Confinement of CR in Dark Matter relic clumps

V. Zhukov
University Karlsruhe and SINP Moscow State University

W. de Boer
University Karlsruhe
Strong evidences for DM existence:
- galactic rotation curves
- large scale structures
- nucleosynthesis and element abundances

Modern cosmology:
- inflation scenario $\Omega \sim 1$, $\Omega_\lambda \sim 0.73$, $\Omega_\chi \sim 0.23$
- bottom-top scenario $P(k) \sim k^n$, $n > 0.95$
  
small structures (clumps) are created first
- universal DM profile for different scales

Cuspy ($\gamma > 0$) profile from Nbody and analytical simulation (NFW parametrization):

$$\rho(r) = \rho_0 \left(\frac{r}{a}\right)^{-\gamma} \left[1 + \left(\frac{r}{a}\right)^\alpha\right]^\frac{\gamma - \beta}{\alpha}$$
DM clumps

Fraction of DM in relic clumps:
depends upon:
- spectrum of primary fluctuations $\delta \sim k^n$
- clumps density profile: $\rho \sim r^{-\alpha}$, $\alpha = 1.5 - 2$
- $r < r_c \sim 10^{-3} - 0.1 r_c$, $\rho_{\text{max}} - ?$
- mass spectrum $d\nu_{\text{cl}}$ and minimum mass $M_{\text{min}}$
$M_{\text{min}} = 10^{-6} - 10^{-8} M_\odot$ is defined by free streaming of DM after decoupling

$\zeta \sim 0.001 - 0.1$ of DM is in relic clumps
the rest is the 'bulk' DM

Clumps distribution in the Galaxy $n_{\text{cl}}$:
- follows the bulk DM distribution (universal profile)
- tidal disruption by Galactic potential can disturb the distribution (depletion near the center)
- large scale structure appears due to 'recent' infalls (CanisM, Sag.)

Ex. smallest clumps:
$M = 10^{-8} M_\odot$, $r \sim 100$ AU, $\langle \rho \rangle \sim 100$ GeV/cm$^3$, $\rho_{\text{max}} \sim 10^{3.5}$ GeV/cm$^3$
$\sim 1 - 100$ clumps/pc$^3$ at $R_\odot = 8.5$ kpc, $\rho_{\text{bulk}} \sim 0.3 - 0.7$ GeV/cm$^3$

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DM can annihilate (or coannihilate) with the averaged cross section $<\sigma v>$ constrained by relic density in time of decoupling $T_{\text{dec}} \sim m_{\chi}/20 \sim 3-50$ GeV

$<\sigma v> = 2 \times 10^{-27}$ cm$^3$ s$^{-1} / \Omega h^2 [0.092 - 0.112]$, $<\sigma v> \sim 2 \times 10^{-26}$ cm$^3$ s$^{-1}$

The dominant end state are fermions
After hadronization and fragmentation stable particles: $p, pb, e^+, e^-, \gamma$

Nowadays ($T \sim 1.8$ K) $<\sigma v>$ can be only smaller

Momentum dependency of $<\sigma v>$ for different annihilation channels in SUSY scenario ($m_{\chi} \sim 60$ GeV)

\[<\sigma v> \propto \frac{1}{T_{\text{dec}}}\]

Yields $Y_i$ per annihilation
SUSY neutralino 60 GeV
DM annihilation (DMA) in the Galaxy

Annihilation signal:

\[ q_i(r,p) = \langle \sigma v \rangle Y_i(p) \int \frac{\rho_{DM}^2(l)}{m^2_\chi} dl \]

\[ q \sim 1/m^2_\chi \cdot 4 \]

 DMA signal / CR background for the bulk galactic DM (different profiles and \( m_\chi \))

\[ 1 \]

Experimental resolution (EGRET, Bess, Caprice, etc) \( \sim 10\% \)

Model uncert. can be much larger.

**Boost factor: if relic clumps exist**

DM annihilation signal \( Q_{DMA} \sim \rho^2 \) is dominated by cusp of smallest DM clumps

\[ \rho_{tot} = \rho_{bulk} + \rho_{cl}, \quad \rho_{cl}^\text{max} \gg \rho_{bulk}^\text{max}, \quad B = Q_{tot}/Q_{bulk}, \quad B = 1-10^4 \] depending on \( \zeta \) and \( \rho_{cl}^\text{max} \)

if \( n_{cl} \sim \rho_{bulk}, \ B \sim 1/\rho_{bulk}, \ Q_{tot} \sim \rho_{bulk} \) -> effective DMA profile instead of DM bulk profile
CR propagation

CR propagation: as a resonant scattering of CR $f(r)$ on MHD turbulences with spectral density $W(k,r)$: $1/k_r \sim r_g = pc/ZeB$

$k \sim 10^{-12} \text{ cm}^{-1}$ for GeV particles in $B \sim 10^{-6} \text{ G}$

