Workshop on Multi-front Exotic phenomena in Particle and Astrophysics (MEPA 2025)

MeV dark bridge

between electromagnetic and neutrino sectors

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with Josef Pradler *[Phys.Rev.D 109 (2024)]*

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I. Motivations

Two leading **early-Universe observable processes:**

1. **Big Bang Nucleosynthesis** (BBN)

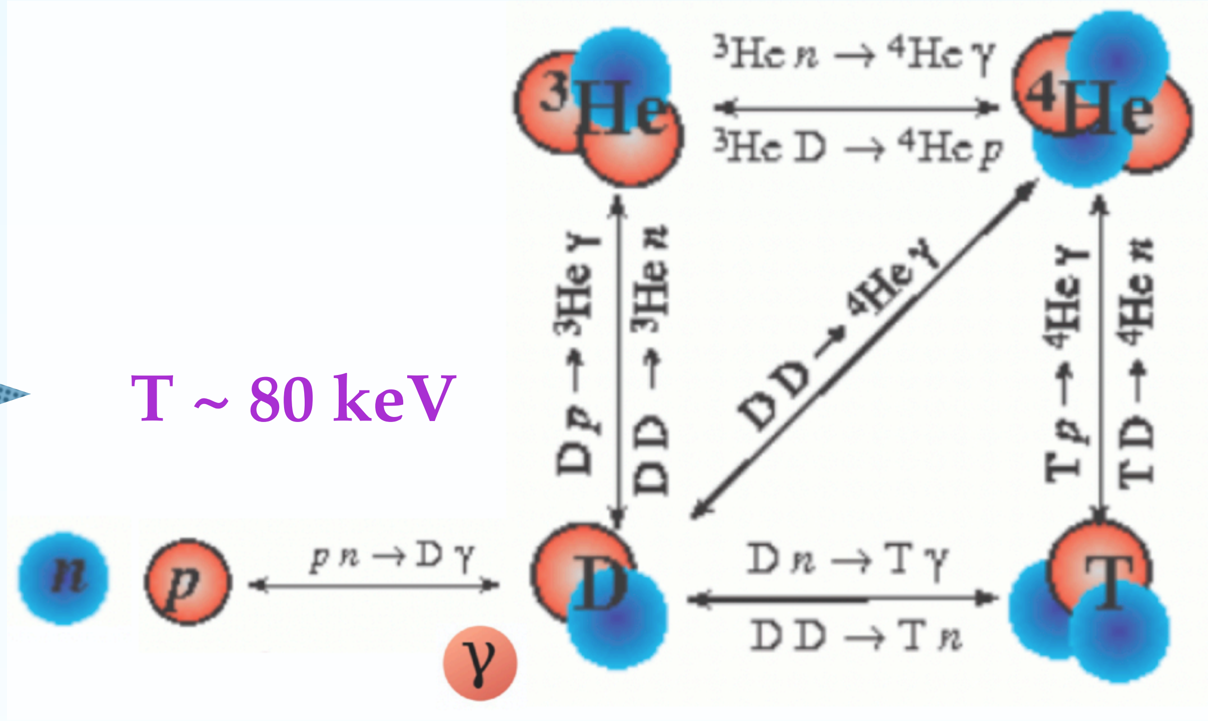
with T_γ from $1\,\mathrm{MeV}$ to keV

$$T_\gamma = T_\nu \text{ at } T_\gamma \sim 3\,\mathrm{MeV}$$

$$n + \nu_e \rightleftharpoons p + e^-, \; n + e^+ \rightleftharpoons p + \bar{\nu}_e$$

gradually decouple.

T ~ 80 keV



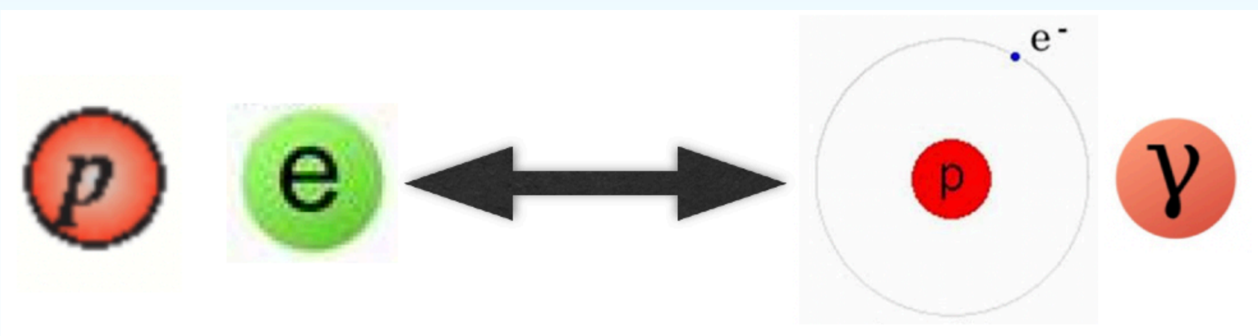
$$Y_p = 0.247 \pm 0.0020$$

$$\mathrm{D/H} = (2.527 \pm 0.030) \times 10^{-5}$$

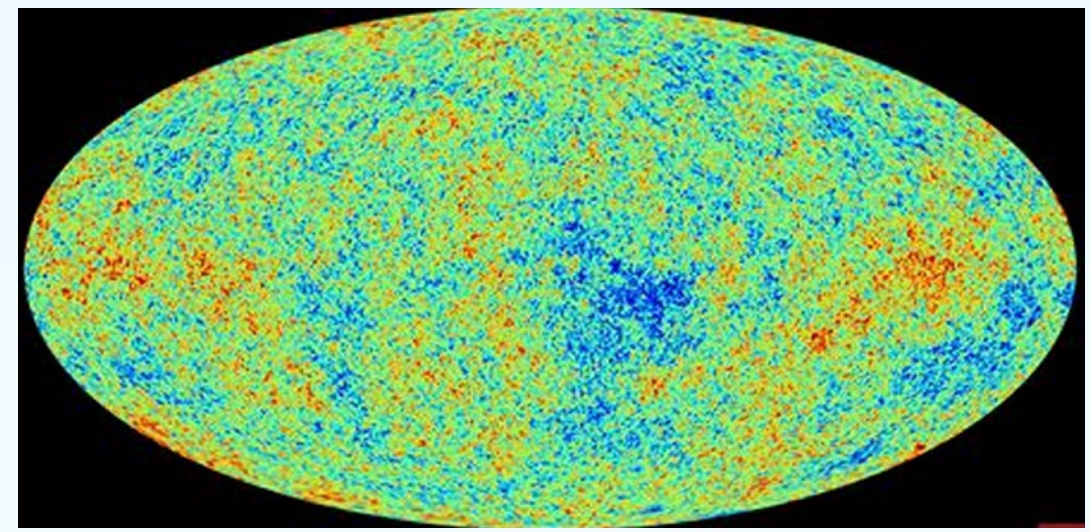
Two leading **early-Universe observable processes:**

2. Cosmic Microwave Background (CMB)

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



decouples.



Universe becomes neutral, so photons start to travel freely.

$$N_{\rm eff}^{\nu} \hat{=} 3 \left(\frac{T_\nu / T_\gamma}{(4/11)^{1/3}} \right)^4 \sim 3 \left(\frac{T_\nu / T_\gamma}{0.7162} \right)^4$$

$2.66 \leq N_{\rm eff} \leq 3.33$ (Planck 2018)

$$T_\gamma \simeq T_\nu / 0.7162 \text{ at } T_\gamma \sim 0.3\,\mathrm{eV}$$

1. **Big Bang Nucleosynthesis** (BBN) $T_\gamma = T_\nu$ at $T_\gamma \sim 3\,\mathrm{MeV}$

2. Cosmic Microwave Background (CMB) $T_\gamma \simeq T_\nu/0.7162$ at $T_\gamma \sim 0.3\,\mathrm{eV}$

SM contribution to this ratio is very simple: $N_{\mathrm{eff}}^{\mathrm{SM}} = 3.043 - 3.045$

i.e. **clear background observation**!

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

$$\sigma v_{\bar{e}e\to\bar{\nu}\nu} \sim \alpha^2 \frac{\mathrm{MeV}^2}{m_Z^4} \sim 10^{-46}\mathrm{cm}^2.$$

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MeV dark state annihilation: $\sigma v_{\phi\phi^*} \geq 10^{-35}\mathrm{cm}^2$

MeV dark state scattering: $\sigma_{\rm MeV\ DM-e} \leq 10^{-40}\mathrm{cm}^2$

$\sigma_{\rm MeV\ DM-\nu} \leq 10^{-31}\mathrm{cm}^2$

MeV particle decay: $\Gamma_{\phi\to\rm SM+SM} \sim \sec^{-1}$

up to Boltzmann suppression **exp[-m/T]**

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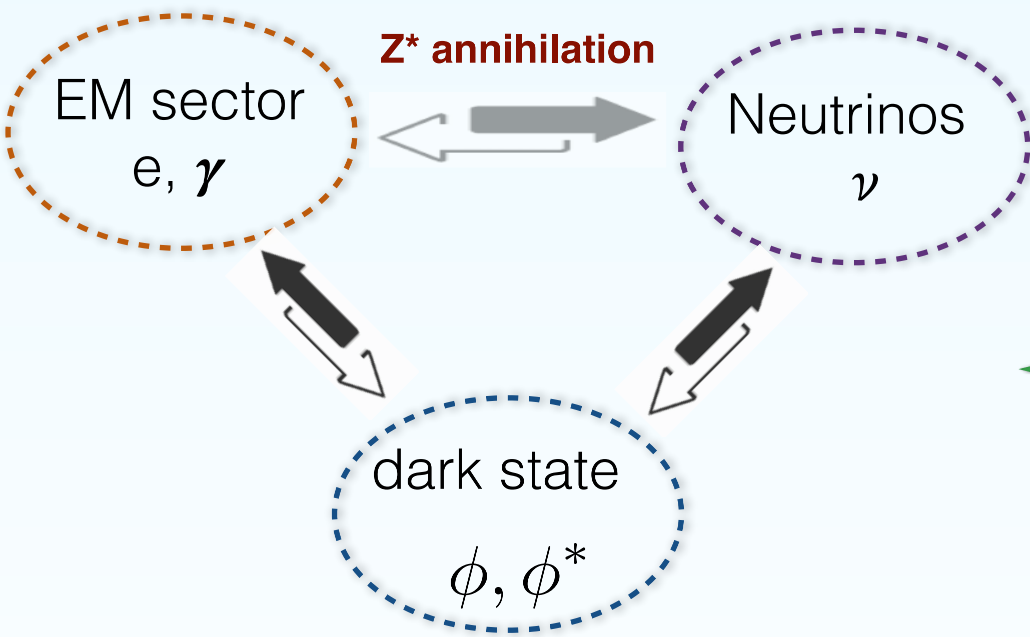


