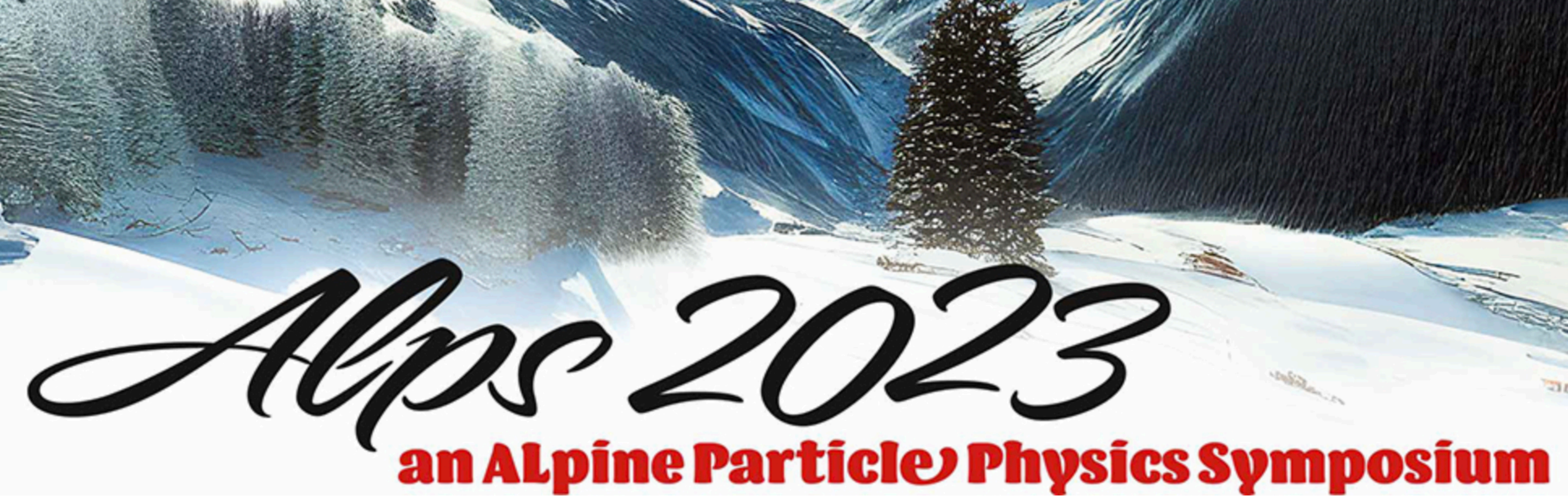

MeV dark matter

in the interplay of visible and neutrino sectors

Xiaoyong Chu

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

with Jui-Lin Kuo, Josef Pradler

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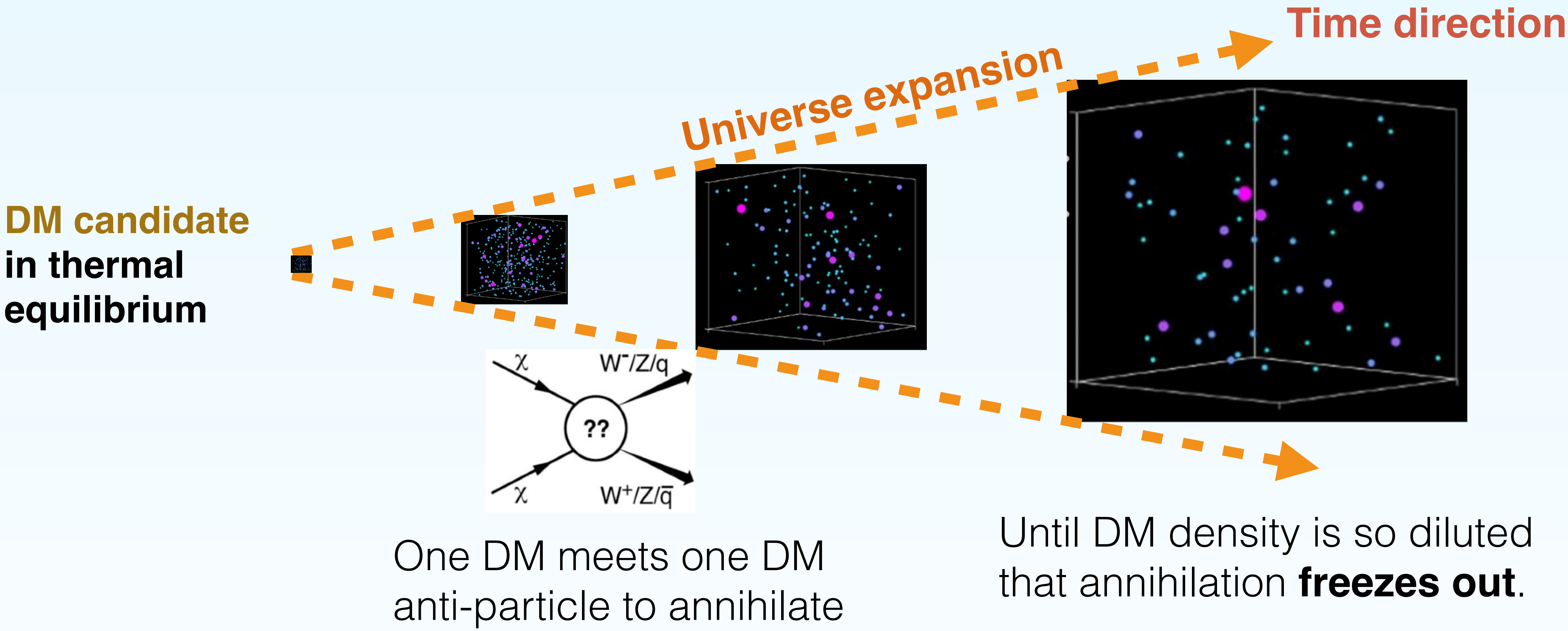
I. Motivations

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

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



<u>That is:</u>

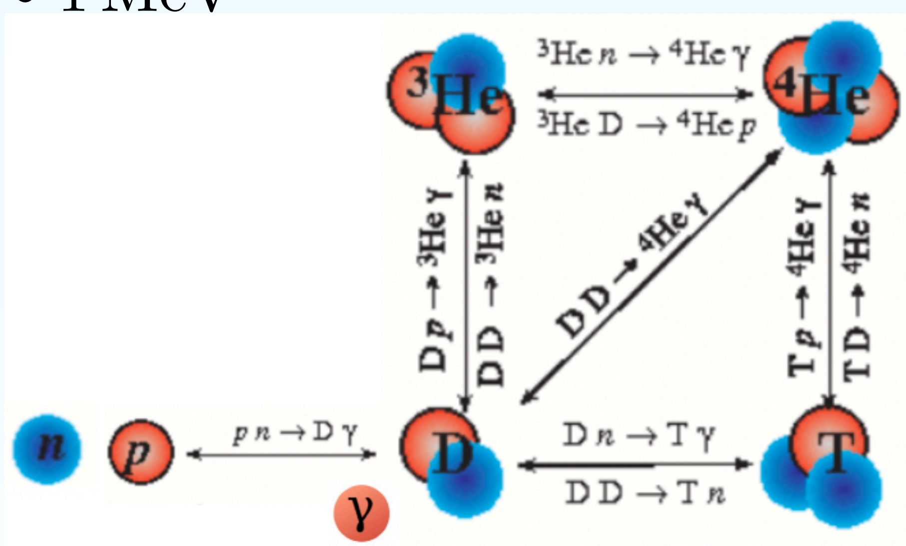
1. DM itself **contributes to the total energy of Universe**;
2. DM **annihilation ejects energy (visibly or invisibly)** during freeze-out;

1. DM itself **contributes to the total energy of Universe**;
2. DM **annihilation ejects energy (visibly or invisibly)** during freeze-out;

Both leads to observable effects for MeV-scale DM:

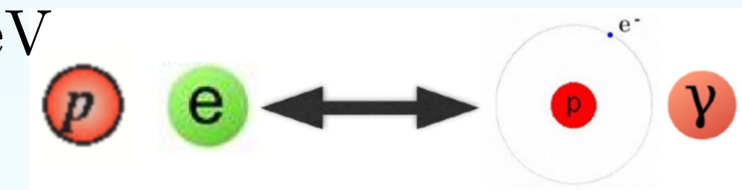
Big Bang Nucleosynthesis (BBN)

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

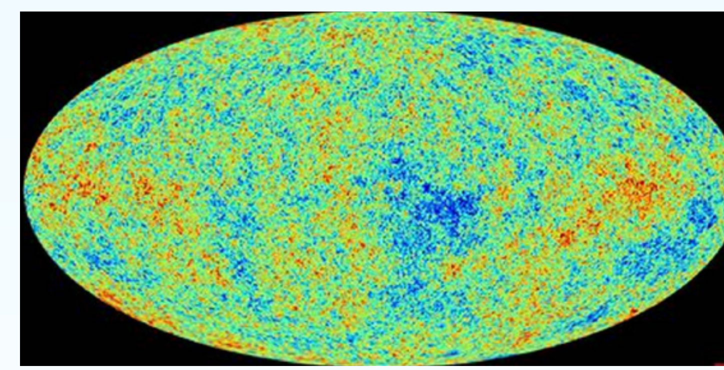


Cosmic Microwave Background (CMB)

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



T_ν/T_γ



Such observables constrain the additional EM and **background energy densities.**

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

1. DM itself **contributes to the total energy of Universe**;
2. DM **annihilation ejects energy (visibly or invisibly)** during freeze-out;

And the reality can be even trickier.

Around T~MeV, visible sector decouples from neutrinos via weak interaction:

$$\sigma v_{\bar{e}e\to\bar{\nu}\nu} \sim \frac{\mathrm{MeV}^2}{m_Z^4} \sim 10^{-31}\mathrm{cm}^3/\mathrm{s}.$$

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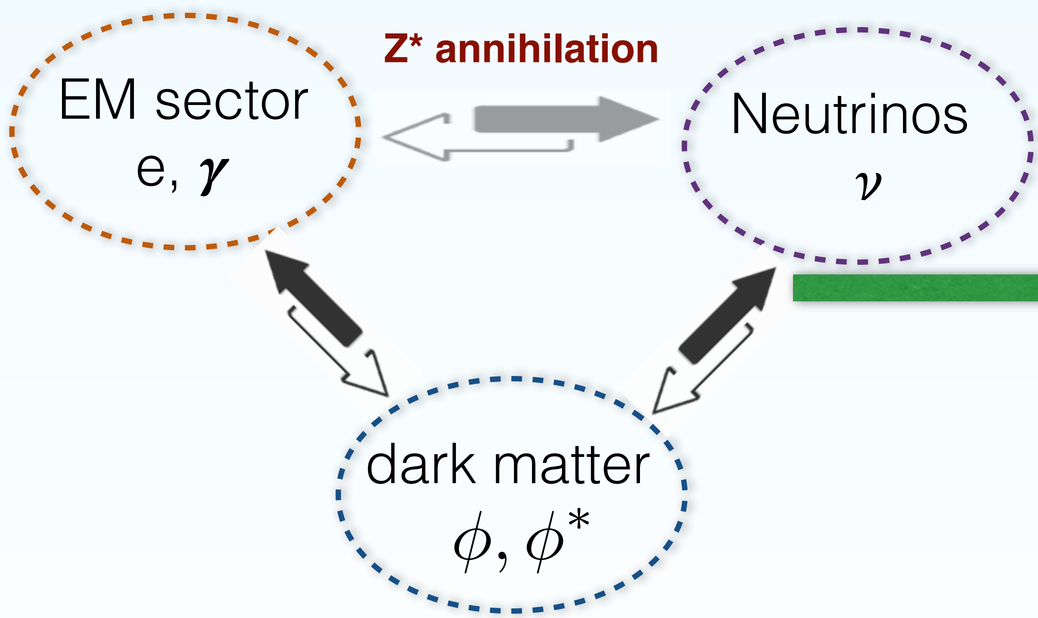
If MeV DM freeze-out involves three sectors:



