Thermal dark matter implies new physics below 100 TeV

Csaba Balázs

Tong Li, Jay Newstead

arXiv:1403.5829

arXiv:1407.0174

II. DM and ELW. SYMMETRY BREAKING

***THE DM ROAD TO NEW PHYSICS BEYOND THE SM*:**

IS **DM** A PARTICLE OF THE ***NEW PHYSICS AT THE ELECTROWEAK ENERGY SCALE*** **?**

YES!

Csaba Balázs

Tong Li, Jay Newstead

arXiv:1403.5829

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summary

if dark matter is thermally produced and
if SM+DM can be described as effective QFT
then new physics is most likely below 100 TeV

outline

thermal production of dark matter

effective field theory framework

WIMP miracle ‘inverted’

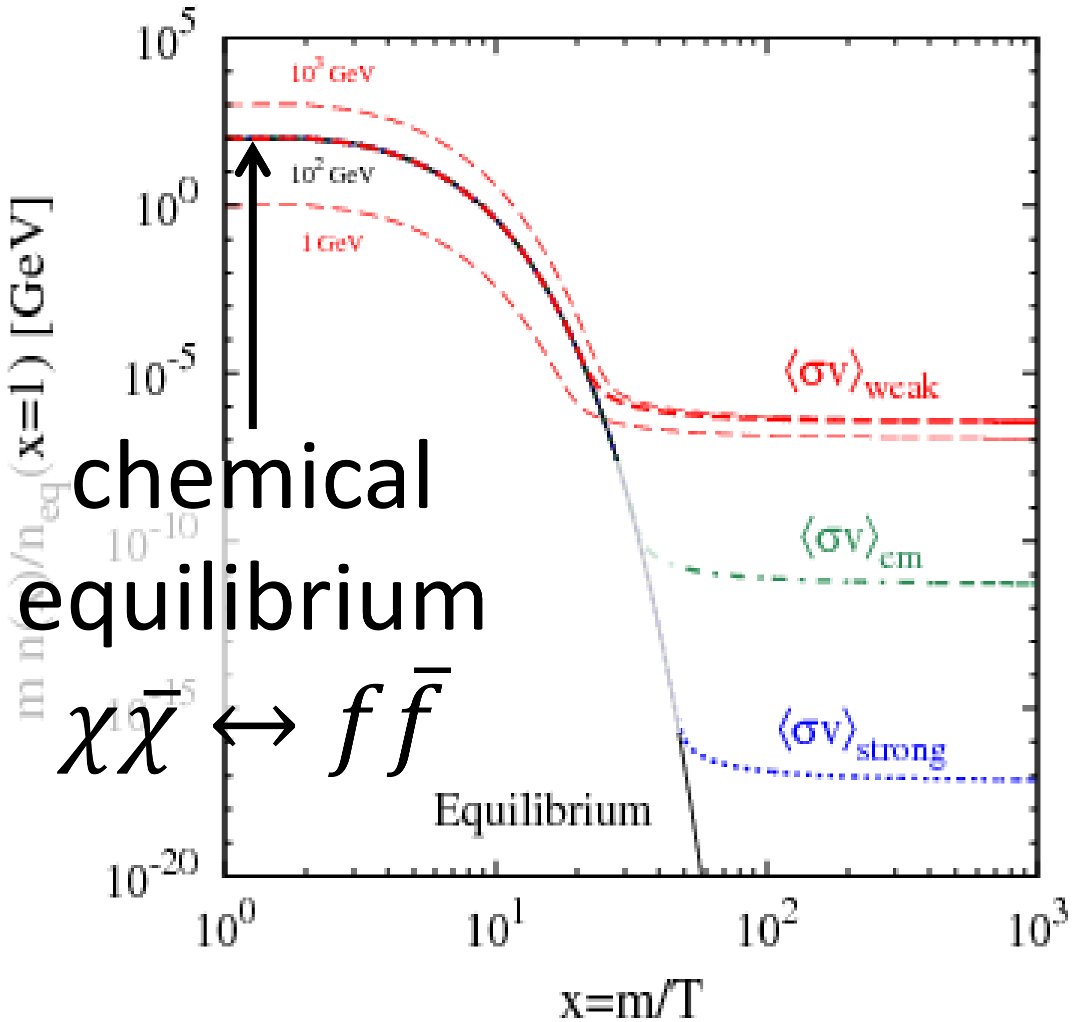
full numerical results

standard cosmology & thermodynamics

$\Rightarrow$

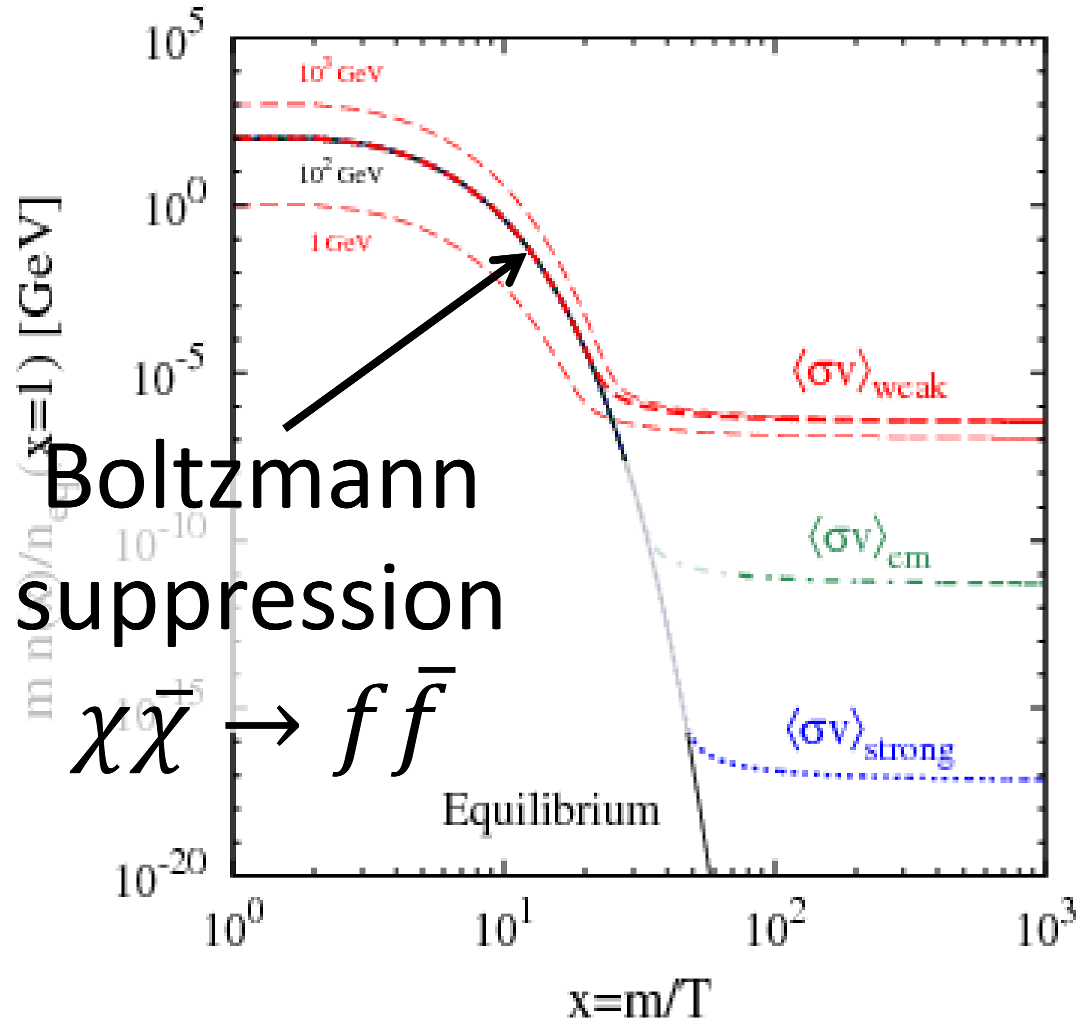
cosmological abundance

standard thermal evolution



