Stability

Nirmal Raj
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INTRODUCTION

This talk is an expedition in idea space. Since this is a journal club, the spirit of which is discussion and not pragmatics, I will deal leanly with phenomenology. First addressed will be stability, then dark matter stability. When we write a model of DM, we do not simply take its stability for granted; we have the decency to specify some microscopic reason. This is usually an assumption of a Z_2 parity, as built into the code of MicrOmegas [1]. Sometimes the Z_2 is a consequence of a symmetry put in for other reasons; a classic example is the matter parity imposed on superfields as a means of preventing B and L violating operators. Applied to individual fields, the matter parity turns into R-parity, which usually ends up giving us a stable DM candidate. Another example is KK parity in universal extra dimension (UED) models.

The QFT landscape of DM stability mechanisms is diverse. The object here is to highlight this diversity, and encourage the audience to entertain model-building DM from the viewpoint of its stability. Notice that we think DM is stable, unlike Ref. [2]. In the absence of evidence of its particulate nature, it is important to derive a model-independent bound on the lifetime of DM; the review in [3] shows how to set this limit as a function of DM mass using the cosmic flux of antimatter, gamma rays and neutrinos. Roughly, for DM in the GeV-TeV range, it is found that $\tau_{\rm DM} \gtrsim 10^{18}$ years. Recall that the age of the universe is 10^{10} years.

In making this talk the review in [4] had been pretty handy, although about half the papers mentioned here are my private sightings at the InspireHEP database. I thank Carlos Alvarado for the many chats we had along the themes here.

STANDARD MODEL

So many symmetries are built into the SM, and so many peculiarities are seen in its spectrum, that the stability of numerous species is guaranteed. Let us review these one by one.

$\boxed{e^{\pm}}$

The simplest mechanism. It is stable because it is the lightest particle charged under an unbroken gauge group, here $U(1)_{\rm EM}$.

$\boxed{\nu_1}$

The lightest neutrino is stable (which we know from the CνB) because it is the lightest fermion of the broken $SU(2)_W$ symmetry. Thus it is protected against decay by Lorentz symmetry.

$\boxed{\nu_{2,3}}$

The other two neutrinos have cosmologically long lifetimes as well. In the SM, their decay (to $\nu_i\gamma$ and $\nu_i\nu_j\nu_k$) is exceptionally rare; the lifetime is predicted to be 10^{37} years ($= 10^{27} \times$ the age of the universe) [5]. This is because their decay rate is highly suppressed by their own mass (sub-eV) in the numerator and by the Fermi scale (100 GeV) in the denominator.

$\boxed{[\pi^0]}$

G-parity is the extension of C-parity to a multiplet and is defined by

$$\mathcal{G} = \mathcal{C}\ e^{i\pi I_2}\ ,$$

where I_2 is the second generator of iso-spin. Just as C-parity eigenstates are neutral (nil quantum charges or magnetic moments), G-parity eigenstates are QCD-neutral. The G eigenvalue is given by $(-1)^{S+L+I}$ for a fermion-antifermion pair such as the pion system, where I is the iso-spin. Thus the triplet (π^+, π^0, π^-) would have an eigenvalue (-1) . Since it would be the lightest G-odd triplet, it would have nothing to decay to. All this might have been true in the SM if G-parity had been exact. But electroweak interactions spoil the picture, so G is not a conserved quantity. We know that the neutral pion decays (to a photon pair 98.8% of the time).

$\boxed{p}$

The proton's lifetime $\gtrsim 10^{33}$ years (or $\gtrsim 10^{23} \times$ the age of the universe) and is long-lived as it is the lightest species charged under $U(1)_B$, an exact global symmetry at tree level. This symmetry emerges by accident when we impose a gauged $SU(3) \otimes SU(2) \otimes U(1)$ as we do in the SM. $U(1)_B$ is broken by higher dimensional operators (dimension 6 onward in the SM).

SM-LIKE DM

With its rich machinery, the Standard Model already shows how to introduce stable particles in new theories.

