Cosmic gamma rays and fundamental physics

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* Introduction: why gamma rays? How?
* Some results related to fundamental physics
* What’s next

Research on cosmic rays is in CERN’s constitution

(...)

1.

The basic programme of the Organisation shall comprise:

(i) The organisation and sponsoring of international co-operation in nuclear research, including co-operation outside the laboratory. This co-operation may include, in particular:

(ii) work in the field of theoretical nuclear physics;

(iii) the promotion of contacts between, and the exchange of, scientists; the dissemination of information, and the provision of advanced training for research workers;

(iv) collaboration with and advising of national research institutions;

(v) work in the field of cosmic rays.
**Thermal radiation: Black Body Spectrum**

- Cosmic Microwave Background: 2.7 K
- A Galactic gas cloud called Rho Ophiuchi: 60 K
- Dim star near the center of the Orion Nebula: 600 K
- The Sun: 6000 K
- Cluster of very bright stars, Omega Centauri, as observed from the space: 60,000 K
- Accretion Disks can reach temperatures >> 10^9 K

But this is still ~1 keV, in the X-Ray band!

**High Energy γ rays: non-thermal Universe**

- Particles accelerated in extreme environments interact with medium
  - Gas and dust; Radiation fields – Radio, IR, Optical, ...; Intergalactic Magnetic Fields, ...
- Gamma rays traveling to us!
  - HE: 30 MeV to 30 GeV
  - VHE: 30 GeV to 30 TeV
- No deflection from magnetic fields, gammas point ~ to the sources
  - Magnetic field in the galaxy: ~ 1μG
    \[ R \text{ (pc)} = \frac{0.01 \text{p (TeV)}}{B \text{ (μG)}} \]
    => for p of 300 PeV @ GC the directional information is lost
    \[ \Rightarrow \text{Gamma rays can trace cosmic rays at energies }~10x \]
- Large mean free path
  - Regions otherwise opaque can be transparent to X/γ

**Studying Gamma Rays allows us to see these aspects of the Universe**
Examples of known extreme environments

GRB

SuperNova Remnants
Pulsars

Active Galactic Nuclei

Accretion Disk 3-10 \( r_s \)
Black Hole Diameter = 2\( r_s \) ~ 4 AU

Cosmic \( \gamma \) rays: different production mechanisms expected to be at work

hadronic cascades

\( p^+ (\gg \text{TeV}) \)

\( \pi^0 \)

\( \gamma \gamma \) (TeV)

\( \pi^- \)

matter

In the VHE region, 
\( dN/dE \sim E^{-\Gamma} \) (\( \Gamma \): spectral index)

To distinguish between had/leptonic origin study Spectral Energy Distribution (SED): (differential flux) \( E^2 \)
New instruments often give unexpected results:

<table>
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<tr>
<th>Telescope</th>
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<th>Intended Use</th>
<th>Actual use</th>
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<td>1965</td>
<td>Sun, moon</td>
<td>neutron stars accreting binaries</td>
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<td>Ionosphere</td>
<td>Pulsars</td>
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<tr>
<td>γ-rays</td>
<td>military</td>
<td>1960?</td>
<td>Thermonuclear explosions</td>
<td>Gamma ray bursts</td>
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</tbody>
</table>

With future new detector can again hope for completely new discoveries.
How do gamma rays reach us?

\[ \gamma_{\text{vis}} \gamma_{\text{dark}} \rightarrow e^+ e^- \]

\[ \sigma(\beta) = 1.25 \times 10^{-2} (1 - \beta^2) \left[ 2(1 - \beta^2) + (1 - \beta^2) \ln \left( \frac{1 - \beta^2}{1 - \beta^2} \right) \right] \text{cm}^2 \]

Max for: 

\[ \gamma \approx \frac{2\varepsilon d^2}{d^2} \left( \frac{100 \text{GeV}}{d} \right)^4 \]

\[ \Phi_{\text{obs}}(E, z) = \Phi_{\text{cm}}(E) \times e^{-\tau(E, z)} \]

\( \tau > 1 \) region of opacity

\( \tau = 1 \) (GRH)

Gamma rays interact with the atmosphere

\( \Rightarrow \) GeV (HE) detection requires satellites; TeV (VHE) can be done at ground
Detection of a high E photon

- Above the UV and below “50 GeV”, shielding from the atmosphere
  - Below the e+e- threshold + some phase space (“10 MeV”), Compton/scintillation
  - Above “10 MeV”, pair production
- Above “50 GeV”, atmospheric showers
  - Pair <-> Brem

Consequences on the techniques

- The earth atmosphere (28 X₀ at sea level) is opaque to X/γ. Thus only a satellite-based detector can detect primary X/γ

- The fluxes of h.e. γ are low and decrease rapidly with energy
  - Vela, the strongest γ source in the sky, has a flux above 100 MeV of 1.3 \(10^{-5}\) photons/(cm²s), falling with \(E^{-1.89}\) => a 1m² detector would detect only 1 photon/2h above 10 GeV

  => with the present space technology, VHE and UHE gammas can be detected only from atmospheric showers
  - Earth-based detectors, atmospheric shower satellites

- The flux from high energy cosmic rays is much larger
Satellite-based and atmospheric: complementary, w/ moving boundaries

- Flux of diffuse extra-galactic photons

Satellite-based detectors: figures of merit

- Effective area, or equivalent area for the detection of $\gamma$
  $A_{\text{eff}}(E) = A \times \text{eff.}$

- Angular resolution is important for identifying the $\gamma$ sources and for reducing the diffuse background

- Energy resolution

- Time resolution
X/gamma detectors

• The electrons ejected or created by the incident gamma rays lose energy mainly in ionizing the surrounding atoms; secondary electrons may in turn ionize the material, producing an amplification effect
• Most space X-ray telescopes consist of detection materials which take advantage of ionization process but the way to measure the total ionization loss differ with the nature of the material
Commonly used detection devices are...
  – gas detectors
  – scintillation counters
  – semiconductor detectors

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X detection (direction-sensitive)

A coded mask (array of opaque blocks) is disposed so that a point source at infinity projects on a position sensitive detector a pattern characteristic of the source direction.

