Dark Matters 2022

Co-genesis in a dark sector

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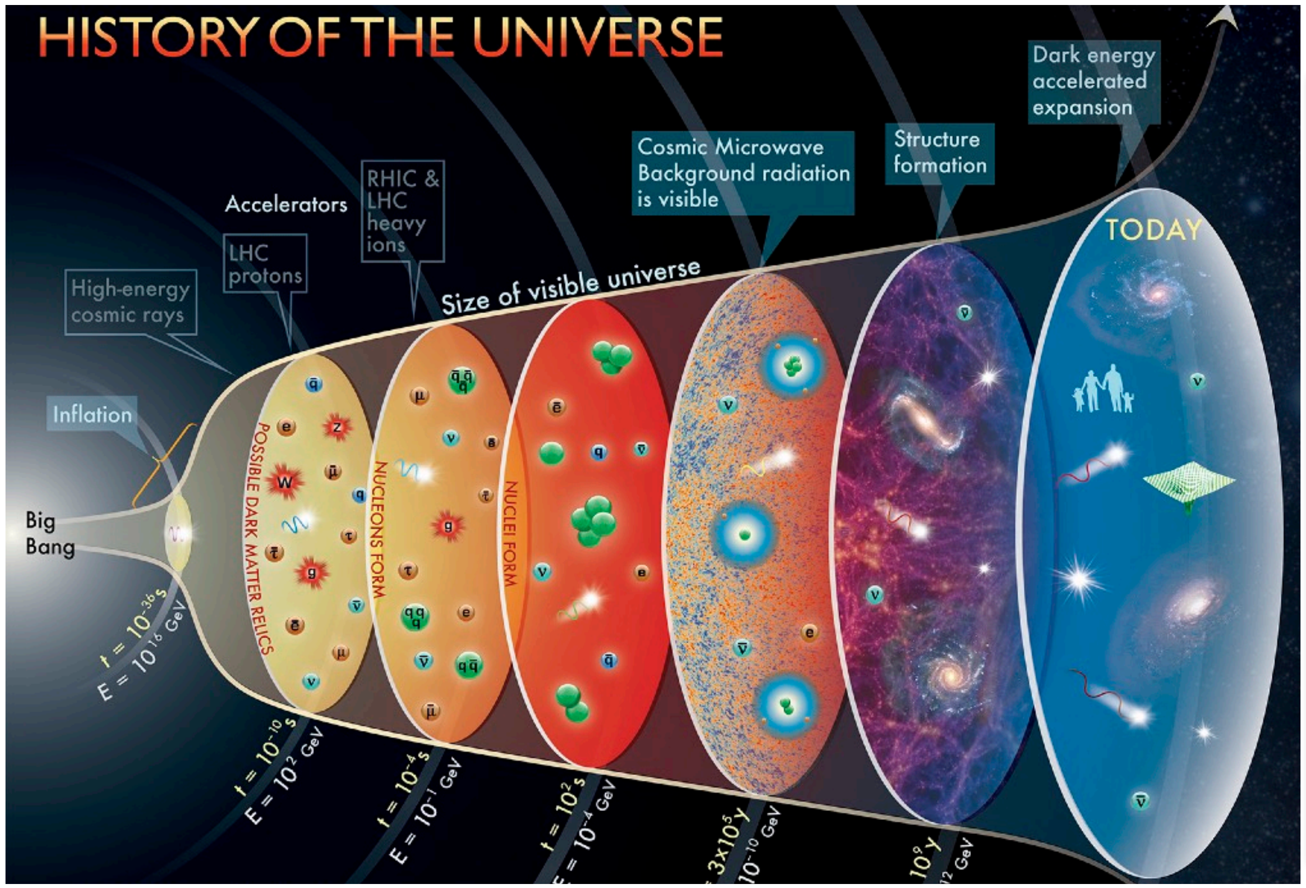
1. Motivations

Standard Cosmology, with remaining puzzles

Time



1. MeV: proton /neutron in equilibrium;

2. Two oscillating modes in T~eV;

3. At present: dark gravity potentials

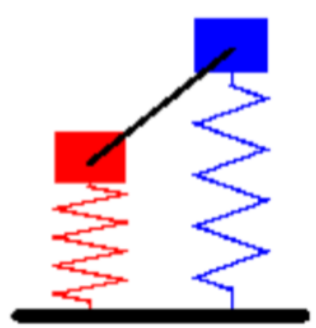
&

little baryon-antibaryon annihilation

$n + p \leftrightarrow D + \gamma \quad p + e \leftrightarrow H + \gamma$

1. nucleosynthesis **2. background radiation** **3. structure formation & cosmic rays**

