Clues to a mysterious Universe
— exploring the interface of particle, gravity and quantum physics

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Towards a full description of MeV dark matter decoupling

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In collaboration with Jui-Lin Kuo, Josef Pradler

— arXiv:2205.05714 and follow-up

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

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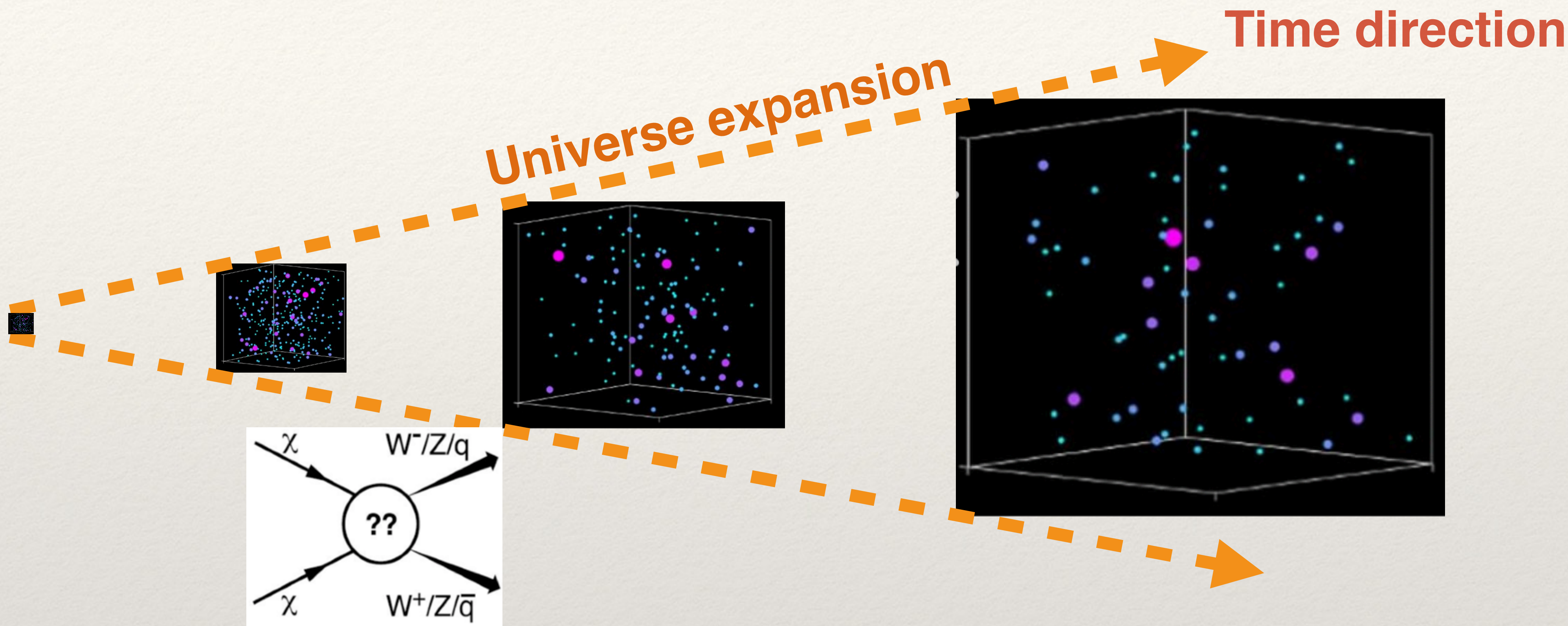
Standard Cosmology is established, where for **Dark Matter (DM):**

the conventional scenario: **Thermal freeze-out** (weakly-interacting massive particle)

DM candidate
in thermal equilibrium



One DM meets one DM anti-particle to annihilate

Until DM density is so diluted that annihilation **freezes out**.

That is:

- DM **contributes to the radiative energy of Universe** while being relativistic;
- DM **ejects energy (visibly or invisibly)** when it becomes non-relativistic.

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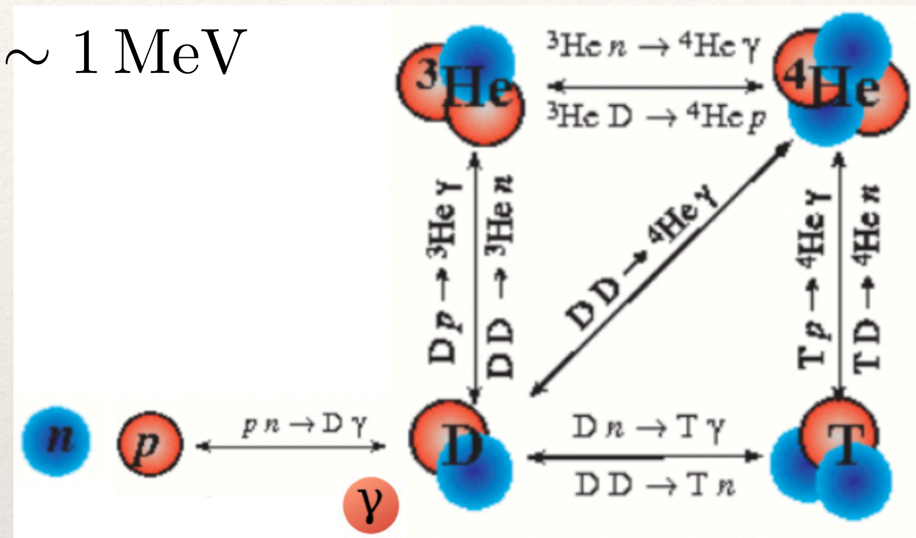
Big Bang Nucleosynthesis (BBN)

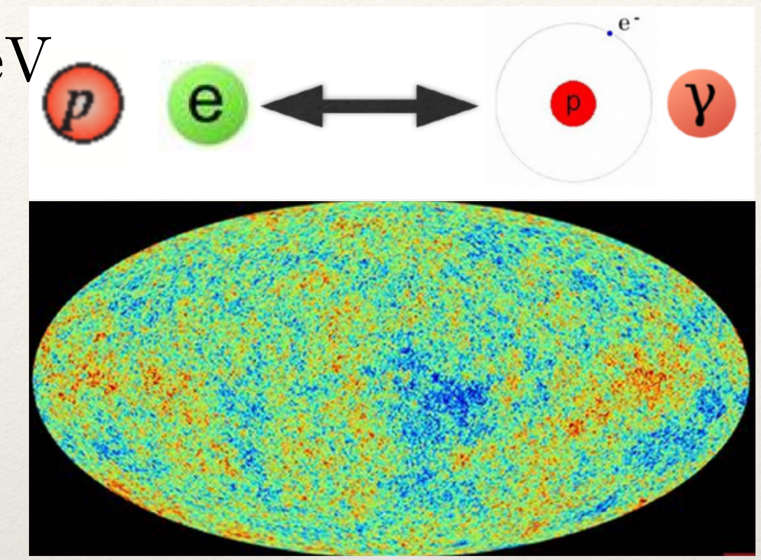
with $T_\gamma \sim 1\,\mathrm{MeV}$



Cosmic Microwave Background (CMB)

with $T_\gamma \sim 0.3\,\mathrm{eV}$

T_ν / T_γ



Both constrain the additional EM and **background energy densities**

(around the two photon temperatures above) .

At a result, observations suggest: **thermal DM mass** should be above MeV.

