Dark Plasma and Cluster Mergers

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[1504.04371 [hep-ph]], M. H., M. Raidal, C. Spethmann, H. Veermäe

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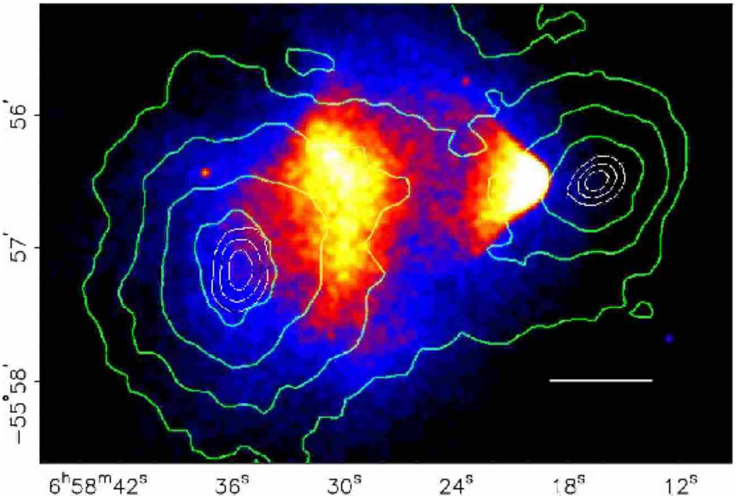
Astrophysical observations

- **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].

1E 0657-558



Astrophysical observations

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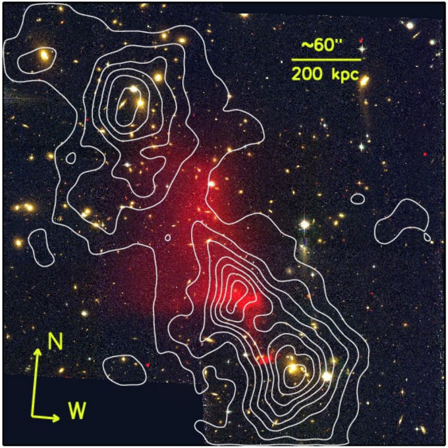
- **Abell 520:** an excess of dark matter observed on top of the visible X-ray emitting gas, between the merging clusters [1401.3356 [astro-ph.CO]].

Abell 520



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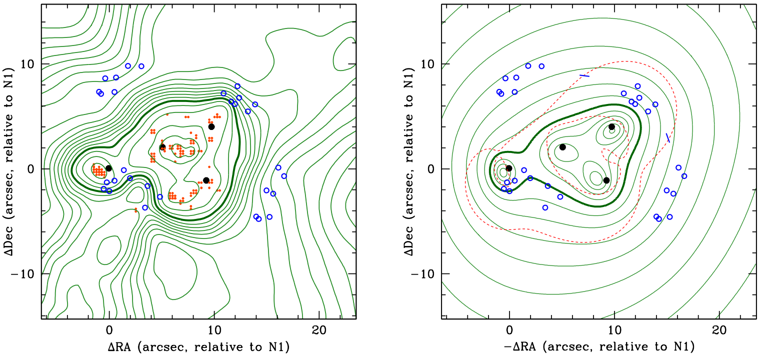
- **1E 0657-558:** in the bullet cluster, the dark matter halo of the subcluster is observed to pass through the main cluster [astro-ph/0309303].
- **Abell 520:** an excess of dark matter observed on top of the visible X-ray emitting gas, between the merging clusters [1401.3356 [astro-ph.CO]].
- **Abell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


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

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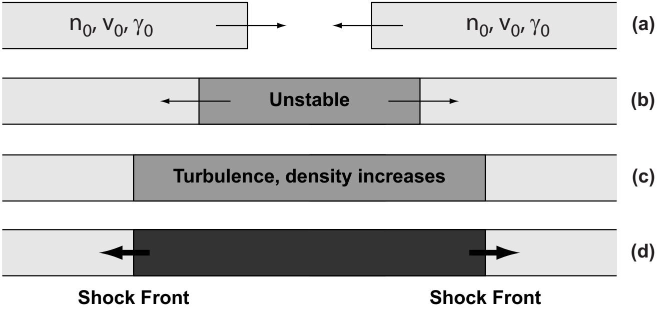
Plasma

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 $2 \to 2$ 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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The model

- The goal is to explain the observed collisional behaviour of DM with energy dissipation caused by collisionless shocks.
- 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*.

Dark 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, $\bar{\chi}\chi \to \gamma_D \gamma_D$.

Observational Constraints

- BBN bound on effective number of neutrino species $N_{\rm eff} < 3.38$ 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: $N_D < 2.35$.

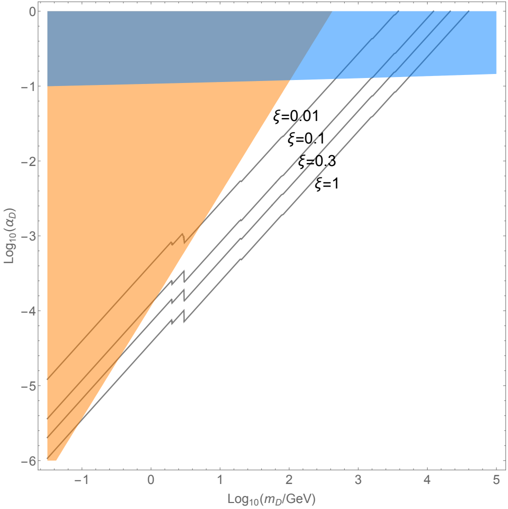
Observational Constraints

- The rate of structure formation is suppressed untill the kinetic decoupling of the dark matter and dark radiation, which occurs at

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

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

Results



Outlook

- More observations required to form a coherent picture of DM dynamics in cluster mergers.
- More detailed analysis on 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...