Coded mask

Position sensitive detector
X detection (direction-sensitive)

Unfolding is a nice mathematical problem!

HE/VHE gamma detectors

- Satellites (AGILE, Fermi)
  - Silicon tracker (+calorimeter)

- Cherenkov telescopes
  (HESS, MAGIC, VERITAS)

- Extensive Air Shower det.
  (ARGO): RPC, scintillators

HEP detectors!
The Cherenkov technique

Incoming γ-ray

θ_c ~ 1°

\( e^+\) Threshold @ sl: 21 MeV

Maximum of a 1 TeV shower:

~ 8 Km asl

~ 200 photons/m² in the visible

Angular spread ~ 0.5°

Image intensity ➔ Shower energy

Image orientation ➔ Shower direction

Image shape ➔ Primary particle

\( E\ast F(>E) \) [TeV/cm²s]

Agile, Fermi, Argo, Hawk; 1 year

Magic, Hess, Veritas, CTA; 50h

\( 10^{-13} \)

\( 10^{-12} \)

\( 10^{-11} \)

\( 10^{-14} \)

10 100 1000 10^4 10^5

E [GeV]
Highlight in γ-ray astrophysics (MAGIC, HESS, VERITAS)

- Thanks mostly to Cherenkov telescopes, imaging of VHE (> 30 GeV) galactic sources and discovery of many new galactic and extragalactic sources: ~ 150 (and >200 papers) in the last 7 years
  - And also a better knowledge of the diffuse gammas and electrons
- A comparable success in HE (the Fermi realm); a 10x increase in the number of sources
- A new tool for cosmic-ray physics and fundamental physics

Main physics results and perspectives (with emphasis on fundamental physics)

- Cosmic Rays
- Transparency of the Universe;
  Tests of Lorentz Invariance;
  Axion-Like Particles
- Search for “WIMP” Dark Matter
Origin of V(HE) Cosmic Rays

- Supernovae may be source of particles up to $>10^{15}$ eV
  - Nuclei receive energy from the shock wave of the supernova explosion
- The sources for ultrahigh cosmic rays are extragalactic: probably, AGN (and GRB?)
- Galactic (~1000 nG) and extragalactic (~0.1 nG?) fields make it difficult to observe directly the sources of CR
  - Gamma rays?

• Remember: despite the opinion of the Fantastic 4, only ~1%-0.1% of the cosmic rays are gammas...
• (In 1998, the Human Torch called his son “Cosmic Ray” in memory of that event)
Standard Model of galactic Cosmic Rays

- Galaxy is a leaky box
  - Energy-dependent escape of CR from the Galaxy
  - CR source spectra $dN/dE = E^{-2.1 \text{ to } 2.4}$, consistent w/ Fermi acceleration mechanism, (*)
    matches $E^{1.7}$ CR spectrum measured at Earth

- Supernova Remnants accelerate cosmic rays
  - Acceleration of CR in shock produced with external medium that lasts $\sim$1000 years
  - SN rate of 1/30 years means $\sim$30 SNR are needed to maintain cosmic ray flux
  - Confirmed by gamma-rays up to 50 TeV observed by HESS

- Model explains most observations, and is consistent with many details


Fermi acceleration

- Fermi's original 2nd-order Fermi acceleration involved randomly moving magnetic clouds that swept up charged particles in the ISM
- A simplified model is
  - Particle moves with energy $E$, shock is moving opposite with velocity $\beta$
  - The CR particle is reflected back and gains an energy

\[
\frac{\Delta E}{E} \simeq \beta
\]

- Particle is reflected back, either by magnetic cloud or outer shock shell moving with lower velocity than the inner shell
- At each cycle particle gains fractional energy $\beta$
  => after $n$ cycles the particle will have energy $E = E_0 (1 + \langle \beta \rangle)^n$
Fermi acceleration

- $E = E_0 (1 + \langle B \rangle)^n \Rightarrow n = \frac{\ln(E/E_0)}{\ln(1 + \langle B \rangle)}$

- At each acceleration, a particle has a probability $P(E,B)$ of escaping. Let us neglect the dependence on $E$, and take an average $<P>$. One has thus

$$\frac{N}{N_0} = p^n \Rightarrow \ln\left(\frac{N}{N_0}\right) = n \ln P = \frac{\ln(E/E_0)}{\ln(1 + \langle B \rangle)} = -s \ln \left(\frac{E}{E_0}\right) \Rightarrow N(>E) \propto E^{-s}$$

$$\Rightarrow \frac{dN}{dE} \propto E^{s-1} = E^{-\Gamma}$$

- For $\langle B \rangle \sim 1/30$, $(1-P) \sim 0.05$ one has $\Gamma \sim 2.7$

Possible acceleration sites

- Wherever you have (had) gravitational collapses, you can convert gravitational potential energy into kinetic energy of particles
  - But you need to confine the particles to accelerate them