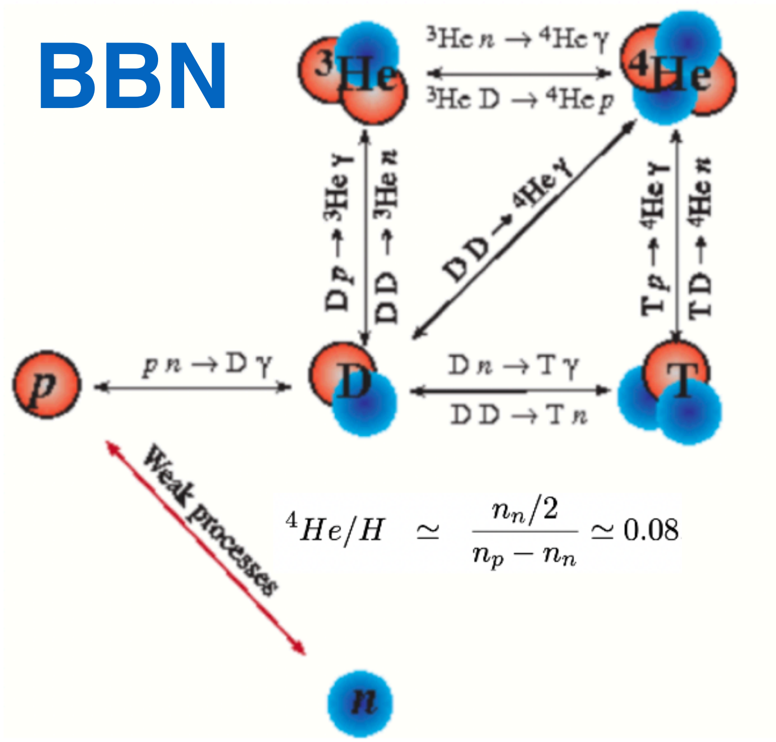
New physics before MeV

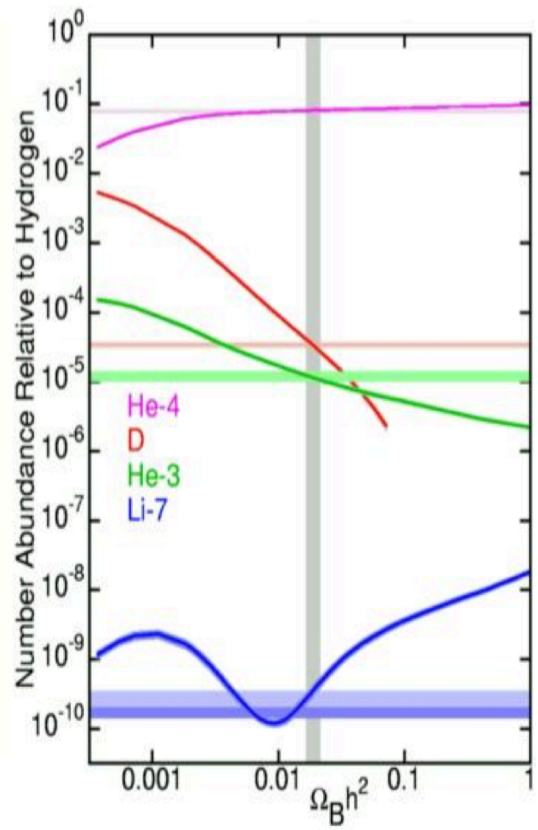


Visible **Dark Matter**

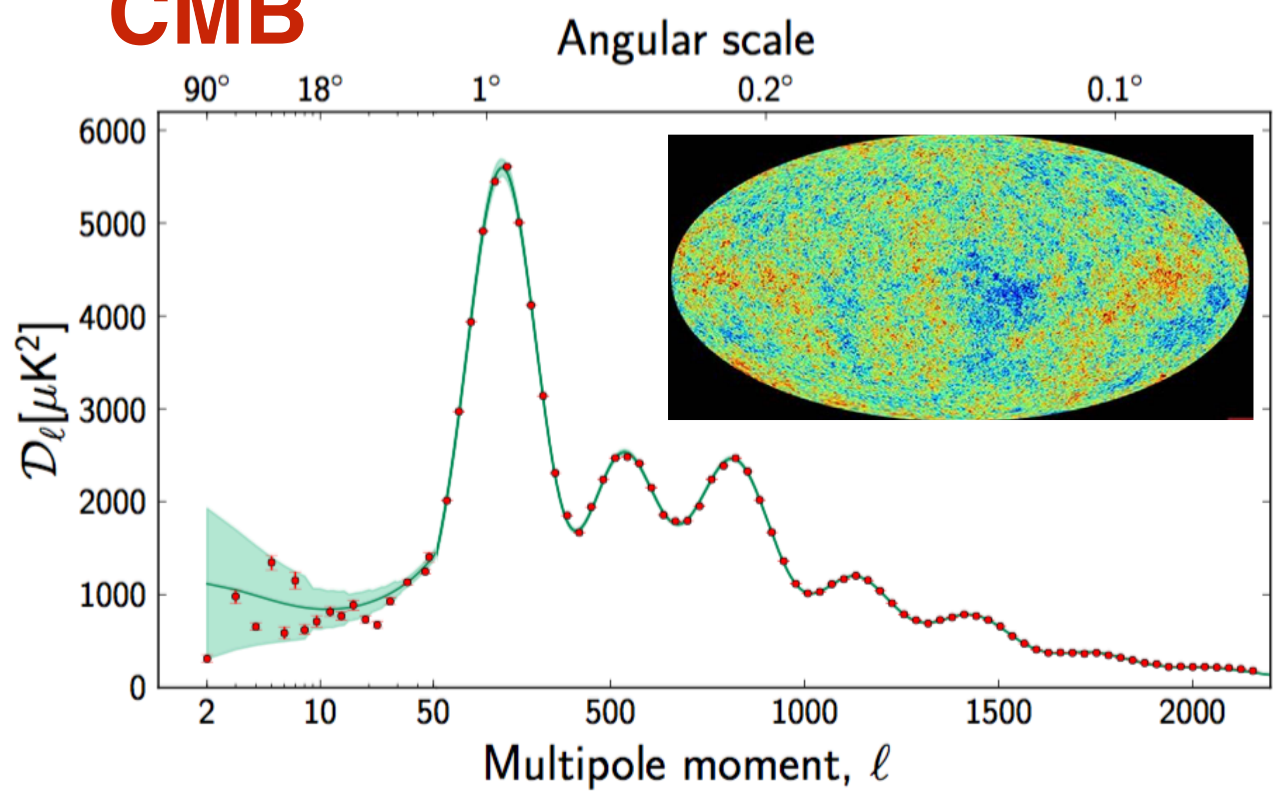
Measurements of precision cosmology

BBN





CMB



$$\Omega_b h^2 = 0.020 \pm 0.0015$$

$$\Omega_b h^2 = 0.02205 \pm 0.00028,$$

$$\Omega_{\rm DM} h^2 = 0.1199 \pm 0.0027$$

That is, $\Omega_b / \Omega_{\rm DM} \sim 1/5$

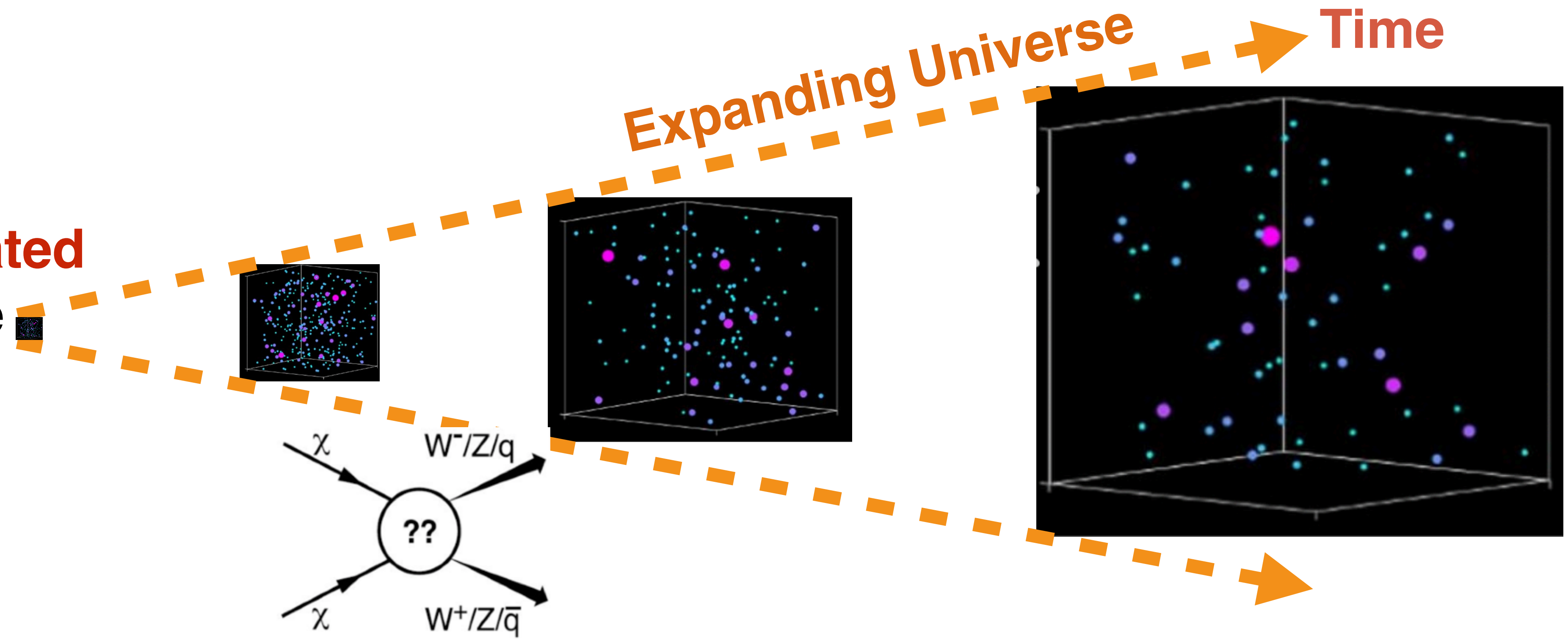
a coincidence, **or not**? → **Co-genesis**

II. To co-generate **dark matter (DM)** & **baryon asymmetry (BAU)**

For DM generation: **freeze-out**/in and so on.

The conventional expectation: **Weakly-Interacting Massive Particles (WIMP)**

Well-populated DM, χ, in the beginning



Until DM can not meet an **anti-DM in a Hubble time:** (freeze-out).

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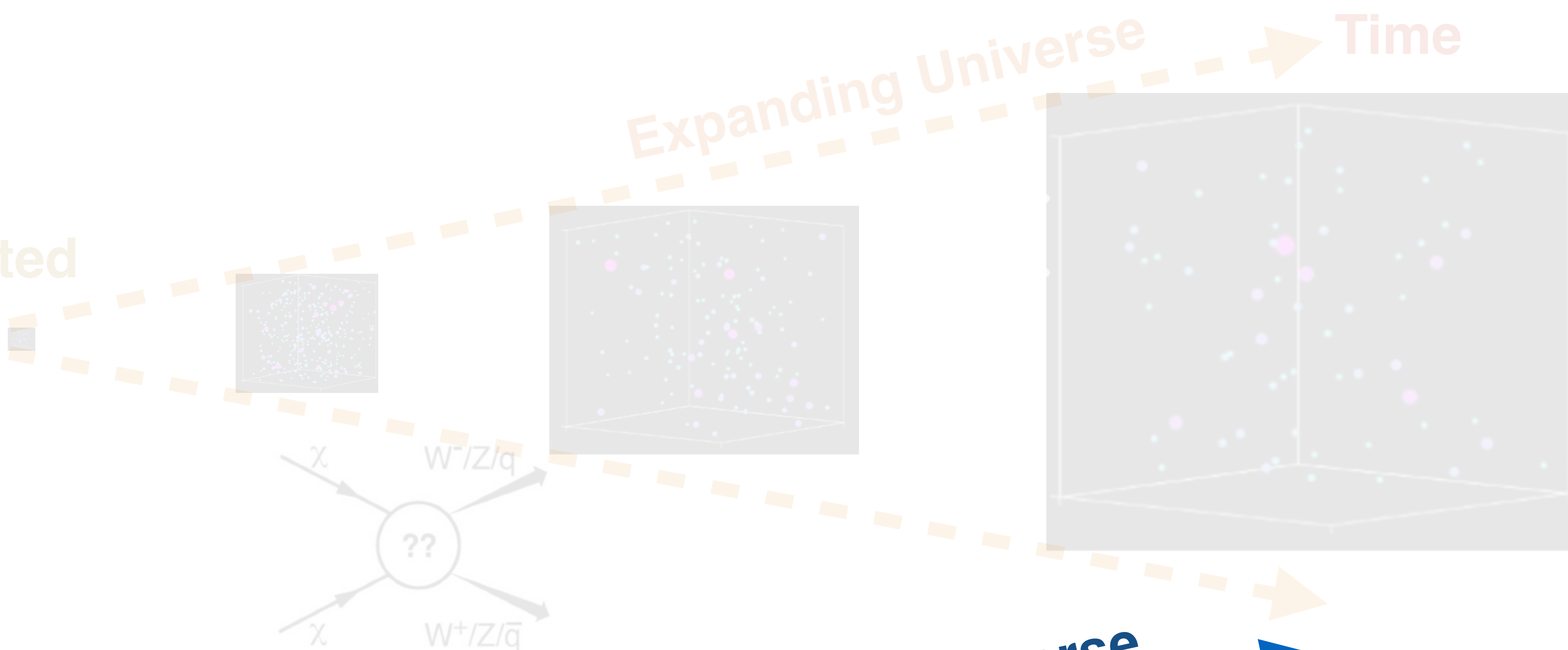
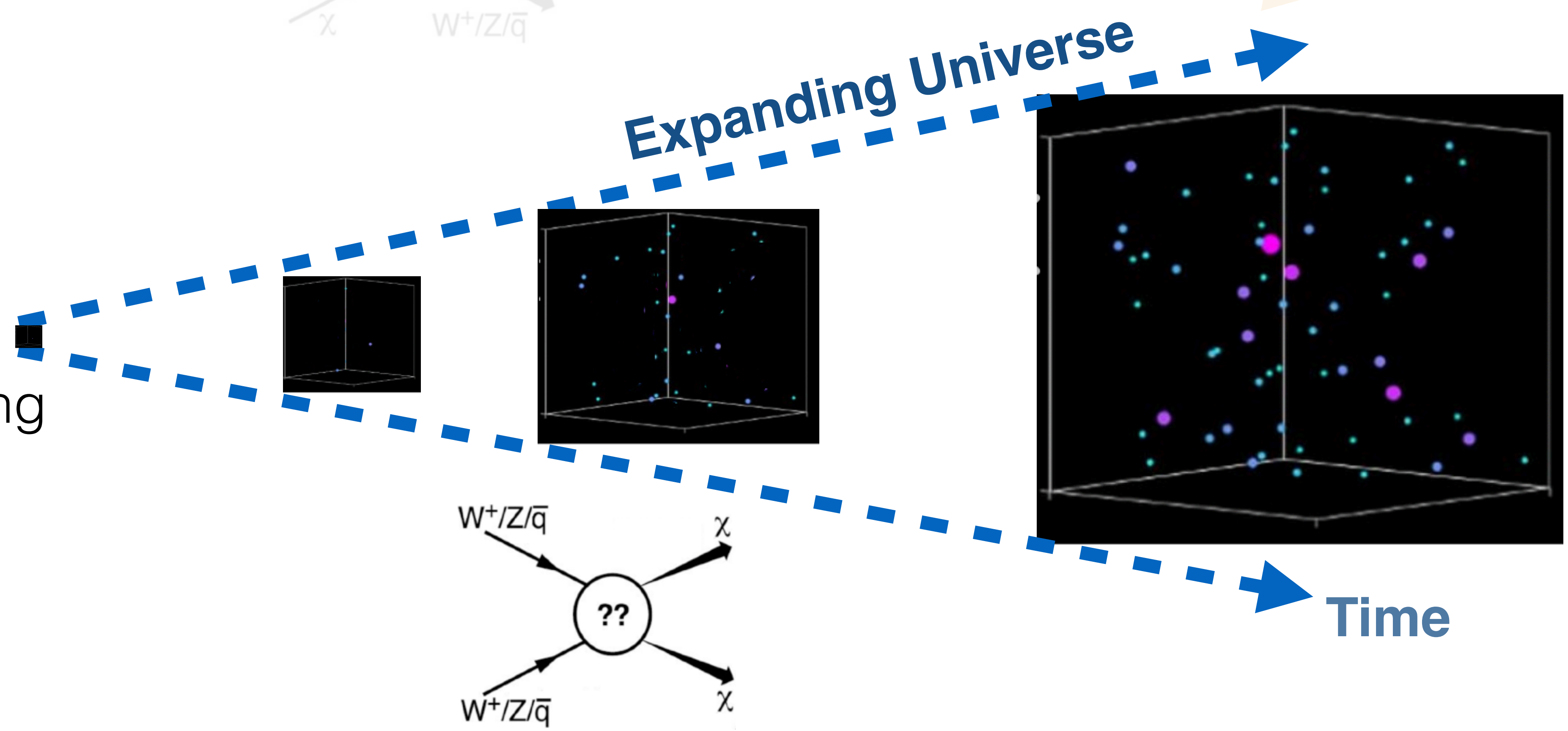


Until DM can not meet an anti-DM in a Hubble time: (freeze-out).

Little DM in the beginning



SM Universe leaks energy into DM slowly**:** (freeze-in).

For BAU generation: Sakharov conditions

$$\frac{n_B}{n_\gamma} \sim 6.1^{+0.7}_{-0.5} \times 10^{-10}$$

1. **C**, **CP** symmetry violation;
2. **Baryon** number violation;
3. Out of equilibrium.*

*Third condition may not be necessary as Universe **expansion violates CPT**: spontaneous baryogenesis [*Cohen&Kaplan 1987, 1988*].

One may use axion/curvature. e.g. gravitational baryogenesis [Davoudiasl et al, hep-ph/0403019]

$$\mathcal{L} \supset \int dx^4 \sqrt{-g} \lambda \frac{\partial_\mu \mathcal{R}}{M_p^2} J^\mu_{B-L}$$

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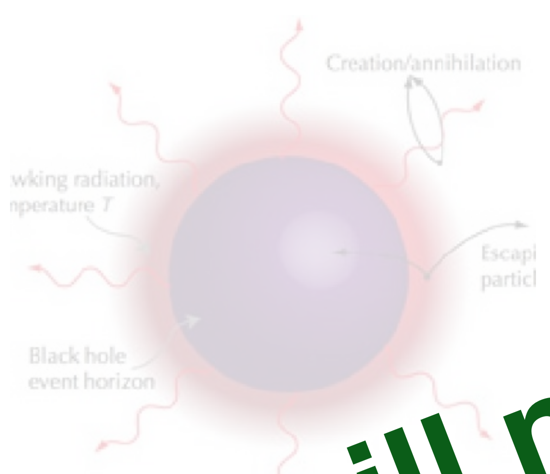
$$\mathcal{L} \supset \int dx^4 \sqrt{-g}\lambda \frac{\partial_\mu \mathcal{R}}{M_p^2} J^\mu_{B-L}$$

Generalised to **reheating by local defects** in early Universe

e.g. primordial black hole evaporation [*A. Hook 1404.0113*]



$$\mathcal{L} \supset \int dx^4 \sqrt{-g} \frac{\partial_\mu \phi}{M_\star} J^\mu_{B-L}$$ yields different "thermal mass" for B and Bbar.

Emission/decay of such defects also **produce DM,** leading to **co-genesis**

Q-balls, locally reheated sphere, cosmic strings, axion quark nuggets, filtered brane, …

will not be discussed here!

[or axion-like DM and/or Affleck-Dine baryogenesis].

Co-genesis, more globally:

$$\Omega_b/\Omega_{\rm DM} \sim 1/5$$

A. **Opposite asymmetry**

$$\Delta_B + \Delta_{\rm DM} = 0$$

conserves a $U(1)_{B-L+X}$ number, requiring only **one new process** and

$m_{DM} \approx 5$ GeV *

*DM may still vary after decoupled.

Models that **conserve a $U(1)_{B-L+X}$ number**, naturally arise in unified models *[Nussinov 1985, Barr, Chivukula & Farhi 1990, …]*:

e.g. Spontaneous co-genesis [*March-Russell&McCullough 1106.4319*]

$$\mathcal{L} \supset \frac{\partial_\mu \phi}{f} J^\mu_X \quad \Rightarrow \quad U_X(T)(n_X - n_{\overline{X}})$$

with $W_X = M_X \overline{X} X + \frac{1}{M_S^2} X^2 U^c D^c D^c$ satisfy $2\mu_X = \mu_{u_R} + 2\mu_{d_R}$

Co-genesis, more globally:

$$\Omega_b/\Omega_{\rm DM} \sim 1/5$$

B. **Converted asymmetry**

$$\Delta_B \sim \Delta_{\rm DM}$$

Generated then leaked. **One process** for **Δ-production**, the **other** for **Δ-conversion**.

