Particle Physics and Astrophysics by Cosmic Gamma-ray Observations

Hiroyasu Tajima
Solar-Terrestrial Environment Laboratory
Nagoya University

Fermi
Detecting Gamma-Ray Pulsars

CTA
Gamma-ray Space Telescope

KMI

October 24–26, 2011
KMI Inauguration Conference on “Quest for the Origin of Particles and the Universe”
Nagoya University, Japan
Outline

* Gamma-ray emissions in the Universe
* Cosmic gamma-ray experiments
  ❖ Fermi Gamma-Ray Space Telescope
  ❖ Imaging atmospheric Cherenkov telescopes
* Gamma-ray science
  ❖ Search for WIMP dark matter
  ❖ Search for origin of cosmic rays
  ❖ Physics with distant gamma-ray candles
* Future prospects
• Synchrotron radiation
• Compton up-scattering
  • CMB (Cosmic Microwave BG)
  • Synchrotron light
  • Interstellar light

\[ \text{Energy Flux (E}^2 \cdot \text{dN/dE)} \]

\[ \propto E^{1/3} \]

\[ \propto E^{-2.2} \]

\[ \propto E^{-1.6} \]
Gamma-ray Emission from Hadrons

- Nuclear interactions with interstellar medium
- Interactions with cosmic microwave background

\[ \gamma \text{ (Cosmic Microwave Background)} \]

\[ p \text{ (UHE)} \rightarrow e^+e^- \]

\[ (\text{Interstellar medium}) \]

\[ \pi^0 \rightarrow \mu^\pm \rightarrow e^\pm \]

\[ p \text{ (Interstellar medium)} \]
Annihilation/Decay of Massive Particles

WIMP Dark Matter Particles
$E_{CM} \sim 100 \text{GeV}$

$\chi \rightarrow W^{-}/Z/q$
$\chi \rightarrow W^{+}/Z/$

Gamma-rays

Neutrinos

$\pi^0, \pi^+, \pi^-, \mu^+, \mu^-, \nu_{\mu}, \bar{\nu}_{e}$

$\gamma, \nu_{\mu}, \bar{\nu}_{e}$

$a few p\bar{p}, d\bar{d}$

Anti-matter
### Gamma-ray Detectors

<table>
<thead>
<tr>
<th></th>
<th>Satellite based pair conversion</th>
<th>Atmospheric Cherenkov telescope</th>
</tr>
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<tbody>
<tr>
<td><strong>Experiments</strong></td>
<td>EGRET, AGILE, Fermi</td>
<td>HESS, VERITAS CANGAROO, MAGIC</td>
</tr>
<tr>
<td><strong>Energy range</strong></td>
<td>0.02 – 200 GeV</td>
<td>0.1 – 100 TeV</td>
</tr>
<tr>
<td><strong>Angular res.</strong></td>
<td>0.04 – 10 deg</td>
<td>~0.1 deg</td>
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<tr>
<td><strong>Collection area</strong></td>
<td>1 m²</td>
<td>10⁵ m²</td>
</tr>
<tr>
<td><strong>Field of view</strong></td>
<td>2.4 sr</td>
<td>10⁻² sr</td>
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<tr>
<td><strong>Duty cycle</strong></td>
<td>~95%</td>
<td>&lt;10%</td>
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</table>

![Diagram of Gamma-ray Detectors](image)
Fermi (GLAST)/LAT Overview

- **LAT (Large Area Telescope)** on board Fermi Observatory
- Satellite experiment to observe cosmic gamma rays
  - Wide energy range: 20 MeV to >300 GeV
  - Large effective area: > 8000 cm² (~6xEGRET)
  - Wide field of view: > 2.4 sr (~5xEGRET)

- Pair-conversion telescope
  - “Clear” signature
  - Background rejection
LAT Instrument Configuration

- **Tracker (TKR): conversion, tracking**
  - Angular resolution is dominated by scattering below ~GeV
  - Converter thickness optimization
- **Calorimeter: energy measurement**
  - 8.4 radiation length
  - Use shower development to compensate for the leakage
- **Anti-coincidence detector:**
  - Efficiency > 99.97%

Si Tracker
- 70 m², 228 µm pitch
- ~0.9 million channels

Large Area Telescope (LAT)