  Large Hadron Collider

  $\mathbf{E} \propto \mathbf{B} \mathbf{R}$

  $R \sim 10 \text{ km}, B \sim 10 \text{T} \quad \Rightarrow \mathbf{E} \sim 10 \text{ TeV}$

  Tycho SuperNova Remnant
### Origin of cosmic rays: 
#### E propto BR

<table>
<thead>
<tr>
<th></th>
<th>B</th>
<th>R</th>
<th>E (eV)</th>
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</thead>
<tbody>
<tr>
<td>IGM</td>
<td>$10^{-4}$ μG</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ISM</td>
<td>3 x 1 μG</td>
<td>100 kpc</td>
<td></td>
</tr>
<tr>
<td>SNR</td>
<td>30 μG</td>
<td>1 pc</td>
<td>$3 \times 10^{16}$</td>
</tr>
<tr>
<td>SMBH</td>
<td>300 μG</td>
<td>$10^4$ pc</td>
<td>$&gt; 10^{21}$</td>
</tr>
<tr>
<td>GRB</td>
<td>$10^9$ G</td>
<td>$10^{-3}$ AU</td>
<td>$0.2 \times 10^{21}$</td>
</tr>
</tbody>
</table>

\[
\frac{E}{1 \text{ PeV}} \approx \frac{B}{1 \mu \text{G}} \times \frac{R}{1 \text{ pc}}
\]

\[
\frac{E}{1 \text{ PeV}} \approx 0.2 \frac{B}{1 \text{ G}} \times \frac{R}{1 \text{ AU}}
\]

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### Cosmic accelerators will always win over human-made

- Proposal of diffusive shock acceleration (Fermi, PR, 1949)

And also: the maximum possible energy for a terrestrial accelerator is ~ 5
Cosmic magnetic fields & CR propagation (CR for astronomy?)

- The same formula can give also the gyroradius
  \[ \frac{r}{1 \text{ pc}} \approx \frac{E}{1 \text{ PeV}} \times \frac{1}{B} \frac{1}{1 \mu \text{G}} \]
- If you want to look at the GC (d ~ 8 kpc) you need \( E > 2 \times 10^{19} \text{ eV} \)
  - But only 1 particle / km^2 / year
  - And: no galactic emitters expected at this energy
- But in principle one could look outside the galaxy, were B is smaller and there are SMBHs...

=> Astronomy with charged CR is impossible

- We need to detect a large statistics of protons with E between \( 10^{19} \text{ eV} \) and \( 10^{21} \text{ eV} \)
- Areas ~ 30 thousand km^2 (1/10 of Italy), ~impossible to find
- Needs satellites
  - EUSO (abandoned)
  - JEM/EUSO
- Waiting for them, gamma rays
Connection gamma/CR

- Study of target-accelerator systems: pinpointing sources of cosmic rays up to the knee
  - New “fresh” cosmic rays interacting with matter near the source OR...
- pp -> nπ0 -> 2nγ
  Secondary γ-rays have ~ 1/10 of the energy of the primary p
  \[
  \frac{dN_\gamma}{dE_\gamma} \propto \frac{dN_p}{dE_p} \otimes D \left( x = \frac{E_\gamma}{E_p} \right)
  \]
- For a power-law proton distribution the γ-ray distribution is again a power law with the same spectral index
  - This property should not be misinterpreted in the sense of a delta-function approximation: in general the γ-ray spectrum at energy Eγ does not trace the proton spectrum at energy E_p/f.
    - any feature in the proton spectrum will reappear smoothed in the γ-ray spectrum (e.g., an exponential cutoff in the proton spectrum, \( \exp[-E_p/E_{\text{cut}}] \), is transformed into a sub-exponential, \( \exp[-(16E_\gamma/E_{\text{cut}})^{1/2}] \))

Sources of CR up to the knee
Cherenkov telescopes & gamma satellites

- Evidence that SNR are sources of CR up to ~1000 TeV (almost the knee) came from morphology studies of RX J1713-3946 (H.E.S.S. 2004)
- Striking evidence from the morphology of SNR IC443 (MAGIC + Fermi/Agile 2010)
Molecular clouds close to IC 443, W51

- γ-ray excess coincides with cloud

More on SED

- PWN: The spectral energy distribution of RX J1713.7-3946 in the VHE γ-ray range indicates a hadronic mechanism at work
- Also VHE photons from pulsars, binaries...

Alessandro De...
Extragalactic sources: situation less clear (Auger?)
Joint HESS-MAGIC-VERITAS campaign on M87 (Science 2009)

- At ~60 Mly
- Shared monitoring HESS, MAGIC VERITAS
- Confirmation of day-scale VHE variability
- Correlation with the nucleus in X & Radio.
- Evidence of central origin of the VHE emission (60 Rs to the BH)

Cen A

- Located at a distance of ~13 Mly, the best candidate as a CR emitter from Auger
- Very faint VHE gamma-ray emitter (HESS 2009)
Orphan flares?

