Sterile neutrino portals to Majorana dark matter

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Based on arXiv: 2203.01946
[L.Coito, C.Faubel, JHG, A.Santamaria, A.Titov]

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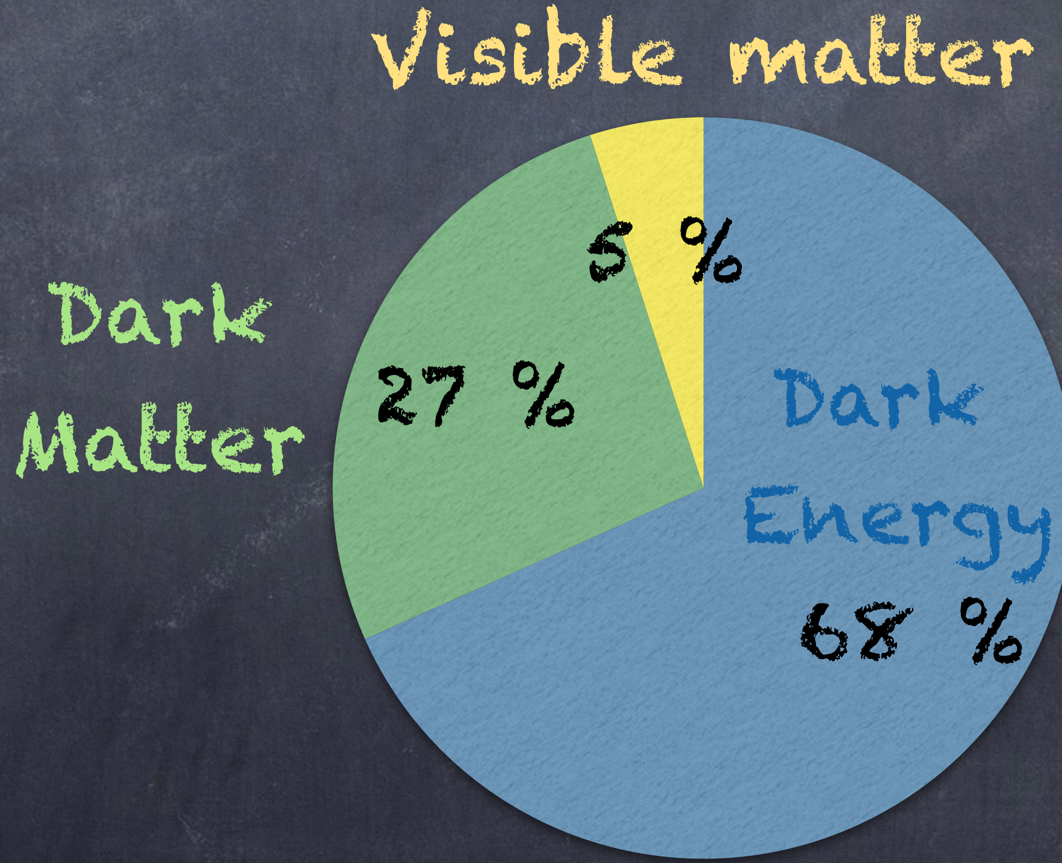
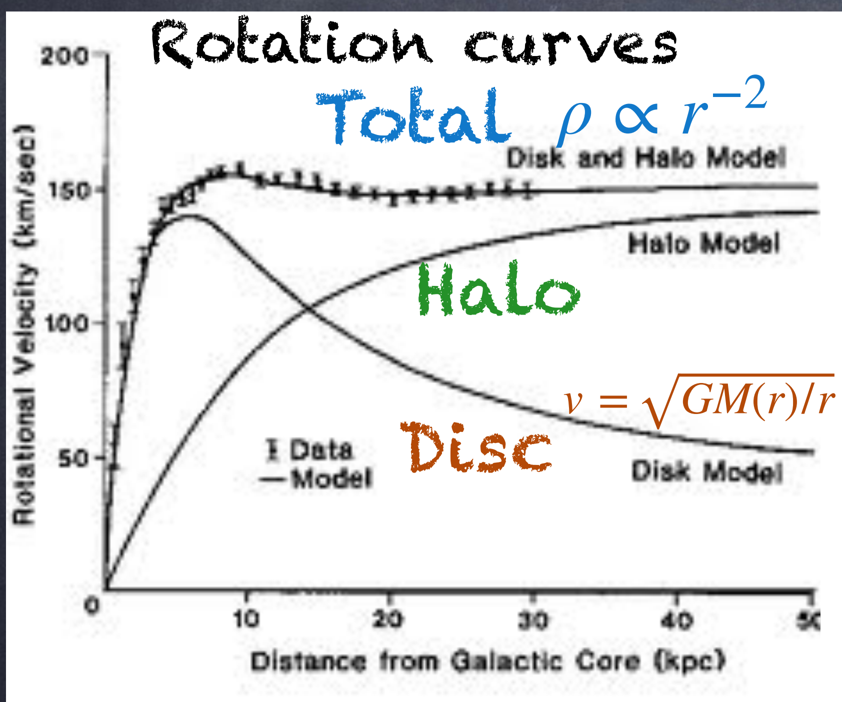
I- Dark matter framework

