I Multi-Messenger (MM) astronomy
II The mass of the photon
I Multi-Messenger (MM) astronomy
AMON seeks to perform a **real-time correlation** analysis of the high-energy signals across all known astronomical messengers - photons, neutrinos, cosmic rays, and gravitational waves - in an effort to:

1. Enhance the combined sensitivity of collaborating observatories to **astrophysical transients** by searching for coincidences in their **sub-threshold** data; and
2. Enable rapid follow-up imaging or archival analysis of the putative astrophysical sources.

http://www.amon.psu.edu
AMON alert system

Two servers redundancy.

The system will receive the incoming event, process it and write the event to the AMON database. The incoming event also triggers a search algorithm, which looks for coincidences in some time range \([t_1, t_2]\) where \(t_2\) is typically the time stamp of the new event. If a significant correlation is found, an AMON event is generated. Typically the significance of the alert will determine to whom it will be distributed.
AMON sub-systems

* Gravitational waves:
  Advanced LIGO, Virgo
* Neutrinos:
  ANTARES, IceCube
* HighEnergy observatories:
  Swift, Fermi satellites
* TeV gamma rays telescopes and observatories:
  HESS, VERITAS, MAGIC, HAWC

HAWC
High Altitude
Water Cherenkov

On the flanks of the Sierra Negra volcano near Puebla, Mexico.
4100 m altitude. Started March 2015.
AMON targets

Most likely MM transient sources:

* Active galactic nuclei (AGNs)
* Gamma-ray bursts (GRBs)
* Supernovae (SNe)
* White dwarves (WDs)
* Neutron stars (NSs).
<table>
<thead>
<tr>
<th>Event class</th>
<th>$\gamma$</th>
<th>$\nu$</th>
<th>$n$</th>
<th>gw</th>
<th>x</th>
<th>IR/O/UV</th>
<th>Radio</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-luminosity GRBs (HL-GRB)</td>
<td>✔</td>
<td>✔</td>
<td></td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Low-luminosity GRBs (LL-GRBs)</td>
<td>✔</td>
<td>✔</td>
<td></td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
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<tr>
<td>Short-hard GRBs (SHBs)</td>
<td>✔</td>
<td>✔</td>
<td></td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
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<tr>
<td>Choked jet SN</td>
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<td></td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
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<tr>
<td>Core-collapse SN</td>
<td>✔</td>
<td>✔</td>
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<td>Blazars</td>
<td>✔</td>
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<td>✔</td>
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<tr>
<td>Primordial black holes (PBHs)</td>
<td>✔</td>
<td>✔</td>
<td></td>
<td></td>
<td></td>
<td>✔</td>
<td>✔</td>
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<tr>
<td>Other exotica</td>
<td>✔</td>
<td>✔</td>
<td></td>
<td></td>
<td></td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>
Thresholds are set to have a decent Signal/Noise ratio. Sub-threshold events can be recovered by exploiting coincidences...

Example of data in IceCube. The normal threshold is 3 muons, to record the data.

Sub-thresholds can be 2 or even 1 muons.
Example: detectors A and B:

\[
\text{rate } R_{\text{detector A}} = 0.2 \text{ Hz} \\
\text{rate } R_{\text{detector B}} = 0.1 \text{ Hz} \\
\text{coincidence window } = 10^{-6} \text{ s}
\]

\[
\Rightarrow \text{random coincidence rate } \sim 0.2 \times 0.1 \times 10^{-6} = 2 \times 10^{-8}
\]

1 year = 3 $10^8$ s

\[
\Rightarrow 6 \text{ background events from random coincidences (false positive)}
\]
Considering the research areas in the sky, the False Positive (FP) rate is given by:

\[
R_{ab}^{(FP)} \approx \frac{R_a}{\Omega_a} \frac{R_b}{\Omega_b} \Delta T \langle \Omega_{ab} \rangle \Delta \Omega_{ab},
\]

\( R_{a,b} \) are the sub-threshold rates for observatory a and b
\( \Omega_{a,b} \) are the fields of view
\( \Delta t \) the time of research window
\( \langle \Omega_{ab} \rangle \) is the time-averaged observation field
\( \Delta \Omega_{ab} \) is the search area for coincidences
N events per year  AMON