if MeV dark state connect EM & ν

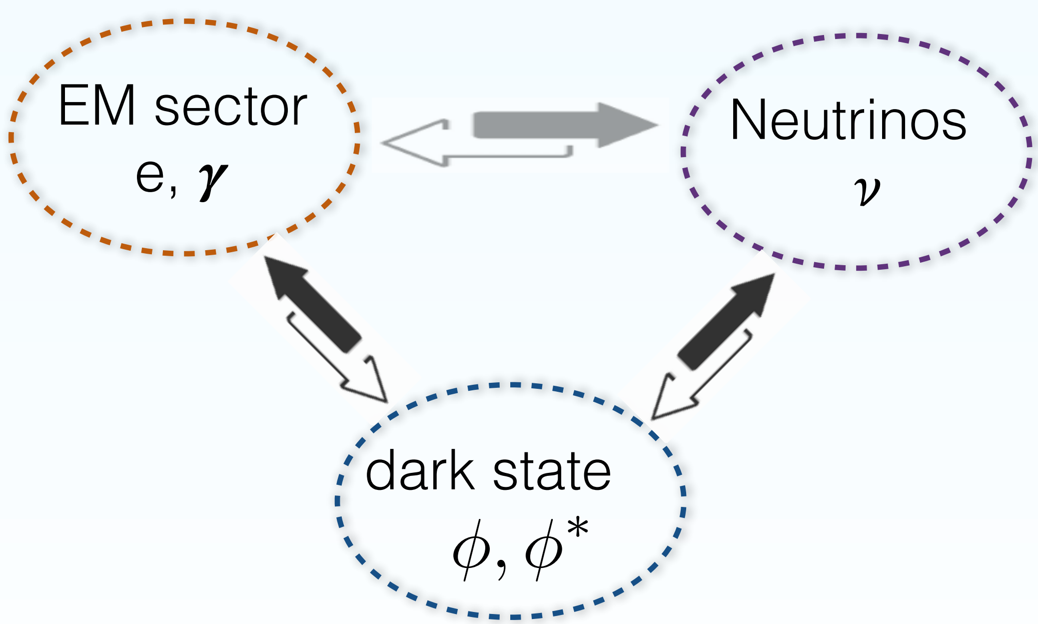
as a bridge

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

As an **extension of the two decoupled sector cases** [e.g. *Escudero 2001.04466, Giovanetti, Lisanti, Liu &Ruderman 2109.03246*]

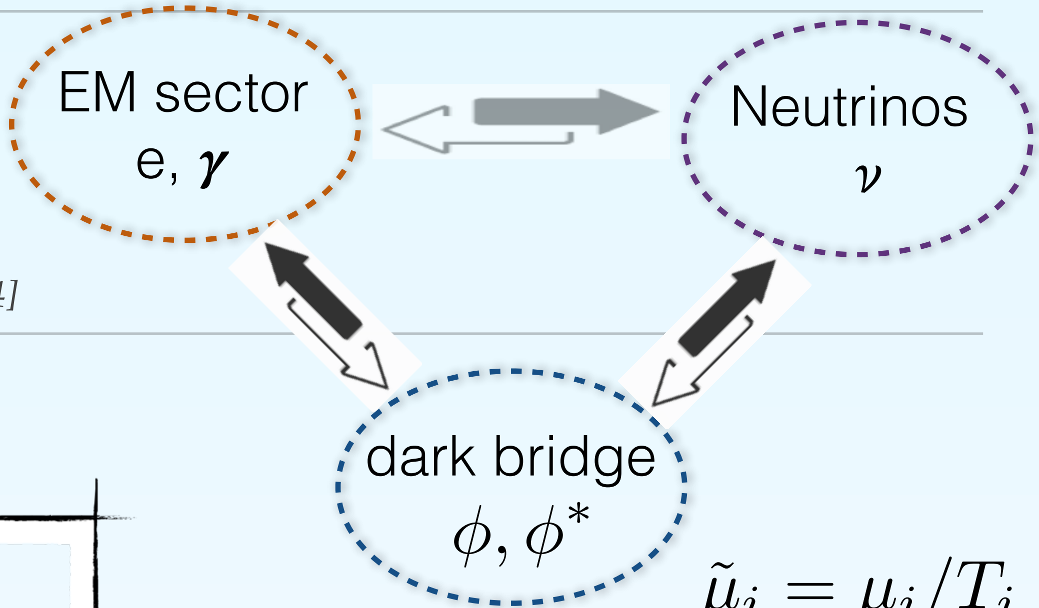
Strong bounds can be obtained on **MeV dark bridge** with **future BBN/CMB measurements!**

II. To describe a three-sector system



To reach **a (nearly) full description of three sectors:**

[naive treatments: M.Escudero 1812.05605, Depta, Hufnagel, Schmidt-Hoberg & Wild 1901.06944]



$\tilde{\mu}_i = \mu_i / T_i$

Self-kinetic equilibrium assumption:

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

A) the **EM sector**

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

B) the **neutrino sector**

C) the MeV **dark bridge**

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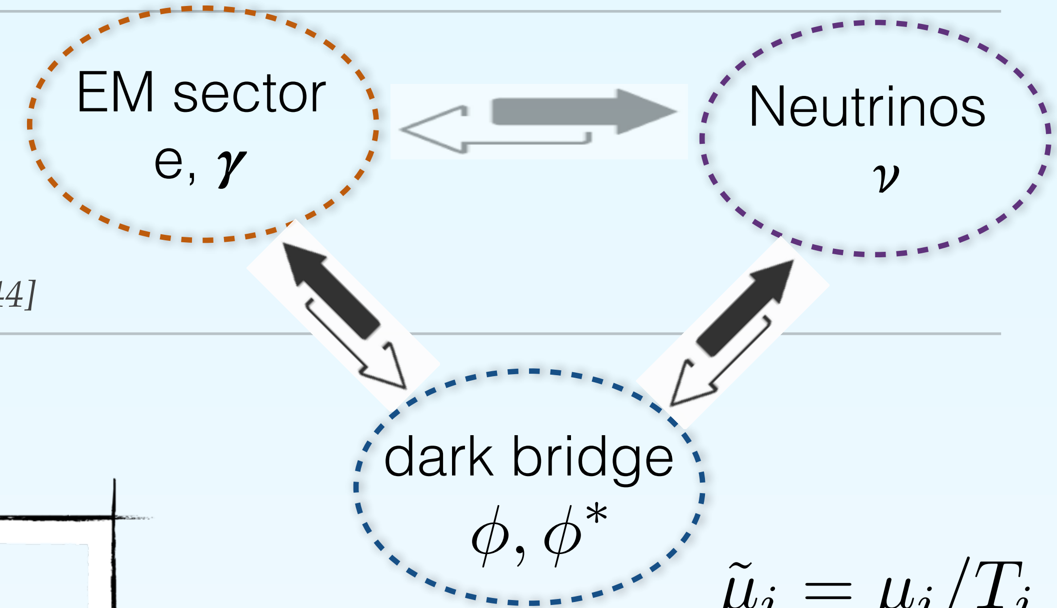


Self-kinetic equilibrium assumption:

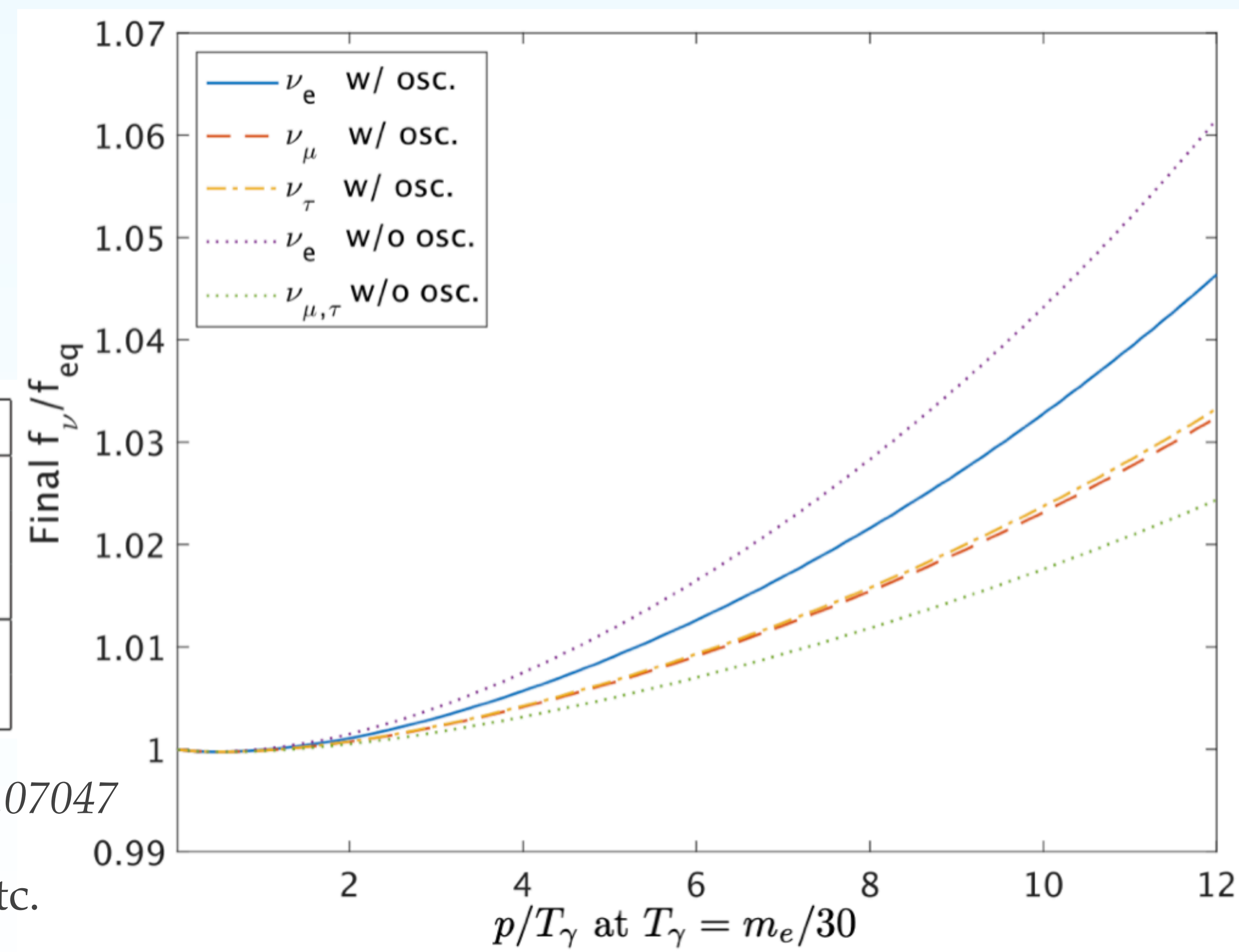
$$f_i(E_i, \mu_i) = \frac{1}{e^{(E_i - \mu_i)/T_i} \mp 1} \equiv \frac{1}{e^{\tilde{E}_i - \tilde{\mu}_i} \mp 1}$$

