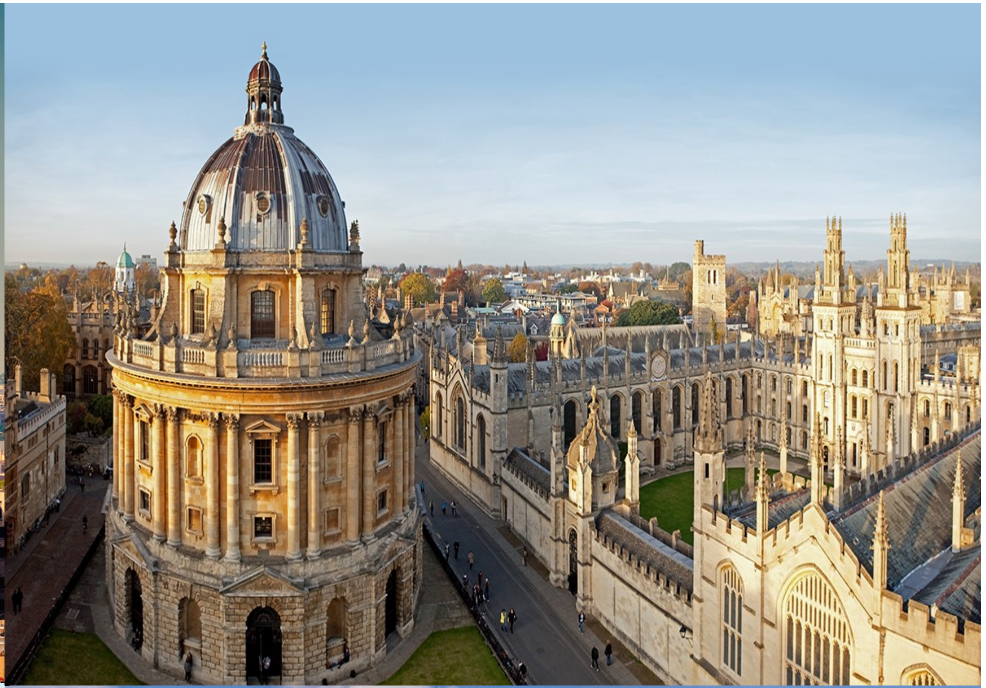
Dark Matter:
from galaxies to us and back

Céline Boehm

Most of my career was spent in Europe



ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

Cosmology

Astronomy
Astrophysics

Particle Physics

Expertise: Dark Matter
CMB/Structure formation
SUSY and model building

Theory & Phenomenology
Though I led a space mission consortium

Subject

Astrophysics	75
Phenomenology-HEP	63
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Theory-HEP	3
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Math and Math Physics	2
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I joined Sydney in 2018 to lead the School of Physics

Ciaran

DM
DD
Astrometry

Markus

CMB
Cosmo

Joseph

Lensing

Zac

Black Holes

Shyam

Particles

Peter

MG

Maura (Durham)

Particles

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Credit for:

- Stop 4-body decay (hep-ph/9907428)
- Stop-neutralino co-annihilation (hep-ph/9911496)
- **Dark Matter interactions & Structure formation (** astro-ph/0012504, astro-ph/0112522, astro-ph/0410591, 1404.7012 **)**
- **Light (thermal) dark matter ; light & heavy DM (**hep-ph/0305261, astro-ph/0309686, hep-ph/0311143 **)**
- **Vector-like fermions & dark photons/ light Z' as dark portals (**hep-ph/0305261**)**
- **Simplified models for generic DM models (**hep-ph/0305261**)**
- **TeVeS CMB & P(k) predictions (**astro-ph/0505519**)**
- High energy photon polarisation