Anti-coincidence Detector
- Segmented scintillator tiles
- 99.97% efficiency

Gamma-ray Burst Monitor

Large Area Telescope (LAT)
LAT Instrument Configuration

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Anti-coincidence Detector  
Segmented scintillator tiles  
99.97% efficiency
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Anti-coincidence Detector
Segmented scintillator tiles
99.97% efficiency
Fermi/LAT Collaboration

Stanford University & SLAC
NASA Goddard Space Flight Center
Naval Research Laboratory
University of California at Santa Cruz
Sonoma State University
University of Washington
Purdue University-Calumet
Ohio State University
University of Denver
Commissariat a l’Energie Atomique, Saclay
CNRS/IN2P3 (CENBG-Bordeaux, LLR-Ecole polytechnique, LPTA-Montpellier)
Hiroshima University
Institute of Space and Astronautical Science
Tokyo Institute of Technology
RIKEN
Instituto Nazionale di Fisica Nucleare
Agenzia Spaziale Italiana
Istituto di Astrofisica Spaziale e Fisica Cosmica
Royal Institute of Technology, Stockholm
Stockholms Universitet

~400 Scientific Members (including
96 Affiliated Scientists,
plus 68 Postdocs and
105 Students)
Particle Background Environment

- TKR trigger rate is monitored throughout South Atlantic Anomaly
- Trigger rate saturates above $\sim 3.7$ kHz/layer
Event Rates

- **Overall trigger rate**: ~1–4 kHz
  - Huge variations due to orbital effects.

- **Downlink rate**: ~0.3–0.7 kHz
  - ~90% from GAMMA filter
  - ~30 Hz from minimum bias filter
  - ~5 Hz from heavy ion filter

- **Rate of photons after the standard background rejection cuts for source study**: ~1 Hz

- **Gamma-ray selection**: Most of the downlinked events are in fact background, final ~ 1000:1 rejection is done in ground processing.
Comparison with Previous Missions

- Number of triggers way beyond 100 billion (134x10^9; 26x10^9 downlinked)
- Number of photons in one year dwarfs previous missions
- Uptime: 99.1%
- All data public
- Processing time: typically 5-10 hours
- 5-year mission, no consumables
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Variable Gamma-ray Sky
Fermi data have been public since 2009 August

- data access: http://fermi.gsfc.nasa.gov/ssc/data/access/
- analysis tool: http://fermi.gsfc.nasa.gov/ssc/data/analysis/
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The Fermi Science Support Center (FSSC) runs the guest investigator program, provides analysis tools for the scientific community, and archive site is the portal to Fermi for all guest investigators.

Look into the "Resources" section for finding schedules, publications, useful where you will be able to find the relevant information and tools to prepare and submit proposals for guest investigator projects. At "Data" you will be able to access the Fermi databases and find the software to analyse them. Address all questions and requests to the helpdesk in "Help".

Quicklist
- 2011 Fermi Symposium
- Fermi Sky Blog
Scientific Impacts of Fermi

* >100 publications (> 2500 citations) in 2.7 years
* “Breakthrough of the Year” in 2009 selected by Science magazine

1. Ardipithecus Ramidus
2. Opening up the gamma-ray sky

* Bruno Rossi Prize 2011 awarded to W.B. Atwood, P. Michelson and Fermi LAT Team by High-Energy Astrophysics Division of AAS
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Nature: 3
Science: 10

* Bruno Rossi Prize 2011 awarded to W.B. Atwood, P. Michelson and Fermi LAT Team by High-Energy Astrophysics Division of AAS

- 271 gamma-ray sources (Hartman et al. 1999)
  - Only 38% (101 sources) have clear “identifications”
Fermi Large Area Telescope 2FGL catalog

1873 sources

- AGN 44.2%
- AGN-Blazar 14.3%
- AGN-Non Blazar 0.5%
- Galaxy 0.6%
- Unass. 30.6%
- Binary 0.2%
- PSR? 1.3%
- PSR 4.4%
- SNR/PWN 3.8%
- No gal. clusters no dwarf spheroidals