$$\tilde{\mu}_i = \mu_i / T_i$$

B) the **neutrino sector**

Tiny non-equilibrium, even with only weak interactions.

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



Akita & Yamaguchi 2005.07047

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

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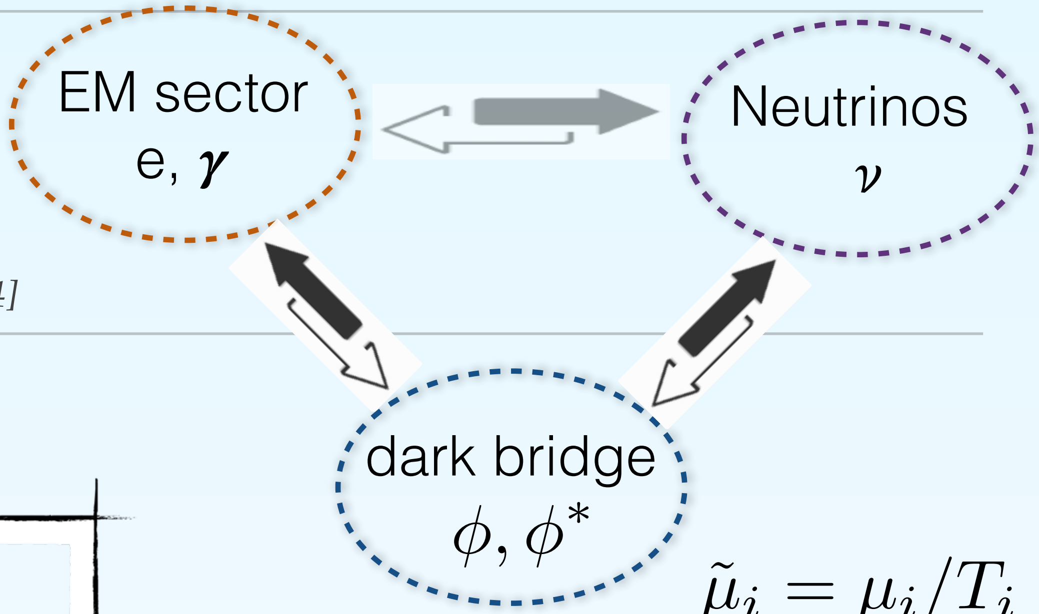


$\tilde{\mu}_i = \mu_i/T_i$

Self-kinetic equilibrium assumption:

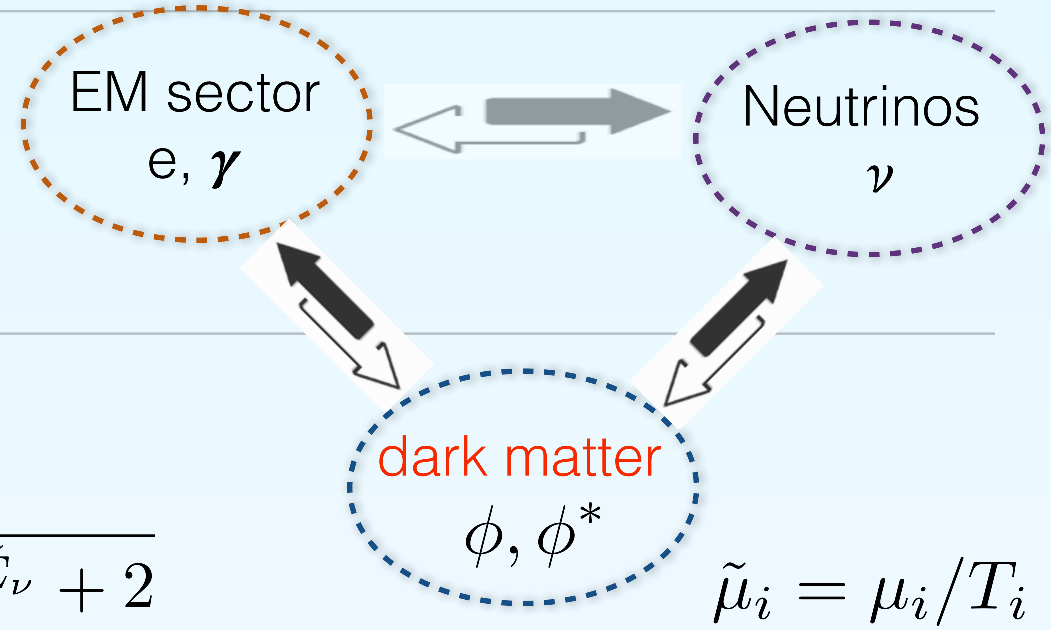
$$f_i(E_i, \mu_i) = \frac{1}{e^{(E_i-\mu_i)/T_i} \mp 1} \equiv \frac{1}{e^{\tilde{E}_i-\tilde{\mu}_i} \mp 1}$$

C) the MeV **dark bridge**

- Before decoupled, scattering with EM/ν makes it **thermally coupled**;
- After, it becomes **non-relativistic** quickly, so at most mild effect after decoupling
  [exceptions are non-trivial velocity-dependence in annihilation, e.g. Binder, Bringmann, Gustafsson &Hryczuk, 2103.01944].
- Even easier with **DM self-interaction (SIDM)**.

Take the case of thermal DM

Tabulation of Rates:



$$\tilde{\mu}_i = \mu_i / T_i$$

1. For the relativistic particles, **neutrino**:

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

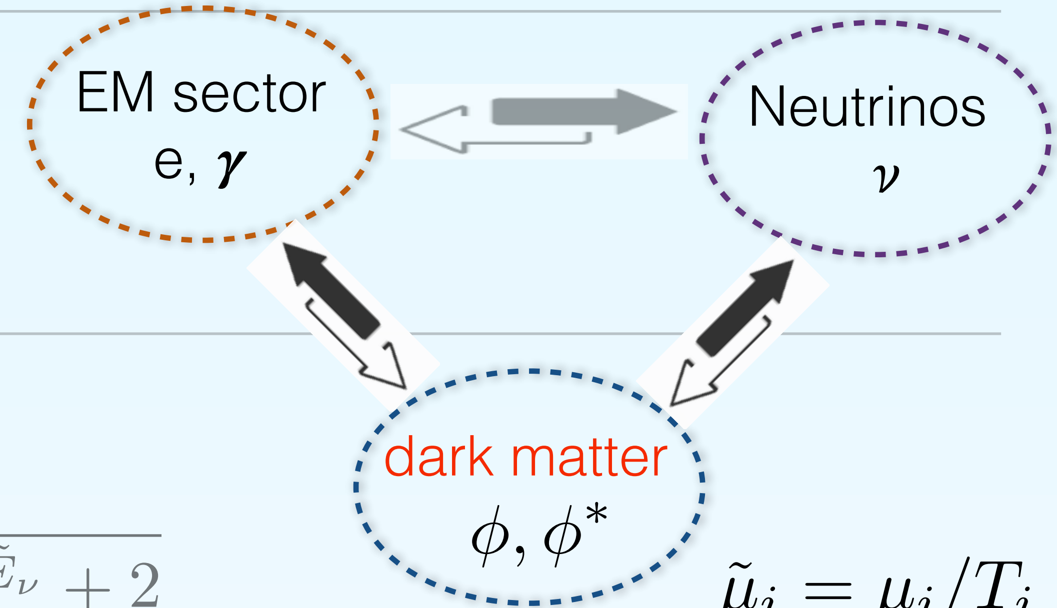
2. For non-relativistic particles, **DM:**

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

3. **EM** sector has negligible chemical potential.

