Observations are confirming the WIMP paradigm

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arXiv:1403.5829, arXiv:1407.0174

Thermal dark matter implies new physics below PeV

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the LHC confirmed the SM

there's no sign of new physics

the SM may be valid up to M_P

a counter argument

quantitative

a counter argument

quantitative
a counter argument
based on
standard cosmology and
effective field theory

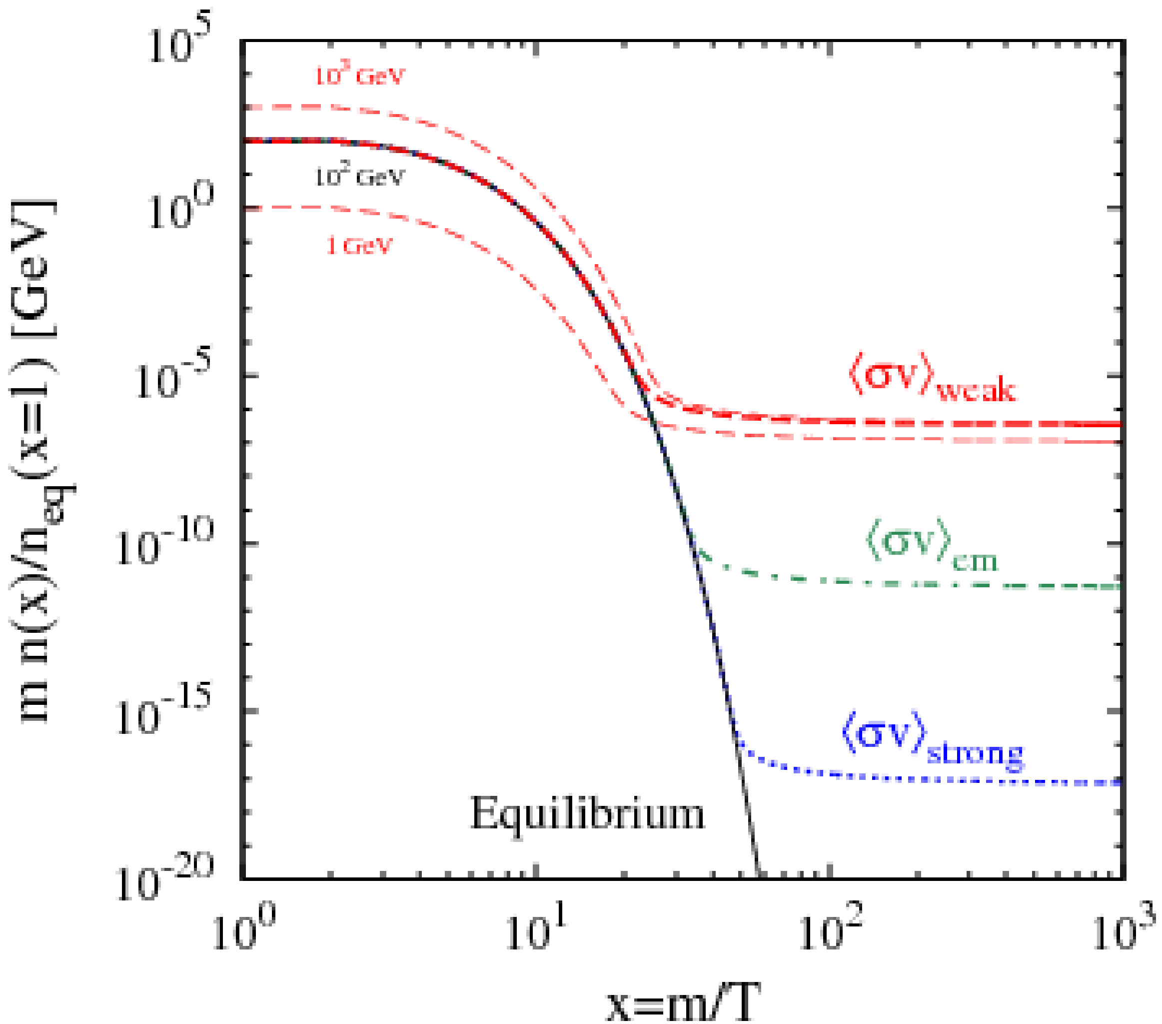
thermal WIMP miracle

standard cosmology & thermodynamics

$\Rightarrow$

cosmological abundance

standard thermal evolution



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

thermal WIMP miracle

standard cosmology & thermodynamics ⇒

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

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

thermal WIMP miracle

$$\sigma \sim 1\,pb$$

thermal WIMP **miracle**

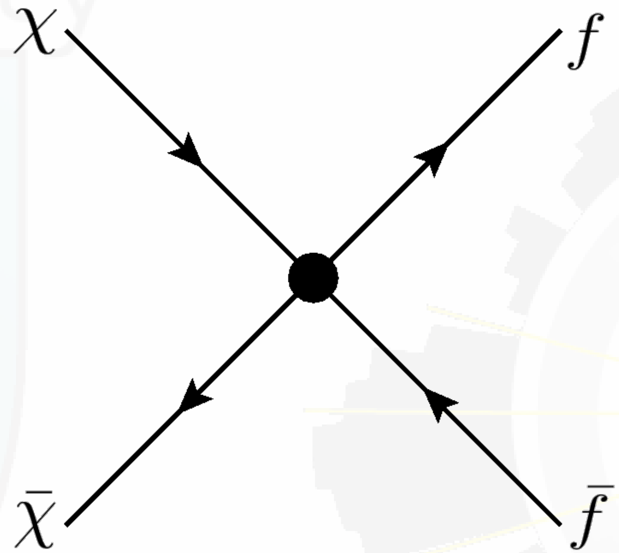
$$\Omega_\chi h^2 = \frac{s_0}{\rho_c/h^2}\left(\frac{45}{\pi g_*}\right)^{1/2}\frac{x_f}{m_{\rm Pl}}\frac{1}{\langle pb\ v\rangle} \sim 0.1$$

