy

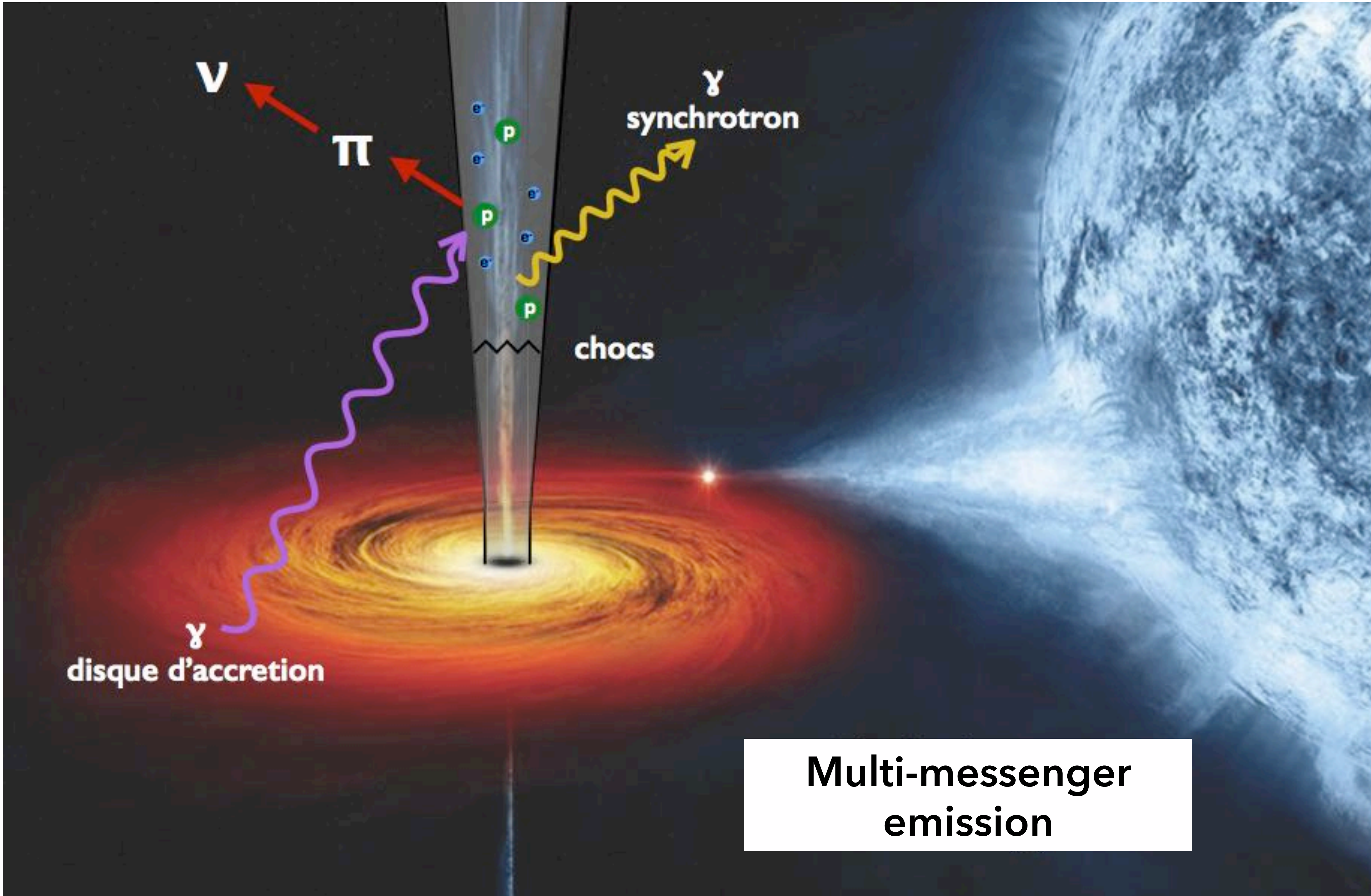


Evolution of binary star systems



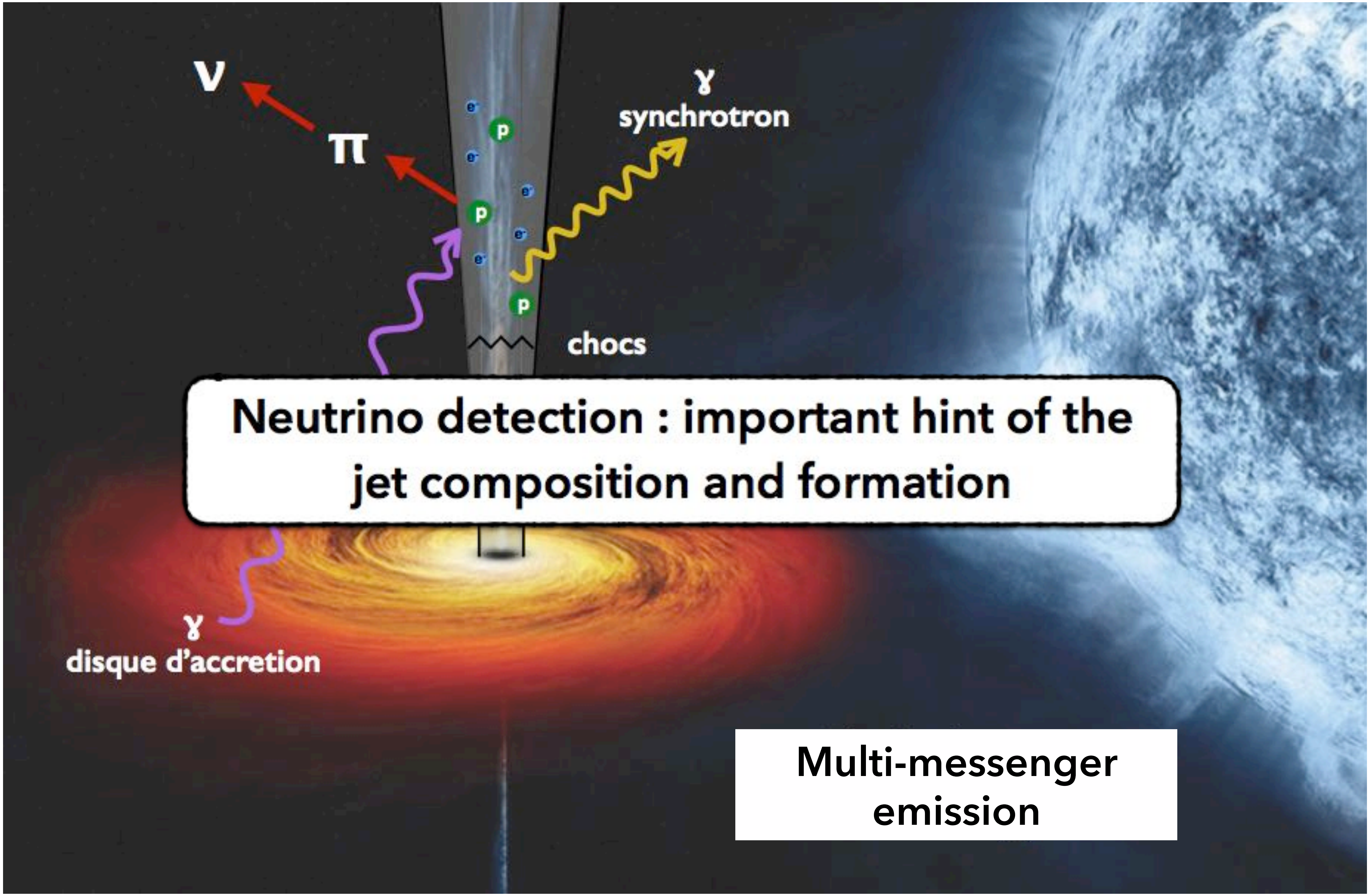
- Most of massive stars live in binary systems
- Undergo mass transfer
- Accretion / ejection processes
- Finish their life as compact object binaries
- short GRB + GW emission during coalescence

X-ray binaries



Multi-messenger emission

X-ray binaries

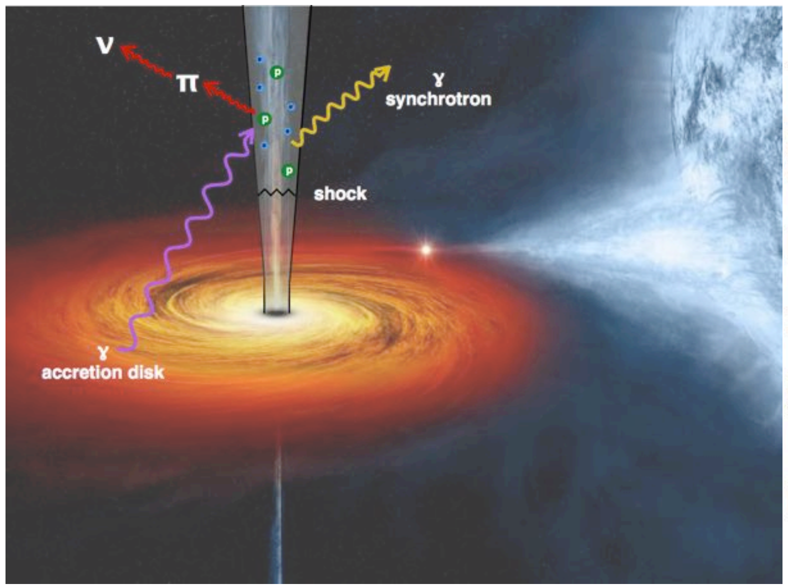


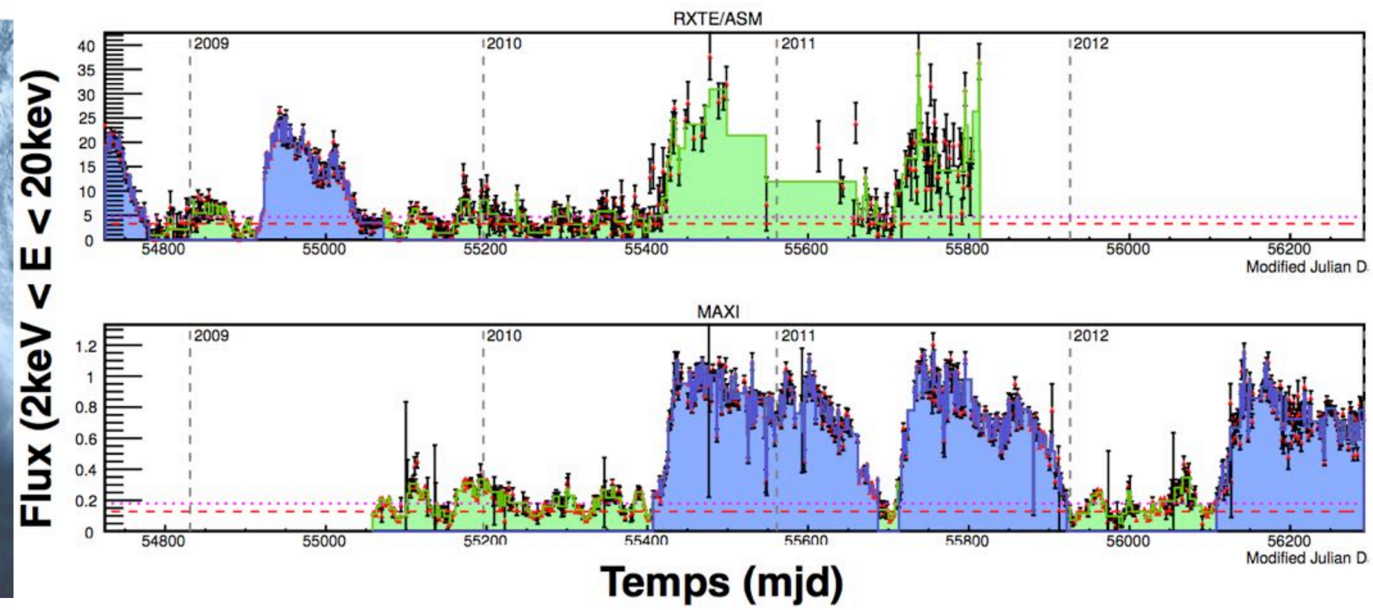
Neutrino detection : important hint of the jet composition and formation

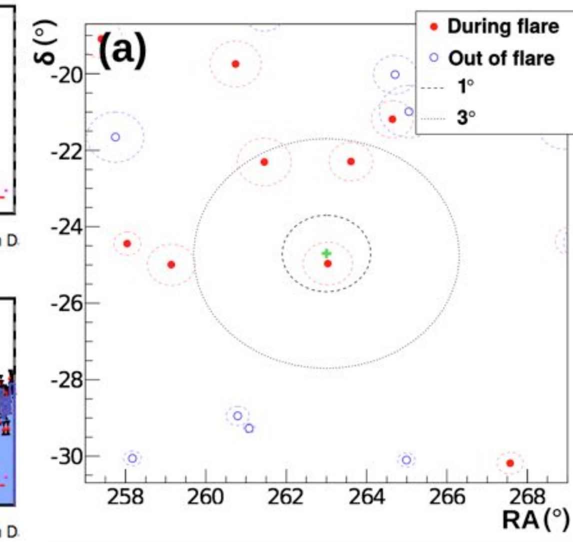
Multi-messenger emission

Neutrino emission of X-ray binaries ?