Credit: Fermi Large Area Telescope Collaboration
Highlights of Fermi Science

~60 pulsars

>1000 AGNs (active galactic nuclei)

extragalactic diffuse

cosmic-ray electron spectra
Highlights of Fermi Science

~60 pulsars

Crab flare

cosmic-ray electron spectra
Imaging Atmospheric Cherenkov Telescope

Cherenkov Light
50 photons/m² (5 pe/m²) at 1TeV
Cherenkov Light
50 photons/m² (5 pe/m²) at 1 TeV
Cherenkov Light
50 photons/m$^2$ (5 pe/m$^2$) at 1 TeV
**Imaging Atmospheric Cherenkov Telescope**

**Cherenkov Light**
50 photons/m² (5 pe/m²) at 1 TeV

**Typical parameters**
- Energy range: 50 GeV ~ 10 TeV
- CR rejection power: >99%
- Angular resolution: ~0.1 degrees
- Energy resolution: ~20%
- Detection area: ~10^5 m²
- Sensitivity: ~1% Crab Flux (10^{-13} erg/cm²s)
IACTs on Earth

- MAGIC
- VERITAS
- HESS
- PACT
- GRAPES
- CANGAROO
106 sources (45 Extragalactics + 61 Galactics) in Nov 2010
Blazars, FSRQs, FR-I, Starburst galaxies
SNRs, PWNe, Pulsar, Binaries, un-IDs
WIMP Search Approaches

* **Accelerator production**
  - Precise measurements of DM properties: mass, cross section
  - UED (KK) vs SUSY

* **Direct detection of WIMP scattering**
  - Measurement of local WIMP density

* **Indirect detection of WIMP annihilation**
  - Distribution of WIMP in the Universe

Those approaches are complimentary
- Different model dependences and sensitivity phase space

\[
\frac{d\Phi_y}{dE_y}(E_y, \varphi, \theta) = \frac{1}{4\pi} \frac{<\sigma_{\text{ann}}v>}{2m_{\text{IMP}}^2} \sum_f \frac{dN_f}{dE_y} B_f \times \int_{\Delta\Omega (\varphi, \theta)} d\Omega' \int_{\text{los}} \rho^2(r(l, \varphi')) dl(r, \varphi')
\]
Multi-pronged approaches

- Galactic center, Milky Way halo, Satellites
- Line emission, Continuum
- CR electrons, Diffuse gamma-ray background

Satellites:
Low background and good source id, but low statistics, astrophysical background
Good Statistics but source confusion/diffuse background

Milky Way halo:
Large statistics but diffuse background

Galactic center:
Good Statistics but source confusion/diffuse background

Search for WIMP with Gamma Ray

Gamma-rays

WIMP Dark Matter Particles $E_{CM} \sim 100\text{GeV}$

Neutrinos

+ a few $p/p, d/\bar{d}$
Anti-matter
Multi-pronged approaches

- Galactic center, Milky Way halo, Satellites
- Line emission, Continuum
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Satellites:
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Galactic center:
Good Statistics but source confusion/diffuse background
Galactic center is expected to have enormous amount of WIMP

- BG in TeV band is relatively low compared with GeV band due to steep Galactic diffuse BG spectrum
**Galactic center is expected to have enormous amount of WIMP**

- BG in TeV band is relatively low compared with GeV band due to steep Galactic diffuse BG spectrum.
Fermi WIMP Search in Dwarf Galaxies

* 10 most promising dSph (dwarf spheroidal) based on distance, Matter/Light (M/L)
  * New DM-dominated dSph is being discovered recently

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<tr>
<th>Name</th>
<th>Distance (kpc)</th>
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<th>M/L</th>
<th>Flux UL (E&gt;0.1 GeV) 10^{-9} c/cm^{2}/s</th>
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<td>23±3</td>
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## Fermi WIMP Search in Dwarf Galaxies

### Upper limits, $\bar{b}b$ channel

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ArXiv 1108.3546v2

### Diagram

[Graph showing WIMP cross section vs. WIMP mass for different dwarf spheroidal galaxies (dSph) with upper limits for the $\bar{b}b$ channel.]

The graph includes data for various dSphs, such as Draco, Ursa Major II, Carina, and Ursa Minor, with upper limits on the WIMP cross section as a function of WIMP mass. The graph also includes a joint likelihood for 10 dSphs combined, highlighting the sensitivity of Fermi observations to WIMP dark matter.

