Fermionic FIMP dark matter models providing low-scale leptogenesis

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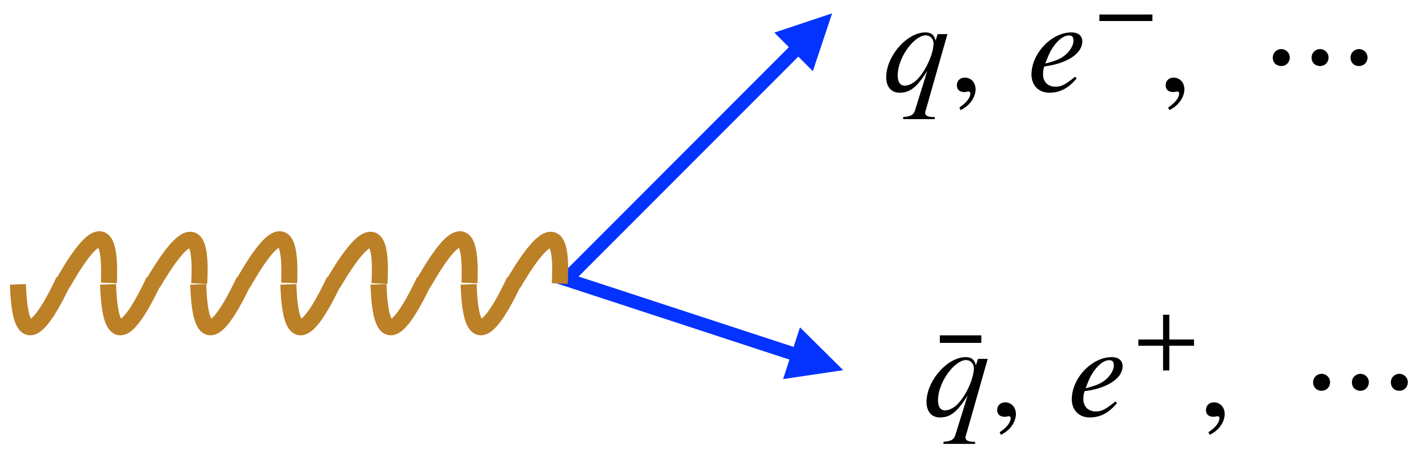
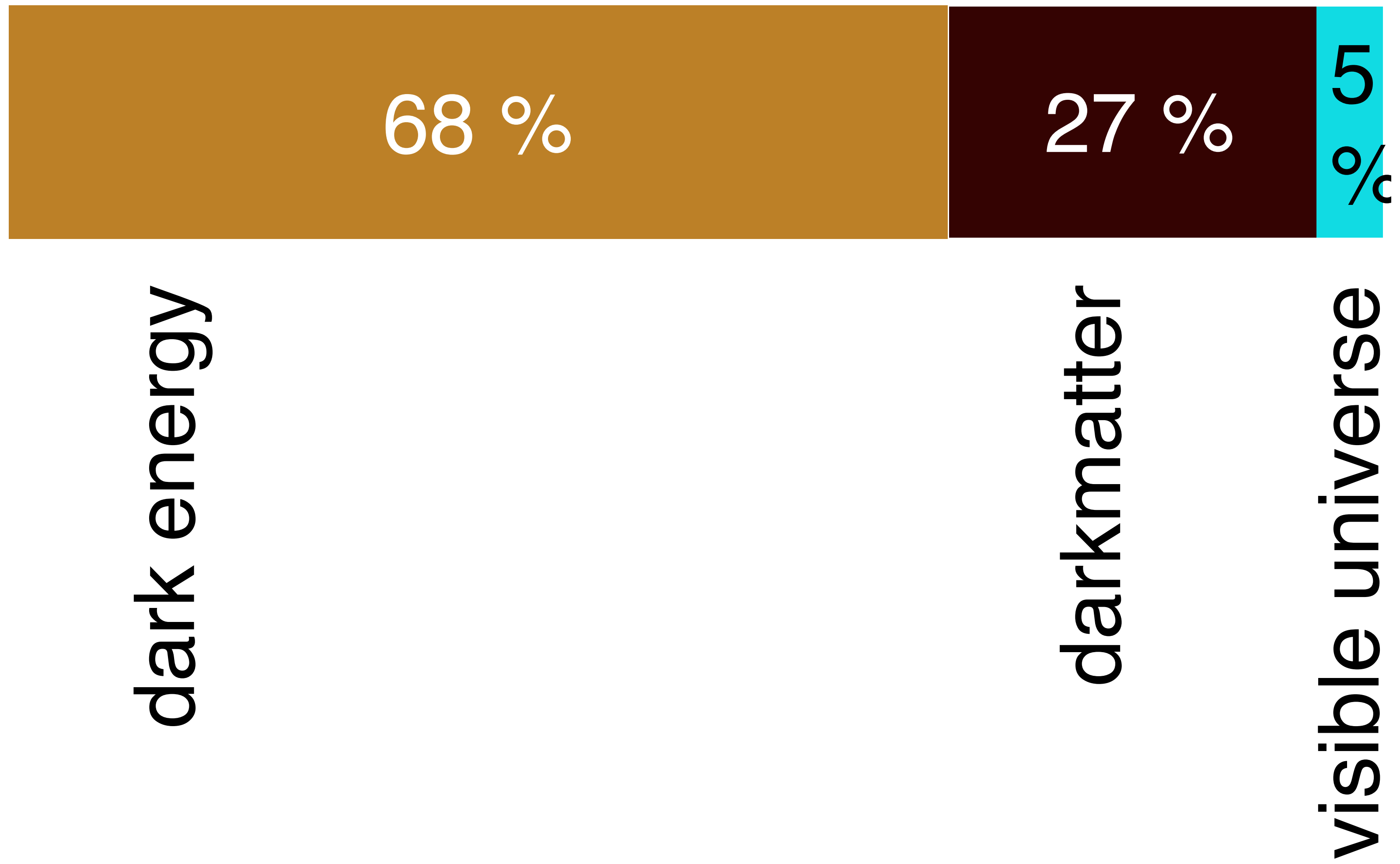
Baryon Asymmetry of the Universe

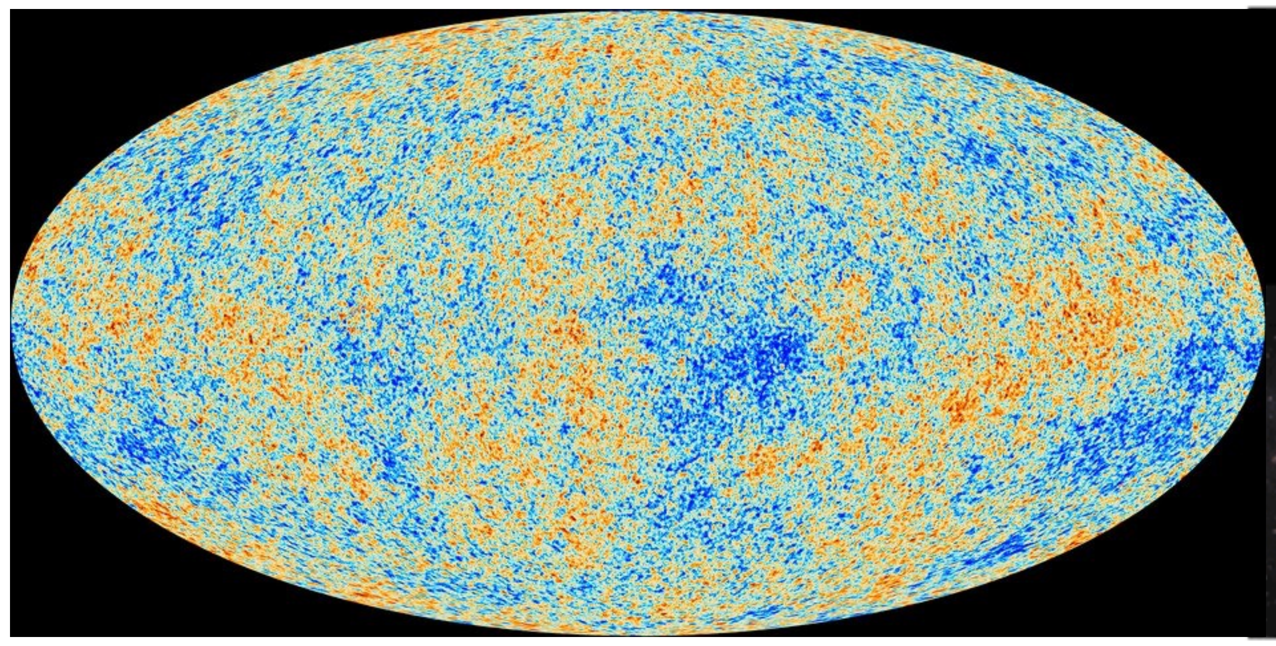


Matter was created in pairs
of particles and antiparticles

But the observable universe
is made of particles, not antiparticles

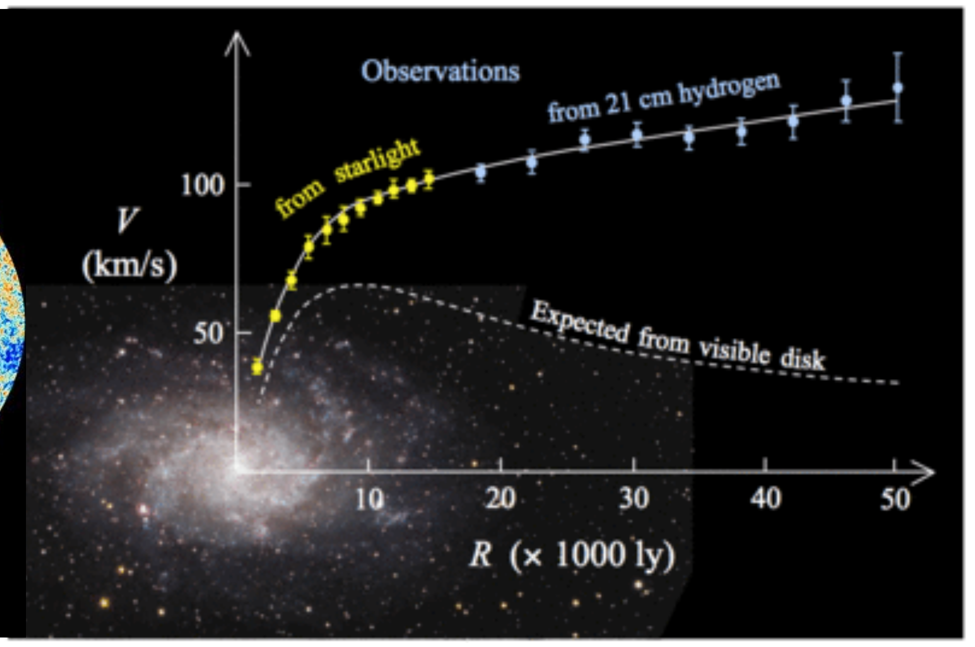
Darkmatter





Anisotropy of CMBR

PLANCK mission



Rotational velocity curve
of galaxies

Recombination and decoupling of photons

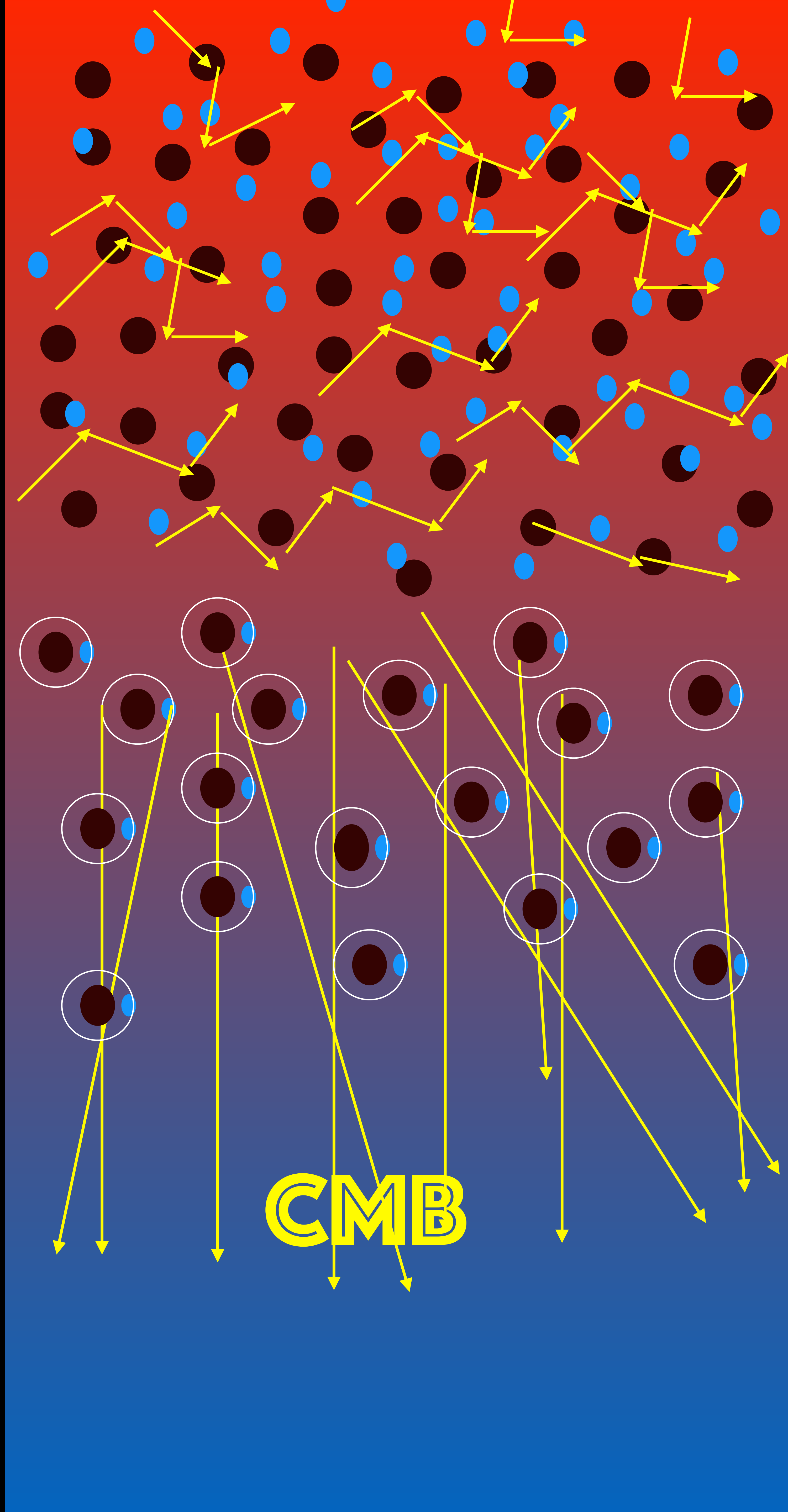
About 400 000 years into the evolution of the universe:

