Dark Matter Self-Interactions via Collisionless Shocks in Cluster Mergers

Christian Spethmann

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M. Heikinheimo, M. Raidal, C.S. and H. Veermäe
(accepted for publication by PLB)

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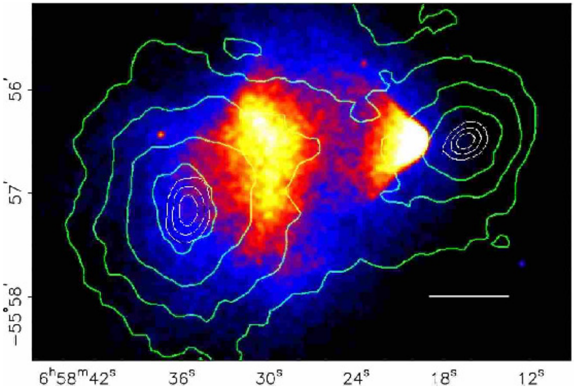
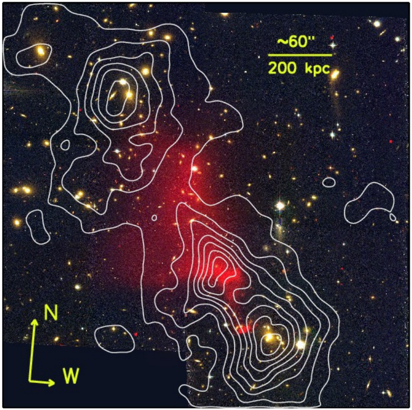
Observational Evidence, Exhibit A: Bullet Cluster



- The two dark matter halos move through each other.
- The visible gas gets shocked and stays behind.

$\Rightarrow$ (Most of) dark matter collisionless!

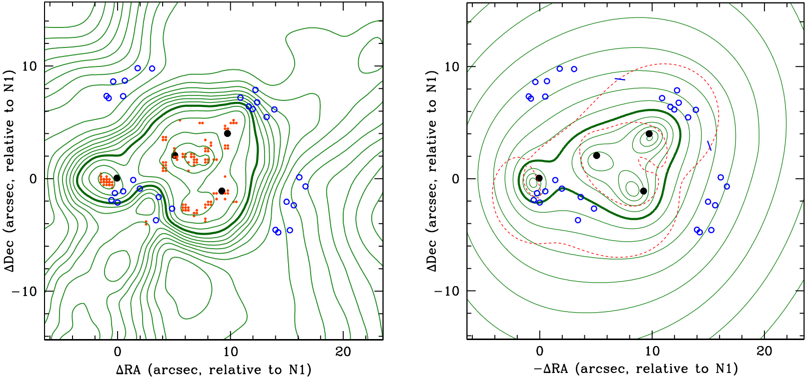
Observational Evidence, Exhibit B: Abell 520



- The visible gas gets shocked and stays behind.
- Microlensing: Excess of dark matter on top of the gas.

$\Rightarrow$ (some component of) dark matter collisional after all?

Observational Evidence, Exhibit C: Abell 3827



- Microlensing: dark matter halos stay behind visible stars.

⇒ Drag force on dark matter from intracluster medium?

Preliminary Conclusions from Evidence

The observations can be explained if:

- Most of dark matter is collisionless (Bullet cluster)
- A subcomponent (10 - 30 %) of dark matter imitates the visible gas (Abell 520)
- The interacting component is slowed down and stays behind (Abell 3827)

$\Rightarrow$ The interacting dark matter is a plasma like the visible gas

$\Rightarrow$ Collisionless Shocks

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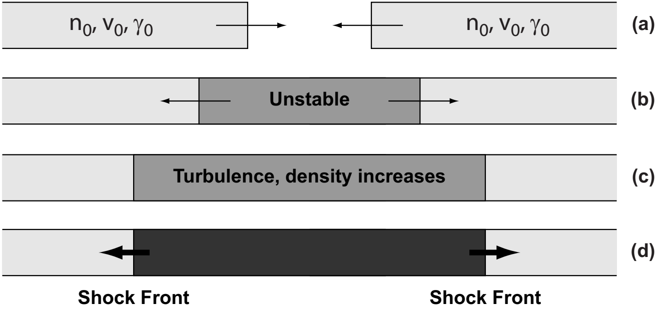
Plasma Physics 101

Some characteristic properties of (astrophysical) plasmas:

- Mix of charge carriers, interacting via long range forces.
- Debye shielding length $\lambda_D = \sqrt{\frac{T}{4\pi\alpha n}}$ (here ~ 10 km).
- Physical size $> \lambda_D$ (bulk interactions dominate over surface effects).
- Collective effects dominate dynamics if $\Lambda = \frac{4\pi}{3}\lambda_D^3 n \gg 1$ (here $\Lambda = 10^{19}$ to 10^{20}).
- Electrostatic interactions dominate over direct $2 \to 2$ scattering
- Plasma instabilities important (see next slides).

