19 June 2014
ILP day
IAP, Paris

Dark Matter models

Marco Cirelli

(CNRS IPhT Saclay)

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Introduction

A matter of perspective:

Introduction

A matter of perspective:

SuSy DM

Non SuSy DM

Introduction

A matter of perspective:

SuSy DM

Non SuSy DM

NON SOLO PIZZA

LA VERDADERA PIZZA Y PASTA ITALIANA
PLAZA P. CANA - BAVARO - 809 552 1547

?

Introduction

A matter of perspective:

SuSy neutralino

other exotic candi- dates

Introduction

A matter of perspective:

Introduction

A matter of perspective:

SuSy neutralino

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A matter of perspective:

Caveat: no categorization is perfect.

DM

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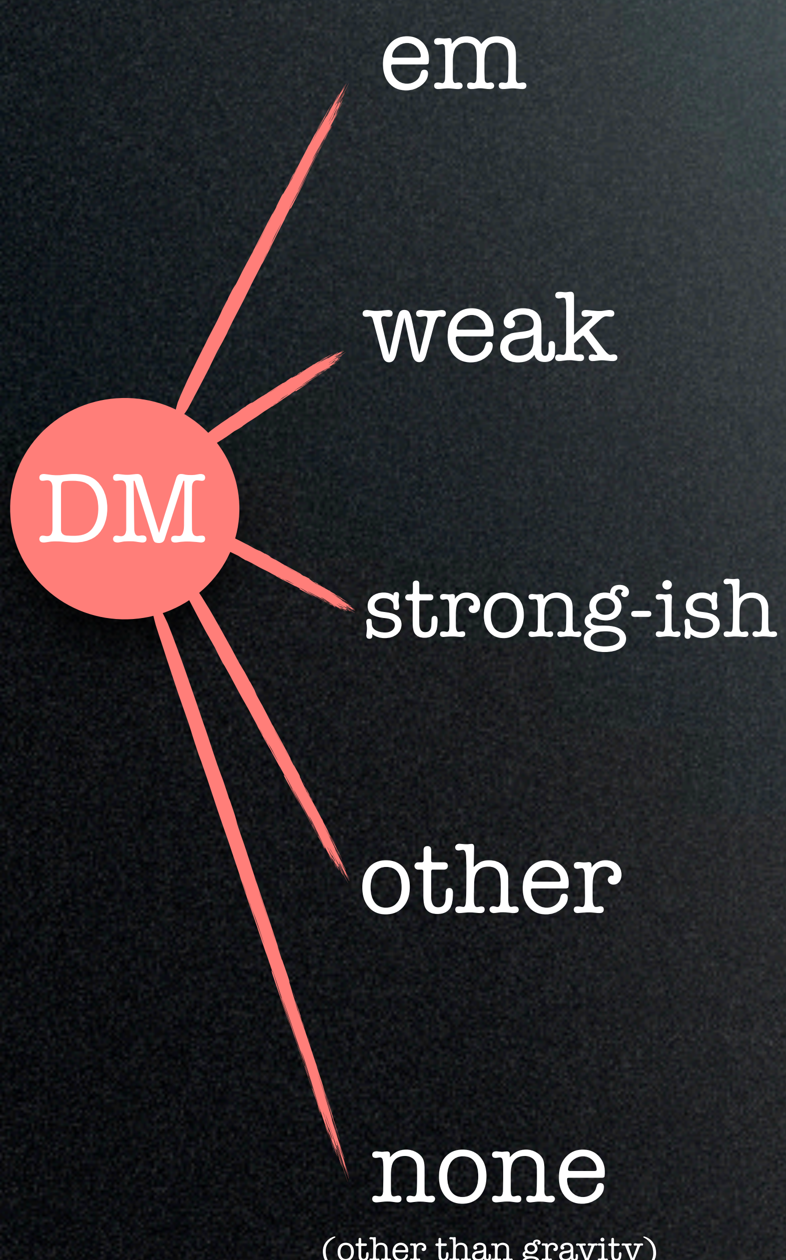
Caveat: no categorization is perfect.

Interactions:



Introduction

Caveat: no categorization is perfect.

A matter of perspective:

Interactions:

DM

- em
- weak
- strong-ish
- other
- none
  (other than gravity)

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A matter of perspective:

Interactions:

- DM
  - em
  - weak
    - neutralino etc
    - Little Higgs DM
    - KK DM
    - Inert Doublet
    - Minimal DM
  - strong-ish
    - TC DM
    - mirror DM
    - } aDM
  - other
    - 'secluded DM'
    - 'WIMPless DM'
  - none (other than gravity)
    - singlet scalar
    - sterile neutrino
    - gravitino
    - axion

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naturalness-inspired

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TC DM, mirror DM } aDM

Introduction

A matter of perspective:

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DM Interactions:		Production mechanism?	Stability?
em			
weak	naturalness-inspired: neutralino etc	thermal freeze out	R parity
	naturalness-inspired: Little Higgs DM	thermal freeze out	T parity
	naturalness-inspired: KK DM	thermal freeze out	K parity
	Inert Doublet	thermal freeze out	Z_2 symmetry
	Minimal DM	thermal freeze out	gauge sym
strong-ish	naturalness-inspired: TC DM (aDM)	‘exhaustion’	Tbaryon #
	mirror DM (aDM)		Z_2 symmetry
other	‘secluded DM’	sort of freeze out	some symmetry
	‘WIMPless DM’	sort of freeze out	some symmetry
none (other than gravity)	singlet scalar	thermal freeze out	Z_2 symmetry
	sterile neutrino	mixing	just long lived
	gravitino	thermal or decay	R parity or just long lived
	axion	misalignment?	just long lived

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DM

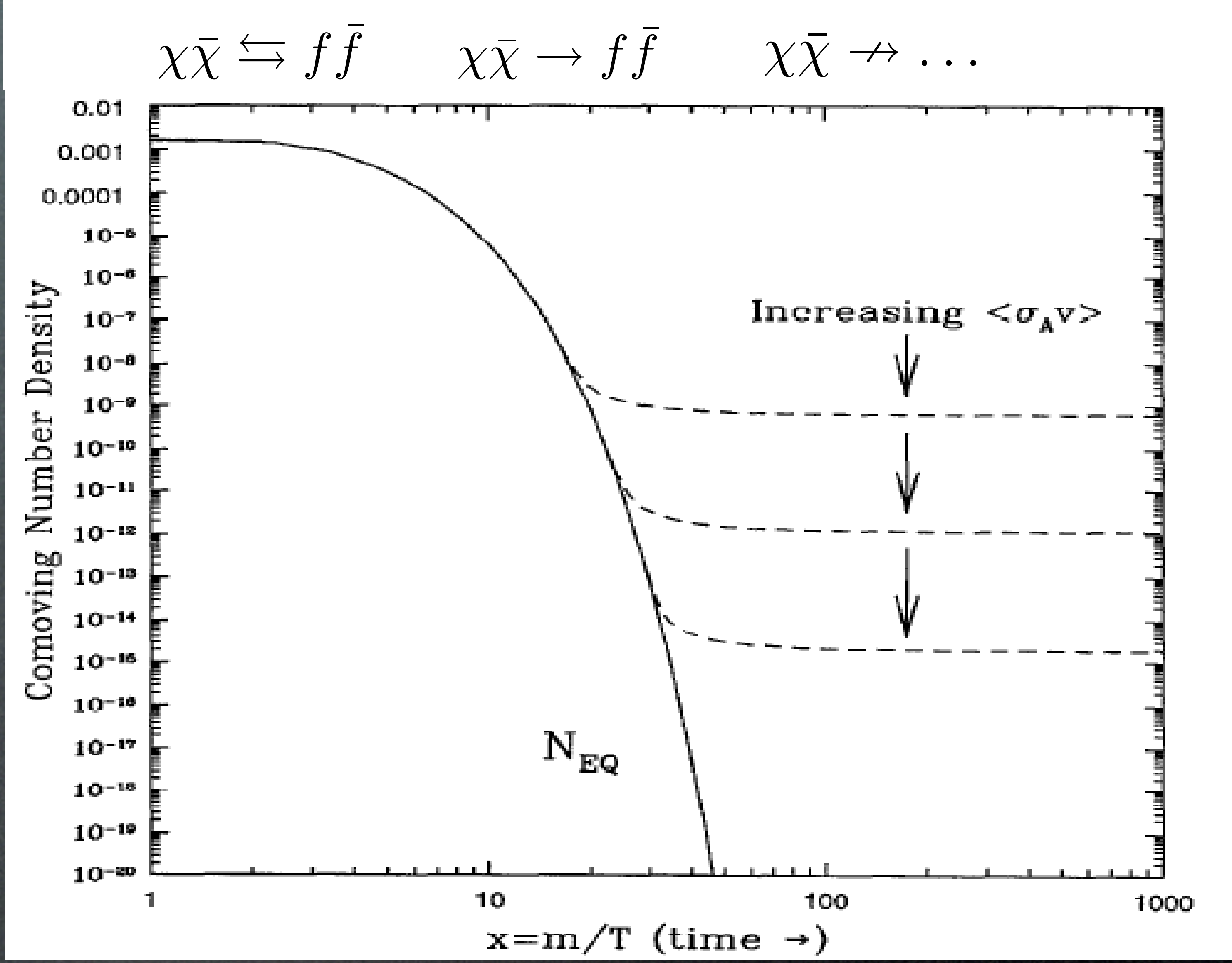
A thermal relic from the Early Universe

Boltzmann equation in the Early Universe:

$$\Omega_X \approx \frac{6\ 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle \sigma_{\mathrm{ann}} v \rangle}$$

Relic $\Omega_{\mathrm{DM}} \simeq 0.23$ for

$$\langle \sigma_{\mathrm{ann}} v \rangle = 3 \cdot 10^{-26} \mathrm{cm}^3/\mathrm{sec}$$



Kolb,Turner, The Early Universe, 1995

Weak cross section:

$$\langle \sigma_{\mathrm{ann}} v \rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{\mathbf{1\ TeV}^2} \Rightarrow \Omega_X \sim \mathcal{O}(\text{few } 0.1)$$

(WIMP)

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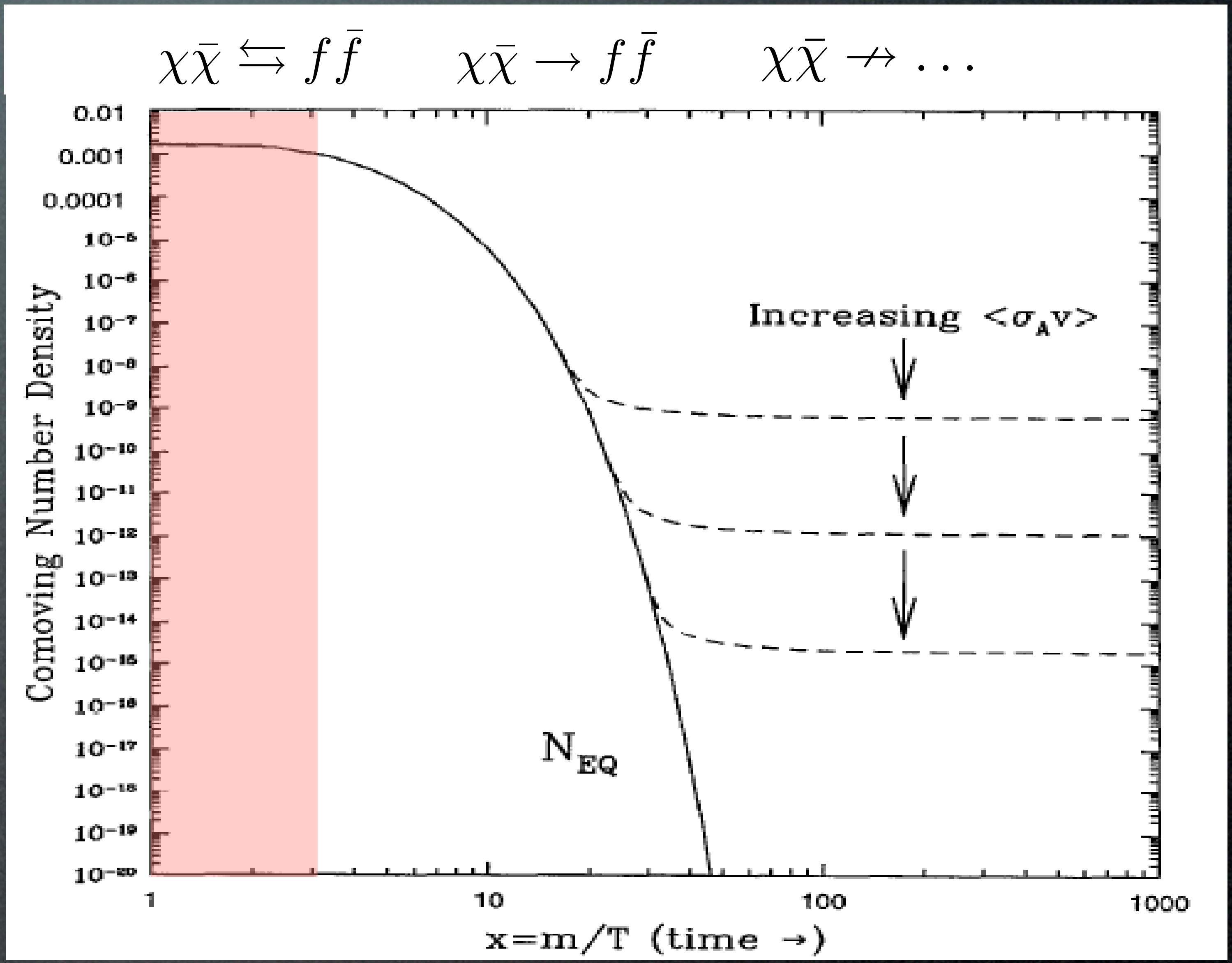