Steigman, Dasgupta, Beacom Phys. Rev. D86 (2012) 023506

standard thermal evolution



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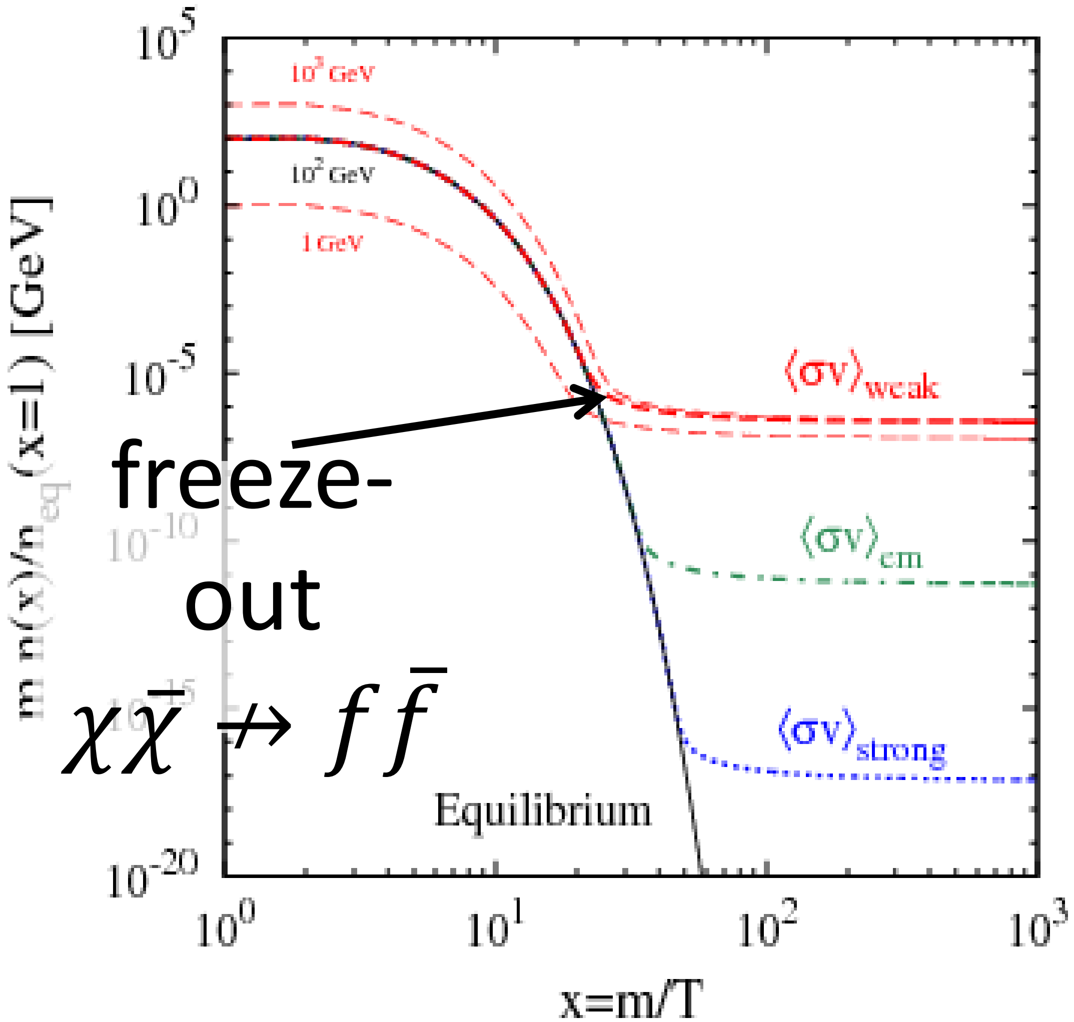
standard thermal evolution



Steigman, Dasgupta, Beacom Phys. Rev. D86 (2012) 023506

standard cosmology & thermodynamics

$$\Rightarrow$$

$$\Omega_\chi h^2 = \frac{s_0}{\rho_c/h^2} \left(\frac{45}{\pi g_*} \right)^{1/2} \frac{x_f}{m_{\rm Pl}} \frac{1}{\langle \sigma v \rangle}$$

Scherrer, Turner Phys. Rev. D33 (1986) 1585

thermal WIMP miracle

$$\Omega_\chi h^2 = \frac{s_0}{\rho_c/h^2}\left(\frac{45}{\pi g_*}\right)^{1/2}\frac{x_f}{m_{\rm Pl}}\frac{1}{\langle \text{pb}\, v\rangle} \sim 0.1$$

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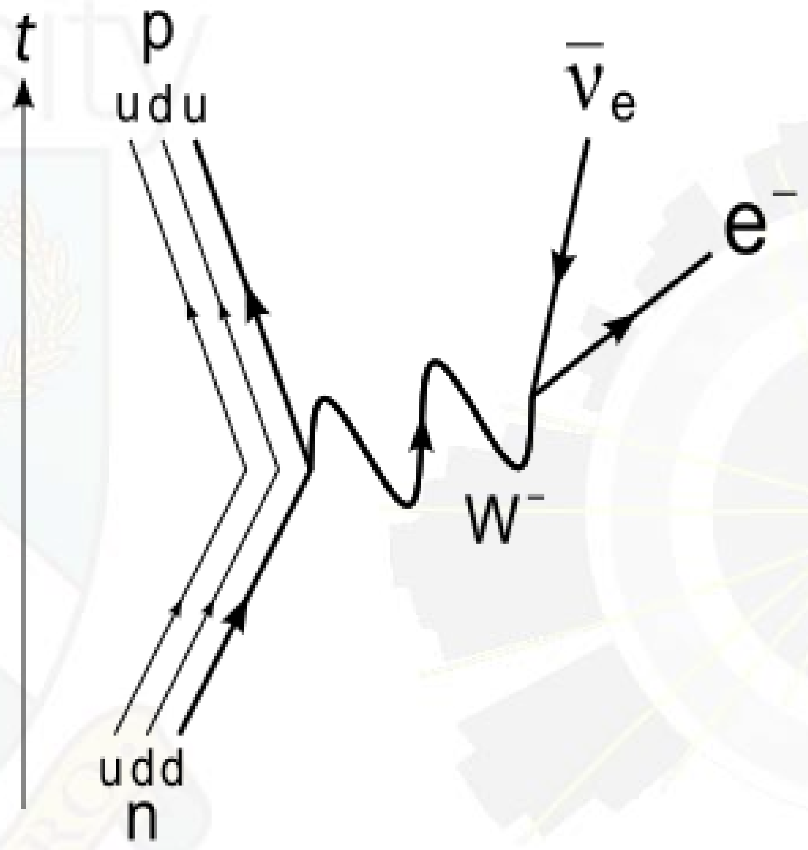
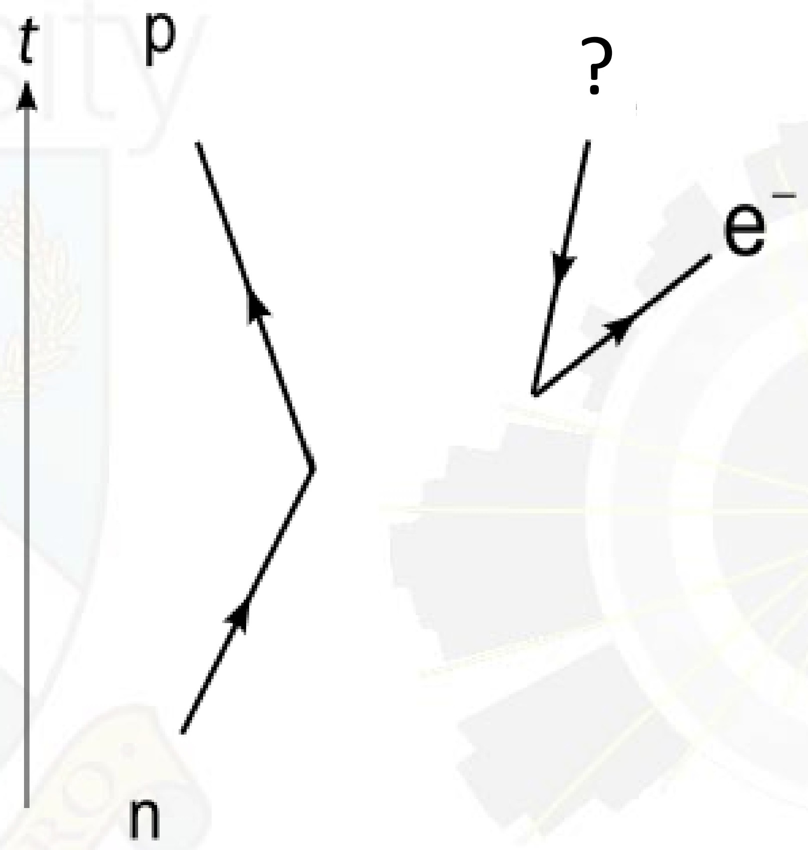
effective interactions



