Dark matter and generation of galactic magnetic fields

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Observations: $B_{gal} \sim$ a few μG
coherence scale is several kiloparsec.
Intergalactic fields: $B \sim 10^{-9}$ G, coherence scale hundreds kiloparsecs.

Origin of large scale, galactic and intergalactic magnetic fields is unknown.

Key elements:

Seeding:
origin of primordial magnetic seeds

Evolution:
contraction, line reconnection, dynamo

Suggested mechanisms of generation of large scale magnetic fields:

Conventional physics.

Either too weak field strength or too short coherence length or both.

New physics.

Generation of B in the very early universe, or at a later stage, during or around recombination, $z = 1000,$ or close to the present day.

Creation during inflation: suppressed by conformal invariance of QED; can be broken either by conformal anomaly or by a new interaction, e.g. by $RA_\mu A^\mu$-term, it also breaks gauge invariance. B with a large coherence length can be created, but very weak.

Postinflationary early universe models all lead to too small coherence scales. E.g. phase transitions might lead to very large B but at tiny scales.

Generation of B at BBN:
$t > 1$ sec, $T < 1$ MeV.
Short coherence scale, $l_c < 1$ pc.
In the case of large and inhomogeneous lepton asymmetry B could be generated at such scales and by chaotic field line reconnection (like Brownian motion) might extend to galactic, but not intergalactic scales.

In all the cases huge, sometimes even unrealistic, dynamo amplification by galactic rotation is necessary.
This could help to amplify galactic magnetic fields from originally weak seed fields, but not intergalactic B.

Additional problem with galactic fields:
Developed magnetic fields $B \sim$ few μG observed in young galaxies, at $z \sim 2$
- when the universe age was about $1/3$ of the present age $T \simeq 14$ Gyr

P. Kronberg at al., Nature 454, 302 (2008)

Creation of seed fields at recombination epoch, and later during large scale structure formation. B_{seed} **can be generated by vortex currents,** but vorticity perturbations are absent in the primordial density perturbations. **However, vorticity may be created by the photon diffusion in the second order of the usual scalar perturbations**

Z. Berezhiani, A. Dolgov,
Astropart.Phys. 21, 59 (2004); astro-ph/03055952003

S. Matarrese, S. Mollerach, A. Notari, A. Riotto,
Phys.Rev. D71, 043502 (2005); astro-ph/0410687

As a result, seed fields can be generated, $B_{\rm seed} \sim 10^{-20}$ G, at the galactic lengthscale ~ 10 kpc. Is it enough ?

What is $B \sim 1$ μG for galactic fields ? It is in fact a dynamo saturation limit when equipartition between the magnetic and turbulent energy densities is achieved: $B^2/8\pi \sim \rho v^2/2$

Dynamo amplification implies

$$B(t) = B_{\rm seed}(t_0) \ \exp\left[(t - t_0)/\tau_{\rm dyn}\right]$$

with e-folding time $\tau_{\rm dyn} = 0.2 \div 0.5$ Gyr
Hence $B_{\rm seed}(t_0) \sim 10^{-20}$ G   at $t_0 \sim 1$ Gyr
is enough for $B(t) \sim \mu$G   at $t = 14$ Gyr

But for $B(t) \sim \mu$G   at $t = 4$ Gyr $(z \simeq 2)$
one needs $B_{\rm seed}(t_0) > 10^{-15}$ G   !!

Consider a protogalaxy rotating in the background of CMB photons. The pressure exerted by photons on electrons is by far larger than that exerted on protons, $F \propto \sigma \propto \alpha/m_{e,p}^2$. So circular electric current, proportional to the rotational velocity, v_{rot}, must be induced. The acceleration is even smaller, $a \propto F/m \propto \alpha/m_{e,p}^3$.

