A new constraint on millicharged dark matter from galaxy clusters

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Based on arXiv: 1603.1959 in collaboration with

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Millicharge?

Fractional EM charge

- no evidence of charge quantization of $U(1)_{EM}$
  - GUT/magnetic monopole is yet to be probed
  - Arbitrarily small fractional charge is possible

- kinetic mixing of multiple U(1) Holdom (1986)

$$\mathcal{L} \supset \epsilon_{ij} F_i^{\mu\nu} F_{j\mu\nu} \quad (i \neq j)$$

  - Allowed from gauge invariance
  - Kinetic mixing generally arises from RG

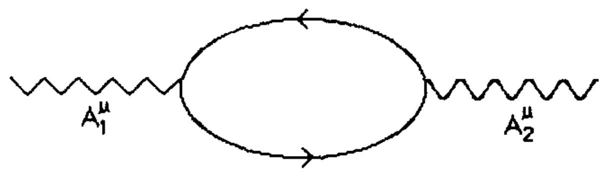


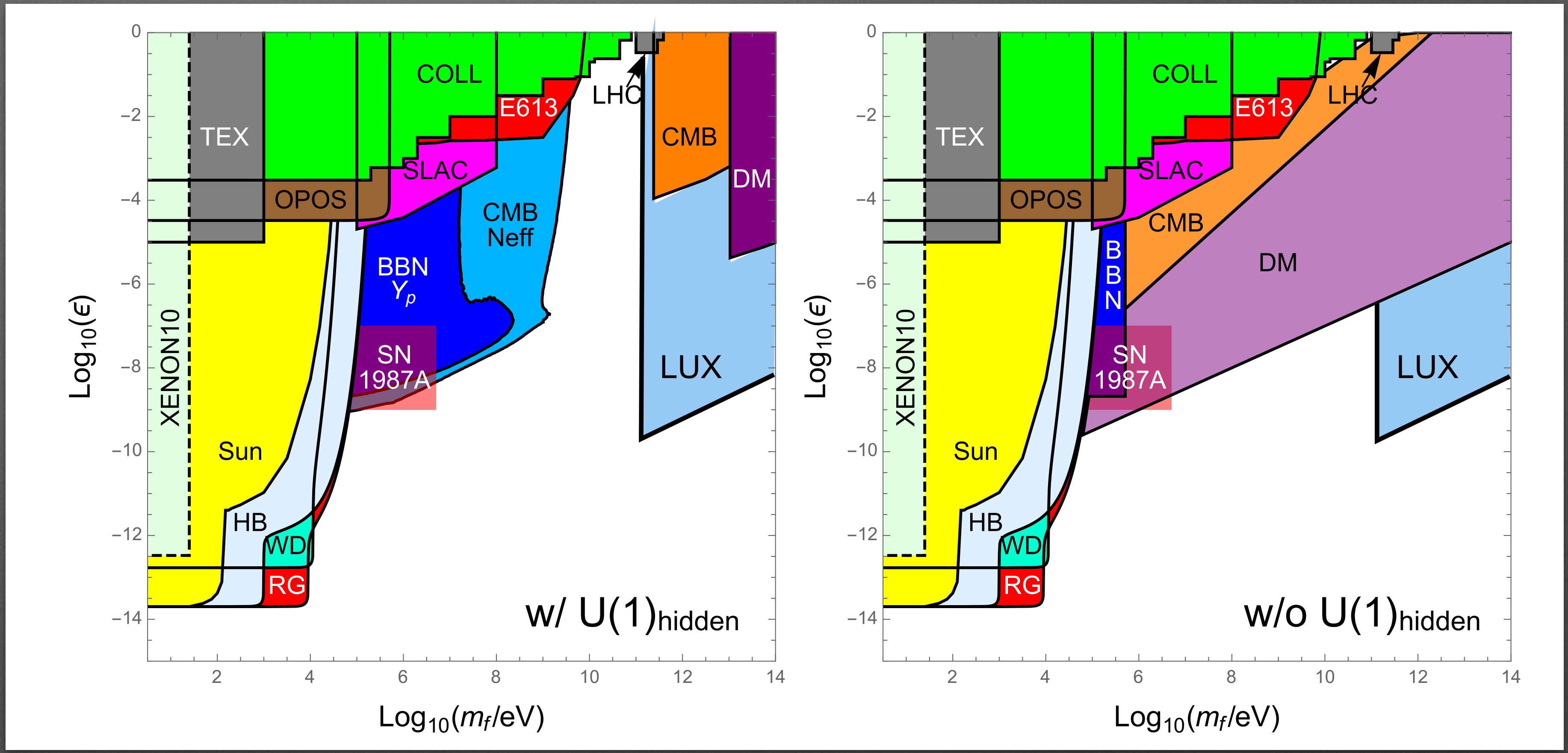
Fig. 1.

Millicharged dark matter?

Dark matter may not be completely dark

- can have a fractional EM charge $\epsilon = \frac{q}{e} \ll 1$
- subject to various constraints:
  - collider
  - astrophysics (cooling of stars, SNe)
  - cosmology (Ω_{DM}, CMB, BBN, …)
  - direct DM detection

Summary of previous constraints



Vinyoles & Vogel (2015)

Summary of previous constraints

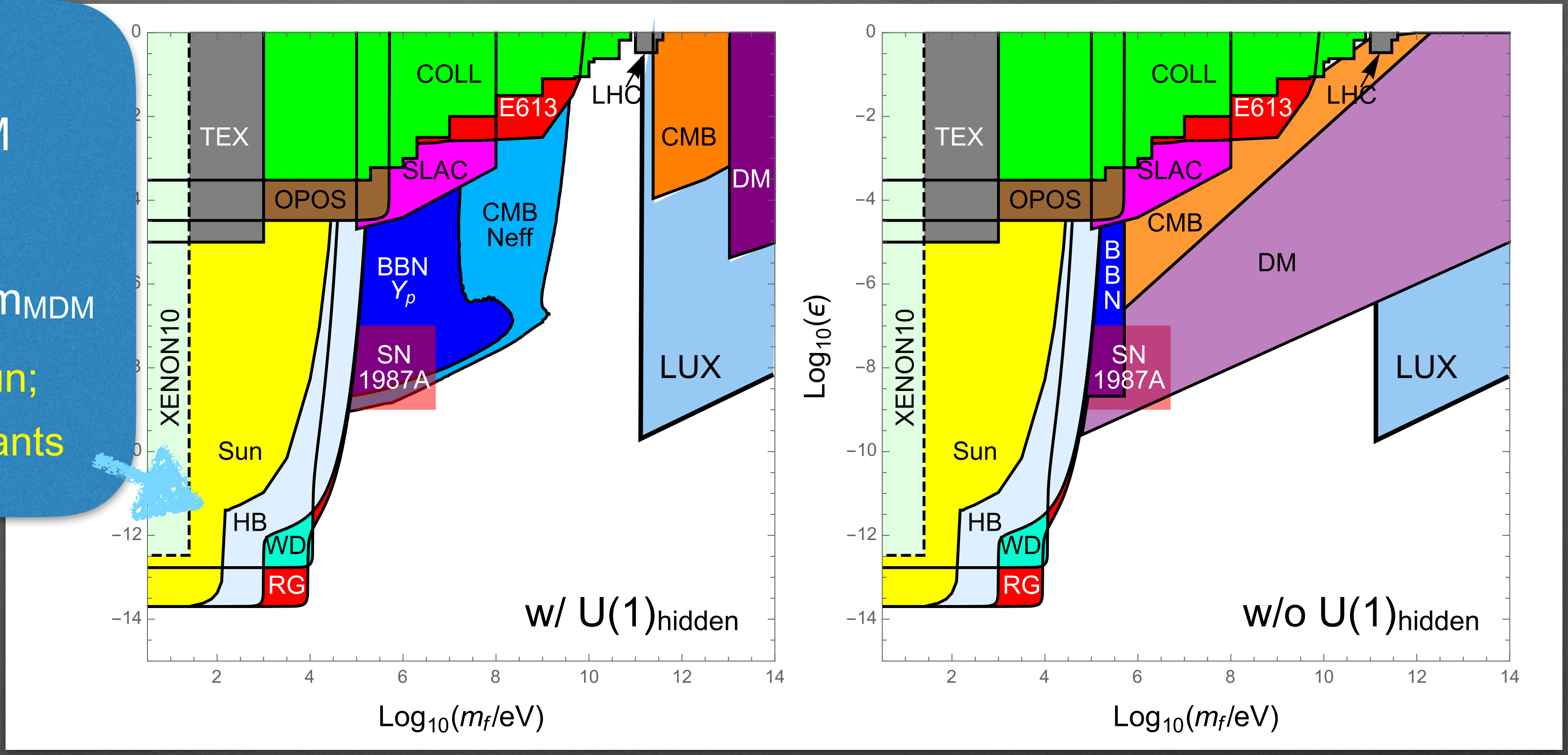
Astrophysical constraints

Modified stellar evolution with MDM emission $\gamma^* \to \chi\bar{\chi}$

Effective only if plasmon mass > $2m_{MDM}$

$$\omega_p^2 = \frac{4\pi\alpha n_e}{m_e},$$

~ 300eV for the Sun; 10keV for red-giants



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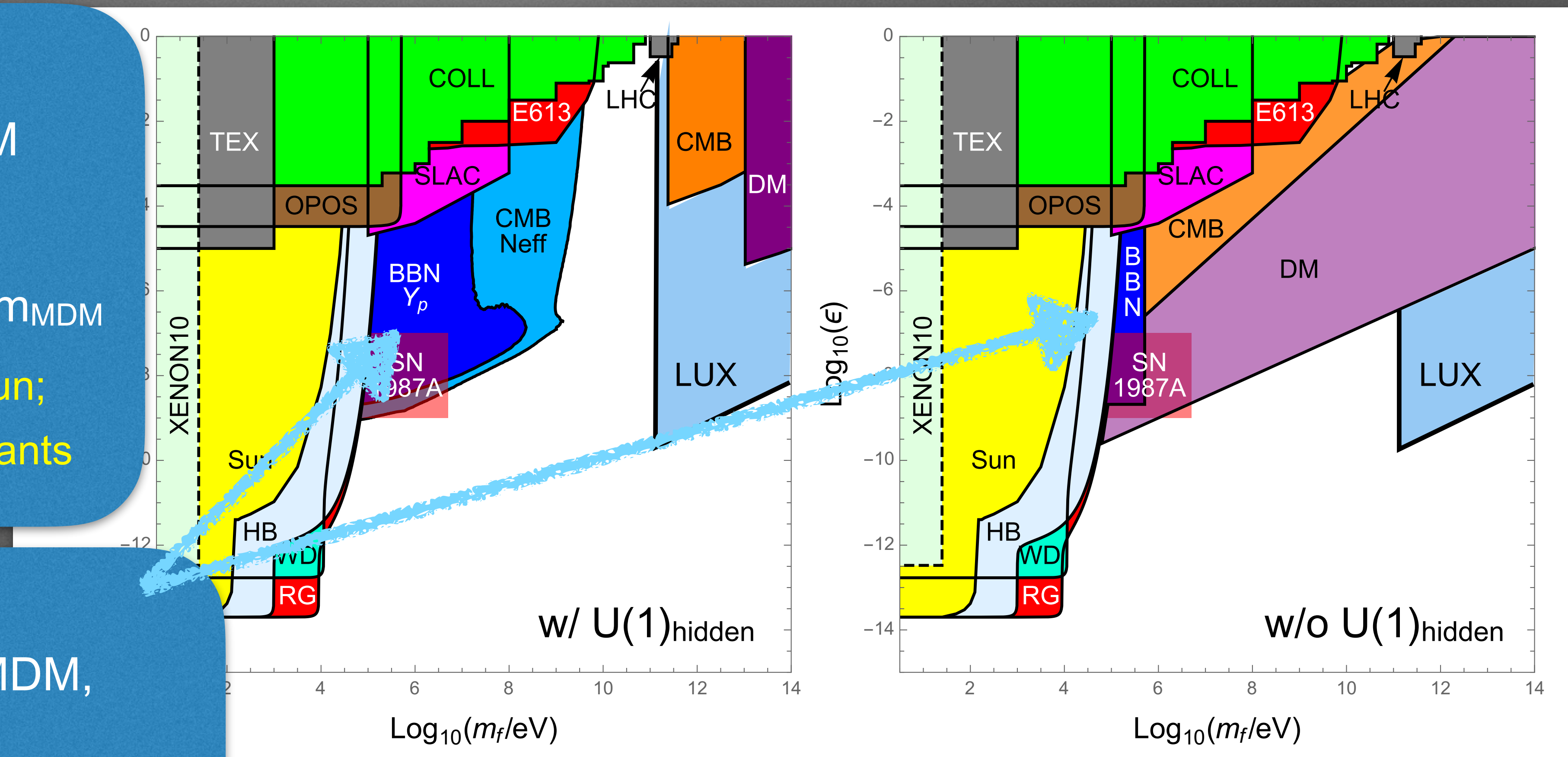
BBN

For $m_{DM} \leq m_e$, e^+e^- annihilate into MDM, while photon is less heated up.