(dark) Sphalerons [*e.g. Shelton & Zurek 1008.1997, Blennow et al. 1009.3159*]

Xogenesis via effective operators [*Buckley&Randall 1009.0270*], and so on..

$$B = -\frac{4}{13}\sum_{i=1}^{N} L_i\left(1+\frac{1}{\pi^2}\frac{m_{l_i}^2}{T^2}\right)$$

[Kuzmin, Rubakov & Shaposhnikov PLB191 171(1987)]

If total **ΔL** vanishes

$$\Delta_\tau = B/3 - L_\tau$$

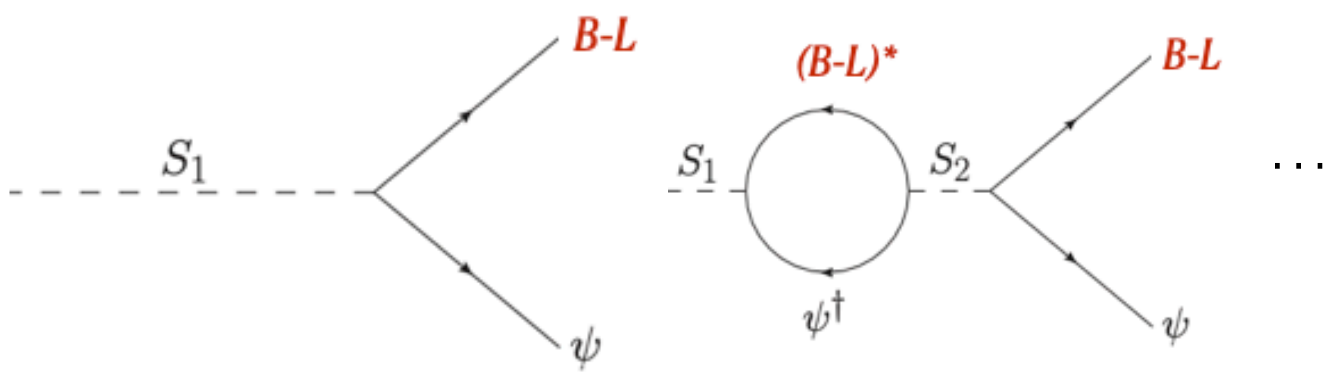
Asymmetry generated by the **secondary contributions of sphaleron** via out-of-equilibrium **flavor violation** [e.g. leptoflavorgenesis, *Mukaida, Schmitz & Yamada 2111.03082*]

Suitable for **multi-component DM**, similar to L-flavors, but easier to have **large CPV**.

Co-genesis, more globally:

$$\Omega_b/\Omega_{\rm DM} \sim 1/5$$

While both may share the **out-of-equilibrium** processes / background (**S**), only **B-L asymmetry** relies on the **CP parameter** via loop interferences:



- Zero-T (or thermal) Feynman diagrams;
- If **S** is out-of-equilibrium mesons, no new CP needed [**mesogenesis**, *Aitken, McKeen et al. 1708.01259, 1810.00880, …*].

C. **Symmetric DM**

$$\epsilon_{CP} \ll 1 \rightarrow n_B/n_\gamma \ll 1$$

Correlation is not obvious, so

- **analytical DM solutions**
- **predicting exact $\epsilon_{\rm CP}$**

important for quantitative study.

The out-of-equilibrium processes can be DM **freeze-in** or **freeze-out**.

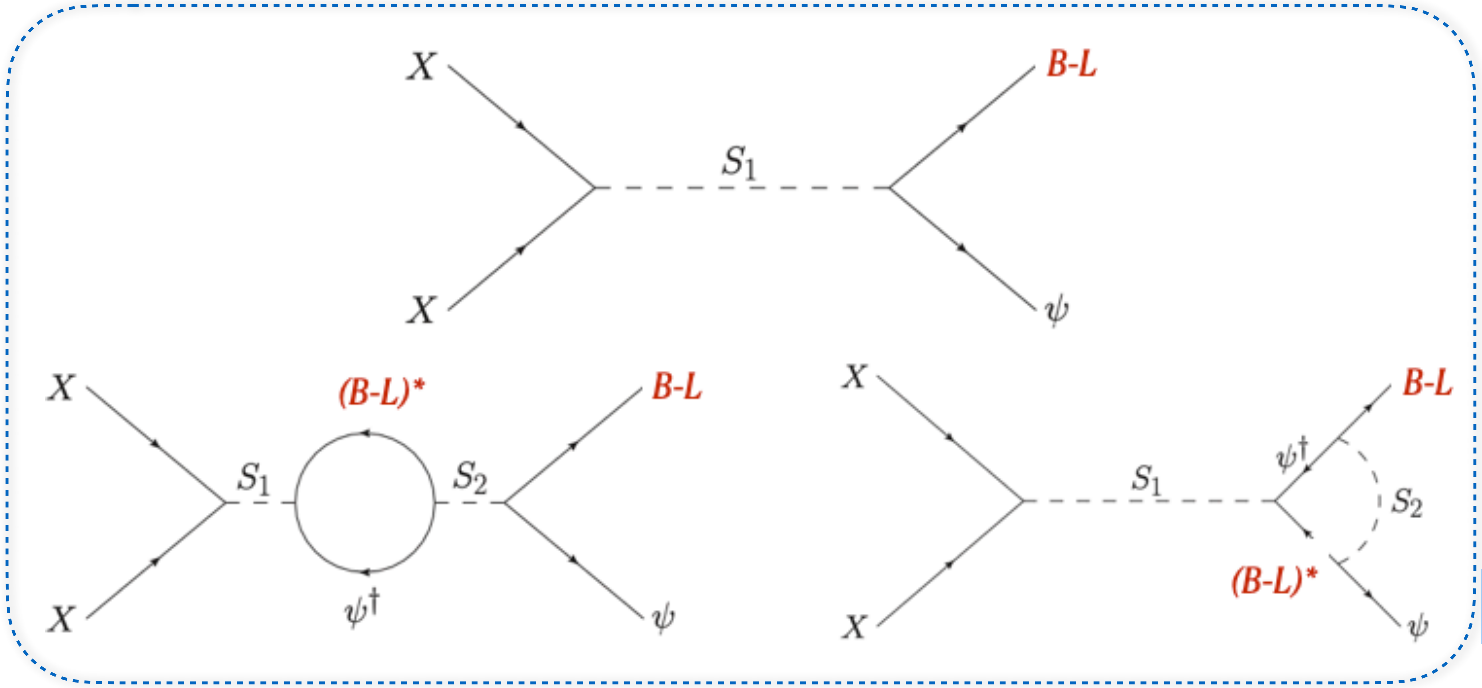
- Freeze-in, e.g. νMSM-like [*Asaka&Shaposhnikov 2005, Shuve&Tucker-Smith 2004.00636…*];
- Freeze-out: **to be discussed below**:

III. Co-genesis for symmetric freeze-out

Case I: WIMPy (thermal) freeze-out

[*McDonald 1009.3227, Cui, Randall & Shuve 1112.2704, etc.*]

DM freeze-out via **intermediate (B-L) violating states** [*Cui's review 1510.04298*]



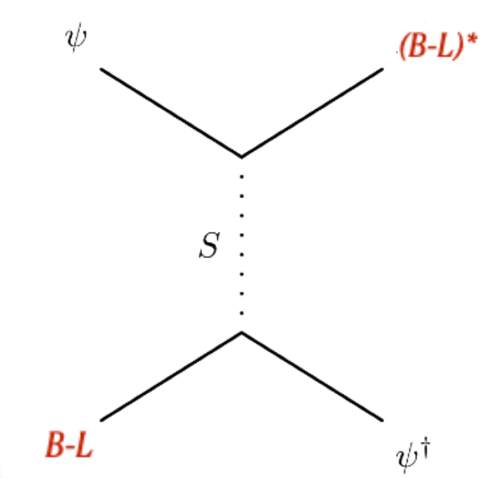
Freeze-out: out-of-equilibrium

$$\frac{dY_X}{dx} = -\frac{2s(x)}{x\,H(x)}\langle\sigma_{\rm ann}v\rangle\left[Y_X^2 - (Y_X^{\rm eq})^2\right]$$

source term

At the same time, intermediate states also induce **wash-out**, e.g.

wash-out suppression



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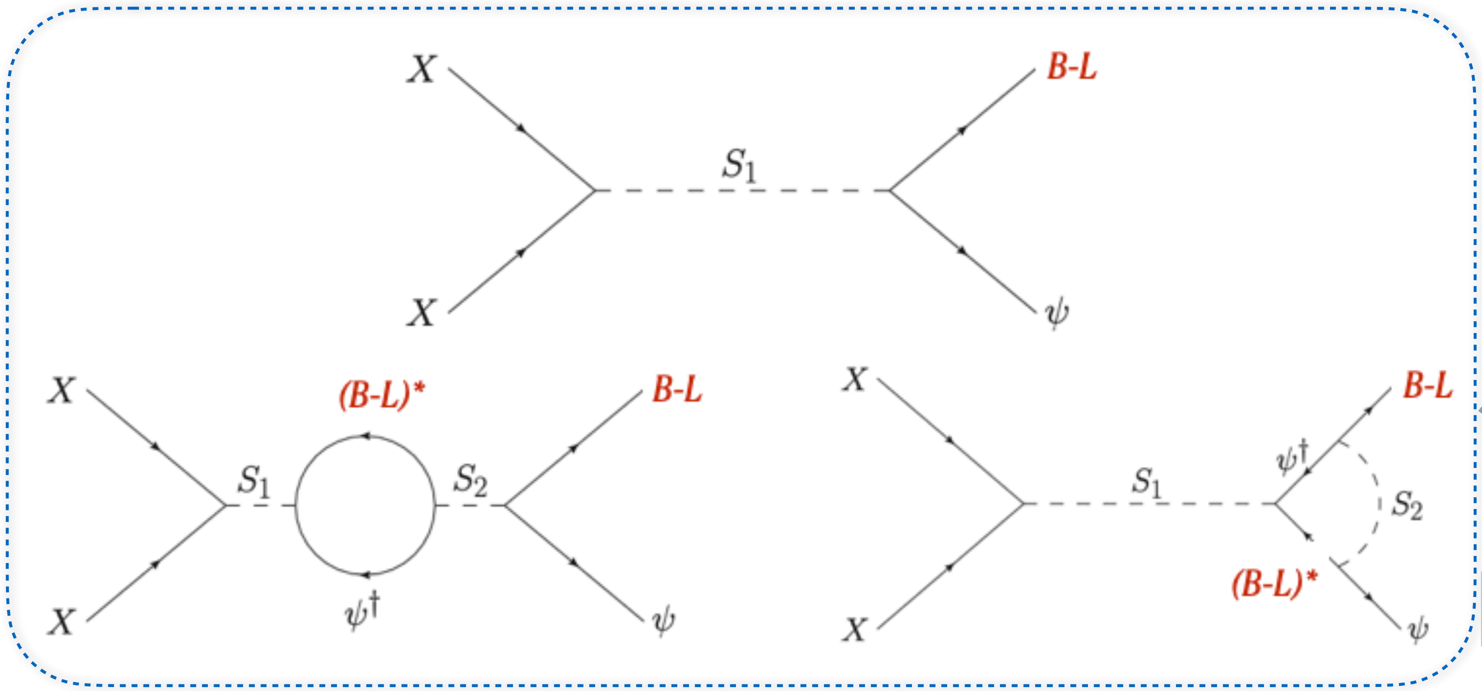

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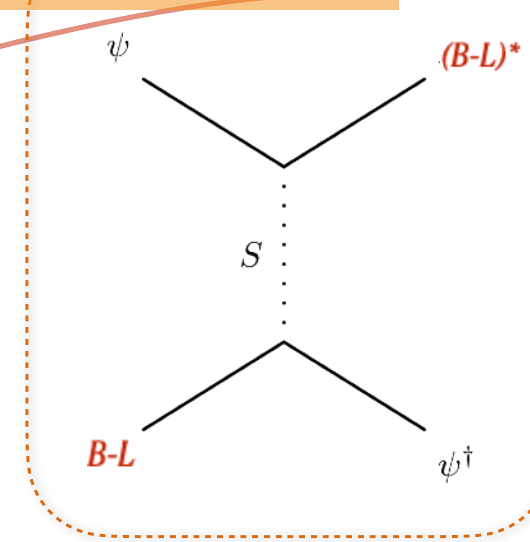