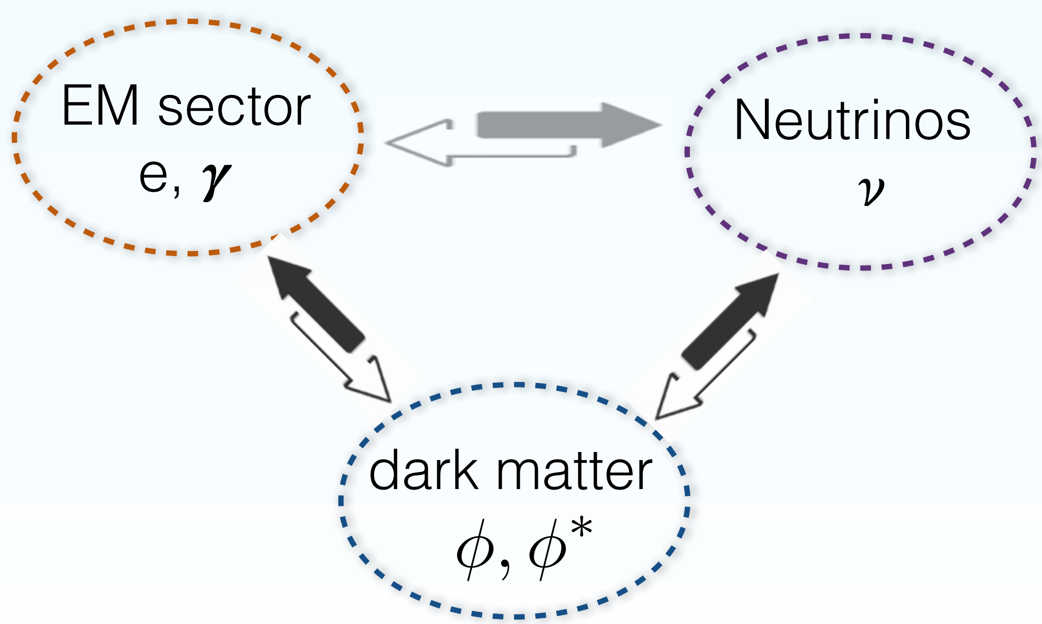
$$\sigma v_{\phi\phi^*} \sim 10^{-26} - 10^{-25}\text{cm}^3/\text{s}.$$

MeV dark matter may **maintain the coupling of EM and** ν, even for branching ratio to EM/ν of $\mathbf{10^{-5}}$.

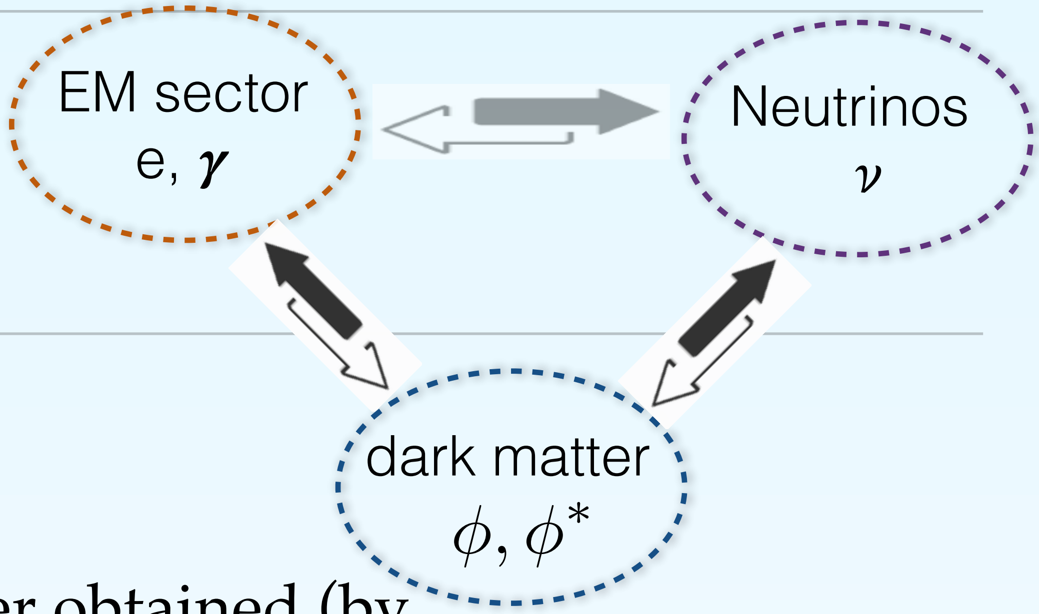
3. MeV dark particle may **connect EM &** ν.

this value does not matter if only two sectors [e.g. recently *Escudero 2001.04466, Giovanetti, Lisanti, Liu &Ruderman 2109.03246*]

II. Improved description of three-sectors



To reach **a (nearly) full description of MeV DM freeze-out**



In earlier work *[M.Escudero 1812.05605]*:

- **Actual DM annihilation cross section** was never obtained (by assuming ~ pico-barn value);
- **Simplified interaction rates** (e.g. massless limit, constant $|\mathcal{M}|$);
- Only include DM pair-**annihilation** processes;
- Only with **Maxwell-Boltzmann** statistics, ….

[Or sudden decoupling: Depta, Hufnagel, Schmidt-Hoberg & Wild 1901.06944]

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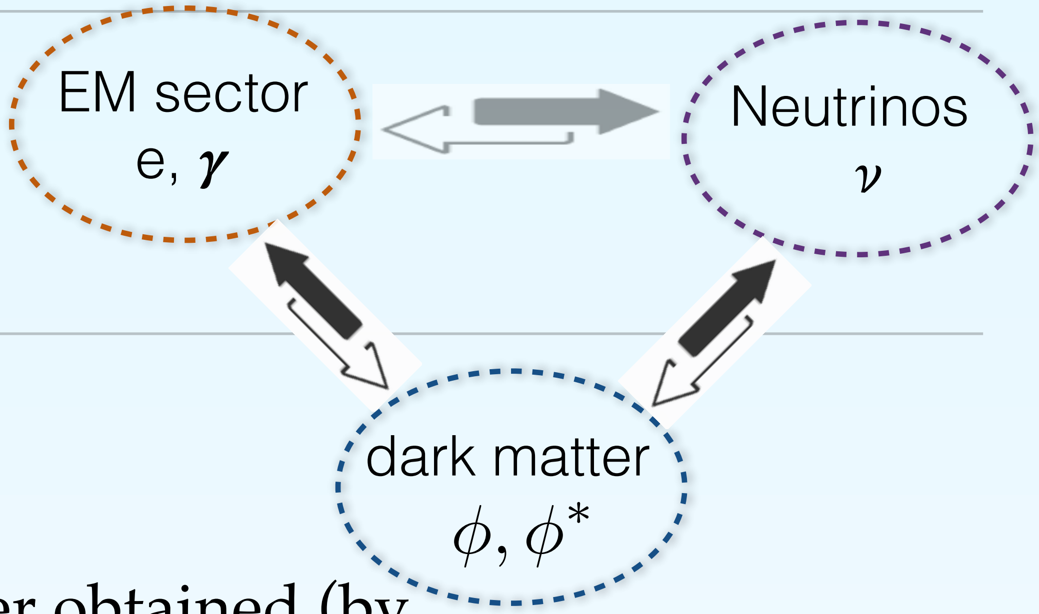

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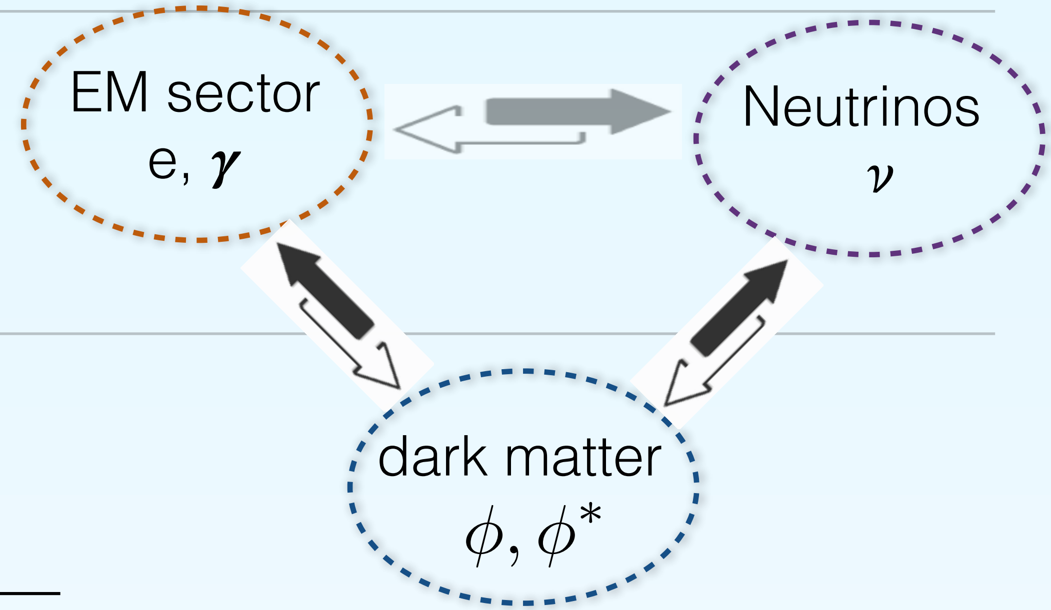
A parametrization to takes into account all the effects above [up to solving the exact momentum distribution functions (MDF) of each sector].

XC, Kuo, Pradler 2205.05714

Solving the momentum distribution of each particle species is very time-consuming, and only leads to tiny corrections.

Simplification introduced:



- **Kinetic equilibrium** within each sector:

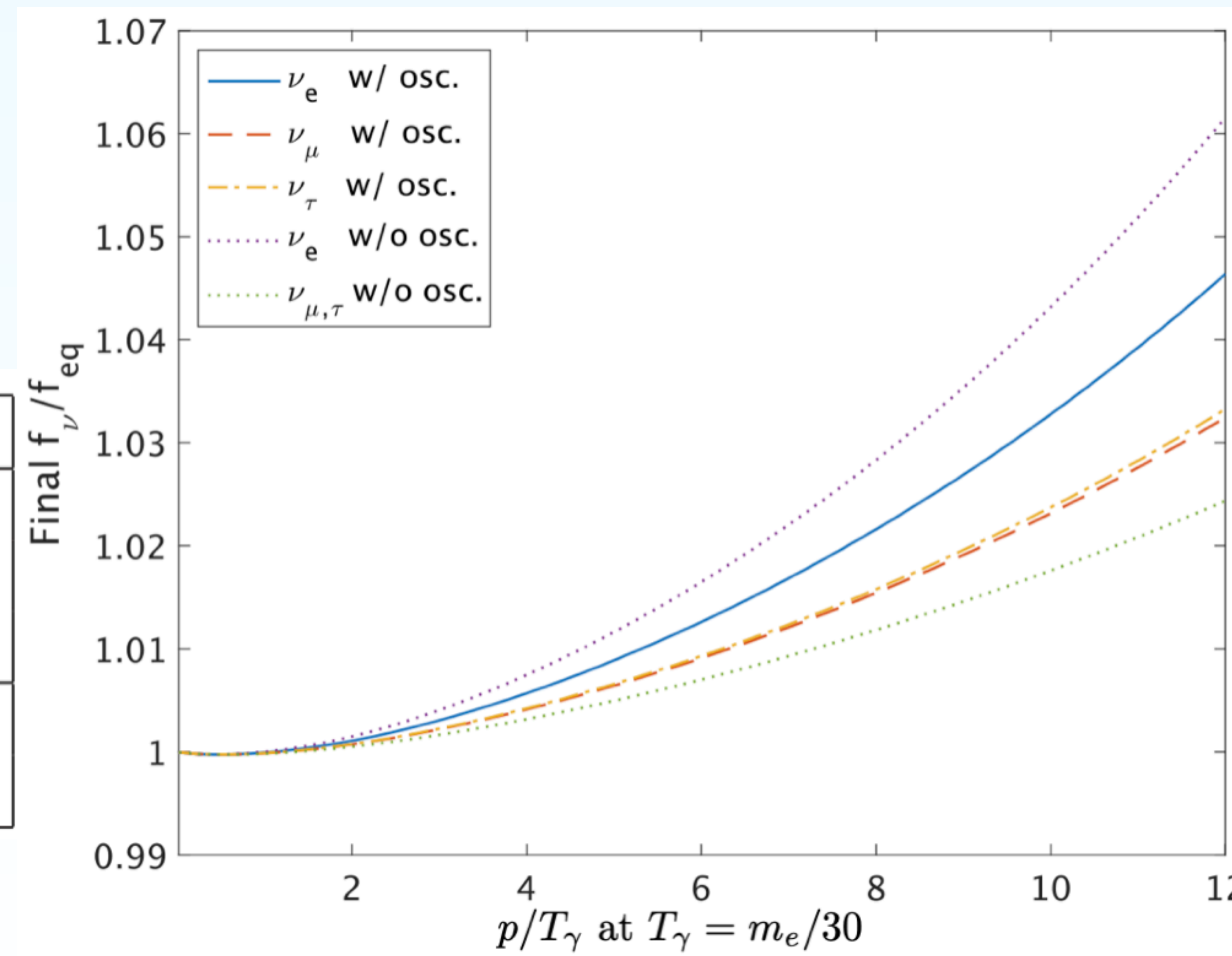
$$f_i(E_i, \mu_i) = \frac{1}{e^{(E_i-\mu_i)/T_i} \mp 1} \equiv \frac{1}{e^{\tilde{E}_i-\tilde{\mu}_i} \mp 1}$$

A) the **neutrino sector**

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

Akita & Yamaguchi 2005.07047

Case	$z_{\rm fin}$	$N_{\rm eff}$
Instantaneous decoupling	1.40102	3.000
No mixing + QED up to $\mathcal{O}(e^2)$	1.39789	3.044
No mixing + QED up to $\mathcal{O}(e^3)$	1.39800	3.043
mixing + QED up to $\mathcal{O}(e^2)$	1.39786	3.045
mixing + QED up to $\mathcal{O}(e^3)$	1.39797	3.044



See also *1606.06986, 1812.05605, 2001.04466, 2012.02726*, etc.

