Neutrinos & gamma rays
Complementary views on the high-energy universe.

Markus Ackermann
Physikseminar
Hamburg, 13.01.2015
What is the connection of the observed non-thermal emission to the cosmic rays at Earth?

What are the sites that can accelerate particles to $> 10^{20}$ eV?

Which cosmic accelerators dominate the CR flux in which energy range?
Are cosmic rays important?

Energy densities in the Milky Way

<table>
<thead>
<tr>
<th>Energy density</th>
<th>Milky Way-like spiral galaxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmic rays</td>
<td>0.8 eV / cm³</td>
</tr>
<tr>
<td>CMB</td>
<td>0.3 eV / cm³</td>
</tr>
<tr>
<td>Starlight</td>
<td>0.5 eV / cm³</td>
</tr>
<tr>
<td>Magnetic fields</td>
<td>~ 0.3 eV / cm³</td>
</tr>
<tr>
<td>Gas pressure</td>
<td>~ 0.5 eV / cm³</td>
</tr>
</tbody>
</table>

> Cosmic rays
  - **heat** the interstellar gas
  - **interact** with the magnetic fields
  - **influence** star formation

→ They are important for Galaxy dynamics
What are the mechanisms driving such extreme particle acceleration?

- Diffusive shock acceleration
- Acceleration in plasma turbulence
- Magnetic reconnection
- Electrostatic gaps

What can we learn about the astrophysical environments?

- gas & photon densities
- magnetic fields
- bulk motion
Signatures of new physics in the universe.

> Some high-energy particles might not have been accelerated…

> …but have been produced in the annihilation or decay of massive particles.

> Many particle physics motivated models for dark matter predict observable signatures in the non-thermal sky.

large scale dark matter distribution

simulated γ-ray emission from dark matter annihilation

www.particlezoo.net
Every messenger is unique.

Charged particles: $p, N, e^\pm$

Photons

Neutrinos
The multi-messenger approach.

> Every messenger is unique.

- Photons
- Neutrinos
- Charged particles: p, N, e±
- Elemental composition: Fe, He
- Energy budget / spectrum
The multi-messenger approach.

> Every messenger is unique.

- Photons
- Neutrinos
- Charged particles: p, N, e±

Elemental composition
Energy budget / spectrum

- Inverse Compton
- Synchrotron
- Photons
- Neutrinos
- Bremsstrahlung
- p-p interactions
The multi-messenger approach.

> Every messenger is unique.

**Charged particles:**
- p, N, e±

**Elemental composition**
- Fe
- He
- e

**Energy budget / spectrum**

**p-p interactions**
- p
- π^0
- π^+
- γ
- μ
- e
- ν_μ
- ν_e

**Photons**

**Neutrinos**
Topics addressed in this talk

> A measurement of the total extragalactic **high-energy** gamma-ray emission in the universe
  
  ▪ …and what we know about the sources that produce it.

> The **connection** to CR production/propagation, dark matter annihilation & new physics.

> The **very special value** of astrophysical neutrinos.
Gamma-ray astronomy.

<table>
<thead>
<tr>
<th><strong>Space based</strong></th>
<th><strong>Ground based</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fermi LAT</strong></td>
<td><strong>HESS, MAGIC, Veritas</strong></td>
</tr>
<tr>
<td>30 MeV - 1 TeV</td>
<td>50 GeV - 100 TeV</td>
</tr>
<tr>
<td>20% of the sky</td>
<td>~ 0.02% of the sky</td>
</tr>
<tr>
<td>~1 m²</td>
<td>~10000 m²</td>
</tr>
<tr>
<td>85% of the year</td>
<td>10% of the year</td>
</tr>
<tr>
<td><strong>Instruments</strong></td>
<td><strong>Field-of-view</strong></td>
</tr>
<tr>
<td><strong>Energy range</strong></td>
<td>~ 0.02% of the sky</td>
</tr>
<tr>
<td><strong>Effective area</strong></td>
<td>~10000 m²</td>
</tr>
<tr>
<td><strong>Duty cycle</strong></td>
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<td></td>
<td>10% of the year</td>
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The GeV gamma-ray sky.

