Early Kinetic Decoupling Effect on Forbidden Dark Matter

刘学文 烟台大学

arXiv: 2301.12199

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Outline

- Early Kinetic Decoupling (EKD): High Accuracy of Calculations
- Dealing with EKD: Coupled Boltzmann Equations (CBE)
- EKD on Forbidden Dark Matter: One order of magnitude larger
- Summary

1 Early Kinetic Decoupling

Boltzmann Equation

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$$E(\frac{\partial}{\partial t} - H\vec{p} \cdot \frac{\partial}{\partial \vec{p}})\, f_\chi = C\, [f_\chi]$$

Boltzmann Equation

- Evolution of Phase space density f_χ

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- Evolution of Phase space density f_χ
- Liouville Operator: Change in spacetime of the DM f_χ
- $C\,[f_\chi]$: Collision term, interactions between DM and other particles (including itself) that may alter f_χ

Boltzmann Equation: Traditional or “Standard” Treatment

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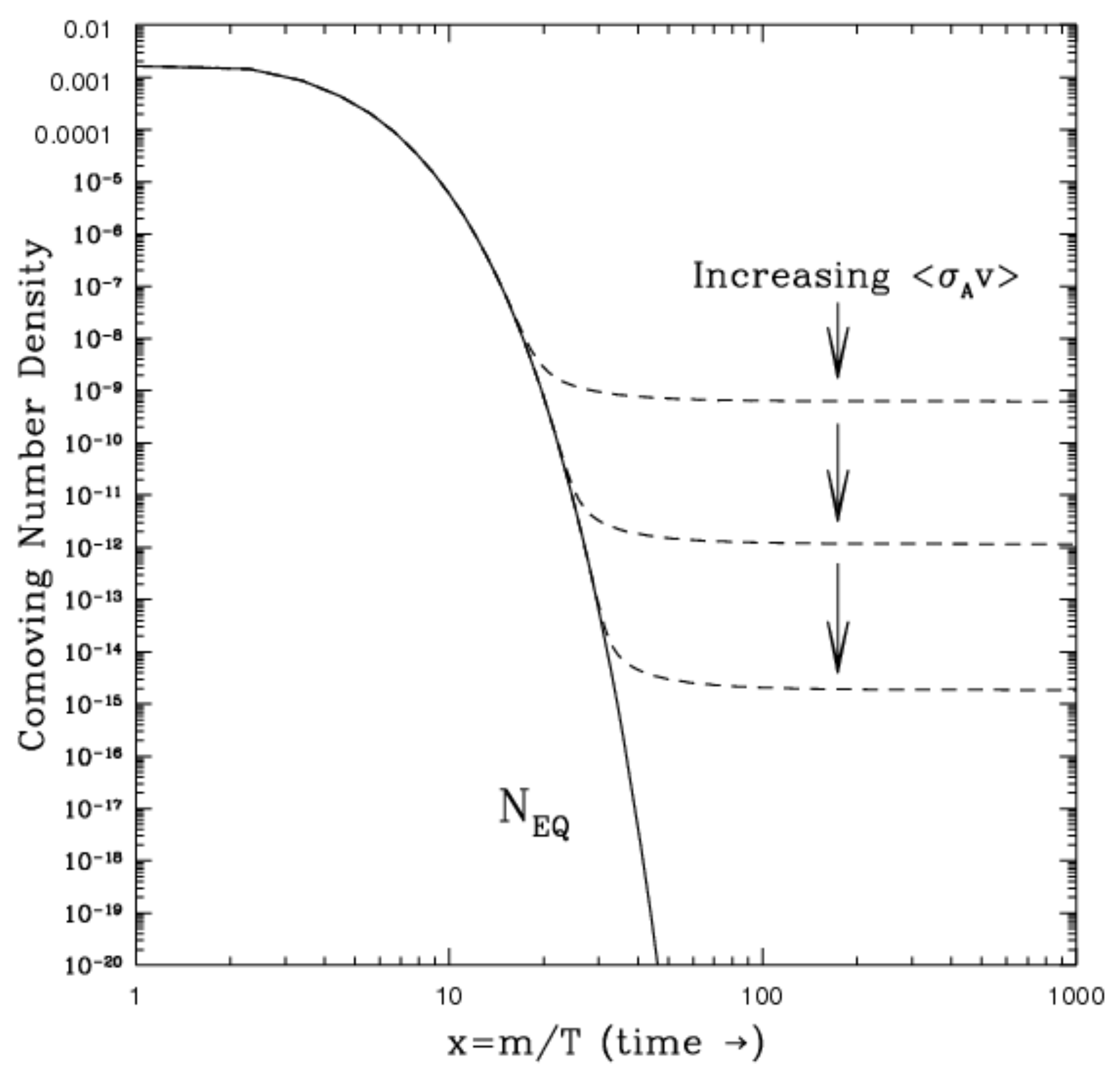

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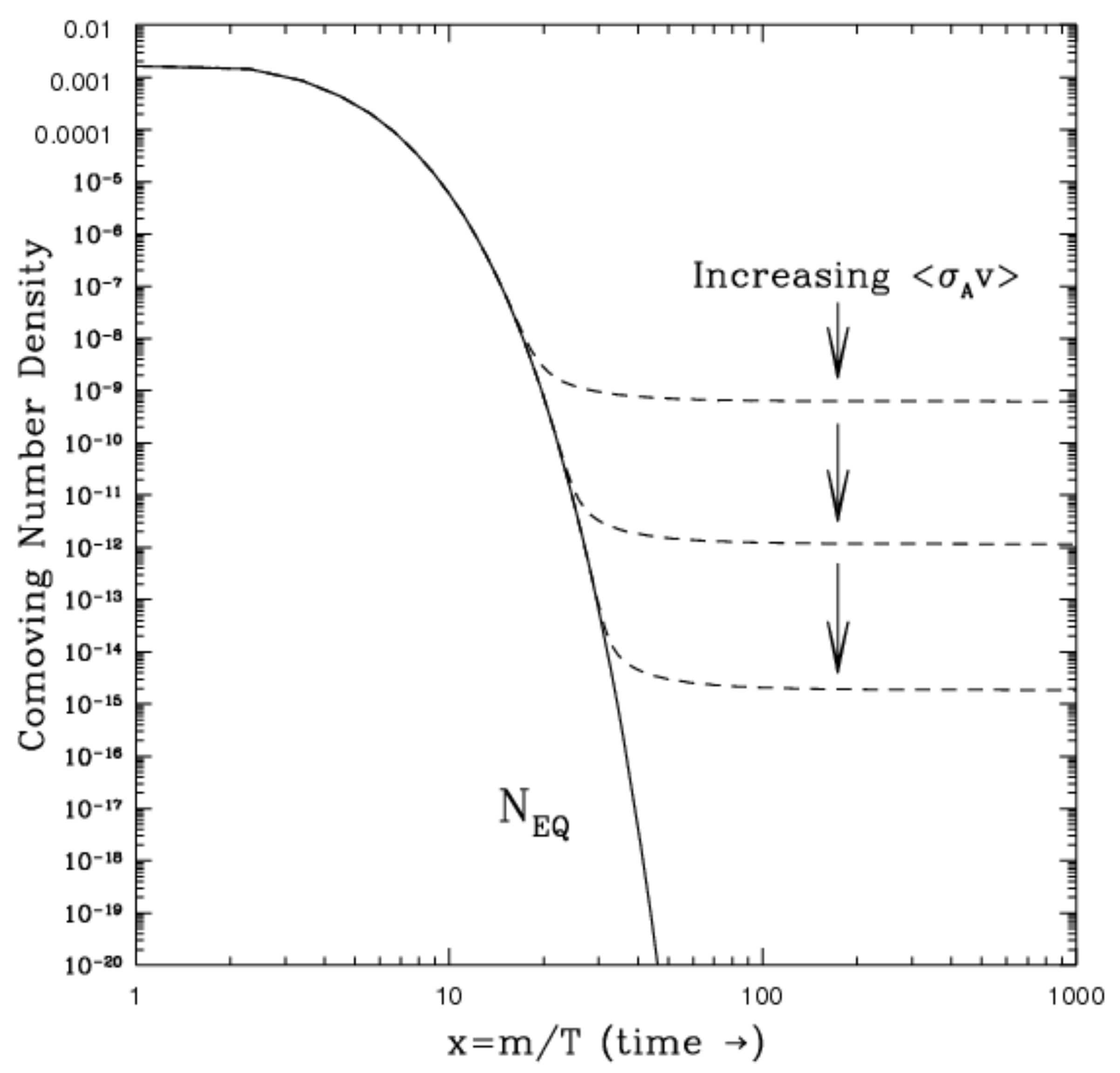

