PASCOS 2019

New Aspects of Millicharged Dark Matter at 21-cm

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1907.XXXXX

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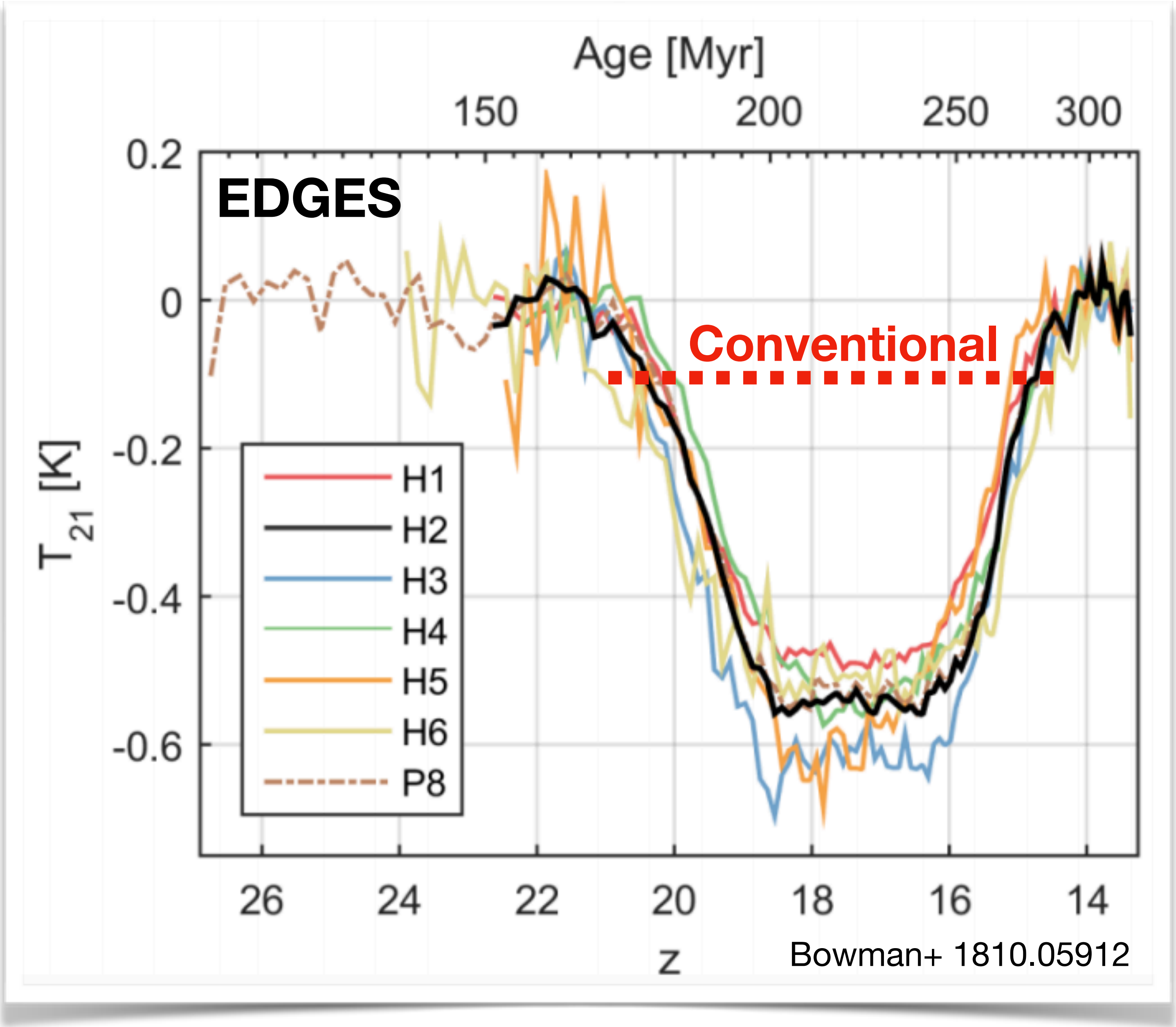
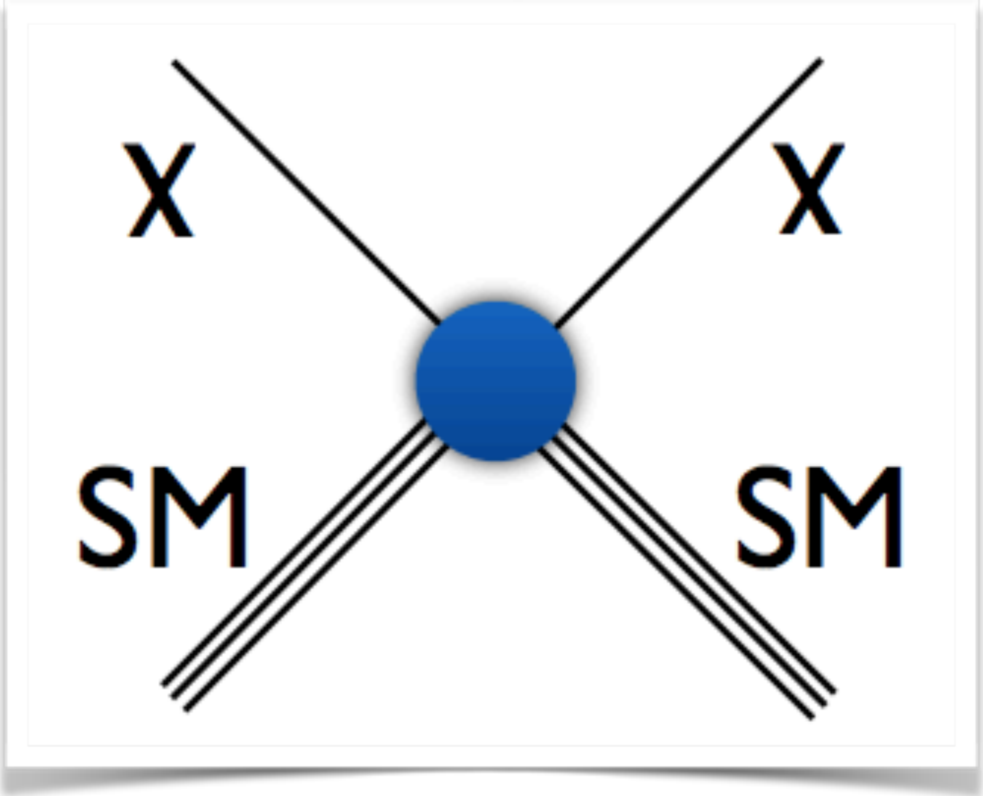
Outline

Dark matter-baryon scattering can leave striking signatures in the 21-cm global signal.





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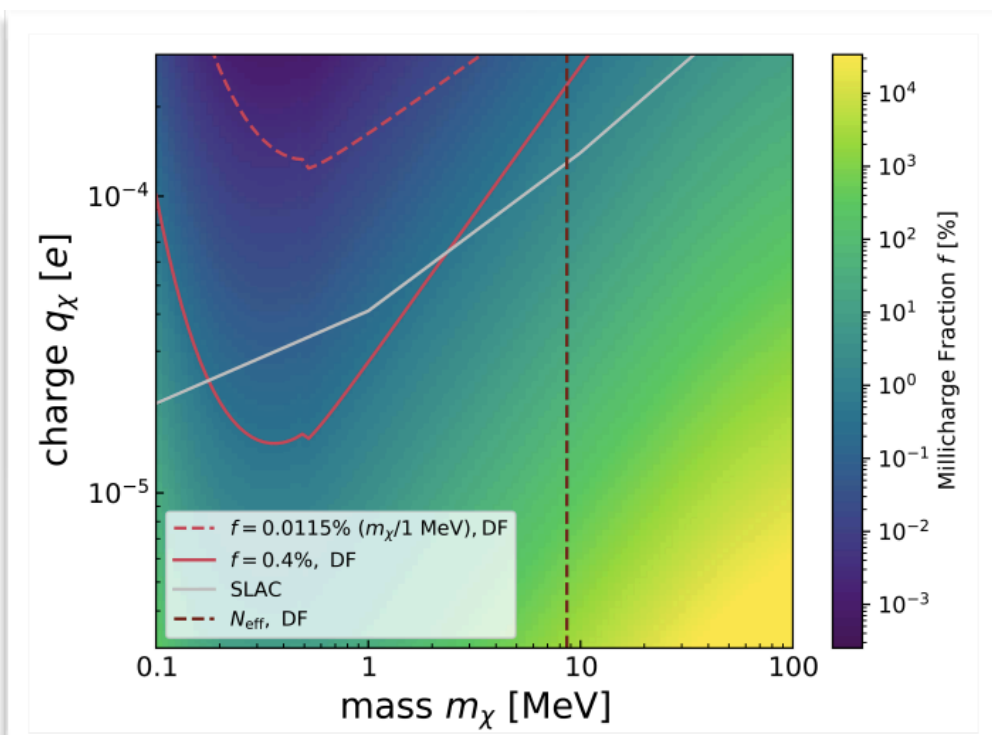
Dark matter-baryon scattering can leave striking signatures in the 21-cm global signal.

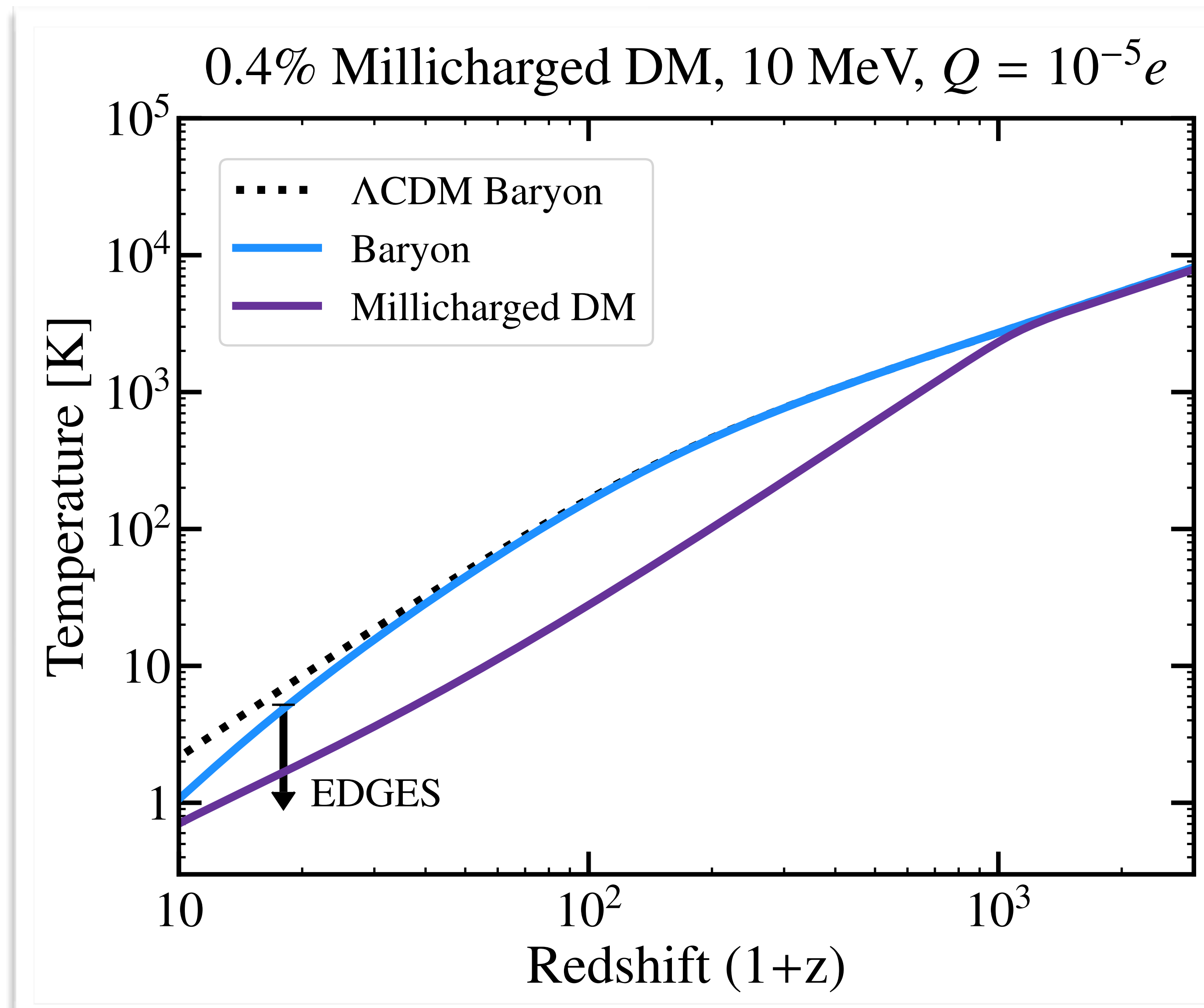
Heat Flow

Baryons → Millicharged DM

The **pure millicharged dark matter** model cannot explain the EDGES strong absorption signal.



Creque-Sarbinowski+ 1903.09154



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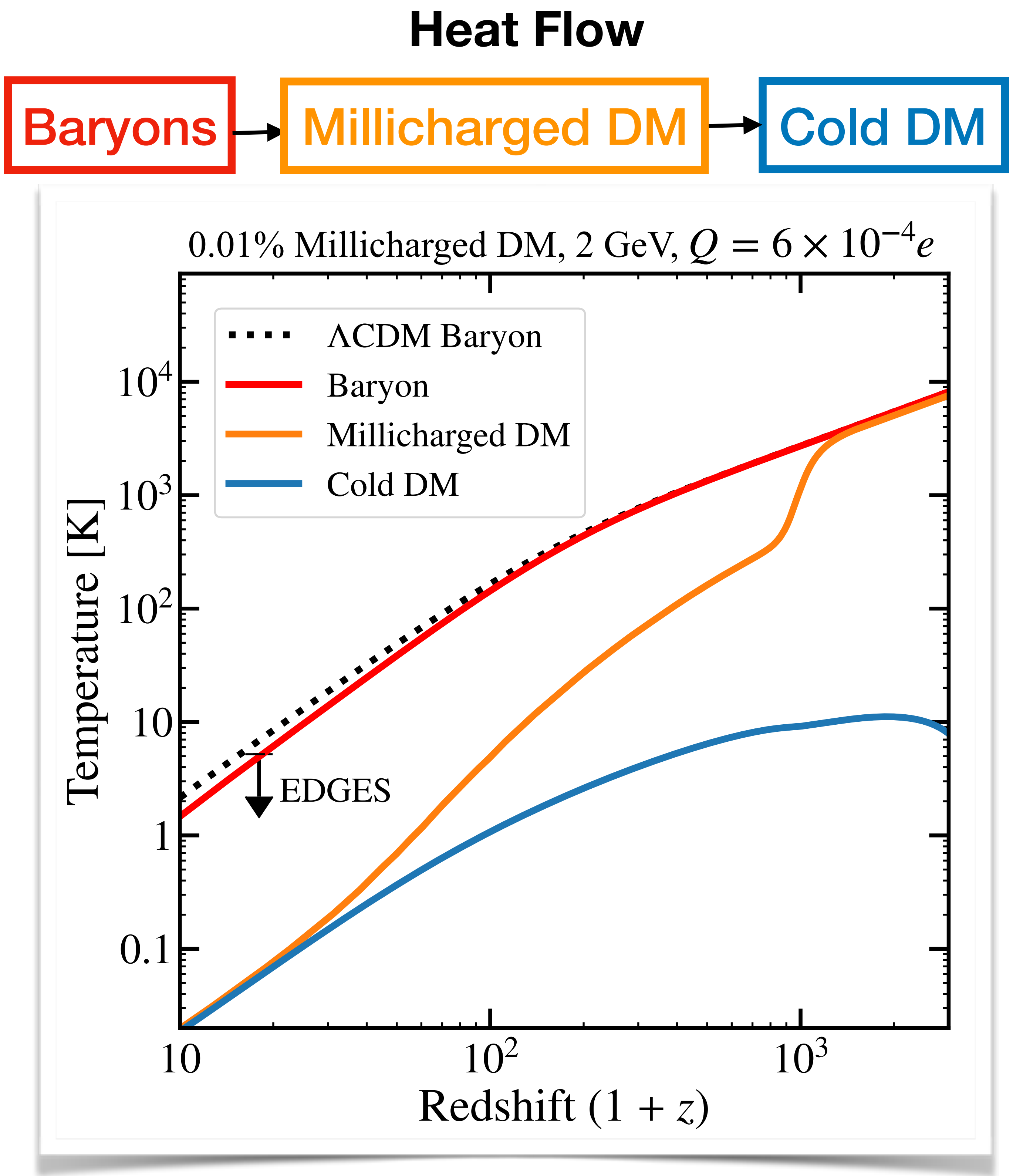
A dark sector with a **millicharged** component *and* a **cold** component, with a **long-range interaction** between them, can do so!



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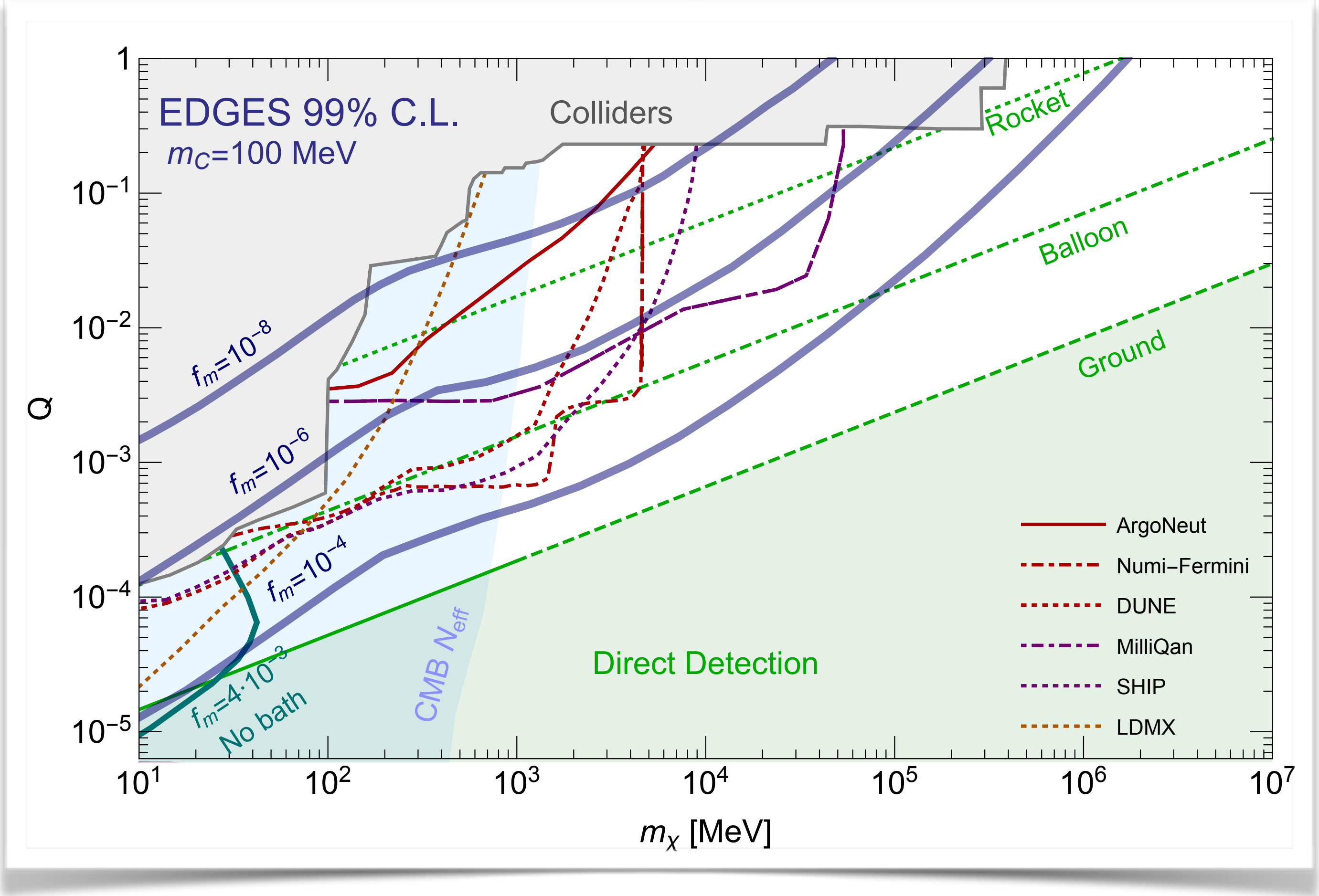

Striking signatures predicted at both **beam** and **direct detection** experiments.