Take the case of thermal DM

Tabulation of Rates:



$\tilde{\mu}_i = \mu_i / T_i$

$$f_\nu(\tilde{E}_\nu, \tilde{\mu}_\nu) \simeq \frac{1}{e^{\tilde{E}_\nu} + 1} + \tilde{\mu}_\nu \frac{1}{e^{\tilde{E}_\nu} + e^{-\tilde{E}_\nu} + 2}$$
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$$f_\phi(\tilde{E}_\phi, \tilde{\mu}_\phi) \simeq \begin{cases} \frac{1}{e^{\tilde{E}_\phi} \mp 1} & \text{before freeze-out} \\ \frac{e^{\tilde{\mu}_\phi}}{e^{\tilde{E}_\phi}} & \text{after freeze-out} \end{cases}$$
$$\to e^{\tilde{\mu}_\phi} f_\phi^{(0)}(\tilde{E}_\phi)$$

Rates between two sectors (a and b) as functions of (T_a, T_b):

Leading **number-changing**: $\gamma \propto \int dE_1 dE_2 ds dt\, f_1^{0,1} f_2^{0,1} \frac{d\sigma_{12\to34}(s)}{dt} v_M$

Leading **energy-transferring**: $\zeta \propto \int dE_1 dE_2 ds dt\, f_1^{0,1} f_2^{0,1} \frac{d\sigma_{12\to34}(s)}{dt} v_M \delta E$

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

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

Self-kinetic equilibrium assumption:

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

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

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

Tabulation of the rates

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

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

Set of Boltzmann equations

III. Precision Freeze-out

To yield a **fixed** abundance $Y_{DM} \hat{=} \frac{n_{\rm DM}}{s_{\rm tot.}}$

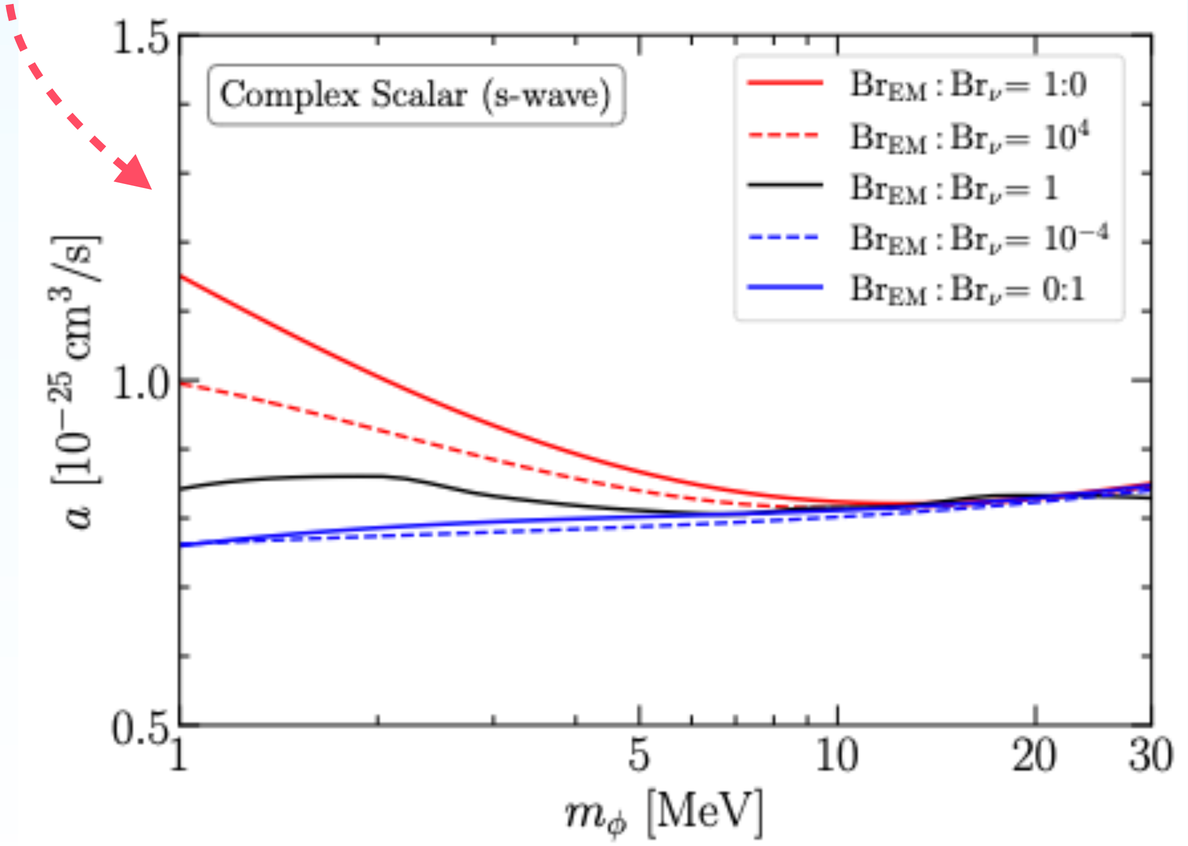
For complex scalar DM $\sigma_{\rm ann} v_M = a + b v_{\rm rel}^2$

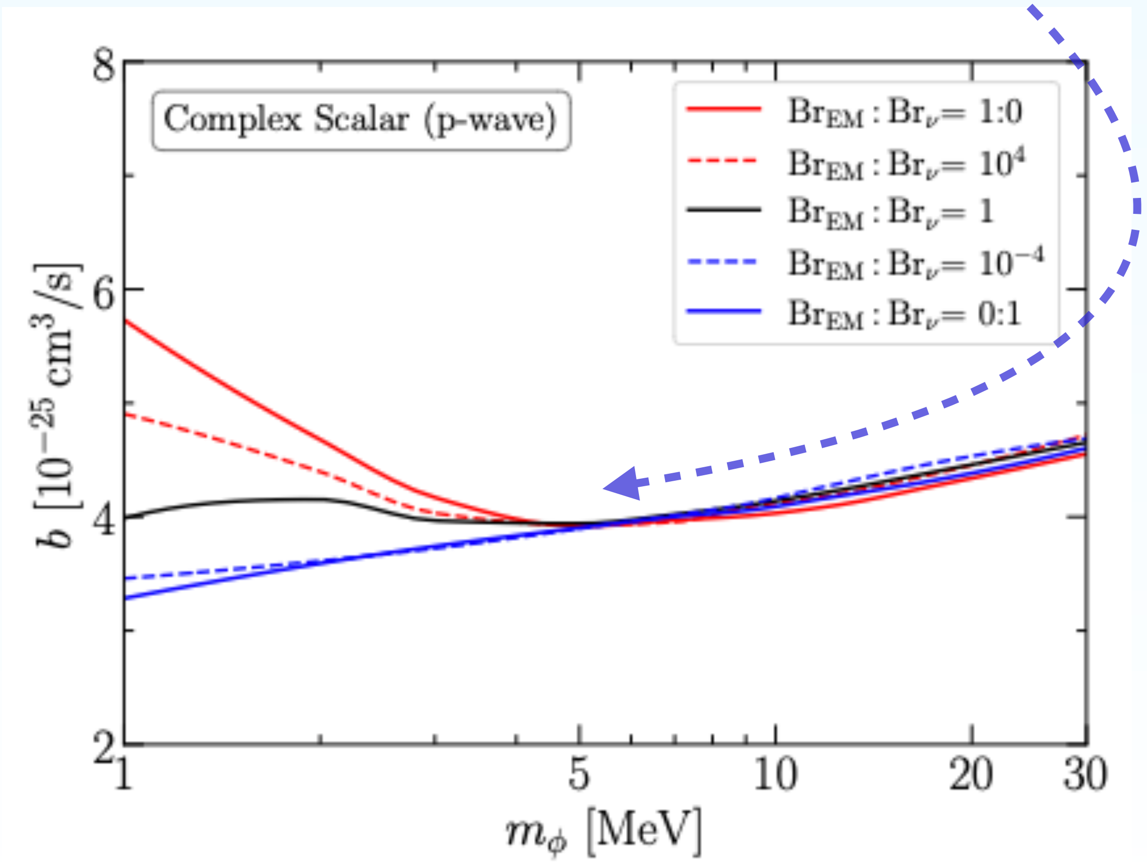
s-wave case

$$-i \sum y_l A(\bar{l}\gamma_5 l) - \mu_A A(\phi^* \phi)$$

p-wave case

$$- i g_\phi Z'^\mu (\phi^* \overleftrightarrow{\partial}_\mu \phi) - g_l Z'^\mu \bar{l} \gamma_\mu l$$





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For complex scalar DM $\quad \sigma_{\rm ann} v_M = a + b v_{\rm rel}^2$