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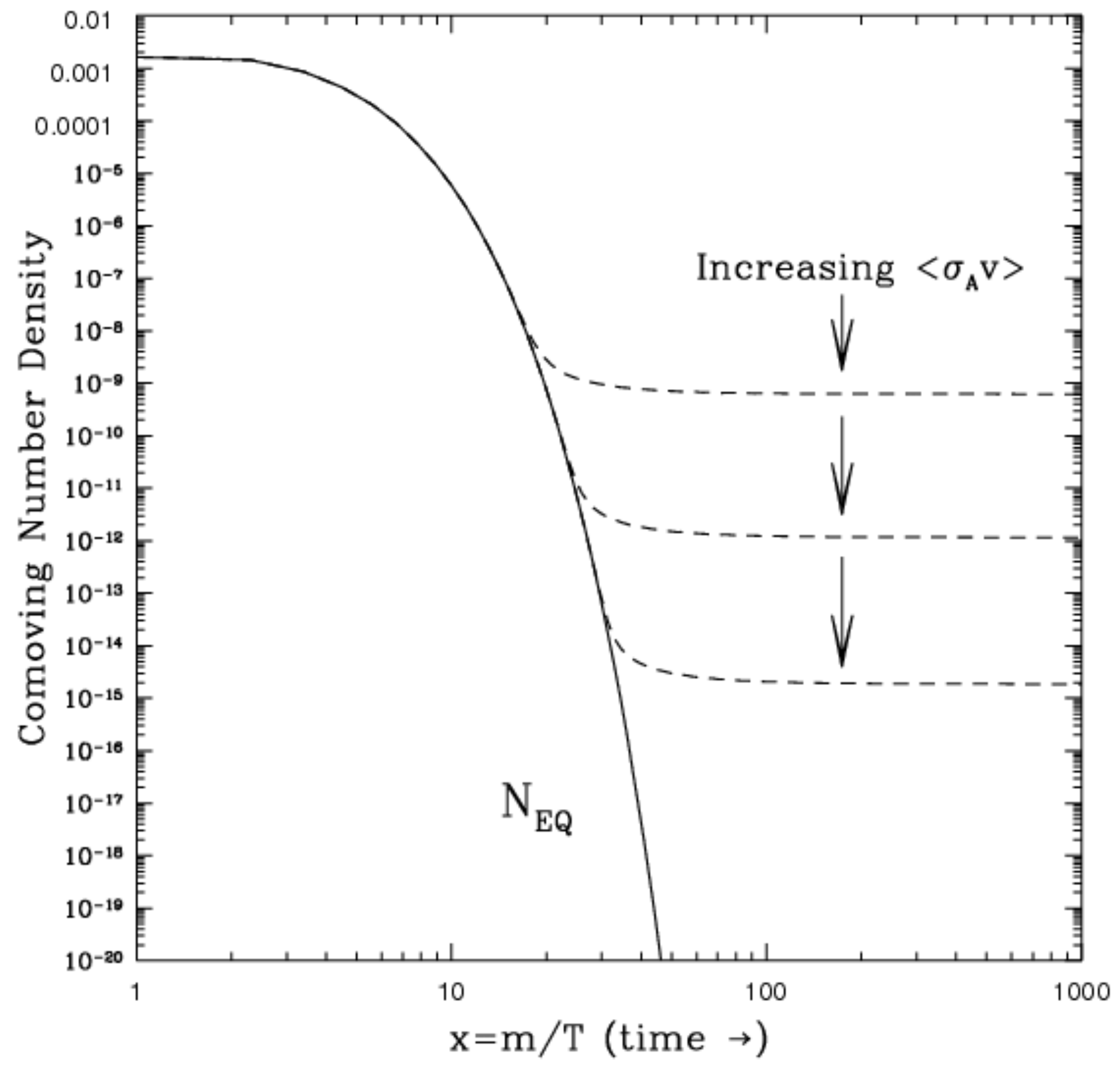
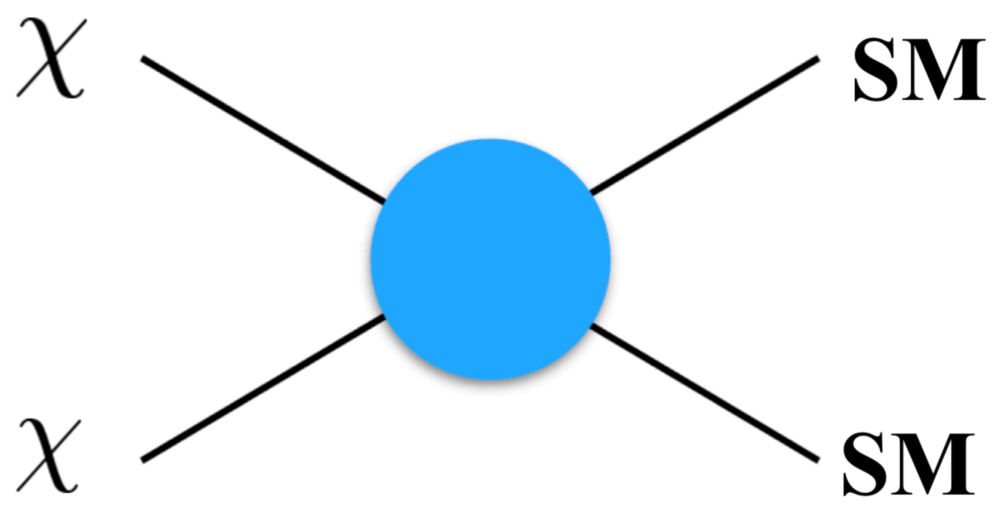
- Using $C[f_\chi] = C_{\mathrm{ann.}}$, from annihilation process





Boltzmann Equation: An assumption

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- Kinetic equilibrium determines the form of the phase space density

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$$f_\chi = \frac{n_\chi}{n_\chi^{\rm eq}} f_\chi^{\rm eq}\,(T_{\rm SM})$$

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- Kinetic equilibrium is NOT satisfied at some scenarios
- DM kinetic decouples from the thermal bath in an EARLY stage
- i.e. Early Kinetic Decoupling
- DM has its own temperature than SM, different phase space density

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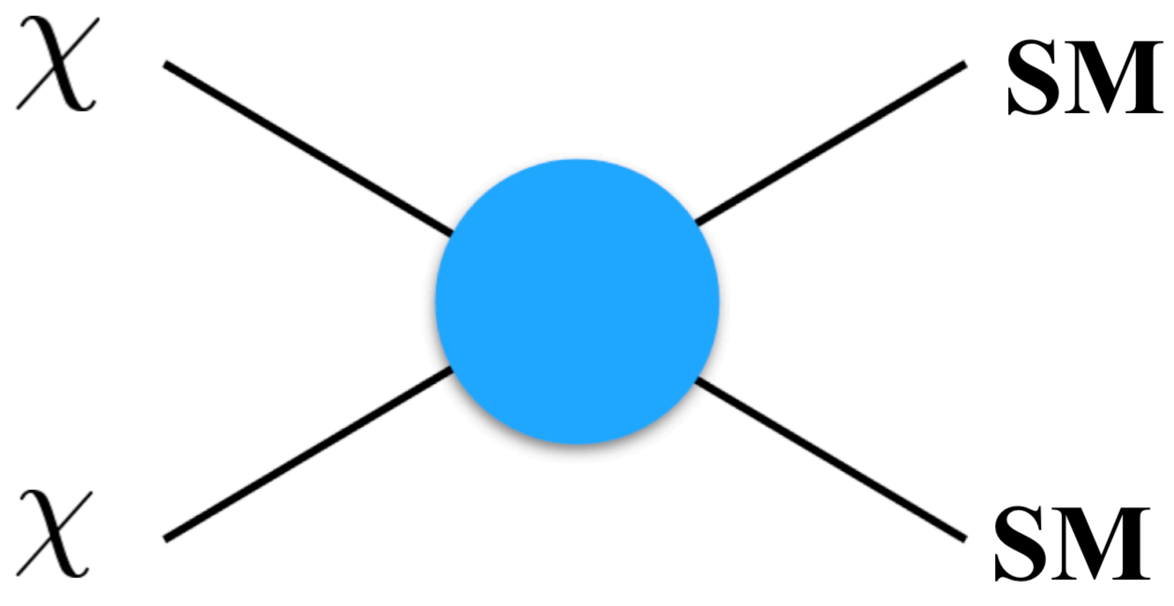
$$f_\chi \left(T_{\mathrm{SM}}\right) \to f_\chi \left(T_{\mathrm{DM}}\right)$$

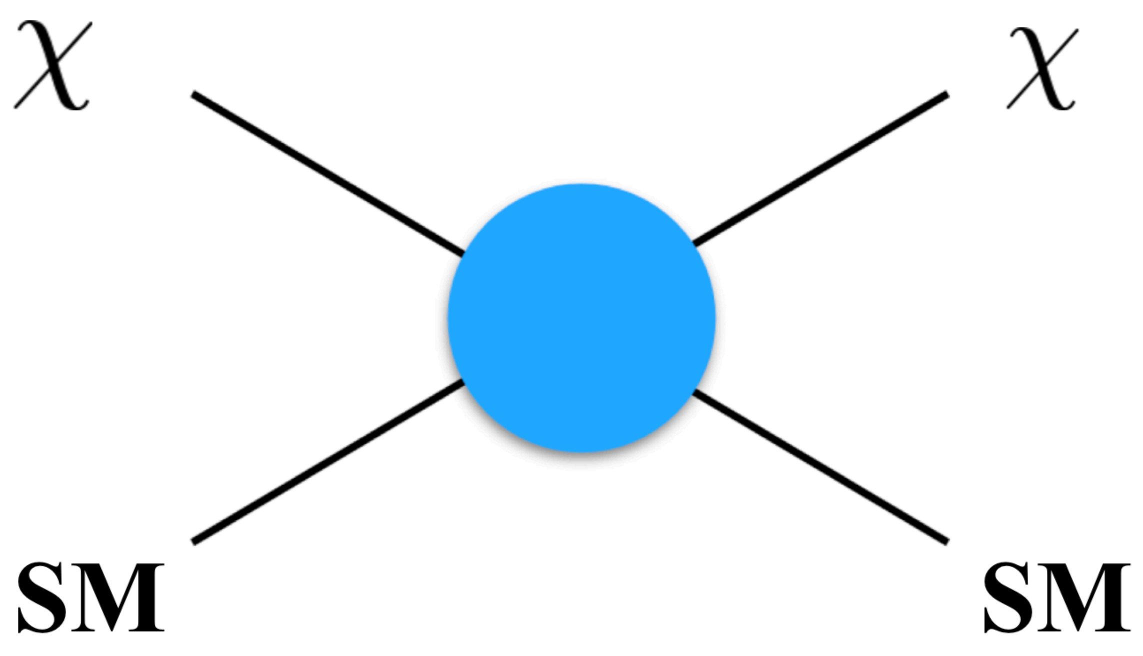
2 Coupled Boltzmann Equations (CBE)

Dealing with Early Kinetic Decoupling

- Including a NEW collision term from elastic scattering



$$C[f_\chi] = C_{\text{ann.}}[f_\chi] + C_{\text{el.}}[f_\chi]$$



- Define the temperature for DM:

$$T_\chi = \frac{g_\chi}{3n_\chi} \int \frac{d^3p}{(2\pi)^3} \frac{\vec{p}^{\,2}}{E} f_\chi(\vec{p})$$

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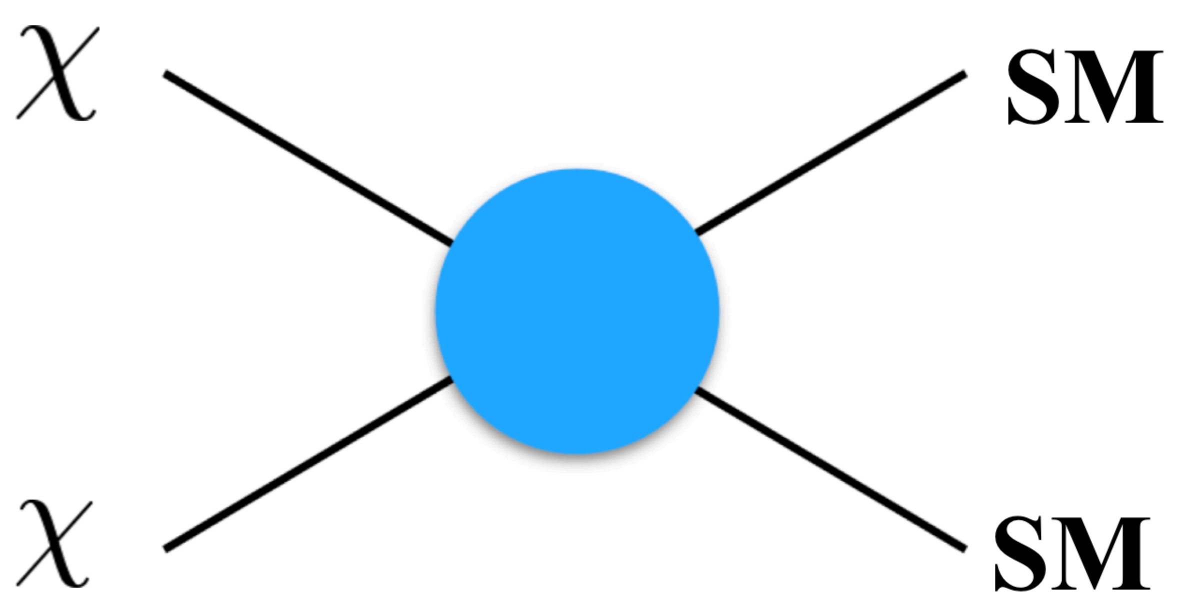
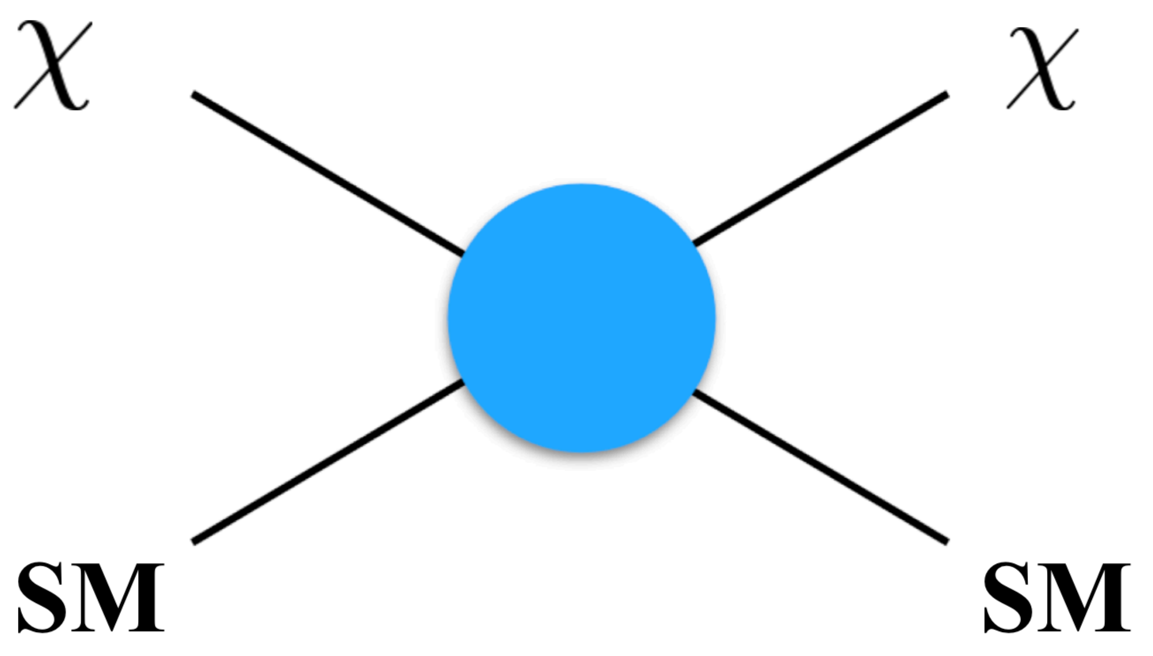