weak scale dark matter cross section

$$\sigma \sim 1\,pb$$

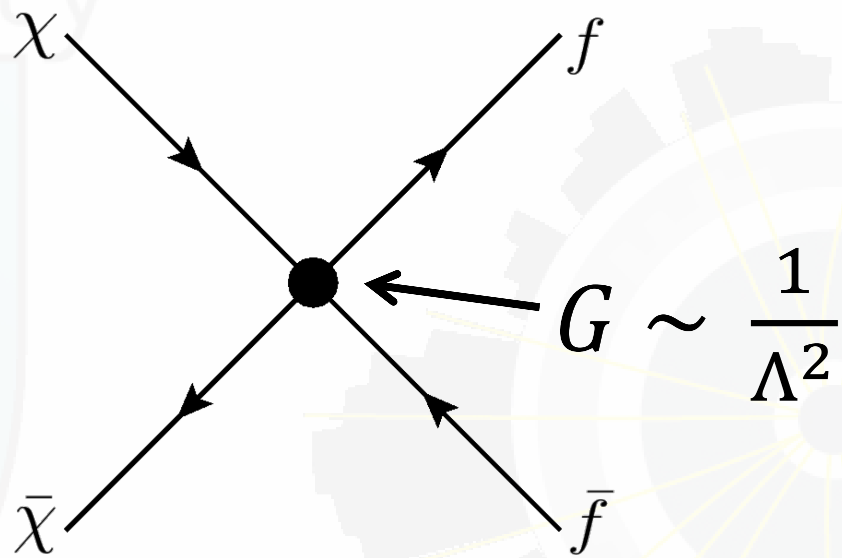
does not imply weak scale new physics

example



dark matter - standard matter
effective interaction

example



dark matter - standard model
effective interaction

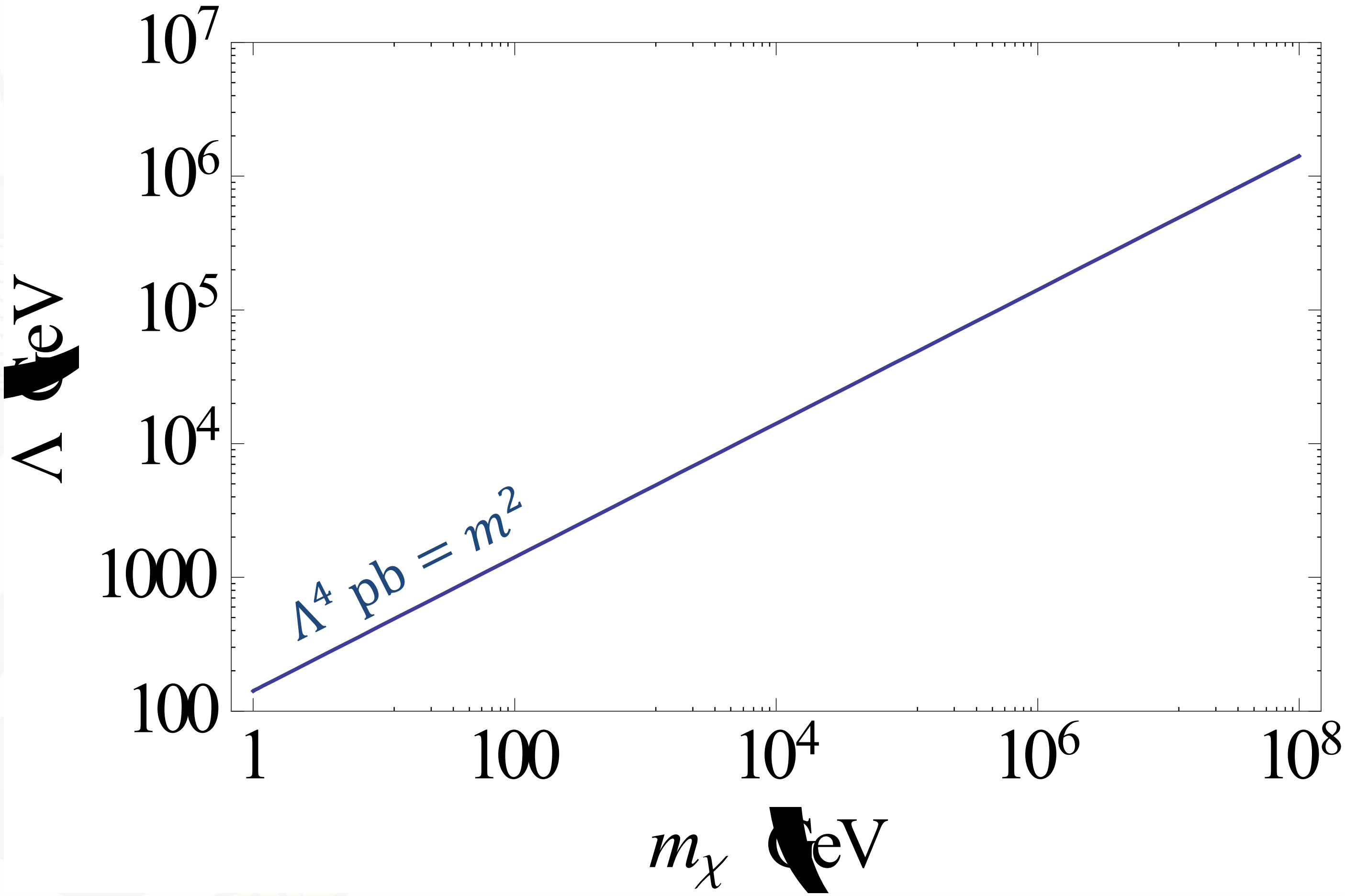
