Multimessengers and fundamental physics with ultra-high energy cosmic rays

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- Charged particles with $E \gtrsim 10^{18}$ eV
- Extragalactic origin
- Flux $\lesssim$ 1 particle km^{-2}yr^{-1}

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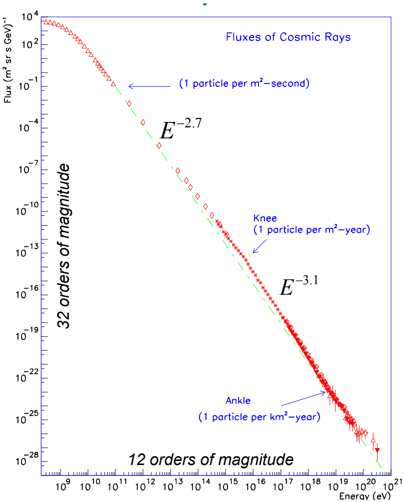
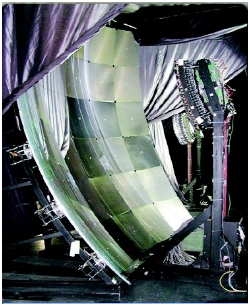
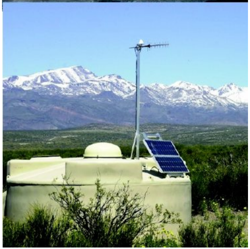
Only indirect observation with extensive air showers in Earth atmosphere



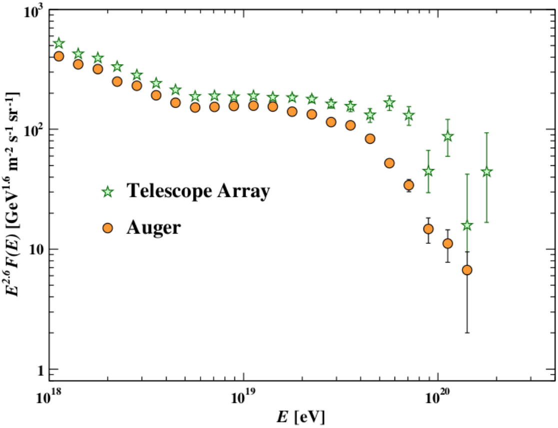




Energy spectrum

Spectrum suppression was observed at $E \gtrsim 4 \cdot 10^{19}\ eV$

HiRes 2007, Pierre Auger 2008, Telescope Array 2012

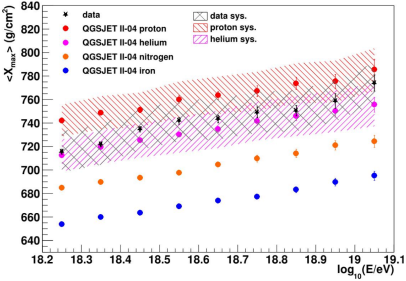


Whether the cut-off is due to GZK effect or due to ending of injection spectrum:

there are no hints for new physics.

Introduction: observables & problems

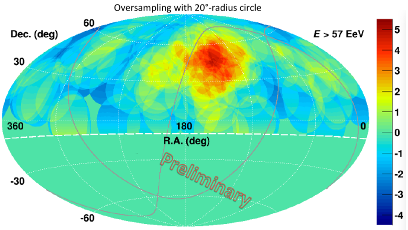
UHECR mass composition?



Still not clear from direct EAS measurements

- Low statistics and high systematics with fluorescence observations of EAS
- Moderate statistics but even higher systematics with surface detector observations of EAS

UHECR sources?

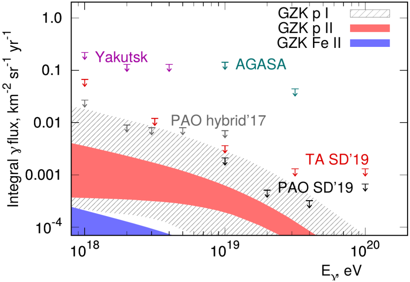


Still not clear from direct EAS measurements

- Hard to detect arrival direction: deflection of (charged) CR in galactic magnetic field