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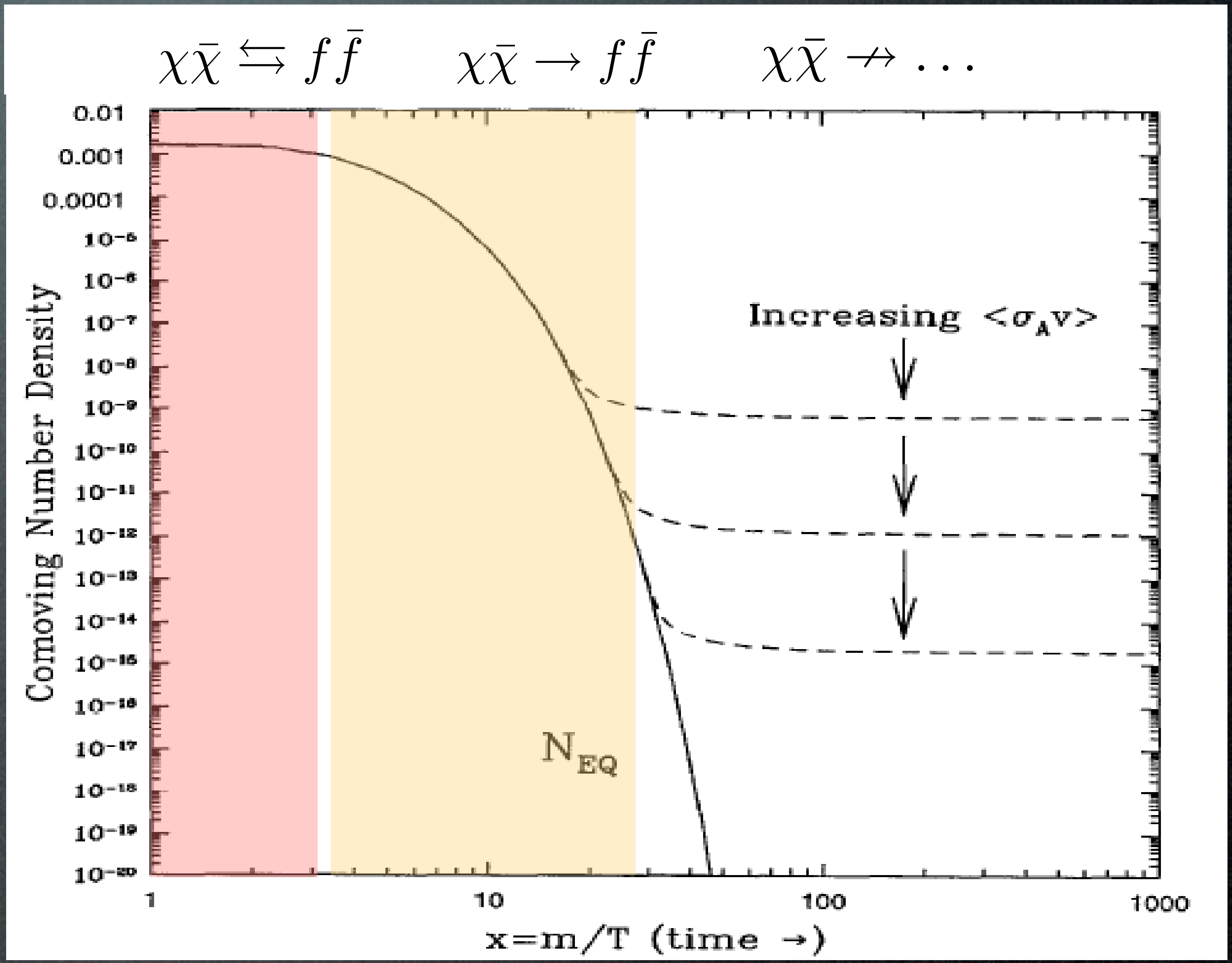

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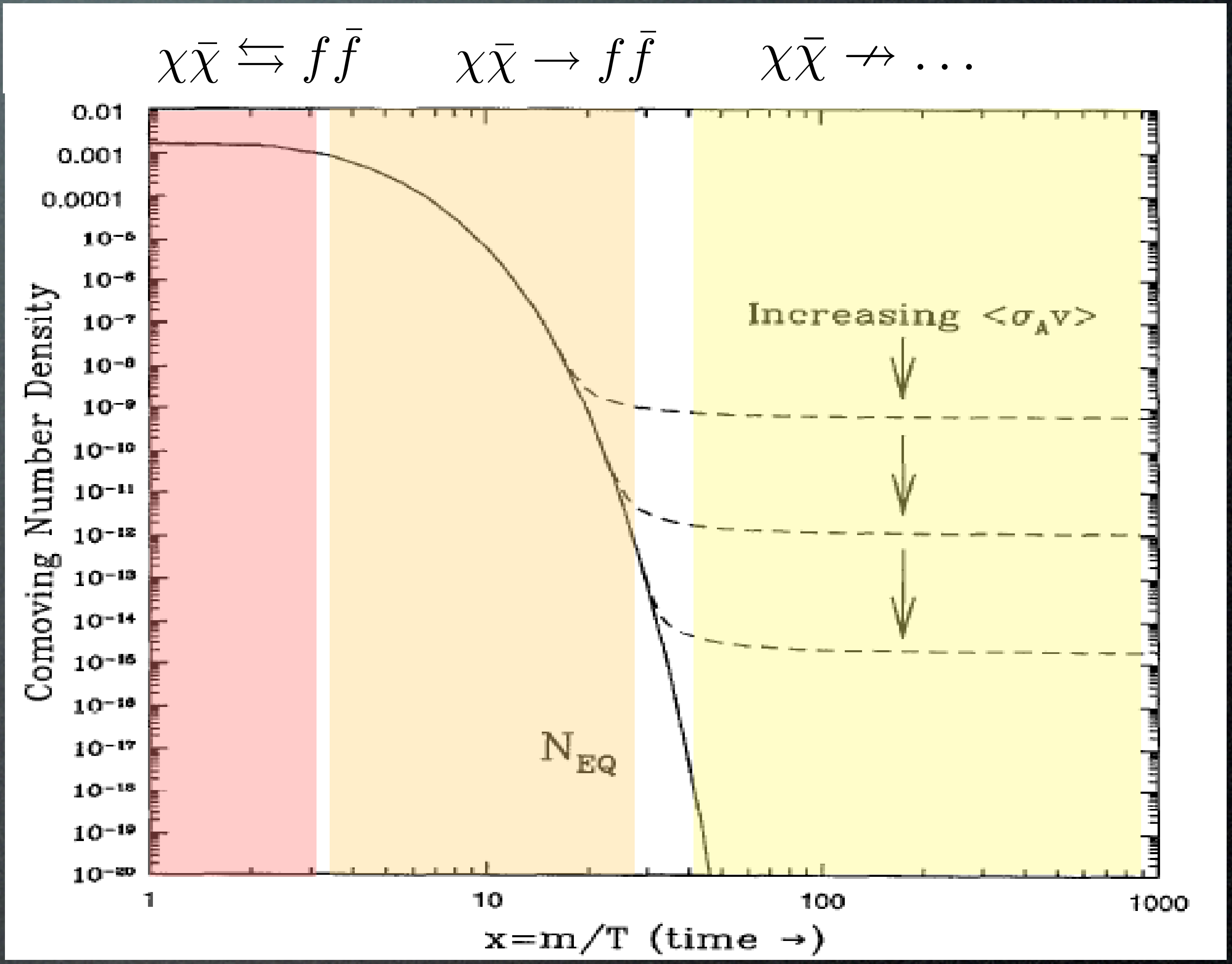

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(WIMP)

Asymmetric DM: a completely different relic

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm B}} \simeq 5$$

Just coincidence? Or: signal of a link?

Possibly a common production mechanism:

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Possibly a common production mechanism:

Baryogenesis:

$$\eta_{\rm B} = \frac{n_{\rm B} - n_{\bar{\rm B}}}{n_\gamma} = 6 \cdot 10^{-10}$$

BBN, CMB...

$$\Omega_{\rm B} \propto m_{\rm B}\, \eta_{\rm B}$$

'Darko'genesis:

$$\eta_{\rm DM} = \frac{n_{\rm DM} - n_{\overline{\rm DM}}}{n_\gamma} \stackrel{?}{=} \eta_{\rm B}$$

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$$\boxed{m_{\rm DM} \simeq 5 \text{ GeV}}$$

Is this the DM of DAMA, CoGeNT, CRESST?!?

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'Darko'genesis:

$$\eta_{\rm DM} = \frac{n_{\rm DM} - n_{\overline{\rm DM}}}{n_\gamma} \overset{?}{=} \eta_{\rm B}$$

A variety of specific models/ideas:

transferring or co-genesis

cfr J. March-Russell

DM stores the anti-B number

via leptogenesis

connection to neutrino masses

Asymmetric DM:
a completely different relic

$$\chi\bar{\chi} \leftrightarrows f\bar{f} \quad \chi\bar{\chi} \rightarrow f\bar{f} \qquad \chi\, ? \nrightarrow \ldots$$

Consider a particle χ:

- subject to $\chi\bar{\chi} \rightarrow \ldots$
- 'heavy' (e.g. 100 GeV)
- 'stable'
- in an expanding Universe
- **A**symmetric abundance
- large annihilation cross sec

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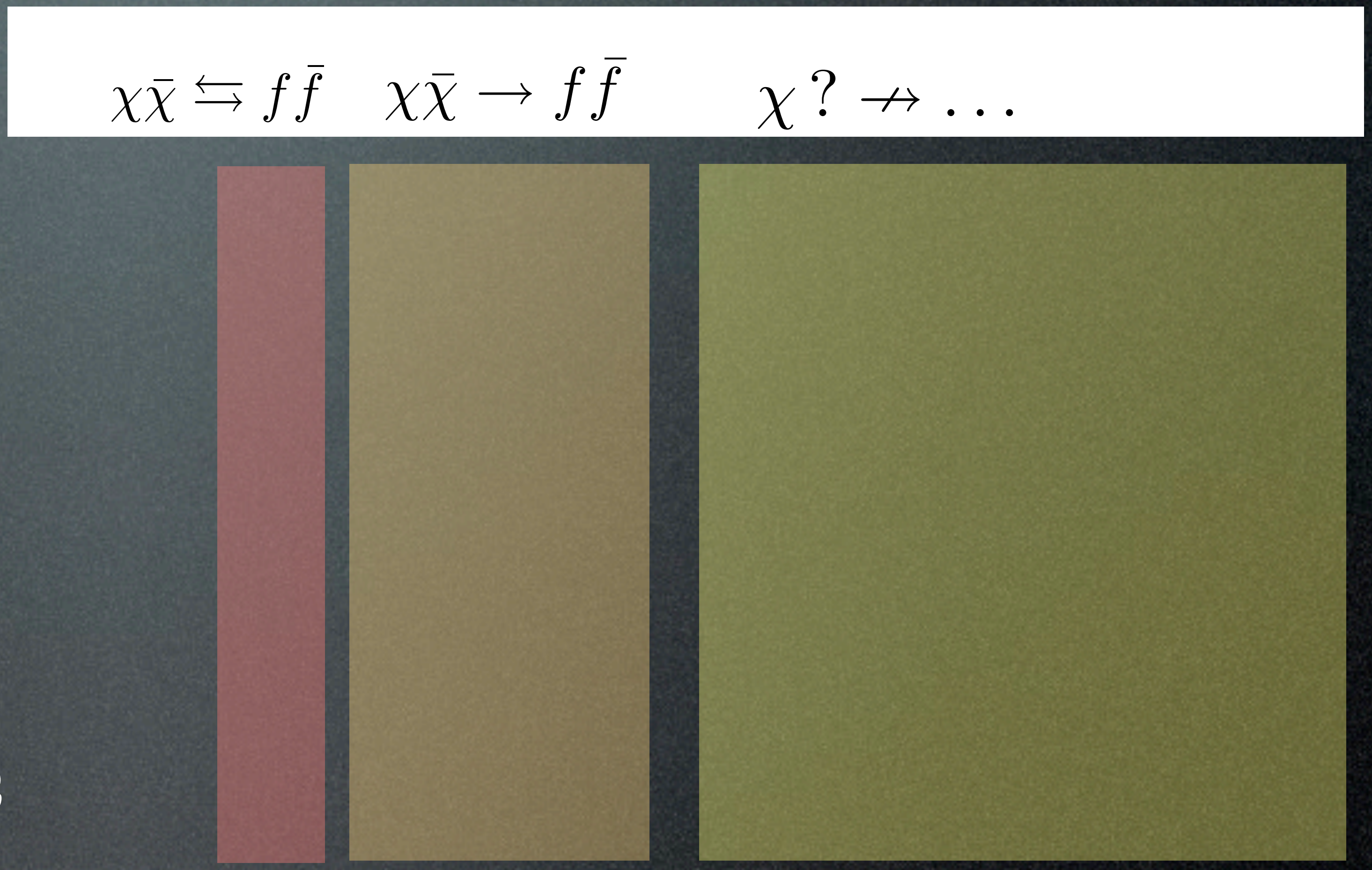

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$$\Omega_{\rm X} \simeq \frac{m_{\rm X}\, s}{\rho_{\rm crit}} \eta_0$$

The relic abundance is determined by η_0 and $m_{\rm X}$.