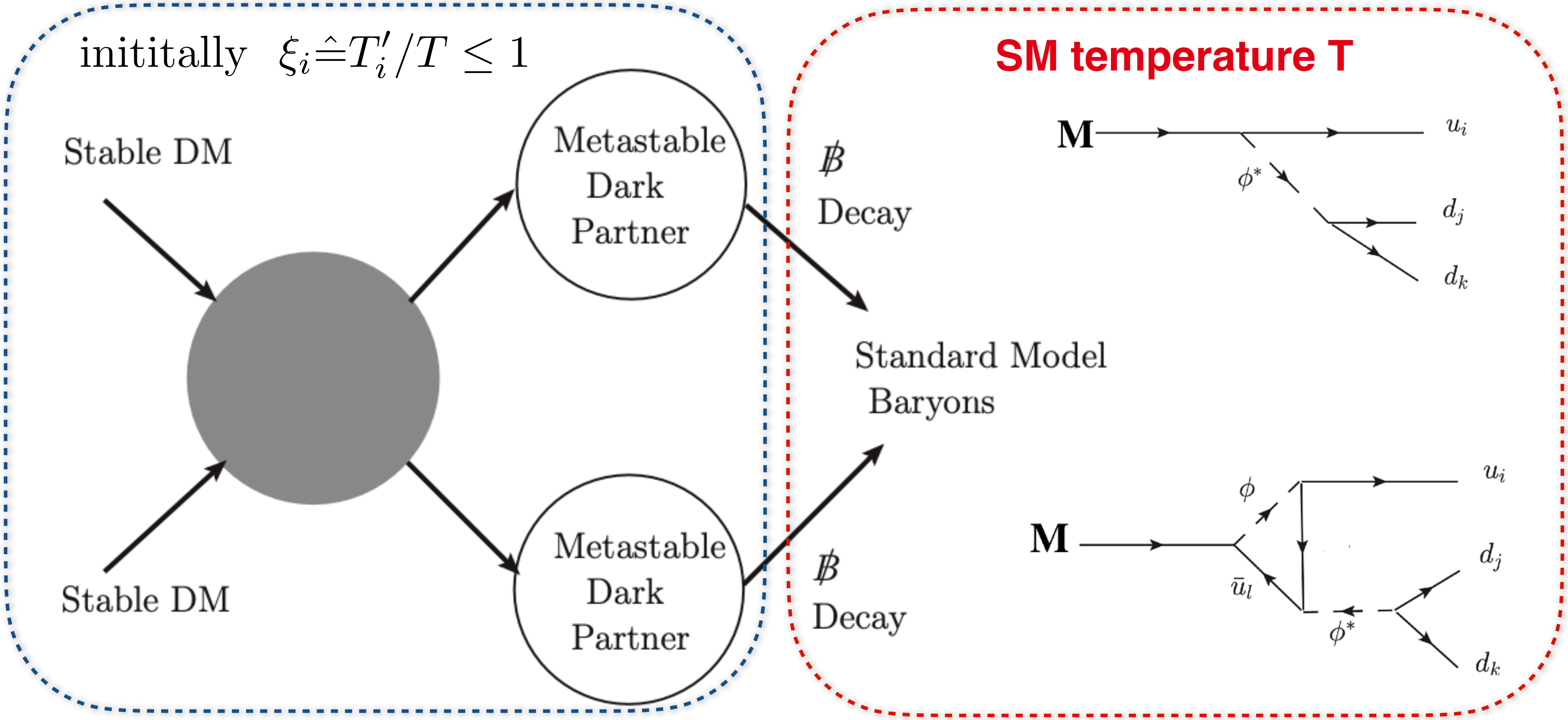
$$Y_B(0) = \epsilon_{\rm CP}\int_0^{T_{\rm D}} \frac{dY_{\chi_B}}{dT}\exp\left(-\int_0^T \frac{\Gamma_{\rm W}(T')}{H(T')}\frac{dT'}{T'}\right)dT$$

Strongly coupled S: typically important wash-out suppression

Case II: WIMPy **dark** freeze-out

[**XC**, Cui, Pradler & Shamma 2112.10784]

Simply assume **final states, M, are not in equilibrium** with SM particles:



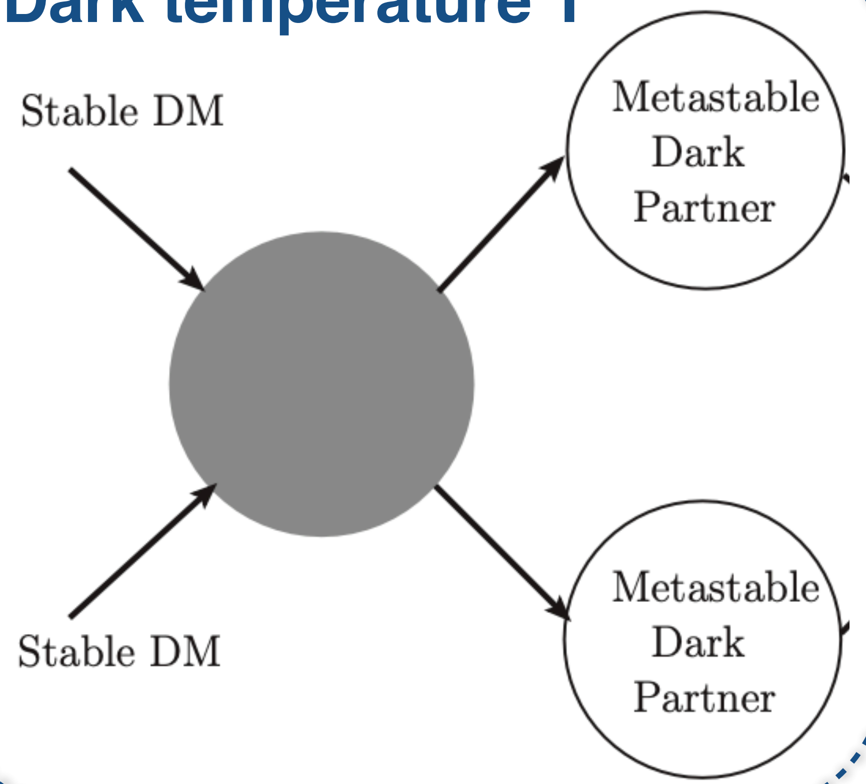
$$\dot{n}_{\rm DM} + 3Hn_{\rm DM} = -\langle \sigma_{\rm DM} v\rangle n^2_{\rm anni.} + \langle \sigma_{\rm creat.} v\rangle n^2_{\rm M}$$

$$Y_B = \epsilon_{\rm CP} Y_{\rm M} \simeq \left(\frac{{\rm Im}[\alpha_j \alpha_m \beta_j^* \beta_m^*]}{|\alpha_j|^2} \frac{m^2_{\chi_2}}{20\pi m_\phi^2} \right) Y_{\rm M}$$

Analytical solutions are possible & **Absence of wash-out**.

Case II: WIMPy **dark** freeze-out

Dark temperature T'



a) If total dark **particle number is conserved**.

e.g. nearly degenerate $m_{DM} \geq m_M \gg T'_{f.o.}$

$$T' \simeq (3\xi_i T)^2/m_{\rm M}\ (\hat{=}\beta T^2/m_{\rm DM})$$

$$\delta = (m_{\rm DM} - m_{\rm M})/m_{\rm DM} \ll 1$$

$$\text{Quasi-static solution: } Y_{\rm M} = \frac{1}{1+(1-\delta)^{-3/2}e^{-\delta m_{\rm DM}/T'}}\,(Y_{\rm DM}+Y_{\rm M})$$

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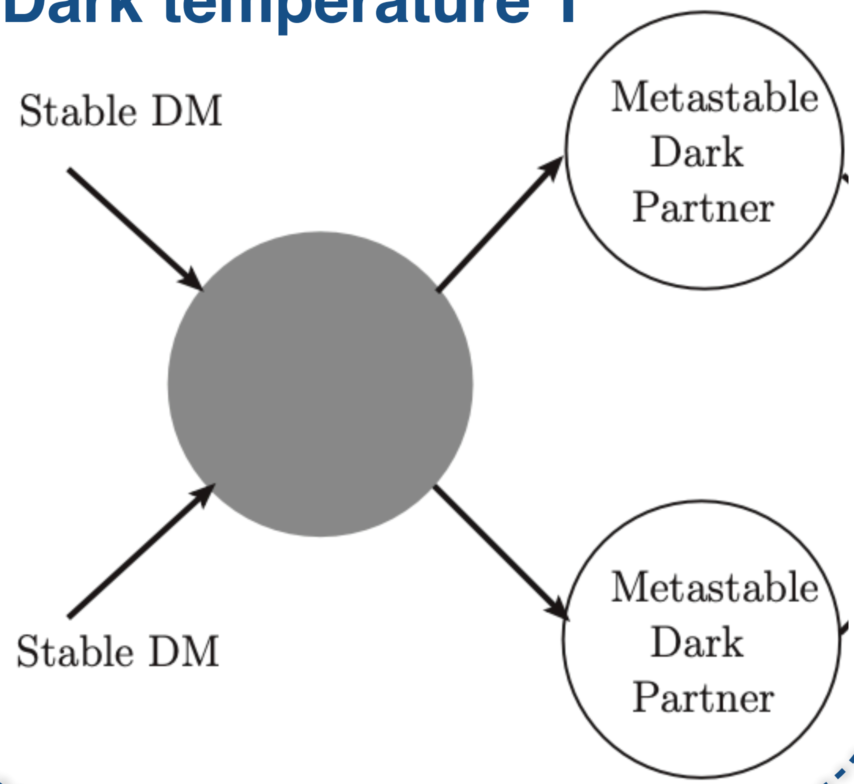

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$$\text{Quasi-static solution: } Y_{\rm M} = \frac{1}{1 + (1-\delta)^{-3/2} e^{-\delta m_{\rm DM}/T'}} (Y_{\rm DM} + Y_{\rm M})$$

Allowing analytical results:

$$Y_{\rm DM} \simeq \frac{1}{\lambda}\left(\frac{1}{\delta\beta}\ln\left[\frac{0.15\lambda\xi_i^3\beta^{1/2}\delta^{1/2}}{(1-\delta)^{3/2}}\frac{g_\chi}{g_{*S}}\right]\right)^{1/2} \quad \text{for s-wave.}$$

$$\lambda = 0.264 g_{*S}/g_*^{1/2} m_{\rm Pl} m_{\rm DM}\sigma_0$$

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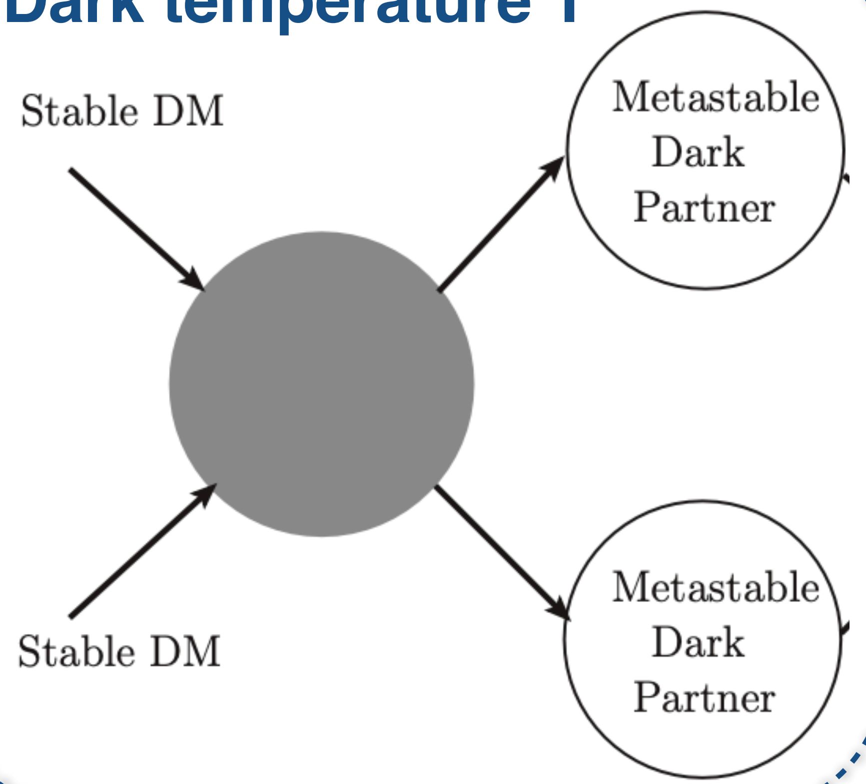
[***XC***, *Cui, Pradler & Shamma 2112.10784*]

