Searches for Dark Matter signals

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Outline

Lecture #1: content

I Introduction: dark matter, search strategies

II Direct searches for the dark matter

III Indirect searches for dark matter (photons)

Lecture #2: content

I Indirect detection for dark matter (neutrinos and antiparticles)

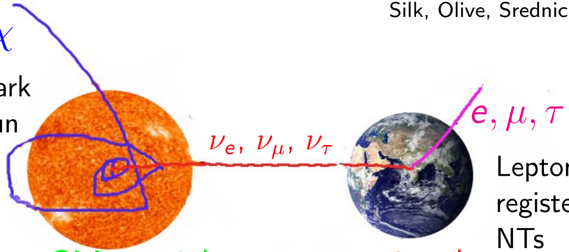
II Dark matter at colliders

III Particular models (asymmetric dark matter, axions...)

Signal from DM annihilations in the Sun (related to DD)

Silk, Olive, Srednicki (1985)

Capture of dark matter in the Sun



Leptons are registered at NTs

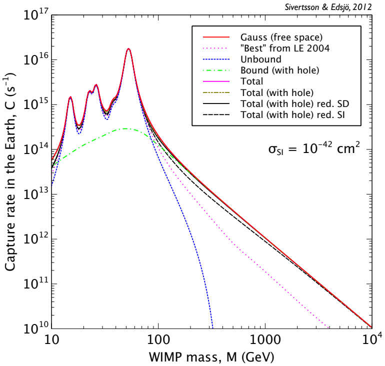
if $\chi\chi \to$ SM particles $\to$ neutrinos!

- DM particles scatter off nuclei in the Sun
- DM can become gravitationally trapped ($m_{DM} \gtrsim 5$ GeV)
- Accumulation and annihilation of DM in the center of the Sun
- Neutrino flux should be observed from the direction towards the Sun
- IceCube, SuperKamiokande, ANTARES, BUST (Baksan) and Baikal

Capture of the DM by the Sun (Earth)

Gould, 1987

- Integration of the Sun volume: $C = \int_0^{R_{Sun}} 4\pi r^2 dr \sum_i \frac{dC_i}{dV}$
- Averaging of the capture probability
  $\frac{dC_i}{dV} = \int_0^{u_{max}} du \frac{f(u)}{u} \left(w\Omega_{v,i}(w)\right), \quad w = \sqrt{u^2 + v_{esc}^2}$
- $f(u) \propto \rho_\chi / m_\chi$ – DM distribution function
- $w\Omega_{v,i}(w) \propto \sigma_i$ – probability of capture DM particle
- Depends on kinematics: (m_χ, m_N), chemical composition of the Sun (Earth)



Earth - resonance capture when $m_\chi \sim m_i$, iron (Fe), oxygen (O), silicon (Si), magnesium (Mg)

Capture by the Earth depends on $\sigma_{\chi p}^{SI}$

Sun is composed mostly of hydrogen (H)

Capture by the Sun depends on $\sigma_{\chi p}^{SD}$ and $\sigma_{\chi p}^{SI}$

Dark matter capture and annihilation in the Sun

Evolution of number of dark matter particles:

$$\frac{dN}{dt} = C - C_A N^2 - C_E N$$

C – capture, $C_A \propto \langle \sigma_A v \rangle$ – annihilation,
C_E – evaporation (important for $m_\chi \lesssim 5$ GeV)

$$N(t) = \sqrt{C/C_A} \tanh t/\tau, \text{ where } \tau = 1/\sqrt{CC_A}$$

Annihilation rate

$$\Gamma_A \equiv \frac{1}{2} C_A N^2 = \frac{C}{2} \tanh^2 t/\tau, \quad t \approx 4.5 \text{ Gyrs}$$