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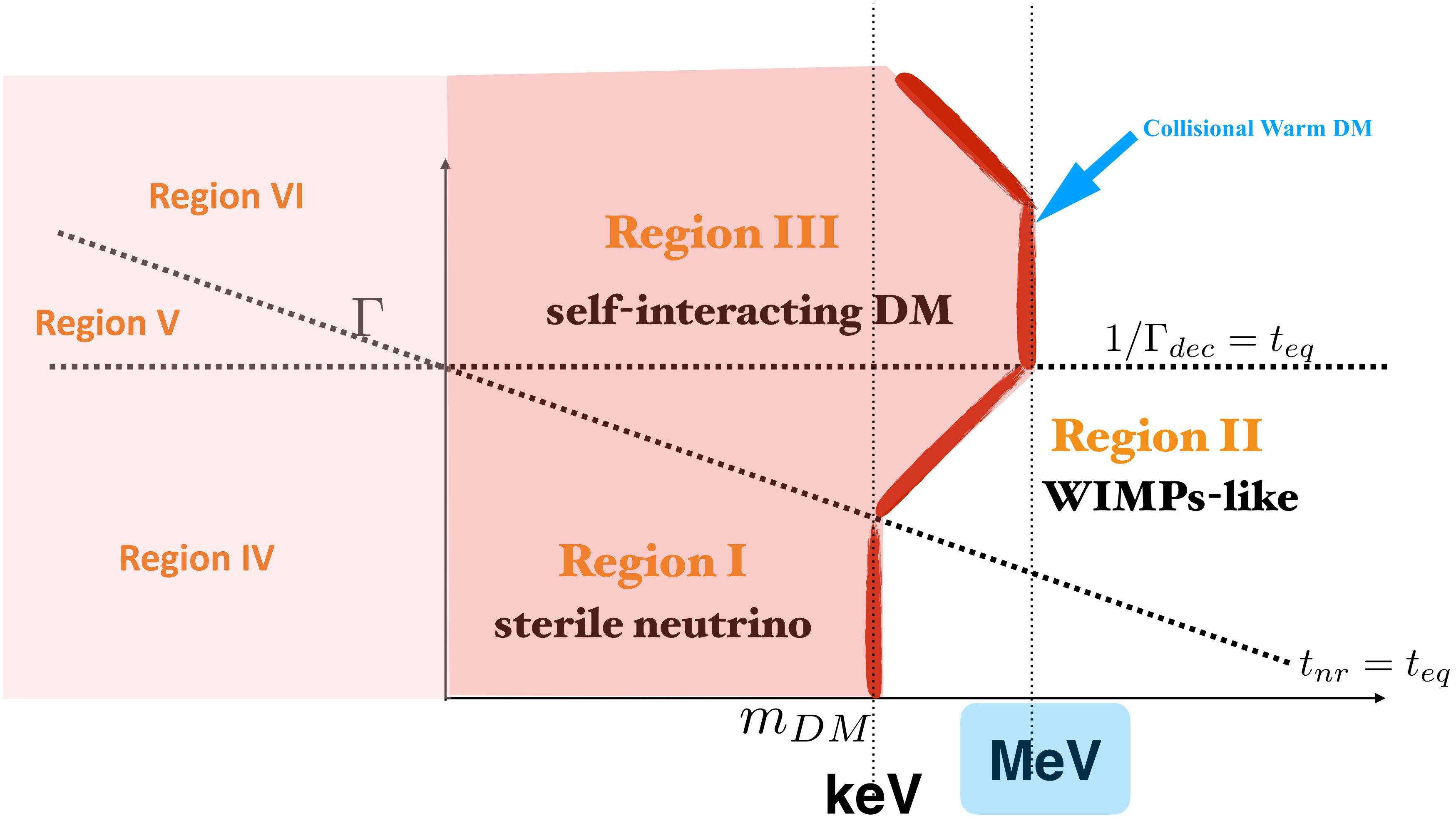
Dark Matter interactions and damping

(astro-ph/0012504, astro-ph/0410591)

Interaction strength vs mass which prevents the formation of small galaxies



Dark Matter cannot be light

PHYSICAL REVIEW LETTERS

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Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[(a)]
Fermi National Accelerator Laboratory,[(b)] *Batavia, Illinois 60510*

and

Steven Weinberg[(c)]
Stanford University, Physics Department, Stanford, California 94305
(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

There is a well-known cosmological argument[1] against the existence of neutrino masses greater than about 40 eV. In the "standard" big-bang cosmology,[2] the present number density of each kind of neutrino is expected[3] to be $\frac{4}{11}$ the number density of photons in the 3°K black-body background radiation, or about 300 cm^{-3}; hence if the neutrino mass were above 40 eV, their mass density would be greater than 2×10^{-29} g/cm^3, which is roughly the upper limit allowed by present estimates[4] of the Hubble constant and the deceleration parameter.

However, this argument would not apply if the neutrino mass were much larger than 1 MeV. Neutrinos are generally expected[2] to go out of thermal equilibrium when the temperature drops to about 10^{10} °K, the temperature at which neutrino collision rates become comparable to the expansion rate of the universe. If neutrinos were much heavier than 1 MeV, then they would already be much rarer than photons at the time when they go out of thermal equilibrium, and hence their number density would now be much less than 300 cm^{-3}.

Of course, the familiar electronic and muonic neutrinos are known to be lighter than 1 MeV. However, heavier stable neutral leptons could easily have escaped detection, and are even required in some gauge models.[5] In this Letter, we suppose that there exists a neutral lepton L^0 (the "heavy neutrino") with mass well above 1 MeV, and we assume that L^0 carries some additive or multiplicative quantum number which keeps it absolutely stable. We will present arguments based on the standard big-bang cosmology to show that the mass of such a particle must be above a lower bound of order 2 GeV.

At first glance, it might be thought that the present number density of heavy neutrinos would simply be less than the above estimate of 300 cm^{-3} by the value $\exp[-m_L/(1\text{ MeV})]$ of the Boltzmann factor at the time the heavy neutrinos go out of thermal equilibrium. If this were the case, then an upper limit of 2×10^{-29} g/cm^{-3} on the present cosmic mass density would require that $m_L\exp[-m_L/(1\text{ MeV})]$ should be less than 40 eV, and hence that m_L should either be less than 40 eV or greater than 13 MeV.