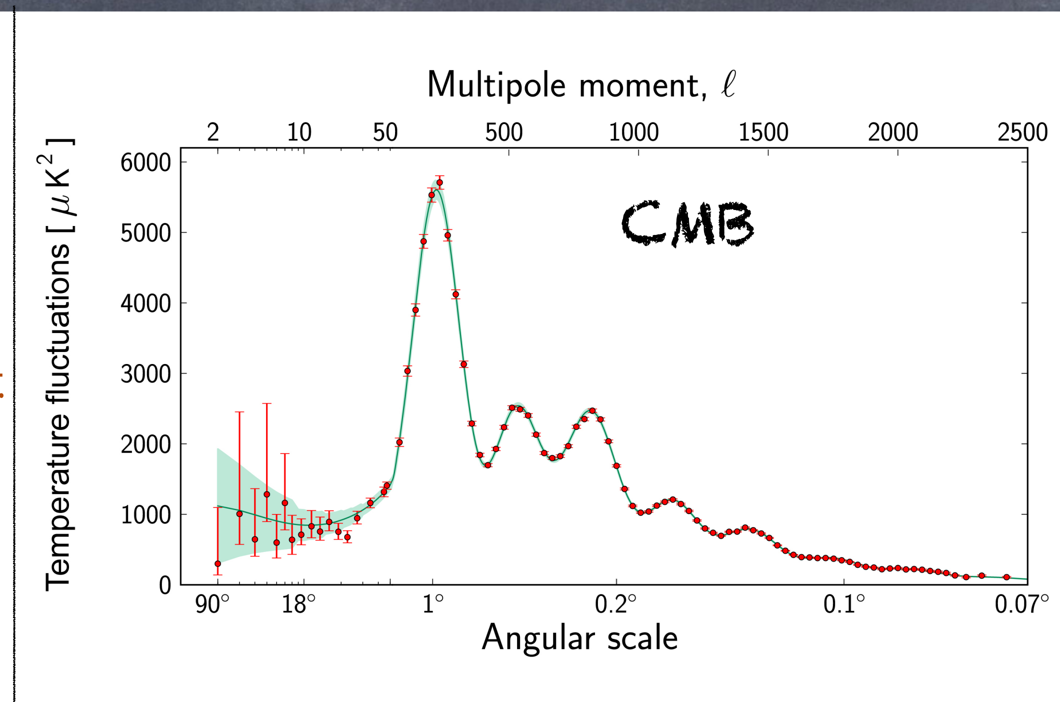


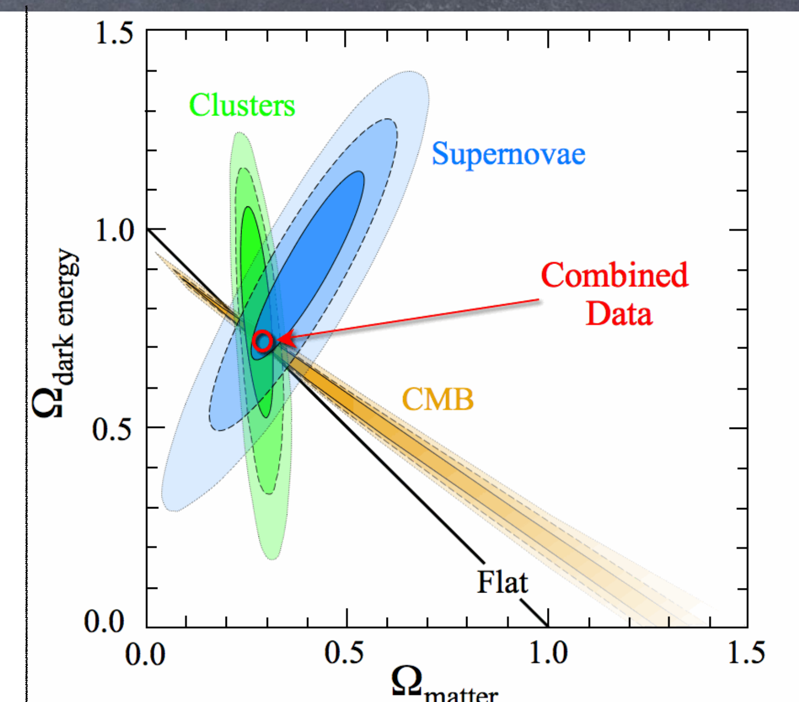
Ford, Rubin 1970

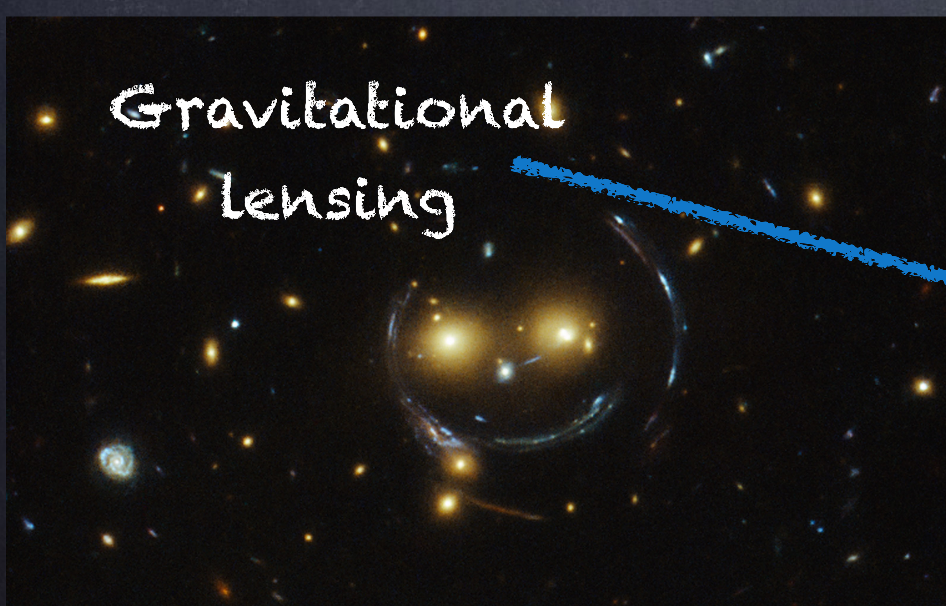
Zwicky 1933

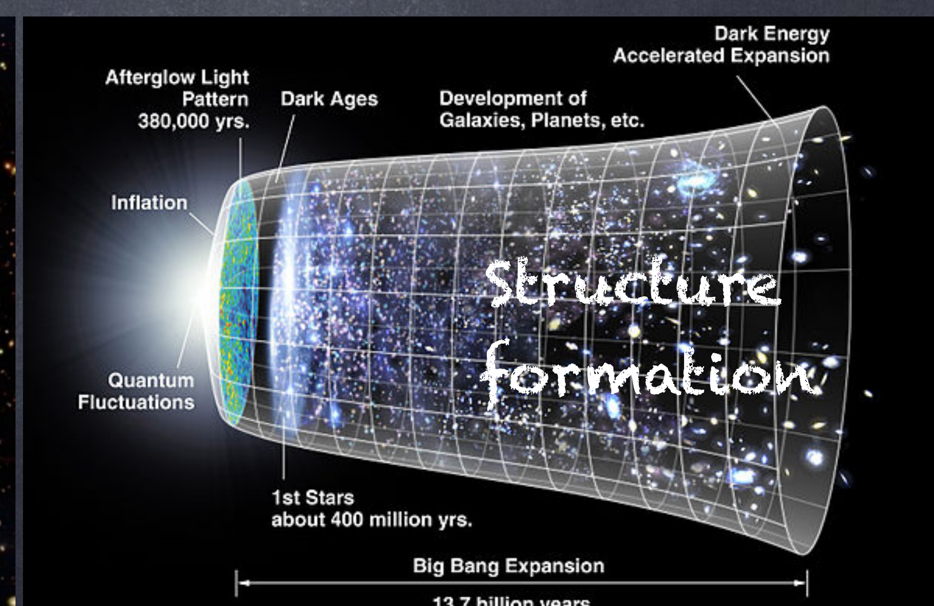
Dark Matter Evidence



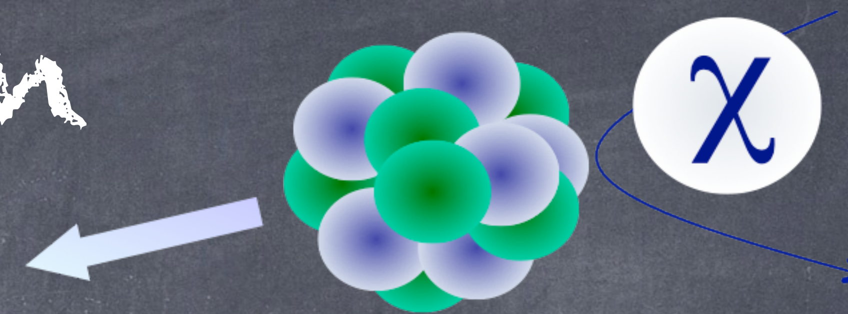




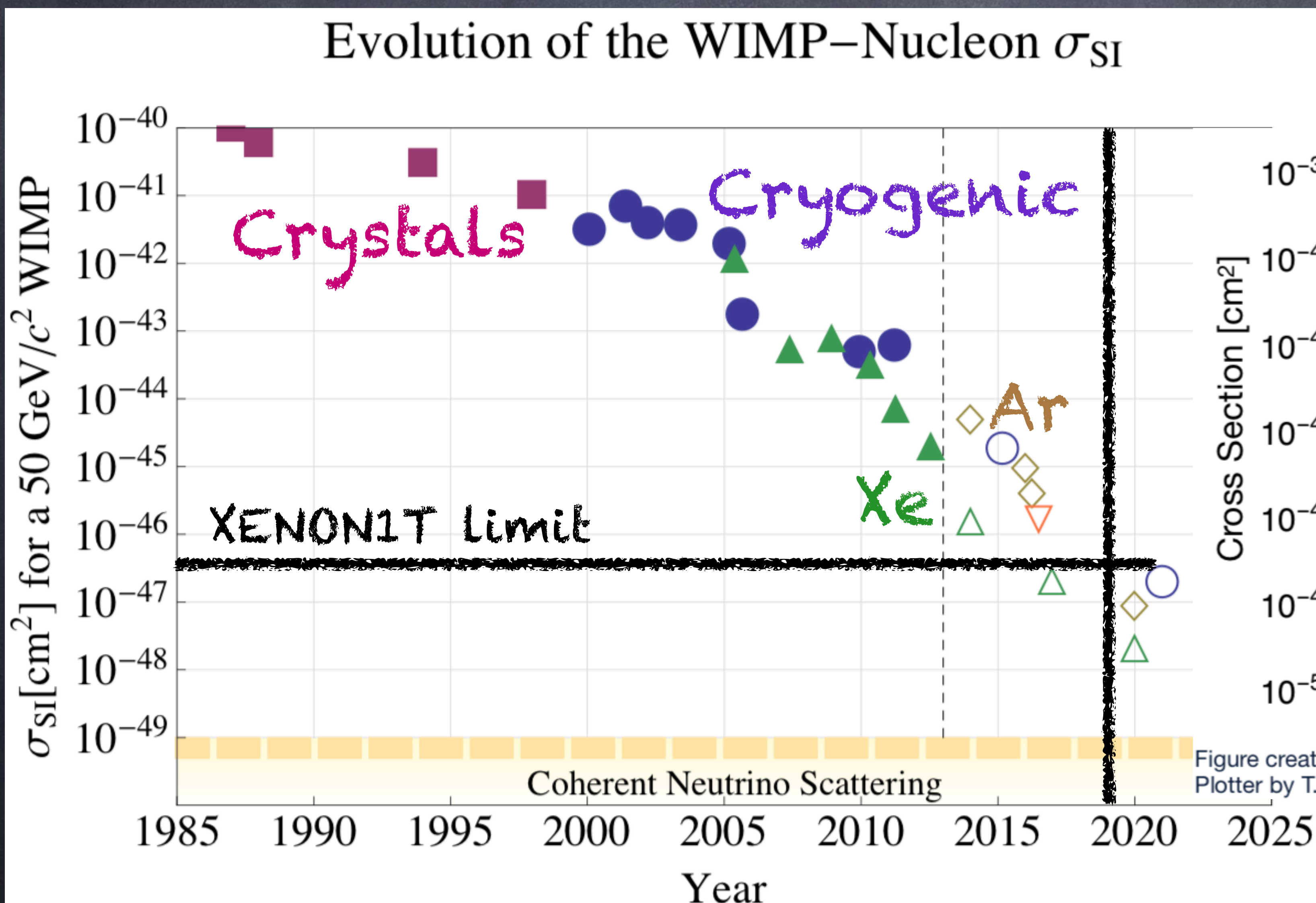


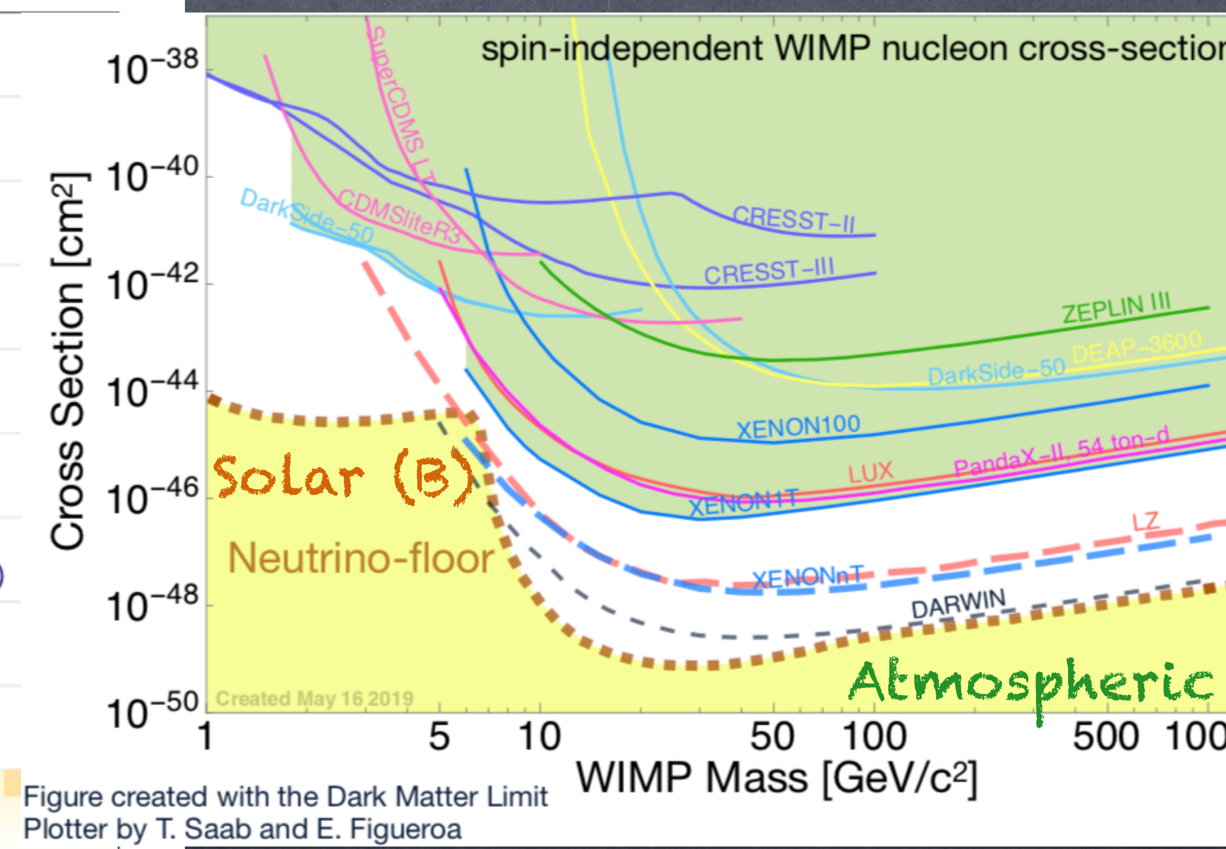


Temporal evolution of WIMPs DD



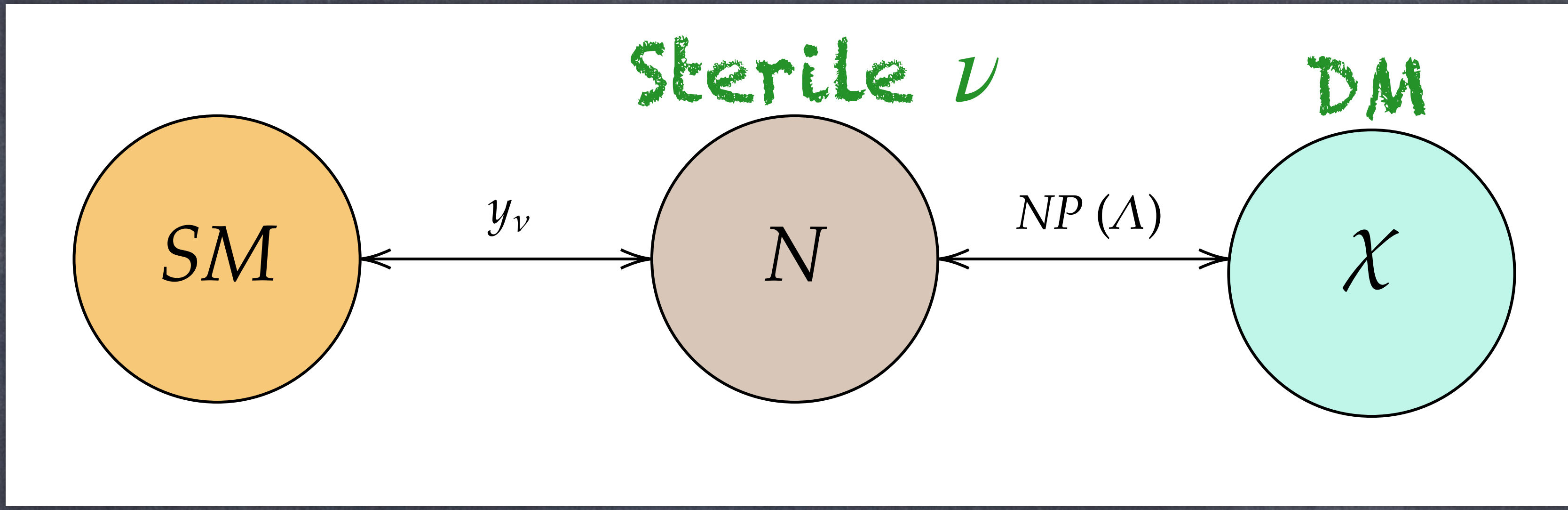
[Goodman and Witten 1985; Drukier, Freese, Spergel 1986]
[Figure from Snowmass WG, 1310.8327]





