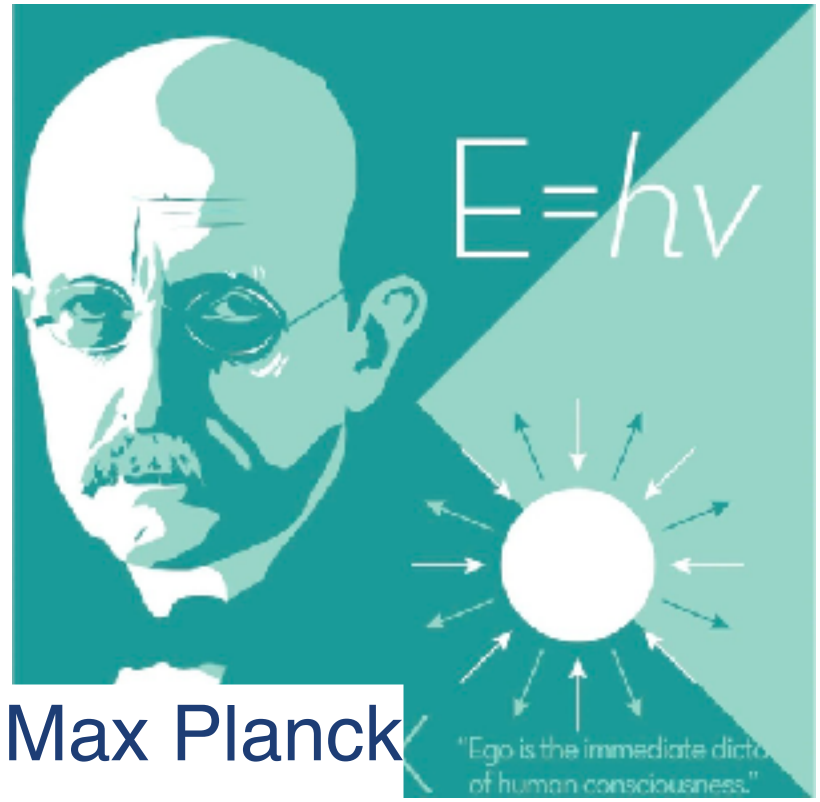
Generalized free continuum fields for Dark Matter using 5D EFT via AdS/CFT

Seung J. Lee

KOREA UNIVERSITY

With Csaki, Hong, Kurup, Perelstein, Xue; PRD 2022
With Csaki, Hong, Kurup, Perelstein, Xue; PRL 2022
With Csaki and Ismail, JHEP 2023
With Perelstein, Ferrante, work in progress
With Hong, Kurup, Lee, work in progress



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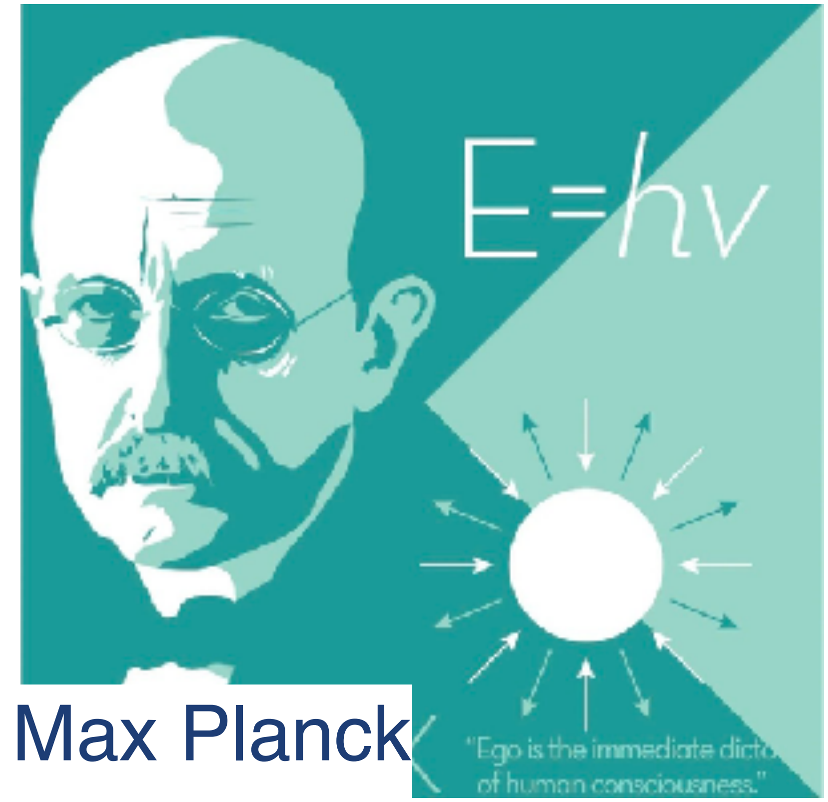

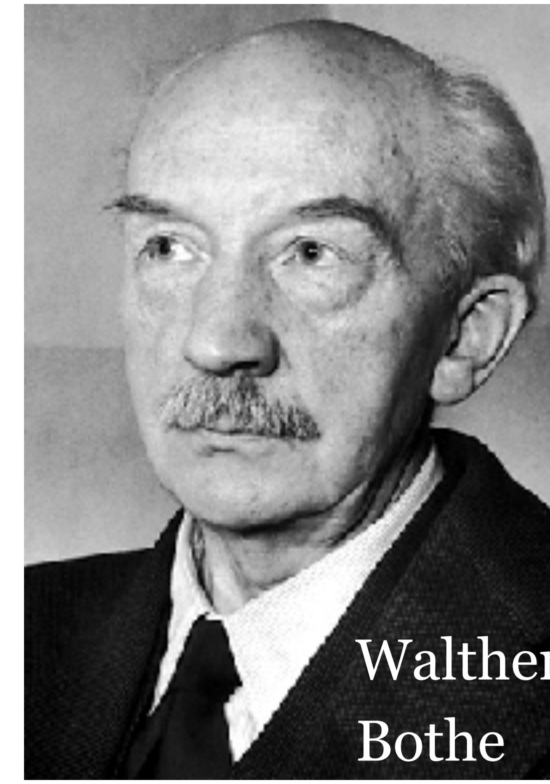

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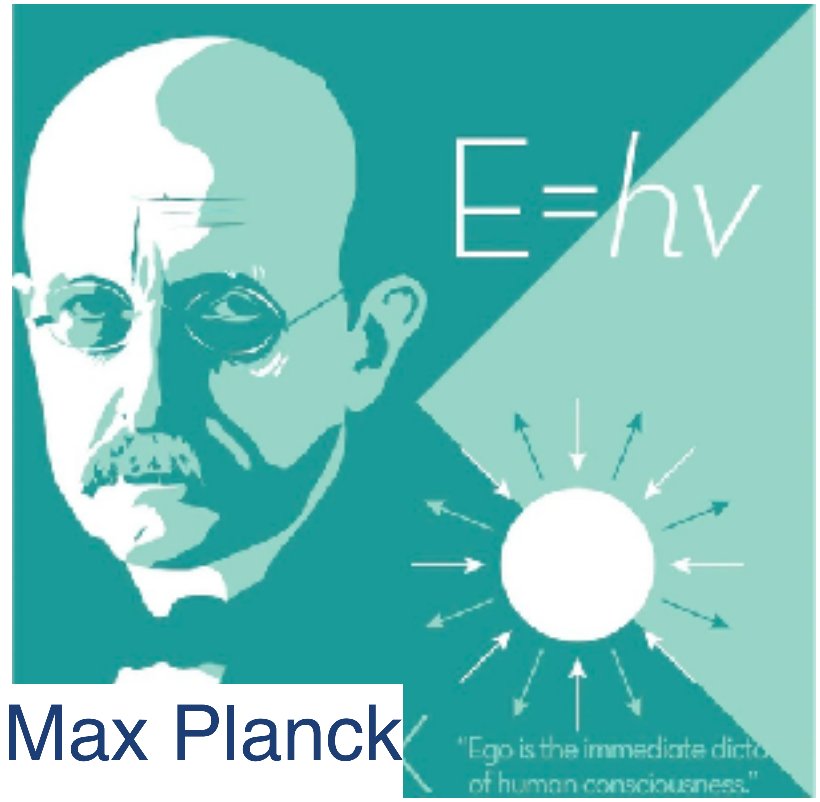

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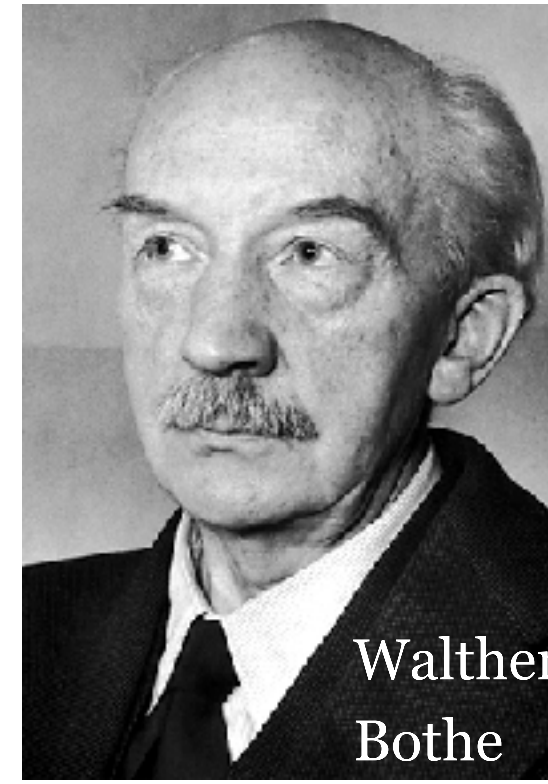
Walther Bothe

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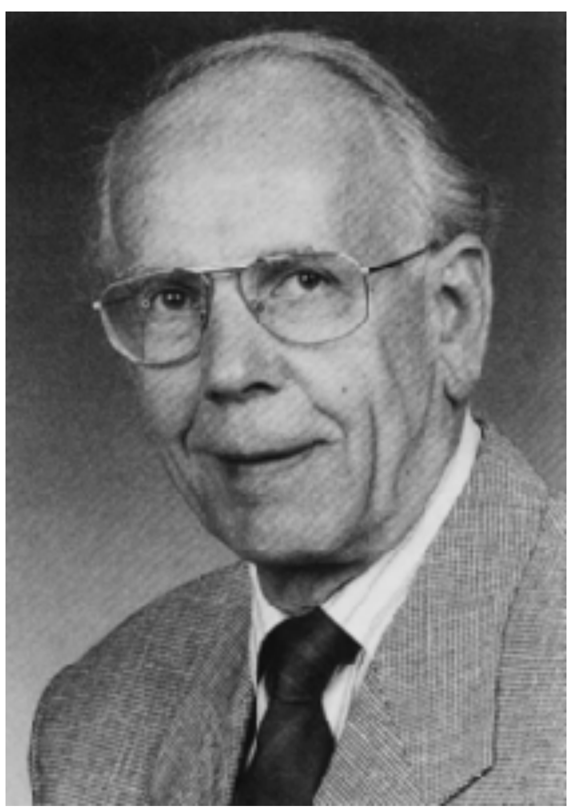
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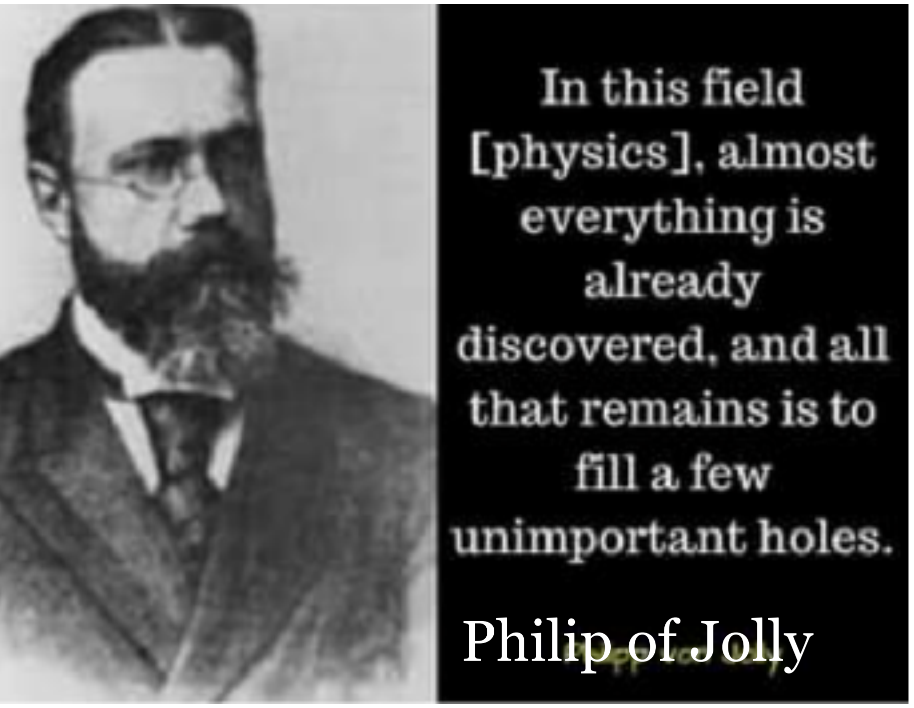

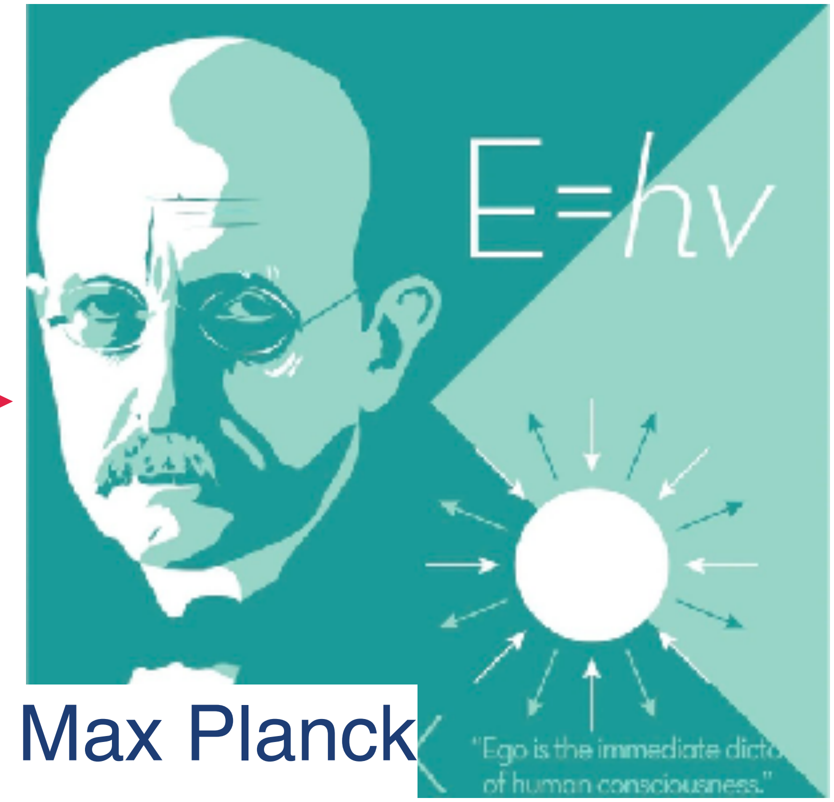

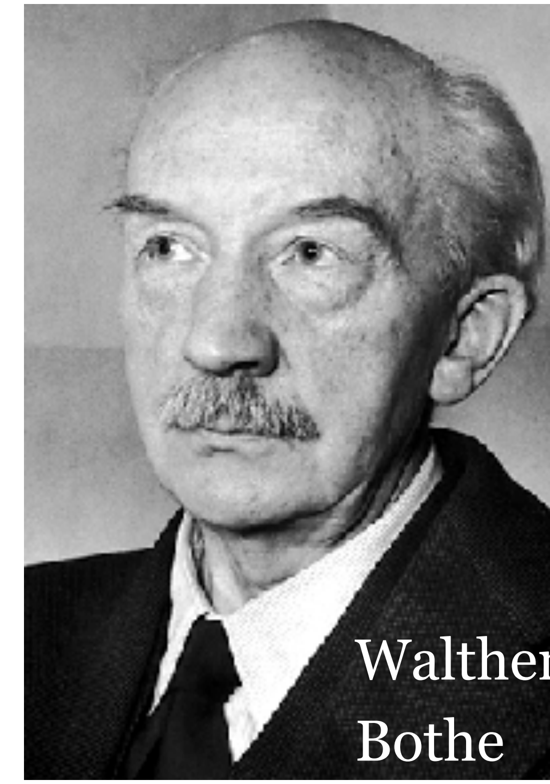

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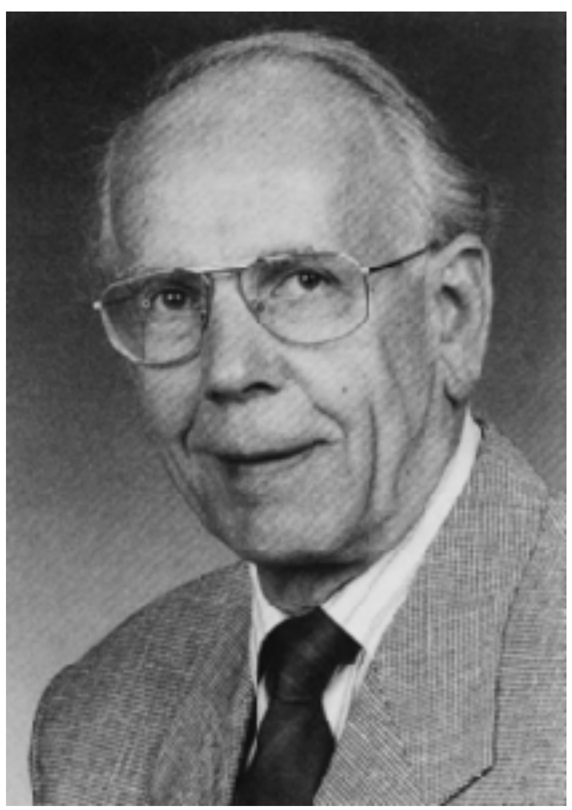

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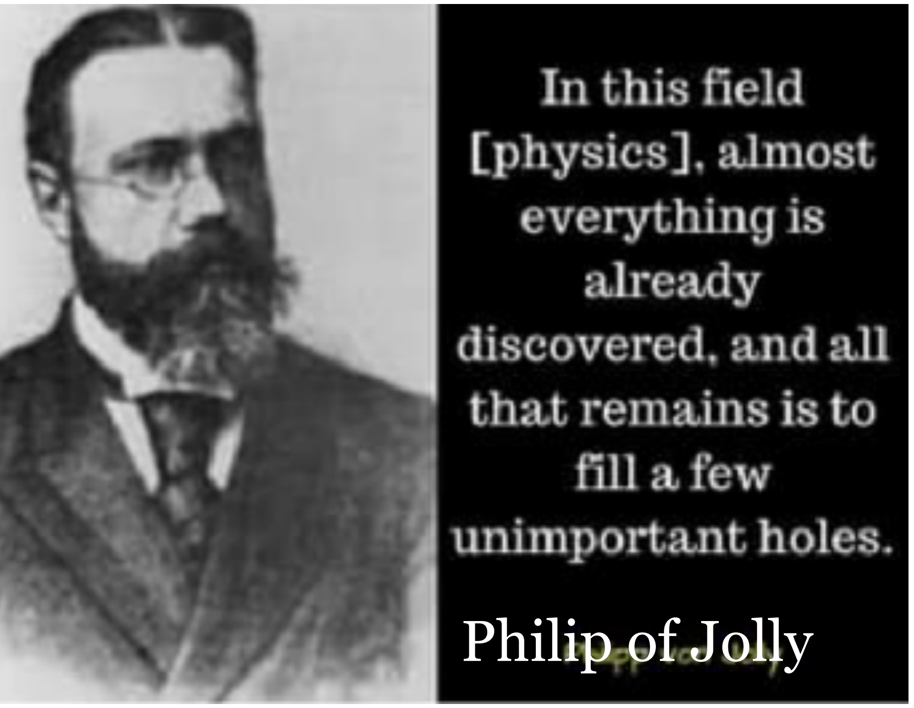

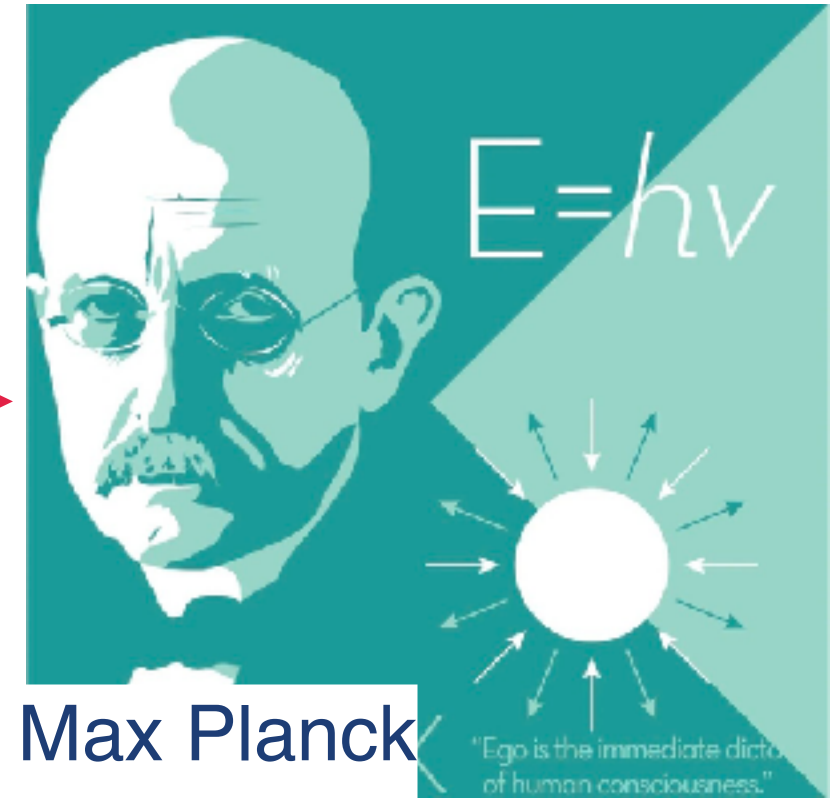

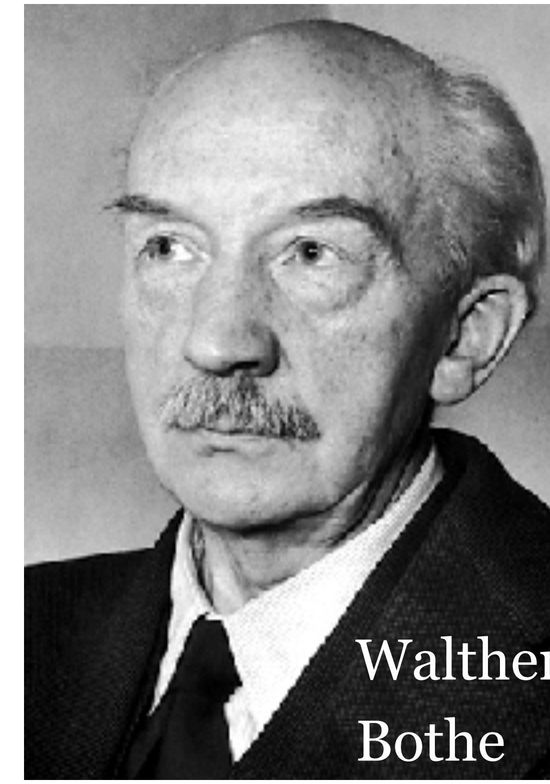

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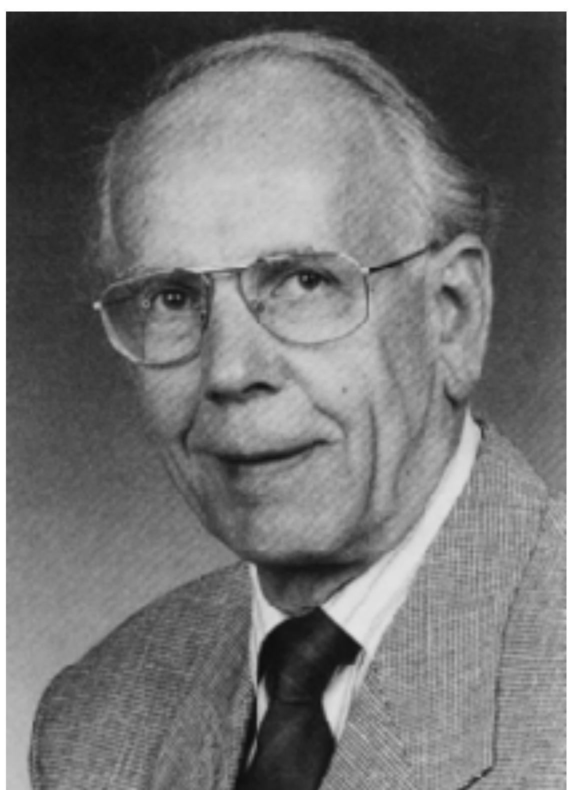

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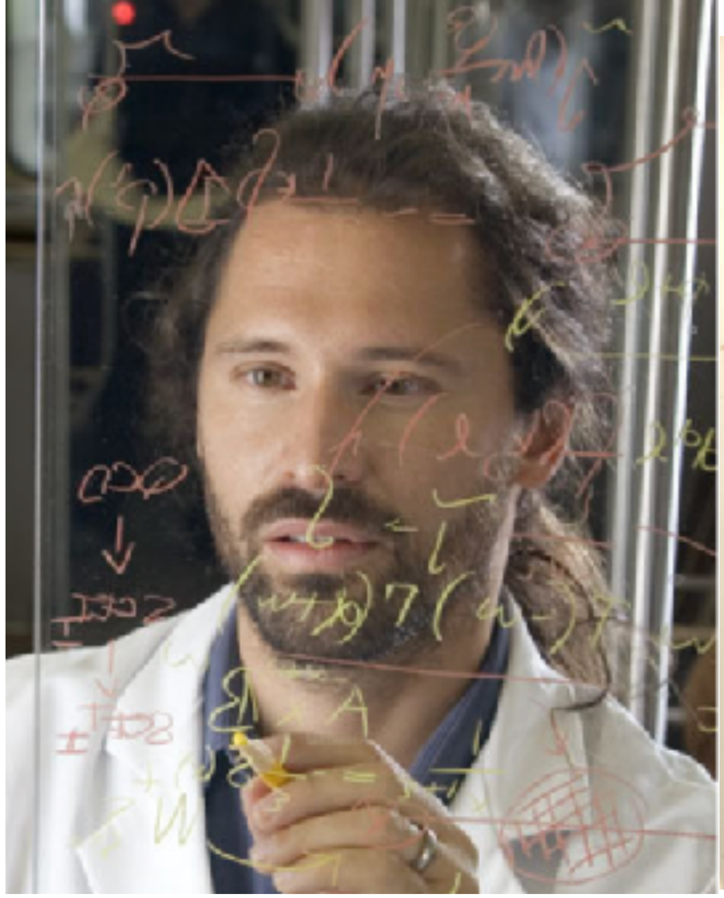

