

Title: Light Dark Matter from Boltzmann Tails

Date: May 17, 2016 01:00 PM

URL: <http://pirsa.org/16050010>

Abstract:

Dark matter can be a thermal relic exponentially lighter than
the weak scale without being exponentially weakly coupled. I will present
three mechanisms to obtain light thermal dark matter with sizable
self-interactions and couplings to the Standard Model.

LIGHT DARK MATTER FROM BOLTZMANN TAILS



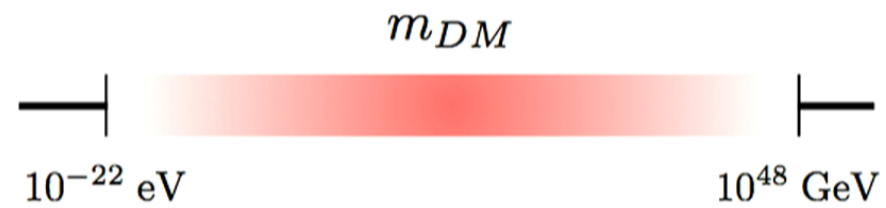
Raffaele Tito D'Agnolo - IAS
5/17/2016 Perimeter Institute



OUTLINE

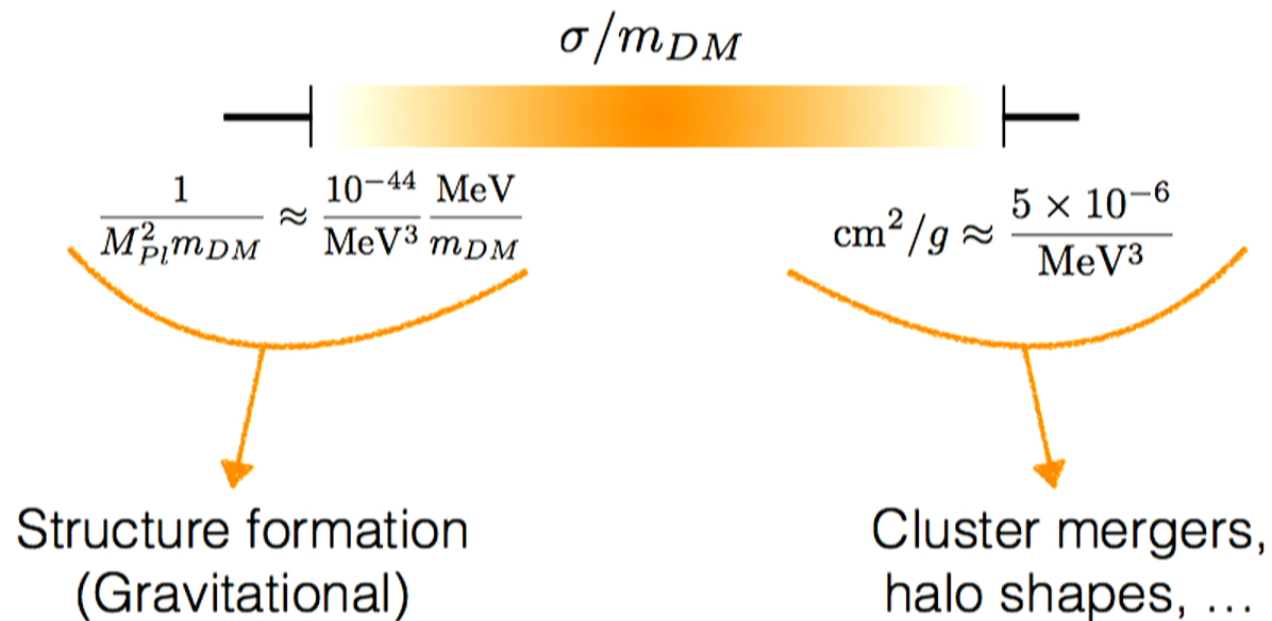
- THERMAL RELCS IN THE $\alpha_d - m_{DM}$ PLANE
- FORBIDDEN DARK MATTER
 - THE MECHANISM
 - DETAILS AND PHENOMENOLOGY
- COANNIHILATION AND COSCATTERING