For $t \gtrsim \tau$ we have an equilibrium between capture and annihilation processes

$$\Gamma_A = \frac{C}{2}$$

Equilibrium is often expected

Neutrino signal from DM annihilations in the Sun

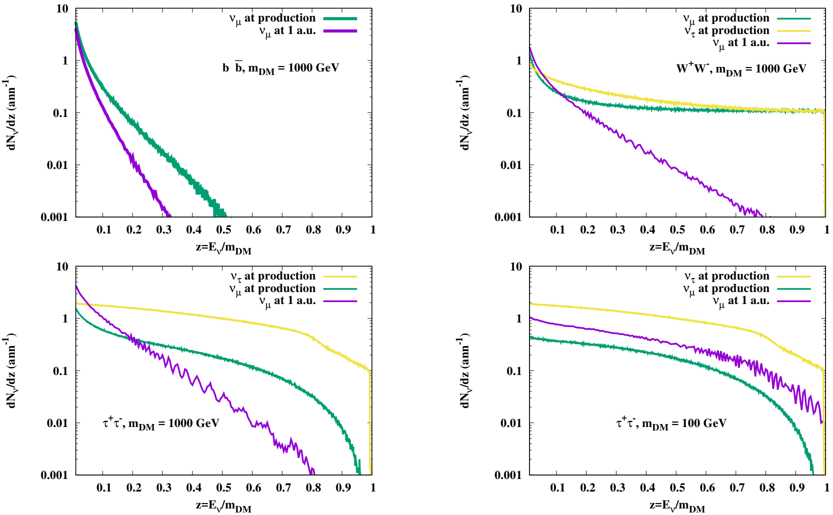
A lot of physical processes:

- Capture of DM particles by the Sun: $\sigma_{\chi p}^{SD}$ and $\sigma_{\chi p}^{SI}$.
- Benchmark channels: $b\bar{b}$, W^+W^-, $\tau^+\tau^-$, $\nu_e\bar{\nu}_e$, $\nu_\mu\bar{\nu}_\mu$, $\nu_\tau\bar{\nu}_\tau$
- (Anti)Neutrinos are produced $\frac{dN_{\nu_j}^{\rm prod}}{dE_{\nu_j}}$
- Propagation of neutrinos in the Sun and Earth: oscillations, interactions. Energy range: $1 - 1000$ GeV (up to 10 MeV).
- Expected muon neutrino and muon fluxes from dark matter annihilation in the Sun

$$\Phi_{\nu_\mu} = \frac{\Gamma_A}{4\pi R^2} \times \sum_{\nu_j,\bar{\nu}_j} \int_{E_{th}}^{m_{DM}} dE_{\nu_j} P_{\nu_\mu}(E_{\nu_j}, E_{th}) \frac{dN_{\nu_j}^{\rm prod}}{dE_{\nu_j}}$$

  where $P_{\nu_\mu}(E_{\nu_j}, E_{th})$ is probability to obtain neutrino or muon at the detector level
- Background – atmospheric neutrinos (isotropic!)
- Experiments - limit on Φ_{ν_μ}, on Γ_A and (if equilibrium is reached) on C and $\sigma_{\chi p}^{SI}, \sigma_{\chi p}^{SD}$

Neutrino energy spectra from DM annihilations in the Sun

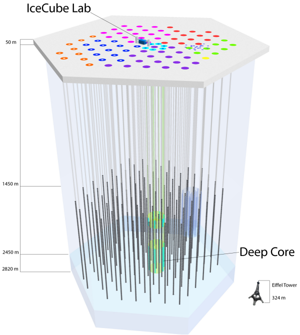


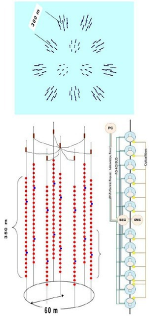
Attenuation of neutrino flux at high energies, ν_τ-regeneration

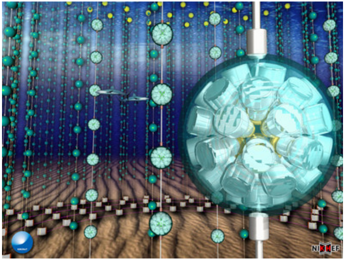
Neutrino detection

1. Neutrino interacts via CC - produce leptons (muons) - Cherenkov light - track events
2. Neutrino interacts via CC or NC - produce hadronic and e/m showers - cascade events

