EXCEPTIONALLY LIGHT THERMAL DARK MATTER

Raffaele Tito D'Agnolo - IAS Princeton
Rutgers University 9/27/2016

THE DARK MATTER MASS

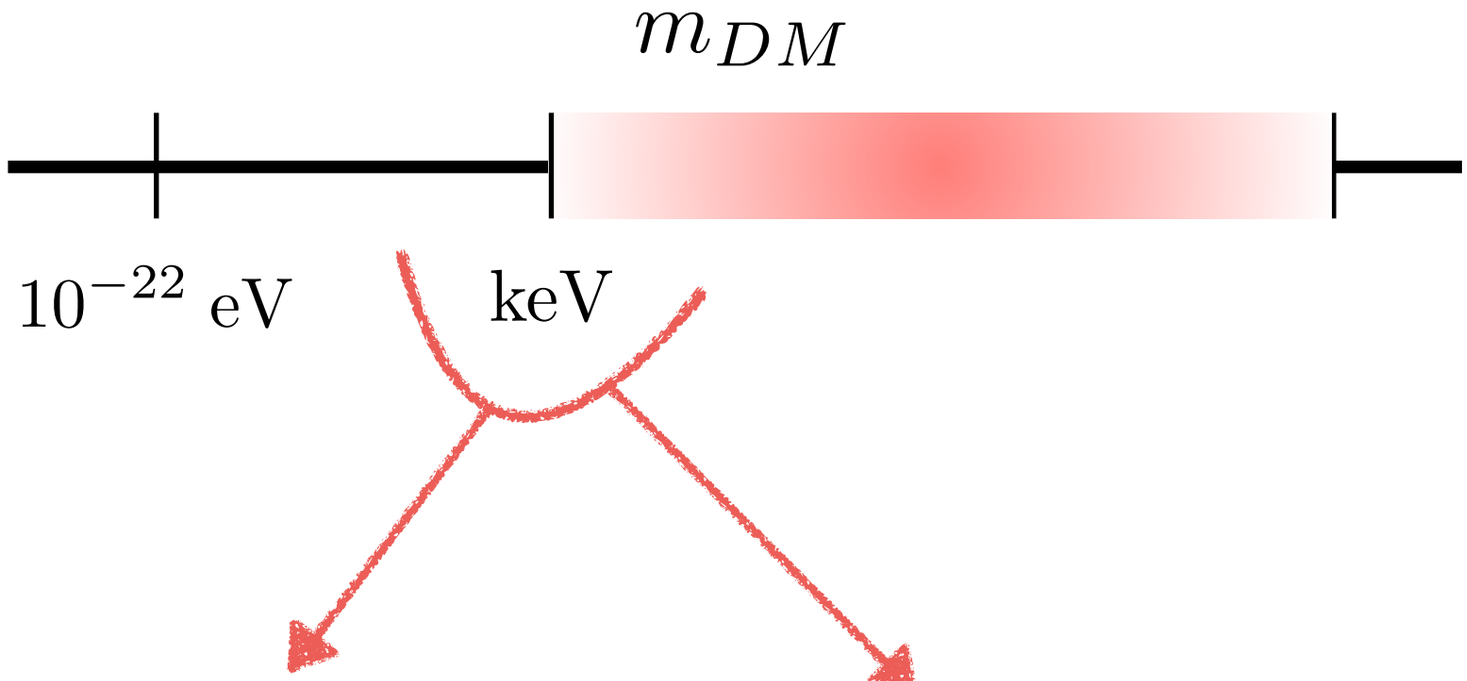
$$m_{DM}$$

10^{-22} eV

10^{48} GeV

80 ORDERS OF MAGNITUDE

THE DARK MATTER MASS



DARK MATTER SELF-INTERACTIONS

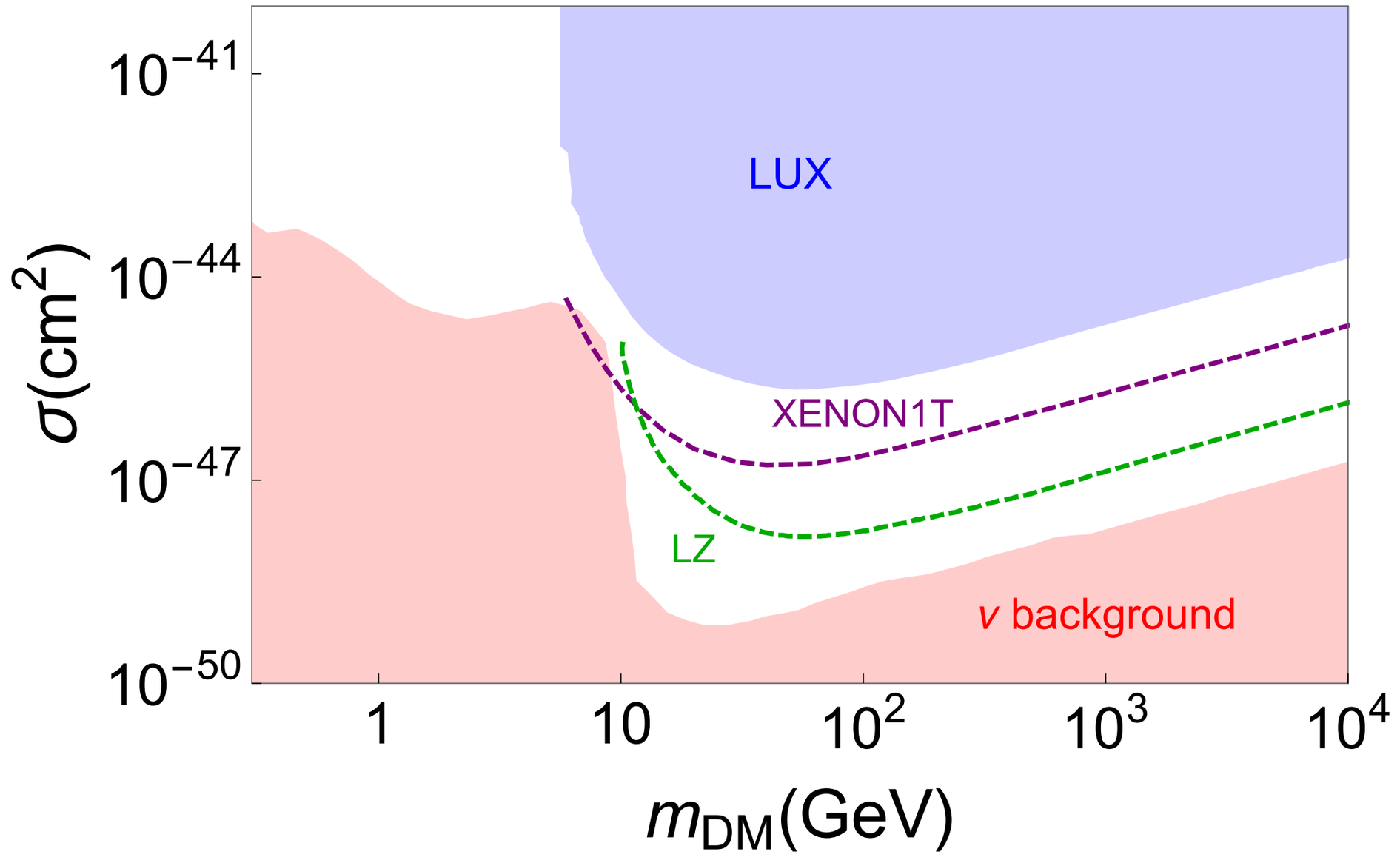
$$\sigma/m_{DM}$$

$$\frac{1}{M_{Pl}^2 m_{DM}} \approx \frac{10^{-44}}{\mathrm{MeV}^3}\frac{\mathrm{MeV}}{m_{DM}}$$

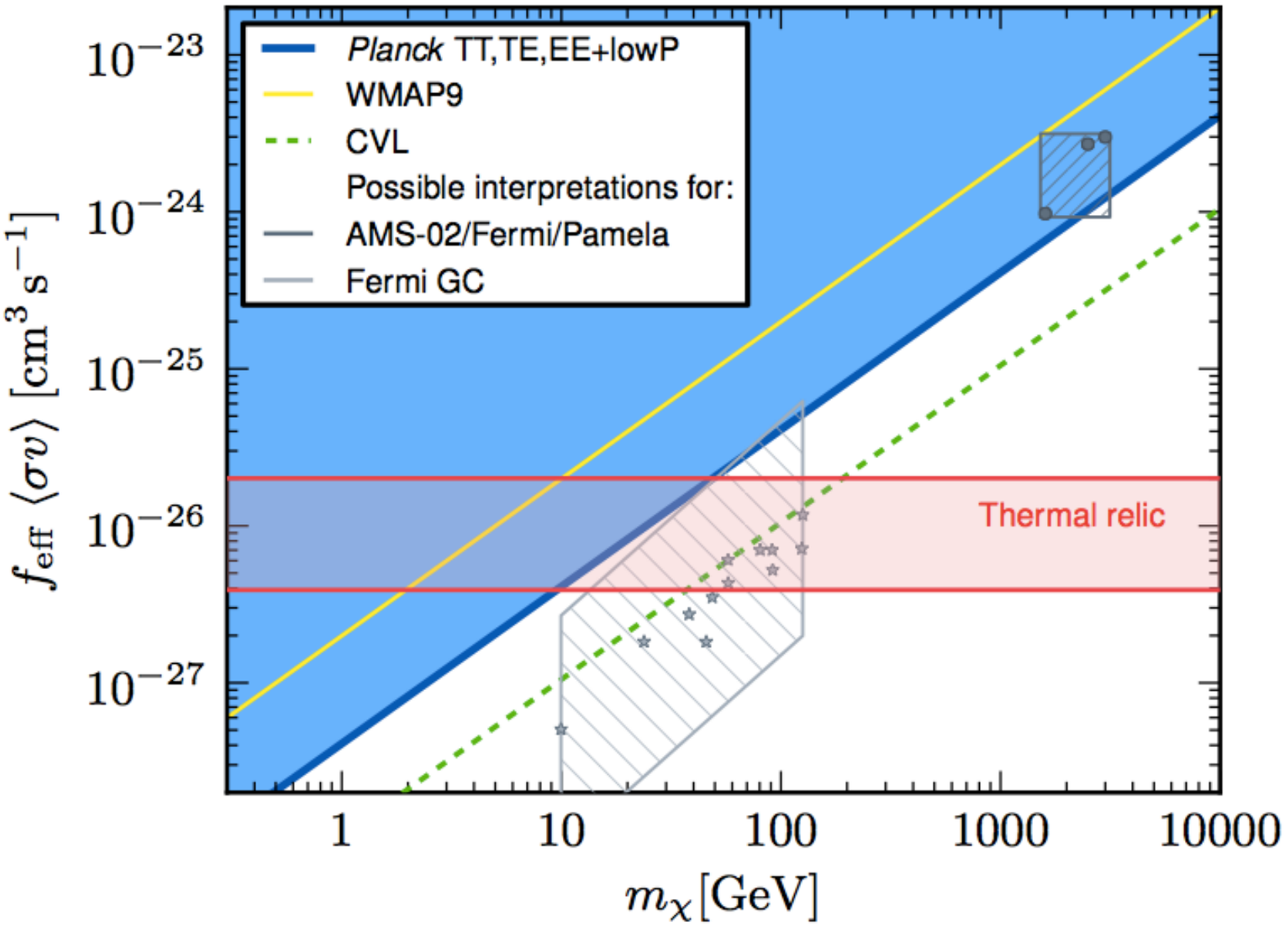
$$\mathrm{cm}^2/g \approx \frac{5\times 10^{-6}}{\mathrm{MeV}^3}$$

50 ORDERS OF MAGNITUDE

DIRECT DETECTION

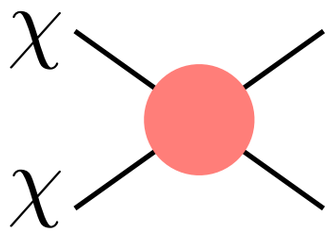


CMB BOUND


Planck TT,TE,EE+lowP
WMAP9
CVL
Possible interpretations for:
AMS-02/Fermi/Pamela
Fermi GC
Thermal relic
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
$f_{\rm eff}\ \langle\sigma v\rangle\ [{\rm cm}^3\,{\rm s}^{-1}]$
1
10
100
1000
10000
$m_\chi\,[{\rm GeV}]$

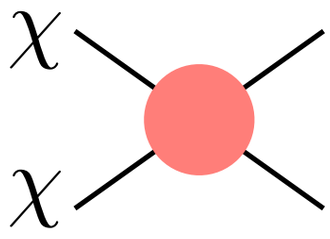
EXCEPTIONAL THERMAL RELICS

WIMPS AND MIRACLES



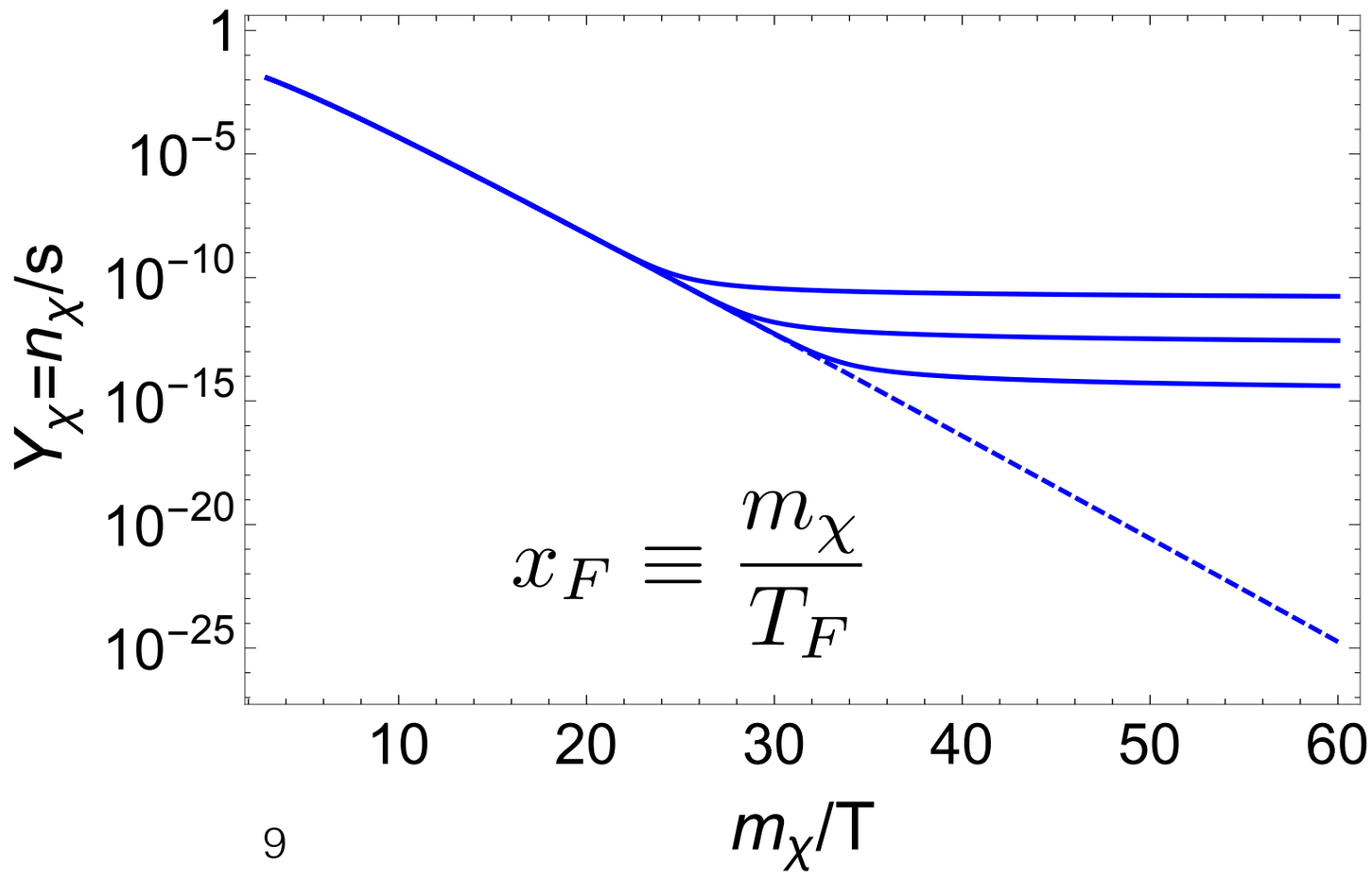
$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left[n_\chi^2 - \left(n_\chi^{eq}\right)^2\right]$$

