Continuum Dark Matter

Wei Xue

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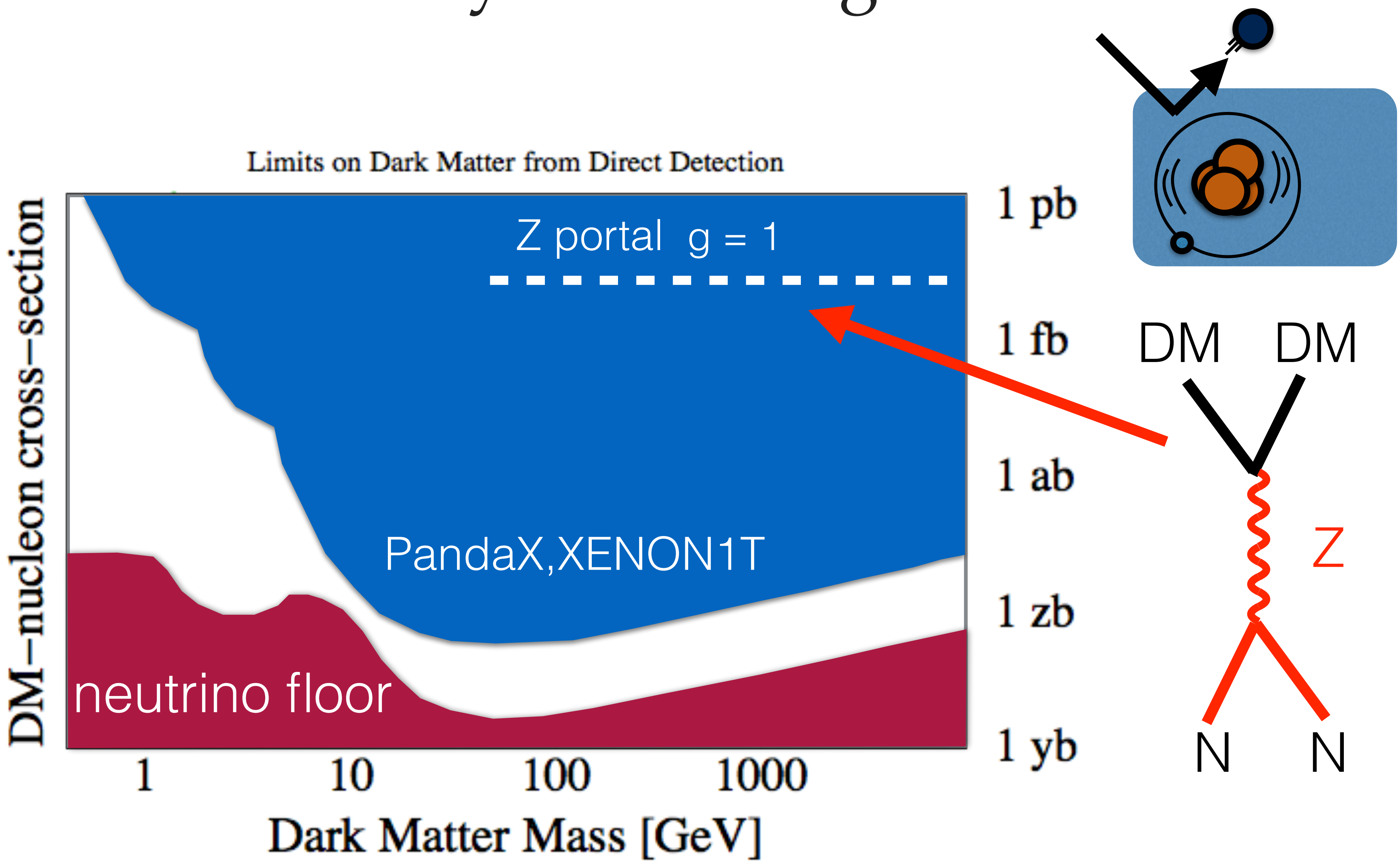
seminar at TD Lee Institute

