A multi-messenger quest for the sources of the highest energy cosmic rays
Origin of ultra-high energy cosmic rays?
A 50 year old mystery

$E_{\text{kin}}$ of $10^{20}$ eV proton = $E_{\text{kin}}$ of tennis ball at 100km/h!
Origin of ultra-high energy cosmic rays? A 50 year old mystery

$E_{\text{kin}}$ of $10^{20}$ eV proton = $E_{\text{kin}}$ of tennis ball at 100km/h!

Image: Hillas 2006
Origin of ultra-high energy cosmic rays? A 50 year old mystery

$1 \text{ EeV} = 10^{18} \text{ eV}$
Origin of ultra-high energy cosmic rays?
A 50 year old mystery

UHECRs
1 EeV = 10^{18} eV

~0.1 km century
~0.1 km year
~2/ month in giant EAS detectors
Origin of ultra-high energy cosmic rays?
A 50 year old mystery

Space & space/balloon
- e.g. JEM-EUSO
- ANITA
- EVA

Ground experiments
- Haverah Park
- KASCADE
- HiRes
- AGASA
- Auger
- ISS-CREAM
- TIGER...

~0.1 m
~0.1 km
~0.1 m
~0.1 km
~0.1 km century
0.1 km
0.1 km year
& space/balloon
e.g. JEM-EUSO
ANITA
EVA
Origin of ultra-high energy cosmic rays? A 50 year old mystery
Origin of ultra-high energy cosmic rays? A 50 year old mystery

Sources?

Extra-Galactic

Galactic SN remnants
Fermi/AGILE

π⁰ decay
Detection
Detection
Detection
3000 km² in Malargue, Argentina

27 Fluorescence telescopes [%15 duty cycle]

1660 Cherenkov tanks [100% duty cycle]

[1.5 km tank spacing]
680 km² in Utah

507 scintillator counters (1.2 km spacing)

3 FD Sites
Candidate sources

Minimum requirement - Confinement:
\[ R_{\text{source}} > r_{\text{armor}} \]

\[ E \leq E_{\text{max}} \sim 1 \text{ EeV} \ Z \left( \frac{B}{1 \mu \text{G}} \right) \left( \frac{R_{\text{source}}}{1 \text{ kpc}} \right) \]

Sources must be extragalactic for \( E > 1-10 \text{ EeV} \)
Candidate sources

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\[ R_{\text{source}} > r_{\text{armor}} \]

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Sources must be extragalactic for \( E > 1-10 \text{ EeV} \)
What information do we have?

Arrival directions

Spectrum/energetics

Secondary products

Composition

Multi-messenger temporal coincidences
What information do we have?

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The energy spectrum

190 000 events!!

50 000 km² sr yr

Pierre Auger Coll. ICRC 2015
The energy spectrum

![Graph showing the energy spectrum with different energy levels and logarithmic scales for energy and differential flux.

- Proton, $\beta = 2.6$, $m = 0$
- Proton, $\beta = 2.35$, $m = 5$
- Iron, $\beta = 2.3$, $m = 0$
- Combined

$E^3 J(E)$ in $\text{eV}^2 \text{km}^{-2} \text{sr}^{-1} \text{yr}^{-1}$

Auger 2013

$\Delta E/E = 14\%$

$E [\text{eV}]$

$10^{18}$  \hspace{1cm} $10^{19}$  \hspace{1cm} $10^{20}$

$\log_{10}(E/\text{eV})$

$17.5$  \hspace{1cm} $18.0$  \hspace{1cm} $18.5$  \hspace{1cm} $19.0$  \hspace{1cm} $19.5$  \hspace{1cm} $20.0$  \hspace{1cm} $20.5$
The energy spectrum

Many ways to fit the spectrum!
Composition

Average depth of shower maximum $<X_{\text{max}}>$
[average deeper for protons than heavy nuclei]
Composition

Average depth of shower maximum $\langle X_{\text{max}} \rangle$ [average deeper for protons than heavy nuclei]
Average depth of shower maximum $<X_{\text{max}}>$
[average deeper for protons than heavy nuclei]
Composition

Average depth of shower maximum $\langle X_{\text{max}} \rangle$

[average deeper for protons than heavy nuclei]
What information do we have?