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Fermi WIMP Search in Dwarf Galaxies

Upper limits, Joint Likelihood of 10 dSphs

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**Notes:**
- 10 dSph combined
- Thermal relic WIMP
- bb channel
- WW channel
- \(\tau^+\tau^-\) channel
- \(\mu^+\mu^-\) channel

---

ArXiv 1108.3546v2
• Origin of cosmic ray protons?
  ➥ Galactic SNRs (Supernova Remnants) are considered as the best candidates for cosmic-rays below “Knee”
    • Only circumstantial evidence
      - Diffusive shock acceleration (Blanford&Eichler 1977)
      - CR energy sum consistent with SNR kinetic energy (Ginzburg&Syrovatskii 1964)
    • No observational evidence for hadronic acceleration
    • Spectral index (~2.7) is difficult to explain
  ➥ Cosmic-rays above “Knee” are considered extragalactic
    • Gamma-ray bursts (GRB)
    • Active Galactic Nuclei (blazar)
    • Merging galaxy clusters
* Origin of cosmic ray protons?

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“Gold-Plated” Supernova Remnant

- HESS TeV gamma-ray observation of RX J1713.7-3946
  - Evidence for particle acceleration > $10^{14}$ eV
  - Morphological similarity with X-ray observation
  - Spectral feature cannot conclusively distinguish leptonic or hadronic origin of gamma rays

Aharonian et al. 2005

HESS/ASCA

Aharonian et al. 2005

HESS/ASCA

Events

- H.E.S.S. data
- NANTEN data

TeV gamma-ray

Molecular clouds

Azimuth (deg.)
Expected Fermi Spectrum for J1713

- Simulated 5-year Fermi observation of RX J1713-3946
- Fermi is expected to positively identify hadronic contribution

![Graph showing Fermi Spectrum for J1713](image)
Fermi Observation of RX J1713.7-3946

- Leptonic model may explain the Fermi spectrum better
- Requires more statistics to distinguish hadronic or leptonic nature of gamma-ray emissions
RX J0852.0–4622: Another TeV SNR

TeV Gamma-ray Image by H.E.S.S. (Aharonian+ 2007)

Contours: ROSAT X-ray (E > 1.3 keV)

Red vertical bars: statistical errors
Black caps: systematic errors

$E^2 dN/dE$ [erg cm$^{-2}$ s$^{-1}$]

$10^{-10}$

$10^{-11}$
RX J0852.0–4622: Another TeV SNR

Contours: ROSAT X-ray (E > 1.3 keV)
Red vertical bars: statistical errors
Black caps: systematic errors

\[ E^2 \frac{dN}{dE} \text{ [erg cm}^{-2} \text{ s}^{-1}] \]

\[ \log_{10}(E/\text{eV}) \]

\( \pi^0 \) decays
IC
sync

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Hard Gamma-Ray Spectra

- Hard gamma-ray can be explained by higher target density for higher energy particles
- Highly inhomogeneous molecular clouds interacting with SNR
- Higher energy protons can penetrate into the cloud core where target gas density is high
Correlation with Matter Density

* Sum of molecular and atomic hydrogen gives good correlation with TeV gamma-ray intensity

Fukui et al. arXiv 1107.0508v4
Young SNR Cassiopeia A

- Last SNR witnessed by human (AD 1680)
- Both leptonic and hadronic interpretation possible
  - **Leptonic (Bremsstrahlung + IC)**
    - $B \sim 0.12$ mG, $W_e \sim 1 \times 10^{49}$ erg
    - Not consistent with X-ray variability ($B \sim 0.5$ mG)
  - **Hadronic ($\pi^0$ decay)**
    - $B > 0.12$ mG, $W_\rho \sim 5 \times 10^{49}$ erg

---

**Leptonic model**

**Hadronic model**  
$I = 2.4$, no break  
$I = 2.1$, $E_{\text{break}} = 10$ TeV
Young SNR Cassiopeia A

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- Both leptonic and hadronic interpretation possible
  - Leptonic (Bremsstrahlung + IC)
    - \( B \approx 0.12 \text{ mG}, \ W_e \approx 1 \times 10^{49} \text{ erg} \)
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  - Hadronic (\( \pi^0 \) decay)
    - \( B > 0.12 \text{ mG}, \ W_p \approx 5 \times 10^{49} \text{ erg} \)

![Graph showing normalized counts/sec/keV vs energy (keV) for various B fields: B = 0.1 mG, B = 0.3 mG, B = 1.0 mG.]