Where are the WIMPs?

What if WIMPs only couple to sterile neutrinos N_R?



- N_R are well motivated by neutrino masses
- DM coupled to SM via N_R: most bounds evaded
- We consider Majorana DM χ, with $m_N < m_\chi$
- Other neutrino portals [Escudero, Batell, Blennow…]

Framework

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

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

Neutrino masses by standard seesaw:

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

Other options:
inverse seesaw, etc.

II- Effective operators and models

Effective operators

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

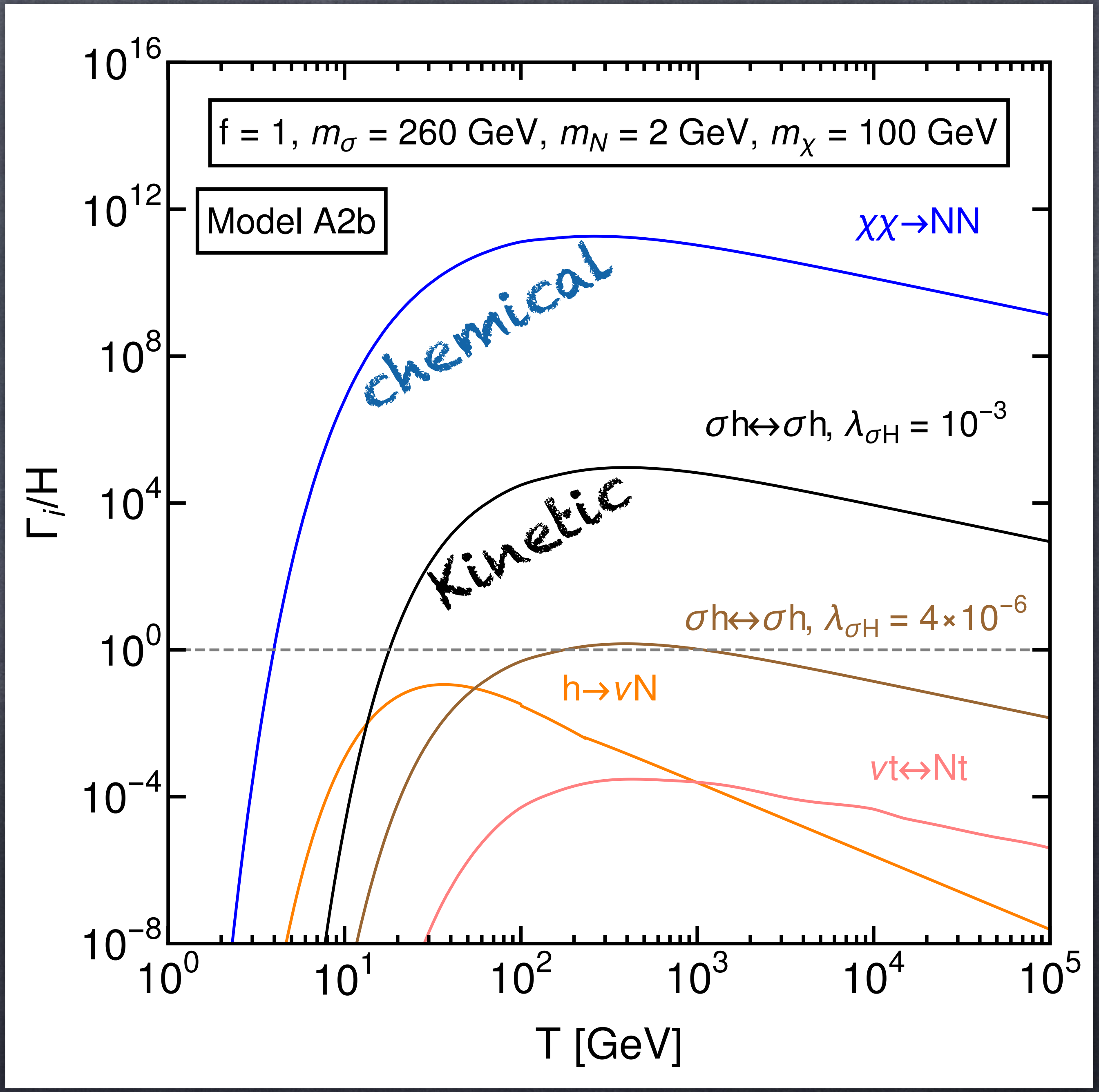
$$\mathcal{O}_2 = (\overline{N_R}\chi_L)(\overline{N_R}\chi_L) = -\frac{1}{2}(\overline{N_R}N_R^c)(\overline{\chi_L^c}\chi_L)\,, \qquad \text{LNV}$$

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

UV completions include new scalars

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 $\chi N \to \chi N$.

