Lezioni 17 e 18

ANTARES, IceCube, Baikal, KM3NeT
Telescopi per Neutrini in mare, lago, ghiaccio:

• Ricostruzione di tracce, ricerca di sorgenti puntiformi di neutrini di H.E.
  • Ricerca di flussi di neutrini in eccesso rispetto ai neutrini atmosferici (neutrini astrofisici "diffusi")
  • Ricerca di neutrini da sorgenti di G.R.B.
  • Ricerca di neutrini dalle "Fermi Bubbles"
  • Ricerche "multimessenger"
The ANTARES experiment

- String-based detector;
- Underwater connections by deep-sea submersible;
- Downward-looking PMTs, axis at 45º to vertical;
- 2475 m deep.

- 12 detection lines
- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs

Junction Box

- 40 km cable to shore

Univ. "La Sapienza" - Dott. in Fisica - High Energy Neutrino Astrophysics
A. A. 2017 - 2018
Data taking periods:

- MILOM : Mar '05 – Mar '06
What do we expect to see as $t = t(z)$? 

for a downgoing muon with $\theta_\mu \sim 180^\circ$
What do we expect to see as $t=t(z)$??

for an inclined muon with $\theta_\mu \sim 90^\circ$
What do we expect to see as $t \equiv t(z)$? 

for an upgoing muon with $\theta_\mu \sim 0^\circ$

$\Delta t_{1,2}$

$\Delta t_{1,i}$

$\mu$

slope $\frac{dz}{dt} = \text{light speed}$
(multi-) muon Event

Example of a **reconstructed down-going muon**, detected in all 12 detector lines:
Up-going track: a neutrino candidate

Example of a reconstructed up-going muon (i.e. a neutrino candidate) detected in 6/12 detector lines:
ANTARES: Coincidence rates from $^{40}\text{K}$ decays

A lot of "spurious hits are detected together with the ones due to the muon tracks: this "optical background" is due to $^{40}\text{K}$ decay and to bioluminescence: selection criteria, based on causality, have been developed to discard hits not related to the tracks.
Background light:
- bioluminescence (bacteria, macroscopic organisms)
- decays of $^{40}K$ (~30 kHz for 10” photomultiplier)

Correlation with water current
- Light bursts by macroscopic organisms – induced by pressure variation in turbulent flow around optical modules ?!
Il sistema di Trigger in un Telescopio per Neutrini

Ad esempio in ANTARES

- Il sistema di trigger in mare è concepito per essere il più semplice e flessibile possibile.
- Il trigger basilare è **L0**: l'ampiezza di un segnale in un PMT supera la soglia (1/3 p.e.)
- Il primo livello di trigger (**L1**) richiede:
  - una coincidenza tra due moduli ottici di un unico piano (storey) (in un intervallo $\Delta t \pm 20$ns)
  - oppure:
    - 1 segnale > 2 p.e. ;
- Il trigger di secondo livello (**L2**) è basato su combinazioni di trigger di primo livello
  - la coincidenza su un singolo storey di un L1 (dovuto a coincidenza) ed un L1(carica) in $\pm 20$ns
  - oppure:
    - la coincidenza di L1 prodotti su storey adiacenti in $\pm 80$ns
    - e permette una prima lettura dell’intero detector.
- Trigger **T3** coincidenza di trigger L1: $L1(i) \cdot L1(i+1)$ oppure $L1(i) \cdot L1(i+2)$
- Trigger **2T3** doppia coincidenze di trigger L1: $[L1(i) \cdot L1(i+1)] \cdot [L1(k) \cdot L1(k+1)]$ o fra piani non immediatamente adiacenti
- Trigger direzionali (come **GC** in ANTARES) si chiede una serie di hit allineati in direzioni privilegiare (ad esempio il Centro Galattico)
- Un più raffinato trigger di terzo livello, basato su coincidenze temporali più stringenti e su un più ampio numero di moduli ottici, sarà effettuato da processori a terra.
Raw Data: PMH single hits distributions

Pulse height distribution, pedestal subtracted
due to single photo-electron (p.e.)

