7 October 2022
LHC Days 2022
Split

Dark Matter theory

Marco Cirelli
(CNRS LPTHE Jussieu)

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Still searching for Dark Matter

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Executive summary

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- DM exists

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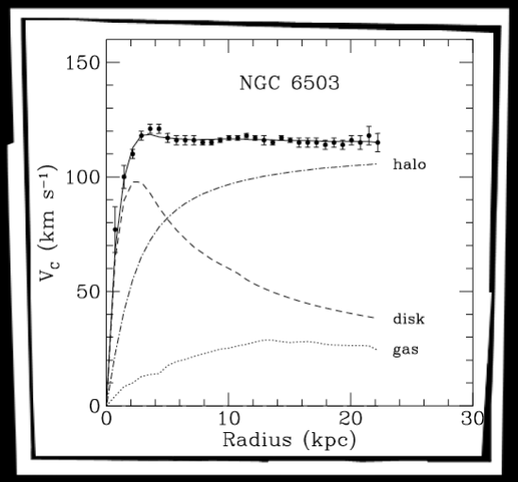
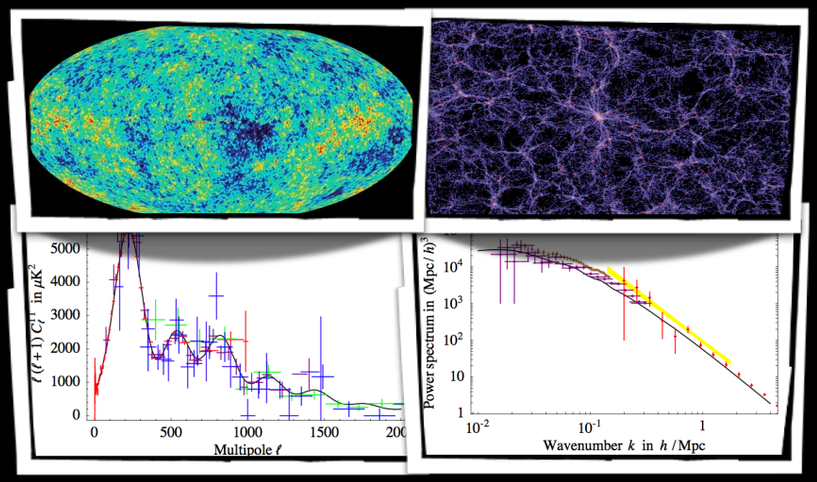


galactic rotation curves

weak lensing (e.g. in clusters)



‘precision cosmology’ (CMB, LSS)

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- it's a new, unknown particle

no SM particle can fulfil

dilutes as $1/a^3$ with universe expansion

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(notice error!)

Planck 2015, 1502.01589 (tab.4)

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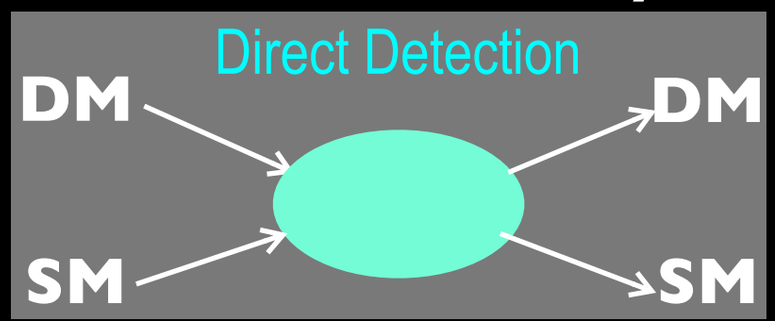

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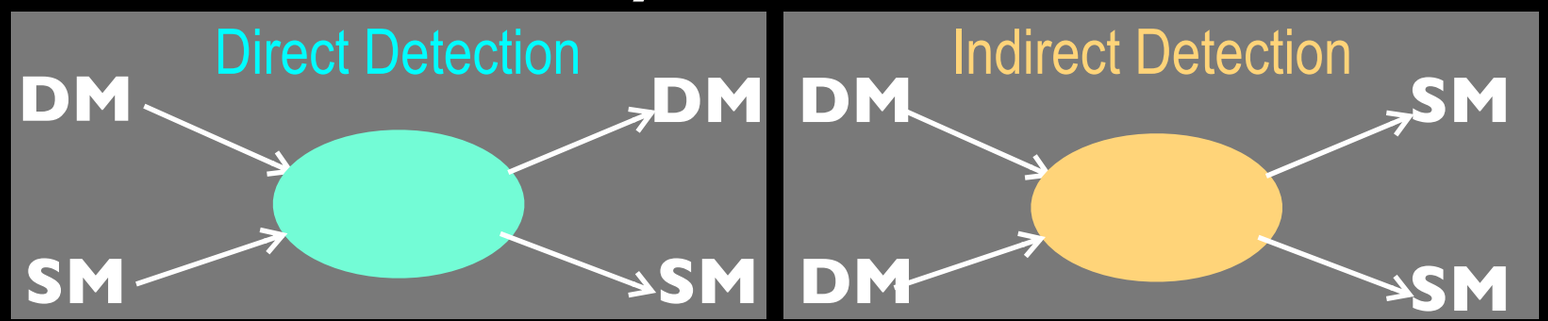

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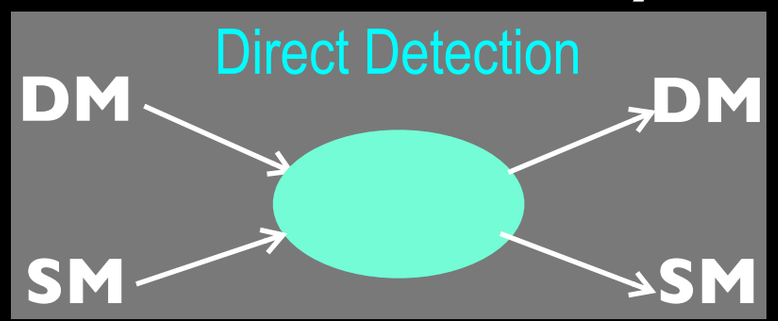

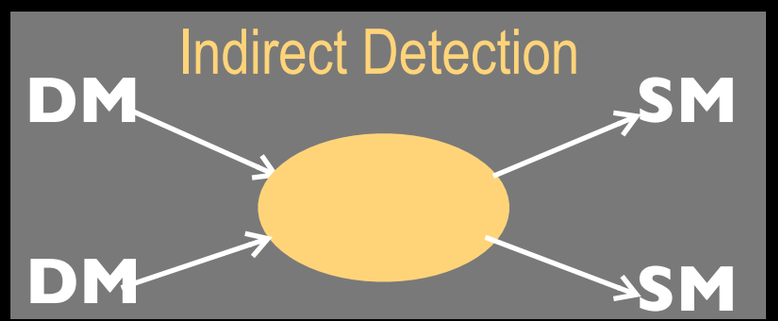

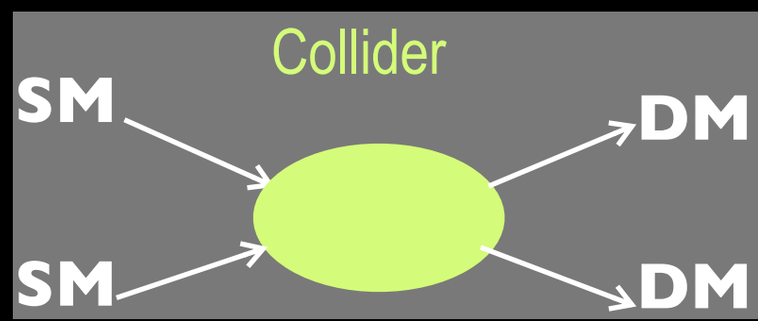

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- Black Holes
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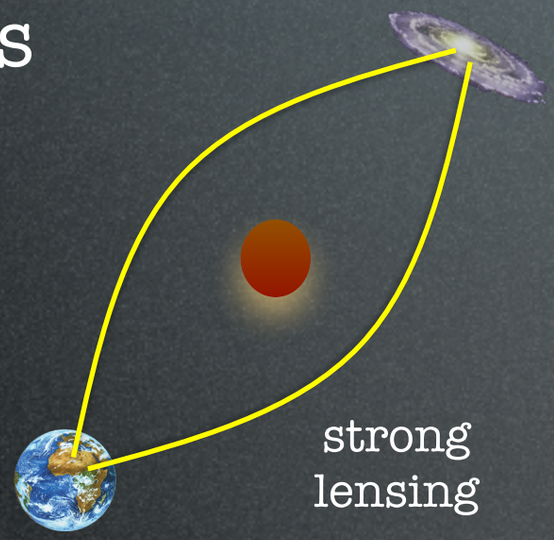
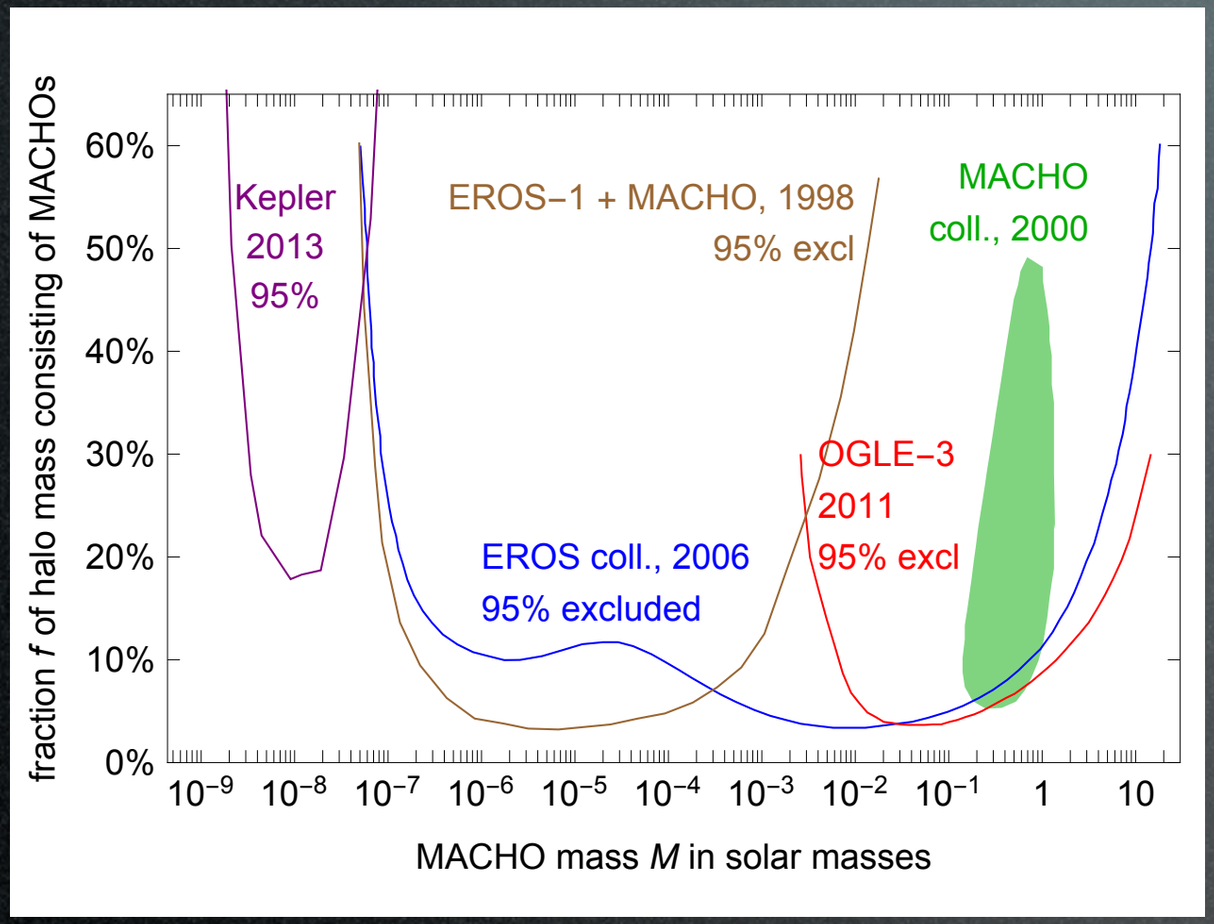


strong
lensing

MACHOs or PBHs as DM



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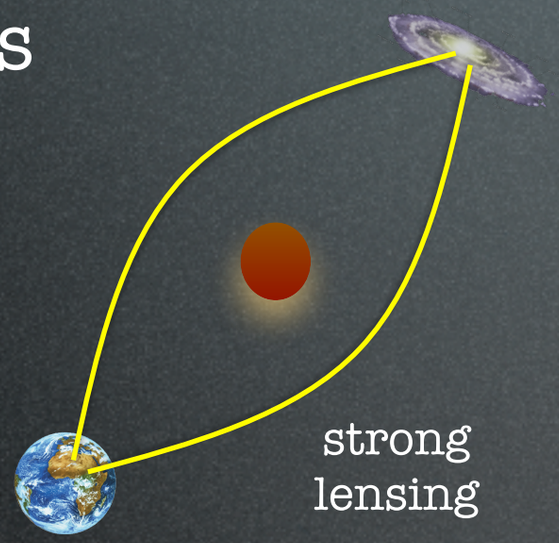

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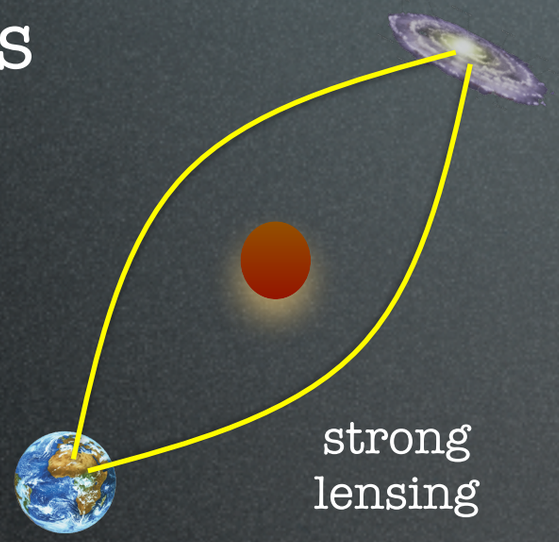

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  too much baryons => Universe full of Helium

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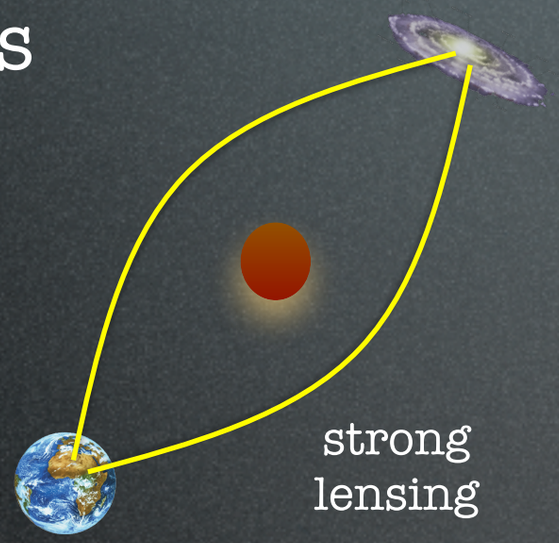

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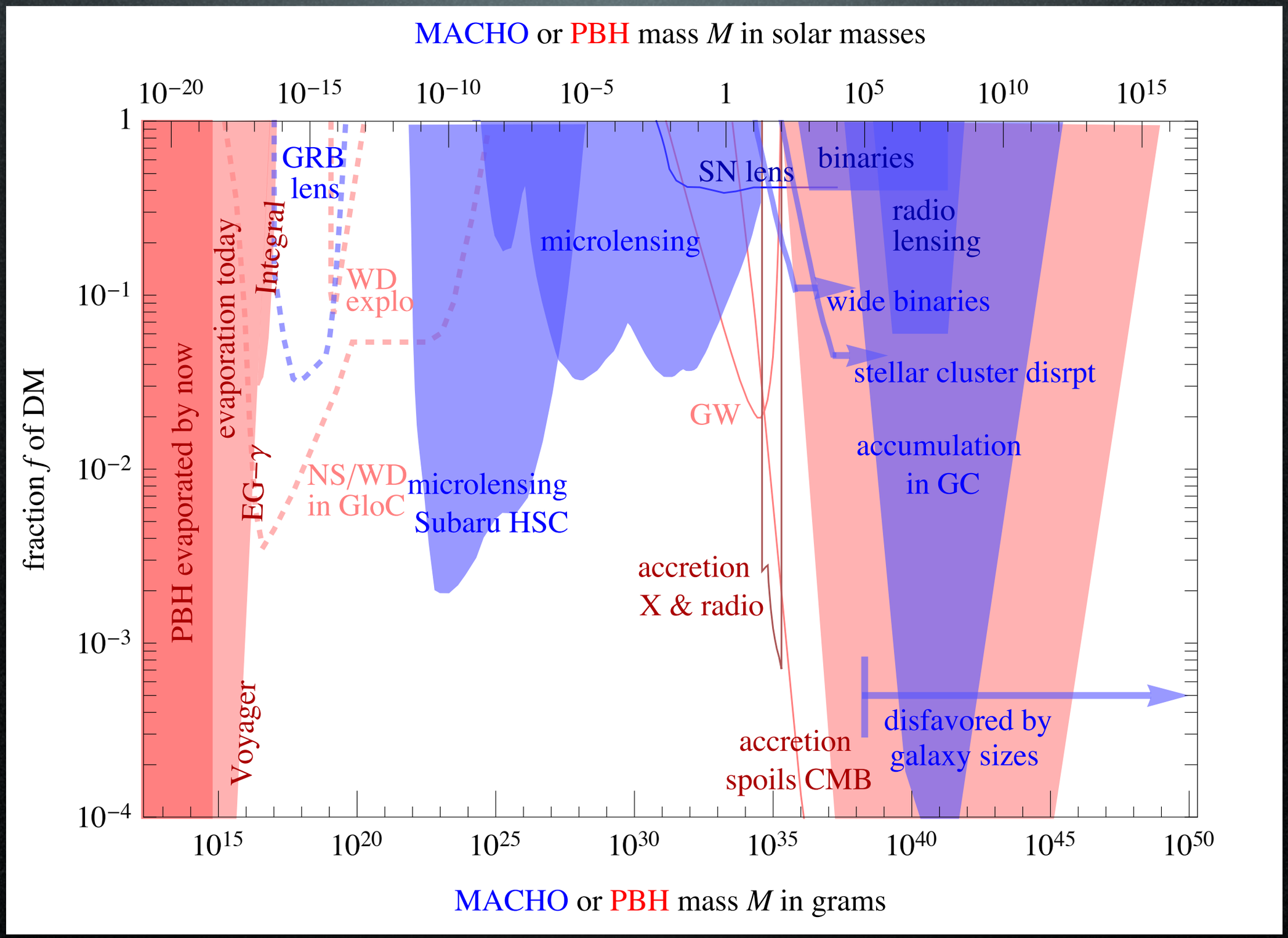
A loophole: Primordial Black Holes!

- produced before BBN
- with masses too small/large to lens
- perhaps LIGO/Virgo are seeing them?

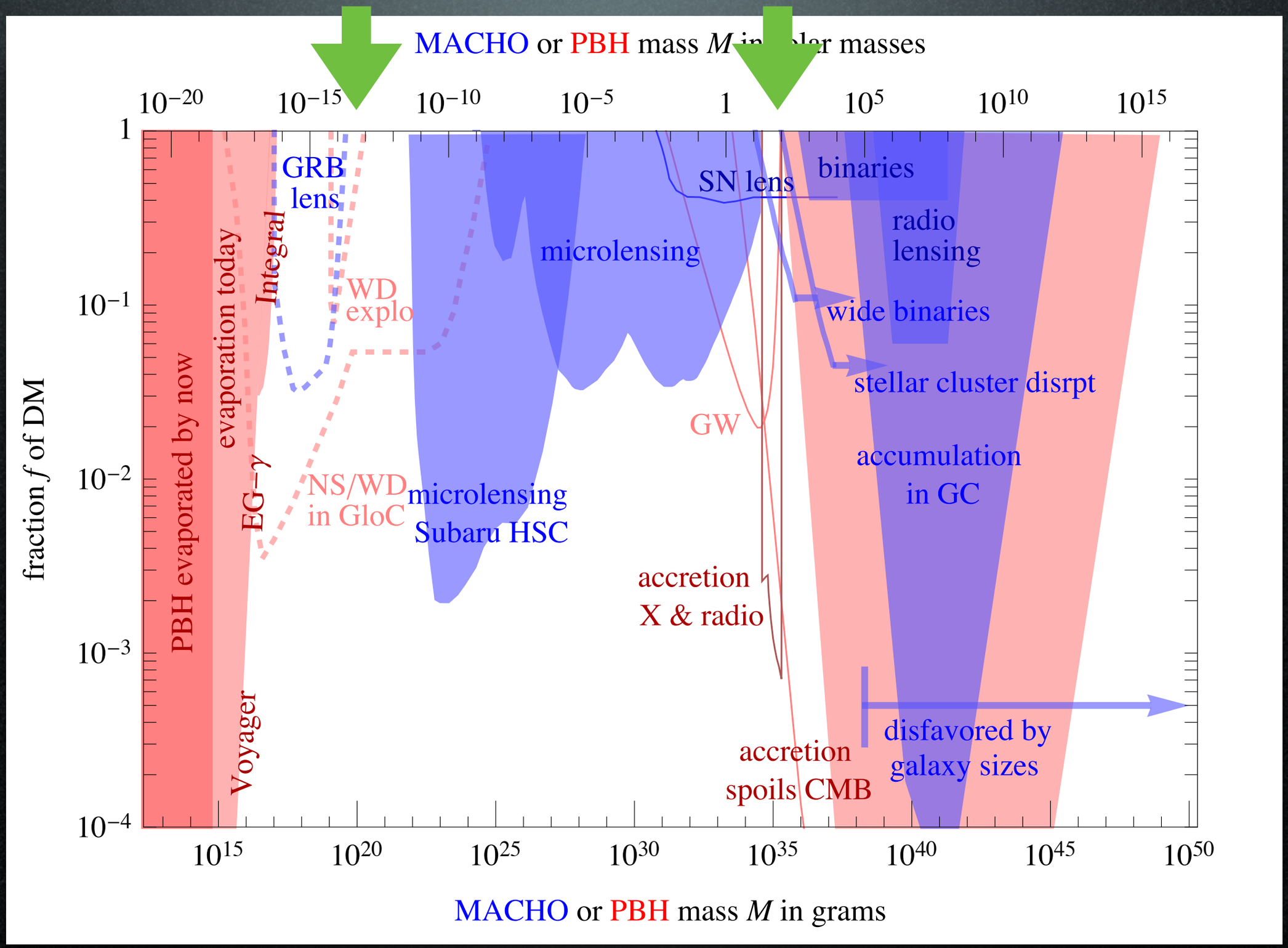
PBHs as DM



M. Cirelli, A. Strumia, J. Zupan, DM review, to appear before the 2082 LHC Days on Mars

PBHs as DM

slivers still open?



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Candidates

The Dark Matter theory space:

Candidates

The Dark Matter theory space:

SuSy DM

Non SuSy DM

Candidates

The Dark Matter theory space:

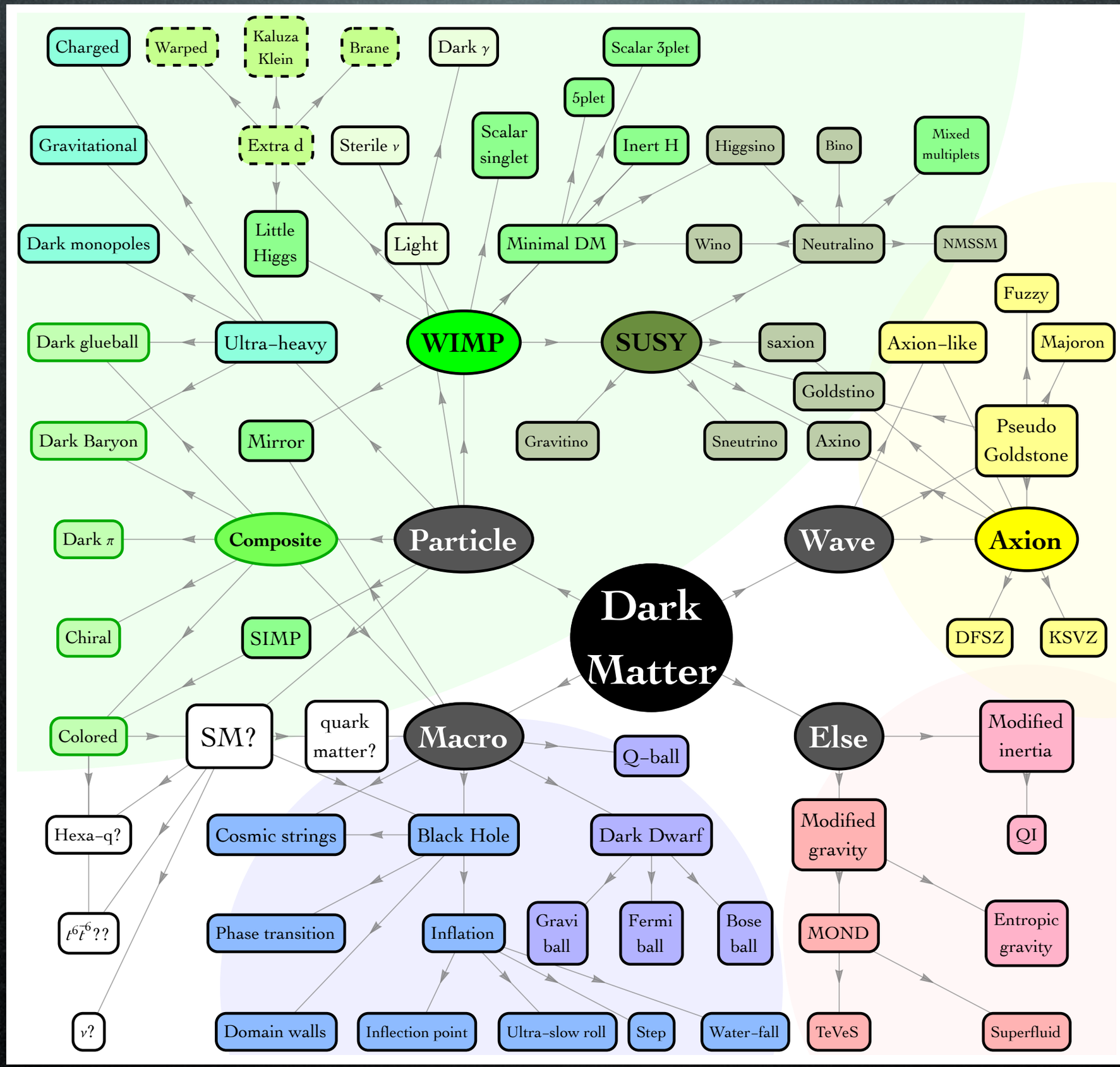
SuSy neutralino

other exotic candi-dates

Candidates

graviballs DM
Large Nightmare DM
omeopathic DM
Ballistic DM
Spectato DM
Undulating DM
Fuzzy DM
Zombie DM
Puffy DM
Cannibal DM
Minimal DM
Impede DM
Axino
Anapole DM
Scalar sing
dipolar DM
Little Higgs DM
Fluffy DM
Asym-metric DM
ELDER DM
SuSy neutralin
self-destructing DM
SIMPs
foamy DM
Rayleig DM
eXciting
Techi-baryon
Inflatable DM
Dichromatic DM
WIMPzillas
charming DM
Vector DM
Forbidden
Leptobary DM
Relentless DM
Concentrated DM
heavy higgs DM
Sterile Neutrino
Luminous DM
Geometric DM
Elko DM
Gravitino
Q-balls
MeV DM
quark
Fluorescent DM
dark photon
Imperfect DM
Higgs ploding
Mimetic DM

Candidates



M. Cirelli, A. Strumia, J. Zupan, DM review, to appear before the 2092 LHC Days on Jupiter

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Caveat: no categorization is perfect.

