Multi-messenger astronomy:

The key to high energy (astro)physics with neutrinos

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High energy $\nu$'s: A new window

MeV $\nu$ detectors:
- Solar & SN1987A $\nu$'s
- Stellar physics (Sun’s core, SNe core collapse)
- $\nu$ physics

$>0.1$ TeV $\nu$ detectors:
- Extend $\nu$ horizon to extra-Galactic scale
  \[
  [\text{MeV } \nu \text{ detectors limited to local (Galactic) sources} \\
  10\text{kt } @ 1\text{MeV} \rightarrow 1\text{Gton } @ \text{ TeV}, \sigma_{\text{TeV}}/\sigma_{\text{MeV}} \sim 10^6 ]
  \]
- Study “Cosmic accelerators”: $p\gamma, pp \rightarrow \pi's \rightarrow \nu's$
- $\nu$ physics

Cosmic accelerators:
- Open questions $\rightarrow$ Prime scientific motivation
- Observed properties $\rightarrow$ Detector characteristics
CRs and their sources:
Open Questions
Open Qs: I. The origin of CRs

<table>
<thead>
<tr>
<th>Cosmic-ray E [GeV]</th>
<th>log ([dJ/dE])</th>
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<tbody>
<tr>
<td>(1)</td>
<td>(10^6)</td>
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<tr>
<td>(10^6)</td>
<td>(10^{10})</td>
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- **Heavy Nuclei**
- **Protons**
- **Lighter**
- **Light Nuclei?**
- **Source:** Supernovae(?)
- **Source?**
- **Galactic**
- **UHE X-Galactic**

Where is the G/XG transition?
Are SNRs the low E CR sources?

- So far, no clear evidence. Electromagnetic observations- ambiguous.

E.g.: “π decay signature” [Ackermann et al. 13]:

![Graph showing gamma-ray flux and proton spectrum](image-url)
UHE, \( >10^{10}\) GeV, CRs

\[
J(>10^{11}\text{GeV}) \sim 1 / 100 \text{ km}^2 \text{ year } 2\pi \text{ sr}
\]

Auger: 3000 km\(^2\)

Fluorescence detector

Ground array
Open Qs: II. UHE Composition

Auger 2010

HiRes 2010 (& TA 2011)
Open Qs: II. UHE Composition

Auger 2010

HiRes 2010 (& TA 2011)

[Wilk & Wlodarczyk 10]*

[*Possible acceptable solution?, Auger collaboration 13]
UHE: Energy production rate & spectrum

Protons

$$\varepsilon^2 \frac{dQ}{d\varepsilon} \propto \text{Const.}$$

$$= 0.5(\pm 0.2) \times 10^{44} \text{ erg/Mpc}^3 \text{ yr} + \text{GZK}$$

[Allard 12]

Mixed composition

[Katz & EW 09]
Open Qs: III. Where is the G-XG transition? @ \( E \leq 10^{18} \text{eV} \)?

\[ \varepsilon^2 \frac{dQ}{d\varepsilon} = \text{Const} \rightarrow @ E \approx 10^{19} \text{eV} \]

- Fine tuning
- Inconsistent with Fermi’s XG \( \gamma \) (<1TeV) flux

[Katz & EW 09]

[Gelmini 11]
Open Qs: IV. Source physics challenges

- Electromagnetic acceleration in astrophysical sources requires
  \[ L > L_B > 10^{14} L_{\text{sun}} \left( \frac{\Gamma^2}{\beta} \right) \left( \frac{\epsilon}{Z \times 10^{20} \text{eV}} \right)^2 \text{erg/s} \]

  [Lovelace 76; EW 95, 04; Norman et al. 95]

- GRB: \( 10^{19} L_{\text{sun}}, M_{BH} \sim M_{\text{sun}} \), \( \dot{M} \sim 1 M_{\text{sun}}/s \), \( \Gamma \sim 10^{2.5} \)

- AGN: \( 10^{14} L_{\text{sun}}, M_{BH} \sim 10^9 M_{\text{sun}} \), \( \dot{M} \sim 1 M_{\text{sun}}/\text{yr} \), \( \Gamma \sim 10^1 \)

- No steady sources at \( d < d_{GZK} \rightarrow \) Transient Sources (AGN flares?)

Energy extraction;
Jet acceleration and content (kinetic/Poynting)
UHE: Do we learn from (an)isotropy?

CR intensity map \( \rho_{\text{source}} \sim \rho_{\text{gal}} \) [Kashti & EW 08]

Galaxy density integrated to 75Mpc [EW, Fisher & Piran 97]
UHE: Do we learn from (an)isotropy?

Biased ($\rho_{\text{source}} \sim \rho_{\text{gal}}$ for $\rho_{\text{gal}} > \bar{\rho}_{\text{gal}}$)

- **Anisotropy @ 98% CL; Consistent with LSS**
  
  [Kotera & Lemoine 08; Abraham et al. 08… Oikonomou et al. 13]

- **Anisotropy of Z at $10^{19.7}$eV implies**
  
  Stronger aniso. signal (due to p) at $(10^{19.7}/Z)$ eV

  Not observed $\rightarrow$ No high Z at $10^{19.7}$eV

  [Lemoine & EW 09]
UHECR experiments: prospects?