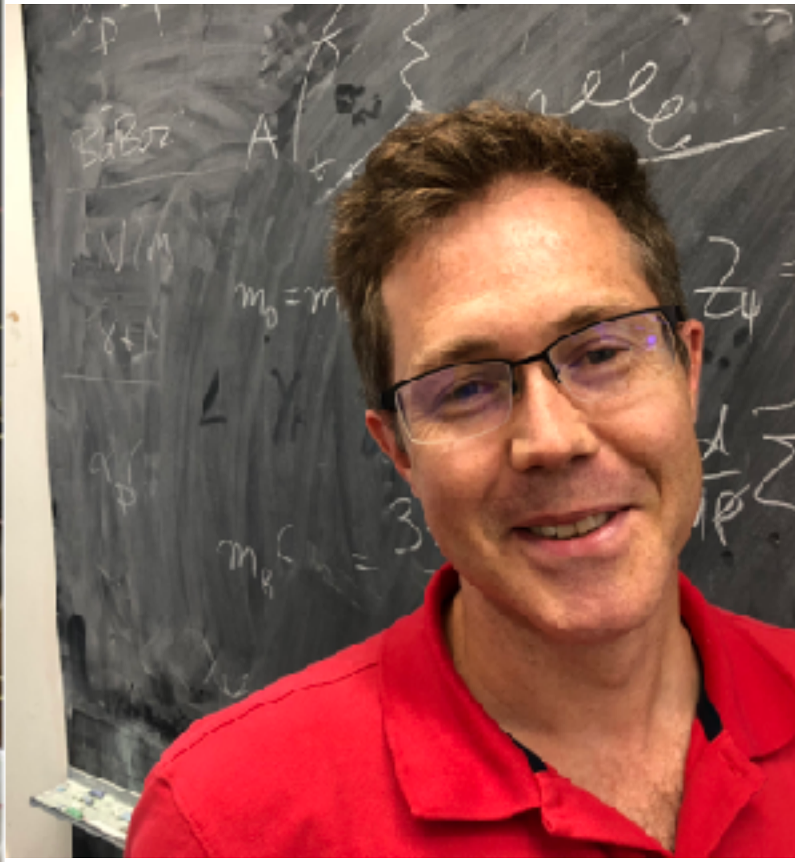


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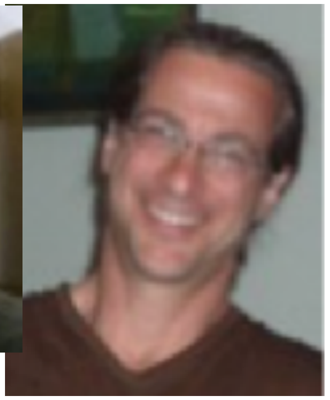

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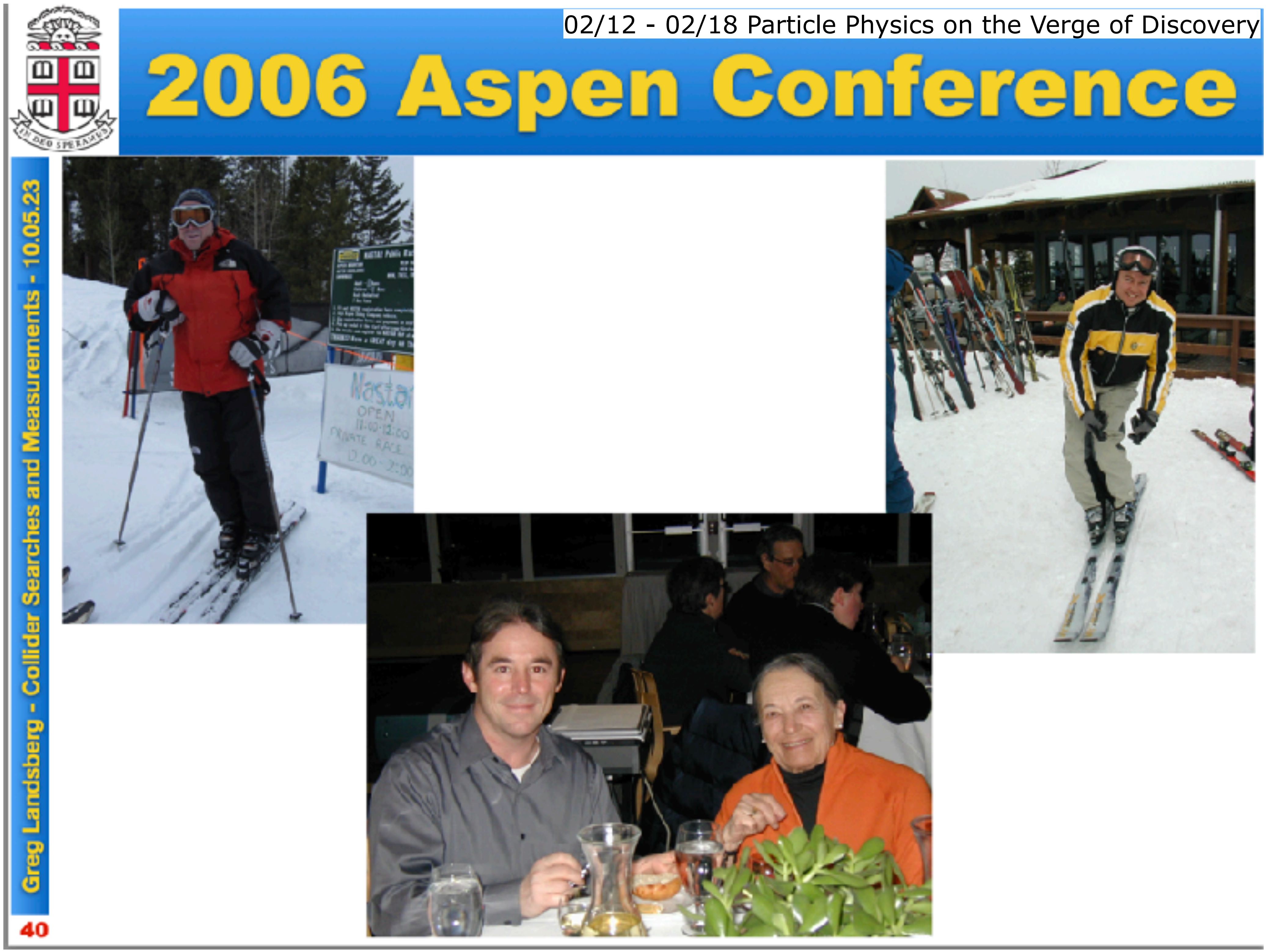

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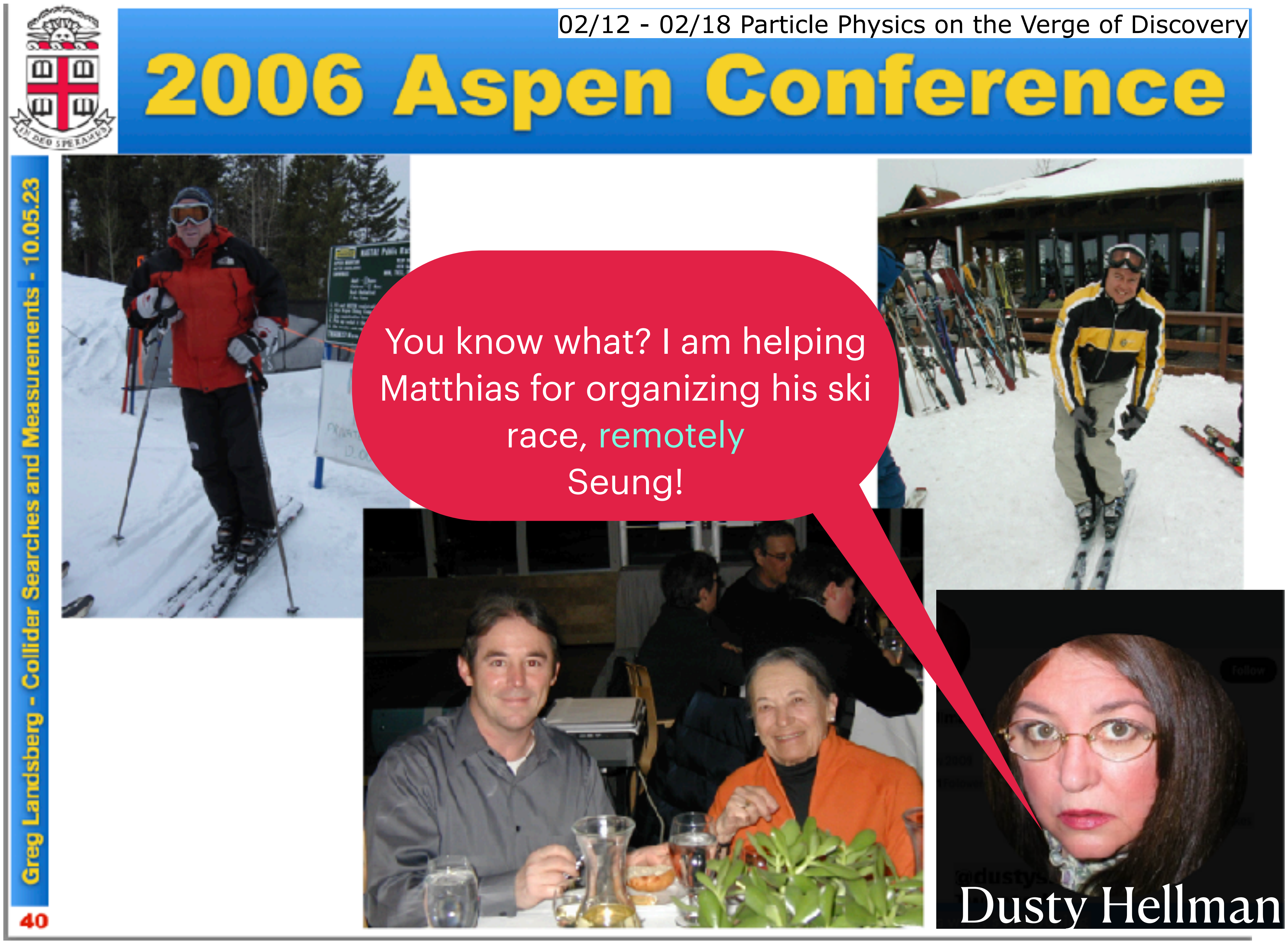

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Explaining the lepton non-universality at the LHCb and CMS within a unified framework

Sanjoy Biswas,[a,b] Debtosh Chowdhury,[b] Sangeun Han[c,d] and Seung J. Lee[c,e]

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WIMP dark matter through the dilaton portal

Kfir Blum,[a] Mathieu Cliche,[b] Csaba Csáki[b] and Seung J. Lee[c,d]

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Continuum naturalness

Csaba Csáki,[a] Gabriel Lee,[a,b] Seung J. Lee,[b,c] Salvator Lombardo[a] and Ofri Telem[a]

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Composite Higgs Models and Unification

work in progress

Sebastian Jäger,[a] Sandra Kvedaraite,[a] Gabriel Lee,[b,c] Seung J. Lee[c,d]

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Got the lesson, and applying it in Korea


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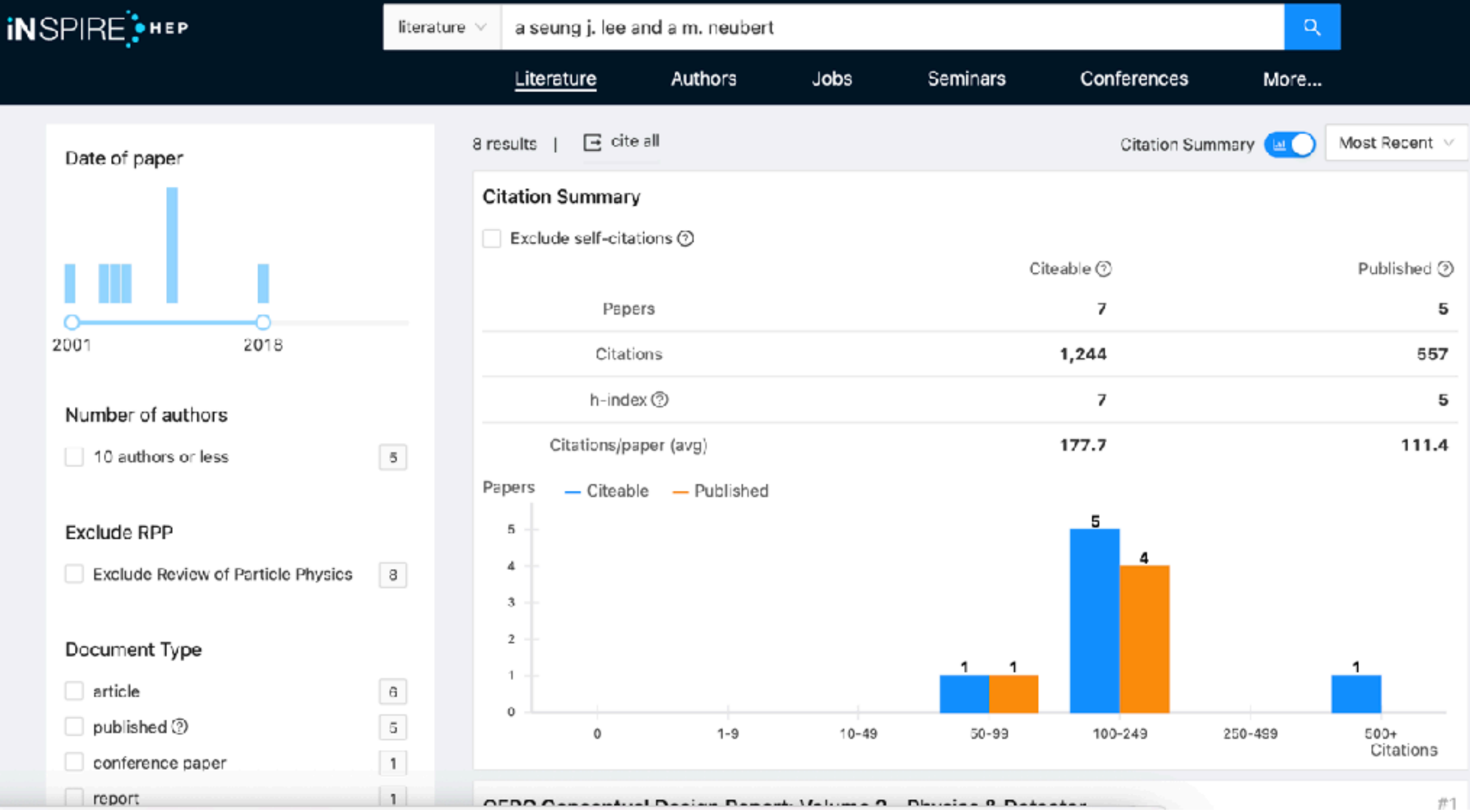
You seem to need a help!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Outline

- 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^{57} eV)
- Composition of Dark Matter
- Interaction of Dark Matter

Gapped Continuum, instead of Resonances

♦ What's New: Dark Matter is made of an ensemble of gapped continuum states

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

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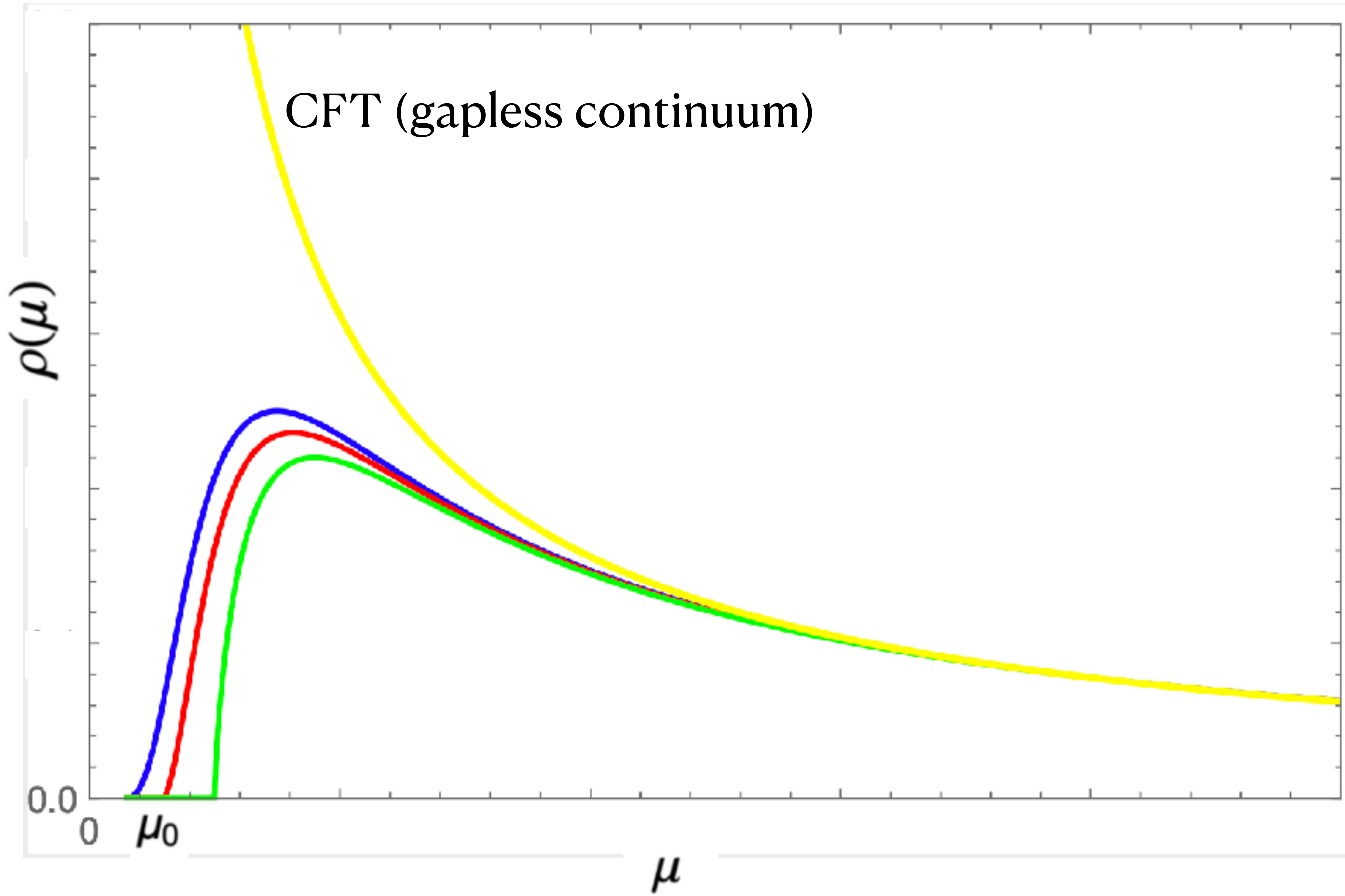
- It's not even clear whether the DM is a localized excitation of quantum field (i.e. particle) that provide successful explanations to the rotation curve of disk galaxies, CMB, and large structure formation.

- 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

CFT Continuum vs Gapped Continuum (IR deformation)



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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Three papers I read and learned:

H. Georgi, Unparticle Physics, Phys. Rev. Lett. 98, 221601 (2007).

M. Neubert, Unparticle physics with jets, Phys. Lett. B 660, 5(2008)

B. Grinstein, K. A. Intriligator, and I. Z. Rothstein, Comments on unparticles, Phys. Lett. B 662, 367 (2008).

Gapp

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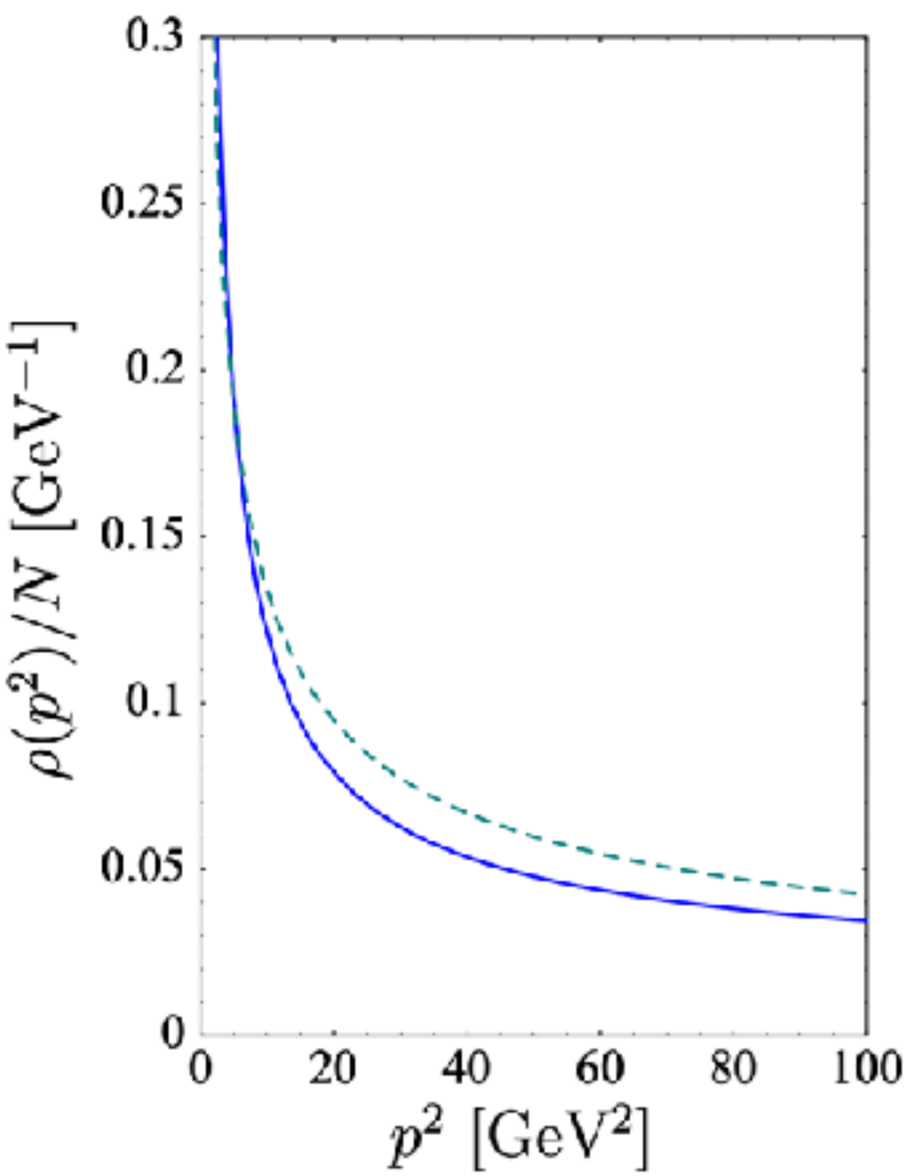
♦ Unparticle

Using methods of EFT, after resummation of Sudakov logarithms the spectral densities of interacting quark and gluon fields in ordinary QFTs such as QCD are virtually indistinguishable from those of "unparticles" of a hypothetical conformal sector coupled to the SM, recently studied by Georgi.

Models in which a hidden sector weakly coupled to the SM contains a QCD-like theory, which confines at some scale much below the characteristic energy of a given process, can give rise to signatures closely resembling those from unparticles.



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m factor (by gapped continuum) for Higgs EFT

olving little hierarchy by Csaki et al (SL), and also by

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

Three papers I read and learned:

H. Georgi, Unparticle Physics, Phys. Rev. Lett. 98, 221601 (2007).

M. Neubert, Unparticle physics with jets, Phys. Lett. B 660, 5(2008)

B. Grinstein, K. A. Intriligator, and I. Z. Rothstein, Comments on unparticles, Phys. Lett. B 662, 367 (2008).

- String Theory (e.g. … et al, Kraus, Trivedi et al, etc): gapped continuum shows up when one has a … (which is dual to N = 4 SU… adjoints)

- Gapped Continuum in pa… …s gap (before Higgs discovery)…

-Quantum Critical Higgs (Hi… …y 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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- 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

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- Unparticles (Georgi): another exam

So, how about DM as a gapped continuum?