- IN SSC, a variability in gamma-ray and X-ray flux is expected to be correlated.
- Observations like orphan flares, where no X-ray flux increase is detected corresponding to a VHE flare, get the SSC model into trouble
  \[ \Rightarrow \text{Hadronic emission} \]

CR: clear synergy with neutrino detectors

- Smoking gun would be a correlation of VHE CR (difficult: magnetic fields) or a neutrino signal
- Many model uncertainties present in the gamma/p relation disappear when studying gamma/neutrino

\[
\frac{dN_{\gamma}}{dE} = \frac{1}{2} \frac{dN_{\nu}}{dE}
\]

(reflects the fact that pions decay into gamma rays and neutrinos that carry 1/2 and 1/4 of the energy of the parent. This assumes that the four leptons in the charged pion decay equally share the charged pion’s energy)
Measurement of spectral features permits to constrain EBL models

\[ \gamma_{\text{VHE}} \gamma_{\text{bck}} \rightarrow e^+ e^- \]

\[ c \leq \frac{2n_{\text{H}_2} \lambda}{E} \approx \left( \frac{500 \text{ GeV}}{E} \right) \text{eV} \]

- Dominant process for absorption:
- Maximal for:
- For gamma rays, relevant background component is optical/infrared (EBL)
- Different models for EBL: minimum density given by cosmology/star formation

Extragalactic Sources

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<tr>
<th>Source</th>
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<tr>
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<tr>
<td>1ES 0414+009</td>
<td>0.29</td>
<td>HESS/Fermi 2009</td>
</tr>
<tr>
<td>3S 0716+71</td>
<td>0.31+0.08</td>
<td>MAGIC 2009</td>
</tr>
<tr>
<td>1ES 0502+675</td>
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<td>PKS 1510-089</td>
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</tr>
<tr>
<td>4C +21.43</td>
<td>0.43</td>
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</tr>
<tr>
<td>3C 66A</td>
<td>0.44</td>
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</tr>
<tr>
<td>3C 279</td>
<td>0.54</td>
<td>MAGIC 2008</td>
</tr>
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</table>
Are our AGN observations consistent with theory?

Selection bias?
New physics?

\[ \phi_{\text{obs}}(E, z) = \phi_{\text{cm}}(E) \times e^{-\tau(E, z)} \]

\[ \tau > 1 \text{ region of opacity} \]

\[ \tau = 1 \]

Attempts to quantify the problem overall

- Analysis of AGN
  - For each data point, a corresponding lower limit on the optical depth \( \tau \) is calculated using a minimum EBL model
  - Nonparametric test of consistency
  - Disagreement with data: overall significance of 4.2 \( \sigma \)
=> Understand experimentally the outliers

(Horns, Meyer 2011)
If there is a problem

Explanations from the standard ones

- very hard emission mechanisms with intrinsic slope $< 1.5$ (Stecker 2008)
- Very low EBL, plus observational bias, plus a couple of "wrong" outliers to almost standard
- $\gamma$-ray fluxes enhanced by relatively nearby production by interactions of primary cosmic rays or $\nu$ from the same source to possible evidence for new physics

- Oscillation to a light "axion"? (DA, Roncadelli & MAnsutti [DARMA], PRD2007, PLB2008)
- Axion emission (Simet+, PRD2008)
- A combination of the above (Sanchez Conde et al. PRD 2009)

Axions

- The "strong CP problem": CP violating terms exist in the QCD Lagrangian, but CP appears to be conserved in strong interactions
- Peccei and Quinn (1977) propose a solution: clean it up by an extra field in the Lagrangian
  - Pseudoscalar, neutral, stable on cosmological scales, feeble interaction, couples to the photon
    - Can make light shine through a wall
  - The minimal (standard) axion coupling $g \propto 1/m$; however, one can have an "ALP" in which $g = 1/M$ is free from $m$
The photon-axion mixing mechanism

\[ L_{\gamma\gamma} = g_{\gamma\gamma} (\vec{E} \cdot \vec{B}) a \]


- Magnetic field 1 nG < B < 1aG (AGN halos). Cells of ~ 1 Mpc

\[ P_{\gamma \rightarrow n} = N P_1 \]

\[ P_1 = \frac{g_{\gamma\gamma} B_T s^2}{4} = 2 \times 10^{-3} \left( \frac{B_T}{1 \text{nG} \ 1 \text{Mpc}} \right) \frac{s}{10^{10} \text{GeV}^{-1}} \]

- \( m_\alpha < 0.02 \text{ eV} \) (direct searches)
- \( g < 10^{-10} \text{GeV}^{-1} \) from the non observation of \( \gamma \)-rays from the SN1987A, and direct searches

If B ~ 0.1 – 1 nG, observations can be explained

- Could also be something else: Whatever (light and almost sterile) particle feebly coupling to the photon
  - Paraphoton
  - Shadow photon
  - New millicharged particles...
Recent confirmation: something not understood

PKS1222:
an alternative discussion of the problem

- Tavecchio, Roncadelli, Galanti, Bonnoli 2012:
  - the $\gamma \rightarrow a$ conversion occurs before most of the photons reach the BLR. Accordingly, ALPs traverse this region unimpeded and
  - Outside, the re-conversion $a \rightarrow \gamma$ takes place either in the same magnetic field of the source or in that of the host galaxy
  - Resulting parameters of the ALP needed to fit the data consistent with DARMA
Summarizing: if the expected photon yield at VHE is different from what we think, what might be wrong?

• The sources are more complicated than we think (but only for sources far away: nearby sources behave well)

• VHE photons are generated on the way (interaction of cosmic rays, neutrinos and photons with intergalactic medium: Sigl, Essey, Kusenko, ...)