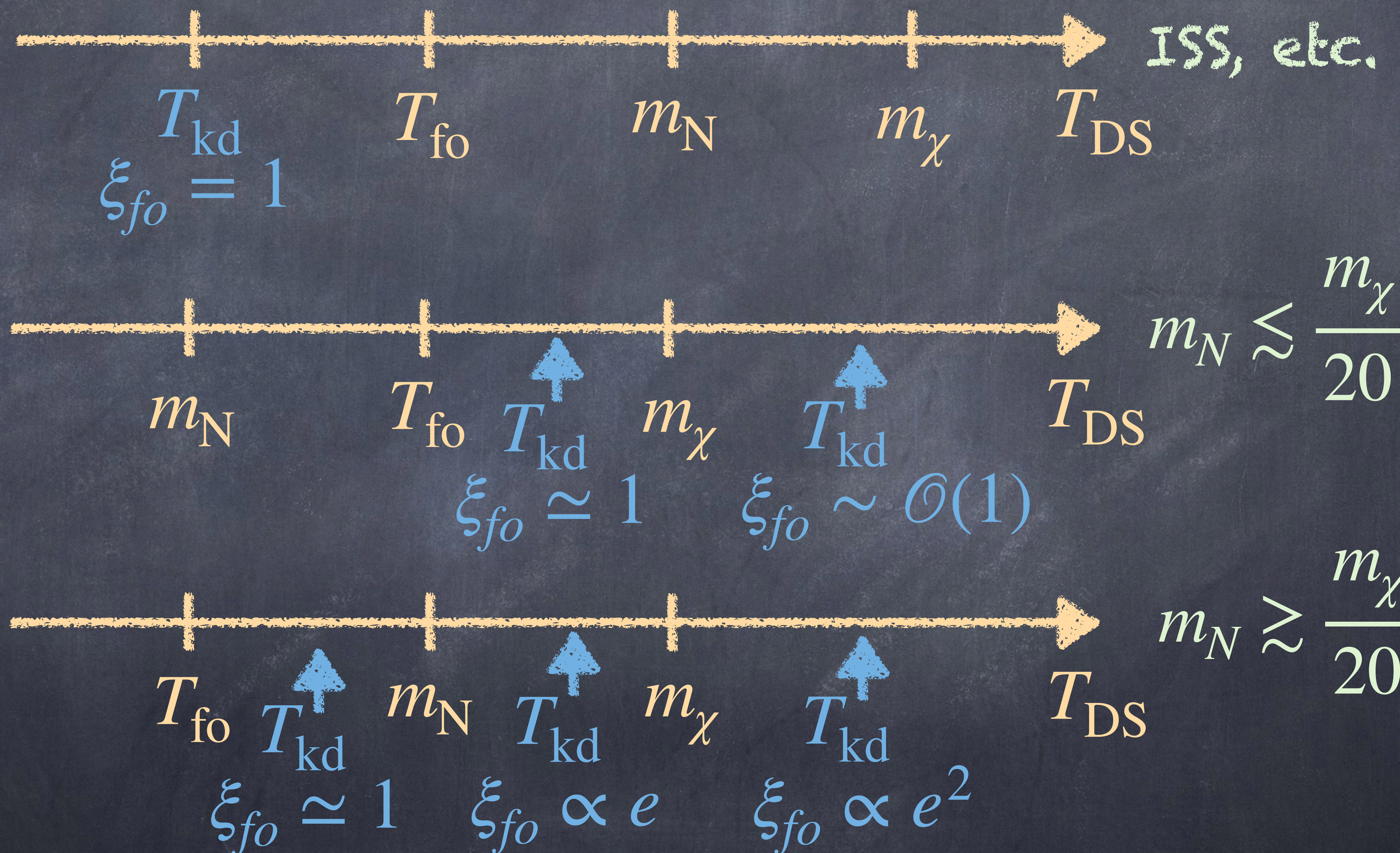


Kinetic decoupling

[Berlin 2016]

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

$$\xi_{init} = 1$$



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

DM annihilations

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

For $m_N = 0$:

$$a = \frac{m_\chi^2}{4\pi\Lambda^4}\left[|c_2|^2 + 4|c_3|^2 + 4\,Re(c_2c_3)\right]$$

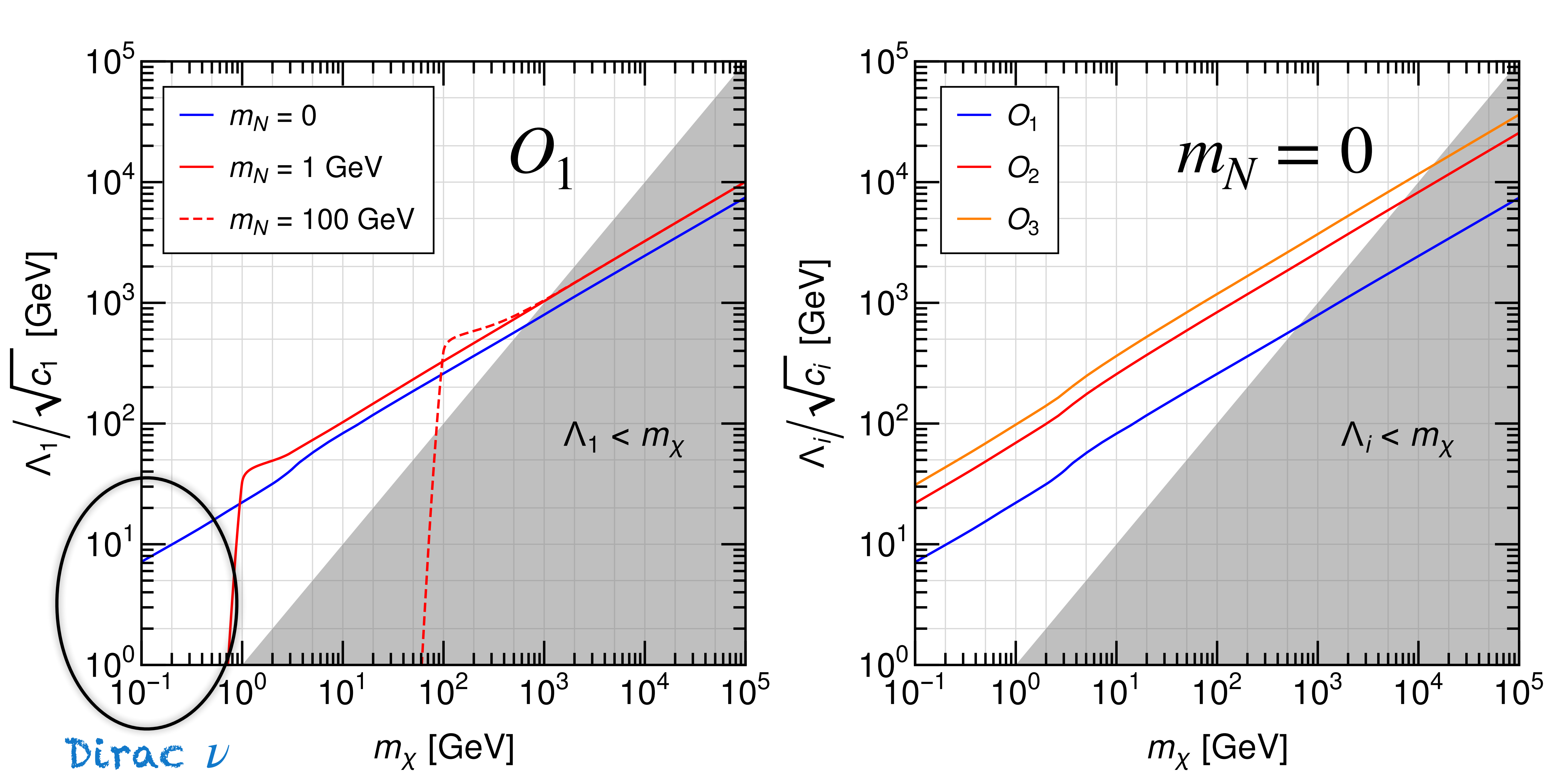
$$b = \frac{m_\chi^2}{12\pi\Lambda^4}\left[c_1^2 + 3|c_2|^2 + 12|c_3|^2 - 12\,Re(c_2c_3)\right]$$

