Fundamental physics with CTA (part 2)

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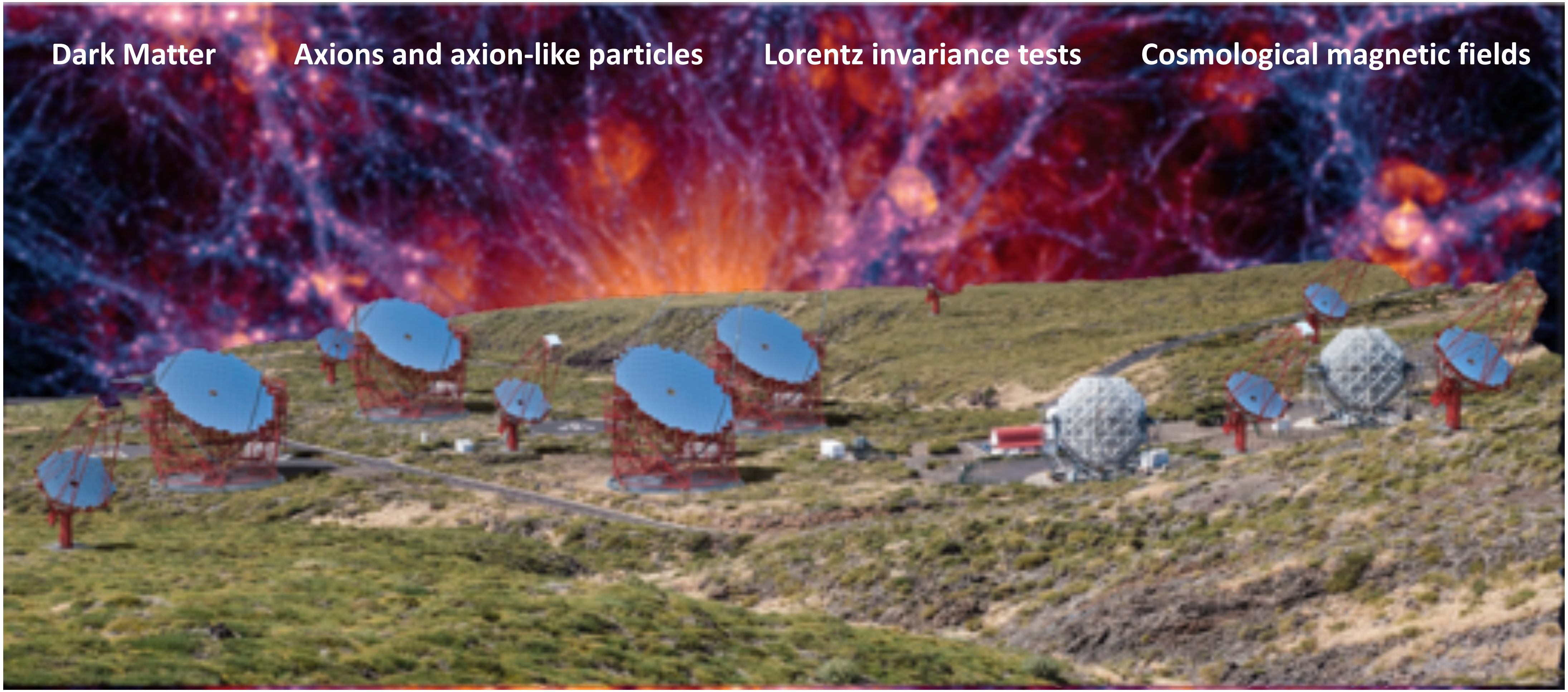
.... continuation, Part 1: Alexey Boyarsky

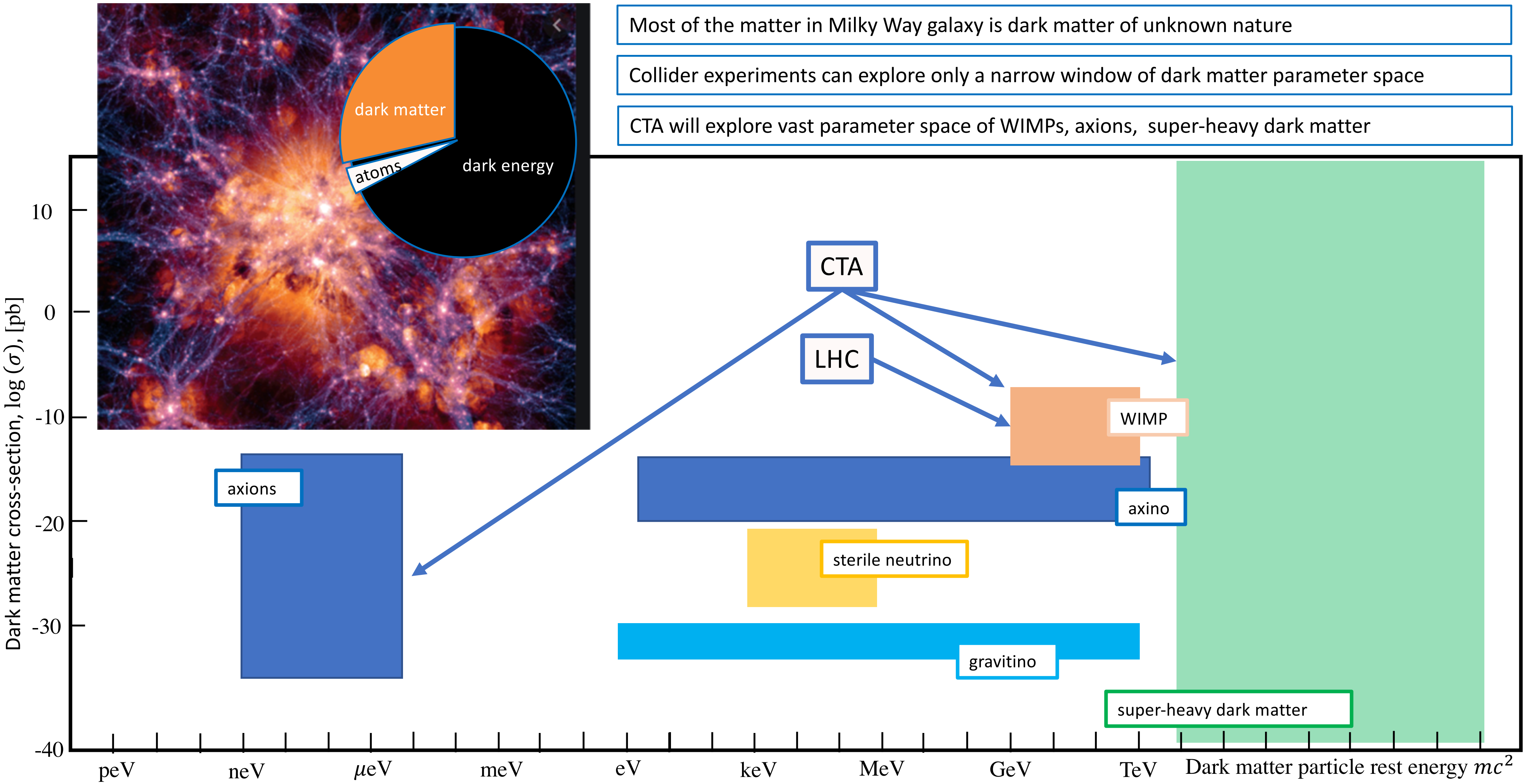


Dark matter

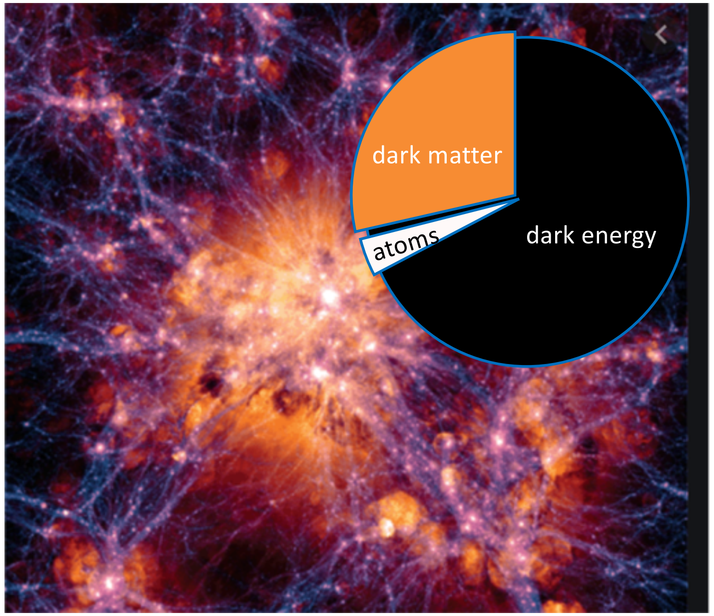
Most of the matter in Milky Way galaxy is dark matter of unknown nature

Collider experiments can explore only a narrow window of dark matter parameter space

CTA will explore vast parameter space of WIMPs, axions, super-heavy dark matter



Signal from annihilating Weakly Interacting Massive Particles (WIMP)

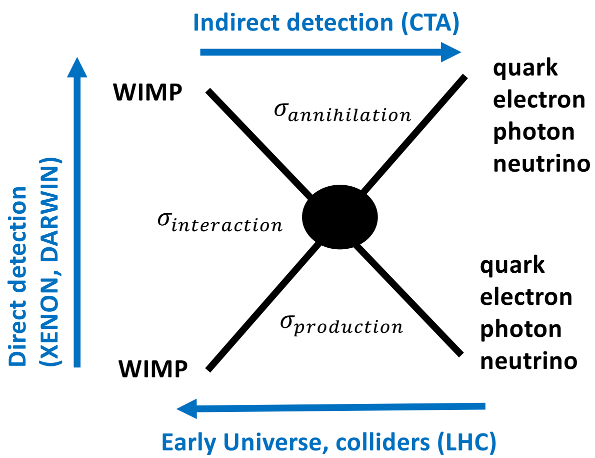


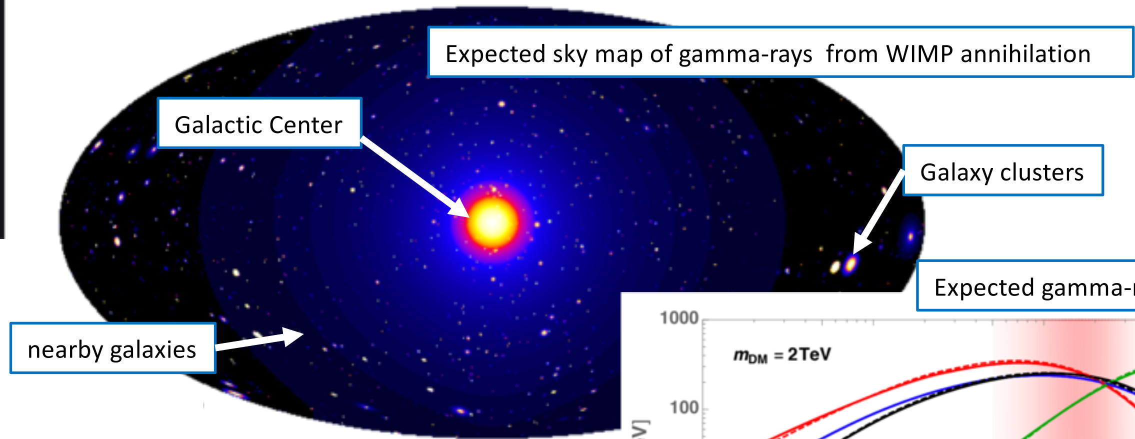
WIMPs with rest energies in GeV-TeV range could have been produced in the Early Universe in collisions of quarks, electrons, neutrinos, if the cross-section of this process is close to