- Leptonic model
- Hadronic model

---

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JAXA ASTRO-H

* History of Japanese X-ray satellite


Hakucho

Tenma

Ginga

ASCA

ASTRO-E (launch vehicle failure)

Suzaku

ASTRO-H

??

Credit: ISAS/JAXA
History of Japanese X-ray satellite


Hakucho
Tenma
Ginga
ASTRO-E (launch vehicle failure)
ASTRO-H
Suzaku

Soft Gamma-ray Detector

Credit: ISAS/JAXA
Taking advantage of Japanese semiconductor detector technologies and space technologies

- Silicon sensors by Hamamatsu photonics
- Space instrument assembly (Mitsubishi Heavy Industries)
- Localization of gamma-ray sources such as radio isotopes
AGN and GRB as Distant Candles

* 10–100 GeV gamma rays can probe early universe

\[ \tau(E,z) = 3 \]

Model Predictions
AGN and GRB as Distant Candles

* 10–100 GeV gamma rays can probe early universe

\[ \tau(E,z) = 3 \]

Model Predictions
Lorentz Invariance Violation (LIV)

* Some QG models predict a violation of Lorentz Invariance at HE:

\[
c^2 p_\gamma^2 = E_\gamma^2 \left[ 1 + \sum_{k=1}^{\infty} s_k \left( \frac{E_\gamma}{M_{QG,k} c^2} \right)^k \right] \quad \Rightarrow \quad v_\gamma^2 = \frac{\partial E_\gamma}{\partial p_\gamma} = c \left[ 1 - s_n \frac{1 + n}{2} \left( \frac{E_\gamma}{M_{QG,k} c^2} \right)^n \right]
\]

QG mass: energy scale where QG effect are expected to be significant

* Time delay between 2 photons of energies \(E_h\) and \(E_l\) emitted simultaneously:

\[
\Delta t = \frac{(1 + n)}{2H_0} \frac{(E_h^n - E_l^n)}{(M_{QG,n} c^2)^n} \int_0^z \frac{(1 + z')^n}{\sqrt{\Omega_m (1 + z')^3 + \Omega_\Lambda}} \, dz'
\]

decompositional distance assuming \(\Lambda CD M\)

* GRB is a excellent light source due to long distance (high z) and short duration

  * Constraint using GRB 080916C: 13.2 GeV photon detected 16.5 sec after trigger
- 30 GeV photon from z=0.9 (7.3B years)
- Quantum Gravity models predicting linear LIV are strongly disfavored

<table>
<thead>
<tr>
<th>choice for t_{start}</th>
<th>limit on Δt (ms)</th>
<th>lower limit on MQG,1/M_{Planck}</th>
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</thead>
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<tr>
<td>start of any observed emission</td>
<td>&lt; 859</td>
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<td>start of main &lt; 1 MeV emission</td>
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<td>&gt; 3.42</td>
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<td>start of &gt; 100 MeV emission</td>
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<td>&gt; 5.12</td>
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<tr>
<td>start of &gt; 1 GeV emission</td>
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<td>&gt; 10.0</td>
</tr>
<tr>
<td>association with &lt; 1 MeV spike</td>
<td>&lt; 10</td>
<td>102</td>
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</tbody>
</table>

![Graph](chart.png)

Particle Physics and Astrophysics by Cosmic Gamma-ray Observations
KMI Inauguration Conference 2011, OCT 24–26, 2011, Nagoya, Japan
CTA (Cherenkov Telescope Array)

- Large collection area (x~30)
- Better angular resolution (0.03°, x~1/3)
- ~1000 of TeV gamma-ray sources
- Optimized telescope configuration
  - LST: ~23 m φ x 4, ~30 GeV – 1 TeV
  - MST: ~12 m φ x 20, ~100 GeV – 10 TeV
  - SST: 4~6 m φ x 40~70, ~1 TeV – 100 TeV
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**Sources**
- Distant AGN, GRB, Pulsars
- Galactic, nearby extragalactic sources
- PeV Galactic cosmic-ray sources
CTA Membership

* 25 countries
* 132 Institutions
* 734 Scientists
Summary and Future Prospect

- Fermi/LAT limit on WIMP cross section is now cut into expected value from thermal relic WIMP
- Gamma-ray observations (with other waveband) are now establishing SNR as a origin of Galactic cosmic rays
- Fermi/LAT observations of distant GRBs gave very stringent constraints on LIV
- CTA is a promising project to open up TeV gamma-ray sky like Fermi

![Graph showing the expected cross section from thermal relic WIMP](image)

- Fermi dSph expected sensitivity
- Fermi dSph combined U.L.
- CTA Galactic center U.L.
- Cherenkov Galactic center U.L.
- Cherenkov individual dSph best U.L.

