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Strongly interacting light dark matter

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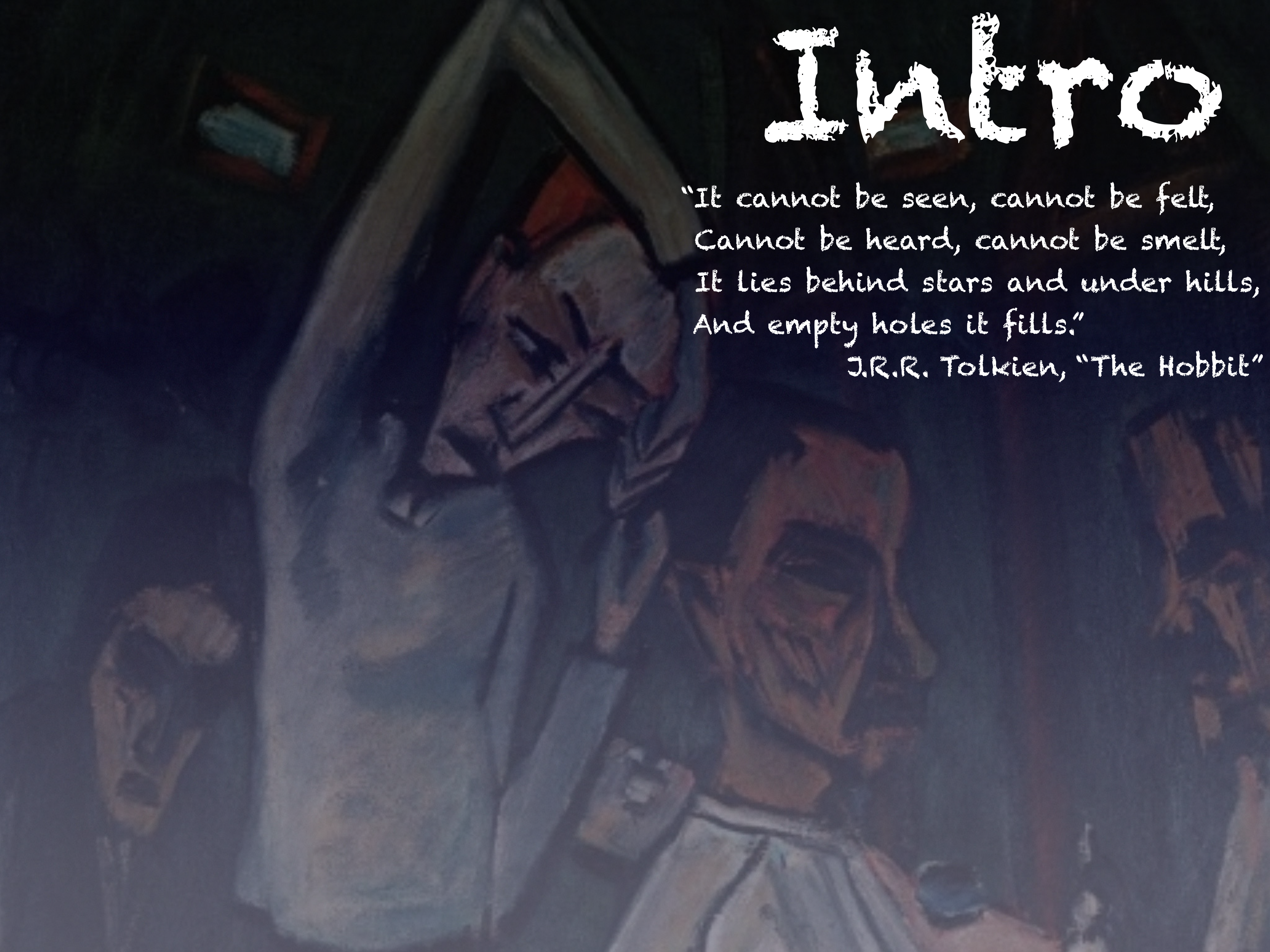
Intro

"It cannot be seen, cannot be felt,
Cannot be heard, cannot be smelt,
It lies behind stars and under hills,
And empty holes it fills."

J.R.R. Tolkien, "The Hobbit"



Intro

5 "golden rules"

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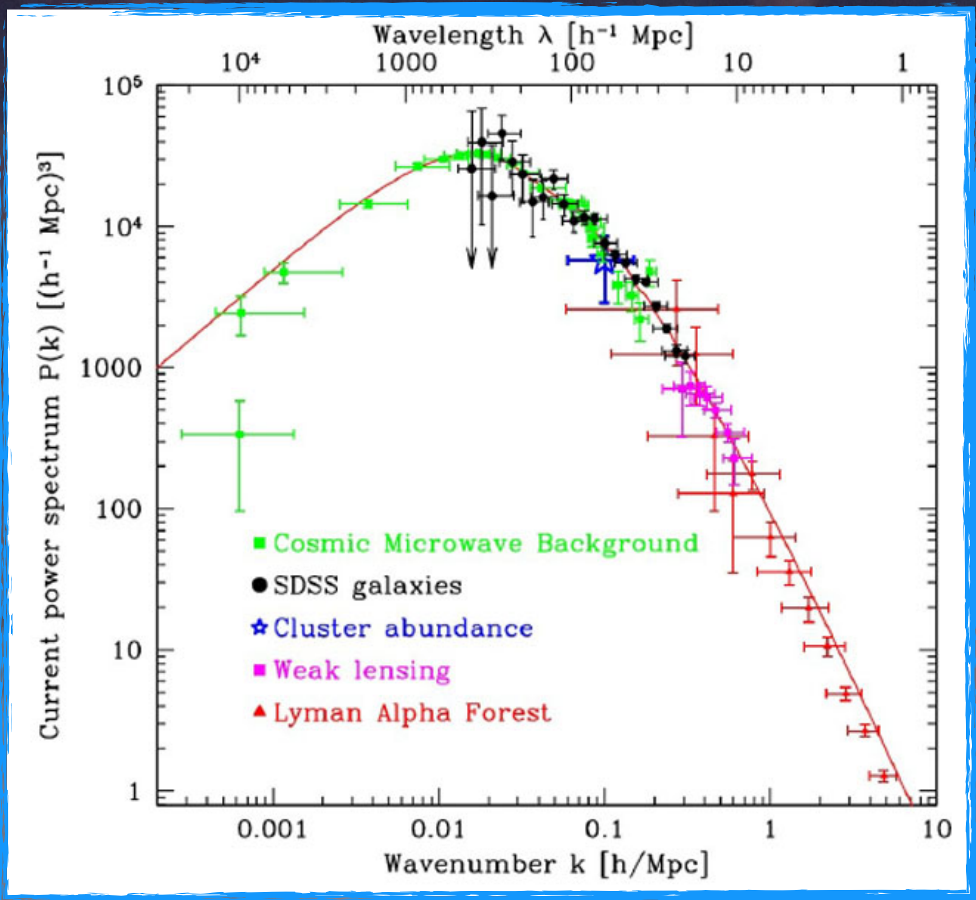
1) DM is optically dark and dissipative-less

Suppressed EM interactions that would spoil shape and amplitude of the matter power spectrum



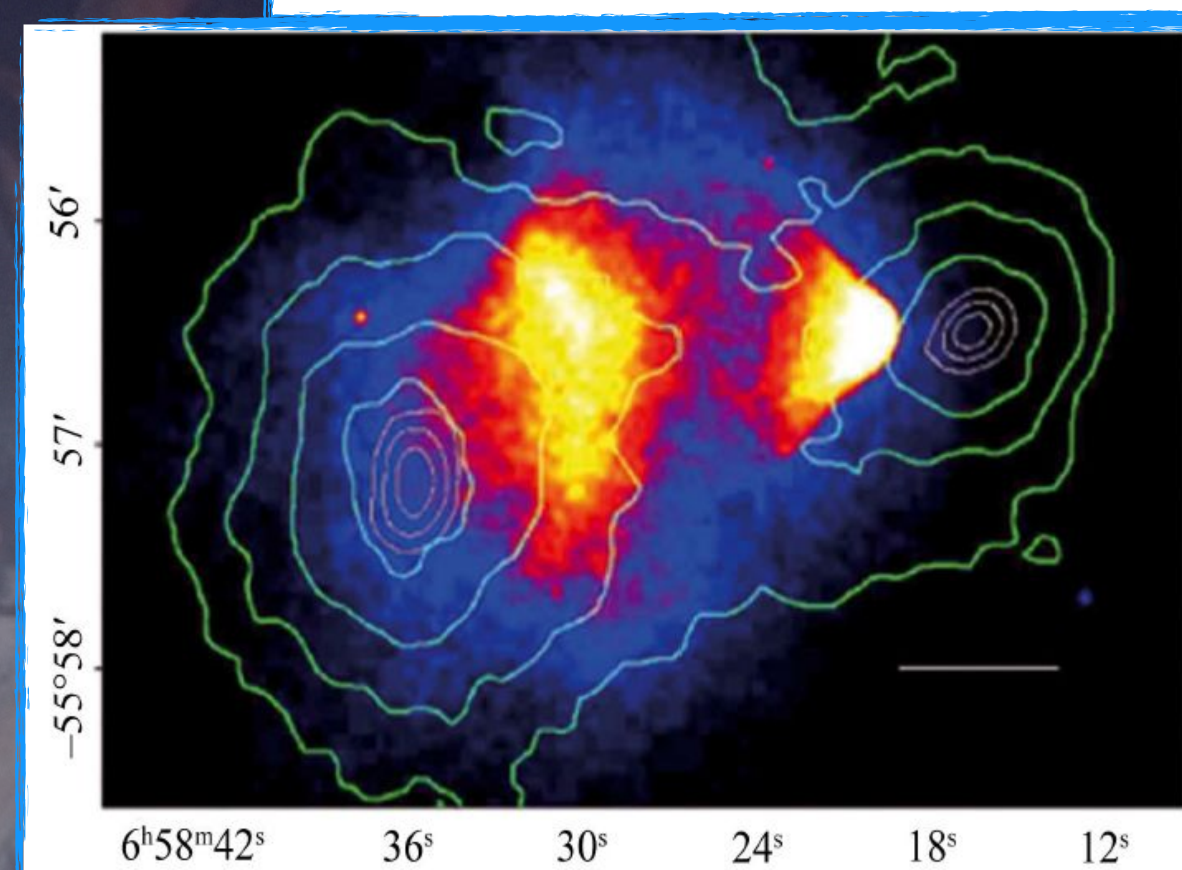
Intro

5 "golden rules"

2) DM is collision-less

If DM-DM interactions are too strong, spherical structures would be obtained rather than triaxial

$$\sigma_{\rm self} \lesssim \left(\frac{m_{\rm DM}}{1\,{\rm GeV}}\right)$$

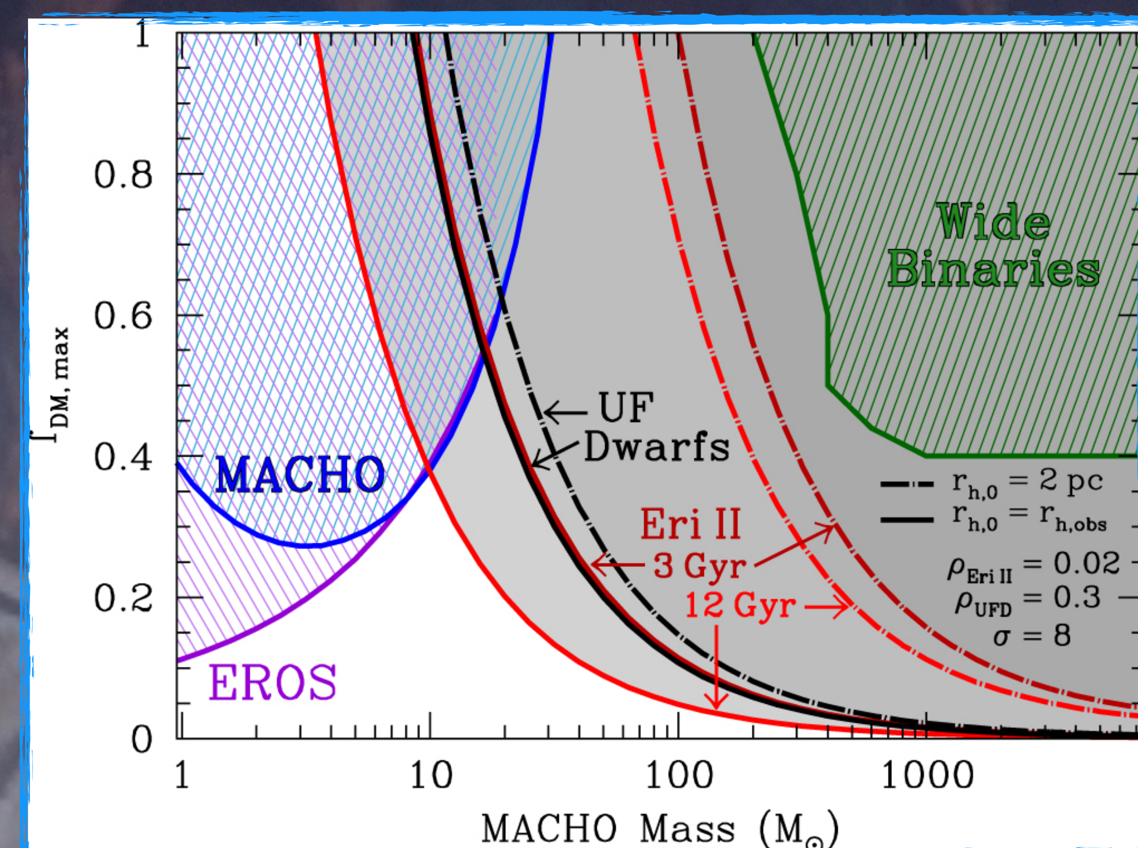


Intro

5 “golden rules”

