Evidence for Dark Matter Self-Interactions via Collisionless Shocks in Cluster Mergers

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Beyond WIMPs: from theory to detection
May 29, 2015

M. Heikinheimo, M. Raidal, C. Spethmann, H. Veermäe,
arXiv:[1504.04371 [hep-ph]] + work in progress

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5 Conclusions and outlook

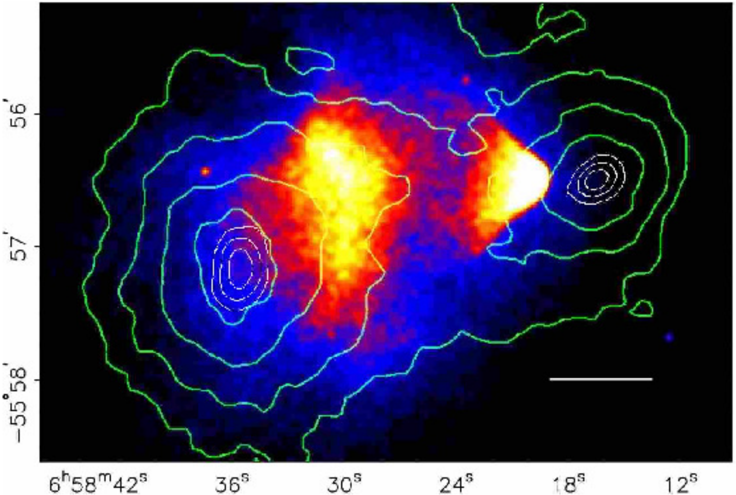
Paradigm shift in DM physics: non-trivially interacting Dark Sector

- DM self-interactions may solve small-scale structure formation problems (core vs cusp, less substructure than in N-body simulations)
- Studies of DM self-interaction have been considered $2 \rightarrow 2$ scatterings
- The aim is to go beyond that and to study collective effects of DM interactions

Astrophysical observations

- 1E 0657-558: in the bullet cluster, the dark matter halo of the subcluster is observed to pass through the main cluster [astro-ph/0309303].

The bullet cluster: 1E 0657-558



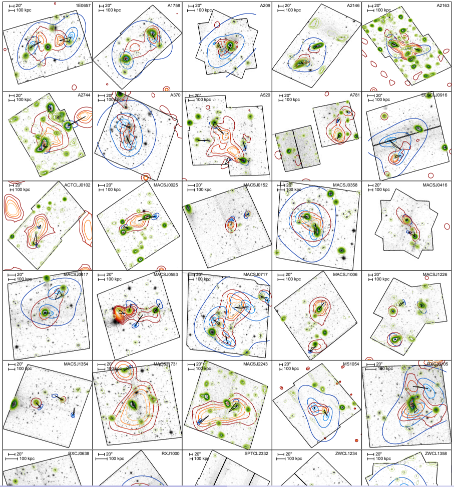
Constraints from the bullet cluster

- Constraint on DM 2 → 2 scattering cross section

$$\frac{\sigma_{DM}}{m} < 1.3\frac{\mathrm{cm}^2}{\mathrm{g}} \approx 2\frac{\mathrm{barn}}{\mathrm{GeV}} \ll 100\frac{\mathrm{barn}}{\mathrm{GeV}}$$

- Less than 30% of DM can be self-interacting

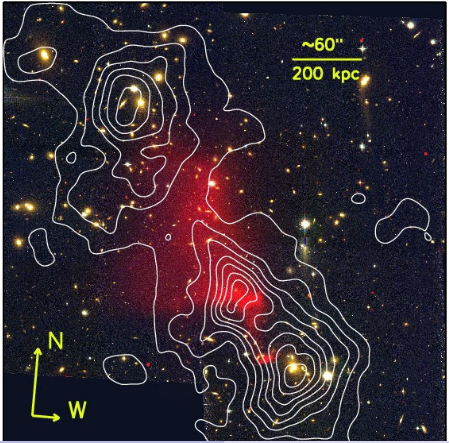
Structure formation: cluster merges



Astrophysical observations

- 1E 0657-558: in the bullet cluster, the dark matter halo of the subcluster is observed to pass through the main cluster [astro-ph/0309303].
- Abell 520: an excess of dark matter observed on top of the visible X-ray emitting gas, between the merging clusters [1401.3356 [astro-ph.CO]].