Jet composition studied by ANTARES





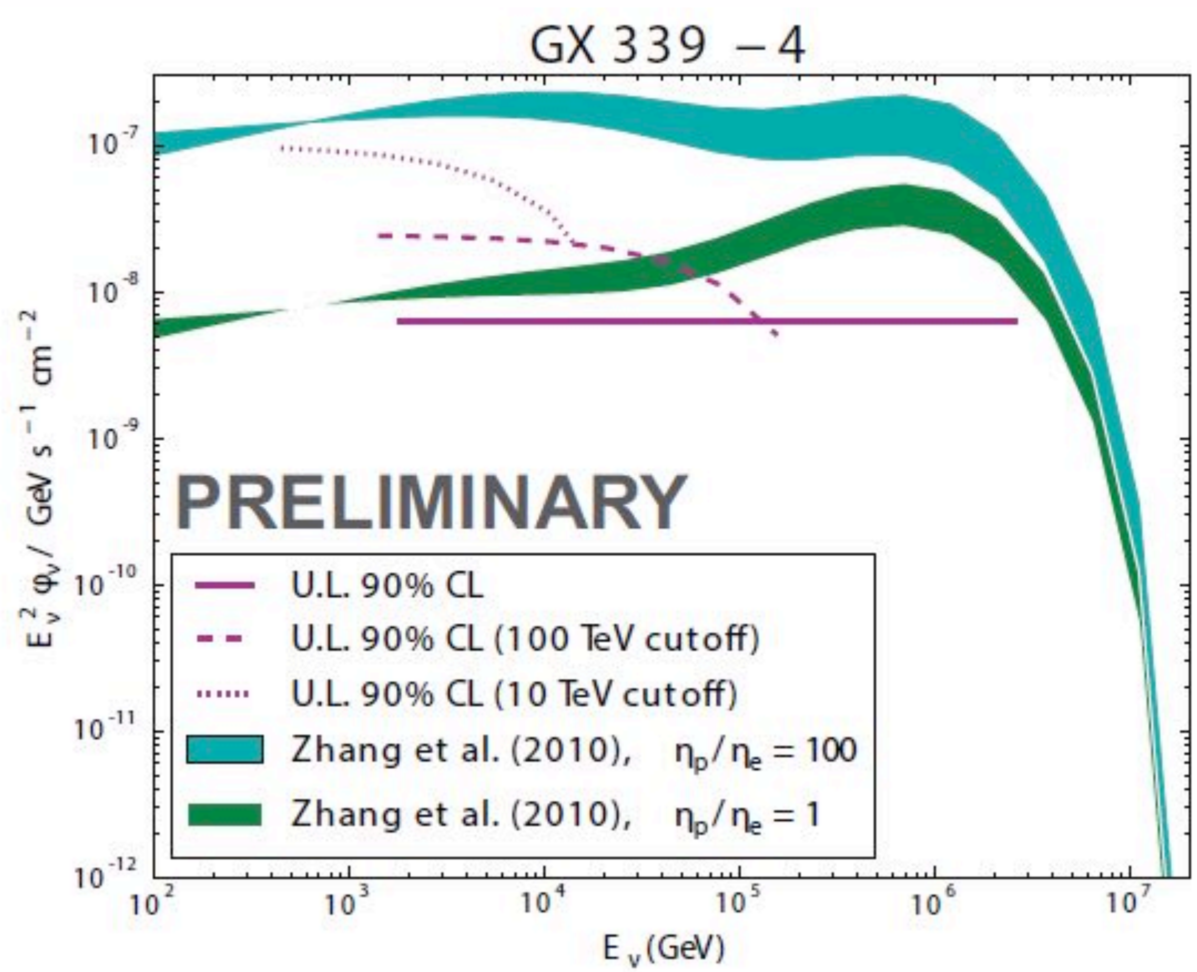


$$\ln \mathcal{L} = \left(\sum_{i=1}^{N} \ln[\mathcal{N}_\mathrm{S} \mathcal{S}_i + \mathcal{N}_\mathrm{B} \mathcal{B}_i] \right) - [\mathcal{N}_\mathrm{S} + \mathcal{N}_\mathrm{B}]$$

$$\mathcal{S}_i = \mathcal{S}^{\mathrm{space}}(\Psi_i(\alpha_s, \delta_s)) \cdot \mathcal{S}^{\mathrm{energy}}(dE/dX_i) \cdot \mathcal{S}^{\mathrm{time}}(t_i + lag)$$

$$\mathcal{B}_i = \mathcal{B}^{\mathrm{space}}(\delta_i) \cdot \mathcal{B}^{\mathrm{energy}}(dE/dX_i) \cdot \mathcal{B}^{\mathrm{time}}(t_i)$$

No detection → **U.L. on the proton energy (based on photo-hadronic models)**



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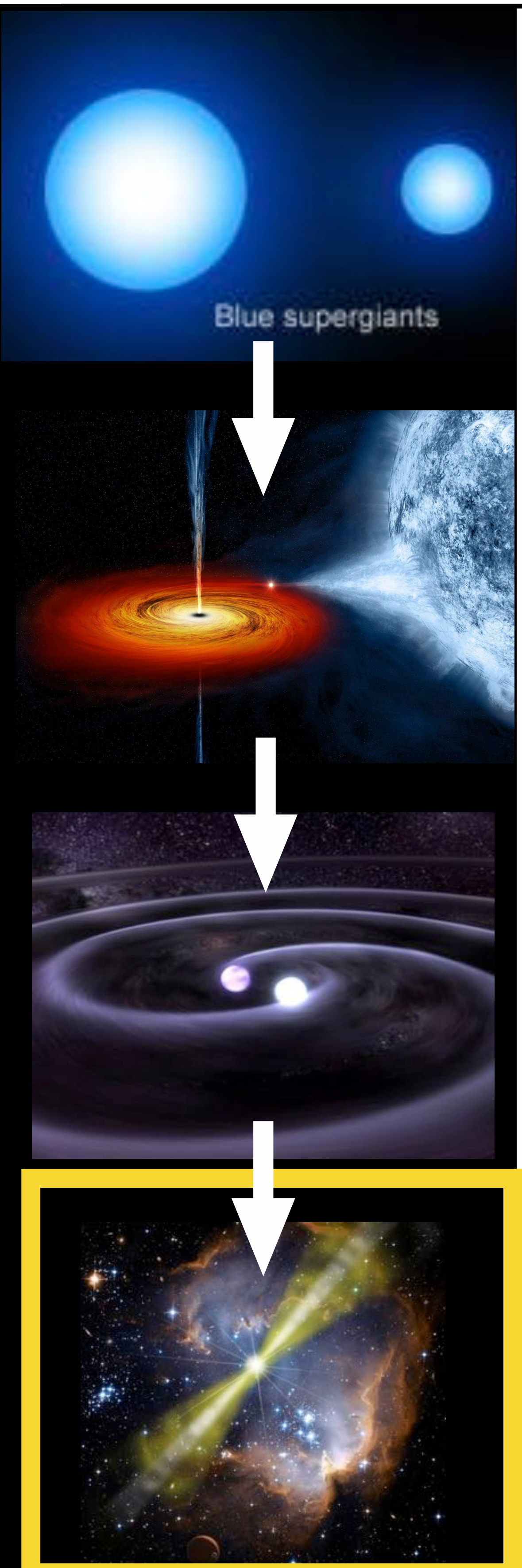
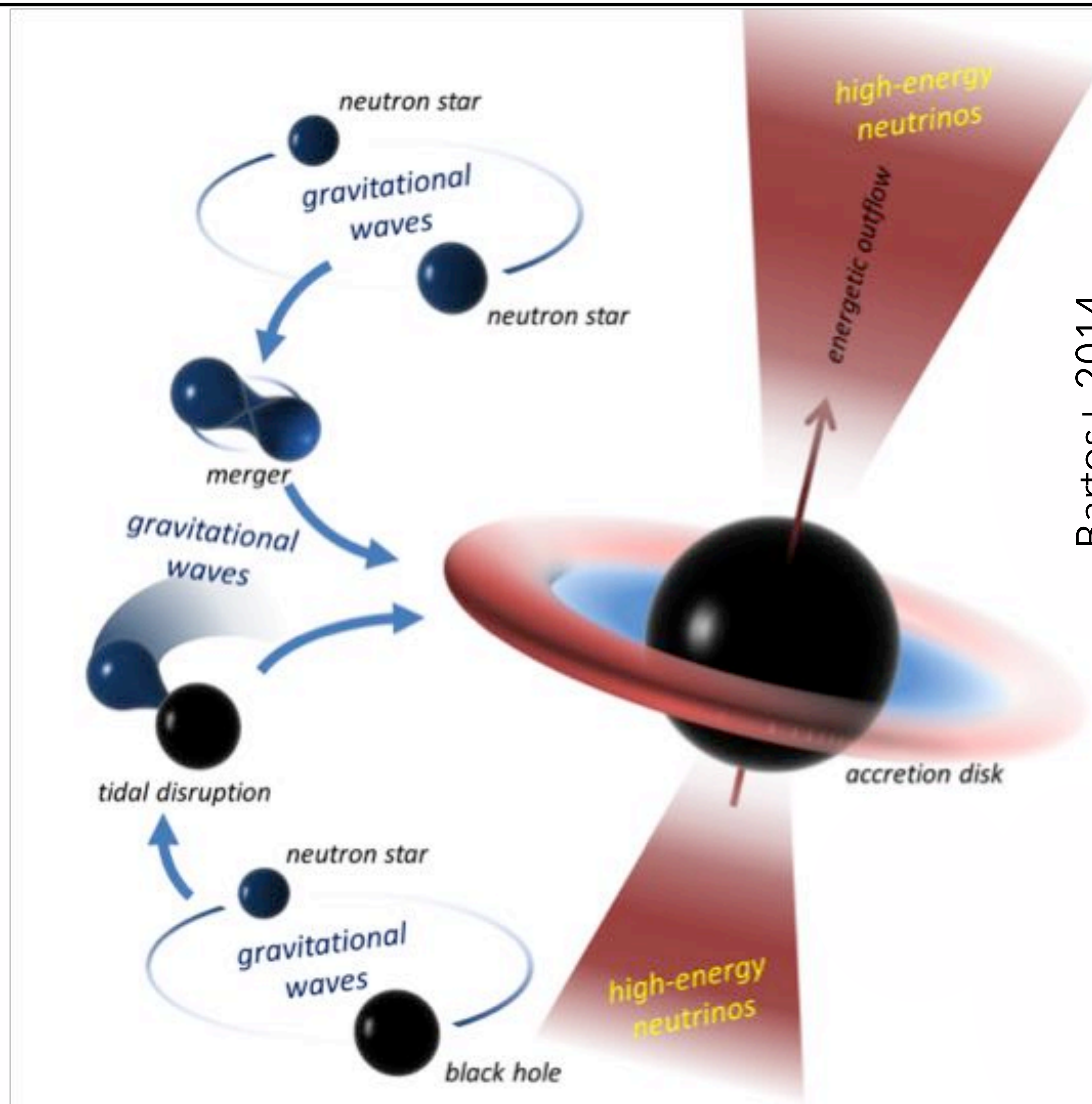


