24 May 2018
New Frontiers in Theoretical Physics
Cortona

Still searching for Dark Matter

Marco Cirelli
(CNRS LPTHE Jussieu)

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LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

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NewDark

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Executive summary

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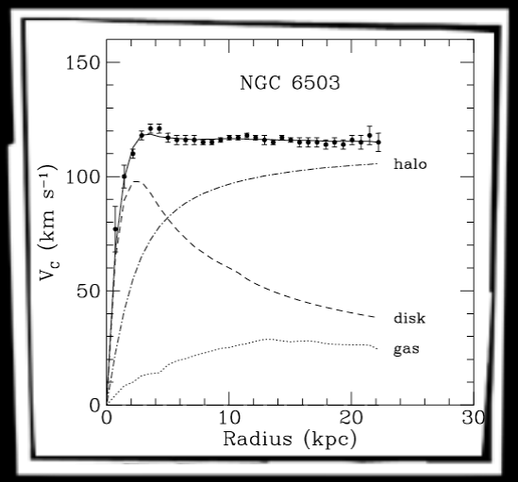
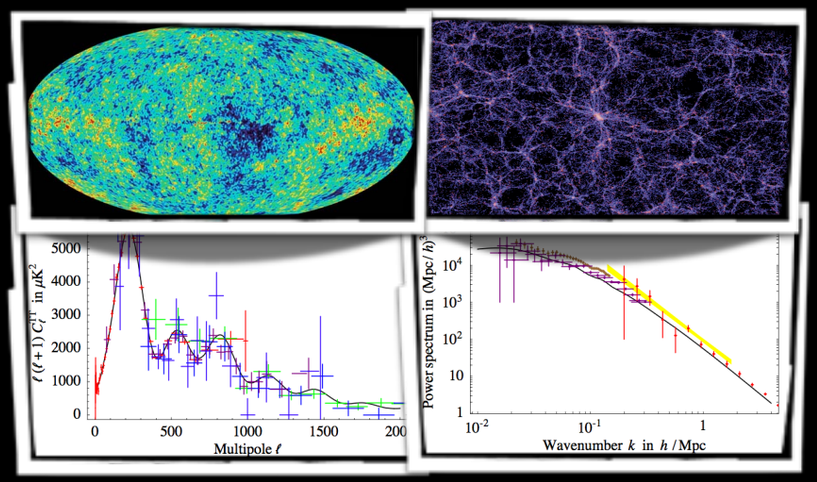


galactic rotation curves

weak lensing (e.g. in clusters)



'precision cosmology' (CMB, LSS)

Executive summary

- DM exists
- it's a new, unknown particle

no SM particle can fulfil

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

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  84% of total matter

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$$\Omega_{\rm DM} h^2 = 0.1188 \pm 0.0010$$

(notice error!)

Planck 2015, 1502.01589 (tab.4)

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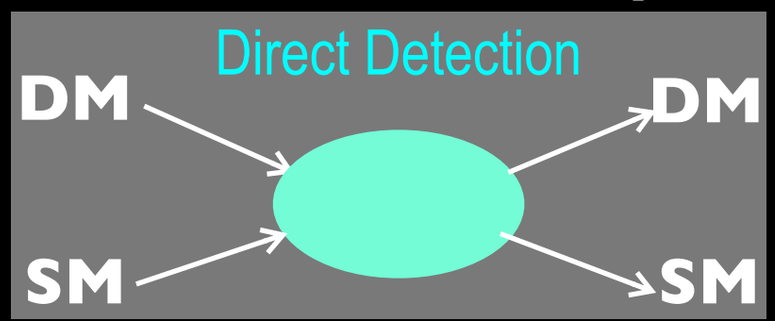

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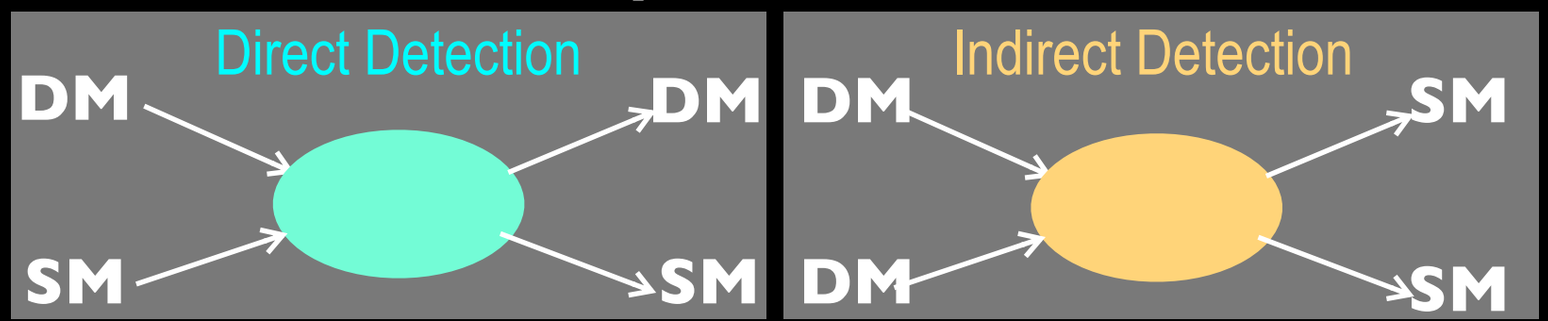

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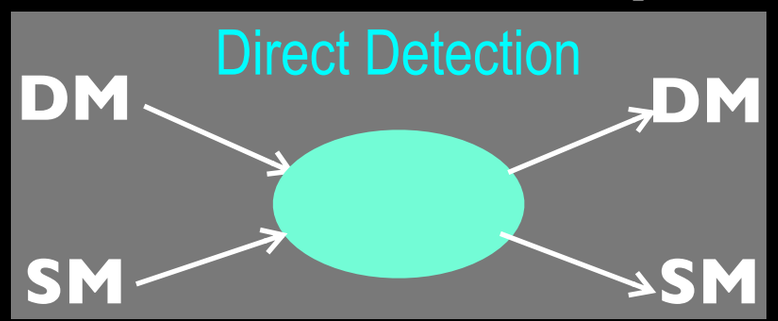

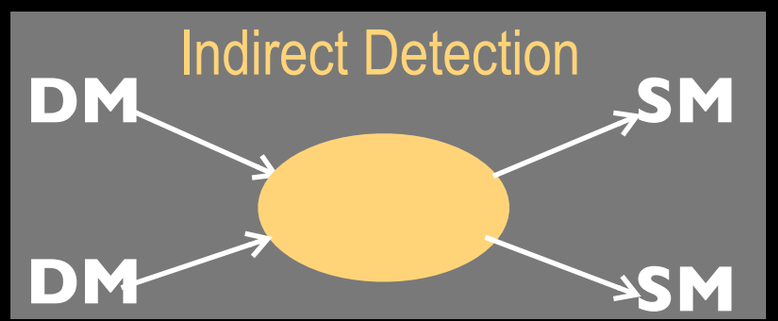

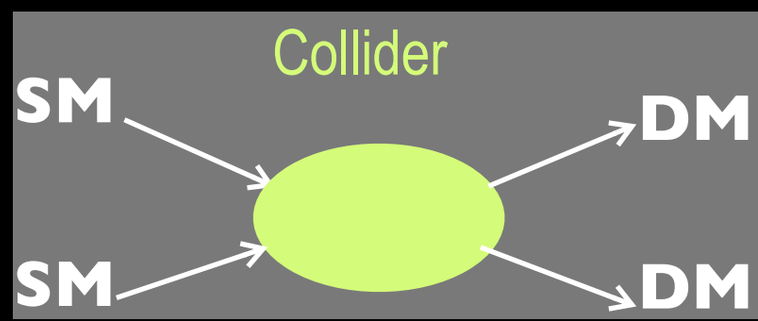

DM can **NOT** be:

an astro *je ne sais pas quoi*:

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- gas

- Black Holes
- brown dwarves

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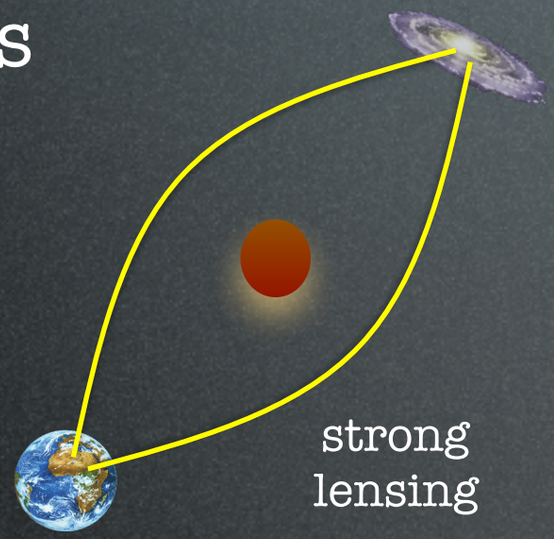
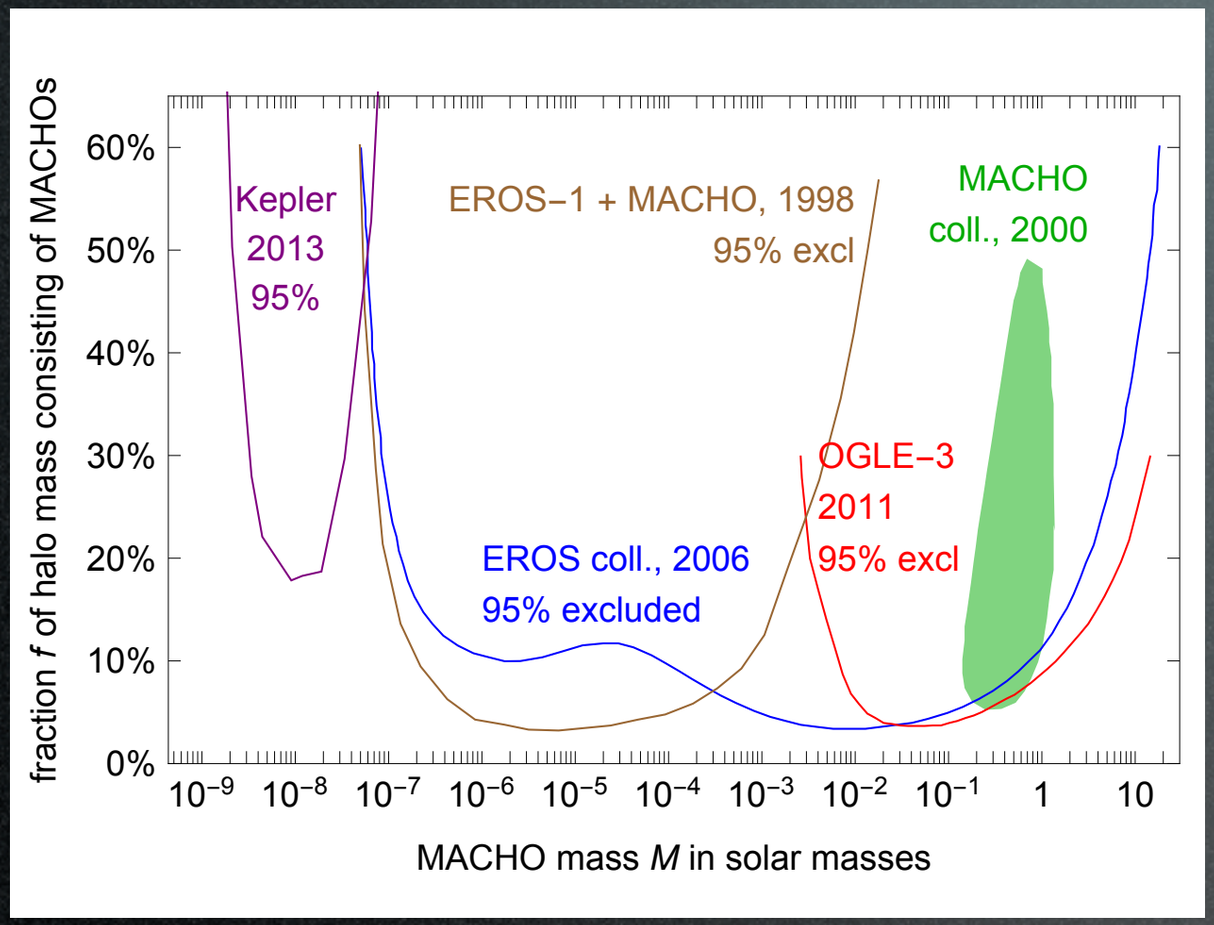


strong
lensing

MACHOs or PBHs as DM



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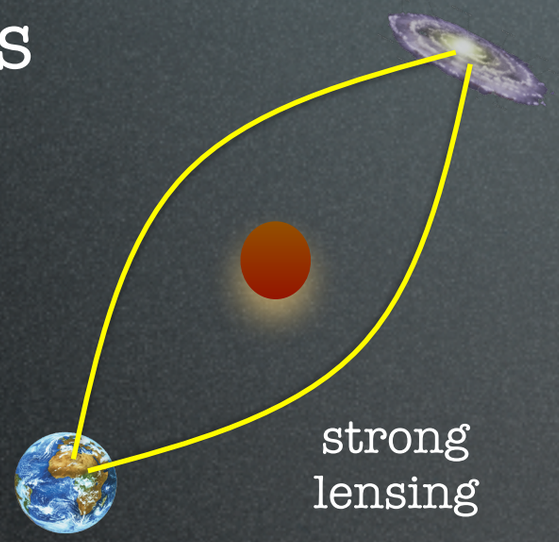

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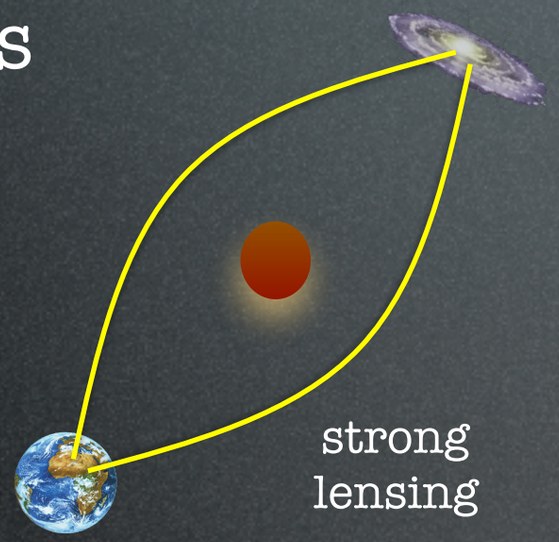

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- BBN computes the abundance of He in terms of primordial baryons:
  too much baryons => Universe full of Helium

- CMB says baryons are 4% max

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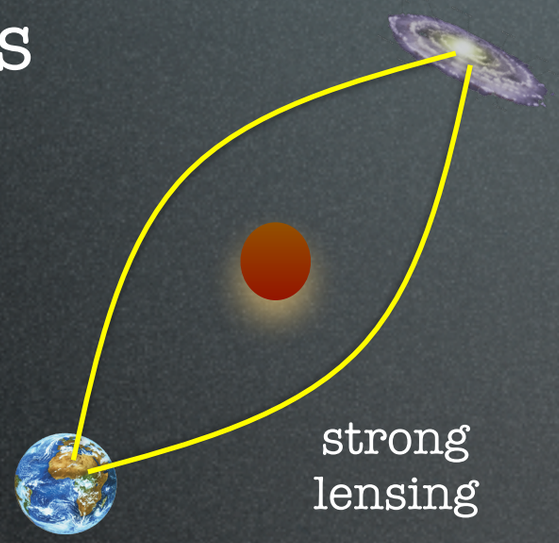

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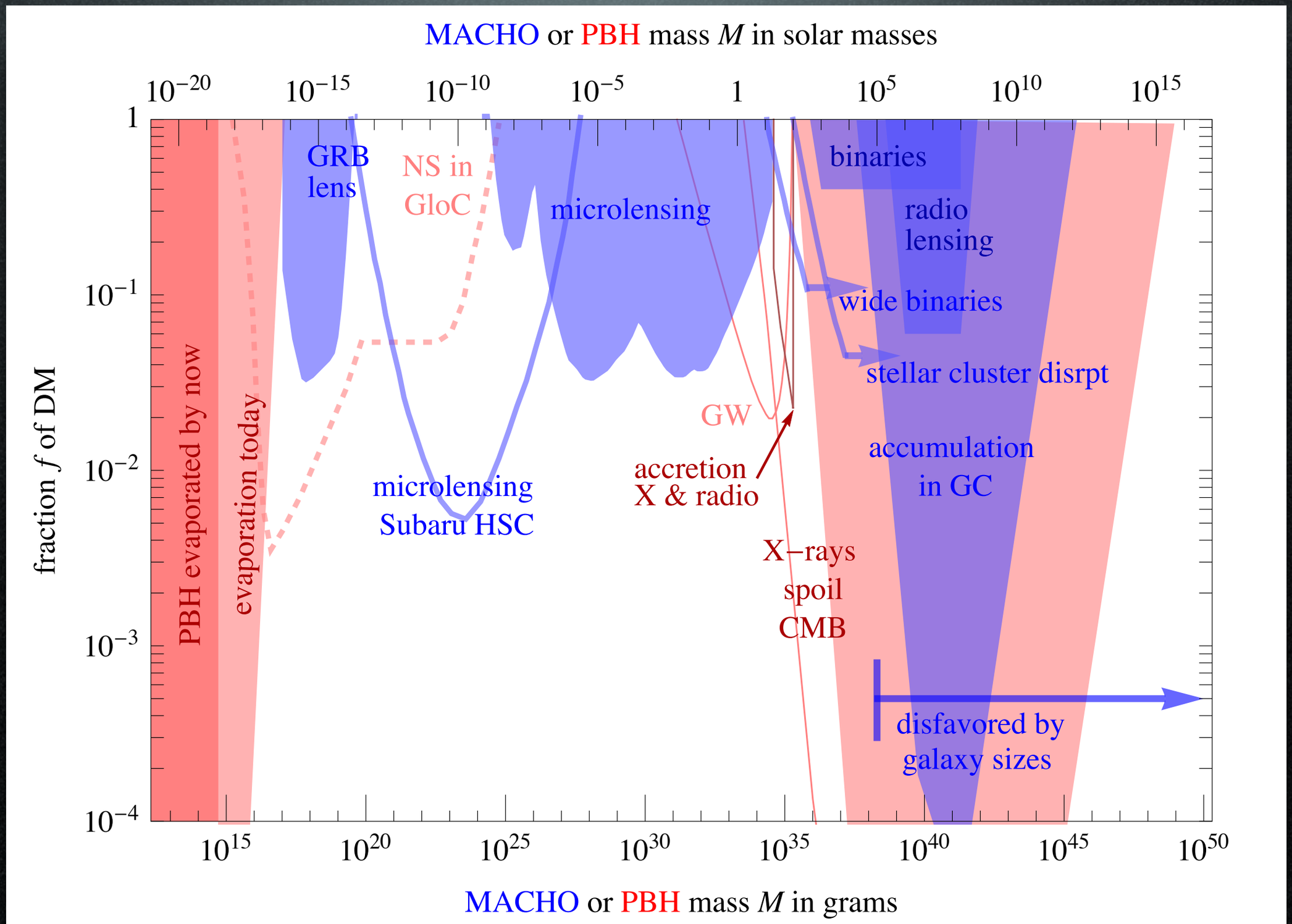
A loophole: Primordial Black Holes!

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

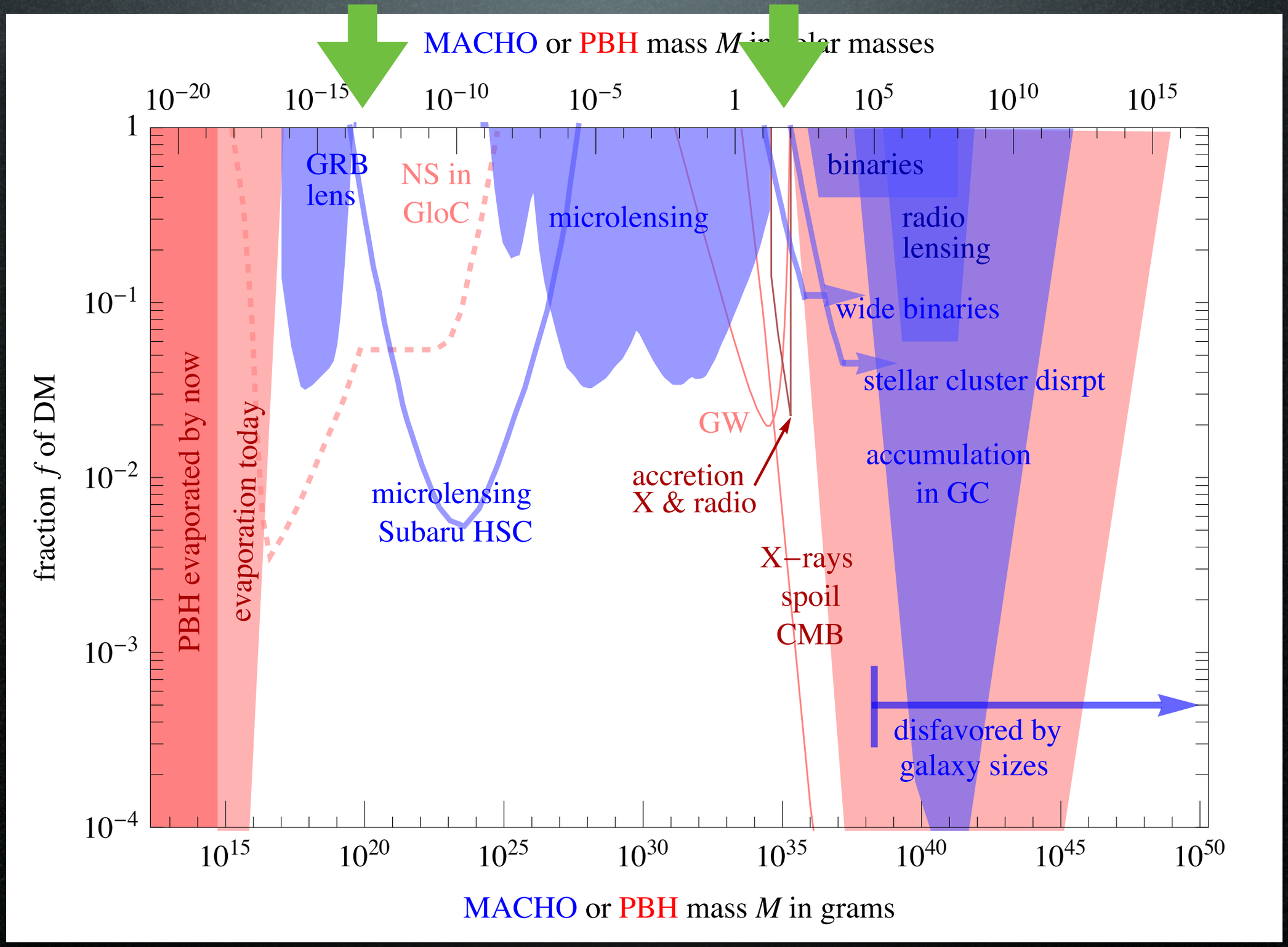
PBHs as DM



M. Cirelli, A. Strumia, J. Zupan, DM review, to appear before the C Convegno Nazionale di Fisica Teorica

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 DM

Non SuSy DM

?

Candidates

The Dark Matter theory space:

SuSy neutralino

other exotic candi-dates

Candidates

A matter of perspective:

Anapole DM
Axino
Minimal DM
Impeded DM
cannibal DM
Scalar singlet
dipolar DM
Little Higgs DM
Fluffy DM
Asym-metric DM
SuSy neutralino
SIMPs
Rayleig DM
Self-inte DM
WISPy DM
Techi-baryon
eXciting DM
GUTzilla DM
inflatable DM
Dichromatic DM
vector DM
charming DM
Forbidden
mirr matte
WIMPles DM
ecluded DM
Relentless DM
heavy higgs DM
Concentrated DM
Sterile Neutrinos
Luminous DM
aluz Klein DM
Gravitino
MeV DM
Q-balls
quark nuggets
Fluorescent DM
dark photon
Imperfect DM
Magnetic inelastic DM
Mimetic DM

Candidates

The Dark Matter theory space:

Caveat: no categorization is perfect.

DM

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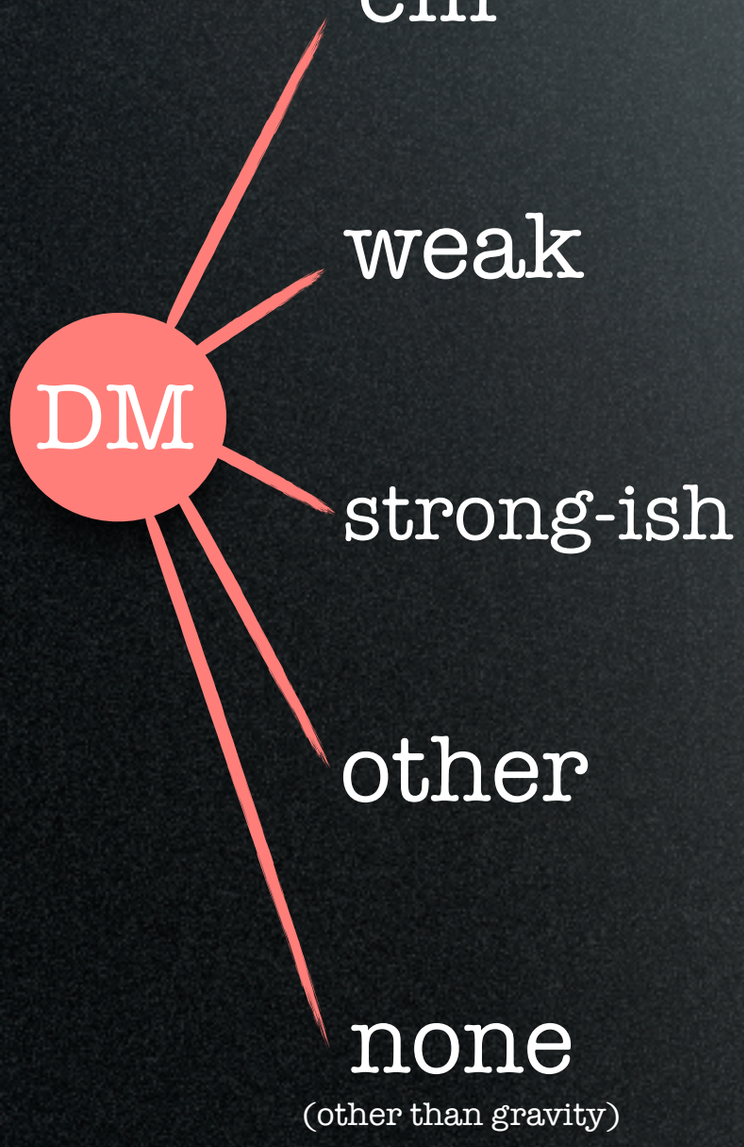

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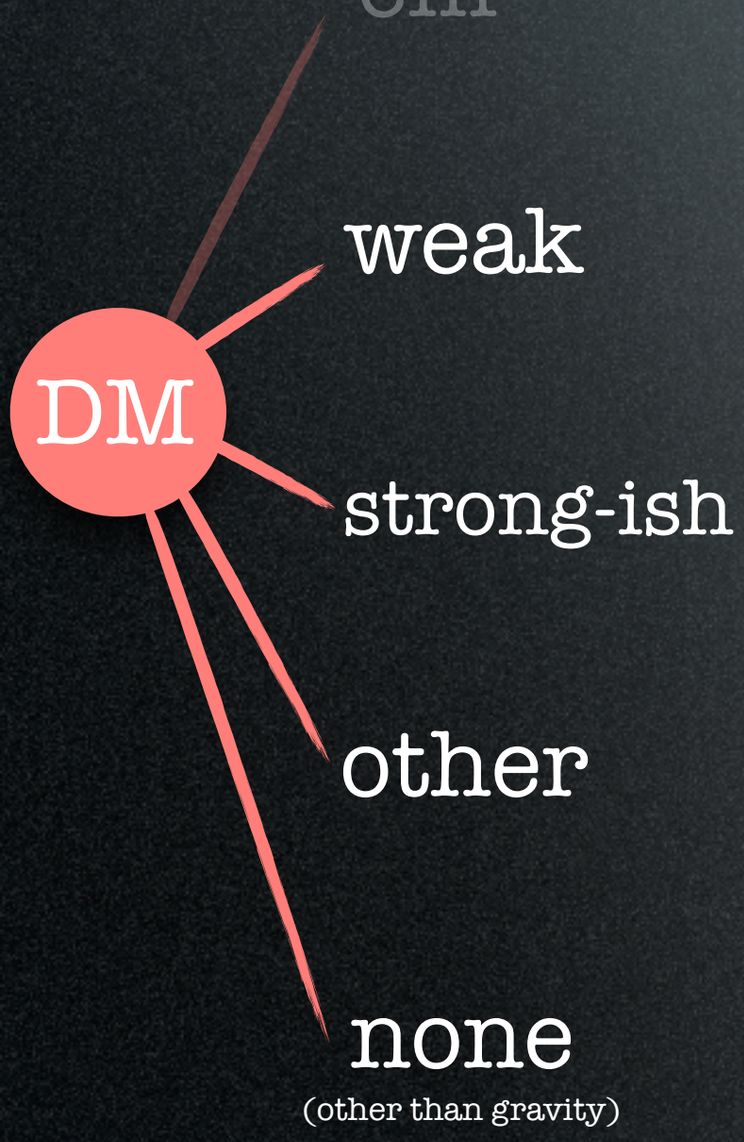

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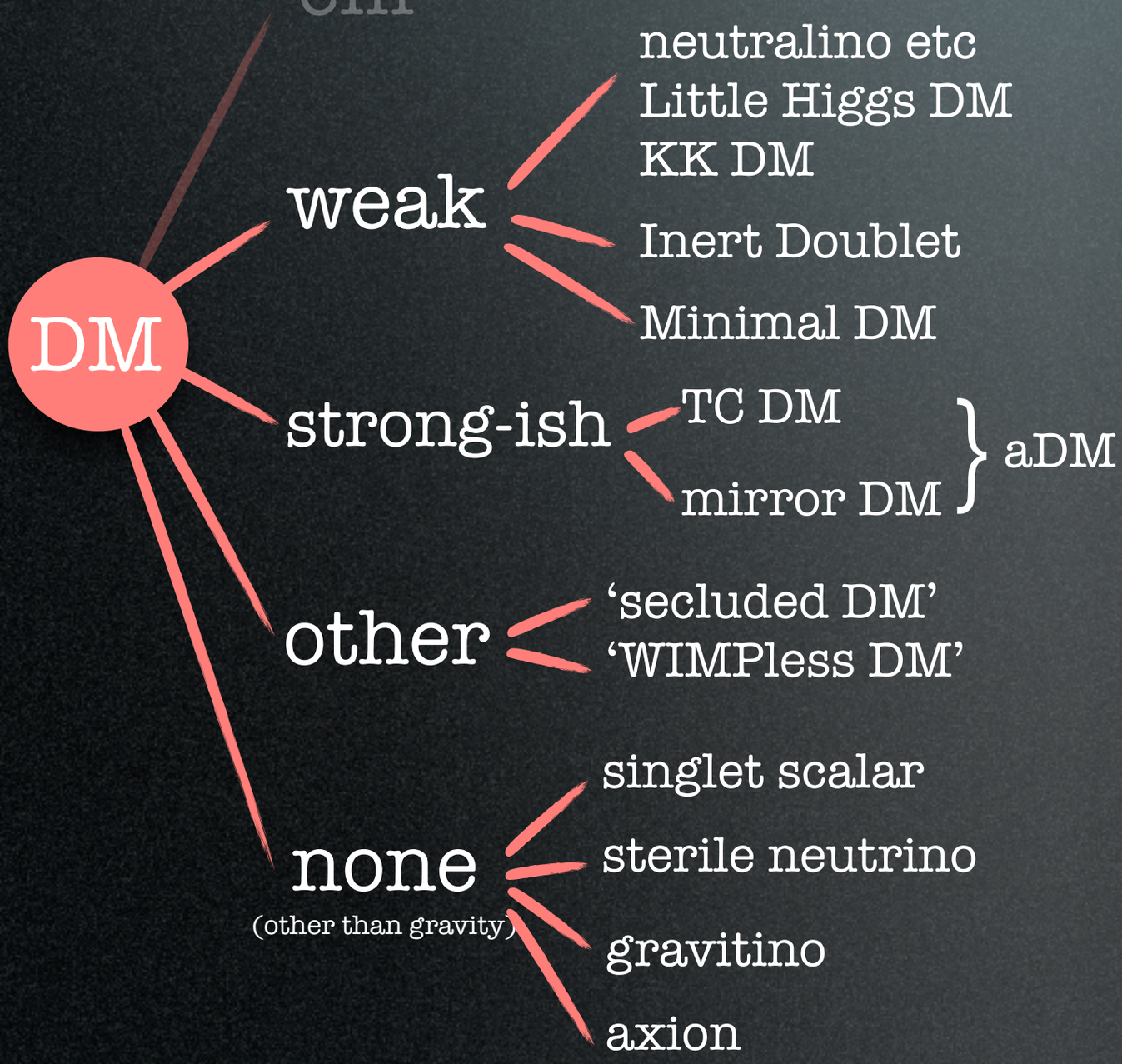

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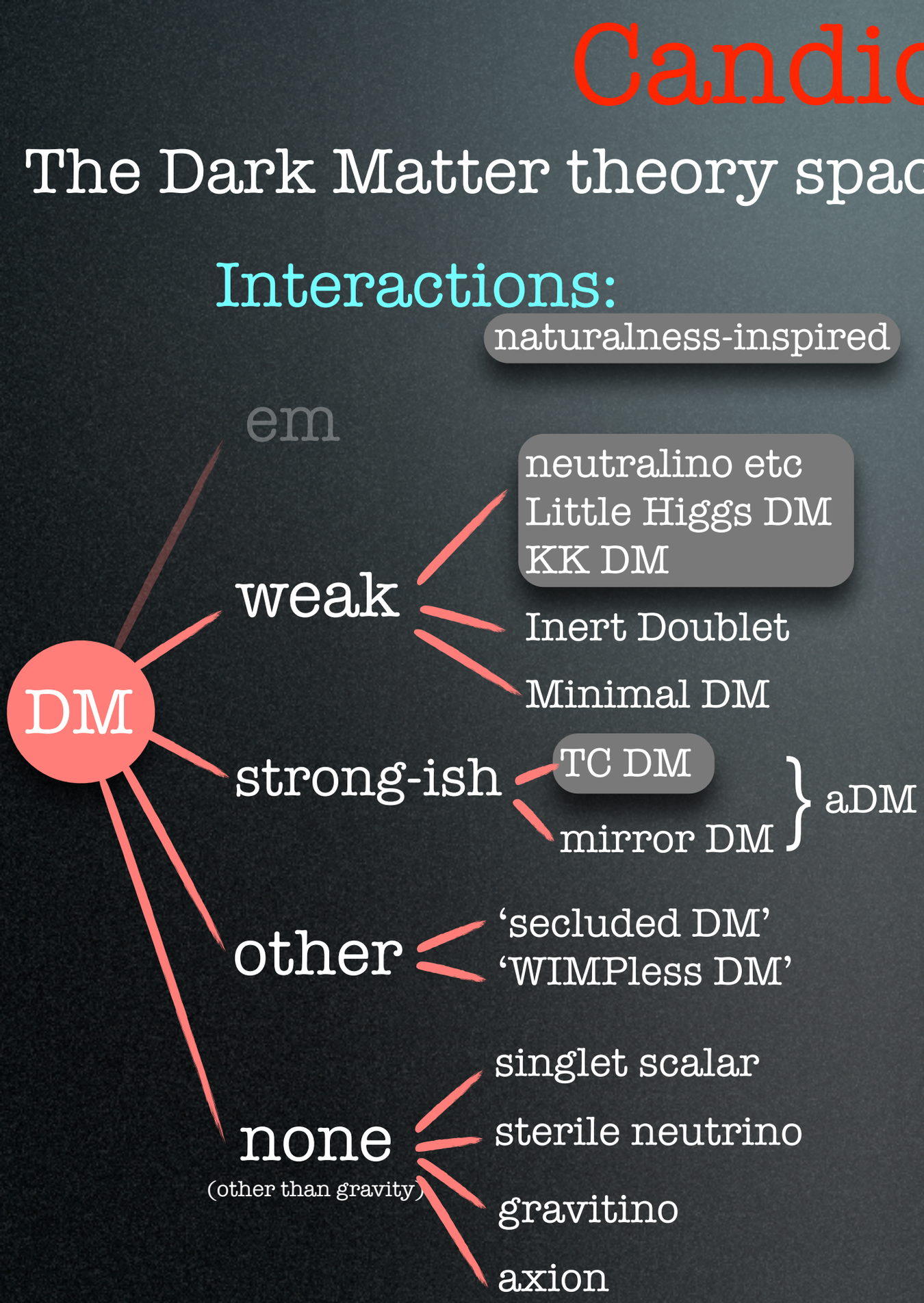
Interactions:

naturalness-inspired



Candidates

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Caveat: no categorization is perfect.