DM

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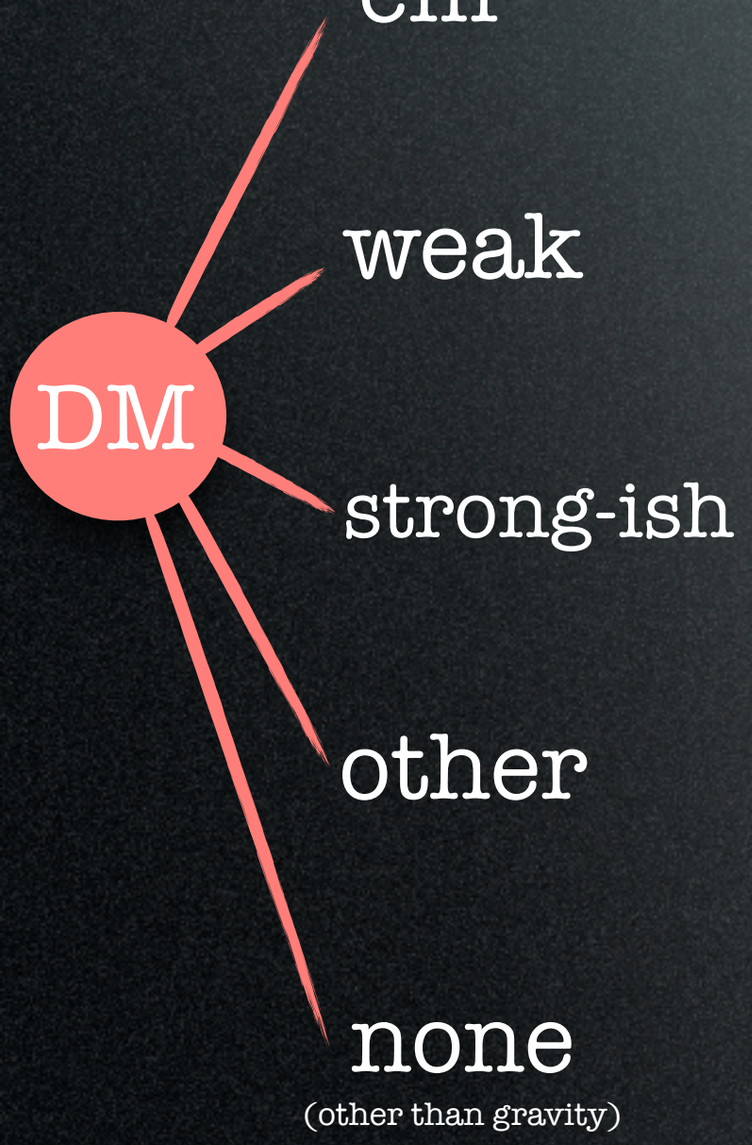
Interactions:



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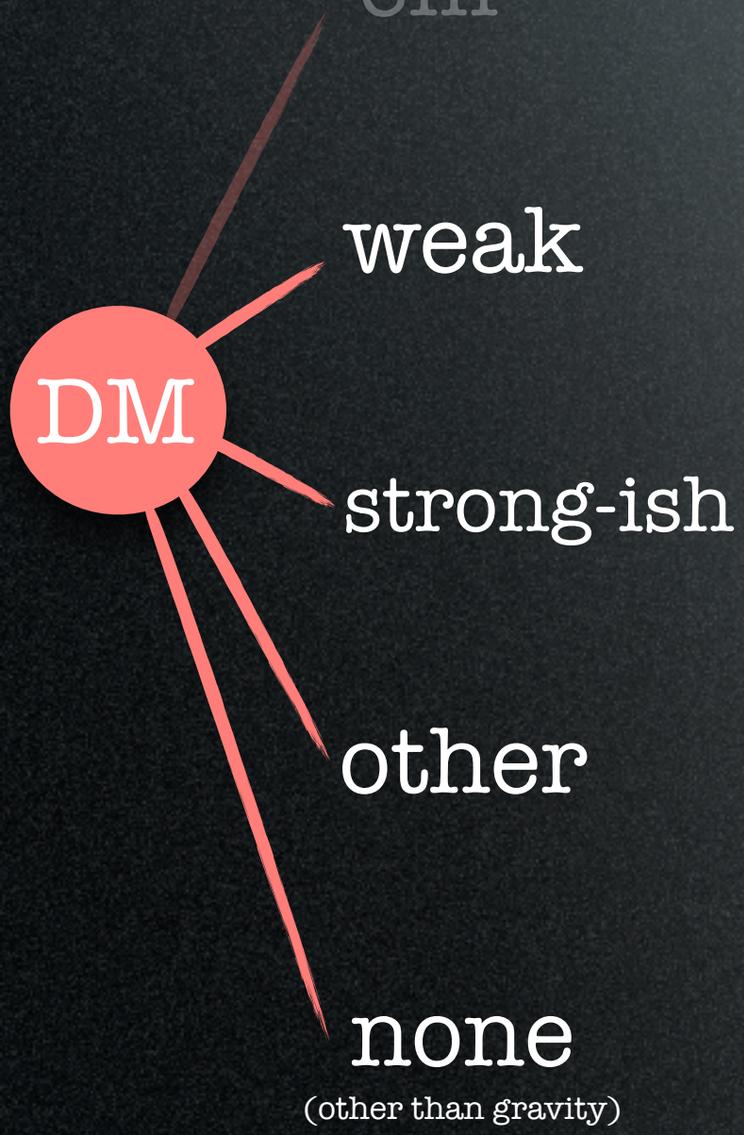

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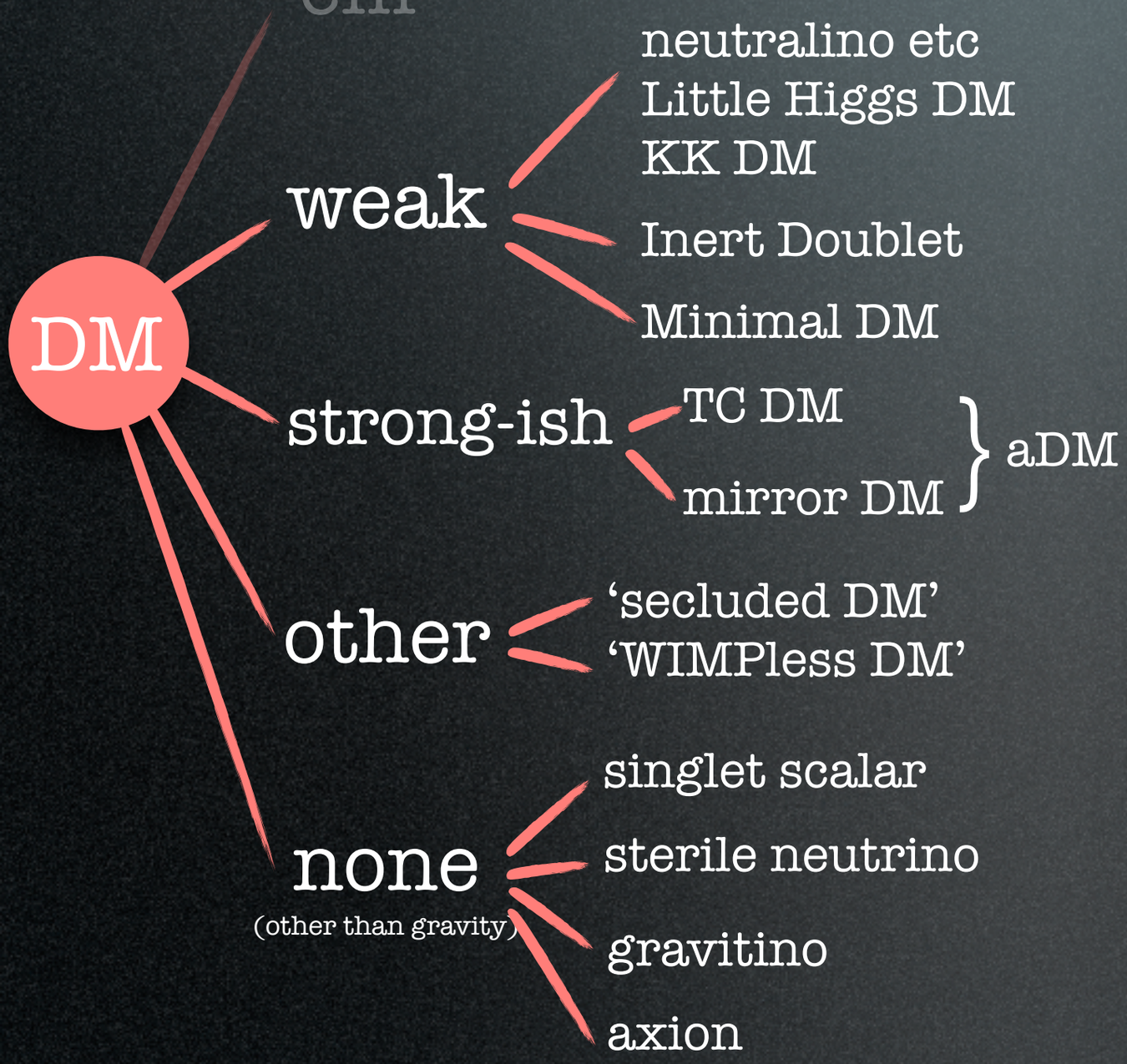

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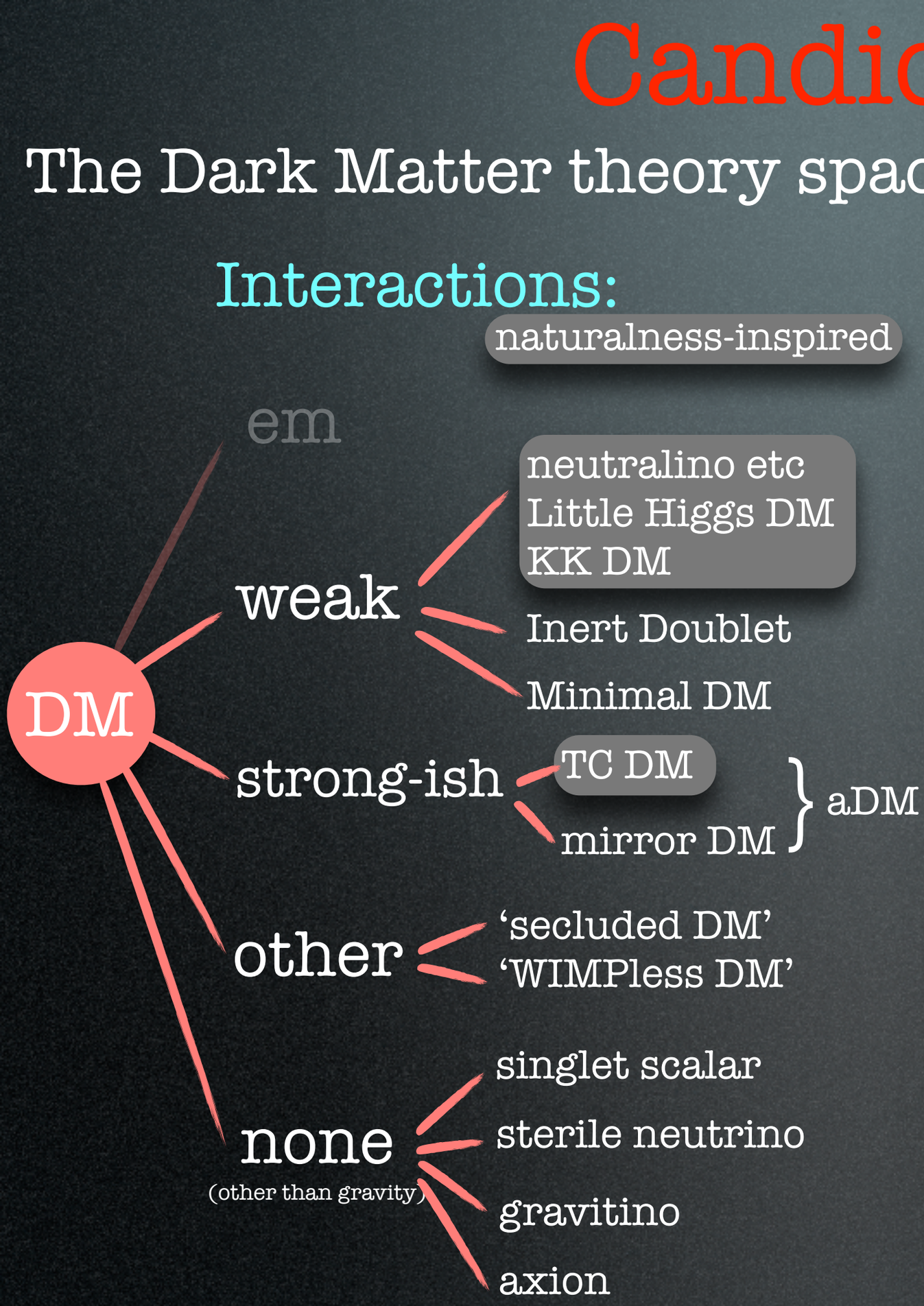
naturalness-inspired



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Interactions: (naturalness-inspired)	Production mechanism?	Stability?
neutralino etc	thermal freeze out	R parity
Little Higgs DM	thermal freeze out	T parity
KK DM	thermal freeze out	K parity
Inert Doublet	thermal freeze out	Z_2 symmetry
Minimal DM	thermal freeze out	gauge sym
TC DM (aDM)	‘exhaustion’	Tbaryon #
mirror DM (aDM)	‘exhaustion’	Z_2 symmetry
‘secluded DM’	sort of freeze out	some symmetry
‘WIMPless DM’	sort of freeze out	some symmetry
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

Production mechanism

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Orthodoxy → **Heterodoxy** → **Heresy**

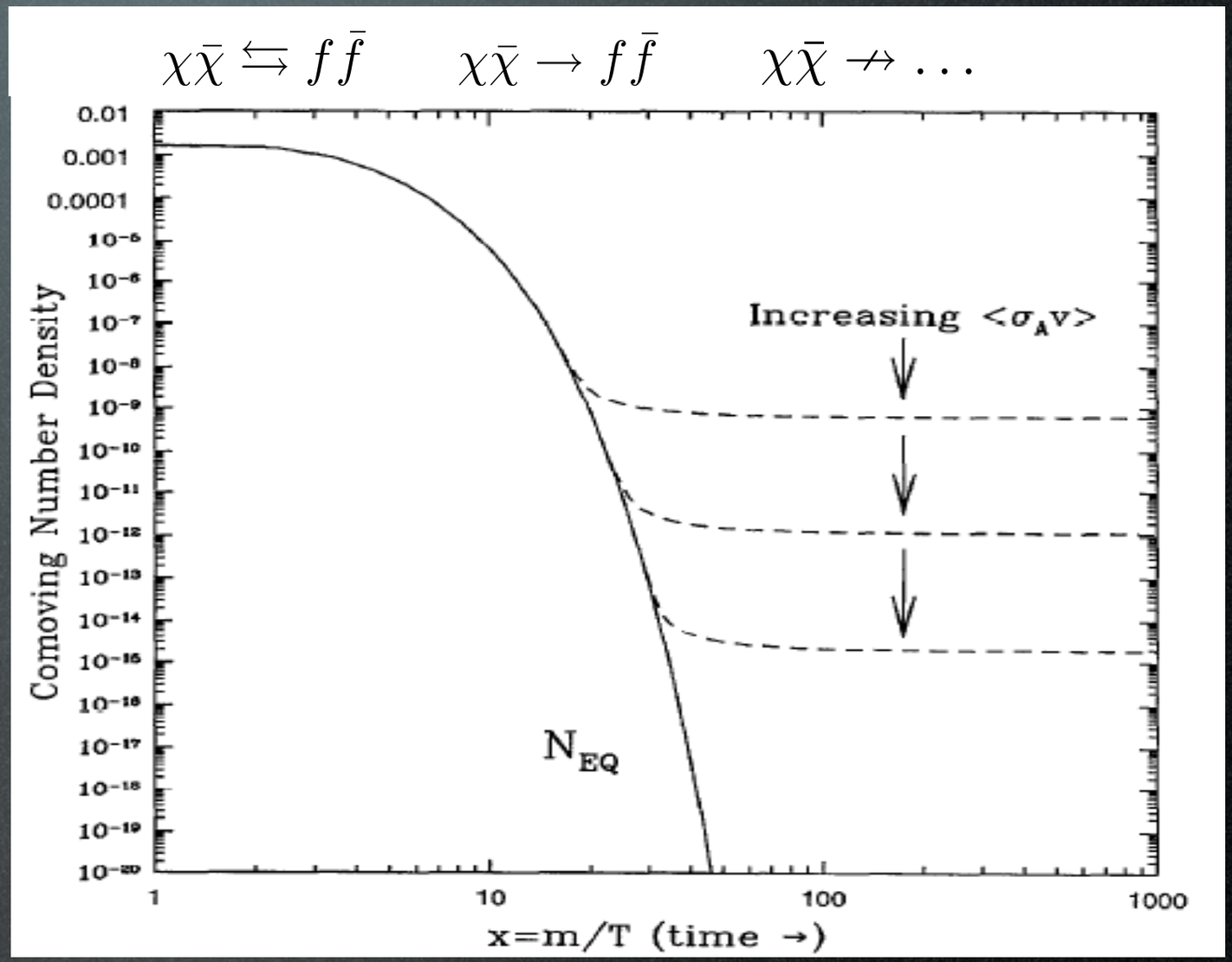
A thermal relic from the Early Universe

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:

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

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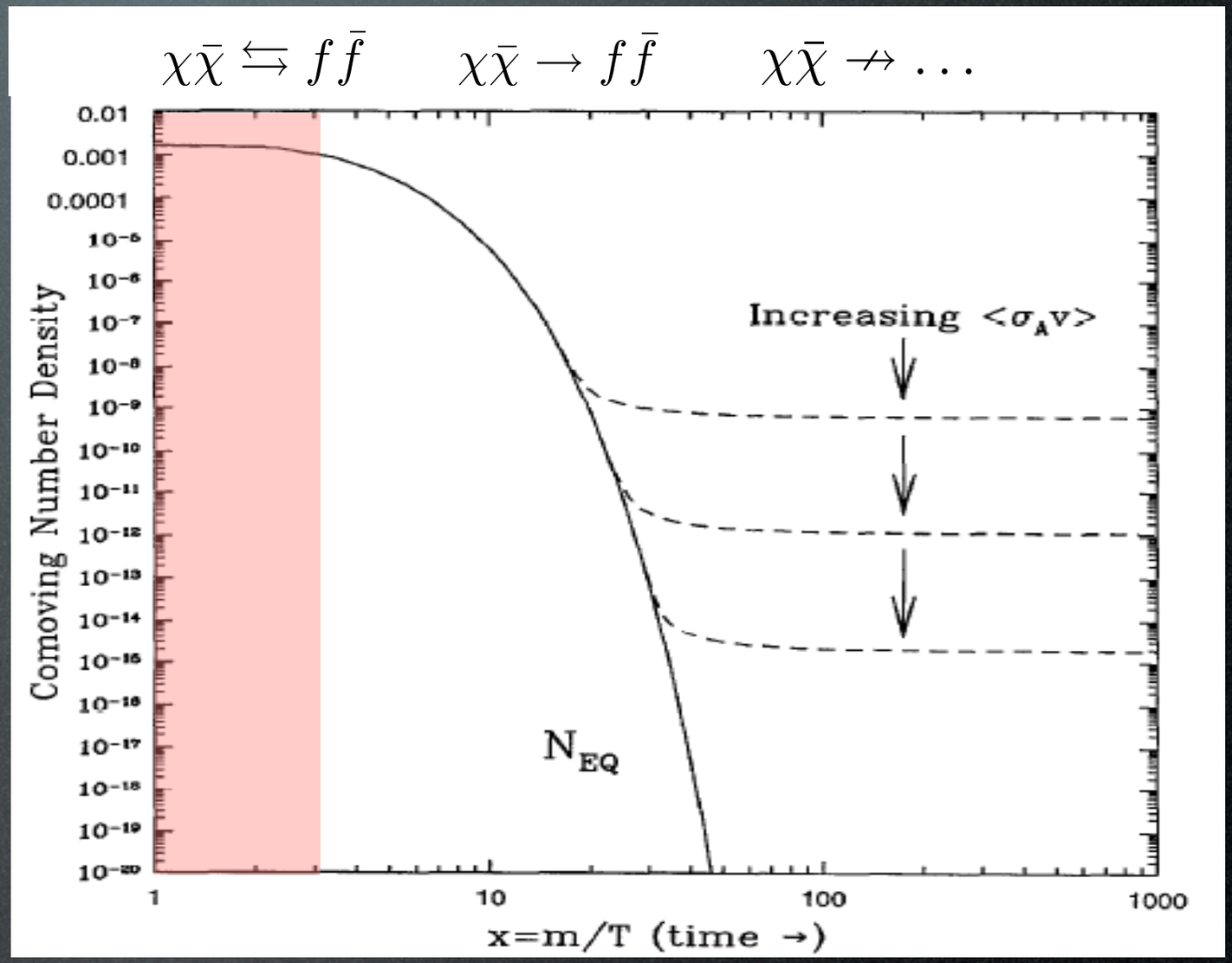

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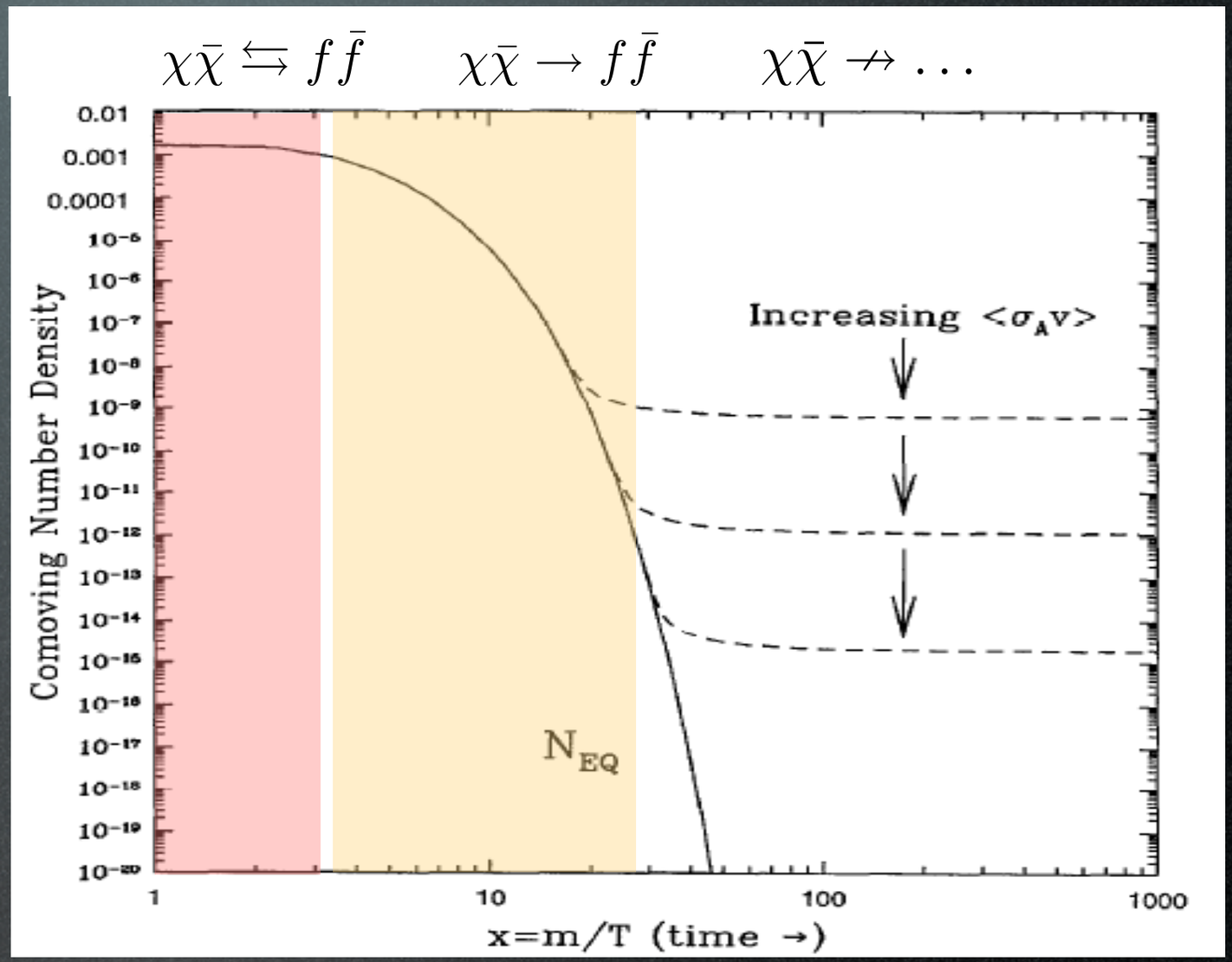