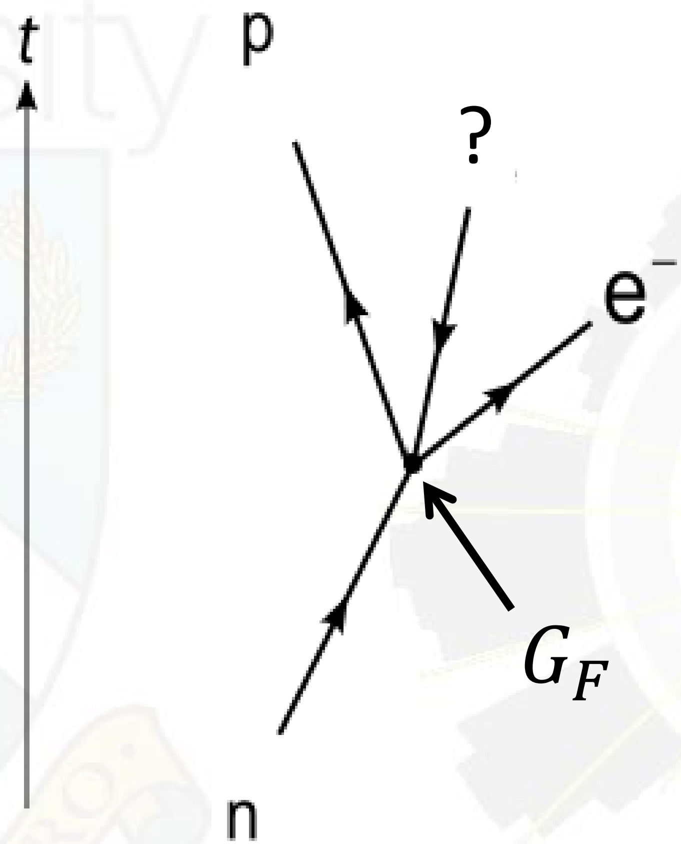
neutron decay

effective interactions



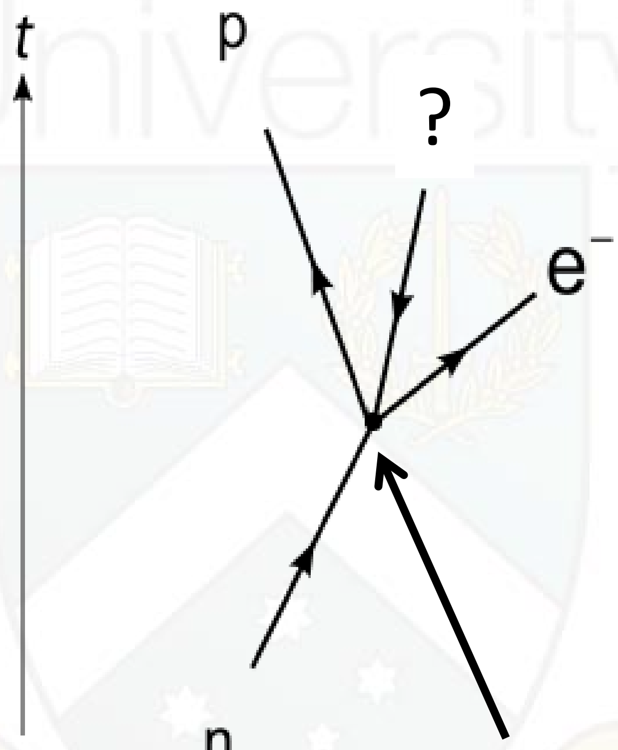
neutron decay

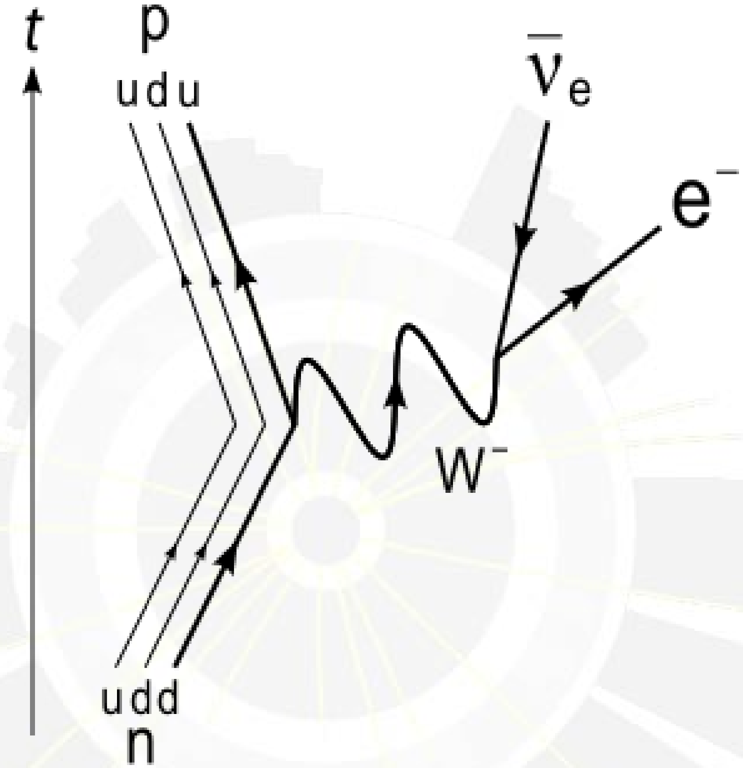
effective interactions



neutron decay

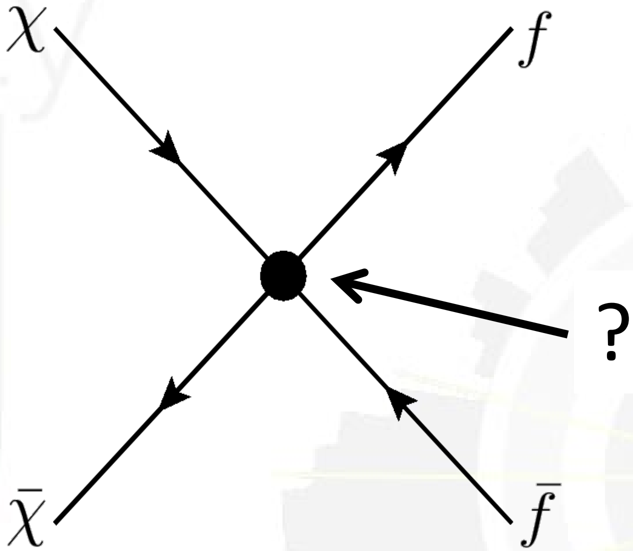
effective interactions





$$G_F = \frac{\sqrt{2}}{8}\frac{g^2}{m_W^2}$$

neutron decay



dark matter - standard model interaction ?

effective field theory is a very general, robust framework to describe new physics

outline

thermal production of dark matter

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WIMP miracle ‘inverted’

full numerical results

WIMP miracle

input: thermal evolution & m_{EW} or g_{EW}

output: σ_{EW} & $\Omega h^2 \sim 1$

WIMP miracle ‘inverted’

