Collider Probes of TeV Scale Dark Sector

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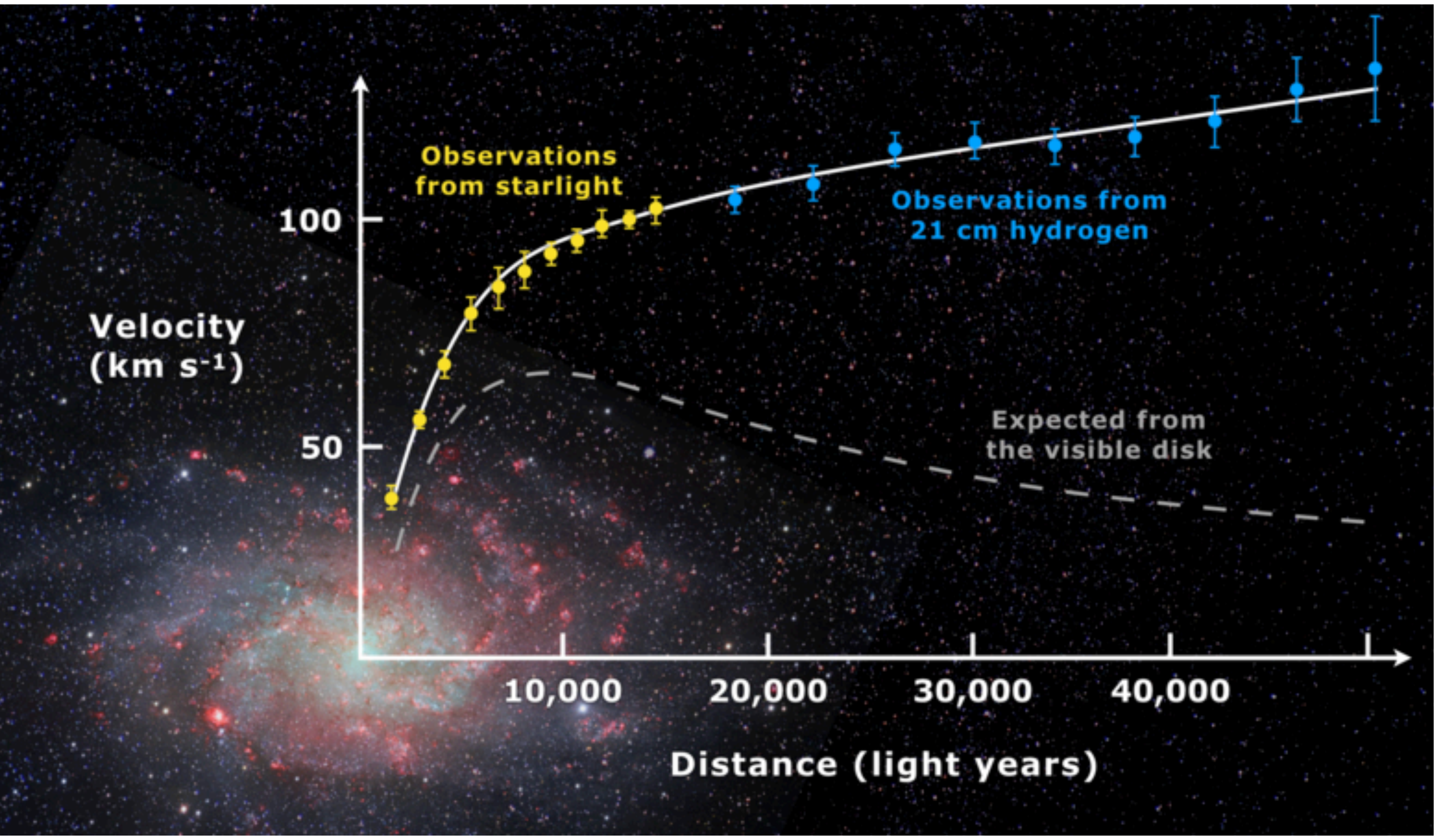
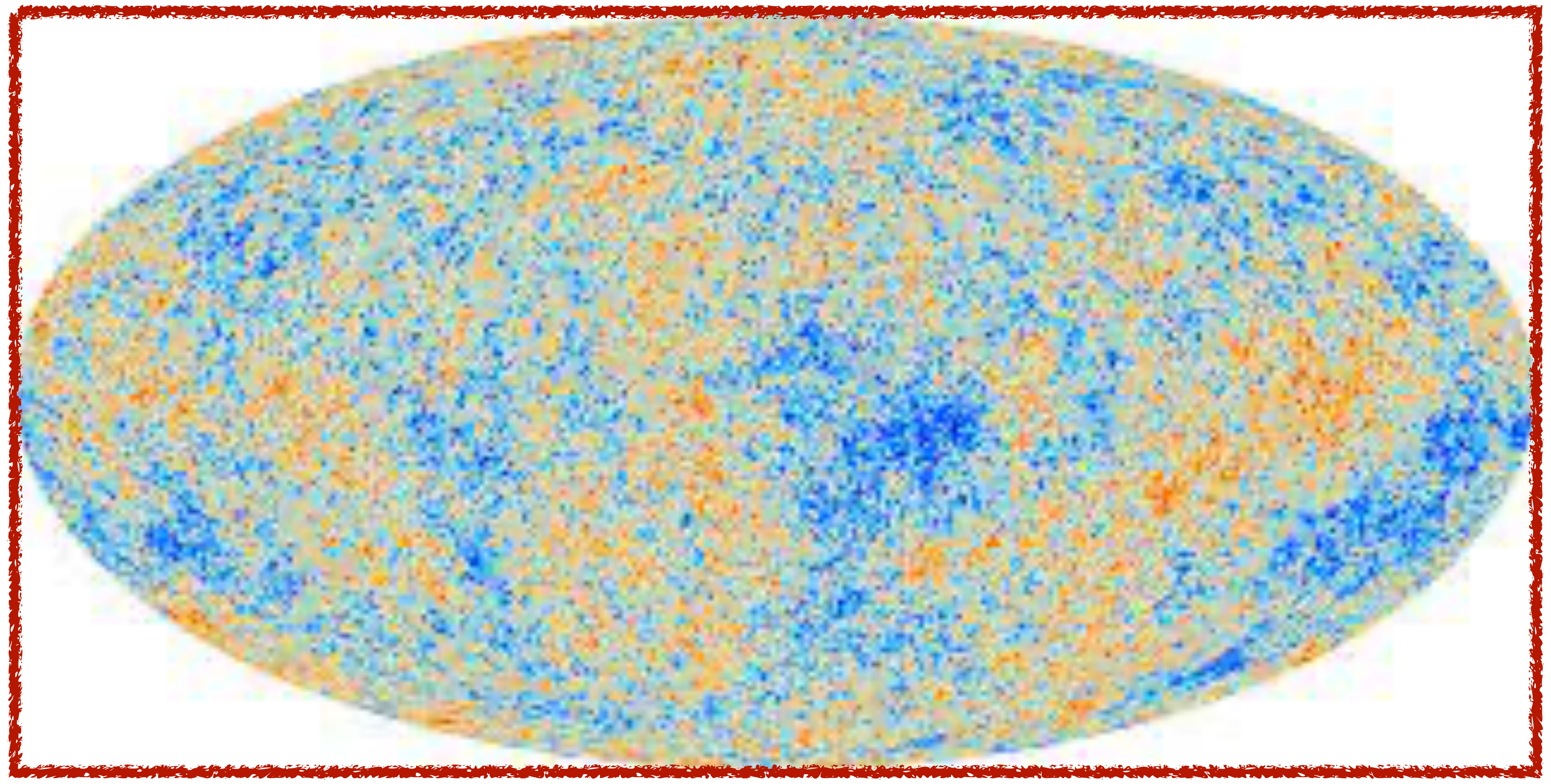
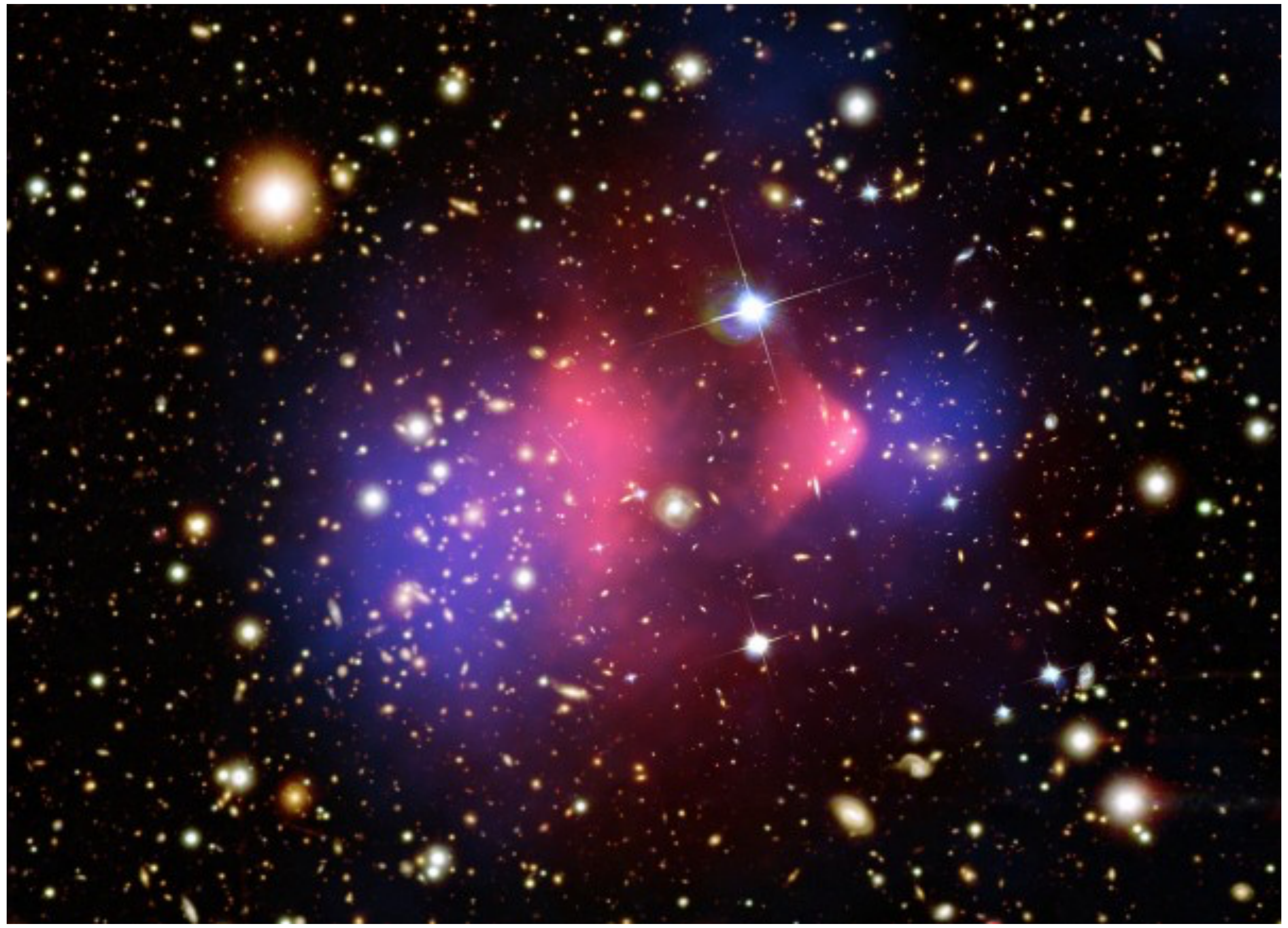
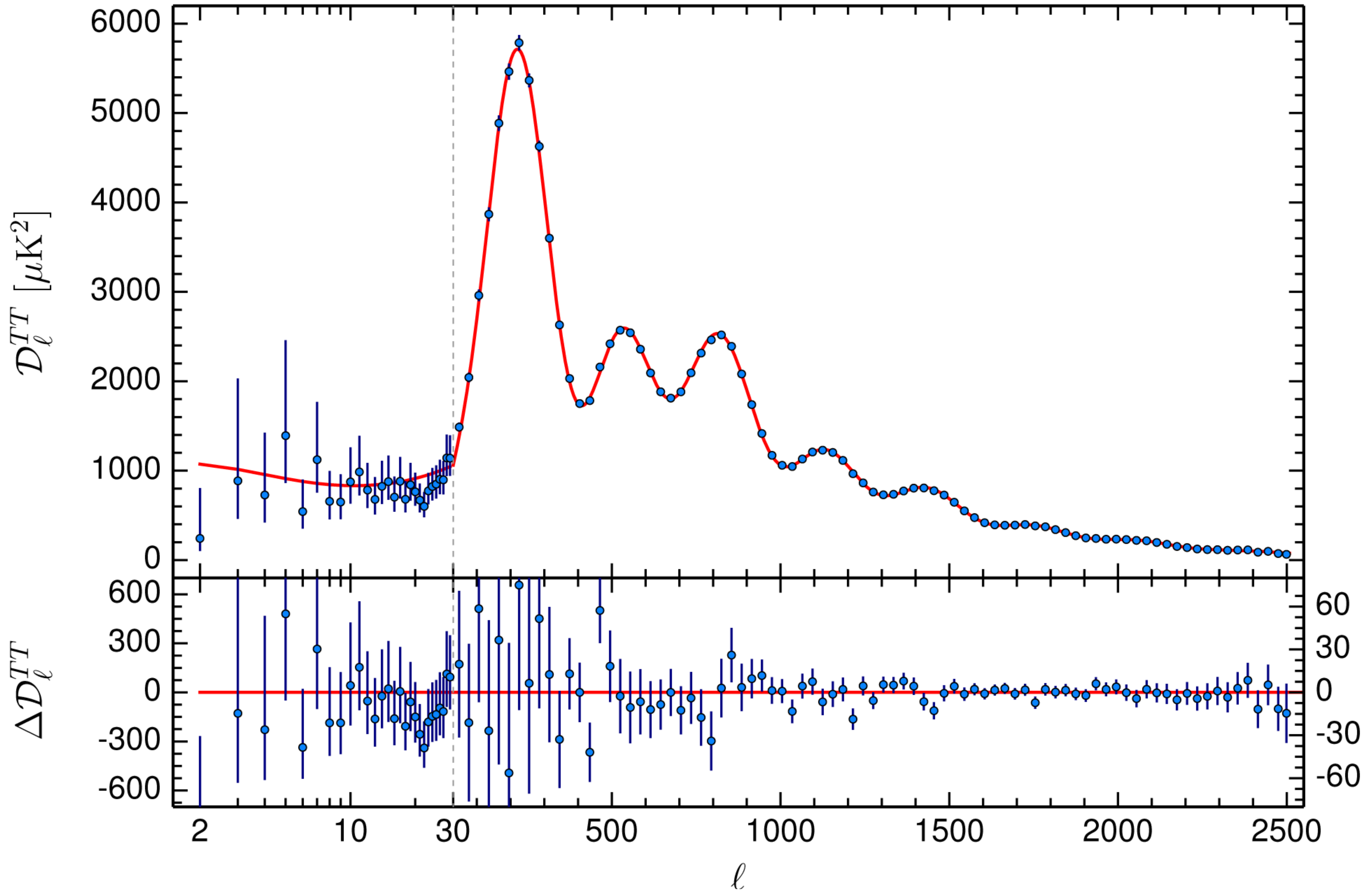
Dark Matter through the ages