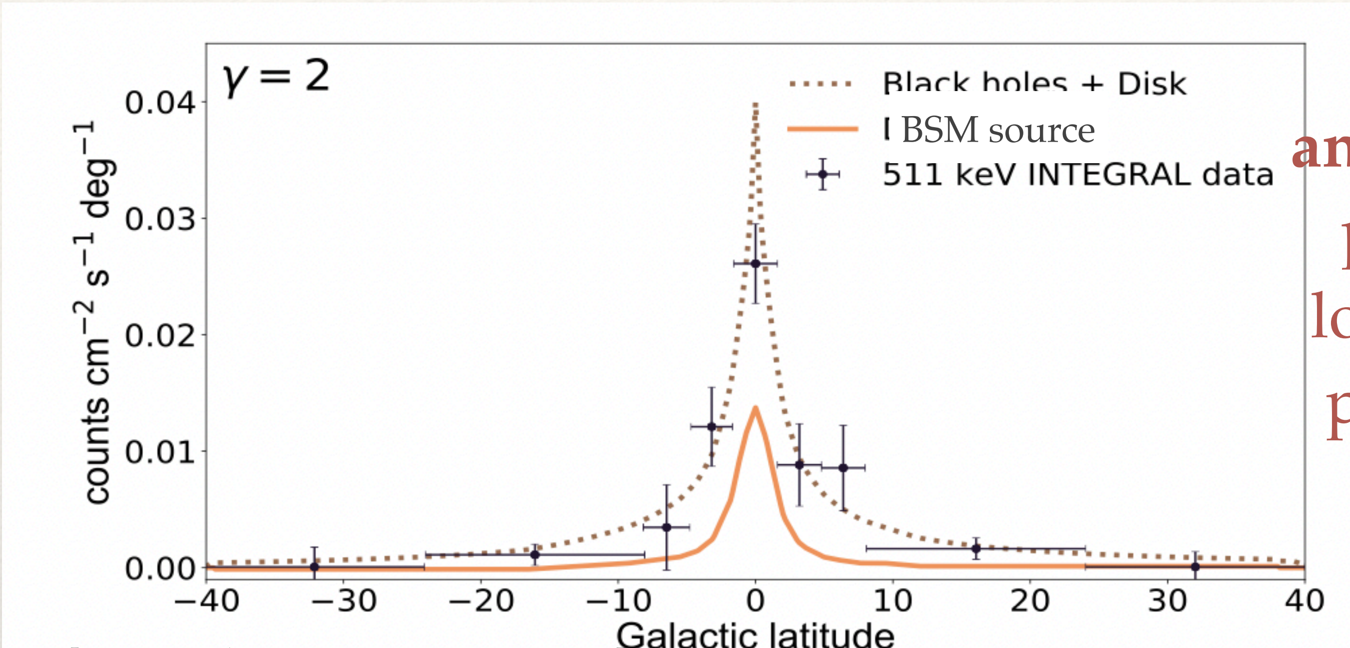
But, **what value** exactly,

if DM couples to both electromagnetic (EM) bath and neutrino?

Solving MeV dark particle freeze-out

is also relevant for the phenomenology of light dark physics.

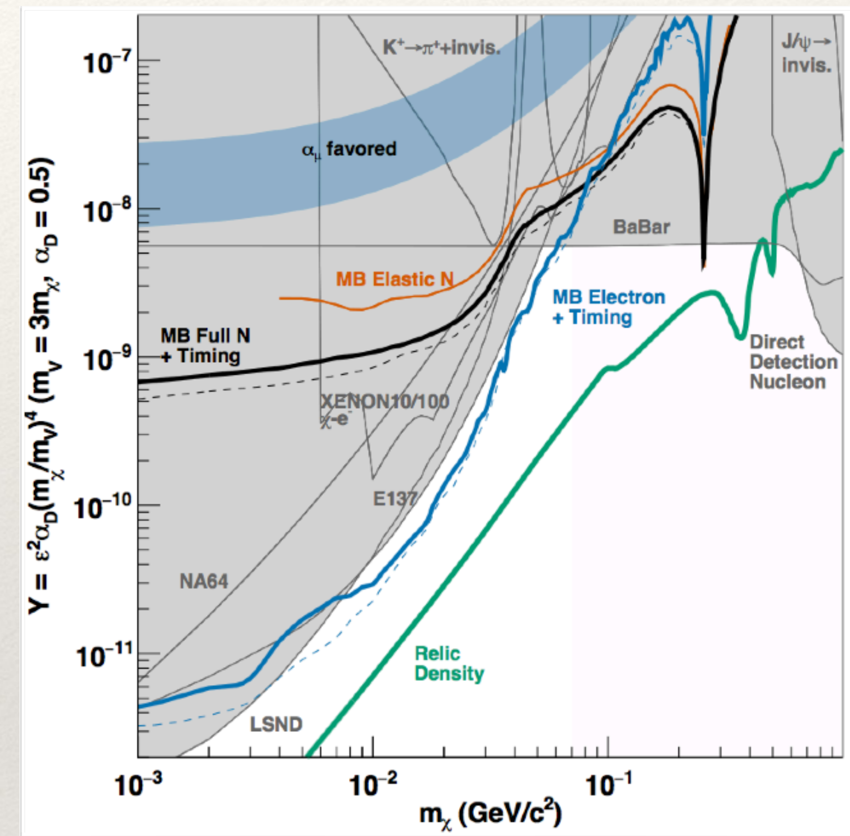
Galactic 511 keV-line excess



[e.g. Keith&Hooper 2103.08611]

DM annihilation produces low-energy positrons?

Intensity-frontier

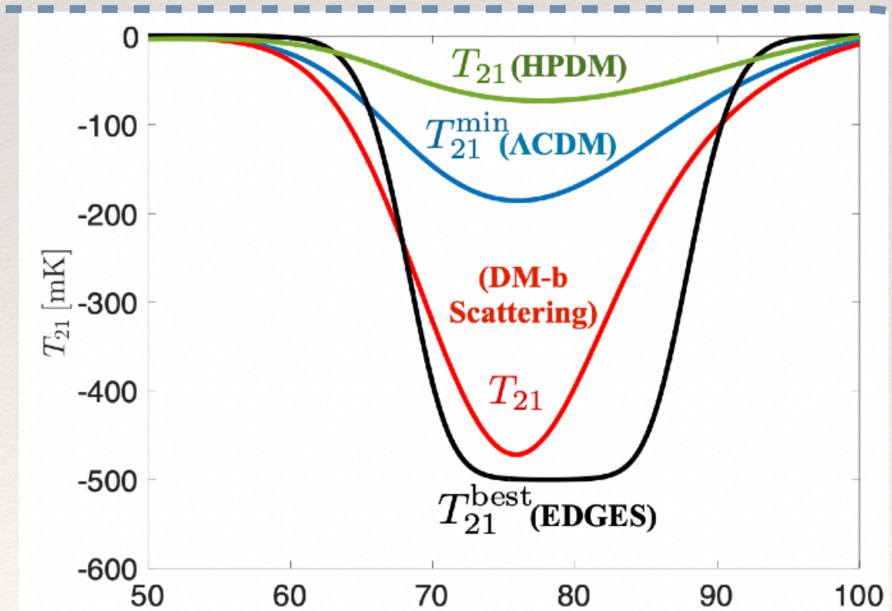


[e.g. MiniBooNE-DM, 1807.06137]

A lower bound from cosmology?

EDGES explanation

Baryon scatters with sub-leading MeV DM to further cool down?