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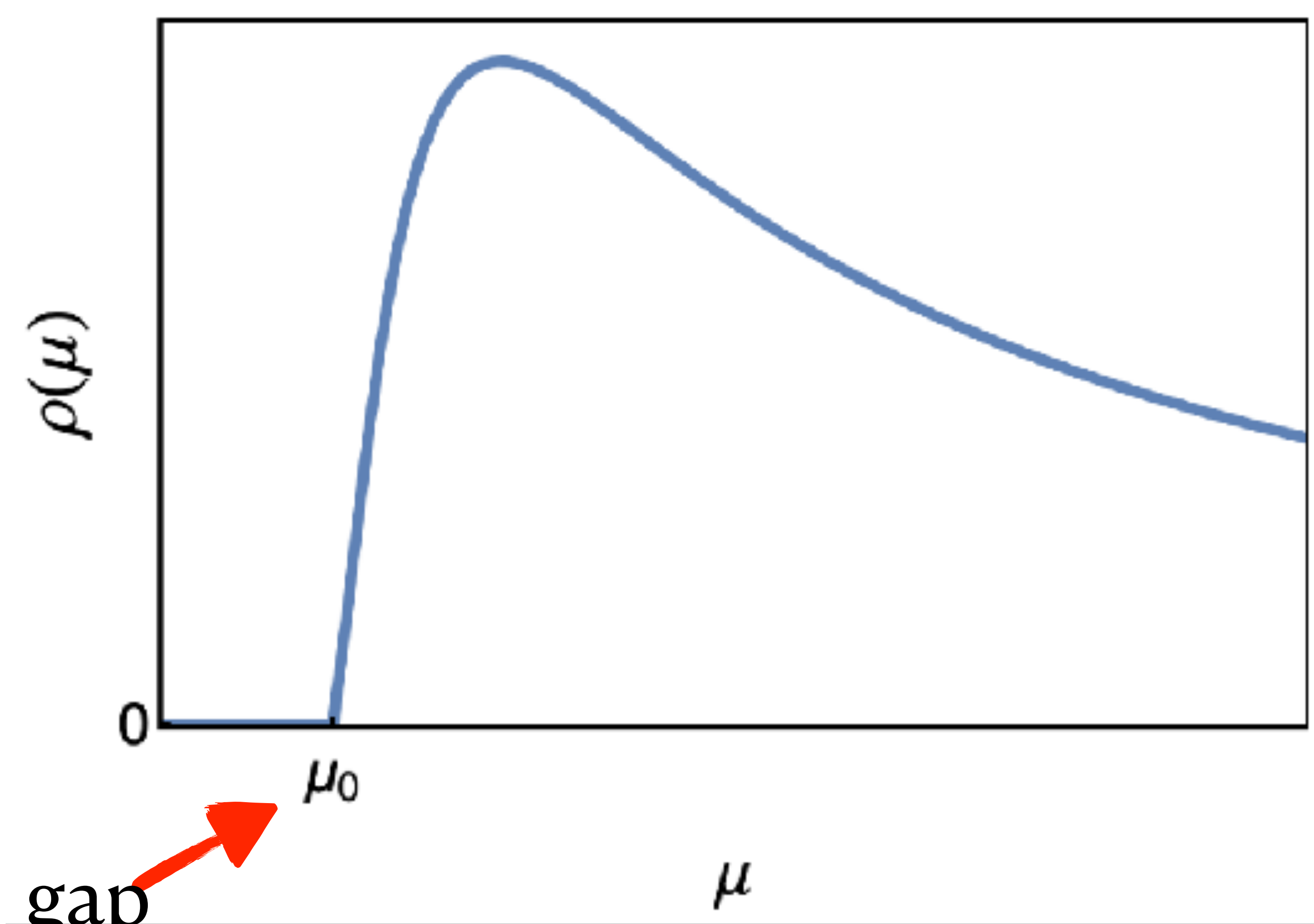
Gapped Continuum, instead of ordinary particles

♦ 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 proportional to $\int \varrho(\mu^2)\, d\mu^2$, 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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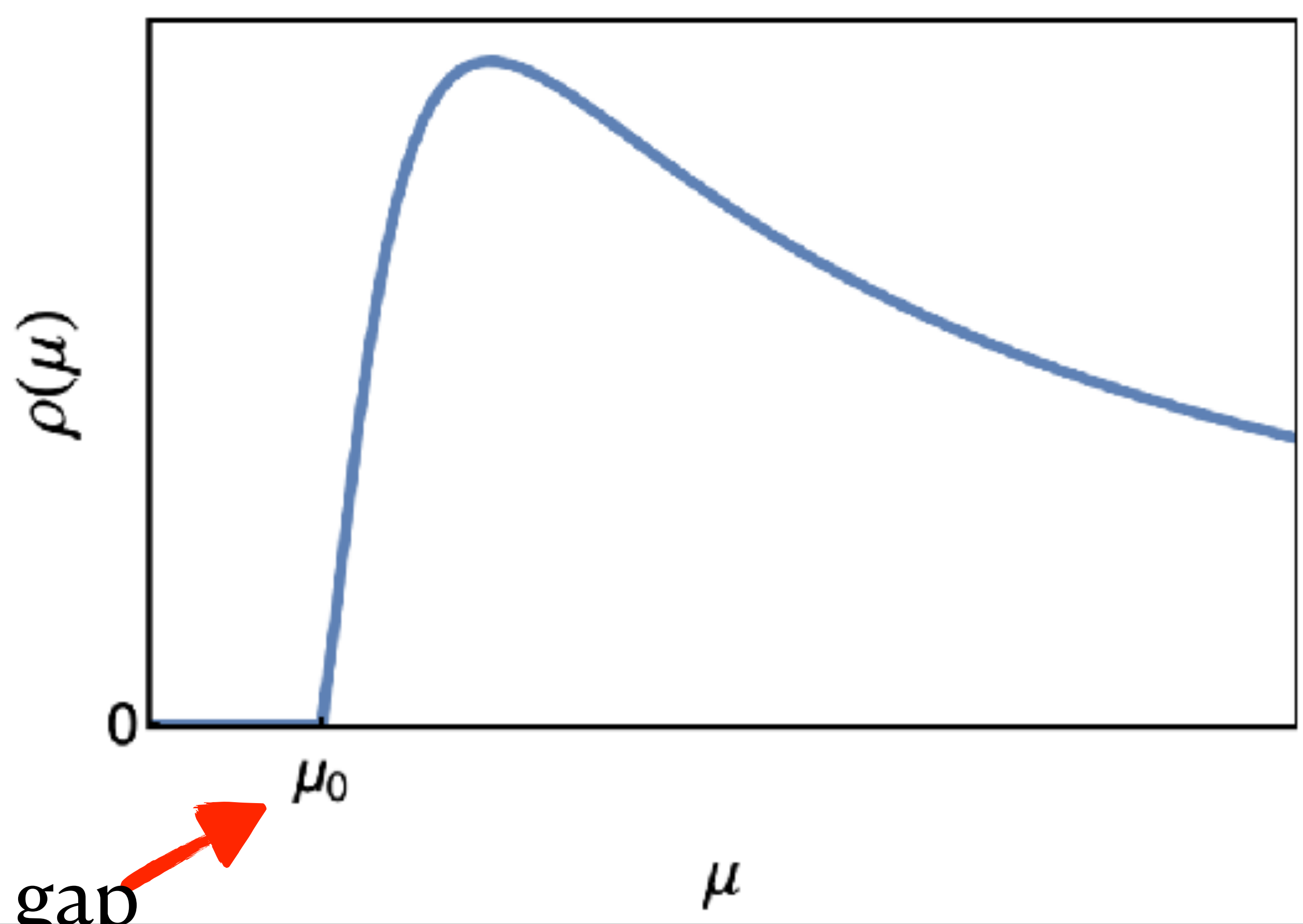

needs to be gapped: consistent with observations e.g. CMB, LSS

Generalized Free Continuum

♦ Continuum Fields

- Consider quadratic action in the momentum space:

$$S_{\text{scalar}} = \int \frac{d^4p}{(2\pi)^4} \phi^\dagger(p) \Sigma(p^2) \phi(p)$$

$$S_{\text{fermion}} = -i \int \frac{d^4p}{(2\pi)^4} \overline{\psi}(p) \Sigma(p^2) \frac{\overline{\sigma}^\mu p_\mu}{p^2} \psi(p)$$

$$S_{\text{vector}} = \frac{1}{2} \int \frac{d^4p}{(2\pi)^4} A_\mu(p) \Sigma(p^2) \left[\eta^{\mu\nu} - \left(1 - \frac{1}{\xi}\right)\right] A_\nu(p)$$

Σ is determined by the two-point correlation function

Källén–Lehmann spectral representation

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-for a particle: $\Sigma(p^2) = p^2 - m^2 + i\epsilon$

$$\rho(\mu^2) = 2\pi\delta(\mu^2 - m^2)$$

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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:

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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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Generalized Free Continuum

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which is designed to properly reproduce the two

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

> This picture is supported by the concrete extra dimensional construction!

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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

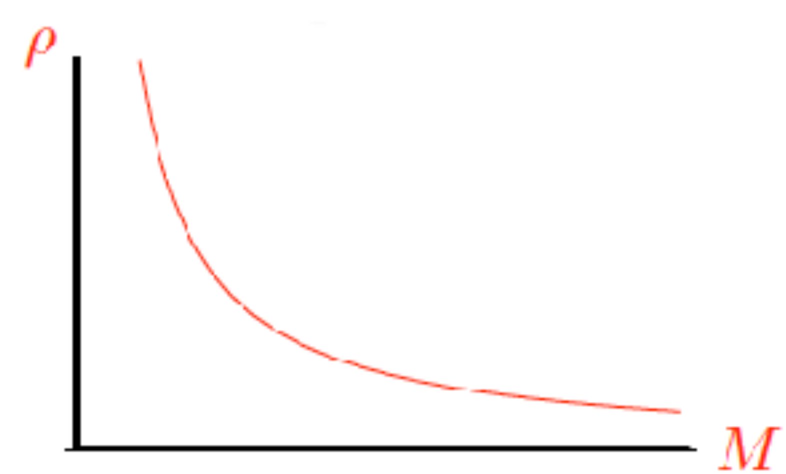
Scaling - 2-point function: $G(p^2) = -\frac{i}{(-p^2+i\epsilon)^{2-\Delta}}$

Can be generated from: $\mathcal{L}_{\mathrm{CFF}} = -\hbar^\dagger \left(\partial^2\right)^{2-\Delta} \hbar$

Georgi
hep-ph/0703260

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

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



AdS/CFT & RS model as EFT

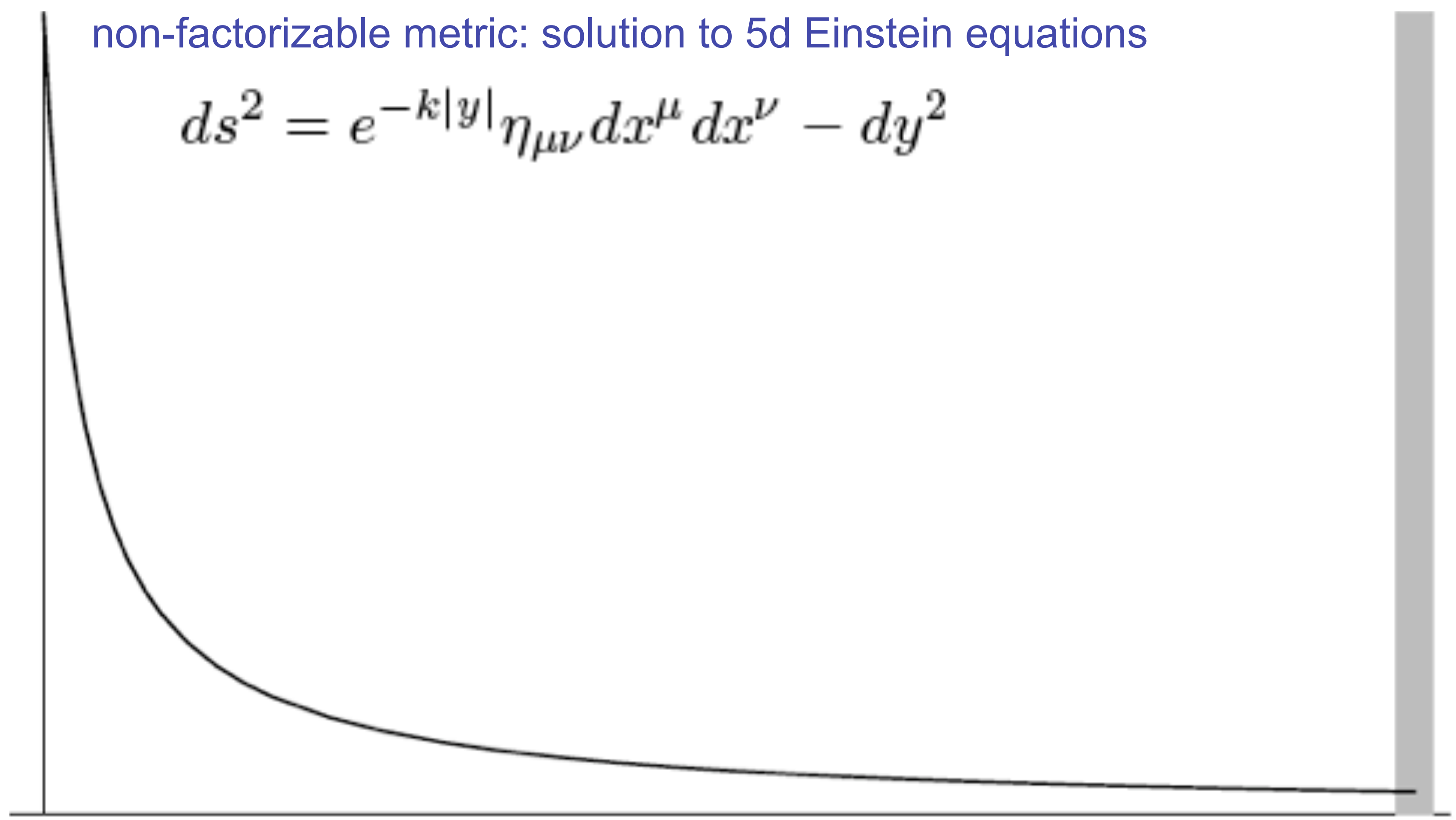
- Gravity weak, because we only feel tail of graviton
- Large curvature along XD: Space-time “warped”
- Scale Invariance (same physics with different scale) along the XD (=> CFT)
- Warped Extra-dimension can be seen as an emergent phenomenon
- Not put it into the theory by hand, but created by strong quantum interaction!

Randall-Sundrum(99)

Higgs

non-factorizable metric: solution to 5d Einstein equations

$$ds^2 = e^{-k|y|}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$



PLANCK (y=0)

TeV (y=b)

AdS/CFT
Madacen 97’
Gubser, Klevanov, Polyakov 98’
Witten 98’

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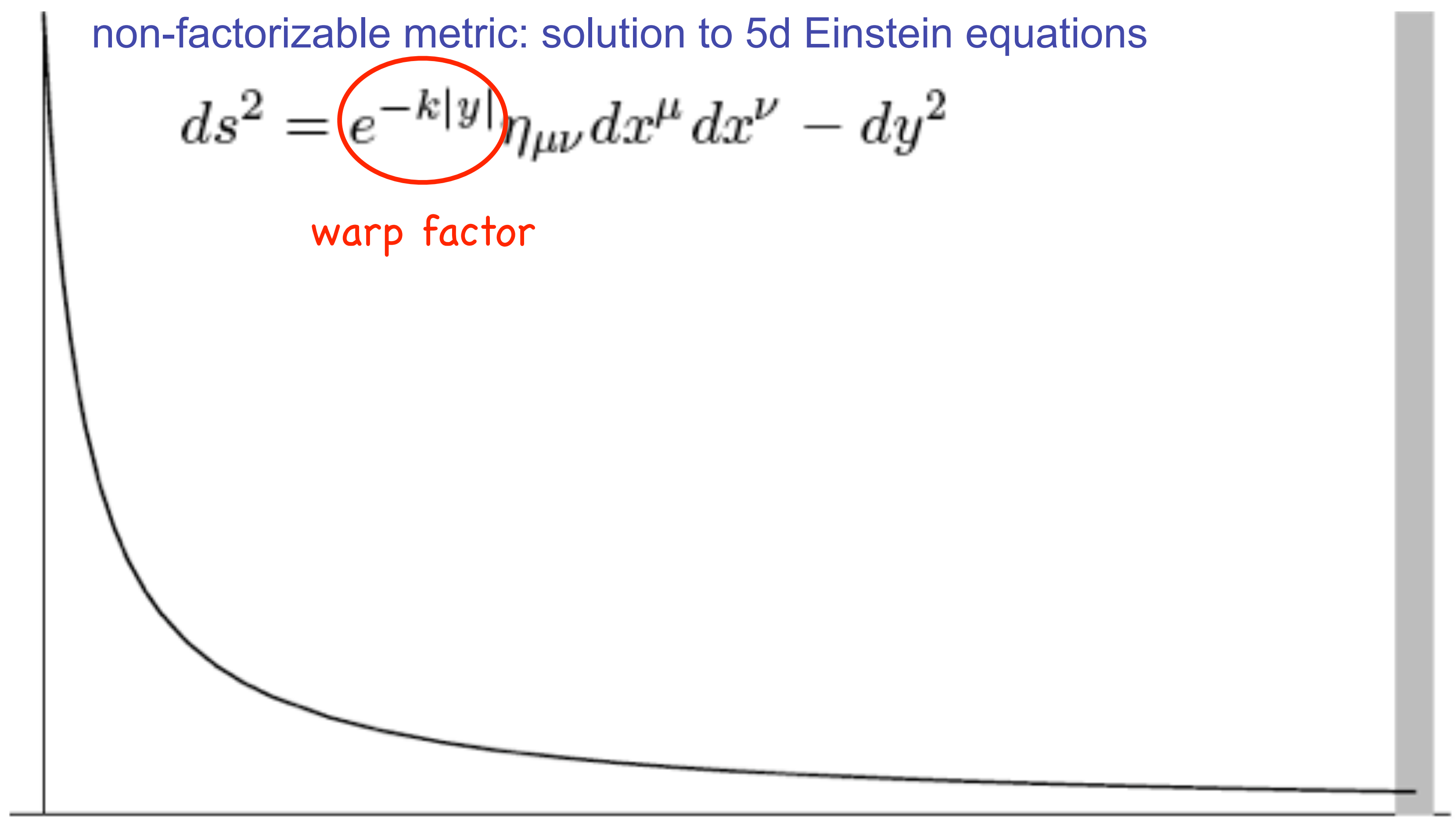

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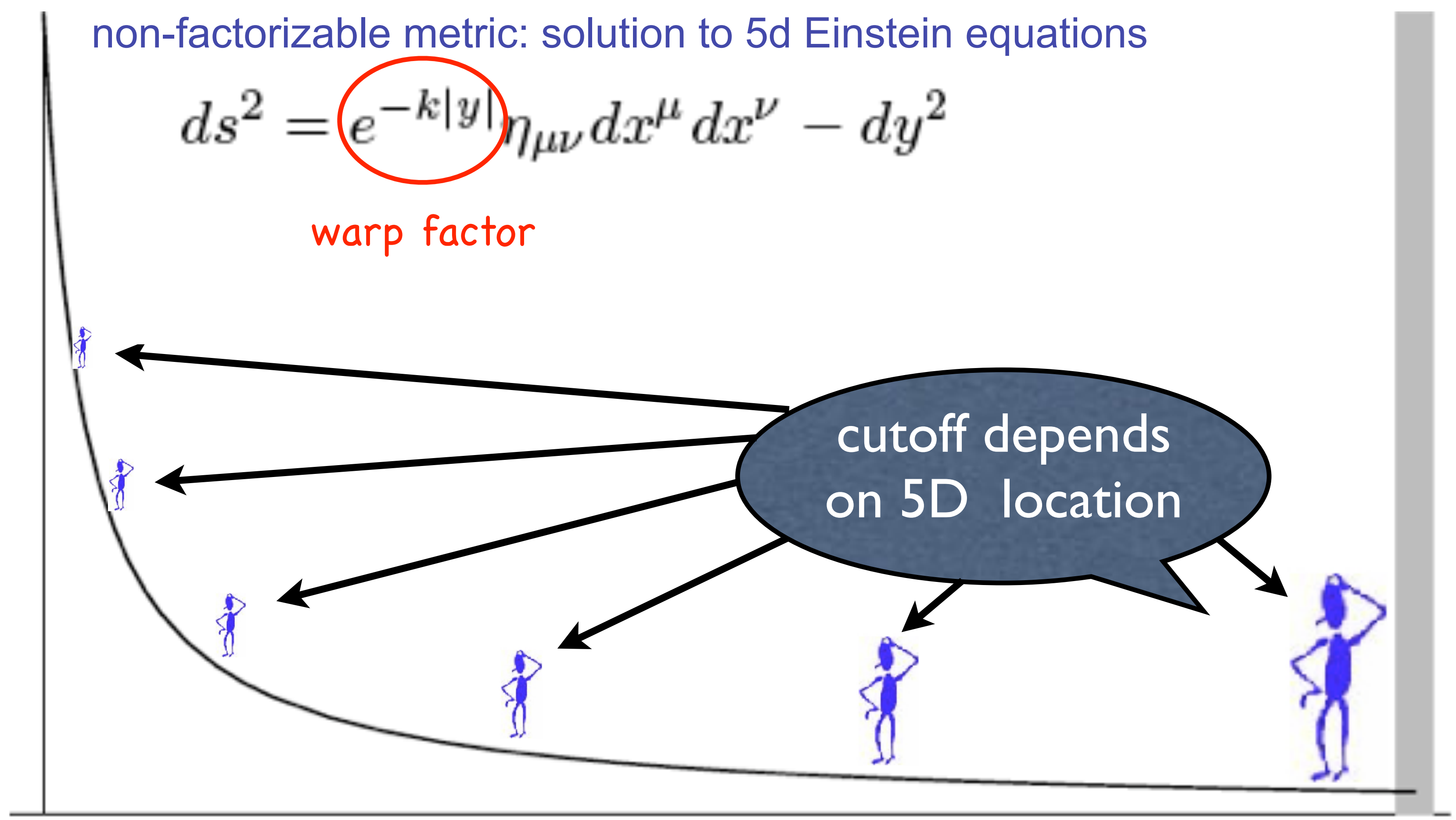

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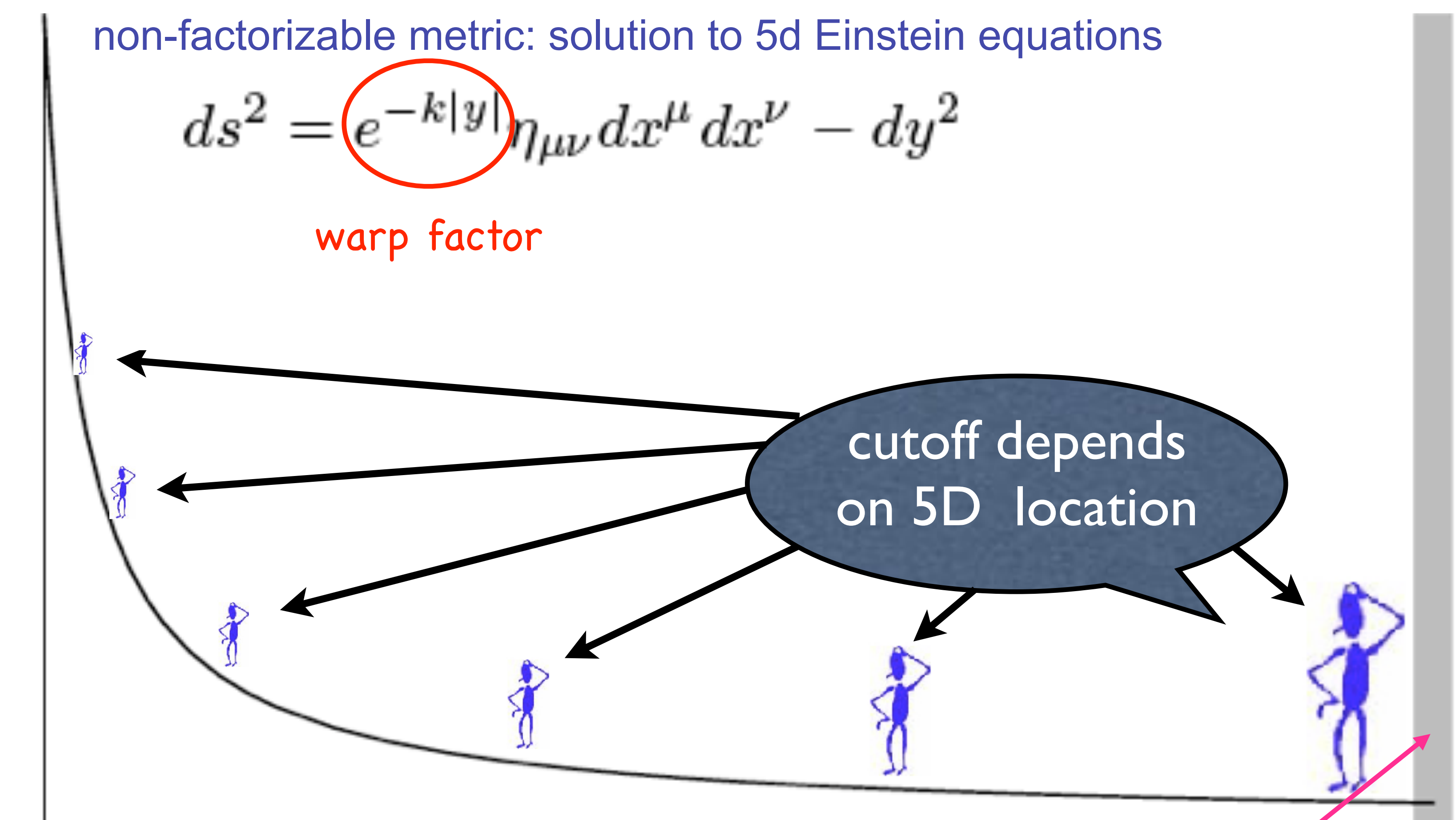


AdS/CFT
Madacen 97'
Gubser, Klevanov, Polyakov 98'
Witten 98'

PLANCK (y=0)