Interactions:		Production mechanism?	Stability?
em			
weak	neutralino etc (naturalness-inspired)	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
strong-ish	TC DM	‘exhaustion’ (aDM)	Tbaryon #
	mirror DM	‘exhaustion’ (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

DM

Production mechanism

Production mechanism

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

Production mechanism

Ορθοδοξία → **Έτεροδοξία** → **Αίρεση**

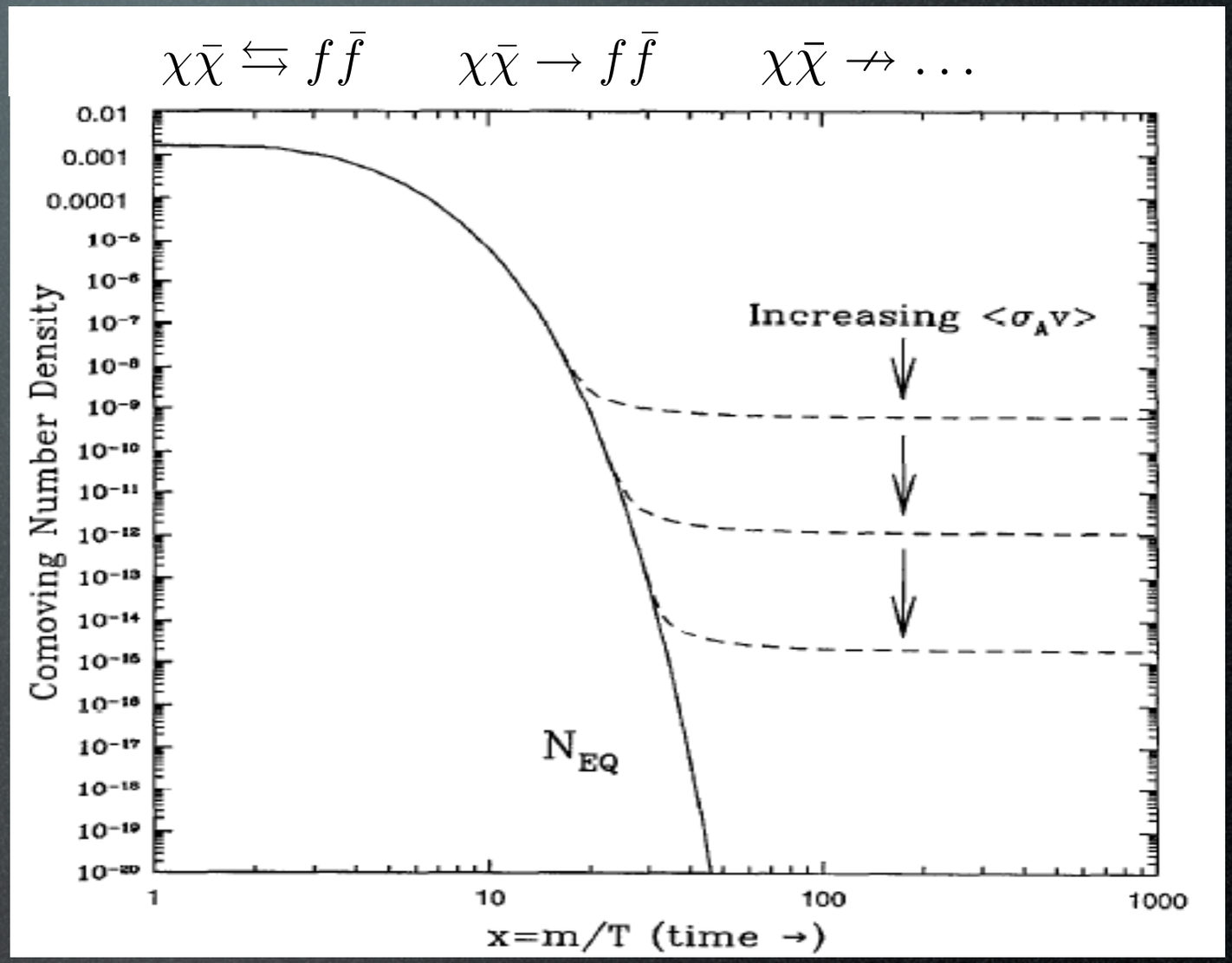
A thermal relic from the Early Universe

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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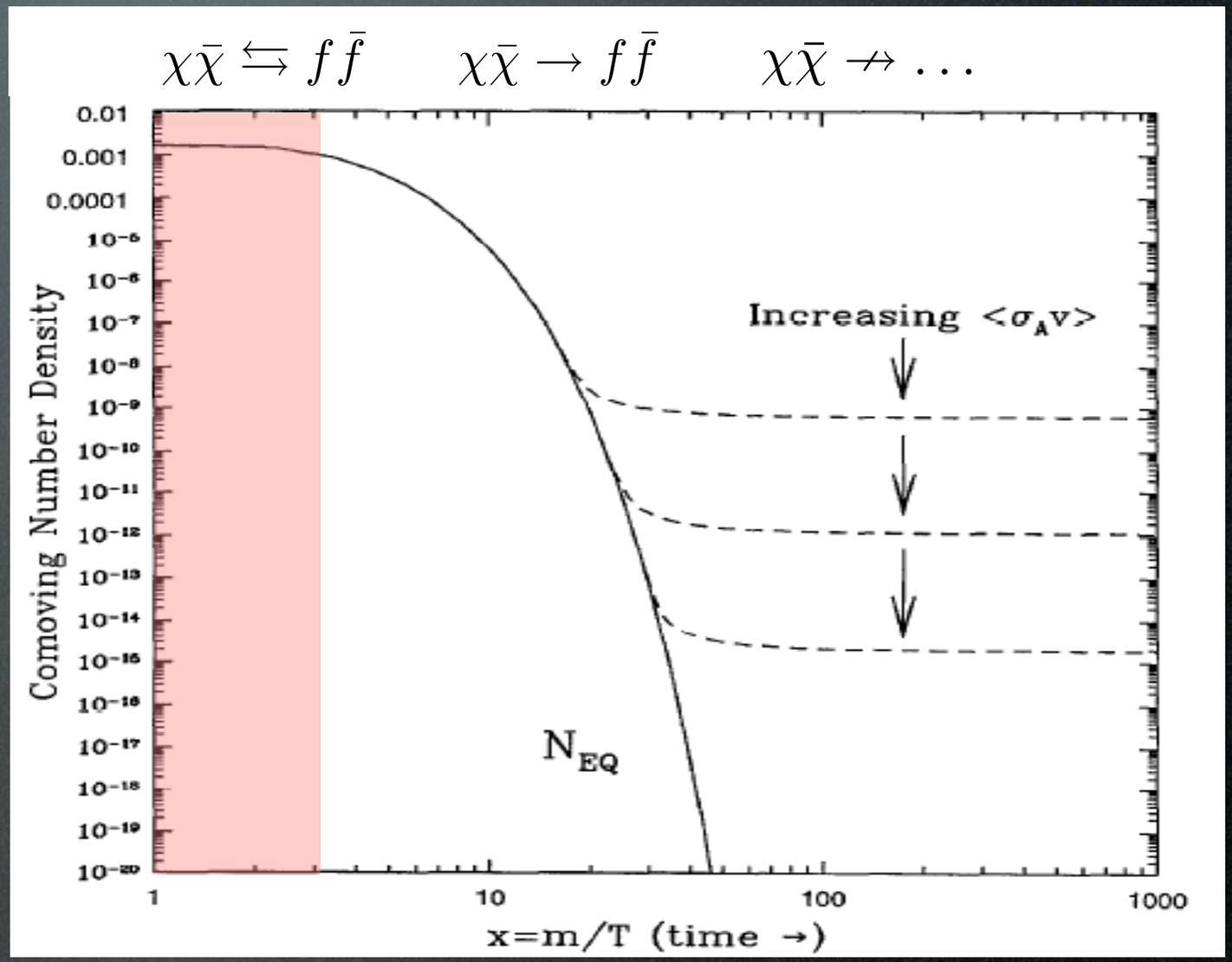

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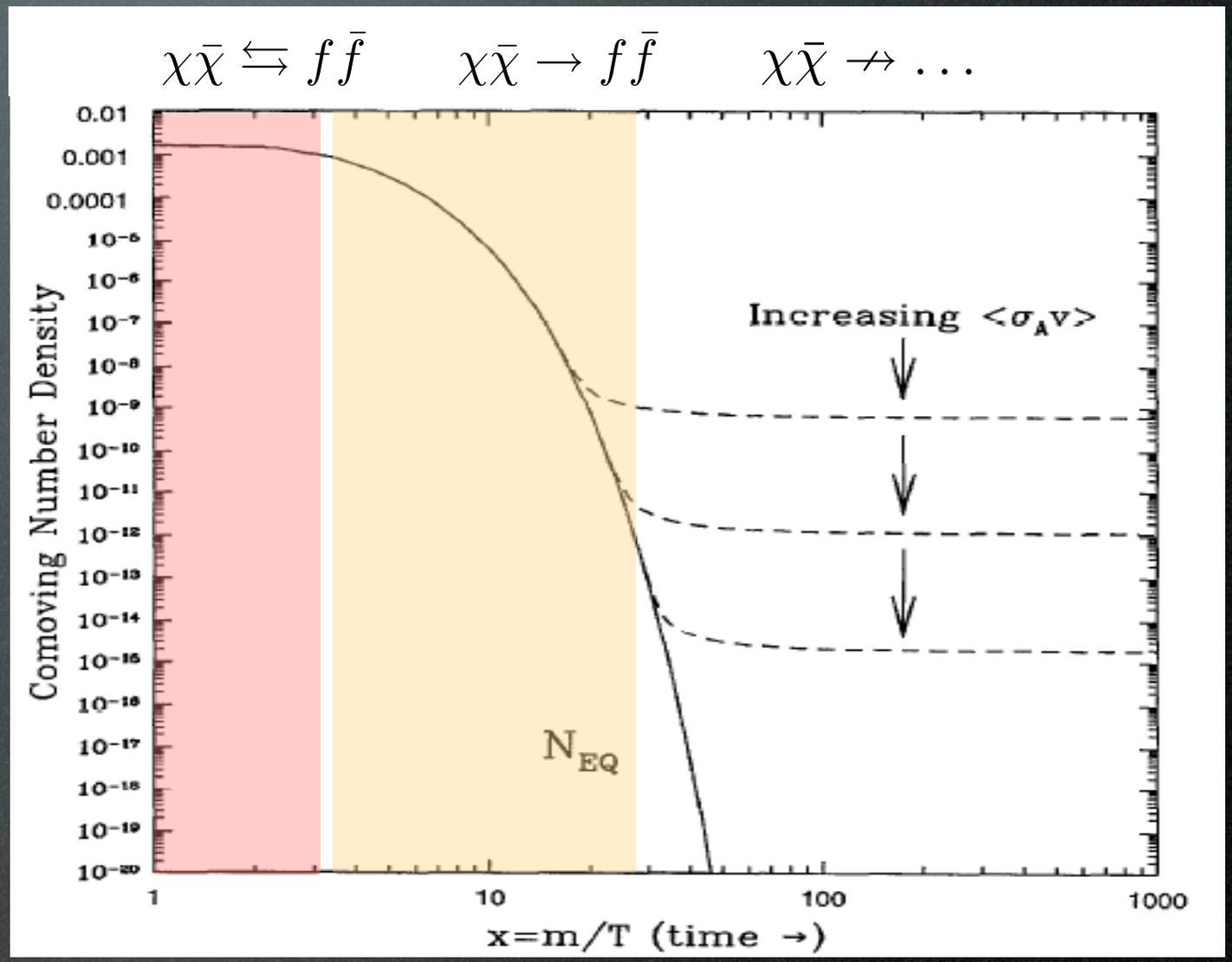

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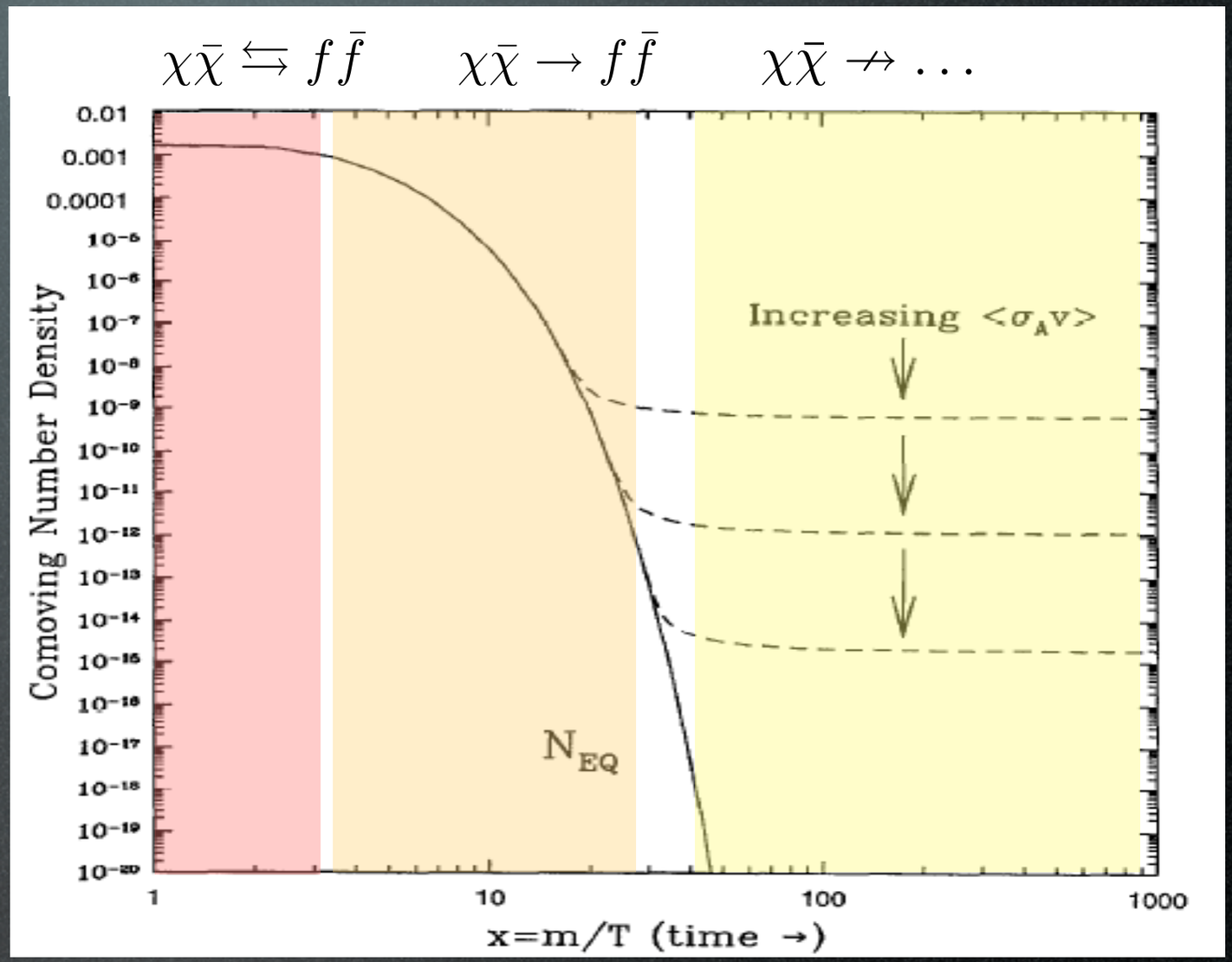

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Asymmetric DM: a completely different relic

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

Just coincidence? Or: signal of a link?

Possibly a common production mechanism:

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BBN, CMB...

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

'Darko'genesis:

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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

Asymmetric DM: a completely different relic

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

Consider a particle χ:

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

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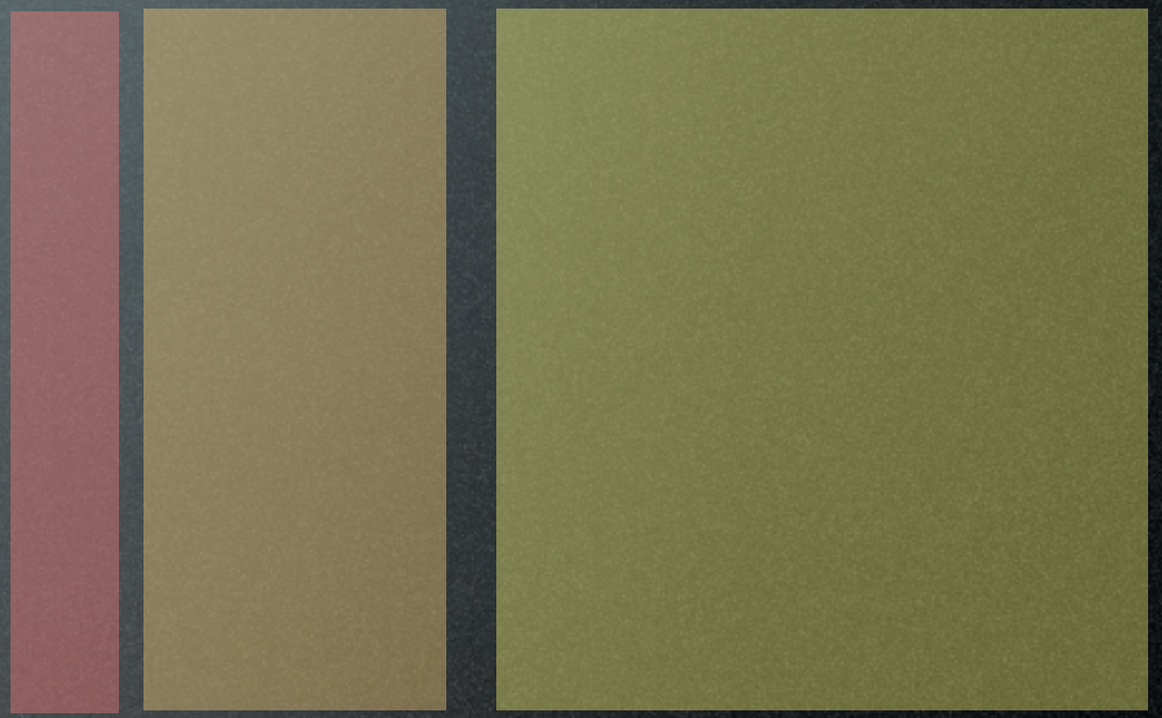


$$\Omega_{\rm X} \simeq \frac{m_{\rm X}\, s}{\rho_{\rm crit}} \eta_0$$

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

Freeze-in:
like rodents in the paleocene

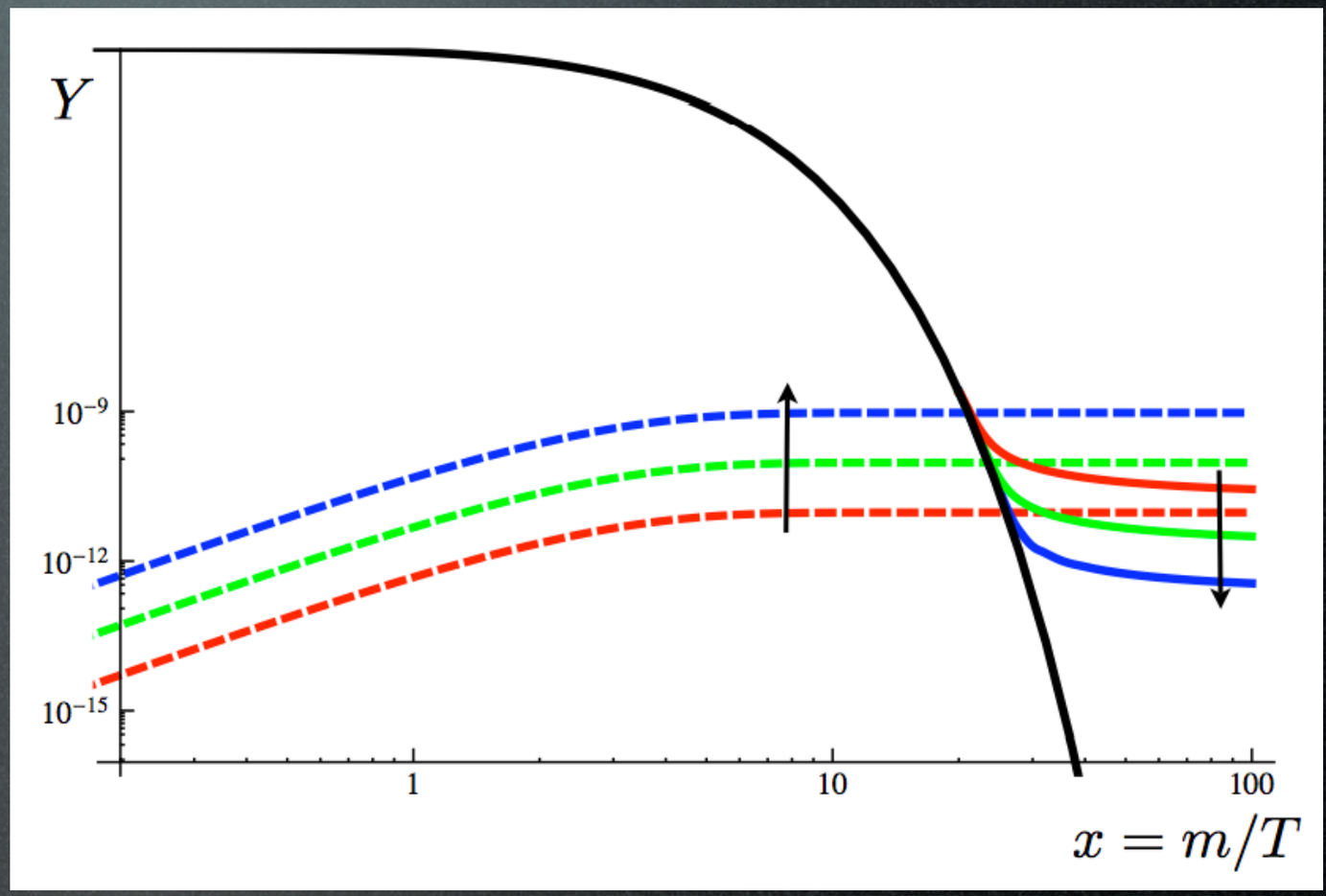
Hall, Jedamzik, March-Russell, West 2009

Freeze-in: like rodents in the paleocene

Hall, Jedamzik, March-Russell, West 2009

Consider a particle χ:

- 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



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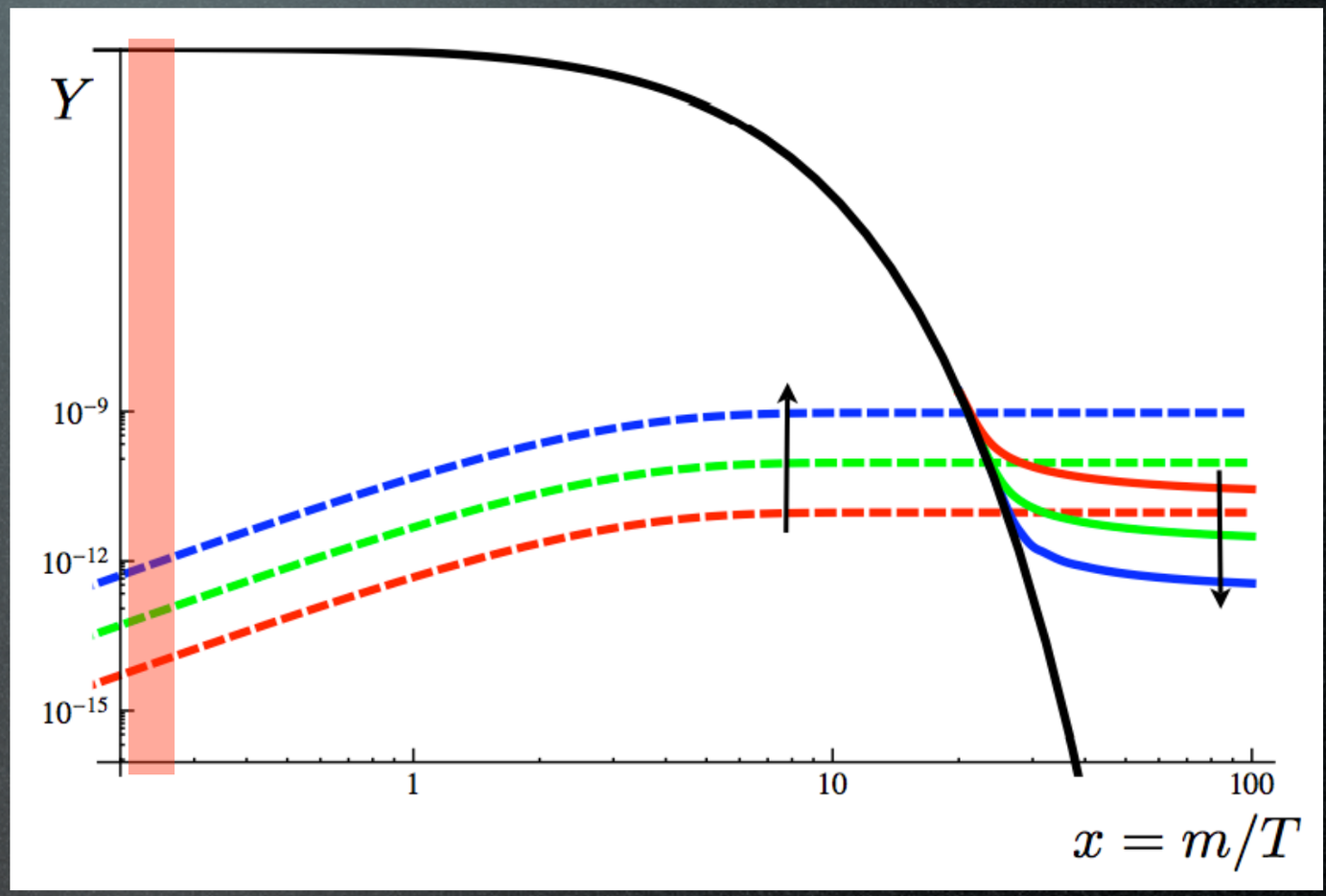
- subject to $f\bar{f} \to \chi, \chi\bar{\chi}$ with a very small rate
- 'heavy' (e.g. 100 GeV)
- 'stable'
- in an expanding Universe
- zero initial abundance



Freeze-in: like rodents in the paleocene

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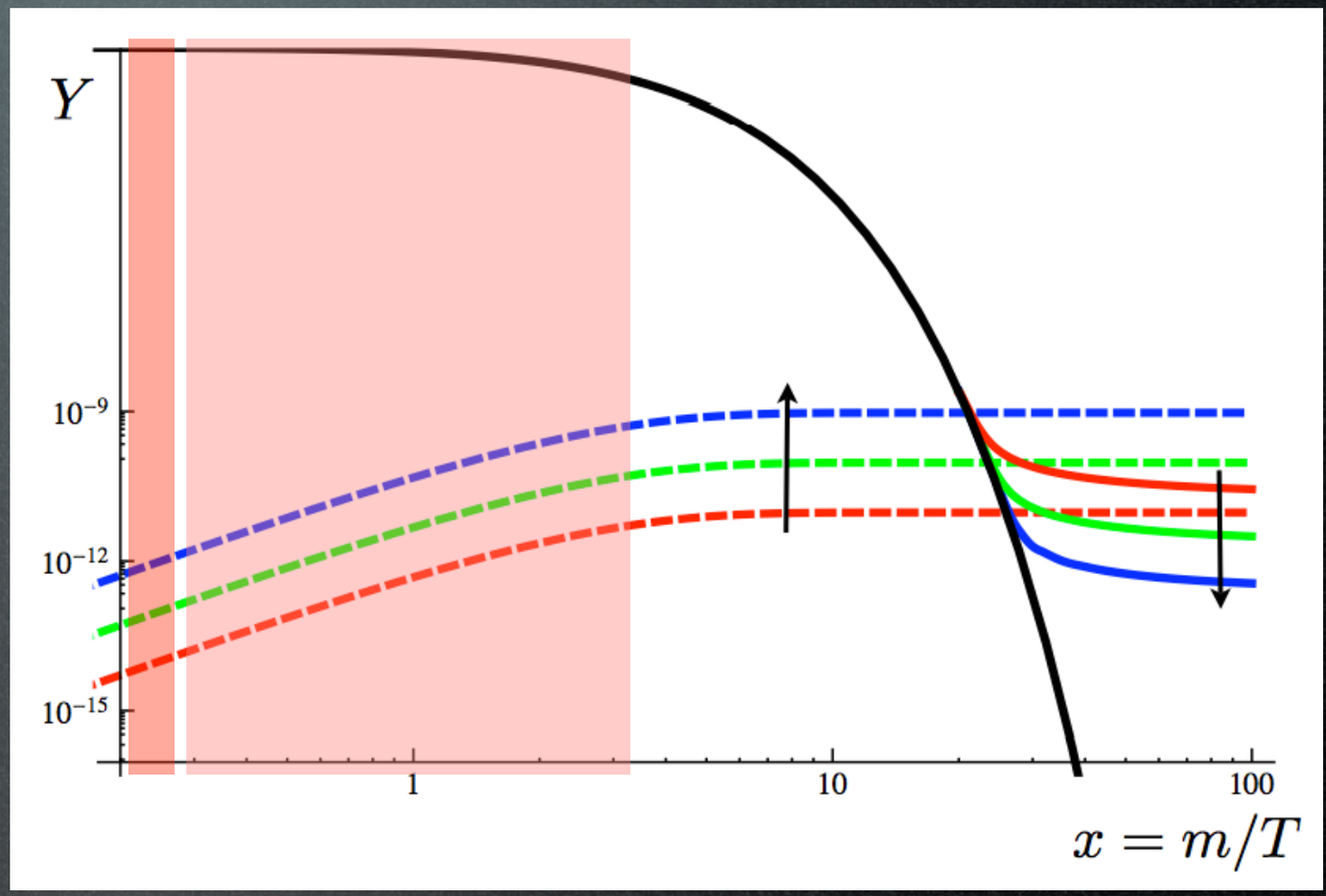

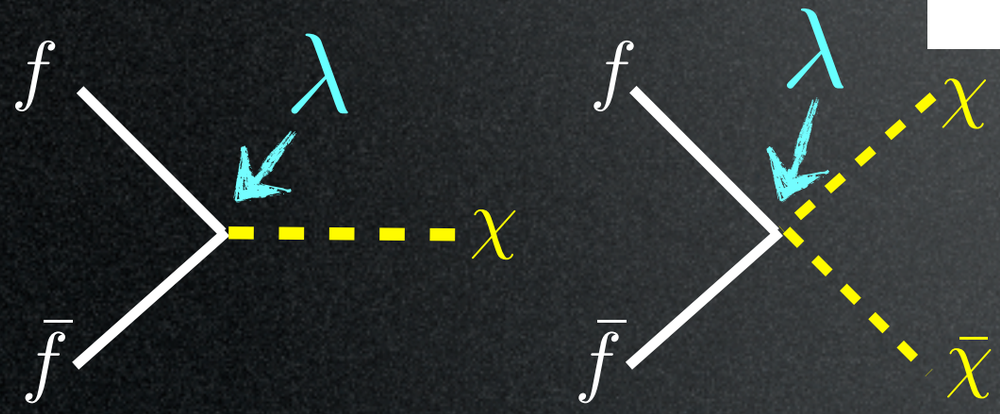

$\lambda \sim 10^{-12}$

very slowly but steadily produced

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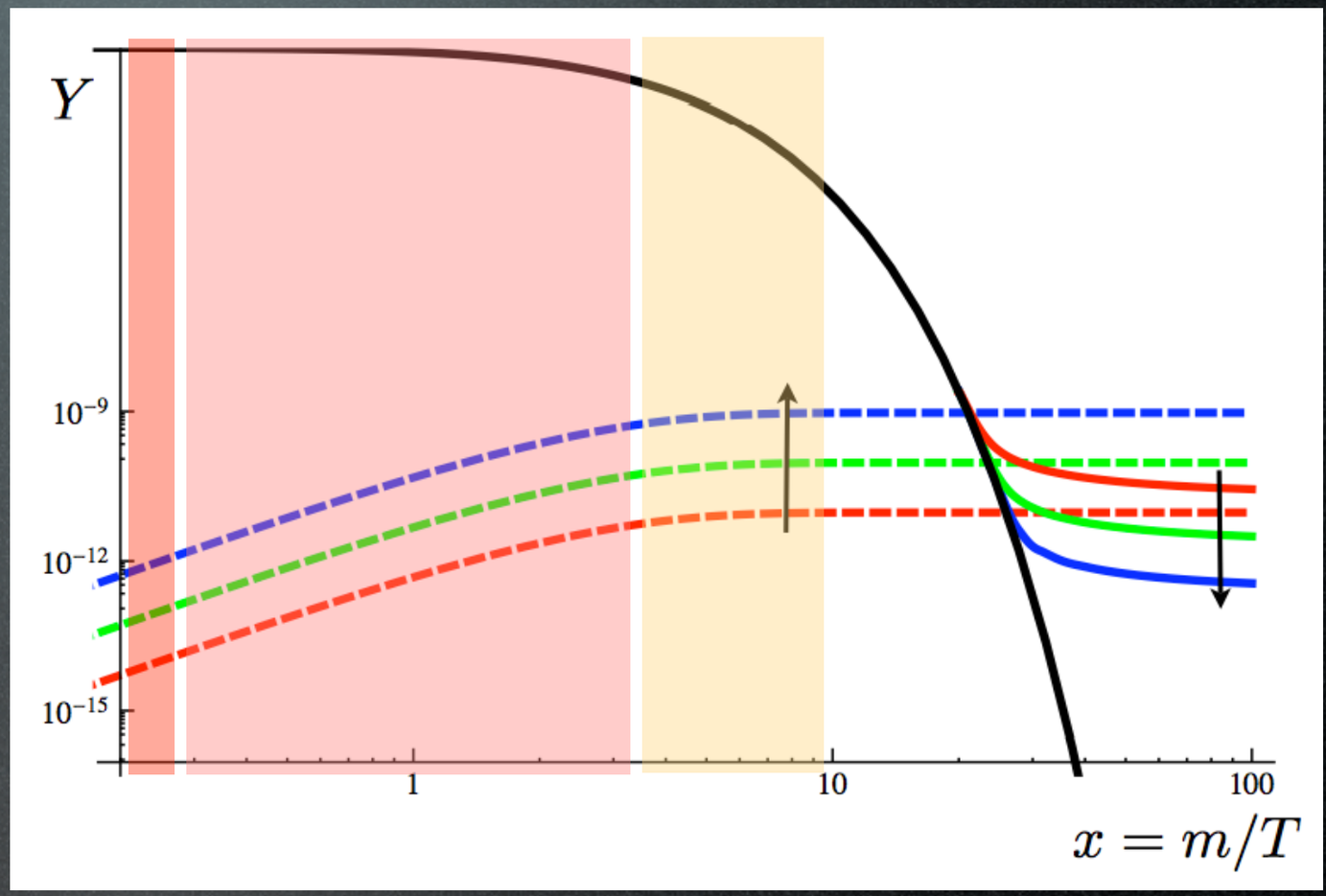

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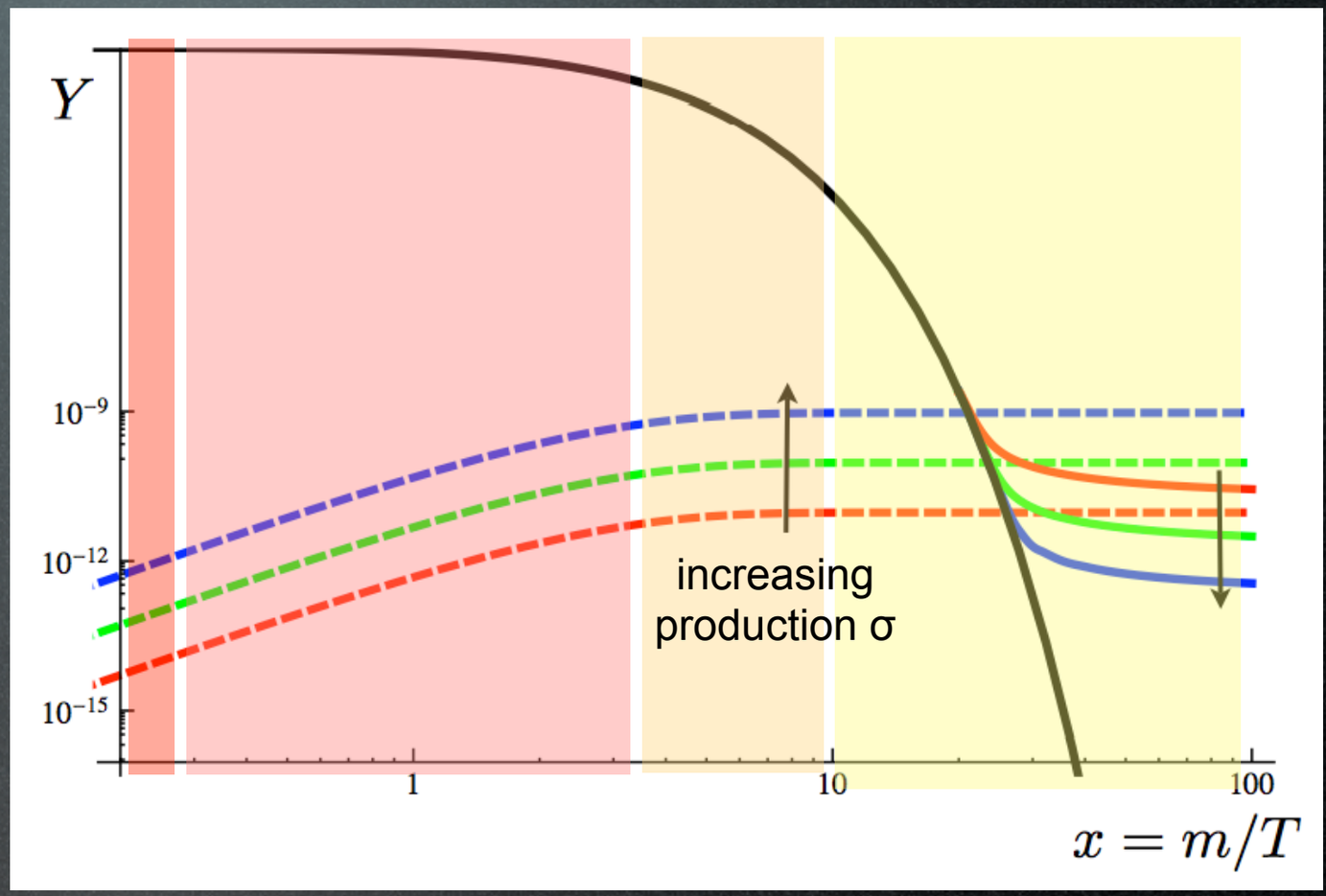
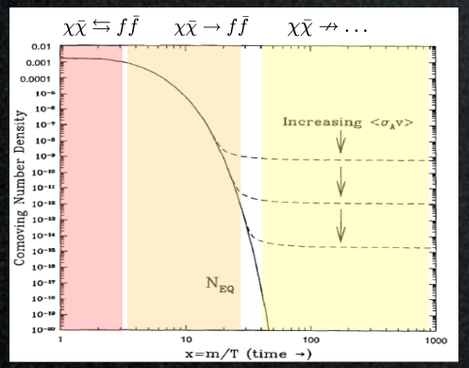
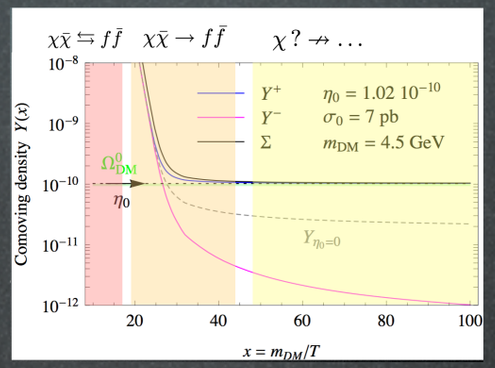


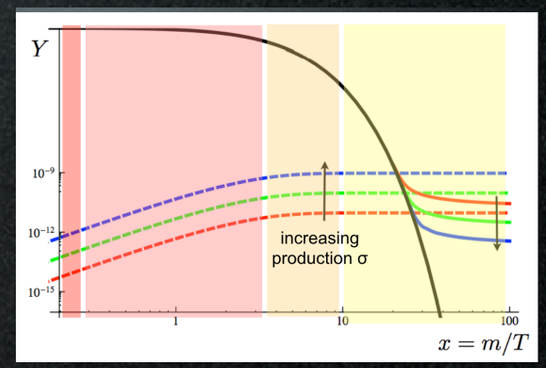
The final abundance is determined by σ (or rather λ).