Hit total charge distribution,
pedestal subtracted

Nominal value if H.V. such to provide Gain=5*10^7
(let's remember that the charge of the electron ~ 1.6*10^{-19} C)
From the ”hit” on the PMT’s to the track reconstruction

The detector extends for ~500m x 500m, a muon crosses it in ~ 2µs. This gives an idea of the possible duration of one event.
The minimum background rate of the PMT’s due to $^{40}$K contribution is 50kHz: the probability that one PMT has a background hit in 2µs is: $2 \cdot 10^{-6} \cdot 5 \cdot 10^4 = 0.1$. ANTARES has ~990 PMTs, the average number of background hits in ~ 2µs is ~100 !!!!

Hits due to $^{40}$K are completely random in time and space

Hits due to a propagating muon follow a natural space/time causality relation.

Before applying any track reconstruction procedure all the hits that do not show a space-time correlation compatible to a particle propagating at the light speed are REJECTED: filtering algorithm.
\[ t_i = T_0 + \frac{d_{\text{muon}}^i}{c} + \frac{d_{\text{photon}}^i}{(c/n)}; \quad t_j = T_0 + \frac{d_{\text{muon}}^j}{c} + \frac{d_{\text{photon}}^j}{(c/n)} \]

\[ (\Delta t_{ij})^{\text{sper}} = t_i - t_j = \frac{(d_{\text{muon}}^i - d_{\text{muon}}^j)}{c} + \frac{(d_{\text{photon}}^i - d_{\text{photon}}^j)}{(c/n)} \]

Procedura per la ricostruzione delle tracce: definizioni

\[ x_\mu = X_0 + c_x * s \]
\[ y_\mu = Y_0 + c_y * s \]
\[ z_\mu = Z_0 + c_z * s \]

\[ s = \text{ascissa curvilinea} \]

\[ c_x = \sin(\theta) \cdot \cos(\phi) \]
\[ c_y = \sin(\theta) \cdot \sin(\phi) \]
\[ c_z = \cos(\theta) \]
Procedimento di Fit-1 - minimizzazione del $\chi^2$

- ai PMT dell’évento si sommano PMT dovuti a $^{40}\text{K}$

- si selezionano PMT che soddisfano le condizioni di essere “segnali” e la causalità

- fissato un set di valori di $X_0, Y_0, Z_0, T_0, \theta, \phi$ si calcola, per ogni PMT con segnali, il tempo di arrivo del fotone sul PMT

- si cerca il valore di $s$ che corrisponde alla minima distanza fra il muone ed il PMT

$s_{\text{min}} = (X_{\text{PMT}} - X_0) c_x + (Y_{\text{PMT}} - Y_0) c_y + (Z_{\text{PMT}} - Z_0) c_z$

-cio permette di calcolare:

il punto sulla traccia del muone che corrisponde alla minima distanza:

$x_\mu = X_0 + c_x * s_{\text{min}}$ ; $y_\mu = Y_0 + c_y * s_{\text{min}}$ ; $z_\mu = Z_0 + c_z * s_{\text{min}}$

la minima distanza del PMT dalla traccia:

$\Delta_{\mu\text{PMT}} = \{(X_{\text{PMT}} - x_\mu)^2 + (Y_{\text{PMT}} - y_\mu)^2 + (Z_{\text{PMT}} - z_\mu)^2\}^{0.5}$

il percorso del fotone:

$d^i_{\text{photon}} = \Delta_{\mu\text{PMT}} / \sin(\theta_{\text{Cherenkov}})$

il percorso del muone fino al punto in cui il fotone è stato emesso:

$d^i_{\mu\text{on}} = (X_0 - x_\mu)^2 + (Y_0 - y_\mu)^2 + (Z_0 - z_\mu)^2\}^{0.5}$

$\Delta_{\mu\text{PMT}} / \tan(\theta_{\text{Cherenkov}})$

e quindi il tempo di arrivo del fotone sul PMT

$t_i = T_0 + d^i_{\mu\text{on}} / c + d^i_{\text{photon}} / (c/n)$
Procedimento di Fit-2 minimizzazione del $\chi^2$

Prendendo come riferimento ad esempio il “primo” “segnale” dell’evento $\rightarrow t_1$ per ogni PMT con segnale possiamo definire le quantità

$$(\Delta t_{i1})_{sper} = t_i^{sper} - t_1^{sper} \quad e \quad (\Delta t_{i1})_{teor} = t_i^{teor} - t_1^{teor}$$