Outline: observables & and opportunities

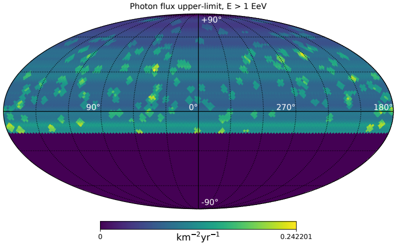
Multimessengers with UHECR



Secondary UHECR signals: UHE γ's & ν's

- Not affected by galactic magnetic fields - point directly to the sources
- Flux depends on UHECR mass composition - independent probe

Fundamental physics with UHECR

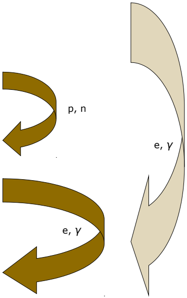


Test for

- Search for heavy dark matter with UHECR: various signatures
- Search for axion-like particles — photon conversion: UHE γ correlation with Blazars Lacertae

All of this is not yet detected - time to improve sensitivity!

- Nuclei
  - $A\gamma_b \to A' N$
  - $A\gamma_b \to A\pi..$
  - $A\gamma_b \to Ae^+e^-$
- Protons and neutrons
  - $N\gamma_b \to N'\pi..$
  - $p\gamma_b \to pe^+e^-$
  - $n \to pe^-\overline{\nu}_e$
- Electron-photon cascades
  - $e\gamma_b \to e\gamma$
  - $\gamma\gamma_b \to e^+e^-$
  - e synchrotron losses

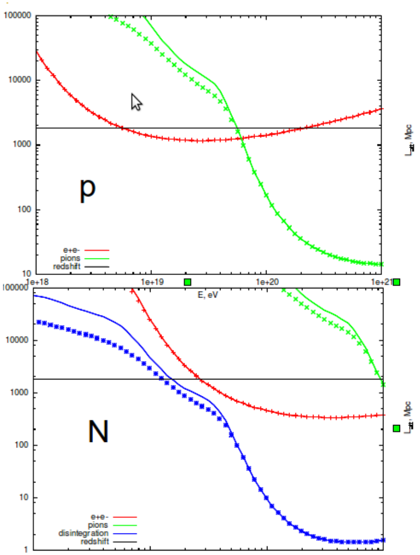


n,p from nuclei photo-desintegration

γ,ν,n from GZK
ν from $\beta-$decay

Diffuse γ-background

UHECR propagation: attenuation lengths



UHE ν and γ production

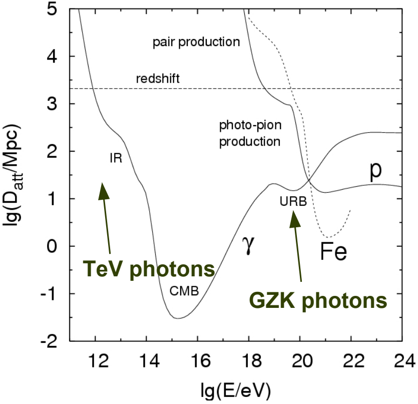
- Decay of mesons from *pp* and *p*γ collisions, e.g.

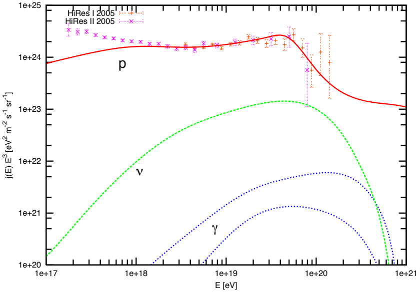
$$
\begin{array}{lll}
p+\gamma_b \to \Delta(1232) \to p+\pi^0 \nearrow \gamma+\gamma & & E_\gamma/E_p \simeq 0.1 \\
\qquad\qquad\qquad\quad \searrow n+\pi^+ \nearrow \mu^+ + \nu_\mu & & \\
\qquad\qquad\qquad\qquad\qquad\qquad \searrow e^+ + \overline{\nu}_\mu + \nu_e & & E_\nu/E_p \simeq 0.05
\end{array}
$$

$E_\nu, E_\gamma \gtrsim$ 1 EeV

- PeV ν detected by IceCube — not from GZK
- Only constraints for UHE ν *IceCube, Auger, Anita*
- Only constraints for UHE γ *Auger, TA, Yakutsk*