- Most of massive stars live in binary systems
- Undergo mass transfer
- Accretion / ejection processes
- Finish their life as compact object binaries
- short GRB + GW emission during coalescence

Compact object coalescence

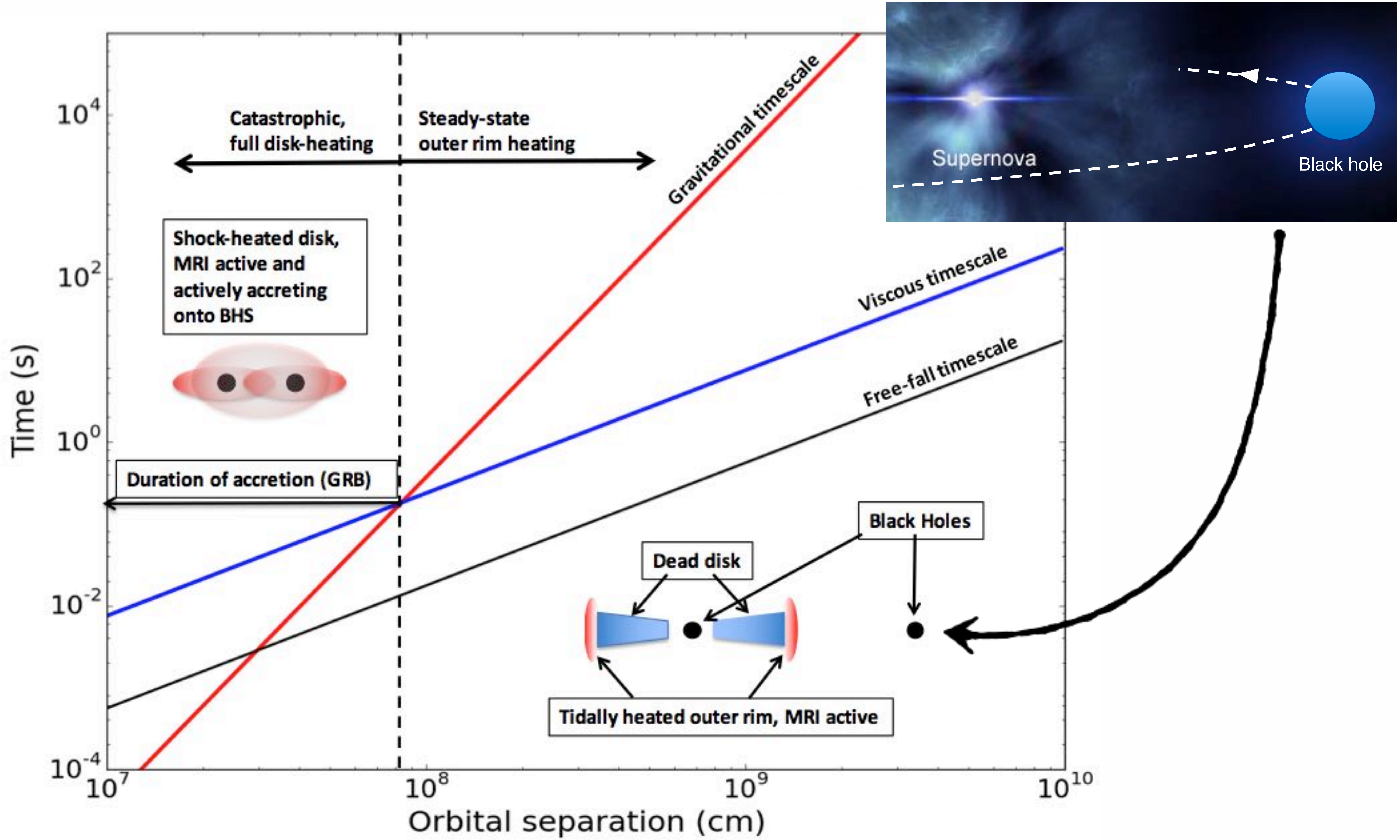
For BH/NS or NS/NS systems :

gravitational waves
+ electromagnetic
+ neutrino emission
expected if ejection process with baryonic component



Bartos+ 2014

Black hole binary coalescence



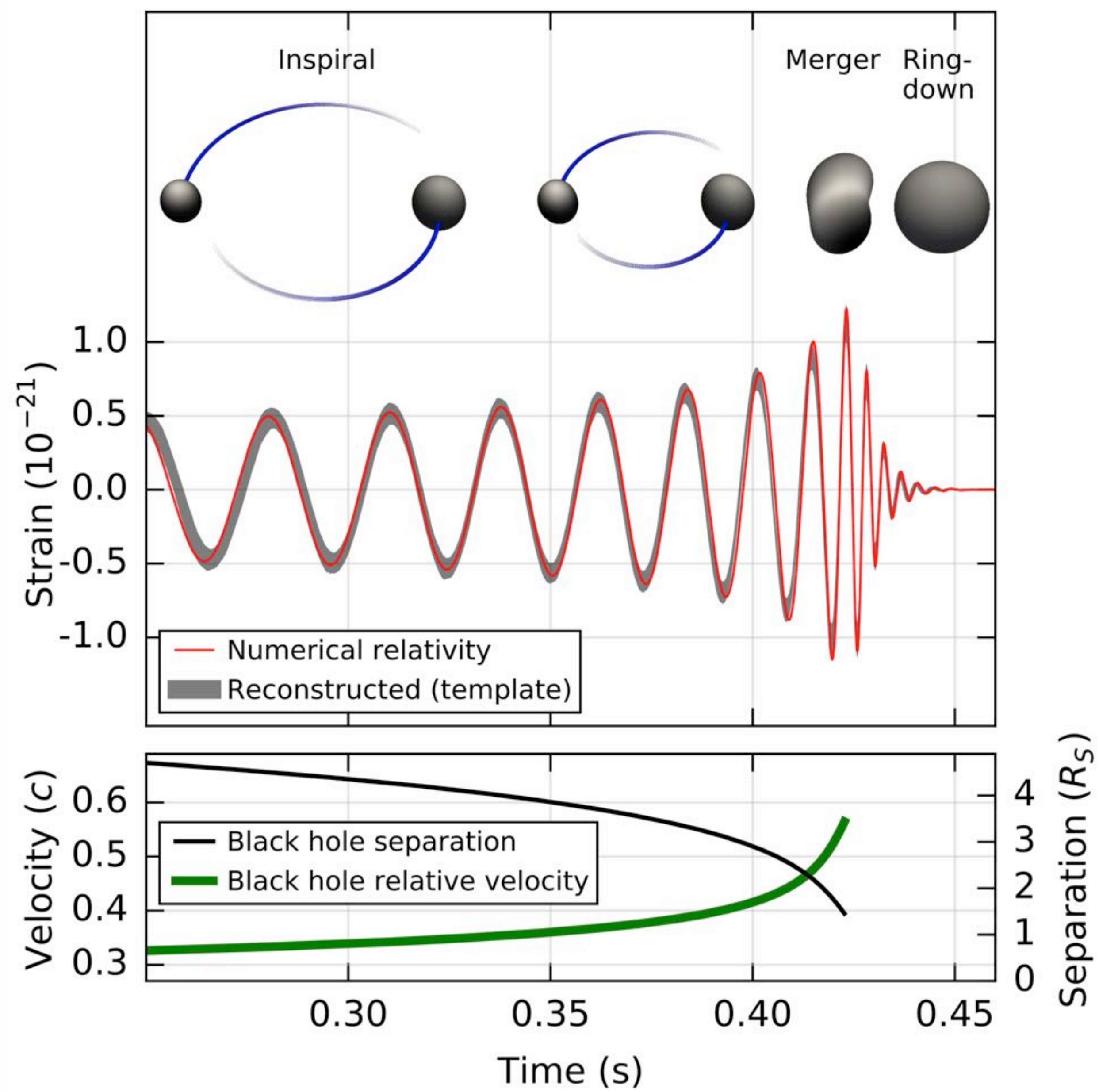
Perna et al., ApJ, 2016, 821, 18

Discovery of GW150914

Sept. 14th, 2015 at 09:50:45 UTC

GW signal recorded by the LIGO Hanford and Livingston detectors

Produced by a stellar-mass binary black hole merger at redshift $z=0.09^{+0.03}_{-0.04}$ (~410 Mpc)



LIGO-Virgo collaborations
PRL 116, 061102, 2016

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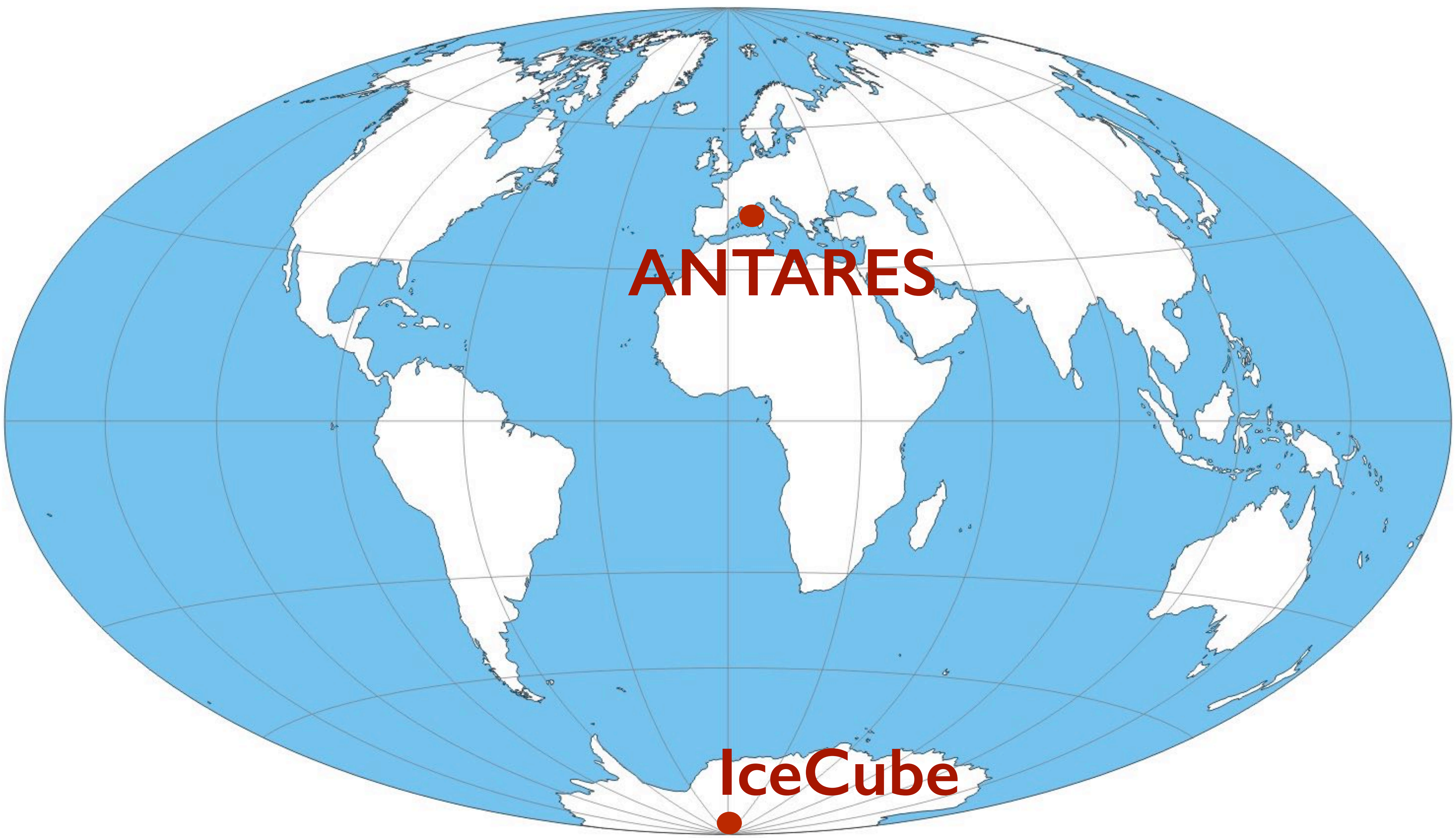
Neutrino follow-up