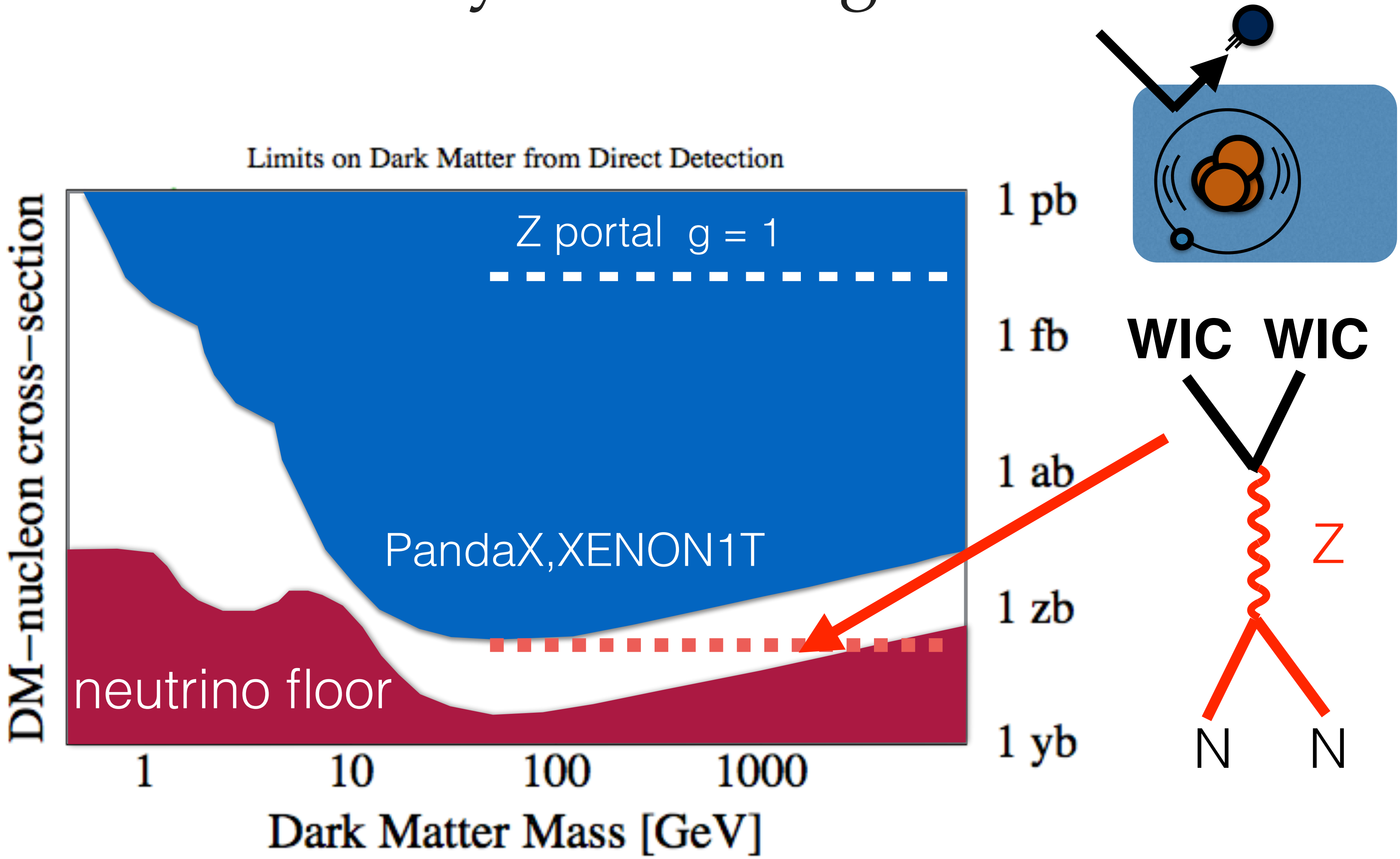
based on works with
Csaba Csaki, Sungwoo Hong, Gowri Kurup, Seung Lee, and Maxim Perelstein

