Higgsed Millicharge particles

Status report

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Project overview

- Happy to be a new scientific project board at DMLab with Felix !
- Our general common research axis will be Feebly Interacting Particles
- Ongoing project, started with Patrick Foldenauer on millicharge particles
  → Today is more of a status report than a full presentation …

All millicharge particles are born equal, but…

Pure Millicharge

χ, massive Dirac fermion with tiny hypercharge Y_χ

MCP : New fermions with tiny electric charge Q

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Kinetic mixing Millicharge

New unbroken $U(1)_D$, kinetic mixing ϵ_B + χ with dark charge

+ *dark QED acting on* χ

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Higgsed Millicharge

New broken $U(1)_D$, dark Higgs with tiny hypercharge Y_S + χ with dark charge

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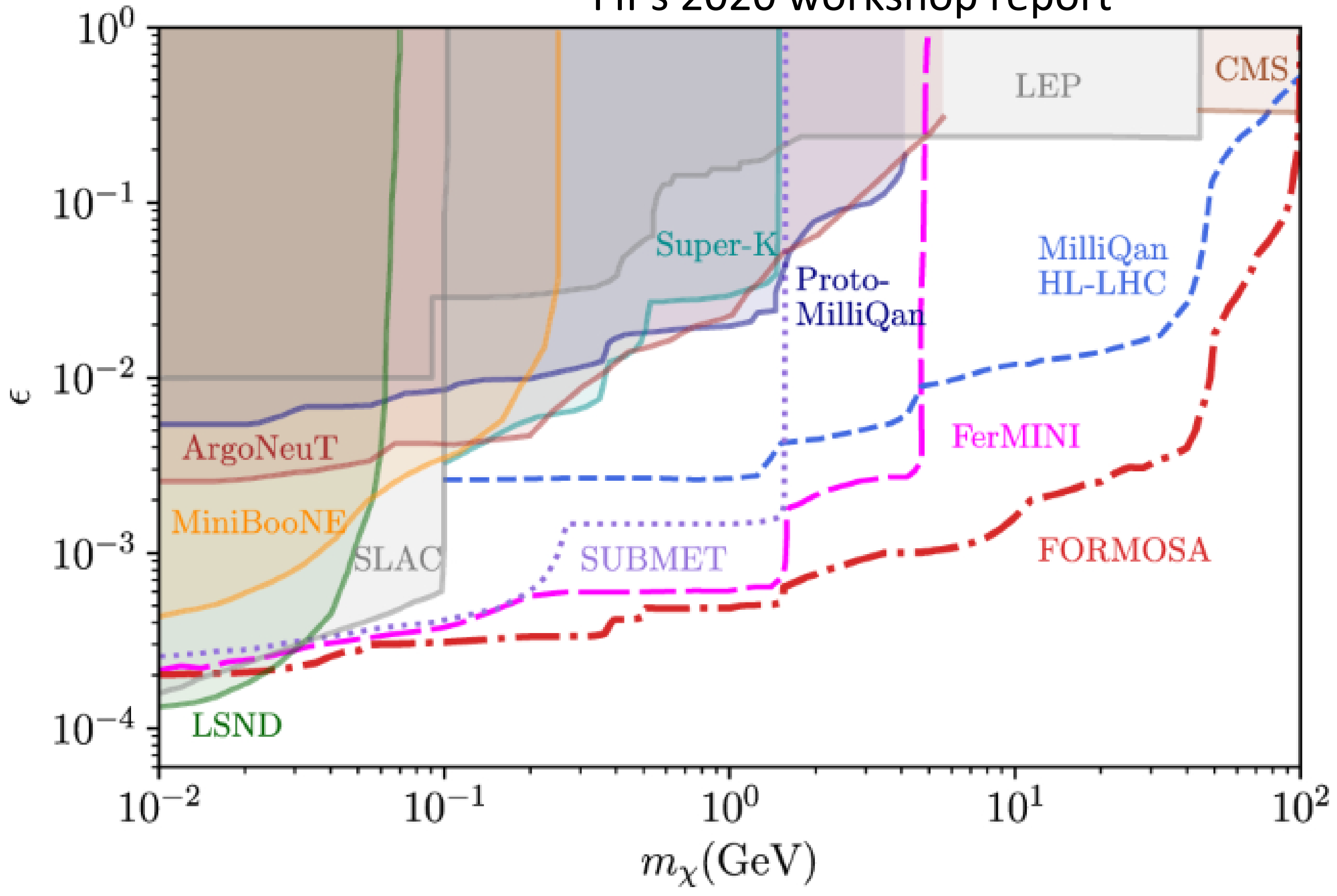
χ, massive Dirac fermion with tiny hypercharge Y_χ

MCP : New fermions with tiny electric charge Q

+ massive dark photon
+ EW effects

Accelerator searches are in full swing

FIPs 2020 workshop report



- Accelerator experiments sensitive to millicharges as small as 10^{-4}

  → much weaker bounds for heavier MCPs

- For couplings in this range, MCPs can be efficiently produced in the early universe and stellar cores