3) DM is smoothly distributed

We have not seen any discreteness effect in DM halos



Intro

5 "golden rules"

4) DM must behave classically to be confined on galactic scales (say, 1 kpc)

$$m_b \gtrsim 10^{-22}\,\mathrm{eV}$$

$$m_f \gtrsim \mathcal{O}(10 - 100$$

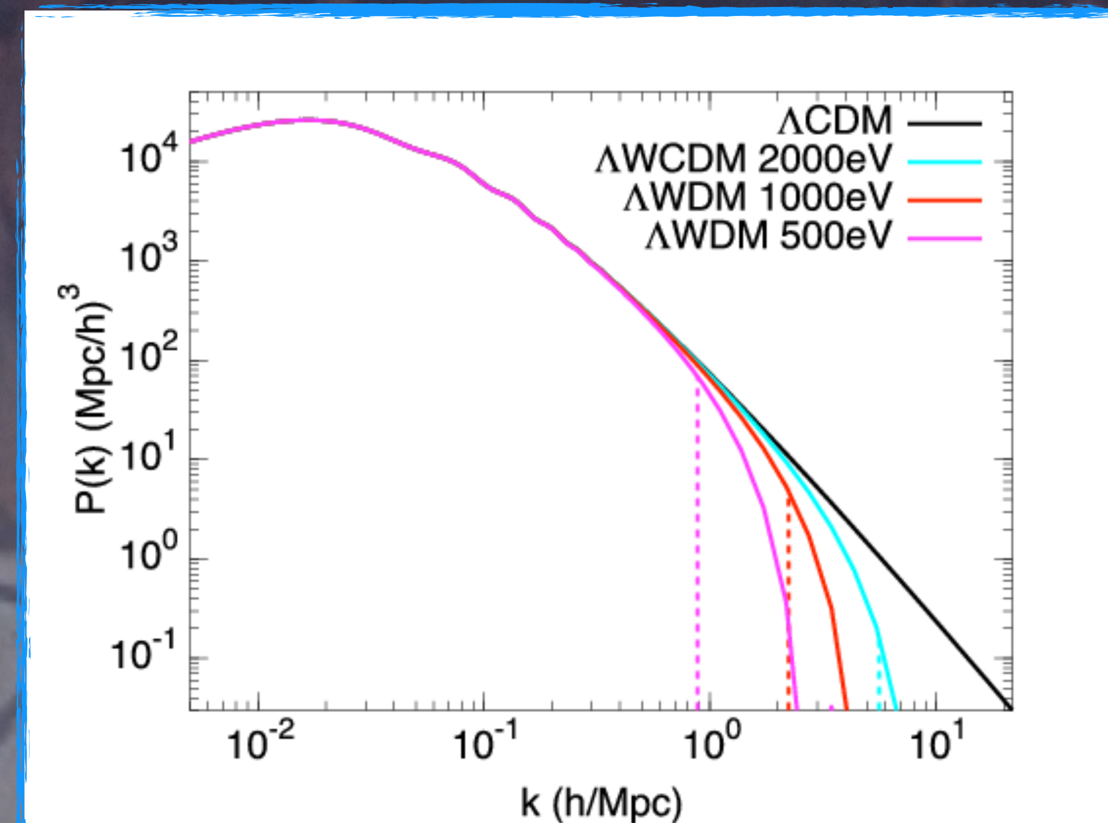
Intro

5 "golden rules"

5) DM is not hot

It cannot be relativistic at matter-radiation equality, since matter perturbations need to grow at that time.

WDM erases small-scale structures in the matter power spectrum

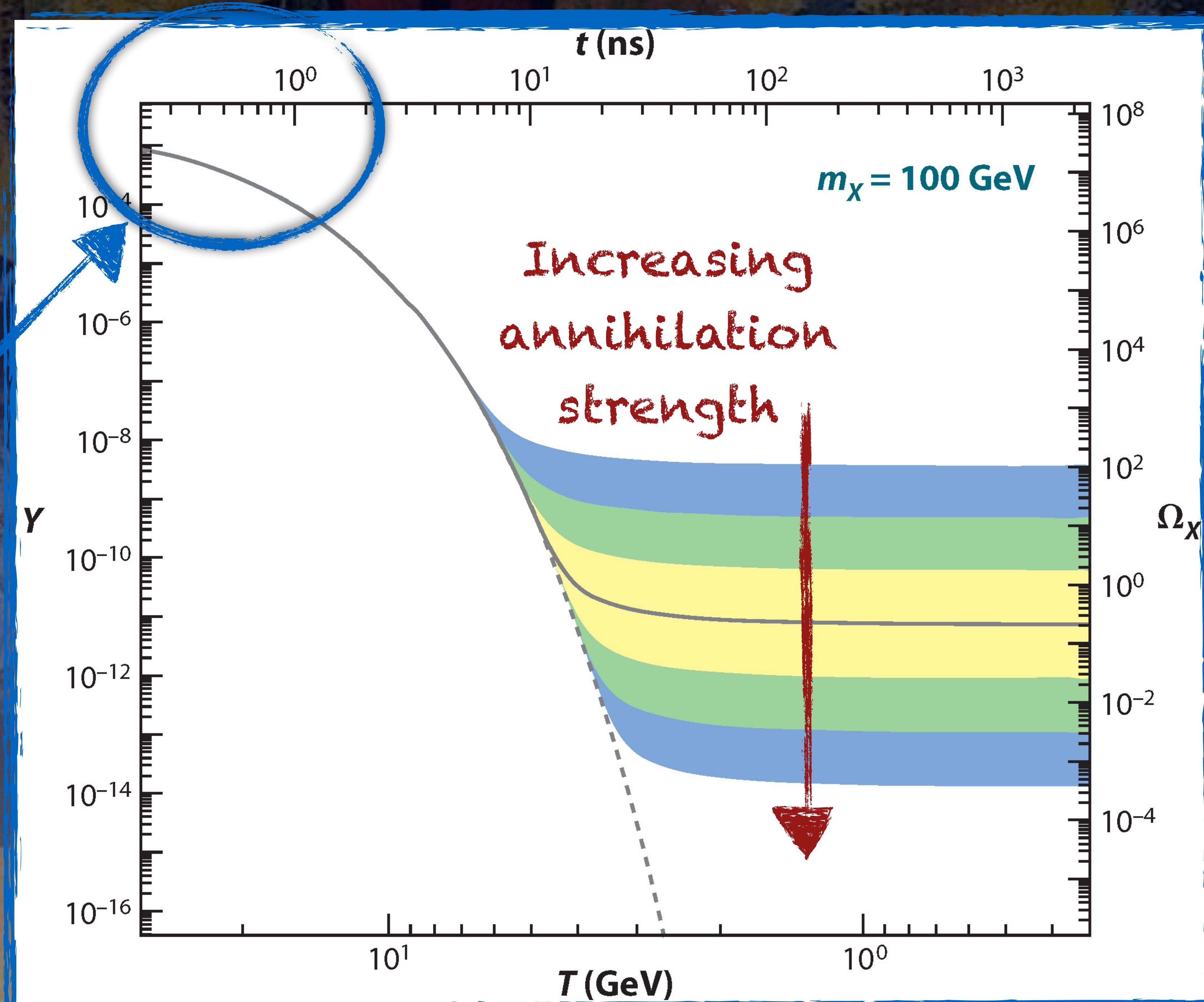


The WIMP miracle

The WIMP miracle

Assume DM is initially in thermal equilibrium

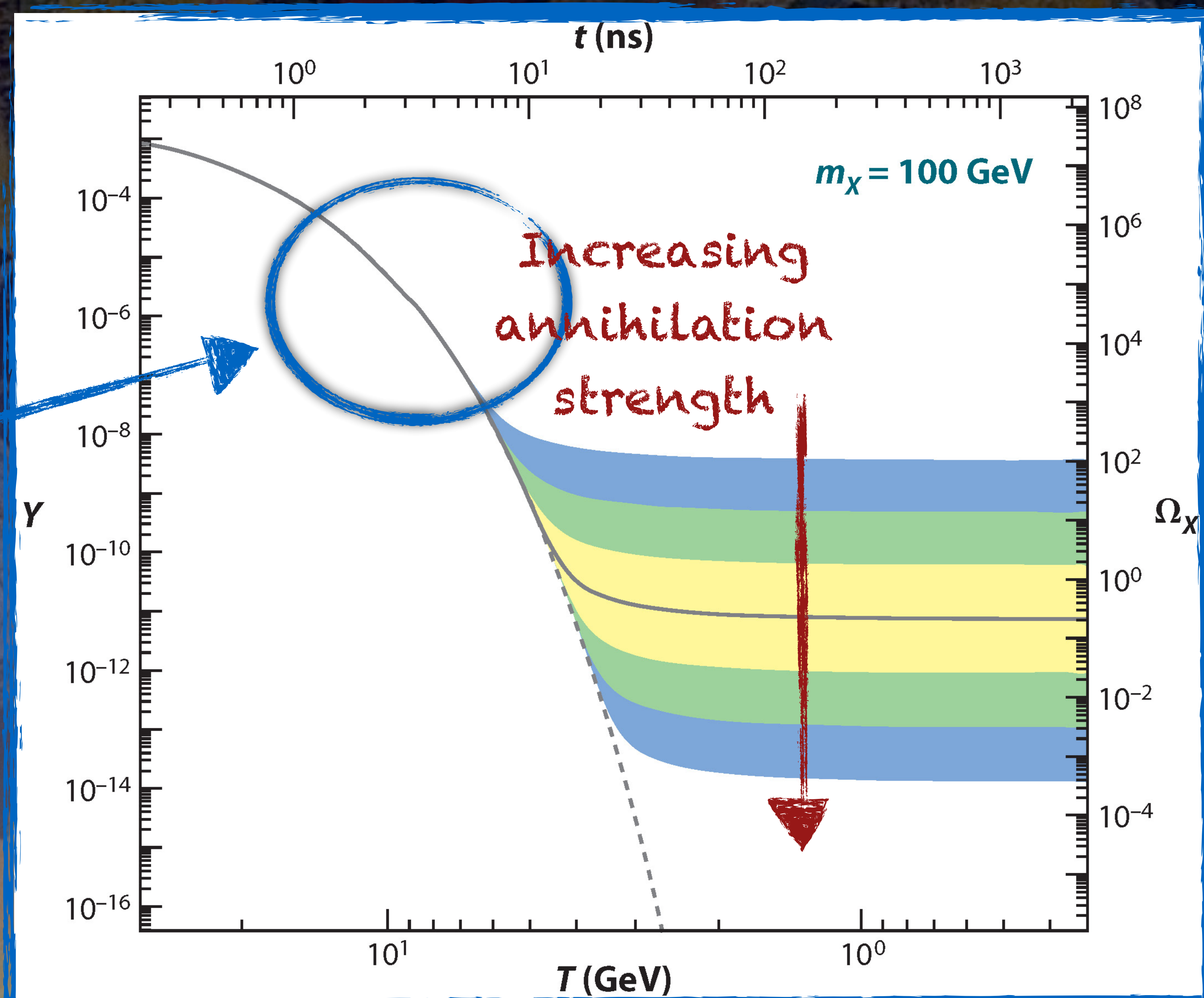
$$\bar{\chi}\chi \;\Leftrightarrow\; \mathrm{SM\,SM}$$