$\mathcal{O}_1$ gives $p-$wave or chirality-supp. (m_N) contributions

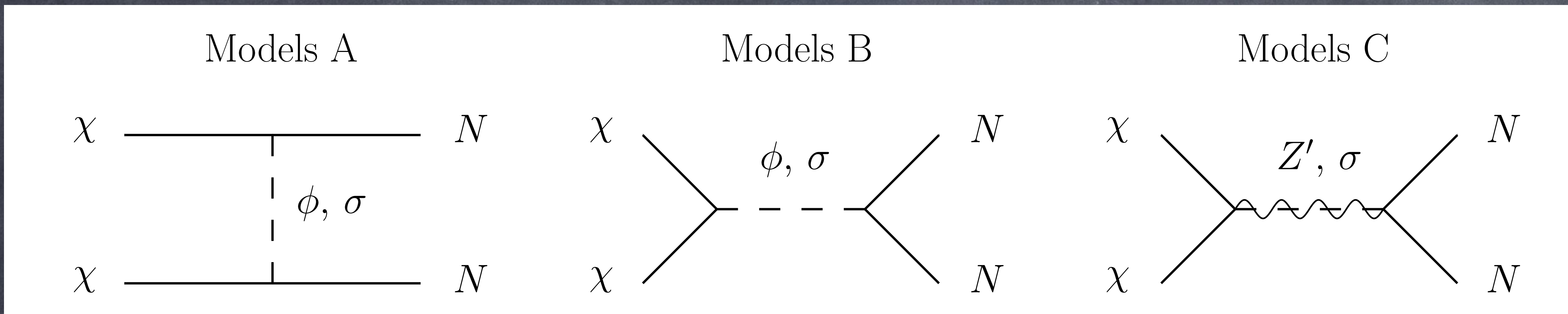
For $c_2 = -2c_3^* \longrightarrow$ p-wave annihilations

Relic abundance

$\chi\chi \to NN$



Models

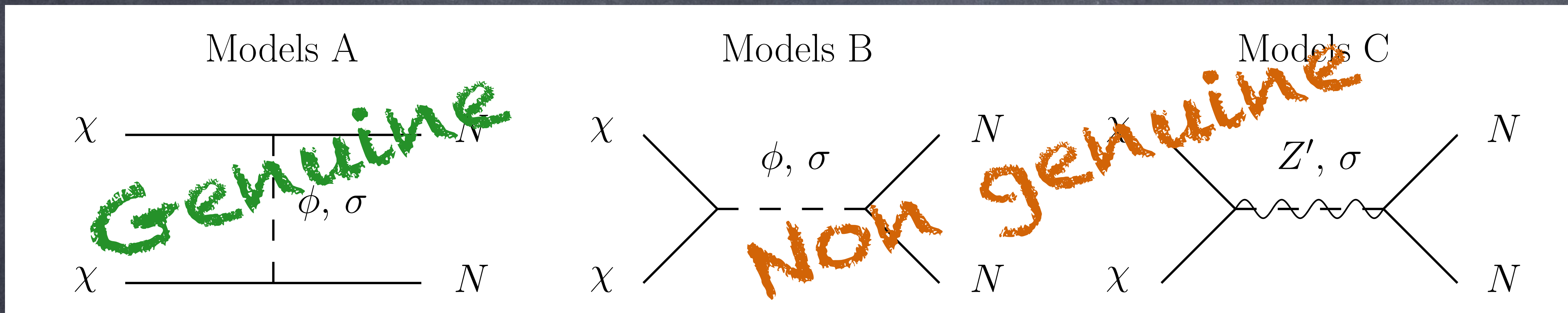


Model	Dark sector particles	Z_2	$U(1)_{B-L}$
A1	Majorana fermion χ	-1	0
	real scalar ϕ	-1	0
A2	Majorana fermion χ	-1	0
	complex scalar σ	-1	-1
B1	Majorana fermion χ	-1	0
	real scalar ϕ	$+1$	0

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	$\frac{\|f\|^2}{m_\phi^2}$	$\frac{f^2}{2m_\phi^2}$	✗	✗	✗	✗	✗
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	✗	$-\frac{2f^*g}{m_\phi^2}$	$\frac{fg}{m_\phi^2}$	$\frac{\|f\|^2}{m_\phi^2}$	$\frac{\|g\|^2}{m_\phi^2}$	$\frac{f\mu_{\phi H}}{m_\phi^2}$	$\frac{g\mu_{\phi H}}{m_\phi^2}$
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: Dirac ν (A2a); $m_N \neq 0$ (A2b); $\mu_\sigma^2 \neq 0$ (A2c)