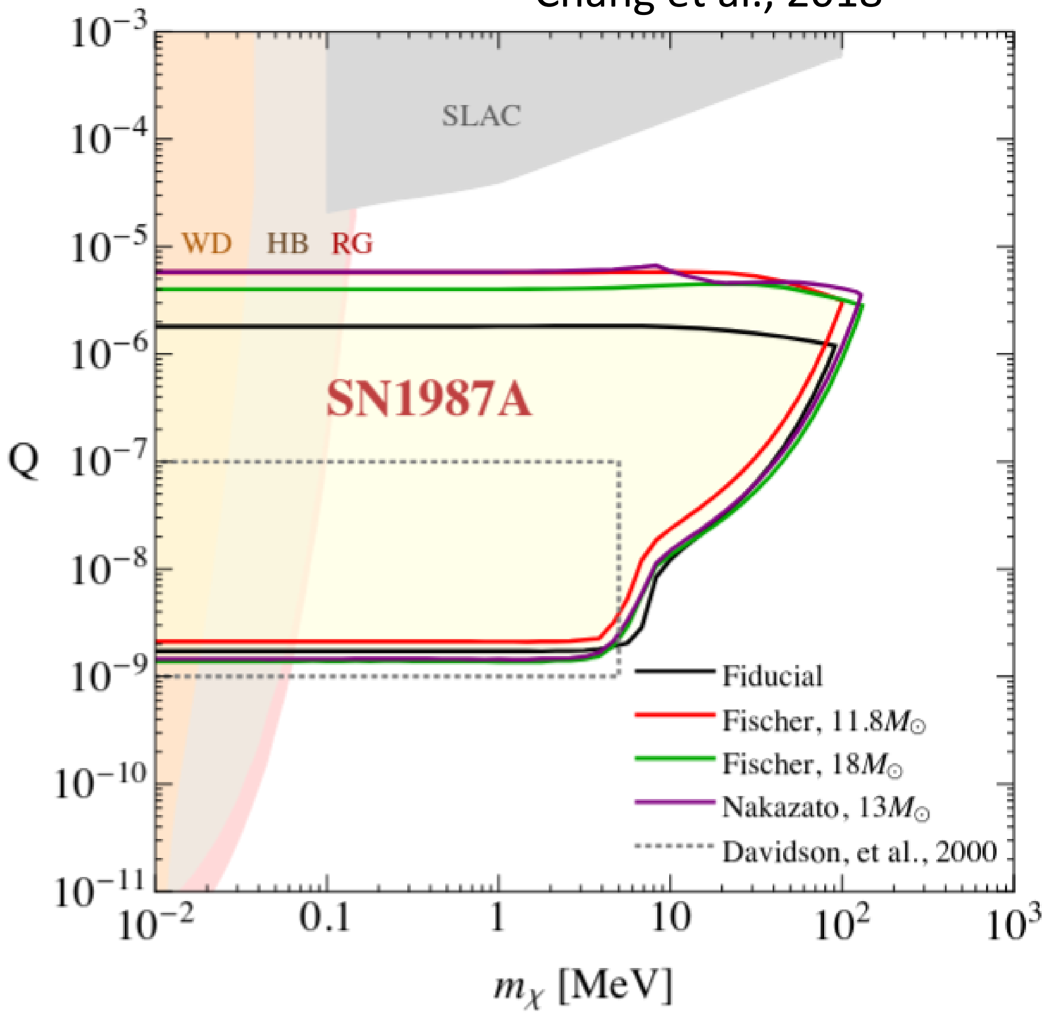
- Are these parameter regions consistent with astrophysics/cosmology ?

Astrohpysical and cosmological constraints on MCPs

MeV-range : SN1987 cooling

Pure millicharge

Chang et al., 2018



- For Q > 10^{-5} MCPs are efficiently trapped in the SN core with a mean free path smaller than neutrinos
- Negligible contribution to cooling and heat transport
- Stellar cooling constraints only apply to MCPs with mass below 100 keV

!! Highly dependent on dark sector structures !!