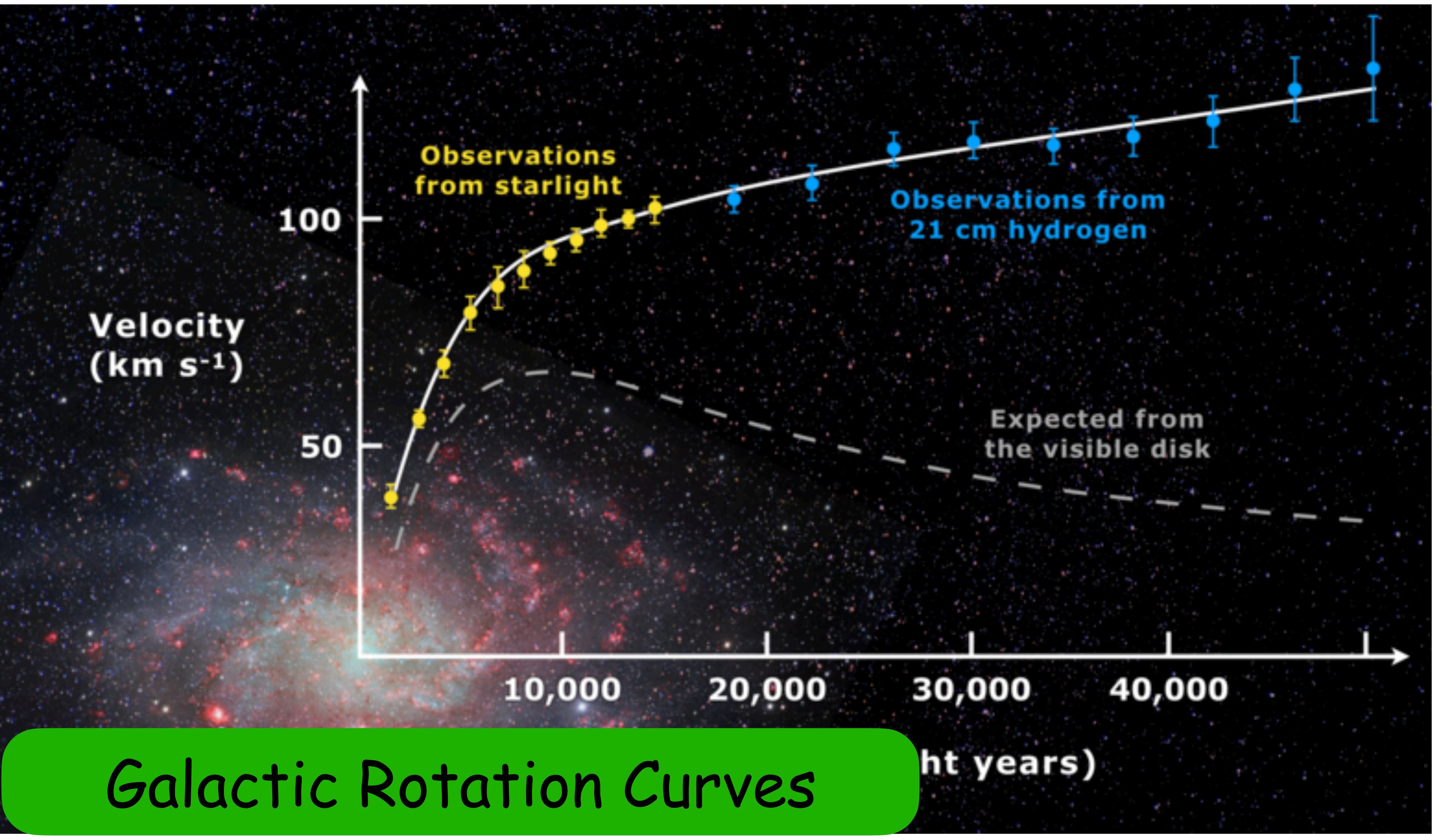




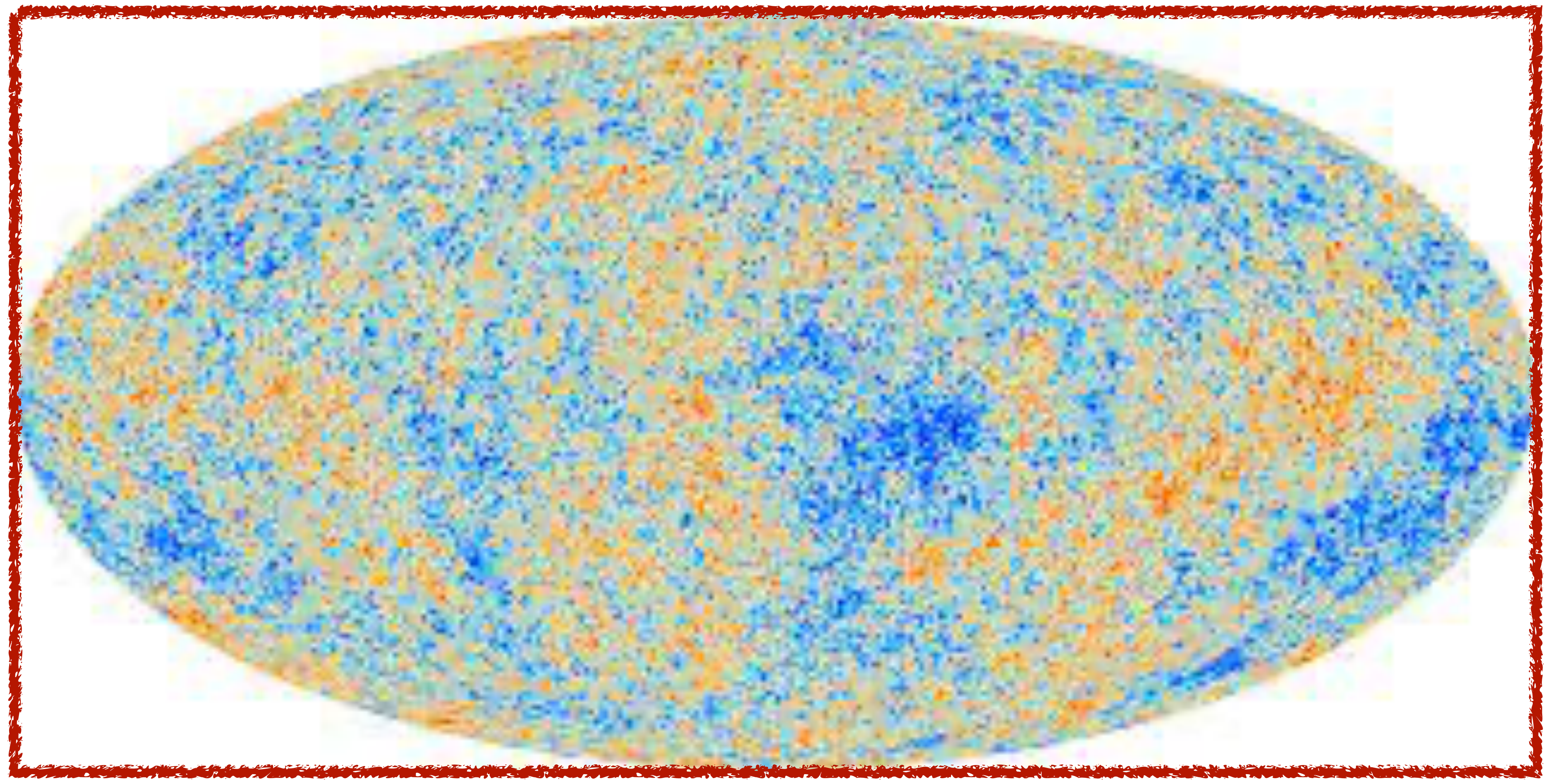




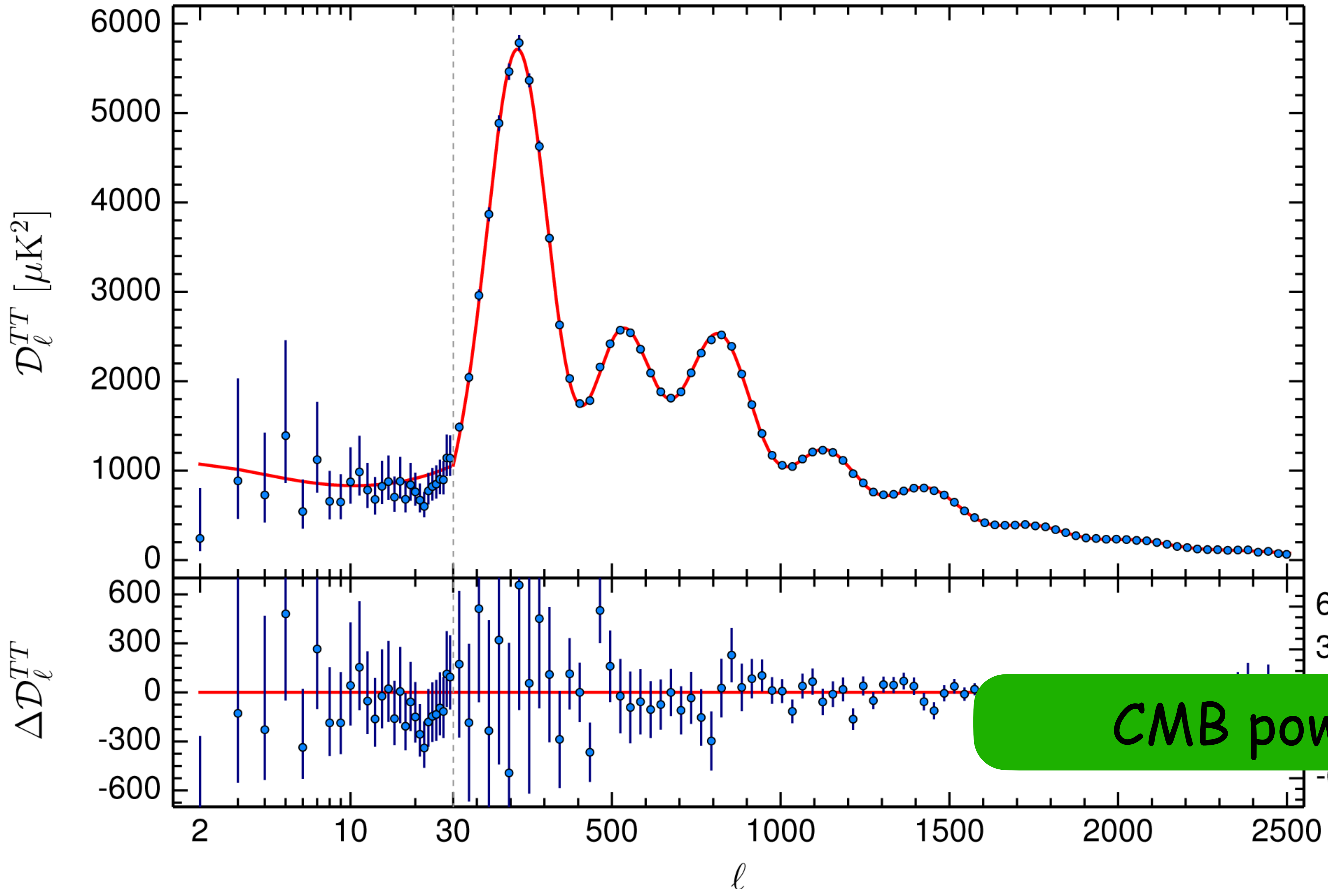
Dark Matter through the ages



Galactic Rotation Curves

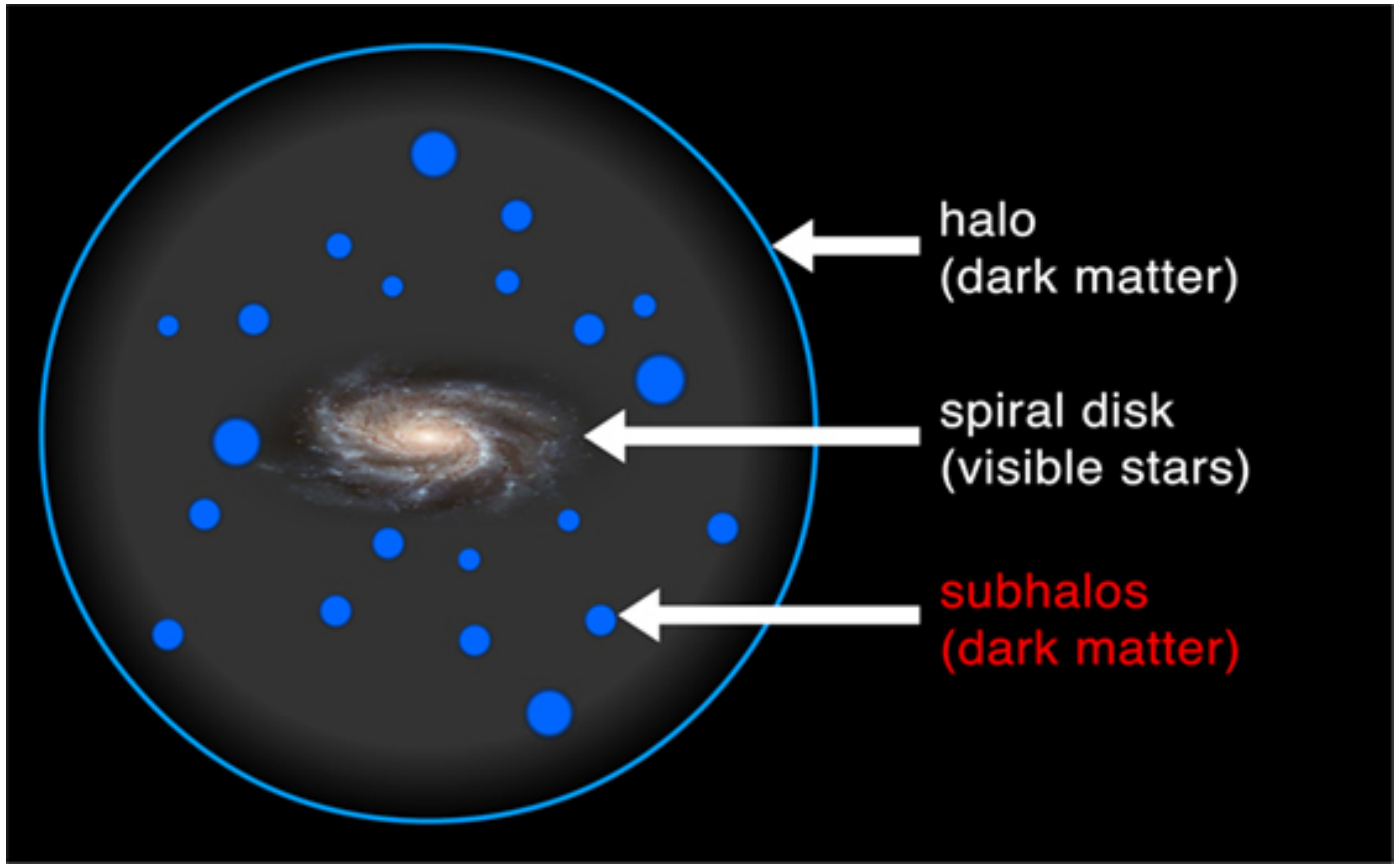


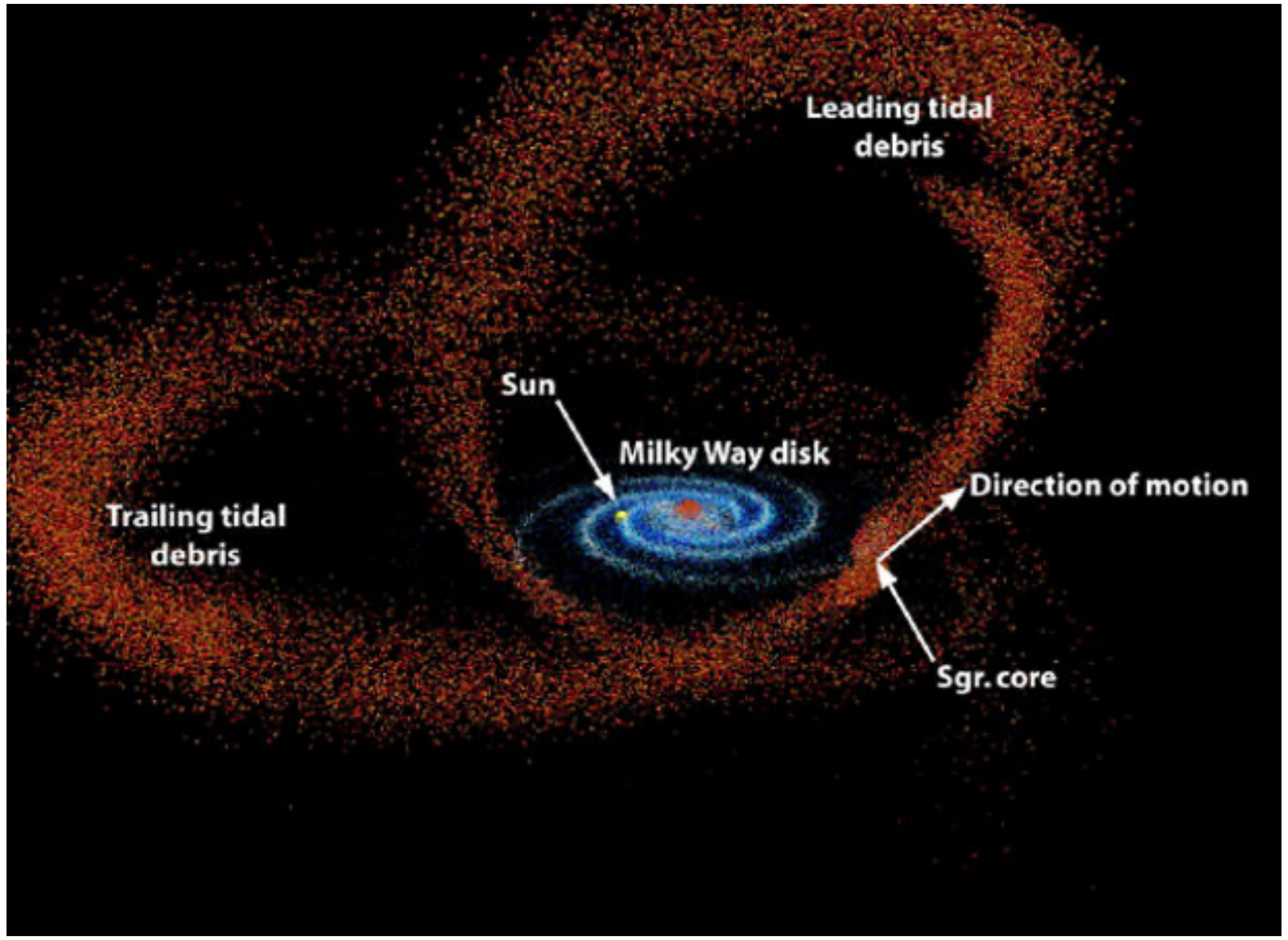
Gravitational Lensing in Bullet Cluster .
Pink- X-Ray image
Blue : Gravitational lensing image



CMB power spectrum

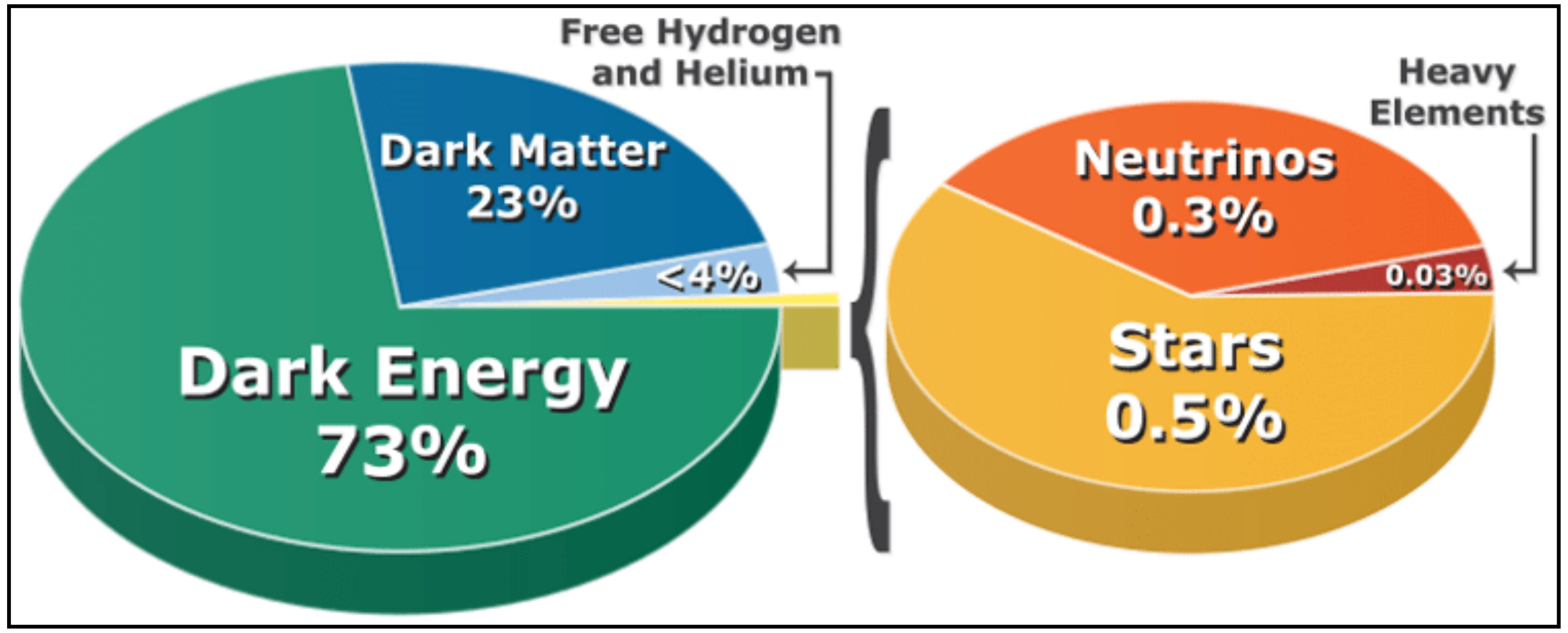
Properties and the Particle Physics of Dark Matter



