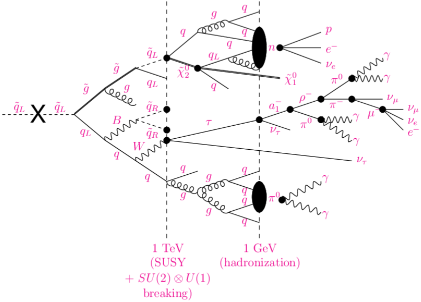
Superheavy dark matter:

from the invention to precise predictions



Michael Kachelrieß, NTNU Trondheim

Outline:

- Introduction:
  - how I met VB
  - UHECRs in 1996
- Superheavy dark matter
- Working out preciser predictions:
  - abundance in gravitational production
  - clustering [*see Slava Dokuchaev's talk*]
  - fragmentation: SUSY-QCD and electroweak
- Conclusions

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- we finished (with Sasha Dolgov) a paper on pion curvature radiation in March 1995
- what to do next?

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    - monopoles, monopolium *[Hill '83]*
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  ⇒ Monte Carlo simulation for SUSY-QCD
  but 2.nd (and last) year of PhD was over

Superheavy dark matter as UHECR source

Ultra-High Energy Cosmic Rays : a Window to Post-Inflationary Reheating Epoch of the Universe ?

V.A. Kuzmin and V.A. Rubakov

Institute for Nuclear Research of Russian Academy of Sciences,
60th October Anniversary Prosp. 7a, Moscow 117312, Russia
E-mails : kuzmin@ms2.inr.ac.ru, rubakov@ms2.inr.ac.ru

Abstract

We conjecture that the highest energy cosmic rays, $E > E_{GZK}$, where $E_{GZK} \sim 5 \cdot 10^{19}$ eV is the Greisen–Zatsepin–Kuzmin cut-off energy of cosmic ray spectrum, may provide a unique window into the very early epoch of the Universe, namely, that of reheating after inflation, provided these cosmic rays are due to decays of parent superheavy long-living X-particles.

These particles may constitute a considerable fraction of cold dark matter in the Universe. We argue that the unconventionally long lifetime of the superheavy particles, which should be in the range of $10^{10} - 10^{22}$ years, might require novel particle physics mechanisms of their decays, such as instantons. We propose a toy model illustrating the instanton scenario.

Generic expected features of ultra-high energy extensive air showers in our scenario are similar to those of other top-down scenarios. However, some properties of the upper part of the cosmic ray spectrum make the instanton scenario distinguishable, at least in principle, from other ones.

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- no figure, no concrete predicition of fluxes

Superheavy dark matter as UHECR source

23 Aug 1997

Ultra-high energy cosmic rays without GZK cutoff

V. Berezinsky[1], M. Kachelrieß[1], and A.Vilenkin[2]
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We study the decays of ultraheavy ($m_X \geq 10^{13}$ GeV) and quasistable (lifetime τ_X much larger than the age of the Universe t_0) particles as the source of Ultra High Energy Cosmic Rays (UHE CR). These particles are assumed to constitute a tiny fraction ξ_X of CDM in the Universe, with ξ_X being the same in the halo of our Galaxy and in the intergalactic space. The elementary-particle and cosmological scenarios for these particles are briefly outlined. The UHE CR fluxes produced at the decays of X- particles are calculated. The dominant contribution is given by fluxes of photons and nucleons from the halo of our Galaxy and thus they do not exibit the GZK cutoff. The extragalactic components of UHE CR are suppressed by the smaller extragalactic density of X-particles and hence the cascade limit is relaxed. We discuss the spectrum of produced Extensive Air Showers (EAS) and a signal from Virgo cluster as signatures of this model.

