Light fermions that arise as composite states in confining gauge theories are stable due to fermion number conservation. This leads to Dark Matter candidates that behave similarly to elementary DM but where the cosmological stability arises automatically from the accidental symmetries of the theory. We present explicit models based on ’t Hooft anomaly matching conditions where DM is charged under the SM. For example an SU(N) gauge theory with fermions in the adjoint rep and triplet of SU(2)$_L$ gives rise to DM made of multiple “Wino” triplets, while SO(N) gauge theories with $N_F = N - 4$ flavors produce neutralino-like systems or SM quintuplets. Compositeness effects are crucial to determine the phenomenology.

**Introduction.** Despite many efforts the nature of Dark Matter (DM) continues to be a mystery. One possible clue is its cosmological stability that suggests the existence of new accidental symmetries beyond baryon number of the Standard Model (SM). In the SM stability of proton and nuclei is an automatic consequence of the gauge structure of the renormalizable lagrangian: given the quantum numbers of SM particles baryon number is an accidental symmetry of the theory that is only broken by dimension 6 operators or higher. Obviously it would be desirable that stability of DM is also a robust feature of the theory, rather than being imposed by hand as often assumed in the literature. The request of DM accidental stability turns out to be very restrictive, demanding either new gauge symmetries [1] or exotic SM representations [2]. One of the simplest realizations of accidental DM is a baryon of dark sector [1, 3], see [4] for realizations with scalars. These scenarios assume QCD-like dynamics, where a dark gauge group confines and breaks chiral symmetries of the fermionic lagrangian. As discussed long ago by ’t Hooft a different phase is in principle possible where the theory confines without chiral symmetry breaking [5]. The framework is very predictive as in the chiral limit massless fermions must arise to match the global anomalies of the UV theory. If the fermions are vectorial a mass can also be included leading to light fermions appropriate for DM. The accidental symmetries of the UV theory imply the stability of the lightest composite fermion.

**General structure.** In this letter we will study the possibility that DM is a composite light fermion of a dark sector arising from ’t Hooft anomaly matching. Because of accidental fermion number conservation the lightest fermion is automatically stable at renormalizable level, leading to cosmological stability under very broad assumptions. We will focus here on sectors with electro-weak charges that give rise to very predictive scenarios.

Differently from DM as a baryon of a dark sector, light composite fermions would behave for many aspects as elementary particles up to corrections $M/\Lambda$ where $\Lambda$ is the compositeness scale. For example if DM has SM charges the annihilation cross-section that controls the thermal abundance of DM is the same of elementary SM multiplets to leading order. This should come as no surprise, at low energies we can compute the pion production cross-section $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ using QED. If DM is produced thermally the abundance is then,

$$\Omega(M_i, \Lambda) = \Omega_{SM}(M_i) + O\left(\frac{M_i^2}{\Lambda^2}\right)$$

An important caveat to this result is provided by light composite singlets where the leading interactions depend instead on the compositeness scale. As we will see the presence of singlets leads to strong constraints on the compositeness scale.

The main technical tool in the construction of explicit models is ’t Hooft anomaly matching conditions [5] and recent generalizations [6]. This allows to determine gauge theories where confinement without chiral symmetry breaking is possible and the quantum numbers of the composite fermions. Our examples are non-supersymmetric theories where the composites can saturate anomalies but we cannot prove confinement without chiral symmetry breaking. Nevertheless we believe that these examples capture the essential features relevant for DM. Confinement without chiral symmetry breaking can be established in supersymmetric theories, see [7].

**SU(N) with 3 adjoints.** Our first example is an SU(N) gauge theory with adjoint fermions transforming as a triplet of SU(2)$_L$. Recently it has been proposed in [8] that SU(N) gauge theories with 3 adjoints may confine without chiral symmetry breaking. In the massless limit anomaly matching conditions can be most simply satisfied with $N^2 - 1$ chiral fermions that transform as triplet of the SU(3) global symmetry. In terms of preons the composite fermions are associated to the gauge invariant operators

$$(O_n)_\alpha = \text{Tr}[G_{\mu_1\alpha_1} \cdots G_{\nu_\alpha_\nu}(\sigma^{\mu\nu})_\beta^\alpha V_\beta]$$

where $V$ is a triplet Weyl fermion in the adjoint of SU(N). The weak gauging of the global symmetry by the electro-weak interactions produces $N^2 - 1$ massless SU(2)$_L$ triplets. In order to avoid low scale Landau poles we will take here $N = 3$. 