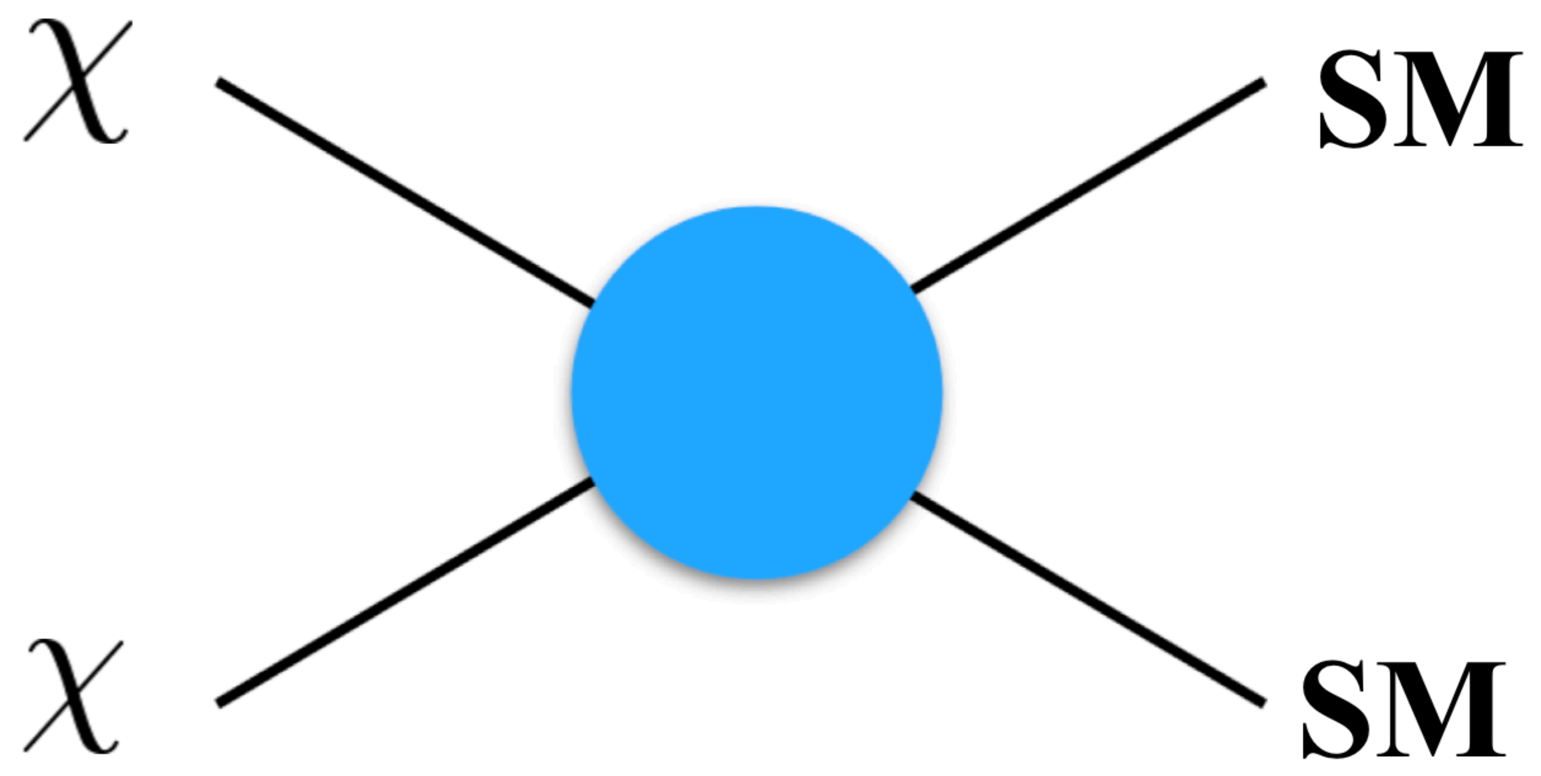
Collision term from annihilation

$$C_{\text{ann.}} = \frac{1}{2g_\chi}\sum\int\frac{d^3p'}{(2\pi)^3 2E_{p'}}\int\frac{d^3k}{(2\pi)^3 2E_k}\int\frac{d^3k'}{(2\pi)^3 2E_{k'}}$$

$$\times(2\pi)^4\delta^4(p+p'-k-k')$$

$$\times\Big[-|\mathscr{M}_{\chi\chi\to\mathscr{B}\mathscr{B}'}|^2 f_\chi(\vec{p})f_\chi(\vec{p}')(1\pm f^{\text{eq}}_{\mathscr{B}}(\vec{k}))(1\pm f^{\text{eq}}_{\mathscr{B}'}(\vec{k}'))$$

$$+|\mathscr{M}_{\mathscr{B}\mathscr{B}'\to\chi\chi}|^2 f^{\text{eq}}_{\mathscr{B}}(\vec{k})f^{\text{eq}}_{\mathscr{B}'}(\vec{k}')(1\pm f_\chi(\vec{p}))(1\pm f_\chi(\vec{p}'))\Big]$$



NEW collision term from elastic scattering

$$C_{\text{el.}} = \frac{1}{2g_\chi} \sum \int \frac{d^3p'}{(2\pi)^3 2E_{p'}} \int \frac{d^3k}{(2\pi)^3 2E_k} \int \frac{d^3k'}{(2\pi)^3 2E_{k'}}$$

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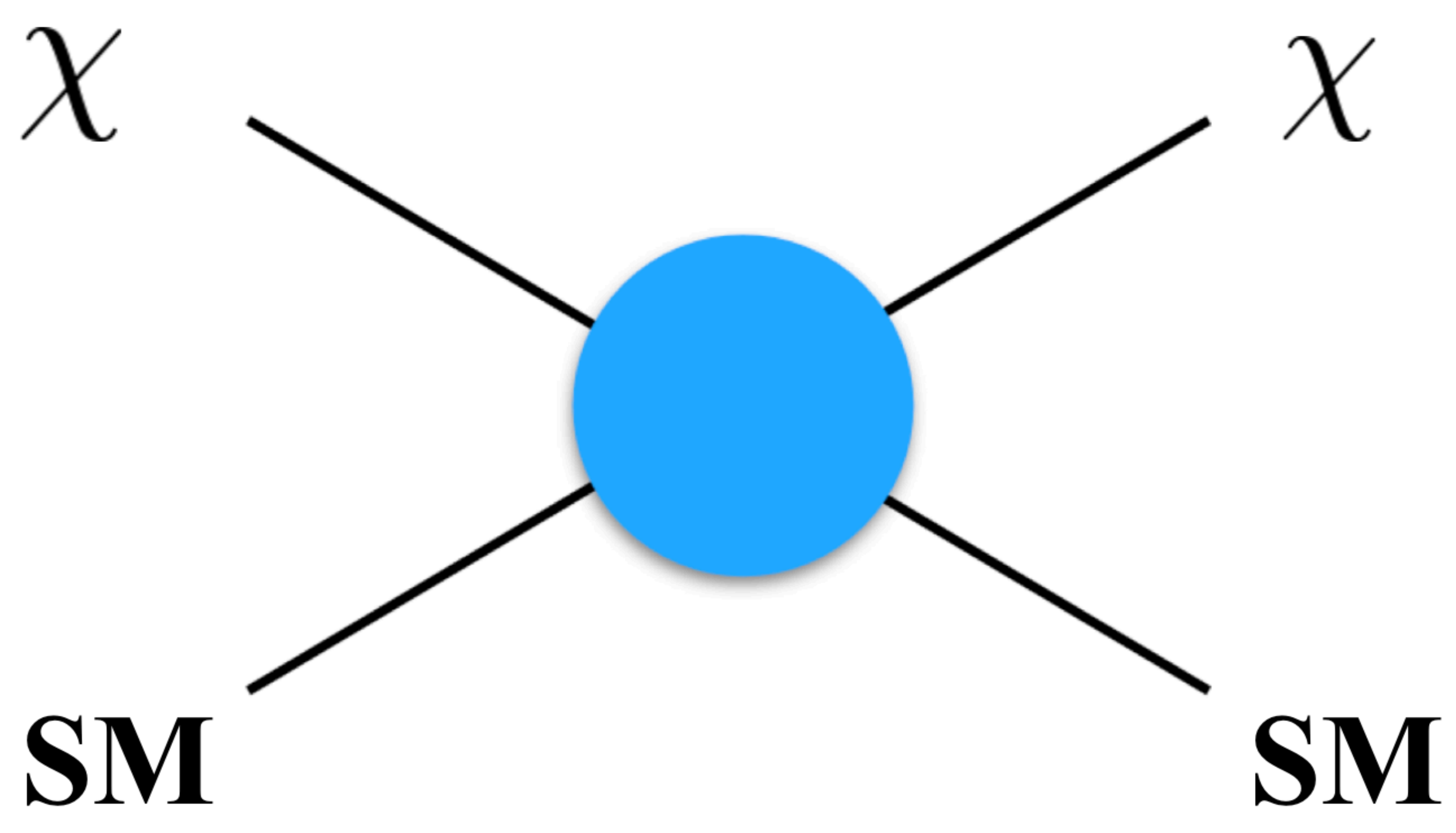
$$\times \Big[-|\mathscr{M}_{\chi\mathscr{B}\to\chi\mathscr{B}}|^2 f_\chi(\vec{p}) f^{\text{eq}}_{\mathscr{B}}(\vec{k})(1 \pm f_\chi(\vec{p}'))(1 \pm f^{\text{eq}}_{\mathscr{B}}(\vec{k}'))$$

$$+ |\mathscr{M}_{\chi\mathscr{B}\to\chi\mathscr{B}}|^2 f_\chi(\vec{p}') f^{\text{eq}}_{\mathscr{B}}(\vec{k}')(1 \pm f_\chi(\vec{p}))(1 \pm f^{\text{eq}}_{\mathscr{B}}(\vec{k})) \Big]$$