- ✓ higher N_{eff} ⬅U(1)' can contribute
- ✓ higher n_b/n_γ at BBN

➡Earlier neutron freeze-out increases Y_p



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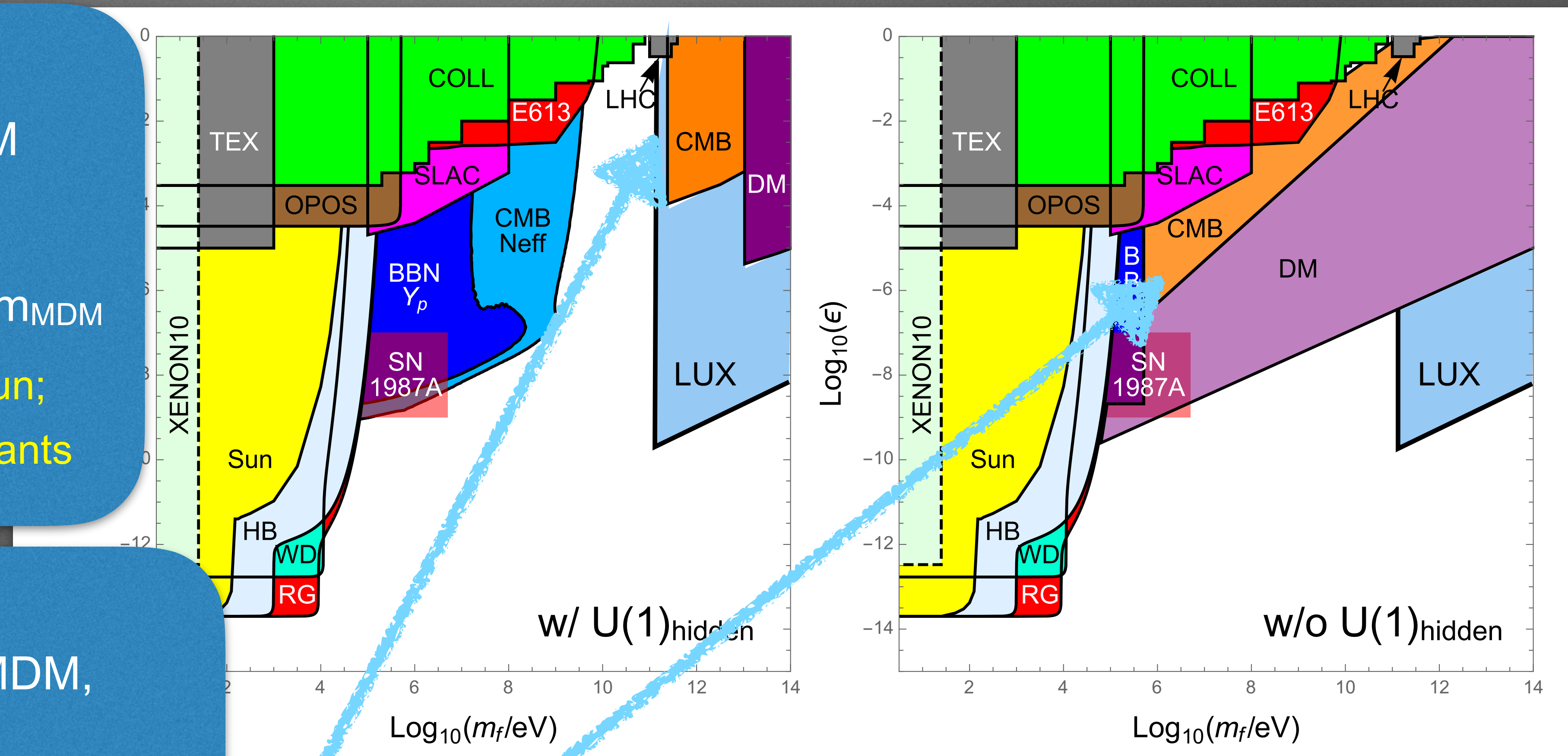

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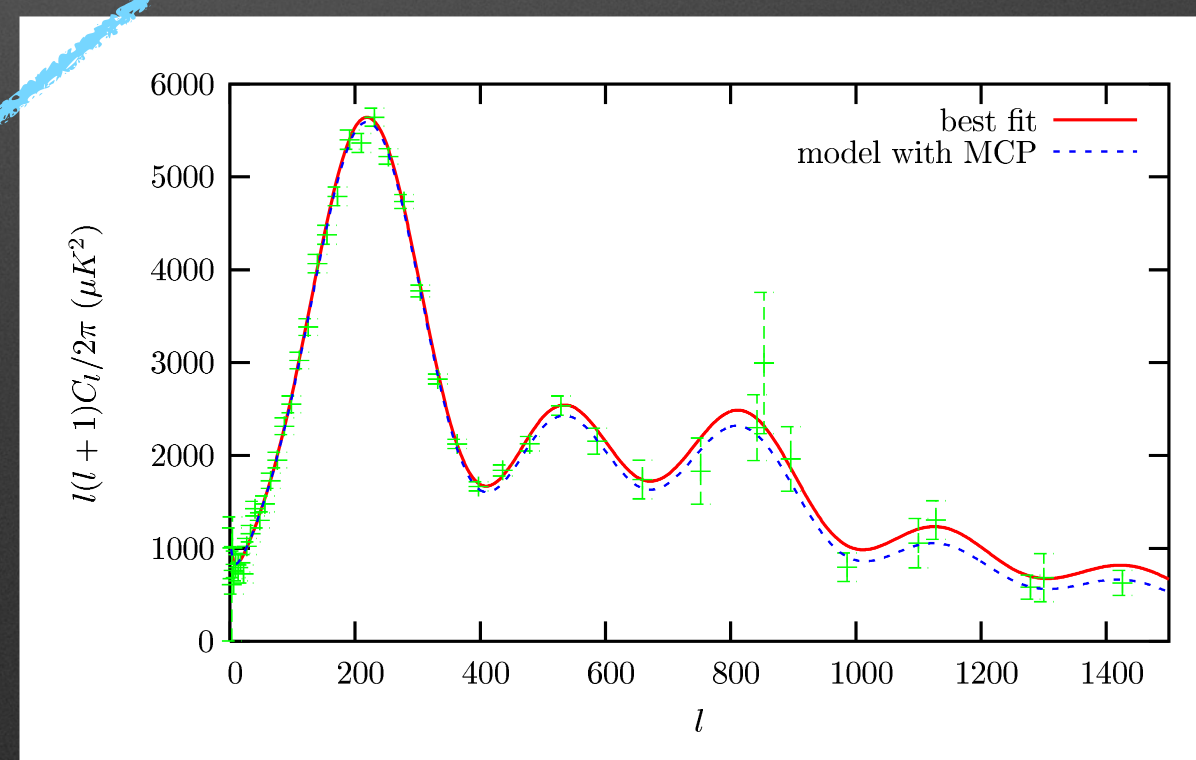
CMB

MDM can kinetically couple to e^- via Coulomb scattering

➡Acoustic oscillation is modified

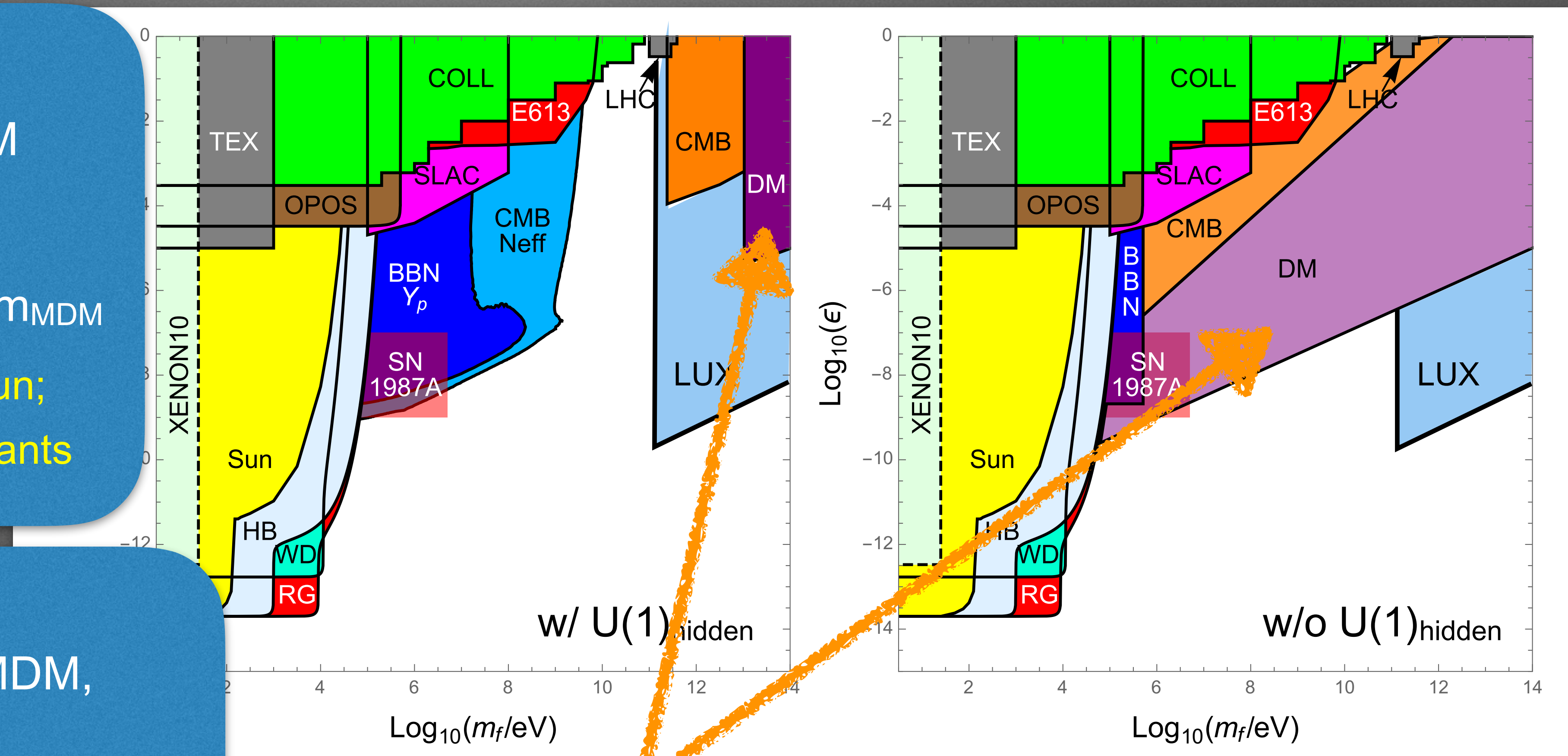
(or enhanced diffusion damping fixed $\Omega_b+\Omega_{mdm}$)

MDM should decouple before recombination



Dubovskya, Gorbunova & Rubtsov (2003)

Summary of previous constraints



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Thermal relic abundance

main process: $\chi\bar{\chi} \leftrightarrow f\bar{f}$

- w/o U(1)’: overclose when thermalized
- w/ U(1)’: MDM annihilates into U(1)’

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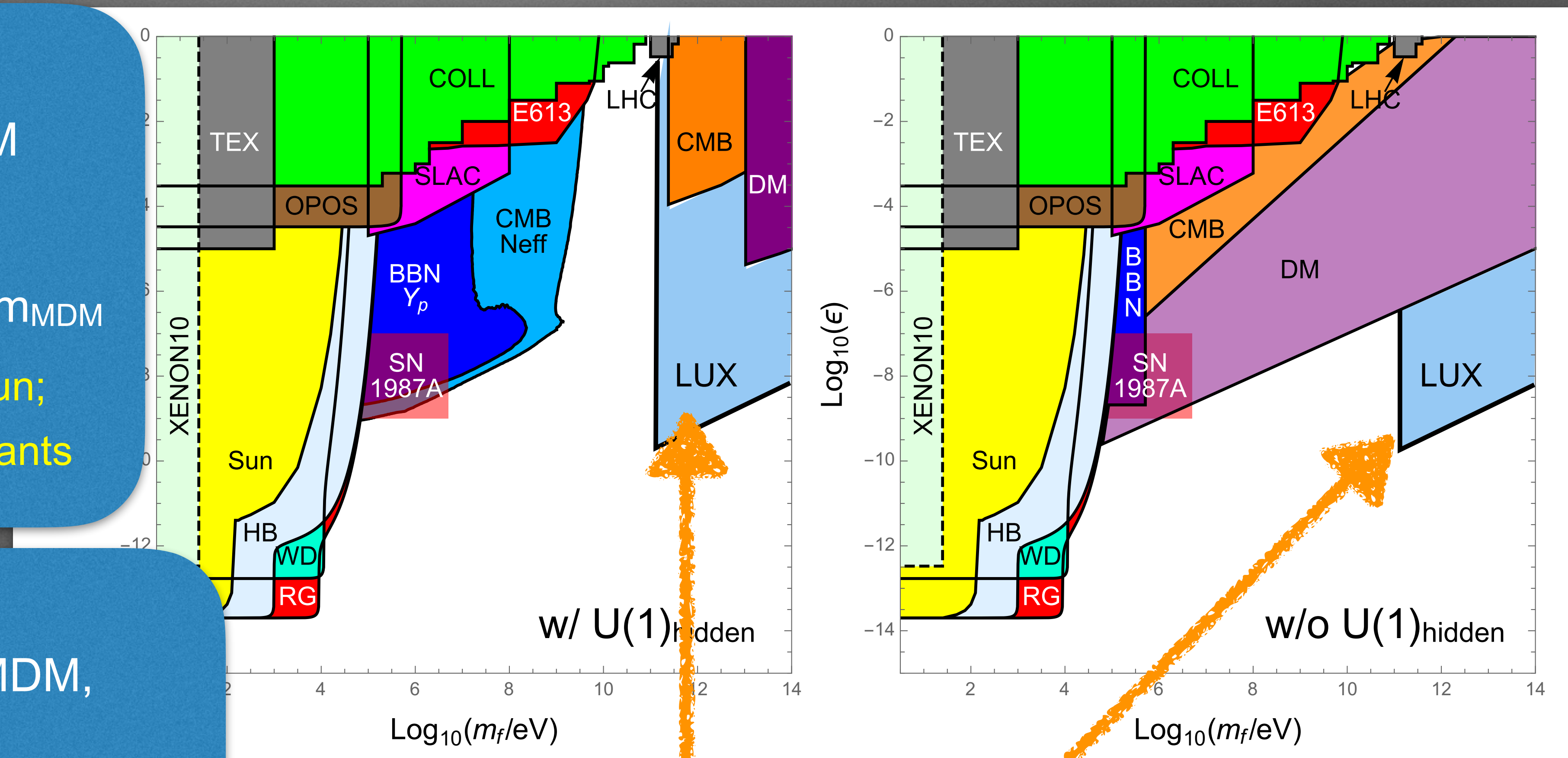

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Direct detection

cross section wrt recoil energy

$$\frac{d\sigma_T}{dE_R}(v,q^2) = 8\pi m_T \frac{\alpha^2\epsilon^2}{v^2\, q^4} Z_T^2\, F_T^2(q^2)$$

➡Equivalent to F_T with $1/q^4$ in short-range interaction

spin-independent ➡ best constraint from LUX

Circumventing direct detection

Chuzhoy & Kolb (2009)