$\frac{1}{r^2} \frac{\partial}{\partial r} D \frac{\partial}{\partial r} f - V_c \frac{\partial f}{\partial r} - \frac{1}{r^2} \frac{\partial}{\partial r} r^2 V_c \frac{p}{3} \frac{\partial f}{\partial p} - \frac{\partial}{\partial p} (\dot{p} f) - \frac{f}{\tau} = -q(p,r)$

diffusion \hspace{1cm} Vc-convection \hspace{1cm} $P$ losses \hspace{1cm} Decays and fragmentation

$D(r) \approx v r^2 B^2 / 12\pi W(k_r,r)$

MHD waves interact with CR

$\frac{\partial W}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} v_a r^2 W - \frac{\partial v_a}{\partial r} \frac{\partial}{\partial k} kW = (G-S)W$

$\text{Alfvén speed } v_a \sim B/\sqrt{4\pi \rho_H}$

growth by CR \hspace{1cm} damping \hspace{1cm} if $V_{str} > v_a$

$W(k)$ is related to the scale of interstellar irregularities, follows $W \sim k^{a-2}$, $a=1/3$ for Kalamogorov spectrum

small scales $1/k < 10^{14} \text{ cm}$ are created by CR streaming(?)

Source term for a DM clump $q_i(r,p) \sim <\sigma v> Y_i(p) \rho_o^2/m_\chi^2$

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**Growth and damping of MHD turbulences**

**Enhancement of the MHD waves by CR streaming:**

\[ G(k, r) \approx \frac{\pi^2 e^2 v_a}{k c^2} \int \int dp \delta(p|\mu) \left( \frac{- eB}{kc} \right) \times \left( \frac{\partial f}{\partial \mu} + \frac{v_ap}{v} \frac{\partial f}{\partial p} \right) \]

- Small at \( E < 1 \text{ GeV} \)
- For DMA products

**Pitch angle scattering** \( \mu = \cos \theta \)

\[ \frac{\partial f}{\partial \mu} \sim \frac{v p^2 c | \mu |}{2 \pi^2 e^2 W} \frac{\partial f}{\partial r} \]

**At resonance** \( v \mu = \Omega/k \)

**Damping:**

1. **Ions-neutral gas friction**

\[ S_H \sim \frac{1}{2} \langle \sigma_\text{col} v_a \rangle n_H \]

- \( <n_H> \sim 1 \text{ cm}^{-3} \)
- \( <n_\text{HI}> \sim 0.01 \text{ cm}^{-3} \)

- Molecular clouds \( n_H \sim 10-1000 \text{ cm}^{-3} \)
- \( <\sigma_\text{col} v> \sim 10^{-9} \text{ cm}^3 \text{ s}^{-1} \)

- MHD are damped in the dense gas clouds (galactic disk, clouds)

2. **Nonlinear damping by MHD waves collisions**

\[ S_{nl} \approx \frac{4\pi v_a W}{B^2 r_g^2} = S_0^0 W \ll S_H \]

- Important in the underdense regions (halo, Local Bubble)

- Damping by CR significant for the Kraichan spectrum, at \( 1/k < 10^{13} \text{ cm} \)

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*Kulsrud 69*

*Wentzel 1974*

*Kulsrud 69*

*Piukin et al. 2006*
MHD waves from DM clumps

DM clump is a constant, point-like source of CR(p,e) can enhance MHD waves.

Steady state solution for $W(r)$ (simplified):

$$W(r) \sim \frac{\exp(-g/r - s_H r)}{r^2(C_0 + s_n e \exp(-g/r - s_H r)/g)}$$

Assumptions:
- spherical symmetry (growth is along B field)
- DM clump is point-like source (cusped profile)
- $f(p) \sim$ const
- no losses
- $V_c \sim$0, small local convection
- $V_a \sim$const, $\delta B/B$ is small
- no interference between electrons and protons...

$W(r)$ dependency for a DM clump

$W(k)$ is cutoff at $\sim m_\chi$

can be extended by cascading

$W(r)$ distribution in Galaxy

GALPROP+DMA

Conventional model
CR confinement in DM clumps

Stability conditions of the confinement zone:
- slow proper motion of clumps \( V_{cl} < \nu_a \)
- large external diffusion \( D_{ext} > D_c \) (\( W_{int} > W_{ext} \))
- slow external convection \( V_c < \nu_a \)

DM clump can create a trapping region with low \( D_c \)

Different environments:
- molecular gas clouds
  \( \rho_{H_2} = 10-1000 \text{ cm}^{-3} \) - strong damping
- underdense regions
  (Local Bubble, galactic halo) \( \rho_H < 0.1 \text{ cm}^{-3} \), low \( W \) density

\[
D_{ext} \gg D_c \\
\tau_c \sim r_{cl}^2 / 2D_c
\]

local variations in diffusion coefficient
and therefore CR density \( f*\nu_{str}/B \sim \text{const} \)