Early Kinetic Decoupling and Coupled Boltzmann Equation

- Integrating the Boltzmann Equation [2103.01944]

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$$g_\chi \int \frac{d^3p}{(2\pi)^3}\frac{1}{E} \quad \text{AND} \quad g_\chi \int \frac{d^3p}{(2\pi)^3}\frac{1}{E}\frac{\vec{p}^{\,2}}{E}\left(E(\frac{\partial}{\partial t} - H\vec{p}\cdot\frac{\partial}{\partial \vec{p}})\,f_\chi = C[f_\chi]\right)$$

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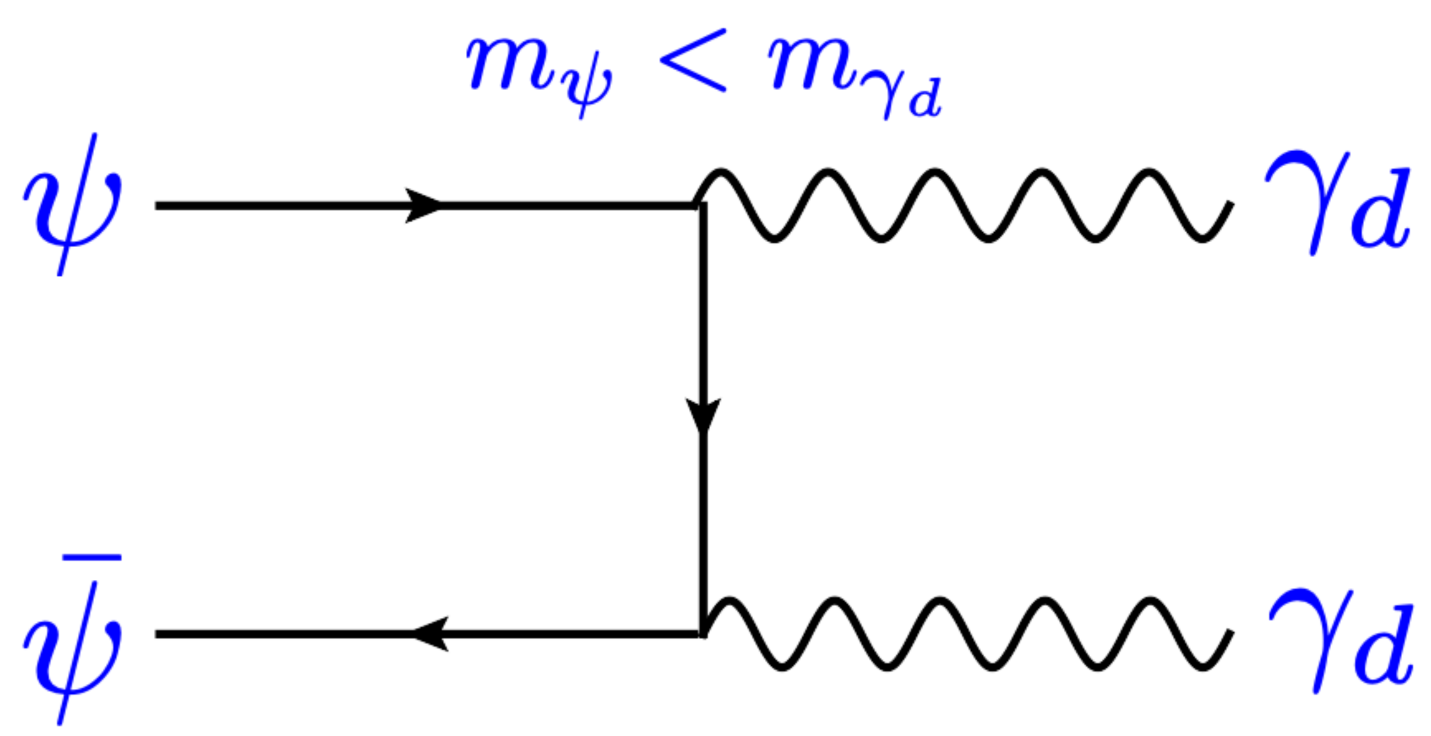
3 EKD on Forbidden Dark Matter

Forbidden Dark Matter

K. Griest, D. Seckel,
Phys.Rev.D 43 (1991) 3191-3203

- Forbidden: $m_\chi < m_{\rm SM}$
- Annihilations are forbidden at zero temperature
- Nonzero at finite temperature.



D'Agnolo, Ruderman, [1505.07107]

Our Forbidden Model

$$-\mathscr{L} \supset g_{ij}\phi\bar{l}_i l_j + g^A_{ij}\phi\bar{l}_i\gamma_5 l_j + g_\chi\phi\bar{\chi}\chi + g^A_\chi\phi\bar{\chi}\gamma_5\chi$$

- Particles: Fermionic DM χ, scalar ϕ , $l_i = \mu, \tau$
- Case: $l_i = e$ excluded by BBN and CMB
- Forbidden: $\Delta \equiv (m_\ell - m_\chi)/m_\chi > 0$
- Annihilation cross section exponentially suppressed

$$\langle\sigma v\rangle_{\chi\chi\to\ell\ell} = \langle\sigma v\rangle_{\ell\ell\to\chi\chi}\frac{(n_\ell^{\mathrm{eq}})^2}{(n_\chi^{\mathrm{eq}})^2} \simeq \langle\sigma v\rangle_{\ell\ell\to\chi\chi}e^{-2\Delta x}$$

Scattering term

- Non-relativistic DM, Fokker-Planck operator [1205.1914, 2004.10041]

$$C_{\rm el.} \simeq \frac{E}{2}\gamma(T)\left[TE\partial_p^2 + \left(2T\frac{E}{p} + p + T\frac{p}{E}\right)\partial_p + 3\right]f_\chi$$

- $\gamma(T)$ is the momentum transfer rate:

$$\gamma(T) = \frac{1}{3g_\chi m_\chi T}\int\frac{d^3k}{(2\pi)^3}f_{\mathscr{B}}^{\rm eq}(E_k)\left[1\mp f_{\mathscr{B}}^{\rm eq}(E_k)\right]\int_{-4k_{\rm cm}^2}^{0}{\rm d}t(-t)\frac{d\sigma}{dt}v \propto e^{-(\Delta+1)x}$$

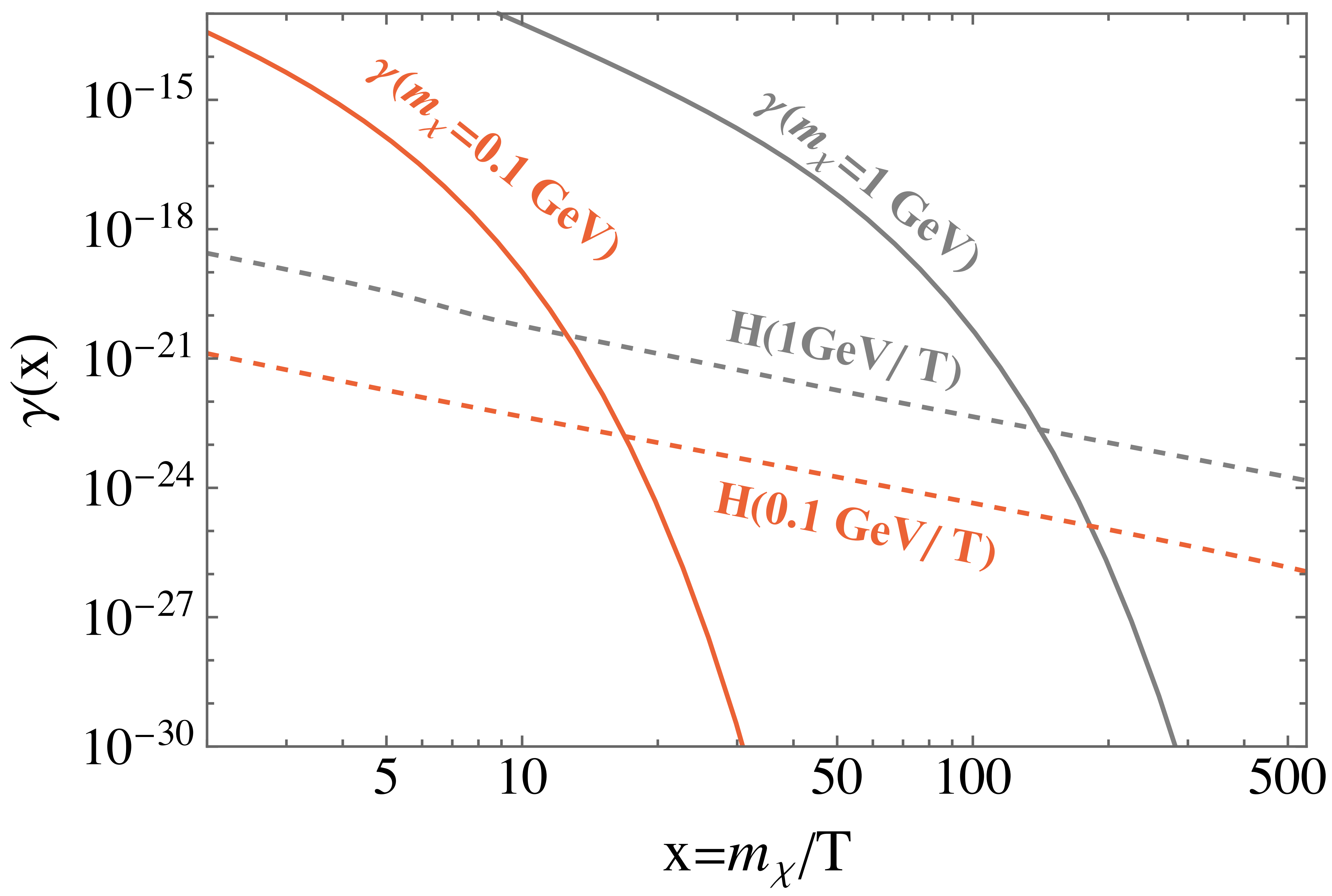
$\Delta + 1 > 1$ implies the scattering frequency experiences a strong suppression

EKD happens in Forbidden Dark Matter

- Hubble rate: $H(T) = \frac{\pi\sqrt{g_{\rm eff}}}{\sqrt{90}}\frac{T^2}{M_{\rm Pl}}$