PACS numbers: 98.70.Sa, 14.80.-j

The observations of Ultra-High Energy Cosmic Rays (UHE CR) reveal the presence of a new, isotropic component at energies $E \geq 1 \cdot 10^{10}$ GeV (for a review see Ref. [1]). This component is thought to have an extragalactic phenomenological approach and treat the density n_X of X-particles and their lifetime τ_X as free parameters fixed only by the requirement that the observed UHE CR flux is reproduced. We calculate the fluxes of nucleons, pho-

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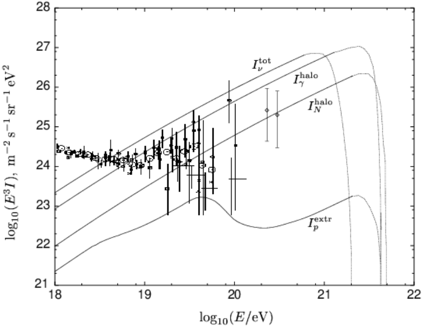

Lifetime:

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  - annihilation $\sigma_{\rm ann} \leq 1/m_X^2 \Rightarrow$ too small flux
  - exception: [see Slava Dokuchaev's talk]
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  - global symmetry broken by grav. wormhole effects, $\tau_X \propto \exp(2S)$
  - symmetry broken by instanton effects, $\tau_X \propto \exp(4\pi^2/g^2)$
  - discrete symmetries forbid operators with $d < 9$
  - crypton or fractionally charged and confined particle of superstring theories

Gravitational creation of SHDM

[Kuzmin, Tkachev '98; Chung, Kolb, Riotto '98]

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$$\ddot{\varphi}_{\boldsymbol{k}} + \left[\boldsymbol{k}^2 + m_{\rm eff}^2(\tau)\right] \varphi_{\boldsymbol{k}} = 0$$

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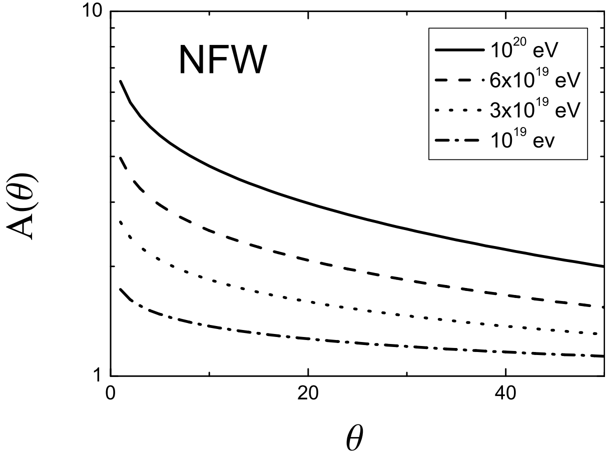
- isocurvature modes: $\delta_X \neq \delta_\gamma$

[Chung et al. '05]

Early Signatures

- Anisotropy: Virgo ⇒ Galactic [*Dubovsky, Tinyakov '98*]



Early Signatures

- Anisotropy: Virgo ⇒ Galactic [*Dubovsky, Tinyakov '98*]
- Fragmentation spectra:
  - composition: $\gamma/p \sim \nu/p \gg 1$, no nuclei
  - spectral shape: steep $\mathrm{d}N/\mathrm{d}E \propto 1/E^{\alpha}$ up to $m_X/2$ with $\alpha \simeq 1.3$–2
  - reliable predictions?

Status of fragmentation functions

MONOPOLONIUM

Christopher T. HILL

Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510, USA

Received 25 November 1982

Status of fragmentation functions

> We may further estimate the spectrum of hadrons and secondary photons, though here we are on somewhat thinner ice. The exact x-distribution for fragmentation of a gluon jet is not known, and only a few properties, such as the total multiplicity and more recent observations of a peak at very low x have been determined [7]. Indeed, it is not clear how much can be determined theoretically. For our purposes the important features are to realize the correct multiplicity, assure that the first moment of the distribution be normalized properly to unity, and try to guess the correct large-x behavior, which we take to be $(1-x)^2$. We will build the multiplicity into the low-x behavior of the distribution. For the leading log QCD multiplicity formula