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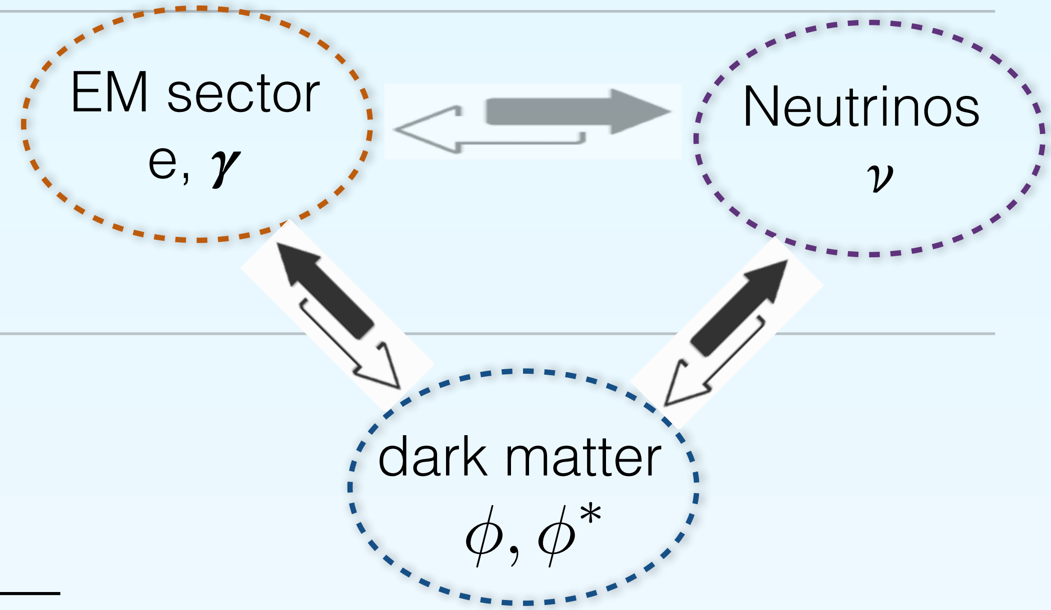

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A) the **neutrino sector**

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

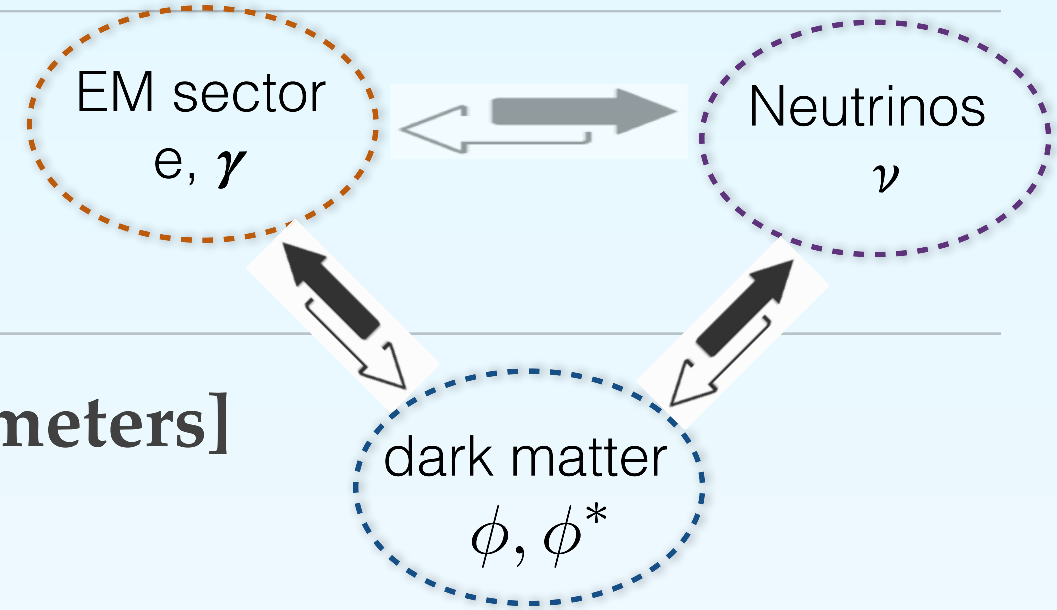
B) the **EM sector**

In general satisfied, with **null chemical potentials** (up to B/L-asymmetry).

C) the **dark sector**

- Depend on **DM self-interaction** (SIDM?);
- Before fully decoupled, scattering with EM/ν makes it close to be thermal;
- It becomes non-relativistic quickly, so little effects after decoupling [with a few exceptions such as second freeze-out, e.g. *Binder, Bringmann, Gustafsson &Hryczuk, 2103.01944*].

Simplification introduced:



- **Minimize multi-integrals: [separate 5 parameters]**

  for the relativistic particles, neutrino:

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

  for non-relativistic particles, **DM:**

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

Calculate the **full number/energy-transfer rates** as **functions of (T_1, T_2)**, e.g.

$$\gamma^{(0)}_{12\leftrightarrow 34} = \frac{g_1 g_2}{(2\pi)^4}\int \frac{ds\,dE_+ dE_-}{2} f_1^{\rm eq} f_2^{\rm eq} \sigma_{12\to 34}\mathcal{F}_{12} \times \left[(1-\Delta_{\rm ann.}) + \Delta_{\rm ann.}(1-\beta_{\rm ann.})\right]\,,$$

$$\zeta^{(0)}_{12\leftrightarrow 12} = \frac{g_1 g_2}{(2\pi)^4}\int dE_1 dE_2 ds dt\, f_1^{\rm eq} f_2^{\rm eq} \frac{d\sigma_{12\to 12}}{dt} \times \mathcal{F}_{12}\langle \Delta_{\rm scatt.}\delta E\rangle\,,$$

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

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

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

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

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

For each two-body process $1+2 \leftrightarrow 3+4$, **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 in our numerical results.

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

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

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

5 variables from 5 ODEs:

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

Multi-integral tables (interaction rates from particle model)

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

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

III. Numerical results in a toy model

Taking a d.o.f.-blind model:

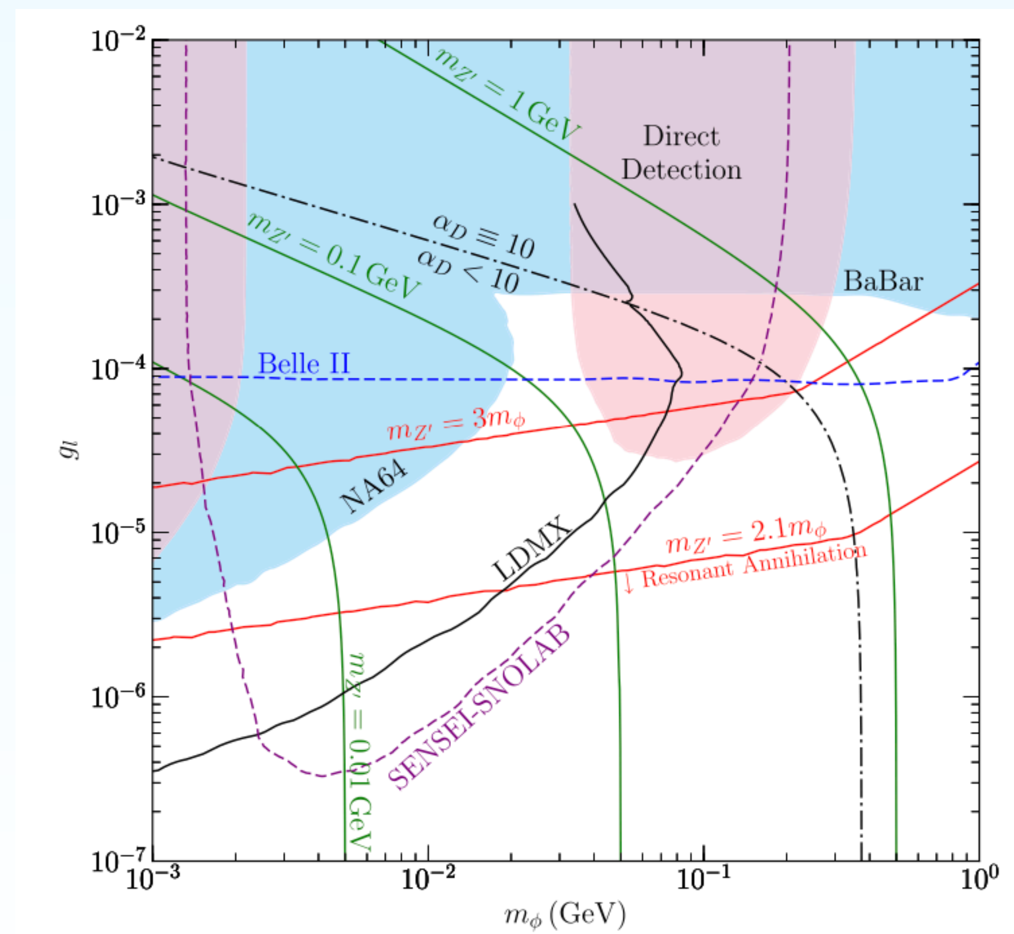
$$\frac{1}{\Lambda_{Z'}^2}(\bar{l}\gamma^\mu l)\,(\phi^* \overleftrightarrow{\partial}_\mu \phi)$$

Annihilation $Br_\nu : Br_e = 3:2$

Nearly maximal DM effects with large $\sqrt{\mathrm{BR}_\nu\,\mathrm{BR}_e}$

Scalar DM, p-wave freeze-out,
constrained to mZ′ ~ 2mDM

Here, Z′ not included in this toy model!