IceCube | Baikal-GVD | KM3NET

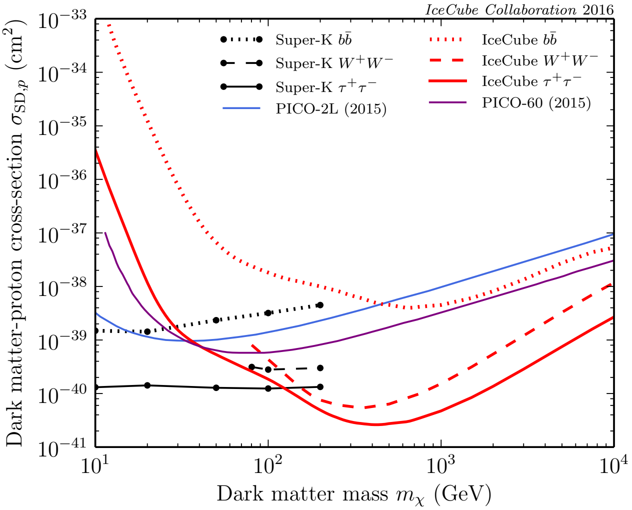






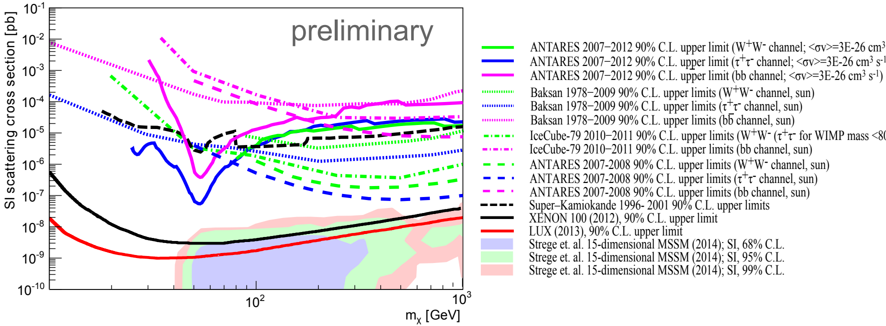
SuperKamiokande, Baksan

Neutrinos from DM annihilation in the Sun



Neutrinos from DM annihilation

Neutrino from the Earth, ANTARES, ICRC2015



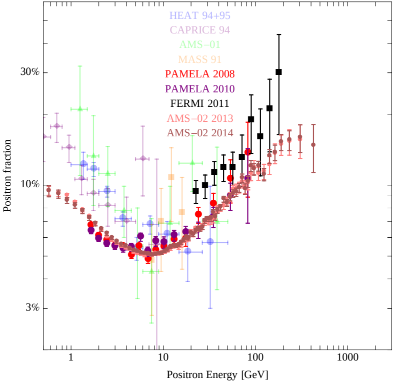
Increase of the sensitivity: models of secluded dark matter, observation of annual modulation of the neutrino signal.

Charged particles

Antimatter: positrons, antiprotons, antideutrons – complimentary to others

- interesting – small background - no antimatter
- interact with magnetic field and media (synchrotron radiation and inverse Compton scattering), deflection
- loose energy, relatively small propagation length: a few kpc for 100 GeV e^+ and larger for $\bar{p}$
- observed excess (rise) in positron fraction

M.Cirelli, ICRC(2015)



– observed by balloon experiments (HEAT)
– confirmed by space experiments

– The spectrum of secondary positrons produced through the collisions of cosmic rays in the interstellar medium is predicted to fall rapidly with energy

– Indicate on existence of nearby primary sources

Dark matter?

No rise in antiproton fraction

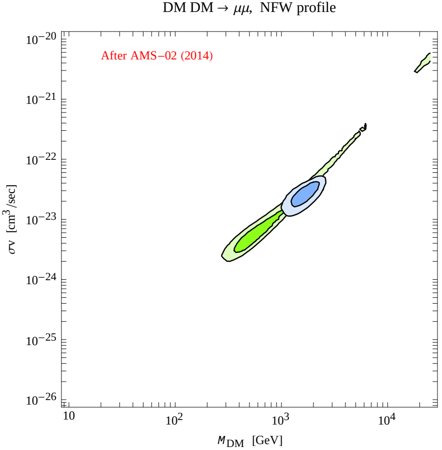
"leptophillic" dark matter?
annihilations into $\mu^+\mu^-$, $\tau^+\tau^-$, 4μ..