- **Arrival directions**
- **Composition**
- **Spectrum/energetics**
- **Multi-messenger temporal coincidences**
- **Secondary products**
UHECR Interactions

GZK process ($E_p > 6 \times 10^{19}$ eV):

Bethe-Heitler pair creation ($E > 6 \times 10^{16}$ eV):

$$p + \gamma_{CMB} \rightarrow pe^+e^-$$
UHECR Interactions

Proton energy loss length [Mpc]

- photo-pion
- BH pair-production
- universe expansion

E [EeV]
UHECR Interactions

Small propagation horizon at the highest energies!
UHECR Interactions

Small propagation horizon at the highest energies!
UHECR Propagation in the intergalactic medium

\[
\theta(E, L) \approx 0.22^\circ Z \left( \frac{L}{10 \text{ Mpc}} \right)^{1/2} \left( \frac{E}{10^{20} \text{ eV}} \right)^{-1} \left( \frac{\lambda}{0.1 \text{ Mpc}} \right) \left( \frac{B}{10^{-9} \text{ G}} \right)
\]

\(\approx 2^\circ \) for \(10^{20} \text{ eV}\) proton

Waxman & Miralda-Escude 1995

Image: Kotera & Olinto 2011
UHECR Propagation in the intergalactic medium

- deflection causes time delay
- larger $Z \rightarrow$ large deflections

$\theta(E, L) \approx 0.22^\circ Z \left(\frac{L}{10 \text{ Mpc}}\right)^{1/2} \left(\frac{E}{10^{20} \text{ eV}}\right)^{-1} \left(\frac{\lambda}{0.1 \text{ Mpc}}\right) \left(\frac{B}{10^{-9} \text{ G}}\right)$

~ $2^\circ$ for $10^{20}$ eV proton

Waxman & Miralda-Escude 1995

Image: Kotera & Olinto 2011
Model of the expected UHECR source distribution: Galaxy surveys

Protons $E > 55$ EeV, PSCz

IRAS PSCz ~full sky ~ 10000 galaxies, ~far-IR selected: excellent probe of star-formation

Calculations take into account:
- proton energy losses
- galaxy weights as a function of redshift
- Auger exposure
- galaxy survey selection functions
Model of the expected UHECR source distribution: Galaxy surveys

Protons $E > 55$ EeV, PSCz

+142 UHECRs with $E > 55$ EeV detected till April 2014, $z<60^\circ$

$$X = \sum_i \frac{(N_{CR,i} - N_{iso,i})}{N_{iso,i}} \left( \frac{N_{M,i} - N_{iso,i}}{N_{iso,i}} \right)$$

Calculations take into account:
- proton energy losses
- galaxy weights as a function of redshift
- Auger exposure
- galaxy survey selection functions
Correlation with galaxy distribution

\[ X = \sum_i \frac{(N_{CR,i} - N_{iso,i}) (N_{M,i} - N_{iso,i})}{N_{iso,i}} \]

- isotropic
- LSS
- \( \theta_{defl} = 3^\circ \)
- \( \theta_{defl} = 5^\circ \)
- data

\( P_{iso} = 7\% \)
\( P_{protons, no deflections} < 0.1\% \)

+ consistent results with 6dFGS and 2MRS galaxy surveys

FO, Connolly, Abdalla, Lahav, Thomas, Waters, Waxman: JCAP05(2013)015 updated Auger dataset
Hotspots in the UHECR sky

**TA**

- 24 events - 20 degree top hat (6.88 exp)

**Auger**

- 14 events - 12 degree top hat (3.23 exp)

- E > 54 EeV

- post-trial: 69%

- post-trial significance ~3.4σ

P. Tinyakov for TA Coll, ICRC 2015

The future: AugerPrime

- Auger surface detector upgrade
- Run 2018-2024
- Composition information shower by shower

Are we going to detect anisotropy? ?

454 Auger UHECRs $E \geq 40$ EeV, 10% proton $X_{\text{max}}$, 5% Swift-BAT AGN, $\theta \leq 3^\circ$, $d \leq 100$ Mpc

$X_{\text{max}}$ - randomly assigned to fit Auger data

All 454 UHECRs

128 protons only
The future: Will better statistics help?