Cross section expected from thermal relic WIMP
Particle Acceleration in SNR

- Young shell-type supernova: SN1006
  - Power law spectrum from rim is best described by synchrotron emission by ultra-relativistic electrons
  - First evidence of particles accelerated to $> 10^{14}$ eV

ASCA image of SN 1006

X-ray spectrum of SN 1006

Koyama et al.

Ozaki
SNR with Multi-wavelength Observations

Radio
GeV electrons

Optical light

X-ray
High temp. plasma
TeV electrons

TeV Gamma ray
TeV electrons
TeV hadrons

Credit: H.E.S.S., NASA/CXC/Rutgers, NRAO/AUI/NSF/GBT/VLA,
Middlebury College/F.Winkler, NOAO/AURA/NSF/CTIO Schmidt & DSS
Gamma-Ray Bursts Overview (1)

- Discovered in 1967
- Cosmological origin
  - Large apparent energy release: $10^{52}$-$10^{54}$
  - Energetics consistent with origin of UHECR
- Peak in $\sim$MeV gamma rays
  - Band function: smoothly joined two power law
  - Synchrotron radiation of ultra-relativistic electrons in jet?
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  - Band function: smoothly joined two power law
  - Synchrotron radiation of ultra-relativistic electrons in jet?

Batse Trigger 907

\begin{align*}
\text{Seconds Since Trigger} & \quad 907016 : 39694.187 \\
\text{Rate (counts s}^{-1} \text{)} & \quad 6.0 \times 10^3, 8.0 \times 10^3, 1.0 \times 10^4, 1.2 \times 10^4, 1.4 \times 10^4, 1.6 \times 10^4, 1.8 \times 10^4 \\
\text{Ch: (1: 4)} & \\
\text{Time Res: 0.500 s} \\
\end{align*}

Batse Trigger 1440

\begin{align*}
\text{Seconds Since Trigger} & \quad 920226 : 29728.491 \\
\text{Rate (counts s}^{-1} \text{)} & \quad 1.0 \times 10^4, 2.0 \times 10^4, 3.0 \times 10^4, 4.0 \times 10^4, 5.0 \times 10^4, 6.0 \times 10^4, 7.0 \times 10^4 \\
\text{Ch: (1: 4)} & \\
\text{Time Res: 0.064 s} \\
\end{align*}

Batse Trigger 577

\begin{align*}
\text{Seconds Since Trigger} & \quad 910725 : 47526.507 \\
\text{Rate (counts s}^{-1} \text{)} & \quad 9.00 \times 10^3, 9.50 \times 10^3, 1.00 \times 10^4, 1.05 \times 10^4, 1.10 \times 10^4, 1.15 \times 10^4, 1.20 \times 10^4, 1.25 \times 10^4 \\
\text{Ch: (1: 4)} & \\
\text{Time Res: 0.500 s} \\
\end{align*}

Batse Trigger 298

\begin{align*}
\text{Seconds Since Trigger} & \quad 910609 : 2907.1153 \\
\text{Rate (counts s}^{-1} \text{)} & \quad 0, 1.0 \times 10^5, 2.0 \times 10^5, 3.0 \times 10^5, 4.0 \times 10^5 \\
\text{Ch: (1: 4)} & \\
\text{Time Res: 0.064 s} \\
\end{align*}

$\alpha = -0.6 \pm 0.07$

$\beta = -3.11 \pm 0.07$

$E_p = 720 \pm 10$ keV
Gamma-Ray Bursts Overview (2)

- **Bimodal Duration Distribution**
  - **Short (< 2s) GRB**: progenitor unknown
    - Merger of compact objects (NS or BH)?
  - **Long (> 2s) GRB**:
    - Association with supernovae
      ⇒ Core-collapse supernovae

- **Gamma-ray emission mechanism not well understood**
High-Energy Emissions from GRB (Past)

- EGRET observations of delayed HE gamma-ray emissions
  - It is not straightforward to explain by conventional electron synchrotron models
  - Proton acceleration?
  - Origin of UHECR?