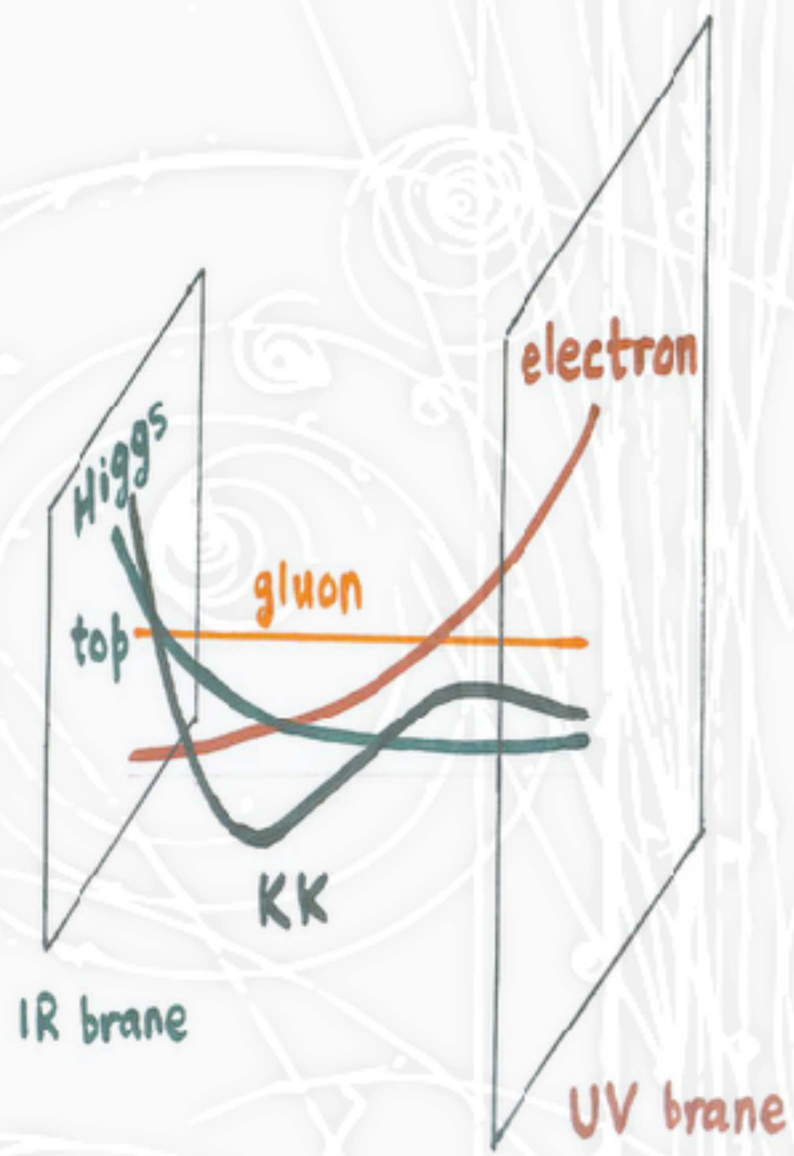
Assume we live here

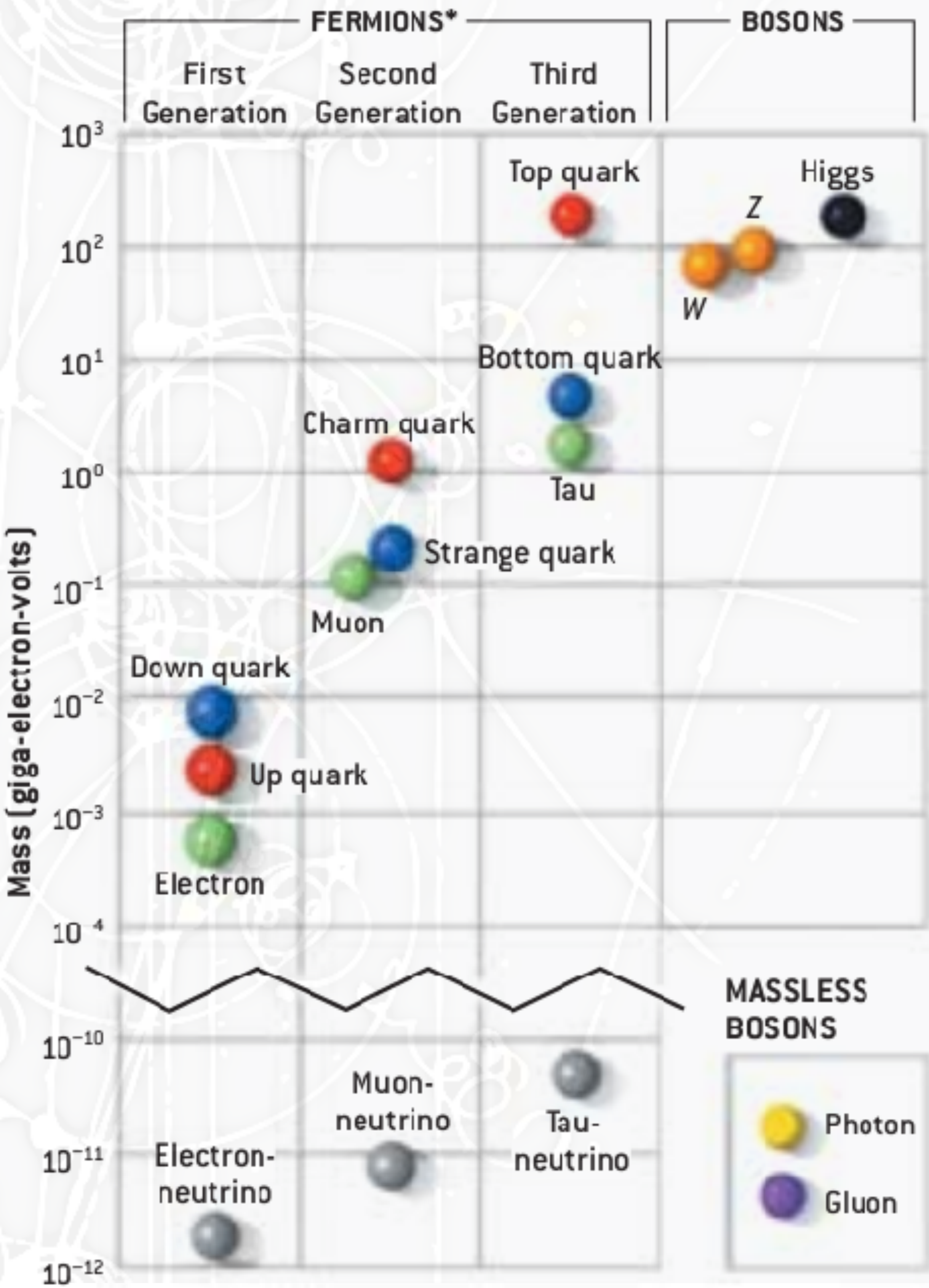
(red shift to TeV scale)

SM localized on IR brane

TeV (y=b)

Hierarchical Mass spectrum from extra dimension





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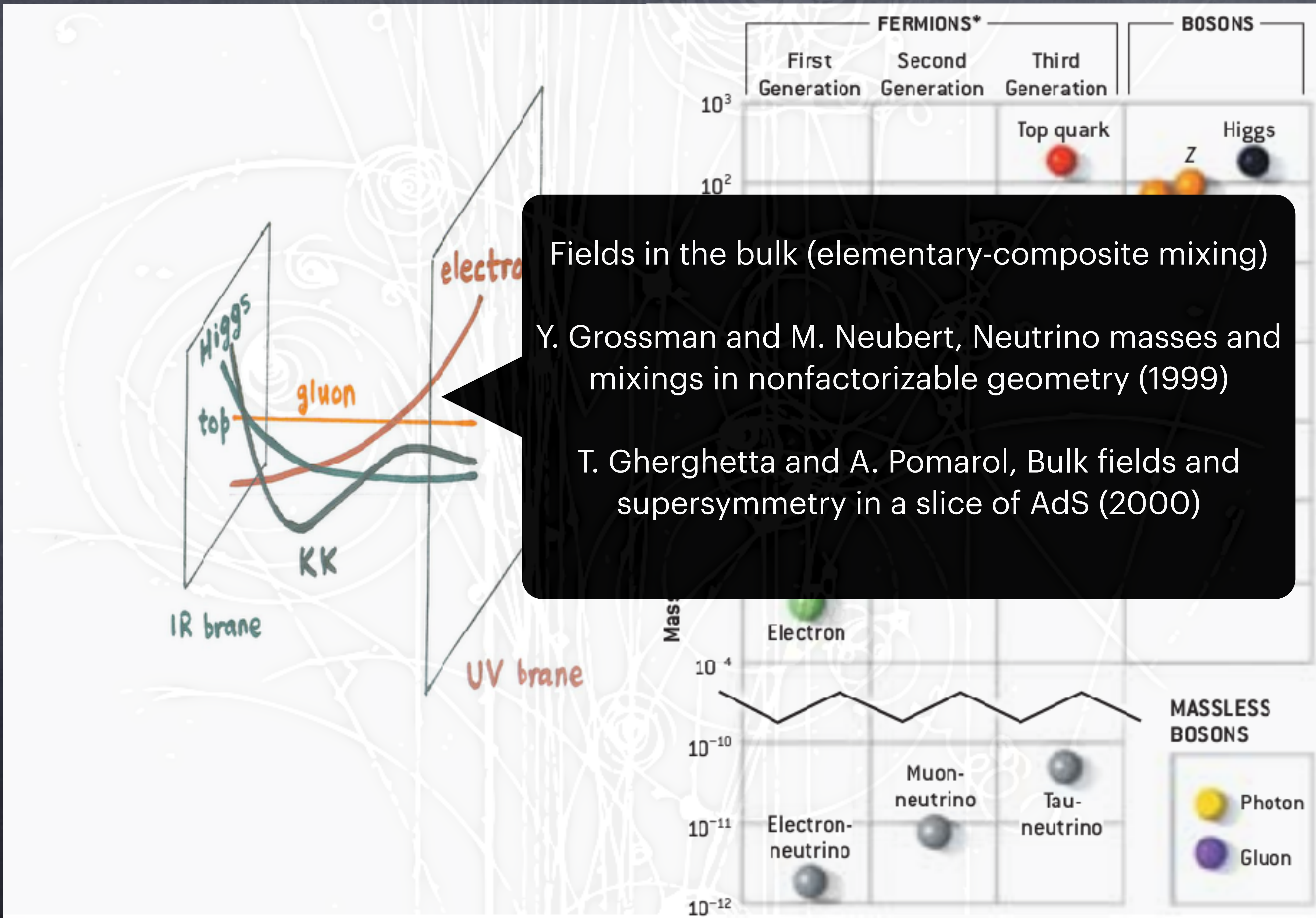


Fields in the bulk (elementary-composite mixing)

Y. Grossman and M. Neubert, Neutrino masses and mixings in nonfactorizable geometry (1999)

T. Gherghetta and A. Pomarol, Bulk fields and supersymmetry in a slice of AdS (2000)

...a dimension

Dynamical origin of fermion bulk masses in a warped extra dimension #1
Aqeel Ahmed (U. Mainz, PRISMA and Mainz U., Inst. Phys. and Brussels U., IIHE and Vrije U., Brussels), Adrian Carmona (U. Mainz, PRISMA and Mainz U., Inst. Phys.), Javier Castellano Ruiz (U. Mainz, PRISMA and Mainz U., Inst. Phys.), Yi Chung (U. Mainz, PRISMA and Mainz U., Inst. Phys. and UC, Davis and Taiwan, Natl. Taiwan U.), Matthias Neubert (U. Mainz, PRISMA and Mainz U., Inst. Phys. and Cornell U., Phys. Dept. and Cornell U., LEPP) (May 23, 2019)
Published in: JHEP 08 (2019) 045 • e-Print: 1905.09833 [hep-ph]
pdf DOI cite claim reference search 16 citations

Diphoton Resonance from a Warped Extra Dimension #2
Martin Bauer (U. Heidelberg, ITP), Clara Hörner (U. Mainz, PRISMA and Mainz U., Inst. Kernphys.), Matthias Neubert (Cornell U., Phys. Dept. and Cornell U., LEPP and U. Mainz, PRISMA and Mainz U., Inst. Kernphys.) (Mar 18, 2016)
Published in: JHEP 07 (2016) 094 • e-Print: 1603.05978 [hep-ph]
pdf DOI cite claim reference search 35 citations

Higgs Production and Decay in Models of a Warped Extra Dimension with a Bulk Higgs #3
Paul R. Archer (U. Mainz, PRISMA and Mainz U.), Marcela Carena (Fermilab and Chicago U., EFI and Chicago U., KICP), Adrian Carmona (Zurich, ETH), Matthias Neubert (U. Mainz, PRISMA and Mainz U. and Cornell U., LEPP) (Aug 22, 2014)
Published in: JHEP 01 (2015) 060 • e-Print: 1408.5406 [hep-ph]
pdf links DOI cite claim reference search 44 citations

Higgs Couplings and Phenomenology in a Warped Extra Dimension #4
Raoul Malm (U. Mainz, PRISMA and Mainz U.), Matthias Neubert (U. Mainz, PRISMA and Mainz U. and Cornell U., LEPP), Christoph Schmell (U. Mainz, PRISMA and Mainz U.) (Aug 19, 2014)
Published in: JHEP 02 (2015) 008 • e-Print: 1408.4456 [hep-ph]
pdf DOI cite claim reference search 24 citations

Higgs Decay into Two Photons at the Boundary of a Warped Extra Dimension #5
Juliane Hahn (U. Mainz, PRISMA and Mainz U.), Clara Hörner (U. Mainz, PRISMA and Mainz U.), Raoul Malm (U. Mainz, PRISMA and Mainz U.), Matthias Neubert (U. Mainz, PRISMA and Mainz U. and Cornell U., Phys. Dept. and Cornell U., LEPP), Kristiane Novotny (U. Mainz, PRISMA and Mainz U.) et al. (Dec 10, 2013)
Published in: Eur.Phys.J.C 74 (2014) 5, 2857 • e-Print: 1312.5731 [hep-ph]
pdf DOI cite claim reference search 19 citations

5D Perspective on Higgs Production at the Boundary of a Warped Extra Dimension #6
Raoul Malm (U. Mainz, PRISMA and Mainz U.), Matthias Neubert (U. Mainz, PRISMA and Mainz U.), Kristiane Novotny (U. Mainz, PRISMA and Mainz U.), Christoph Schmell (U. Mainz, PRISMA and Mainz U.) (Mar 22, 2013)
Published in: JHEP 01 (2014) 173 • e-Print: 1303.5702 [hep-ph]
pdf DOI cite claim reference search 45 citations

Higgs Production in a Warped Extra Dimension #7
Marcela Carena (Fermilab and Chicago U., KICP and Chicago U., EFI), Sandro Casagrande (Munich, Tech. U., Universe), Florian Goertz (Zurich, ETH), Ulrich Haisch (Oxford U., Theor. Phys.), Matthias Neubert (Mainz U., Inst. Phys.) (Apr, 2012)
Published in: JHEP 08 (2012) 156 • e-Print: 1204.0008 [hep-ph]
pdf links DOI cite claim reference search 55 citations

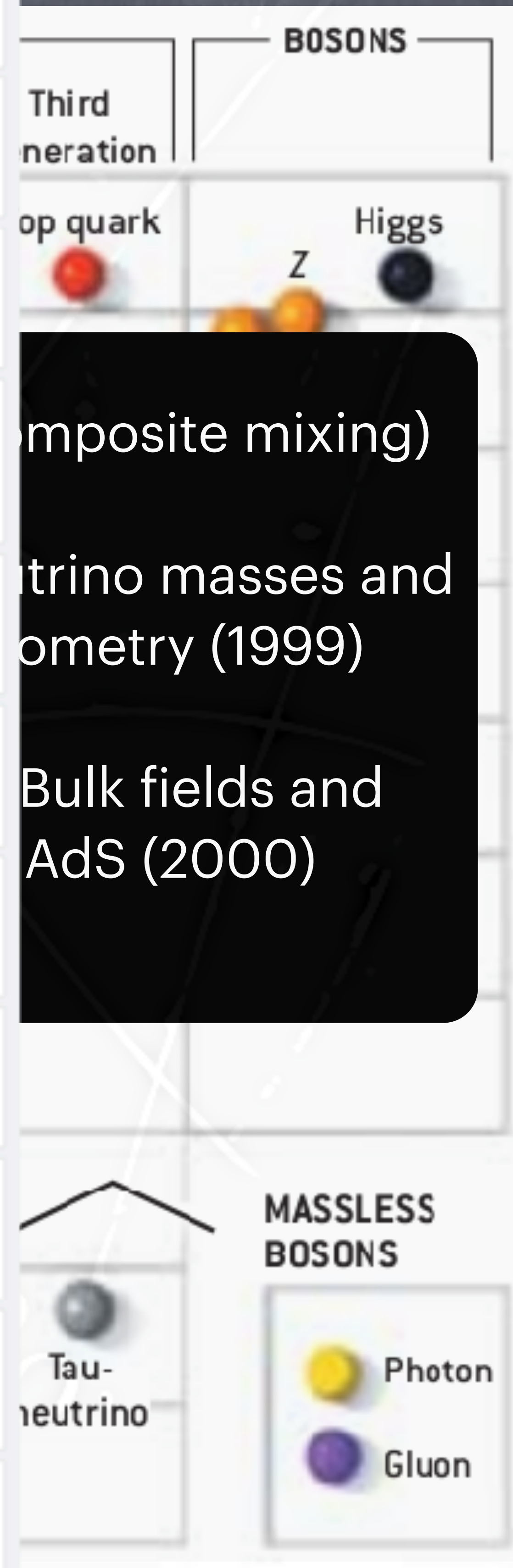
A Solution to the Flavor Problem of Warped Extra-Dimension Models #8
Martin Bauer (Mainz U., Inst. Phys.), Raoul Malm (Mainz U., Inst. Phys.), Matthias Neubert (Mainz U., Inst. Phys.) (Oct, 2011)
Published in: Phys.Rev.Lett. 108 (2012) 081603 • e-Print: 1110.0471 [hep-ph]
pdf DOI cite claim reference search 41 citations

The Custodial Randall-Sundrum Model: From Precision Tests to Higgs Physics #9
Sandro Casagrande (Munich, Tech. U., Universe), Florian Goertz (Mainz U., Inst. Phys.), Uli Haisch (Mainz U., Inst. Phys.), Matthias Neubert (Mainz U., Inst. Phys. and Heidelberg U.), Torsten Pfoh (Mainz U., Inst. Phys.) (May, 2010)
Published in: JHEP 09 (2010) 014 • e-Print: 1005.4315 [hep-ph]
pdf DOI cite claim reference search 104 citations

Flavor Physics in the Randall-Sundrum Model: II. Tree-Level Weak-Interaction Processes #10
M. Bauer (Mainz U., Inst. Phys.), S. Casagrande (Munich, Tech. U., Universe), U. Haisch (Mainz U., Inst. Phys.), M. Neubert (Mainz U., Inst. Phys.) (Dec, 2009)
Published in: JHEP 09 (2010) 017 • e-Print: 0912.1625 [hep-ph]
pdf DOI cite claim reference search 126 citations

Little Randall-Sundrum models: epsilon(K) strikes again #11
M. Bauer (Mainz U., Inst. Phys.), S. Casagrande (Mainz U., Inst. Phys.), L. Grunder (Mainz U., Inst. Phys.), U. Haisch (Mainz U., Inst. Phys.), M. Neubert (Mainz U., Inst. Phys.) (Nov, 2008)
Published in: Phys.Rev.D 79 (2009) 076001 • e-Print: 0811.3678 [hep-ph]
pdf DOI cite claim reference search 57 citations

Flavor Physics in the Randall-Sundrum Model: I. Theoretical Setup and Electroweak Precision Tests #12
S. Casagrande (Mainz U., Inst. Phys.), F. Goertz (Mainz U., Inst. Phys.), U. Haisch (Mainz U., Inst. Phys.), M. Neubert (Mainz U., Inst. Phys.), T. Pfoh (Mainz U., Inst. Phys.) (Sep, 2008)
Published in: JHEP 10 (2008) 094 • e-Print: 0807.4937 [hep-ph]
pdf DOI cite claim reference search 207 citations



mposite mixing)

trino masses and
ometry (1999)

Bulk fields and
AdS (2000)

Dark Matter Continuum Spectral Density from 5D Model

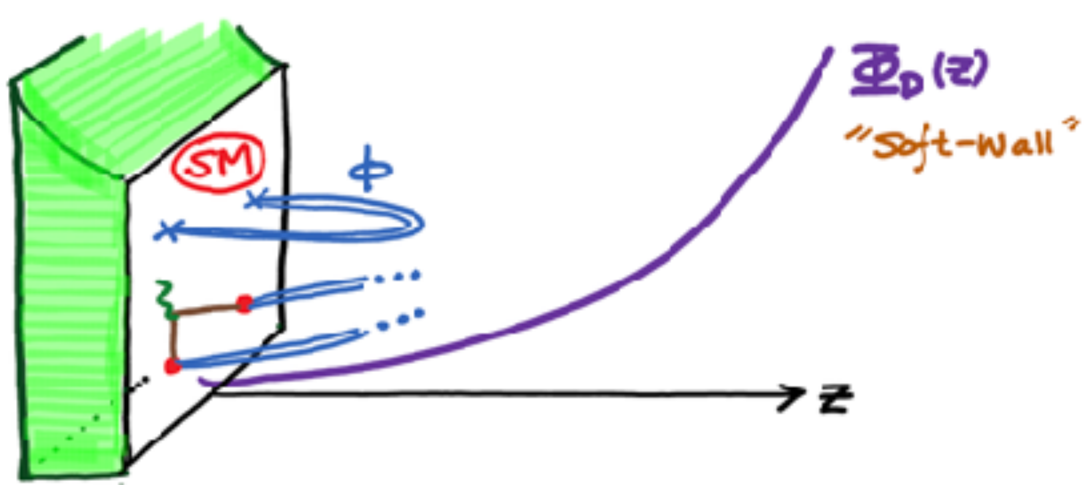
♦ modeling generalized free continuum by Warped 5D model

$$\mathrm{d}s^2 = e^{-2A(y)}\mathrm{d}x^2 + \mathrm{d}y^2$$

- 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

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



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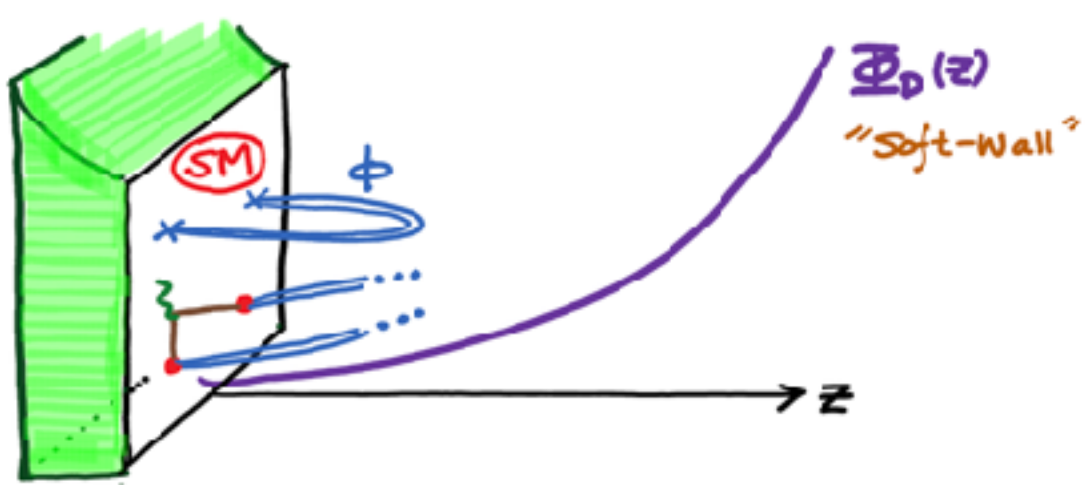
- The superpotential (w/ relation V = $3W'^2 - 12W^2$) leading to the desired 5D background : $W = k(1+e^{\phi})$ (fully includes the backreaction of the metric to the presence of the scalar field)



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

$$\phi(y) = -\log\left(k(y_s - y)\right),$$

Dark Matter Continuum Spectral Density from 5D Model

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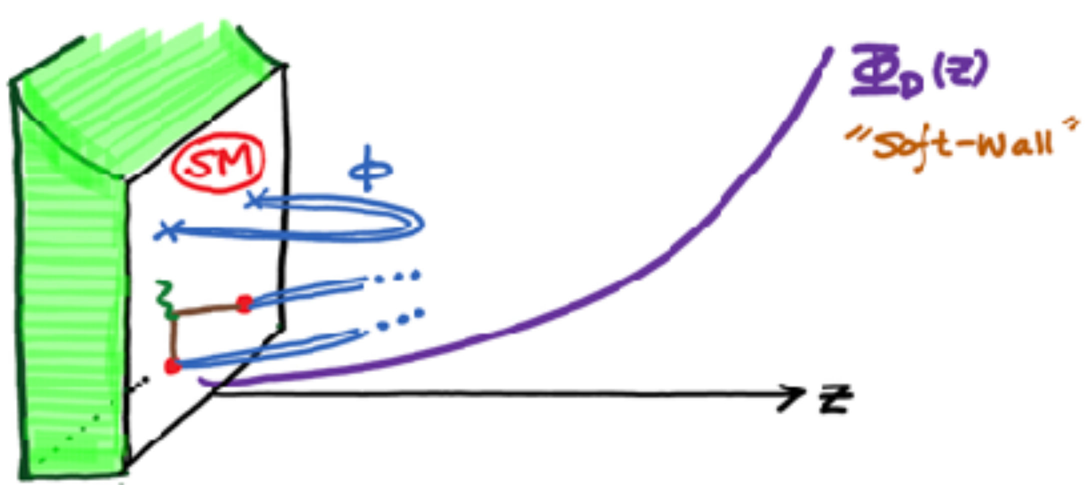
The 5D action of the coupled scalar-gravity system

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

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

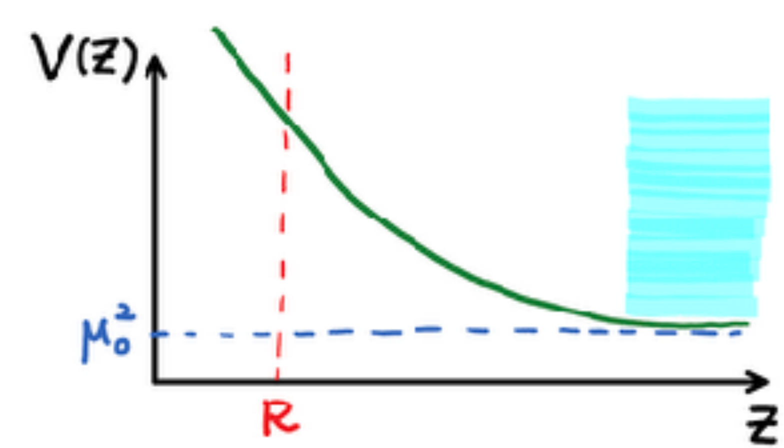
"Schrödinger Eqn'

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

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

if $V \xrightarrow[z \to \infty]{} \mu_0^2$ = finite => Continuum! 1D QM problem

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



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$V(z) = \frac{e^{-2ky}}{4y_s^2}\left[4m^2(y_s - y)\right.$

Quantum Gravity?
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)

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$z \to \infty$

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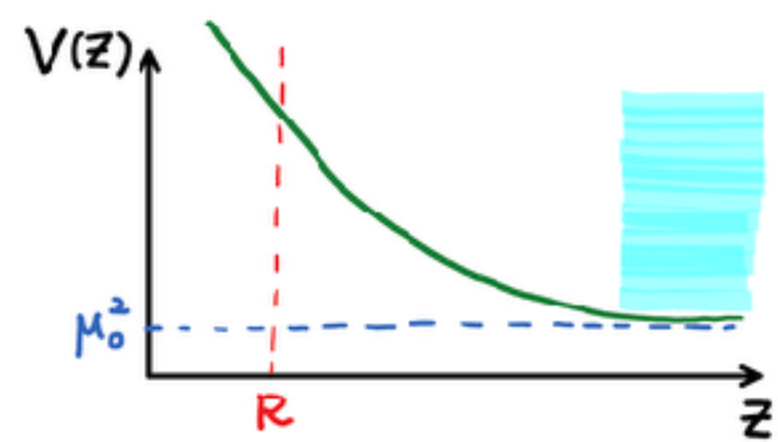

What’s so new for gapped continuum as a DM?