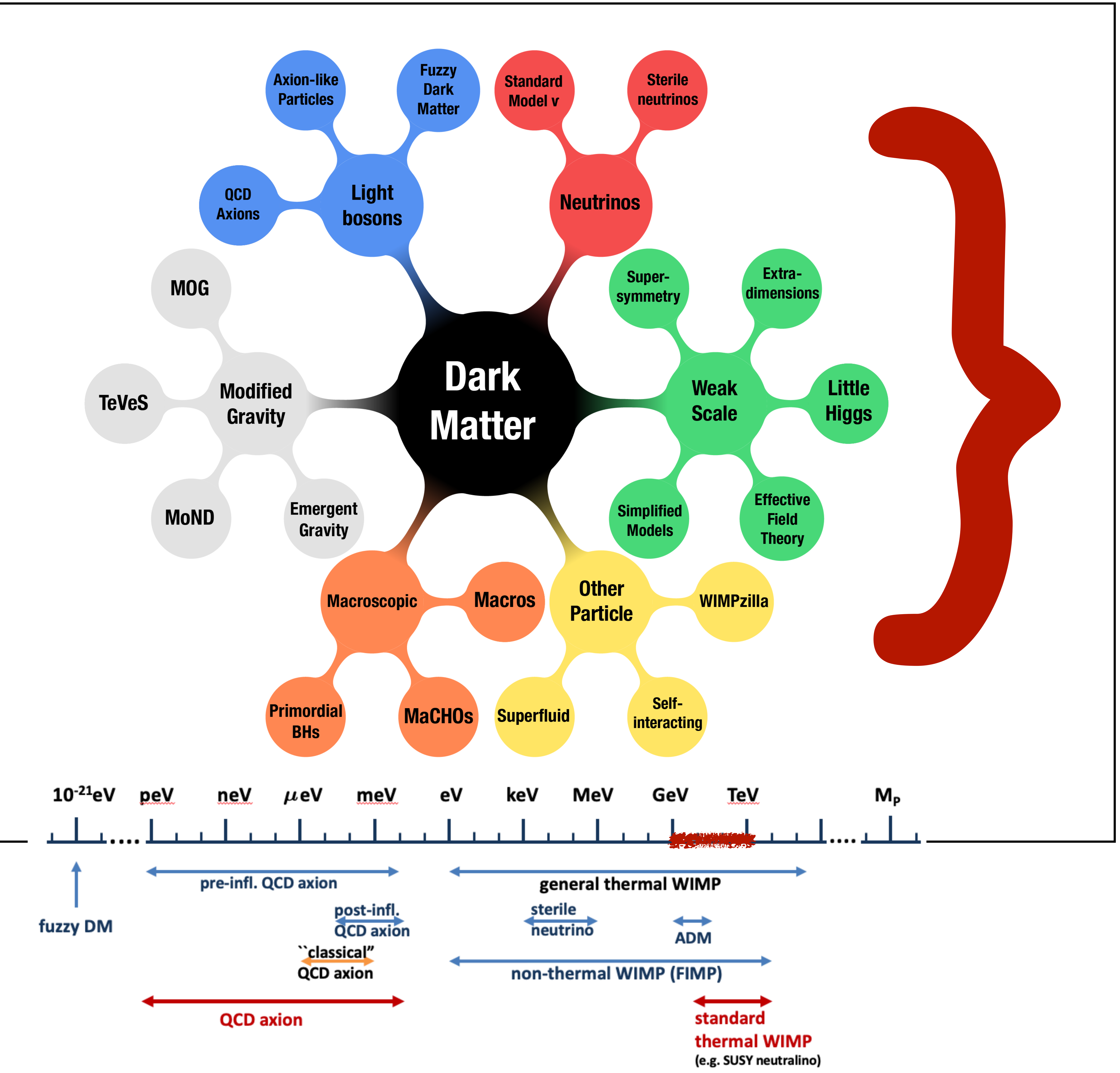


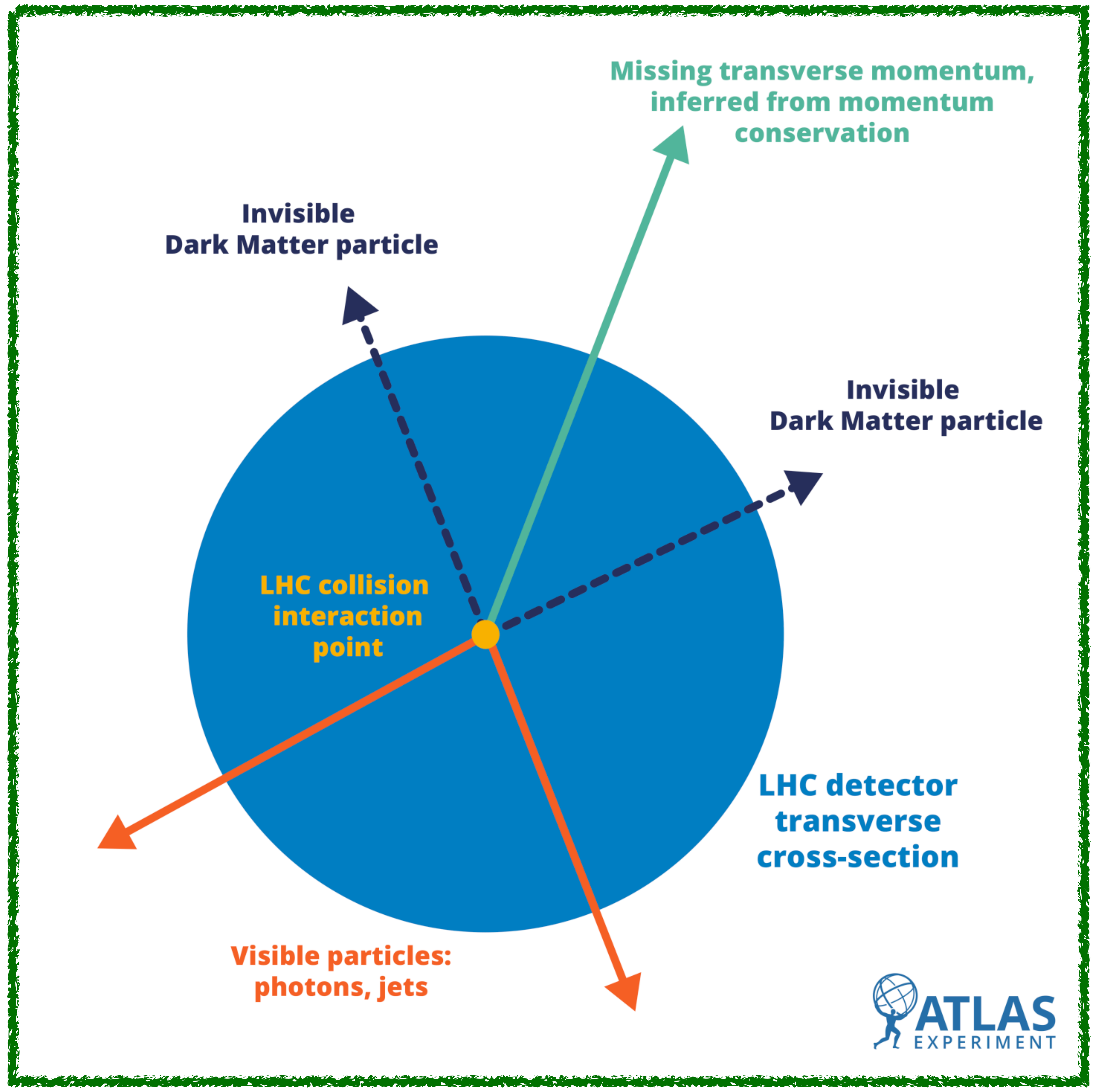
- Cold and Neutral: Non relativistic today.
- Preserves the success of Big Bang Nucleosynthesis (Formation of Atoms and Nuclei in the early Universe)
- "Almost" **Dark** with respect to other forces of nature.
- Collisionless within the DM sector at large scales.
- Stable, on Cosmological time scales.
- Forms halos in the galaxy

Dark Matter belongs in Astronomy/Cosmology .
Why should we care about colliders ?