Large annihilation cross section - Sommerfeld enhancement???

No end of the rise

Astrophysical sources (pulsars, supernova remnants, ...)

M.Cirelli, ICRC2015

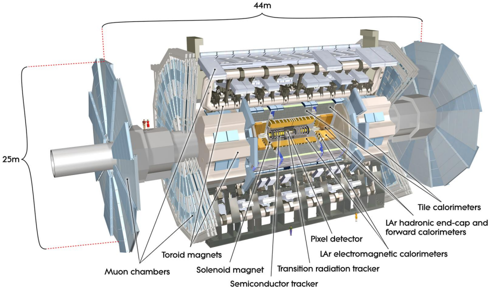


Still unclear: further studies are required (understanding background, measuring space asymmetry of the signal, ...)

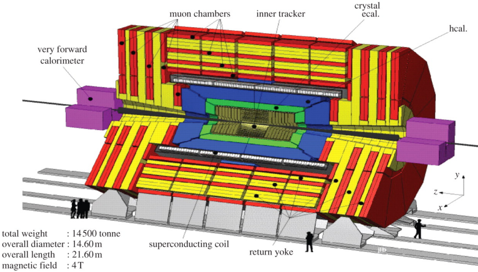
Searches for dark matter at colliders

We have LHC experiments

ATLAS



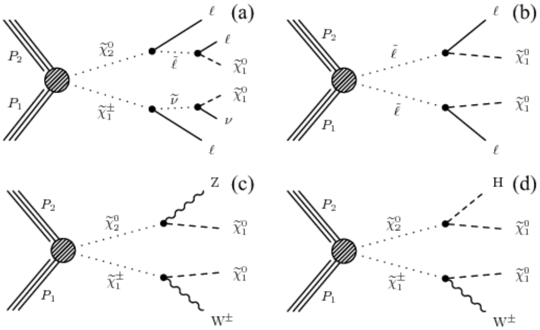
CMS



If dark matter is not very heavy - production in *pp* collisions?

Dark matter at the LHC: searches strategies

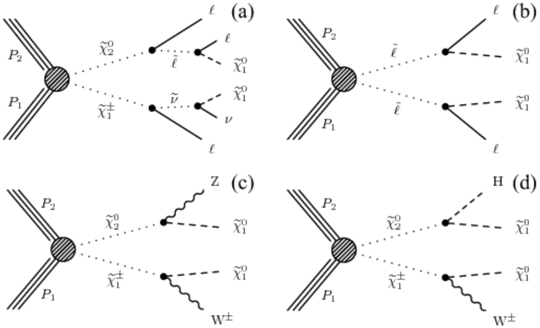
- Model dependent approach - particular signature in a particular model



- Model independent approach ???

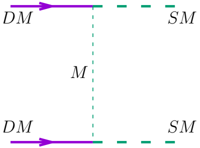
Dark matter at the LHC: searches strategies

- Model dependent approach - particular signature in a particular model

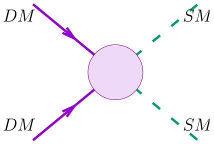


- Model independent approach ???

- Effective Field Theory approach:
  Let us describe DM interactions by possible set of (nonrenormalizable) operators, suppressed by scale Λ



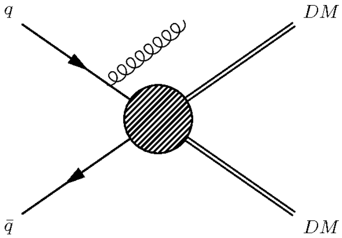
$$\sim \frac{g^2}{M^2} \to \frac{1}{\Lambda^2}$$



- Types of effective interactions (for Majorana fermion)

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\ \bar{q}q$	m_q/M^3
D4	$\bar{\chi}\gamma^5\chi\ \bar{q}\gamma^5 q$	m_q/M^3
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\ \bar{q}\gamma_\mu\gamma^5 q$	$1/M^2$
D11	$\bar{\chi}\chi\ G^a_{\mu\mu} G^{a\mu\nu}$	α_s/M^3

Dark matter at the LHC: signatures



$pp \to \chi\chi$ - no visible particles in the final state: dark matter particles leave no trace in the detector

Production with spectator particles – visible nonconservation of transverse momentum

Missing energy E_T^{miss} signature!!!