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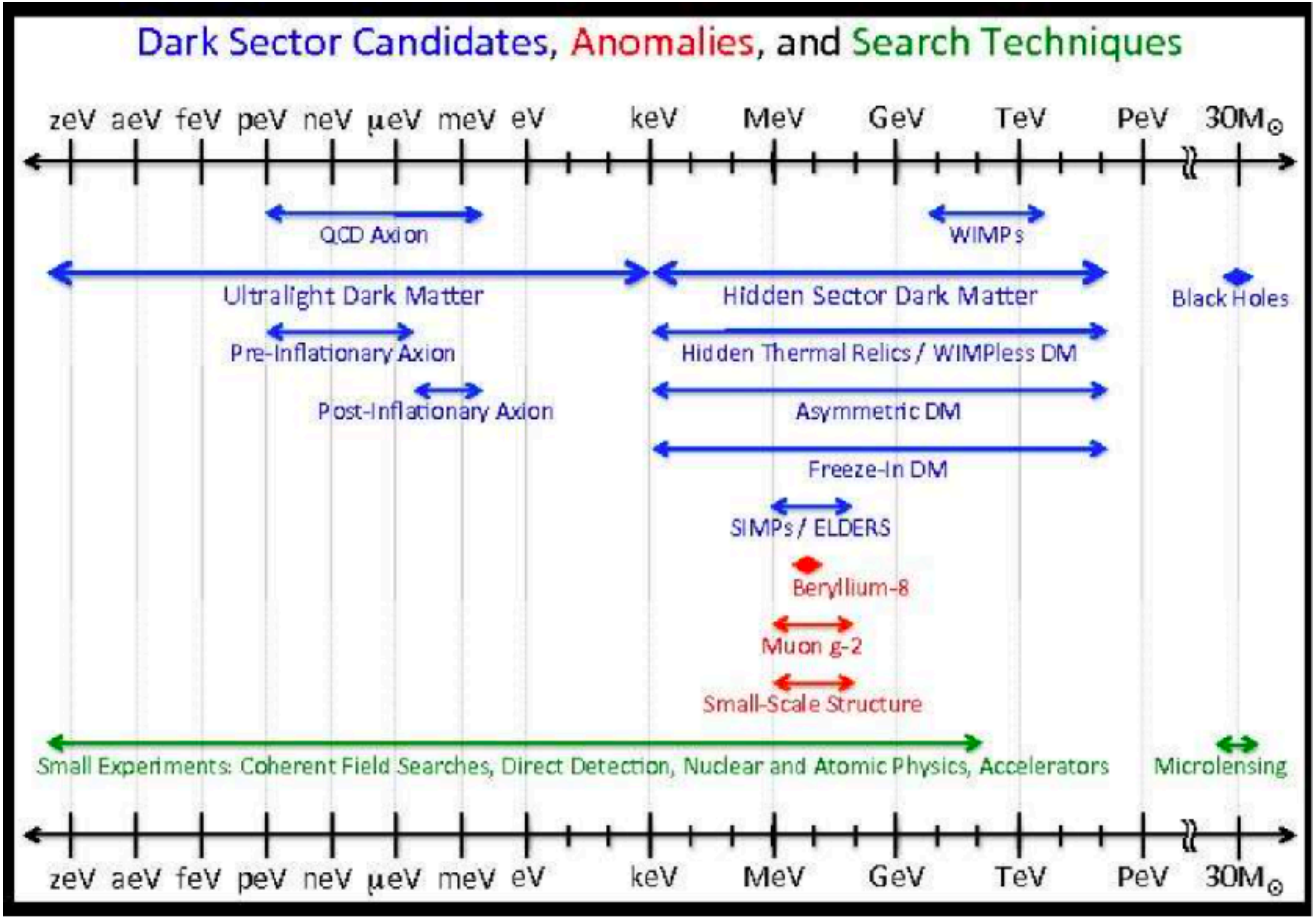
- Gapped Continuum as a DM can give striking new experimental signatures in colliders and cosmic microwave background measurements

- 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 ?



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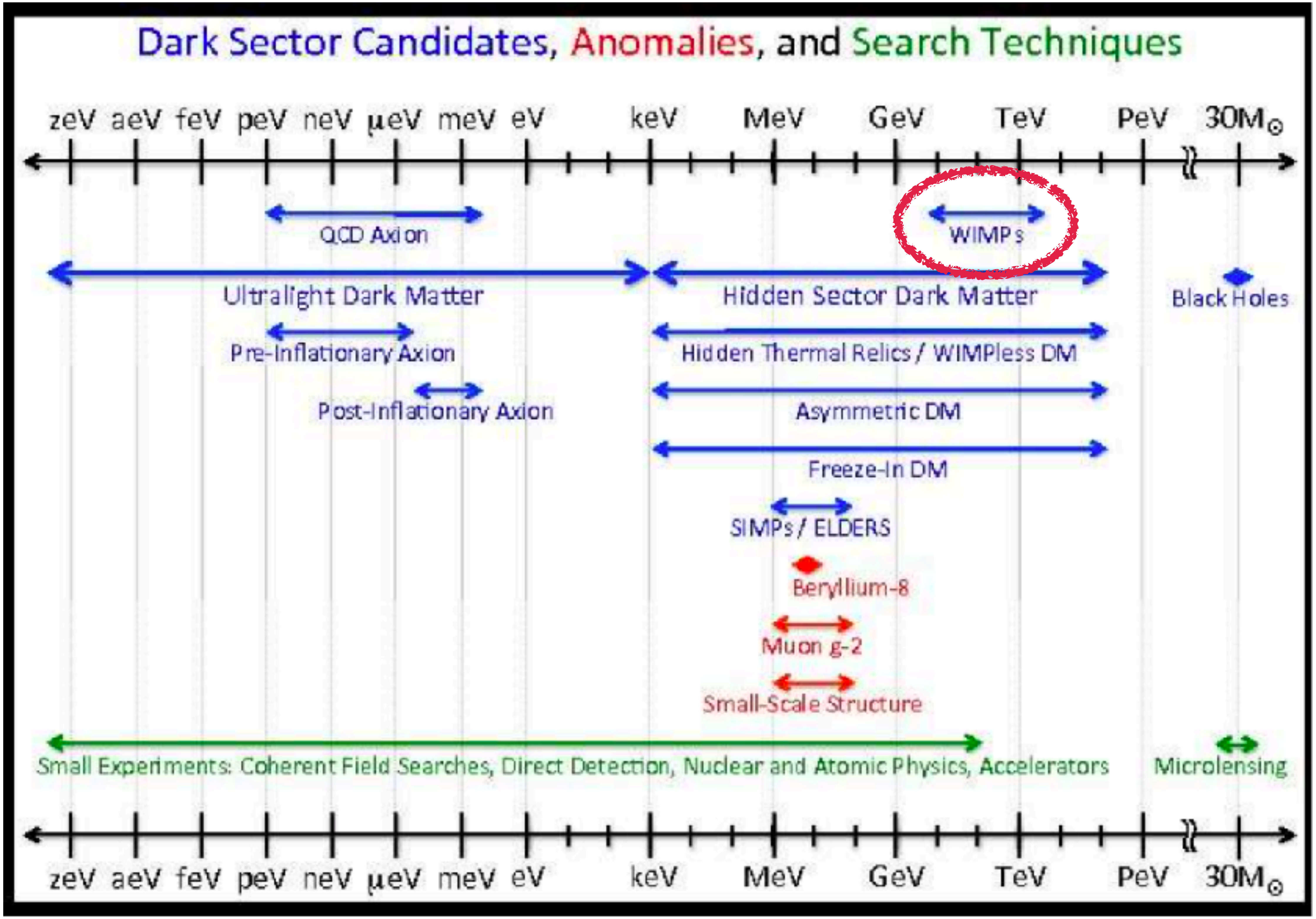
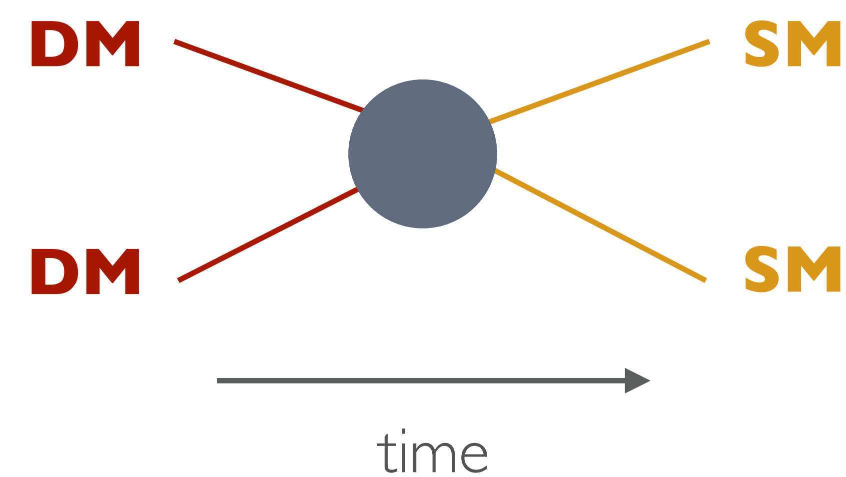


THE WIMP MIRACLE

Insensitive to the initial conditions of the Universe:

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

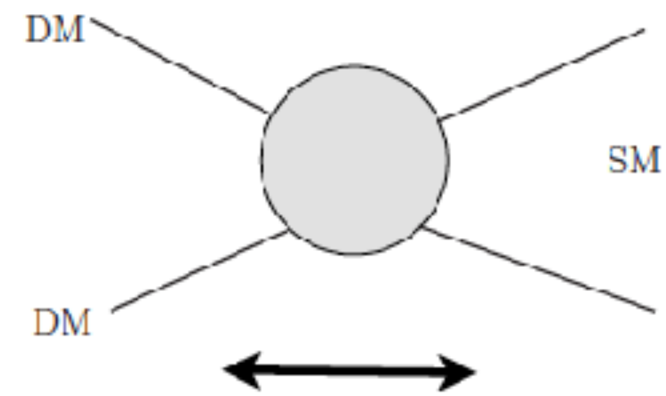
$$\text{Relic abundance} \propto \frac{1}{\text{ann. rate}}$$



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. $\langle \sigma v \rangle \sim \frac{g_{\mathrm{D}}^4}{m_{\mathrm{DM}}^2}$

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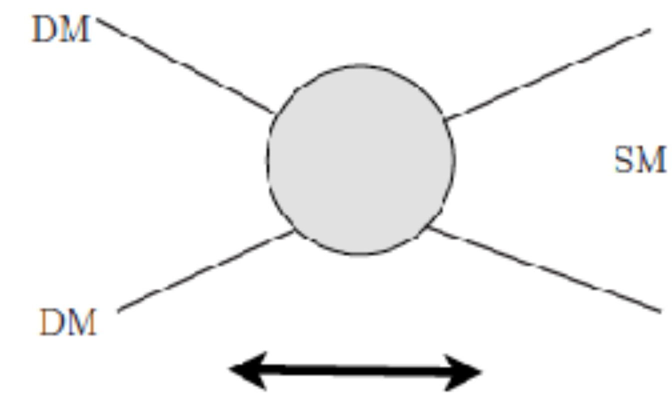
Moore's Law works in DM!



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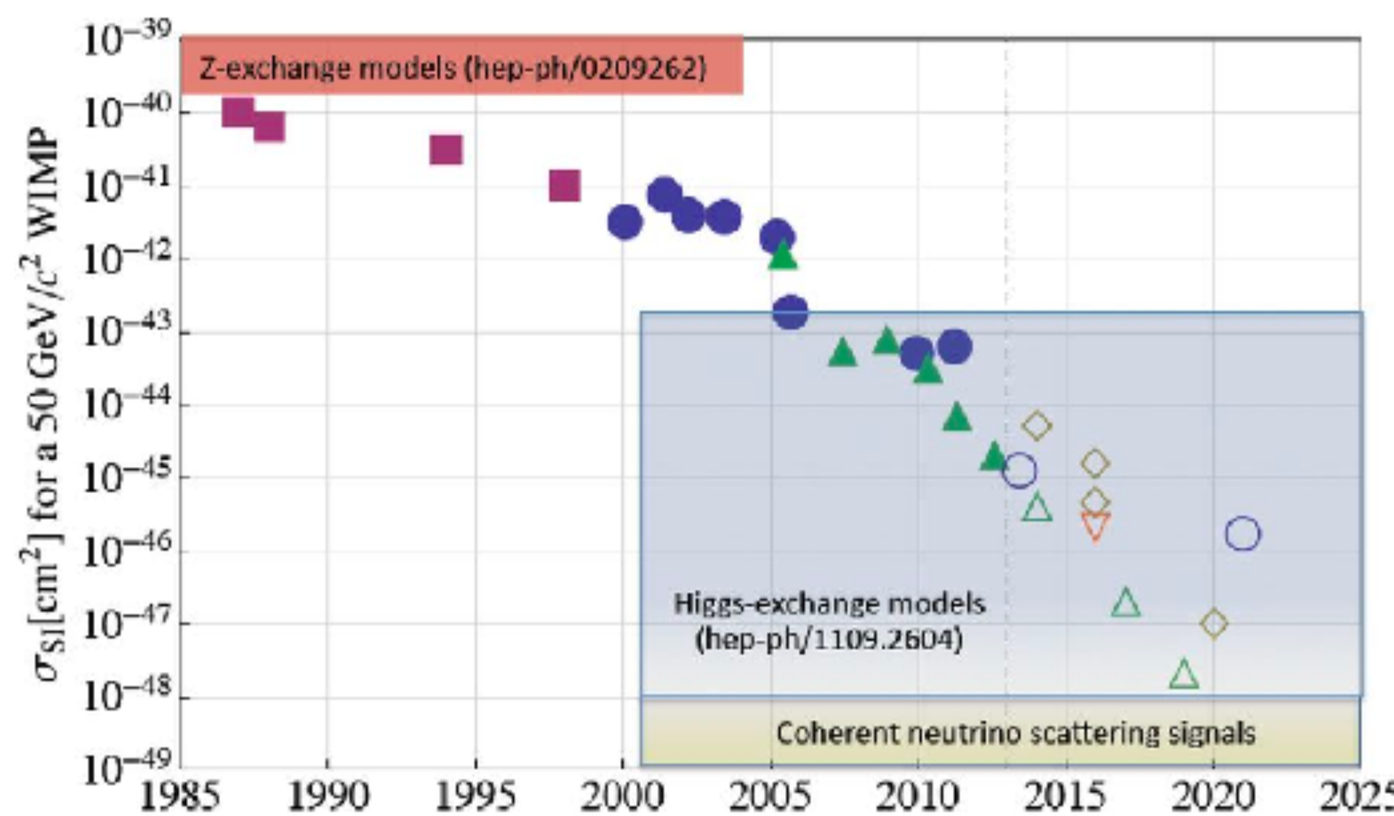

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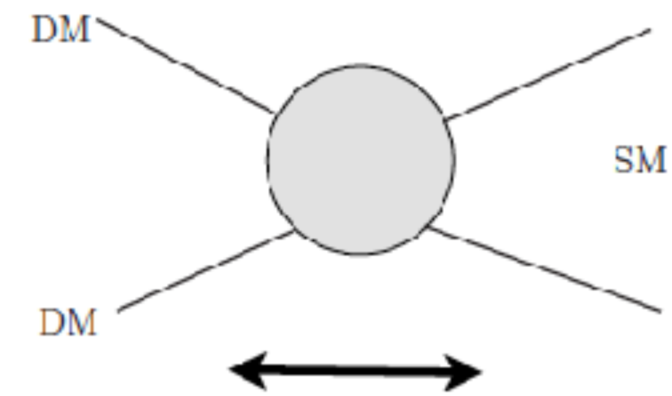
Moore's Law works in DM!

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



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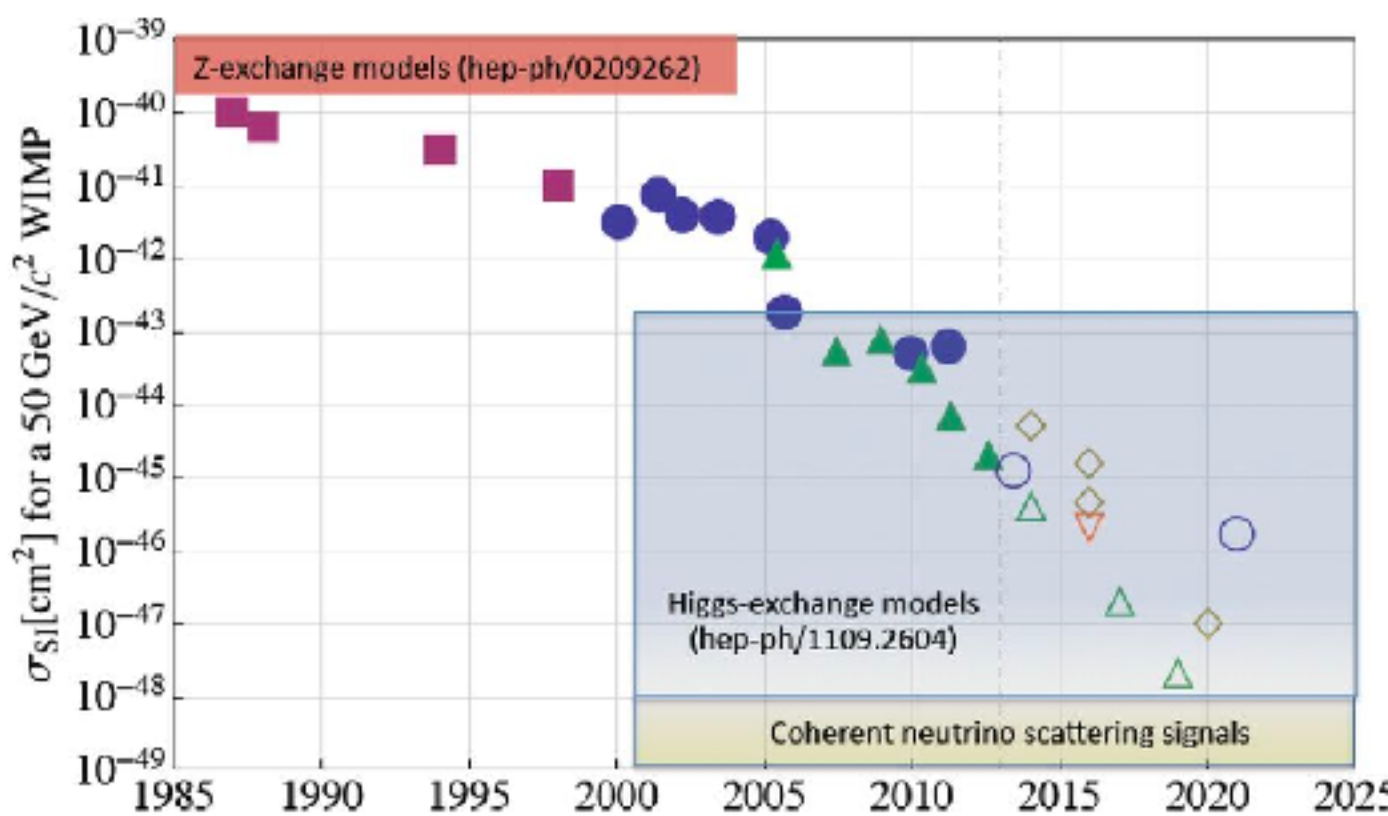

Been searching for WIMPs…

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?

Theory of Gapped Continuum DM

We develop a new formalism to deal with above questions and develop a realistic gapped continuum models to perform concrete DM phenomenology which would distinguish it from ordinary particle DM scenarios. Different areas for gapped continuum DM study for our project include:

- Gapped Continuum QFT
- Equilibrium and Non-equilibrium Thermodynamics
- Freeze-out of DM (and also Freeze-in DM)
- Gapped continuum DM from warped space model
- Realistic model building of gapped continuum DM
- Phenomenological study (both in terms of astrophysics/cosmology and collider)

Gapped Continuum QFT

Gapped Continuum Hilbert Space

- single-mode sector of the Hilbert space for continuum state consists of states $|p, \mu^2\rangle$

continuous parameter!

$$\hat{\mathbf{P}}\,|\mathbf{p},\mu^2\rangle = \mathbf{p}\,|\mathbf{p},\mu^2\rangle,$$
$$\hat{H}\,|\mathbf{p},\mu^2\rangle = \sqrt{\mathbf{p}^2+\mu^2}\,|\mathbf{p},\mu^2\rangle.$$

- Completeness relation (spectral density $\varrho(\mu^2)$ as the density of states):

$$\int \frac{d\mu^2}{2\pi}\,\rho(\mu^2)\int \frac{d^3p}{(2\pi)^3}\frac{1}{2E_{\mathbf{p},\mu^2}}\,|\mathbf{p},\mu^2\rangle\langle\mathbf{p},\mu^2| = 1.$$

The completeness relation can also be rewritten as

$$\int \frac{d^4p}{(2\pi)^4}\rho(p^2)|\mathbf{p},\mu^2\rangle\langle\mathbf{p},\mu^2| = 1,$$

normalization (one particle state):

$$\langle\mathbf{p}',\mu'^2|\mathbf{p},\mu^2\rangle = \frac{2E_{\mathbf{p},\mu^2}}{\rho(\mu^2)}\,(2\pi)^4\delta^3(\mathbf{p}-\mathbf{p}')\,\delta(\mu^2-\mu'^2)$$

$p_0 = E_{\mathbf{p},\mu^2} = \sqrt{\mathbf{p}^2+\mu^2}$, and $p^2 = p_0^2 - \mathbf{p}^2$.

Gapped Continuum QFT

♦ Gapped Continuum Hilbert Space

- multi-mode states are built as direct products of single-mode states. e.g SM+SM→ DM+DM

$$\langle(\mathbf{p_1},\mu_1^2),(\mathbf{p_1},\mu_1^2)|\mathrm{Texp}\left(-i\int dtH_I(t)\right)|\mathbf{k}_A,\mathbf{k}_B\rangle_{\mathrm{SM}}\equiv(2\pi)^4\delta^4(k_1+k_2-p_1-p_2)\,i\mathcal{M}.$$

- Production cross-section:

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- Production cross-section:

$$\sigma(q\bar{q}\to\chi^\dagger\chi)=\frac{32\pi\alpha_s}{9s}\mathrm{Im}\Pi(s)$$

$$i\Pi^{\mu\nu,ab}(q)=\left(-g^{\mu\nu}+\frac{q^\mu q^\nu}{q^2}\right)\delta^{ab}i\Pi(q^2)$$

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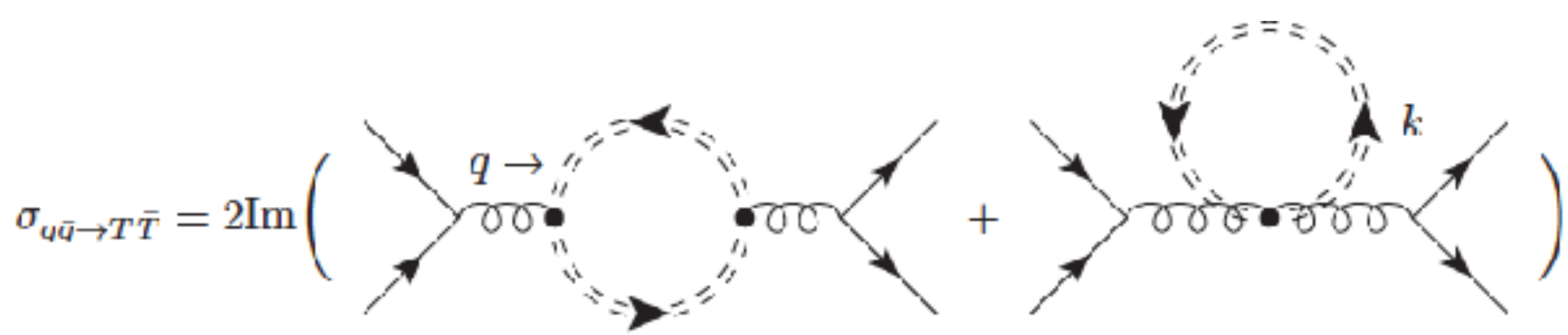

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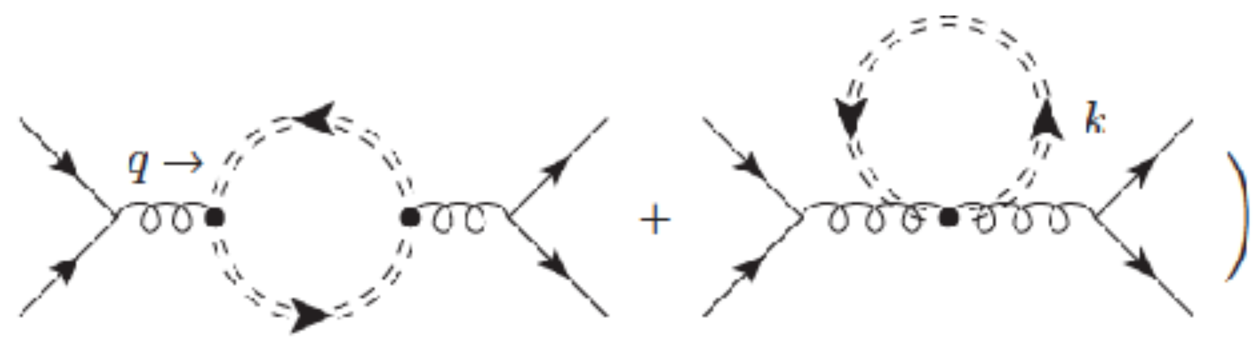
$\sigma_{q\bar{q}\to T\bar{T}} = 2\mathrm{Im}\Big($



$\Big)$

$$\sigma=\frac{1}{2E_A}\frac{1}{2E_A}\frac{1}{|v_A-v_B|}\int\frac{d\mu_1^2}{2\pi}\rho(\mu_1^2)\int\frac{d\mu_2^2}{2\pi}\rho(\mu_2^2)\int d\Pi_1^{\mu_1^2}\,d\Pi_2^{\mu_2^2}\,(2\pi)^4\delta^4(k_1+k_2-p_1-p_2)\,|\mathcal{M}|^2$$

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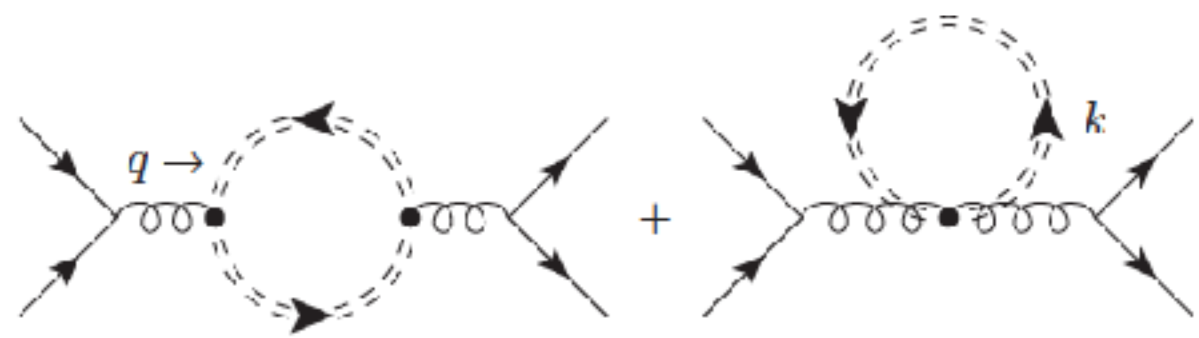

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3D Lorentz-invariant phase space (LIPS) volume element: $d\Pi^{\mu^2}=\frac{d^3p}{(2\pi)^3}\frac{1}{2E_{\mathbf{p},\mu^2}}$

Equilibrium and Non-equilibrium Thermodynamics

♦ Equilibrium Thermodynamics

- Consider a dilute, weakly-coupled gas made out of the single-mode Gapped Continuum states

define the dimensionless phase-space density $f(p,\mu^2)$:

$$N = V \int \frac{d\mu^2}{2\pi}\, \rho(\mu^2) \int \frac{d^3p}{(2\pi)^3}\, f(\mathbf{p},\mu^2)$$

If interactions among particles in the gas are strong enough to maintain them in thermal and chemical equilibrium with each other:

occupation number: $$f(\mathbf{p},\mu^2) = \frac{1}{e^{\beta(E_{\mathbf{p},\mu^2}-\lambda)} \pm 1} \approx e^{-\beta(E_{\mathbf{p},\mu^2}-\lambda)}$$

- Free energy: $$F = \frac{1}{\beta} V \int \frac{d\mu^2}{2\pi}\, \rho(\mu^2) \int \frac{d^3p}{(2\pi)^3} \ln\left(1 - e^{-\beta E_{\mathbf{p},\mu^2}}\right)$$

$$\begin{aligned} u &= \frac{1}{V}\left(\beta \frac{\partial F}{\partial \beta}|_V + F\right) &&= \int \frac{d\mu^2}{2\pi}\, \rho(\mu^2)\, \mathcal{U}(\mu^2) \\ P &= -\frac{\partial F}{\partial V}|_\beta, &&= \int \frac{d\mu^2}{2\pi}\, \rho(\mu^2)\, \mathcal{P}(\mu^2) \end{aligned}$$

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-For T > μ_0 : energy and pressure are dominated by modes with $\mu_0 < \mu < T$, which behave as a relativistic gas

-At T < μ_0, energy and pressure are dominated by modes with $\mu \approx \mu_0$ (with details depending on behavior of spectral density in that region), which behave as a gas of non-relativistic particles. In this regime, the continuum gas can play the role of cold dark matter.