electrons bound to protons to form hydrogen

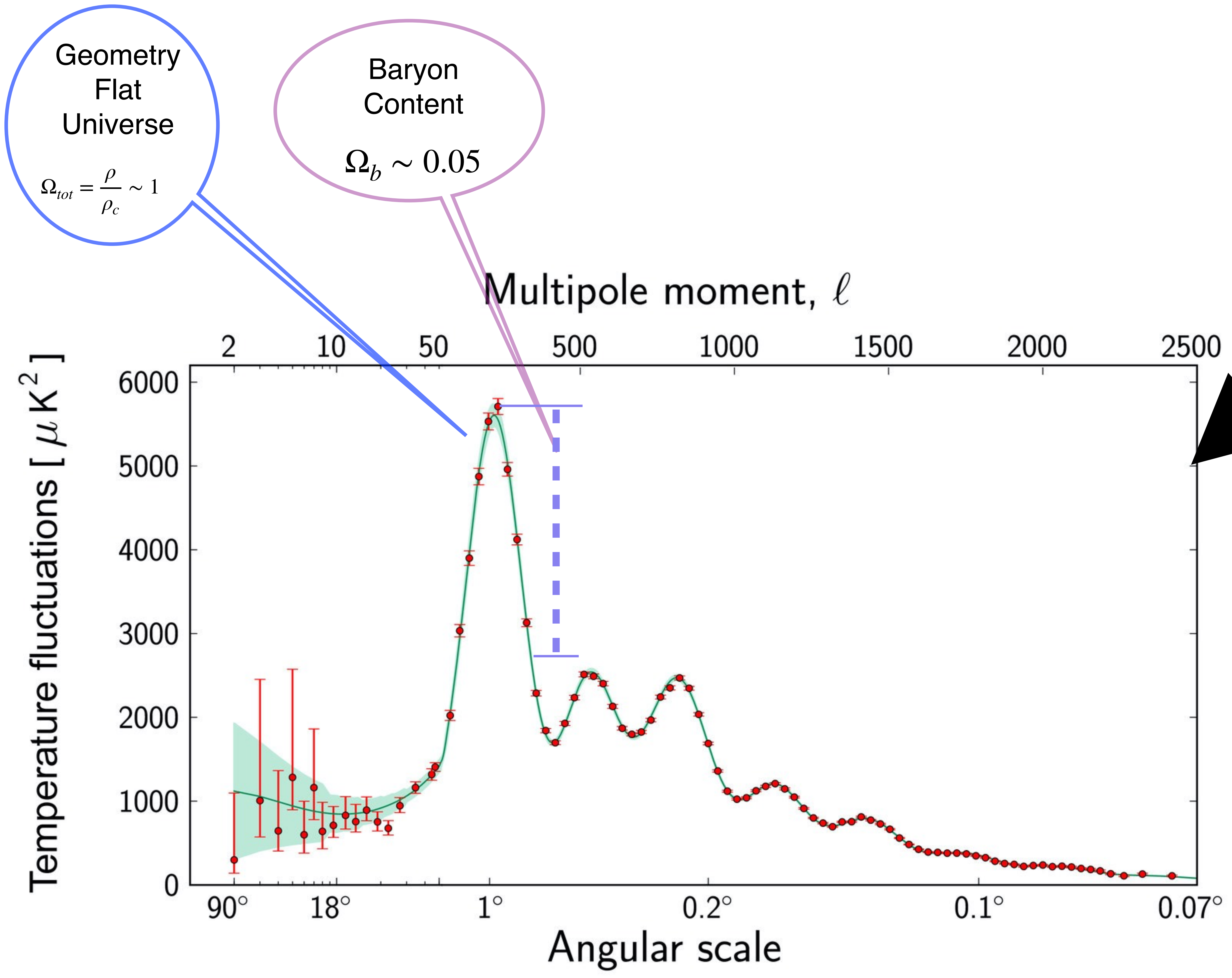
The universe becomes transparent.
Photons do not interact with atoms, rather, propagate freely:

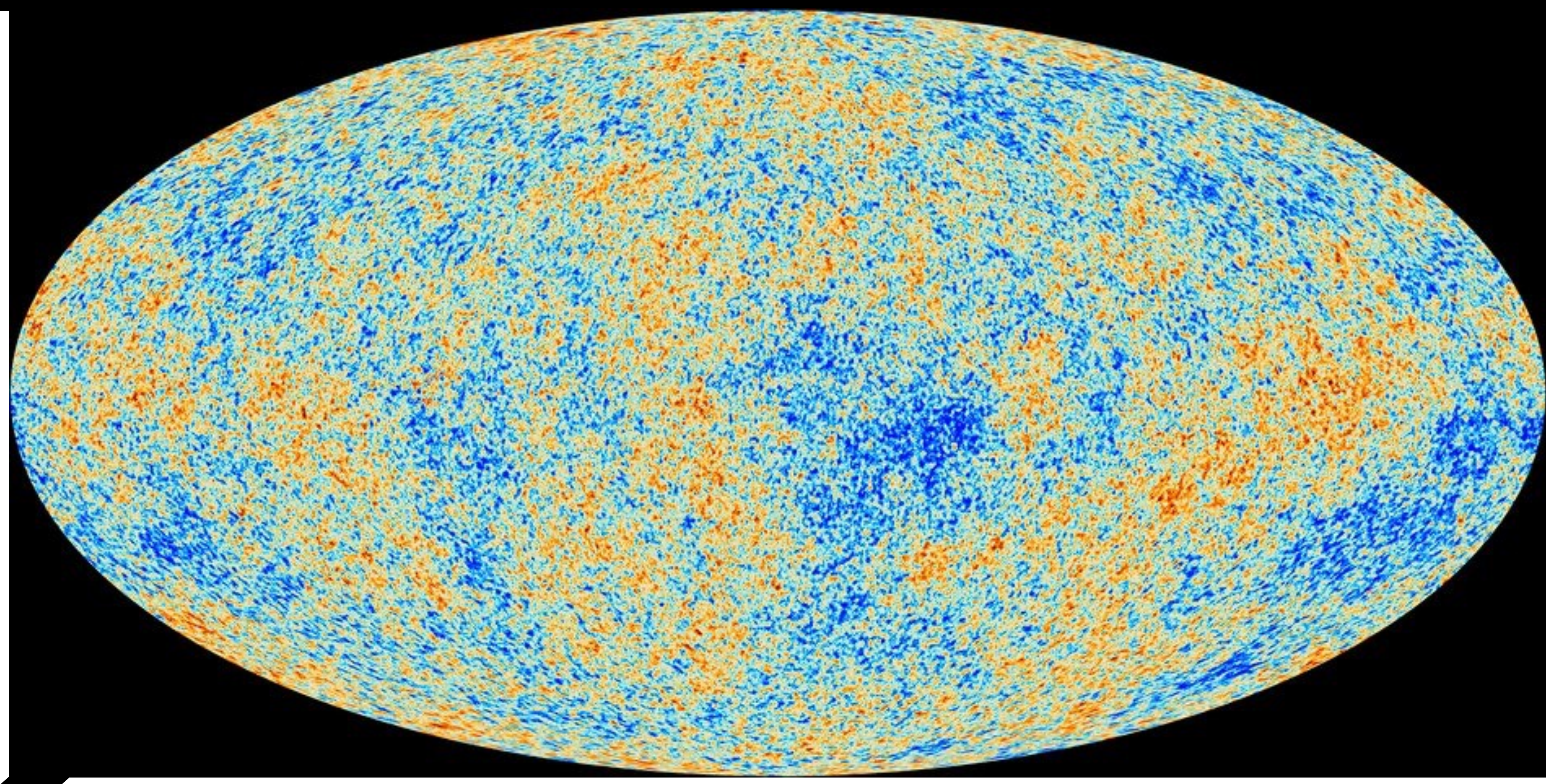
The Cosmic Microwave Background

Interaction of photons in the plasma would leave signatures in the CMBR.



CMBR Anisotropy





Anisotropy of CMBR

$$\Delta T = \sum_{\ell,m} a_{\ell m} Y_\ell^m(\theta, \phi)$$

Power spectrum

baryons - # antibaryons

Non-zero baryon content: $n_B = n_b - n_{\bar{b}}$

Baryon asymmetry

$$\Omega = \frac{\rho}{\rho_{critical}}$$

$$\rho_{critical} = 8 \times 10^{-10} \quad \text{kg m}^{-1}\text{s}^{-2}$$

$$\rho_b = \Omega_b \, \rho_{critical}$$

$$\Omega_b = 0.05 \quad \Longrightarrow \quad \rho_b = 4 \times 10^{-11} \quad \text{kg m}^{-1}\text{s}^{-2}$$

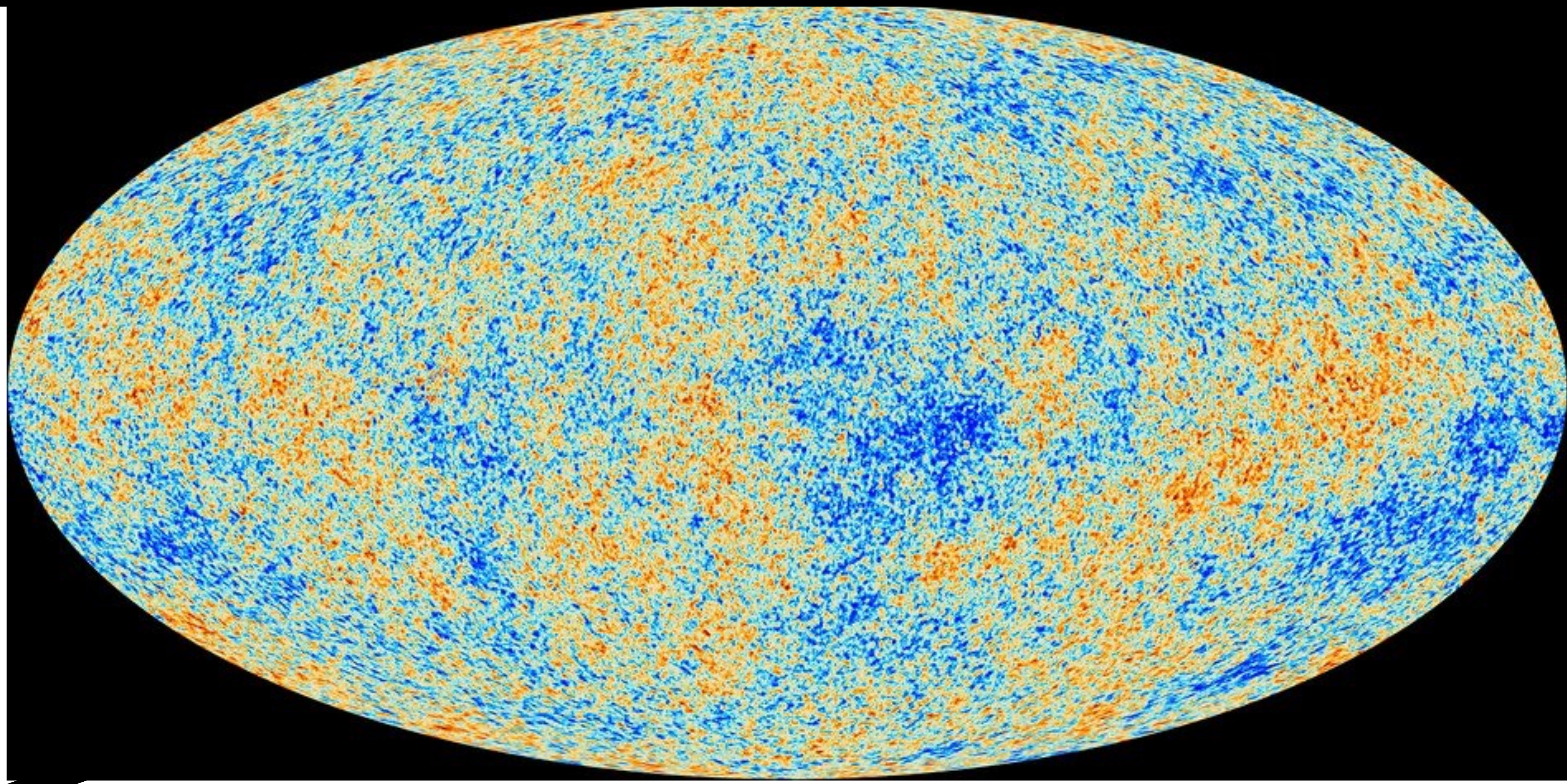
$\Longrightarrow$ Baryon number density, $n_B = \frac{\rho_b}{m_p c^2} \approx 0.03 \ \text{m}^{-3}$

Also, for $T_{CMB} = 2.726 \quad K$, photon number density, $n_\gamma \approx 4 \times 10^8 \quad \text{m}^{-3}$

