Can the multi-component dark matter be visible due to its inner luminescence?

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Content:

- Minimal hypercolor scenario of the DM: vectorlike heavy H-quarks, stable DM candidates, estimation of their masses;
- EW mass-splitting (H-pion triplet); B – H-pion mass splitting;
- Decays of unstable charged H-pions;
- Transition between the DM components;
- Final state radiation;
- Regions and objects of high DM density can be seen due to inner luminescence;
- Discussion and open questions

New degrees of freedom are introduced as representations of some gauge symmetry group.

- any form of matter is built from fermions, vector bosons are necessary to ensure an integrity of a complex structures;
- beyond the SM we need to keep precision parameters of the SM and predict some detectable effects of new states phenomenology;
- here, possible manifestation of BSM physics is discussed in the SM extensions having extra fermions – hyper-quarks.

Minimal scenario SU(2nF =4)

- the SM is extended by heavy H-quarks in a pseudoreal representation of some additional symplectic group;
- the global flavor symmetry for n**F** Dirac fermions carrying symplectic hypercolor is SU(2n**F**), and it is broken by hyperquark condensate to its symplectic subgroup Sp(2nF);
- the symmetry is broken by nonzero hyperquark masses and interactions of hyperquarks with the Higgs boson which is considered as the almost “standard” SM boson (with a small mixing with an extra scalar, hyper-sigma-meson);
- a set of pseudo-Nambu-Goldstone (pNG) states arises.

Linear sigma-model is used as a base to consider interactions of pNG states (including the sigma-meson) and their chiral partners with (constituent) H-quarks and gauge bosons (as in low-energy hadron physics)

- the model is consistent with precision EW data for physically reasonable masses' values of new particles;
- P-T parameters: **T = 0** if the hypercharge of H-quark doublets is zero and h–σ mixing is absent;
- constraints for S and U

  $S_{exp} = 0.00 \pm 0.10$ and $U_{exp} = 0.08 \pm 0.11$

  are fulfilled when the h–$\tilde{\sigma}$ mixing angle is small, **$\sin\theta \ll 0.1$**;

  $M_\pi \geq 0.1$ TeV and $M_Q \geq 0.2$ TeV;
- this small mixing results in approximate relation:

  $M_\sigma \sim \sqrt{3} M_\pi$;
- known characteristics of the SM Higgs boson are in agreement with the existence of new degrees of freedom;
- It is postulated that the constituent H-quarks interact with the gauge bosons as the fundamental H-quarks.

In the minimal SU(4) scenario neutral (the lightest) H-pion and the neutral singlet H-baryons B0 are stable. They can be interpreted as the DM candidates.

- zero hypercharges of the H-quarks -> the Lagrangian is free from anomalies and is invariant under an additional symmetry—hyper G-parity;
- H-gluons and all SM fields do not changed under G-transformations -> the lightest invariant under G-symmetry, odd H-hadron, becomes **stable, it is the neutral component of H-pion triplet, H-pion, $\tilde{\pi}^0$;**
- two global U(1) symmetry groups -> **two H-baryon states stable—the neutral singlet H-baryon B0 and \bar B0.**
- the DM candidates for the DM are distinct: $\tilde{\pi}^0$ is WIMP, but B0 is a H-hadron which does not participate in EW tree level interactions (only via H-quark, H-pion and scalar loops with (pseudo)scalar exchanges (via Higgs boson and/or $\tilde{\sigma}$).

The lightest (pseudo)scalar H-hadrons in Sp(2nF) model with two and three flavors of H-quarks for zero mixing. The lower half of the Table lists the states presenting only in three-flavor variant of vector H-color scenario, SU(6). T is weak isospin, G and B are H-G-parity and H-baryon number, Q em – is electric charge in positron units:

$e = |e|$). The H-quark charges are $Q^{U}_{em} = (Y_Q + 1)/2$, $Q^{D}_{em} = (Y_Q - 1)/2$, and $Q^{S}_{em} = Y_S$.