effective field theory

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

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

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

~~reverse WIMP miracle~~



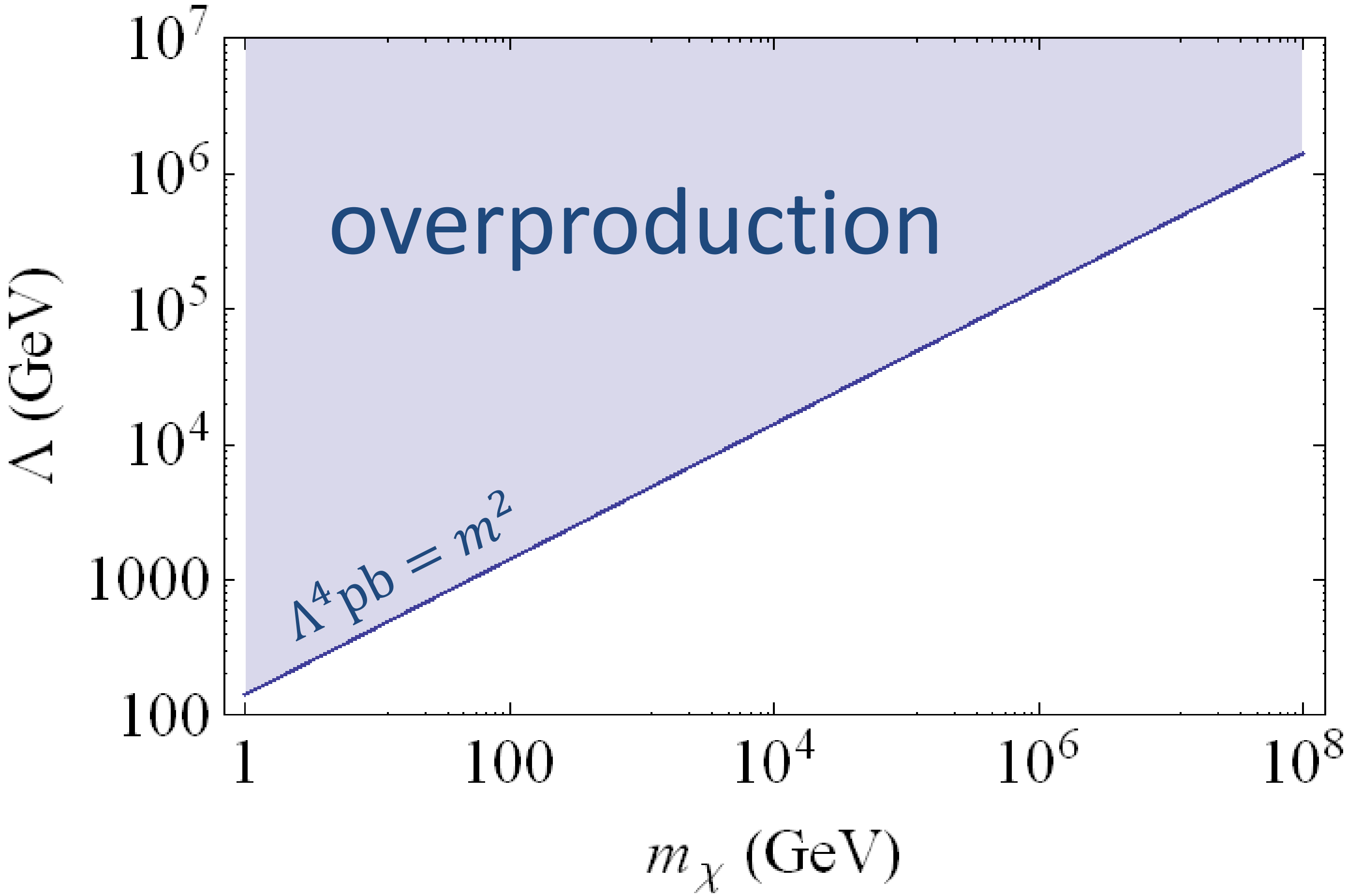
$\sigma \sim 1$ pb is realized for a range of m_χ and Λ