Fermi LAT, 4-year sky map, $E > 1$ GeV

Fermi LAT images the full non-thermal sky above 100 MeV
The GeV gamma-ray sky.

Fermi LAT, 4-year sky map, E > 1 GeV

> Fermi LAT images the full non-thermal sky above 100 MeV
The GeV gamma-ray sky.

Fermi LAT, 4-year sky map, $E > 1$ GeV

Resolved sources

Galactic diffuse emission
(CR interactions with the interstellar medium)
Inverse Compton
$\pi^0$-decay
Bremsstrahlung
The GeV gamma-ray sky.

Fermi LAT, 4-year sky map, \( E > 1 \) GeV

- Resolved sources
- Isotropic diffuse emission (IGRB)
- Galactic diffuse emission
  - (CR interactions with the interstellar medium)
    - Inverse Compton
    - \( \pi^0 \)-decay
    - Bremsstrahlung
The extragalactic GeV gamma-ray sky.

Fermi LAT, 4-year sky map, $E > 1$ GeV

Resolved sources

Isotropic diffuse emission (IGRB)

The extragalactic sky

$> \text{Fermi LAT images the full non-thermal sky above 100 MeV}$
The extragalactic GeV gamma-ray sky.

Fermi LAT images the full non-thermal sky above 100 MeV
A census of the sky: 3FGL

> 3FGL: 3rd Fermi LAT gamma-ray source catalog based on 4 years of data
  - Systematic scan of the sky for sources, source identification or association
  - Replaces 2FGL based on 2 years of data

<table>
<thead>
<tr>
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<th>2FGL</th>
<th>3FGL</th>
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<tbody>
<tr>
<td>Total</td>
<td>1873</td>
<td>3033</td>
</tr>
<tr>
<td>Unassociated</td>
<td>649</td>
<td>992 (33%)</td>
</tr>
<tr>
<td>AGNs</td>
<td>991 + 28 (ID) (57%)</td>
<td>1691 + 66 (ID) (58%)</td>
</tr>
<tr>
<td>PSRs</td>
<td>25 + 83 (ID)</td>
<td>29 + 137 (ID)</td>
</tr>
<tr>
<td>PWN</td>
<td>3 (ID)</td>
<td>2+9 (ID)</td>
</tr>
<tr>
<td>SNR</td>
<td>4 +6 (ID)</td>
<td>11+12 (ID)</td>
</tr>
<tr>
<td>GLC</td>
<td>11</td>
<td>15</td>
</tr>
<tr>
<td>SBG</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>HMB</td>
<td>4 (ID)</td>
<td>3 (ID)</td>
</tr>
<tr>
<td>spp</td>
<td>58</td>
<td>51</td>
</tr>
<tr>
<td>Others</td>
<td>7 (gal+Nova+)</td>
<td>11 (gal+Nova+BIN+)</td>
</tr>
<tr>
<td>Extended</td>
<td>12</td>
<td>25</td>
</tr>
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<td>High/Low</td>
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Active Galactic Nuclei:
- Blazars
- Radio Galaxies
- Seyfert Galaxies

No compelling association to a known source

Starburst Galaxies

Elisabetta Cavazzuti
5th Fermi Symp.
Nagoya, 2014
Active Galactic Nuclei

> The overwhelming majority of extragalactic LAT sources are Active Galactic Nuclei (AGN)

> **Blazars:**
  - Observer line-of-sight into the relativistic jet
  - Relativistic doppler boost of intensities

> **Misaligned AGN:**
  - Large viewing angle to jet
  - Characterization by radio emission properties
The 3rd LAT AGN catalog

> 1591 high-latitude LAT sources associated with AGN
  - 1559 associated with Blazars
  - 32 associated with misaligned radio Galaxies

> Blazars are the dominant extragalactic gamma-ray sources

> Large fraction of unidentified sources are likely Blazars.

Benoit Lott
5th Fermi Symp.
Nagoya, 2014
Star-forming / Starburst Galaxies.