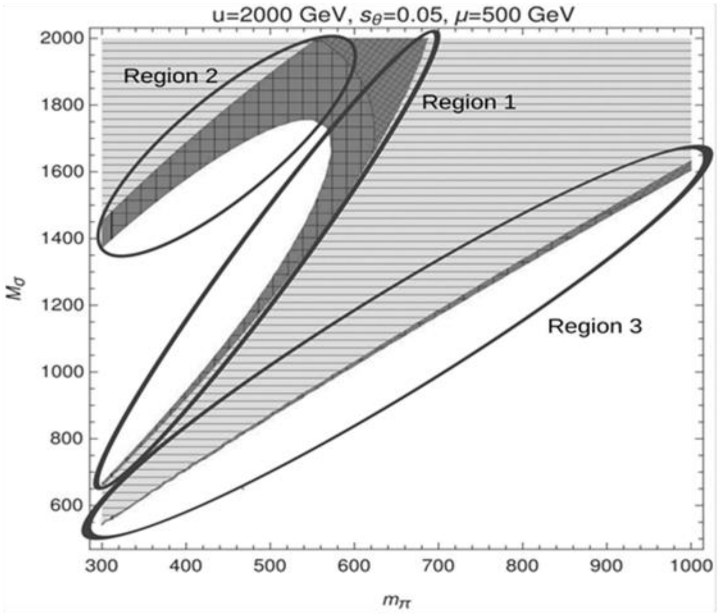
state	H-quark current	$T^{\tilde{G}}(J^{PC})$	$\tilde{B}$	Q_{em}
σ	$\bar{Q}Q + \bar{S}S$	$0^+(0^{++})$	0	0
η	$i(\bar{Q}\gamma_5 Q + \bar{S}\gamma_5 S)$	$0^+(0^{-+})$	0	0
a_k	$\bar{Q}\tau_k Q$	$1^-(0^{++})$	0	$\pm 1, 0$
π_k	$i\bar{Q}\gamma_5\tau_k Q$	$1^-(0^{-+})$	0	$\pm 1, 0$
A	$\bar{Q}^C \varepsilon\omega Q$	$0\ (0^-\ )$	1	Y_Q
B	$i\bar{Q}^C \varepsilon\omega\gamma_5 Q$	$0\ (0^+\ )$	1	Y_Q
f	$\bar{Q}Q - 2\bar{S}S$	$0^+(0^{++})$	0	0
η'	$i(\bar{Q}\gamma_5 Q - 2\bar{S}\gamma_5 S)$	$0^+(0^{-+})$	0	0
$\mathscr{K}^\star$	$\bar{S}Q$	$\frac{1}{2}\ (0^+\ )$	0	$Y_Q/2 - Y_S \pm 1/2$
$\mathscr{K}$	$i\bar{S}\gamma_5 Q$	$\frac{1}{2}\ (0^-\ )$	0	$Y_Q/2 - Y_S \pm 1/2$
$\mathscr{A}$	$\bar{S}^C \omega Q$	$\frac{1}{2}\ (0^-\ )$	1	$Y_Q/2 + Y_S \pm 1/2$
$\mathscr{B}$	$i\bar{S}^C \omega\gamma_5 Q$	$\frac{1}{2}\ (0^+\ )$	1	$Y_Q/2 + Y_S \pm 1/2$

Numerical solution of the kinetic equations system in a phase diagram in terms of $M_{\tilde{\sigma}}$ and $m_{\tilde{\pi}}$ parameters -> interval of possible values of mass (with ah account of co-annihilations due to small mass splitting in H-pion triplet – see the next slide)

Region 1: $M_{\tilde{\sigma}} > 2m_{\tilde{\pi}^0}$ and $u \geq M_{\tilde{\sigma}}$. At small angles of mixing, s_θ, and large masses of H-pions it is possible to obtain a significant fraction of H-pions.

Region 2: the same relation between $M_{\tilde{\sigma}}$, $m_{\tilde{\pi}^0}$, u but the H-pion mass is smaller, $m_{\tilde{\pi}} \approx 300 - 600$ GeV . Here the H-pion fraction is small.

Region 3: $M_{\tilde{\sigma}} < 2m_{\tilde{\pi}}$. This region is always possible and it is presented in all figures. Note, here the process $\tilde{\sigma} \to \tilde{\pi}\tilde{\pi}$ is obviously absent and two-photon signal from reaction $pp \to \tilde{\sigma} \to \gamma\gamma X$ could be, in principle, detected at the LHC. The H-pion fraction in the DM relic can be large if the mass $m_{\tilde{\pi}^0}$ is large and the mixing angle is small.