UF UNIVERSITY of FLORIDA

WIMP and Weakly Interacting Continuum

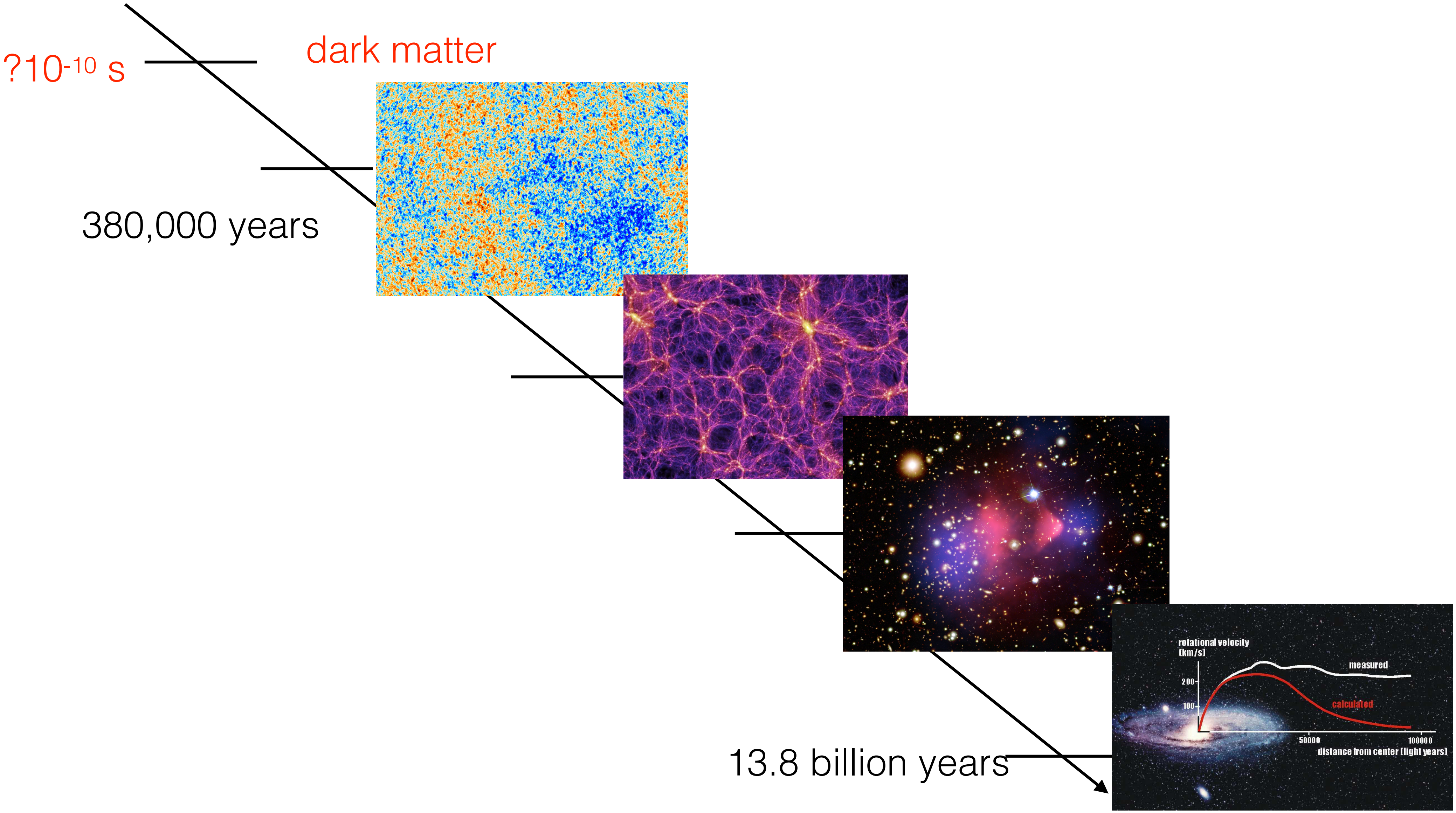


WIMP and Weakly Interacting Continuum

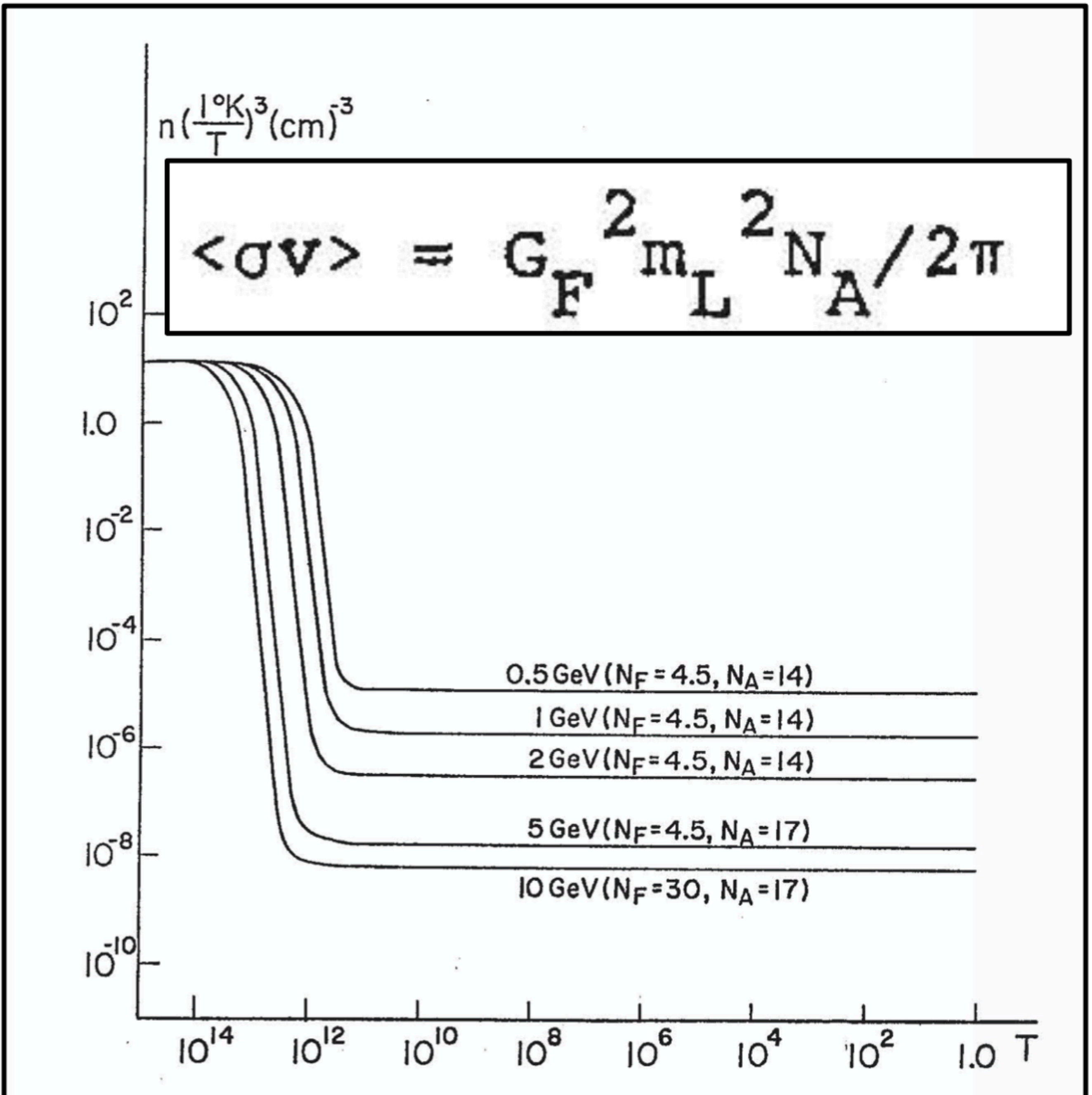


Outline

- Physics of continuum states — arXiv: 2105.07035
- Z-portal Weakly Interacting Continuum (WIC) — arXiv: 2105.14023