Dark Matter at Colliders





Comment : Even in the event of a missing energy signature, we can't be sure it is dark matter

Classifying Dark Sector Searches

Theoretical Considerations

Theoretical Considerations for freeze-out :

$$\Omega_{\rm DM}h^2 \sim 0.12 \times \left(\frac{M_{\rm DM}}{2\ \rm TeV}\right)^2 \left(\frac{0.3}{g_{\rm eff}}\right)^4 \quad \longrightarrow \quad M_{DM} \sim \mathcal{O}(\text{few GeV}) \rightarrow \mathcal{O}(\text{10's TeV})$$

Cosmological considerations (lower bound, $\mathcal{O}(\text{few GeV})$) — Unitarity (upper bound, $\mathcal{O}(\text{10's TeV})$)

Can we push/evade these limits for colliders ?

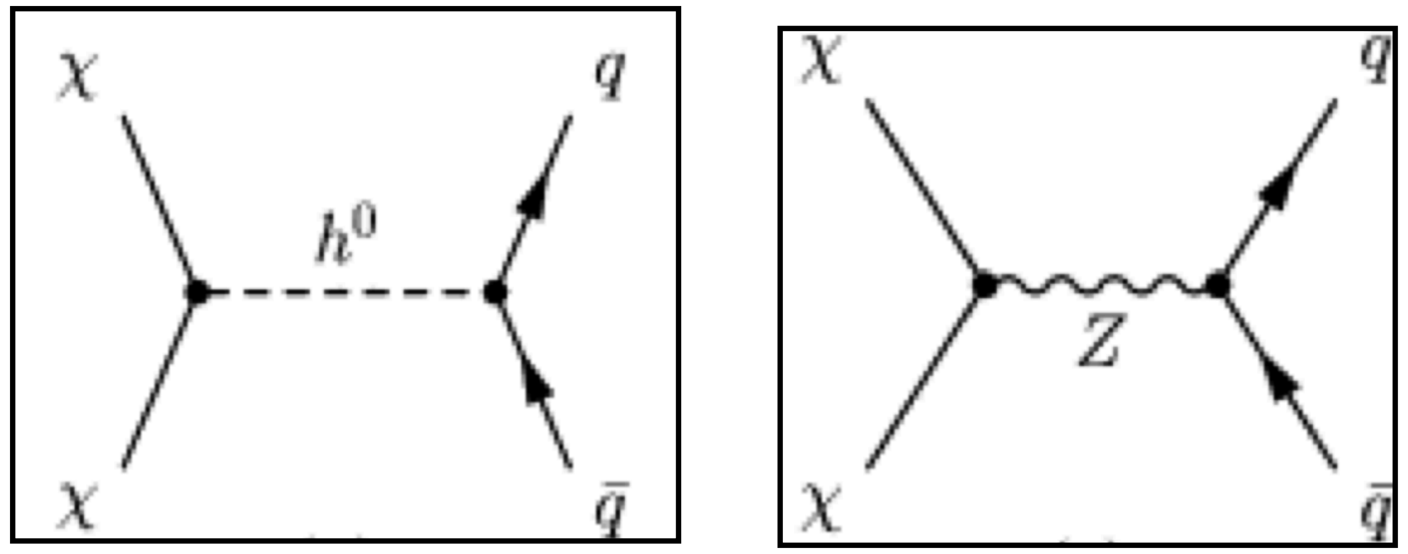
1. Relic Considerations : Superwimp mechanisms, non-thermal production
2. Collider Considerations : Build Bigger Colliders.

Heavy vs light Neutralino

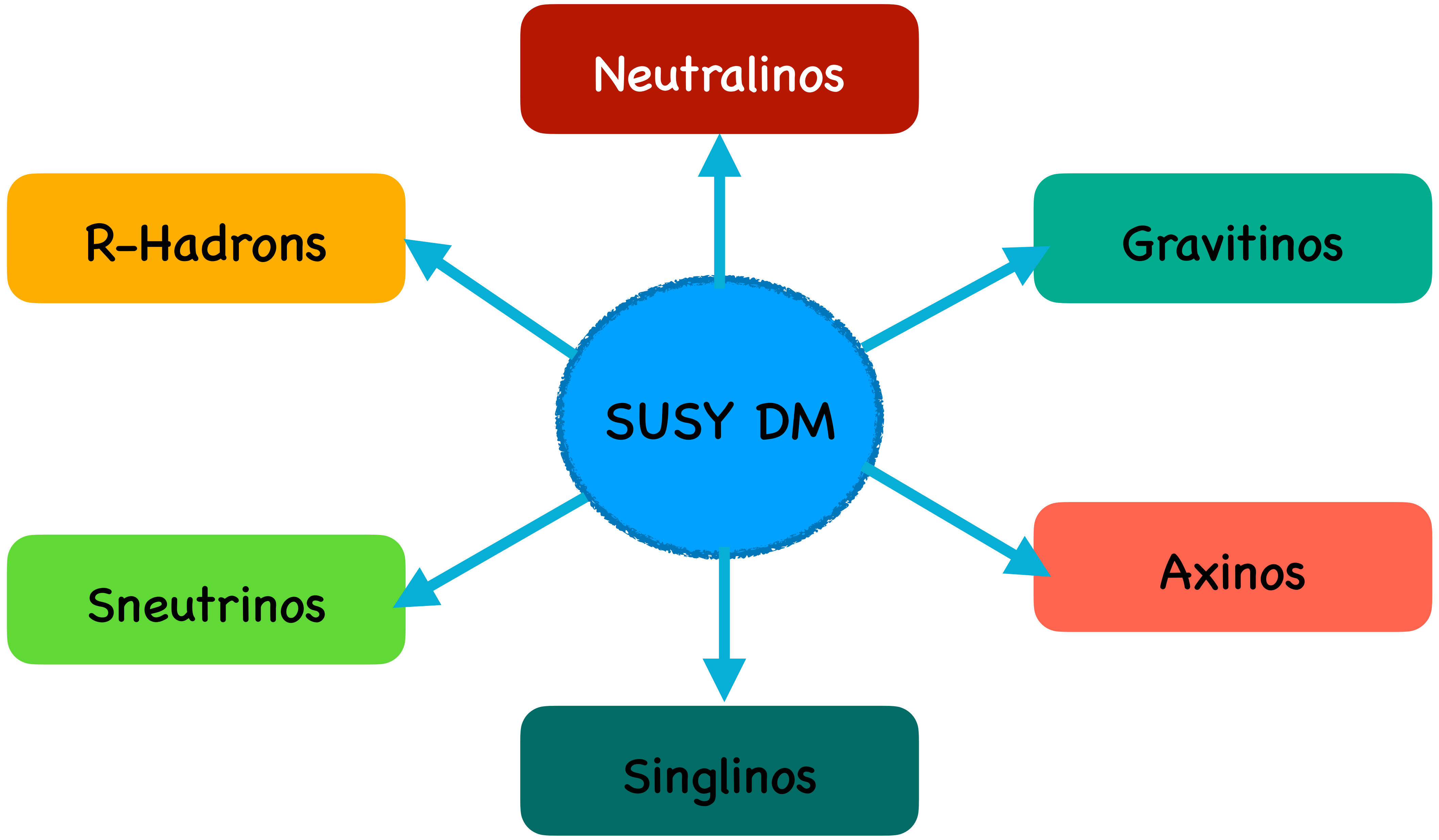
Example 1:

Is the light thermal SUSY neutralino dead ?

For thermal freeze-out need efficient annihilation mechanism to deplete the abundance for SUSY DM



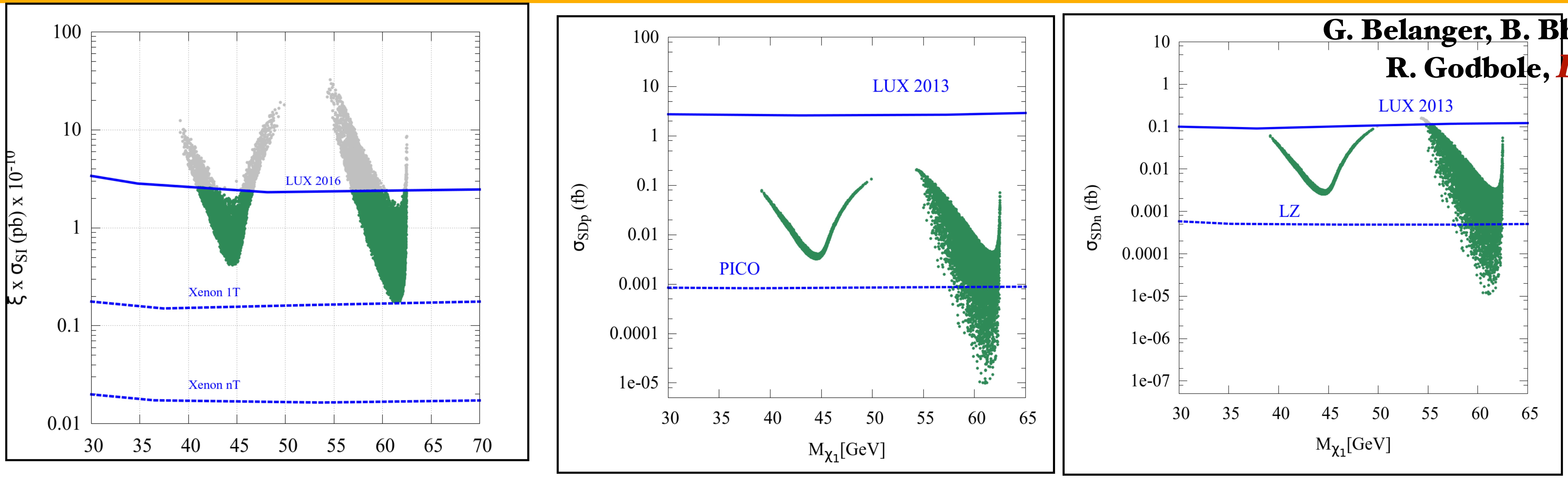
Higgs/Z Funnel, Dark Matter annhilation into SM through the Higgs

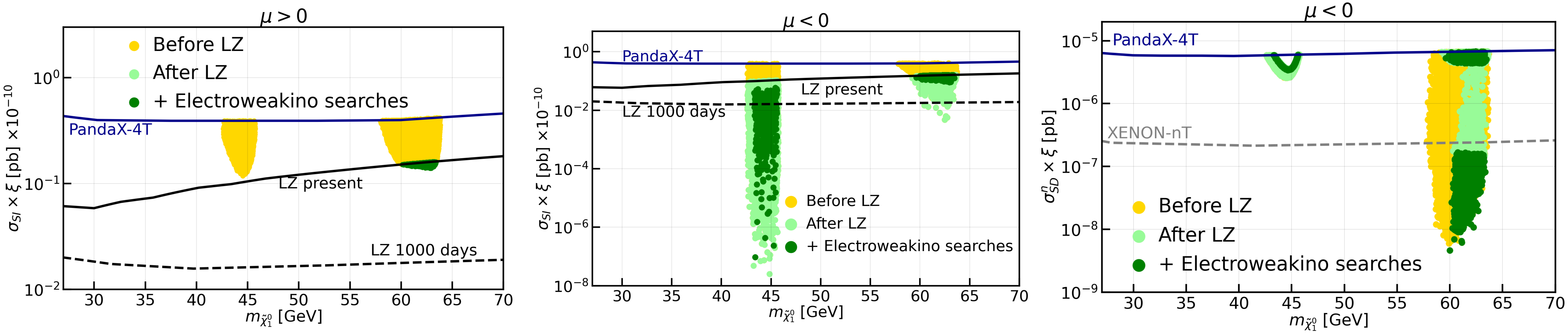


1. Depending on the mass and the gauge content of the neutralino, it can annihilate via a variety of channels.
2. Requires a mediator particle that interacts with the standard model.