Dark Matter-Baryon Scattering

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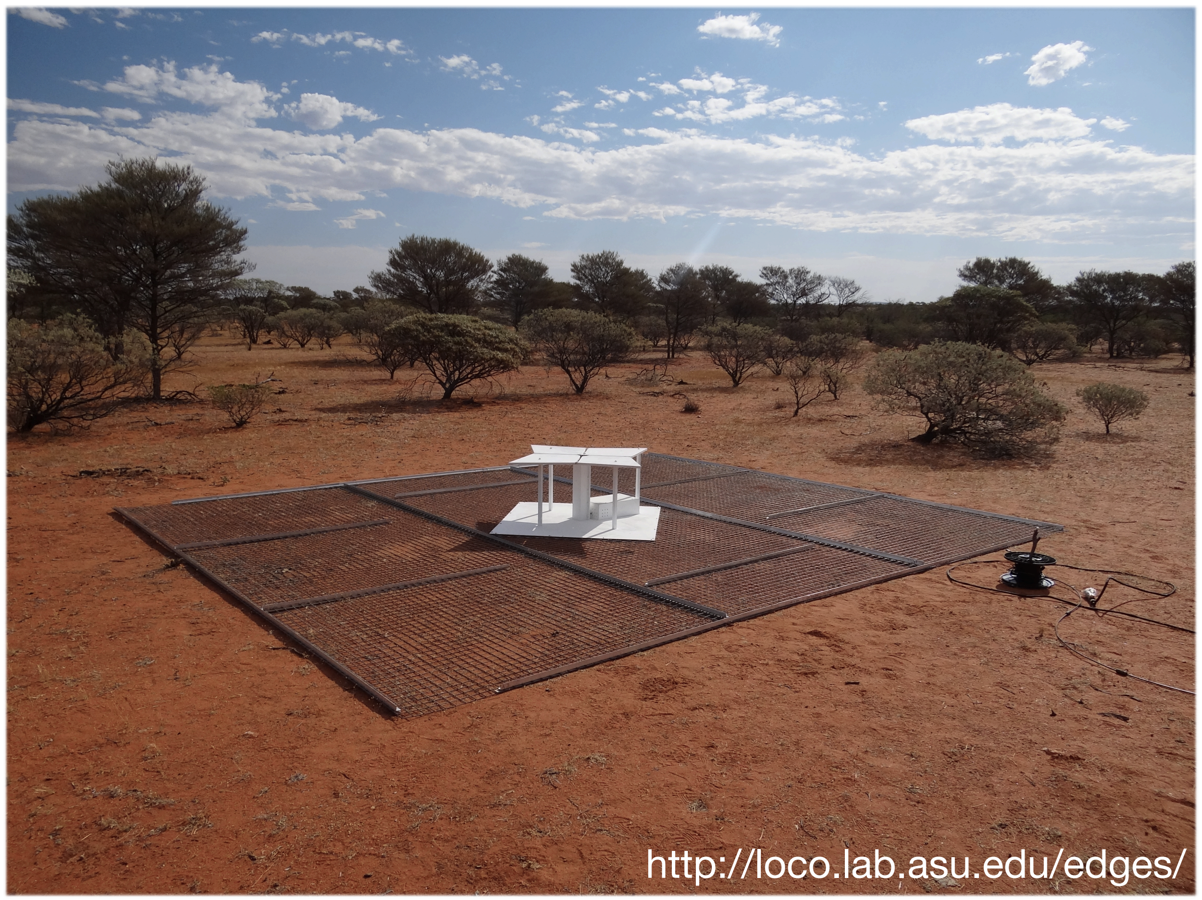
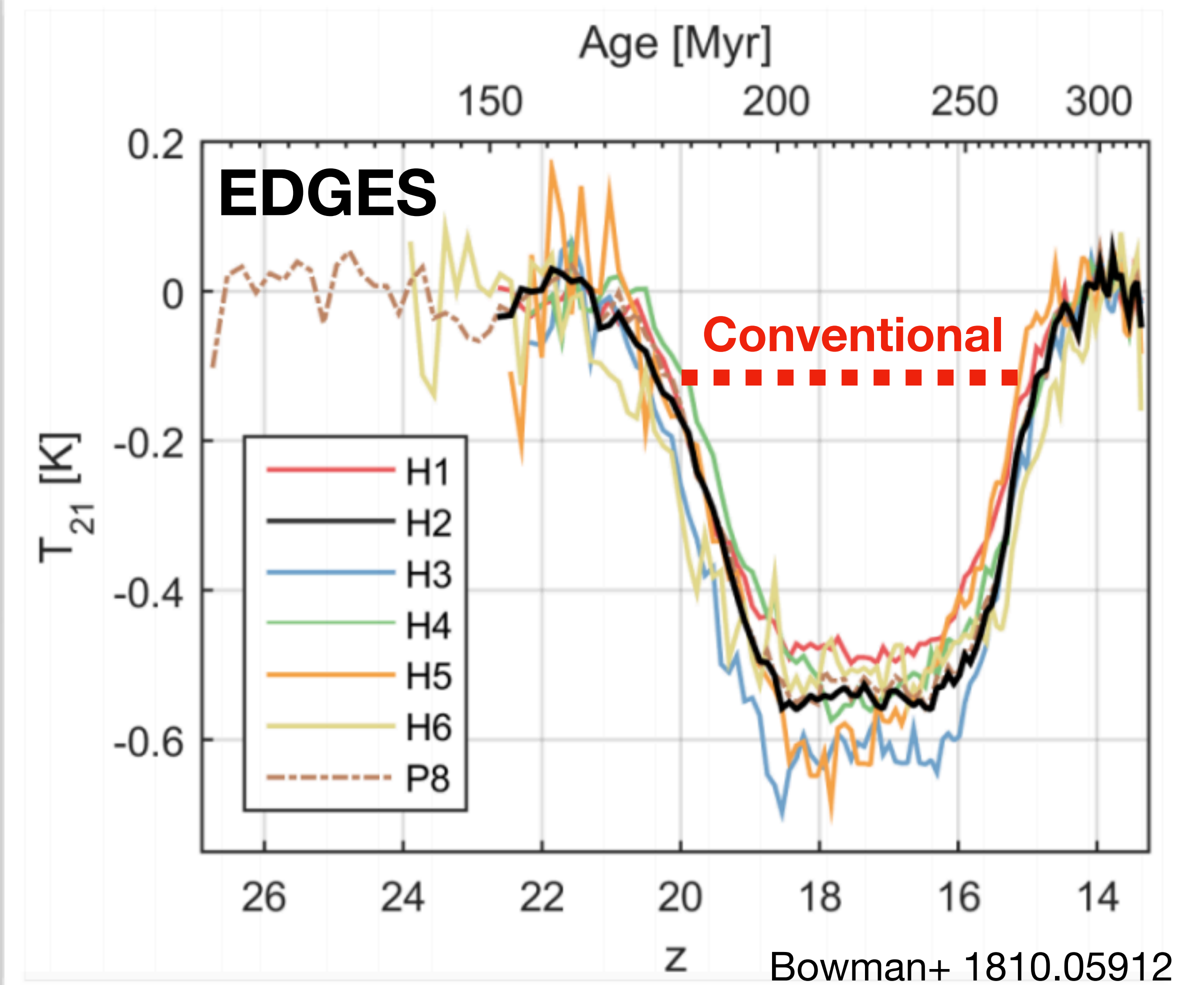
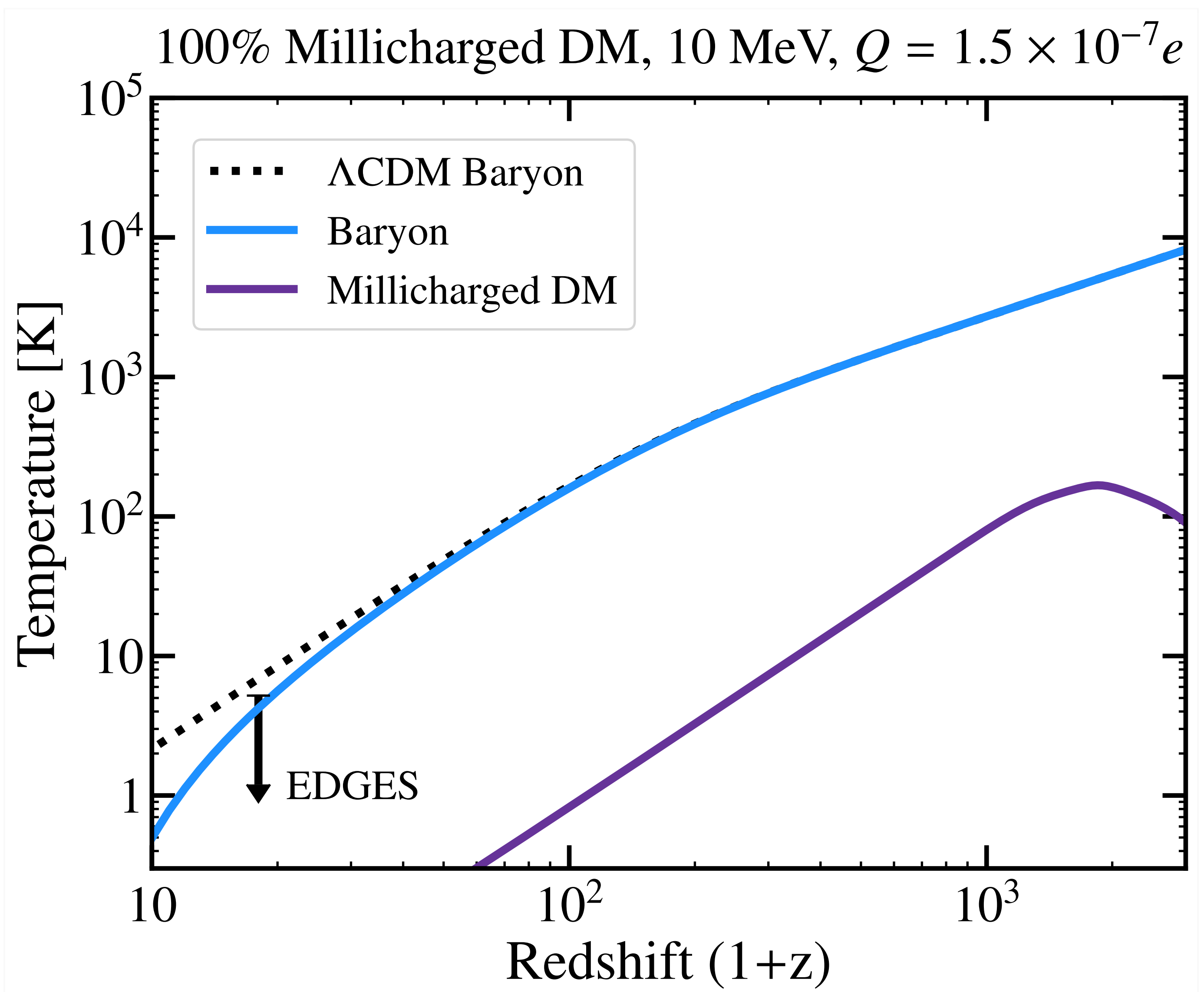
EDGES Experiment

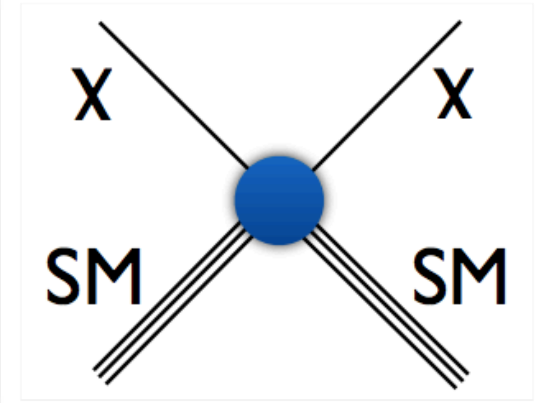




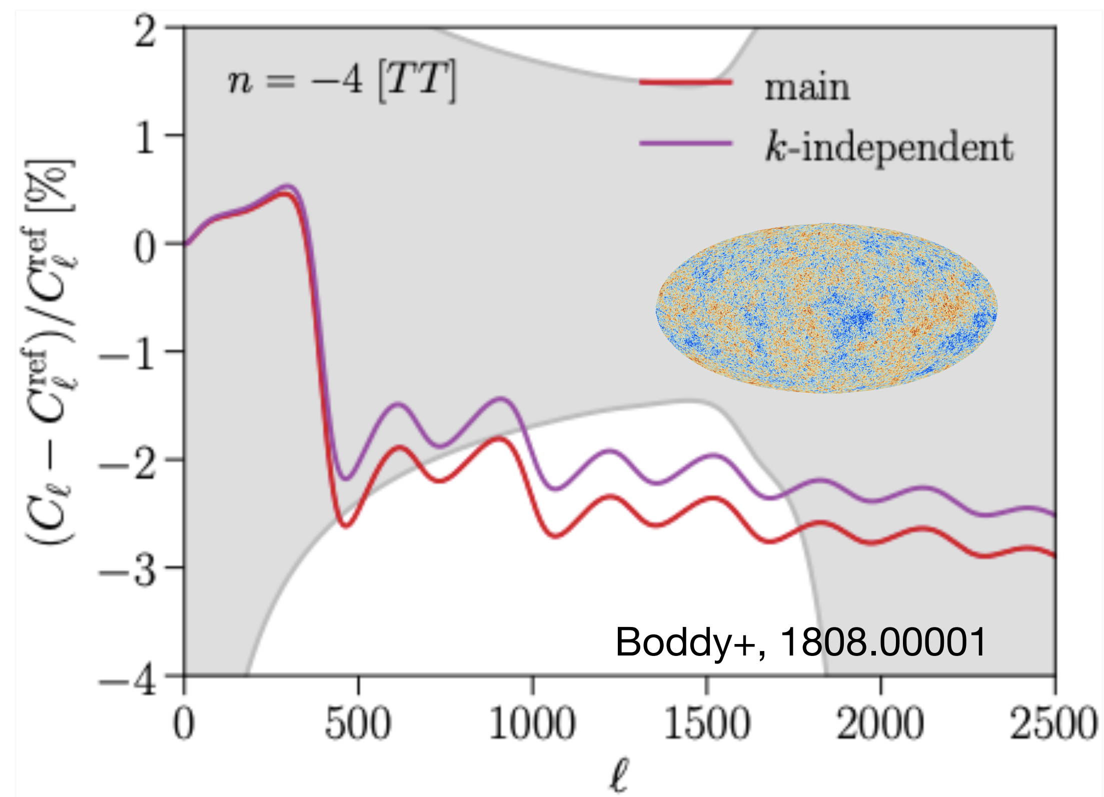
First measurement of the **21-cm global signal**. **Larger absorption** than expected!
Suggests a **lower baryon temperature** than expected at $z \sim 17$:
at most 5.2 K instead of the conventional expectation, **6.8 K**.

Dark Matter-Baryon Scattering



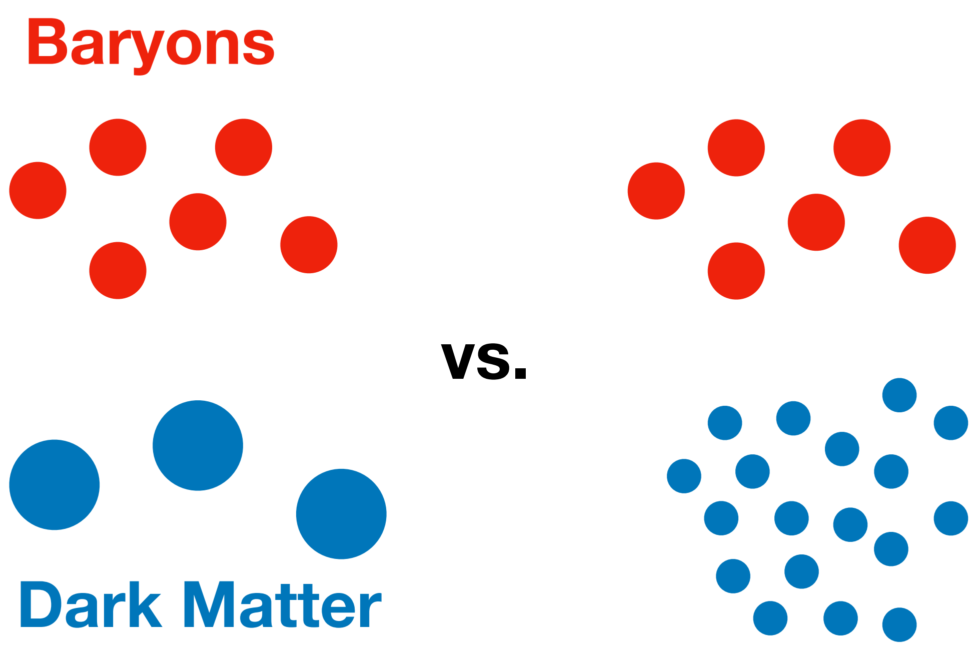


Blum+1311.2937,
Xu+ 1802.06788,
Slatyer+ 1803.09734,
de Putter+ 1805.11616,
Boddy+, 1808.00001,
…

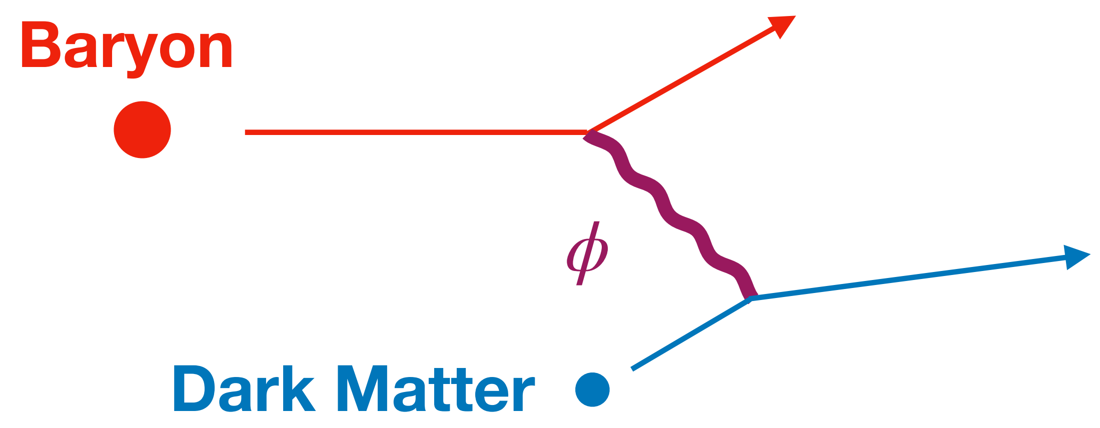


Significant impact on **thermal history of the universe**.
Interesting target for **CMB** and **21-cm** experiments.

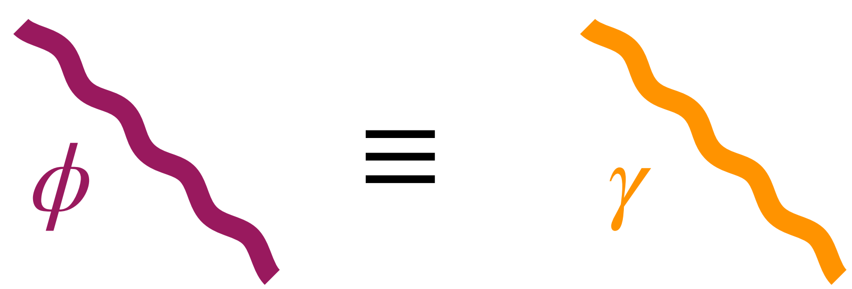
Baryon Cooling Requirements



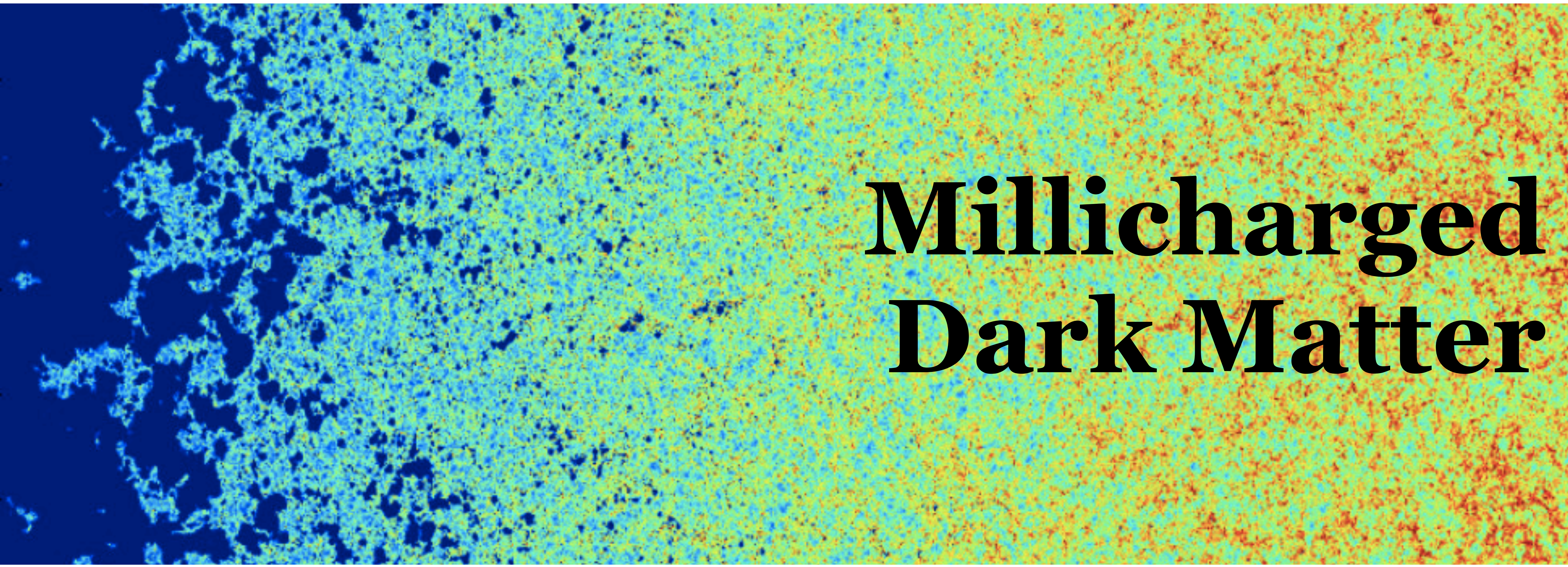
High heat capacity: $m_{\mathrm{DM}} \lesssim$ GeV.