input: thermal evolution and $\Omega h^2 \sim 1$

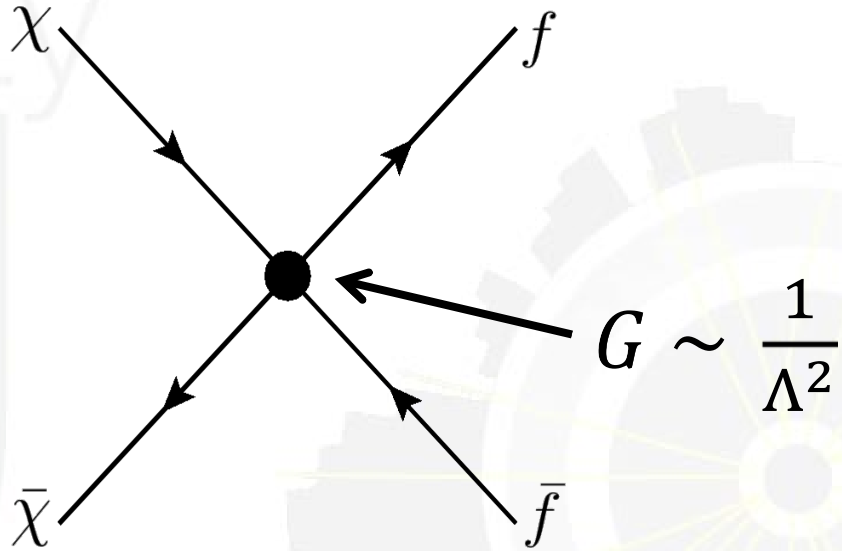
output: m_{DM} & g_{DM}

latter allows to set upper limits on m_{DM} & g_{DM}

thermal freeze out requires

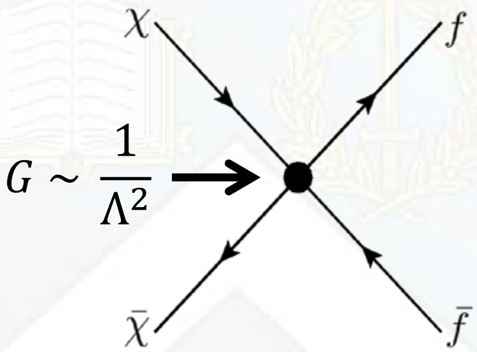
$$\sigma \sim \text{pb}$$

but this does not imply a WIMP



dark matter - standard model
effective interaction

effective field theory

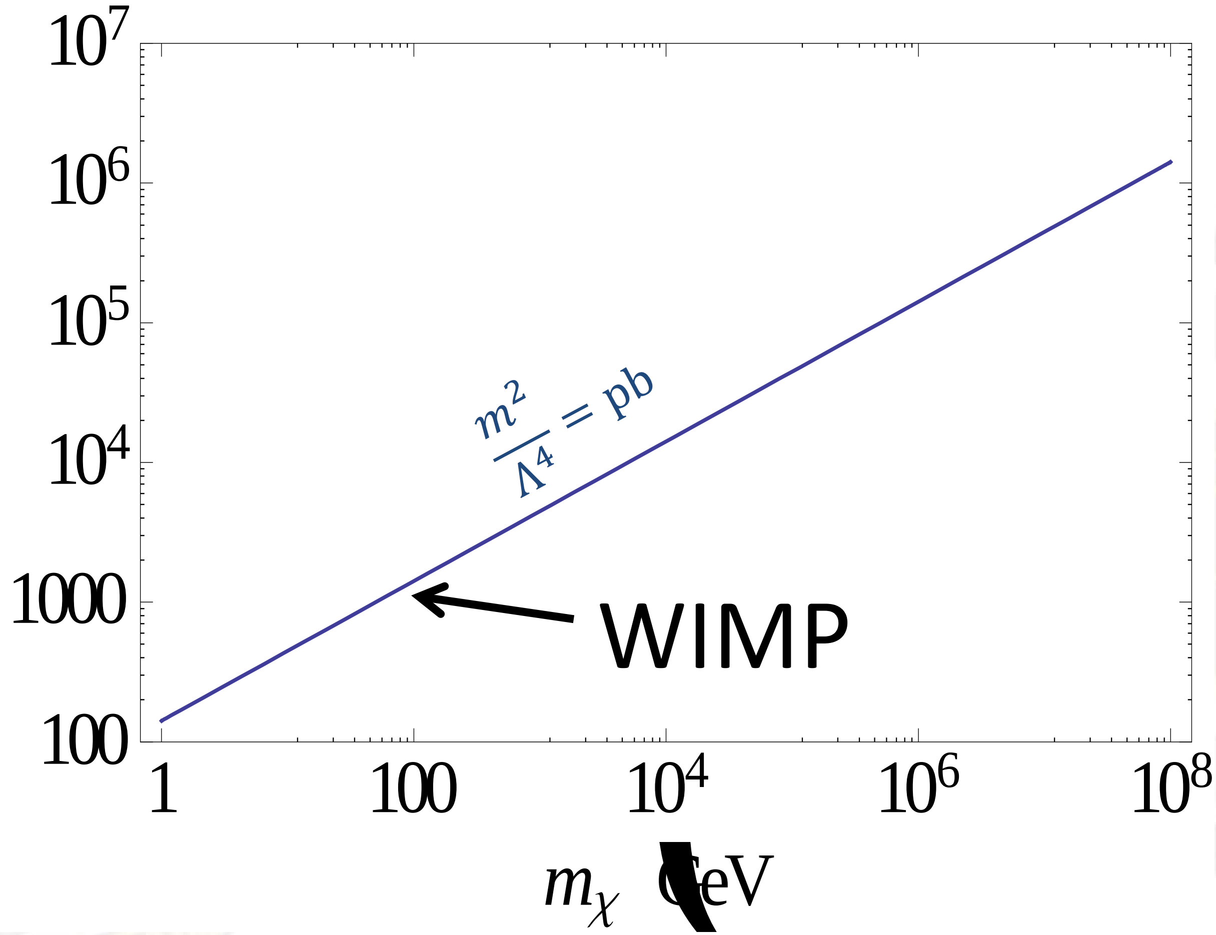


$$\sigma \sim m_\chi^2/\Lambda^4$$

complex scalar dark matter, $m_f = 0$, cold limit

$\sigma \sim 1$ pb is realized for a range of m_χ and Λ

extended WIMP miracle



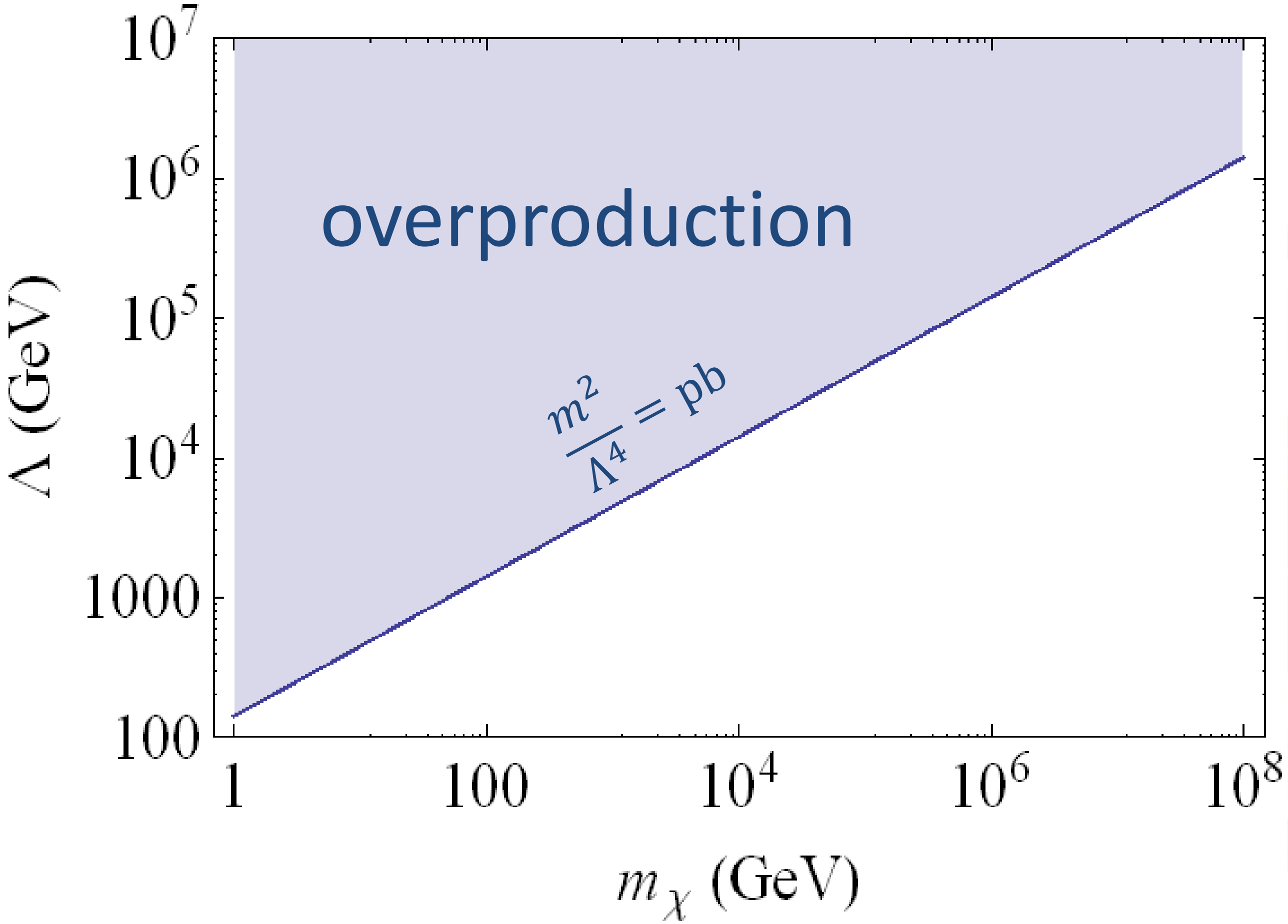
$\sigma \sim 1$ pb is realized for a range of m_χ and Λ

