# DARK MATTER INDIRECT SEARCHES AS OF 2021

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I discuss a few selected recent developments in indirect searches for Dark Matter concerning: electrons, positrons, antiprotons, photons and antinuclei. This summary is an updated version of a similar one given at Rencontres de Blois 2019.

## 1 Introduction

Cosmology and astrophysics provide several convincing evidences of the existence of Dark Matter (DM). The observation that some mass is missing to explain the internal dynamics of galaxy clusters and the rotations of galaxies dates back respectively to the '30s and the '70s. The observations from weak lensing, for instance in the spectacular case of the so-called 'bullet cluster', provide evidence that there is mass where nothing is optically seen. More generally, global fits to a number of cosmological datasets (Cosmic Microwave Background, Large Scale Structure and also Type Ia Supernovae) allow to determine very precisely the amount of DM in the global energy-matter content of the Universe at $\Omega_{\rm DM}h^2 = 0.1199 \pm 0.0027$ [1a].

All these signals pertain to the gravitational effects of Dark Matter at the cosmological and extragalactical scale. Searches for explicit manifestation of the DM particles that are supposed to constitute the halo of our own galaxy (and the large scale structures beyond it) have instead so far been giving negative results, but this might be on the point of changing, perhaps thanks to 'indirect searches'. These searches aim at detecting the signatures of the annihilations or decays of DM particles in the fluxes of Cosmic Rays (CRs), intended in a broad sense: charged particles (electrons and positrons, antiprotons, antideuterium, antihelium), photons (gamma rays, X-rays, synchrotron radiation), neutrinos. In general, a key point of all these searches is to look for channels and ranges of energy where it is possible to beat the 'background' from ordinary astrophysical processes. This is for instance the basic reason why searches for charged particles focus on fluxes of antiparticles (positrons, antiprotons etc.), much less abundant in the Universe than the corresponding particles, and searches for photons or neutrinos have to look

[a] Here $\Omega_{\rm DM} = \rho_{\rm DM}/\rho_c$ is defined as usual as the energy density in Dark Matter with respect to the critical energy density of the Universe $\rho_c = 3H_0^2/8\pi G_N$, where $H_0$ is the present Hubble parameter. $h$ is its reduced value $h = H_0/100\ {\rm km\,s^{-1}Mpc^{-1}}$.

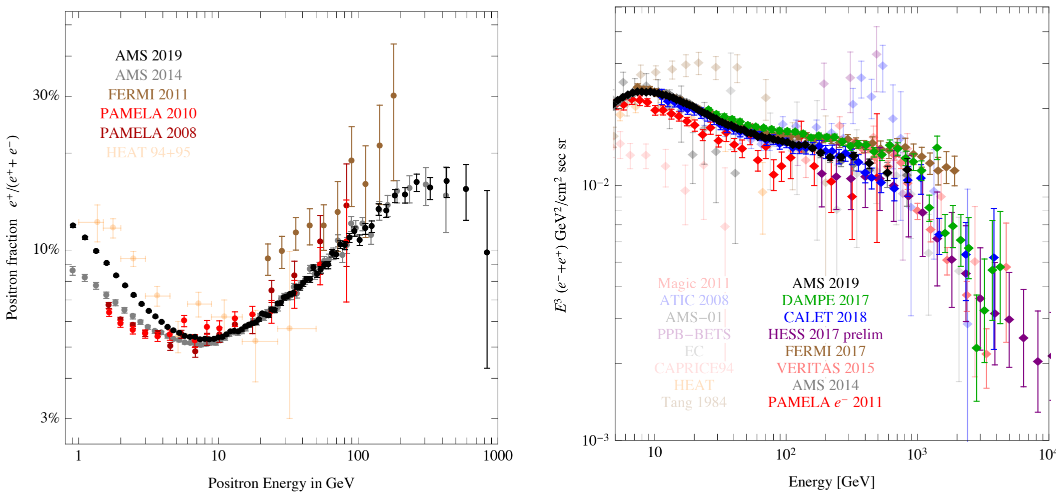


Figure 1 – A compilation of recent and less recent data in charged cosmic rays. Left: positron fraction. Right: sum of electrons and positrons.

at areas where the DM-signal to astro-noise ratio can be maximized. Pioneering works have explored indirect detection (ID) as a promising avenue of discovery since the late-70's. Since then, innumerable papers have explored the predicted signatures of countless particle physics DM models.