Pressure force acting on electrons:

$$\vec{F} \sim \vec{v}\sigma_{e\gamma}n_{\gamma}\omega_{\gamma} = e\,\vec{v}\,B_F$$

where $\sigma_{e\gamma} = 8\pi\alpha^2/3m_e^2 = 6.65\times10^{-25}\ \mathrm{cm}^2$, $\alpha = e^2 = 1/137$ **(CGS system of units)**, **and thus factor** $B_F = \sigma_{e\gamma}\rho_{\gamma}/e$ **is**

$$B_F(z) = 3.4 \times 10^{-30}(1+z)^4\ \mathrm{eV}^2/e$$

or

$$B_F(z) = 5.8 \times 10^{-28}(1+z)^4\ \mathrm{G}$$

$$j = e n_e v_{\text{reg}}, \qquad v_{\text{reg}} = \tau_{ep} F / 2 m_e$$

$$j = \kappa E = \kappa F / e$$

Conductivity, κ is determined by ep scattering. The collision time is

$$\tau_{ep} = \frac{m_e^2 \langle v_e^2 \rangle}{4\pi \alpha^2 \langle 1/v_e \rangle n_e L_e} \simeq \frac{m_e^{1/2} T_e^{3/2}}{4\pi \alpha^2 n_e L_e},$$

where $L_e \sim 10$ and $\langle v_e^2 \rangle = T_e/m_e$. So

$$\kappa = \frac{e^2 n_e \tau_{ep}}{2 m_e} \simeq \frac{T_e^{3/2}}{8\pi \alpha L_e m_e^{1/2}}.$$

Note, that the conductivity does not depend on the density of charge carriers, n_e, unless the latter is so small that the resistance is dominated by neutral particles.

Thus the difference between rotational velocities of e and p is $\Delta v_e = \tau_{ep} F / 2 m_e$ and the current $j = e n_e \Delta v_e$. Naively estimating B by the Biot-Savart law as $B \sim 4\pi j R$ where R is the galaxy radius, we find that for a typical galaxy with $R \sim 10$ kpc $v_{\mathrm{rot}} \sim 100$ km/s: $B \sim \mu$G, very close to the observed value without any dynamo. HOWEVER THIS IS WRONG! Time to reach stationary (Biot-Savart) limit is longer than the cosmological time.

MHD equation modified by presence of external force:

$$\partial_t \vec{B} = \textcolor{red}{\vec{\nabla} \times \vec{F}/e} + \vec{\nabla} \times (\vec{v} \times \vec{B}) +$$
$$\frac{1}{4\pi\kappa}(\Delta\vec{B} - \partial_t^2\vec{B}), \quad \textcolor{blue}{\vec{F} = e\,\vec{v}B_F}$$

Origin: $J = \kappa(\vec{E} + \vec{v} \times \vec{B} + \textcolor{red}{\vec{F}/e})$

In the limit of high conductivity, the second term in the equation, the advection term, can lead to dynamo amplification of magnetic seed fields once the value of the latter is non-zero.

But without source term $\vec{\nabla} \times \vec{F}/e$ MHD equation CANNOT generate non-zero magnetic seeds: if $\vec{B} = 0$ at $t = t_0$, then $\vec{B} = 0$ FOREVER

Assuming $B = 0$ at $t = 0$, we find that the source term induces:

$$\vec{B}(t) = \int_0^t dt\, \vec{\nabla} \times \vec{F}/e$$

$$= \int_{t_0}^t dt\, [B_F \vec{\nabla} \times \vec{v} + (\vec{\nabla} B_F) \times \vec{v}], \quad B_F = \sigma_{e\gamma} \rho_\gamma / e$$

The largest value of the magnetic seed is generated around the hydrogen recombination and photon decoupling, $z_{\text{rec}} \sim 10^3$, or $t_{\text{rec}} \sim 5 \times 10^5$ yr. Earlier the plasma was strongly coupled and the relative motion of electrons and protons was negligible.

The seed field generated at this epoch with coherence length $\lambda \sim 1 \text{ kpc}$, corresponding to the present scale of a typical galaxy ~ 1 Mpc, is

$$B_\lambda \sim \Omega_\lambda t_{\text{rec}} B_F(t_{\text{rec}}) \lesssim 10^{-20}\, G,$$

where $\Omega_\lambda = |\vec{\nabla} \times \vec{v}|_\lambda \lesssim 10^3 (\delta T/T)^2/\lambda$. However such seed is still too weak. The seeds with the coherence length $\sim$ a few kpc and $B_{\text{seed}} > 10^{-15}$ G are needed to fit the observations.