Large scattering cross section.
Constraints favor $\sigma \propto v^{-4}$ enhancement,
i.e. **light mediator exchange**.



Mediator must be light compared to momentum transfer, i.e. $m_\phi \lesssim$ keV. **Severe constraints** favor identifying ϕ with the **photon**, i.e. **millicharged dark matter**!



Millicharged Dark Matter

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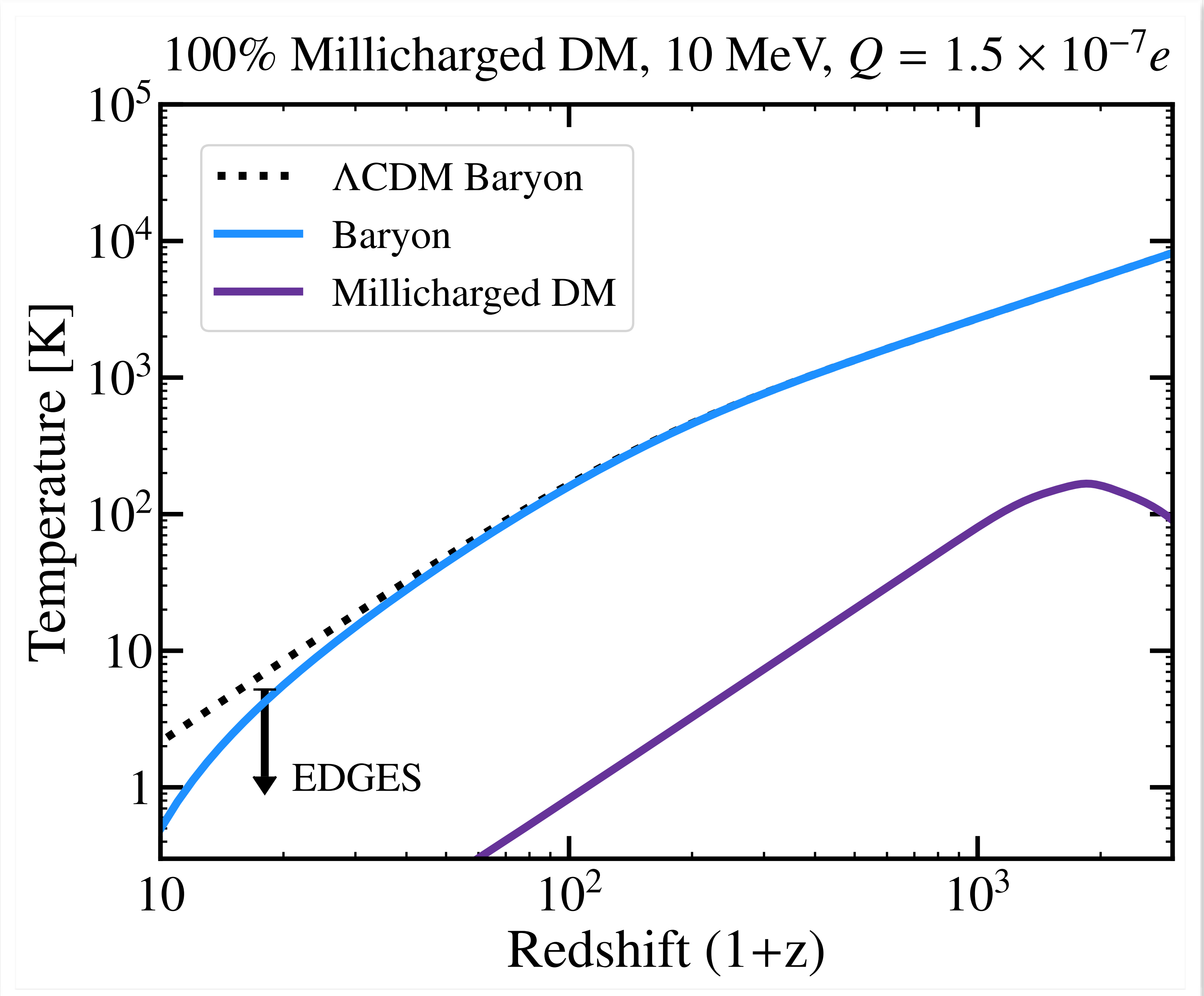
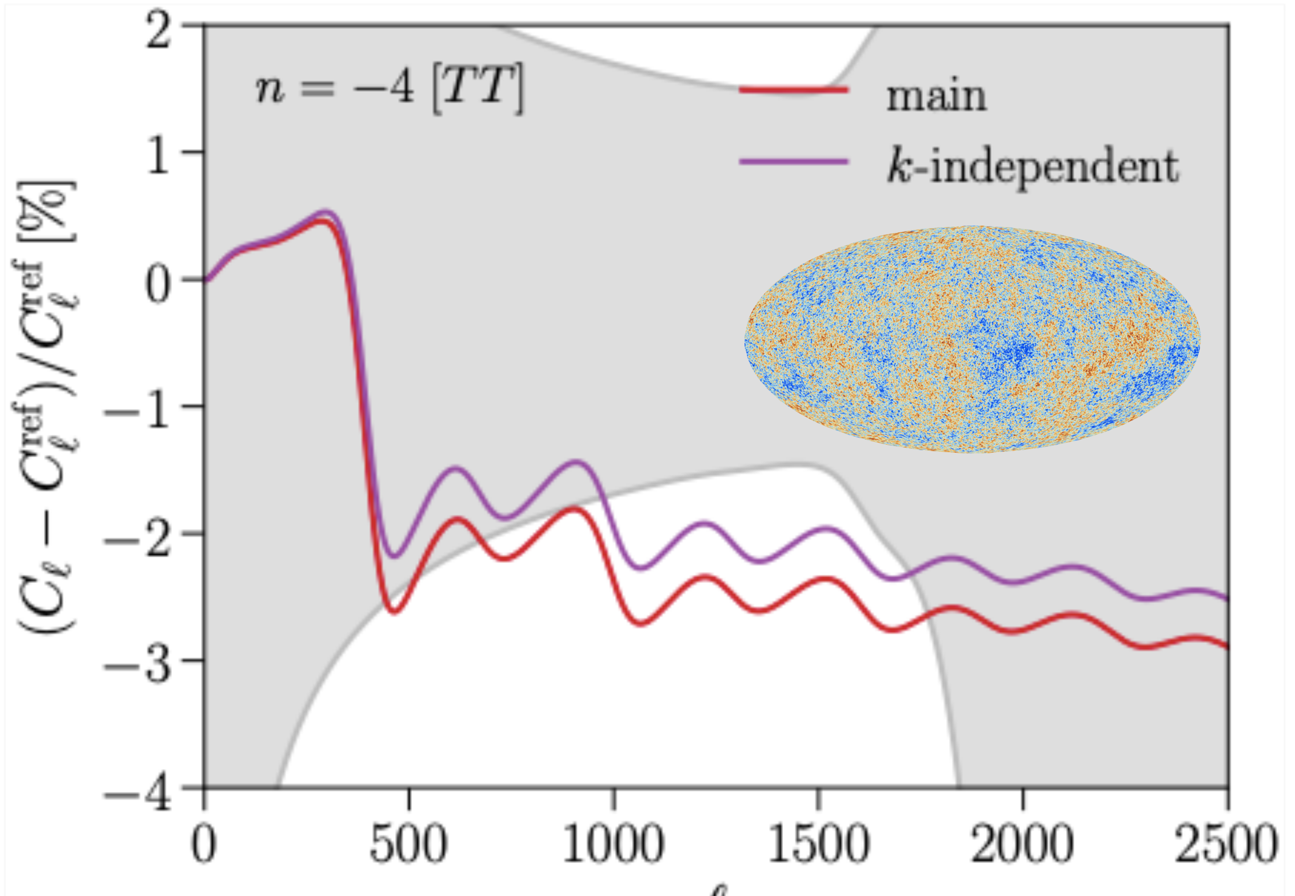
Millicharged Cooling

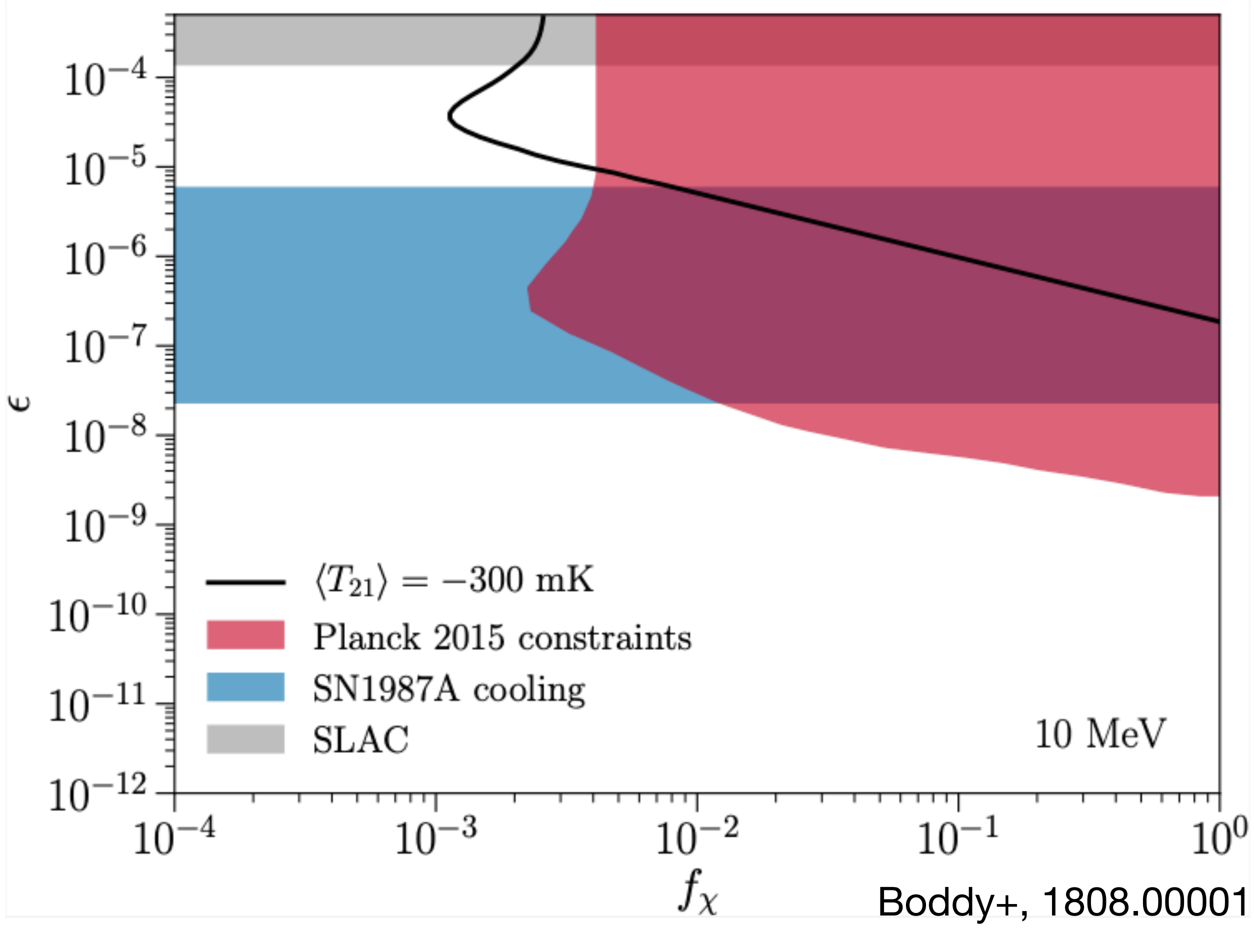


100% millicharged dark matter can do the job. **However…**

CMB Constraints



Boddy+, 1808.00001

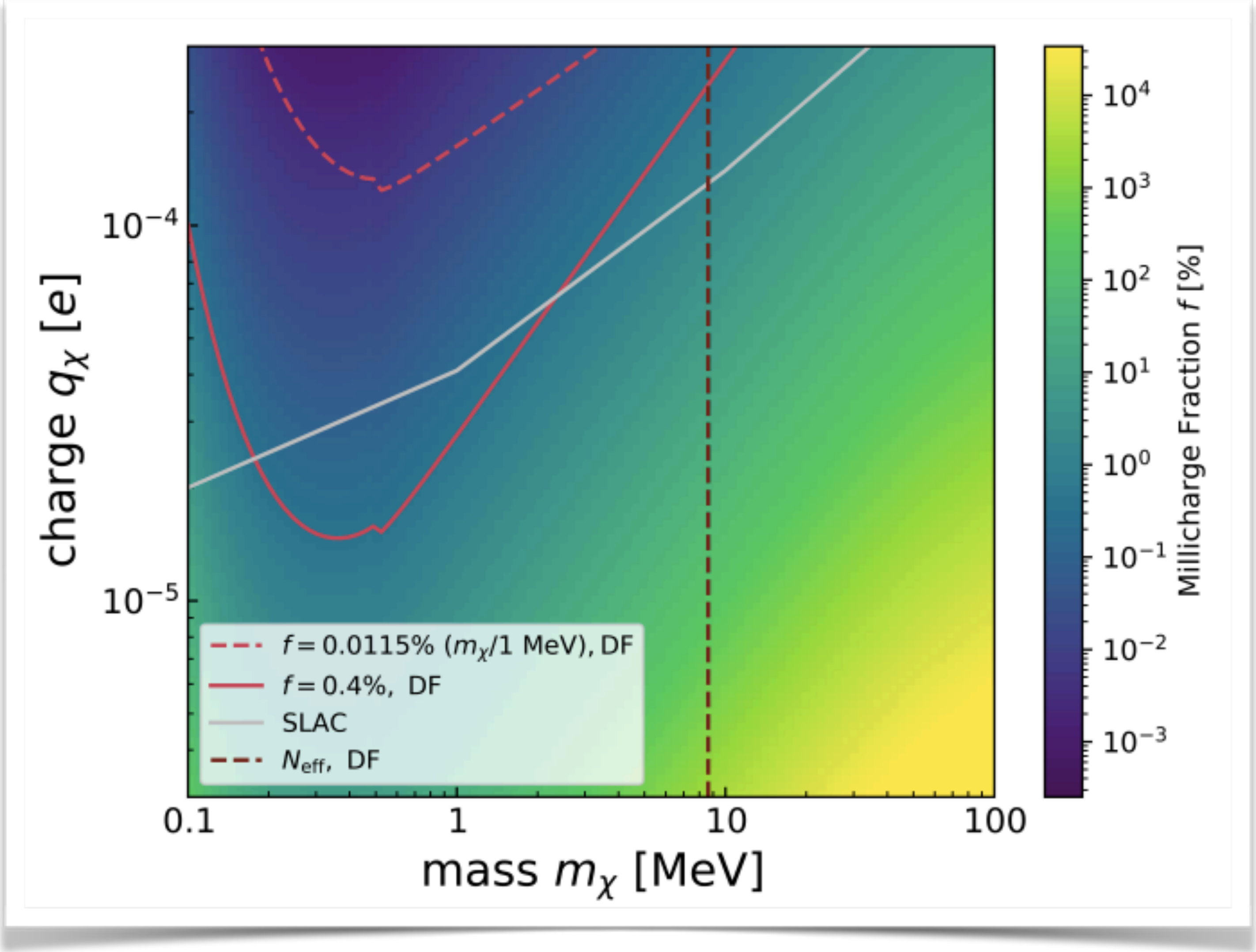


Boddy+, 1808.00001

Constrained by **cosmic microwave background power spectrum**: dark matter-baryon scattering affects the **acoustic oscillations** and the **sound speed**.

Millicharged dark matter limited to **less than 0.4% of all dark matter** by mass density.

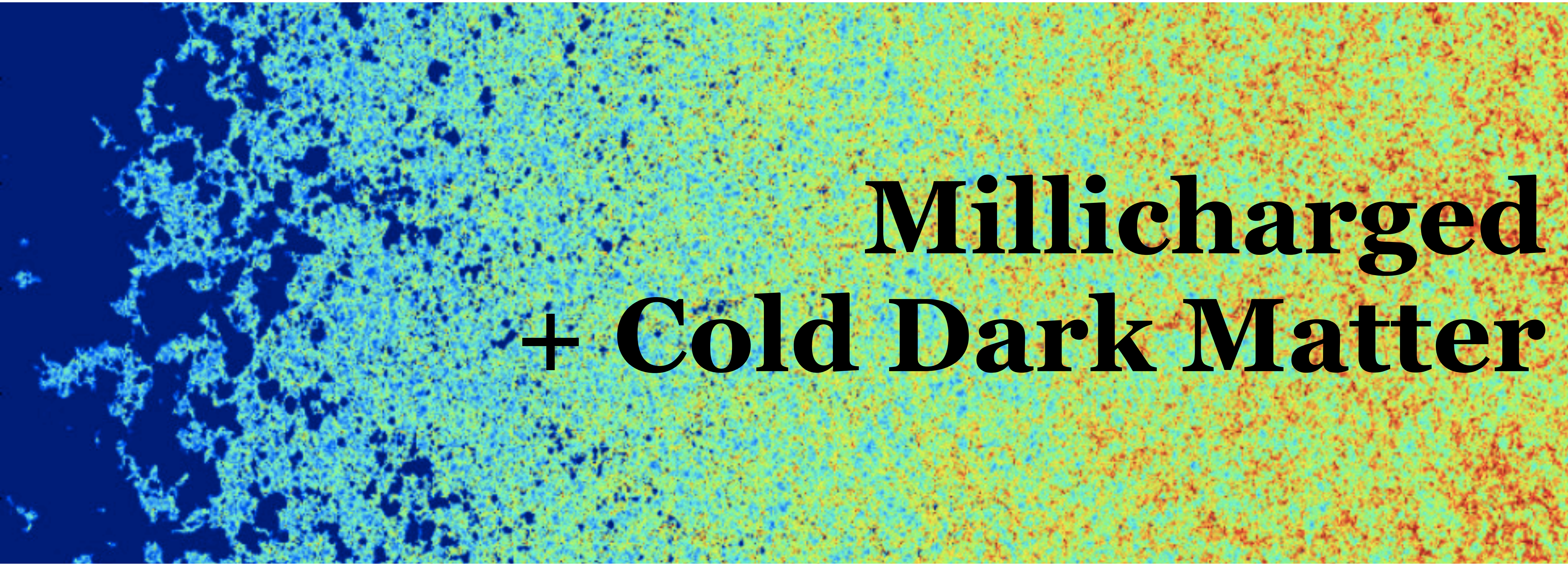
N_{eff} Constraints



Berlin+ 1803.02804, Creque-Sarbinowski+ 1903.09154

Constraints on N_{eff} from **CMB power spectrum** are important, as millicharged particles can **thermalize** in the early universe. **Closes all available parameter space**.