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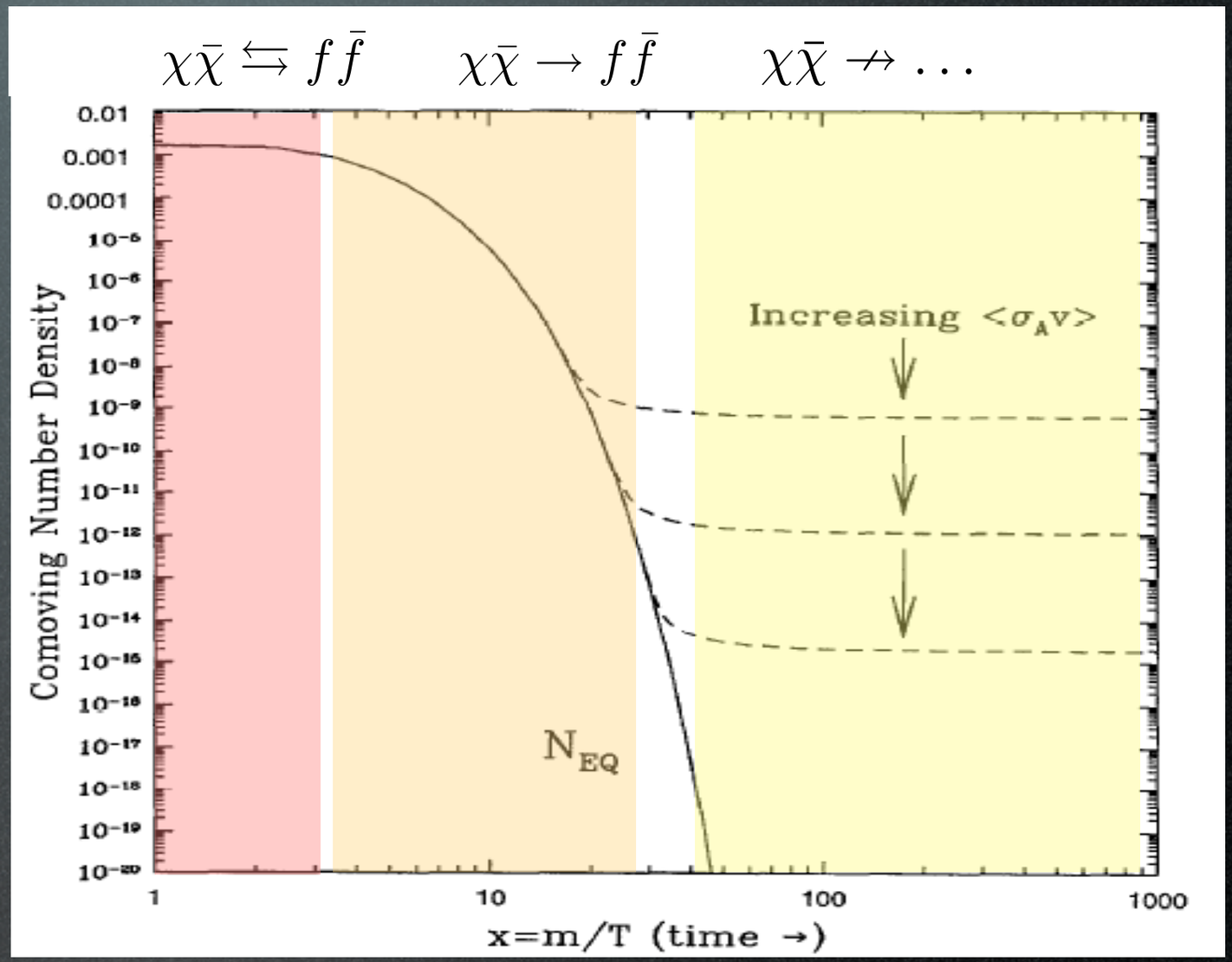

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Asymmetric DM: a completely different relic

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Just coincidence? Or: signal of a link?

Possibly a common production mechanism:

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BBN, CMB...

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A variety of specific models/ideas:

see review **Petraki**, Volkas 1305.4939

transferring or co-genesis

DM stores the anti-B number

via leptogenesis

connection to neutrino masses

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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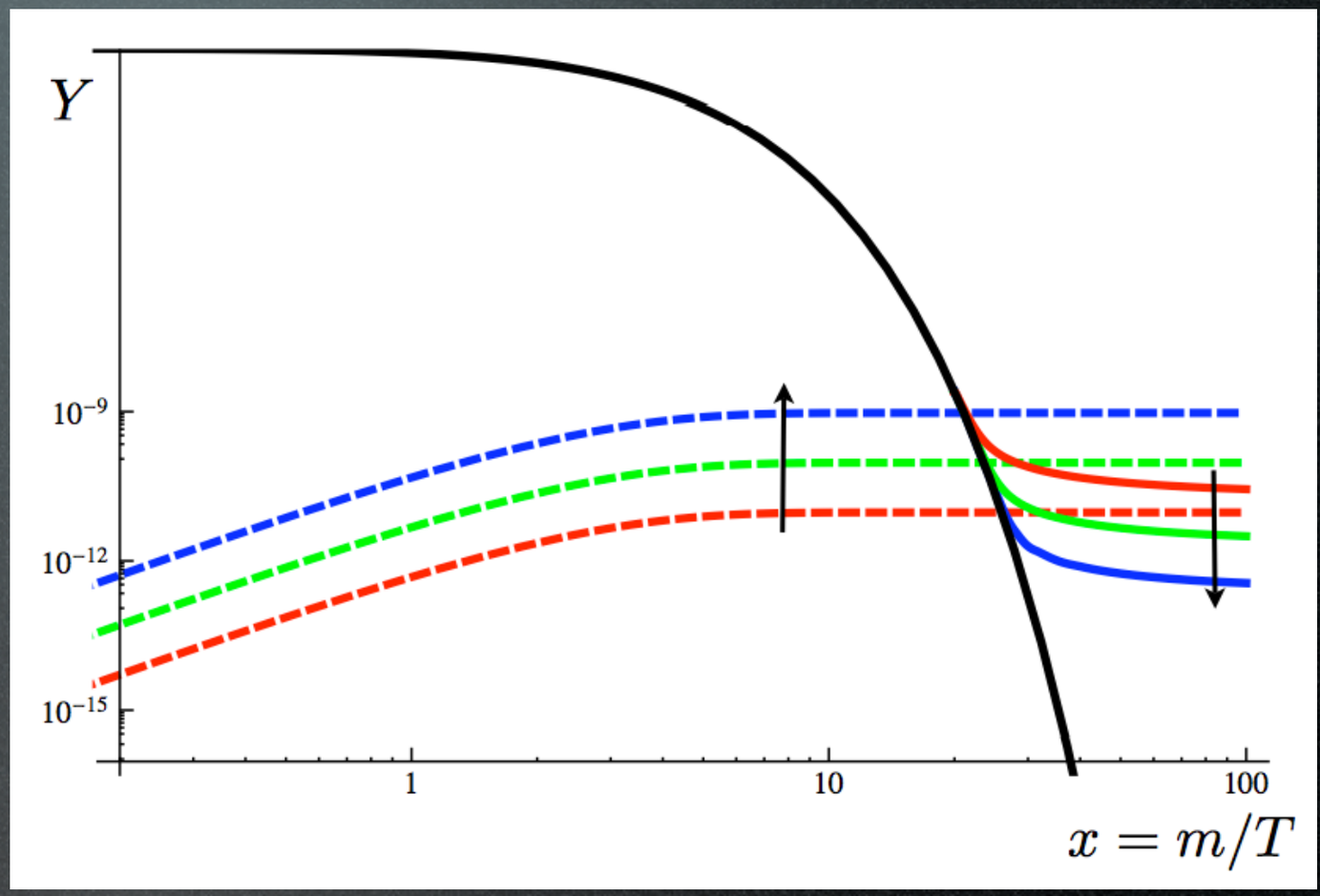
- 'stable'
- in an expanding Universe
- zero initial abundance



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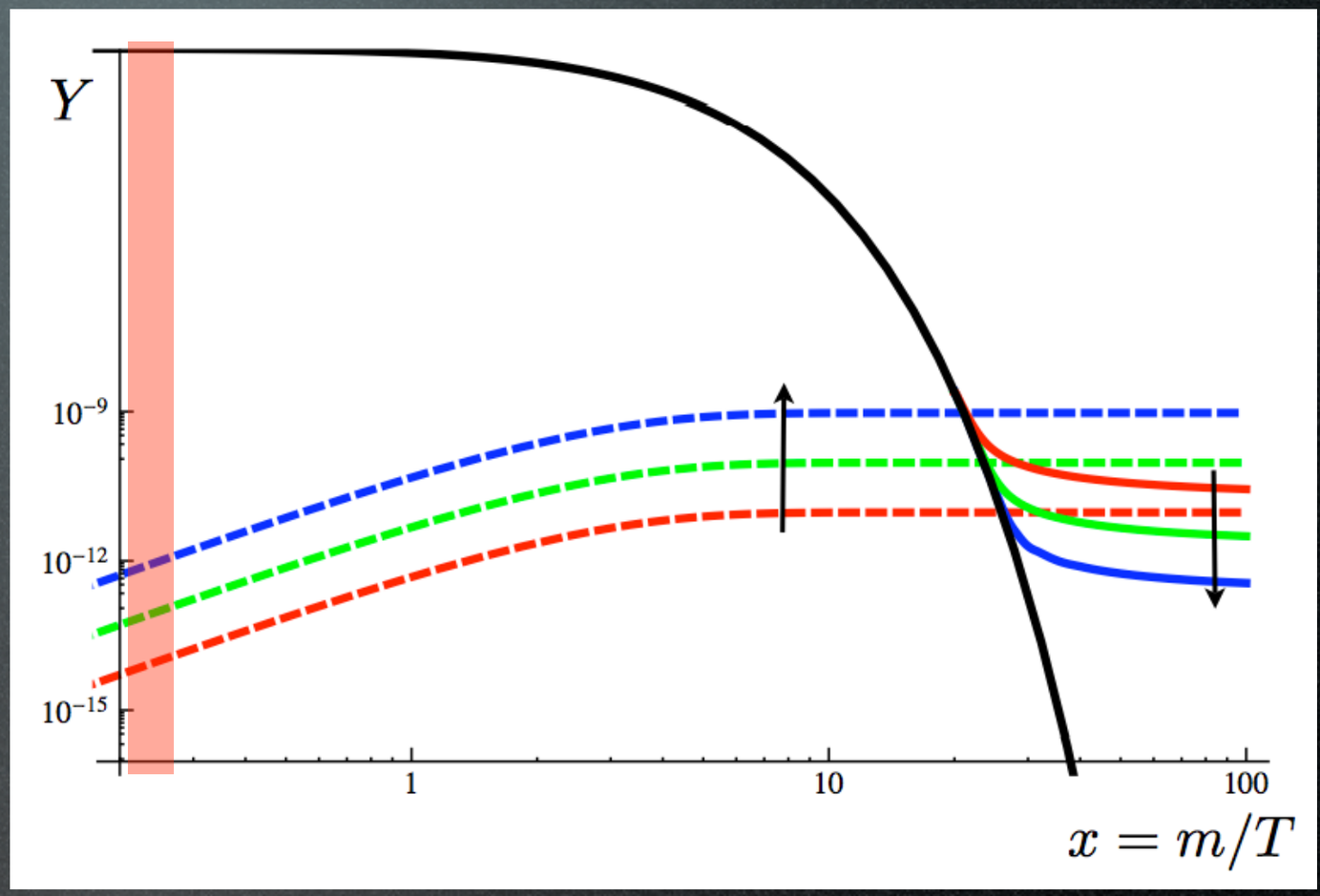

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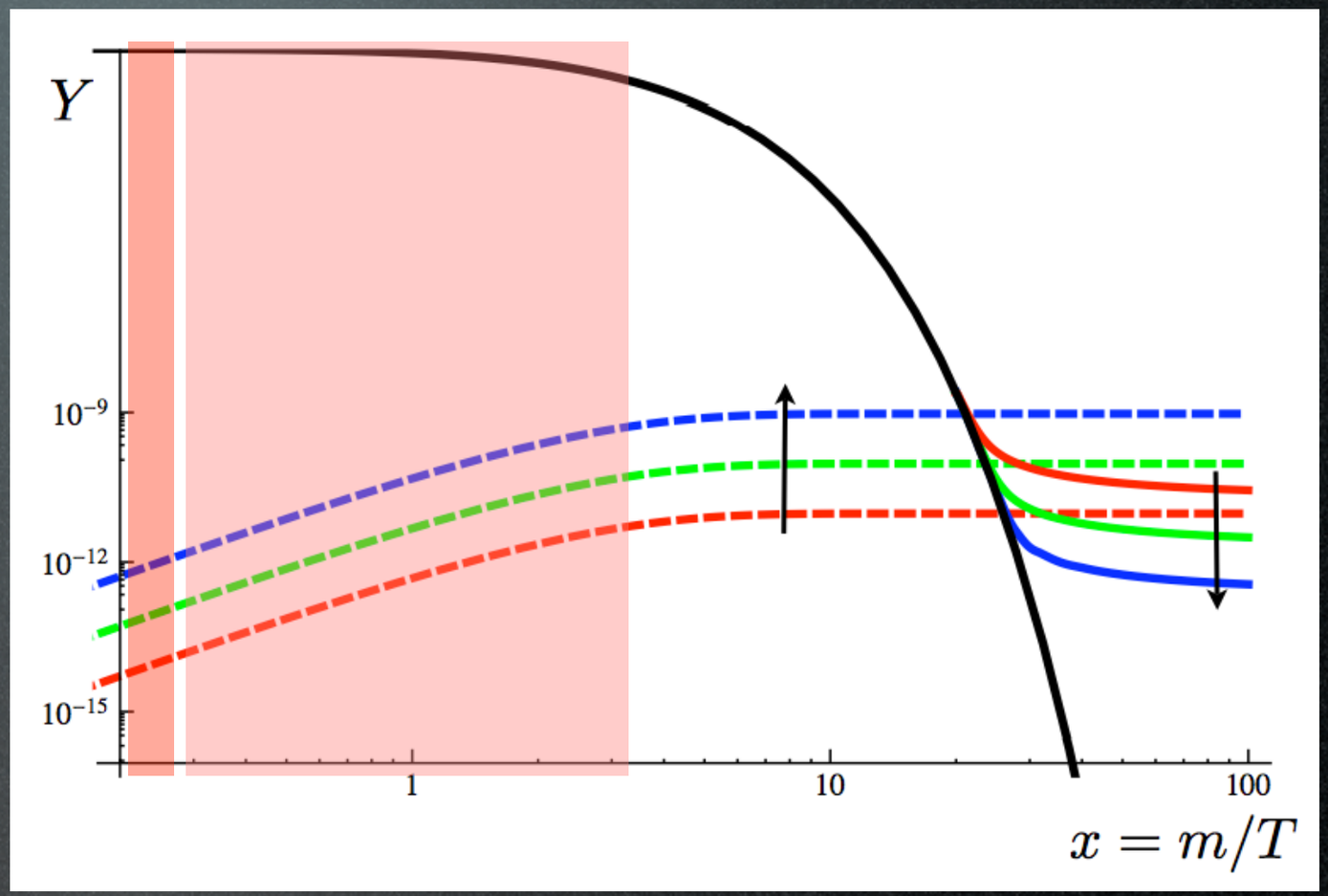
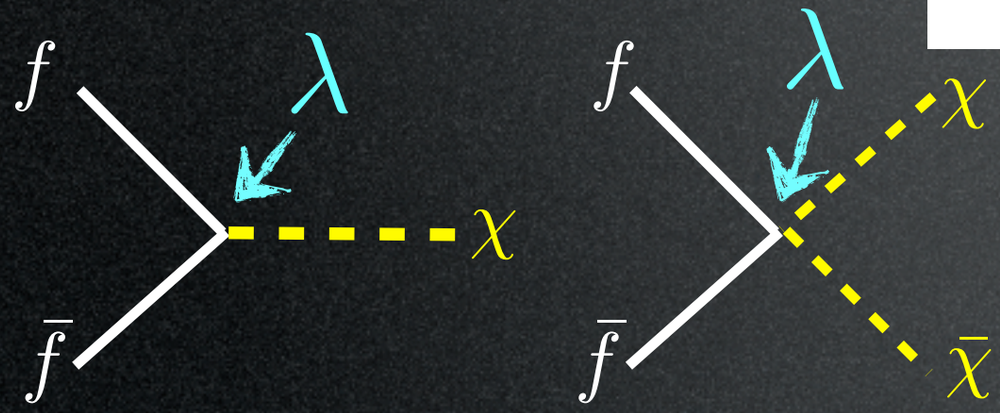
- subject to $f\bar{f} \to \chi, \chi\bar{\chi}$ with a very small rate
- 'heavy' (e.g. 100 GeV)
- 'stable'
- in an expanding Universe
- zero initial abundance





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

very slowly but steadily produced

Freeze-in: like rodents in the paleocene

Hall, Jedamzik, March-Russell, West 2009

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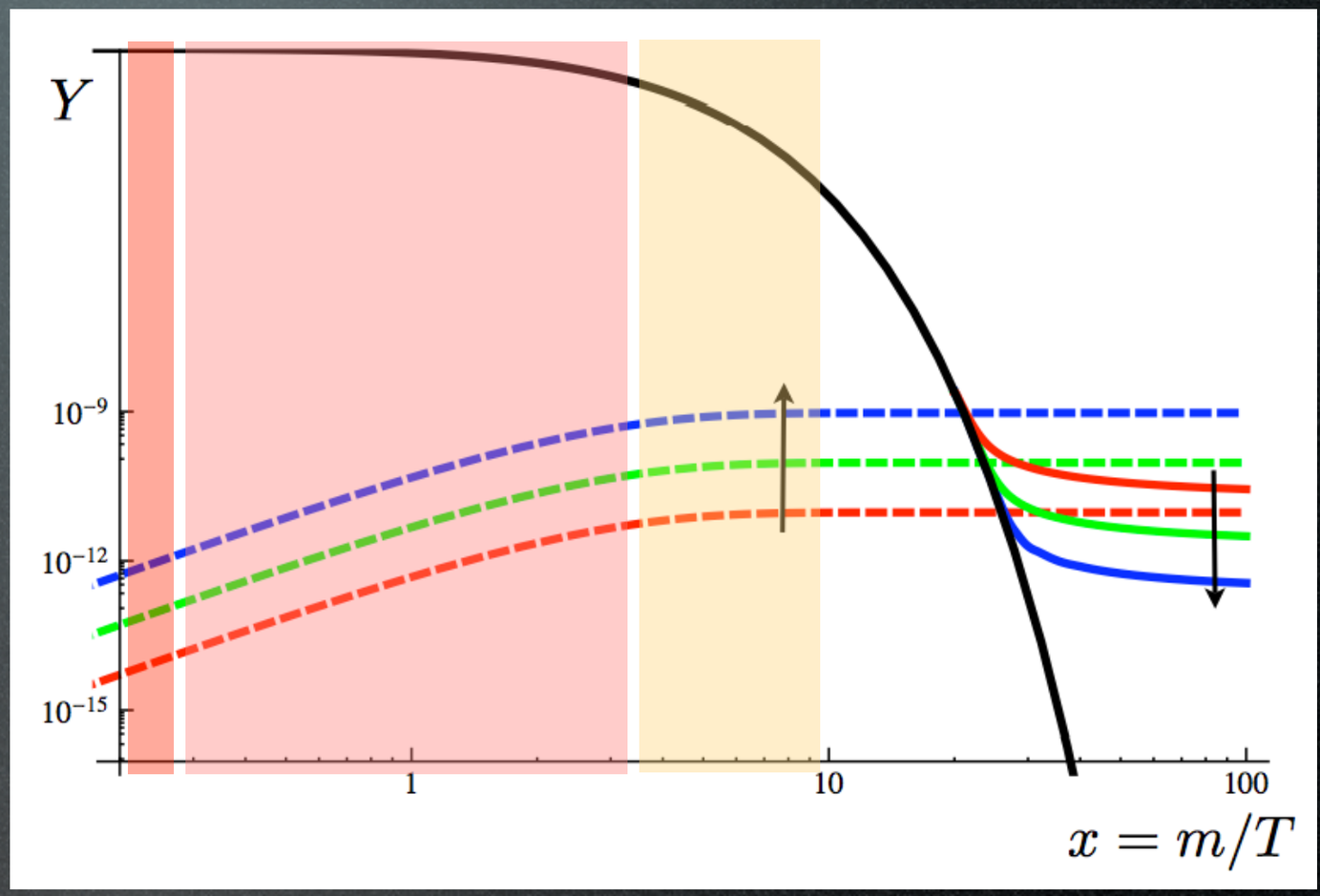

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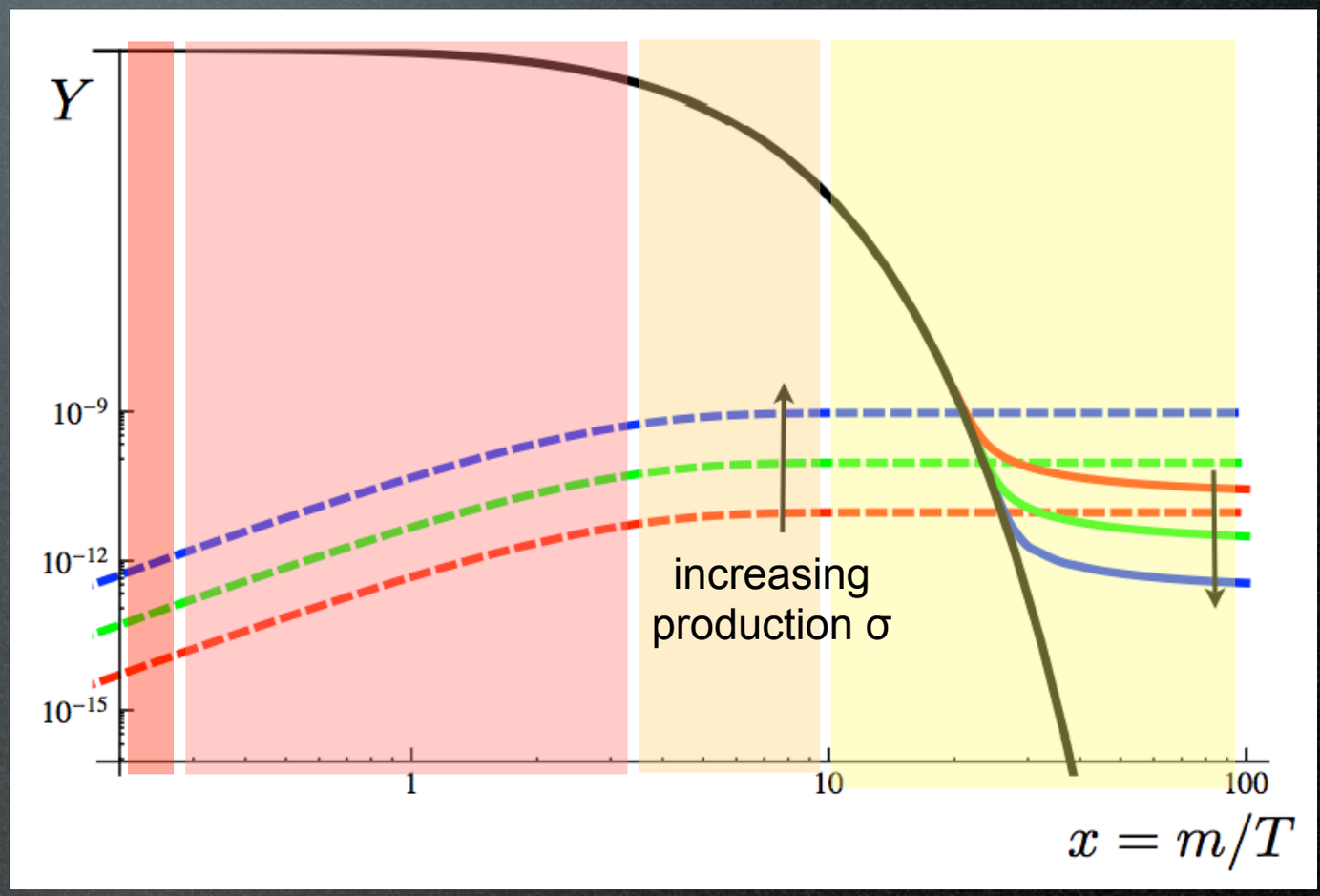
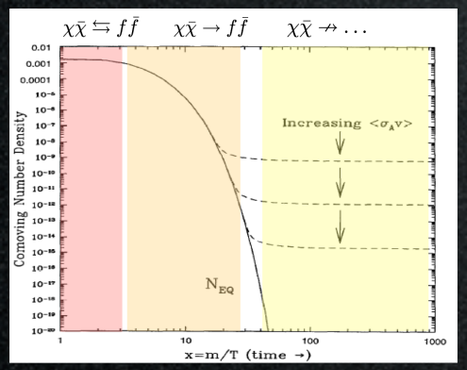
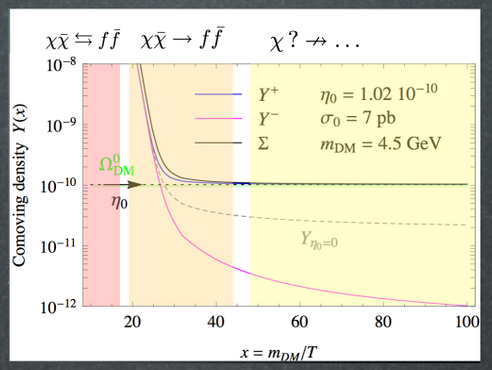


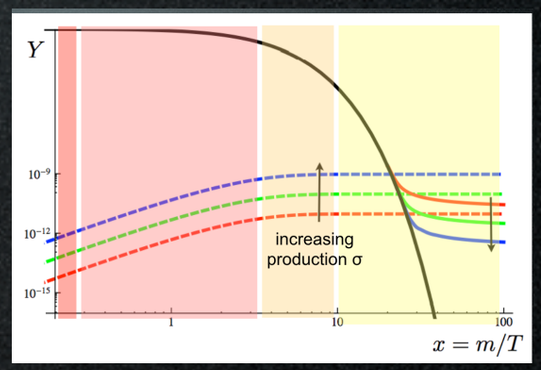
The final abundance is determined by σ (or rather λ).