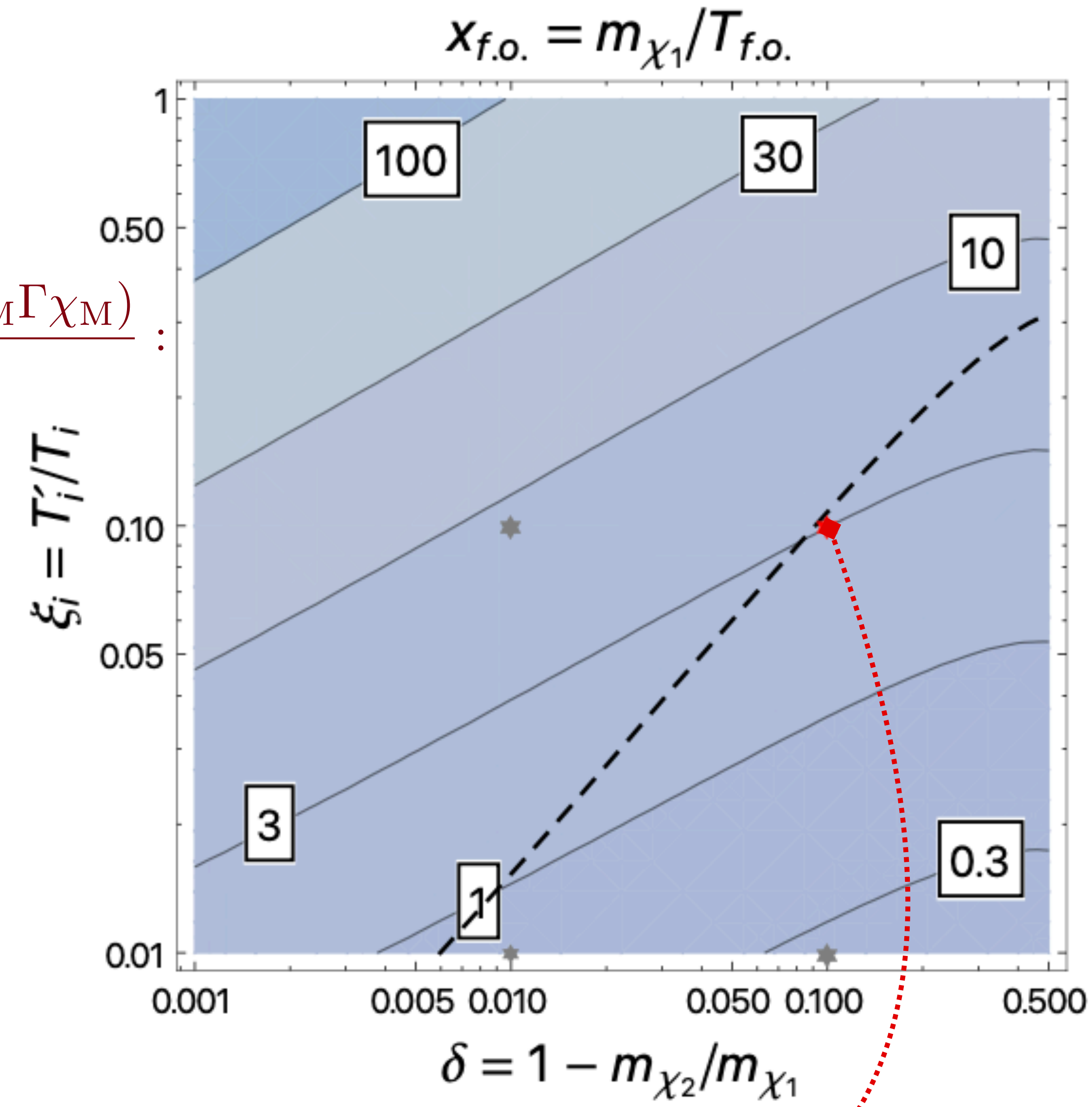
Dark temperature T'

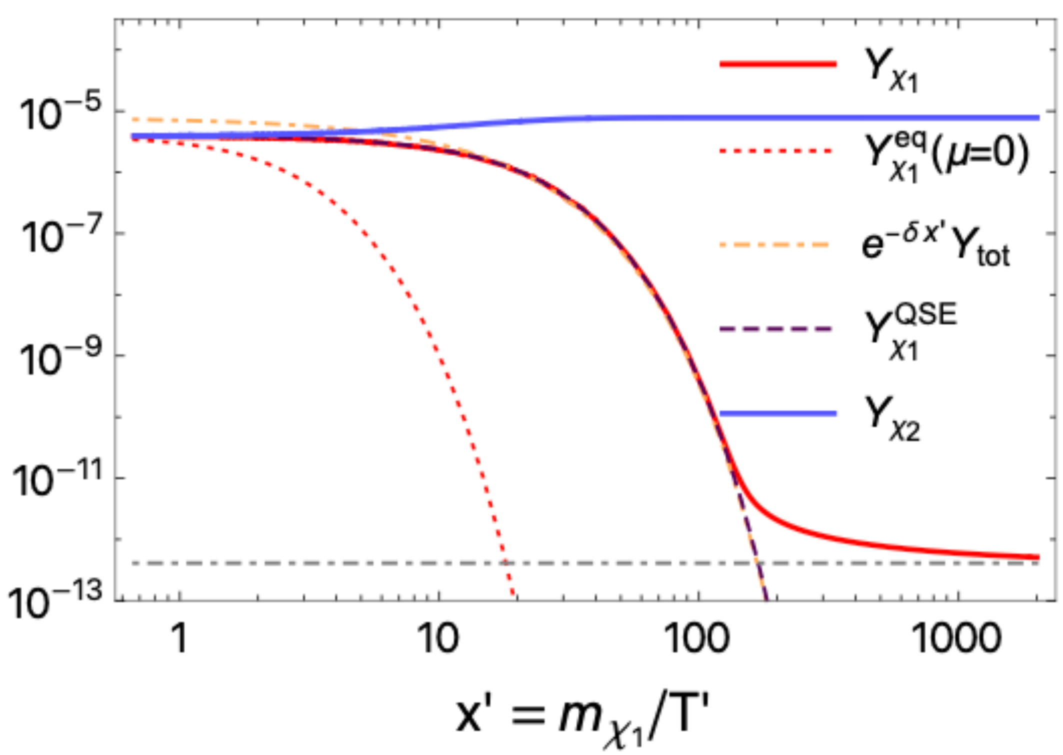


a) If total dark **particle number is conserved**.

For **1 TeV DM**

via $\frac{(\bar{\chi}_{\rm DM}\Gamma\chi_{\rm DM})(\bar{\chi}_{\rm M}\Gamma\chi_{\rm M})}{(4\,{\rm TeV})^2}$:





Agree with numerical calculations well.

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[***XC***, *Cui, Pradler & Shamma 2112.10784*]

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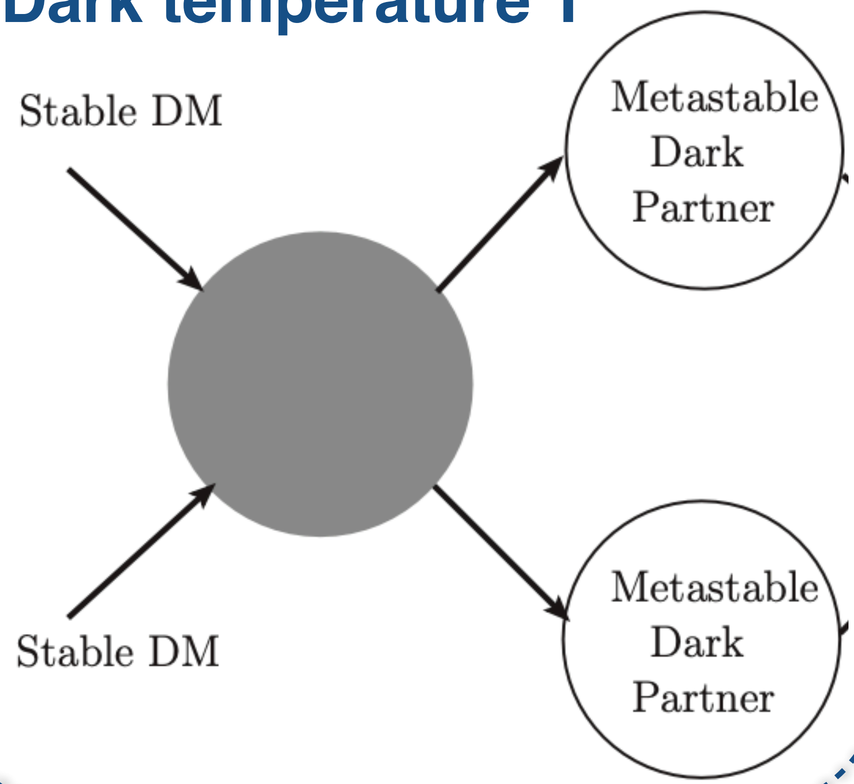


b) if allows **number-changing** of dark partner M:

$$m_{DM} \gg T'_{f.o.} \gg m_M$$

A dark freeze-out, with $\xi \equiv T'/T \simeq \text{const.}$

$$Y_{\rm DM} \simeq \frac{\xi}{\lambda} x_{f.o.} \propto \frac{\xi}{\langle \sigma_{\rm anni.} v \rangle} \quad \text{for s-wave freeze-out}$$

It converges to conventional WIMP results with ***ξ***=1, as shown in the literature

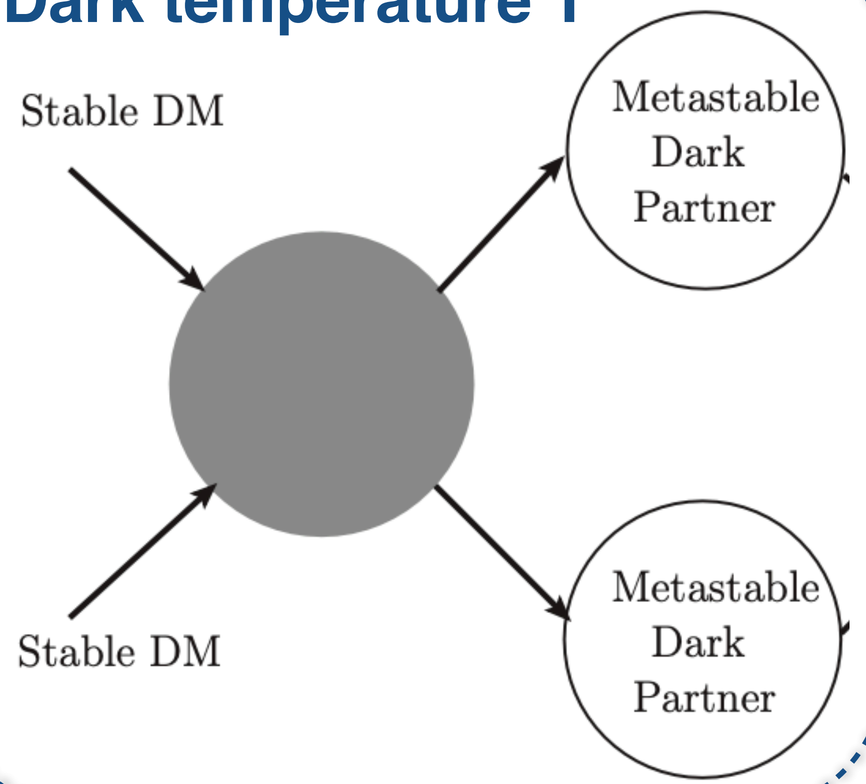
[*Ackerman et al. 0810.5126, Feng et al.0808.2318,* ***XC****, Hambye & Tytgat 1112.0493*].

$$\mathbf{Y}_{\rm M} \propto \xi^{\mathbf{3}} \quad \text{(or given by SIMP-like freeze-out)}$$

Case II: WIMPy **dark** freeze-out

[***XC***, *Cui, Pradler & Shamma 2112.10784*]

Dark temperature T'



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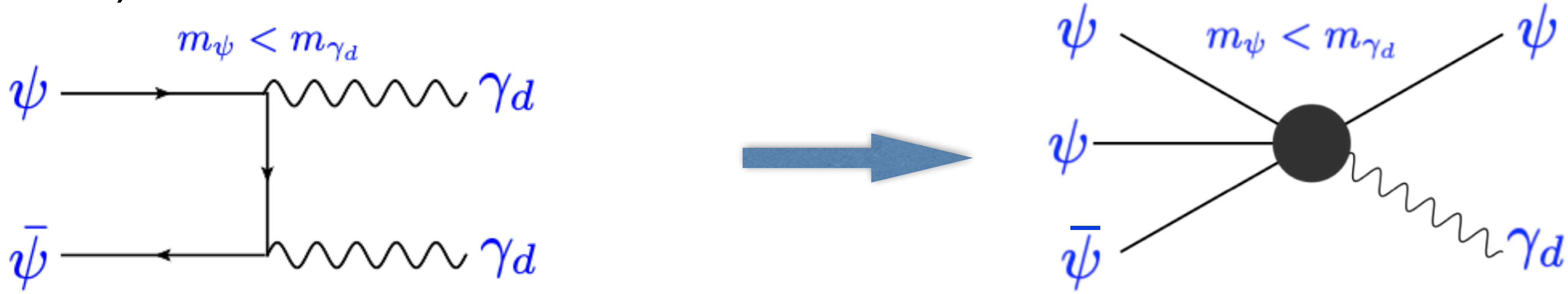
To combine a & b:

$$\frac{\Omega_B}{\Omega_{\rm DM}} = \epsilon_{CP} \frac{m_p}{m_{\rm DM}} \times \begin{cases} 0.42 \frac{g_\chi}{g_*} \frac{\xi_i^3 \lambda}{(2n+1)\beta^n} \frac{1}{x_{\rm f.o.}^{2n+1}} - 1 & \text{near-degenerate} \\ 0.42 \frac{g_\chi}{g_*} \frac{\xi_i^3 \lambda}{(n+1)\xi_{\rm f.o.}^{-n}} \frac{1}{x_{\rm f.o.}^{n+1}} - 1 & \text{hierarchical} \end{cases}$$

To **suppress wash-out** in DM freeze-out:

Many models contains a **heavy partner** (may be **heavier than DM**).

