The MAGIC Transient Multi-Messenger Program

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LAPP

on behalf of the MAGIC Collaboration

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Outline

- From time domain to multi-messenger astrophysics
- The MAGIC Telescopes
  - Experience gained with GRB
- MAGIC multi messenger programs
  - GW follow-up
  - Neutrino astronomy
- Conclusion
Transient events are relatively common in HE astrophysics.

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>DURATION</th>
<th>ENERGY RELEASE</th>
<th>ENERGY SOURCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGR</td>
<td>msec-sec</td>
<td>$10^{44}$ erg</td>
<td>B-field</td>
</tr>
<tr>
<td>GRB</td>
<td>msec-min</td>
<td>$10^{52-54}$ erg</td>
<td>Gravity (?)</td>
</tr>
<tr>
<td>TDE</td>
<td>min-months</td>
<td>$10^{52}$ erg</td>
<td>Gravity</td>
</tr>
<tr>
<td>SN/Nova</td>
<td>min-years</td>
<td>$10^{44}$ erg</td>
<td>Gravity/nuclear</td>
</tr>
<tr>
<td>AGN</td>
<td>hrs-days</td>
<td>$10^{43}$ erg/s</td>
<td>Gravity</td>
</tr>
</tbody>
</table>

Some definitions:

**HE**: 50 MeV – 50 GeV

**VHE**: 50 GeV – 10 TeV

Their detection in the VHE band is still an open question.
The VHE «transient» sky

«Transient non-electromagnetic» astronomy:

• HE neutrino
• UHECR
The VHE «transient» sky

«Transient non-electromagnetic» astronomy:

- HE neutrino
- UHECR
- GW counterpart
IACT for time-domain astronomy

Why IACT?

Much better instrument in the 10-100 GeV range
(overlapping region with space-based telescopes)

- Larger effective area & photon statistics
- Good sensitivity

\[
\text{Fermi-LAT} \quad 1 \text{ hour} \\
\text{CTA} \quad 10 \text{ years}
\]

Funk & Hinton, 2012
The MAGIC telescopes

- Roque de Los Muchachos Observatory, (2200 m)
- 2 x 17 m IACT
- Sensitivity (50h; 5σ) \(\sim 0.66\%\) Crab above 220 GeV
- Threshold energy at low zenith angle: \(\sim 50\) GeV
- Fast pointing speed: \(\sim 30\) s for 180°
- Dedicated KOP on GRB follow-up

\[\text{Preliminary Spectral Index} \sim 4\times\text{improvement in the last decade}\]
\[\rightarrow 10\times\text{in the lowest energy side}\]
The MAGIC telescopes

Since the beginning, MAGIC was equipped with a dedicated GRB alert system

- Recently adapted for a multi-messenger approach
- Works ongoing for implementing VOEvent standard

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>MESSENGER</th>
<th>RECEIVED</th>
<th>AUTOMATIC REPOINTING</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRB</td>
<td>X-rays/γ-rays</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>SGR/AXP</td>
<td>X-rays/γ-rays</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>AGN (FLARES)</td>
<td>γ-rays</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>GW</td>
<td>GW</td>
<td>yes</td>
<td>planned</td>
</tr>
<tr>
<td>Neutrino</td>
<td>ν</td>
<td>yes</td>
<td>planned</td>
</tr>
<tr>
<td>FRB</td>
<td>radio</td>
<td>planned</td>
<td>planned</td>
</tr>
</tbody>
</table>
MAGIC experience in GRB

Still poorly-populated region (~10% of GRBs)

\[ z \sim 1 \text{ is not a limit anymore!} \]

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>REDSHIFT</th>
<th>DISCOVERER</th>
<th>YEAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>B 0218+35</td>
<td>0.944</td>
<td>MAGIC</td>
<td>2014</td>
</tr>
<tr>
<td>PKS 1441+25</td>
<td>0.939</td>
<td>MAGIC</td>
<td>2015</td>
</tr>
<tr>
<td>3C 279</td>
<td>0.536</td>
<td>MAGIC</td>
<td>2006</td>
</tr>
</tbody>
</table>

- **Dedicated alert system for GCN com.**
  - Zenith < 60°
  - Moon distance > 30°
  - Sun zenith > 103°
  - + Fermi-GBM filters

- **GRB Alert rate**
  - ~7/8 GRB follow-up/year
  - + 1/2 GRB (GBM)
  - Duty cycle ~ 10% (~100 GRB so far)
  - + Late Time Observations

MAGIC almost doubled the VHE horizon in the past 3 years

30% in z<1.5 range
MAGIC experience in GRB/transient

Some scientific outputs:

**GRB 090102**

- **Synch + SSC model**

\[
\begin{align*}
E_{52} &= 4.5; \ T=T_0 + 4 \ \text{ks} \\
\varepsilon_e &= 0.1; \ \varepsilon_B = 0.01 \\
z &= 1.547; \ n = 1 \ \text{cm}^{-3}
\end{align*}
\]

