

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



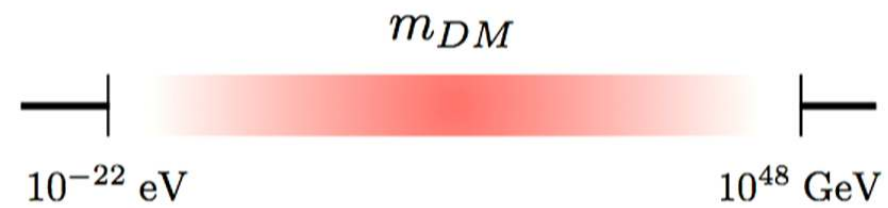
Raffaele Tito D'Agnolo - IAS  
5/17/2016 Perimeter Institute



# OUTLINE

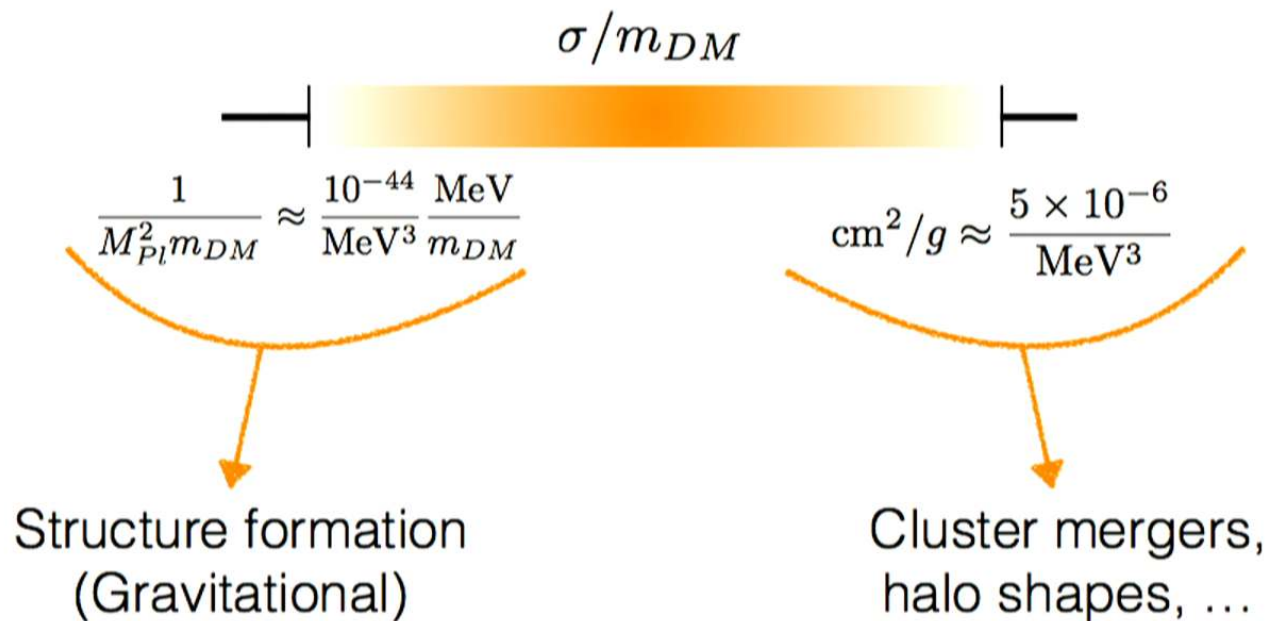
- THERMAL RELCS IN THE  $\alpha_d - m_{DM}$  PLANE
- FORBIDDEN DARK MATTER
  - THE MECHANISM
  - DETAILS AND PHENOMENOLOGY
- COANNIHILATION AND COSCATTERING

