2022 Chung-Ang University Beyond the Standard Model Workshop

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Continuum Dark Matter

Seung J. Lee

With Csaki, Hong, Kurup, Perelstein, Xue; 2105.14023 [hep-ph]
With Csaki, Hong, Kurup, Perelstein, Xue; 2105.07035 [hep-ph]

With Hong, Kurup, Lee, work in progress
With Perelstein, Ferrante, work in progress
With Csaki, Ismail, Nakli, Suzuki, work in progress

Outline

- Introduction
- Gapped Continuum
- Gapped Continuum QFT
- Equilibrium and Non-equilibrium Thermodynamics
- Z-portal Model for Gapped Continuum DM
- Summary

DM-what we don't know

- Mass of Dark Matter (range: 10^{-22} to 10^{67} eV)
- Composition of Dark Matter
- Interaction of Dark Matter

Gapped Continuum, instead of Resonances

♦ **Our Proposal:** Dark Matter is made of an ensemble of gapped continuum states

- It's not even clear whether the DM that provide successful explanations to the rotation curve of disk galaxies, CMB, and large structure formation is a localized excitation of quantum field (i.e. particle)

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- It's not even clear whether the DM that provide successful explanations to the rotation curve of disk galaxies, CMB, and large structure formation is a localized excitation of quantum field (i.e. particle)

- continuum with a mass gap is not so uncommon in condensed matter physics: e.g. edge state in fractional quantum hall effect, topological superfluid, 2D Ising model, 2d SU(2) Thirring model, 2d SU(N) Yang-Mills theory in large-N limit ,etc

Gapped Continuum, instead of Resonances

- The appearance of a continuum is very common in QFT's: e.g. spectrum of CFTs necessarily forms a continuum since the theory does not admit any mass scales (no mass gap).
- Unparticles (Georgi): another example of gapless continuum
- String Theory (e.g. Gubser et al, Kraus, Trivedi et al, etc): gapped continuum shows up when one has a large number of D3 branes distributed on a disc (which is dual to N = 4 SUSY broken to N = 2 via masses for two chiral adjoints)
- Gapped Continuum in particle physics: -Softwall model (Higgs with a small mass gap (before Higgs discovery) by Terning et al, Falkowski et al

-Quantum Critical Higgs (Higgs pole + gappend continuum: after Higgs discovery) by Csaki et al (SL): for off-shell form factor (by gapped continuum) for Higgs EFT

-Continuum Naturalness (for solving little hierarchy by Csaki et al (SL), and also by Quiros et al)

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So, how about DM as a gapped continuum?
(never explored before!)

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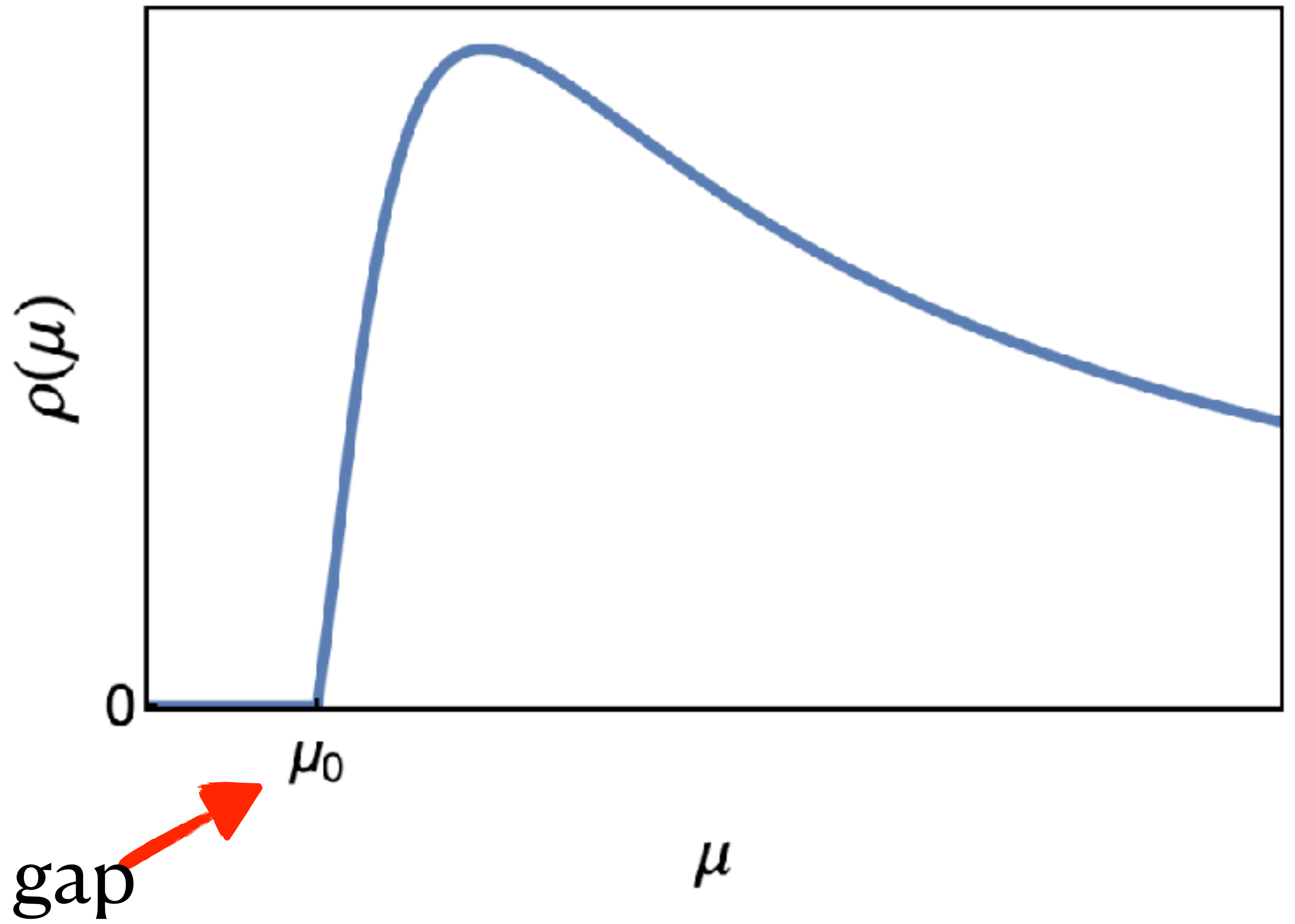
Gapped Continuum, instead of ordinary particles

♦ Continuum DM: singly-excited states are characterized by a continuous parameter μ^2, in addition to the usual 3-momentum p

The parameter μ^2 plays the role of mass in the kinematic relation $p^2 = \mu^2$ for each state. The number of states is prop
$\varrho(\mu^2)\, d\mu^2$, where ϱ is the spectral density of the theory

$$\langle 0|\Phi(p)\Phi(-p)|0\rangle = \int \frac{d\mu^2}{2\pi} \frac{i\rho(\mu^2)}{p^2 - \mu^2 + i\epsilon}$$



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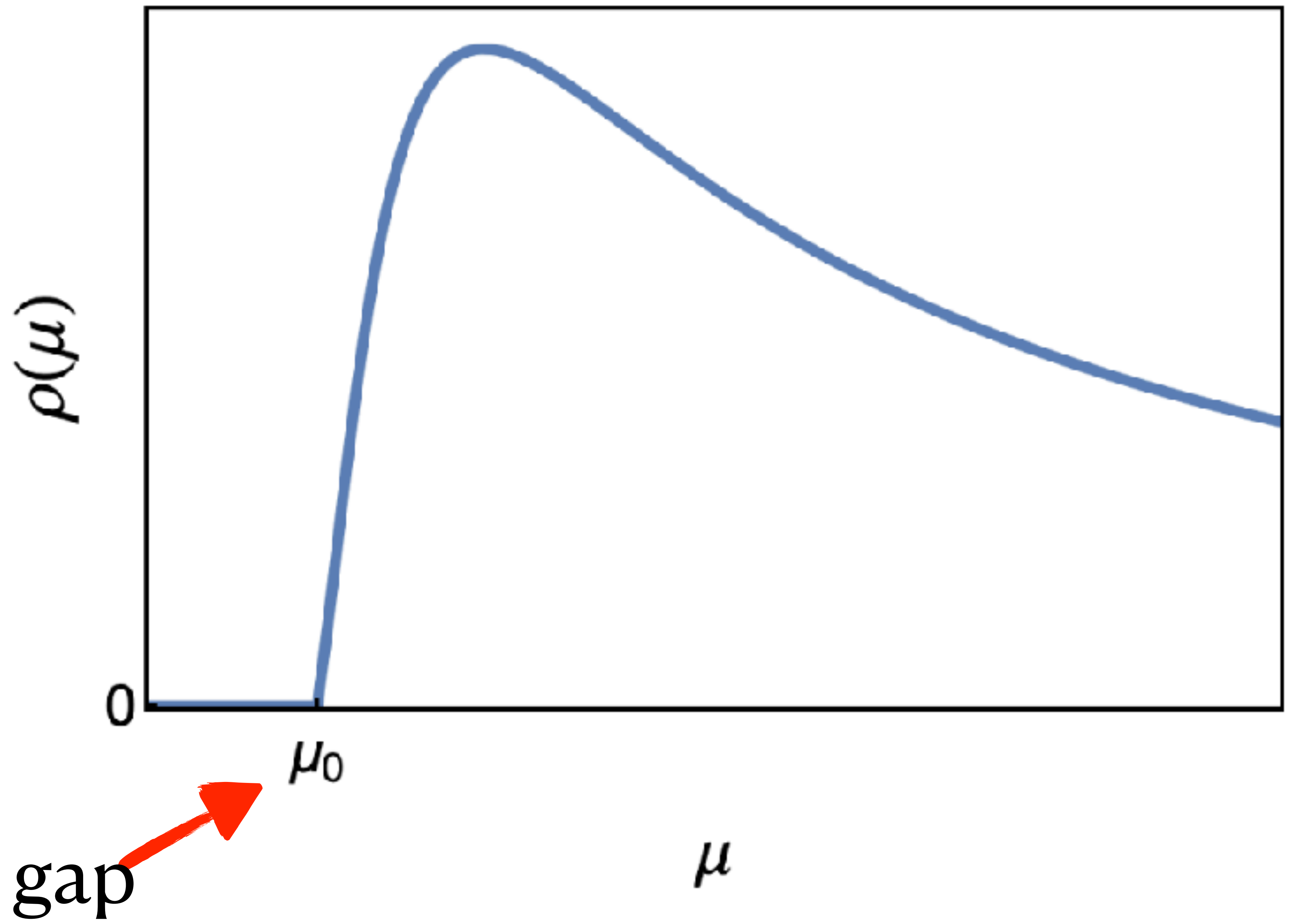
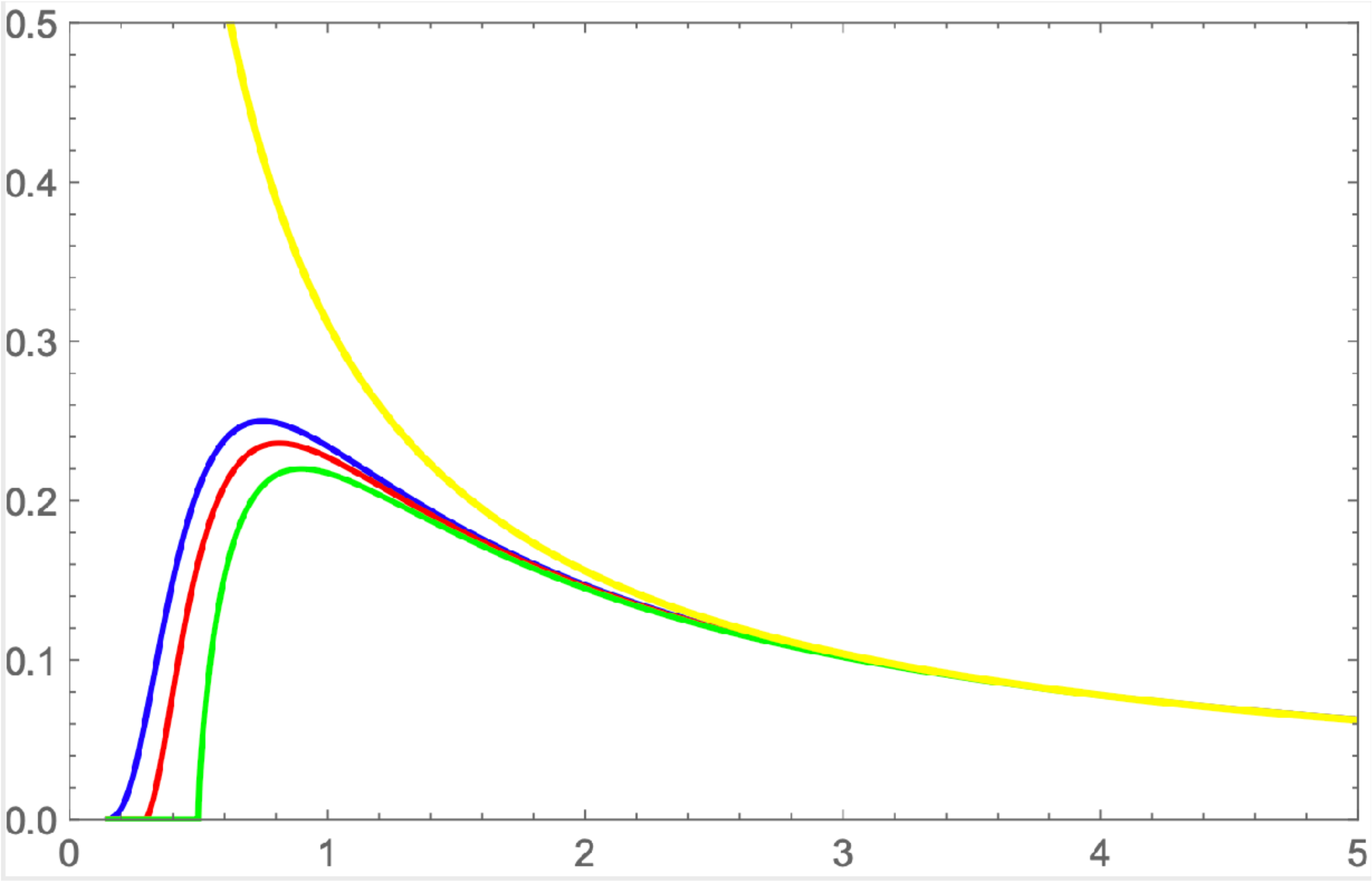


needs to be gapped: consistent with observations e.g. CMB, LSS

CFT Continuum vs
Gapped Continuum (IR deformation)



Physics of Gapped Continuum DM

- CFT continuum case:

  - It's often stated that CFT's and theories with continuum spectra do not have a particle interpretation and no S-matrix can be defined: interactions leading to a non-trivial fixed point are also essential for producing the continuum spectrum of the theory
  - by turning off the interactions, the spectrum changes from continuum into that of an ordinary free particle, hence the asymptotic states defined in the usual manner would not capture the physics of the system properly
  - this means that one needs to find an alternative approach for defining scattering processes

- Our theoretic description of gapped continuum: Generalized Free Continuum (continuum analog of Generalized Free Fields: Greenberg 1961)

Also: Polyakov, early '70s- skeleton expansions

CFT completely specified by 2-point function-rest vanish

CFT Continuum

Generalized Free Fields

Polyakov, early '70s- skeleton expansions

CFT completely specified by 2-point function - rest vanish

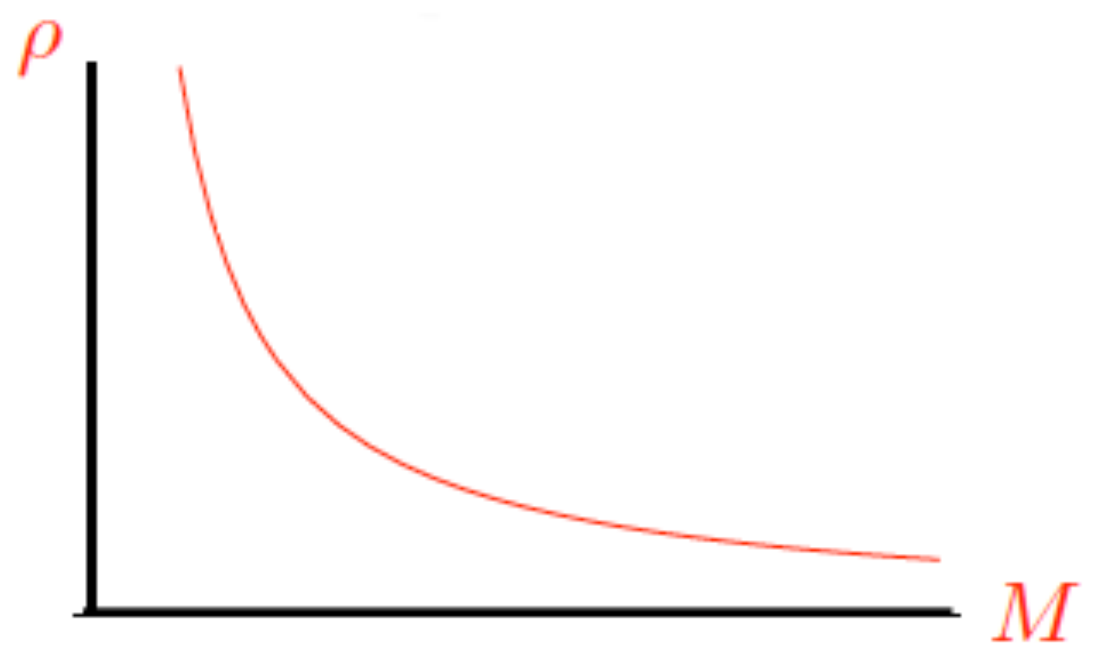
Scaling - 2-point function: $G(p^2) = -\frac{i}{(-p^2 + i\epsilon)^{2-\Delta}}$

Can be generated from: $\mathcal{L}_{\rm GFF} = -\mathcal{h}^\dagger \left(\partial^2\right)^{2-\Delta} \mathcal{h}$

Georgi
hep-ph/0703260

Branch cut starting at origin - spectral density purely a continuum:

$$G(p) \sim \int_{\mu^2}^{\infty} dM^2 \frac{\rho(M^2)}{p^2 - M^2}$$



Generalized Free Continuum

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-consider the case that the effects of the strong interactions can be captured by the fact that there is a non-trivial continuum (with a mass gap), and described by:

$$S = \int \frac{d^4p}{(2\pi)^4}\, \Phi^\dagger(p)\Sigma(p^2)\Phi(p)$$

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which is designed to properly reproduce the two-point function of theory

$$\int d^4x \, e^{ip(x-y)} \langle 0|T\Phi(x)\Phi^\dagger(y)|0\rangle = \langle 0|\Phi(p)\Phi^\dagger(-p)|0\rangle = \frac{i}{\Sigma(p^2)} = \int \frac{d\mu^2}{2\pi} \frac{i\,\rho(\mu^2)}{p^2 - \mu^2 + i\epsilon}$$

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This picture is supported by the concrete extra dimensional construction!

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Dark Matter Continuum Spectral Density from 5D Model

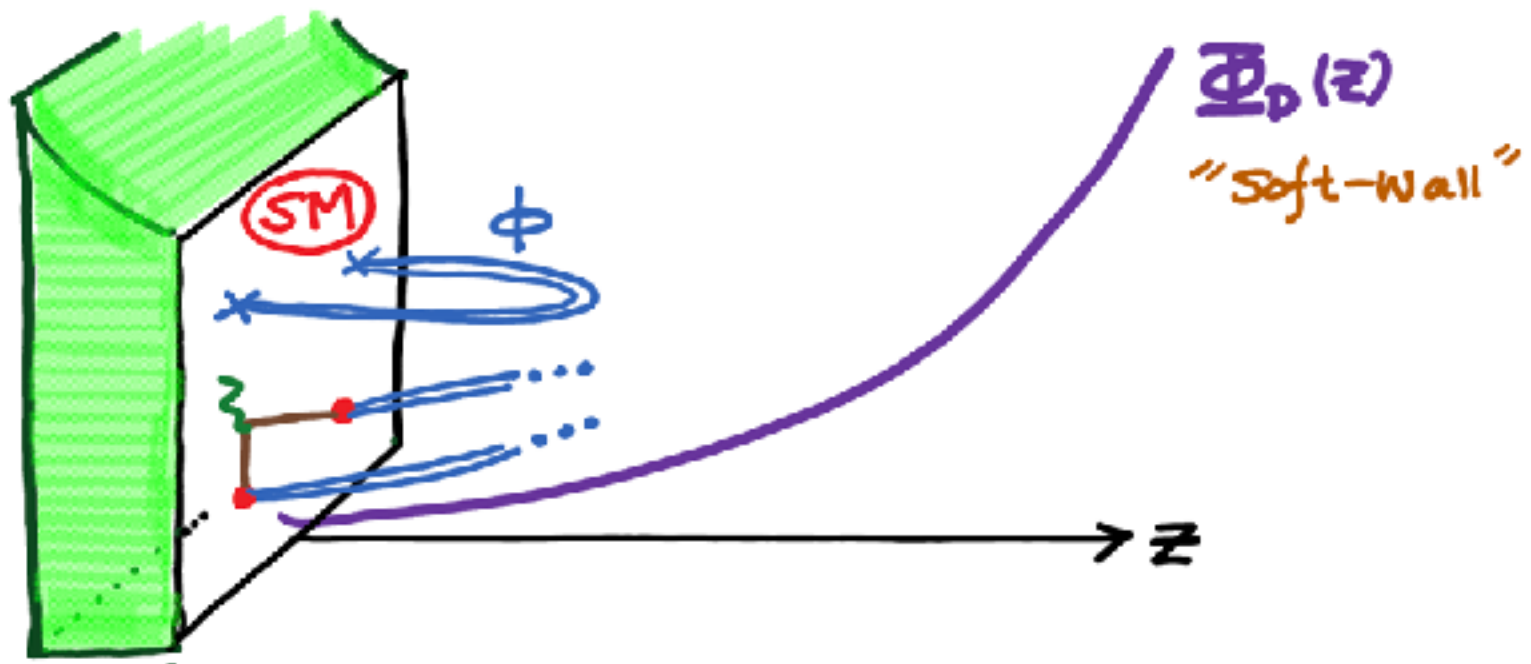
♦ modeling generalized free continuum by Warped 5D model

$$ds^2 = e^{-2A(y)}dx^2 + dy^2$$

- warped 5D setup we will have a 3-brane placed at the position z = R, which from the point of view of the gapped continuum field will be a UV brane cutting off the space

The 5D action of the coupled scalar-gravity system

$$S = \int d^5x\sqrt{g}\left(-M^3R + \frac{1}{2}(\partial\phi) - V(\phi)\right) - \int d^4x\sqrt{g^{ind}}V_4(\phi)$$



y_s = finite distance location of the curvature singularity where the spacetime ends in the y coordinates

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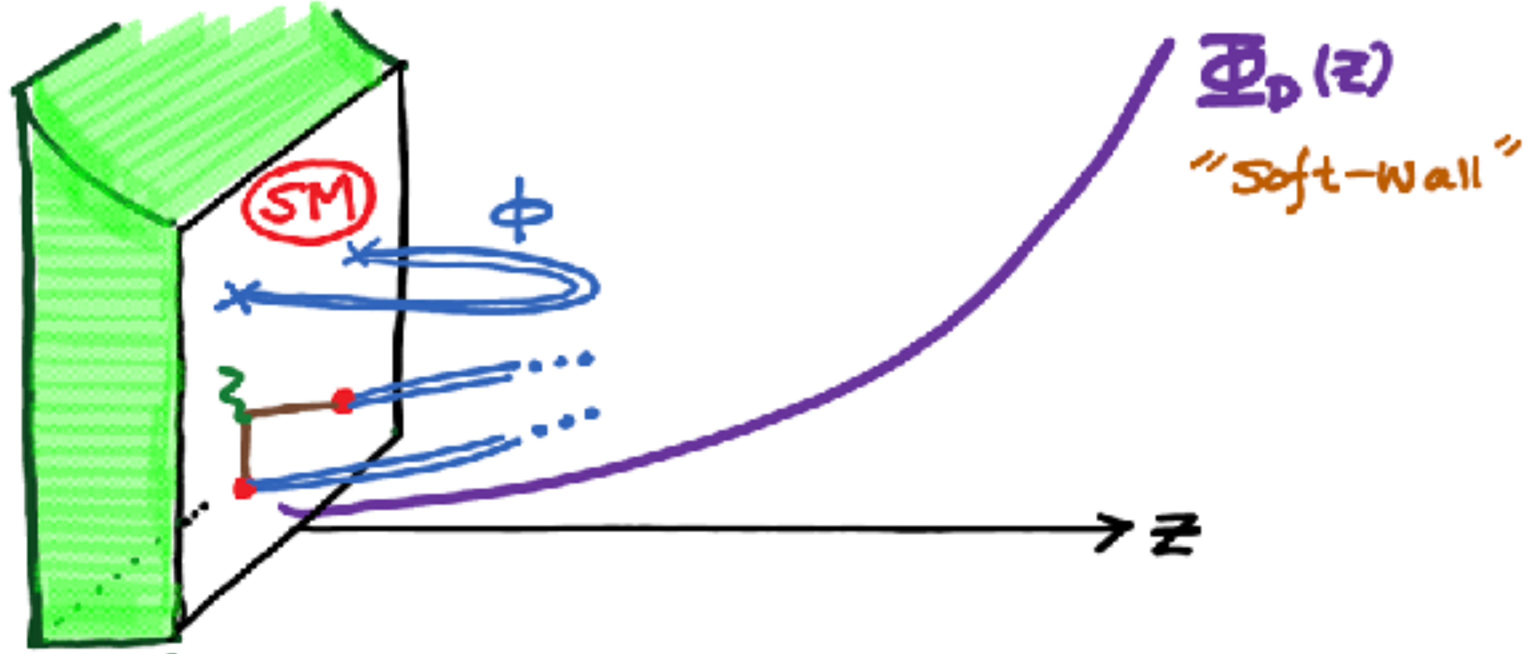
- The superpotential (w/ relation $V = 3W'^2 - 12W^2$) leading to the desired 5D background : $W = k(1+e^{\phi})$ (fully includes the backreaction of the metric to the presence of the scalar field)