- (pre-LHC) Monte Carlo simulations: PYTHIA, Herwig $\sqrt{s} \lesssim 30$ TeV

Status of fragmentation functions

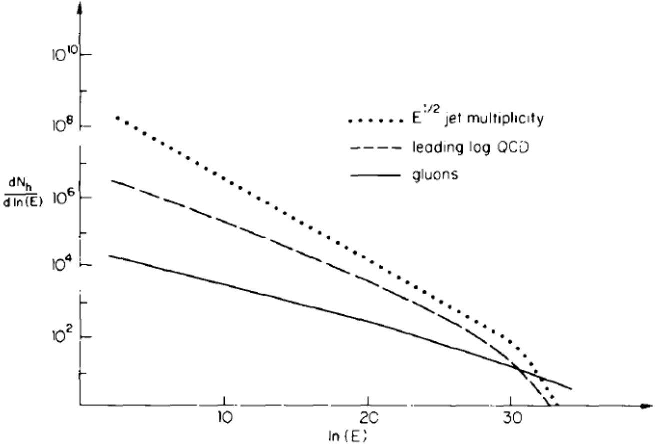
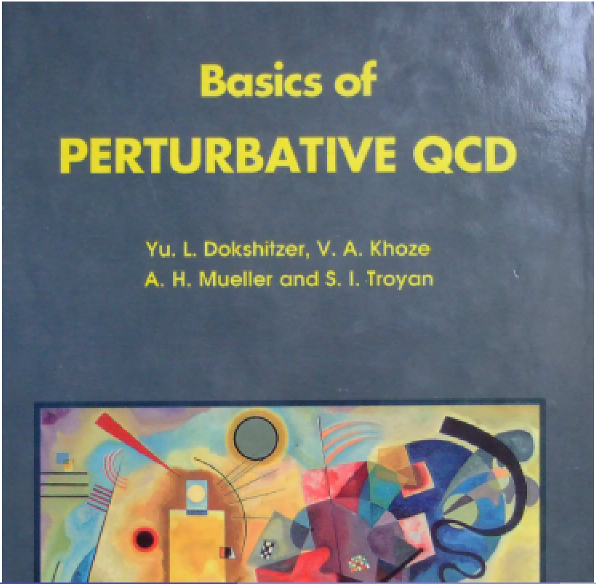


Fig. 3. Charged hadron spectrum (a) leading log QCD, (b) $E^{1/2}$ multiplicity, and (c) gluon spectrum. γ-distribution ~ $\frac{1}{3}$ hadron distribution.

Fragmentation function in MLLA



Fragmentation function in MLLA

124 Guide to Color Coherence

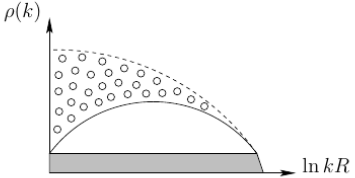


Figure 4.8: The effect of color coherence on particle energy spectrum $\rho(k) = dn/d\ln k$. Dotted area corresponds to the contribution which is removed when turning from the incoherent model (*dashed*) to the coherent one (*solid*). Shaded area shows the old-fashioned plateau (without taking account of bremsstrahlung).

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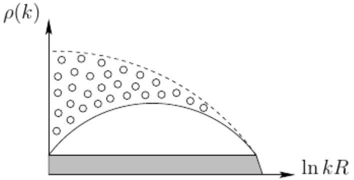
124 *Guide to Color Coherence*



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- and what is effect of SUSY?