Energy radiated in GW: ~5 x 10^{54} erg

Is a fraction of this energy emitted in neutrinos ? + Demonstrate synergies

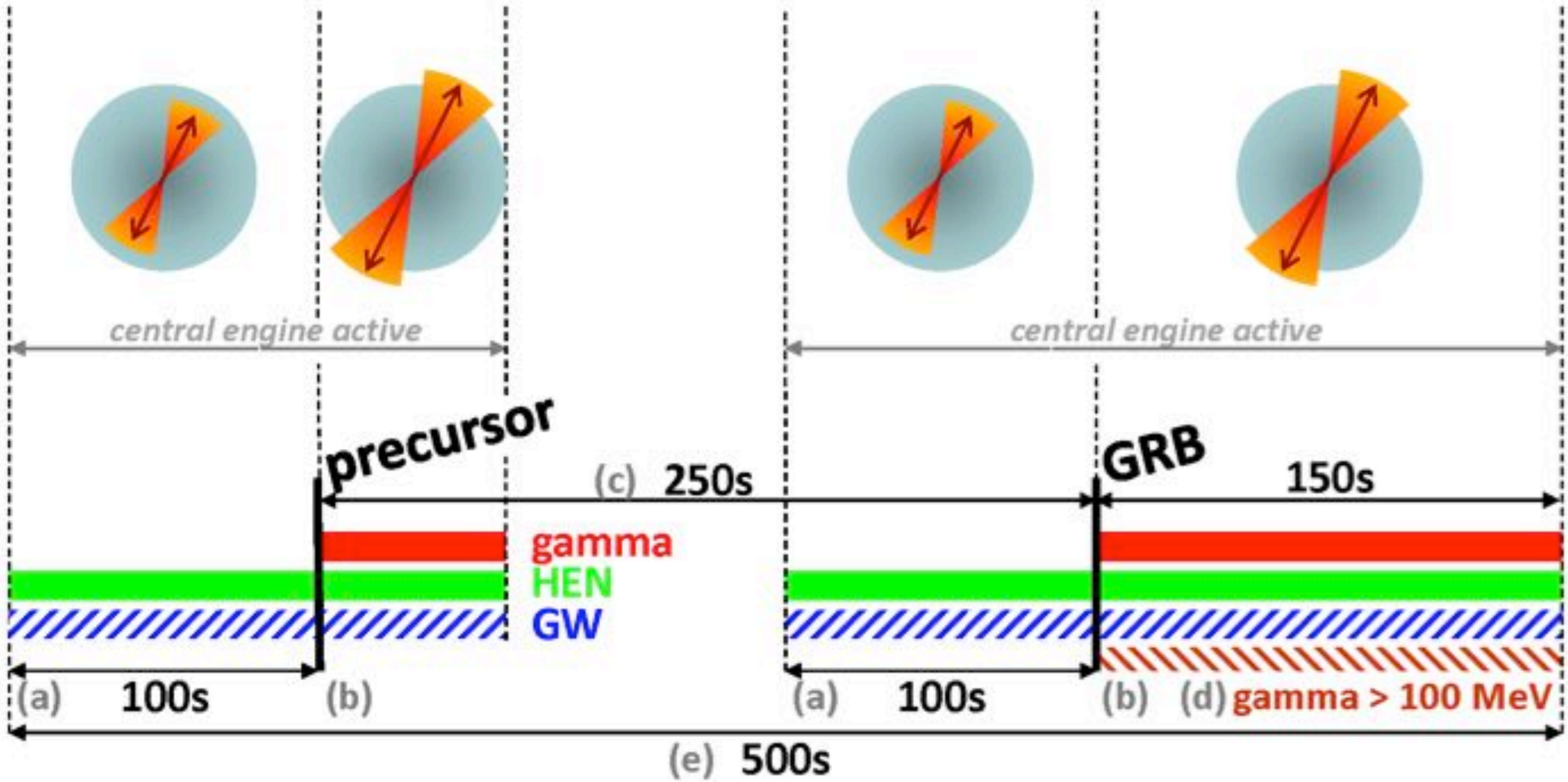
Joint ANTARES - IceCube - LIGO/Virgo analysis

Phys. Rev. D (in press) : [arXiv 1602.05411]



Neutrino follow-up

In the case of a short GRB



Baret et al., Astrop. Phys., 2011, 35, 1-7

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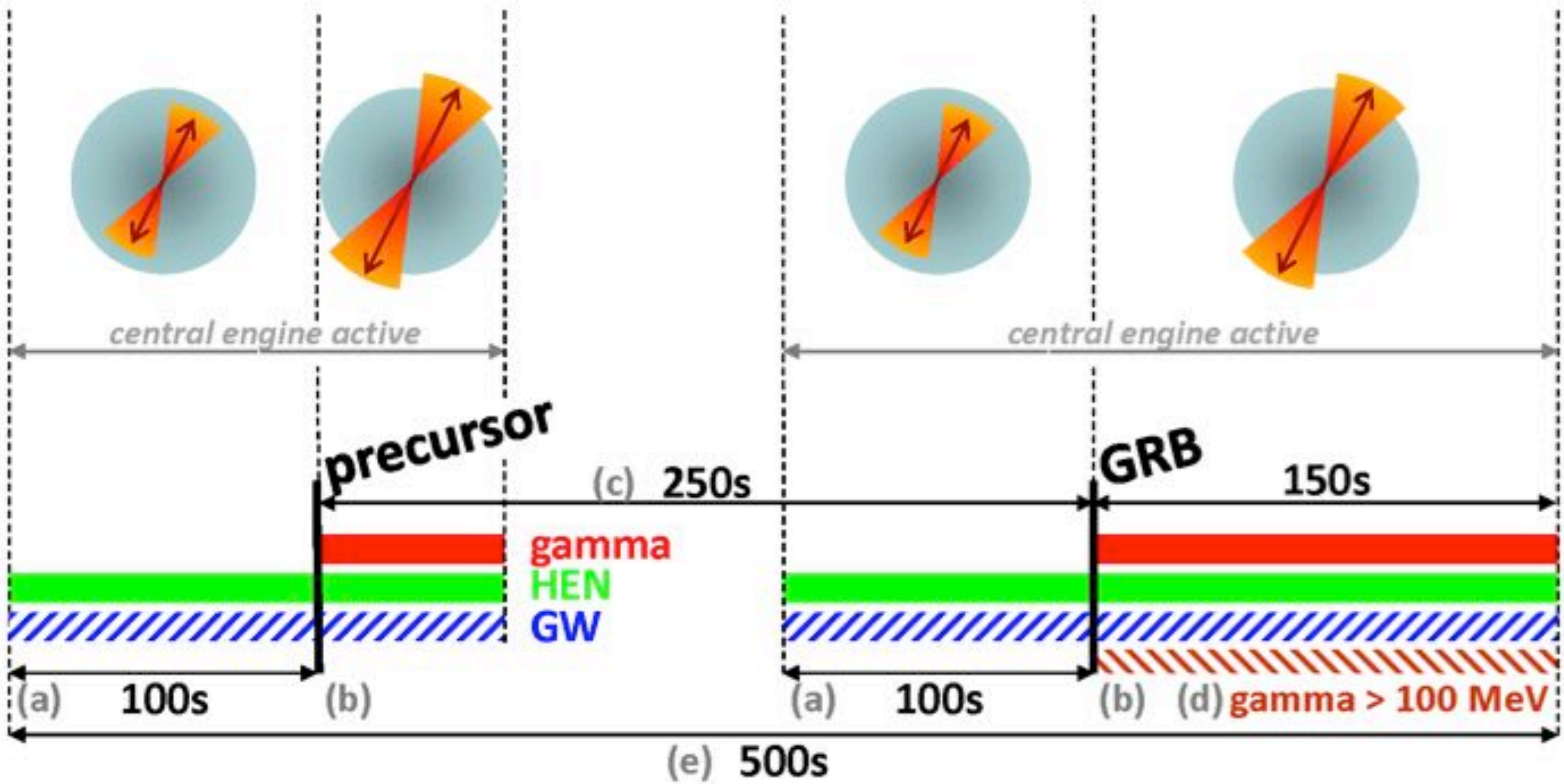


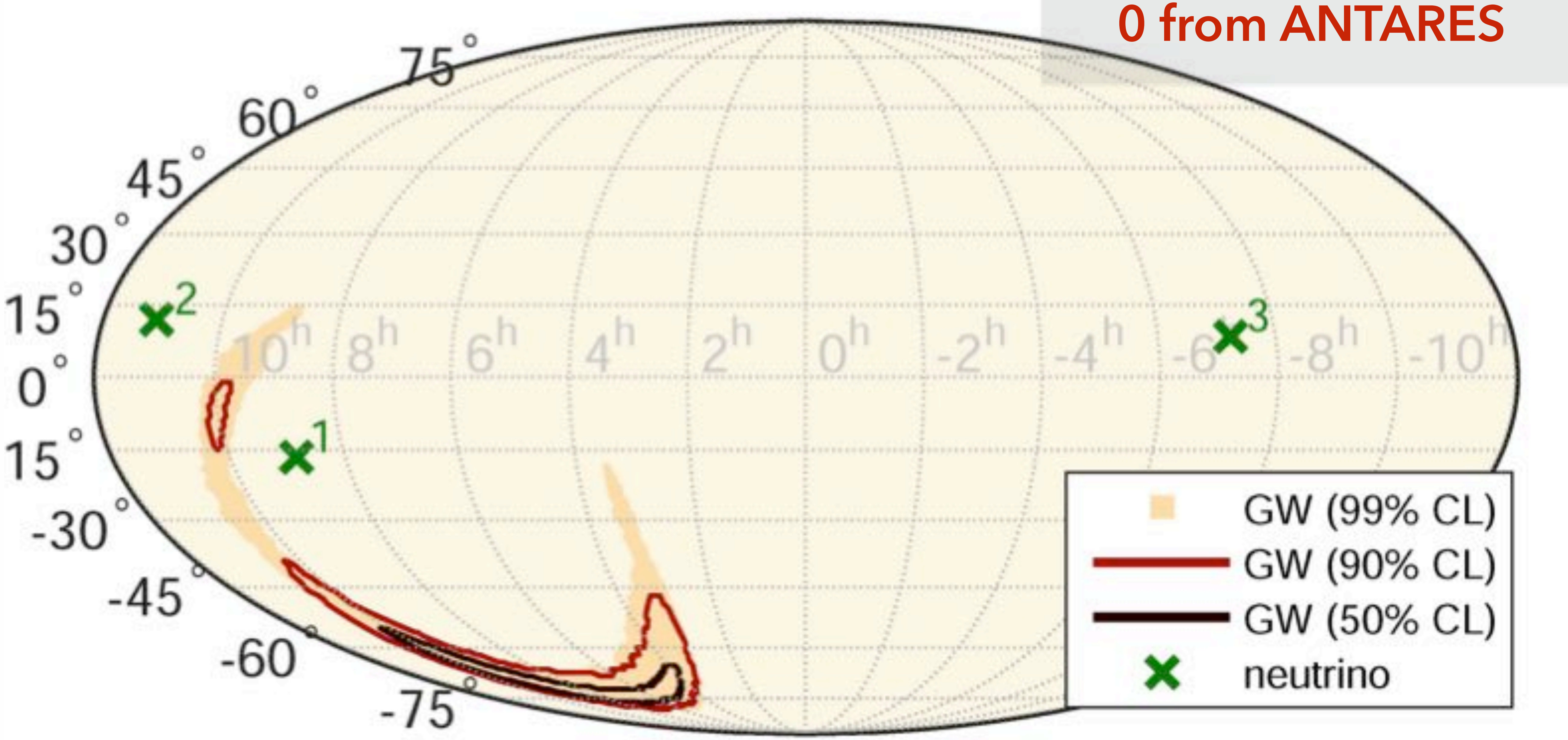
Baret et al., Astrop. Phys., 2011, 35, 1-7