Millicharged + Cold Dark Matter



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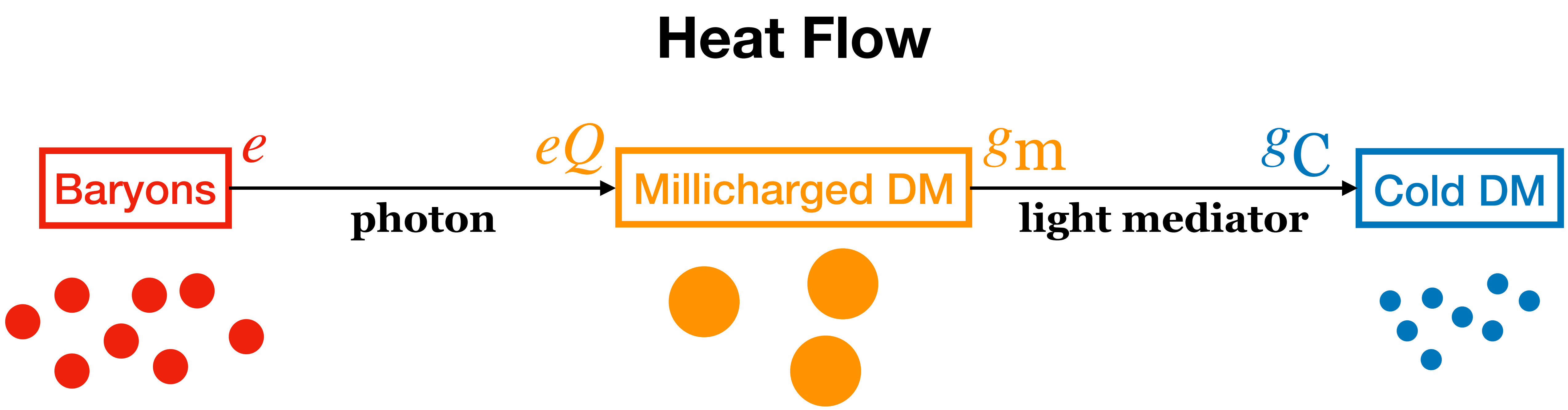
Millicharged + Cold Dark Matter



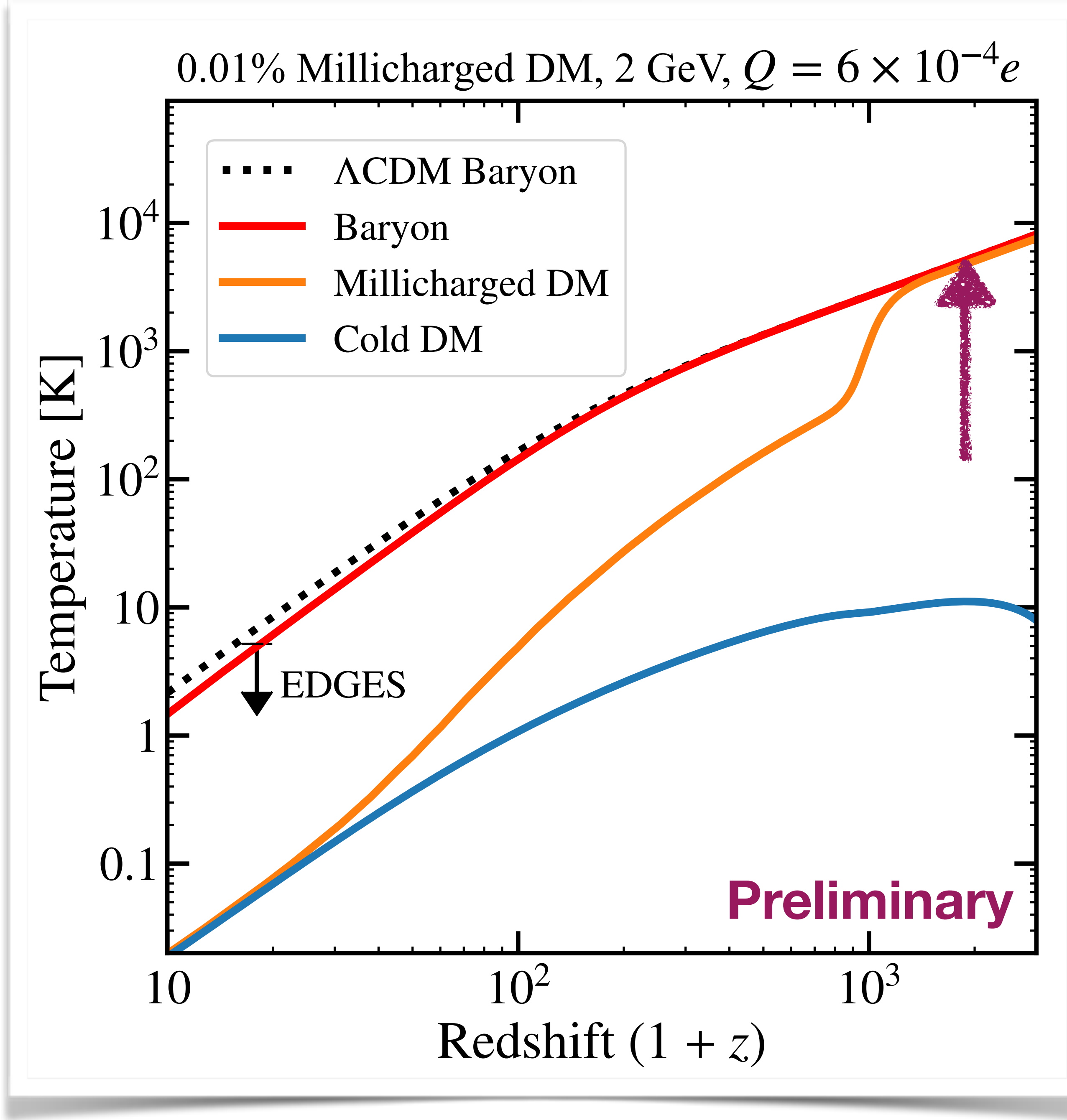
Scattering with **neutral H and He** are **important**.

$\lesssim 0.4\,\%$ of dark matter.
Can be **up to TeV in mass**!

$\gtrsim 99.6\,\%$ of dark matter
Relatively light ($\lesssim 20$ GeV)
for **high heat capacity**.

Temperature Evolution

Initial **tight coupling** between millicharged DM and baryons.



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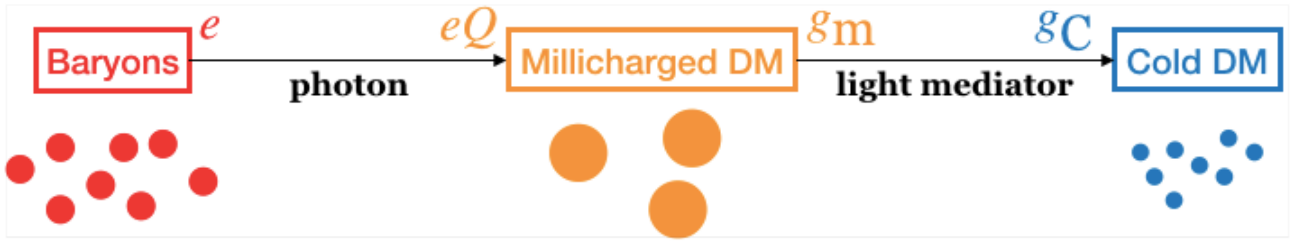
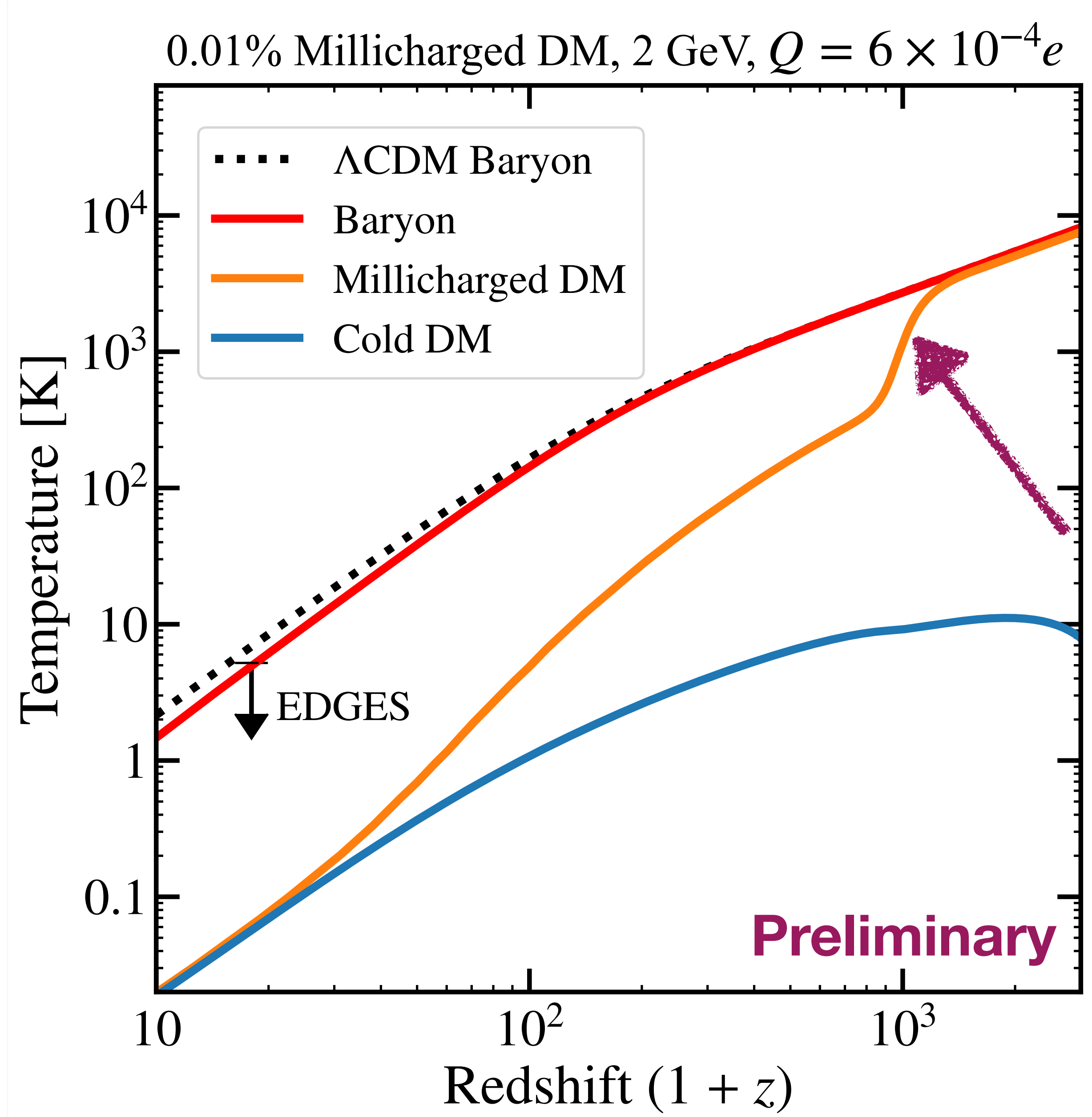


Initial **tight coupling** between millicharged DM and baryons.

Recombination happens, decreasing the number of charged particles in baryons.



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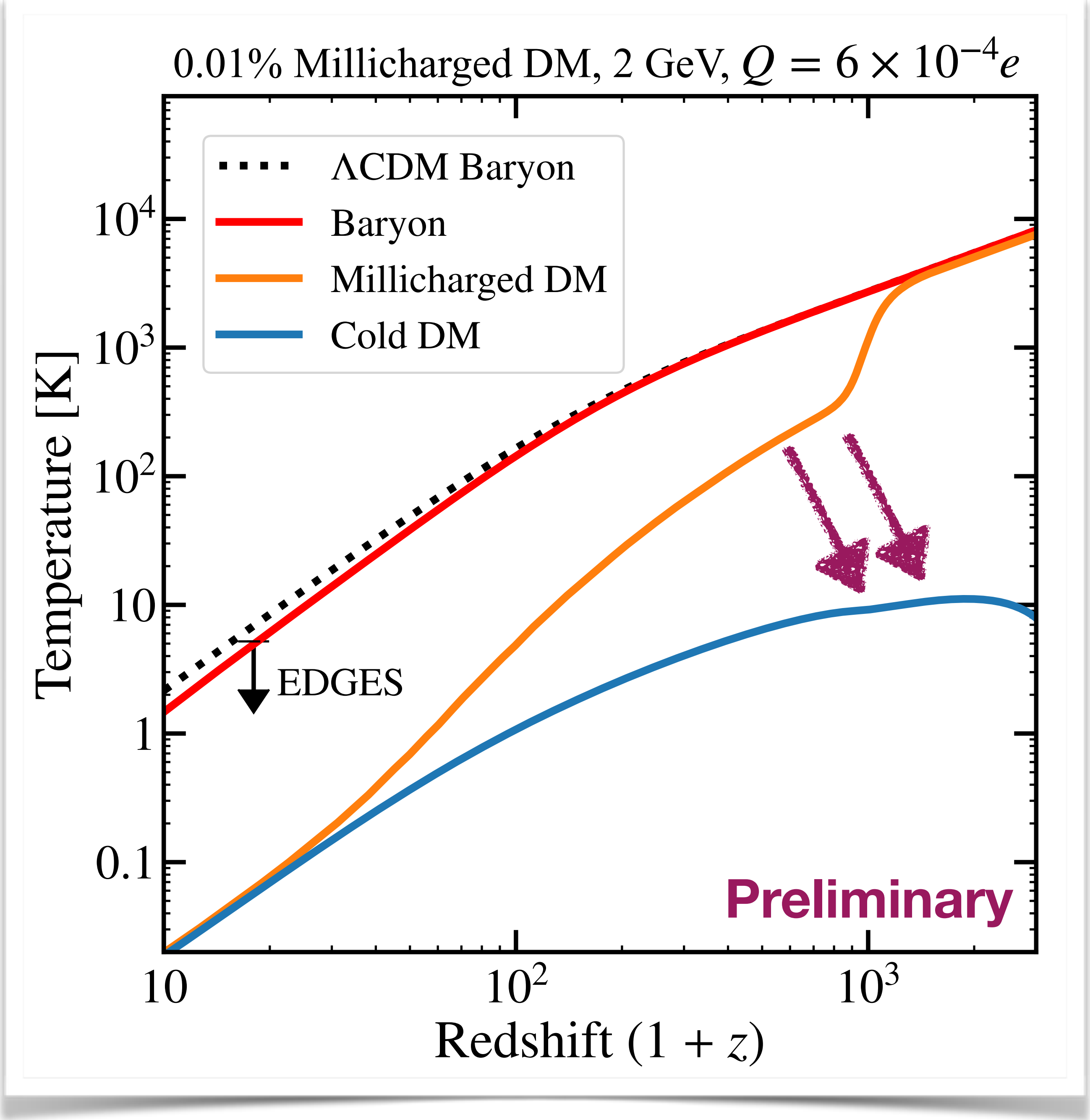
Heat transfer between millicharged and cold DM **cools the millicharged DM**.



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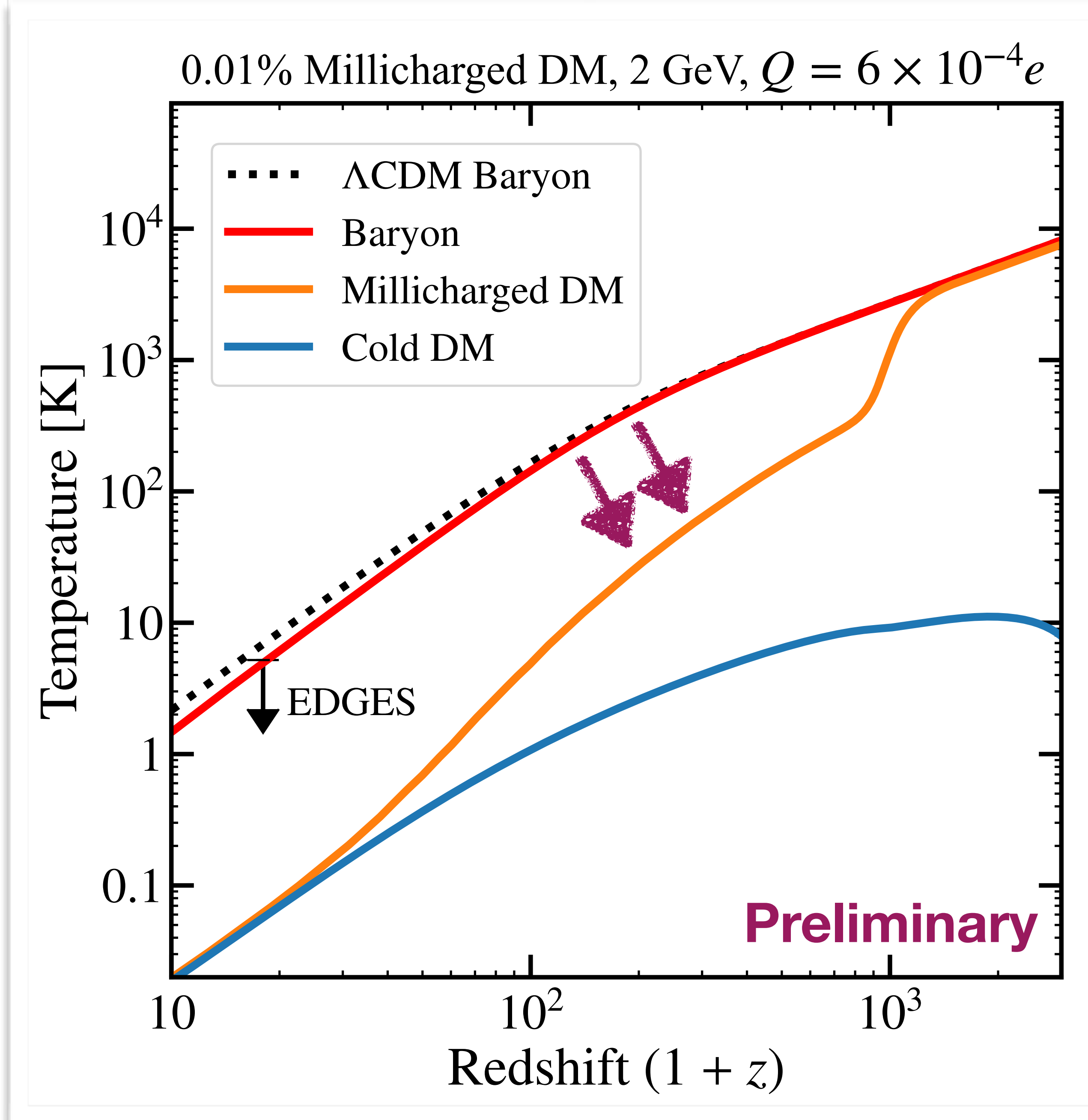

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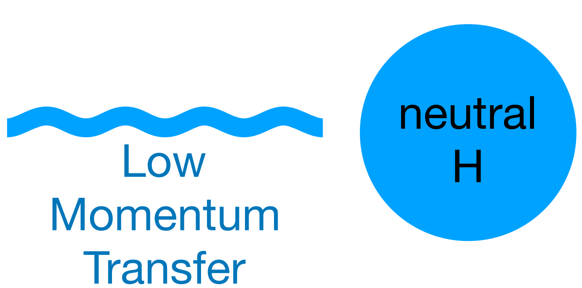
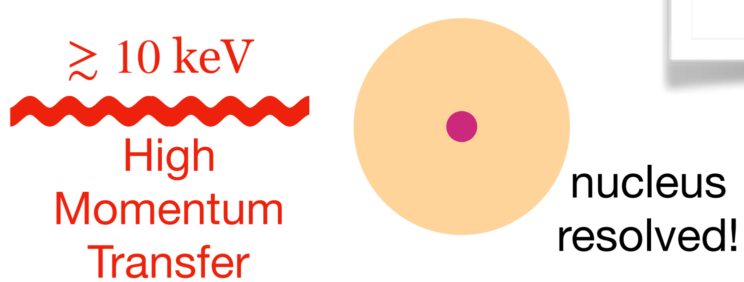
Recombination happens, decreasing the number of charged particles in baryons.

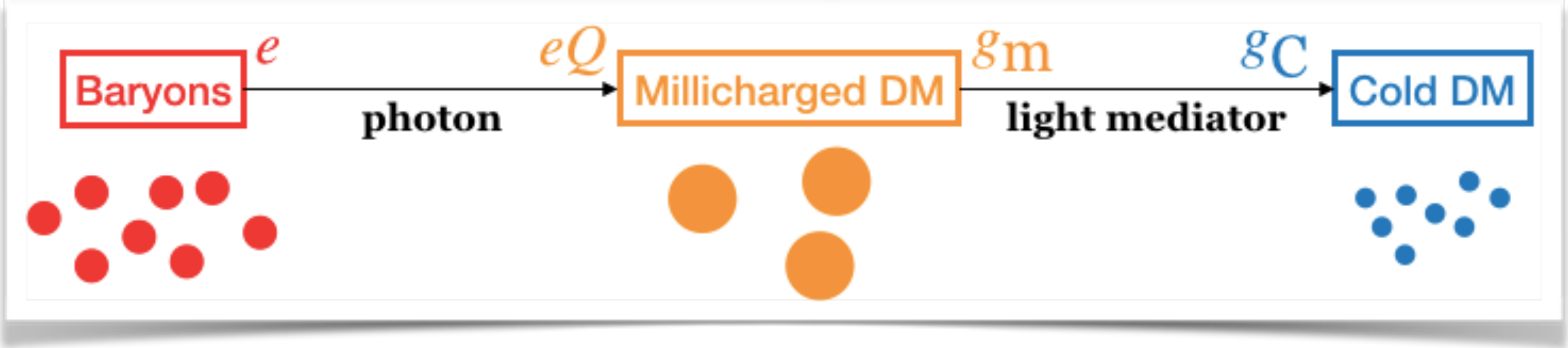
Heat transfer between millicharged and cold DM **cools the millicharged DM**.