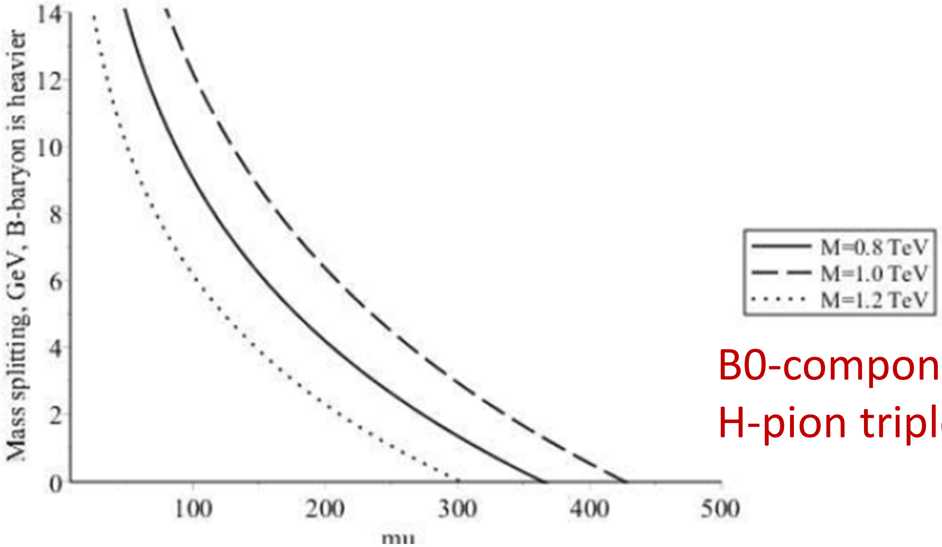
We fix the DM masses in the region 0.8 – 1.2 TeV.
Important: in all regions (of parameters the part of H-pions is no more than 0.25 – 0.35 from the total DM density.

The reason: H-pion components have a large number of annihilation channels due to EW interactions, H-baryons, B0, burn out only through scalar tree level channels and loop diagrams with H-quarks and/or H-pions.

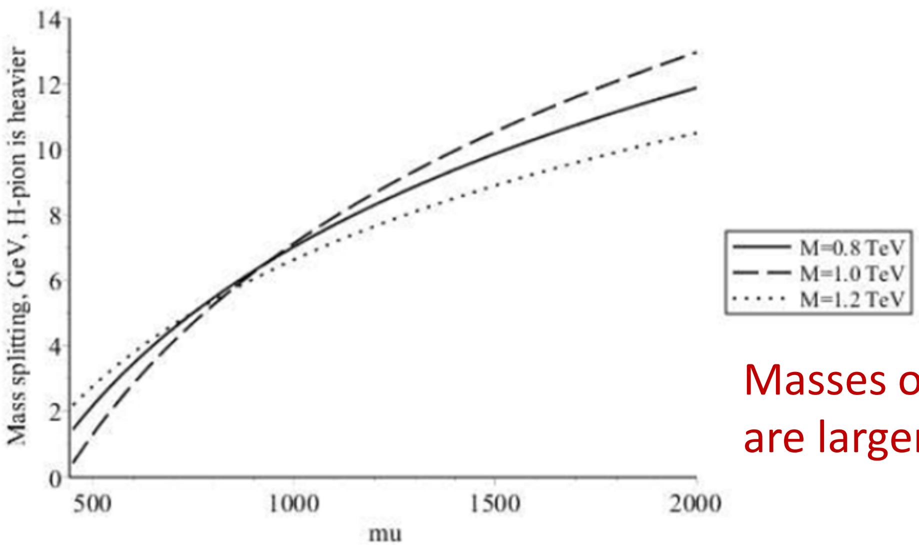
Mass splitting in the H-pion triplet is purely EW, and it is nearly constant and small ≈ 0.16 GeV<<Mπ = MB;

$$\Delta M_{B\tilde{\pi}} = \frac{-g_2^2 m_{\tilde{\pi}}}{16\pi^2}\left[8\beta^2 - 1 - (4\beta^2-1)\ln\frac{m_{\tilde{\pi}}^2}{\mu^2} + 2\frac{M_W^2}{m_{\tilde{\pi}}^2}\left(\ln\frac{M_W^2}{\mu^2} - \beta^2\ln\frac{M_W^2}{m_{\tilde{\pi}}^2}\right)\right.$$
$$\left. - 8\frac{M_W}{m_{\tilde{\pi}}}\beta^3\left(\arctan\frac{M_W}{2m_{\tilde{\pi}}\beta} + \arctan\frac{2m_{\tilde{\pi}}^2 - M_W^2}{2m_{\tilde{\pi}}M_W\beta}\right)\right],$$

One-loop -mass splitting between the DM components can be O(10 GeV) and depends on M_σ and the renormalization parameter μ