- Summary and outlook


?10-10 s
dark matter
380,000 years
rotational velocity [km/s]
200
100
measured
calculated
50000
100000
distance from center [light years]
13.8 billion years

e



$$\langle \sigma v \rangle = G_F^{\,2} m_L^{\,2} N_A / 2\pi$$

FIG. 1

Operated by Universities Research Association Inc. under contract with the Energy Research and Development Administration

Ben Lee (1935 — June 1977)

Steven Weinberg (1933— July 2021)

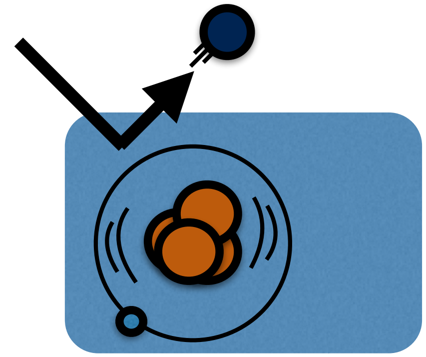
Weakly Interaction Dark Matter (WIMP)

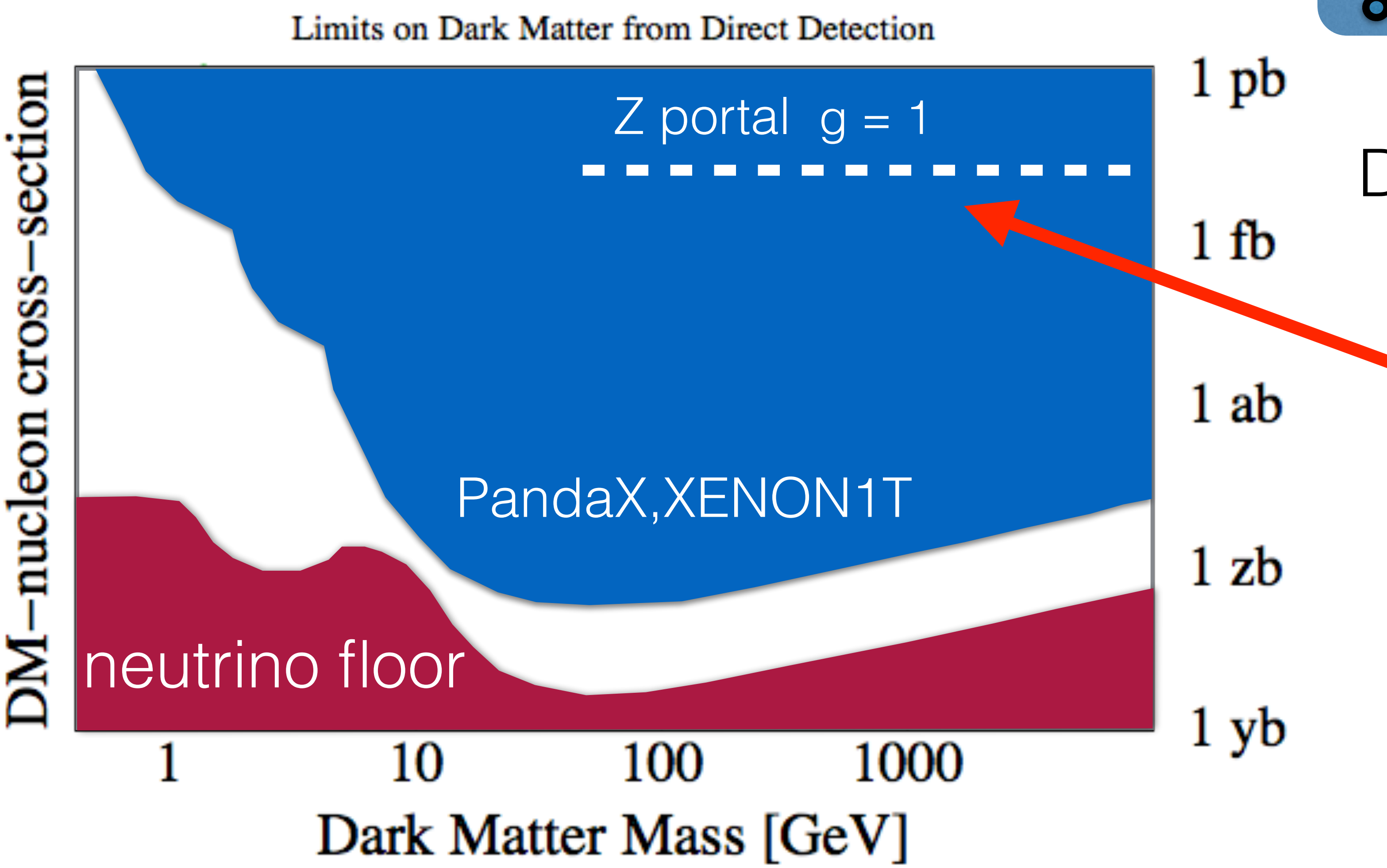
- thermal dark matter
  initial condition insensitive