s-wave case

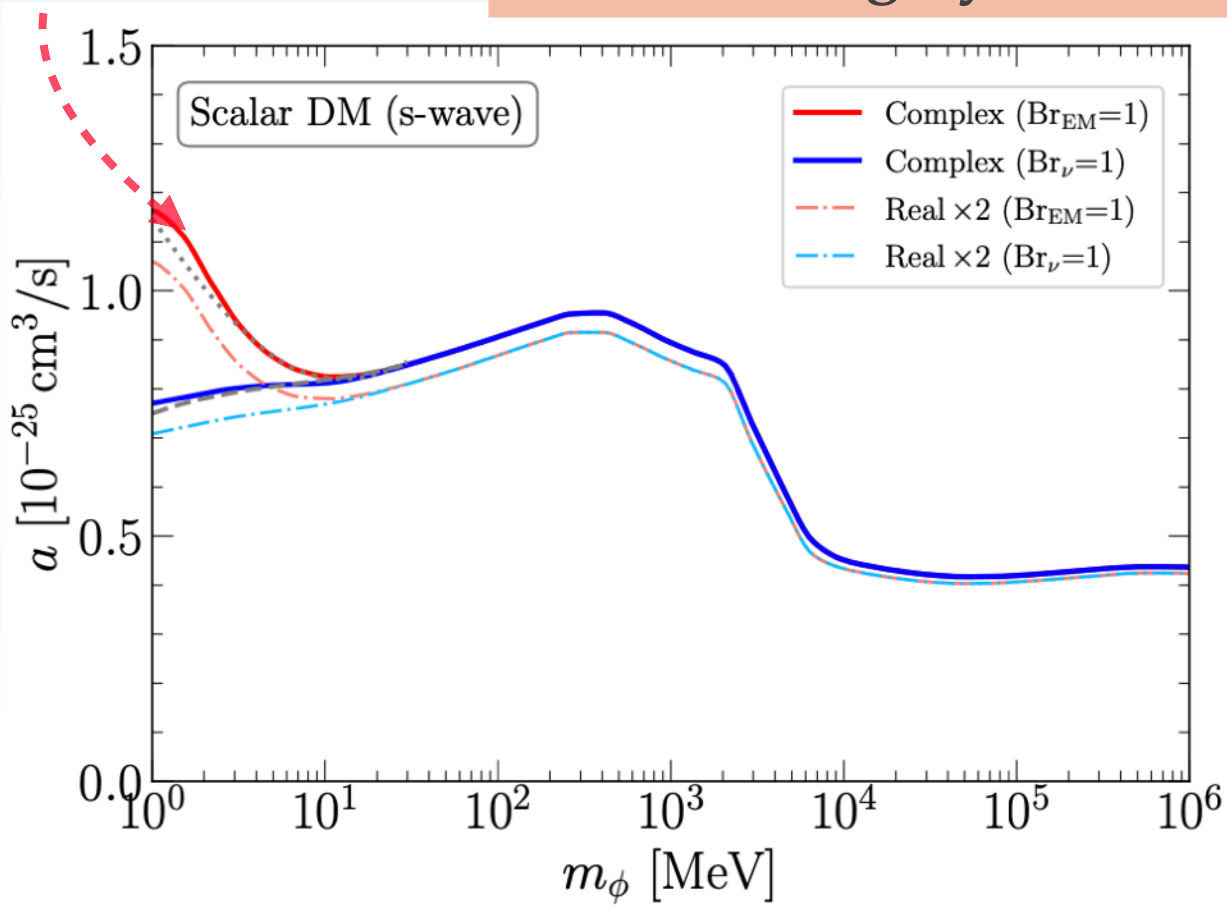
p-wave case

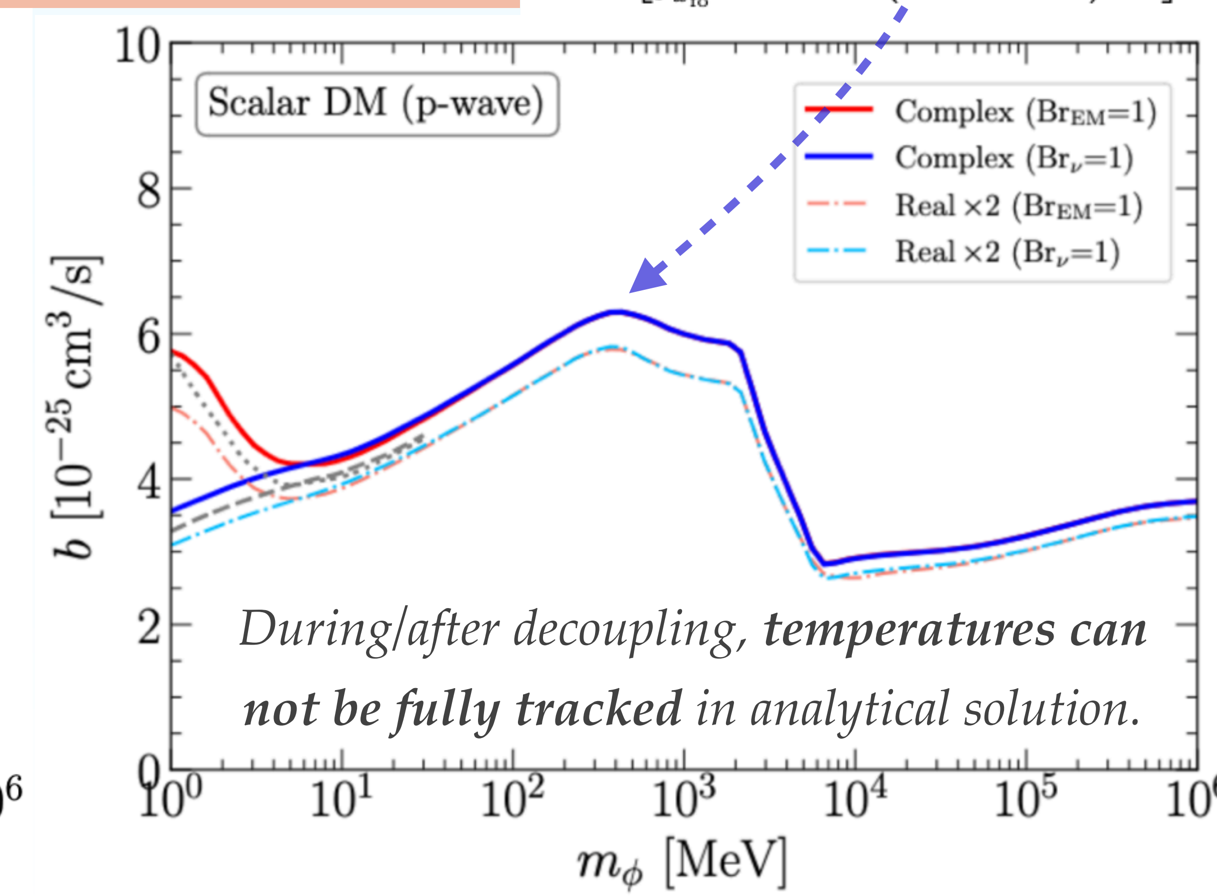
For $\mathrm{Br}_{\rm EM}\mathrm{Br}_{\nu} = 0$

compare with analytical solutions

(**numerical: gray lines**; *analytical: coloured*)

$$Y_\infty \simeq \left[\int_{x_{\rm fo}}^{\infty} \frac{\hat{s}\langle\sigma_{\rm ann} v\rangle}{Hx} \left(1 - \frac{1}{3}\frac{d\ln g_{\hat{s}}}{d\ln x}\right) dx \right]^{-1}$$

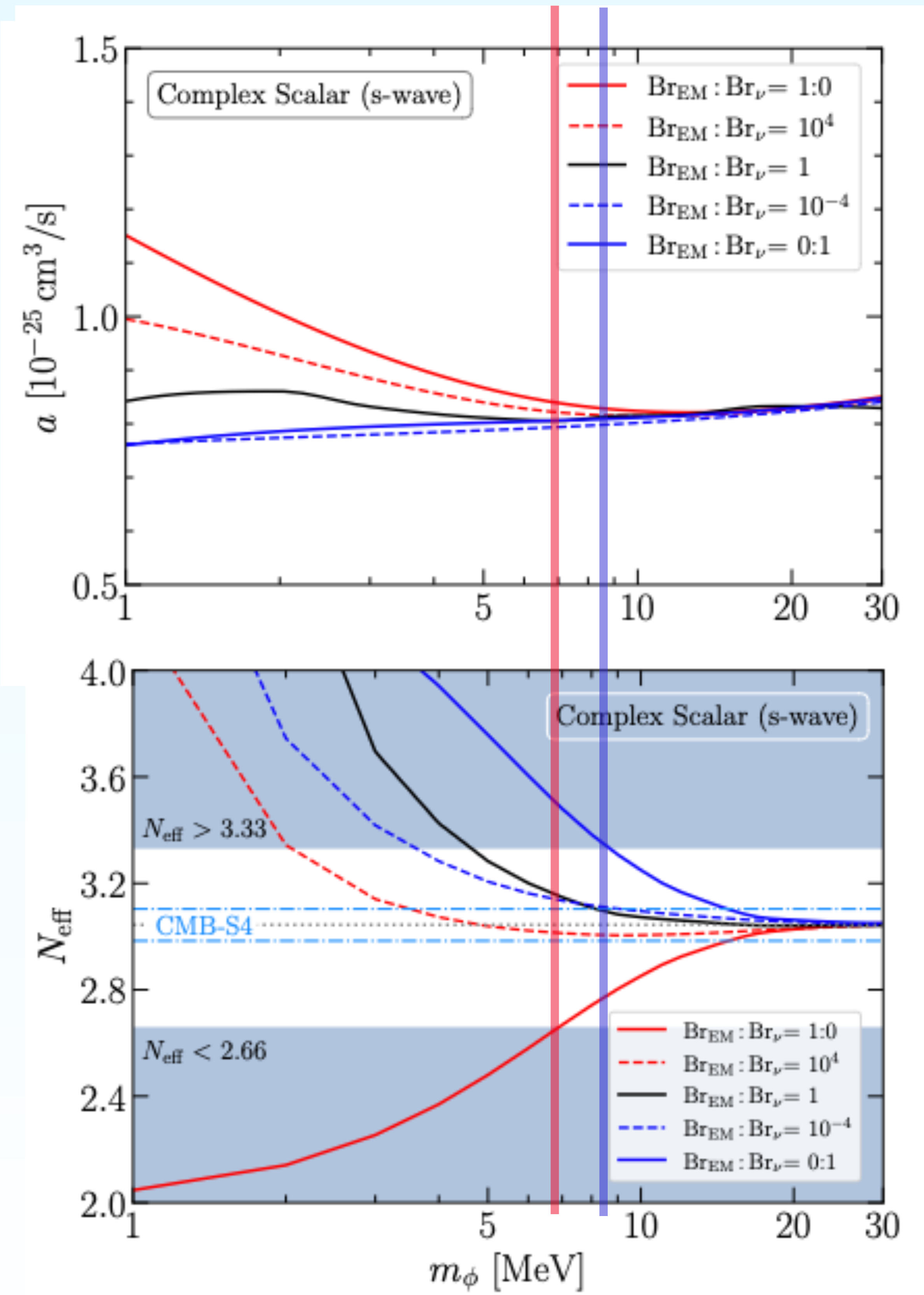




Bounds on DM mass from

$2.66 \leq N_{\rm eff} \leq 3.33$ (Planck 2018)

Complex scalar [**s-wave**]