WIMPS AND MIRACLES

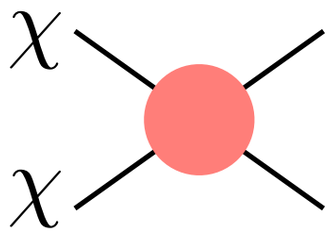


$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left[n_\chi^2 - \left(n_\chi^{eq}\right)^2\right]$$

$$n_\chi\langle\sigma v\rangle_F \approx H_F$$



WIMPS AND MIRACLES



$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left[n_\chi^2 - \left(n_\chi^{eq}\right)^2\right]$$

$$n_\chi\langle\sigma v\rangle_F \approx H_F \longrightarrow \Omega_\chi h^2 \sim m_\chi n_\chi \sim \frac{m_\chi}{\langle\sigma v\rangle_F}$$

$$\langle\sigma v\rangle_F \approx \frac{1}{(20\ \mathrm{TeV})^2}$$

THREE EXCEPTIONS

K. Griest, D. Seckel, ‘89

1. FORBIDDEN CHANNEL ANNIHILATIONS

2. COANNIHILATION

3. ANNIHILATION NEAR A POLE

FOUR EXCEPTIONS

1. FORBIDDEN CHANNEL ANNIHILATIONS

2. COANNIHILATION

3. ANNIHILATION NEAR A POLE

4. COSCATTERING → **RTD, Josh Rudermann**
In preparation

FOUR EXCEPTIONS

1. FORBIDDEN CHANNEL ANNIHILATIONS

2. COANNIHILATION

3. ANNIHILATION NEAR A POLE

4. COSCATTERING

THREE NEW EXCEPTIONS

WIMP

$$\langle \sigma v \rangle = \frac{\alpha_d^2}{m_{DM}^2} P(v^2) = \frac{\alpha_d^2}{m_{DM}^2} \left(p_0 + p_1 \frac{T}{m_{DM}} \right) + \ldots$$

FORBIDDEN
COANNIHILATION
COSCATTERING

$$\langle \sigma v \rangle = \frac{\alpha_d^2}{m_{DM}^2} P(v^2) e^{-\Delta \frac{m_{DM}}{T}}$$

THREE NEW EXCEPTIONS

$$\alpha_d \sim \alpha_W$$

$$m_{DM} \sim m_Z e^{-\Delta x_F} \ll \mathrm{TeV}$$

THREE NEW EXCEPTIONS

$$m_{DM} \sim m_Z e^{-\Delta x_F} \ll \text{TeV}$$

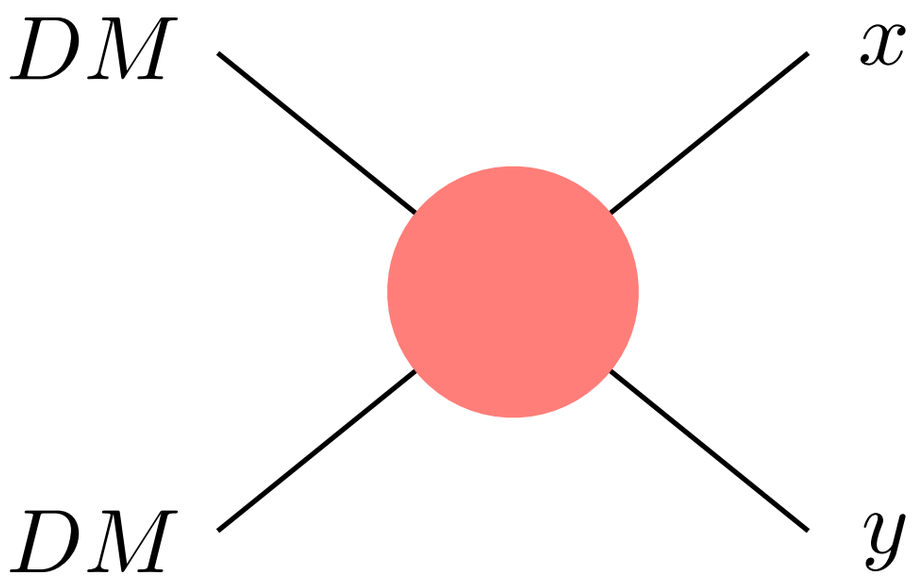
$$\langle \sigma v \rangle_{\text{CMB}} \ll \langle \sigma v \rangle_{\text{F}}$$

FORBIDDEN DARK MATTER

RTD, J. Ruderman

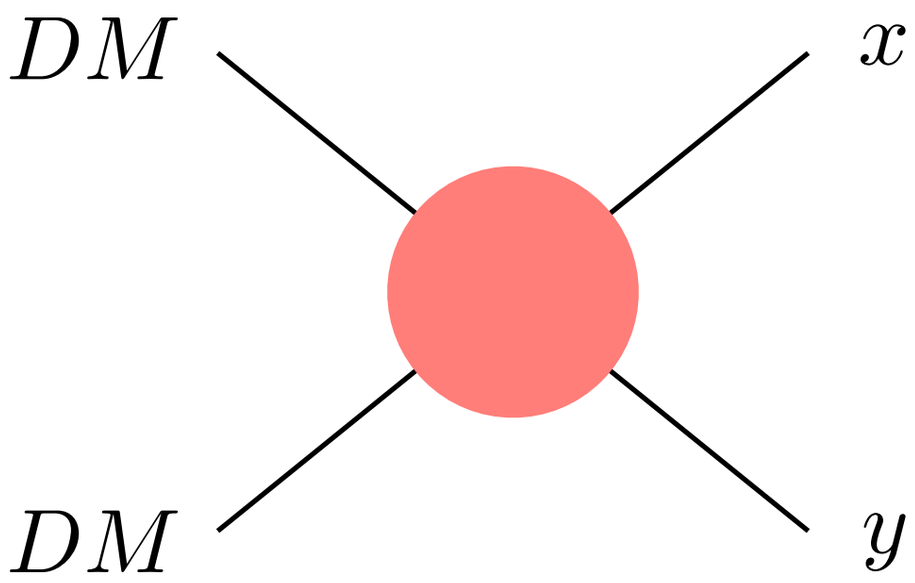
Phys.Rev.Lett. 115 (2015) 6, 061301

FORBIDDEN CHANNEL ANNIHILATIONS



$$2m_{DM} < m_x + m_y$$

FORBIDDEN CHANNEL ANNIHILATIONS

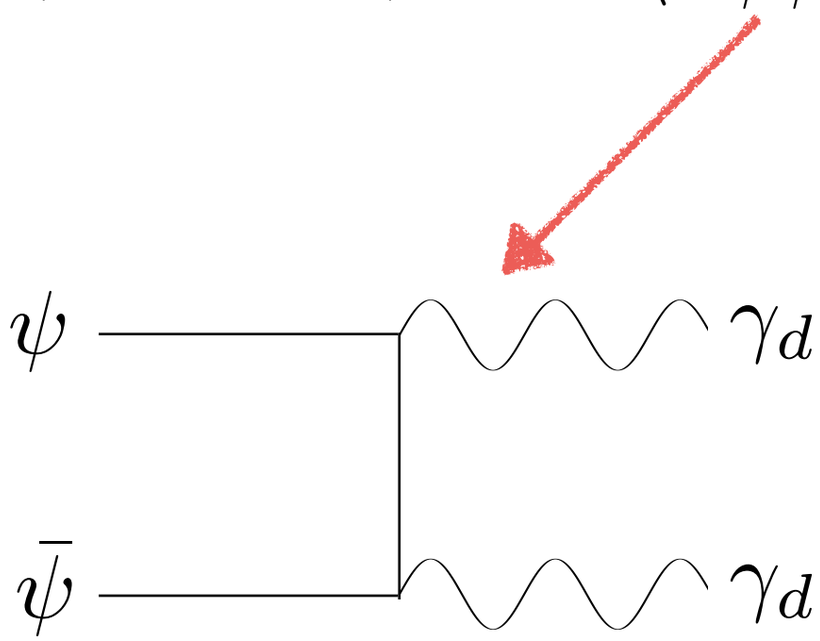


$$\langle \sigma v \rangle_F \sim \frac{\alpha_d^2}{m_{DM}^2} e^{-x_F \Delta}$$

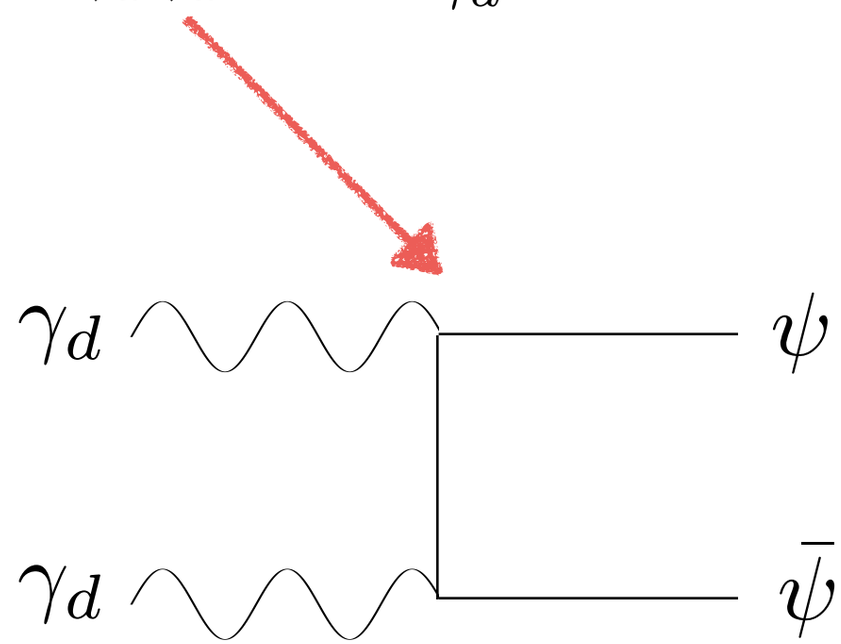
$$\Delta = \frac{(m_x + m_y) - 2m_{DM}}{2m_{DM}}$$

RELIC DENSITY

$$\dot{n}_\psi + 3Hn_\psi = -\left\langle \sigma_{\psi\bar{\psi}}\, v \right\rangle n_\psi^2 + \left\langle \sigma_{\gamma_d\gamma_d}\, v \right\rangle \left(n_{\gamma_d}^{eq}\right)^2$$



Forbidden



RELIC DENSITY

$$\dot{n}_\psi + 3Hn_\psi = -\left\langle \sigma_{\psi\bar{\psi}}\, v \right\rangle n_\psi^2 + \left\langle \sigma_{\gamma_d\gamma_d}\, v \right\rangle \left(n_{\gamma_d}^{eq}\right)^2 = 0$$

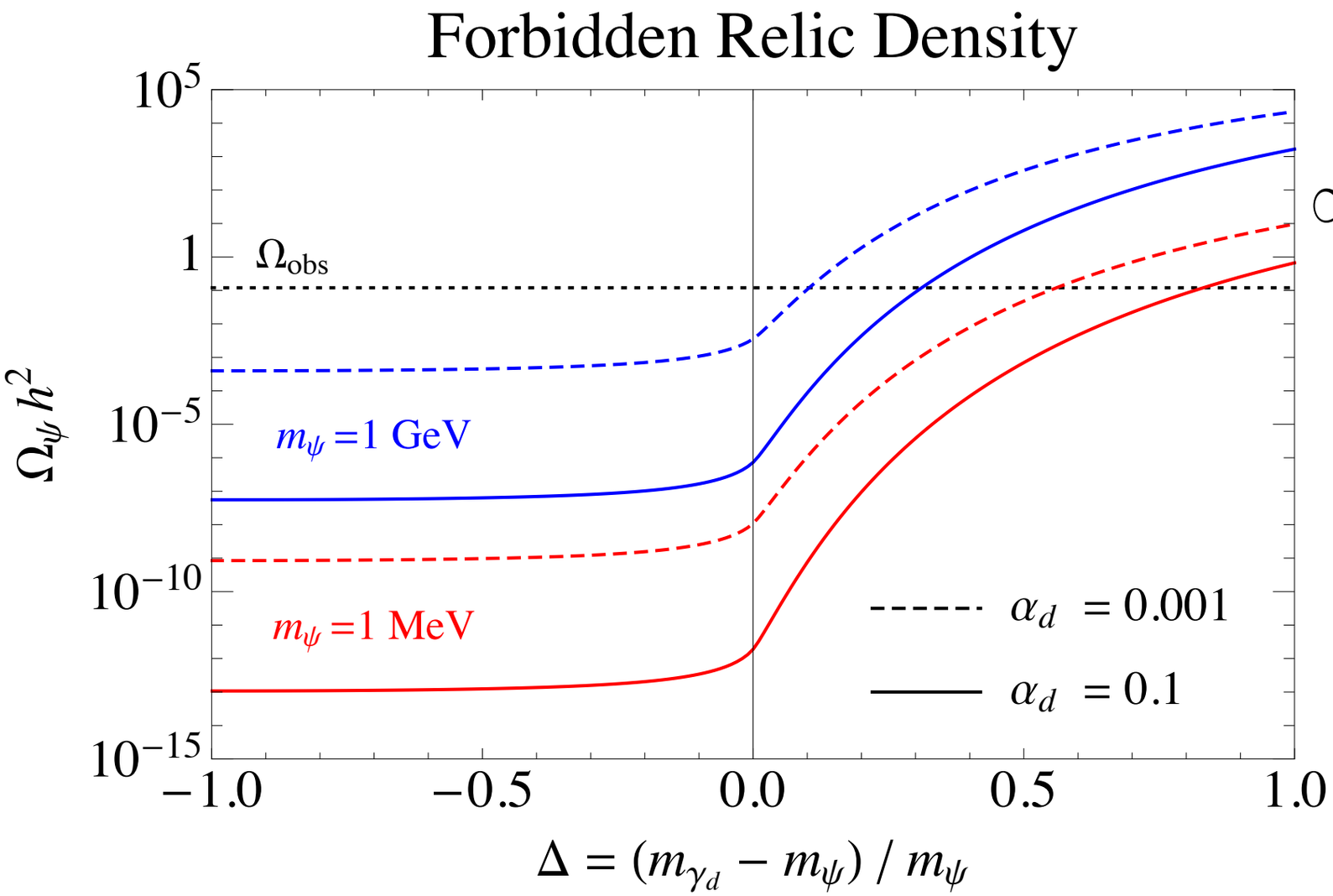
in equilibrium

RELIC DENSITY

$$\dot{n}_\psi + 3Hn_\psi = -\left\langle \sigma_{\psi\bar{\psi}}\, v \right\rangle n_\psi^2 + \left\langle \sigma_{\gamma_d\gamma_d}\, v \right\rangle \left(n_{\gamma_d}^{eq}\right)^2 = 0$$

$$\left\langle \sigma_{\psi\bar{\psi}}\, v \right\rangle = \frac{\left(n_{\gamma_d}^{eq}\right)^2}{\left(n_\psi^{eq}\right)^2} \left\langle \sigma_{\gamma_d\gamma_d}\, v \right\rangle \approx 8\pi f_\Delta \frac{\alpha_d^2}{m_\psi^2}\, e^{-2\Delta x}$$