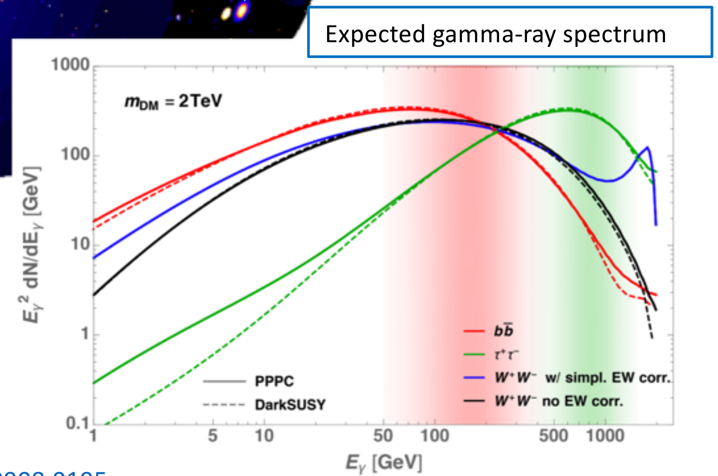
$$< \sigma v > \simeq 3\times10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

The same process leads to annihilation of WIMPs into conventional particles in the halo of Milky Way, its satellite galaxies, in nearby galaxy clusters.

The strongest signal is from Milky Way central region. The energy range of γ-rays from WIMP annihilation is $E_\gamma \sim 0.1\ m_{WIMP}c^2$.

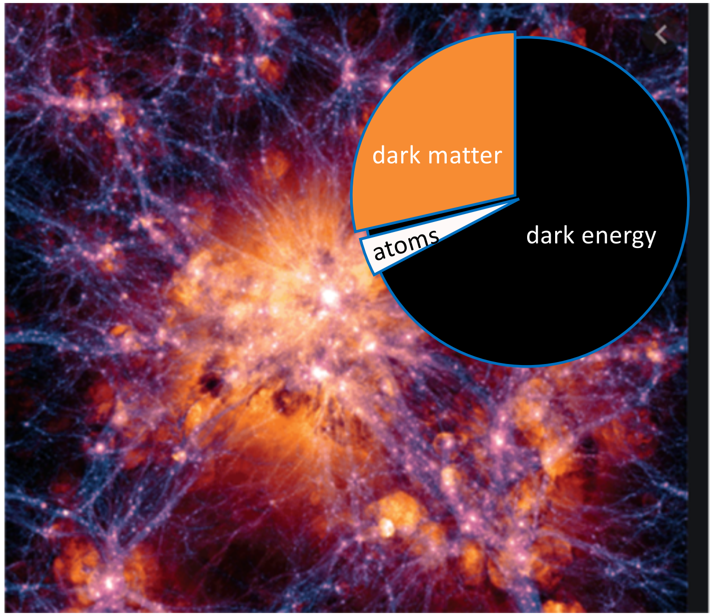




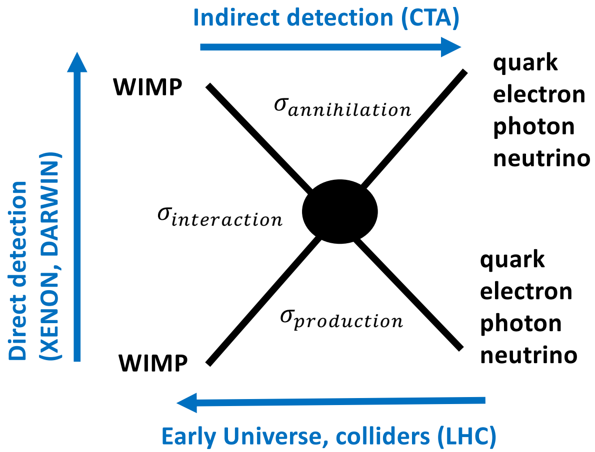


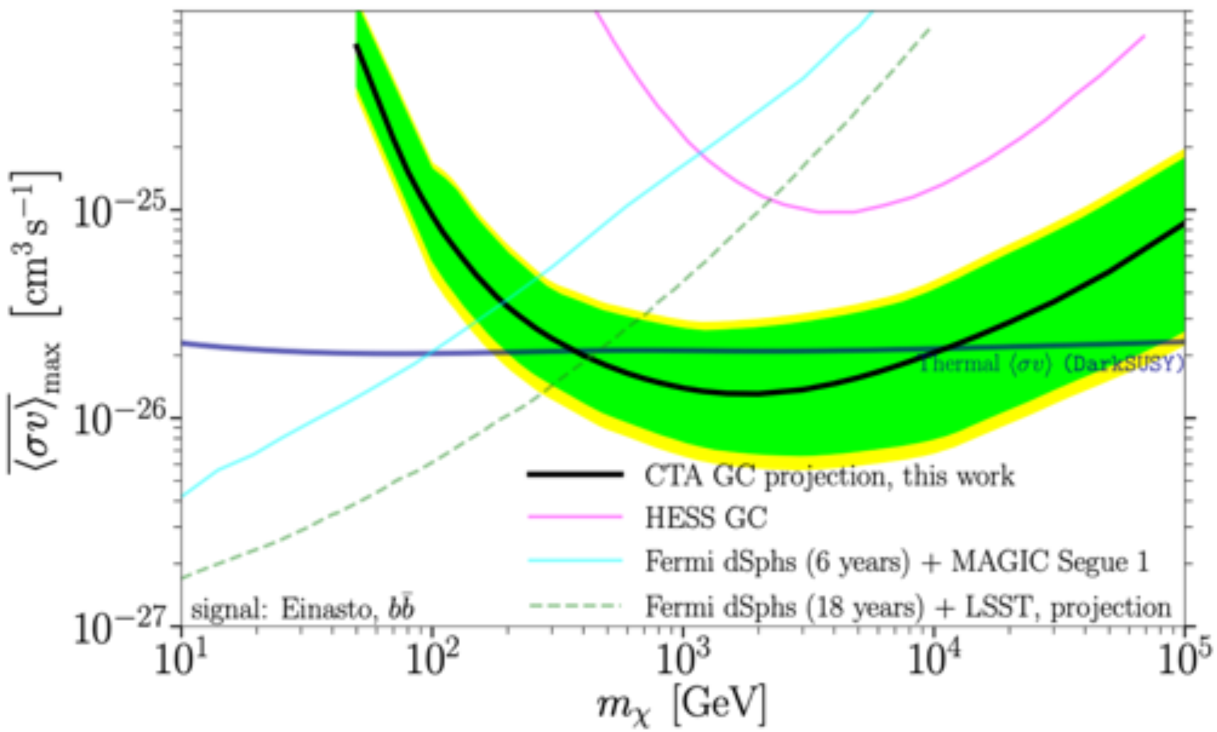
Latest update: Cherenkov Telescope Array Consortium, https://arxiv.org/abs/2007.16129; Pieri et al., https://arxiv.org/abs/arXiv:0908.0195

Signal from annihilating Weakly Interacting Massive Particles (WIMP)



CTA will reach sensitivity sufficient for the probe of the expected WIMP annihilation cross-section, $< \sigma v > \simeq 3\times10^{-26}\ \mathrm{cm}^3/\mathrm{s}$, for the WIMP mass $m_{WIMP}c^2$ ~0.3-100 TeV.





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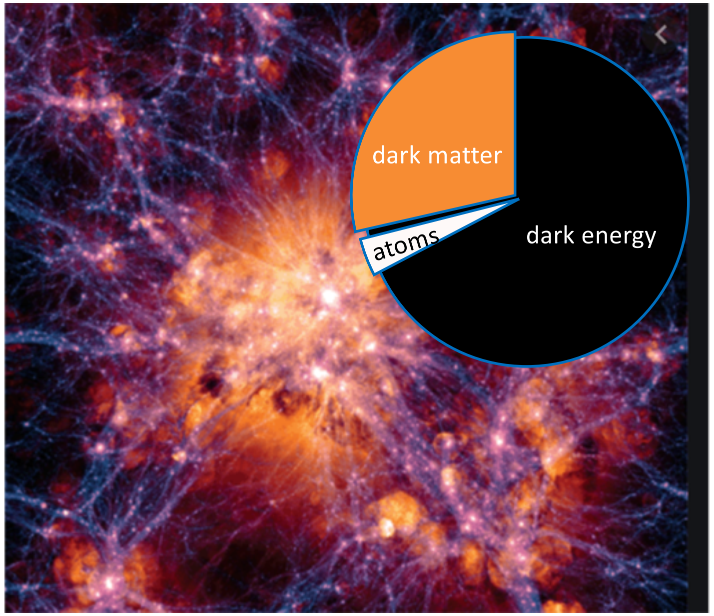
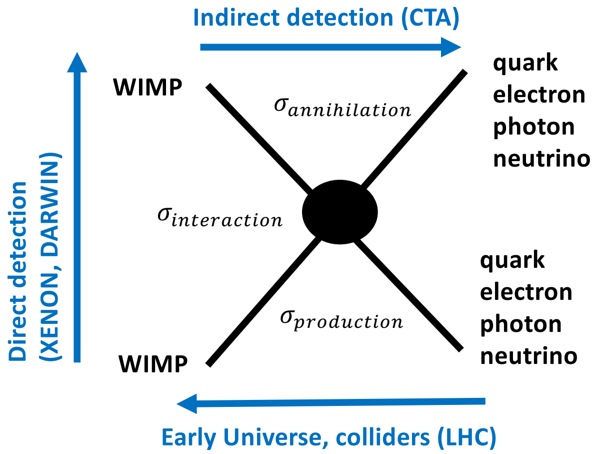
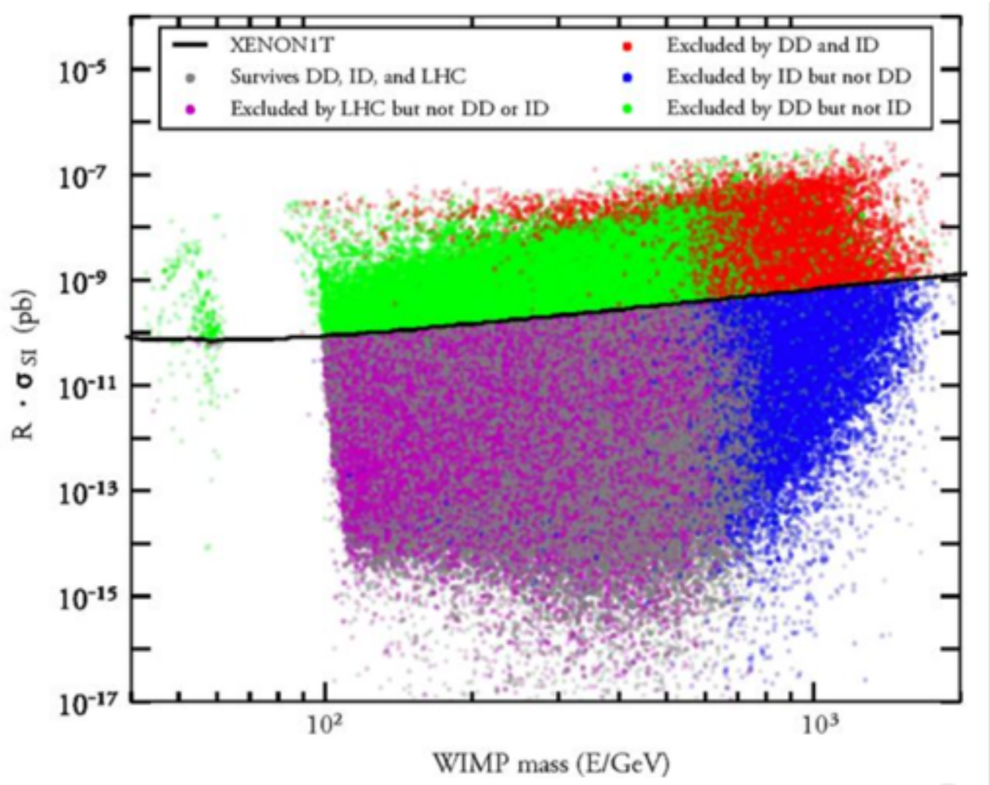
Signal from annihilating Weakly Interacting Massive Particles (WIMP)