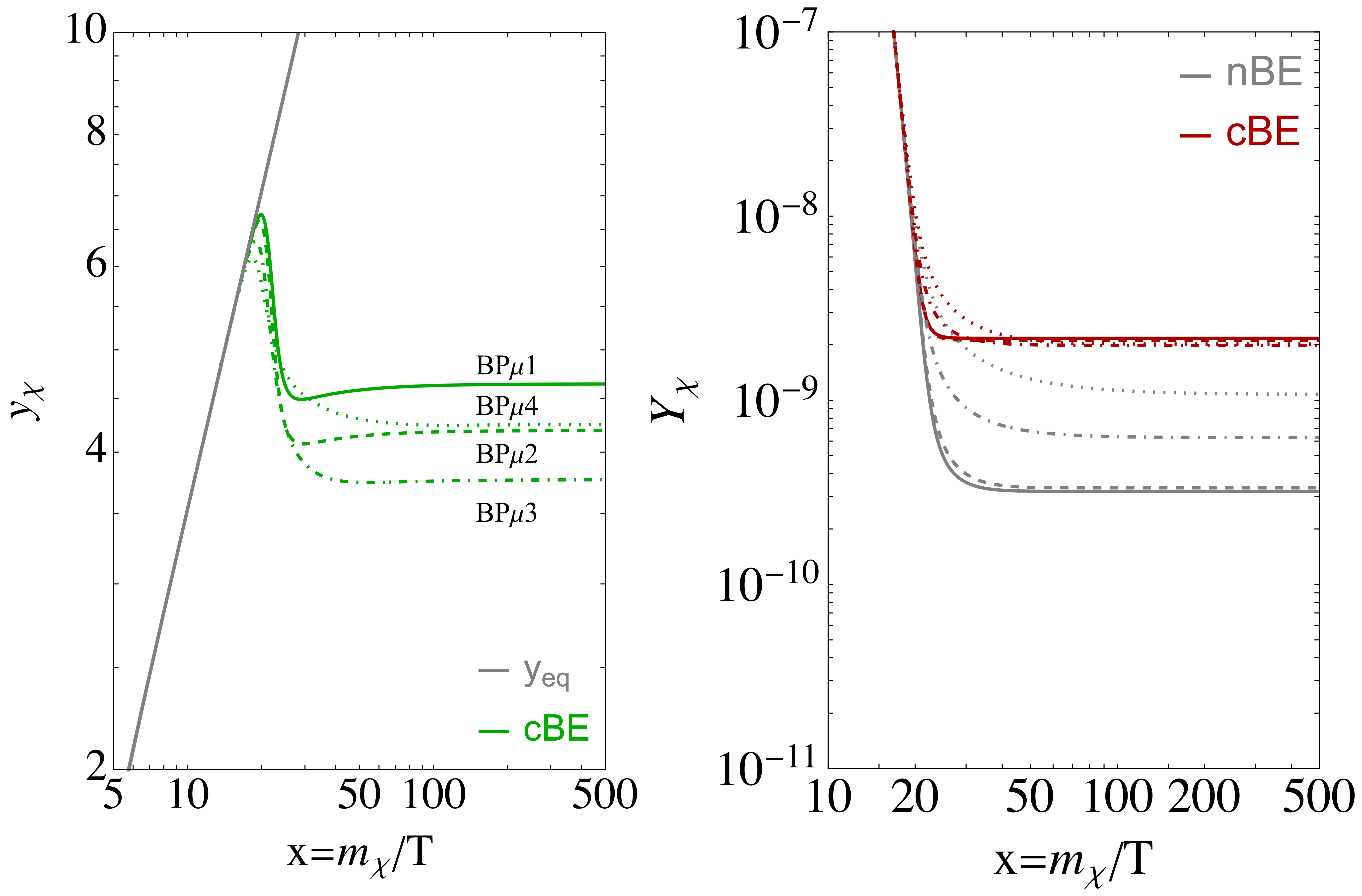
- $\gamma(T)$ becoming comparable with H(T) happens much earlier than traditional WIMP

- The kinetic decoupling starts at x~20 (freeze-out time)



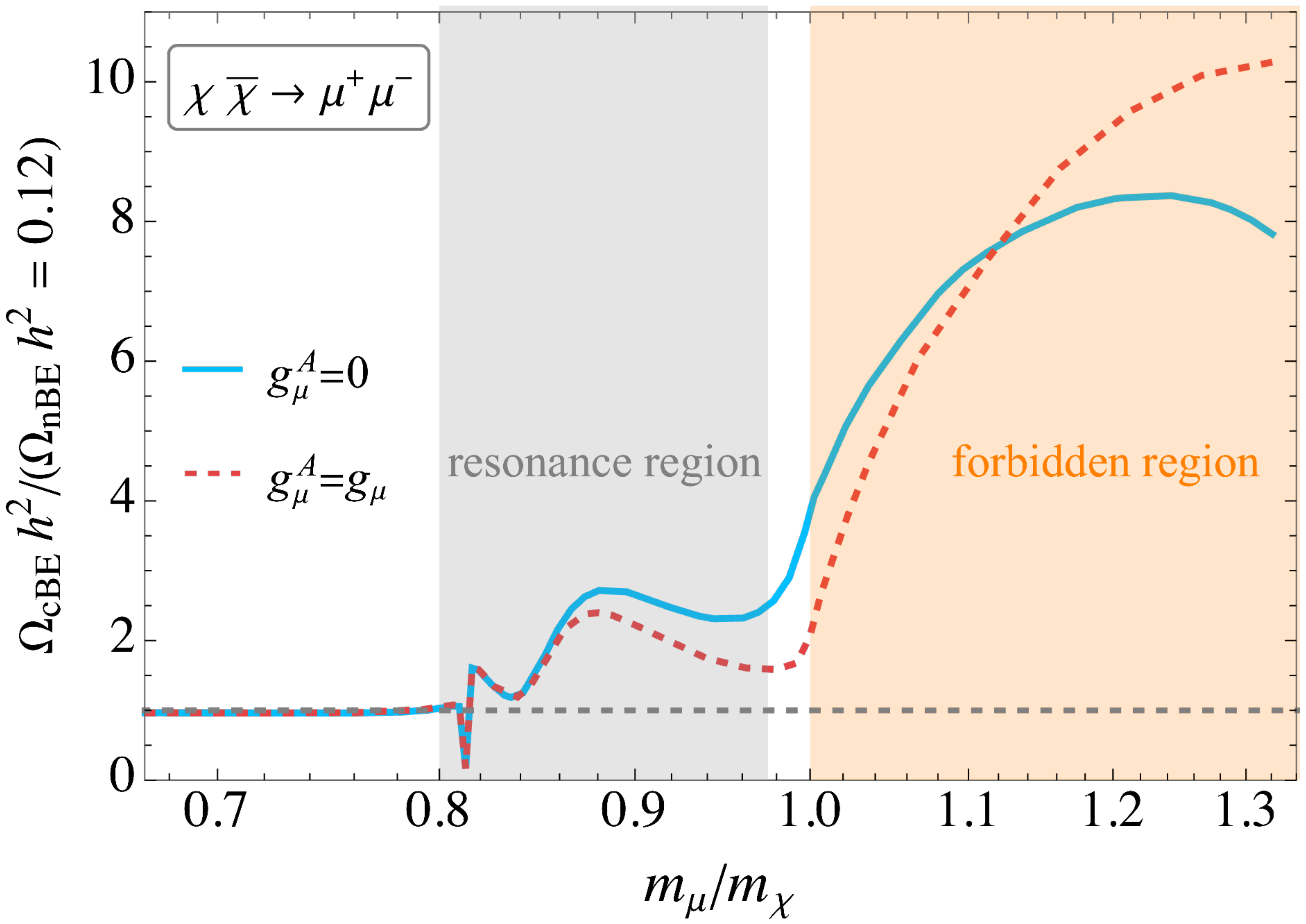
EKD on Forbidden Dark Matter

- A drop of the temperature and a large DM yield for CBE treatment
- there is a cooling phase during the evolution
- the decreased kinetic energy of DM particles suppresses the forbidden annihilation rate, which gives rise to larger abundances.



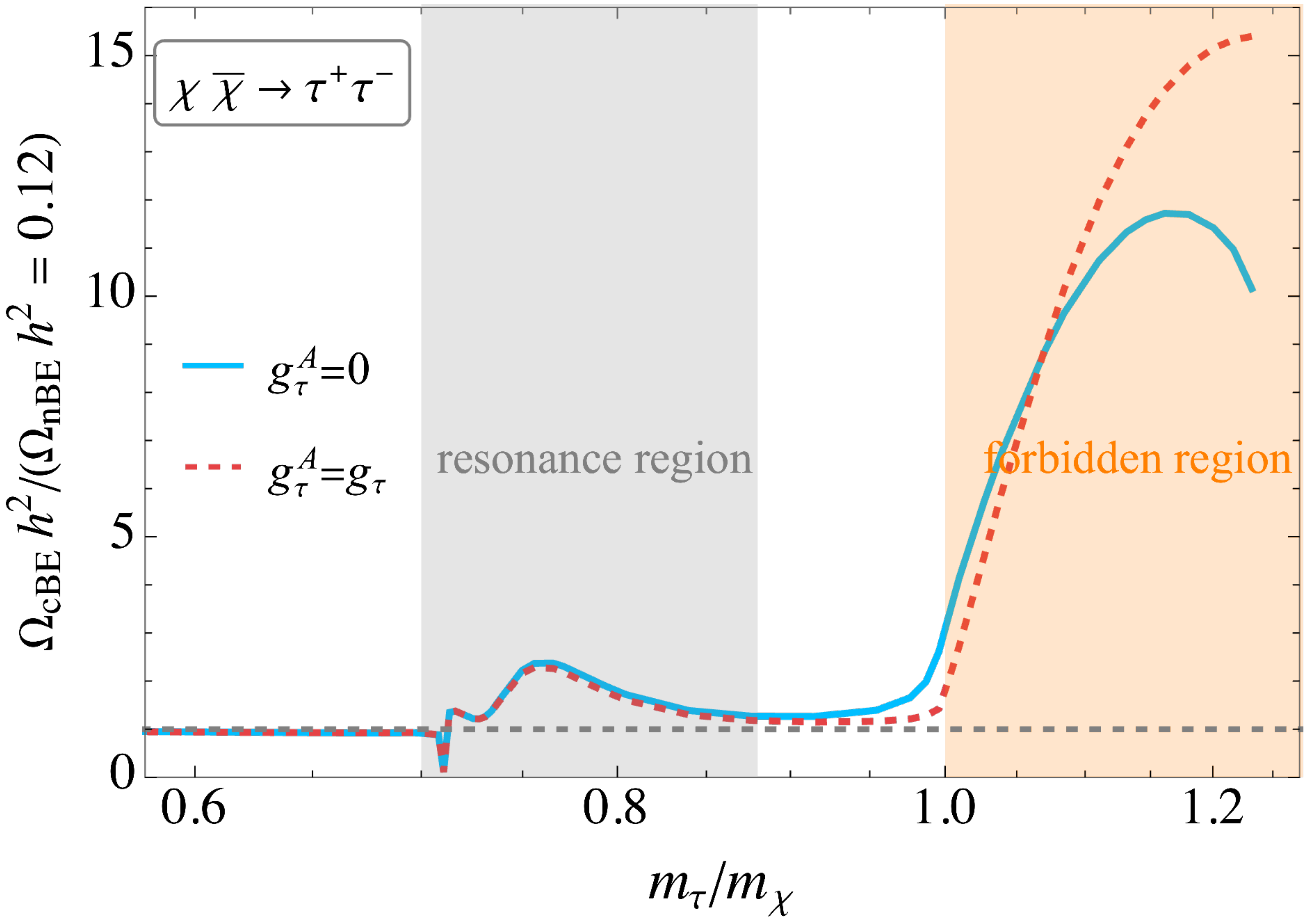
EKD effect on Forbidden Dark Matter

- $\mu\mu$ channel
- Forbidden region: $m_\mu / m_\chi > 1$
- $\Omega_{\rm cBE} h^2 / \Omega_{\rm nBE} h^2 \sim 2 - 10$
- Resonance region: see 1706.07433, 2004.10041



