The multi-component dark matter structure and its possible observed manifestations.

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Outline

- hypercolor extension of the SM: vectorlike H-quarks, two stable DM candidates from different sources, estimation of their masses from kinetics;
- EW mass-splitting for H-pion triplet; B – H-pion mass splitting – two possible cases;
- transition between the DM components: decays of charged H-pions;
- transition between the DM components: annihilation;
- final state radiation;
- possible luminosity of dense DM regions or objects;
- summary

To extend the SM , extra degrees of freedom should be introduced as representations of some gauge symmetry group.

- all forms of the matter are built from fermions, vector bosons are important structural elements of the theory, ensuring the integrity of the entire structure;
- experience of going beyond the SM shows that such extensions can be reliably aligned with the well-known results of the SM and predict an interesting and (possibly) rich phenomenology of new states;
- we discuss some type of the SM extensions having extra fermions – hyper-quarks only(singlet or mirror heavy quarks, dark atoms -> SIMPs?).

New particles for the SM generalization

- it has a sense only if some of the problems of the SM can be solved - if the hidden mass origin can be understood in a consistent way, in particular;
- at present we do not see any type of extensions where all the SM problems in their entirety are solved simultaneously;
- possible effects of SUSY are shifted possibly to much higher energies as it is demonstrated by the LHC.
- the LEP paradox remains without an answer - we do not see any manifestations of new physics not only at 100 GeV but also at O(1TeV).

SU(2 n**F**) scenario

- the SM can be 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(2 n**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;
- It is considered as the almost “standard” SM boson having only small mixing with an additional scalar state, H-sigma;
- the model contains a set of pseudo-Nambu-Goldstone (pNG) states.

Linear sigma-model 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)

- additional fermions contribute into PT- parameters, the model is consistent with precision electroweak (EW) data for all physically reasonable mass values of new particles;
- parameter **T = 0** if the hypercharge 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 provided when the mixing angle is small, **$\sin\theta << 0.1$**;

- **$M_\pi \geq 0.1$ TeV and $M_Q \geq 0.2$ TeV;**
- small h–σ mixing, $\sin\theta \ll 1$, leads to approximate relation:

$M_\sigma \sim \sqrt{3} M_\pi$;

- known characteristics of the SM Higgs boson does not changed by new degrees of freedom;
- It is also postulated that the constituent H-quarks interact with the gauge bosons as the fundamental H-quarks.

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

- when the H-quarks hypercharges are zero, the Lagrangian is free from anomalies and is invariant under an additional symmetry—hyper G-parity;
- H-gluons and all SM fields are left intact by G-transformations -> the lightest invariant under G-symmetry, odd H-hadron, becomes stable, it is the neutral component oh H-pion triplet, H-pion, π0;
- the numbers of doublet *(and singlet in SU(6) variant!)* quarks are conserved due to two global U(1) symmetry groups -> two H-baryon states stable—the neutral singlet H-baryon B0 (and its anti-partner \bar B) and the lightest state in doublet B with a fractional charge ± ½ *(in SU(4) model these exotic states are absent).*
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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.

T is weak isospin, G and B are H-G-parity and H-baryon number, Q em – is electric charge in positron units:

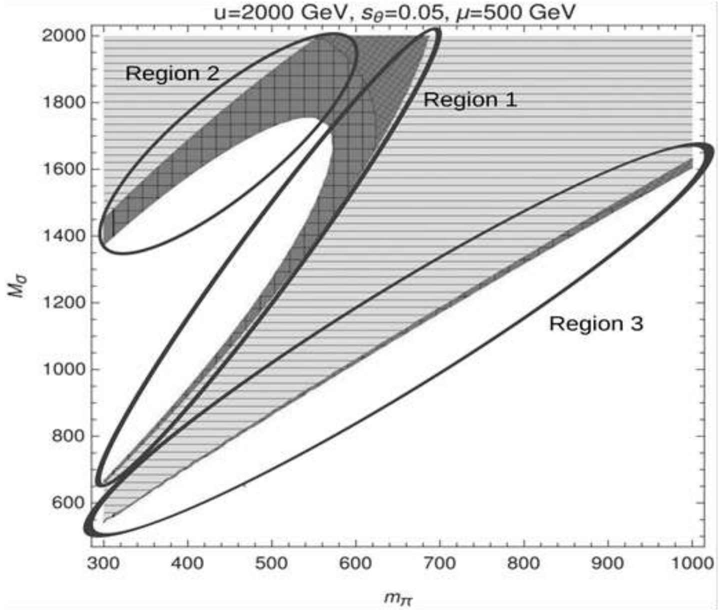
$e = |e|$). The H-quark charges are $Q^U_{em} = (Y_Q + 1)/2$, $Q^D_{em} = (Y_Q - 1)/2$, and $Q^S_{em} = Y_S$