Fragmentation function in Gaussian approx. and SUSY

VOLUME 79, NUMBER 26 PHYSICAL REVIEW LETTERS 29 DECEMBER 1997

Cosmic Necklaces and Ultrahigh Energy Cosmic Rays

Veniamin Berezinsky[1] and Alexander Vilenkin[2]
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(Received 28 April 1997; revised manuscript received 15 October 1997)

The fragmentation function is calculated using the decay of X particle into QCD partons (quark, gluons, and their supersymmetric partners) with the consequent development of the parton cascade. We have used the fragmentation function in the Gaussian form as obtained in the modified leading logarithm approximation in [19,20]. Additionally, we took into account the supersymmetric corrections to the coupling constant α_s at large Q^2. The explicit form of the fragmentation function at small x is found as

$$W_N(m_X, x) = \frac{K_N}{x} \exp\left(-\frac{\ln^2 x/x_m}{2\sigma^2}\right), \qquad (5)$$

where $2\sigma^2 = (1/6)[\ln(m_X/\Lambda)]^{3/2}$, $x = E/m_X$, $x_m = (\Lambda/m_X)^{1/2}$, $\Lambda = 0.234$ GeV with the normalization constant K_N to be found from energy conservation assuming that about 10% of initial energy (m_X) is transferred to nucleons.

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first attempt to incorporate SUSY in FF

Topological defect models: Necklaces

+ "generic" in SUSY-GUTs
+ produced during reheating

- typical density: one per horizon/correlation length
- main energy loss low-energy radiation?

favourable models for UHECRs:

- monopole-antimonopole pairs
- hybrid defects: cosmic necklaces
  - $G \to H \otimes U(1) \to H \otimes Z_2$
  - monopoles $M \sim \eta_m/e$ connected by strings $\mu_s \sim \eta_s^2$
  - parameter $r = M/(\mu_s d)$:
  - $r \ll 1$ normal string dynamics
  - $r \gg 1$ non-rel. string network

Limiting spectrum in SUSY-QCD

[VB, MK '98]

derivation in QCD:

1. DGLAP: 2×2 matrix eq. for $\{q, g\}$ and $\xi = \alpha_s(Q^2)/(4\pi)\ln(Q^2/Q_0^2)$
2. Melin transform pdf's: $D(j, \xi) = \int \mathrm{d}x\, x^{j-1} D(x, \xi)$
3. diagonalise and find leading term for $j \to 1$

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4. LLA $\to$ MLLA: reinterprete argument ξ

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derivation in SUSY-QCD:

1. $\{q, g\} \to \{g, \tilde{g}\}$
2. $b_{\mathrm{QCD}} \to b_{\mathrm{SUSY-QCD}}$
3. $m_{\tilde{g}} = 0$

Limiting spectrum in SUSY-QCD

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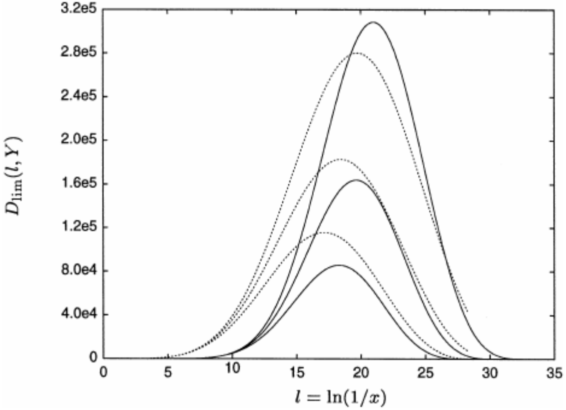
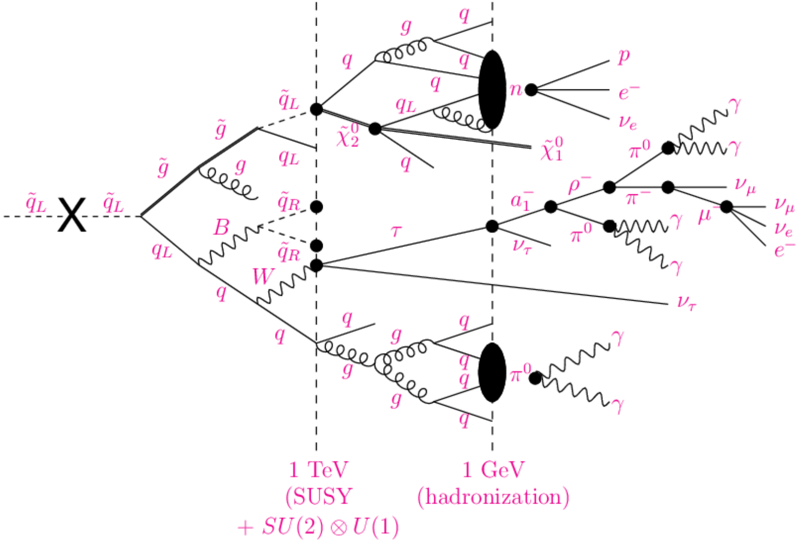