Collisionless Shocks (12min talk cartoon version)



Counter-streaming plasma ⇒ plasma instabilities
⇒ large EM fieds ⇒ saturation regime (non-linear)
⇒ shock waves ⇒ energy dissipation

Typical time scale: $\sim 100\ \omega_p^{-1} = 100 \left(\frac{4\pi\alpha n}{m}\right)^{-1/2}$

[1502.00626 [physics.plasm-ph]].

Are Collisionless Shocks Real?

- Observations of visible astrophysical plasmas:
  - Earth's bow shock
  - Expansion of supernova remnants
  - Galaxy collisions and cluster mergers
- Numerical Studies:
  - Particle in cell (PIC) simulations
- Experimental Studies:
  - electron-positron plasmas
  - ionized gases produced with laser pulses
- Dedicated numerical studies of dark plamas (in progress).

$\Rightarrow$ YES, and they will affect dark matter dynamics if massless dark force carriers are present.

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A Concrete Model of Dark Plasma

Details of the model:

- 70% of DM generic WIMP, 30% *dark plasma*.
- One Dirac fermion charged under an unbroken $U(1)$ gauge group:

$$\mathcal{L} = \frac{1}{4} F_{D\mu\nu} F_D^{\mu\nu} + \bar{\chi} \left(i \not{D} - m_D \right) \chi .$$

- No kinetic mixing term $F_{D\mu\nu} F^{\mu\nu}$ (highly constrained).
- Dark matter abundance is produced as thermal relic from annihilation into dark photons, $\bar{\chi}\chi \to \gamma_D \gamma_D$.

Observational Constraints (1), BBN

- Big Bang Nucleosynthesis: $N_{\text{eff}} < 3.38$
  $\Rightarrow$ Constrains temperature of dark photons during BBN.
- Dark photon temperature

$$T_D = T_\gamma \left(\frac{g_{*s,\gamma}(T_\gamma) g_{*s,D}(T_*)}{g_{*s,D}(T_D) g_{*s,\gamma}(T_*)} \right)^{1/3},$$

  (thermal equilibrium assumed at T_*).
- Constrains number of fermions in the dark sector:
  $N_D < 2.35$

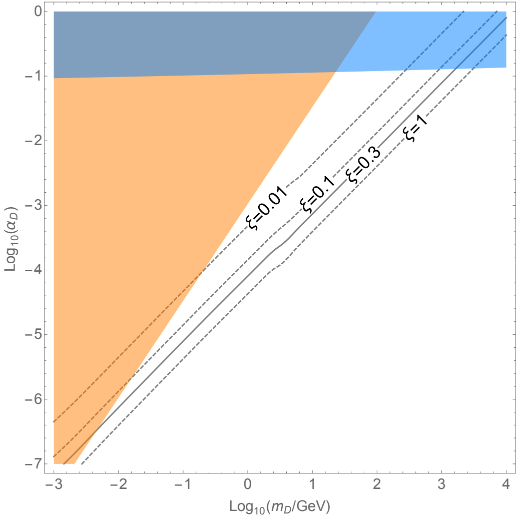
Observational Constraints (2), CMB/SSS

- Structure formation suppressed until kinetic decoupling of the dark matter and dark radiation, which occurs at

$$T_{\mathrm{kin}} = \left(\frac{4\pi}{45} g_*\right)^{\frac{1}{4}} \sqrt{\frac{135}{64\pi^3}} \frac{m_D^{\frac{3}{2}}}{\sqrt{m_P}\alpha_D}.$$

- If $T_{\mathrm{kin}} > 640$ eV, only multipoles above $l > 2500$ are affected in the CMB, and thus temperatures above this limit are unconstrained by PLANCK.
- For $T_{\mathrm{kin}} \approx 500$ eV the small scale structure is suppressed for structures below the size of $\sim 10^9 M_\odot$, alleviating the missing satellites problem.

Exclusion plot: DM mass vs. coupling constant



- orange: disfavoured by kinetic decoupling (CMB)
- blue: Landau pole $\Lambda < M_P$
- black lines: fraction of observed DM density

Outlook: Where to go from here?

- Conflicting observations of different cluster mergers, low resolution of weak lensing mass reconstruction

  $\Rightarrow$ More observations required!

- Effects of dark plasma dynamics on galactic and cluster halos, structure formation etc.

  $\Rightarrow$ More simulations required!

- Natural explanation for the partially interacting dark matter scenario, *e.g.* partially ionized dark atoms?

  $\Rightarrow$ More modelbuilding required!

The Minimal Take Home Message

1. Collisionless shocks dictate the dynamics of rare astrophysical plasmas.
2. Dark matter coupled to dark radiation behaves the same way.
3. Considering only $2 \to 2$ scattering is in this case not adequate.

For the full story: 1504.04371