Objectives for next generation instrument:
- 10 - 30 x Auger annual exposure
- 40 EeV < E < 1000 EeV
- 1000-2000 events/5 years

JEM-EUSO: Are we going to detect UHECR anisotropy?

2100 events, E>50 EeV, n₀ ~ 10⁻² Mpc⁻³

P(not isotropic | unbiased) > 99.7%

Yes!

With ≈ 600 protons

99% CL
Looking for sources at UHE energies: Secondaries

- UHECRs
- Neutrinos: Ideal messengers
  - **BUT** Low interaction cross-section/Hard to detect
- UHE photons/γ-rays: Absorption by photon backgrounds/dust
  - **BUT** High Statistics
- B-fields: deflections/time delays

\[ p + \gamma \rightarrow \begin{cases} 
\pi^0 & \rightarrow \gamma\gamma \\
\pi^\pm & \rightarrow e^+e^- + \nu\bar{\nu}
\end{cases} \]
Photons

Space - direct

Fermi

1e6

1e9

1e12

1e15

1e18

1e21

eV

Ground-Air shower (Cherenkov)

HAWC

Space (proposed)

HESS

MAGIC

AUGER

Swift

JEM-EUSO

UV photon

Extensive Air Shower (EAS)
Photons

Space - direct

Fermi

1e6

1e9

Swift

1e12

1e15

Ground-Air shower (Cherenkov)

1e18

1e21

HESS

MAGIC

HAWC

AUGER

JEM-EUSO

Space (proposed)
Photons

Space - direct

Ground-Air shower (Cherenkov)

VHE Gamma-ray sky

Source Types
- PWN
- Binary XRB PSR Gamma BIN
- HBL IBL FRI FSRQ Blazar LBL AGN (unknown type)
- Shell SNR/Molec. Cloud Composite SNR Superbubble
- Starburst
- DARK UNID Other
- uQuasar Star Forming Region Globular Cluster Cat. Var. Massive Star Cluster BIN BL Lac (class unclear) WR

Space (proposed)

HESS

MAGIC

AUGER

Swift

Fermi

JEM-EUSO
Photons

Space - direct

Ground-Air shower (Cherenkov)

VHE Gamma-ray sky

Blazars

• AGN with jet face-on
• 90% of extragalactic γ-ray sources
• 50+ TeV blazars (see TeVCat)
• 1000+ in GeV [2LAC, Fermi Coll 2011]

Space (proposed)
Blazar emission

PKS 2155–304

optical  x-ray

electron synchrotron

Fermi (GeV)  HESS (TeV)

inverse Compton? hadronic?
Blazar emission

\[ E_\gamma = \frac{m_e^2}{\varepsilon_{\text{background}}} \approx 2.6 \times 10^{11} \text{ eV} \left( \frac{\varepsilon_{\text{background}}}{1 \text{ eV}} \right) \]

Pair production threshold:
Extreme Hard-Spectrum TeV Blazars

EBL de-absorbed

Tavecchio 2013
Blazar TeV emission

Leptonic

$\gamma > \text{GeV}$  $\gamma_{\text{EBL}}$  $e^+e^-$  $E < 260 \text{ GeV}$
Blazar TeV emission

Leptonic

UHECR

IC Cascade

e.g., Essey et al 2010a,b, Murase et al 2012, Tavecchio 2014...
Blazar TeV emission

Leptonic

\[ \gamma_{\text{EBL}} \rightarrow e^+ e^- \]
\[ \gamma > \text{GeV} \]
\[ E < 260 \text{ GeV} \]

UHECR

IC Cascade

\[ \text{UHECRs} \rightarrow \gamma_{\text{CMB}} \]

Takami et al. 2014

e.g., KUV 00311−1938 (z = 0.61)
Blazar TeV emission

UHECR IC Cascade

NB IGMFs may significantly dilute emission!