$(\Delta t_{i1})_{teor}$ funzione dei parametri $X_0, Y_0, Z_0, \theta, \phi$ o meglio di $X_0, Y_0, Z_0, c_x, c_y, c_z$

Con fit basato su MINUIT si sceglie il set di valori $\tilde{X}_0, \tilde{Y}_0, \tilde{Z}_0, \tilde{T}_0, \tilde{\theta}, \tilde{\phi}$ che minimizza

$$\sum \left[ \frac{(\Delta t_{i1})_{teor} - (\Delta t_{i1})_{sper}}{\sigma_{i1}} \right]^2$$

La procedura di fit inizia fornendo a MINUIT i valori di $\theta$ e $\phi$ ottenuti dal “prefit” ed imponendo alla retta così definita di passare per un punto che corrisponde al “baricentro” di tutti i PMT che hanno superato il “filtro”

Le condizioni $c_x^2 + c_y^2 + c_z^2 = 1$ e $X_0^2 + Y_0^2 + Z_0^2 = R^2$ non vengono “imposte” prima del fit. Il fit viene effettuato sulle 6 variabili in modo da far lavorare MINUIT in uno spazio dei parametri quanto più “lineare”

Costringo il “fit” a restare nella regione fisica dei parametri aggiungendo un contributo al $\chi^2$ quando $c_x^2 + c_y^2 + c_z^2 \neq 1$ o quando $X_0^2 + Y_0^2 + \neq R^2$
Reconstructing the muon track direction: $\chi^2$ strategy

Track reconstruction based on $\chi^2$ fit of the photon arrival times on fired PMTs

Multi-line track fit of tracks reconstructed as upward-going 2008 data

downward-going MC atmospheric muons

up-going MC atmospheric neutrinos

Elevation angle distribution for events with $Q<1.4$
Data points are compared with the MonteCarlo predictions for atmospheric down-going muons and up-going neutrinos

A Fast Algorithm for Muon Track Reconstruction and its Application to the ANTARES Neutrino Telescope, Astroparticle Physics 34, Issue 9, (2011) 652-662
Reconstructing the muon track direction: a maximum likelihood approach (1)

This method is based on the knowledge of the propagation of photons in the medium (water/ice) due to absorption, attenuation, diffusion. By means of M.C. simulations it is possible to define the “hit” time $t_j^{\text{theor}}$ for the PMT$_j$ if a muon with parameters $x_0, y_0, z_0, \theta$ and $\phi$ crosses the detector. It is possible to define, for each PMT$_j$, a Probability Density Function (PDF) that, assuming a set of values for the fit parameters gives the probability that it (the PMT) is hit at the time $t_j^{\text{exper}}$.

Namely the PDF gives the probability for the “time residual” $t_j^{\text{theor}} - t_j^{\text{exper}}$ for each set of values $x_0, y_0, z_0, \theta$ and $\phi$.

For each possible set of track parameters the probability to obtain the observed event can be calculated: this probability is the "likelihood" of the event. This likelihood only take into account the probability of the "time" of the hits. In principle it could also include the hit amplitude and the muon energy.

$$\text{Likelihood} = L = P(\text{event}|\text{track}) \equiv P(\text{hits} | \vec{p}, \vec{d}) = \prod_i P(t_i | t_i^{th}, a_i, b_i, A_i)$$

Where $t_i =$ time of hit $i$, $A_i =$ amplitude of hit $i$, $t_i^{th}$ is the expected arrival time if $\vec{d} \equiv (d_x, d_y, d_z)$ is the muon trajectory and $\vec{p} \equiv (p_x, p_y, p_z)$ is the muon position at a given time $t_0$. 
The components of $\vec{v}$ parallel and perpendicular to the muon direction are $l = \vec{v} \cdot \vec{d}$ and $k = \sqrt{\vec{v}^2 - l^2}$ respectively. The arrival time of the light in $\vec{q}$ is then given by

$$t^{th} = t_0 + \frac{1}{c} \left( l - \frac{k}{\tan \theta_c} \right) + \frac{1}{v_g} \left( \frac{k}{\sin \theta_c} \right)$$
In practice the maximum of the "event probability" is obtained by obtaining the minimum of the quantity $-\log(L)$ searching for the best set of parameters for the muon track.