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Equilibrium and Non-equilibrium Thermodynamics

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- Consider a dilute, weakly-coupled gas of “continuum" states, but do not assume that it is in thermal and/or chemical equilibrium

phase-space density is function of time: $f(p,\mu^2,t)$:

Boltzmann equation for toy model with 2 ↔ 2 scattering ($m_{SM} \ll \mu_o$):

$$E_\mu \frac{\partial f(\mathbf{p},\mu^2,t)}{\partial t} = -\frac{1}{2}\int \frac{d\mu'^2}{2\pi}\,\rho(\mu'^2)\int d\Pi_{\mu'}\,d\Pi_A d\Pi_B\,(2\pi)^4\delta^4(k_A+k_B-p-p')$$

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$$\times|\mathcal{M}|^2\,\left(f f'(1\pm f_A)(1\pm f_B) - f_A f_B(1\pm f)(1\pm f')\right),$$

- Generalization to gas in FRW background:

$$E_\mu \frac{\partial f(E,\mu^2,t)}{\partial t} - \quad H|\mathbf{p}|^2\frac{\partial f(E,\mu^2,t)}{\partial E} = -\frac{1}{2}\int \frac{d\mu'^2}{2\pi}\,\rho(\mu'^2)\int d\Pi_{\mu'}\, d\Pi_A d\Pi_B$$

$$\times(2\pi)^4\delta^4(k_A+k_B-p-p')\,|\mathcal{M}|^2\,\left(f f' - f_A f_B\right).$$

$H = \dot{a}/a$ is the Hubble, $|\mathbf{p}|^2 = E^2-\mu^2$;

Freeze-Out of Gapped Continuum DM

- **Evolution of DM number density**

(Integrating both sides of the Boltzmann equation)

$$\frac{\partial n}{\partial t} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{\rm eq}^2)$$

identical to that of the usual particle cold relic!

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$\longrightarrow$ can use the usual formula for relic density

continuum physics

$$\langle \sigma v \rangle = \frac{1}{n_{\rm eq}^2} \int \frac{d\mu^2}{2\pi} \rho(\mu^2) \int \frac{d\mu'^2}{2\pi} \rho(\mu'^2) \int d\Pi_{\mathbf{p}}^{\mu^2} \, d\Pi_{\mathbf{p}'}^{\mu'^2} \, d\Pi_A d\Pi_B$$
$$\times (2\pi)^4 \delta^4(k_A + k_B - p - p') \, |\mathcal{M}|^2 \, \exp\left(-\beta(E_A + E_B)\right) \, .$$

Freeze-Out of Gapped Continuum DM

$m_{SM} \ll \mu_0$

annihilation: DM+DM ↔ SM+SM

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

T

sufficiently strong coupling between the SM and DM

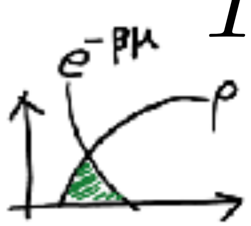
$T > \mu_0$

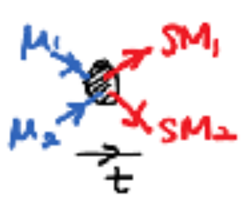
annihilation is in equilibrium, DM particles are at the same temperature T as the SM and is at zero chemical potential

DM remains in equilibrium and do not freeze out

mass gap

$T = \mu_0$





$T \lesssim \mu_0$

annihilation rate drops exponentially, and annihilations decouple

"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)

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  - Add another complex scalar field χ which is a doublet under $SU(2)_L$ and carries $U(1)_Y$ charge $-1/2$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_\Phi + \mathcal{L}_\chi + \mathcal{L}_{\rm int}$$

$$\mathcal{L}_\Phi = \Phi^\dagger(p)\Sigma(p^2)\Phi(p)$$

$$\mathcal{L}_\chi = (D_\mu\chi)^\dagger (D^\mu\chi) - m_\chi^2\chi^\dagger\chi$$

$$\mathcal{L}_{\rm int} = -\lambda\Phi\,\chi H + \text{c.c.}$$

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

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

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

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

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

Dark Matter Continuum Spectral Density from 5D Model

- **Warped 5D model**
  - Scalar gapped continuum: $$\mathcal{L} = \sqrt{g}\left[\frac{1}{2}g^{MN}D_M\Phi^\dagger D_N\Phi - V(\Phi)\right]$$

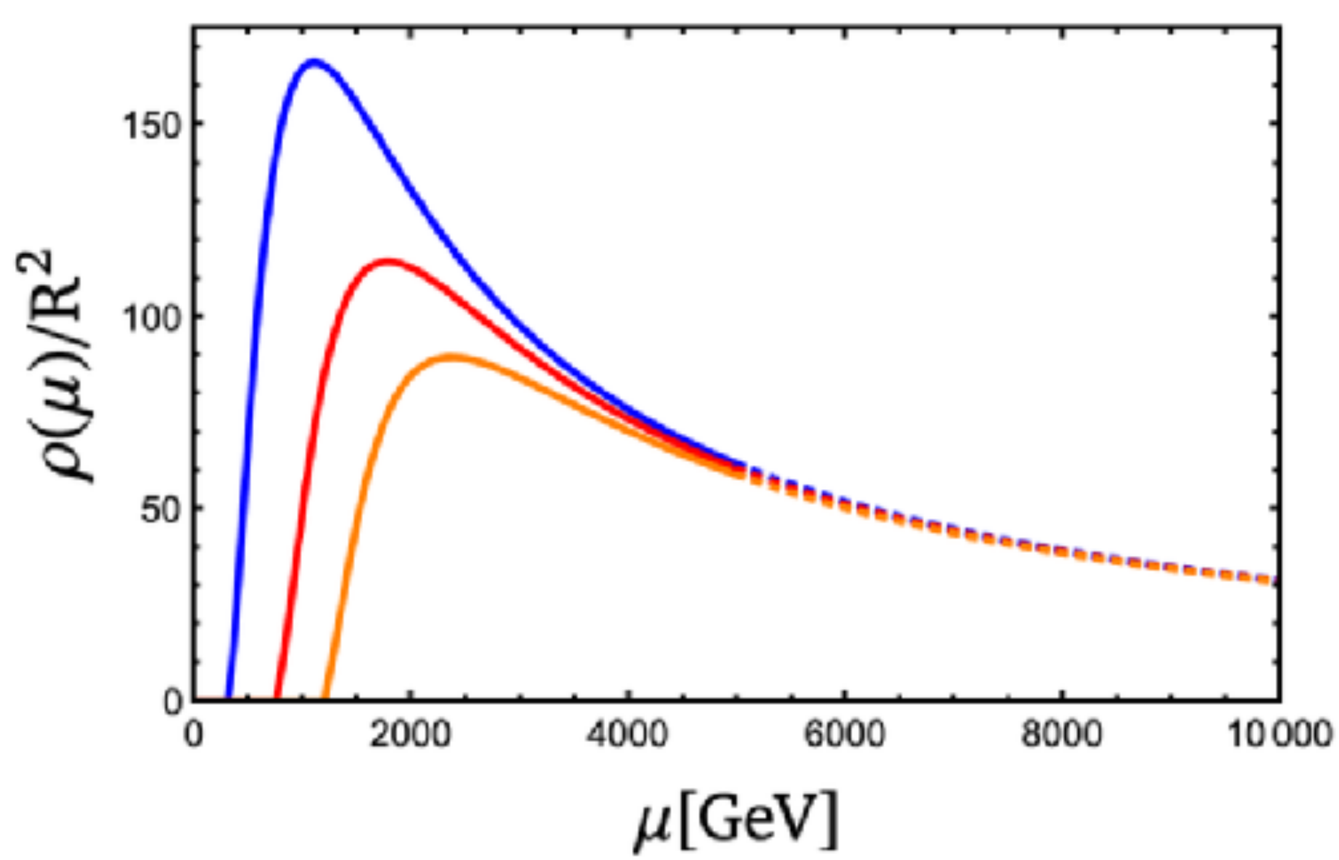
In conformally flat coordinate, Schrödinger form of eom: $\psi = e^{-\frac{3}{2}A}\Phi$

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

$$V(z) = \frac{3}{4y_s^2}e^{-2ky}\left(5k^2(y-y_s)^2 - 10k(y-y_s) + 3\right)$$

$$G(R,R;p) = \left(\frac{\Phi'(R,p)}{\Phi(R,p)}\right)^{-1}$$

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



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

$$\rho(p) = \frac{1}{\pi}\mathrm{Im}\,G(R,R;p). \quad \rightarrow \quad \boxed{\rho(\mu^2) \propto \left(\frac{\mu^2}{\mu_0^2} - 1\right)^{1/2}}$$

Dark Matter Continuum Spectral Density from 5D Model

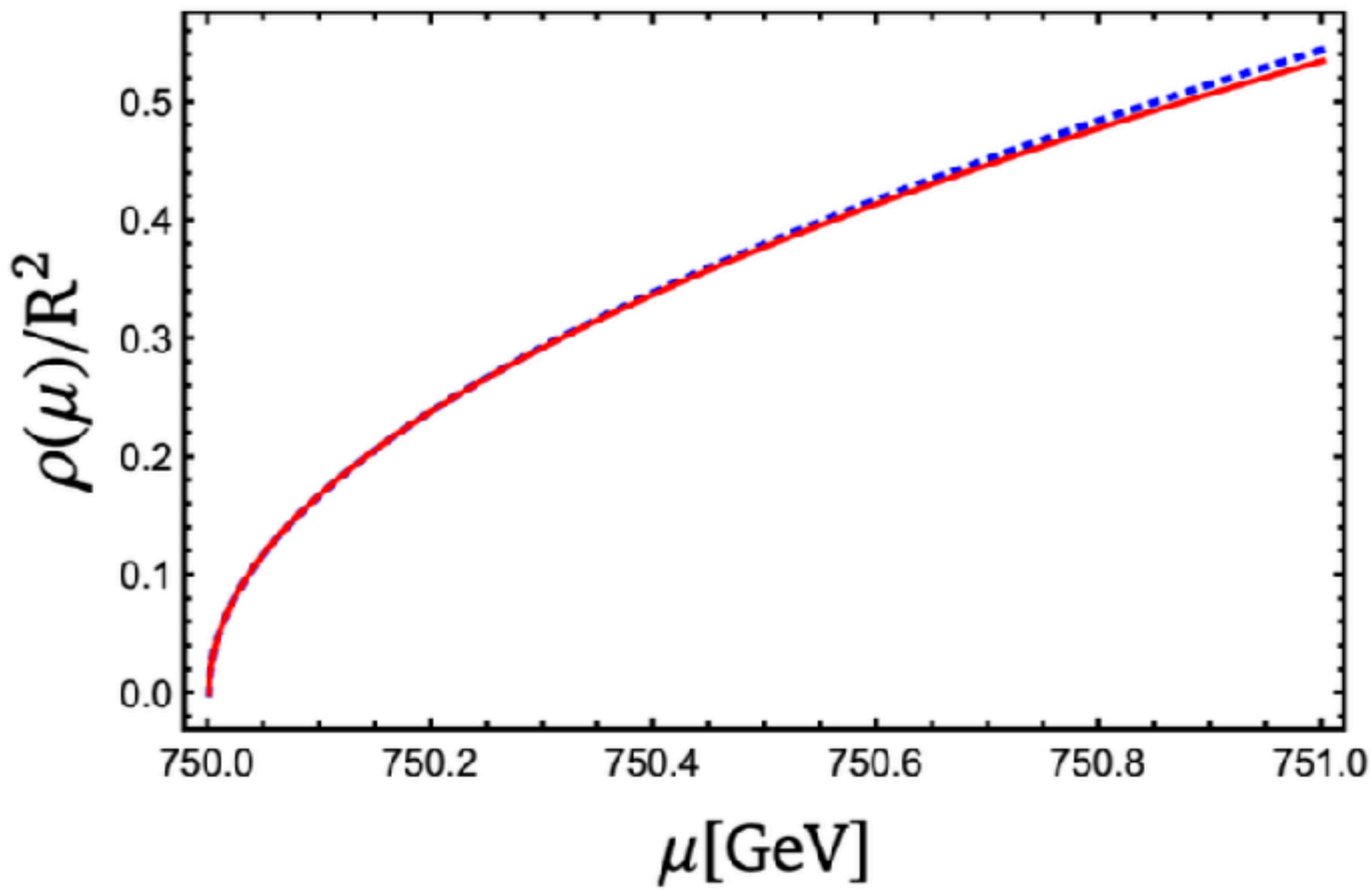
♦ Warped 5D r

- Scalar gap

In conformally

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

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



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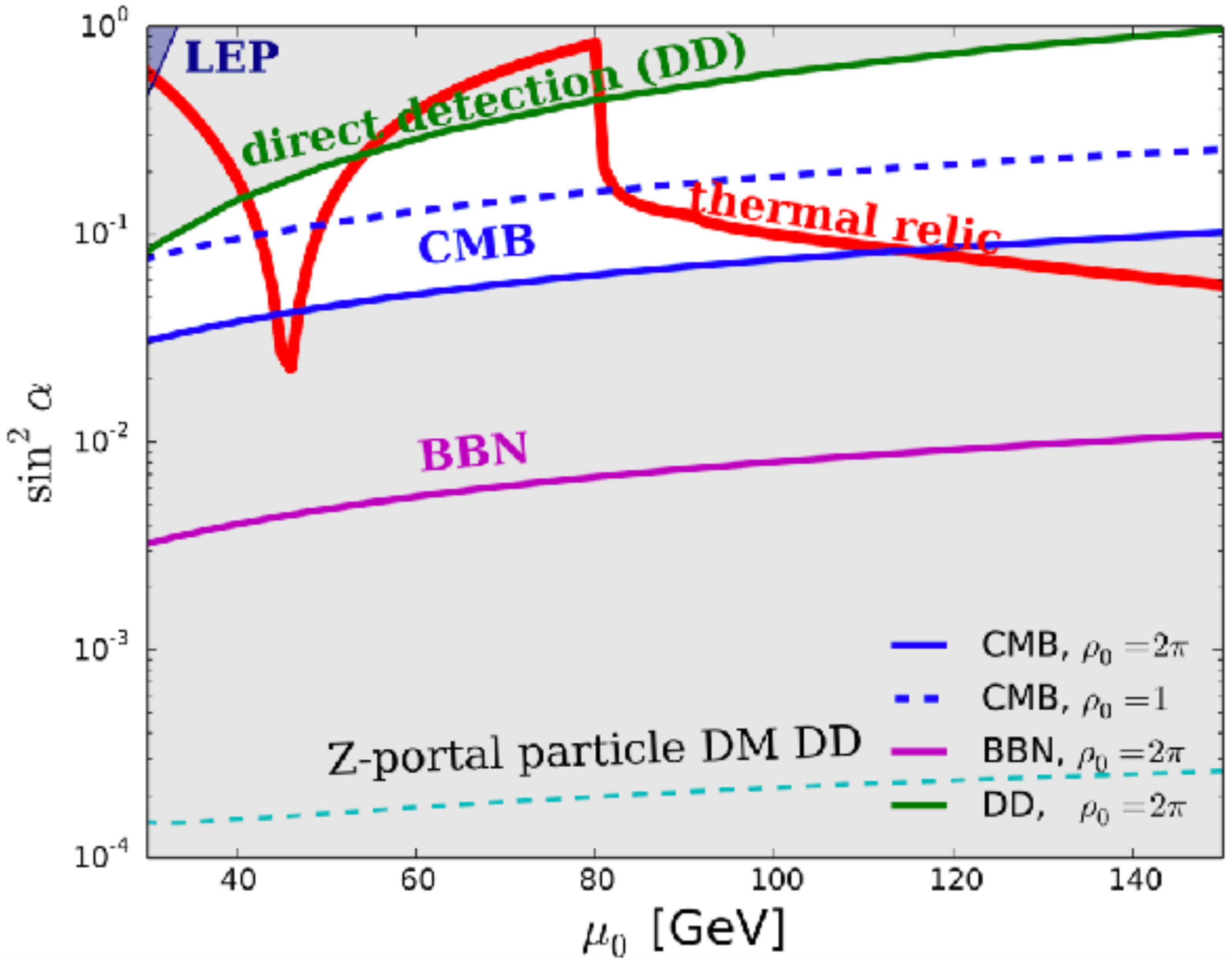
Gapped Continuum Z-portal DM

♦ 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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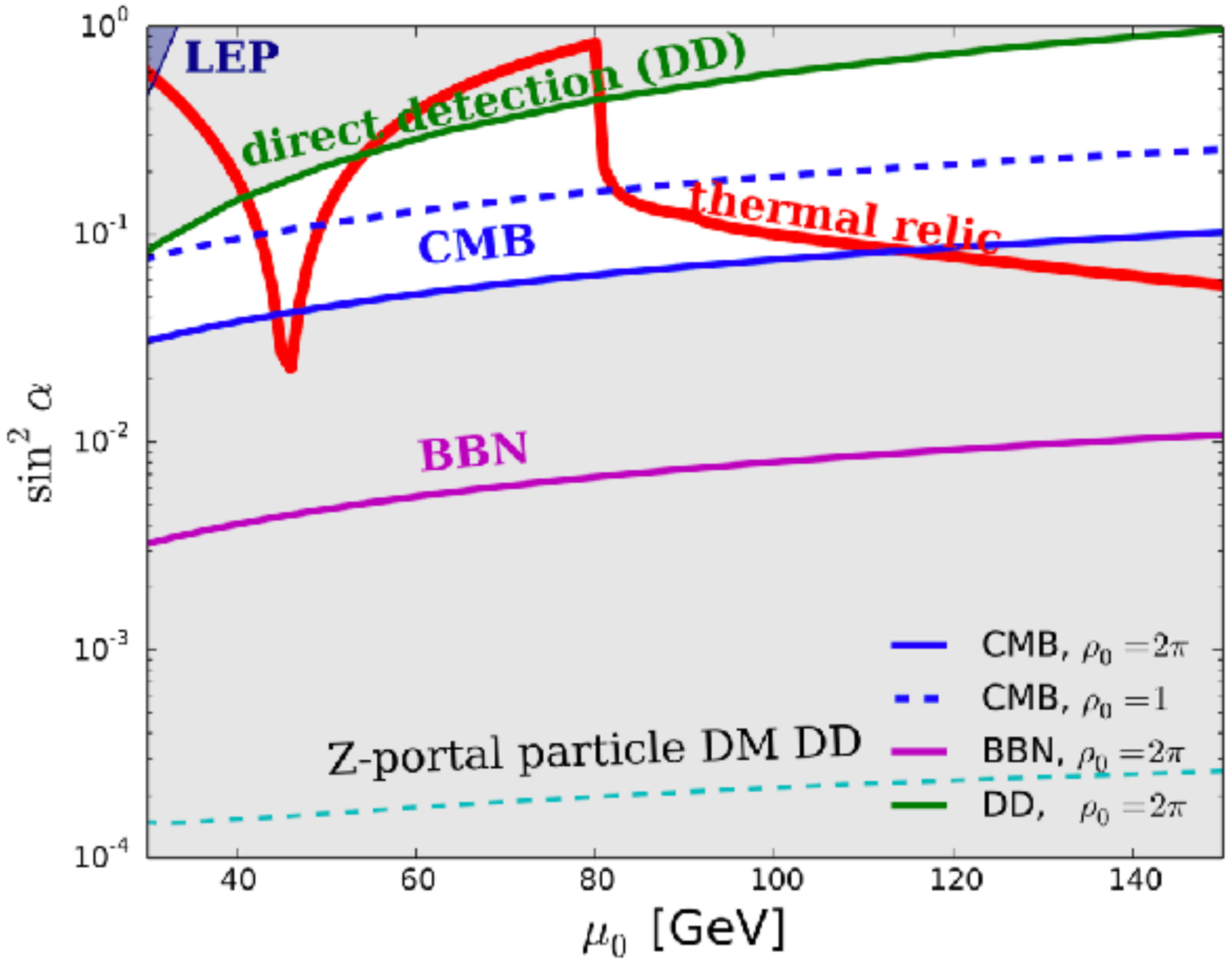
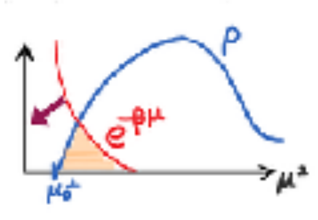
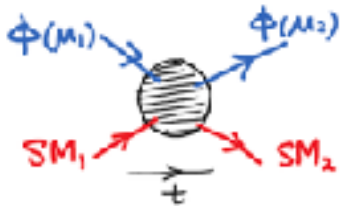


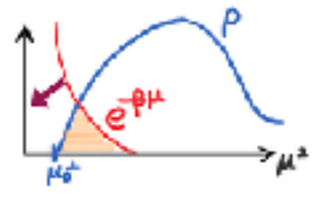
The salient feature of the gapped continuum DM: there is a generic rate suppression, which makes it compatible with the current null result of direct detection experiments.