However, the true lower bound on the heavy-neutrino mass is considerably more stringent.

Toggle citing-articles panel

Volume 69B, number 1 — PHYSICS LETTERS — 18 July 1977

LIMITS ON MASSES AND NUMBER OF NEUTRAL WEAKLY INTERACTING PARTICLES

P. HUT
Institute for Theoretical Physics, University of Utrecht, Utrecht, Netherlands

Received 25 April 1977

Limits on the masses and number of neutral weakly interacting particles are derived using cosmological arguments. No such particles with a mass between 120 eV and 3 GeV can exist within the usual big band model. Similar, but much more severe, restrictions follow for particles that interact only gravitationally. This seems of importance with respect to supersymmetric theories.

Following an idea, put forward by Shvartsman [1], Steigman et al. [2] presented arguments leading to an upper limit to the number of different types of massless neutrinos, which may be summarized as follows.

According to the hot big bang model all forms of matter in the universe, even neutrinos, are initially in thermal equilibrium. The total energy density of relativistic particles is then given at a temperature T by

$$\rho = \kappa a T^4. \tag{1}$$

a is the radiation density constant, appearing in the black-body radiation law, and κ is given by

$$\kappa = \tfrac{1}{2}(n_b + \tfrac{7}{8}\, n_f). \tag{2}$$

The quantities n_b and n_f are the total number of internal degrees of freedom of the different types of bosons and fermions respectively. For a photon gas $\kappa = 1$, while for a mixture of photons, electrons, electron and muon neutrinos, together with their antiparticles, $\kappa = 9/2$.

A second expression for the total energy density ρ is given as a function of the expansion time t by solving the Einstein equations in a radiation dominated homogeneous and isotropic universe,

$$\rho = 3/32\,\pi G t^2, \tag{3}$$

where G is the gravitational coupling constant, $G = 6.7 \times 10^{-45}$ MeV$^{-2\ddagger}$. Combining (1) and (3) we get

$$T = (3/32\,\pi G a)^{1/4}\,\kappa^{-1/4}\,t^{-1/2}. \tag{4}$$

‡ We use units such that $\hbar = c = k = 1$, and the temperature is expressed in MeV.

Adding more types of neutrinos relative to the standard big bang model increases the value of κ. This would have the following observable effect.

The neutron/proton ratio is given by the equilibrium value $n/p = \exp\{-(m_n - m_p)/T\}$ as long as the rate of weak interactions, like e.g. $n + e^+ \rightleftharpoons p + \bar{\nu}_e$, is high enough. But this ratio freezes in soon after the time between successive collisions grows bigger than, say, the expansion time. The mean free time is $\tau = (\sigma N)^{-1}$ as long as the electrons are relativistic. The cross section $\sigma \sim T^2$ and the number density of protons and neutrons $N \sim R^{-3}$, where R is the scale factor of the expanding universe. At these early times the number of nucleons is far smaller than the number of photons, electrons, positrons and neutrinos, so the cooling proceeds adiabatically like $T \sim R^{-1}$. Therefore $N \sim T^3$ and thus

$$\tau = \text{const.} \times T^{-5}. \tag{5}$$

Putting $t = \tau$ in (4), from (5) we get an effective temperature T_f at which the neutron/proton ratio freezes in, given by

$$T_f = \text{const.} \times \kappa^{1/6}. \tag{6}$$

When the temperature falls off further nearly all neutrons are captured to form deuterium and subsequently helium. In the standard model $T_f \approx 1$ MeV $\approx 10^{10}$ K and the abundance by weight of helium produced in this way is $Y \approx 0.23$ to 0.27, depending on the present density of nucleons in the universe. An observational upper limit [4] $Y \lesssim 0.29$ agrees well with the standard model.

Increasing now the number of neutrino types would

Dark Matter cannot be light

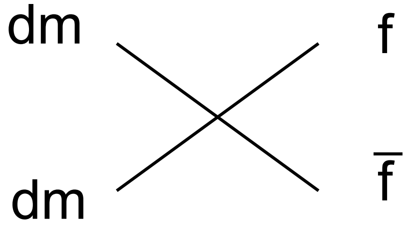
$$\frac{dn}{dt} = -3Hn - \sigma v (n^2 - n_0^2)$$

Solution — no particle physics needed

$$\Omega h^2 \simeq \frac{3 \times 10^{-27} \mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle}$$

$$\sigma v \sim 3\ 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

The Hut, Lee&Weinberg argument



$$\sigma\ v \propto \frac{m_{dm}^{\ 2}}{m_w^{\ 4}} \quad \Rightarrow \quad \Omega_{\mathrm{DM}} h^2 \propto m_{\mathrm{DM}}^{-2}$$

In principle, one value for $\Omega_{DM} h^2$ so there should be only one value for the dark matter mass
In practice, $\Omega_{DM} h^2$ not know with certainty + DM particle properties unknown so there is a range of masses

Dark Matter can be light after all

astro-ph/0208458v3

Are light annihilating Dark Matter particles possible?