Due to the theory prejudices of particles at the weak scale being good candidates (the so called 'WIMP miracle'), the mass range around TeV-ish DM has been thoroughly explored in recent years and is still the focus of intense explorations. I will focus mostly on it in the following, but I will take a detour towards other candidates (sub-GeV particles and Primordial Black Holes) as well.

## 2 Electrons and positrons

Since more than 10 years there has been a flurry of positive results from a few indirect detection experiments looking at the fluxes of electrons and positrons, pointing in particular to 'excesses' at the TeV and sub-TeV scale. A selection of these results is collected in fig. 1.

Notorious data from the PAMELA satellite [2] showed a steep increase in the energy spectrum of the positron fraction $e^+/(e^+ + e^-)$ above 10 GeV up to 100 GeV. Qualitatively, these findings have been confirmed and extended by the FERMI satellite [3] and by the AMS-02 experiment on board the ISS [4,5]. In the measurement of the sum of electrons and positrons $(e^+ + e^-)$, data up to 1 TeV and beyond are provided by the FERMI satellite [6], AMS-02 [7], the HESS [9], MAGIC [10] and VERITAS [11] telescopes, the CALET experiment [12] and the DAMPE satellite [13]. The situation is more confuse than it used to be a few years ago. The indication for a cutoff at about 1 TeV is not so clear, and the datasets are not in full agreement among themselves.

In any case, these signals are striking because they imply the existence of a source of *'primary'* $e^+$ (and $e^-$) other than the ordinary astrophysical ones. This unknown new source can well be of astrophysical nature, e.g. one or more pulsar(s) / pulsar wind nebula(æ), supernova remnants etc. It is however very tempting to try and read in these 'excesses' the signature of DM, in terms of annihilations or decays. Indeed, by properly modeling the DM annihilation (or decay) channel, the DM mass and the annihilation cross section (or decay rate), and convoluting with the information on the propagation process [b] and the DM galactic profile, one can determine the expected CR fluxes and compare them with the data. Of course, a proper treatment of the background from astrophysics is crucial to obtain meaningful results (this step often represents

[b] On this aspect, recent progress has allowed to better constrain the propagation schemes and transport parameters in the Galaxy, see [14] and references therein.

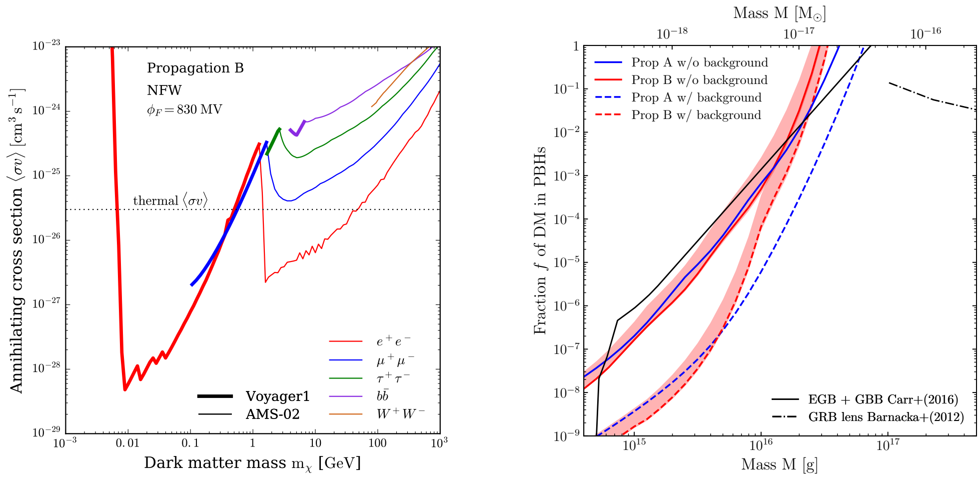


Figure 2 – Bounds from VOYAGER-1 data on sub-MeV DM (left) and on PBHs (right).