Now: new DM particles, X, instead of CMB photons. The generated current is proportional to the cross-section of Xe-elastic scattering, σ_{Xe}, to n_X/n_e, and to $p_X = m_X v_{rot}$. Therefore, to produce stronger than CMB force on electrons, σ_{Xe} should be large. This is possible if X have long range interaction, so σ_{Xe} is strongly enhanced at low momentum transfer. So we consider millicharged particles with the mass from a few keV to several MeV.

How millicharged particles appear ?

Ordinary particles: Stardard model
$SU(3) \times SU(2) \times U(1) \rightarrow SU(3) \times U(1)_{\mathrm{em}}$

$$L = -\tfrac{1}{4} F_{\mu\nu} F^{\mu\nu} + e Q_f A_\mu \overline{f} \gamma^\mu f$$

Imagine a dark sector of X-particles with gauge $U(1)'$ factor

$$L' = -\tfrac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + e Q'_X A'_\mu \overline{X} \gamma^\mu X$$

Kinetic mixing: $\quad L_{\mathrm{mix}} = \tfrac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$

Two options:
A. $U(1)_{\mathrm{em}} \times U(1)'$ is **unbroken: photon + massless paraphoton**
B. $U(1)_{\mathrm{em}} \times U(1)'$ is Higgsed by VEV of "mixed" scalar $\phi(Q, Q')$: photon remains masless, paraphoton becomes massive
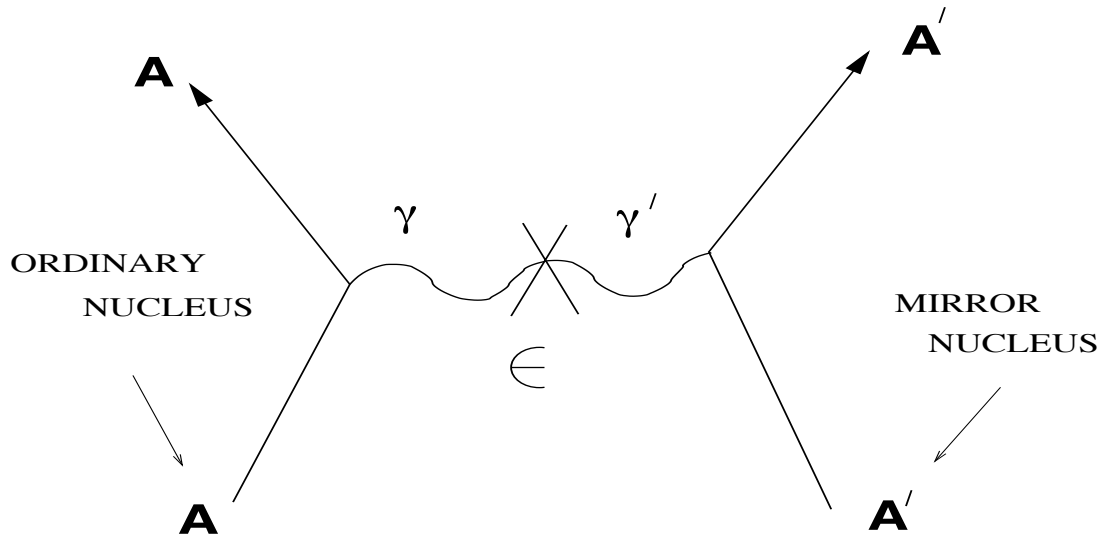
Figure 1: ordinary and dark particle scattering via kinetic mixing

Dark sector may be presented as asymmetric mirror sector with spontaneously broken mirror parity, $v'_W \gg v_W \sim 100\,\mathrm{GeV}$

Z.B., Mohapatra, 1995

Z.B., Dolgov, Mohapatra, 1996

Bounds on X-particle charge, $e' = \epsilon e$:

If $m_X < m_e$, from ortho-positronium invisible decays follows $\epsilon < 3.4 \cdot 10^{-5}$. For $m_X = 1$ MeV: $\epsilon < 4.1 \times 10^{-4}$. For $m_X = 100$ MeV $\epsilon < 5.8 \times 10^{-4}$. We assume that $m_X > 10$ keV to avoid strong limits on e' from the stellar evolution.