Zhang & Mészaros, 2001

\[
\begin{align*}
\nu_{m}^{\text{Sc}} &= 1.3 \times 10^{22} \left(\frac{\varepsilon_e}{\varepsilon_B}\right)^4 \left(\frac{p-2}{p-1}\right) \\
\times \frac{E_5^{3/4}n^{-1/4}t_h^{-9/4}}{(1+z)^{5/4}} \left(1+z\right)^{5/4} \\
\nu_{c}^{\text{Sc}} &= 1.2 \times 10^{25} (1 + Y_e)^{-4} \\
\times \frac{E_5^{5/4}n^{-9/4}t_h^{-1/4}}{(1+z)^{-3/4}} \left(1+z\right)^{-3/4}
\end{align*}
\]


**Sw J1644+57**

- **SED modeled in Burrows et al. 2011**

Very High Energy Observation of the peculiar transient event SwJ1644+57 with the MAGIC telescopes and AGILE


\[
\begin{align*}
\tau_{\gamma\gamma} &\approx 10^4 \left(\frac{\nu_{1/3}}{t_{\text{var}}}\right)^{-10/3} \\
\delta &\lesssim 50 \left(\frac{\nu_{1/3}}{t_{\text{var},2}}\right)^{3/10}
\end{align*}
\]

MAGIC ULs \(\tau_{\gamma\gamma} > 10\)

\[XRT + BAT (31 h) \]
\[XRT (4.5 \text{ days}) \]
\[XRT (6.5 - 9.5 \text{ days}) \]
\[TNG (2.5 & 4.5 \text{ days after trigger}) \]
\[Fermi (28/3-4/4) \]
\[AGILE (2 & 5 \text{ days integration}) \]
MAGIC GW follow-up program

Coalescence of compact objects (CBC)
- Known waveform
- Energy emitted in GW: $10^{-2} M_\odot c^2$
- Possible association with short GRB (hints of macro-/kilonovae)
  - Similar dynamic time-scale
  - No association to SN
  - Older population in galaxy

Core-collapse of massive stars
- Possible association to long GRB (progenitors type Ic SN)

Can we have EM emission from BH-BH mergers?
- Fermi/GBM detected a weak sGRB 0.4 seconds after the 1\textsuperscript{st} GW detection. Not confirmed by INTEGRAL $\Rightarrow$ A hint, but not significant enough.

Many theories:
- Two BHs merging inside a star Loeb ApJL 2016
- Binary system massive star – BH, 2\textsuperscript{nd} BH formation Janiuk+ 2016
- .....
Electromagnetic (EM) follow up observations will play a key role in localizing the GW source and constraining the physical nature of these events.

**IACT are suitable instruments for VHE follow up**

**Pro:**
- GW transients are currently detectable in the nearby universe $\lesssim 200$ Mpc
- GW mostly prominently expected from energetic transients

**Con:**
- Limited duty cycle

**Observationally:**
- Fast slewing, big effective area, good sensitivity
- MAGIC has a good expertise on GRB hunt to be exploited!
- VHE counterpart: if any it puts strong constraint on model
- VHE U.L. important to determine cut-off in extrapolated X-ray and HE $\gamma$-ray spectra
MAGIC GW follow-up program

Problem:
- No coordinates in the alert (Prob. Skymap is received)
- Large uncertainties

• An example iPTF on G194575 – 14 hours after the alert
• 161 fields 1114 square degrees!
• ~40 transients
The MAGIC follow up of GW151226

**Trigger G211182** identified by the online Burst analysis

2015-12-26 03:38:54 UTC  **GW151226**

T\(_{\text{notice}}\): 2015-12-27 17:40:00 UTC  
T\(_{\text{start}}\): 2015-12-28 21:00:00 UTC

- **Probability skymap:**
  - median 50% credible region \(~ 430\,\text{deg}^2\)
  - 90% credible area \(~ 2200\,\text{deg}^2\)

- **False Alarm Rate (FAR):**
  - passing threshold \(~ 1/\text{month}\)
  - later refined to \(< 1/100\,\text{years}\)
The MAGIC follow up of GW

Status after O1
- MAGIC signed in 2014 an MoU with LVC to join the follow-up program of GW event candidates
- Four 2.5 x 2.5 deg region pointed. No excesses found

GW 1: PGC1200980 (OT MASTER GCN#18729)
RA,Dec (J2000): 02:09:05.8, +01:38:03.0
Duration: 42 min

GW 2: strip from GW map
RA,Dec (J2000): 02:38:38.93, +16:36:59.27
Duration: 56 min (moonlight conditions)

GW 3: Field VST (GCN#18734)
Duration: 28 min (moonlight conditions)

GW 4: Field VST (GCN#18734)
Duration: 30 min (moonlight conditions)
The MAGIC follow up of GW

Status for O2 (6-25 alerts expected)

- For O2 run we are discussing our reaction and pointing criteria:
  - Immediate repositioning/late follow up
  - Scanning mode? n pointings? association mode? (closebygalaxies)
  - Dedicated analysis tools
The MAGIC neutrino program