EKD effect on Forbidden Dark Matter

- Similar results for $\tau\tau$ channel
- $\Omega_{\rm cBE}h^2/\Omega_{\rm nBE}h^2 \sim 2 - 15$



Parameter space of $\chi\chi \to \mu^+\mu^-$

- Conclusion:

  Viable parameter space shrinks by EKD

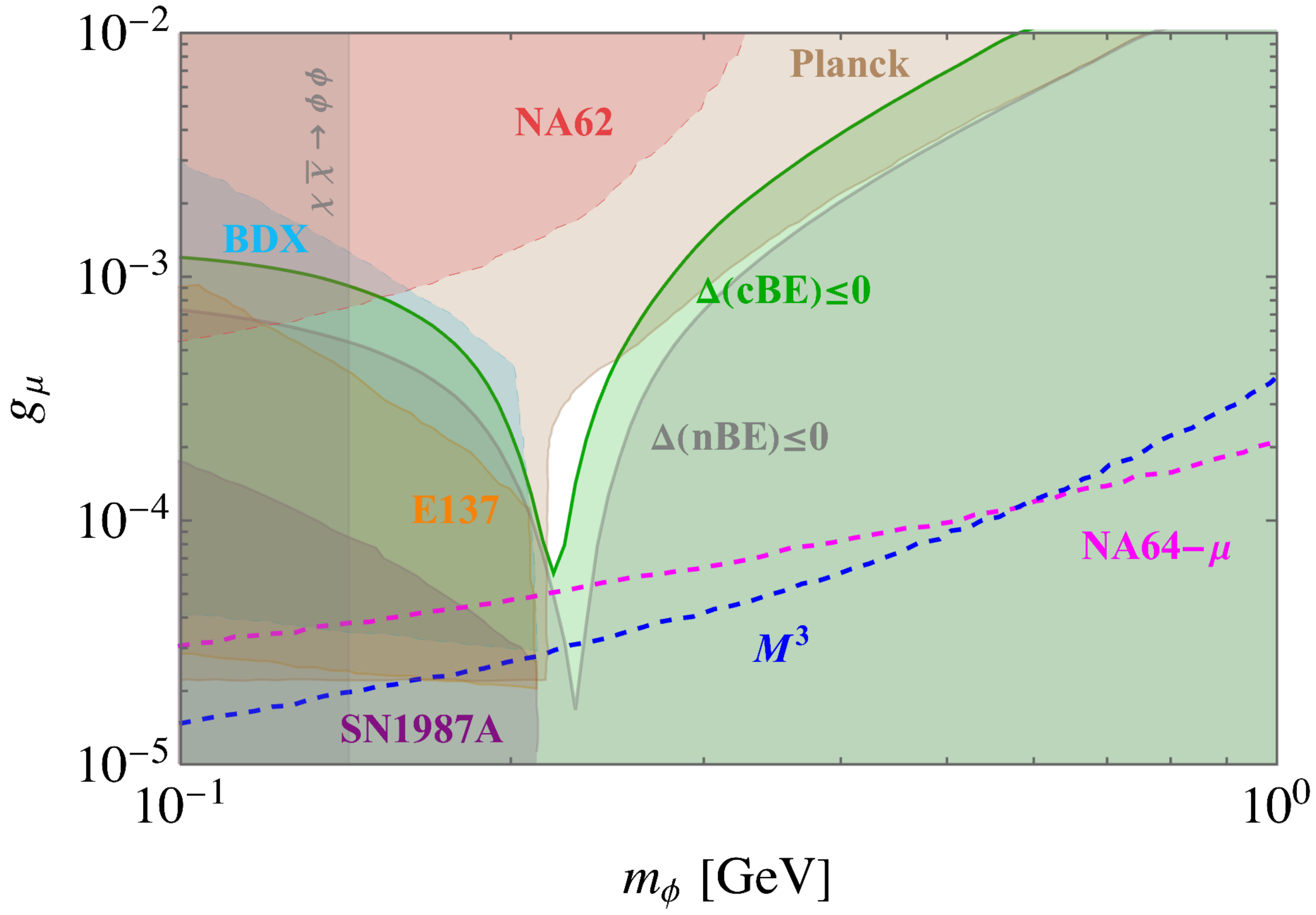
- Constraints:

  (1) Planck (CMB) : $\chi\chi \to \gamma\gamma$

  (2) SN 1987A: $\gamma p \to p\phi$ energy loss process

  (3) SLAC E137 and JLab BDX: NA62 : $K \to \mu\nu\phi$

  (4) NA64-μ and M^3 : $\mu N \to \mu N + \phi$



Parameter space of $\chi\chi \to \tau^+\tau^-$

- Conclusion:

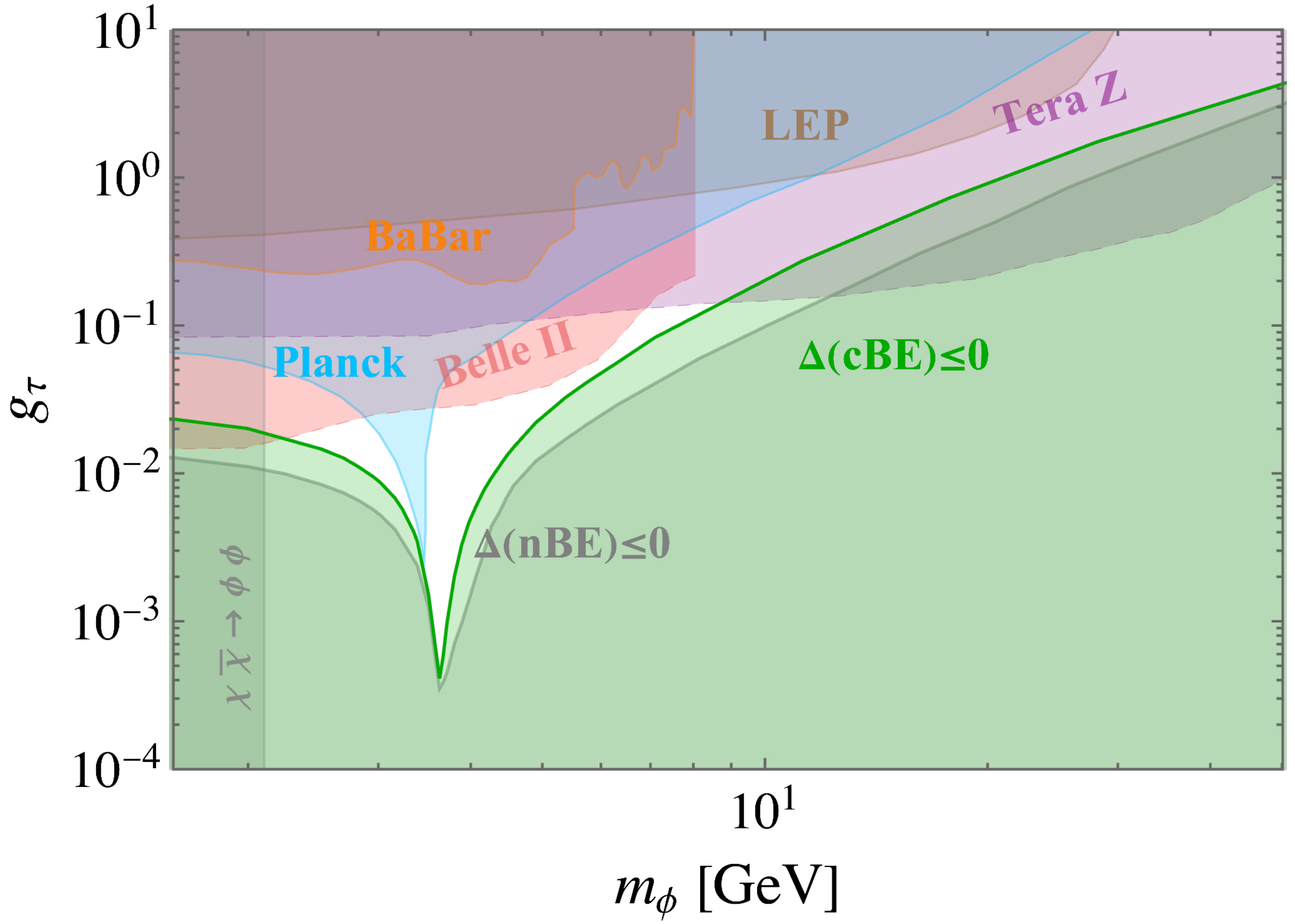
  Same conclusion on relic density

- Constraints:

  (1) Planck (CMB) : $\chi\chi \to \gamma\gamma$

  (2) Babar and Belle II (50 ab^-1)$e^+e^- \to \gamma + inv$.

  (3) LEP and Tera : $Z \to \tau^+\tau^- + \phi$



Summary

- Early Kinetic Decoupling effect is an indispensable ingredient.

- Effects on Forbidden DM:

  The decreased kinetic energy of DM particles suppresses the forbidden annihilation rate, which gives rise to larger abundances, up to an order of magnitude larger

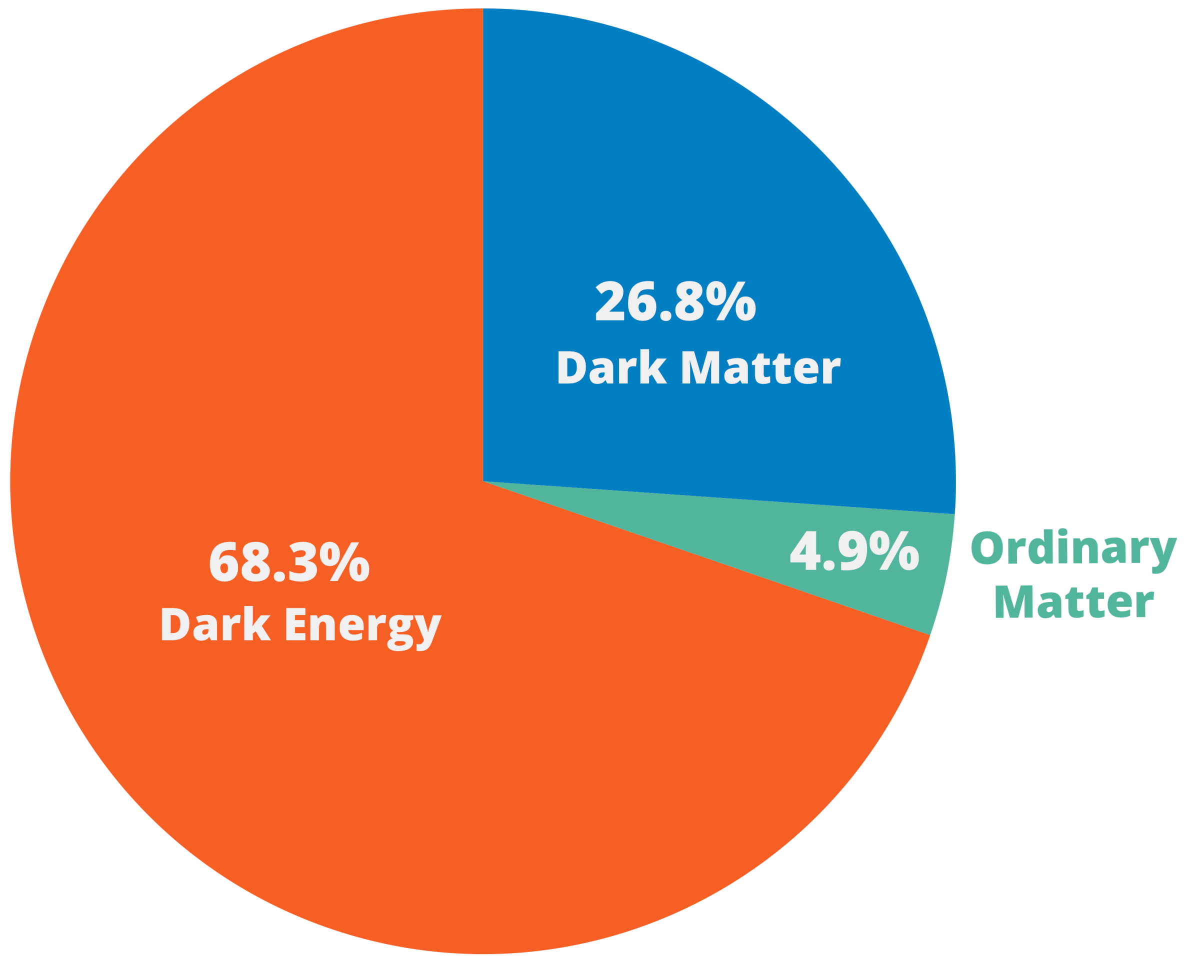
- EKD on other scenarios: Resonant annihilation of dark matter, Sommerfeld-enhanced annihilation (new work to appear), etc.