THE DARK MATTER MASS



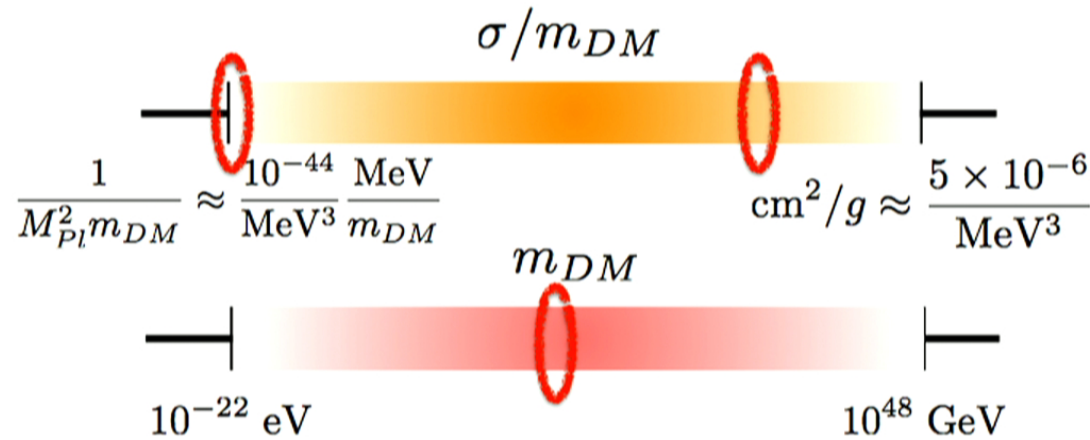
80 ORDERS OF MAGNITUDE

DARK MATTER SELF-INTERACTIONS

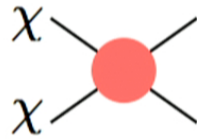


WIMPS AND MIRACLES

MOST OF THE MODEL BUILDERS ATTENTION HAS BEEN FOCUSED IN A TINY FRACTION OF PARAMETER SPACE



WIMPS AND MIRACLES



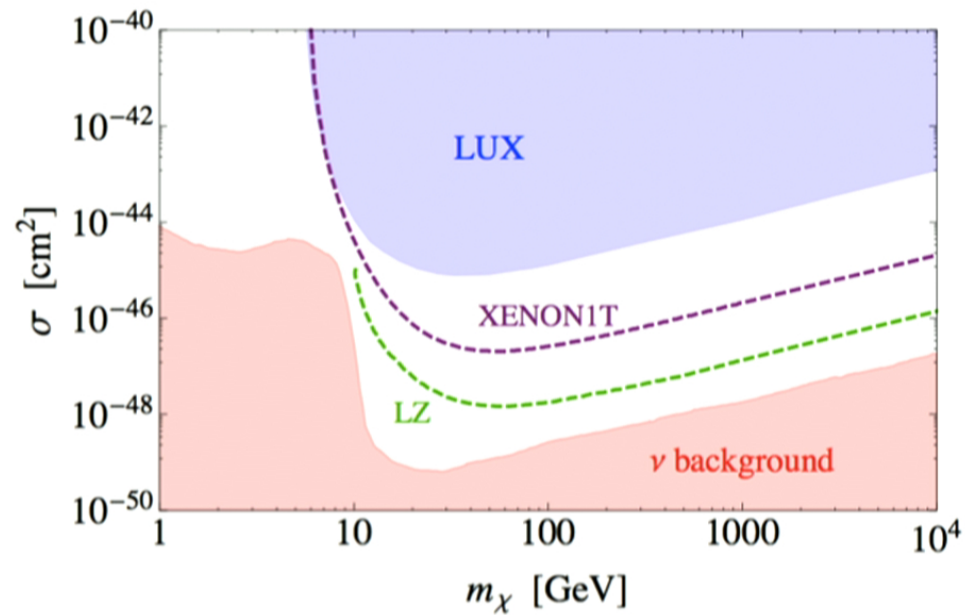
$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle [n_\chi^2 - (n_\chi^{eq})^2]$$

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

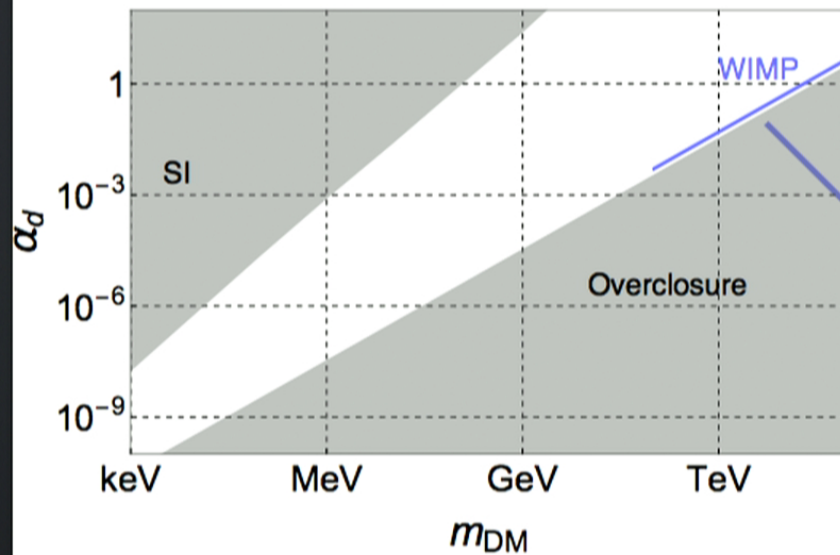
$$\langle\sigma v\rangle_F \approx \frac{1}{(20 \text{ TeV})^2}$$

WIMPS AND MIRACLES

AND THE WINDOW IS CLOSING



THERMAL RELICS

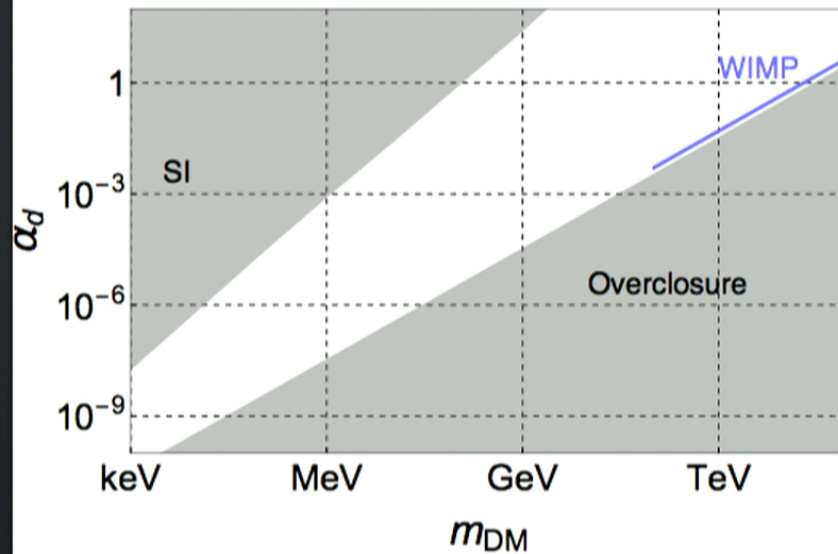


$$\Omega_{DM} h^2 \sim \frac{1}{\langle \sigma v \rangle_F}$$

$$\langle \sigma v \rangle_F \sim \frac{\alpha_d^2}{m_{DM}^2}$$

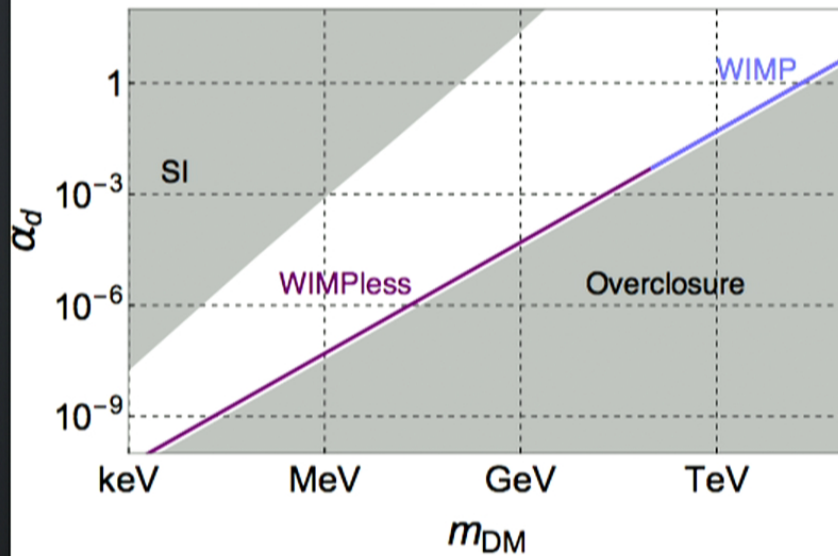
$$\alpha_d \sim \alpha_W, \quad m \sim m_Z$$