BBN bounds can be relaxed if the lepton asymmetry is non-zero.

ZB, Dolgov, Tkachev, JCAP 1302, 010 (2013); arXiv:1211.4937

Kinetic kixing parameter ϵ can be a dynamical d.o.f. changing in time.
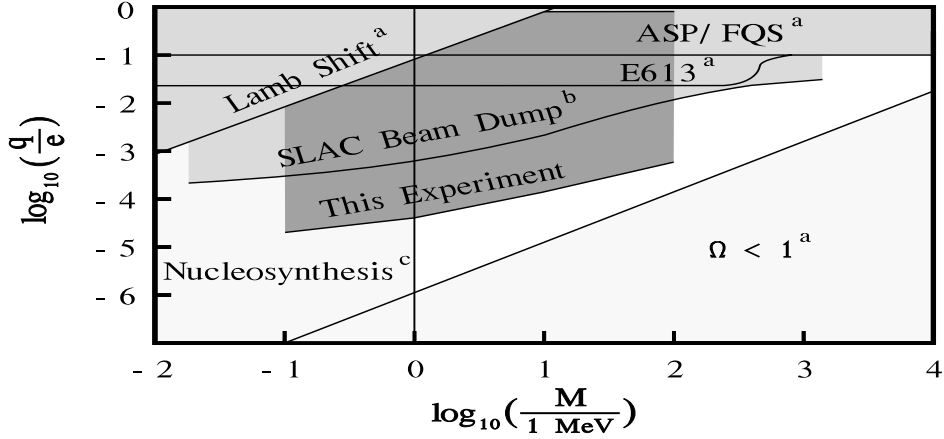
ZB, Karshenboim, Kobakhidze, 2013

Figure 2: Millicharge vs. particle mass, Prinz et al., PRL 81, 1175 (1998)

If X-particles were thermally produced, their abundance would be:

$$\Omega_X h^2 \approx 0.023 \, x_f \, g_{*f}^{-1/2} \left(\frac{v \sigma_{\mathrm{ann}}}{1 \text{ pb}} \right)^{-1},$$

where

$$x_f \equiv \frac{m_X}{T_f} = 10 + \ln \frac{g_X \, x_f^{1/2} \, m_X}{g_{*f} \, MeV},$$

where g_X is the number of the spin states of X-particle and g_{*f} is the effective number of particle species in the plasma at $T = T_f$.

If $m_X < m_e$, X-particles can annihilate only into photons with

$$v\sigma(X\bar{X} \to 2\gamma) = \frac{\pi\alpha'^2}{m_X^2},$$

where $\alpha' = e'^{\,2}/4\pi = \epsilon^2\alpha$. Thus

$$\Omega_X h^2 \approx 150 \left(\frac{10^{-5}m}{\epsilon^2\,\mathrm{keV}}\right)^2.$$

Hence X's would be overproduced if $\epsilon < 3.4{\cdot}10^{-5}$. Additional annihilation into $\bar{\nu}\nu$ or dark photons could help. CMB demands $\Omega_X h^2 < 0.005$ or so

If $m_X > m_e$, then $X\bar{X} \to e^+ e^-$ and:

$$v\sigma(X\bar{X} \to e^+ e^-) = \frac{\pi \alpha \alpha'}{m_X^2}.$$

Correspondingly:

$$\Omega_X h^2 = 0.012 \left(\frac{10^{-5} m}{\epsilon \, \text{MeV}} \right)^2.$$

Hence, e.g. for $m_X = 10$ MeV and $\epsilon = 3 \cdot 10^{-5}$, X-particles can make all DM. Nevertheless Ω_X wlll be taken as free parameter.

