Dark Matter in the light of no signals

Juan Herrero García

Napoli, 13th of September 2023

TeV Particle Astrophysics (TeVPA)

Direct Dark Matter searches session

Universitat de València
IFIC Institut de Física Corpuscular
CSIC Consejo Superior de Investigaciones Científicas
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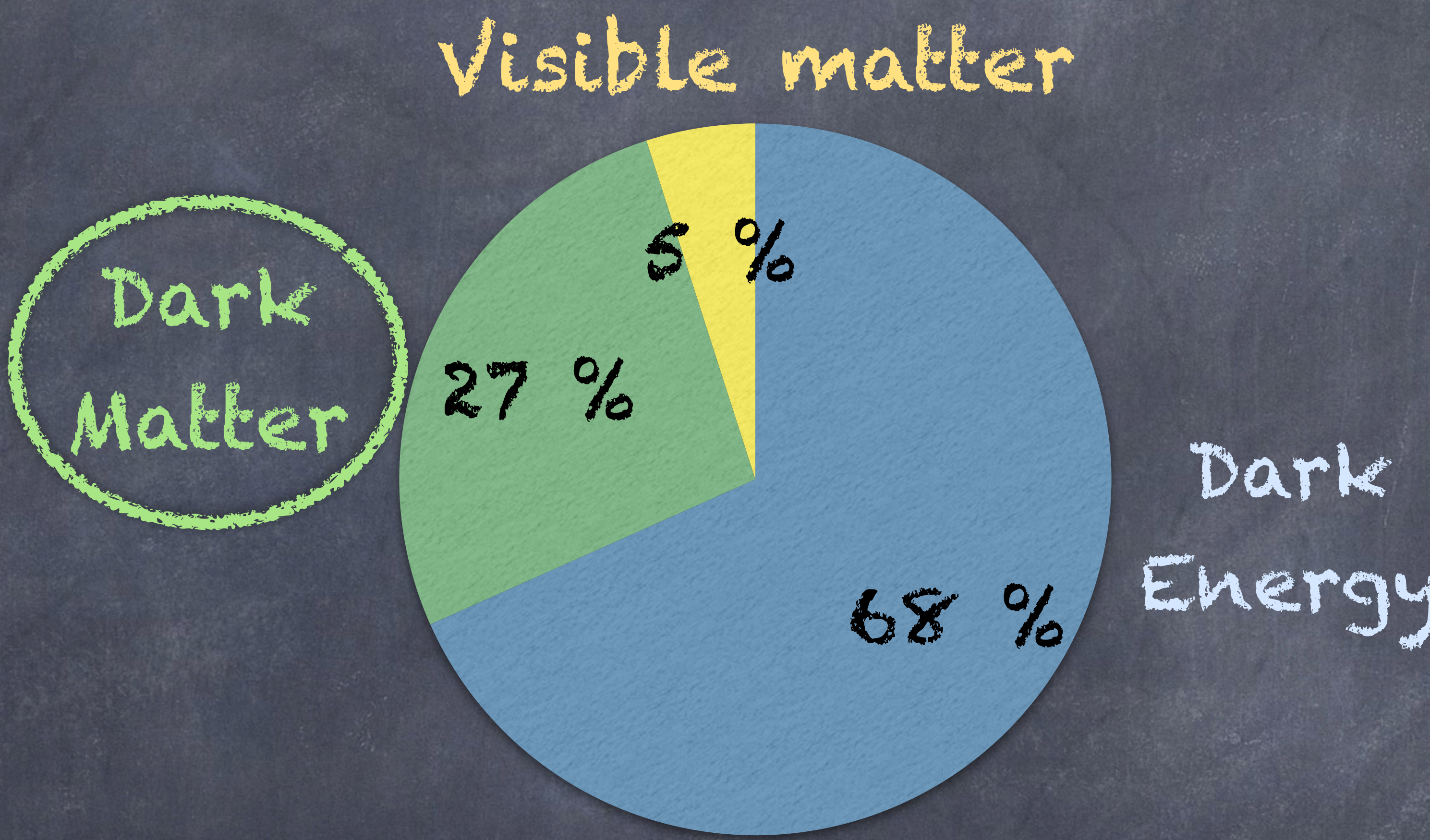
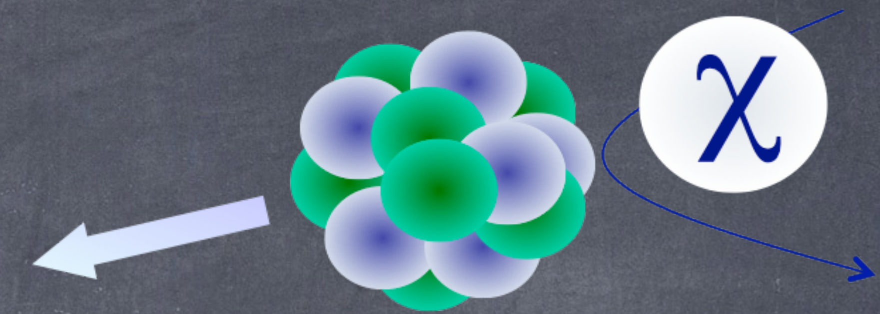
A Dark Universe

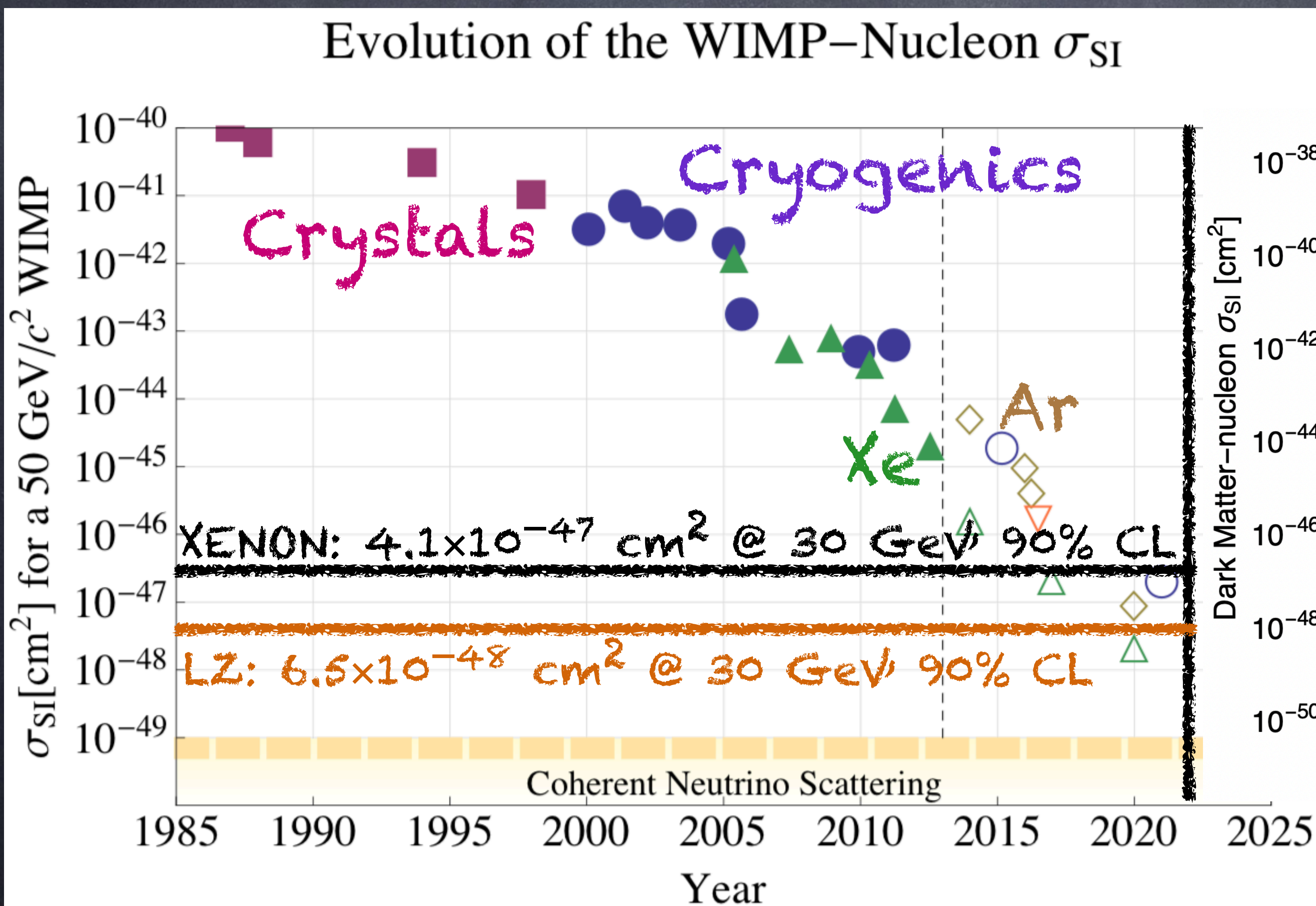


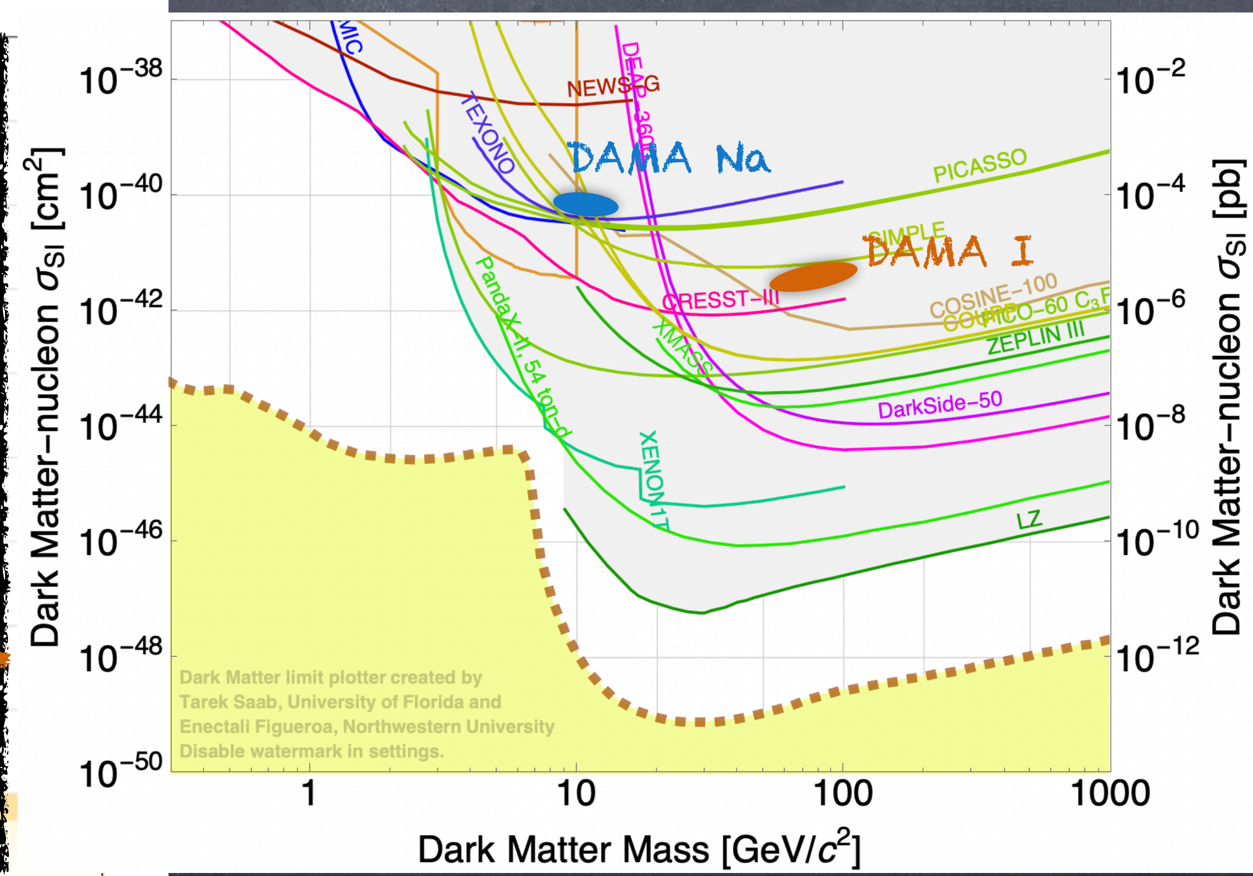
Lots of evidence,
from many different scales,
of the existence of cold non-baryonic DM

WIMPs Direct Detection: temporal evolution



[Goodman, Witten 1985; Drukier, Freese, Spergel 1986]
[Figure from Snowmass WG, 1310.8327]





Dark situation: where are the WIMPs?

From the experimental side, to probe the WIMP paradigm, large detectors are required:

New Consortium XLZD 2027 $(40t - 100t)$:
XENON + LZ + DARWIN [2203.02309]

Global Argon DM Coll. ARGO $(100t - 300t)$:
ARDM + DEAP + DARKSIDE

Next decade crucial, with
2 possible situations

Situation 1: A signal is observed

- New "golden epoch" for DM, like that of neutrinos
- Goal: robust & precise determination of DM parameters
- Ideally, independently of astrophysical uncertainties
- Need several signals from different methods and experiments to break degeneracies

Complementarity: DD & ν from Sun

We can gain info by combining different methods

Information gain

DD	ν from Sun	**Lessons**
No	No	Keep trying... Does DM interact non-gravitationally? Other candidates (PBH, axions, etc.)?
No	Yes	No lower limit to $\mathcal{R}_{\mathrm{DD}}$ from $\Gamma^{\nu}_{\mathrm{Sun}}$ DM disc? DM self-interactions? Inelastic DM?
Yes	No	Halo-independent lower limit on the capture: $\Rightarrow$ Upper limits on BRs [Blennow et al, JCAP 05 (2015) 036] SD dominated by neutrons? Asymmetric DM?
Yes	Yes	Check lower limit $\Rightarrow$ If fulfilled, extract DM properties

Situation 2:
No signal is observed

- Simplest WIMP paradigm needs revisiting
- From the theory side, we need DM models with suppressed (DD) signals

II - Dark Matter models with suppressed signals

Example 1: Pseudo-Nambu Goldstone boson DM from spontaneously broken global U(1)

[Coito, Faubel, JHG, Santamaria, JHEP 11 (2021) 202]

$\Longrightarrow$ Thanks to Goldstone boson's derivative couplings, DM may evade DD limits

Global U(1) and Dark CP $S \to S^*$

[Coimbra 2013, Gross 2017, Alanne 2020, Arina 2020, Muhlleitner 2020, Lebedev 2021]

$S \equiv \frac{1}{\sqrt{2}}\left(v_s + \rho' + i\theta\right) \implies S \to S^*$ $(\theta \to -\theta)$: θ stable, DM

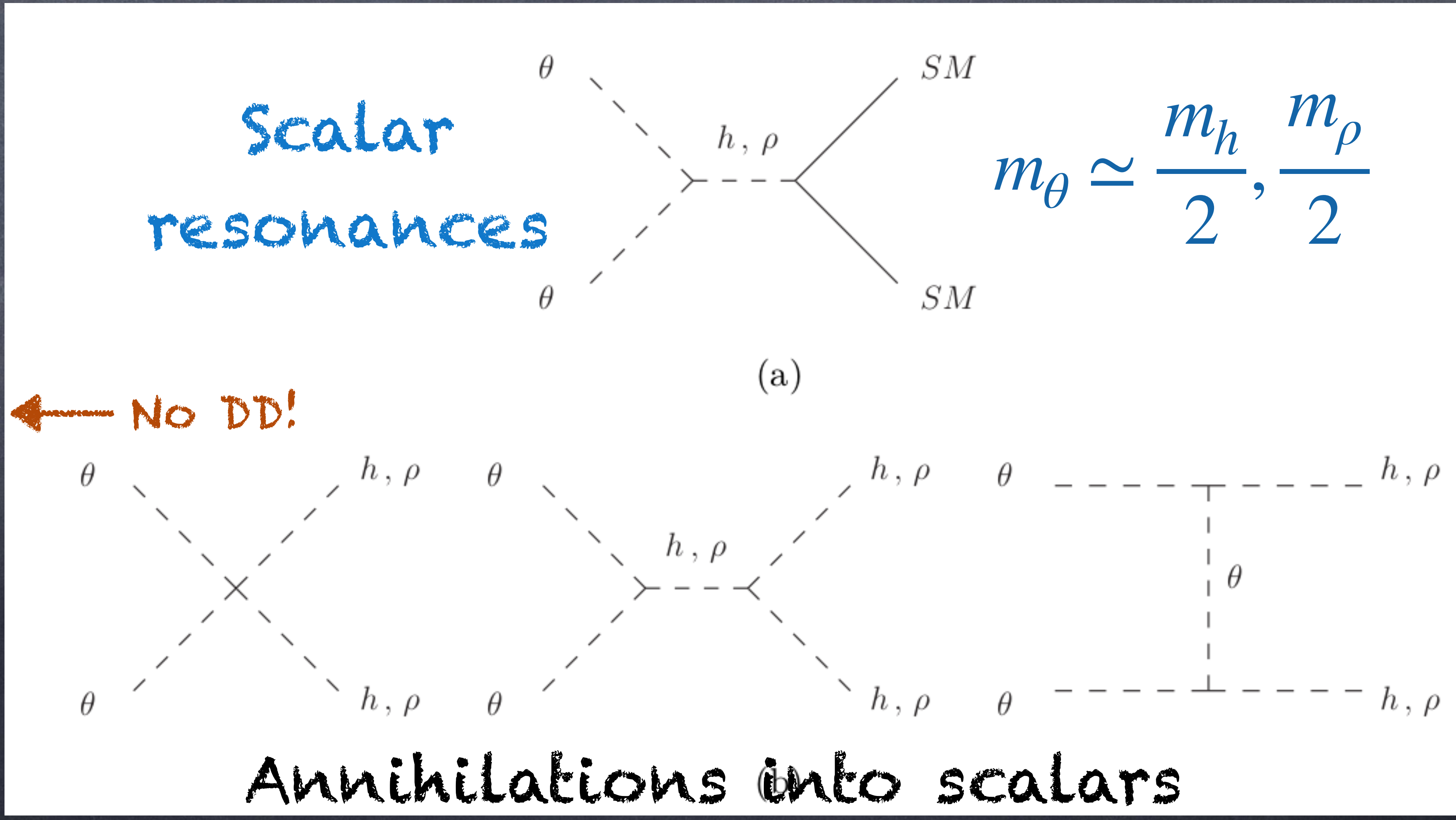
U(1) soft breaking:

Linear: $V_1 = \frac{1}{2}\mu^3 S$

Quadratic: $V_{Z_2} = \frac{1}{2}\mu_S^2 S^2$ ← No DD!