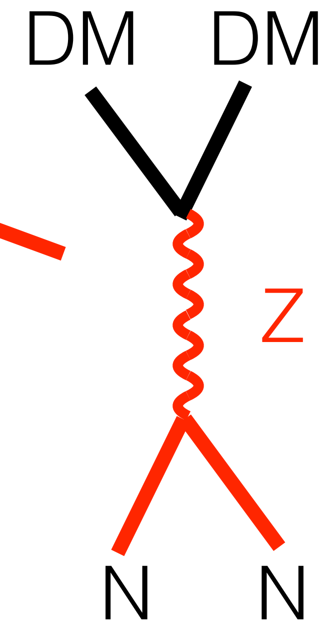
- WIMP miracle
  mass ~ TeV , g ~ 0.1

- detections

WIMP and Direct Detection







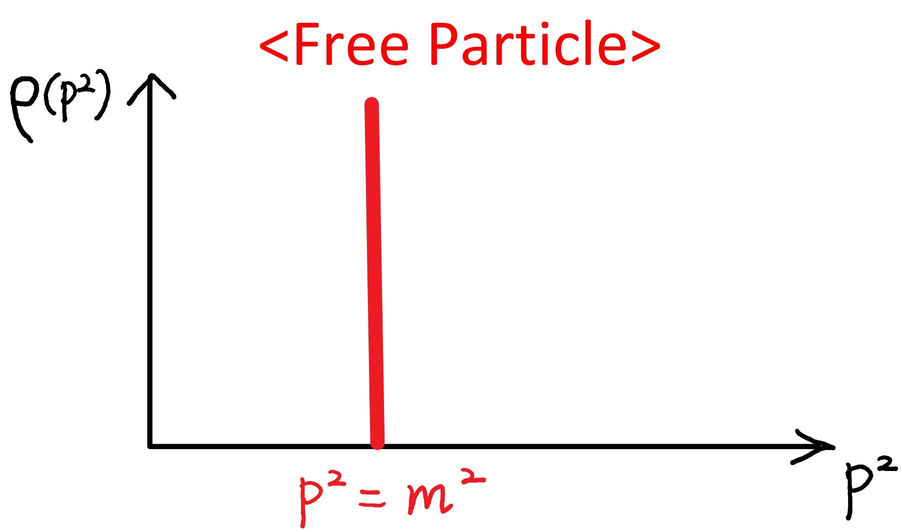
Continuum States

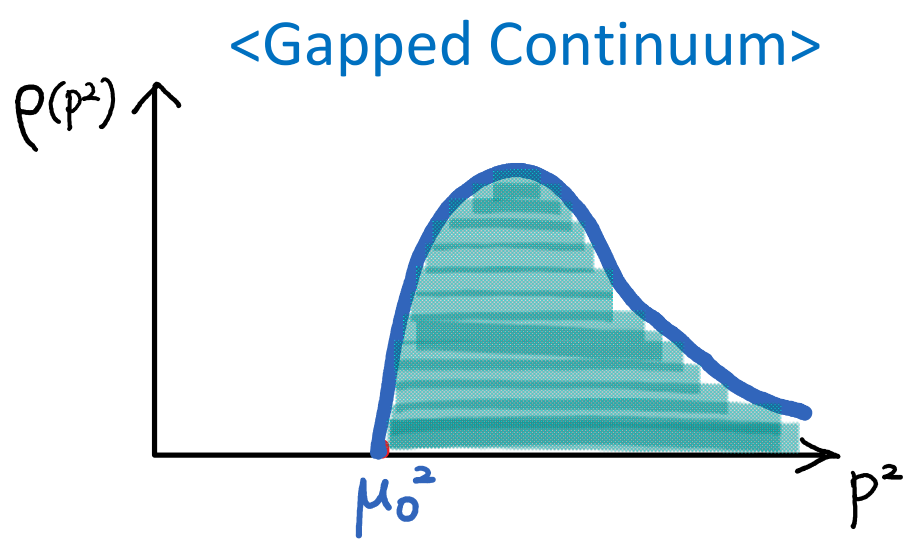
- the Källen-Lehmann representation

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

- a normal particle correlation function $\rho(\mu^2) = 2\pi\,\delta(\mu^2 - m_0^2)$

- a continuum state





Motivation of Weakly Interacting Continuum

- Continuum DM a possible IR phase of field theory
  (i) confining: e.g. atomic DM
  (ii) gappless (GB): e.g. strongly interacting massive particles (SIMP)
  (iii) gapped continuum : continuum DM

- Continuum DM is a new paradigm
  NOT particle dark matter

- Continuum DM has rich phenomenology
  (i) DM direct detection
  suppression of direct detection rate -> revival of Z-portal
  (ii) DM indirect detection
  continuously late decays: CMB, BBN
  (iii) Colliders
  several steps of cascade decays

Infinite 5D Toy Model

- a scalar propagator in 5D

$$\langle \Phi(x^\mu, z)\Phi(0)\rangle = \int \frac{d^5P}{(2\pi)^5} \frac{i}{P^2 - m_0^2 + i\epsilon} e^{-i(p\cdot x - zk)}$$

- 4D "brane" at z = 0, a non-trivial gapped continuum state appears

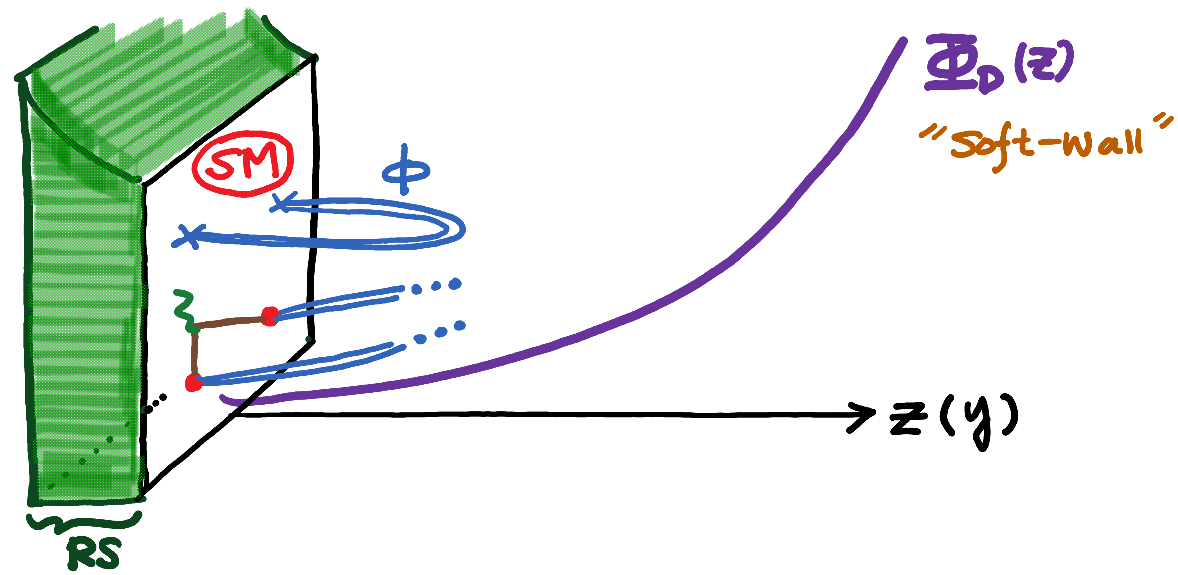
$$\langle \Phi(p, z=0)\Phi(-p, z=0)\rangle = \int_{m_0^2}^{+\infty} \frac{ds}{2\pi} \frac{i}{p^2 - s + i\epsilon} \rho(s)$$