B0-component mass Is larger than masses of H-pion triplet



Masses of H-pion triplet
are larger than the B0-component mass

BB -> pair of charged H-pions -> decays of charged H-pion

$$\Gamma\left(\tilde{\pi}^{\pm} \longrightarrow \tilde{\pi}^{0} l^{\pm} \nu_{l}\right) = \frac{G_{F}^{2} m_{\tilde{\pi}^{\pm}}^{3}}{24\pi^{3}} \int_{q_1^2}^{q_2^2} \overline{\lambda}\left(q^{2}, m_{\tilde{\pi}^{0}}^{2}; m_{\tilde{\pi}^{\pm}}^{2}\right)^{3/2} \cdot \left(1 - \frac{3m_l^2}{2q^2} + \frac{m_l^6}{2q^6}\right) dq^2,$$

via intermediate decaying W-boson

$$\Gamma\left(\tilde{\pi}^{\pm} \longrightarrow \tilde{\pi}^{0} l^{\pm} \nu_{l}\right) = 6 \cdot 10^{-17}\ \mathrm{GeV},$$

$$\Gamma\left(\tilde{\pi}^{\pm} \longrightarrow \tilde{\pi}^{0} \pi^{\pm}\right) = \frac{G_{F}^{2}}{\pi} f_{\pi}^{2} \left|U_{ud}\right|^{2} m_{\tilde{\pi}}^{\pm} \left(\Delta m_{\tilde{\pi}}\right)^{2} \overline{\lambda}\left(m_{\pi^{\pm}}^{2}, m_{\tilde{\pi}^{0}}^{2}; m_{\tilde{\pi}^{\pm}}^{2}\right)$$

with production of standard charged decaying pion

$$\Gamma\left(\tilde{\pi}^{\pm} \longrightarrow \tilde{\pi}^{0} \pi^{\pm}\right) = 3 \cdot 10^{-15}\ \mathrm{GeV},$$

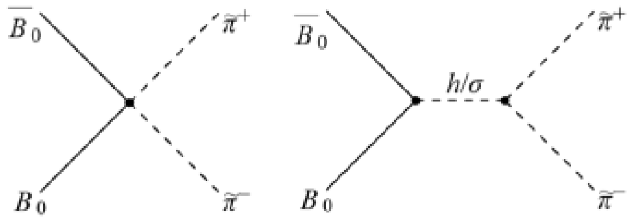
BB -> pair of charged H-pions -> total cross-section

$$\sigma v\left(B\bar{B} \to \tilde{\pi}^+\tilde{\pi}^-\right) = \frac{\lambda\left(m_{\tilde{\pi}}^2, m_{\tilde{\pi}}^2, s\right)}{16\pi M_B^2}\left|\frac{\lambda_3}{4} - \frac{g_{h\tilde{\pi}\tilde{\pi}}^2}{s - M_H^2} - \frac{g_{\tilde{\sigma}\tilde{\pi}\tilde{\pi}}^2}{s - M_{\tilde{\sigma}}^2 + iM_{\tilde{\sigma}}\Gamma_{\tilde{\sigma}}}\right|^2$$

$$\lambda_3 = \frac{1}{2u^2}(-m_{\tilde{\pi}}^2 + M_{\tilde{\sigma}}^2 C_\theta^2 + M_H^2 S_\theta^2),$$

$$g_{h\tilde{\pi}\tilde{\pi}} = -S_\theta \frac{M_H^2 - m_{\tilde{\pi}}^2}{2u},$$

$$g_{\tilde{\sigma}\tilde{\pi}\tilde{\pi}} = -C_\theta \frac{M_{\tilde{\sigma}}^2 - m_{\tilde{\pi}}^2}{2u},$$