*Bœhm, **XC**, Kuo, Pradler [2010.02954]*

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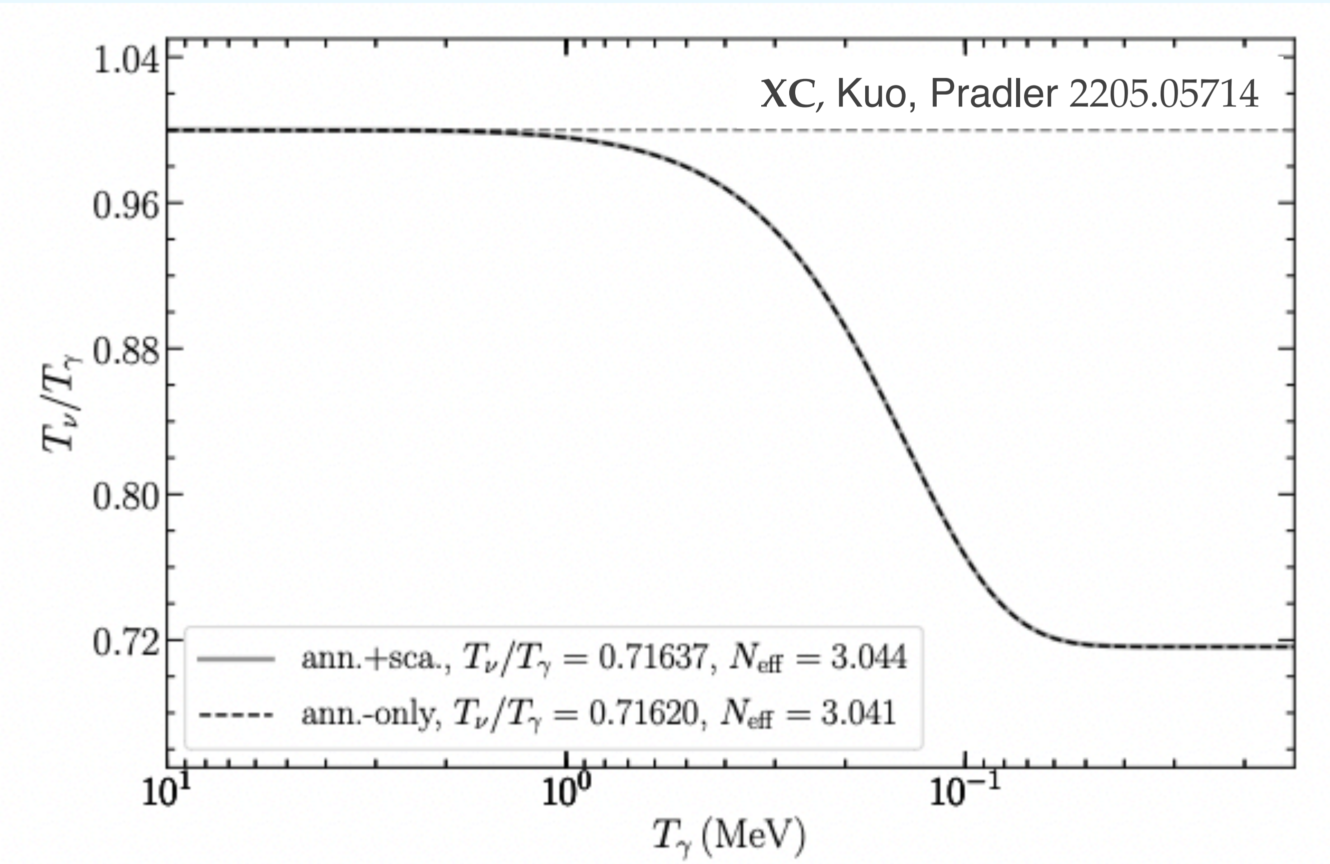

1. We re-produce the standard results with **SM interaction rates in the literature**:

Most important process:

$$\sigma v_{\bar{e}e\to\bar{\nu}\nu}$$

Bennett, Buldgen, Pastor et al. 2012.02726

Standard-model corrections to $N_{\rm eff}^{\rm SM}$	Leading-digit cont
m_e/T_d correction	+0.04
$\mathcal{O}(e^2)$ FTQED correction to the QED EoS	+0.01
Non-instantaneous decoupling+spectral distortion	−0.005
$\mathcal{O}(e^3)$ FTQED correction to the QED EoS	−0.001
Flavour oscillations	+0.0005
Type (a) FTQED corrections to the weak rates	$\lesssim 10^{-4}$

Taking a d.o.f.-blind model:

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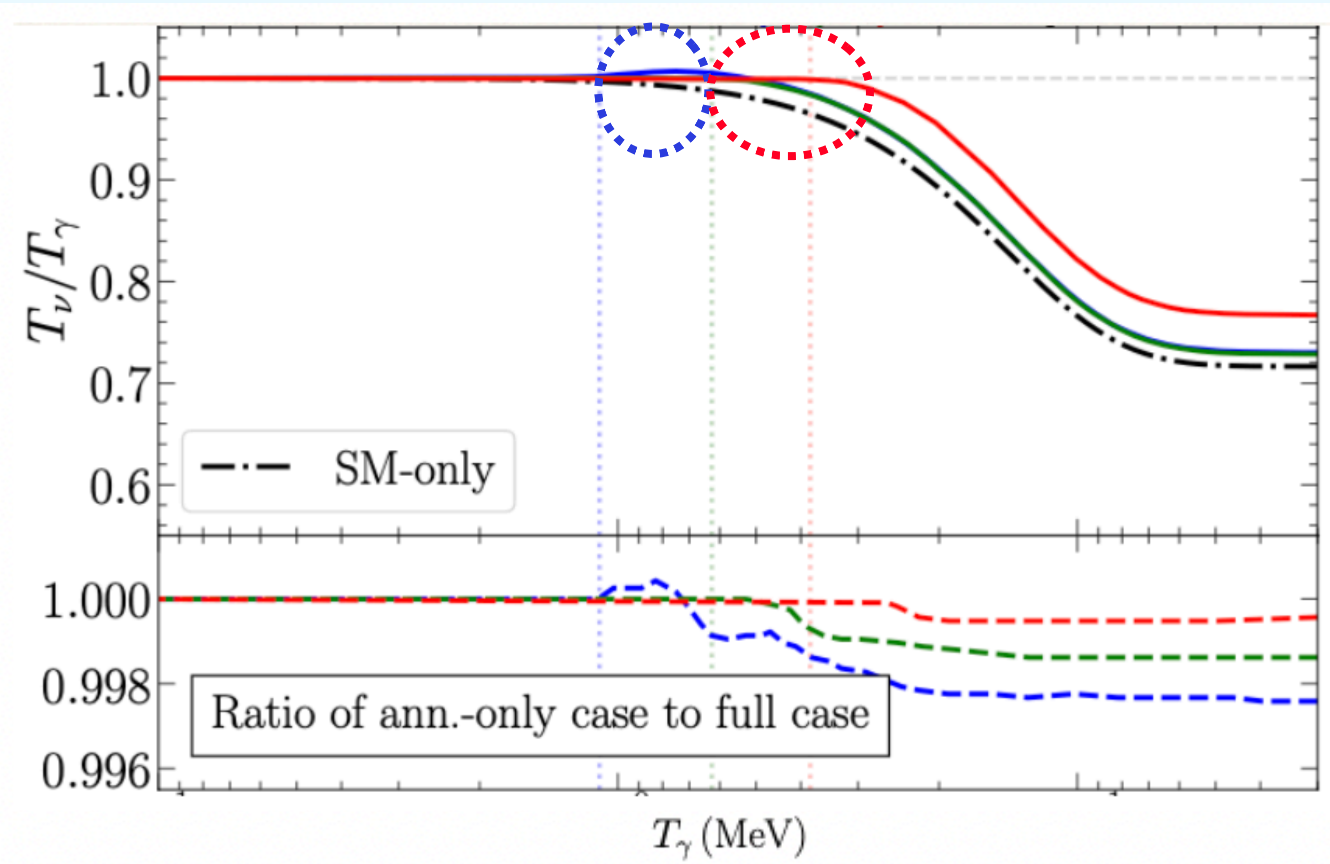
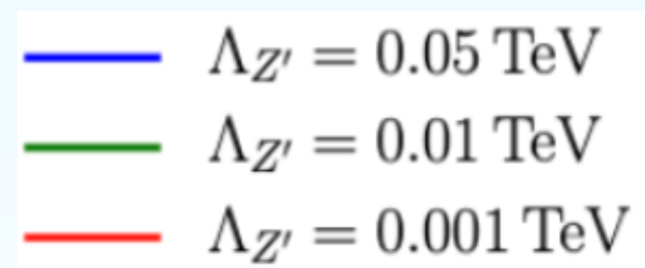


2. One then adds a **5 MeV complex scalar** thermal DM, which freezes out:



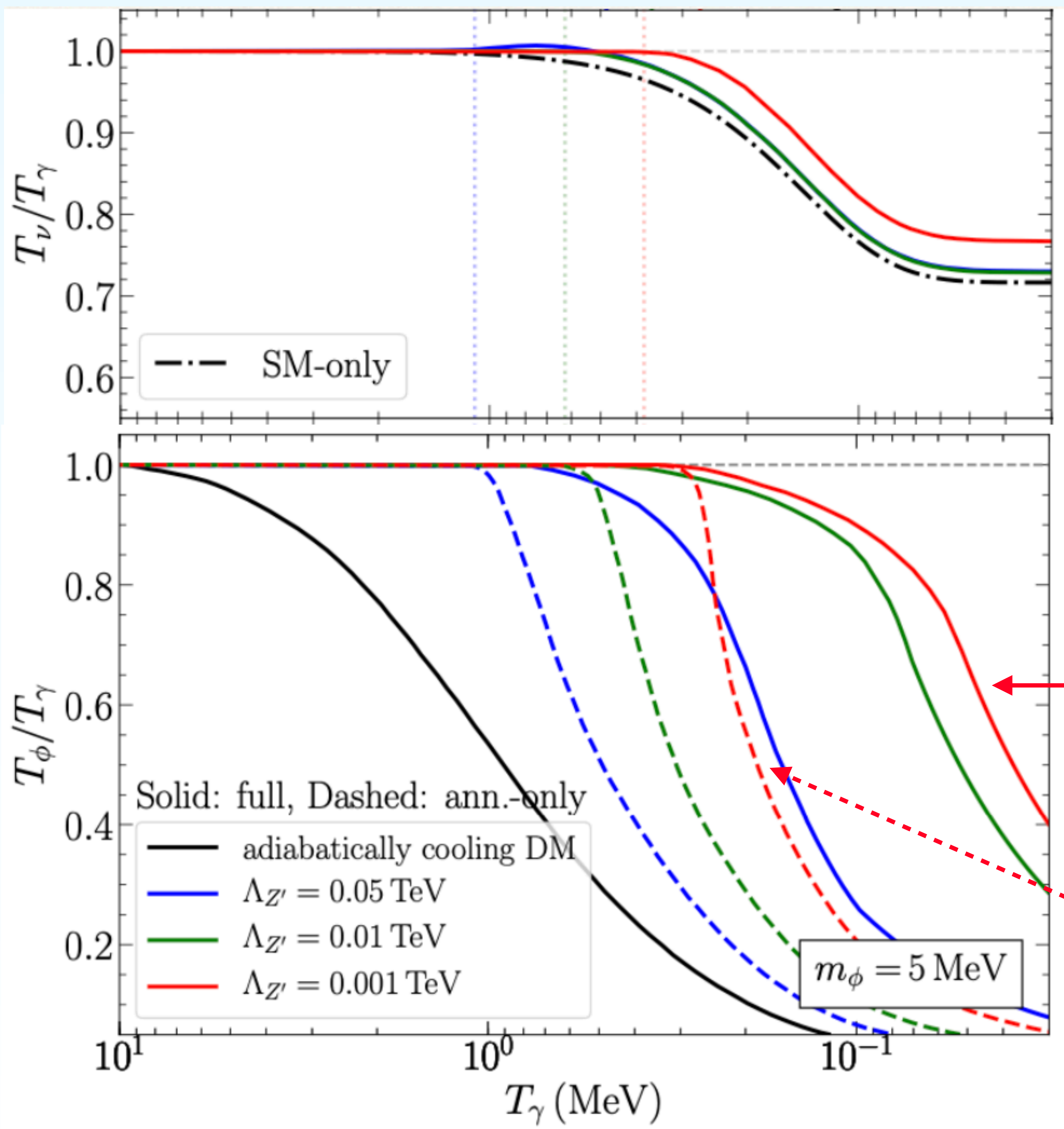
increase interactions

- DM annihilates, **heating up one sector** (either EM or ν);
- DM connects both sectors, **reducing the temperature difference**.

Taking a d.o.f.-blind model:

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

Annihilation $Br_\nu : Br_e = 3 : 2$



3. Regarding the DM final abundance:

- **DM temperature** is in between photon and neutrino temperatures, before it gradually decouples.

