Multimessenger search for heavy dark mater

Mikhail Kuznetsov

in collaboration with
Oleg Kalashev

INR
Institute for Nuclear Research
of the Russian Academy of Sciences

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Outline

- Motivation
- High–energy particles from heavy dark matter decay
- Constraints on DM parameters from photon data

  O. Kalashev, MK, PRD '16
- Test of DM decay interpretation of IceCube neutrino

  MK, JETP Lett. '17
- Search for DM decay signal in cosmic-ray anisotropy

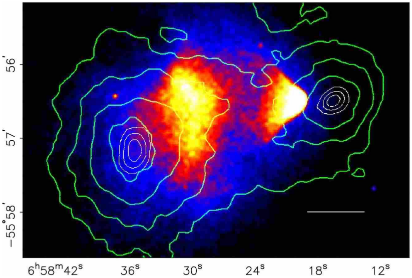
  O. Kalashev, MK, JETP Lett. '17

Dark matter problem

- Velocity of galaxies in clusters
- Galaxies rotation curves
- Gravitational lensing in clusters
- CMB angular spectrum
- BAO scale
- Large scale structure formation
  etc.

$\Longrightarrow$

$$\Lambda\text{CDM}, \ \frac{\Omega_{DM}}{\Omega_c} = 0.26$$



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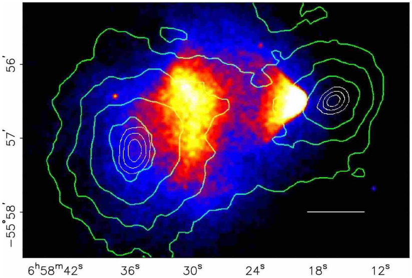


WIMP: $m_\chi \sim$ TeV

Good:

- Motivated by SUSY (LSP) and cosmology (WIMP miracle)
- Potentially accessible for direct detection

Bad:

- SUSY is not found at ~ 2 TeV ATLAS '16
- WIMPs are not directly detected yet LUX '13, Xenon100 '12

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

1. Non-thermal generation 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 ($\sigma_{AX}^{\mathrm{est.}} \sim 10^{-55} cm^2$)
3. Indirect detection sensitive only to decay, but not to annihilation: $\sigma_{\mathrm{ann.}} \lesssim \frac{1}{M_X^2}$
4. We conservatively consider masses $10^7 \leq M_X \leq 10^{16}$ GeV (although there are some mass constraints from cosmology)

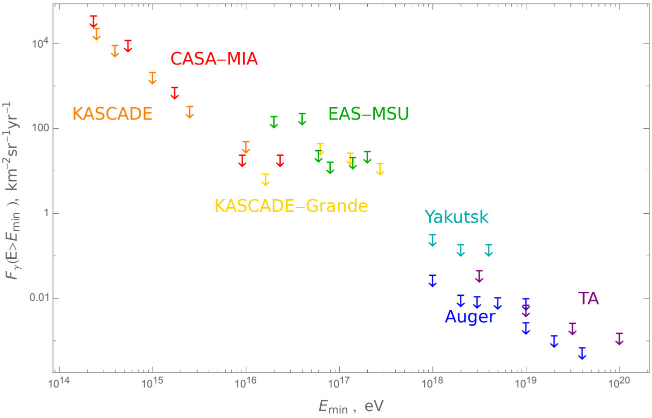
Heavy dark matter decay physics

- We describe decay in terms of primary decay channels like $X \to b\bar{b}$, $X \to \mu^+\mu^-$ etc.
- It is possible to describe the model with the given decay branching ratios.
- Decay cascade forms with full or partial hadronization and we have some set of $\{e^{\pm}, p, \bar{p}, \gamma, \nu_{e,\mu,\tau}, \bar{\nu}_{e,\mu,\tau}\}$ in final state.