Freeze-in: like rodents in the paleocene

Hall, Jedamzik, March-Russell, West 2009

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Consider a particle χ:

- subject to $f\bar{f} \to \chi, \chi\bar{\chi}$ with a very small rate
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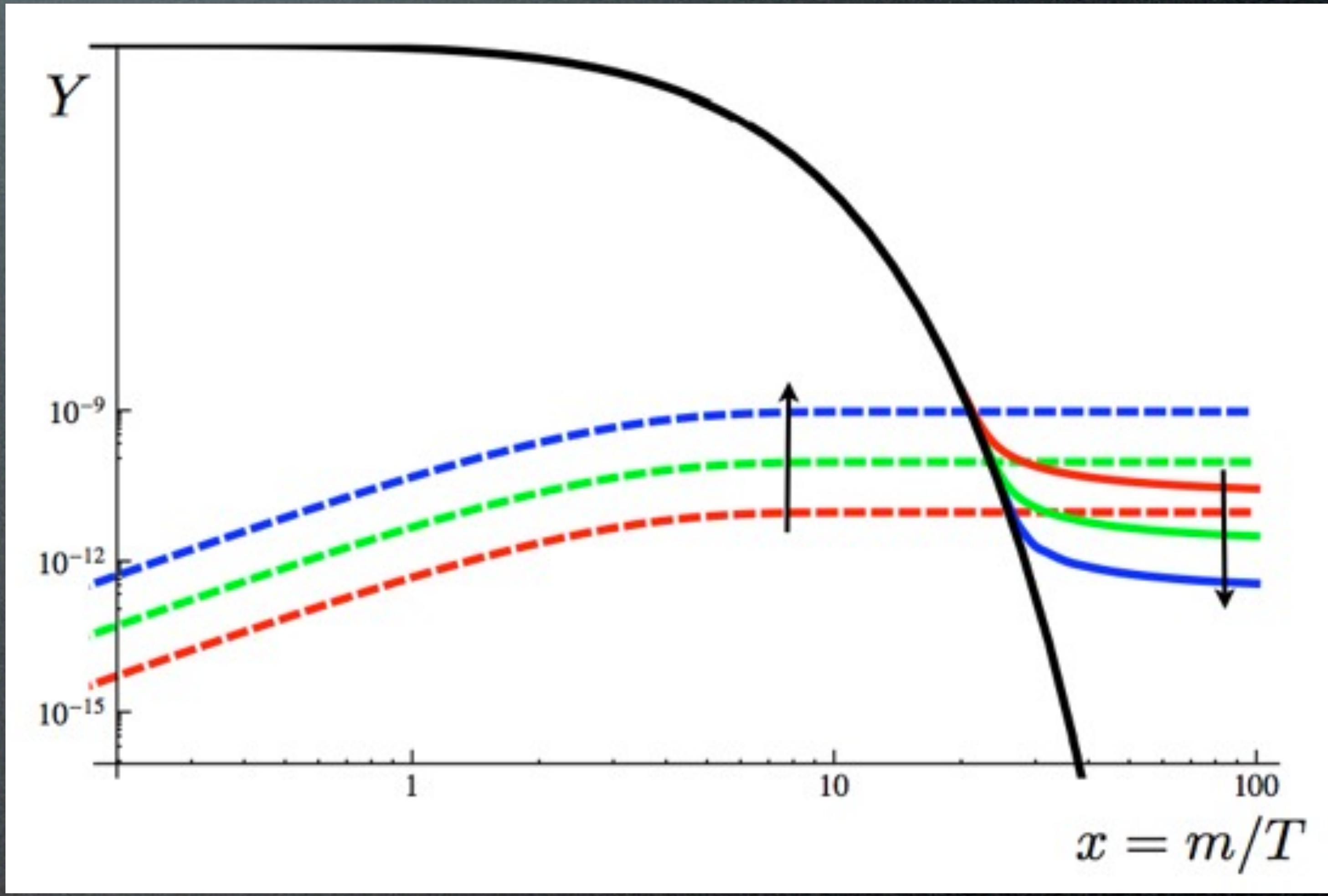

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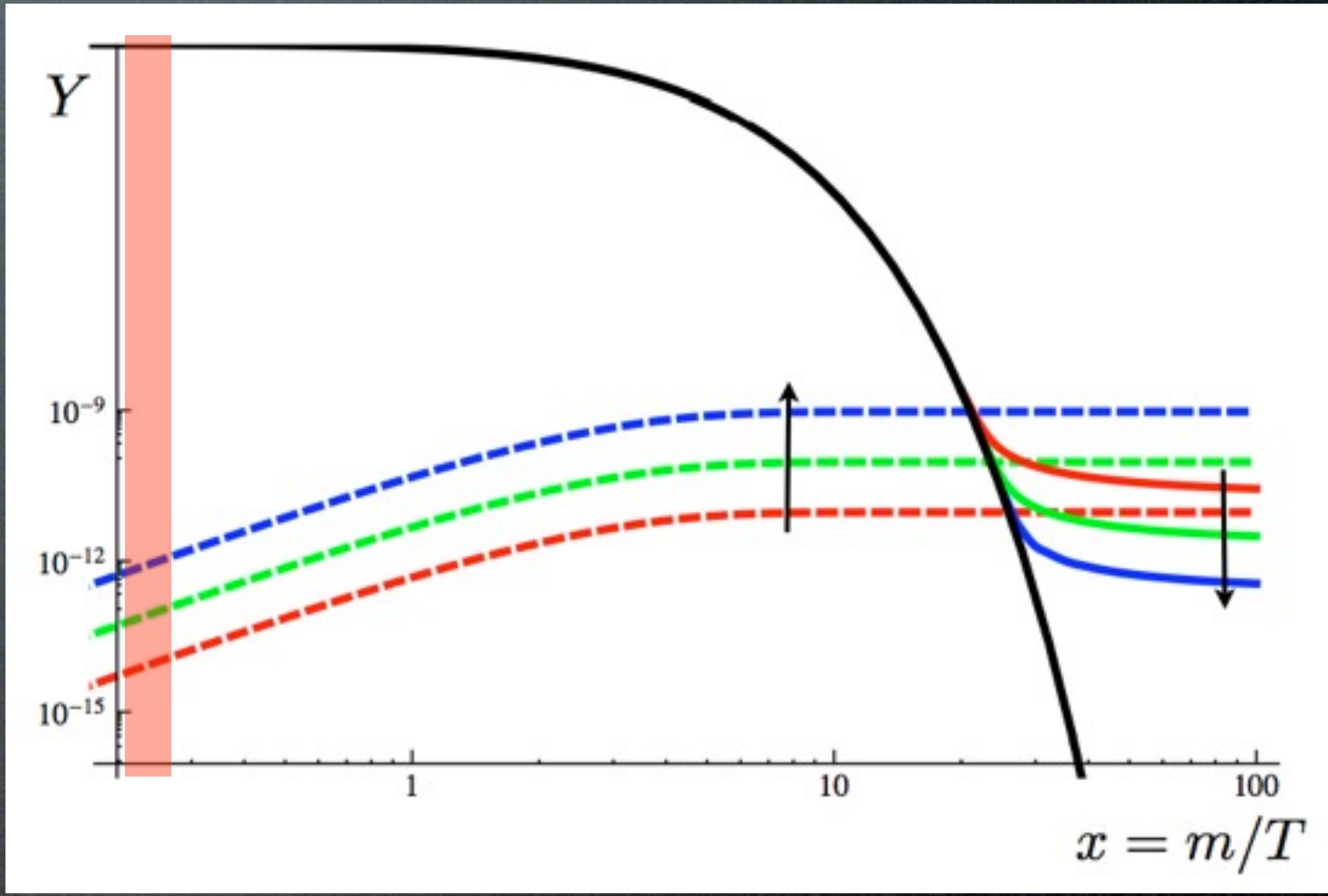

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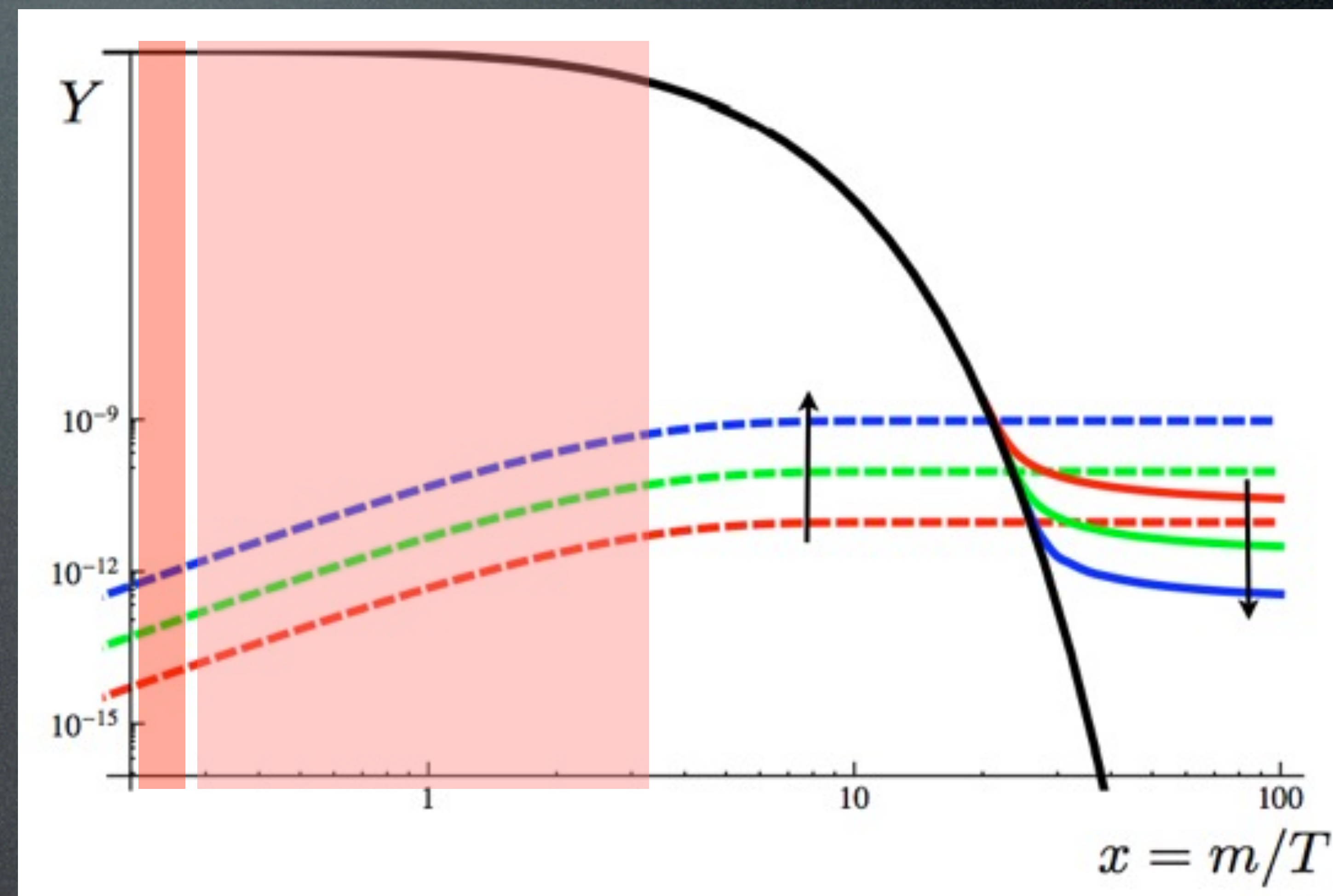