- 4 starburst galaxies detected with the LAT
- 4 local “normal” galaxies detected.
  - Andromeda, LMC, SMC & Milky Way
- Weak gamma-ray sources, but very abundant in the universe
# Sources on the extragalactic gamma-ray sky

<table>
<thead>
<tr>
<th>Source Type</th>
<th>Number of sources visible</th>
<th>Luminosity</th>
<th>Density in the universe</th>
</tr>
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<tbody>
<tr>
<td>Blazars</td>
<td>~ 1500</td>
<td>bright</td>
<td>low</td>
</tr>
<tr>
<td>Misaligned active Galaxies</td>
<td>32</td>
<td>medium</td>
<td>medium</td>
</tr>
<tr>
<td>Starforming Galaxies</td>
<td>8</td>
<td>dim</td>
<td>high</td>
</tr>
<tr>
<td>Unknown</td>
<td>~ 1000</td>
<td>?</td>
<td>?</td>
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The extragalactic GeV gamma-ray sky

Fermi LAT, 4-year sky map, $E > 1$ GeV

Isotropic diffuse emission (IGRB)

> Fermi LAT images the full non-thermal sky above 100 MeV
**Strong sources:** All sources can be detected individually.

30 events / source
Source detection: Intermediate sources

- **Intermediate sources**: Some sources can be detected individually.
- Source detection efficiency is $< 100\%$
Source detection: Weak sources

> **Weak sources**: Cannot be detected individually

> Isotropic distribution of events (if source distribution is isotropic)

0.3 events / source
The real case: A mixture of weak & strong sources

> Part of the intensity of a source population can be resolved into individual sources
> The remaining part **contributes to a diffuse background.**
> Dependent on instrument sensitivity, PSF and population properties.
The origin of the IGRB in the LAT energy range.

Undetected sources

**Blazars**
- Dominant class of LAT extragalactic sources.

**Misaligned active Galaxies**
- 27 sources resolved in 2FGL.

**Star-forming galaxies**
- Some galaxies outside the local group resolved by LAT.

**GRBs + High-latitude pulsars**
- Only small contributions expected.

Diffuse processes

**Intergalactic shocks**
- produced in galaxy cluster mergers

**Dark matter annihilation**
- Potential signal dependent on nature of DM.

**Interactions of UHE cosmic rays with the EBL**
- Strongly dependent on evolution of UHECR sources.
Derivation of the isotropic gamma-ray background.

\[ \text{Solar disk and IC} + \text{Resolved sources (2FGL)} + \text{Isotropic emission} = \text{Isotropic \( \gamma \)-ray background (IGRB)} \]

Not used in analysis:
- Galactic plane
- Regions with dense molecular clouds
- Regions with non-local atomic hydrogen clouds

- Interstellar gas
- Inverse Compton (IC)
- Loop I / Local Loop
- Galactic diffuse emission

Contamination from CR induced background
Results from the IGRB fit.

- **IGRB and CR contributions** to isotropic emission
- **Spectral fit of IGRB** by power-law with exponential cutoff.

> Based on **50 months of reprocessed LAT data**.

> **Average intensities** ($|b| > 20^\circ$) attributed to model templates.

> **Baseline foreground model** used.

The IGRB spectrum

> Error bars:
- statistical error
- + syst. error from effective area parametrization
- + syst. error from CR background subtraction

> Yellow band:
- systematic uncertainties from foreground model variations.

> IGRB spectrum can be parametrized by single power-law + exponential cutoff.

> Spectral index \(~ 2.3\) , cutoff energy \(~ 250\ \text{GeV}\).

> It is not compatible with a simple power-law \(\chi^2 > 85\).
The isotropic and the total extragalactic background.

Intensity that can be **resolved into sources** depends on:
- the sensitivity of the instrument.
- the exposure of the observation.

→ The **isotropic γ-ray background** depends on the sensitivity to identify sources.

→ Important as an **upper limit on diffuse processes**.

→ The **total extragalactic γ-ray background** is instrument and observation independent.