RELIC DENSITY



$$\propto \frac{m_\psi^2}{\alpha_d^2} e^{2x_F \Delta}$$

Simple analytic formula agrees at the % level with MicrOmegas

RTD, J. Ruderman
In preparation

COANNIHILATION AND COSCATTERING

A SIMPLE MODEL

$$-\mathcal{L} \supset m_\psi \psi^c \psi + \frac{m_\chi}{2}\chi^2 + \delta m \chi\psi + \frac{y}{2}\phi\psi^c\psi$$

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$$-\mathcal{L} \supset m_\psi \psi^c \psi + \frac{m_\chi}{2}\chi^2 + \delta m \chi\psi + \frac{y}{2}\phi\psi^c\psi$$

$$m_\psi \gtrsim m_\chi$$

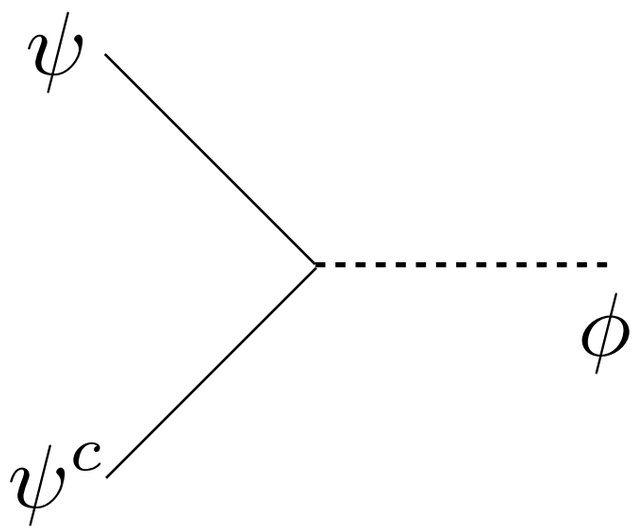
ψ ————————

χ ———————— = DARK MATTER

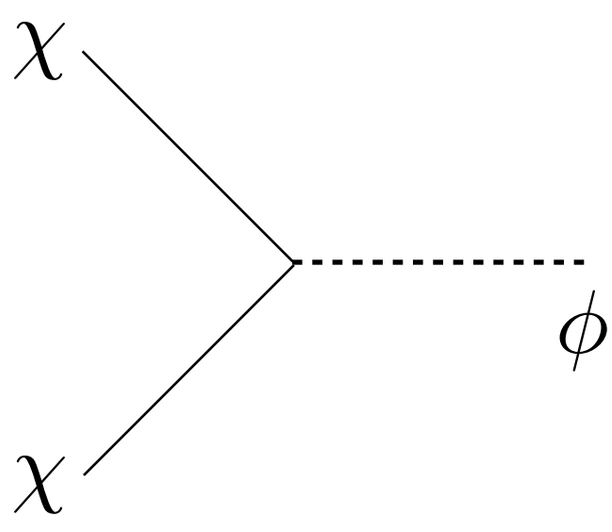
A SIMPLE MODEL

$$-\mathcal{L} \supset m_\psi \psi^c \psi + \frac{m_\chi}{2}\chi^2 + \delta m \chi\psi + \frac{y}{2}\phi\psi^c\psi$$

$$\delta \equiv \frac{\delta m}{m_\chi} \ll 1$$

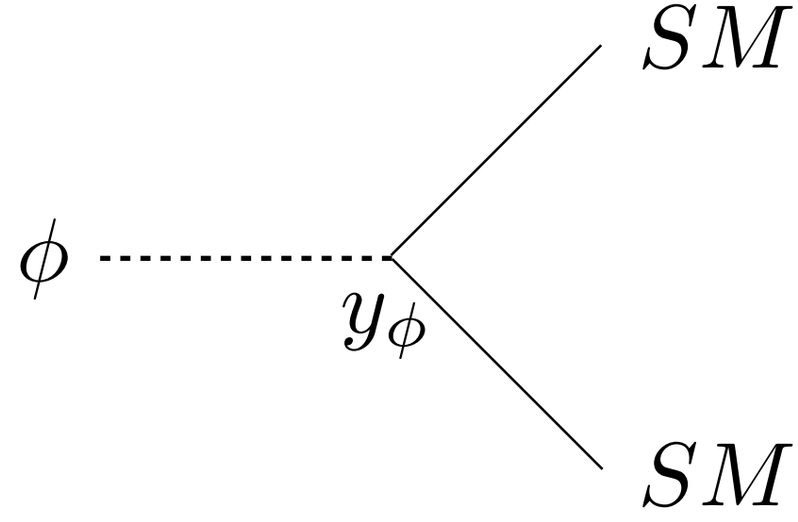


$\gg$



A SIMPLE MODEL

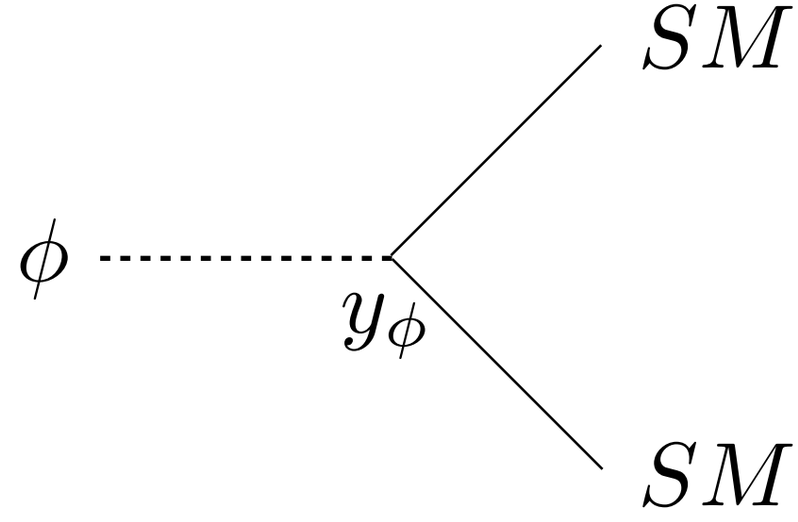
$$-\mathcal{L} \supset m_\psi \psi^c \psi + \frac{m_\chi}{2}\chi^2 + \delta m \chi\psi + \frac{y}{2}\phi\psi^c\psi$$



$$y_\phi \ll 1 \qquad\qquad y_\phi^2 \gtrsim \frac{H_F}{m_\phi}$$

A SIMPLE MODEL

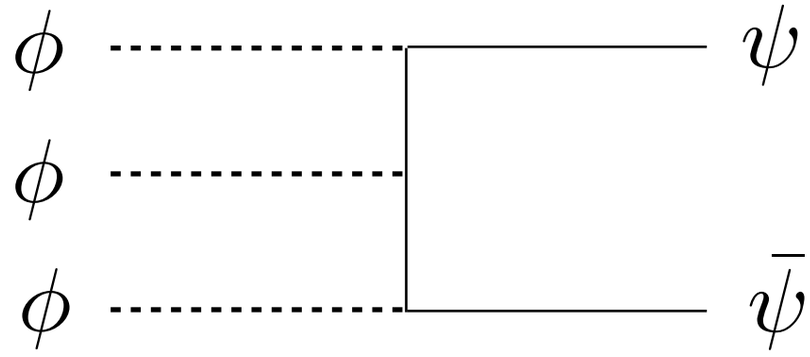
$$-\mathcal{L} \supset m_\psi \psi^c \psi + \frac{m_\chi}{2}\chi^2 + \delta m \chi\psi + \frac{y}{2}\phi\psi^c\psi$$



$$n_\phi = n_\phi^{\rm eq} \qquad T_{\phi,\chi,\psi} = T_{SM} \sim a^{-1}$$

CANNIBALISM

$$y_\phi^2 \lesssim \frac{H_F}{m_\phi}$$



$$m \to T$$

Carlson, Hall, Machacek

Astrophys.J. 398 (1992) 43-52

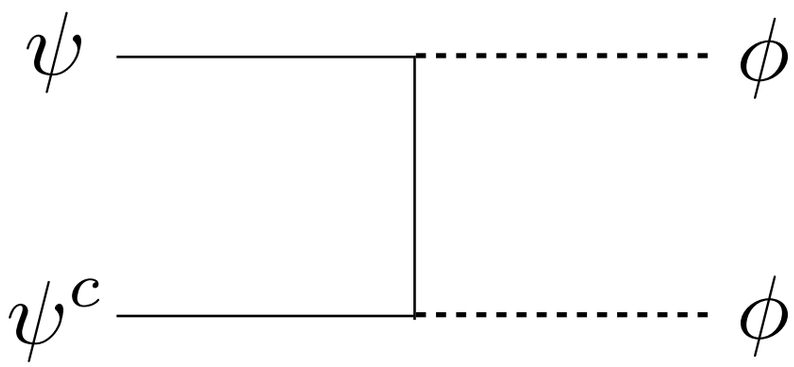
Farina, Ruderman,

Pappadopulo,Trevisan

2016

A SIMPLE MODEL

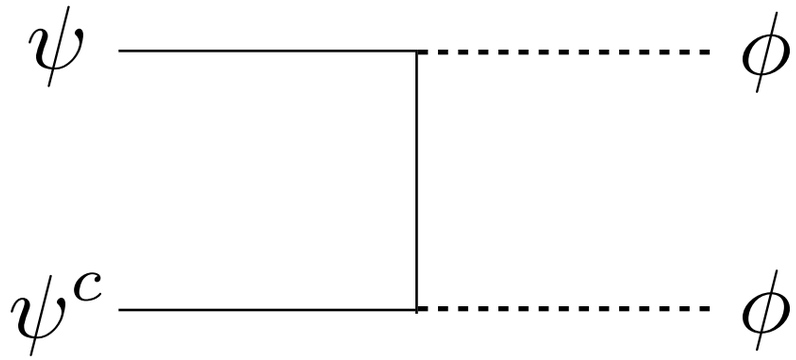
ANNIHILATIONS



$$\Gamma_a = n_\psi \langle \sigma v \rangle \sim n_\psi \frac{y^4}{m_\psi^2}$$

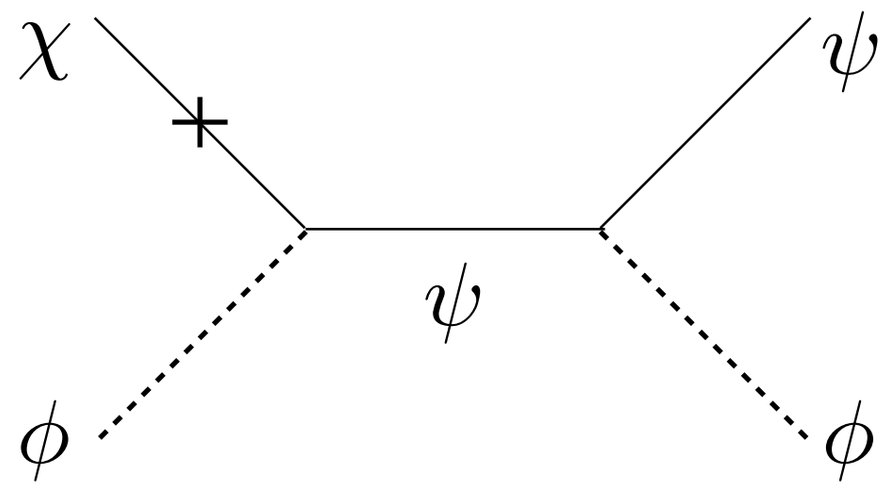
A SIMPLE MODEL

ANNIHILATIONS



$$\Gamma_a = n_\psi \langle \sigma v \rangle \sim n_\psi \frac{y^4}{m_\psi^2}$$

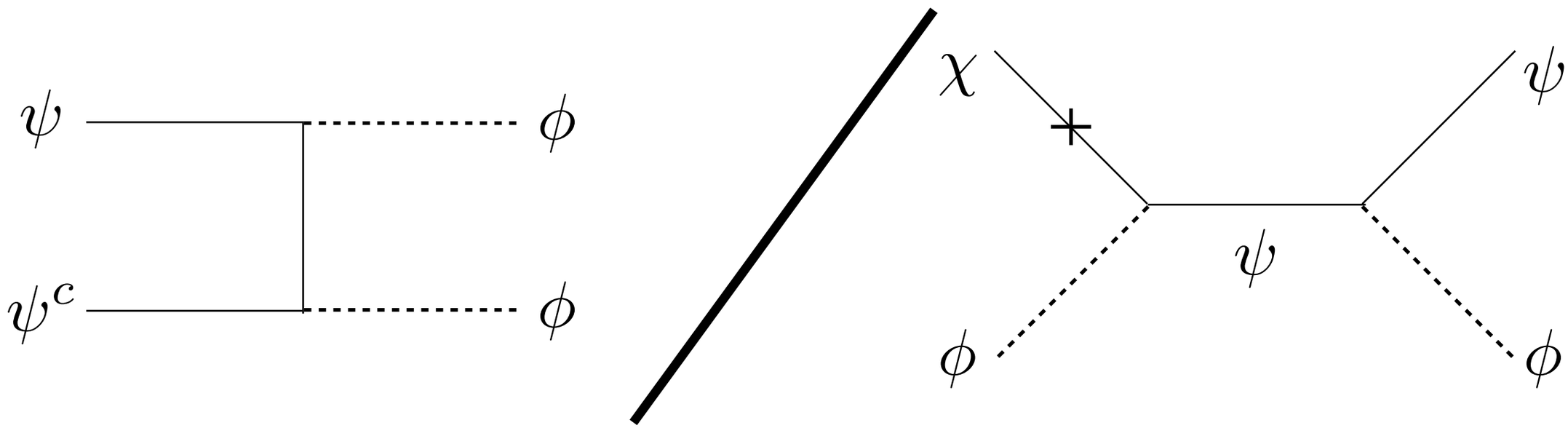
SCATTERING/DECAYS



$$\Gamma_s = n_\phi \langle \sigma v \rangle \sim n_\phi \frac{y^4 \delta^2}{m_\psi^2} e^{-\Delta \frac{m_\chi}{T}}$$

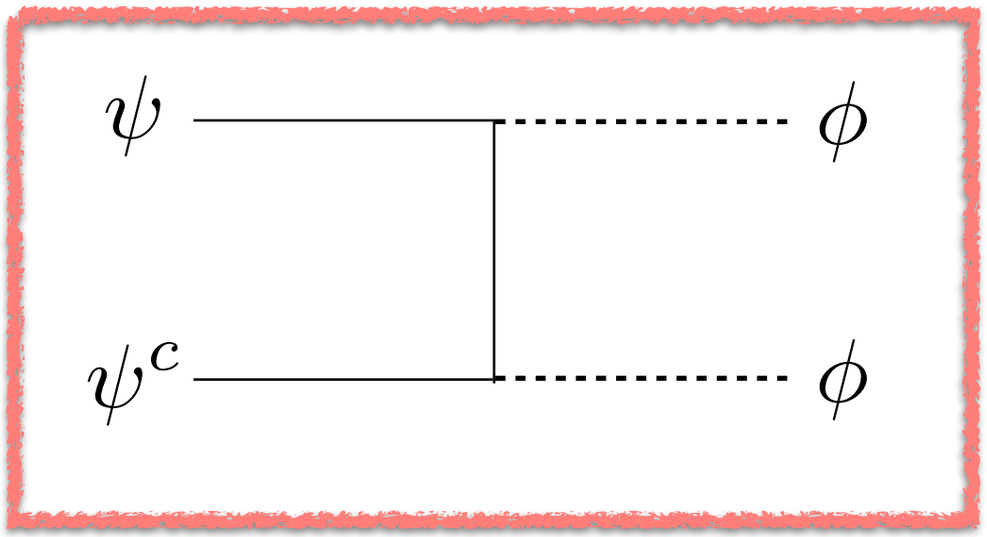
$$\Delta \equiv \frac{m_\psi - m_\chi}{m_\chi}$$

COANNHILIATION OR COSCATTERING?