• Something is wrong in the $\gamma \gamma \rightarrow e^+ e^-$ rate calculation
  – Vacuum energy (new sterile particles coupling to the photons): DARMA, ...
    • For example an ALP: consistent values for $m$, $g=(1/M)$ in a range not experimentally excluded (“Se non e’ vero e’ ben pensato”)
  – $\gamma \gamma \rightarrow e^+ e^-$ cross section
    QED calculations appears to be in a safe region; then it must be
    • the boost (Lorentz transformations; relativity)

Is Lorentz invariance exact?

• For longtime violating Lorentz invariance/Lorentz transformations/Einstein relativity was a heresy
  – Is there an aether? (Dirac 1951)
  – Many preprints, often unpublished (=refused) in the ’90s

• Then the discussion was open
  – Trans-GZK events? (AGASA collaboration 1997-8)
  – LIV => high energy threshold phenomena: photon decay, vacuum Cherenkov, GZK cutoff (Coleman & Glashow 1997-8)
  – GRB and photon dispersion (Amelino-Camelia et al. 1997)
  – Framework for the violation (Colladay & Kostelecky 1998)
  – LIV and gamma-ray horizon (Kifune 1999)
  – ...
LIV? New form of relativity?

- Von Ignatowsky 1911: {relativity, omogeneity/isotropy, linearity, reciprocity} \(\Rightarrow\) Lorentz transformations with “some” invariant \(c\) (Galilei relativity is the limit \(c \rightarrow \infty\))
- CMB is the aether: give away isotropy?
- QG motivation: give away linearity? (A new relativity with 2 invariants: “c” and \(E_P\))

- In any case, let’s sketch an effective theory...
  - Let’s take a purely phenomenological point of view and encode the general form of Lorentz invariance violation (LIV) as a perturbation of the Hamiltonian (Amelino-Camelia+)

A heuristic approach: modified dispersion relations (perturbation of the Hamiltonian)

- We expect the Planck mass to be the scale of the effect

\[
E_P = \sqrt{\frac{\hbar c}{G}} \approx 1.2 \times 10^{19}\text{GeV}
\]

\[
H^2 = m^2 + p^2 \rightarrow H^2 = m^2 + p^2 \left(1 + \frac{E}{E_P} + \ldots\right)
\]

\[
H \frac{p}{p \gg} \rightarrow p \left(1 + \frac{m^2}{2p^2} + \frac{E}{2E_P} + \ldots\right)
\]

\[
v = \frac{\partial H}{\partial p} \approx 1 - \frac{m^2}{2p^2} + \frac{E}{E_P} \Rightarrow v \ll 1 + \frac{E}{E_P}
\]

\[\Rightarrow\text{ effect of dispersion relations at cosmological distances can be important at energies well below Planck scale: } \Lambda_{\chi} \ll T \Lambda E \frac{E}{E_P}\]
**Other effects of LIV: modified thresholds (Coleman-Glashow); transparency (Kifune 99)**

\[
v = \frac{\partial H}{\partial p} = 1 - \frac{m^2}{2p^2} + \frac{\xi}{E_p} \frac{p}{E_p}
\]

- **\(\xi < 0\):**
  - Increased transparency (threshold \(\gamma \gamma \rightarrow ee\) moves forward)

- **\(\xi > 0\):**
  - Electron becomes superluminal for energies larger than \(E_{\text{max}} / \sqrt{2}\) => Vacuum Cherenkov Radiation.

\[
c_e = c_e(1 + \delta), \quad 0 < \text{abs}(\delta) << 1 \quad \text{Coleman & Glashow; Stecker and Glashow}
\]

1. **If \(\delta < 0 \Rightarrow c_e < c_{\gamma} \Rightarrow\) decay \(\gamma \rightarrow e^+e^-\) kinematically allowed for gamma with energies above**
   \[E_{\text{max}} = m_e \sqrt{2/\text{abs}(\delta)}\]
   - \(E_{\gamma} \geq 100\) TeV \(\Rightarrow\) abs(\(\delta\)) \(< 5 \times 10^{-17}\)

2. **If \(\delta > 0 \Rightarrow c_e > c_{\gamma} \Rightarrow\) electrons become superluminal for energies larger than**
   \(E_{\text{max}} / \sqrt{2} \Rightarrow\) Vacuum Cherenkov Radiation.
   - \(E_{\gamma} > 2\) TeV from cosmic electron radiation \(\Rightarrow\) abs(\(\delta\)) \(< 2 \times 10^{-14}\)
   - Modification of \(\gamma \gamma \rightarrow e^+e^-\) threshold, Using Mkn 501 and Mkn 421 spectra observations up to \(E_{\gamma} > 20\) TeV
   \(\Rightarrow\) abs(\(\delta\)) \(< 1.3 \times 10^{-15}\)

From MAGIC Mkn501 (taken as a LIV signal): \(|\delta| \sim 2 \times 10^{-15}\)
Astrophysical constraints: time of flight

- Effect of dispersion relations at cosmological distances can be important at energies well below Planck scale:

\[ v_\gamma \approx 1 + \frac{\xi}{E_P} \Rightarrow \Delta t_\gamma \approx T \Delta E \frac{\xi}{E_P} \]
Rapid variability

MAGIC, Mkn 501
Doubling time ~ 2 min

HESS PKS 2155
z = 0.116
July 2006
Peak flux ~15 x Crab
~50 x average
Doubling times
1-3 min
\( R_{\text{BH}}/c \sim 1 \times 10^4 \text{s} \)