not to overproduce dark matter

$$\frac{m_\chi^2}{\Lambda^4} \sim \sigma \gtrsim \text{pb}$$

must hold

no dark matter overproduction



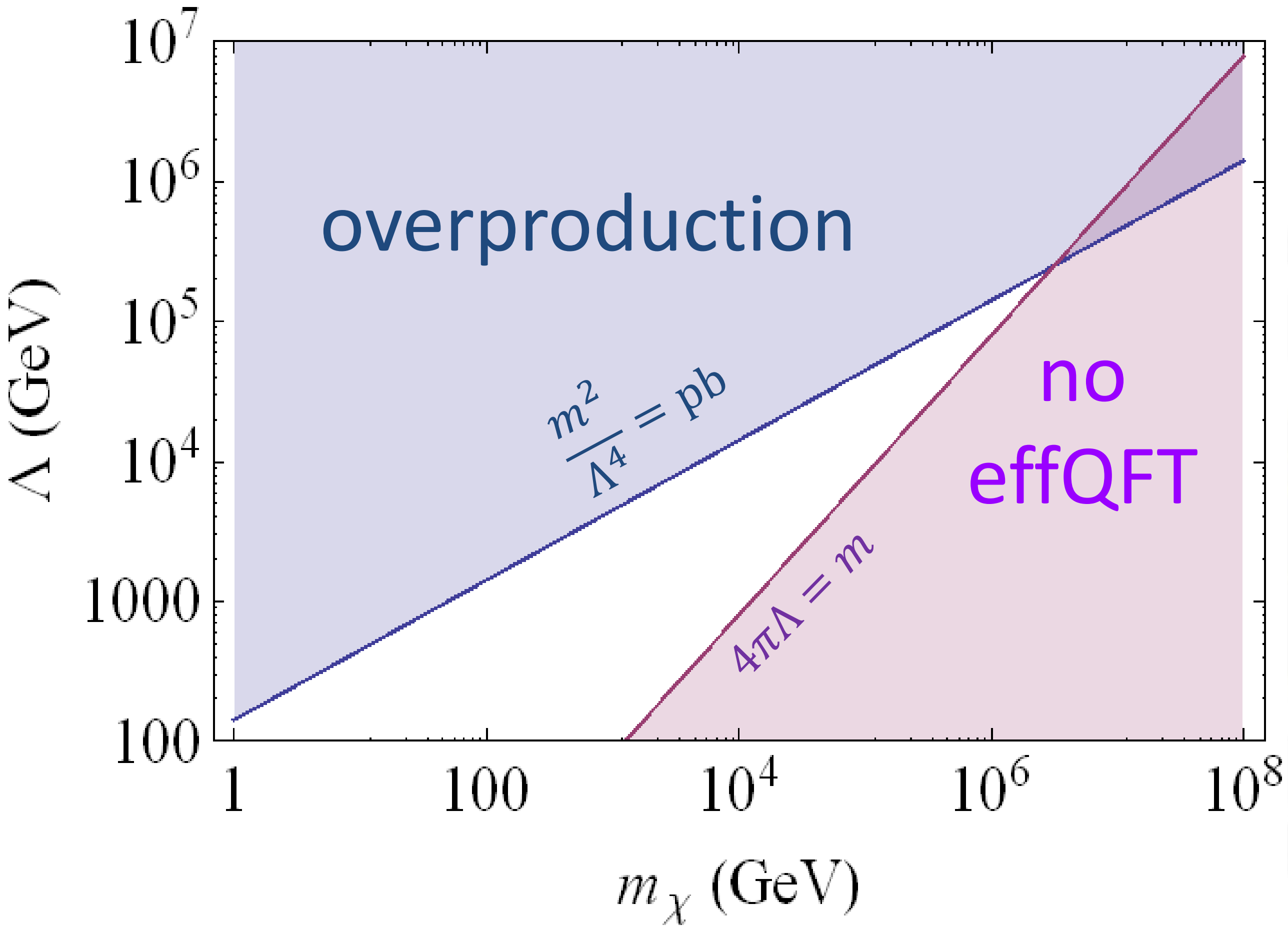
halves the parameter space

an effective field theory with

$$m_\chi \gtrsim 4\pi\Lambda$$

breaks down

if effective field theory description desired



then upper limit on new physics scale $\Lambda \lesssim 100$ TeV

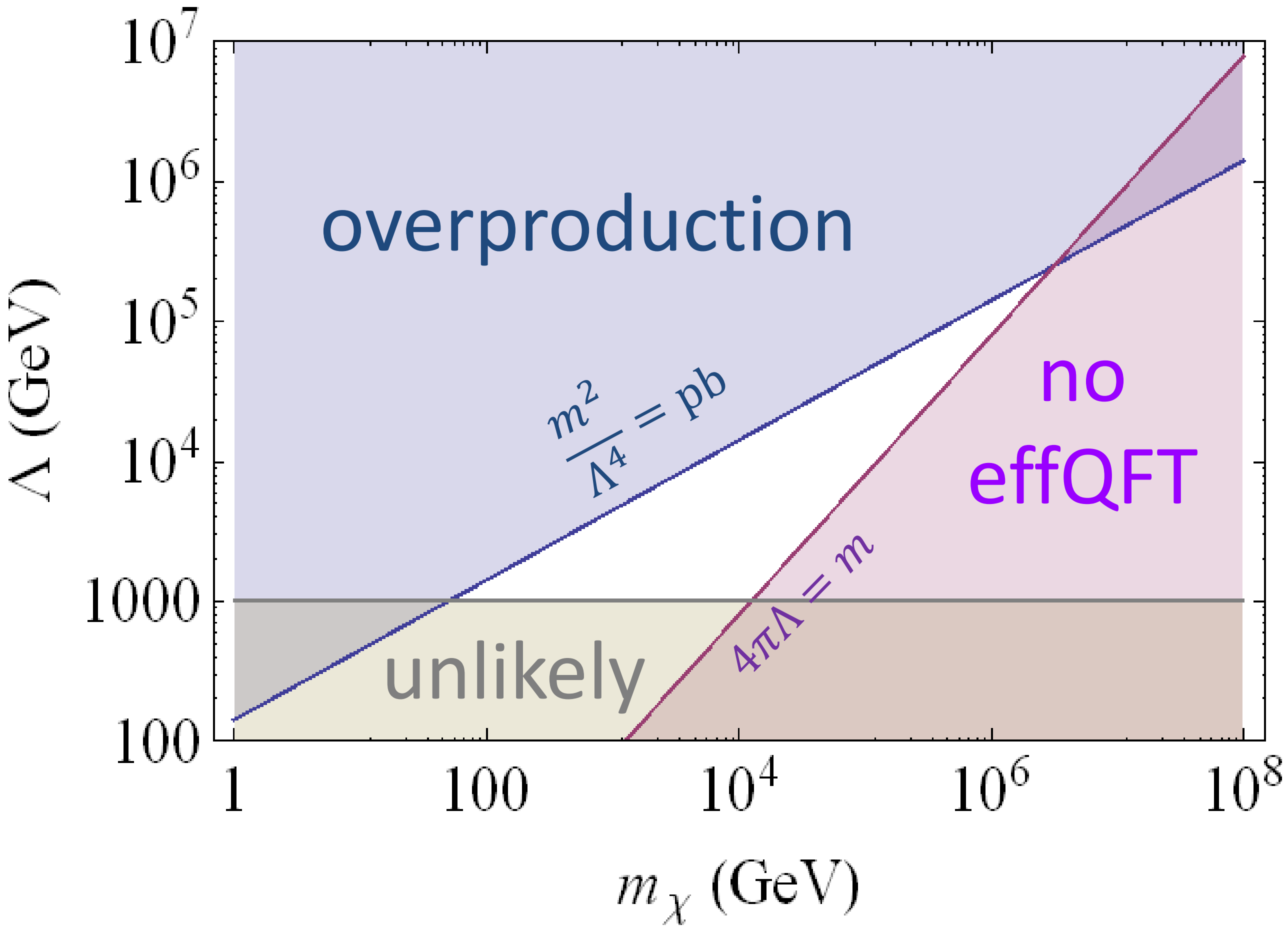
~~reverse WI~~MP miracle

if

$$\Lambda_{\text{new phyiscs}} \lesssim \text{TeV}$$

is unlikely

if new physics $\lesssim$ TeV is improbable



then both upper and lower limit on new physics scale

outline

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WIMP miracle - ‘inverted’

full numerical results

assumptions

1 DM thermally produced via freeze-out

2 SM+DM described as effective QFT

DM-SM interactions

$$\mathcal{L}_\chi = \sum_{i,f} C_i \mathcal{O}_{i,f}$$

Dirac fermion (DF)