The quality of the track fit is quantified by the parameter

$$\Lambda \equiv \frac{\log(L)}{N_{\text{hits}} - 5} + 0.1 \times (N_{\text{comp}} - 1)$$

where $N_{\text{comp}}$ is the number of times the repeated initial steps of the reconstruction converged to the same result. In general, $N_{\text{comp}} = 1$ for badly reconstructed events while it can be as large as nine for well reconstructed events.
The variable

\[ \Lambda \equiv \frac{\log(L)}{N_{\text{hits}}^{-5}} + 0.1 \times (N_{\text{comp}} - 1) \]

can be used to reject badly reconstructed events, in particular atmospheric muons badly reconstructed as up-going. In addition, assuming that the likelihood function near the fitted maximum follows a multivariate Gaussian distribution, the error on the zenith and azimuth angles are estimated from the covariance matrix. The angular uncertainty on the muon track direction, \( \beta \), is obtained from these errors.
Positions of reconstructed tracks of atmospheric muons at time of first triggered hit
- Identify cosmic (diffuse) $\nu$ as an excess, over the atm. $\nu$, at high energies
- search for point like sources (events clustering in galactic coordinates)
- time and/or space coincidence with other astrophysical signals ($\gamma$, p, GW, …) in a multi-messenger strategy

Remember, the Earth is opaque also for $\nu$ at very high energies
Expected Performances

Neutrino effective area

Angular resolution

Risoluzione in energia

• For $E_{\nu} < 10$ PeV, $A_{\text{eff}}$ grows with energy due to the increase of the interaction cross section and the muon range.

• For $E_{\nu} > 10$ PeV the Earth becomes opaque to neutrinos.

• For $E_{\nu} < 10$ TeV, the angular resolution is dominated by the $\nu$-$\mu$ angle.

• For $E_{\nu} > 10$ TeV, the resolution is limited by track reconstruction uncertainties.

$\sigma_{E}/E \approx 3$
for ($1 \text{ TeV} \leq E \leq 10 \text{ TeV}$)

$\sigma_{E}/E \approx 2$
for ($E > 10 \text{ TeV}$)
ANTARES: sample of reconstructed tracks

Distribution of the cosine of the zenith angle showing events with $\Lambda > -5.2$ and $\beta < 1$.

Selecting up-going events we reject the major background distribution due to atmospheric muons but we are still affected by the atmospheric neutrino bgk.
ANTARES Performances

- 12-line data taking since 2008; physics duty cycle ≈ 85% (sea campaigns/high bioluminescence periods)

- ~20 atmospheric muons per sec
  - directional cut
  - + quality cut on likelihood of track fit (based on PDFs of hit time residuals)

- ~5 atmospheric neutrinos per day (> 7000 neutrinos detected so far)
- Real-time data processing
- Effective area ≈ 1 m² at 30 TeV
- Median angular resolution 0.3° - 0.4°
- Visibility: ¾ of the sky, most of the Galactic Plane
Downgoing muon analysis

• Track reconstruction based on $\chi^2$ fit
• Main contributions to systematics:
  \[ \frac{\Delta \lambda_{\text{abs}}}{\lambda_{\text{abs}}} \sim \pm 20\% \]
  \[ \text{OM acceptance (High angle)} \sim \pm 35\% \]
  \[ \text{PMT eff Area} \sim \pm 20\% \]

• Monte Carlo: two approaches
  1\textsuperscript{st} approach:
    CORSIKA 6.2 +\textit{QGSJET} 01
    Primary CR models used:
    - Polygonato (Hörandel)
    - NSU (Bugaev)
  2\textsuperscript{nd} approach:
    - MUPAGE (parameterization)
Coincidences between adjacent storeys (low E atmospheric muons)

Analysis performed on 5-line detector data

Energy threshold \( \sim 4 \text{ GeV} \)

Data/MC ratio \( \approx 1.1 \)

- Data: low-background (<100 kHz) \(^{40}\text{K}\) runs with 5-line and 10-line detector. Effective live time = 4.1 hours with 5 lines + 3.2 hours with 10 lines (52.5 line-hours)

- Monte Carlo: MUPAGE, Geant4 angular acceptance. Resulting curve is rescaled to account for low-efficiency & dead OMs in real data
Event rate as a function of floor depth

By repeating the analysis for every detector storey, the effect of muon flux reduction with depth is directly measured.