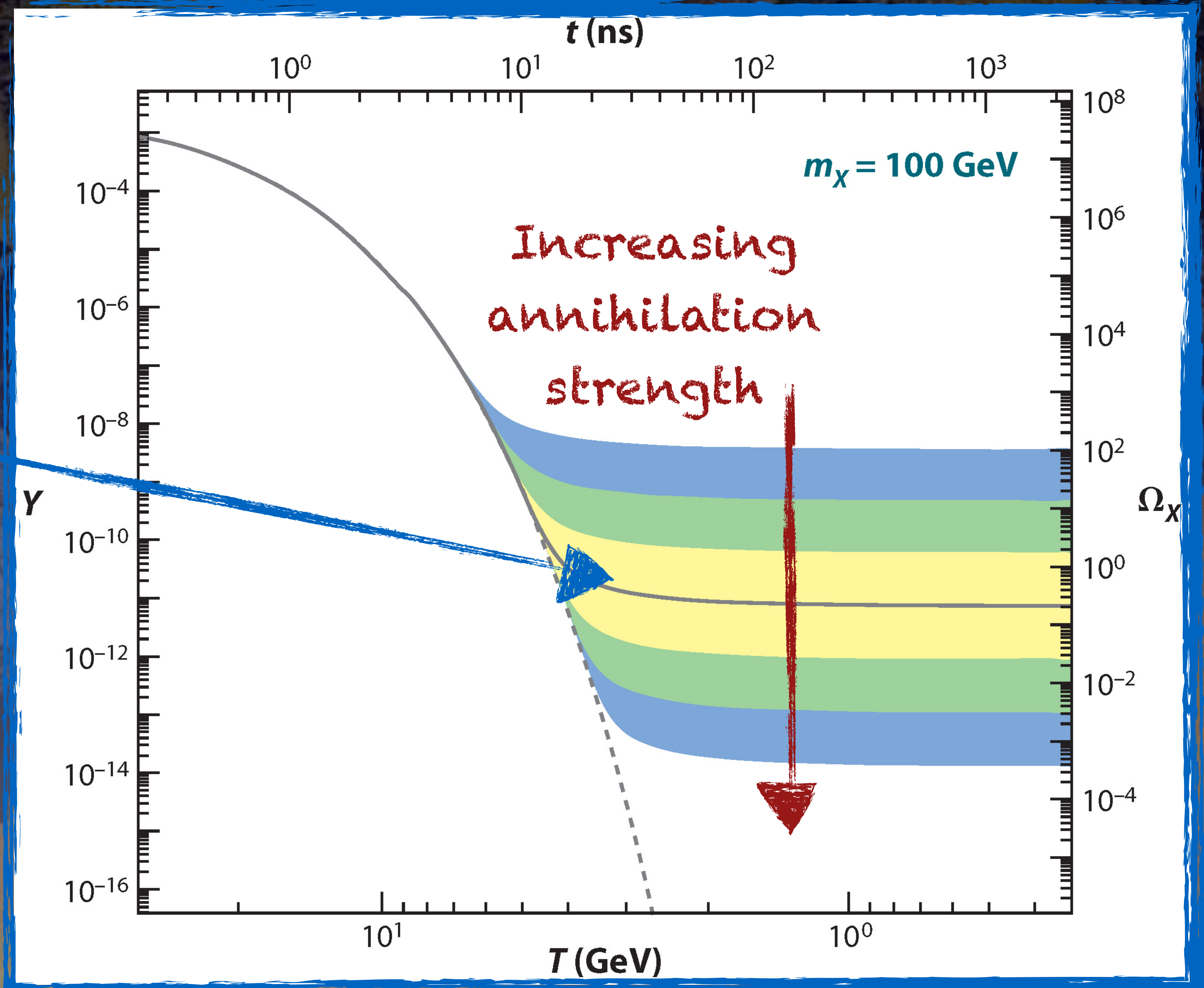
The WIMP miracle

Universe cools

$$\bar{\chi}\chi \rightarrow \mathrm{SM\,SM}$$



The WIMP miracle



The WIMP miracle

$$\Omega_{\rm DM}h^2 \approx \frac{10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle\sigma v_{\rm rel}\rangle} \approx \underbrace{0.1 \times \left(\frac{0.01}{\alpha_{\rm DM}}\right)^2 \times \left(\frac{m_{\rm DM}}{100\,\mathrm{GeV}}\right)^2}_{\text{assuming the scaling } \langle\sigma \mathrm{v}_{\rm rel}\rangle \sim \alpha_{\rm DM}^2/\mathrm{m}_{\rm DM}^2}$$

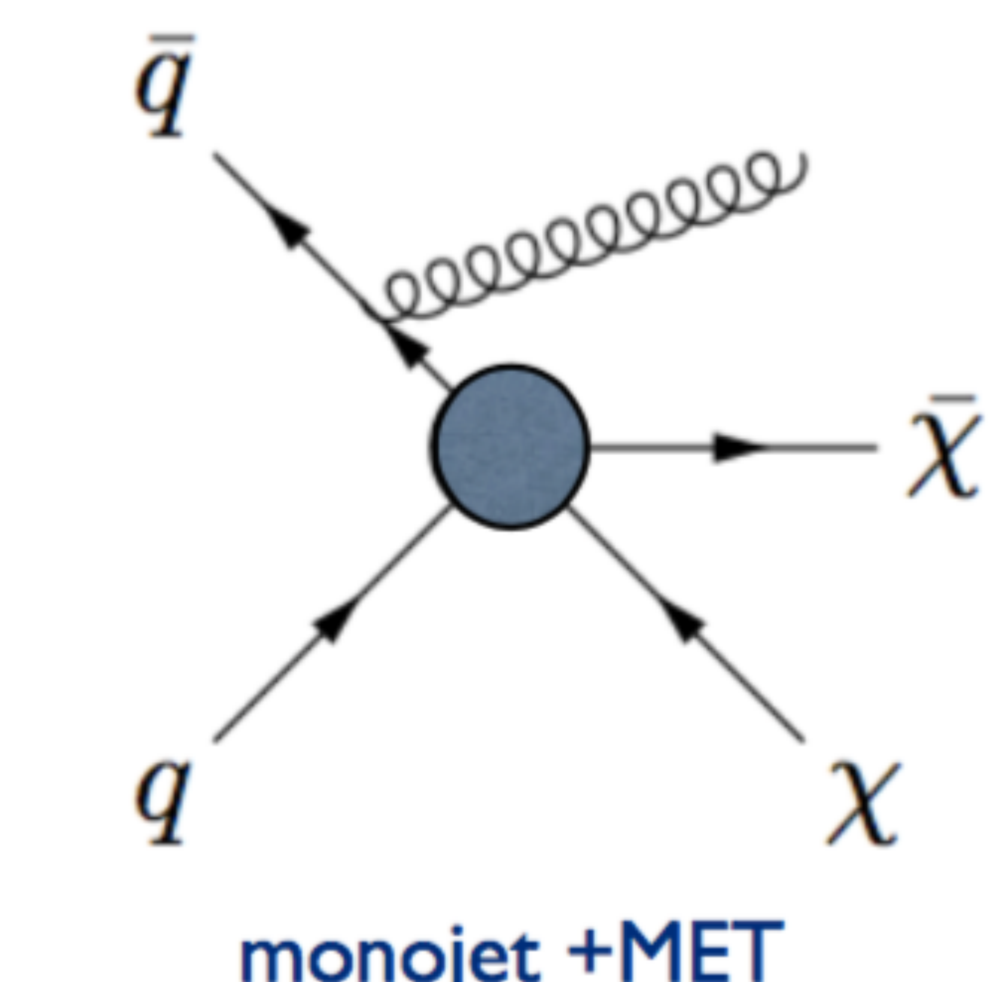
Measured by Planck (0.1199 \pm 0.0027)