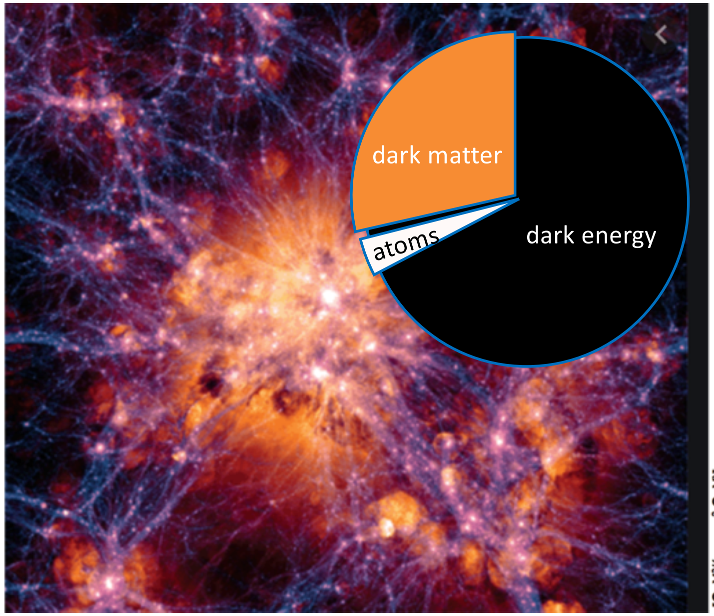
Direct detection (DD) experiments like XENON, DARWIN, indirect detection (ID) observation with CTA (and also IceCube, HERD, LHAASO,…) and collider searches (LHC) provide complementary probes of WIMP parameter space, because they probe different,





Latest update: Cherenkov Telescope Array Consortium, https://arxiv.org/abs/2007.16129, Cahill-Rowley et al., https://arxiv.org/abs/1305.6921

Signal from decaying (super)heavy dark matter particles

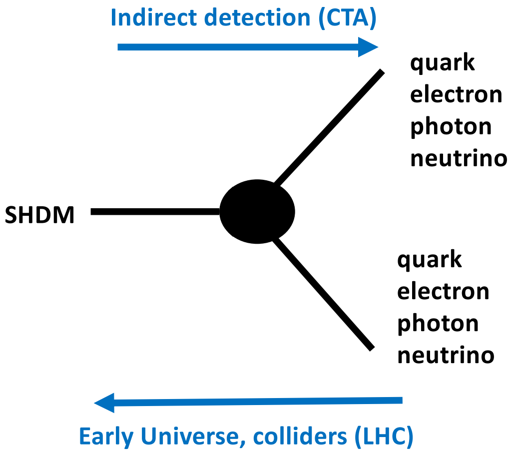


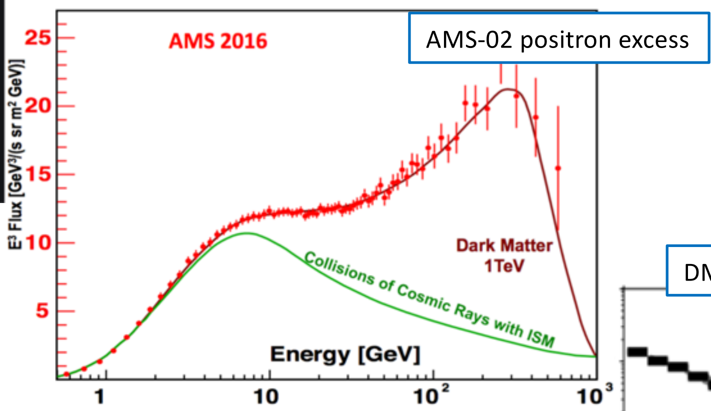
Unstable heavy dark matter particles that could have been produced in high-energy particle interactions in the Early Universe might survive as dark matter today if their life time is much longer than the age of the Universe

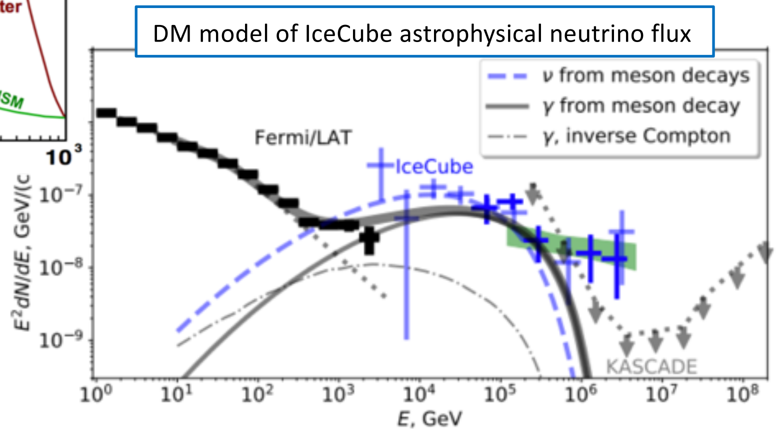
$$\tau \gg 10^{10}\ \mathrm{yr}$$

Dark matter decays in the Milky Way halo can inject cosmic ray particles, like positrons, thus explaining the "positron anomaly" observed by PAMELA and AMS-02.

Dark matter decays can also produce neutrinos thus explaining the astrophysical neutrino signal detected by IceCube.

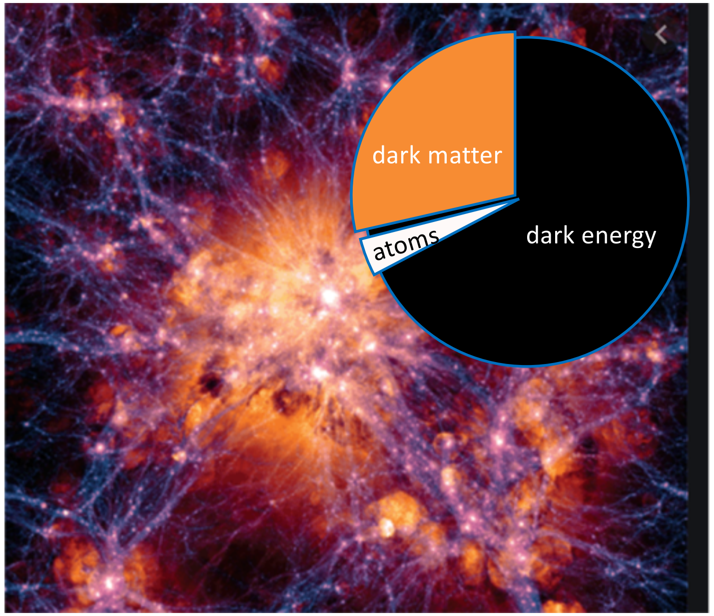






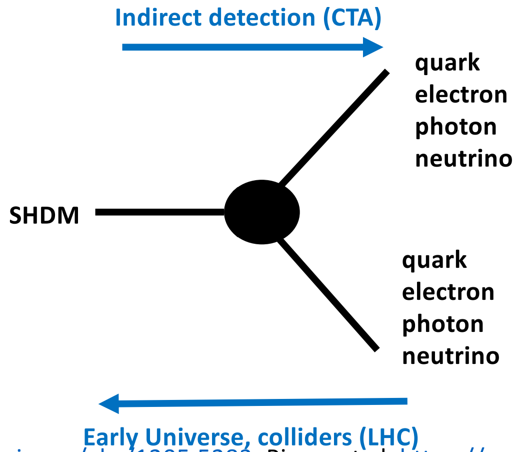
M.Cirelli et al,, https://arxiv.org/abs/1205.5283, Pierre et al, https://arxiv.org/abs/1401.7330, Neronov et al, https://arxiv.org/abs/1802.09983

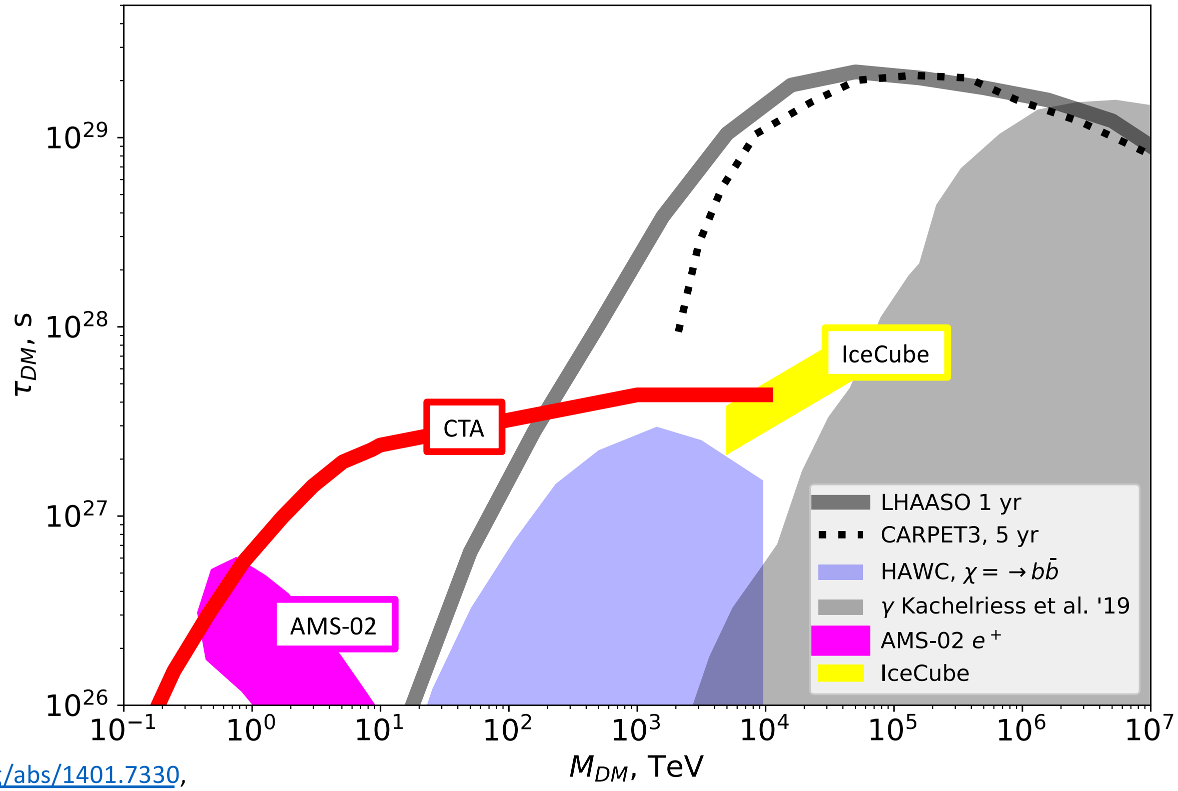
Signal from decaying (super)heavy dark matter particles



Similarly to annihilating WIMPs, the strongest signal is expected from the Milky Way halo. However, it is less concentrated toward the Galactic Center.

