Connecting neutrino Astrophysics to Multi-TeV to PeV gamma-ray Astronomy with TAIGA

Astrophysics and Experiments

Martin Tluczykont

Magellan Workshop
Hamburg 2016

• Overview UHE gamma-ray regime
• Connecting multi-TeV/PeV neutrinos with gamma-rays
• Status of TAIGA
Physics and sources of UHE gamma-rays
VHE-UHE Gamma-ray astronomy

- H.E.S.S. survey, hard sources
- MGRO J1908+06
- HESS J1908+06
VHE-UHE Gamma-ray astronomy
VHE-UHE Gamma-ray astronomy

Petropoulo et al. 2015: 5 ν's

π⁰

Pevatron

Inv. Compton
Neutrinos and Gamma-Rays
Neutrinos & UHE gamma-rays

• The IceCube signal (Aartsen et al. 2013, 2014)
  - 1st 3 years of full IceCube data: 37 UHE neutrinos (30 TeV – 2 PeV)
  - Presence of astrophysical component favoured (5 σ).
  - 8 BL Lac objects possibly neutrino event counterparts (Padovani & Resconi 2014)

• Lepto-hadronic emission model (Petropoulo et al. 2015)
  - Blob + B-field with Doppler factor δ, isotropic proton and electron injection
    interaction with B-field and secondaries → particle populations:
    - Protons (Sy., pair production, photopi)
    - Electrons and positrons (Sy., IC)
    - Photons (+ neutrons, neutrinos)
PG 1553+113 (z = 0.4)

Petropoulo et al. 2015

PeV π^0 hump

Petropoulo et al. 2015
H 1914-194 (z=0.137)

Petropoulo et al. 2015

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π⁰ hump and neutrino event fluxes

Petropoulo et al. 2015
π^0 hump and neutrino event fluxes

Mrk 421 (ID 9)
1ES 1011+496 (ID 9)
PG 1553+113 (ID 17)

Petropoulo et al. 2015

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$e^+e^-$ pair production: opacity problem & opportunity

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Attenuation from production of $e^+e^-$

Galactic objects (Moskalenko 2006)

extragalactic objects

Primack et al. 2011
Modifications of absorption

- Axion-like particles: absorption-free propagation

\[ \gamma \rightarrow X - - - - - - - - - - - - - - - - - - - X \rightarrow \gamma \]

- Lorentz Invariance violation
  (e.g. Colladay et al. 1998, Protheroe&Meyer 2000, Kostelecky et al. 2011, Rubtsov et al. 2014, Fairbairn et al. 2015)
Lorentz Invariance Violation (LIV)

- LIV: modified dispersion relation / momentum-dependent photon mass → modified kinematics:

\[ \beta_γ^2 = 1 - (\frac{E_γ}{M_{LVn}})^n \]
\[ m_γ^2 = \frac{E_γ^{2+n}}{(M_{LVn})^n} \]

\[ x_{γγ}(E_γ)^{-1} = \frac{1}{8E_γ^2β_γ} \int_{\epsilon_{min}}^{\epsilon_{max}} d\epsilon \frac{n(\epsilon)}{\epsilon^2} \int_{s_{min}}^{s_{max}(\epsilon,E_γ)} ds \left( s - m_γ^2(E_γ)c^4 \right) \sigma(s) \]

\[ s_{min} = 4m_e^2, \]
\[ s_{max}(\epsilon,E_γ) = m_γ^2(E_γ) + 2\epsilon E_γ(1 + \beta_γ), \]
\[ \epsilon_{min} = \frac{s_{min} - m_γ^2(E_γ)}{2E_γ(1 + \beta_γ)} \]

→ modified kinematically allowed range
→ suppression of e⁺e⁻ pair production cross section

Fairbairn et al. 2015
LIV effect on attenuation

sources considered:
\( z < 0.1 \)

\[ P(\text{arrival}) \]

\[ E_\gamma [\text{TeV}] \]

- \( M_{LV1} = 10^{19} \text{GeV} \)
- \( M_{LV1} = 10^{20} \text{GeV} \)
- \( M_{LV1} = 10^{21} \text{GeV} \)
- \( M_{LV1} = 10^{22} \text{GeV} \)

Fairbairn et al. 2015
Observatories for UHE gamma-rays
Key to Multi-TeV-PeV: Area