Production mechanism

Ορθοδοξία → **Έτεροδοξία** → **Αίρεση**







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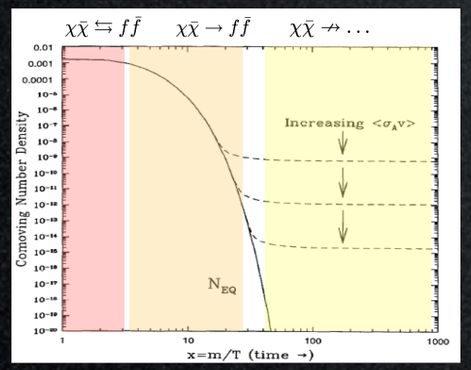

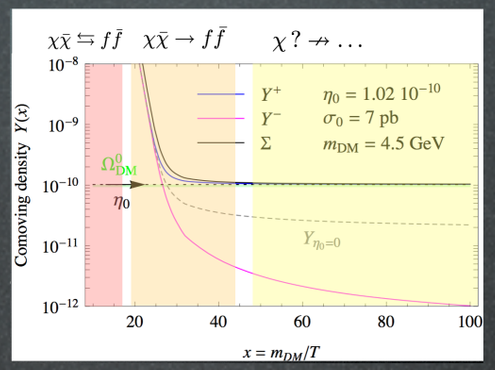

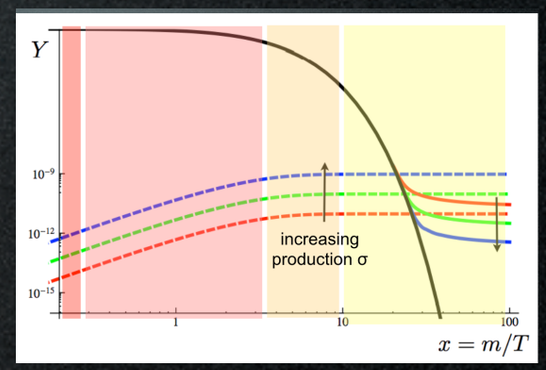

Other possibilities: mixing/oscillations,
misalignment,
…

Interactions

Ορθοδοξία → **Έτεροδοξία** → **Αίρεση**

Interactions

Ορθοδοξία → **Έτεροδοξία** → **Αίρεση**

WIMPs: μη αλληλεπιδρούσα

αυτοαλληλεπιδρούσα σκοτεινή ύλη

WIMPs: αυτοαλληλεπιδρούσα σκοτεινή ύλη

Credit: **Kallia Petraki**
(both the physics and the greek)

WIMPs are effectively collisionless

"bullet cluster" - NASA
astro-ph/0608247

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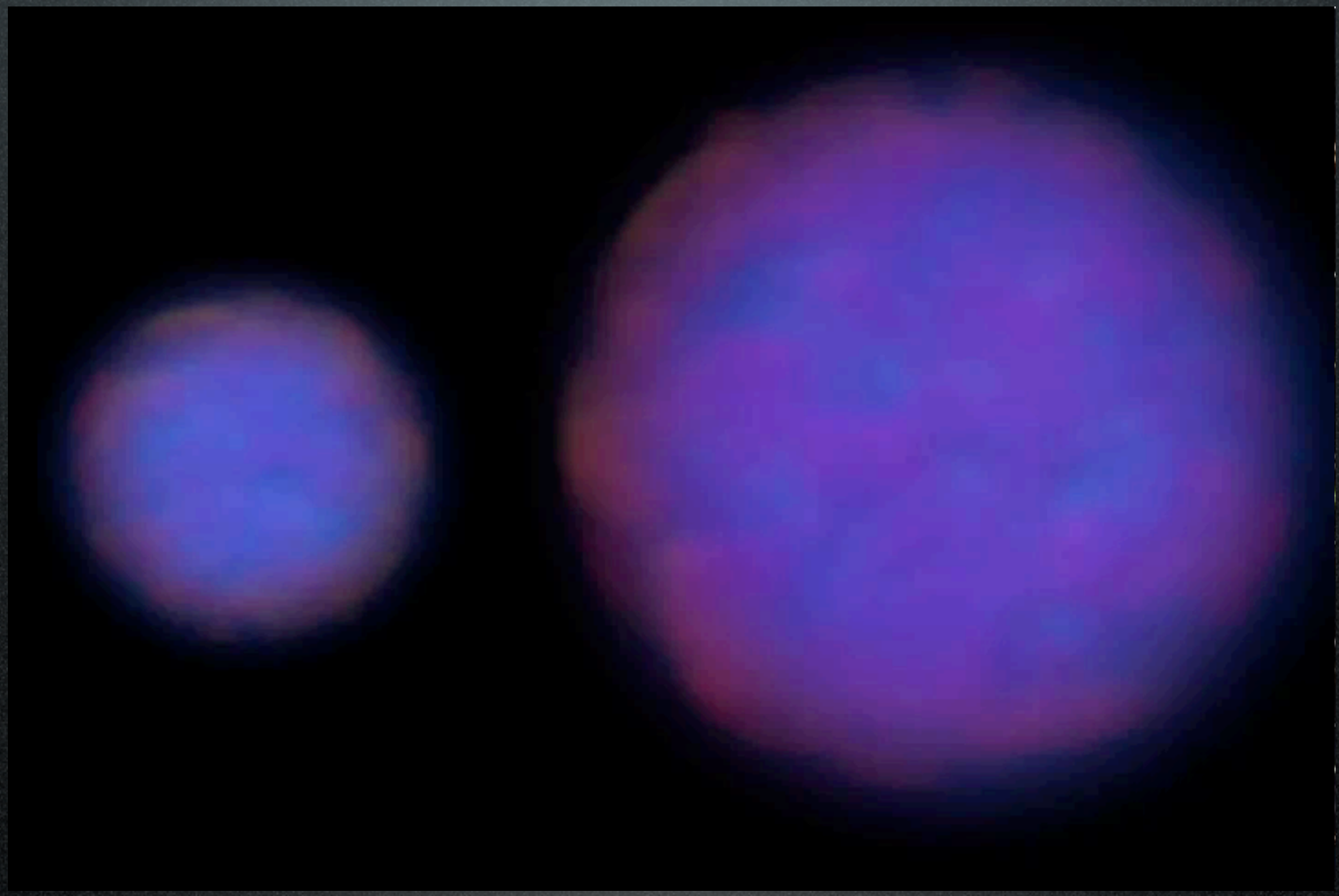

chandra.harvard.edu

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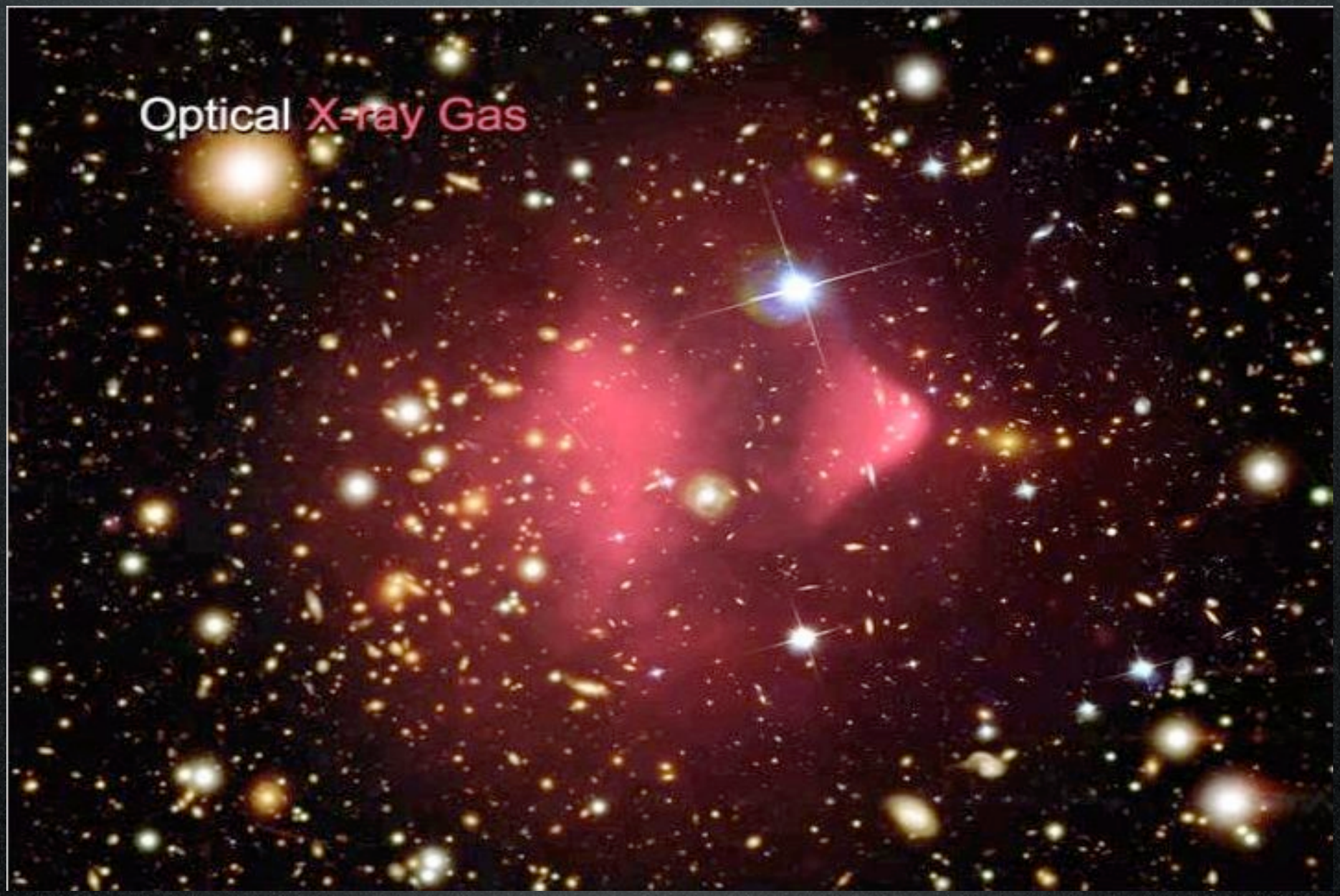

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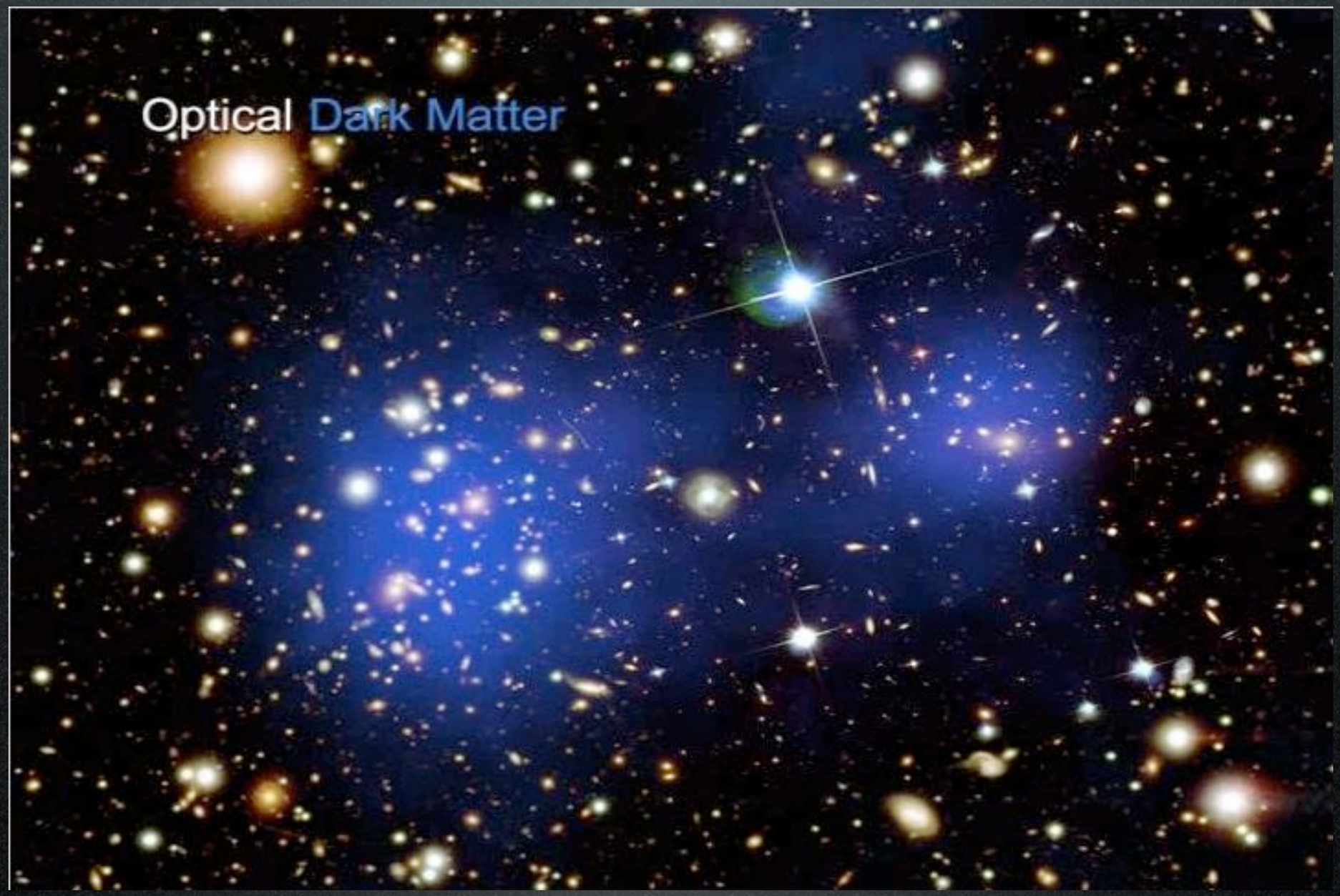

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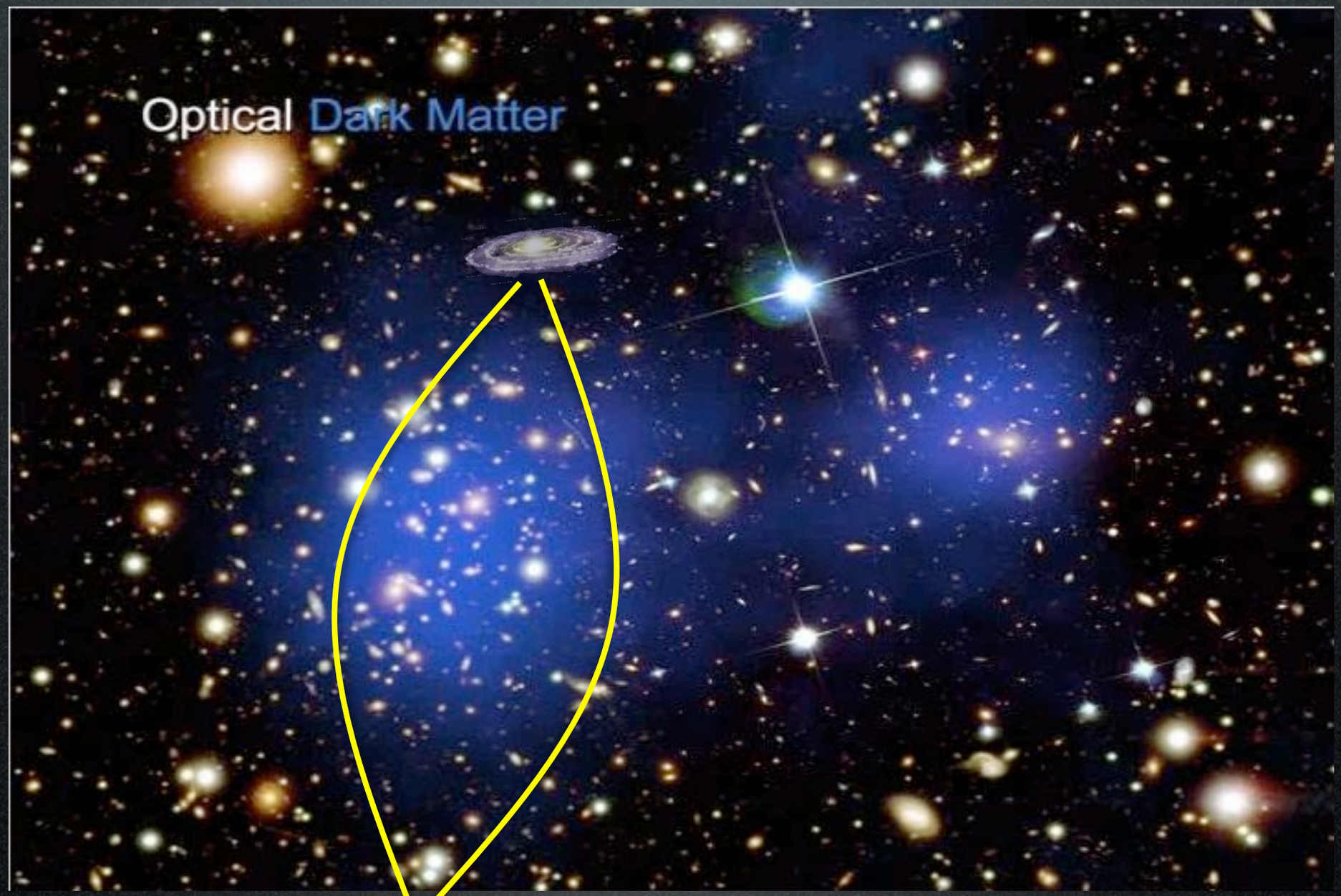

weak lensing

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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

WIMPs are effectively collisionless

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Harvey et al., 1503.07675

but there are also actually indications of possible positive detection!
(e.g. Harvey et al., MNRAS 1504.03388)
(σ/m = 3 barn/GeV)

Dark interactions for DM

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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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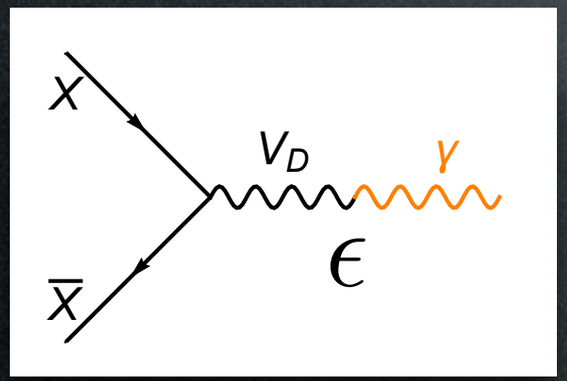

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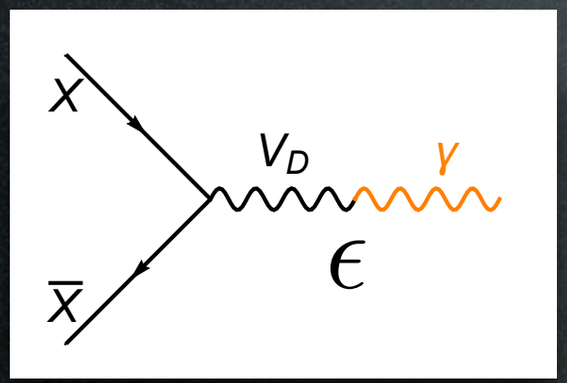

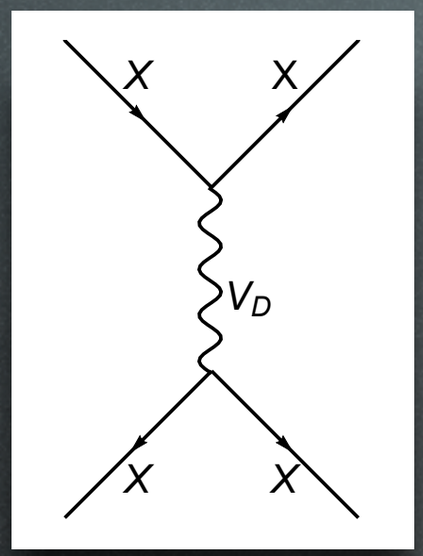

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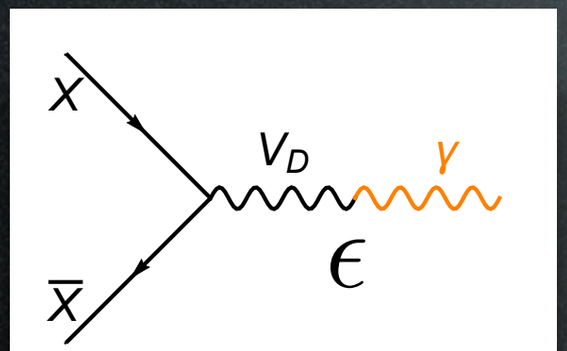

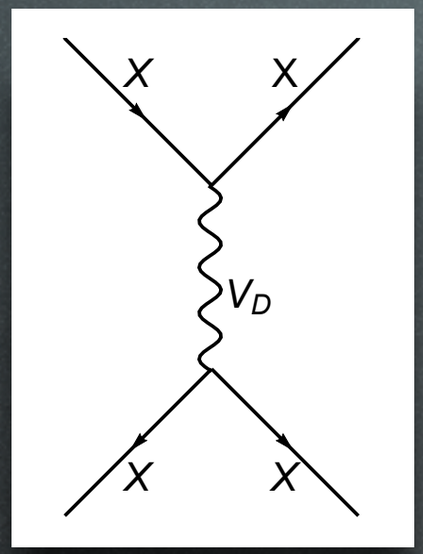

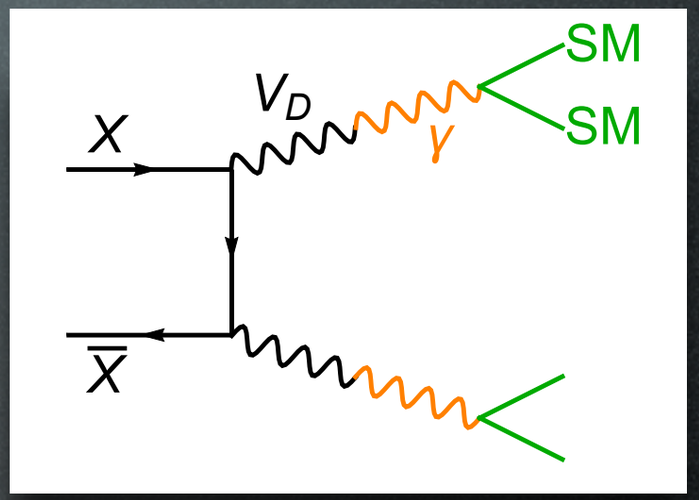

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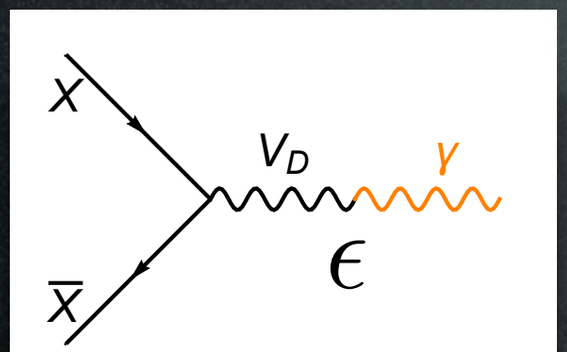

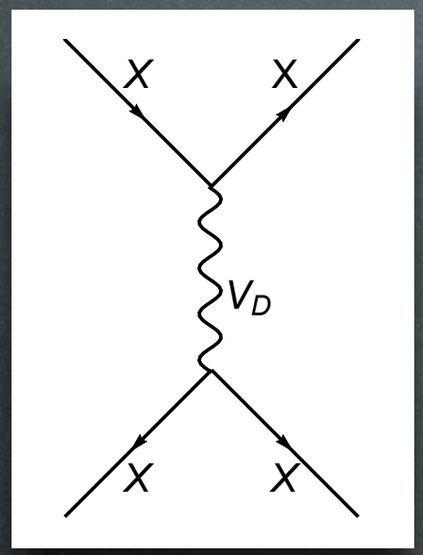

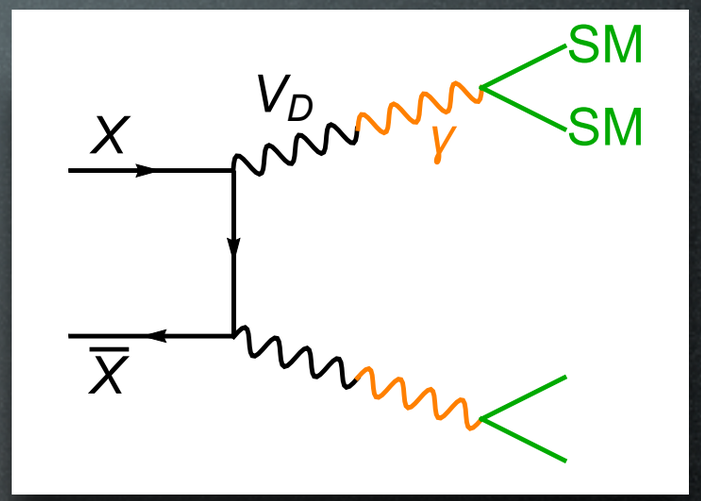

size of the XX system

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

range

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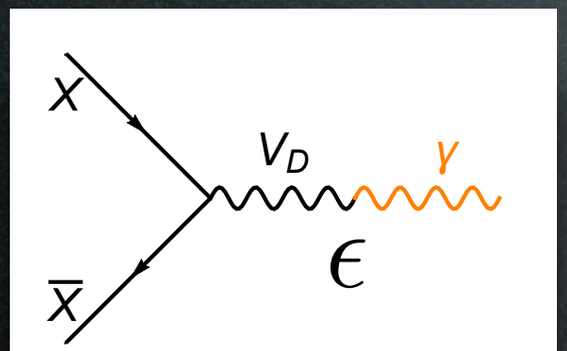

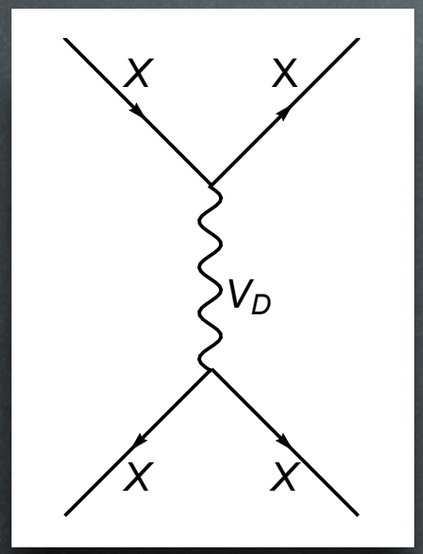

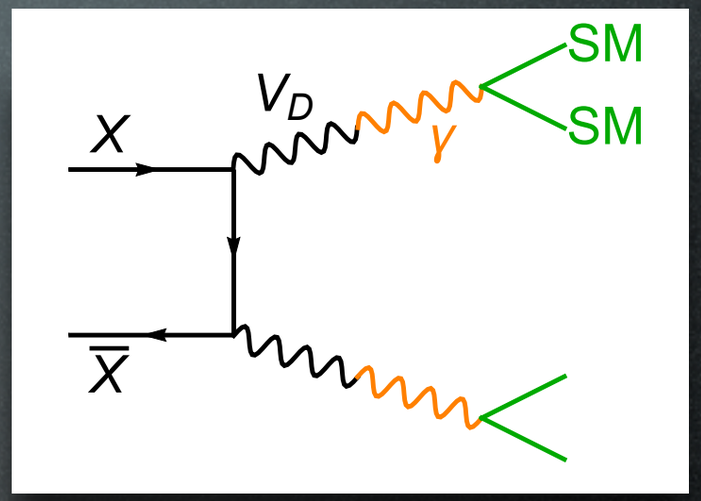

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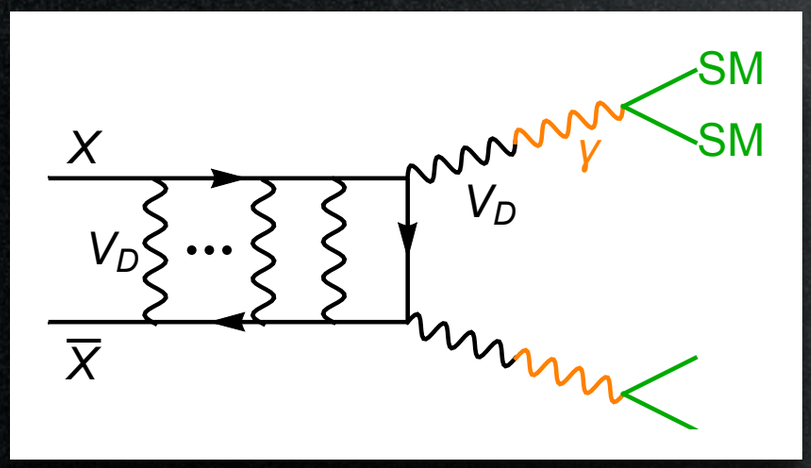

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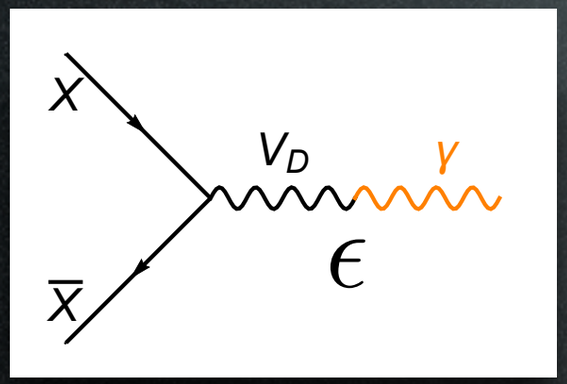