not to overproduce dark matter

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

must hold

~~reverse WIMP miracle~~

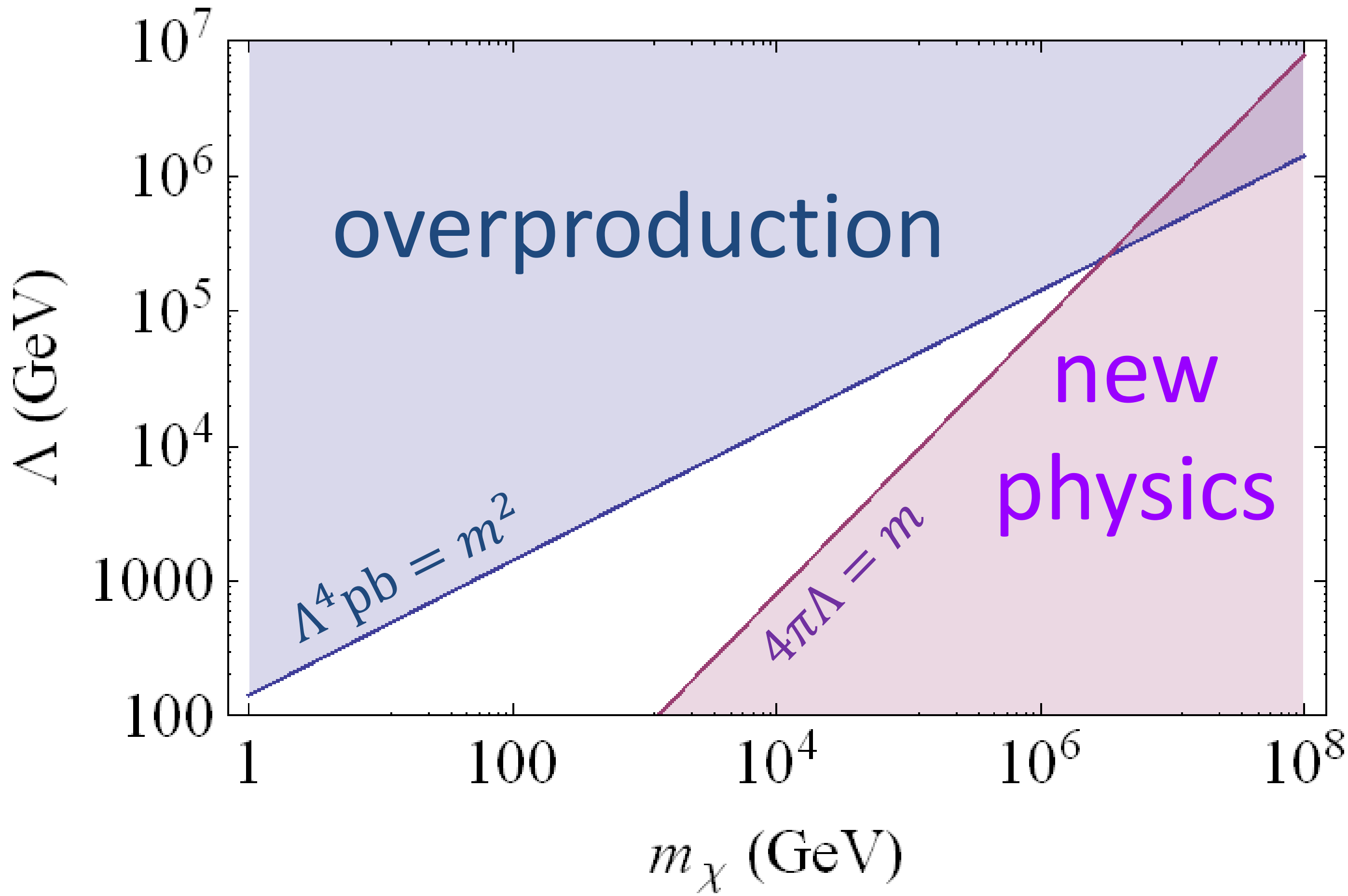


$m_\chi^2/\Lambda^4 \gtrsim$ pb not to overproduce dark matter an effective field theory with

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

breaks down

~~reverse WI~~MP miracle



acceptable dark matter only for $m_\chi \lesssim \mathrm{PeV}$

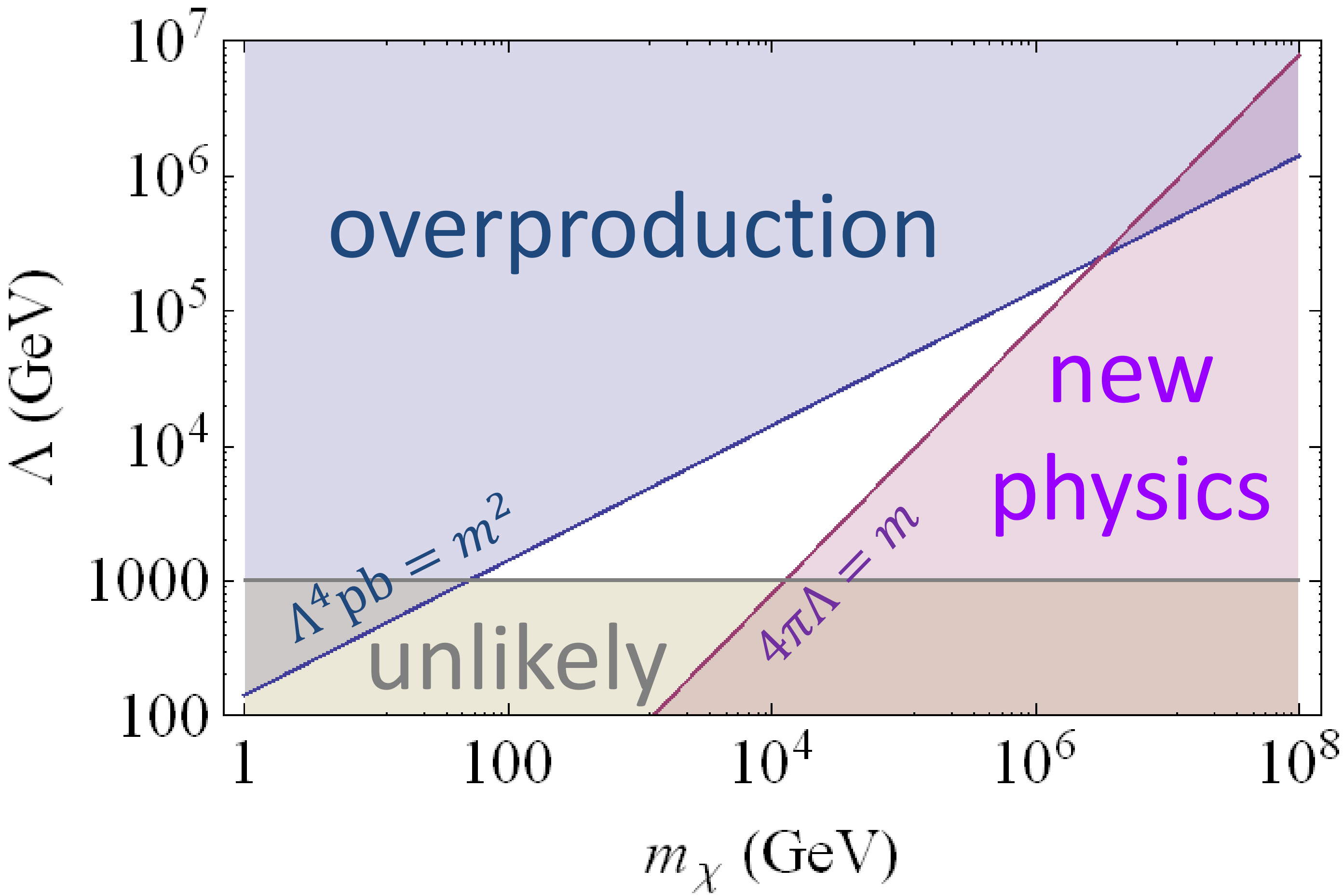
~~reverse WI~~MP miracle

if

$$\Lambda_{\text{new phyiscs}} \lesssim 1\ \text{TeV}$$

is unlikely

if new physics $\lesssim$ TeV is improbable



then the WIMP miracle is ‘reversed’

this was the cartoon version of
our parameter extraction exercise

now, to the real thing…

assumptions

DM thermally produced via freeze-out

SM+DM described as effective QFT

DM-SM interactions

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

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

Dirac fermion (DF)