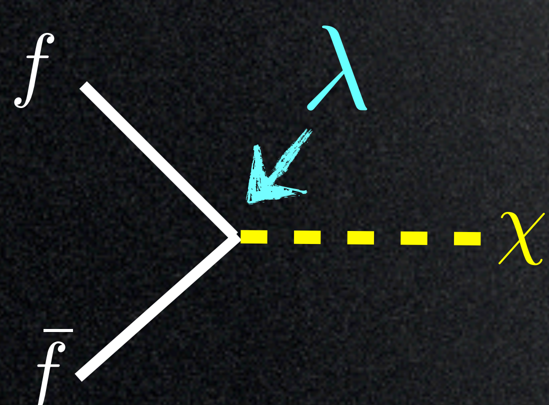

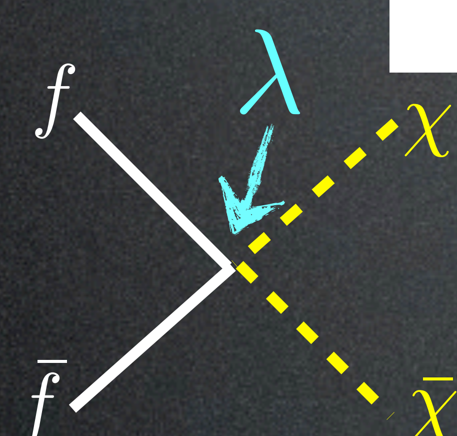

$\lambda \sim 10^{-12}$

very slowly but steadily produced

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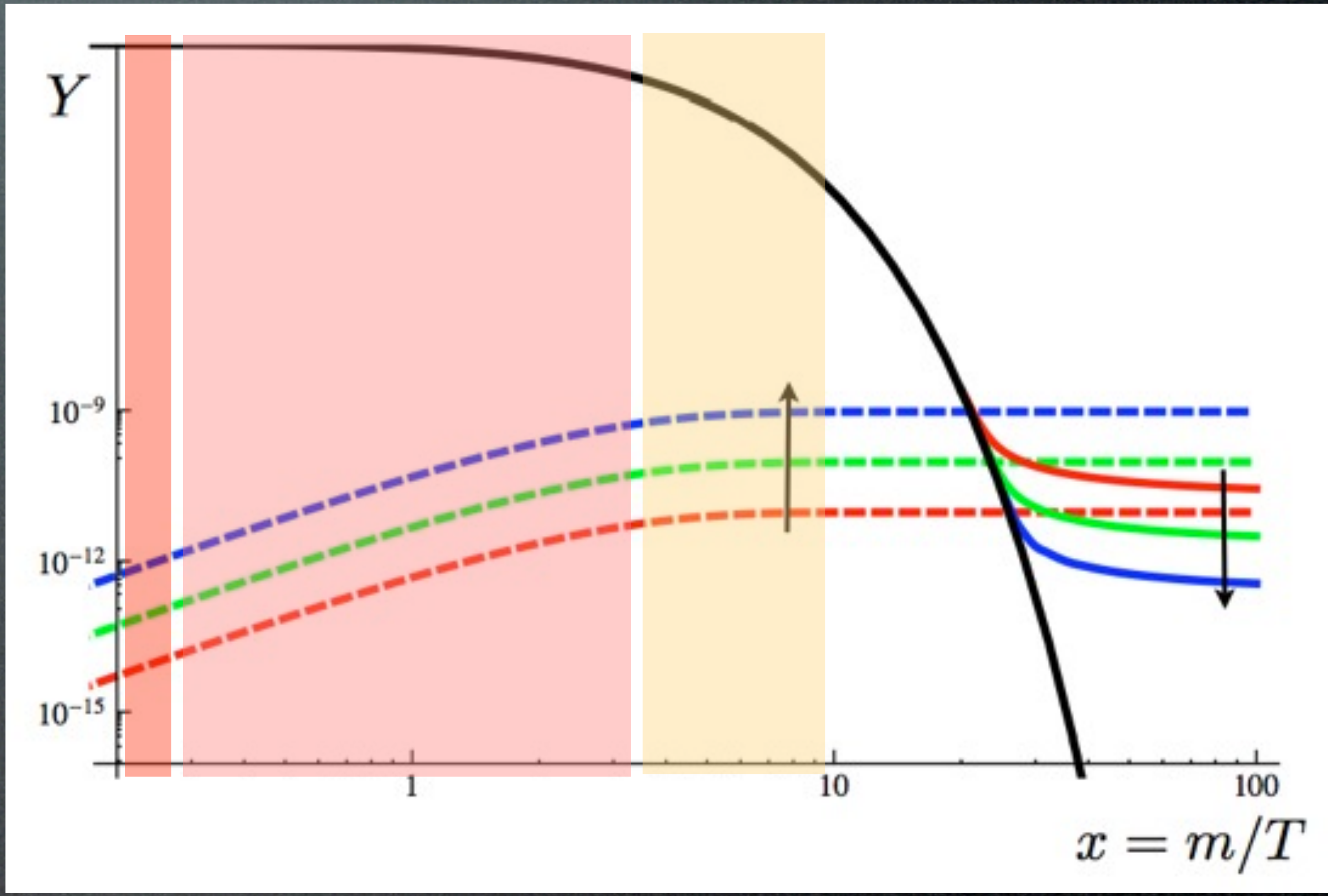

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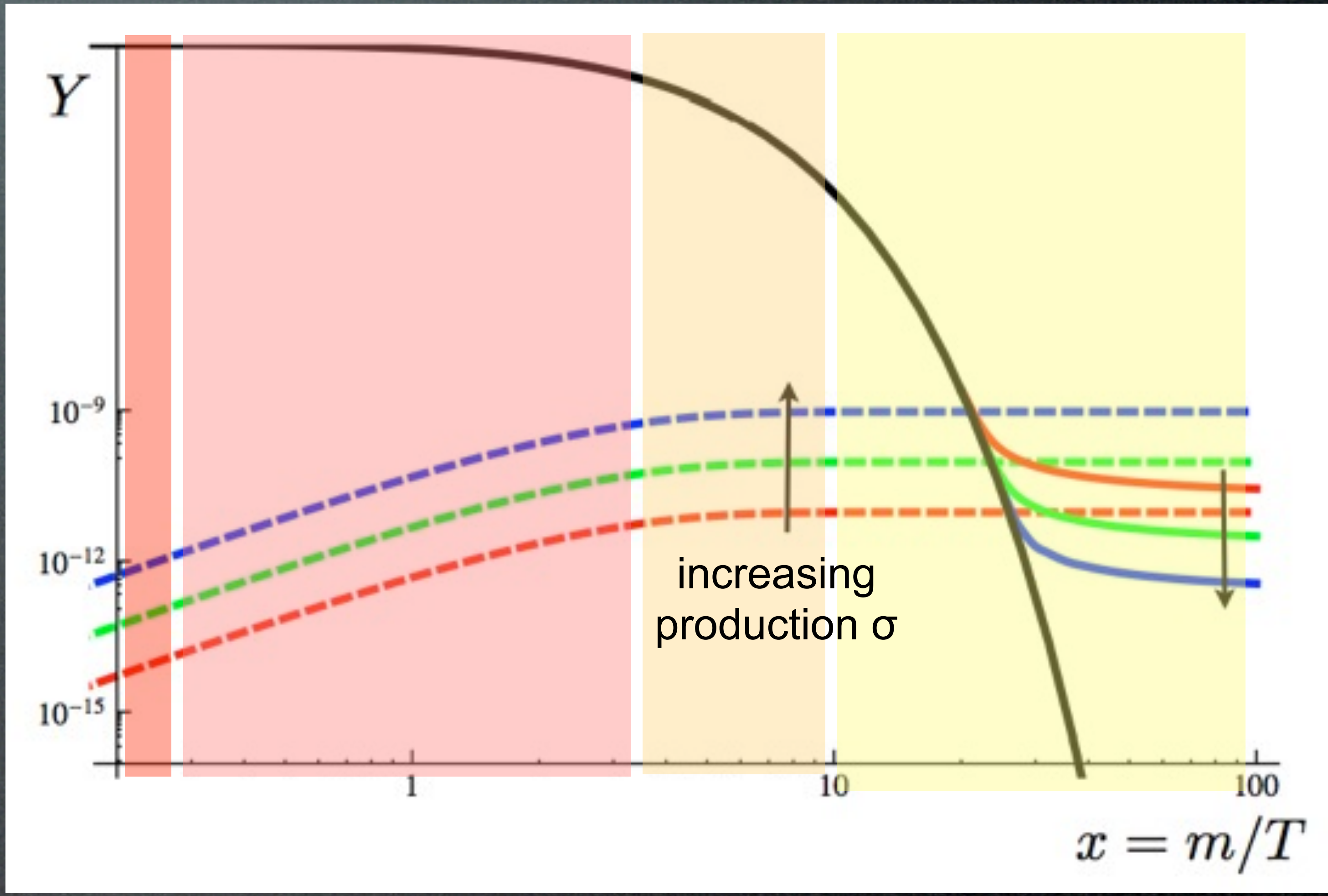

The final abundance is determined by σ (or rather λ).

Minimal Dark Matter

Minimalistic approach

On top of the SM, add only one extra multiplet $\mathcal{X} = \begin{pmatrix} \mathcal{X}_1 \\ \mathcal{X}_2 \\ \vdots \end{pmatrix}$

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \bar{\mathcal{X}}(i\not{D} + M)\mathcal{X}$$ if $\mathcal{X}$ is a fermion

$$\mathscr{L} = \mathscr{L}_{\rm SM} + |D_\mu \mathcal{X}|^2 - M^2|\mathcal{X}|^2$$ if $\mathcal{X}$ is a scalar

and systematically search for the ideal DM candidate...

Minimalistic approach

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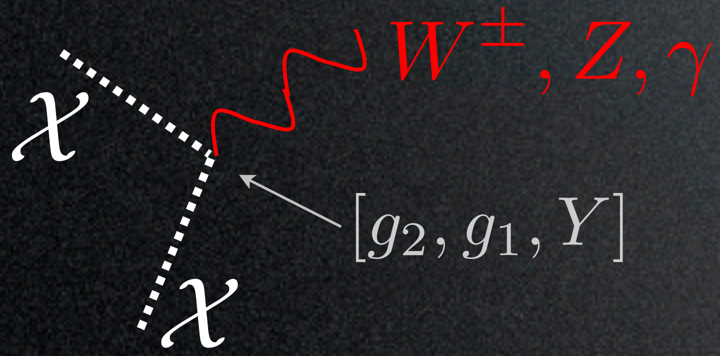
gauge interactions



the only parameter,
and will be fixed by $\Omega_{\rm DM}$.

(other terms in the scalar potential)

(one loop mass splitting)

and systematically search for the ideal DM candidate...

The ideal DM candidate is

weakly int., massive, neutral, stable

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weakly int., massive, neutral, stable

$SU(2)_L$	$U(1)_Y$	spin
$\underline{2}$		
$\underline{3}$		
$\underline{4}$		
$\underline{5}$		
$\underline{7}$		

$$\chi = \begin{pmatrix} \chi_1 \\ \chi_2 \\ \vdots \\ \chi_n \end{pmatrix}$$

these are all possible choices:

$n \leq 5$ for fermions

$n \leq 7$ for scalars

to avoid explosion in the running coupling

$$\alpha_2^{-1}(E') = \alpha_2^{-1}(M) - \frac{b_2(n)}{2\pi} \ln \frac{E'}{M}$$

$\longleftarrow$ ($\underline{6}$ is similar to $\underline{4}$)

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$SU(2)_L$	$U(1)_Y$	spin
$\underline{2}$	$1/2$	
$\underline{3}$	0	
	1	
$\underline{4}$	$1/2$	
	$3/2$	
$\underline{5}$	0	
	1	
	2	
$\underline{7}$	0	

Each multiplet contains a neutral component with a proper assignment of the hypercharge, according to

$$\boxed{Q = T_3 + Y} \equiv 0$$

e.g. for $n = 2$: $T_3 = \begin{pmatrix} +\frac{1}{2} \\ \\ -\frac{1}{2} \end{pmatrix} \Rightarrow |Y| = \frac{1}{2}$

e.g. for $n = 3$: $T_3 = \begin{pmatrix} +1 \\ 0 \\ -1 \end{pmatrix} \Rightarrow |Y| = 0 \text{ or } 1$

etc.