Fig. 1. Limiting spectrum $D_{\rm lim}(l,Y)$ as function of $l = \ln(1/x)$ for SUSY-QCD (solid lines) and QCD (dashed lines), both cases for $m_X = 10^{12}$ GeV (bottom), $m_X = 10^{13}$ GeV (middle) and $m_X = 10^{14}$ GeV (top). The QCD spectrum is scaled up by a factor 30.

Is a factor 30 difference reasonable?



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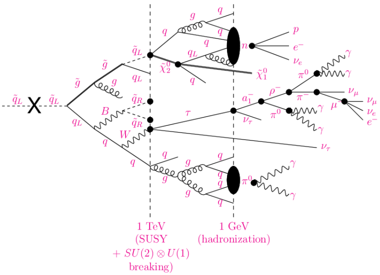

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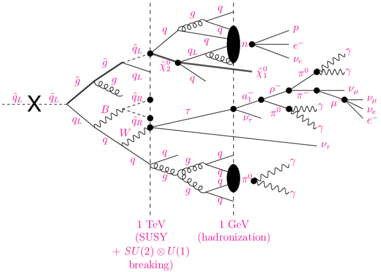

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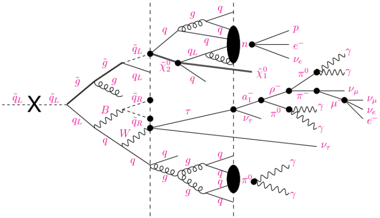

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- – QCD: approximation $\Lambda \simeq Q_0$ is ok, not for SUSY-QCD

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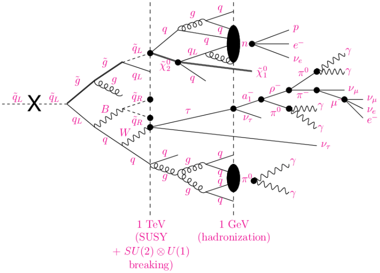

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Only understood having SUSY-QCD Monte Carlo [MK, VB '00]

- including mass thresholds, correct running of α_s
- getting finally LSP spectra

Electroweak cascades:

- consider Bremsstrahlung, $X \to \bar{f}fV$:

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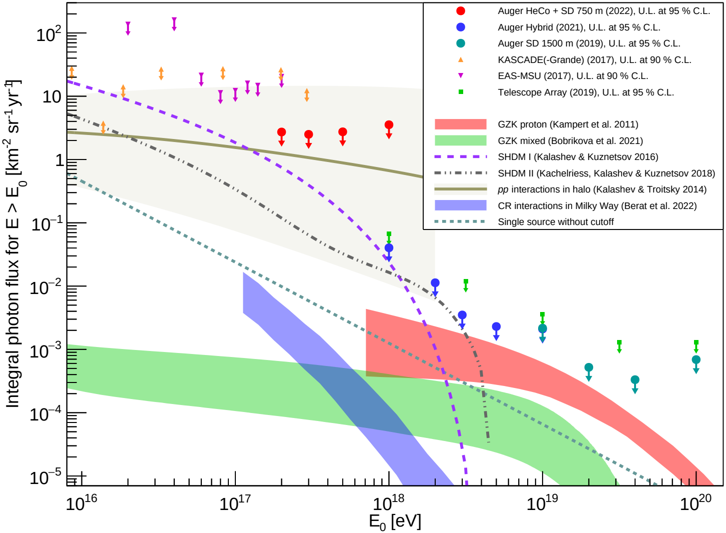
- (modified) DGLAP description possible

Reliable predictions?