Gapped Continuum Nature of DM



- **Direct detection**
  - quasi elastic scattering (QES): DM(μ_1) + $SM_1 \rightarrow$ DM(μ_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~10^{-3})



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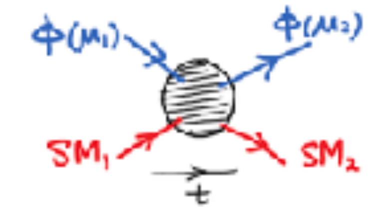

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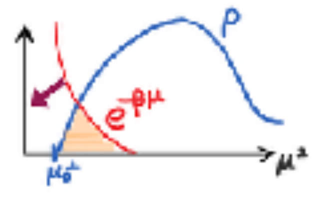
=> If incoming DM state has $\mu_1 = \mu_0 + \Delta$, accessible final continuum modes are in very narrow window $\mu_2 \in [\mu_0, \mu_0+\Delta+Q]$. For weak scale μ_0, this basically means that the integral appearing in the QES cross section is constrained to a tiny interval in μ, and leads to a significant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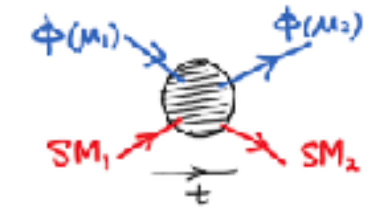

♦ Direct detection

- quasi elastic scatter
  - even after freez
    distribution is p … e
    decays are imp … ough
    the earth with n

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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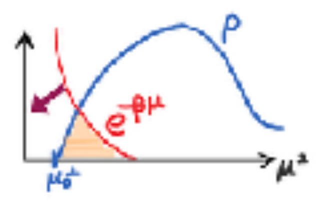

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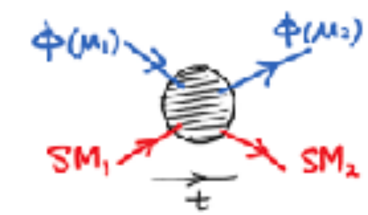

- Direct detection
  - quasi elastic sca
    - even after f
      distribution
      decays are i
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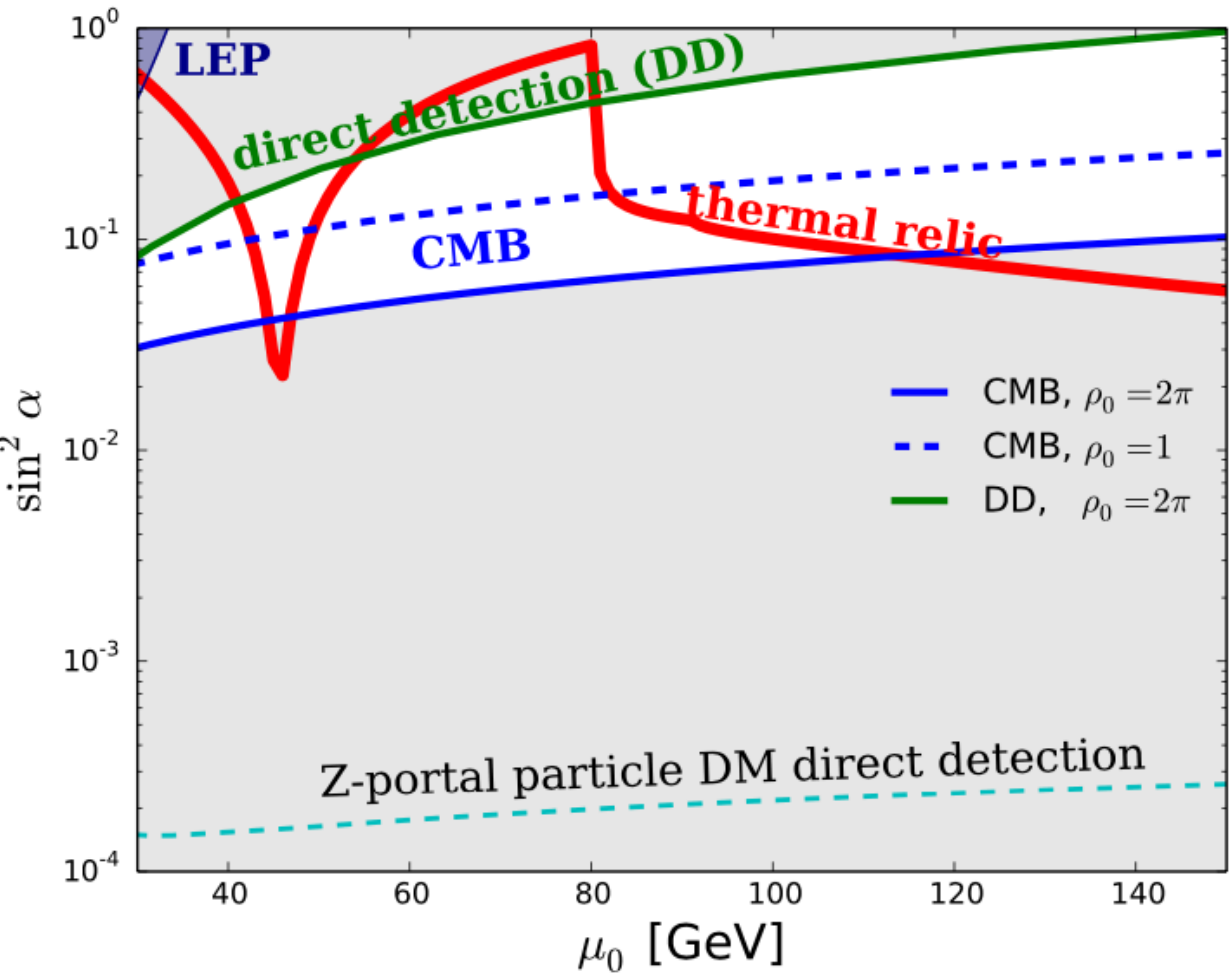

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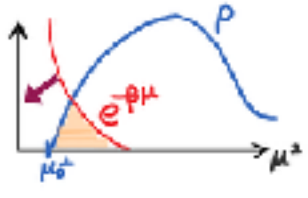

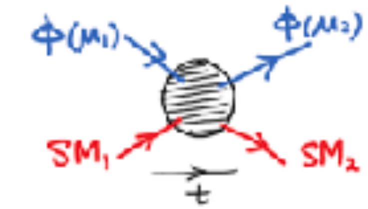

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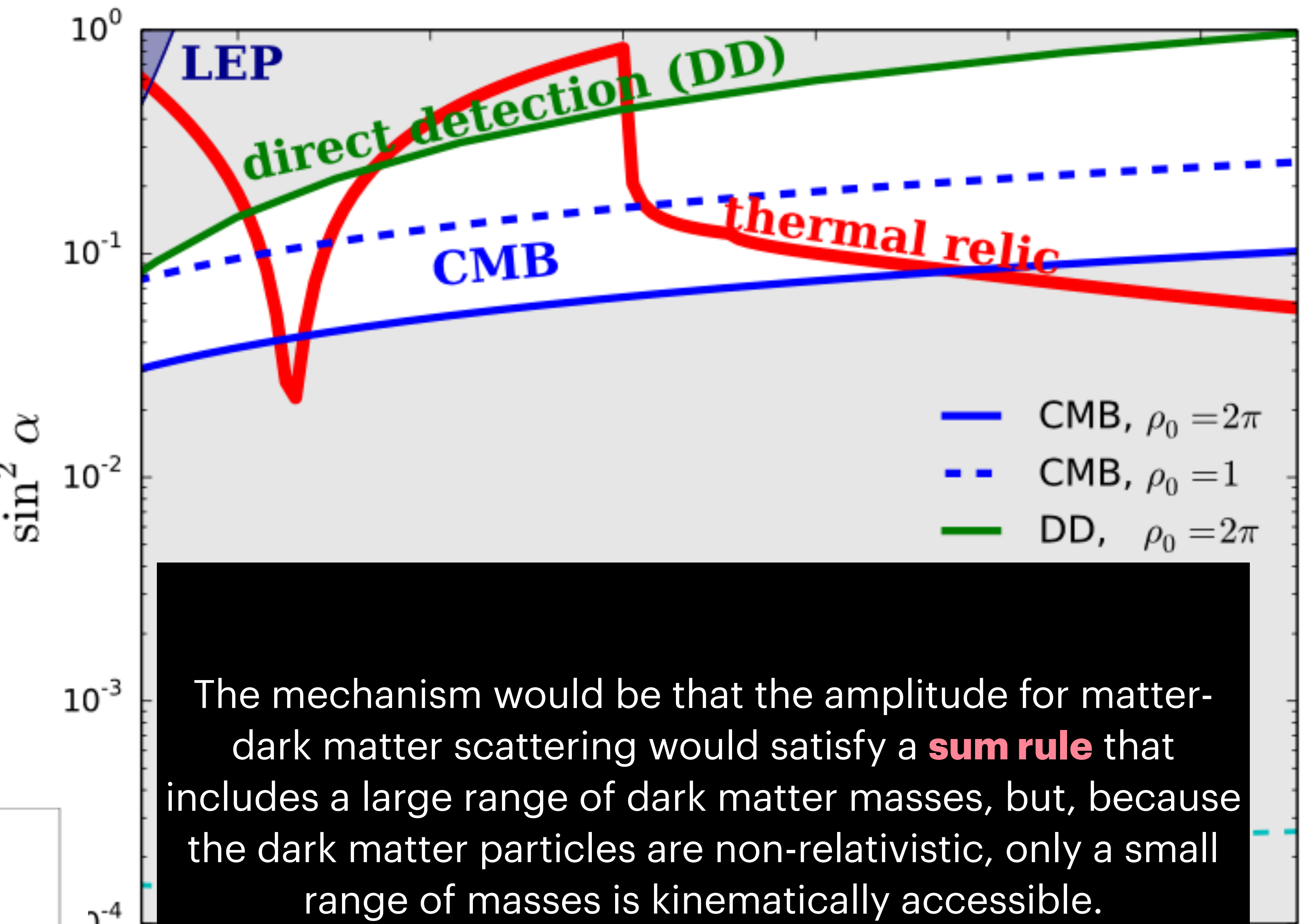
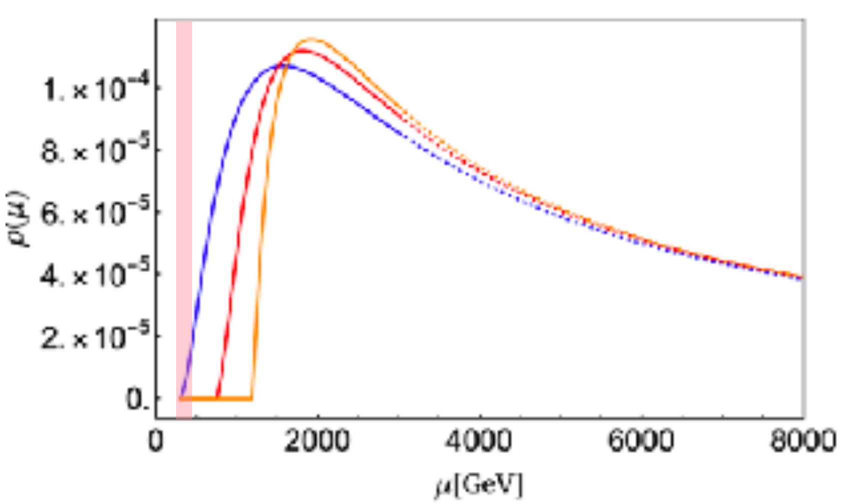


The mechanism would be that the amplitude for matter-dark matter scattering would satisfy a **sum rule** that includes a large range of dark matter masses, but, because the dark matter particles are non-relativistic, only a small range of masses is kinematically accessible.



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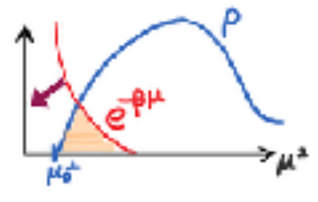
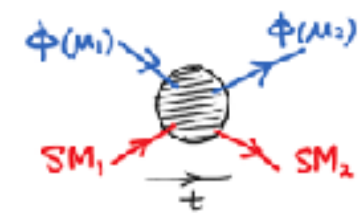


Gapped Continuum Nature of DM



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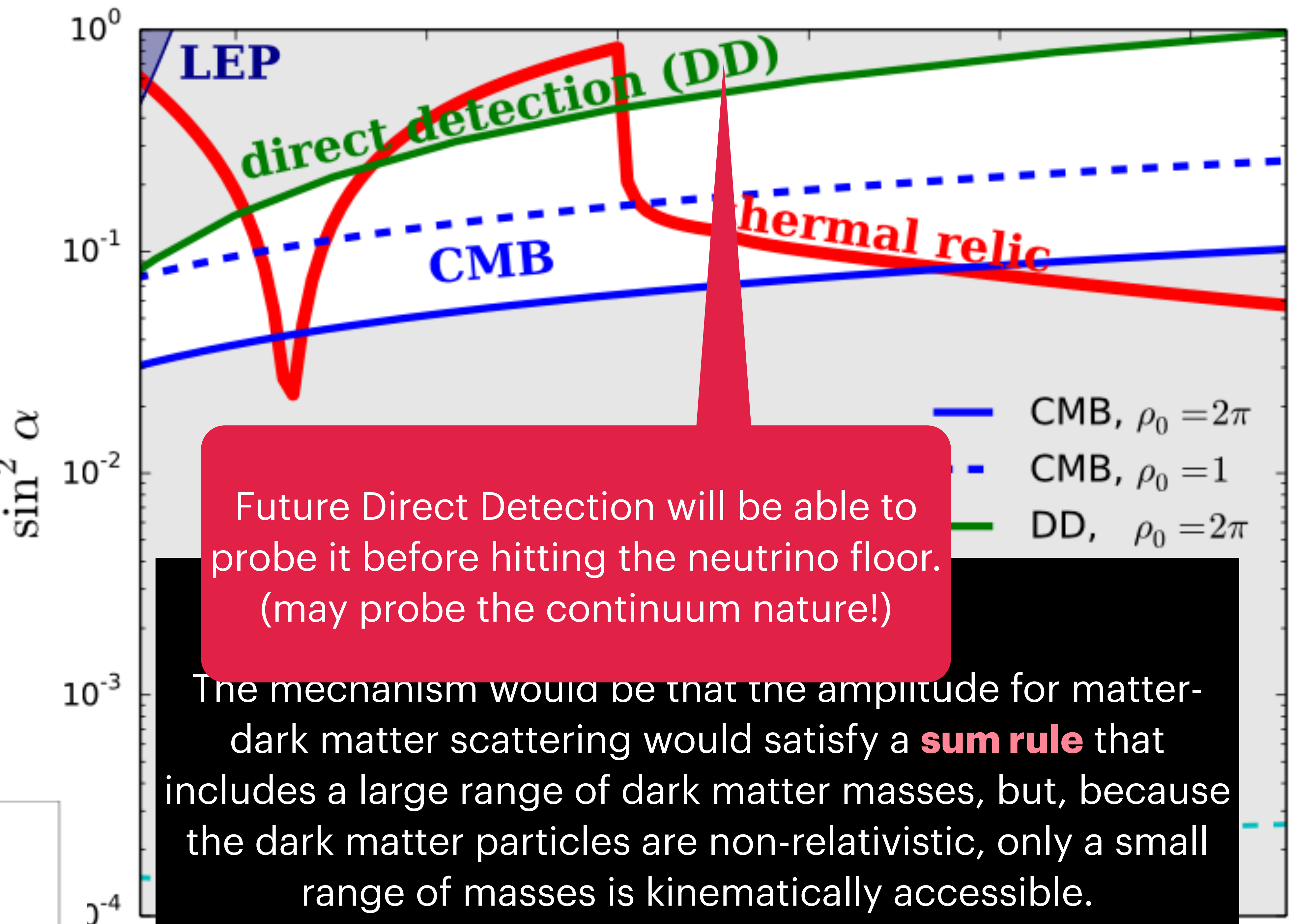

Future Direct Detection will be able to probe it before hitting the neutrino floor. (may probe the continuum nature!)

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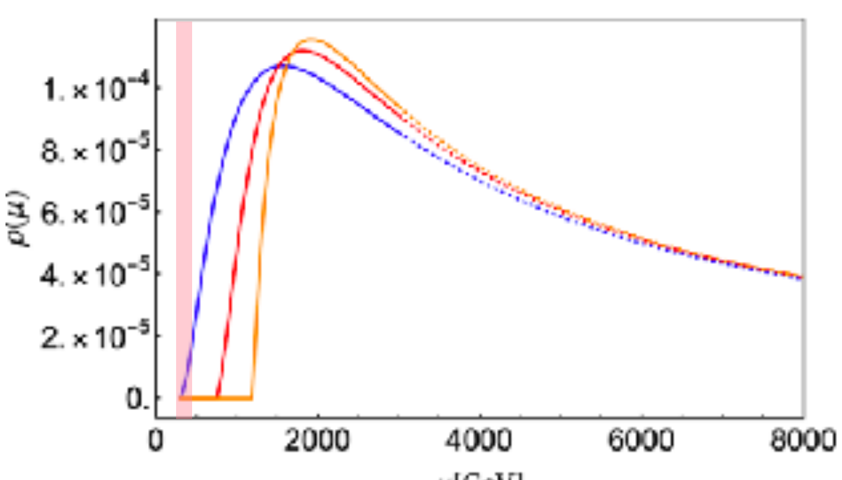

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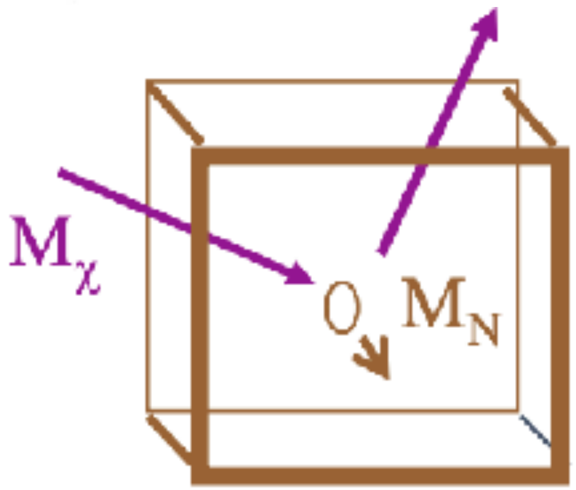
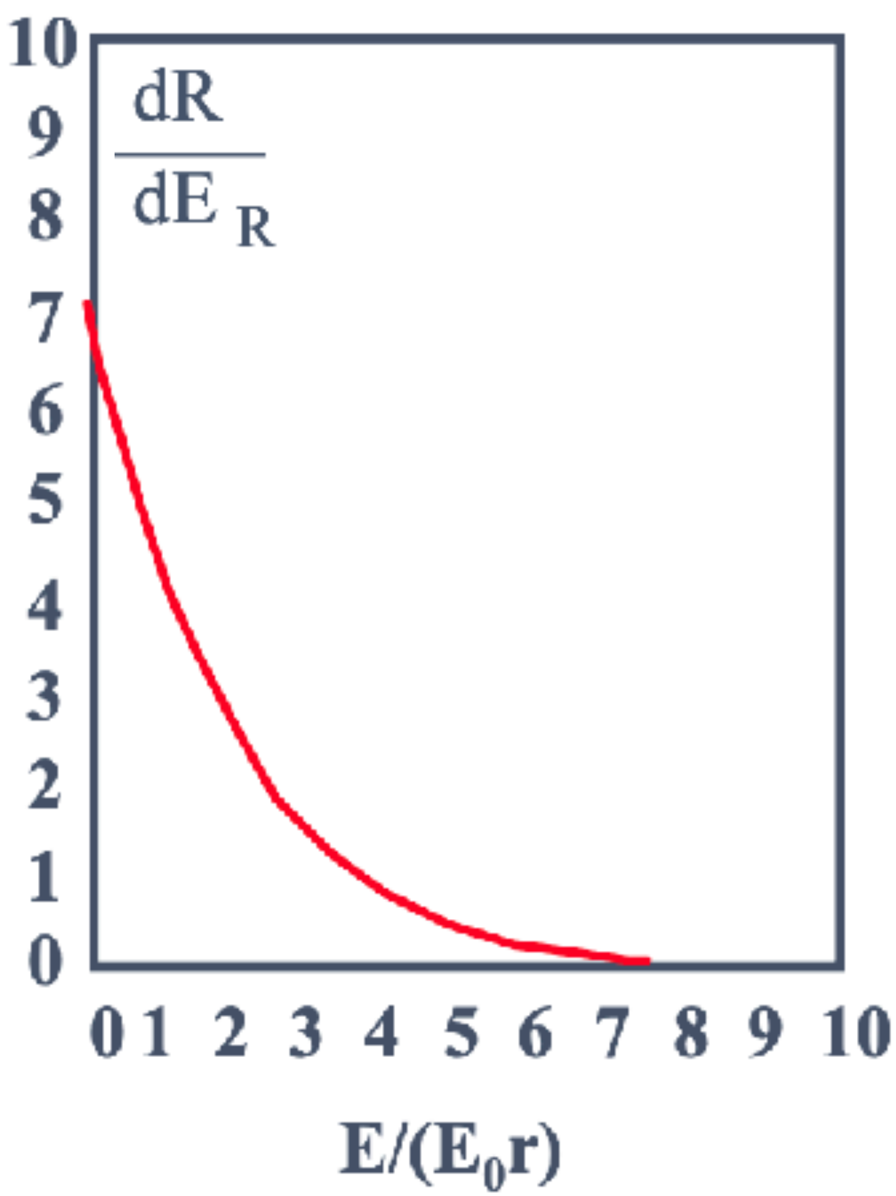
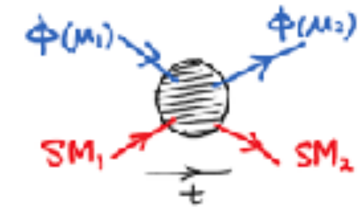
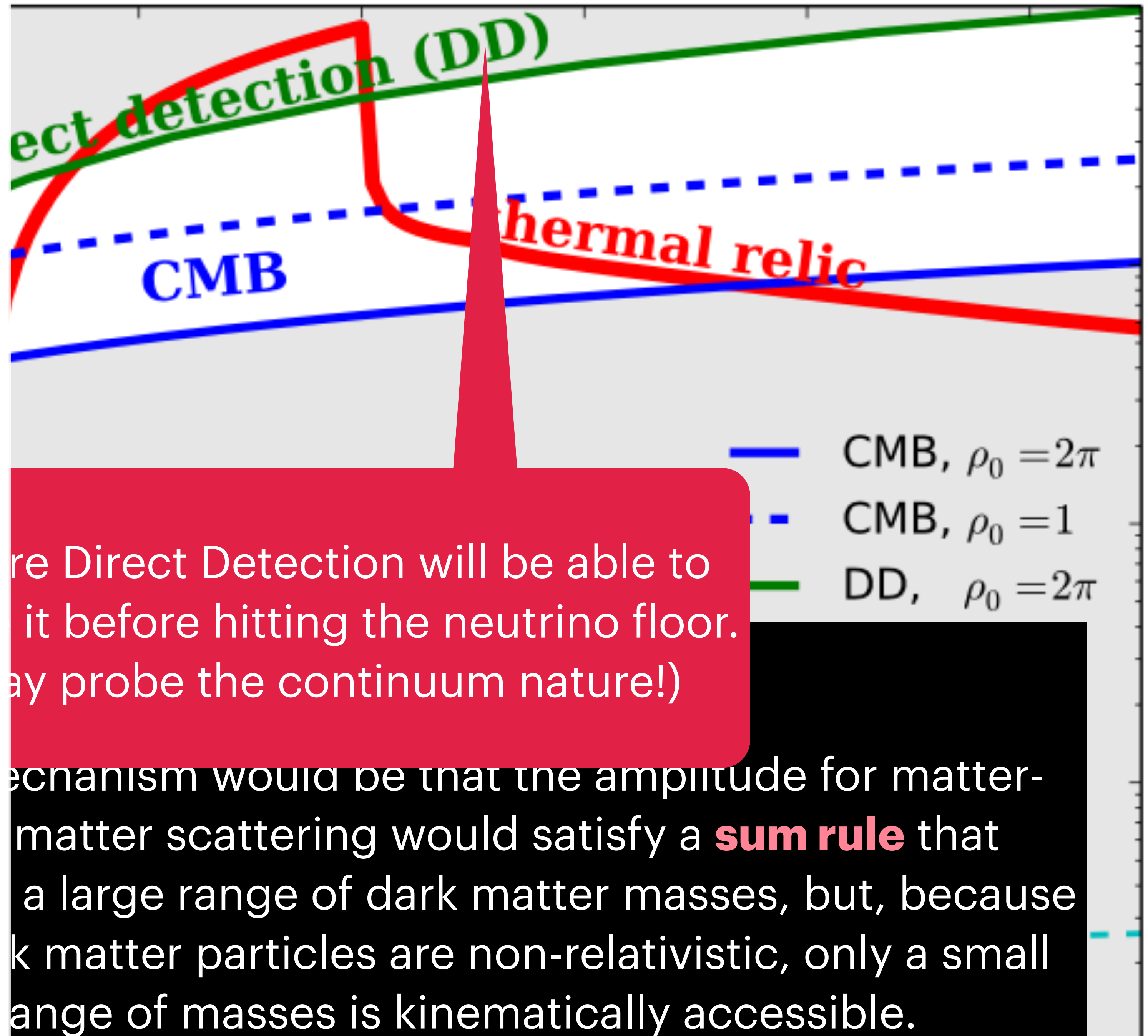


Ge, Si, NaI, LXe, …



uum Nature of DM





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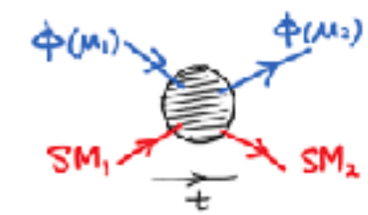

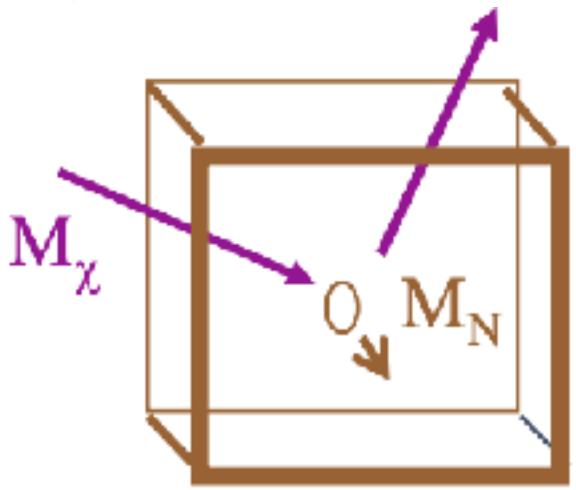

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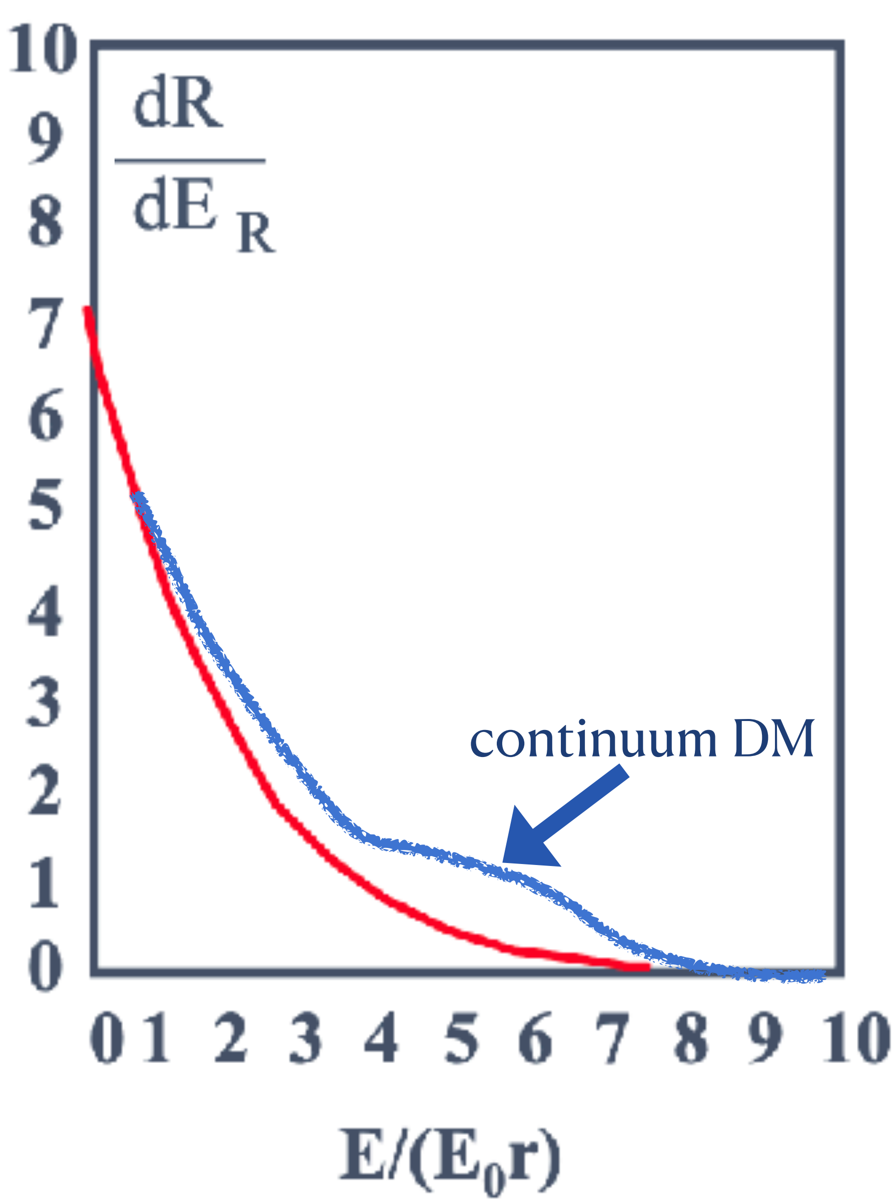