After corrections for the presence of dead channels and uneven efficiencies of the OMs, as measured with $^{40}$K, the fluctuations of data points are compatible with statistical errors.

Systematic errors mainly in normalization ($+50/-35\%$), otherwise $\sim 3\%$.

"Measurement of the atmospheric muon flux with a 4 GeV Threshold in the ANTARES neutrino telescope"

Astroparticle Physics 33 (2010) 86-90

\[
\Phi(h) = \Phi_0 e^{(h_0-h)/\lambda}
\]

Line 1-5 + Line 1-10 data set

\[
\Phi_0 = 1.18 \pm 0.01(stat) \pm 0.63(syst) \cdot 10^{-3} \text{ m}^{-2} \text{s}^{-1}
\]

at \( h_0 = 2200 \text{ m} \) with \( \lambda = 540 \pm 25 \text{ m} \)
2007 and 2008 data analysis: $\nu_\mu$ from point sources

The selected sample of tracks dominated by up-going atmospheric $\nu_\mu$ and mis-reconstructed down-going muons.

The $\Lambda$ quality cut enhances the $\nu_\mu$ component in the up-going reconstructed tracks sample.

- Reconstruction algorithm (max. **Likelihood strategy**) optimized to reach angular resolution $\leq 0.2^\circ$ for $E_\mu > $ TeV and to reduce the atmospheric muon background
- Blinding policy followed
- Cut $\cos(\theta_{\text{zenith}}) > 0$ to select "up-going" $\mu$

Look for neutrinos into the "up-going tracks".

Selected up-going reconstructed tracks From MC: angular error estimate $< 1^\circ$
ANTARES: search for point like sources

Search for point-like sources at their known location


**ANTARES 2007+2008 preliminary Skymap Galactic Coordinates**

2040 up-going $\nu_\mu$

**ANTARES: flux limits on 24 candidate point sources and sensitivity (median expected limit)**

$7.5 \times 10^{-8} \text{ (E/GeV)^{-2 GeV^{-1} s^{-1} cm^{-2} \left[ \delta<48^\circ \right]}}$ (the part of the sky always visible)
The ANTARES search for point-like $\nu$ sources based on two kind of events

- Tracks: $\nu_\mu$ or $\nu_\tau \rightarrow \mu$
  - Interaction can occur far from the detector providing a large Effective Volume
  - Angular resol. $< 0.4^\circ$ for $E_\nu > 10$ TeV
  - Energy resol. $\sim$ factor 3

- Electronic or hadronic showers: NC and $\nu_e$ or $\nu_\tau \rightarrow$ showers
  - Events contained in the detector: smaller Effective Volume,
  - Energy resolution $\sim 5$-10%
  - Median angular resolution $\sim 3^\circ$
ANTARES: search for point like sources

9 years of ANTARES data searching for all neutrino flavours:
7629 “tracks” + 180 “shower” events passed the selection criteria

\[
\log \mathcal{L}_{\text{sig+bkg}} = \sum_{S=\text{tr.,sh.}} \sum_{\tau=S} \log[\mu_{\text{sig}}^\tau \cdot \mathcal{F}_{\text{sig}}^\tau(\delta) \cdot \mathcal{P}_{\text{sig},i}^\tau(E_i) + \mathcal{N}^\tau \cdot \mathcal{B}_i^\tau \cdot \mathcal{P}_{\text{bkg},i}^\tau(E_i)] - \mu_{\text{sig}}
\]

so far …. no significant excess has been found

ANTARES Phys.Rev. D96 (2017) no.8, 082001

Candidate Sources
Blue: Tracks
Red: Cascades
IC HESSE tracks

equatorial coordinates

GC region
**ANTARES: search for point like sources**

- **ANTARES 2007-15 sensitivity**
  - **ANTARES 2007-15 sensitivity (E < 100 TeV)**
  - **ANTARES 2007-15 limits (candidate list)**
  - **ANTARES 2007-15 limits (candidate list for HESE events)**
  - **ANTARES 2007-15 limits (1° declination bands)**

- **IceCube 7 years sensitivity** [ApJ 835(2017)2 151]
- **IceCube 3 years MESE sensitivity** (E < 100 TeV) [ApJ 824(2016)2 L28]
- **IceCube 7 years limits** [ApJ 835(2017)2 151]