Drag force from X-particles on electrons:

$$\vec{F} = \vec{v}\,\sigma_{eX}\,n_X\,m_X\,v_{rel} = e\vec{v}B_F$$

where

$$v_{rel}\sigma_{eX} = \frac{4\pi\alpha\alpha'L}{m_X^2 v_{rel}^3},$$

$$m_X n_X = 10\,\Omega_X h^2 \kappa(z)(1+z)^3\,\mathrm{keV/cm^3},$$

where $\kappa(z)$ is the dark matter over-density in galactic halo with respect to its mean density at redshift z.

If $m_X < m_e$, then

$$B_F = \frac{\epsilon_5^2}{m_{\mathrm{keV}}^2}\frac{\Omega_X h^2 \kappa(z)(1+z)^3}{v_{100}^3} \times 10^{-15}\ \mathrm{G}$$

If $m_X > m_e$, then

$$B_F = \frac{\epsilon_5^2}{m_{\mathrm{MeV}}^2}\frac{\Omega_X h^2 \kappa(z)(1+z)^3}{v_{100}^3} \times 10^{-21}\ \mathrm{G}$$

$$= m_{\mathrm{MeV}}\frac{\kappa(z)(1+z)^3}{v_{100}^3} \times 10^{-23}\ \mathrm{G}$$

DM of X-particles and LLS formation.
Light X's. Prior to recombination $\tau_{Xe} < t_U$ and X's are frozen in $e\gamma$-liquid. After recombination and till reionization they behave as usual WDM. After reionization τ_{Xe} again becomes smaller than the cosmological time and thus the rotating ordinary matter in a protogalaxy would transfer a part of angular momentum to X-particles and involve it in its turbulent motion.

Estimate of field generated by light X.
We use the obtained above equations but integrate till reionization, $z = 6$ and thus $t_u = 1$ Gyr, $R = 100$ kpc and $\kappa = 100$, $v_{rot} = 10$ km/sec and impose the limit $\Omega_x h^2 = 0.007$ to find:

$$B = \frac{\epsilon_5^2}{m_{keV}^2} \cdot 10^{-11}\, G.$$

B can rise by factor 100, becoming 10^{-9} G, when the protogalaxy shrinks from 100 kpc to 10 kpc, by far larger then the minimal necessary strength of the seed.

Heavier X: $m_X > m_e$, so larger charge is allowed, $\epsilon > 10^{-4}$. X-particles can make all dark matter. After reionization, electron scatterings would not force X-particles into galaxy rotation and thus the effective integration time can be larger and magnetic fields as large as 10^{-12} G can be generated.

511 keV photon shining from the Galaxy bulge (INTEGRAL/SPI)

Can be explained via $\overline{X}X \to e^+e^-$ annihilation in dark matter halo, if

$$\left(\frac{\Omega_X h^2}{m_{\mathrm{MeV}}}\right)^2 \frac{v\sigma(\overline{X}X \to e^+e^-)}{1 \text{ pb}} \simeq (0.5-1.5)\times 10^{-5}$$

can be satisfied when
$m_X \sim (5-10) \text{ MeV}$ **and** $\epsilon = (0.8-1.3)\cdot 10^{-4}$

pleasant artefact !!!

Concluson.

Existence of millicharged particles with mass in keV - MeV range allows to:

1. Explain the origin of galactic and intergalactic magnetic fields.

2. Introduce DM with time dependent interaction with normal matter: time dependent kinetic mixing ϵ and time variation of α

3. To be tested in direct experiment: positronium, atomic physics, anom. magn. moments, dark matter search

4. To solve or smooth down problems of galactic satellites, angular momentum, and cusps in galactic centres.

5. Very interesting possibilities with mirror matter (exact or asymmetric mirror) which presently is perhaps a best candidate for dark matter (can explain $\Omega_{DM}/\Omega_B \sim 5$, DAMA vs. XENON, etc.) and can bring to many pleasant surprises

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