THERMAL RELICS



Semi-Annihilation
D'Eramo, Thaler
1003.5912
Not parametrically different

THERMAL RELICS



WIMPless Miracle

Feng, Kumar 0803.4196

$$\alpha_d \sim \frac{m}{20 \text{ TeV}}$$

$$m \ll m_Z$$

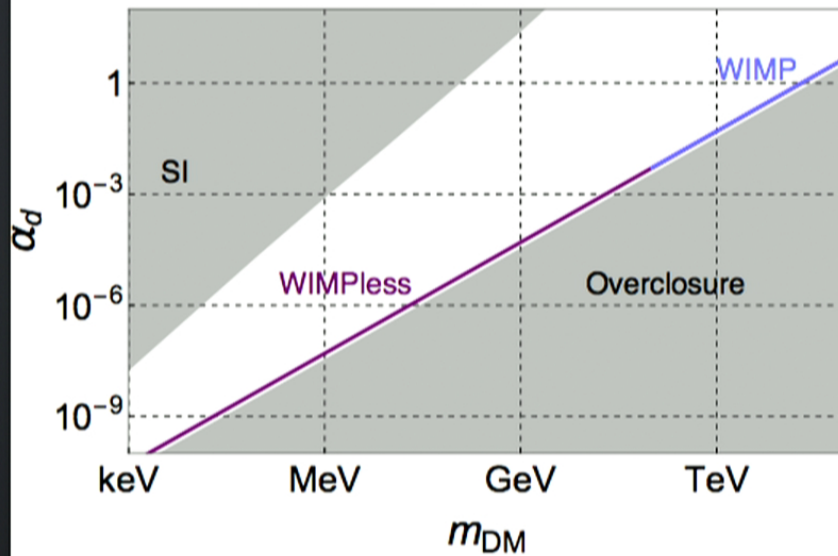
Heavy Mediators

Bohem, Fayet

hep-ph/0305261

$$\langle \sigma v \rangle_F \sim m_{DM}^2 / \Lambda^4$$

THERMAL RELICS



WIMPless Miracle

Feng, Kumar 0803.4196

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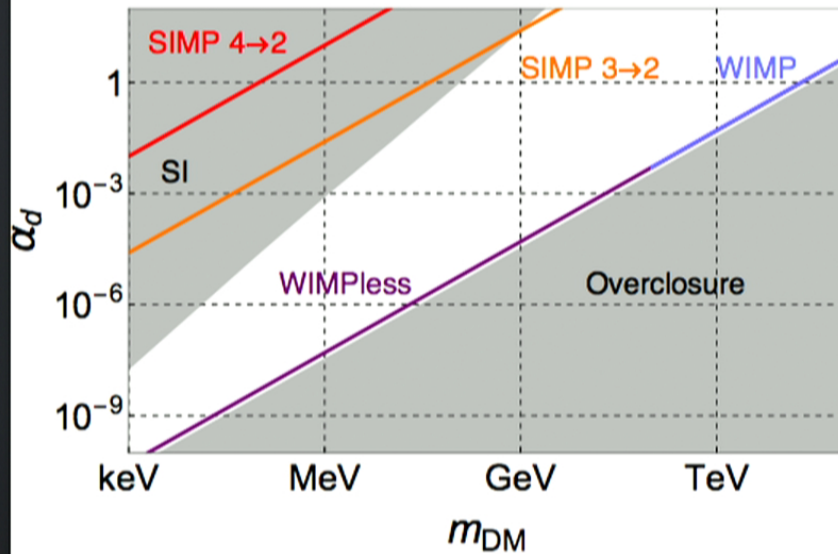
Heavy Mediators

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$$\langle \sigma v \rangle_F \sim m_{DM}^2 / \Lambda^4$$

THERMAL RELICS



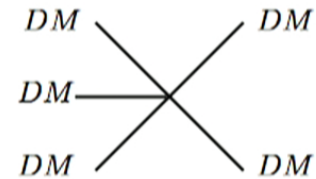
SIMP Miracle

Carlson, Hall, Machacek

Astrophys.J. 398 (1992) 43-52

Hochberg, Kuflick, Volansky, Wacker

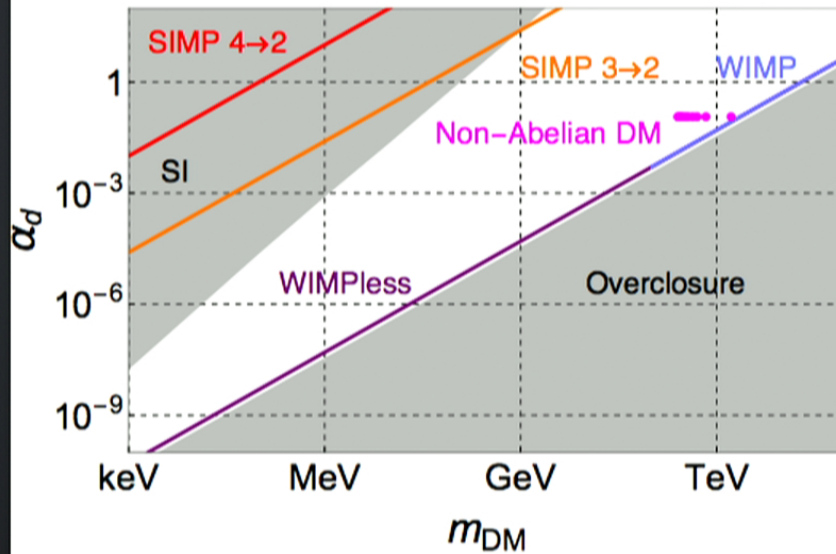
1402.5143



$$m_{DM} \sim \alpha_d (T_{eq} M_{Pl})^{1/3}$$

$$\approx 100 \text{ MeV}$$

THERMAL RELICS



Non-Abelian DM

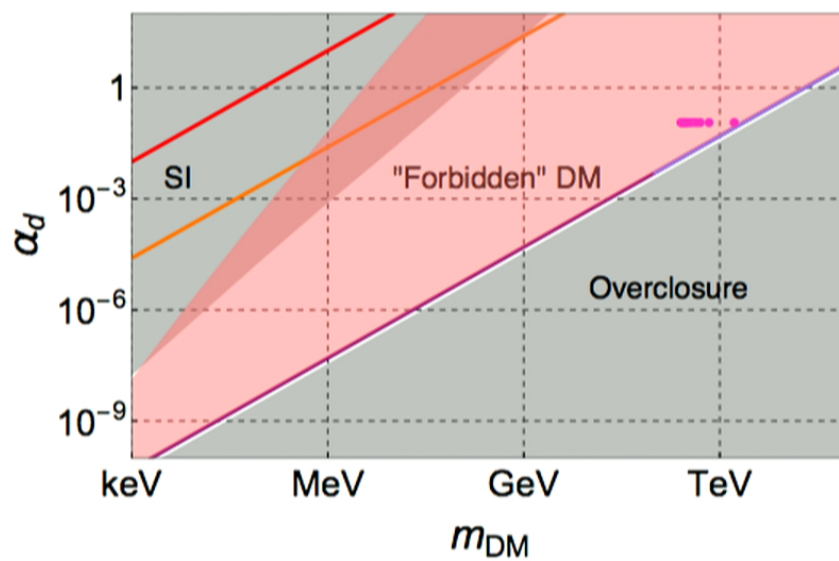
Buen-Abad, Marques-Tavares,

Schmaltz

1505.03542

$$\langle \sigma v \rangle_F \sim \frac{1}{N} \frac{\alpha_W^2}{m_W^2}$$

TODAY



FORBIDDEN DARK MATTER



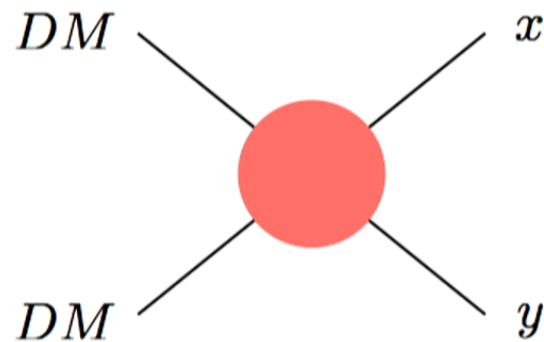
RTD, J. Ruderman
Phys.Rev.Lett. 115 (2015) 6, 061301