The Light Neutralino: Alive in 2017 and may be dead in 2023

G. Belanger, B. Bhattacharjee, R. Barman, R. Godbole, **DS**. *PRD2017, 095018*

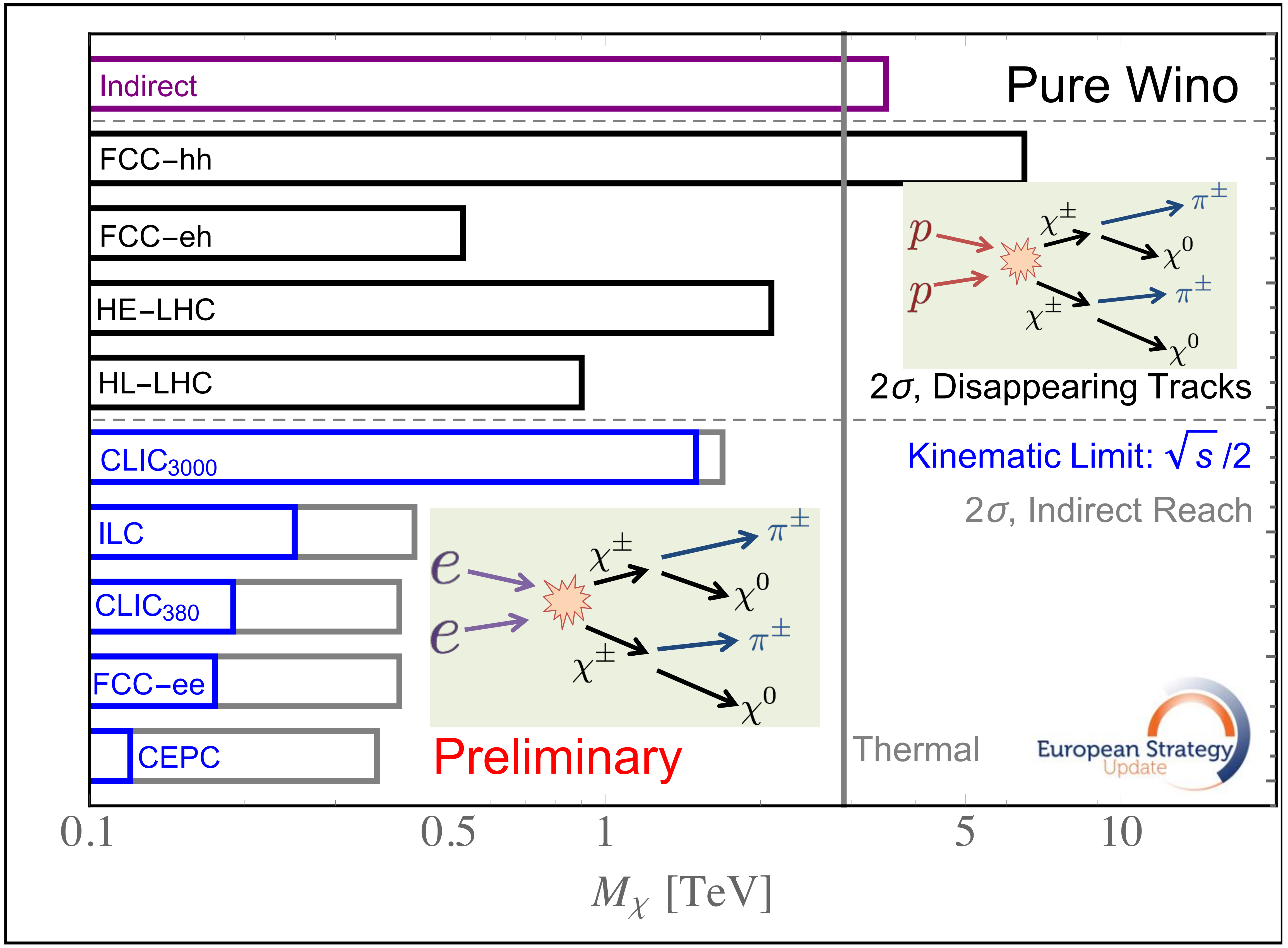


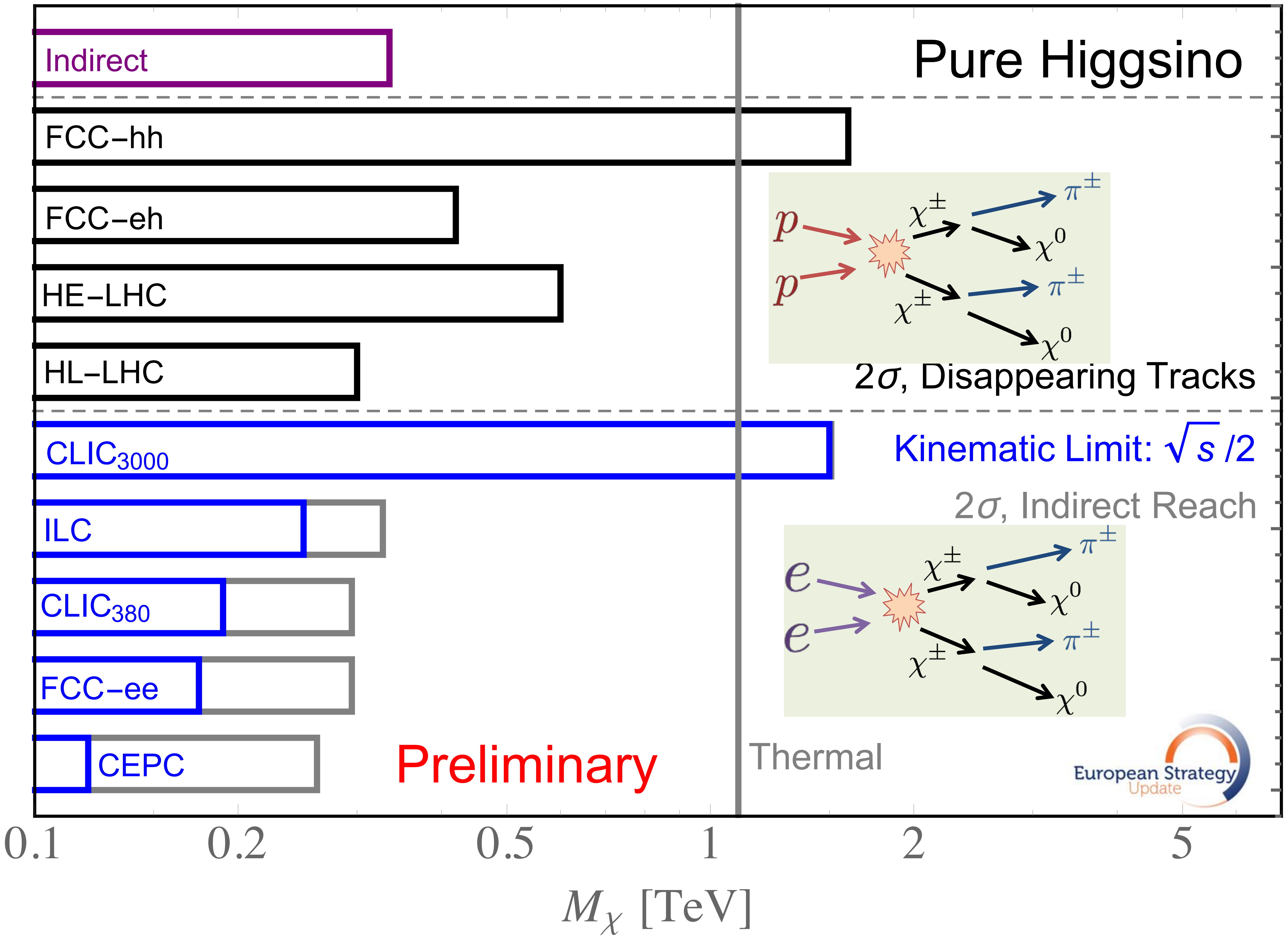


The allowed regions consistent with constraints from H-> Invisible , Z-> Invisible, gaugino searches and direct detection are at the Z resonance and the Higgs resonance

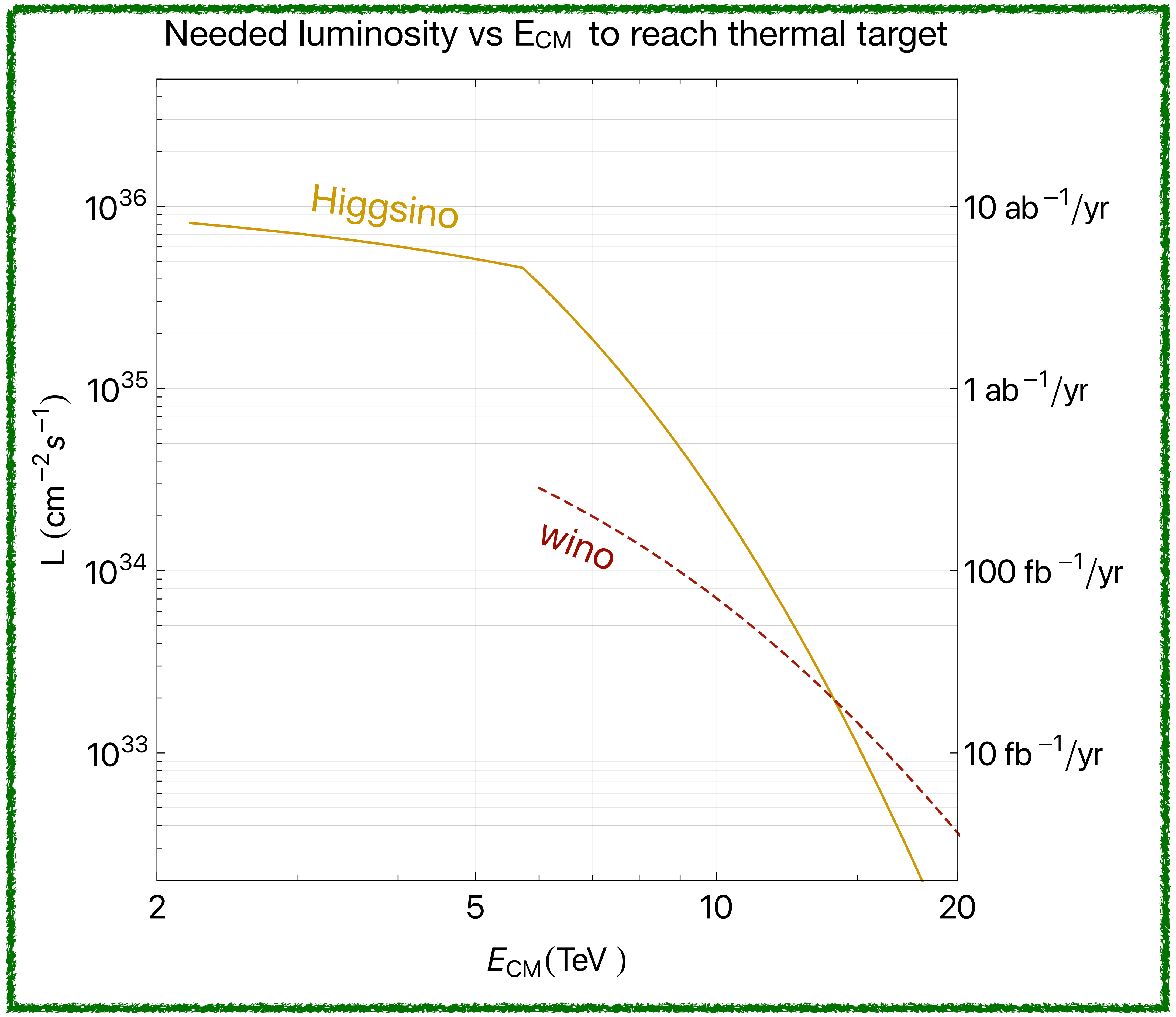
G. Belanger, B. Bhattacharjee, R. Barman, R. Godbole, ***R. Sengupta***. *PRL2023*

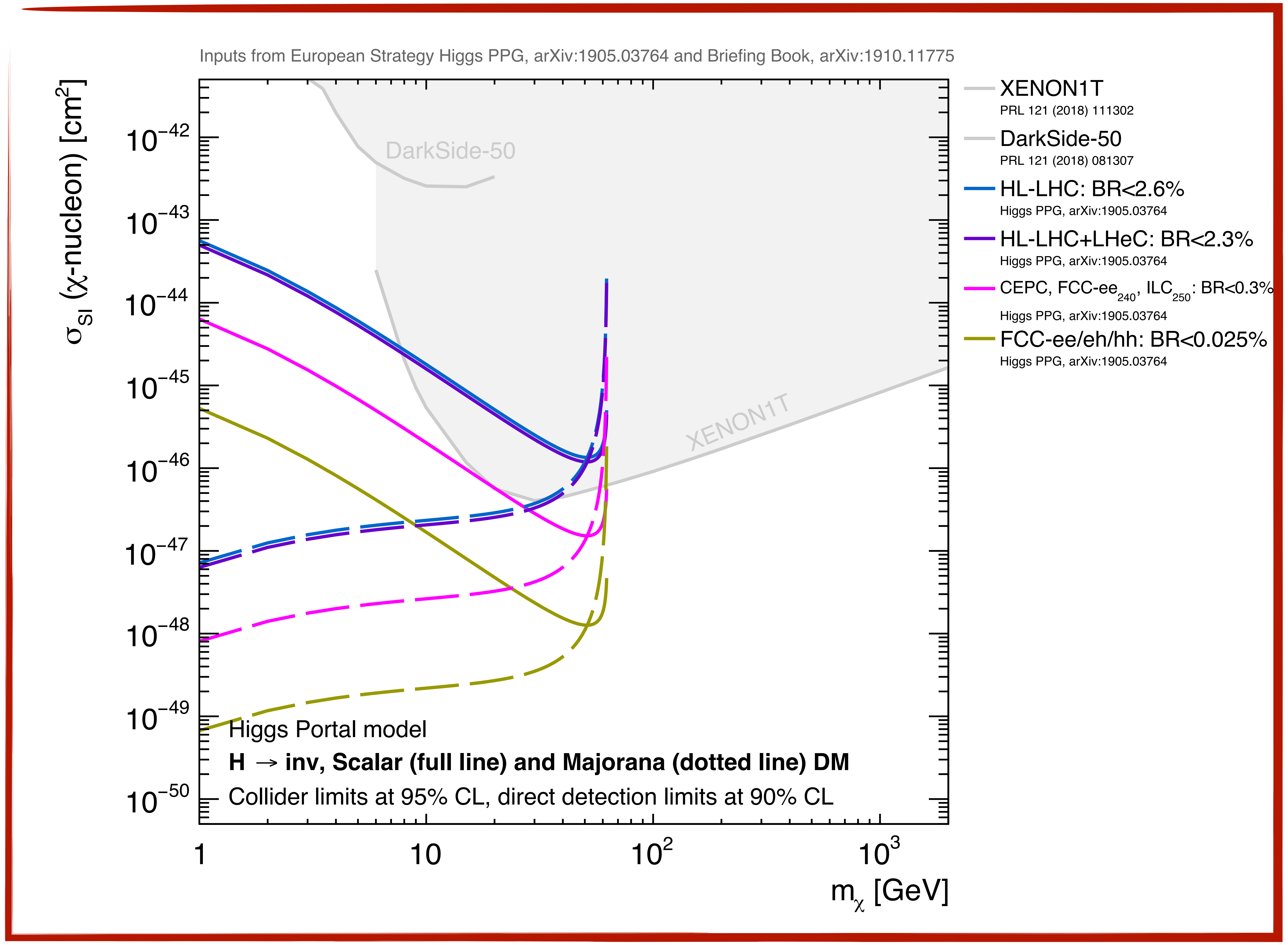
Heavy neutralinos, Winos and Higgsinos





Heavy neutralinos and light neutralinos





Lepton Collider Projections: Higgsinos And WINO

Z. Liu and L.-T. Wang, *Physics at Future Colliders: the Interplay Between Energy and Luminosity*, in *2022 Snowmass Summer Study*, 4, 2022 [2205.00031].