C. Boehm[1], T. A. Enßlin[2], J. Silk[1]
[1] Denys Wilkinson Laboratory, Astrophysics Department, OX1 3RH Oxford, England UK;
[2] Max-Planck-Institut für Astrophysik Karl-Schwarzschild-Str. 1, Postfach 13 17, 85741 Garching
(Dated: 22 August 2002)

We investigate the status of light Dark Matter (DM) particles from their residual annihilation and discuss the range of the DM mass and total annihilation cross section compatible with gamma-rays experiment data. We find that particles as light as a few MeV or up to ~ 10 GeV could represent an interesting alternative to the standard picture of very massive WIMPs.

Introduction

The accurate measurement of galactic rotation curves, the CMB spectrum, the primordial abundances of light elements, together with our understanding of structure formation provide convincing evidence in favor of the existence of Dark Matter [1]. While the MACHOs searches [2] indicate that an astrophysical solution is rather unlikely, most efforts are now concentrated on searches for Weakly Interacting Massive Particles (WIMPs) [3]. These particles would belong to the Cold Dark Matter scenario (CDM) and would i) suffer from negligible damping effects, ii) make up the non-baryonic matter in the Universe. Considering fermions only and assuming Fermi interactions, it was concluded [4] that this last argument constrains the DM mass (m_{dm}) to be greater than a few GeV. Later, within the framework of supersymmetry, it was realized that the range $m_{dm} \gtrsim O(100$ GeV) could even be more interesting. But the direct and indirect detection searches for very massive particles remain unsuccessful [5], so there is still room for other possibilities.

Many alternatives to the CDM model have been proposed subsequent to the discrepancy [6] between observations and CDM numerical simulations on small scales which, in predicting cuspy haloes, could be in contradiction with current observations [7]. Among them, one finds the collisionless Warm Dark Matter scenario

by any cosmological/astrophysical arguments, they could compete with the collisionless WDM and CDM scenarios but would, on the other hand, probably fail in predicting flat galactic cores at ~ 1 kpc despite their quite large annihilation rate. Interestingly enough, they could escape present DM direct detection experiments (which so far are only sensitive to masses greater than ~ 7 GeV), as well as accelerator experiments, as briefly discussed in the next section. They would be compatible with the blackbody spectrum measurement and will not yield any ^4He photodissociation (for $m_{dm} > 26$ MeV) provided our (s-wave) cross sections satisfy the relation $(m_{dm}/\,\text{MeV}) > 5\left[\langle\sigma v\rangle_{ann}/3\times10^{-27}\,\text{cm}^3\,\text{s}^{-1}\right](\Omega_{dm}h^2)^2$ (assuming DM particles to be their own anti particles and using the D measurement only) [12].

In the following, we focus on the indirect detection signature of these light candidates. We show that the flux of photons from particles having $1 \lesssim m_{dm} \lesssim 100$ MeV is in conflict with observations unless their P-wave (instead of S-wave) annihilation cross section satisfies the relic density requirement and find that particles in the mass range [1-15] GeV [3] are quite interesting (especially if $m_{dm} \sim 10$ GeV) because they could lead to radiative and radio fluxes of the order of the observed ones.

Acceptable values of the cross sections

A strong constraint on any DM candidate is that the

hep-ph/0305261

Scalar Dark Matter candidates

C. Bœhm

Denys Wilkinson Laboratory, 1 Keble Road, OX1 3RH, Oxford, England, UK

P. Fayet

Laboratoire de Physique Théorique de l'ENS, 24 rue Lhomond, 75231 Paris Cedex 05, France [1]

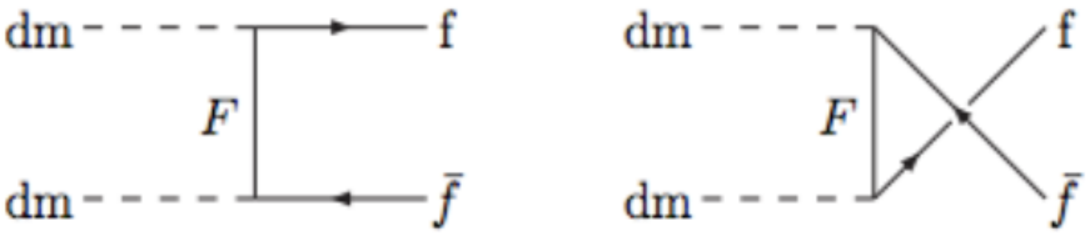
Abstract

We investigate the possibility that Dark Matter could be made of scalar candidates and focus, in particular, on the unusual mass range between a few MeV's and a few GeV's. After showing why the Lee-Weinberg limit (which usually forbids a Dark Matter mass below a few GeV's) does not necessarily apply in the case of scalar particles, we discuss how light candidates ($m_{dm} < O(\text{GeV})$) can satisfy both the gamma ray and relic density constraints. We find two possibilities. Either Dark Matter is coupled to heavy fermions (but if $m_{dm} \lesssim 100$ MeV, an asymmetry between the Dark Matter particle and antiparticle number densities is likely to be required), or Dark Matter is coupled to a new light gauge boson U. The (collisional) damping of light candidates is, in some circumstances, large enough to be mentioned, but in most cases too small to generate a non linear matter power spectrum at the present epoch that differs significantly from the Cold Dark Matter spectrum. On the other hand, heavier scalar Dark Matter particles (*i.e.* with $m_{dm} \gtrsim O(\text{GeV})$) turn out to be much less constrained. We finally discuss a theoretical framework for scalar candidates, inspired from theories with $N = 2$ extended supersymmetry and/or extra space dimensions, in which the Dark Matter stability results from a new discrete (or continuous) symmetry.