- (SUSY) QCD cascade: *[MK, VB '00, Toldra, Sarkar '02, Aloisio, MK & VB '03,,...]*
  - $Q^2 \to \infty$ is an attractor
  - $\Rightarrow$ evolving initial data from Q_0^2 to $Q^2 \gg Q_0^2$ is “safe”
  - for not too small x: standard DGLAP – or Monte Carlo
- EW cascade: *[MK, VB '02, Barbot, Drees '03,..., Bauer et al. '20]*
  - mass effects are more important
  - large range with $g^2/(8\pi)\ln^2(m_X^2/m_W^2) \approx 1$

Exclusion limits: photons

[PAO '22]



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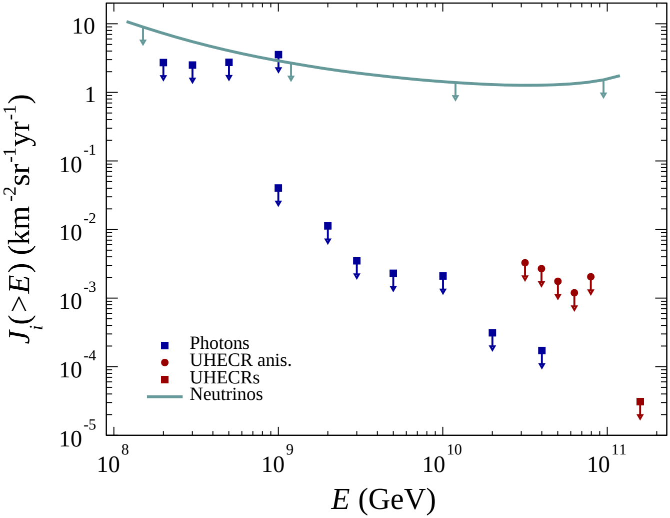
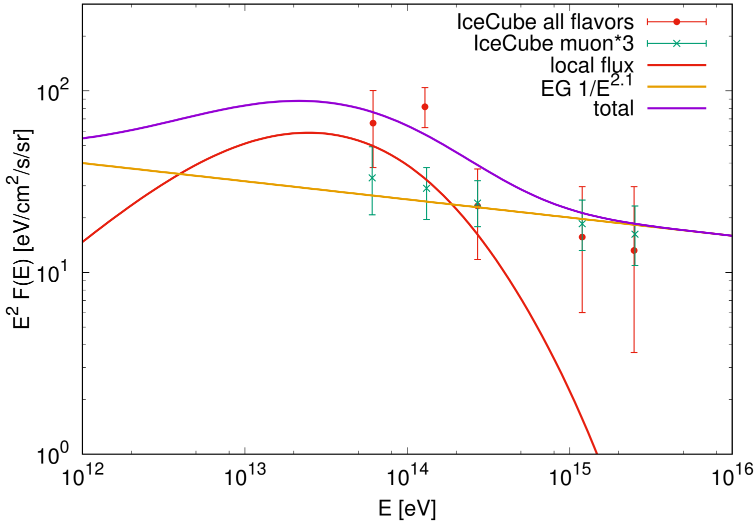


A revival: contribution to diffuse neutrino flux?