Solution $A(y) = -\log\left(1-\frac{y}{y_s}\right) + ky,$

y_s = finite distance location of the curvature singularity where the spacetime ends in the y coordinates $\phi(y) = -\log\left(k(y_s - y)\right),$

soft wall & continuum

- Scalar gapped continuum: $\mathcal{L} = \sqrt{g}\left[\frac{1}{2} g^{MN} D_M \Phi^\dagger D_N \Phi - V(\Phi)\right]$

In conformally flat coordinate, Schrödinger form of eom:

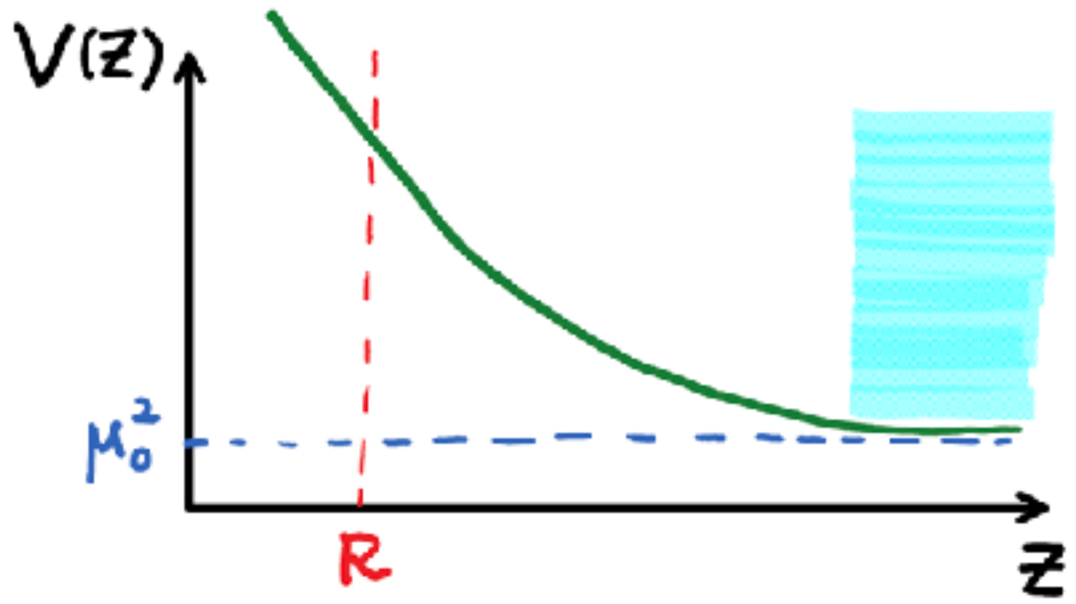
EOM: $\left(-\partial_y^2 + \hat{V}(y)\right)\Psi(p,y) = e^{2A(y)} p^2 \Psi(p,y)$ $\Psi(p,y) = e^{-2A(y)}\Phi(p,y)$

"Schrödinger Eqn" $- \ddot{\psi} + V(z)\psi = p^2\psi$

$$V(z) = \frac{e^{-2ky}}{4y_s^2}\left[4m^2(y_s - y)^2 + 15\left(1 + k(y_s - y)\right)^2 - 6\right]$$

if $V \to \mu_0^2$ = finite ($z \to \infty$) => Continuum! 1D QM problem

=> continuum begins at: $\mu_0^2 = \frac{9}{4y_s^2} e^{-2ky_s}$



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Quantum Gravity?
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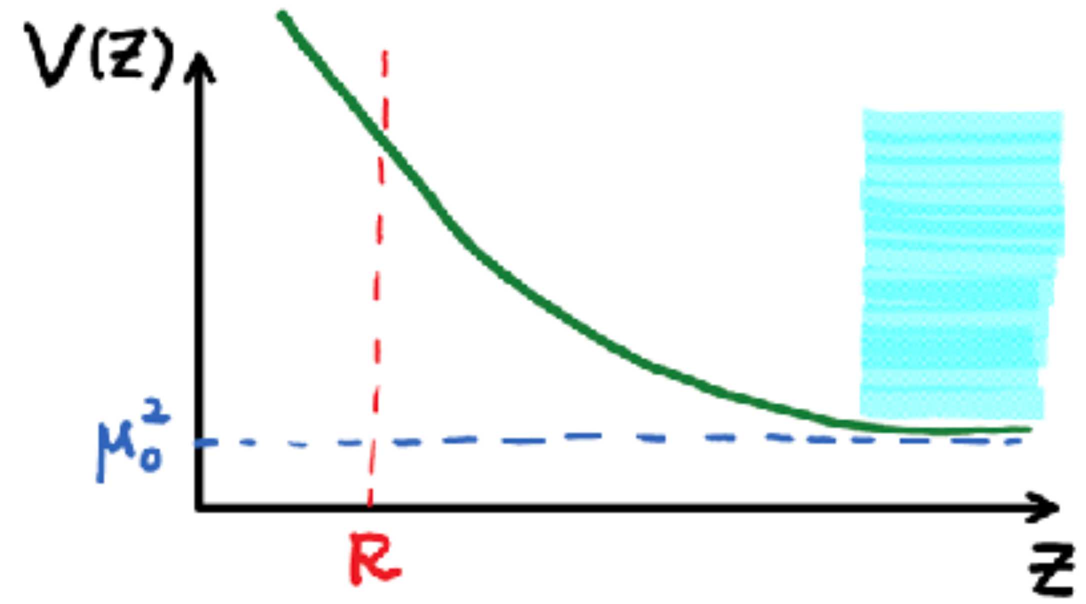

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- One may not simply plug gapped continuum into formalism developed for particle DM: need a new theoretical framework for dealing with gapped continuum in order to calculate the relic density of DM, and to deal with the finite temperature physics necessary for describing general features of cosmological history of DM

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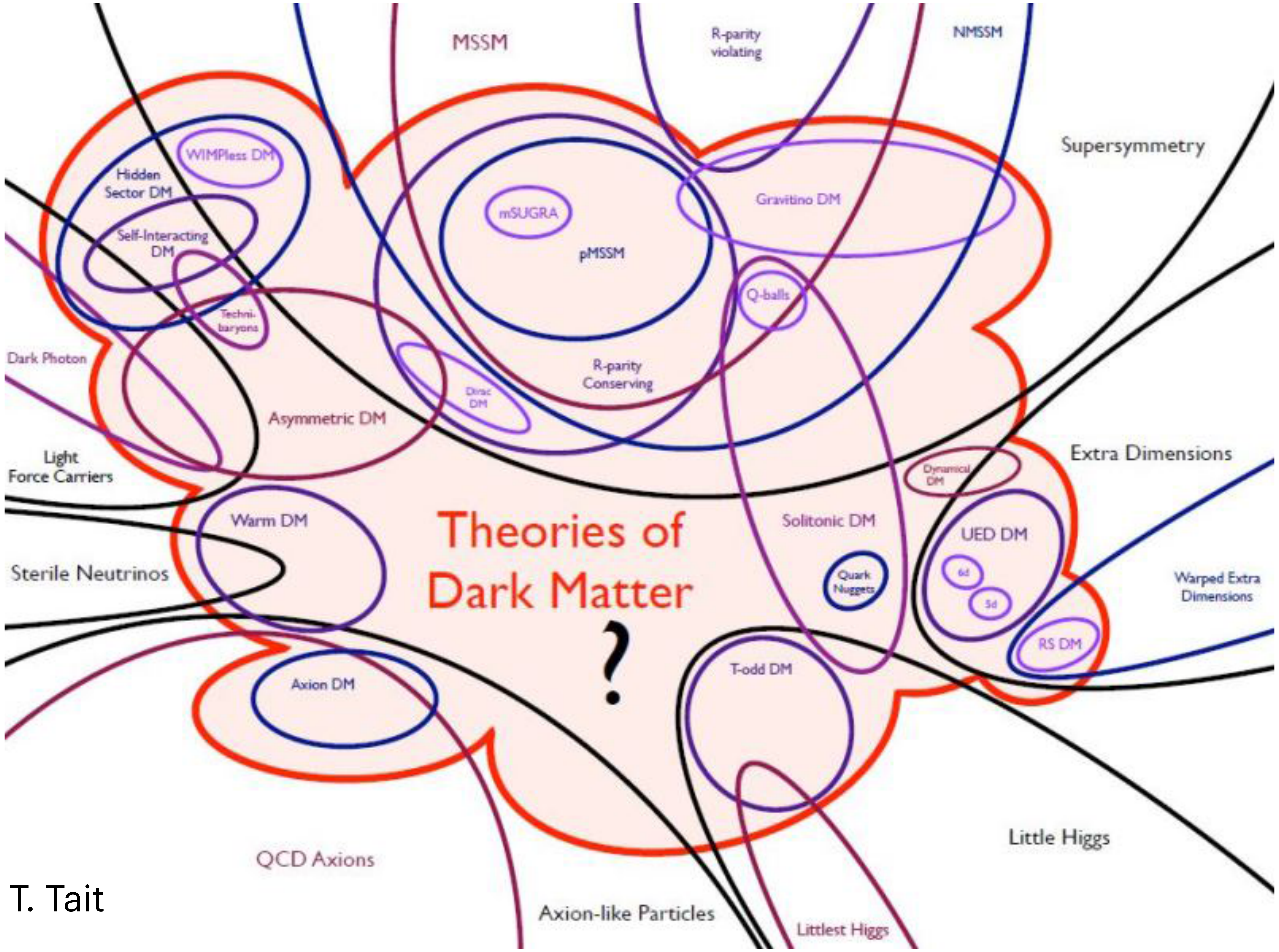
- Gapped Continuum as a DM can give striking new experimental signatures in colliders and cosmic microwave background measurements

- The strong suppression of direct detection signals (will show later) reopens the possibility of a Z-mediated dark sector again (and also other continuum version of WIMP models).

Theories of DM ?



T. Tait

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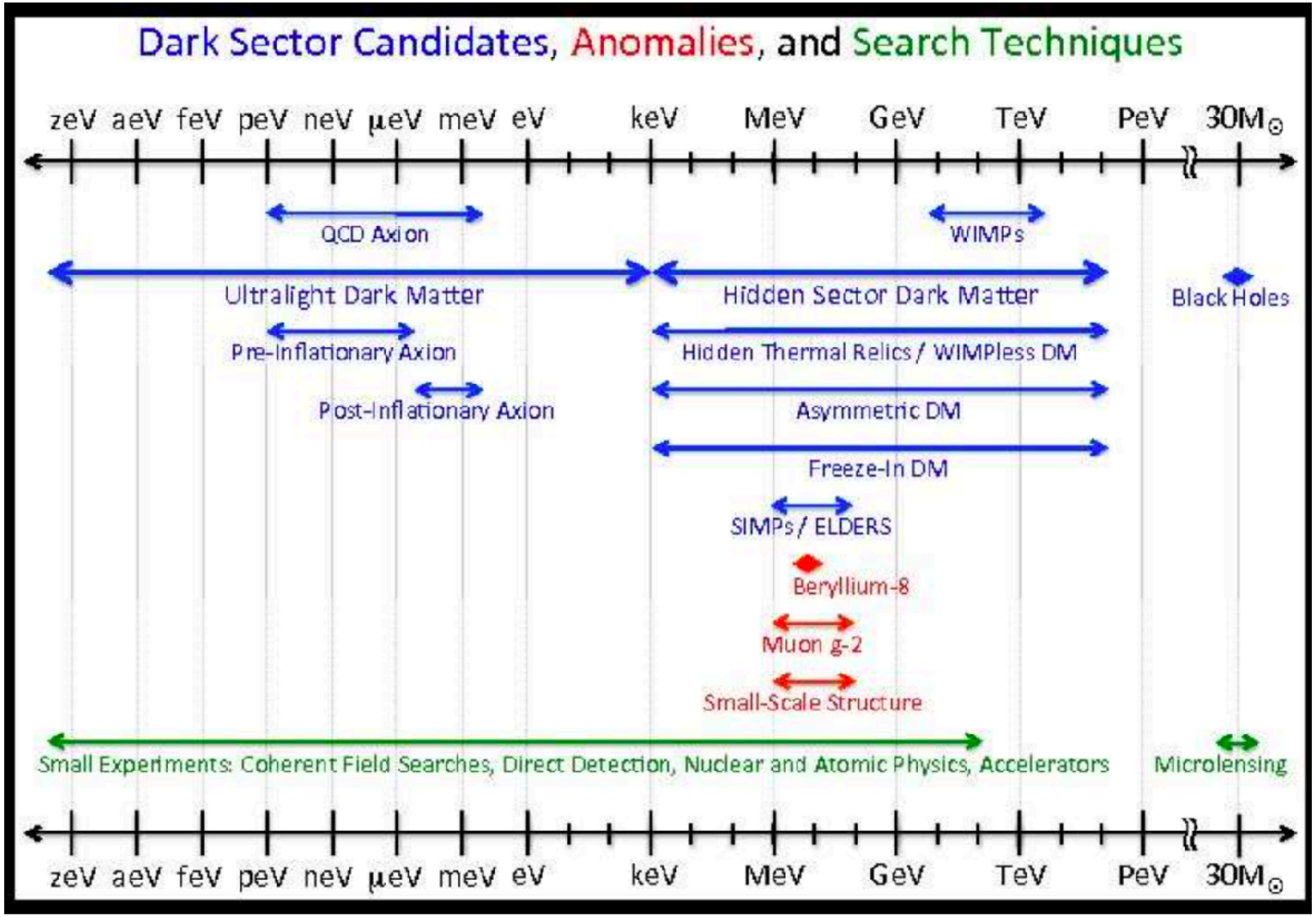

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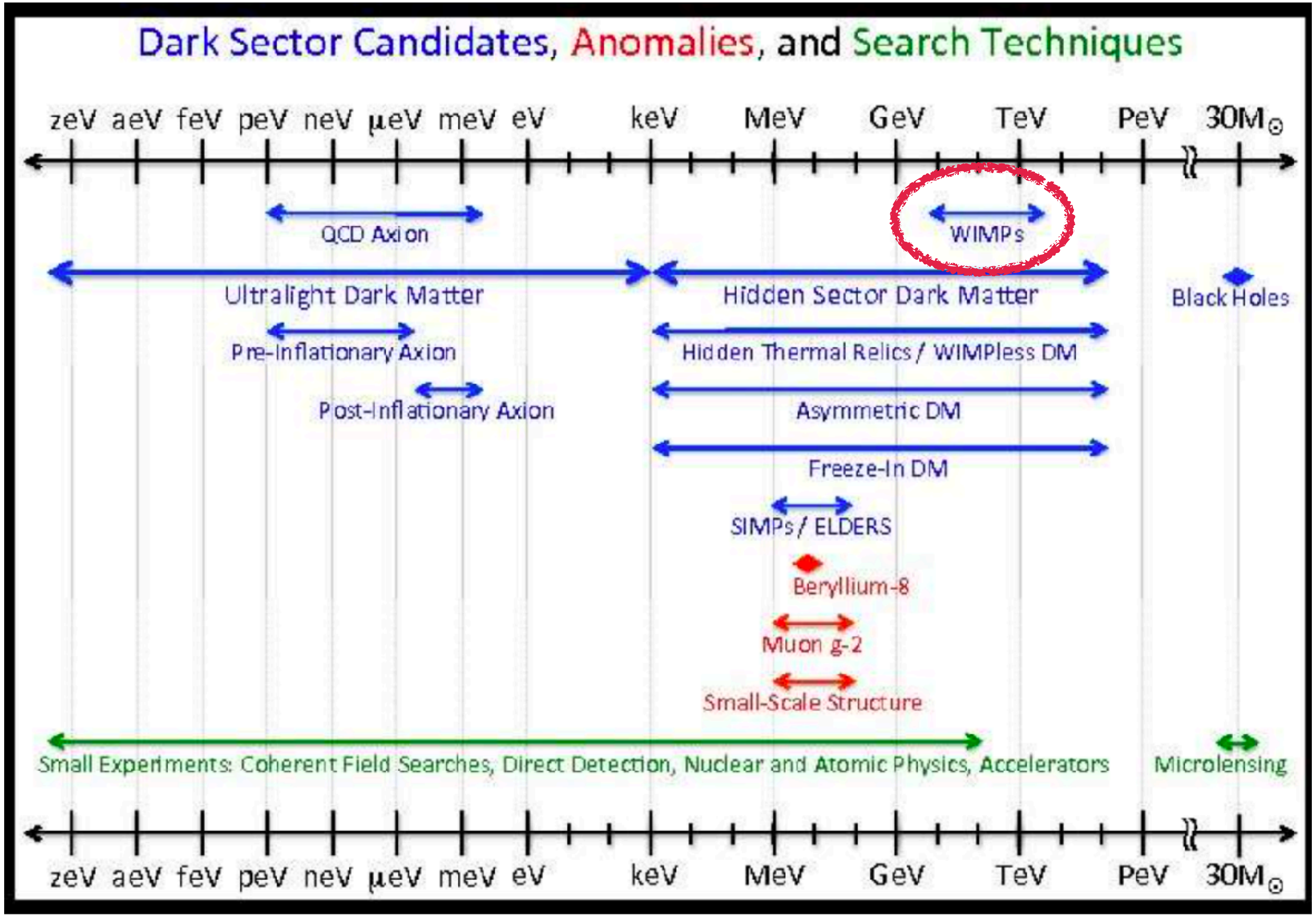
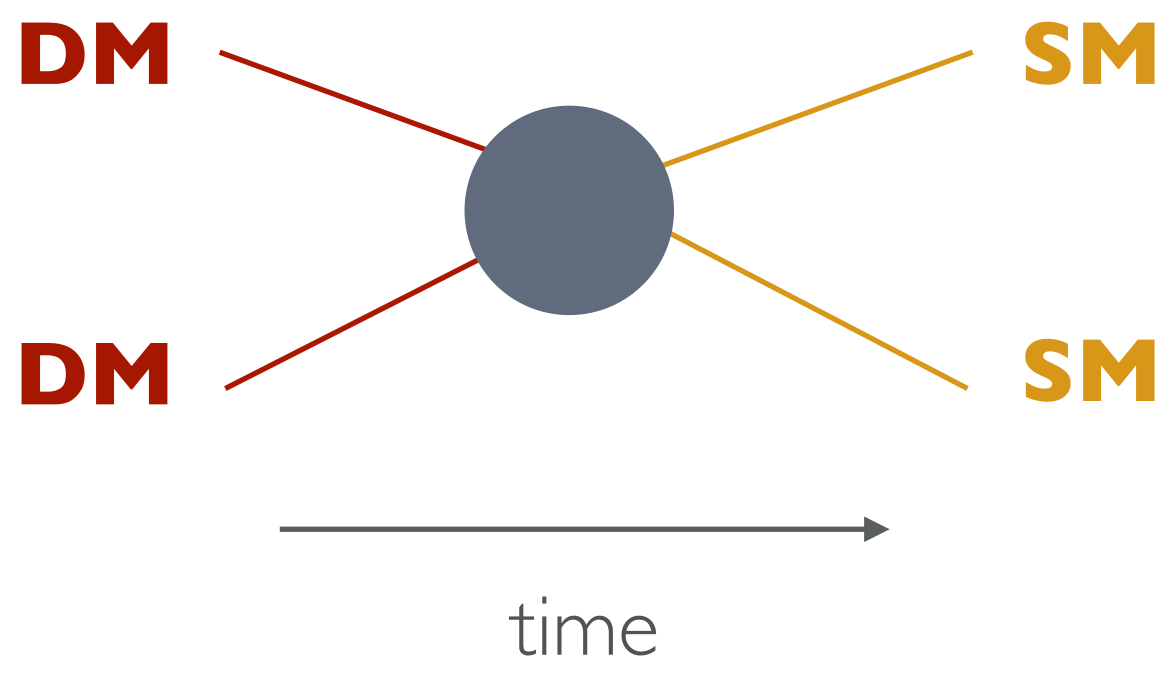


THE WIMP MIRACLE

Insensitive to the initial conditions of the Universe:

due to the thermal equilibrium between the DM and SM gases in the early Universe

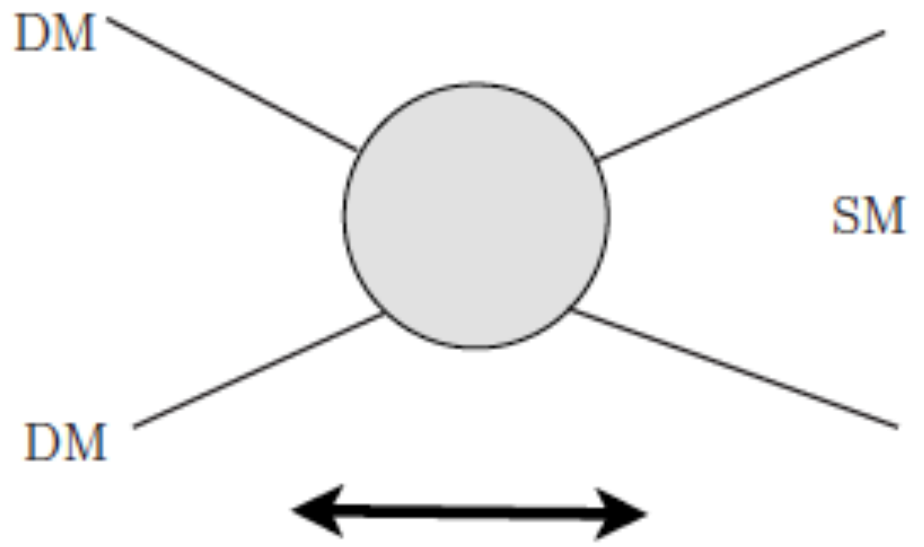
$$\text{Relic abundance} \propto \frac{1}{\text{ann. rate}}$$



Correct relic abundance for dark matter mass around the TeV scale and weak-force interactions

WIMP Dark Matter

- Original idea of WIMP Miracle



Rate in thermal eq. $\langle \sigma v \rangle \sim \frac{g_D^4}{m_{DM}^2}$

WIMP Dark Matter

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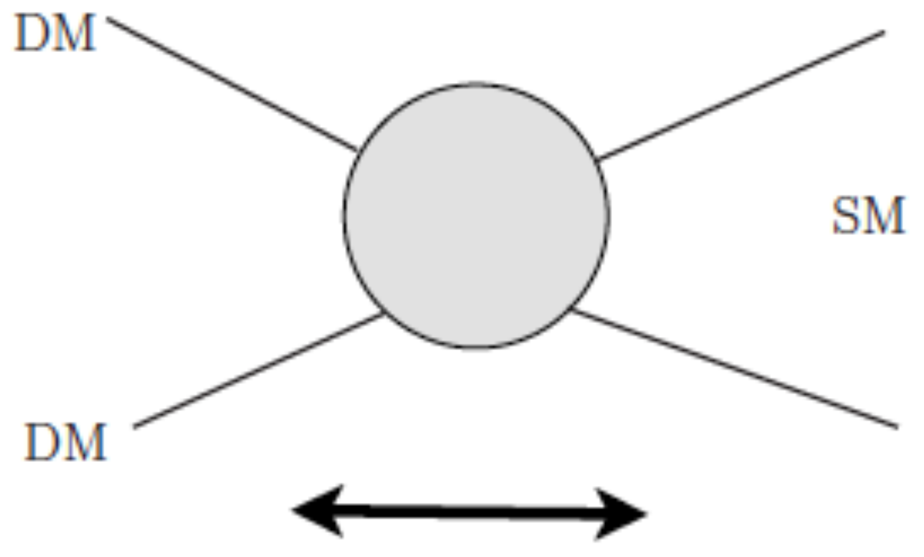
Moore's Law works in DM!