Dark Matter can be light after all

astro-ph/0208458v3 hep-ph/0305261

vector-like fermions

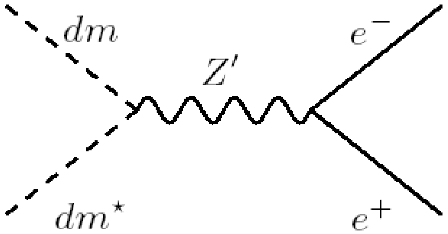


$$\sigma v \propto \frac{1}{m_F^4} \left(\left(C_l^2 + C_r^2 \right) m_f + 2 C_l \, C_r \, m_F \right)^2$$

$$\sigma v \propto \frac{1}{m_F^2}$$

The cross section is not proportional to the DM mass. One can achieve the thermal value by playing on the value of the mediator mass and couplings.

dark photons/Z'



$$\sigma v \propto v^2 \, \frac{m_{\rm DM}^2}{m_{Z'}^4} \, g_{\rm DM}^2 \, g_e^2$$

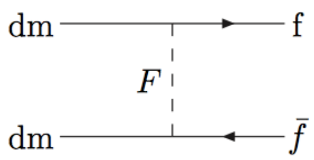
$$m_{\rm DM} \simeq m_{Z'}$$

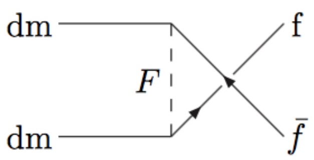
The cross section is proportional to the DM mass but The mass of the mediator can be adjusted to make the cross section match the thermal value.

Simplified models

hep-ph/0305261

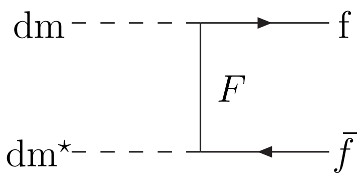
9.1.1 *Majorana Dark Matter*





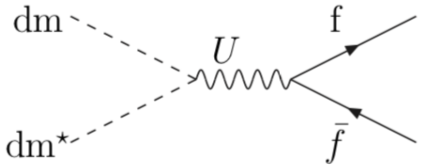
$$
\begin{aligned}
|\mathcal{M}|^2 = {} & 8\,T_0\, m_{dm}^2 \left(2\, C_l\, C_r\, m_{dm} + (C_l^2 + C_r^2)\, m_f\right)^2 \\
& + \frac{8\, p_{dm}^2}{3} \Big[2\,T_0 \Big(2\, m_{dm}^2\, (2\,C_l^4 + 9\,C_l^2\, C_r^2 + 2\,C_r^4) \\
& \quad + 6\, C_l\, C_r\, (C_l^2 + C_r^2)\, m_{dm}\, m_f - (C_l^4 + 12\,C_l^2\, C_r^2 + C_r^4)\, m_f^2 \Big) \\
& - 4\,T_1\, (C_l^2 + C_r^2)\, m_{dm} \sqrt{m_{dm}^2 - m_f^2}\, \left((C_l^2 + C_r^2)\, m_{dm} + 2\, C_l\, C_r\, m_f\right) \\
& + 3\, m_{dm}^2\, T_{20} \left(2\, C_l\, C_r\, m_{dm} + (C_l^2 + C_r^2)\, m_f\right)^2 \\
& + m_{dm}^2\, T_{21} \Big(4\,(C_l^4 + 3\,C_l^2\, C_r^2 + C_r^4)\, m_{dm}^2 \\
& \quad + 20\, C_l\, C_r\, (C_l^2 + C_r^2)\, m_{dm}\, m_f + (C_l^4 + 18\, C_l^2\, C_r^2 + C_r^4)\, m_f^2 \Big)/3 \Big].
\end{aligned}
$$

9.1.4 *Non self-conjugate scalar Dark Matter*



$$\sigma v \propto \frac{1}{m_F^4} \left((C_l^2 + C_r^2)\; m_f + 2 C_l\, C_r\, m_F\right)^2$$

9.2 *Annihilation cross sections associated with the production of a U boson*



$$\sigma_{ann}\, v_{rel} \simeq v_{dm}^2 \sqrt{1 - \frac{m_f^2}{m_{dm}^2}}\; \frac{C_U^2\, \left[4\, m_{dm}^2\, (f_{U_l}^2 + f_{U_r}^2) - m_f^2\, (f_{U_l}^2 - 6 f_{U_l} f_{U_r} + f_{U_r}^2)\right]}{12\,\pi\, (m_U^2 - 4\, m_{dm}^2)^2}$$