Production mechanism

Orthodoxy → **Heterodoxy** → **Heresy**







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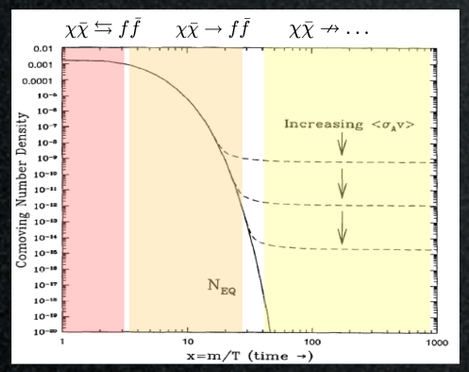

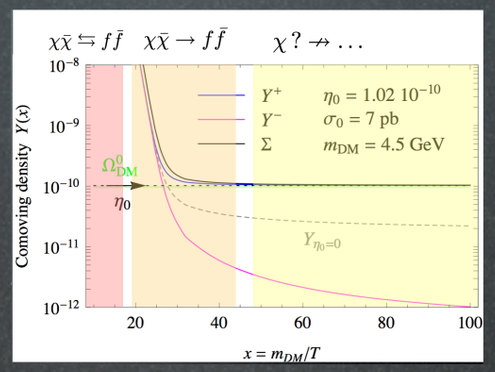

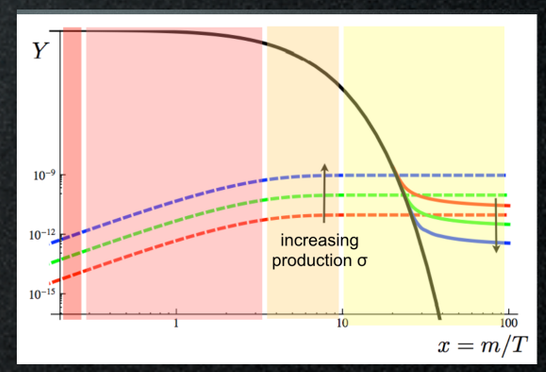

Other possibilities: mixing/oscillations,
misalignment,
…

Interactions

Orthodoxy → **Heterodoxy** → **Heresy**

WIMPs are effectively collisionless

"bullet cluster" - NASA
astro-ph/0608247

WIMPs are effectively collisionless

$$\frac{\sigma_{\rm DM}}{m_{\rm DM}} < 0.78\ \frac{\rm barn}{\rm GeV}$$

from stat analysis of DM 'not lagging behind' in 30 clusters
Harvey et al., 1503.07675

Dark interactions for DM

Dark interactions for DM

An old idea

"we suggest that the dark matter particles should have an elastic scattering cross-section"

Spergel, Steinhardt 1999

$$\sigma_{XX} = 8.1 \times 10^{-25}\,\mathrm{cm}^2 \left(\frac{m_x}{\mathrm{GeV}}\right)\left(\frac{\lambda}{1\mathrm{Mpc}}\right)^{-1}$$

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with a modern incarnation:
'secluded Dark Matter' or 'hidden sector DM'

Pospelov, Ritz et al 0711.4866

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

Nomura, Thaler 0810.539

Dark U(1) DM

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$$\mathcal{L} = \bar{X}(i\not{D} - M_{\rm DM})X - \frac{1}{4}F_{D\mu\nu}F_D^{\mu\nu} - \frac{\epsilon}{2}F_{D\mu\nu}F_Y^{\mu\nu}$$

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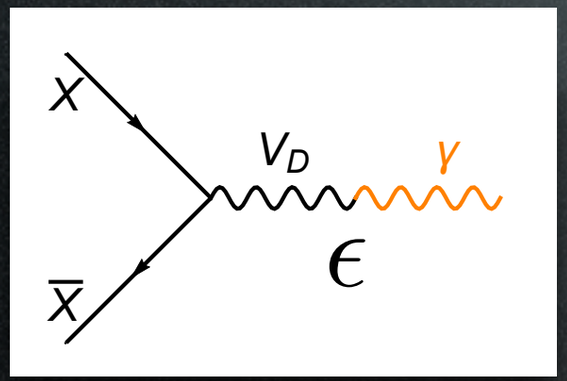

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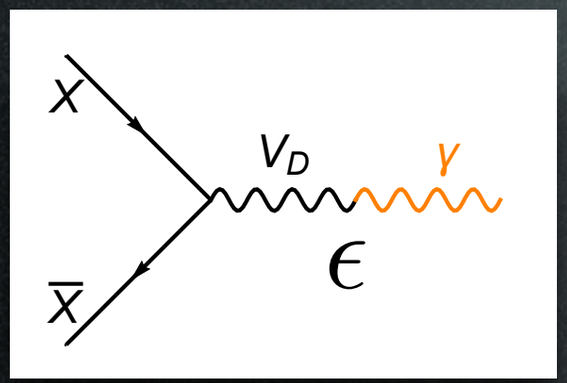

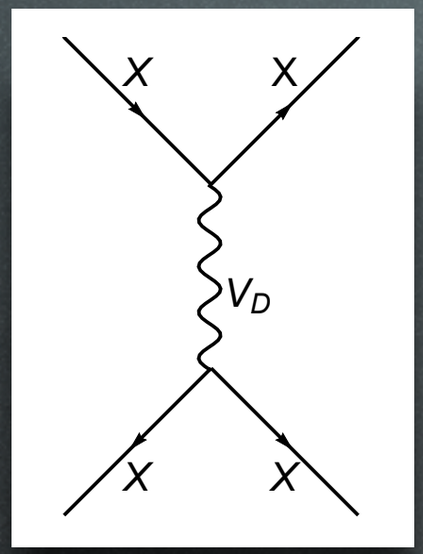

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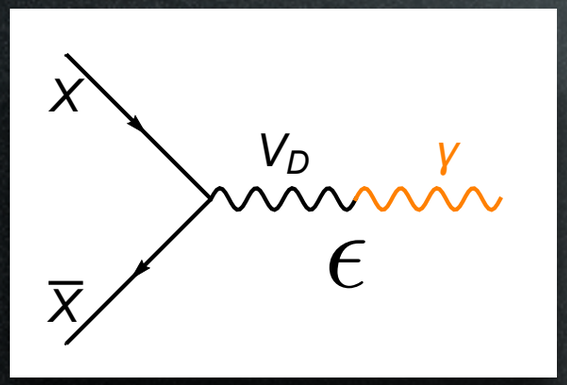

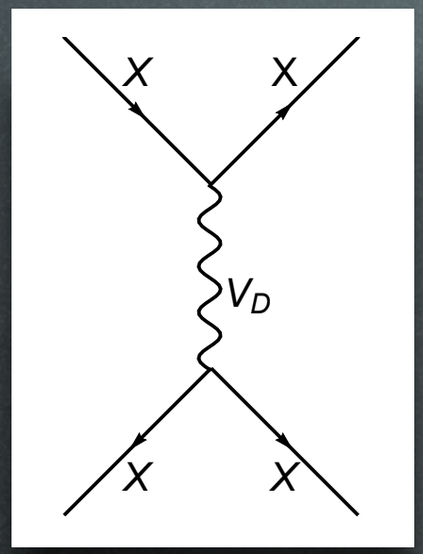

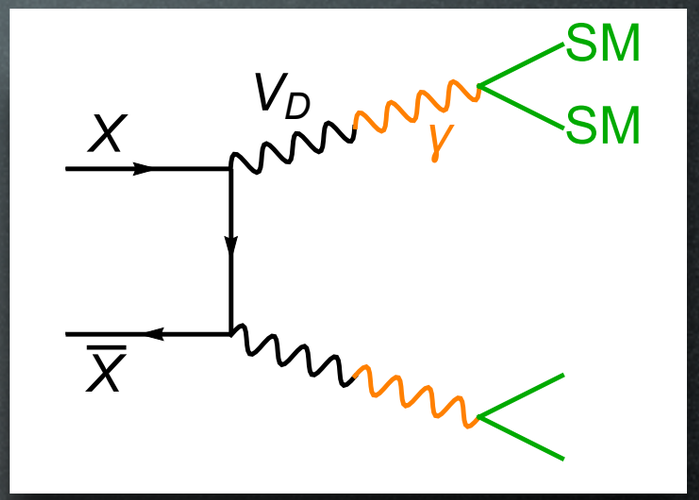

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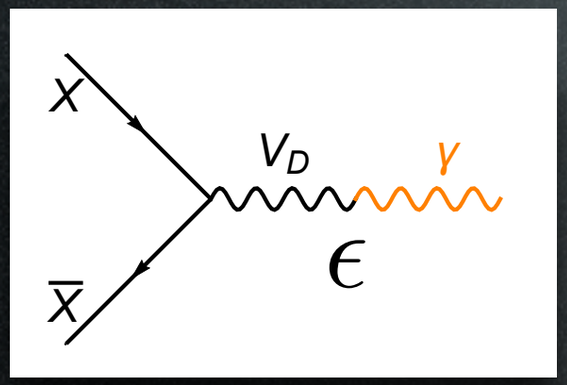

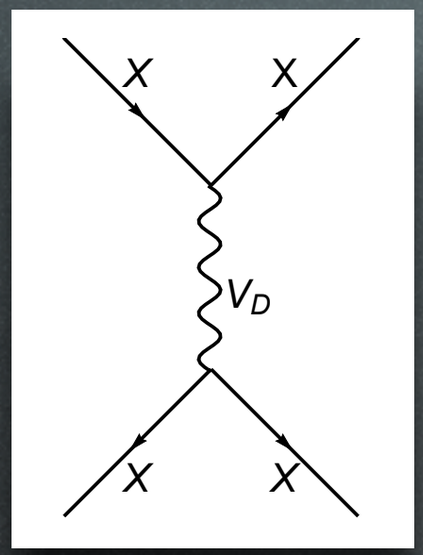

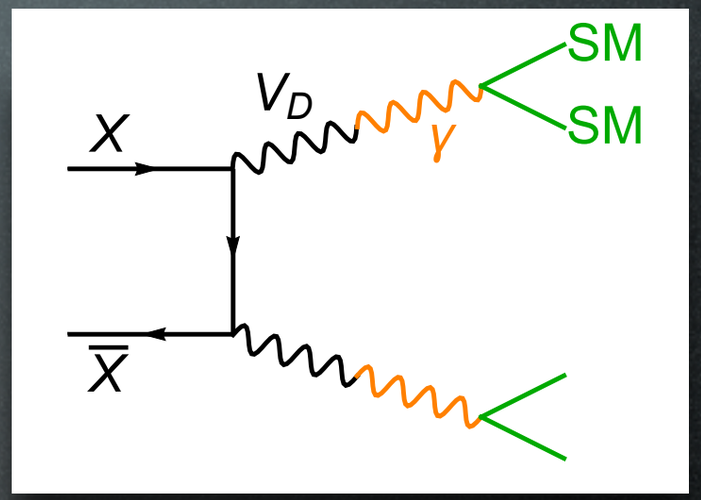

size of the XX system

If $\alpha M/2m_V \gtrsim 1$, the force is long range:

range

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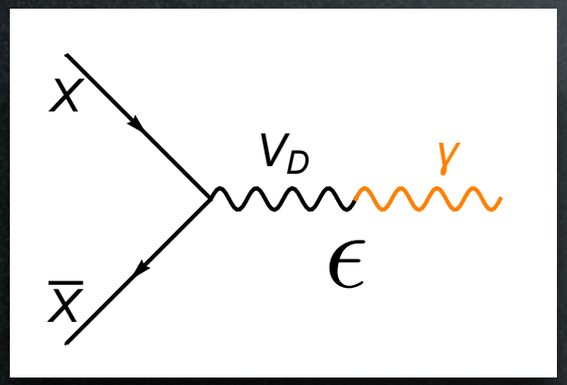

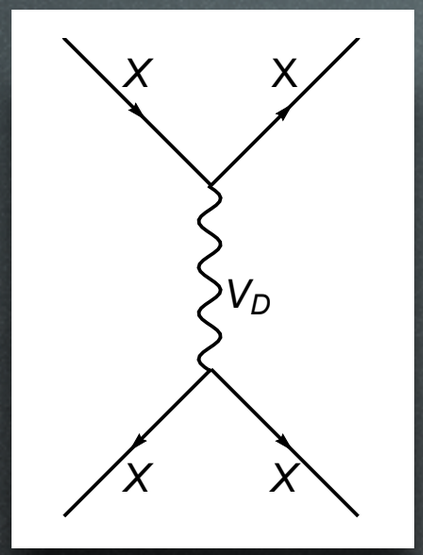

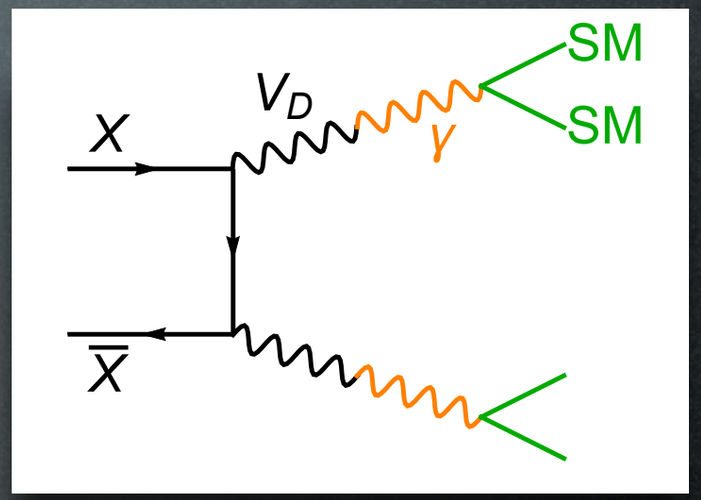

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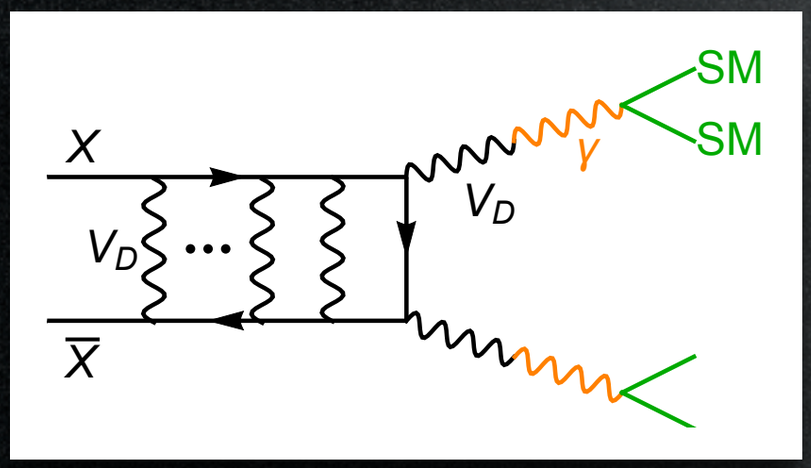

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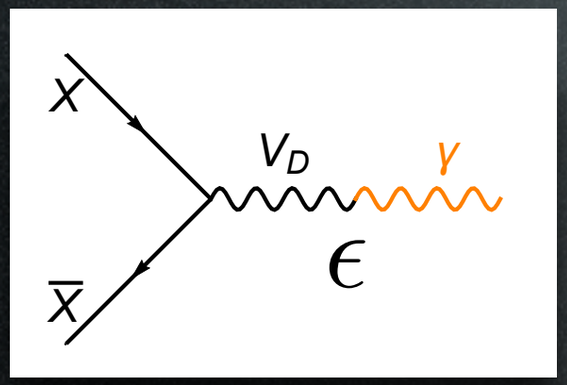

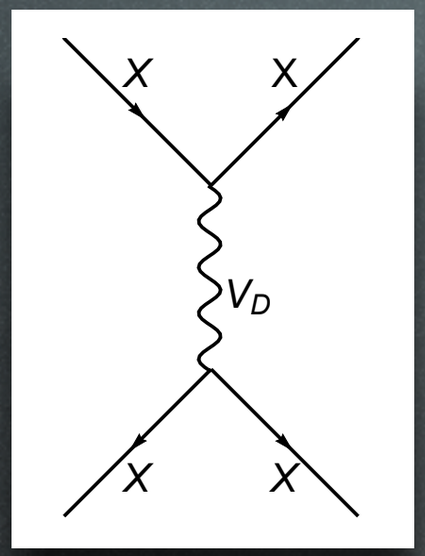

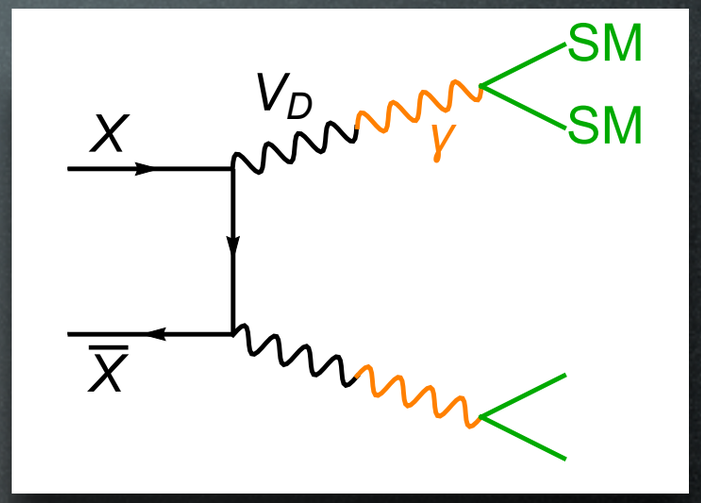

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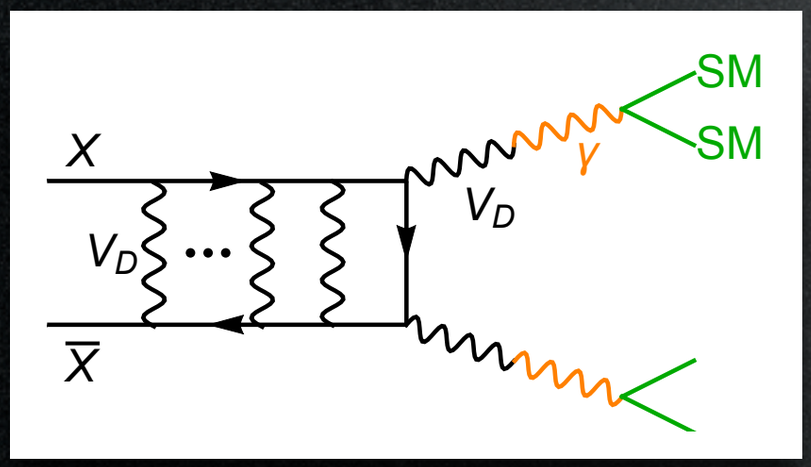

Petraki+ 2015+
An+ 1604.01776
etc

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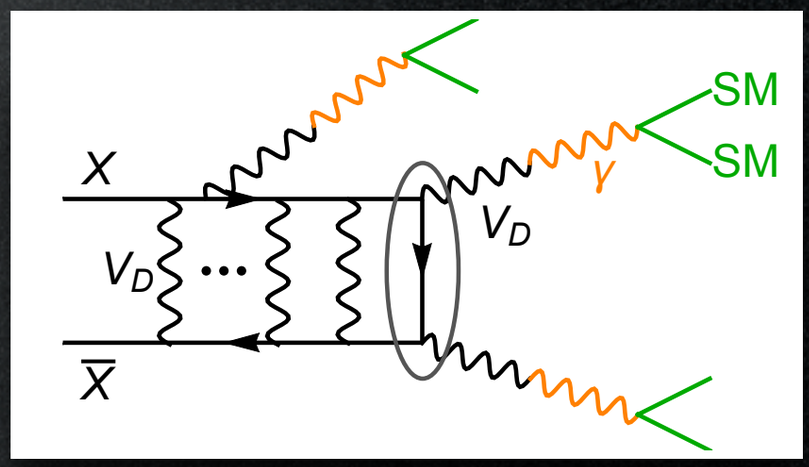
emitted dark photon



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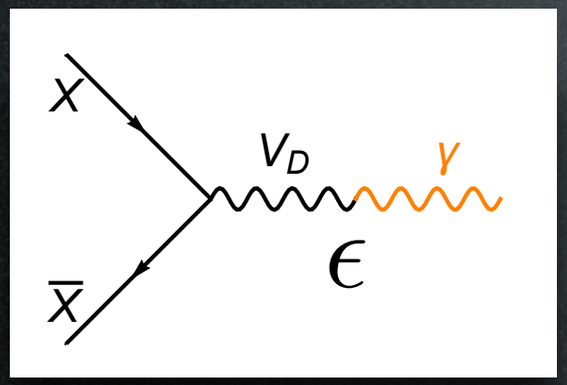

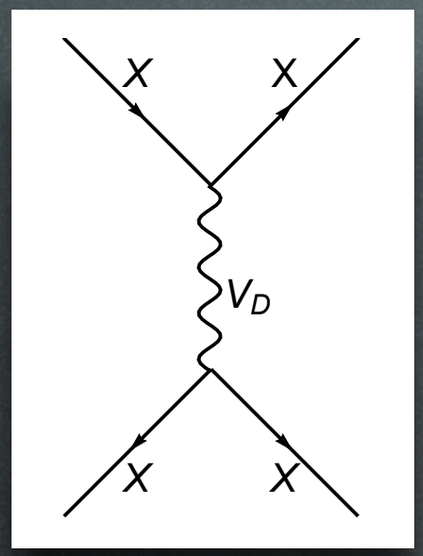

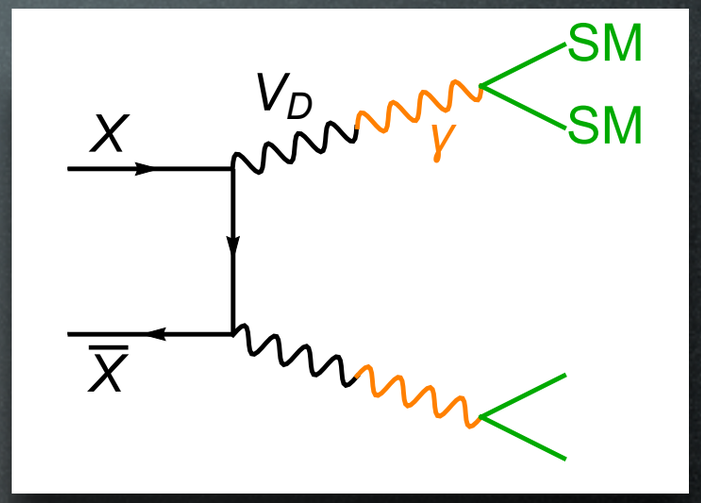

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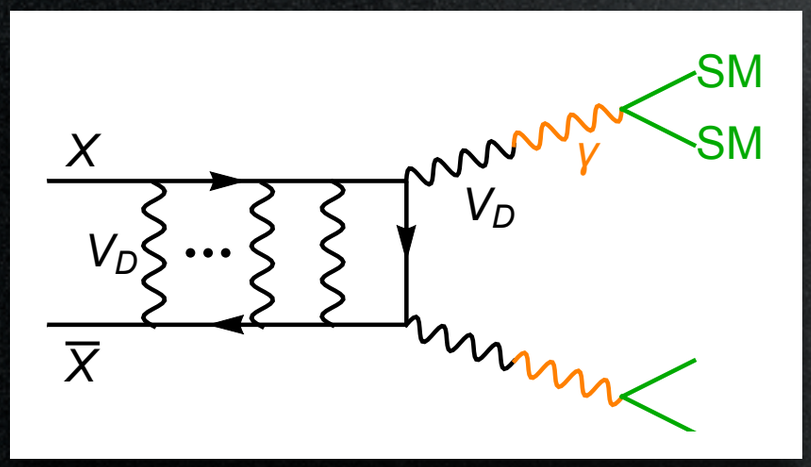