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$SU(2)_L$	$U(1)_Y$	spin
$\underline{2}$	$1/2$	S
		F
$\underline{3}$	0	S
		F
	1	S
		F
$\underline{4}$	$1/2$	S
		F
	$3/2$	S
		F
$\underline{5}$	0	S
		F
	1	S
		F
	2	S
		F
$\underline{7}$	0	S

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$SU(2)_L$	$U(1)_Y$	spin	M (TeV)
$\underline{2}$	$1/2$	S	0.43
		F	1.2
$\underline{3}$	0	S	2.0
		F	2.6
	1	S	1.4
		F	1.8
$\underline{4}$	$1/2$	S	2.4
		F	2.5
	$3/2$	S	2.4
		F	2.5
$\underline{5}$	0	S	5.0
		F	4.5
	1	S	3.5
		F	3.2
	2	S	3.5
		F	3.2
$\underline{7}$	0	S	8.5

The mass M is determined by the relic abundance:

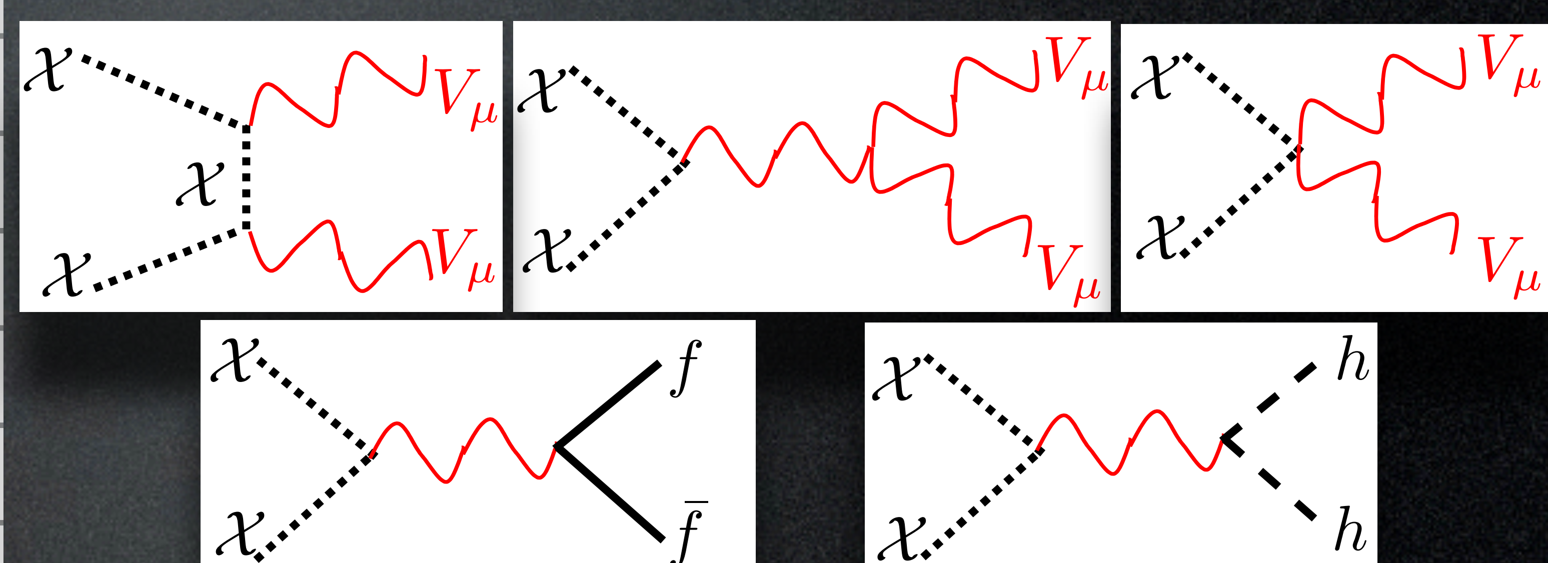
$$\Omega_{\rm DM} = \frac{6\ 10^{-27}{\rm cm}^3{\rm s}^{-1}}{\langle \sigma_{\rm ann} v\rangle} \simeq 0.24$$

for $\mathcal{X}$ scalar

$$\langle \sigma_A v\rangle \simeq \frac{g_2^4\ (3-4n^2+n^4)+16\ Y^4 g_Y^4 + 8 g_2^2 g_Y^2 Y^2 (n^2-1)}{64\pi\ M^2\ g_{\mathcal{X}}}$$

for $\mathcal{X}$ fermion

$$\langle \sigma_A v\rangle \simeq \frac{g_2^4\ (2n^4+17n^2-19)+4Y^2 g_Y^4 (41+8Y^2)+16 g_2^2 g_Y^2 Y^2 (n^2-1)}{128\pi\ M^2\ g_{\mathcal{X}}}$$



(- include co-annihilations)
(- computed for $M \gg M_{Z,W}$)

The ideal DM candidate is
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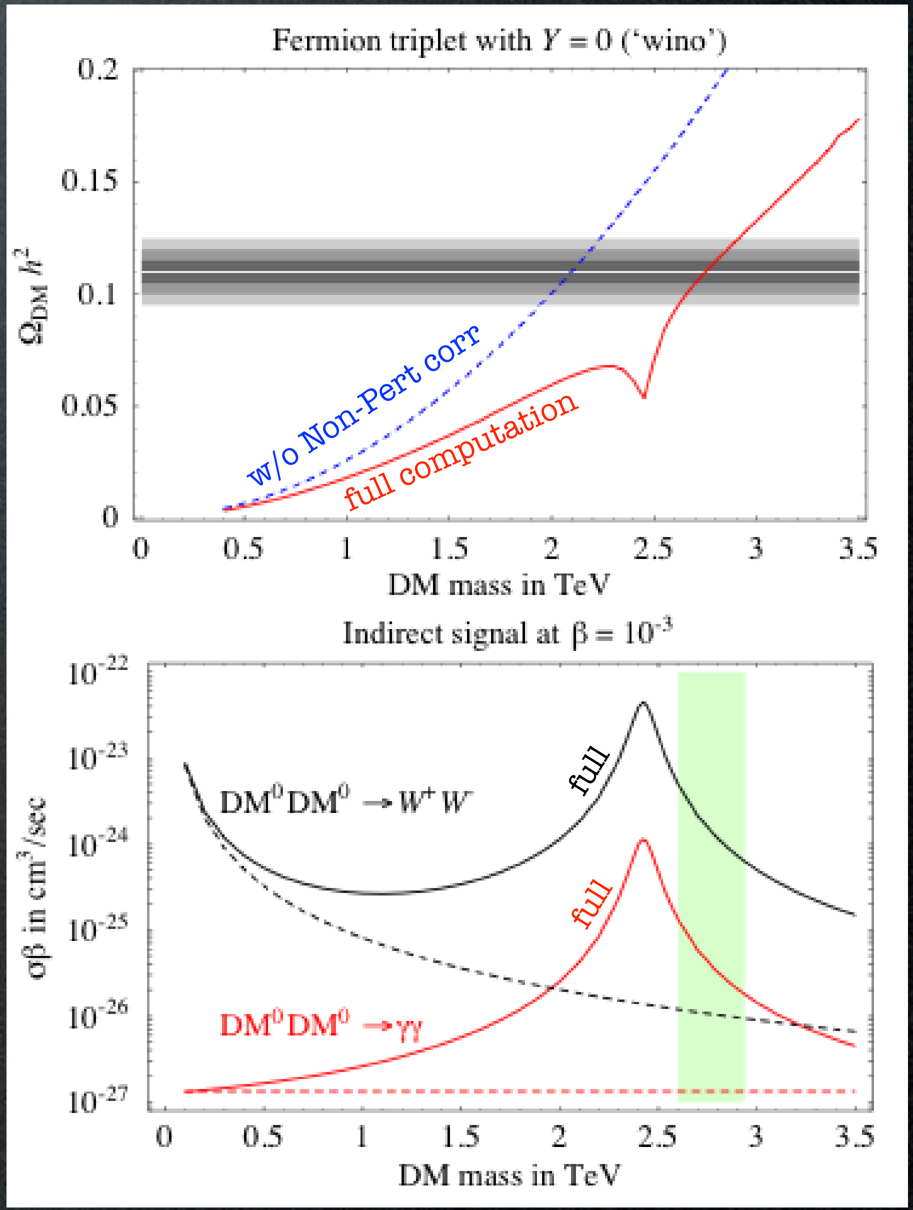
$SU(2)_L$	$U(1)_Y$	spin	M (TeV)
$\underline{2}$	$1/2$	S	
		F	1.0
$\underline{3}$	0	S	2.5
		F	2.7
	1	S	
		F	
$\underline{4}$	$1/2$	S	
		F	
	$3/2$	S	
		F	
$\underline{5}$	0	S	9.4
		F	10
	1	S	
		F	
	2	S	
		F	
$\underline{7}$	0	S	25

Non-perturbative corrections
(and other smaller corrections) (more later)
induce modifications:

$$\langle \sigma_{\rm ann} v \rangle \rightsquigarrow R \cdot \langle \sigma_{\rm ann} v \rangle + \langle \sigma_{\rm ann} v \rangle_{p-\rm wave}$$

with $R \sim \mathcal{O}(\text{few}) \to \mathcal{O}(10^2)$



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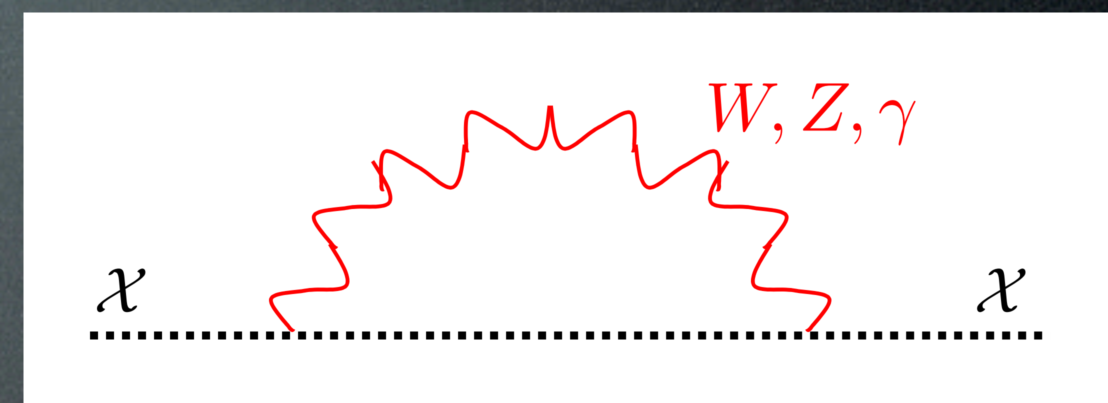
$SU(2)_L$	$U(1)_Y$	spin	M (TeV)	ΔM(MeV)
2	1/2	S		348
		F	1.0	342
3	0	S	2.5	166
		F	2.7	166
	1	S		540
		F		526
4	1/2	S		353
		F		347
	3/2	S		729
		F		712
5	0	S	9.4	166
		F	10	166
	1	S		537
		F		534
	2	S		906
		F		900
7	0	S	25	166

EW loops induce a mass splitting ΔM inside the n-uplet:

tree level



$$M_Q - M_{Q'} = \frac{\alpha_2 M}{4\pi}\left\{(Q^2 - Q'^2)s_{\rm W}^2 f\left(\frac{M_Z}{M}\right) + (Q - Q')(Q + Q' - 2Y)\left[f\left(\frac{M_W}{M}\right) - f\left(\frac{M_Z}{M}\right)\right]\right\}$$

with $f(r) \stackrel{r\to 0}{\longrightarrow} -2\pi r$

The neutral component is the lightest

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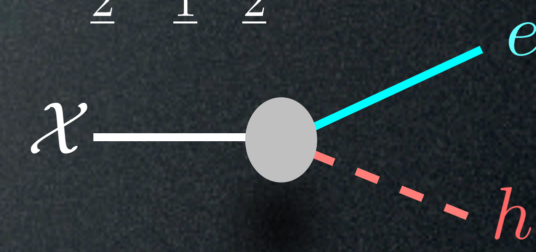
weakly int., massive, neutral, stable

$SU(2)_L$	$U(1)_Y$	spin	M (TeV)	ΔM(MeV)	decay ch.
$\underline{2}$	$1/2$	S		348	EL
		F	1.0	342	EH
$\underline{3}$	0	S	2.5	166	HH^*
		F	2.7	166	LH
	1	S		540	HH, LH
		F		526	LH
$\underline{4}$	$1/2$	S		353	HHH^*
		F		347	(LHH^*)
	$3/2$	S		729	HHH
		F		712	(LHH)
$\underline{5}$	0	S	9.4	166	(HHH^*H^*)
		F	10	166	—
	1	S		537	$(HH^*H^*H^*)$
		F		534	—
	2	S		906	$(H^*H^*H^*H^*)$
		F		900	—
$\underline{7}$	0	S	25	166	—

List all allowed SM couplings:

← e.g. $\begin{array}{ccc} 1/2 & -1 & 1/2 \\ \mathcal{X} & E & H \\ \underline{2} & \underline{1} & \underline{2} \end{array}$



← e.g. $\begin{array}{cccc} 1/2 & -1/2 & 1/2 & -1/2 \\ \mathcal{X} & L & H & H^* \\ \underline{4} & \underline{2} & \underline{2} & \underline{2} \end{array}$

dim=5 operator, induces

$\tau \sim \Lambda^2 \mathrm{TeV}^{-3} \ll t_{\mathrm{universe}}$

for $\Lambda \sim M_{\mathrm{Pl}}$

The ideal DM candidate is

weakly int., massive, neutral, stable

$SU(2)_L$	$U(1)_Y$	spin	M (TeV)	ΔM(MeV)	decay ch.
$\underline{2}$	$1/2$	S		348	EL
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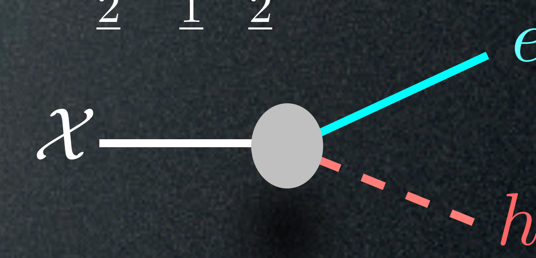

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for $\Lambda \sim M_{\mathrm{Pl}}$

No allowed decay!

Automatically stable!

The ideal DM candidate is

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and

not excluded

by direct searches!