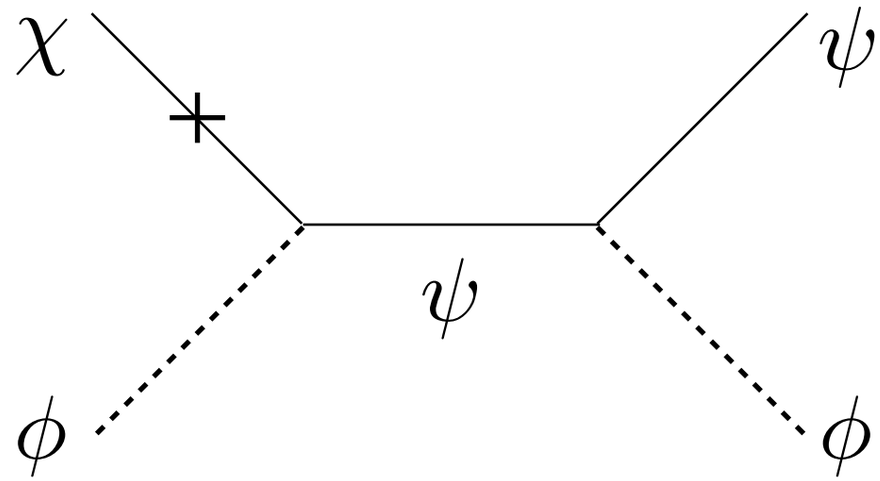


$$\sim \delta^{-2} e^{-\left(1-\frac{m_\phi}{m_\chi}\right)x}$$

COANNIHILATION

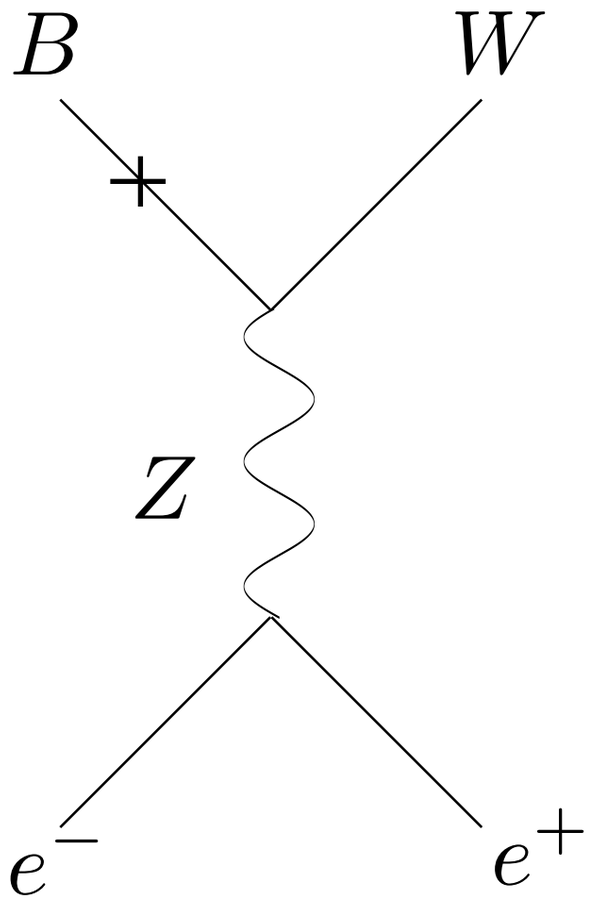


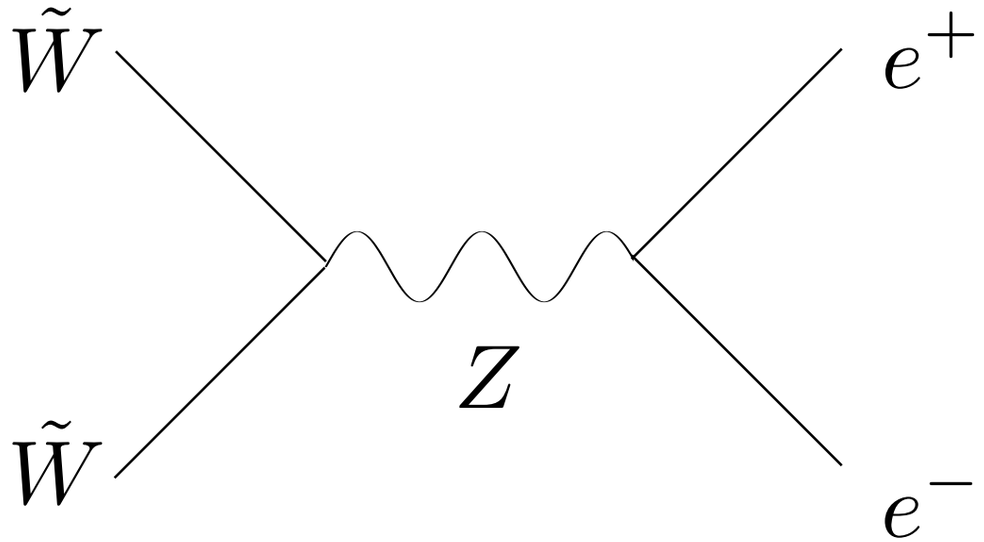
ANNIHILATIONS
FREEZE-OUT FIRST



SUSY DARK MATTER

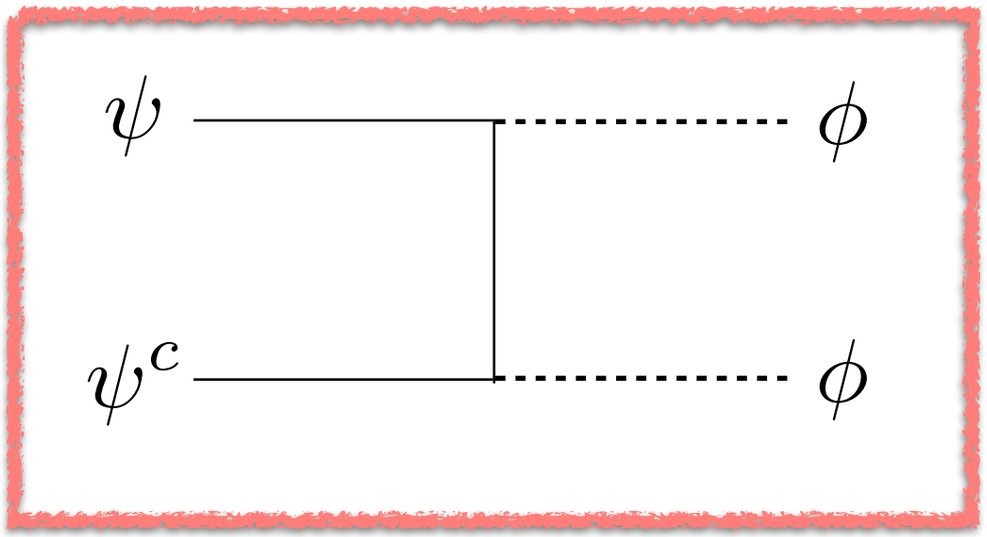
$\psi \to \tilde{W}$ $\chi \to \tilde{B}$ $\phi \to e^{\pm}$





WITH A VERY DECOUPLED BINO

COANNIHILATION



$$m_\psi \gtrsim m_\chi \qquad \Delta \equiv \frac{m_\psi - m_\chi}{m_\chi}$$

$$T_F \approx 20 m_\psi = 20(1+\Delta) m_\chi$$

$$\sim e^{\Delta x_F}$$

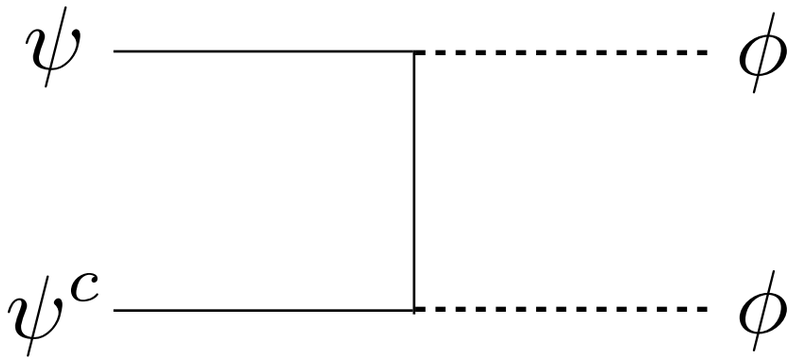
COANNIHILATION

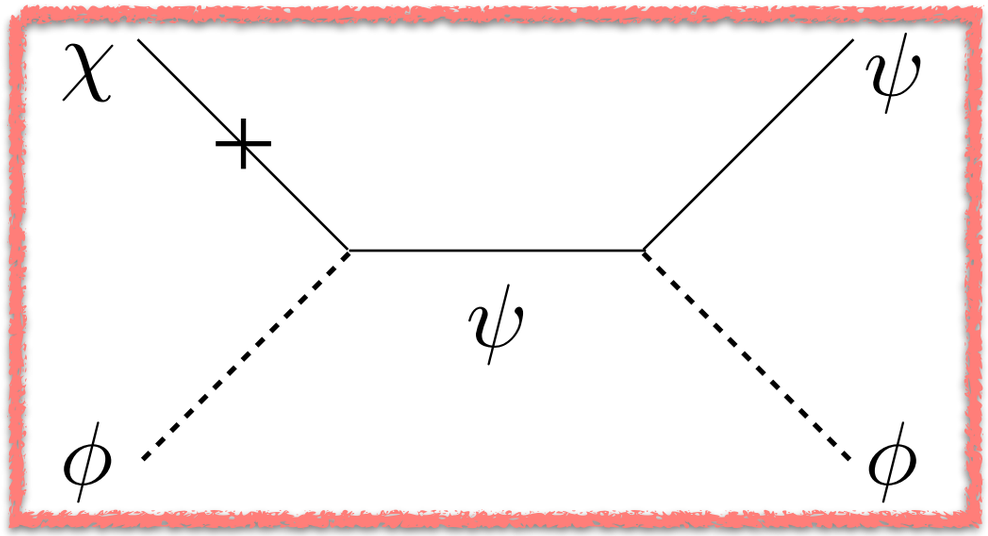
K. Griest, D. Seckel, ‘89

$$\langle \sigma_{\rm eff} v \rangle \approx \frac{\alpha_d^2}{m_\psi^2} (1+\Delta)^3 e^{-2\Delta x}$$