In what follows, we will survey models that avail the philosophy of every avenue mentioned above in order to stabilize DM.

Hidden charge

Consider a fermion charged under a $U(1)'$ gauge with strength e':

$$\mathcal{L} \supset \bar{\psi}(i\partial\!\!\!/_\mu - ie' A'_\mu - m')\psi \ . \quad (1)$$

If ψ is the lightest species under $U(1)'$, then it is stable like the electron is. If the dark sector is further sequestered from the SM (say, by not allowing gauge kinetic mixing with $U(1)_{\rm EM}$), it may evolve with its own temperature, T'. The free parameters determining the phenomenology of these models are then m', e' and T'. The above arguments hold also for scalar QED$'$:

$$\mathcal{L} \supset -(D^\mu\Phi)^\dagger(D_\mu\Phi) - m^2\Phi^\dagger\Phi - \frac{\lambda'}{4}(\Phi^\dagger\Phi)^2. \quad (2)$$

This will necessitate a portal to the SM higgs sector: $c\ |\Phi|^2|H|^2$. This class of DM models has been called "hidden charge dark matter" [6–8].

Remnant fermion

The Lagrangian in Eq. 1 could also be terms remaining from the breaking of a group like $U(1)'$. Now, like the neutrino, ψ is stable simply because it's the lightest fermion in the set-up. One may now need to introduce one or more scalars to break the symmetry, which may provide interesting phenomenology through a higgs portal. The consequences of this model were explored in [9].

Suppressed decay

In SUSY models where R-parity is violated, the gravitino $\tilde{g}$ is assumed to be DM. It appears stable because its decay to SM states is suppressed by $M_{\rm Planck}$. Similarly, if DM is axions or keV-heavy right-handed neutrinos, the decay operator is suppressed by some high scale as well as (the fifth power of) their own mass. These candidates are similar to $\nu_{2,3}$.

Dark pion

In the SM, G-parity is not a good symmetry. Fermions charged under $SU(2)_W$ are chiral, and the $U(1)_Y$ charges are different for Q, u^c and d^c. This non-vectorial nature of the quarks ultimately – post-chiral symmetry breaking – lifts the degeneracy among the pions. Now suppose we started out with N_f fermions ψ_i that are *vector-like* under $SU(2)_W$, and say they were also part of a new confining group $SU(N)'$:

$$\mathcal{L} \supset -\frac{1}{4}G'_{\mu\nu}G'^{\mu\nu} + \bar{\psi}(i\partial\!\!\!/ + g'_s\mathcal{G}'^a T^a + g_2 W\!\!\!/^a J^a)\psi, \quad (3)$$

where T^a are the generators of the fundamental representation of $SU(N)'$ and $J^{1,2,3}$ are $N_f \times N_f$ isospin matrices. Then chiral symmetry breaking would result in massive pions with G-parity intact. After EWSB, loop corrections may induce mass splittings in the multiplet. The electrically neutral component is then the lightest G-odd state, is hence stable, and may be dark matter. Such a possibility was explored in [10]. The dark pions can annihilate weakly and hence be WIMPs of $\sim$ TeV mass. Just as $U(1)_B$ in the SM, G is an accidental symmetry of the input gauge symmetries. In consequence G may be violated by higher dimensional operators. Terms such as $F_Y^{\mu\nu}\bar{\psi}\sigma_{\mu\nu}\psi/\Lambda$ and $\bar{\psi}J^a\psi H^\dagger J^a H/\Lambda$ destabilize the dark pions at dimension-5, necessitating their elimination by inclusion of an extra global Peccei-Quinn symmetry. See [11] for a list of accidental symmetries due to confinement that may stabilize DM.

Minimal : SM symmetries

The proton came out stable on cosmological timescales without having to extend the SM gauge symmetries. Physicists have wondered if we can similarly obtain DM stability *gratis*, viz., if from merely the SM gauge group it can emerge by an accident of the field content.