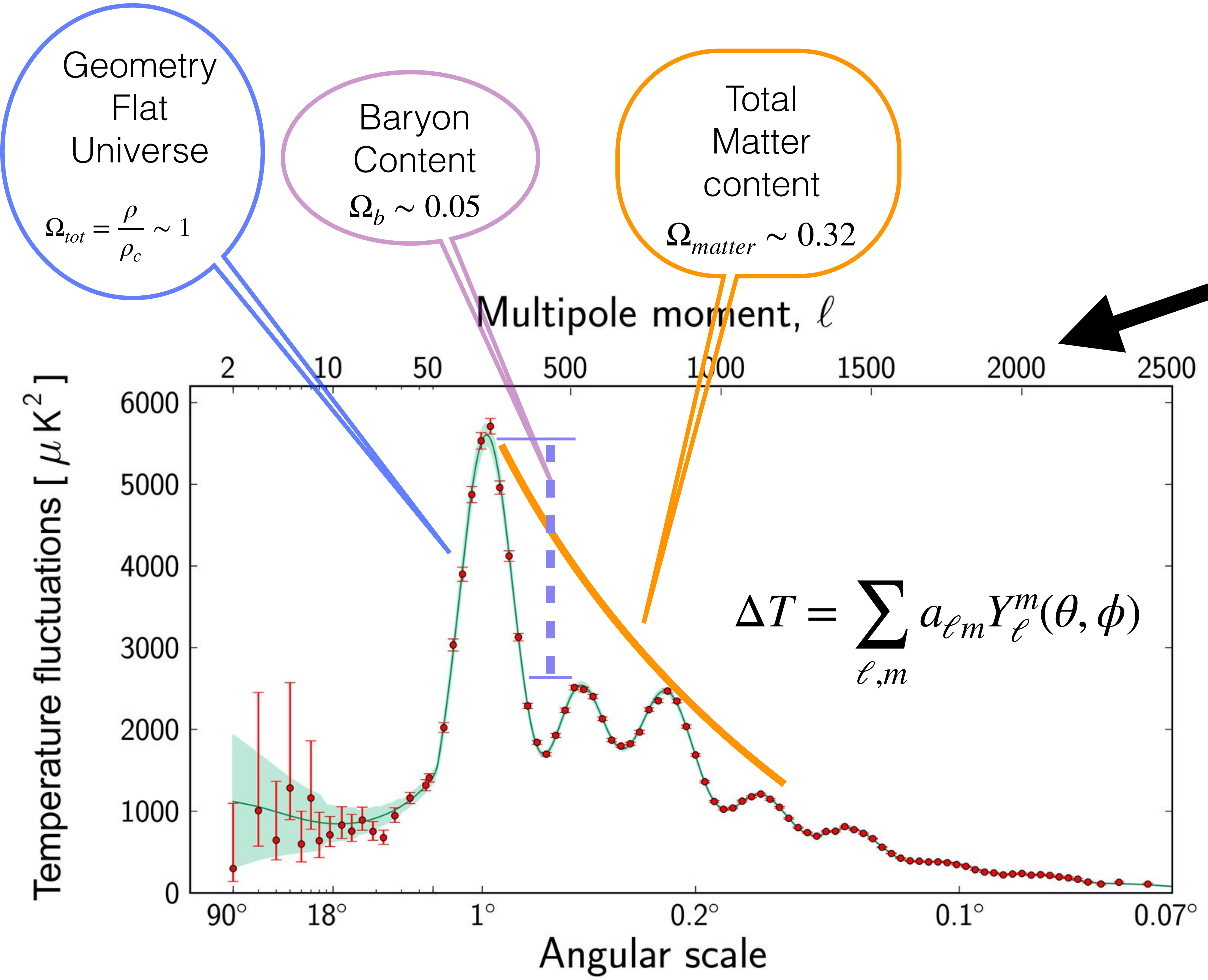
Baryon to photon number density $\eta_B = \frac{n_B}{n_\gamma} \approx 10^{-10}$

Darkmatter

27% of the total energy content of the Universe is darkmatter, as against 5% accounts for visible matter



Anisotropy of CMBR



Total matter content, 32 %
Baryonic (visible) matter, 5%
Darkmatter, 27%

Standard way of quoting the darkmatter relic density:

$$\Omega_{DM} h^2 = 0.27 \times 0.665^2 = 0.119$$

$H = h\ 100\ (\mathrm{km/s})/\mathrm{Mpc}$ Hubble constant

Darkmatter - perspective of particle physics

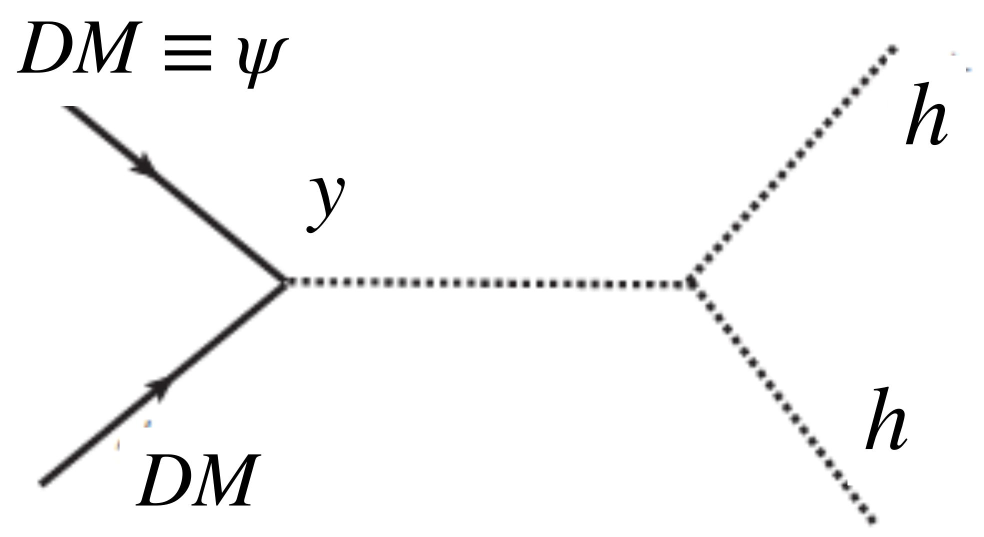
Assuming that the DM is a new elementary particle,

To get the right value of $\Omega_{DM}h^2 = 0.119,$ the following possibility can be considered.

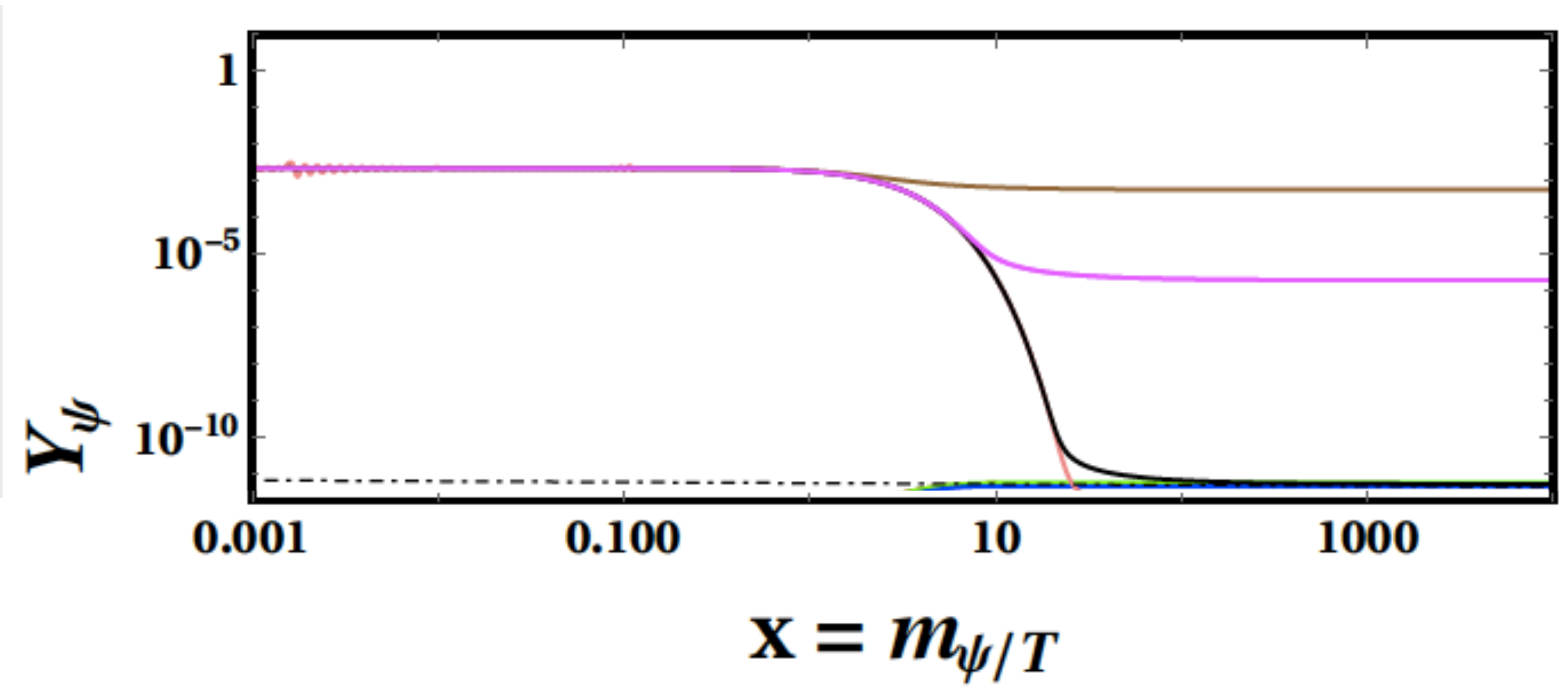
DM particles in thermal equilibrium in the early universe: $DM\,.\,DM \leftrightarrow SM\,.\,SM$

As the universe expands and cools, it goes out of equilibrium around $T \sim M$

Further, expansion of the universe with $\langle \sigma v \rangle \sim H$, the Hubble constant, the co-moving density of the DM particle remains the same: the relic density.



The cross section, σ depends on the mass of DM and its coupling with the SM sector.



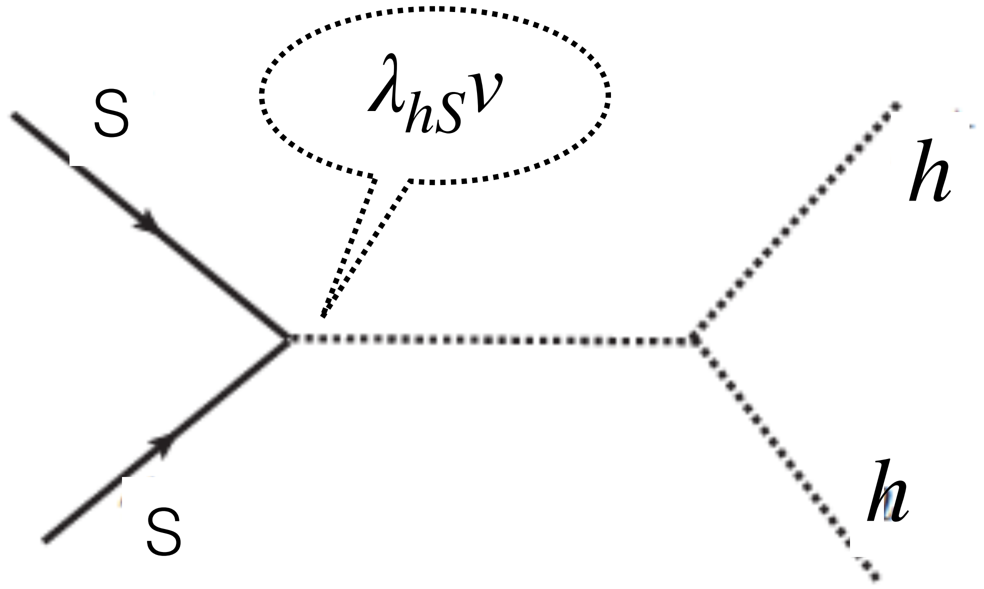
$$Y_\psi = \frac{n_\psi}{s}$$

It turns out that $M \sim$ GeV $-$ TeV with weak coupling $y \sim 0.01$ gives the right relic density.