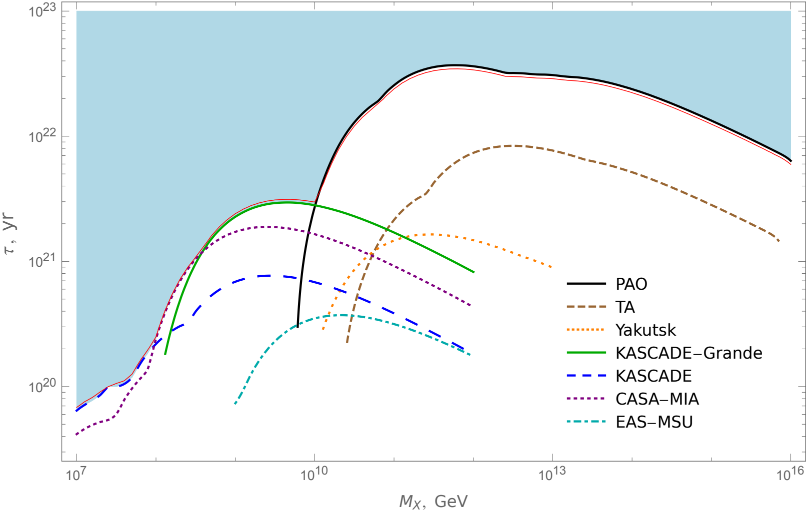
- We consider $X \to q\bar{q}$ channel (the only one which is calculable at highest energies):
- Analytical calculation using fragmentation functions and DGLAP equations Aloisio et al. '03.
- Dominant ($\sim 90\%$) γ and ν contributions are from $\pi^0 \to \gamma\gamma$ and $\{\pi \to \mu\nu_\mu, \quad \mu \to e\nu_\mu\nu_e\}$ processes.
- For γ flux only the galactic DM contribution is relevant. For ν — both galactic and extragalactic.
- We take into account $\gamma \to e^+e^- \to \gamma$ cascades on cosmic photon backgrounds Kalashev, Kido '14.

High energy gamma-rays: observational data

- Indirect observation through extensive air showers for $E \geq 100$ TeV.
- Gamma-rays at $E \geq 100$ TeV are not detected yet, although upper-limits are set.

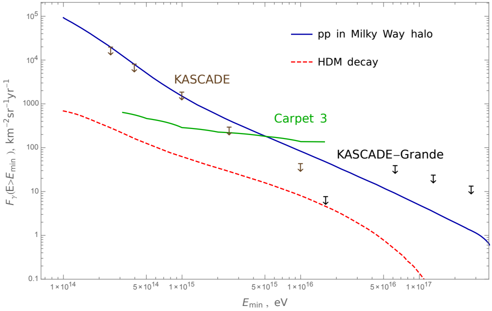


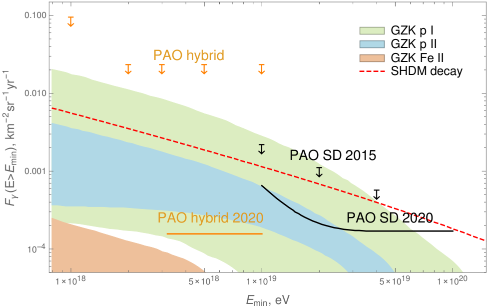
We compare the DM model γ-flux with the data and derive constraints on DM lifetime.



High energy gamma-rays: HDM vs cosmogenic

In case of gamma-ray detection the additional observables are needed to discern its origin.

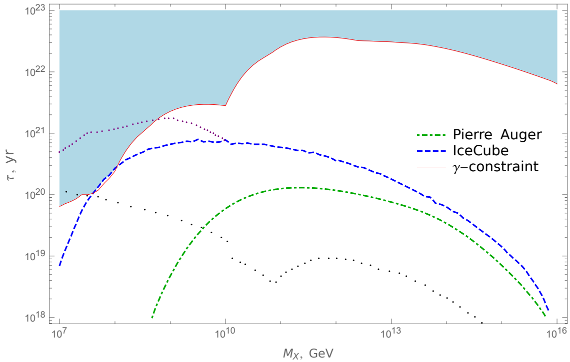




High-energy neutrino: observation and constraints on HDM

IceCube have detected neutrino with energies up to PeV IceCube '13.
We use the refined dataset with zero atmospheric neutrino background IceCube '16.

For comparison we use the results of Pierre Auger of non-detection of $E > 10^{17}$ eV neutrino Pierre Auger '15.



The HDM decay interpretation of IceCube events is disfavored (at least for hadronic decay channel)

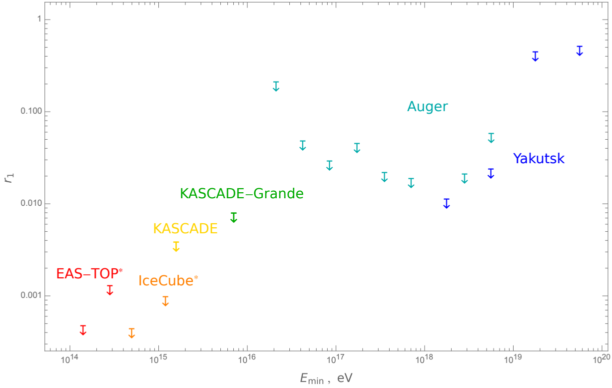
Cosmic–ray anisotropy: observations

The most common is the harmonic analysis in right ascension α.