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	$\chi^\mu\chi_\mu\bar f\gamma_5 f$	$\frac{i m_f}{2\Lambda^2_{V2}}$
V3	$X^{\mu\nu}X_{\mu\nu}\bar f f$	$\frac{m_f}{4\Lambda^4_{V3}}$
V4	$X^{\mu\nu}X_{\mu\nu}\bar f\gamma_5 f$	$\frac{i m_f}{4\Lambda^4_{V4}}$

Vector boson (VB)

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

Majorana fermion (MF)

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

Real/complex (RS/CS) scalar

“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

observables

dark matter relic abundance

DM-nucleon elastic scattering cross section

some cosmic gamma rays

mono-jets

data

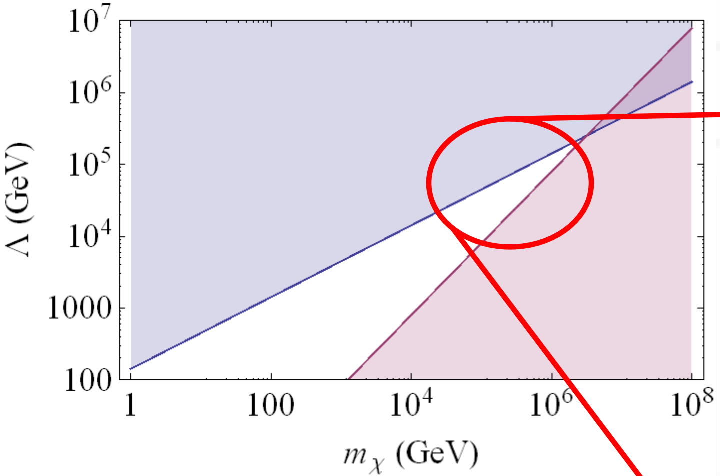
Planck

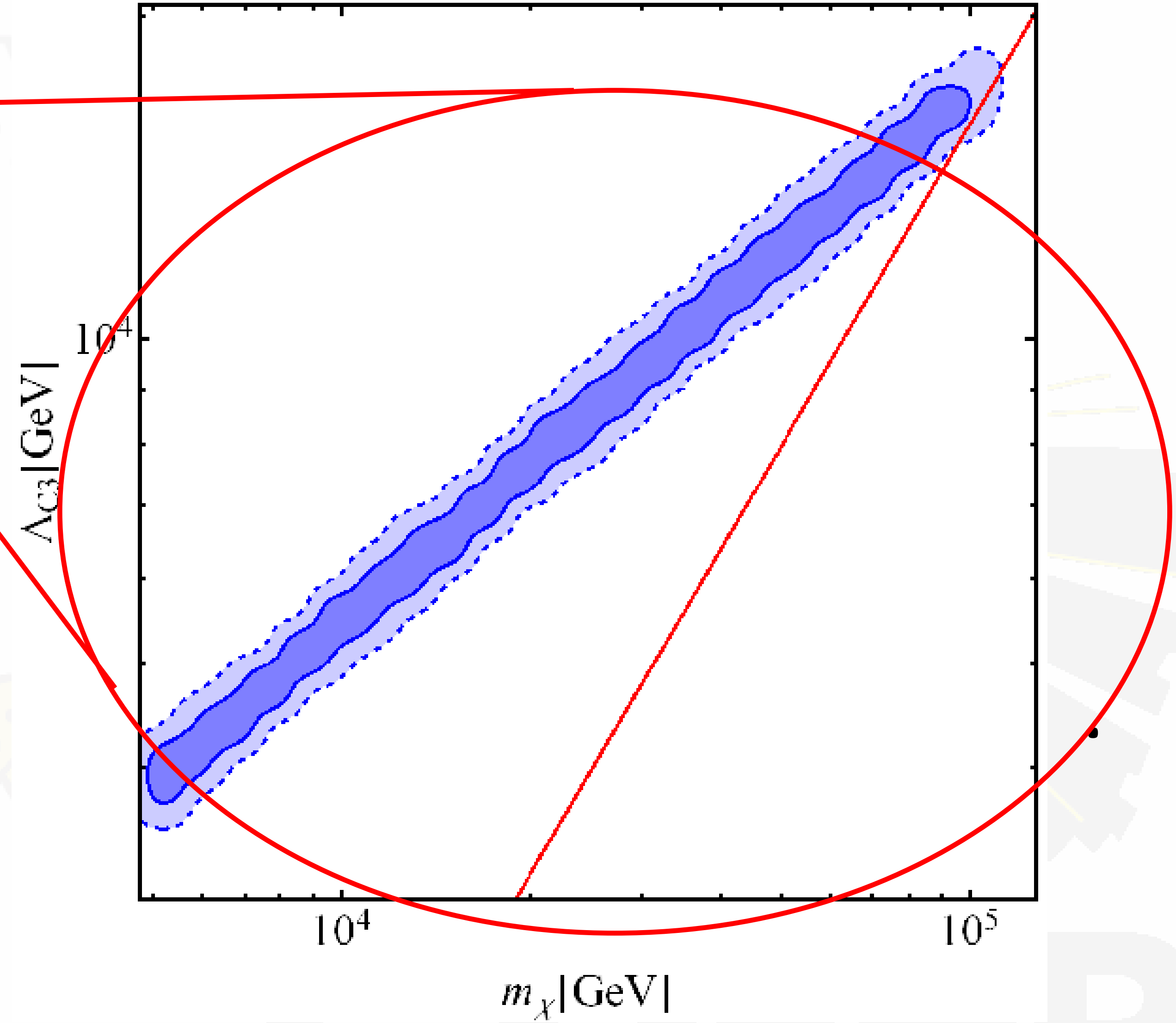
LUX, CDMSlite, XENON100

Fermi-LAT