Petraki+ 2015+
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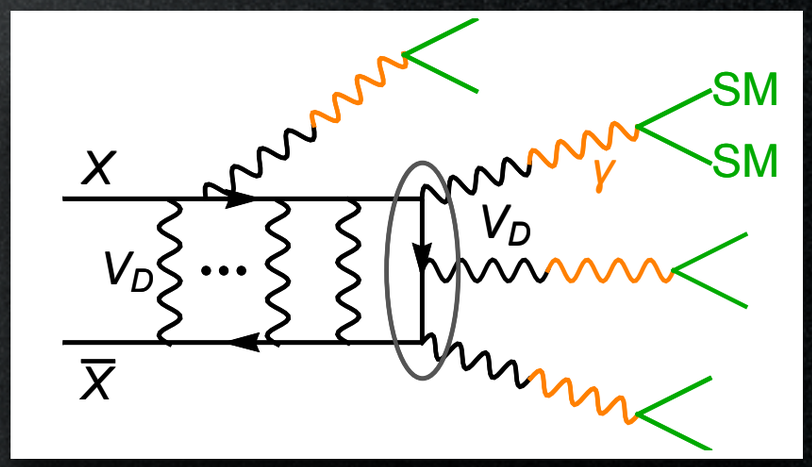

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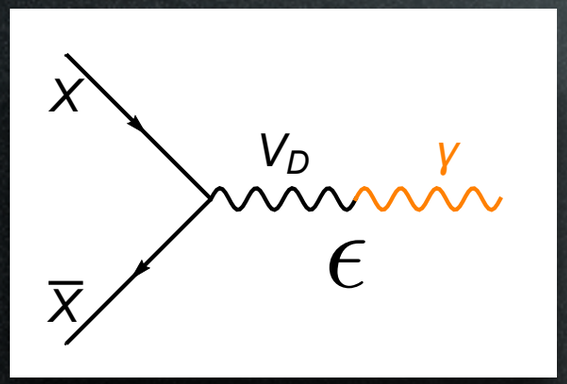

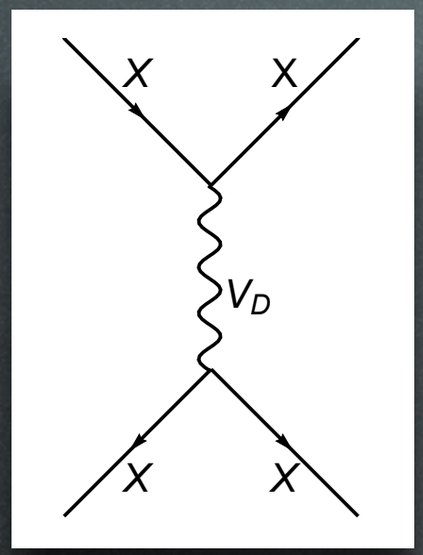

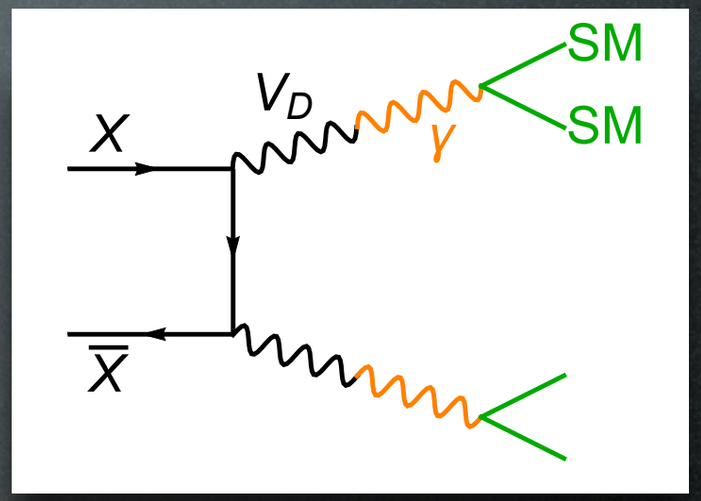

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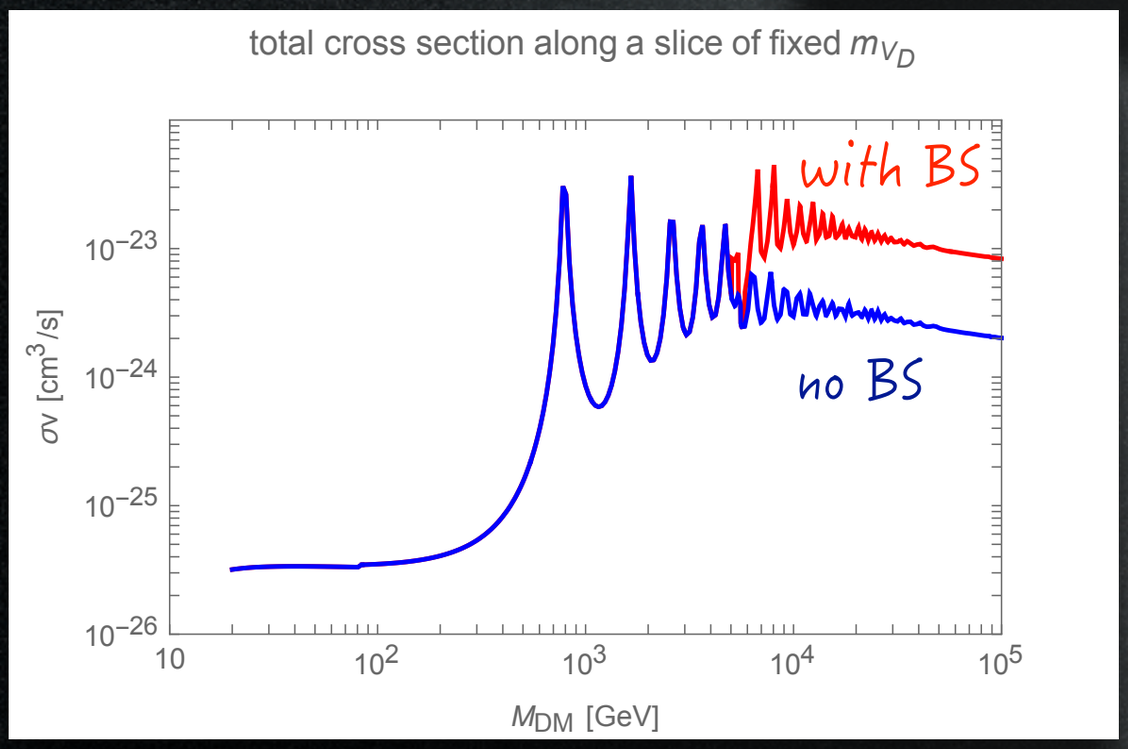

Petraki+ 2015+
An+ 1604.01776
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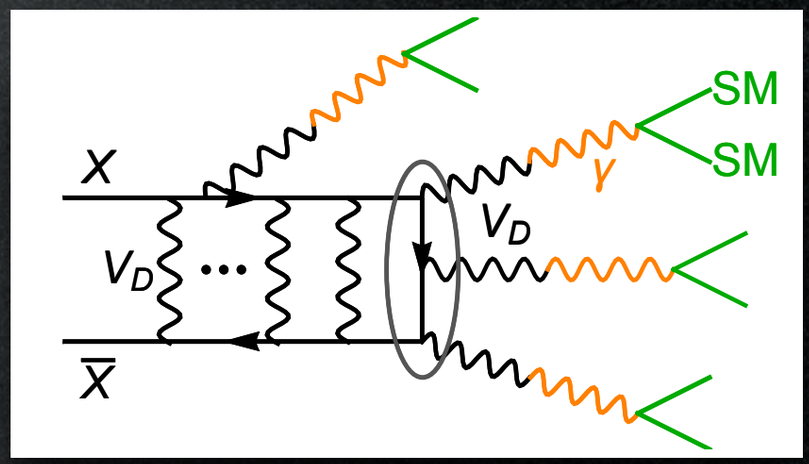
Cirelli, Panci, Petraki,
Sala, Taoso 1612.07295



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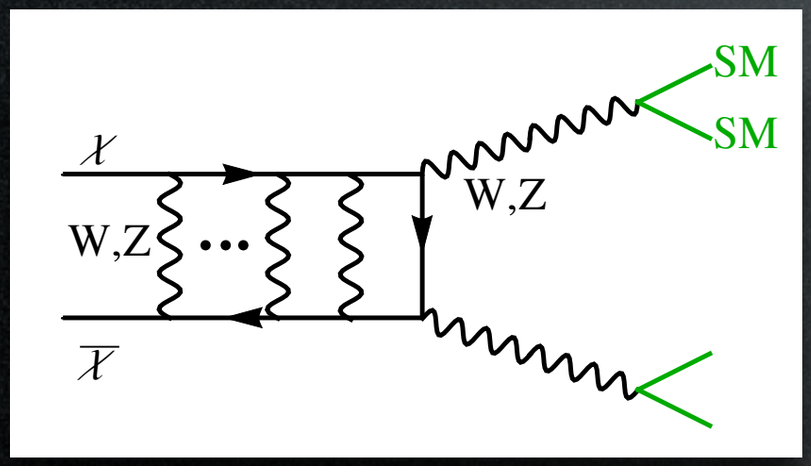

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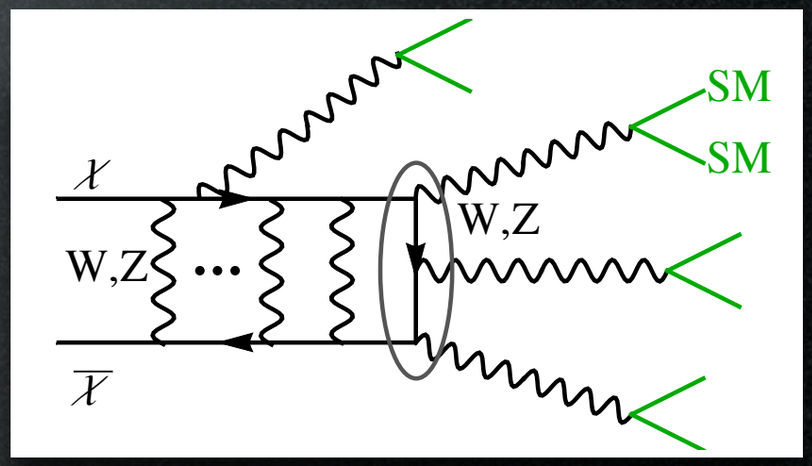

Petraki+ 2015+

Mitridate, Redi, Smirnov, Strumia 1702.01141

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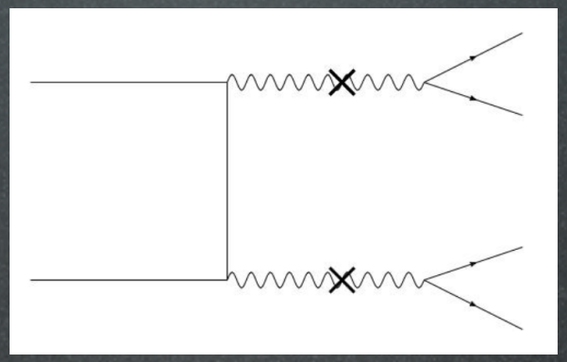
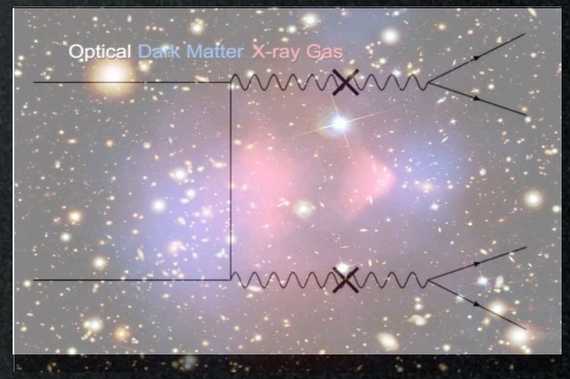
Orthodoxy → **Heterodoxy** → **Heresy**

collisionless



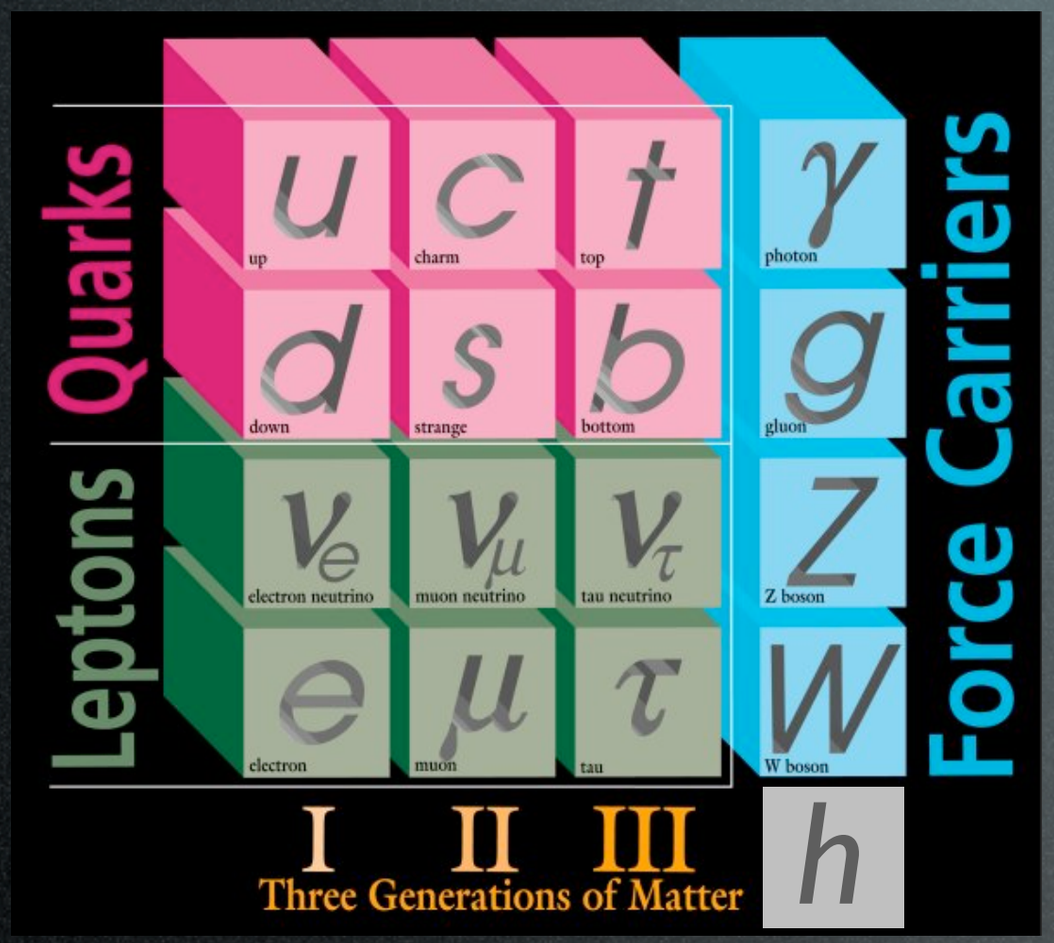
self-interacting



Stability

Orthodoxy → **Heterodoxy** → **Heresy**

SuSy DM in 2 minutes



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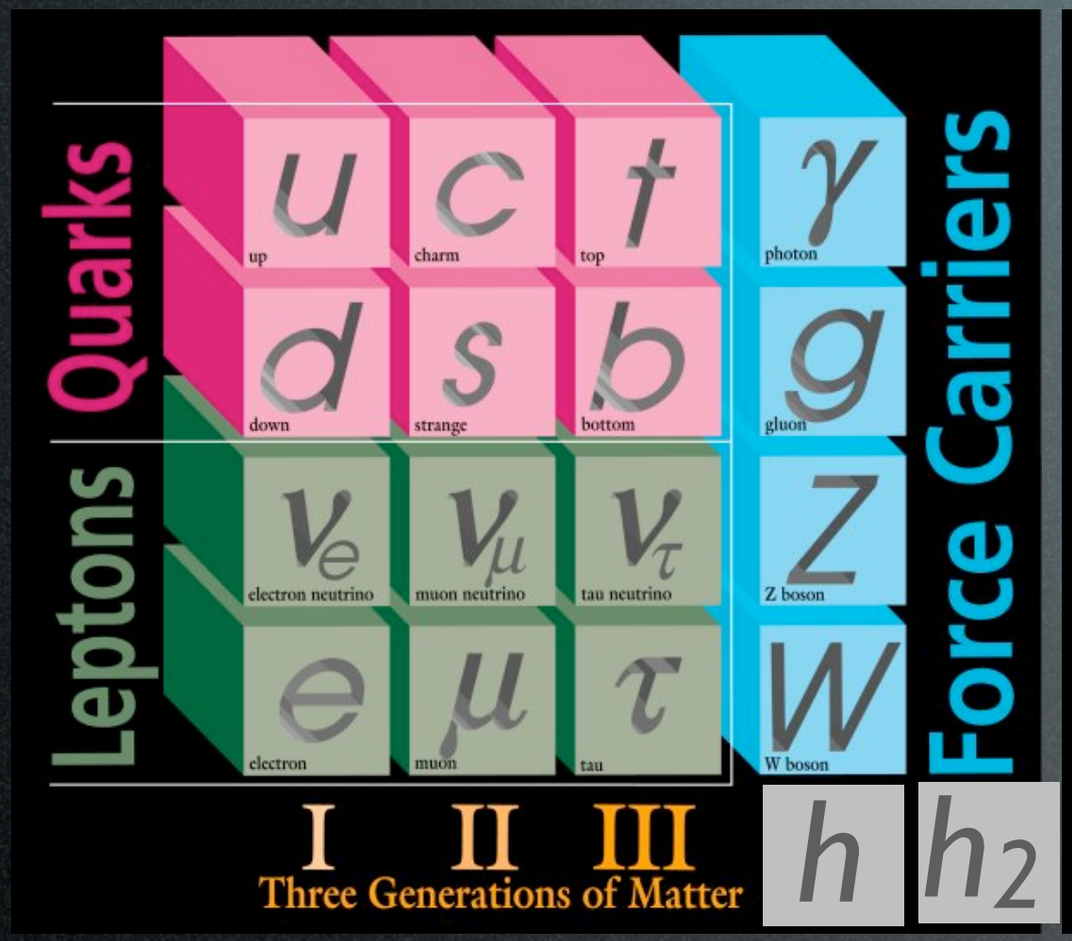
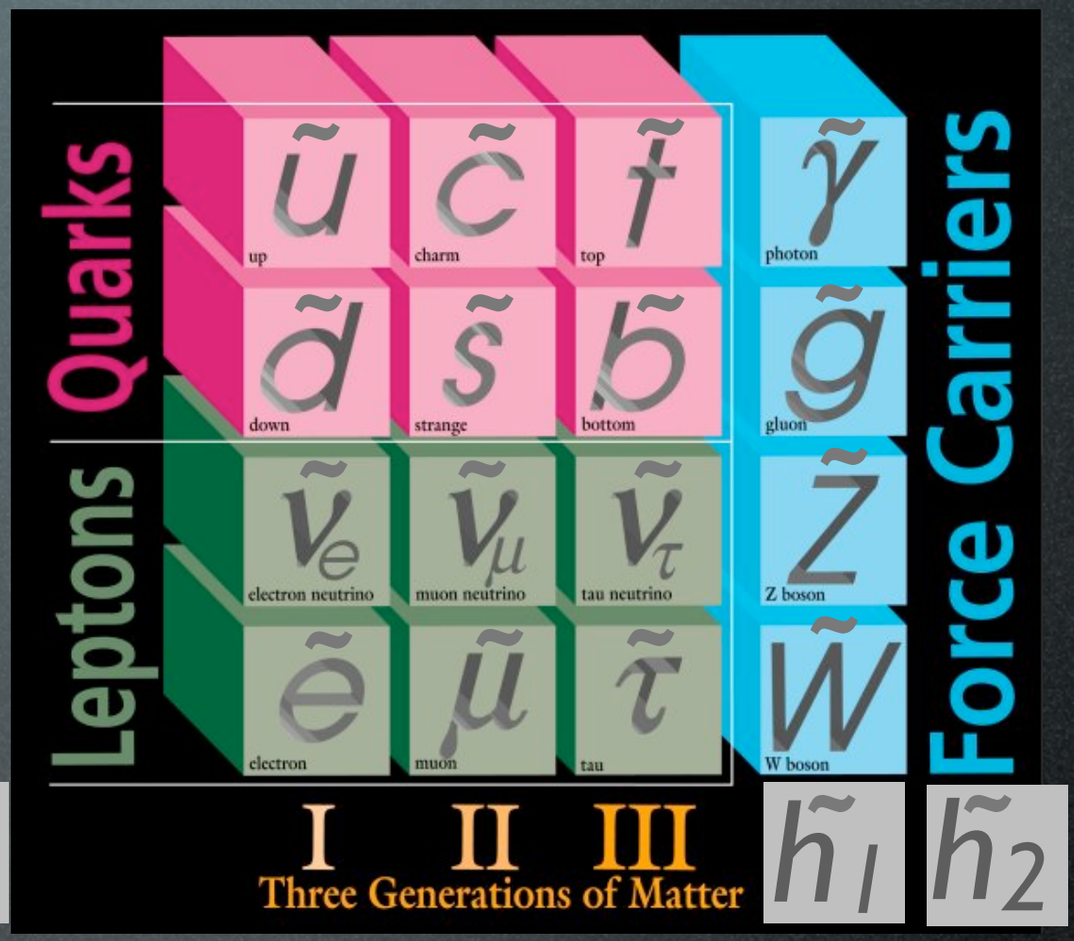
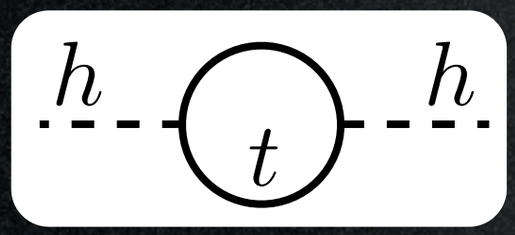
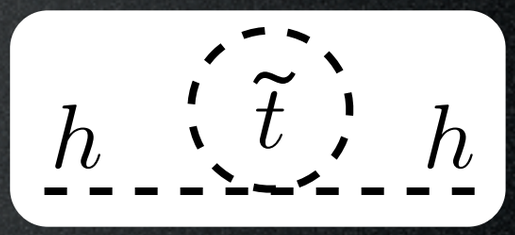