Relativistic degrees of freedom

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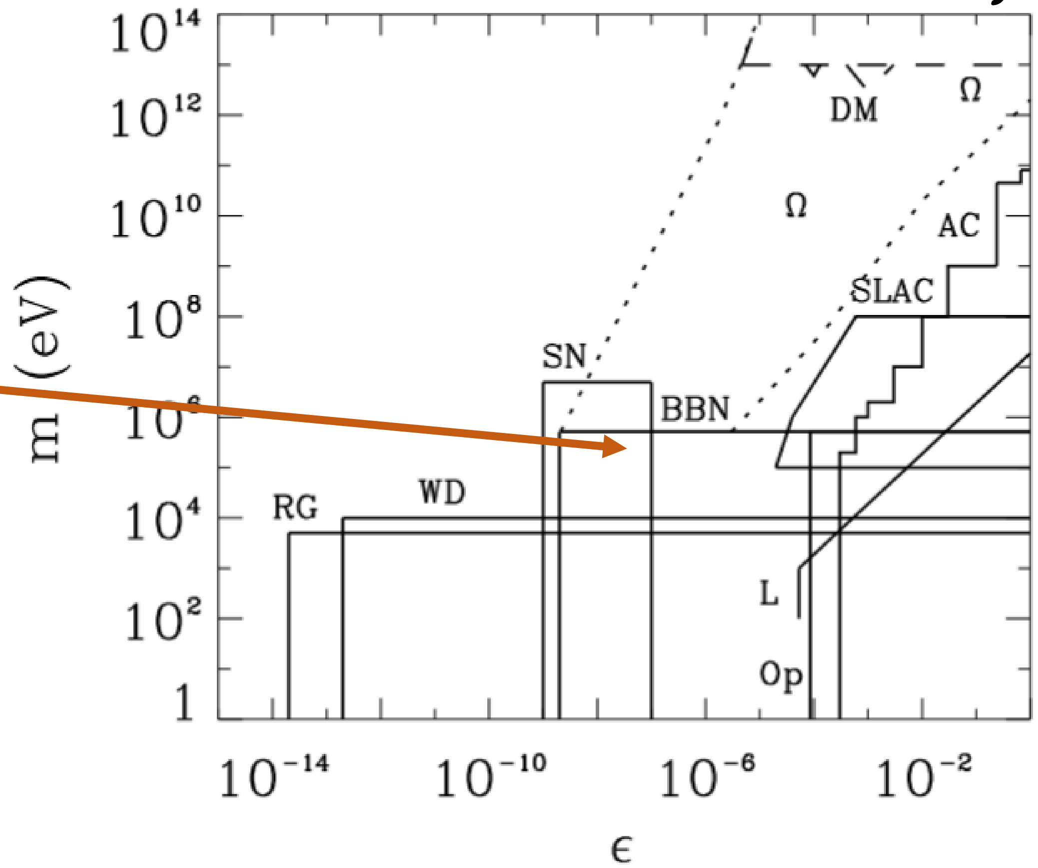
→ Significant contribution to the total energy density (and hence the expansion rate)

→ Robustly excluded by BBN measurements

Pure millicharge



Davidson et al., 1999

MCP relic density : freeze-out

- Since they are stable and thermalised, can they be DM ?
  - → For heavier MCP masses, the particles become Boltzmann-suppressed and freeze out
  - → For Q ~ 10^{-4} - 10^{-3} MCPs could be all of DM

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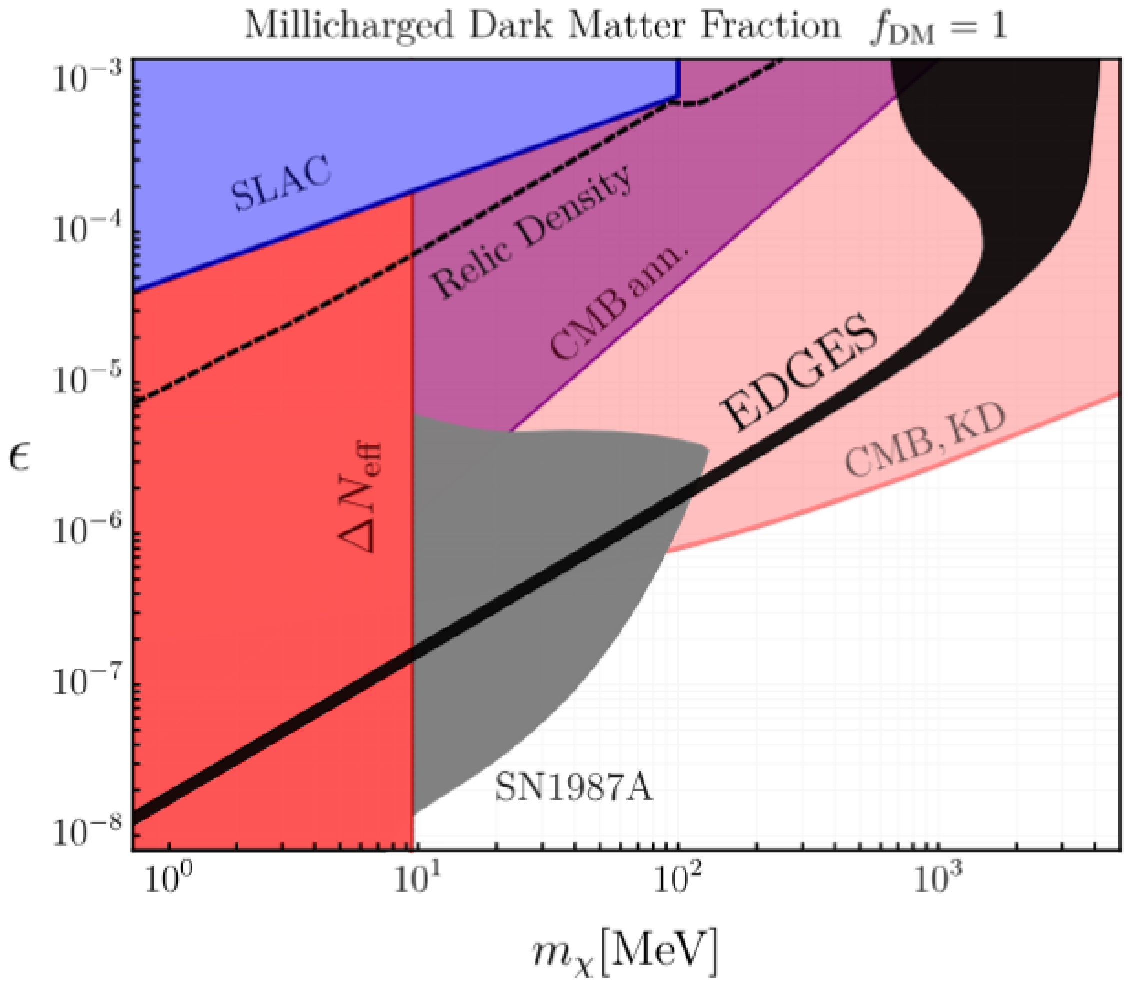
- Problem: such scenario leads to strong CMB constraints