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	$Y_Q/2 + Y_S \pm 1/2$

Minimal SU(2nF=4) hypercolor scenario: an additional heavy H-quarks, σ-model as an effective field model, a set of pseudo-Nambu-Goldstone states

- the model admits the existence of additional global symmetries. It leads to conservation of hyper- flavours and a generalization of the G-parity of QCD. These symmetries prevent the decay of some of the pNG states;
- for zero hypercharges of hyperquark doublets,neutral hyperpion and neutral singlet diquark, hyperbaryon, (and possibly the lightest of the charged states of the hyperbarion doublet in the case of SU(6)) are stable;
- there are candidates for the DM in its two-component form, one of the components, H-pion, is WIMP, and the other component does not participate in EW tree level interactions: only via hyperquark or hyperpion loops, or through (pseudo)scalar exchanges (via Higgs boson and/or sigma-meson).

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)



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.

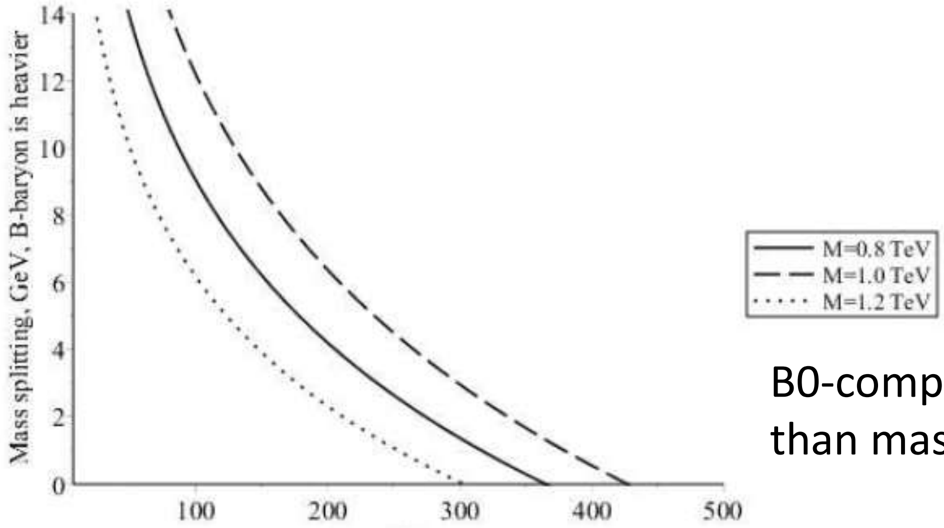
Region 3: $M_{\tilde{\sigma}} < 2m_{\tilde{\pi}}$. This region is always possible and it is presented in all figures. Note, here the process $\tilde{\sigma} \to \tilde{\pi}\tilde{\pi}$ is obviously absent and two-photon signal from reaction $pp \to \tilde{\sigma} \to \gamma\gamma X$ could be, in principle, 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 use the DM particles mass values in the region 0.8 – 1.2 TeV. Important: in all regions (see the phase diagram) 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.