# THE DARK MATTER MASS



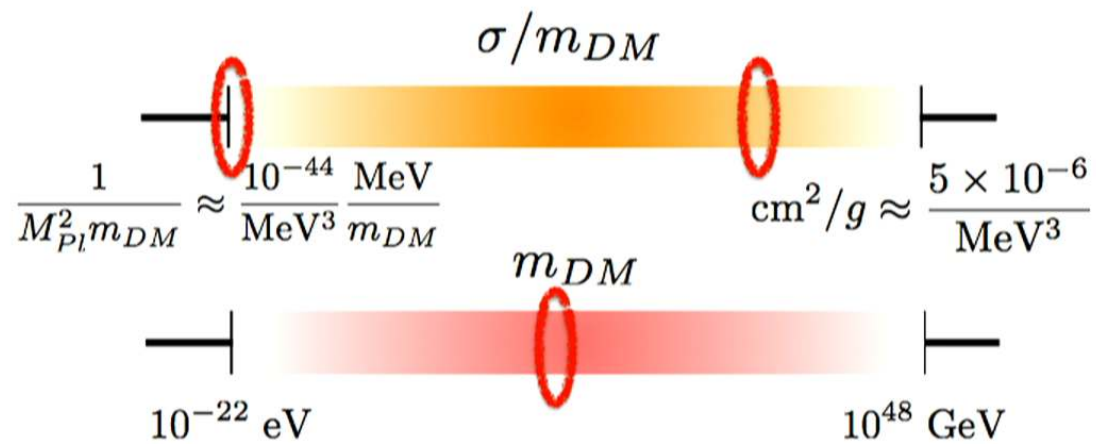
80 ORDERS OF MAGNITUDE

# DARK MATTER SELF-INTERACTIONS

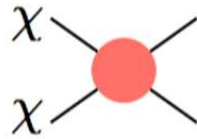


# WIMPS AND MIRACLES

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



# WIMPS AND MIRACLES



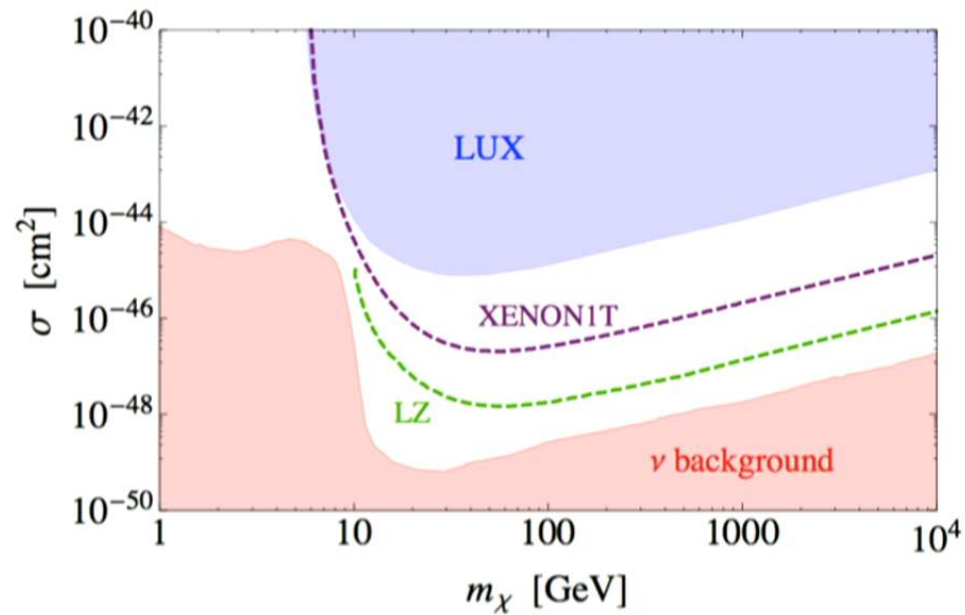
$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle [n_\chi^2 - (n_\chi^{eq})^2]$$

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

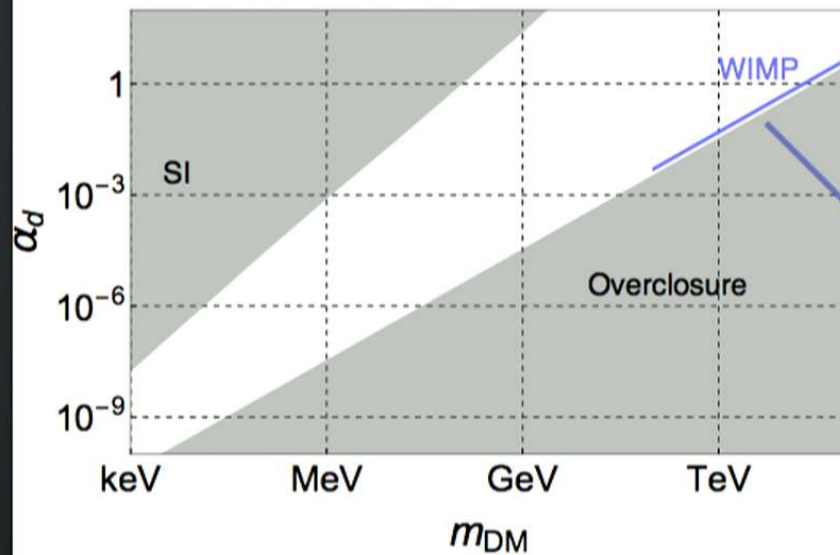
$$\langle\sigma v\rangle_F \approx \frac{1}{(20 \text{ TeV})^2}$$

# WIMPS AND MIRACLES

AND THE WINDOW IS CLOSING



# THERMAL RELICS

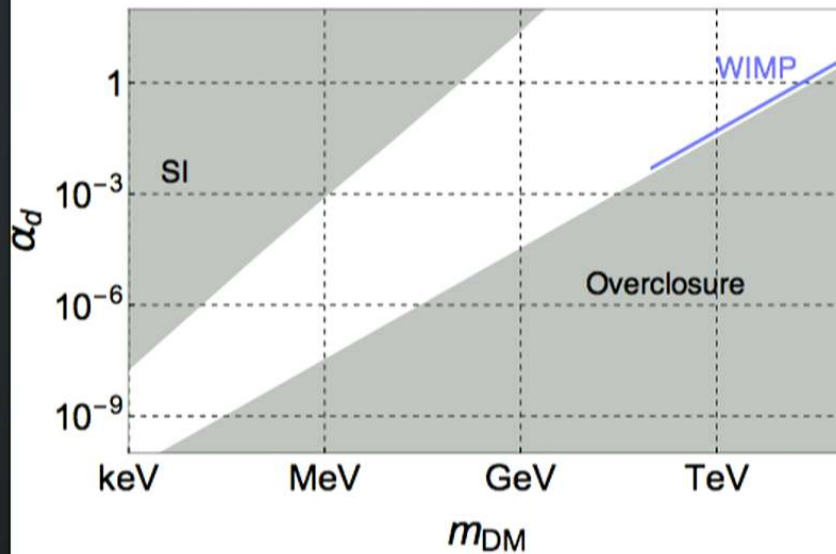


$$\Omega_{DM} h^2 \sim \frac{1}{\langle \sigma v \rangle_F}$$

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

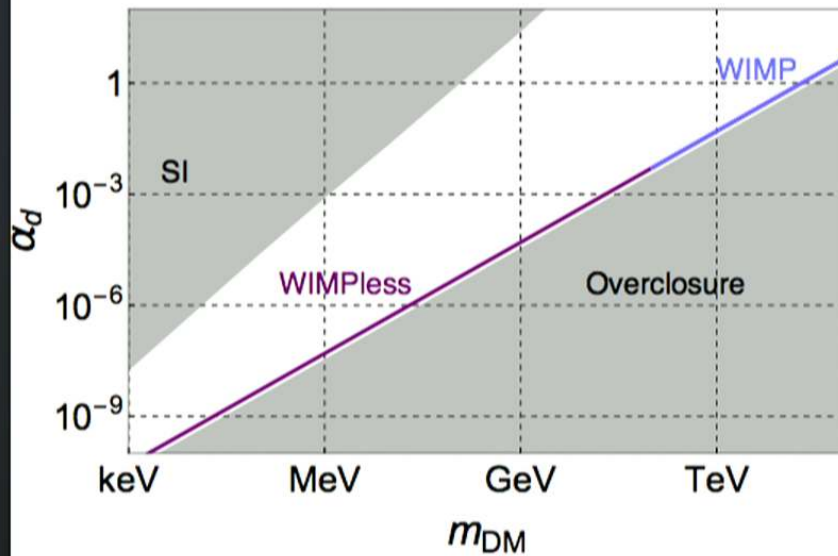
$$\alpha_d \sim \alpha_W, \quad m \sim m_Z$$