$$\Delta \equiv \frac{m_\psi - m_\chi}{m_\chi}$$

COSCATTERING



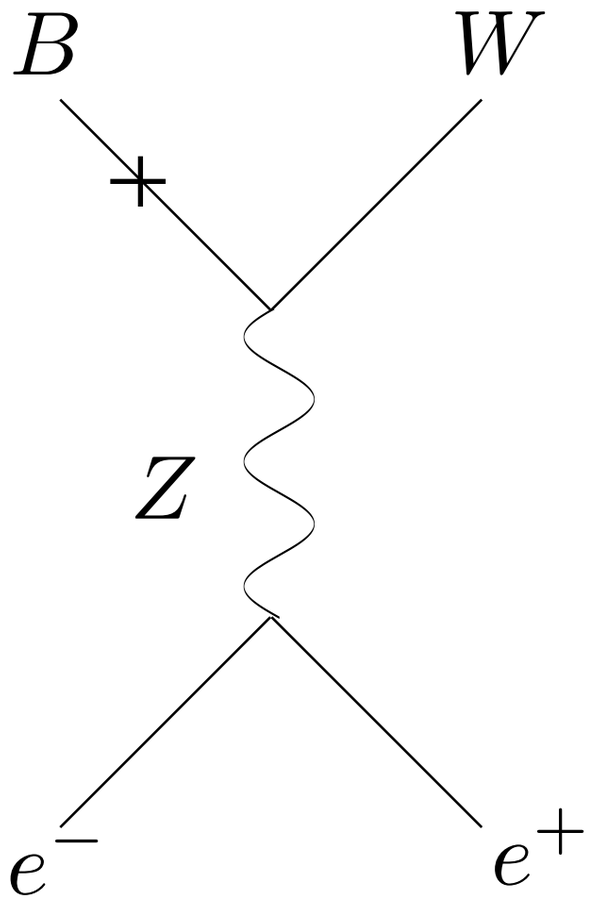


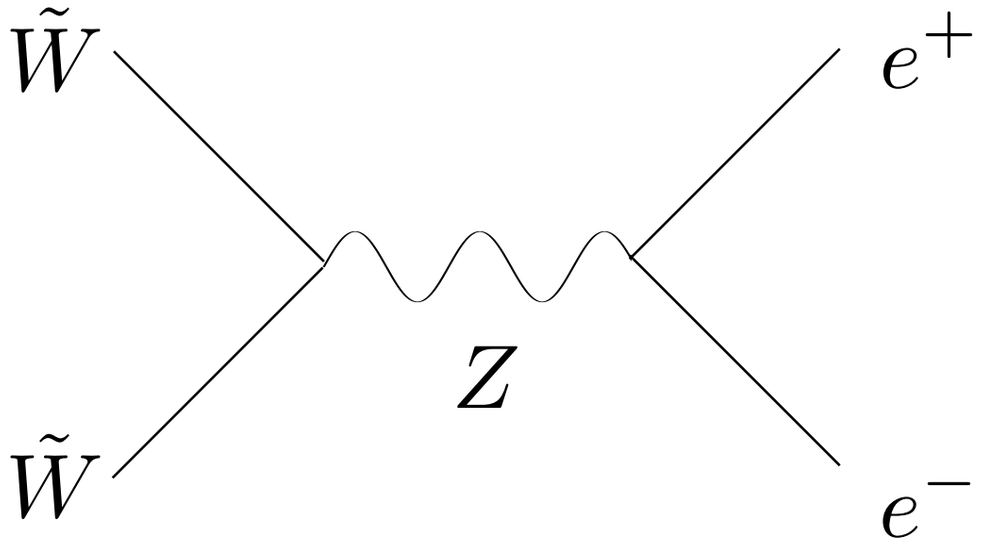
SCATTERING
FREEZES-OUT FIRST

SUSY DARK MATTER

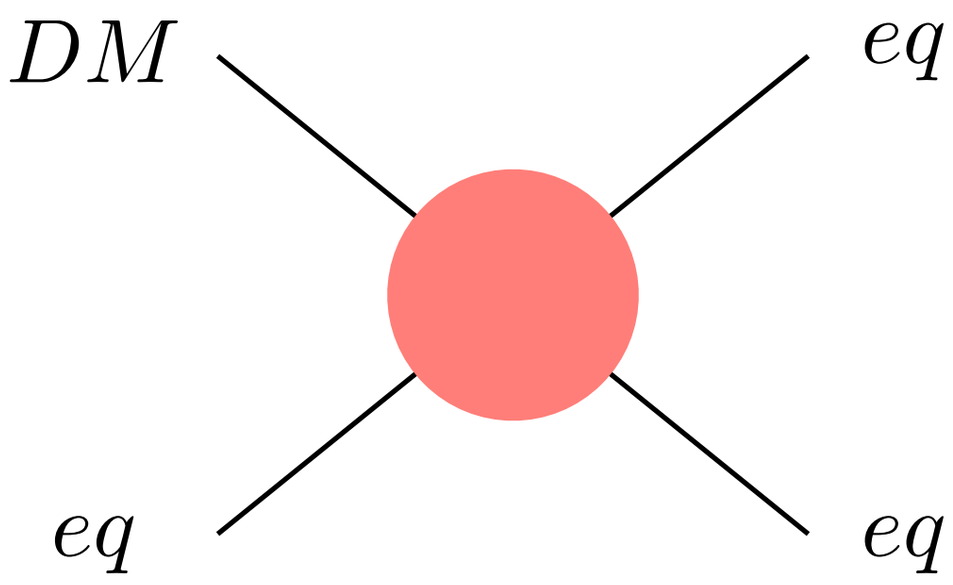
$$m_\phi \sim m_{\chi,\psi}$$

$$m_e \ll m_{\tilde{B},\tilde{W}}$$



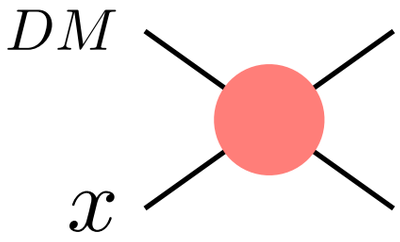


COSCATTERING



NEW SET OF BOLTZMANN EQUATIONS
NEW PARAMETRICS FOR FREEZE-OUT

COSCATTERING

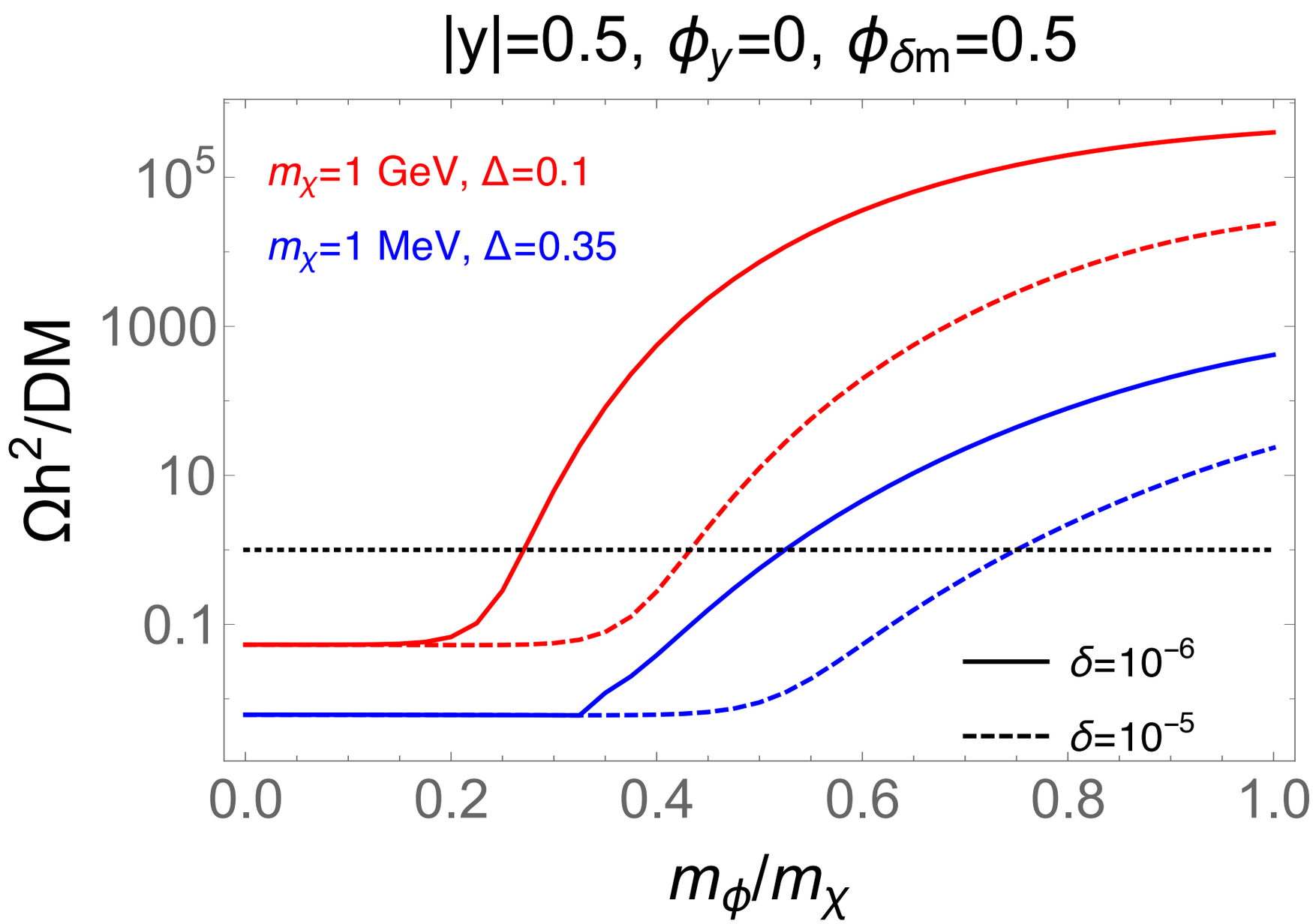


$$\frac{dn_{DM}}{dt} + 3Hn_{DM} = -\langle\sigma v\rangle n_{DM} n_x + ...$$

$$n_x \langle\sigma v\rangle_F \approx H_F \longrightarrow \Omega_{DM}h^2 \sim n_{DM} \sim \left(\frac{1}{\langle\sigma v\rangle_F}\right)^{m_{DM}/m_x}$$

$$n_{DM} \langle\sigma v\rangle_F \approx H_F \longrightarrow \Omega_{DM}h^2 \sim n_{DM} \sim \frac{1}{\langle\sigma v\rangle_F}$$ WIMP

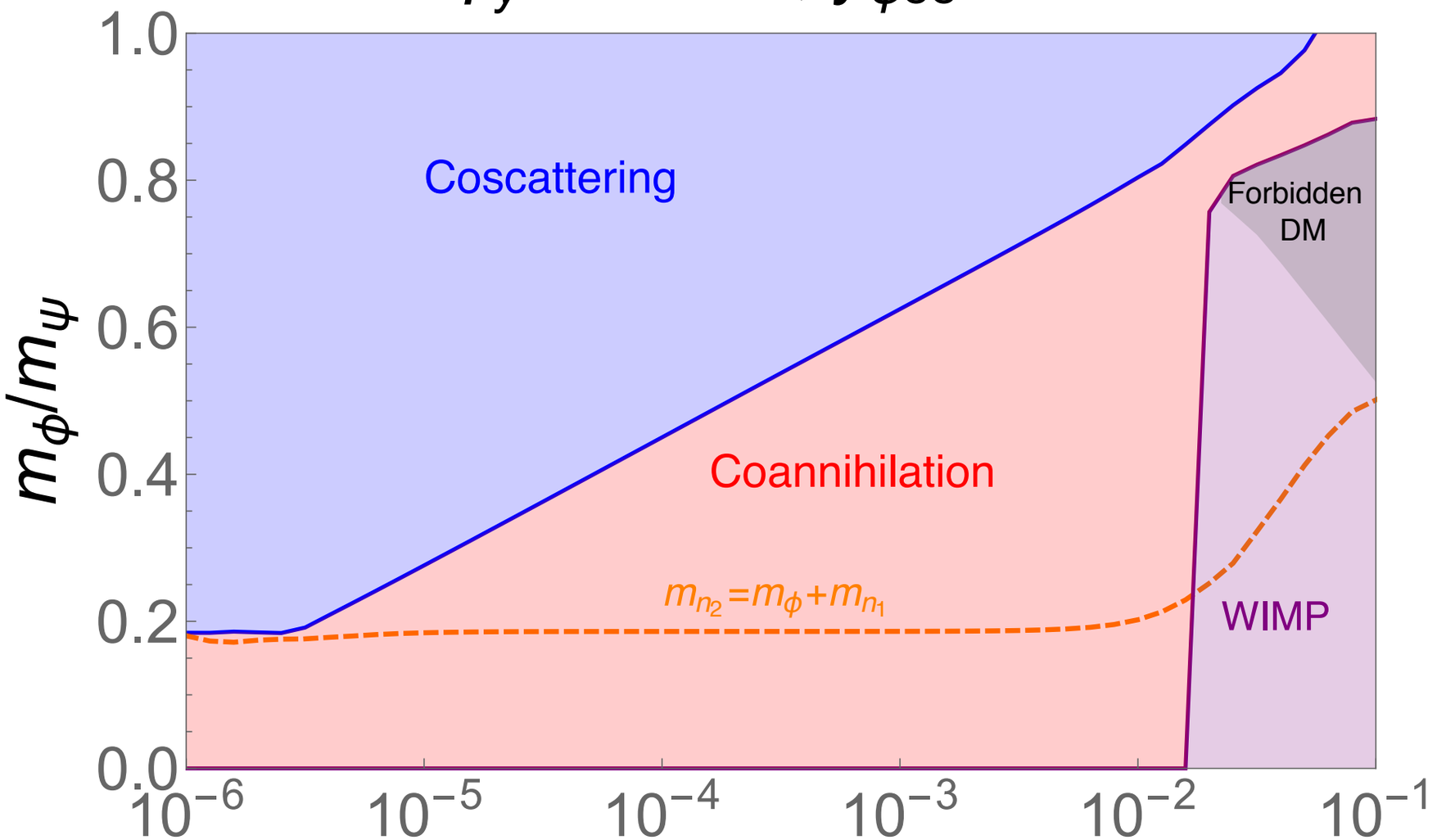
COSCATTERING



ALL TOGETHER

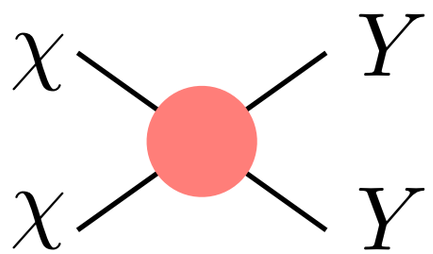
m_χ=1 GeV, |y|=0.5, $\phi_{\delta m}$=0.5,

$\phi_y=-\pi/\sqrt{2}$, $y_{\phi ee}=10^{-6}$



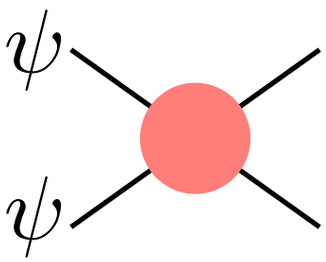
ALL TOGETHER

FORBIDDEN



$m_Y \gtrsim m_\chi$ $\quad$ $\Omega_\chi h^2 \sim e^{2\frac{m_Y - m_\chi}{m_\chi} x_F}$

COANNIHILATION

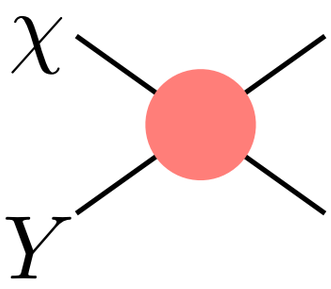


$\psi \leftrightarrow \chi$

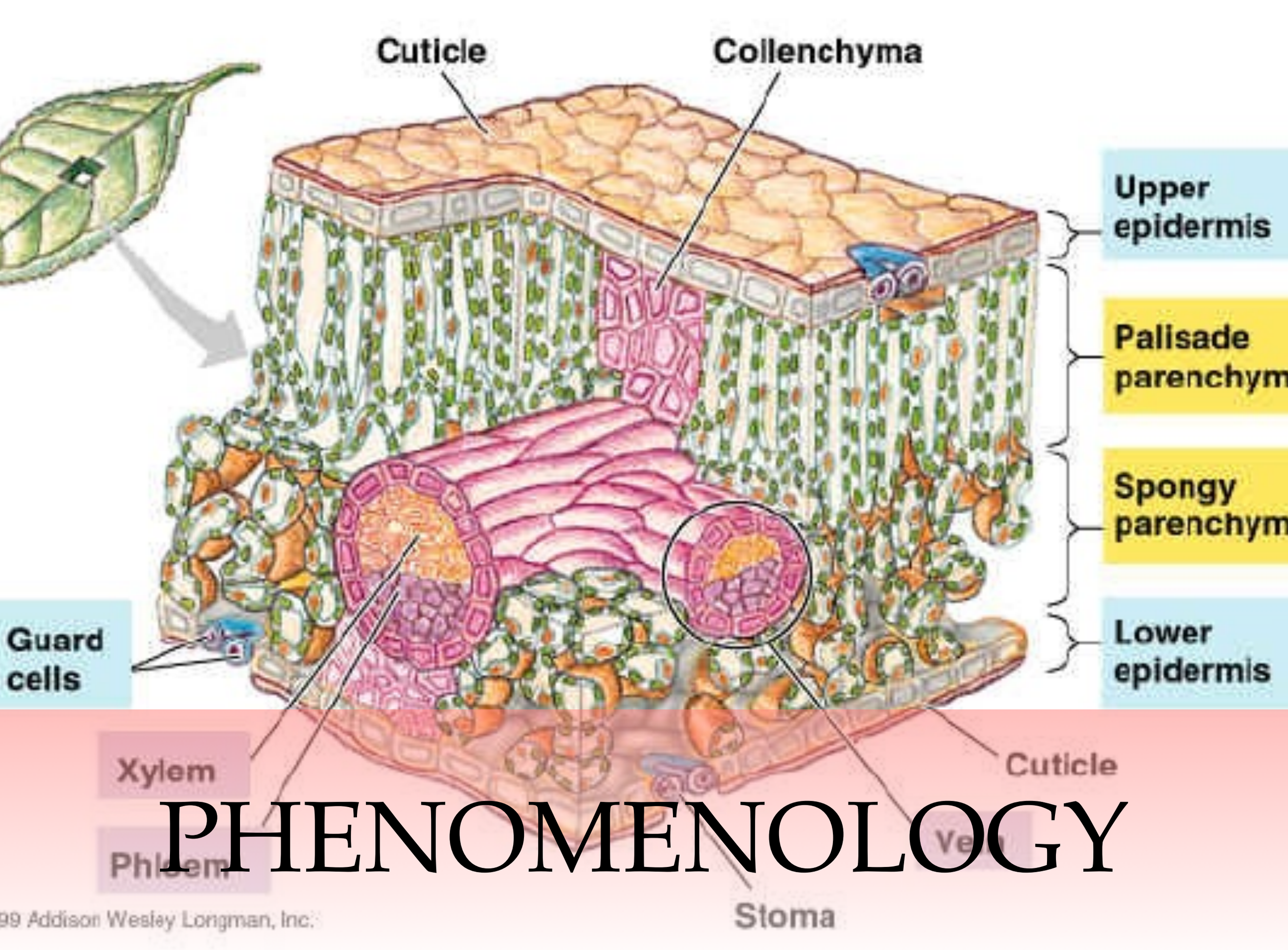
IN EQ.