UHE ν and γ: probe for UHECR

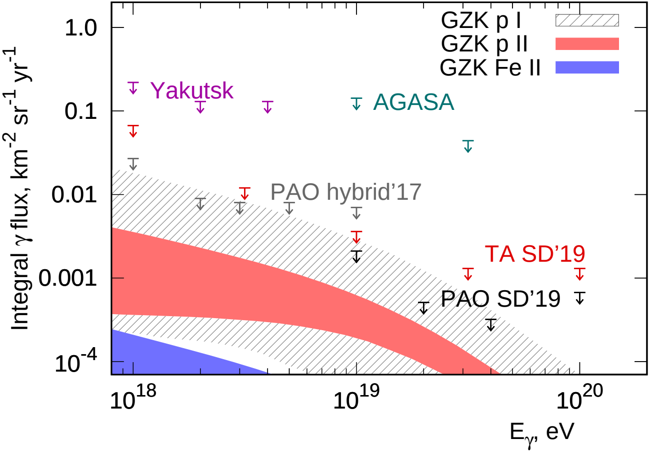




Gelmini et al. 2007

	UHE ν	UHE γ
UHECR Direction	+	+
UHECR Source evolution	+	–
UHECR Local source density	–	+

Diffuse UHE photons flux limits

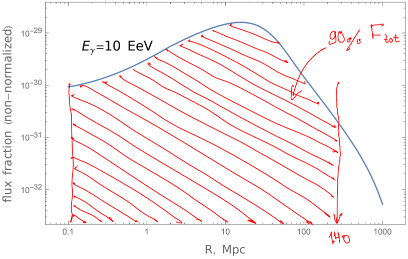


- Diffuse UHE γ limits are already probe most optimistic GZK predictions
- A separation between proton and nuclei predictions allows one to probe UHECR compostion

There is a way to improve these results

Prospect for target GZK photon search

- Assume that sources of UHECR are trace the Large Scale Structure
- Simulate the UHECR propagation and find distance from which 90% of secondary UHE photons arrives
- Maka a cut on this distance and perform a target search for UHE γ from LSS directions.

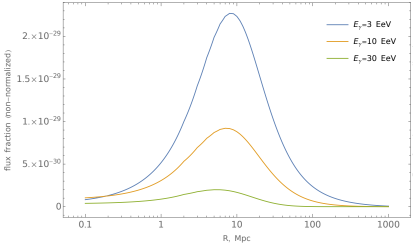


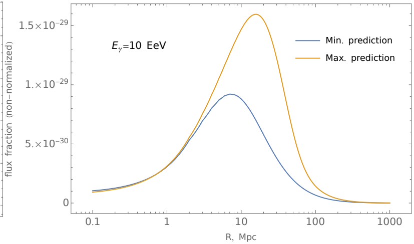
E_γ, EeV	max. flux $R_{90\%}$	min. flux $R_{90\%}$
3	310 Mpc	350 Mpc
10	140 Mpc	170 Mpc
30	45 Mpc	40 Mpc

Prospect for target GZK photon search: parameter dependence

γ-flux depends on:

- Primary proton injection spectrum (moderately)
- Value of extragalactic magn. field (strongly)
- Model of interstellar radio background (strongly)





The most promising energy region for UHECR composition probe is $E_\gamma > 10^{18.5}$ eV.
But attenuation for this region is the smallest

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LSS $\simeq$ whole sky

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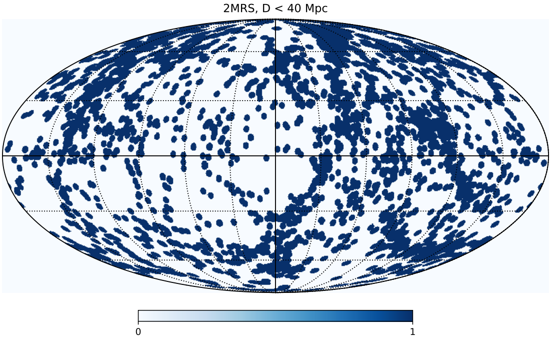
Some source weighting is needed for target search

Prospect for target GZK photon search: sensitivity improvement



Rough estimate of sensitivity improvement is $Q \equiv 4\pi/\Omega_{LSS}$
With angular resolution $\sigma = 1.92^\circ$ at $E_\gamma > 30 EeV$ and without source weighting:

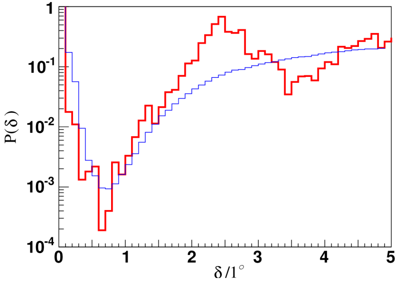
$$\boxed{Q \simeq 1.5}$$

$\Downarrow$

Flux weighting and angular resolution improvement is needed for more efficient UHE γ search

- Correlations of UHECR with distant Blazars Lacertae (BL Lacs) were observed by HiRes experiment *Gorbunov et al. 2004, HiRes 2005*
- The significance of result is 3.5σ
- Still not excluded by modern experiments

P-value vs. angular distance from sources

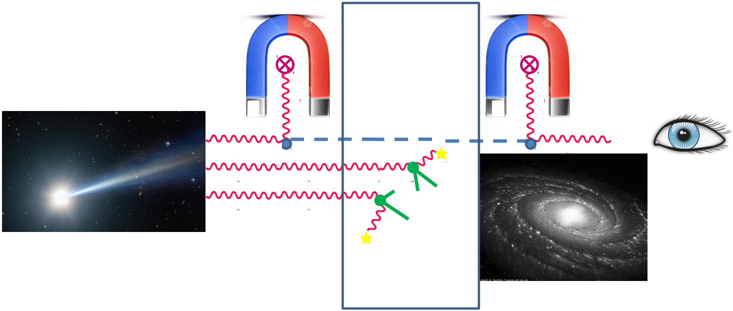


Cosmic ray		BL Lac	
α, deg.	δ, deg.	name	z
17.8	−12.5	RBS 0161	0.234
48.5	5.8	RX J03143+0620	?
118.7	48.1	TXS 0751+485	?
123.8	57.0	RX J08163+5739	?
137.2	33.5	Ton 1015	0.354
162.6	49.2	MS 10507+4946	0.140
169.3	25.9	RX J11176+2548	0.360
209.9	59.7	RX J13598+5911	?
226.5	56.5	SBS 1508+561	?
229.0	56.4	SBS 1508+561	?
253.7	39.8	RGB J1652+403	?
265.3	46.7	OT 465	?
300.2	65.1	1ES 1959+650	0.047

BL Lac – UHECR correlation properties

- $E > 10^{19}$ eV
- Small separation angle ($\sim 0.8°$) between BL Lacs and UHECR: not possible with charged particles due to gal.magnetic field
- Sources are too distant: indications for the anomalous high attenuation length of neutral particles
- The fraction of correlated events is $\eta \sim 2\%$: consistent with recent diffuse UHE γ limits
- The only viable explanation is $\mathrm{UHE}\gamma \rightarrow ALP \rightarrow \mathrm{UHE}\gamma$ conversion

Fairbairn et al. 2009



How to test this result?

It is possible with large statistics of modern UHECR experiments and their sensitivity to UHE γ

The sensitivity needed was estimated

Gorbunov et al. 2005

$$\boxed{Q = \frac{S}{\sqrt{B}} \sim \frac{\eta\sqrt{NF}}{\sigma}}$$

where N is number of detected events, σ is angular resolution of experiment, F is geographical factor of experiment and η is fraction of UHE photons among detected events.

$$Q = \frac{S}{\sqrt{B}} \sim \frac{\eta\sqrt{NF}}{\sigma}$$

- Geography: the majority of BL Lacs are located in the Northern Hemisphere:
  $F_{\mathrm{HiRes}} = 1.38$; $F_{\mathrm{TA}} = 1.41$; $F_{\mathrm{Auger}} = 0.53$.

Probe of BL Lac – UHE γ correlation with modern experiments

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- Angular resolution for γ: larger for FD experiments:
  $\sigma_{\mathrm{HiRes}} = 0.6^\circ$; $\sigma_{\mathrm{TA\ SD}} = 2.65^\circ$; $\sigma_{\mathrm{Auger\ hybrid}} = 0.7^\circ$.