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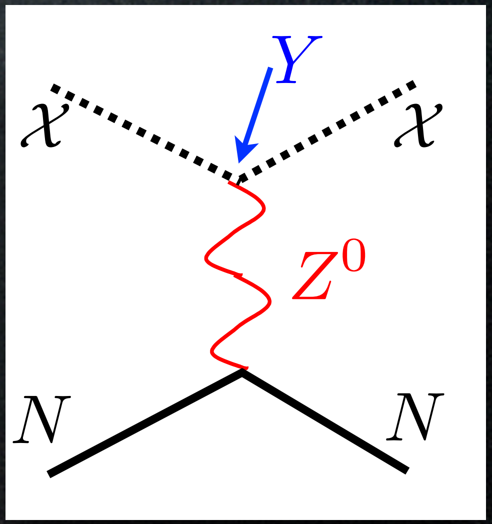
and **not excluded** by direct searches!

Candidates with $Y \neq 0$ interact as



$\sigma \simeq G_F^2 M_N^2 Y^2$ Goodman Witten 1985

$\gg$ present bounds

e.g. Xenon

need $Y = 0$

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We have a winner!

and a 2° place

(other terms in the scalar potential)

Recap:

A fermionic $SU(2)_L$ quintuplet with $Y = 0$
provides a DM candidate with $M = 10$ TeV,
which is fully successful:

- neutral
- ***automatically*** stable

like proton stability in SM!

and

not yet discovered by DM searches.

A scalar $SU(2)_L$ eptaplet with $Y = 0$ also does.

(Other candidates can be cured via non-minimalities.)

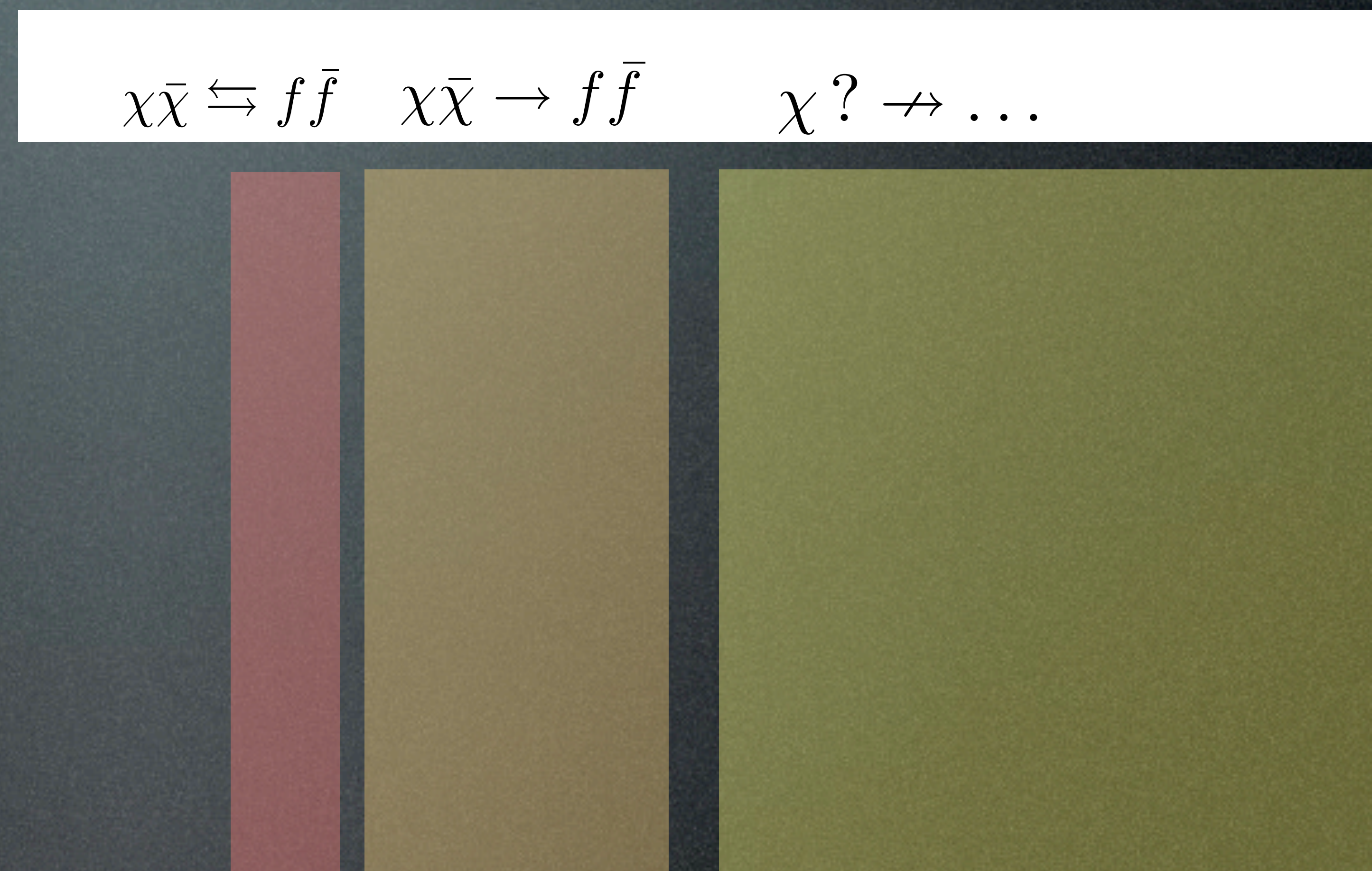
Asymmetric Dark Matter

Nussinov 1985
D.B.Kaplan 1992
Farrar, Zaharijas 2005
Zurek 2009
+ many many >2009

A completely different relic from the Early Universe

Provided:

- an initial asymmetry
- strong enough annihilations



$$\Omega_X \simeq \frac{m_X\, s}{\rho_{\rm crit}} \eta_0$$

The relic abundance is determined by η_0 and m_X.

Asymmetric **Oscillating** DM

Cirelli,
Panci,
Servant,
Zaharijas
1110.3809

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Asymmetric 'freeze-out'

The correct Ω_{DM} can not be obtained.

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Asymmetric 'freeze-out'

Oscillations repopulate $\overline{\mathrm{DM}}$
Annihilations restart

Temporary 'freeze-out'

Final freeze-out

The correct Ω_{DM} can be obtained.

Formalism

The system: - oscillations $\mathrm{DM} \leftrightsquigarrow \overline{\mathrm{DM}}$
- annihilations $\mathrm{DM}\,\overline{\mathrm{DM}} \to X\,X$
- scatterings $\mathrm{DM}\ X \to \mathrm{DM}\ X$

Formalism

coherent

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incoherent

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→ density matrix formalism

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incoherent

$\Rightarrow$ density matrix formalism

Density matrix:

$$\mathcal{Y} = \begin{pmatrix} Y^{+} & Y^{+-} \\ Y^{-+} & Y^{-} \end{pmatrix}$$

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Density matrix:

(comoving) number density of DM

superposition DM-$\overline{\mathrm{DM}}$

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(comoving) number density of $\overline{\mathrm{DM}}$

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(comoving) number density of $\overline{\mathrm{DM}}$

Evolution in time:

$$\begin{aligned}\mathcal{Y}'(x) \quad = \quad & -\frac{i}{x\,H(x)}\Big[\mathcal{H},\mathcal{Y}(x)\Big] \\ & -\frac{s(x)}{x\,H(x)}\left(\frac{1}{2}\Big\{\mathcal{Y}(x),\Gamma_{\rm a}\,\bar{\mathcal{Y}}(x)\,\Gamma_{\rm a}^{\dagger}\Big\} - \Gamma_{\rm a}\,\Gamma_{\rm a}^{\dagger}\,\mathcal{Y}_{\rm eq}^{2}\right) \\ & -\frac{1}{x\,H(x)}\Big\{\Gamma_{\rm s}(x),\mathcal{Y}(x)\Big\}.\end{aligned}$$

$$\mathcal{H} = \begin{pmatrix} m_{\rm DM} & \delta m \\ \delta m & m_{\rm DM} \end{pmatrix}$$

$$\Gamma_{\rm a} \propto \sigma_{\rm ann}$$

Formalism

The system:

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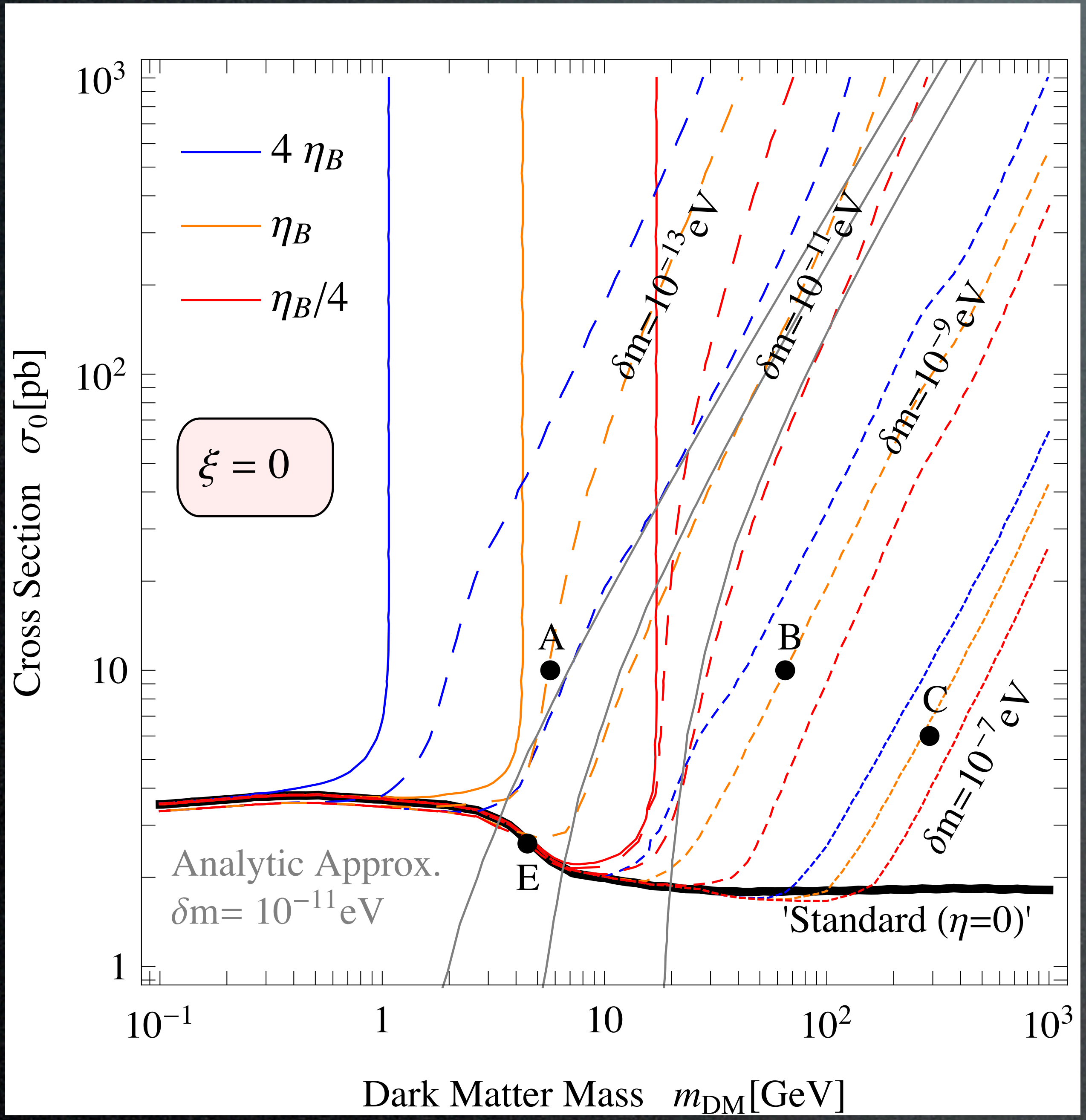
$\Gamma_{\mathrm{a}} \propto \sigma_{\mathrm{ann}}$

$$-\frac{1}{x\,H(x)}\Big\{\Gamma_{\mathrm{s}}(x),\mathcal{Y}(x)\Big\}. \quad \text{scatterings}$$