• Unlikely to identify the sources.

• Composition?
astronomy to the rescue
HE $\nu$: UHECR bound

• $p + \gamma \rightarrow N + \pi$
  $\pi^0 \rightarrow 2\gamma$; $\pi^+ \rightarrow e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$

→ Identify UHECR sources
  Study BH accretion/acceleration physics

• For all known sources, $\tau_{\gamma p} \leq 1$:

$$\varepsilon_v^2 \frac{dj_v}{d\varepsilon_v} \leq \Phi_{WB} \equiv 10^{-8} \zeta \left( \frac{\varepsilon^2 dQ / d\varepsilon}{10^{44} \text{erg/Mpc}^3 \text{yr}} \right) \frac{\text{GeV}}{\text{cm}^2 \text{s sr}}$$

$$\zeta = 1, 5 \quad \text{for} \quad f(z) = 1, (1 + z)^3$$

• If X-G p's:

$$\varepsilon_v^2 \frac{dj_v}{d\varepsilon_v} (10^{19} \text{eV}) = \Phi_{WB}$$

[EW & Bahcall 99; Bahcall & EW 01]

[EB & Berezinsky & Zatsepin 69]

→ Identify primaries, determine $f(z)$
"Hidden" (ν only) sources

Violating UHECR bound
Bound implications: $\nu$ experiments

$$\frac{\varepsilon^2 dQ}{d\varepsilon} = 0.5 \times 10^{44} \text{ erg/Mpc}^3\text{yr}$$

2 flavors,
Consistent with Isotropy and
with $\nu_e:\nu_\mu:\nu_\tau=1:1:1$ ($\pi$ deacy + cosmological prop.).
IceCube’s detection: Implications

- Unlikely Galactic: $\varepsilon^2 \Phi_\gamma \sim 10^{-7}(E_{0.1\text{TeV}})^{-0.7}\text{GeV/cm}^2\text{s sr}$ [Fermi]
  $\Rightarrow \varepsilon^2 \Phi_\nu \sim 10^{-9}(E_{0.1\text{PeV}})^{-0.7}\text{GeV/cm}^2\text{s sr} \ll \Phi_{\text{WB}}$

- DM decay?
  The coincidence of $50\text{TeV} < E < 2\text{PeV}$ $\nu$ flux, spectrum (& flavor) with the WB bound is unlikely a chance coincidence.

- XG distribution of sources,
  $\varepsilon^2(dQ/d\varepsilon)_{\text{PeV-EeV}} \sim \varepsilon^2(dQ/d\varepsilon)_{>10\text{EeV}}, \tau_{\gamma p(pp)} > 1$ [“Calorimeters”]
  Or:
  $\varepsilon^2(dQ/d\varepsilon)_{\text{PeV-EeV}} \gg \varepsilon^2(dQ/d\varepsilon)_{>10\text{EeV}}, \tau_{\gamma p(pp)} << 1$
  & Coincidence over a wide energy range.

- $\varepsilon^2(dQ/d\varepsilon) \sim \varepsilon^0$ implies: p, G-XG transition at $\sim 10^{19}\text{eV}$. 
StarBurst galaxies
Radio, IR & γ-ray (GeV-TeV) observations →
Starbursts are calorimeters for E/Z reaching at least 10PeV;
Were predicted to produce the observed ν signal.
\[ \pi \text{ production: } p/A \rightarrow p/\gamma \]

- \[ \pi \text{ decay } \rightarrow \nu_e: \nu_\mu: \nu_\tau = 1:2:0 \ (\text{propagation}) \rightarrow \nu_e: \nu_\mu: \nu_\tau = 1:1:1 \]

- \[ p(A)-p: \frac{\varepsilon_n}{\varepsilon_p} \sim 1/(2\times3\times4)\sim0.04 \ (\varepsilon_p \rightarrow \varepsilon_A/A); \]
  - IR photo dissociation of \( A \) does not modify \( \Gamma \);
  - Comparable particle/anti-particle content.

- \[ p(A)-\gamma: \frac{\varepsilon_n}{\varepsilon_p} \sim (0.1-0.5)x(1/4)\sim0.05; \]
  - Requires intense radiation at \( \varepsilon_\gamma \gtrsim A \text{ keV}; \)
  - Comparable particle/anti-particle content,
    \( \nu_e \) excess if dominated by \( \Delta \) resonance \( (\frac{d\log n_{\gamma}}{d\log \varepsilon_\gamma} < -1) \).

[Spector, EW & Loeb 14]
Some comments RE next steps

• The most natural explanation of
  Isotropic, $\nu_e: \nu_\mu: \nu_\tau = 1:1:1$, $\phi \sim \phi_{WB}$ at $\sim$ TeV–2PeV

Is: - UHE CRs are p’s, produced by
  - XG sources with $\varepsilon^2 (dQ/d\varepsilon) \sim$ const. from $\sim$PeV to $>10$EeV,
  - residing in “calorimeters” (starbursts?).
  - G/XG transition @ $\sim$10EeV.
    ($\pi^0$'s cascade to $<0.1$TeV, consistent w/Fermi’s limit).