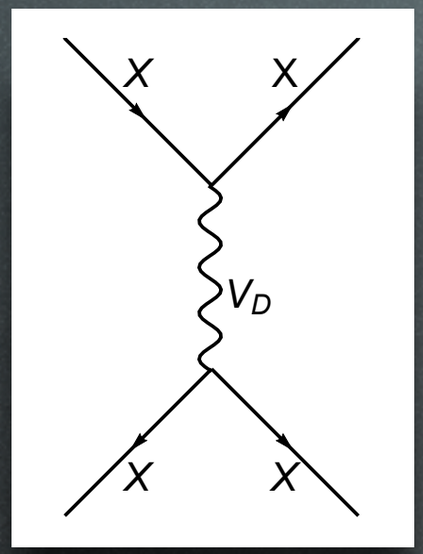

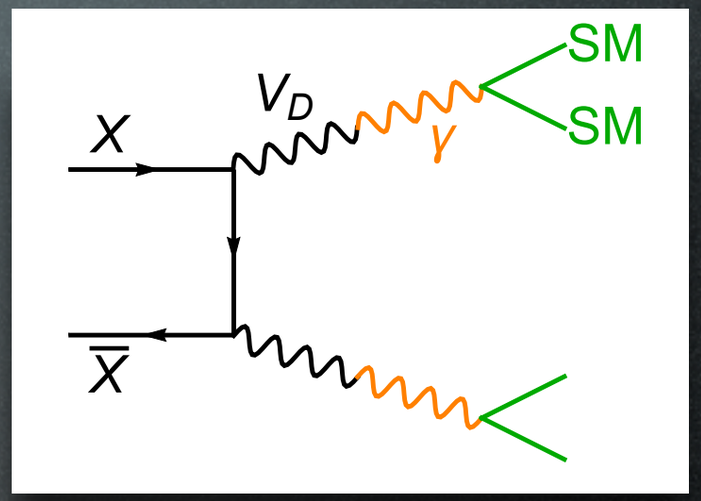

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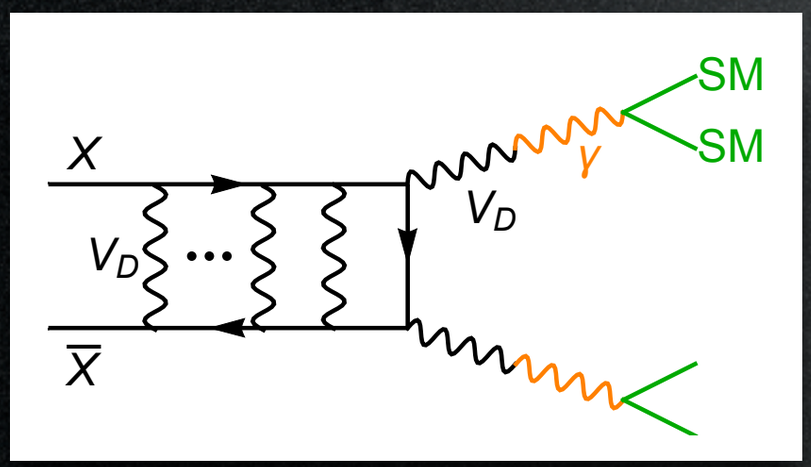
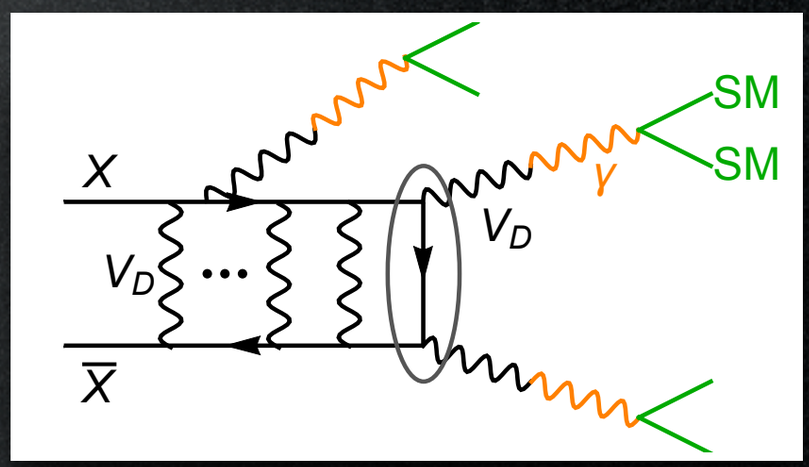
emitted dark photon



Petraki+ 2015+
An+ 1604.01776
etc



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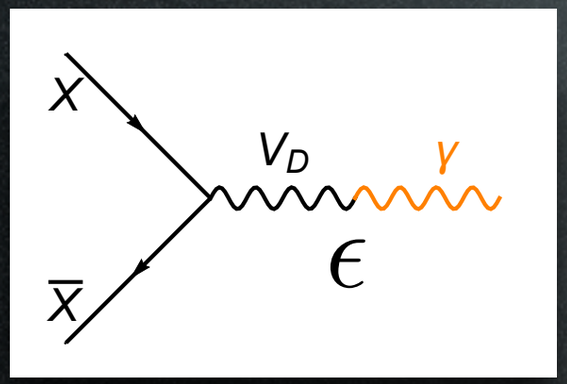

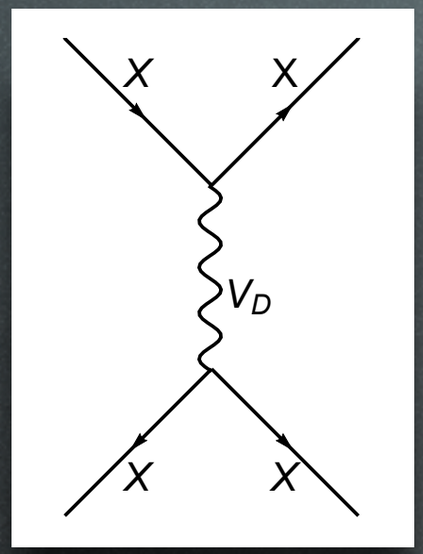

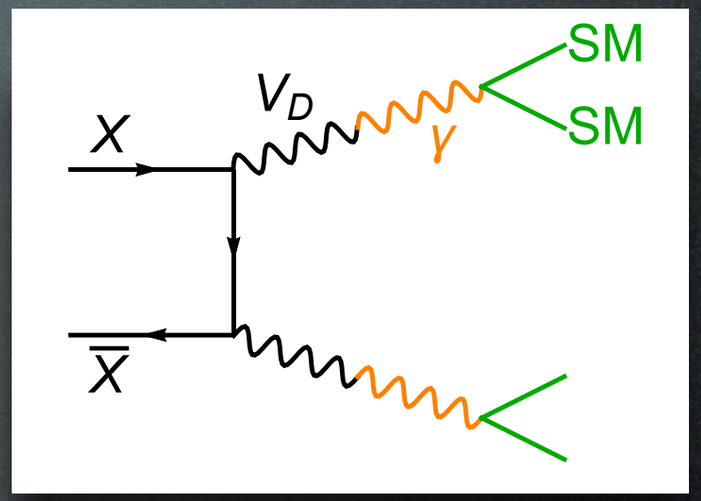

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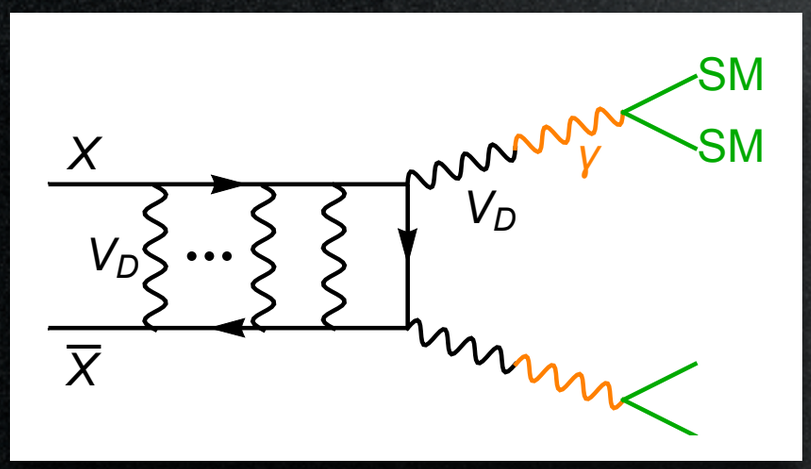

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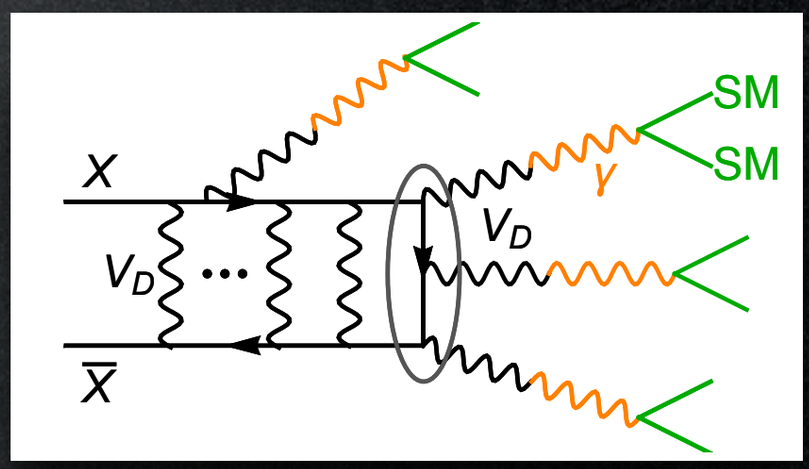

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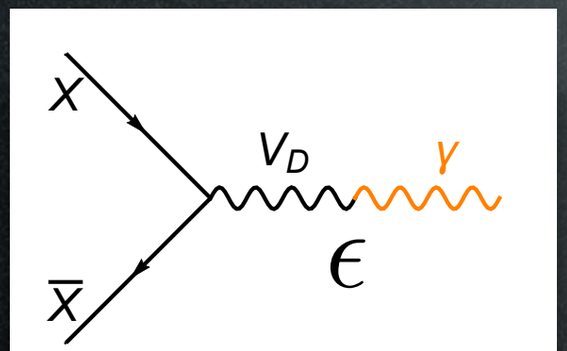

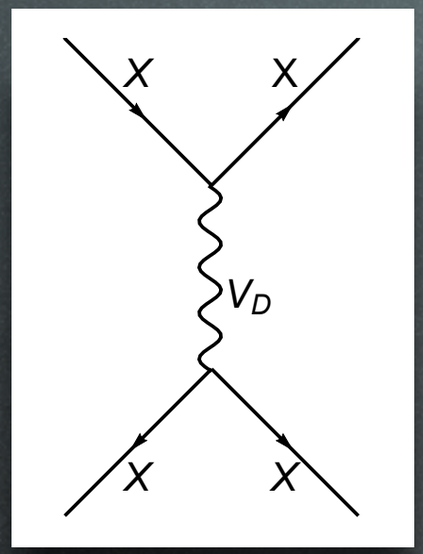

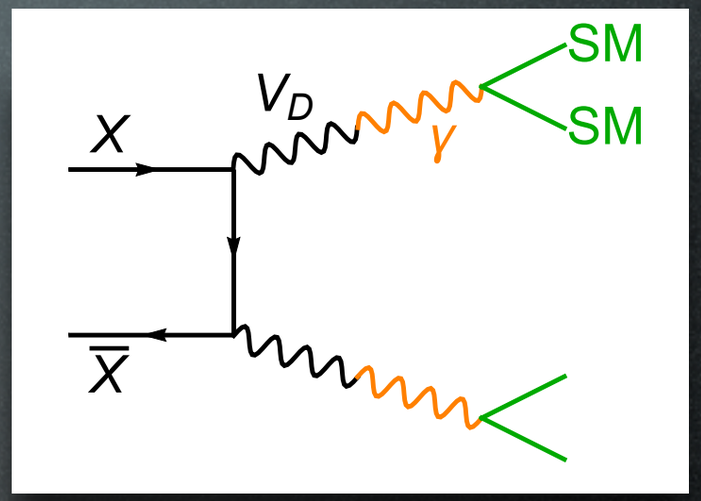

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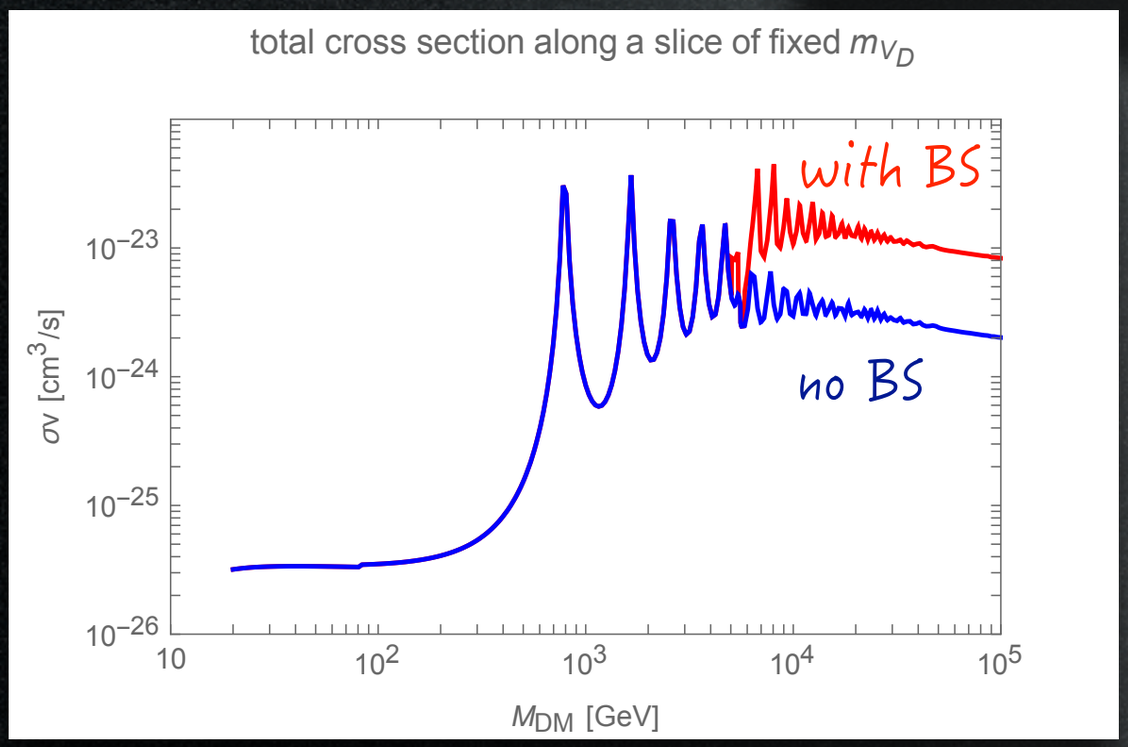

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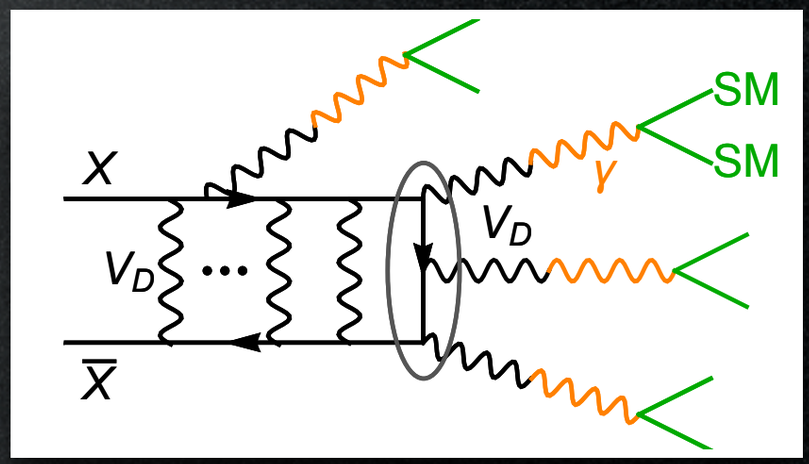
Cirelli, Panci, Petraki,
Sala, Taoso 1612.07295

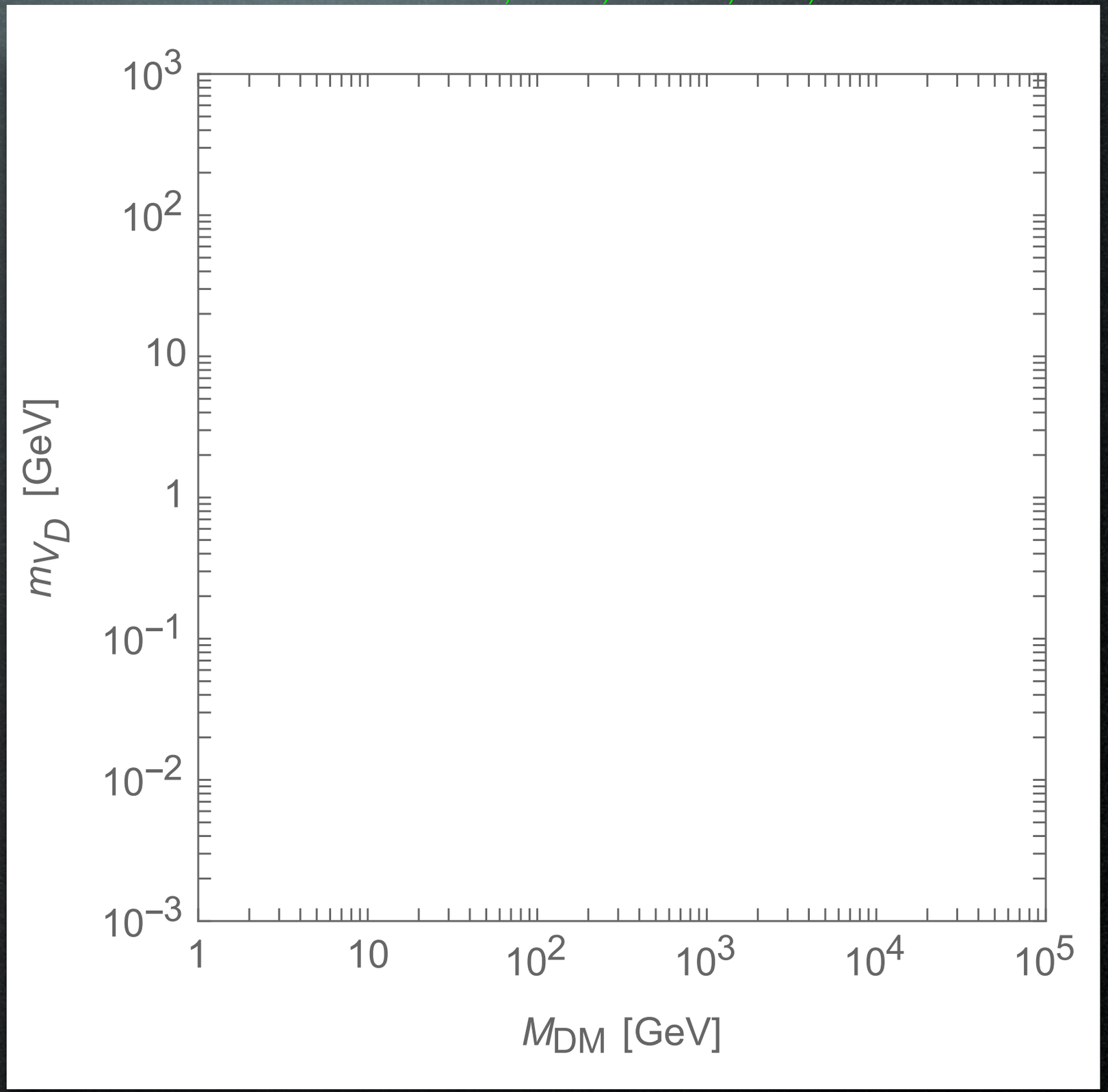


Phenomenology

Phenomenology

Setting the stage

Cirelli, Panci, Petraki, Sala, Taoso 1612.07295

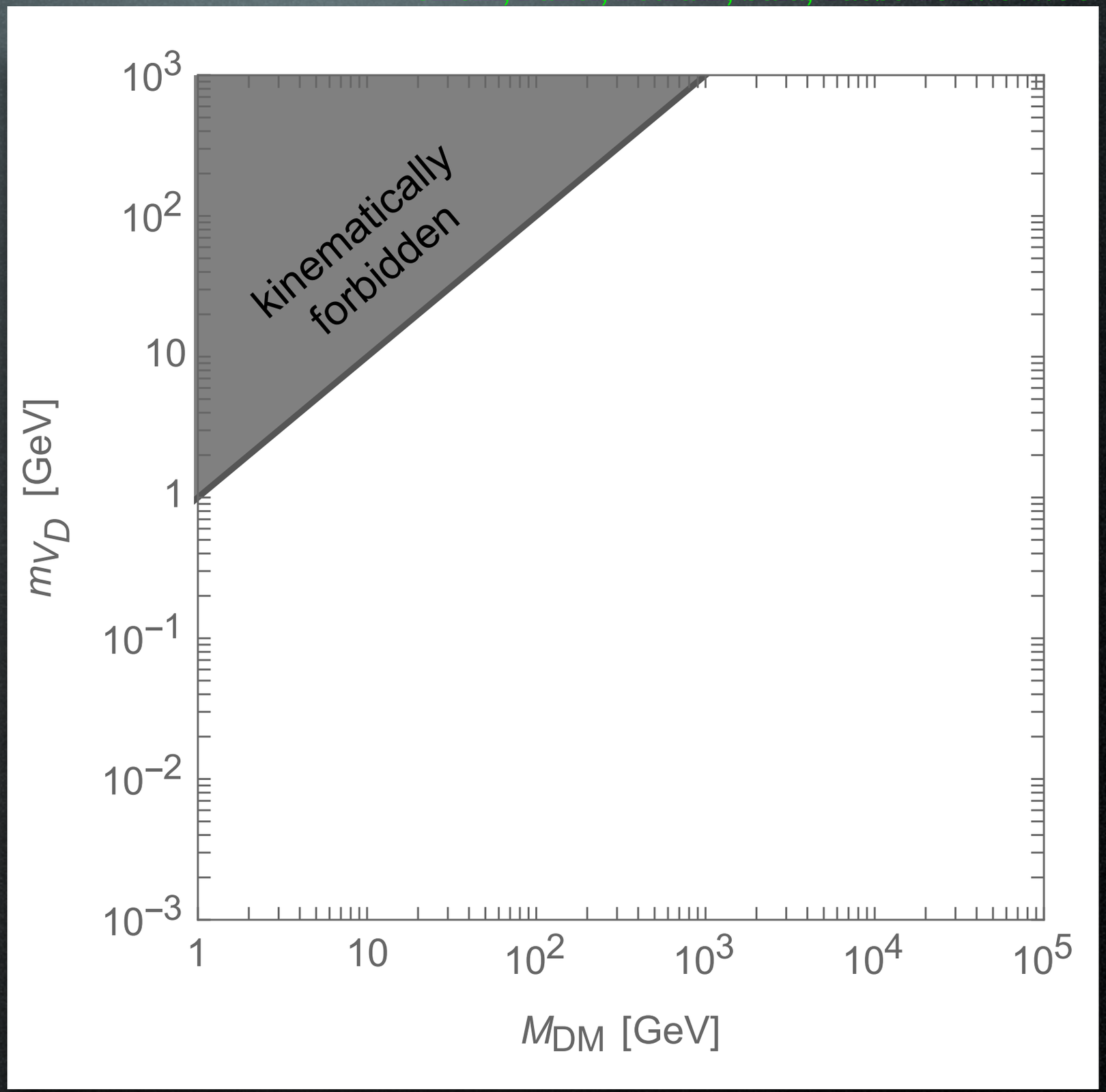


Phenomenology

Setting the stage

α_D fixed by
relic abundance

Cirelli, Panci, Petraki, Sala, Taoso 1612.07295



Phenomenology

Setting the stage

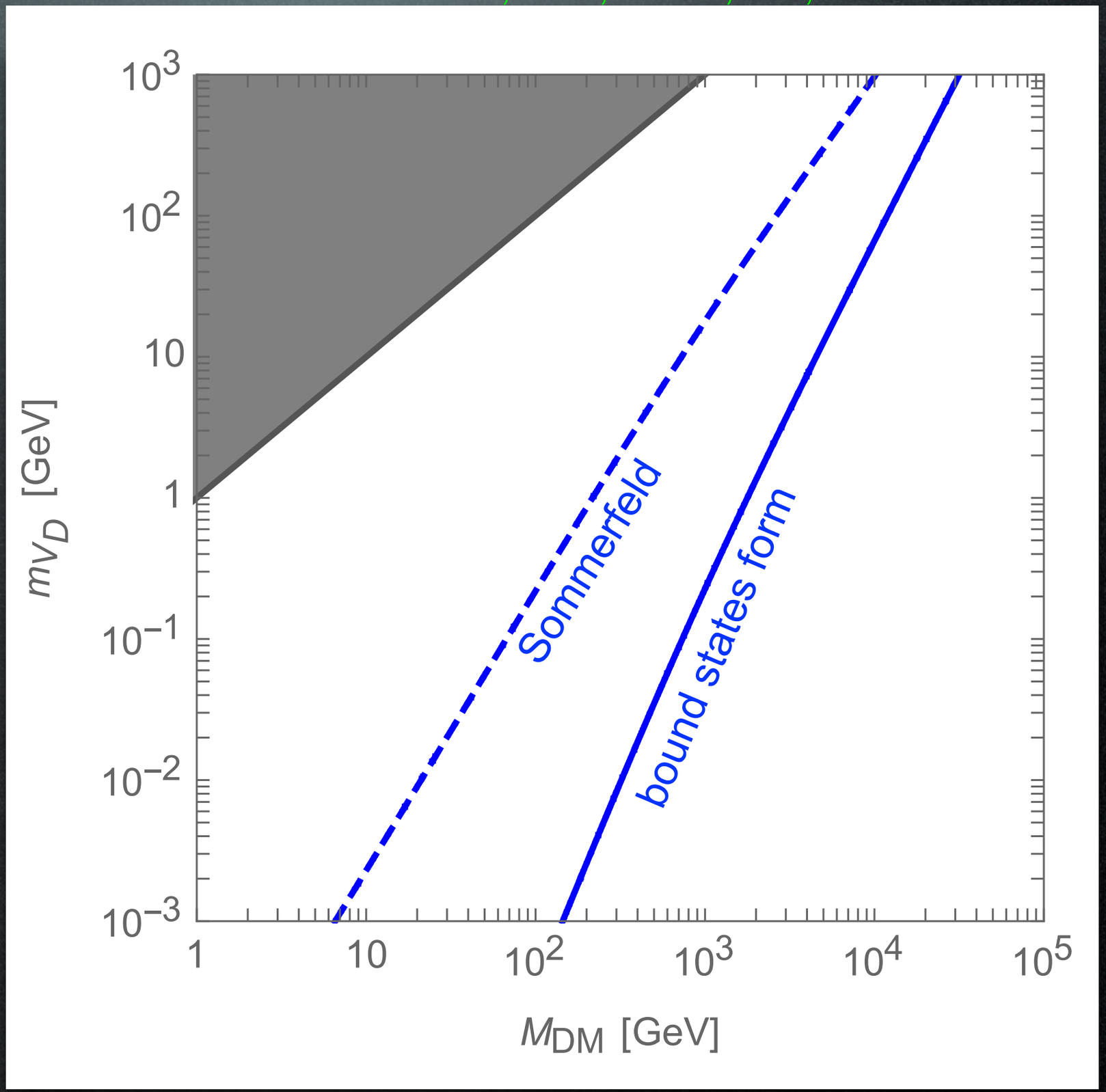
Sommerfeld

$$\alpha M/2m_V \gtrsim 1$$

bound states form

$$\alpha^2 M/4m_V \gtrsim 1$$

Cirelli, Panci, Petraki, Sala, Taoso 1612.07295



Phenomenology

Setting the stage

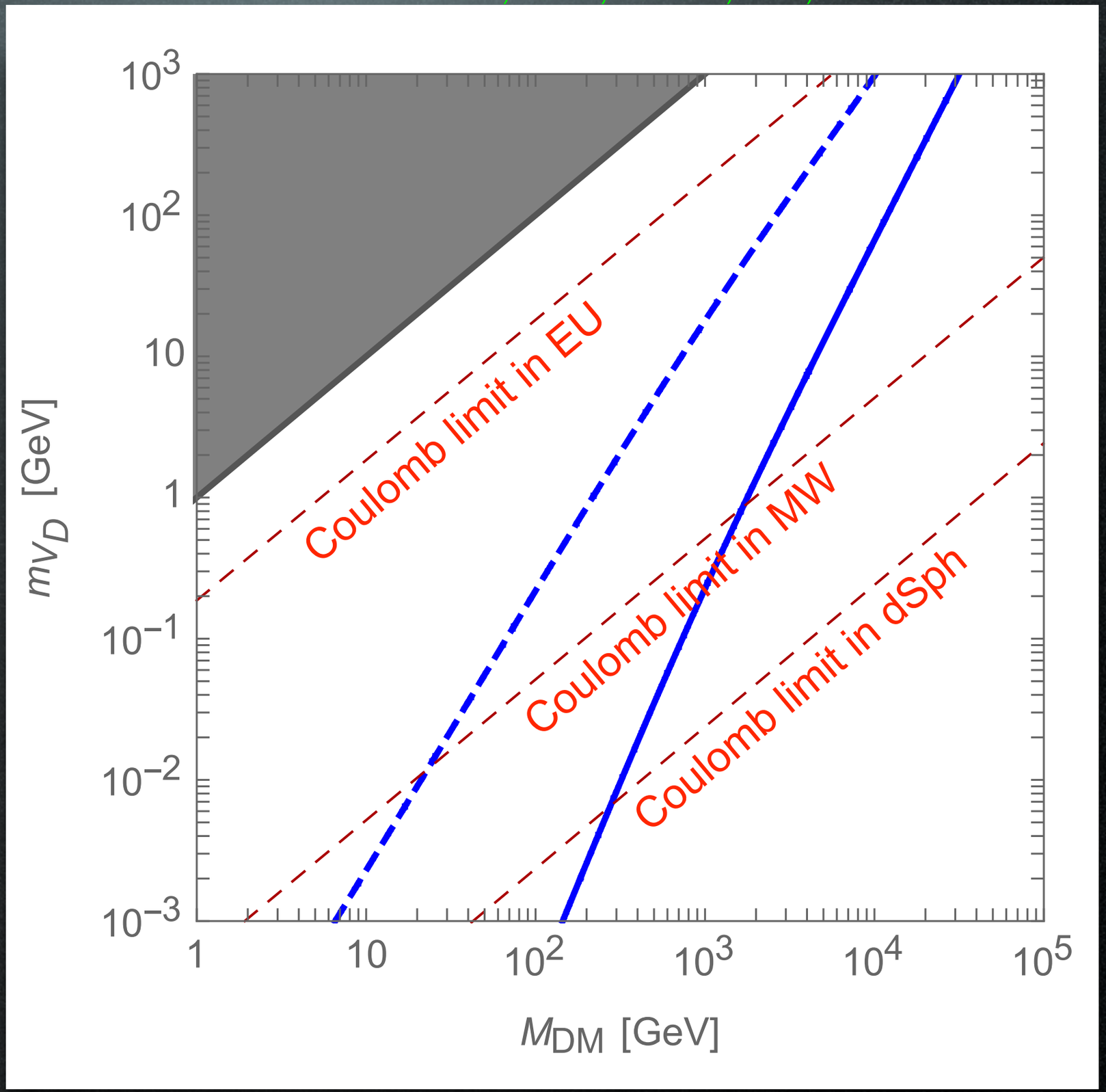
Coulomb limit

$$\frac{M\, v_{\rm rel}}{2} \gtrsim m_V$$

transferred momentum

mediator mass

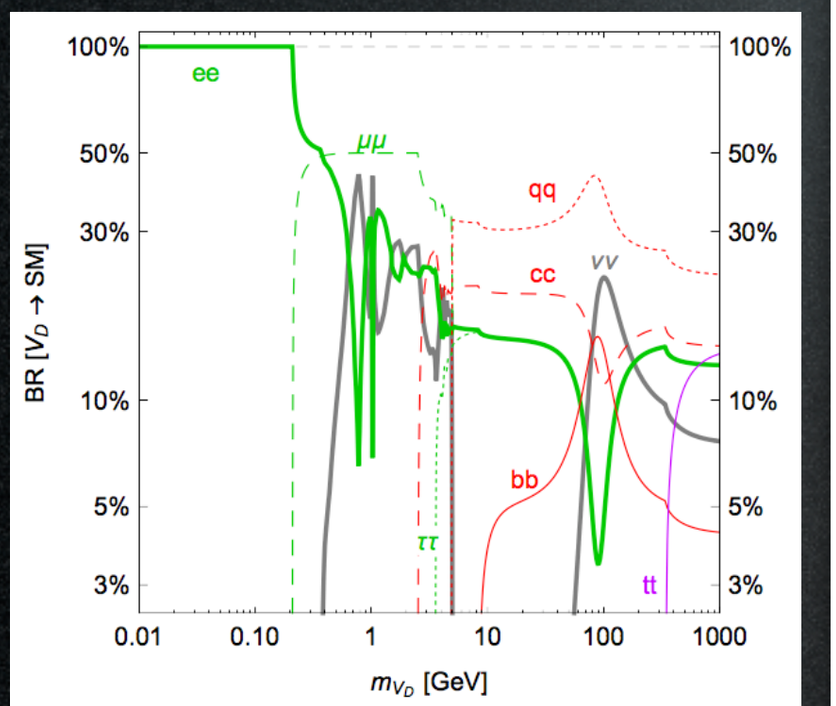
Cirelli, Panci, Petraki, Sala, Taoso 1612.07295



Phenomenology

Setting the stage

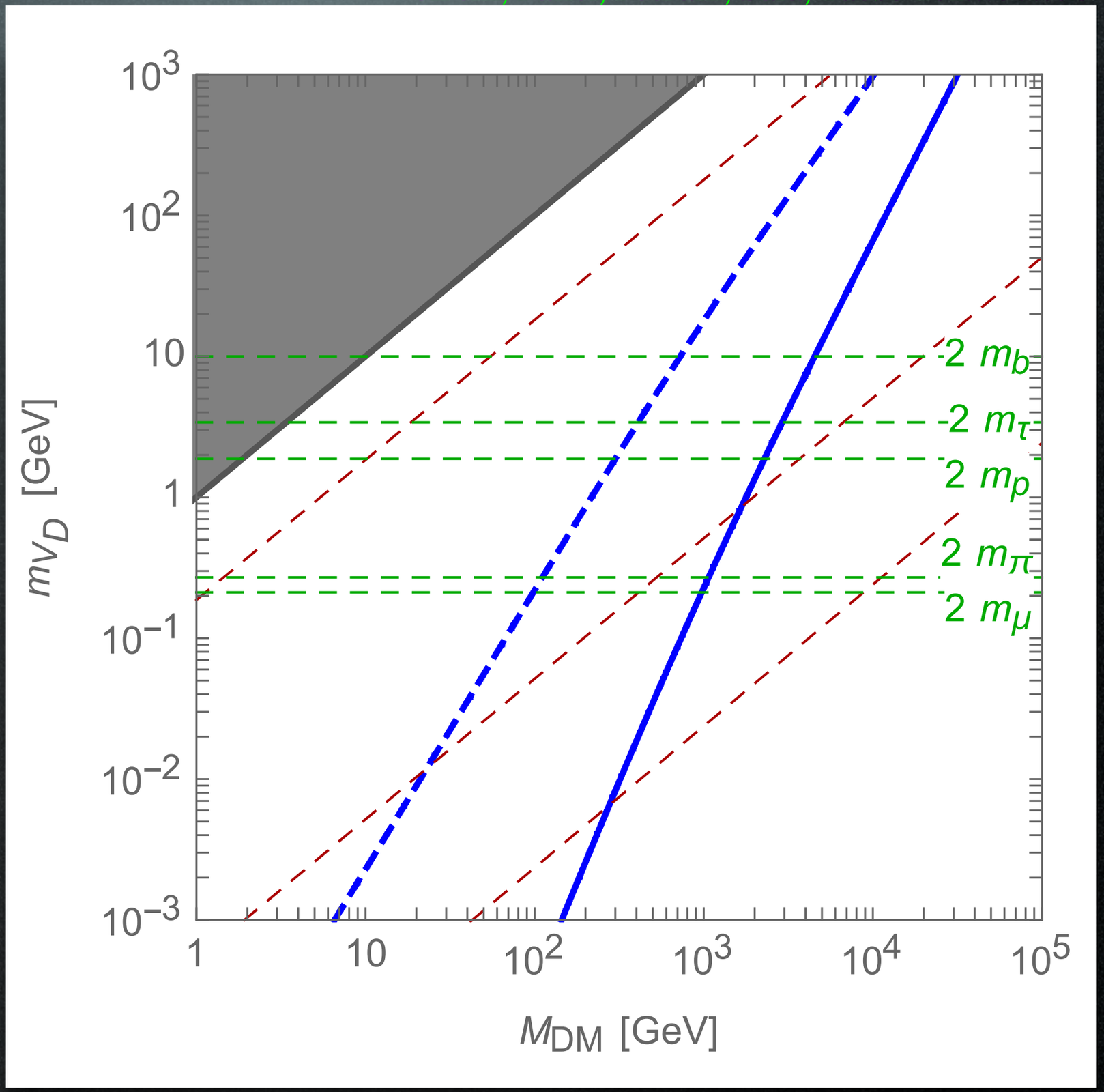
Dark photon decay channels



$$\Gamma(V_D \to f\bar{f}) = \frac{N_f}{24\pi} m_{V_D} \sqrt{1 - \frac{4m_f^2}{m_{V_D}^2}} \left[g_{f_L}^2 + g_{f_R}^2 - \frac{m_f^2}{m_{V_D}^2}(g_{f_L}^2 + g_{f_R}^2 - 6 g_{f_L} g_{f_R}) \right]$$