[e.g. Ely D. Kovetz in Blois 2019]

Other anomalies, etc…

To describe DM freeze-out

A three-sector system with a benchmark model

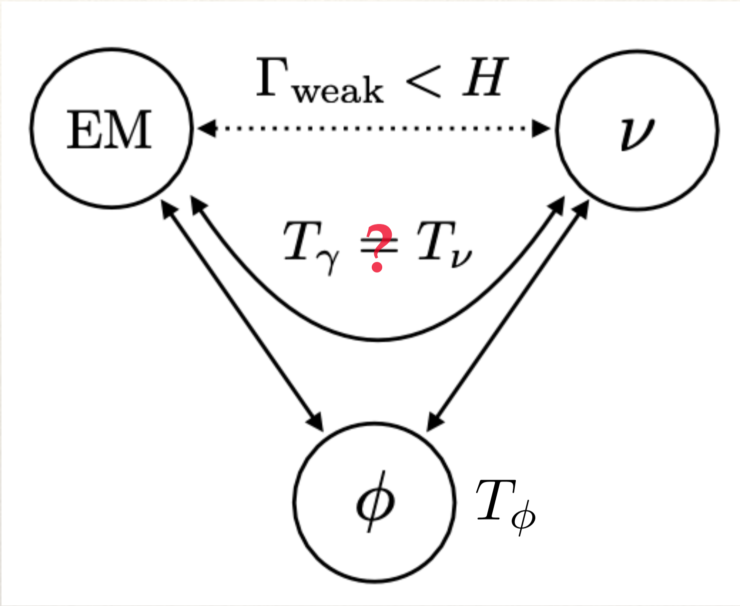
$$\frac{1}{\Lambda_{Z'}^2}(\bar{l}\gamma^\mu l)\,(\phi^* \overleftrightarrow{\partial}_\mu \phi)$$

[complex scalar DM, with p-wave annihilation]

In earlier works

[M.Escudero 1812.05605 & N.Sabti, M.Escudero, et al, 1910.01649]:

- **Actual DM annihilation cross section** was never obtained for such a three-sector system;
- Neglecting scattering processes, only Maxwell-Boltzmann statistics, ….



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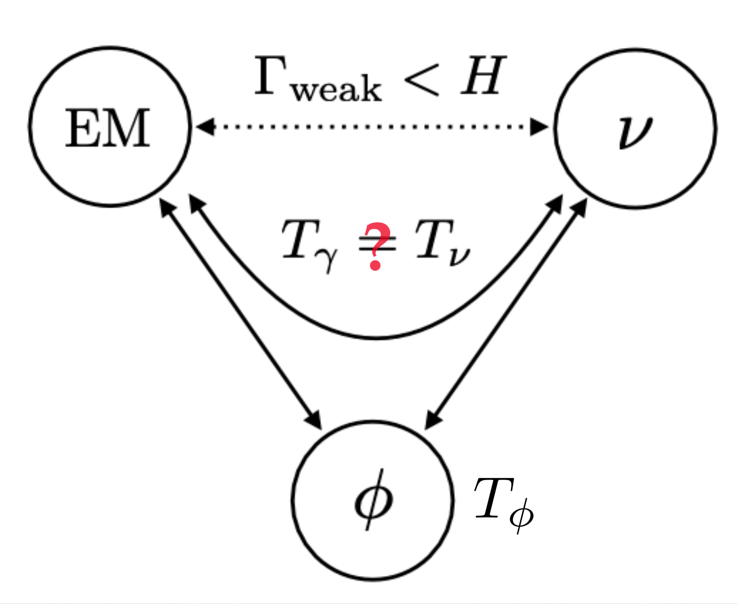

We work out **the actual DM annihilation cross section**, and, at the same time, obtain **the ratio of neutrino-to-photon temperature** consistently.

Solving the **momentum distribution** of each particle species is **extremely time-consuming**, we have to make some simplifications too.

Two simplifications introduced: $\frac{1}{\Lambda_{Z'}^2}(\bar{l}\gamma^\mu l)\,(\phi^* \overleftrightarrow{\partial}_\mu \phi)$

1. **Kinetic equilibrium** for each sector: $f_i(E_i, \mu_i) = \frac{1}{e^{(E_i-\mu_i)/T_i} \mp 1} \equiv \frac{1}{e^{\tilde{E}_i - \tilde{\mu}_i} \mp 1}$

A) the **EM sector**

Obviously satisfied, with **null chemical potentials** (up to asymmetries).

B) the **neutrino sector**

Non-equilibrium neutrinos contribute negligibly even in SM-only case.

C) the **dark sector**

depending on **DM self-interaction**.

Evidences for strongly self-interacting DM?

2. **Further separate T and μ for**:

B) the relativistic **neutrino**

$$f_\nu(\tilde{E}_\nu, \tilde{\mu}_\nu) \simeq \frac{1}{e^{\tilde{E}_\nu}+1} + \tilde{\mu}_\nu \frac{1}{e^{\tilde{E}_\nu} + e^{-\tilde{E}_\nu} + 2}$$
$$= f^{(0)}(E_\nu) + \tilde{\mu}_\nu f^{(1)}(E_\nu)\,.$$

C) the non-relativistic **DM**

$$f_\phi(\tilde{E}_\phi, \tilde{\mu}_\phi) \simeq \begin{cases} \frac{1}{e^{\tilde{E}_\phi} \mp 1} & \text{before freeze-out} \\ \frac{e^{\tilde{\mu}_\phi}}{e^{\tilde{E}_\phi}} & \text{after freeze-out} \end{cases}$$
$$\to e^{\tilde{\mu}_\phi} f_\phi^{(0)}(\tilde{E}_\phi)$$

To calculate exactly **MeV DM freeze-out:**

Solving the number/energy densities by including all two-body processes:

$$\frac{dn_i}{dt} + 3Hn_i = g_i \int \frac{d^3p_i}{(2\pi)^3 E_i} C[f_i] \equiv \frac{\delta n_i}{\delta t} \,,$$
$$\frac{d\rho_i}{dt} + 3H(\rho_i + p_i) = g_i \int \frac{d^3p_i}{(2\pi)^3 E_i} \delta E \, C[f_i] \equiv \frac{\delta \rho_i}{\delta t} \,,$$

For each two-body process **1 + 2 ↔ 3 + 4**, **the phase space factor:**

$$J = f_1 f_2 (1 \pm f_3)(1 \pm f_4)(1 - e^{-\tilde{\mu}_1 - \tilde{\mu}_2 + \tilde{\mu}_3 + \tilde{\mu}_4} e^{\tilde{E}_1 + \tilde{E}_2 - \tilde{E}_3 - \tilde{E}_4})$$

3f and 4f terms not included yet.

$$\frac{\delta n_i}{\delta t} = \sum_{i \neq j} a_{ij} \, \beta_{ij}(\tilde{\mu}_i, \tilde{\mu}_j) \, \gamma_{ij}(T_i, T_j) \,,$$
$$\frac{\delta \rho_i}{\delta t} = \sum_{i \neq j} b_{ij} \, \beta_{ij}(\tilde{\mu}_i, \tilde{\mu}_j) \, \zeta_{ij}(T_i, T_j) \,,$$

Scan the two temperatures to **obtain all numerical values of multi-integrals**.