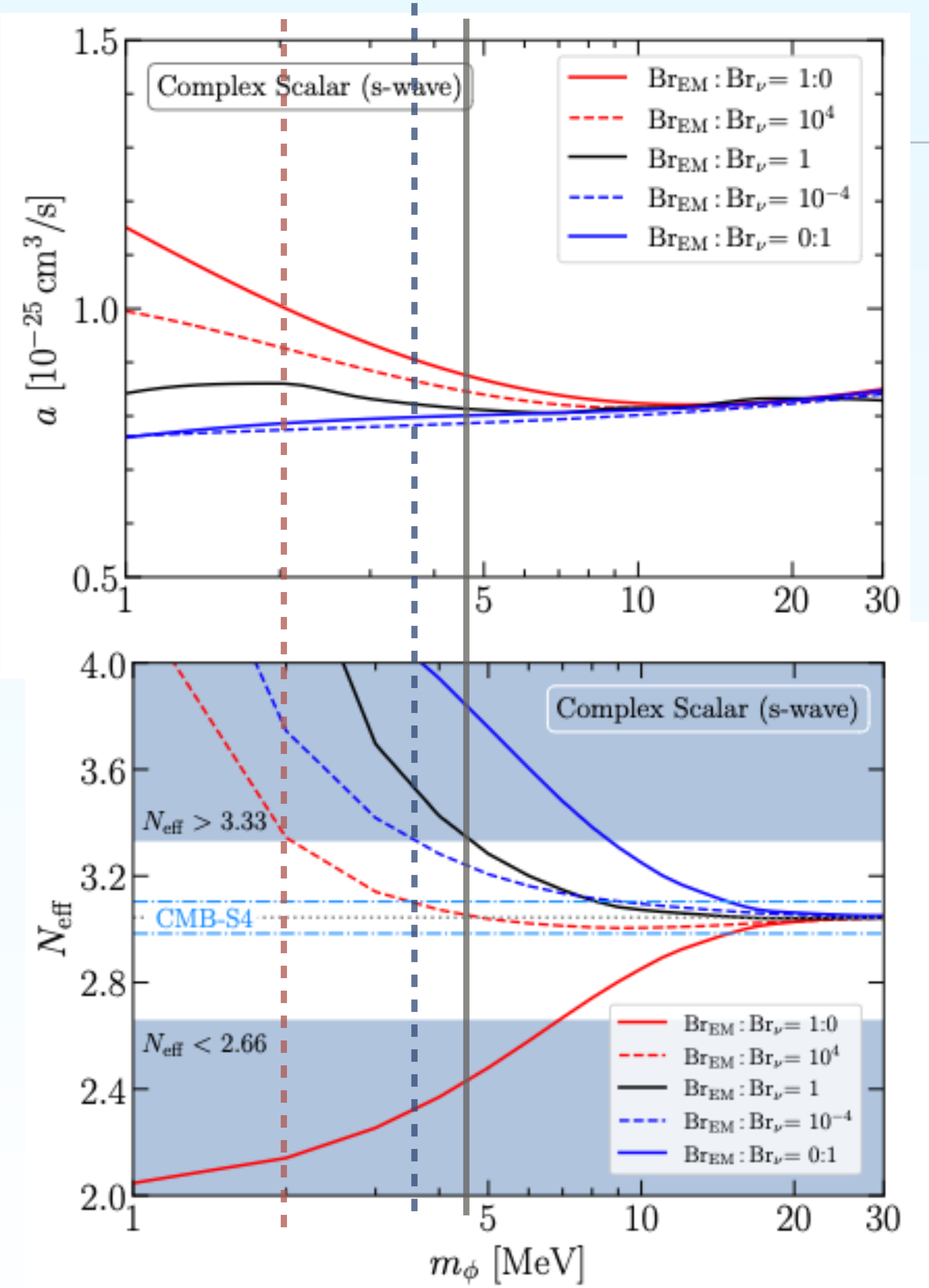
EM-only channel: $m_\phi \geq 6.9\,\mathrm{MeV}$

Neutrino-only channel: $m_\phi \geq 8.7\,\mathrm{MeV}$

For $\mathrm{Br_{EM}Br_\nu} = 0$

- Bounds are insensitive to s- or p-wave, or to exact annihilation cross sections, as evolution is the same until very late.

Complex scalar [**s-wave**]



Bounds on DM mass from

$2.66 \leq N_{\rm eff} \leq 3.33$ (Planck 2018)

$\mathrm{Br_{EM}} : \mathrm{Br}_\nu$	1:0	10^4	1	10^{-4}	0:1
Complex scalar (*s*-wave)	6.9	2.0	4.8	3.8	8.7
Complex scalar (*p*-wave)	6.9	2.9	5.2	3.9	8.7
Dirac fermion (*s*-wave)	9.5	2.5	5.0	4.1	11.2
Dirac fermion (*p*-wave)	9.5	3.0	5.7	4.3	11.2

For $\mathrm{Br_{EM}}\mathrm{Br}_\nu \neq 0$

- Lighter DM **maintains $T_\gamma = T_\nu$,** even after e+e- annihilation

  → **tend to increase $N_{\rm eff}$.**

- **heavy DM maintains $T_\gamma = T_\nu$ before e+e- annihilation, same as only SM.**

  → **weaker bounds from CMB!**

IV. **For entertaining**

Neff bound may disappear

For $\mathrm{Br}_{\mathrm{EM}}\mathrm{Br}_{\nu} \neq 0$

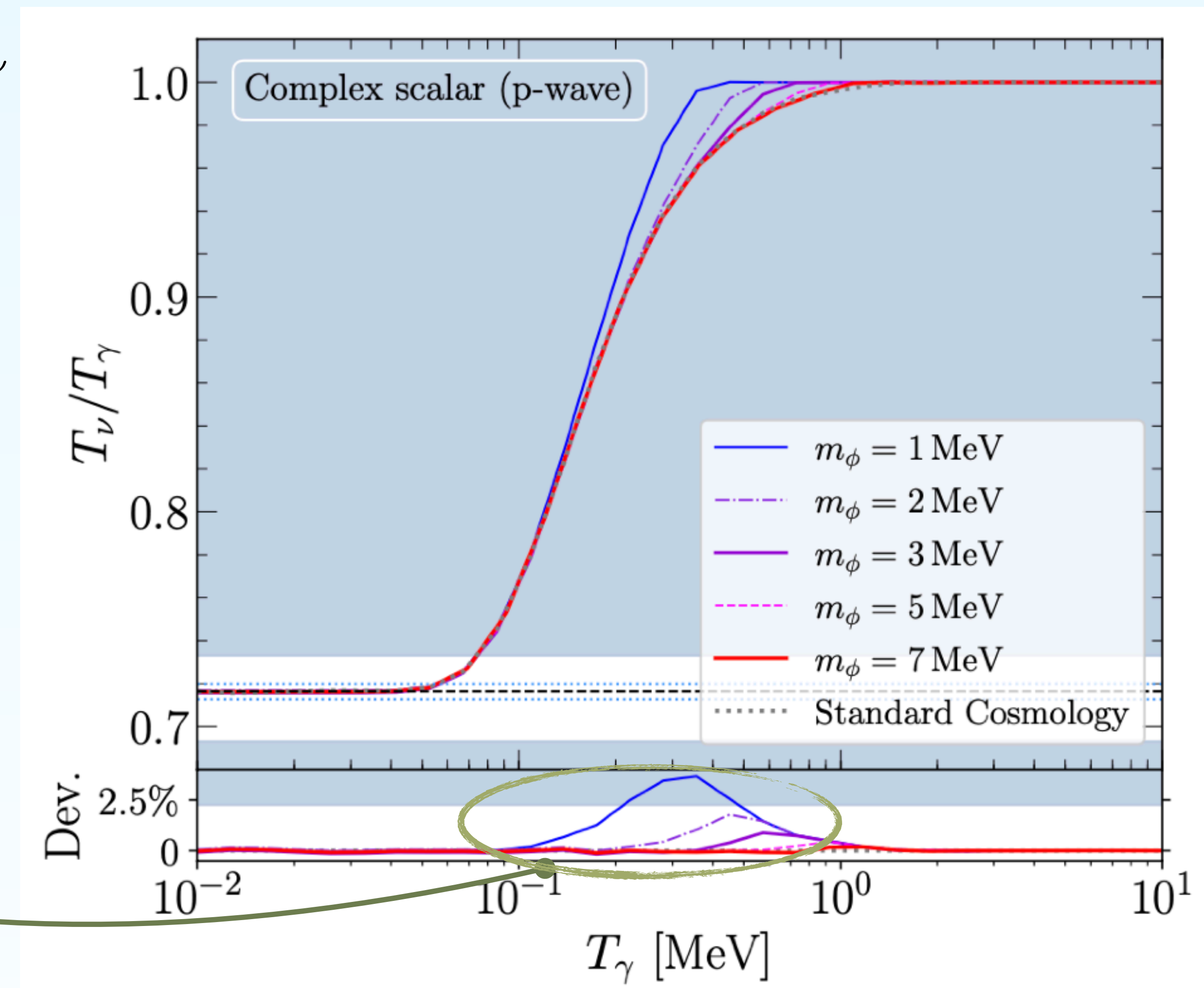
- before decoupling, it **maintains** $\mathbf{T}\gamma = \mathbf{T}\nu$:
- **DM heats up one sector, only after it decouples from the other:**

reduce the EM heating from e+e- annihilation;

if cancel out

increase **EM sector** heating by DM annihilation;

if $Br_e \gg Br_\nu$



Only a short period of extra radiation

also alleviates the BBN Neff bound.

If dark matter dominantly annihilates into the **EM sector**.

.

At this moment, MeV DM annihilation should be be below:

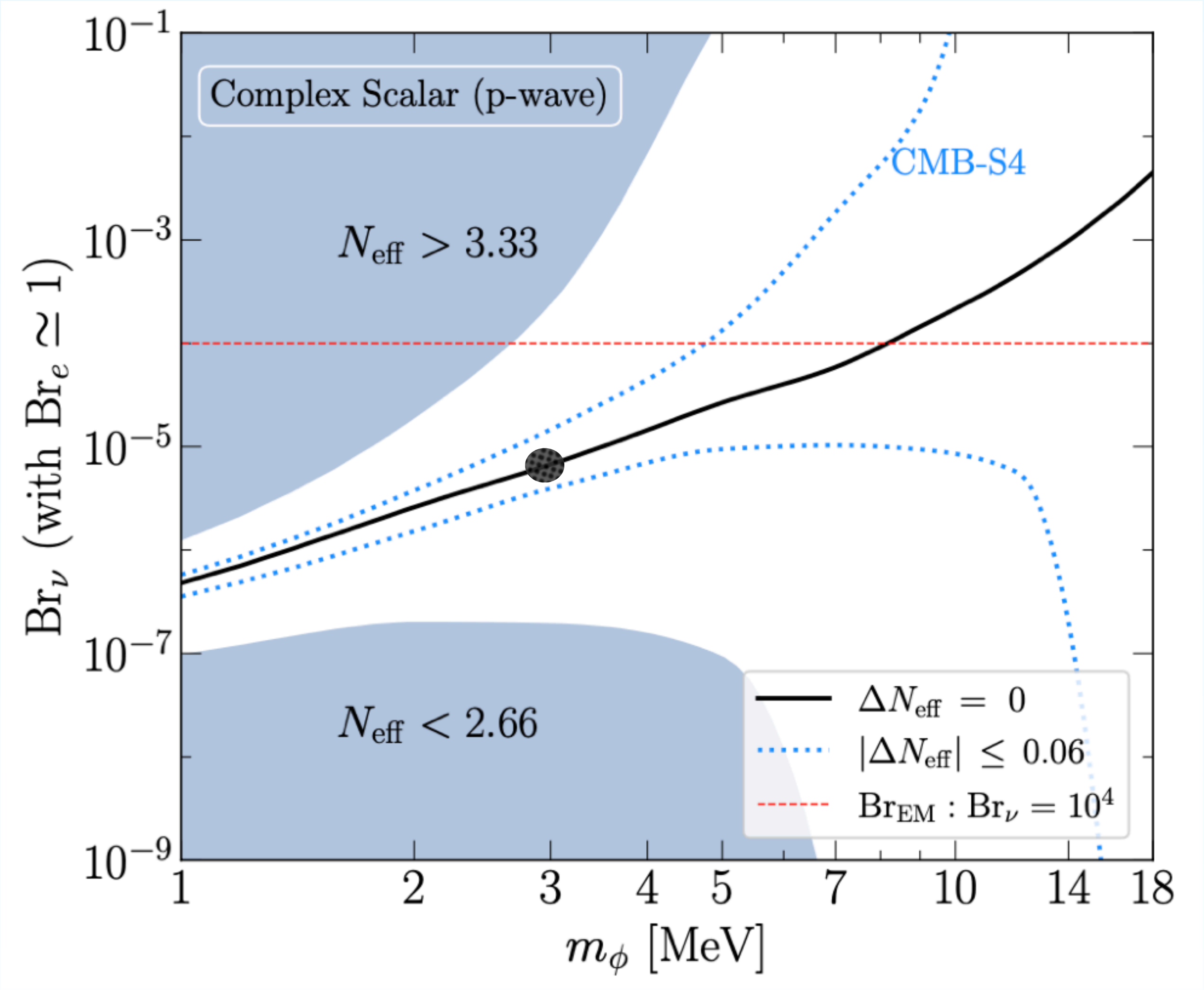
- **10^{-3} - 10^{-4} pico-barn** **for e/γ-line case [s-wave]:**

  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*

❖ Only **p-wave freeze-out** allowed by indirect search;

BBN N_{eff} bounds for the black line:



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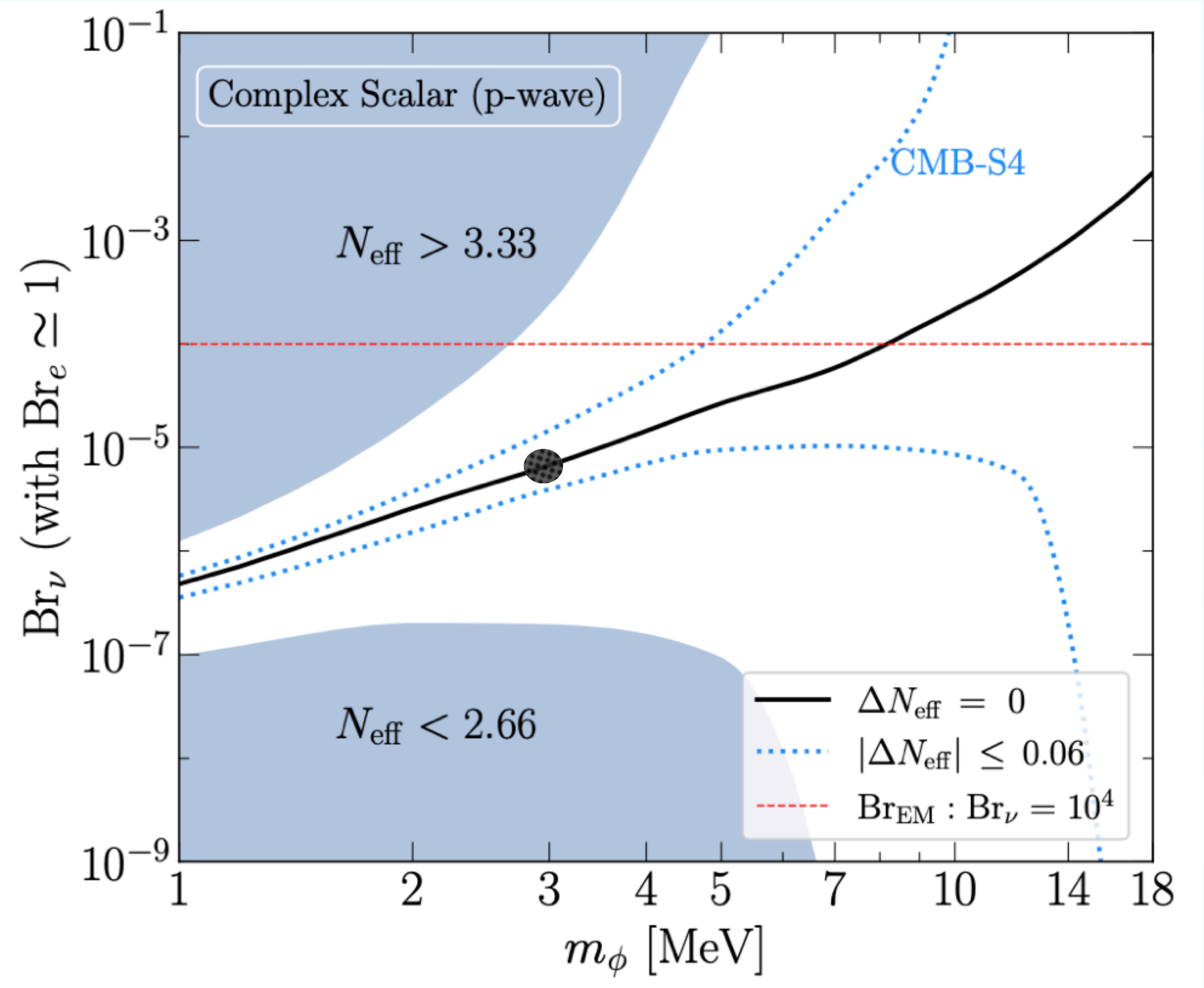
- **10-100 pico-barn** **for ν-only case [s-wave]:** *Super-K/…, e.g. Argüelles et al. 1912.09486*

- Only **p-wave freeze-out** allowed by indirect search;

- BBN N_{eff} bounds along the black line: $m_\phi \gtrsim 3\,\mathrm{MeV}$



BUT:

Photodisintegration excludes thermal dark states that decay into EM particles [P.F.Depta, M.Hufnagel, K.Schmidt-Hoberg 2011.06519].

Such fine-tuning is mostly for entertaining.

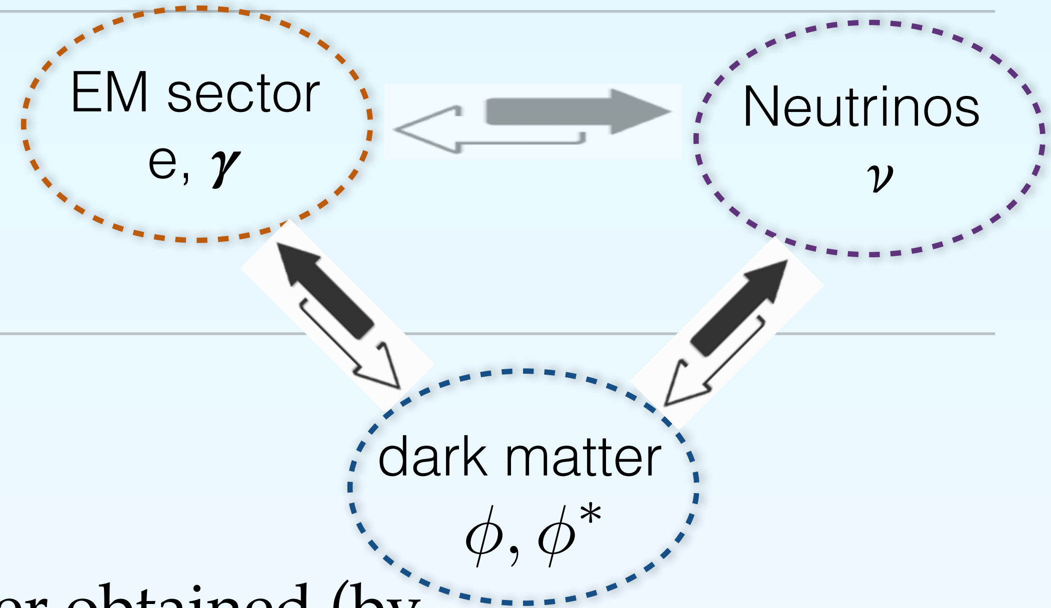
V. Conclusions

Conclusions

- With better BBN/CMB measurements, we should improve the precision of **theoretical calculations in MeV physics** too.
- A **numerically-fast treatment** of **MeV dark bridge (into both EM/neutrino)** can be fairly **precise,** without solving the exact momentum distribution functions.
- We obtain the **full history** of MeV dark state decoupling, and can apply it to various dark sector **models:**
  - Decaying dark particles,
  - Elastic scattering of asymmetric DM
  - Delicate BBN constraints, …

Thanks!