(DM-SM scattering is important here)

Taking a d.o.f.-blind model:

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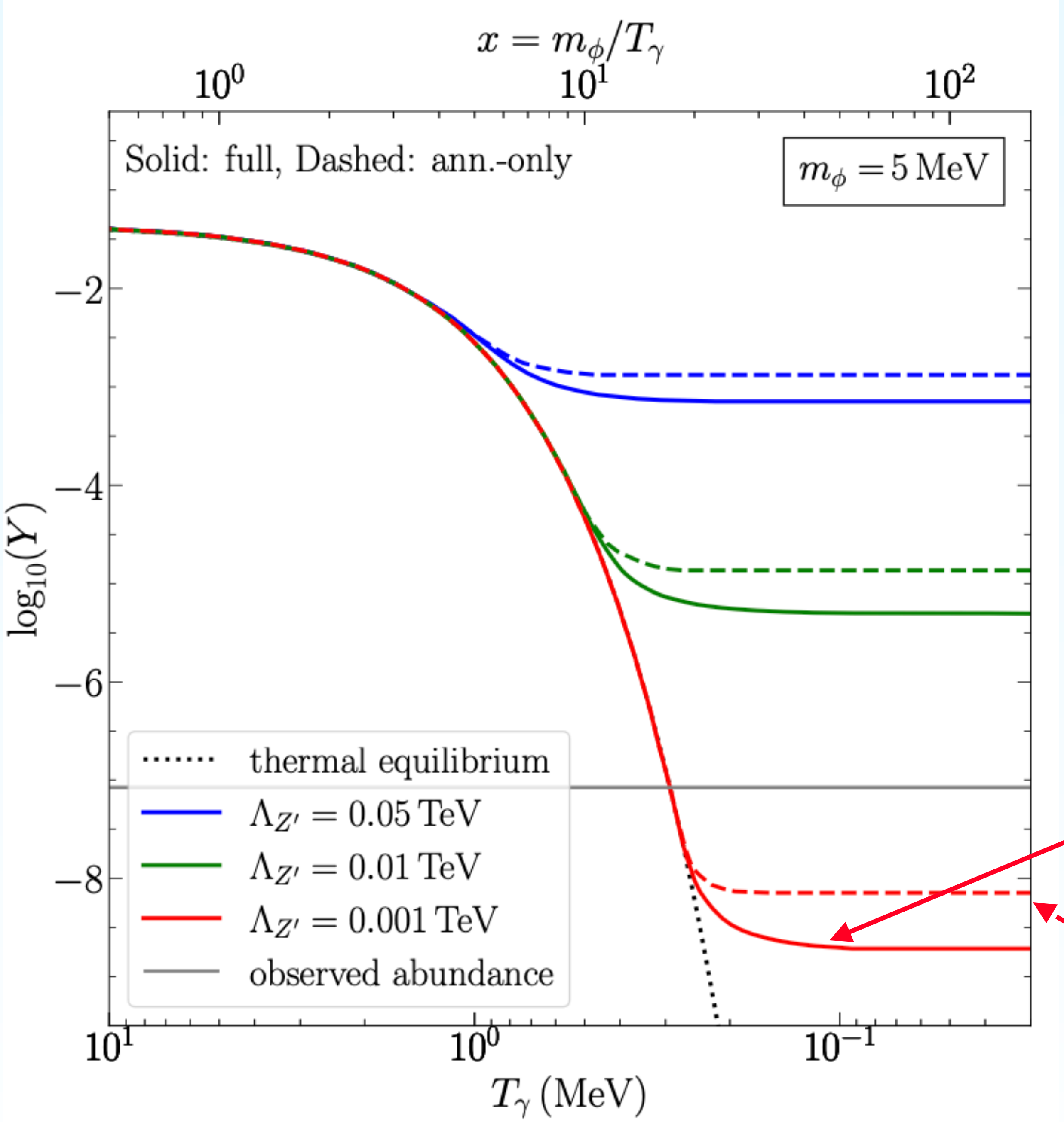
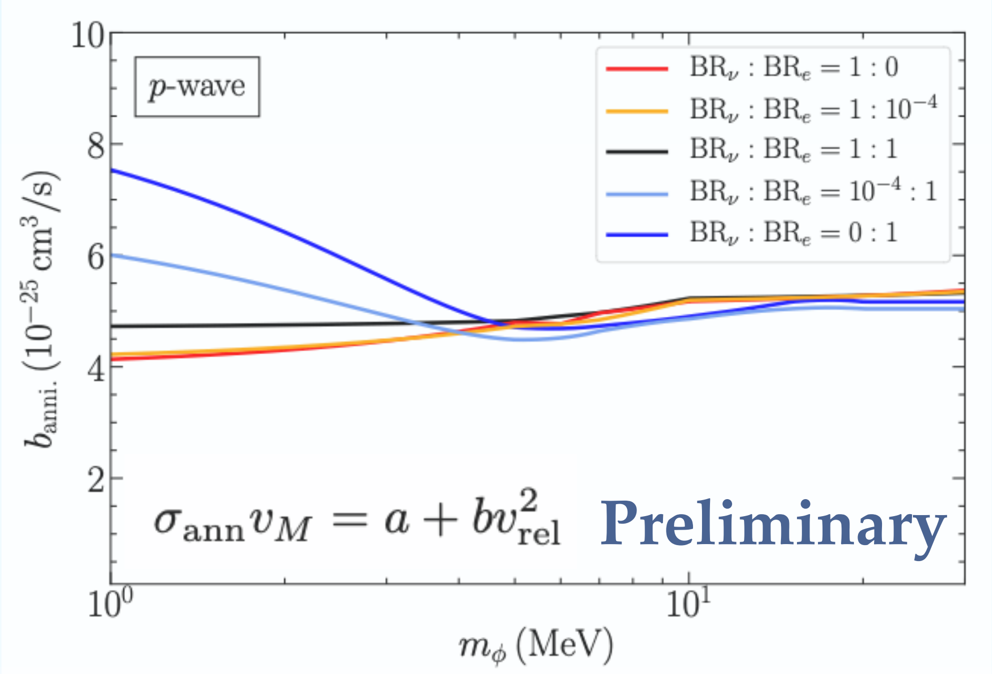
Annihilation $Br_\nu : Br_e = 3:2$





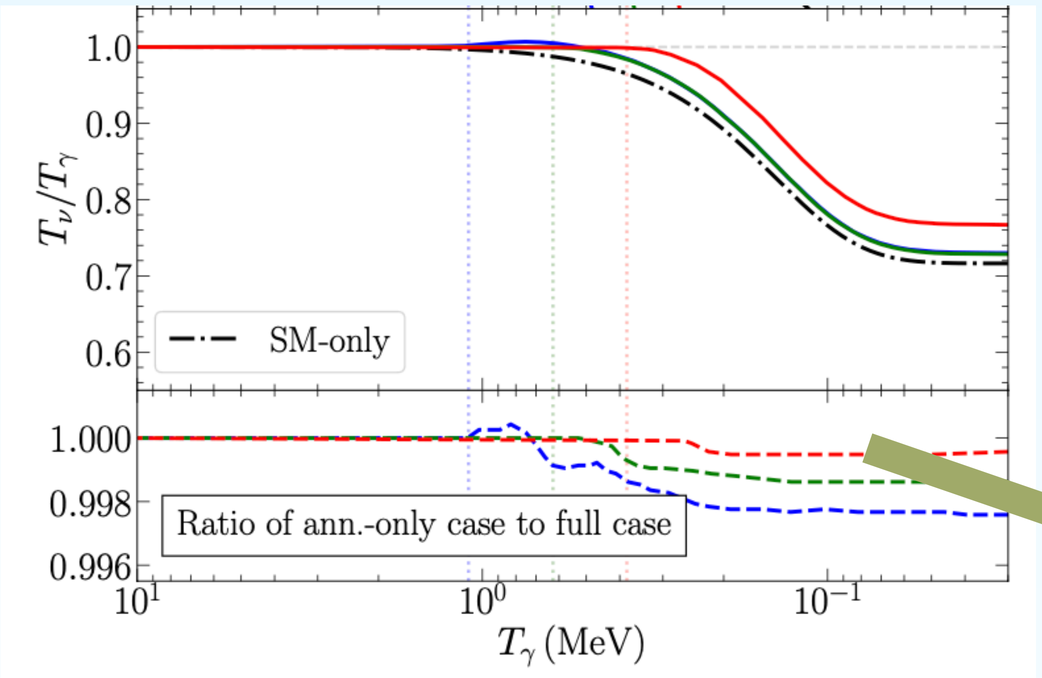
3. Regarding the DM final abundance:

Calculating **DM temperature** is crucial for **p-wave** freeze-out.

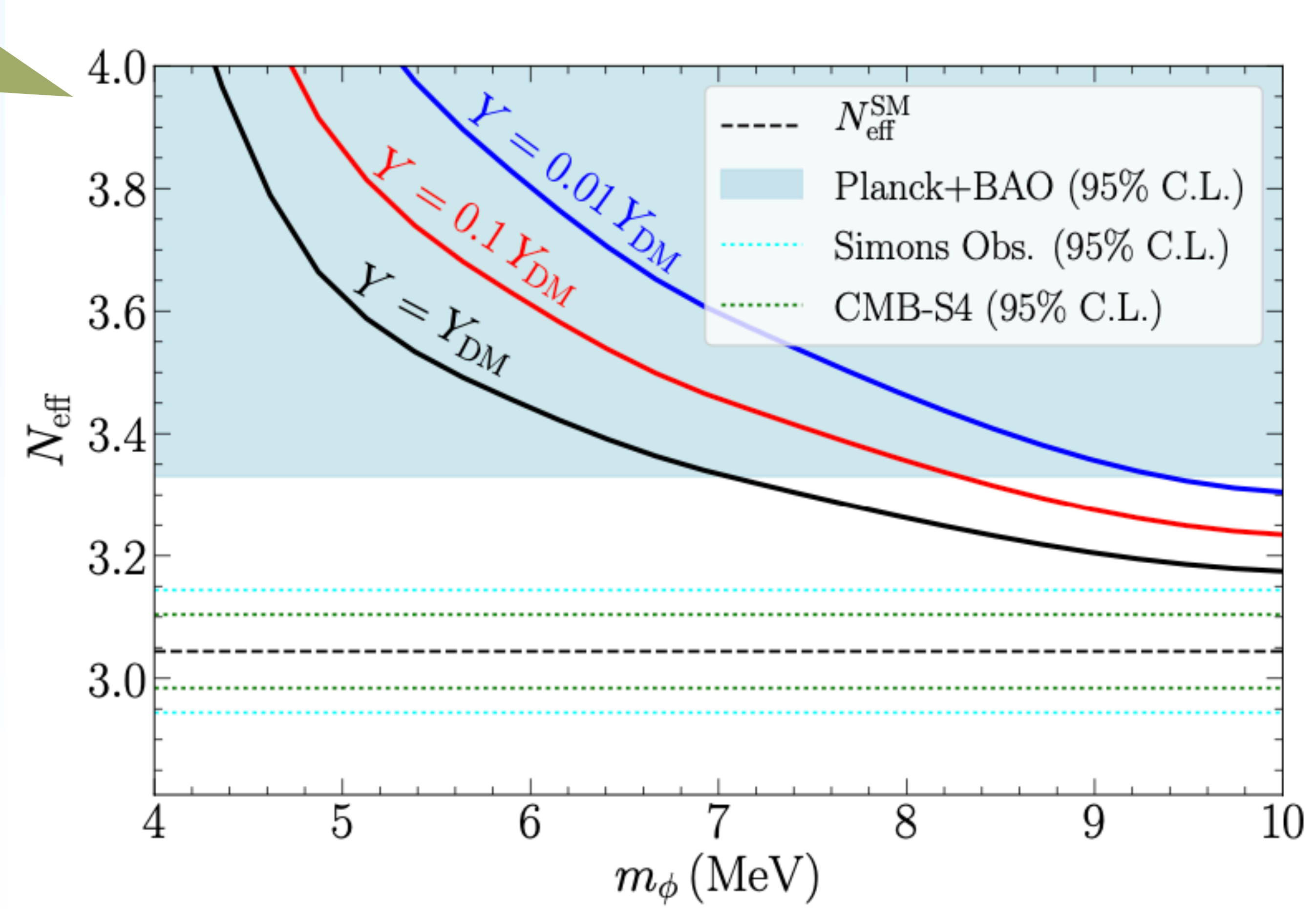
If without DM-SM scattering.