  → Dominant limit comes from requiring DM decoupling at the time of baryon-photon recombination

Pure millicharge



Berlin et al., arXiv:1803.02804

Can MCPs actually be dark matter ?

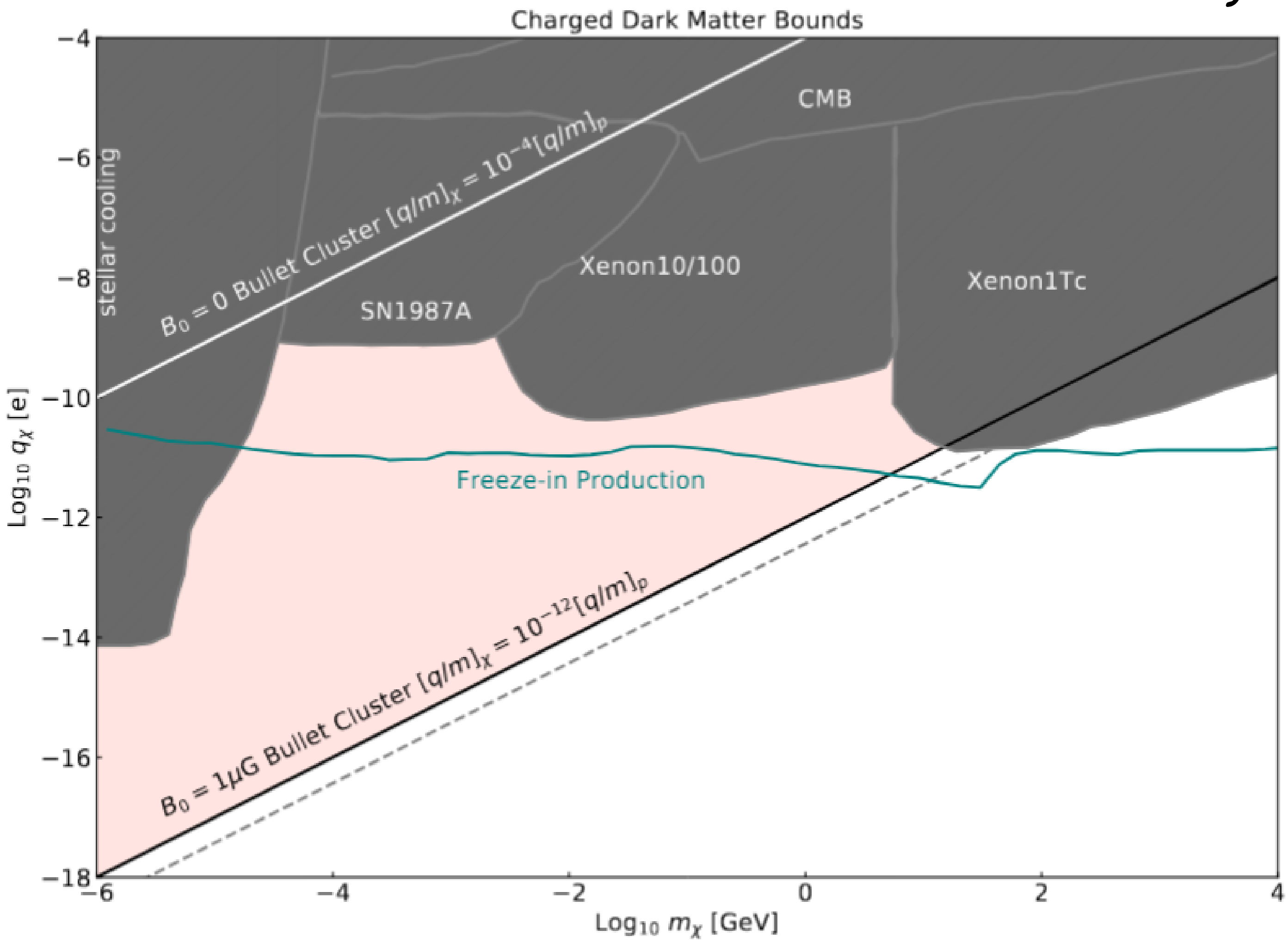
- Various papers have pointed out that millicharged dark matter experiences plasma instabilities

  → Mostly the product of having a long-range interaction available …

- Extremely strong constraints on the charge of dark matter from the Bullet Cluster