(ZZ, WW negligible)

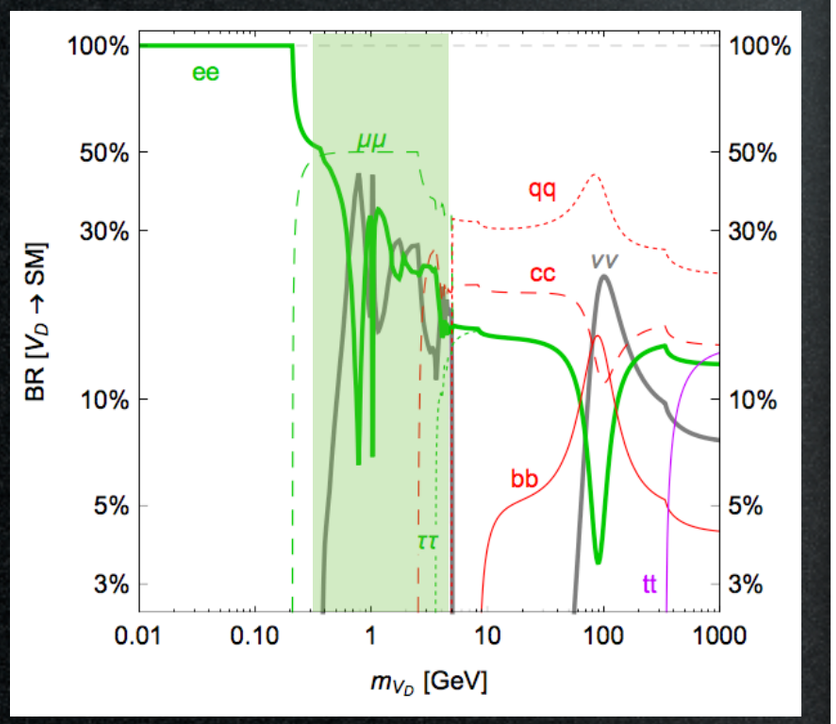
Cirelli, Panci, Petraki, Sala, Taoso 1612.07295



Phenomenology

Setting the stage

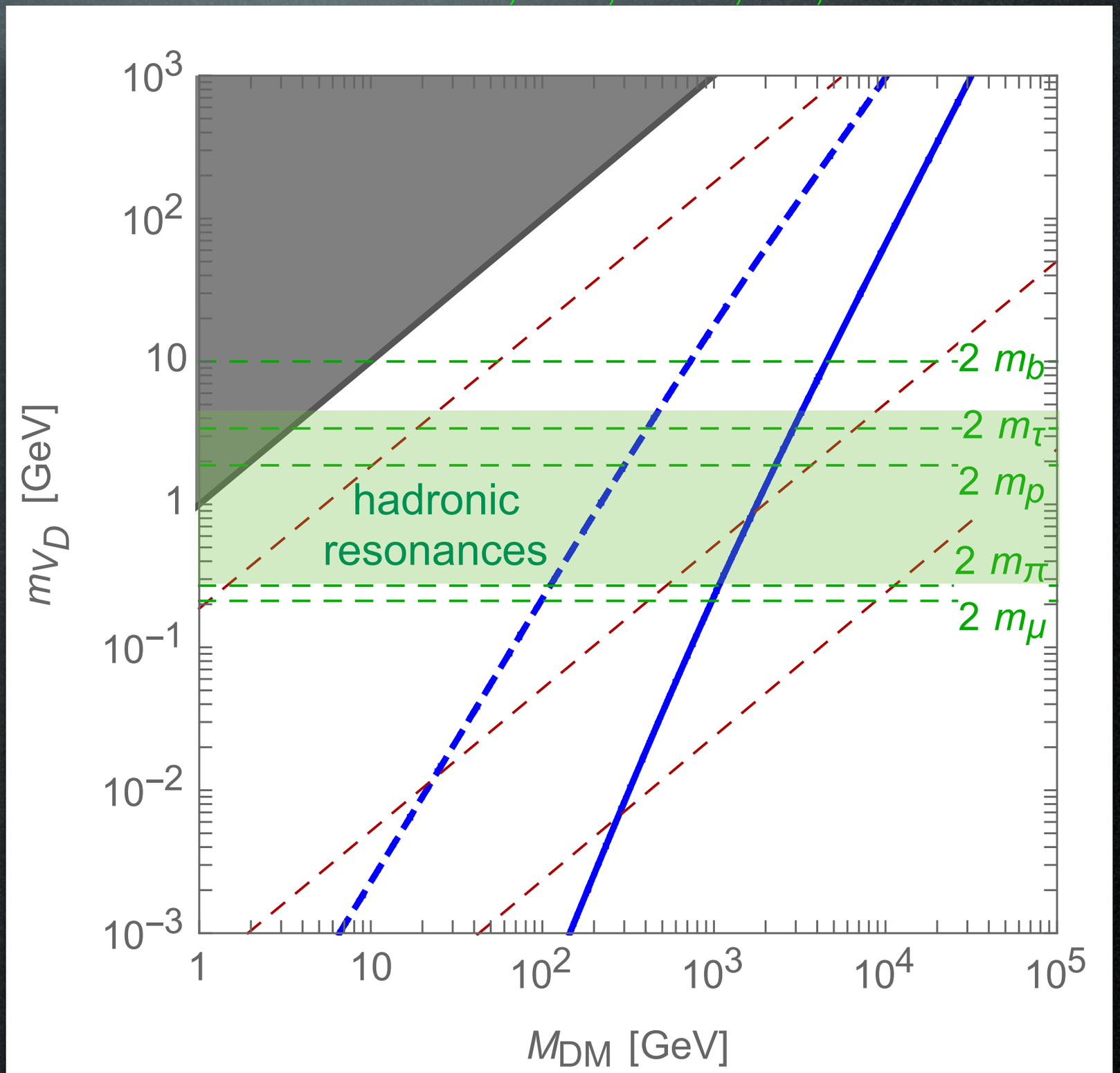
Dark photon decay channels



$$\Gamma(V_D \to f\bar{f}) = \frac{N_f}{24\pi} m_{V_D} \sqrt{1 - \frac{4m_f^2}{m_{V_D}^2}} \left[g_{f_L}^2 + g_{f_R}^2 - \frac{m_f^2}{m_{V_D}^2}(g_{f_L}^2 + g_{f_R}^2 - 6 g_{f_L} g_{f_R}) \right]$$

(ZZ, WW negligible)

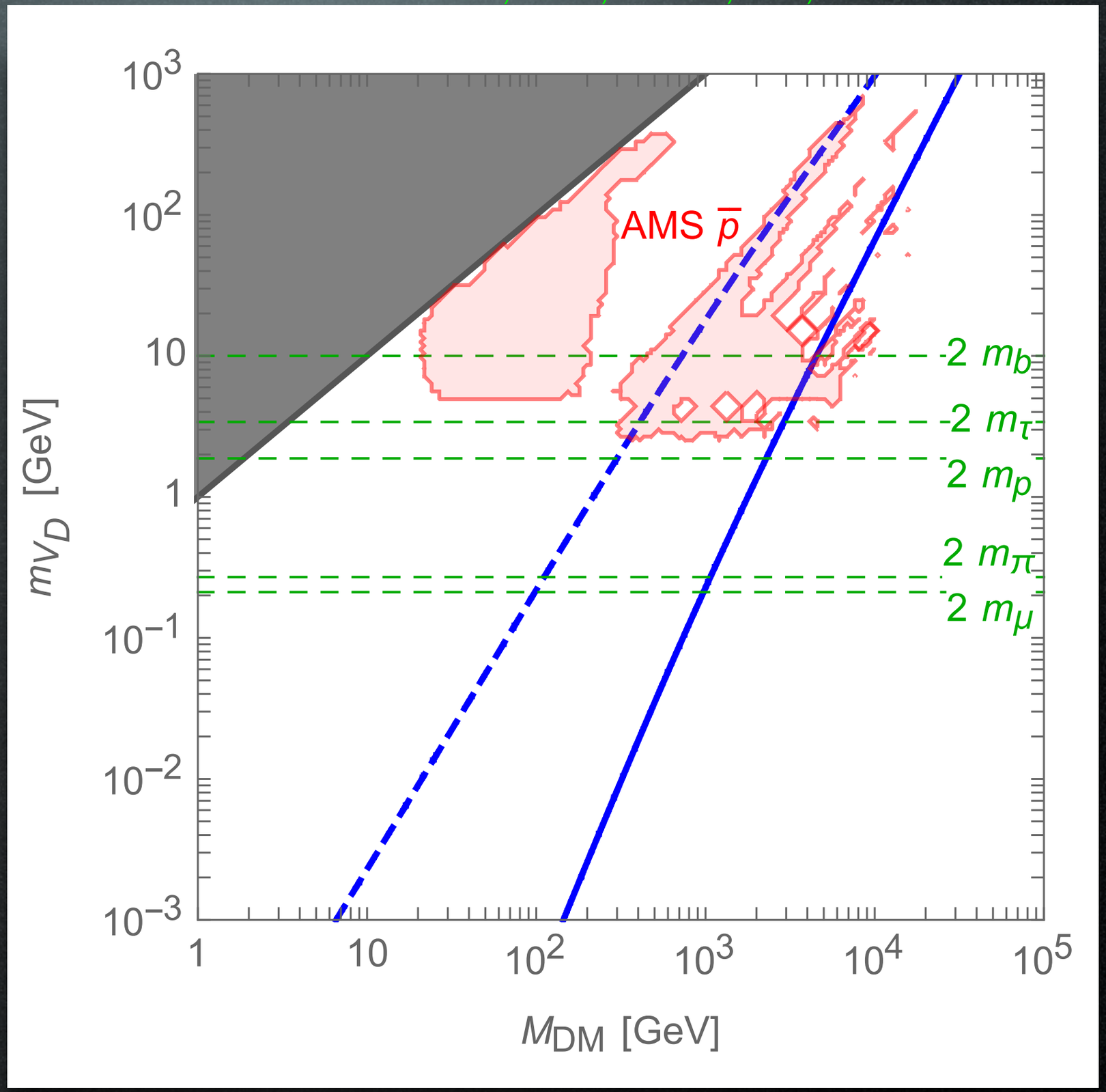
Cirelli, Panci, Petraki, Sala, Taoso 1612.07295



Phenomenology

Antiproton constraints:

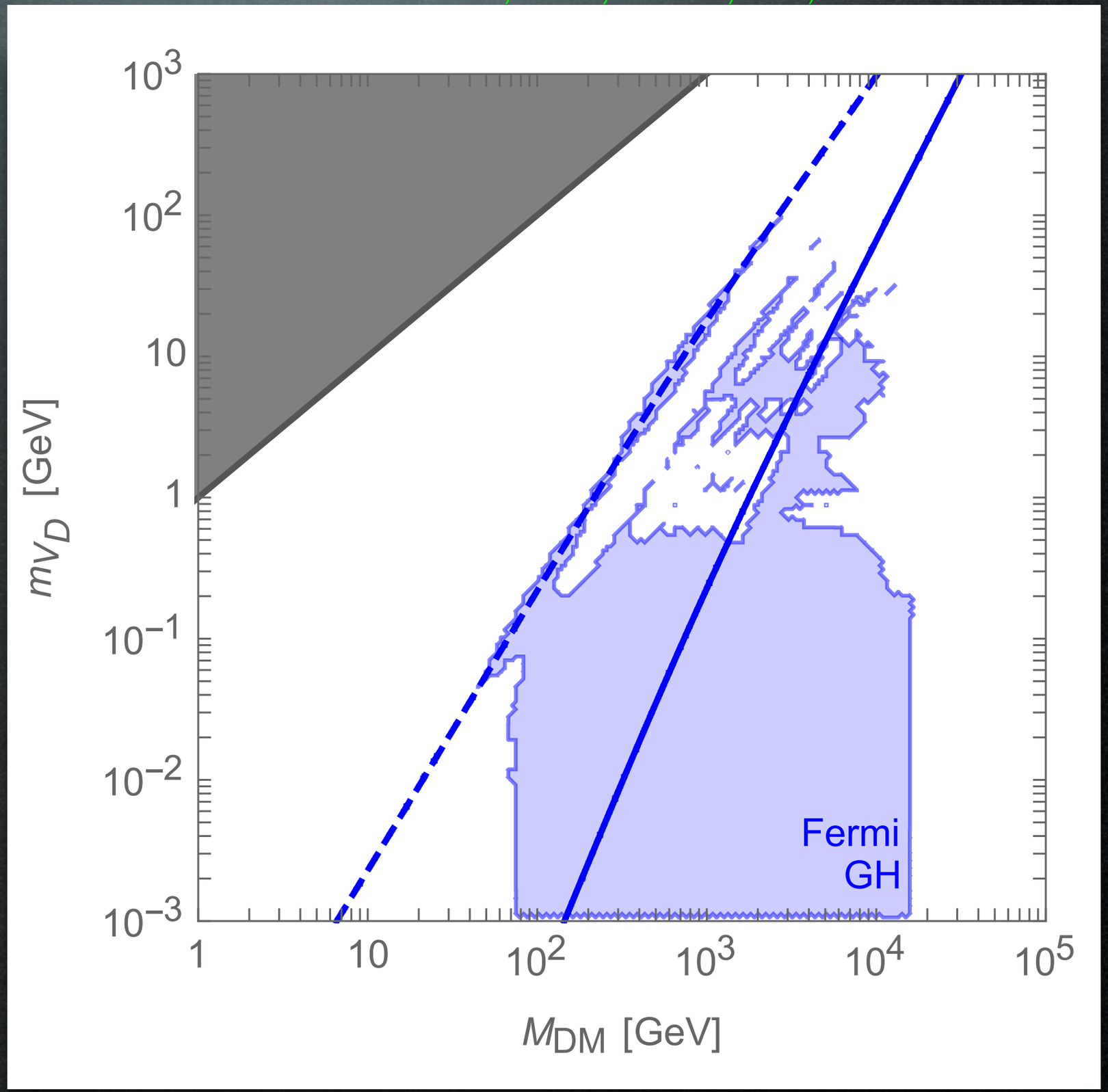
Cirelli, Panci, Petraki, Sala, Taoso 1612.07295



Phenomenology

GH gamma constraints:

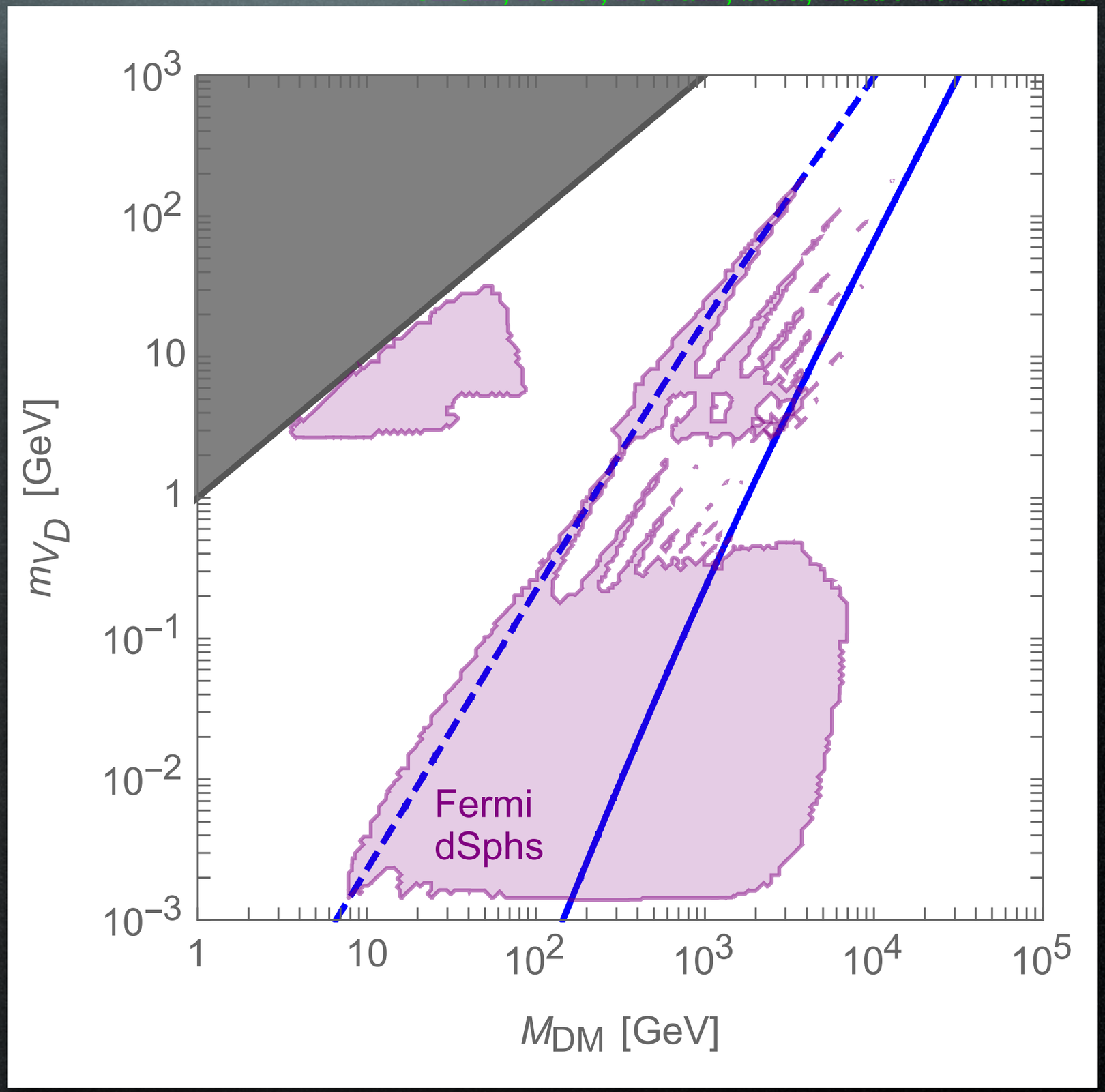
Cirelli, Panci, Petraki, Sala, Taoso 1612.07295



Phenomenology

Dwarfs gamma constraints:

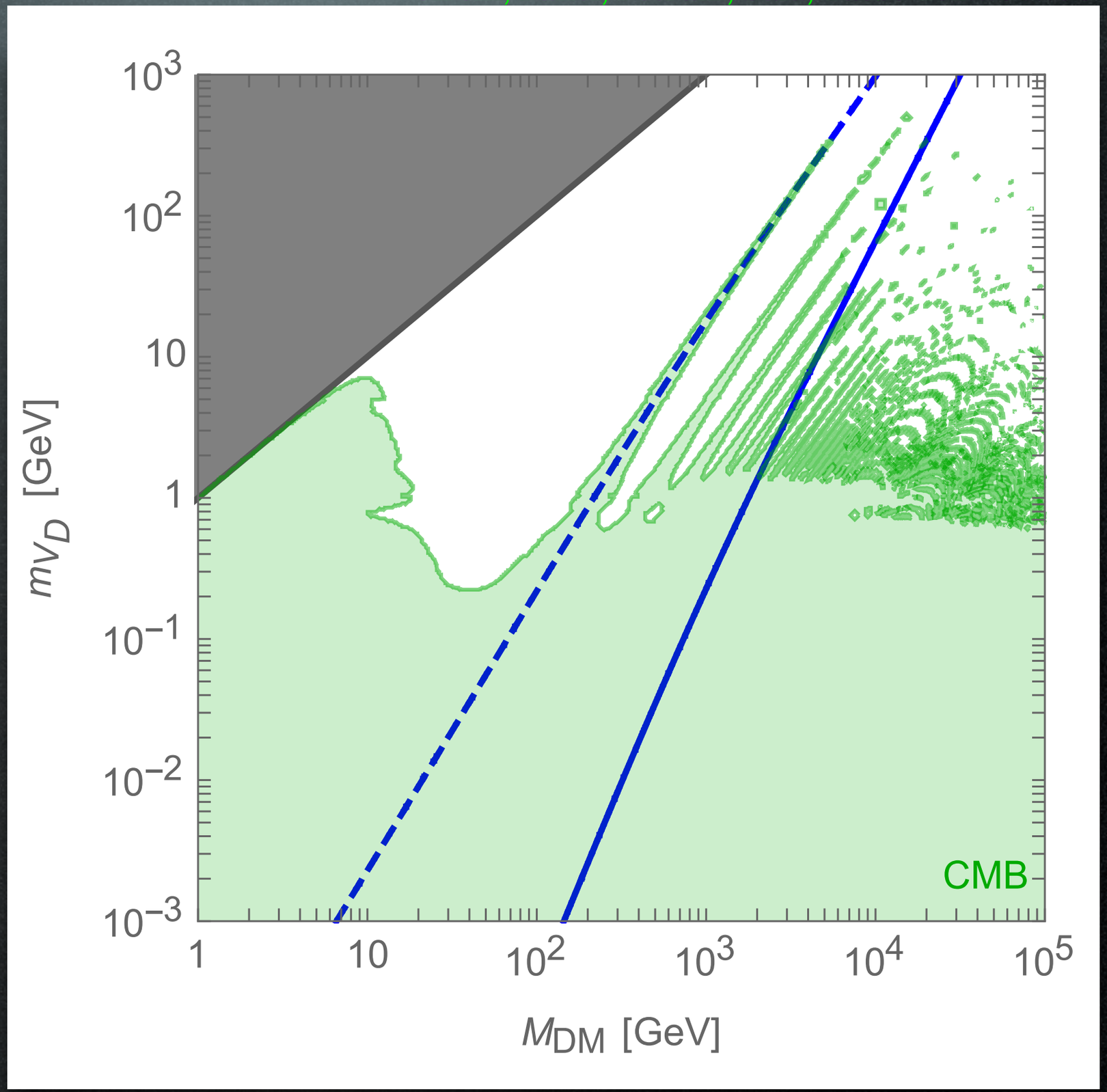
Cirelli, Panci, Petraki, Sala, Taoso 1612.07295



Phenomenology

CMB constraints:

Cirelli, Panci, Petraki, Sala, Taoso 1612.07295



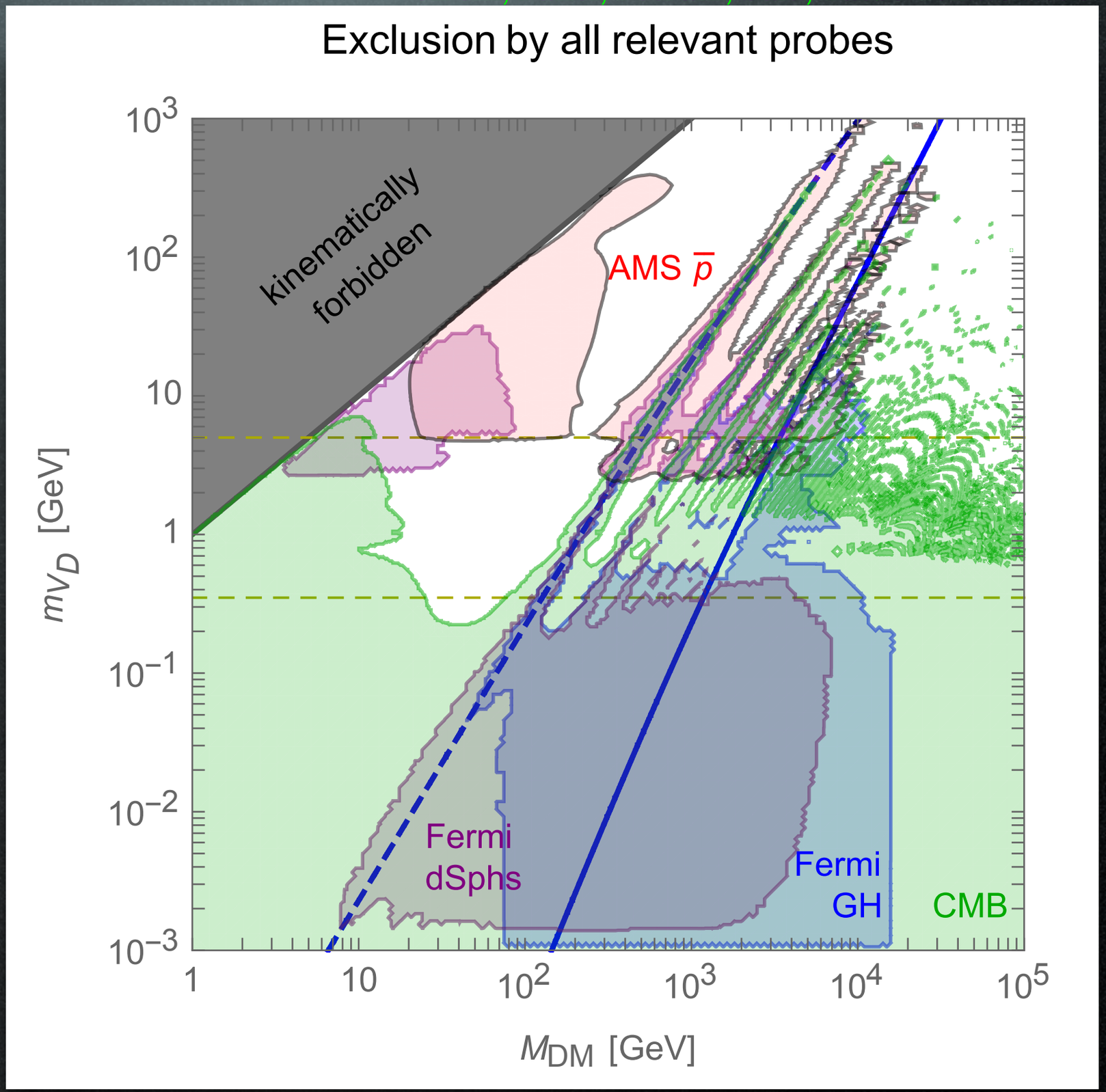
based on tools from:

Slatyer, 1506.03811

Phenomenology

All constraints:

Cirelli, Panci, Petraki, Sala, Taoso 1612.07295



Caveat: other constraints possible, e.g. from AMS positrons, HESS dwarfs, HAWC dwarfs…

WIMPs are effectively collisionless

WIMPs are, in fact, self-interacting

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WIMP DM mass: multi-TeV

Mediator mass: M_W, M_Z

WIMPs are, in fact, self-interacting

WIMP DM mass: multi-TeV

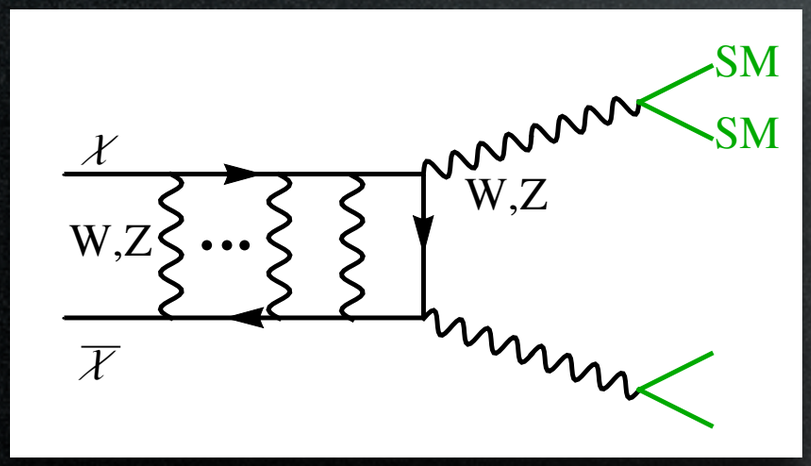
Mediator mass: M_W, M_Z

size of the XX system

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

range

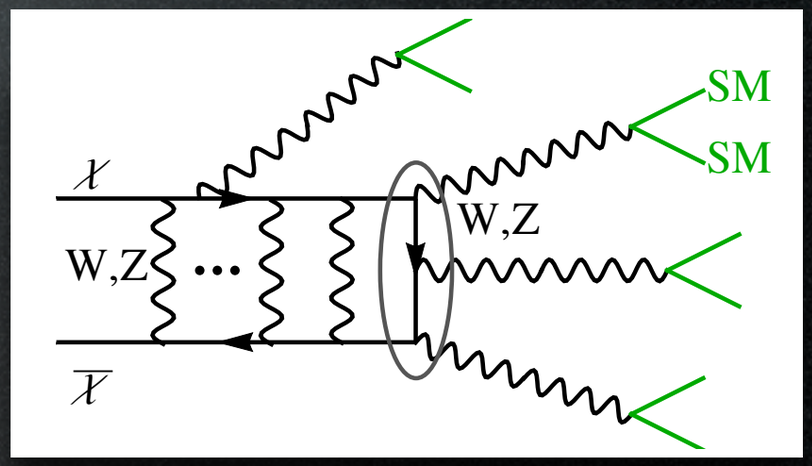
Sommerfeld enhanced



binding energy of the XX system

If $\alpha^2 M/4m_V \gtrsim 1$, bound states form

emitted dark photon



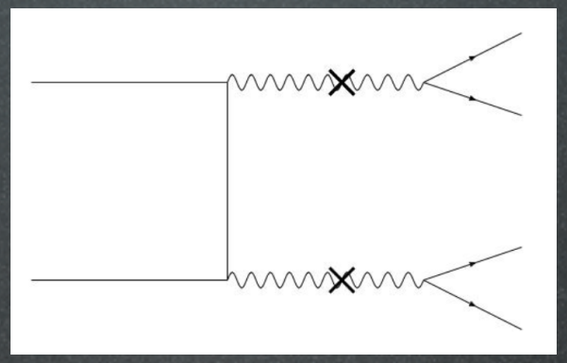
Petraki+ 2015+

Mitridate, Redi, Smirnov, Strumia 1702.01141

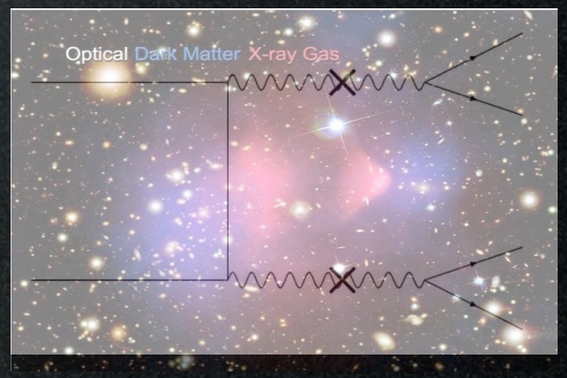
Interactions

Ορθοδοξία → **Έτεροδοξία** → **Αίρεση**

collisionless



self-interacting

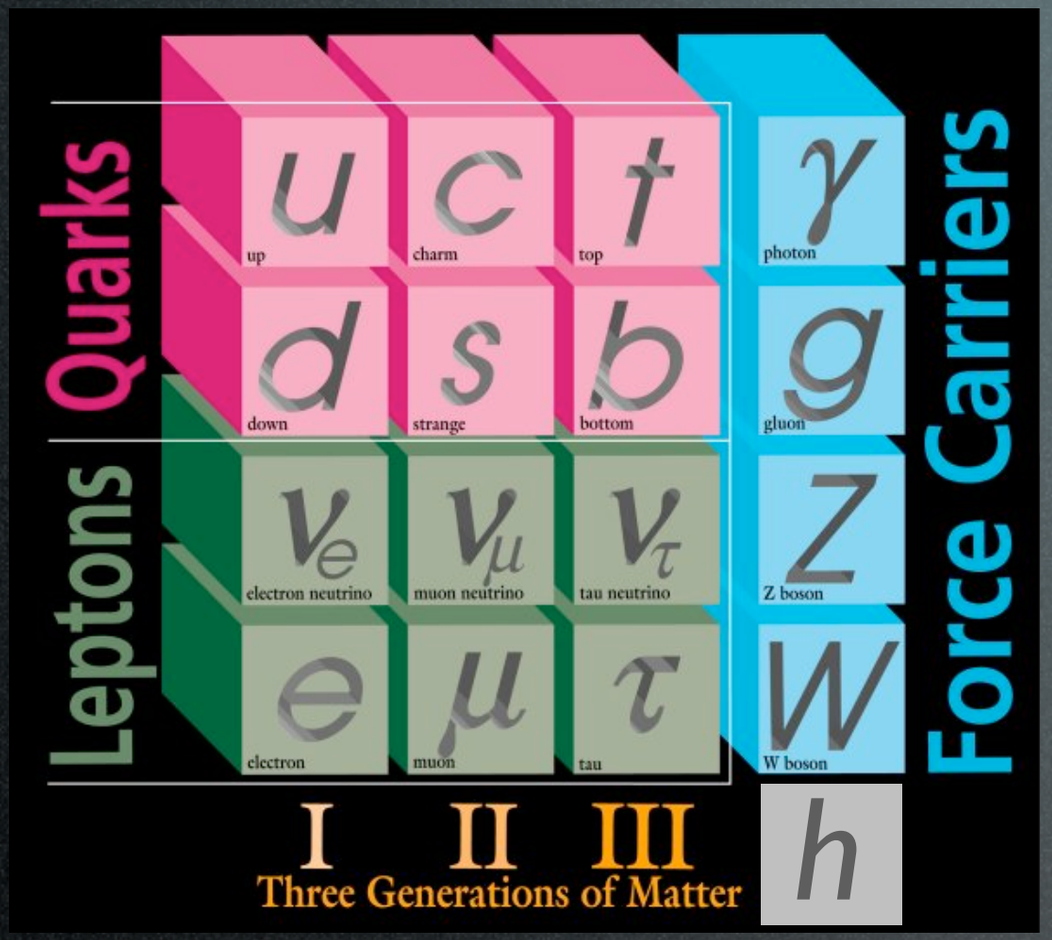


Credit: **Kallia Petraki** LPTHE Jussieu
(both the physics and the greek)