Cubic: $V_{Z_3} = \frac{1}{2}\mu_3 S^3$

Quartic: $V_{Z_4} = \frac{1}{2}\lambda_4 S^4$



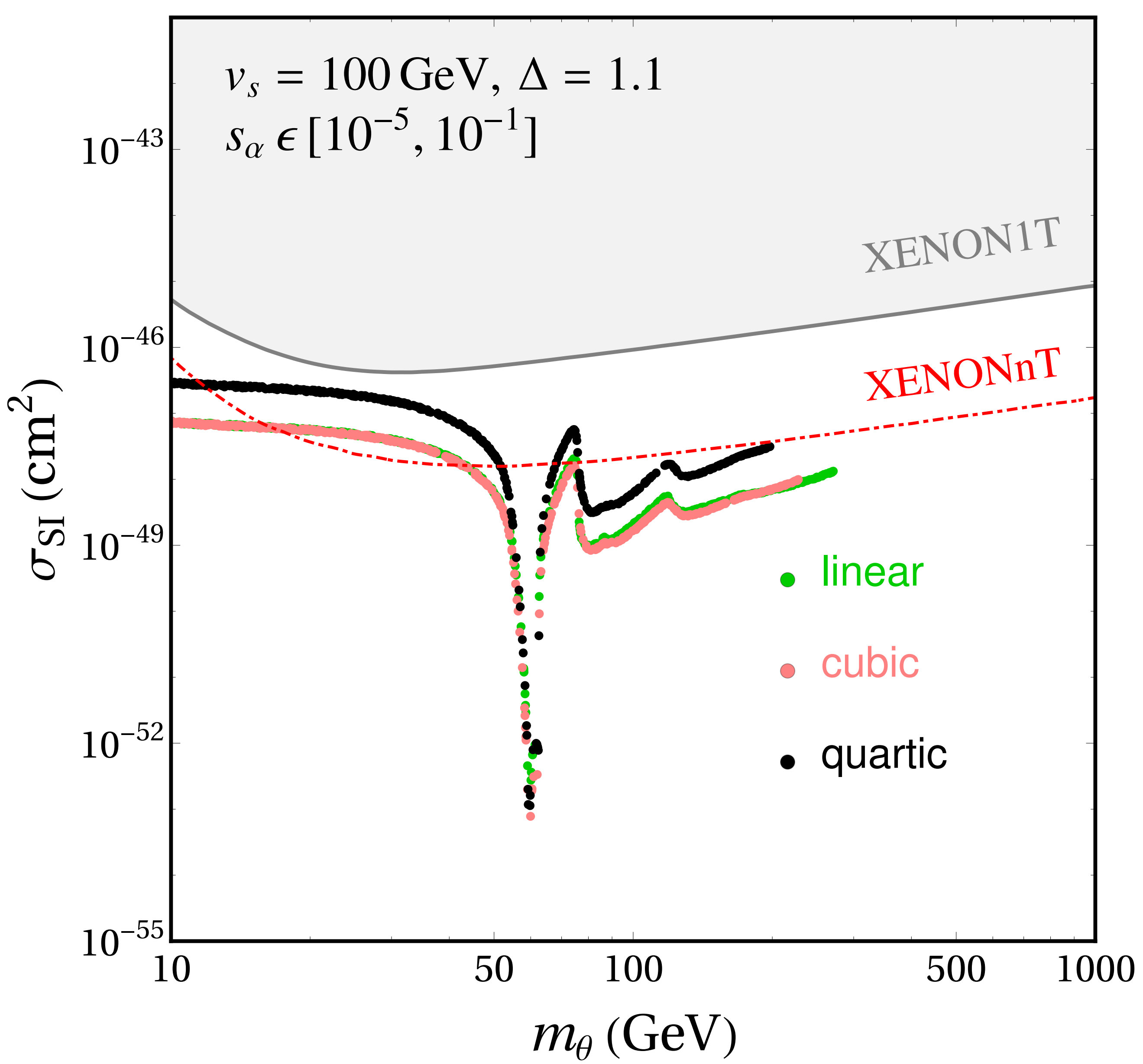
Only 4 free parameters: $v_s, m_\theta, m_\rho, s_\alpha$

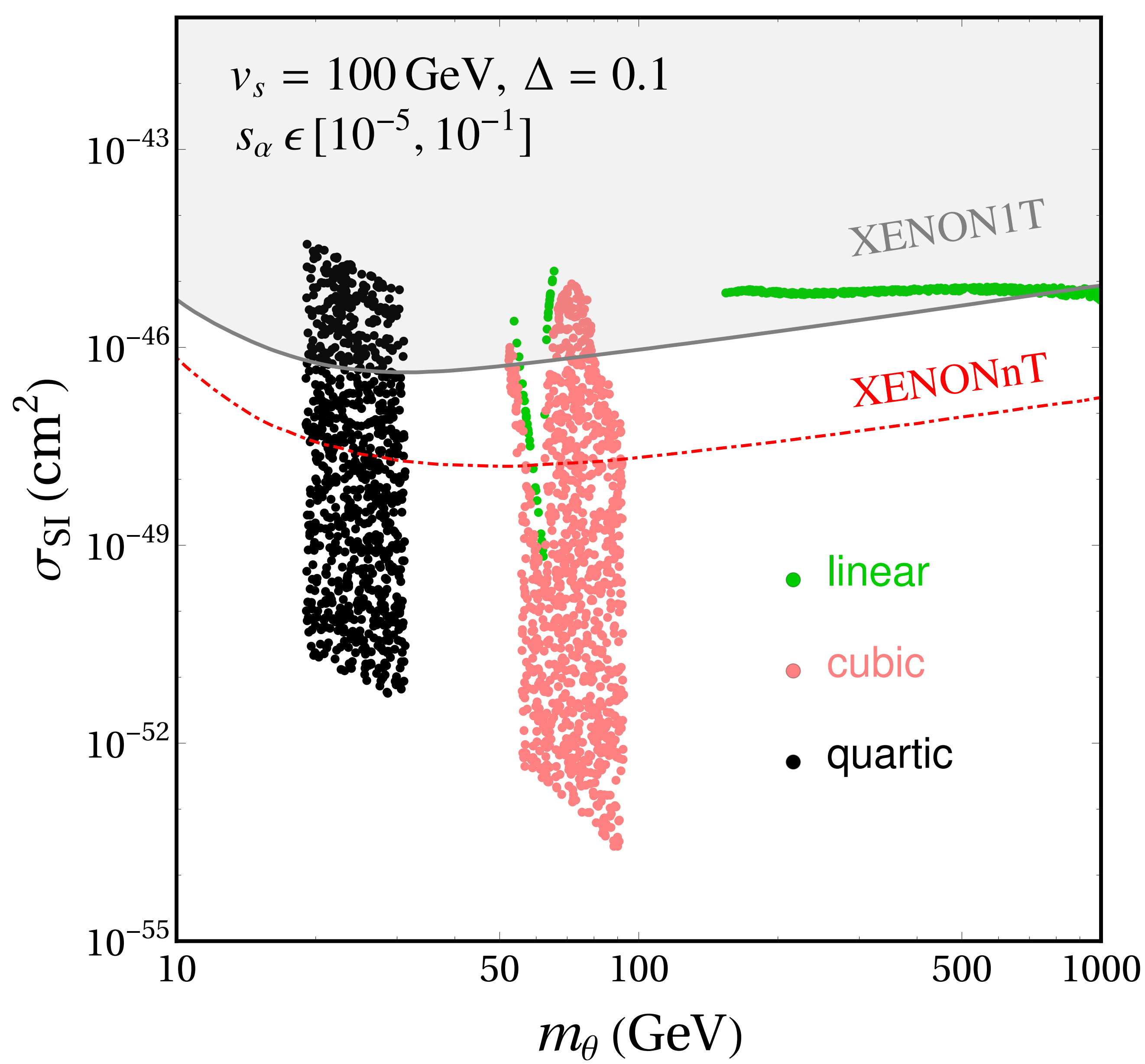
$$\Delta = \frac{m_\rho - m_\theta}{m_\theta}$$

Results

Resonance of ρ

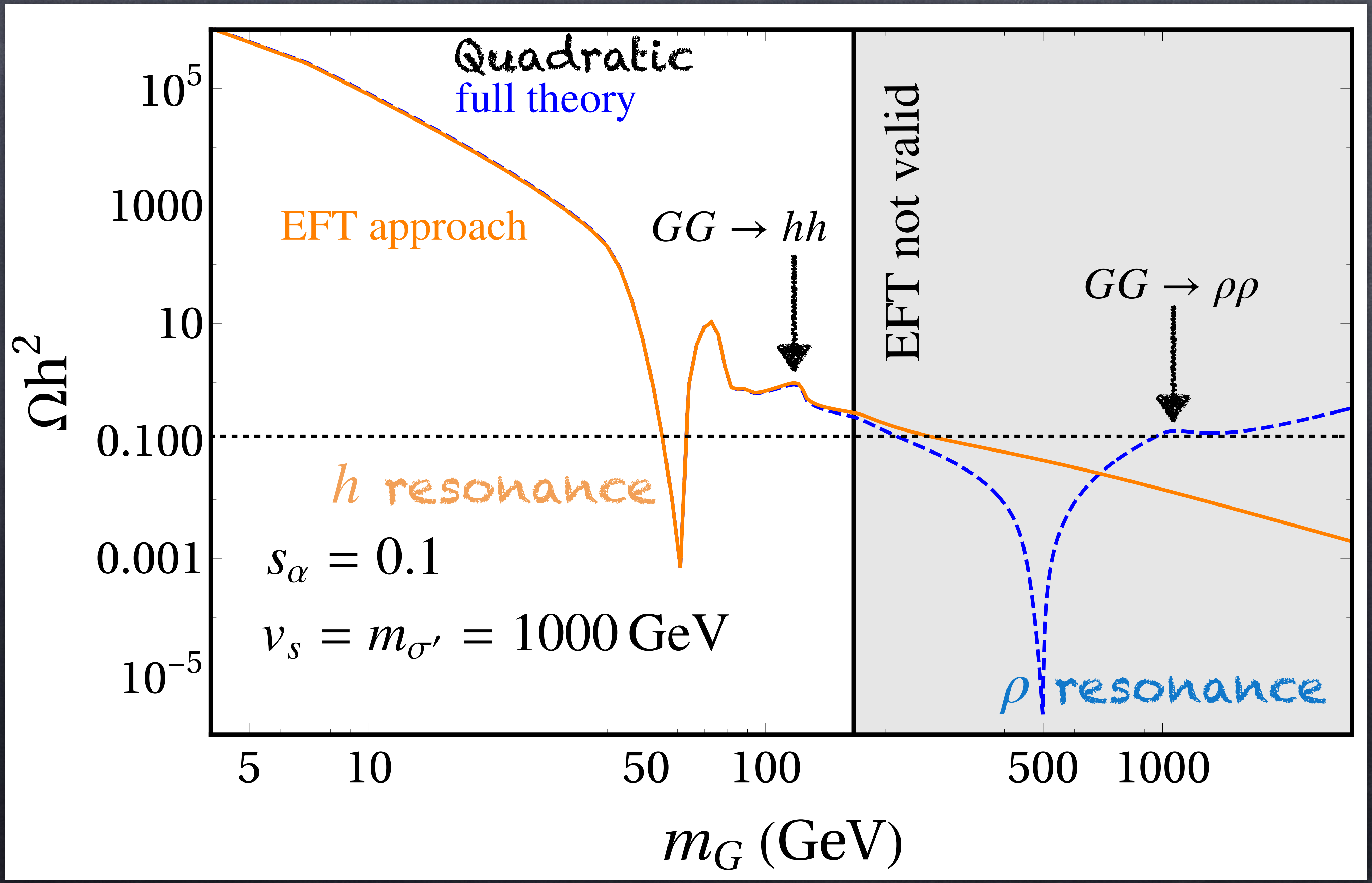
Forbidden: $m_\theta \lesssim m_\rho, m_h$





Goldstone limit $m_G \ll v_s \sim m_{\sigma'}$: EFT

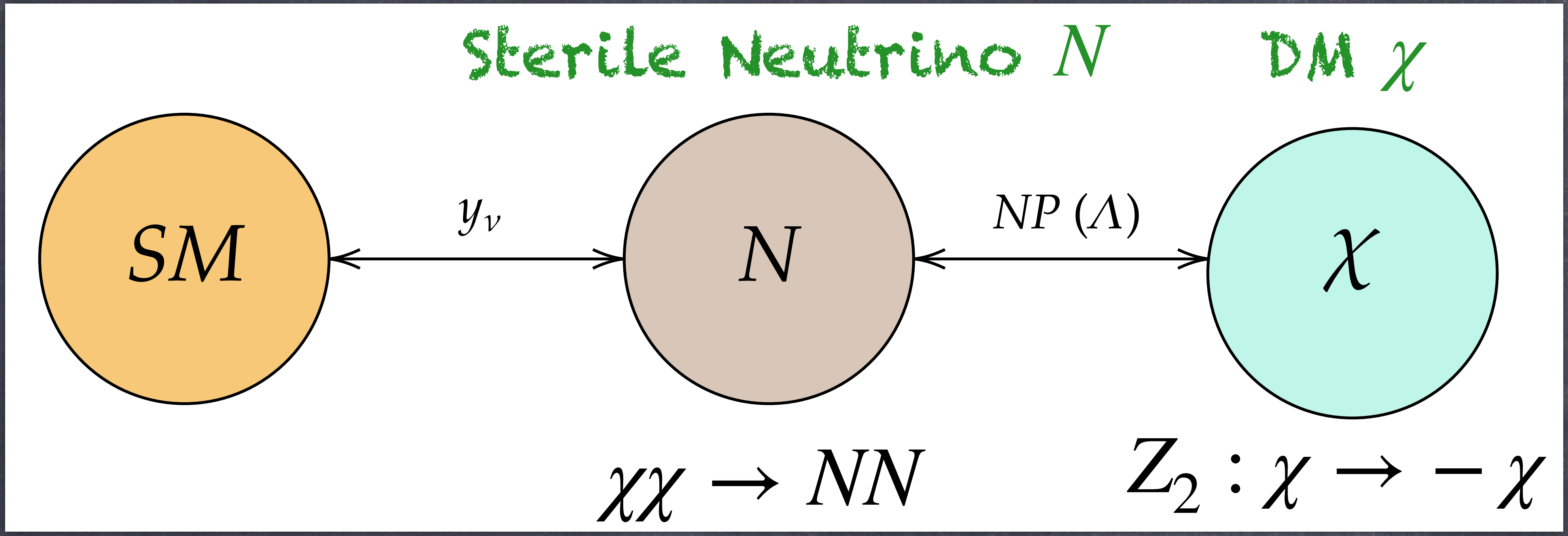
$$\mathscr{L}_{\rm EFT} \supset \frac{c_{\rm G}}{v_s^2}\left(|H|^2 - \frac{v^2}{2}\right)(\partial G)^2 \qquad S = \frac{1}{\sqrt{2}}\left(v_s + \sigma'\right) e^{iG/v_s}$$



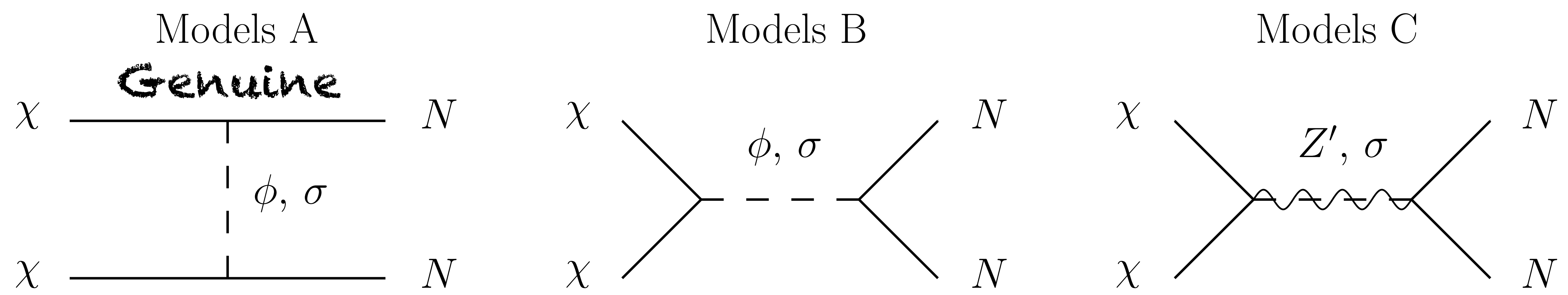
Example 2: Sterile neutrino portal

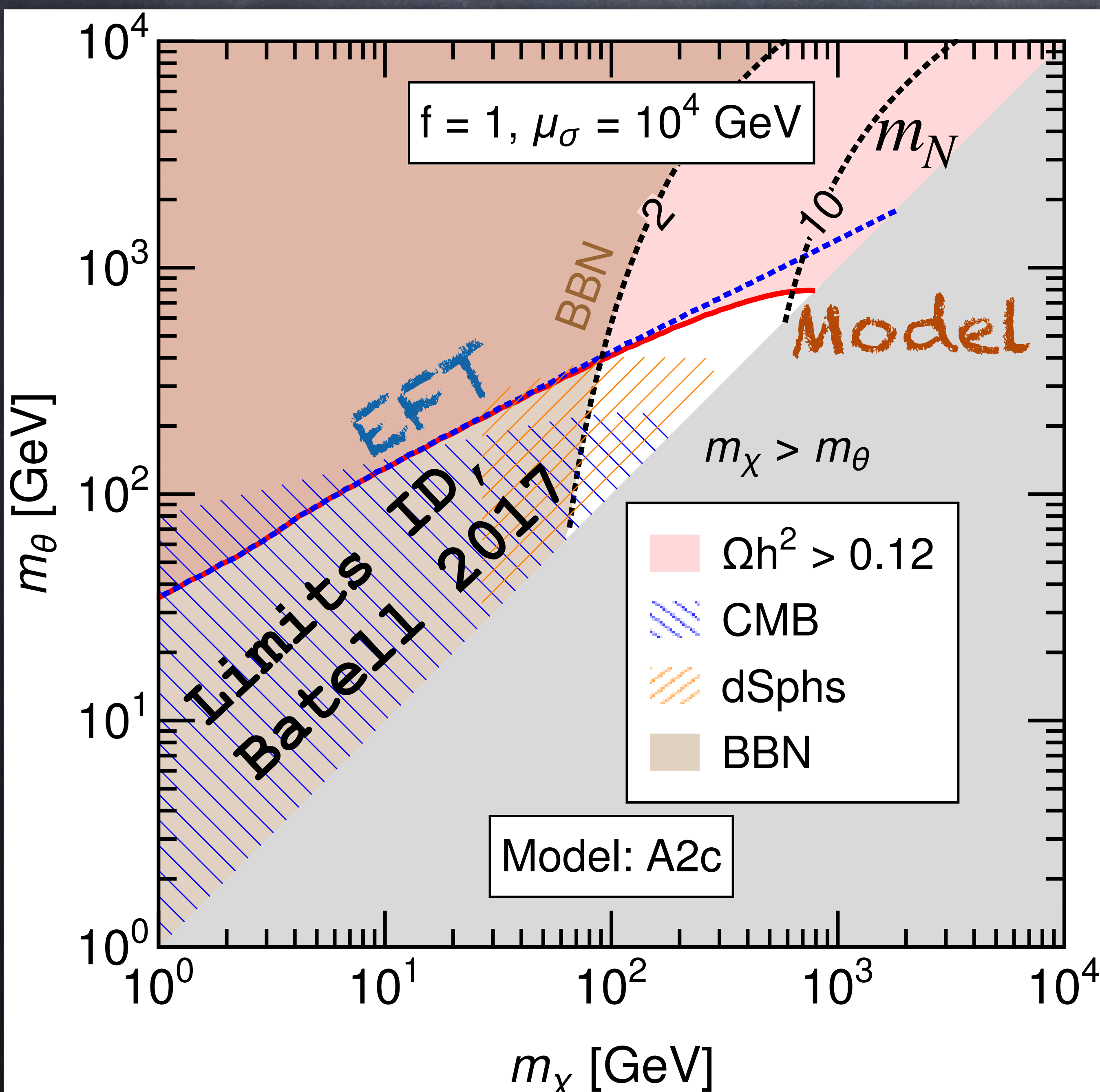
[Coito, Faubel, JHG, Santamaria, Titov, JHEP 08 (2022) 086]

[See also Escudero, Rius, Sanz, 2017]



- Well-motivated by light m_ν: seesaw, $m_\nu = m_D^2/m_N$
- Majorana DM χ, abundance via freeze-out of $\chi\chi \to NN$
- EFT operators, i.e. $(\overline{N_R}\chi_L)(\overline{\chi_L}N_R)$, and UV completions





DD at 1 loop

[JHG, Molinaro, Schmidt, EPJC 2018]

Connection DM-ν:

Dirac $\nu \leftrightarrow p$-wave (sub-GeV)

III - Extended Dark Sectors

Visible Sector:

Multi-component: $\gamma, \nu, e, p\,(\mathrm{H}, \mathrm{He}\ldots)\ldots$

Asymmetric: $n_B/n_\gamma \simeq 6\cdot 10^{-10}$

Dark Sector:

Several components?

Partially-asymmetric?

Multi-component dark sectors:
symmetries, asymmetries and conversions,
D. Vatsyayan, A. Bas, JHG, JHEP10 (2022) 075

For an asymmetric freeze-in 2DM model with suppressed signals:

See talk by Giacomo Landini on Thursday (PP)

[JHG, G. Landini, D. Vatsyayan, *JHEP* 05 (2023) 049]

Multi-component DM

[A. Bas, JHG, D. Vatsyayan, JHEP10(2022)075]

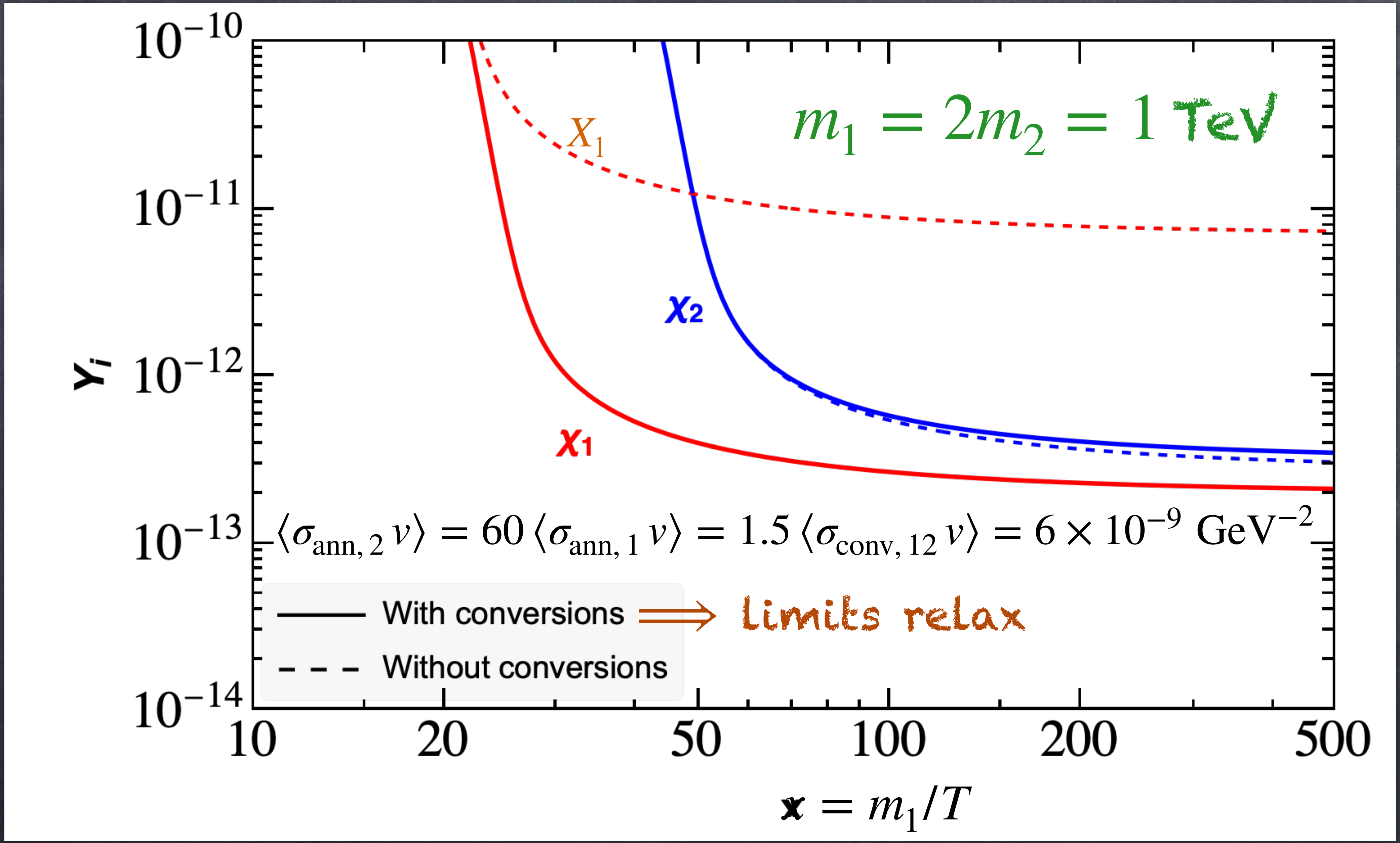
- Conversions $\chi_i\bar{\chi}_i \to \chi_j\bar{\chi}_j$: change individual n_i but not n_t

1. Without conversions: Ω dominated smallest annihilations
2. With conversions: Ω reduced

$$\Omega_t = \Omega_1 + \Omega_2 \propto \frac{1}{\langle \sigma_{\text{ann},\,1}\, v\rangle + \langle \sigma_{\text{conv},\,12}\, v\rangle} + \frac{1}{\langle \sigma_{\text{ann},\,2}\, v\rangle}$$

$\Longrightarrow$ Smaller couplings to SM: limits relaxed!