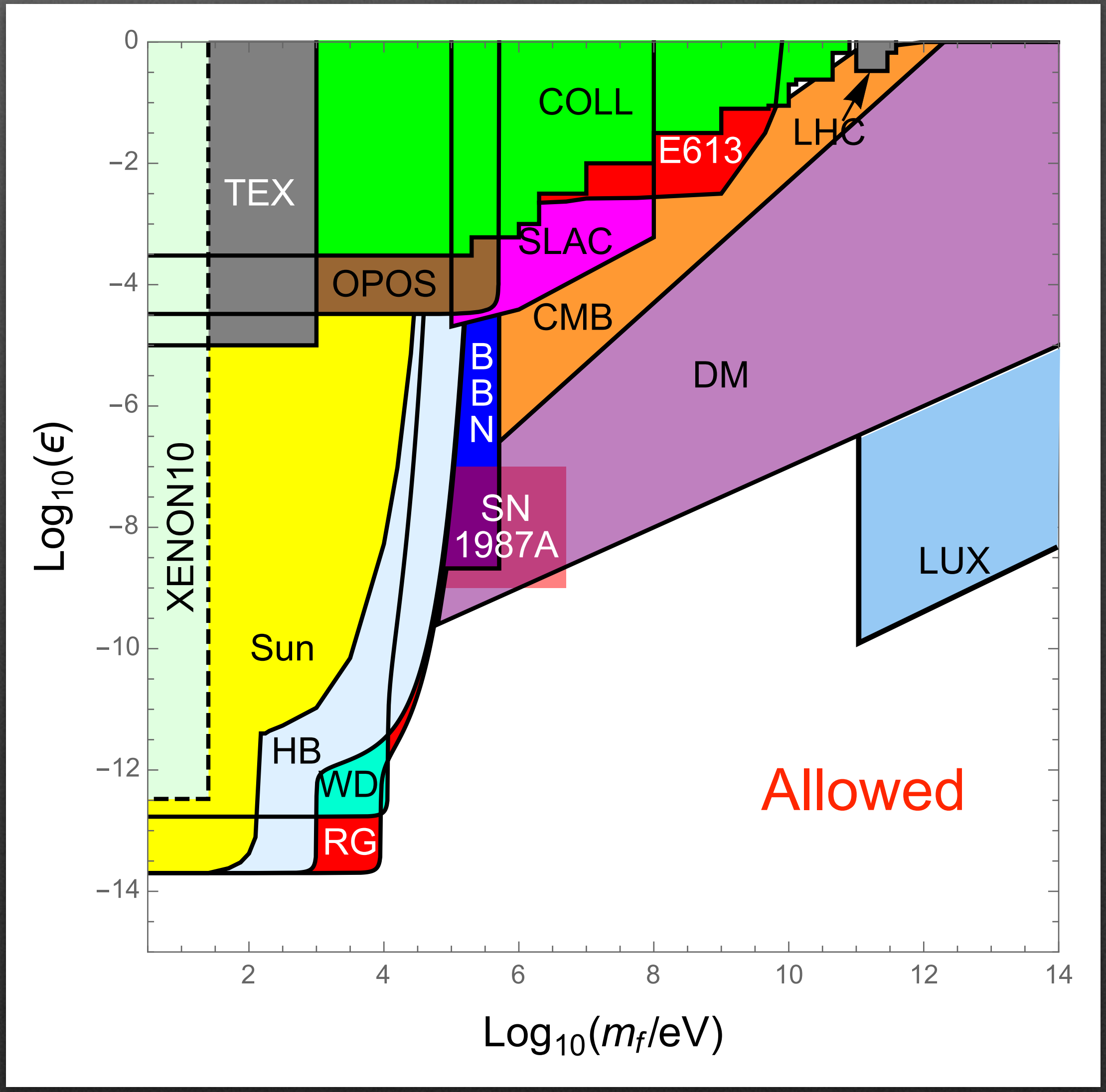
Charged DM may be absent in Milky Way

- MDM is accelerated by past supernova explosions (Fermi acceleration). MDM cannot lose energy efficiently and be expelled from Milky Way.

$$\tau_{\mathrm{rel},p} \approx 300 \text{ years} \left(\frac{e}{q_X}\right)^2 \left(\frac{m_X}{m_p}\right) \left(\frac{v_X}{100 \text{ km s}^{-1}}\right)^3 \times \left(\frac{n_p}{10^{-2}\mathrm{cm}^{-3}}\right)^{-1},$$

- DM from Milky Way halo cannot reach galaxy due to Galactic magnetic fields mostly parallel to Galactic plane (thickness~100pc).

$$R_g = 10^{-9}\mathrm{pc} \left(\frac{m_X}{m_p}\right) \left(\frac{e}{q_X}\right) \left(\frac{v_X}{300 \text{ km s}^{-1}}\right) \left(\frac{B}{1\mu\mathrm{G}}\right)^{-1}$$



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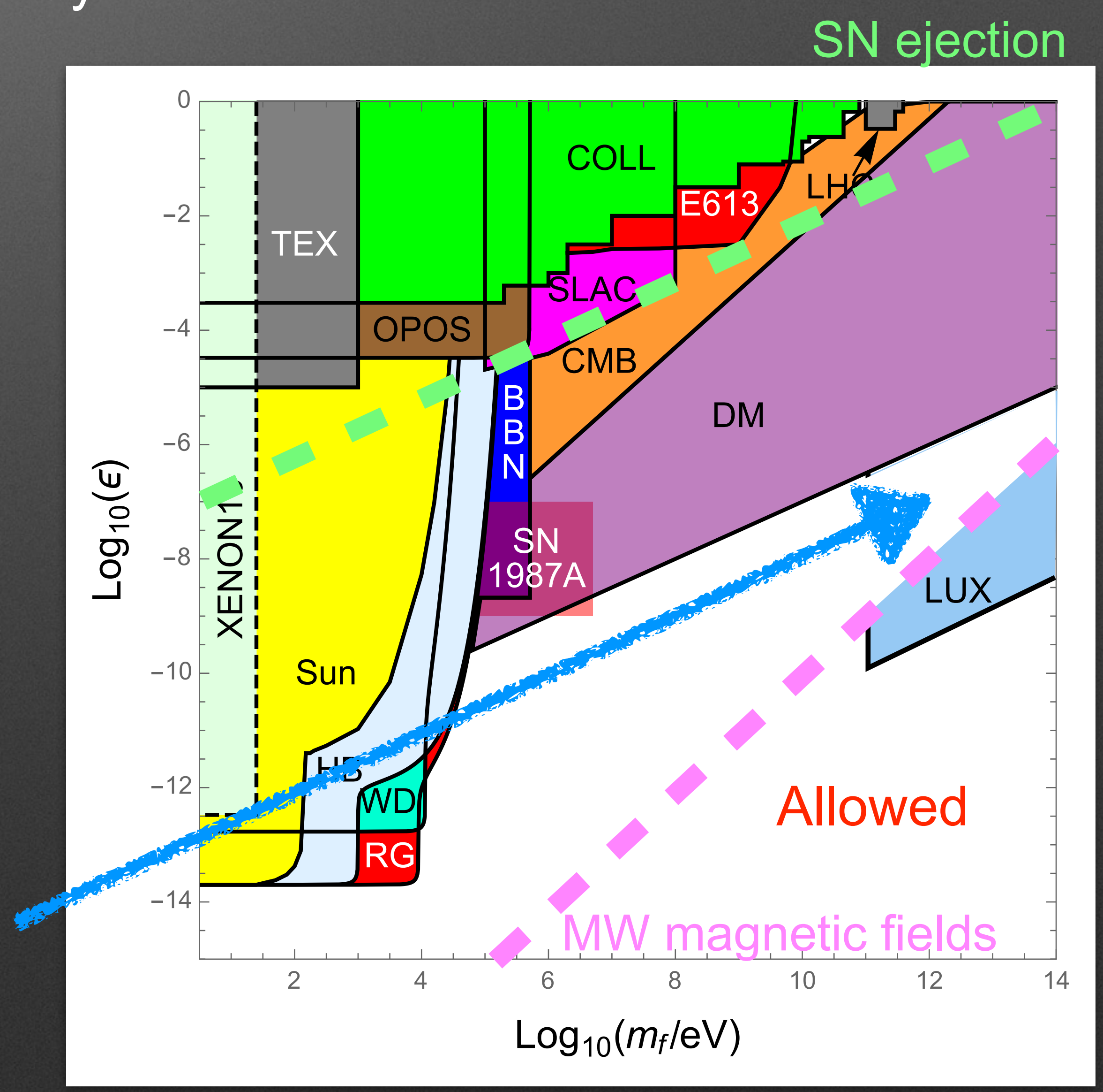
These arguments open up a window of MDM.

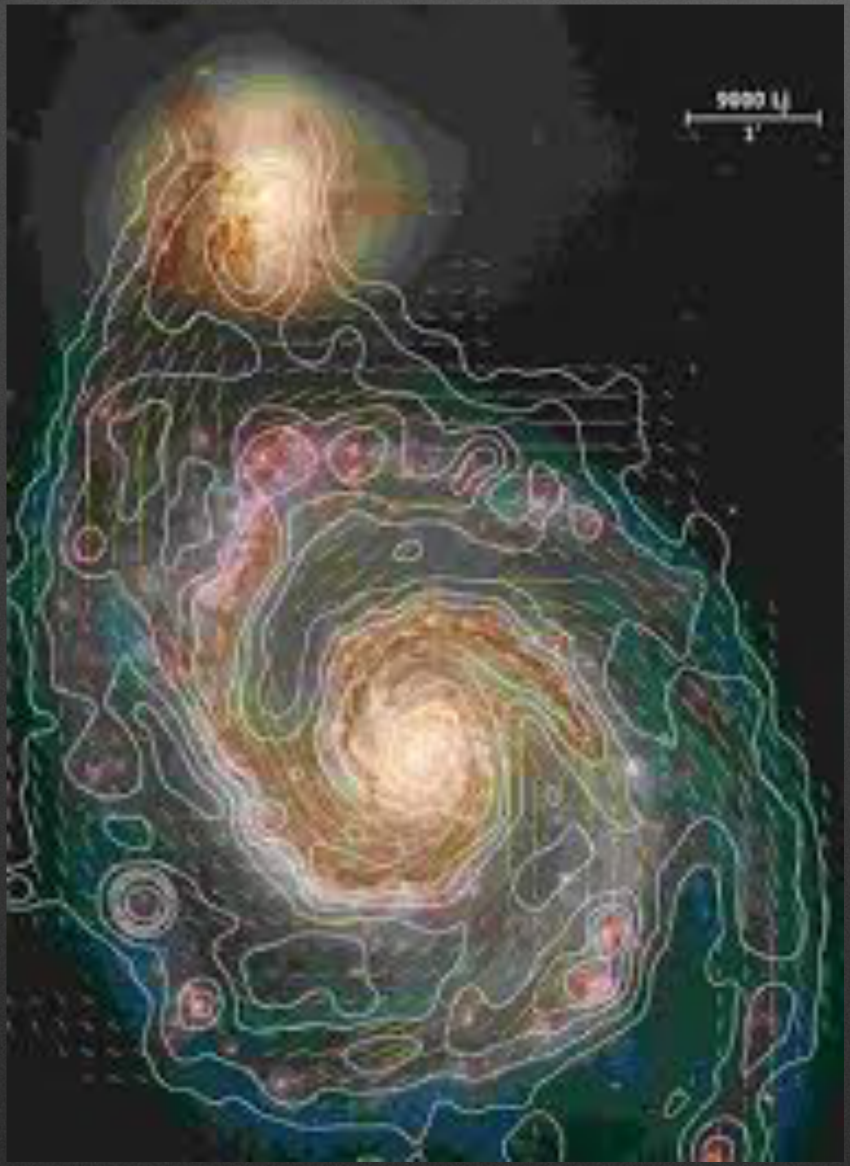
$$10^{-11}\frac{m_{\mathrm{DM}}}{\mathrm{GeV}} \lesssim \epsilon \lesssim 3\times 10^{-3}\left(\frac{m_{\mathrm{DM}}}{\mathrm{GeV}}\right)^{1/2}$$



Galaxy to galaxy clusters?

K. Kadota, TS & H. Tashiro (2016)

If motion of MDM is modified at galaxy scales, what will happen at larger scales like galaxy clusters?



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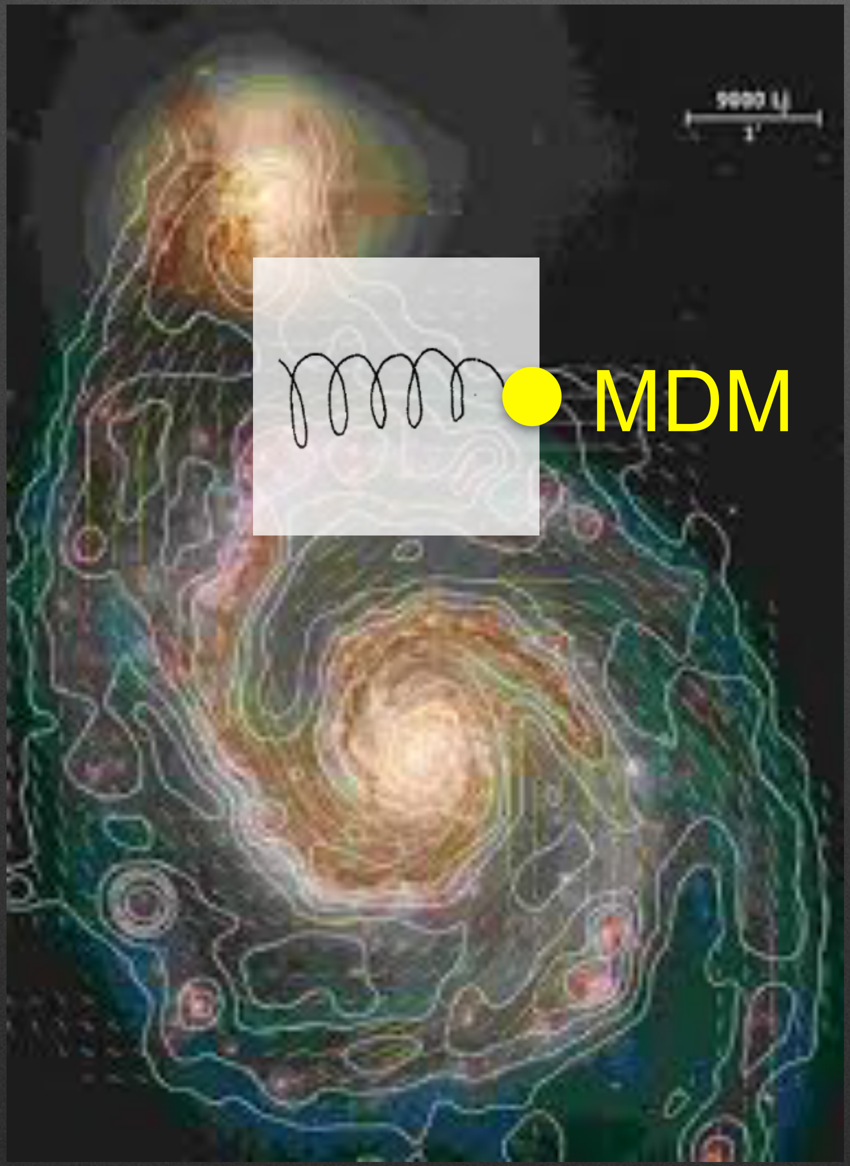