CTA will reach sensitivity sufficient for the probe of the Dark Matter contributions to the positron and astrophysical neutrino signals, by observing gamma-ray signal from dark matter decays in the halo of the Milky Way.





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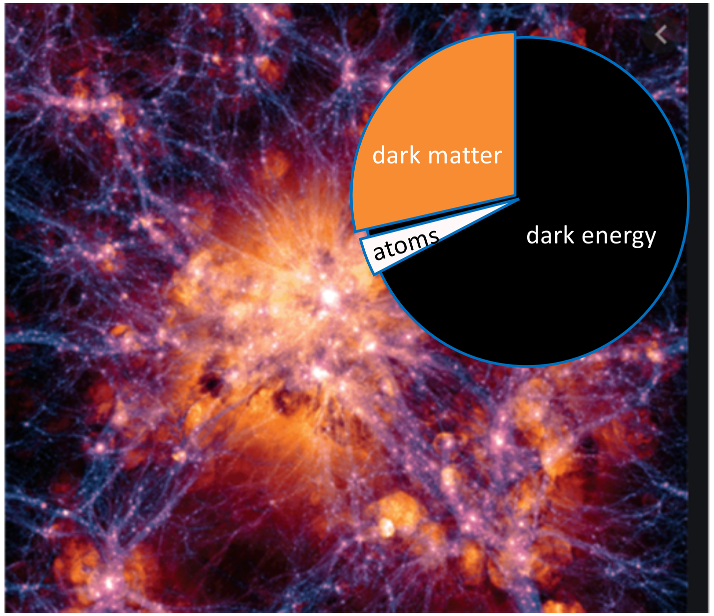
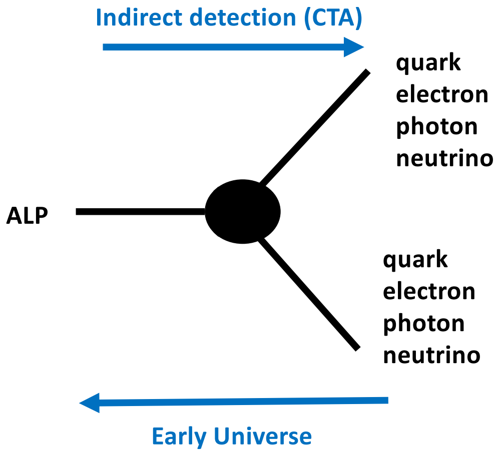
Neronov et al, https://arxiv.org/abs/1802.09983, https://arxiv.org/abs/2001.00922, https://arxiv.org/abs/2001.11881

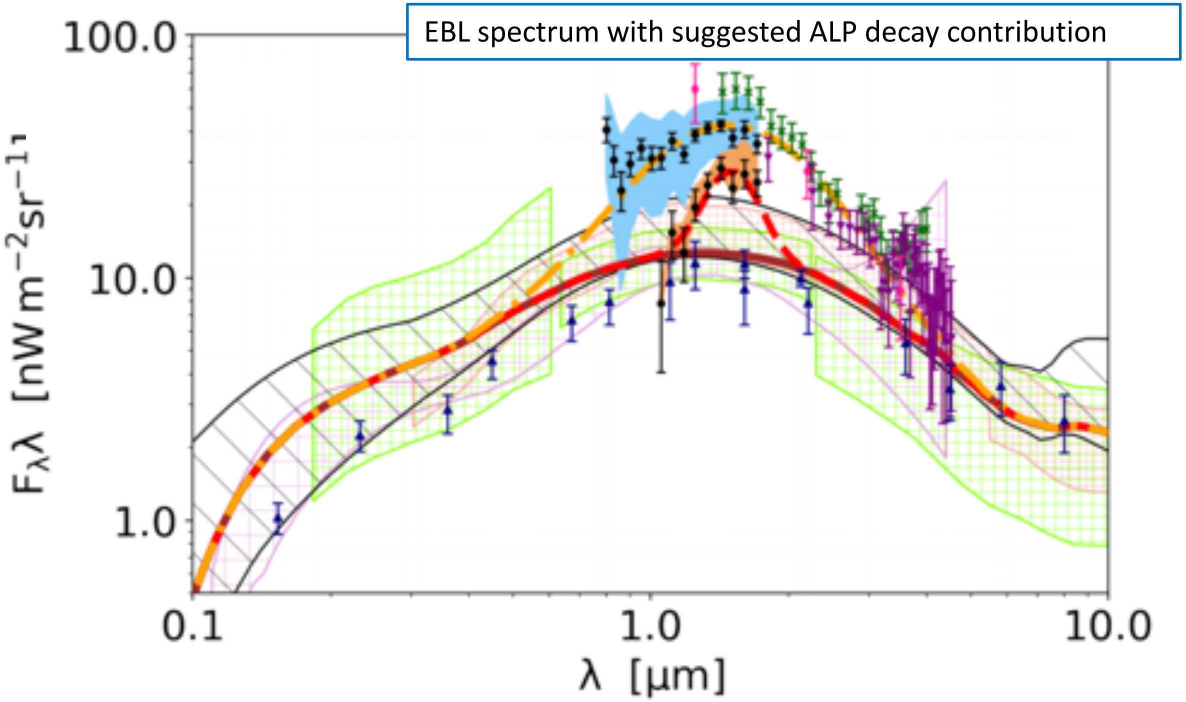
Signal from decaying (very)light axion-like particles (ALPs)



Dark matter particles can also be very light (rest energies in sub-eV range), but imitate the properties of ”cold” dark matter made of heavy particles, through Bose-Einstein condensate. Axions and axion-like particles (ALPs) are the best-known example of such light dark matter.

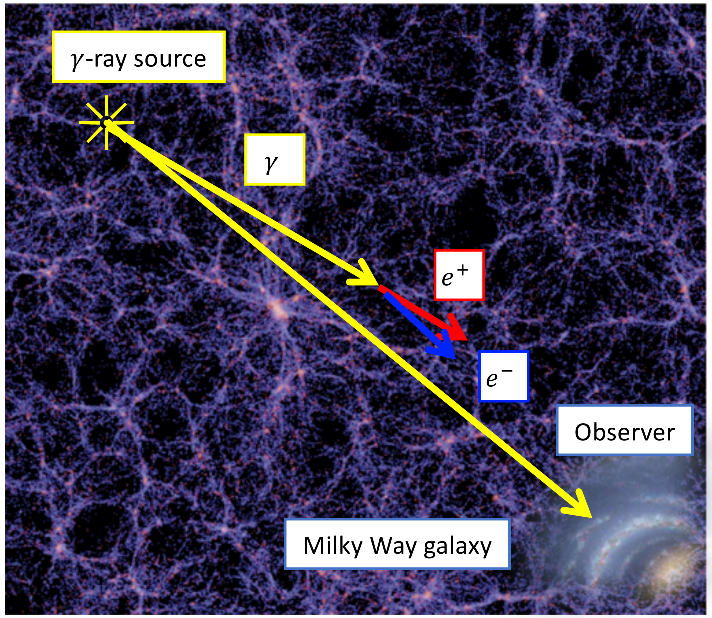
ALPs are unstable particles and have a radiative decay channel into two photons. Photons from ALP decays in all galaxies accumulated over the age of the Universe form a “bump” at the energy $E_{ph} = m_a c^2/2$ in the spectrum of Extragalactic Background Light (EBL).





Perrcei, Quinn, 1977, Arias et al., https://arxiv.org/abs/1201.5902, Grin et al. https://arxiv.org/abs/astro-ph/0611502, Korochkin et al., https://arxiv.org/abs/1911.13291

Signal from decaying (very)light axion-like particles (ALPs)

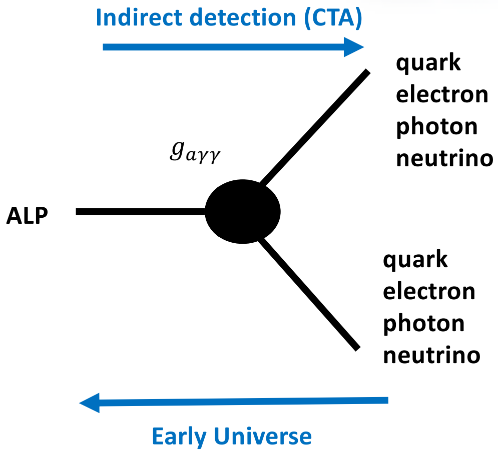


Cherenkov telescopes can do precision measurements of the EBL spectrum via observation of effect of attenuation of γ-ray flux by electron-positron pair production on EBL photons:

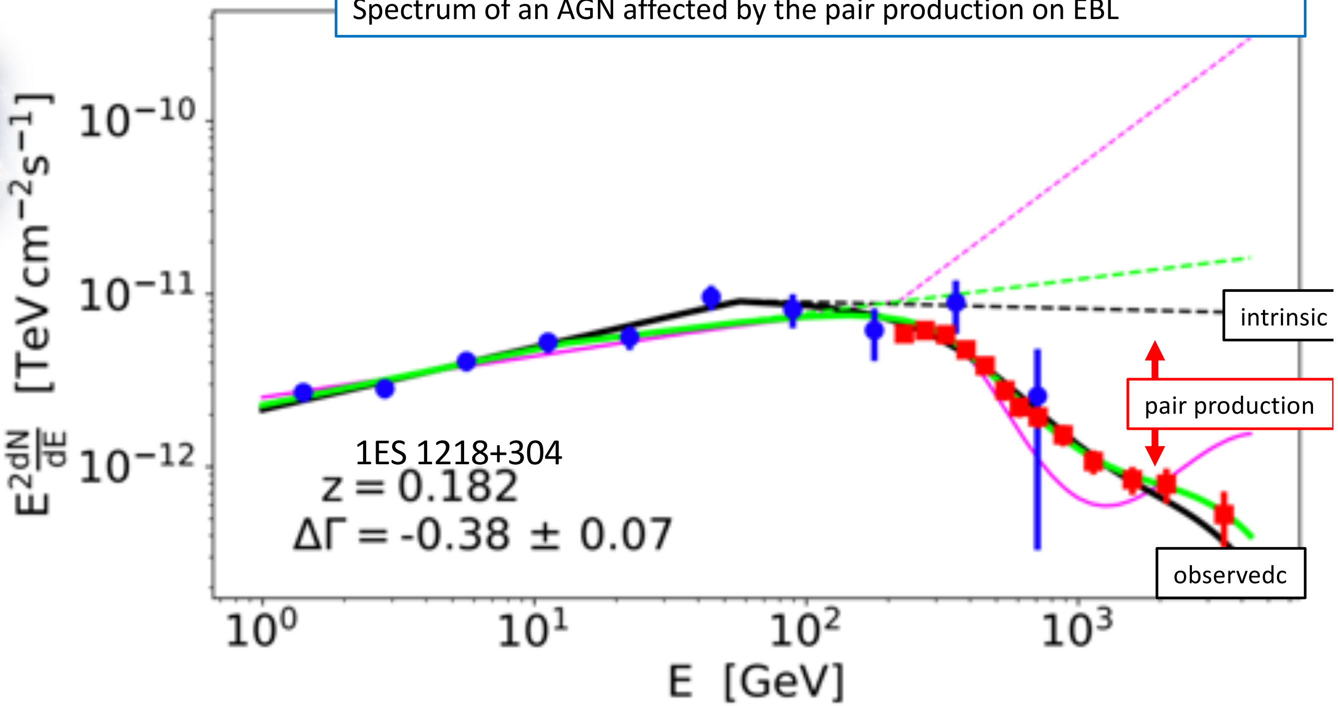
$$\gamma + \gamma \rightarrow e^+ + e^-$$

This effect reduces γ-ray flux from extragalactic sources (active galactic nuclei, AGN) at the energy $E_\gamma \simeq 4\, m_e c^2/\epsilon$ in the TeV band for interactions with EBL photons.