This is the so-called WIMP miracle

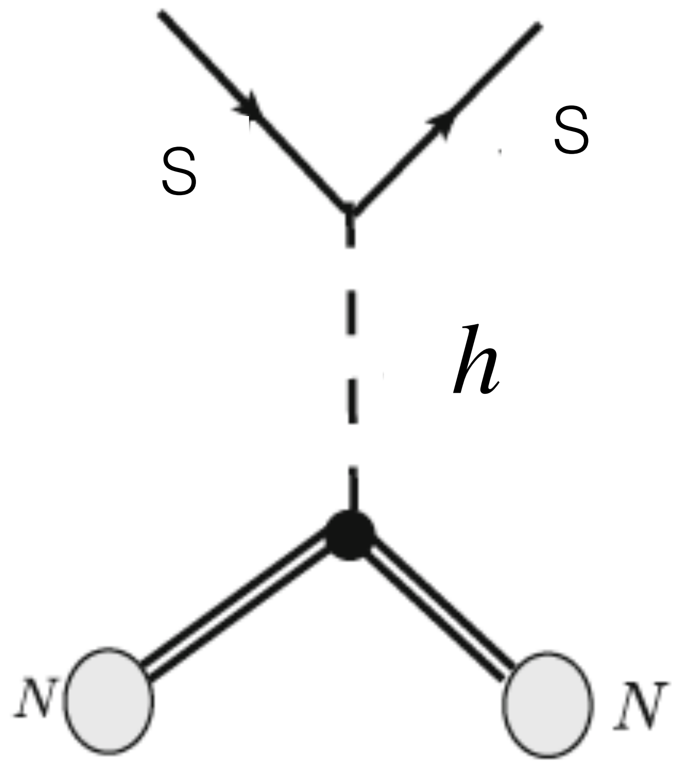
Darkmatter - WIMP examples

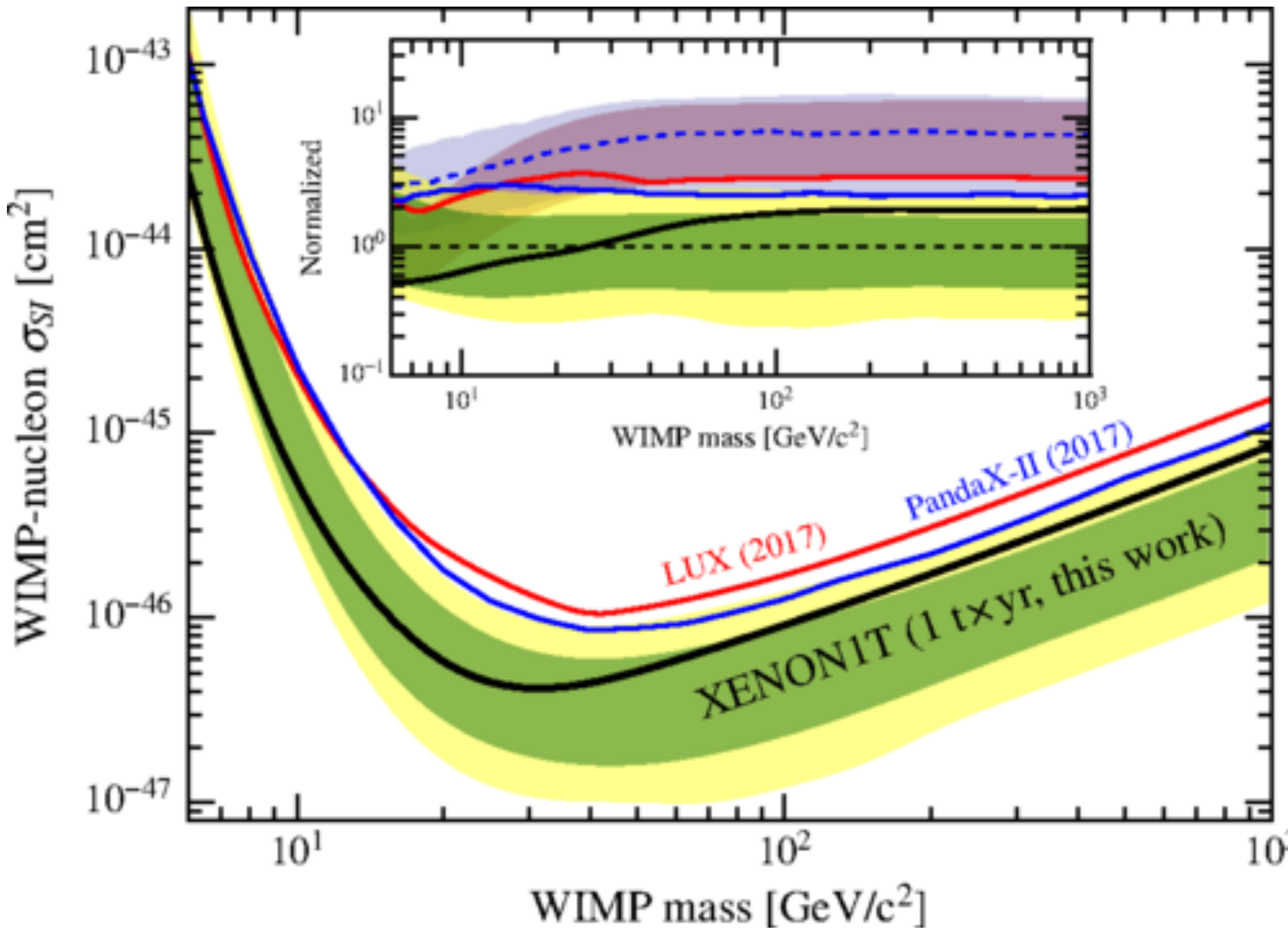
Singlet extensions of the SM. $\mathscr{L} = \mathscr{L}_{SM} + \mu^2 S^2 + \lambda_{hS} S^2 \phi^\dagger \phi + \lambda_S S^4$



Stability of the DM is ensured by a discrete parity symmetry (Z_2) under which S is odd while all other particles are even. ϕ is the SM Higgs

Direct detection reaction $S.N \rightarrow S.N$
is also governed by the same coupling.





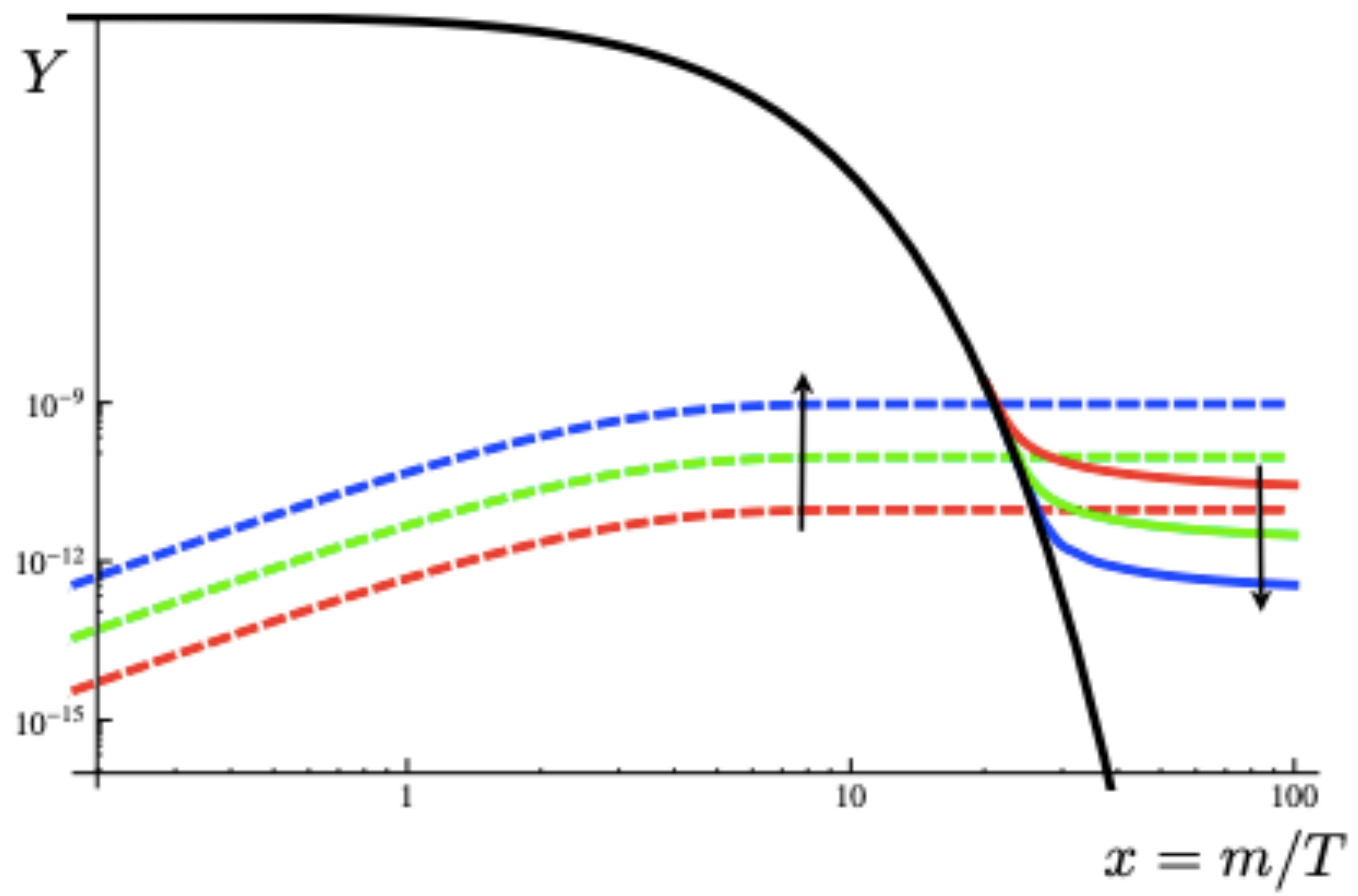
From the direct detection experiments, the couplings are so constrained, that it is very difficult to have the annihilation cross section sufficient to get the right relic density.

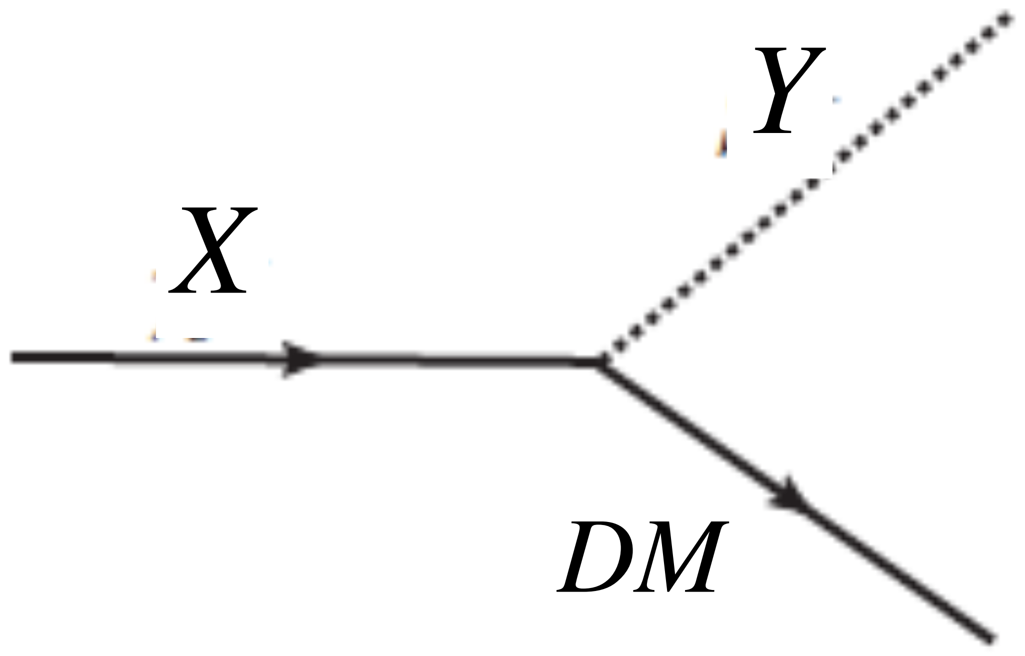
Phys. Rev. Let, 121 (2018) 111302

FIMP Darkmatter

An attractive alternative is to consider the Feebly Interacting Massive Particle (FIMP) darkmatter

DM density in the early universe was negligible or zero. It is built through its slow production via (most of the time) decay of a partner particle.





Direct detection experiments are irrelevant in these cases, and therefore unaffected by the constraints from there.

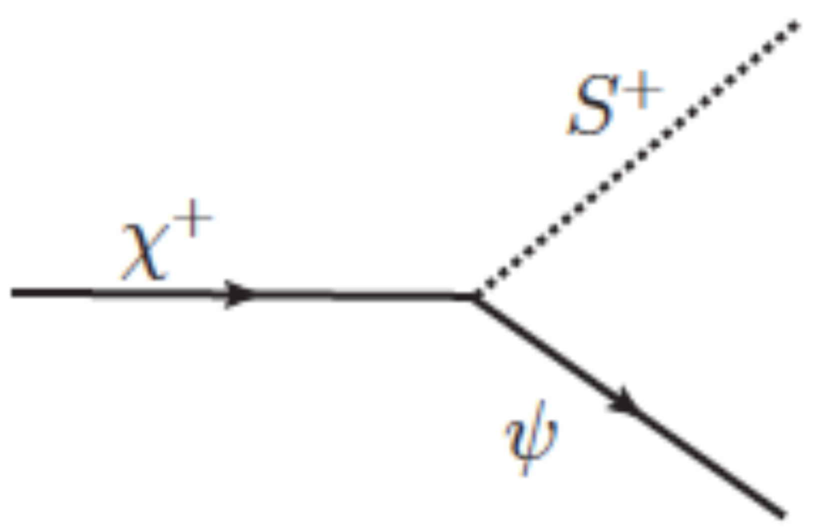
L. J. Hall, K. Jedamzik, J.M-Russell and S.M.West, JHEP03(2010)080

A specific model

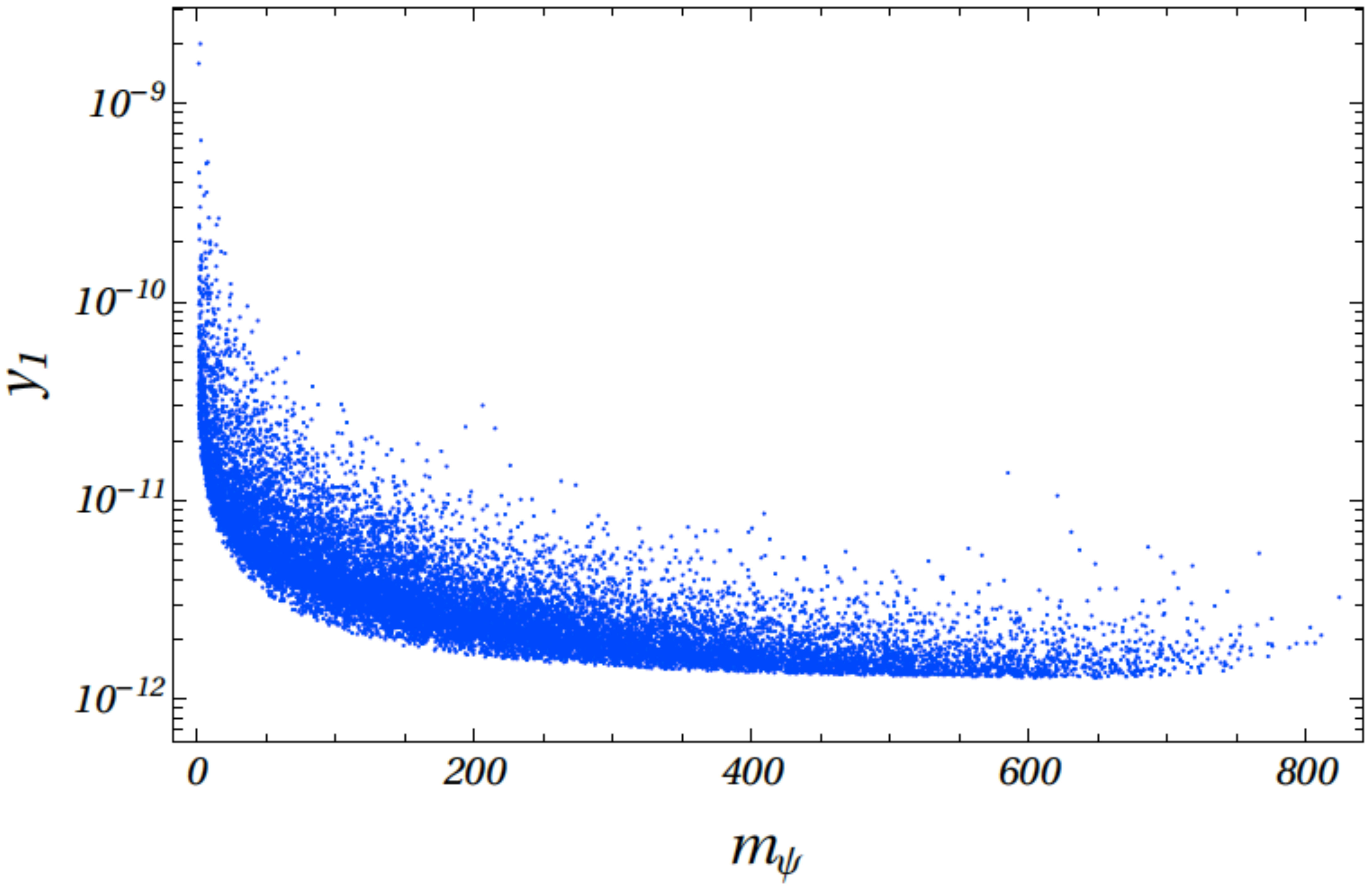
$$\mathcal{L}_m = \mathcal{L}_{SM} + (D_\mu S)^\dagger D_\mu S + \bar{\chi}\, i\gamma^\mu D_\mu \chi + \bar{\psi}\, i\gamma^\mu \partial_\mu \psi + \sum_i \bar{N}_i\, i\gamma^\mu \partial_\mu N_i - m_\chi \bar{\chi}\chi - m_\psi \bar{\psi}\psi - \sum_{ij} m_{Nij} \bar{N}_i N_j$$
$$- (y_1 \bar{\chi} S \psi + \sum_{ij} y_{2ij} \bar{N}_i S l_j + \sum_{ij} Y_{Nij} \bar{L}_i \tilde{\phi} N_j + h.c) - (\mu_S^2 S^\dagger S + \lambda (S^\dagger S)^2 + \lambda_1 S^\dagger S \phi^\dagger \phi),$$