DMA contributions:
- \( \gamma \) from \( \chi\chi \rightarrow \text{ffbar} \rightarrow \gamma + X \)
- \( \gamma \) from DMA e+,e- via IC ,Brems.
- p+,p-, e+, e- from \( \chi\chi \rightarrow \text{ffbar} \rightarrow p,e+X \)
- radio from e+,e- synchrotron losses
Isotropic and uniform propagation model:

- $D$- isotropic diffusion and uniform
- averaged gas density $<nH>$, no gas clouds

Normalize CR primary density to locally observed at $R=8.5$ kpc

$Z_h \sim 4$ kpc
$D \sim 10^{28}$ cm$^2$ s
$V_{conv} < 10$ km/s
$n(r,z<100$pc$) \sim 1$ cm$^{-3}$

$\delta(100$ GeV$)<10^{-3}$
$T_{esc} \sim Z_h^2/D$
$X = vnT_{esc} \sim 7$ g/cm$^2$

Use locally measured secondaries to constrain the galactic global parameters ($D, Z, V_a, V_c$)

Fails to explain gamma rays unless proton (e) interstellar spectrum has a strong break at 1-10 GeV

Variations in gas, sources, ISRF, etc

Strong break in p spectrum at 10 GeV

$\chi^2=0.635399$

Conventional Model CM (GALPROP)

B/C

$V_a \sim 30$ km/s

$B_e^{10}/B_e^9$

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Inhomogeneous model: a possibility

But propagation is not uniform:
- DM clumps trapping zones with small $D_c$
- gas is clumpy, ~50% in H2 clouds 10-1000 cm$^{-3}$
- Local Bubble, underdense regions, large W is possible
- trapping in magnetic mirrors
- two zones model, convective halo driven by CR....

Propagation in non homogeneous medium:
Kulsrud, Pearce 69
Ptuskin, Soutoul, Osborne 90
Zwibel, Shull 82,
Padoan, Scalo 2006
Chandran 2000 , etc....

Assumptions:
- Large $D_d$ in the gal. disk $z_d$ ~100pc
- Small $D_h$ in the halo, large $V_{conv}$
- Clumpy zones with local confinement (DM clumps, trapping in clouds, etc) $D_c$

Confinement zones with $D_c < D_d$:
- increase the grammage $X$ locally
($r_{cl} \sim 10$ pc, $n_{cl} = 200$ cm$^{-3}$)

$$X = v\bar{n} \frac{Z_d^2}{D_d} + \sum_n v n_{cl} \frac{r_{cl}^2}{D_c}$$

$$\frac{D_c}{D} \sim \frac{N_{cl} n_{cl} r_{cl}^2}{n_z h^2} \sim N_{cl} * 10^{-2}$$

- isotropize CR $f = f_d + f_{cl}$

$$\delta \sim \frac{D}{v} \frac{1}{f} \frac{\partial f}{\partial x} \approx \frac{D}{v} \frac{1}{f} \left( \frac{\partial f_d}{\partial x} - \sum_{N_{cl}} \frac{\partial f_{cl}}{\partial x} \right)$$
Ex: isotropic propagation model with DMA

EGRET excess interpreted as a DMA signal (SUSY neutralino) $m_{\chi} \sim 60$ GeV
Boost factor $\sim 50 \rightarrow$ DM clumps

DeBoer et al. 2005

Reconstruct DMA effective profile (clumps distribution) from angular profiles

But too many $p^-$ and $e^+$ from DMA in isotropic CM

DMA antiprotons (1 GeV) in CM DM rings like structure from 'EGRET' profiles (GALPROP+DMA)

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Decouples locally observed CR secondaries (B, Be, etc) from charged DMA and gamma rays

**GALPROP (Moscalenko, Strong) modified:**
including DMA using 'EGRET' profile, anisotropic nonuniform propagation (AD+DMA)

More parameters, more freedom, for ex:

\[ Z_d = 200 \text{ pc} \quad D_d = 10^{30} \text{ cm}^2 \text{ s} \quad n(r,z), snr(r,z) \text{ (Lorimer et al)} \]
\[ Z_h = 4 \text{ kpc} \quad D_h = 10^{28} \text{ cm}^2 \text{ s} \quad V_c = z \frac{dV}{dz} = 20 \text{ km/s/kpc} \]
\[ nH_2 \text{ scaling} \sim 40 \]
Summary

- Annihilation in cuspy relic DM clumps can produce MHD waves with scales \( k > \frac{eB}{m_{\chi}} \) and confine charged CR.

- The confinement zones will contribute to small scale variations in propagation parameters. These variations can decouple locally observed fluxes from the galactic averages.

- The confinement zones can isotropize CR and produce secondaries locally thus allowing larger diffusion coefficient in the galactic disk.

- The annihilation signal can be attributed to the gamma rays, antiprotons and positrons. In inhomogeneous medium the DMA charged contributions can be not directly related to the gamma rays from DMA.