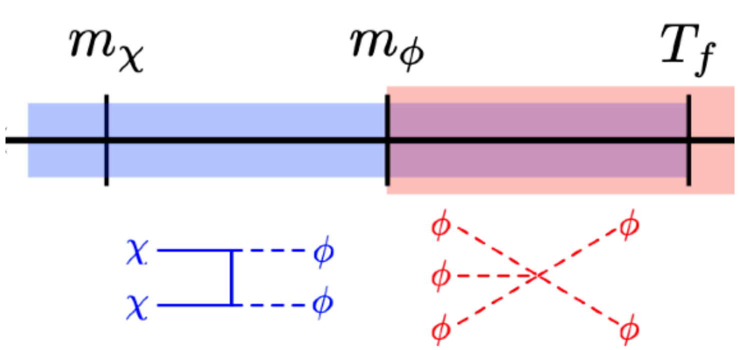
- (Enabled) **forbidden annihilation**



[*Griest & Seckel PRD43, 3191(1991), D'Agnolo & Ruderman 1505.07107*]

[*Cline, Liu, Slatyer & Xue 1702.07716*]

- **Cannibal annihilation**

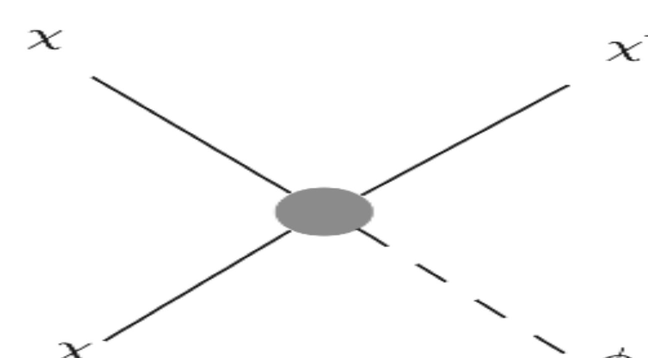


[*Carlson, Machacek & Hall, ApJ398, 43(1992), Pappadopulo, Ruderman & Trevisan 1602.04219, etc.*]

- **Meta-stable bound states** [see Petraki's talk]

  - *Also semi-annihilation/catalysed/inverse-decay/multi-step+ freeze-out*

[1003.5912,1705.08450, 1803.02901, 1906.00981, 2003.04900, 2004.07705,2102.02447, 2111.14857,…]



Symmetric DM in a **general BAU set-up:**

1. **C**, **CP** symmetry violation;
2. **Baryon** number violation;
3. Out of equilibrium.

source term

wash-out suppression

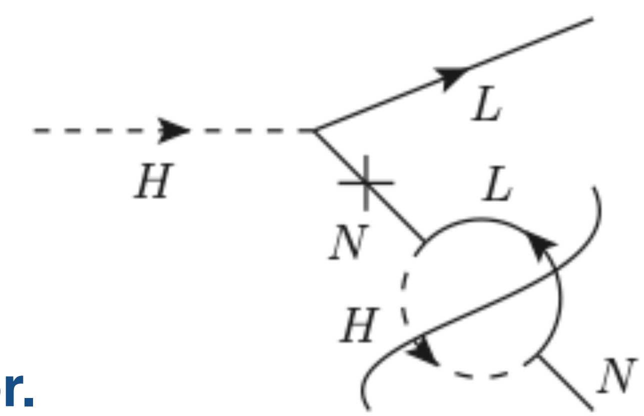
$$\frac{dY_{B-L}}{dt} = (\epsilon_{\rm CP}\Gamma_V)(Y_N - Y_N^{\rm eq}) - \Gamma_{\rm wash-out}\, Y_{B-L}$$

Sufficient BAU abundance can be obtained from:

- **Early decoupling** of wash-out: a naive example above

To suppress wash-out, one may alternatively **stop EW sphaleron** processes when **ΔB** reaches its maximum:

[e.g. *Hambye & Teresi 1606.00017, where the BEH scalar may decay to generates* **ΔL** due to thermal corrections]



More freedom to have phase transition in a dark sector.

Symmetric DM in a **general BAU set-up:**

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Sufficient BAU abundance can be obtained from:

- **Strong deviation** from chemical equilibrium

Simplest: **thermal** leptogenesis

N - heavy Majorana neutrino

$$Y_N - Y_N^{\rm eq} = \frac{1}{\Gamma_{\rm tot}}\frac{dY_N}{dt} \simeq \frac{1}{\Gamma_{\rm tot}}\frac{dY_N^{\rm eq}}{dt} \ll 1$$

Symmetric DM in a **general BAU set-up:**

1. **C**, **CP** symmetry violation;
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source term — wash-out suppression

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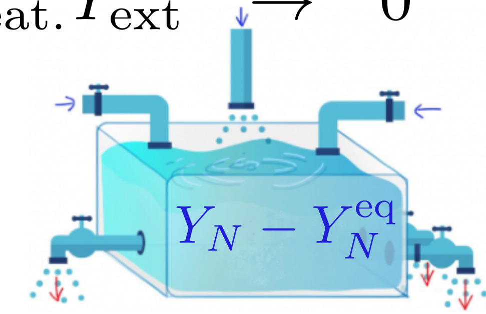
New: **quasi-static equilibrium** (QES)

【instead of thermal equilibrium】

$$\frac{dY_N}{dt} = -\Gamma_{\rm tot}(Y_N - Y_N^{\rm eq}) + \Gamma_{\rm creat.} Y_{\rm ext} \xrightarrow{\text{large rates}} 0$$

$$(Y_N - Y_N^{\rm eq}) \simeq \frac{\Gamma_{\rm creat.}}{\Gamma_{\rm tot}} Y_{\rm ext}$$



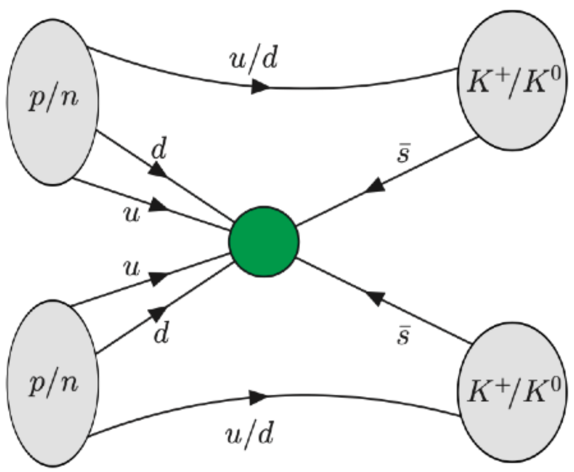
Dark sector naturally serves as external sources!

IV. Relevant **experimental searches**

A meta-stable **B-violating** particle *[χ_M-like particle]*

Set it to be a Majorana fermion χ_M with $\mathcal{L}_{|\Delta B|=1} \supset \frac{\alpha_j}{\Lambda^2} (\bar{u}_j P_L \chi_M) (\bar{d}_k P_L d_l^c) + h.c.$

1. Strong constraints from **di-nucleon decay & n-nbar oscillation**:



[*Aitken, MaKeen et al. 1708.01259*]

e.g. for (uds): $\frac{\alpha_j^2}{m_M \Lambda^4} \lesssim \frac{10^{-10}}{\text{TeV}^5}$

To have successful baryogenesis and nucleosynthesis, we choose **heavy quarks**, e.g. (cds), (udb).

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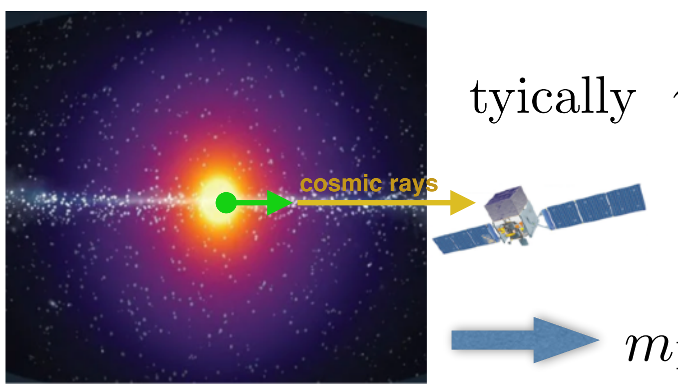
1. Strong constraints from **di-nucleon decay & n-nbar oscillation**:

→ **heavy quarks**, e.g. (cds), (udb).

2. **On-shell χ_M from DM annihilations**:

at **Galactic centre**: indirect detection

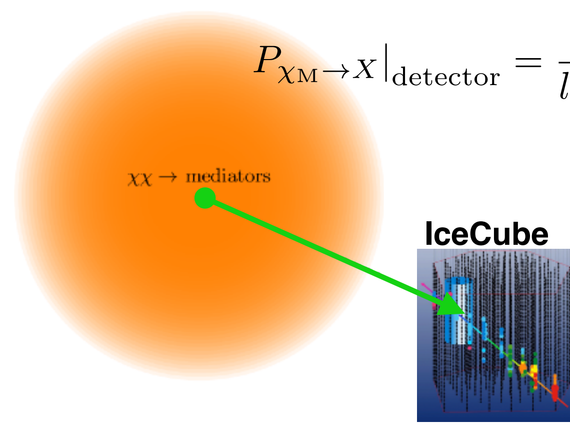


tyically $\tau_M \sim 10^{-7} - 10^{-2}\,\mathrm{sec}$

→ $m_{DM} \geq \mathcal{O}(10^2)\,\mathrm{GeV}$

inside **the Sun**: DM (in)direct detection

$$P_{\chi_M \to X}|_{\rm detector} = \frac{V_{\rm detector}}{l_M \cdot 4\pi r^2_{\rm Earth}} \approx 0.8 \times 10^{-13} \left(\frac{0.02\,\mathrm{sec}}{\tau\sqrt{m^2_{DM}/m^2_M - 1}}\right)$$



assuming one event per year:

→ $\sigma^{SI}_{\chi N} \sim 10^{-45} - 10^{-46}\,\mathrm{cm}^2$

Weak even in this best scenario.

A meta-stable **B-violating** particle *[χ_M-like particle]*

Set it to be a Majorana fermion χ_M with $\mathcal{L}_{|\Delta B|=1} \supset \frac{\alpha_j}{\Lambda^2} \left(\bar{u}_j P_L \chi_{\rm M}\right) \left(\bar{d}_k P_L d_l^c\right) + h.c.$

1. Strong constraints from **di-nucleon decay & n-nbar oscillation**:

→ **heavy quarks**, e.g. (cds), (udb).

2. **On-shell χ_M from DM annihilations**:

→ $m_{\rm DM} \geq \mathcal{O}(10^2)\,{\rm GeV}$

→ $\sigma^{\rm SI}_{\chi N} \sim 10^{-45} - 10^{-46} {\rm cm}^2$

Weak even in this best scenario.