$$\rho(s) = \frac{1}{2\sqrt{s - m_0^2}}$$

Gapped Continuum from 5D UV Model

- warped 5D background

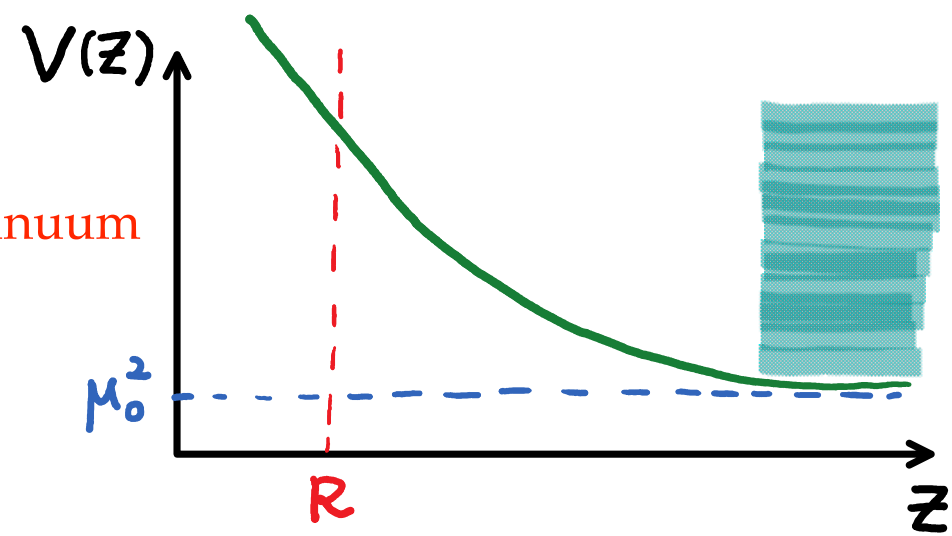
$$ds^2 = e^{-2A(y)}dx^2 - dy^2$$



- Schrödinger equation (1D QM problem)

$$-\frac{d^2\psi}{dz^2} + V(z)\,\psi = p^2\psi$$

$$V(z \to \infty) = \mu_0^2 \quad \Rightarrow \text{Gapped continuum}$$



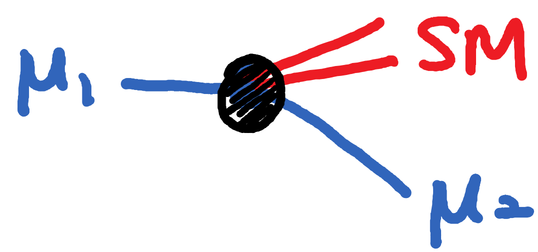
Physics of Gapped Continuum

- 4D effective field theory $\mathscr{L}_{\text{int}}$

  i) Higgs portal
  $$\mathscr{L} = \lambda H^\dagger H \Phi^\dagger \Phi$$
  ii) Z portal
  $$\mathscr{L} = g(\partial_\mu \Phi^\dagger \Phi - \Phi^\dagger \partial \Phi) Z^\mu + \cdots$$

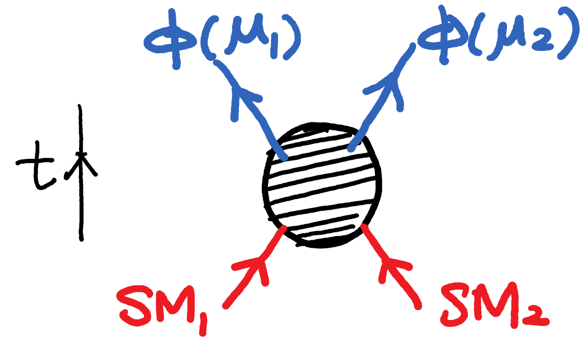
- continuum decay even with Z_2 symmetry

  There is no symmetry to forbid the decay of
  $\Phi(\mu_1) \rightarrow \Phi(\mu_2) + \text{SM}$
  continuum "number" is conserved



Physics of Gapped Continuum

- scattering (continuum as the final states)



Rate to produce continuum

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

$d\Pi_\mu = \frac{d^3p}{(2\pi)^3}\frac{1}{2E_\mu}$ is the Lorentz-invariant phase space

Thermodynamics of Gapped Continuum

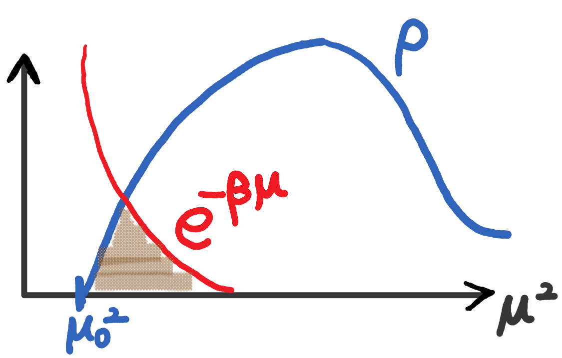
- The number density of excitations between μ^2 and $\mu^2 + \mathrm{d}\mu^2$