To this end did the authors of [12–14] present a framework of "minimal DM". It was realized that if DM was lodged in sufficiently large multiplets of $SU(2)_W$, its interactions with the SM are only possible via irrelevant operators. To see this, begin by introducing a new $SU(2)$ doublet fermion, Ψ. To have renormalizable interactions with the SM, we need a combination of SM fields that has dimension 5/2 and is an $SU(2)$ doublet. Because of the half-integer dimension required, we necessarily need the participation of SM fermions. This is possible through gauge interactions or a Yukawa term involving the Higgs doublet. Now suppose Ψ were an $SU(2)$ quadruplet instead. Then we need a combination of SM fields of dimension 5/2 that is an $SU(2)$ *quadruplet*. However, the highest $SU(2)$ multiplicity of our SM fermions is a doublet. Even in combination with the higgs doublet, we can only get at best a triplet. To accomplish a quadruplet, we need to go to a higher dimension and construct something like $LHH\Psi/\Lambda$.

We can restrict the structure of the multiplet based on phenomenology. First, we find that if its interactions are suppressed by dimension-5 (dimension-6), the lifetime is given by $\tau_{\rm DM} \sim 8\pi\Lambda^2/m_{\rm DM}^3$ ($\tau_{\rm DM} \sim 8\pi\Lambda^4/m_{\rm DM}^5$). If we want $\Lambda < M_{\rm Planck}$, the DM lifetime in the dim-5 case is short of the age of the universe. On the other hand, even if we impose $\tau_{\rm DM} \sim 10^{18}$ years, we get $\Lambda \simeq 10^{14}$ GeV in the dim-6 case. Therefore, we wish to construct multiplets that only have dim-6 interactions or more. This requires fermions that are 5-plets or higher and scalars that are 6-plets or higher. Second, the multiplet must have an electrically neutral component. This must be kept in mind when the hypercharge is assigned. Third, to avoid large nuclear scattering cross-sections that may

lead to large direct detection rates, one may wish to kill tree level interactions with the Z. So we want Y and T_3 to vanish, which is only possible for an odd multiplet. Putting all these together, one constructs $SU(2)$ multiplets with the following multiplicities:

$$n = 5, 7, 9, ...(\text{fermions}),$$
$$n = 7, 9, 11, ...(\text{scalars}).$$

What the above authors attempted with higher representations and non-renormalizable operators, Ref. [15] managed to do at the renormalizable level by introducing a single field. Namely, an SM singlet that is an antisymmetric tensor, $\mathcal{B}_{\mu\nu}$. [1] The Lagrangian is given by

$$\begin{aligned}\mathcal{L} \supset \quad & \frac{1}{4}\partial_\lambda \mathcal{B}^{\mu\nu}\partial^\lambda \mathcal{B}_{\mu\nu} - \frac{1}{2}\partial_\rho \mathcal{B}^{\rho\nu}\partial^\mu \mathcal{B}_{\mu\nu} - \frac{m_{\mathcal{B}}^2}{4}\mathcal{B}^{\mu\nu}\mathcal{B}_{\mu\nu} \\ & - \lambda_{\mathcal{B}}\mathcal{B}^{\mu\nu}\mathcal{B}_{\nu\lambda}\mathcal{B}^{\lambda\rho}\mathcal{B}_{\rho\mu} + c_{\mathcal{B}}\mathcal{B}^{\mu\nu}\mathcal{B}_{\mu\nu}(H^\dagger H) \qquad (4)\end{aligned}$$

The last term, a higgs portal, is the sole tree-level interaction of $\mathcal{B}_{\mu\nu}$ with the SM! The term $\mathcal{B}_{\mu\nu}\bar{\psi}_L\sigma^{\mu\nu}\psi_R$ vanishes for SM fermions due to chiral symmetry. The operator $\mathcal{B}_{\mu\nu}F_Y^{\mu\nu}$ is allowed, but vanishes for an on-shell $\mathcal{B}_{\mu\nu}$ and leads to a non-dynamical tensor for off-shell $\mathcal{B}_{\mu\nu}$, which pre-empts matching the low-energy theory with some UV completion. Hence the Wilson coefficient of this term is taken to vanish. The term $\mathcal{B}_{\mu\nu}\mathcal{B}_\lambda^\nu F_Y^{\lambda\mu}$ is absent since $\mathcal{B}_{\mu\nu}$ is antisymmetric.