the most tricky one in the actual analysis). As a result, the DM needed to fit the data has to: have a mass in the TeV / multi-TeV range, have a very large annihilation cross section (of the order of $10^{-23}\text{cm}^3/s$, orders of magnitude larger than the cosmological prejudice) and be leptophilic (to avoid contradicting antiproton bounds for such a large cross section, see the next section). So a global Dark Matter interpretation of the leptonic 'excesses' can be attempted. However, even restricting to leptonic data only, some tension is present. Most importantly, a significant tension exists with constraints from gamma rays and from the CMB. While we do not discuss them here, we just comment that the CMB ones stem from the fact that DM annihilations in the Early Universe inject energy that modifies the properties of the microwave background, mainly via the induction of excessive ionized material at early redshift. These constraints have the advantage of being insensitive to the usual astrophysical uncertainties that affect the gamma and charged CR ray bounds (e.g. the DM profile), but they can be evaded if the cross section is suppressed at low velocities or early times.

As a result, an interpretation in terms of Dark Matter seems less and less likely.

### *2.1 Electrons and positron at (very) low energy*

At the other end of the energy spectrum, electrons and positrons of an energy between a few MeV and 1 GeV prove to be very useful in testing Dark Matter as well. These have been measured by the VOYAGER-1 spacecraft, which has recently left the heliosphere. As such, it is exposed to low energy charged particles which otherwise would be screened by the solar magnetic field and its wind. By imposing that the flux of low energy $e^\pm$ originating from the annihilation (or decay) does not exceed the VOYAGER-1 measurements, Ref. [15] has imposed bounds on GeV and sub-GeV DM as presented in fig. 2.

The same data can be used to constrain a completely different candidate of Dark Matter: Primordial Black Holes (PBHs). The proposal [16,17] that DM could consist of PBHs instead of unknown elementary particles has recently and deservedly come back to the attention of the community (see [18,19,20] for milestone reviews). These objects would be generated in the Early Universe when sufficiently large density perturbations in the primordial plasma collapse gravitationally. If they are formed early enough, the material of which they are made is subtracted very early on from the baryonic budget and therefore they are not subject to the cosmological constraints from primordial nucleosynthesis and the CMB. A number of possible mechanisms exist which could generate the needed large primordial fluctuations, invoking more or less exotic cosmological inflationary ingredients. In general terms, the expected mass of a PBH is connected to the time $t$ at which it was created, $M \sim c^3 t/G \simeq 10^{15}(t/10^{-23}\text{sec})\text{g} \simeq 5\times 10^{-19}(t/10^{-23}\text{sec})M_\odot$, where $c$ is the speed of light, $G$ the Newton constant and $M_\odot \simeq 2 \times 10^{33}$ g is the mass of the

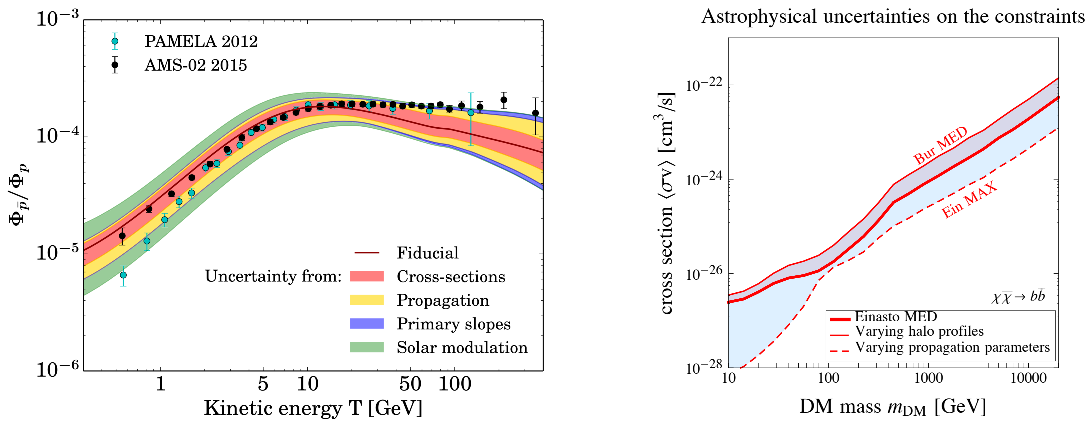


Figure 3 – Antiproton measurements by Pamela and Ams-02 compared to the astrophysical prediction and its uncertainties, and the constraints on DM annihilation that originate from them. Figures from Giesen et al. 2015.