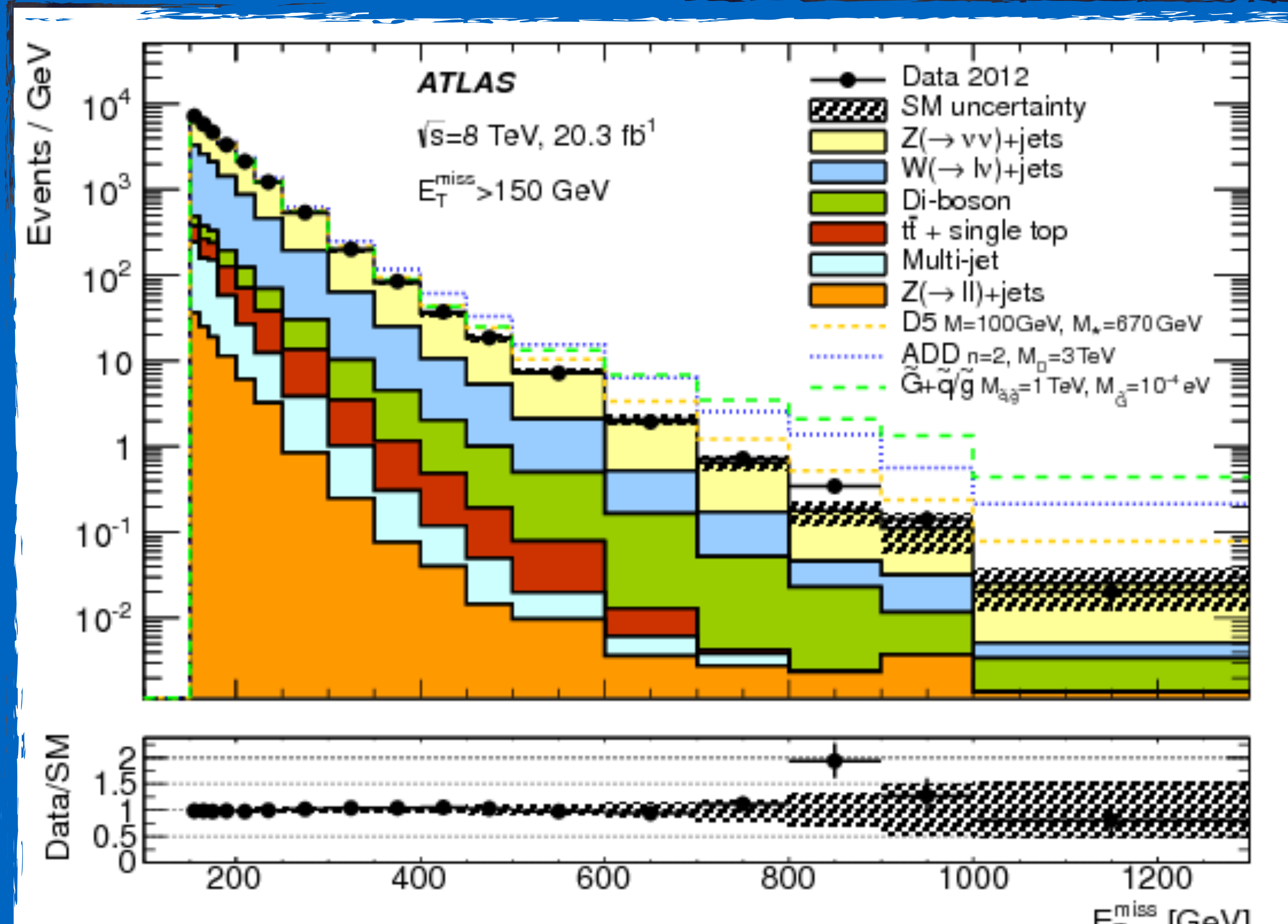
arXiv:1303.5076

DM @ LHC

DM @ LHC

$$\frac{(\bar{\chi}\gamma^{\mu}\chi)(\bar{q}\gamma_{\mu}q)}{\Lambda^2}$$

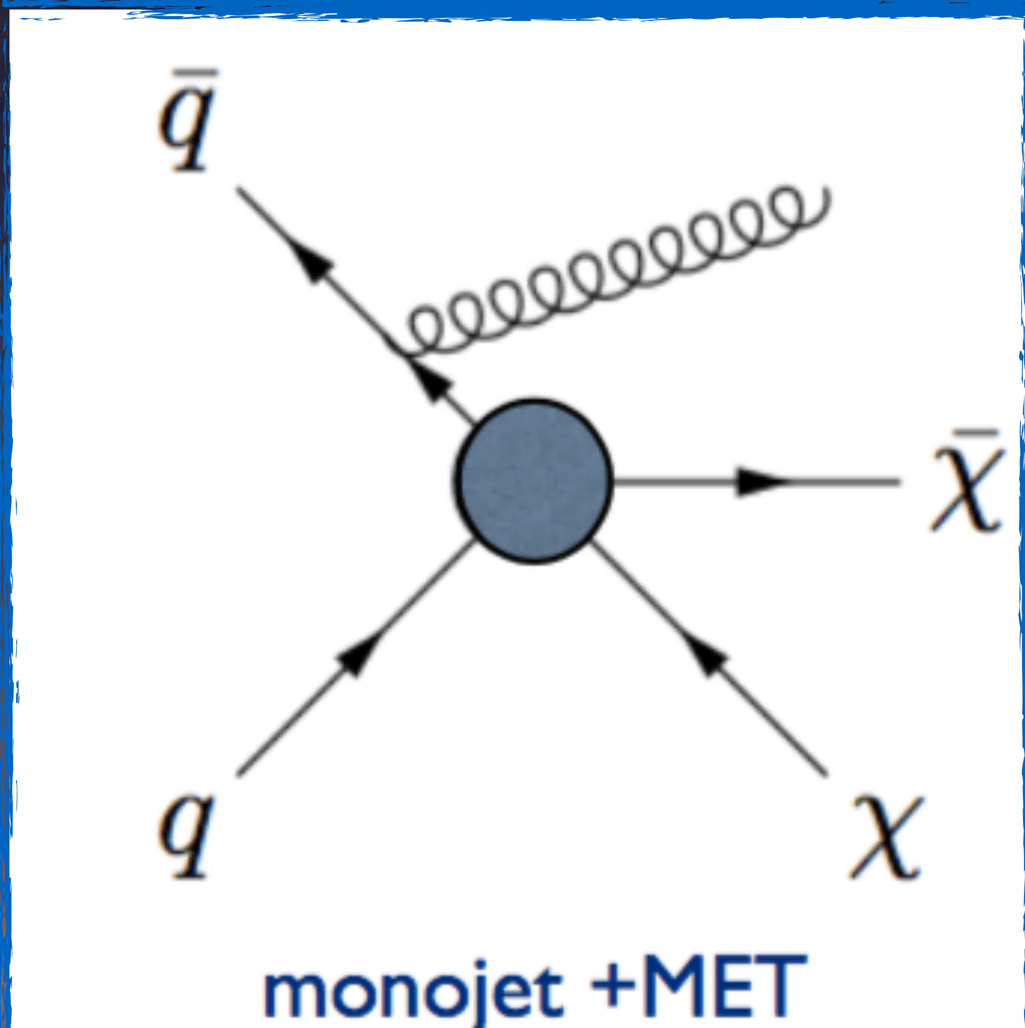


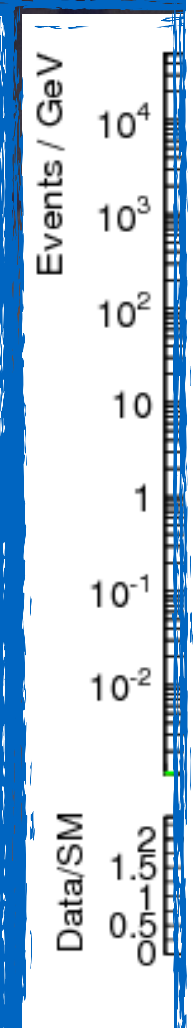


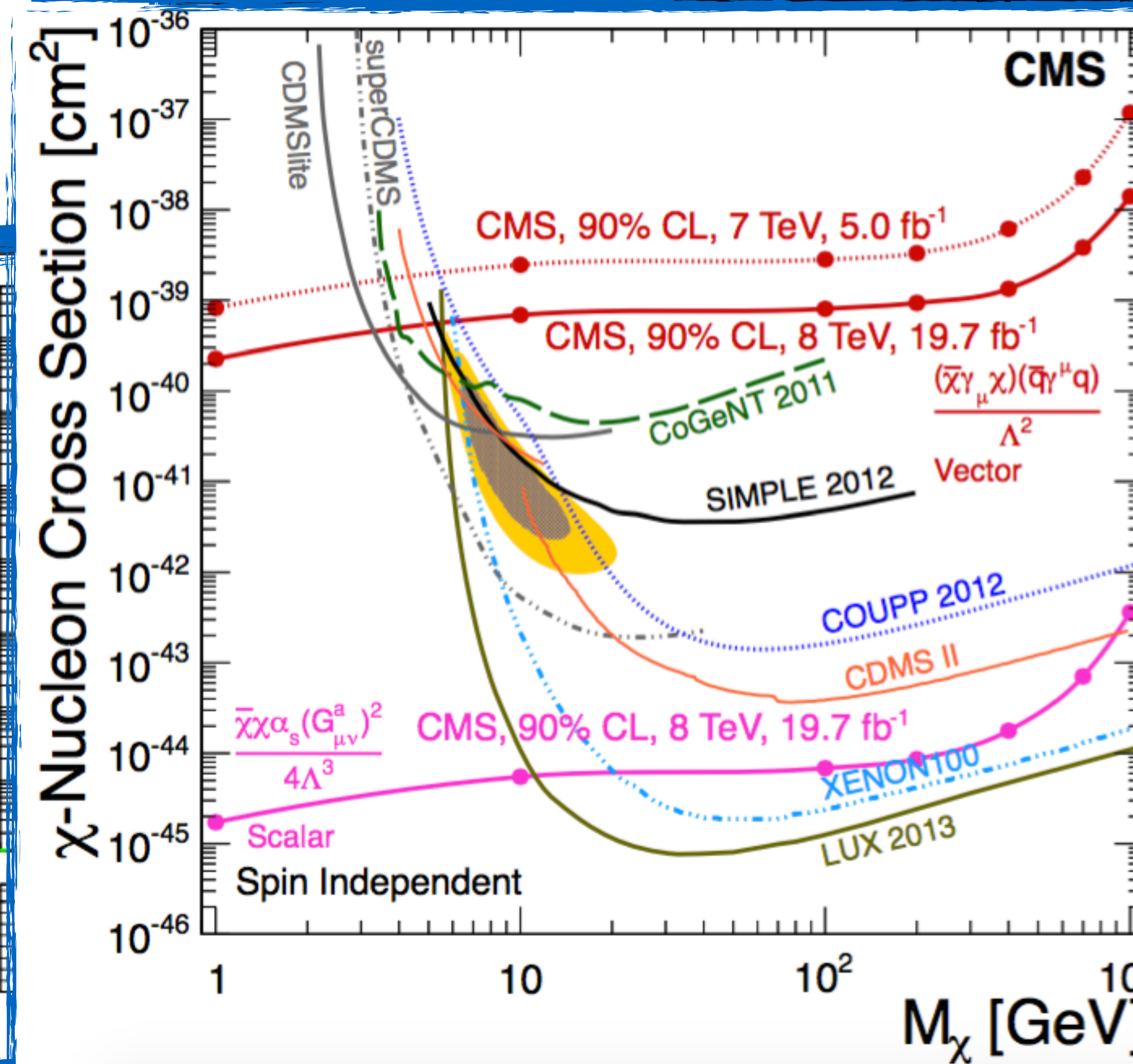
DM @ LHC

GeV-range favored for LHC searches!