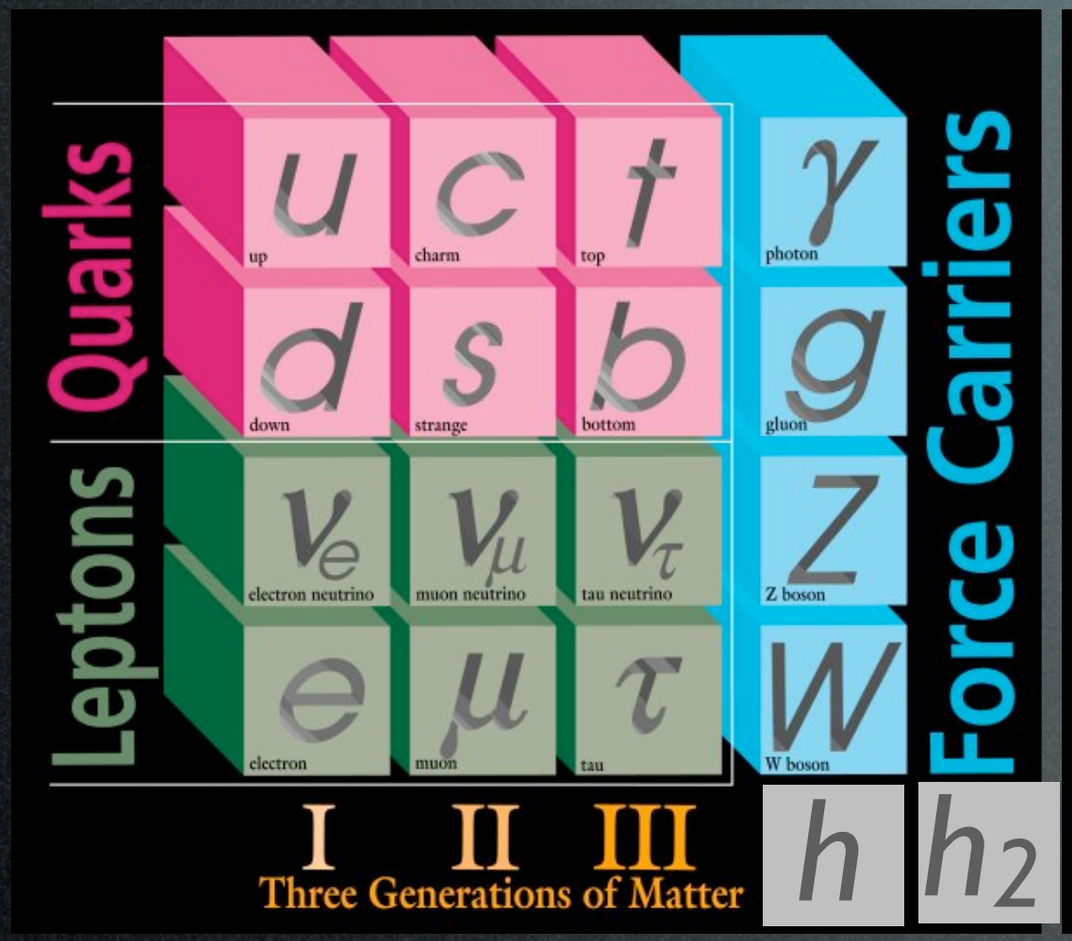
Stability

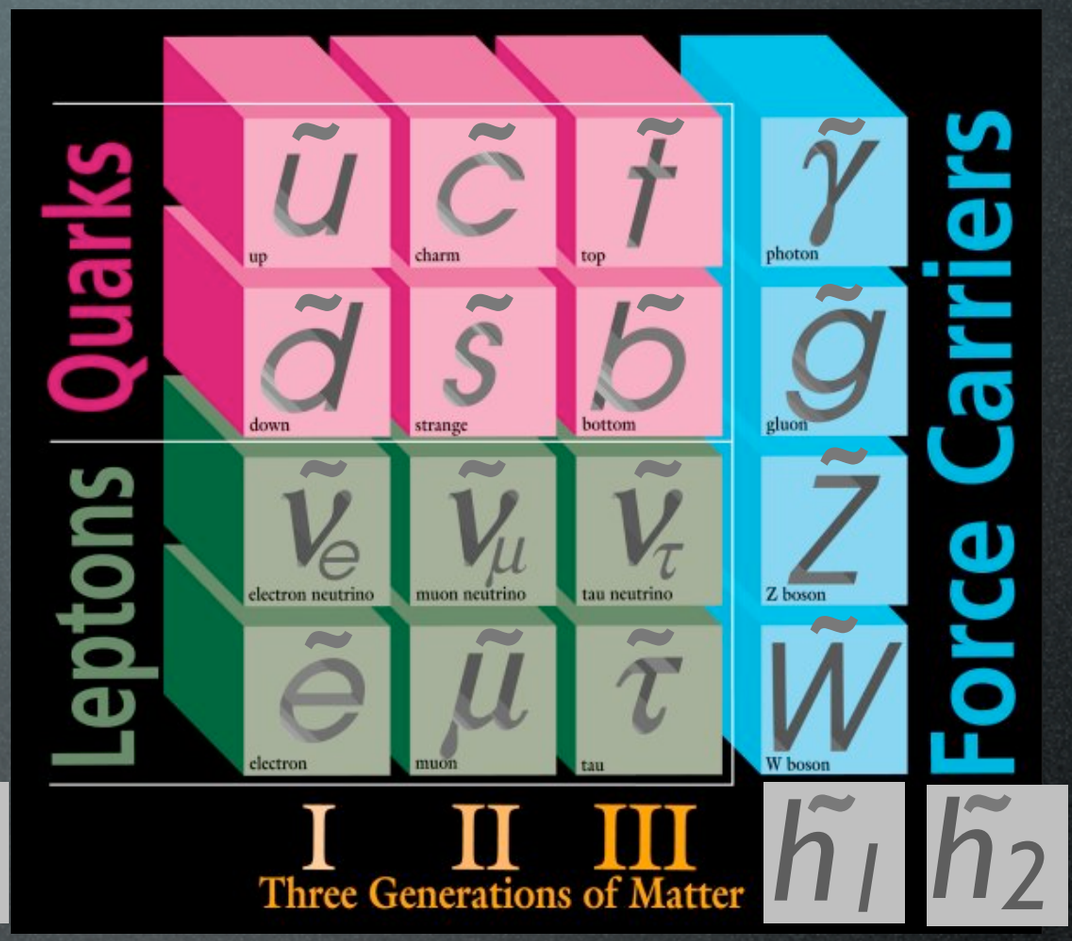
Ορθοδοξία → **Έτεροδοξία** → **Αίρεση**

SuSy DM in 2 minutes

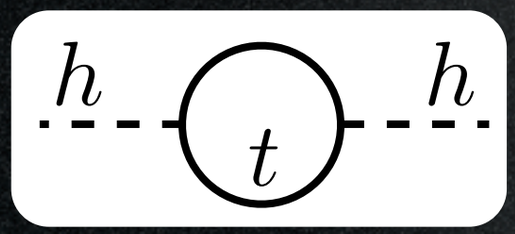


SuSy DM in 2 minutes

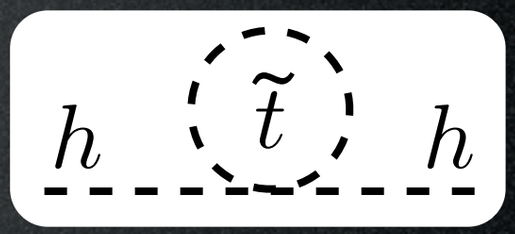




$m_{\mathrm{h}} \simeq 125\ \mathrm{GeV}$

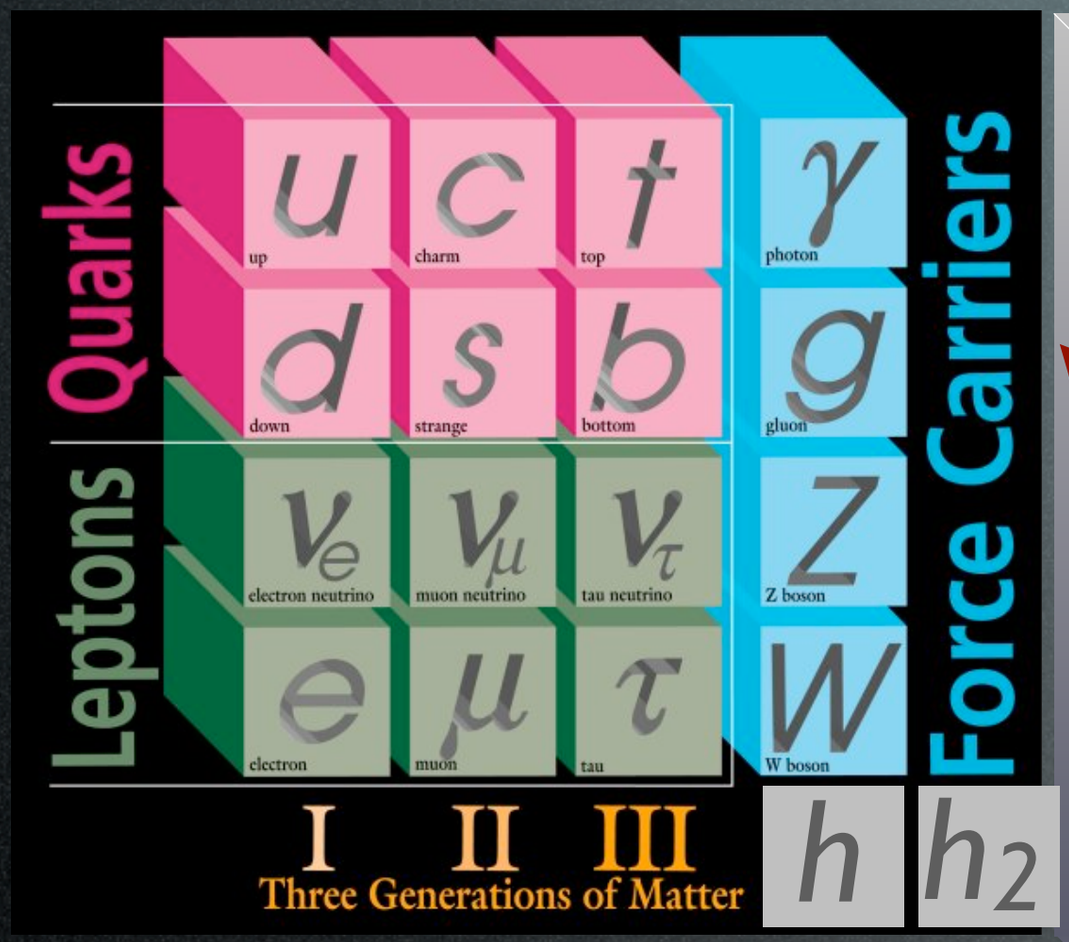


$\Delta m_{\mathrm{h}} \propto 10^{19}\ \mathrm{GeV}$

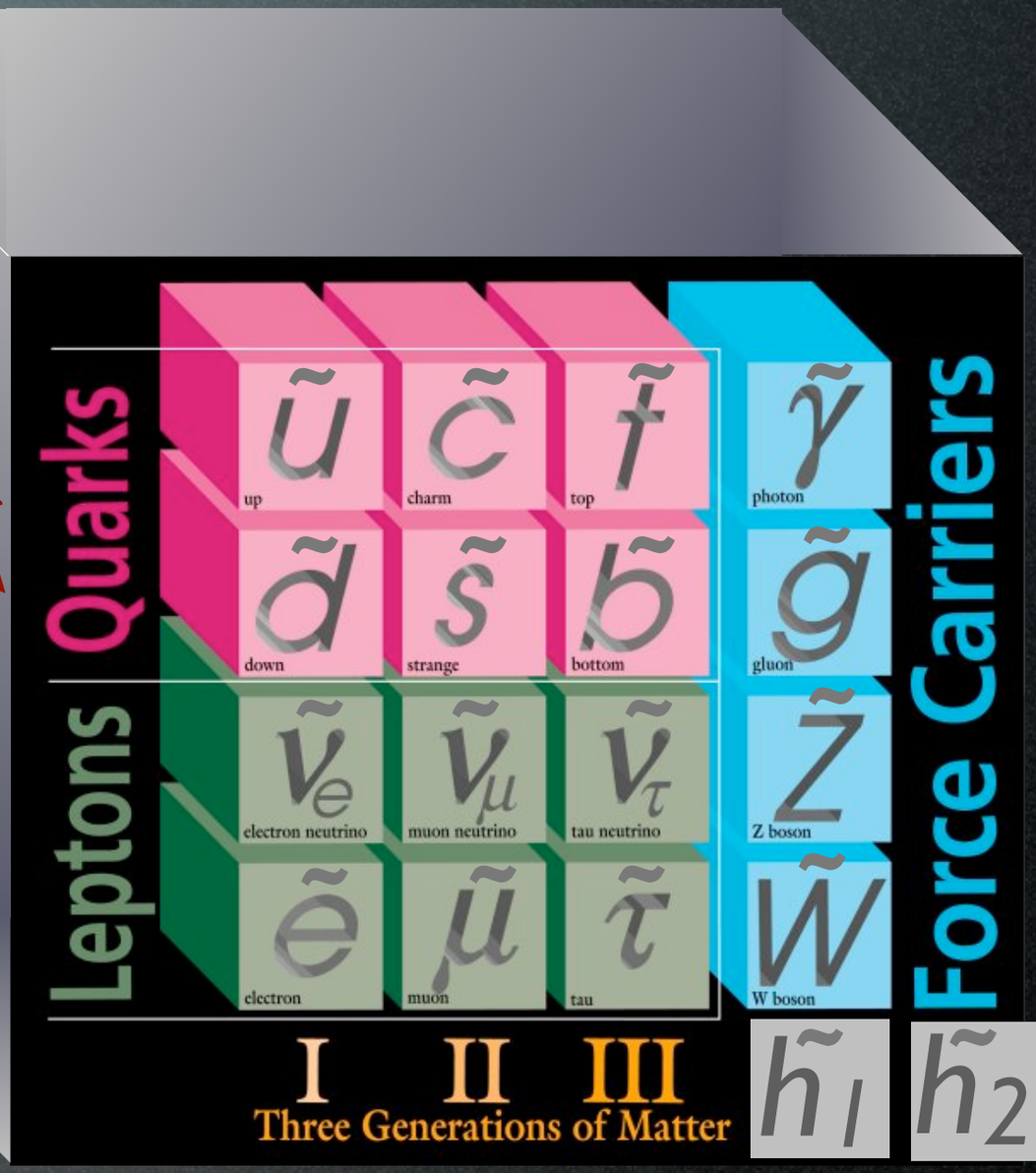


$\Delta m_{\mathrm{h}} \propto -10^{19}\ \mathrm{GeV}$

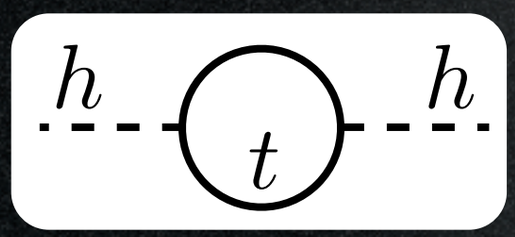
SuSy DM in 2 minutes



200 GeV



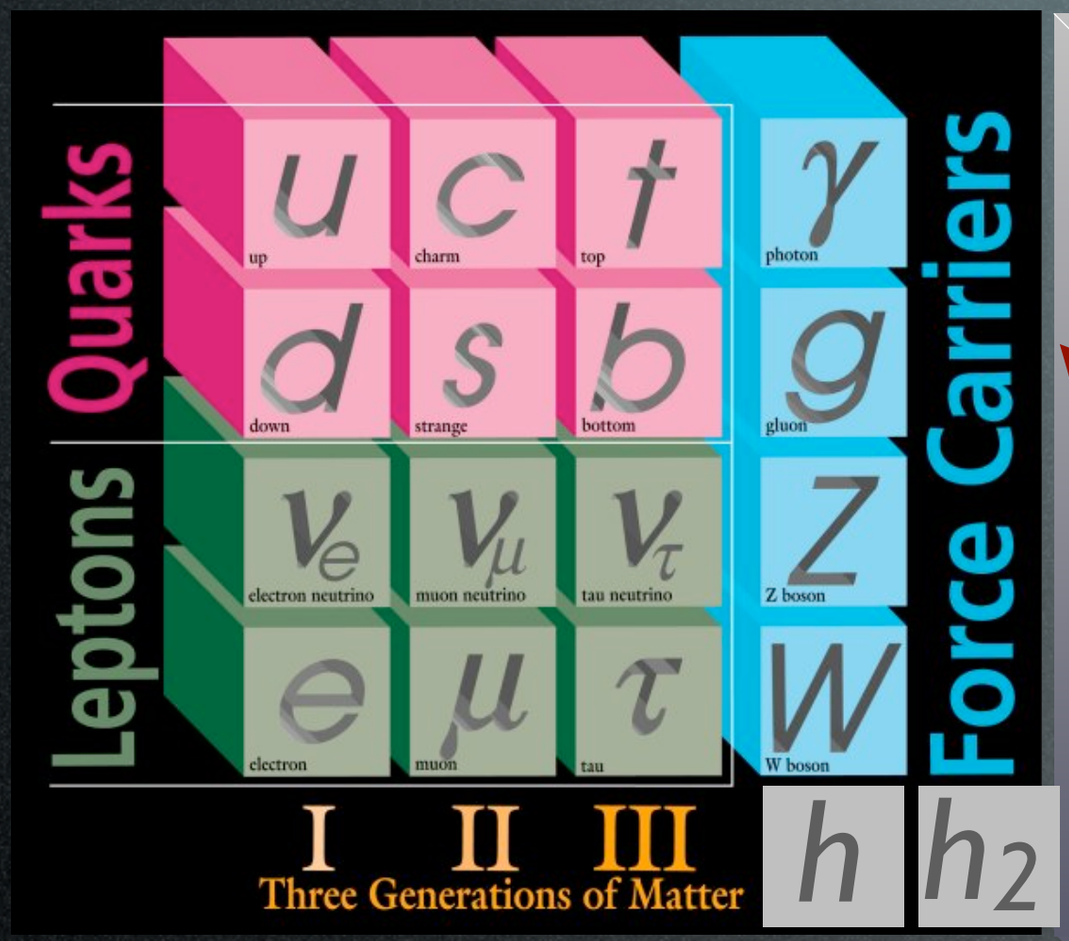
$m_{\rm h} \simeq 125$ GeV



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

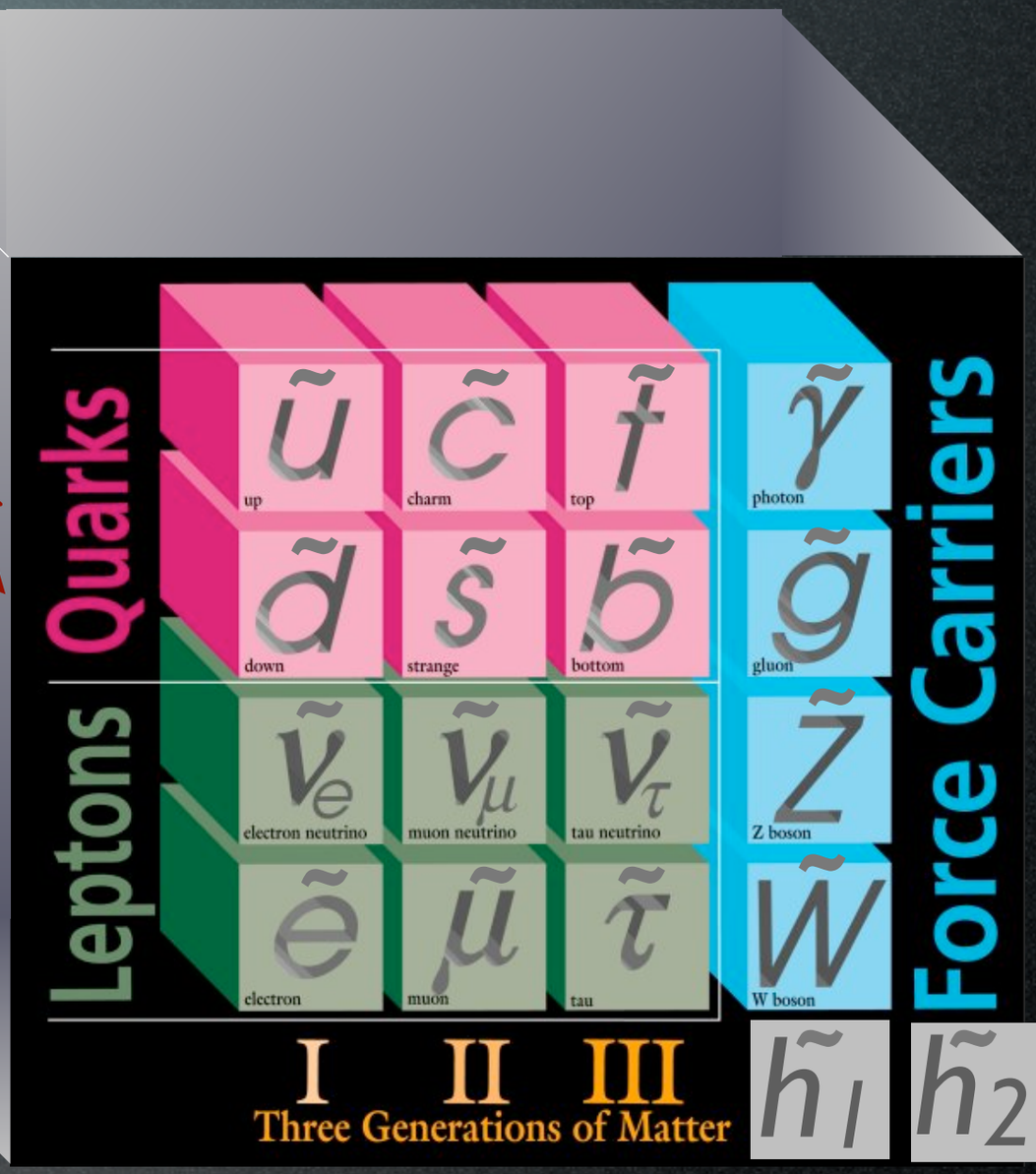
$\Delta m_{\rm h} \propto -10^{19}$ GeV

SuSy DM in 2 minutes



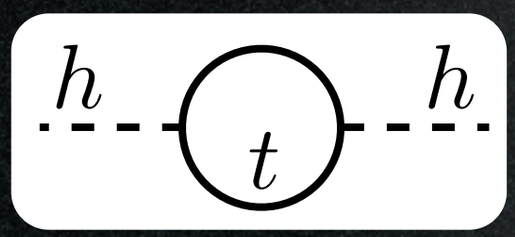
$R = +1$

200 GeV



$R = -1$

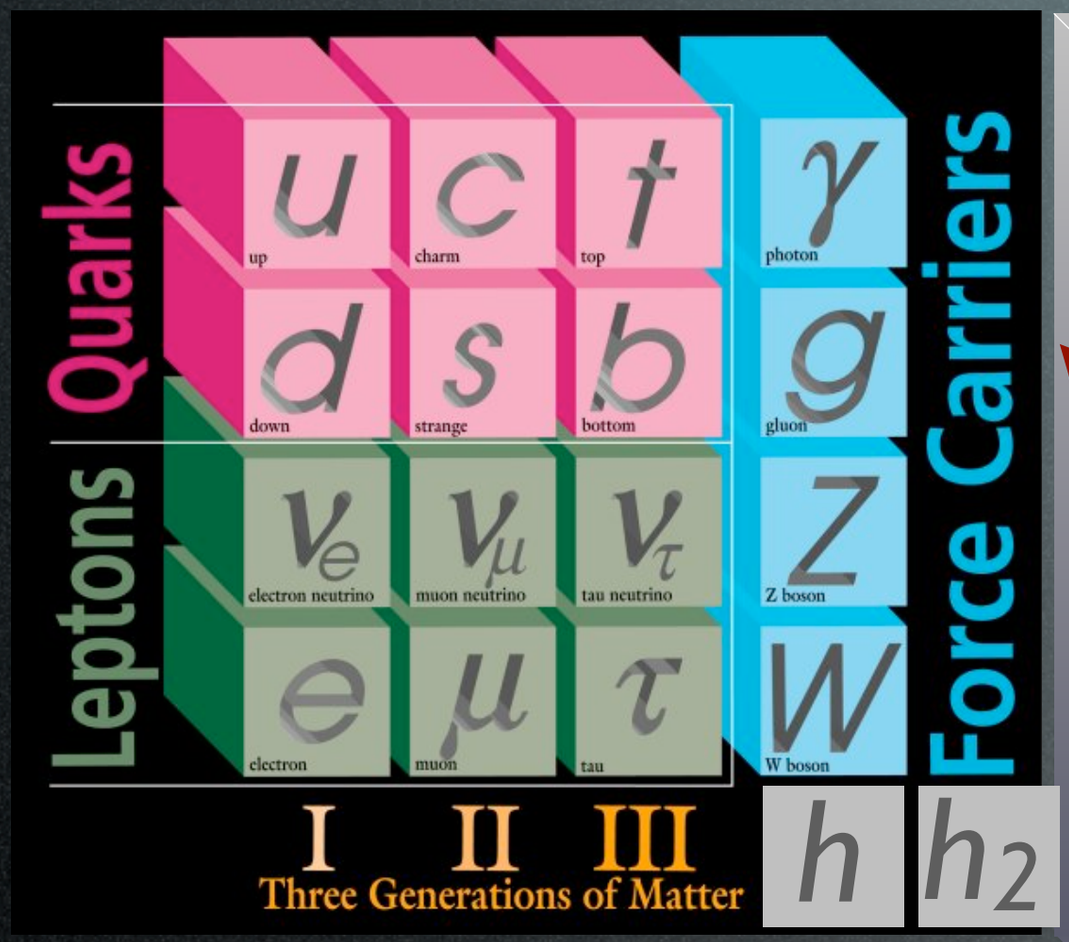
$m_{\mathrm{h}} \simeq 125$ GeV



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

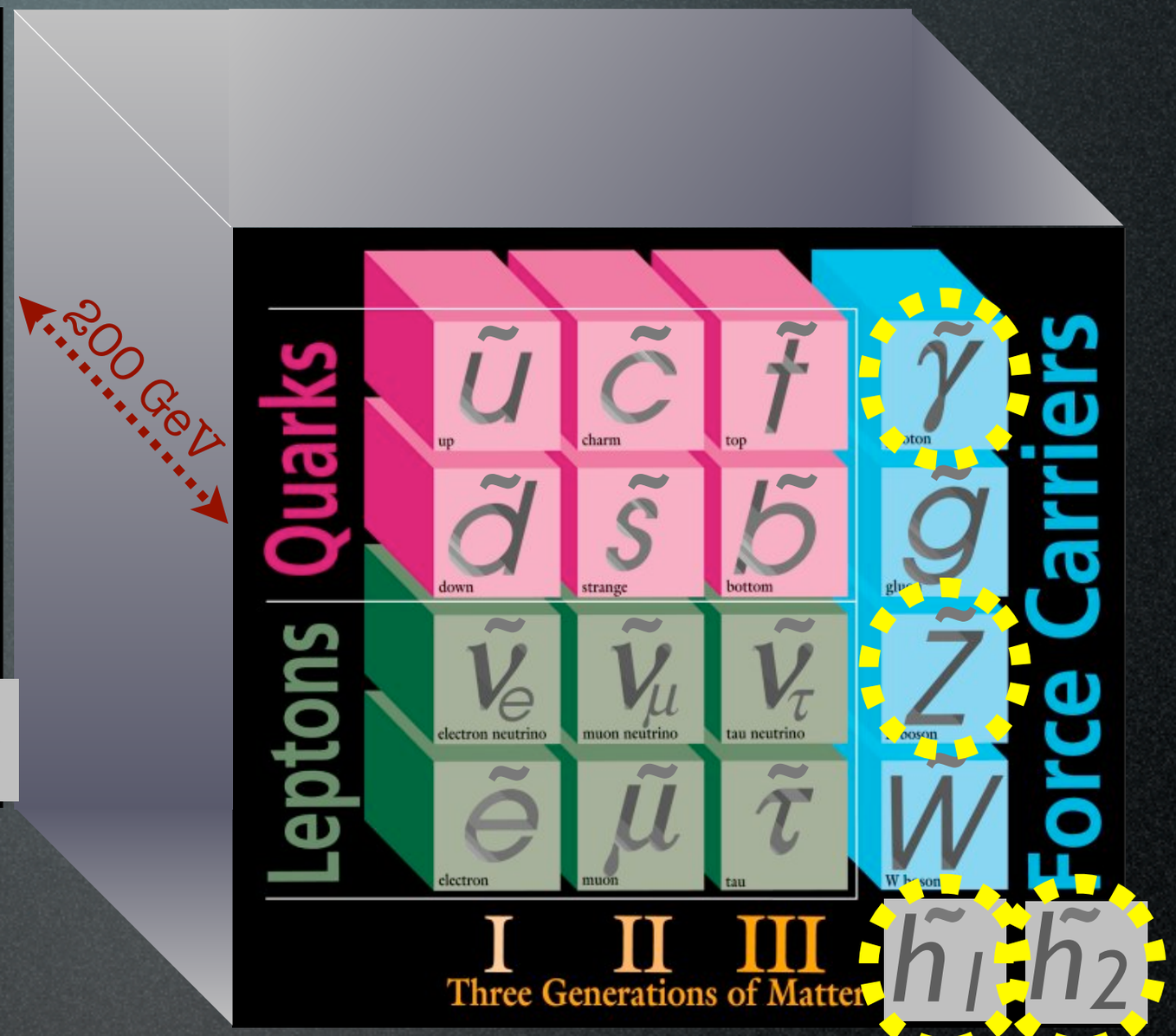
$\Delta m_{\mathrm{h}} \propto -10^{19}$ GeV