Effect of conversions



Number density of heavy χ_1 (light χ_2) DM reduces (increases)

Relic-abundance scaling: power-law behaviour

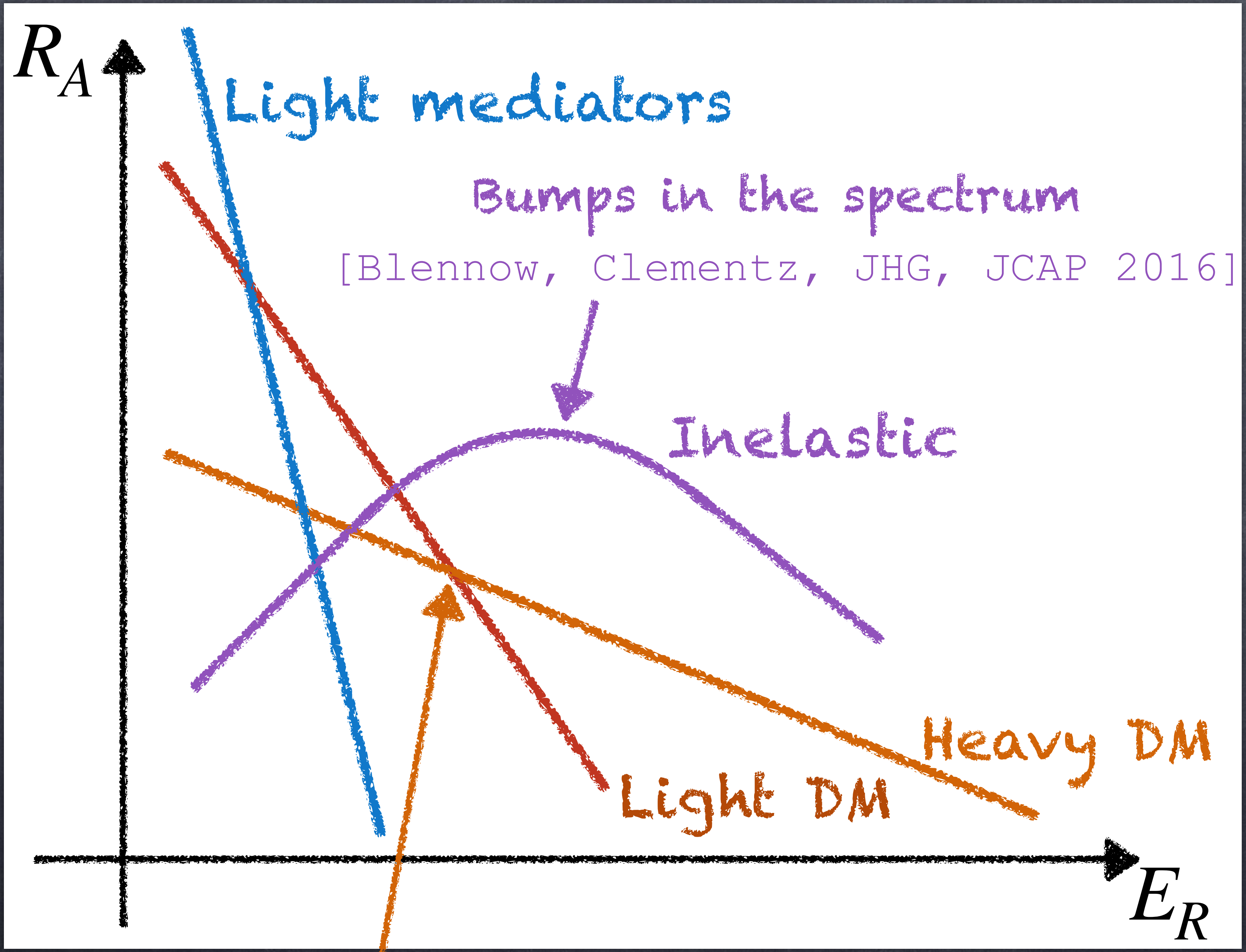
Suppressed by mass $\Longrightarrow$ lighter species dominates

		Symmetric		Partially-Asymmetric	
Model	σ	Ann.	Ann.+Conv.	Ann.	Ann.+Conv.
Mass-independent	$\neq f(m_i)$	$\sim m^0$	$\sim m^{-1}$	$\sim \eta\, m$	$\sim \eta\, m$
Heavy mediators	$\sim m_i^2/\Lambda^4$	$\sim m^{-2}$	$\sim m^{-[3,2]}$	$\sim \eta\, m^{[1,-2]}$	$\sim \eta\, m^{[1,-2]}$
Light mediators	$\sim 1/m_i^2$	$\sim m^2$	$\sim m^{[0,2]}$	$\sim \eta\, m^{[1,2]}$	$\sim \eta\, m^{[1,2]}$

Several components with similar abundances

For significant conversions, heavier (lighter) components are more asymmetric (symmetric)

Multi DM in Direct Detection



Kinks in the spectrum [JHG, Scaffidi, White, Williams JCAP 2017]

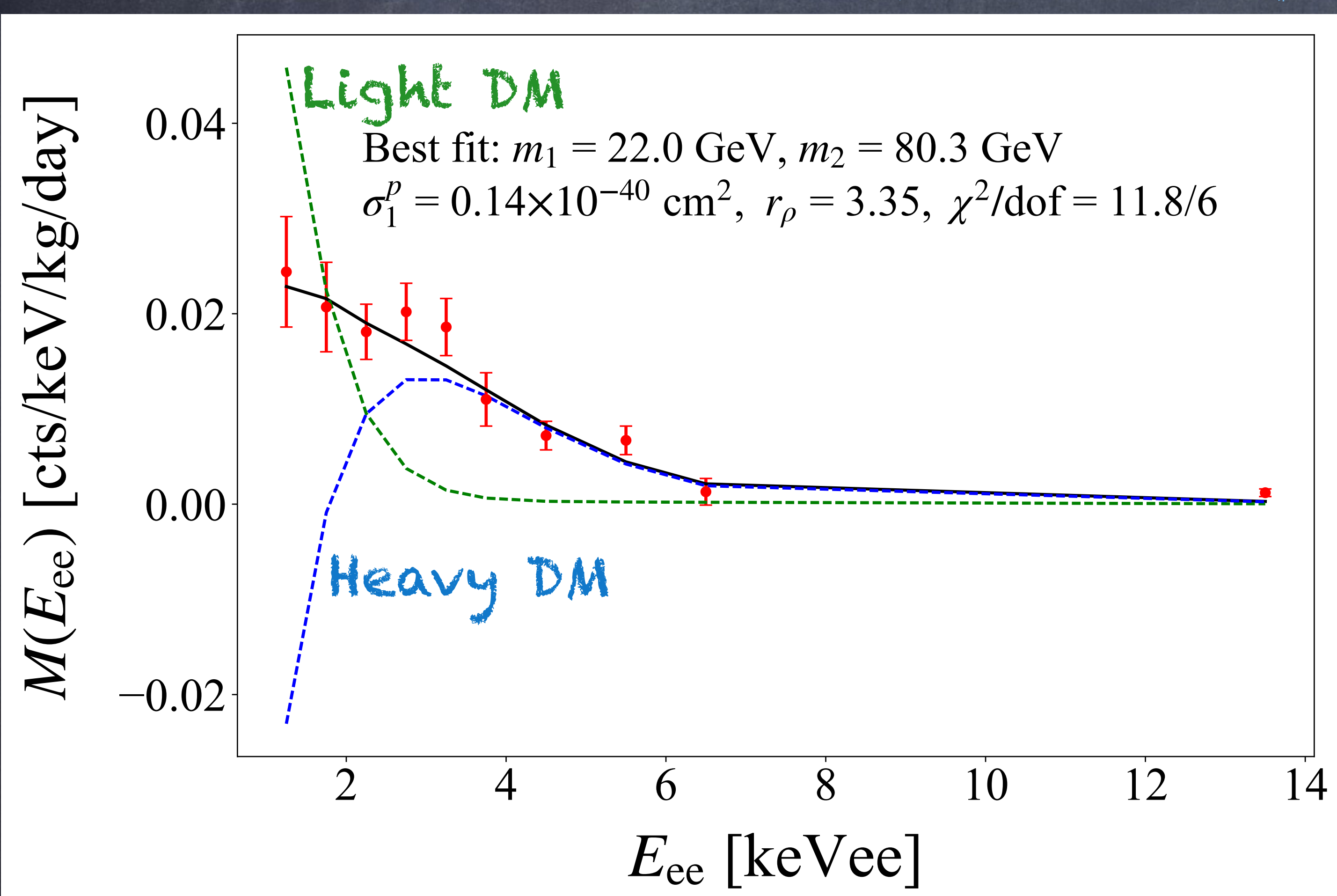
Time-dependent rates

[JHG, Scaffidi, White, Williams PRD 2018]

Example: DAMA Phase-II results

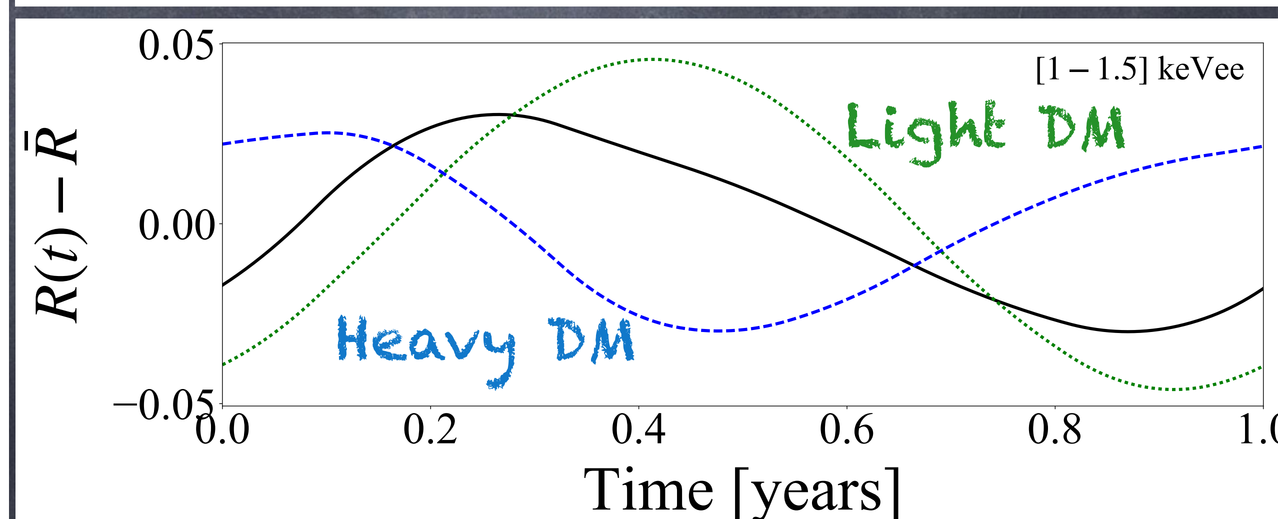
Smoking guns of 2DM at low E_R:

Partial cancellations (< 2 KeVee)



Non-sinusoidal behaviour

2DM	m_1	m_2	σ_1^p	r_ρ	$\chi^2_{\min}$/dof	p-value	$\mathcal{Z}$
$r_\sigma = 1$	22.0	80.3	0.14	3.35	11.8/6	0.07	1.84



$r_\sigma = \sigma_2/\sigma_1$ $\qquad$ $r_\rho = \rho_2/\rho_1$

Archivio di Stato di Napoli

IV - Conclusions

Conclusions

- Overwhelming evidence for DM from different scales, but still no signal...
- Need new well-motivated models with suppressed signals
- Some examples: PNGB DM, annihilations into ν_R, multi-DM, asymmetric freeze-in...
- Dark sector? Visible sector as a "guide": multi-component and asymmetric, with some smoking guns.

Grazie mille!

James Webb
Carina Nebula

Back-up

DD

Are WIMPs alive?

Negative view:

Standard Z-mediated "ruled-out"

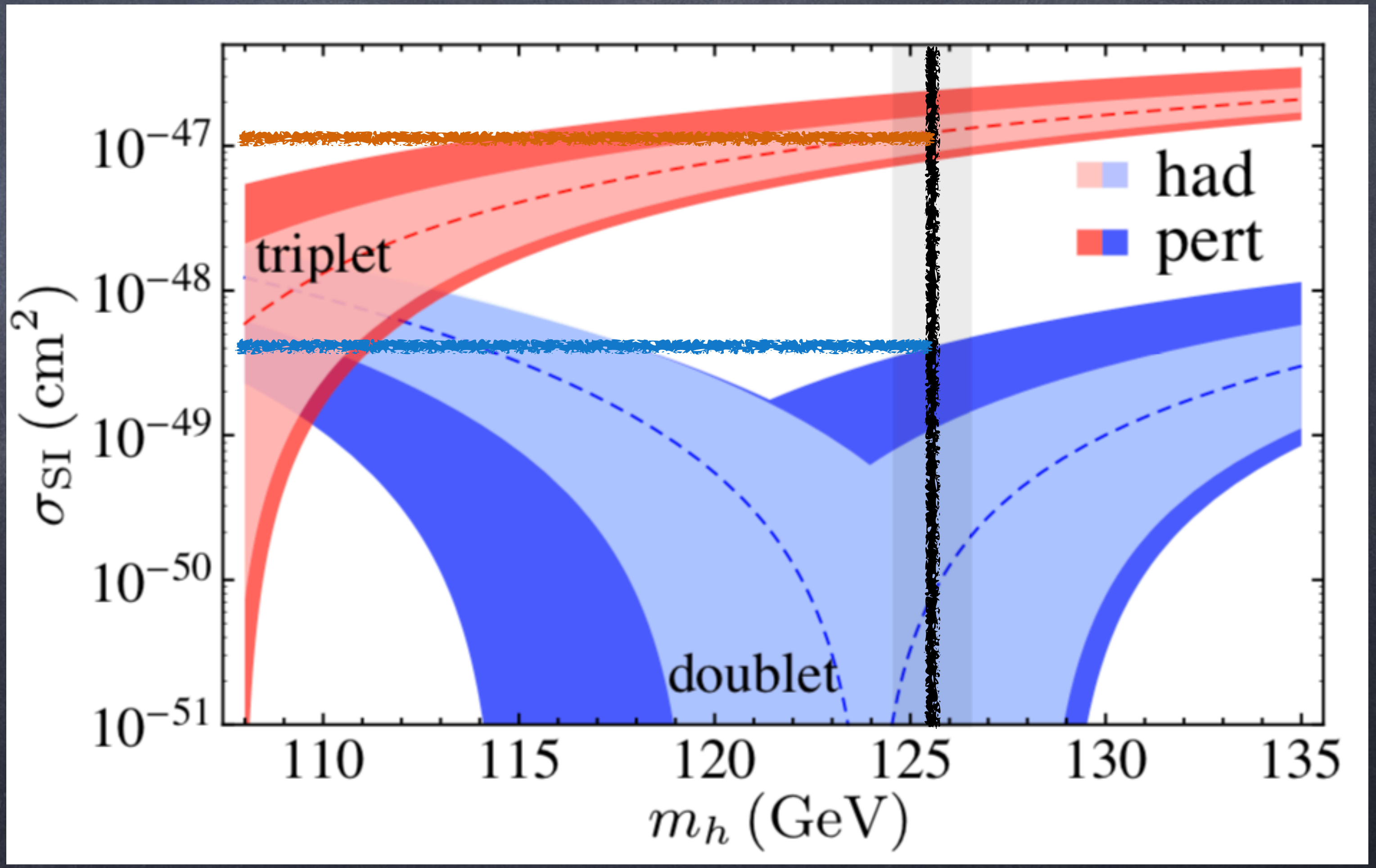
Standard h-mediated "disfavoured" for $m < 500$ GeV

Standard Z' $B-L$, "disfavoured"

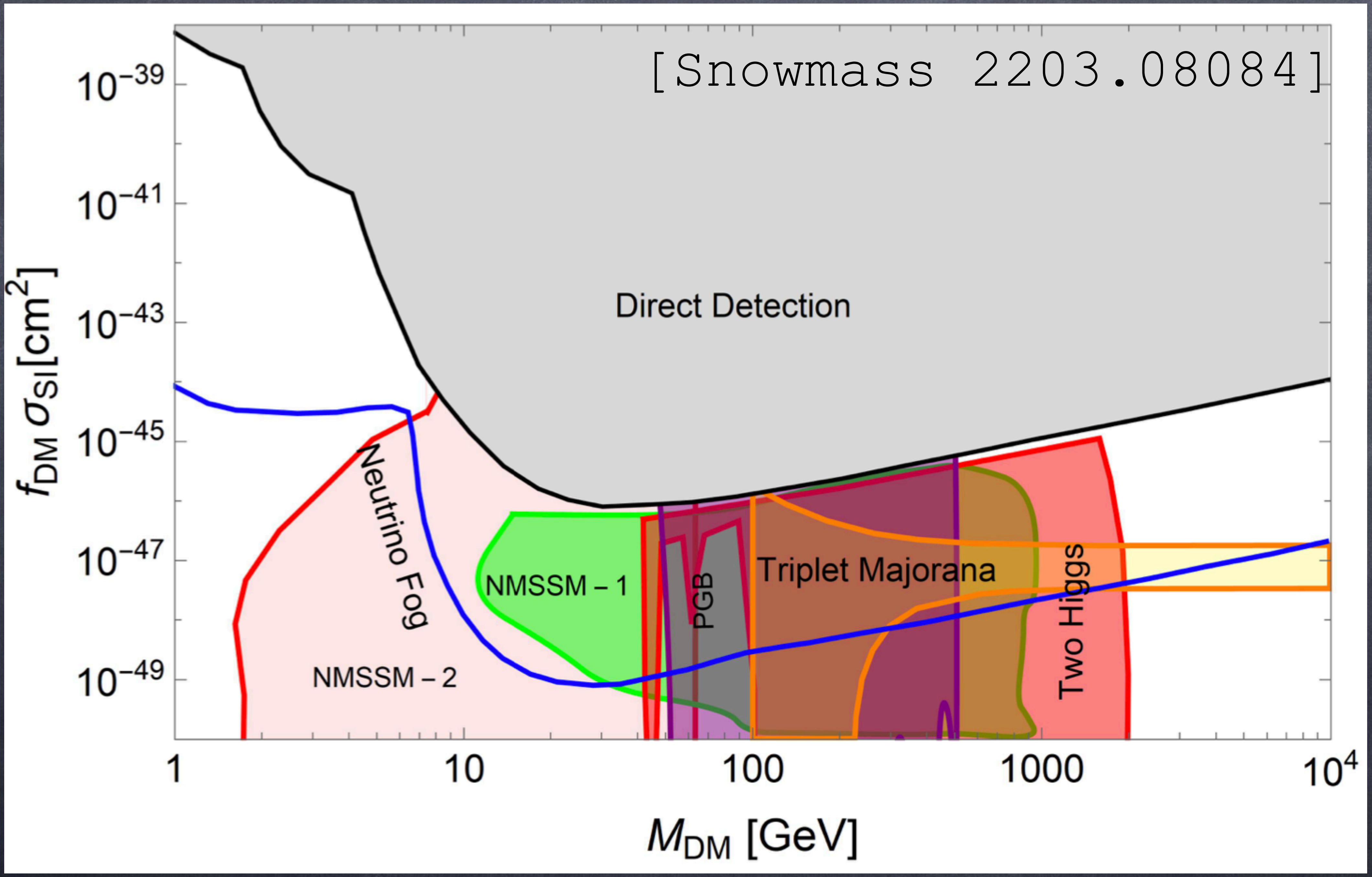
Positive view:

Well-motivated, viable models! E.g., SUSY Higgsino

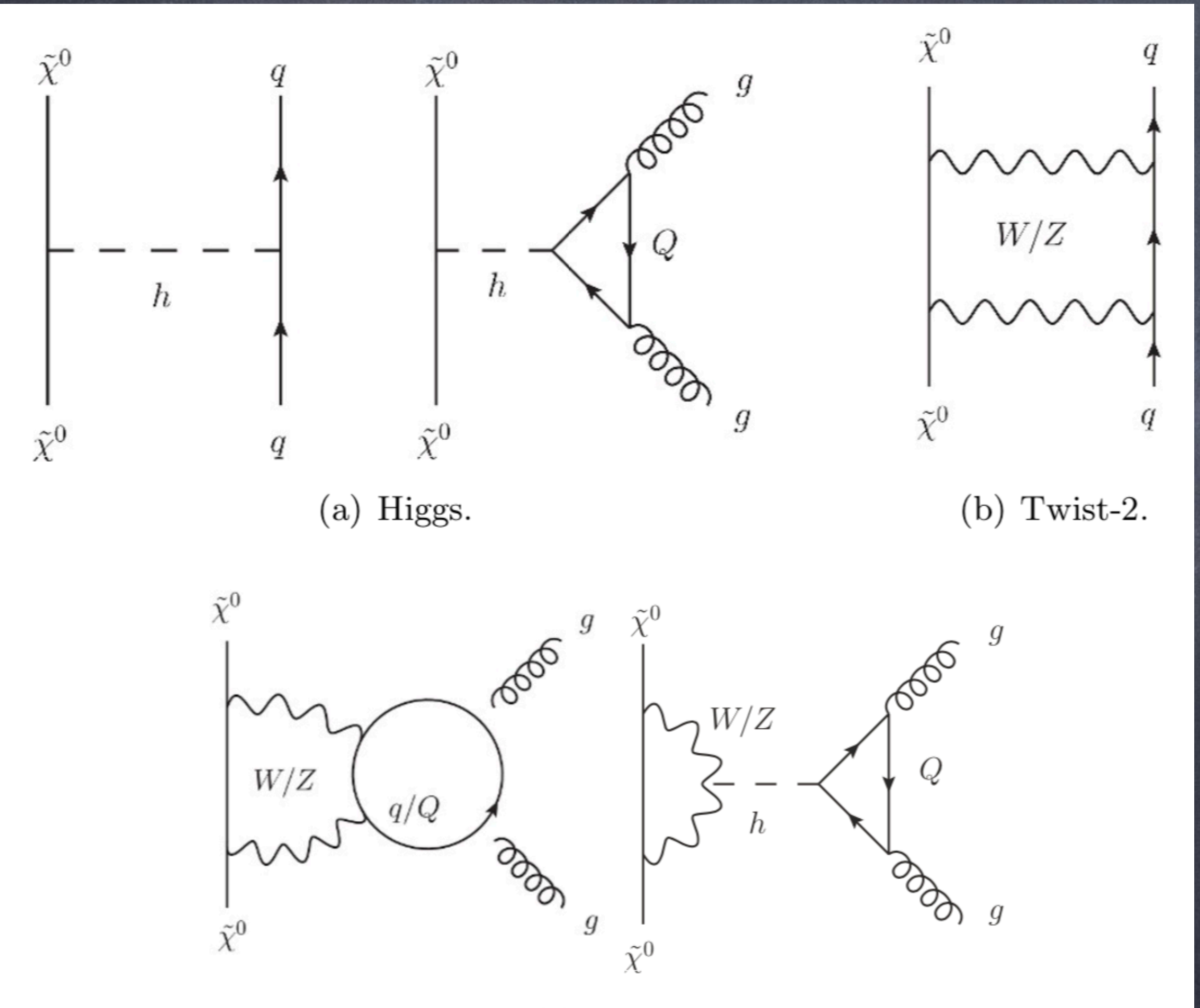
[Hissano, Fig. from Hill et al]



Well-motivated viable models



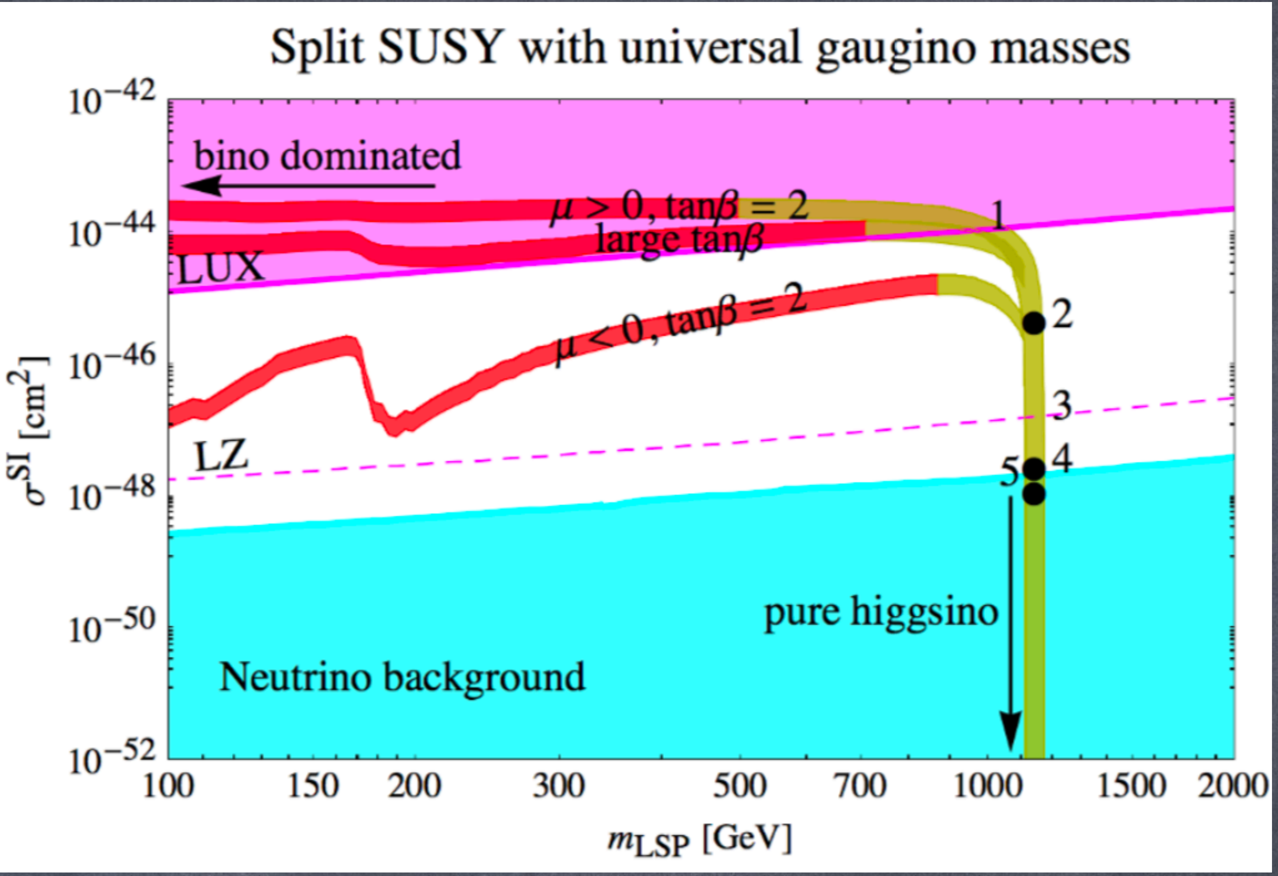
[Figures from Cortona 2015. See also Bramante 2016. Computations by Hissano & Hill et al]

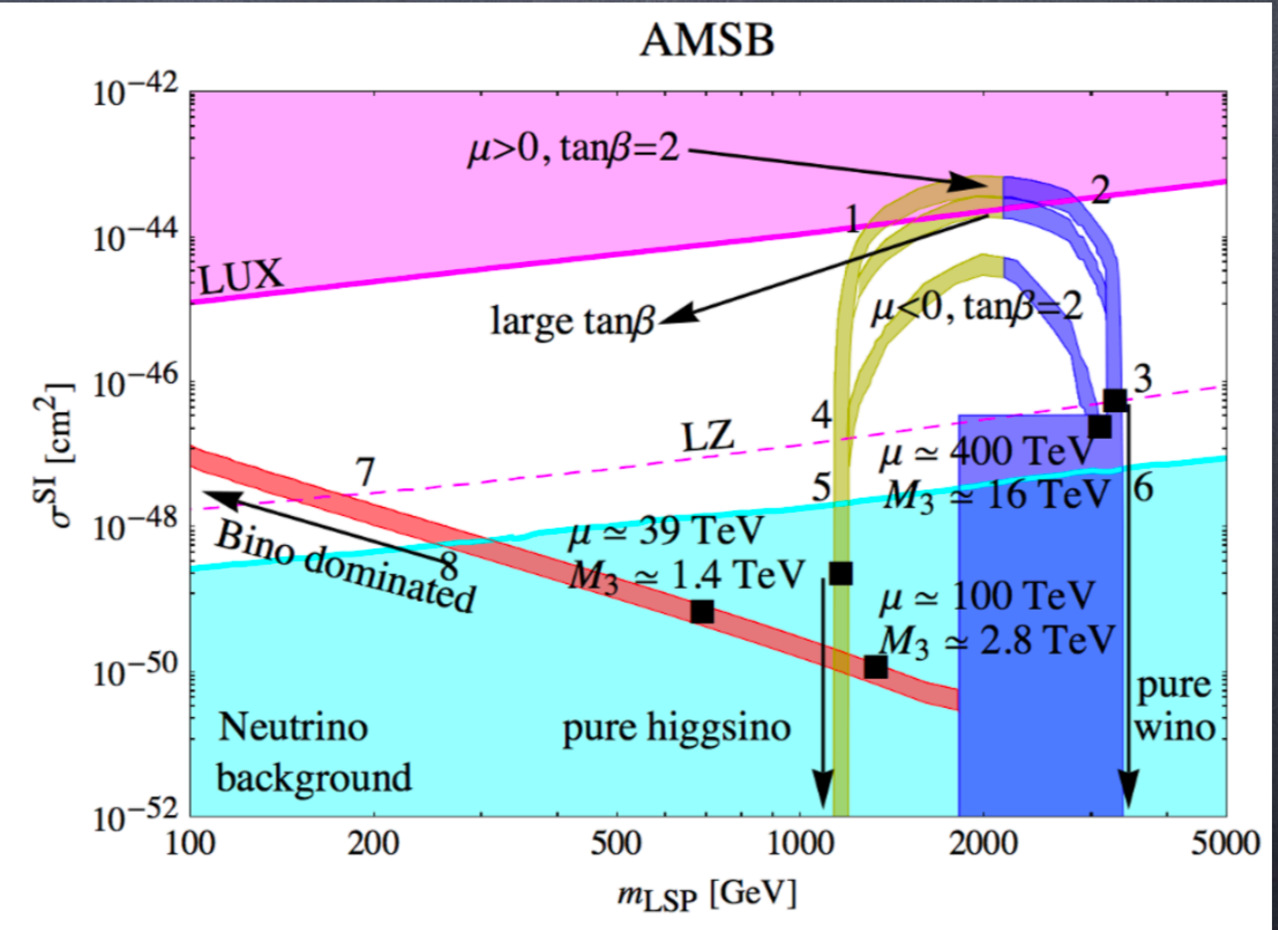


(a) Higgs.

(b) Twist-2.

(c) Gluon.

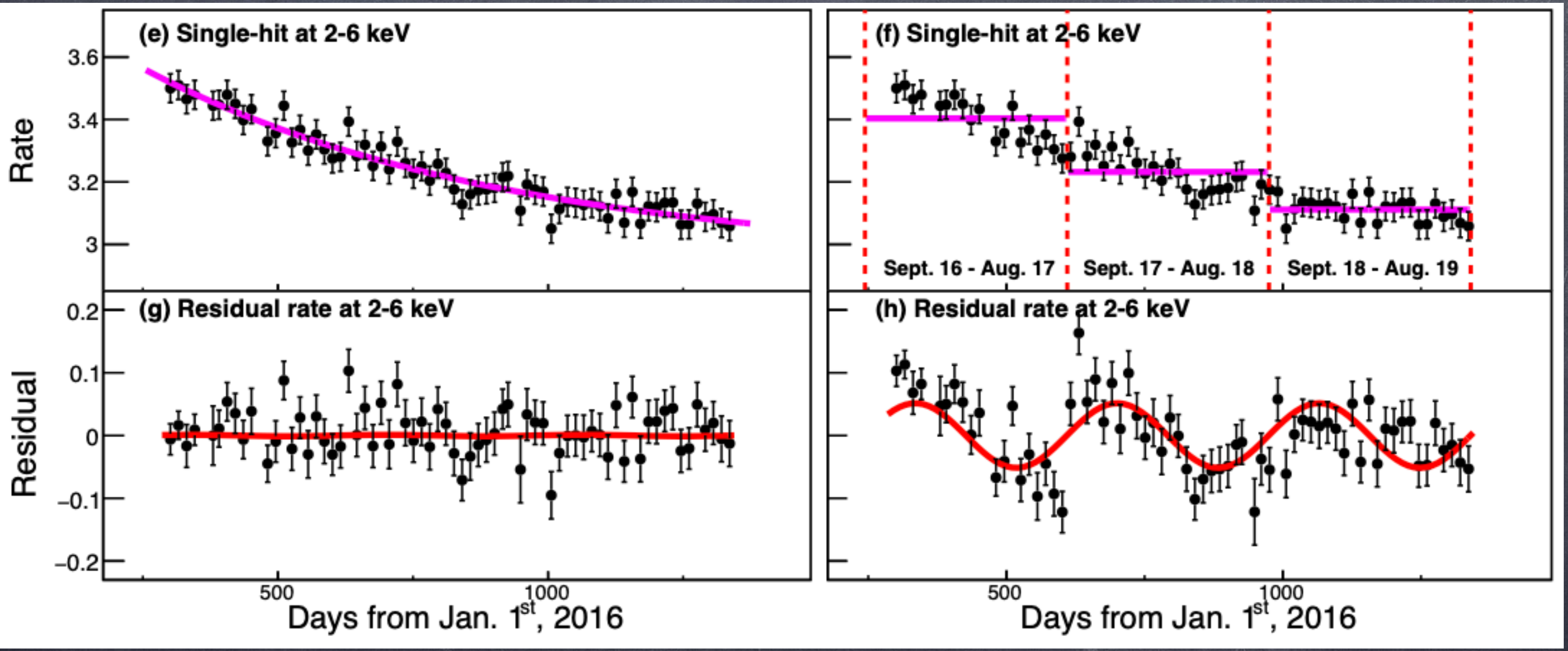




DAMA explanation?

[Buttazo et al JHEP 20, 137 (2020)]

⟹ Substraction of non-constant background [COSINE-100 2208.05158]



counts/kg/keV/day	1–6 keV	2–6 keV
This work	-0.0441±0.0057	-0.0456±0.0056
DAMA/LIBRA	0.0105±0.0011	0.0095±0.0008
COSINE-100	0.0067±0.0042	0.0050±0.0047
ANAIS-112	-0.0034±0.0042	0.0003±0.0037

Opposite phase...

SABRE?

PNGB DM

[Coito, Faubel, JHG, Santamaria, JHEP 11 (2021) 202]

Global U(1) and dark CP

[Coimbra 2013, Gross 2017, Alanne 2020, Arina 2020, Muhlleitner 2020, Lebedev 2021]

$S \equiv \frac{1}{\sqrt{2}}\left(v_s + \rho' + i\theta\right)$ $\Longrightarrow$ DM θ stabilised by dark CP: $S \to S^*,\ \theta \to -\theta$

Breaking terms

$$V_1 = \frac{1}{2}\mu^3 S + \mathrm{H.c.},$$

$$V_{Z_2} = \frac{1}{2}\mu_S^2 S^2 + \mathrm{H.c.},$$

$$V_{Z_3} = \frac{1}{2}\mu_3 S^3 + \mathrm{H.c.},$$

$$V_{Z_4} = \frac{1}{2}\lambda_4 S^4 + \mathrm{H.c.}.$$

Minimal model	$\lambda_{SI} \propto -\left(\frac{\beta_{h\theta\theta}\, c_\alpha}{m_h^2} + \frac{\beta_{\rho\theta\theta}\, s_\alpha}{m_\rho^2}\right)$
Linear	$\frac{s_\alpha c_\alpha}{v_s m_h^2 m_\rho^2} m_\theta^2 (m_h^2 - m_\rho^2)$
Quadratic	No DD 0 at tree level!
Cubic	$-\frac{s_\alpha c_\alpha}{v_s m_h^2 m_\rho^2} m_\theta^2 (m_h^2 - m_\rho^2)$
Quartic	$-2\frac{s_\alpha c_\alpha}{v_s m_h^2 m_\rho^2} m_\theta^2 (m_h^2 - m_\rho^2)$

Only 4 free parameters: $v_s, m_\theta, m_\rho, s_\alpha$

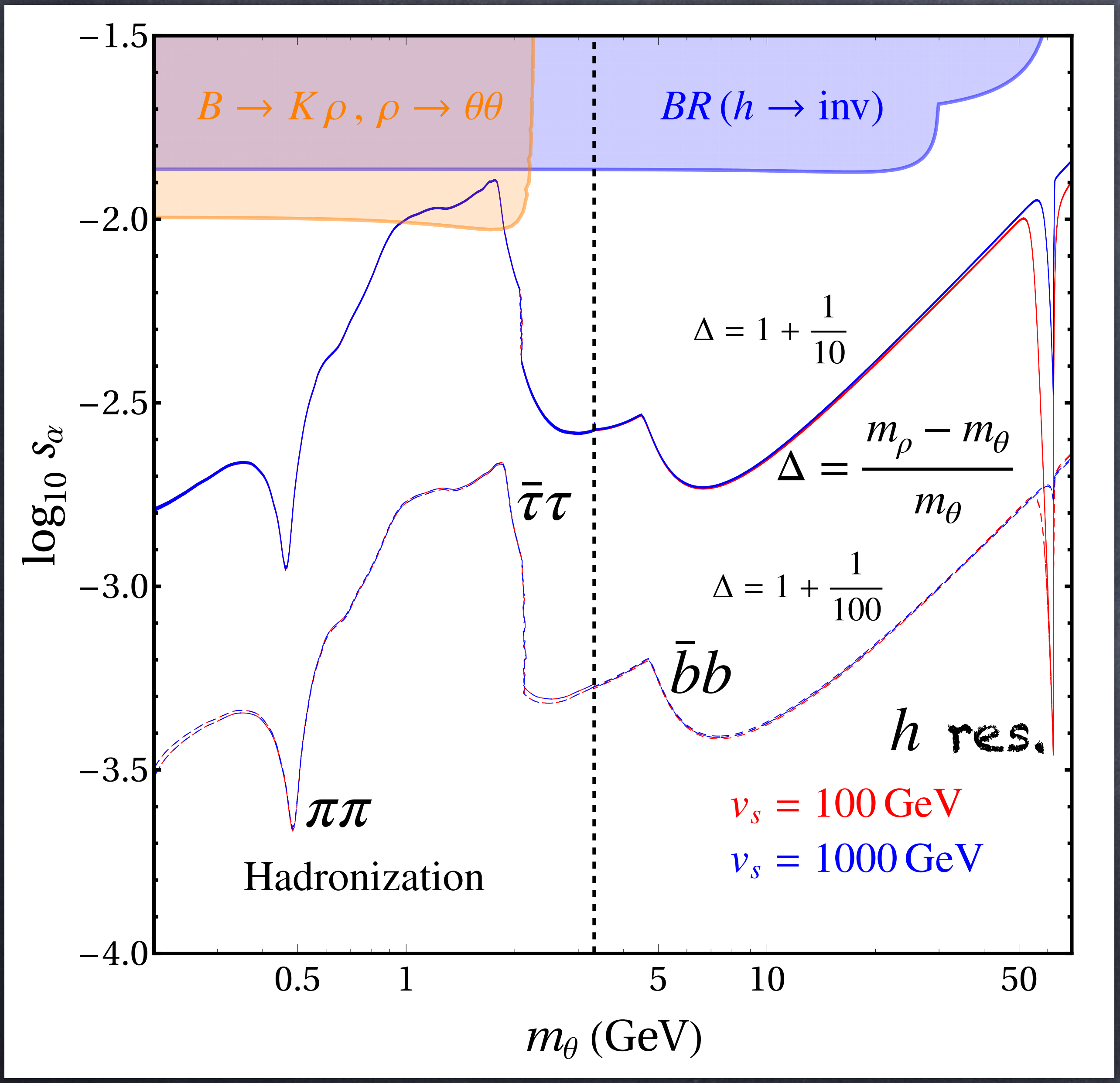
Possible symmetries of the potential

Respected by $S \equiv \frac{1}{\sqrt{2}}\left(v_s + \rho' + i\theta\right)$ kinetic terms:

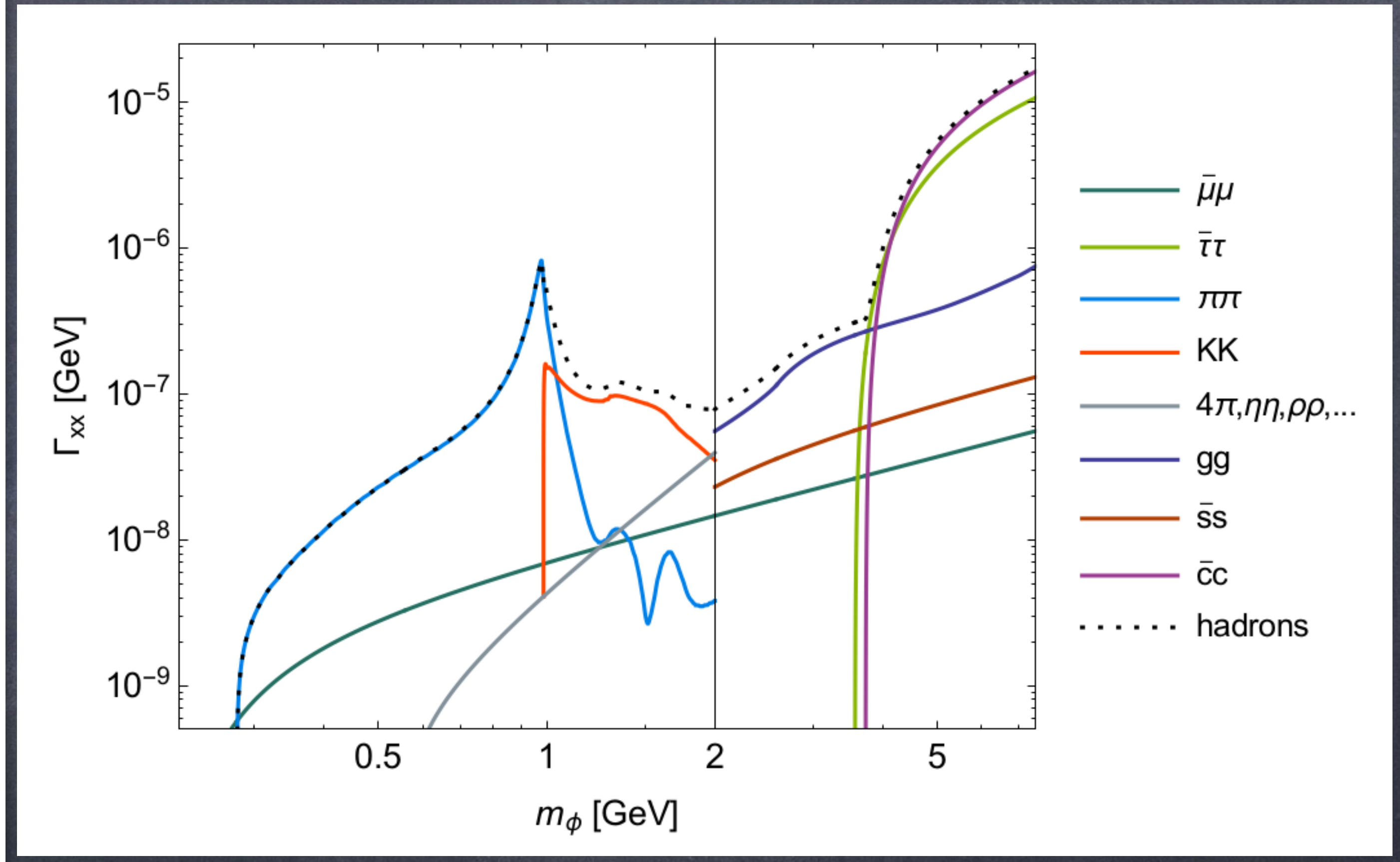
- DCP: $S \to S^*$ $(\theta \to -\theta)$, real couplings
- Z_2 symmetry, $S \to -S$
- Z_3 symmetry, $S \to e^{i\,2\pi/3}S$
- Z_4 symmetry, $S \to iS$

We take the softest U(1) breaking term in each case

Z_2 results, ρ resonance

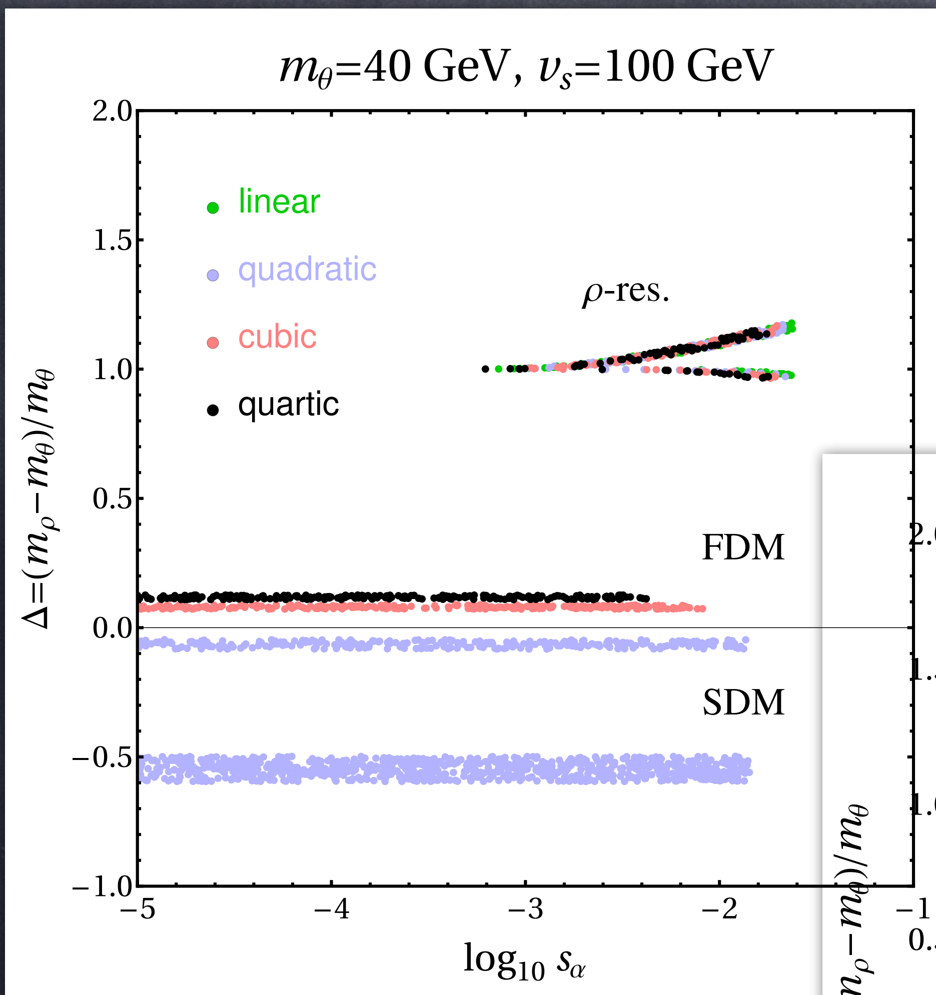


[Winkler, PRD99 (2019) 015018]

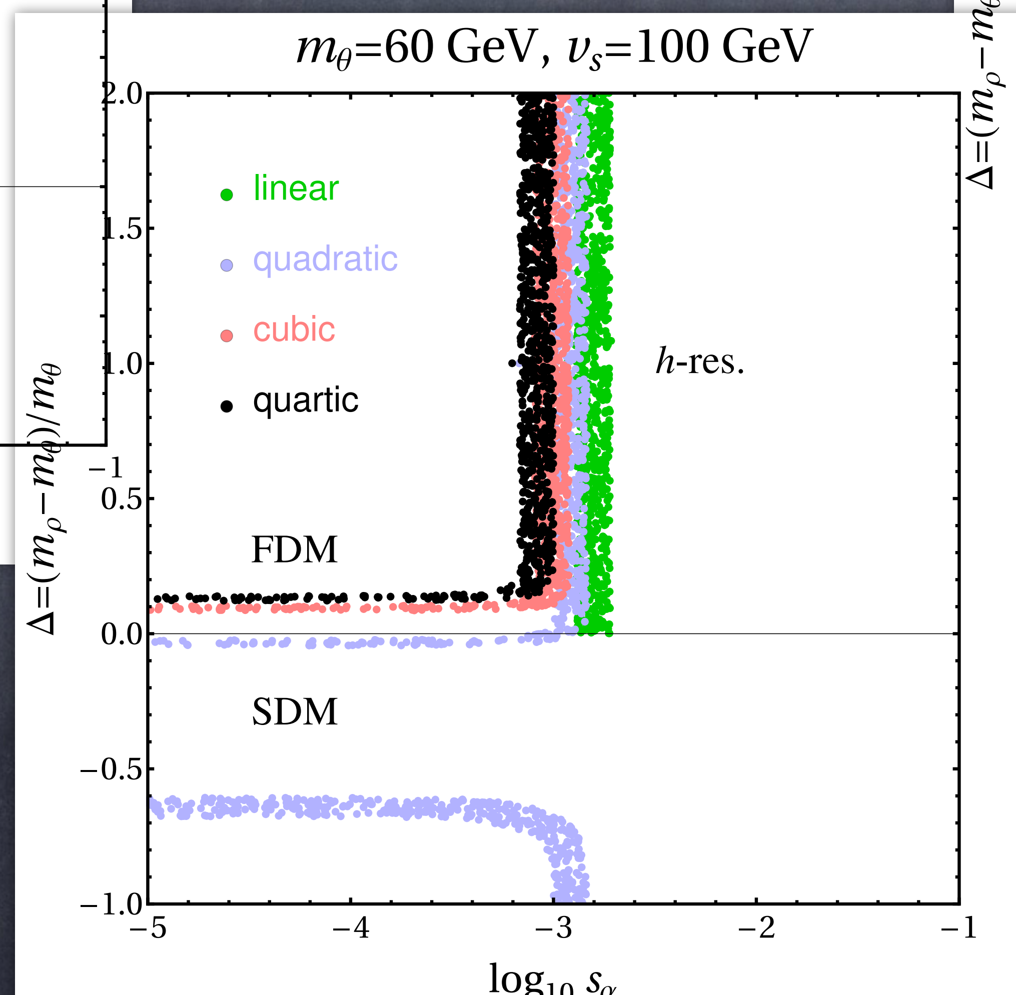


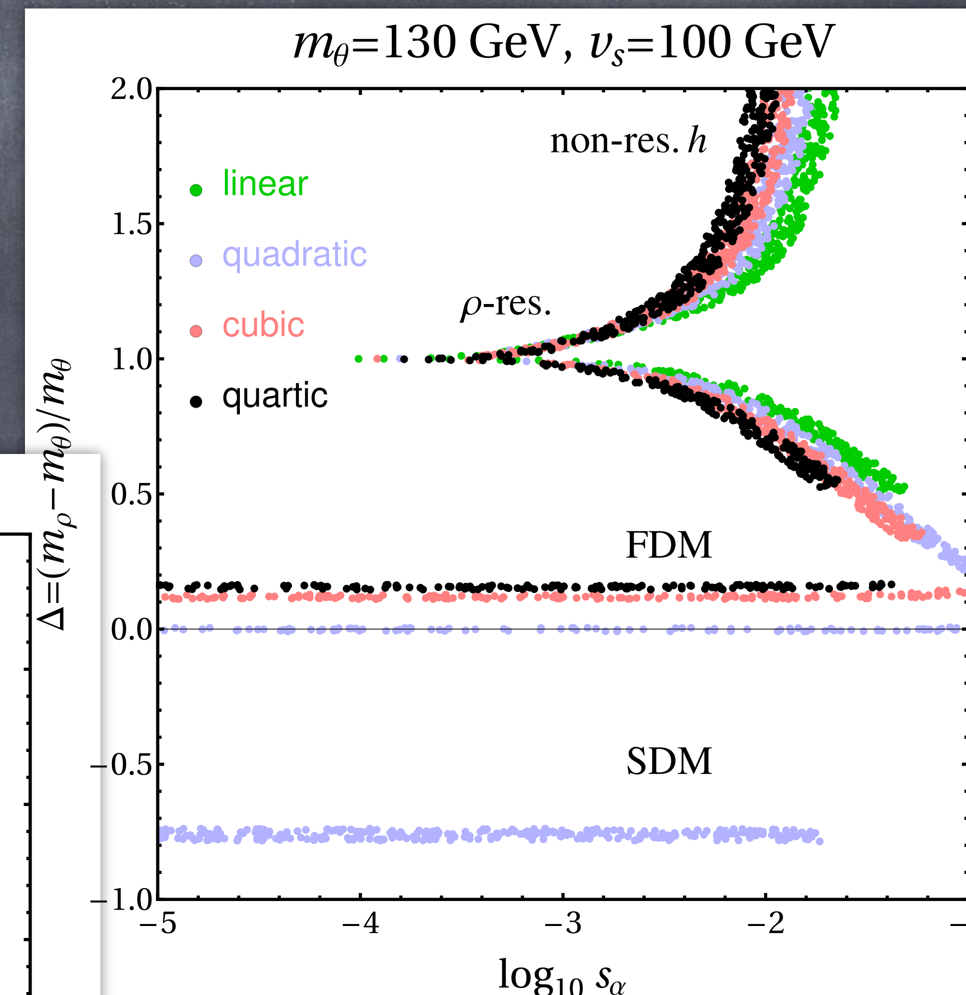
[Note: Uncertainties due to kinetic decoupling, Berlin 2016, Binder 2021]

Results minimal models



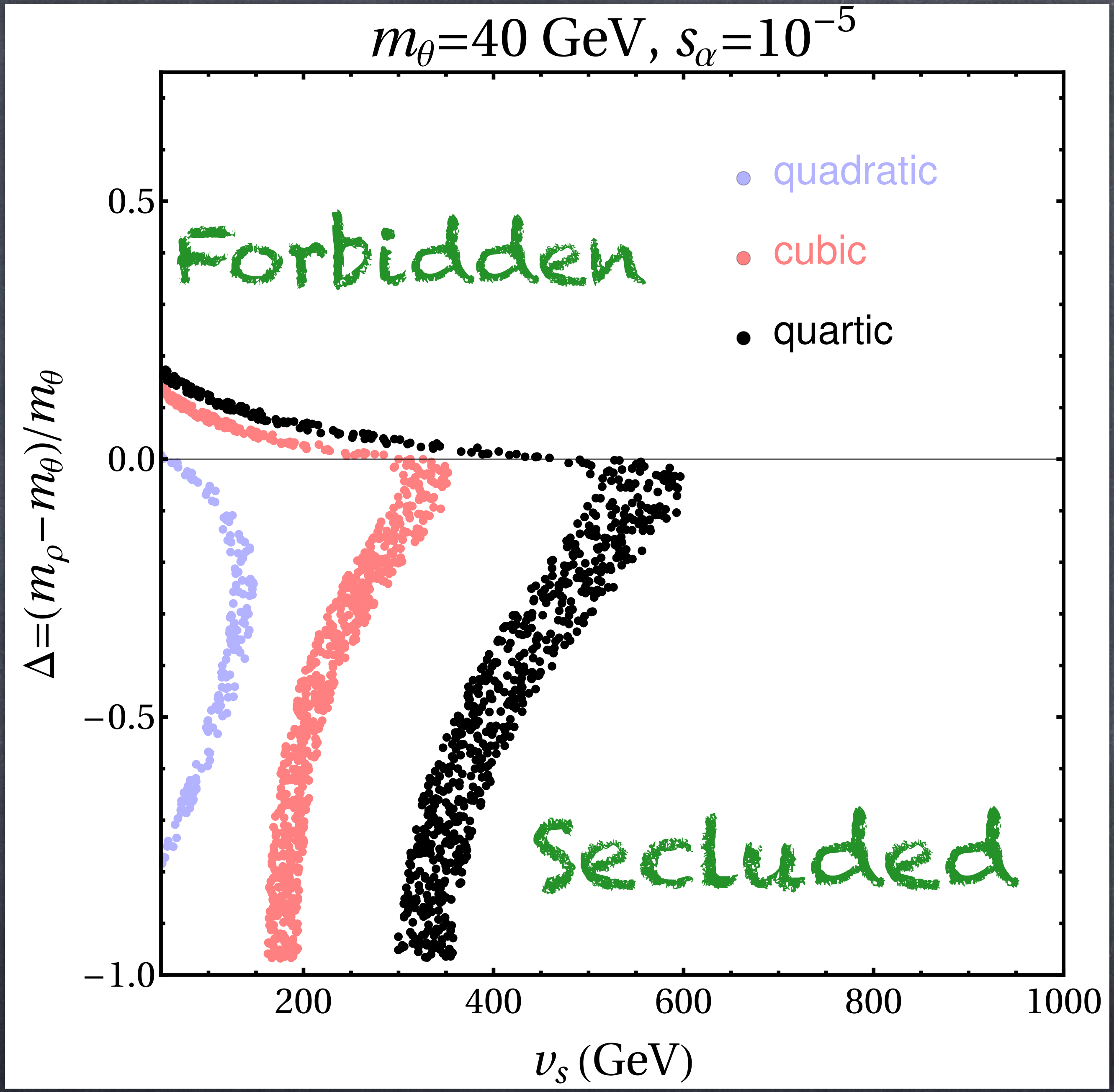
$$\Delta = \frac{m_\rho - m_\theta}{m_\theta}$$





Difficult to disentangle models in resonances

Results



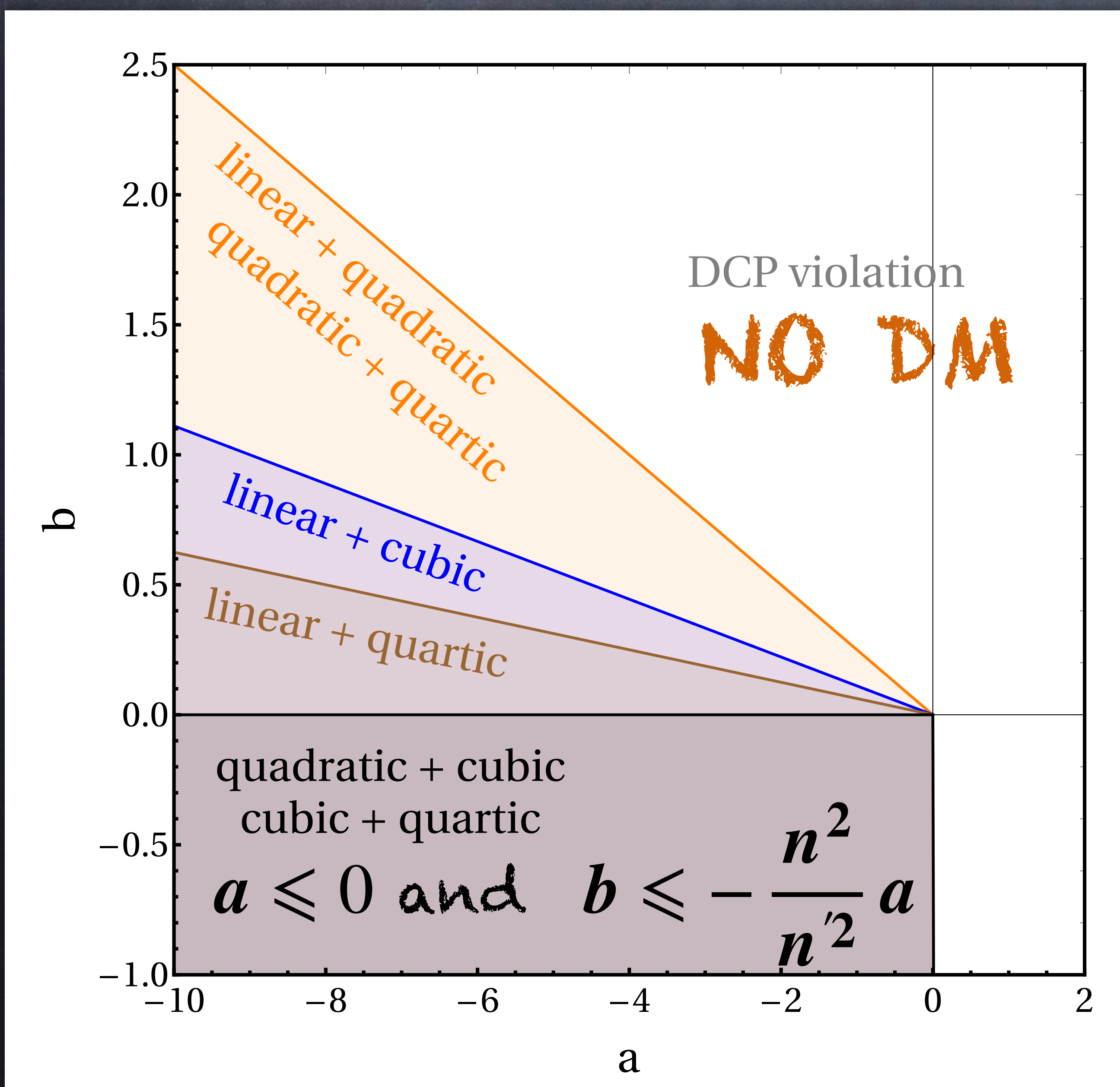
Possible to disentangle in secluded/forbidden

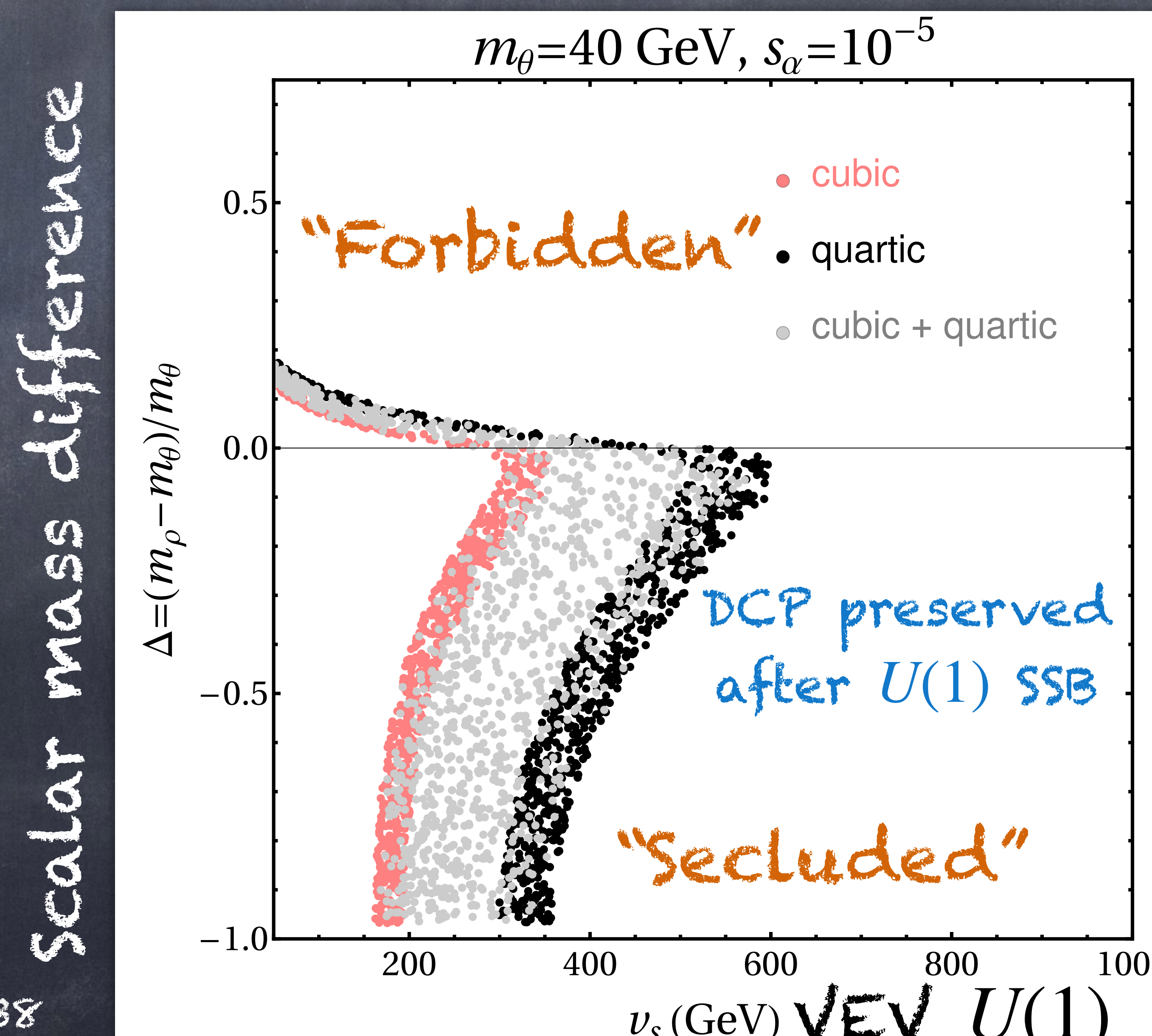
Beyond minimal models

[See also Haber 2012]