**SU(N) with N adjoints.** Our second example is the NM multiplets to leading order. This should come as no surprise, at low energies we can compute the pion production cross-section $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ using QED. If DM is produced thermally the abundance is then,
Since the gauge theory is vector-like a mass $M_V$ can be added to the elementary fermions. The mass term breaks the SU(3) global symmetry to SO(3) allowing the composite fermions to also acquire a mass. Since the composite fermions are in a reducible representation of the global symmetry we expect their mass to be split by strong interactions, $M_i = c_i M_V$. It seems natural that fermions associated to higher dimensional operators are heavier but we cannot prove it or estimate the splitting. We will assume that $c_i$’s are order one numbers in what follows. In addition electro-weak interactions will further split different multiplet, $\Delta M_i/M_i \sim \alpha_2/(4\pi) \log \Lambda/M_i$ effectively renormalizing $c_i$. As in models with elementary triplets the charged components of each multiplet are split by $\Delta M = 165$ MeV.

Notably the underlying gauge theory is the same employed in Ref. [9] where theories with fermions in the adjoint of SU(N) were shown to produce an accidental DM candidate. Assuming the standard pattern of symmetry breaking $SU(3) \rightarrow SO(3)$, the bound state made of adjoint fermions and gluons, the “gluequark”, is a triplet of SU(2)$_L$ that is stable due fermion parity that is only violated by the dimension 6 operator, $V^a G^a_{\mu\nu} \sigma^{\mu\nu} L H$ suppressed by a scale $\Lambda_{UV}$. For $M_V < \Lambda$ the mass of the gluequark is expected to be of order $\Lambda$.

If confinement produces massless chiral fermions the discrete symmetry still guarantees the stability of the lightest fermion, but the DM phenomenology is entirely different. First, the gluequarks have multiplicity $N^2 - 1$. The lifetime induced by the parity violating operator becomes,

$$\frac{1}{\tau_{DM}} \sim \frac{M_{DM} \Lambda^4}{8\pi \Lambda_{UV}^4} \sim \frac{10^{-28}}{s} \left(\frac{M_{Pl}}{\Lambda_{UV}}\right)^4 \left(\frac{\Lambda}{100 \text{ TeV}}\right)^4 \left(\frac{M_{DM}}{\text{TeV}}\right),$$

which is parametrically larger than in the composite regime by a factor $M_{DM}/\Lambda$. Moreover the gluequarks now behave at low energies as elementary electro-weak triplets. Since the DM thermal abundance is determined by electro-weak interactions the critical mass is in the TeV range, rather than $O(100)$ TeV as in [1, 9]. If dim 6 operators are suppressed by the Planck scale cosmological stability demands $\Lambda < 1000$ TeV. It is also conceivable that quantum gravity effects are further suppressed so that larger values of $\Lambda$ become allowed.

In the effective theory below $\Lambda$ at the renormalizable level all the triplets $\lambda_i$ are stable. They can decay into each other through dimension 7 operators suppressed by the compositeness scale [10],

$$\frac{\alpha_2 \alpha_e \lambda_i^a \lambda_j^b W^{\mu \nu} W^{b \mu \nu}}{\Lambda^3},$$

where we included a loop factor in the NDA estimate as for dipole operators [11]. For $\Delta M > 2 M_{W^i}$ this gives a lifetime,

$$\frac{1}{\tau_{DM}} \sim \frac{\alpha_2^2 \alpha_e^2 M_W^2}{192 \pi^3 \Lambda^6} \sim \frac{10^{-28}}{s} \left(\frac{M_{W^i}}{\text{TeV}}\right)^7 \left(\frac{10^{11} \text{ GeV}}{\Lambda}\right)^6$$

If decay to W’s is kinematically forbidden the main decay is through photon emission with a rate obtained replacing $\alpha_2 \rightarrow \alpha_{em}$.

Different regimes are realised depending on the scale of compositeness:

For $\Lambda \gtrsim 10^{11}$ GeV all the triplets could be cosmologically stable if dim 6 parity violating operators are suppressed, giving rise to multi-component DM made of neutral components of triplets. The thermal abundance is determined by annihilation into SM particles as for elementary Winos. The tree level s-wave annihilation cross-section of each multiplet reads,