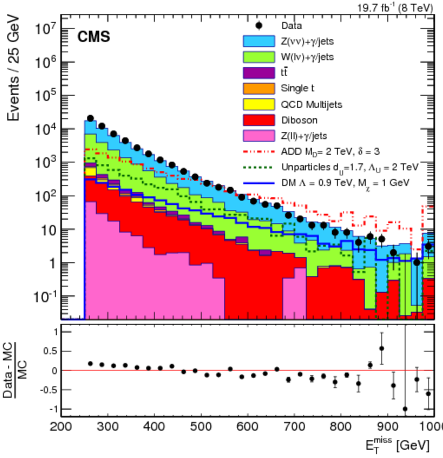
- Monojets events $pp \to \text{jet} + E_T^{miss}$
- Monophoton events $pp \to \gamma + E_T^{miss}$
- Mono-Z or mono-H events $pp \to Z(H) + E_T^{miss}$

Dark matter at the LHC

Background for $pp \to \text{jet} + E_T^{miss}$

- $pp \to Z + \text{jets} \to \nu\bar{\nu} + \text{jets}$
- $pp \to W + \text{jets} \to \nu l + \text{jets}$, lepton escapes detection
- $pp \to t\bar{t}$
- $pp \to \text{multijets}$
- ...

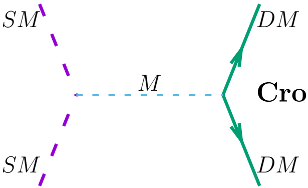
CMS, arxiv:1408.3583



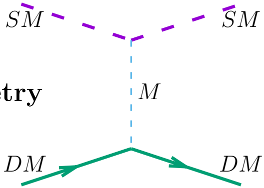
No deviation from the background $\to$ set upper limits on the production cross section $\sigma(pp \to \chi\bar{\chi} + \text{jet})$

Dark matter at the LHC: relation to direct and indirect detection methods

Production | **Scattering**

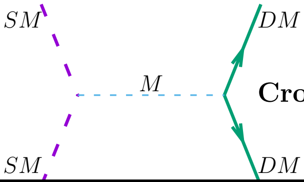


Crossing symmetry



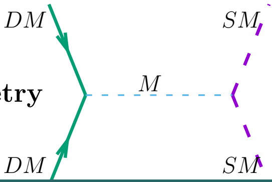
$$\sigma(pp \to \chi\bar{\chi} + X) \sim \frac{g_p^2 g_\chi^2}{(q^2 - M^2)^2 + M^2\Gamma^2} E^2$$

$$\sigma(\chi p \to \chi p) \sim \frac{g_p^2 g_\chi^2}{M^4} \mu_r^2$$



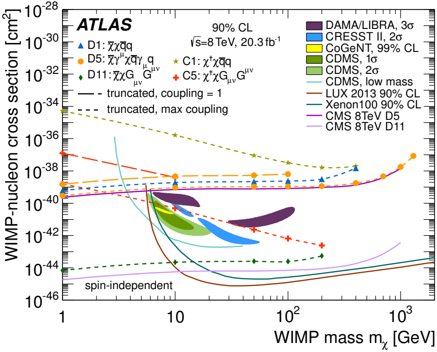
Crossing symmetry

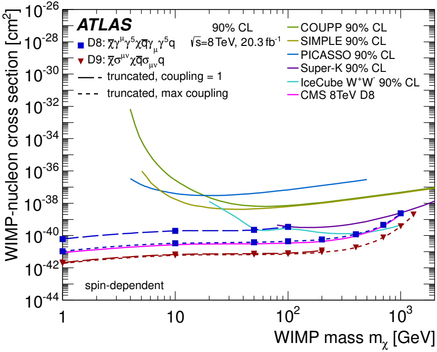
Annihilation



Limits on $\sigma(pp \to \chi\chi + \text{jet})$ can be recalculated to limits on $\sigma^{SI}_{\chi p}$ and $\sigma^{SD}_{\chi p}$