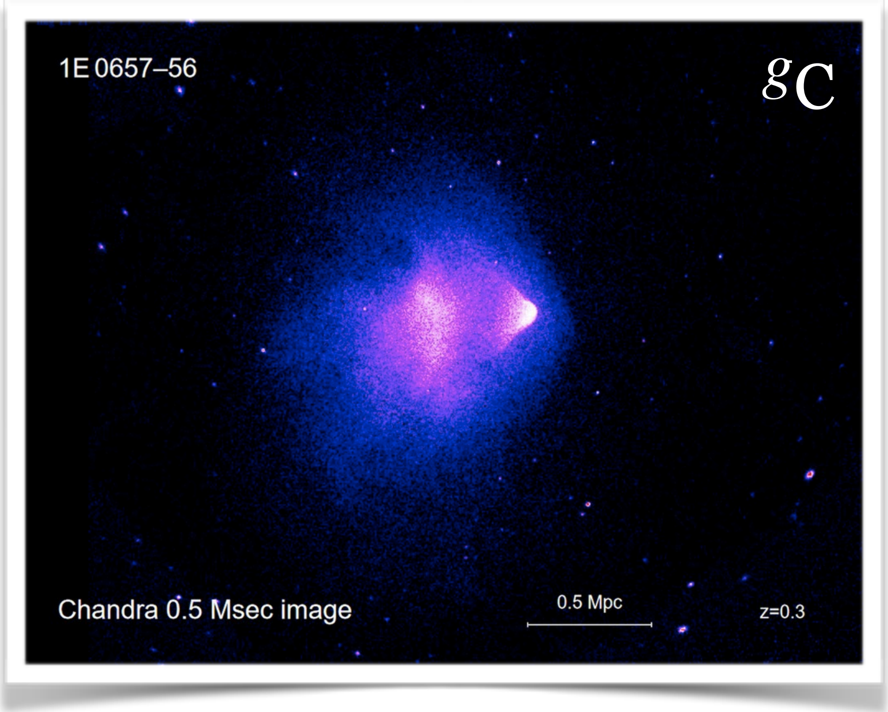
Millicharged DM **cools baryons**. Also scatters off **neutral H and He**!





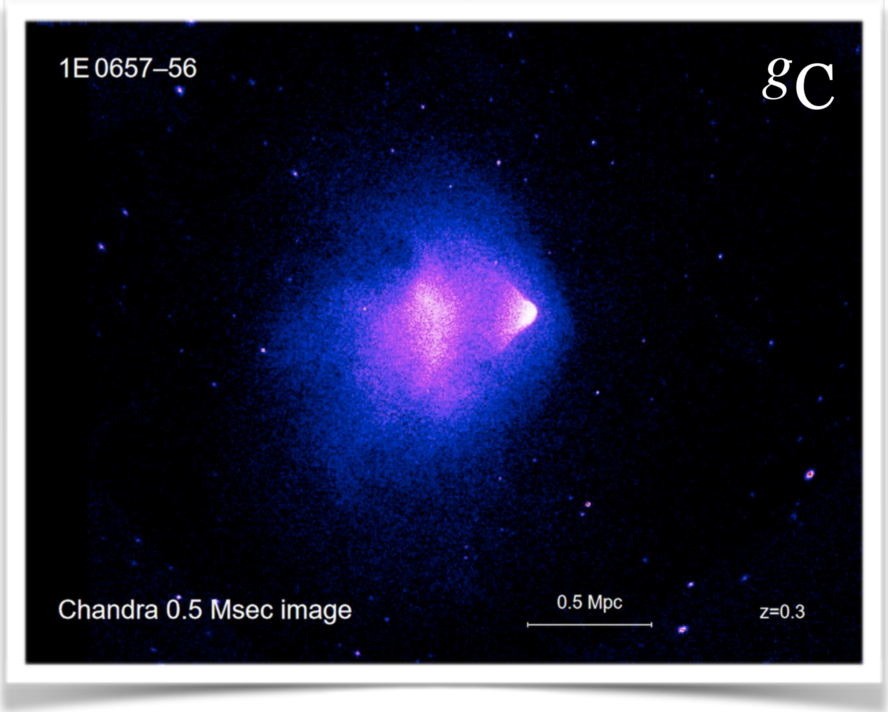
Constraints on Dark Sector?

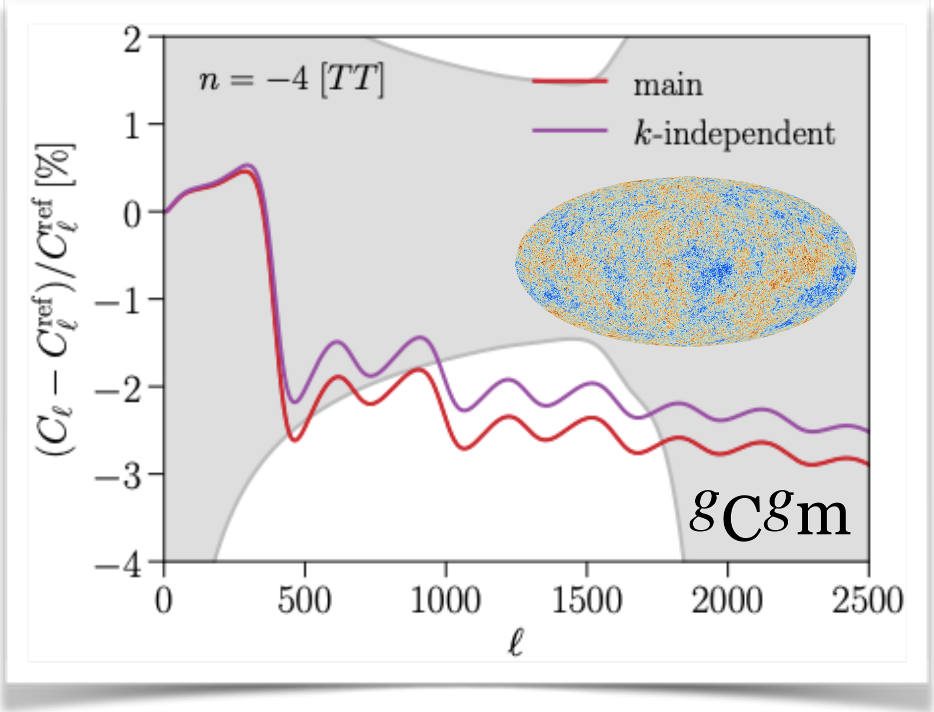




Self-interaction constraints set very weak limits on g_C .

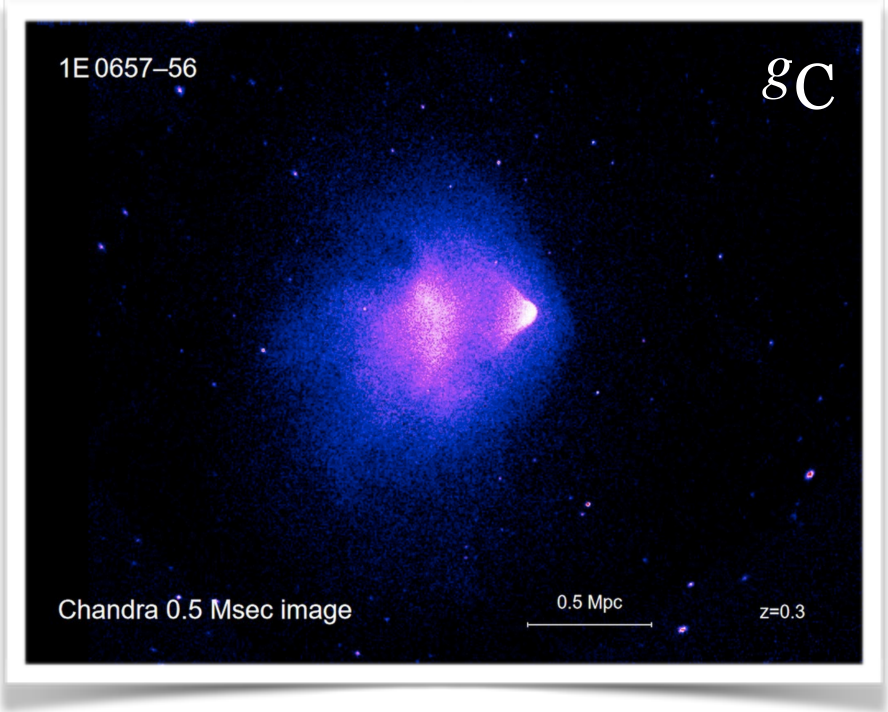
Constraints on Dark Sector?

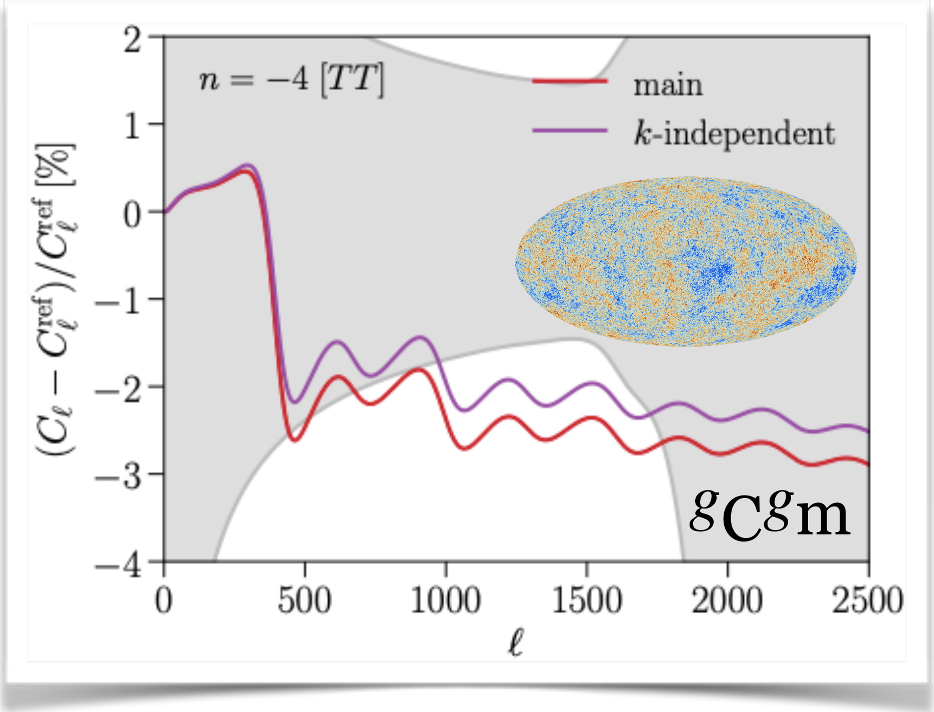


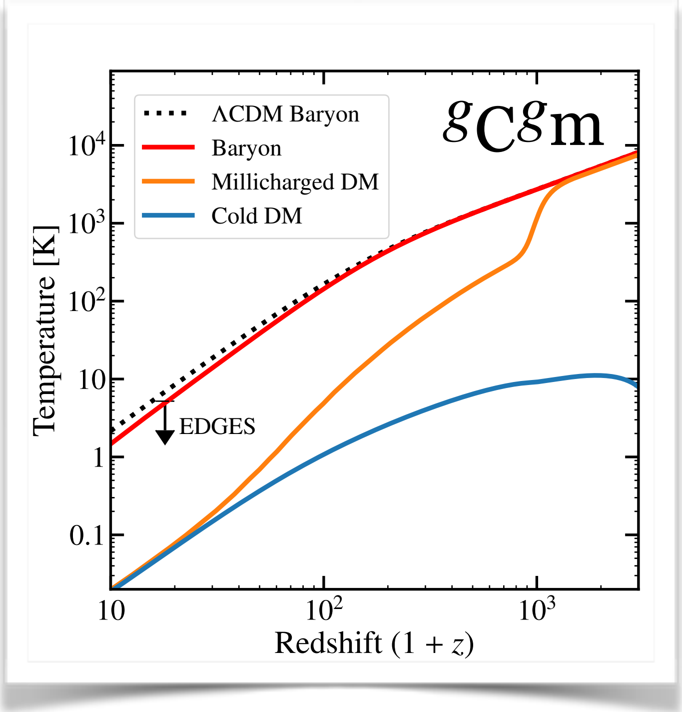


Same **CMB** constraints on dark matter-baryon interactions now limits both **millicharged fraction** ($f_\mathrm{m} \lesssim 0.4\,\%$) and $g_\mathrm{C} g_\mathrm{m}$ from limits on **momentum transfer** to dark matter.

Constraints on Dark Sector?

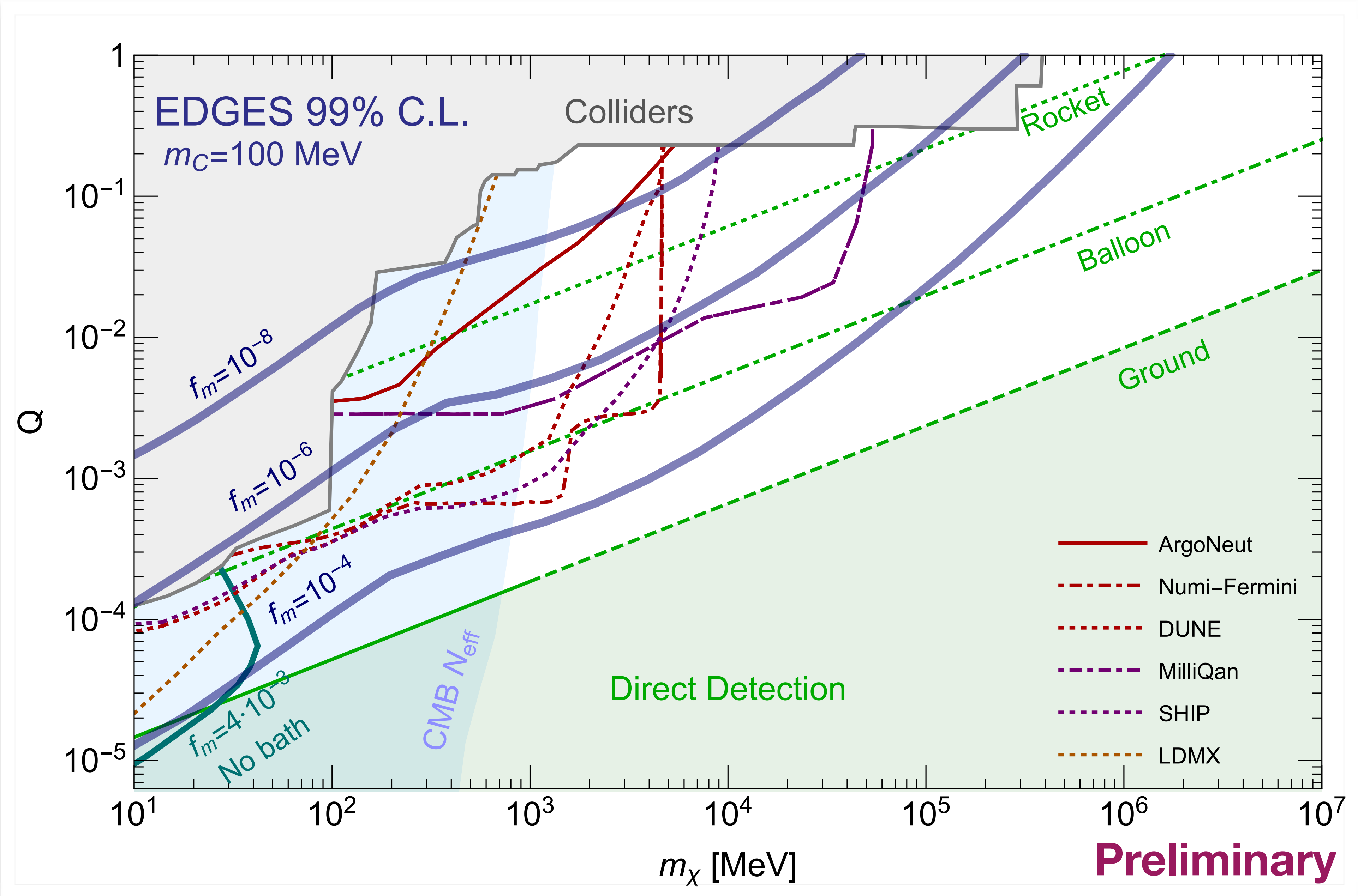






Requiring **tight coupling** between millicharged dark matter and baryons sets limits on $g_m g_C$ as a function of Q.

Millicharged Dark Matter Constraints



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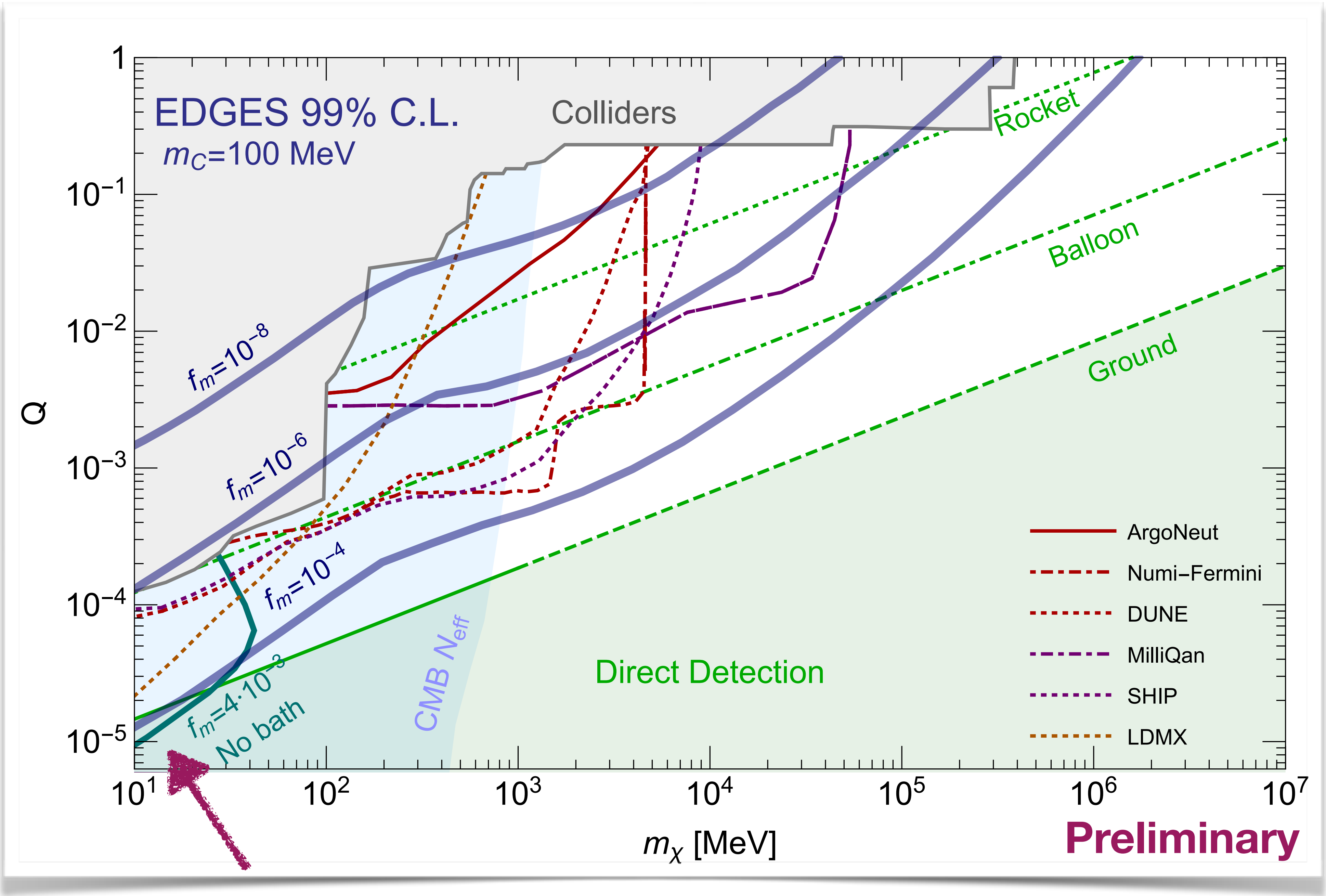
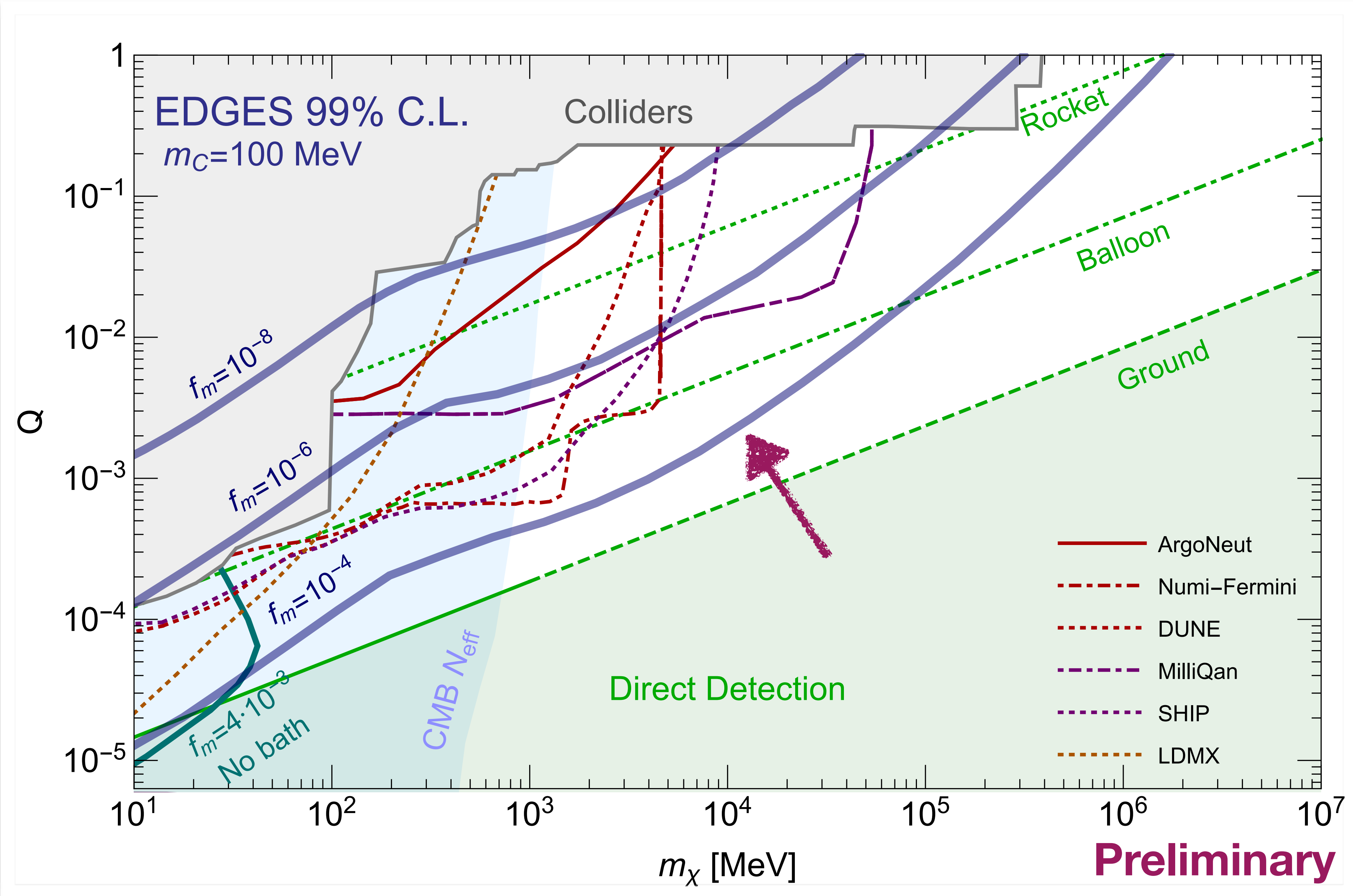