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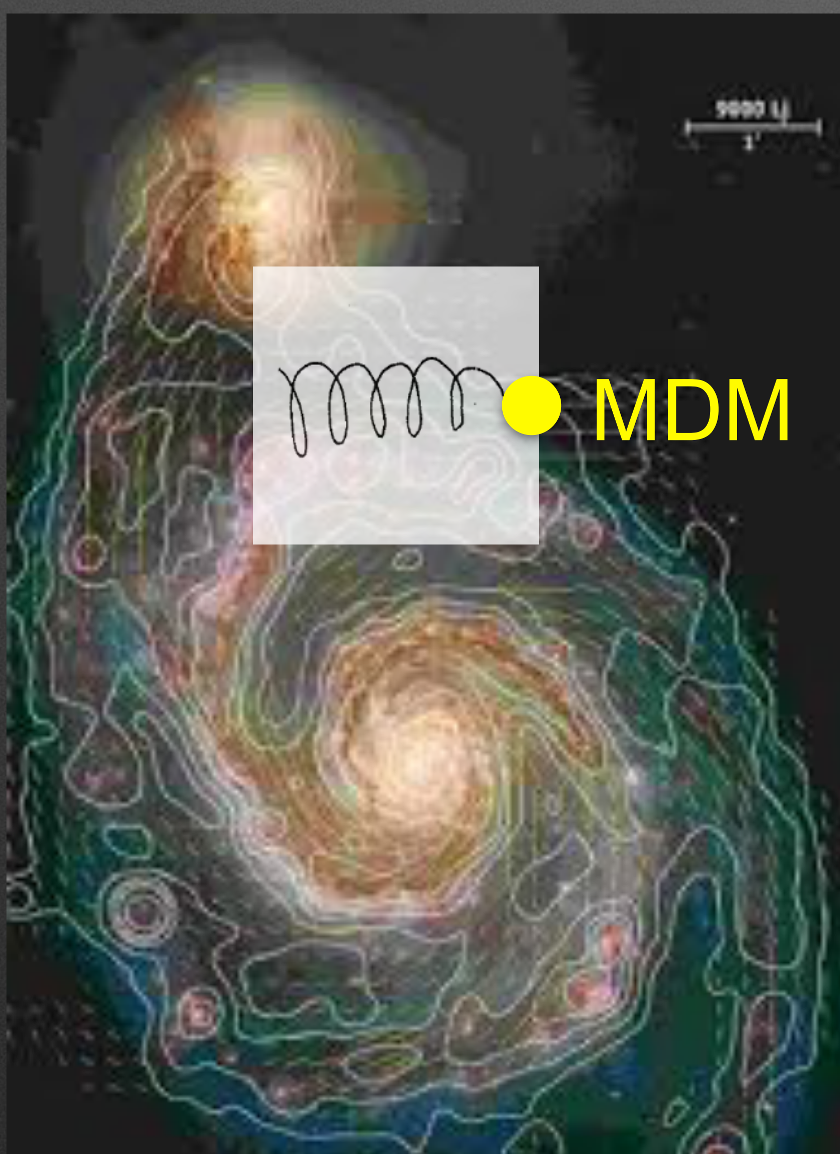
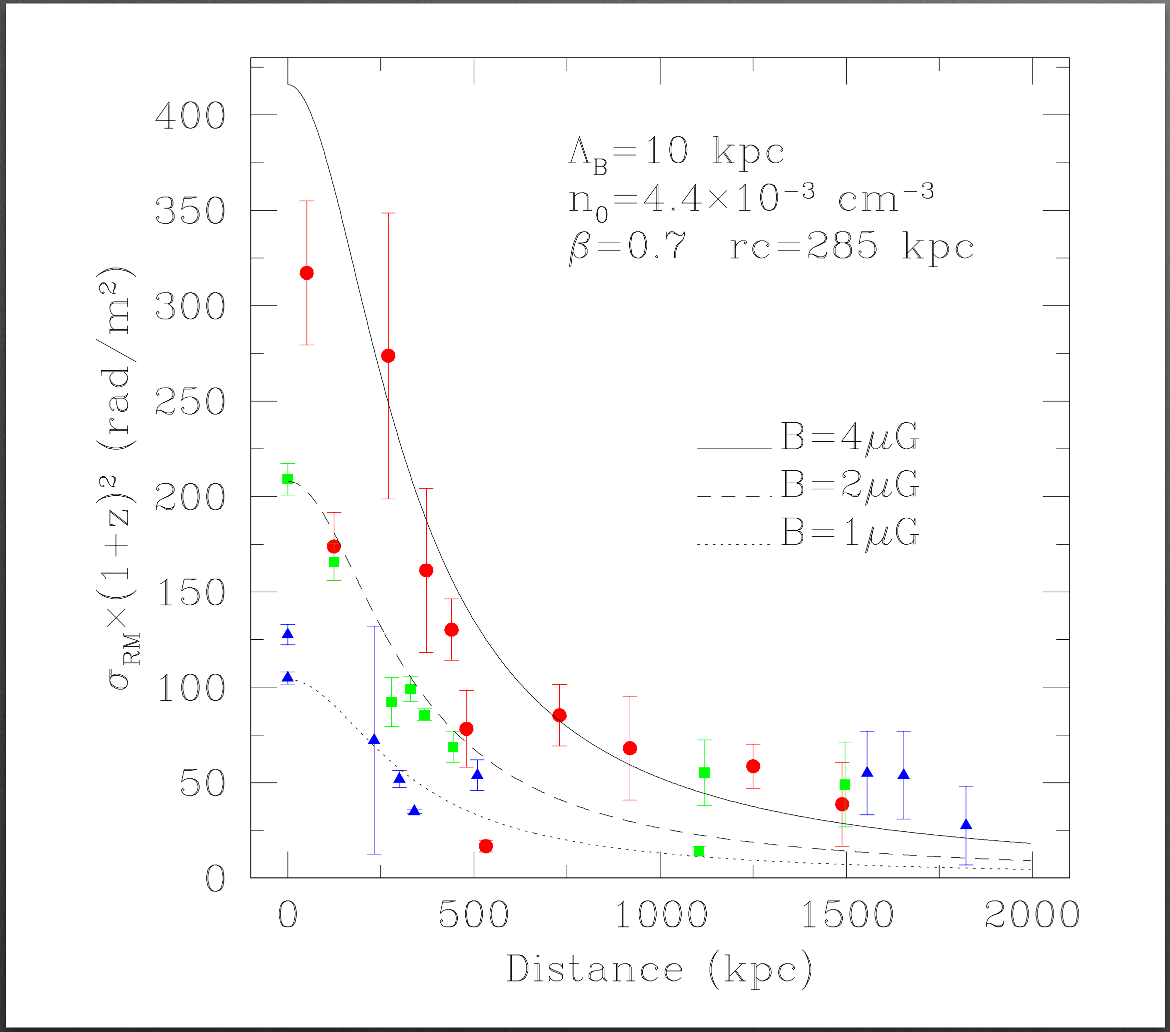
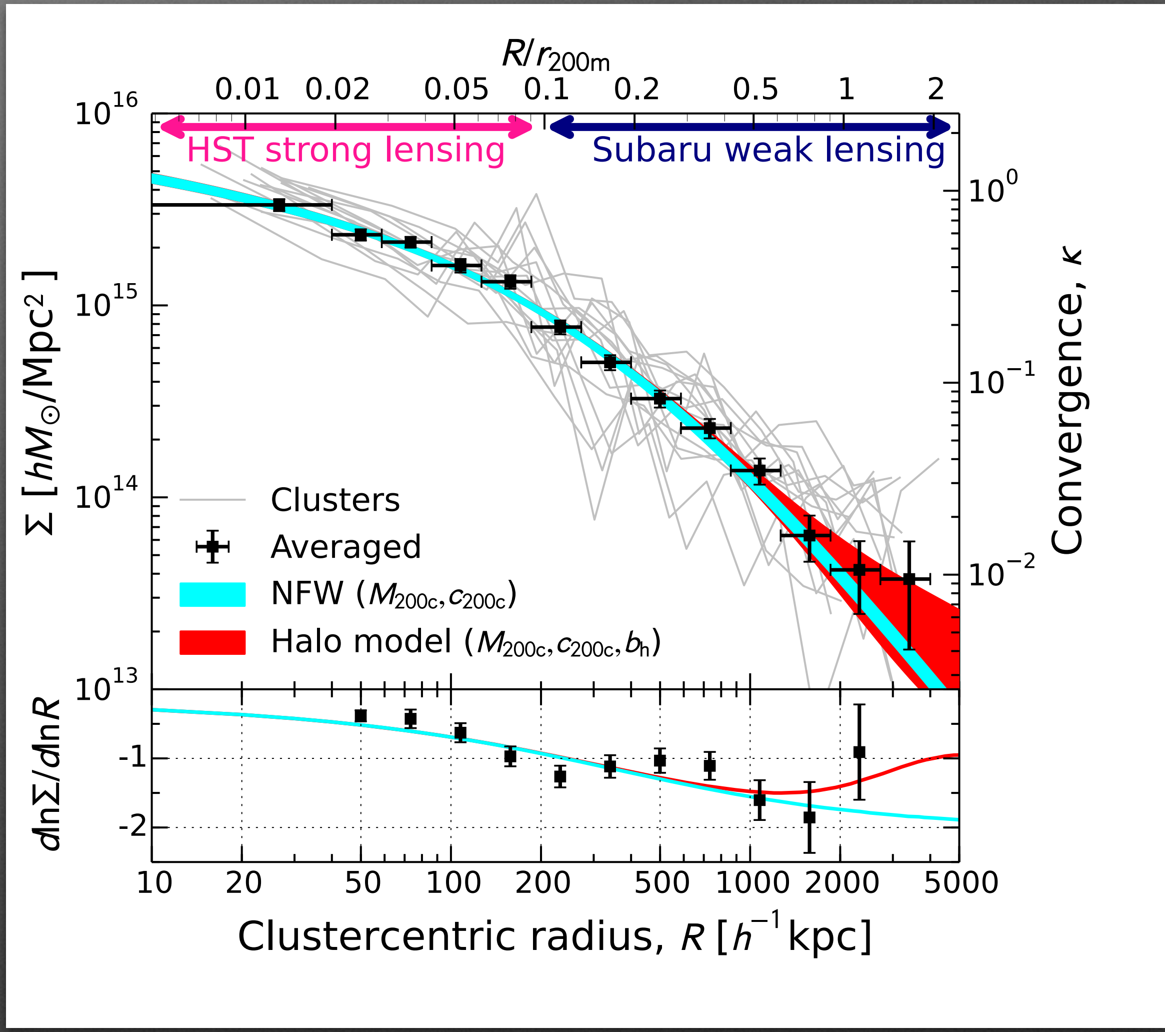


Two facts about galaxy clusters



Govoni+ (2010)



Umetsu+ (2015)

✓Magnetic fields exist also in galaxy clusters

B = a few μG (Faraday rotation measure)

✓Observed density distribution is consistent with CDM predictions

- steep profile Navarro Frenk White (1996)

A constraint from galaxy clusters

Lorentz force should be subdominant

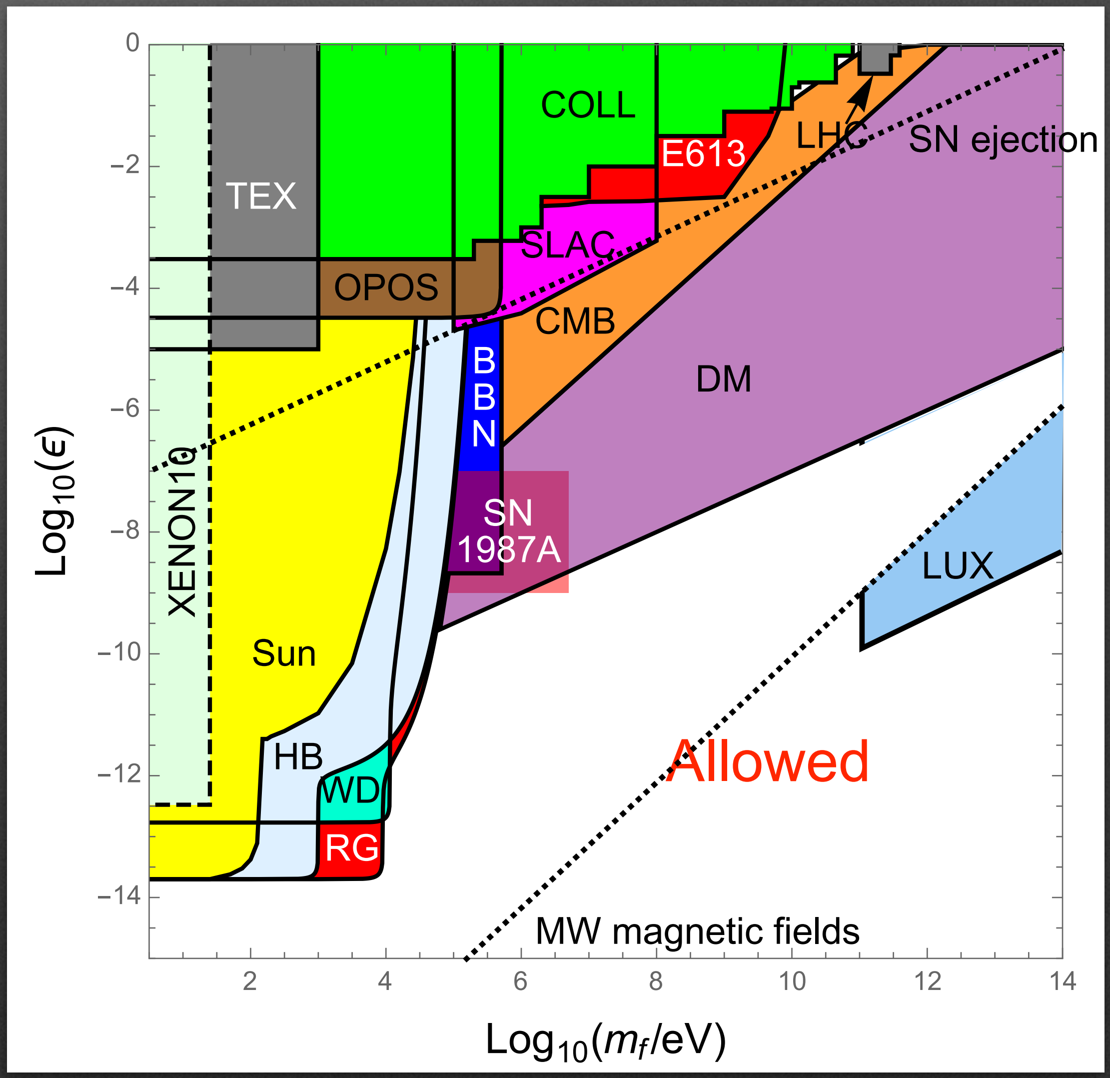
- Otherwise DM distribution in clusters should differ from CDM predictions.