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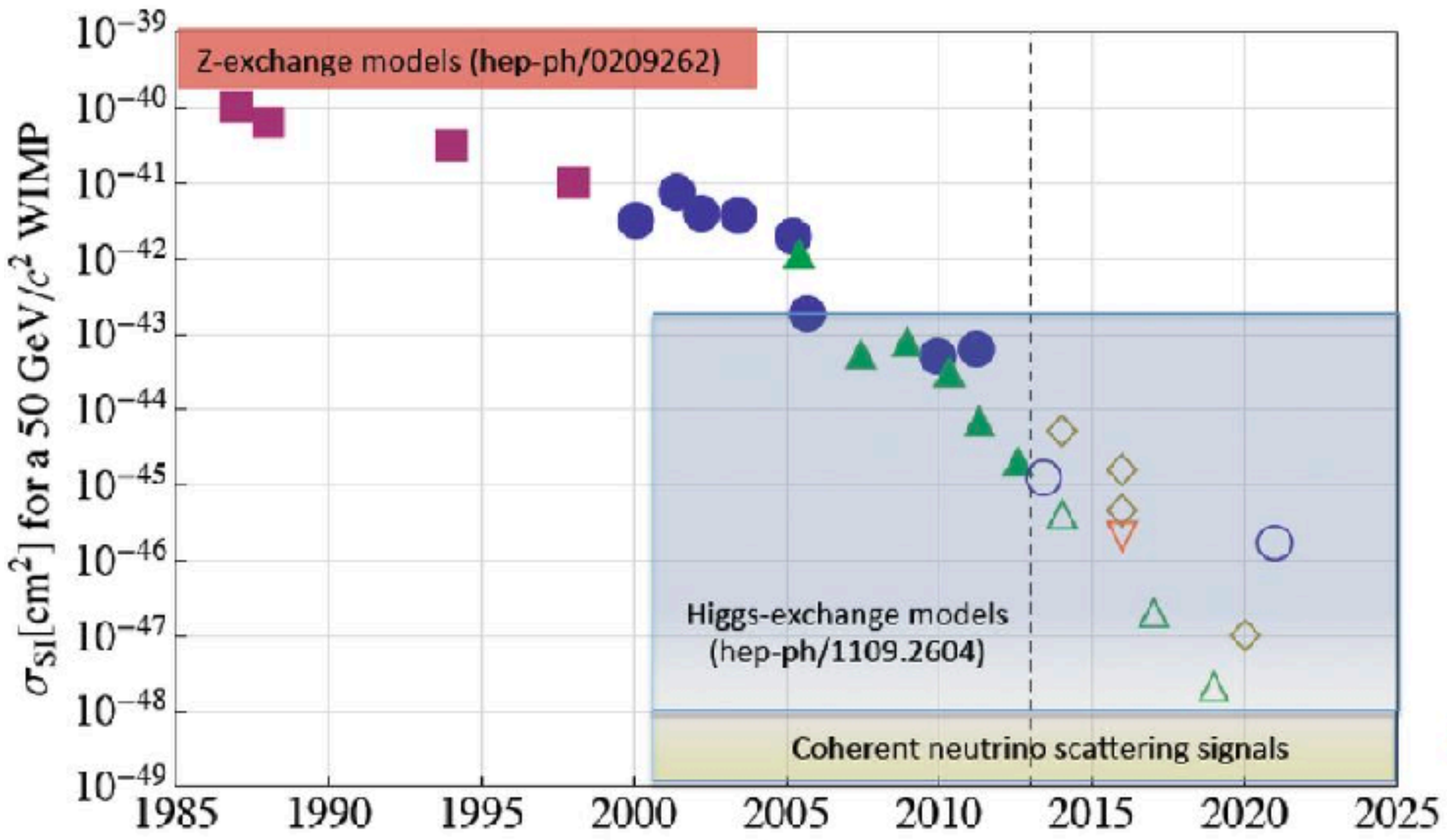

WIMP Dark Matter

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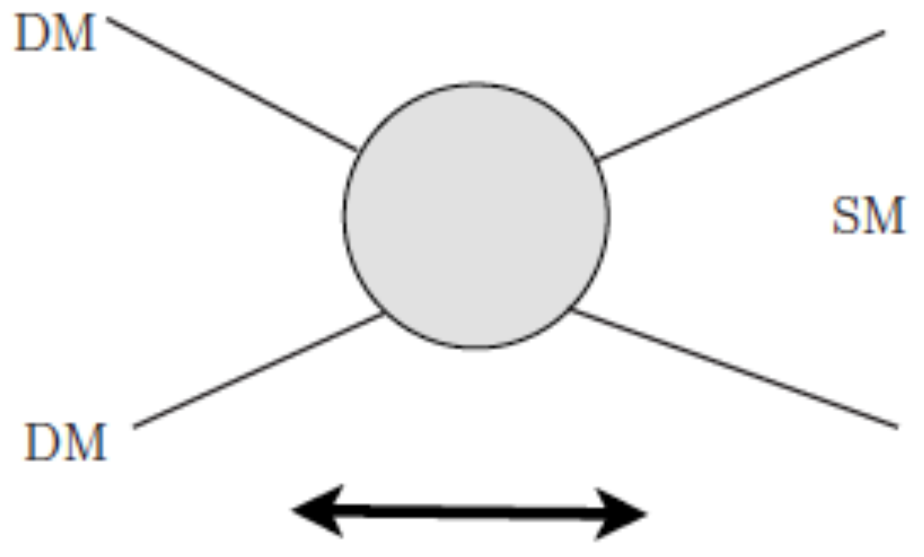
Moore's Law works in DM!

- Z boson exchange excluded except for fine-tuned corners of parameter space, and requiring tuning for Higgs mediation as well



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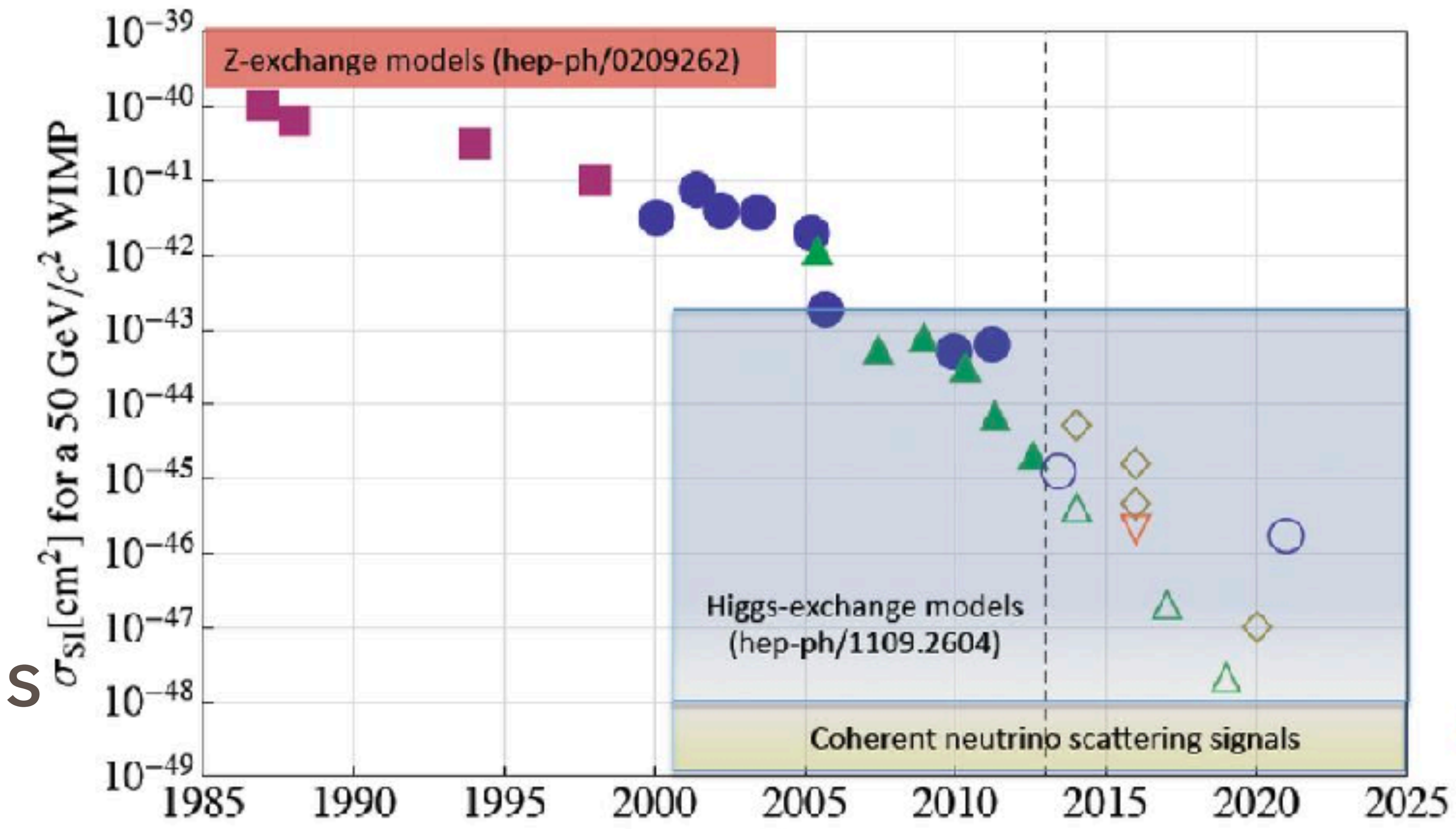


Been searching for WIMPs…

The dominant paradigm is being challenged.

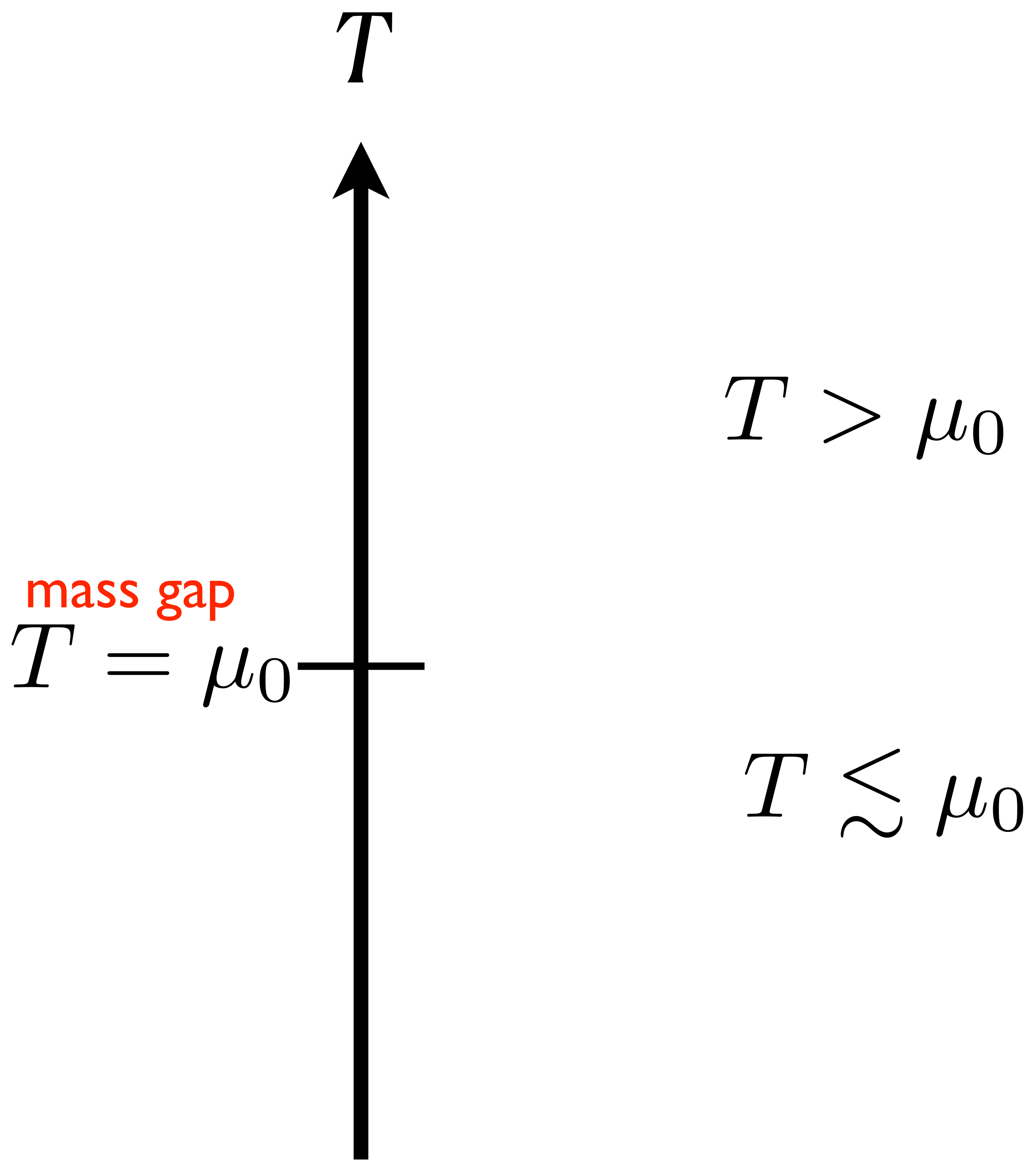
Is there another DM paradigm that gives qualitatively different signatures, but still provide the same level of simple, elegance and compelling explanation as WIMP?

Freeze-Out of Gapped Continuum DM

$m_{SM} \ll \mu_0$

annihilation: DM+DM ↔ SM+SM

quasi-elastic scattering (QES): DM+SM ↔ DM+SM



$$f_{\rm DM} = e^{-\beta\left(E_{\mathbf{p},\mu^2} - \lambda(t)\right)}, \qquad f_{\rm SM} = e^{-\beta|\mathbf{p}|}.$$

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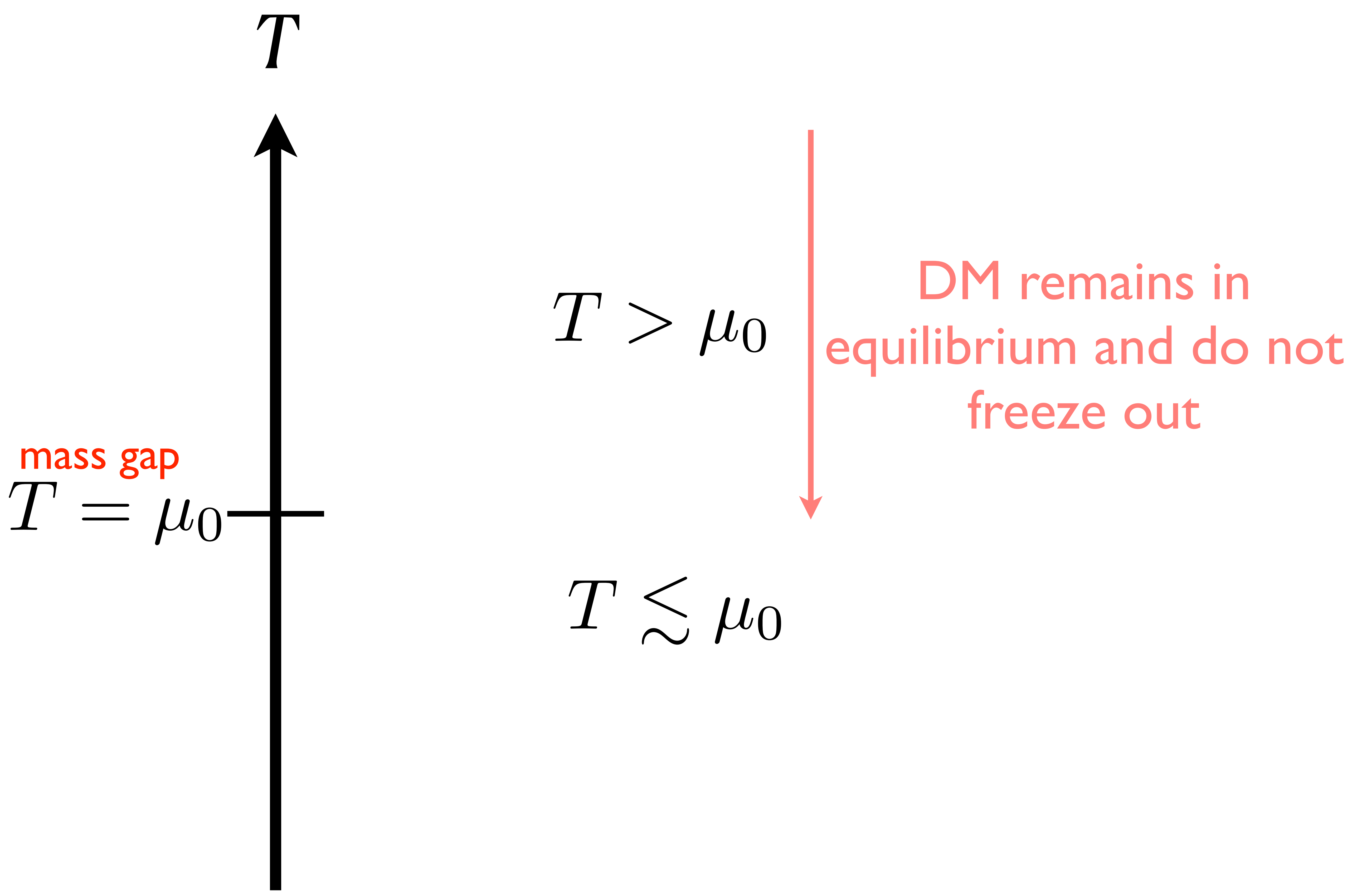

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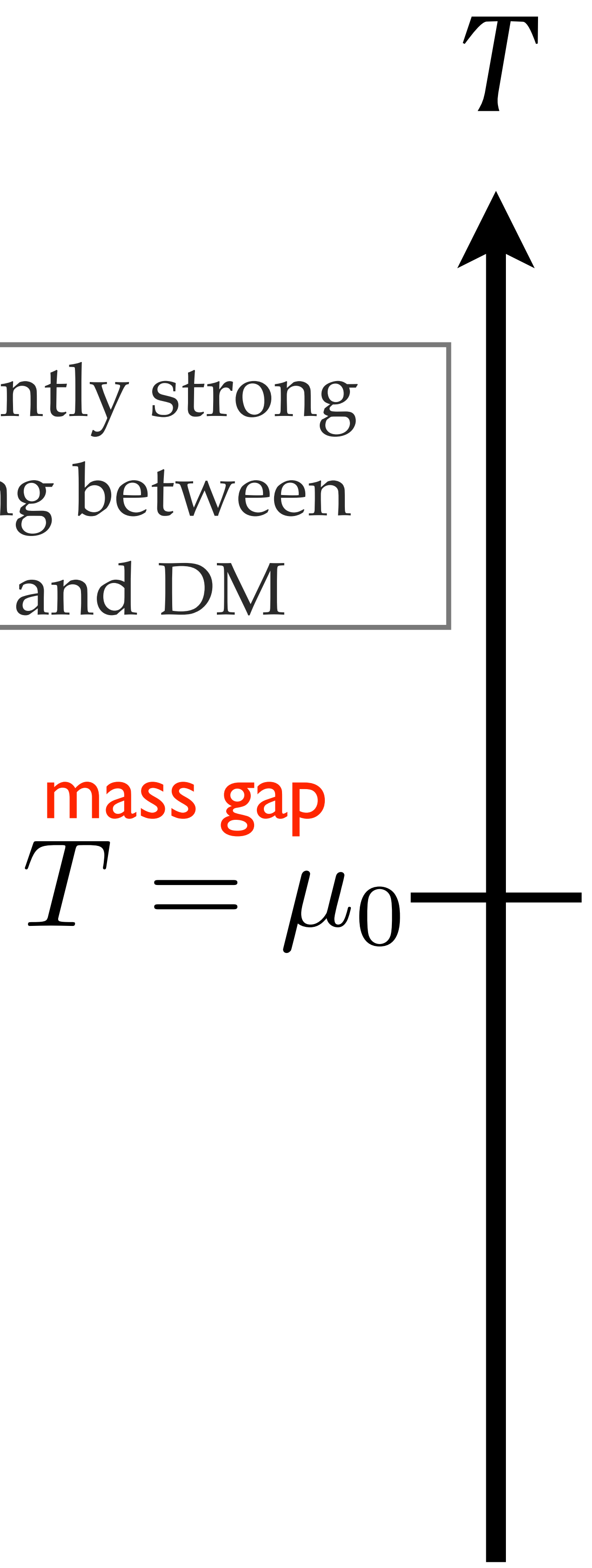

sufficiently strong coupling between the SM and DM

annihilation is in equilibrium, DM particles are at the same temperature T as the SM and is at zero chemical potential

$T > \mu_0$

DM remains in equilibrium and do not freeze out

$T \lesssim \mu_0$

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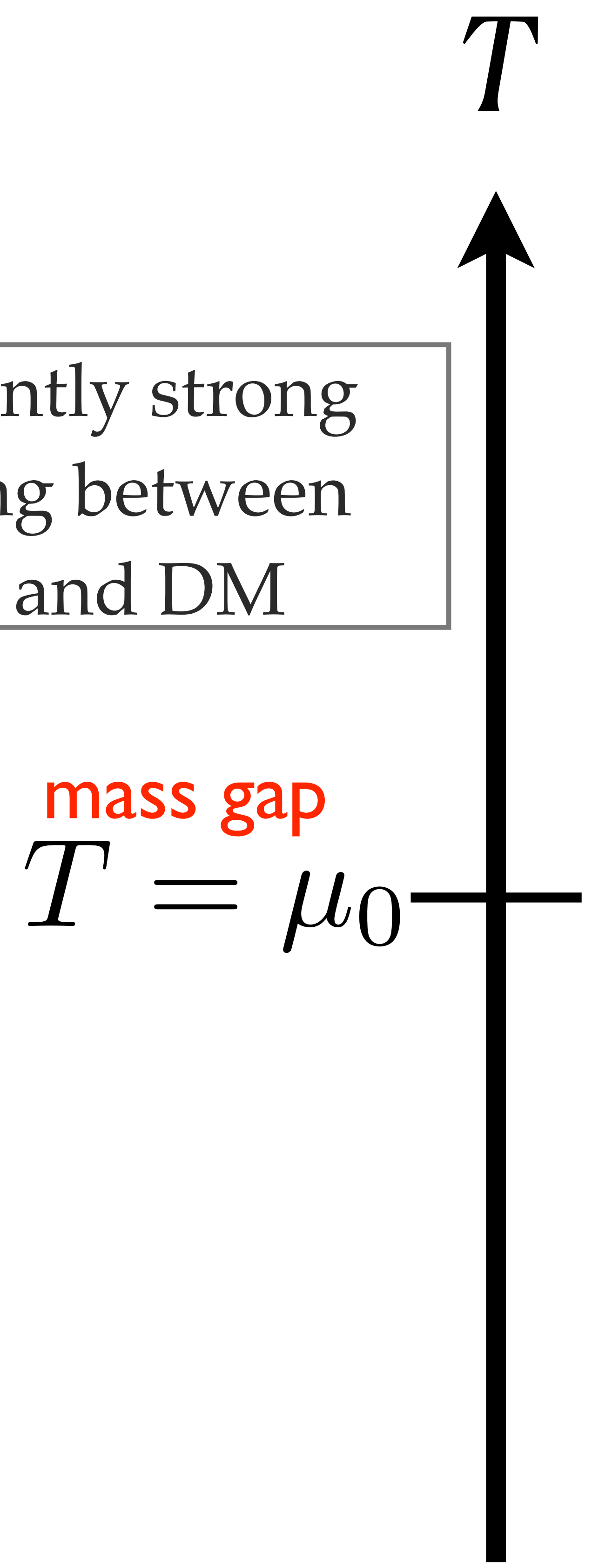

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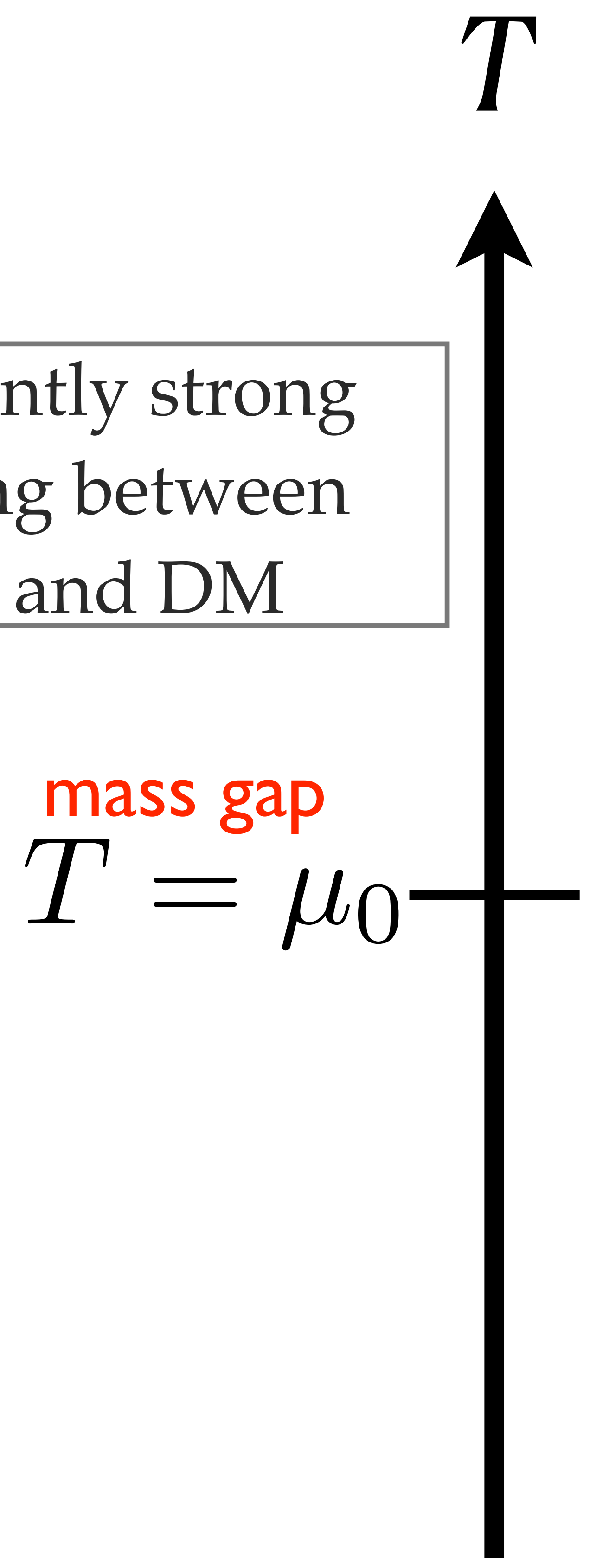

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"Freeze out"

rate of quasi-elastic scattering of a DM particle does not experience an exponential drop : maintain thermal equilibrium between the SM and DM (same T, and chemical)

$$f_{\rm DM} = e^{-\beta\left(E_{\mathbf{p},\mu^2} - \lambda(t)\right)}, \qquad f_{\rm SM} = e^{-\beta|\mathbf{p}|}.$$

Gapped Continuum Z-portal DM

- Z-portal Model (with Z_2 symmetry)
  - Consider a complex scalar field Φ with no SM gauge quantum numbers (this plays the role of DM field, and is lifted to 5D)
  - Add another complex scalar field χ which is a doublet under $SU(2)_L$ and carries $U(1)_Y$ charge $-1/2$

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{\Phi} + \mathcal{L}_{\chi} + \mathcal{L}_{int}$$
$$\mathcal{L}_{\Phi} = \Phi^\dagger(p)\Sigma(p^2)\Phi(p)$$
$$\mathcal{L}_{\chi} = (D_\mu \chi)^\dagger (D^\mu \chi) - m_\chi^2 \chi^\dagger \chi$$
$$\mathcal{L}_{int} = -\lambda \Phi \chi H + \text{c.c.}$$

includes couplings to the SM Z and $U(1)_Y$

spectral density: $\rho(p^2) = \frac{1}{\pi} \text{Im}\Sigma^{-1}(p^2)$

- When the Higgs gets a vev, L_{int}-term induces mass mixing between Φ and the neutral components of χ. The mass eigenstates are

$$\tilde{\Phi} = \cos\alpha\, \Phi + \sin\alpha\, \chi^0, \qquad \tilde{\chi}^0 = -\sin\alpha\, \Phi + \cos\alpha\, \chi^0.$$