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All described by **5 variables:**

$$T_\gamma, (T_\nu, \tilde{\mu}_\nu), (T_\phi, \tilde{\mu}_\phi)$$

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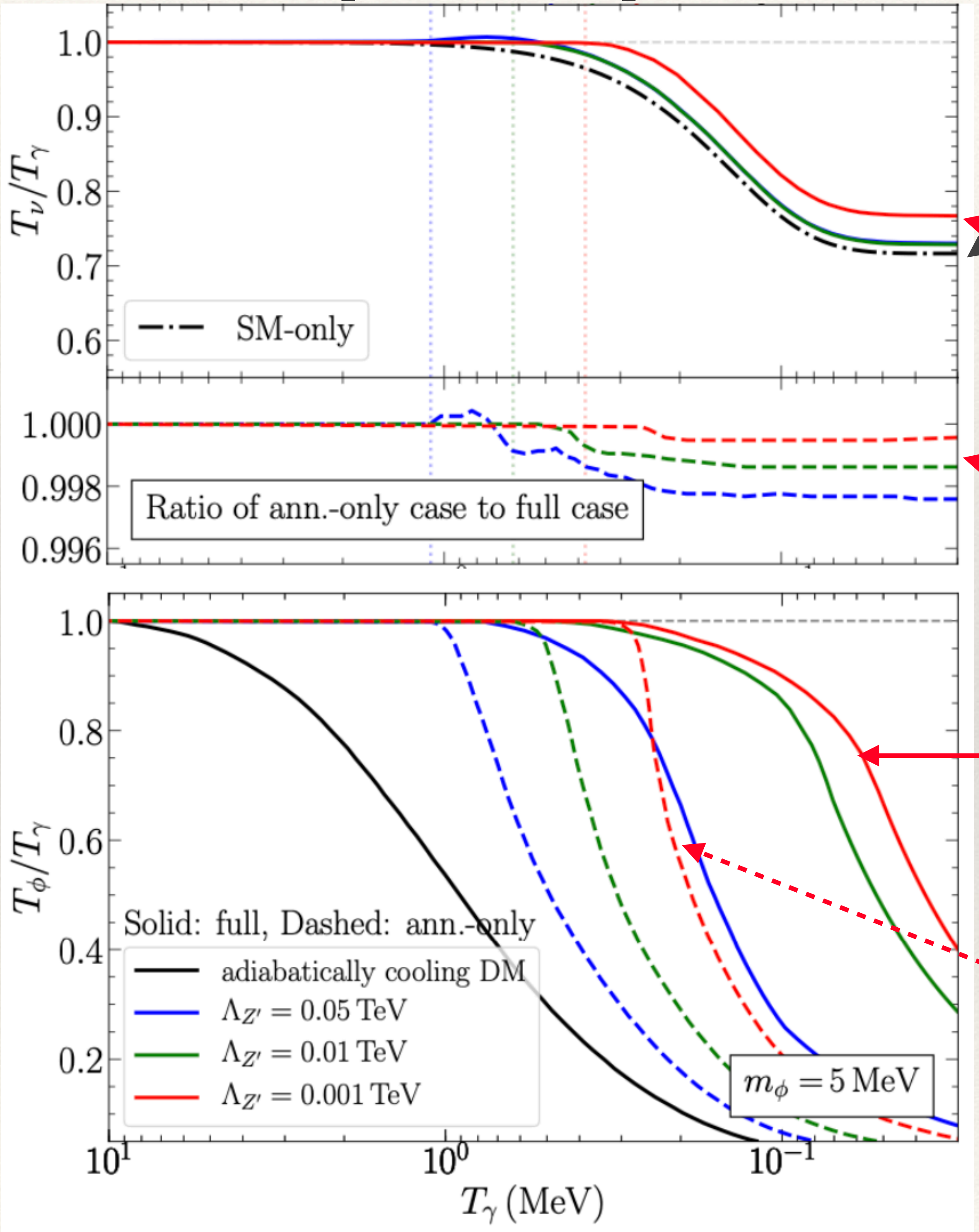
Our numerical results

How the system evolves:

$$\frac{1}{\Lambda_{Z'}^2}(\bar{l}\gamma^\mu l)\,(\phi^* \overleftrightarrow{\partial}_\mu \phi)$$

Temperature evolution

w.r.t. to photon temperature



- The standard value **with only weak interaction** for neutrino:
- **Larger coupling** allows photon bath to heat up neutrino via DM.
- Energy transfer is mostly induced by **DM pair annihilation/creation.**
- **DM temperature** is in between photon and neutrino temperatures, before it gradually decouples.

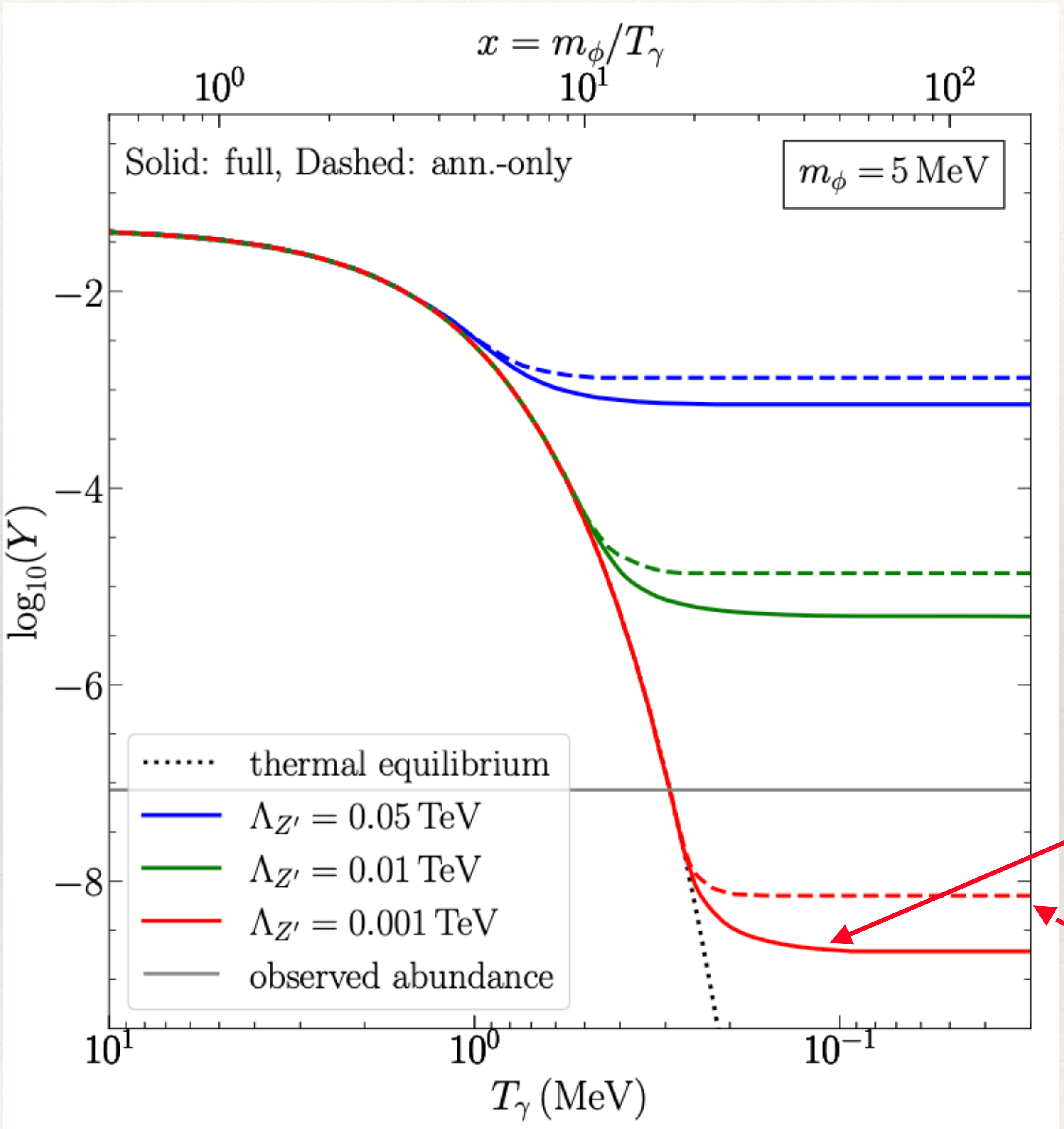
(DM-SM scattering is important here)