3. **Neutron electric dipole moment** bounds on CP-violations:

→ use only **right-handed quarks** and left-handed anti-quarks

(to have further Yukawa suppression [see e.g. *N.Yamanaka et al. 1703.01570*])

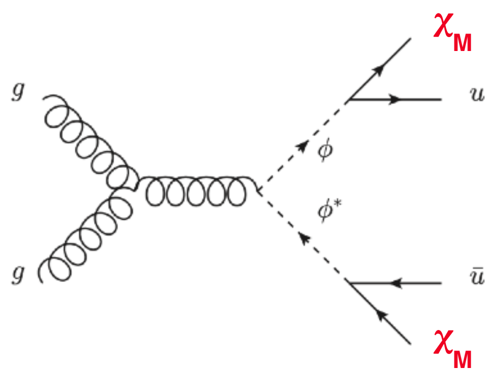
A **meta-stable** B-violating particle *[χ_M-like particle]*

- **Collider**: displaced vertices & missing ET

$$\mathcal{L}_{\rm UV} \supset \alpha_j\, \phi(\bar{u}_j P_L \chi_{\rm M}) + h.c.$$

coloured heavy scalar

Meta-stable fermion



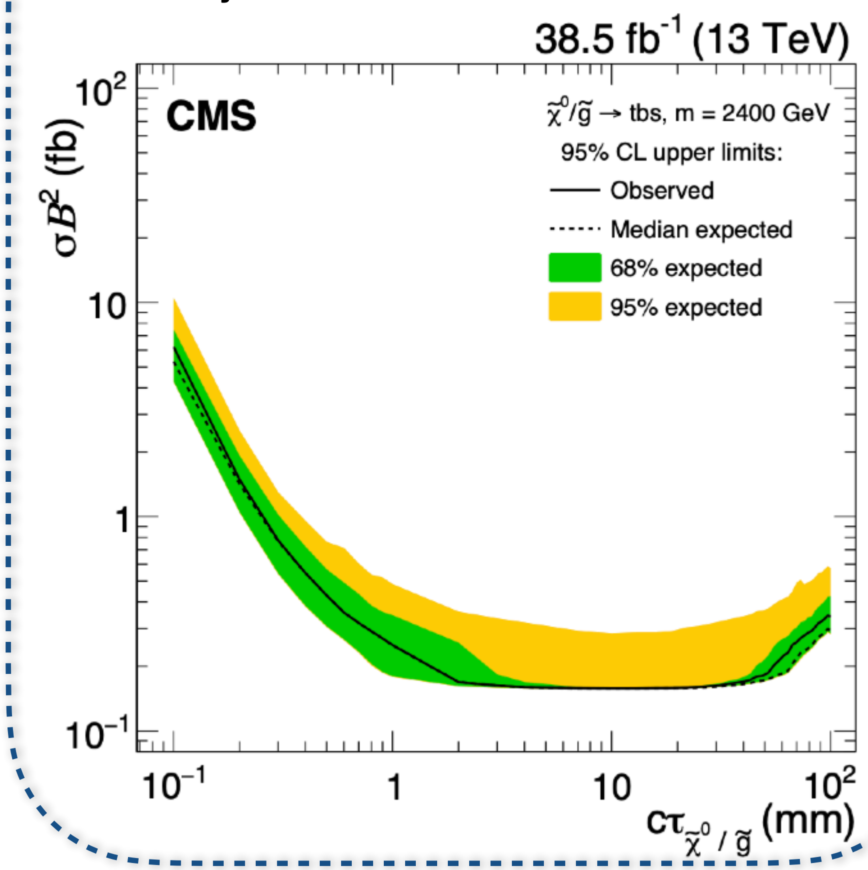
With 10 TeV scalar, production is suppressed: $\sigma_{\rm M} \sim \left(\frac{|\alpha|}{10^{-2}}\right)^4$ fb.

Small coupling to create visible displaced vertices:

$$c\gamma\tau_{\rm M} = 4\,{\rm cm}\left(\frac{\gamma}{10}\right)\left(\frac{10^{-4}}{|\alpha|}\right)^2\left(\frac{1\,{\rm TeV}}{m_{\rm M}}\right)^5\left(\frac{m_\phi}{10\,{\rm TeV}}\right)^4$$

→ **Undetectable in LHC**, maybe possible in HL-LHC.

Displaced vertices search in multijet events [*CMS 1803.03078*]:



A **meta-stable** B-violating particle *[χ_M-like particle]*

- **Collider**: displaced vertices & missing ET

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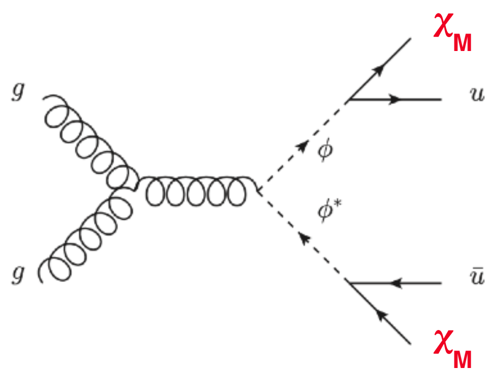


- **A early matter-dominated (EMD) Universe?**

TeV dark freeze-out at t ~ 10^{-10} sec, and χ_M **may dominate** later before BBN.

(leading to density dilution, which conserves $\Omega_B/\Omega_{\rm DM}$)

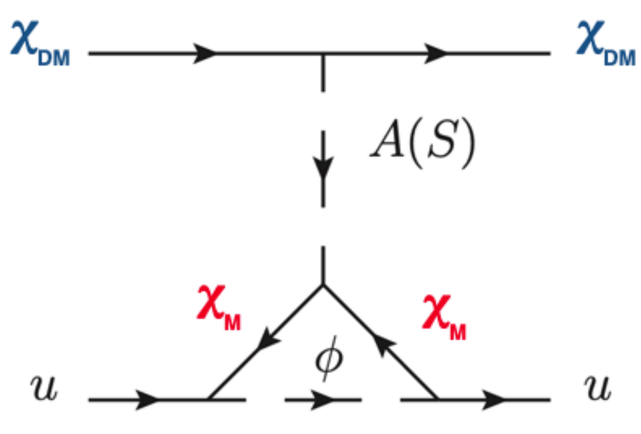
During EMD, the **sub-horizon density perturbations grow** linearly, at most:

$$L_{\rm co-moving} = \tau_{\rm M} \left(\frac{s(T_{\rm EDM})}{s(T_0)}\right)^{1/3} \approx 10^{-5}\sqrt{\frac{\tau_{\rm M}}{0.02\,{\rm s}}}\,{\rm Mpc}\,,$$

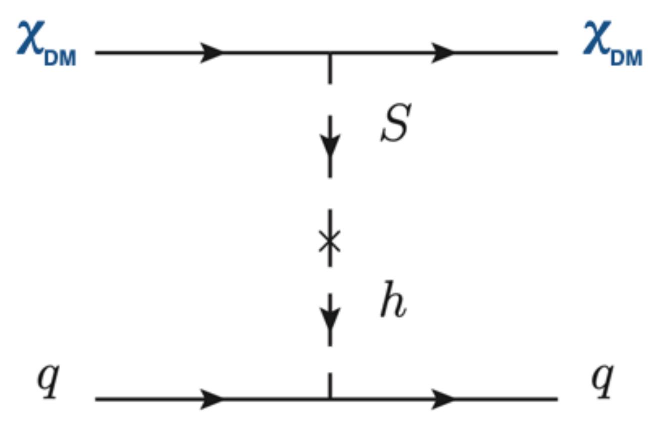
which corresponds to $10^{-4}M_\odot$, and future Pulsar Timing Arrays may reach it [*K. Zurek et al 2005. 03030, 2012.09857, …*].

DM signals within concrete models

- **DM direct detection**:



a) loop-induced



b) direct portals

a) suppressed by large intermediate scales

$$\sigma^{\rm SI}_{\chi N} \sim \frac{f_N^2}{256\pi^5}\left[\frac{\alpha^2 m_{\rm M} m_\chi m_N^2}{m_\phi^2 m_S^2 (m_\chi + m_N)}\right]^2$$

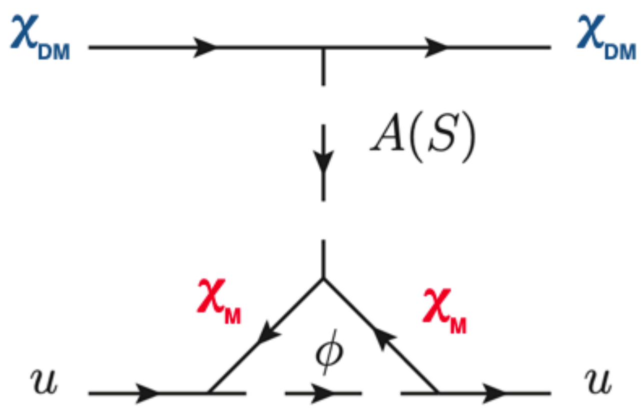
b) suppressed by small mixing

$$\sigma^{\rm SI}_{\chi N} \sim 10^{-42}\theta^2_{Sh}\,{\rm cm}^2$$

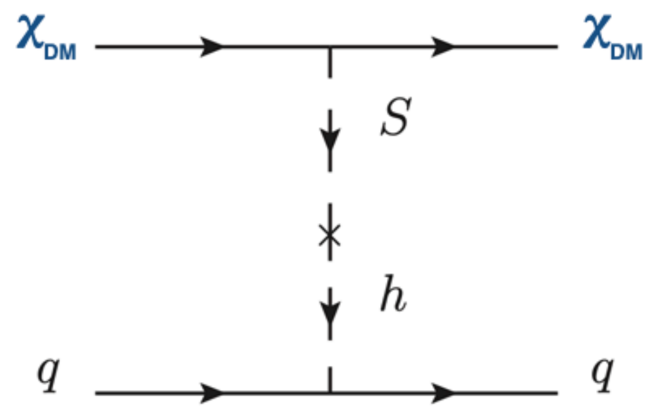
➡ **unlikely** for a decoupled sector.

DM signals within concrete models

- **DM direct detection**:



a) loop-induced



b) direct portals

a) suppressed by large intermediate scales

$$\sigma^{\rm SI}_{\chi N} \sim \frac{f_N^2}{256\pi^5}\left[\frac{\alpha^2 m_{\rm M} m_\chi m_N^2}{m_\phi^2 m_S^2 (m_\chi + m_N)}\right]^2$$

b) suppressed by small mixing

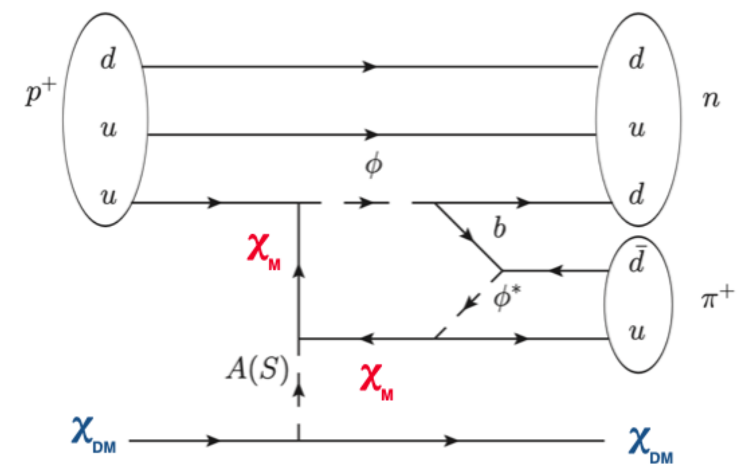
$$\sigma^{\rm SI}_{\chi N} \sim 10^{-42}\theta^2_{Sh}\,{\rm cm}^2$$

→ **unlikely** for a decoupled sector.

- **Exotic signatures:**

e.g. DM-induced **proton decay**

→ Unlikely in the Local Group, maybe in neutron star, to be investigated *[Huang&Zhao 1312.0011]*.



V. Conclusions

Conclusions

- **Standard cosmology**, including DM&BAU, is well established;
- The similar DM&BAU abundances: shared origin, coincidence, or anthropic principle?
- For **asymmetric DM, a shared origin** could be theoretically natural;
- **Symmetric DM** within co-genesis needs to be quantitatively explored.
- **Dark sector** naturally provides **suppressed wash-out** and/or **strong deviation** from SM thermal equilibrium.