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

III- Phenomenology

Models' features

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

Dirac ν

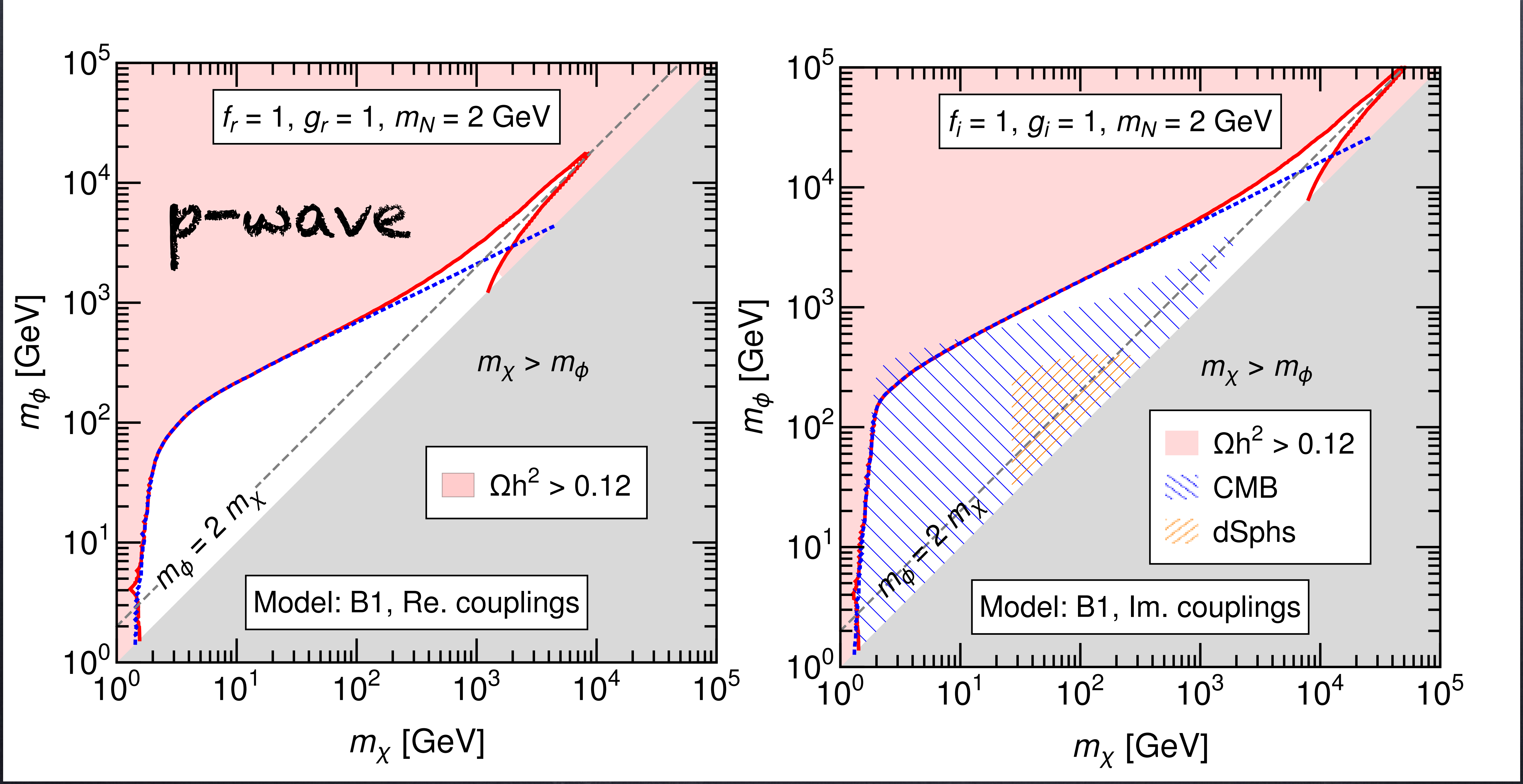
$m_N \neq 0$

$m_N \neq 0$ loop

Genuine Non-genuine

Model B1

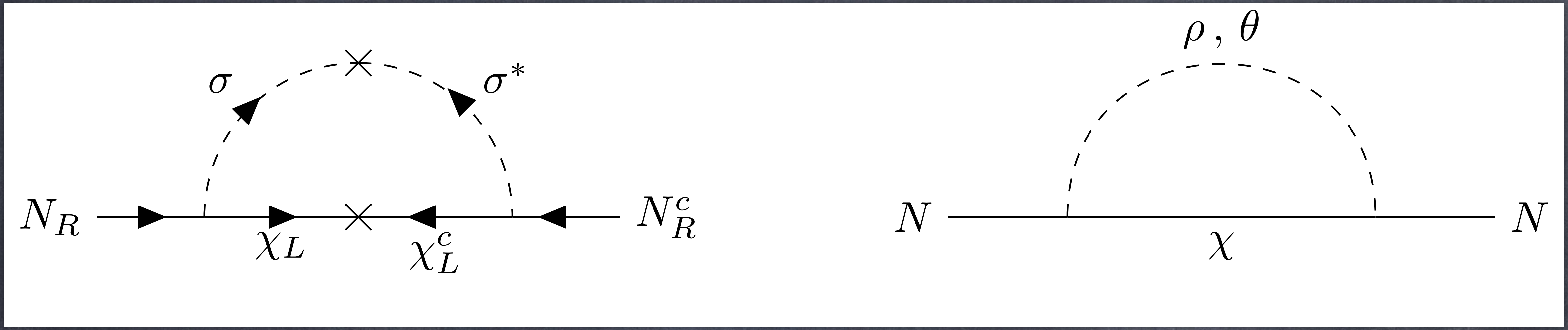
$$\mathscr{L}_{\rm A2c} \supset -f\overline{N_R^c}N_R\phi - g\overline{\chi_L^c}\chi_L\phi + \text{H.c.}\,.$$