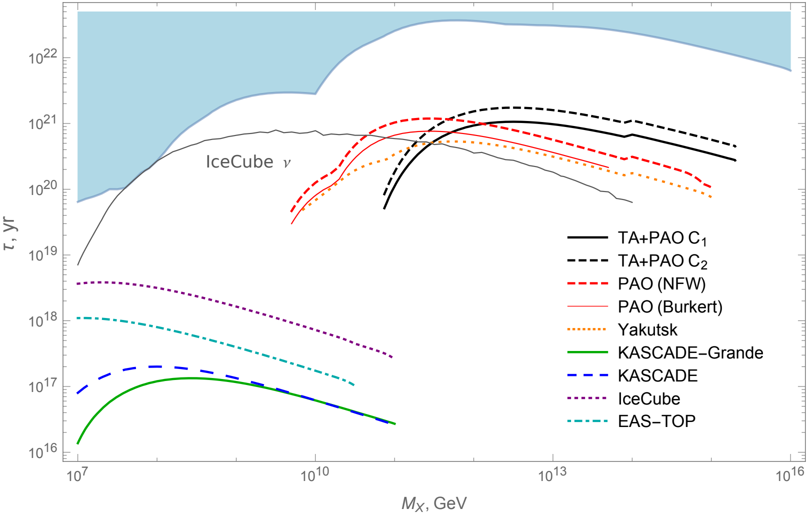
$$J(\alpha, E) = a_0(E) + \sum_n \left[a_n(E)\sin(n\alpha) + b_n(E)\cos(n\alpha)\right] \; ; \quad r_1(E) = \sqrt{a_1^2 + b_1^2}$$

At $100 - 1000$ TeV the anisotropy of order $r_1 \sim 10^{-4}$ was discovered. EAS-TOP '09; IceCube '16

At higher energies only indications and upper-limits exist. KASCADE '04; KASCADE-Grande '15; Pierre Auger '15; Yakutsk '14; Pierre Auger & TA '14



Cosmic–ray anisotropy: constraints on HDM



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.
- If the CR anisotropy is detected without gamma-rays

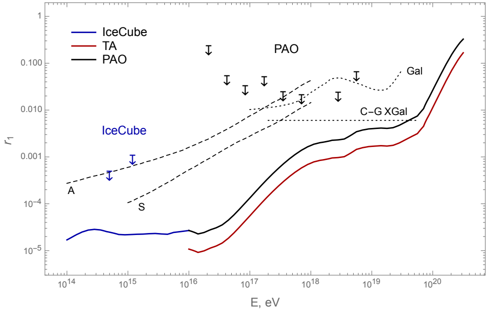
$\Downarrow$

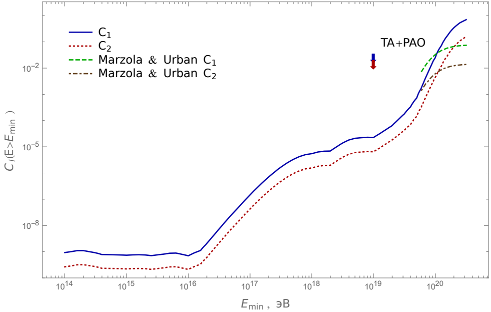
The anisotropy is not of DM origin

- If the gamma-rays are detected

$\Downarrow$

We need to look on CR anisotropy beyond first harmonic to discern gamma-ray origin





Conclusions

1) The most stringent conservative constraints were set for the lifetime of the dark matter with masses $10^7 \leq M_X \leq 10^{16}$ GeV
2) It was shown that the heavy dark matter decay interpretation of IceCube events is disfavored (at least for hadronic decay channel)
3) It was shown that the most perspective direction for the heavy dark matter search is the search of the high energy γ-rays, while the neutrino and CR anisotropy could be the tools for γ-rays origin clarification.

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Thank you!

Backup: primary decay channels vs. QFT DM models

The example of couplings that yield $X \to q\bar{q}$ decay channel:

$$\tilde{\phi}\bar{Q}U, \quad \phi\bar{Q}D \quad \Rightarrow \quad X \to q\bar{q}, \quad 100\%$$

$$Q = \begin{pmatrix} u \\ d \end{pmatrix}, \phi = \begin{pmatrix} X_1 \\ X_2 \end{pmatrix}, \tilde{\phi} = i\sigma^2\phi^*$$

$$XG_{\mu\nu}G^{\mu\nu} \quad \Rightarrow \quad X \to \mathrm{hadrons}, \quad 100\%$$