With these restrictions one sees that the Lagrangian has picked up an *accidental* Z_2 symmetry that had had no manual input. If $\mathcal{B}_{\mu\nu}$ is charged odd under it, it is stable, and can play dark matter. Since interactions with fermions and gauge bosons are forbidden, the Z_2 is preserved at all orders and for operators of any dimension. For instance, the Wilson coefficients of operators like $\mathcal{B}_{\mu\nu}\bar{\psi}_L\sigma^{\mu\nu}H\psi_R, \mathcal{B}_{\mu\nu}H^\dagger W^{\mu\nu}H, \partial^\mu\mathcal{B}_{\mu\nu}\partial_\rho F_Y^{\rho\nu}$ are uniformly zero.

The immediate concern here is that, $\mathcal{B}_{\mu\nu}$ being a tensor, the total cross-section of $\mathcal{B}_{\mu\nu}\mathcal{B}_{\mu\nu}$ scattering grows with energy: $\sigma_{\rm tot}(s) \sim s$. A new physics scale is needed to unitarize the theory, a scale consisting presumably of fermions charged under a confining group (as is the case with the QCD ρ meson). The unitarity bound $\sigma < 16\pi/s$ is not violated for $\sqrt{s} \lesssim 5m_{\mathcal{B}}$ for $c_{\mathcal{B}} = 0.1$. Therefore the UV completion is not important to DM phenomenology when the process in question occurs at an energy much lower than the mass of DM.

MECHANISMS BSM

Next − to − minimal

The "minimal" models above essayed to give a long-lived particle by carefully choosing the particle content without upsetting the gauge symmetry structure of the SM, $G_{\rm SM}$. Some authors have tried to take this approach to a next-to-minimal level. In these models, DM interactions are allowed to obey some of the approximate symmetries of SM as well.

In [16], the principle of minimal flavor violation (MFV) is invoked to give DM its stability. The SM has an approximate $SU(3)^5$ flavor symmetry broken by the Yukawa couplings. MFV desires that new physics interactions respect the $G_q \equiv SU(3)^3$ symmetry of the quark sector, and that any violation of quark flavor is through Yukawa spurions that break this symmetry. The idea is to choose the G_q representations for DM such that no decay operator that is a singlet under $G_{\rm SM} \otimes G_q$ can be constructed. This involves some calisthenics with group theory, which the interested reader may navigate in the paper. The idea was applied to asymmetric DM in [17], where the DM decay operator, instead of being banished, was suppressed by Yukawa spurions.

An A_4 flavor symmetry for the neutrino mixing angles was considered in [18]. A_4 is the group of even permutations of four objects and is isomorphic to the tetrahedron symmetry group. A higgs sector with three new scalar doublets was introduced. One of the higgses gets a vev, breaking the A_4 to a Z_2, providing a stable DM particle in a linear combination of the other two higgs fields. This is reminiscent of the DM candidate one obtains from two higgs doublet models with an inert higgs. The paper predicts $\theta_{13} = 0$, which has since been measured as $\sin^2 2\theta_{13} = 0.092 \pm 0.021$ [19].

Ref. [20] is like the minimal DM models discussed above, in that DM decays are suppressed by introducing multiplets having irrelevant interactions with the SM, except here $U(1)_B$ and $U(1)_L$ are also imposed. The paper also lists operators that survive proton decay after B and L violation.