MAGIC programs on neutrino

- External alerts/targets
- Exotic $\tau$-neutrino

September 2015:
- ANTARES detected «bright» neutrino
- Possible counterpart from *swift*

- 4 hours of observation
- Very high zenith ($65^0 - 70^0$)

MAGIC observation of the ANTARES-detected neutrino sky region

ATel #6203: Razmik Mirzoyan on behalf of the MAGIC Collaboration on 21 Oct 2015: 18:12 UT

Credentialed Certification: Razmik.Mirzoyan@mpi.mpg.de

Subjects: X-ray, Gamma Ray, $>$GeV, TeV, VHE, UHE, Neutrinos, Cosmic Rays

The MAGIC telescopes performed follow-up observations in the very high energy band (VHE, $E>$100 GeV) of a $\sim$3 degree-diameter sky region centered at the proposed X-ray counterpart of the ANTARES-detected neutrino event (#ATel 7957). MAGIC observed the source under non-optimal conditions due to the large zenith angle (above 60 deg), starting from Sep. 3 at 20:54 UT, 2.5 days after ANTARES detection. Observations were carried out for 6 nights, ending on Sep. 8, and collecting a total on-source exposure of 4 hours. We neither detected significant emission from the location of the X-ray source, nor found any other gamma-ray source within the $\sim$3 degree field of view of MAGIC. The preliminary analysis centered on the proposed X-ray counterpart gave an integral flux upper limit at 95 % c.l. of $4.7e^{-12} cm^{-2} s^{-1}$ above $E>$500 GeV, which corresponds to 8% of the Crab Nebula flux above the same energy, assuming a Crab-like spectral index. The nightly light curve above 300 GeV did not show any hint of a transient signal. The MAGIC contact persons for these observations are R. Mirzoyan (razmik.mirzoyan@mpi.mpg.de), A. Carosi (alessandro.carosi@oa-roma.inaf.it), K. Noda (knoda@mppmu.mpg.de) and G. Pedaletti (giovanna.pedaletti@desy.de). MAGIC is a system of two

No significant detection
UL: $\sim$8% CU $E>$500 GeV

- Earth skinned technique for PeV $\tau$-neutrino
- Positive feasibility study: first results soon!
The MAGIC neutrino program


No clear correlation with known astrophysical sources, nor with Galactic plane.

Extragalactic origin?

What can be the sources of these neutrinos? Are they transient or steady? Hadronic emission?

- Observation of archival HESE directions
- Real-time follow-up

IceCube events observed by MAGIC

A. Carosi – MAGIC Multi Messenger Transient Program – La Thuile, 2017 March 18-25
The MAGIC neutrino program

**HESE-37**
(deposited energy 30 TeV)

- 7.5 h in Jan/feb 2016
- Zenith 8-30 deg
- E > 120 GeV
- UL: 0.7-4.0 \( \times 10^{-11} \) cm\(^{-2}\) s\(^{-1}\)
  (95% CL - 1-10% CU)

**HESE-38**
(deposited energy 200 TeV)

- 5.7 h in Feb/Mar 2016
- Zenith 15-50 deg
- E > 120 GeV
- UL: 0.9-3.9 \( \times 10^{-11} \) cm\(^{-2}\) s\(^{-1}\)
  (95% CL - 2-10% CU)
The MAGIC neutrino program

From Apr 2016 IceCube started to issue alerts through the GCN

<table>
<thead>
<tr>
<th>HESE 160427A</th>
<th>HESE 160731A</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 2 h taken on 2016/04/29 (T0+42h)</td>
<td>• 1.3 h taken on 2016/07/31 (T0+16h)</td>
</tr>
<tr>
<td>• Zenith 18-26 deg</td>
<td>• Zenith 45-65 deg</td>
</tr>
<tr>
<td>• Hot sopt @0.3 deg -&gt; 2.1 σ after trials</td>
<td>• Bad atmospheric conditions (Ethr = 600 GeV)</td>
</tr>
<tr>
<td>• Further analysis ongoing for ULs</td>
<td>• No signal (<a href="https://atel.psu.edu">ATel #9315</a>)</td>
</tr>
</tbody>
</table>

First results presented in summer conf:
* K. Satalecka@Gamma16
* K. Noda@TeVPa 2016
* D.Gora@Neutrino2016
Conclusion

• Gamma-ray photons in the > 10 GeV energy band offer a powerful diagnostic tools for the emission processes and physical conditions of extreme transient events in a multi-messenger framework, yielding rich scientific rewards.

• Observations in both electromagnetic and non-electromagnetic channels are becoming an «hot topics» for MAGIC and other facilities and the follow up of GW and neutrino currently has the highest priority (even within CTA)

• In the last year, the alert system has been tuned in order to manage alerts of these types although further developments are still ongoing

• Dedicated GW & neutrino follow-up programs are currently on-going and MAGIC started to collect data. Although a detection at VHE is still missing, MAGIC is ready for playing its role!