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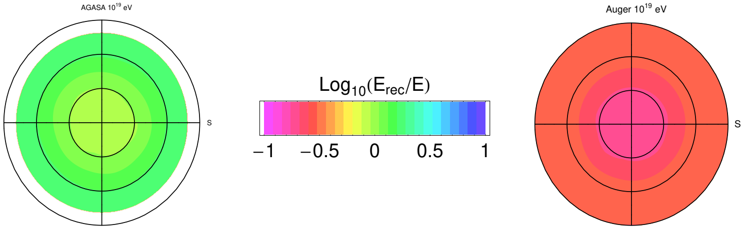
- Angular resolution for γ: larger for FD experiments:
  $\sigma_{\rm HiRes} = 0.6^\circ$; $\sigma_{\rm TA\ SD} = 2.65^\circ$; $\sigma_{\rm Auger\ hybrid} = 0.7^\circ$.
- Number of events: $N_{\rm SD}$ is ~ 10 times larger than $N_{\rm FD}$

Probe of BL Lac – UHE γ correlation with modern experiments

$$Q = \frac{S}{\sqrt{B}} \sim \frac{\eta\sqrt{NF}}{\sigma}$$

Main problem:

Energy reconstruction: for fluorescence detectors the energy scale for protons is the same as for photons. For SD it is not so. *Troitsky et al. 2009*



Therefore, the same cut on E_γ yields different γ fraction:
$\eta_{\mathrm{HiRes}} \simeq 2\%$; $\eta_{\mathrm{TA\ SD}} \simeq 0.5\%$; $\eta_{\mathrm{Auger}} \simeq 0.1\%$.

I will discuss a possible probe with TA SD.

Prospect for probe of BL Lac – UHE γ correlation with TA SD

TA SD reconstruction improved with Neural Net (preliminary). *Kalashev ACAT-2019*

- Angular resolution for γ: $\sigma = 2.65^\circ \to \sigma = 2.13^\circ$
- $p - \gamma$ classification: cut the UHECR sample to increase η: $\eta \simeq 0.5\% \to \eta \simeq 68\%$

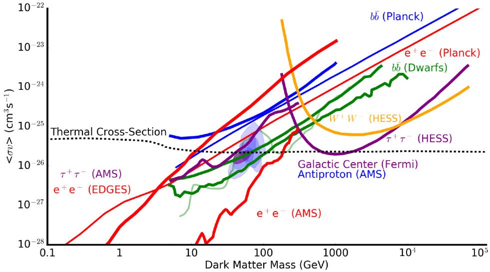
Resulting sensitivity improvement comparing to HiRes (preliminary):

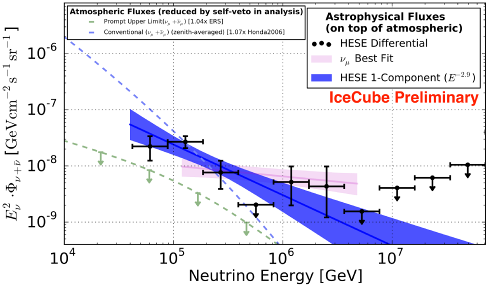
$$\boxed{Q_{\mathrm{TA\ SD\ NN}}/Q_{\mathrm{HiRes}} \simeq 2.7}$$

$$\Downarrow$$

TA can either confirm the BL Lac — UHE γ correlation with significance $> 5\sigma$ or constrain the total UHE γ fraction from BL Lac to $\eta \simeq 0.5\%$ with 95%C.L.

- Standard thermal WIPM DM was not detected yet
- IceCube observed several PeV ν that cannot be a product of WIMP annihilation
- Can it be a product of heavy DM decay?





Heavy dark matter (HDM)

Particles X with mass $M_X \gg 100$ TeV and lifetime $\tau \gg 10^{10}$ yr

Kuzmin, Rubakov '97; Berezinsky et al. '97; Birkel, Sarkar '98

1. Naturally to generate non-thermally in the early Universe:
   - Non-stationary gravitational fields
   - Non-equilibrium plasma
   - Inflaton decay (preheating)
2. Particle concentration is too low $\Rightarrow$ non-accessible for direct detection ($\sigma_{AX}^{\text{est.}} \sim 10^{-55} cm^2$)
3. Indirect detection sensitive only to decay, but not to annihilation: $\sigma_{\text{ann.}} \lesssim \frac{1}{M_X^2}$
4. Consider masses $10^6 \leq M_X \leq 10^{16}$ GeV (although there are some mass constraints from cosmology)

Can we probe HDM with UHECR?

Sure!