Additional particles, all $SU(2)_L$ singlets

Fields	Spin	Y	Z_2
S^+	0	+2	+
N_1, N_2,N_3	$\frac{1}{2}$	0	+
χ^+	$\frac{1}{2}$	+2	−
ψ	$\frac{1}{2}$	0	−



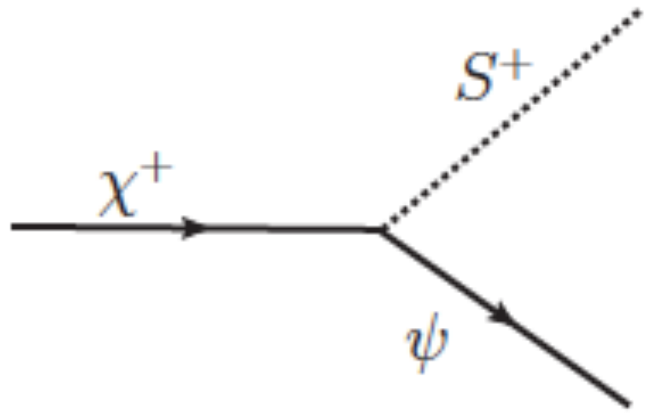
DM production



m_χ, m_S : 150 – 1000 GeV $\qquad m_\chi > m_S + m_\psi$

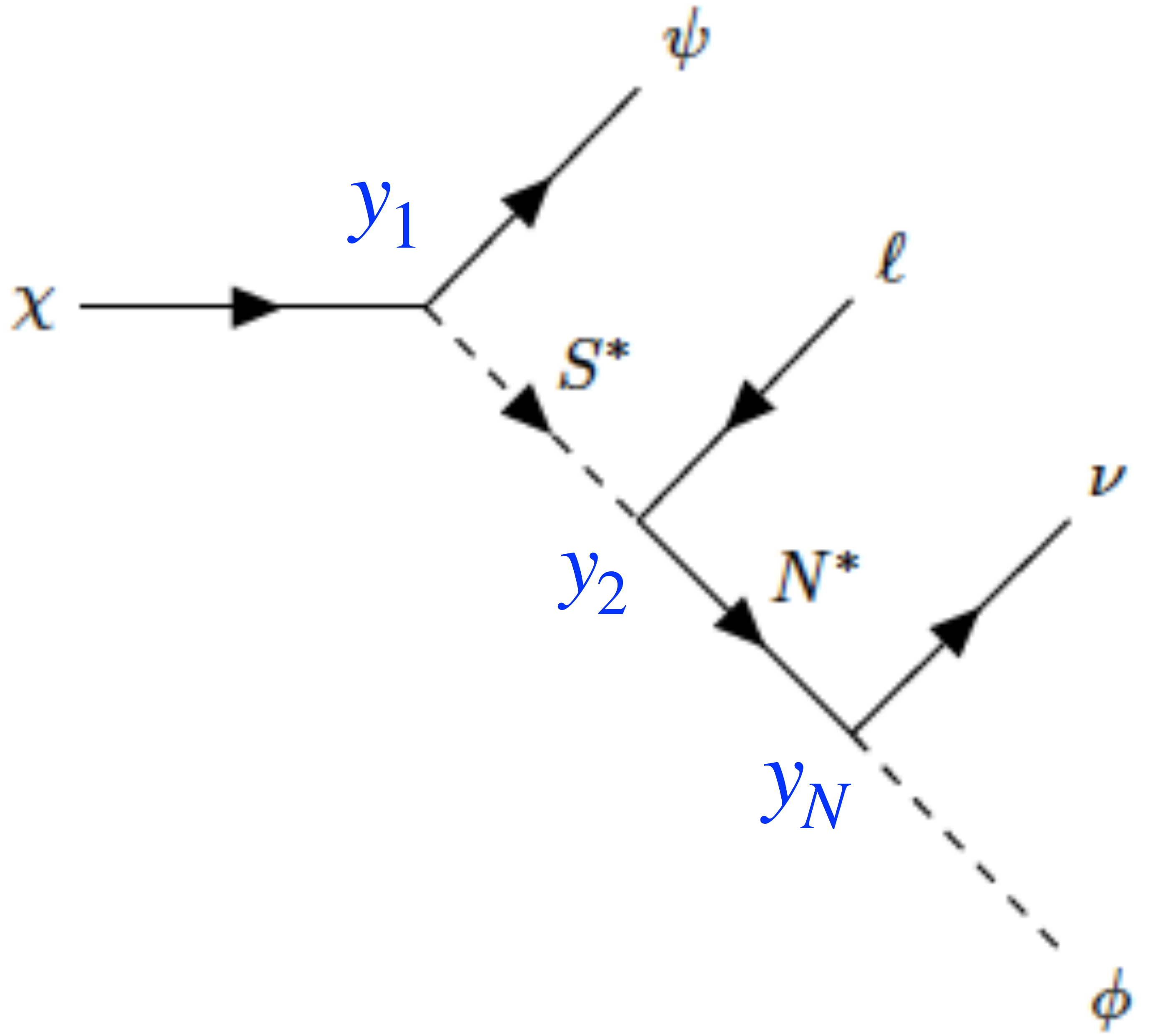
DM through 4-body decay

For $m_\chi < m_S + m_\psi$



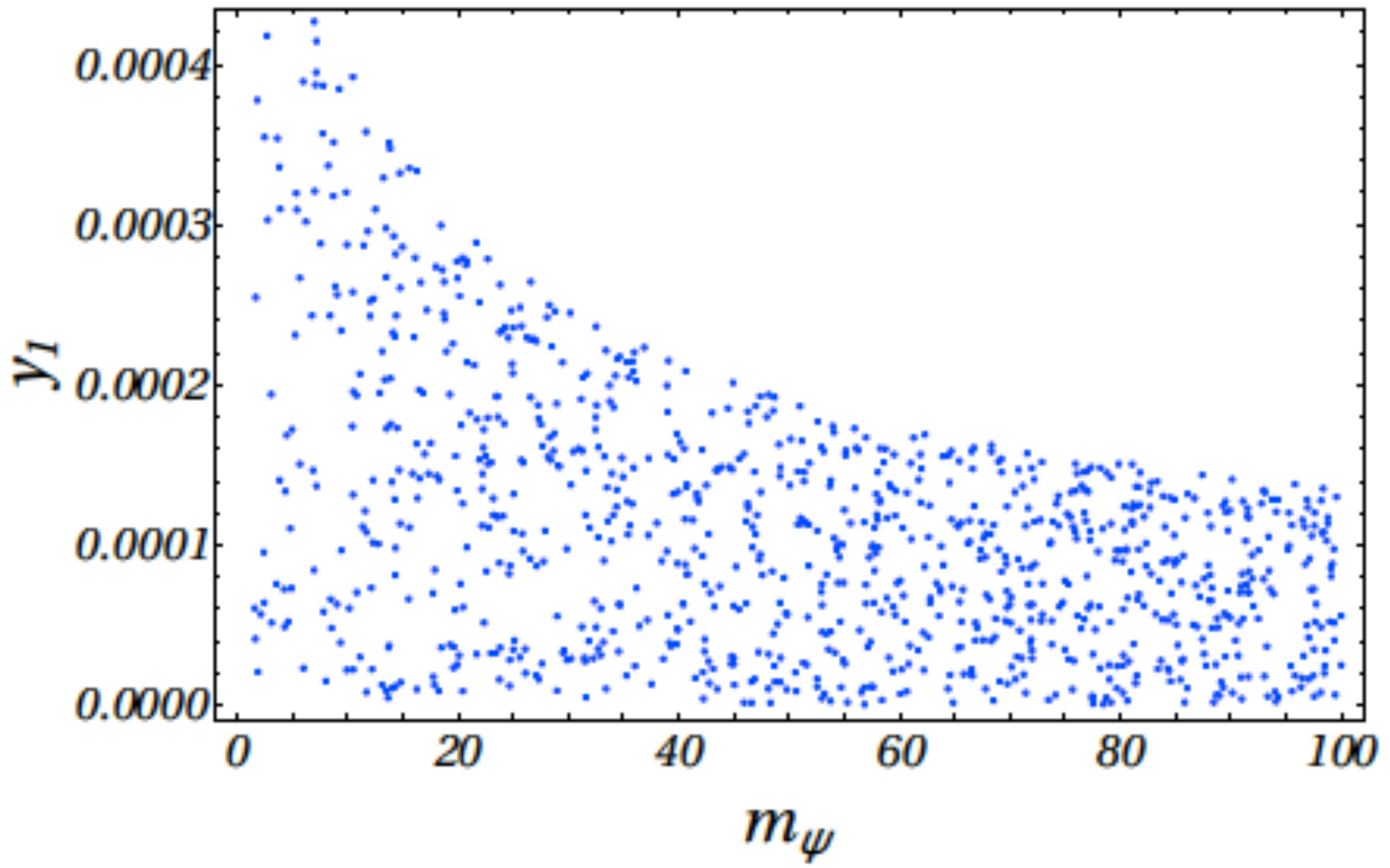
not possible

We can, however consider the 4-body decay,



$m_\chi,\ m_S$: 150 – 1000 GeV $\quad m_\chi < m_S + m_\psi$

All points satisfy the observed DM relic density



For the leptogenesis that we would discuss soon, we consider $m_N > m_S, \quad y_2 \sim 10^{-3} - 10^{-1}$

The model also can generate neutrino mass through Type-I seesaw, for this we have set $m_N \sim 20$ TeV, $y_N \sim 10^{-8}$

Baryon asymmetry through Lepton asymmetry

Sakharov Conditions (1967) to generate baryon asymmetry in the Universe

1. Interactions with Baryon number violation
2. C and CP violation
3. Departure from thermal equilibrium

It was soon realised that it is difficult to achieve this in the SM and in its simple extensions.

Leptogenesis - M. Fukugita and T. Yanagida, Phys. Lett. B 174, 45 (1986).

Generate lepton number asymmetry through lepton number violating processes.
Transfer the lepton number asymmetry to baryon number asymmetry through topological sphaleron processes during the first-order electroweak phase transition.

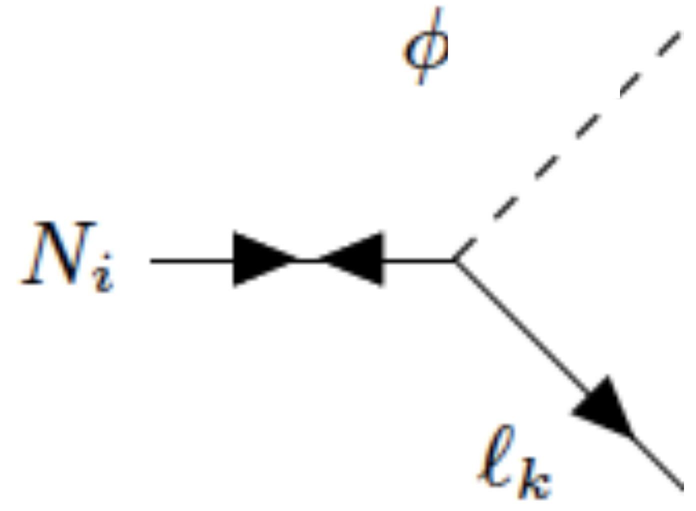
$n_B = C\, n_L$ C being some constant, depending on the number of degrees of freedom present.