How the system evolves:

DM abundance evolution

w.r.t. to photon temperature

$$\frac{1}{\Lambda_{Z'}^2}(\bar{l}\gamma^\mu l)\,(\phi^* \overleftrightarrow{\partial}_\mu \phi)$$



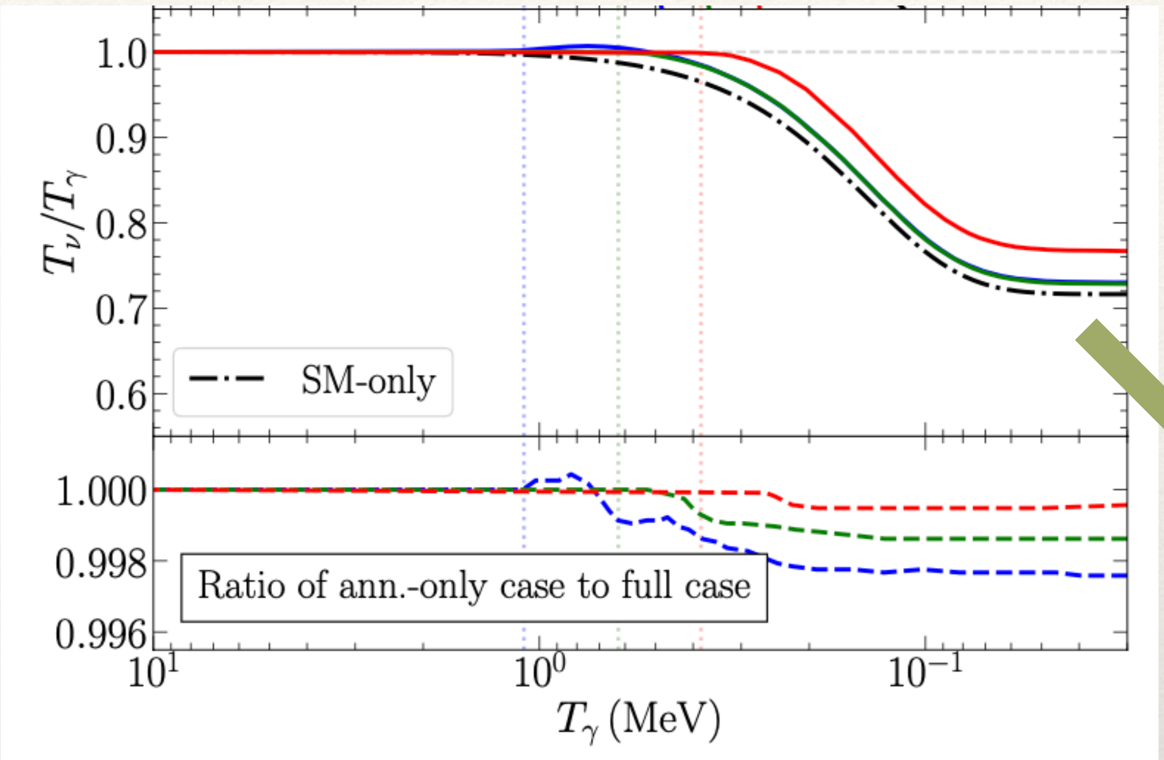
- **Tracking DM temperature** is important for p-wave annihilation.

$$\langle \sigma_{\rm ann} v_M \rangle_{\rm p-wave} = b\,\langle v_{\rm rel}^2 \rangle = b\,(6T_\phi/m_\phi)$$

(DM-SM scattering is important here)

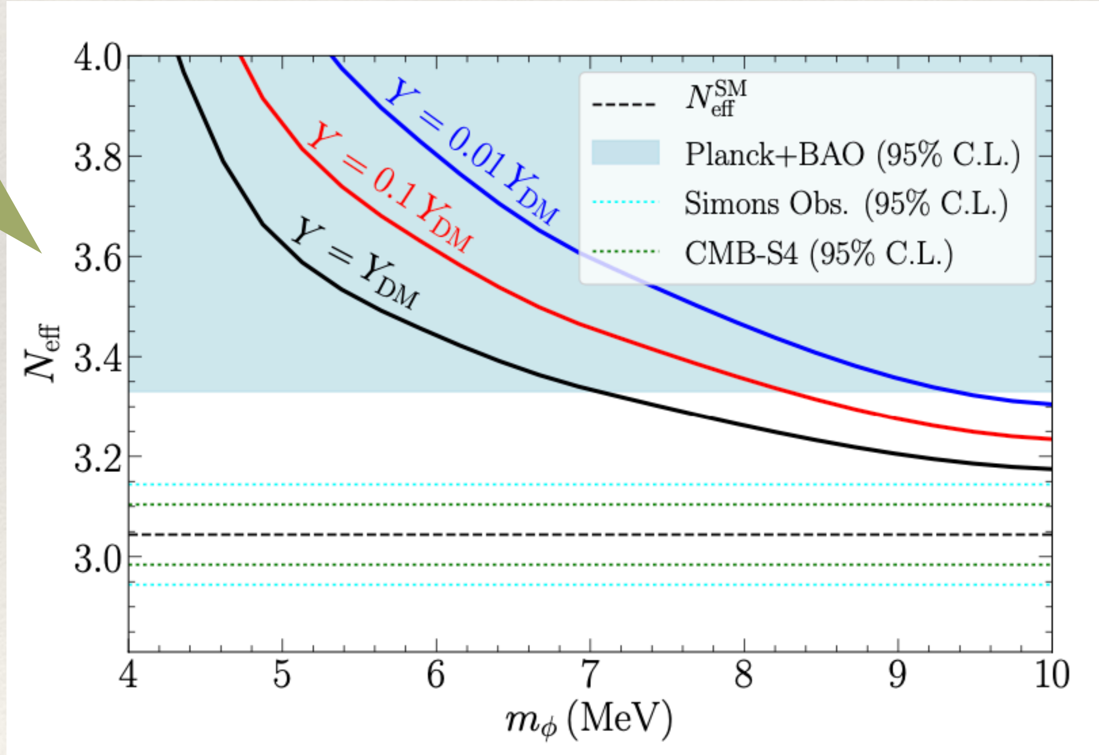
Taking current Planck bounds: $2.66 \leq N_{\rm eff} \leq 3.33$

around CMB, $0.686 \leq T_\gamma/T_\nu \leq 0.739$



Our bound: m_ϕ > 7 MeV (p-wave)

- **8.5/4.6 MeV** for e/**ν**-only case [Neff, s-wave], *1910.01649;*
- **70/200 GeV** for e/**γ**-line case [all, s-wave], e.g. 1511.08787.