An ALP "bump" in the EBL spectrum at the energy $\epsilon \simeq 1$ eV leads to a "dip" in the γ-ray spectrum because of excess absorption of γ-rays with energies $E_\gamma \simeq 1$ TeV.

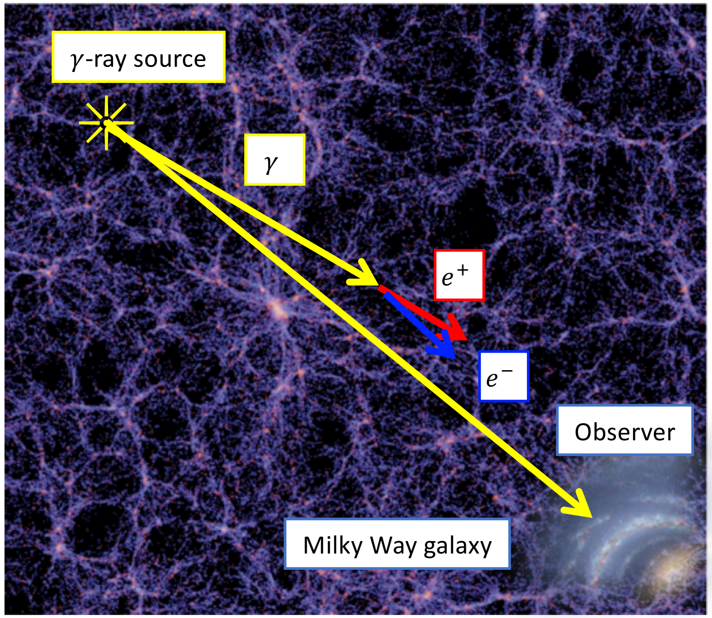


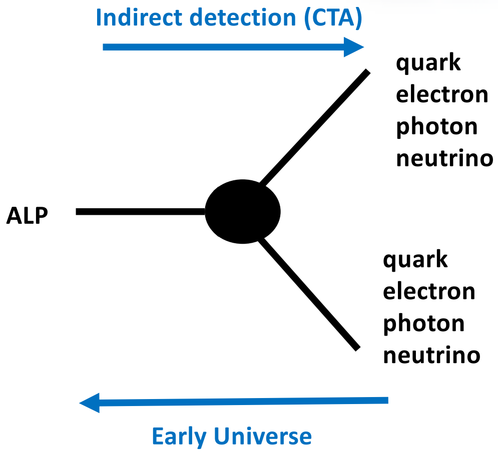
Spectrum of an AGN affected by the pair production on EBL



Kalashev et al., https://arxiv.org/abs/1808.05613, Korochkin et al., https://arxiv.org/abs/1911.13291

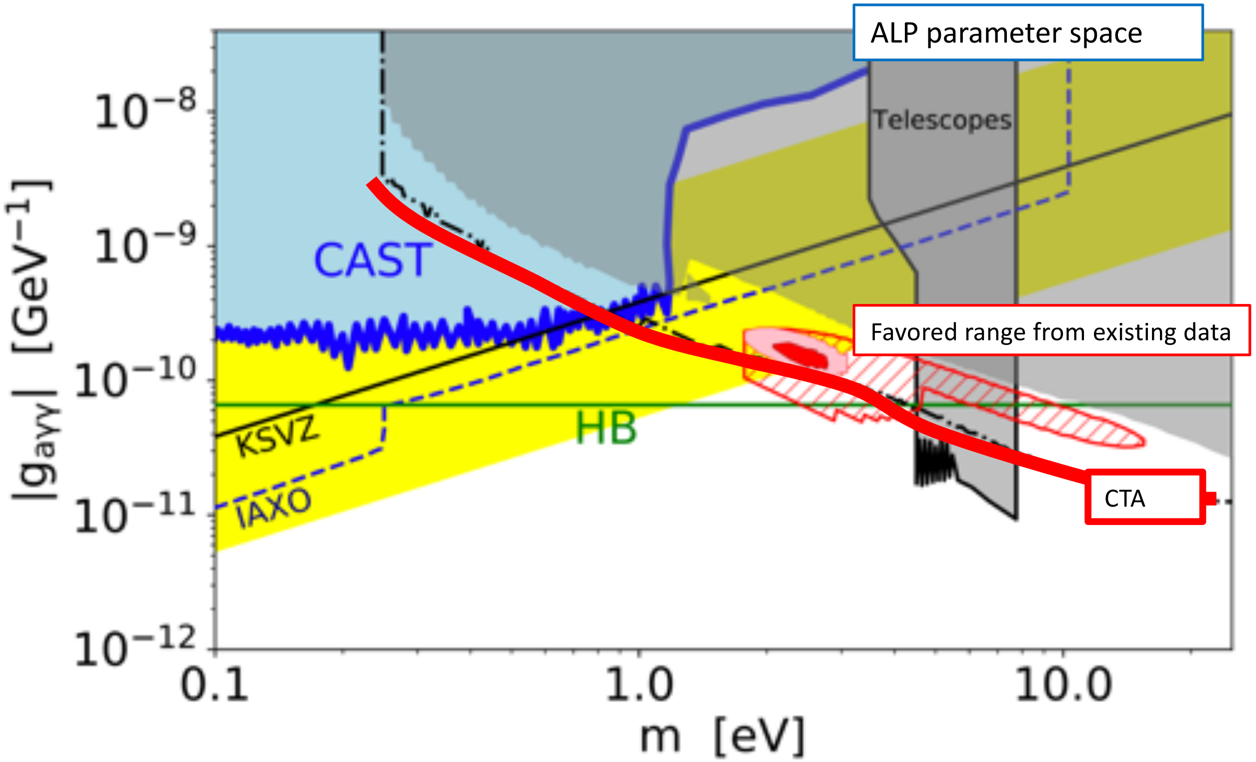
Signal from decaying (very)light axion-like particles (ALPs)





Existing Cherenkov telescope data are consistent with a possibility of existence of a bump in the EBL spectrum, produced by ALPs with rest energies $mc^2 \sim 1$ eV. CTA will improve the precision of EBL measurements through γ-ray absorption. It will test the hypothesis of existence of 1 eV scale ALPs.

ALP searches with CTA will be complementary to those with “Solar axion telescopes” (CAST/ IAXO) at CERN.



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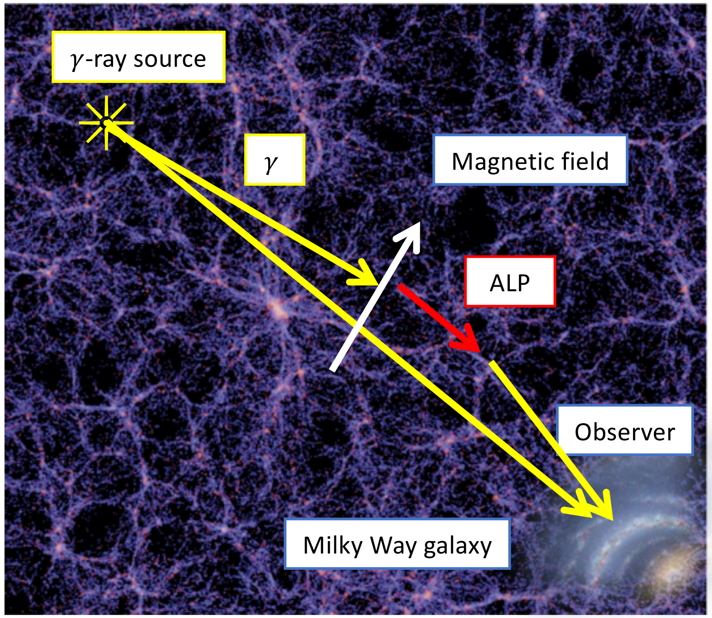
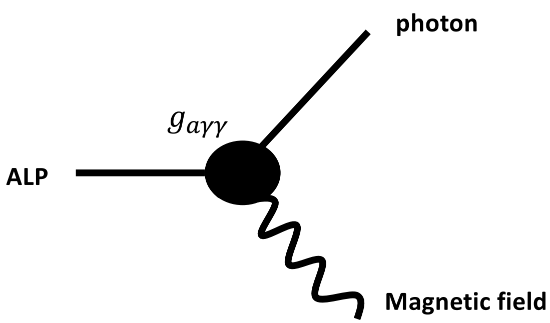
Gamma-ray – ALP oscillations in magnetic fields

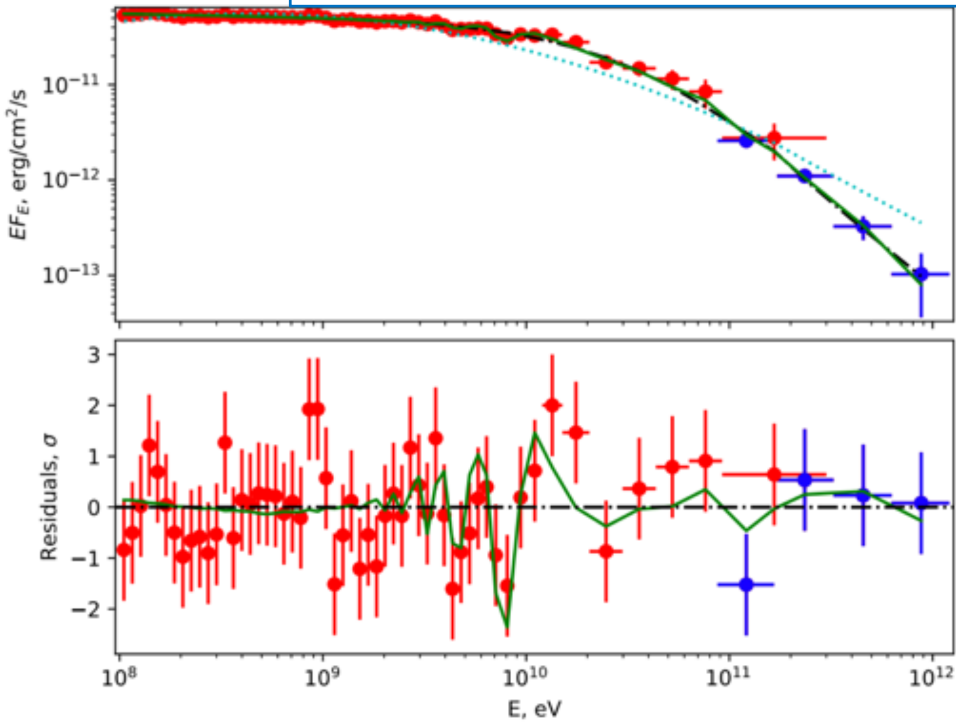


ALPs of still smaller masses, $mc^2 \sim 10^{-6}$eV, produce an effect on γ-ray signal from distant AGN, through on γ-ray – ALP oscillations in magnetic fields. The oscillations induce oscillatory behaviour in the γ-ray spectra.

