High Energy Gamma Ray and Neutrino Astronomy

John Beacom
The Ohio State University

NGC 253
How Is This Talk Topic Even Possible?

High Energy **Gamma Ray and Neutrino Astronomy**

- Energy $E$ large (!)
- Luminosity $L$ large (!)
- Pointing $\theta$ small (!)

And what about detecting those neutrinos…?
Plan of the Talk

Is there a high energy universe to discover? Is it important for astro- and particle physics?

Motive: Charged Cosmic Rays Exist

Means: Gamma Ray and Neutrino Production

Opportunity: Gamma Ray Astronomy

Opportunity: Neutrino Astronomy

Judgment: Concluding Perspectives
Motive: Charged Cosmic Rays Exist

How are they given such large energies?
What are their sources?
Made energetic:
Natural Accelerators (or unnatural ones)
Magic of shocks giving up kinetic energy
Requirement of escape
E arbitrarily large; nonthermal power-law spectrum

Born energetic:
Dark Matter (or a new heavy thing)
Magic of annihilation or decay giving up mass energy
Requirement of Standard Model final states
E large but less than $M_{DM}$; calculable spectra

But what about luminosity, pointing?
Charged cosmic rays of many species are detected

**Energy:** up to $10^{20}$ eV

**Luminosity:** large (seen 100 years ago, $U_{CR} \sim U_{\text{starlight}}$)

**Pointing:** isotropic

**Origin and sources unknown ... so what about pointing?**
“Beam on” ... somewhere

Need to find some experts on pointing

Results of required Environmental Impact Study:
Charged cosmic rays always come with appreciable fluxes of gamma rays and neutrinos

Gamma rays and neutrinos (and only these) can provide pointing ... but what about detection?
**Means:** Gamma Ray and Neutrino Production

Why must there be gamma rays and neutrinos?

How well are their spectra known?
Accelerators

Cosmic rays were seemingly cleanly accelerated, but the accelerating fields require matter and radiation

No ideal accelerator exists

Cosmic rays must interact in the sources and en route

If there are any accelerated charged particles, then gamma rays and neutrinos are inevitable

E arbitrarily large; nonthermal power-law spectrum
Sample Charged Cosmic Ray Interactions

- **Hadronic mechanism**
  \[ p + p \rightarrow p + p + \pi^0, \ p + n + \pi^+ \]
  \[ \pi^0 \rightarrow 2\gamma, \ \pi^\pm \rightarrow e^\pm + 3\nu \]

- **Leptonic mechanism**
  \[ e^- + \gamma \rightarrow \gamma + e^- \]

- **Nuclear (A*) mechanism**
  \[ A' + \gamma \rightarrow A^* + X \]
  \[ A^* \rightarrow A + \gamma \]
Dark Matter

Dark matter seemingly does not interact, but the dark matter self-annihilation cross section is nonzero

\[ <\sigma_A v> \sim \frac{1}{\Omega_{DM}} \sim \text{weak scale} \]

Annihilation in the early universe due to high density; annihilation in the late universe due to clumping

If there are any Standard Model final states, then gamma rays and neutrinos are inevitable

E large but less than \( M_{DM} \); calculable spectra
Opportunity: Gamma Ray Astronomy

How can we detect and identify these?

What have we learned so far?
Gamma rays are not detected directly, but only through the consequences of their EM interactions.

\[
\gamma + A \rightarrow e^+ + e^- + A
\]

\[
e + A \rightarrow e + \gamma + A
\]

ing ionization, etc.

Gamma rays point, but they can be attenuated and do not uniquely reveal their birth processes or energies.
Gamma Ray Detectors

below ~ 0.3 TeV

- shower in detector

~ 0.3-30 TeV

- Cerenkov from shower in air

- EGRET, Fermi

above ~ 3 TeV

- shower at ground

- HESS, VERITAS, MAGIC

- Milagro, HAWC
Sub-GeV Gamma Ray Skymap

Credit: NASA/DOE/Fermi LAT Collaboration

Fermi Collaboration (2009)
Sources are High-Energy and Luminous

supernova remnant RX J1713.7-3946

HESS Collaboration (2006)
Diffuse Gamma Ray Spectra

Ajello, Fermi Collaboration (2011)
Total cross section and average mass density known, but...