arXiv:1502.01518



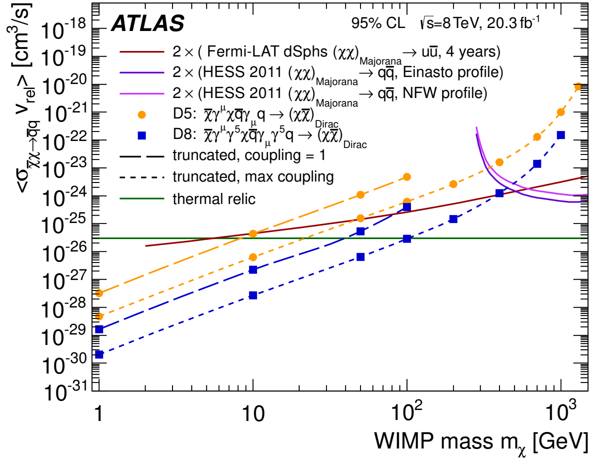


Searches at colliders are especially sensitive to light DM particles

Dark matter at the LHC: limits on $\langle\sigma_A v\rangle$

Collider limits can be recaculated to limits on $\langle\sigma v\rangle$

arXiv:1502.01518



Annihilations to quarks and gluons can be probed

Dark matter at the LHC: beyond EFT approximation

- EFT – model-independent approach results in very contraining results
- EFT – can fail in particular situations, be careful when interpreting the results!

Let's return to the parametric estimates:

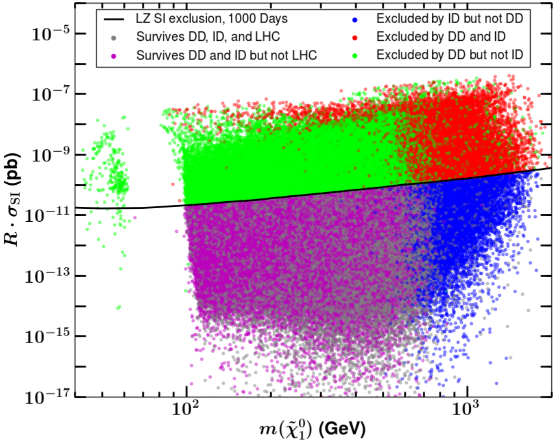
$$\sigma(\chi p \to \chi p) \sim \frac{g_p^2 g_\chi^2}{M^4} \mu_r^2 \qquad \sigma(pp \to \chi\bar{\chi} + X) \sim \frac{g_p^2 g_\chi^2}{(q^2 - M^2)^2 + M^2\Gamma^2} E^2$$

- Light mediator $M \ll \sqrt{s}$: direct detection is more sensitive
  However, the light mediator can be produced on shell...
- Resonance region (in s-channel): strong dependence of the width of mediator, recalculations are not model-independent

Complementary of different DM searches

Different approaches to dark matter searches are sensitive to different parts of the parameter space

Case of neutralino dark matter in pMSSM (arXiv:1405.6716)



Different methods to search for dark matter probe different parts in parameter space

Asymmetric dark matter

- From observations $\rho_{DM} \sim \rho_B$ – a coincidence (like for WIMP models)???
- Dark matter and baryonic matter may have common origin. May be dark matter has an asymmetry and related to BAU!
- $n_{DM} \sim n_B$, hence $m_{DM} \sim m_B \sim \text{GeV}$
- If thermally produced, one can calculate relic abundance like in WIMP case – requires larger annihilation cross section:

$$r_\infty \equiv \frac{n(\bar{\chi})}{n(\chi)} \approx \exp\left(-2\langle\sigma v\rangle / \langle\sigma_{WIMP} v\rangle\right), \quad \text{at} \;\; r_\infty \ll 1$$

- Asymmetric dark matter can be produced non-thermally
- Signatures:
  - Indirect searches - No annihilations
  - Direct detection - OK
  - Collider searches - OK

Asymmetric dark matter: an example

arXiv:1008.2399

- "Neutron" portal: Ψ, Φ - two-component dark matter

$$-\mathcal{L}_{int} = \frac{\lambda_a}{M^2}\bar{X}_a d_R \bar{u_R}^C d_R + \zeta_a \bar{X}_a \Psi^C \Phi^* + \text{h.c.}$$