Label	Operator $\mathcal{O}_{i,f}$	Coefficient C_i
D1	$\bar\chi\chi\bar f f$	$\frac{m_f}{\Lambda^3_{D1}}$
D2	$\bar\chi\gamma_5\chi\bar f f$	$\frac{im_f}{\Lambda^3_{D2}}$
D3	$\bar\chi\chi\bar f\gamma_5 f$	$\frac{im_f}{\Lambda^3_{D3}}$
D4	$\bar\chi\gamma_5\chi\bar f\gamma_5 f$	$\frac{m_f}{\Lambda^3_{D4}}$
D5	$\bar\chi\gamma^\mu\chi\bar f\gamma_\mu f$	$\frac{1}{\Lambda^2_{D5}}$
D6	$\bar\chi\gamma^\mu\gamma_5\chi\bar f\gamma_\mu f$	$\frac{i}{\Lambda^2_{D6}}$
D7	$\bar\chi\gamma^\mu\chi\bar f\gamma_\mu\gamma_5 f$	$\frac{i}{\Lambda^2_{D7}}$
D8	$\bar\chi\gamma^\mu\gamma_5\chi\bar f\gamma_\mu\gamma_5 f$	$\frac{1}{\Lambda^2_{D8}}$

Vector boson (VB)

Label	Operator $\mathcal{O}_{i,f}$	Coefficient C_i
V1	$\chi^\mu\chi_\mu\bar f f$	$\frac{m_f}{2\Lambda^2_{V1}}$
V2	$\chi^\mu\chi_\mu\bar f\gamma_5 f$	$\frac{im_f}{2\Lambda^2_{V2}}$
V3	$X^{\mu\nu}X_{\mu\nu}\bar f f$	$\frac{m_f}{4\Lambda^4_{V3}}$
V4	$X^{\mu\nu}X_{\mu\nu}\bar f\gamma_5 f$	$\frac{im_f}{4\Lambda^4_{V4}}$

Majorana fermion (MF)

Label	Operator $\mathcal{O}_{i,f}$	Coefficient C_i
M1	$\bar\chi\chi\bar f f$	$\frac{m_f}{2\Lambda^3_{M1}}$
M2	$\bar\chi\gamma_5\chi\bar f f$	$\frac{im_f}{2\Lambda^3_{M2}}$
M3	$\bar\chi\chi\bar f\gamma_5 f$	$\frac{im_f}{2\Lambda^3_{M3}}$
M4	$\bar\chi\gamma_5\chi\bar f\gamma_5 f$	$\frac{im_f}{2\Lambda^3_{M4}}$
M5	$\bar\chi\gamma^\mu\gamma_5\chi\bar f\gamma_\mu f$	$\frac{1}{2\Lambda^2_{M5}}$
M6	$\bar\chi\gamma^\mu\gamma_5\chi\bar f\gamma_\mu\gamma_5 f$	$\frac{1}{2\Lambda^2_{M6}}$

Real/complex (RS/CS) scalar

Label	Operator $\mathcal{O}_{i,f}$	Coefficient C_i
R1	$\chi\chi\bar f f$	$\frac{m_f}{2\Lambda^2_{R1}}$
R2	$\chi\chi\bar f\gamma_5 f$	$\frac{im_f}{2\Lambda^2_{R2}}$
C1	$\chi^\dagger\chi\bar f f$	$\frac{m_f}{\Lambda^2_{C1}}$
C2	$\chi^\dagger\chi\bar f\gamma_5 f$	$\frac{im_f}{\Lambda^2_{C2}}$
C3	$\chi^\dagger\partial_\mu\chi\bar f\gamma^\mu f$	$\frac{1}{\Lambda^2_{C3}}$
C4	$\chi^\dagger\partial_\mu\chi\bar f\gamma^\mu\gamma_5 f$	$\frac{1}{\Lambda^2_{C4}}$

“The whole is greater than the sum of its parts.”