Many possible final states, with different gamma ray spectra

Real uncertainties in dark matter clumping

Abazajian et al. (2010)

See Geringer-Sameth and Koushiappas (to appear)
Opportunity: Neutrino Astronomy

How can we detect and identify these?

What have we learned so far?
Neutrinos are not detected directly, but only through the consequences of their weak interactions: EM showers, hadronic showers, and muon tracks.

\[
\begin{align*}
\nu_e + n &\rightarrow e^- + p \\
\nu_\mu + n &\rightarrow \mu^- + p \\
\nu_\tau + n &\rightarrow \tau^- + p
\end{align*}
\]

Plus charge conjugates
Plus neutral-current channels

Neutrinos point, and flavors can help reveal the parent processes, but neutrinos are hard to detect.
IceCube at the South Pole is complete
Size $\sim 1\,\text{km}^3$
Sees the Northern sky

Similar plans for the Mediterranean Sea (km3net)
Neutrino Skymap ... Background Dominated

IceCube Collaboration (2011)
Neutrino Sources

Vela Jr. supernova remnant

IceCube (2011): no sources seen yet in blind or directed searches

Limits approaching models and will soon improve with more data, better analysis techniques, and more gamma ray data

Kistler, Beacom (2006)
Diffuse Neutrino Spectra

IceCube Collaboration (2011)
What if dark matter annihilation tries to hide from us?

The hardest SM case is pure neutrinos.

Even then, there will be good sensitivity.

Beacom, Bell, Mack (2006)

IceCube and Super-K can make big improvements.

Rott, IceCube Collaboration (2011)
Judgment: Concluding Perspectives
<table>
<thead>
<tr>
<th>cosmic rays</th>
<th>gamma rays</th>
<th>neutrinos</th>
</tr>
</thead>
<tbody>
<tr>
<td>energetic</td>
<td>direct</td>
<td>revealing</td>
</tr>
<tr>
<td>divertable</td>
<td>stoppable</td>
<td>untrustworthy?</td>
</tr>
</tbody>
</table>
Essential link between astrophysics and physics:
Astrophysics is unrivaled in its prospecting power, and laboratory work is essential for decisive tests.

Essential link between theory and experiment:
Theory must play an empirical and synthetic role, and experiment must present generic constraints.

Lots of great work being done by young theorists:
These people are well positioned to help make big discoveries; don’t let them fall through the cracks!
Conclusions

Great unsolved questions in high energy astronomy:
Origin of cosmic rays, nature of gamma ray sources,
particle properties of dark matter and neutrinos, etc.

Big steps in sensitivity give new opportunities:
Probing extremes of energy, distance, density, and
fields that cannot be matched in the laboratory

Neutrino observations can be decisive:
Even a few neutrinos can identify a hadronic source,
the emission energy scale, hidden sources, etc.
**Astrophysical Neutrino Sources**

**MeV: Thermal Sources**
- Milky Way supernova, ~ few per century
- nearby supernovae, ~ 1 per year
- Diffuse Supernova Neutrino Background, constant flux

**TeV: Nonthermal Sources**
- steady sources, e.g., Milky Way supernova remnants
- varying sources, e.g., Active Galactic Nuclei
- transient sources, e.g., gamma-ray bursts
- possible sources from dark matter annihilation

**EeV: Extreme Sources**
- almost certain flux from UHE cosmic ray propagation
- likely fluxes from those accelerators directly
- possible sources from supermassive particle decays
CCAPP at Ohio State

Center for Cosmology and AstroParticle Physics

ccapp.osu.edu

Postdoctoral Fellowship applications welcomed in Fall