SuSy DM in 2 minutes

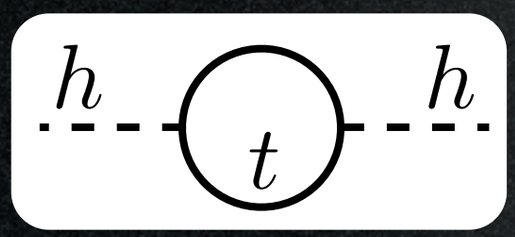


$R = +1$

200 GeV



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

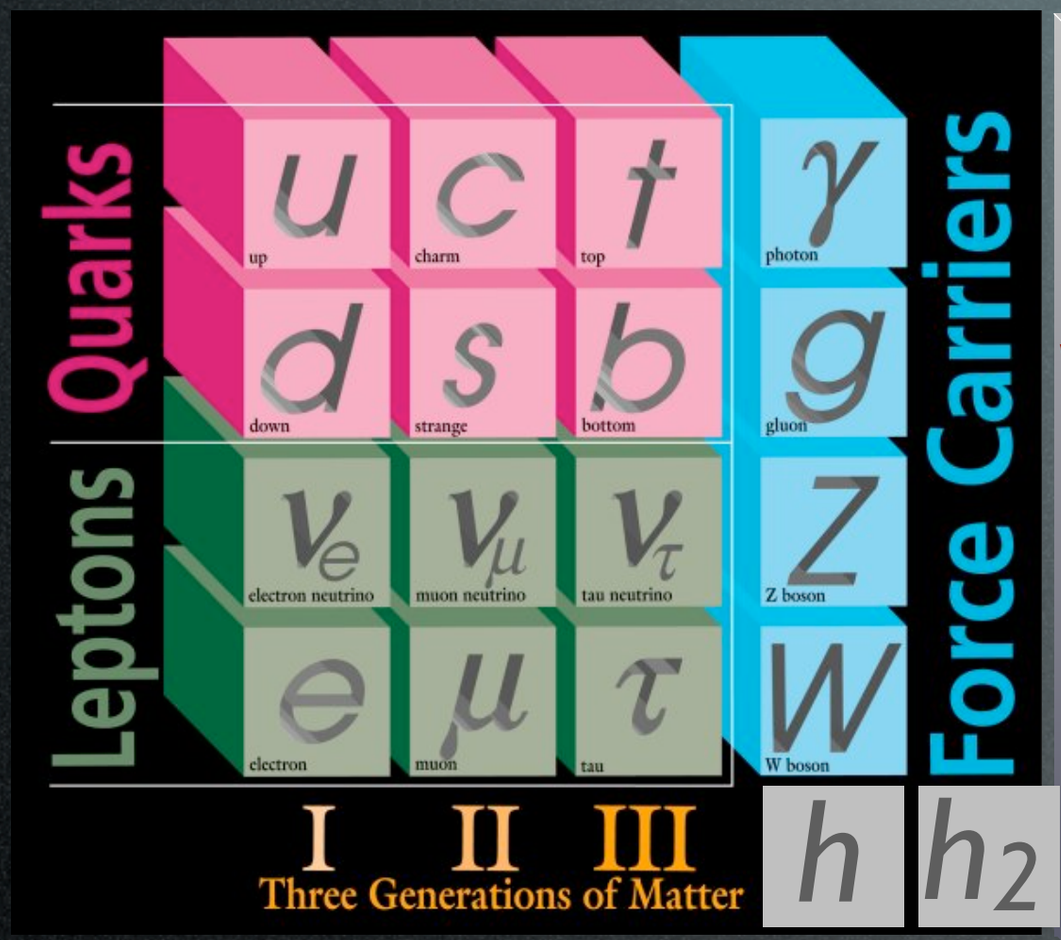


$\Delta m_{\rm h} \propto 10^{19}$ GeV

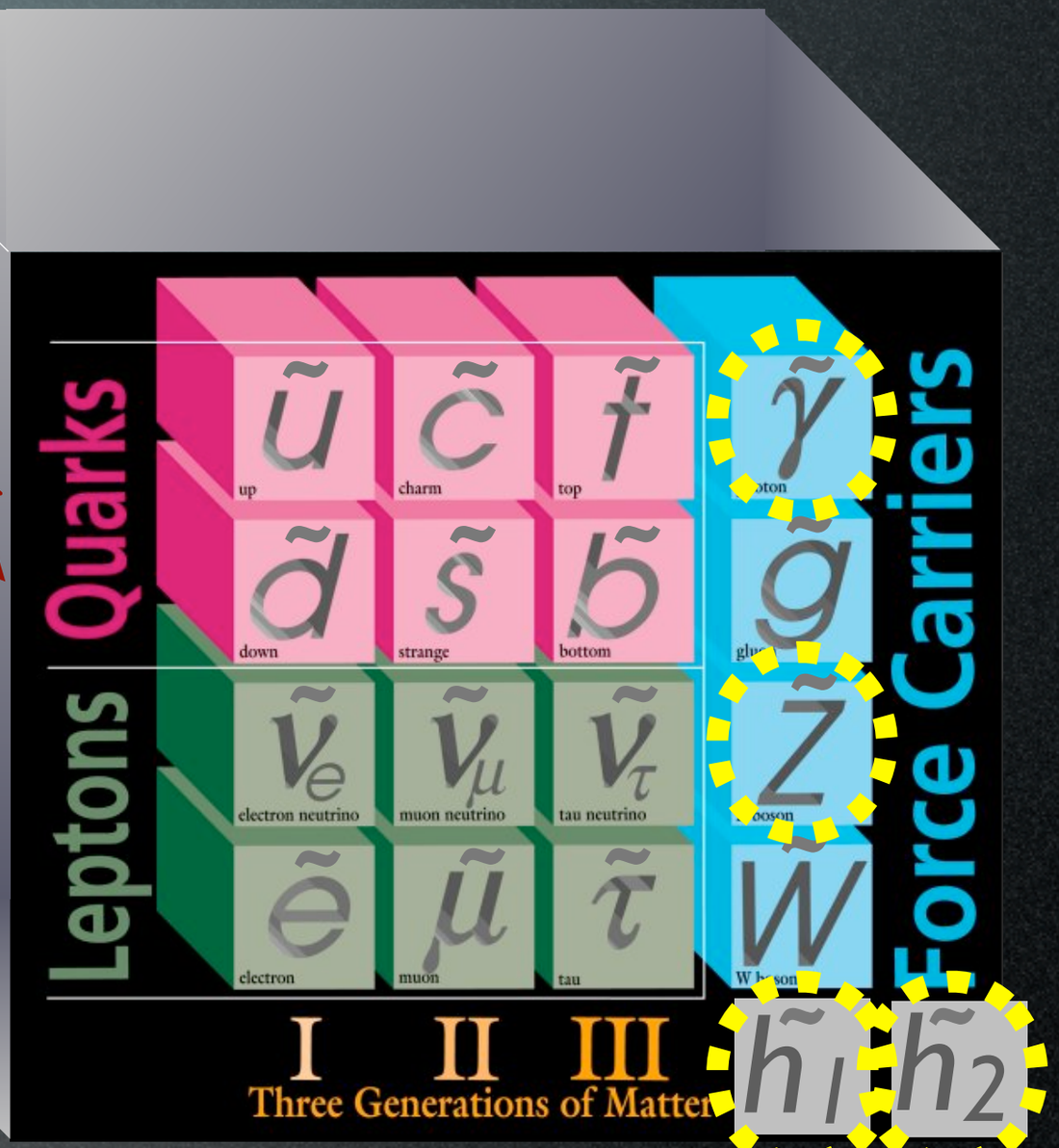
$R = -1$

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

SuSy DM in 2 minutes



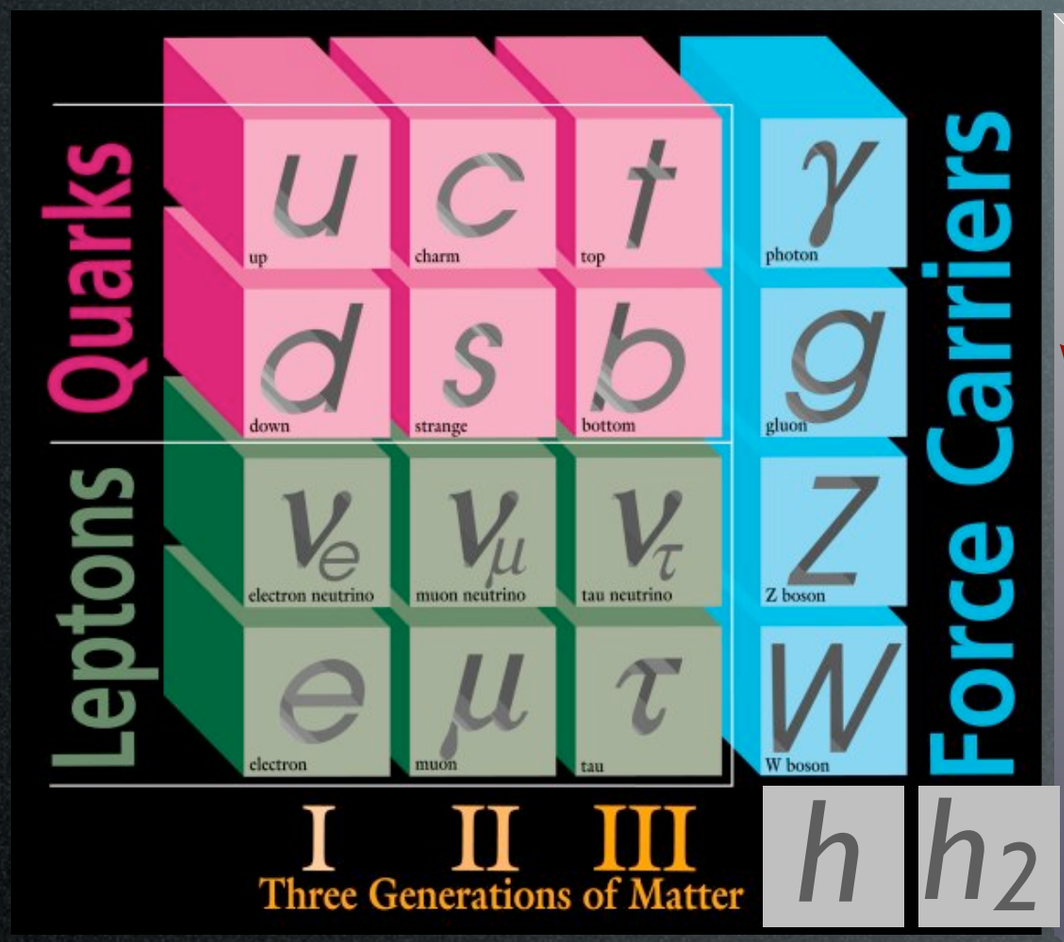
200 GeV



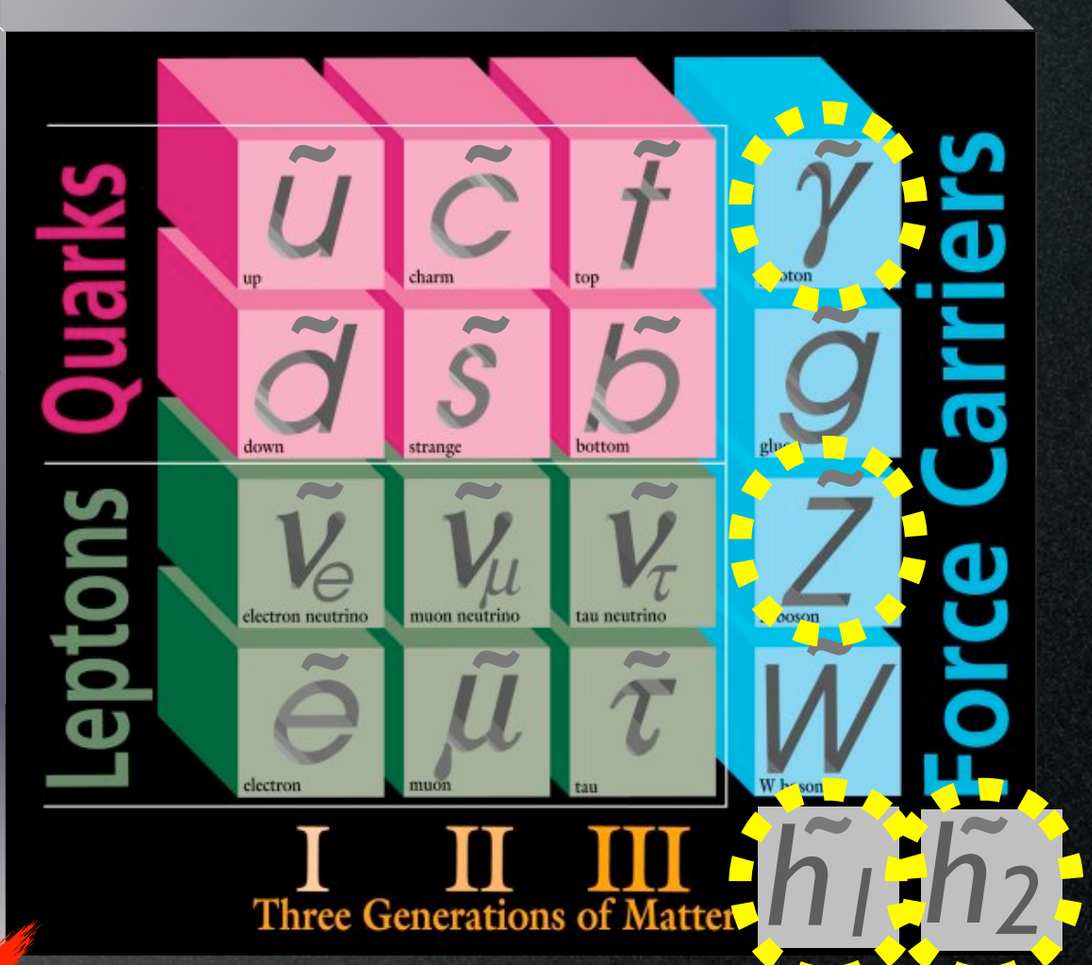
$R = +1$

$R = -1$

SuSy DM in 2 minutes



200 GeV

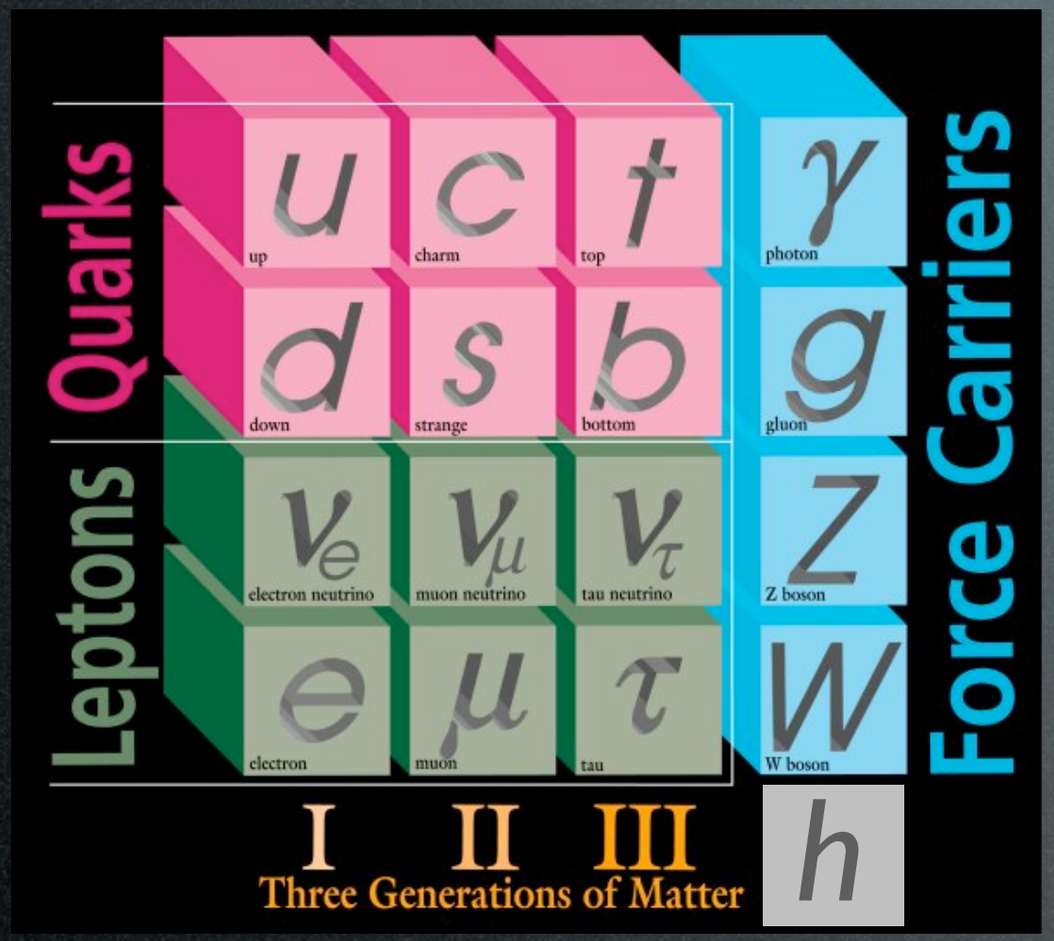


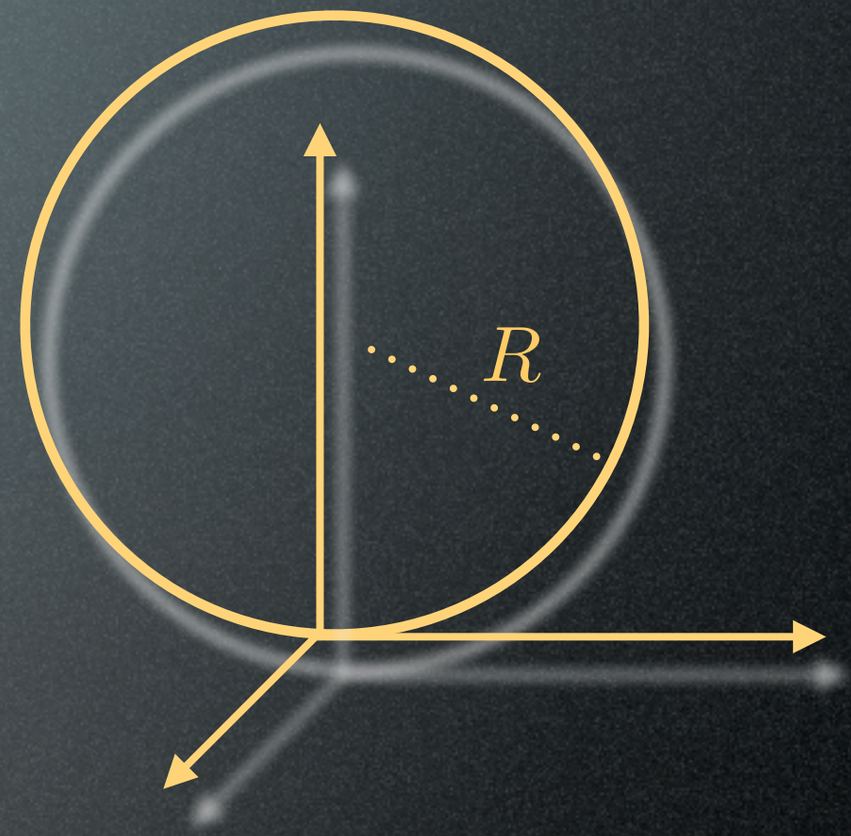
$R = +1$

$R = -1$

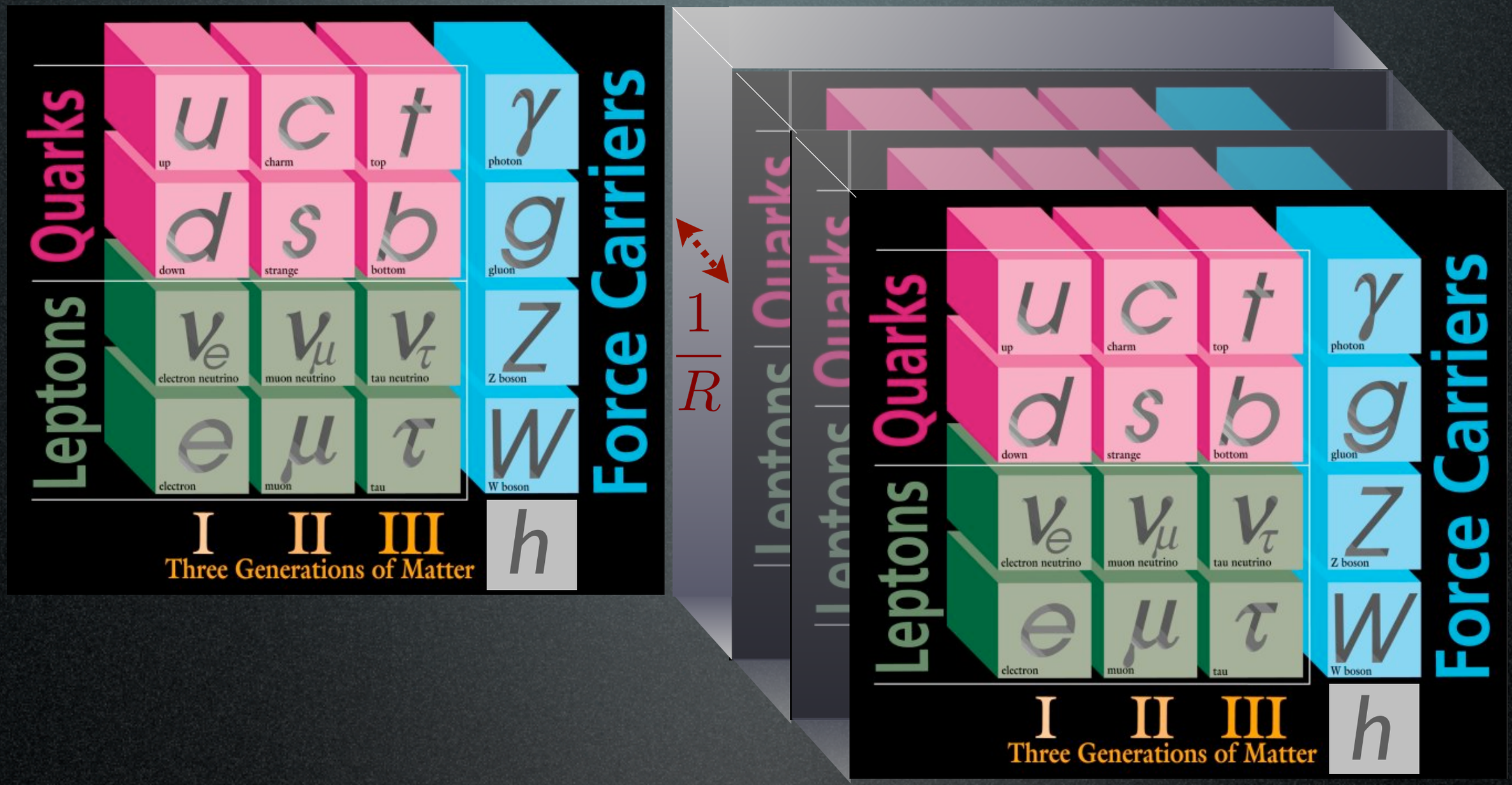
prevent
proton decay

ExDim DM in 2 minutes

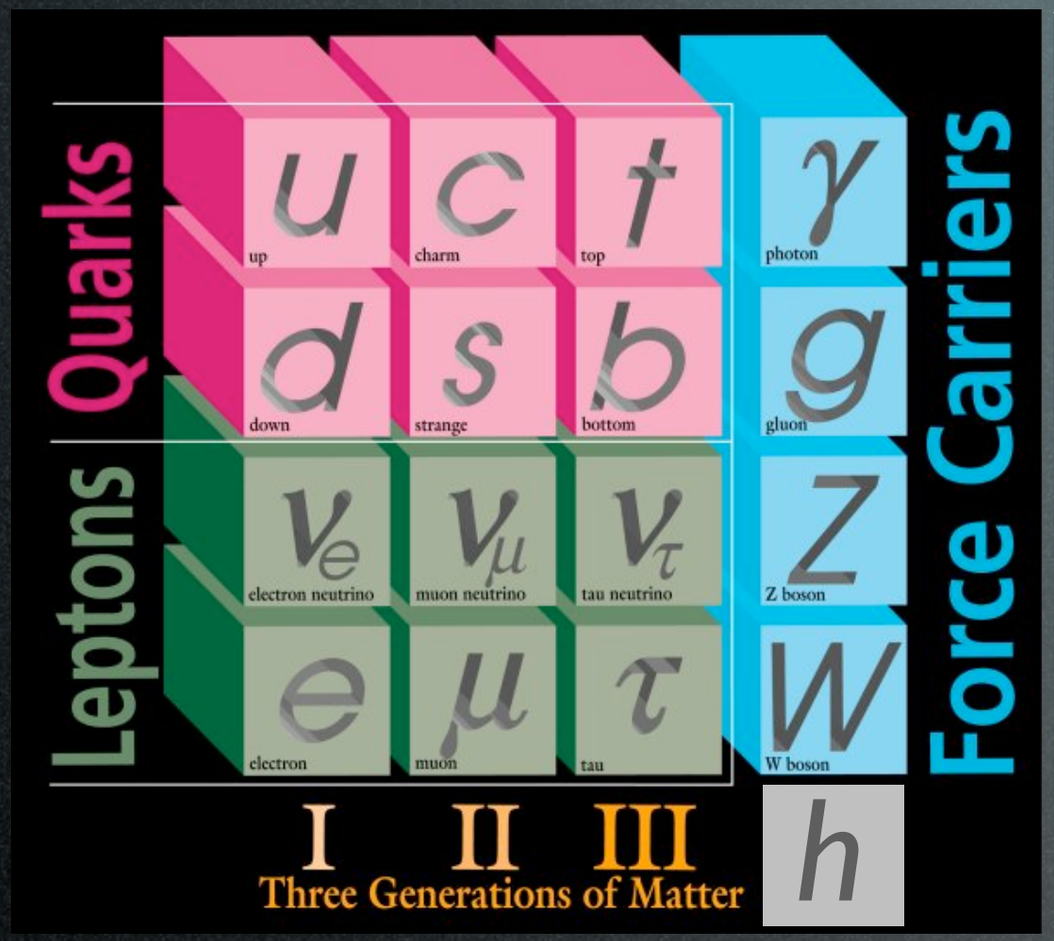




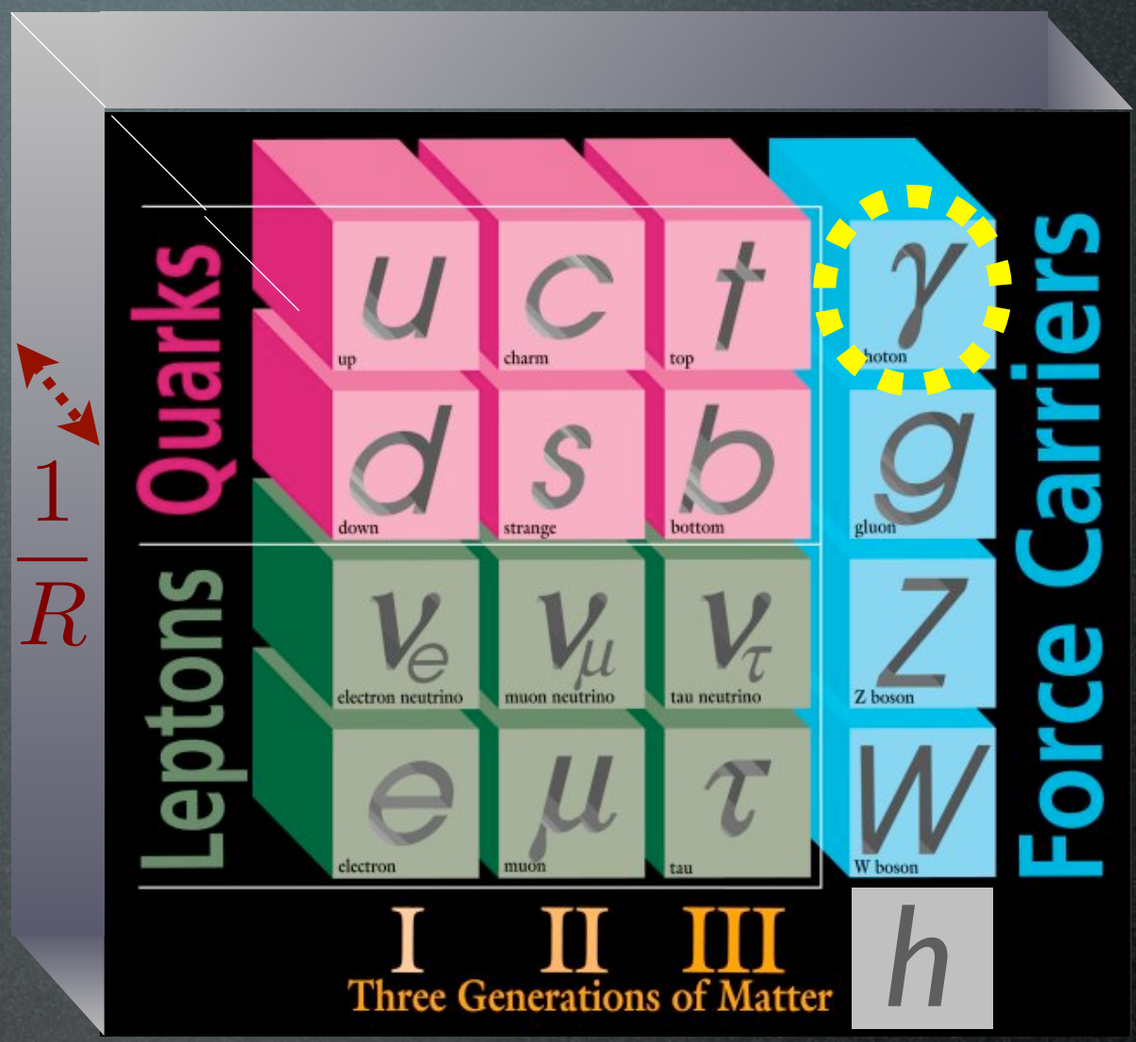
ExDim DM in 2 minutes



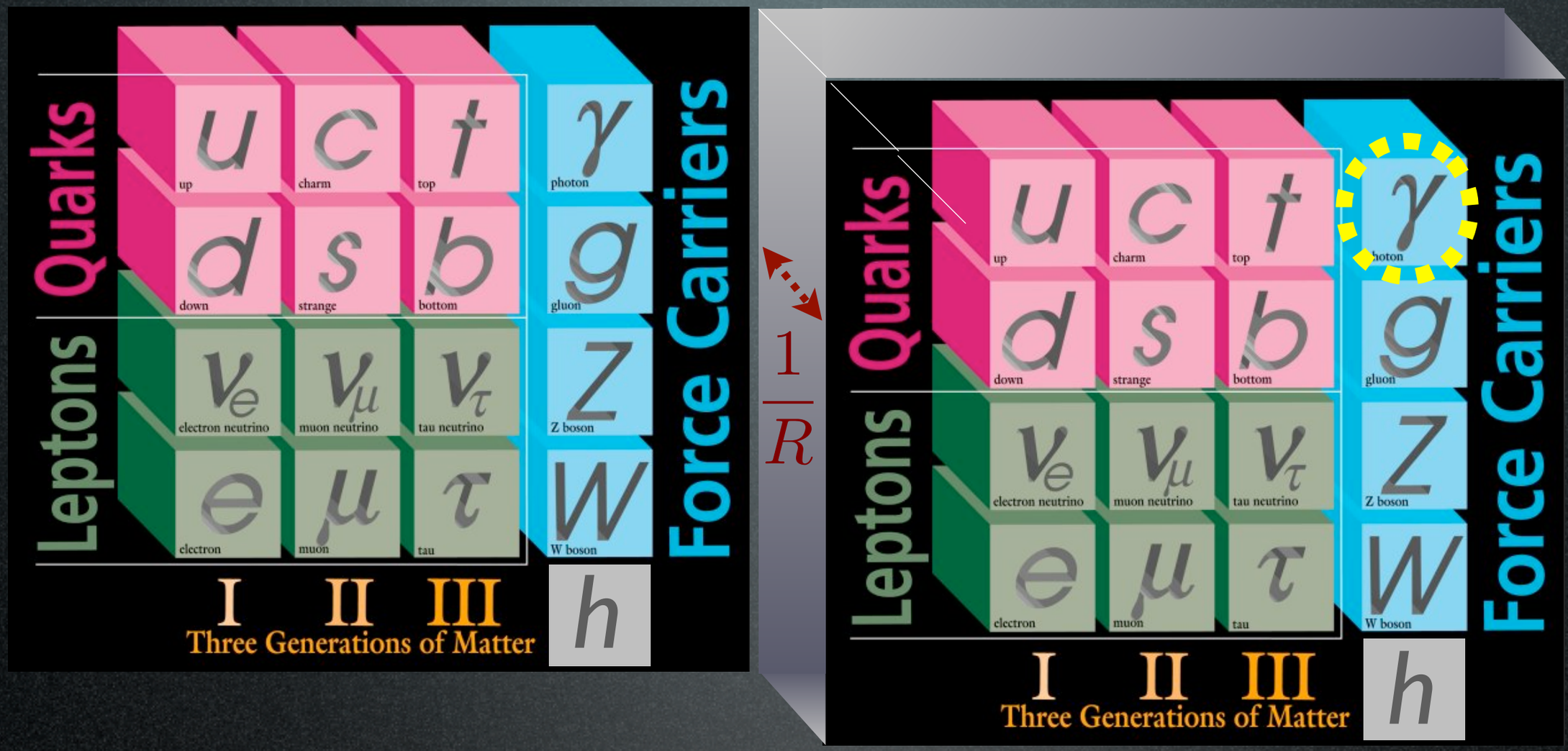
ExDim DM in 2 minutes



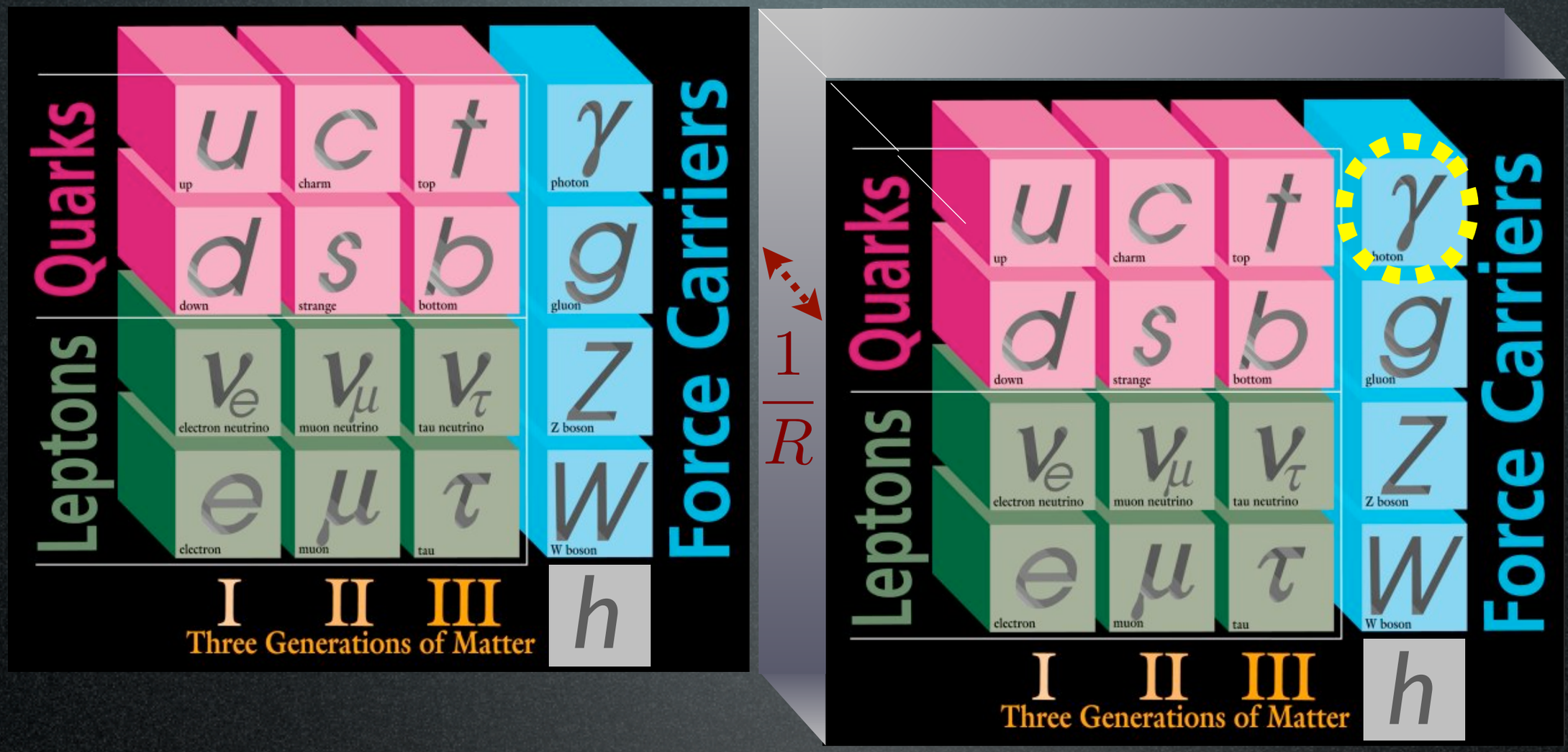
$\frac{1}{R}$



ExDim DM in 2 minutes



ExDim DM in 2 minutes



conservation of 5D momentum

(on orbifold boundary conditions, needed to have chiral SM fermions)

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...

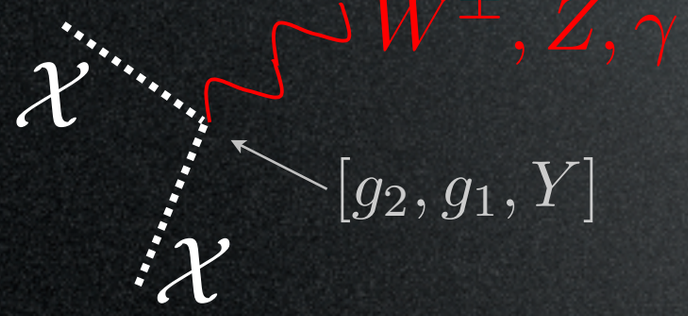
Minimalistic approach

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

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

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

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etc.

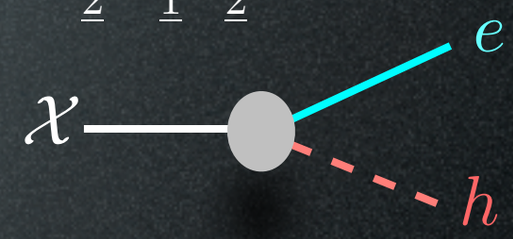
The ideal DM candidate is

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

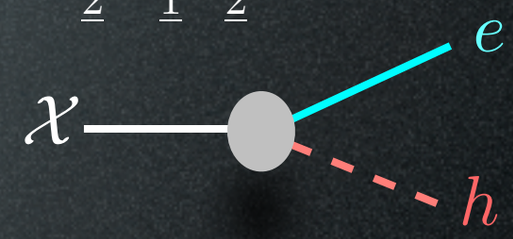
The ideal DM candidate is

weakly int., massive, neutral, stable

$SU(2)_L$	$U(1)_Y$	spin	M (TeV)	ΔM(MeV)	decay ch.
$\underline{2}$	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. $\underset{\underline{2}}{\chi}\underset{1/2}{E}\underset{\underline{1}}{}\underset{-1}{H}\underset{\underline{2}}{}\underset{1/2}{}$



e.g. $\underset{\underline{4}}{\chi}\underset{1/2}{L}\underset{\underline{2}}{}\underset{-1/2}{H}\underset{\underline{2}}{}\underset{1/2}{H^*}\underset{\underline{2}}{}\underset{-1/2}{}$

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

Ορθοδοξία → **Έτεροδοξία** → **Αίρεση**

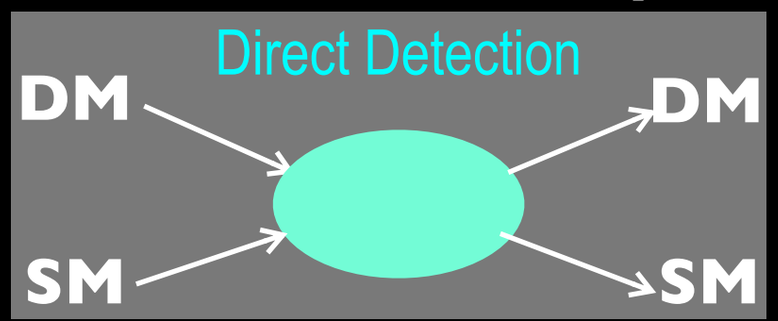
'ad hoc' symmetry

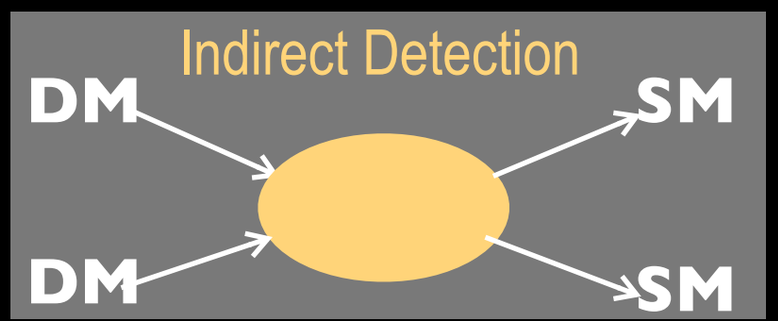
automatically
stable

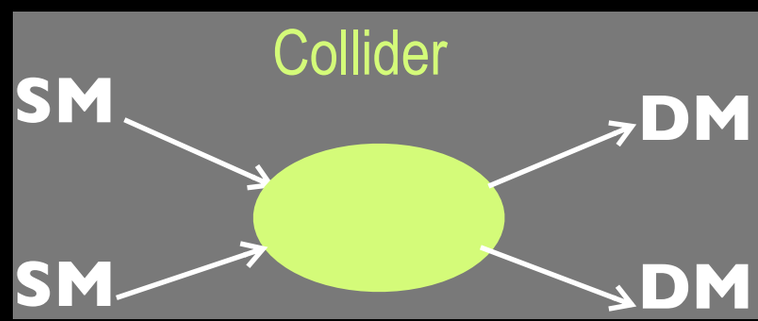
(like Minimal
Dark Matter)

Executive summary

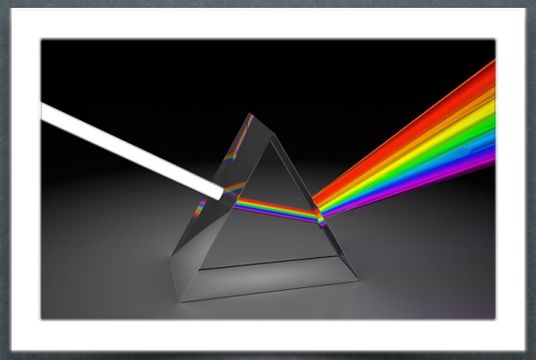
- DM exists
- it's a new, unknown particle — *no SM particle can fulfil* — *dilutes as $1/a^3$ with universe expansion*
- makes up 26% of total energy
  84% of total matter — $\Omega_{\rm DM} h^2 = 0.1188 \pm 0.0010$ *(notice error!)*
- neutral particle *'dark'...*
- cold or not too warm — *p/m <<1 at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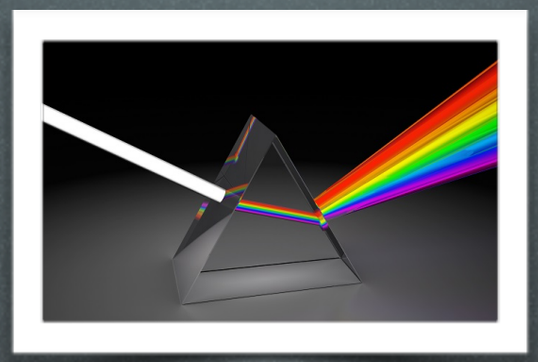

SuSy neutralino

multi-TeV self-interacting leptophilic decaying asymmetric Dark Matter

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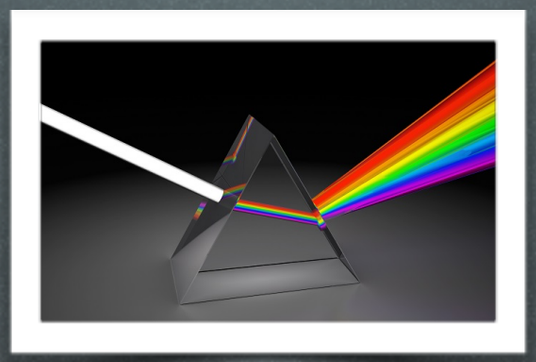

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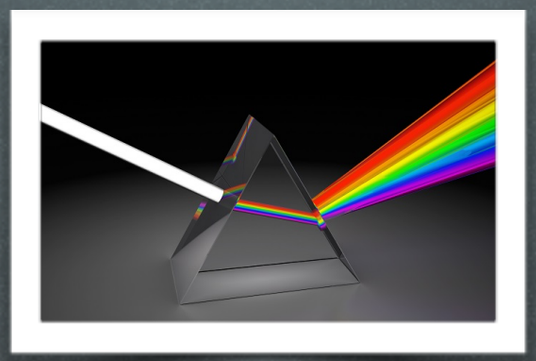

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Backup slides

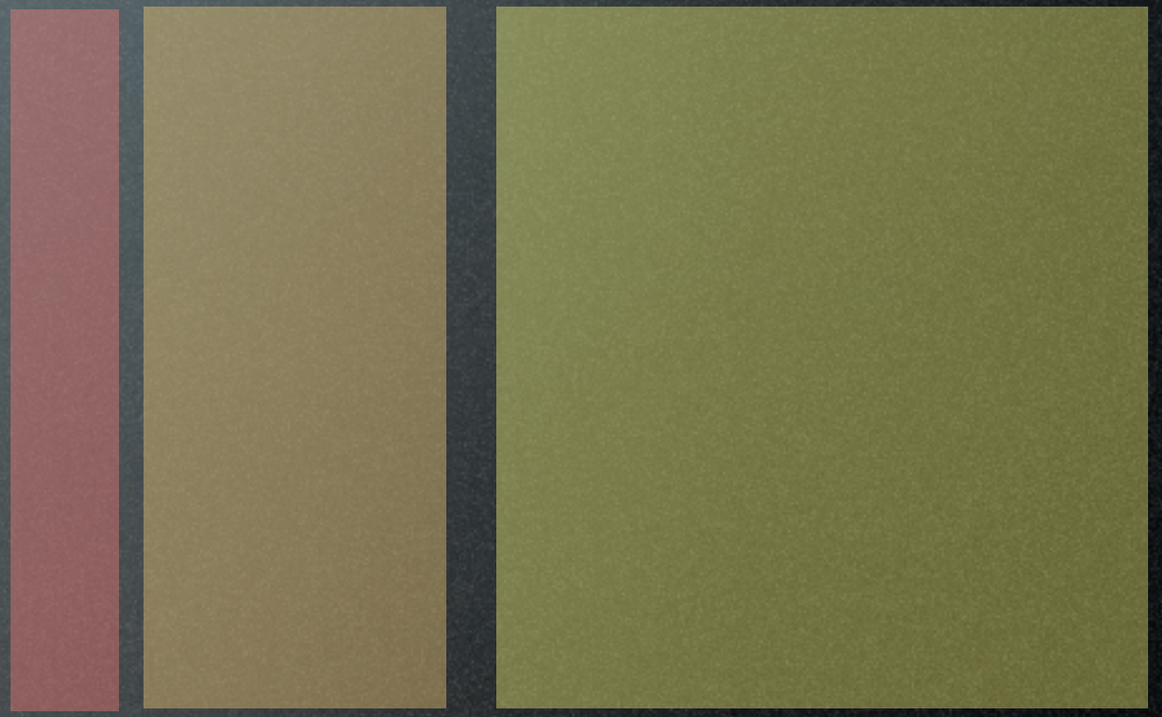
Asymmetric Dark Matter

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

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



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

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

Asymmetric **Oscillating** DM

Cirelli, Panci, Servant, Zaharijas 1110.3809

Asymmetric Oscillating DM

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

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Asymmetric ‘freeze-out’

The correct Ω_{DM} can not be obtained.