Tests of Lorentz violation: the name of the game

LEGS, PKS 2155

Lag(s)?
Quite some interest on Mkn 501 flare by MAGIC...

\[ \nu_{\gamma} = c \left( 1 + \frac{E}{M_\nu} + \frac{2}{3} \frac{E}{M_\nu} + \ldots \right) \]

**1st order**

\[ (\Delta t)_{\text{obs}} = \left( \frac{\Delta E}{E_0} \right) \frac{1}{H_0} \int_0^1 dz' \frac{(1 + z')}{\Omega_\Lambda (1 + z')^3 + \Omega_M} \]

- **MAGIC Mkn 501, PLB08** (with J. Ellis et al.)
  - \( E_{\gamma1} \sim 0.04 M_\odot (z \sim -25) \)
  - \( E_{\gamma1} > 0.02 M_\odot \)
- **HESS PKS 2155, PRL08**
  - \( E_{\gamma1} > 0.06 M_\odot \)
- **GRB X-ray limits:** \( E_{\gamma1} > 0.11 M_\odot \) (Fermi, but...)

> 1 GeV

---

**LIV in Fermi vs. MAGIC+HESS**

- **GRB080916C at** \( z=4.2 \): 13.2 GeV photon detected by Fermi 16.5 s after GBM trigger. At 1st order

\[ (\Delta t)_{\text{obs}} = \left( \frac{\Delta E}{E_0} \right) \frac{1}{H_0} \int_0^1 dz' \frac{(1 + z')}{\Omega_\Lambda (1 + z')^3 + \Omega_M} \]

- The MAGIC result for Mkn501 at \( z=0.034 \) is \( \Delta t = (0.030 \pm 0.012) \) s/GeV, for HESS at \( z=0.116 \), according to Ellis et al., Feb 09, \( \Delta t = (0.030 \pm 0.027) \) s/GeV
- \( \Delta t \sim (0.43 \pm 0.19) K(z) \) s/GeV

Extrapolating, you get from Fermi (26 + 11) s

(J. Ellis et al., Feb 2009)

**SURPRISINGLY CONSISTENT:**

**DIFFERENT ENERGY RANGE**

**DIFFERENT DISTANCE**
BUT: Fermi GRB 090510  GRB 090902

- \( z = 0.903 \pm 0.003 \)
- prompt spectrum detected, significant deviation from Band function at high E
- High energy photon detected: 31 GeV at \( T_0 + 0.83 \) s
  [expected from Ellis & al. (12 \pm 5) s]
- tight constraint on Lorentz Invariance Violation:
  - \( E_{s1} = M_{q6} > \text{several } M_{\text{Planck}} \)

\( z = 1.8 \pm 0.4 \)
- one of the brightest GRBs observed by LAT
- after prompt phase, power-low emission persists in the LAT data as late as 1 ks post trigger:
  highest E photon so far detected: 33.4 GeV, 82 s after GBM trigger
  [expected from Ellis & al. (26 \pm 13) s]
- much weaker constraints on LIV \( E_s \)

\( \Rightarrow \) Fermi rules, and 1\textsuperscript{st} order violations appear unlikely

\[ \text{2}\textsuperscript{nd} \text{ order? Cherenkov rules!} \]

\[ (\Delta t)_{\text{obs}} \approx \frac{3}{2} \left( \frac{\Delta E}{E_{s2}} \right)^2 H_0^{-1} \int_0^z d\zeta' \frac{(1 + \zeta')^2}{\sqrt{\Omega_M (1 + \zeta')^3 + \Omega_\Lambda}} \]

\[ E_{s2} > 6 \times 10^{10} \text{ GeV} (\sim 10^{-9} M_p) \text{ (HESS, MAGIC)} \]

A no-loss situation:
if propagation is standard, cosmology with AGN
If propagation is standard, cosmology with AGN

GRH depends on the γ-ray path and there the Hubble constant and the cosmological densities enter ⇒ if EBL density and intrinsic spectra are known, the GRH might be used as a distance estimator

\[ \frac{dl}{dz} = \frac{c}{H_0 (1+z)^2} \left[ (1+z)^2 (\Omega_M z + 1) - \Omega_L z (z+2) \right]^{\frac{1}{2}} \]

GRH behaves differently than other observables already used for cosmology measurements.

EBL constraints are paving the way for the use of AGN to fit \( \Omega_M \) and \( \Omega_L \) …

\[ \tau(E,z) = \int_{0}^{\infty} \frac{dl}{dE} \int_{0}^{\infty} \frac{dx}{2} \int_{0}^{\infty} dV \frac{x}{V(x+1)^2} \left[ 2 \pi \sigma \right] \]

Using the foreseen precision on the GRH (distance at which \( \tau(E,z)=1 \)) measurements of 20 extrapolated AGN at \( z>0.2 \), cosmological parameters can be fitted.

⇒ The \( \Delta \chi^2 = 2.3 \) 2-parameter contour might improve by a factor 2 the 2004' Supernovae combined result!
The Dark Matter Problem

Measure rotation curves for galaxies:

For large $r$, we expect:

$$G \frac{M}{r^2} = \frac{v^2(r)}{r} \implies v(r) \sim \frac{1}{\sqrt{r}}$$

we see: flat or rising rotation curves

Hypothesized solution: the visible galaxy is embedded in a much larger halo of Dark Matter (neutral; weakly interacting; mix of particles and antiparticles - in SUSY Majorana)

Which signatures for gamma detectors?