# THERMAL RELICS



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

# THERMAL RELICS



## WIMPless Miracle

Feng, Kumar 0803.4196

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

$$m \ll m_Z$$

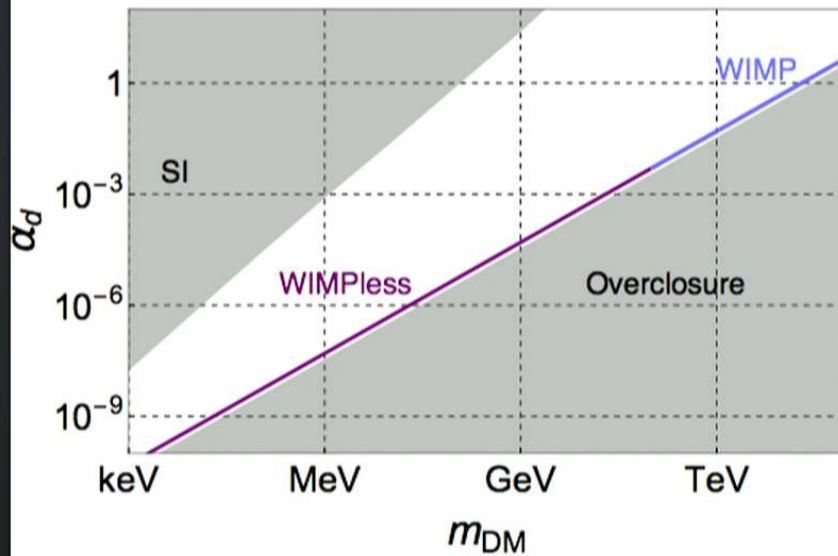
## Heavy Mediators

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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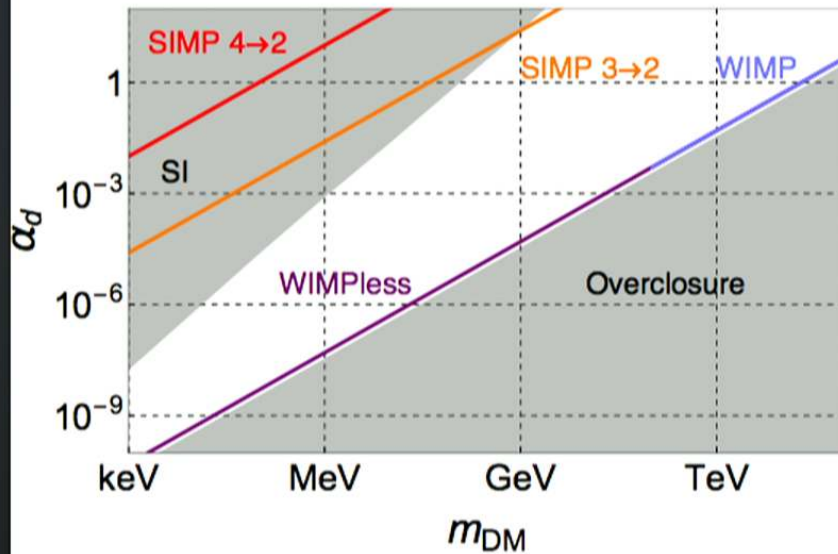
## Heavy Mediators