Triange inequality

A very interesting mechanism for DM stability was put forth by Francesco D'Eramo and Jesse Thaler in [21], that I have not seen elsewhere. Imagine a sector comprised of three or more fields, $\{\chi_i\}$, charged under some symmetry. If the masses of at least three of the χ_i satisfy

$$m_{\chi_a} < m_{\chi_b} + m_{\chi_c}, \qquad (5)$$

for all combinations of (a, b, c), then decays like $\chi_a \to \chi_b\chi_c$ (and $\chi_a \to \chi_b\chi_c S$, where S is a singlet) are kinematically forbidden. Thus all the fields obeying the triangle inequality of Eq. 5 are stable. Many models in the literature are already subsumed into this picture. The simplest way to arrange it is a symmetry insuring mass degeneracy – making the triangle equilateral. A Z_3 symmetry may be imposed by hand.

[1] Massive tensors have already been in use in QCD to describe spin-1 mesons like $\rho(770)$ and $a_1(1260)$ at low energies.

More dynamically, the gauge bosons of a non-abelian group can constitute DM. Consider a simple $SU(2)'$ Lagrangian:

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + (\partial^\mu\phi^\dagger + ig'T_a A'^\mu_a\phi^\dagger)(\partial_\mu\phi - ig'T_a A'_{a\,\mu}\phi) + V(\phi, H) \quad (6)$$

with ϕ an $SU(2)'$ scalar multiplet that breaks the group with a vev v_ϕ. After symmetry breaking, the gauge bosons acquire a mass $g'v_\phi/2$. More importantly, they form the triplet of a remnant, accidental symmetry: a custodial $SO(3)$. [Contrast this against EWSB, $SU(2)_W \otimes U(1)_Y \to U(1)_{\rm EM}$, where no custodial symmetry remains.] This is the "hidden vector DM" discussed in [22–24]. Of course, other continuous symmetries can do the trick as well, such as flavor and baryon/ lepton symmetries.

D'Eramo and Thaler give an interesting way to construct an isosceles triangle. Imagine a sector with N_b vector-like fermions β_i, β_i^c that play the role of baryons. We then have N_b^2 mesons π_i^j in the adjoint representation of $U(N_b)$. Now,

$$\mathcal{L} \supset i\bar\beta_i\bar\sigma^\mu\partial_\mu\beta_i + i\bar\beta^c{}_i\bar\sigma^\mu\partial_\mu\beta_i^c + (\partial_\mu\pi_i^j)^\dagger(\partial^\mu\pi_i^j) - (m_{\beta_i}\beta_i^c\beta_i + \lambda\beta_j^c\pi_i^j\beta_i + \text{h.c.}) - V(\pi_i^j)\ . \quad (7)$$

The Yukawa coupling allows the decay $\pi_i^j \to \beta_i\bar\beta_j^c$, however, if the triangle inequality of Eq. 5 is satisfied, the pions and baryons can together make up dark matter! The above models have a unique annihilation process due to their symmetries, $\chi_i\chi_j \to \chi_k S$. This process, "semi-annihilation", can modify the calculation of DM freeze-out in non-trivial fashion.

Spacetime parity

We saw already that invariance under Lorentz transformations can stabilize DM, if it is the lightest fermion of a broken gauge group. Another spacetime operation may be responsible for DM stability: parity. This possibility was proposed by [25]. To see how it works, imagine a theory which respects parity P, such as a model that extends the SM gauge group as $SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_Y$. There are two higgs fields now, H_L and H_R, transforming under P as $H_L(x,t) \leftrightarrow H_R(-x,t)$. When the $SU(2)_L \otimes SU(2)_R$ spontaneously breaks with $\langle H_R\rangle \gg \langle H_L\rangle$, so does P. But applying parity twice transforms the higgs fields back to the original state: $H_{L,R}(x,t) \leftrightarrow H_{L,R}(x,t)$. Therefore P^2 remains unbroken.

Now introduce a singlet fermion ψ. Suppose the action of P^2 on ψ did *not* return it to its original state: $P^2\psi = \eta^2\psi$, $\eta^2 \neq 1$. If all other fields in the theory behaved normally under squared parity (if in their case $\eta^2 = 1$) then ψ cannot decay to any of them, and hence will be stable! Moreover, $\eta = \pm i$ implies ψ has a Majorana mass [26], since under P a Majorana fermion transforms as $\psi \to i\gamma_0\psi$ (and under $P^2, \psi \to -\psi$). The presence of Majorana mass terms for both ψ and neutrinos is crucial here; otherwise the P^2 phase of ψ can be rotated away in a different field basis. Although this paper explains how ψ can be stable DM, it does not explore its phenomenology.