For large enough M_X and any decay channel hadronic / electroweak cascade develops

$$\Downarrow$$

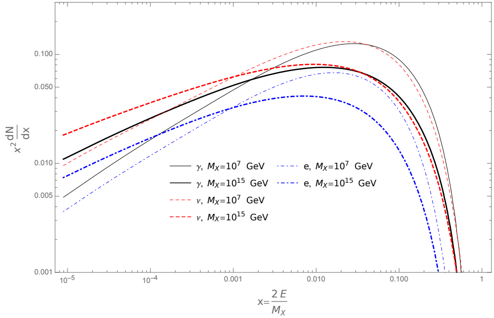
The final state contains all stable **SM** particles.

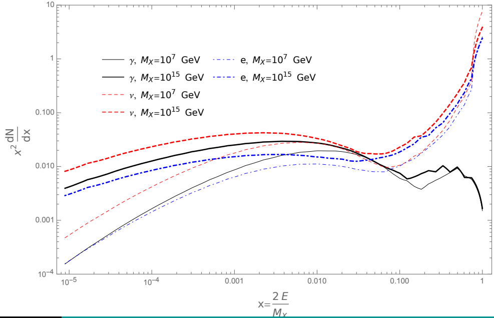
$$\Downarrow$$

There is a number of signatures in UHECR

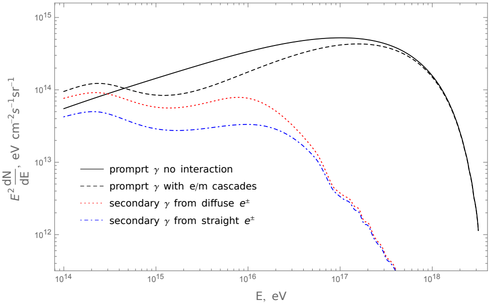
- Dipole in UHECR spatial distribution
- Flux of UHE γ
- Flux of UHE ν

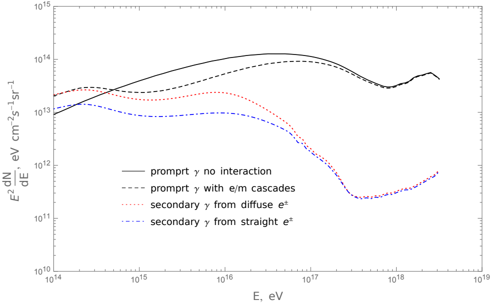
- Decay for two primary channels: $X \to q\bar{q}$ and $X \to \nu\bar{\nu}$
- $X \to q\bar{q}$ yields the softest injection spectrum in both γ and ν; $X \to \nu\bar{\nu}$ — the hardest.
- Analytical calculation with fragmentation functions and DGLAP equations *Aloisio et al. '03; Kachelriess, Kalashev & MK '18*.



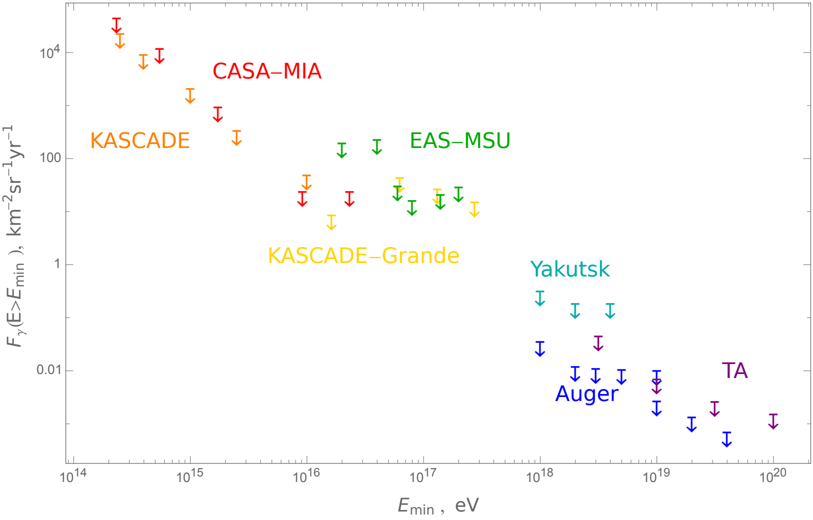


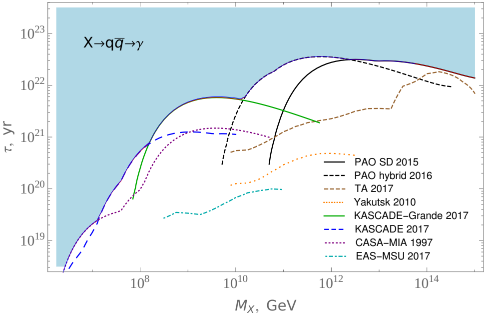
- For UHE γ flux only the galactic DM contribution is relevant. For ν — both galactic and extragalactic.
- Take into account $\gamma \to e^+e^- \to \gamma$ cascades on cosmic photon backgrounds *Kalashev, Kido '14*.