$$\rightarrow \quad qBv \lesssim \frac{GM_{\rm halo} m_{\rm DM}}{R_{\rm halo}}$$

- For typical galaxy clusters:

$$\left.\begin{aligned} R_{\rm halo} &\simeq 1{\rm Mpc} \\ M_{\rm halo} &\simeq 10^{14} M_\odot \end{aligned}\right\} \rightarrow v \simeq 10^4 {\rm km/sec}$$

$$B \simeq 1\mu{\rm G}$$



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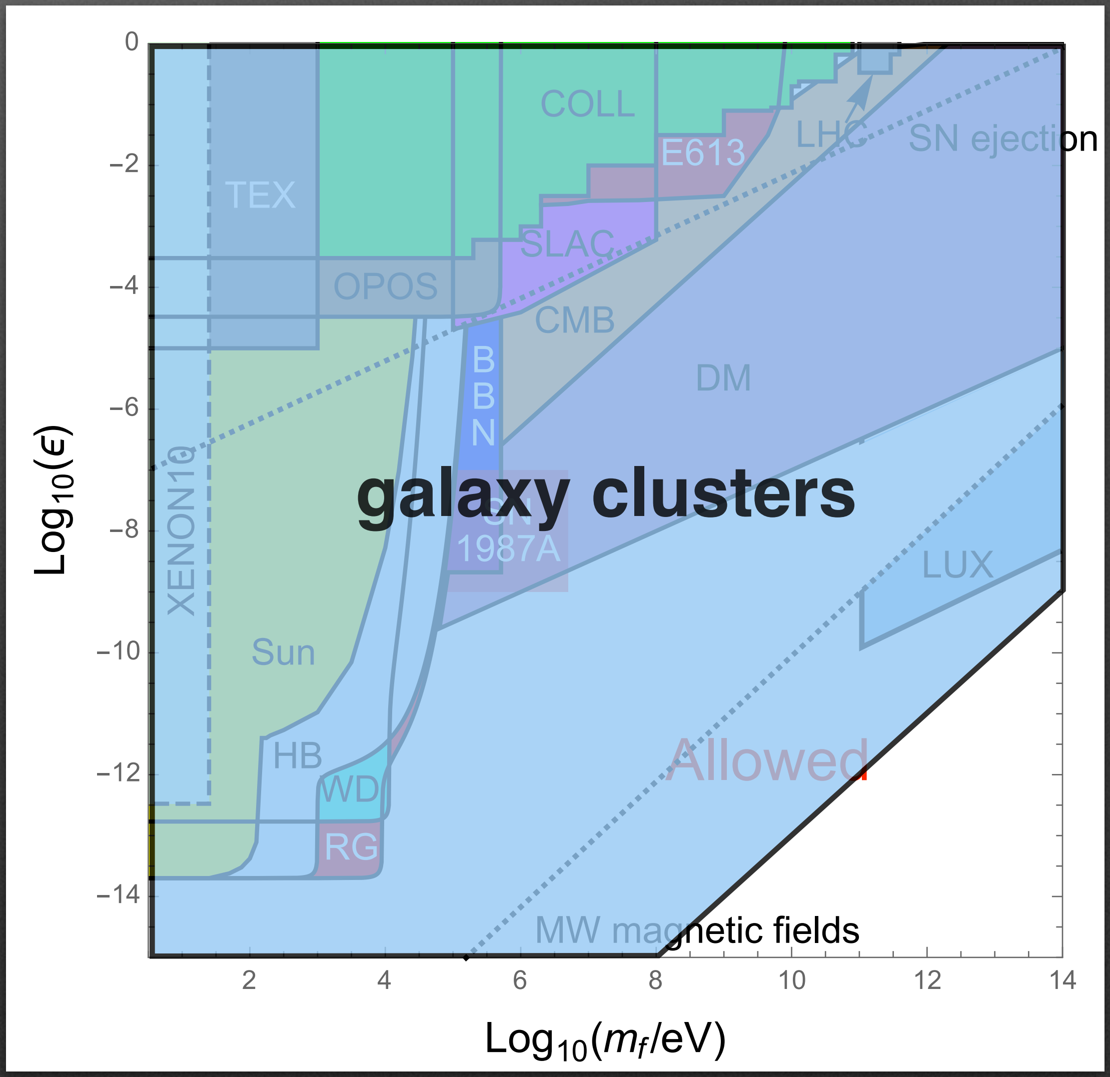
$$\epsilon \lesssim 10^{-14}\frac{m_{\rm DM}}{\rm GeV}$$

- Tighter than any of previous constraints as long as DM is 100% MDM
- Independent of existence of $U(1)_{\rm hidden}$ and DM asymmetry



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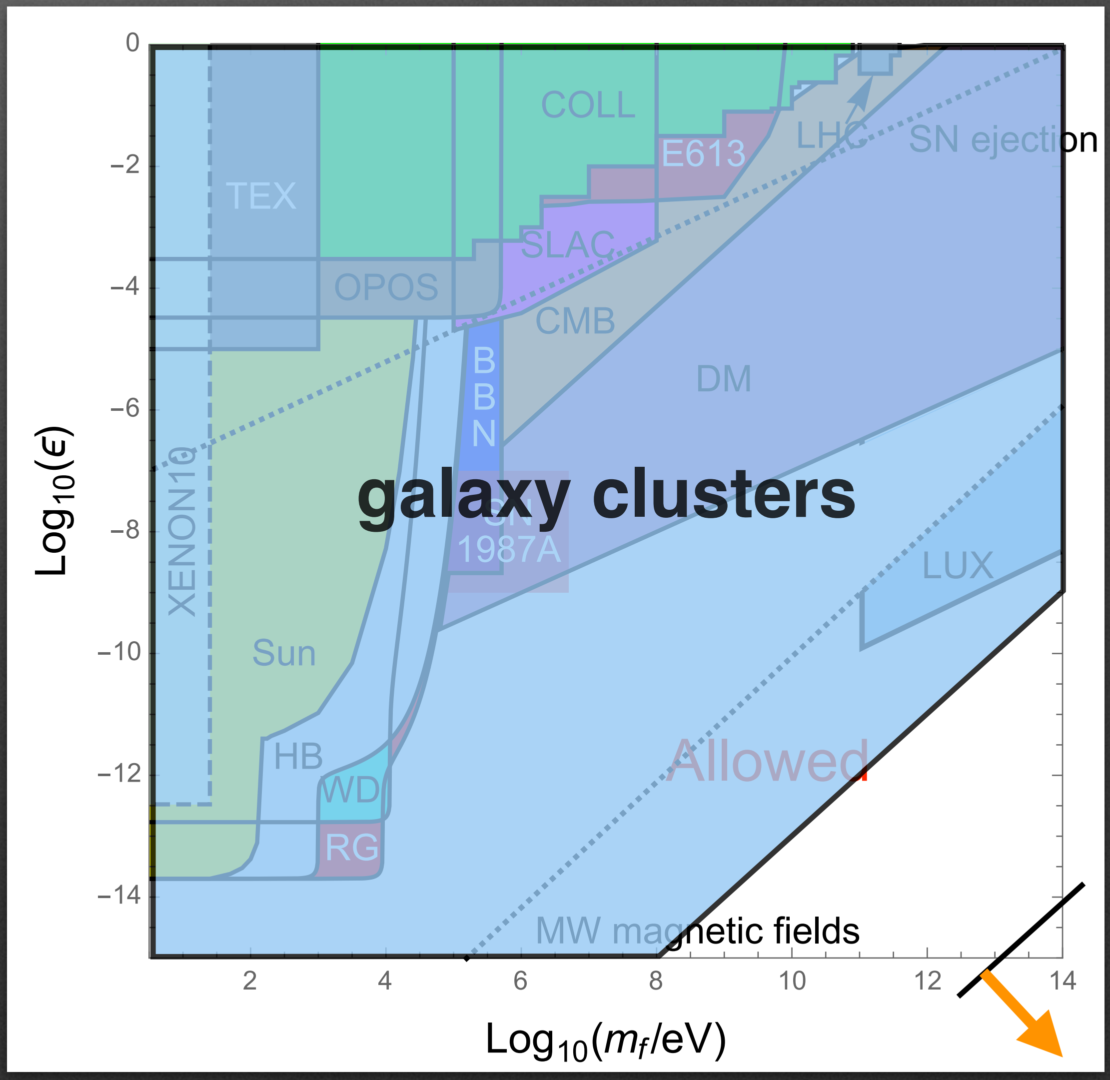

EM weaker than gravity

Back-reaction?

Impact of MDM on dynamics of magnetic fields

- Momentum transfer equation (assuming local homogeneity)

$$m_x \frac{\partial}{\partial t}(n_x \vec{u}_x) = q_x e n_x \left[\vec{E} + \frac{1}{c}\vec{u}_x \times B\right] + n_x \sum_y \mu_{xy}\gamma_{xy}(\vec{u}_x - \vec{u}_y)$$

- Generalized Ohm's law

$$\frac{\partial}{\partial t}\vec{j} = e^2\left[n_b\left(\frac{1}{m_e} + \frac{1}{m_p}\right) + \frac{2\epsilon^2 n_{\rm DM}}{m_{\rm DM}}\right]\vec{E} + \frac{e^2}{c}\left[n_b\left(\frac{\vec{u}_e}{m_e} + \frac{\vec{u}_p}{m_p}\right) + \frac{\epsilon^2 n_{\rm DM}(\vec{u}_\chi + \vec{u}_{\bar{\chi}})}{m_{\rm DM}}\right] \times \vec{B} + \gamma_{ei}\vec{j}_b$$

- By integrated this into Maxwell eqs., evolution eq. of magnetic fields is obtained

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negligible in MDM
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$$j_{\rm DM} \sim \mathcal{O}\left(\epsilon \frac{m_N}{m_{\rm DM}}\right) j_b$$

suppressed

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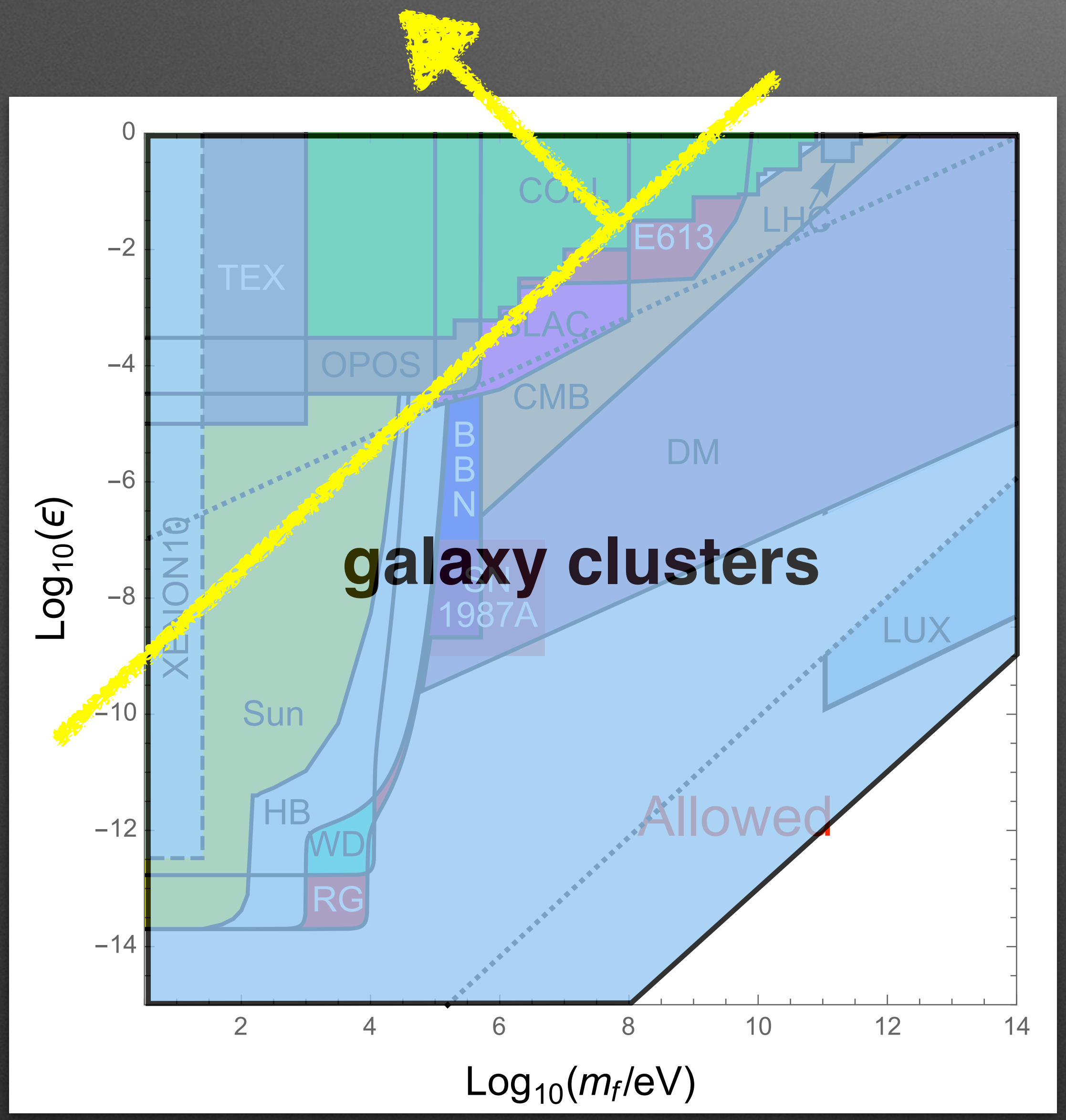
- By integrated this into Maxwell eqs., evolution eq. of magnetic fields is obtained
  - MDM contribution is subdominant for $\epsilon/m_{\rm DM}$ [GeV] < 1.
  - Magnetic fields are frozen into baryonic gas.