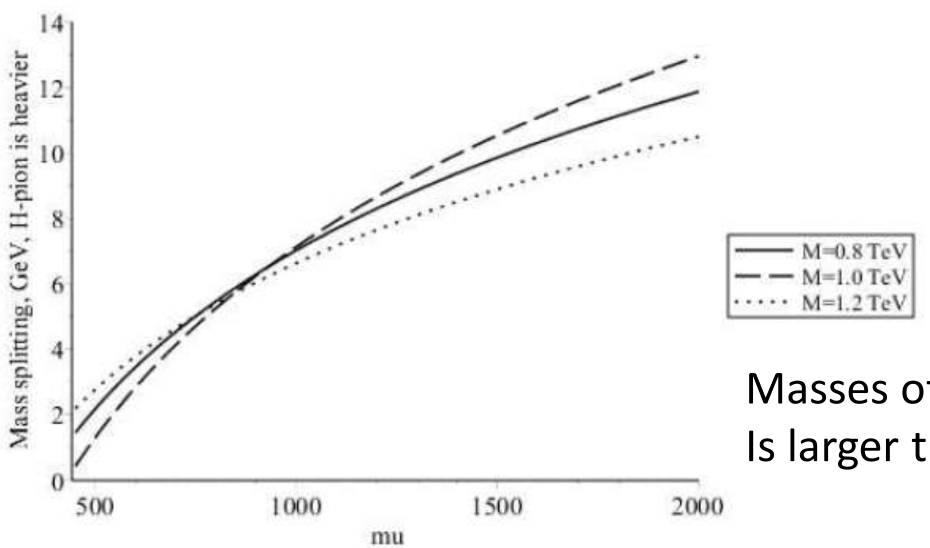
- 1st stage: both DM components have equal masses - mass splitting in the H-pion triplet is purely EW, and it is nearly constant and small ≈ 0.16 GeV<<M_π = M_B;
- 2nd stage: mass splitting between the DM components can be ~ O(10 GeV) and depends on M_σ and an extra parameter μ (due to connection of components with different H-quark sources and H-vacuum structures)

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

Mass-splittings between DM components



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



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

Transition between the DM components
B0 is heavier!

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

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

via intermediate
decaying W-boson

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

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

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 ->cross-section

$$\sigma v\left(B\bar{B}\to\tilde{\pi}^{+}\tilde{\pi}^{-}\right)=\frac{\lambda\left(m_{\tilde{\pi}}^{2},m_{\tilde{\pi}}^{2},s\right)}{16\pi M_{B}^{2}}\left|\frac{\lambda_{3}}{4}-\frac{g_{h\tilde{\pi}\tilde{\pi}}^{2}}{s-M_{H}^{2}}-\frac{g_{\tilde{\sigma}\tilde{\pi}\tilde{\pi}}^{2}}{s-M_{\tilde{\sigma}}^{2}+iM_{\tilde{\sigma}}\Gamma_{\tilde{\sigma}}}\right|^{2}$$

$$\lambda_{3}=\frac{1}{2u^{2}}(-m_{\tilde{\pi}}^{2}+M_{\tilde{\sigma}}^{2}C_{\theta}^{2}+M_{H}^{2}S_{\theta}^{2}),$$

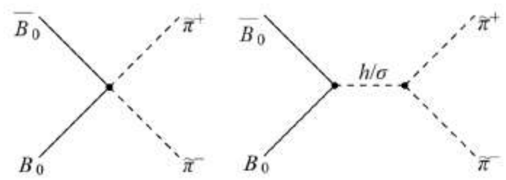
$$g_{h\tilde{\pi}\tilde{\pi}}=-S_{\theta}\frac{M_{H}^{2}-m_{\tilde{\pi}}^{2}}{2u},$$