THREE EXCEPTIONS

- FORBIDDEN CHANNEL ANNIHILATIONS
- COANNIHILATION
- ANNIHILATION NEAR A POLE

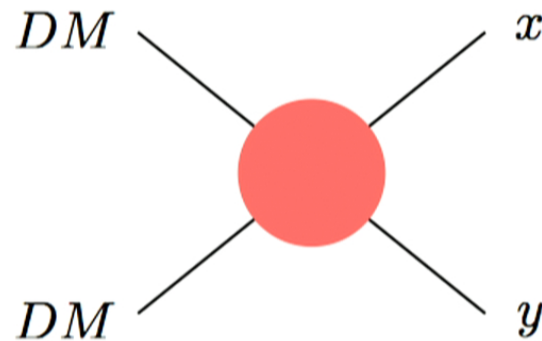
Griest and Seckel
Phys.Rev. D43 (1991) 3191-3203

FORBIDDEN CHANNEL ANNIHILATIONS



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

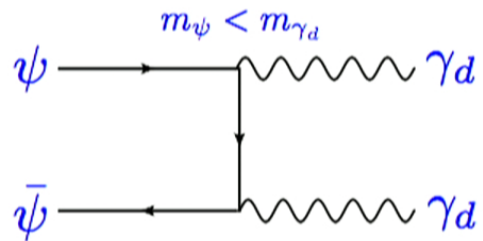
FORBIDDEN CHANNEL ANNIHILATIONS



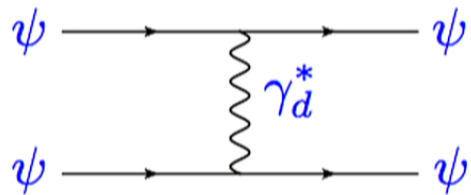
$$\langle \sigma v \rangle_F \sim \frac{\alpha_d^2}{m_{DM}^2} e^{-x_F \Delta}$$

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

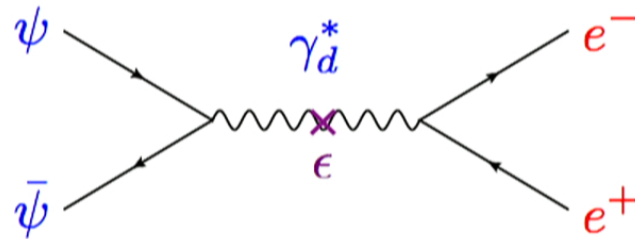
1) forbidden annihilations:



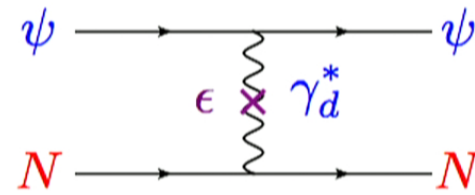
2) self-interactions:



3) indirect detection:

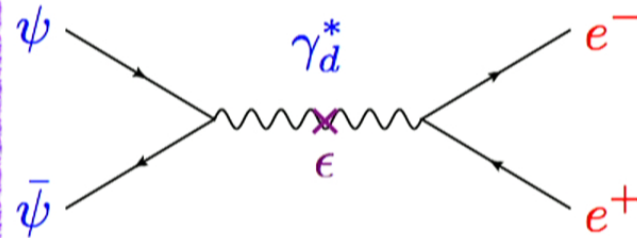


4) direct detection:

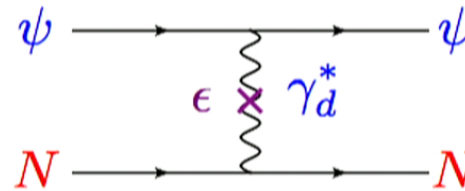


$$\mathcal{L} \supset \epsilon F_{\mu\nu}^d F_{SM}^{\mu\nu}$$

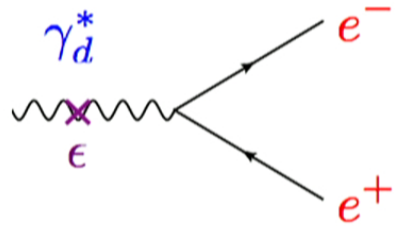
3) indirect detection:



4) direct detection:



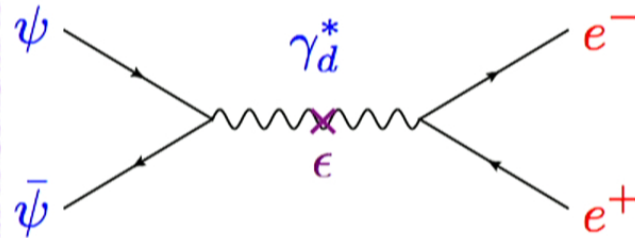
$$\mathcal{L} \supset \epsilon F_{\mu\nu}^d F_{SM}^{\mu\nu}$$



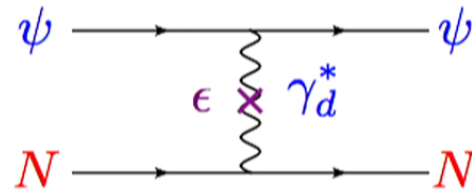
$$n_{\gamma_d} = n_{\gamma_d}^{eq}$$

$$T_{\text{dark}} = T_{\text{SM}} \sim a^{-1}$$

3) indirect detection:

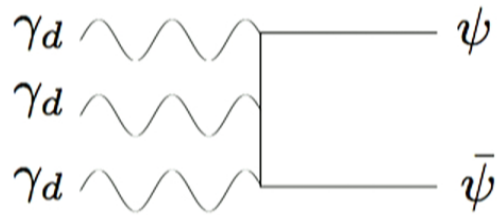


4) direct detection:



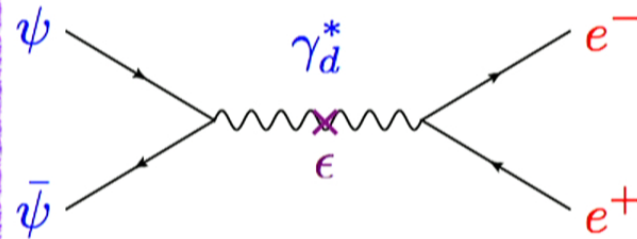
$$\mathcal{L} \supset \epsilon F_{\mu\nu}^d F_{SM}^{\mu\nu}$$

$$\epsilon = 0$$

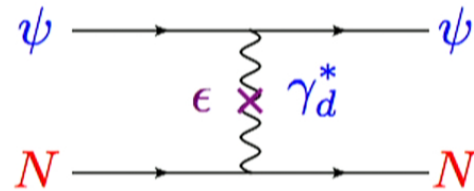


$$m \rightarrow T$$

3) indirect detection:



4) direct detection:



$$\mathcal{L} \supset \epsilon F_{\mu\nu}^d F_{SM}^{\mu\nu}$$

$$\epsilon = 0$$

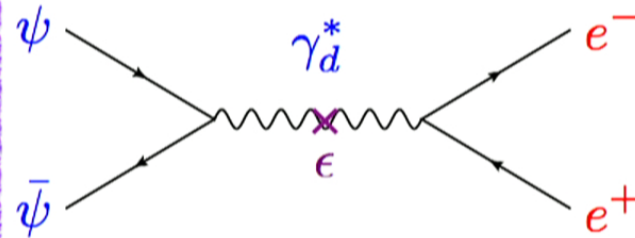
$$T_{\text{dark}} \sim \log a^{-1}$$

$$T_{\text{SM}} \sim a^{-1}$$

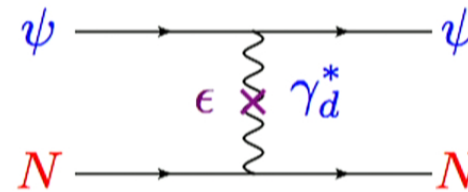
Carlson, Hall, Machacek

Astrophys.J. 398 (1992) 43-52

3) indirect detection:

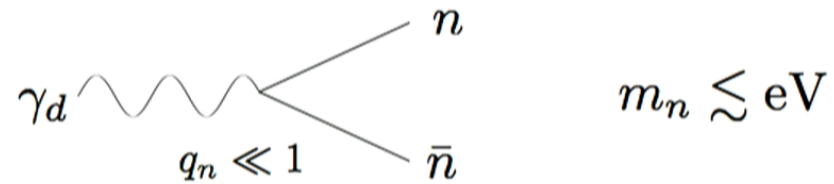


4) direct detection:



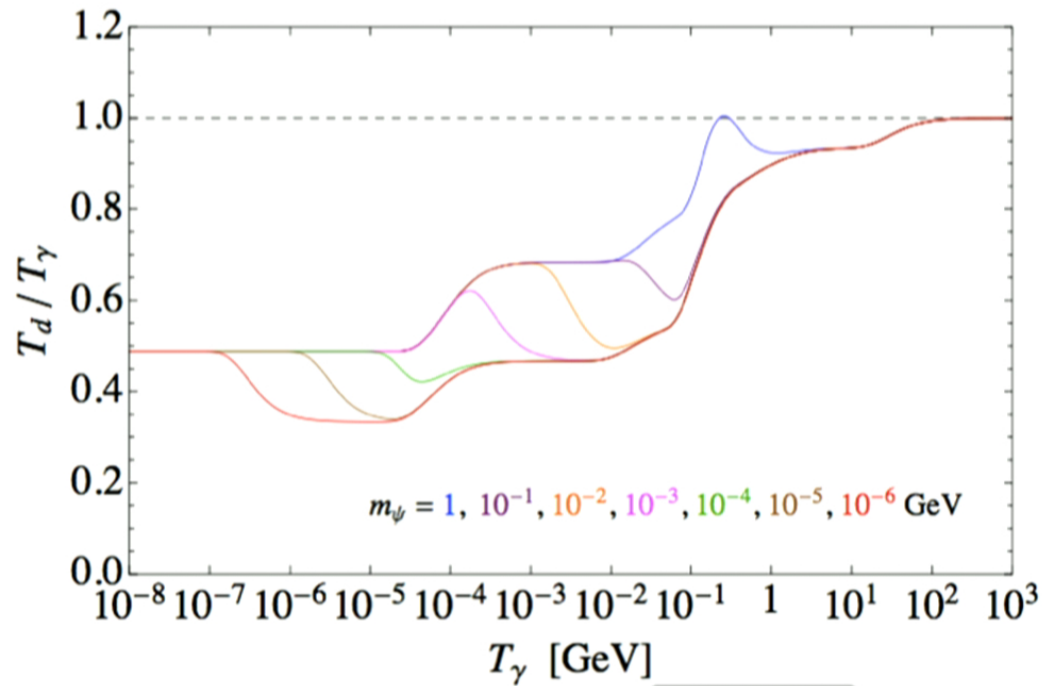
FROM DARK SECTOR COOLING

DARK RADIATION



$$T_{\text{dark}} = T_n \sim a^{-1}$$

DARK RADIATION



$$N_{\text{eff}} \sim (T_d/T_\gamma)^4$$

$$\Omega_n h^2 \sim (T_d/T_\gamma)^3$$

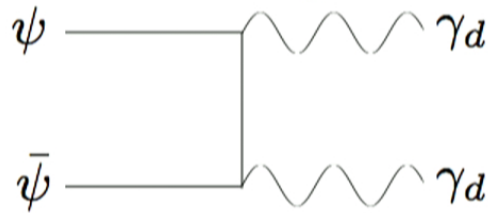
No problem with
overclosure and
Hubble

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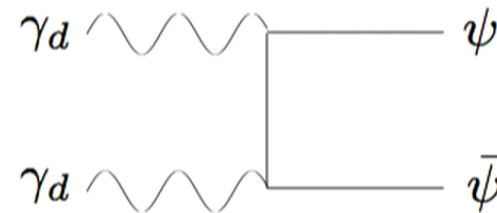
29