Thanks

BACKUP SLIDES

Motivation

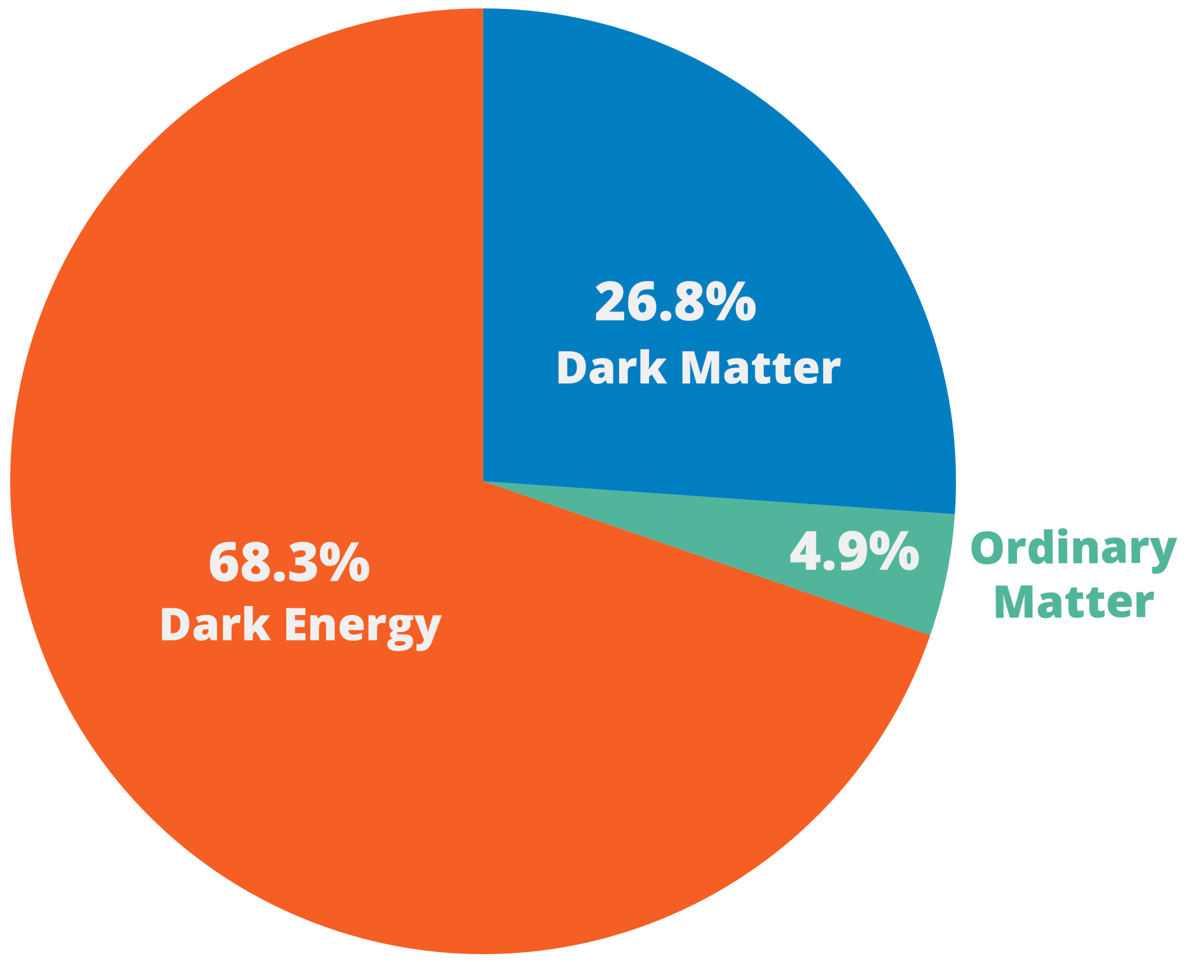
Motivation



Relic Density measurement from Planck2018

Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012	0.02236 ± 0.00015	0.02237 ± 0.00015
$\Omega_c h^2$	0.1206 ± 0.0021	0.1177 ± 0.0020	0.1158 ± 0.0046	0.1202 ± 0.0014	0.1200 ± 0.0012
$100\theta_{MC}$	1.04077 ± 0.00047	1.04139 ± 0.00049	1.03999 ± 0.00089	1.04090 ± 0.00031	1.04092 ± 0.00031
τ	0.0522 ± 0.0080	0.0496 ± 0.0085	0.0527 ± 0.0090	$0.0544^{+0.0070}_{-0.0081}$	0.0544 ± 0.0073

Motivation



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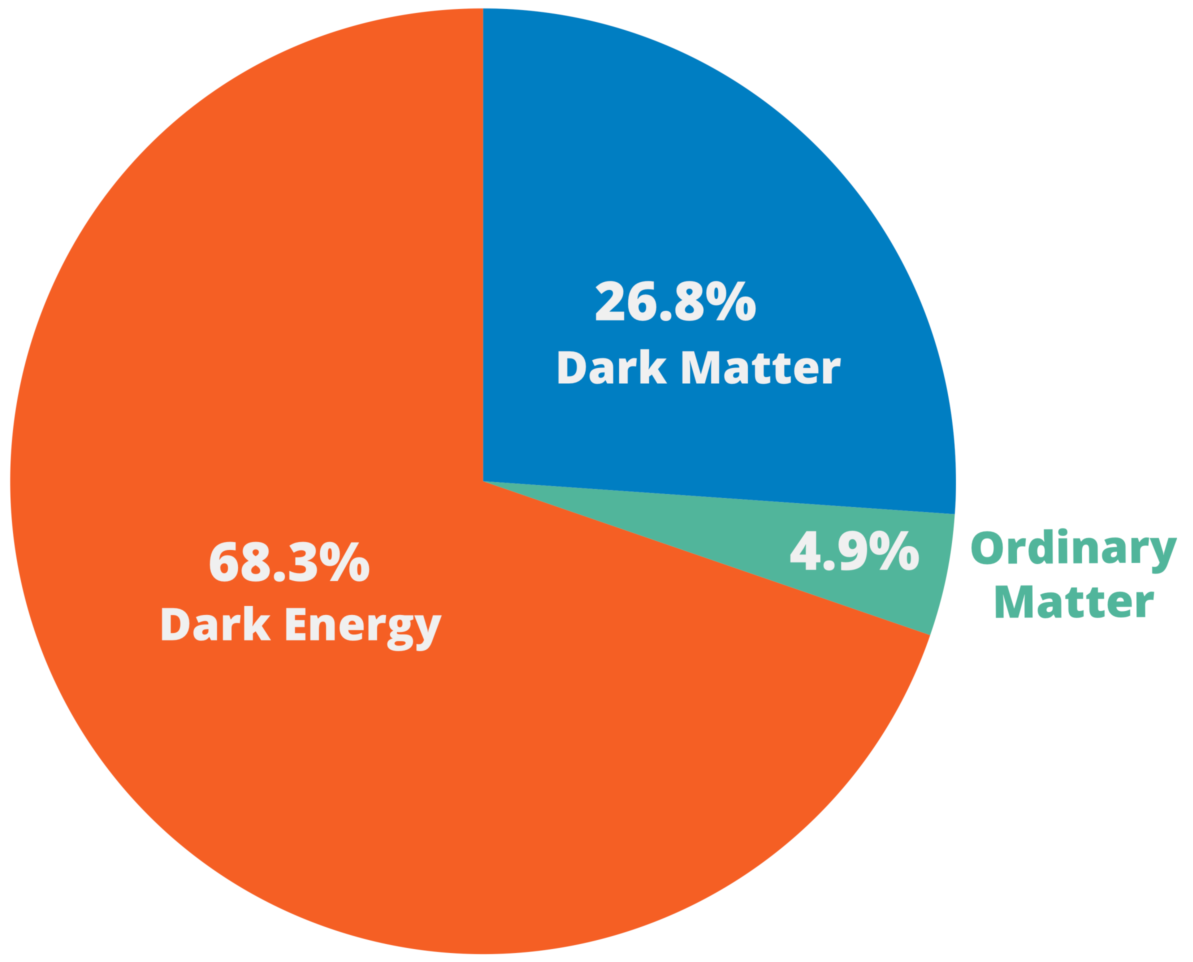
Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012	0.02236 ± 0.00015	0.02237 ± 0.00015
$\Omega_c h^2$	0.1206 ± 0.0021	0.1177 ± 0.0020	0.1158 ± 0.0046	0.1202 ± 0.0014	0.1200 ± 0.0012
$100\theta_{MC}$	1.04077 ± 0.00047	1.04139 ± 0.00049	1.03999 ± 0.00089	1.04090 ± 0.00031	1.04092 ± 0.00031
τ	0.0522 ± 0.0080	0.0496 ± 0.0085	0.0527 ± 0.0090	$0.0544^{+0.0070}_{-0.0081}$	0.0544 ± 0.0073