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

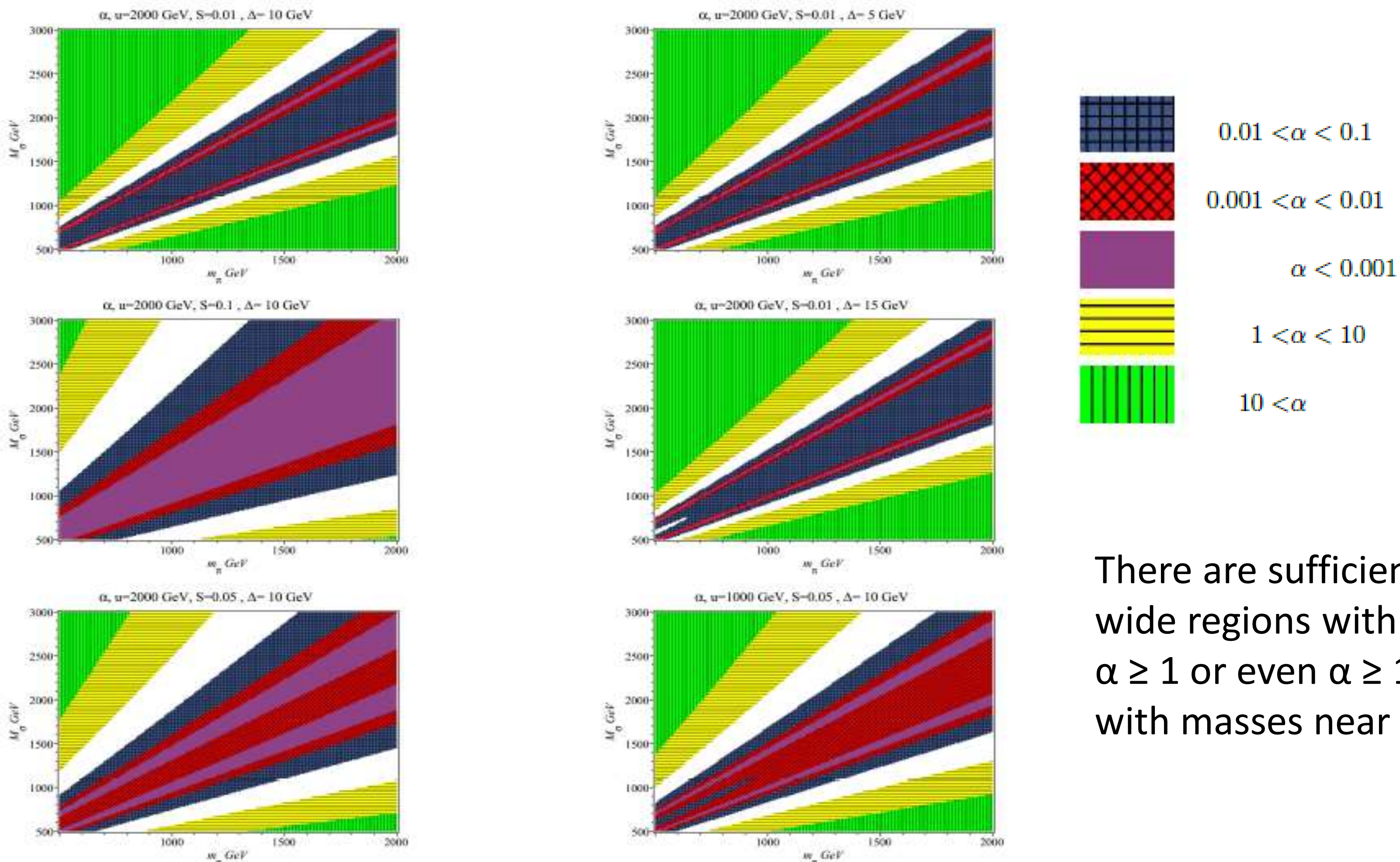
Let’s look on possible regions of parameter α
in dependence of model parameters (v.e.v., θ, Δ)

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

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



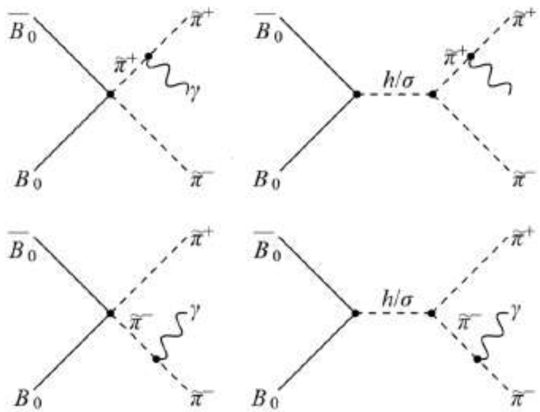
Phase diagrams in Mσ-Mπ plane



There are sufficiently wide regions with α ≥ 1 or even α ≥ 10 with masses near 1 TeV