Abell 520



Abell 520: implications

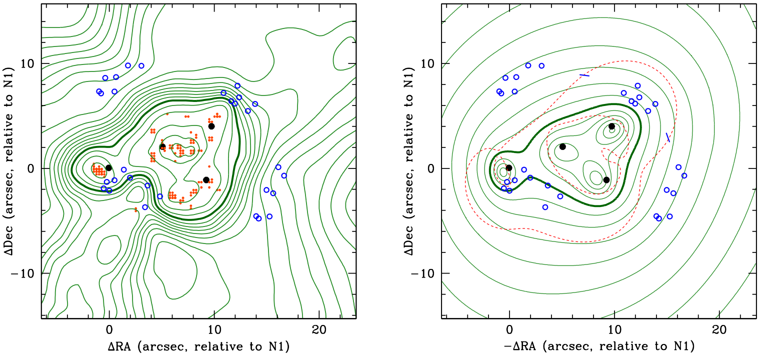
- The direct observational evidence for DM self-interactions
- Numerical simulations show that formation of new sub-cluster in Abell 520 cannot be explained with DM $2 \to 2$ scatterings

F. Kahlhoefer, K. Schmidt-Hoberg, M. T. Frandsen and S. Sarkar, Mon. Not. Roy. Astron. Soc. 437, 2865 (2014)

Astrophysical observations

- 1E 0657-558: in the bullet cluster, the dark matter halo of the subcluster is observed to pass through the main cluster [astro-ph/0309303].
- Abell 520: an excess of dark matter observed on top of the visible X-ray emitting gas, between the merging clusters [1401.3356 [astro-ph.CO]].
- Abell 3827: a separation between the dark matter halo and the visible stars observed in the central four galaxies [1504.03388 [astro-ph.CO]].

Abell 3827


ΔDec (arcsec, relative to N1)
10
0
−10
0
10
20
ΔRA (arcsec, relative to N1)
−ΔRA (arcsec, relative to N1)

Abell 3827: implications

- Another direct observational evidence for DM self-interactions
- The drag force can be created by DM 2 → 2 scatterings or collective effects

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Observational implications for DM

- Sub-component of DM must behave in collisions as ionized gas: must be able to dissipate energy
    - The double-disc DM?
- The halo must remain tri-axial: should not radiate effectively to cool to a disc
- The suitable DM candidate:
  pair plasma of particles with mass m

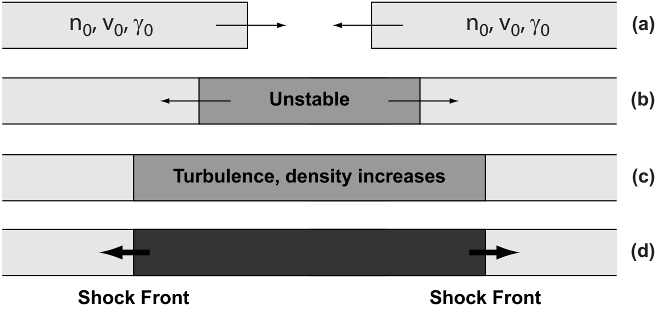
Plasma

Plasma is a fluid, where

- the size of the fluid is large compared to the Debye shielding length $\lambda_D = \sqrt{\frac{T}{4\pi\alpha n}}$ (bulk interactions dominate over surface effects),
- collective effects are present: $\Lambda = \frac{4\pi}{3}\lambda_D^3 n \gg 1$,
- electrostatic interactions dominate over $2 \to 2$ scattering: $\omega_p = \sqrt{\frac{4\pi\alpha n}{m}} \gg \Gamma_{2\to 2}$.

Collisionless shocks

In counter-streaming plasma, electromagnetic instabilities can cause shock waves that lead to energy dissipation even if the mean free path determined by the 2 → 2 scattering is much larger than the size of the system [1502.00626 [physics.plasm-ph]].



Collisionless shocks

- Collisionless shocks are observed *e.g.* in the Earth's bow shock, in the expansion of supernova remnants into the interstellar medium and in X-ray emitting hydrogen plasma in galaxy collisions and cluster mergers.
- Collisionless shocks are studied numerically with particle in cell (PIC) simulations, and experimentally with electron-positron plasmas and ionized gases produced with laser pulses.
- Currently, numerical simulations of nonrelativistic pair-plasmas have not yet been performed.

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Dark plasma

- The goal is to explain the observed collisional behaviour of DM with energy dissipation caused by collisionless shocks
    - The plasma instability growth can be estimated in a linear regime: analytic estimates possible
    - The saturation phase (and energy dissipation) is non-linear: numerical simulations needed
- From observations of the bullet cluster, the fraction of collisional DM can be no more than 30%.
- In our minimal model we assume that 70% of DM is a generic WIMP, and 30% consists of *dark plasma*.