$\Omega_\chi h^2 \sim e^{2\frac{m_\psi - m_\chi}{m_\chi} x_F}$

COSCATTERING



$m_Y \lesssim m_\chi$ $\quad$ $\Omega_\chi h^2 \sim e^{2\frac{m_\psi - m_\chi}{m_Y} x_F}$



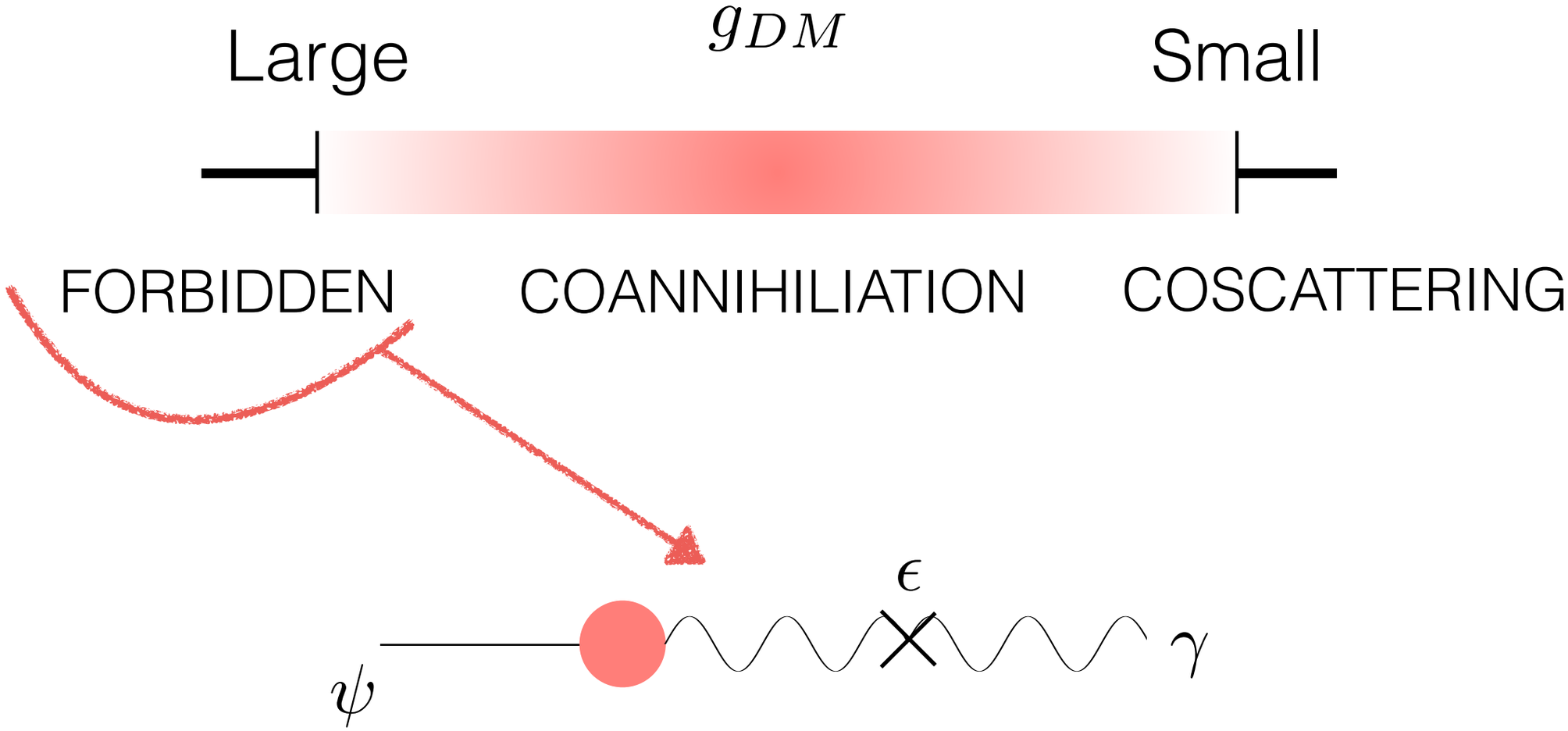
PHENOMENOLOGY

COUPLING TO THE SM

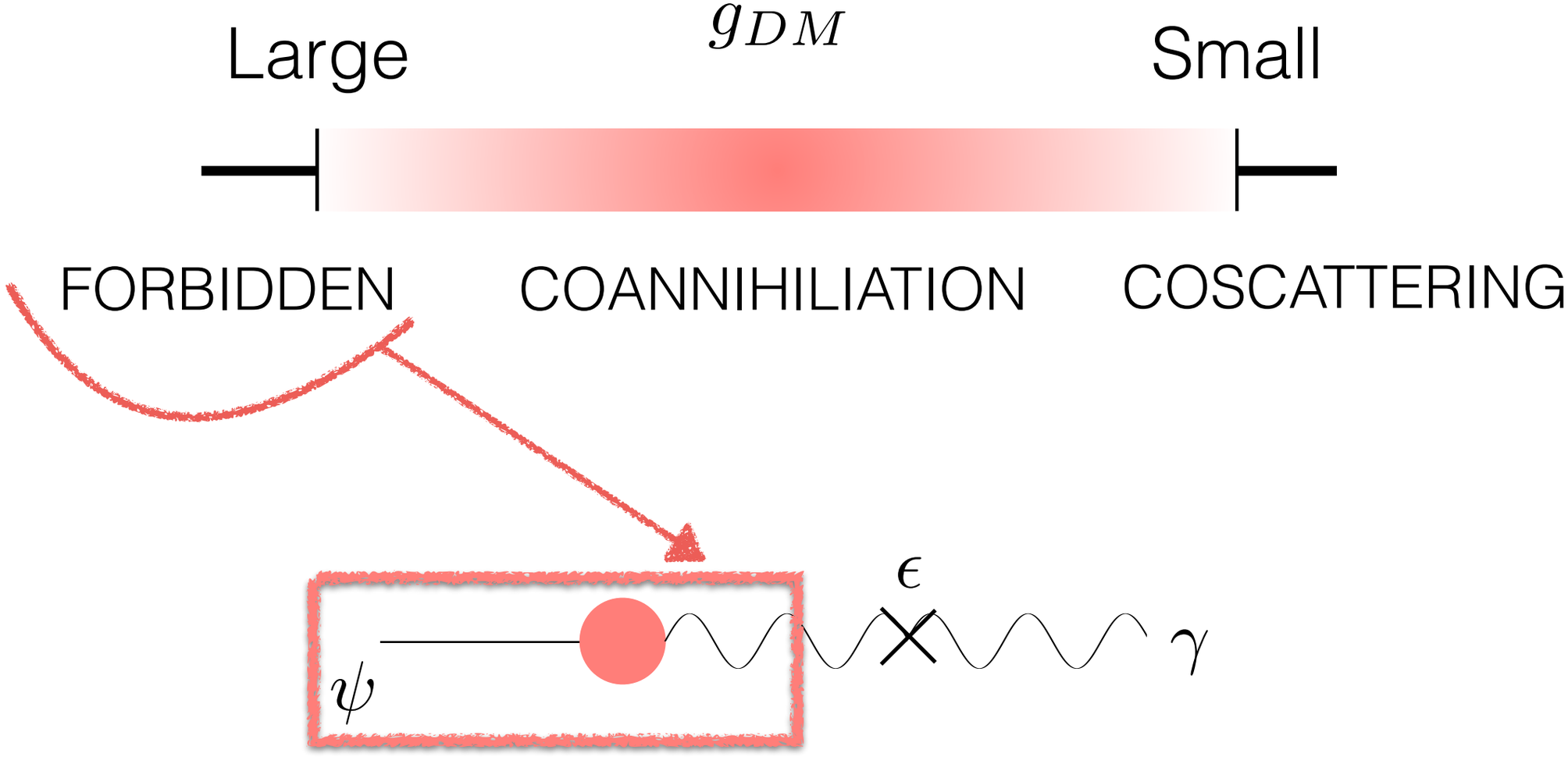
FORBIDDEN COANNIHILIATION COSCATTERING

N.B. IF PRESENT

FORBIDDEN


Large
g_{DM}
Small
FORBIDDEN
COANNIHILIATION
COSCATTERING
ϵ
ψ
γ

SELF-INTERACTIONS OF FORBIDDEN DM



SELF-INTERACTIONS

$$\frac{\sigma_{SI}}{\langle \sigma v \rangle} \approx 10^9 \frac{m_{DM}}{\mathrm{MeV}}$$

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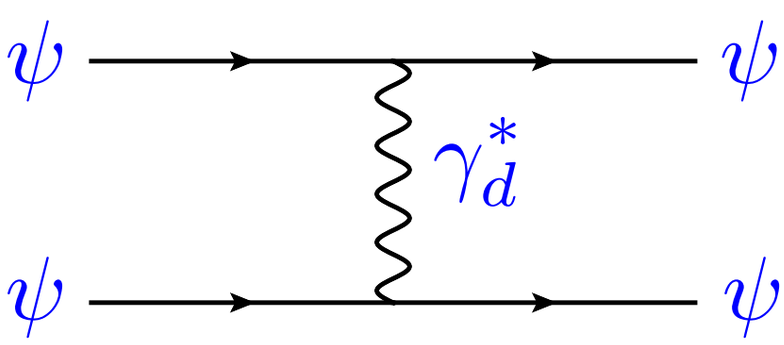
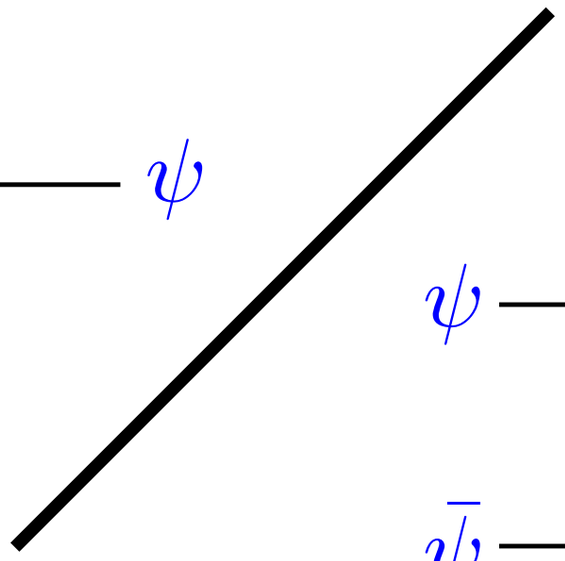
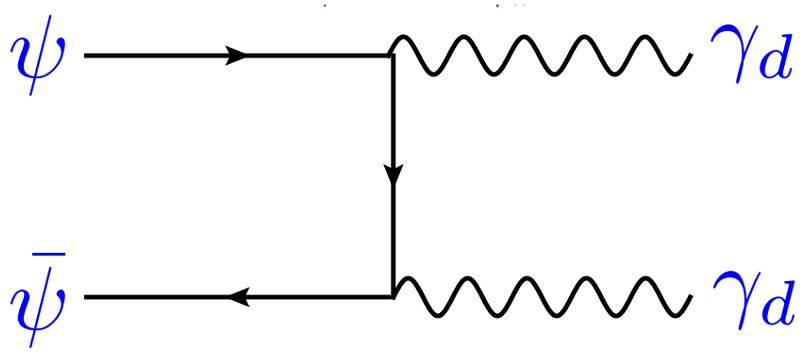
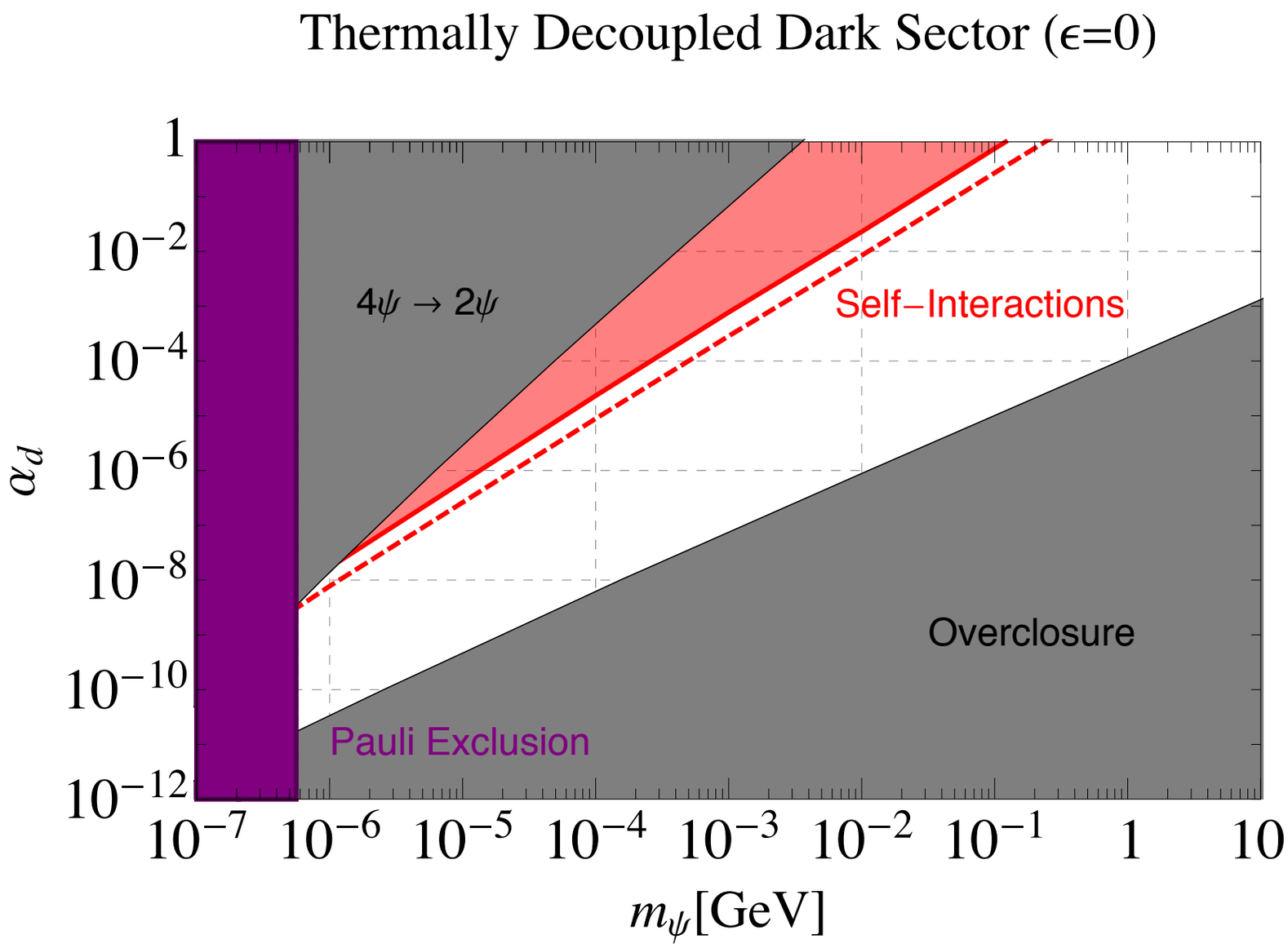