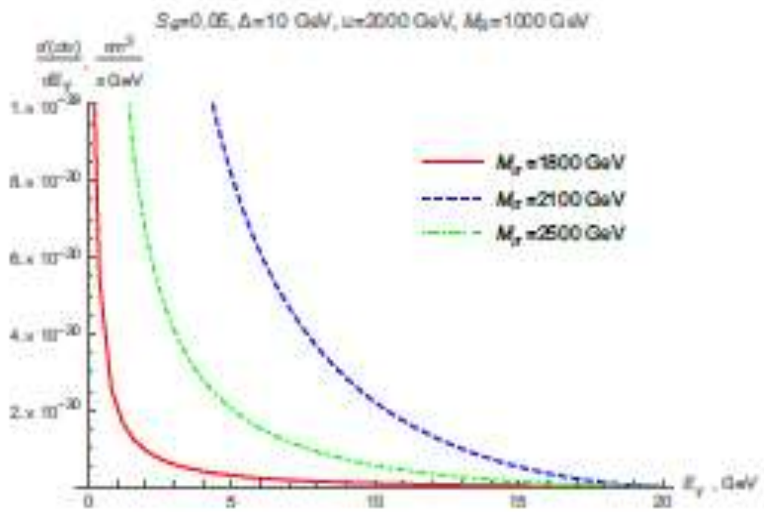
Annihilation of BB pair to charged H-pions with FSR

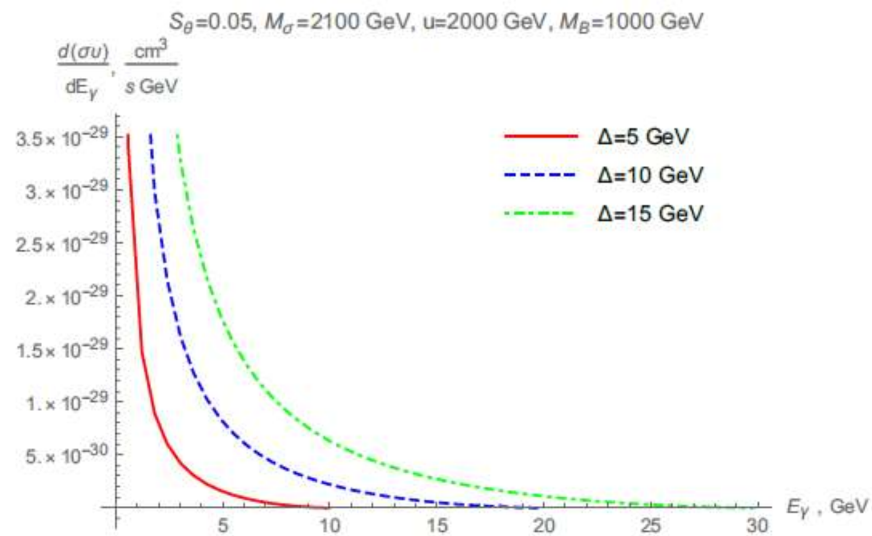
$$\frac{d\sigma v\left(B\bar{B}\to\tilde{\pi}^+\tilde{\pi}^-\gamma\right)}{dE_\gamma}E_\gamma^2=\frac{4\alpha E_\gamma\sigma v\left(B\bar{B}\to\tilde{\pi}^+\tilde{\pi}^-\right)}{\pi M_B\sqrt{M_B^2-m_{\tilde{\pi}}^2}}\Bigg(-2\sqrt{M_B(M_B-E_\gamma)}\sqrt{M_B(M_B-E_\gamma)-m_{\tilde{\pi}}^2}+ +\left(m_{\tilde{\pi}}^2+2(E_\gamma-M_B)M_B\right)\log\left[-1+\frac{2\s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