<table>
<thead>
<tr>
<th>Event Detection</th>
<th>IceCube</th>
<th>ANTARES</th>
<th>LIGO-Virgo</th>
<th>Auger</th>
<th>BAT</th>
<th>GBM</th>
<th>LAT</th>
<th>HAWC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above thresh.</td>
<td>~0</td>
<td>~0</td>
<td>~0</td>
<td>~0</td>
<td>~100</td>
<td>~250</td>
<td>~10</td>
<td>~10</td>
</tr>
<tr>
<td>Subthreshold</td>
<td>8.8 × 10⁴</td>
<td>2.9 × 10⁴</td>
<td>3.2 × 10³</td>
<td>2.4 × 10⁵</td>
<td>1.4 × 10⁵</td>
<td>3.1 × 10²</td>
<td>3.9 × 10⁴</td>
<td>2.6 × 10⁴</td>
</tr>
<tr>
<td>IceCube</td>
<td>30</td>
<td>1.5</td>
<td>35</td>
<td>1.8</td>
<td>11</td>
<td>10</td>
<td>24</td>
<td>6.5</td>
</tr>
<tr>
<td>ANTARES</td>
<td>1.5</td>
<td>0.5</td>
<td>12</td>
<td>1.1</td>
<td>0.7</td>
<td>3.5</td>
<td>7.1</td>
<td>0.6</td>
</tr>
<tr>
<td>LIGO-Virgo</td>
<td>35</td>
<td>12</td>
<td>N/A</td>
<td>8.4</td>
<td>53</td>
<td>0.6</td>
<td>16</td>
<td>10</td>
</tr>
</tbody>
</table>

3-fold coinc. 0.15 0.03 0.31

IceCube: threshold: 3 mu, sub-threshold:1 mu
IceCube neutrinos, HAWC TeV observatory, Pierre Auger cosmics (neutrons with very high Lorentz boost).

Primordial BHs (PBH) produced at the BigBang with M~ 5 \times 10^{14} g undergo explosive evaporation. Mass loss by Hawking radiation:

\[
\frac{dM}{dt} = -\frac{\alpha(M)}{G^2 M^2}
\]

Temperature will increase with time:

\[
T = \frac{1}{8\pi k_B} \frac{\hbar c^3}{GM}
\]

For a T above the QCD scale (200 MeV), quark and gluons are emitted which subsequently hadronize, producing hadrons, photons, neutrinos.

primordial BHs in AMON
primordial BHs in AMON

HAWC will be able to exclude almost the full possible range, but it might not be capable to distinguish the physical origin of possible detections.

AMON will allow different triggering conditions, to study the components of the candidate BH decay.

Effective volumes for multimessenger PBH search. Values are averaged over $4\pi$ sr, with only those regions of overlapping sensitivity contributing to each pairwise calculation.

<table>
<thead>
<tr>
<th>Observatories</th>
<th>Trigger conditions</th>
<th>$V_{SM}^{(eff)}$ [pc$^3$]</th>
<th>$V_{SUSY}^{(eff)}$ [pc$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A HAWC B</td>
<td>$n_\gamma \geq 20$</td>
<td>0.0374</td>
<td>0.245</td>
</tr>
<tr>
<td>A IceCube B</td>
<td>$n_\gamma \geq 1$</td>
<td>$n_\gamma \geq 13$</td>
<td>$9.8 \times 10^{-5}$</td>
</tr>
<tr>
<td>A IceCube B</td>
<td>$n_\gamma \geq 2$</td>
<td>$n_\gamma \geq 13$</td>
<td>$1.3 \times 10^{-6}$</td>
</tr>
<tr>
<td>A HAWC B</td>
<td>$n_\gamma \geq 13$</td>
<td>$n_n \geq 1$</td>
<td>$1.3 \times 10^{-7}$</td>
</tr>
<tr>
<td>A Auger B</td>
<td>$n_n \geq 1$</td>
<td>$n_\nu \geq 1$</td>
<td>$4.9 \times 10^{-9}$</td>
</tr>
<tr>
<td>A IceCube B</td>
<td>$n_\nu \geq 1$</td>
<td>$n_\nu \geq 1$</td>
<td>$4.9 \times 10^{-9}$</td>
</tr>
</tbody>
</table>
GRBs

Long-duration high-luminosity GRB
Seconds-minutes burst of gammas
z ~ 1-3  ~ 100 events/year
Believed to come from M > 25 solar-mass undergoing core collapse to a BH.
Collapsar model proven valid by the observation of the subsequent formation of a SN.