Results

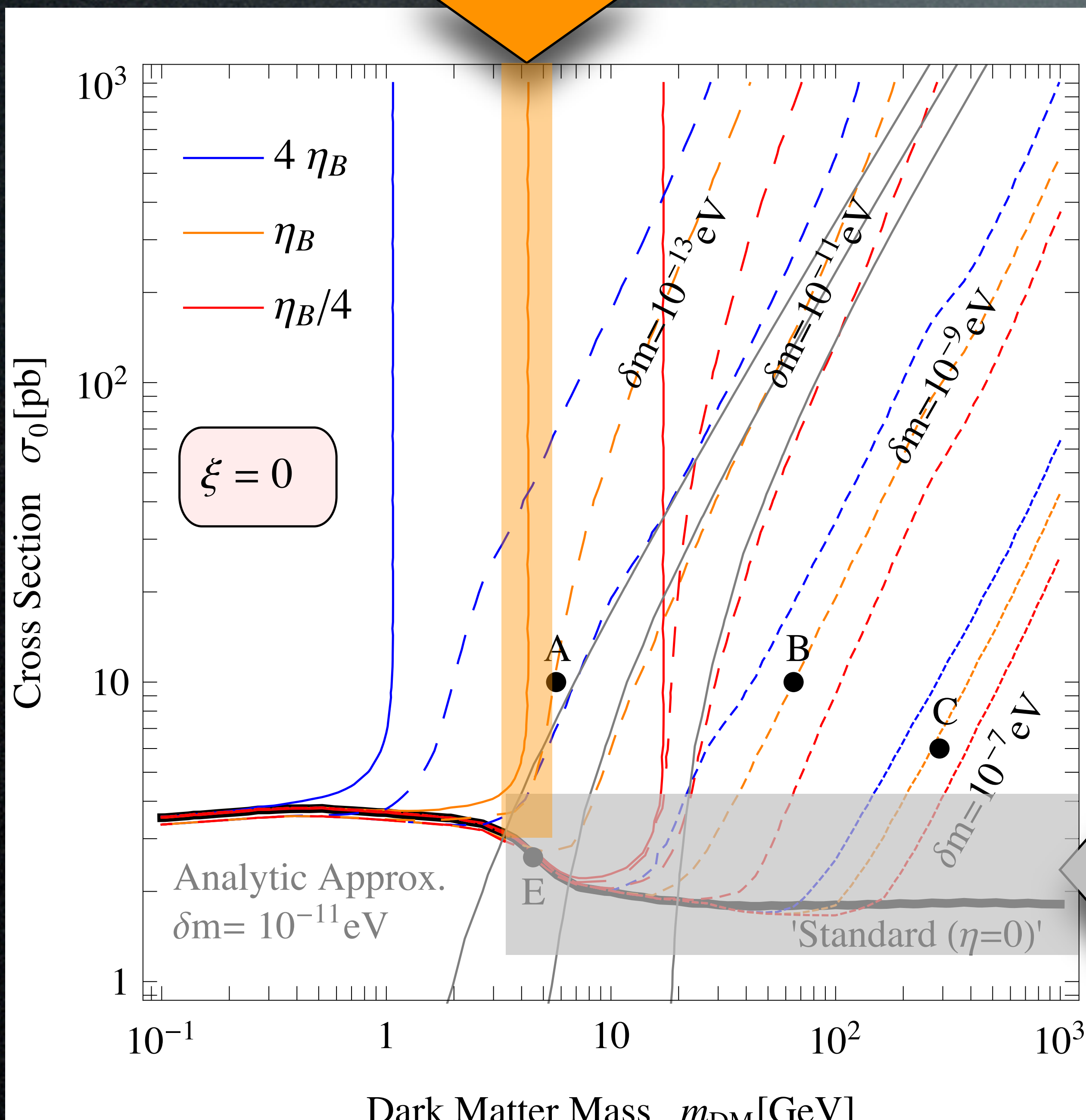
Parameter space: isolines of correct $\Omega_{\rm DM}$



Results

Parameter space: isolines of correct Ω_{DM}

standard aDM



standard WIMP miracle

The region at large m_{DM} and larg-ish σ_0 is open for business.

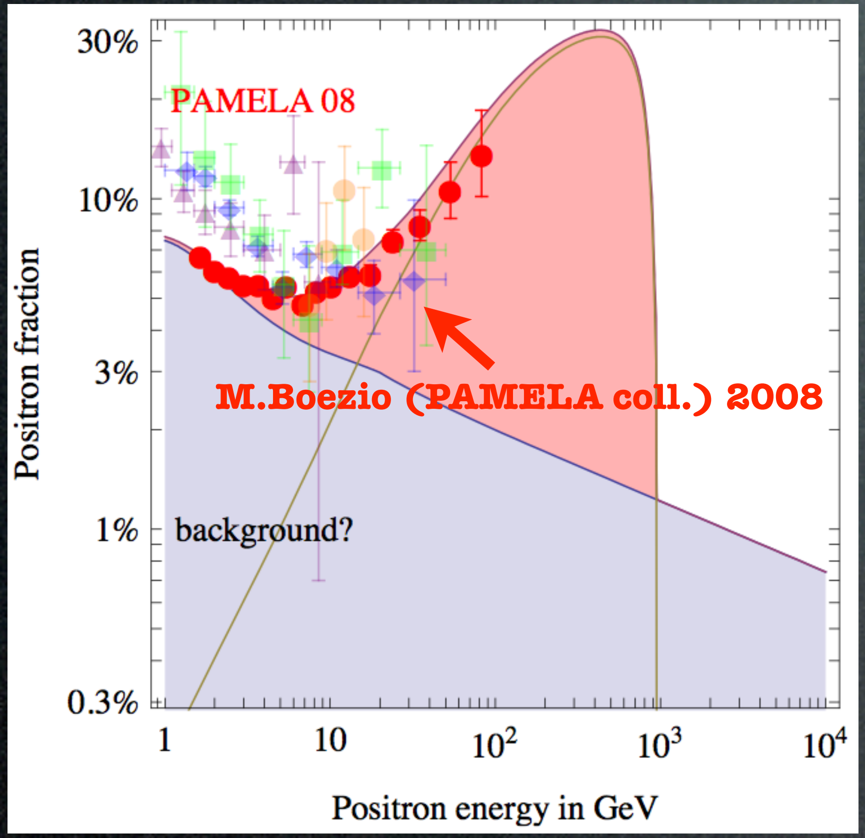
‘Secluded’ Dark Matter

Pospelov, Ritz, Voloshin 2007
Arkani-Hamed, Finkbeiner, Slatyer, Weiner 2008
+ many many **many** >2009

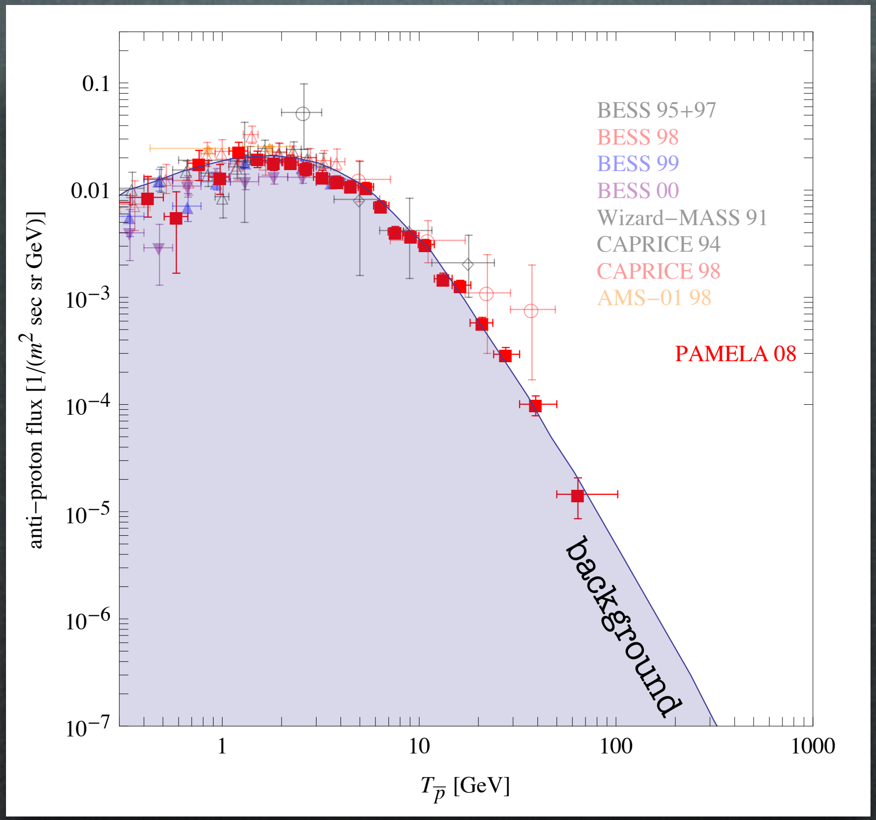
Main motivation

Main motivation

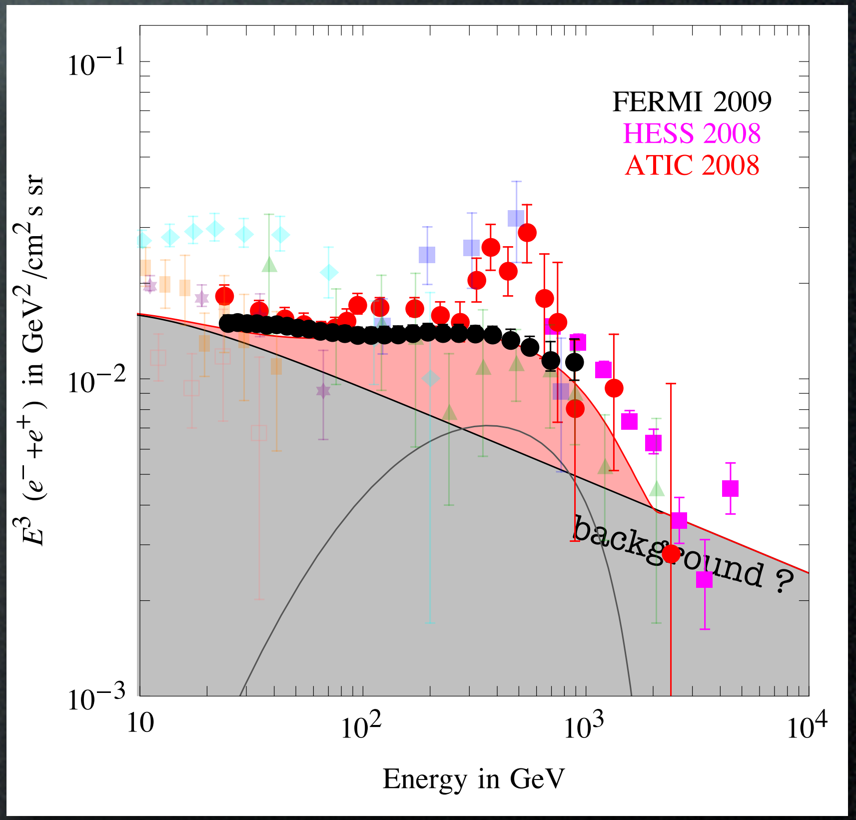
positron fraction



antiprotons



electrons + positrons



Are these signals of Dark Matter?

YES: few TeV, leptophilic DM with huge $\langle \sigma v \rangle \approx 10^{-23}\, \mathrm{cm}^3/\mathrm{sec}$

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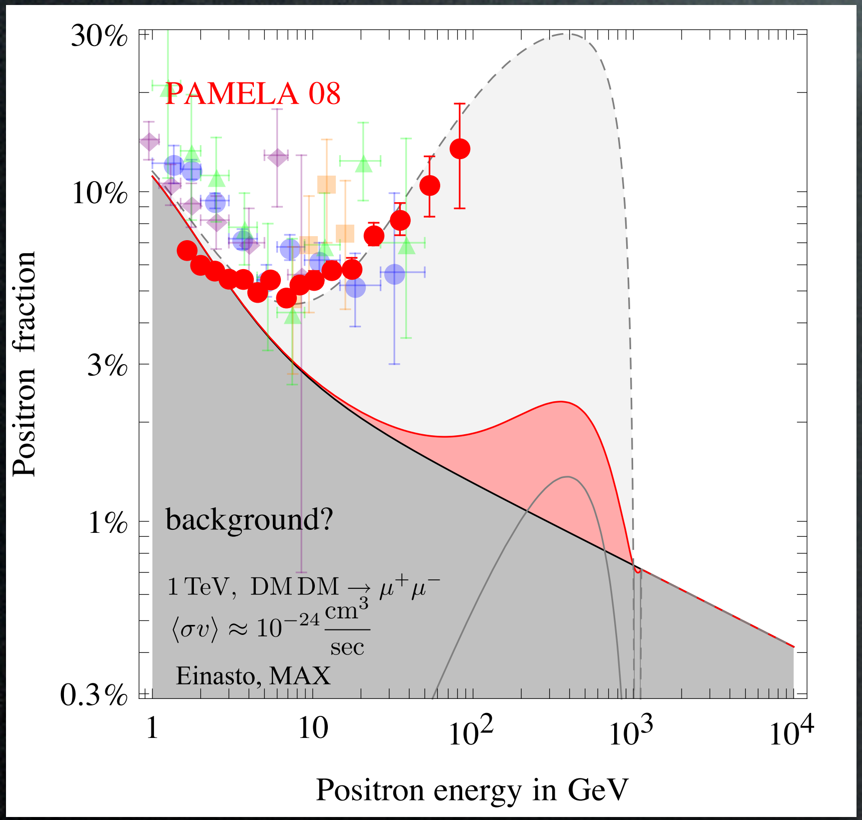