Cruz & McQinn, arXiv:2202.12464
Lasenby, arXiv:2007.00667
Medvedev & Loeb, arXiv:2406.15750

Pure millicharge



Cruz & McQinn, arXiv:2202.12464

Suppressing the MCP abundance (I)

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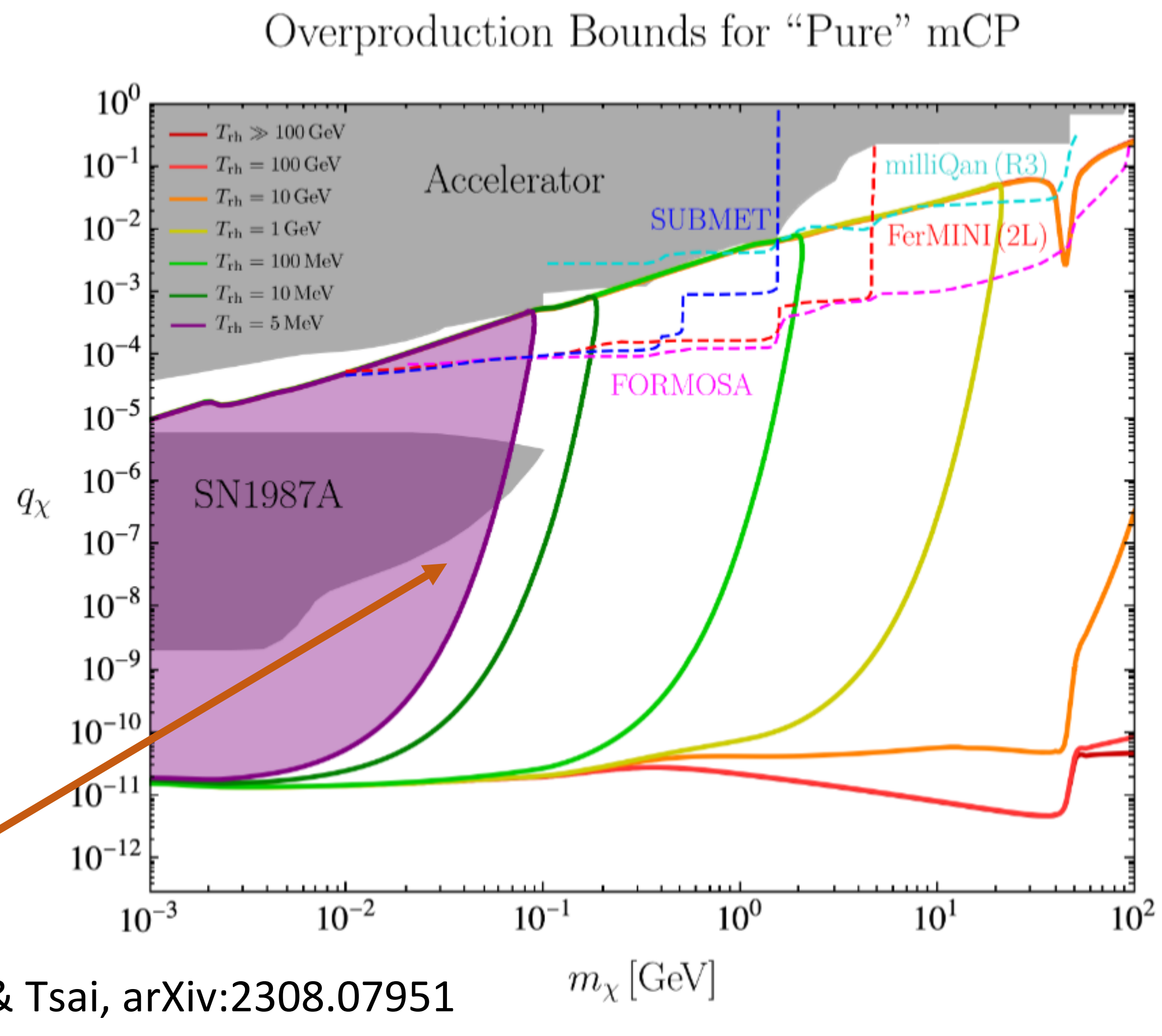
- Possible solution: Modification of standard cosmology
- Example: Low reheating temperature

  → Exponential suppression of MCP abundance if their mass is greater than T_{RH}



Also include CMB limits from earlier on

Gan & Tsai, arXiv:2308.07951

Suppressing the MCP abundance (II)