$$\frac{(\bar{\chi}\gamma^{\mu}\chi)(\bar{q}\gamma_{\mu}q)}{\Lambda^2}$$







DM @ LHC

Energy

$$\frac{(\bar{\chi}\gamma^{\mu}\chi)(\bar{q}\gamma_{\mu}q)}{\Lambda^2}$$

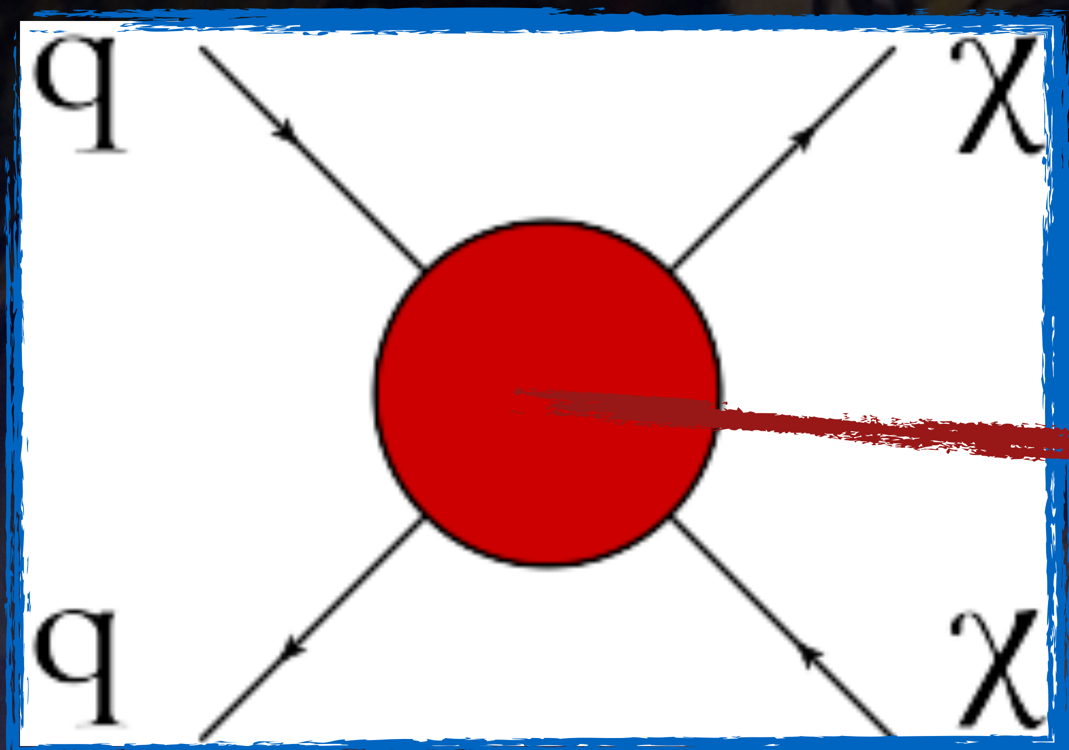
makes sense only if

$E \ll \Lambda$

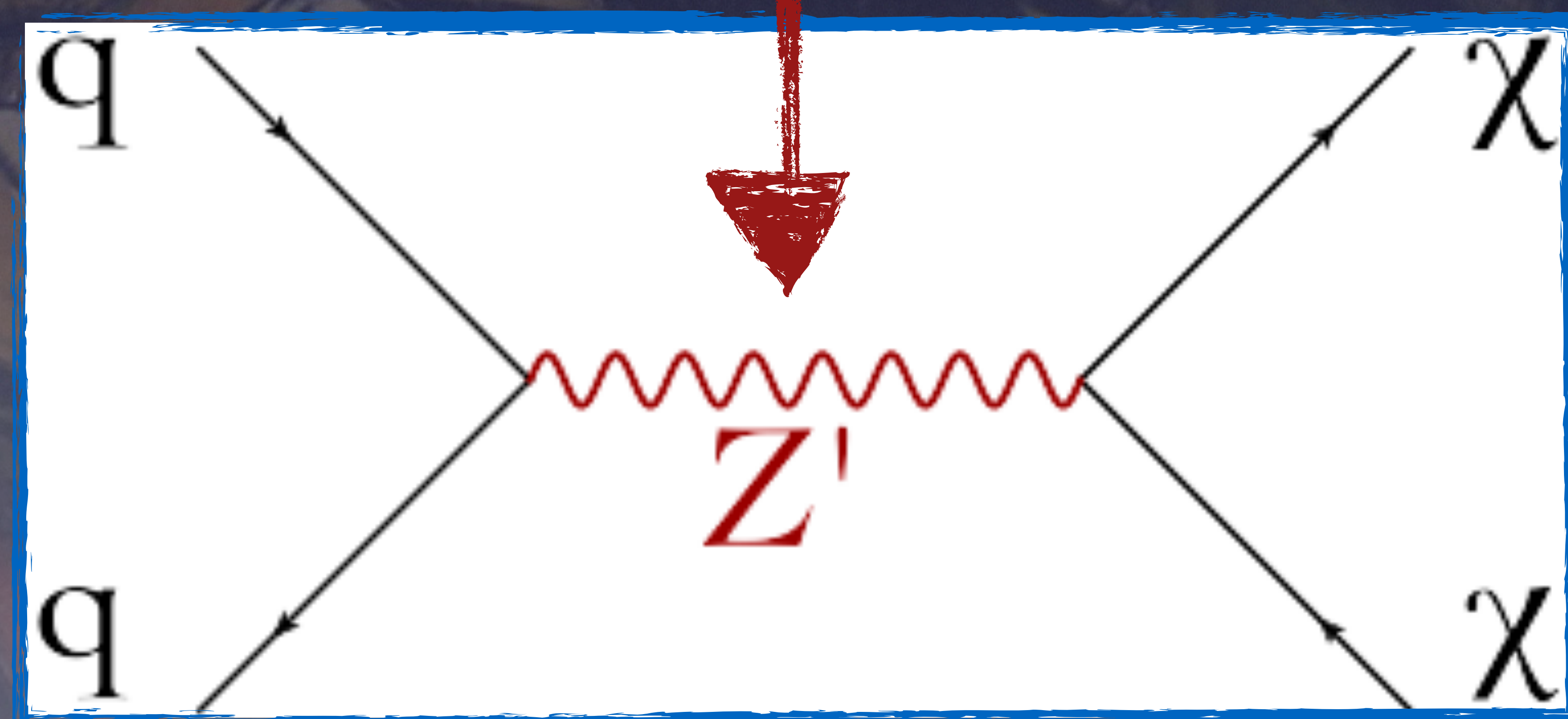
$E_{\text{parton c.o.m.}} \sim$ TeV

$\Lambda \sim O(100)$ GeV

DM @ LHC



From EFT to simplified models



Talk by
Daniele Barducci

DM EFT @ LHC

DM EFT @ LHC

$$\frac{(\bar{\chi}\gamma^{\mu}\chi)\,(\bar{q}\gamma_{\mu}q)}{\Lambda^2}$$

DM EFT @ LHC

~~$$\frac{(\bar{\chi}\gamma^{\mu}\chi)(\bar{q}\gamma_{\mu}q)}{\Lambda^2}$$~~

$$\mathcal{L}_{\rm eff} = \frac{g_*^2}{M^2}(\bar{\chi}\gamma^{\mu}\chi)(\bar{q}\gamma_{\mu}q)$$

DM EFT @ LHC

$$\frac{(\bar{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu q)}{\Lambda^2}$$

$$\mathcal{L}_{\rm Fermi} = \frac{G_{\rm F}}{\sqrt{2}}\left[\bar{u}_n\gamma^\mu(1-\gamma_5)u_p\right]\left[\bar{u}_{\nu_e}\gamma\right.$$

$$\frac{G_{\rm F}}{\sqrt{2}} = \frac{g_L^2}{M_W^2}$$

$$\mathcal{L}_{\rm eff} = \frac{g_*^2}{M^2}(\bar{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu q)$$

DM EFT @ LHC

$$\frac{(\bar{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu q)}{\Lambda^2}$$

$$c_i \approx (\text{coupling})^{n_i-2}$$

$$\mathcal{L}_{\text{eff}} = \sum_{i,d} c_i \frac{{}_d\mathcal{O}_i}{M^{d-4}}$$

$$\mathcal{L}_{\text{eff}} = \frac{g_*^2}{M^2}(\bar{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu q)$$

DM EFT @ LHC

DM EFT @ LHC

$$\Omega_{\rm DM} h^2 \approx \frac{10^{-26}\,{\rm cm}^3\,{\rm s}^{-1}}{\langle \sigma v_{\rm rel}\rangle} \approx \underbrace{0.1 \times \left(\frac{0.01}{\alpha_{\rm DM}}\right)^2 \times \left(\frac{m_{\rm DM}}{100\,{\rm GeV}}\right)^2}_{\text{assuming the scaling } \langle\sigma {\rm v}_{\rm rel}\rangle \sim \alpha^2_{\rm DM}/{\rm m}^2_{\rm DM}}$$

$$\mathcal{L}_{\rm eff} = \frac{g_*^2}{M^2}\left(\bar{\chi}\gamma^\mu\chi\right)\left(\bar{q}\gamma_\mu q\right) \quad \Longrightarrow \quad \langle \sigma {\rm v}_{\rm re}$$

DM EFT @ LHC

Strong coupling

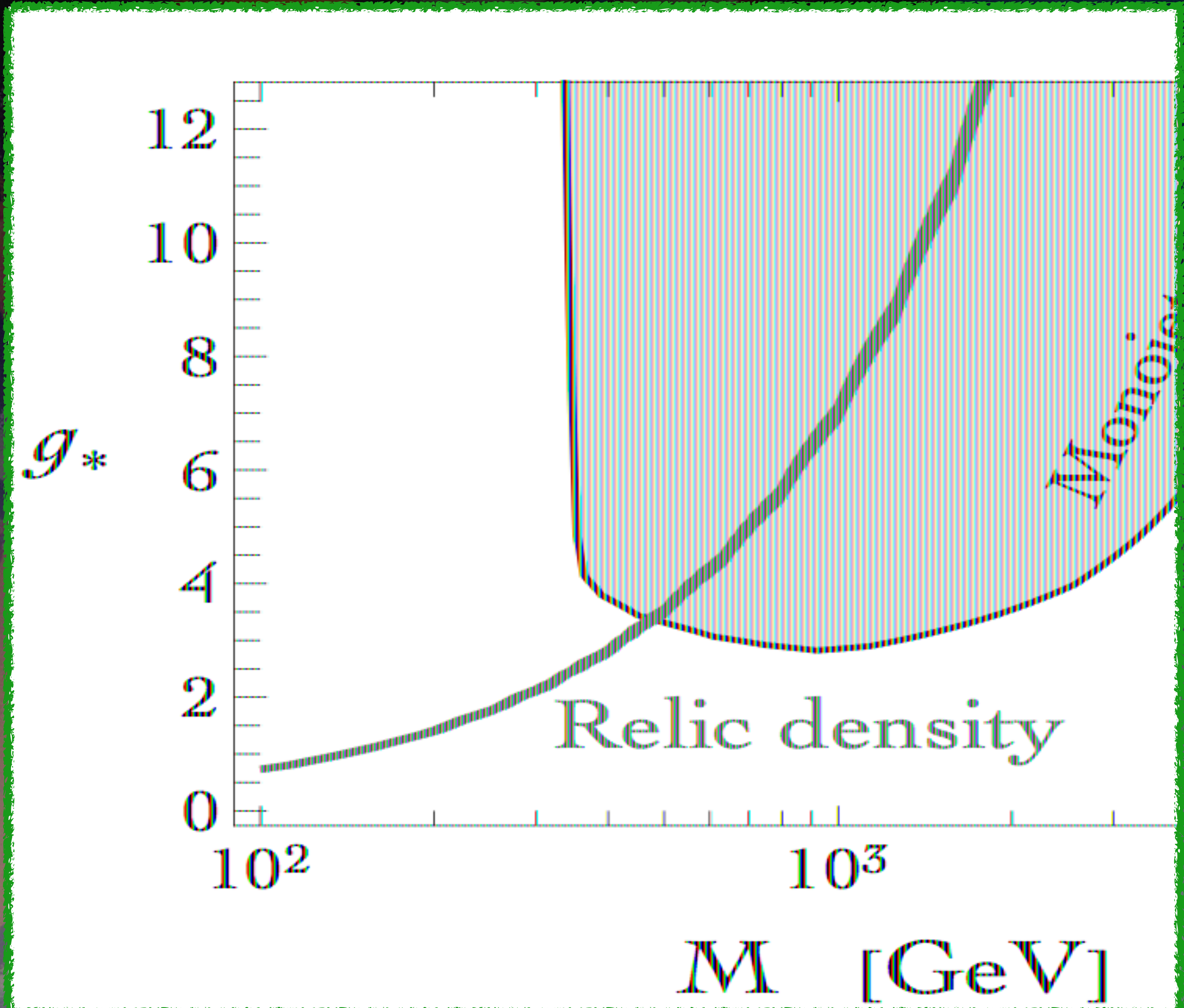
Light DM

TeV-scale new sector

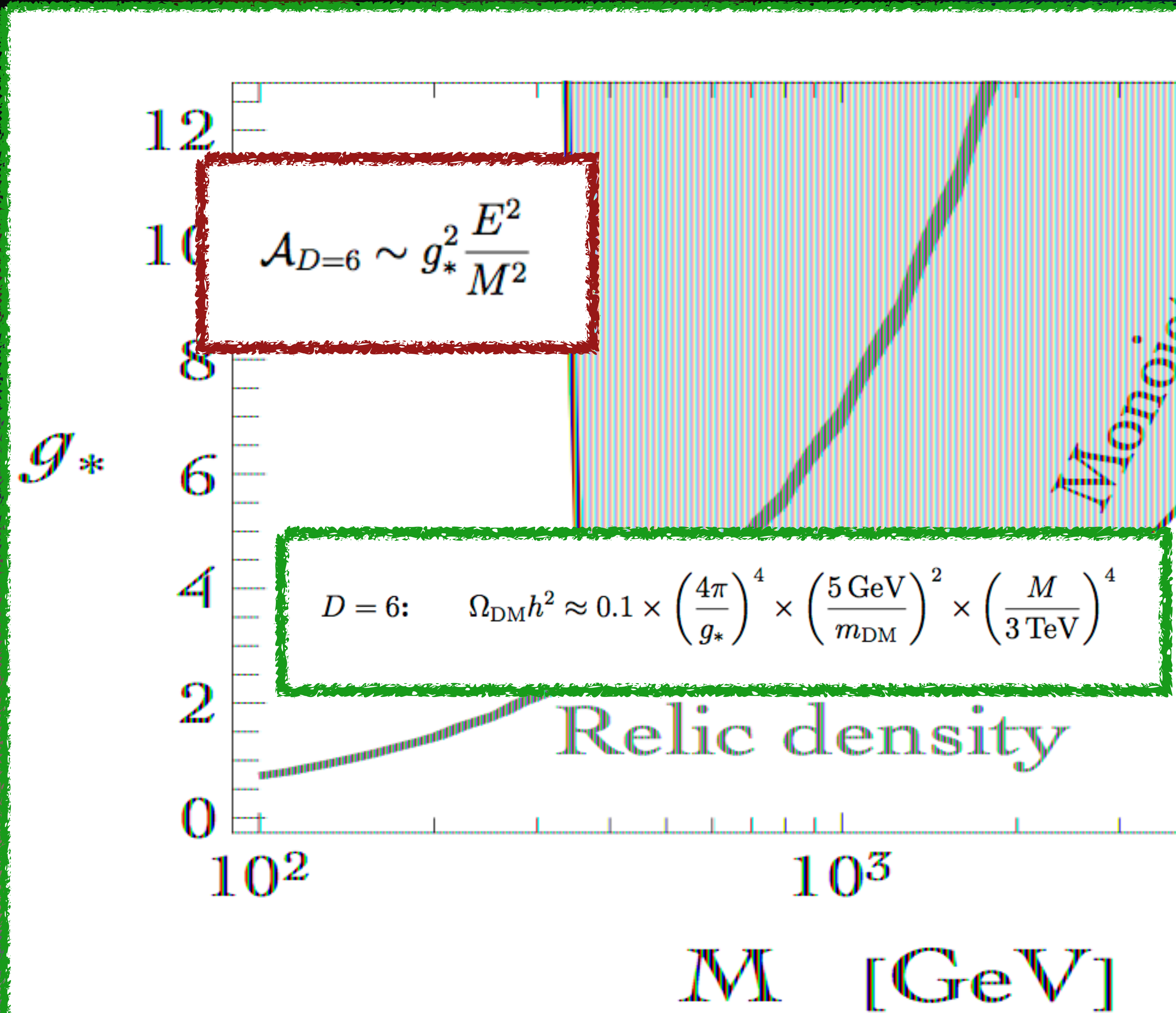
$$D = 6: \qquad \Omega_{\rm DM} h^2 \approx 0.1 \times \left(\frac{4\pi}{g_*}\right)^4 \times \left(\frac{5\,{\rm GeV}}{m_{\rm DM}}\right)^2 \times \left(\frac{M}{3\,{\rm TeV}}\right)^4$$

$$\mathcal{L}_{\rm eff} = \frac{g_*^2}{M^2}\,(\bar{\chi}\gamma^\mu\chi)\,(\bar{q}\gamma_\mu q) \qquad \Longrightarrow \qquad \langle \sigma v_{\rm re}$$