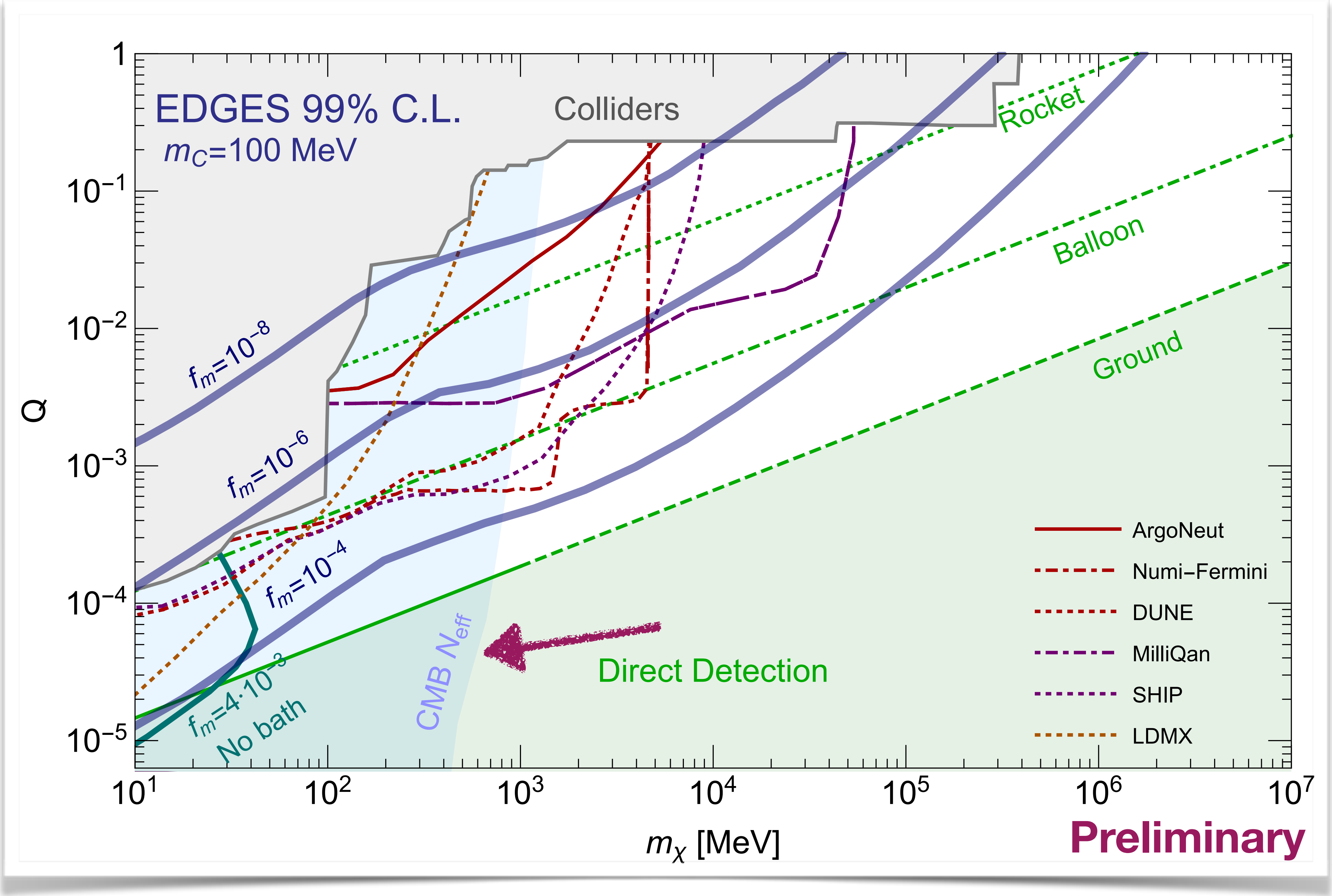
Pure millicharged model: ruled out by **N_{eff} constraints**.

Millicharged Dark Matter Constraints



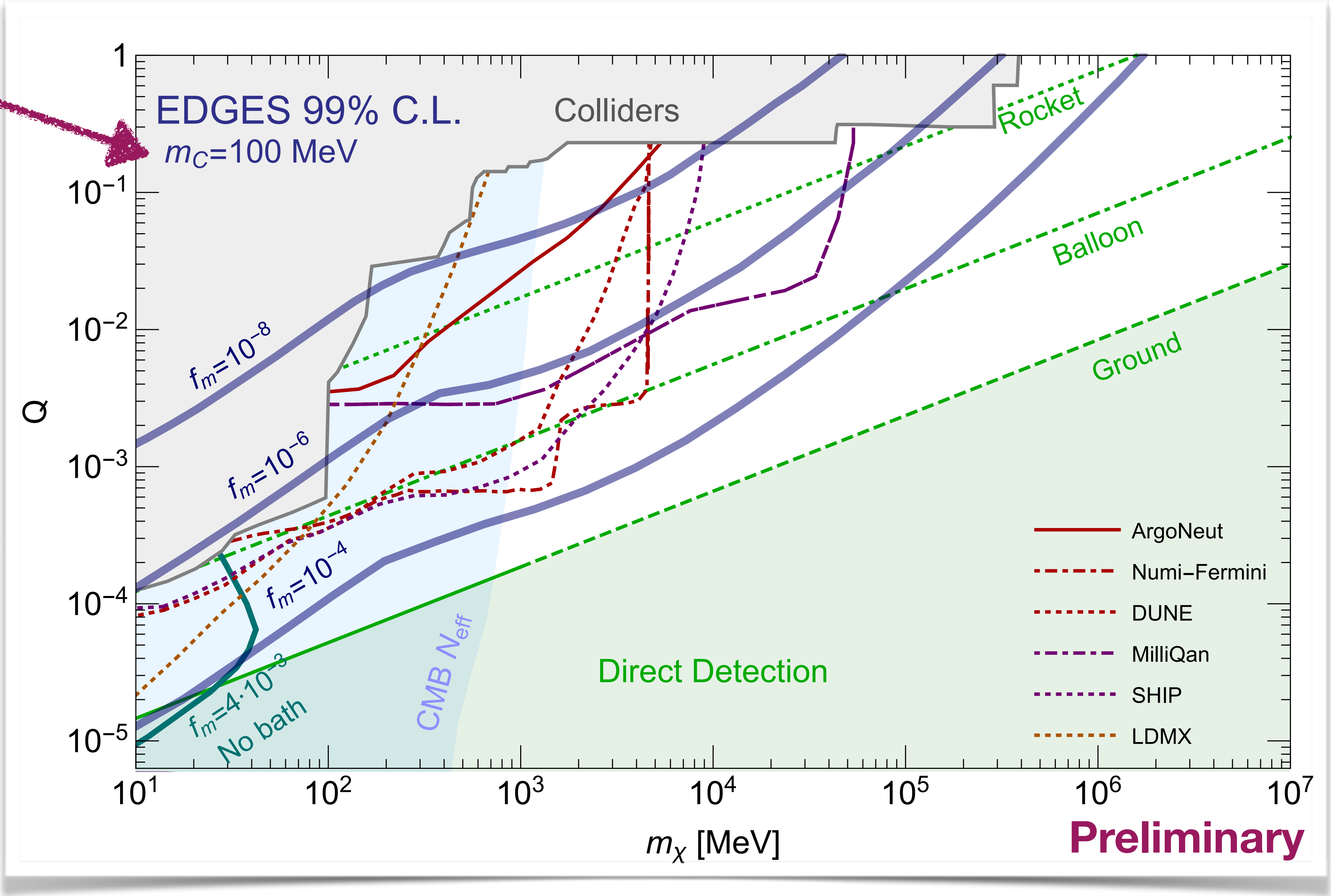
Our work: millicharged + cold dark matter model.
Small millicharged fraction of $10^{-8} \lesssim f_m \lesssim 4 \times 10^{-3}$ allowed.

Millicharged Dark Matter Constraints



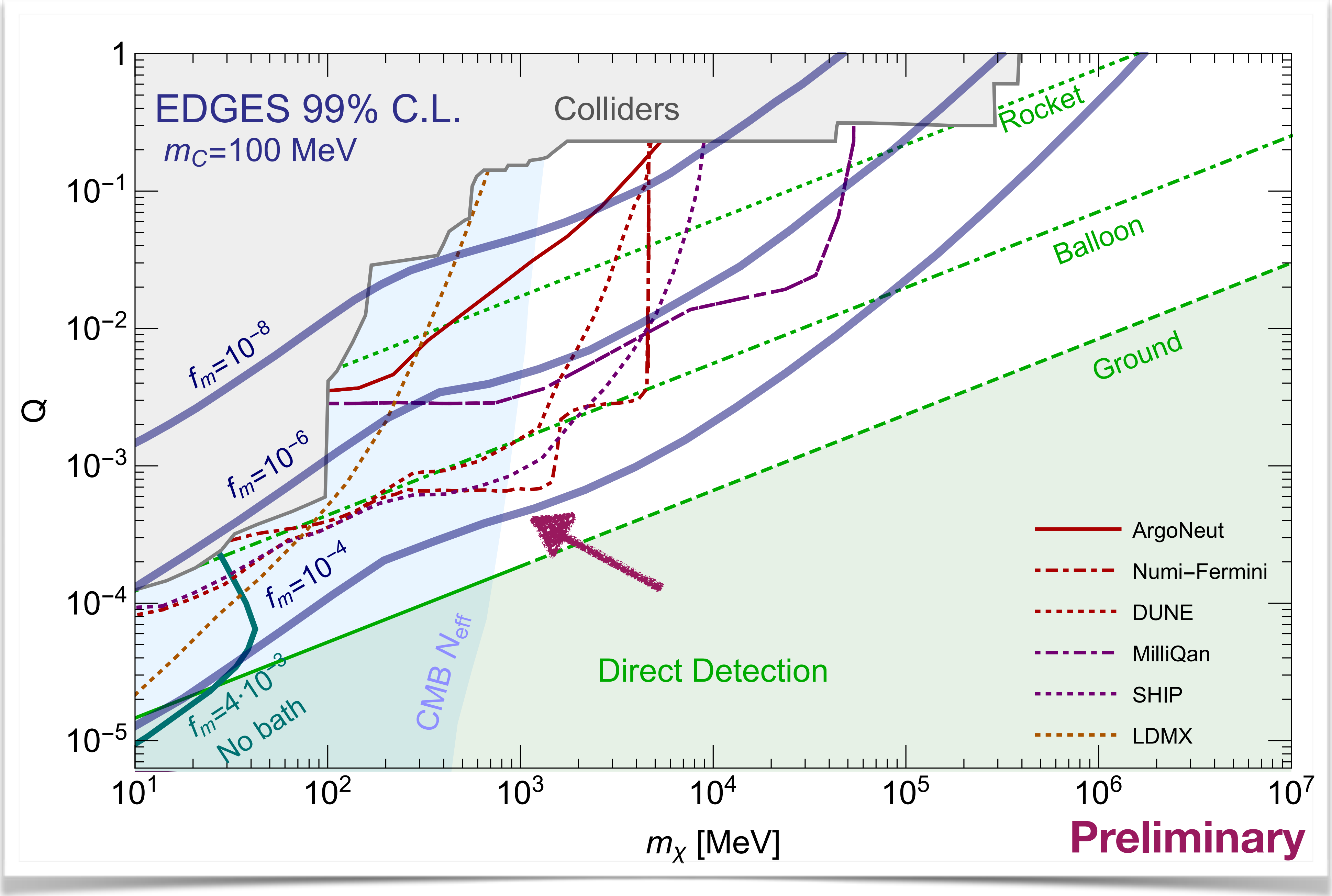
Millicharged dark matter **annihilate in the early universe to light mediators**: N_{eff} limits require $\gtrsim$ GeV mass for millicharged dark matter.

Millicharged Dark Matter Constraints



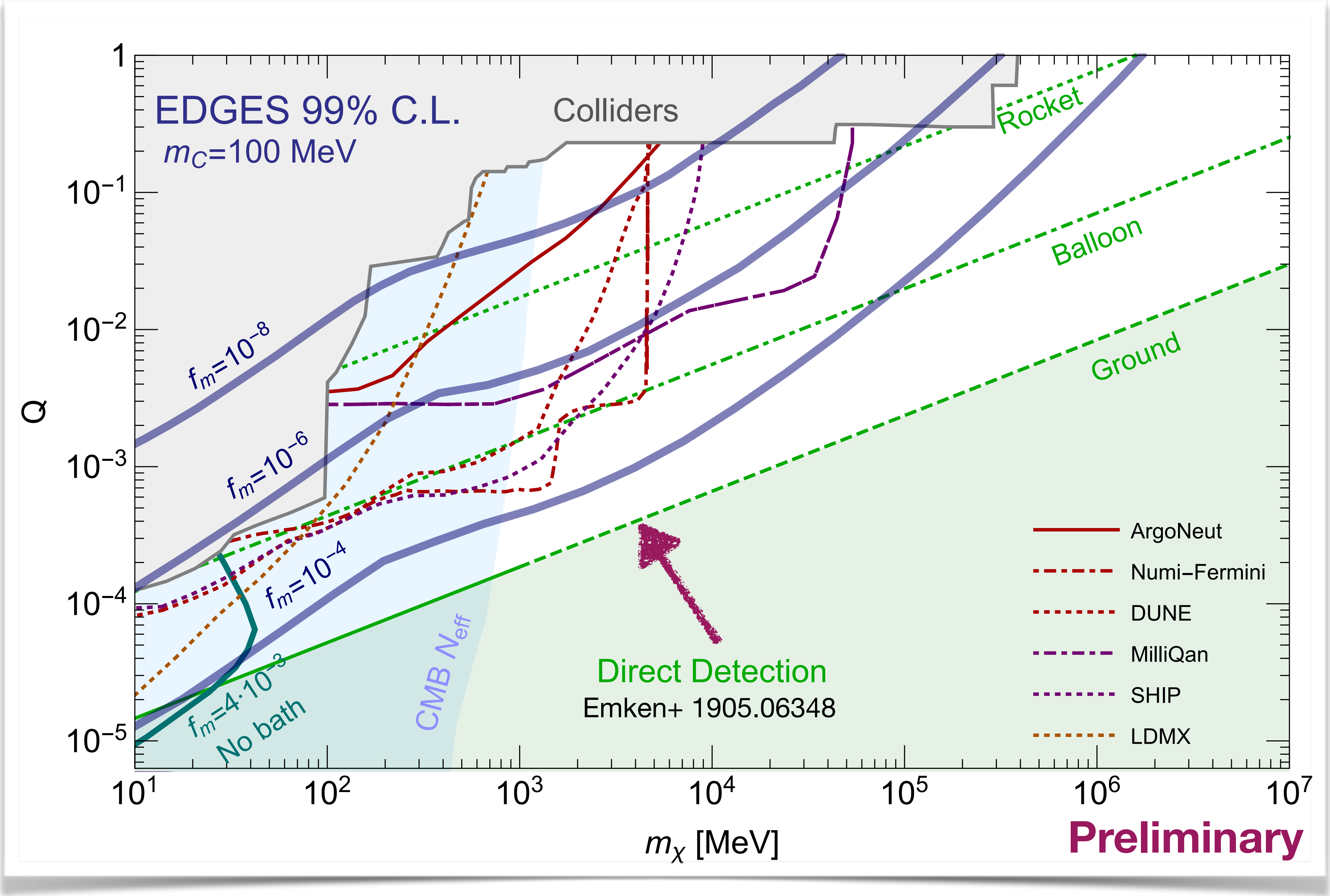
Relatively **independent** of cold dark matter mass, as long as $m_C \lesssim 10$ GeV.

Millicharged Dark Matter Constraints



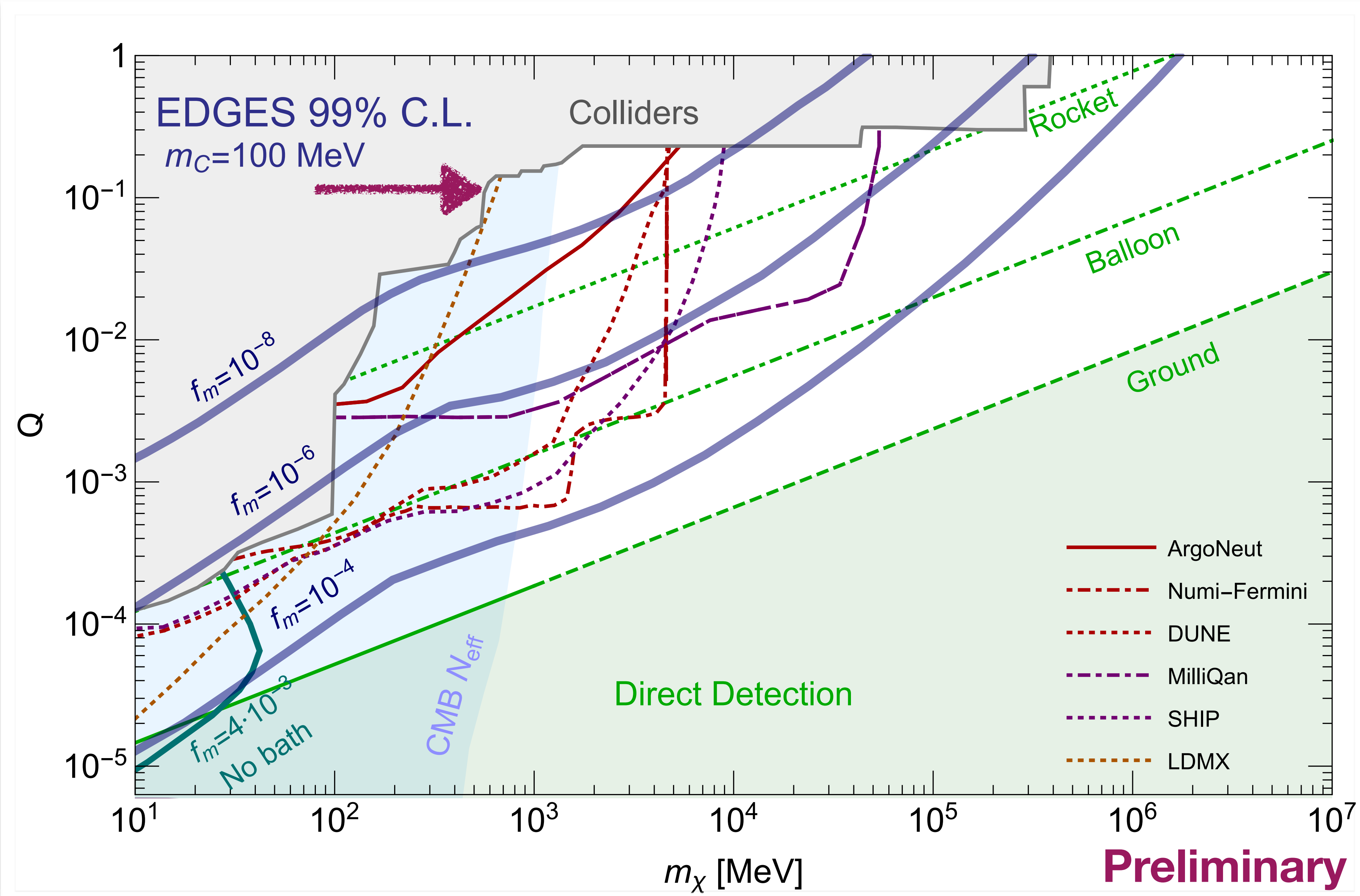
Change in Q - $m_{\rm m}$ behavior at $m_{\rm m} \sim$ GeV due to growing importance of **scattering with neutral H and He**.