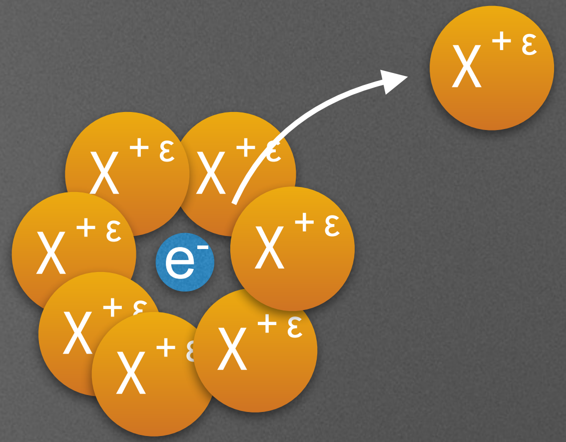
Back-reaction?

Back-reaction needs to be taken into account



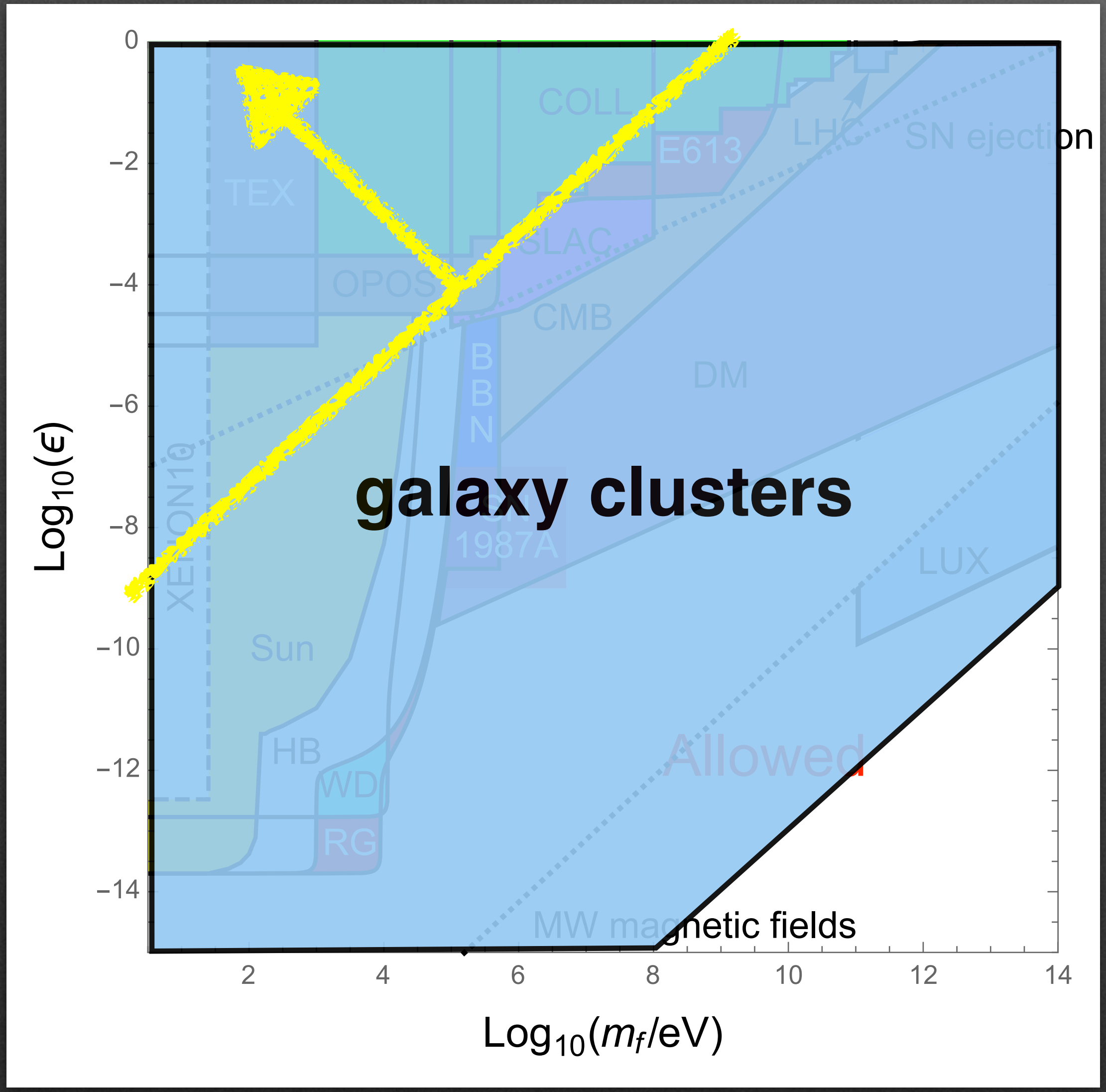
- Excluded by other constraints.
- It's unlikely that observed density profile can be realized in such a strongly coupled regime.

Neutralization?



If DM is neutralized in clusters, our constraints is inapplicable

backreaction



- Ionization energy: independent of DM asymmetry

$$E_{\rm ion} \sim O(10)\ \varepsilon^4\ ({\rm m/GeV})\ {\rm keV}$$

- Symmetric DM: DM (charge ε) recombines with aniti-DM (-ε)
- Asymmetric DM: O(1/ε) DMs recombine with e^-/p^+

- MDM might be neutralized if $E_{\rm ion} > T_{\rm gas} \sim O(1)$ keV in clusters.

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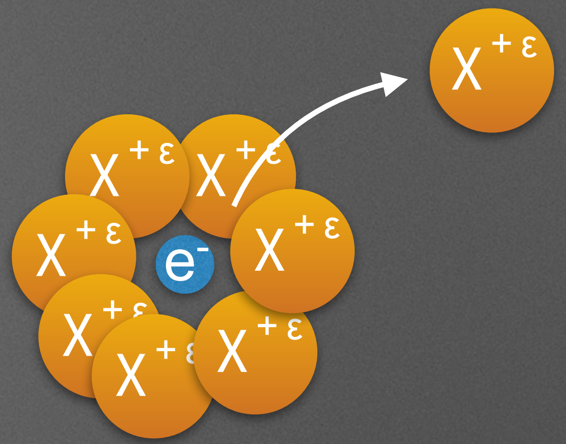

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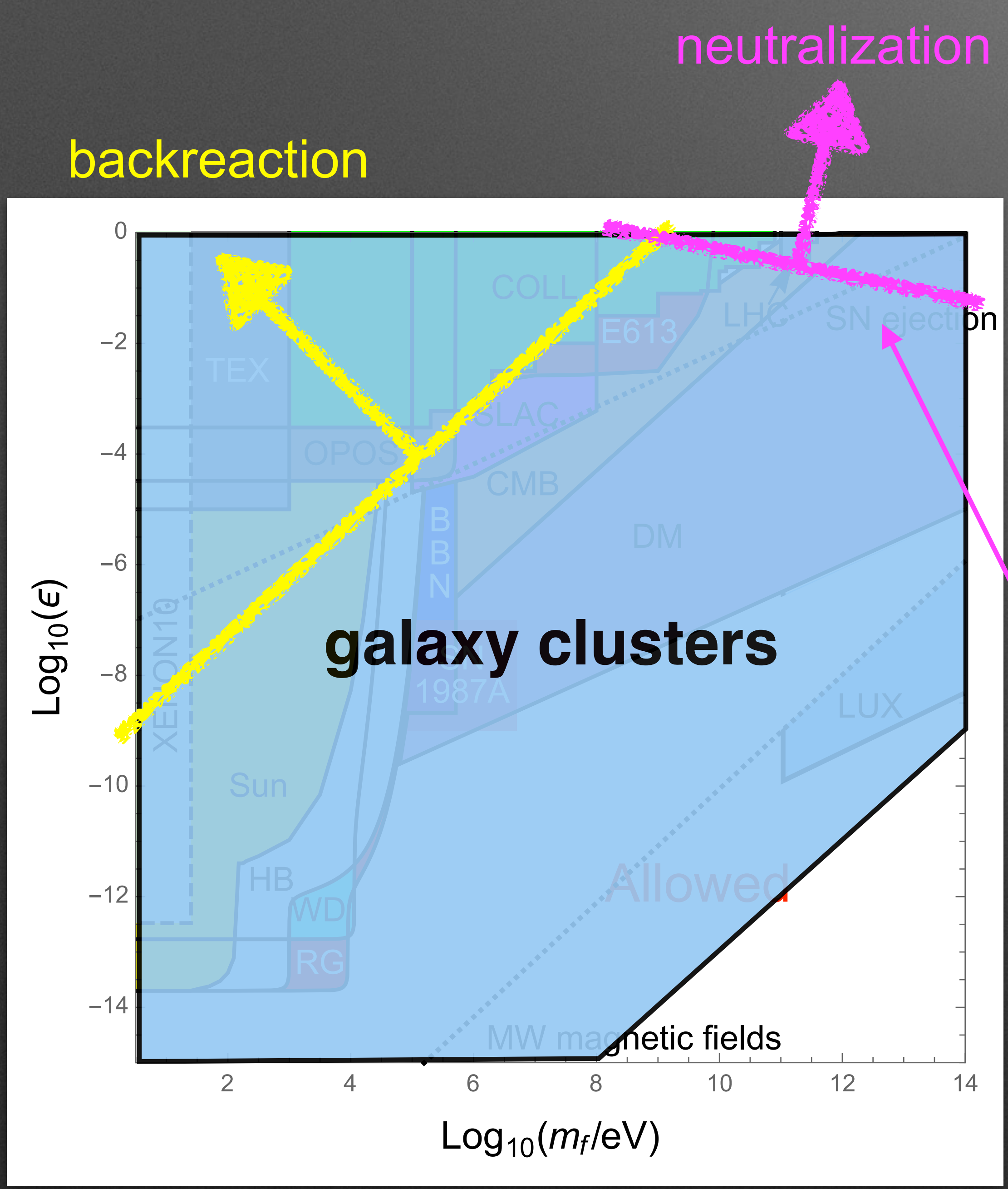

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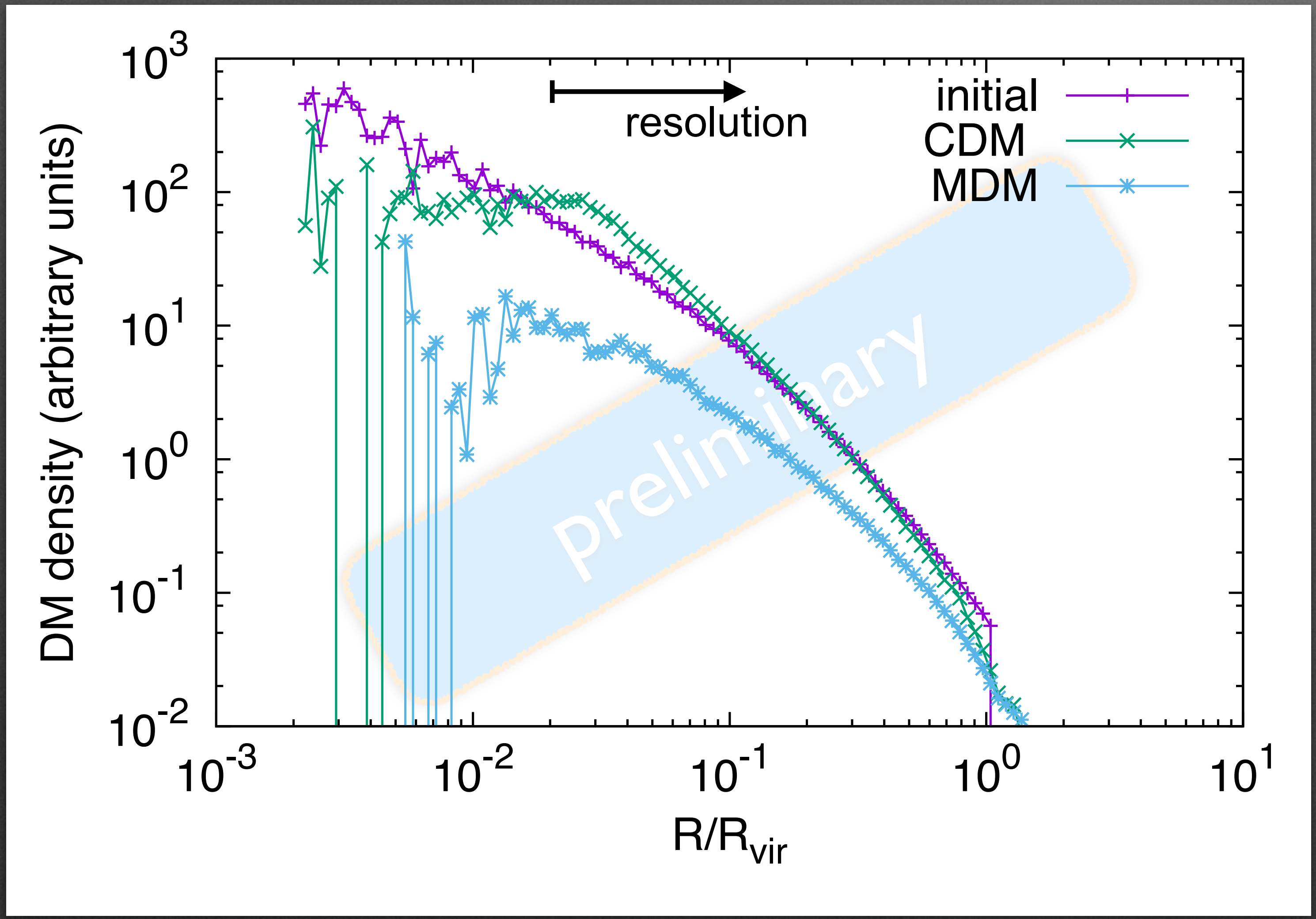
Possibility for DM to be neutralized

- However, such a region is covered by other constraints.
- Whether neutralization can be really achieved within $t_{\rm age}$ is model-dependent.