DM EFT @ LHC



DM EFT @ LHC

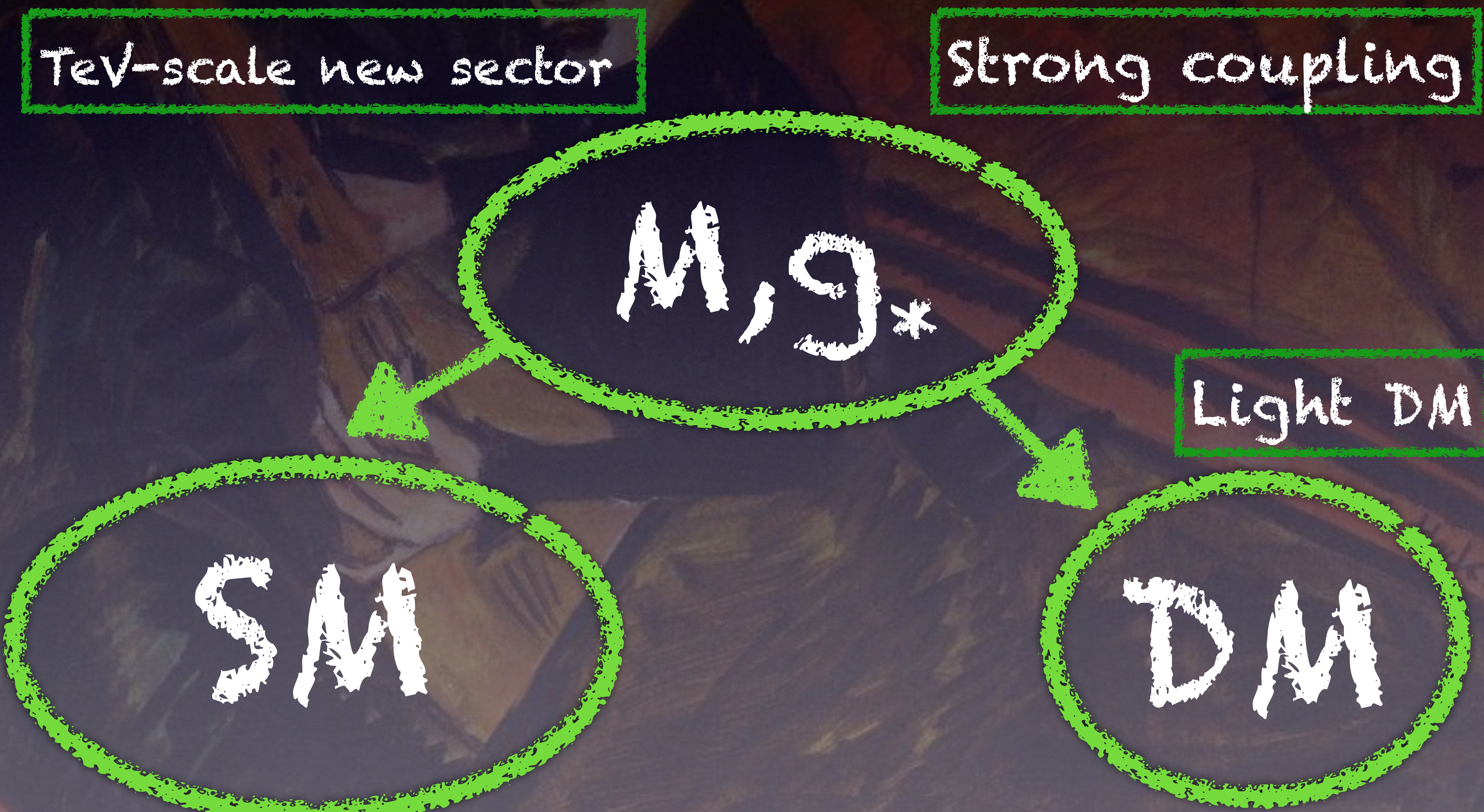


$$\mathcal{A}_{D=6} \sim g_*^2 \frac{E^2}{M^2}$$

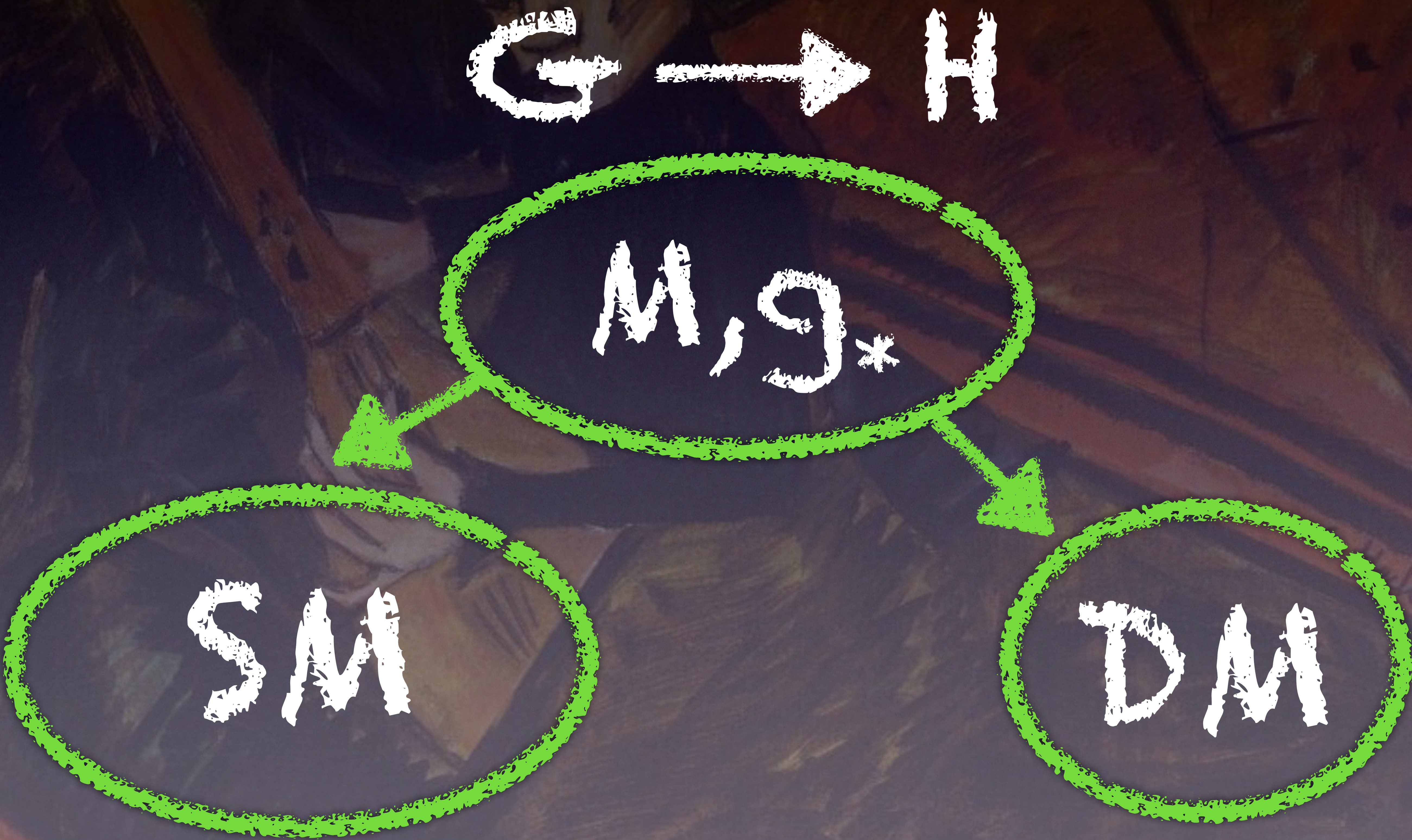
$$D = 6: \quad \Omega_{\rm DM} h^2 \approx 0.1 \times \left(\frac{4\pi}{g_*}\right)^4 \times \left(\frac{5\,\text{GeV}}{m_{\rm DM}}\right)^2 \times \left(\frac{M}{3\,\text{TeV}}\right)^4$$


SILDM

SILDM



SILDM



SILDM

$$G \rightarrow H$$

$$U(1) \rightarrow Z_2$$

1 Goldstone boson
DM is a real scalar

SILDM

G → H

SU(2) → U(1)