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

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



New bound: m_ϕ > 7 MeV (p-wave)



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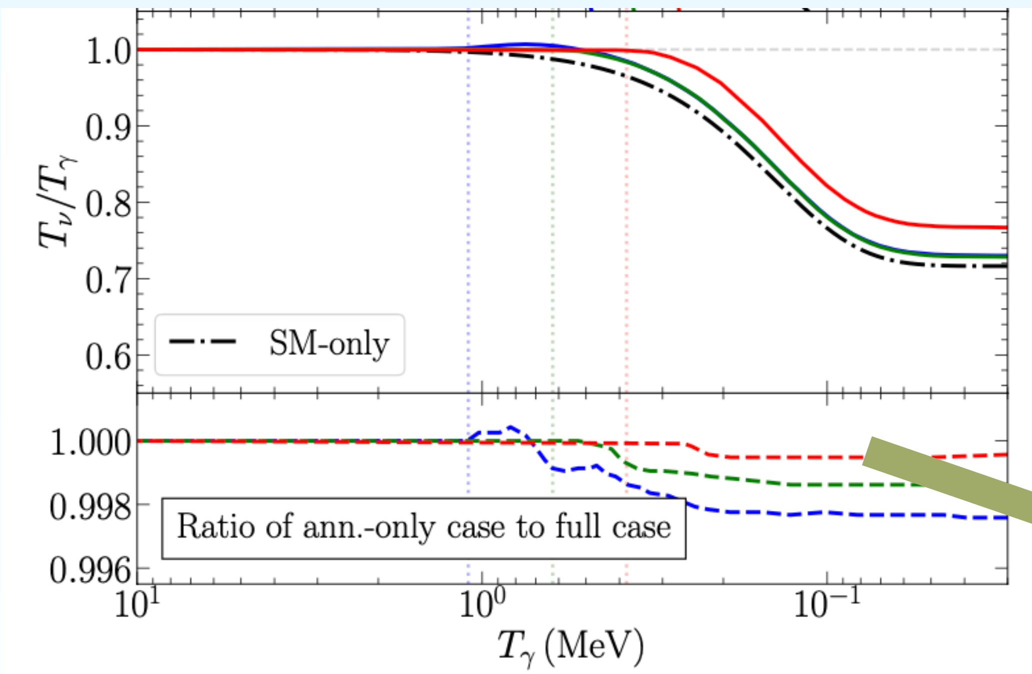


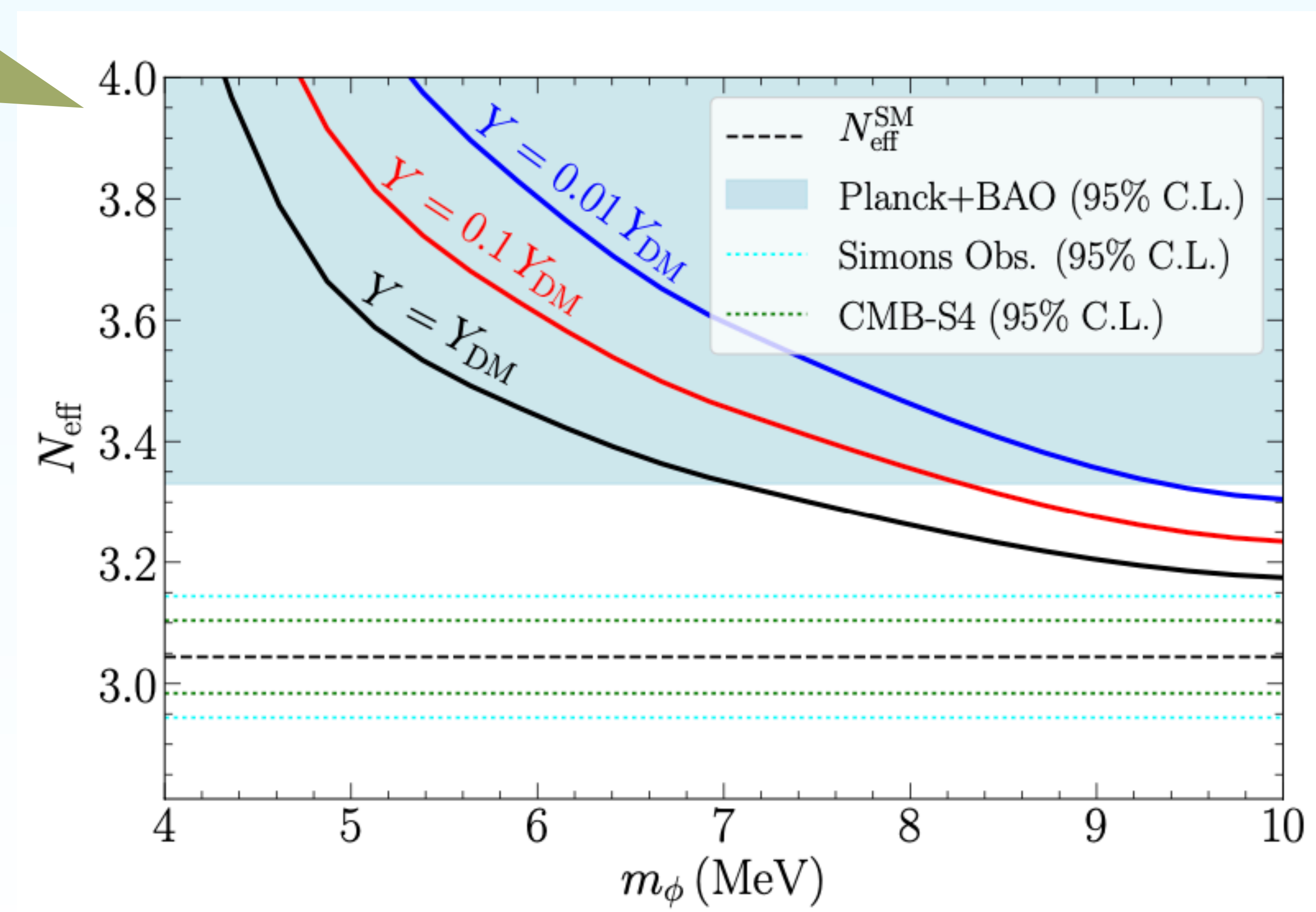
New bound: m_ϕ > 7 MeV (p-wave)

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

This should be due to

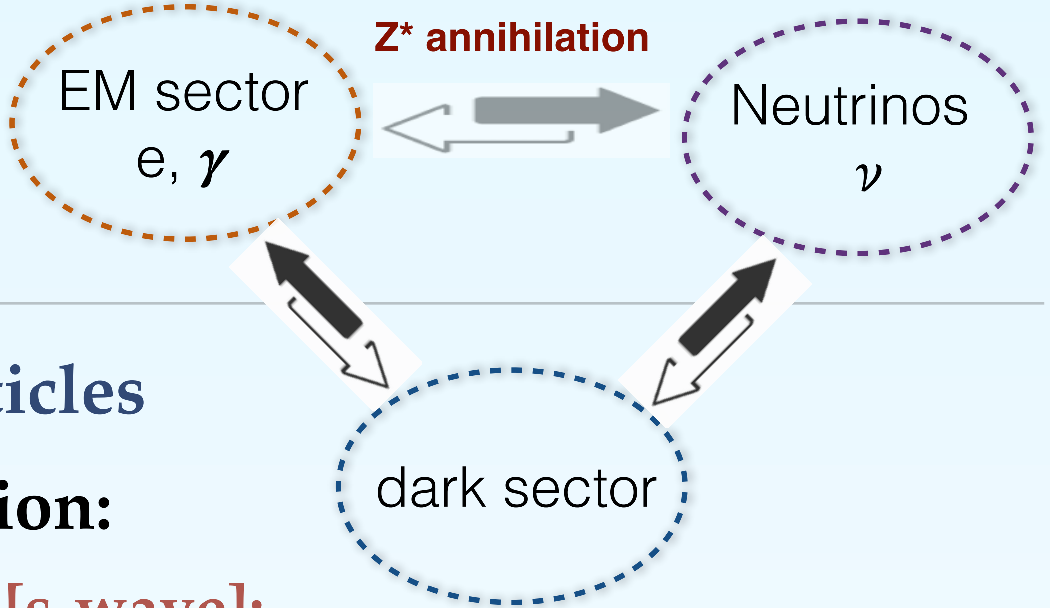
- **Stronger annihilation** for MeV DM;
- Cross section even larger at high DM velocities for **p-wave** freeze-out.

Scattering hardly affects EM/ν sectors in the case of contact interactions.



IV. Further applications

Beyond DM



- **Can be generalized to decaying MeV particles**

  due to **constraints on MeV DM annihilation:**

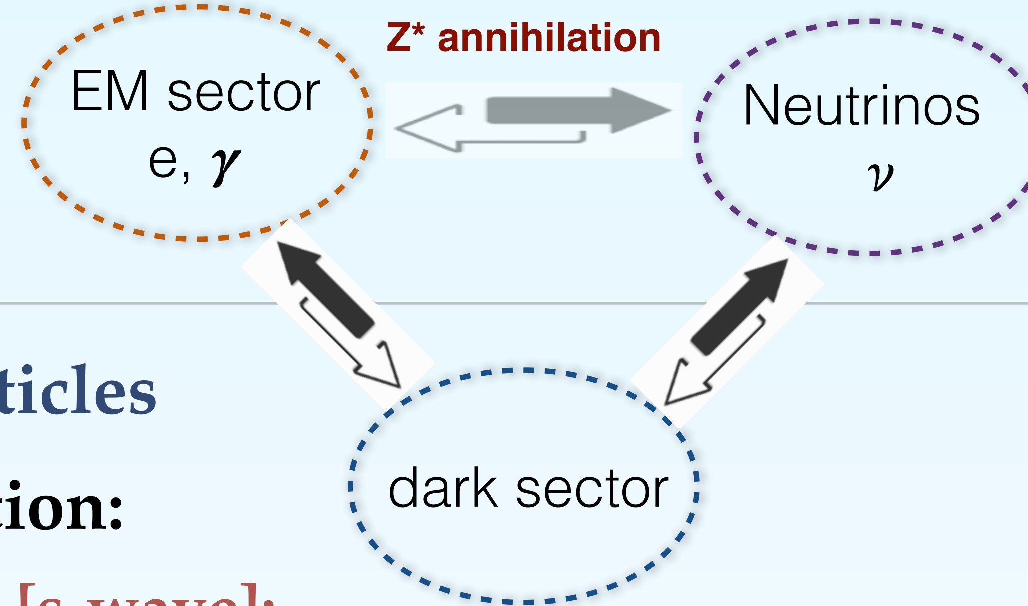
  - **10^{-3} - 10^{-4} pico-barn for e/γ-line case [s-wave];**

    CMB/X-ray experiments/…, e.g. Liu&Slatyer 1803.09739, Cirelli et al, 2303.08857

  - **10-100 pico-barn for ν-only case [s-wave];**

    Super-K/…, e.g. Argüelles et al. 1912.09486

Beyond DM and CMB



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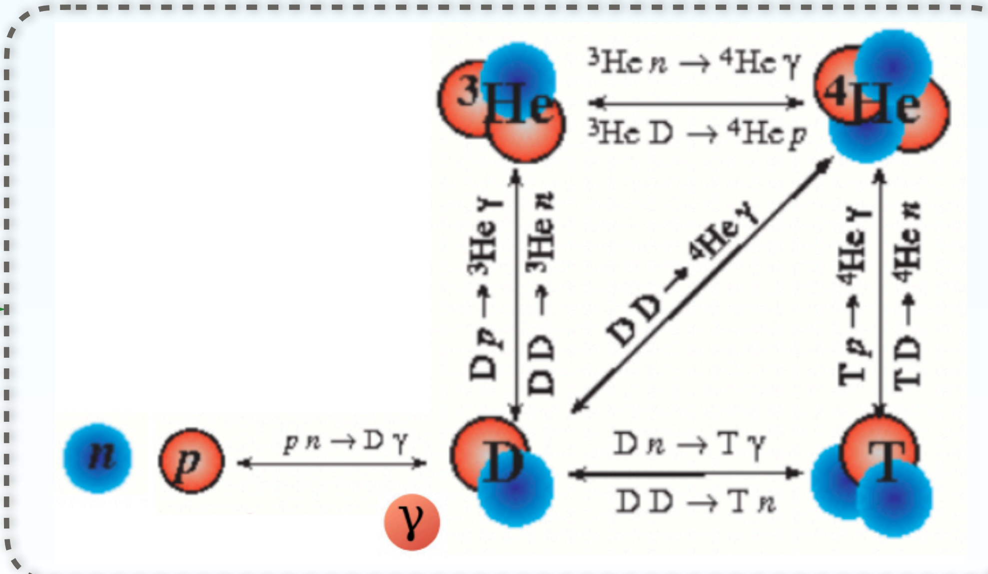
  - **10-100 pico-barn** for ν-only case [s-wave];

    Super-K/…, e.g. Argüelles et al. 1912.09486

- Impose bounds from **BBN observables**

MeV dark particles could **maintain the coupling of EM and ν**, even for branching ratio to EM/ν of **10^{-5}**.