Even if breaking terms are real, CP may be spontaneously broken:

$$V_{\rm sb} = v_s^4 \left[a \cos\left(n\frac{G}{v_s}\right) + b \cos\left(n'\frac{G}{v_s}\right)\right] \qquad n, n' = 1,2,3,4 \qquad S = \frac{1}{\sqrt{2}}\left(v_s + \sigma'\right) e^{iG/v_s}$$





PNGB Limit $m_G \ll v_s$: EFT

$$\mathscr{L}_{\rm EFT} \supset \frac{c_{\rm G}}{v_s^2}\left(|H|^2 - \frac{v^2}{2}\right)(\partial G)^2 - \frac{1}{2}m_{\rm G}^2 G^2 + \lambda_{\rm HG}\left(|H|^2 - \frac{v^2}{2}\right)G^2$$

$$V_{\rm break} = \frac{1}{2}\lambda_n S^n + {\rm H.c.}$$

$$m_G^2 = -\lambda_n \frac{v_s^{n-2}}{2^{n/2}} n^2$$

$$c_{\rm G} = -s_\alpha \frac{v_s}{v}, s_\alpha \simeq \frac{\lambda_{HS} v}{2\lambda_S v_s}$$

$$\lambda_{\rm HG} = -c_{\rm G}\frac{n}{2}\frac{m_{\rm G}^2}{v_s^2}$$

DD with EFT

$$\frac{c_{\rm G}}{v_s^2}\left(|H|^2-\frac{v^2}{2}\right)(\partial G)^2 \to$$

$$\to \frac{c_{\rm G}}{v_s^2}\left[m_G^2\left(|H|^2-\frac{v^2}{2}\right)G^2 - G\partial_\mu\left(|H|^2\right)\partial^\mu G\right]$$

$$\lambda_{\rm HG} \to \lambda_{\rm HG} + m_G^2\frac{c_{\rm G}}{v_s^2} = c_G\frac{m_G^2}{v_s^2}\left(1-\frac{n}{2}\right)$$

No DD at tree level for $n = 2$

Radiative corrections, $\mu_S^2 S^2$ term

[See also Lebedev 2021]

$$\frac{1}{2}\lambda_2 (S^\dagger S) S^2 \longrightarrow \lambda_2^{(1)} \simeq \frac{\lambda_S^2}{(4\pi)^2}\frac{\mu_S^2}{m_\rho^2}$$

$$\frac{1}{2}\lambda_{H2} |H|^2 S^2 \longrightarrow \lambda_{H2}^{(1)} \simeq \frac{\lambda_{HS}\lambda_S}{(4\pi)^2}\frac{\mu_S^2}{m_\rho^2}$$

$$\frac{1}{2}\lambda_4 S^4 \longrightarrow \lambda_4^{(1)} \simeq \frac{\lambda_S^2}{(4\pi)^2}\frac{\mu_S^4}{m_\rho^4}$$

Only λ_{H2} is phenomenologically relevant, but it is loop-suppressed

Constraints

- Perturbativity, stability, global minimum ($v = 246$ GeV, $v_s \neq 0$)
- Higgs boson properties, $s_\alpha \ll 1$
- Relic abundance, $0.5 \leqslant \Omega_\theta / \Omega_{\text{obs}} \leqslant 1$
- Direct detection, XENON1T limits
- Higgs $\text{BR}(h \to \text{inv}) < 0.16$ (CMS 90 % CL)

$$\text{BR}(h \to \text{inv}) = \frac{\sum_{i=\theta,\rho} \Gamma(h \to ii)}{c_\alpha^2 \Gamma_h^{\text{SM}} + \sum_{i=\theta,\rho} \Gamma(h \to ii)}$$

DM into sterile neutrinos

[Coito, Faubel, JHG, Santamaria, Titov, JHEP 08 (2022) 086]

Framework

DM stability by a Z_2 symmetry, $\chi \to -\chi$:

$$\mathscr{L}_4 = \mathscr{L}_{\rm SM} - \left[\frac{1}{2} m_N \overline{N_R^c} N_R + \frac{1}{2} m_\chi \overline{\chi_L} \chi_L^c + y_\nu \overline{L} \tilde{H} N_R + \text{H.c.}\right]$$

Neutrino masses by standard seesaw:

$$m_\nu \simeq \frac{m_{\rm D}^2}{m_N}$$

Other options:
Inverse seesaw, etc.

Effective operators

$$\mathcal{O}_1 = (\overline{N_R}\chi_L)(\overline{\chi_L}N_R) = -\frac{1}{2}(\overline{N_R}\gamma_\mu N_R)(\overline{\chi_L}\gamma^\mu \chi_L)\,,$$ LNC

$$\mathcal{O}_2 = (\overline{N_R}\chi_L)(\overline{N_R}\chi_L) = -\frac{1}{2}(\overline{N_R}N_R^c)(\overline{\chi_L^c}\chi_L)\,,$$ LNV

$$\mathcal{O}_3 = (\overline{N_R^c}N_R)(\overline{\chi_L^c}\chi_L) = -\frac{1}{2}(\overline{N_R^c}\gamma_\mu \chi_L)(\overline{\chi_L^c}\gamma^\mu N_R)\,.$$ LNV

UV completions include new scalars

DM annihilations

$$\sigma v_{\chi\chi\to NN} = a + b\frac{v^2}{4}$$

For $m_N = 0$:

$$a = \frac{m_\chi^2}{4\pi\Lambda^4}\left[|c_2|^2 + 4|c_3|^2 + 4\,Re(c_2 c_3)\right]$$

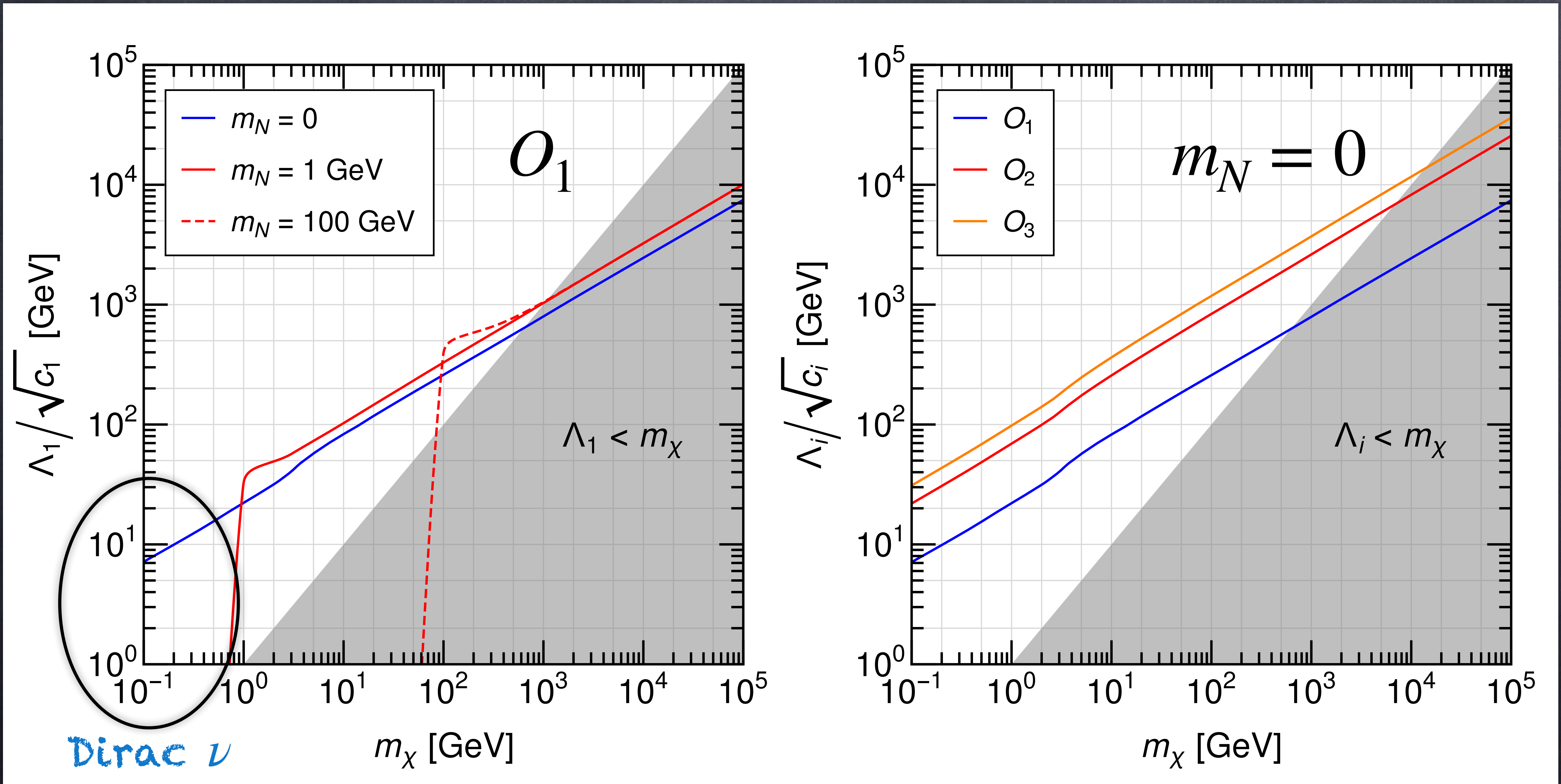
$$b = \frac{m_\chi^2}{12\pi\Lambda^4}\left[c_1^2 + 3|c_2|^2 + 12|c_3|^2 - 12\,Re(c_2 c_3)\right]$$

$\mathcal{O}_1$ gives $p-$wave or chirality-suppressed ($\propto m_N^2$) $\langle\sigma v\rangle_{\rm ann}$

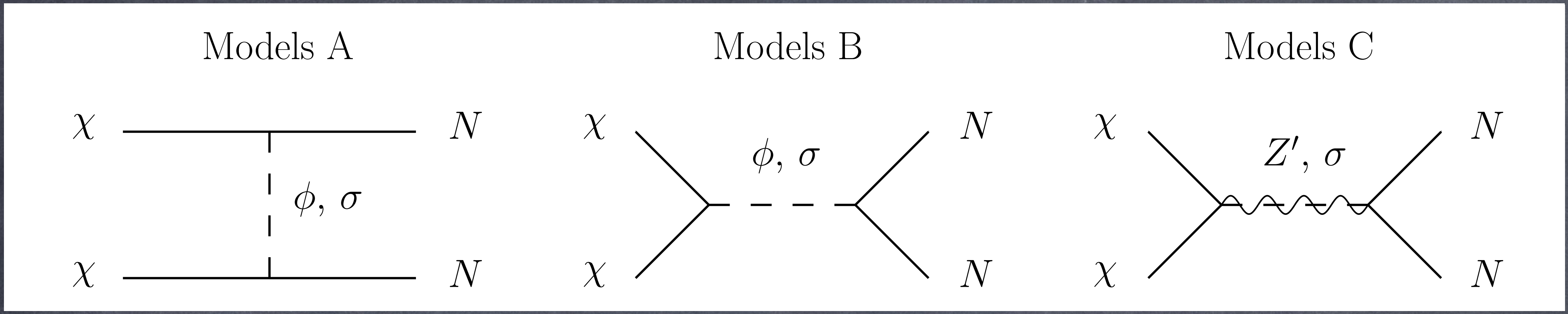
For $c_2 = -2c_3^* \longrightarrow p-$ wave annihilations

Relic abundance $\chi\chi \to NN$

$\mathcal{O}_1 = (\overline{N_R}\chi_L)(\overline{\chi_L}N_R)$ $\mathcal{O}_2 = (\overline{N_R}\chi_L)(\overline{N_R}\chi_L)$ $\mathcal{O}_3 = (\overline{N_R^c}N_R)(\overline{\chi_L^c}\chi_L)$



Models

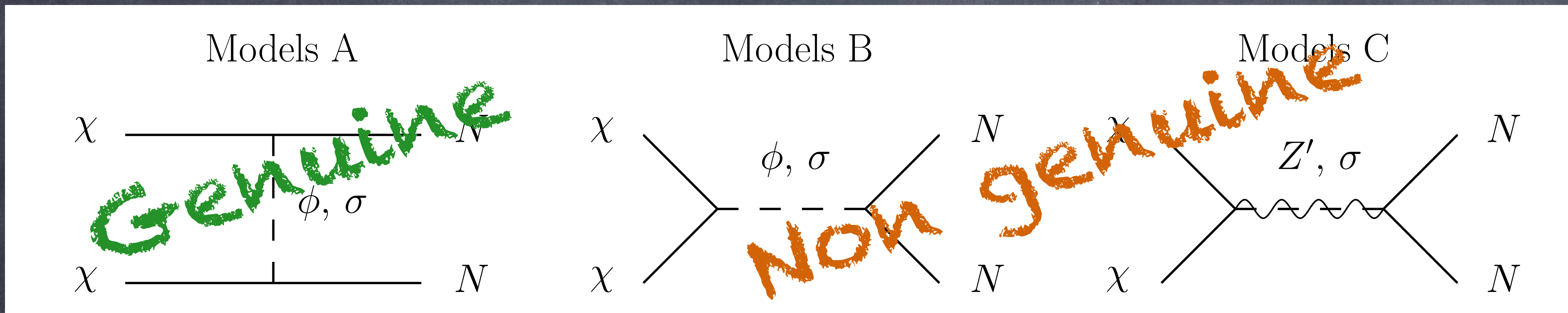


Model	Dark sector particles	Z_2	$U(1)_{B-L}$
A1	Majorana fermion χ	-1	0
	real scalar ϕ	-1	0
A2	Majorana fermion χ	-1	0
	complex scalar σ	-1	-1
B1	Majorana fermion χ	-1	0
	real scalar ϕ	$+1$	0

Model	Dark sector particles	Z_2	$U(1)_{B-L}$
B2	chiral fermion χ_L	-1	$+1$
	complex scalar σ	$+1$	$+2$
C1	Majorana fermion χ	-1	0
	massive vector boson Z'	$+1$	0
C2	chiral fermion χ_L	-1	$+1$
	complex scalar σ	$+1$	$+2$
	gauge boson Z'	$+1$	0

C2, gauged $B-L$: 2 N_R + 1 χ_L

Models



Model	Dark sector particles	Z_2	$U(1)_{B-L}$
A1	$f\overline{N_R}\chi_L\phi$		
A2	$f\overline{N_R}\chi_L\sigma$		
B1	$f\overline{N_R^c}N_R\phi - g\overline{\chi_L^c}\chi_L\phi$		

Model	Dark sector particles	Z_2	$U(1)_{B-L}$
B2	$f\overline{N_R^c}N_R\sigma + g\overline{\chi_L^c}\chi_L\sigma$		
C1	$g_N\overline{N_R}\gamma^\mu N_R Z'_\mu + g_\chi\overline{\chi_L}\gamma^\mu\chi_L Z'_\mu$		
C2	$f\overline{N_R}\gamma^\mu N_R Z'_\mu + f\overline{\chi_L}\gamma^\mu\chi_L Z'_\mu$		

→ + couplings to SM

MATCHING TIME

$(\overline{N_R}\chi_L)(\overline{\chi_L}N_R)$ $(\overline{N_R}\chi_L)(\overline{N_R}\chi_L)$ $(\overline{N_R^c}N_R)(\overline{\chi_L^c}\chi_L)$ $(\overline{N_R^c}N_R)(\overline{N_R}N_R^c)$ $(\overline{\chi_L^c}\chi_L)(\overline{\chi_L}\chi_L^c)$ $(\overline{N_R^c}N_R)(H^\dagger H)$ $(\overline{\chi_L^c}\chi_L)(H^\dagger H)$

Self interactions — Coupling to SM

Model	c_1/Λ^2	c_2/Λ^2	c_3/Λ^2	c_4/Λ^2	c_5/Λ^2	c_{NH}/Λ	$c_{\chi H}/\Lambda$
A1	$\frac{\lvert f\rvert^2}{m_\phi^2}$	$\frac{f^2}{2m_\phi^2}$	✗	✗	✗	✗	✗
A2a	$\frac{f^2}{m_\sigma^2}$	✗	✗	✗	✗	✗	✗
A2b	$\frac{f^2}{m_\sigma^2}$	✗	✗	✗	✗	✗	✗
A2c	$\frac{f^2}{m_\sigma^2}$	$-\frac{f^2\mu_\sigma^2}{2m_\sigma^4}$	✗	✗	✗	✗	✗
B1	✗	$-\frac{2f^*g}{m_\phi^2}$	$\frac{fg}{m_\phi^2}$	$\frac{\lvert f\rvert^2}{m_\phi^2}$	$\frac{\lvert g\rvert^2}{m_\phi^2}$	$\frac{f\mu_{\phi H}}{m_\phi^2}$	$\frac{g\mu_{\phi H}}{m_\phi^2}$
B2	✗	$-\frac{fg}{m_s^2}$	$\frac{fg}{2m_s^2}$	$\frac{f^2}{2m_s^2}$	$\frac{g^2}{2m_s^2}$	$\frac{f\lambda_{\sigma H}v_\sigma}{\sqrt{2}m_s^2}$	$\frac{g\lambda_{\sigma H}v_\sigma}{\sqrt{2}m_s^2}$
C1	$\frac{2g_N g_\chi}{m_{Z'}^2}$	✗	✗	$-\frac{g_N^2}{m_{Z'}^2}$	$-\frac{g_\chi^2}{m_{Z'}^2}$	✗	✗
C2	$\frac{2g'^2 Q_N Q_\chi}{m_{Z'}^2}$	$-\frac{fg}{m_s^2}$	$\frac{fg}{2m_s^2}$	$\frac{f^2}{2m_s^2}-\frac{g'^2Q_N^2}{m_{Z'}^2}$	$\frac{g^2}{2m_s^2}-\frac{g'^2Q_\chi^2}{m_{Z'}^2}$	$\frac{f\lambda_{\sigma H}v_\sigma}{\sqrt{2}m_s^2}$	$\frac{g\lambda_{\sigma H}v_\sigma}{\sqrt{2}m_s^2}$

Genuine: A2a Dirac ν; A2b $m_N \neq 0$; A2c $\mu_\sigma^2 \neq 0$

Non-genuine: B1 Real scalar; B2 Global; C1 Effective; C2 Gauge

Models' features

Feature \ Model	A1	A2a	A2b	A2c	B1	B2	C1	C2
s-wave $\langle \sigma v \rangle_{\chi\chi \to NN}$	✓	✗	✓	✓		✗	✓	✓
DD @ tree level	✗	✗	✗	✗	✓	✓	✗	✓
Self-interactions	✗	✗	✗	✗	✓	✓	✓	✓