$$\langle \sigma_i v_{rel} \rangle = \frac{37 \pi \alpha_e^2}{12 M_i^2},$$

which should be multiplied by the appropriate Sommerfeld enhancement factors, see [12] for precision computations. The abundance of each component is inversely proportional to its annihilation cross-section. Since a thermal Wino has a mass 2.9 TeV the critical abundance of DM is now obtained for $\sum_i M_i^2 \approx (3 \text{ TeV})^2$, if DM is a thermal relic. Contrary to [13] DM triplets are not degenerate and this leads to distinctive features. The numerical thermal abundance of each DM component is $n_i \propto M_i$ so that heaviest specie is the most abundant. The astrophysical signals will depend on the distribution of masses. In particular each DM component can annihilate into photons giving rise to monochromatic photons with a rate rescaled by $(M_i/3 \text{ TeV})^4$ compared to a Wino of the same mass comprising the totality of DM. For a single triplet in fact the rate from the galactic center is in strong tension with HESS constraints [14], under the assumption of Einasto or NFW DM profile. Necessarily in our case $M_i < 3$ TeV weakening the constraints. The details depend on the value $c_i$. If the masses are almost degenerate the relic abundance is reproduced for $M_i \approx 1$ TeV and the astrophysical signals are reduced by a factor 8 compared to a Wino. If the multiplets are split then each component would annihilate producing monochromatic photon of energy $E_\gamma \approx M_i$ with approximately constant intensity. Lines split by at least 10% can be resolved by HESS [15] or CTA [16]. Resolution up to per cent level could be reached by future experiments such as HERD [17]. Current bounds from HESS are shown in Fig. 2.

For $10^9 \text{ GeV} \lesssim \Lambda \lesssim 10^{11}$ GeV the lifetime of heavier states is longer than the age of the universe but their decay can produce astrophysical signal. For $10^5 \text{ GeV} \lesssim \Lambda \lesssim 10^9$ GeV heavier triplets decay after freeze-out into the lightest component. This slightly off-sets the DM abundance because each decay yields exactly 1 DM particle. The DM abundance is reproduced for $M_i \sum_i M_i \approx 10^9$ GeV.
(3 TeV)$^2$. For $\Lambda \sim 10^6$ GeV the lifetime is around 1 s potentially affecting Big Bang Nucleosynthesis. Similarly if the decay takes place during recombination bounds from the energy injected in the SM plasma could arise.

Finally for $\Lambda \lesssim 100$ TeV the decay rate of heavier states is faster than Hubble at freeze-out. Therefore different species remain in equilibrium co-annihilating with each other [18]. If the splitting is significant the abundance becomes the one of an elementary Wino while for small splittings the abundance is modified approaching 8 times the Wino value.

Triplets in the TeV range can be searched at colliders through disappearing tracks. A single triplet with mass 3 TeV is borderline at a 100 TeV collider [19]. In the composite scenario the multiplicity and possibly the lower mass reproducing thermal abundance makes DM within reach of future colliders.

**SO(N) with N-4 fundamentals.** Our second example is an SO(N) gauge theory with $N - 4$ fundamental fermions (F) and 1 adjoint (A). In the massless limit the anomaly free global symmetry is $SU(N - 4) \times U(1)$. Anomalies can be matched by the massless fermion,

$$\Psi^i = F^i_\alpha A^\alpha_{\alpha \beta} F^j_\beta$$

in the symmetric rep of $SU(N - 4)$. The quantum numbers of the preons and composite fermions are thus given by,

| Name | $SO(N)$ | $SU(N - 4)$ | $U(1)$ |
|------|----------|-------------|--------|
| F    | $\square$ | $\square$   | $-\frac{N-2}{N-4}$ |
| A    | $\square$ | 1           | 1      |
| $\Psi$ | 1       | $\square$   | $-\frac{N}{N-4}$ |

(8)

The fermion content is identical to $N = 1$ supersymmetric SO(N) Yang-Mills with $N - 4$ flavors that is known to confine without chiral symmetry breaking but the composite fermions are different in our case.

Adding masses $M_{F,A}$ for the elementary fermions breaks the global symmetries allowing to generate a mass for the composites. The spurionic quantum number of mass deformation follow directly from eq. (8). In order to match the global symmetries, to leading order the mass term for the composite fermions must be proportional to $M_F^2 M_A$. Two structures can be written down compatibly with the symmetries,

$$\mathcal{L}_M = a_1 M_A \text{Tr} |M_F \Psi|^2 + a_2 M_A \text{Tr} M_F \Psi \Psi | + h.c.$$  

(9)

where $M_F$ is an $(N - 4) \times (N - 4)$ matrix and $a_{1,2}$ are determined by the dynamics.

This setup allows to construct theories with Majorana DM (Sp(N) gauge theories could be used to produce pseudo-real DM, see [20] for a related construction).