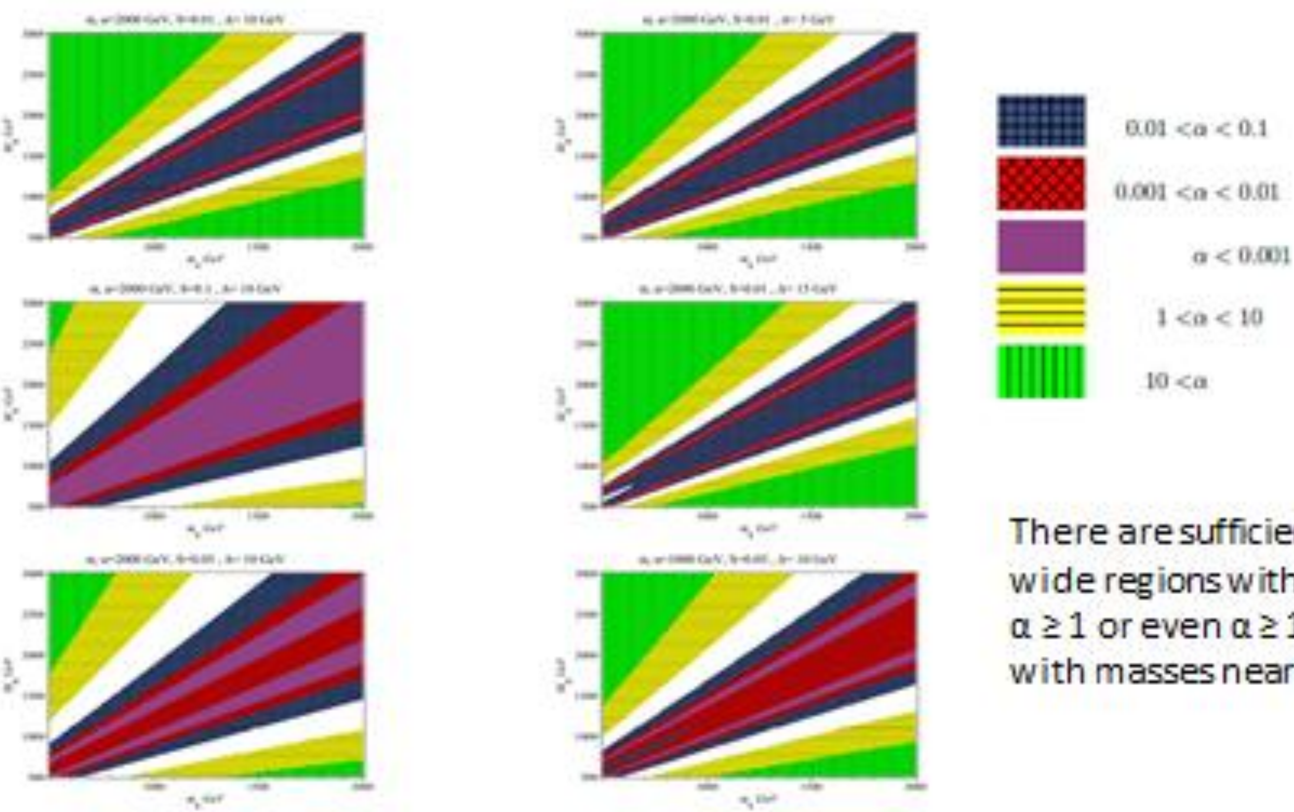
Possible regions of parameter α
in dependence on model parameters (v.e.v., θ, Δ)

$$\alpha = \frac{\sigma v\left(BB \to \tilde{\pi}^+\tilde{\pi}^-\right)}{\sigma v\left(BB \to SM\right)}$$

$$\Delta = M_B - m_{\tilde{\pi}} > 0$$

Phase diagrams for the studying of parameter α

Phase diagrams in Mσ-Mπ plane



There are sufficiently wide regions with $\alpha \geq 1$ or even $\alpha \geq 10$ with masses near 1 TeV

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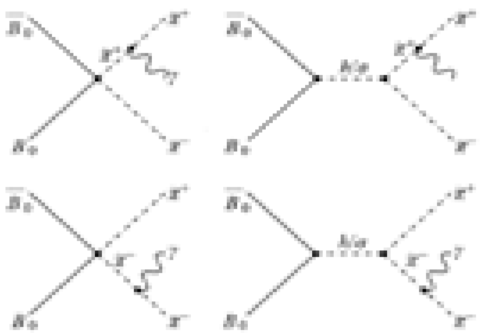
The DM pair of B0B0 transition to pair of charged H-pions with the final state radiation (FSR) and their subsequent decay into $\tilde{\pi}^0\,\tilde{\pi}^0$ pair + leptons +neutrinos