ID limits, Batell 2017

Model A2c: $m_N = 0$

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



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

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

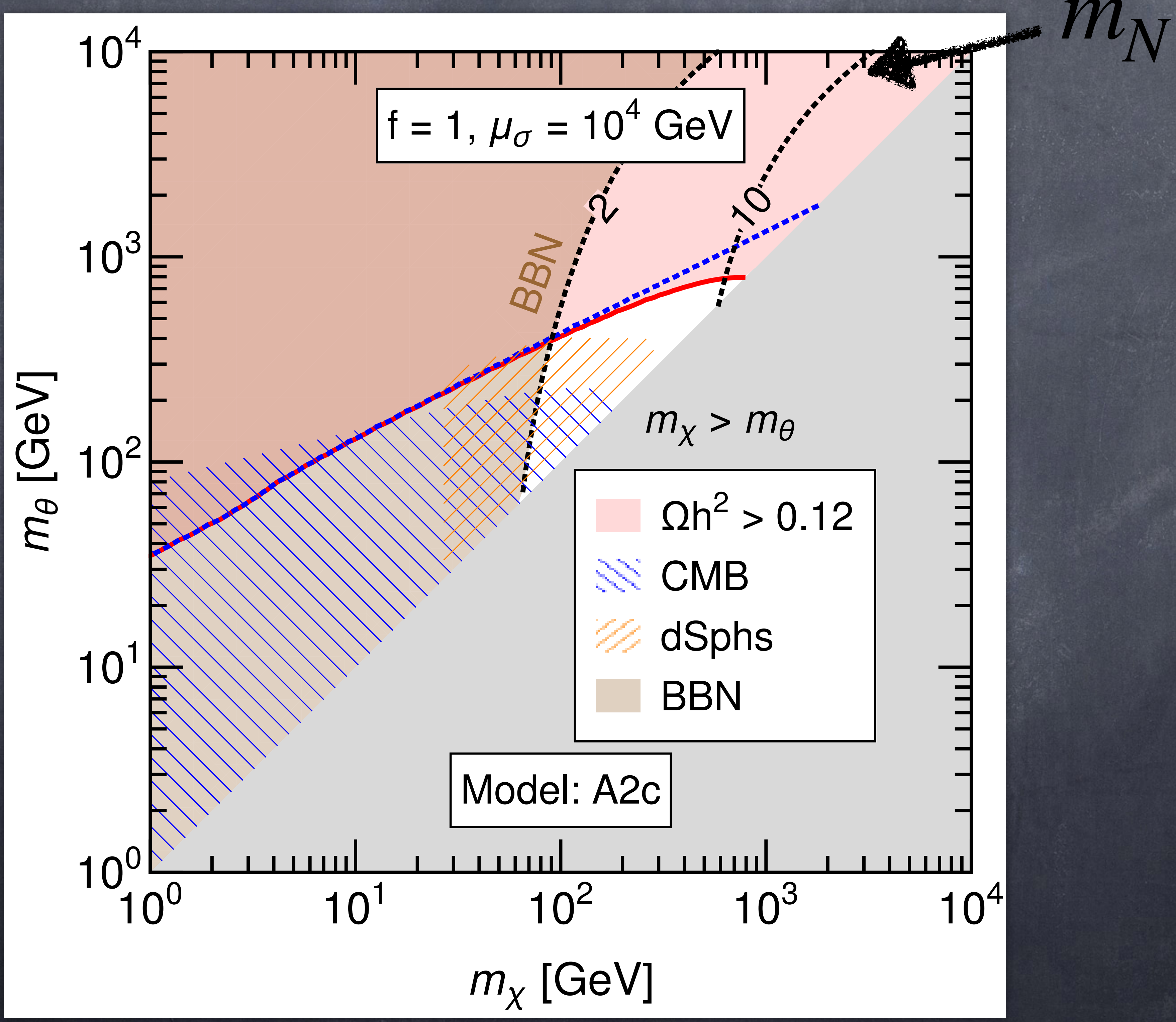
Need $n_\chi \geq 2$

Casas-Ibarra generalisation:

$$n_\chi = n_N = 1$$

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

Model A2c



m_N
f = 1, μ_σ = 10^4 GeV
BBN
2
10
$m_\chi > m_\theta$
$\Omega h^2 > 0.12$
CMB
dSphs
BBN
Model: A2c
m_θ [GeV]
m_χ [GeV]
10^0
10^1
10^2
10^3
10^4

IV- Conclusions

Conclusions

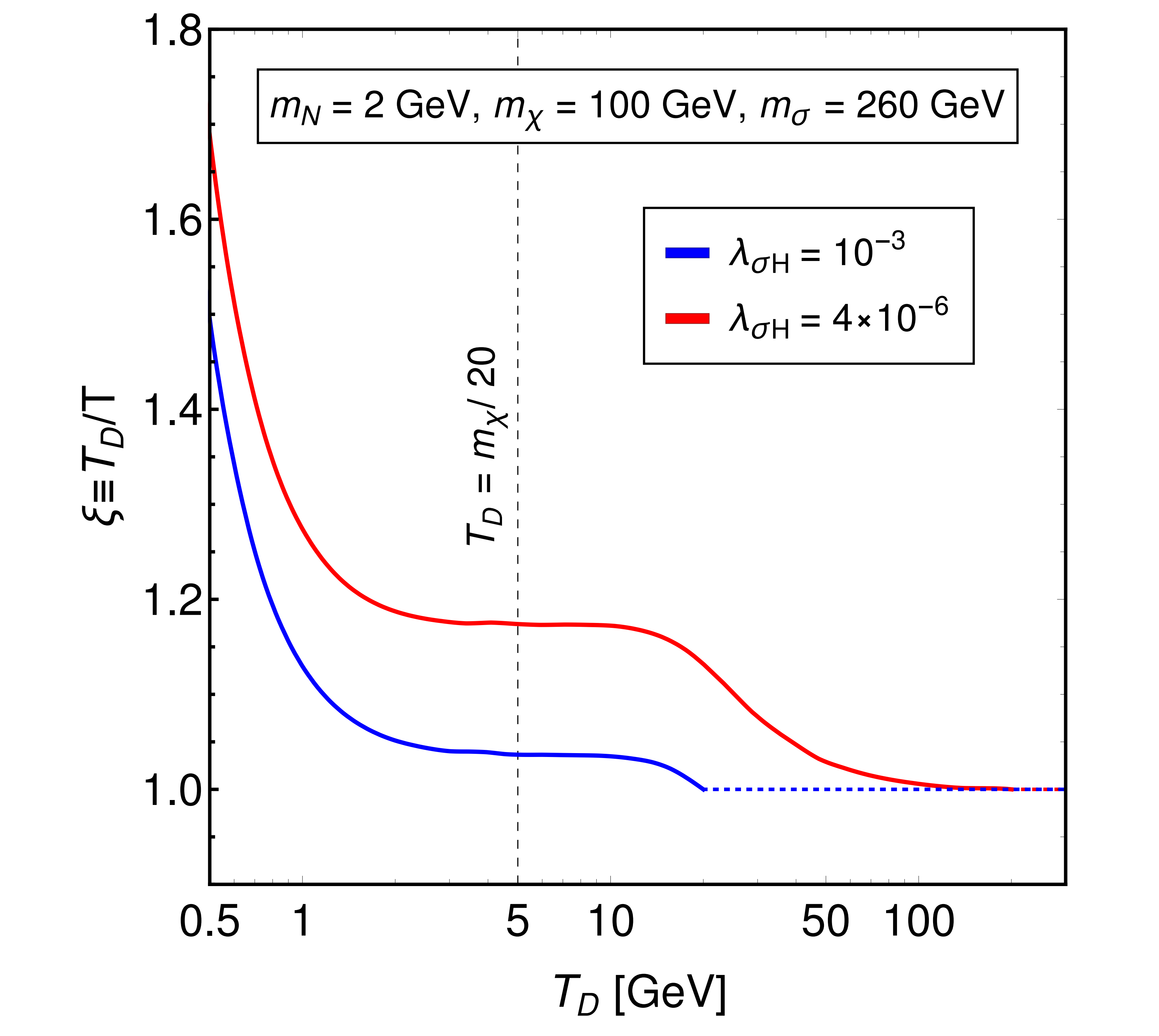
- WIMPs still one of the best motivated DM candidates.
- If coupled to SM only via N_R, they evade most limits. Connection to m_ν.
- Genuine models involve $t-$channel mediators, with new Z_2-odd scalars, that are early on in kinetic eq. with SM.
- For Dirac ν, $p-$wave and light thermal DM are possible.
- For Majorana ν, m_N may be generated at 1 loop.


"WIMPs...
It is now or never...
Aint gonna live forever..."
Merci!

BACK-UP

DS temperature T_D

[Berlin 2016]



Could N be long-lived enough to create a period of MD?

- For the mixings and masses of N that reproduce m_ν, even if N is relativistic at f.o., it decays soon (and before BBN) [Berlin 2016]
- Therefore, it never dominates ρ_U.
- And there is no entropy injection after fo.