Generating lepton number asymmetry in the standard set up

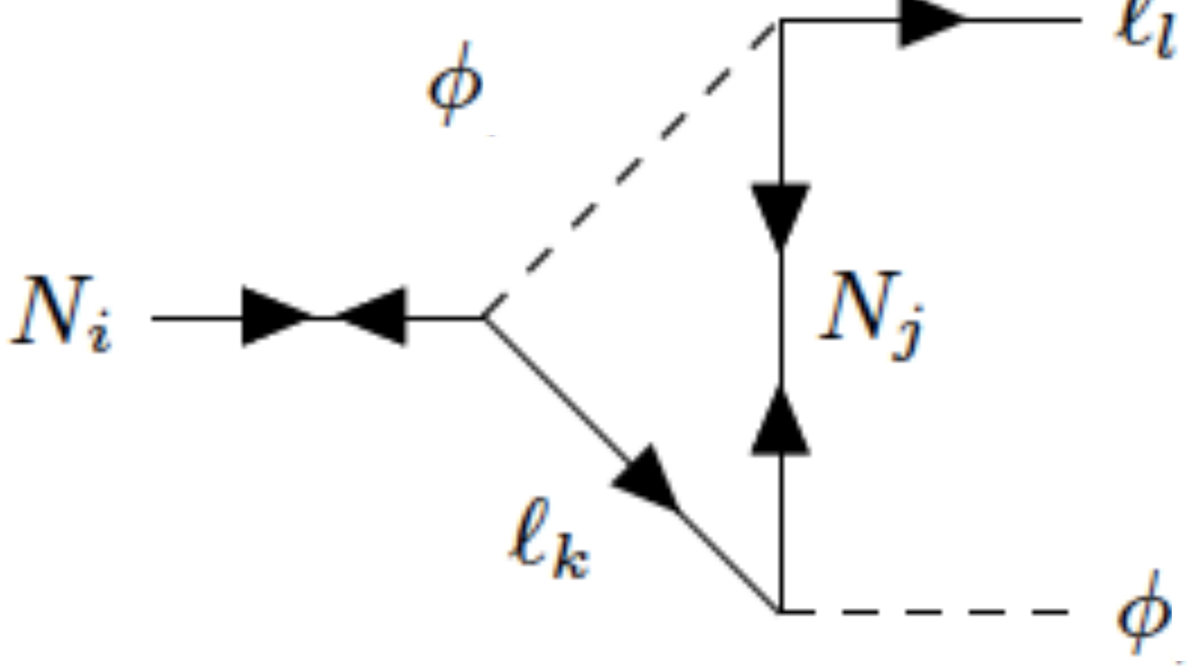
The heavy neutral lepton N being a Majorana fermion leads to lepton number violating decays:

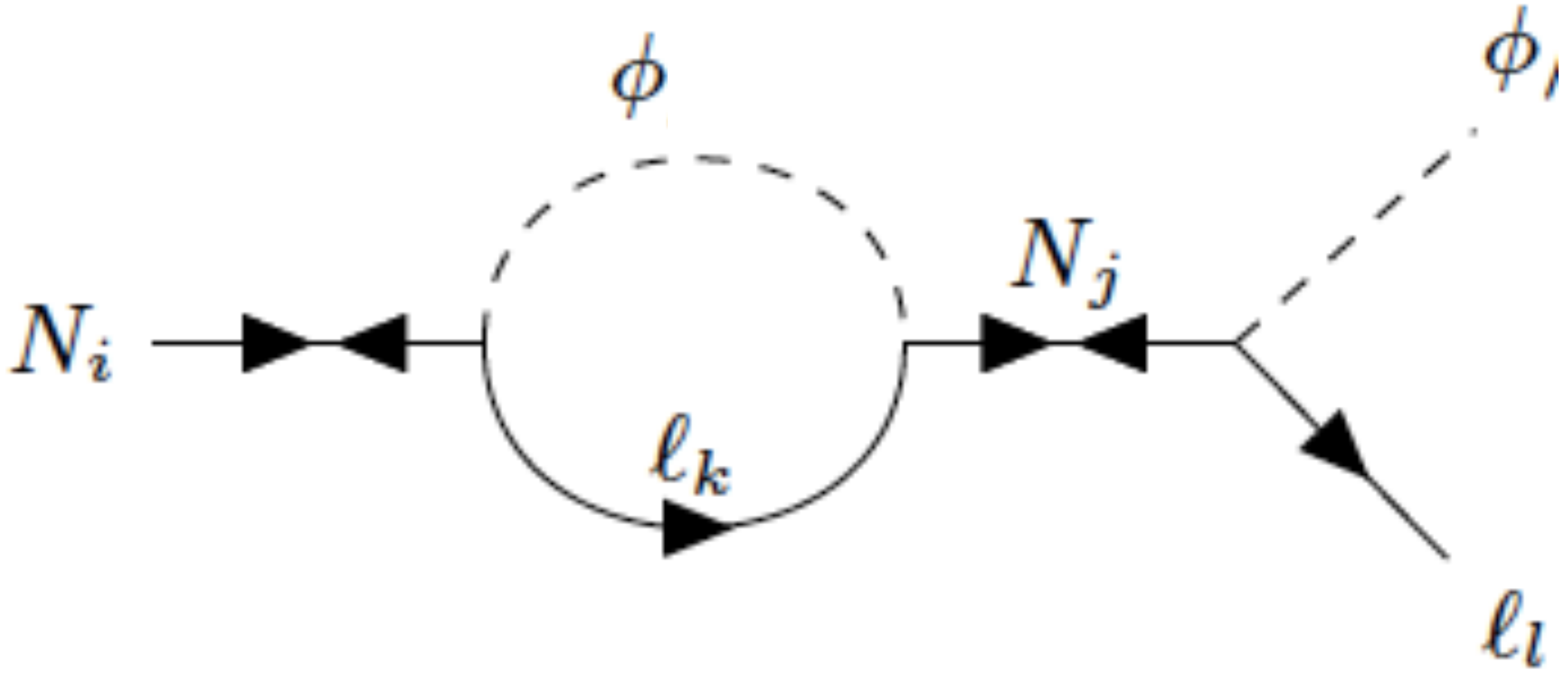
$$N \to \ell\phi, \quad \text{and} \quad N \to \bar{\ell}\bar{\phi},$$

(ϕ being the SM Higgs boson)



CP-violation is generated through the interference between the above tree-level process and the one-loop processes





CP-violation is parameterised as, $$\epsilon_1 = \frac{\Gamma(N_1 \to \ell\phi) - \Gamma(N_1 \to \bar{\ell}\bar{\phi})}{\Gamma(N_1 \to \ell\phi) + \Gamma(N_1 \to \bar{\ell}\bar{\phi})}$$

Generating lepton number asymmetry in the standard set up

Lepton number asymmetry: $$Y_L = Y_\ell - Y_{\bar{\ell}} = \frac{n_\ell - n_{\bar{\ell}}}{s}$$ s : entropy density

Thermal evolution (Boltzmann equation): $$Hsz\,\frac{dY_L}{dz} = \epsilon_1 \,\langle \Gamma(N_1 \to \ell\phi)\rangle$$

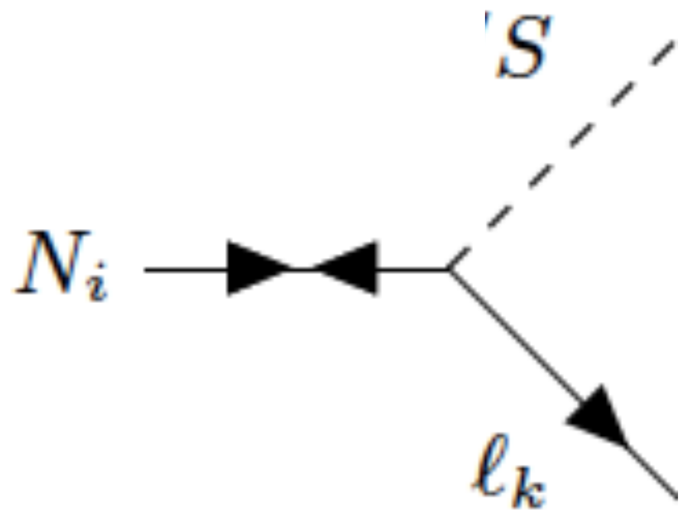
$z = \frac{M_{N_1}}{T}$, with T asTemperature; $\langle \Gamma(N_1 \to \ell\phi)\rangle$: thermal averaged decay rate

Details show that with the above standard leptogenesis process, the heavy neutrino is required to be very heavy ($m_{N_1} \sim 10^9$ GeV) to get the observed baryon asymmetry.

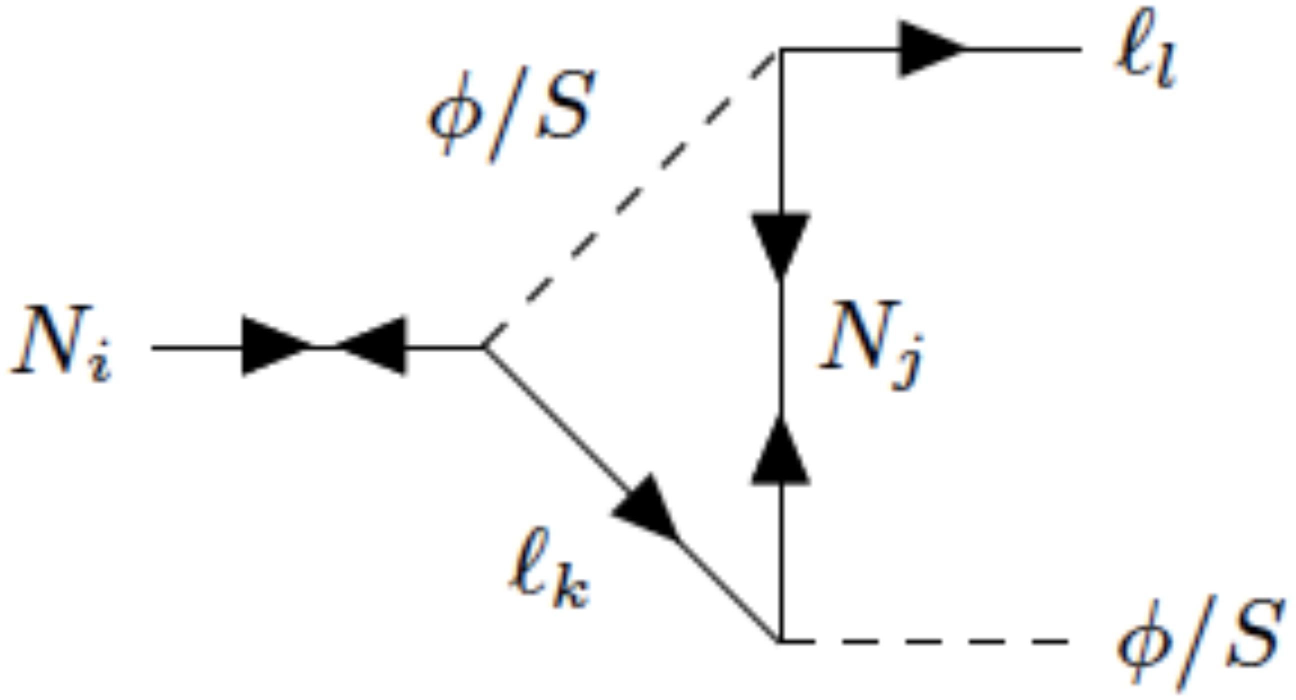
Generating lepton number asymmetry in the present set up

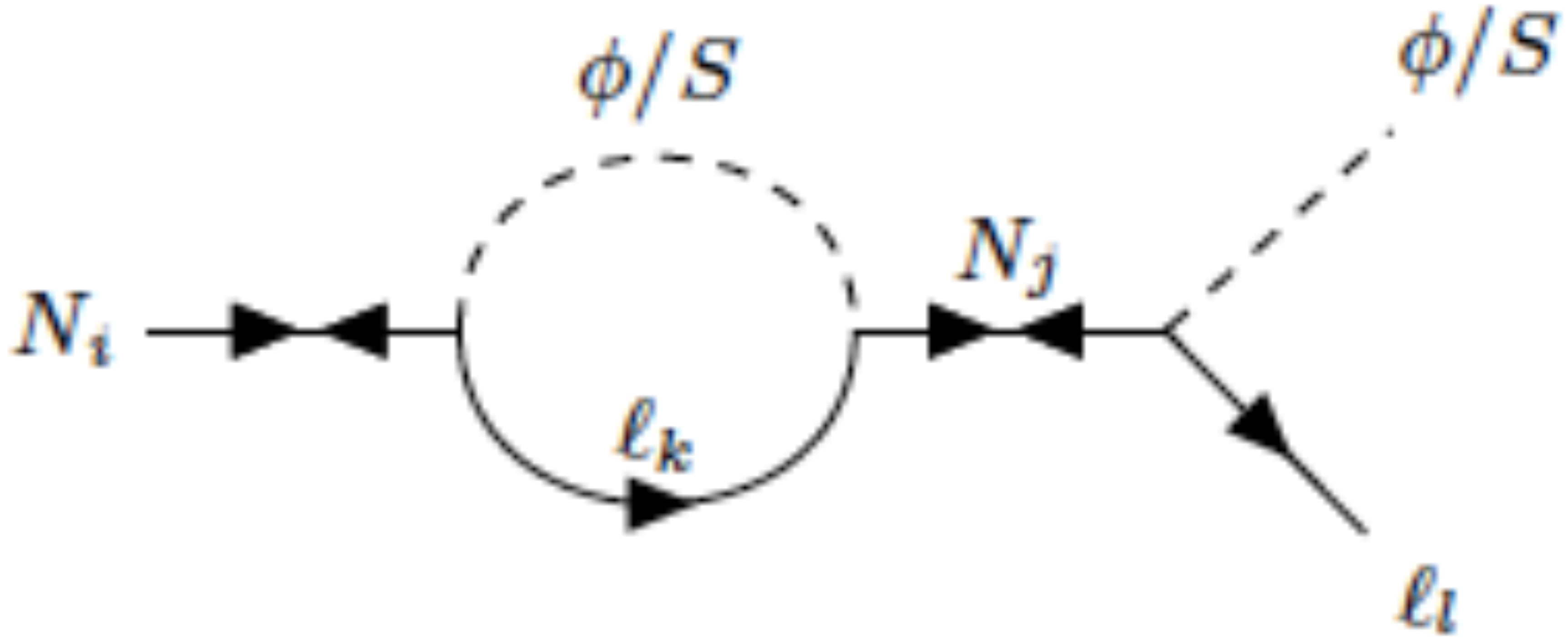
In the present set up, we have an additional interaction for the heavy N, leading to

$$N \to \ell S^+, \qquad \text{and} \qquad N \to \bar{\ell} S^-,$$



And the one-loop processes get additional contributions as well:





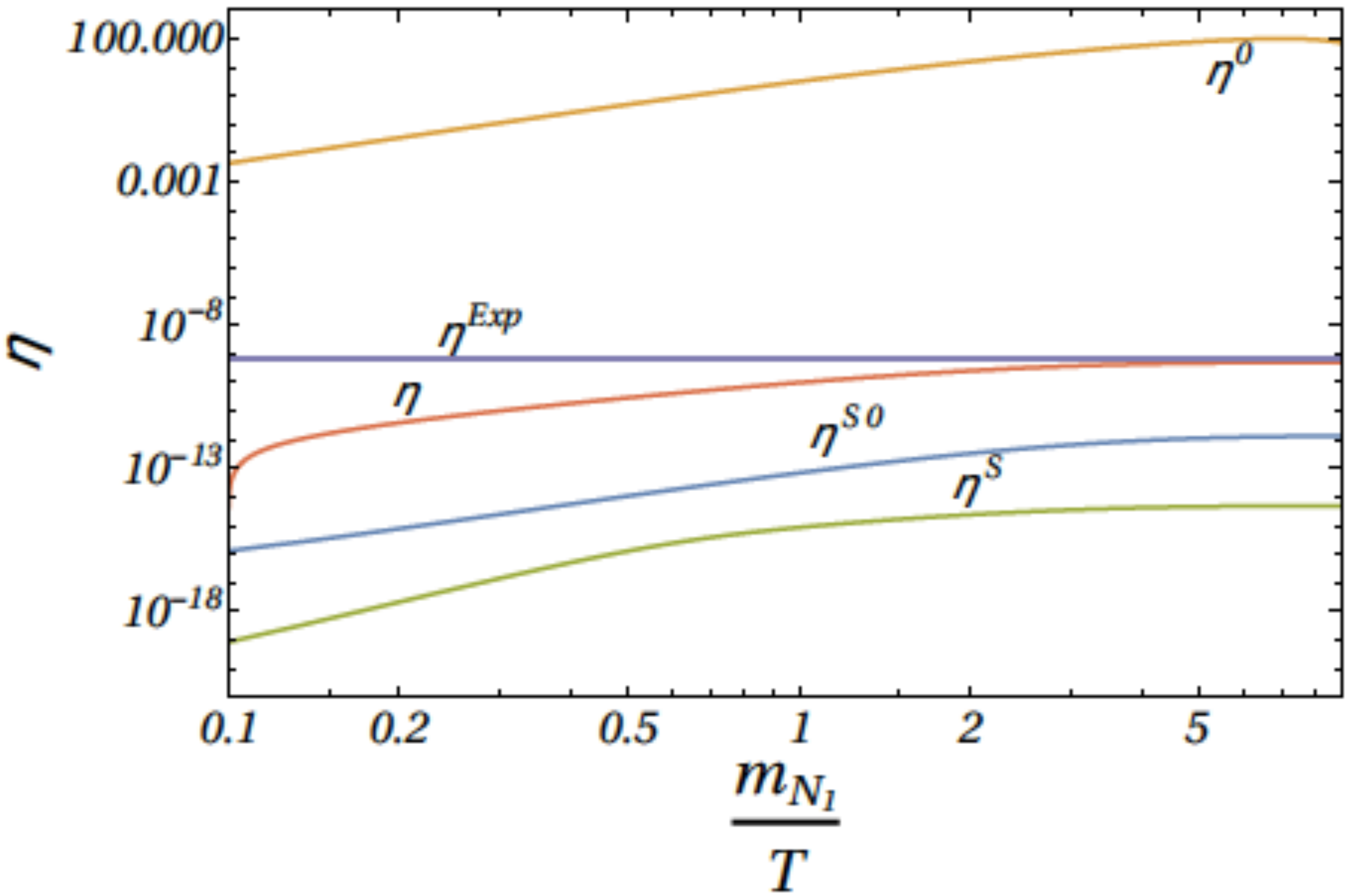
Providing additional CP-violation:

$$\epsilon_2 = \frac{\Gamma(N_1 \to \ell S) - \Gamma(N_1 \to \bar{\ell}\bar{S})}{\Gamma(N_1 \to \ell S) + \Gamma(N_1 \to \bar{\ell}\bar{S})}$$

Notice also that $\epsilon_1 = \dfrac{\Gamma(N_1 \to \ell\phi) - \Gamma(N_1 \to \bar{\ell}\bar{\phi})}{\Gamma(N_1 \to \ell\phi) + \Gamma(N_1 \to \bar{\ell}\bar{\phi})}$ is affected through the virtual exchange of S

$$m_{N_1} = 10\ \text{TeV}, \quad m_{N_2} = 10^4\ \text{TeV}, \quad m_{N_3} = 10^5\ \text{TeV}$$

$$\kappa_{12} = (2 + 0.055\ i) \cdot 10^{-3}, \qquad \kappa_{13} = (4.5 + 5.5\ i) \cdot 10^{-4} \qquad \kappa_{ij} = y_{2i\ell} y^*_{2j\ell}$$



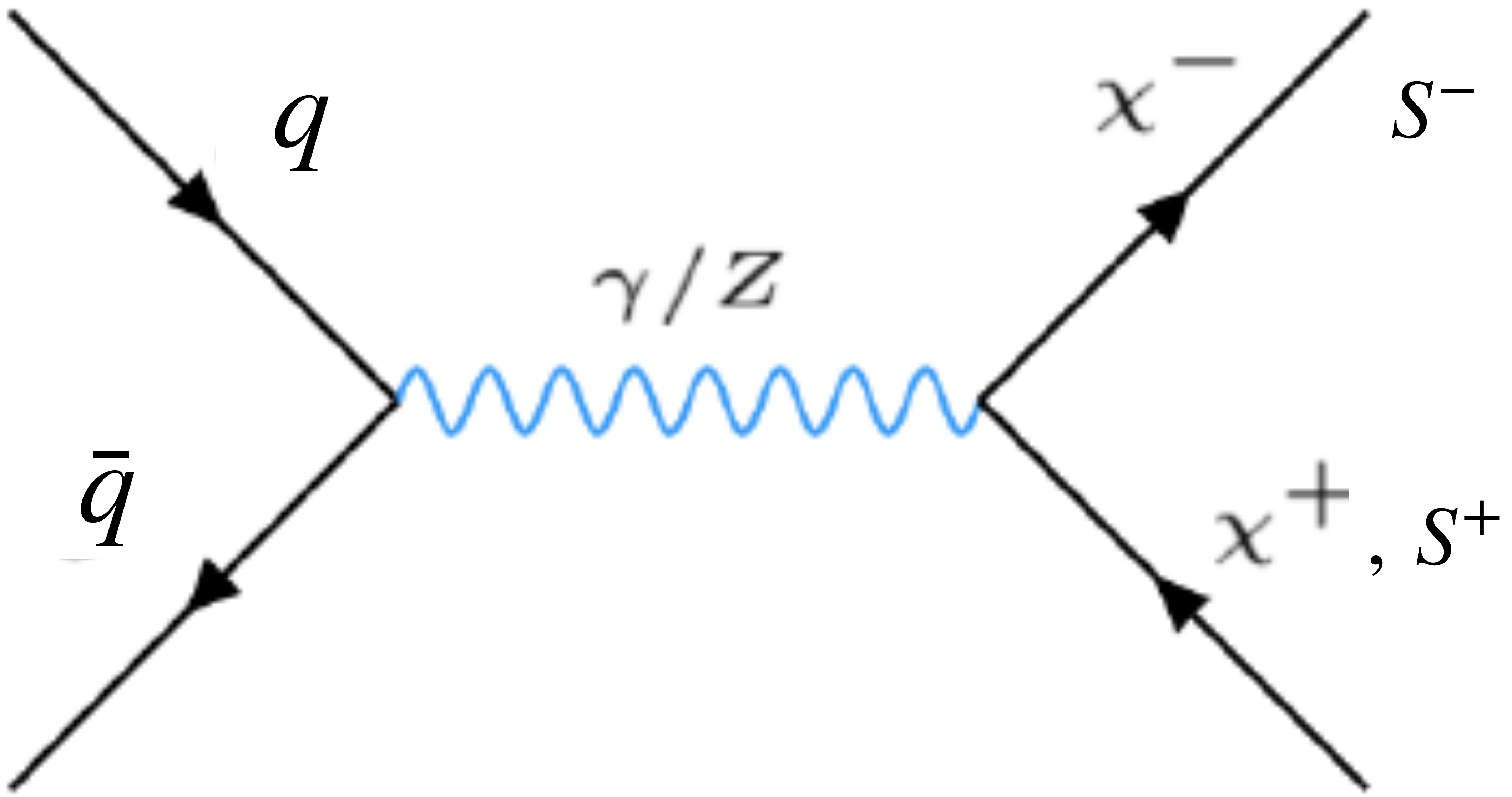
η^{S0}: standard case without scattering effects

η^{S}: standard case including scattering effects

η^{0}: our model without scattering effects

η: our model including scattering effects

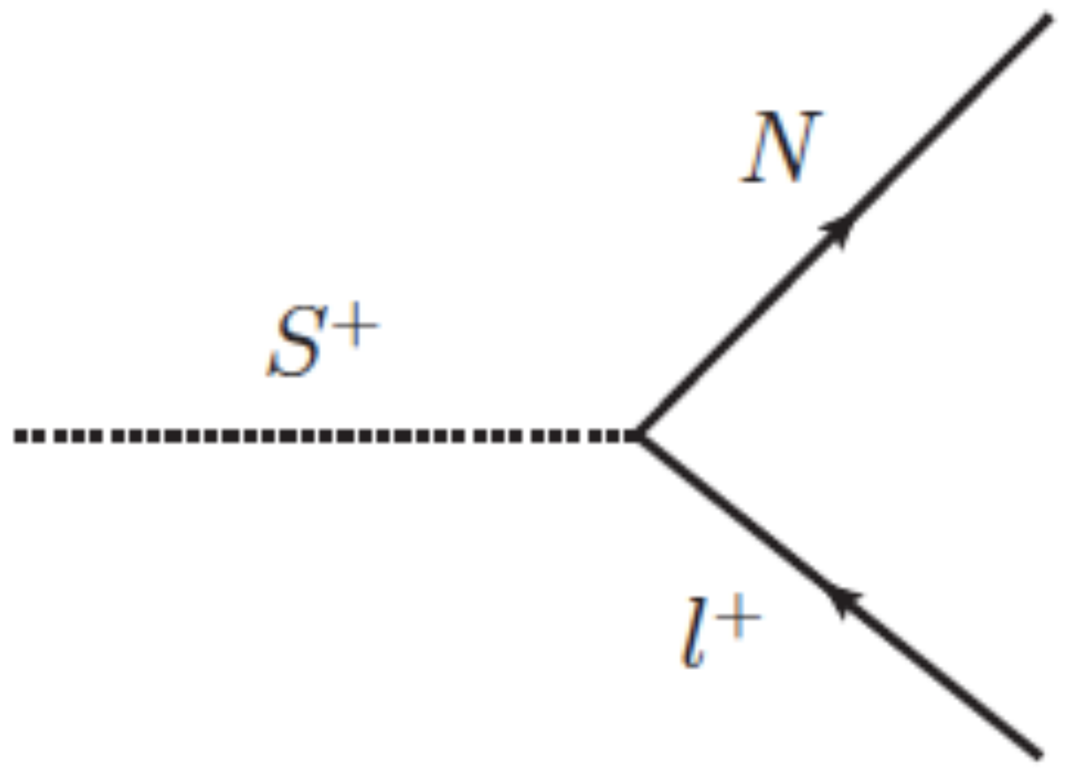
Collider effects

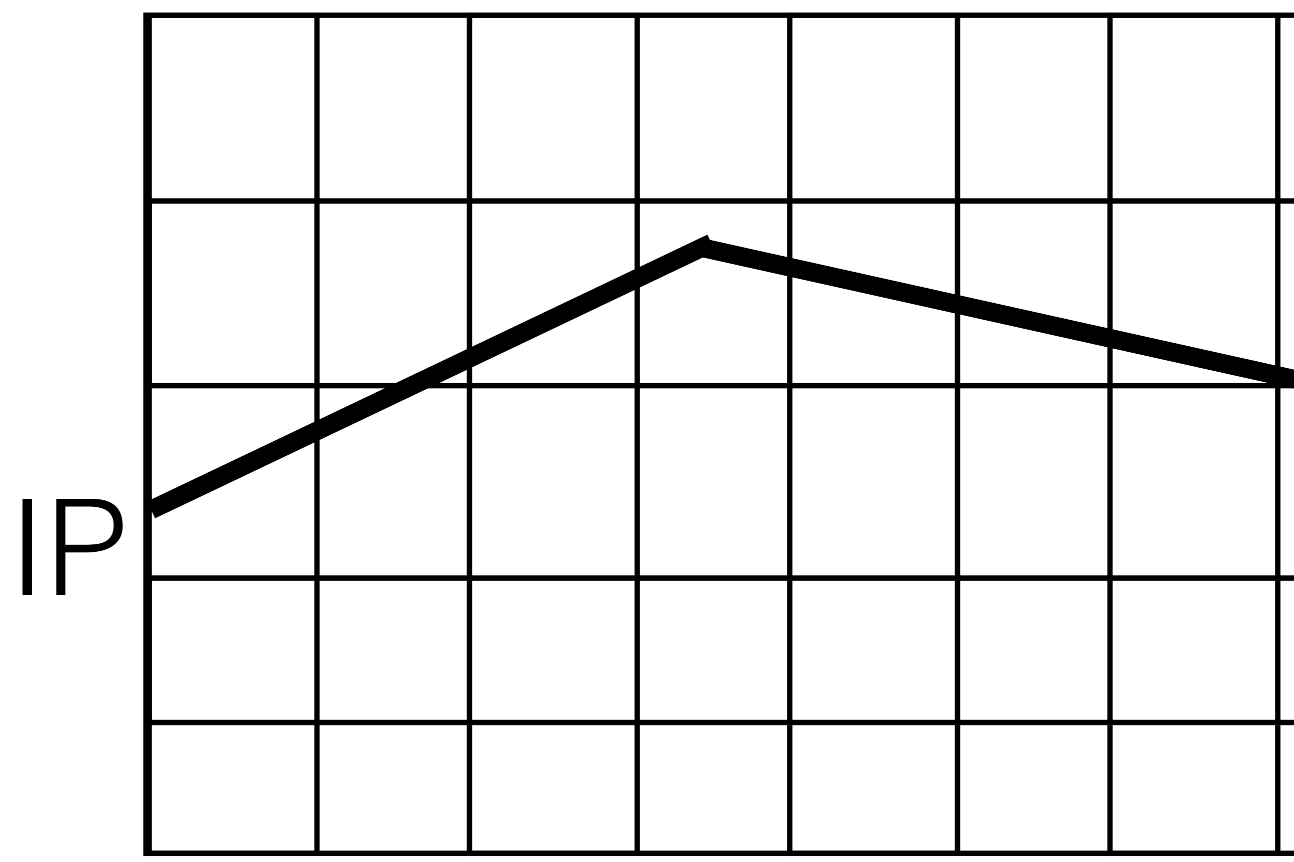


These charged particles could live long enough to decay in the detector, or outside the detector.