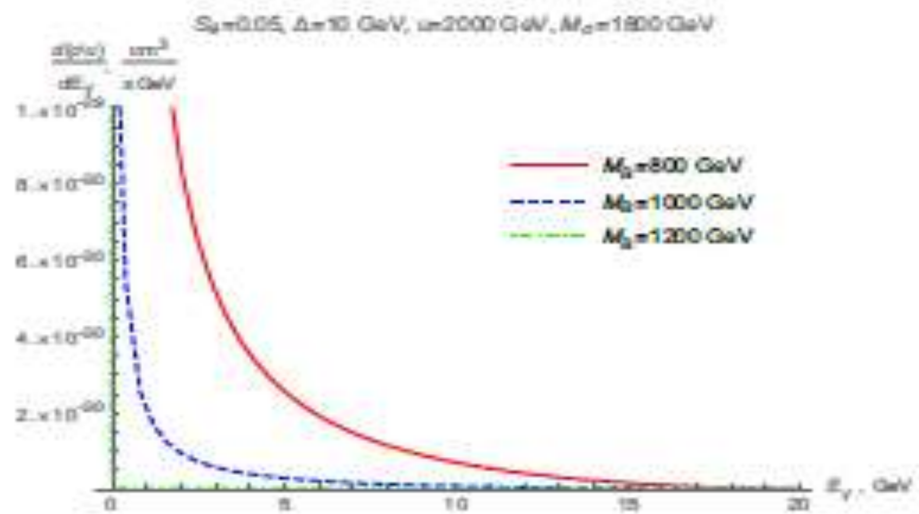


Energies of diffuse photons – up to 10-20 GeV.