DISTINGUISHING

Some authors have investigated whether it is possible to tell the DM stabilization mechanism at a collider. The focus here has been mostly on distinguishing among the discrete Z_n parities. I comment briefly on these papers.

Ref. [27] uses spectral features to tell between a Z_2 and Z_3. With Z_3, the event may have either one or two DM particles, but with Z_2, only one. If the decay happens through off-shell intermediate particles, the invariant mass of the visible objects must have two kinematic edges for Z_3. For Z_2, as is well known from supersymmetry searches, we have only one edge. If the intermediates are on-shell, certain decay chains may additionally produce a cusp in the SM invariant mass distribution. In [28], they take this idea further to include the invisible particles in the invariant mass calculation; thus an M_{T_2} variable can be used as a distinguisher between Z_2 and Z_3. A comprehensive exploration of these methods can be seen in [29], where stabilization symmetries upto Z_5 are distinguished. These ideas were used in [30] to distinguish between the multi-component dynamical dark matter of [2] and the usual stable varieties. Several spectacular features in the invariant mass distribution may be produced by dynamical DM.

Ref. [31] attempts to distinguish between parity-symmetry-stabilized DM and DM stabilized by other kinds of symmetries. Models were constructed to give long-lived particles whose time-of-flight may be measured at the LHC. The signature of two long-lived particles plus large missing momentum was then shown to effectively discriminate between the cases; the parity case led to suppressed signals.

[1] G. Blanger, F. Boudjema, A. Pukhov and A. Semenov, Comput. Phys. Commun. **192**, 322 (2015) doi:10.1016/j.cpc.2015.03.003 [arXiv:1407.6129 [hep-ph]].

[2] K. R. Dienes and B. Thomas, "Dynamical Dark Matter: I. Theoretical Overview," Phys. Rev. D **85**, 083523 (2012) [arXiv:1106.4546 [hep-ph]].