9 years of ANTARES data:
7629 “tracks” + 180 “shower”

**ANTARES Phys.Rev. D96 (2017) no.8, 082001**
The ANTARES search for point-like $\nu$ sources based on two kind of events

- Tracks: $\nu_\mu$ or $\nu_\mu \rightarrow \mu$
- Interaction can occur far from the detector providing a large *Effective Volume*
- Angular resol. $< 0.4^\circ$ for $E_\nu > 10$ TeV
- Energy resol. $\sim$ *factor 3*

- Electronic or hadronic showers: NC and $\nu_e$ or $\nu_\tau \rightarrow$ showers
- Events contained in the detector: smaller *Effective Volume*,
- Energy resolution $\sim 5$-10%
- Median angular resolution $\sim 3^\circ$
Joint IceCube + ANTARES search for $\nu$ sources

Skymap of pre-trial p-values for the combined ANTARES 2007/12 and IceCube 40, 59, 79 point-source analyses.

The red circle indicates the location of the most significant cluster: (0.7$\sigma$ post-trial significance)
**Search for all-sky diffuse flux of cosmic neutrinos**

- Updated analysis: 2008-2011 (855 days livetime); muon neutrinos only
- Optimisation tuned on burn sample of 10% data
- Reconstruction of atmospheric $\nu_\mu$ energy spectrum with unfolding procedure

**Main challenges:**
- Low (<1%) contamination by atmospheric muons
- Upgoing tracks with strict quality cuts

![Cumulative $\Lambda$ distribution for zenith $> 100^\circ$ and $\beta < 1^\circ$](image1.png)

**Final sample:** 1531 neutrinos, 5 muons (est. background)

![Logarithmic plot of $E_\mu$ vs. $Q$](image2.png)

Reliable neutrino energy estimator based on muon dE/dx
ANTARES (2013): search for a flux of “diffuse $\nu_\mu$”: results

- Updated analysis: 2008-2011 (855 days livetime); muon neutrinos only
- Optimisation tuned on burn sample of 10% data
- Reconstruction of atmospheric $\nu_\mu$ energy spectrum with unfolding procedure

Improved limit on diffuse cosmic $\nu_\mu$ flux

$E^2 \Phi_{90\% \text{ c.l.}} = 3.2 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$

(energy range 45 TeV $\rightarrow$ 6.3 PeV)

Upper bound on AGN and GRBs $\nu$ fluxes from observed HE CRs (accelerated $p$ interacting on $\gamma$s) if $p$s escape from source

$$\frac{d\Phi}{dE} E_\nu^2 \lesssim 2 \cdot 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

assuming CR spectrum $dN/dE \propto E^{-2}$ (Waxman & Bahcall, PRD59 1999)
ANTARES physic’s goals

Search for Diffuse flux of Cosmic Neutrinos

- Neutrinos from:
  - Unresolved AGN
  - "Z-bursts"
  - "GZK like" proton-CMB interactions
- Top-Down models Neutrinos

Their identification out of the more intense background of atmospheric neutrinos (and $\mu$) is possible at very high energies ($E_\mu >>$ TeV) and requires good energy reconstruction.

Found 8 “shower events” for $10 \text{ TeV} < E_{\text{SH}} < 100 \text{ TeV}$ when 5 expected. Compatible with IceCube signal

Search here !!!

arXiv:1703.02432v1

Data

Univ. "La Sapienza" – Dott. in Fisica - High Energy Neutrino Astrophysics
Latest ANTARES results on the search for diffuse $\nu$ flux

Tracks
Data: 2007-2015 (2451 live-days)
Above $E_{\text{cut}}$: Bkg: 13.5 ± 3 evts, IC-like signal: 3 evts
Observed: 19 evts

Cascades
Data: 2007-2013 (1405 live-days)
Above $E_{\text{cut}}$: Bkg: 5 ± 2 evts, IC-like signal: 1.5 evts
Observed: 7 evts

ANTARES combined upper limits and sensitivities for 9 years data sample (2007-2015) tracks + cascades