Gonzalez, Nature 2003 424, 749

Hurley et al. 1994

Two $\gamma >$GeV @~$T_0$

18 GeV $\gamma$ @ ~$T_0+75$ min
EGRET High-Energy GRB Spectra

- 5 EGRET bursts with >50 MeV observations in 7 years
  - No evidence of cutoff or extra HE component in the summed spectrum

Dingus et al. 1997
## Common Features of LAT GRBs

<table>
<thead>
<tr>
<th>GRB</th>
<th>long or short</th>
<th># of events &gt; 100 MeV</th>
<th># of events &gt; 1 GeV</th>
<th>Highest Energy (arrival time)</th>
<th>Delayed HE onset</th>
<th>Long-lived HE emission</th>
<th>Extra component</th>
<th>Cutoff</th>
<th>Redshift</th>
</tr>
</thead>
<tbody>
<tr>
<td>080825C</td>
<td>long</td>
<td>~10</td>
<td>0</td>
<td>~0.6 GeV (~T₀+28 s)</td>
<td>✔</td>
<td>✔</td>
<td>?</td>
<td>?</td>
<td></td>
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<tr>
<td>080916C</td>
<td>long</td>
<td>&gt;100</td>
<td>&gt;10</td>
<td>~13 GeV (~T₀+17 s)</td>
<td>✔</td>
<td>✔</td>
<td>hint</td>
<td>?</td>
<td>4.35</td>
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<tr>
<td>081024B</td>
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<td>~10</td>
<td>2</td>
<td>~3 GeV (~T₀+0.6 s)</td>
<td>✔</td>
<td>✔</td>
<td>?</td>
<td>?</td>
<td></td>
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<tr>
<td>081215A</td>
<td>long</td>
<td>—</td>
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<td>090217</td>
<td>long</td>
<td>~10</td>
<td>0</td>
<td>~1 GeV (~T₀+15 s)</td>
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<td>090323</td>
<td>long</td>
<td>~20</td>
<td>&gt;0</td>
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<td>090328</td>
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<td>~20</td>
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<td>0.736</td>
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<td>090510</td>
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<td>&gt;150</td>
<td>&gt;20</td>
<td>~31 GeV (~T₀+0.8 s)</td>
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<td>✔</td>
<td>?</td>
<td>0.903</td>
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<td>090626</td>
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<td>~20</td>
<td>&gt;0</td>
<td>—</td>
<td>—</td>
<td>✔</td>
<td>—</td>
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<tr>
<td>090902B</td>
<td>long</td>
<td>&gt;200</td>
<td>&gt;30</td>
<td>~33 GeV (~T₀+82 s)</td>
<td>✔</td>
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<td>?</td>
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<tr>
<td>090926A</td>
<td>long</td>
<td>&gt;150</td>
<td>&gt;50</td>
<td>~20 GeV (~T₀+25 s)</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>2.106</td>
</tr>
</tbody>
</table>
Delayed HE Gamma-ray Emission

* Opacity due to $\gamma\gamma \rightarrow e^+e^-$ in the first peak?
  * No evidence of spectral cut-off

* Late arrival of highest energy gamma rays

GRB 090926

GRB 080916C

8 – 250 keV

0.26 – 5 MeV

All LAT events

> 100 MeV

> 1 GeV

13.2 GeV photon

Science 323 1688A (2009)
Delayed HE Gamma-ray Emission

- Opacity due to $\gamma\gamma \rightarrow e^+e^-$ in the first peak?
- No evidence of spectral cut-off
- Late arrival of highest energy gamma rays

GRB 090926

GRB 080916C

8 – 250 keV

0.26 – 5 MeV

4 – 250 keV

All LAT events

> 100 MeV

> 1 GeV

13.2 GeV photon

Science 323 1688A (2009)
HE (>100 MeV) emission shows different temporal behavior

- Temporal break in LE emission while no break in HE emission
  - Indication of cascades induced by ultra-relativistic ions?
  - Angle-dependent scattering effects?
Extra Component

- Extra spectral component inconsistent with Band function
  - Both in low- and high-energy regions
- This is a challenge to theoretical model
  - Low energy excess difficult to explain by inverse Compton
  - Early afterglow?