RELIC DENSITY

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



Forbidden



RELIC DENSITY

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

↓
in
equilibrium

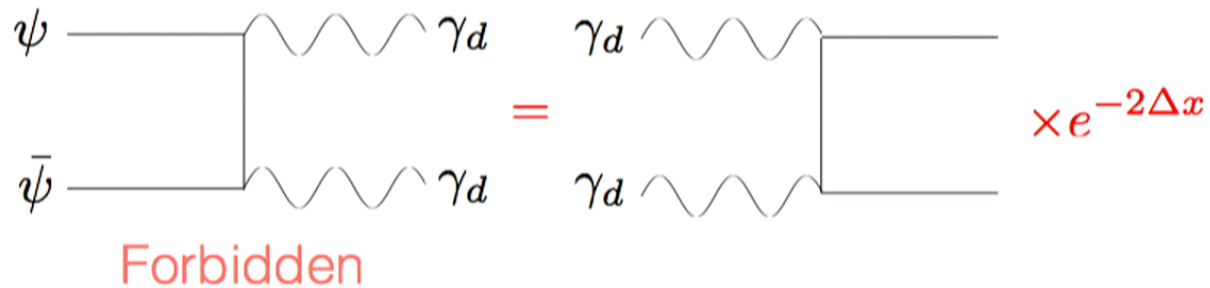
RELIC DENSITY

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

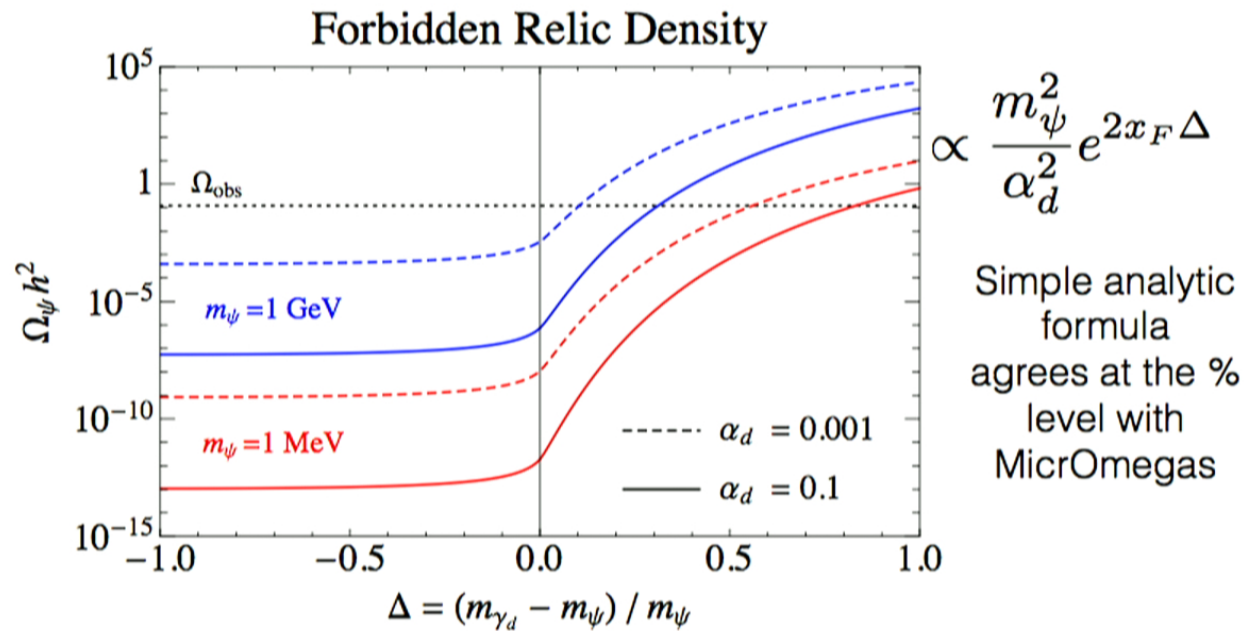
$$\langle \sigma_{\psi\bar{\psi}} v \rangle = \frac{(n_{\gamma_d}^{eq})^2}{(n_\psi^{eq})^2} \langle \sigma_{\gamma_d\gamma_d} v \rangle \approx 8\pi f_\Delta \frac{\alpha_d^2}{m_\psi^2} e^{-2\Delta x}$$

RELIC DENSITY

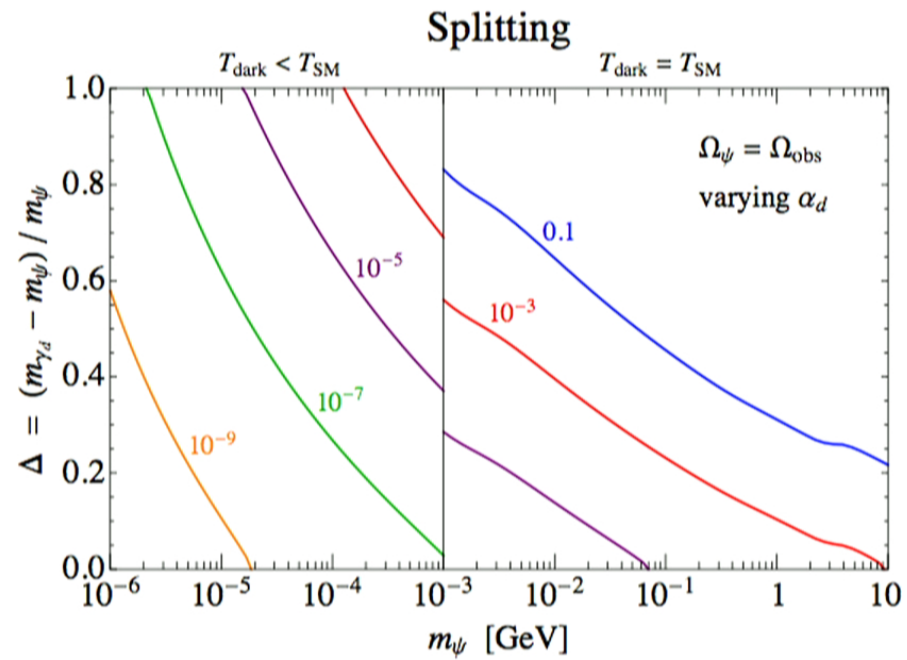
$$\dot{n}_\psi + 3Hn_\psi = -\langle \sigma_{\psi\bar{\psi}} v \rangle n_\psi^2 + \langle \sigma_{\gamma_d\gamma_d} v \rangle (n_{\gamma_d}^{eq})^2$$