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# THERMAL RELICS



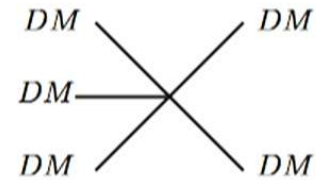
## SIMP Miracle

Carlson, Hall, Machacek

*Astrophys.J.* 398 (1992) 43-52

Hochberg, Kuflick, Volansky, Wacker

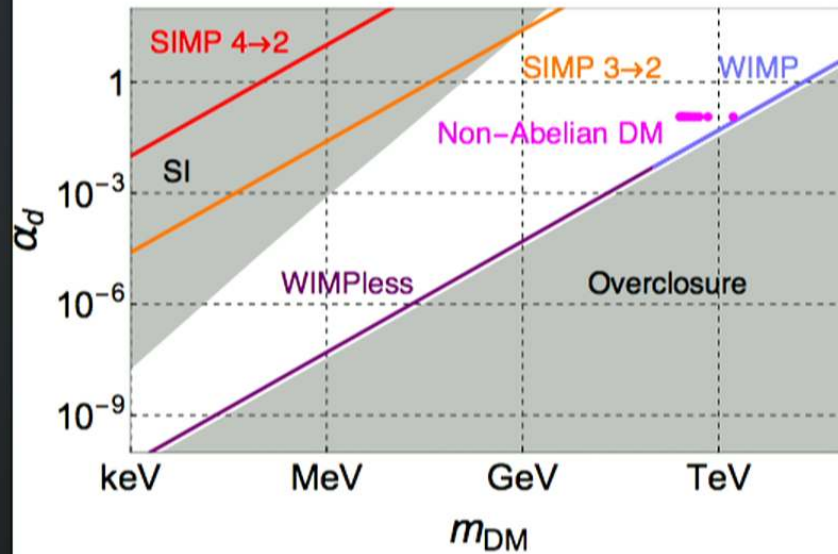
1402.5143



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

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

# THERMAL RELICS



## Non-Abelian DM

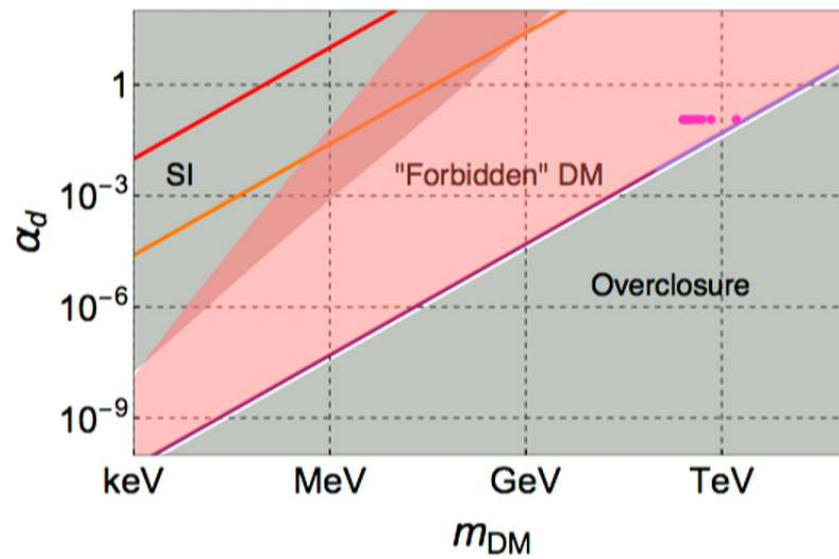
Buen-Abad, Marques-Tavares,

Schmaltz

1505.03542

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

# TODAY



# FORBIDDEN DARK MATTER



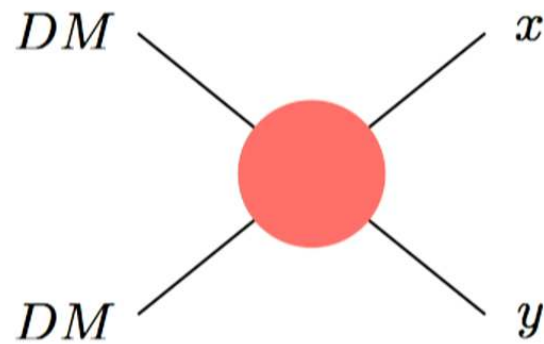
RTD, J. Ruderman  
**Phys.Rev.Lett. 115 (2015) 6, 061301**

# THREE EXCEPTIONS

- FORBIDDEN CHANNEL ANNIHILATIONS
- COANNIHILATION
- ANNIHILATION NEAR A POLE

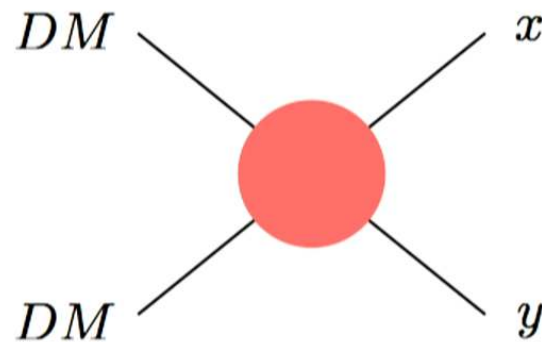
Griest and Seckel  
Phys.Rev. D43 (1991) 3191-3203

# FORBIDDEN CHANNEL ANNIHILATIONS



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

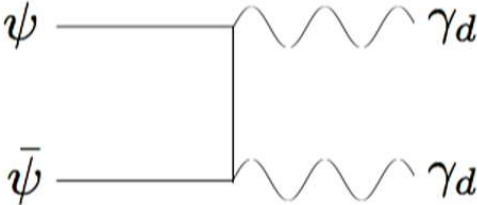
# FORBIDDEN CHANNEL ANNIHILATIONS



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

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

# A WORKING MODEL



The diagram shows a fermion loop. Two external fermion lines, labeled  $\psi$  and  $\bar{\psi}$ , enter from the left and meet at a vertex. From this vertex, a wavy line labeled  $\gamma_d$  goes up and then right. From the top-right vertex, another wavy line labeled  $\gamma_d$  goes down and then left, meeting the  $\bar{\psi}$  line at a second vertex. A vertical line connects the two vertices on the left, completing the loop.

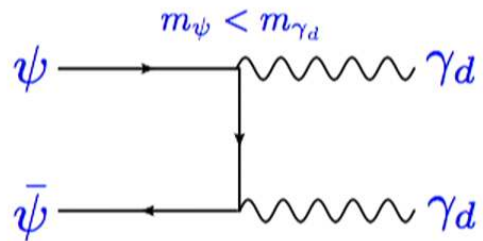
$$m_{\gamma_d} \gtrsim m_\psi$$
$$\Delta \equiv \frac{m_{\gamma_d} - m_\psi}{m_\psi}$$

$\psi$  SM singlet, charged under  $U(1)_d$

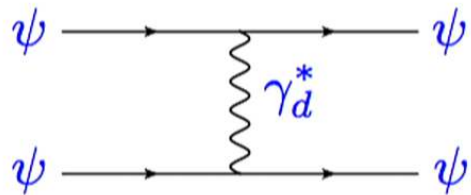
Pospelov, Ritz, Voloshin

Phys.Lett. B662 (2008) 53-61

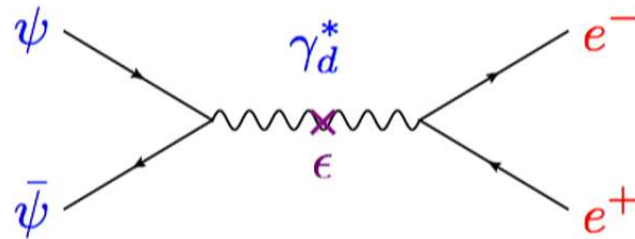
1) forbidden annihilations:



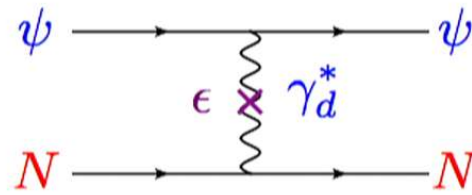
2) self-interactions:



3) indirect detection:

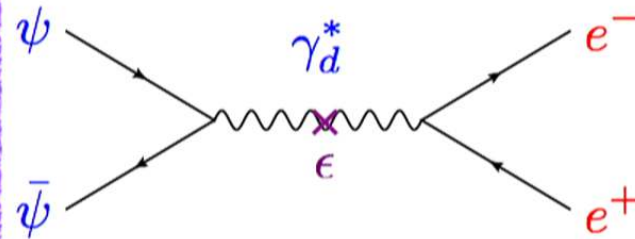


4) direct detection:

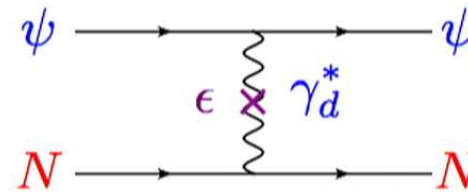


$$\mathcal{L} \supset \epsilon F_{\mu\nu}^d F_{SM}^{\mu\nu}$$

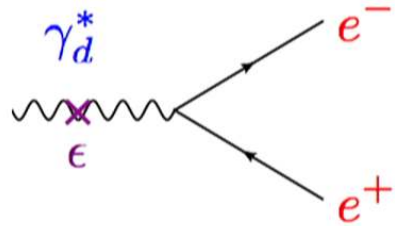
3) indirect detection:



4) direct detection:



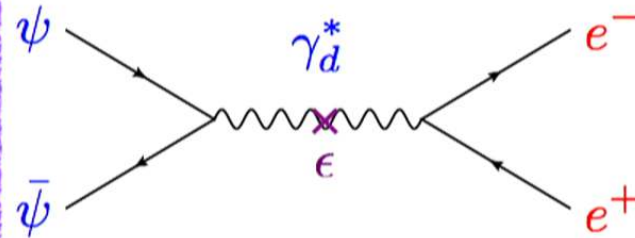
$$\mathcal{L} \supset \epsilon F_{\mu\nu}^d F_{SM}^{\mu\nu}$$



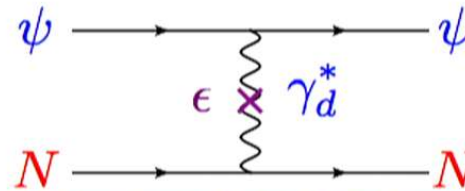
$$n_{\gamma_d} = n_{\gamma_d}^{eq}$$

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

3) indirect detection:

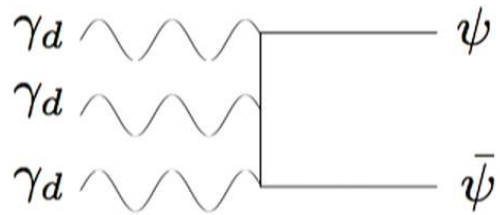


4) direct detection:



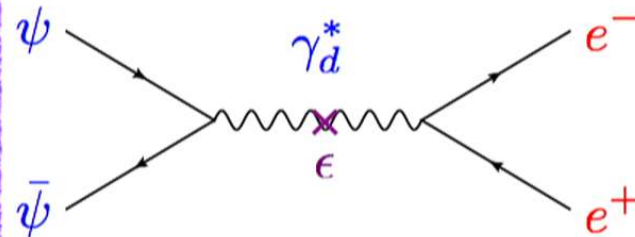
$$\mathcal{L} \supset \epsilon F_{\mu\nu}^d F_{SM}^{\mu\nu}$$

$$\epsilon = 0$$

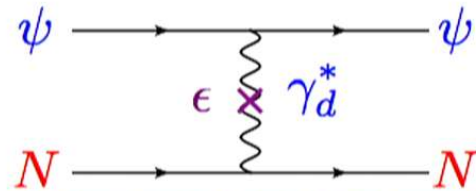


$$m \rightarrow T$$

3) indirect detection:



4) direct detection:



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

$$\epsilon = 0$$

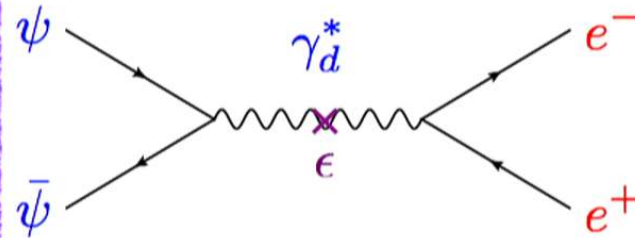
$$T_{\text{dark}} \sim \log a^{-1}$$

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

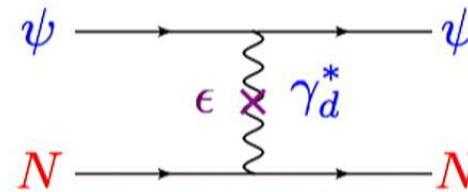
Carlson, Hall, Machacek

Astrophys.J. 398 (1992) 43-52

3) indirect detection:

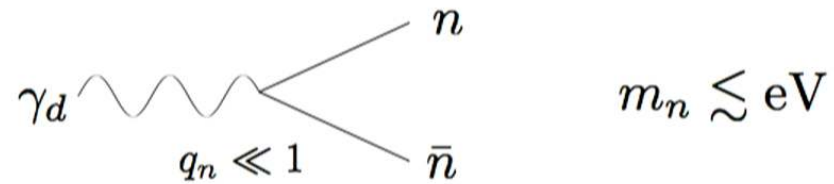


4) direct detection:



FROM DARK SECTOR COOLING

# DARK RADIATION

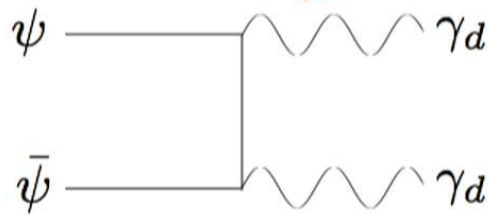


$$T_{\text{dark}} = T_n \sim a^{-1}$$

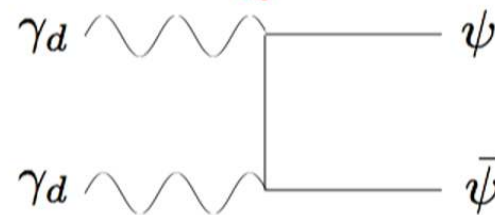


# RELIC DENSITY

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



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

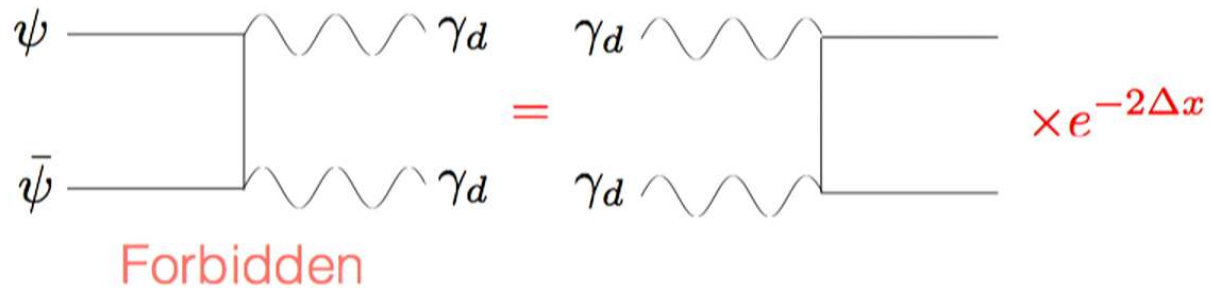
# RELIC DENSITY

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

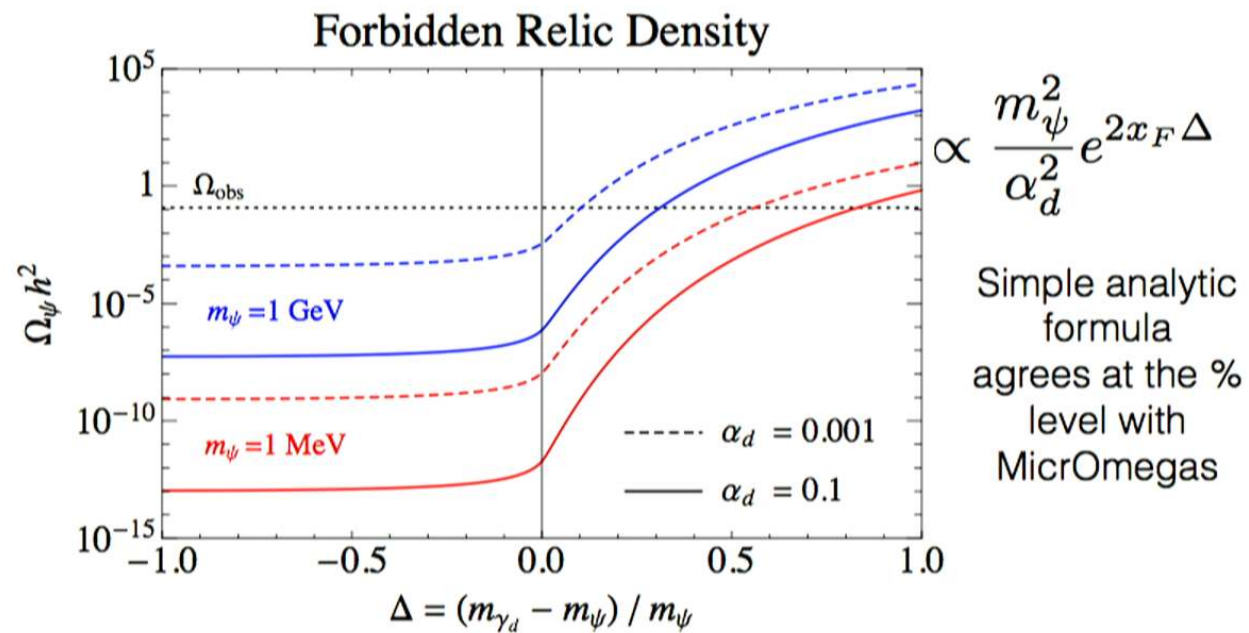
$$\langle \sigma_{\psi\bar{\psi}} v \rangle = \frac{(n_{\gamma_d}^{eq})^2}{(n_\psi^{eq})^2} \langle \sigma_{\gamma_d\gamma_d} v \rangle \approx 8\pi f_\Delta \frac{\alpha_d^2}{m_\psi^2} e^{-2\Delta x}$$

# RELIC DENSITY

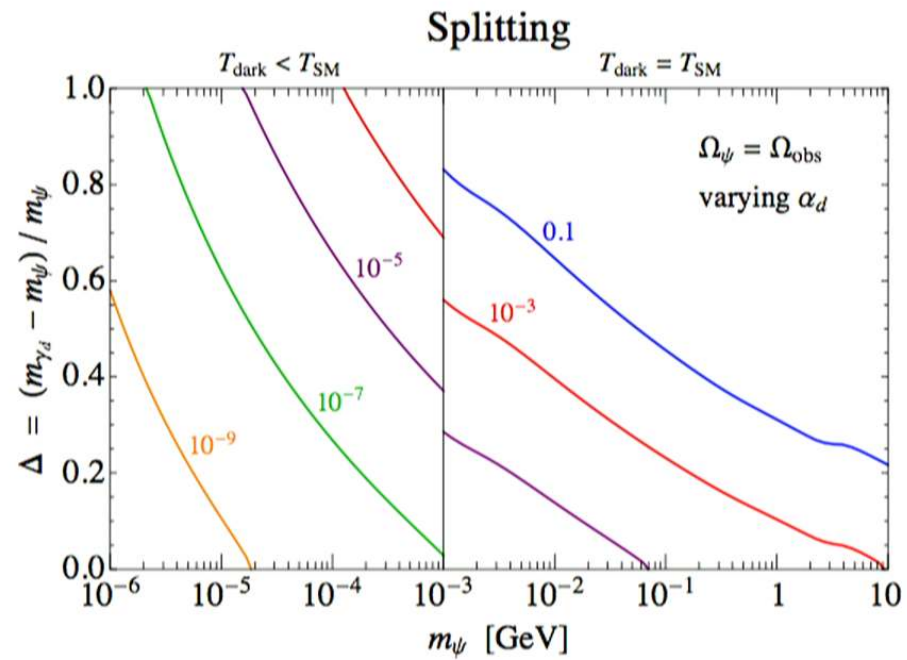
$$\dot{n}_\psi + 3Hn_\psi = -\langle \sigma_{\psi\bar{\psi}} v \rangle n_\psi^2 + \langle \sigma_{\gamma_d\gamma_d} v \rangle (n_{\gamma_d}^{eq})^2$$