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

where the phase-space density in equilibrium

$$f(\mathbf{p},\mu^2) \;\approx\; e^{-\beta E_\mu}$$

- When the temperature is low



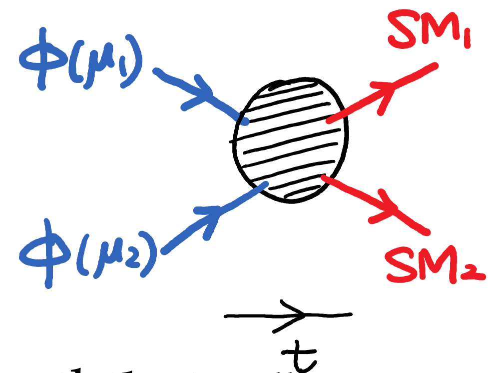
$$n_{\rm eq} = \int \frac{d\mu^2}{2\pi}\,\rho(\mu^2)\int \frac{d^3p}{(2\pi)^3}\, e^{-\beta E_\mu}$$

Thermodynamics of Gapped Continuum

- Boltzmann equations (continuum as the initial states)

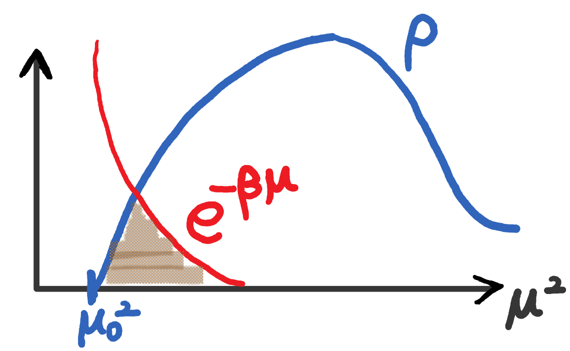
the same form as the regular DM

$$\frac{\mathrm{d}n}{\mathrm{d}t} + 3Hn = -\langle \sigma v \rangle \left(n^2 - n_{\mathrm{eq}}^2\right)$$



- Are the results the same? (sum over all the "co-annihilation")

$$\langle \sigma v \rangle = \frac{1}{n_{\mathrm{eq}}^2} \int \frac{d\mu_1^2}{2\pi} \rho(\mu_1^2) \int \frac{d\mu_2^2}{2\pi} \rho(\mu_2^2) \int d\Pi_{\mu_1} d\Pi_{\mu_2} d\Pi_A d\Pi_B$$
$$\times \exp\left(-\beta(E_A + E_B)\right) (2\pi)^4 \delta^4(k_A + k_B - p - p') \,|\mathcal{M}|^2$$



considering $T \ll \mu_0$,

$$\exp\left(-\beta(E_A + E_B)\right) \simeq \exp\left(-\beta(\mu_1 + \mu_2)\right)$$

$\langle \sigma v \rangle \simeq$ the thermal cross section of particle with mass μ_0

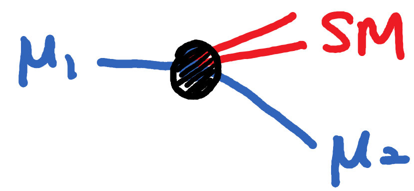
$+\mathcal{O}(T/\mu_0)$

Gapped continuum in the final states

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

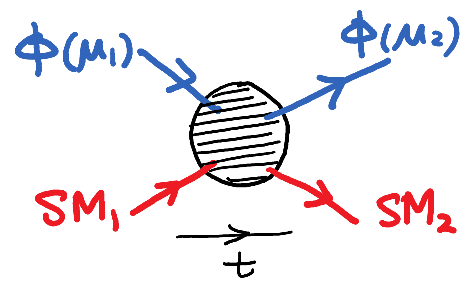
- continuum state decay

$$\Phi(\mu_1) \to \Phi(\mu_2) + \mathrm{SM}$$

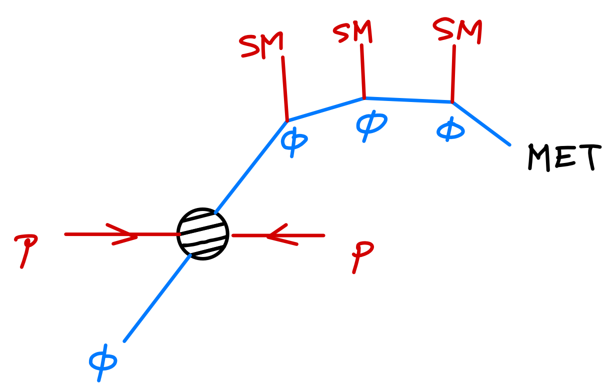


- DM direct detection

$$\Phi(\mu_1) + \mathrm{SM} \to \Phi(\mu_2) + \mathrm{SM}$$



- colliders



Z-portal Weakly Interacting Continuum