2 Goldstone bosons

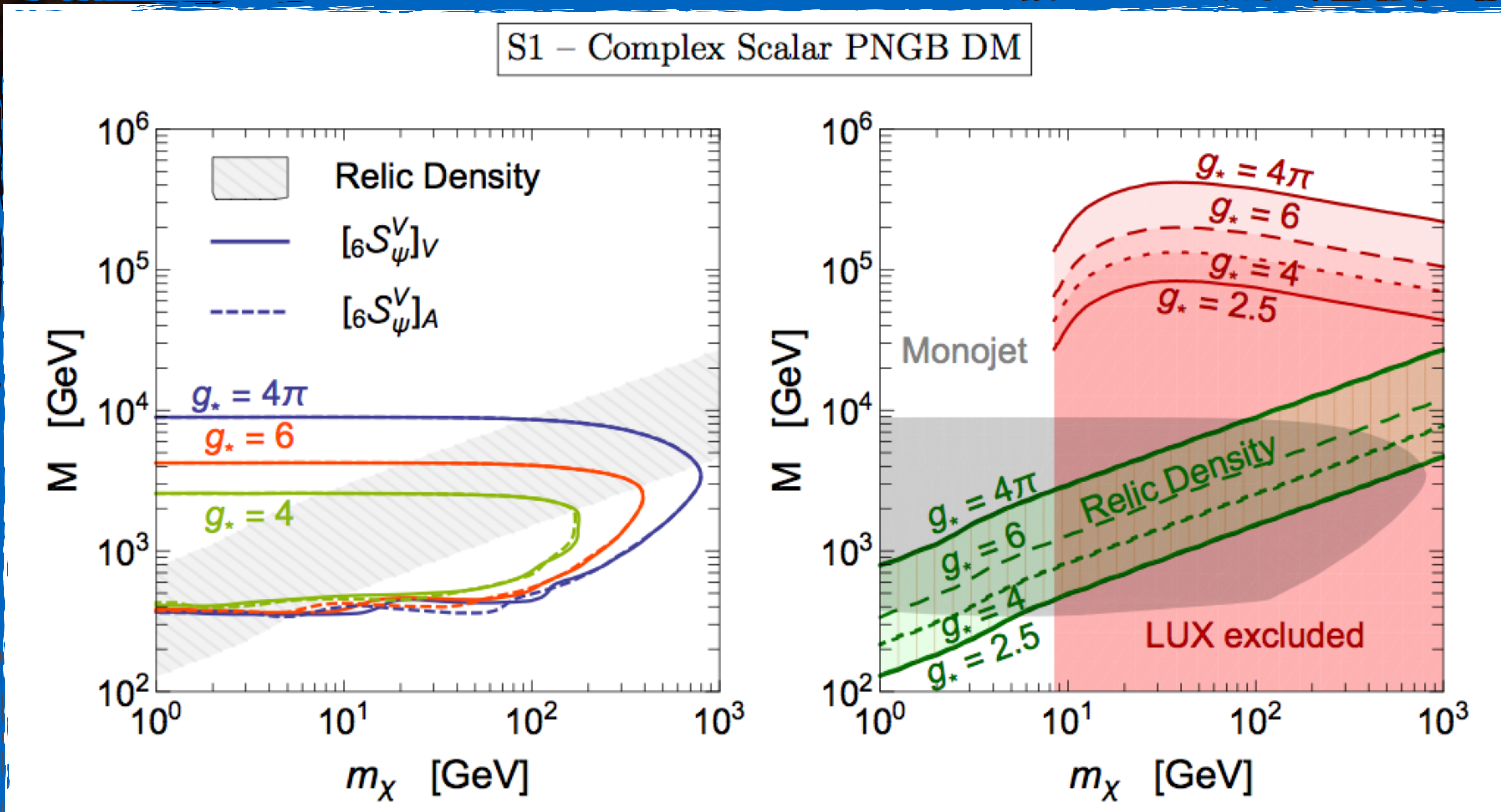
DM is a complex scalar

SILDM

1) CLASSIFICATION OF OPERATORS

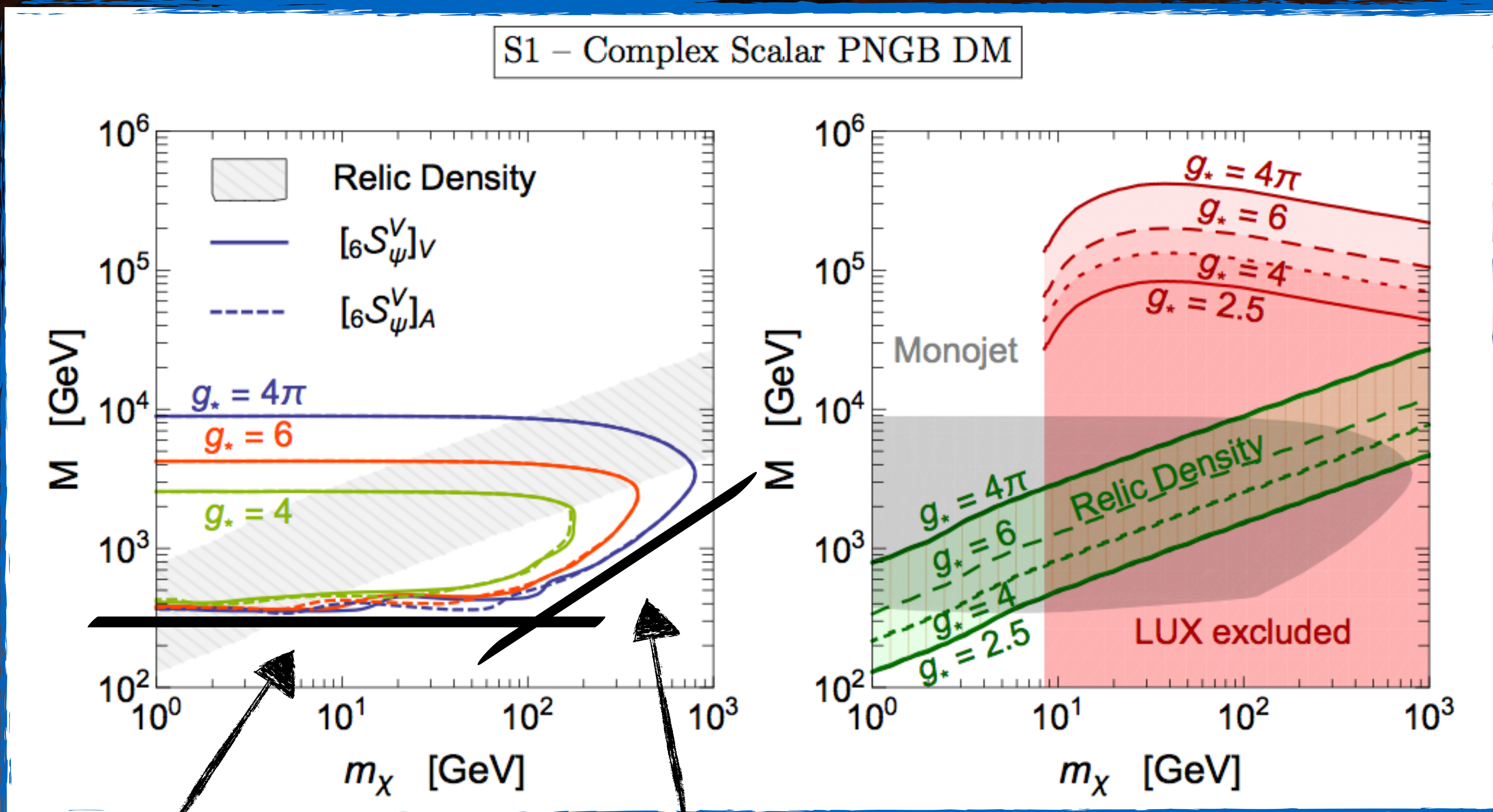
Complex scalar dark matter				
Unsuppressed			Suppr	
Name	Operator	Wilson coeff.	Name	Operato
dim = 6				
${}_6\mathcal{S}_\psi^V$	$\phi^\dagger \overleftrightarrow{\partial}_\mu \phi \psi^\dagger \bar{\sigma}^\mu \psi$	$c_\psi^V g_*^2/M^2$	${}_6\mathcal{S}_\psi^{\not{s}}$	$\lvert\phi\rvert^2 \psi\psi H$
dim = 8				
${}_8\mathcal{S}_\psi^T$	$\partial^\mu \phi^\dagger \partial^\nu \phi \psi^\dagger \bar{\sigma}_\mu D_\nu \psi$	$C_\psi^T g_*^2/M^4$		
			${}_8\mathcal{S}_\psi^S$	$\partial^\mu \phi^\dagger \partial_\mu \phi \psi$
${}_8\mathcal{S}_V^S$	$\partial^\mu \phi^\dagger \partial_\mu \phi V_{\rho\nu}^a V^{a\,\rho\nu}$	$C_V^S g_*^2/M^4$	${}_8\mathcal{S}_V^{\not{s}}$	$\lvert\phi\rvert^2 V_{\mu\nu}^a V^a$
${}_8\mathcal{S}_V^T$	$\partial^\mu \phi^\dagger \partial^\nu \phi V_{\mu\rho}^a V_\nu^{a\,\rho}$	$C_V^T g_*^2/M^4$		

SILDM



S1 – Complex Scalar PNGB DM
Relic Density
$[_6S^V_\psi]_V$
$[_6S^V_\psi]_A$
$g_* = 4\pi$
$g_* = 6$
$g_* = 4$
M [GeV]
m_χ [GeV]
$g_* = 4\pi$
$g_* = 6$
$g_* = 4$
$g_* = 2.5$
Monojet
Relic Density
$g_* = 4\pi$
$g_* = 6$
$g_* = 4$
$g_* = 2.5$
LUX excluded
M [GeV]
m_χ [GeV]

SILDM



$M < 2p_{\mathrm{T}}^{\mathrm{cu}}$

$M < 2m_{\mathrm{DI}}$

SILDM

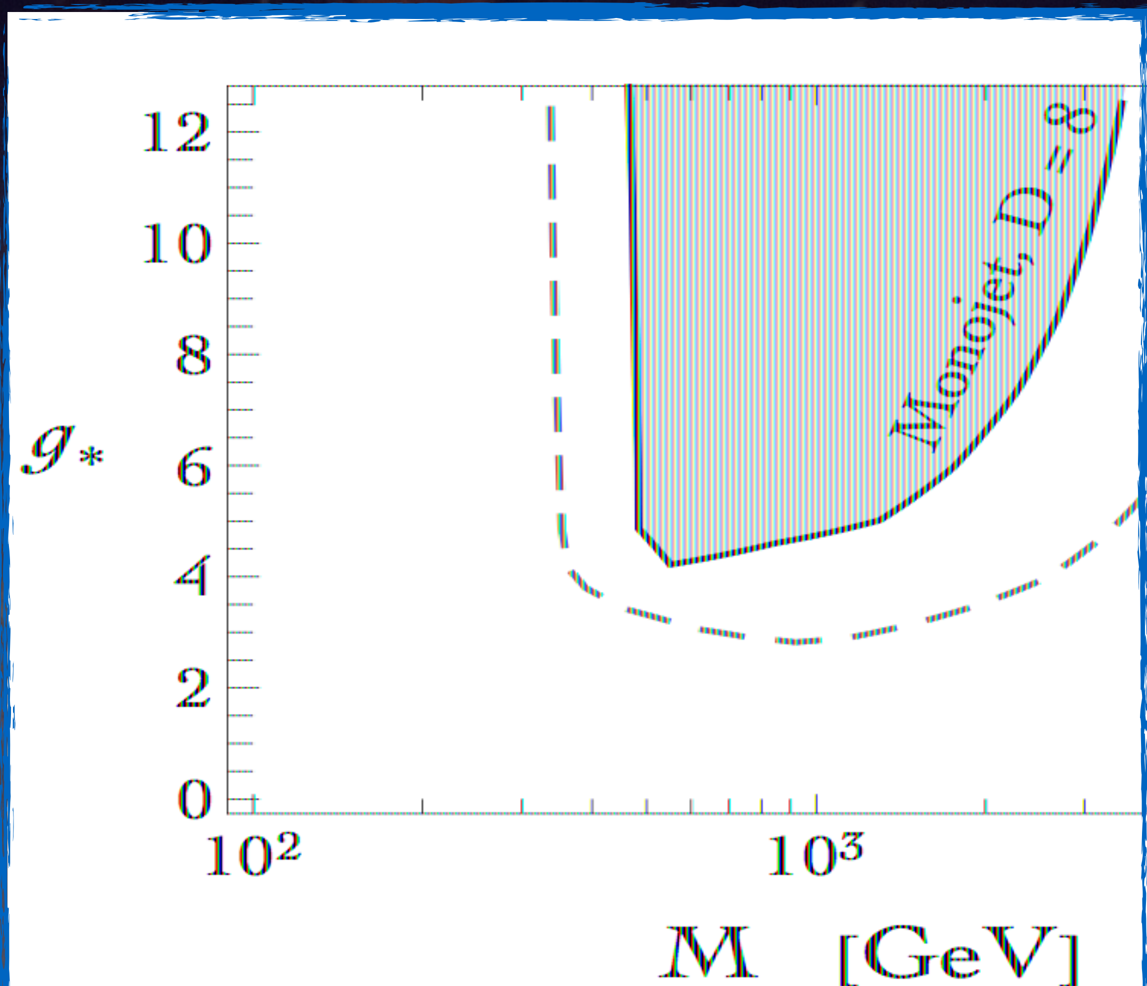
2) ROLE OF HIGHER-DIMENSIONAL OPERATORS

$U(1) \rightarrow Z_2$

Complex scalar dark matter				
Unsuppressed			Suppr	
Name	Operator	Wilson coeff.	Name	Operato
dim = 6				
${}_6\mathcal{S}^V_\psi$	$\psi^\dagger \overleftrightarrow{\partial}_\mu \phi \phi^\dagger \bar{\sigma}^\mu \psi$	$c^V_\psi g_*^2/M^2$	${}_6\mathcal{S}^{\not{s}}_\psi$	$\vert\phi\vert^2 \psi\psi H$
dim = 8				
${}_8\mathcal{S}^T_\psi$	$\partial^\mu \phi^\dagger \partial^\nu \phi \psi^\dagger \bar{\sigma}_\mu D_\nu \psi$	$C^T_\psi g_*^2/M^4$		
			${}_8\mathcal{S}^S_\psi$	$\partial^\mu \phi^\dagger \partial_\mu \phi \psi$
${}_8\mathcal{S}^S_V$	$\partial^\mu \phi^\dagger \partial_\mu \phi V^a_{\rho\nu} V^{a\,\rho\nu}$	$C^S_V g_*^2/M^4$	${}_8\mathcal{S}^{\not{s}}_V$	$\vert\phi\vert^2 V^a_{\mu\nu} V^a$
${}_8\mathcal{S}^T_V$	$\partial^\mu \phi^\dagger \partial^\nu \phi V^a_{\mu\rho} V^{a\,\rho}_\nu$	$C^T_V g_*^2/M^4$		