# RELIC DENSITY



# RELIC DENSITY

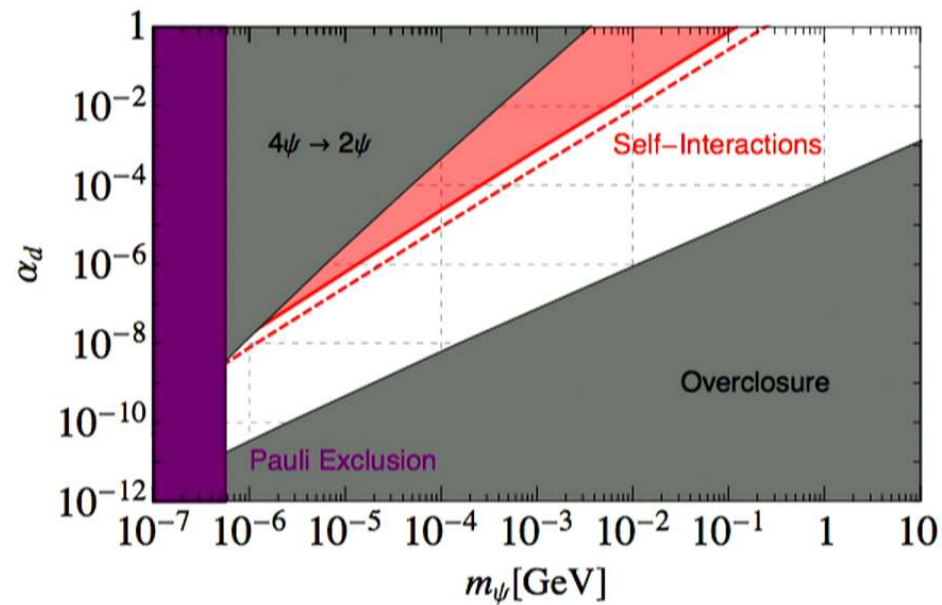


# SELF-INTERACTIONS

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

# SELF-INTERACTIONS

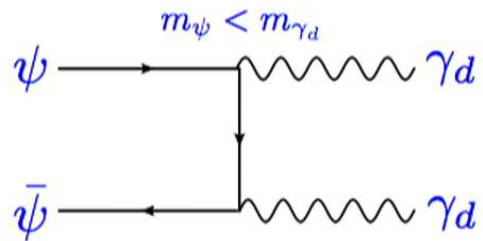
Thermally Decoupled Dark Sector ( $\epsilon=0$ )



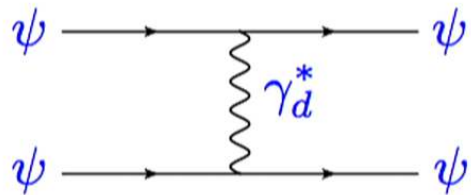
Page 40 of 56

40

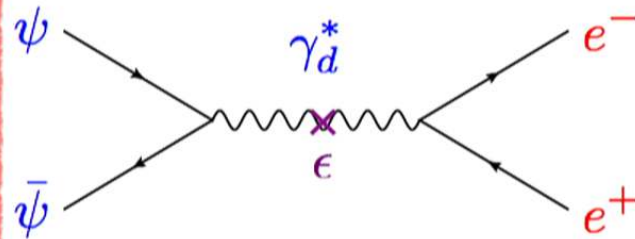
1) forbidden annihilations:



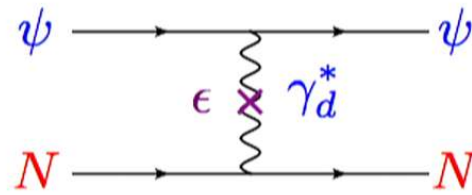
2) self-interactions:



3) indirect detection:

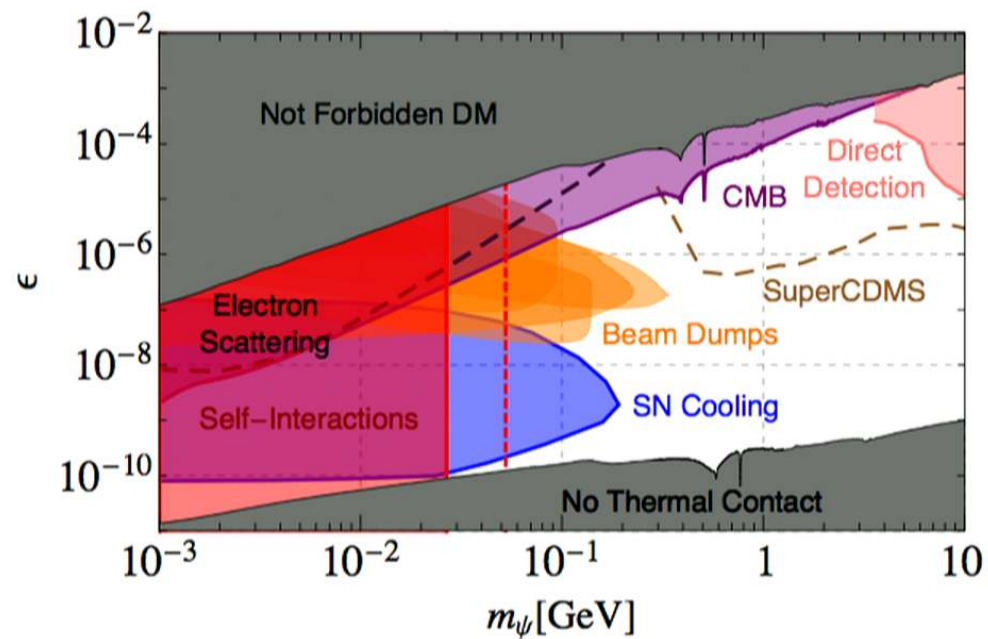


4) direct detection:



# ALL THE SIGNALS

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

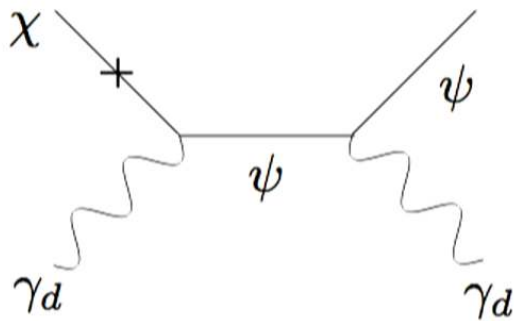


RTD, F. D'Eramo, J. Ruderman  
In preparation



# COANNIHILATION AND COSCATTERING

# COANNIHILATION

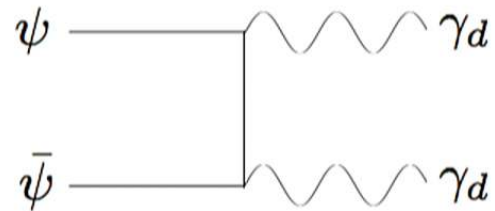
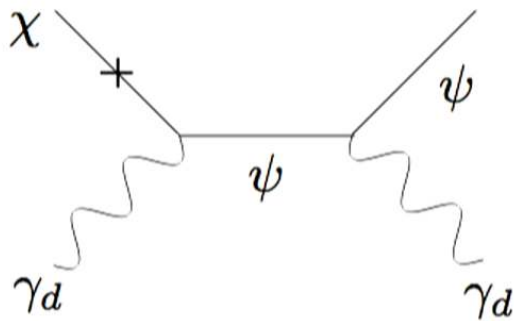