Univ. "La Sapienza" – Dott. in Fisica - High Energy Neutrino Astrophysics

A. A. 2017-2018
Search for a neutrino emission from the Fermi bubbles

- Excess of γ- (and X-)rays in extended “bubbles” above and below Galactic Center
- Homogenous intensity, hard (E⁻²) spectrum with probable cutoff

- Origin still debated; promising Galactic wind model involves hadronic processes (Crocker & Aharonian, PRL 2011):
  - accelerated cosmic rays interacting with ISM → π → γ, ν
  - CR expected cutoff at 1 – 10 PeV
  - Φ_ν ≈ 0.4 x Φ_γ

- In the field of view of ANTARES background estimated from average of 3 non-overlapping “off-zone” data regions (same size, shape and average detector efficiency)
ANTARES: search for $\nu_\mu$ from the Fermi Bubbles: results

- 12-line data sample: May 2008- Dec 2011 (806 days livetime); muon neutrinos only
- $E_\nu$ estimation based on Artificial Neural Networks procedure
- optimisation tuned on off-zone background events

$N_{\text{obs}} = 16$
$\langle N_{\text{bkg}} \rangle = 11$

No excess observed

50 TeV cutoff
100 TeV cutoff
500 TeV cutoff
No cutoff

on-zone
off-zone average
expected signal ($\neq$ cutoff)

Solid: 90% CL limits
Dotted: model predictions

PRELIMINARY
The evolution of astronomy

• From Traditional Astronomy (Optics) to Multi-Wavelength Astronomy:
  
  observations of light in the visible band are complemented by radio, X-ray and $\gamma$ astronomy

Galileo Galilei showing the Doge of Venice how to use the telescope (1858), fresco by Giuseppe Bertini (1825–1898)

http://mwmw.gsfc.nasa.gov/

… and to Multi-Messengers Astronomy: HE-CR, photons, neutrinos, GW …
Multi-messenger approach

- Alerts and follow-up program: TAToO

- Large sky coverage, high duty cycle
- No hypothesis on the nature of the source
- Sensitivity improved: 1 doublet is 3σ discovery, 1 triplet is 5σ!
- System active since 2009 with optical telescopes, now extended to SWIFT/XRT

Astropart. Phys. 35 (2012) 530
Un esempio di ricerca di $\nu$ da sorgente puntiforme in un contesto "multimessenger"

**Ricerca di $\nu$ da corpi astrofisici noti come Sorgenti di Gamma Ray Burst**

- Conoscendo le coordinate della sorgente si cerca un **eccesso statistico di tracce di $\nu$ provenienti da quella posizione**:  
  - Il segnale aspettato può essere stimato calcolando il **flusso di neutrini a partire dal flusso dei fotoni misurati** tenendo conto della accettanza del rivelatore per una sorgente posta nella posizione del GRB;  
  - il **fondo**, supposto isotropicamente distribuito, può essere stimato dai dati osservati;  
  - rispetto alla usuale "ricerca di $\nu$ da sorgente puntiforme" il **segnale ed il fondo vengono cercati solo in coincidenza temporale con il GRB**: il fondo è così integrato per <200s invece che per 3-5 anni !!!!!
Search for $\nu$ from sources of Gamma Ray Burst

- Gamma Ray Bursts are short bursts of gamma rays, a few seconds in duration
- Brighter than rest of gamma ray sky
- Afterglow lasting much longer
- First time observed in Vela satellites (1960s)
- Several generations of satellite-based observations have shown:
  - Extra galactic origin
  - Gamma-ray emission beamed
- Several models have been proposed: Fireball model is successful at explaining the observed photons
- Realistic to believe that baryons are also accelerated so neutrinos may also be produced.
A multi-messenger approach: “GRB trigger”

Data taking triggered by a satellite (FERMI, SWIFT, INTEGRAL)

GCN (Gamma-ray Coordination Network) alerts trigger the recording of all the low level triggers. A continuous buffer ensures the availability of the data before the alert.