Annihilation of BB pair to charged H-pions with FSR

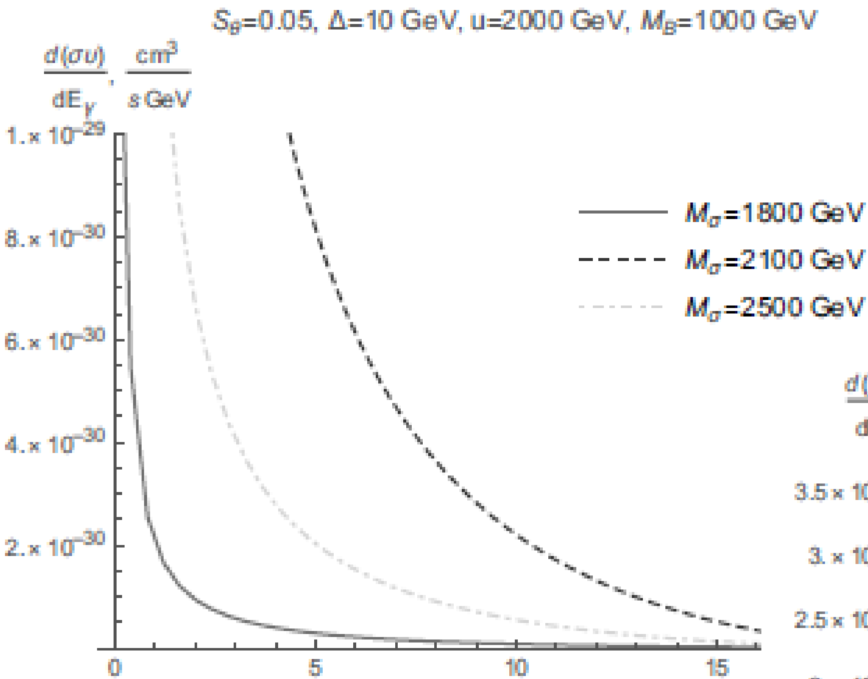
$$\frac{d\sigma v\,(B\bar{B}\to\tilde{\pi}^+\tilde{\pi}^-\gamma)}{dE_\gamma}E_\gamma^2=\frac{4\alpha E_\gamma\sigma v\,(B\bar{B}\to\tilde{\pi}^+\tilde{\pi}^-)}{\pi M_B\sqrt{M_B^2-m_{\tilde{\pi}}^2}}\Bigg(-2\sqrt{M_B(M_B-E_\gamma)}\sqrt{M_B(M_B-E_\gamma)-m_{\tilde{\pi}}^2}+$$
$$+\left(m_{\tilde{\pi}}^2+2(E_\gamma-M_B)M_B\right)\log\left[-1+\frac{2\sqrt{M_B(M_B-E_\gamma)}}{\sqrt{M_B(M_B-E_\gamma)}+\sqrt{M_B(M_B-E_\gamma)-m_{\tilde{\pi}}^2}}\right]\Bigg)$$

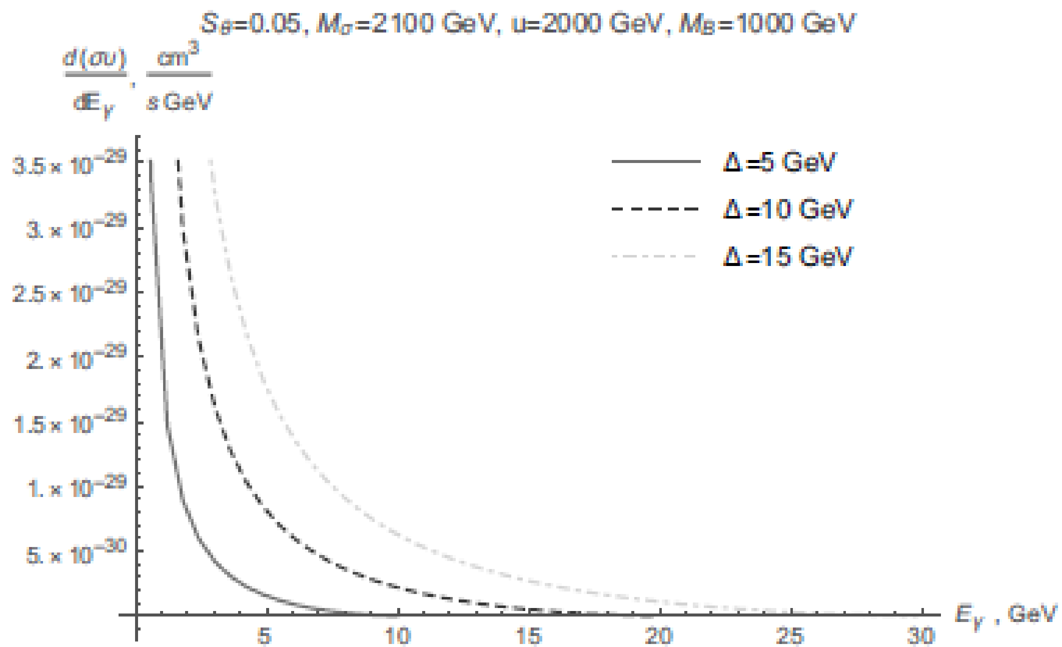


Energies of diffuse photons – up to 10-20 GeV.