Most luminous transients E ~ 10^{51-52} erg, collimated ~5 degrees,

Internal-shock model:
relativistic jet  with Lorentz γ = 10^{2-3}

Fermi-accelerated electrons, in plasma shocks, with production of gammas by synchrotron and inverse Compton effects.
Shocks also accelerate protons, which will photo-produce pions. Pions will give neutrinos.
Neutrino-flux / gamma-flux ratio has been quantified (Guetta et al., arXiv:astro-ph/0302524 see later) and is used to set limits in IceCube data analysis.
GRBs

- A standard picture
- Fundamental Questions
  - Central engine?
  - Prompt emission?
  - Progenitor?
- BH and magnetar formation
- Extreme plasma physics
- Origin of UHECRs
- GRB-SN connection

Meszaros 2001
GRBs

Hypothesis on the central engine:

```
BH-torus
```

```
suspended accretion (magnetic field)
```

```
proto-magnetar
```

Probes:
- Direct probe by observation of GWs from the central engine
- Indirect by the MM approach
GRBs

**BH-torus:**
GW from non-axisymmetric instabilities

MBH ~ 10 $M_\odot$ and $M_{\text{disk}}$ ~ 1 $M_\odot$
detectable from 100 Mpc by advLIGO, VIRGO

**Protomagnetars:**
GW from misaligned rotation of distorted protomagnetars

arXiv 1012.0001v2
detectable from Virgo cluster by advLIGO
GRB

Internal/External shock model

The model open the possibility for particle acceleration by Fermi 1st order
GRB-UHECR hypothesis

Fermi acceleration of protons \( \varepsilon_p < e r B \)

Auger: E density UHECRs at \( 10^{20}\text{eV} \approx 2 \times 10^{-22} \text{erg cm}^{-3} \)

GZK distance \( \sim 50 \text{ Mpc} \) =>
CR emissivity \( \sim c \times 2 \times 10^{-22} \text{erg cm}^{-3}/50 \text{ Mpc} \sim 4 \times 10^{43} \text{erg Mpc}^{-3} \text{yr}^{-1} \)

which is \( \sim \)consistent with the observations
neutrino production in GRB

![Diagram of neutrino production in GRB]

- Photoproduction
- decay chain
- bulk Lorentz boost $O(100)$
neutrino production in GRB

D. Guetta et al.

Protons produce pions predominantly via

\[ p\gamma \rightarrow \Delta \rightarrow n\pi^+ \quad p\gamma \rightarrow \Delta \rightarrow p\pi^0 \]

cross-section

in the comoving frame, proton E threshold:

\[ \sigma_{\Delta} \sim 5 \times 10^{-28}\text{cm}^2 \]

\[ \epsilon'_p \geq \frac{m^2_{\Delta} - m^2_p}{4\epsilon'_\gamma} \]

in the observer frame

\[ \epsilon_p \geq 1.4 \times 10^{16} \frac{\Gamma_{2.5}^2}{\epsilon_{\gamma,\text{MeV}}} \text{eV} \]

resulting in a neutrino energy

\[ \epsilon_{\nu}(\text{eV}) = \frac{1}{4} \bar{x}_{p\pi} \epsilon_p \geq 7 \times 10^{14} \Gamma_{2.5}^2 / \epsilon_{\gamma} \]

\[ x_{p\pi} \sim 0.2 \] is the average energy transfer from p to the pion,
\[ \epsilon_{\gamma} \] the gamma energy in MeV, \[ \Gamma_{2.5} = \Gamma / 10^{2.5}, \Gamma \sim 300 \] is the bulk Lorentz boost.
The 1/4 assumes an equal sharing among the 4 decay products

\[ \pi^+ \rightarrow \nu_\mu \mu^+ \rightarrow \nu_\mu e^+ \nu_e \bar{\nu}_\mu \]

From BATSE catalog photon flux \( \rightarrow \) neutrino flux
neutrino production in GRB

![Graph showing neutrino spectrum](image)

Solid line: 10 ms GRB, with $\Gamma \sim 300$
Dashed: 50 ms GRB, with $\Gamma \sim 1440$
neutrinos and gammas in AMON

Detection of one neutrino in IceCube, and a photon in a X-ray observatory (Swift BAT,...)

- two diagonals: theoretical GRB models (gamma: Lorentz boost of the jet producing the GRB)
- red line: typical threshold
- assume power law for both neutrino and X rays

\[
\text{gain} = \frac{\text{Sensitivity}^{\text{AMON}}}{\text{Sensitivity}^{\text{Status quo}}}
\]
neutrinos and GW in AMON

* Distance for an above threshold detection at LIGO/VIRGO

\[ D_{GW} \approx 80 \text{ Mpc} \left( \frac{E_{GW}^{iso}}{10^{-2} M_\odot} \right)^{1/2} \]

\( E_{GW}^{iso} \) is the isotropic equivalent GW energy emission of the source

* IceCube side, the threshold is 3 neutrinos.