ALP – γ-ray oscillations can take place in galaxy or galaxy cluster hosting γ-ray source, in the intergalactic magnetic field (IGMF), in the magnetic field of the Milky Way galaxy.

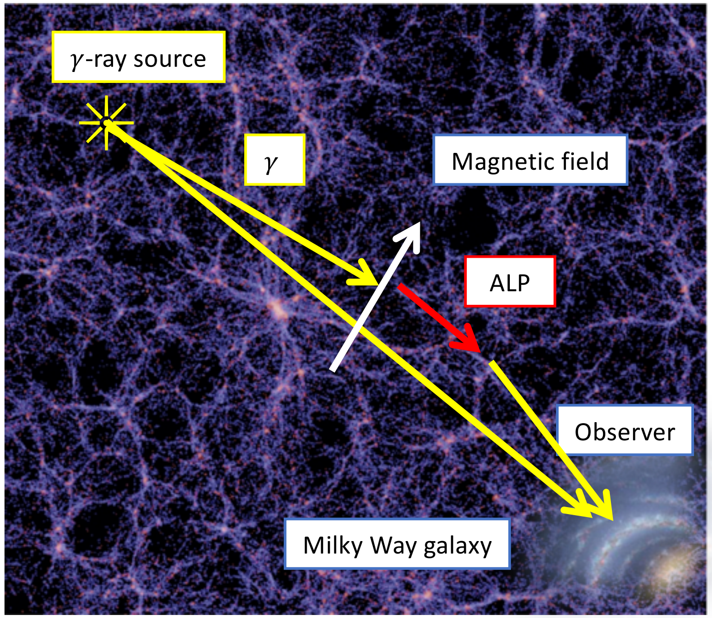


Example of AGN spectrum (NGC 1275) affected by ALP – γ-ray oscillations in magnetic field of galaxy cluster (Perseus)

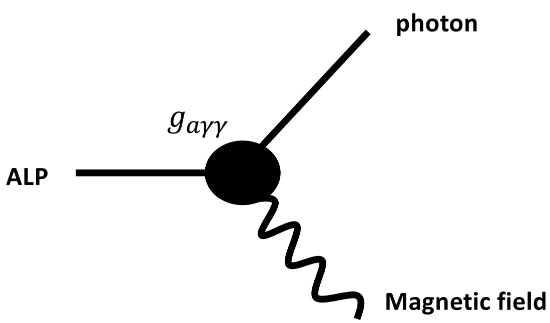


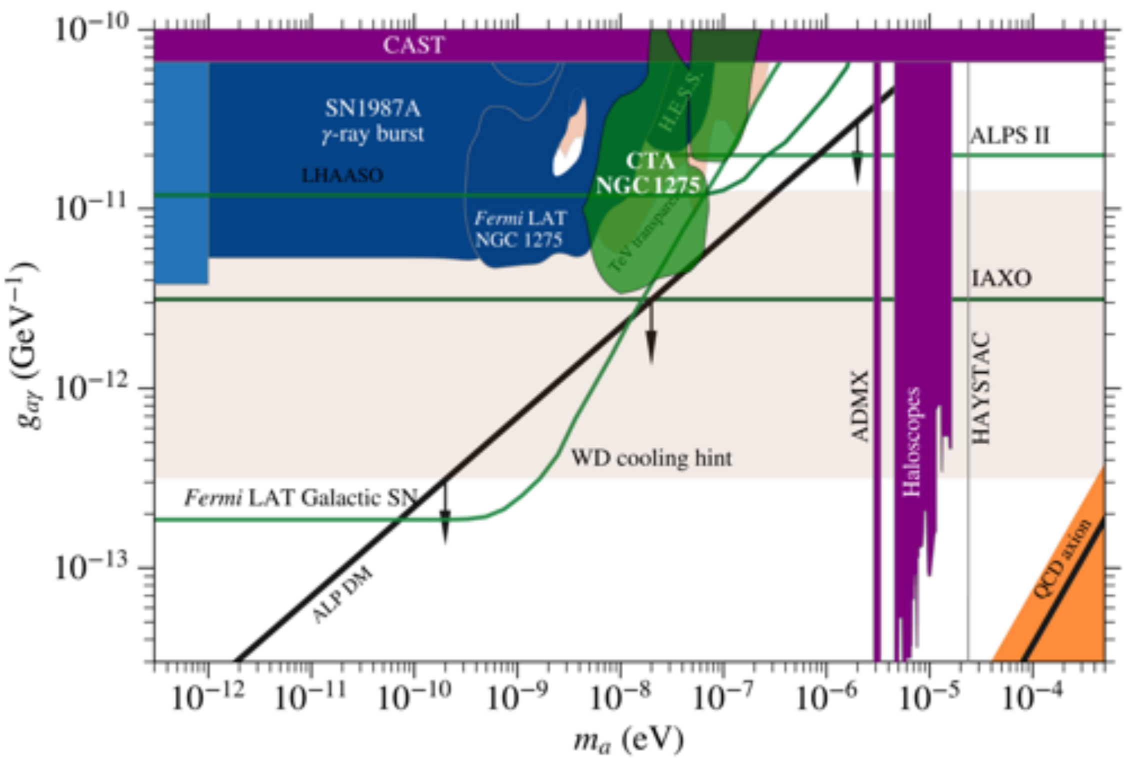
Sikivie 1983, Fermi-LAT Collab. https://arxiv.org/abs/1603.06978 , Malyshev et al. https://arxiv.org/abs/1805.04388, Doro et al., https://arxiv.org/abs/1208.5356

Gamma-ray – ALP oscillations in magnetic fields



Observations of ALP-gamma-ray conversion effect occurring during propagation of gamma-rays from the sources to the Earth by CTA will explore previously inaccessible range of ALP parameter space of ALPs with masses in the μeV range.





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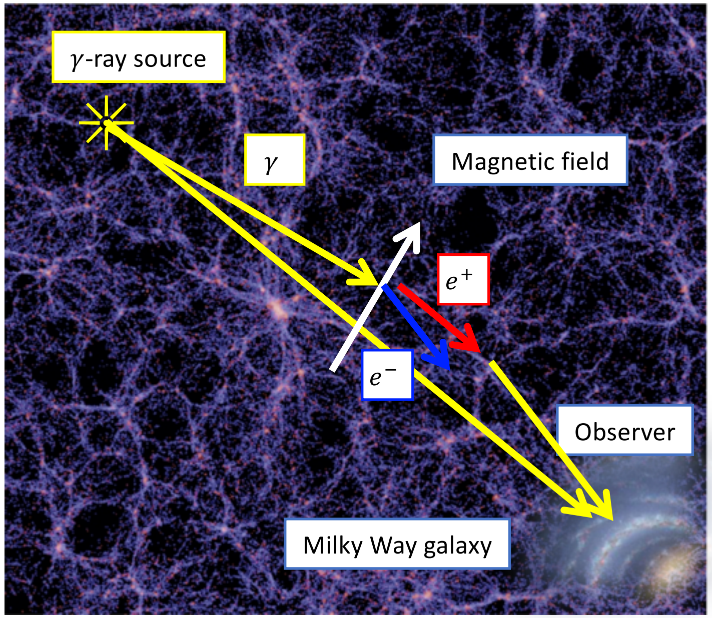
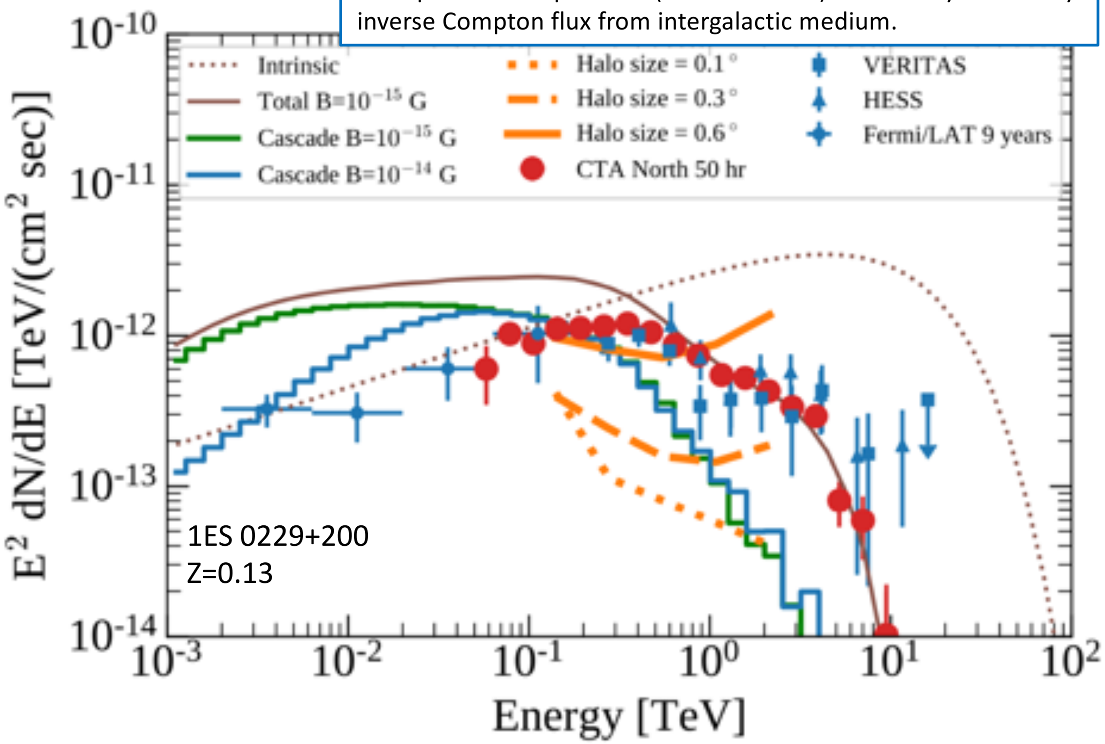
Intergalactic / cosmological magnetic fields



Gamma-rays propagating through intergalactic medium interact with low-energy EBL photons and produce electron-positron pairs. These pairs re-generate gamma-rays through inverse Compton scattering. Electrons and positrons are deflected by intergalactic magnetic field (IGMF).