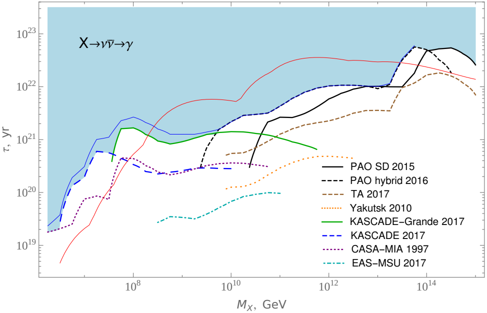


High energy gamma-rays: observational data

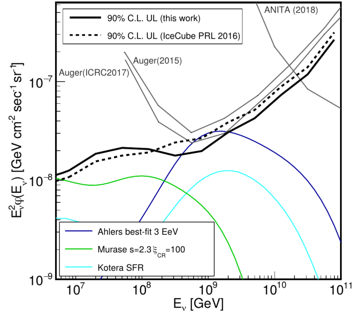


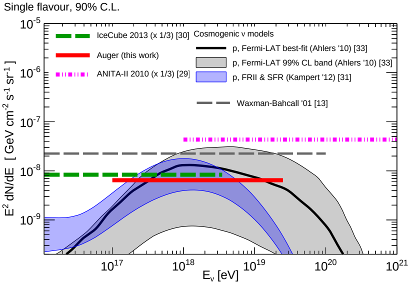


Constraints on DM lifetime from comparison of the DM model γ-flux with the high-energy γ limits



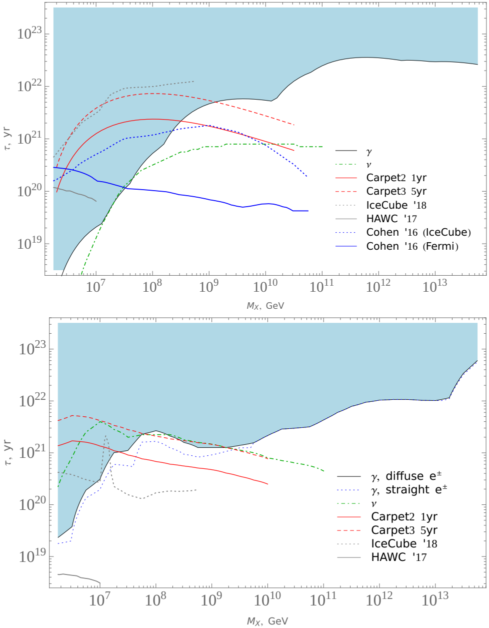
Highest energy observed event has $E \simeq 2$ PeV, for higher energies upper-limits are set *IceCube '18, Auger '15*





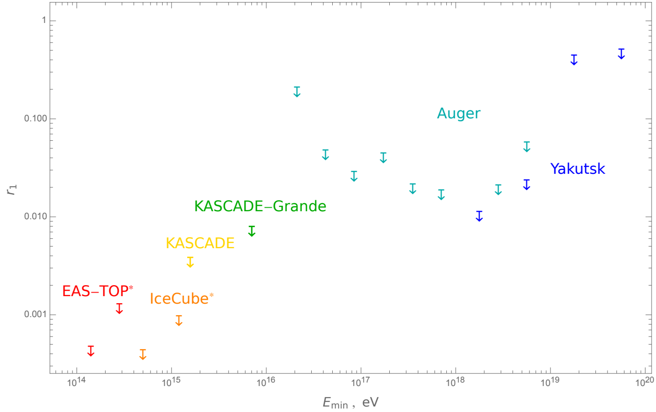
High energy neutrino: constraints on heavy dark matter

Explanation of IceCube highest energy events by decay of HDM with $M_X \gtrsim 10^8$ GeV is ruled out by non-observation of UHE γ