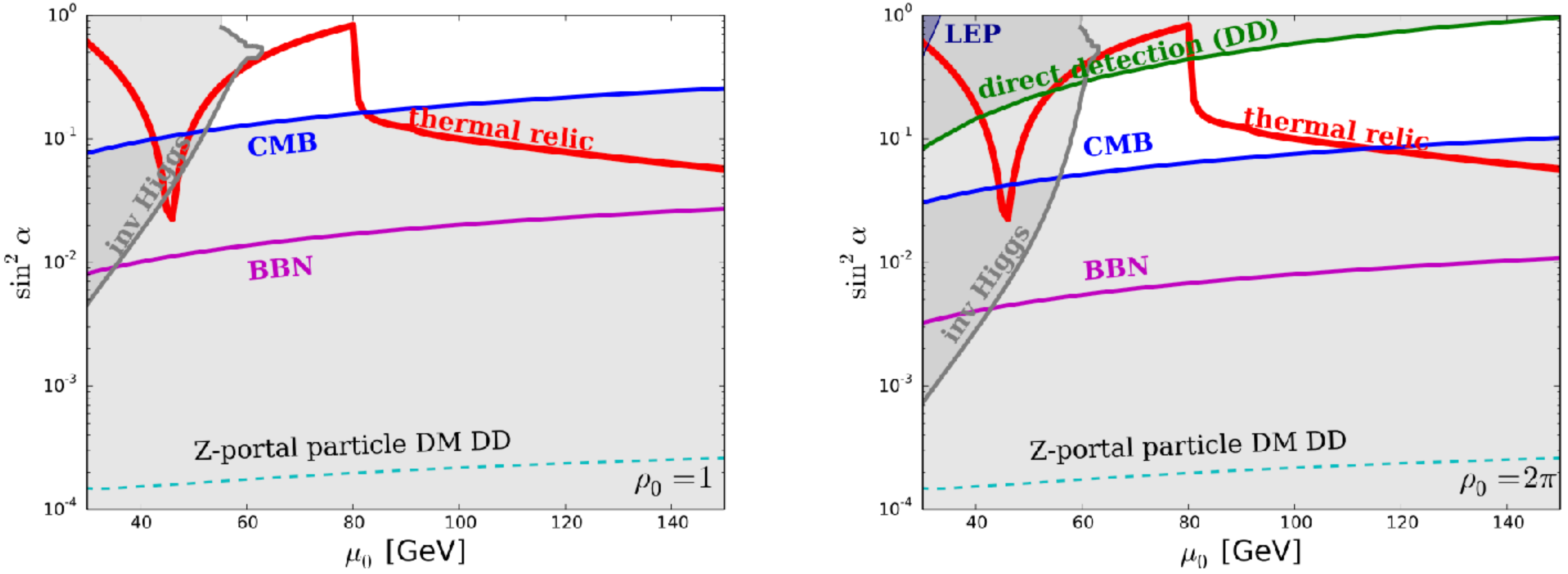
Gapped Continuum Z-portal DM

♦ Z-portal Model

$$\mathcal{L} = \sqrt{g^2 + g'^2}\,\sin^2\alpha\,\left(\tilde{\Phi}_2\partial_\mu\tilde{\Phi}_1 - \tilde{\Phi}_1\partial_\mu\tilde{\Phi}_2\right)\,Z^\mu$$

The mixing angle is given by

$$\tan 2\alpha = \frac{2\lambda v}{m_\phi^2 - m_\chi^2}$$



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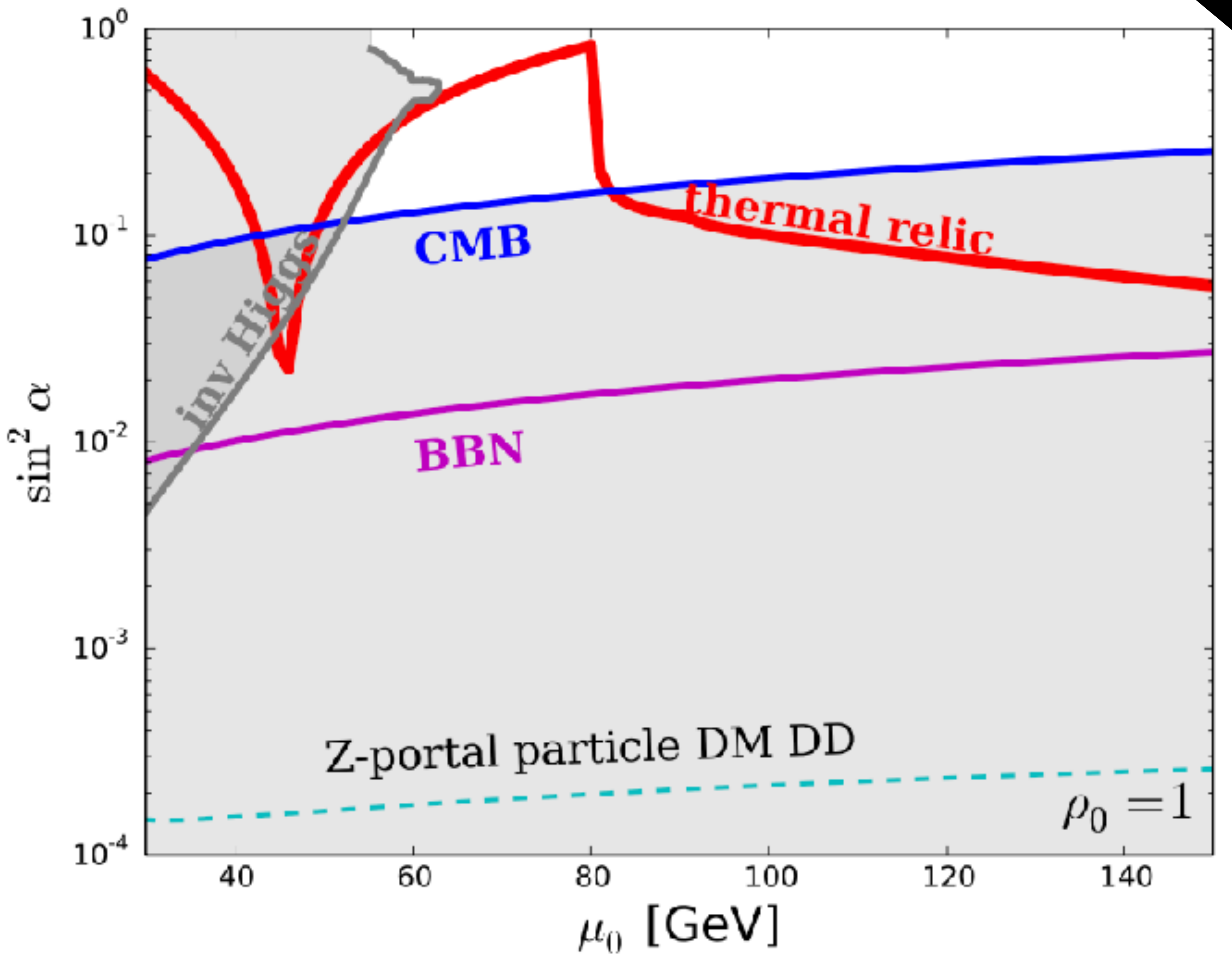
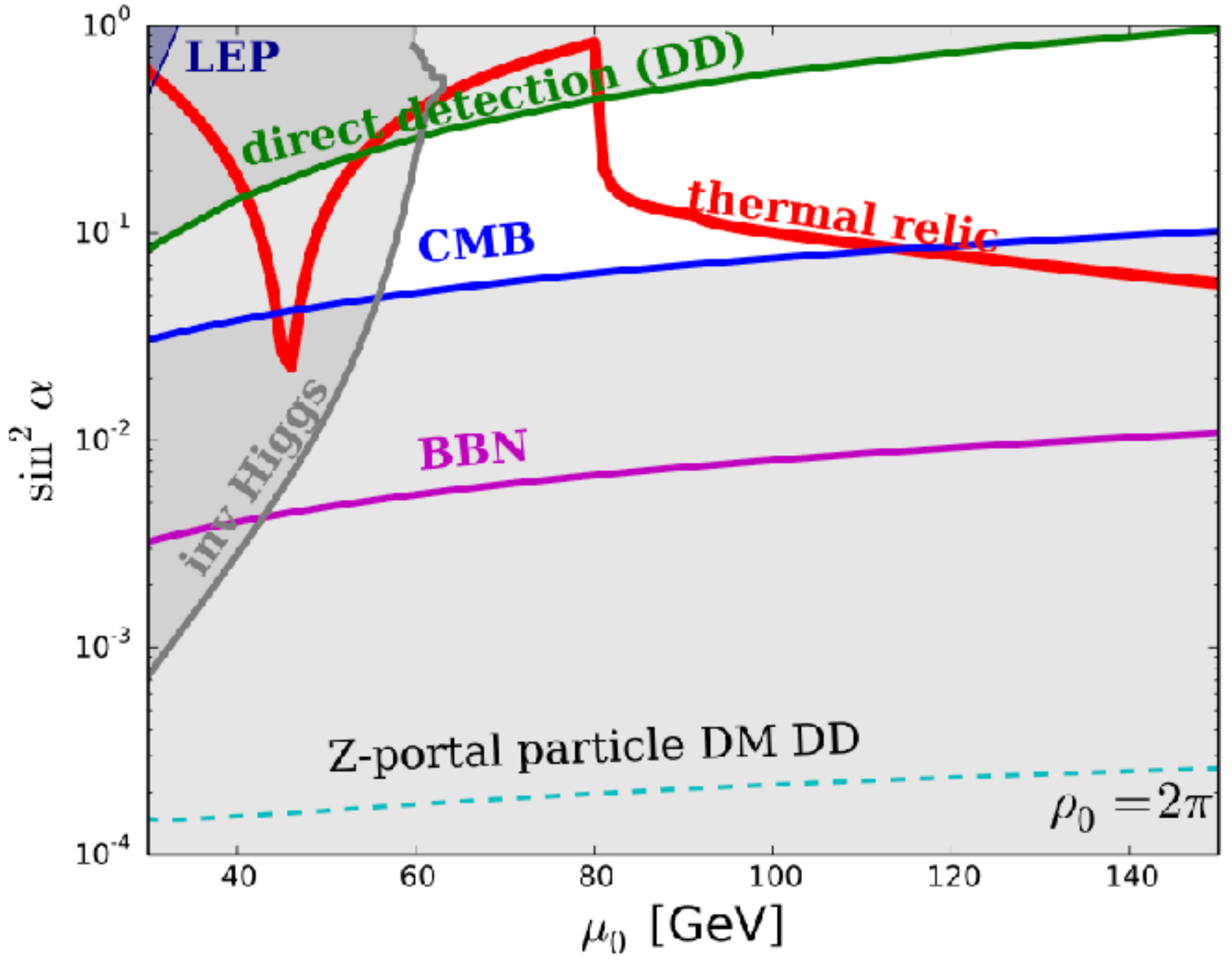
The salient feature of the gapped continuum DM: there is a generic rate suppression, which makes it compatible with the current null result of direct detection experiments.





Gapped Continuum Nature of DM

- Late decay
  - decay within the continuum state: $DM(\mu_1) \rightarrow DM(\mu_2) + SM$
    - Since all continuum states carry the same quantum number, such decays will necessarily occur continuously throughout the history of the universe.
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    - In the early universe: DM in thermal and chemical equilibrium with the SM
    - As temperature drops below the gap scale μ_0, DM decouples from the SM and the total number of DM states is frozen out, just like for the usual thermal-relic particle DM
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    - In the early universe: DM in thermal and chemical equilibrium with the SM
    - As temperature drops below the gap scale μ_0, DM decouples from the SM and the total number of DM states is frozen out, just like for the usual thermal-relic particle DM
    - However, the mass distribution of the DM states continues to evolve, thanks to the above decays
    - The decays shift the distribution towards lower masses, closer to the gap scale.
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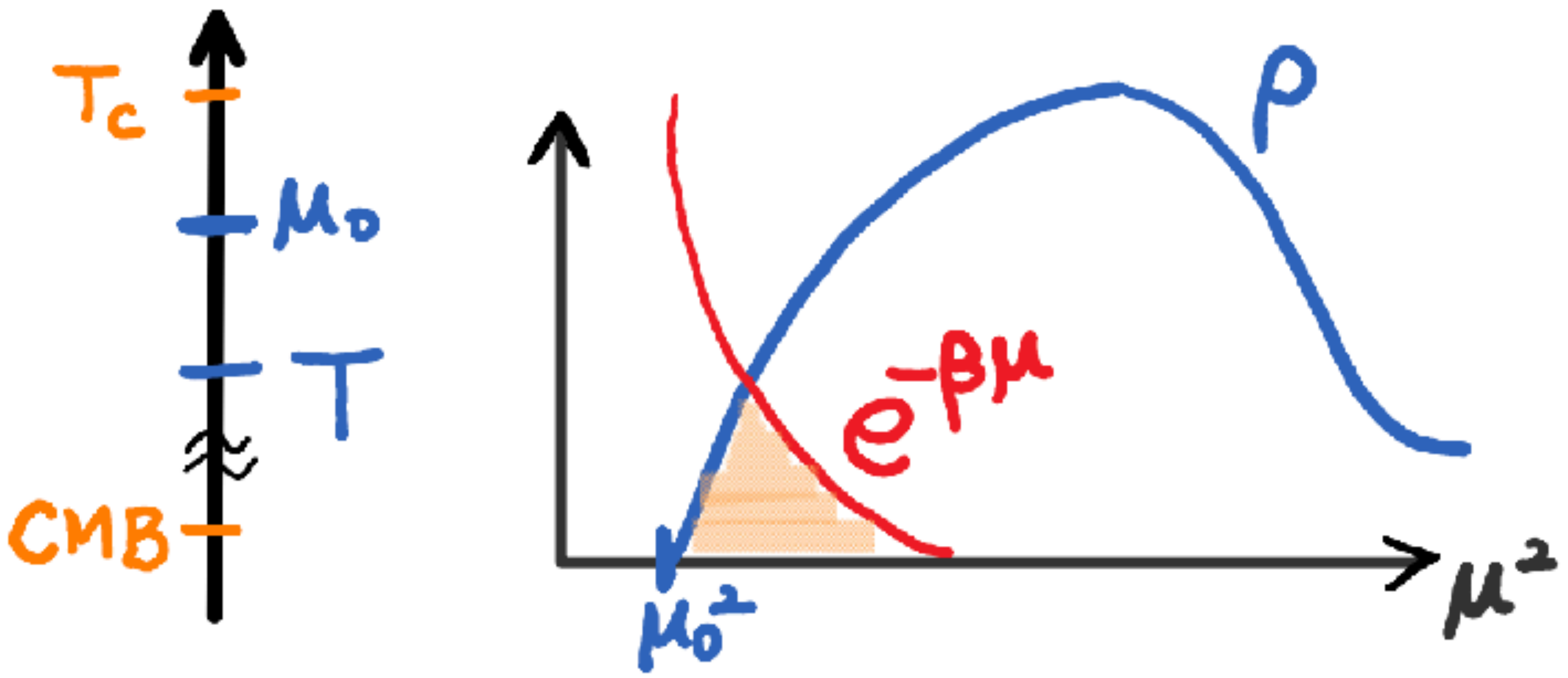

$$n = \int \frac{d\mu^2}{2\pi} \int \frac{d^3p}{(2\pi)^3}\, \rho(\mu^2)\, e^{-\beta E_\mu}$$

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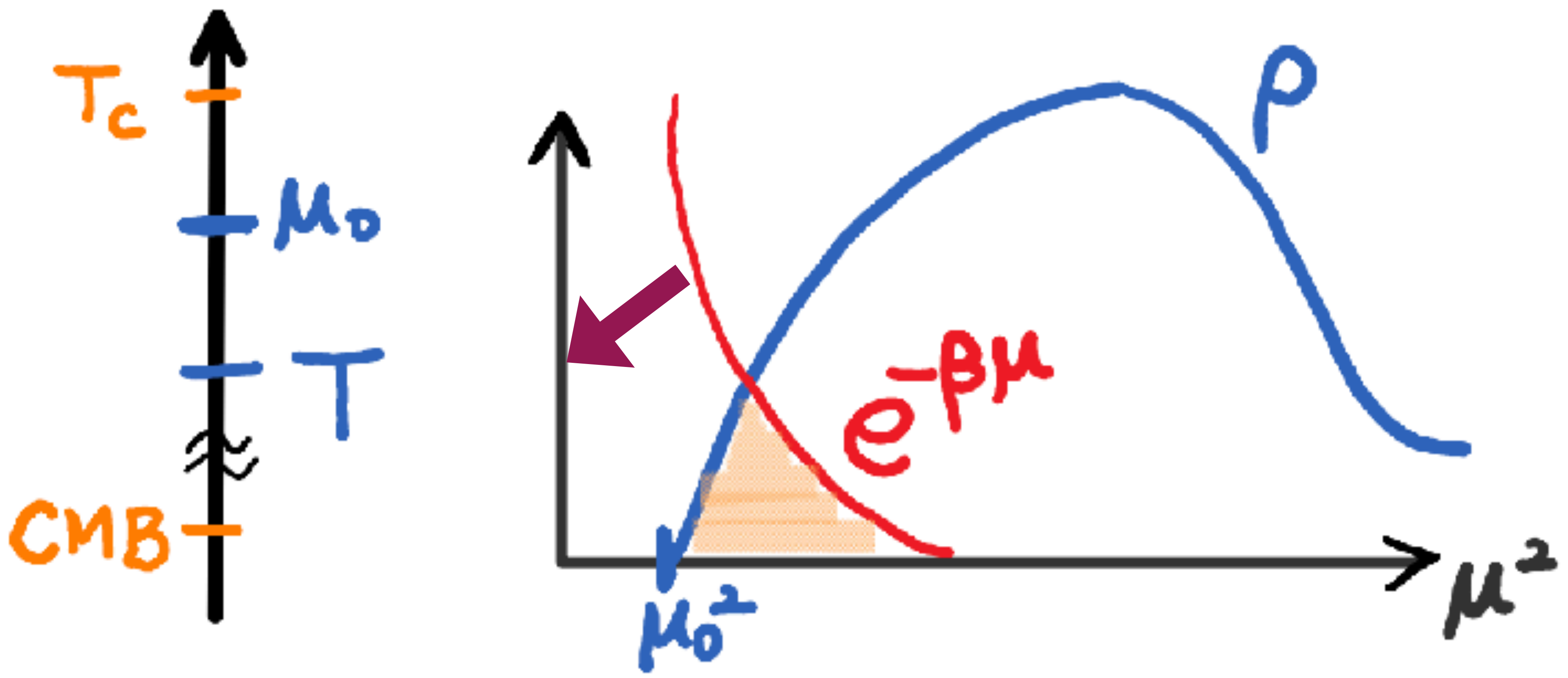

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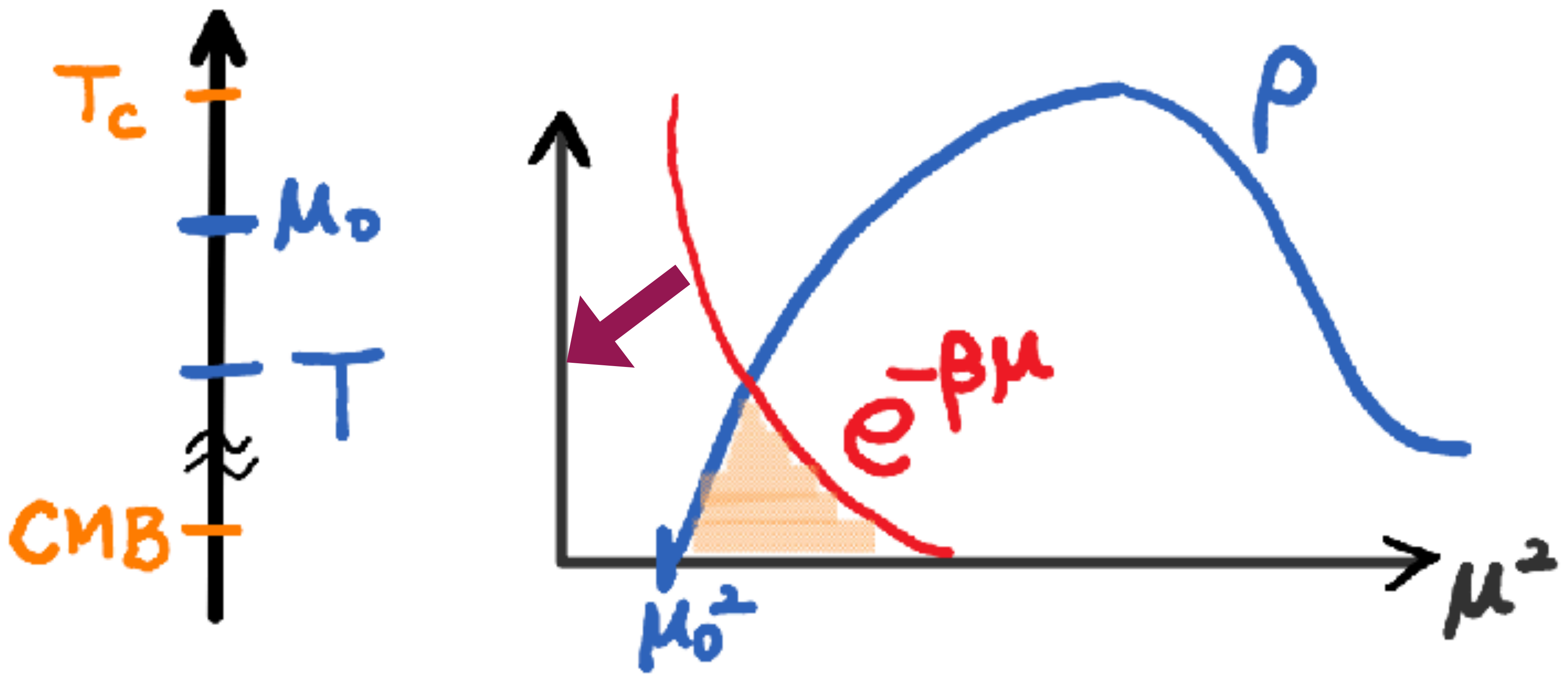

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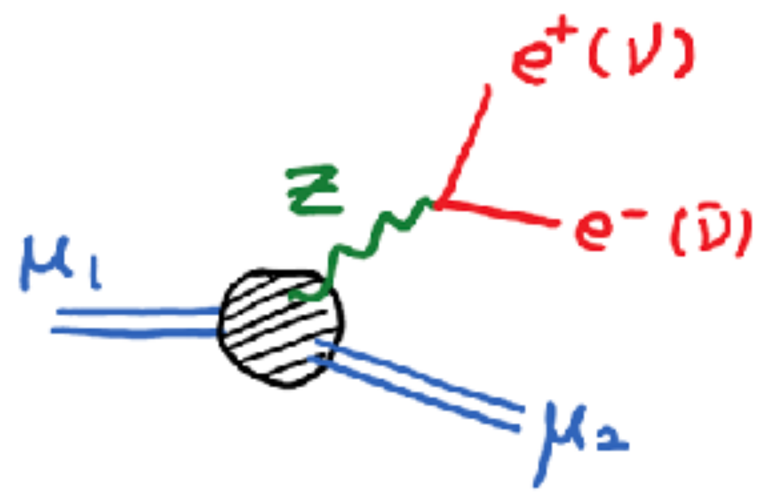
- The decays shift the distribution towards lower masses, closer to the gap scale.
- Lifetime of a DM state increases with decreasing mass, due to both phase-space suppression and the fact that there are fewer states for it to decay into.
- e.g. in our model, DM states are currently clustered within a few hundred keV above the gap scale (on average, each DM state undergoes roughly one decay per Hubble time)

Gapped Continuum Nature of DM

- Late decay ($T > T_{CMB}$)



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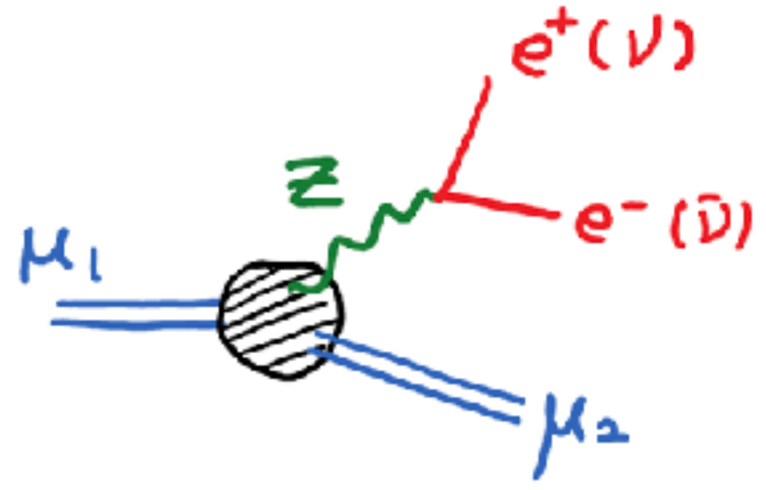