- ➜ Online ANTARES and IceCube data
- ➜ Event selection from neutrino point-source searches

Neutrino follow-up

Within ±500 s from GW alert

3 IceCube candidates
0 from ANTARES



➜ Consistent with the background expectations (4.4 events for IceCube; 10^{-2} for ANTARES)

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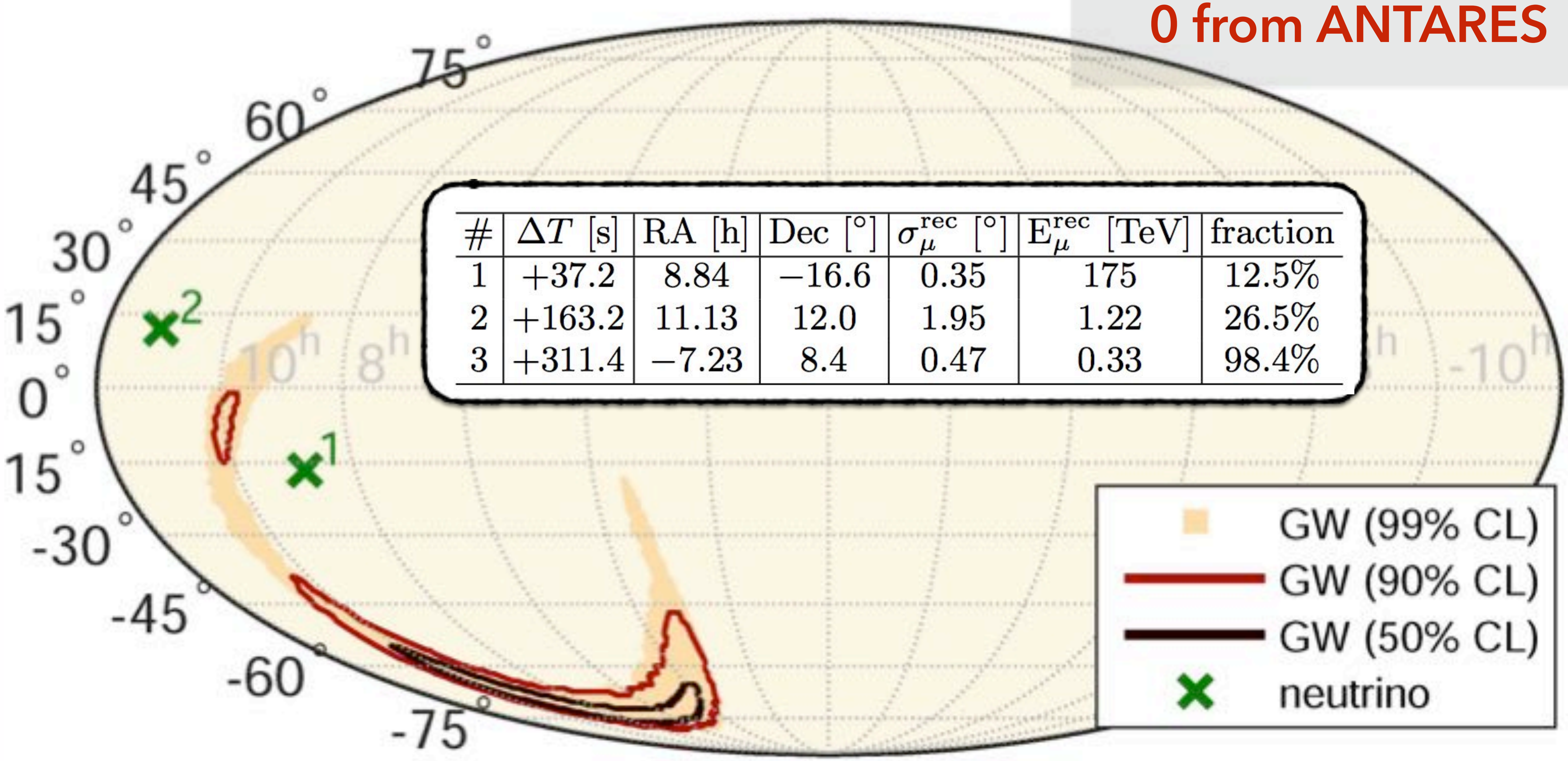
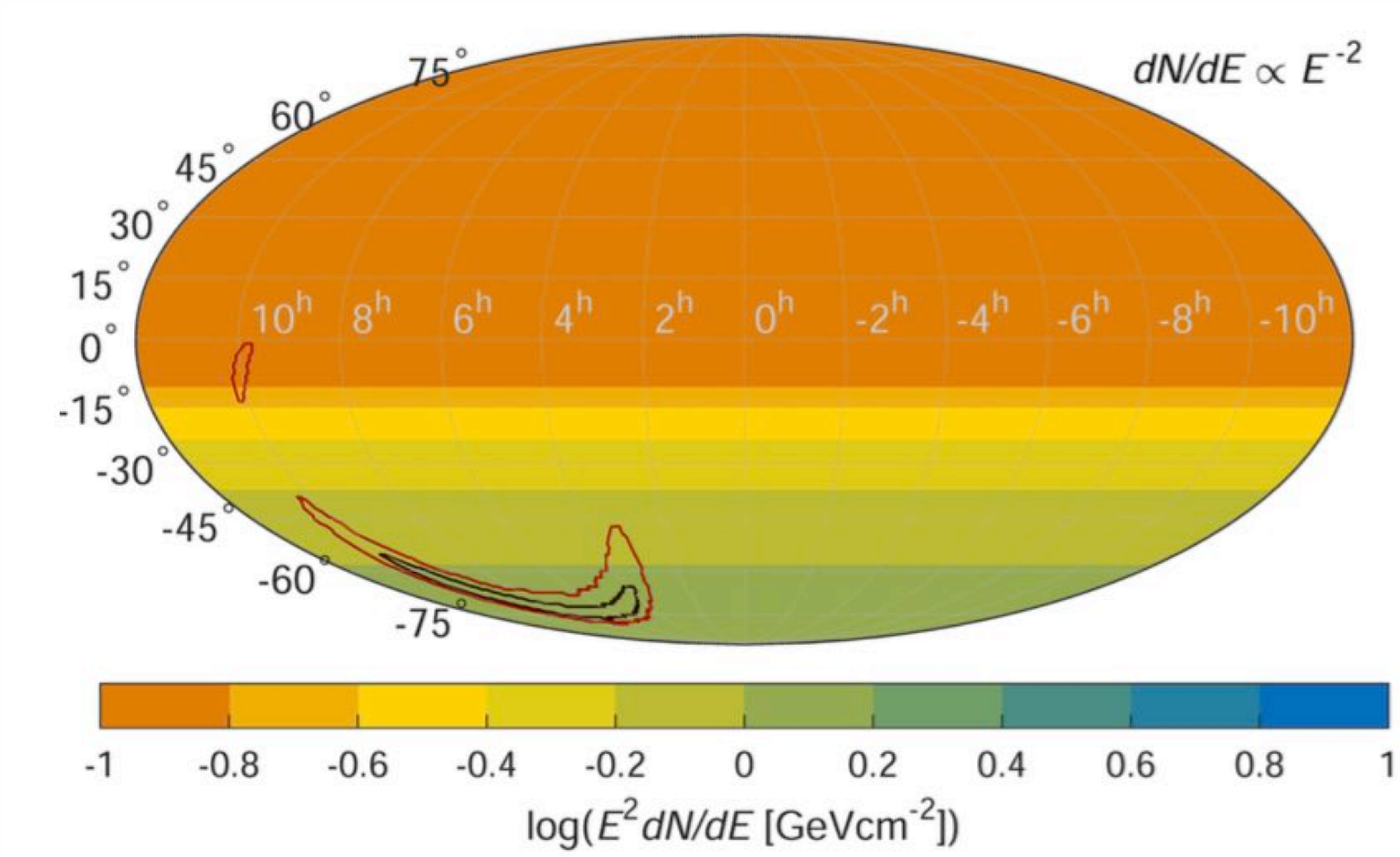


#	ΔT [s]	RA [h]	Dec [°]	σ_μ^{rec} [°]	E_μ^{rec} [TeV]	fraction
1	+37.2	8.84	−16.6	0.35	175	12.5%
2	+163.2	11.13	12.0	1.95	1.22	26.5%
3	+311.4	−7.23	8.4	0.47	0.33	98.4%

➜ Consistent with the background expectations (4.4 events for IceCube; 10^{-2} for ANTARES)

Neutrino follow-up

90% upper limit on the spectral fluence



http://arxiv.org/abs/1602.05411

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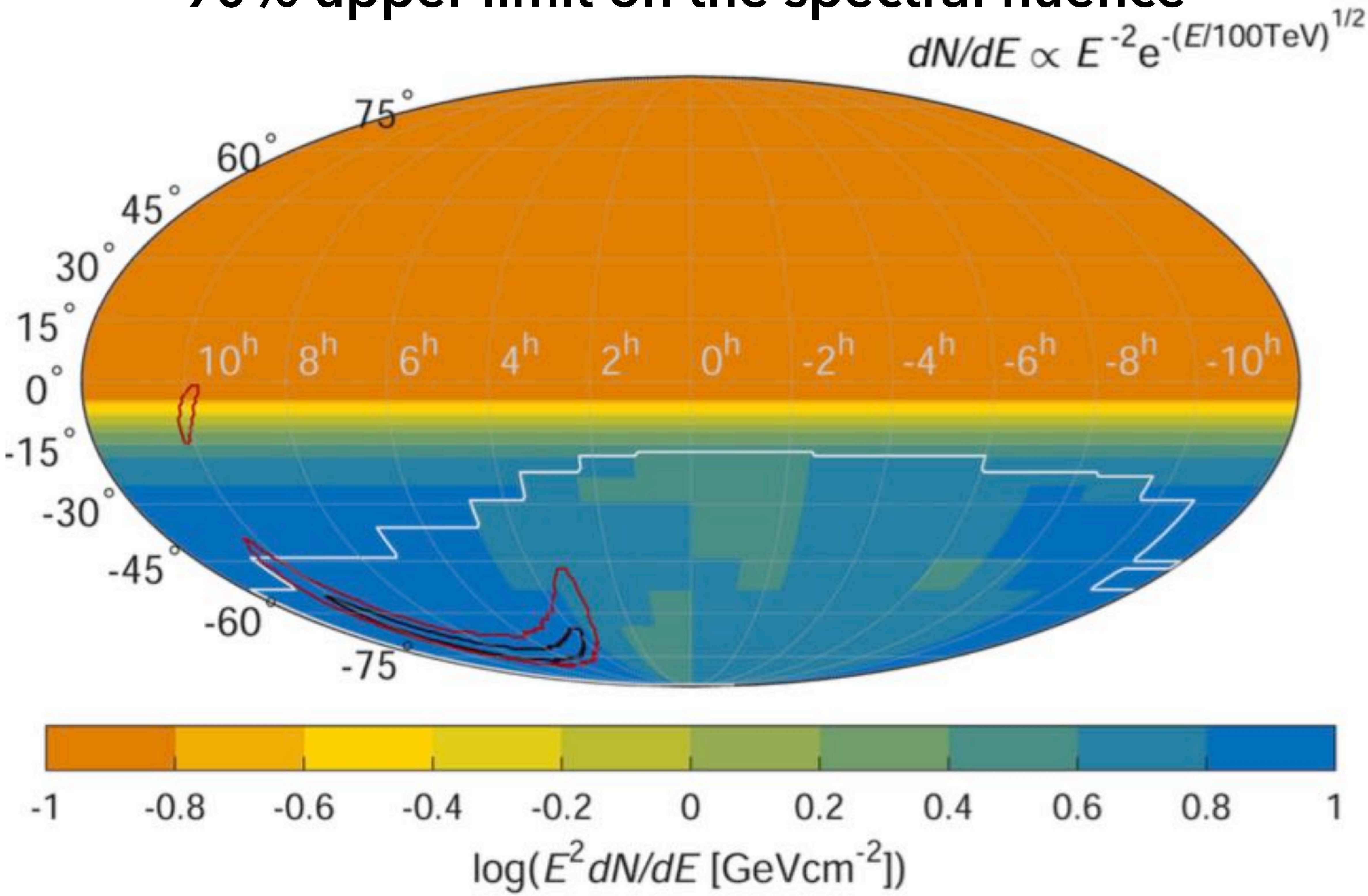