Simplest examples are:

- $N_F = 3$: The elementary fermions transform as a triplet of SU(2)$_L$. The composite fermions are then,

$$\square = 6 = 1 + 5$$

(10)

giving rise to a singlet and SU(2)$_L$ quintuplet. Note that since the only parameter is the elementary triplet mass $M_V$ the ratio of $M_1$ and $M_5$ is fixed in terms of $a_{1,2}$. The existence of a singlet changes the abundance of DM compared to the elementary quintuplet scenario [2]. All the singlet interactions are controlled by the compositeness scale through higher dimension operators such as,

$$\frac{a_2 a_{\alpha \beta}}{\Lambda^3} \lambda^a_{\alpha \beta} \lambda^b_1 W_{\mu \nu} W^{b \mu \nu}, \quad \frac{g_2^2}{\Lambda^2} \lambda^2_1 \lambda^2_1, \quad \frac{g_2^2}{\Lambda^2} f_{SM}^2$$

(11)

The first operator allows the heavier state to decay with a lifetime (5). The last two operators (induced for example by composite spin-1 tree level exchange) allow the singlet to annihilate into quintuplets or SM fermions with a cross-section $\sigma v \sim \pi a_2^2 M_F^2 / \Lambda^4$.

The cosmological abundance depends strongly on the compositeness scale. In the mass range considered, for $\Lambda \lesssim 100$ TeV, singlet and quintuplet are in equilibrium at least until freeze-out due to the fast decays of the heavier state. The abundance of DM is thus determined by co-annihilation of the two states. If $M_5 < M_1$ the result is similar to the elementary quintuplet where the thermal abundance of DM is reproduced for $M_{DM} \approx 14$ TeV [21]. For larger values of $\Lambda$ the abundance is modified by late time decays of the singlet. The thermal abundance can be reproduced for $M < 14$ TeV changing the experimental predictions, see [22] for a recent discussion. In Fig. 2 we show the relic abundance of quintuplets obtained by solving the coupled singlet-quintuplet Boltzmann equations for different splittings and $\Lambda$. 

![FIG. 1. Indirect detection constraints for DM triplets annihilation to photons in the galactic center. The black line is the NLL annihilation cross-section [15]. Red and blue regions are HESS exclusion limits [14] respectively for Einasto and NFW DM profiles, rescaled to account for the different numerical abundance. Also shown in dashed brown and green are the projections for DM with core radii 0.5 and 2 kpc extracted from [15]. If the multiplets are degenerate bounds 8 times stronger apply.](image-url)
The mass term \( \Delta \) so that the singlet co-annihilates strongly. very small scale \( \Lambda \) or a small splitting with the quintuplet
Reproducing the critical DM abundance requires either a cross-section into SM generates a large abundance of DM.

The elementary lagrangian contains, symmetry with extra singlet and triplets with hyper-charges. The resulting system is similar to neutralinos in super-symmetry with extra singlet and triplets.

Compositeness has particularly dramatic effects for SM singlets. They can decay through high dimension operators suppressed by the compositeness scale and their interactions are completely controlled by \( \Lambda \). In particular singlets tend to overclose the universe if the compositeness scale is large.

The lightest composite fermion required by 't Hooft anomaly matching conditions is automatically stable. This potential danger would be eliminated introducing a small mixing with singlet such that the Majorana states are split by 100 KeV or more.

Outlook. In this letter we proposed a new realization of accidental DM based on confining gauge theories. If the theory confines without chiral symmetry breaking, the lightest composite fermion required by \( \Lambda \) can be suitable for DM.

While DM is fundamentally composite it behaves as elementary up to corrections \( M/\Lambda \) for what concerns annihilation and low energy processes. Explicit models often feature several states cosmologically stable up to compositeness effects, leading to multi-component DM or effects in the thermal abundance of DM. Compositeness has particularly dramatic effects for SM singlets. They can decay through high dimension operators suppressed by the compositeness scale and their interactions are completely controlled by \( \Lambda \). In particular singlets tend to overclose the universe if the compositeness scale is large.

For high compositeness scale DM can be made of several SM multiplets leading to a distinctive phenomenology within the reach of future experiments. Among potential signals are multiple photon lines in the TeV range that could be resolved by future experiments. High luminosity LHC or 100 TeV collider could also discover the new states more easily than elementary multiplets in light of multiplicity and smaller mass.

Many extensions of this work can be envisaged. In the examples presented we focused on Majorana DM. Dirac DM could be constructed in theories that preserve dark baryon number, most simply in SU(N) gauge theories with fundamentals. We leave a thorough classification of possible models and the detailed phenomenology to future work. In non-supersymmetric gauge theories we cannot prove that the dynamics realizes confinement without chiral symmetry breaking. In supersymmetric gauge theories however very well known examples exist [7]. Using the results of [25] supersymmetry breaking effects can be included in a controllable way allowing to construct explicit models within theoretical control. Finally the addition of scalars is expected to lead to many other scenarios with composite light fermions [26] that can be suitable for DM.

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**FIG. 2.** Relic abundance estimate of DM made of SU(2)_L quintuplets for different values of \( \Lambda \). Solid and dashed lines correspond to \( \Delta M/M = 0.02 \) and \( \Delta M/M = 0.1 \) respectively.
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