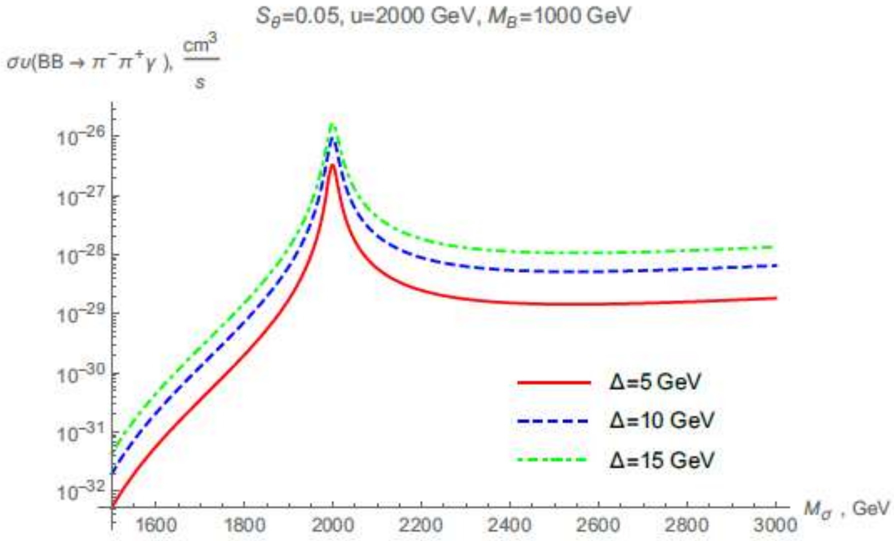
Differential cross-section with FSR





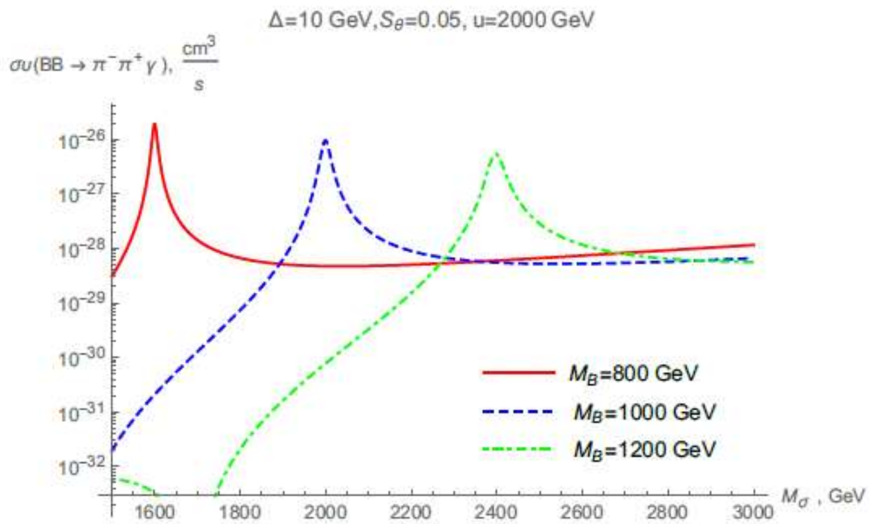


Total cross-section with FSR



Obviously, there is a resonance

In the s-channel diagrams near M_σ



Maximum value of the cross-section at the resonance is ≈ 10^(-26) cm^3/s
For typical velocity v ≈ 10-^(-3)

The total cross-section is almost independent on M_σ for masses above 2 – 2.4 TeV

Flux of photons

Astrophysical J- factor

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

$$\langle\sigma\nu\rangle dN/dE\gamma = d(\langle\sigma\nu\rangle)/dE\gamma \cdot N\gamma$$

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 $1^{\rm o}$ and standard NFW profile

$$J \approx 10^{21}$$

To estimate the flux from dwarf galaxies an average values

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

Expected (small) fluxes of photons from GC or dwarfs

- Total $\Phi(E_\gamma)$ from GC varied in the limits:

$$\Phi(E_\gamma) \approx (0.9 - 1.5)\cdot (10^{-12} - 10^{-14})\ cm^{-2}s^{-1}$$

- J-factor can be 10 or even 100 times more if the parameter γ changes from 1 to 1.4 to take into account the DM spike in the DM distribution near the GC, the flux increases up to

$$\Phi(E_\gamma) \approx (0.9 - 1.5)\cdot (10^{-10} - 10^{-12})\ cm^{-2}s^{-1}$$

- Average $\Phi(E_\gamma)$ from dwarfs varied in the limits:
  - $\Phi(E_\gamma) \approx (0.5 – 0.8)\cdot (10^{-13} - 10^{-15})\ cm^{-2}s^{-1}$
  - $\Phi(E_\gamma) \approx (0.4 – 0.6)\cdot (10^{-11} - 10^{-13})\ cm^{-2}s^{-1}$

Is the dark matter absolutely dark?

- Possibility of FSR from (unstable) charged 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, but this transition should have an intermediate stage with charged states from extended set of degrees of freedom -> 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, they can be produced at different stages and contribute to features of evolution processes.
- 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.

Some detail on the possible radiation

- The assumed effect of small flux of low-energy photons from regions with the increased DM density is specific -> it does not lead to the resorption of the DM clumps, the particle number density does not change in this process.
- Of course, there occurs also the "ordinary" annihilation of DM components into two photons or into pairs of SM particles with subsequent photon emission from finite bosons, leptons and quarks.
- However, monochromatic photons with energies of the order of the masses of DM particles are separated by an energy gap in the full spectrum of emitted photons.
- Unfortunately, a large background is produced by diffuse FSR from the SM particles; the total flux can be noticeably larger than the indicated effect. So the analysis of the structure of the spectrum low-energy photons is a difficult task.
- The detection and selection of a (nearly constant) photonic component with energies of the order of 1-10 GeV can indicate the presence of some structure in the DM mass spectrum, or the possibility of transitions between exited levels in the spectrum of states, as can occur in the hadronic DM scenario.
- 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 not very far (~ 0.1 pc) from our telescopes, the low-energy limited flux of photons can be seen and recognized.

Some additional and open questions

- Inverse case when the neutral H-pions are heavier also should be considered, however, annihilation into the (lighter) B-components for the case is difficult -> the diffuse photons production takes place mostly due to VIB from H-pions and/or H-quarks loops, corresponding cross-section is lower.
- Stable DM candidates can be produced from H-quark-gluon plasma at early stages at more large temperatures due to the scale of H-vacuum condensates is higher, H-hadronization occurs before QCD hadronization, so the photons from transitions between various H-states can contribute significantly to the total density of radiation.
- This process can maintain the temperature - a kind of delay mechanism that prevents cooling during expansion, in accordance with the Le Chatelier principle.
- Processes with H-quarks participation, H-hadronization and radiation.
- These features should be analyzed separately.
- 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.