Aristotle CA 350 BC

all operators (for same spin) included at once

they interfere and conspire

more parameters: more flexibility

data

Planck

LUX, CDMSlite, XENON100

Fermi-LAT

LHC

observables

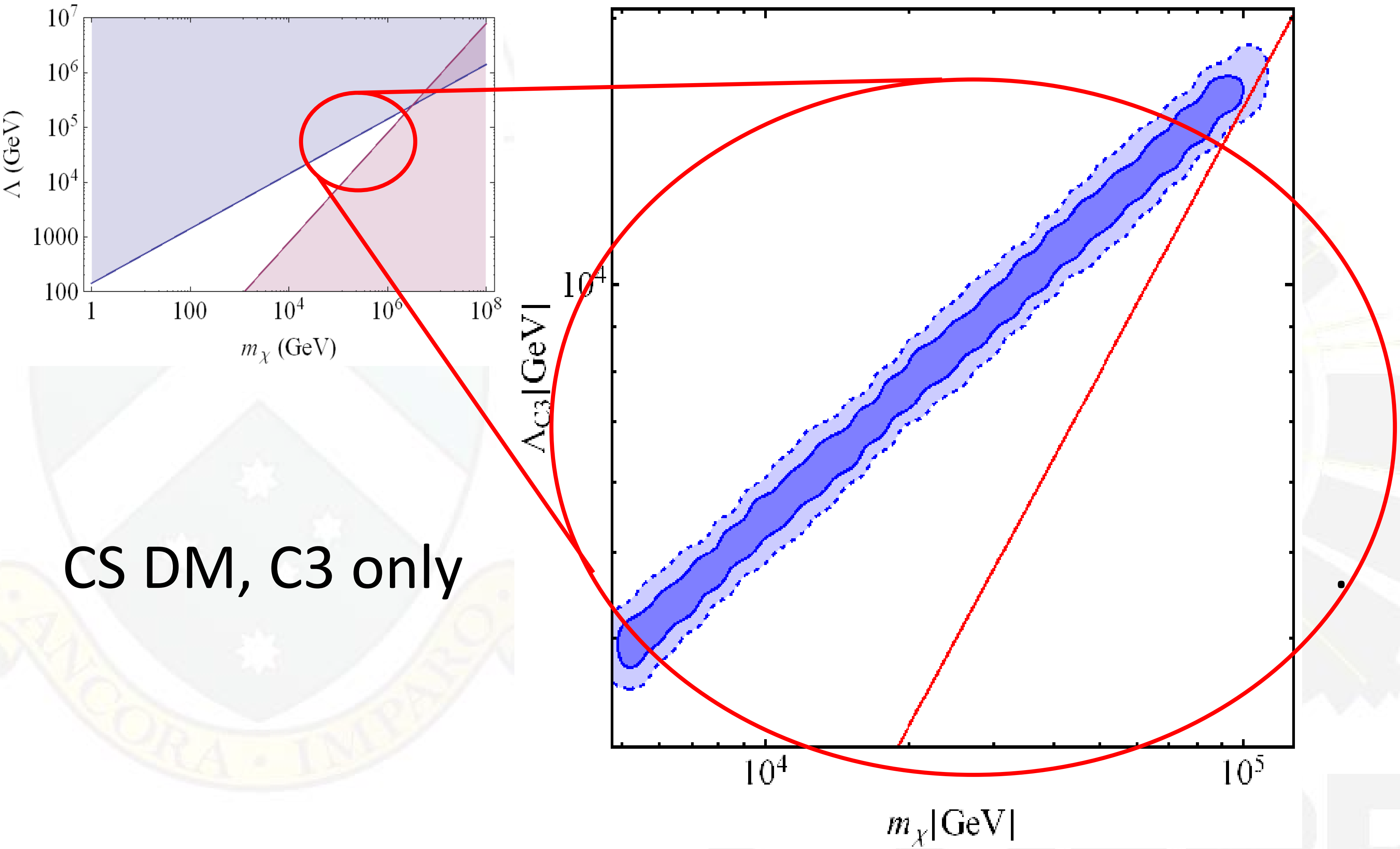
dark matter relic abundance

DM-nucleon elastic scattering cross section

some cosmic gamma rays

mono-jets

posterior probability distributions

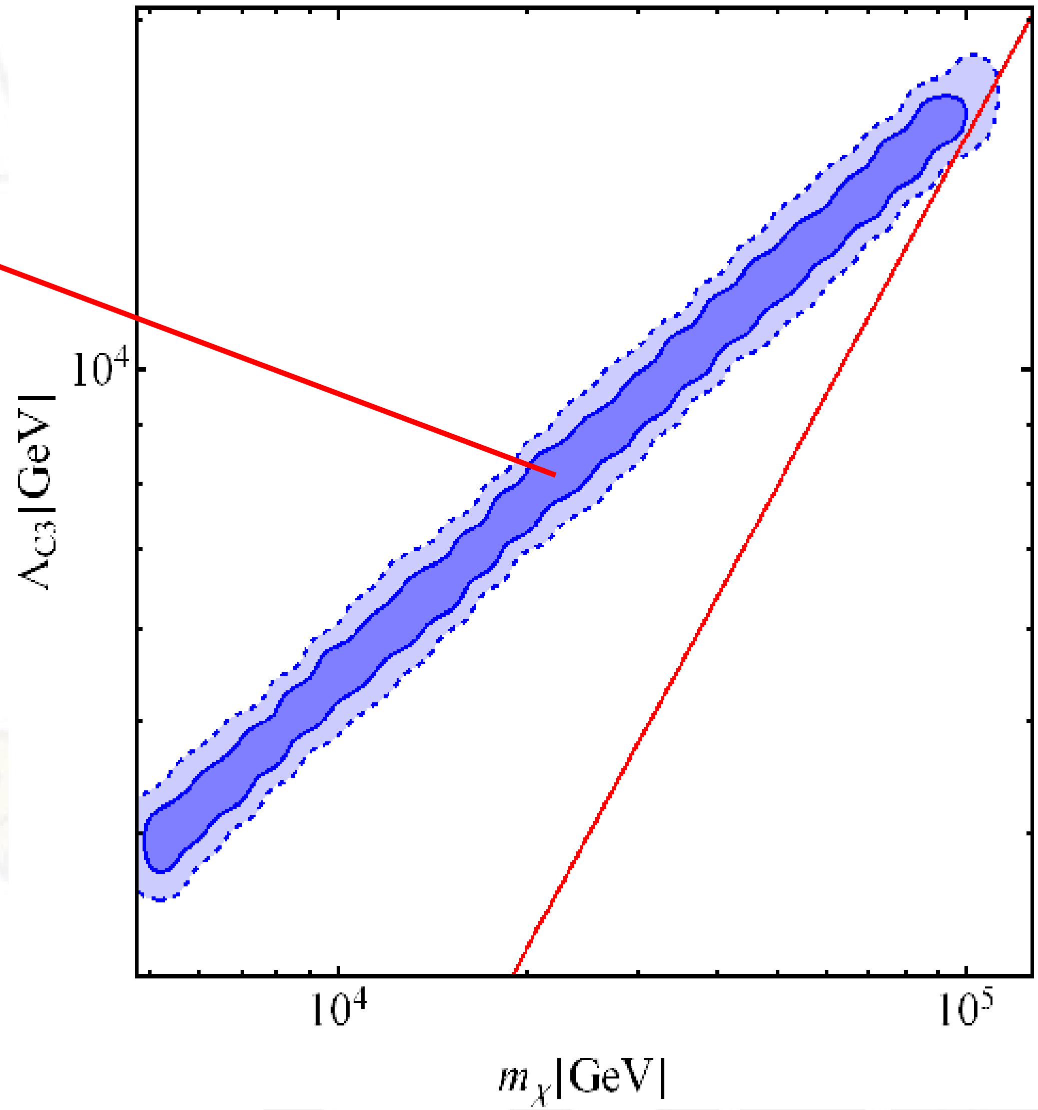


CS DM, C3 only

posterior probability distributions

Ωh^2
preferred

CS DM, C3 only

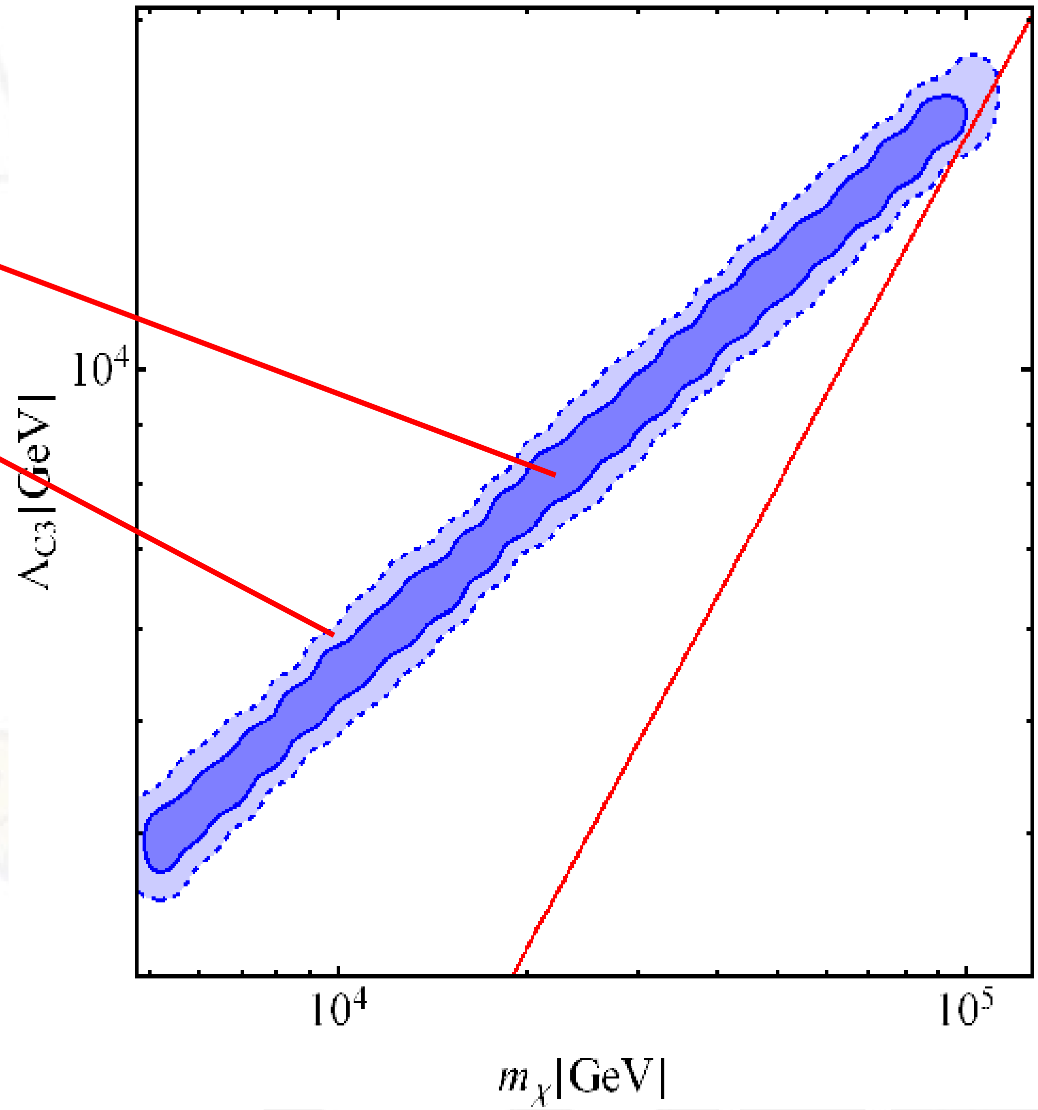


posterior probability distributions