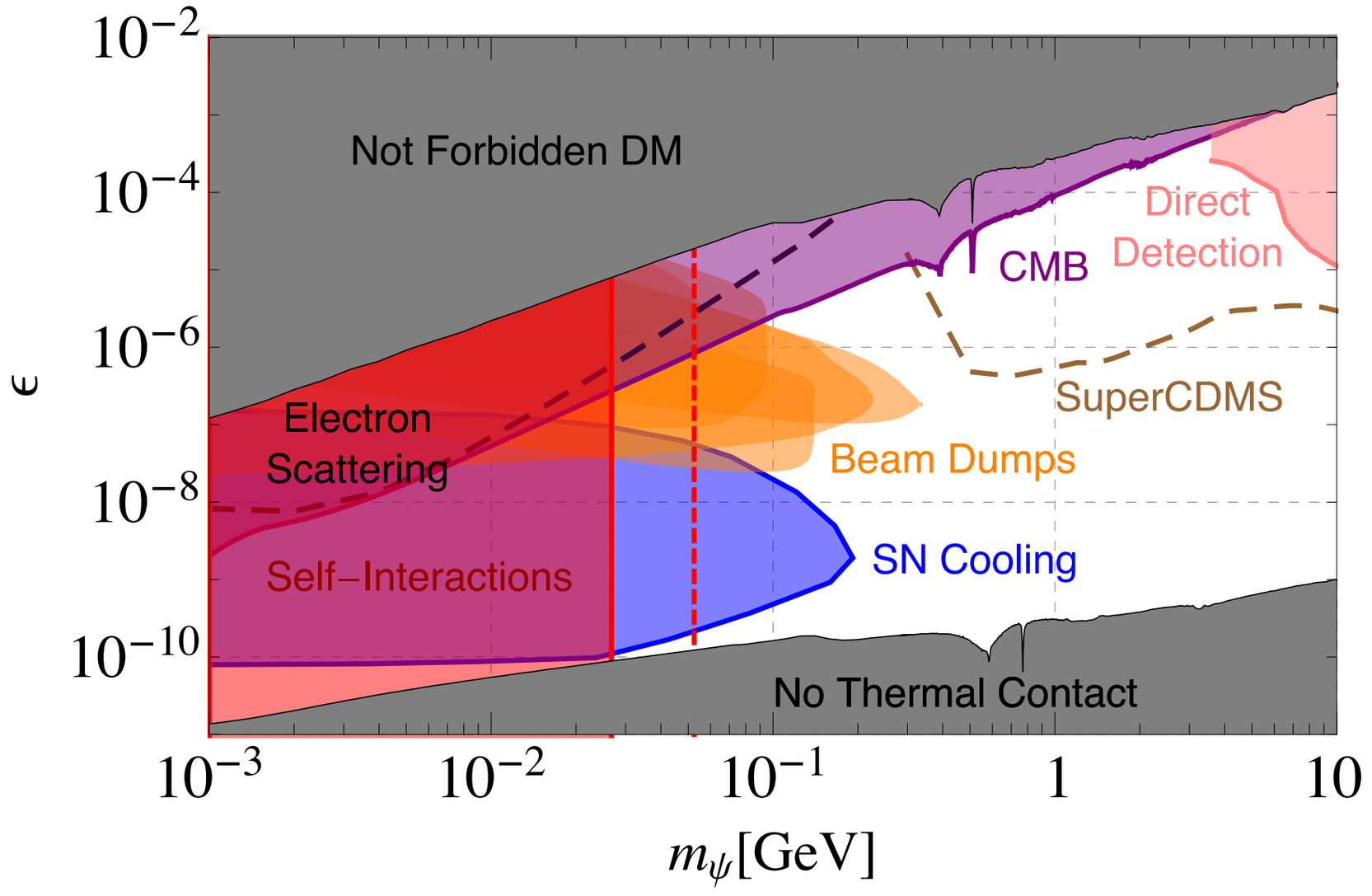
$$\sim e^{2x_F \Delta}$$

SELF-INTERACTIONS

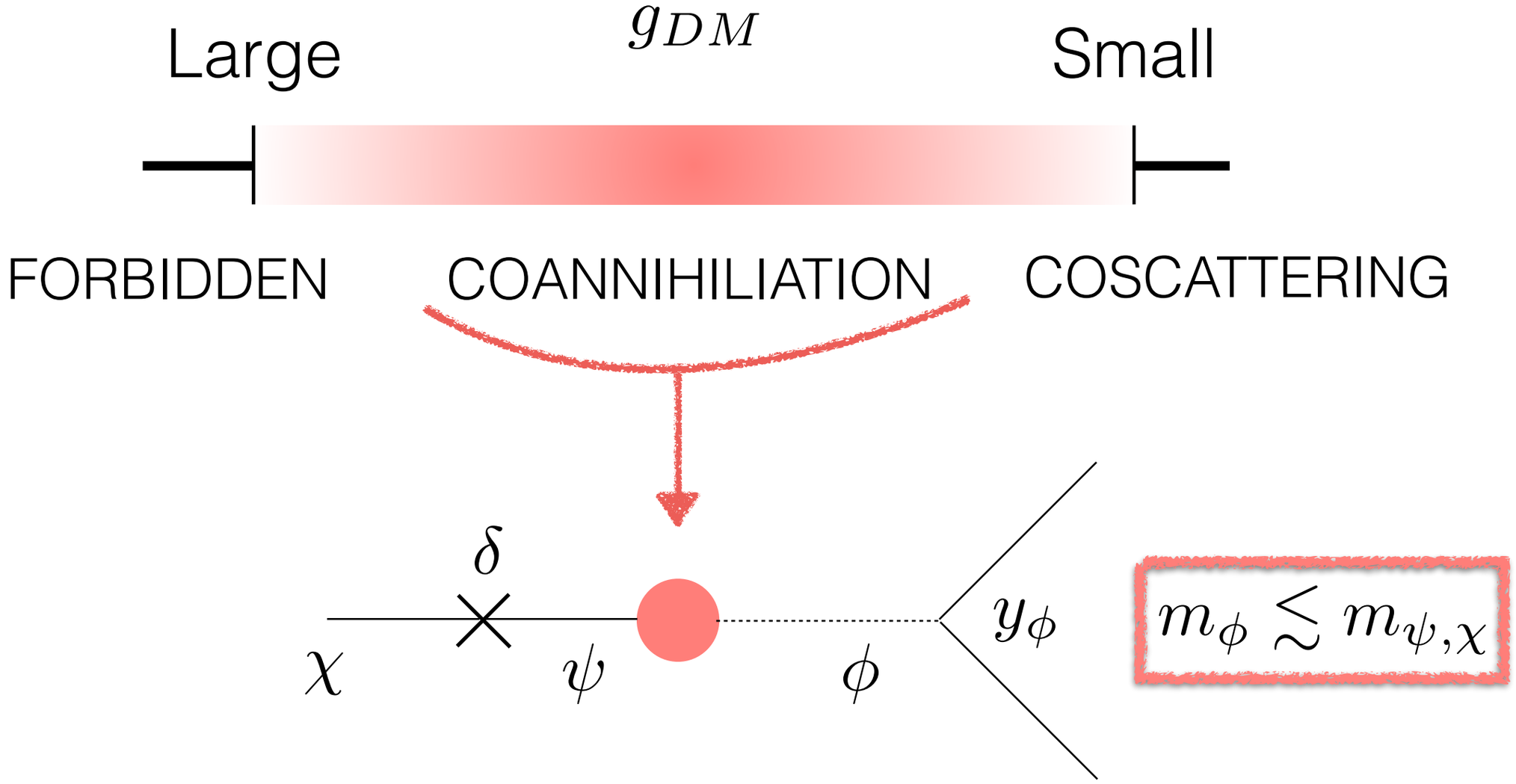


FORBIDDEN PHENOMENOLOGY

Signals from Kinetic Mixing (α_d=0.1)



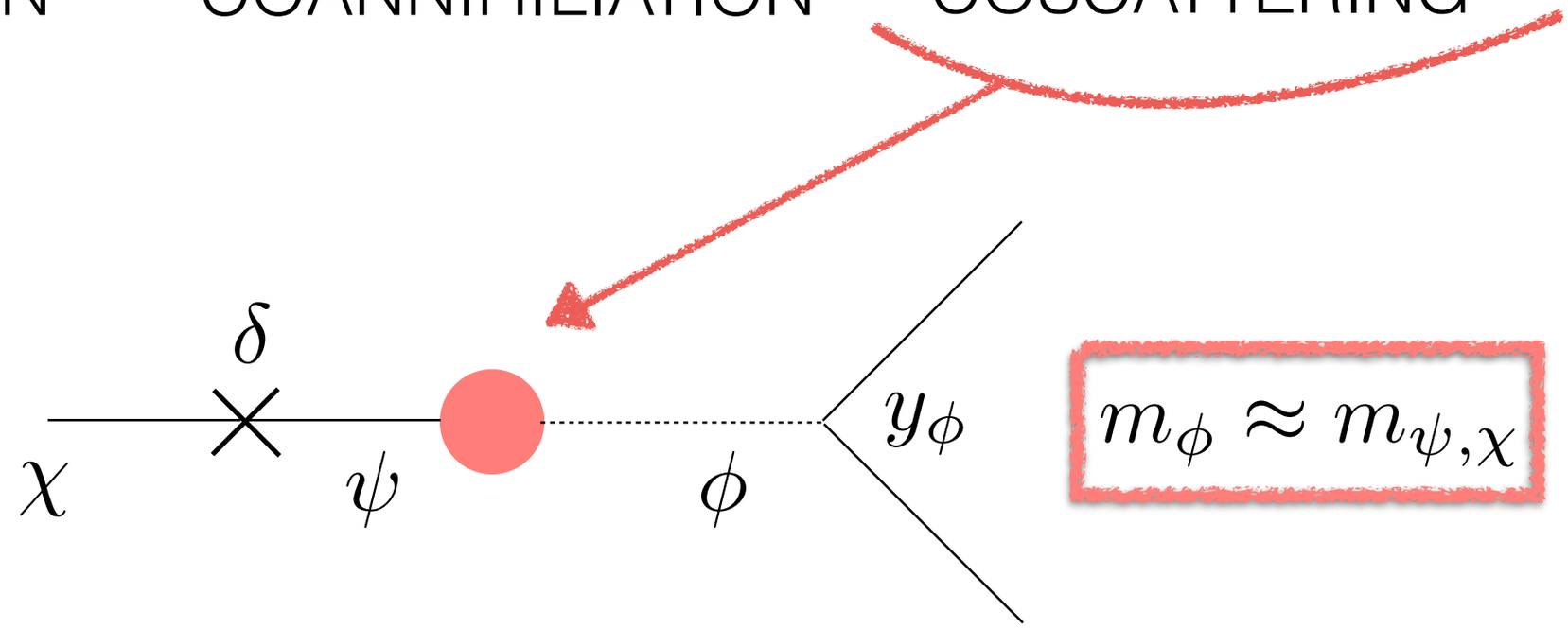
COANNIHILATION



COSCATTERING

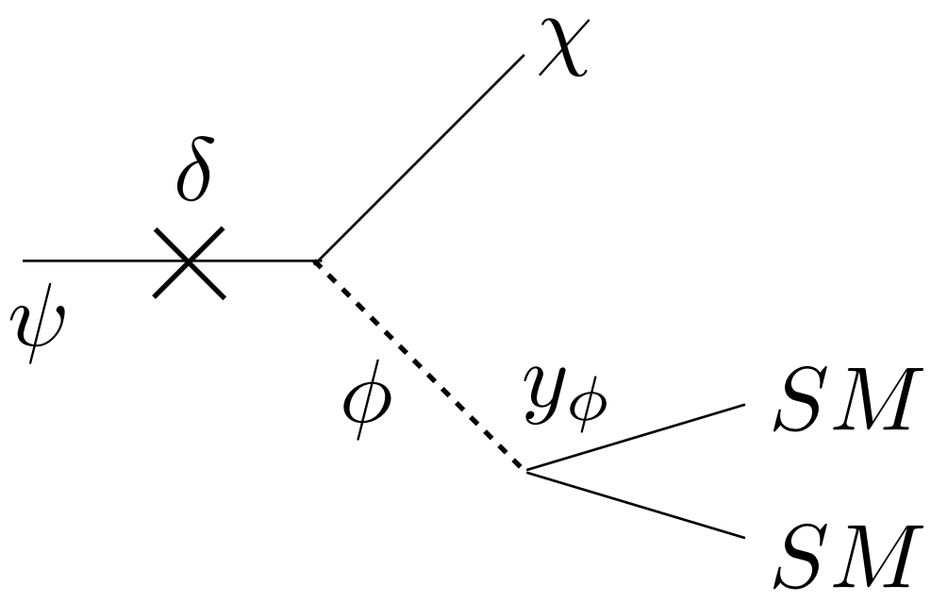
Large g_{DM} Small

FORBIDDEN COANNIHILIATION COSCATTERING



LATE TIME DECAYS

$$m_\phi \approx m_{\psi,\chi}$$



$$\delta, y_\phi \ll 1$$

BBN

$$\tau_\psi \gtrsim 1s$$

CMB

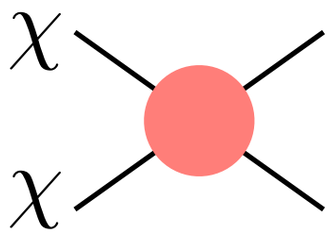
$$\tau_\psi \gtrsim 10^{12}s$$

CONCLUSION

- IF DARK MATTER ANNIHILATIONS REQUIRE FINITE TEMPERATURE OR MIXING WITH OTHER STATES
  - THE RELIC DENSITY CAN BE ENHANCED BY AN EXPONENTIAL BOLTZMANN FACTOR
  - $m_{DM} \sim v e^{-x_F \Delta}$
- JUST A SMALL STEP AWAY FROM A WIMP THERE IS A VARIETY OF THERMAL DARK MATTER MODELS WITH COMPLETELY DIFFERENT PHENOMENOLOGY
- FORBIDDEN CHANNEL ANNIHILATIONS, COANNIHILATION AND COSCATTERING ARE GENERAL MECHANISMS
  - RICH PHENOMENOLOGY: SELF-INTERACTIONS, LOW ENERGY DIRECT DETECTION, CMB, BBN, …
  - PLENTY OF MODEL BUILDING OPPORTUNITIES: FORBIDDEN SIMP, FORBIDDEN p-WAVE, FORBIDDEN INTO SM CHANNELS, … (AND COANNIHILATING SIMP, COANNIHILATING p-WAVE, …)