$X_{1,2}$ – heavy mediators. Baryonic charge: $B_{X_a} = -(B_\Psi + B_\Phi) = 1$, Proton and DM particles are stable if

$$|m_\Psi - m_\Phi| < m_p + m_e < m_\Psi + m_\Phi$$

- Nonthermal production of dark matter in decays $X_a \to \Psi\Phi$
- Generating BAU due to asymmetry $\Gamma(X_a \to udd) - \Gamma(\bar{X}_a \to \bar{u}\bar{d}\bar{d})$ – generates asymmetry in dark sector
- Collider searches: $d + d \to \bar{u} + X$, $X \to$ invisible or $X \to$ 3jets
- Direct searches: induced baryon decay: $\Phi + p \to \pi^+ + \bar{\Psi}$

Signatures are very model dependent!

Axions and Axion-Like-Particles (ALPs)

- Strong CP-problem

$$\mathcal{L}_{CP} = \frac{g_s^2 \theta_{QCD}}{32\pi^2} \text{Tr}\ G_{\mu\nu} \tilde{G}^{\mu\nu}$$

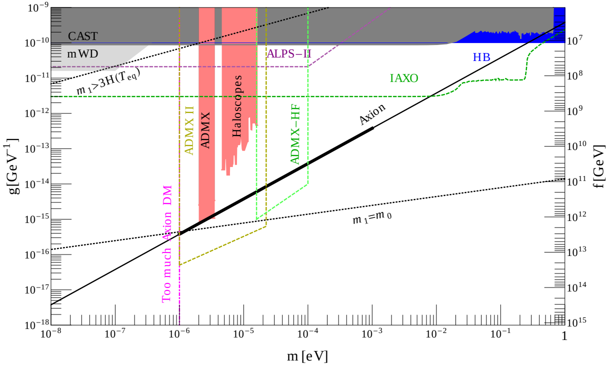
- Non-zero θ_{QCD} violates CP, results in EDM of nucleons, experimentally $|\theta_{QCD}| \lesssim 10^{-10}$
- Let's promote θ_{QCD} to a dynamical field, spontaneous breaking of a chiral symmetry, f_a – energy scale of the symmetry breaking
- Interaction lagrangian a – axion or axion-like particle (ALP)

$$\mathcal{L}_{int} = -\frac{\alpha_s}{8\pi f_a} C_{ag} a G_{\mu\nu} \tilde{G}^{\mu\nu} - -\frac{\alpha}{8\pi f_a} C_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} - \sum \frac{C_{af} f}{2f_a} \partial_\mu a \bar{f} \gamma^\mu \gamma^5 f$$

- For large f_a, ALPs can be cosmologically stable – dark matter candidate!
- Different mechanisms of ALP production
- Experimental signatures with photons – axion-photon transition in magnetic field.

Axions and Axion-Like-Particles (ALPs)

Parameter space of ALPs



- Light-shining-through-a-wall experiments (laser,opaque wall, magnetic field)
- Helioscopes (axion can be produced in the Sun)
- Dark matter axion – resonant haloscopes (microwave resonator in a strong magnetic field, axions convert into photons of resonant frequency)

Sterile neutrinos

- ''Leptonic'' portal:

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{N}_a\gamma^\mu\partial_\mu N_a - y_{\alpha a}H^\dagger\bar{L}_\alpha N_a - \frac{M_a}{2}\bar{N}_a^c N_a + \text{h.c.}$$

– can account for masses of active neutrinos
– mixing with active neutrinos,

$$\nu_\alpha = \cos\theta\nu_1 + \sin\theta\nu_2, \quad \nu_s = -\sin\theta\nu_1 + \cos\theta\nu_2$$

– Dark matter candidates - keV mass range
– unstable, $\nu_s \to \nu_\alpha + \gamma$, searches for monochromatic X-ray line in spectrum,
– observations on XMM-Newton X-ray cosmic observatory of several galaxies (including Andromeda galaxy) – excess of X-rays at 3.5 keV
– dark matter interpretation is questionable – no signal from several galaxy clusters (Virgo cluster)

Conclusions

- Dark matter still remains the mystery
- Many models, many ideas to detect
- Indications – need further studies
- Hopefully, this huge work will result in great discoveries!