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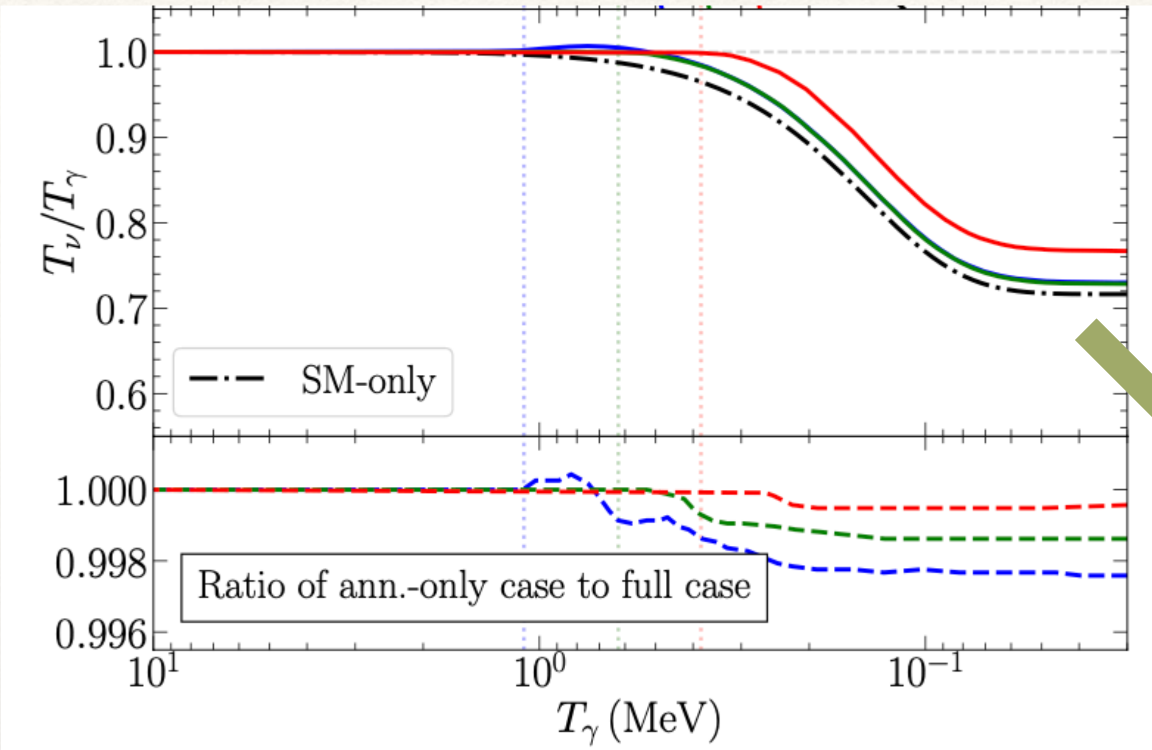

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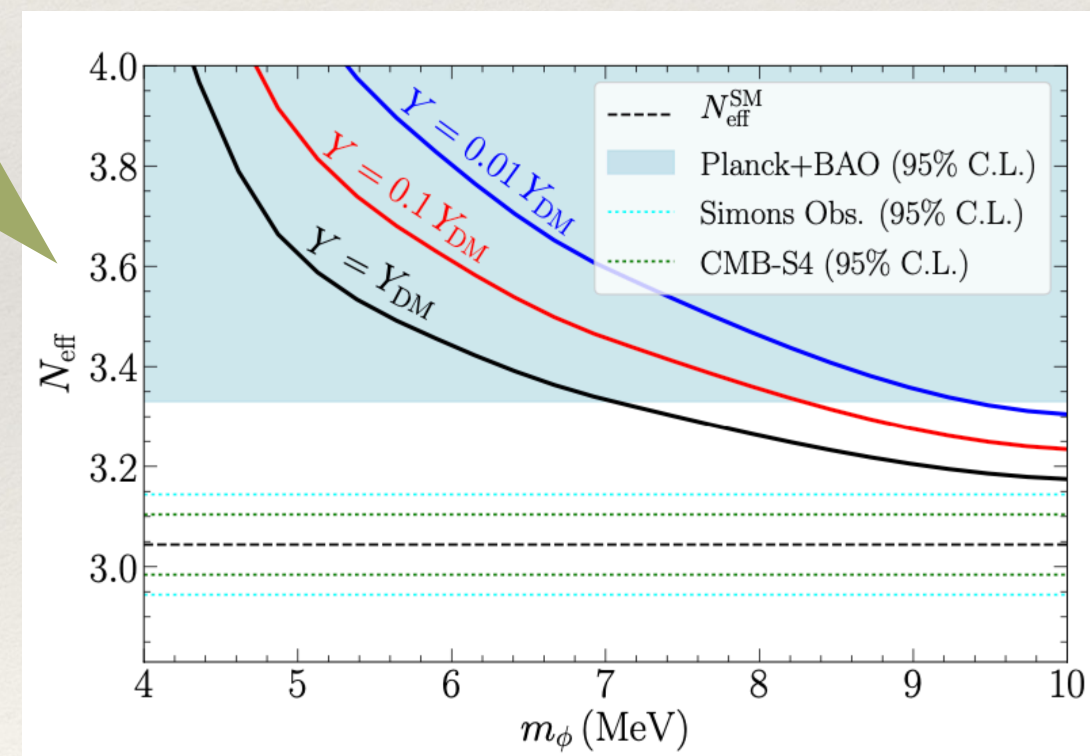
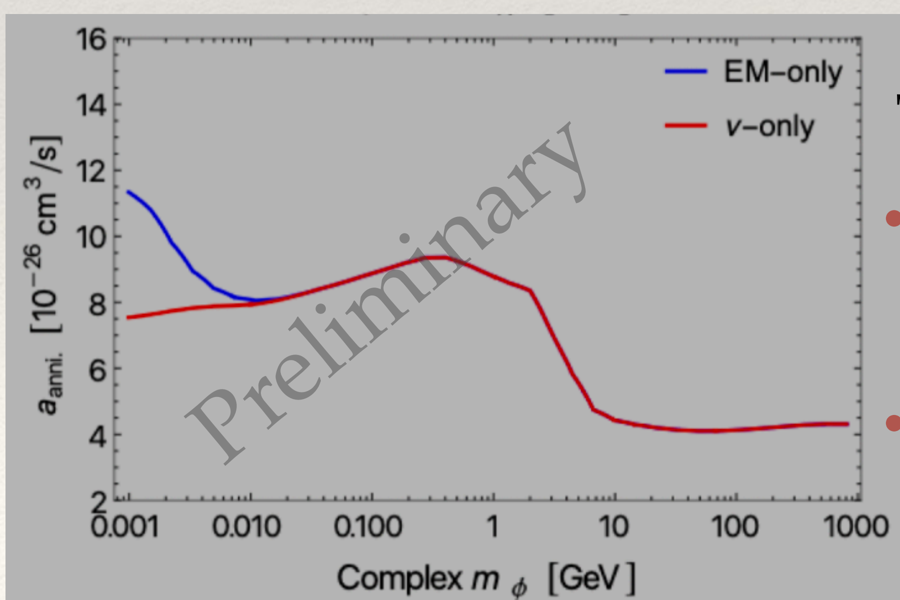
stronger than previous results (which use pre-fixed **constant** cross sections, **4.5 MeV** *[N. Sabti, et al, 1910.01649]*).





This is due to:

- **Larger cross section** needed for MeV DM;
- Enhancement in **p-wave** before freeze-out.