BACKUP

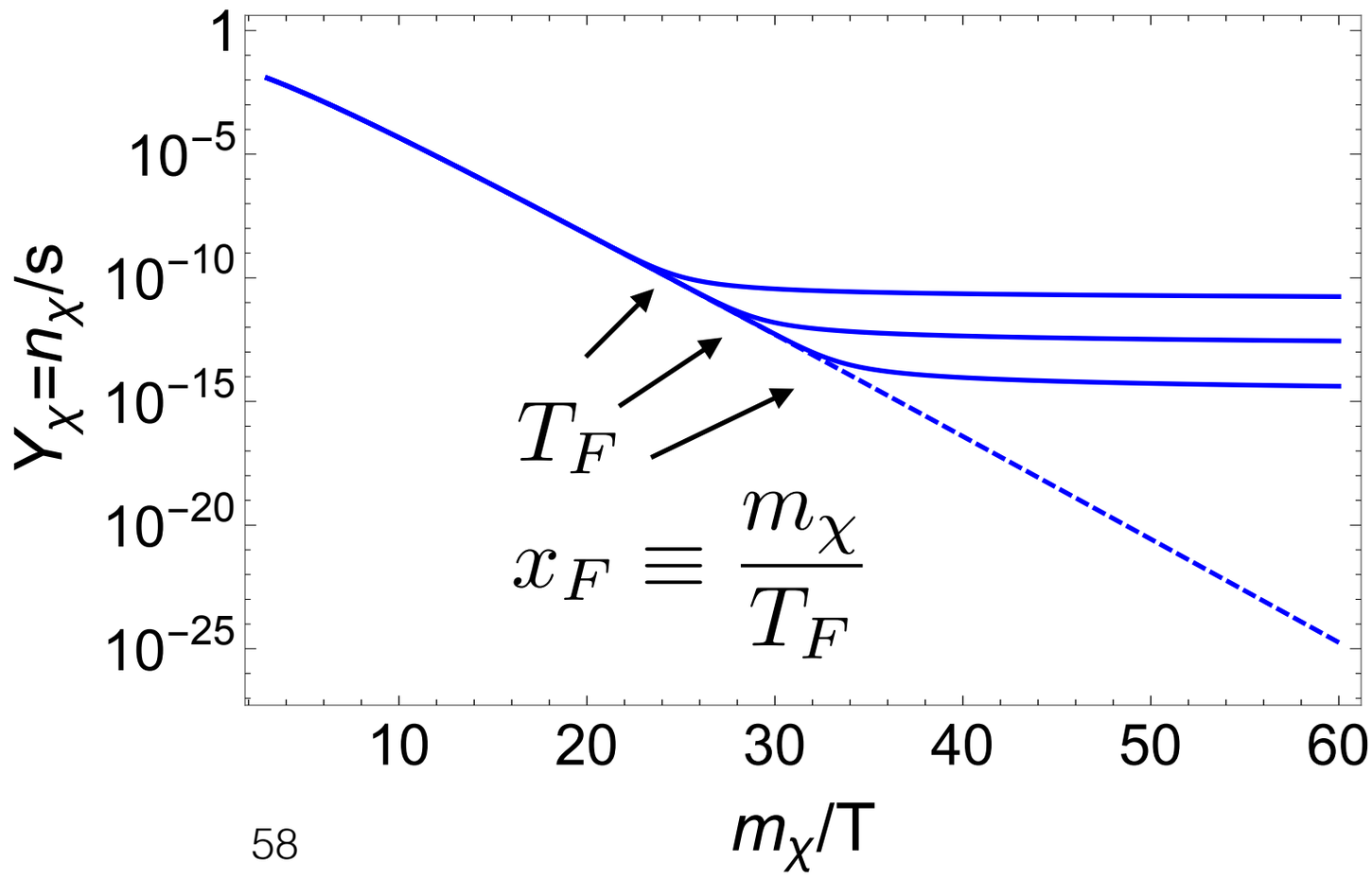
WIMPS AND MIRACLES



$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left[n_\chi^2 - \left(n_\chi^{eq}\right)^2\right]$$

$$n_\chi \sim e^{-x}$$

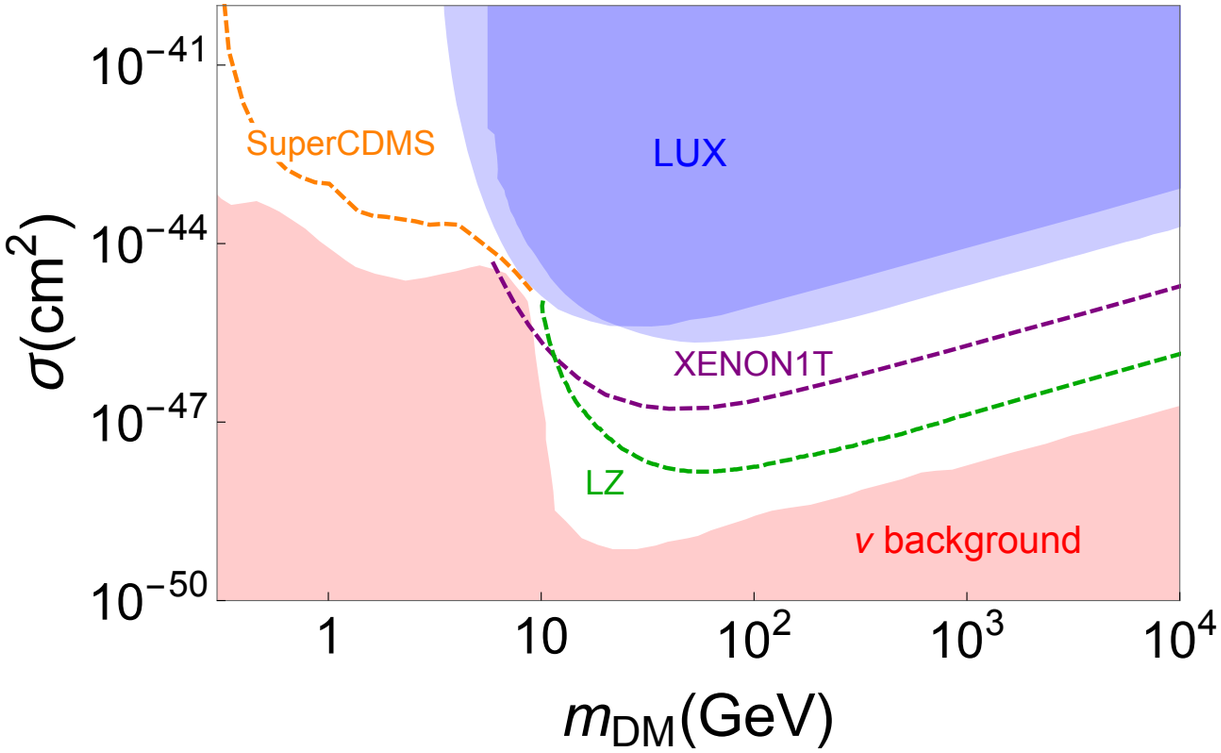
$$x_F \sim \log\frac{1}{\langle\sigma v\rangle}$$



LOW MASS DIRECT DETECTION

S. Derenzo, R. Essig, A.Massari, A.Soto, T.-T. Yu

2016



Detecting Ultralight Bosonic Dark Matter via Absorption in Superconductors

Yonit Hochberg,[1] Tongyan Lin,[1] and Kathryn M. Zurek[1]

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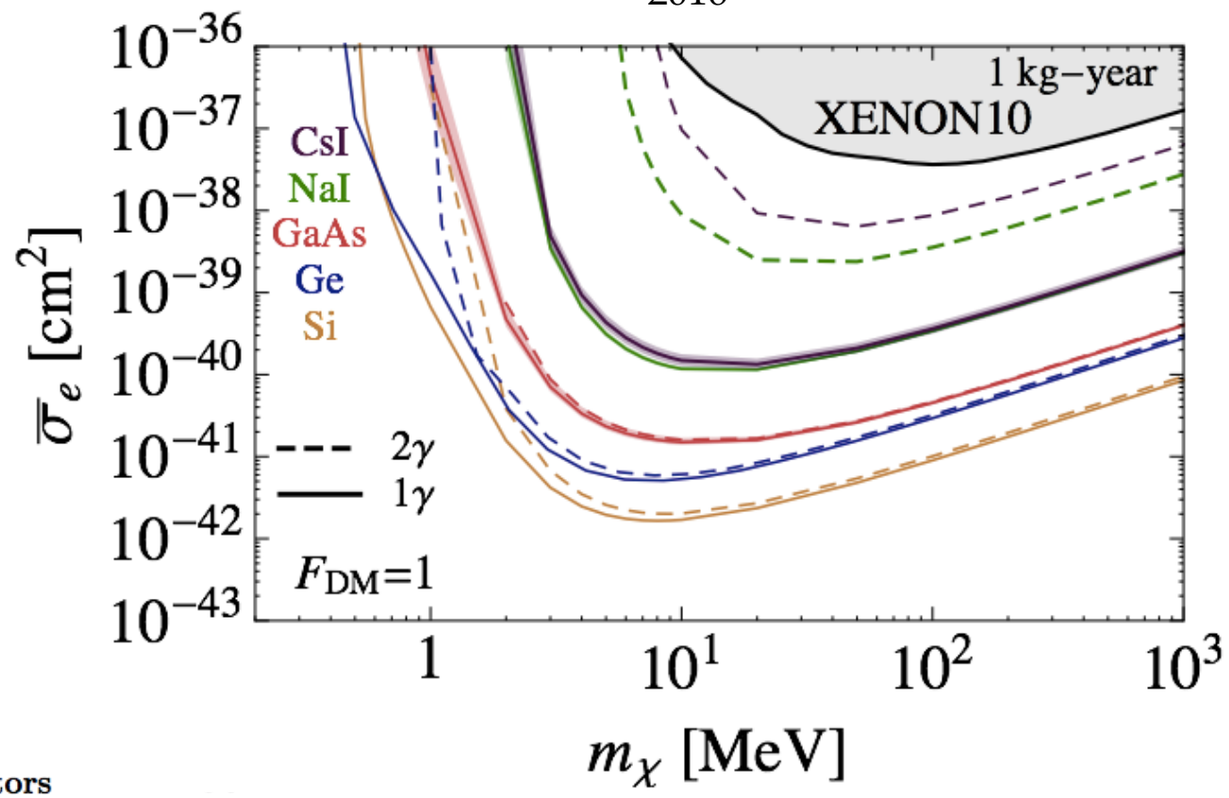
Berkeley Center for Theoretical Physics, University of California, Berkeley, CA 94720

Absorption of light dark matter in semiconductors

Yonit Hochberg,* Tongyan Lin,† and Kathryn M. Zurek‡
Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720
Berkeley Center for Theoretical Physics, University of California, Berkeley, CA 94720

(Dated: August 9, 2016)



On the Detectability of Light Dark Matter with Superfluid Helium

Katelin Schutz[1] and Kathryn M. Zurek[1]

[1] *Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720*
Berkeley Center for Theoretical Physics, University of California, Berkeley, CA 94720

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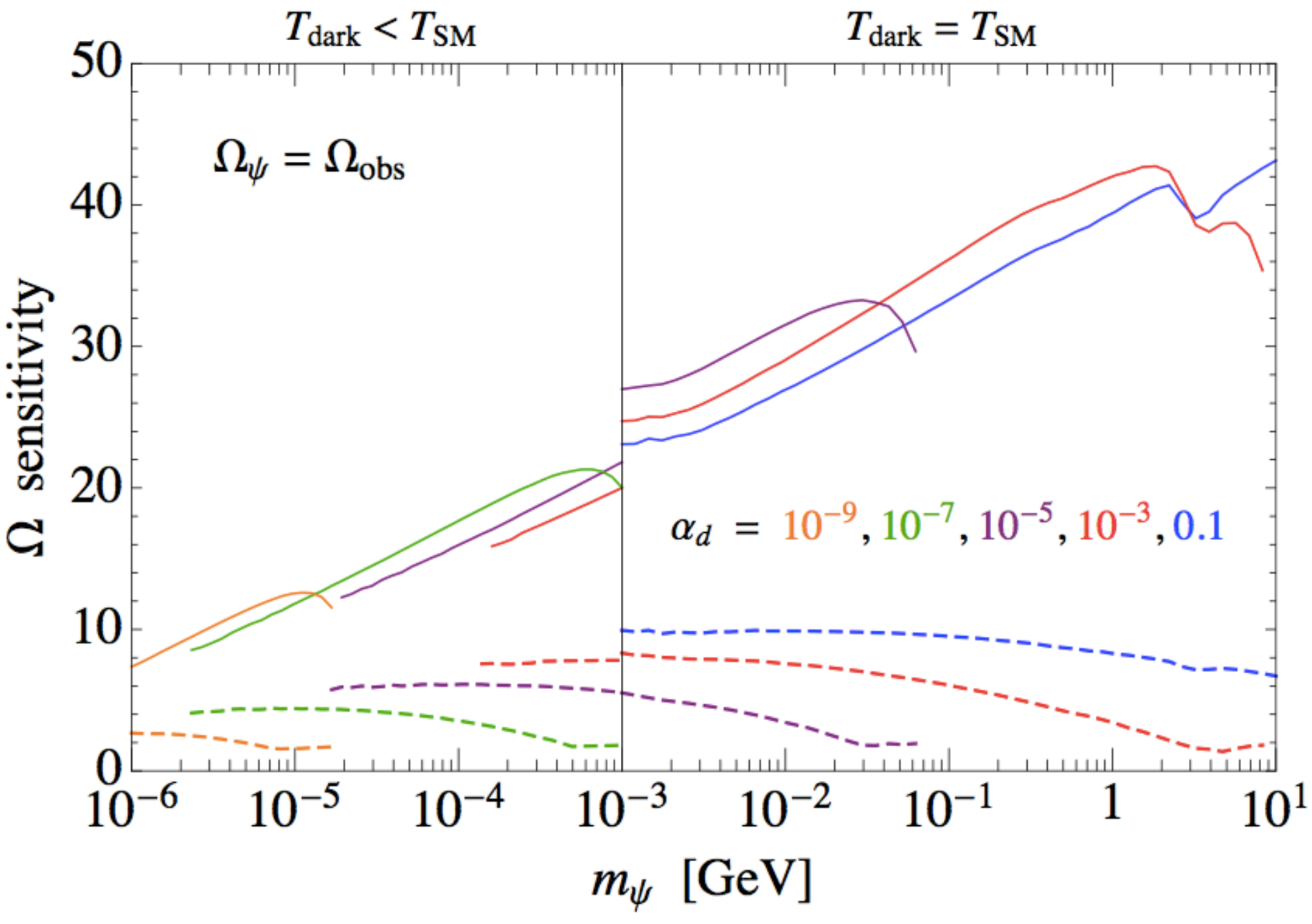
FORBIDDEN TUNING

$$\frac{d\log\Omega}{d\log p_i}$$

$$p_i = (m_\psi, m_{\gamma_d})$$
$$= (m_\psi, \Delta)$$



COUPLING TO THE SM