Simulation

Hasegawa, Ichiki, Kadota, TS & Tashiro, in progress

3-dim N-body simulation of DM single halo in MDM model



- Halo size: a Coma-like cluster

  $M_{halo}=10^{15}\ M_{sun}$, R_{halo}=2.8Mpc

- Magnetic fields (fixed configuration):

  B=1μG, $\lambda_{coherence}$=50kpc (coarser than reality)

- Initial profile: NFW
- Number of particles: ~2x10^5
- Simulation time: t_{age} ~ 10 $t_{freefall}$
- MDM charge/mass ratio

$$\frac{\epsilon}{m[\mathrm{GeV}]} = 10^{-13}$$

- Modification of profile is apparent. Smoother profile in MDM.
- In CDM, NFW is quasi-stable. Yet not rigorously examined; scrutiny check is underway.

Summary

We have discussed constraints on millicharged dark matter

- MDM is possible for GUT nor magnetic monopole are not confirmed. In models with dark U(1), MDM can be achieved via kinetic mixing.

- We proposed a new constraint on MDM from magnetic fields in galaxy clusters. For density profile of DM halo to be consistent with CDM prediction & observations, Lorentz force should not dominate gravitational one. Our constraint assumes DM is pure MDM.

- Our constraint is tighter than any of previous constraints regardless of presence of $U(1)_{hidden}$ or DM asymmetry. Backreaction & neutralization are irrelevant. Numerical simulation is in progress.

Thank you for your attention!

Astrophysical constraints

Holdom (1986); Davidson, Hannestad, Raffelt (2000), …

Modified stellar evolution

- Produced via plasmon decay $\gamma^* \to \chi\bar{\chi}$

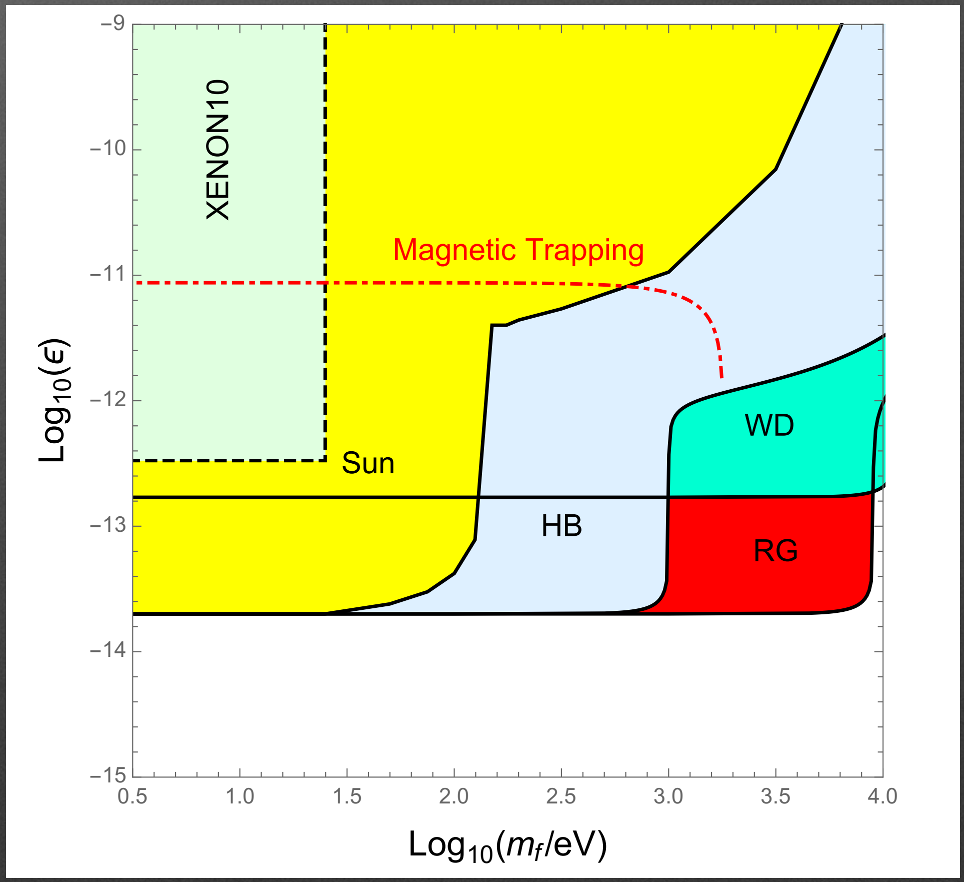
  If MDM mass < $\omega_p/2$, production is efficient

  - plasmon mass: $$\omega_p^2 = \frac{4\pi\alpha n_e}{m_e},$$

    ~ 300eV for the Sun; 10keV for red-giants

  - decay rate: $$\Gamma_{\gamma^*} = \frac{\alpha}{3}\frac{Z}{\omega}\left(\omega_p^2 + 2m_f^2\right)\sqrt{1 - \frac{4m_f^2}{\omega_p^2}}$$

- MDM escapes if (cyclotron radius)>(stellar radius)



Vinyoles & Vogel (2015)

⇨ MDM channel should be subdominant:

$$\epsilon \lesssim 2 \times 10^{-14}$$ for MDM mass < 10keV.

cf. white dwarfs are less constraining because MDM escapes only from surface.

Relic MDM abundance

Thermal production

- main processes $\chi\bar{\chi} \leftrightarrow f\bar{f}$ cf. 2γ suppressed

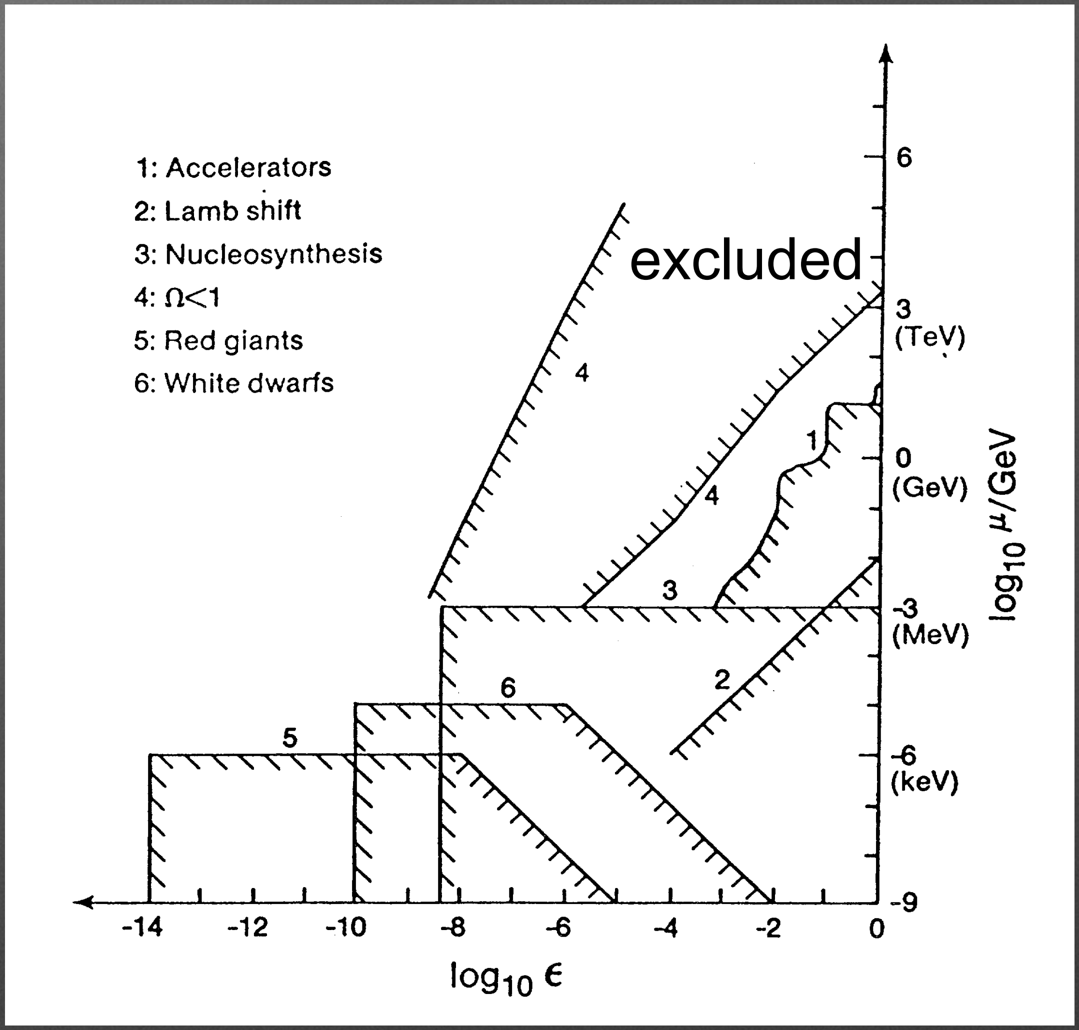
$$(\sigma_{\rm an} v_{\rm rel})_{f\bar{f}} = \frac{\pi\alpha_{\rm em}^2\epsilon^2}{m_X^2} q_f^2 N_c \sqrt{1-\frac{m_f^2}{m_X^2}}\left(1+\frac{m_f^2}{2m_X^2}\right)$$

- Relic abundance (equilibrium assumed)

$$\Omega_{\rm MDM}h^2 \simeq 0.1\times\left(\frac{m}{\rm GeV}\right)^2\left(\frac{\epsilon}{10^{-3}}\right)^{-2}$$

- MDM is fully thermalized only if

$$\epsilon > 10^{-7}\left(\frac{m}{\rm GeV}\right)^{1/2}.$$



Davidson, Campbell & Bailey (1991)

Thermal relics with observed Ω_m~0.24 is incompatible with e.g, CMB.
In principle, symmetric MDM should be produced non-thermally.

Caveat: if $U(1)_{\rm hidden}$ exists, MDM can annihilate into hidden photons and relic abundance can be suppressed significantly.

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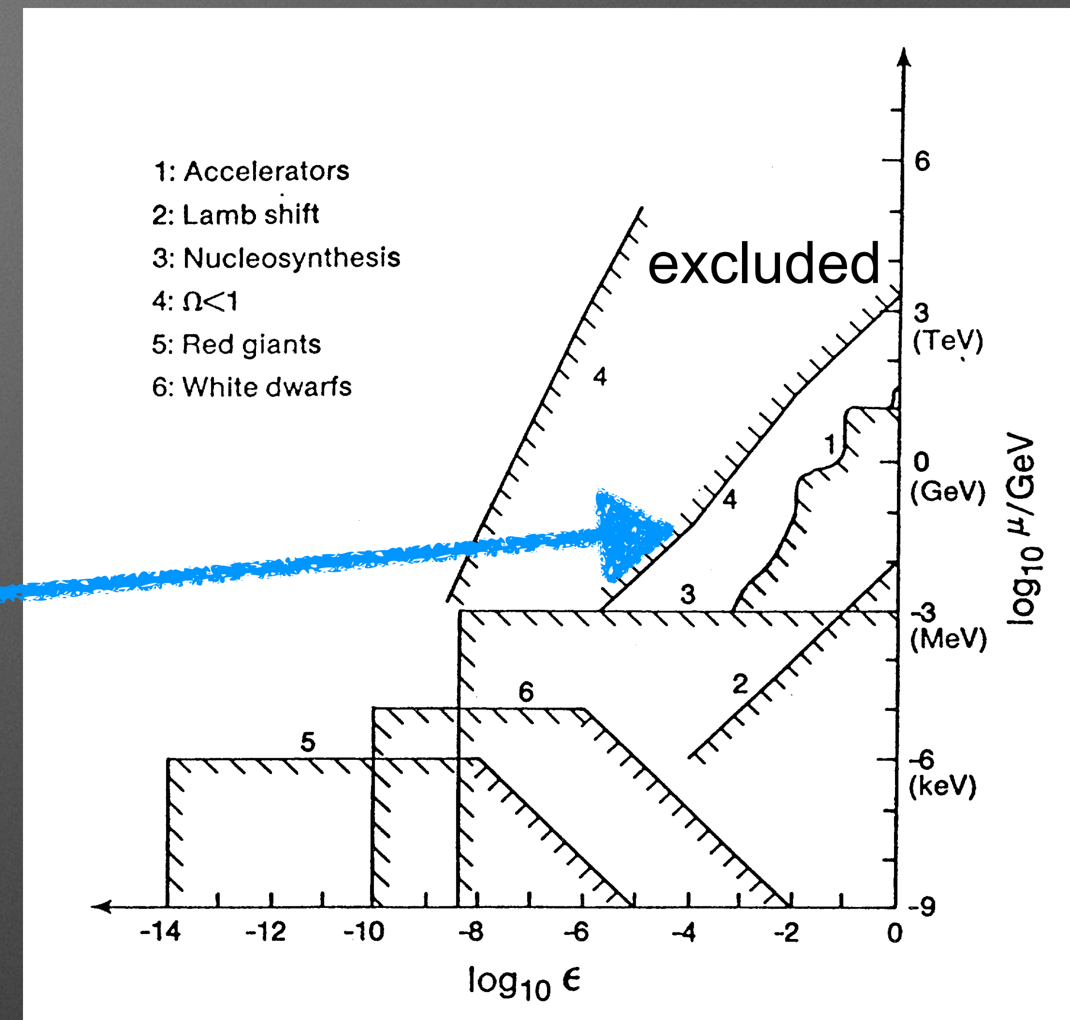