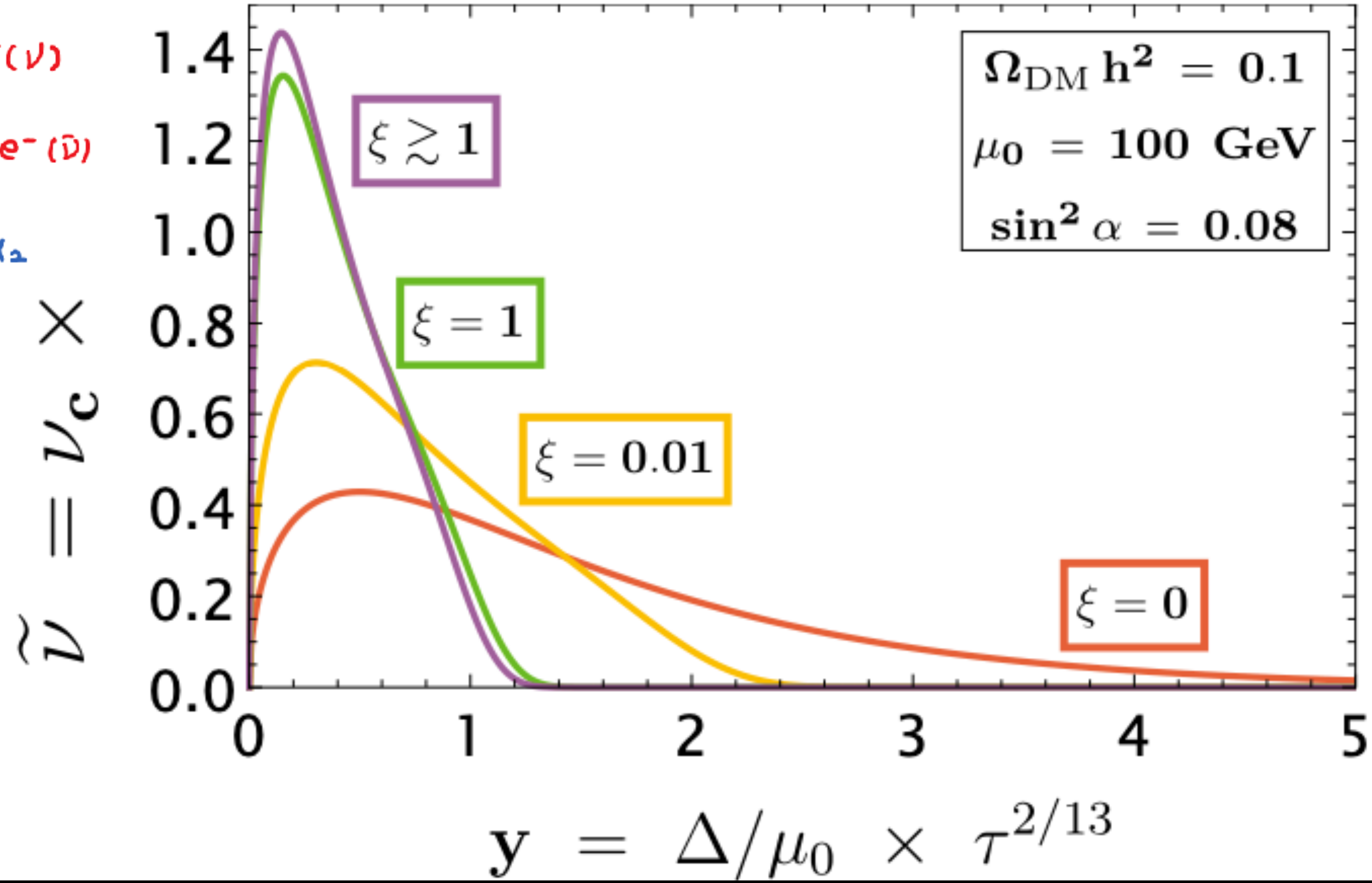

$\xi = \log(t/t_d)$, where $\tau = \Gamma_0 t$ and t_d is the time at decoupling

$\Delta = \mu - \mu_0$

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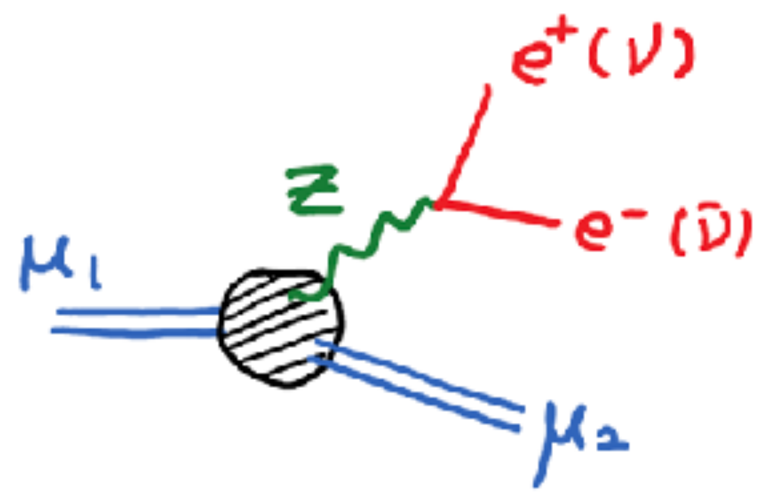

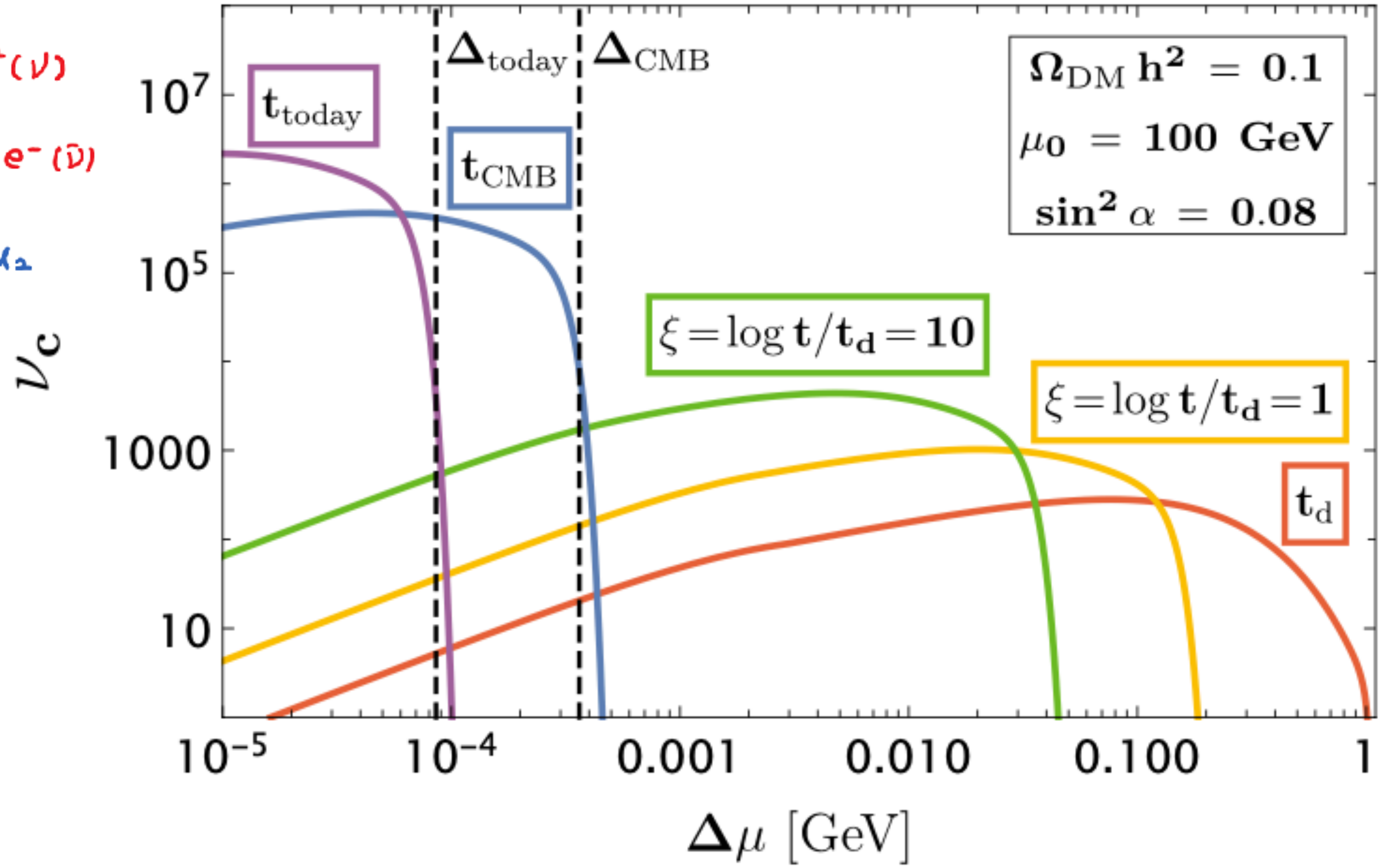

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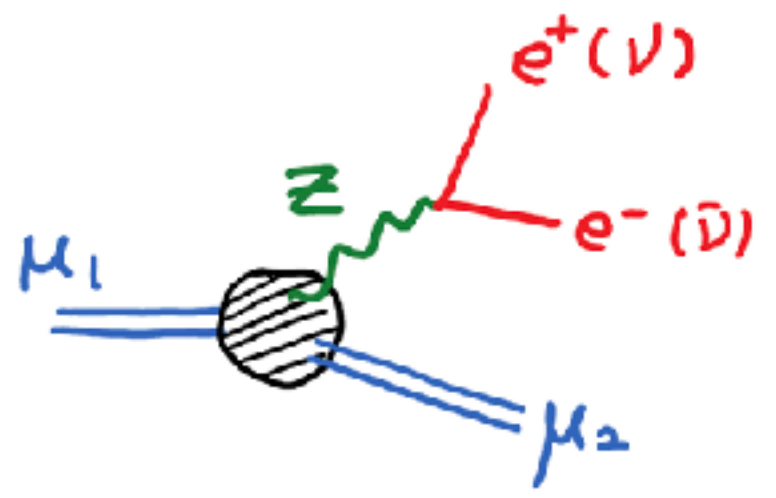

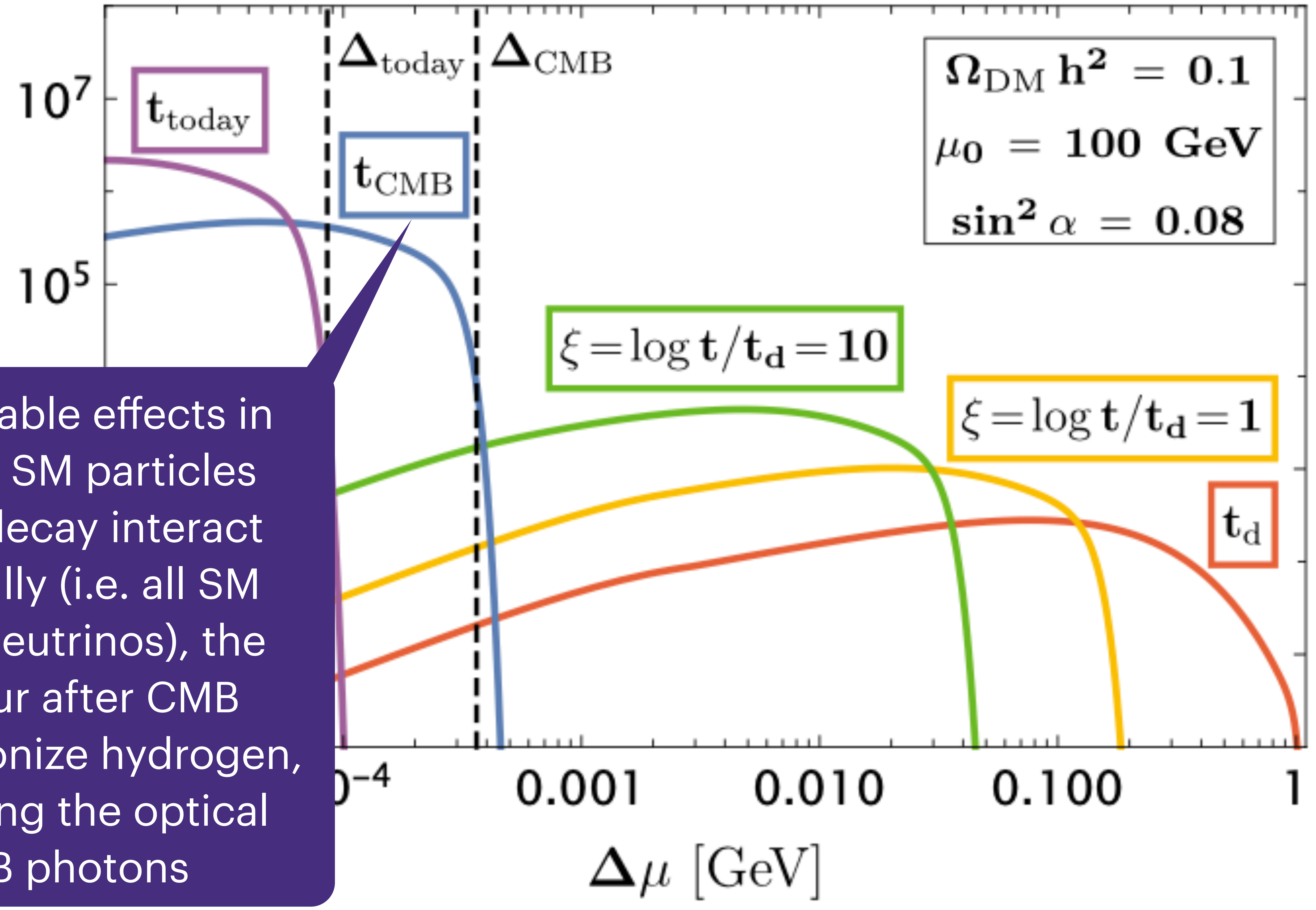

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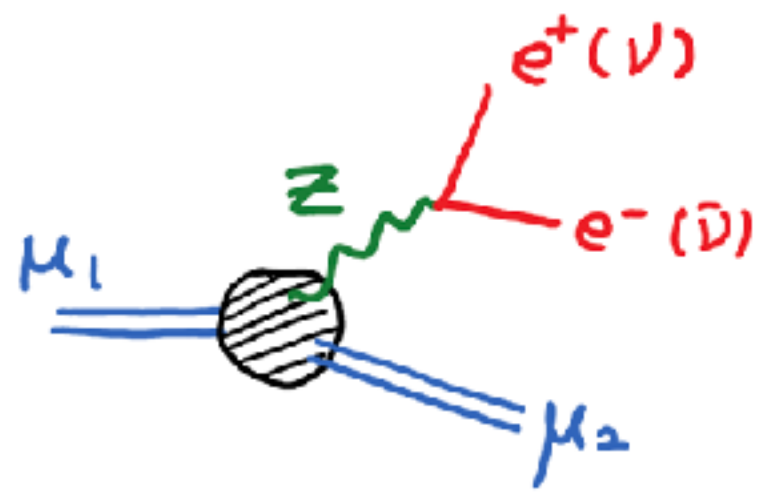

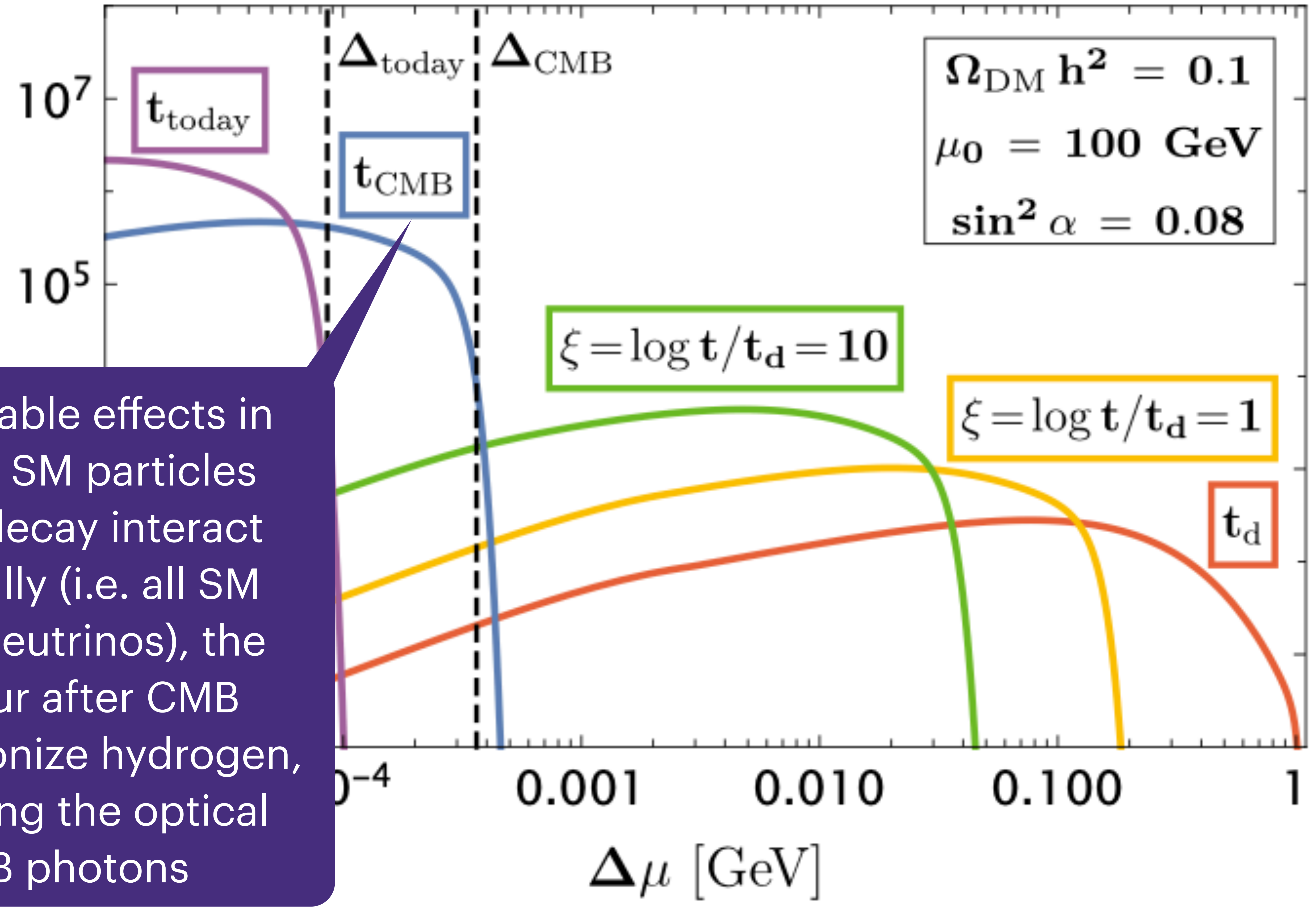

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To avoid this, late decay (to e^+e^-) needs to end by $T > T_{CMB}$
=> gives a **lower bound** on the effective coupling

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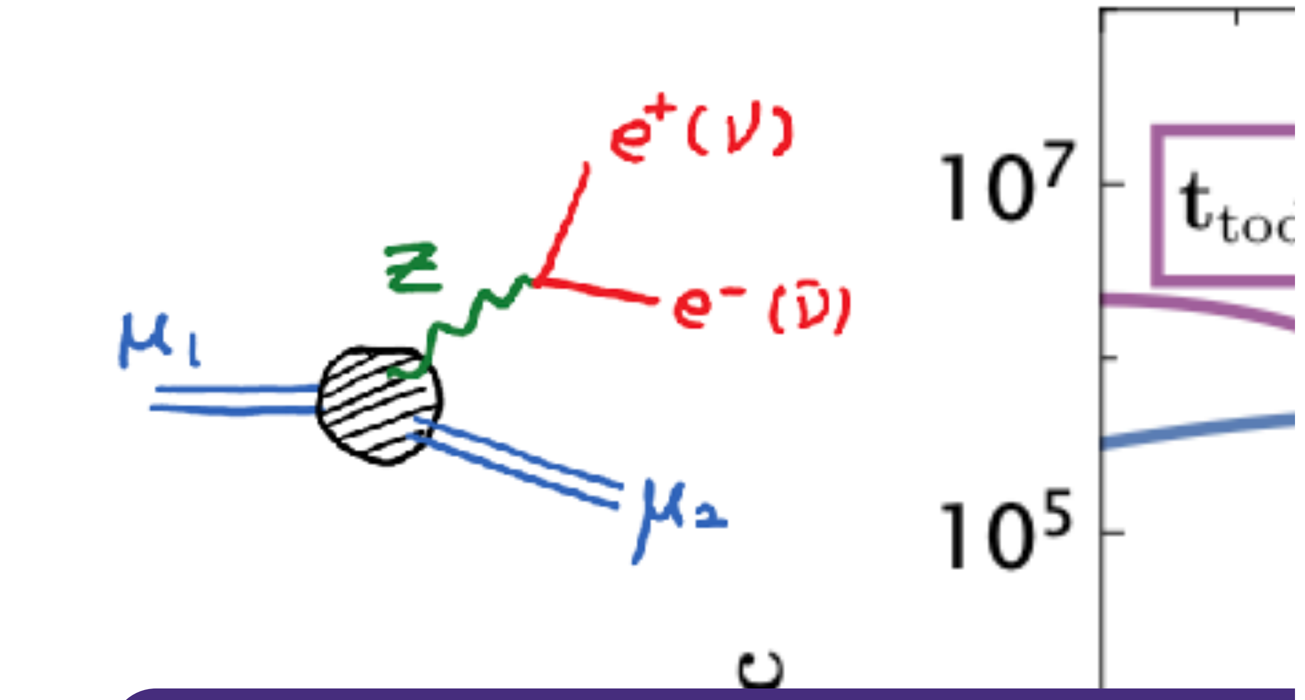

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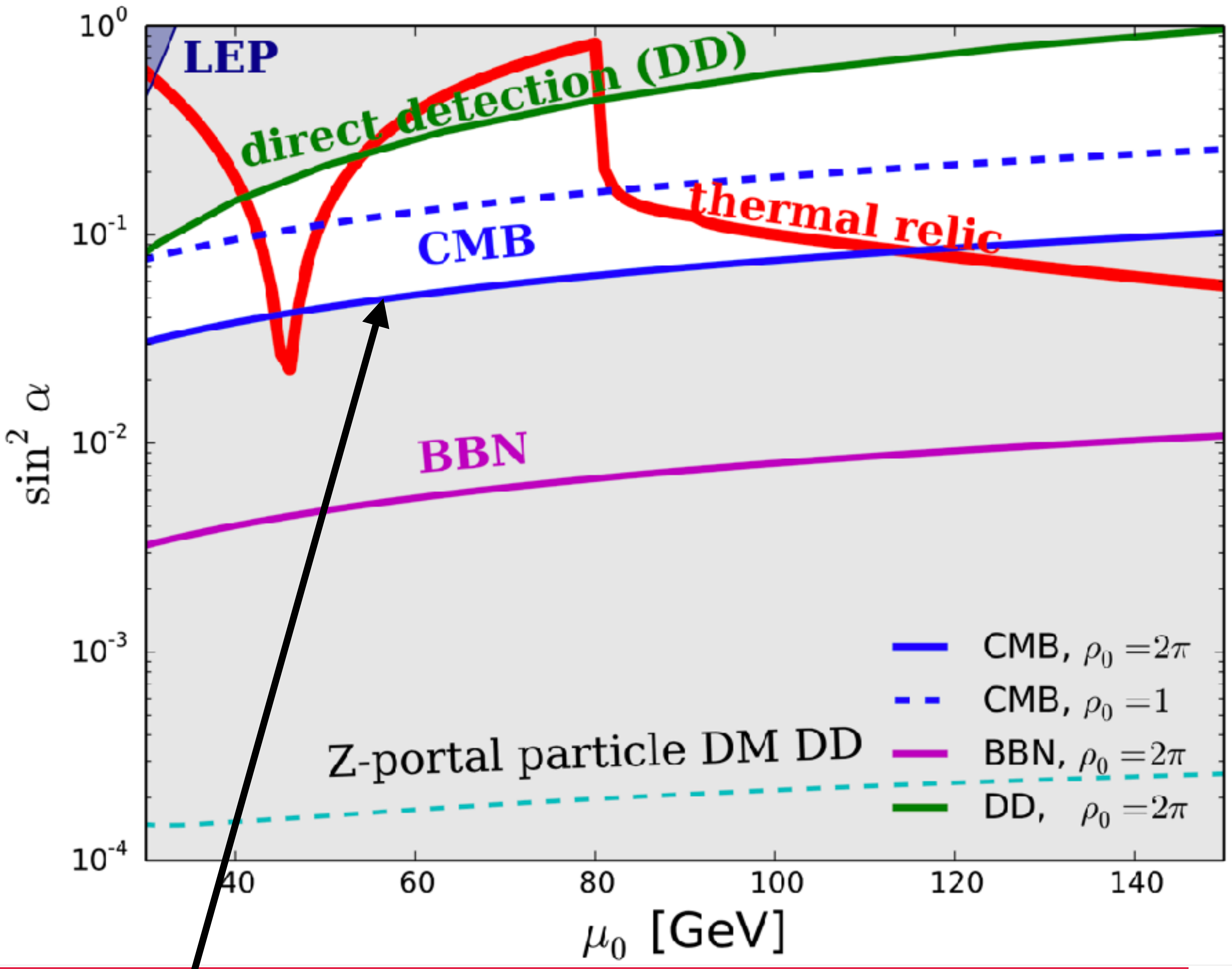

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Gapped Continuum Nature of DM

- Direct detection
  - quasi elastic scattering (QES): $DM(\mu_1) + SM_1 \rightarrow DM(\mu_2) + SM_2$
    - even after freeze out, distribution of DM state keeps evolving: distribution is peaked at the mass gap (μ_0)at very late time (these decays are important for CMB physics), and DM states pass through the earth with non-relativistic speed ($v \sim 10^{-3}$)

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=> If incoming DM state has $\mu_1 = \mu_0 + \Delta$, accessible final continuum modes are in very narrow window $\mu_2 \in [\mu_0, \mu_0 + \Delta + Q]$. For weak scale μ_0, this basically means that the integral appearing in the QES cross section is constrained to a tiny interval in μ, and leads to a significant suppression of the rate

$$\sigma \sim \int \frac{d\mu_2^2}{2\pi} \rho(\mu_2^2)\, \hat{\sigma}\,(\mu_1, \mu_2)$$

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Q is the kinetic energy of the collision in the center-of-mass frame

$\Delta \ll \mu_0$ in today's universe, while $Q \ll \mu_0$ as long as ambient DM is non-relativistic.

$$\sigma_{\text{cont}} \sim \left(\frac{\Delta + Q}{\mu_0}\right)^{1+r} \sigma_{\text{particle}}$$

e.g. $\Delta \sim 100$ keV at the present time, while $Q \sim 1$ keV
μ_0 at the weak scale → $\sim 10^9$ suppression

r is a positive number that depends on the behavior of the spectral density near the gap (r=1/2 for XD)