To reach **a (nearly) full description of three sectors, taking dark matter (DM) freeze-out**

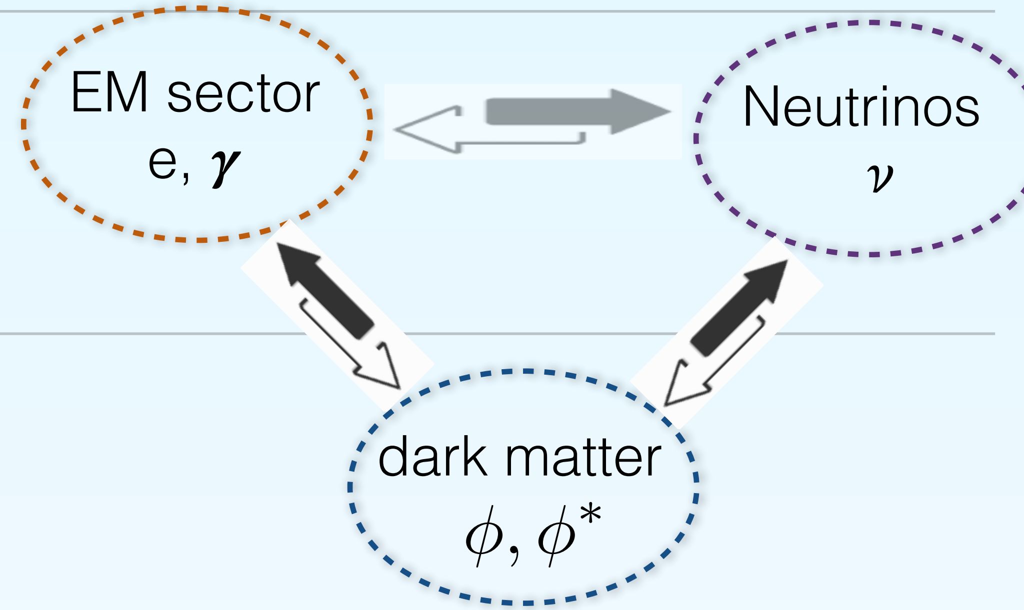


In earlier work *[M.Escudero 1812.05605]*:

- **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]

To reach **a (nearly) full description of three sectors, taking dark matter (DM) freeze-out**



$|\mathcal{M}|$

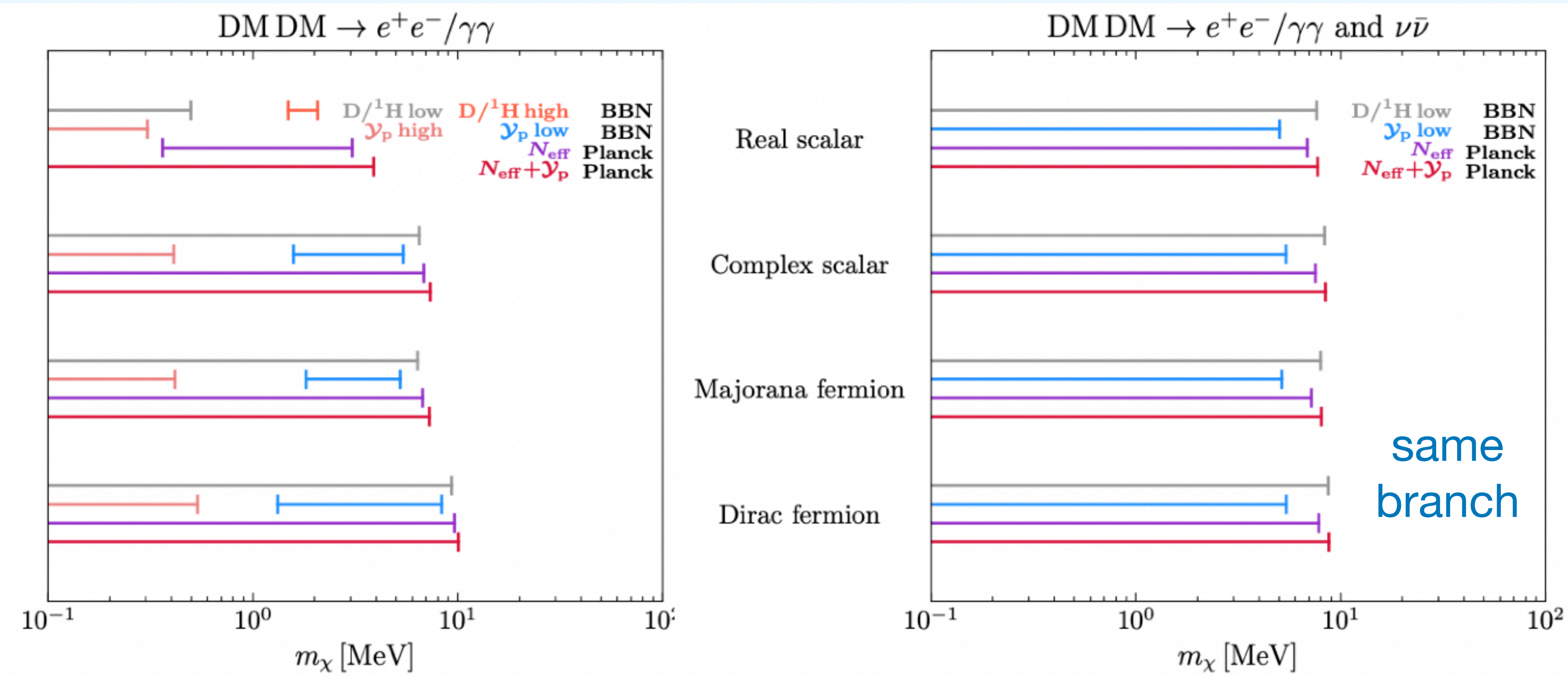
We develop a **parametrization to include all the effects above**

[up to solving the exact momentum distribution functions (MDF) of each sector].

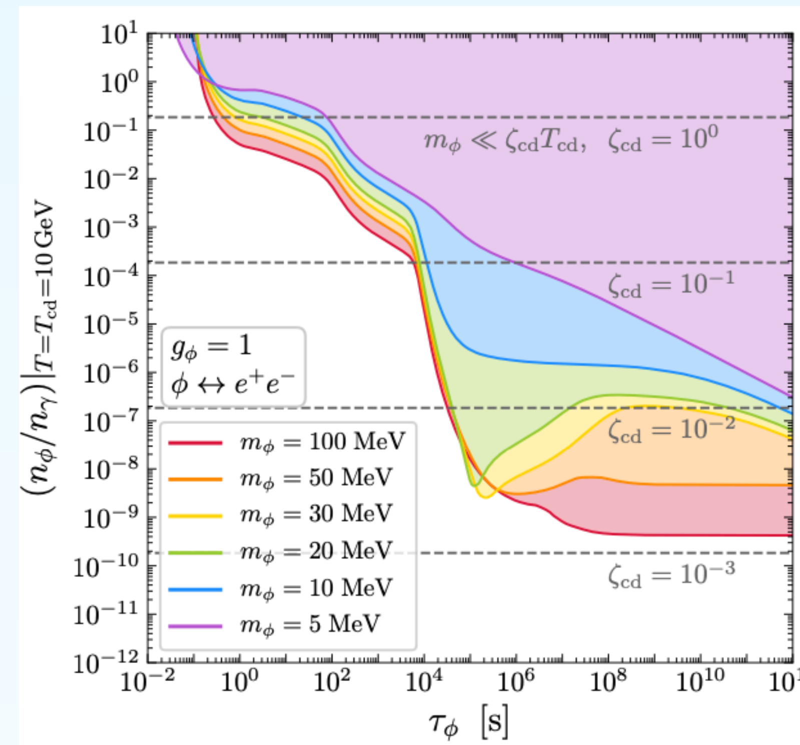
Solving the momentum distribution of each particle species is very time-consuming, and only leads to tiny corrections.

Previous CMB/BBN results on s-wave DM freeze-out

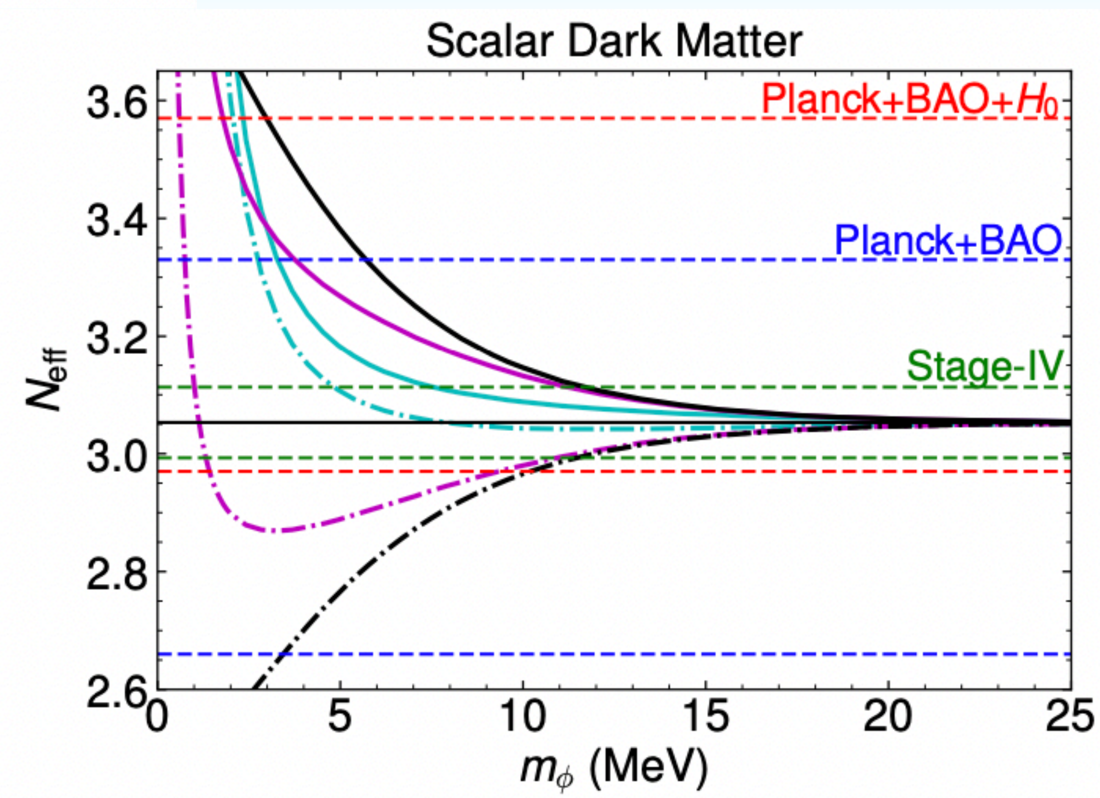
[Depta, Hufnagel, Schmidt-Hoberg & Wild 1901.06944]
sudden decoupling induced by DM annihilation into e/ν



EM energy ejection [Depta, Hufnagel, Schmidt-Hoberg 2011.06519]



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



Previous **Non-N_{eff}** results on s/p-wave DM freeze-out

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