RELIC DENSITY



RELIC DENSITY

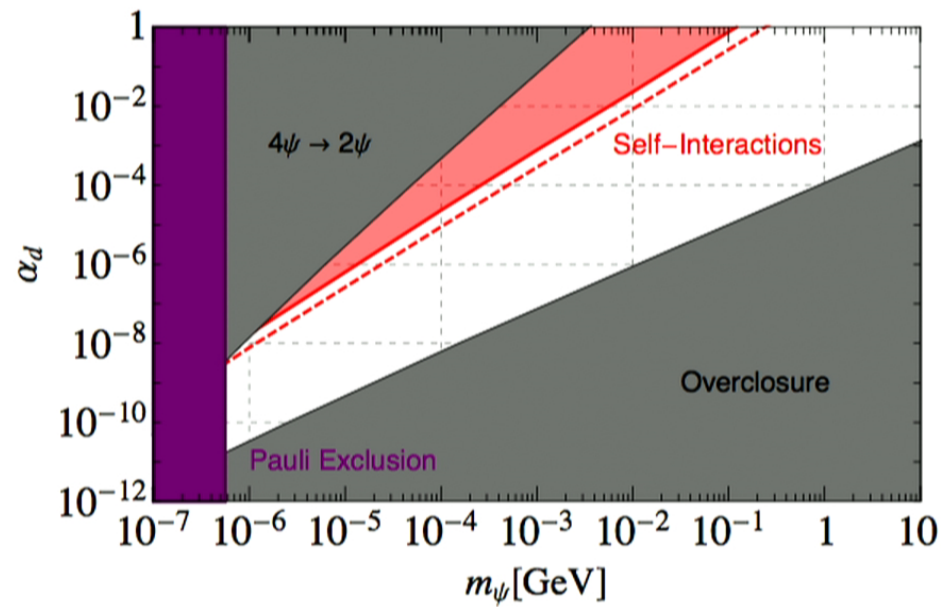


SELF-INTERACTIONS

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

SELF-INTERACTIONS

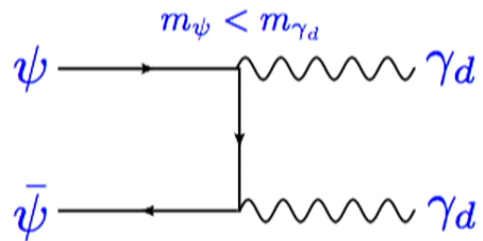
Thermally Decoupled Dark Sector ($\epsilon=0$)



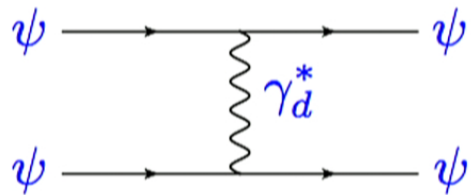
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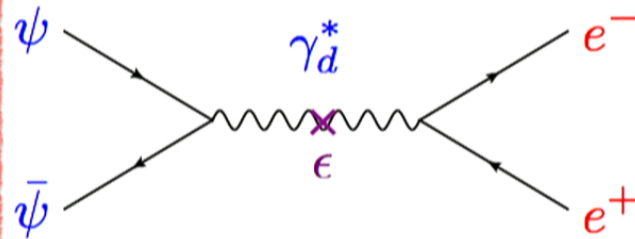
1) forbidden annihilations:



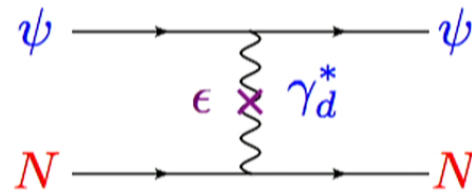
2) self-interactions:



3) indirect detection:

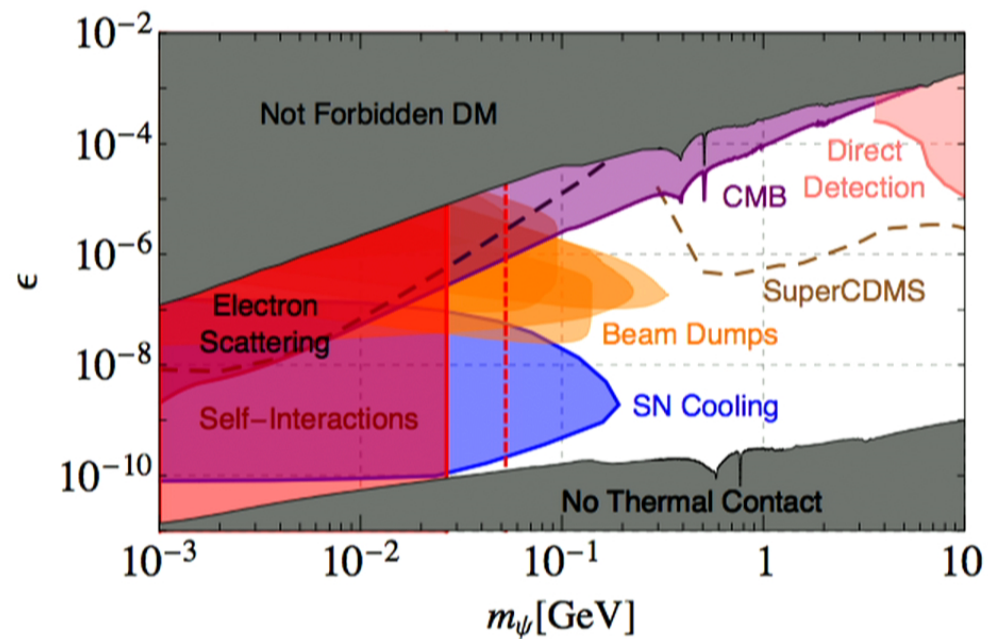


4) direct detection:



ALL THE SIGNALS

Signals from Kinetic Mixing ($\alpha_d=0.1$)

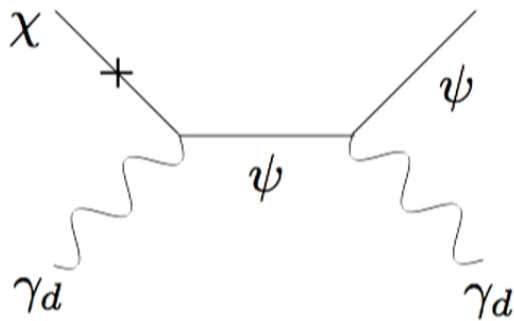


RTD, F. D'Eramo, J. Ruderman
In preparation



COANNIHILATION AND COSCATTERING

COANNIHILATION

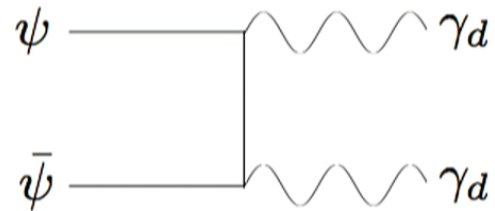
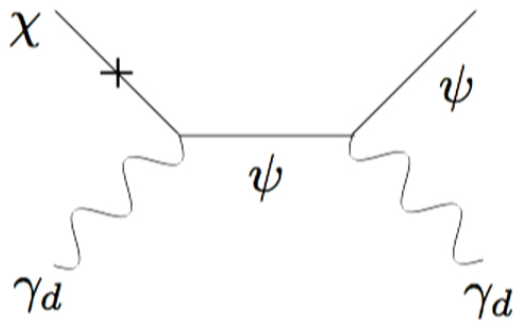