Without AMON: post-correlation from catalogues

**With AMON:** only one neutrino is required, \( D_{GW} \) is multiplied by 2, using the pointing information from the neutrino

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Integration limit (Mpc)</th>
<th>Neutrino threshold</th>
<th>( V^{(eff)} ) [Mpc(^3)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW+CN</td>
<td>80</td>
<td>( n_\nu \geq 3 )</td>
<td>( 4.6 \times 10^2 )</td>
</tr>
<tr>
<td>AMON</td>
<td>160</td>
<td>( n_\nu \geq 1 )</td>
<td>( 5.9 \times 10^4 )</td>
</tr>
</tbody>
</table>

=> The effective volume of detection is multiplied by 100
II  A photon mass bound

Photon mass measurements

The behaviour of static magnetic fields would be modified by a non-zero photon mass.

An upper limit to the photon mass can be inferred through satellite measurements of planetary magnetic fields.

The Charge Composition Explorer spacecraft was used to derive an upper limit of $6 \times 10^{-16}$ eV with high certainty. This was slightly improved in 1998 by Roderic Lakes in a laboratory experiment that looked for anomalous forces on a Cavendish balance. The new limit is $7 \times 10^{-17}$ eV.

Studies of galactic magnetic fields suggest a much better limit of less than $3 \times 10^{-27}$ eV, but there is some doubt about the validity of this method.
Photon mass in Maxwell equations

Schroedinger: massive Maxwell equations

\[
\begin{align*}
\nabla \cdot \mathbf{E} &= 4\pi \rho - \mu^2 V, \\
\nabla \cdot \mathbf{B} &= 0, \\
\nabla \times \mathbf{E} &= -\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t}, \\
\nabla \times \mathbf{B} &= \frac{1}{c} \frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c} \mathbf{j} - \mu^2 \mathbf{A},
\end{align*}
\]

\[
\mu = \frac{1}{\lambda_c} = \frac{mc}{\hbar} = \frac{m (\text{in g})}{3.52 \times 10^{-38} \text{ cm}^{-1}}
\]

Solution are Yukawa-like:

\[
V(r) = -\frac{q \ e^{-\mu r}}{r}
\]
Photon mass, Proca equation

Lagrangian density for massive J=1 particle

\[ \mathcal{L} = -\frac{1}{16\pi}(\partial^\mu A^\nu - \partial^\nu A^\mu)(\partial_\nu A_\mu - \partial_\mu A_\nu) + \frac{m^2 c^2}{8\pi \hbar^2} A^\nu A_\nu. \]

Euler-Lagrange \(\Rightarrow\) Proca equation

\[ \partial_\mu(\partial^\mu A^\nu - \partial^\nu A^\mu) + \left(\frac{mc}{\hbar}\right)^2 A^\nu = 0 \]

Equivalent to

\[ \left[ \partial_\mu \partial^\mu + \left(\frac{mc}{\hbar}\right)^2 \right] A^\nu = 0 \quad \text{with} \quad \partial_\mu A^\mu = 0 \]

... similar to Klein-Gordon equation.

For \( m = 0 \) \(\Rightarrow\) Maxwell photon
Photon mass in the Galaxy

Galaxy:
M~ $10^{12}$ solar masses
B ~ $2 \times 10^{-6}$ G, with homogeneity scale d ~ 300 pc

Contribution from a photon mass to the (magnetic) energy density in the Galaxy:

$$\epsilon_A = \frac{1}{8} \mu^2 A^2 \sim \frac{1}{8} \mu^2 B^2 d^2$$

where from B = rot A, we have introduced the order of magnitude A ~ Bd.

The total energy cannot exceed the total mass of the Galaxy:

$$M/V = \rho < \frac{1}{8} \mu^2 B^2 d^2 / c^2$$

gives $\mu < 3 \times 10^{-14}$ cm$^{-1}$ => $m<10^{-51}$ g

This calculation should be done in the framework of General Relativity...
Proca Lagrangian
\[ \mathcal{L} = -\frac{1}{16\pi} F^\mu{}_{\nu} F_{\mu\nu} - \frac{1}{c} j^\nu A_\nu + \frac{\mu^2}{8\pi} A_\mu A^\mu \quad \mu = \frac{mc}{\hbar} \]

Lorentz gauge =>
\[ \Box A_\alpha + \mu^2 A_\alpha = \frac{4\pi}{c} J_\alpha \] (*)

static limit =>
\[ \nabla^2 A_\alpha - \mu^2 A_\alpha = -\frac{4\pi}{c} J_\alpha \]

source is a point charge q at rest at the origin, only Coulomb potential is non-zero:
\[ \Phi(x) = q \frac{e^{-\mu r}}{r} \]