[3] A. Ibarra, D. Tran and C. Weniger, "Indirect Searches

for Decaying Dark Matter," Int. J. Mod. Phys. A **28**, 1330040 (2013) [arXiv:1307.6434 [hep-ph]].
[4] T. Hambye, "On the stability of particle dark matter," PoS IDM **2010**, 098 (2011) [arXiv:1012.4587 [hep-ph]].
[5] `http://arxiv.org/pdf/1411.0308v1.pdf`
[6] J. L. Feng, H. Tu and H. B. Yu, "Thermal Relics in Hidden Sectors," JCAP **0810**, 043 (2008) [arXiv:0808.2318 [hep-ph]].
[7] L. Ackerman, M. R. Buckley, S. M. Carroll and M. Kamionkowski, "Dark Matter and Dark Radiation," Phys. Rev. D **79**, 023519 (2009) [arXiv:0810.5126 [hep-ph]].
[8] J. L. Feng, M. Kaplinghat, H. Tu and H. B. Yu, "Hidden Charged Dark Matter," JCAP **0907**, 004 (2009) [arXiv:0905.3039 [hep-ph]].
[9] M. Pospelov, A. Ritz and M. B. Voloshin, "Secluded WIMP Dark Matter," Phys. Lett. B **662**, 53 (2008) [arXiv:0711.4866 [hep-ph]].
[10] Y. Bai and R. J. Hill, "Weakly Interacting Stable Pions," Phys. Rev. D **82**, 111701 (2010) [arXiv:1005.0008 [hep-ph]].
[11] O. Antipin, M. Redi, A. Strumia and E. Vigiani, "Accidental Composite Dark Matter," JHEP **1507**, 039 (2015) [arXiv:1503.08749 [hep-ph]].
[12] M. Cirelli, N. Fornengo and A. Strumia, "Minimal dark matter," Nucl. Phys. B **753**, 178 (2006) [hep-ph/0512090].
[13] M. Cirelli, A. Strumia and M. Tamburini, "Cosmology and Astrophysics of Minimal Dark Matter," Nucl. Phys. B **787**, 152 (2007) [arXiv:0706.4071 [hep-ph]].
[14] M. Cirelli and A. Strumia, "Minimal Dark Matter: Model and results," New J. Phys. **11**, 105005 (2009) [arXiv:0903.3381 [hep-ph]].
[15] O. Cata and A. Ibarra, "Dark Matter Stability without New Symmetries," Phys. Rev. D **90**, no. 6, 063509 (2014) [arXiv:1404.0432 [hep-ph]].
[16] B. Batell, J. Pradler and M. Spannowsky, "Dark Matter from Minimal Flavor Violation," JHEP **1108**, 038 (2011) [arXiv:1105.1781 [hep-ph]].
[17] F. Bishara and J. Zupan, "Continuous Flavor Symmetries and the Stability of Asymmetric Dark Matter," JHEP **1501**, 089 (2015) [arXiv:1408.3852 [hep-ph]].
[18] M. Hirsch, S. Morisi, E. Peinado and J. W. F. Valle, "Discrete dark matter," Phys. Rev. D **82**, 116003 (2010) [arXiv:1007.0871 [hep-ph]].
[19] F. P. An *et al.* [Daya Bay Collaboration], "Observation of electron-antineutrino disappearance at Daya Bay," Phys. Rev. Lett. **108**, 171803 (2012) [arXiv:1203.1669 [hep-ex]].
[20] C. Cheung and D. Sanford, "Effectively Stable Dark Matter," arXiv:1507.00828 [hep-ph].
[21] F. D'Eramo and J. Thaler, "Semi-annihilation of Dark Matter," JHEP **1006**, 109 (2010) [arXiv:1003.5912 [hep-ph]].
[22] T. Hambye, "Hidden vector dark matter," JHEP **0901**, 028 (2009) [arXiv:0811.0172 [hep-ph]].
[23] T. Hambye and M. H. G. Tytgat, "Confined hidden vector dark matter," Phys. Lett. B **683**, 39 (2010) [arXiv:0907.1007 [hep-ph]].
[24] C. Arina, T. Hambye, A. Ibarra and C. Weniger, "Intense Gamma-Ray Lines from Hidden Vector Dark Matter Decay," JCAP **1003**, 024 (2010) [arXiv:0912.4496 [hep-ph]].
[25] R. Kuchimanchi, "P stabilizes dark matter and with CP can predict leptonic phases," Eur. Phys. J. C **74**, 2726 (2014) [arXiv:1209.3031 [hep-ph]].
[26] `http://ccdb5fs.kek.jp/cgi-bin/img_index?198406038`
[27] K. Agashe, D. Kim, M. Toharia and D. G. E. Walker, "Distinguishing Dark Matter Stabilization Symmetries Using Multiple Kinematic Edges and Cusps," Phys. Rev. D **82**, 015007 (2010) [arXiv:1003.0899 [hep-ph]].
[28] K. Agashe, D. Kim, D. G. E. Walker and L. Zhu, "Using $M_T 2$ to Distinguish Dark Matter Stabilization Symmetries," Phys. Rev. D **84**, 055020 (2011) [arXiv:1012.4460 [hep-ph]].
[29] G. F. Giudice, B. Gripaios and R. Mahbubani, "Counting dark matter particles in LHC events," Phys. Rev. D **85**, 075019 (2012) [arXiv:1108.1800 [hep-ph]].
[30] K. R. Dienes, S. Su and B. Thomas, "Distinguishing Dynamical Dark Matter at the LHC," Phys. Rev. D **86**, 054008 (2012) [arXiv:1204.4183 [hep-ph]].
[31] D. G. E. Walker, "Dark Matter Stabilization Symmetries and Long-Lived Particles at the Large Hadron Collider," arXiv:0907.3142 [hep-ph].