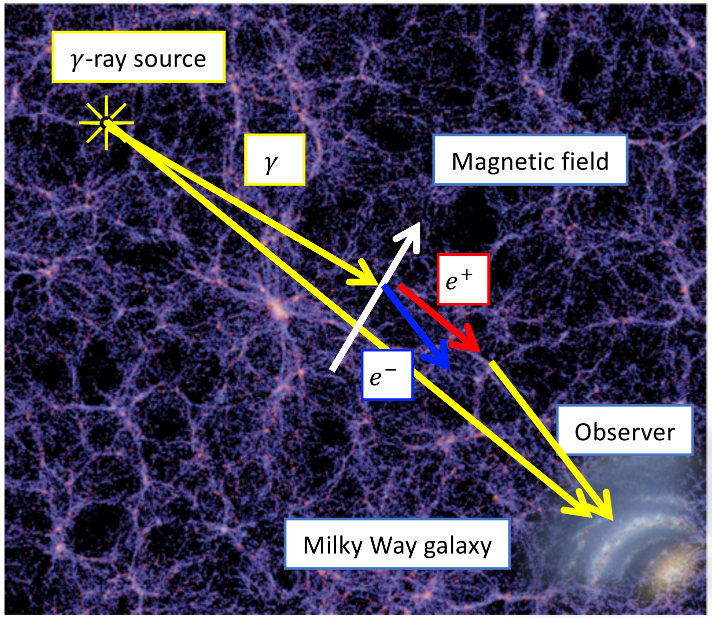
Observations of secondary inverse Compton emission from e^+e^- pairs can be used to measure IGMF.

Example of AGN spectrum (1ES 0229+200) affected by secondary inverse Compton flux from intergalactic medium.



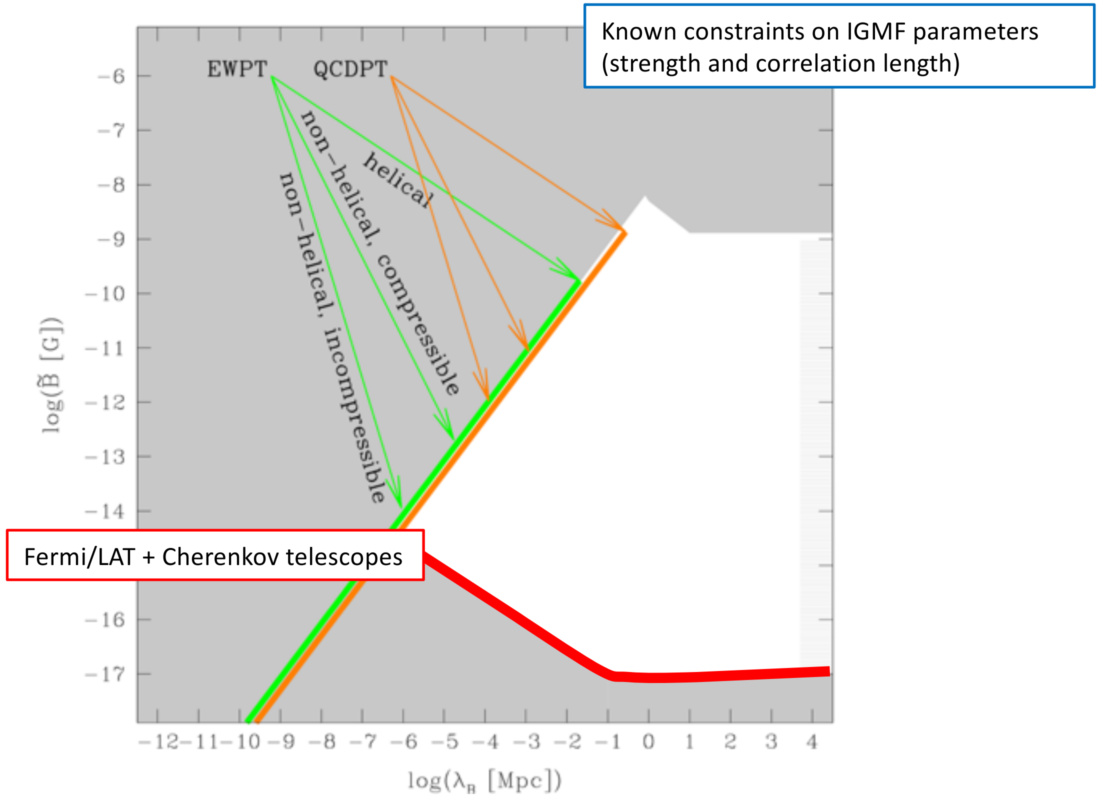
Neronov, Vovk https://arxiv.org/abs/1006.3504, Fermi LAT collab. https://arxiv.org/abs/1804.08035 , Korochkin et al. https://arxiv.org/abs/2007.14331

Intergalactic / cosmological magnetic fields



Existing γ-ray measurements prove existence of non-zero IGMF in the voids of the Large Scale Structure (however, do not yet provide measurements of IGMF).

IGMF in the voids is probably a relic field from cosmological phase transitions: Electroweak EWPT), quark confinement (QCDPT) or from Inflationary epoch. It carries information on physical state of the Universe $\leq 10\ \mu$s from the Big Bang.



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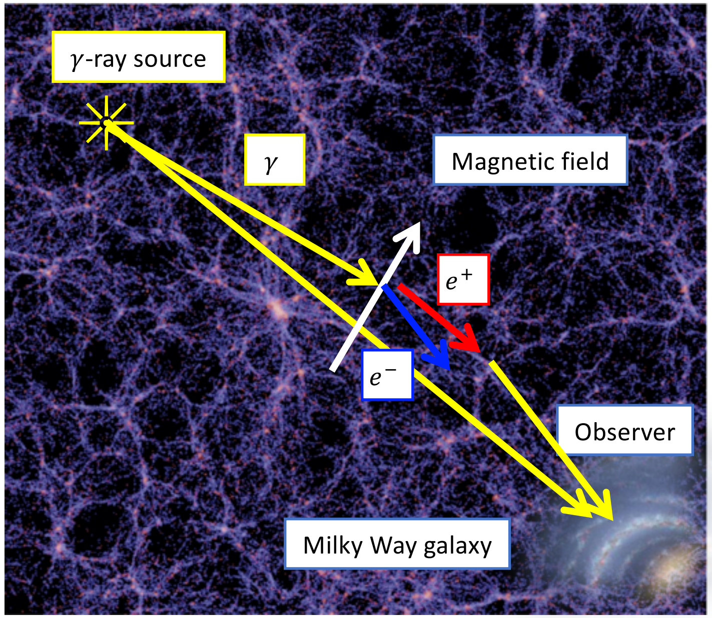
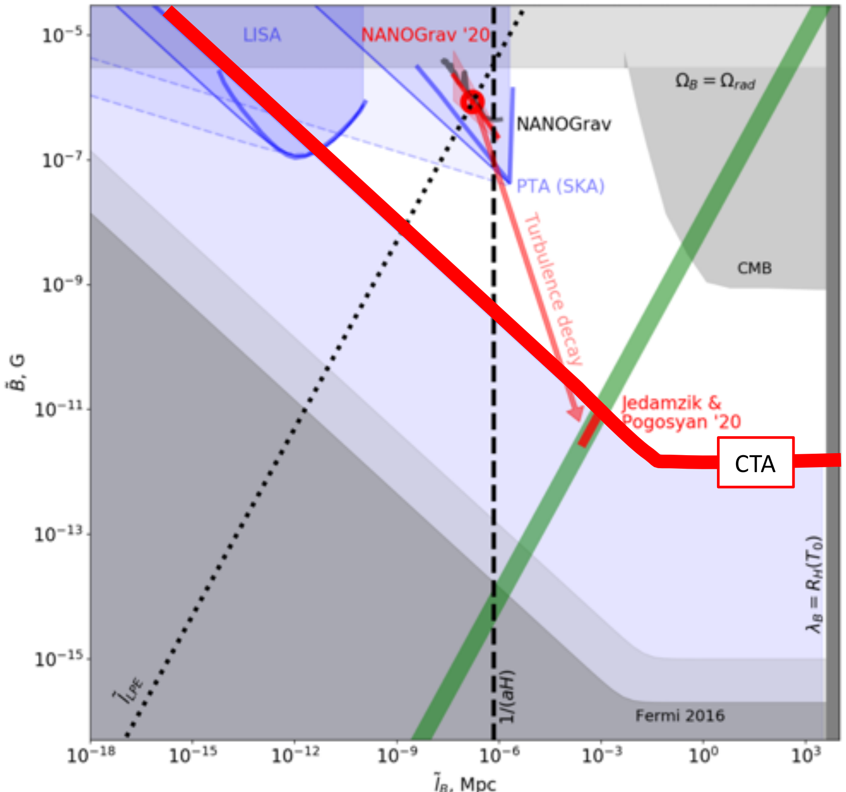


CTA will explore large part of IGMF parameter space, perhaps provide first measurements of IGMF and provide evidence for its cosmological origin.

Probe of cosmological magnetic field with CTA, complemented by CMB and gravitational wave (GW) detector probes has a potential to identify the “beyond Standard Model” phenomena that took place $\leq 10\ \mu$s from the Big Bang and resulted in production of the Dark Matter and Baryon Asymmetry of the Universe.



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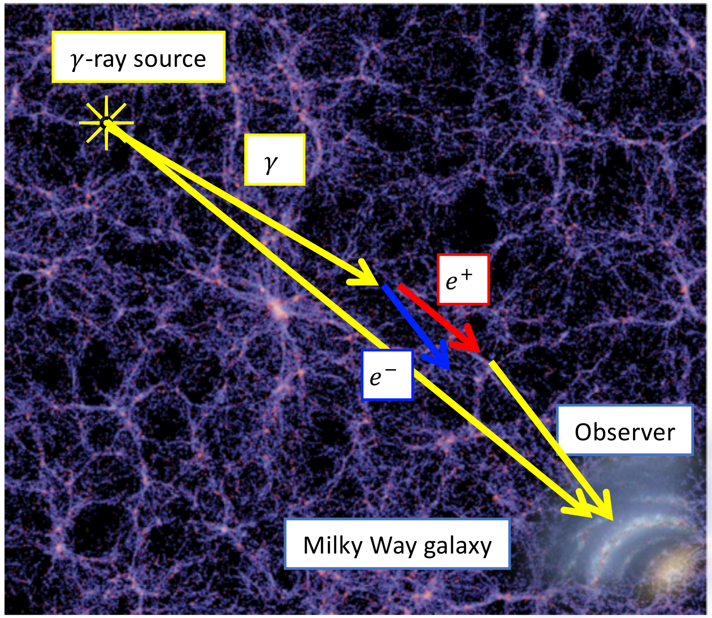
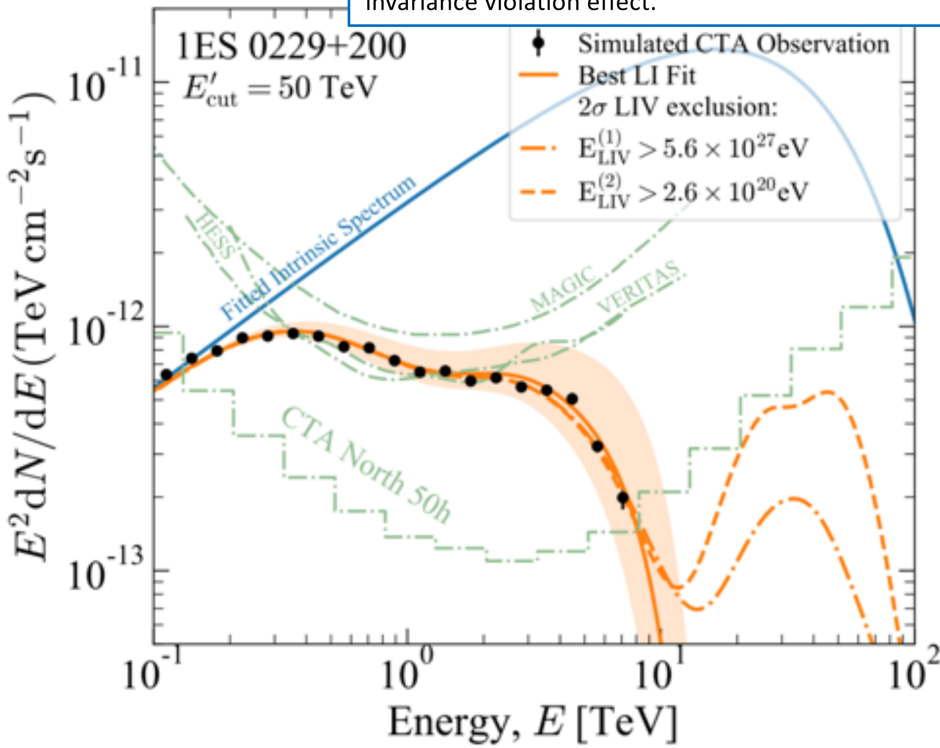
Test of Lorentz invariance principle