$m_{\rm h} \simeq 125$ GeV

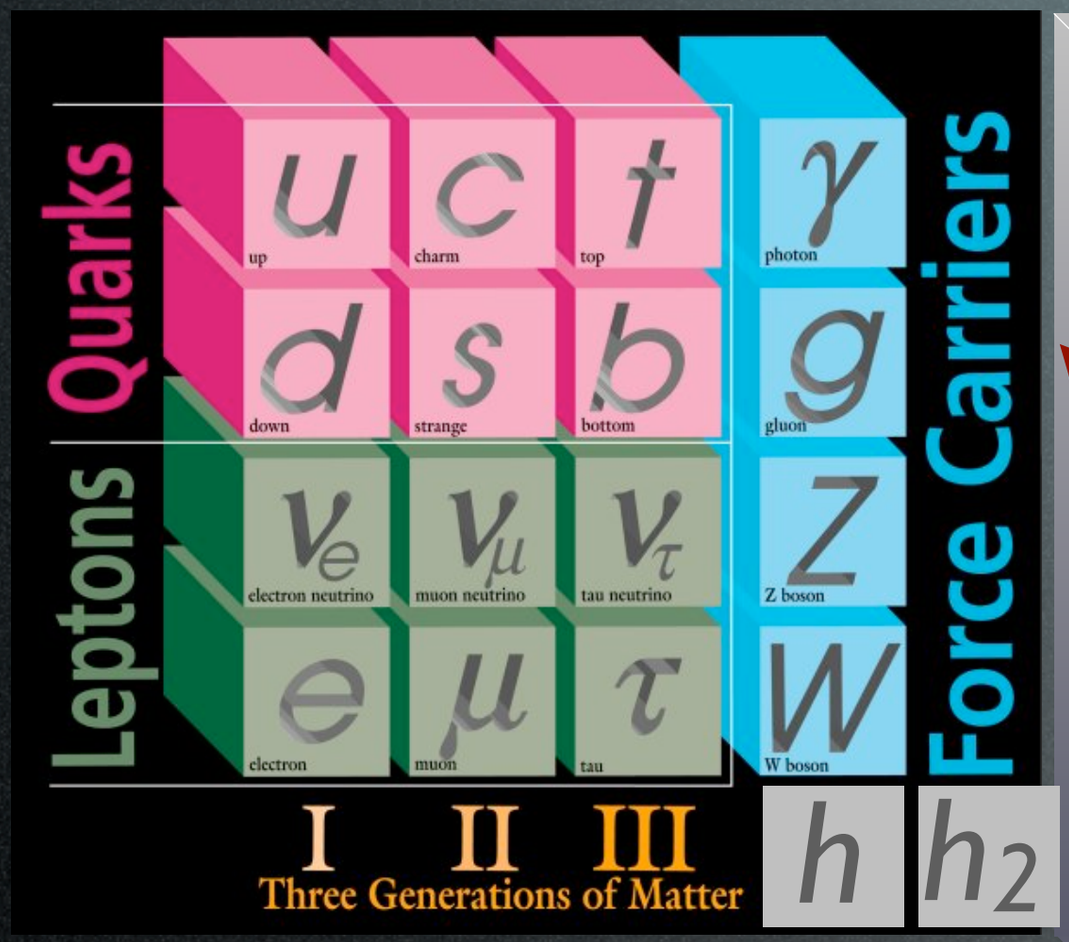


$\Delta m_{\rm h} \propto 10^{19}$ GeV

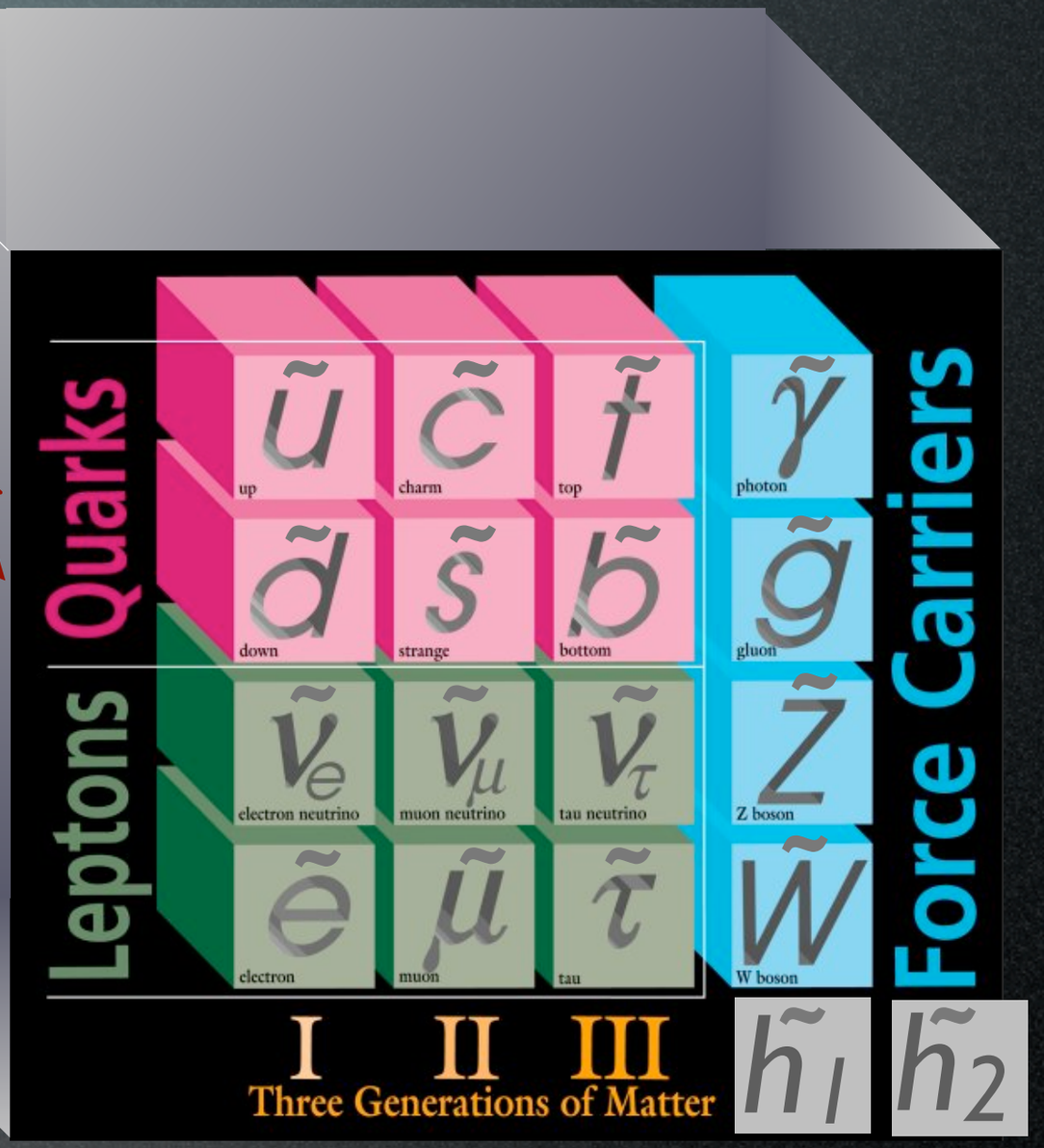


$\Delta m_{\rm h} \propto -10^{19}$ GeV

SuSy DM in 2 minutes



200 GeV



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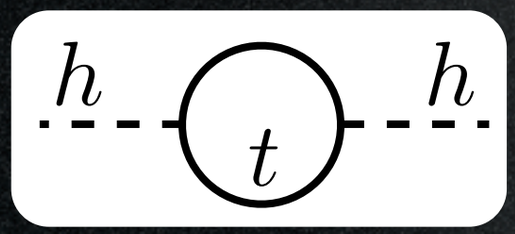

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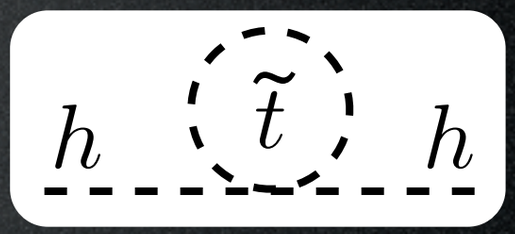

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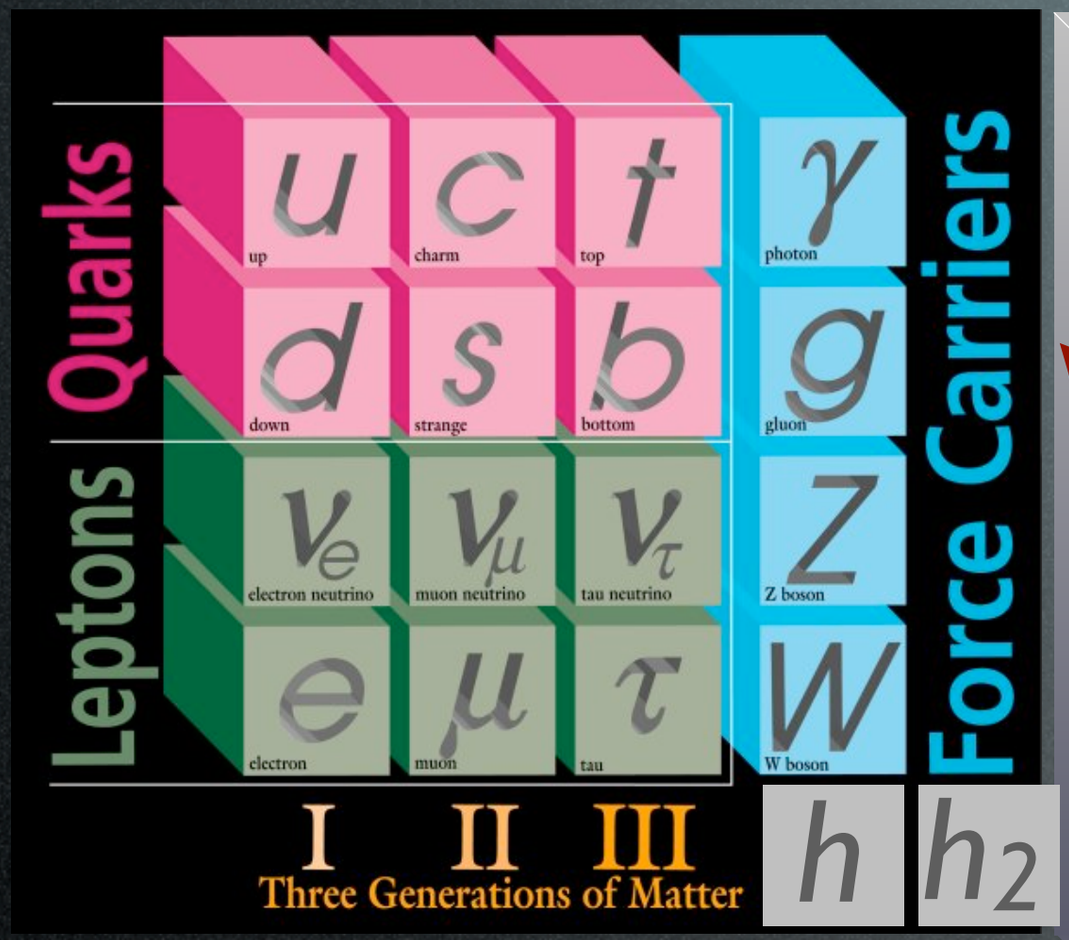
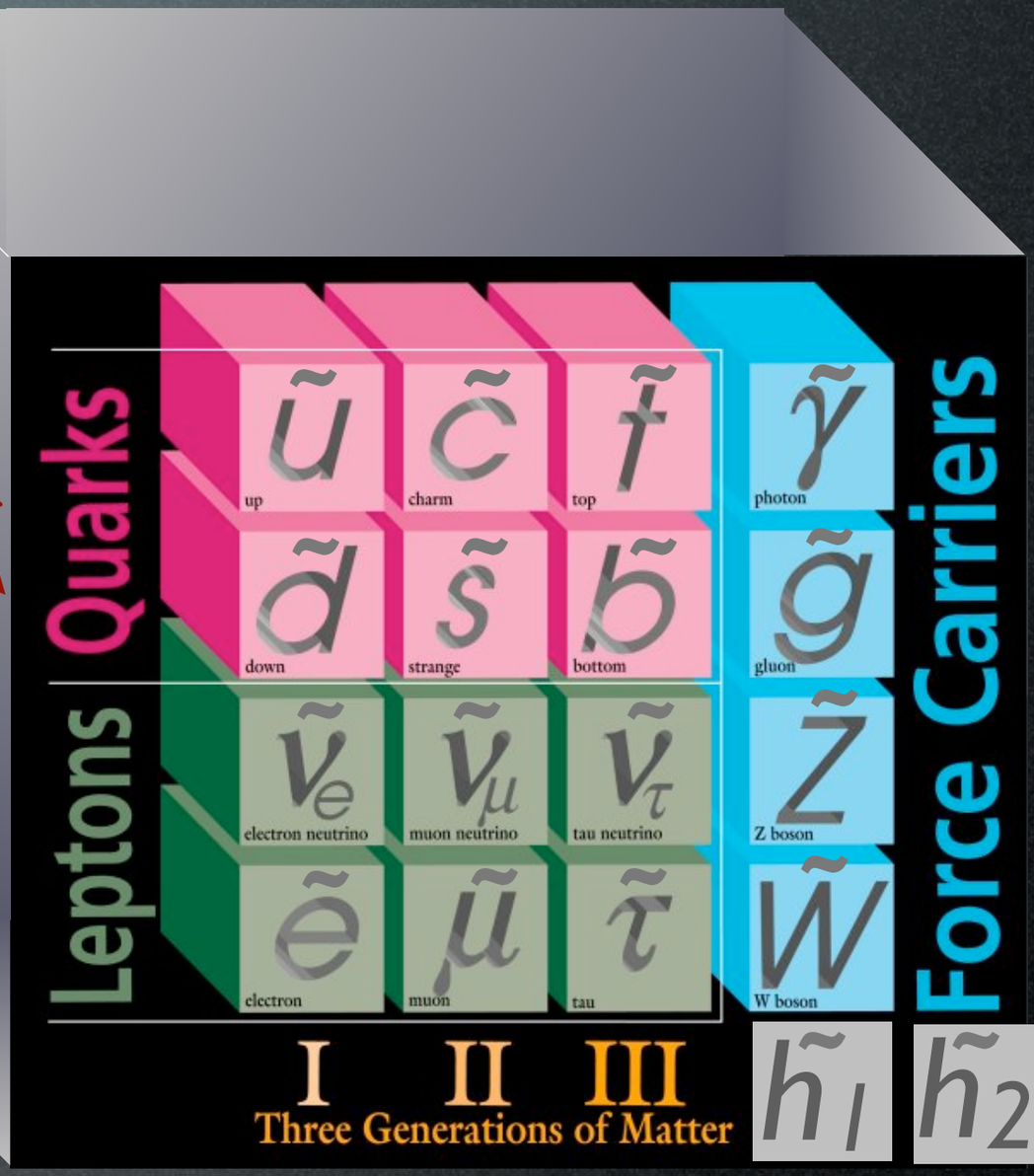
SuSy DM in 2 minutes

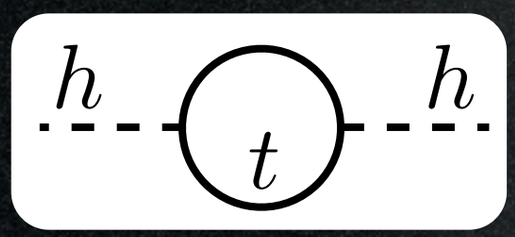


200 GeV



$R = +1$

$m_{\mathrm{h}} \simeq 125\ \mathrm{GeV}$

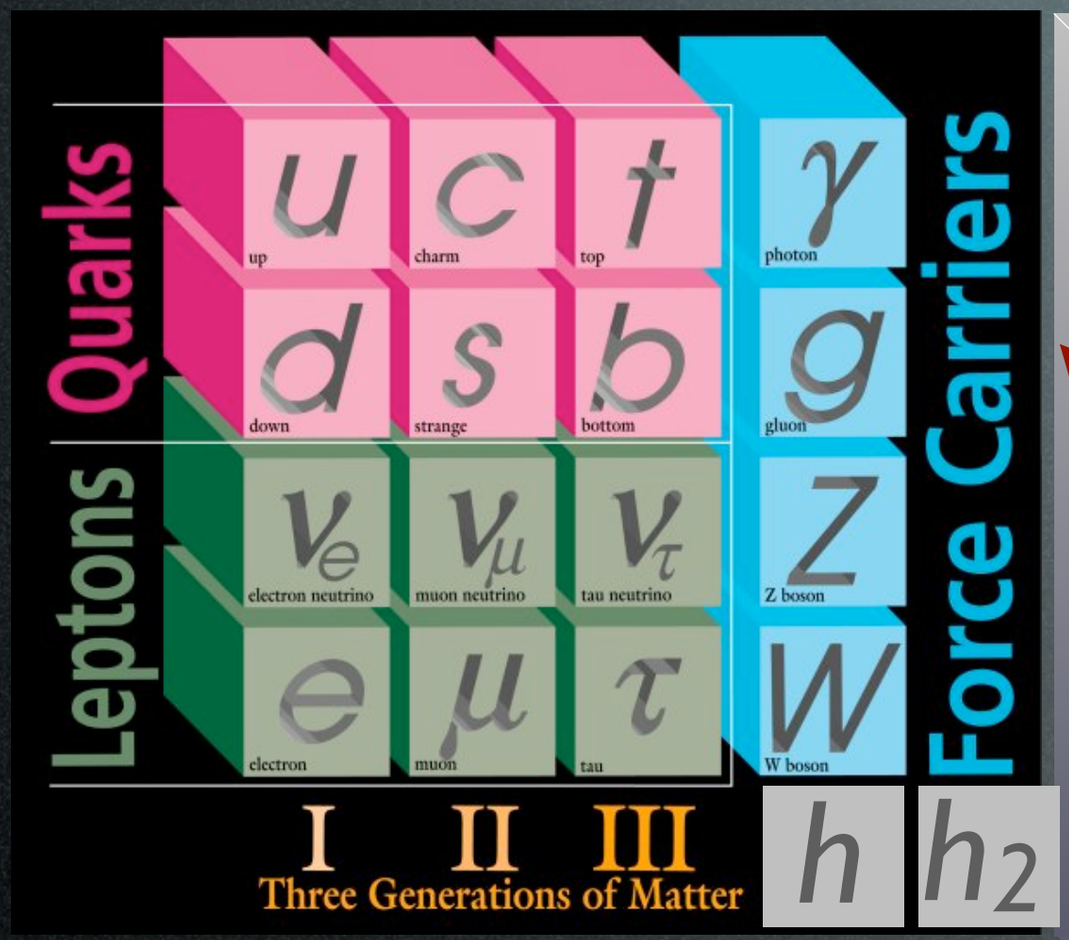


$\Delta m_{\mathrm{h}} \propto 10^{19}\ \mathrm{GeV}$

$R = -1$

$\Delta m_{\mathrm{h}} \propto -10^{19}\ \mathrm{GeV}$

SuSy DM in 2 minutes



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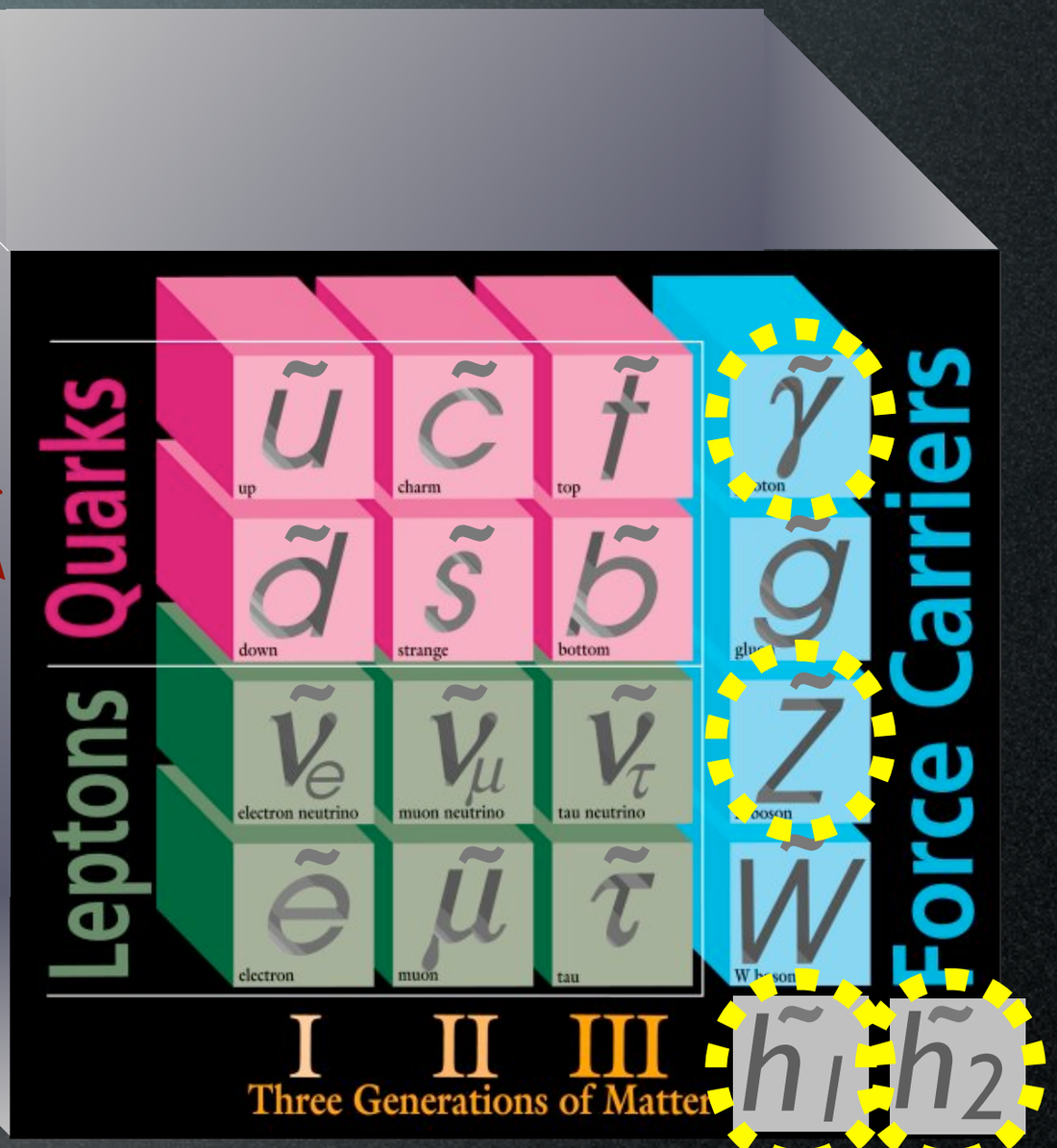
200 GeV



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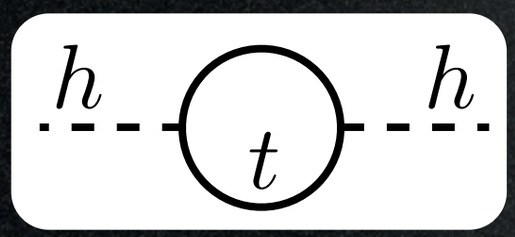

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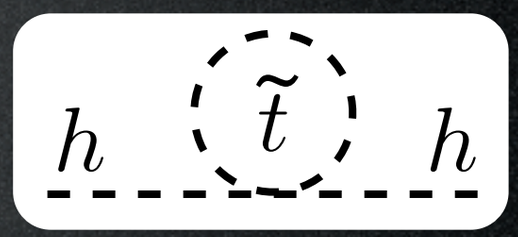

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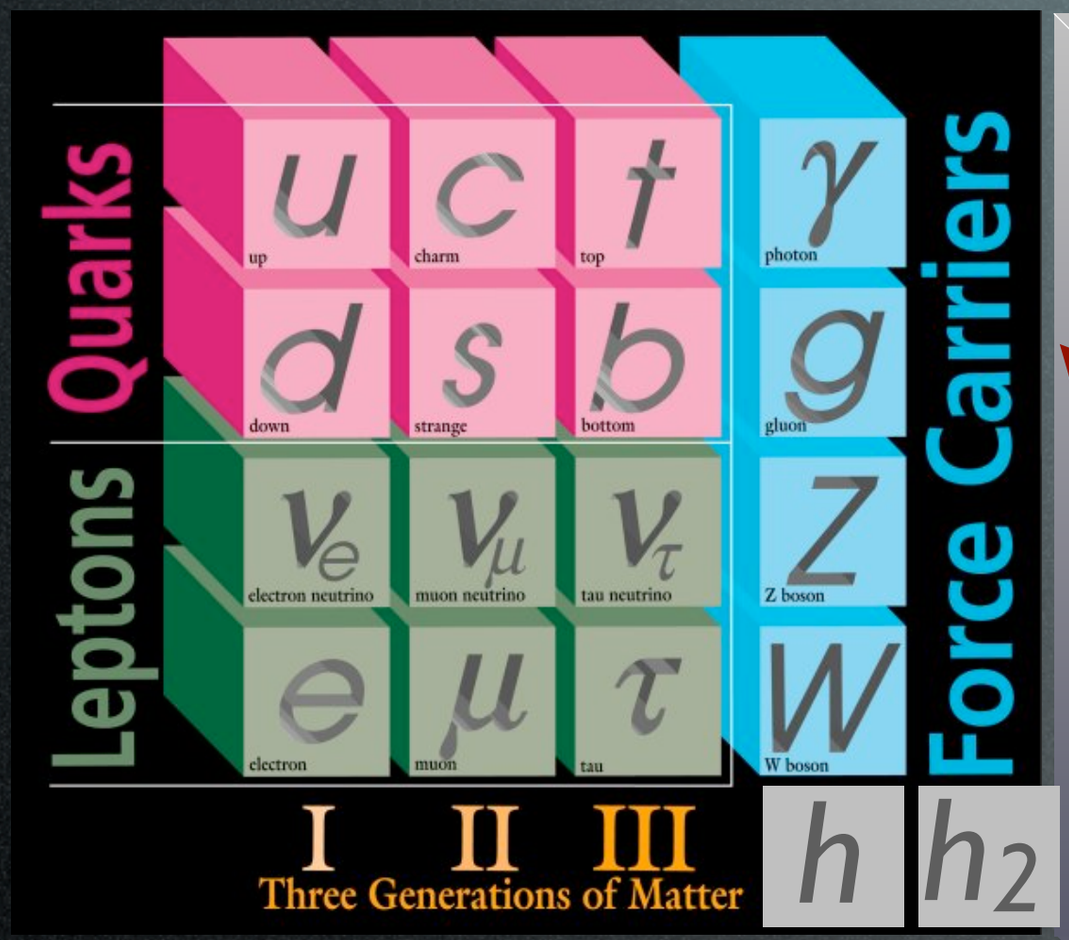
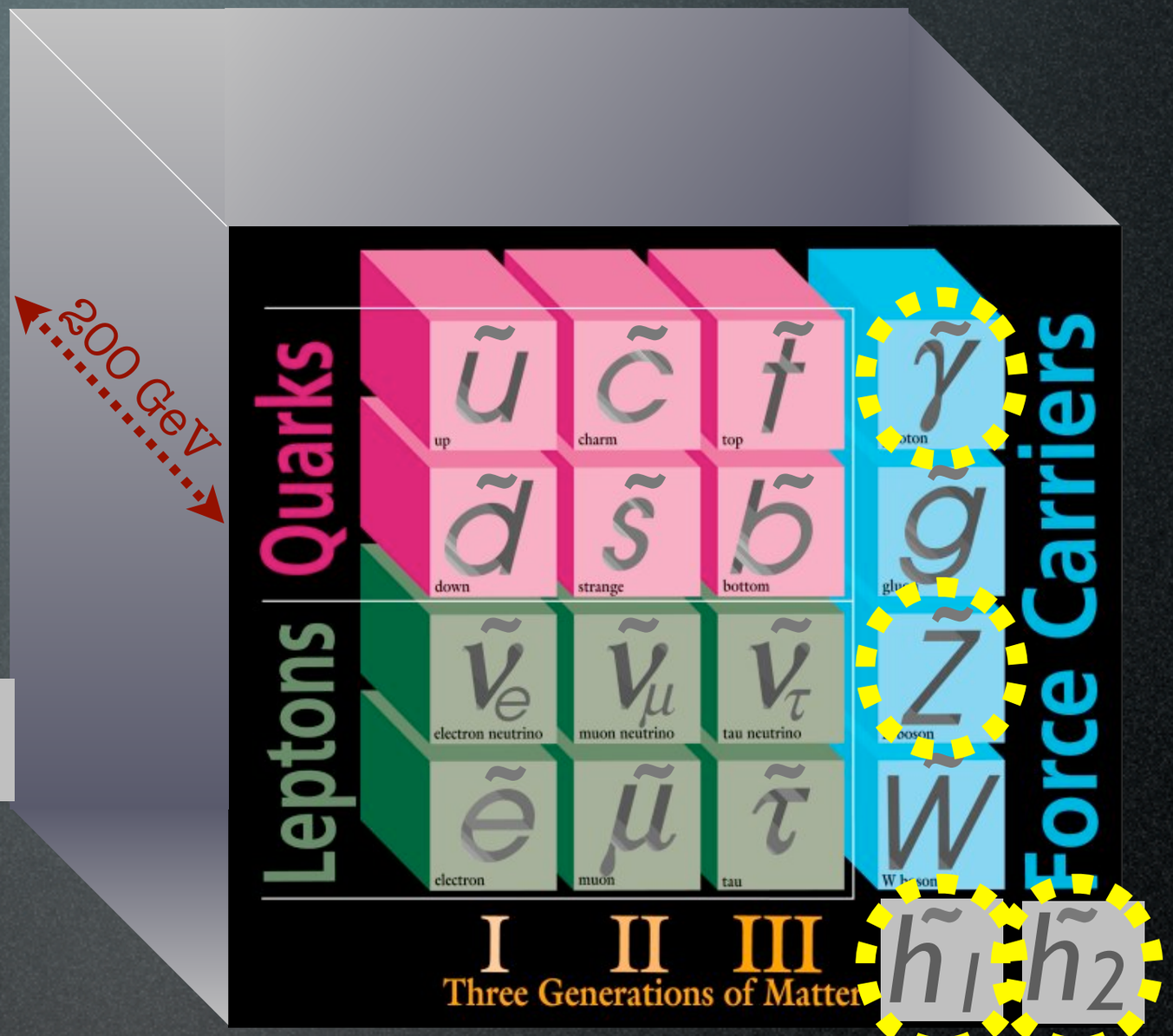
SuSy DM in 2 minutes