Conclusions

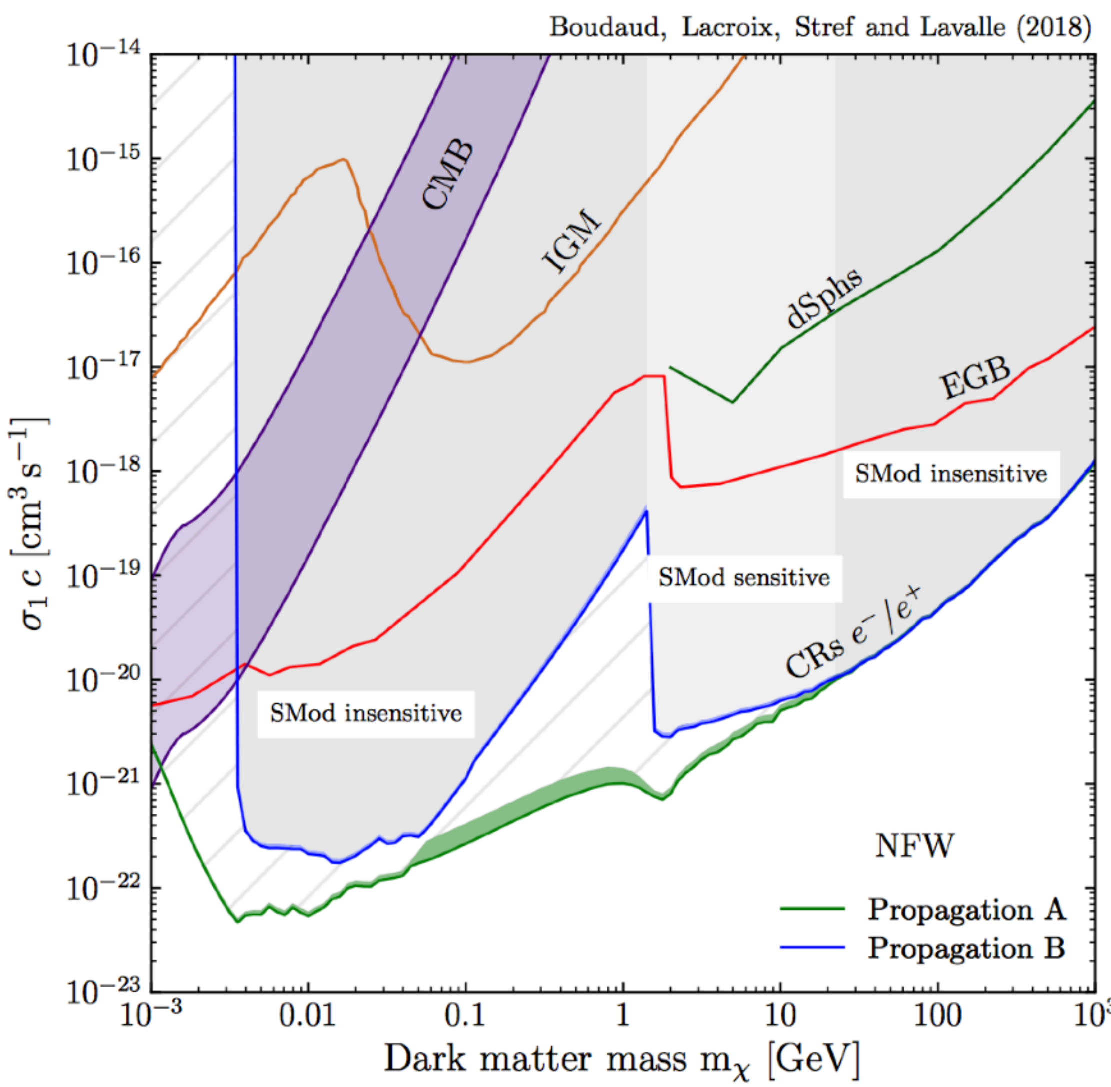
Conclusion and Prospects

- With better BBN/CMB measurements, we should improve the precision of **theoretical calculations in MeV physics** too.
- A consistent numerical treatment of **MeV DM freeze-out (into both EM/neutrino)** is provided here, without solving the exact momentum distribution functions.
- We can now obtain the **full history** of MeV DM decoupling, and will apply it to more cases (DM spins, **varying branching ratio**).
  - **BBN constraints** are crucial for fine-tuned branching ratios.

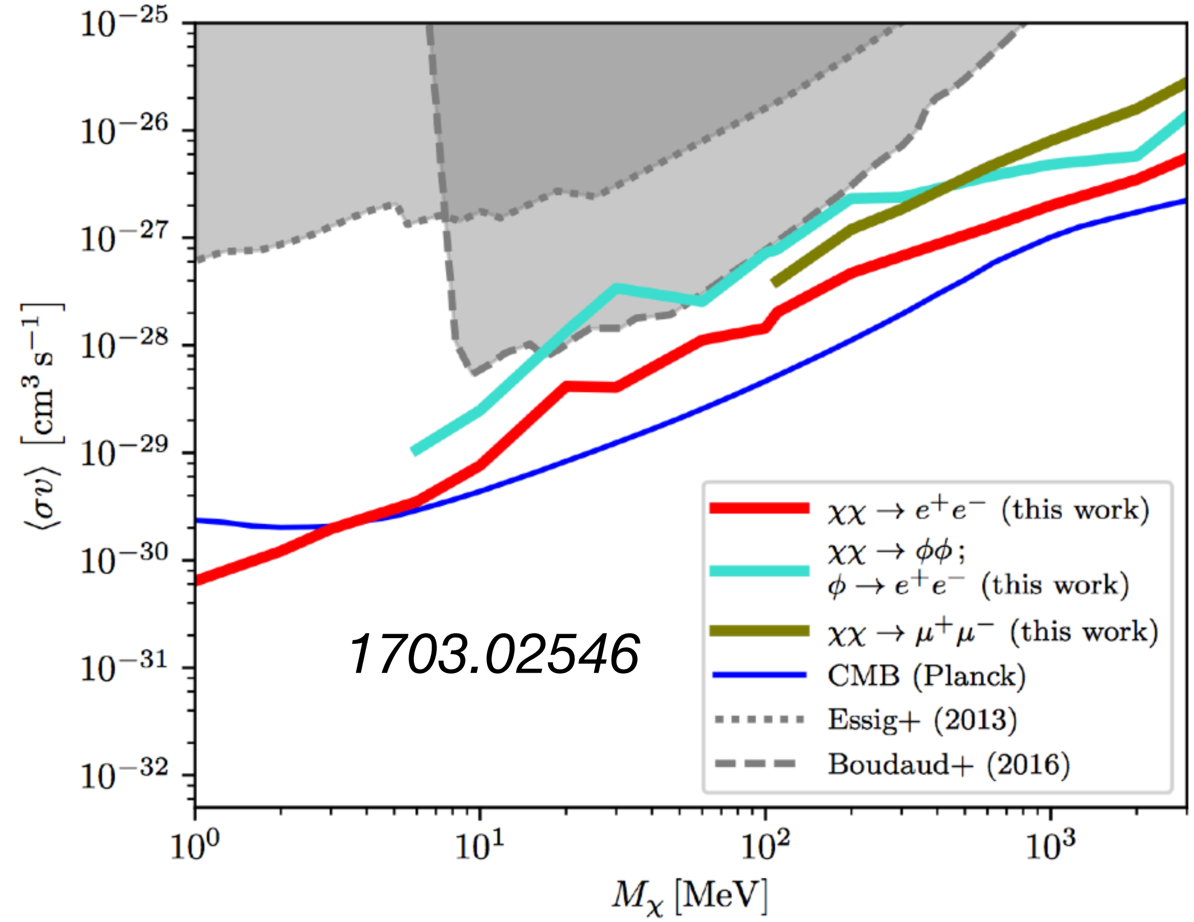
Thanks!