LHC

posterior probability distributions



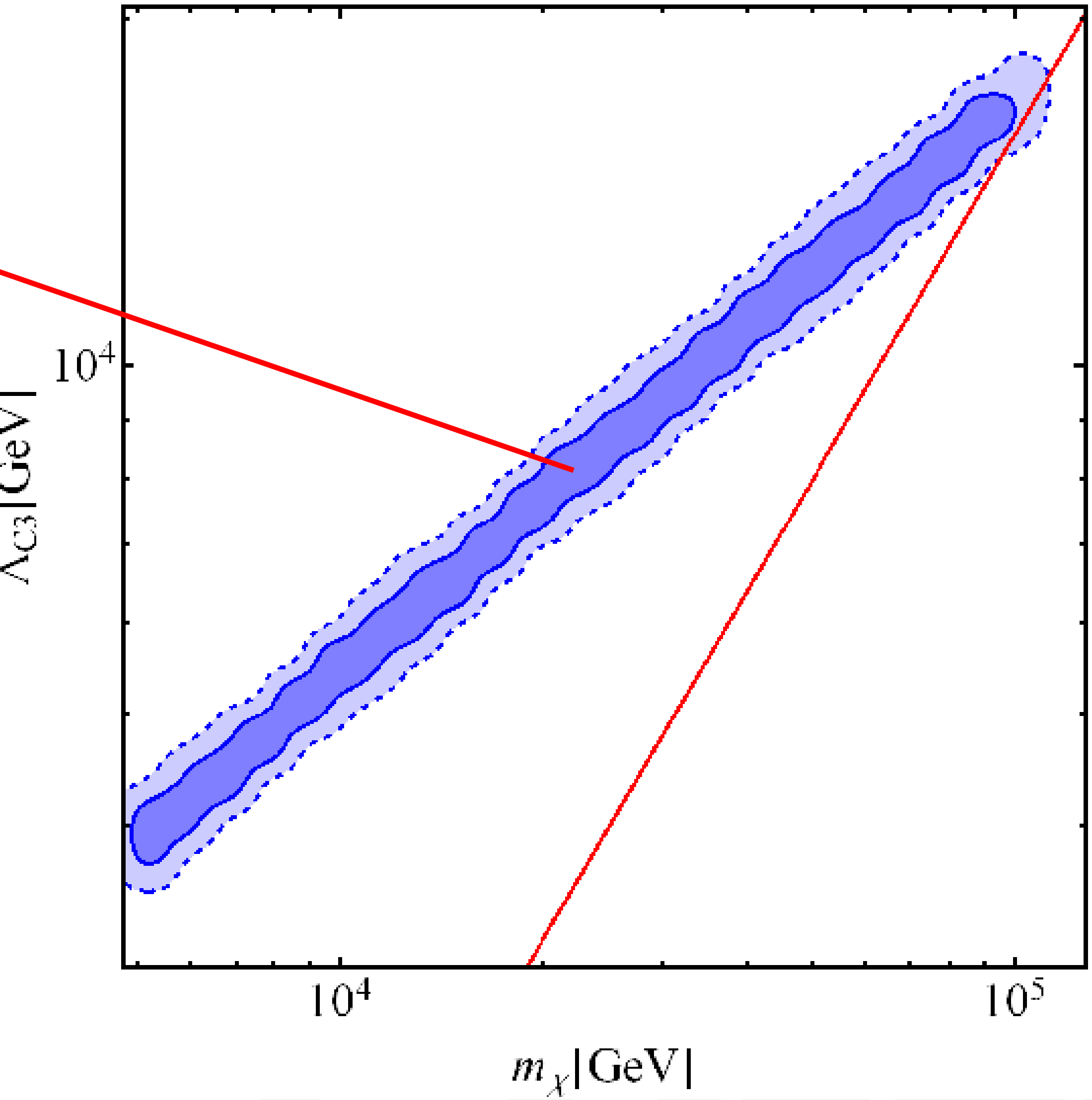


CS DM, C3 only

posterior probability distributions

Ωh^2 preferred

CS DM, C3 only

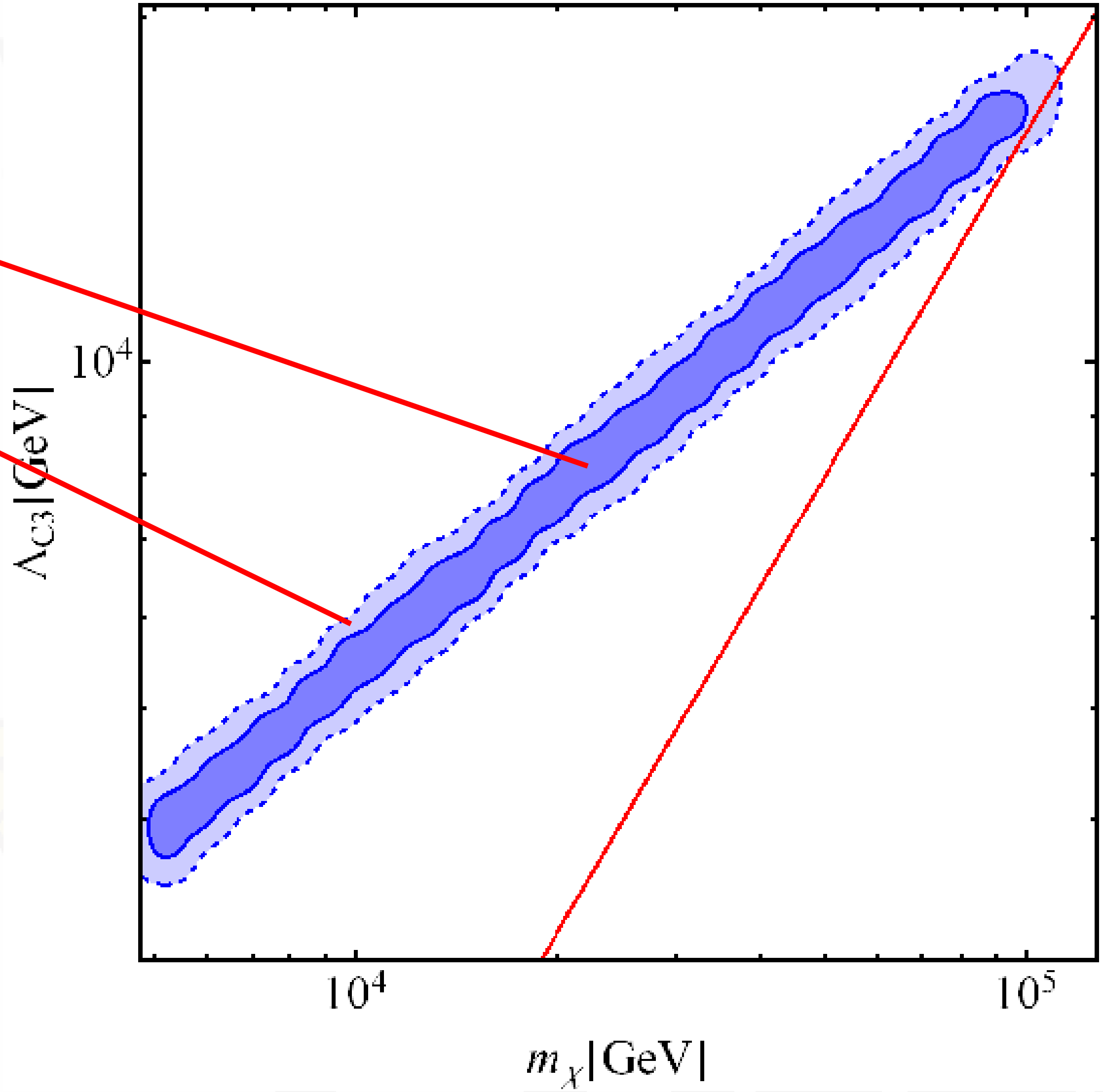


posterior probability distributions

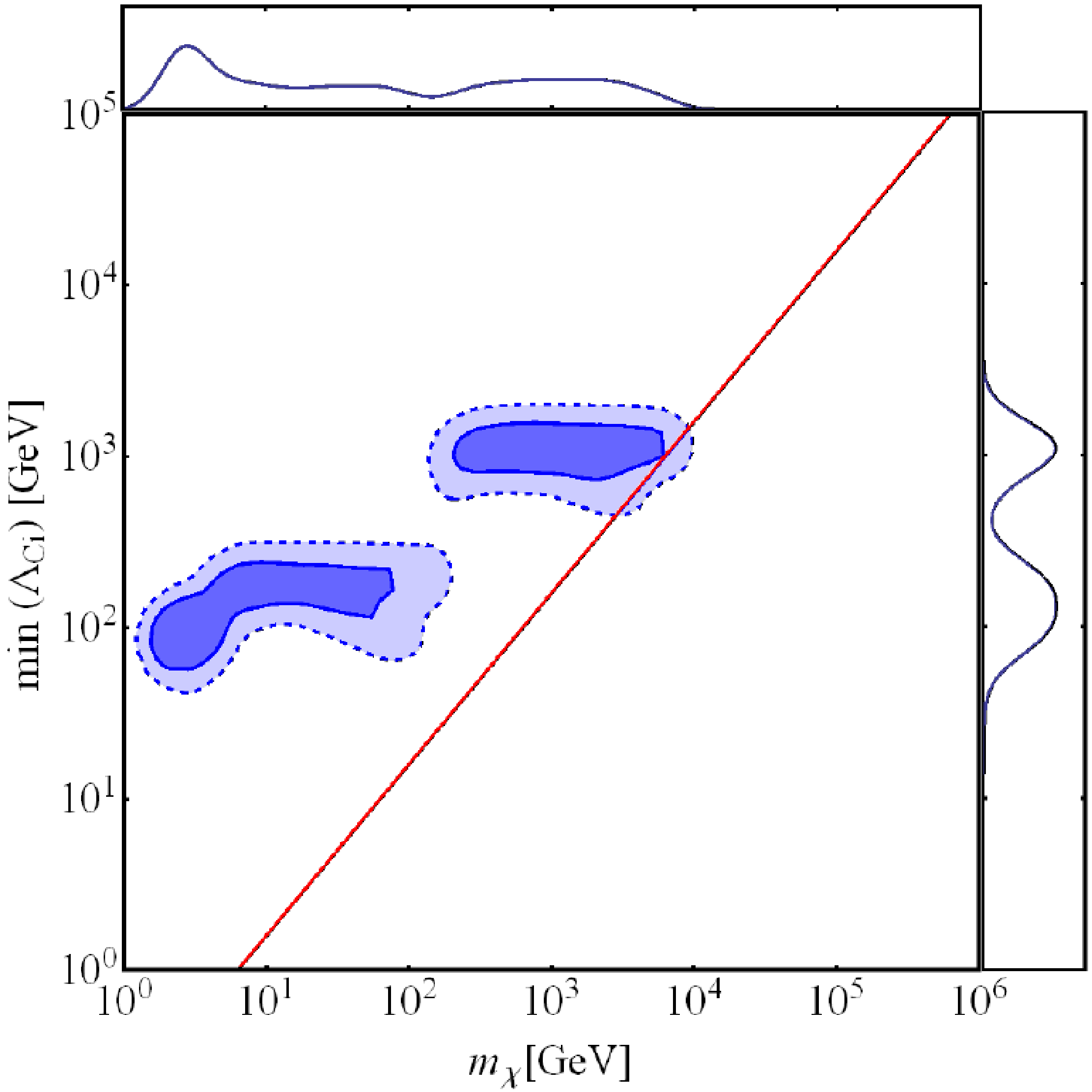
68% CR

95% CR

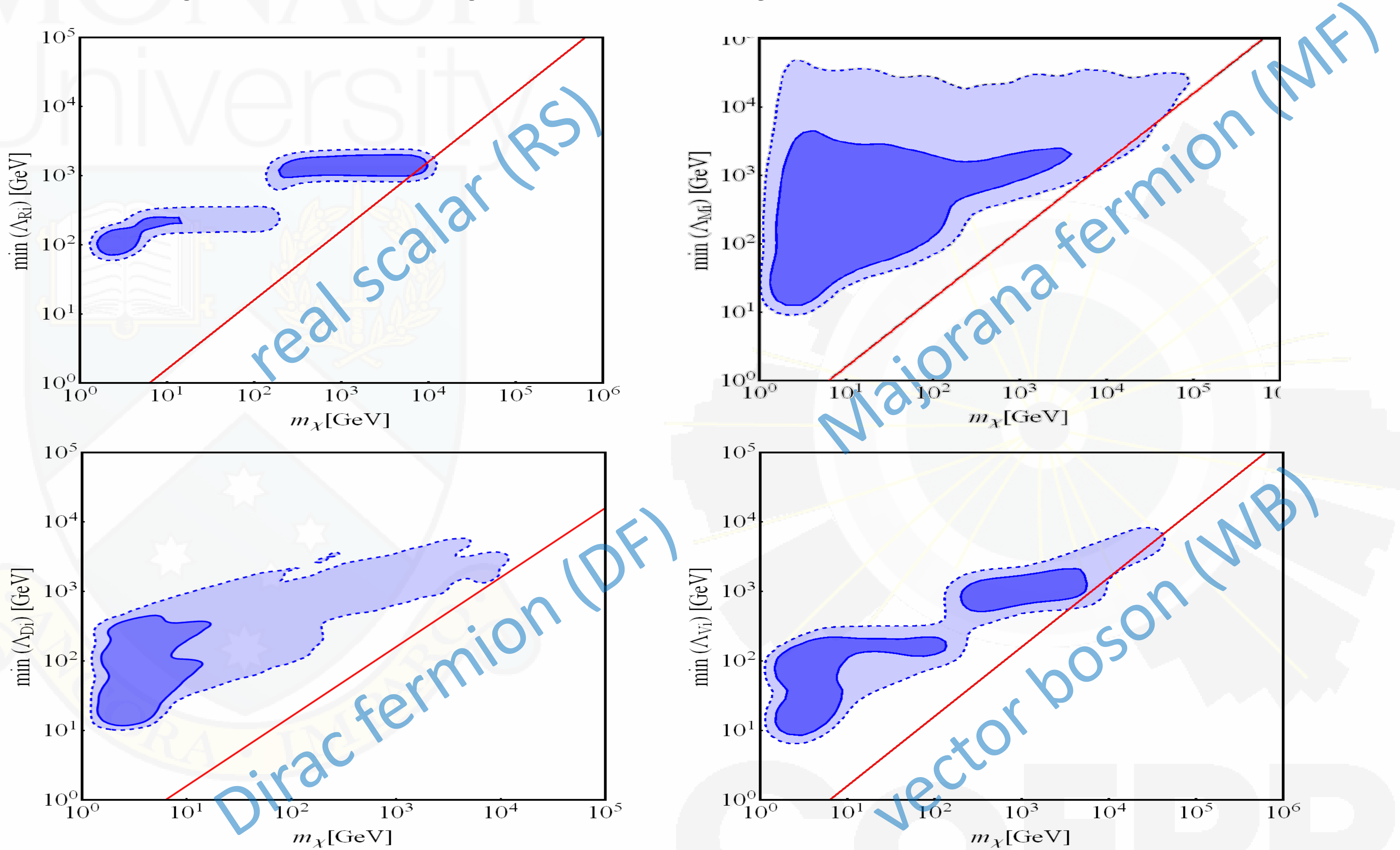
CS DM, C3 only