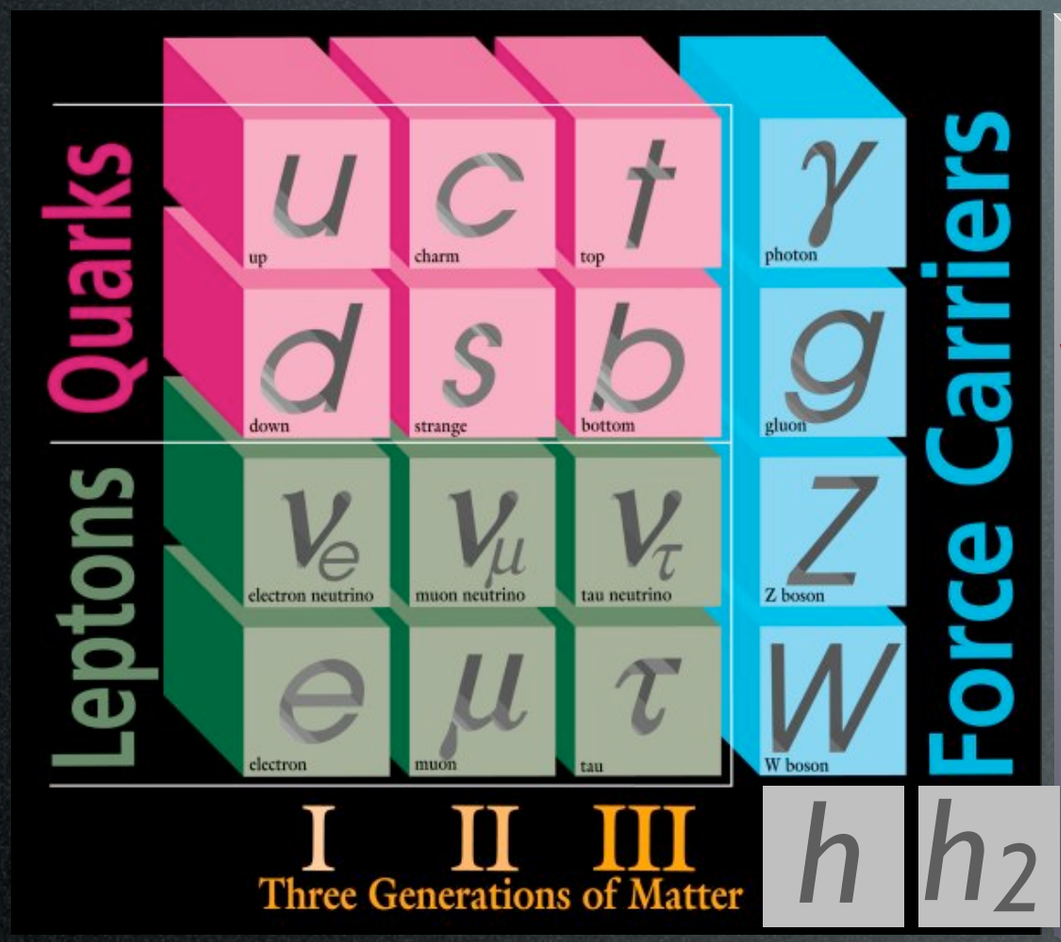
$R = +1$

200 GeV

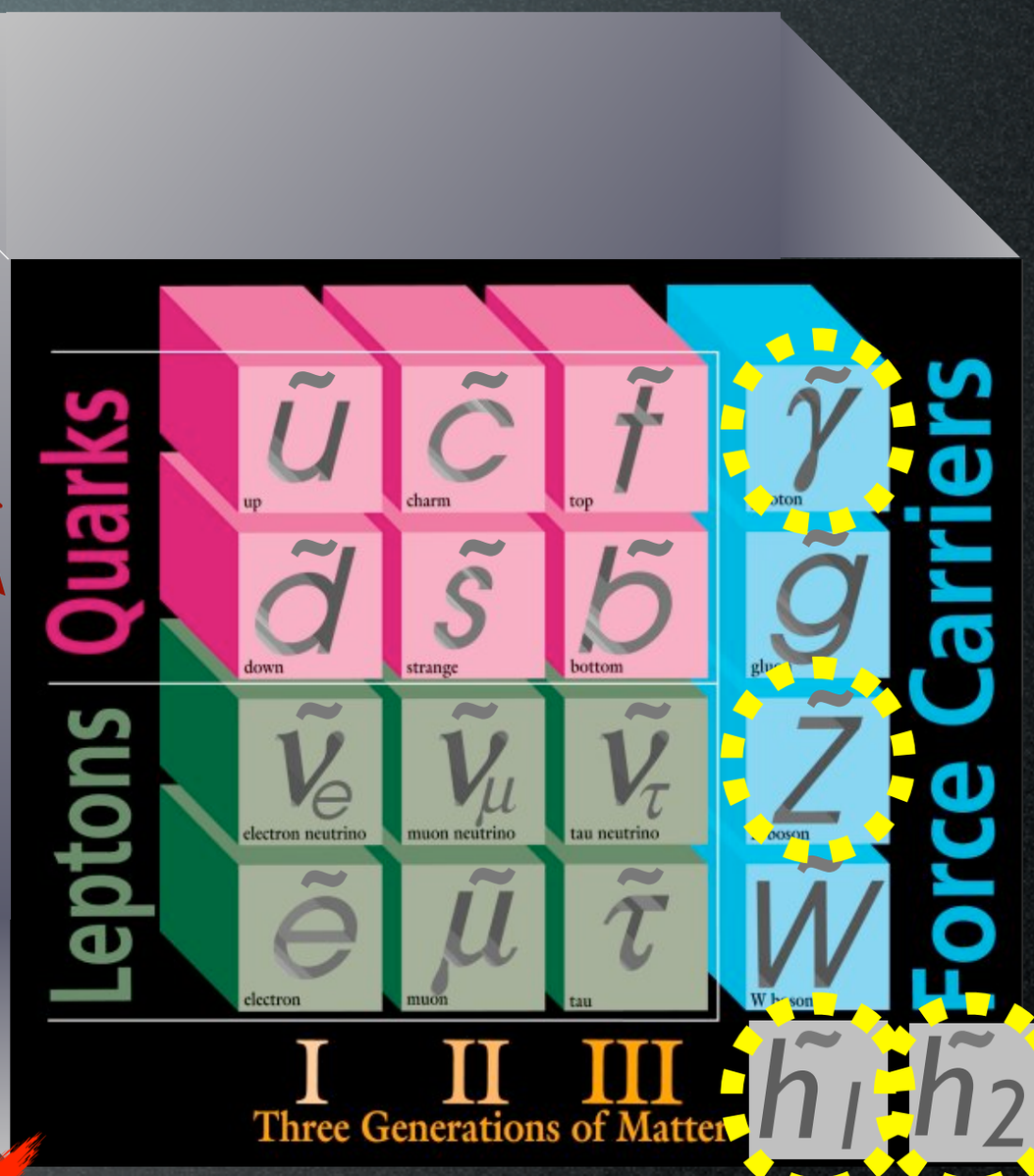


$R = -1$

SuSy DM in 2 minutes



200 GeV



$R = +1$

$R = -1$

prevent
proton decay

Minimalistic approach

On top of the SM, add only one extra multiplet $\mathcal{X} = \begin{pmatrix} \chi_1 \\ \chi_2 \\ \vdots \end{pmatrix}$

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

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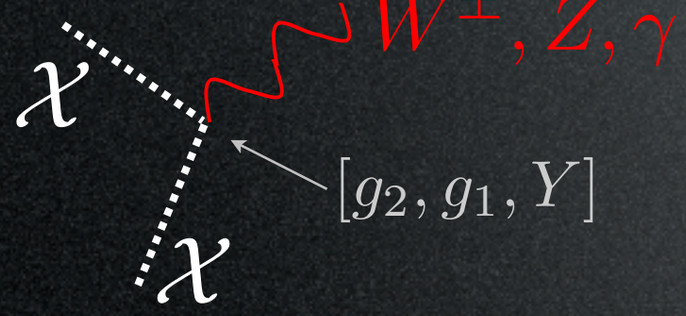
gauge interactions



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
$\underline{2}$		
$\underline{3}$		
$\underline{4}$		
$\underline{5}$		
$\underline{7}$		

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

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

these are all possible choices:

$n \leq 5$ for fermions

$n \leq 7$ for scalars

to avoid explosion in the running coupling

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

The ideal DM candidate is

weakly int., massive, neutral, stable

$SU(2)_L$	$U(1)_Y$	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

$$Q = T_3 + Y \equiv 0$$

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.

The ideal DM candidate is

weakly int., massive, neutral, stable

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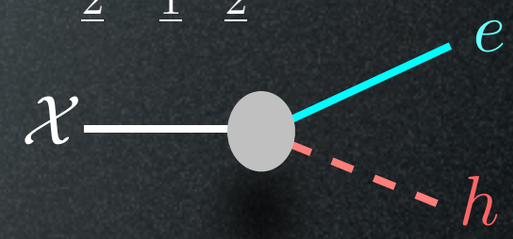
$SU(2)_L$	$U(1)_Y$	spin	M (TeV)	ΔM(MeV)	decay ch.
$\underline{2}$	1/2	S		348	EL
		F	1.0	342	EH
$\underline{3}$	0	S	2.5	166	HH^*
		F	2.7	166	LH
	1	S		540	HH, LH
		F		526	LH
$\underline{4}$	1/2	S		353	HHH^*
		F		347	(LHH^*)
	3/2	S		729	HHH
		F		712	(LHH)
$\underline{5}$	0	S	9.4	166	(HHH^*H^*)
		F	10	166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



← e.g. $\underset{\underline{4}}{1/2}\ \underset{\underline{2}}{-1/2}\ \underset{\underline{2}}{1/2}\ \underset{\underline{2}}{-1/2}$ $\mathcal{X}LHH^*$

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.
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List all allowed SM couplings:

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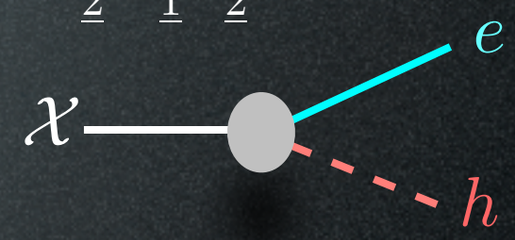


← e.g. $\underset{\underline{4}}{\mathcal{X}}\underset{\underline{2}}{L}\underset{\underline{2}}{H}\underset{\underline{2}}{H^*}$ with $1/2\ -1/2\ 1/2\ -1/2$

dim=5 operator, induces

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

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

No allowed decay!

Automatically stable!

Decaying DM

DM need not be absolutely stable,
just $\tau_{\rm DM} \gtrsim \tau_{\rm universe} \simeq 4.3\ 10^{17}{\rm sec}$.

The current CR anomalies can be due to decay with:

$$\tau_{\rm decay} \approx 10^{26}{\rm sec}$$

Motivations from theory?

- dim 6 suppressed operator in GUT Arvanitaki, Dimopoulos et al., 2008+09

$$\tau_{\rm DM} \simeq 3 \cdot 10^{27}{\rm sec} \left(\frac{1\ {\rm TeV}}{M_{\rm DM}}\right)^5 \left(\frac{M_{\rm GUT}}{2 \cdot 10^{16}\,{\rm GeV}}\right)^4$$

- or in TechniColor Nardi, Sannino, Strumia 2008
- gravitino in SuSy with broken R-parity...

Stability

Orthodoxy → **Heterodoxy** → **Heresy**

‘ad hoc’ symmetry

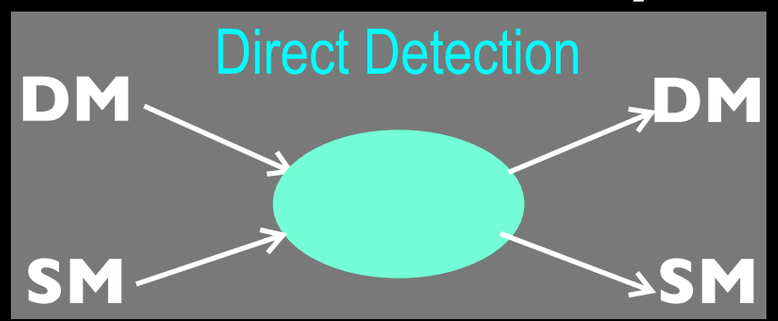
automatically
stable

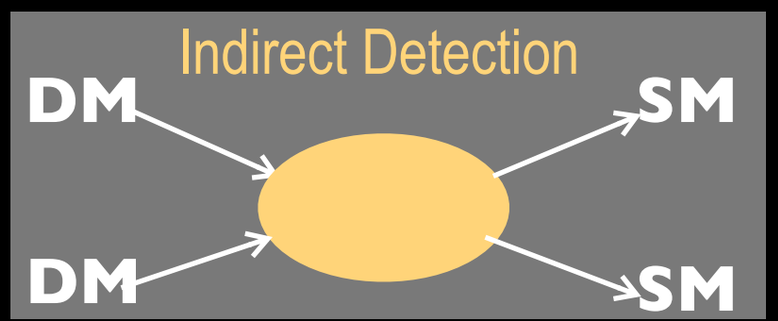
(like Minimal
Dark Matter)

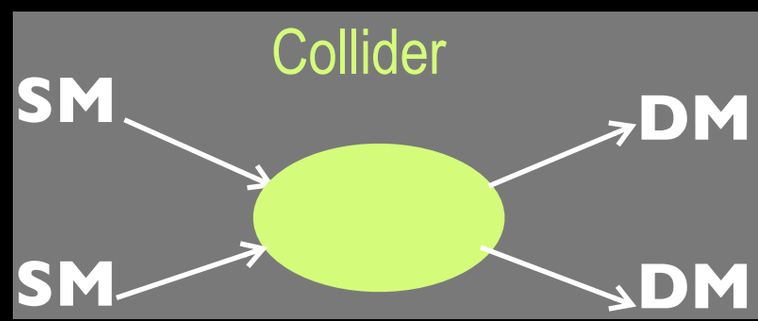
Executive summary

- DM exists
- it's a new, unknown particle — *no SM particle can fulfil* — *dilutes as $1/a^3$ with universe expansion*
- makes up 26% of total energy, 84% of total matter — $\Omega_{\rm DM} h^2 = 0.1188 \pm 0.0010$ *(notice error!)*
- neutral particle *'dark'...*
- cold or not too warm — *p/m <<1 at CMB formation*

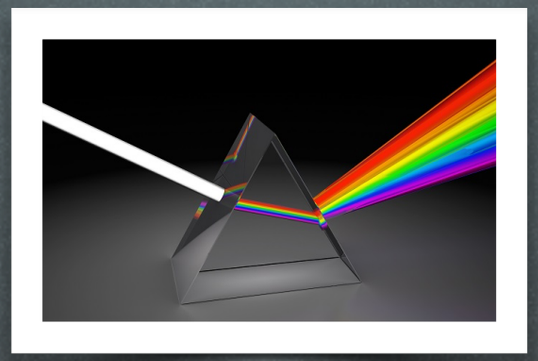
- very feebly interacting — *-with itself -with ordinary matter ('collisionless')*
- stable or very long lived — $\tau_{\rm DM} \gg 10^{17}{\rm sec}$
- possibly a relic from the EU
- searched for by







The Dark Matter theory spectrum



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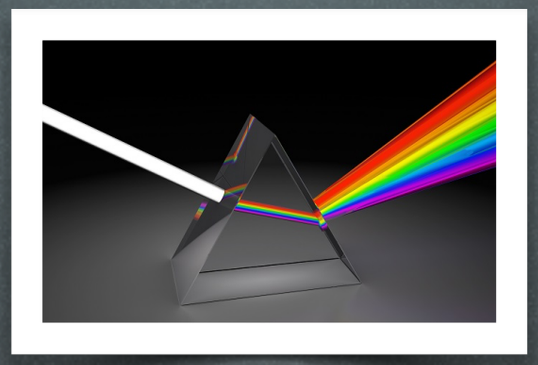

SuSy neutralino

multi-TeV self-interacting leptophilic decaying asymmetric cannibal Dark Matter

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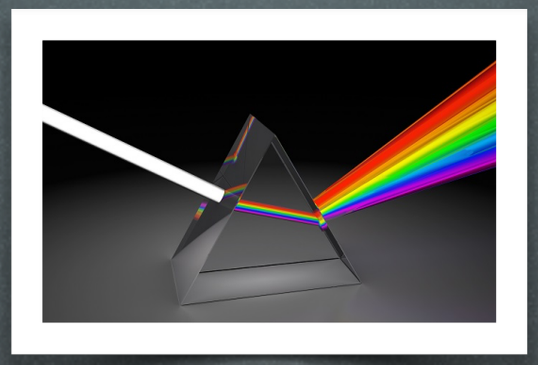


SuSy neutralino

multi-TeV self-interacting leptophilic decaying asymmetric cannibal Dark Matter

Backup slides

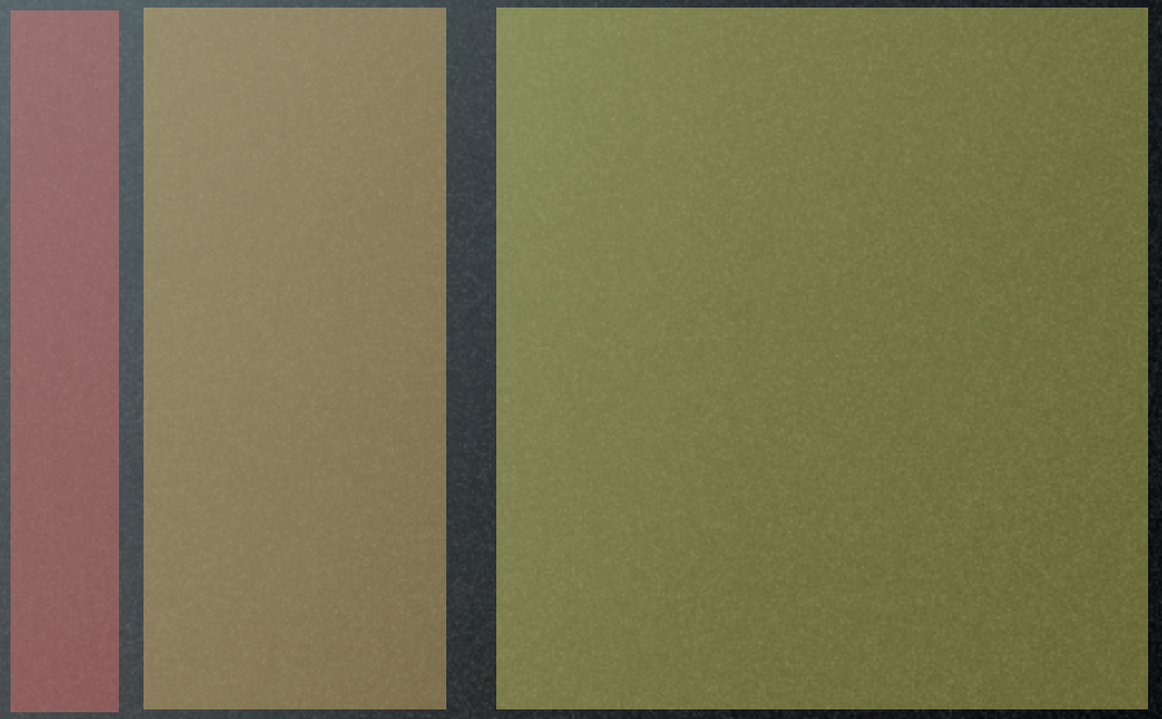
Asymmetric Dark Matter

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

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



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

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

Asymmetric **Oscillating** DM

Cirelli, Panci, Servant, Zaharijas 1110.3809

Asymmetric Oscillating DM

Cirelli, Panci, Servant, Zaharijas 1110.3809

A small $\mathrm{DM}/\overline{\mathrm{DM}}$ mass splitting induces $\mathrm{DM} \leftrightsquigarrow \overline{\mathrm{DM}}$ oscillations.

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Cirelli, Panci, Servant, Zaharijas 1110.3809

A small $\mathrm{DM}/\overline{\mathrm{DM}}$ mass splitting induces $\mathrm{DM} \leftrightsquigarrow \overline{\mathrm{DM}}$ oscillations.

Asymmetric ‘freeze-out’

The correct Ω_{DM} can not be obtained.

Asymmetric Oscillating DM

Cirelli, Panci, Servant, Zaharijas 1110.3809

A small $\mathrm{DM}/\overline{\mathrm{DM}}$ mass splitting induces $\mathrm{DM} \leftrightsquigarrow \overline{\mathrm{DM}}$ oscillations.

Asymmetric 'freeze-out'

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

Asymmetric Oscillating DM

Cirelli, Panci, Servant, Zaharijas 1110.3809

A small $\mathrm{DM}/\overline{\mathrm{DM}}$ mass splitting induces $\mathrm{DM} \leftrightsquigarrow \overline{\mathrm{DM}}$ oscillations.