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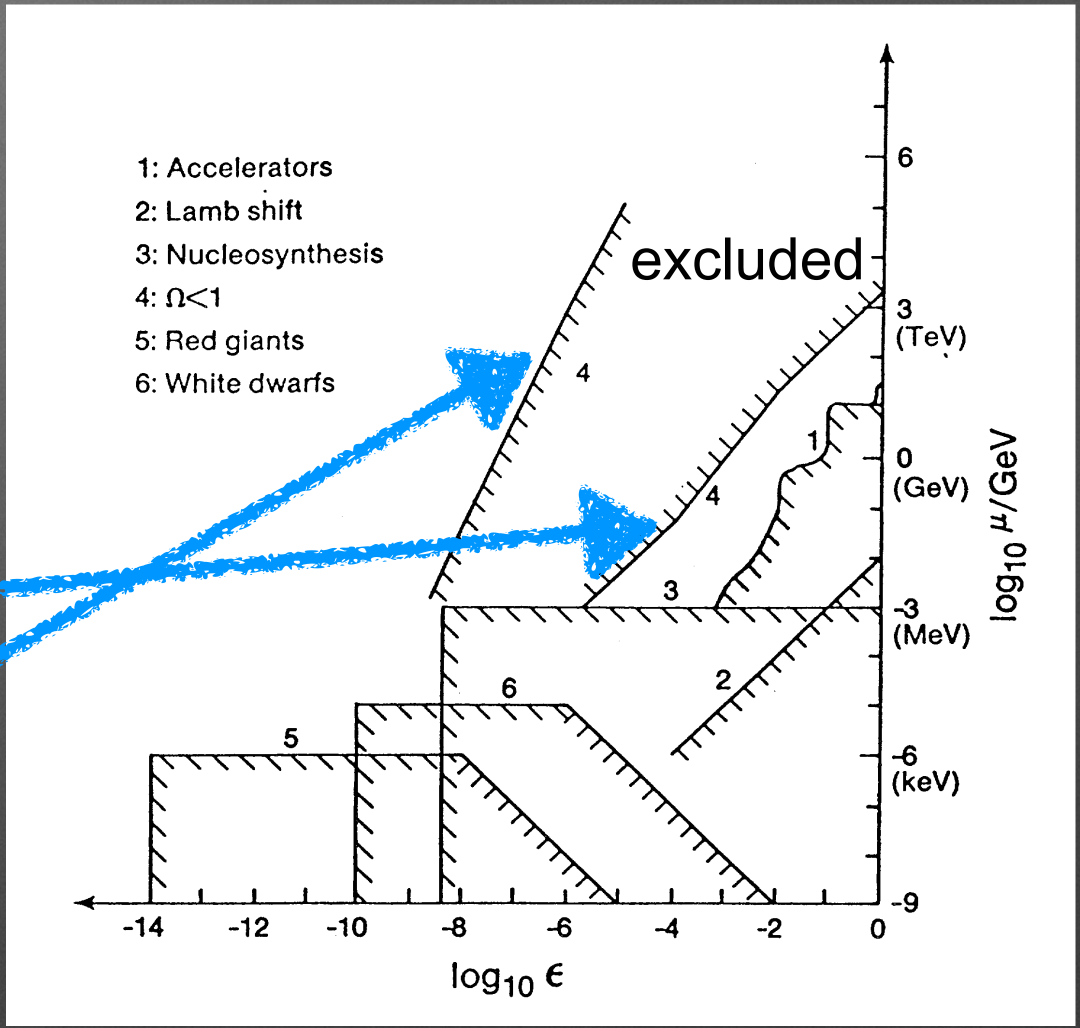

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Structure formation & CMB

Coupling with baryon via Coulomb scattering

$$\frac{d\sigma_{Xb}}{d\Omega_*} = \frac{\alpha_{\rm em}^2 \epsilon^2}{4\mu_b^2 v_{\rm rel}^4 \sin^4(\theta_*/2)}$$

cf. Compton scattering is further suppressed by ε^2.

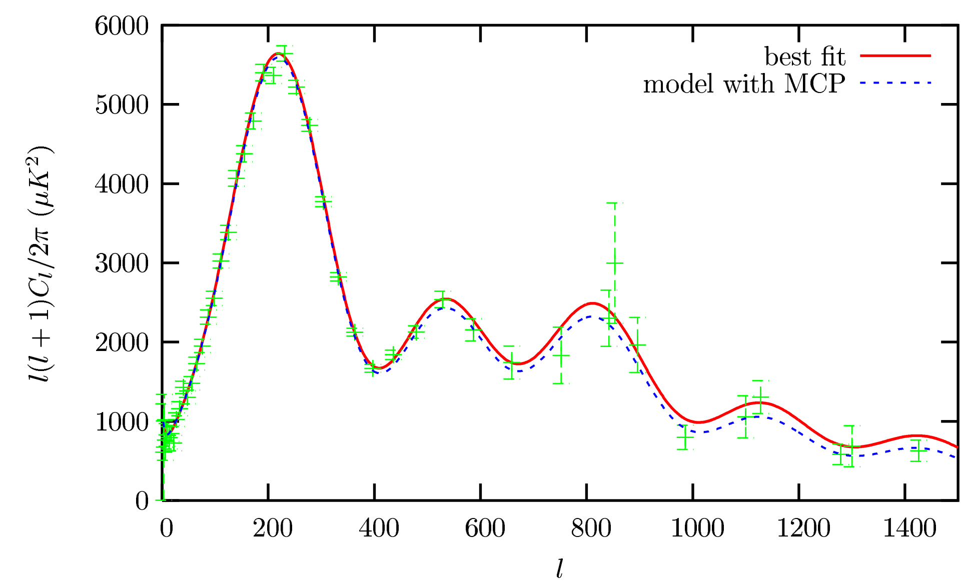

Figure 3: Two different CMB anisotropy spectra compared with extended WMAP dataset. Solid line represents the best fit model without millicharged particles, $\Omega_b h_0^2 = 0.022$. Dashed line corresponds to model with $\Omega_b h_0^2 = 0.014, \Omega_{mcp} h_0^2 = 0.007$.

Dubovskya, Gorbunova & Rubtsov (2003)

- Acoustic oscillation is modified
  - When MDM and baryon tightly couple, they collectively act as heavy baryon.
  - Given fixed $\Omega_b + \Omega_{mdm}$, Silk damping is enhanced.

- MDM should have kinetically decoupled from baryon before recombination

$$\epsilon \lesssim 2.24 \times 10^{-4} \left(\frac{M}{1\ \rm TeV}\right)^{1/2}$$

⇨ thermal relic MDM is excluded

Caveat: if $U(1)_{\rm hidden}$ exists, MDM acoustic-oscillates at late-times (kinetic recoupling), which leads to tighter constraints from matter power spectrum. Kamada+ (2013)

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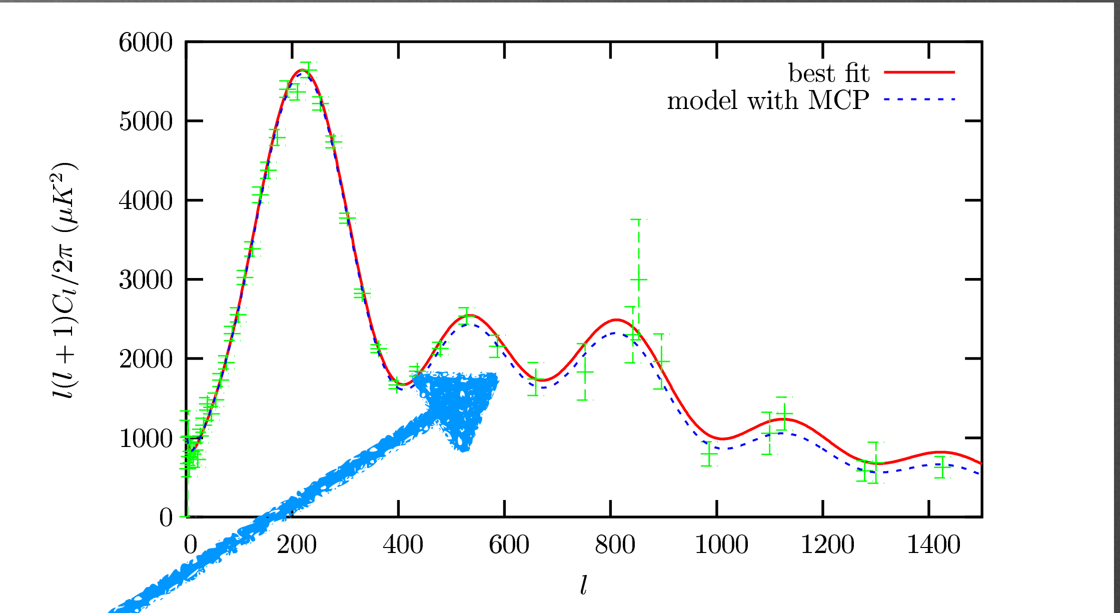

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BBN constraints

Effects on BBN

- Relevant only when $m_{DM} \leq m_e$
- e^+e^- annihilate also into MDM. Meanwhile photon is less heated up.

✓ higher $N_{\rm eff}$ $\Delta N_{\rm eff} \simeq 6.9 \left(\frac{\epsilon}{10^{-8}}\right)^2$

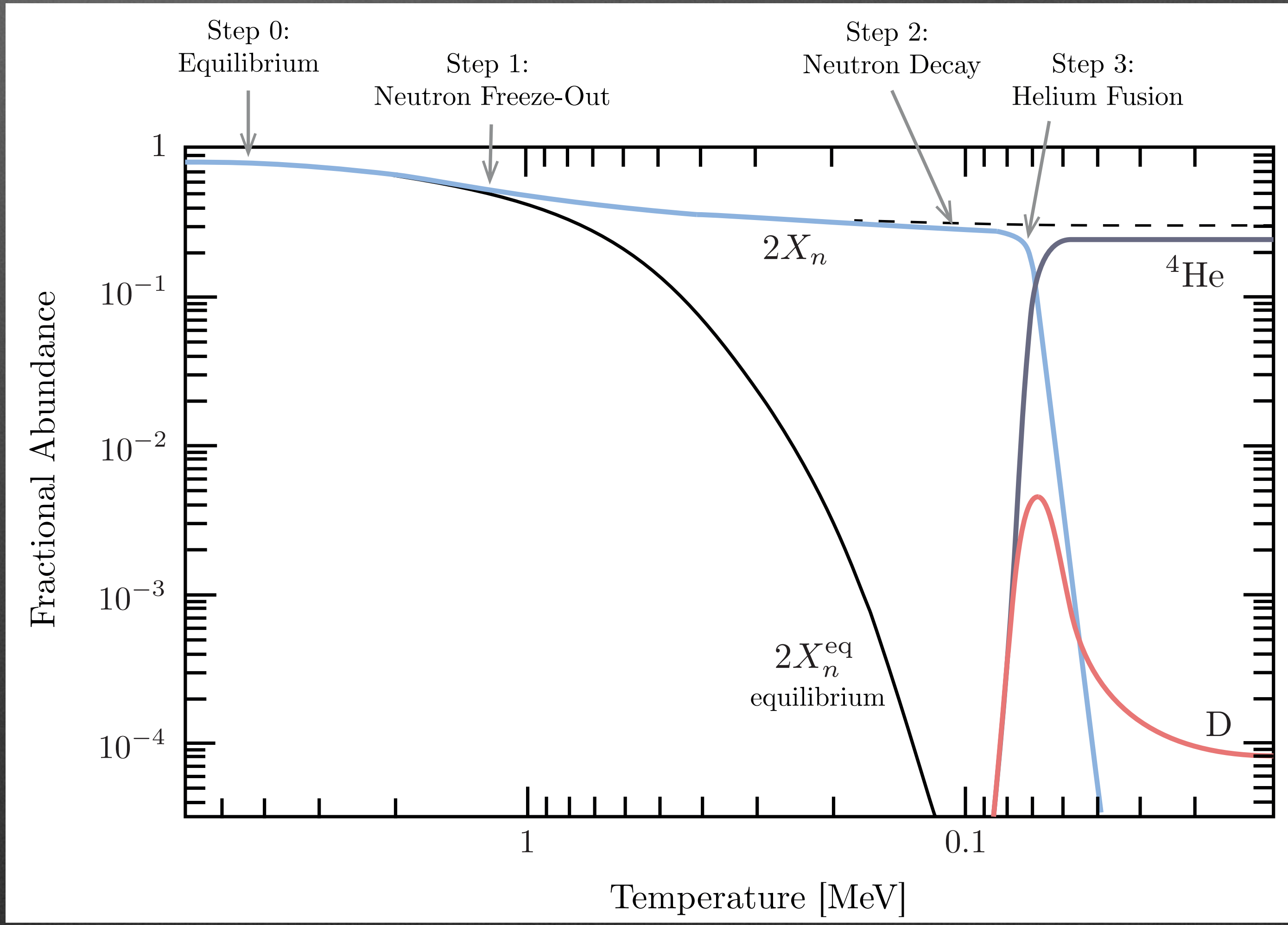
If $U(1)_{\rm hidden}$ exist, $N_{\rm eff}$ is increased further

✓ higher n_B/n_γ

(MDM also annihilates after BBN
but well before recombination)

- Earlier freeze-out of neutrons & onset of BBN enhance ^{4}He abundance.

$\epsilon < 2.1 \times 10^{-9}$. (for $m_{DM} \leq m_e$)



(c) D. Baumann

Direct detection

Coulomb scattering of nuclei with MDM

- Nucleonic matrix element

$$\mathcal{M}_N = \frac{16\pi\alpha}{q^2}\epsilon Q_N m_\chi m_N$$ ⇦ spin-independent scattering

- Non-relativistic diff. cross-section wrt. recoil energy $E_{\rm R}=q^2/2m_T$

$$\frac{\mathrm{d}\sigma_T}{\mathrm{d}E_{\rm R}}(v,q^2) = 8\pi m_T \frac{\alpha^2\epsilon^2}{v^2\, q^4} Z_T^2\, F_T^2(q^2)$$

F_T: the form factor (i.e. charge distribution in nuclei)
m_T: mass of target nucleus

➡ Equivalent to exotic form factor with $1/q^2$ in short-range interaction

- Current tightest constraint comes from LUX.

$$\epsilon \lesssim 7.6\times 10^{-10}\left(\frac{M}{1\ \mathrm{TeV}}\right)^{1/2}$$