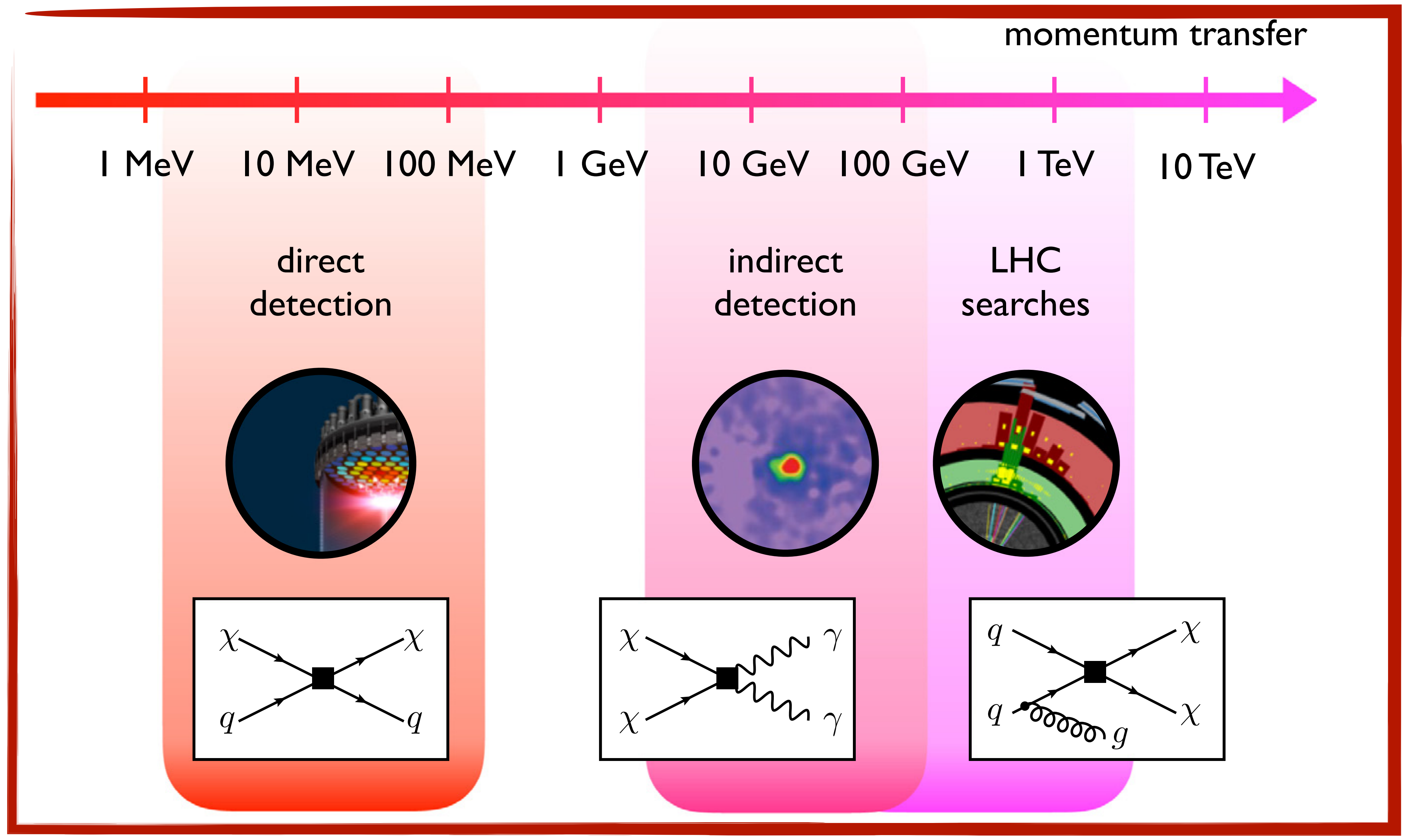
EFTs and simplified models

$$\mathcal{L}_{\text{DM-EFT}} = \sum_{f=u,d,s,c,b,t,e,\mu,\tau} \left(\frac{C_1^f}{\Lambda^2} \bar{f} f \bar{\chi} \chi + \frac{C_2^f}{\Lambda^2} \bar{f} \gamma_5 f \bar{\chi} \gamma_5 \chi + \cdots \right)$$

The most typical basis for Direct and indirect Detection

Described by the mass of the dark matter, and the couplings $\{m_\chi \,,\; C_n^f/\Lambda^2\}$

Justified for $q^2 \ll \Lambda^2$



LHC DM simplified models

Working group

$$\mathcal{L}_{\text{DM-simp}} = -ig_\chi a \bar{\chi} \gamma_5 \chi - ia \sum_j \left(g_u y_j^u \bar{u}_j \gamma_5 u_j + g_d y_j^d \bar{d}_j \gamma_5 d_j + g_\ell y_j^\ell \bar{\ell}_j \gamma_5 \ell_j \right)$$

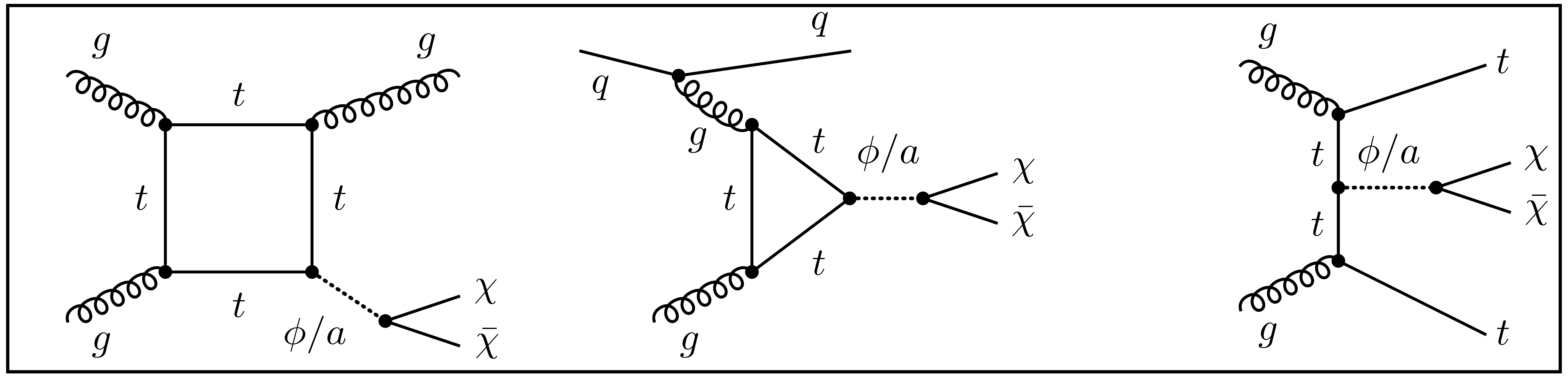
Instead, work in a basis of simplified Models with a generic mediator and couplings

Simplified models s-channel vs t-channel

$$\mathcal{L}_{\text{fermion},\phi} \supset -g_\chi \phi \bar{\chi}\chi - \frac{\phi}{\sqrt{2}} \sum_i \left(g_u y_i^u \bar{u}_i u_i + g_d y_i^d \bar{d}_i d_i + g_\ell y_i^\ell \bar{\ell}_i \ell_i \right) ,$$

$$\mathcal{L}_{\text{fermion},a} \supset -i g_\chi a \bar{\chi}\gamma_5\chi - \frac{ia}{\sqrt{2}} \sum_i \left(g_u y_i^u \bar{u}_i \gamma_5 u_i + g_d y_i^d \bar{d}_i \gamma_5 d_i + g_\ell y_i^\ell \bar{\ell}_i \gamma_5 \ell_i \right)$$

$$\{m_\chi,\ m_{\phi/a},\ g_\chi,\ g_u,\ g_d,\ g_\ell\}$$

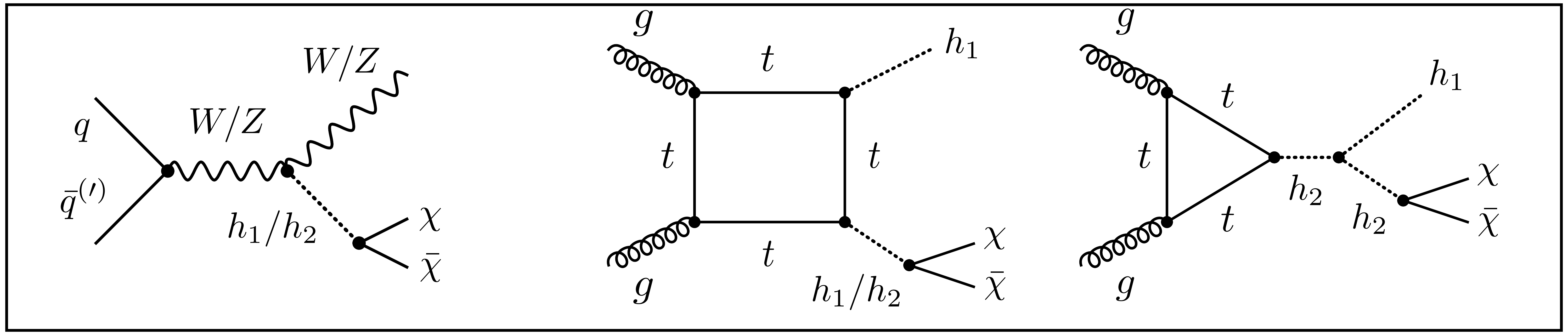


Dominant decay modes if

$$m_{\phi/a} > 2m_t \quad g_u \gtrsim g_\chi$$

Fermion singlet DM

$$\mathcal{L}_{\text{fermion},H} \supset -\mu_s s^3 - \lambda_s s^4 - y_\chi \bar{\chi}\chi s - \mu_p s|H|^2 - \lambda_p s^2 |H|^2$$



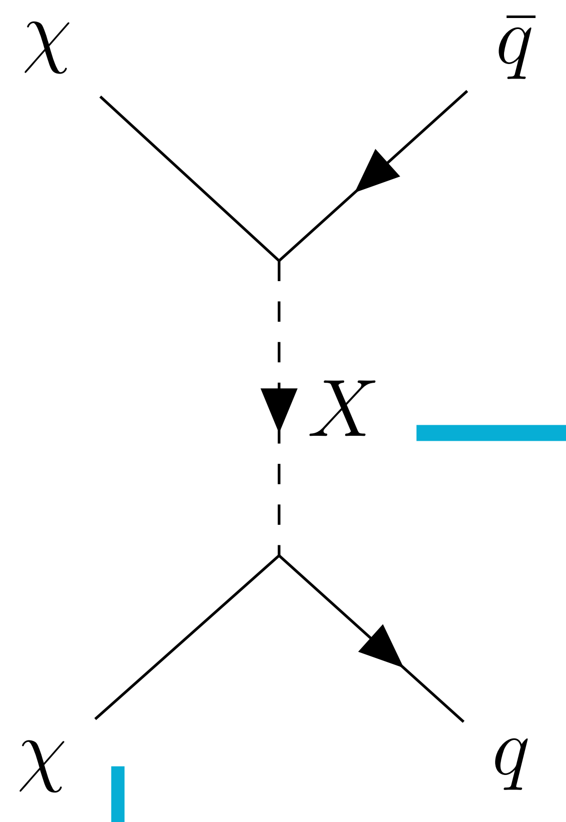
t-channel models

1. Strong constraints from direct detection searches
2. Strong constraints from collider searches
3. Radiative (1-loop) effects can be strong in direct detection

Let's illustrate this using a Simplified Model

$$\mathcal{L} \supset \sum_i (D_\mu X_i)^\dagger (D^\mu X_i) + \sum_{i,j} \left(g_{\mathrm{DM},ij} X_i^\dagger \bar{\chi} P_R q_j + g^*_{\mathrm{DM},ij} X_i \bar{q}_j P_L \chi \right)$$

A Majorana Fermion Dark Matter (Neutralino) interacting with Scalar Colored Scalar Mediators (Squarks)



QCD Colored Mediators

Dark Matter particle:
A Majorana Fermion

$$\langle \sigma v \rangle \simeq N_c^f g_{DM}^4 \left[\frac{m_f^2 \sqrt{1 - \frac{m_f^2}{m_\chi^2}}}{64\pi (m_{\tilde{q}}^2 + m_\chi^2 - m_f^2)^2} + \beta^2 \left\{ \frac{m_\chi^2 \sqrt{m_\chi^4 + m_{\tilde{q}}^4}}{32\pi (m_\chi^2 + m_{\tilde{q}}^2)^4} + \mathcal{O}(m_f^2) \right\} \right]$$

Velocity independent part (s wave) Velocity dependent part (p wave)