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

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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

The system:

coherent

- oscillations $\mathrm{DM} \leftrightsquigarrow \overline{\mathrm{DM}}$

- annihilations $\mathrm{DM}\,\overline{\mathrm{DM}} \to X\,X$
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incoherent

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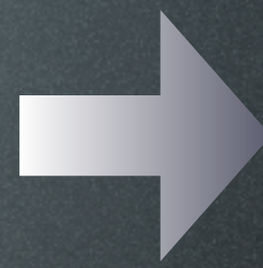

density matrix formalism

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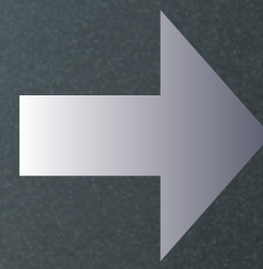

density matrix formalism

Density matrix:

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

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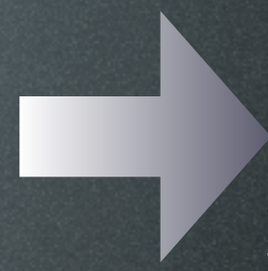

density matrix formalism

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

(comoving) number density of DM

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

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

Formalism

The system:

coherent

- oscillations $\mathrm{DM} \leftrightsquigarrow \overline{\mathrm{DM}}$

- annihilations $\mathrm{DM}\,\overline{\mathrm{DM}} \to X\,X$
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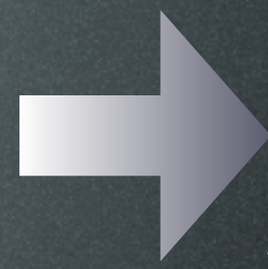

density matrix formalism

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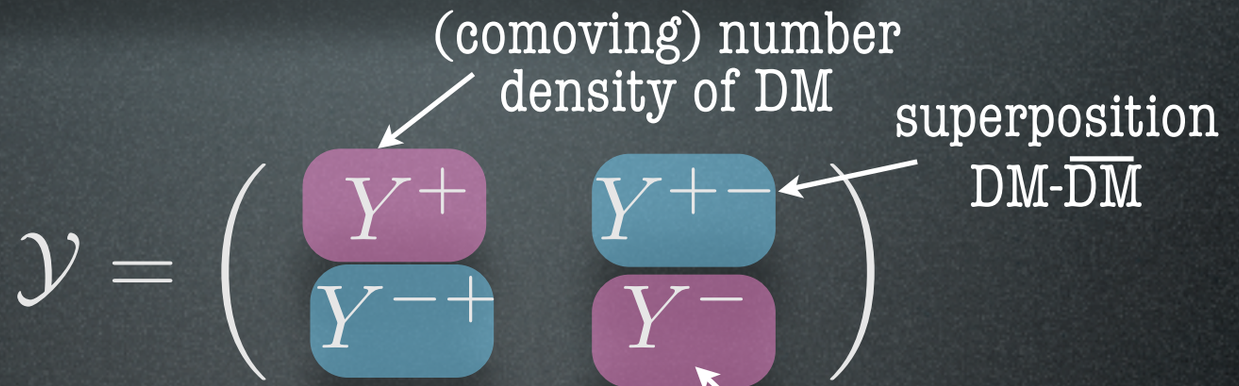

Evolution in time:

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

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

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

Formalism

The system:

coherent

- oscillations $\mathrm{DM} \leftrightsquigarrow \overline{\mathrm{DM}}$

- annihilations $\mathrm{DM}\,\overline{\mathrm{DM}} \to X\,X$
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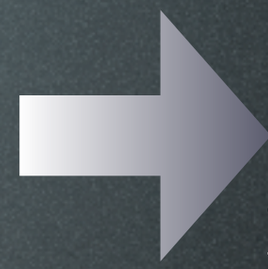

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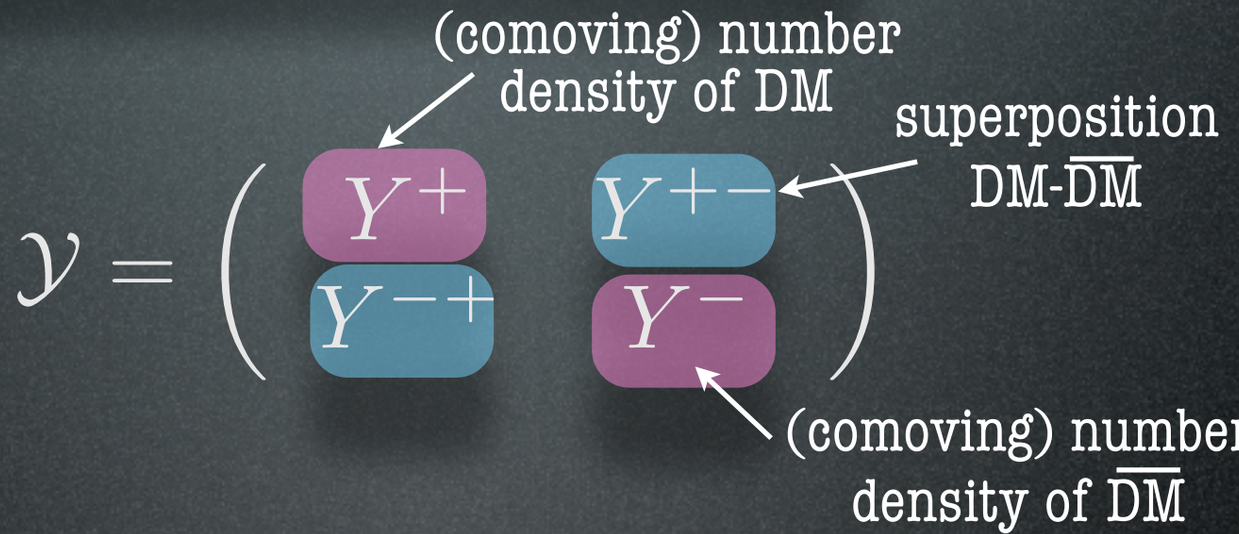


Evolution in time:

$$\mathcal{Y}'(x) = -\frac{i}{x\,H(x)}\Big[\mathcal{H}, \mathcal{Y}(x)\Big]$$ **oscillations**

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

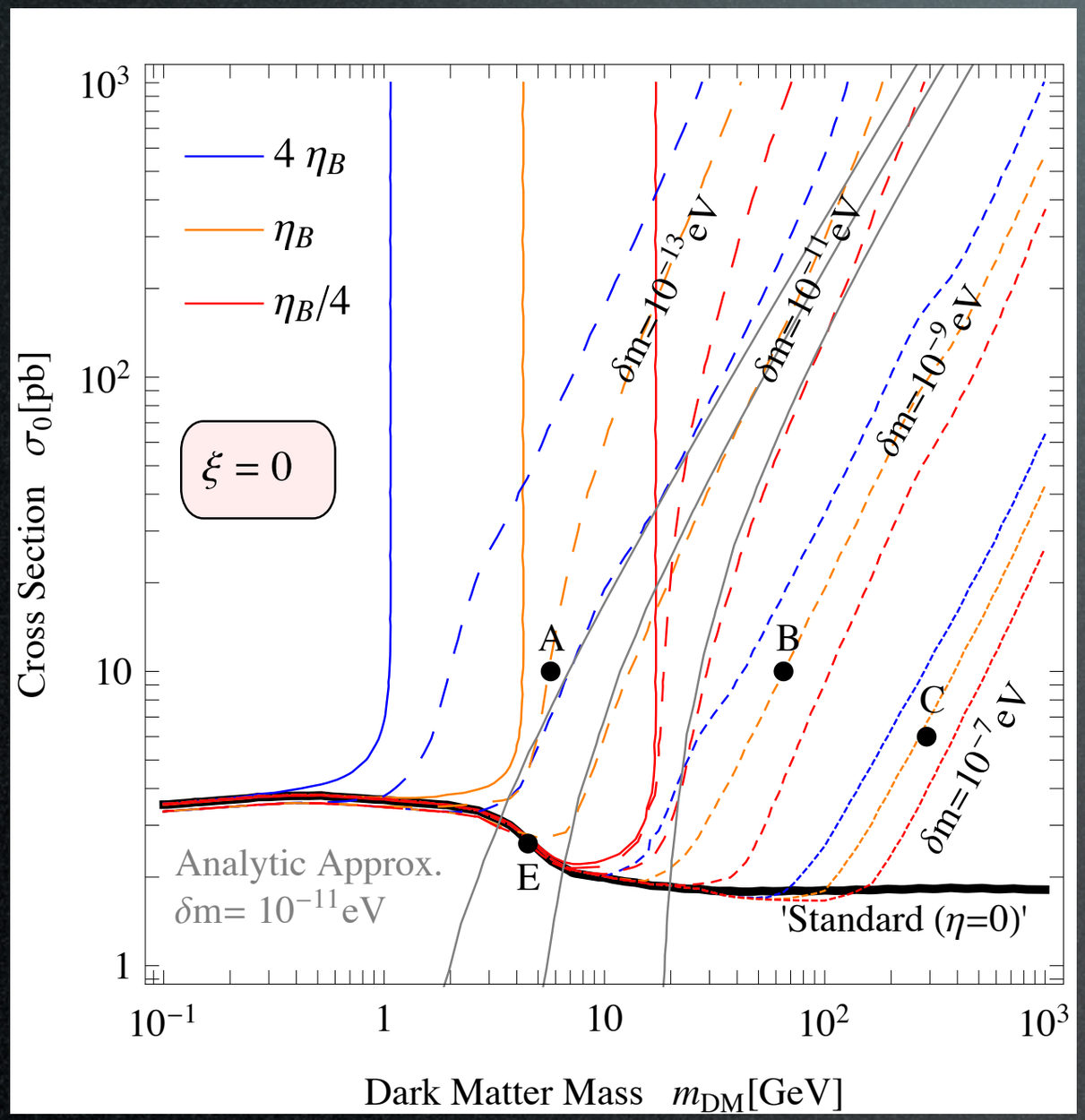
$$-\frac{s(x)}{x\,H(x)}\left(\frac{1}{2}\Big\{\mathcal{Y}(x), \Gamma_{\mathrm{a}}\,\bar{\mathcal{Y}}(x)\,\Gamma_{\mathrm{a}}^{\dagger}\Big\} - \Gamma_{\mathrm{a}}\,\Gamma_{\mathrm{a}}^{\dagger}\,\mathcal{Y}_{\mathrm{eq}}^{2}\right)$$ **annihilations**

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

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

Results

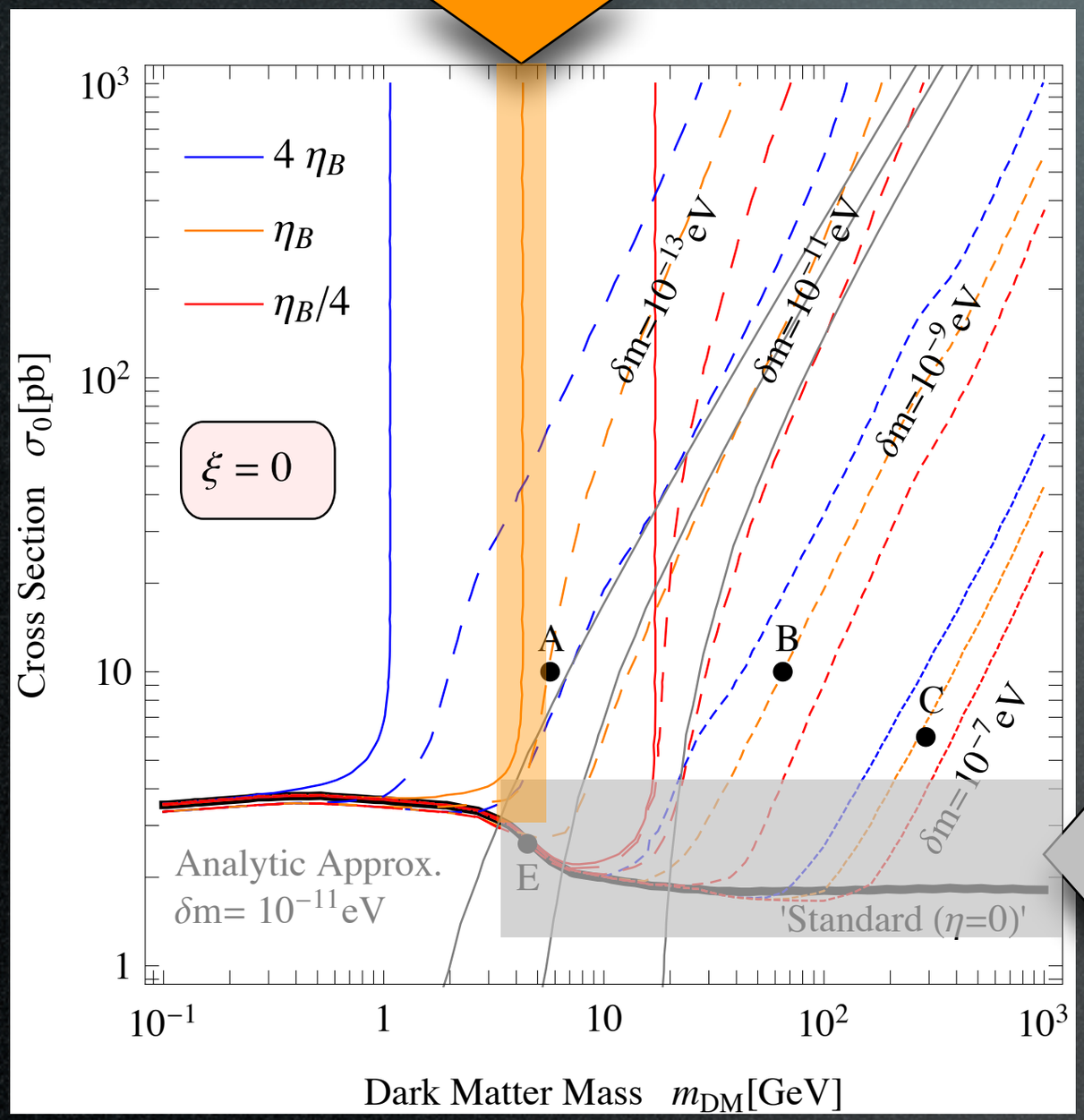
Parameter space: isolines of correct $\Omega_{\rm DM}$



Results

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

standard aDM



standard WIMP miracle

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

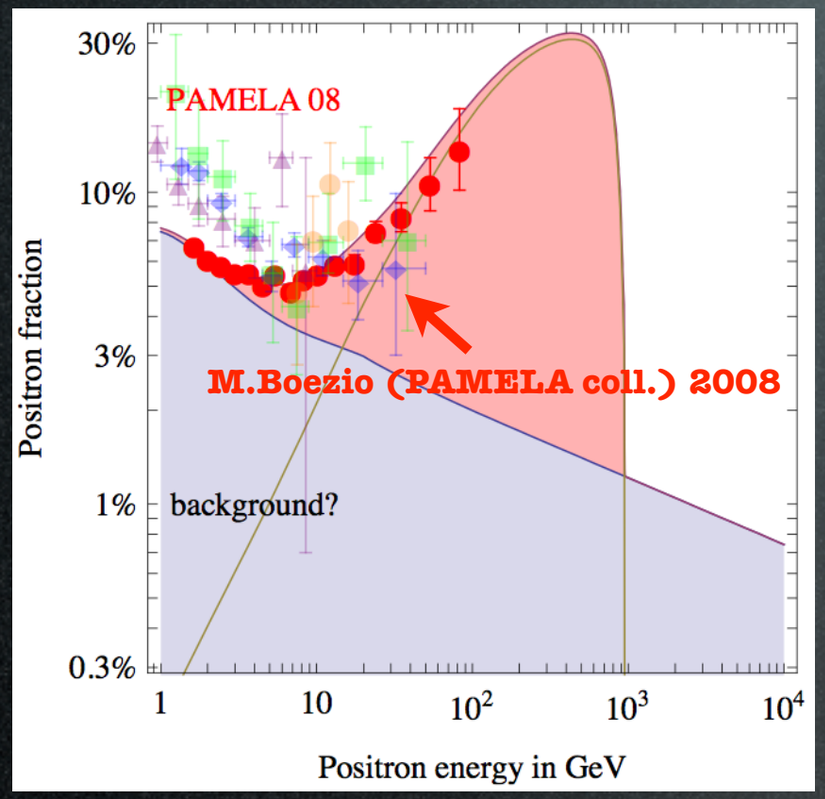
‘Secluded’ Dark Matter

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

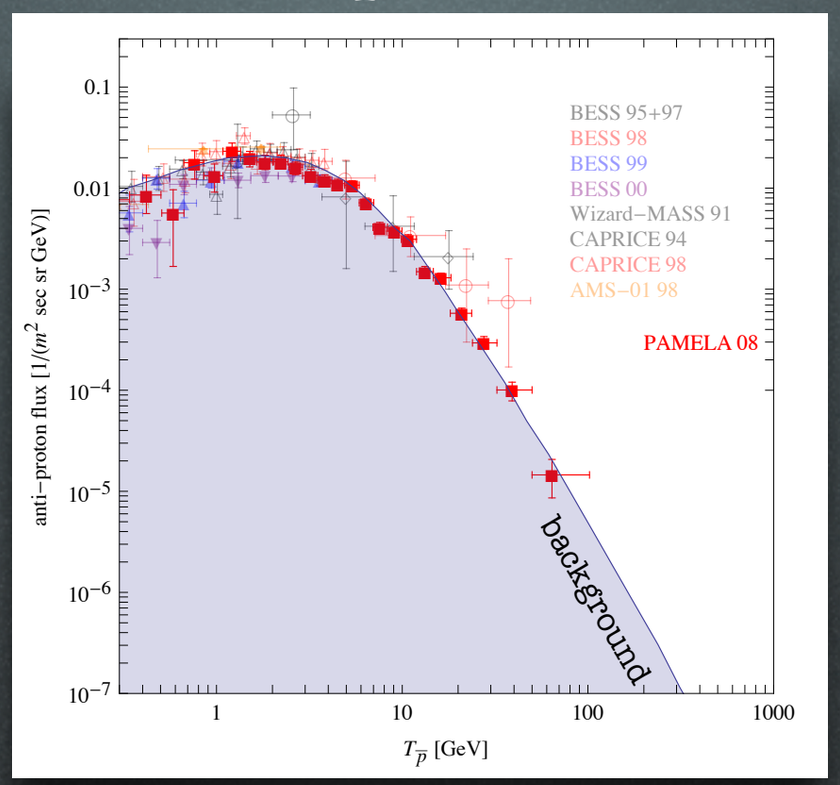
Main motivation

Main motivation

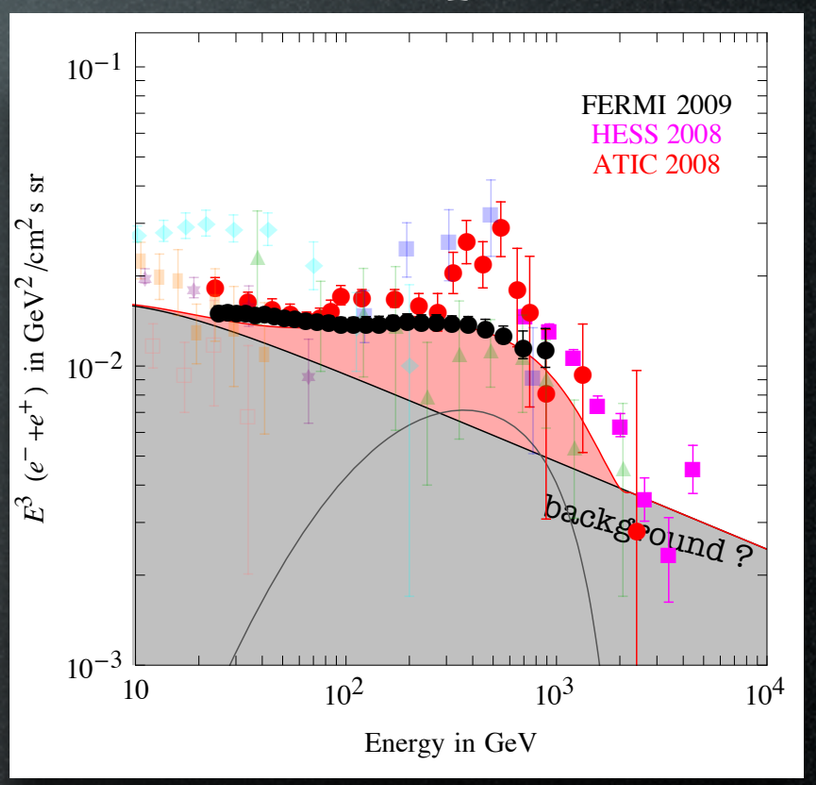
positron fraction



antiprotons



electrons + positrons

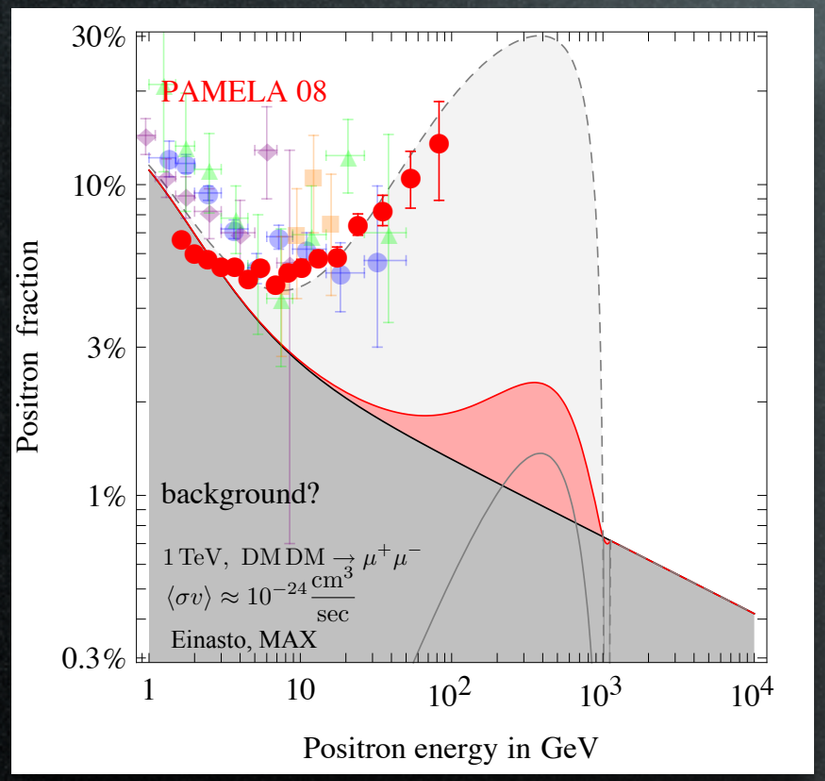


Are these signals of Dark Matter?

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

Main motivation

positron fraction



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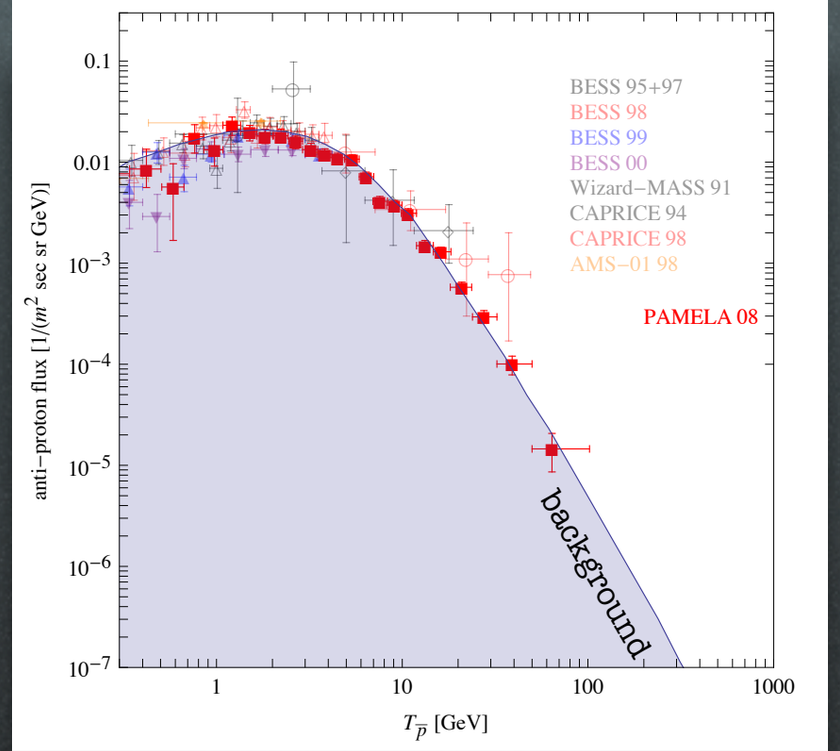

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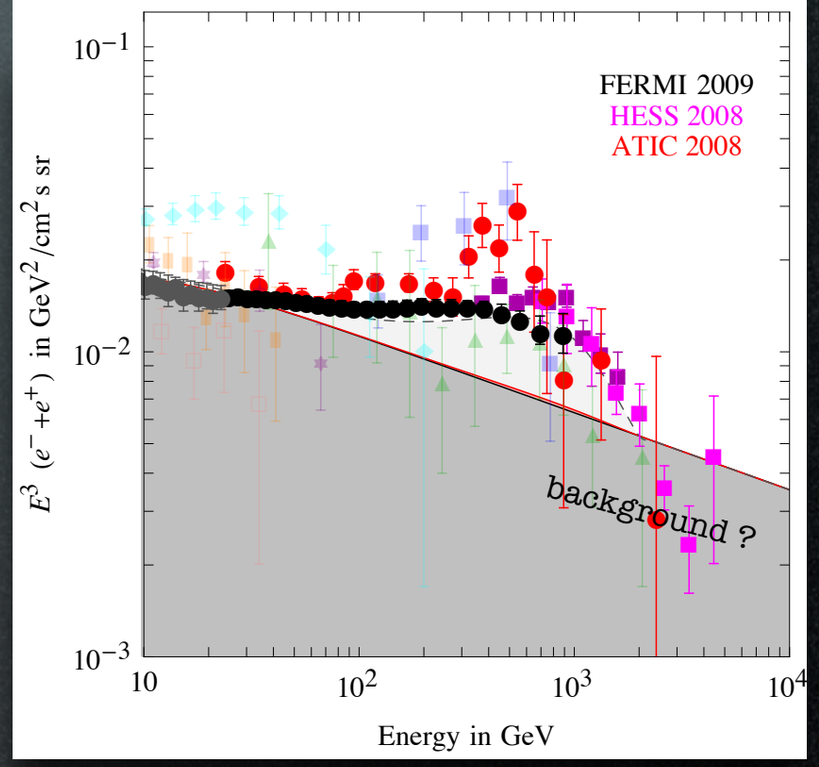


Are these signals of Dark Matter?

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"

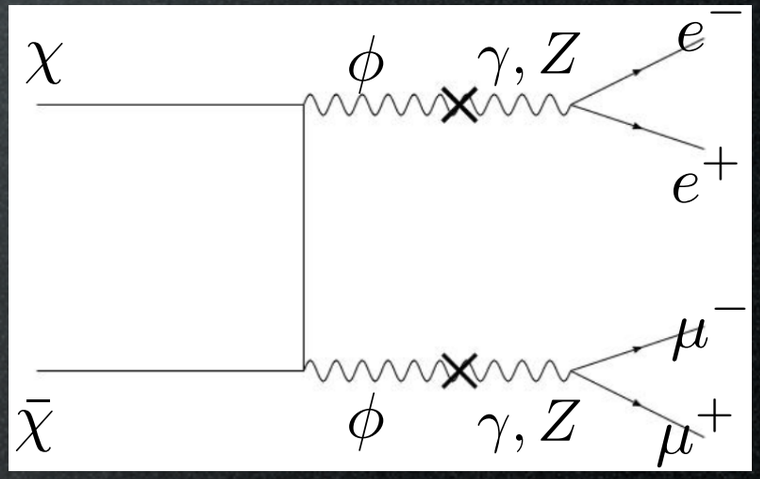
Arkani-Hamed, Weiner, Finkbeiner et al. 0810.0713
0811.3641

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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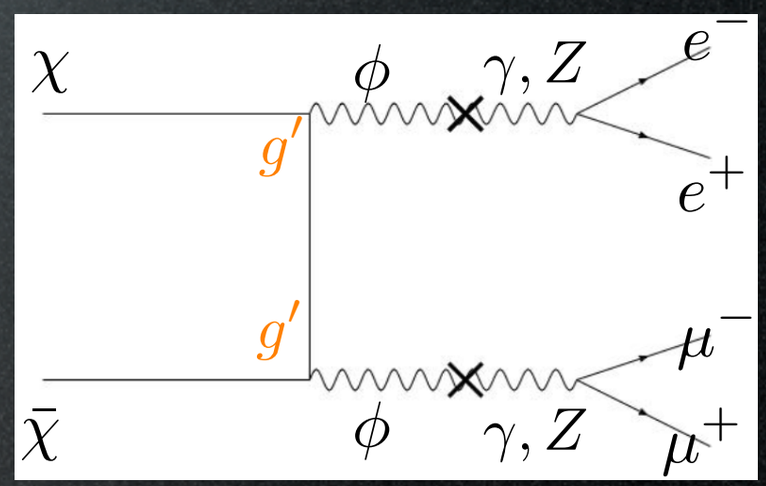

Production mechanism:

just thermal freeze-out
of these annihilations

same idea in: WIMPless DM Feng, Kumar 2008

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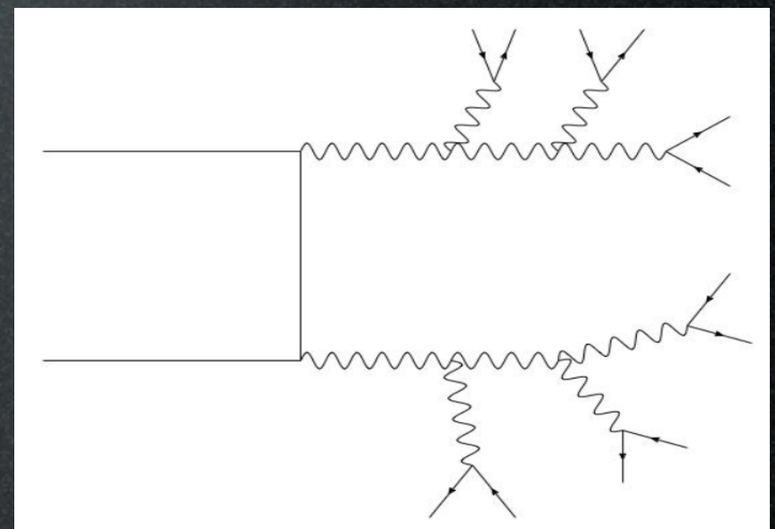


- decays only into e^+e^- or $\mu^+\mu^-$
for kinematical limit

Extras:

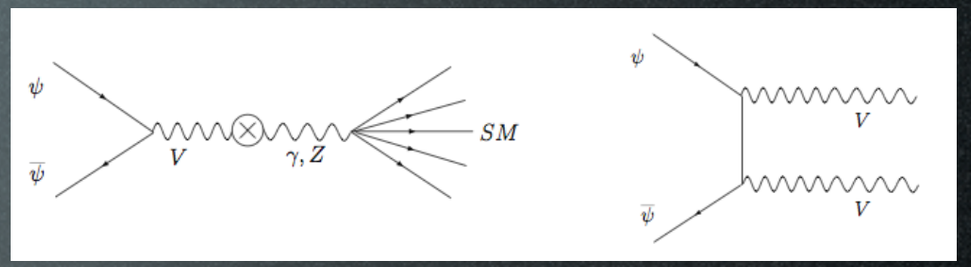
χ is a multiplet of states and ϕ is non-abelian gauge boson:
splitting $\delta M \sim 200$ KeV (via loops of non-abelian bosons)
- inelastic scattering explains DAMA
- eXcited state decay $\chi\chi \to \chi\chi^*$ explains INTEGRAL
$\hookrightarrow e^+e^-$

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

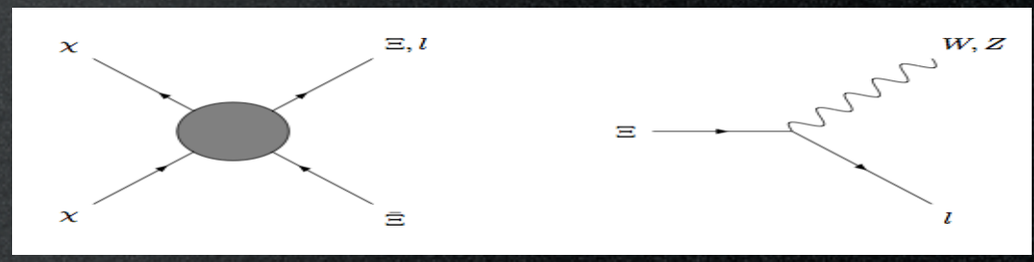
  Park, Shu 0901.0720

- 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]