Probing light DM and light mediators
In low energy experiments

Dark matter search in a Beam-Dump eXperiment (BDX) at Jefferson Lab #276

BDX Collaboration • M. Battaglieri (INFN, Genoa) et al. (Jun 11, 2014)

e-Print: 1406.3028 [physics.ins-det]

pdf links cite 27 citations

Strong Constraints on Sub-GeV Dark Sectors from SLAC Beam Dump E137 #277

Brian Batell (Chicago U., EFI), Rouven Essig (YITP, Stony Brook), Ze'ev Surujon (YITP, Stony Brook) (Jun 10, 2014)

Published in: *Phys.Rev.Lett.* 113 (2014) 17, 171802 • e-Print: 1406.2698 [hep-ph]

pdf links DOI cite 150 citations

The Character of Dark Matter #278

Jonathan Henry Maynard Davis (Durham U.) (Jun 4, 2014)

pdf links cite 0 citations

Search for light vector boson production in $e^+e^- \to \mu^+\mu^-\gamma$ interactions with the KLOE experiment #279

KLOE-2 Collaboration • D. Babusci (Frascati) et al. (Apr 30, 2014)

Published in: *Phys.Lett.B* 736 (2014) 459-464 • e-Print: 1404.7772 [hep-ex]

pdf DOI cite 105 citations

Theoretical Analysis of Hidden Photon Searches in High-Precision Experiments #280

Tobias Berenek (Mainz U.) (Apr 11, 2014)

links cite 0 citations

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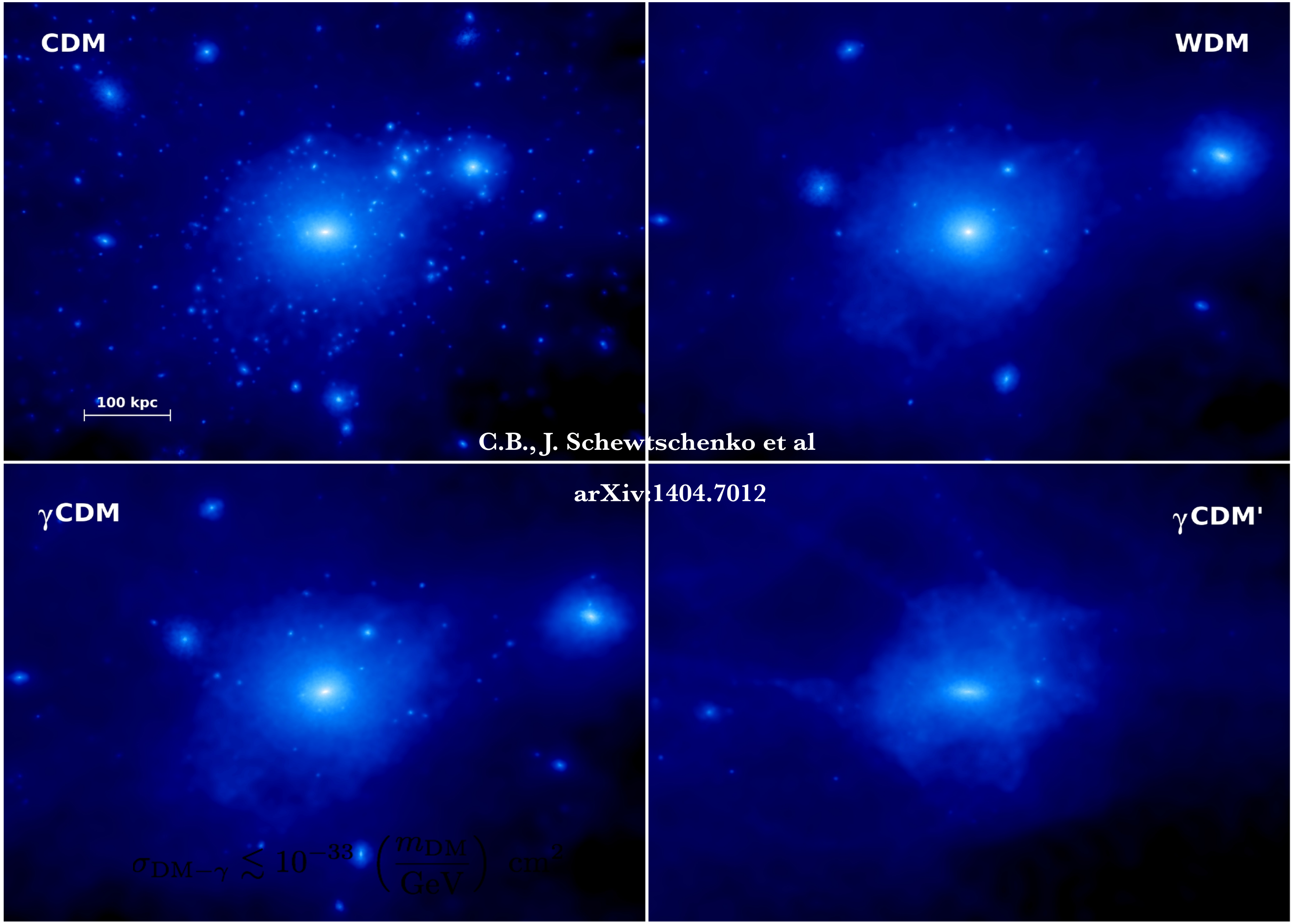