Sun. Moreover, realistic production mechanisms predict not just a unique mass for all PBHs but rather an extended mass function.

Here, we are particularly interested in the mass range above the evaporation limit ($4 \times 10^{14}$ g) and below the lowest lensing limit ($10^{17}$ g). In this range, PBHs are Hawking evaporating right now, emitting particles with a characteristic spectrum centered around tens of MeV. The constraints imposed by Voyager-1 are reported in fig. 2, right.

## 3 Antiprotons

In the antiproton channel, data have been published by Pamela since 2008 [21,22,23] and then by Ams-02 [24]. The data-sets from the two experiments, in terms of the $\bar{p}/p$ ratio, reported in fig. 3, are in very good mutual agreement, although the Ams-02 ones are of course much more accurate and extend to higher energies.

In the Ams presentation strategy [25], the public is often perhaps led to believe that the data are at odds with the predictions from astrophysics and therefore that a new component (Dark Matter!) has to be invoked. However, despite the extent to which everybody would love Ams to find something extraordinarily new, this is at best premature. Indeed, including, in the computations of the predictions from astrophysics, all recent developments, the discrepancy is largely reabsorbed. Such developments include: (i) the measurement of the primary proton and Helium spectra (which, impinging on the interstellar medium, produce the bulk of the astrophysical antiprotons), as delivered by Ams itself [26] ; (ii) the results on the antiproton spallation production cross section [27]; (iii) updated propagation schemes…

The qualitative conclusion is quite apparent: contrarily to the leptonic case, there is no unambiguous excess in antiproton data. One could then derive constraints [28]. This is what is reported in the right panel of fig. 3 for one specific example. Fixing a benchmark DM profile (Einasto) and the Med propagation scheme, the constraints exclude the thermal annihilation cross section $\langle\sigma v\rangle = 3 \cdot 10^{-26}$ cm$^3$/s for $m_{\rm DM} \sim 150$ GeV. The modification of the profile or the propagation scheme has the effect of spanning the shaded band, i.e. affecting the bounds by a factor of a few.

### *3.1 An anti-proton excess at low energies?*

Some works claimed an excess of antiprotons with respect to the predicted astrophysical background and interpreted it in terms of Dark Matter annihilations [50,30,31,32,33,34]. A first claim was based on Pamela data, while a more recent claim is based on the Ams data released in 2015. The putative excess sits at kinetic energies of around 10 to 20 GeV and can be fit by a 80 GeV DM particle annihilating into $b\bar{b}$ with roughly thermal cross section. The fact that these properties are so typical of vanilla WIMP DM and so close to the ones needed to explain the GC GeV excess in gamma-rays (sec. 4.1) adds considerable interest.

On the other hand, significant uncertainties are present for low energy antiprotons, mostly related to which propagation model is assumed (and how its parameters are determined), how solar modulation effects are modelled and which antiproton production cross sections are assumed. The recent detailed analyses in [35,36] conclude that the data are consistent with a purely secondary origin and that the global significance of the excess drops to only $\sim 1\sigma$ once all uncertainties are included. Further reducing the uncertainties will shed further light on any possible excess. These results will be soon updated [37], including the most recent data from AMS (so far rather unexploited) and state-of-the-art galactic propagation methods.

## 4 Photons

### *4.1 The GeV $\gamma$ excess from the Galactic Center*

Several authors reported since 2009 the detection of a gamma-ray excess from the inner few degrees around the GC (extending out up to 10 or 20 degrees) at energies between 0.5 and 5 GeV [38,39,40]. The spectrum and the (almost) spherical morphology of the emission are found to be compatible with those expected from annihilating DM particles: to fix the ideas, the results of one of the most detailed analysis [41] confirm the presence of this excess at a high level of significance (if taken at face value) and find this signal to be best fit by 31-40 GeV DM particles distributed according to a (contracted) NFW profile and annihilating into $b\bar{b}$ with $\langle\sigma v\rangle = (1.4-2)\times 10^{-26}$ cm$^3$/s, compatible with the cross section suggested by DM as a thermal relic. As different groups worked on the issue, it was realized that other good fits are also possible, notably into leptonic channels (pointing to lighter DM) and gauge boson channels (pointing to heavier DM). The FERMI collaboration itself published a long-awaited paper [42] essentially confirming the findings.