(*) in the absence of sources, an oscillator has constraint
\[ \omega^2 = c^2 k^2 + \mu^2 c^2 \]

if \( \omega_0 \) is the resonant frequency for \( \mu = 0 \)
\[ \omega^2 = \omega_0^2 + \mu^2 c^2 \Rightarrow \frac{\Delta \omega}{\omega_0} \approx \frac{\mu^2 c^2}{2\omega_0^2} \]
Photon mass measurement

LC oscillator. C are two concentrical spheres of radius a and b. The capacitance is increased by (assuming $\mu b << 1$)

$$\mu^2 a^2 b / 3$$

$$\Rightarrow \text{instead of } \frac{\Delta \omega}{\omega_0} \sim \frac{\mu^2 c^2}{2\omega_0^2} \text{ the actual effect of a non-zero mass of the photon is}$$

$$\frac{\Delta \omega}{\omega_0} = O(\mu^2 d^2) \text{ with } d \text{ representing the characteristic dimension of the system}$$

more general case: $$\frac{\Delta F_{\alpha\beta}}{F^0_{\alpha\beta}} = O(\mu^2 d^2) \text{ with } F \text{ the e.m. field}$$

To measure the tiny mass we need a “large box”
Photon mass measurement.

* The difference in time of arrival of radiation of different frequencies with the same origin. Difference in time of arrival is:

\[
\delta t = \frac{1}{8\pi c} m^2 L (\lambda_A^2 - \lambda_B^2)
\]

\(\Rightarrow\) can exploit astronomical sources, but limited by the dispersion of light in the magnetic interstellar medium (1970 result with Crab pulsar gives \(\sim 6 \times 10^{-12}\) eV)

* The B lines from a magnetic dipole are modified by the presence of the Yukawa term, to keep \(\text{div } B = 0\). For a dipole \(D\), instead of the usual formula

\[
B = \frac{D}{r^3} (3\hat{z} \cdot \hat{r} \hat{r} - \hat{z})
\]

we have:

\[
B = \frac{De^{-\mu r}}{r^3} [(1 + \mu r + \frac{1}{3} \mu^2 r^2)(3\hat{z} \cdot \hat{r} \hat{r} - \hat{z}) - \frac{2}{3} \mu^2 r^2 \hat{z}]
\]

In particular the last term indicates an antiparallel component. Using the terrestrial survey in 1924, Schroedinger \(\Rightarrow m < 1.9 \times 10^{-47}\) g

* The exponential decay of B can be probed by altitude measurements by satellites. 1970 results gave \(m < 3 \times 10^{-48}\) g
Pioneer-10

- Imaging Photopolarimeter
- Geiger Tube Telescope
- Meteoroid Detector Sensor Panel
- Helium Vector Magnetometer
- Ultraviolet Photometer
- Main Antenna
- Plasma Analyzer
- Trapped Radiation Detector
- Cosmic Ray Telescope
- Infrared Radiometer
- Charged Particle Instrument
- Radioisotope Thermoelectric Generator

[Diagram of Pioneer-10 spacecraft with labeled components]
Pioneer-10 and Jupiter’s B field

B-field ~ dipole 4.3 Gauss (10 times B field on Earth).

Pioneer made ~3200 measurements taken at a distance in [2.48, 13.1]xR_J where R_J =71372 km is Jupiter radius.

Spherical harmonic expansion (uniform contribution+dipole+quadrupole+octupole) from least-square fit of 134 averaged vector-field values.

Fit is reasonable in terms of “root mean residuals”, but not perfect. Systematic effects not small.

=> m < 8 x 10^{-49} g  
Photon mass

All this criticized by Adelberger, Dvali, Gruzinov
arXiv hep-ph/0306245v2

Photon mass bound destroyed by Vortices
Exe 6

Quelles sont les informations contenues dans cette plaquette ?
Two astroparticle detectors are placed at 10 km distance. They detect a 10 ns burst of ~500 particle each, with a delay of 3 microseconds. Assume that the source is very far, and that the astroparticle speed is $c$. Estimate the source minimal angular position w.r.t. the zenith.

After the burst, the experiments continuously monitor in that direction.

1) What is the minimal number of detections by each one of the experiments in a time window of 100ns, to obtain a signal significance of at least 5sigmas, if the background rate on each detector is 10 pulses/microsecond?

2) What is the value when the coincidence of the two detector is required in a coincidence time window of 1 microsecond?