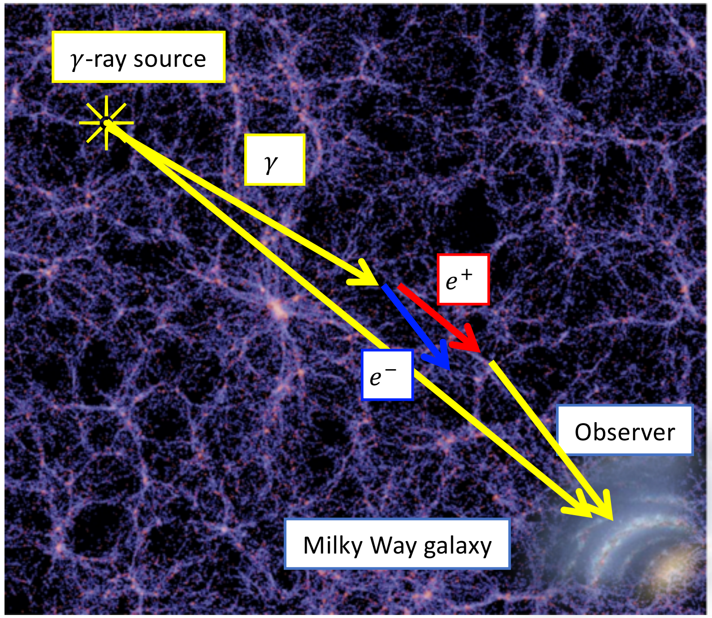
Possible modification of energy-momentum relation, $E^2 = m^2c^4 + p^2$, modifies the pair production threshold and hence modifies the attenuation of the γ-rays by interactions with EBL. The effect is characterised by energy scale(s) perhaps determined by quantum gravity effects at an energy $\mathrm{E_{LIV}}$.

Example of AGN spectrum (1ES 0229+200) affected by Lorentz invariance violation effect.



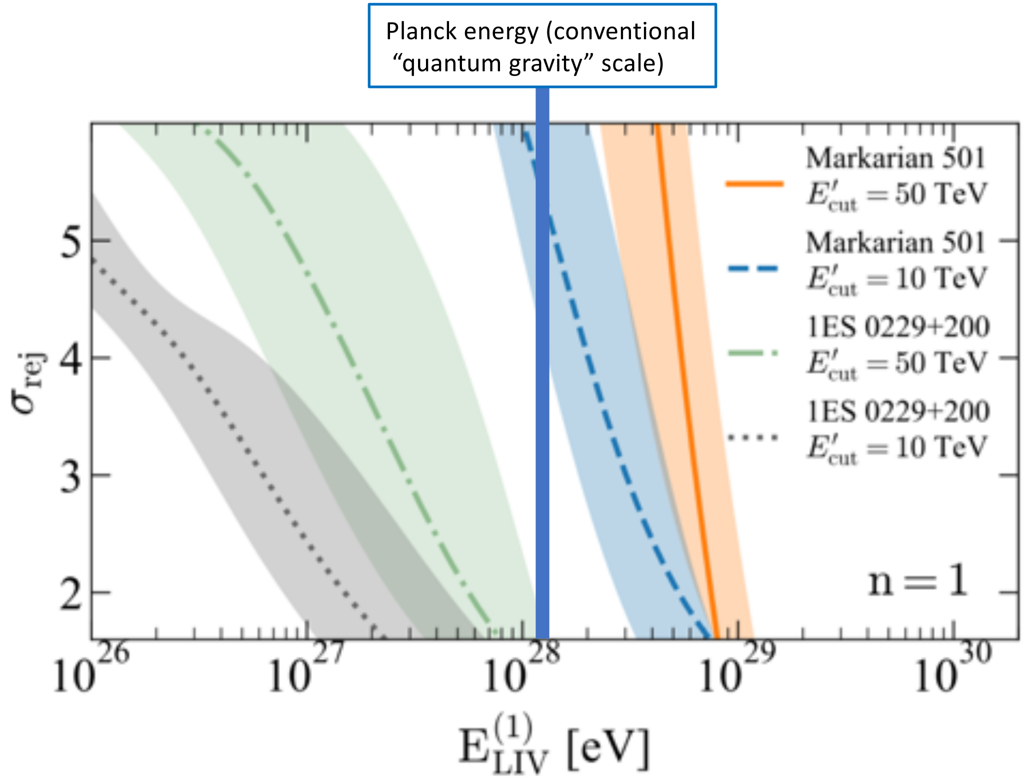
Latest update: CTA consortium, https://arxiv.org/abs/2010.01349

Test of Lorentz invariance principle



CTA will reach sensitivity level sufficient for verification of Lorentz invariance violation in first order of E_{LIV} for E_{LIV} of the order of Planck energy scale,

$$E_{Pl} = \sqrt{\frac{c^5\hbar}{G_N}}$$



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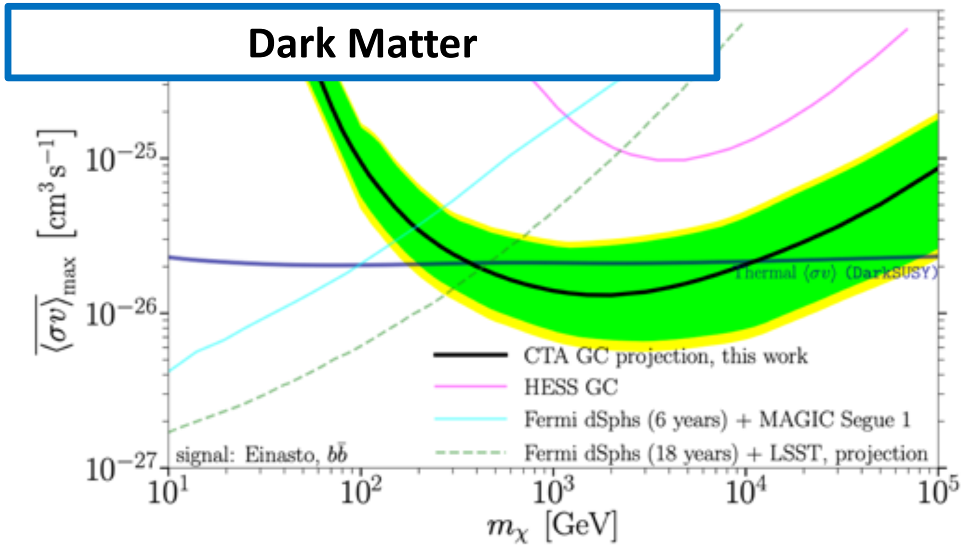
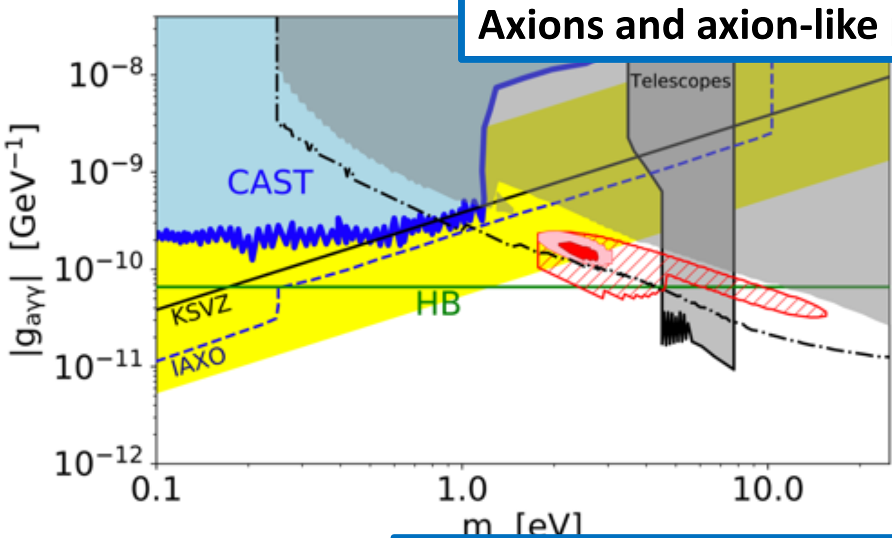
Fundamental physics with CTA

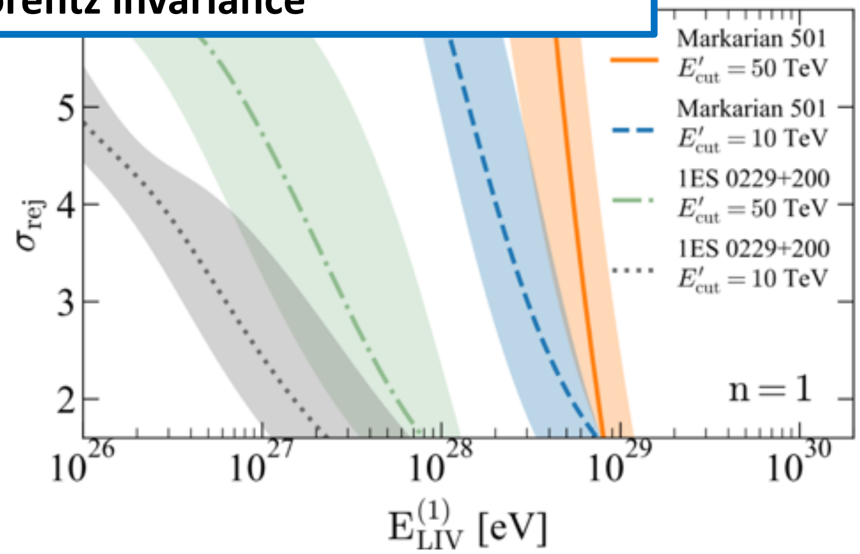
Dark Matter



Axions and axion-like particles



Lorentz invariance



Cosmological magnetic field