SILDM

2) ROLE OF HIGHER-DIMENSIONAL OPERATORS



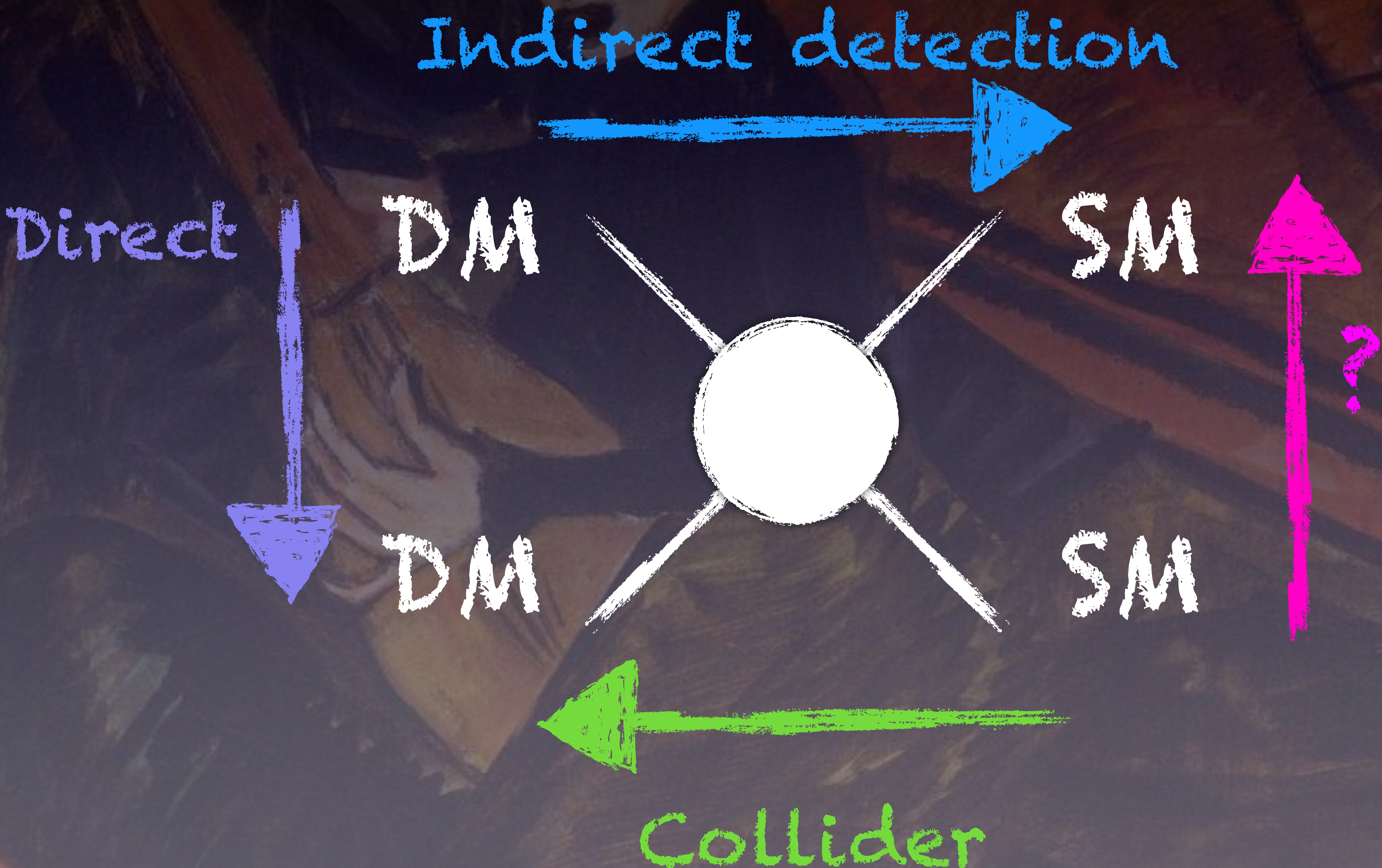
at LHC $E \gg r$

dim 8 $\mathcal{A}_{2\to 2}^{D=8} \sim \left(\frac{E}{M}\right)^4$

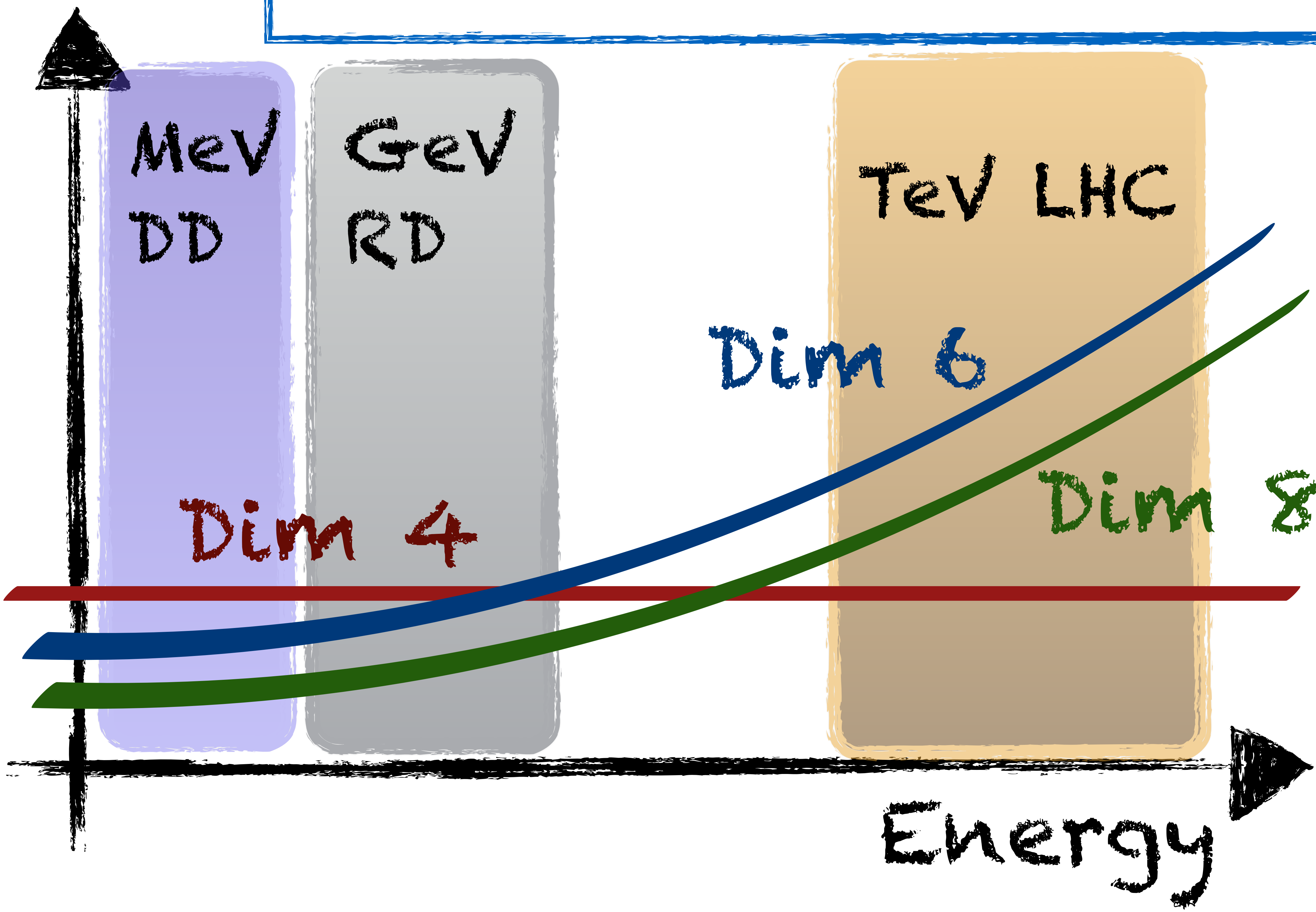
suppressed dim 6 $\mathcal{A}_{2\to 2}^{D=6} \sim \left(\frac{m_{\rm DM}}{M}\right.$

SILDM

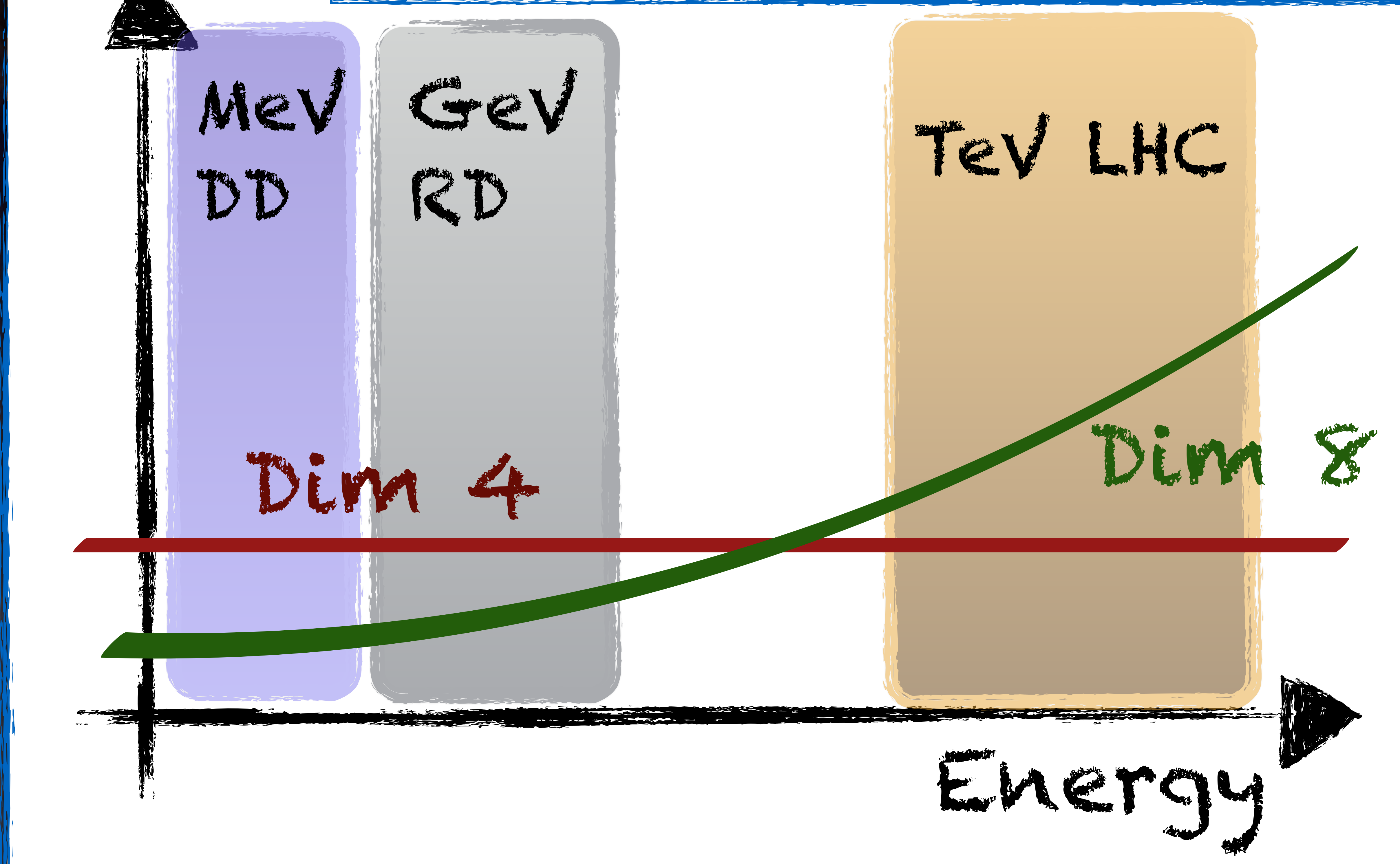
3) DM COMPLEMENTARITY



$$\mathcal{L}_{\text{eff}} = \sum_{i,d} c_i \frac{{}_d\mathcal{O}_i}{M^{d-4}} \quad \Longrightarrow \quad \mathcal{A}_i \sim c_i \frac{E^{d-4}}{M^{d-4}}$$



$$\mathcal{L}_{\text{eff}} = \sum_{i,d} c_i \frac{{}_d\mathcal{O}_i}{M^{d-4}} \quad \Longrightarrow \quad \mathcal{A}_i \sim c_i \frac{E^{d-4}}{M^{d-4}}$$



Conclusions

Conclusions

Theories in which DM arises as the pNGB of a new, strongly interacting dark sector

The structure of the interactions is shaped by the underlying symmetries

The effective field theory approach is theoretical motivated, and well-suited for LHC analysis