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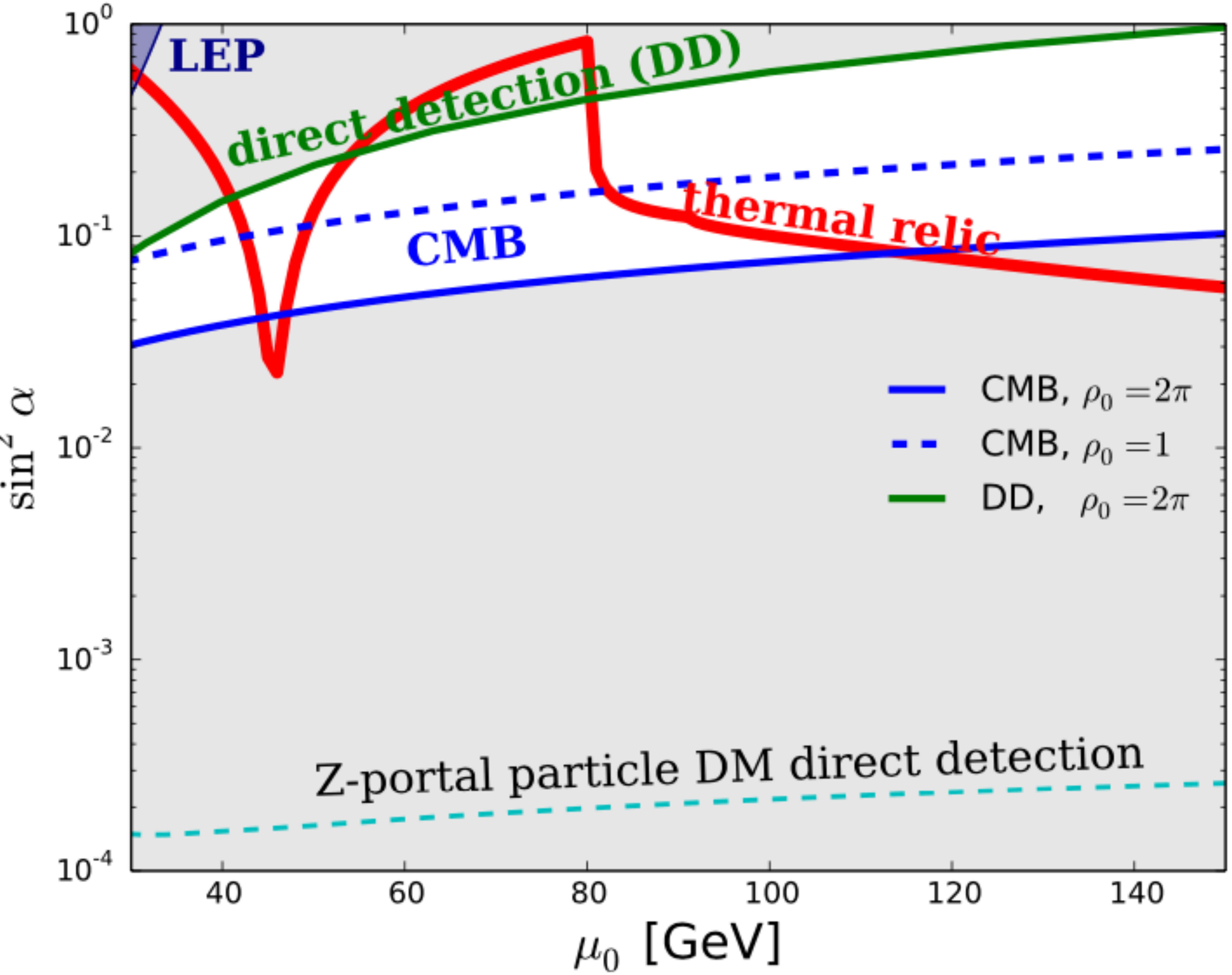

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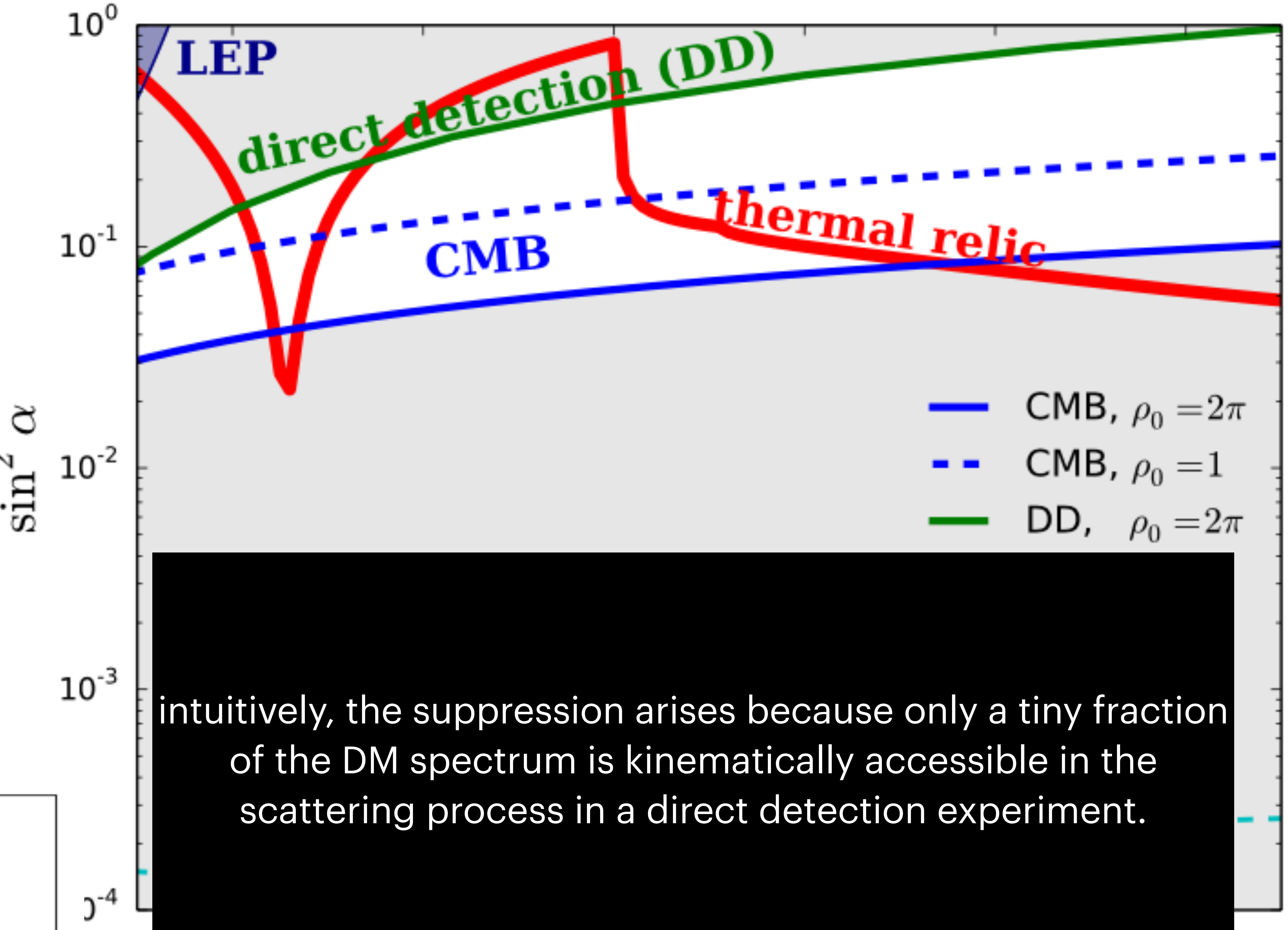

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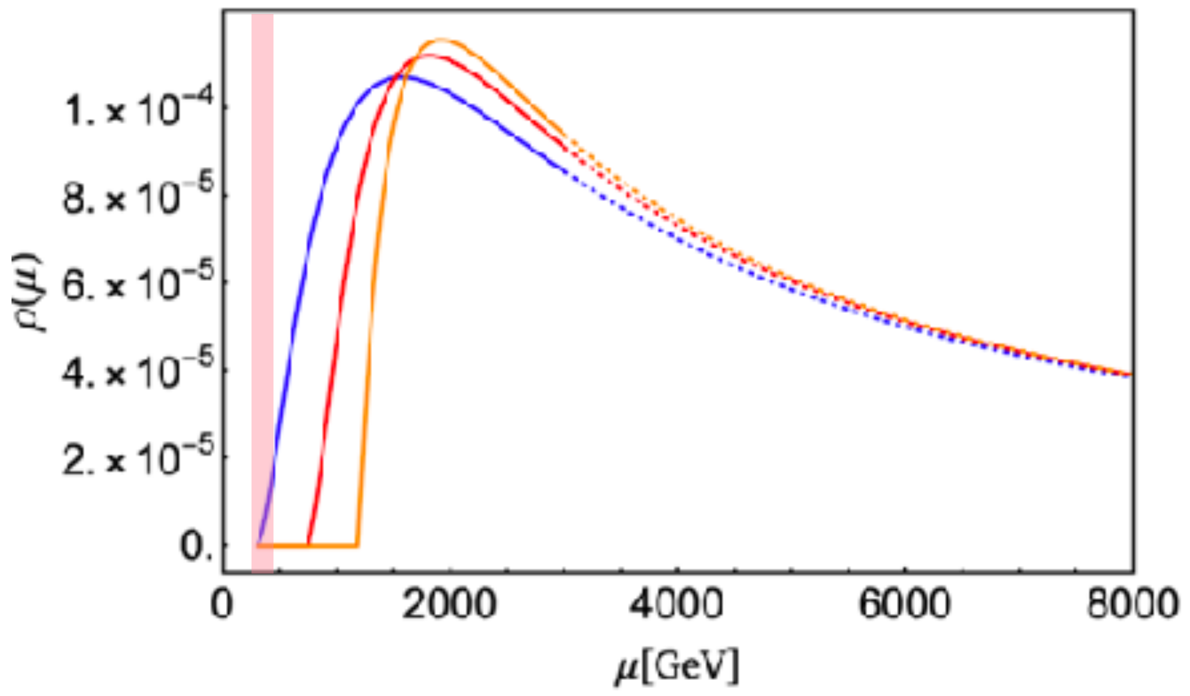

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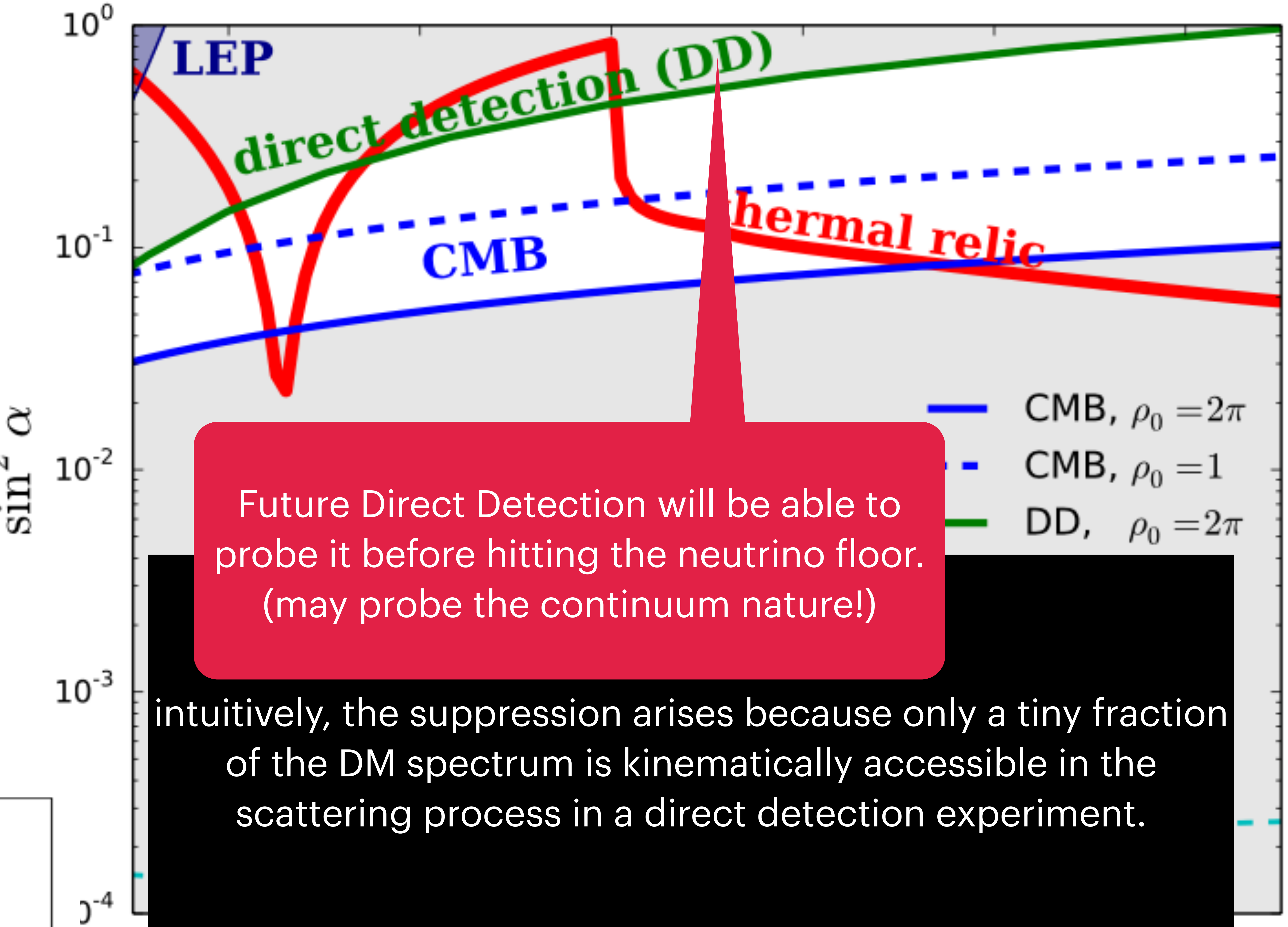

Future Direct Detection will be able to probe it before hitting the neutrino floor. (may probe the continuum nature!)

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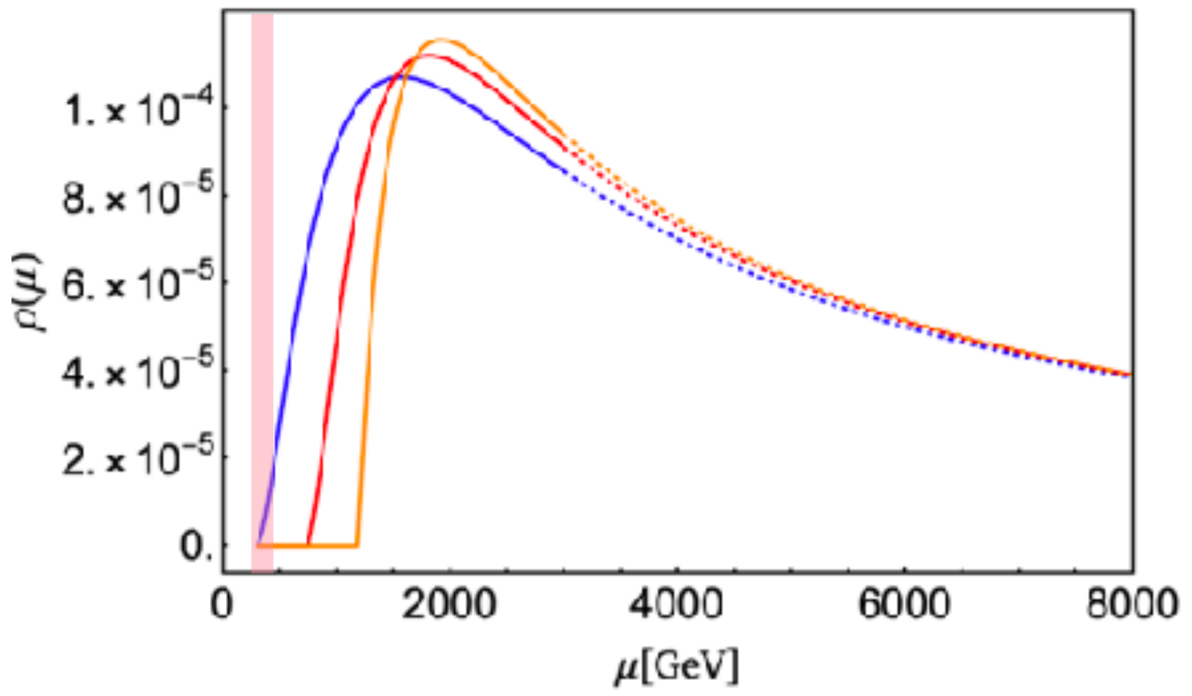

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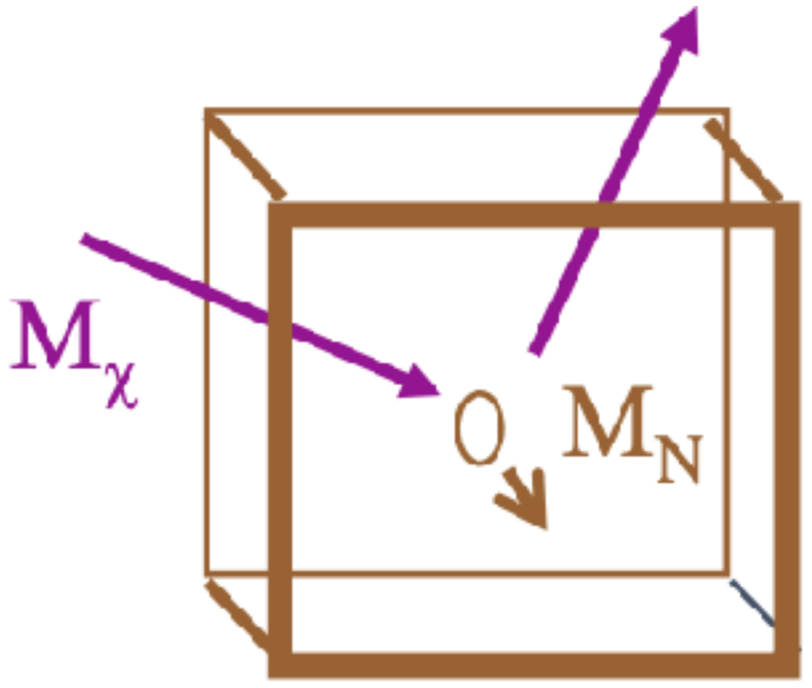

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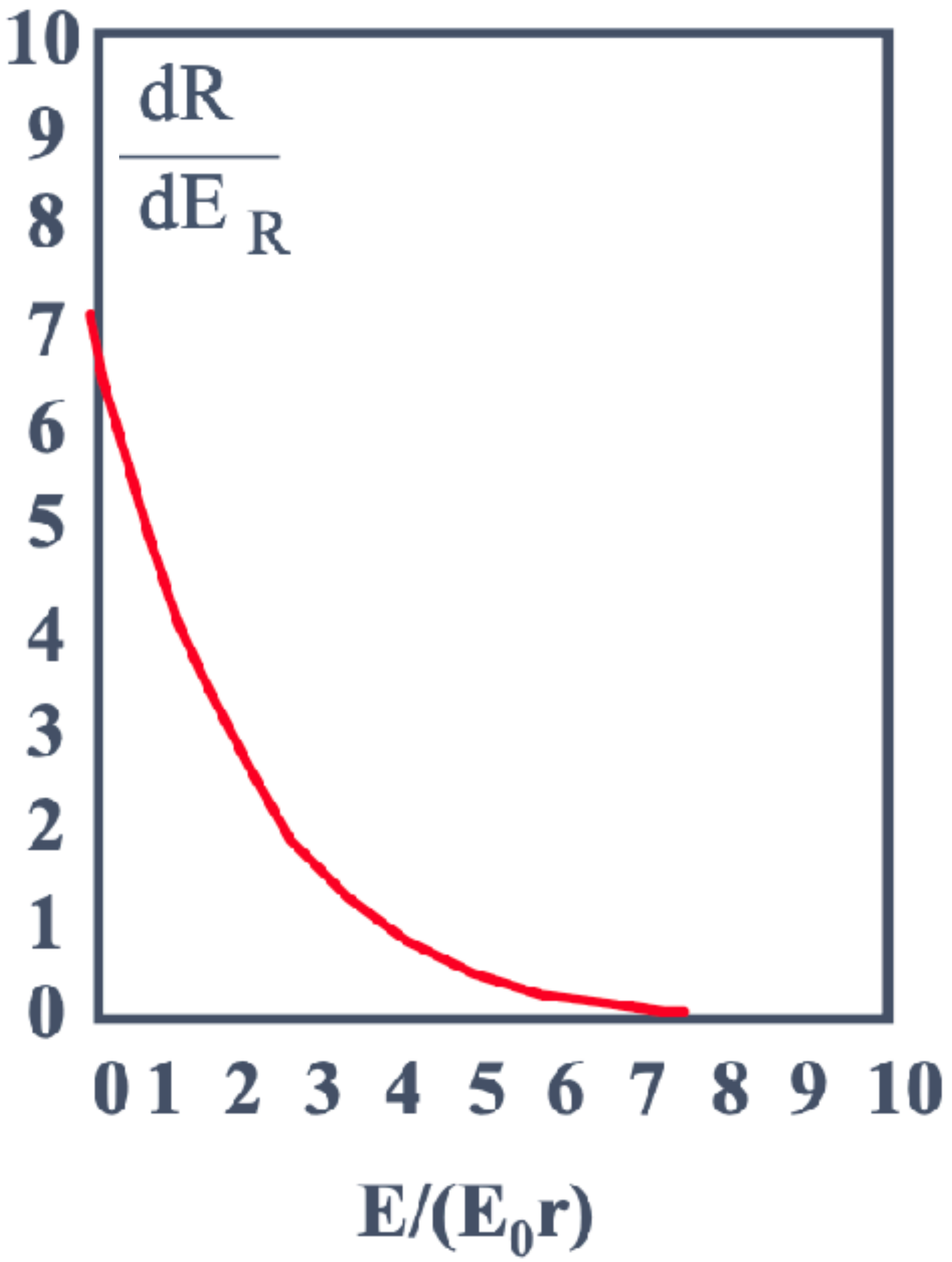

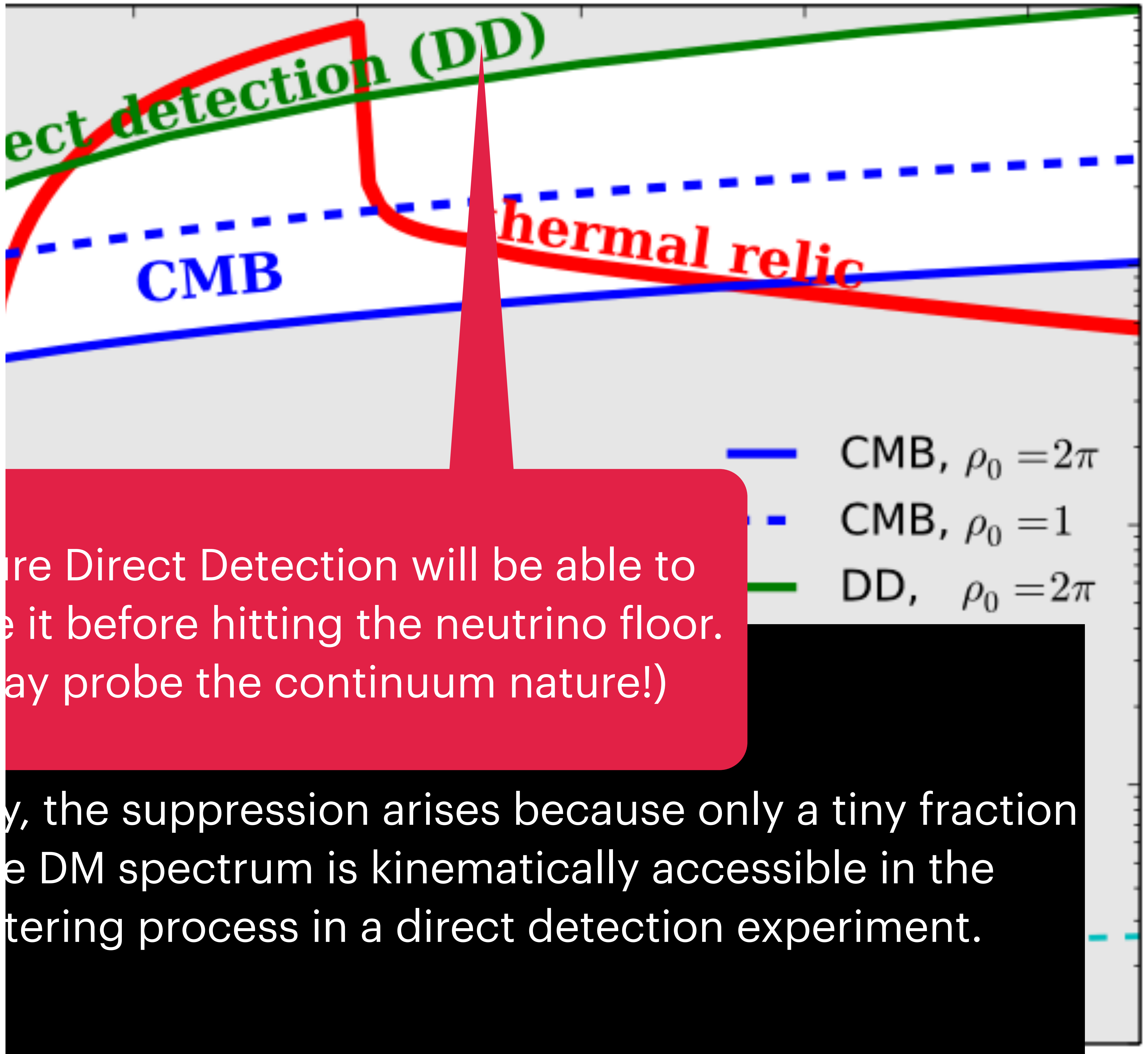

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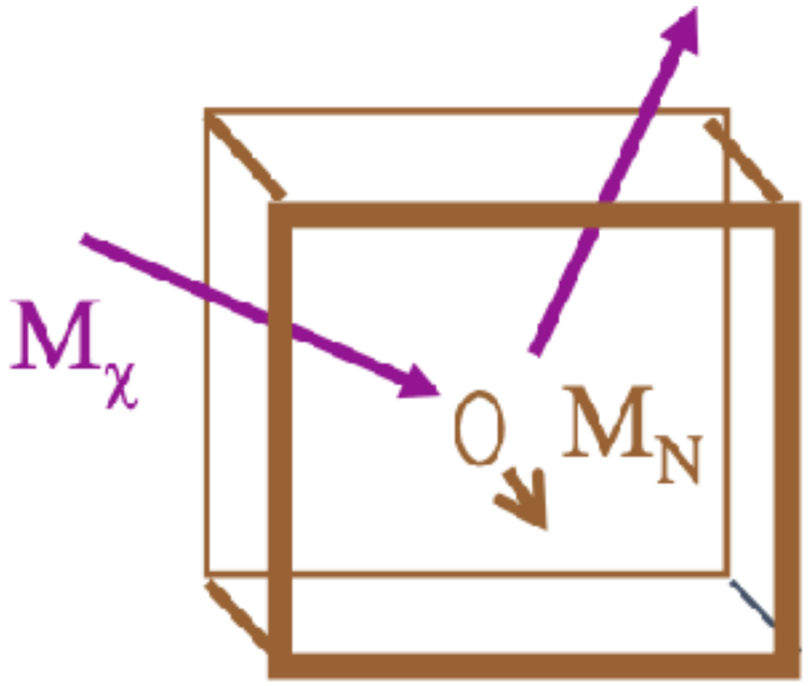