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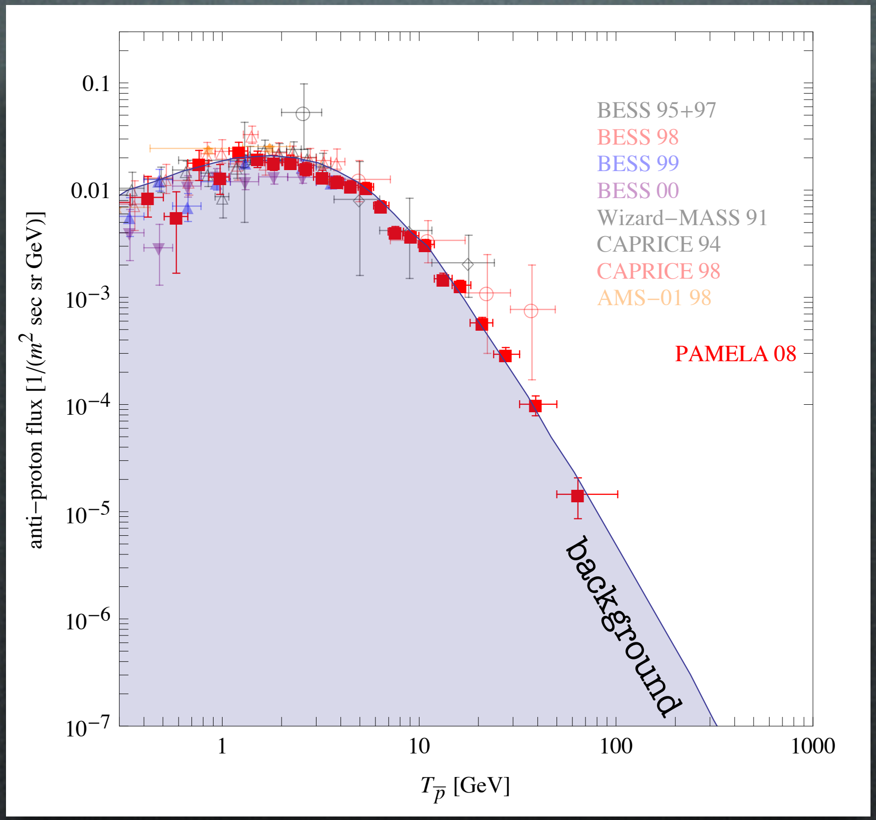

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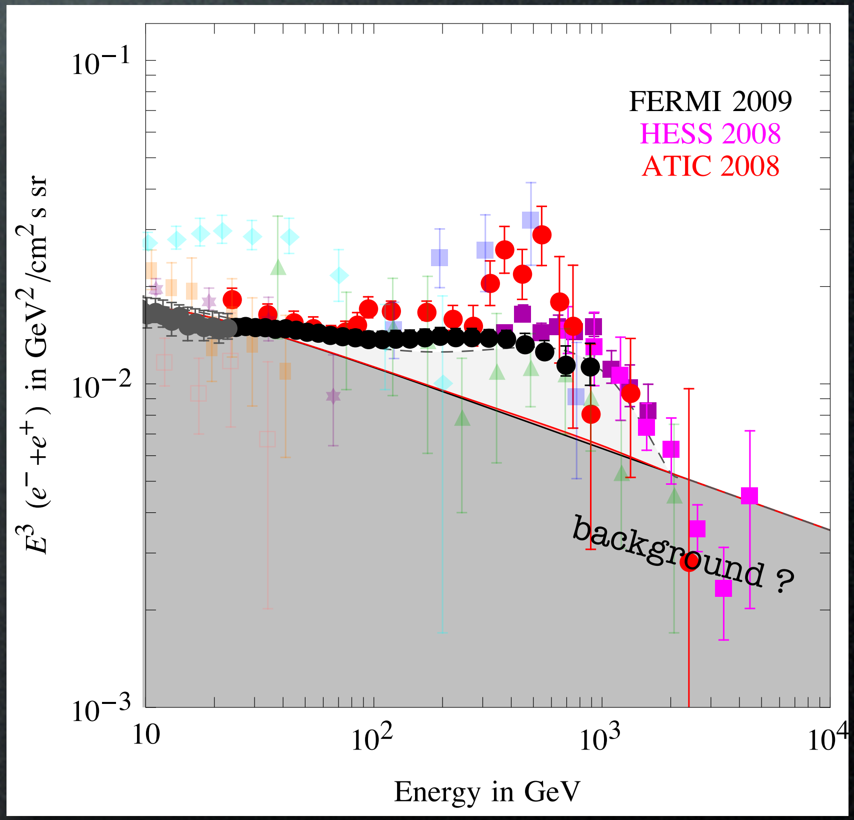

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NO: a formidable ‘background’ for future searches

The "Theory of DM"

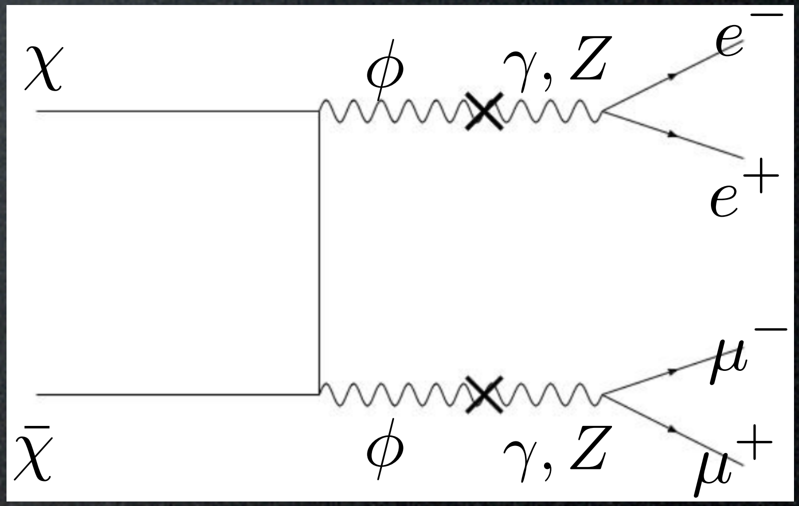
Arkani-Hamed, Weiner, Finkbeiner et al. 0810.0713
0811.3641

Basic ingredients:

χ Dark Matter particle, decoupled from SM, mass $M \sim 700+$ GeV

ϕ new gauge boson ("Dark photon"),
couples only to DM, with typical gauge strength, $m_\phi \sim$ few GeV
- mediates Sommerfeld enhancement of $\chi\bar{\chi}$ annihilation:
$\alpha M / m_V \gtrsim 1$ fulfilled

- decays only into e^+e^- or $\mu^+\mu^-$
for kinematical limit



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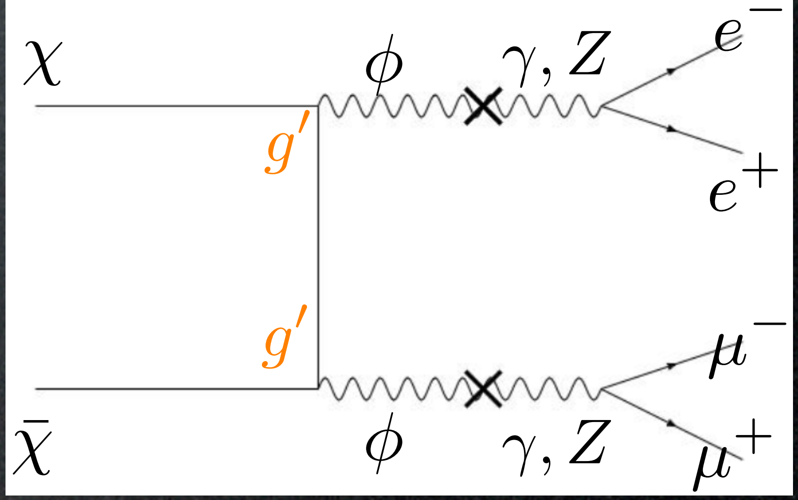

Production mechanism:

just thermal freeze-out
of these annihilations

same idea in: WIMPless DM Feng, Kumar 2008

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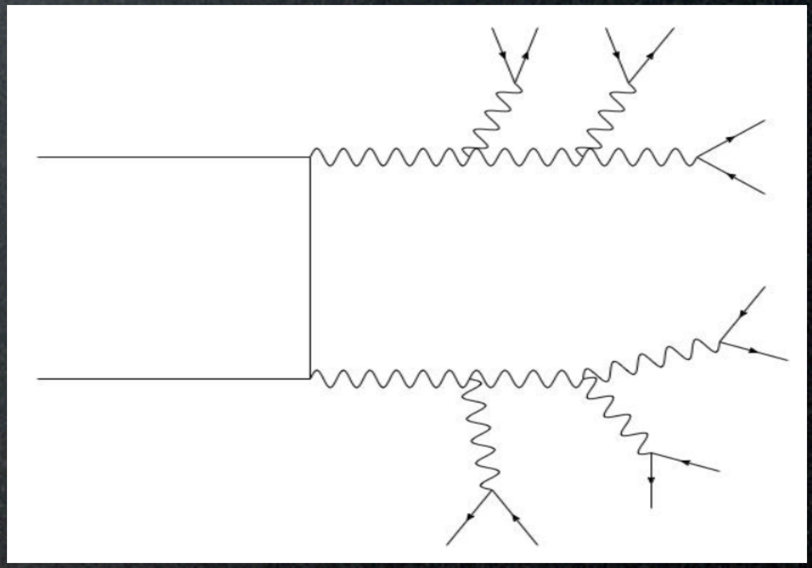


Extras:

χ is a multiplet of states and ϕ is non-abelian gauge boson:

splitting $\delta M \sim 200$ KeV (via loops of non-abelian bosons)

- inelastic scattering explains DAMA
- eXcited state decay $\chi\chi \to \chi\chi^*$ explains INTEGRAL

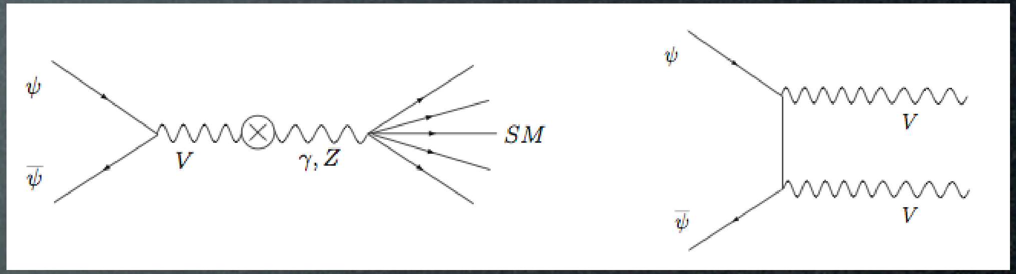
$\hookrightarrow e^+e^-$

Variations

(selected)

- pioneering: Secluded DM, U(1) Stückelberg extension of SM

  Pospelov, Ritz et al 0711.4866 P.Nath et al 0810.5762



- Axion Portal: ϕ is pseudoscalar axion-like

  Nomura, Thaler 0810.5397

- singlet-extended UED: χ is KK RNnu, ϕ is an extra bulk singlet

  Bai, Han 0811.0387

- split UED: χ annihilates only to leptons because quarks are on another brane

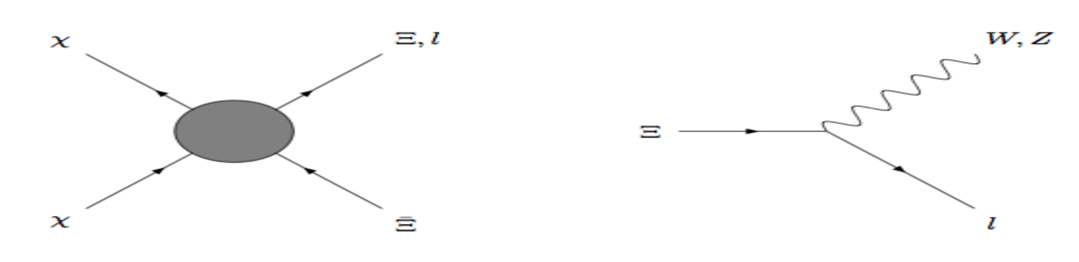
  Park, Shu 0901.0720

- DM carrying lepton number: χ charged under $U(1)_{L_\mu - L_\tau}$, ϕ gauge boson

  Cirelli, Kadastik, Raidal, Strumia 0809.2409 Fox, Poppitz 0811.0399 $(m_\phi \sim \text{tens GeV})$

- New Heavy Lepton: χ annihilates into Ξ that carries lepton number and decays weakly $(\sim \text{TeV})$ $(\sim 100\text{s GeV})$

  Phalen, Pierce, Weiner 0901.3165



- ......

[jump to conclusions]

‘Conclusions’

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‘New’ DM models (newborn of infant) are growing and reaching maturity

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are growing and reaching maturity

* It’s fair to say that,
like any newborn,
they build on the expertise
of giants,
i.e. ‘old’ SuSy DM.

‘Conclusions’

‘New’ DM models (newborn of infant) are growing and reaching maturity

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I picked 3 recent ideas:

1. Minimal DM: the simplest, so-far-overlooked WIMP possibility?
2. Asymmetric DM: a paradigm of a ‘new’ production mechanism?
3. Secluded DM: the harbinger of a rich dark sector?

but the list of new interesting directions is bottomless.