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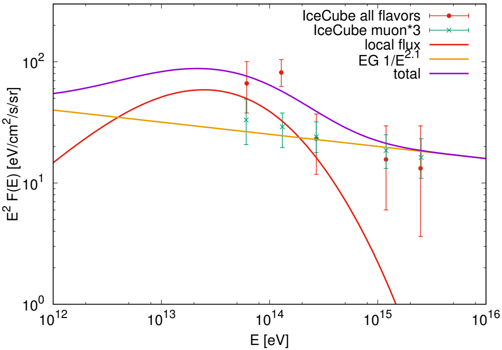
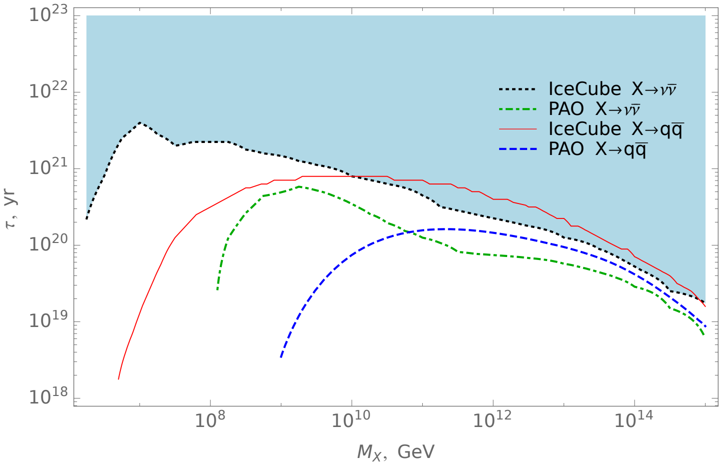


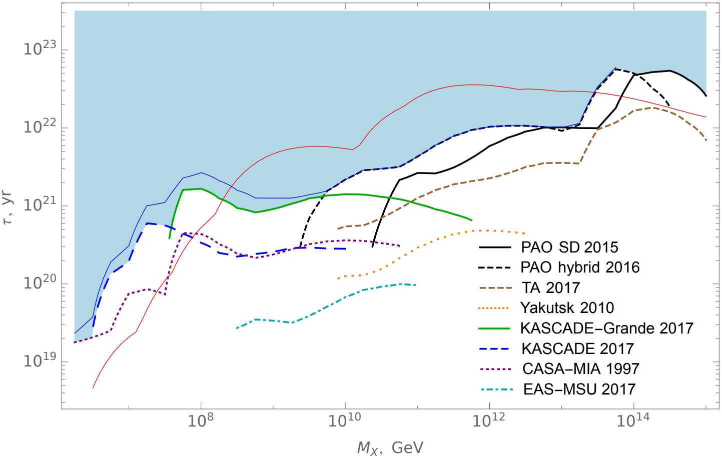
- possible sources:
  - extended CR halo [*Taylor, Gabici, Aharonian '14*]
  - extended nearby CR sources [*Andersen, MK, Semikoz '17, Bouyahiaoui, MK, Semikoz '21*]
  - heavy dark matter [*Feldstein et al. '13, Esmaili, Serpico '13,...*]

Exclusion plots for $X \to \bar{\nu}\nu$: neutrino constraints



[*MK, Kalashev, Kuznetsov '18*]

Exclusion plots for $X \to \bar{\nu}\nu$: gamma constraints



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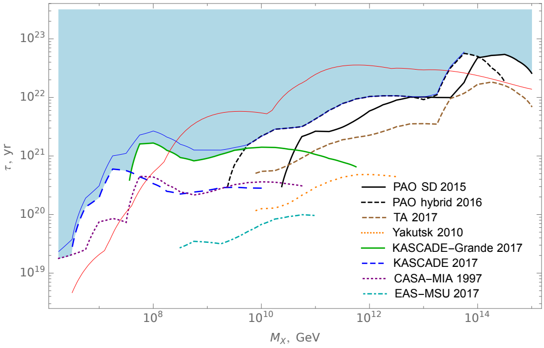
Exclusion plots for $X \to \bar{\nu}\nu$: constraints



[*MK, Kalashev, Kuznetsov '18*]

- significant contribution from only leptonic decay still possible

Conclusions

- WIMP paradigm in crisis ⇒ mass range of DM is wide open
- SHDM is an interesting DM candidate
  - Gravitational creation of DM with $m_X \sim 10^{11}$
  - probes inflation & GUT physics
  - photon & neutrino searches most promising
- SUSY-QCD & electroweak bremsstrahlung: now included in "standard" MC simulations
- illustrates nicely Venya's way to do physics