→ Useful for **comparisons with source population models**.
Comparison of LAT IGRB and EGB measurements

> Total extragalactic gamma-ray background (EGB) = IGRB + resolved sources.
> **Integrated intensity** of IGRB about **30% below** measurement in Abdo et al. 2010.
> **Compatible** within systematic uncertainties.
> **Main differences**: Improved diffuse foreground and CR background models.

Why is it so important?

Cosmic x-ray and gamma-ray background now measured over 9 orders of magnitude in energy.

The universe is transparent to gamma-rays (E<~10 GeV) to z > 10.
Contributions of known extragalactic sources.

At low energies:
- 10% - 20% contribution from star-forming galaxies
- 10% - 50% from misaligned AGN

Blazars seem to dominate at GeV energies.

~ 30% left for diffuse processes
Constraints on gamma-ray emission from DM annihilation.

Tight limits on contributions from diffuse processes, e.g. dark matter annihilation.
Constraints on the density of primordial black holes

> Primordial black holes evaporate into gamma rays (and other particles).

> $T_{BH} \sim 1/M_{BH}$
And the next step is....
No, **NOT** CTA !!*

* Disclaimer: This statement is true ONLY for the measurement of the diffuse gamma-ray background.

CTA will do a lot of great science!!!!
Cherenkov telescopes, the EGB, and cosmic-ray electrons.

Cherenkov telescopes cannot distinguish photons and electrons at high confidence!
The high-energy EGB cut-off.

Pair production in the Extragalactic Background Light introduces an energy dependent $\gamma$-ray horizon.

→ **Cut-off feature** in the EGB spectrum above $\sim 100$ GeV.

- If the bulk of the intensity comes from $z > 0.1$ sources.
The gamma-ray horizon and the neutrino domain.

Learned & Mannheim, 2000
The gamma-ray horizon and the neutrino domain.

And the next step is....
Discovery of astrophysical neutrinos.

- Astrophysical neutrinos are the only way to probe the non-thermal processes in the distant universe above tens of TeV.
- Good that IceCube has proven sensitive enough to see them.
The astrophysical neutrino flux must arise from multiple sources.

- No sources seen in (more sensitive) Point Source analysis

Part of it is from high Galactic latitudes.

-Points to an extragalactic origin.

Event distribution is compatible with an isotropic neutrino flux.
Signatures of neutrinos in IceCube

**Tracks**
μ from CC-νμ interactions **outside** the instrumented volume

**Starting tracks**
μ from CC-νμ interactions **inside** the instrumented volume

**Showers**
v_e, v_τ and v_μ-NC interactions

Aartsen et al., 2014
Signatures of neutrinos in IceCube

**Tracks**
\[ \mu \text{ from } \text{CC-}v_\mu \text{ interactions} \]
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Aartsen et al., 2014

![Diagram showing tracks and showers in IceCube](image)
Signatures of neutrinos in IceCube

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outside the instrumented volume

**Starting tracks**
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inside the instrumented volume

**Showers**
νe, ντ and νµ-NC interactions

---

Aartsen et al., 2014

several more searches, partly using construction phase data
Combination of searches in a global fit.

Global Fit of Astrophysical $\nu$ Spectrum

several more searches, partly using construction phase data

Lars Mohrmann, DESY
Extragalactic gamma rays and neutrinos.

Spectral index: $\Gamma = 2.5 \pm 0.08$

- NO indications for cutoff
- NO indications for a two-component spectrum

Lars Mohrmann, DESY
Extragalactic gamma rays and neutrinos.
The cosmic-ray / gamma / neutrino connection

> Cosmic rays interact with a target medium close to the source.

> Neutrino/Gamma production via p-p collisions

> Reprocessing of gamma rays to GeV energies

**PeV cosmic rays**

```
p

π^0

π^+/-

γ

μ

e

ν_μ

ν_e

v_μ

TeV-PeV Neutrinos
```

Target medium

p-p collisions

M82
The cosmic-ray / gamma / neutrino connection

- Cosmic rays interact with a target medium close to the source.
- Neutrino/Gamma production via p-p collisions
- Reprocessing of gamma rays to GeV energies
If extragalactic p-p collisions produce the observed $\nu$ → hard $\nu$-spectrum below 10 TeV needed.