See K. Mohan, DS, T. Tait, B.Yan, C.P Yuan. JHEP 05 (2019) 115

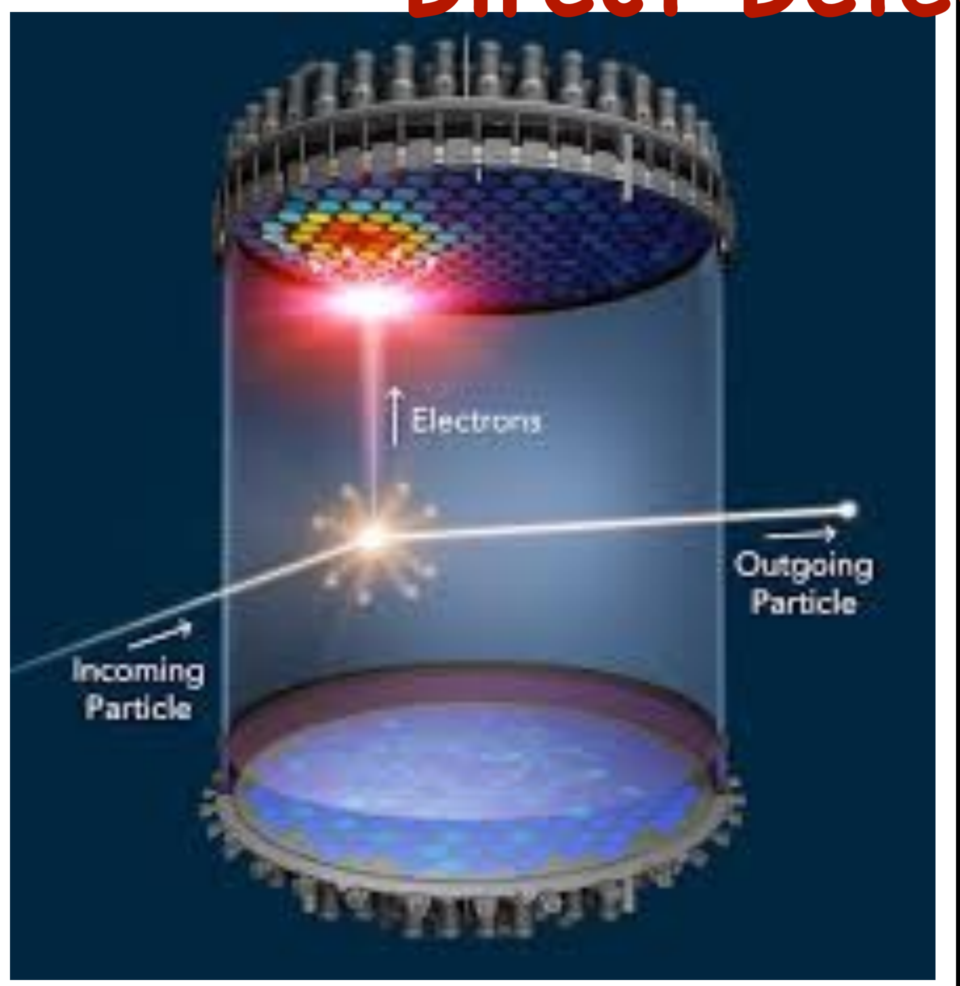
Spin-Independent : Coherent interaction with the whole Atomic Nucleus

Spin-Dependent : For Axial Vector coupling, couples to the spin of the Nucleus

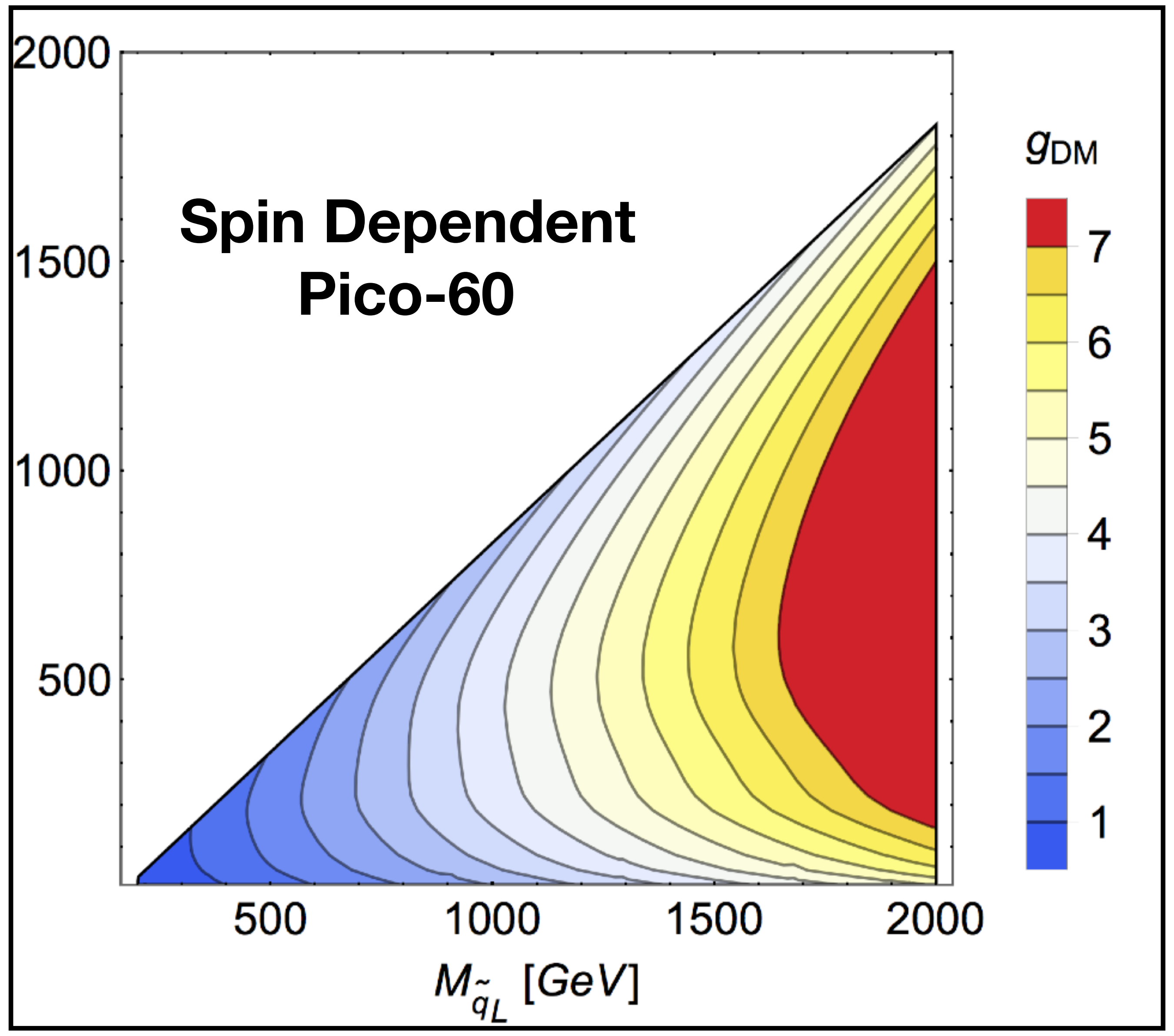
- Given a DM model, we need to calculate the spin-independent and spin-dependent cross sections at the quark level and match it at the nucleon level using form factors
- Spin-Indepedent limits at tree level more constraining than the spin-dependent part

Is the spin-independent 1-loop more sensitive than the tree level spin-dependent direct detection limit?

Direct Detection



Source: KIPAC



Direct Detection of Dark Matter 101

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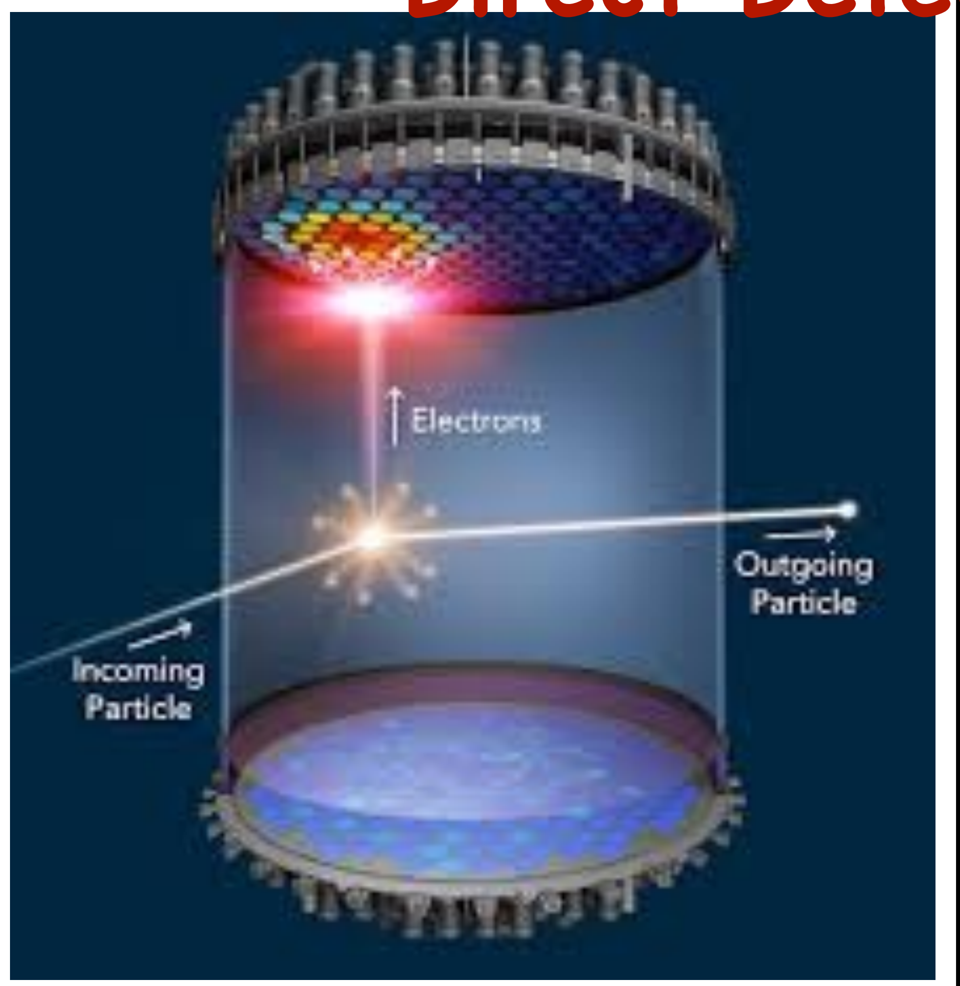
Direct Detection



Source: KIPAC

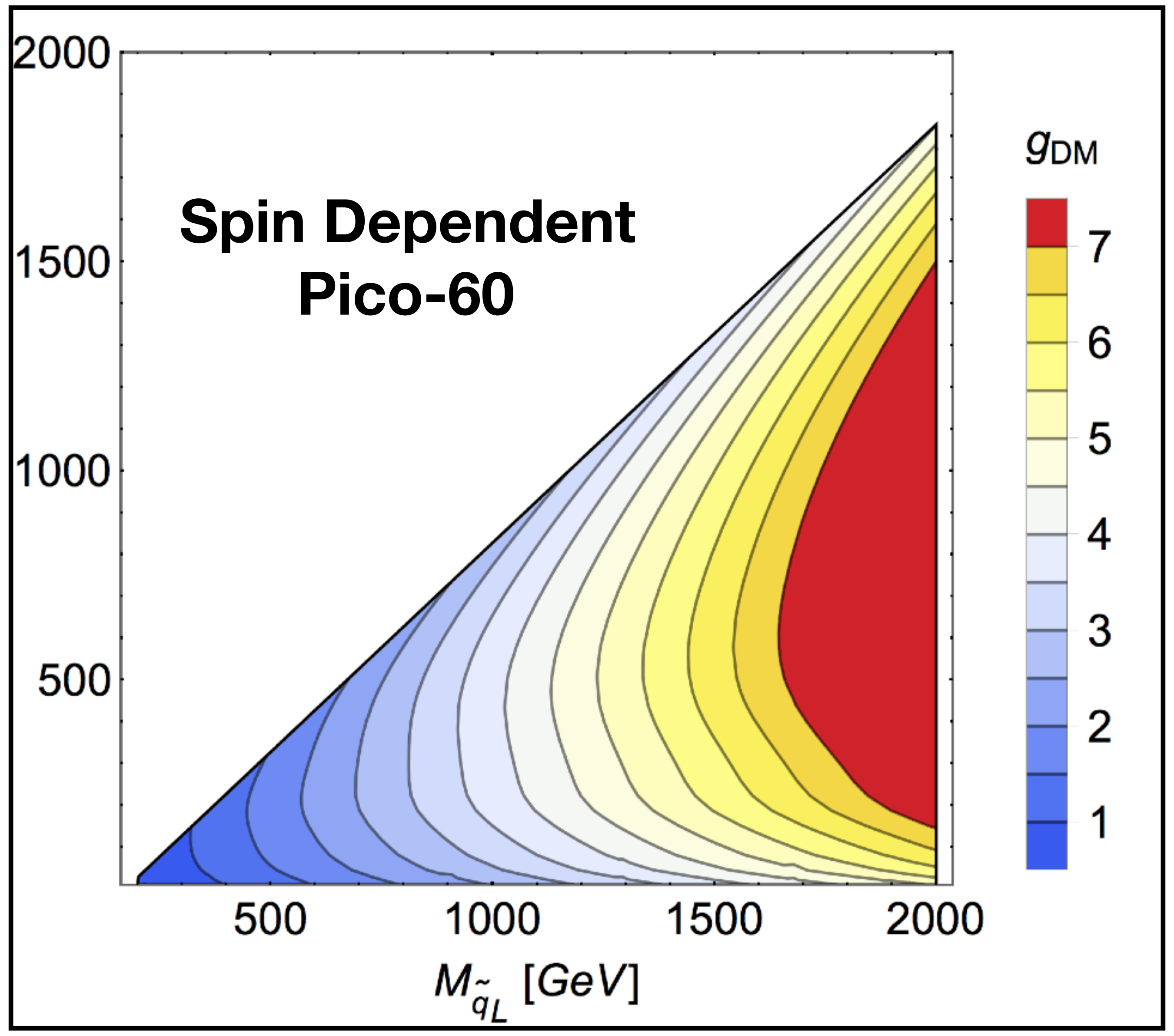
- Given a DM model, we need to calculate the spin-independent and spin-dependent cross sections at the quark level and match it at the nucleon level using form factors
- Spin-Indepedent limits at tree level more constraining than the spin-dependent part

$$\mathcal{M} = (-ig_{DM})^2(\bar{\chi}P_R u)\frac{i}{p^2 - M_{\tilde{u}}^2}(\bar{u}P_L\chi)$$

$$\approx \frac{ig_{DM}^2}{M_{\tilde{u}}^2 - m_\chi^2}\frac{1}{8}[(\bar{\chi}\gamma^\mu\chi)(\bar{u}\gamma_\mu u) - (\bar{\chi}\gamma^\mu\gamma^5\chi)(\bar{u}\gamma_\mu\gamma_5 u)]$$

SI = 0 for Majorana fermion
at tree level, Vector Bilinear vanishes

$$\sigma_p = \frac{4}{\pi}\left(\frac{M_\chi m_p}{M_\chi + m_p}\right)^2 |\langle\mathcal{M}_{DD}\rangle_{NR}|^2$$



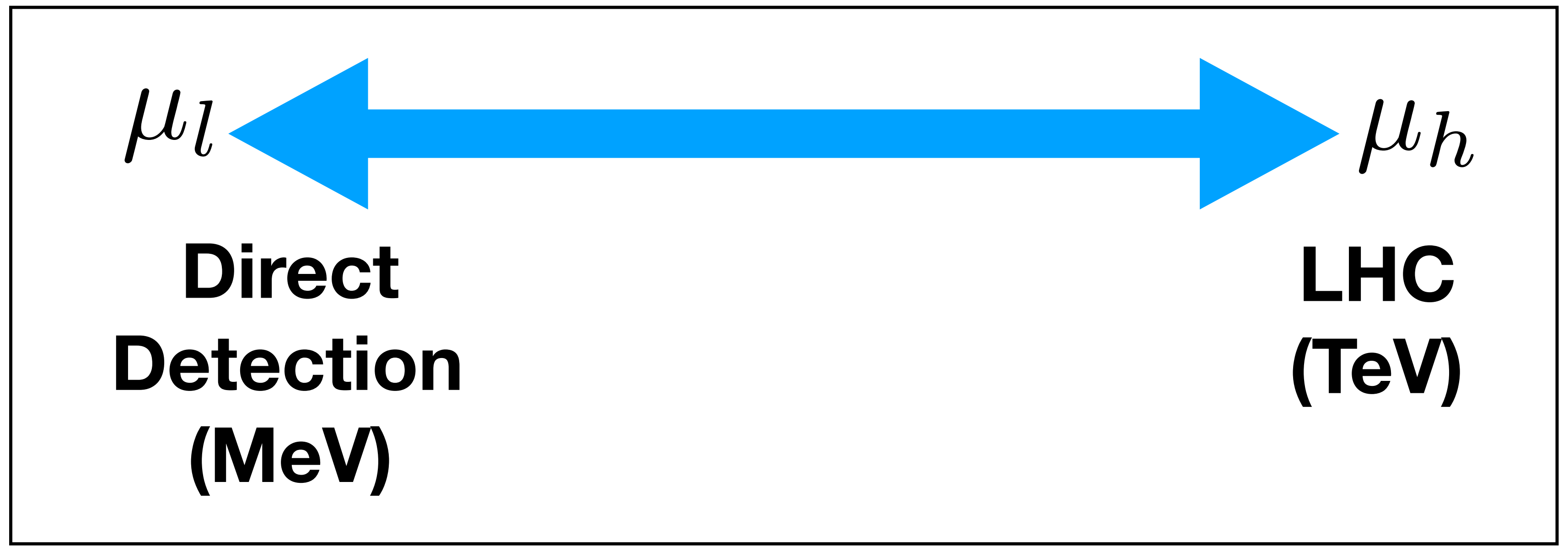
Is the spin-independent 1-loop more sensitive than the tree level spin-dependent direct detection limit?