$t = -250\ s$

$t = 0\ s$

$t = 20\ s$

$t = 200\ s$

$t = 1\ h$

All data is written to disk

Specific data filtering and reconstruction by searching for an excess of events in the GRB direction (offline)

GCN=Gamma Ray Burst Coordination Network
Searches for transient sources GRB

Curve di luce dei Gamma-Ray Bursts

Diverse tipologie di emissione
Analisi risolta temporalmente
**Searches for transient sources GRB**

### Spettro $\gamma$

1. **Smoothly broken power law (SBPL):**
   \[
   \frac{dN}{dE} \propto \begin{cases} 
   E^\alpha & E < E_\gamma \\
   E^\beta & E \geq E_\gamma 
   \end{cases}
   \]

2. **Cut-off power law (CPL):**
   \[
   \frac{dN}{dE} \propto E^\alpha e^{-E/E_\gamma}
   \]

3. **Band:**
   \[
   \frac{dN}{dE} \propto \begin{cases} 
   E^\alpha e^{-E/E_\gamma} & E < (\alpha - \beta)E_\gamma \\
   E^\beta & E \geq (\alpha - \beta)E_\gamma 
   \end{cases}
   \]

\[\alpha, \, \beta, \, E_\gamma \text{ forniti dai satelliti}\]
Searches for transient sources GRB

Neutrinos from Cosmic Accelerators (numerico): include la risonanza della $\Delta^+$ ed emissioni a più alta energia

\[ p + \gamma \rightarrow K^+ + \Lambda/\Sigma \]

\[ K^+ \rightarrow \mu^+ + \nu_\mu \]

\[ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \]

\[ \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \]
Searches for transient sources GRB

Spettro di $\nu$ da sorgenti p-$\gamma$

\[
\frac{dN(E_\nu)}{dE_\nu} \propto \left\{ \begin{array}{l}
\left( \frac{E_1}{\text{GeV}} \right)^{\alpha_\nu} \left( \frac{E_\nu}{\text{GeV}} \right)^{-\alpha_\nu} E_\nu < E_1 \\
\left( \frac{E_1}{\text{GeV}} \right)^{\beta_\nu} \left( \frac{E_\nu}{\text{GeV}} \right)^{-\beta_\nu} E_1 \leq E_\nu < E_2 \\
\left( \frac{E_1}{\text{GeV}} \right)^{\beta_\nu} \left( \frac{E_2}{\text{GeV}} \right)^{\gamma_\nu-\beta_\nu} \left( \frac{E_\nu}{\text{GeV}} \right)^{-\gamma_\nu} E_\nu \geq E_2
\end{array} \right.
\]

$\alpha_\nu = 3 + \beta$  \hspace{1cm} $\beta_\nu = 3 + \alpha$  \hspace{1cm} $\gamma_\nu = 2 + \beta_\nu$

\[E_1 = 5 \times 10^5 \text{GeV} \left( \frac{1}{1 + z} \right)^2 \left( \frac{\Gamma}{10^{2.5}} \right)^2 \left( \frac{\text{MeV}}{E_\gamma} \right)
\]

\[E_2 = 10^7 \text{GeV} \frac{1}{1 + z} \sqrt{\frac{e_E}{e_B}} \left( \frac{\Gamma}{10^{2.5}} \right)^4 \left( \frac{t_{\text{var}}}{0.01 \text{s}} \right) \sqrt{\frac{10^{52} \text{erg/s}}{L_{\gamma}^{\text{iso}}}}
\]

\[
\int_0^\infty dE_\nu F_\nu(E_\nu) = \frac{1}{8} f_P (1 - (1 - (x_{\nu \rightarrow \pi})) \Delta R / \lambda_{p\gamma}) \int_{E_{\min}}^{E_{\max}} dE_\gamma F_\gamma(E_\gamma)
\]
Searches for transient sources (GRB, flaring AGN, …)

- Multi-messenger search for transient sources: time AND direction known
  - reduced background
  - improved sensitivity:
- 2-3 $\nu$ per source sufficient to claim 5$\sigma$ discovery (50% prob.)
  (even 1$\nu$ for very short transients such as GRBs !)

Search for neutrinos in coincidence with GRBs

- Stacking analysis of GRBs from 2008 – 2011:
  297 long GRBs, total prompt emission duration: 6.55 hours
  Multi-messenger info from FERMI/SWIFT/GCN

- GRB simulations of expected neutrino fluence:
  - NeuCosmA [Hümmer et al. (2010)]
  - Guetta [Guetta et al. (2004)]

- Quality cut optimized for NeuCosmA model & highest signal discovery probability

- No event found within 10° window from GRB
  (expected 0.48 (Guetta), 0.0041 (NeuCosmA))