$\chi = \text{DARK MATTER}$

$\Gamma(\chi \rightarrow \psi)$ IN EQUILIBRIUM

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

COANNIHILATION



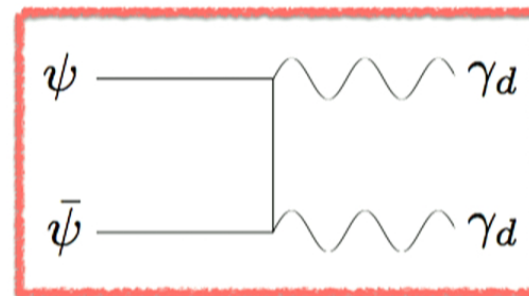
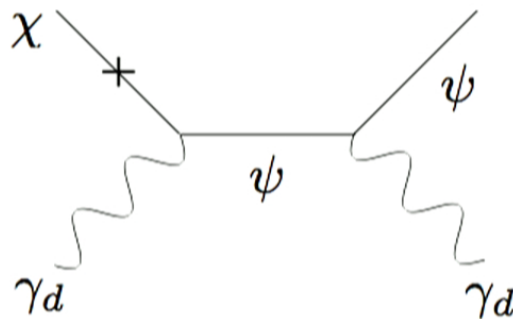
$$\langle \sigma v \rangle_F \sim \frac{\alpha_d^2}{m_\psi^2} e^{-\Delta x_F}$$

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

45

A FOURTH EXCEPTION

ORDINARY COANNIHILATION

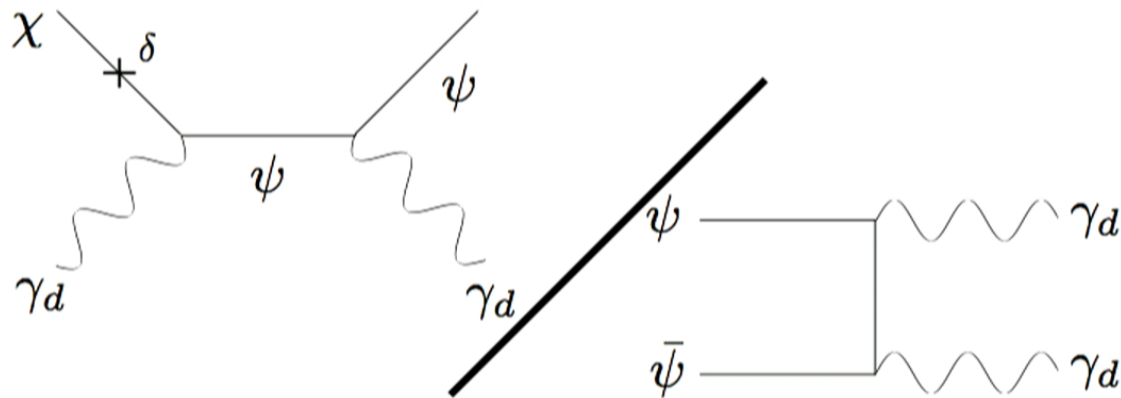


$$\frac{\Gamma(\psi\bar{\psi} \rightarrow \gamma_d\gamma_d)}{\Gamma(\chi \rightarrow \psi)} \sim n_\psi \sim e^{-x_F} \ll 1$$

A FOURTH EXCEPTION

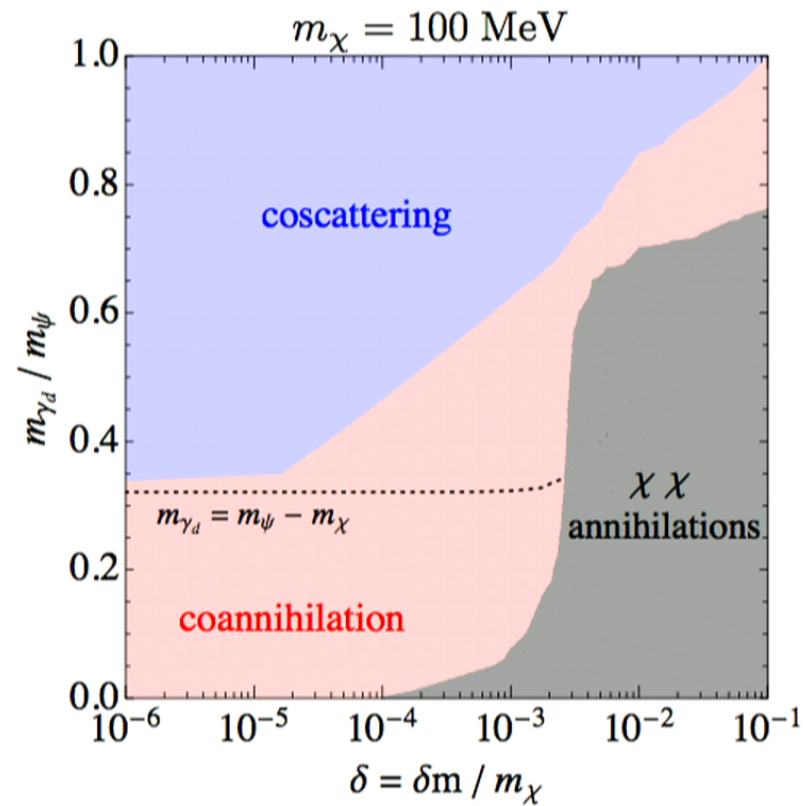
IF

$$m_{\gamma_d} \sim m_\psi$$

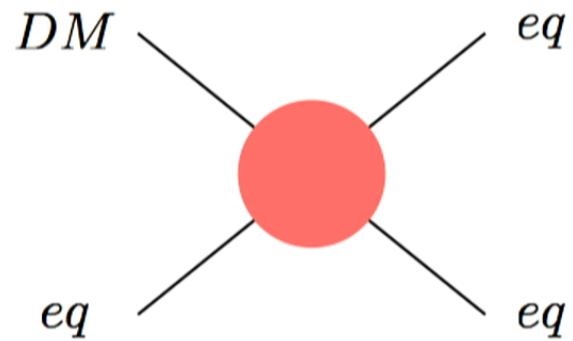


$$\sim \delta^2$$

A FOURTH EXCEPTION

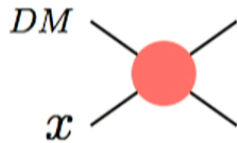


COSCATTERING



NEW SET OF BOLTZMANN EQUATIONS
NEW PARAMETRICS FOR FREEZE-OUT

COSCATTERING



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

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

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

CONCLUSION

- IF DARK MATTER ANNIHILATIONS REQUIRE FINITE TEMPERATURE
 - THE RELIC DENSITY IS ENHANCED BY AN EXPONENTIAL BOLTZMANN FACTOR
 - $m_{DM} \sim v e^{-x_F \Delta}$
- THIS IS A GENERAL MECHANISM: FORBIDDEN CHANNEL ANNIHILATIONS, COANNIHILATION, ...
 - RICH PHENOMENOLOGY: SELF-INTERACTIONS, LOW ENERGY DIRECT DETECTION, CMB, DARK PHOTON, ...
 - PLENTY OF MODEL BUILDING OPPORTUNITIES: FORBIDDEN SIMP, FORBIDDEN p-WAVE, FORBIDDEN INTO SM CHANNELS, ... (AND COANNIHILATING SIMP, COANNIHILATING p-WAVE, ...)