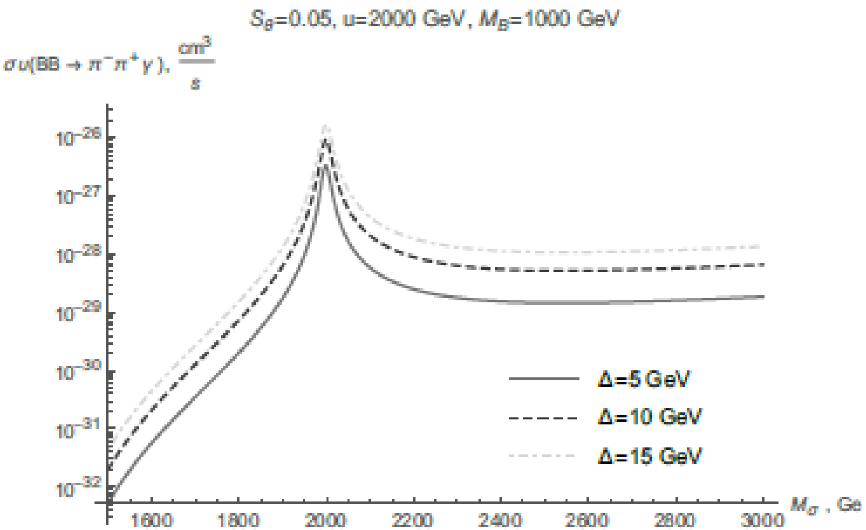
Differential cross-section with the FSR for the process

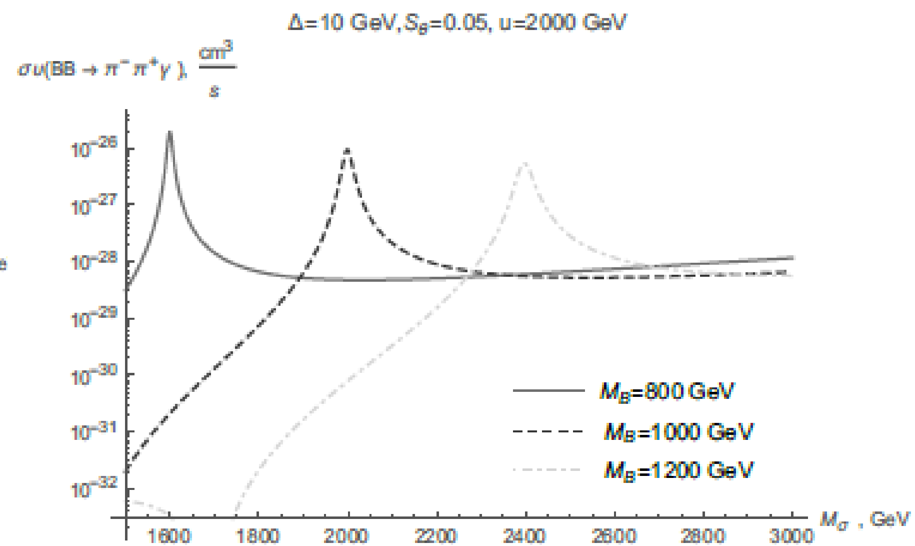
$$B^0 B^0 \to \tilde{\pi}^+ \tilde{\pi}^- \gamma$$





Total cross-section with the FSR is almost independent on $\tilde{\sigma}$ − meson mass when its value is $\geq (2.0\ - 2.5)\ TeV$





There is an obvious resonance due to s-channel conribution

Maximum value of cross section is ≈ 10^(-26) cm^3/s near the resonance for v ≈ 10^(-3)

For the estimation of corresponding photon flux

Flux of photons

Astrophysical J- factor

- $d\Phi/dE_\gamma = \frac{\Delta\Omega}{4\pi}\left[\frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\frac{{\rm d}N_\gamma}{{\rm d}E}(E)\right]\left[\frac{1}{\Delta\Omega}\int {\rm d}\Omega \int_0^\infty {\rm d}l\ \rho^2(l,\theta,\phi)\right]$

$<\sigma v> dN/dE\gamma = d(<\sigma v>)/dE\gamma \cdot N\gamma$

The DM density profile $\rho(l,\theta,\phi)$ – NFW
Limits in integrals are defined by the source considered

For the GC with the angular resolution of 1^0 and standard NFW profile

$J \approx 10^{21}$

To estimate the flux from dwarf galaxies an average values

$J \approx 10^{17.7} - 10^{19.6}$

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Expected (small) fluxes of photons from GC or dwarfs