Dirac ν

$m_N \neq 0$

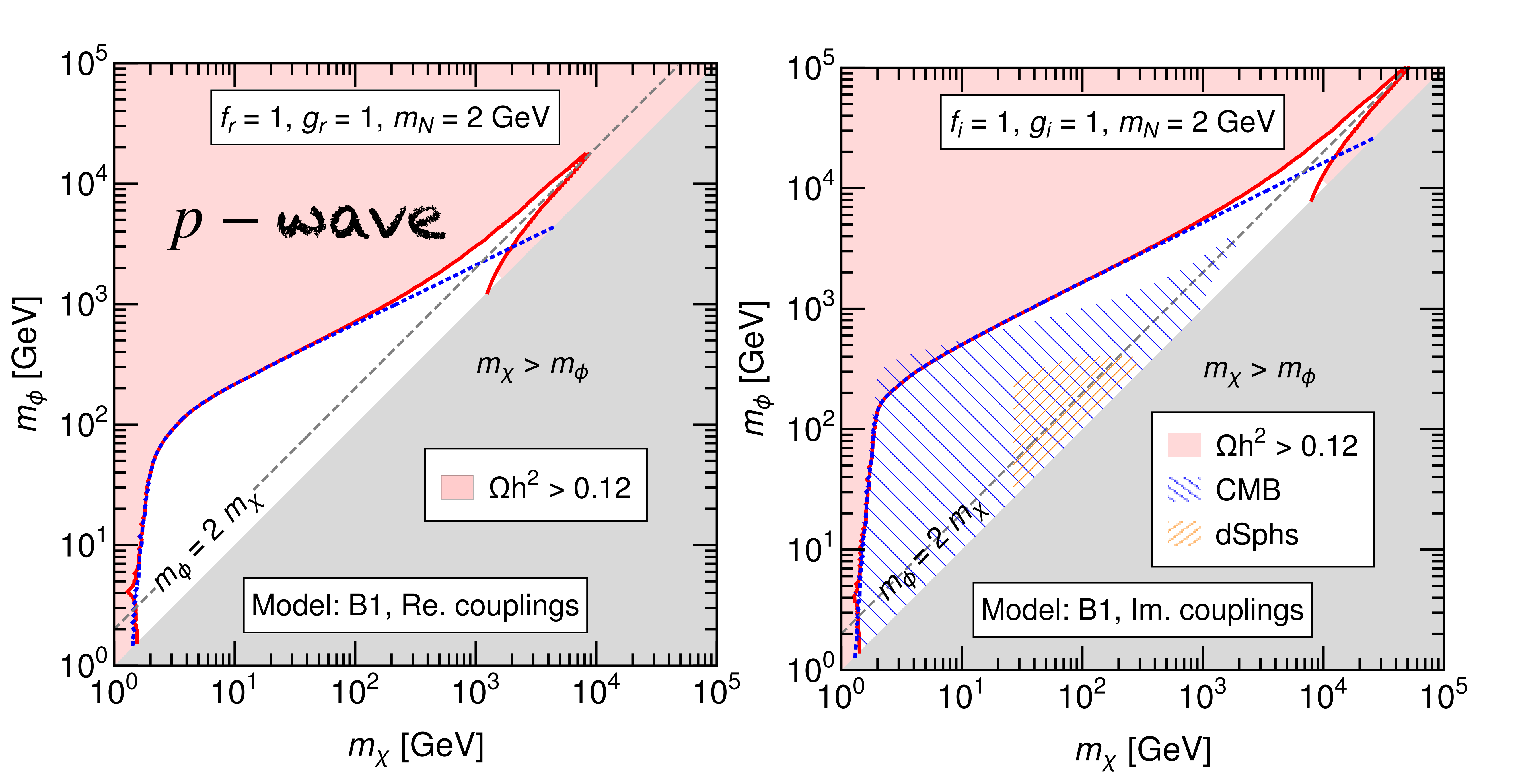
$m_N \neq 0$ loop

$g^* \in R$

Genuine Non-genuine

Model B1

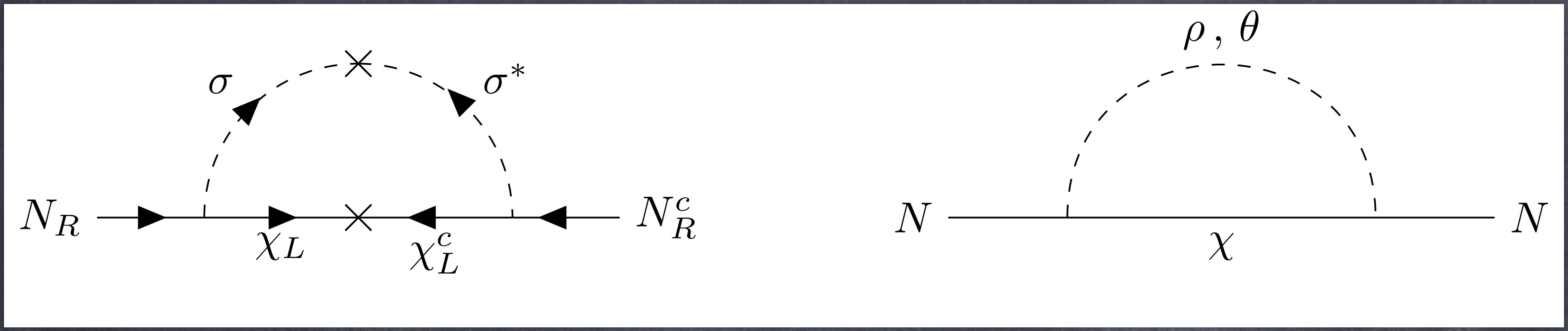
$$\mathscr{L}_{\rm A2c} \supset -f\overline{N_R^c}N_R\,\phi - g\overline{\chi_L^c}\chi_L\,\phi + \text{H.c.}\,.$$



ID limits, Batell 2017

Model A2c: $m_N = 0$

$$\mathscr{L}_{\rm A2c} \supset -f\overline{N_R}\chi_L\sigma - \frac{1}{2}m_\chi\overline{\chi_L}\chi_L^c - \frac{1}{2}\mu_\sigma^2\sigma^2 + \text{H.c.}.$$



Scotogenic-like mass. For $m_{\chi_k} \ll m_\rho, m_\theta$:

$$\left(m_N\right)_{ij} \approx \frac{\mu_\sigma^2}{16\pi^2 m_\sigma^2}\sum_{k=1}^{n_\chi} f_{ik}^* f_{jk}^* m_{\chi_k}$$

Need $n_\chi \geq 2$

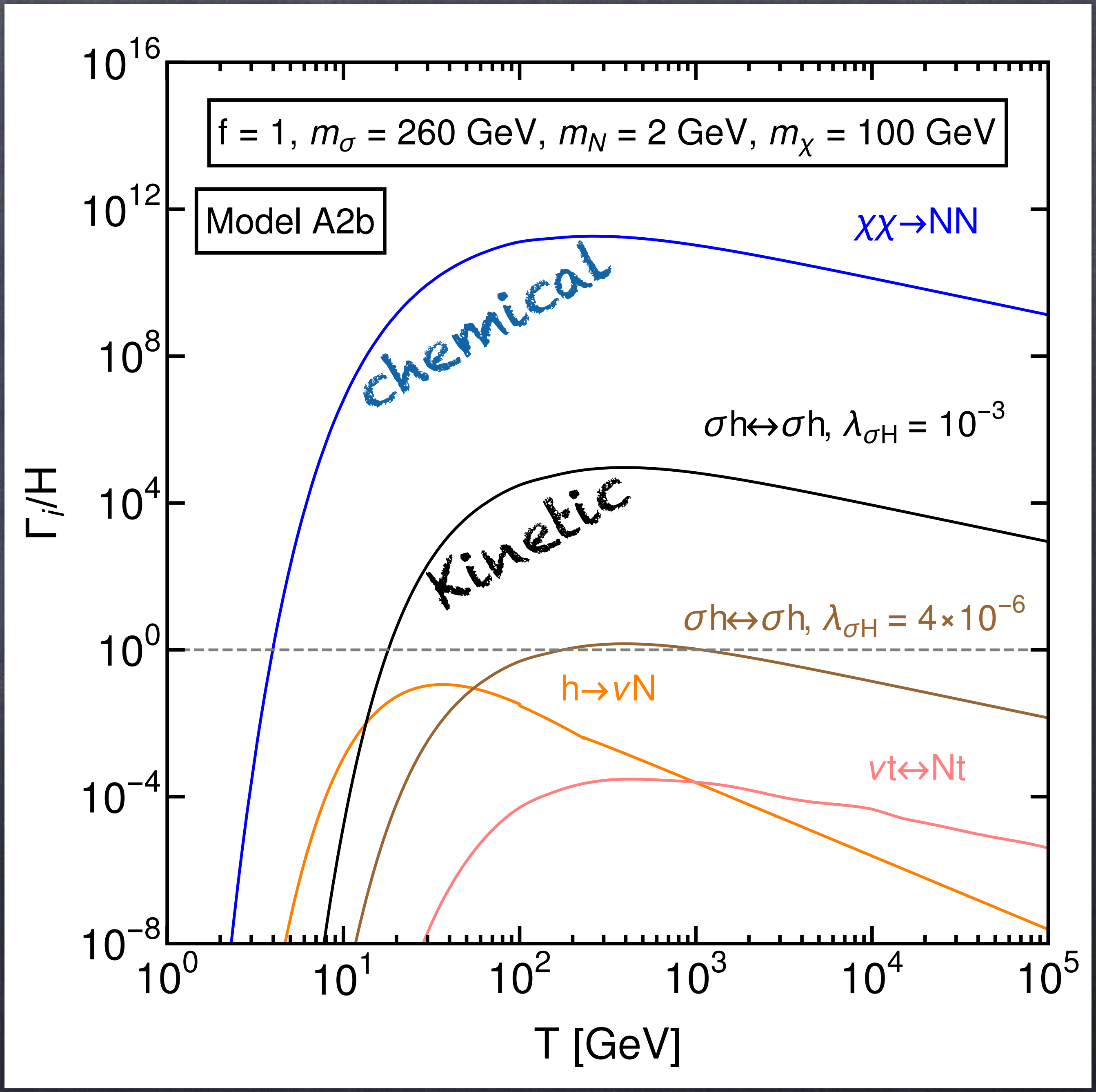
Casas-Ibarra generalisation:

$$n_\chi = n_N = 1$$

$$f = 4\pi\frac{y_\nu\, v_h\, m_\sigma}{\sqrt{2\, m_\nu\, m_\chi\, \mu_\sigma^2}}$$

Thermal Equilibrium

- Chemical f.o. of $\chi\chi \to NN$.
- Kinetic eq. early on with SM via $\lambda_{\sigma H}|H|^2|\sigma|^2$ for $\lambda_{\sigma H} \gtrsim 10^{-6}$.
- Kinetic eq. within the DS via $\chi N \to \chi N$.

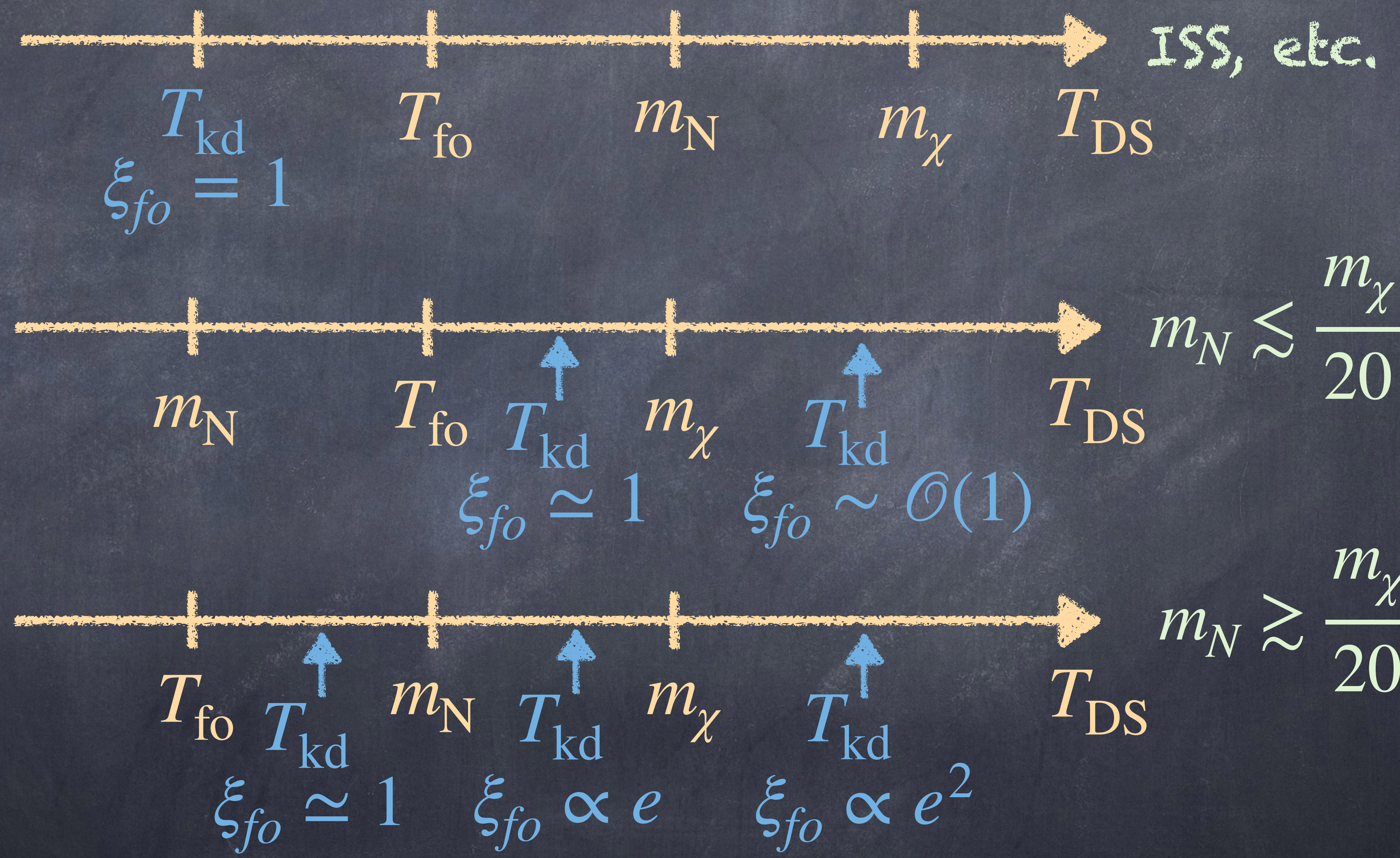


Kinetic decoupling

[Berlin et al 2016, Binder et al 2021]

$$\xi = \frac{T_\mathrm{D}}{T_\mathrm{SM}}$$

$$\xi_{init} = 1$$



$\rightarrow$ up to $\mathcal{O}(1)$ uncertainty in Ω

Multi DM

[D. Vatsyayan, A. Bas, JHG, JHEP10 (2022) 075]

Partially-asymmetric framework

[Graesser et al 2011]

$$\rho_{\rm DM} = s\sum_i m_i \eta_i \left(1 + 2\frac{r_{\infty,i}}{1-r_{\infty,i}}\right)$$

For multi-DM:

$$\eta_i \equiv Y_i^+ - Y_i^- \qquad r_i \equiv \frac{Y_i^-}{Y_i^+}$$

$r_i \to 1$: symmetric

$r_i \to 0$: asymmetric

$$\frac{dr_1}{dx} = -\frac{s\eta_1}{Hx}\left[\langle\sigma_{\rm ann,\,1}\, v\rangle\left(r_1 - \bar r_1\zeta^2(r_1)\right) + \langle\sigma_{\rm conv,\,12}\, v\rangle\left(r_1 - \frac{r_2\bar r_1}{\bar r_2}\frac{\zeta^2(r_1)}{\zeta^2(r_2)}\right)\right]$$

$x = m_1/T$

$$\frac{dr_2}{dx} = -\frac{s\eta_2}{Hx}\left[\langle\sigma_{\rm ann,\,2}\, v\rangle\left(r_2 - \bar r_2\zeta^2(r_2)\right) - \langle\sigma_{\rm conv,\,12}\, v\rangle\frac{\eta_1^2(1-r_2)^2}{\eta_2^2(1-r_1)^2}\left(r_1 - \frac{r_2\bar r_1}{\bar r_2}\frac{\zeta^2(r_1)}{\zeta^2(r_2)}\right)\right]$$

$$\bar r_i \equiv e^{-2\sinh^{-1}\left(\frac{\eta_i}{2\bar Y_i}\right)} \qquad \zeta(r_i) \equiv \frac{1-r_i}{1-\bar r_i}$$

Analytical approximation

$$f_c \equiv \frac{\sigma_c}{\sigma_1}$$

$$\Phi_i(x, m_i) \equiv \int_{x_{f_i}}^{x} dx' x'^{-k-2} g_*^{1/2}$$

$$r_1(x) \simeq \bar{r}_{1,f}\, e^{-\lambda_a (1+f_c)\, \eta\, \Phi_1(x,m_1)}$$

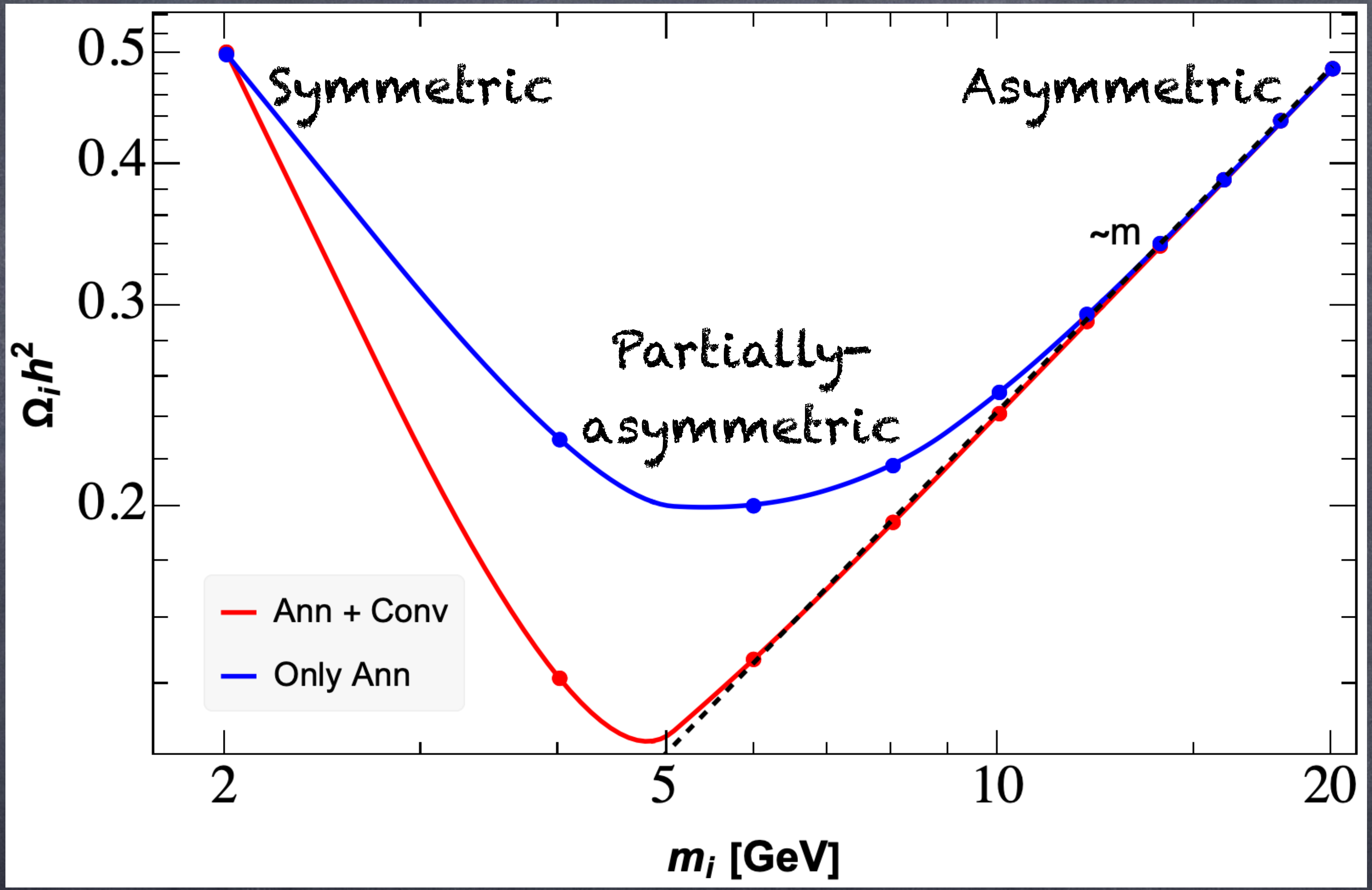
$$\lambda_{a,i} = \sqrt{\frac{\pi}{45}}\, M_{Pl}\, m_1\, \sigma_i$$

$$r_2(x) \simeq \bar{r}_{2,f}\, e^{-\lambda_a\, \eta\, \Phi_2(x,m_2)}$$

If conversions are significant:

- Heavier components ⇒ symmetric part gets reduced exponentially by conversions!
- Lighter components ⇒ mostly symmetric

Partially-asymmetric DM



- Symmetric case → almost independent of m, depends on σ
- Completely asymmetric → $\propto \eta\, m$

2DM, symmetric, $m_1 > m_2$

- Conversions $\chi_i\bar{\chi}_i \to \chi_j\bar{\chi}_j$ change n_i but not n_t.
- Boltzmann Eqs.:

$$\frac{dY_1}{dx} = -\frac{s}{Hx}\left[\langle\sigma_{\text{ann},1}v\rangle\,(Y_1^2 - \bar{Y}_1^2) + \langle\sigma_{\text{conv},12}v\rangle(Y_1^2 - \frac{Y_2^2}{\bar{Y}_2^2}\bar{Y}_1^2)\right]$$

$$\frac{dY_2}{dx} = -\frac{s}{Hx}\left[\langle\sigma_{\text{ann},2}v\rangle\,(Y_2^2 - \bar{Y}_2^2) - \langle\sigma_{\text{conv},12}v\rangle(Y_1^2 - \frac{Y_2^2}{\bar{Y}_2^2}\bar{Y}_1^2)\right]$$

$x = m_1/T$

Discrete symmetries

[S.P. Martin 1992, Batell 2011]

- $\phi \to \omega^q \phi\,, \quad \omega = \exp\left(\frac{2\pi i}{\mathcal{N}}\right),\, q = 0,\, \ldots, \mathcal{N}-1$
- $Z_2, Z_3 : \{0,1\} \to$ 1 DM. $Z_4 : \{0,1,2\} \to$ 2DM if $m_{\phi_2} < 2m_{\phi_1}$.
- $Z_{\mathcal{N}}$: up to $\frac{\mathcal{N}}{2}$ DM scalar [Yaguna 2020]. $\mathcal{N} \geq 4$, o:
- $Z^{n_1}_{\mathcal{N}_1} \times Z^{n_2}_{\mathcal{N}_2} \times \ldots \times Z^{n_k}_{\mathcal{N}_k} \Rightarrow \begin{cases} n_1 + n_2 + \ldots + n_k \text{ at least} \\ \prod_{i=1}^{k} c_i^{n_i} - 1 \text{ as maximum} \end{cases}$