Millicharged Dark Matter Constraints



Direct detection (e.g. SENSEI) sets lower limits. Must be **above ground** due to large Q, and **suppressed by small fraction**.

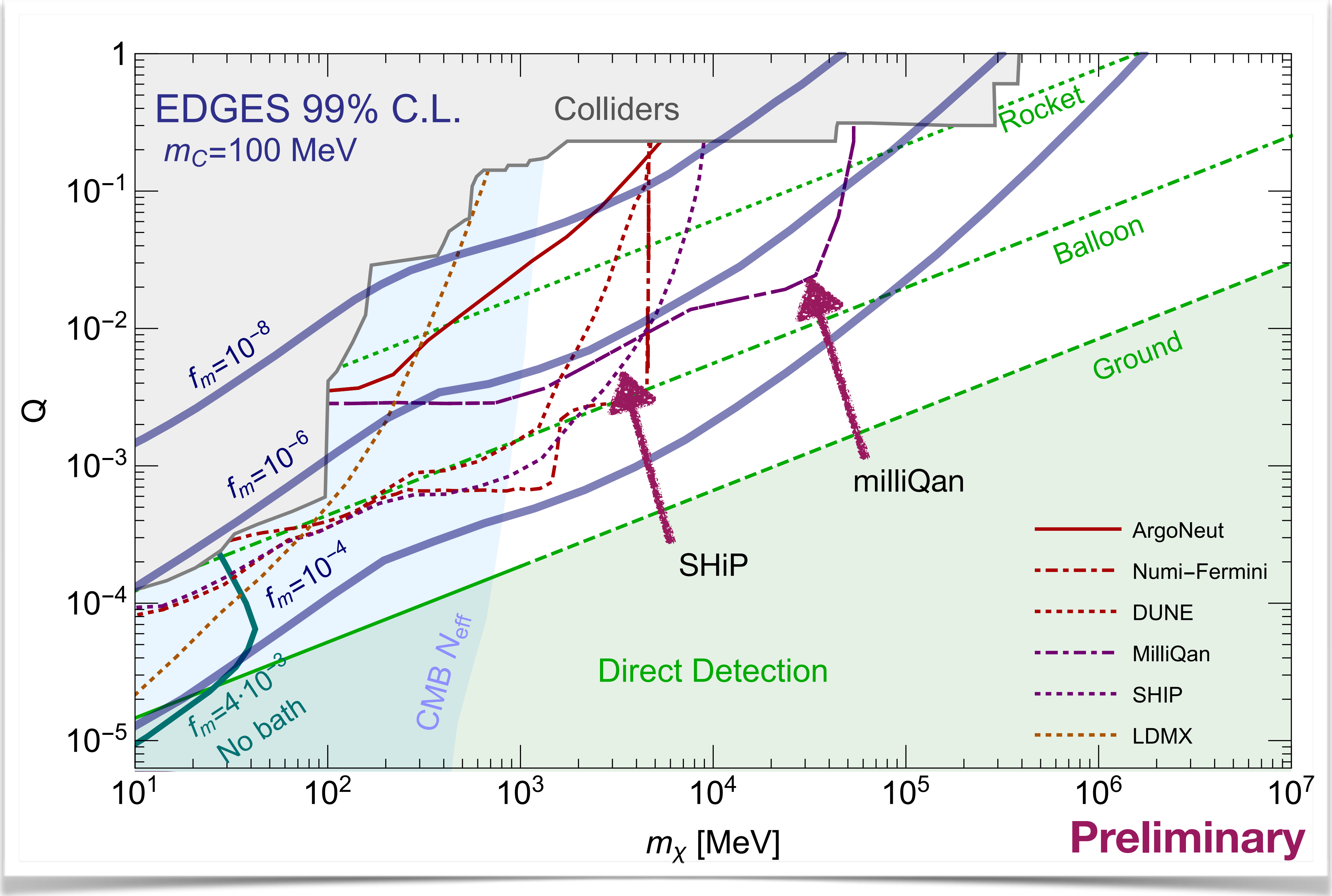
Millicharged Dark Matter Constraints



Beam experiment limits on millicharged particles from combination of SLAC milliQ, CMS, LSND and MiniBooNE.

Prinz+ hep-ex/9804008,
Davidson+ hep-ph/0001179,
Badertscher+ hep-ex/0609059,
Chatrchyan+ 1210.2311,
Magill+ 1806.03310

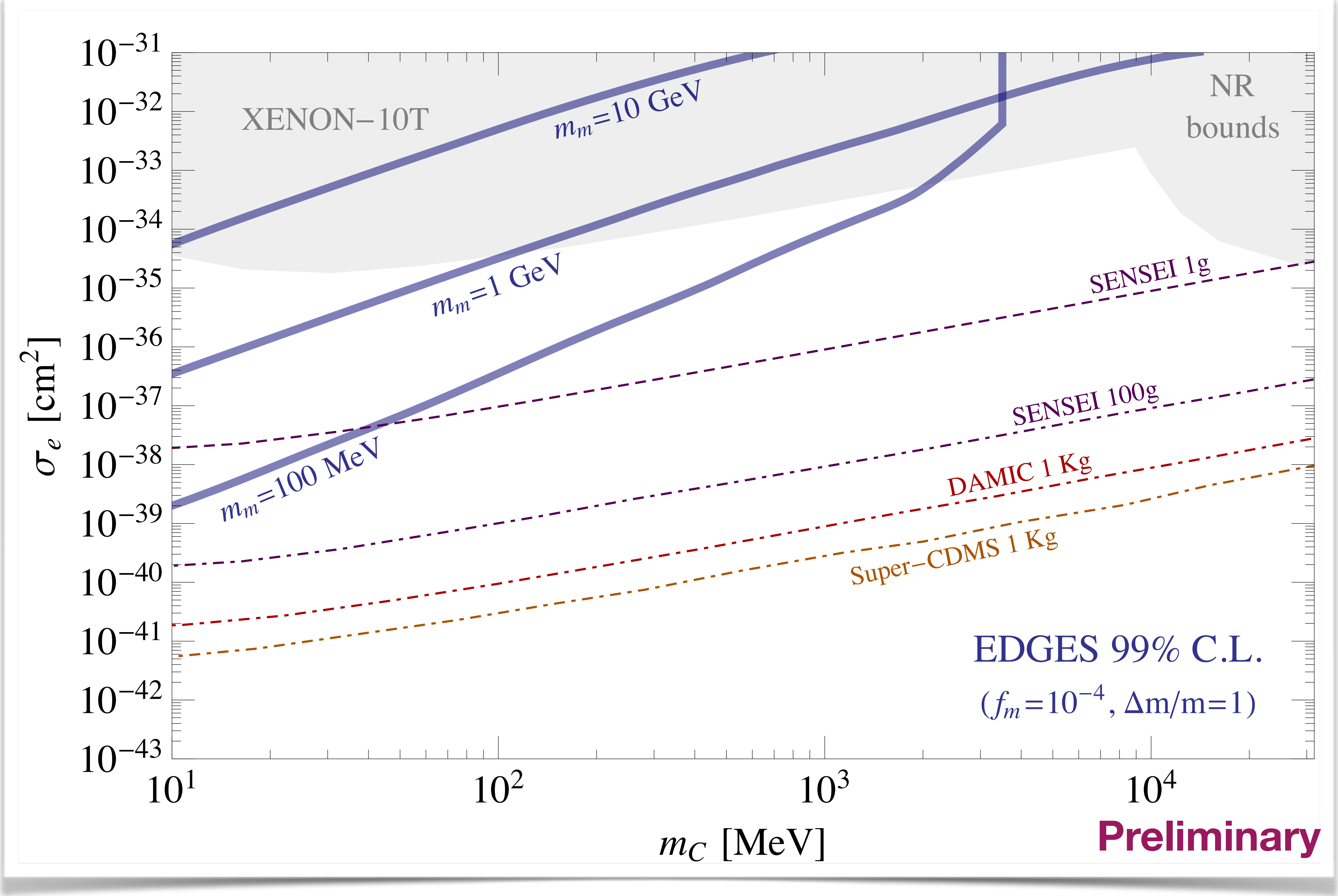
Millicharged Dark Matter Constraints



Future beam experiments will be very important, particularly **milliQan** and **SHiP**.

Haas+ 1410.6816,
Magill+ 1806.03310,
Kelly+ 1812.03998,
Harnik+ 1902.03246,
Berlin+ 1807.01730

Cold Dark Matter Constraints



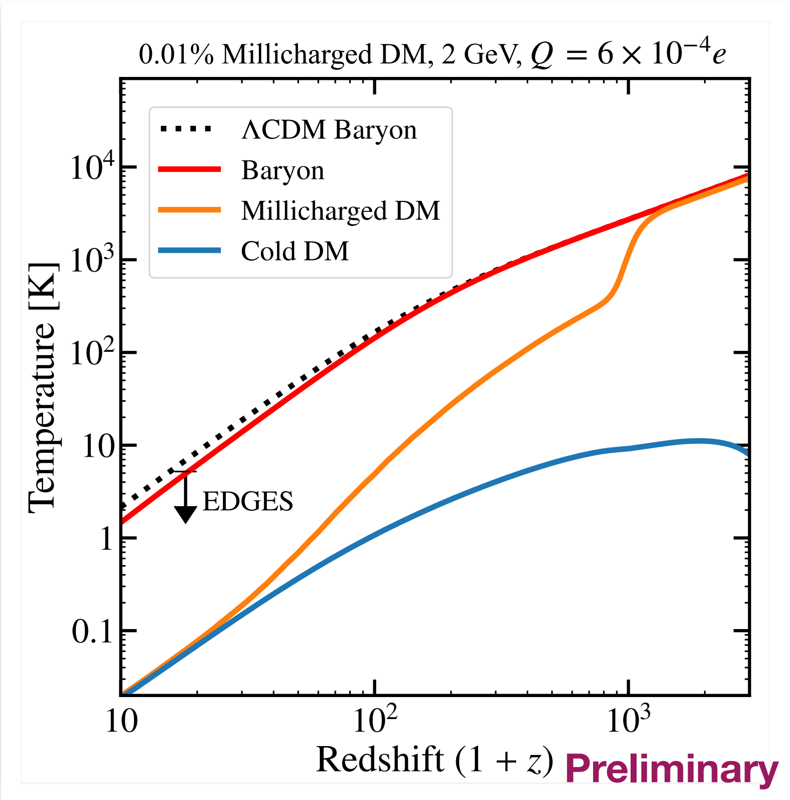
Cold dark matter has a **model dependent** interaction with baryons at one-loop. Most naive implementation a **prime target** for upcoming **direct detection** experiments.

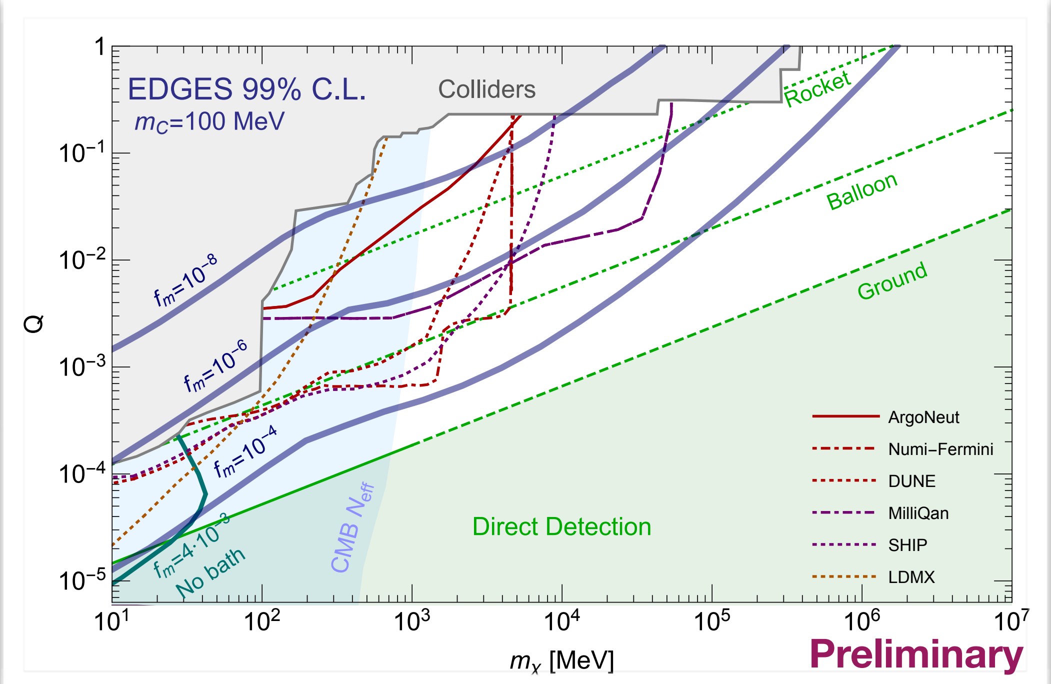
Conclusion

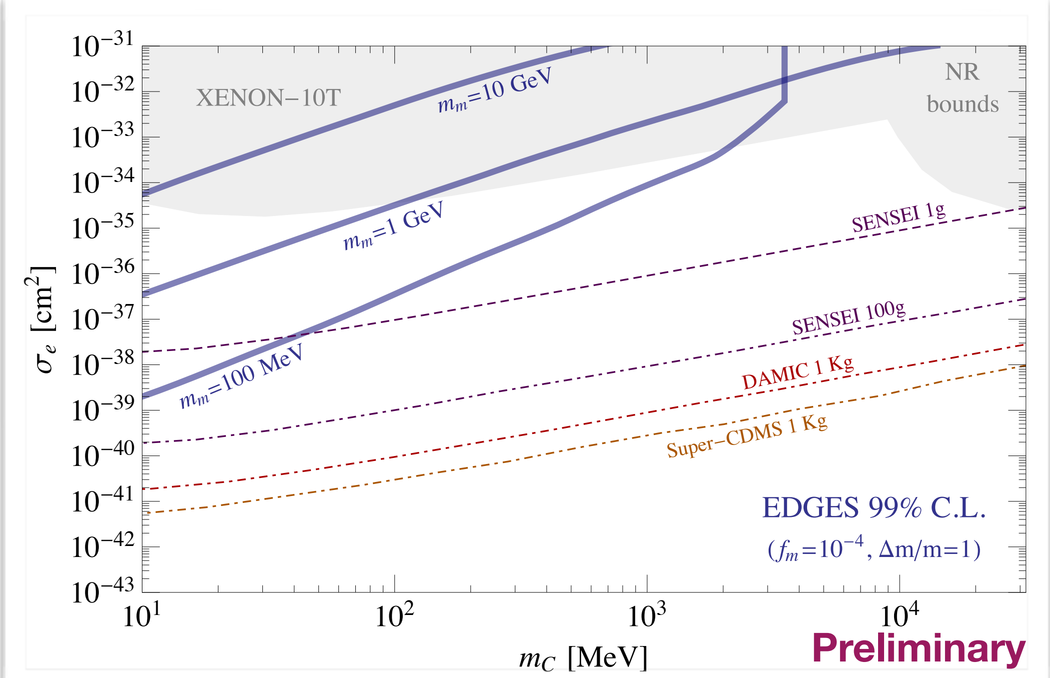
1. **Millicharged + cold dark matter** can consistently produce striking 21-cm signatures, and can explain the EDGES observation.

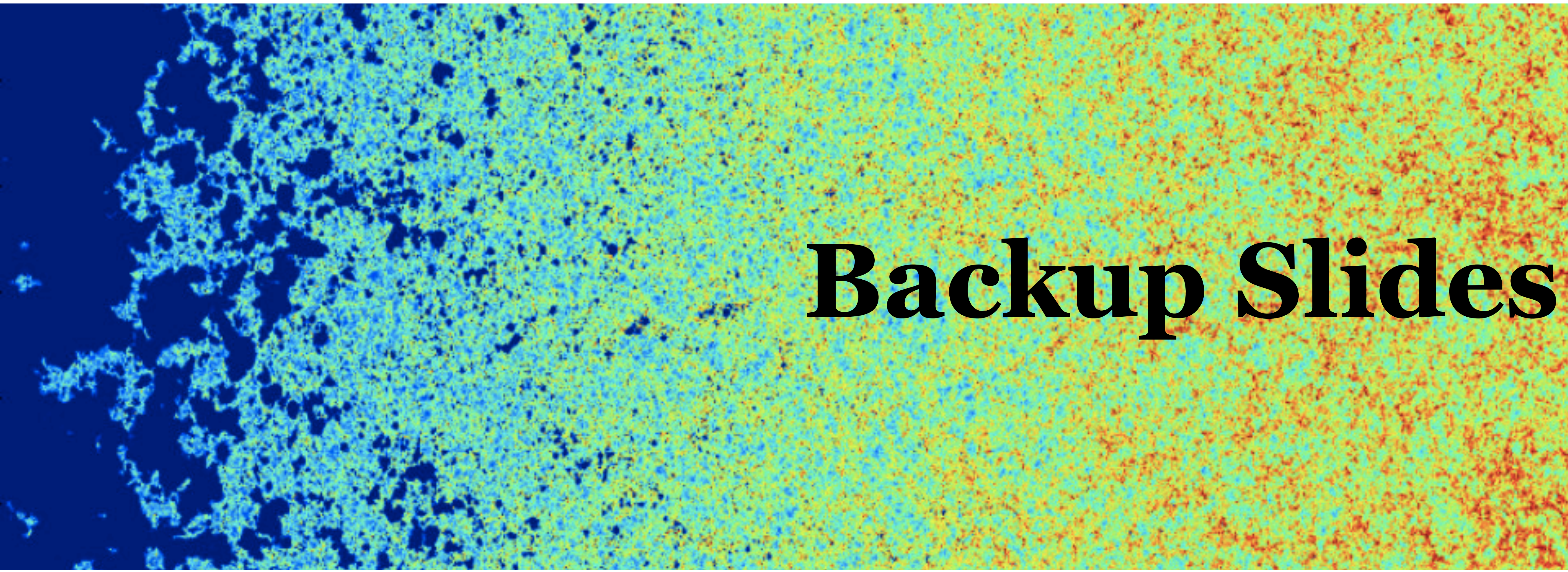
2. **Broad range of parameter space** allowed: GeV $\lesssim m_{\mathrm{m}} \lesssim$ TeV with $f_{\mathrm{m}} \lesssim 0.4\,\%$, and $m_{\mathrm{C}} \lesssim 10$ GeV.