With the exact energy evolution

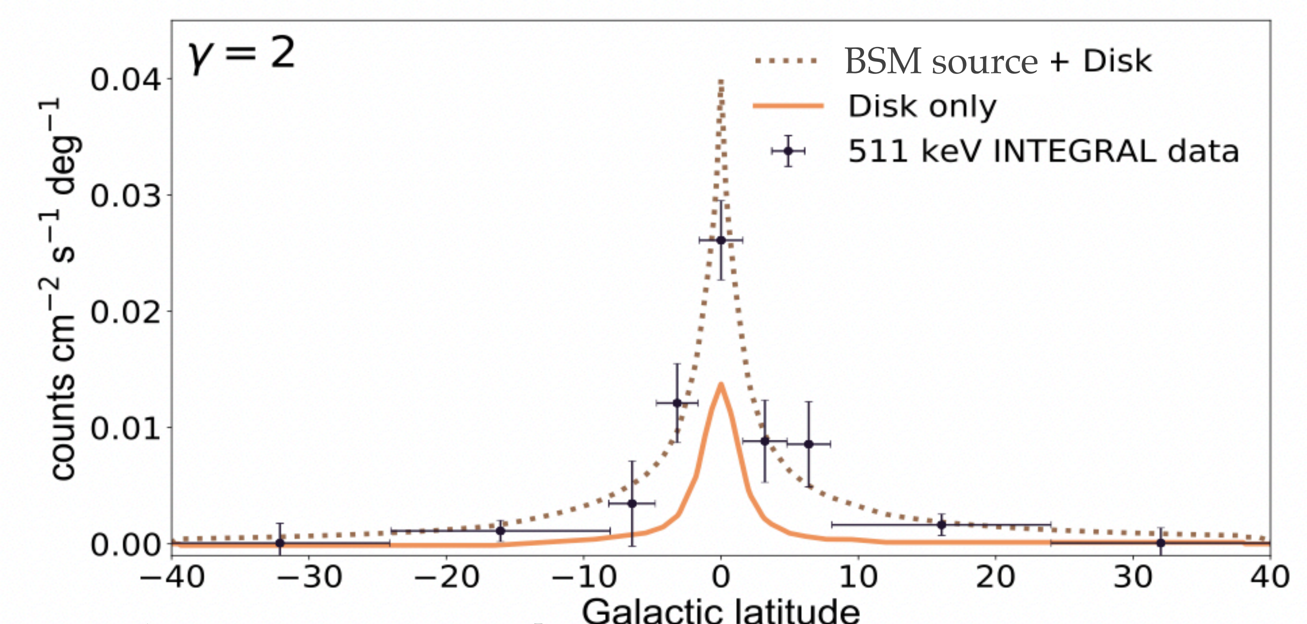


To be precise, EM cascade may be needed

[e.g. Poulin& Serpico 1503.04852, Hufnagel, Schmidt-Hoberg & Wild,1808.09324].

Anomalies related to MeV dark matter?

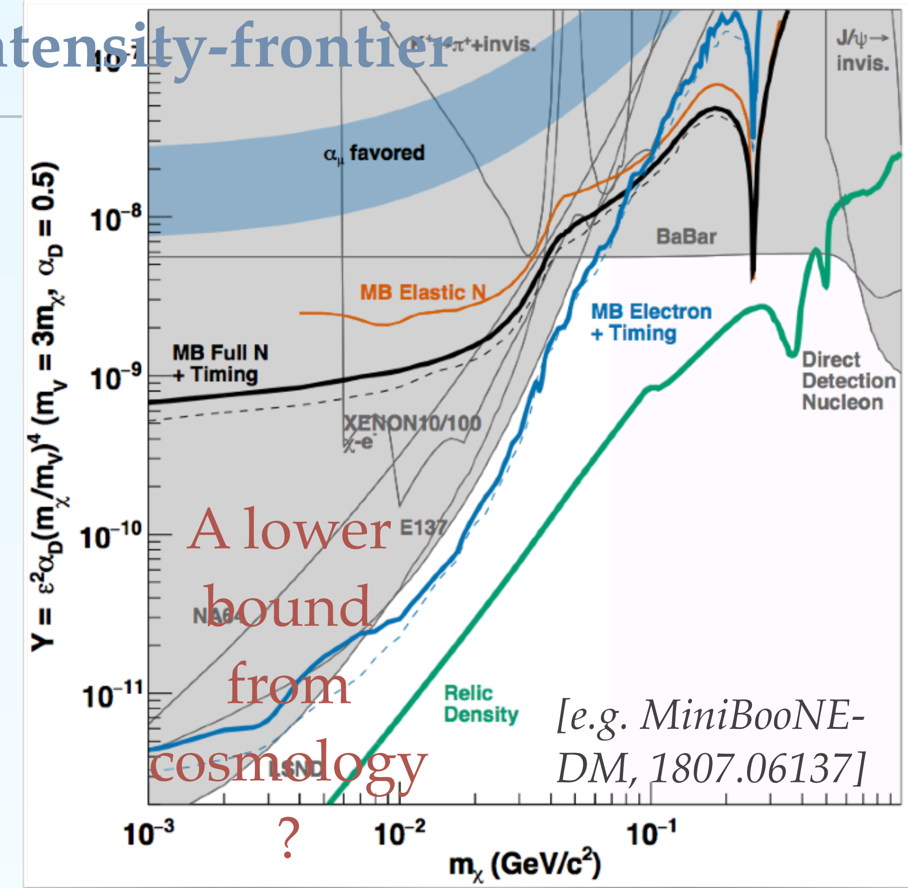
Galactic 511 keV-line excess



[e.g. Keith&Hooper 2103.08611]

DM annihilation produces low-energy positrons?

Intensity-frontier



A lower bound from cosmology ?

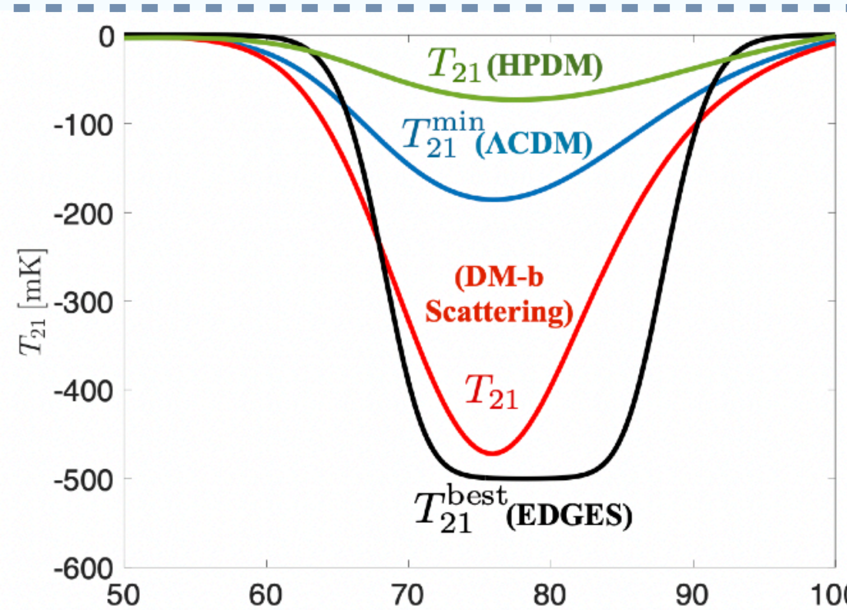
[e.g. MiniBooNE-DM, 1807.06137]

EDGES explanation

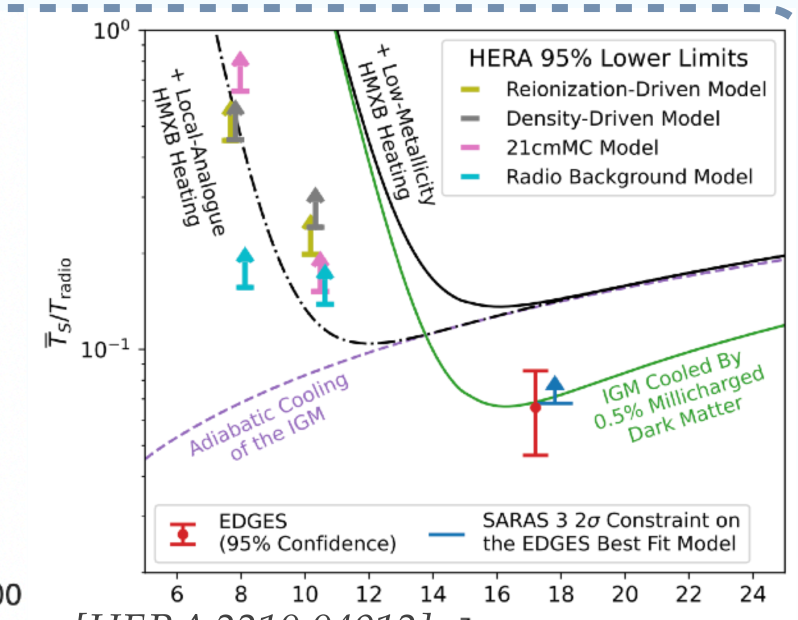
Baryon scatters with sub-leading MeV DM?

Probably less serious now

[SARAS, 2112.06778]



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



[HERA 2210.04912]

etc.