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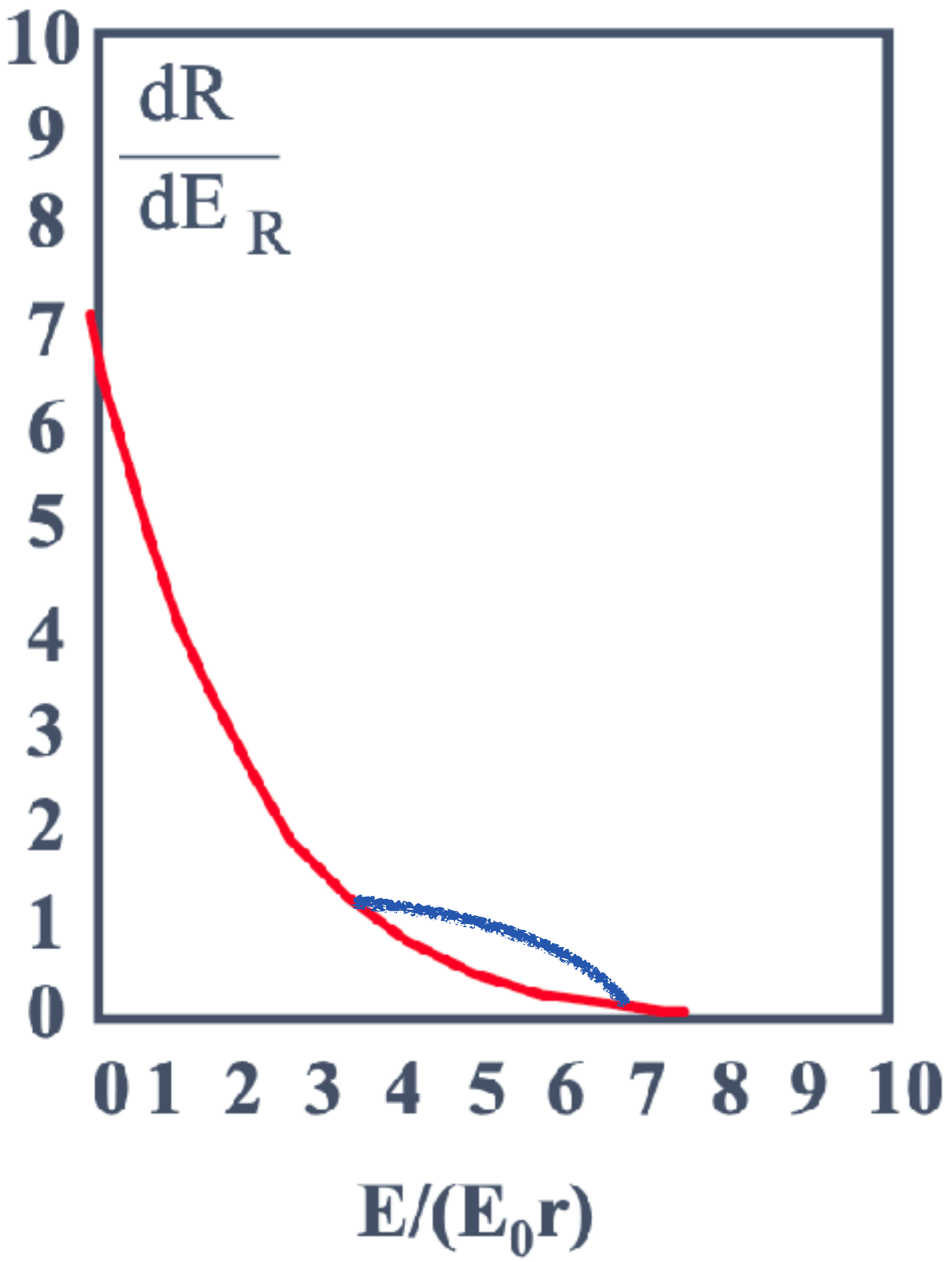

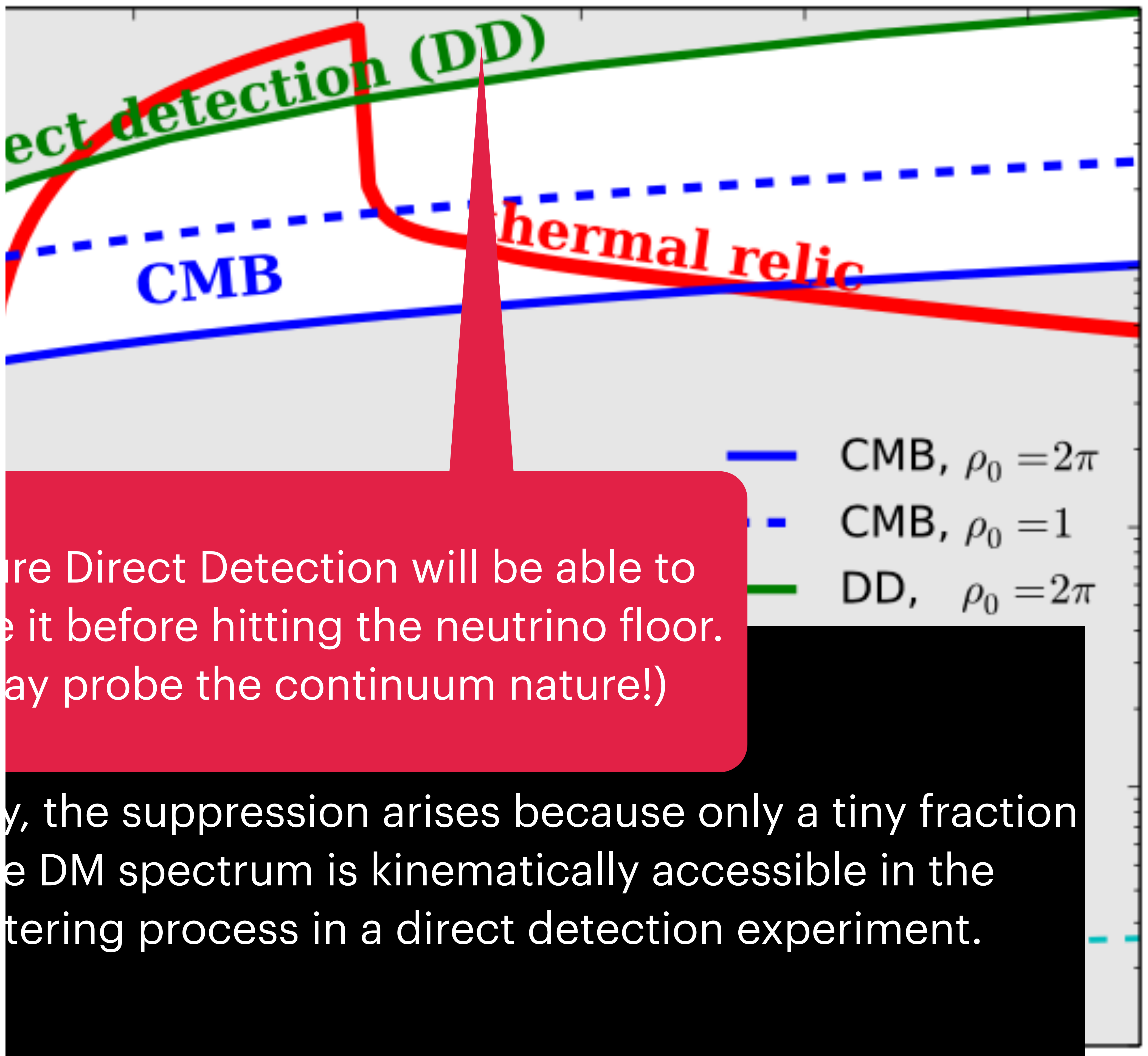

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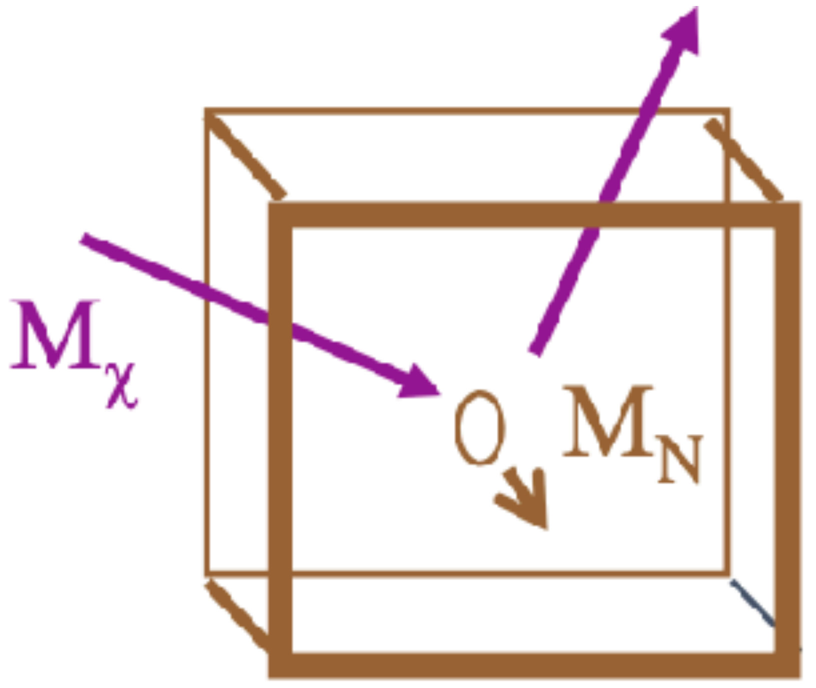

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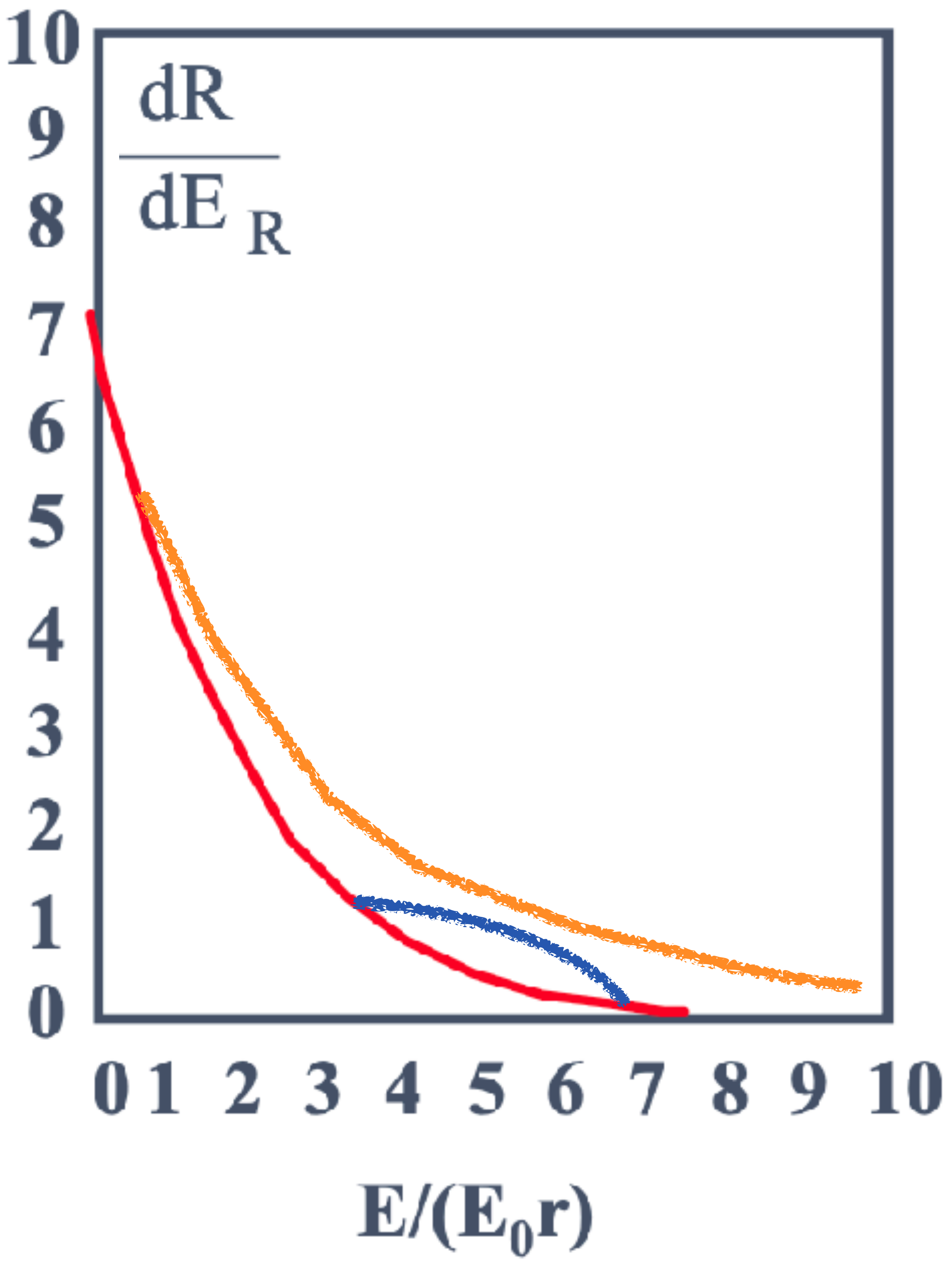

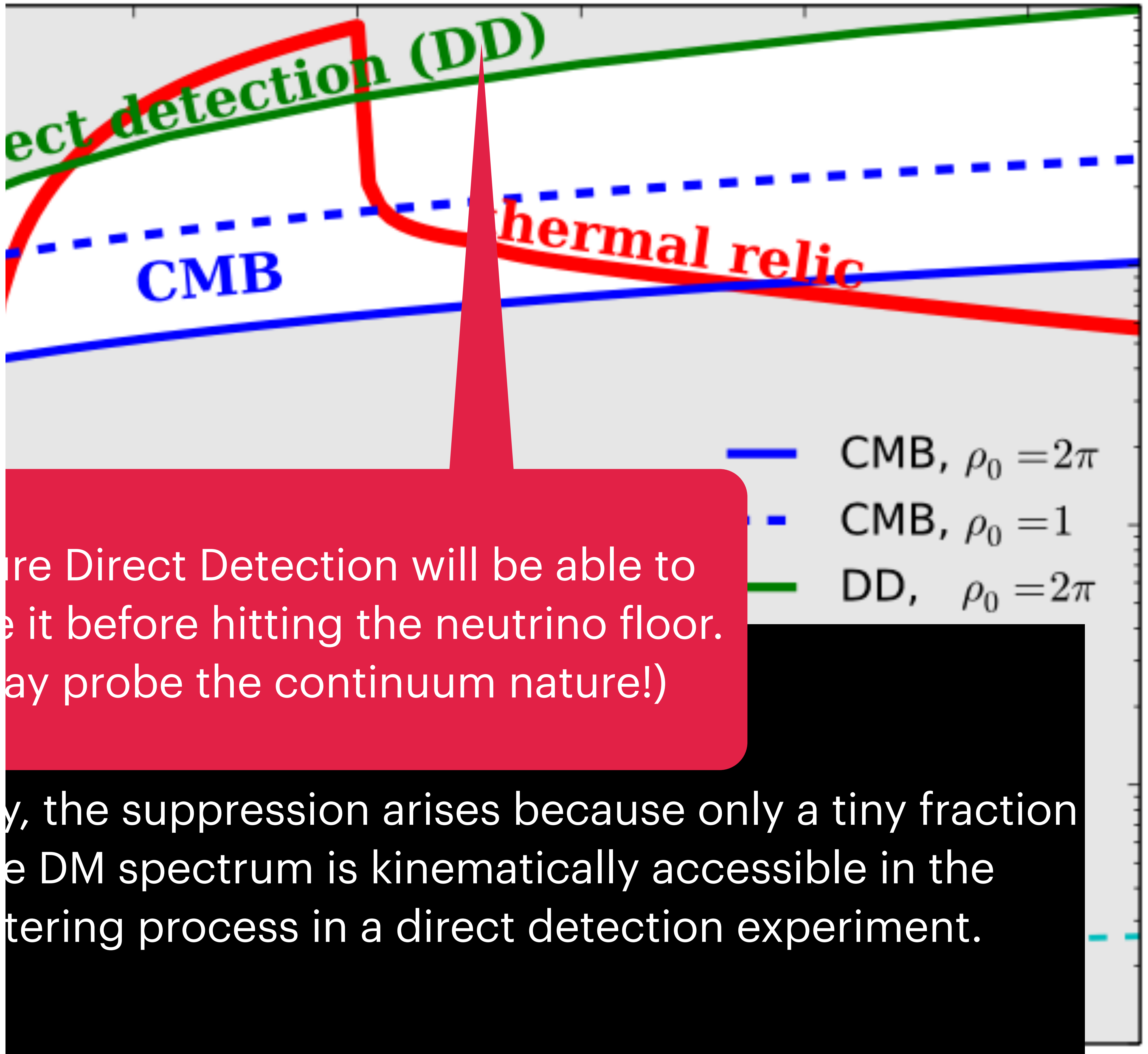

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♦ Indirect Detection

$\mathrm{DM}(\mu_1) + \mathrm{DM}(\mu_2) \rightarrow \mathrm{SM}_1 + \mathrm{SM}_2$

- Since there is no continuum state in the final state, the rates of these processes are unsuppressed :

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♦ Indirect Detection

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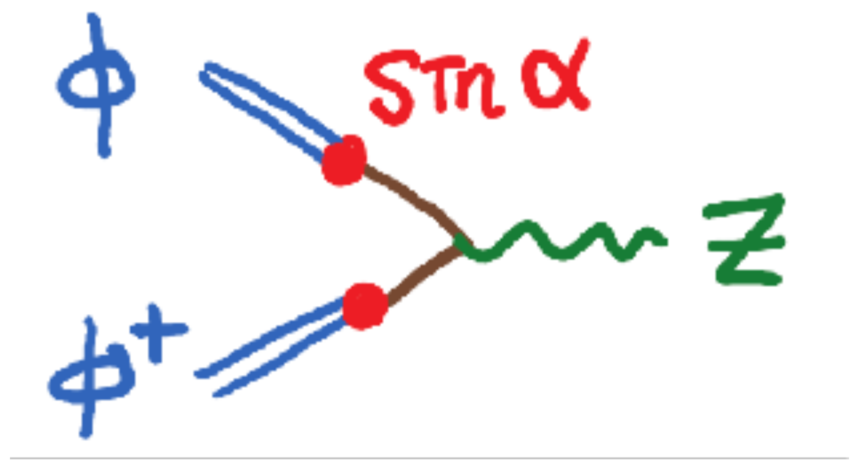
- Since there is no continuum state in the final state, the rates of these processes are unsuppressed :

  $\mu_1 \approx \mu_2 \approx \mu_0$ in the current universe $\Rightarrow$ both rates and kinematics of annihilation in the galactic halos are basically identical to those of particle DM

Gapped Continuum Nature of DM

- Colliders Phenomenology
  - for low energy experiments (low compared to gap scale): e.g. LEP bound for Z-portal WIC:

Same suppression mechanism (by continuum kinematics) as in Direct Detection appl



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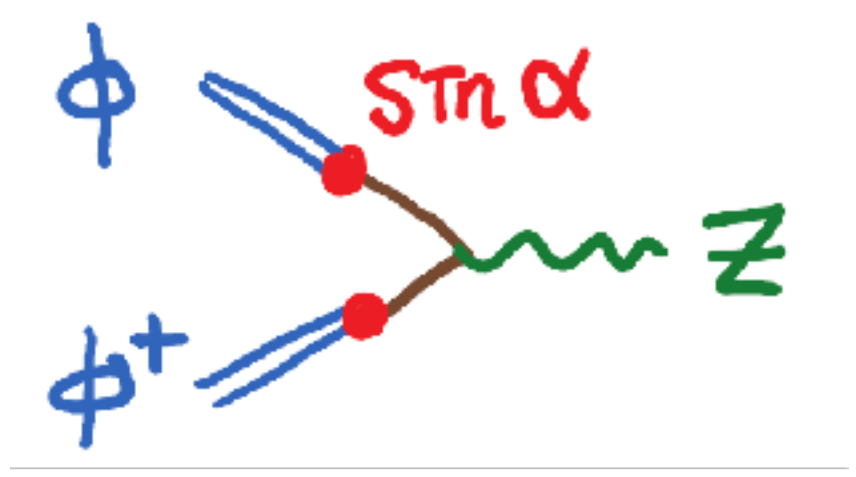

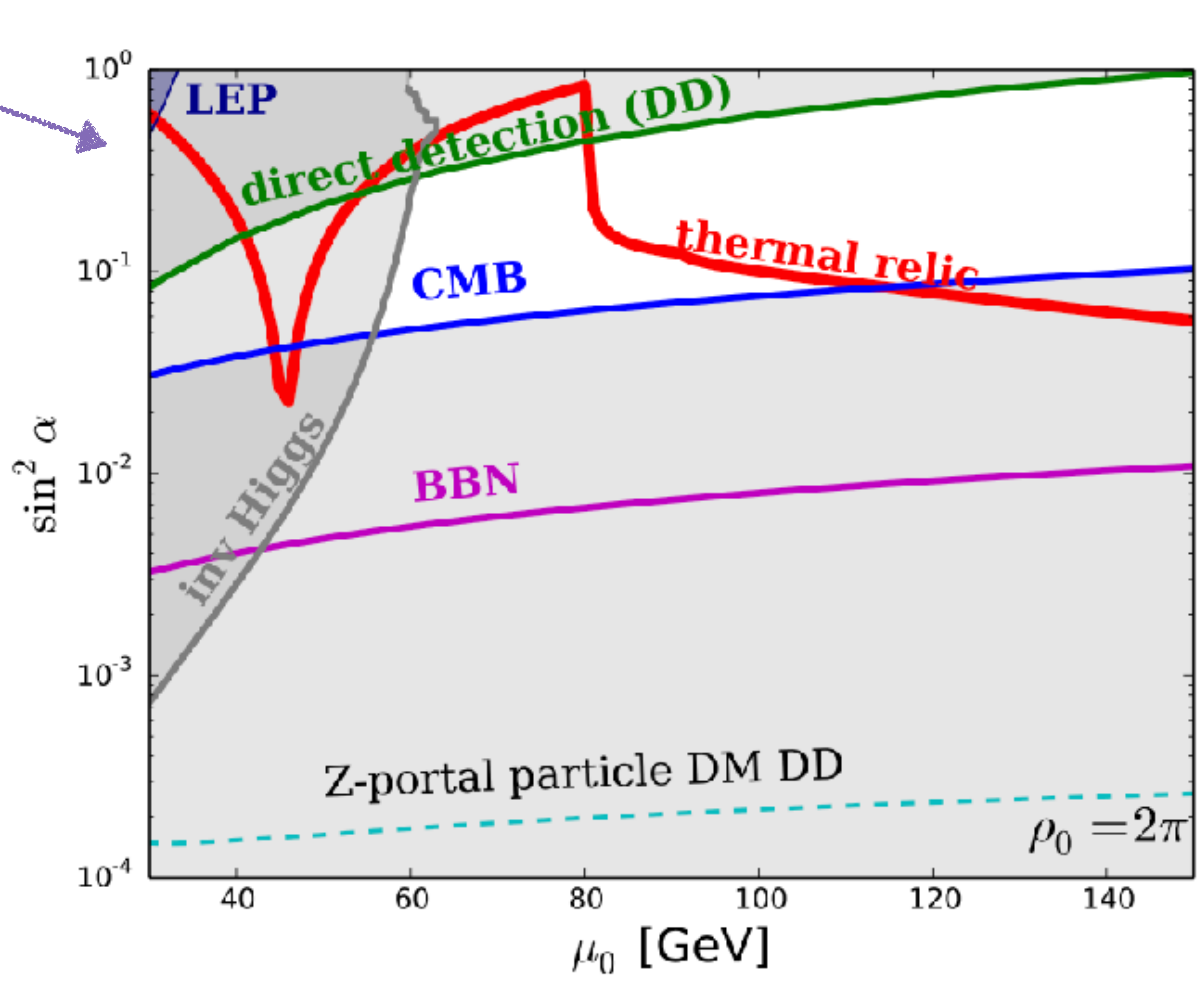

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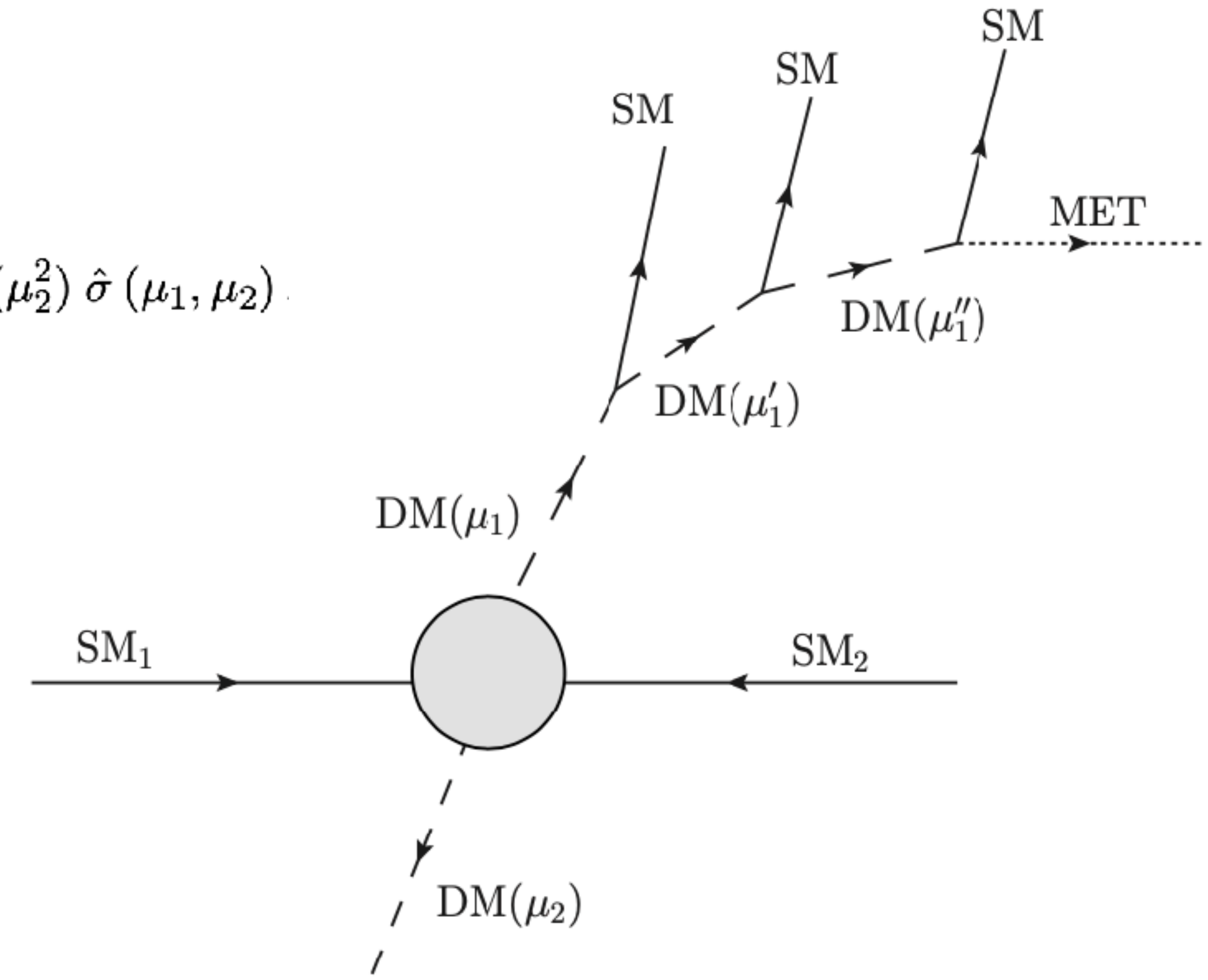
- for high enough energy: (no suppression, an rich pheno)
  SM1+SM2 → DM(μ_1) + DM(μ_2)

$$\sigma \sim \int \frac{d\mu_1^2}{2\pi} \rho(\mu_1^2) \int \frac{d\mu_2^2}{2\pi} \rho(\mu_2^2)\, \hat{\sigma}\,(\mu_1, \mu_2)$$