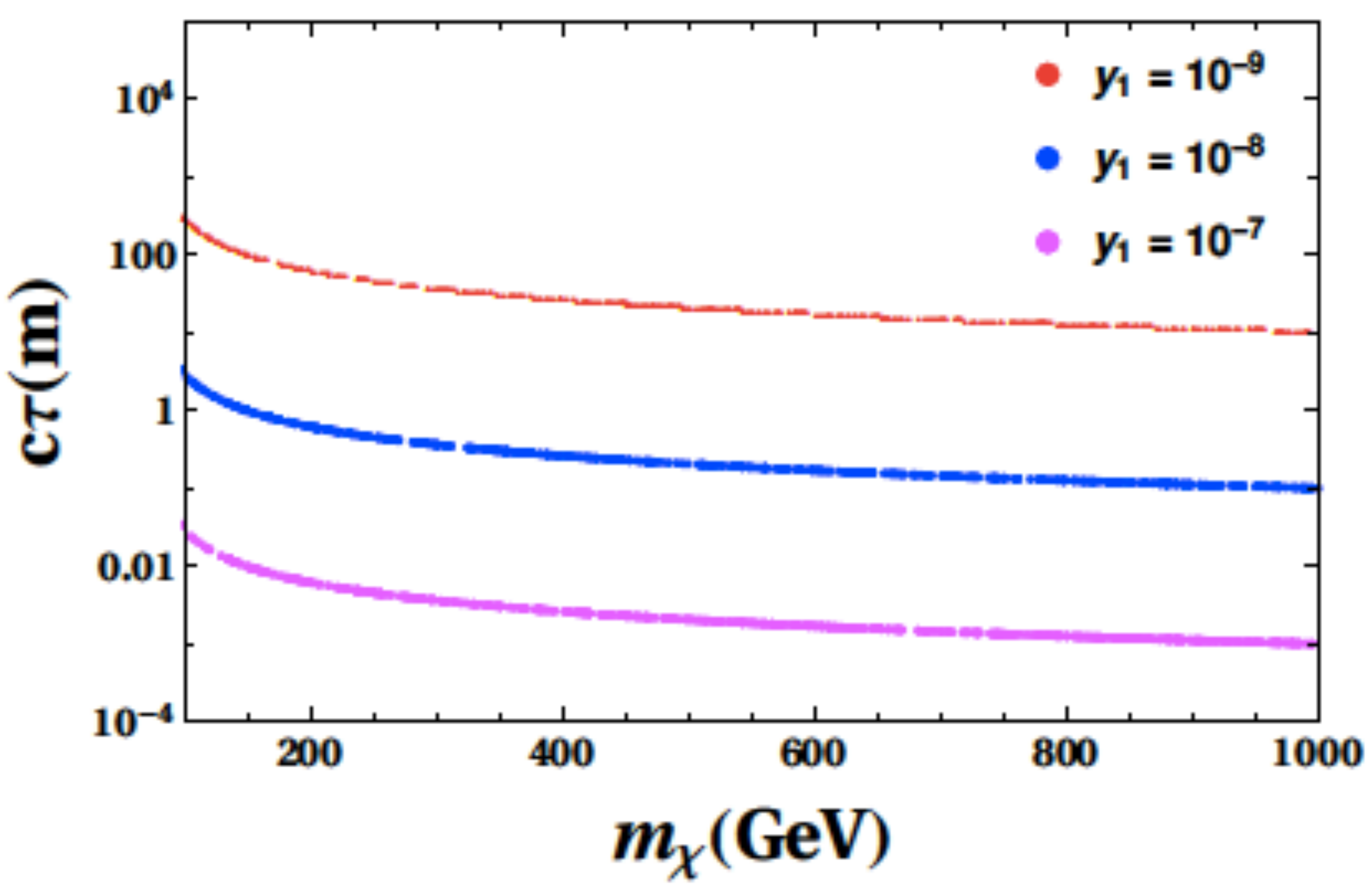
Signatures:

heavy charged particle tracks (like muon, but larger ionisation)



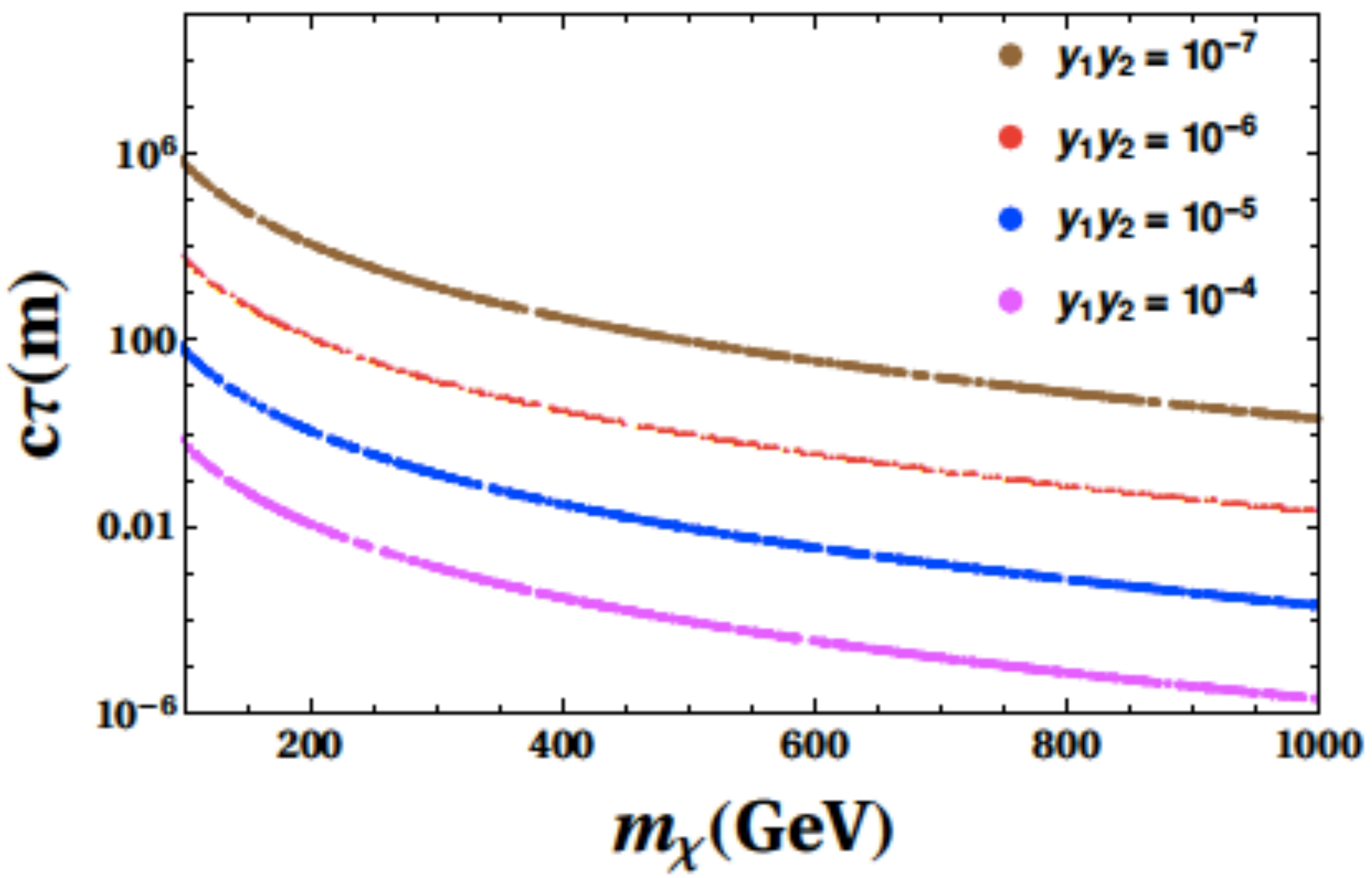


Collider effects - LLP - charged fermion $\chi^{\pm}$



case with $m_\chi > m_S + m_\psi$

y_1	m_χ	m_ψ	m_S	$c\tau$ (m)
10^{-8}	200	130	65	55
		65	65	72
		65	130	110
	1000	900	65	63
		65	65	88
		65	900	710

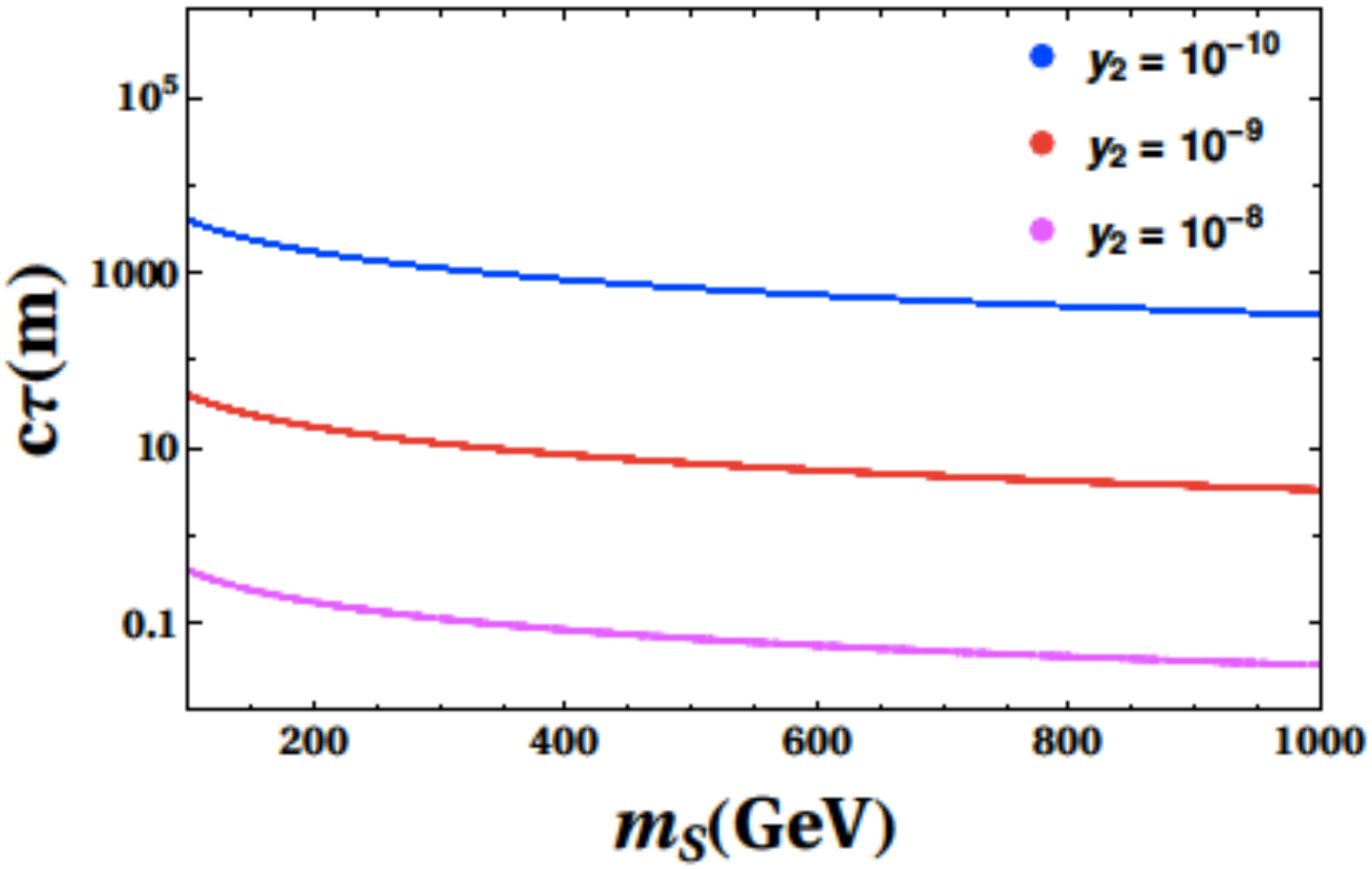


case with $m_\chi < m_S + m_\psi$

$y_1 y_2$	m_χ	m_ψ	m_S	$c\tau$ (m)
10^{-6}	40	1	65	166
	100	60	120	69
	500	400	300	1
		400	1000	155
	1000	800	800	1
		900	500	8
		300	800	0.002

Collider effects:

LLP - charged scalar $S^{\pm}$



	m_ψ	m_S	m_χ	y_1	Ωh^2	$\sigma_{pp\to S^+S^-}$ (pb)	$\Gamma_{S^+\to N\ell}$ (GeV)	$c\tau$ (m)
BP 1	56	165	473	7.53×10^{-13}	0.12	0.01436	9.21×10^{-18}	21.5
BP 2	101	77	613	1.18×10^{-13}	0.118	0.2441	3.3×10^{-18}	60.0
BP 3	99	188	195	1.38	0.12	0.008762	1.07×10^{-17}	18.5
BP 4	83	127	143	2.25	0.119	0.0376	6.76×10^{-18}	29.5
BP 5	73	199	137	5.06	0.118	0.007063	1.13×10^{-17}	17.5

Thank you !

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Sreemanti Chakraborti, LAPTH, Annecy, France