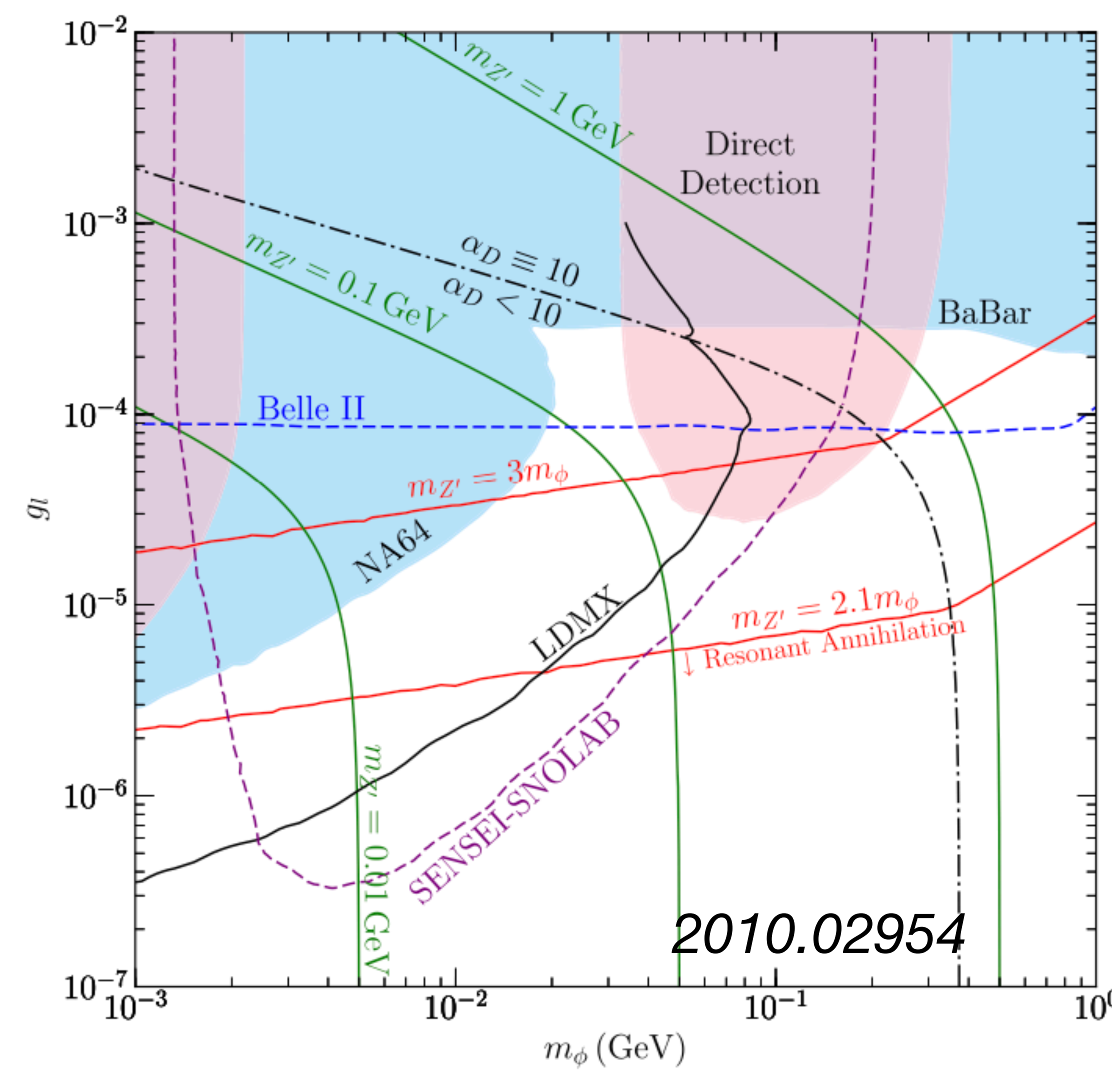
Non-Neff Bounds on DM

$$\langle \sigma v \rangle = \langle \sigma v \rangle_{s\text{-wave}} + \langle \sigma v \rangle_{p\text{-wave}} + \text{higher orders}$$
$$= \sigma_0\, c + \sigma_1\, c \,\langle \frac{v_r^2}{c^2} \rangle + \mathcal{O}\left(\frac{v_r^4}{c^4}\right) ,$$



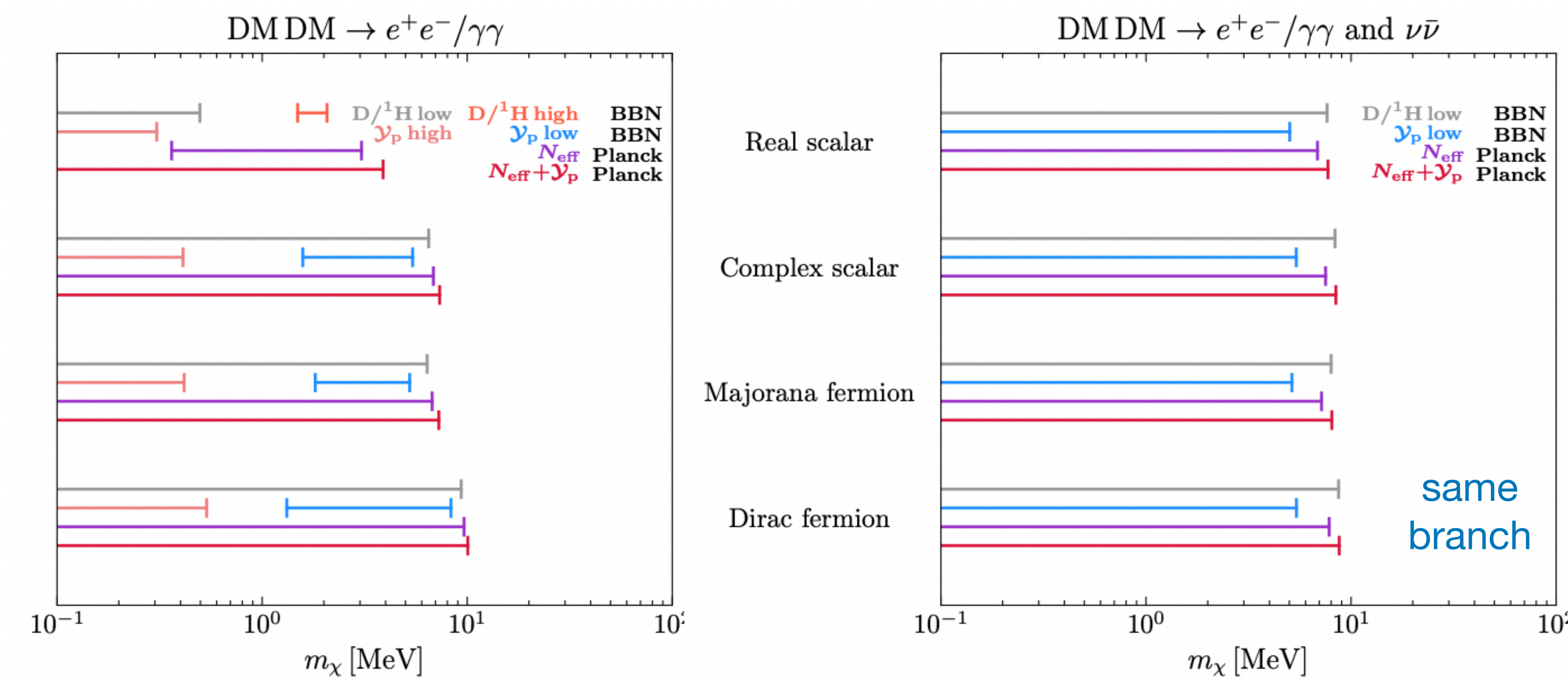
$$C[f_1] = -\frac{S g_2}{2} \int d\Pi_{i=2,3,4}\, (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - p_4)$$
$$\times J \frac{1}{g_1 g_2} \sum_{\text{spins}} |\mathcal{M}_{12\leftrightarrow 34}|^2 .$$





Previous CMB/BBN on s-wave DM

1901.06944: sudden decoupling induced by DM annihilation into e/ν



Thermalised and non-mu neutrinos + MB statistics in collision rates + zero-mass electron
【**with DM: 1812.05605,** 1910.01649】