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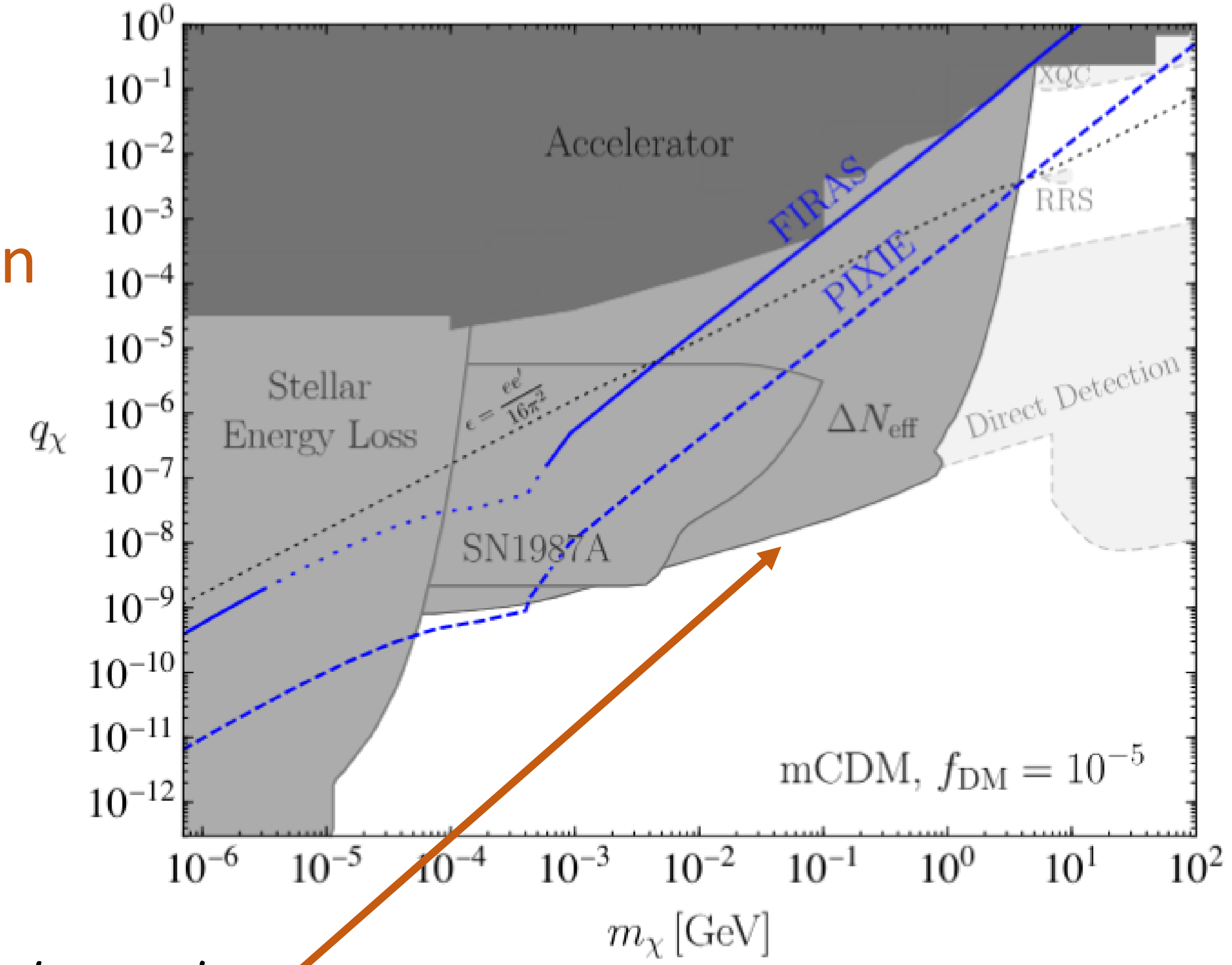
Kinetic mixing millicharge

- Alternative avenue: use additional dark sector states (dark photon, dark Higgs boson) as additional annihilation channels to deplete MCP abundance
- Challenge: Lighter states need to decay into SM to avoid reappearance of ΔN_{eff} constraint
  - →Prediction of additional light (and long-lived?) particles
- Relevant parameter space opens for accelerator searches !