Discovery of new physics will help 😉 *[+ muonic g-2, cosmic ray excesses, H0 tension, …].*

Backup

Flavor violation [2111.03082]:

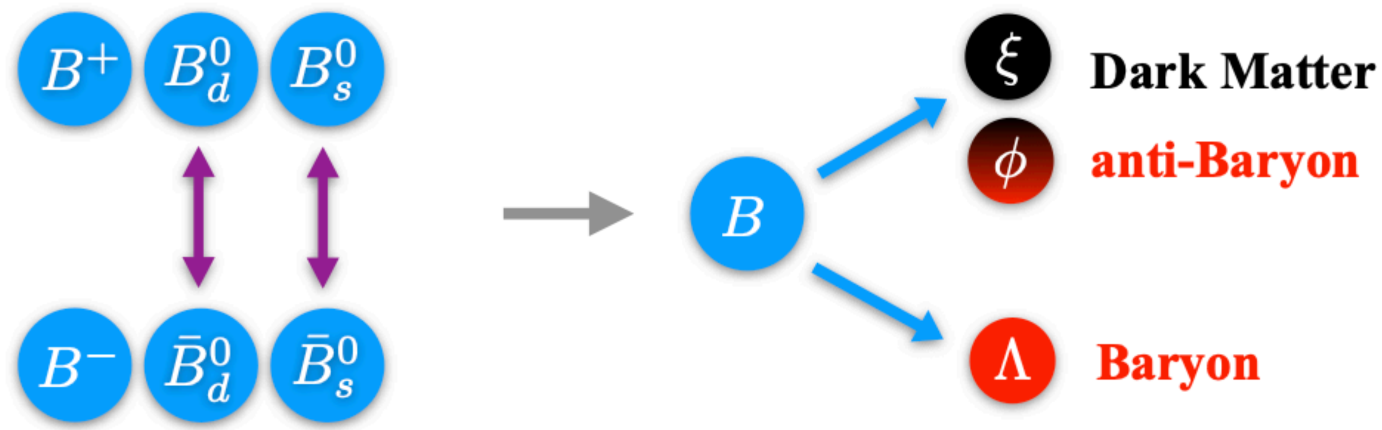
baryon asymmetry after sphaleron decoupling is given

$$Y_B \simeq \frac{3A(x_{\rm Sp})}{13\pi^2} \sum_{f=e,\mu,\tau} y_f^2 Y_{\Delta_f},$$

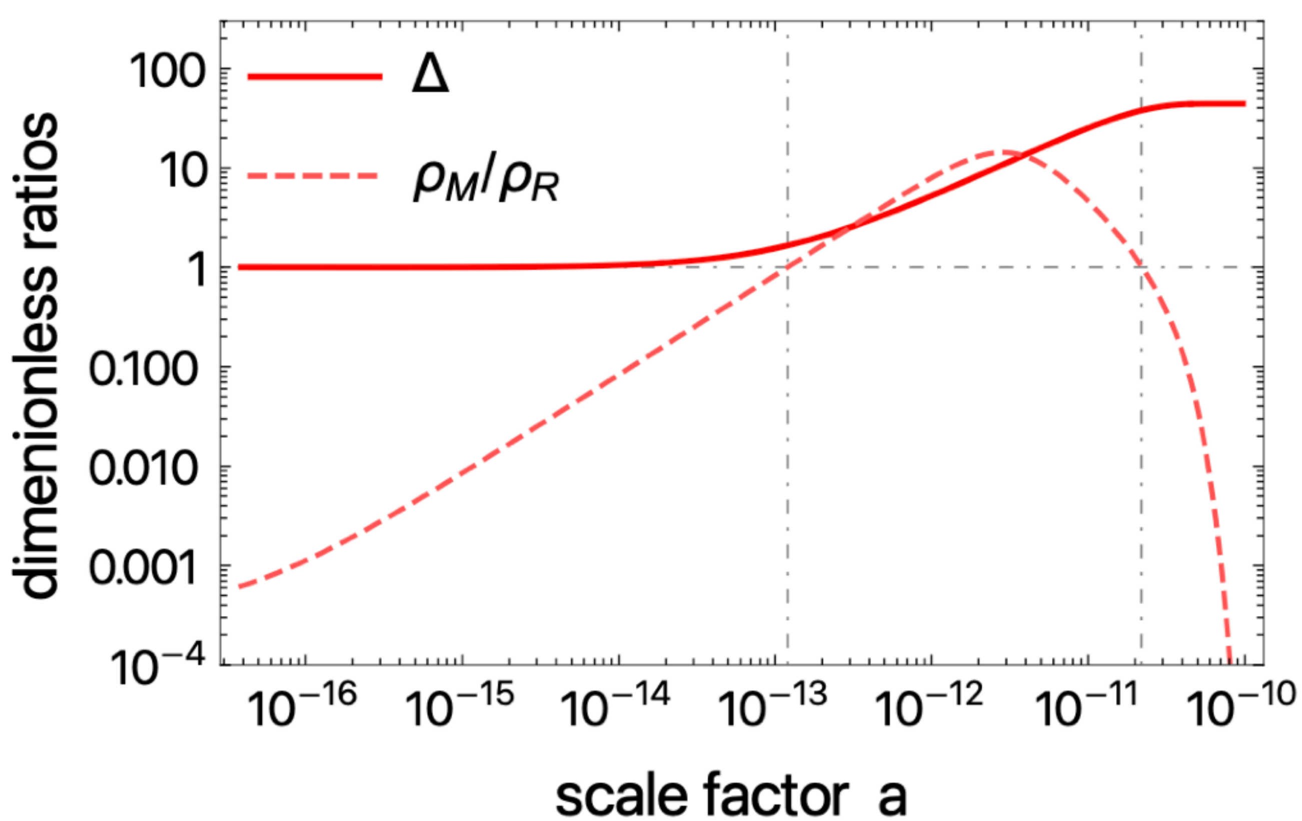
for vanishing total $B-L$, where

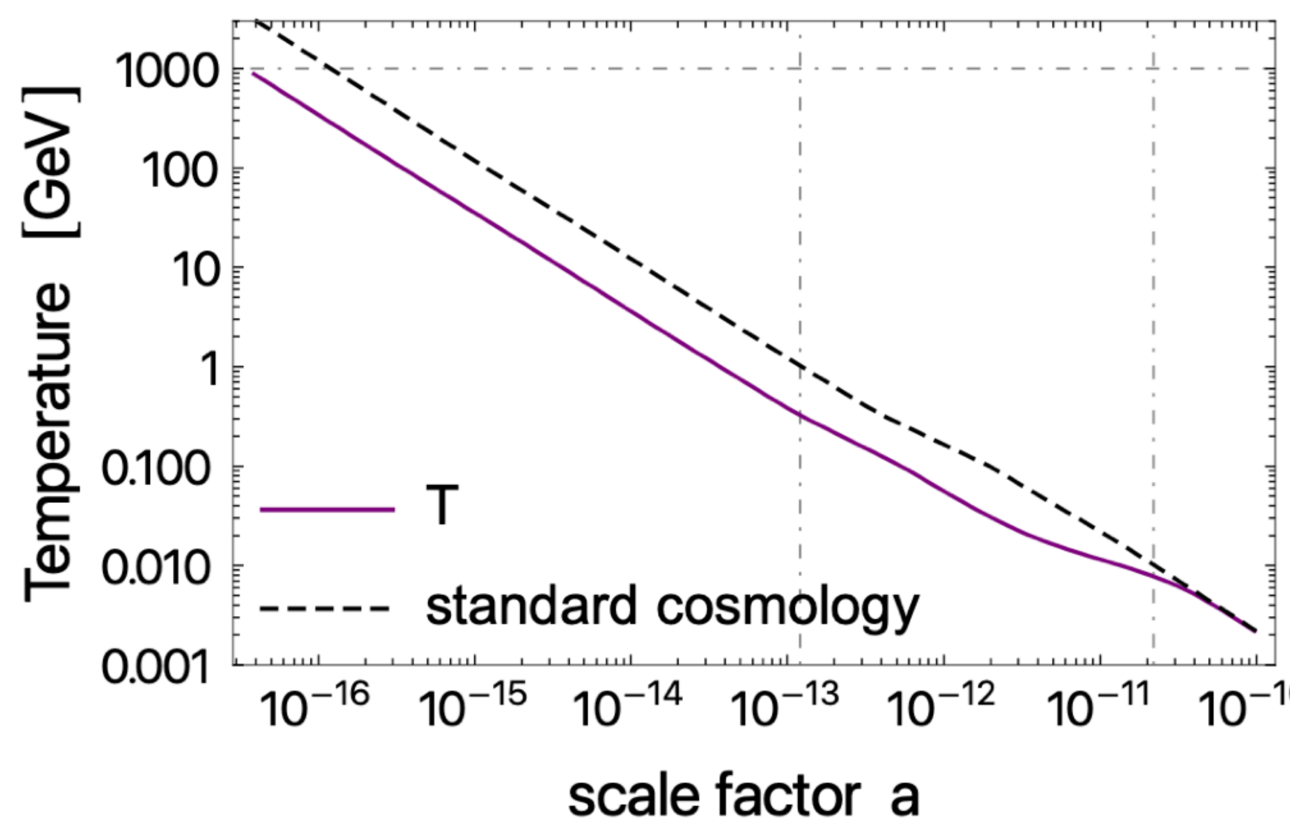
$$A(x) \equiv \frac{13(1034+2473x^2+792x^4)}{48(869+333x^2)}, \quad A(x_{\rm Sp}) \simeq 1.3.$$

Mesogenesis [1810.00880, 2101.02706, 2109.09751,…]



Entropy dilution:



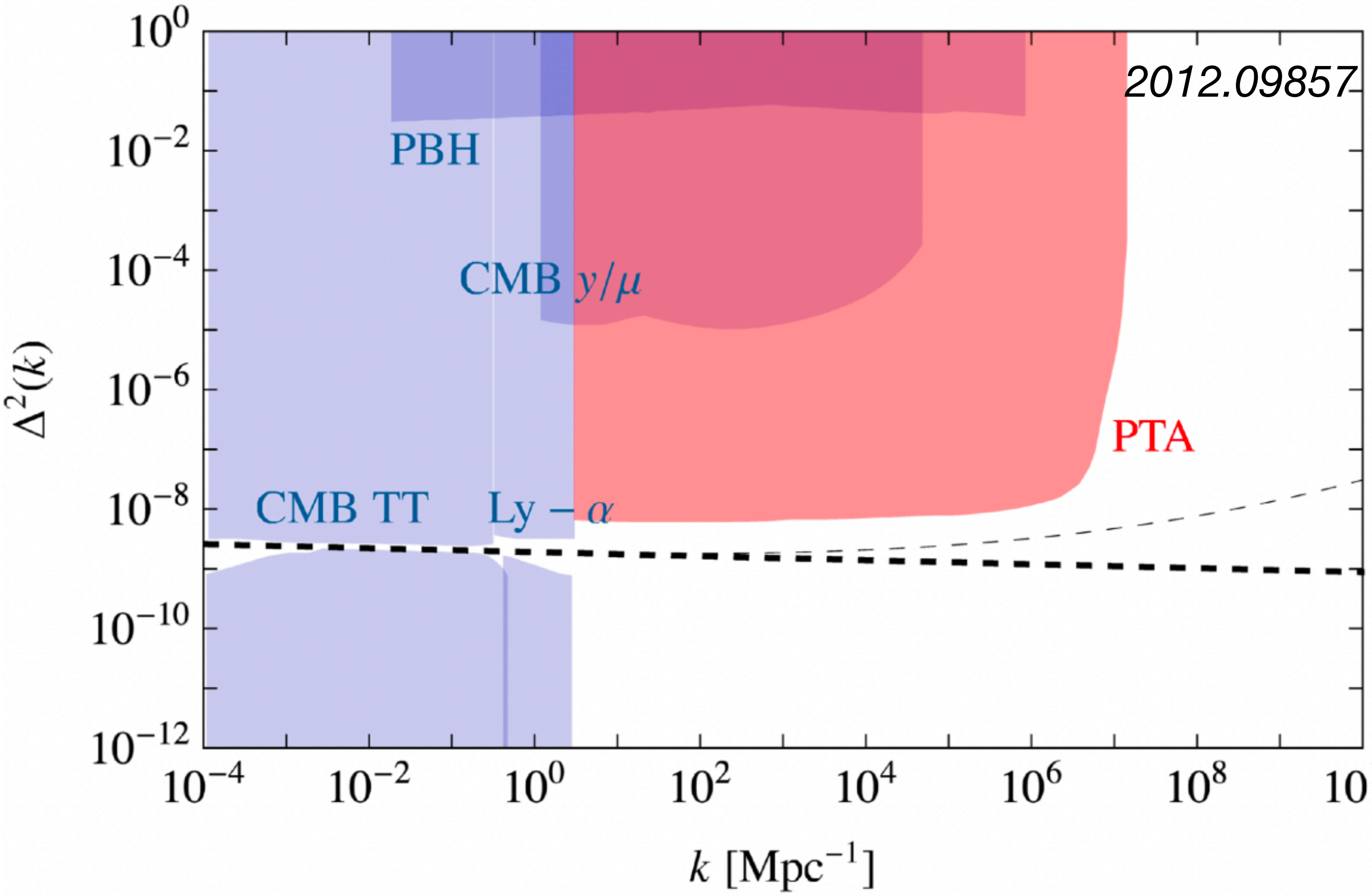


Sub-halo scale detection?

Still need the **halo-mass distributions** *from PTA, CTA, lensing, astrometry, stellar streams, …*

Also probed by distortions in primordial GW in the far future.

[1804.01991, 1903.04218, 2002.08962, 2005.03030, 2009.06639, 2012.09857]



- **Astrometry** from Nancy Grace Roman Space Telescope 【2108.10886】