C.B., J. Schewtschenko et al

arXiv:1404.7012

$$\sigma_{\mathrm{DM}-\gamma} \lesssim 10^{-33} \left(\frac{m_{\mathrm{DM}}}{\mathrm{GeV}}\right) \mathrm{cm}^2$$

Understanding the γ-ray emission from the globular cluster 47 Tuc: evidence for dark matter?

Anthony M. Brown,[1,*] Thomas Lacroix,[2] Sheridan Lloyd,[1] Céline Bœhm,[3,4,5,6] and Paula Chadwick[1]

[1] *Centre for Advanced Instrumentation, Department of Physics, University of Durham, South Road, Durham, DH1 3LE, UK*
[2] *Laboratoire Univers & Particules de Montpellier (LUPM), Université de Montpellier, CNRS, Université de Montpellier, Montpellier, France*
[3] *School of Physics, University of Sydney, Camperdown, NSW 2006, Australia*
[4] *Institute for Particle Physics Phenomenology, Durham University, South Road, Durham, DH1 3LE, United Kingdom*
[5] *LAPTH, U. de Savoie, CNRS, BP 110, 74941 Annecy-Le-Vieux, France*
[6] *Perimeter Institute, 31 Caroline St N., Waterloo Ontario, Canada N2L 2Y5*

(Dated: June 8, 2018)

47 Tuc was the first globular cluster observed to be γ-ray bright, with the γ-rays being attributed to a population of unresolved millisecond pulsars (MSPs). Recent kinematic data, combined with detailed simulations, appears to be consistent with the presence of an intermediate mass black hole (IMBH) at the centre of 47 Tuc. Building upon this, we analyse 9 years of *Fermi*-LAT observations to study the spectral properties of 47 Tuc with unprecedented accuracy and sensitivity. This 9-year γ-ray spectrum shows that 47 Tuc's γ-ray flux cannot be explained by MSPs alone, due to a systematic discrepancy between the predicted and observed flux. Rather, we find a significant preference (TS = 40) for describing 47 Tuc's spectrum with a two source population model, consisting of an ensemble of MSPs and annihilating dark matter (DM) with an enhanced density around the IMBH, when compared to an MSP-only explanation. The best-fit DM mass of 34 GeV is essentially the same as the best-fit DM explanation for the Galactic centre "excess" when assuming DM annihilation into $b\bar{b}$ quarks. Our work constitutes the first possible evidence of dark matter within a globular cluster.

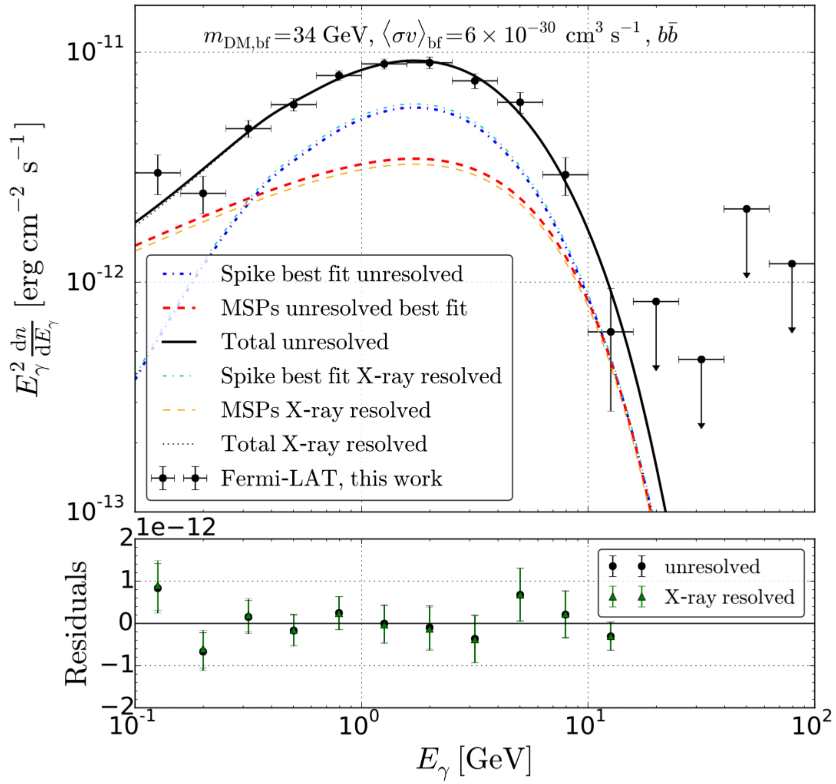

FIG. 1. Best 'DM + MSP' fit to 47 Tuc's γ-ray spectrum, for both methods for characterising the MSP contribution. DM annihilation via the $b\bar{b}$ channel, For both MSP scenarios considered, best-fit DM mass was found to be 34 GeV, with $\langle\sigma v\rangle \sim 6 \times 10^{-30}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$.