The minimal model of dark pair plasma

- The minimal model for dark plasma is one Dirac fermion charged under an unbroken $U(1)$ gauge group:

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

- We neglect the kinetic mixing term $F_{D\mu\nu} F^{\mu\nu}$ as it is highly constrained.
- The dark matter abundance is produced as a thermal relic by the annihilation into dark photons, $\bar{\chi}\chi \to \gamma_D \gamma_D$.

Numerical results

- 30% of correct relic abundance is obtained for $\alpha_D \approx 4.5 \times 10^{-5} \frac{m_D}{\mathrm{GeV}}$.
- For $R = 200$ kpc and $M = 4 \cdot 10^{13} M_\odot$ halo we obtain: $\lambda_D \approx$ 45.8 km $\sqrt{\frac{m_D}{\mathrm{GeV}}}$, $\Lambda \approx 5.5 \cdot 10^{18} \sqrt{\frac{m_D}{\mathrm{GeV}}} \gg 1$, $\lambda_{\mathrm{mfp}} = \lambda_D \frac{\Lambda}{\log \Lambda} \approx 189$ kpc $\left(\frac{m_D}{\mathrm{GeV}}\right)$.
- The plasma instability formation time can be estimated:

$$\tau_s \approx 10^3 \omega_p^{-1} \approx 85.3\ \mathrm{s} \sqrt{\frac{m_D}{\mathrm{GeV}}}.$$

- The shock waves most certainly form!
- Characteristic bremsstrahlung time $t_{\mathrm{brems}} \approx 4.7 \cdot 10^{19}$ yr, where the dependence on the DM mass cancels out

Observational Constraints: BBN

- BBN bound on effective number of neutrino species $N_{\rm eff} = 3.04 + 2\left(\frac{T_D}{T_\gamma}\right)^4 = 3.15 \pm 0.23$ constrains the temperature of the dark photons during BBN.
- The dark photon temperature is given as

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

  where the two sectors are assumed to be in thermal equilibrium at T_*.
- This constrains the number of fermions in the dark sector: $N_D < 2.35$.

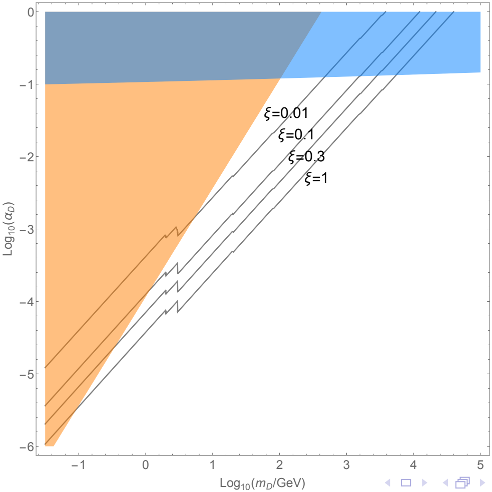
Observational Constraints: CMB

- The rate of structure formation is suppressed until the 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.

Results: lower bound on DM mass



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Symmetric atomic DM

Can one do better and explain all DM properties with such a model?

- Extend the model with more flavours: χ_1, χ_2 with (approximately) equal masses
- Bound states $\bar{\chi}_1\chi_2$ can form most of the DM: the symmetric dark atoms that are thermally produced
- Subdominant fraction remains ionized or is re-ionized in cluster mergers
- Sommerfeld enhancement is needed to boost the recombination into symmetric atoms after DM freeze-out
- Work in progress ...

Interesting predictions of this scenario: to do list

- Dark plasma heats up and does not radiate effectively: in the centres of halos there must be isothermal dark plasma cores. A solution to the core vs cusp problem?
  - N-body simulations with baryons and dark cores needed
- Dark collisionless shocks are a generic property of structure formation. There should be dark Fermi mechanism for dark cosmic ray acceleration with E^2
  - Dark CR feedback for structure formation?
  - Has IceCube detected very high-energy dark cosmic rays instead of neutrinos?

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Conclusions

- Cluster mergers hint that self-interacting DM collective effects may dominate over $2 \rightarrow 2$ scatterings
- Collisionless shocks in dark pair plasma may explain the observations
- We show that such shocks form quickly, and they may solve the small-scale structure problems
- Such a DM is thermal relic
- Interesting implications for halo profiles and dark cosmic rays

Outlook

- More observations required to form a coherent picture of DM dynamics in cluster mergers.
- Detailed simulations of non-relativistic dark plasma needed to understand its effects on galactic and cluster halos, structure formation etc.
- Further model building required for explaining naturally the partially interacting dark matter scenario, *e.g.* partially ionized dark atoms...