Of course, one should not forget that, in very general terms, the identification of an 'excess' strongly relies on the capability of carefully assessing the background over which the excess is supposed to emerge. The claim under scrutiny constitutes no exception, quite the contrary. The extraction of the residuals strongly relies on the modeling of the diffuse gamma-ray background (in particular the one publicly made available by the FERMI collaboration) as well as on additional modeling of astrophysical emissions, e.g. from FERMI bubbles, isotropic component, unresolved point sources, molecular gas... While this is probably the best that can be done, it is not guaranteed to be (and in general is not expected to be) the optimal strategy. In any case, it seems consensual at this point that an excess with respect to the expected templates does exist.

Also, before invoking Dark Matter one should not forget that there might be alternative astrophysical explanations. A population of milli-second pulsars (MSP) has been extensively discussed since the beginning [43]. Actually, detailed studies have shown that an interpretation in terms of a large number of unresolved point sources is statistically favored with respect to a diffuse emission [44,45], although [47] have questioned the soundness of the method and therefore brought back the DM hypothesis. Directly detecting the MSPs remains challenging: some positive claims by the FERMI Collaboration [46] have later been corrected; more could be done with future telescopes such as SKA, by detecting their associated radio emission.

Other early alternative interpretations include the possibility of a spectral break in the emission of the central Black Hole and the possibility that past isolated injections of charged particles (electrons or protons, in one or more bursts, possibly connected with the activity of the central Black Hole), can produce secondary radiation able to account for the anomalous signal. While reproducing all the details of the observed emission might be not easy with these models, they represent additional plausible and useful counterexamples to the DM interpretation.

Testing the DM interpretation by looking at associated signals is also difficult: taking into account all the different uncertainties, neither the antiproton constraints nor the CMB nor the

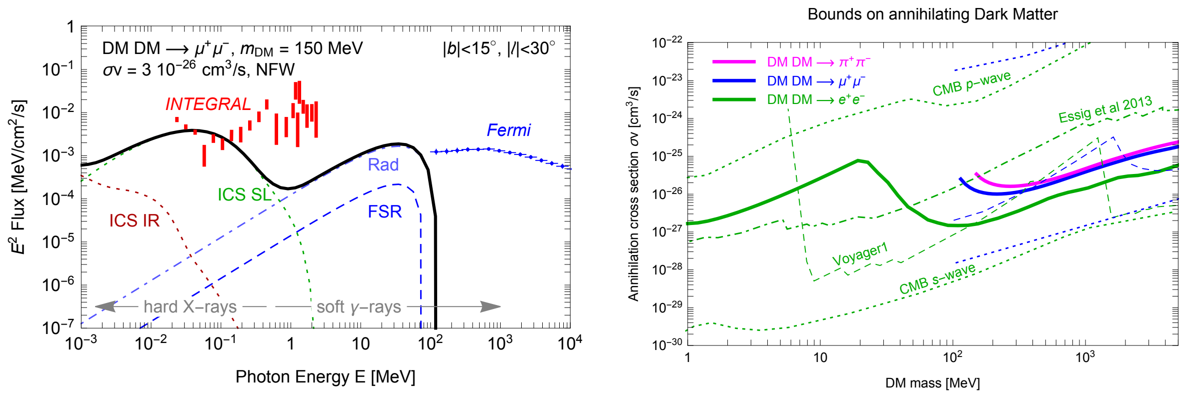


Figure 4 – Sub-GeV DM and X-rays. Left: the X-ray spectrum produced (including via Inverse Compton Scattering) by the annihilation of a 150 MeV particle into muons, compared to the INTEGRAL data. Right: Constraints in the usual mass / annihilation cross section plane, imposed by X-rays and other methods.

$\gamma$-ray constraints from FERMI observations of dwarf galaxies are able to unambiguously rule out or confirm the DM interpretation of the GC GeV excess [48,49,50,51,1].