$Z_{\mathcal{N}}$

[Batell 2011]

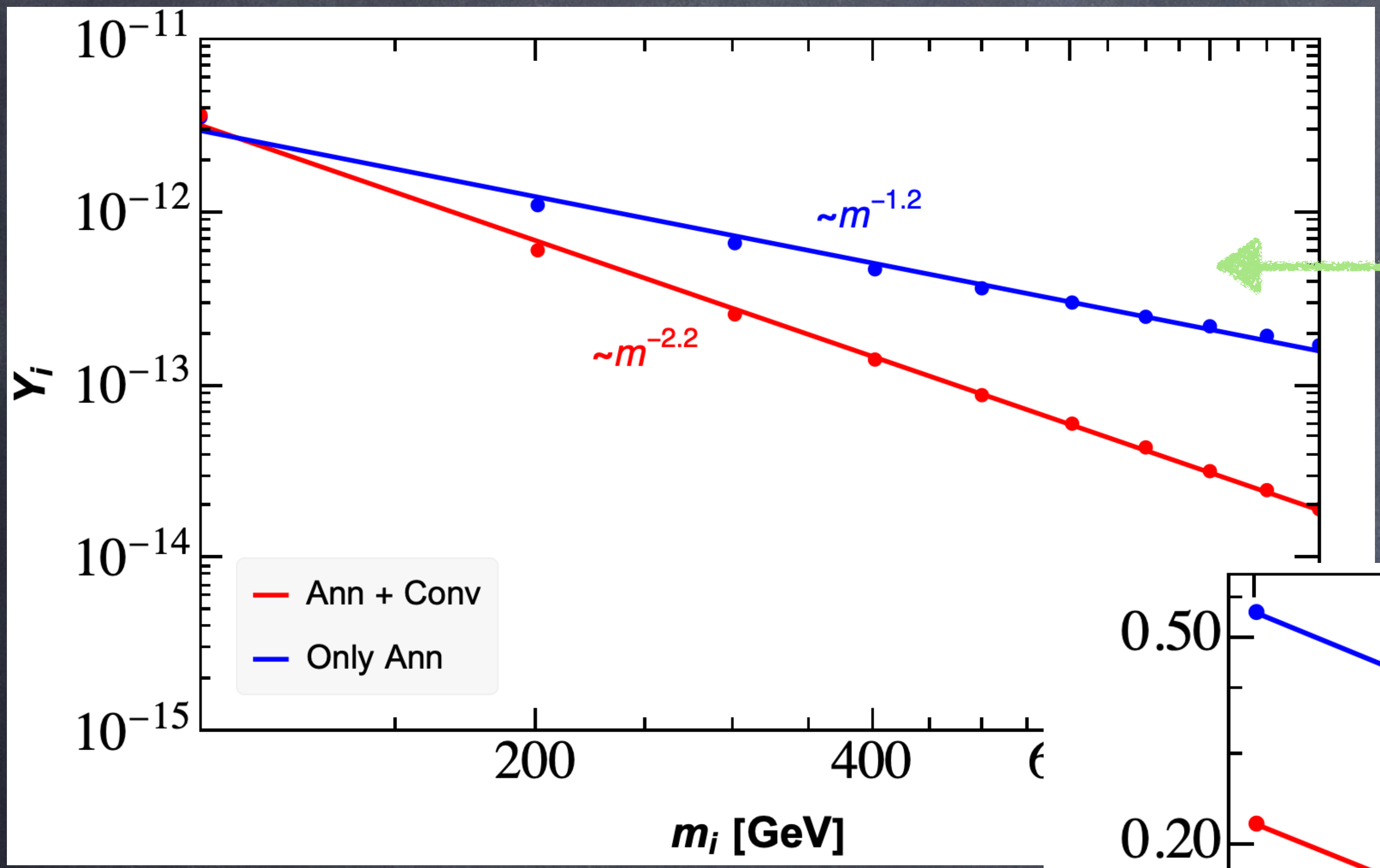
- $\mathcal{N}$ prime: lightest with non-trivial $Z_{\mathcal{N}}$ charge is always stable. Heavier particles stable if decay modes kinematically forbidden.

- $\mathcal{N}$ composite number: $\mathcal{N} = p_1^{s_1} p_2^{s_2} \dots p_k^{s_k}$, where p_i is prime and s_i is natural

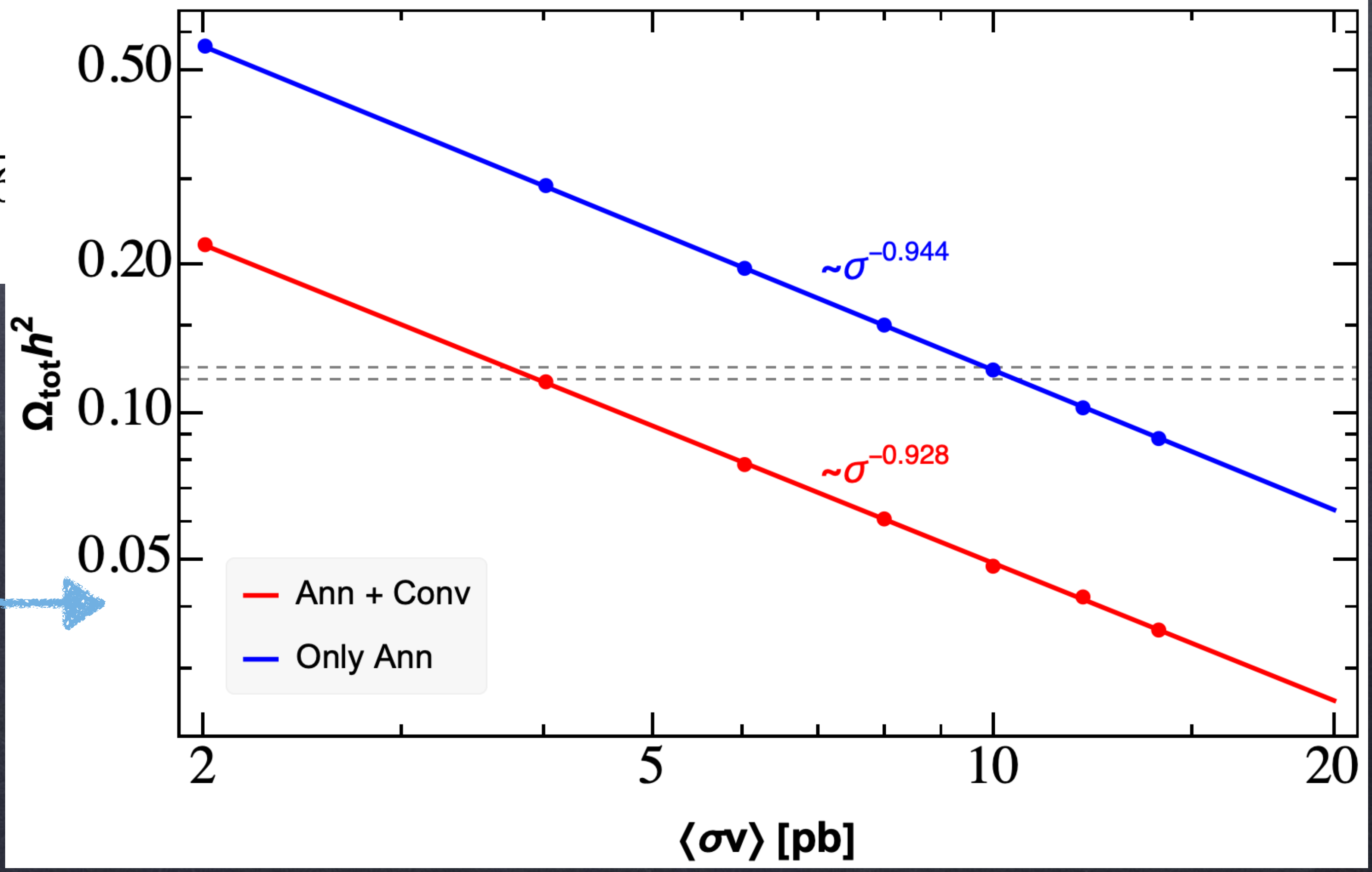
$$Z_{\mathcal{N}} \simeq Z_{p_1^{s_1}} \times Z_{p_2^{s_2}} \times \dots \times Z_{p_k^{s_k}},$$

At most $s_1 + s_2 + \dots + s_k$ stable particles (spectrum).

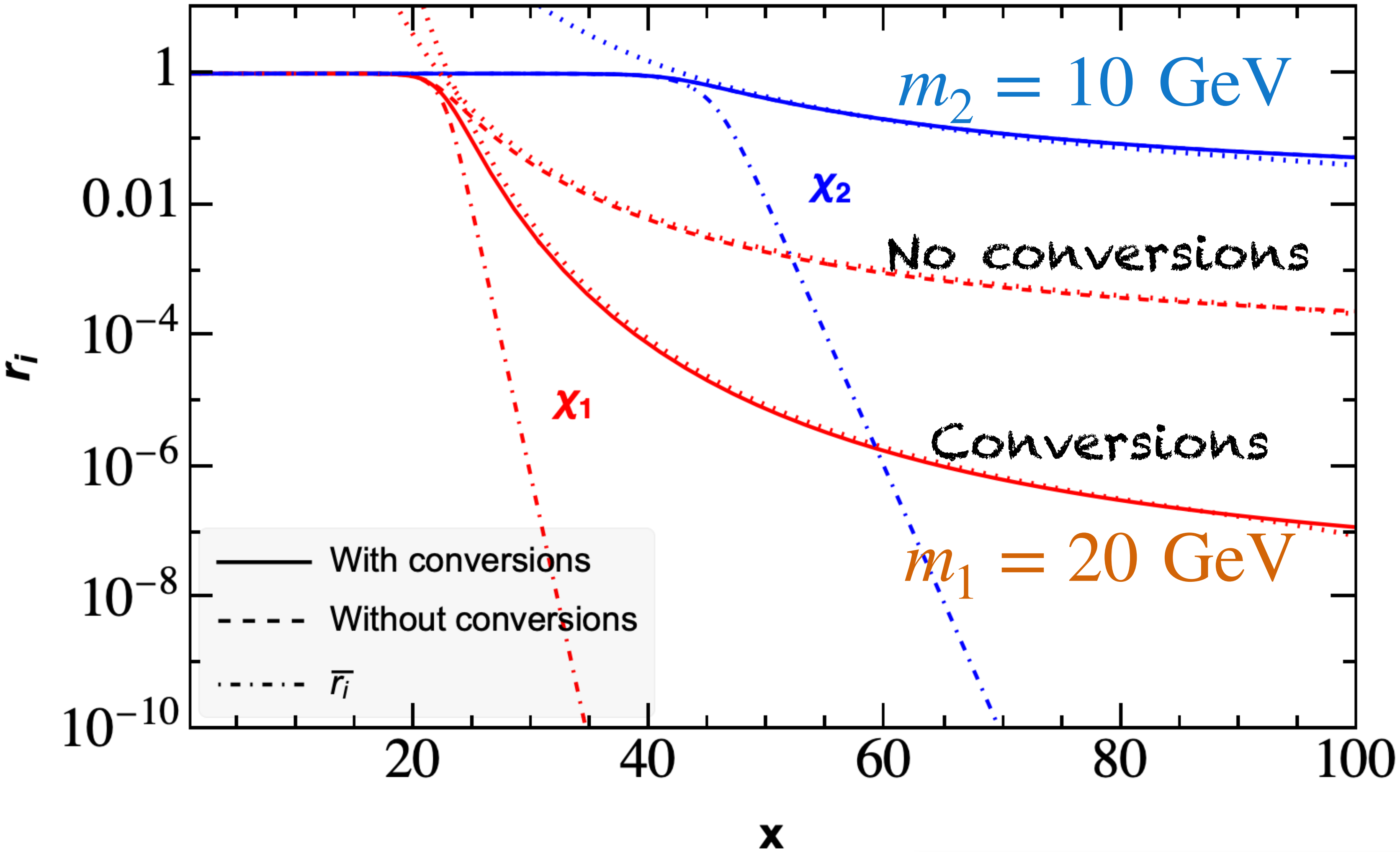
10 DM components



With conversions, heavier components more suppressed



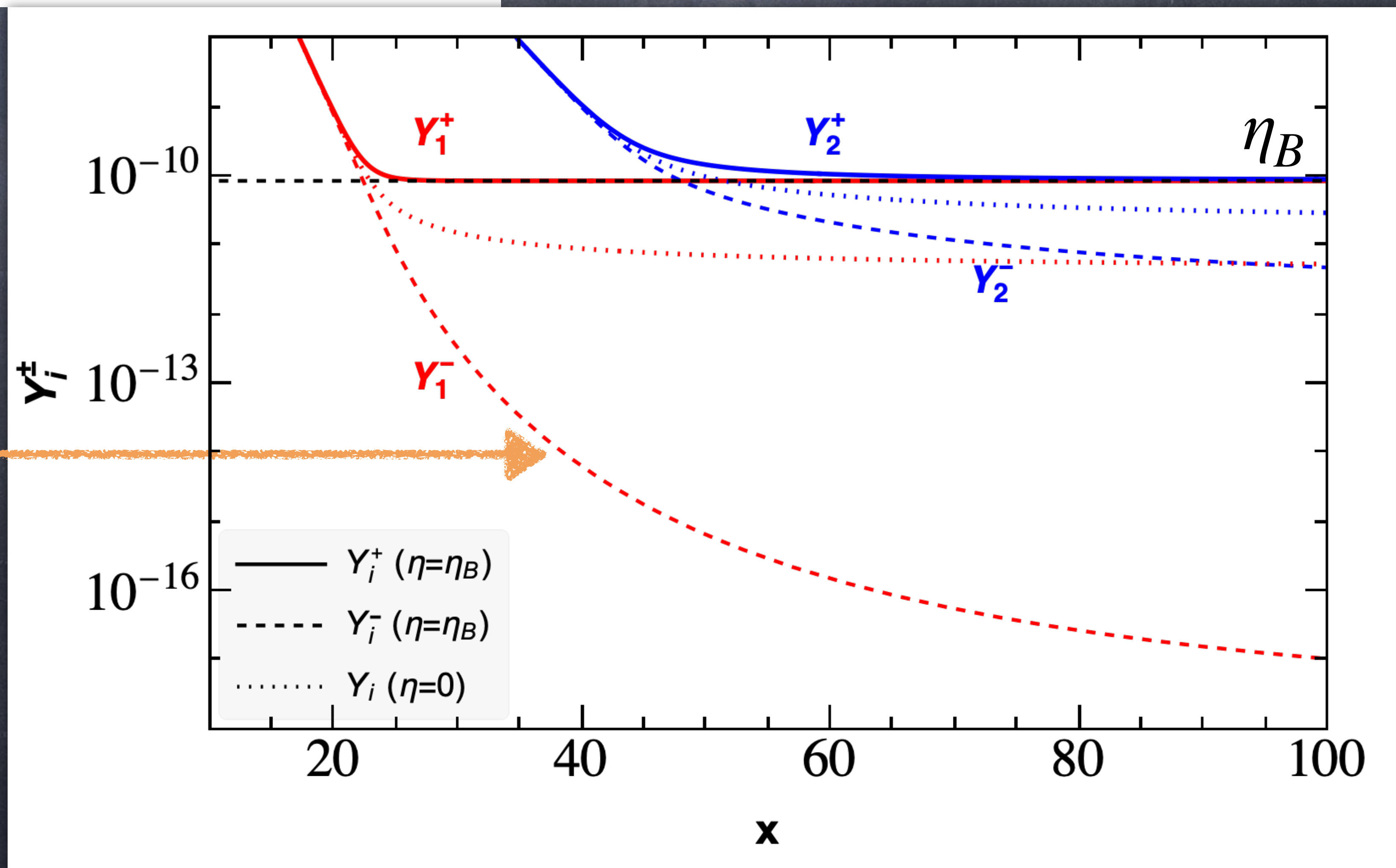
Small couplings with conversions: limits relax!



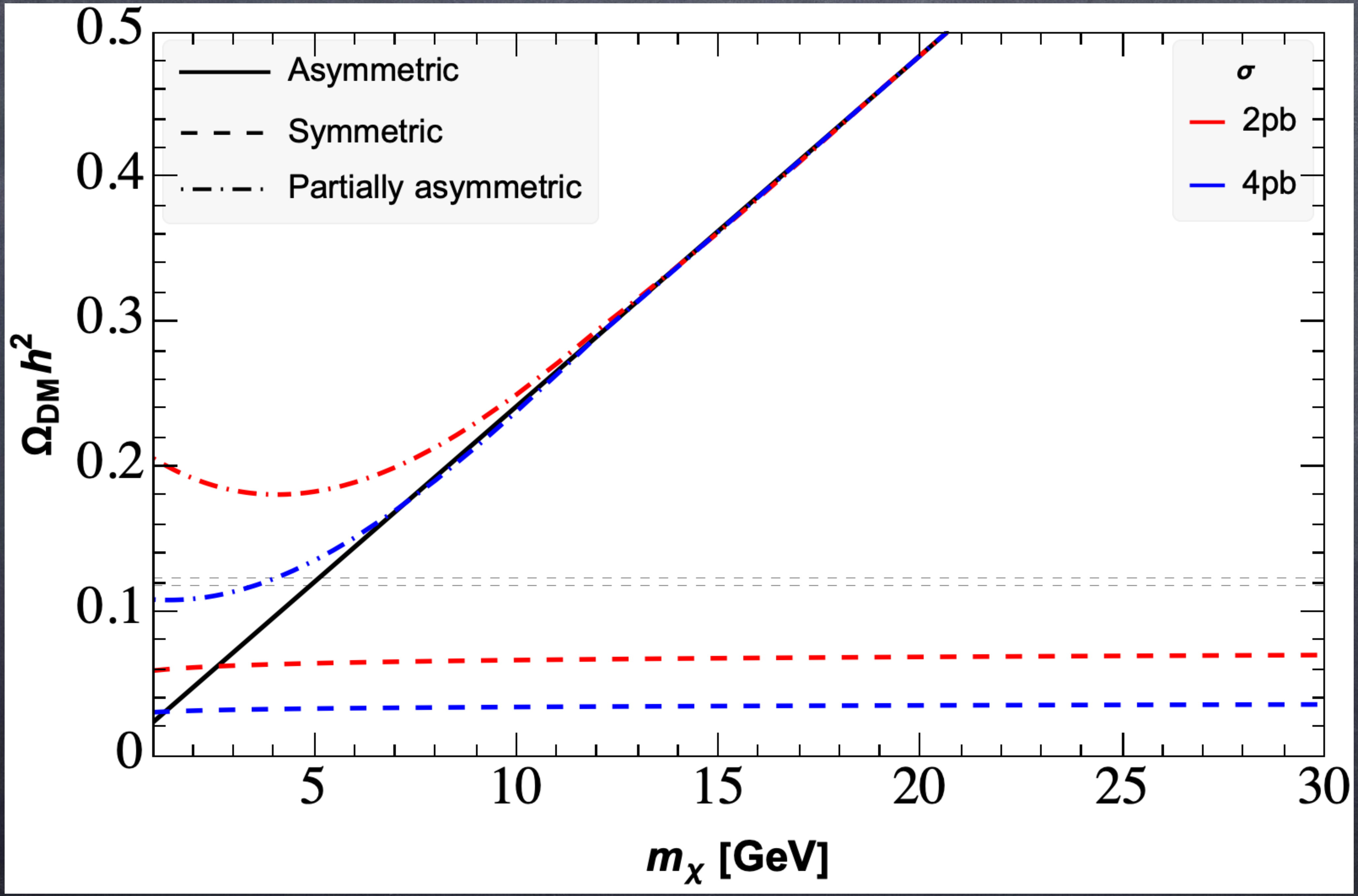
Asymmetries with conversions: 2DM

$$\eta_{1,2} = \eta_B \sim 10^{-10}$$

Heavier: more asymmetric



Partially asymmetric



Effective models

- Can parameterise cross-sections in many models as:

$$\langle \sigma_{\text{ann, i}} v \rangle \sim \begin{cases} a_i \dfrac{1}{m_i^2} \text{ for } \Lambda \ll m_i & \\ b_i \dfrac{m_i^2}{\Lambda^4} \text{ for } \Lambda \gg m_i & \end{cases},$$

LM

HM

$$\langle \sigma_{\text{conv, ij}} v \rangle \sim \begin{cases} c_{ij} \dfrac{(m_i^2 - m_j^2)^{1/2}}{m_i^3} \text{ for } \Lambda \ll m_i \\ d_{ij} \dfrac{m_i (m_i^2 - m_j^2)^{1/2}}{\Lambda^4} \text{ for } \Lambda \gg m_i \end{cases}$$

LM

HM

2DM direct detection

$$r_\rho \equiv \frac{\rho_2}{\rho_1} \qquad r_\sigma \equiv \frac{\sigma_2^p}{\sigma_1^p}$$

$$R_A(E_R) \propto \frac{\rho_{\rm loc}\,\sigma_1^p}{(1+r_\rho)\,m_1}\left[\eta(v_{m,A}^{(1)}) + r_\rho\, r_\sigma \frac{m_1}{m_2}\eta(v_{m,A}^{(2)})\right]$$

$$\eta(v_{m,A}^{(\beta)}) = \int_{v>v_{m,A}^{(\beta)}} d^3v \frac{f_{\rm det}^{(\beta)}(\mathbf{v})}{v},\ \beta = 1,2$$

Competing effects: which DM dominates, heavier or lighter, depends on E_R