1000 hours, 10 γ rays

- 0.1 km²
- 1 km²
- 10 km²
- 100 km²
VHE-UHE Gamma-ray Astronomy

integral flux / erg cm$^{-2}$ s$^{-1}$

$10^{-14}$ $10^{-13}$ $10^{-12}$ $10^{-11}$ $10^{-10}$

energy/TeV

$10^{-1}$ $1$ $10$ $10^2$ $10^3$ $10^4$

HAWC

CTA survey

TAIGA 1 km$^2$

TAIGA 10 km$^2$

CTA point-source

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Tunka-HiSCORE → TAIGA (ТАЙГА)
Air Cherenkov imaging and timing

Imaging arrays
H.E.S.S. Telescopes

Timing arrays (non-imaging)

Past: Themistocle, AIROBICC
Today: HiSCORE, TAIGA
TAIGA
Tunka Advanced Instrument for Gamma ray and cosmic ray physics

Since 2014
- Total: 28 stations
- Tilting mode
- 0.25 km²

2016:
- First telescope under construction
- Hybrid timing+imaging
TAIGA timing stations

- Four 8'' PMTs
- Winston cones, light collection 0.5 m²
- GHz readout
- 60° FoV
- “Tilting” for extension of sky coverage
- **Sub-ns** time resolution & array-wide time synchronization

2 systems: O(500 ps)
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TAIGA Imaging Telescopes

- Dish: Davies-cotton tesselated, 34 mirrors (60cm)
- 4.3 m dish diameter
- 4.75 m focal length
- F/D ~ 1.2
- 397 PMT camera foV 10°
- Proven design components
30 Mirrors (1\textsuperscript{st} IACT)

Construction activities @ IExpPh, Hamburg

Glueing test sample

Test sample in Climate chamber

Climate chamber
Timing and imaging hybrid detection
First-time implementation with TAIGA
Hybrid imaging + timing monoscopic

Classical Imaging stereoscopic

~100 m

600 m
Real data

Reconstruct using two different subarrays

Tested for 9-station array

Resulting resolutions (hadrons):

- Direction: 0.19°
- Core position: 4m
- Energy: 10%

Epimakhov et al.
Porelli et al.
@ PoS, ICRC 2015
Time calibration

HiSCORE-9: LED calibration

Fit Residuals: All stations

T-cal systems yield comparable accuracies (<0.5 ns)

White Rabbit in laboratory: <60 ps resolution achievable (PoS ICRC 2015, Wischnewski et al.)
Summary

- Access to UHE gamma-ray regime
  Motivation also from neutrino events
- TAIGA timing array operational, 0.25 km²
- $1^{st}$ TAIGA IACT under construction
- New hybrid imaging+timing operation
  Goal: $10^{-13}$ erg cm$^{-2}$ s$^{-1}$ @ 100 TeV
- Future: muon detectors

References:

2014: Astroparticle Physics, 2014arXiv1403.5688T
2013NIMPA.712..137H, arXiv:1302.3957
2013: ICRC 1146, 1158, and 1164
http://wwwiexp.desy.de/groups/astroparticle/score/
http://tunka-hrjrg.desy.de/
Sky coverage

Standard observation mode: station points to zenith
Tilted mode: inclined along the north-south axis.

Tilting: coverage of different parts of the sky.

Tilted south mode: 110 h on the Crab Nebula, after weather corrections.
Cosmic ray origin

Adapted from Donato & Medina-Tanco 2008

Gammas from Galactic Cosmic rays:

\[ E_\gamma \sim \frac{E_{CR}}{10} \]
Radiation fields

- Interstellar radiation field (ISRF)
- Extragalactic background (EBL)
- Cosmic microwave background (CMB)
LIV sensitivity from gamma-rays

• Current limits (γ-velocities):

\[ M_{LV1} = 9.23 \times 10^{19} \text{ GeV}, \quad M_{LV2} = 1.3 \times 10^{11} \text{ GeV} \]

(Fermi GRBs, Vasileiou et al. 2013)
\[ M_{LV1} = 2.1 \times 10^{18} \text{ GeV}, \quad M_{LV2} = 6.2 \times 10^{10} \text{ GeV} \]

(AGN, Abramowski et al. 2011).

• VHE: (CTA, Fairbairn et al. 2015)

expect competitive limits on \( M_{LVn} \)
\[ \sim 10^{19} \text{ (n = 1)} \]
\[ \sim 10^{12} \text{ (n =2)} \]

• VHE / UHE:

LIV → gamma-rays >10 PeV might be detectable from BL Lacs
Absorption ($e^+e^-$), Galactic

Many Galactic sources:
Weak absorption up to 300 TeV

Universal feature:
Distance-dependent absorption above 300 TeV
LIV sensitivity from gamma-rays

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LIV \( \rightarrow \) gamma-rays >10 PeV might be detectable from BL Lacs