- Self-annihilating WIMPs, if Majorana (as the neutralino in SUSY), can produce:
  - Photon lines ($\gamma\gamma$, $\gamma Z$)
  - Photon excess at $E < m$ from hadronization
- Excess of antimatter (annihilation/decay)
- Excess of electrons, if unstable

$$\Phi \propto \sigma \langle v \rangle \frac{\rho^2}{m^2} \int_{\text{los}} dl$$

Look to the closest point with $M << L$
Many Places to Seek DM!

**Satellites**
Low background and good source id, but low statistics, astrophysical background

**Galactic Center**
Good statistics but source confusion/diffuse background

**Milky Way Halo**
Large statistics but diffuse background

**Spectral Features**
Lines, endpoint Bremsstrahlung,...
No astrophysical uncertainties, good source Id, but low sensitivity because of expected small BR

**Extra-galactic**
Large statistics, but astrophysics, galactic diffuse backgrounds

Results from GC

- **EGRET**: 3C J174.2-2815 (Hartman et al. 1999)

Extra-galactic:
- **MAGIC** (2004-2005, IZA, 25ke) - 7.3 std. dev, cool HESS spectrum (Albert et al., 2006, 638, L101)

Large Astrophysical Backgrounds for DM Search!

[Buckley 2011]
γ-ray detection from the GC

- detection of γ-rays from GC by Cangaroo, Whipple, HESS, MAGIC
- hard $E^{-2.2}$ spectrum
  fit to $\chi$-annihilation continuum
  spectrum leads to: $M_\chi > 14$ TeV
- other interpretations possible (probable)
  Galactic Center: very crowded sky region, strong exp.
  evidence against cuspy profile

no real indication of DM...
The spectrum is featureless!!!
dSph

Milky Way satellites Sagittarius, Draco, Segue1, Willman1, Perseus, ...

- proximity (< 100 kpc)
- no central BH (which may change the DM cusp)
- large M/L ratio (low baryonic content)
- No signal for now...

Results dominated by Fermi observations of Segue1 in the Leo constellation at ~23 kpc from the Sun luminosity is ~300x the Sun, M/L ~3400

small improvement by stacking

- Still a factor of >4 larger than a possible signal, even at low mass and in the most favorable assumptions
  - Majorana WIMP, DM profiles
- What could improve it?
  - A "boost" of f_\rho given by an anomalous DM concentration in subhalos
  - At 100 GeV, an improvement by a factor of 30 in sensitivity

Data-driven line searches (1)

- Very recently, one paper claims a positive signal (a ~4\sigma photon excess at ~130 GeV from Fermi data)
  - C. Weniger, arXiv:1204.2797

Selection of the region based on data
Large overlapping with The Fermi “bubbles”
Data-driven line searches (2)

- Confirmed by independent analyses
  - Tempel+, arXiv:1205.1045; Sahmet&Koushiappas, 1206.0796; Su&Finkbeiner, 1206.1616

Not confirmed by a “blind” line search by the official Fermi team on May 14 (But warning: it’s a different thing)

- Prospects for present Cherenkov telescopes: bad. Fermi: wait several years. LHC? Future Cherenkov?

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Cosmic rays: the ATIC anomaly

No peaks;
a possible excess might have standard/astrophysical explanations

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Cosmic rays: the PAMELA anomaly

Moon shadow observation mode developed for the MAGIC telescopes [MAGIC ICRC 2011]

sensitivity (50h): 300-700 GeV: ~4.4% Crab measurement possible in few years

DM: interplay with accelerators

- LHC may find candidates but cannot prove that they are the observed Dark Matter, nor localize it
- Direct searches (nuclear recoil) may recognize local halo WIMPs but cannot prove the nature and composition of Dark Matter in the sky
- LHC reach limited to some 200-600 GeV; IACT sensitivity starts at some ~200 GeV (should improve)
**A wish list for the future**

- Galactic sources & CR
  - extend E range beyond 50 TeV
  - better angular resolution
  - larger FOV

- AGN & gamma prop
  - monitor many objects simult.
  - extend E range under 50 GeV
  - 10x sources

- New particles, new phenomena
  - dark matter and astroparticle physics
  - better flux sensitivity
  - lower threshold

---

**The CTA concept (a possible design)**

- **2 arrays: north+south**
  - all-sky coverage

- **core array**
  - 100 GeV-10 TeV
  - ~ 23 ø = 12 m telescopes

- **low energy section**
  - $E_{\text{thresh}} \sim 10$ GeV
  - 4 ø = 23 m telescopes

- **high energy section**
  - ~ 35 ø = 6-7 m tel.
  - on 10 km² area

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CTA operation modes

- Monitoring 4 telescopes
- Survey mode: Full sky at current sensitivity in ~1 year
- Deep field ~1/3 of telescopes

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- Crab 10% Crab
- Fermi
- Magic-II
- Agile, Fermi, Argo, Hawc: 1 year
- Magic, Hess, Veritas, CTA: 50h

Far universe
Pulsars
Fundamental physics

Cosmic rays at the knee

\[ E \times F(>E) \ [\text{TeV/cm}^2\text{s}] \]

Agile, Fermi, Argo, Hawk: 1 year
Magic, Hess, Veritas, CTA: 50h
Relevance to high energy physics