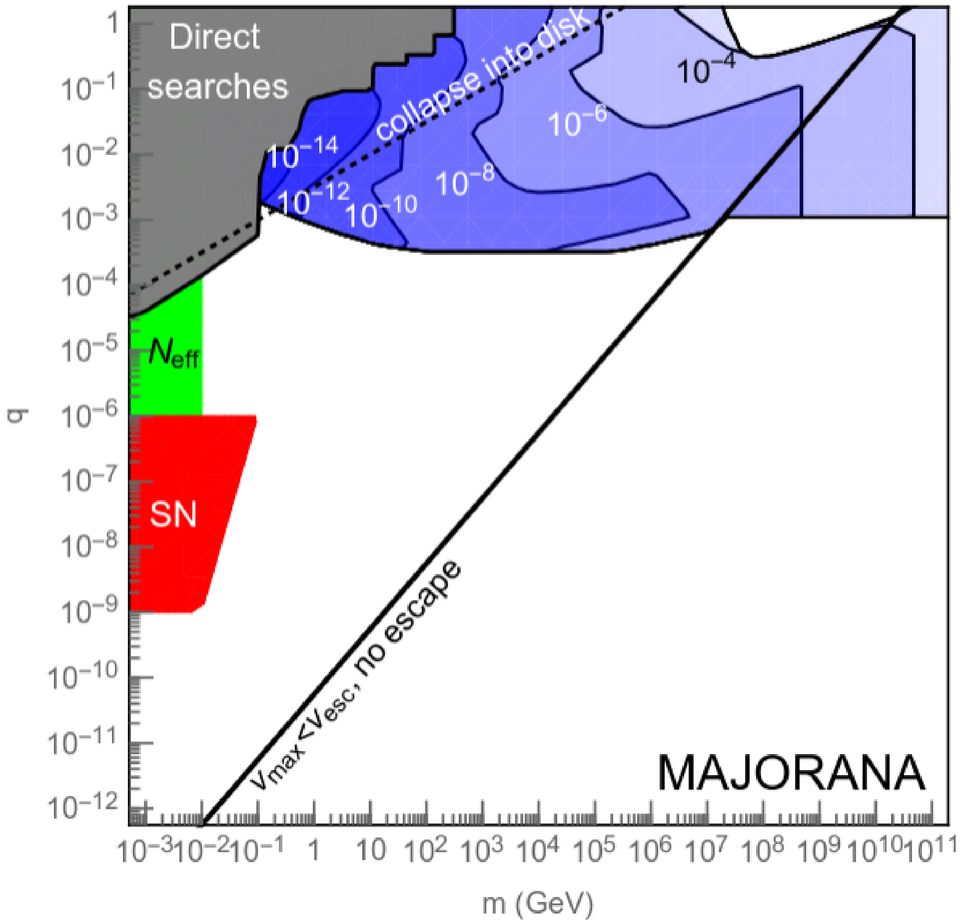
Model with massless dark photon

Berlin et al., arXiv:2211.05139

Direct detection constraints?

- The evolution of a cosmological population of MCPs depends on many factors
  - Diffusion in magnetic fields
  - Expulsion through supernova shocks
  - Collapse into disk
- Rock overburden may attenuate the flux of MCPs in experiments
- In non-minimal models, a large self-interaction component may arise

→ Calculation of direct detection constraints highly non-trivial



Dunsky et al., arXiv:1812.11116

Building millicharge particles dark sectors

Kinetically mixed millicharge

- We use a new *unbroken* $U(1)_D$ *symmetry along with* a “kinetic mixing” term

  → Could be loop generated, or seen as a convenient way of expressing that the $U(1)_D$ current has a small hypercharge component

Kinetic mixing term

$$\mathcal{L}_{A'} = -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \boxed{\frac{1}{2}\frac{\varepsilon}{\cos\theta_w}B_{\mu\nu}F'^{\mu\nu}}$$

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- We then re-define the gauge bosons to get a properly normalised fields

  → We actually have a SO(2) redefinition freedom afterwards since both the photon and the dark photon are massless

$$\begin{pmatrix} A_\mu \\ Z_\mu \\ X_\mu \end{pmatrix} \rightarrow \begin{pmatrix} 1 & 0 & -\frac{c_\theta\,\epsilon_B}{\sqrt{1-\epsilon_B^2}} \\ 0 & 1 & \frac{s_\theta\,\epsilon_B}{\sqrt{1-\epsilon_B^2}} \\ 0 & 0 & \frac{1}{\sqrt{1-\epsilon_B^2}} \end{pmatrix} \begin{pmatrix} A_\mu \\ Z_\mu \\ X_\mu \end{pmatrix}$$

Two (equivalent) choices

- We are thus left with two equivalent descriptions of the interactions

The standard « Dark photon » convention (which is similar to the massive case)

$$\mathcal{L} \subset e j_\mu^{em} A_\mu + (g_X j_\mu^X - c_W \epsilon_B j_\mu^{em}) X^\mu$$

The usual « millicharge » convention

$$\mathcal{L} \subset (e j_\mu^{em} - g_X c_W \epsilon_B j_\mu^X) A_\mu + g_X j_\mu^X X^\mu$$

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- In both cases the dark photon does NOT decouple from the physics of the problem since it couples directly to the millicharge particles.

→Thus the millicharge relics created using this mechanism have in any case a extra « dark QED » interaction that may dramatically affect their evolution

Gan and Tsai: 2308.07951

A massive dark photon: higgsed millicharge

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- Idea: we can use a new dark Higgs singlet, with dark charge q_D AND a small hypercharge q_Y

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$$+ (D^\mu S)^*(D_\mu S) + \mu_S^2|S|^2 - \frac{\lambda_S}{2}|S|^4$$

Dark Higgs potential

(suppose for now the dark charges chosen to avoid dark Yukawa coupling)

Precision constraints

- A new Higgs scalar singlet with non-zero hypercharge q_Y is an open-door to EW precision physics problems …
  - → We expect to have to take $v_S \ll v_{EW}$ et $q_Y \ll 1$
  - → More complex Higgs sectors (or dark-charged SM-like Higgs doublets) may have more relaxed constraints

As a first estimate, we can take the shift in the Z boson mass

$$\rho_0 - 1 = \frac{m_W^2}{m_Z^2\, c_W^2} - 1 \sim -6 q_Y^2 \frac{v_S^2}{v_{EW}^2} \quad \Rightarrow \quad \frac{m_X}{m_Z}\frac{q_Y}{q_D} \leq O(0.005)$$

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- We thus need either a light dark photon or a small ratio $\delta = \frac{q_Y}{q_D}$
  - →One still needs to tune the « millicharge ratio » : δ
- Millicharge particles are a direct prediction of modified EW-breaking sector