Arriving energy flux, Kotera, Allard, Lemoine 2011
Secondary UHECR synchrotron emission

UHECR seeded synchrotron:

Gabici, Aharonian 2005, 7
Kotera, Allard, Lemoine 2011

filament/galaxy cluster
B > nG
typically ~few Mpc

Peak synchrotron energy:

\[ E_{\gamma,\text{syn}} \sim 68 \text{ GeV} \left( \frac{B}{10 \text{ nG}} \right) \left( \frac{E_e}{10^{19} \text{ eV}} \right)^2 \]
UHECR synchrotron pair echo/halo

**1ES 0229+200**

$L_{\text{CR,ISO}} = 10^{46.5} \text{ erg s}^{-1}$

Injection spectral index = 2

$E_{\text{MAX}} = 10^{20.5} \text{ eV}$

**1ES 1218+304**

$L_{\text{CR,ISO}} = 5 \times 10^{47} \text{ erg s}^{-1}$

$B_3 = 100 \text{ nG}$

Injection spectral index = 2

$E_{\text{MAX}} = 10^{20.5} \text{ eV}$

**RGB J0710+591**

$L_{\text{CR,ISO}} = 10^{47} \text{ erg s}^{-1}$

$B_3 = 100 \text{ nG}$

Injection spectral index = 2

$E_{\text{MAX}} = 10^{20.5} \text{ eV}$
How will we establish if UHECR emission?

**UHECR signatures:**

- TeV tail - UHECR IC/high redshift
- Halo energy dependence/spatial extension
- Orphan flares

**OR:**

- Correlated/rapid variability [leptonic/UHE neutral emission]

**Fermi, HAWC, CTA!**

**L_{cr,19} = 10^{46} \text{ erg s}^{-1} \quad d = 1 \text{ Gpc}**

**Kotera, Allard, Lemoine 2011**
Arrival directions

Spectrum/energetics

Secondary products

Composition

Multi-messenger temporal coincidences
Arrival directions

Secondary products

Spectrum/energetics

Composition

Multi-messenger temporal coincidences
Multimessenger coincidences

Most violent phenomena must appear at multiple wavelengths-messengers
Multimessenger coincidences

Most violent phenomena must appear at multiple wavelengths-messengers

Transient discoveries  ->  Combine all fundamental forces
The Astrophysical Multimessenger Observatory Network (AMON)

+Follow-up:
  Swift XRT&UVOT
  VERITAS  MASTER

Soon to sign MOU:
  LIGO  HESS  MAGIC
  Palomar Transient Factory

Large Millimeter Telescope Array
How can we find UHECR sources with AMON?

Auger datasets suitable for transient searches:

- UHE Hadrons [delayed by magnetic fields/directions scrambled]
- UHE neutrons
  \[ L_n \sim c \cdot \tau_n \cdot \gamma_n \approx 9 \left( \frac{E_n}{1 \text{ EeV}} \right) \text{kpc} \]
  [c.f. MW radius \approx 8 \text{kpc}]
- UHE Photons -loss length up to 30 Mpc
- UHE Neutrinos

Galactic neutrons detectable!
### How can we find UHECR sources with AMON?

<table>
<thead>
<tr>
<th>Event class</th>
<th>Prompt</th>
<th>Delayed</th>
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<tr>
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<tr>
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*✓✓ UHE neutrinos at flux levels detectable by Auger*
How can we find UHECR sources with AMON?

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UHE $\gamma$s $\approx$ few x 10 Mpc

*✓✓ UHE neutrinos at flux levels detectable by Auger
AMON discovery potential: Example
Cosmic Neutrino Sources

<table>
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<tr>
<th>Alert</th>
<th>Status quo</th>
<th>AMON</th>
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</thead>
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<td>IceCube “2ν” alerts (10 yr⁻¹)</td>
<td>IceCube 35ν-Nγ* alerts + “2ν” alerts (5 yr⁻¹)</td>
<td></td>
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</table>

Follow-up (Swift UVOT/XRT)  70 pointings  70 pointings

*ν-Nγ alerts: coincidence between at least single IceCube/Antares and Fermi-LAT/Swift-BAT/HAWC

AMON Team 2013
Outlook

- **AugerPrime, TA upgrade, JEM-EUSO**
  Anisotropy detection in 5 years, if $H \geq 10\%$ at highest energies
  (if composition information)

- **HAWC, CTA, HESS-2**
  Gamma-rays can unambiguously identify UHECR sources - need TeV spectra of high-z sources, timing (flares), angular resolution (halos)

- Multi-messenger astroparticle physics is happening NOW

- **AMON**
  Subthreshold multi-messenger transients, huge gain in discovery potential