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Quantifying the evidence for dark matter in CoGeNT data

Jonathan H. Davis,[a] **Christopher McCabe,**[a] **and Céline Bœhm**[a,b]

[a]Institute for Particle Physics Phenomenology, Durham University, South Road, Durham, DH1 3LE, United Kingdom

[b]LAPTH, U. de Savoie, CNRS, BP 110, 74941 Annecy-Le-Vieux, France

E-mail: j.h.davis@durham.ac.uk, christopher.mccabe@durham.ac.uk, c.m.boehm@durham.ac.uk

Abstract. We perform an independent analysis of data from the CoGeNT direct detection experiment to quantify the evidence for dark matter recoils. We critically re-examine the assumptions that enter the analysis, focusing specifically on the separation of bulk and surface events, the latter of which constitute a large background. This separation is performed using the event rise-time, with the surface events being slower on average. We fit the rise-time distributions for the bulk and surface events with a log-normal and Pareto distribution (which gives a better fit to the tail in the bulk population at high rise-times) and account for the energy-dependence of the bulk fraction using a cubic spline. Using Bayesian and frequentist techniques and additionally investigating the effect of varying the rise-time cut, the bulk background spectrum and bin-sizes, we conclude that the CoGeNT data show a preference for light dark matter recoils at less than 1σ.

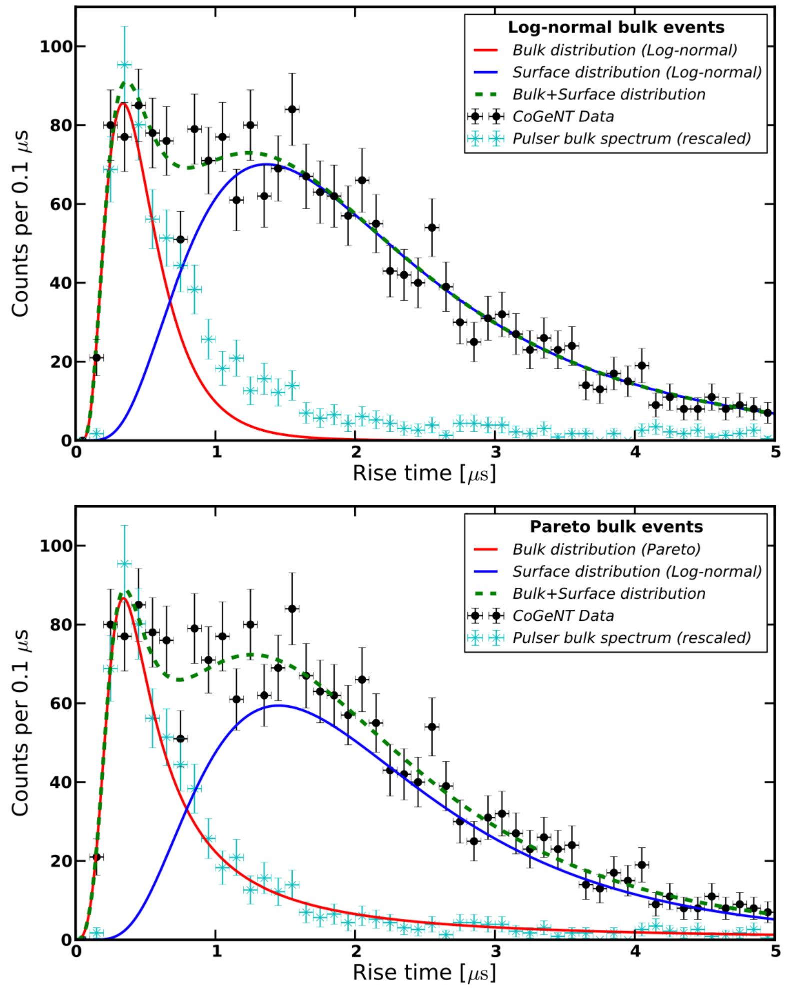

Figure 1. Bulk (red solid line) and surface (blue solid line) event distributions as a function of rise-time for energies between 0.5 $\mathrm{keV_{ee}}$ and 0.9 $\mathrm{keV_{ee}}$. The pulser data (cyan points) mimics the behaviour of bulk events. In the upper panel both populations are fit with log-normal distributions, while in the lower panel the bulk population is fit with a Pareto distribution. Both the log-normal and Pareto bulk distributions (when summed with the surface distribution) give good fits to the CoGeNT data (black points) but the slower fall off of the Pareto distribution at large rise-time is better able to fit the pulser data.

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