Extension of SU(4) scenario to SU(6) with additional singlet H-quark

- Possible existence of stable pNG-objects with fractional electric charges (±1/2) in the most interesting and challenging consequence of SU (6) extension.
- In view of the very strong restrictions on the presence of such objects in the Universe, it will either be necessary to introduce an additional symmetry in the model, prohibiting such states,
- or discuss the physical effects that allow such particles to be "hidden" inside massive objects (dark stars?)in the Universe, or they should annihilate at the early stages, possibly leaving some specific traces (regions with the increased density of “normal” DM and radiation of high-energy photons, contribution to CMB, some substructure in the DM acoustic peak?).
- Another scenarios with complex structure and rich phenomenology of the SM extensions, multi- component dark matter, multi- messenger analysis of possible signals should be considered.

Dark matter inside the massive objects

- This type of annihilation, in fact, the transition between the DM components, is interesting from the point of view of 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.

Thank you for attention!

Thanks to organizers!

Stay healthy and safe!

CMB and acoustic oscillations

- The anisotropy of the cosmic microwave background is divided into two types: primary anisotropy, due to effects that occur at the surface of last scattering and before; and secondary anisotropy, due to effects such as interactions of the background radiation with intervening hot gas or gravitational potentials, which occur between the last scattering surface and the observer.
- The structure of CMB anisotropies is principally determined by two effects: acoustic oscillations and diffusion damping(or collisionless damping - Silk damping). The acoustic oscillations arise because of a conflict in the photon-baryon hot system in the early universe. The pressure of the photons tends to erase anisotropies, whereas the gravitational attraction of the baryons, moving at speeds much slower than light, makes them tend to collapse to form regions with very high density. These two effects compete to create acoustic oscillations, which give the microwave background its characteristic peak structure. The peaks correspond, roughly, to resonances in which the photons decouple when a particular mode is at its peak amplitude.
- The peaks contain interesting physical signatures. The angular scale of the first peak determines the Universe curvature (not the its topology. The next peak—ratio of the odd peaks to the even peaks—determines the reduced baryon density. The third peak can be used to get information about the dark-matter density.
- The locations of the peaks give important information about the nature of the primordial density perturbations. There are two fundamental types of density perturbations called *adiabatic* and *isocurvature*. A general density perturbation is a mixture of both, and different theories that purport to explain the primordial density perturbation spectrum predict different mixtures.

Appendix.

- The global symmetry of two-color H-QCD with 2nF Dirac quarks in the limit of zero masses is $SU(2\text{nF})$, with the chiral group being its subgroup, $SU(\text{nF})L \otimes SU(\text{nF})R \subset SU(2\text{nF})$ (valid for any symplectic gauge theory);

  The group $SU(2)$ is isomorphic to the group $Sp(2)$ in the simplest case of two flavors nF = 2;

- The quark condensate breaks the Pauli–Gursey symmetry to its subgroup $Sp(2\text{nF})$;

  In the limit mQ → 0, gW → 0 Lagrangian has a global $SU(4)$ symmetry (rotations in the space of the four initial chiral fermion fields);

- The Lagrangian with nonzero mQ can be rewritten in the form revealing explicitly the violation of symmetry $SU(4) \to Sp(4)$ by the mass term;

  For mQ = 0 the Lagrangian retains the full $SU(4)$ symmetry but, as in QCD -> the dynamical symmetry breaking by v.e.v. $\langle UU + DD \rangle \neq 0$. It has the mass term structure and -> the dynamical breaking of the symmetry $SU(4) \to Sp(4)$.
  The broken generators of SU(4) or SU(6) would be accompanied by a set of pNG states.

- The global SU(6) symmetry is broken dynamically to its Sp(6) subgroup. The mass terms of H-quarks could break the symmetry further to Sp(4) X Sp(2).

  The case of two-flavor model (without the singlet H-quark) is completely analogous to the three-flavor model but is simpler than latter one—the global SU(4) symmetry is broken dynamically to its Sp(4) subgroup by the condensate of doublet H-quarks;