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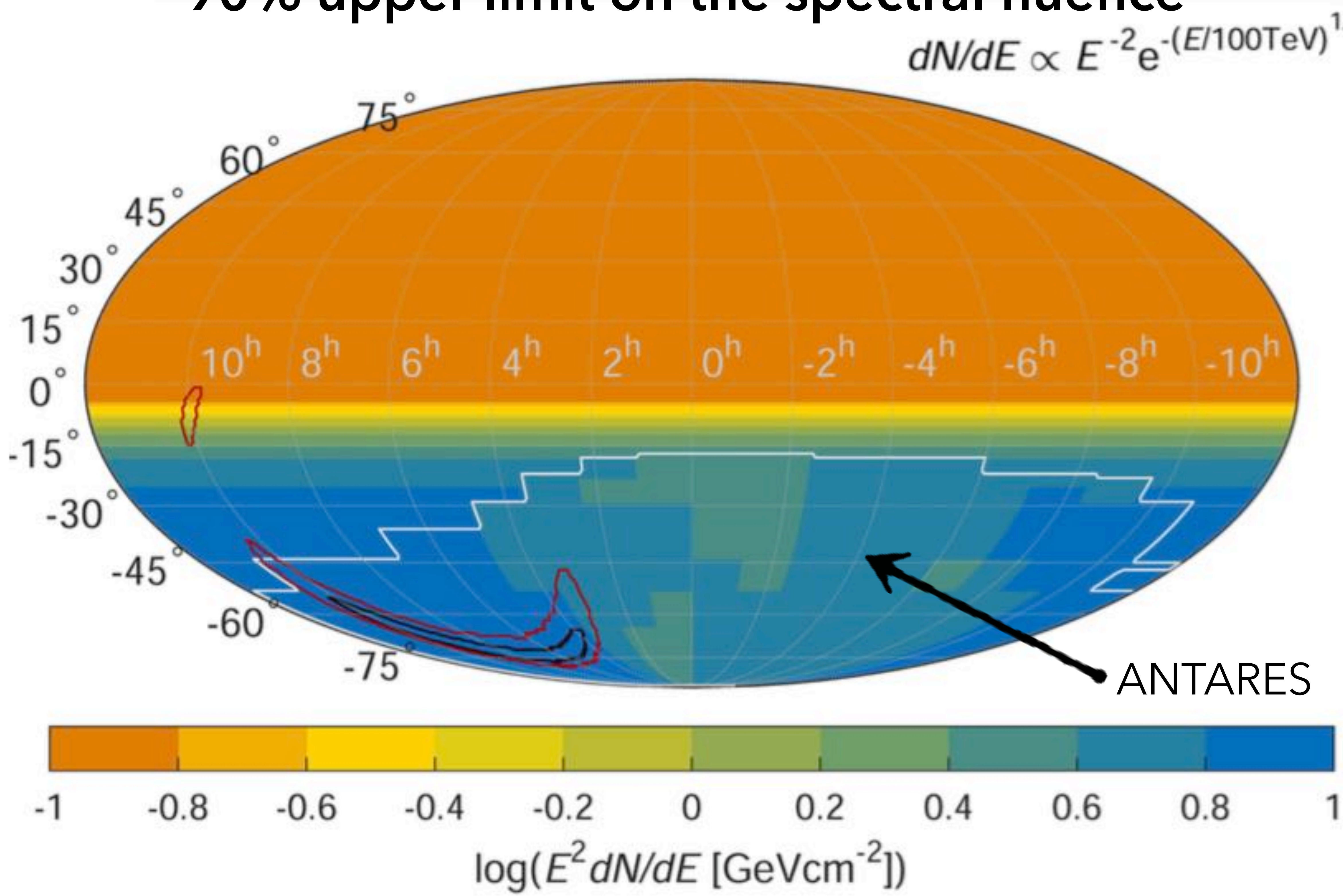

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Neutrino follow-up

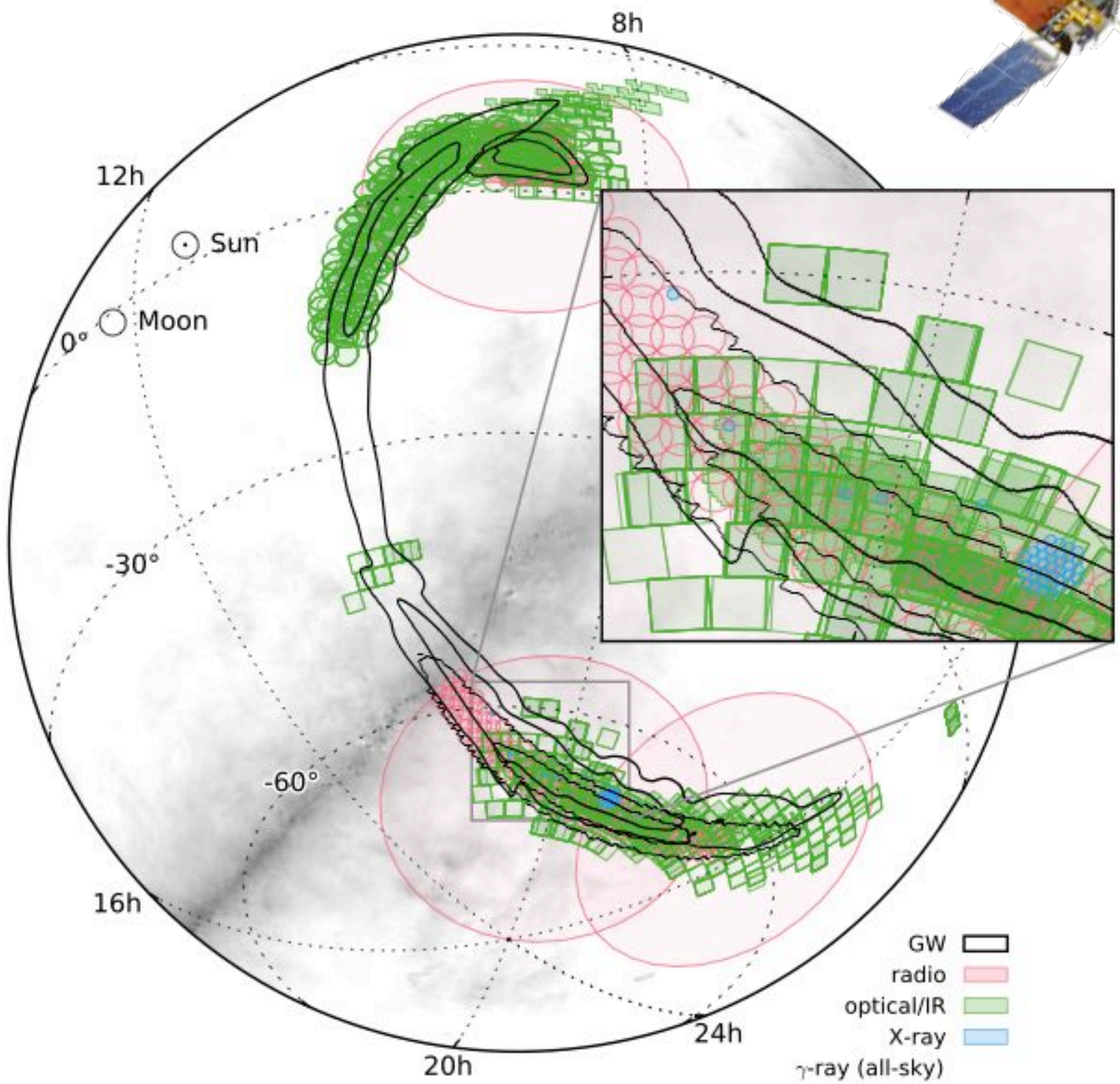
Constraints on the total energy emitted in neutrinos

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

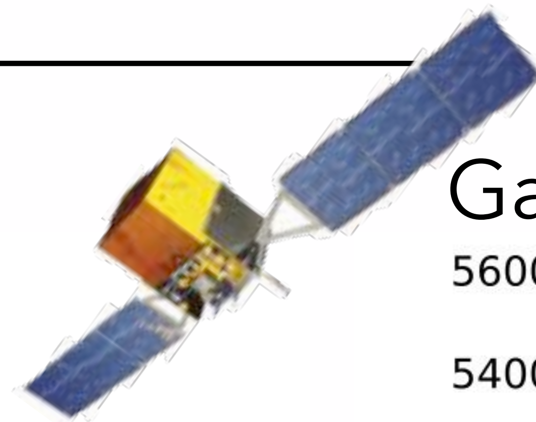
at $d=410^{+160}_{-180}$ Mpc

- Energy radiated in GW: ~5 x 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)

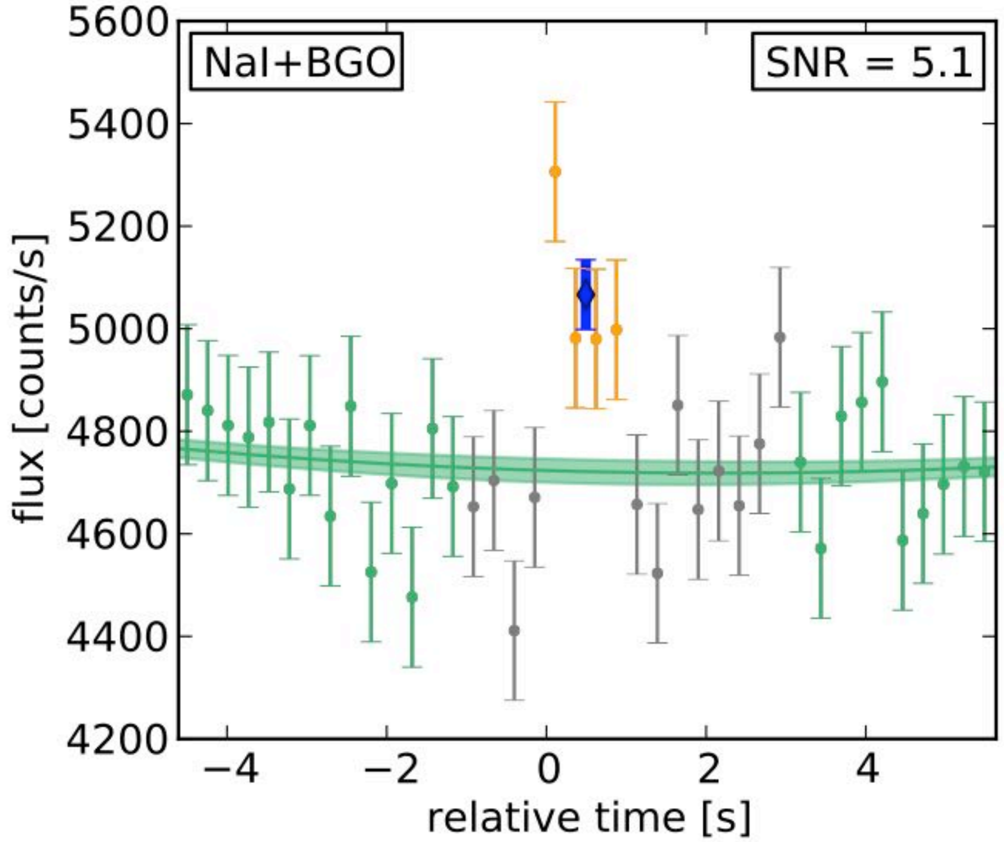
Electromagnetic follow-up



Abbott et al., 2016, ApJL (arXiv:1602.08492)



Gamma-ray counterpart ?