Asymmetric ‘freeze-out’

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

Temporary ‘freeze-out’

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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

The system:

coherent

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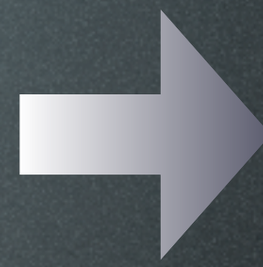

density matrix formalism

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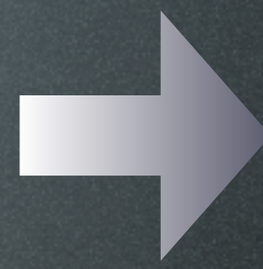

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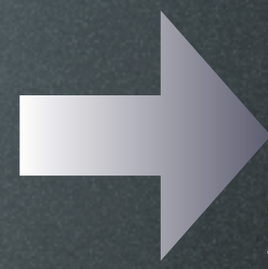

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(comoving) number density of DM

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

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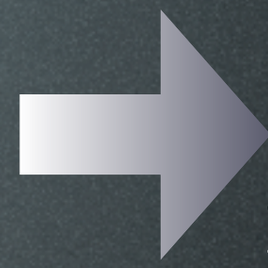

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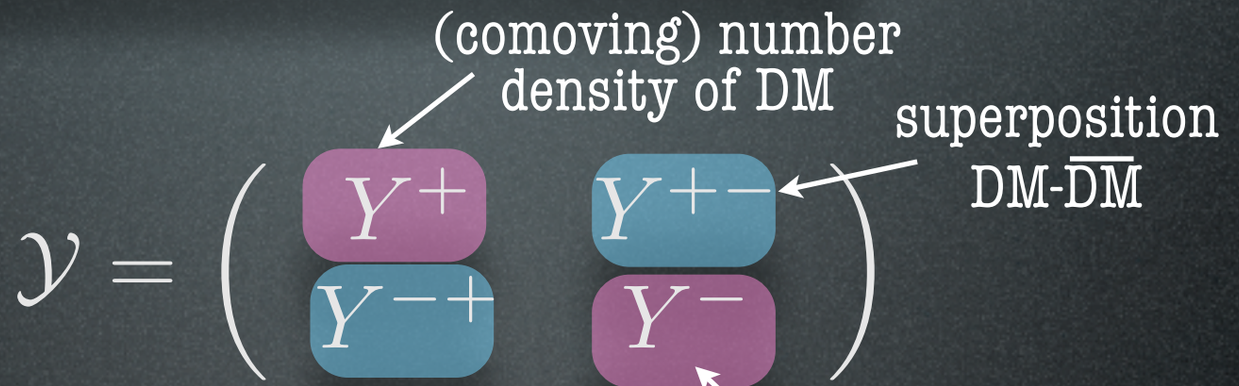

Evolution in time:

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

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

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

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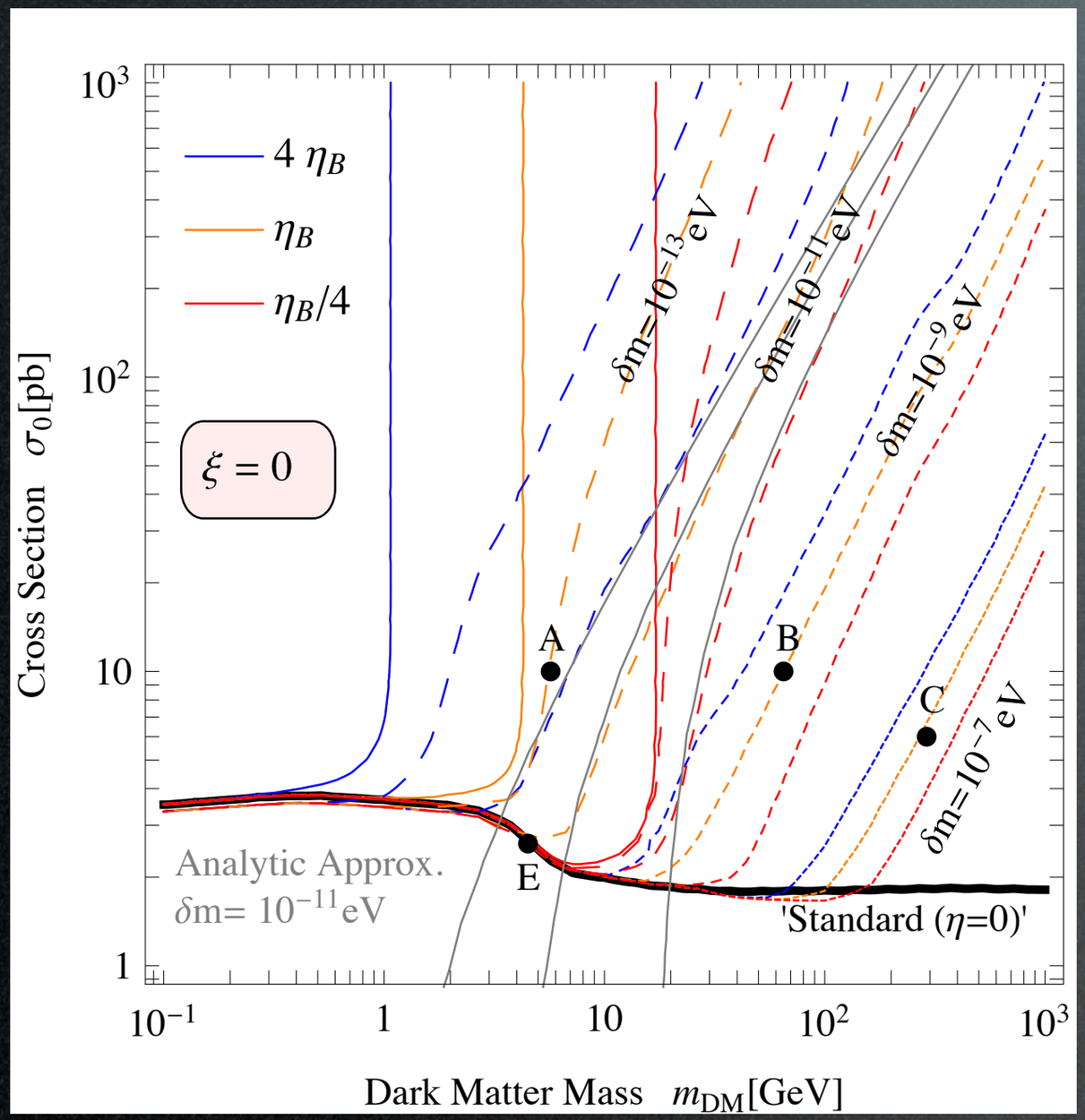
$$-\frac{s(x)}{x\,H(x)}\left(\frac{1}{2}\Big\{\mathcal{Y}(x), \Gamma_{\mathrm{a}}\,\bar{\mathcal{Y}}(x)\,\Gamma_{\mathrm{a}}^{\dagger}\Big\} - \Gamma_{\mathrm{a}}\,\Gamma_{\mathrm{a}}^{\dagger}\,\mathcal{Y}_{\mathrm{eq}}^{2}\right)$$ **annihilations**

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

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

Results

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



Results

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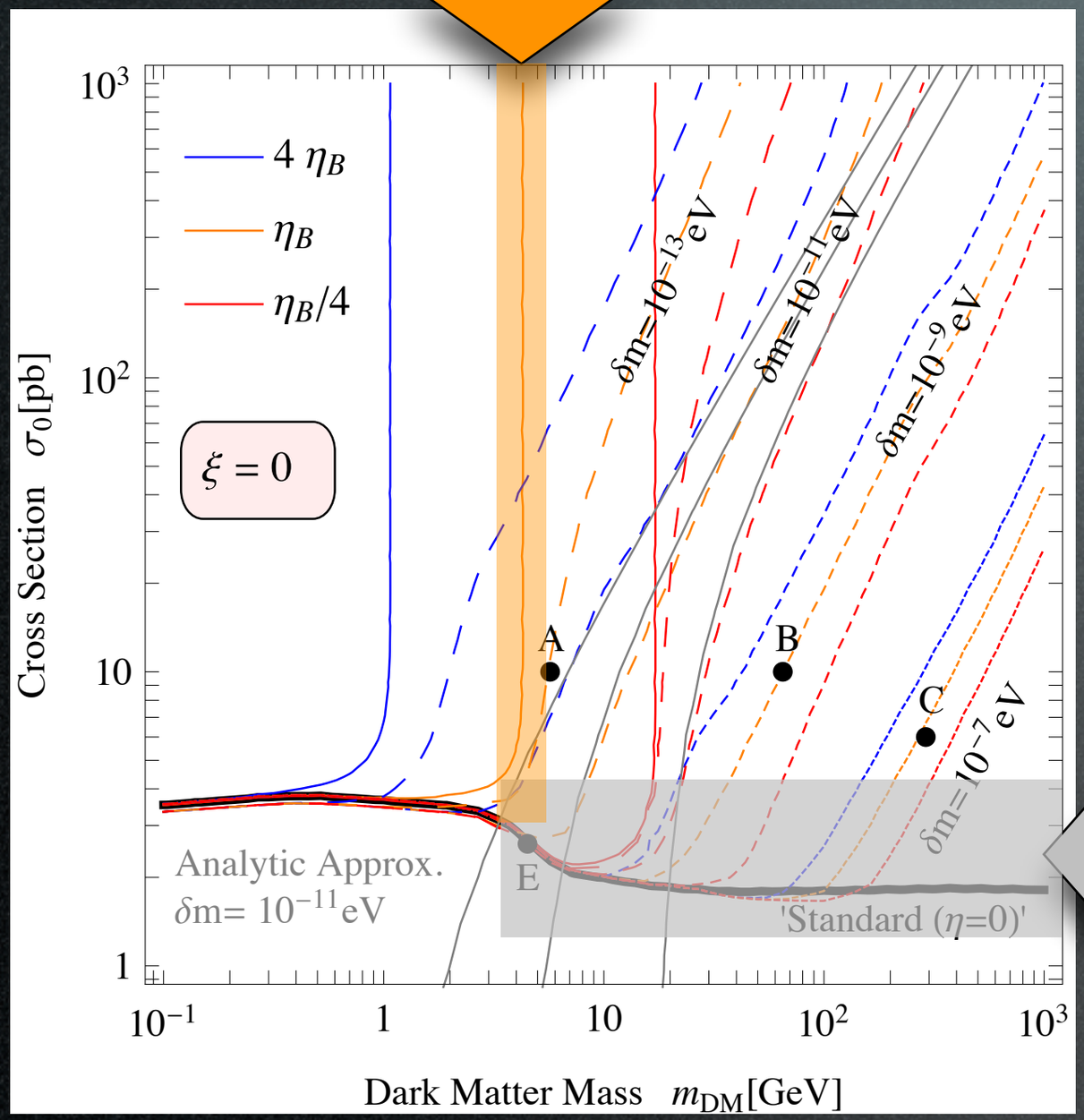
standard
aDM



standard
WIMP
miracle

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

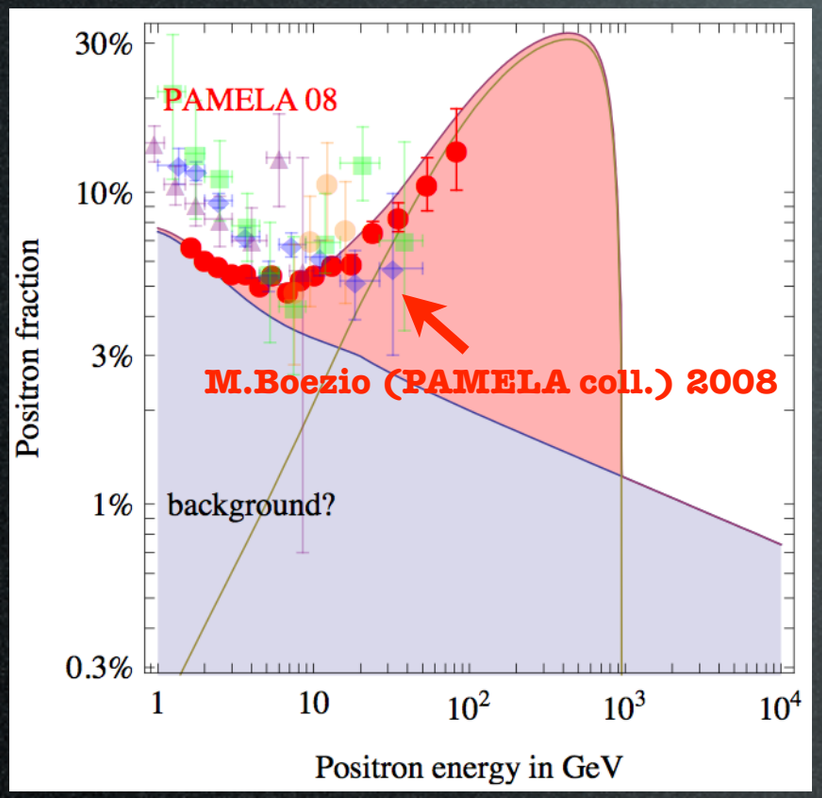
‘Secluded’
Dark Matter

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

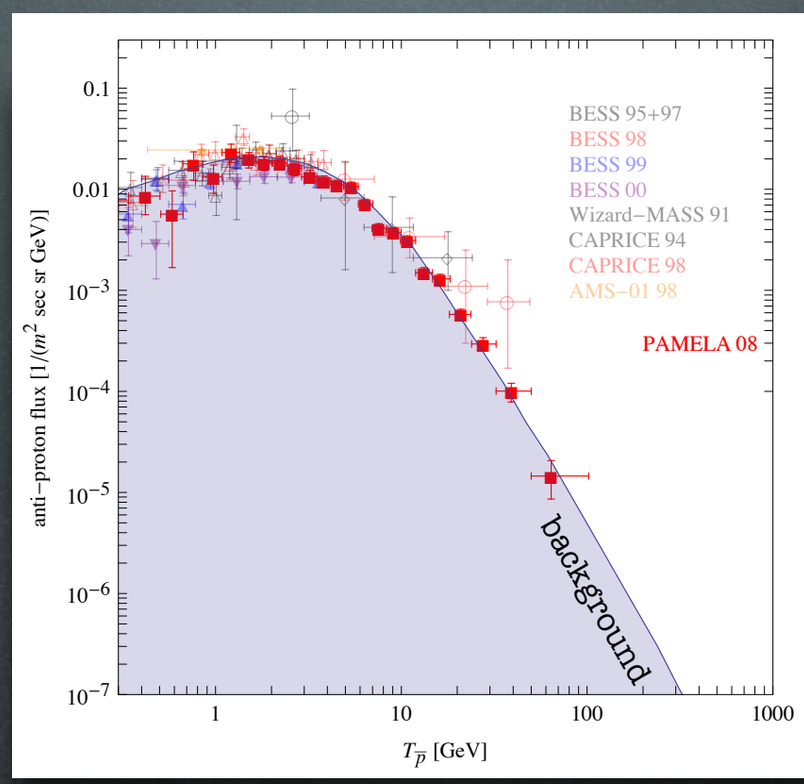
Main motivation

Main motivation

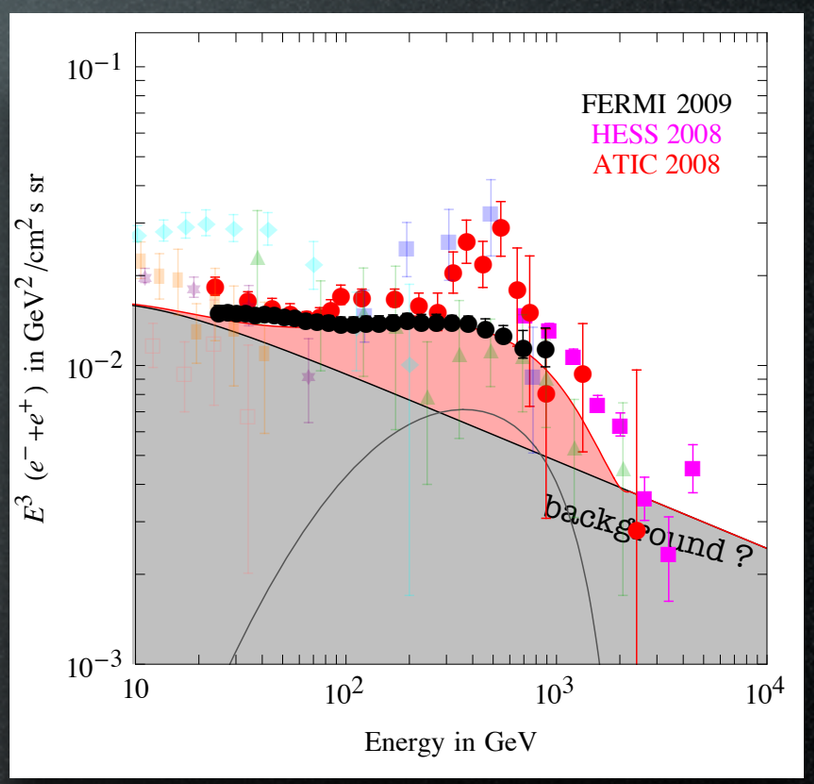
positron fraction



antiprotons



electrons + positrons



Are these signals of Dark Matter?

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

Main motivation

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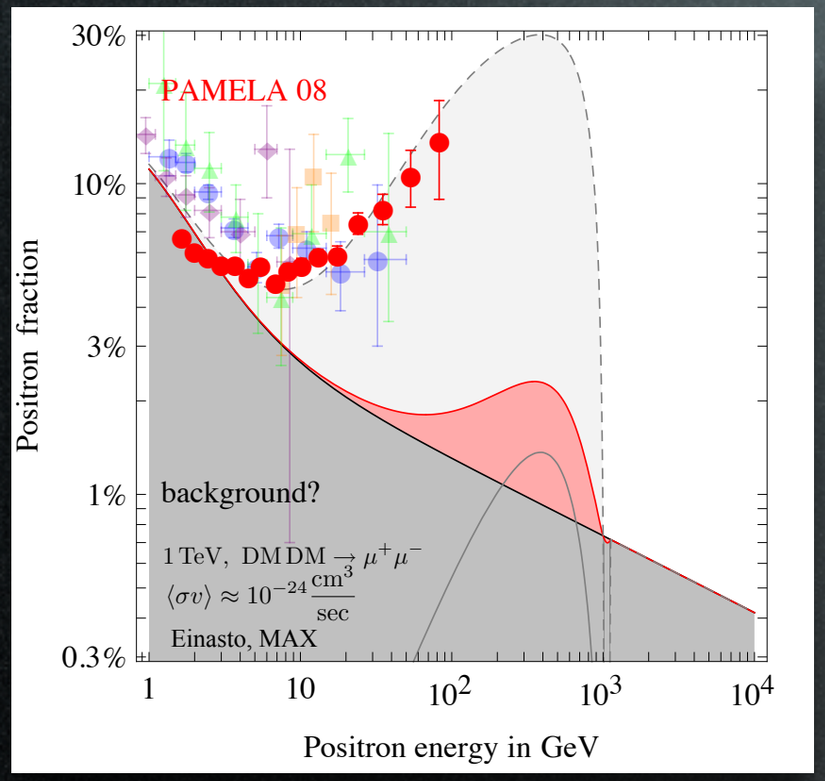

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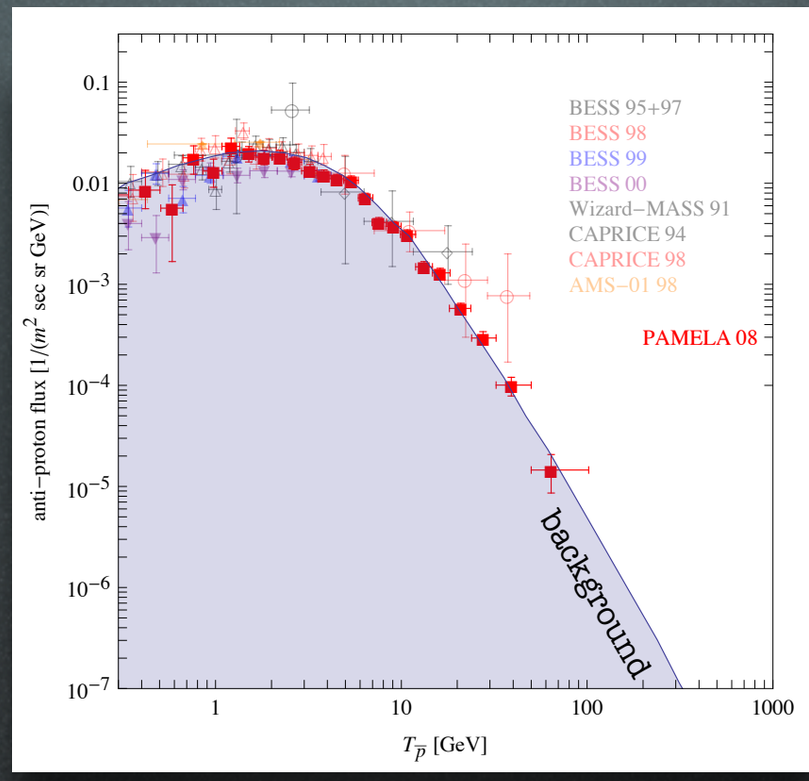

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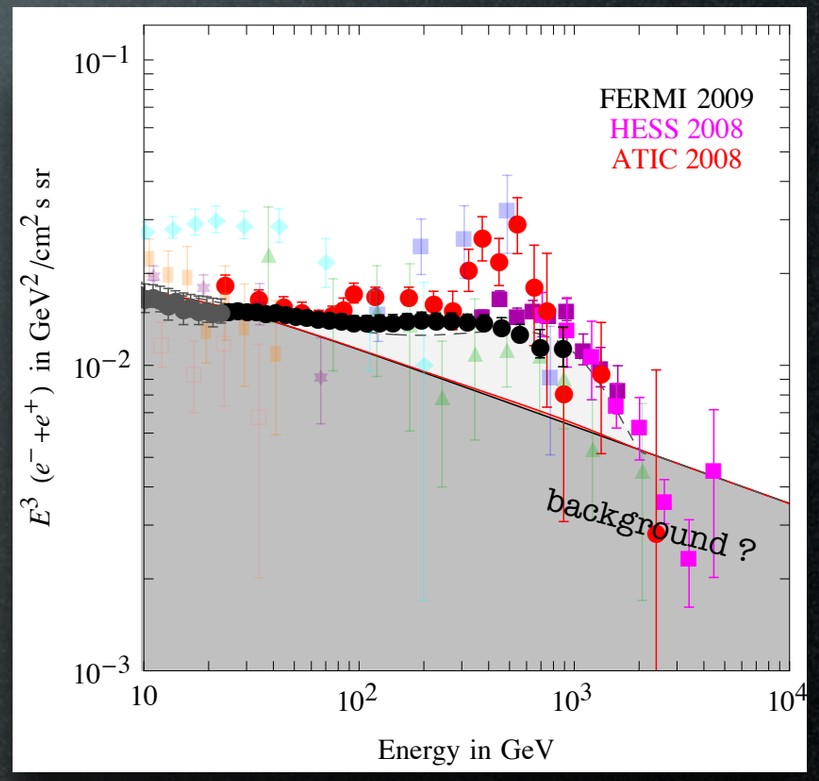

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YES: few TeV, leptophilic DM
with huge $\langle\sigma v\rangle \approx 10^{-23}\,\text{cm}^3/\text{sec}$

NO: a formidable 'background' for future searches

The "Theory of DM"

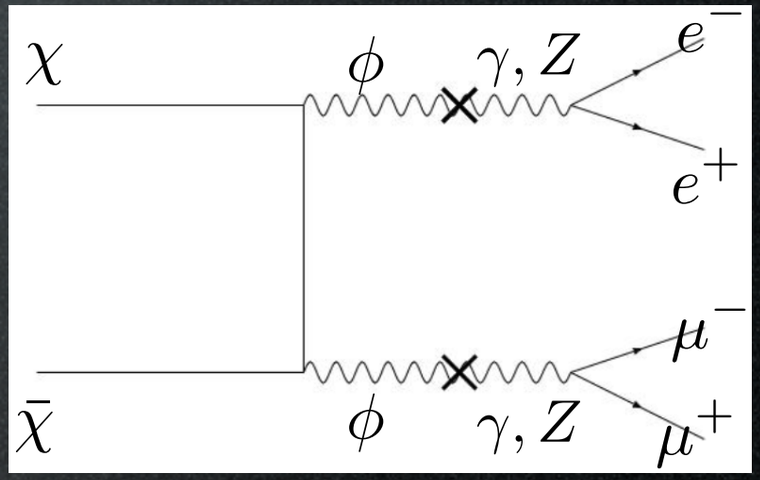
Arkani-Hamed, Weiner, Finkbeiner et al. 0810.0713
0811.3641

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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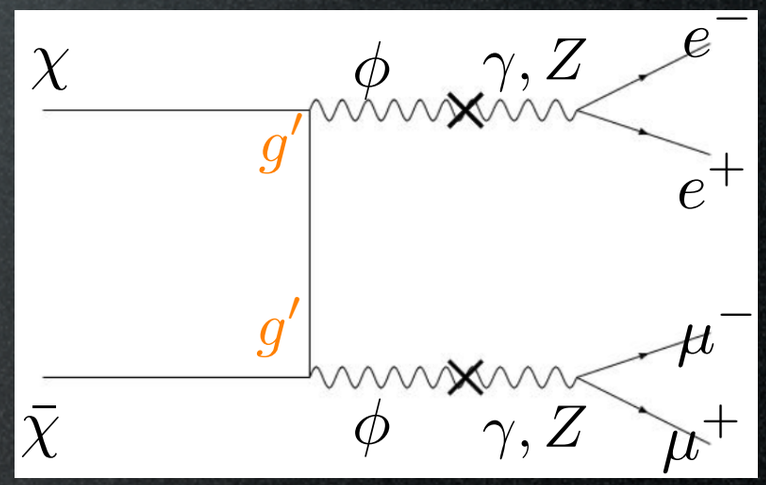

Production mechanism:

just thermal freeze-out
of these annihilations

same idea in: WIMPless DM Feng, Kumar 2008

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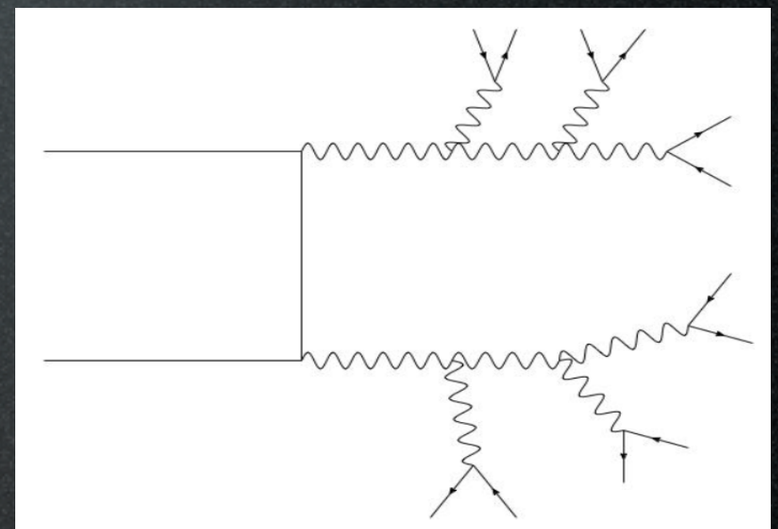


Extras:

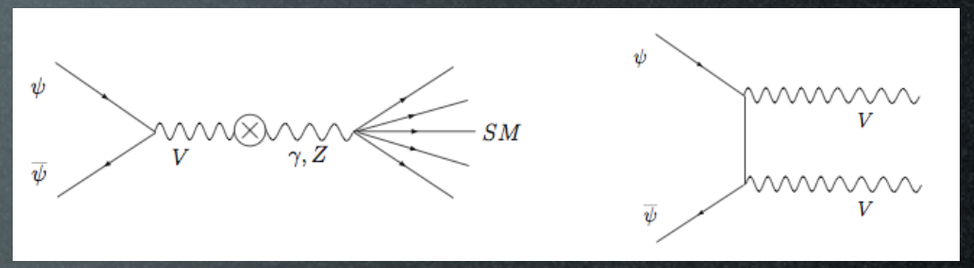
χ is a multiplet of states and ϕ is non-abelian gauge boson:
splitting $\delta M \sim 200$ KeV (via loops of non-abelian bosons)
- inelastic scattering explains DAMA
- eXcited state decay $\chi\chi \to \chi\chi^*$ explains INTEGRAL
$\hookrightarrow e^+e^-$

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

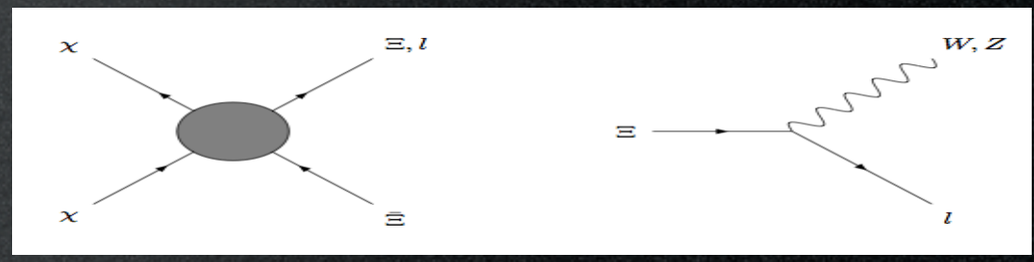
  Park, Shu 0901.0720

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

  Cirelli, Kadastik, Raidal, Strumia 0809.2409 Fox, Poppitz 0811.0399

- 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]