• The number of events provided by IceCube
  ($\sim$1/yr @ $E>1$ PeV, $\sim$10/yr @ $E>0.1$PeV)
  will not be sufficient for an accurate determination of
  spectrum, flavor ratio and (an)isotropy.

• An (independent) confirmation of
  \{XG p @ UHE, G/XG transition @ 10 EeV\}
  will be provided by the detection of GZK $\nu$’s.
The key next step: 
EM source identification

- Identify >10PeV CR sources; 
  
  ν & EM observations will enable us to 
  resolve key open Qs in the accelerators’ physics 
  (BH jets, particle acceleration, collisionless shocks...), 
  determine UHECR source identity.

- Fundamental/ν physics 
  - \( \pi \) decay \( \rightarrow \) \( \nu_e:\nu_\mu:\nu_\tau = 1:2:0 \) (Osc.) \( \rightarrow \) \( \nu_e:\nu_\mu:\nu_\tau = 1:1:1 \) 
    \( \rightarrow \) \( \tau \) appearance 
  - GRBs: ν-γ timing (10s over Hubble distance) 
    \( \rightarrow \) LI to 1:10^{16}; WEP to 1:10^6 a 
  * Understanding the source w/ EM crucial 
    (e.g. strong B may lead to \( \nu_e:\nu_\mu:\nu_\tau = 1:2:2 @ high E \) [Kashti & EW 05]) 

- Optimistic (>100’s of ν’s with flavor identification): 
  Constrain flavor mixing, new phys. 
  [Blum, Nir & EW 05; Winter 10; Pakvasa 10]
Identifying the sources

• The angular resolution of ν-“telescopes”, ~1deg or worse, will not allow one to identify cosmologically distributed sources; Multiple events will constrain $L_\nu$ (but will not identify).

• Steady UHECR sources are unlikely detectable: $A_{\text{effective}}(10^{14}\text{eV }\nu \sim 10^{-4}\text{km}^2) \sim 10^{-7.5}$ $A_{\text{effective}}(10^{19}\text{eV CR} \sim 10^{3.5}\text{km}^2)$
  $\rightarrow$ Not detectable in $\nu$’s unless $L_\nu \gg 100L_{CR}$, which Cannot be the case since $Q_{CR} \sim Q_\nu$.

• The only hope is to associate a $\nu$ with an EM transient. Luckily, UHECR sources must be bright transients. Required: Wide field EM monitoring, and
  Real time alerts for follow-up of high $E_\nu$ events.

• Note: $\Phi_\nu$(source) may be $\ll \Phi_\nu$(calorimeter)$\sim \Phi_{WB}$ [$\Phi_\nu$(GRB) $\sim 0.1 \Phi_{WB}$], $P$(nearby source for efficient follow up)$\sim A^{3/2}$. 
IceCube’s GRB limits

- No $\nu$’s associated with ~200 GRBs (~2 expected).
- IC analyses overestimate GRB flux predictions, and ignore model uncertainties.
- IC is achieving relevant sensitivity.

$$\epsilon_{\nu,b} = 500 \left( \frac{\epsilon_{\gamma,b}}{1\text{MeV}} \right)^{-1}$$

$$\Gamma^2 \text{TeV} \approx 1\text{PeV}$$

$$\Phi_{\text{GRB}} \approx 0.2\Phi_{\text{WB}}$$

[Hummer, Baerwald, and Winter 12; see also Li 12; He et al 12]
The cosmic ray spectrum

[From Helder et al., SSR 12]
The cosmic ray generation spectrum

$E^2 \frac{dQ}{dE} \text{ [erg/Mpc}^3 \text{ yr]}$

$10^{43} \quad 10^{44} \quad 10^{45}$

$10^{-1} \quad 10^{3} \quad 10^{5} \quad 10^{7} \quad 10^{9} \quad 10^{11}$

MW CRs, Starbursts (+ CRs~SFR)

XG $\nu$’s

XG CRs

A single source?

[Katz, EW, Thompson & Loeb 14]
What is required for the next stage of the $\nu$ astronomy revolution

• Significantly (x10) larger effective A/V @ E>~0.1 PeV → Accurate spectrum, flavor content, (an)isotropy.

• Adequate sensitivity for detecting the $\sim10\text{EeV}$ GZK $\nu$'s.

• EM association- Bright transients are the prime targets. Via: Wide field EM monitoring, and Real time alerts for follow-up of high E $\nu$ events.

• Combined $\nu$ & EM observations will enable us to
  - Identify the CR (UHE & G-CR) sources,
  - Resolve open “cosmic-accelerator” physics Qs (related to BH-jet systems, particle acc., rad. mechanisms),
  - Constrain $\nu$ physics, LI, WEP.