Connaughton et al., 2016, ApJL, arXiv:1602.03920

Neutrino angular error : <0.5°²
GW angular error : ~100°²

⇒ Neutrino counterpart could constrain the position of the GW event on the sky !

What's next ?

- First neutrino follow-up
- Thanks to previous GW+ HEN studies (e.g. ANTARES/LIGO-Virgo 2013)
- O2 LIGO+Virgo about to start
- Expected detection rate ~2–400 Gpc^{-3} yr^{-1}
- Coincident neutrino/GW detection ?
- Can significantly constrain the GW source position
- Would open a new era

Back-up

Multi-messenger program

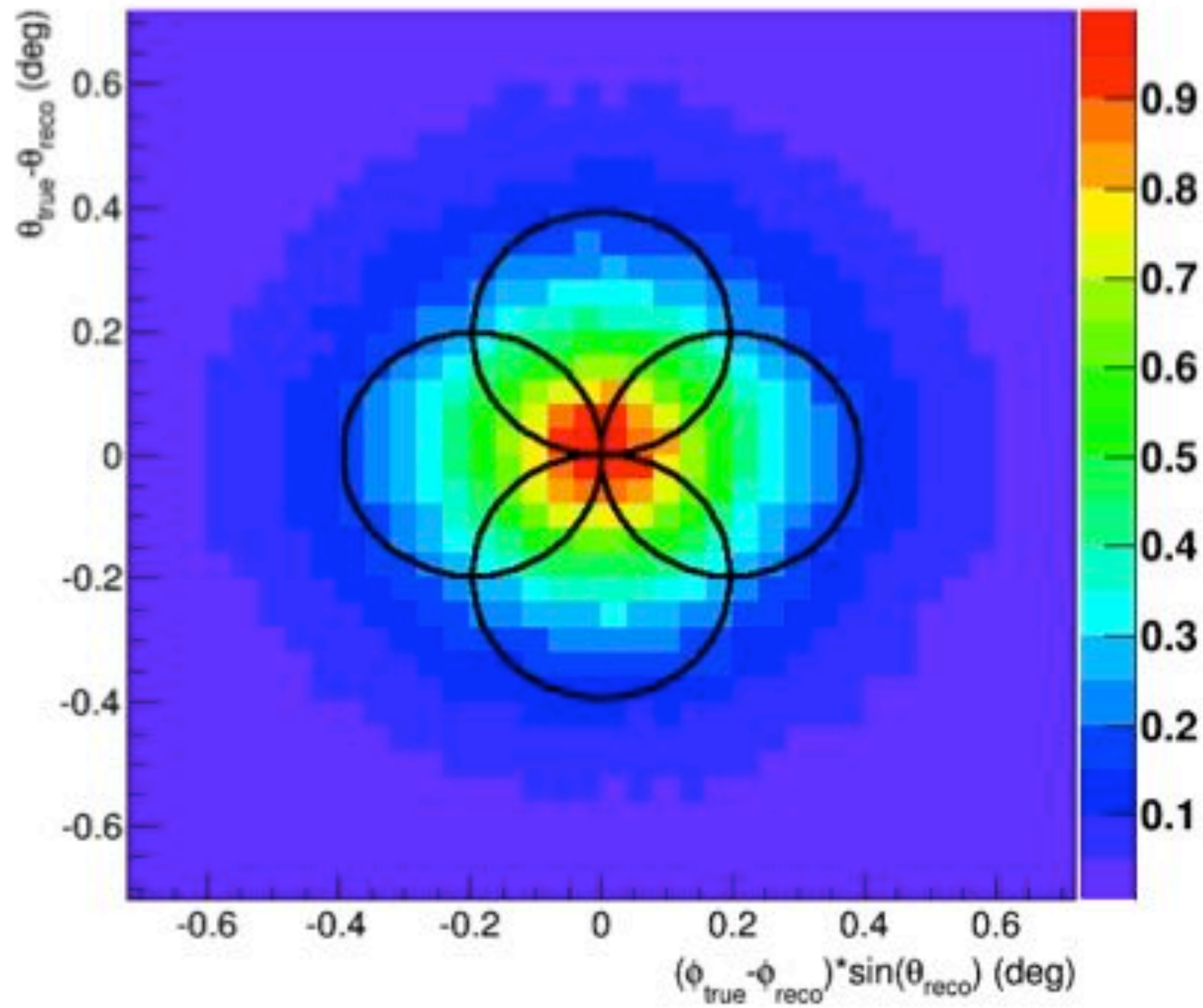


Figure 8. Each *Swift*-XRT observation of an ANTARES trigger consists of 4 tiles (black circles), which covers an area of radius of ∼ 0.4°. With such a mapping, 72% of the the bi-directional uncertainty of a TAToO alert is covered.

Adrián-Martinéz et al, JCAP 02(2016)062

Multi-messenger program

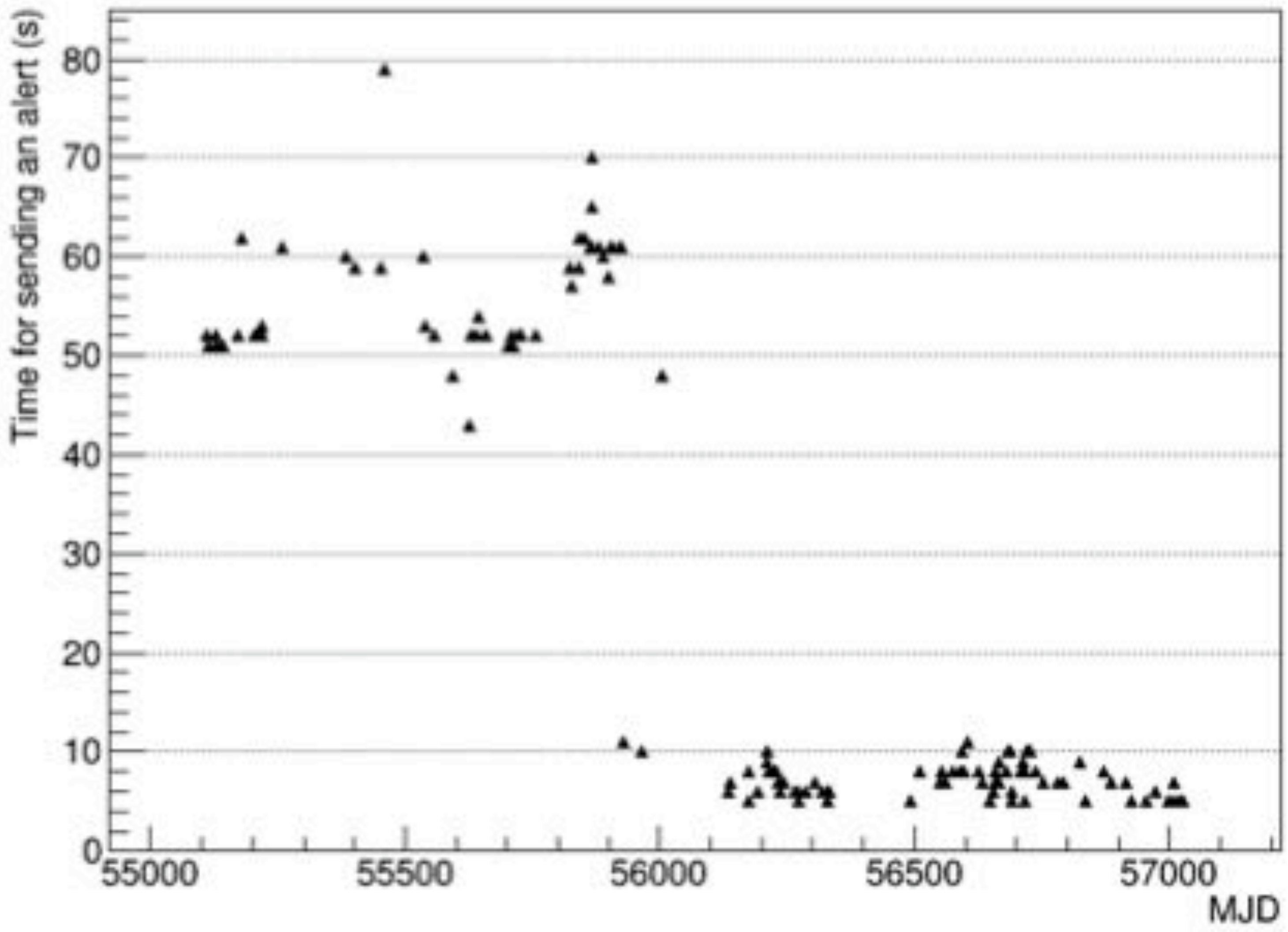


Figure 3. Distribution of the delay between the time of the neutrino detection and the time at which the alert message is sent for the 150 triggers. The step from 50 to 5 seconds beginning of 2012 corresponds to an upgrade of the ANTARES DAQ system.

Adrián-Martinéz et al, JCAP 02(2016)062

Multi-messenger program

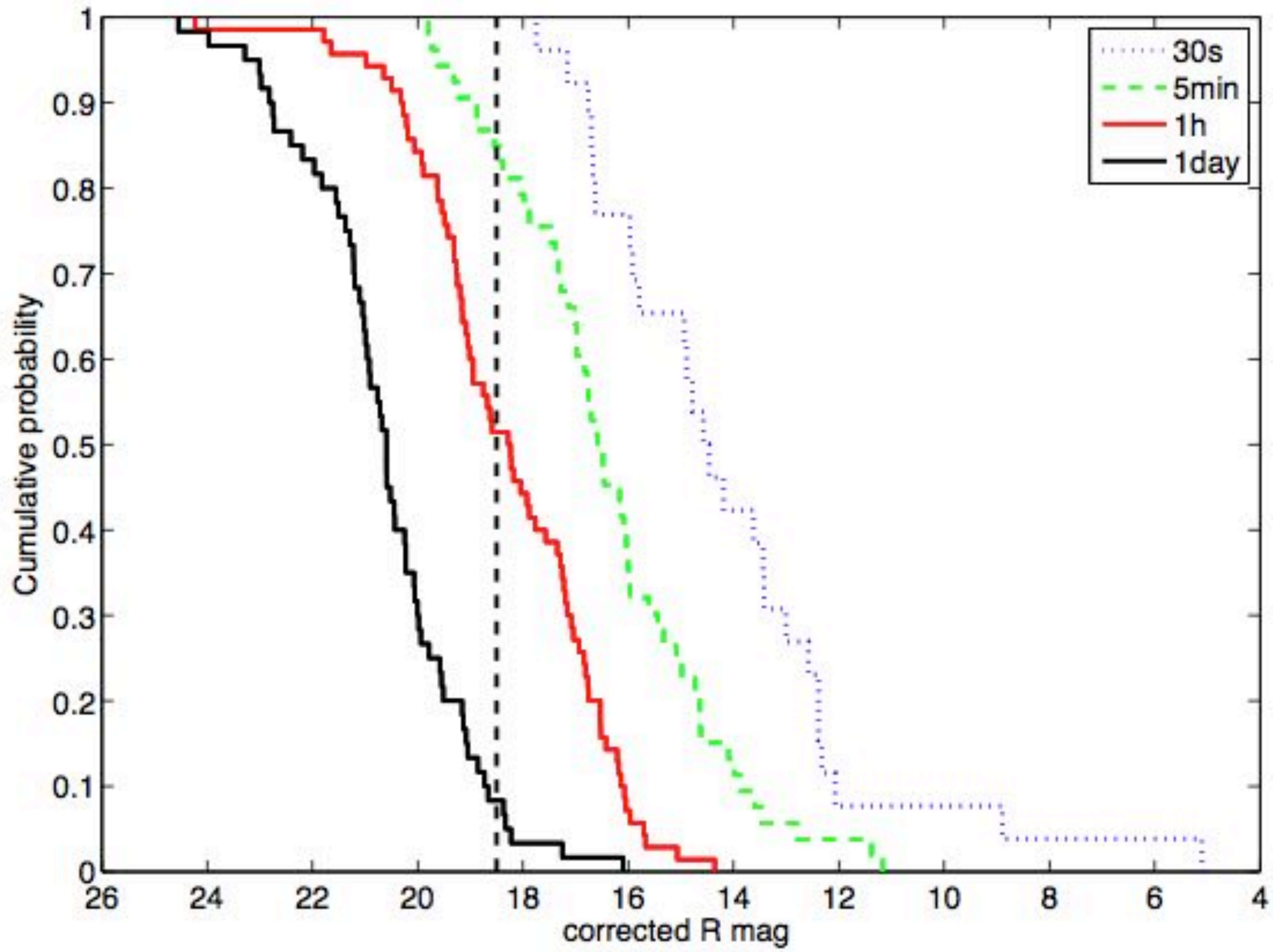


Figure 10. Cumulative distribution of afterglow magnitudes for 301 detected GRBs (figure 9). Each line corresponds to different times after burst. The vertical dashed line represents the limiting magnitude of the optical telescopes.