- Total $\Phi(E\gamma)$ from GC varied in the limits:
- $\Phi(E\gamma) \approx (0.9 - 1.5)\cdot (10^{-14} - 10^{-12})$ $1/(cm^2 \cdot s)$
- J-factor can be in 10 or even 100 times larger if the parameter γ is changed from 1 to 1.4 to take into account the DM spike in the DM distribution near the GC, then the flux increases up to
- $\Phi(E\gamma) \approx (0.9 - 1.5)\cdot (10^{-12} - 10^{-10})$ $1/(cm^2 \cdot s)$
- An average $\Phi(E\gamma)$ from dwarfs is in the limits:
- $\Phi(E\gamma) \approx (0.5 – 0.8)\cdot (10^{-15} - 10^{-13})$ $1/(cm^2 \cdot s)$
- $\Phi(E\gamma) \approx (0.4 – 0.6)\cdot (10^{-13} - 10^{-11})$ $1/(cm^2 \cdot s)$

Possibility of FSR from charged H-mesons (components of the pNG triplet, in the case) is a specifics of the SM extensions with a complex structure -> multi-component DM.

Heavy DM component transforms into the light one, this transition should have an intermediate stage with (unstable) charged states (from extended set of states, then it is possible to get photons from VIB +FSR . Here is exactly the same case.

Such scenarios should be analyzed carefully if the mass splitting is large, O(M**DM**), then these states have different T freeze-out, tit is necessary to consider different stages of their evolution and their features.
In this minimal scenario the mass splitting << DM mass, there arises diffuse photons with energies in a narrow limited area. It is an admixture of diffuse photons to monochromatic radiation from annihilations. Can these photons be visible and detected?
This effect is too small to explain the excess of GeV photons from GC.

Discussion-1

- This low-energy radiation from regions with the high DM density does not lead to the resorption of the DM clumps, the particle number density does not change in this process.
- Of course, there are processes of "ordinary" annihilation of the DM components into two photons (or pairs of SM particles with subsequent photon emission from final charged states).
- Monochromatic photons (from DM+DM -> 2 γ) with energies ~ M_{DM} are separated by an energy gap in the full photon spectrum.
- Large background is produced by diffuse FSR from the SM particles; the total flux can be noticeably larger than this transition effect -> analysis of the low-energy photons spectrum is a difficult task.
- Detection and selection of a (nearly constant) radiation with energy ~ 1-10 GeV can demonstrate the presence of some hierarchy in the DM mass spectrum, or the possibility of transitions between exited levels in the spectrum of states (it can occur in some SIMP scenarios).
- This radiation also should be collimated with a some (small) angular aperture if it comes from some “point sources” – GC, dwarf galaxies, subhaloes or other types of DM clumps.

If the DM clump is close (~ 0.1 pc) to space telescopes, such low-energy photon flux can be seen and recognized.

Discussion-2 and an open questions

- It should be also considered the case when $\tilde{\pi}^0$ is heavier than B0, but annihilation into B0B0 is difficult -> diffuse photons are generated by VIB diagrams with W, H-pions and/or H-quarks loops, corresponding cross-section is lower up to an order.
- Stable DM candidates can be produced at early stages at more large temperatures H-hadronization can occur before QCD hadronization, so the photons from transitions between various H-states can contribute to the total density of radiation.
- This process should maintain the temperature - a kind of delay mechanism that prevents cooling during expansion, in accordance with the Le Chatelier principle.

Open questions: **mass spectrum and decay channels for heavier unstable states, H-hadronization, contributions of H-mesons and H-quark loops, the case with large mass splitting, DM production at early epoch and so on…**

Such types of processes can be considered in other scenarios with multicomponent DM where transitions between components are possible and there occur radiation from intermediate charged states.

Thank you for attention!

Thanks to organizers!

Dark matter accumulating inside the massive objects

This type of annihilation, in fact, the transition between the DM components, is interesting from the point of view of the DM accumulation inside massive objects – red giants, white dwarfs and the possible dark stars at early stage. In this case, photons, leptons, and neutrinos generated during the transition between components will heat up the interior of the gravitationally coupled system more slowly than the annihilation of DM into SM particles would do (this reaction, of course, also takes place, but with a noticeably smaller cross section for some parameter values). In the case, the dark star life time in the relatively “cold” state can increase.

Then, the gravitating mass of the object also changes slowly. The energies of the emission photons from such objects will belong to significantly different regions, separated by a gap of the order of the DM particles mass. Such an analysis would make sense for (early) dark stars with long lifetimes. For such objects, thermonuclear heating is actually replaced by energy release during the annihilation of DM particles. The discussed effect shows that the presence of a special structure of DM states can be important in the study of dark stars, for example. Namely, the luminosity of dark stars can be provided also by low-energy component which is induced by transitions between the DM states.