The resulting currents

- In the mass basis we finally obtain the gauge interactions of the form

$$\mathcal{L}_{\text{int}} = -(A^{\mu}, Z^{\mu}, Z'^{\mu})\; J_{\mu}^{\text{phys}}$$

- If the dark photon mass is much smaller than the Z mass we get :

$$J_{\mu}^{\text{phys}} = \begin{pmatrix} e(j_{\mu}^{em} - \delta\, j_{\mu}^{x}) \\ s_{\theta}\, \epsilon_B\, g_x\, j_{\mu}^{x} + g_z j_{\mu}^{Z} \\ g_x\, j_{\mu}^{x} + \left(\frac{e^2\,\delta}{g_x} - c_{\theta}\, e\, \epsilon_B\right) j_{\mu}^{em} \end{pmatrix}.$$

Millicharge generation

Dark sector interactions

Kinetic mixing

Summary

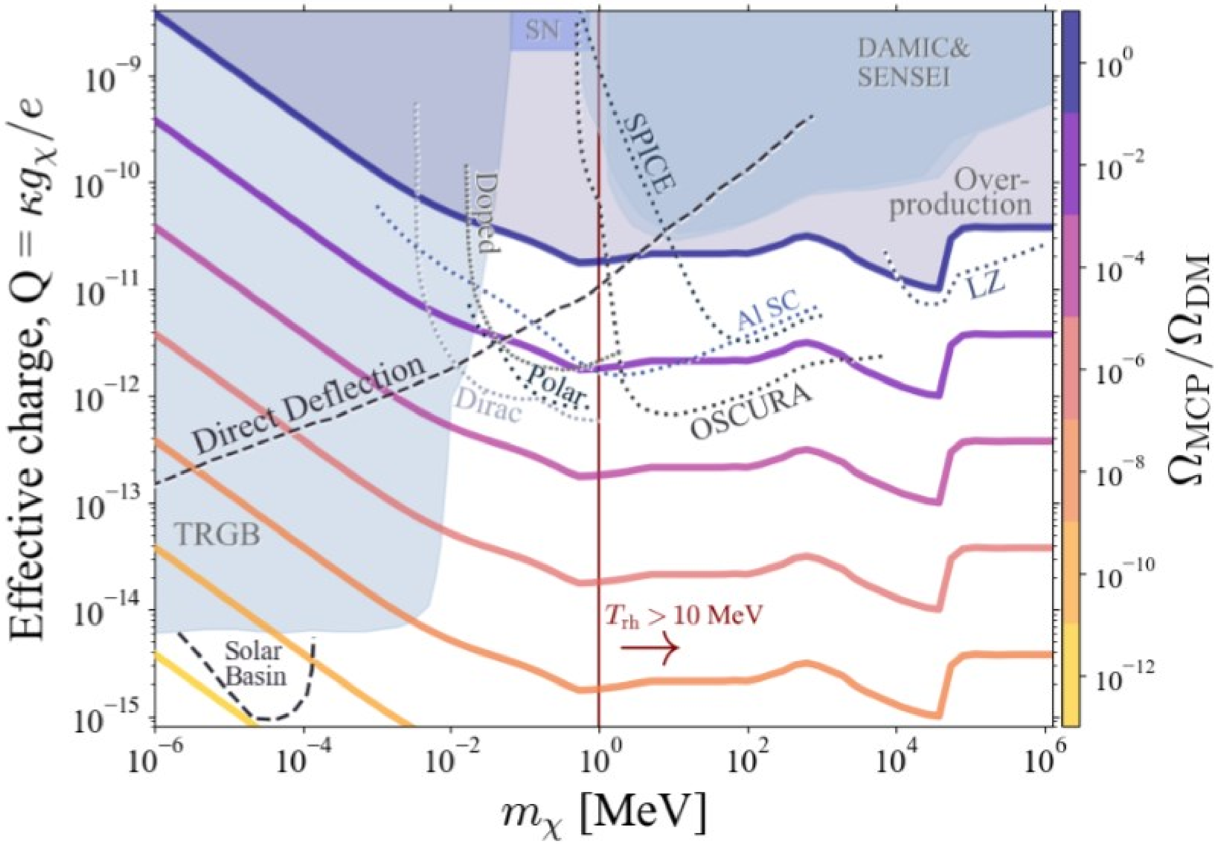
- For accelerator searches to actually be relevant, we must ensure that the MCP relic aboundance is depleted
  - →Preferentially via something that can further decay into SM particles and not dark radiation

- Complete constructions based on dark Higgs mechanisms could work
  - →Copious signatures at accelerators since the dark sector is richer
  - →They however do bring quite a lot of additional constraints to be fully explored and still feature the tuning of a small charge.
  - →Relic aboundance currently being estimated to check if the density of MCP can be sufficiently depleted

Backup

Direct detection constraints?

- Direct detection experiments place strong constraints even on the interactions of dark matter subcomponents
- Necessary to deplete abundance by many orders of magnitude?



Iles et al., arXiv:2407.21096

No CMB limits for smaller relic fraction

- CMB constraints at recombination falls off very quickly if relic density smaller the