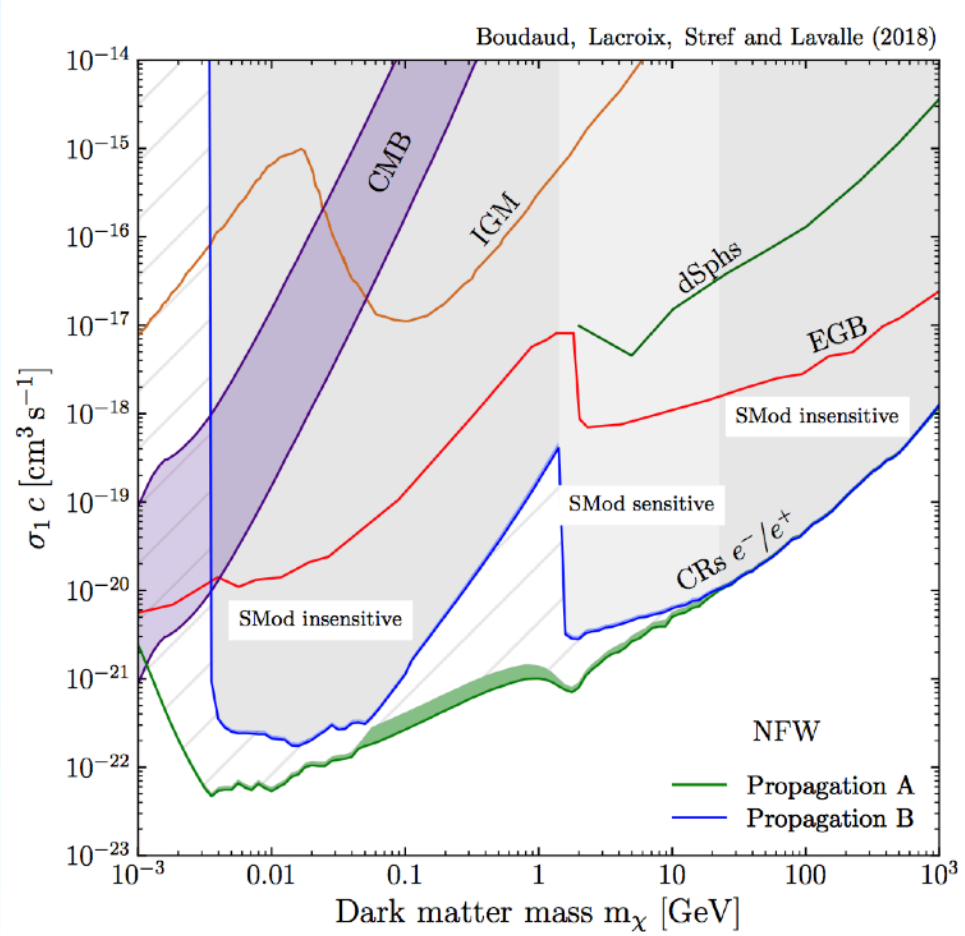
Conclusions

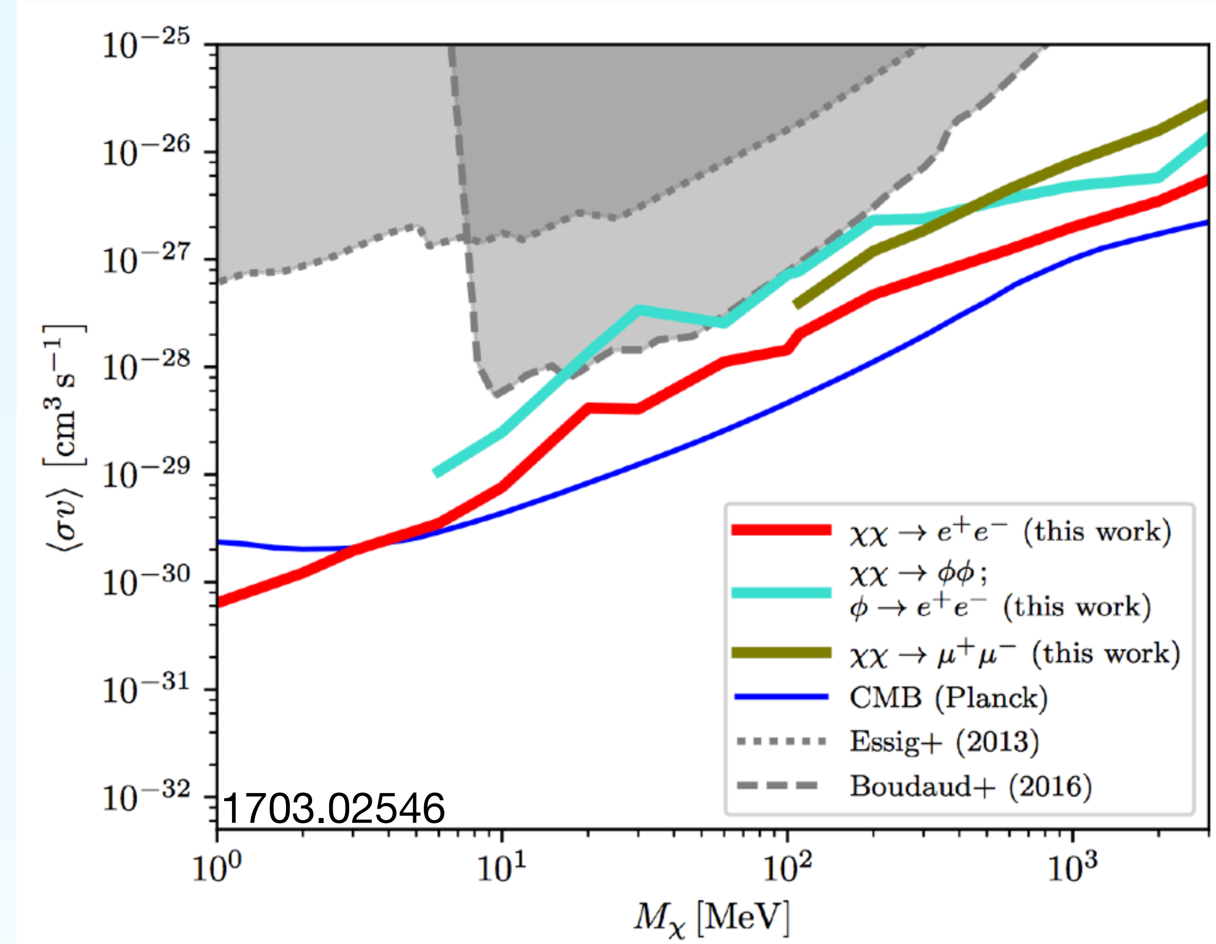
- With better BBN/CMB measurements, we should improve the precision of **theoretical calculations in MeV physics** too.
- A numerical treatment of **MeV DM freeze-out (into both EM/neutrino)** can be very **precise,** without solving the exact momentum distribution functions.
- We can now obtain the **full history** of MeV DM decoupling, and are applying it to various **DM spins, branching ratios:**
  - Decaying dark particles,
  - BBN constraints,…

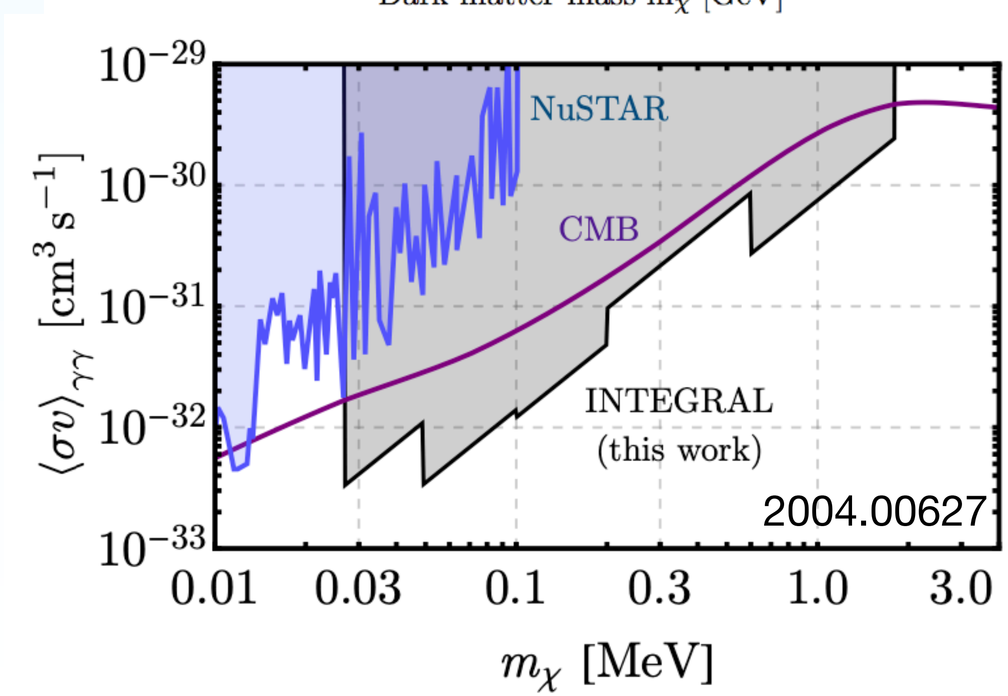
Thanks!

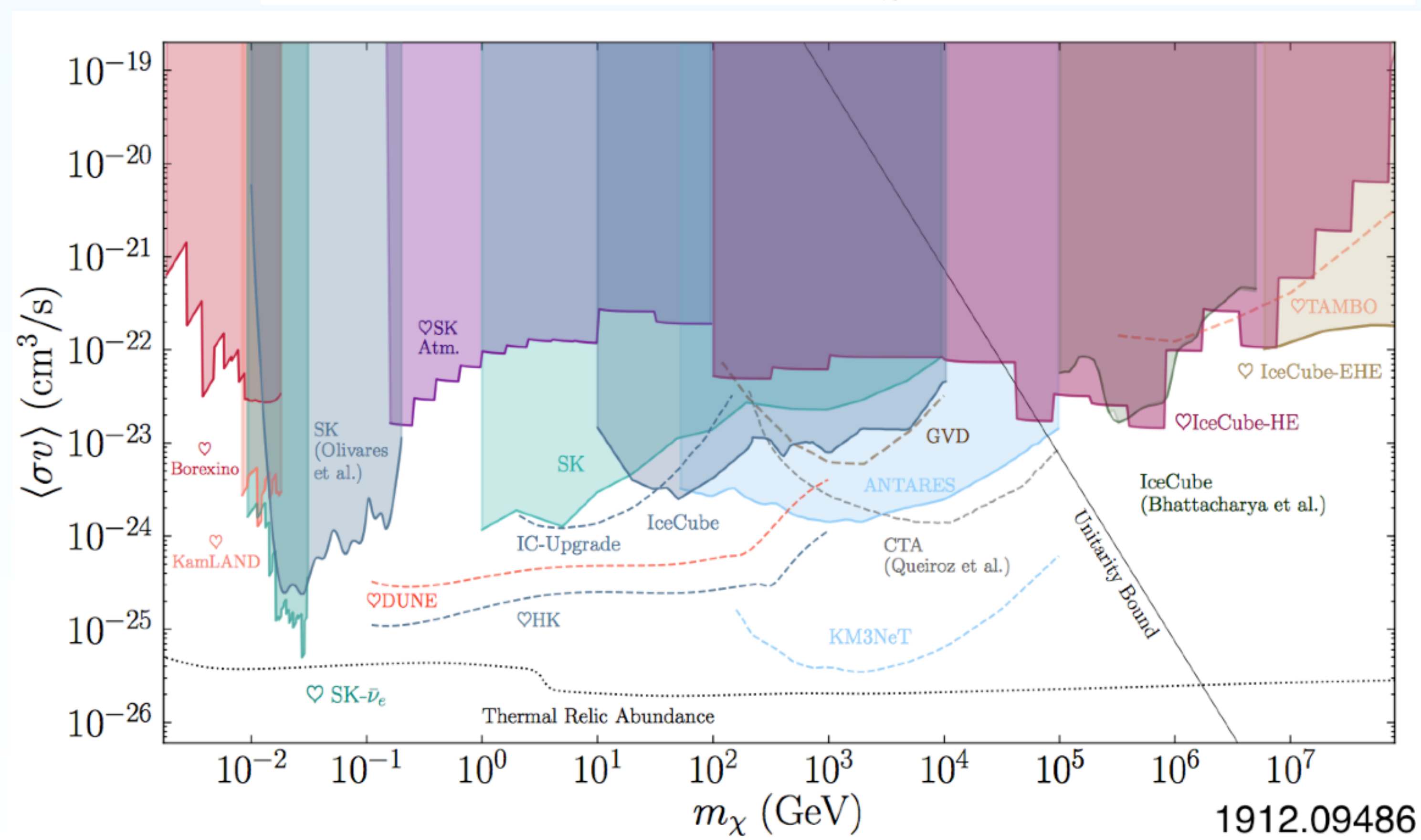
Non-Neff Bounds on DM freeze-out

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





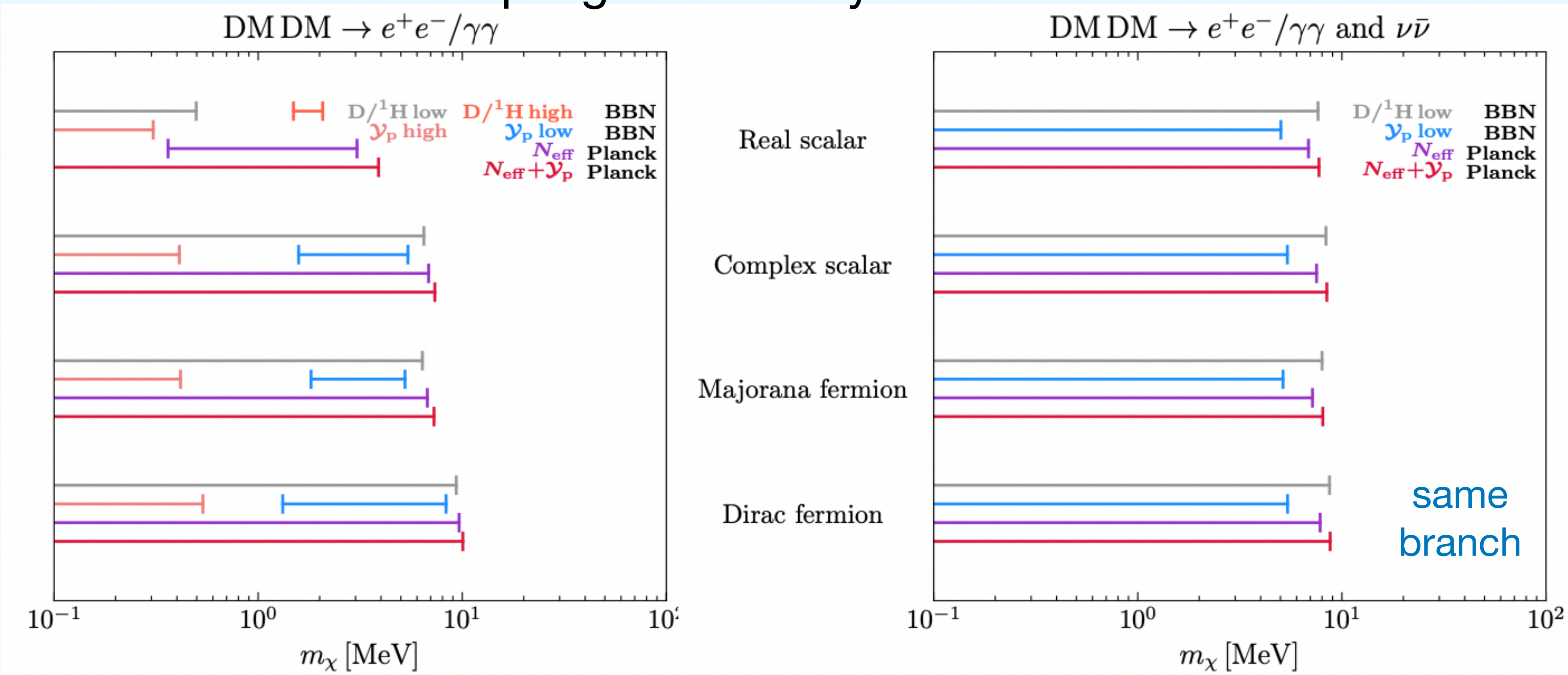




Previous CMB/BBN on s-wave DM

[Depta, Hufnagel, Schmidt-Hoberg & Wild 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】