• Physics
  – Energy: TeV energy scale (particle acceleration, elementary processes in the Universe)
  – Evolution of the Universe
  – Fundamental physics
    • Search for cosmological Dark Matter
    • Axion-like particles and new particles
    • Probe Quantum gravity (space time structure of vacuum) – close to the Planck Scale
  – Hadronic interactions (Gamma / Hadron separation)
  – Synergy with neutrino detectors

• Cutting edge technologies developed in HE physics
  – High QE advanced photodetectors, HPDs, SiPMs
  – Analogue signal transmission via optical fibers
  – Readout system 2GHz ultra fast analogue ring sampler
  – Ultra fast trigger system
  – Large data flow, massive computing (GRID computing)

Summary

• Clear interplay between VHE (γ) astrophysics and fundamental physics; this model of cooperation has worked well, and can work well in the future
  – We are confident that this exchange between complementary worlds will be useful, as history of particle physics demonstrated

• Cosmic Rays:
  – SNR as galactic sources established
    • Astronomy with charged CR is difficult
    • Astronomy with neutrinos will be difficult
    • VHE photons can be the pathfinder

• Still no detection of DM
  – The information from no detection is not as good as for accelerators

• A few clouds might hide new physics
  – Photon propagation

• Rich fundamental science (and astronomy/astrophysics) from gamma rays
  – HEA is exploring regions beyond the reach of accelerators
  – A “simple” extension of present detectors is in progress: CTA
TeV Astronomy: Highlights

Over 350 publications in high-impact journals:

- **Pulsars**: *Science* 322, 1221 (2008)
- **Galactic Survey**: *Science* 307, 1839 (2005)
- **Lorentz Invariance**: *Phys Rev Letters* 101, 170402 (2008)

Results from **HESS, MAGIC and VERITAS**
Highlight in gamma-ray astrophysics
(MAGIC, HESS, VERITAS)

- Thanks mostly to Cherenkov telescopes, imaging of VHE (> 100 GeV) galactic sources and discovery of many new galactic and extragalactic sources: ~ 150 (and >200 papers) in the last 7 years
  - And also a better knowledge of the diffuse gammas and electrons
- MAGIC is one of the 3 main actors, with some special characteristics
  - With a clear INFN identity (coordination of physics, leadership in AGN, ...)
  - ~1 refereed publication/month
  - 4 publications in “Science”
Crab pulsar

First detection of a pulsar above 25 GeV with special “sum” trigger

+ T. Saito thesis 2010, VERITAS 2011, MAGIC2011:
  Extension of spectrum to 400 GeV:
  inconsistent with the exponential + cutoff extrapolation (>50)
  Challenging result for pulsar models

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World-wide Collaboration
  25 countries
  132 institutes
  >800 scientists

The future in VHE gamma ray astronomy:

10 fold sensitivity of current instruments
10 fold energy range
improved angular resolution
two sites (North / South)
operated as observatory
Design study phase concluded in Fall 2010

- Design Concepts for the Cherenkov Telescope Array (arXiv:1008.3703)

FP7-supported Preparatory Phase: Fall 2010 – Fall 2013
- Technical design, sites, construction and operation cost
- Legal, governance and finance schemes
- Small + medium-sized telescope prototypes

Aim for
- start of deployment in early 2014
- first data in 2016/17
- base arrays complete in late 2018
- expanded mid-energy array driven by US
- total cost below 200 M€
**Design: 23 m Large Telescopes**

optimized for the range below 200 GeV

- 27.8 m focal length
- 4.5° field of view
- 0.1° pixels
- 400 m² dish area
- 1.5 m sandwich mirror facets
- On (GRB) target in < 20 sec.

![Carbon-fibre structure](Image)

**Design: Medium-Sized 12 m Telescope**

optimized for the 100 GeV to ~10 TeV range

- 16 m focal length
- 7-8° field of view
- 0.18° pixels
- 100 m² dish area
- 1.2 m mirror facets
Under study:
- dual-mirror optics with compact photo sensor arrays
- single-mirror optics
- PMT-based and silicon-based sensors

⇒ Not yet conclusive which solution is most cost-effective

Telescope characteristics

- Wavelength range: 300 – 600 nm
- Mirror PSF: $O(1')$ on axis, worse off axis
- Pixel size: $0.1^\circ – 0.2^\circ$
- Source localization: 5” – 10” for source centroid
- Image rate: kHz
- Exposure time:
  - single image: $O(10 \text{ ns})$
  - typical source: 10 – 50 h
Hardware key elements:

- **O(100) Telescope structures/drives:** very resistant, reliable, accurate, light-weight (LST)

- **O(10,000) m² Mirrors:** good quality, stable in extreme conditions, cheap, light-weight

- **O(2-3 x10,000) camera channels:**
  * **Photosensors:** PMT (and eventually SiPMs)
* **Readout Electronics**: fast, low dissipation, compact, reliable, cheap

- **Timing/Synchronization**: comparable to LHC machine requirements

- **Trigger/Data**: comparable to LHC experiments

**CTA performance: angular resolution**

- Angular resolution improves as more telescopes used in reconstruction
- Angular resolution closer to theoretical limit

![Angular resolution graph](image)
CTA: Expectations for Galactic plane survey

H.E.S.S.

CTA, for same exposure

expect ~1000 detected sources

CTA schedule (optimistic)

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Very funding dependent!
System fully operational in 2018