### *4.2 X-ray constraints on sub-GeV Dark Matter*

Let us go back to the low end of the mass spectrum, considering DM particles with a mass between a few MeV and a few GeV. As mentioned above, their annihilations can be constrained by the $e^{\pm}$ measured by VOYAGER-1. Is there any other way to constrain these particles? The answer is positive and it involves looking at a range of energies much lower than that of the DM mass. The basic idea is the following: the electrons and positrons produced in the Galactic halo by the annihilations of DM particles with a mass $m \simeq 1$ GeV have naturally an energy $E \lesssim 1$ GeV; they undergo Inverse Compton scattering (ICS) on the low energy photons of the ambient bath (the CMB, infrared light and starlight) and produce X-rays, which can be searched for in X-ray surveys. Indeed, the ICS process increases the photon energy from the initial low value $E_0$ to a final value $E \approx 4\gamma^2 E_0$ upon scattering off an electron with relativistic factor $\gamma = E_e/m_e$. Hence, a 1 GeV electron will produce a $\sim 1.5$ keV X-ray when scattering off the CMB ($E_0 \approx 10^{-4}$ eV). By the same token, a mildly-relativistic MeV electron will produce a $\sim$ 0.15 keV X-ray when scattering off UV starlight ($E_0 \approx 10$ eV). An example of a spectrum of X-rays (or soft $\gamma$-rays) produced by a DM particle of mass 150 MeV, annihilating into muons, is presented in fig. 4 (left panel). Beside the final state radiation (FSR) and muon radiative decay (Rad) components, the different contributions of ICS are represented. It is apparent that these allow to reach the sensitivity of the data.

So one can use X-ray observations to impose constraints on sub-GeV DM that would otherwise fall below the sensitivity of the more conventional gamma-ray searches. In [52], the data from the INTEGRAL X-ray satellite [53] have been used to this purpose. The result is presented fig. 4 (right panel), for the different annihilation channels open at these values of DM mass.

## 5 Antinuclei

Antinuclei such as antideuterium and antihelium can be produced in DM annihilations when two or more antinucleons coalesce. In principle, they are a powerful tool for DM discovery because the astrophysical background, in the range of energies where the DM production peaks, is highly suppressed for kinematical reasons. This is why they are actively researched.

Concerning antideuterons, currently only the upper bound from BESS is available, and it is not competitive to impose bounds on DM. The upcoming balloon experiment GAPS [55] will hopefully reach the sensitivity to test some of the proposed DM models where a non-negligible flux of $\bar{d}$ is produced, compatibly with the constraints from antiprotons.

Concerning antihelium, the situation is more intriguing. Starting from late 2016, the AMS collaboration has announced (by press releases and presentation slides, without papers published yet) that they see a few events compatible with antihelium [56]. As of late 2021, the reports are of 8 events (of which 6 $^3\overline{\rm He}$ and 2 $^4\overline{\rm He}$) after about 8 years of data taking. If confirmed, this would point to a surprising and unexpected production, either from astrophysics or from DM. From DM, in particular, the process is expected to be extremely suppressed since 3 (4) nucleons need to coalesce for the production of $^3\overline{\rm He}$ nuclei ($^4\overline{\rm He}$). Initial calculations [57,58] indeed had found a predicted flux many orders of magnitude below the estimated sensitivity of AMS, especially after the constraints from not producing too many antiprotons in the same annihilations are taken into account. The astrophysical flux is also very small (but closer to the reach of the experiments). Still, a large uncertainty is due to the value of the coalescence momentum $p_0$ which effectively parametrizes the process and which appears at a high power in the yield formulæ. Several works [59,60,61,62,63] have indeed argued that DM or astrophysical productions are possible in principle, e.g. increasing the coalescence parameter to values much larger than initially thought or including previously neglected standard model process.

## 6 Generic conclusions

Dark Matter exists and discovering what it is made of is certainly one of the major open problems in particle physics and cosmology nowadays. The key to finding out the answer will probably lie in a tight collaboration among the many different disciplines involved in the quest, including in particular particle physics beyond the Standard Model and CR physics, which is directly relevant for DM ID. As I expressed elsewhere, the potential problem, in my view, is that progress in both communities might be too slow for the needs (or the wishes) of the other side. In the recent past, there are many examples of cases in which some parts of the DM particle theory community has jumped too quickly on the interpretation of cosmic ray data, without a full understanding of the 'astrophysics-related' issues and thus reaching maybe unmotivated conclusions. In the even more recent past, there are other examples of some parts of the CR community crying 'Dark Matter!' too quickly, perhaps without a full control of the context. Given the important stakes, it is perhaps more worthwhile to stay focussed and work fruitfully towards the common goal.

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