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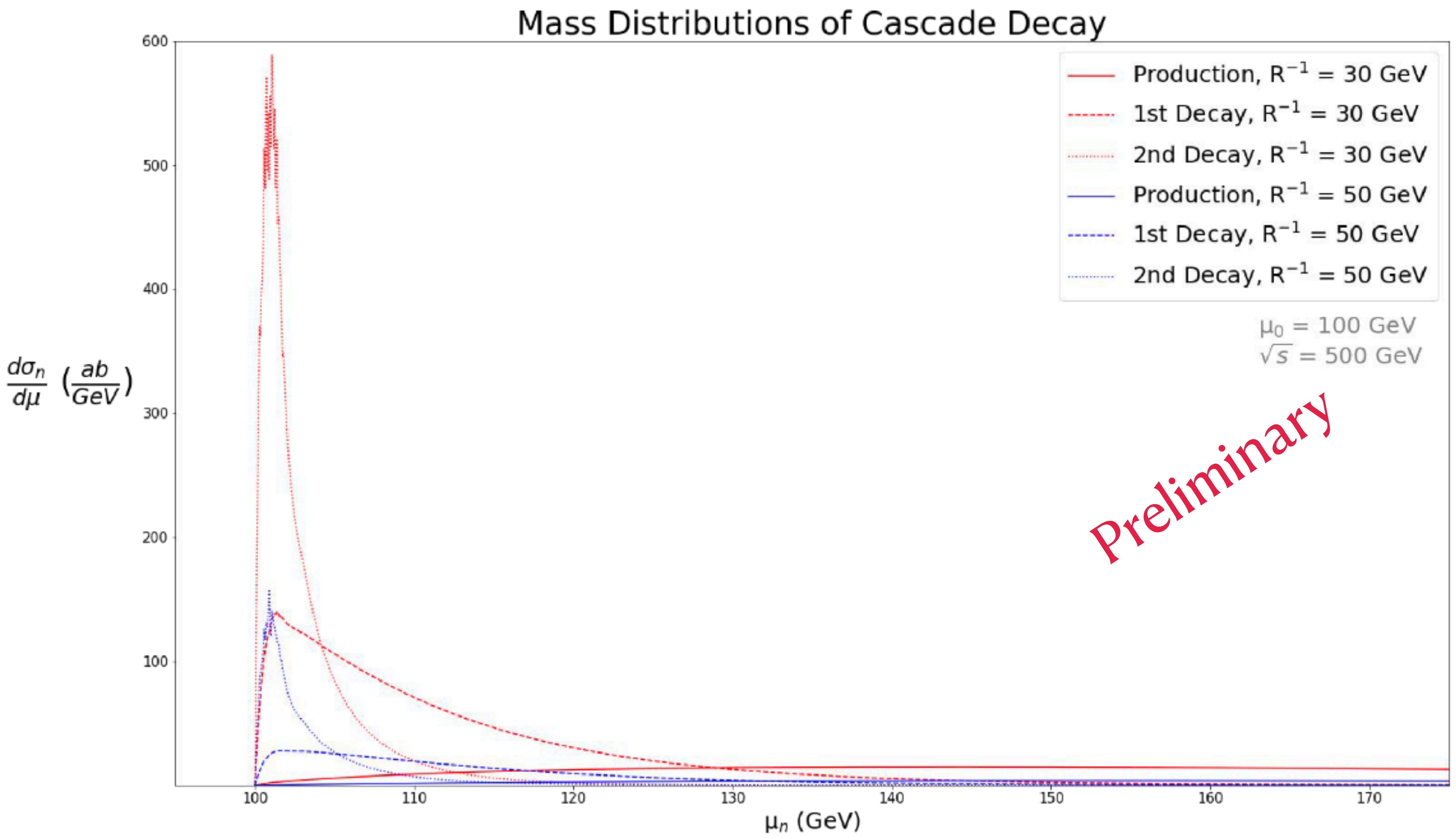


Dark Matter Continuum Spectral Density from 5D Model

- Warped 5D model

  - Scalar gapped continuum: $$\mathcal{L} = \sqrt{g}\left[\frac{1}{2}g^{MN}D_M\Phi^\dagger D_N\Phi - V(\Phi)\right]$$

In conformally flat coordinate, Schrödinger form of eom: $\psi = e^{-\frac{3}{2}A}\Phi$

$$\left(-\partial_z^2 + \hat{V}(z)\right)\Psi(z) = p^2\Psi(z)$$

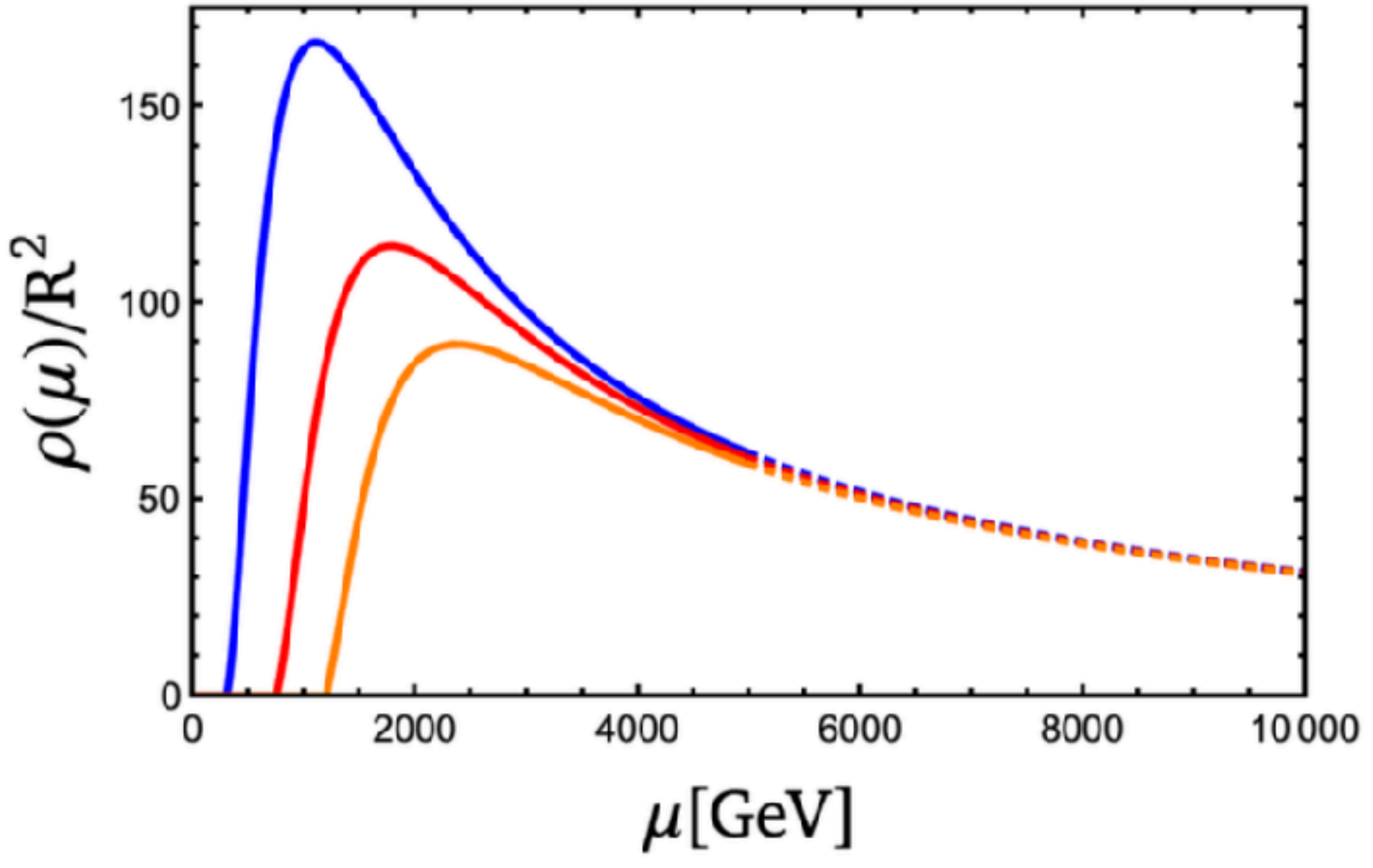
$$V(z) = \frac{e^{-2ky}}{4y_s^2}\left[4m^2(y_s - y)^2 + 15\left(1 + k(y_s - y)\right)^2 - 6\right]$$

after integrating out bulk:

$$S = \int \frac{d^4p}{(2\pi)^4}\,\Phi^\dagger(p)\Sigma(p^2)\Phi(p)$$

$$\rho(p^2) = -2\,\mathrm{Im}\frac{1}{\Sigma(p^2)}$$

$$\Sigma(p) = \frac{1}{R}\left.\frac{f'(z,p)}{f(R,p)}\right|_{z=R}$$



Dark Matter Continuum Spectral Density from 5D Model

- Warped 5D model

  - Scalar gapped continuum near the gap:

In conformally flat coordinate, Schrödinger form of eom:

$$\left(-\partial_z^2 + \hat{V}(z)\right)\Psi(z) = p^2\Psi(z)$$

$$\lim_{z\to\infty}\hat{V}(z) = \mu_0^2\left(1 + e^{-2z(2\mu_0/3)} + \frac{8}{3}e^{-z(2\mu_0/3)}\right)$$

$$\Psi(z,\mu) = C\,L_m^n(3e^{-2z\mu_0/3})\exp\left(\frac{3}{2}\sqrt{1-\frac{\mu^2}{\mu_0^2}}\log\left(e^{-\frac{2\mu_0 z}{3}}\right) - \frac{3}{2}e^{-\frac{2\mu_0 z}{3}}\right)$$

can expand the arguments of the Laguerre polynomial around the mass gap

$$\rho(p) = \frac{1}{\pi}\mathrm{Im}\,G(R,R;p).$$

→

$$\rho(\mu^2) \propto \left(\frac{\mu^2}{\mu_0^2} - 1\right)^{1/2}$$

Dark Matter Continuum Spectral Density from 5D Model

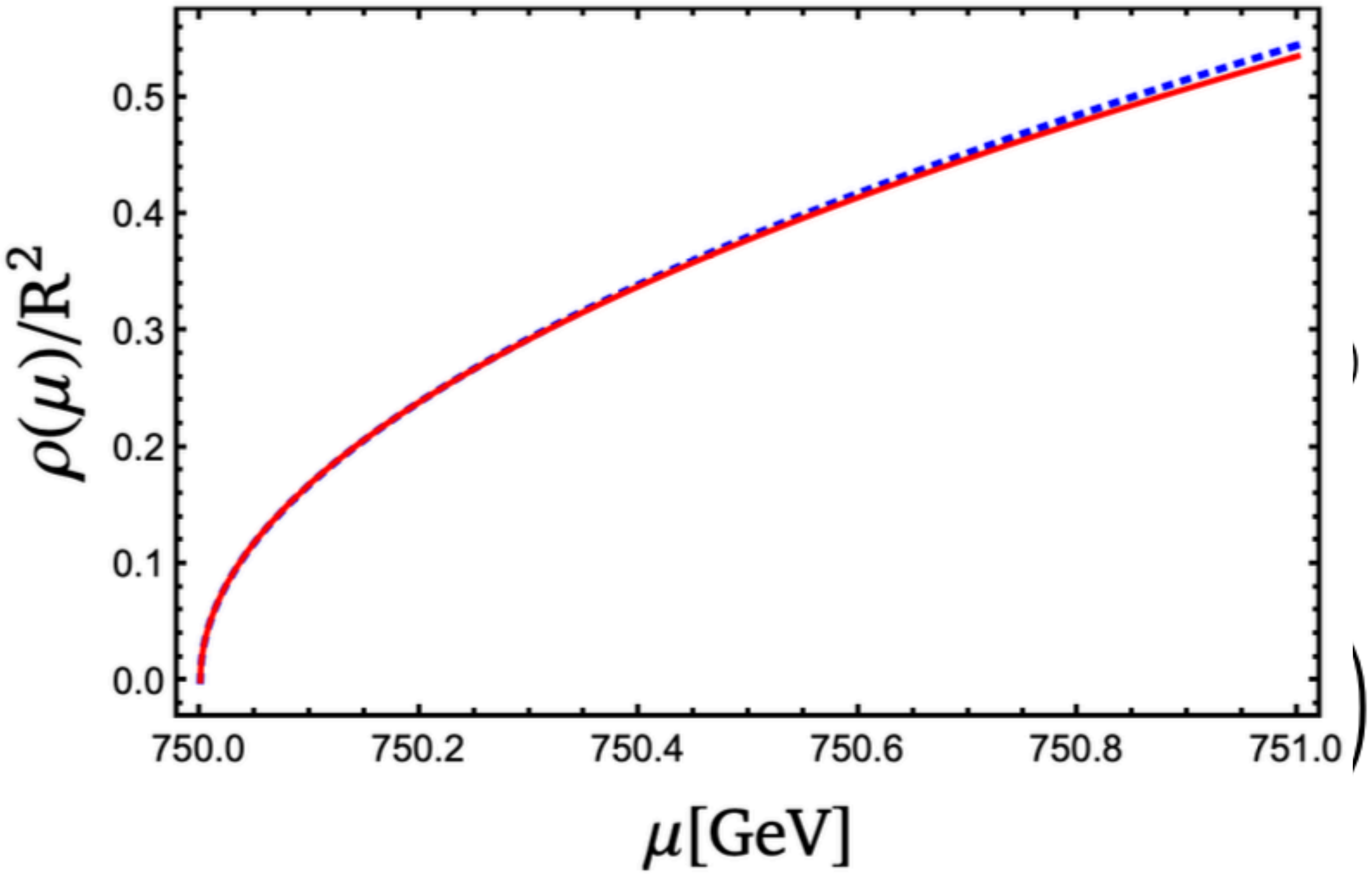
♦ Warped 5D r

- Scalar gap

In conformally r

$\lim_{z\to\infty} \hat{V}(z) = \mu$

$\Psi(z,\mu) = ($



can expand the arguments of the Laguerre polynomial around the mass gap

$$\rho(p) = \frac{1}{\pi}\mathrm{Im}\, G(R,R;p).$$

→

$$\rho(\mu^2) \propto \left(\frac{\mu^2}{\mu_0^2} - 1\right)^{1/2}$$

Summary

New DM Paradigm → Weakly Interacting Massive Particle → Weakly Interacting Massive Continuum

1. Gapped Continuum DM = theoretically and phenomenologically motivating!

2. Continuum Kinematics : late decay, relaxation of direct detection bound

3. Revival of Weakly Interacting Massive Continuum (WIC) !

4. Many possible models + many detailed pheno study to be done.

5. Continuum Collider Physics = totally new → needs a systematic investigations a

6. Many more (including continuum freeze-in DM, etc)

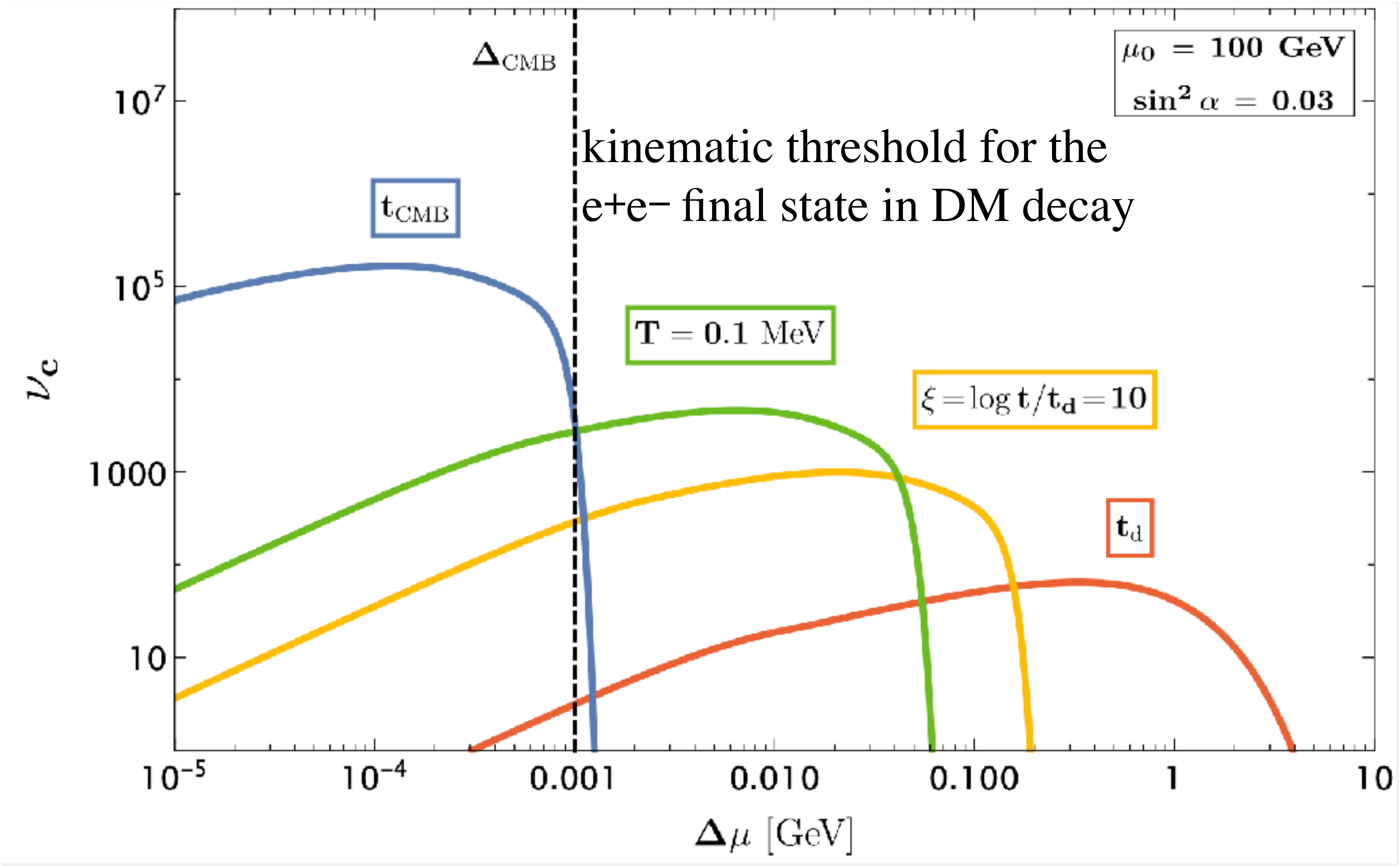
Back-up

Electromagnetic Energy Injection After Recombination

-important constraints on the model arises from re-ionization of Hydrogen by DM decays after recombi

-at most ~0.1% H ionization fraction for points on the boundary obtained by the simple criterion

$\Gamma = H(t_{CMB})$



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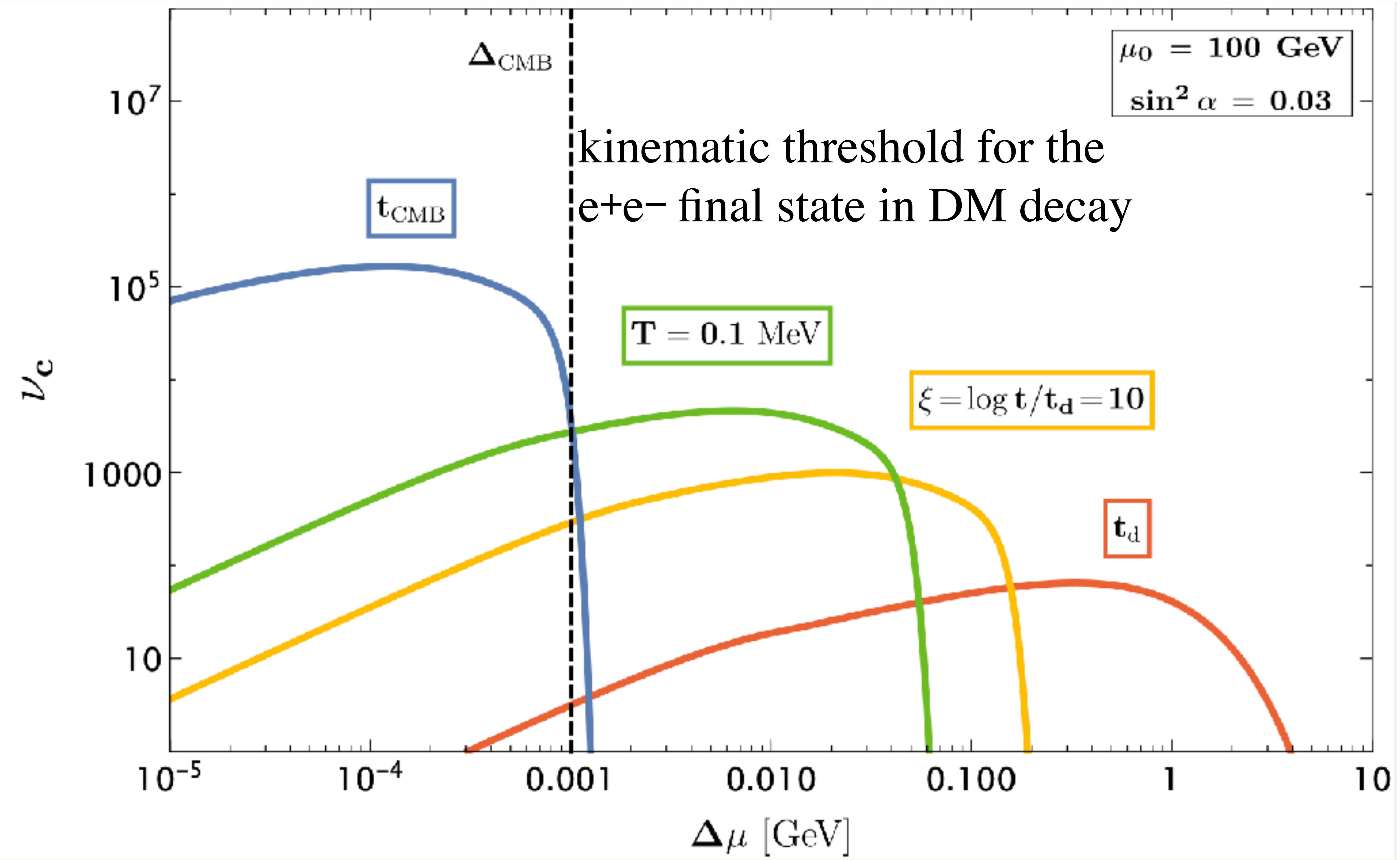

DM mass distribution as a function of time for a sample parameter point. Only about 0.2% of DM particles lie on the tail above this threshold.

Normalization of Spectral Density

$$S_{\rm eff} = \int_{\rm UV} d^4x\, e^{-4A}\Phi^\dagger(x,y)\partial_y\Phi(x,y)|_{y=0}$$
$$= \int_{\rm UV} \frac{d^4p}{(2\pi)^4}\,\hat\Phi^\dagger(p)\left(e^{-3A(z)}\frac{f'(z,p)}{f(R,p)}\right)_{z=R}\hat\Phi(p)$$

$$\int d^4x\sqrt{g}(D_\mu H D^\mu H e^{2A} + D_\mu\chi D^\mu\chi e^{2A} - \hat\lambda k^{\frac{1}{2}}\Phi\chi H + h.c.)_{z=R}$$

In order to get the proper 4D effective action with $\lambda = \hat\lambda k e^{-A}$ of the order of the electroweak scale we need the field redefinitions $H \rightarrow He^{-A}, \chi \rightarrow \chi e^{-A}, \Phi \rightarrow \Phi e^{-\frac{3}{2}A}\sqrt{R}$.

$$\Sigma(p) = \frac{1}{R}\left.\frac{f'(z,p)}{f(R,p)}\right|_{z=R},$$