...but difficult to explain spectra considerably harder than $\Gamma \sim 2$ in p-p scenario.

First hint at p-$\gamma$ interactions being the dominant neutrino production mechanism?

Or maybe that part of the signal is Galactic?
A proper calculation.

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> …but difficult to explain spectra considerably harder than $\Gamma \sim 2$ in p-p scenario.

> First hint at p-$\gamma$ interactions being the dominant neutrino production mechanism?

> Or maybe that part of the signal is Galactic?

[Murase, MA & Lacki’13; updated with Fermi 1410.3696]
Search for correlation of $\nu$ to the sample of Fermi Blazars.

> Most of the extragalactic GeV gamma-ray emission is from Blazars.
> Most of the emission is resolved in individual Fermi LAT sources.
> Search for neutrino emission spatially coincident with 2LAC Blazar sample.
> Neutrino dataset for point source analysis used (several $10^5$ events).

All blazars from 2-LAC – 862 objects

Thorsten Glüsenkamp, DESY
Extragalactic gamma rays and neutrinos.

Fermi LAT Blazars are NOT responsible for most of the observed $\nu$'s.

Upper limit on neutrino flux from Fermi Blazars

IceCube preliminary

$E_{\nu}^2 \Phi_{\nu}$ [GeV s$^{-1}$ sr$^{-1}$ cm$^{-2}$] vs $E_{\nu}$ [GeV]
Ultra-high energy protons produce gamma-rays and neutrinos during propagation.
Ultra-high energy protons produce gamma-rays and neutrinos during propagation.
The cosmic-ray / gamma / neutrino connection (II)

- High-energy cosmic rays interact with the EBL during propagation.

- Neutrino/Gamma production via $\pi\gamma$-interactions

- Reprocessing of gamma rays to GeV energies

EBL = extragalactic background light
The cosmic-ray / gamma / neutrino connection (II)

> High-energy cosmic rays interact with the EBL during propagation.

> Neutrino/Gamma production via $p\gamma$-interactions

> Reprocessing of gamma rays to GeV energies

EBL = extragalactic background light
Multi-messenger constraints on UHECR properties.

- CR, neutrino and gamma-ray spectrum from propagation code.
- Cosmological evolution of sources corresponds to **FR-II galaxy evolution**.
- CR sources produce protons.

Multi-messenger constraints on UHECR properties.

> CR, neutrino and gamma-ray spectrum from propagation code.
> Cosmological evolution of sources corresponds to **GRB evolution**.
> CR sources produce protons.

What we learned so far.

> The origin of more than half of the EGB can be attributed to known source populations.
  - Allows strong constrains on exotic processes in the universe.

> We see the signatures of CR acceleration / interaction up to tens of PeV in energy.
  - The origin seems to be at least partly extragalactic.

> The astrophysical neutrino spectrum between 20 TeV and 3 PeV can be described by a single power-law with index $\alpha = 2.5$.

> The EGB constrains the low-energy neutrino spectrum.
  - required hard spectrum might create tensions to an origin from p-p collisions.

> LAT Blazars are not responsible for the bulk of astrophysical neutrinos.

> There is likely no connection between the observed neutrinos and the ultra-high-energy cosmic rays
  - Need to observe a signal at higher energies.
What we will learn soon …..

→ Narrow down the source population(s) that produce high-energy cosmic rays.

> Improved accuracy of EGB measurement above 100 GeV.
> Better constraints on spectral parameters of $\nu$-flux, extended energy range.
> Find out if there is a Galactic contribution or anisotropy to the $\nu$-flux.
> More stringent constraints on extragalactic multi-PeV CR accelerators from the combination of EGB and astrophysical $\nu$’s.
> Discovery of sub-dominant $\nu$-flux contributions from Blazars, Radio Galaxies, or UHECR?
From discovery to high-statistics neutrino astronomy.

> ~100 more strings, 6 - 10 km$^3$ instrumented volume.
> Optimized for 10 TeV - 10 PeV astrophysical neutrinos.
> ~100 M€ Investment.
Backup.