3. Very testable at **beam experiments** and **direct detection**, both current and future.









Backup Slides

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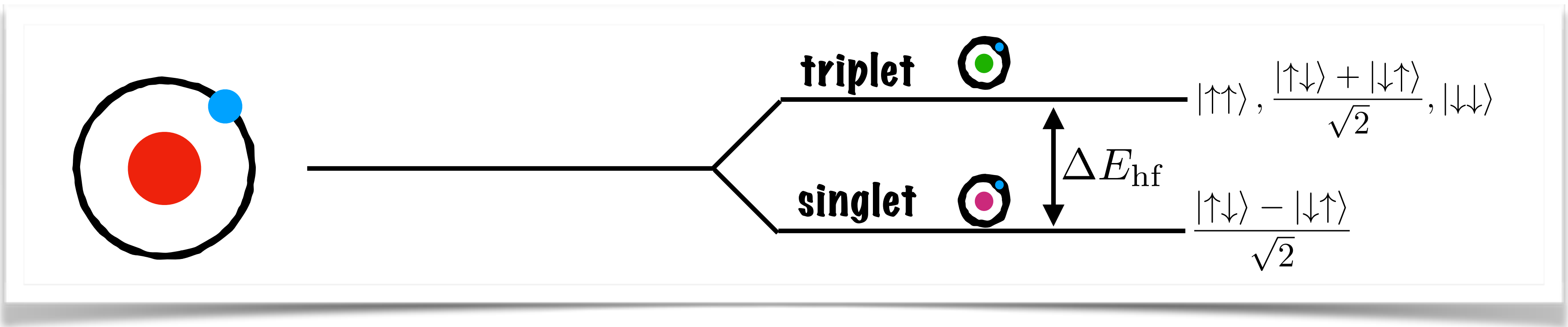
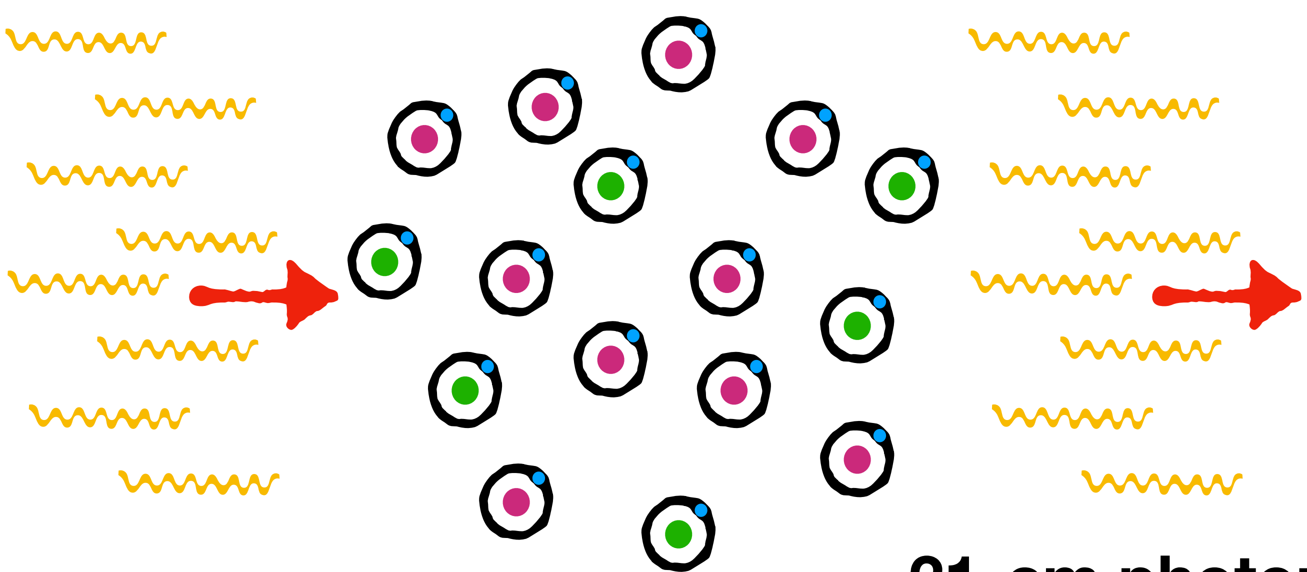
21-cm Absorption/Emission





21-cm photons

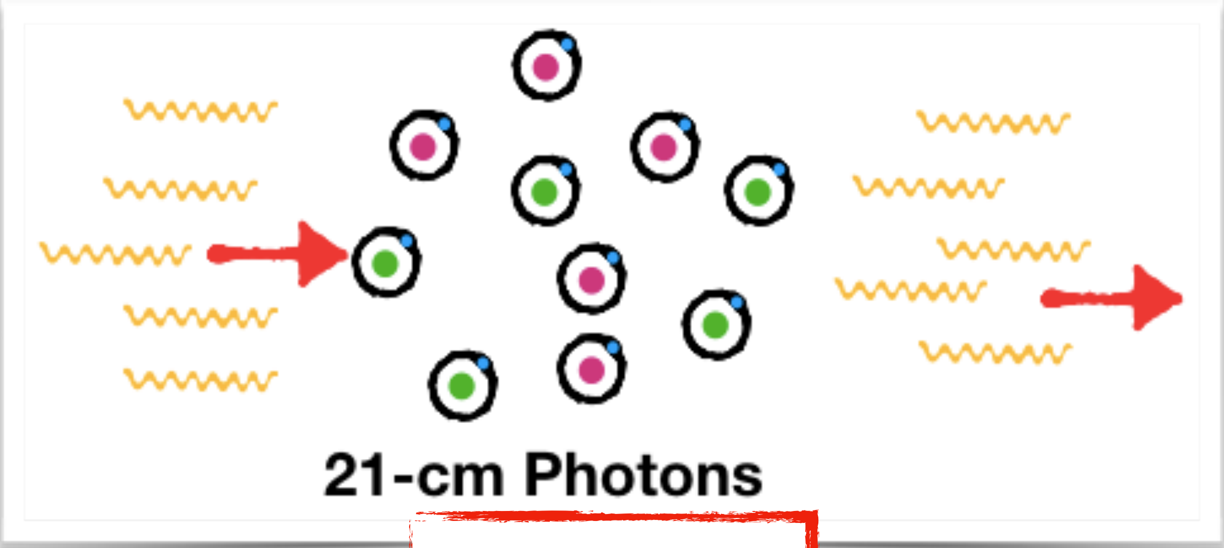
Two-level system, occupancy characterized by **spin temperature**:

$$\frac{n_2}{n_1} = 3e^{-\Delta E_{\rm hf}/T_S}$$

If neutral hydrogen were in **equilibrium** with a background source of 21-cm radiation, e.g. the **CMB**,

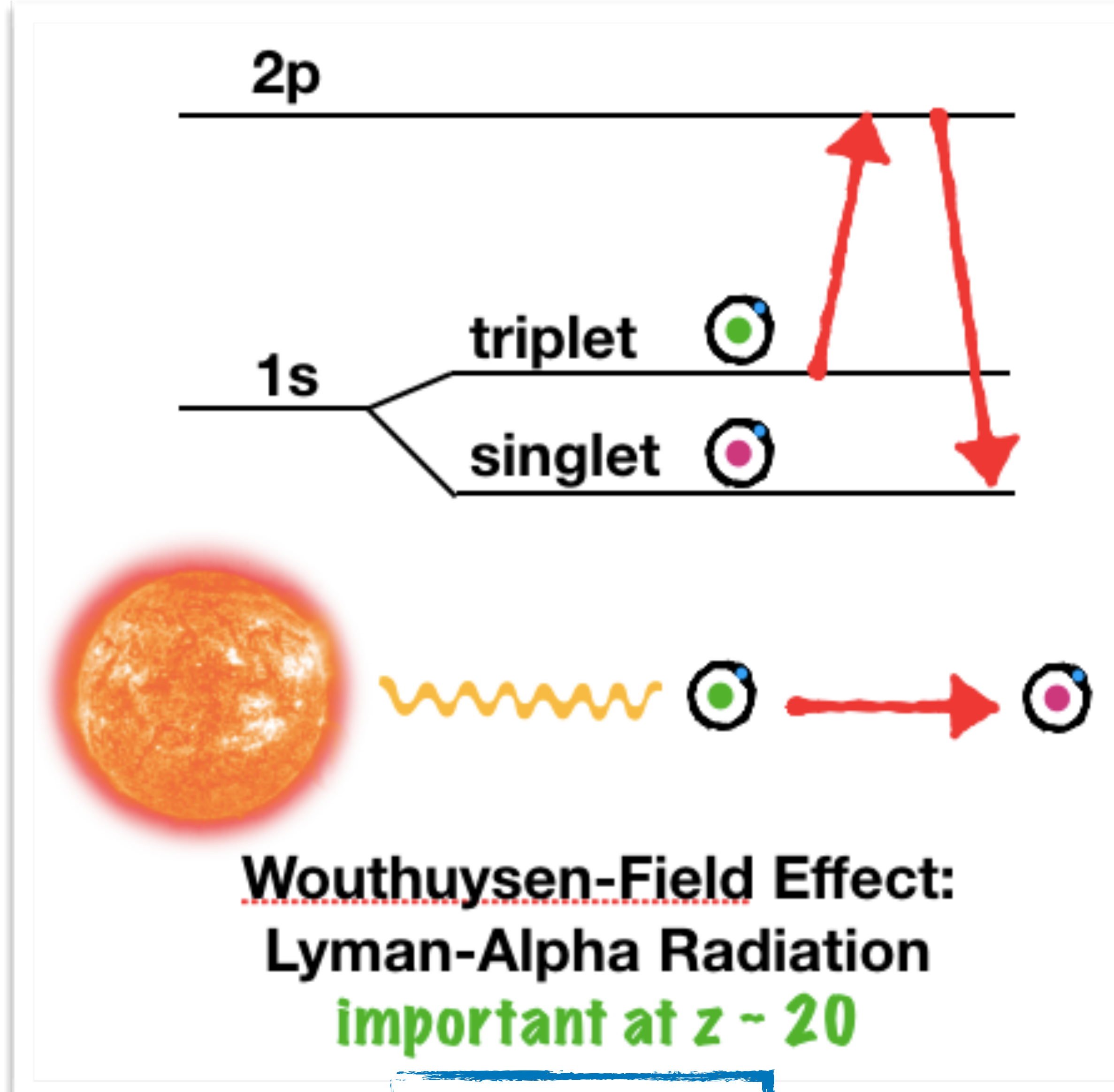
$$T_S = T_R$$

21-cm Processes



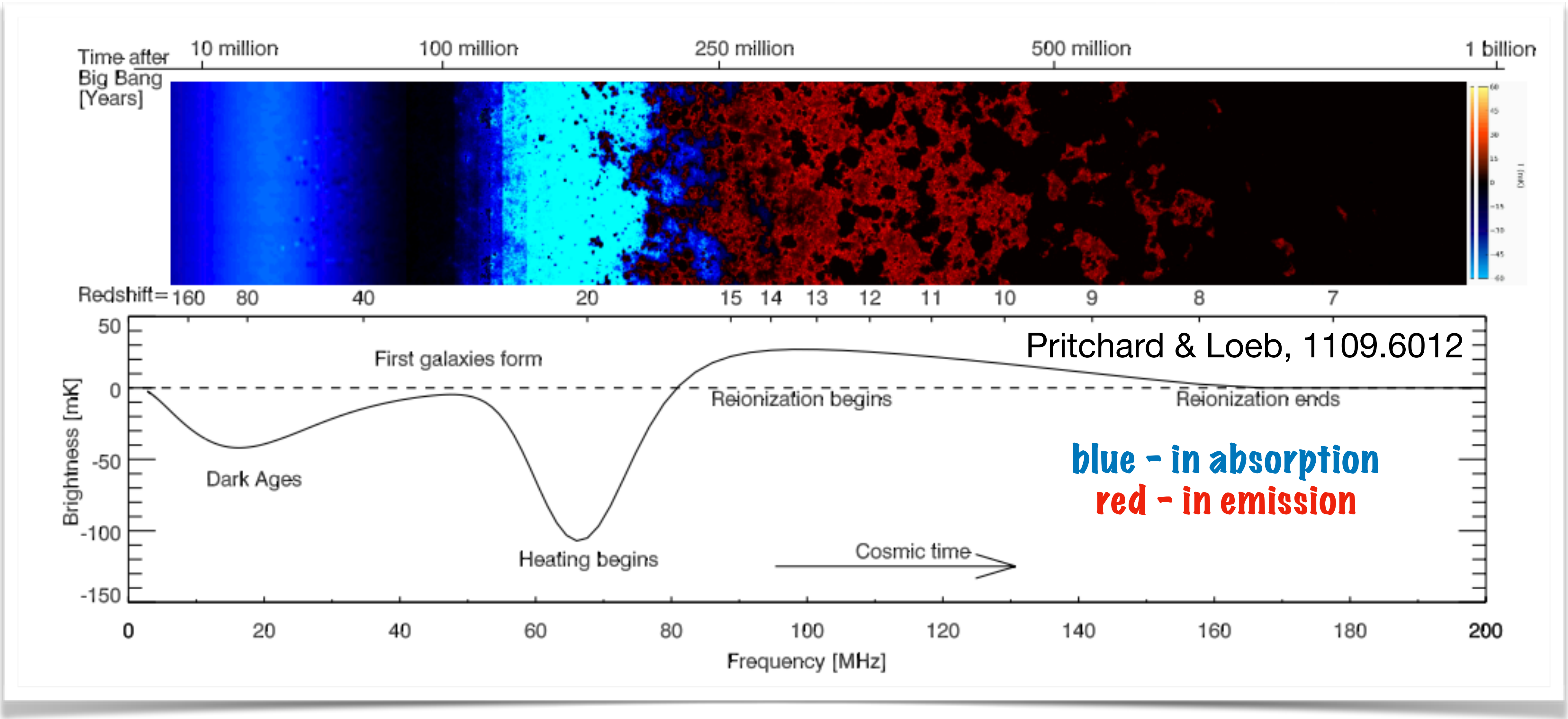
$$T_S \rightarrow T_R$$

$$T_S \rightarrow T_m$$



$$T_S \rightarrow T_m$$

21-cm Cosmology



Measure the brightness of the sky in MHz, relative to CMB temperature. Constrains the ratio of **baryon temperature** T_m to **21-cm radiation temperature** T_R in the early universe, T_m/T_R.

Evolution Equations

$$\frac{dT_{\rm b}}{d\log a} + 2T_{\rm b} = \frac{2f_{\rm m}\rho_{\rm DM}}{3H(1+x_e+\mathcal{F}_{\rm He})}\sum_j \frac{x_j\mu_{j{\rm m}}}{m_{\rm m}+m_j}\left[I^D_{j{\rm m}} + \frac{T_{\rm m}-T_{\rm b}}{m_{\rm m}u^2_{j{\rm m}}}I^T_{j{\rm m}}\right] + \frac{\Gamma_{\rm Comp}}{H}(T_\gamma - T_{\rm b}),$$

$$\frac{dT_{\rm C}}{d\log a} + 2T_{\rm C} = \frac{2f_{\rm m}\rho_{\rm DM}}{3H}\frac{\mu_{\rm mC}}{m_{\rm m}+m_{\rm C}}\left[I^D_{\rm mC} + \frac{T_{\rm m}-T_{\rm C}}{m_{\rm m}u^2_{\rm mC}}I^T_{\rm mC}\right],$$

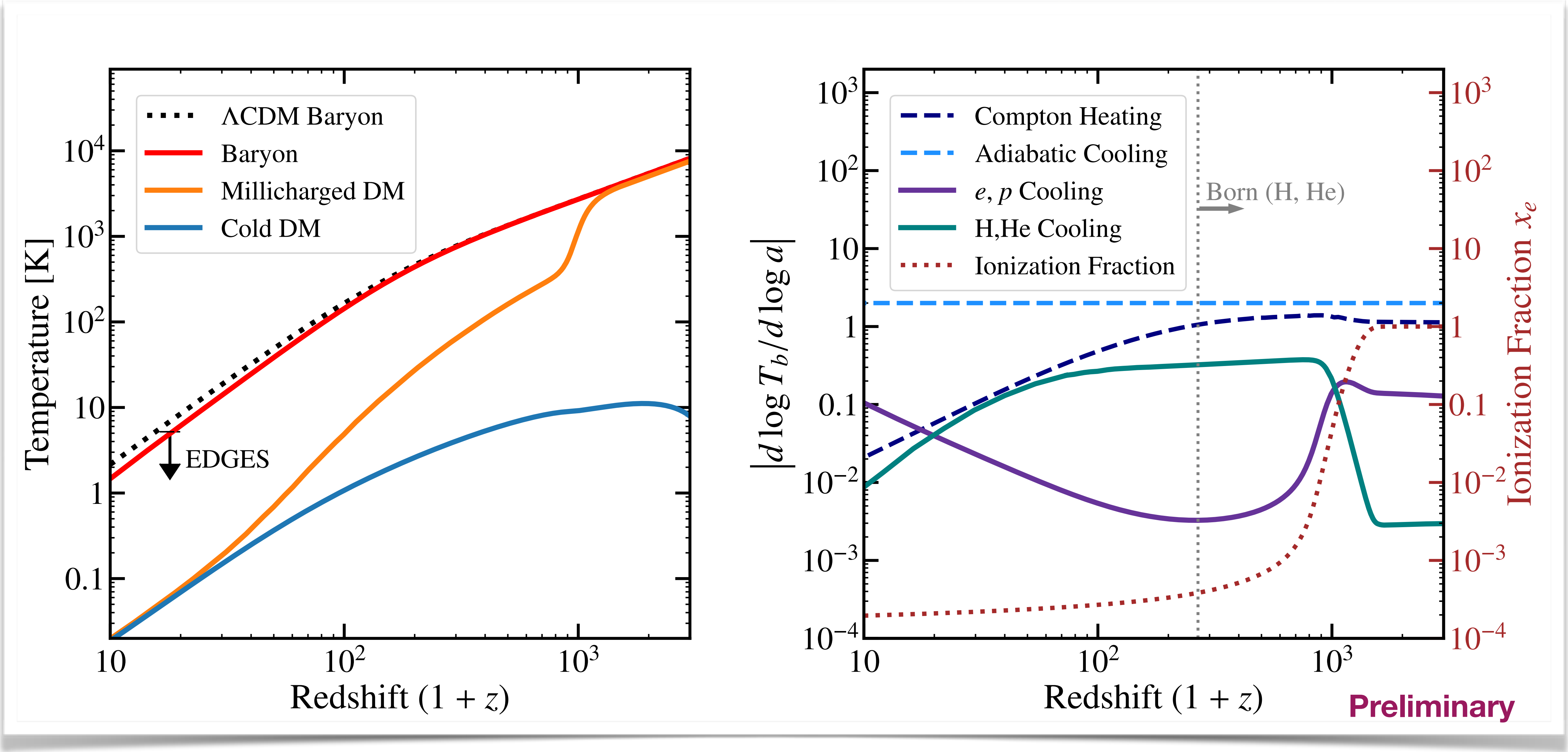
$$\frac{dT_{\rm m}}{d\log a} + 2T_{\rm C} = \frac{2(1-f_{\rm m})\rho_{\rm DM}}{3H}\frac{\mu_{\rm mC}}{m_{\rm m}+m_{\rm C}}\left[I^D_{\rm mC} + \frac{T_{\rm C}-T_{\rm m}}{m_{\rm C}u^2_{\rm mC}}I^T_{\rm mC}\right] + \frac{2}{3H}\sum_j\frac{n_j m_j \mu_{j{\rm m}}}{m_{\rm m}+m_j}\left[I^D_{j{\rm m}} + \frac{T_{\rm b}-T_{\rm m}}{m_i u^2_{j{\rm m}}}I^T_{j{\rm m}}\right]$$

$$\frac{dV_{\rm bm}}{d\log a} + V_{\rm bm} = -\left(\frac{\rho_{\rm m}}{\rho_{\rm b}}+1\right)\sum_j\frac{\rho_j}{m_{\rm m}+m_j}\frac{I^D_{j{\rm m}}}{HV_{\rm bm}} + \frac{\rho_{\rm C}}{m_{\rm m}+m_{\rm C}}\frac{I^D_{\rm mC}}{HV_{\rm mC}},$$

$$\frac{dV_{\rm mC}}{d\log a} + V_{\rm mC} = -\frac{\rho_{\rm m}+\rho_{\rm C}}{m_{\rm m}+m_{\rm C}}\frac{I^D_{\rm mC}}{HV_{\rm mC}} + \sum_j\frac{\rho_j}{m_{\rm m}+m_j}\frac{I^D_{j{\rm m}}}{HV_{\rm bm}},$$

$$\frac{dx_e}{d\log a} = -\frac{C}{H}\left(n_H\mathcal{A}_B x_e^2 - 4(1-x_e)\mathcal{B}_B e^{3E_0/(4T_\gamma)}\right).$$

Rates Plot


ΛCDM Baryon
Baryon
Millicharged DM
Cold DM
Temperature [K]
EDGES
Redshift (1 + z)
Compton Heating
Adiabatic Cooling
e, p Cooling
H,He Cooling
Ionization Fraction
Born (H, He)
|d log T_b / d log a|
Ionization Fraction x_e
Redshift (1 + z)
Preliminary

CMB and SI Limit

CMB:

$$\sigma_T^{\mathrm{mC}}(V_{\mathrm{rel}})\, V_{\mathrm{rel}}^4 \lesssim \frac{m_{\mathrm{C}} + m_{\mathrm{m}}}{m_p} \left(1 + \frac{\Omega_{\mathrm{b}}}{f_{\mathrm{m}} \Omega_{\mathrm{DM}}}\right) \times 1.7 \times 10^{-41}\,\mathrm{cm}^2$$

Self-Interaction:

$$\frac{\alpha_{\mathrm{C}}^2}{m_{\mathrm{C}}^3} \lesssim 10^{-11}\,\mathrm{GeV}^{-3}$$

Scattering

Momentum Transfer Cross Section

$$\sigma_T^{\text{bm}} \simeq \frac{2\pi Q^2 \alpha_{\text{em}}^2}{\mu_{\text{m}}^2 v_{\text{rel}}^4} \log\left(\frac{T_{\text{b}} m_p \mu^2 v_{\text{rel}}^4}{Q^2 \alpha_{\text{em}}^3 \rho_{\text{b}}}\right)$$

$$\sigma_T^{\text{mC}} = \frac{2\pi \alpha_{\text{C}} \alpha_{\text{m}}}{\mu_{\text{mC}}^2 v_{\text{rel}}^4} \log\left(\frac{\mu_{\text{mC}}^2 v_{\text{rel}}^4}{\alpha_C \alpha_m m_\phi^2}\right)$$

Non-Minimal Cold DM