Adrián-Martinéz et al, JCAP 02(2016)062

Multi-messenger program

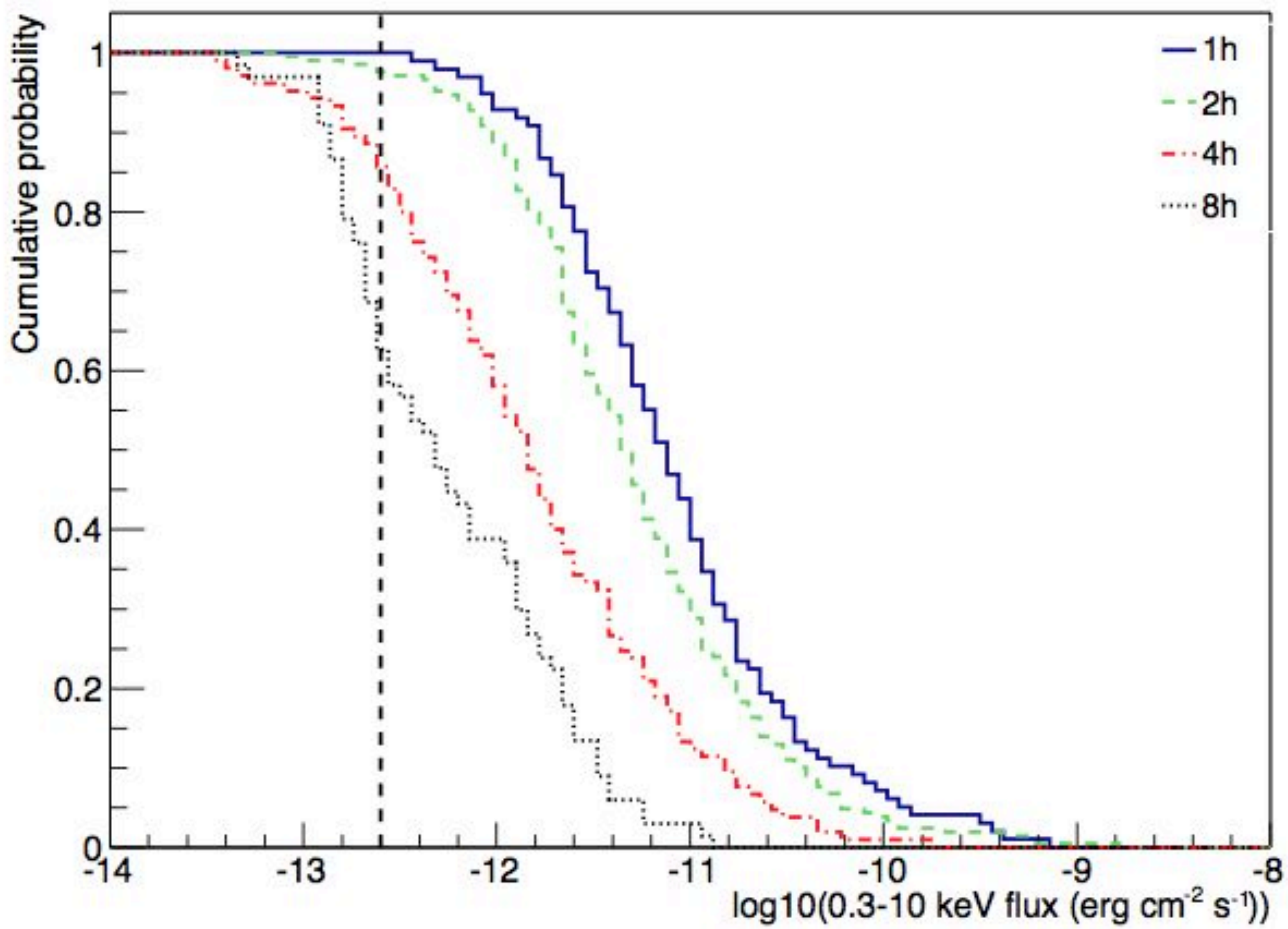


Figure 12. Cumulative distribution of X-ray afterglow magnitudes for 689 GRBs detected by the *Swift*-XRT since 2007. Each line represents different times after bursts. The vertical dashed line represents the sensitivity reached with a 2 ks exposure.

Multi-messenger program

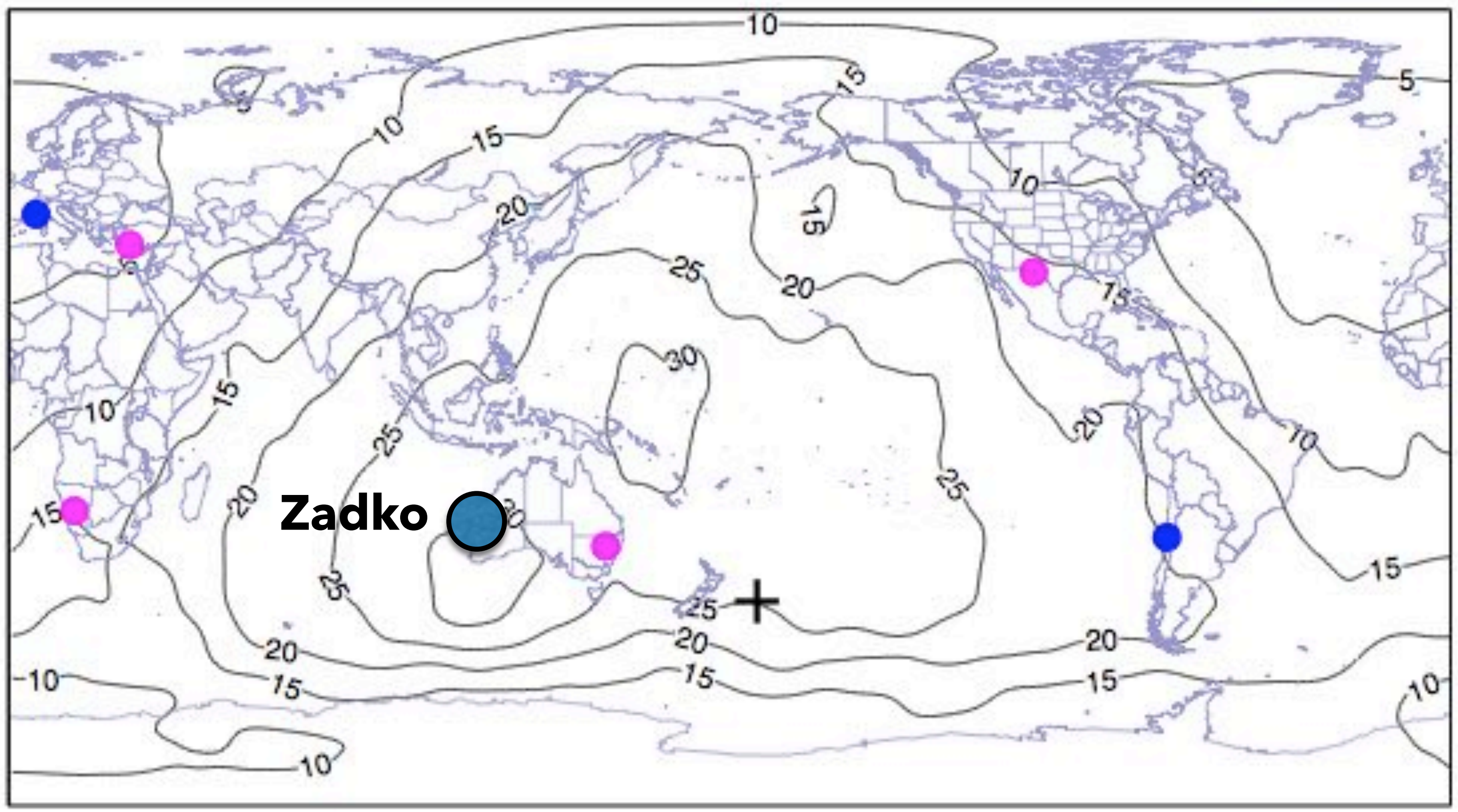


Figure 5. Probability to observe immediately an ANTARES neutrino alert as a function of the location of a telescope in the world. To be observable by the telescope, the neutrino direction should have an elevation above horizon and should happended during the night. To compute the contours as percentage, the visible areas of 140 ANTARES alerts are superposed. 30 means that 30 percents of the alerts (i.e. 42 alerts) were visible immediately at that place. Blue and magenta points are the locations of TAROT and ROTSE telescopes respectively. The black cross indicates the antipodal point of the ANTARES experiment.

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Spectral fluence U.L.

Energy range	Limit [GeV cm^{-2}]
100 GeV – 1 TeV	150
1 TeV – 10 TeV	18
10 TeV – 100 TeV	5.1
100 TeV – 1 PeV	5.5
1 PeV – 10 PeV	2.8
10 PeV – 100 PeV	6.5
100 PeV – 1 EeV	28

TABLE II. Upper limits on neutrino spectral fluence ($\nu_\mu + \bar{\nu}_\mu$) from GW150914, separately for different spectral ranges, at Dec $= -70°$. We assume $dN/dE \propto E^{-2}$ within each energy band.

IceCube candidate neutrinos

1) p-value of observing 3 background events when expecting 4.4 :

$$1 - F_{\text{pois}}(N_{\text{observed}} \leq 2, N_{\text{expected}} = 4.4) = 0.81$$

2) Most significant event :

#	ΔT [s]	RA [h]	Dec [°]	σ_μ^{rec} [°]	$\text{E}_\mu^{\text{rec}}$ [TeV]	fraction
1	+37.2	8.84	−16.6	0.35	175	12.5%
2	+163.2	11.13	12.0	1.95	1.22	26.5%
3	+311.4	−7.23	8.4	0.47	0.33	98.4%

proba. that at least one candidate (out of 3) has an energy high enough to make it appear even less background-like : $1 - (1 - 0.125)^3 \approx 0.33$

3) Position in the sky :

$\Omega_{\text{gw}} = 590\,\text{deg}^2$ (90% C.L. skymap) and then $\Omega_{\text{gw}}/\Omega_{\text{all}} \approx 0.014$

Proba. that at least one of the 3 candidates has a position consistent with 90% C.L. skymap :

$$1 - (1 - 0.014)^3 \approx 0.04$$

Fluence definition

Fluence = flux integrated over a certain emission period of interest (useful for transient phenomena)

- Spectral fluence : $\frac{\mathrm{d}N}{\mathrm{d}E} = \phi_0 E^{-2}$

- Spectral fluence normalisation : $\phi_0 = \frac{\mathrm{d}N}{\mathrm{d}E} E^2$

- Energy fluence : $\mathcal{F} = \int_{E_{min}}^{E_{max}} E \mathrm{d}N = \int_{E_{min}}^{E_{max}} E \phi_0 E^{-2} \mathrm{d}E$