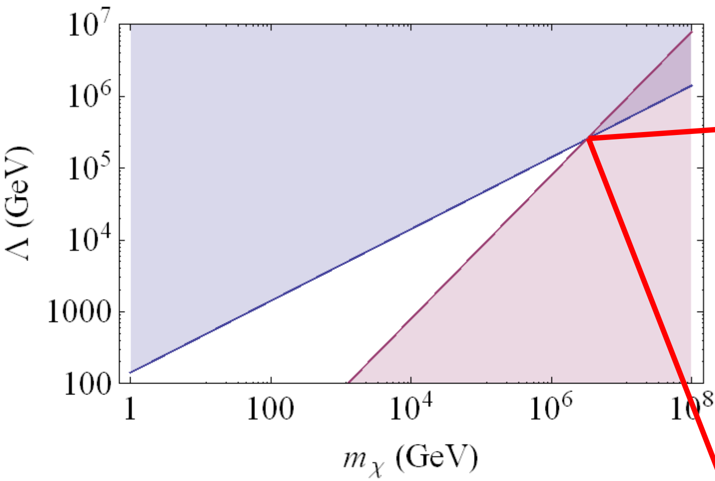
complex scalar dark matter – all operators



posterior probability distributions



acceptable dark matter density



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 is well below PeV at 95% CL

conclusion

if dark matter is thermally produced and if DM+SM can be described as effective QFT

then new physics is most likely below PeV