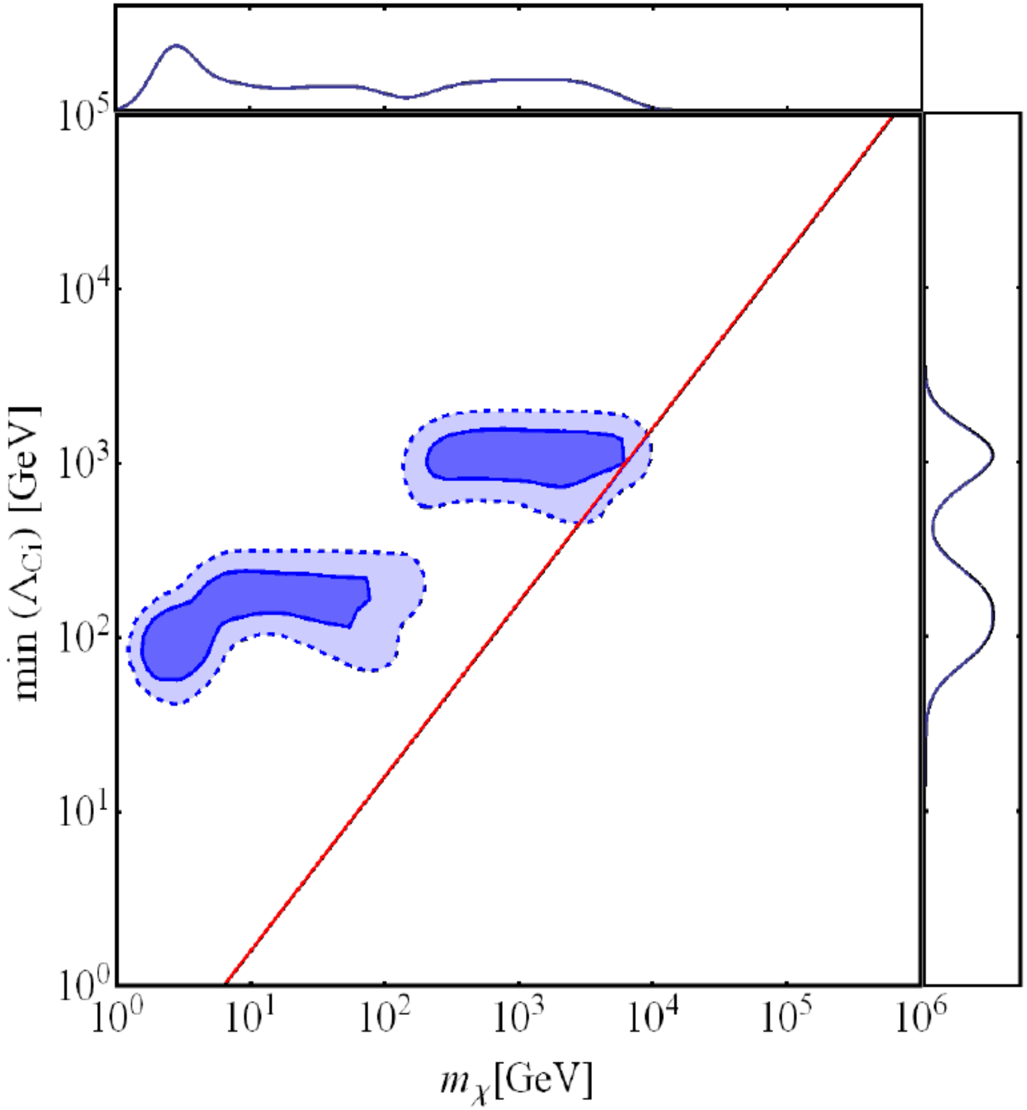
68% CR

95% CR

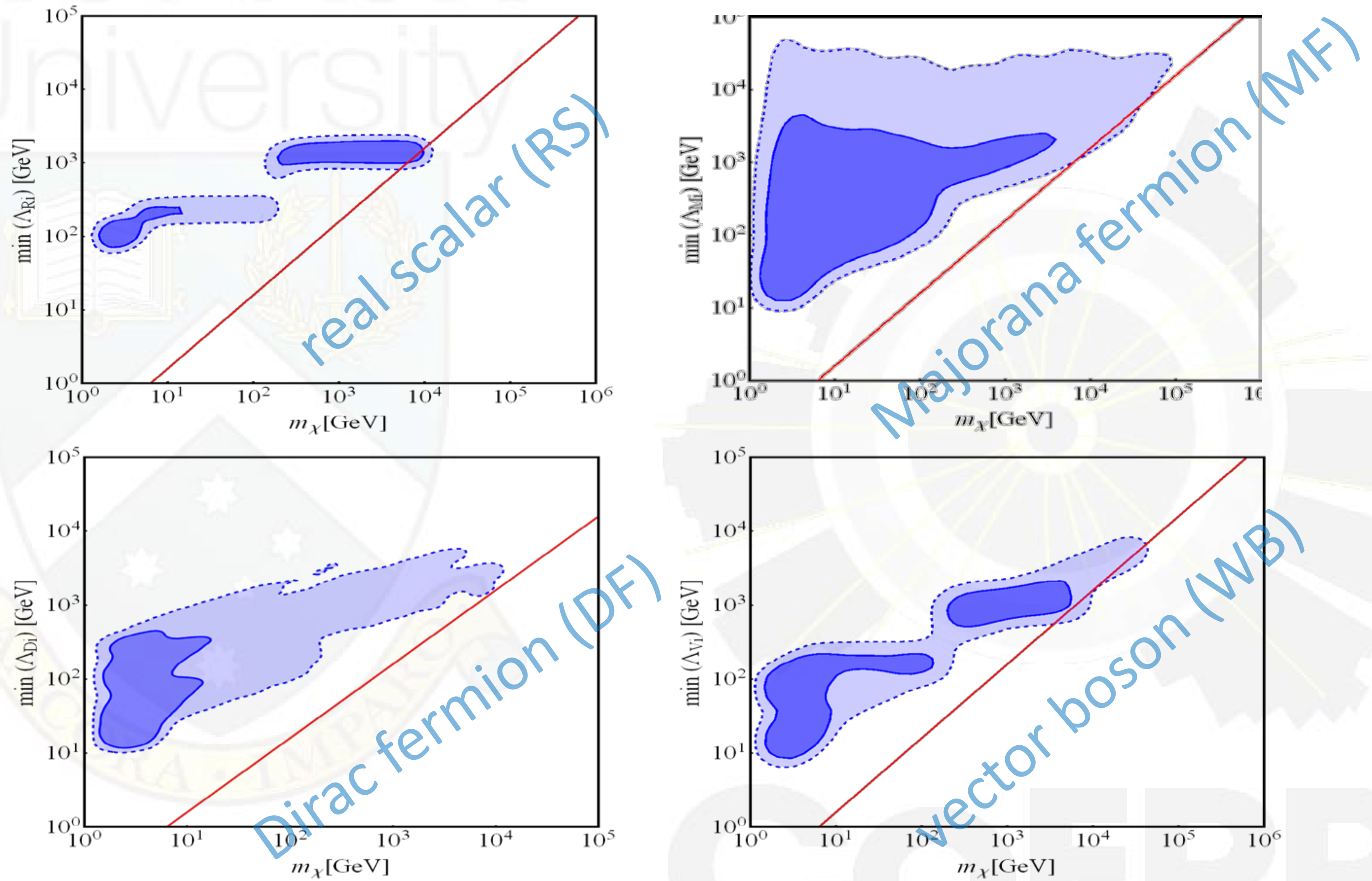
CS DM, C3 only



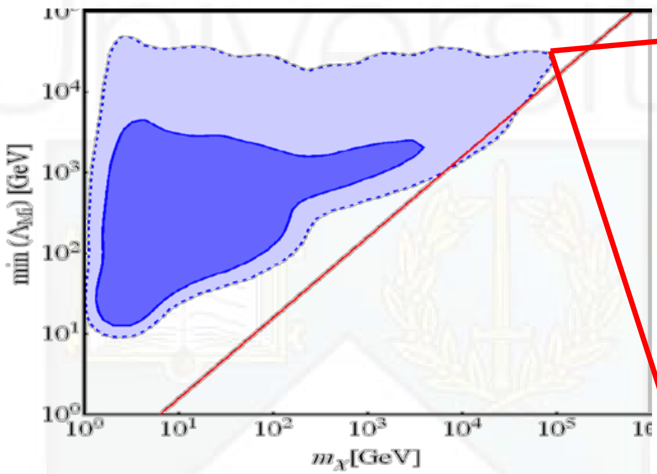
complex scalar dark matter – all operators



posterior probability distributions



acceptable dark matter density implies …



Model	m_χ (GeV)	Λ (GeV)
DF	3.0×10^4	4.7×10^3
MF	8.8×10^4	1.4×10^4
CS	4.5×10^4	7.1×10^3
RS	1.1×10^4	1.6×10^3
VB	4.8×10^4	7.7×10^3

… new physics scale below 100 TeV at 95% CL

conclusion

if dark matter is thermally produced and
if SM+DM can be described as effective QFT
then new physics is most likely below 100 TeV