---

**GRB 090902B**


---

**GRB 090510**

Time-integrated photon spectrum (0.5 s – 1.0 s)
• Narrow spikes correlated in all energy band
  • Common origin

Spectral cutoff - GRB 090926A

PRELIMINARY
Narrow spikes correlated in all energy band
- Common origin
- Significant spectral break
  - Shape is not constrained
  - If cutoff due to $\gamma$-$\gamma$ absorp.
    • 1st direct measurement of bulk Lorentz factor ($\Gamma \sim 200-700$)
## Implications on GRB Models

* Implications on GRB gamma-ray emission models
  - **Internal Shock**
    - Leptonic models (Synchrotron Self-Compton) Ryde 2010, Toma 2010
    - Hadronic models Asano 2009, Razzaque 2009
  - **External Shock**
    - Early afterglow Ghisellini 2010, Kumar & Barniol Duran 2009, Piran 2010

<table>
<thead>
<tr>
<th>Variability during prompt phase</th>
<th>Delayed onset</th>
<th>Low energy excess</th>
<th>Long-lived HE emission</th>
<th>Other features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptonic</td>
<td>✓</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Hadronic</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>High B-field, large $E_{\text{ISO}}$ (x~10)</td>
</tr>
<tr>
<td>Early afterglow</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>High Lorenz factor</td>
</tr>
</tbody>
</table>
Constraints on Bulk Lorentz Factor

- Large luminosity and short variability time imply large optical depth due to $\gamma\gamma \rightarrow e^+e^-$
  - Small emission region: $R \sim c\Delta t$
  - $\tau_{\gamma\gamma}(E) \sim (11/180)\sigma_T N_{>1/E}/4\pi R^2$
    - $\tau_{\gamma\gamma}(1 \text{ GeV}) \sim 7 \times 10^{11}$ for fluence=$10^6 \text{ erg/cm}^2$, $z=1$, $\Delta t=1 \text{ s}$
- Relativistic motion ($\Gamma \gg 1$) can reduce optical depth
  - Larger emission region: $R \sim \Gamma^2 c\Delta t$
  - Reduced # of target photons: $N_{>1/E} \propto \Gamma^{2\beta+2}$ (note: $\beta \sim -2.2$)
    - Blue shift of energy threshold: $E_{\text{th}} \propto \Gamma$
    - Blue shift of spectrum: $N(E) = (\Gamma E)^{\beta+1}$
    - Overall reduction of optical depth: $\Gamma^{2\beta-2} \sim \Gamma^{-6.4}$
- Possible selection bias due to large $E_{\text{ISO}}$
- Assume common emission region for all gamma rays
Long and Short GRBs

- Long & short GRBs do not show significant difference in HE spectral properties
- Short GRBs show higher energy output in HE region than long GRBs
Long and Short GRBs

* Long & short GRBs do not show significant difference in HE spectral properties
* Short GRBs show higher energy output in HE region than long GRBs

![Graph showing the comparison between long and short GRBs in terms of energy output.](image)
Null-Hypothesis Test with Likelihood Ratio

* Minimal assumptions: intrinsic γ-ray spectrum does not harden above \( \sim 10 \text{ GeV} \) (conservative in case of spectral cutoff)
* Null-hypothesis (H0): [power law] + [predicted EBL]
* Alternative model (H1): EBL opacity normalization left as a free parameter
* Test-Statistics = \( L(H0)/L(H1) \)
• Stecker’s “baseline” and “fast evolution” models are rejected
  • > 5σ post-trial significance for 1 source (J1016+0513)
  • > 10σ significance with stacking analysis
• Other models cannot be constrained significantly
<table>
<thead>
<tr>
<th>Array layout</th>
<th>06</th>
<th>07</th>
<th>08</th>
<th>09</th>
<th>10</th>
<th>11</th>
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<tbody>
<tr>
<td>Telescope design</td>
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<td>Component prototypes</td>
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</table>

Design

Prototype

Array