$\chi = \text{DARK MATTER}$

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

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

# COANNIHILATION



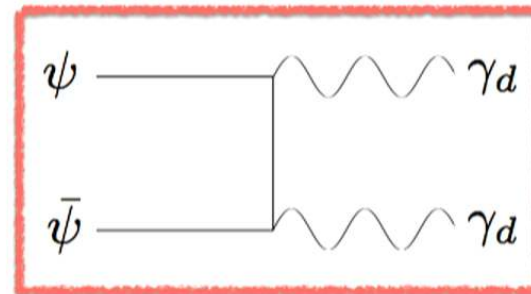
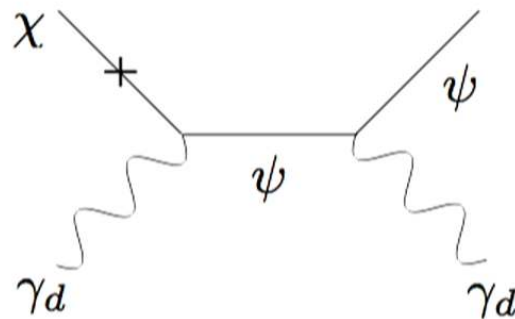
$$\langle \sigma v \rangle_F \sim \frac{\alpha_d^2}{m_\psi^2} e^{-\Delta x_F}$$

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

45

# A FOURTH EXCEPTION

ORDINARY COANNIHILATION

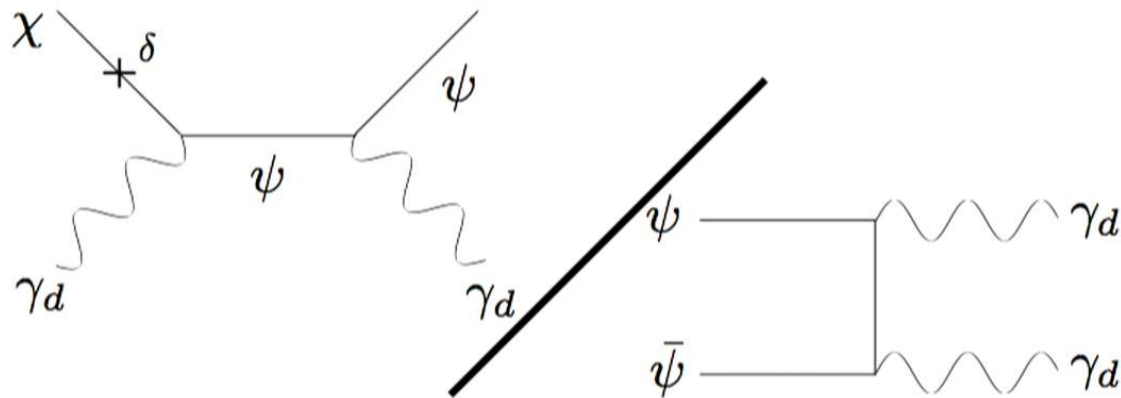


$$\frac{\Gamma(\psi\bar{\psi} \rightarrow \gamma_d\gamma_d)}{\Gamma(\chi \rightarrow \psi)} \sim n_\psi \sim e^{-x_F} \ll 1$$

# A FOURTH EXCEPTION

IF

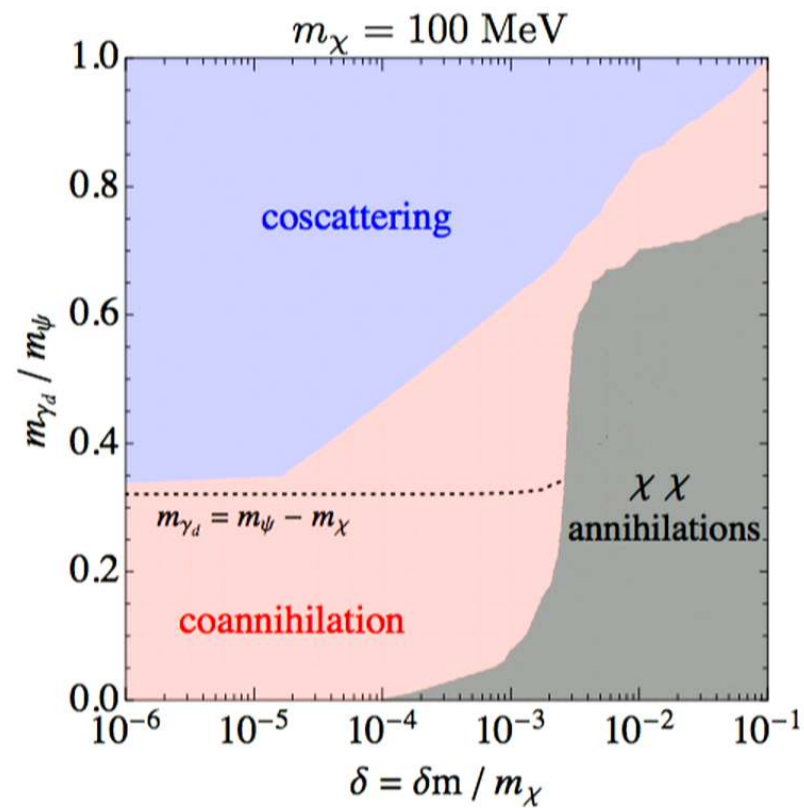
$$m_{\gamma_d} \sim m_\psi$$



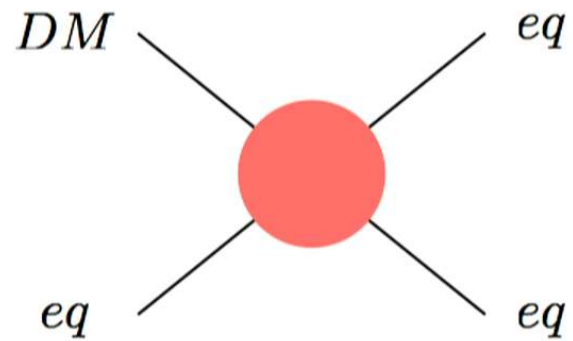
$$\sim \delta^2$$

47

# A FOURTH EXCEPTION

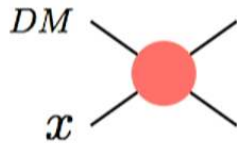


# COSCATTERING



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, ...)