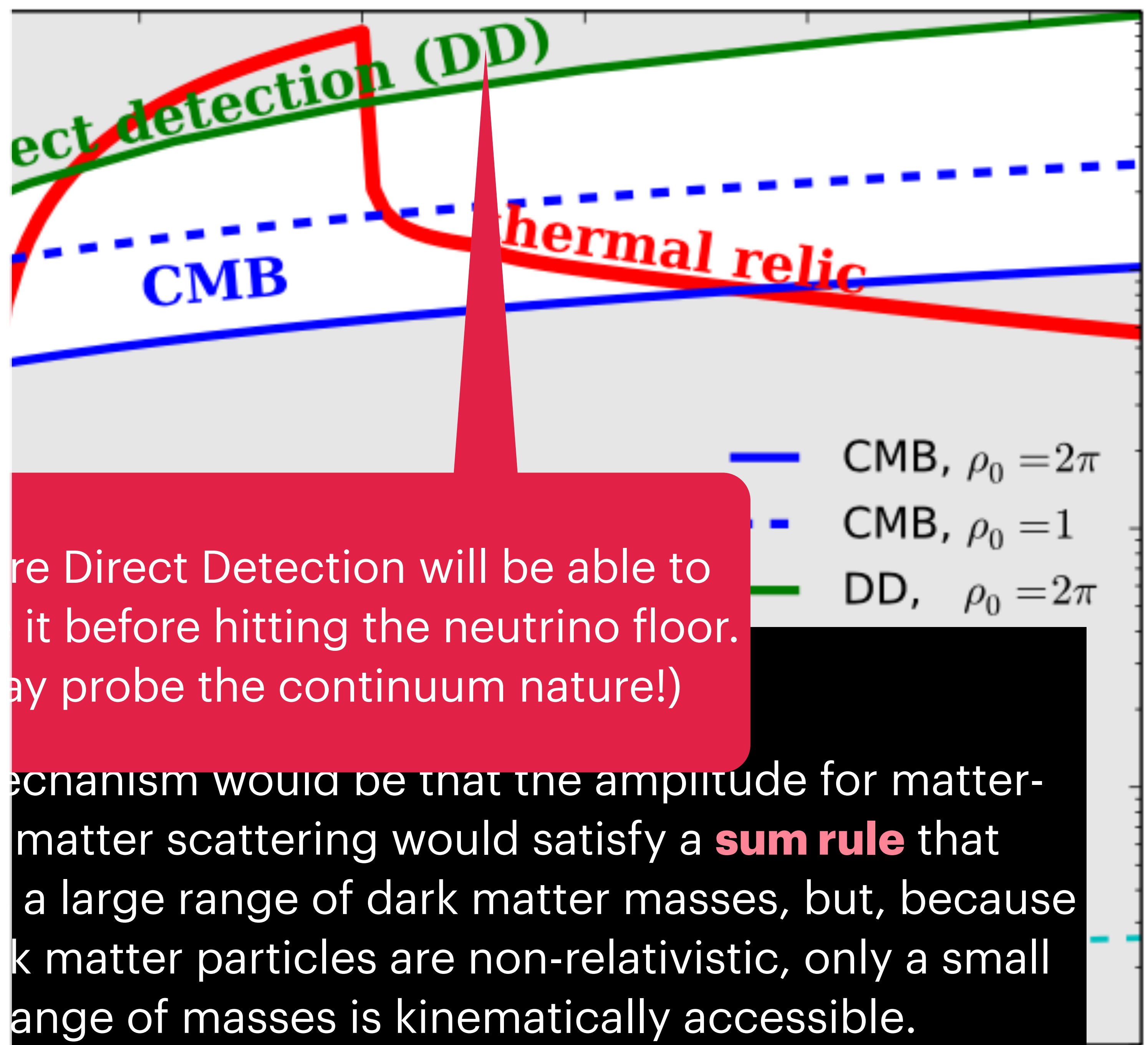

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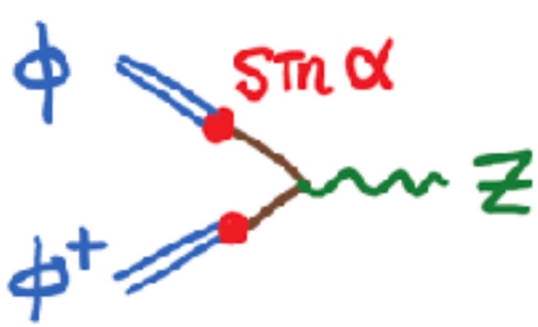
  - for low energy experiments (low compared to gap scale): e.g. LEP bound for Z-portal WIC:

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



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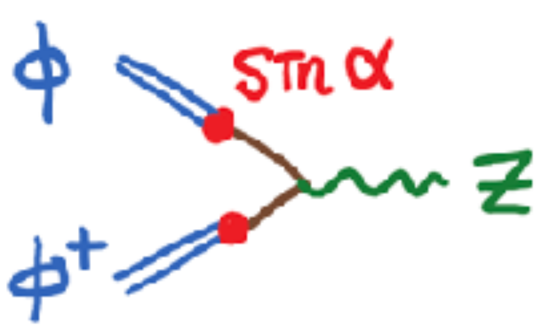
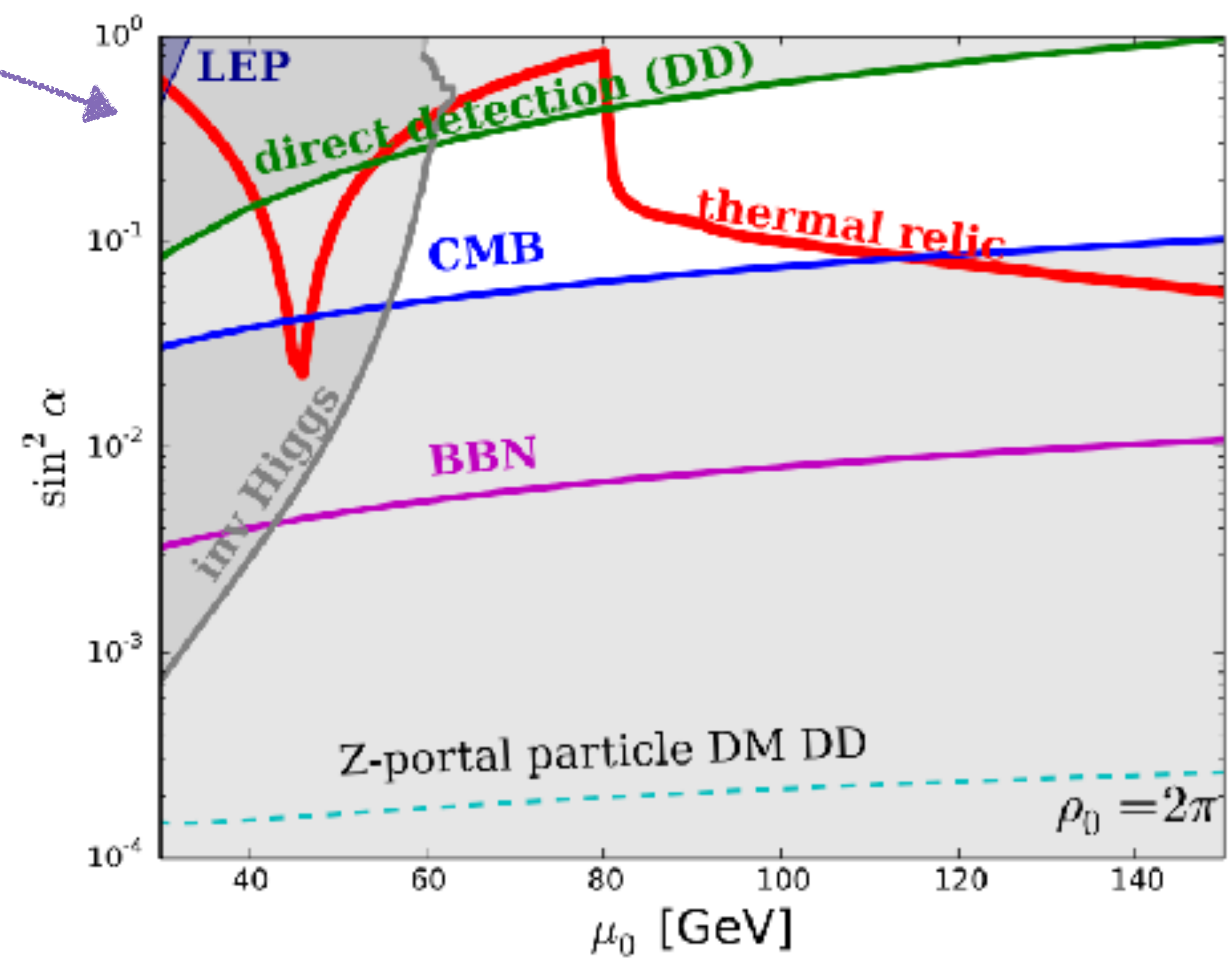


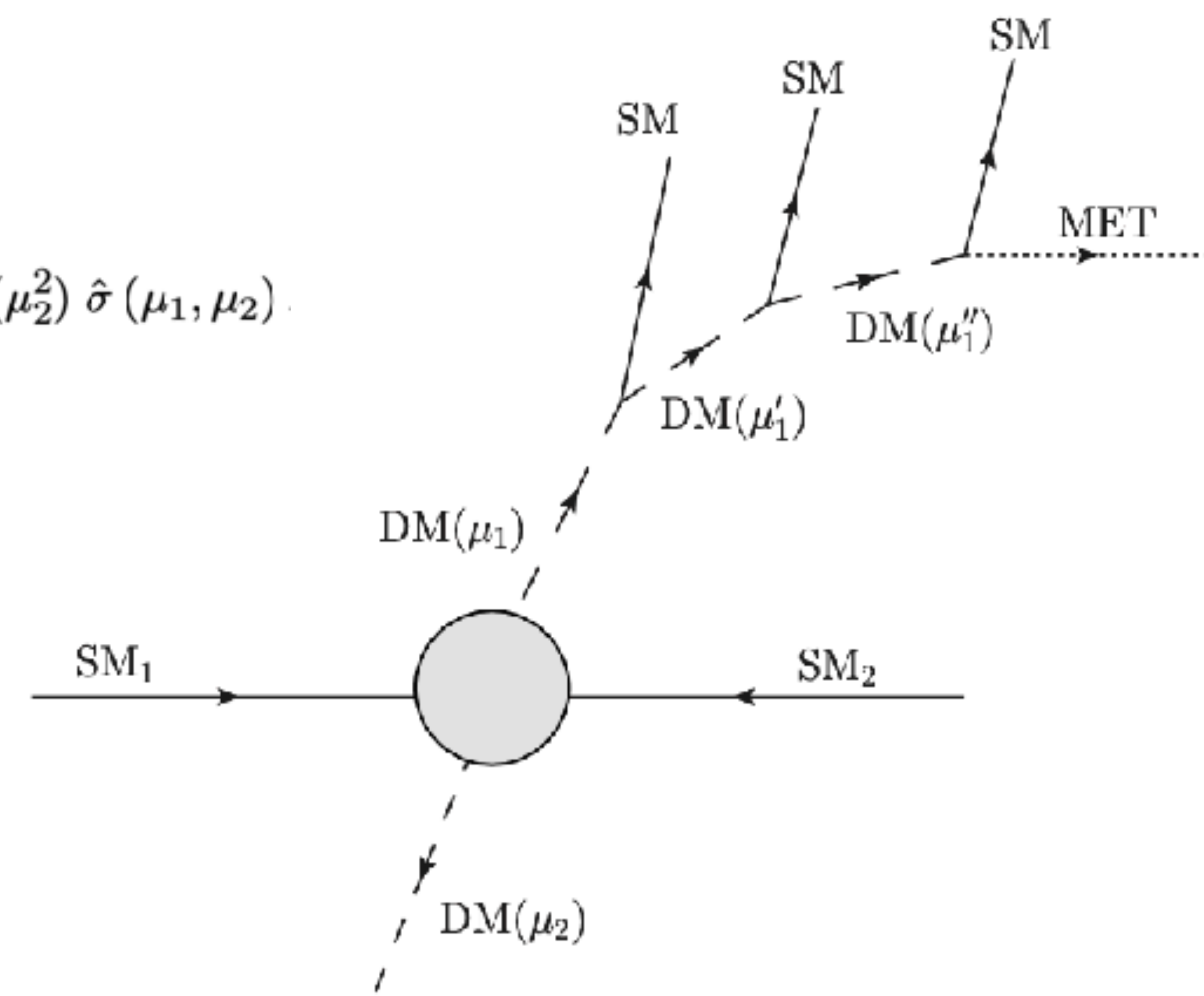


Gapped Continuum Nature of DM

♦ Colliders Phenomenology with S. Ferrante & M. Perelstein

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

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



Gapped Continuum Nature of DM

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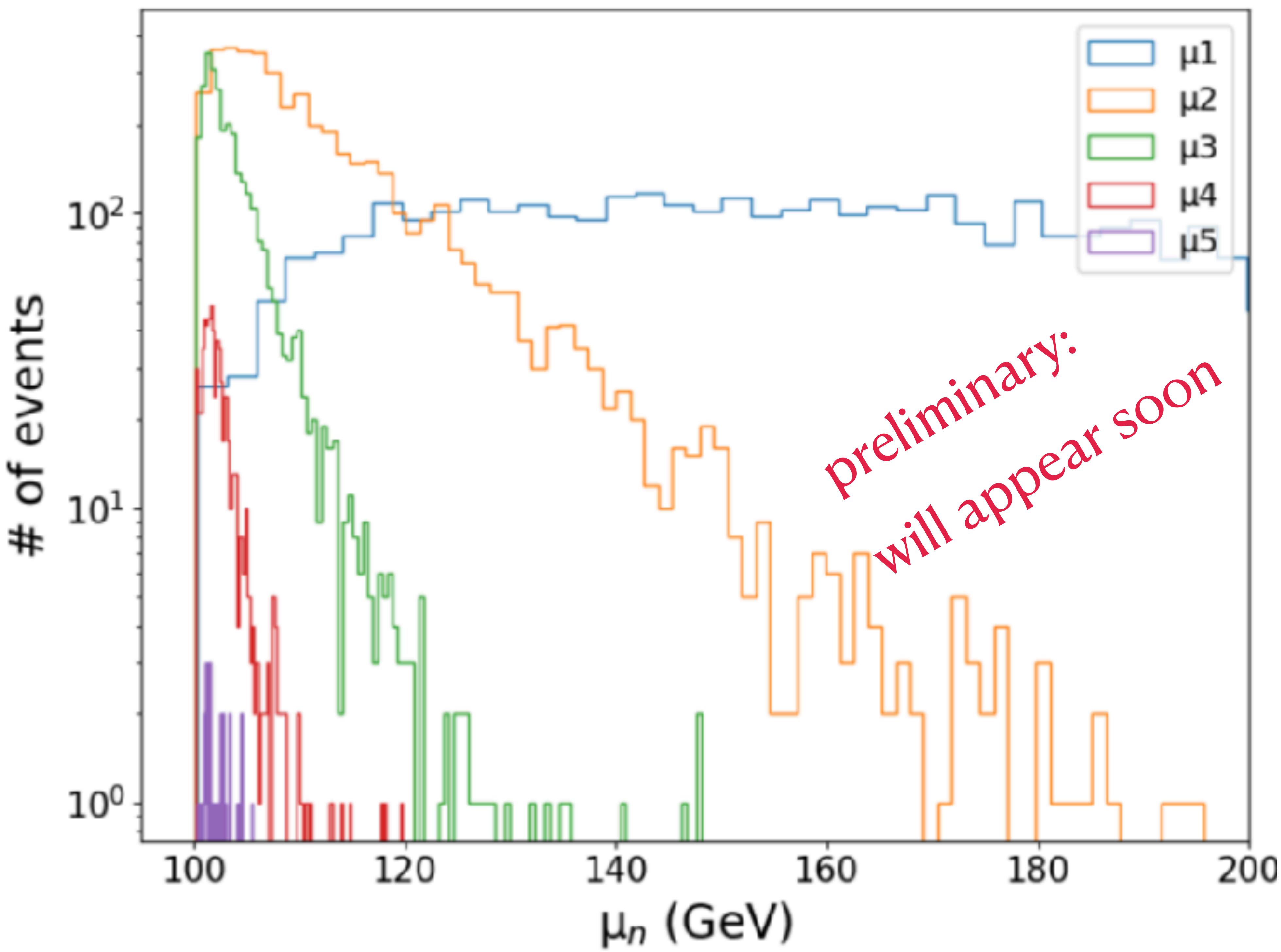
for l
SM1

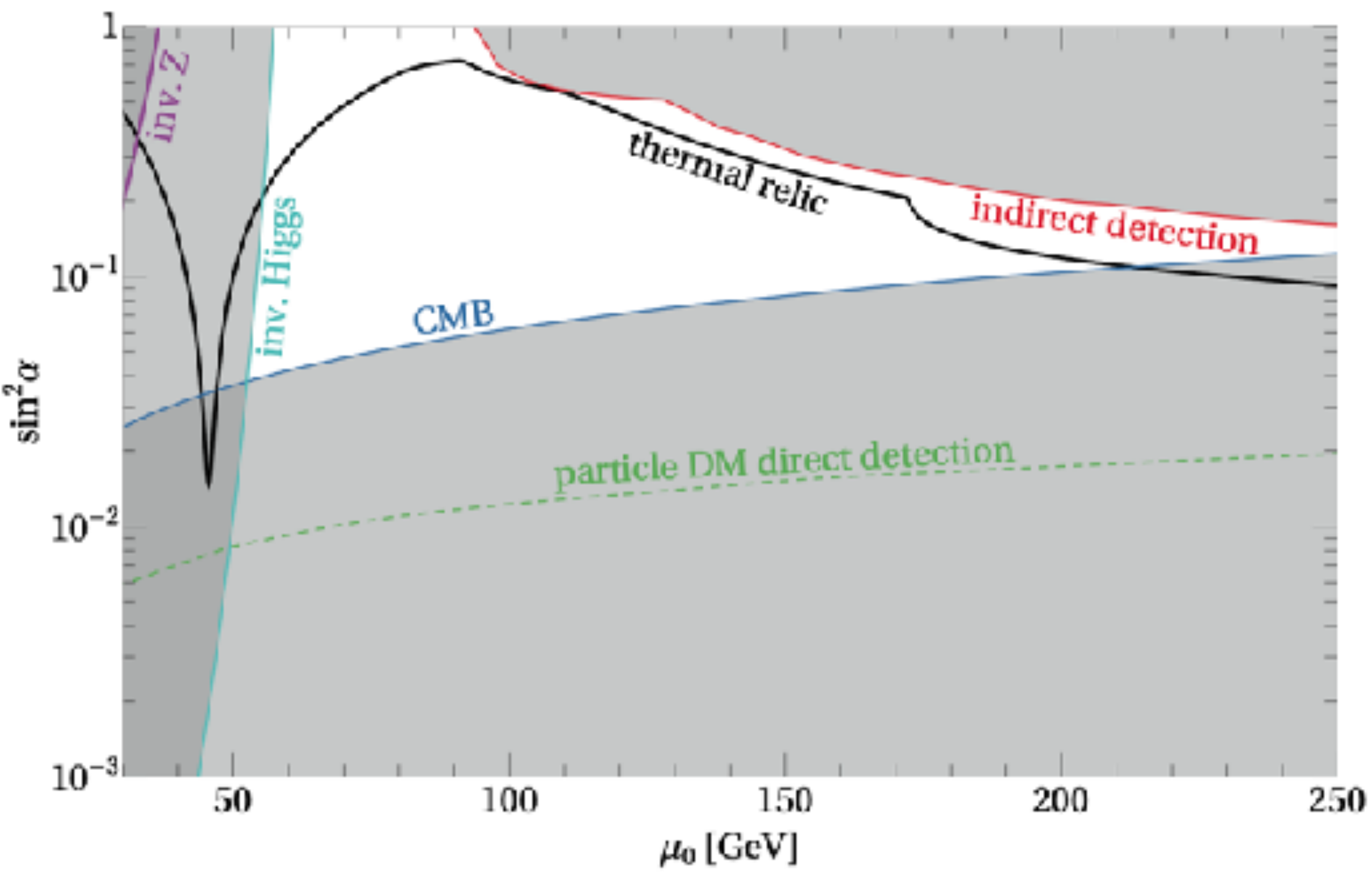
$\sigma \sim \int$

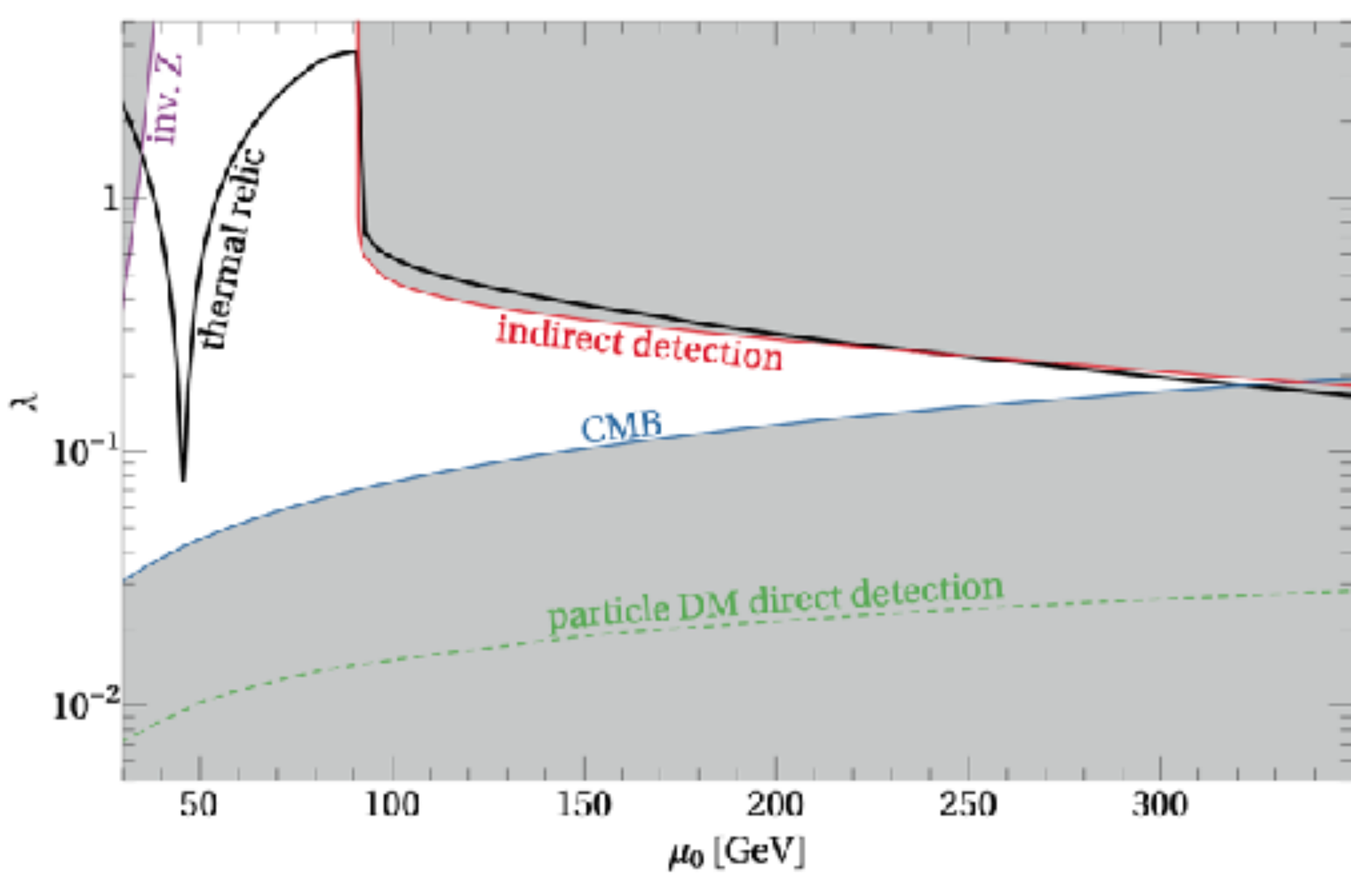


Gapped Continuum Nature of DM

with C. Csaki & A. Ismail

- Other DM candidates: fermions, vectors





$$\mathcal{L}_\psi = i\overline{\psi}_L \Sigma(p^2)\overline{\sigma}^\mu p_\mu \psi_L$$

$$\mathcal{L}_\chi = i\overline{\chi}_L \overline{\sigma}^\mu D_\mu \chi_L + i\overline{\chi}_R \sigma^\mu D_\mu \chi_R - M(\overline{\chi}_L \chi_R + \overline{\chi}_R \chi_L)$$

$$\mathcal{L}_{\text{int}} = -\kappa \overline{\chi}_R \psi_L H.$$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_\psi - \frac{g_Z \sin^2\alpha}{2} \overline{\psi}_L \not{Z} \psi_L.$$

$$\sin\alpha = \frac{\kappa v}{\sqrt{2}M}$$

$$\mathcal{L}_V = \frac{1}{2} V_\mu(p) \Sigma(p^2) \left[\eta^{\mu\nu} - (1 - \frac{1}{\xi})\right] V_\nu(p)$$

$$\mathcal{L}_{\text{int}} = \frac{g_Z \lambda}{4} \epsilon^{\mu\nu\rho\sigma} V_\mu Z_\nu V_{\rho\sigma}$$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_V + \mathcal{L}_{\text{int}}.$$

Summary

Happy
60th
Birthday!

1. Everything is EFT (my first lesson learned from Matthias)
2. Gapped Continuum DM = theoretically and phenomenologically motivating!
3. A gapped continuum arises naturally near the quantum critical point. We model DM as a continuum 5-dimensional field coupled to the SM particles on the brane in the soft-wall model
4. Revival of Weakly Interacting Massive Continuum (WIC) !
5. Many possible models + many detailed pheno study to be done.
6. Continuum Phenomenology = totally new → needs a systematic investigations
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Summary

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Happy 10th Birthday! MITP

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Danke Sehen!