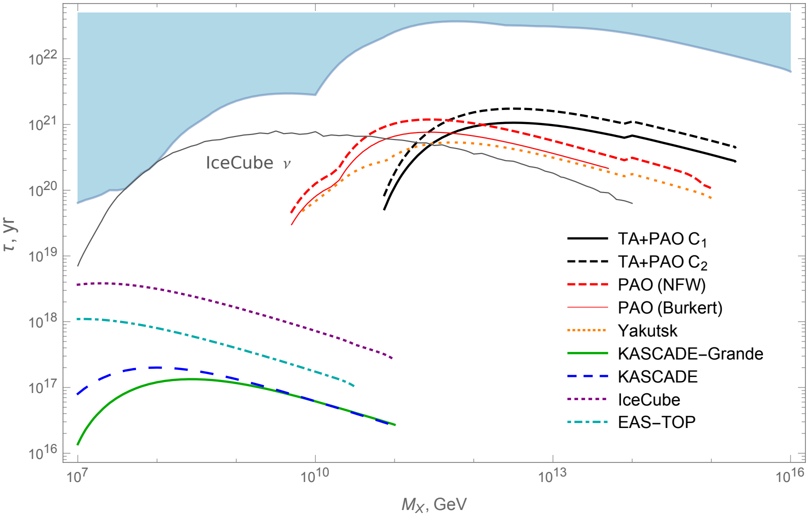


Observable: amplitude of dipole in harmonic analysis over right ascension

$$J(\alpha, E) = a_0(E) + \sum_n \left[a_n(E)\sin(n\alpha) + b_n(E)\cos(n\alpha)\right] \; ; \quad r_1(E) = \sqrt{a_1^2 + b_1^2}$$



Cosmic–ray anisotropy: constraints on HDM

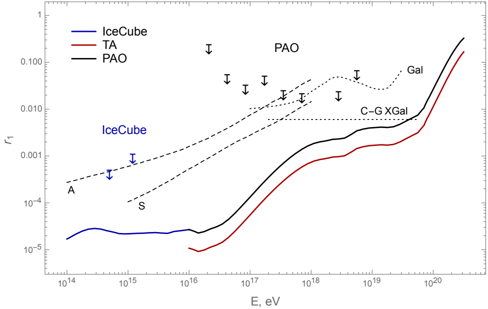


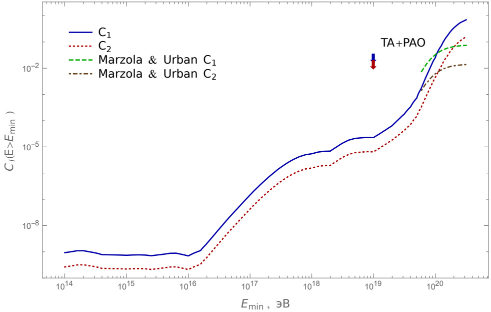
UHECR anisotropy probes heavy dark matter not so efficient as UHE γ and ν limits.

Prospects of indirect search for heavy dark matter

How large is the anisotropy of cosmic–rays induced by the allowed heavy dark matter?

- Running experiments are more sensitive to dark matter decay gamma-rays than to the respective anisotropy.
- The detected CR anisotropy is not of DM origin
- Vise-versa, future orbital UHECR detectors assumed to be more sensitive to HDM induced UHECR anisotropy than to UHE γ signal





Conclusions

UHECR is a viable probe for fundamental physics and an interesting target for multimessenger studies

- UHECR sources and composition can be probed with UHE γ rays
- Photon—ALP mixing hypothesis can be tested indirectly by modern UHECR observatories
- Decaying heavy dark matter can be efficiently searched for with UHE γ ray observation

Thank you!

Backup slides

- Deflection in galactic magnetic field:

$$\frac{\Delta\Theta}{Z} \simeq 2.5^\circ \frac{100\mathrm{EeV}}{E} \frac{B}{3\mu\mathrm{G}}$$

- Extragalactic magnetic field in voids:

$$\frac{\Delta\Theta}{Z} \lesssim 0.4^\circ \frac{100\mathrm{EeV}}{E} \frac{B}{0.1\mathrm{nG}} \frac{\sqrt{L\lambda_{cor}}}{10\mathrm{Mpc}}$$

- Recent constraints on B_{EG} and its correlation length λ_{cor}:

$$10^{-17}\mathrm{G} \lesssim B_{\mathrm{EG}} \lesssim 10^{-9}\mathrm{G}$$

$$\lambda_{cor} \gtrsim 1\mathrm{pc}$$

R. Durrer & A. Neronov 2013