Motivation



Relic Density measurement from Planck2018

Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012	0.02236 ± 0.00015	0.02237 ± 0.00015
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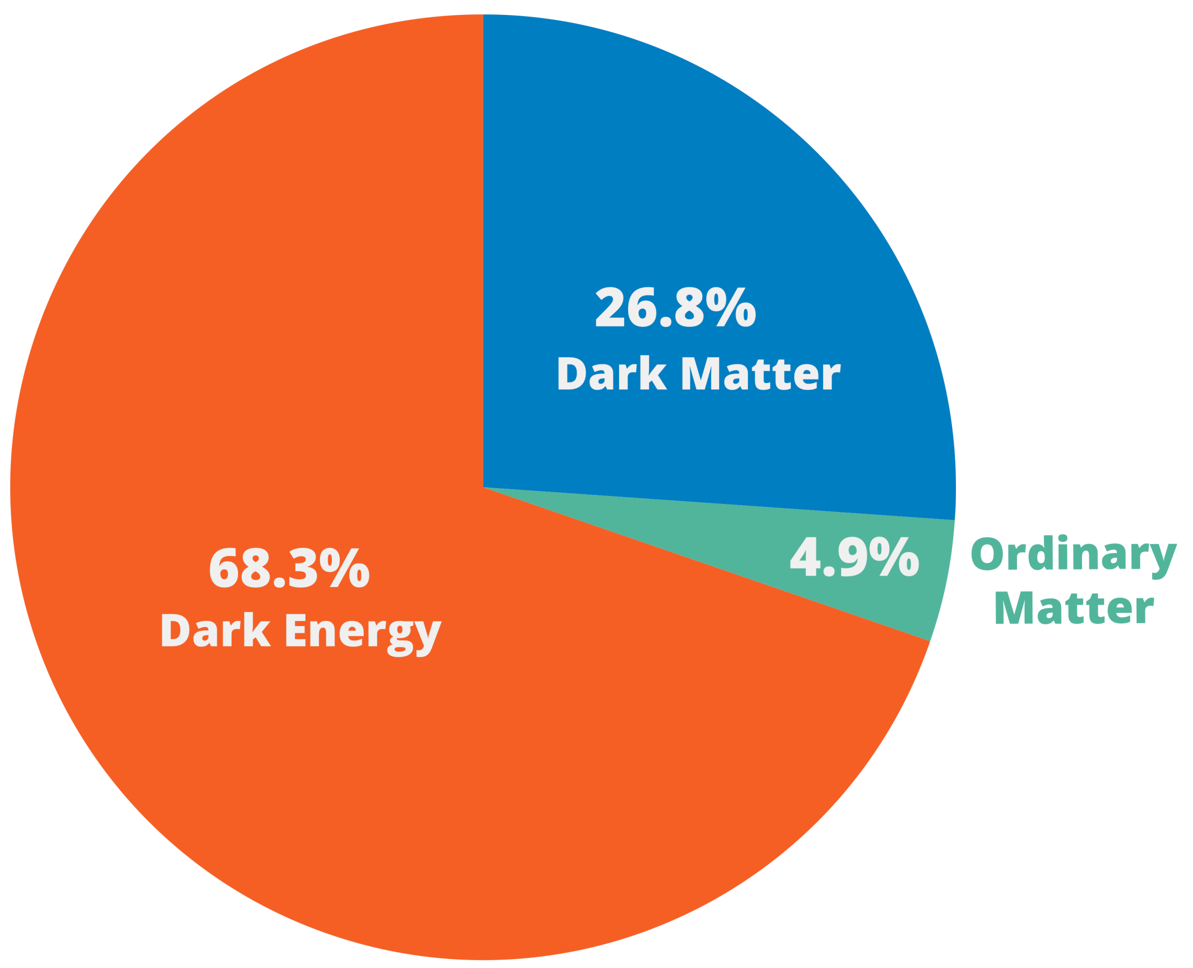
High precision of Measurements

Motivation



Relic Density measurement from Planck2018

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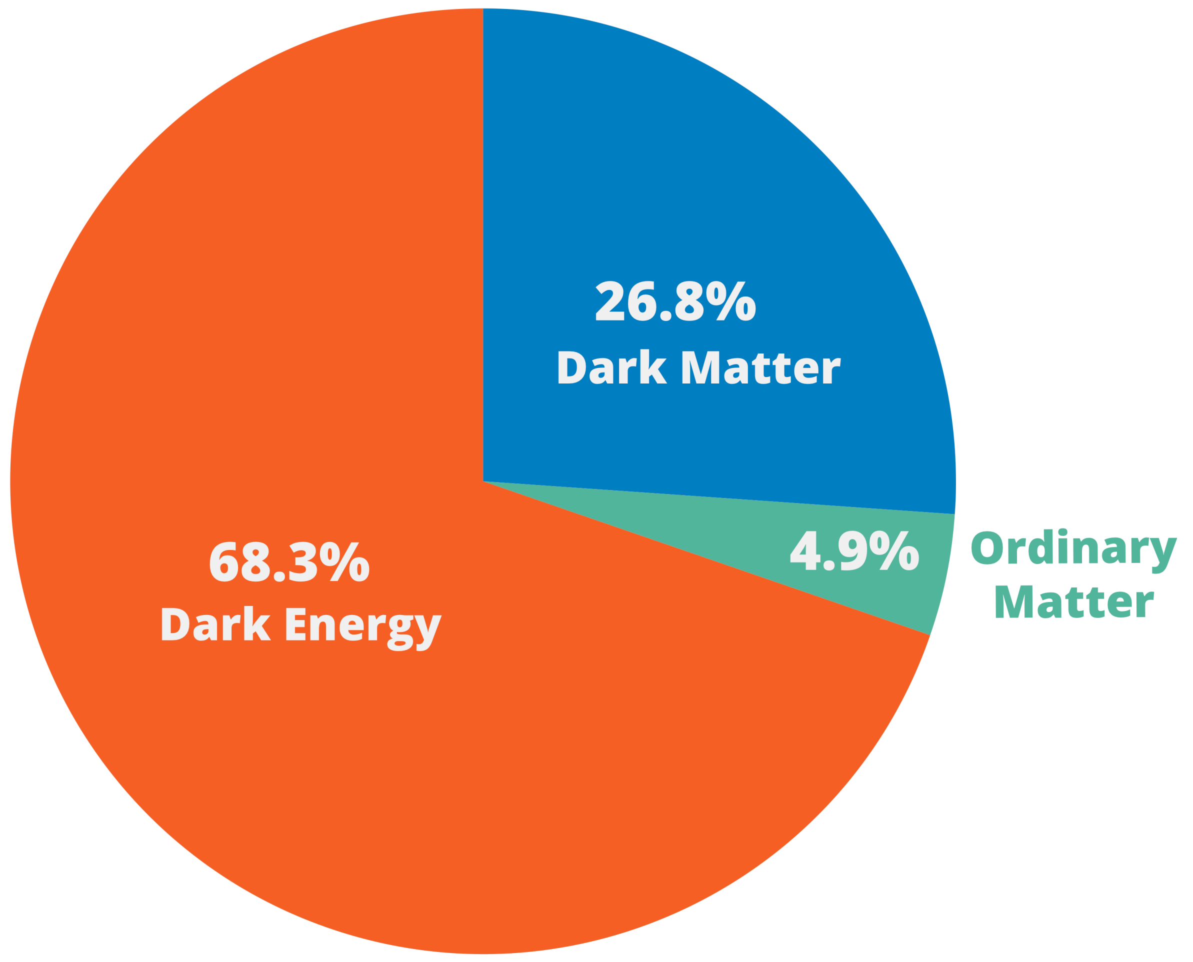
High precision of Measurements →

Motivation



Relic Density measurement from Planck2018

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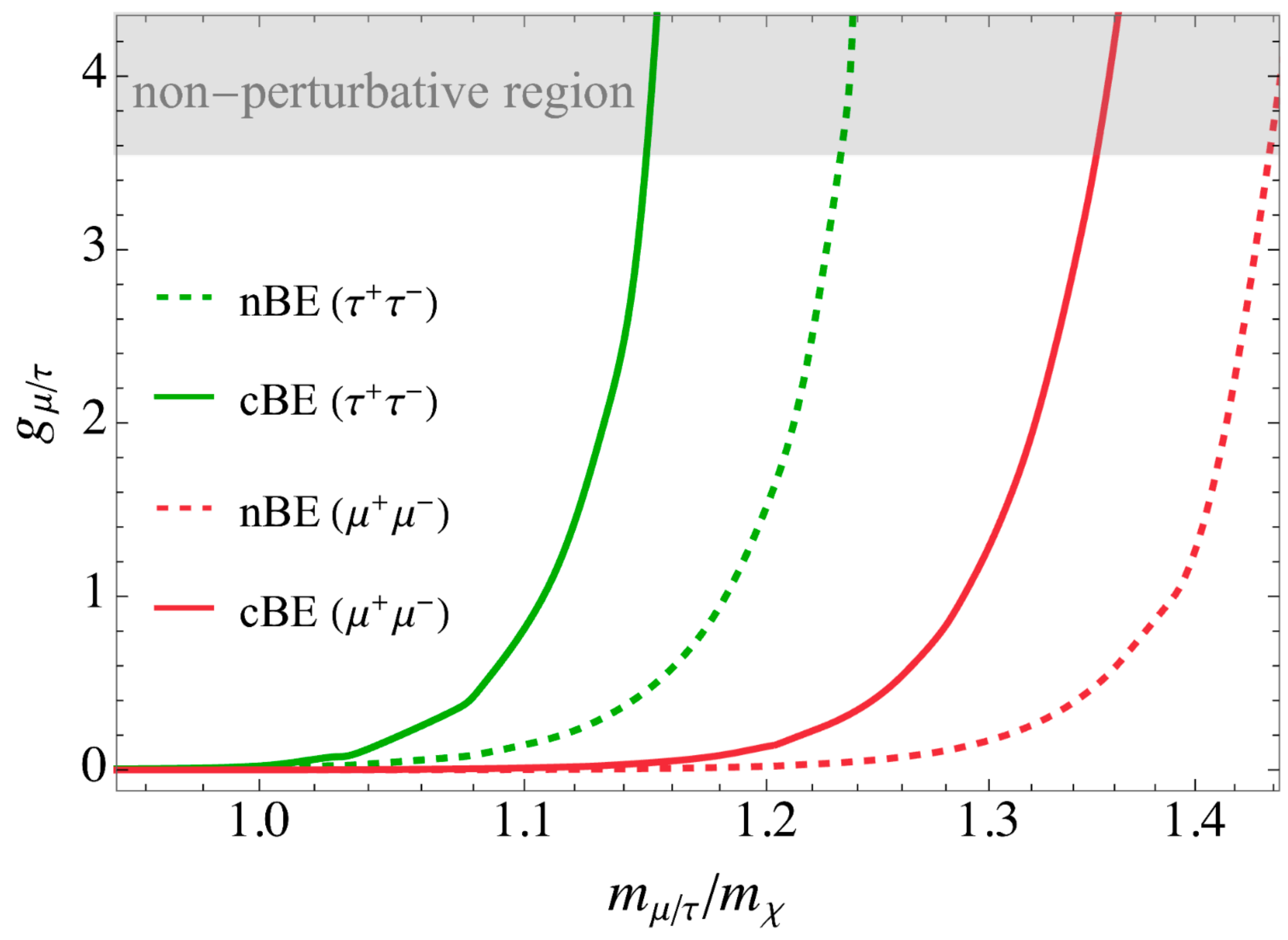
τ	0.0522 ± 0.0080	0.0496 ± 0.0085	0.0527 ± 0.0090	$0.0544^{+0.0070}_{-0.0081}$	0.0544 ± 0.0073

High precision of Measurements → High Accuracy of Calculations

Upper Boundary on mass ratio

- Fulfill $\Omega h^2 = 0.12$
- Gray region: perturbativity $g_\ell < \sqrt{4\pi}$
- Smaller m_μ/m_χ ratios are allowed from perturbativity requirement compared to nBE



Literature on the EKD

- Resonant annihilation of dark matter: [1706.07433], [2004.10041], [2103.01944]
- Sommerfeld-enhanced annihilation: [2103.01944]
- Sub-threshold annihilation (also known as the forbidden annihilation): [2103.01944]
- Others: [1910.01549, 1912.02870, 2104.03238, 2104.05684, 2106.01956, 2111.01267, 2201.06456, 2204.07078]