We need to describe the effective theory of DM-Nucleon interaction at one loop

See K. Mohan, DS, T. Tait, B.Yan, C.P Yuan. JHEP 05 (2019) 115

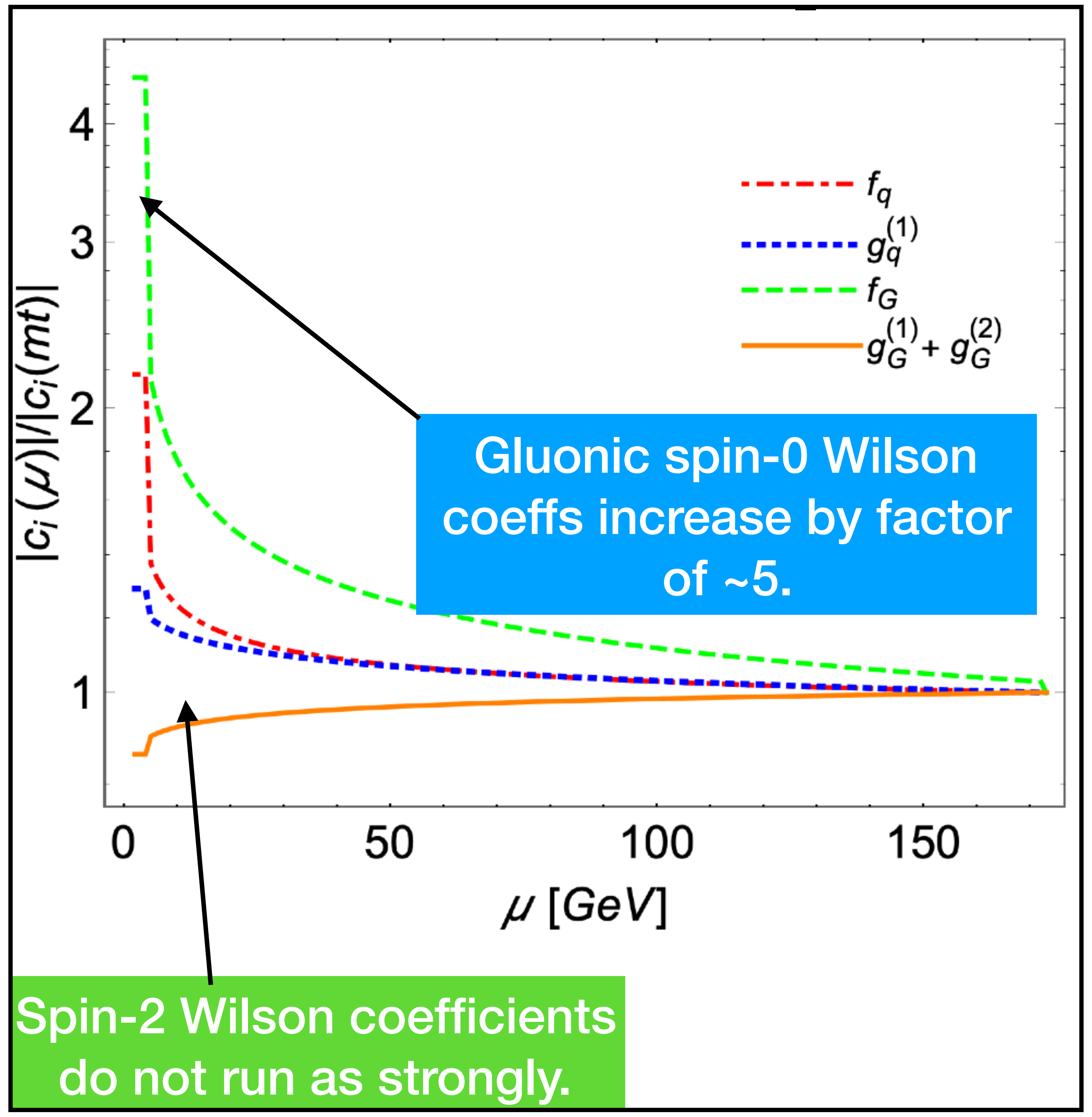
Constraints for the Simplified Model

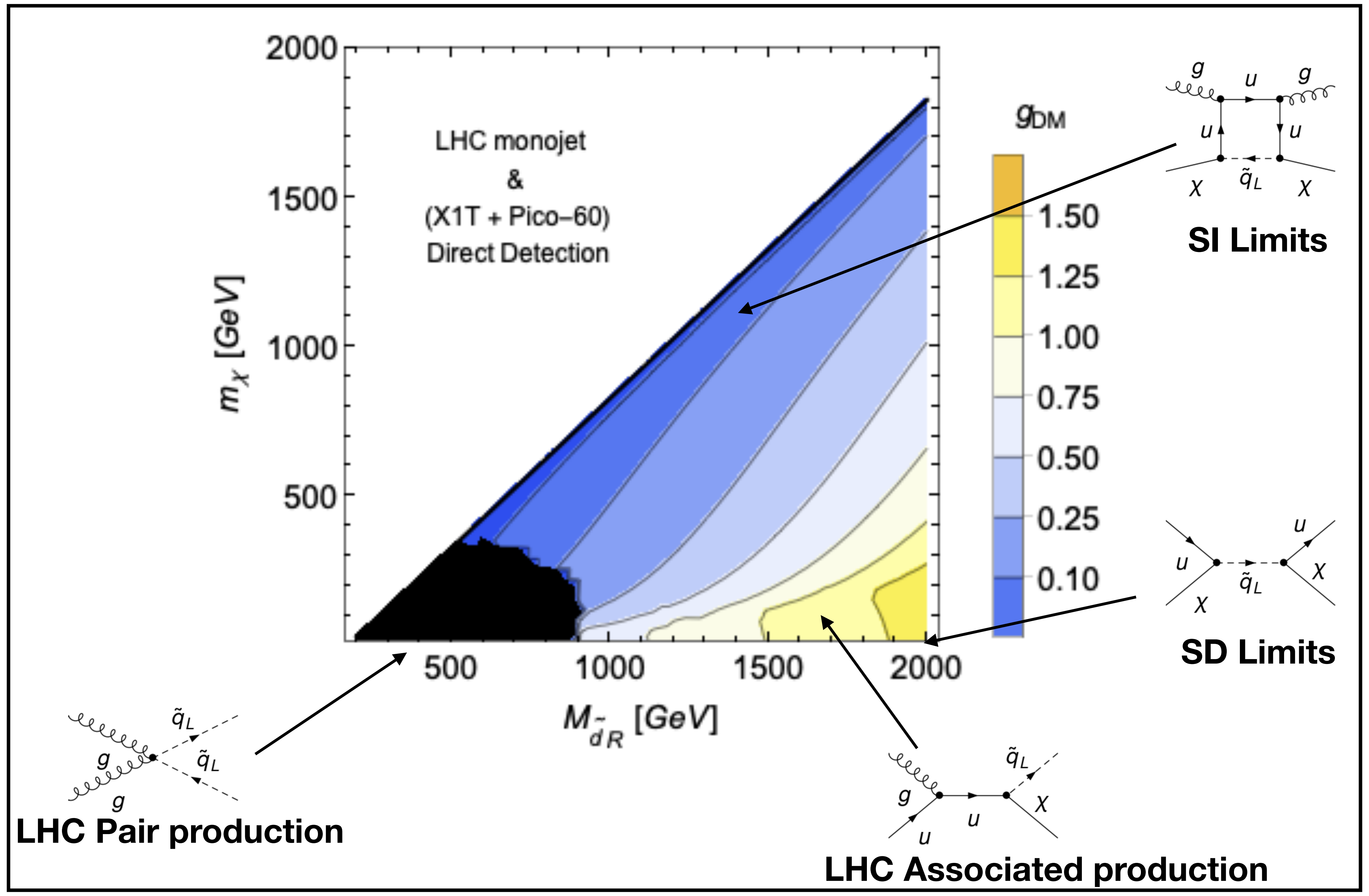
We also need a Renormalization Group Evolution



At what scale do we define coupling and masses?

If at nuclear scale, to compare to LHC we should run up, for the reverse, run down.





Take home message

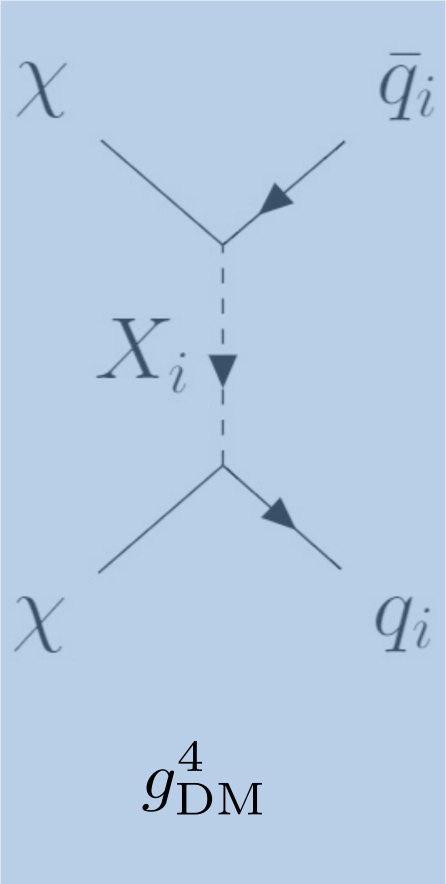
Precision Calculations can significantly improve constraints on the coupling (DM interaction)

Factor 4 enhancement in cross-section

See K. Mohan, DS, T. Tait, B.Yan, C.P Yuan. JHEP 05 (2019) 115 for details

Let's go deeper into the same model, think of small mass gap between DM and mediator

$$\delta \equiv \frac{m_X - m_\chi}{m_\chi} \equiv \frac{\Delta m}{m_\chi}, \quad \Delta m \equiv m_X - m_\chi$$



Large mass gap,
only relevant process

Coannihilations, Radiative and Non-Perturbative Effects in Relic Density Calculation

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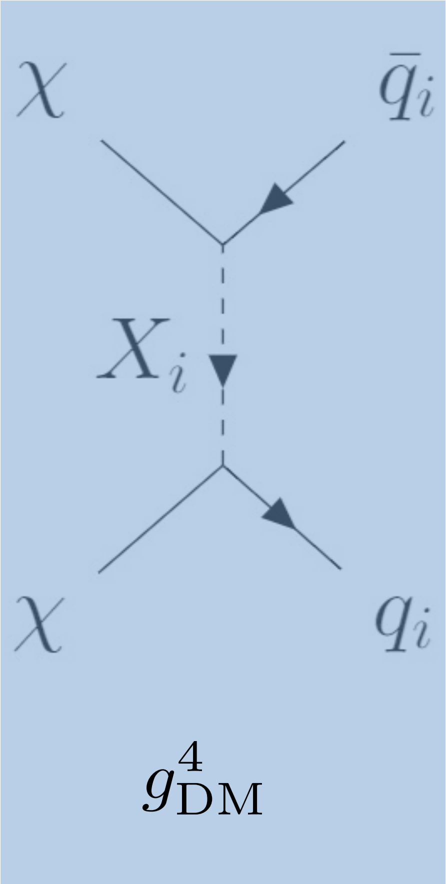

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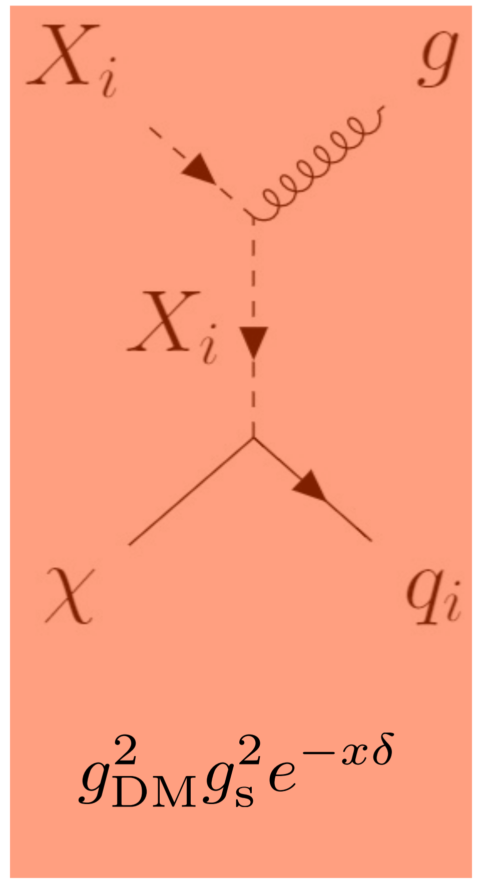

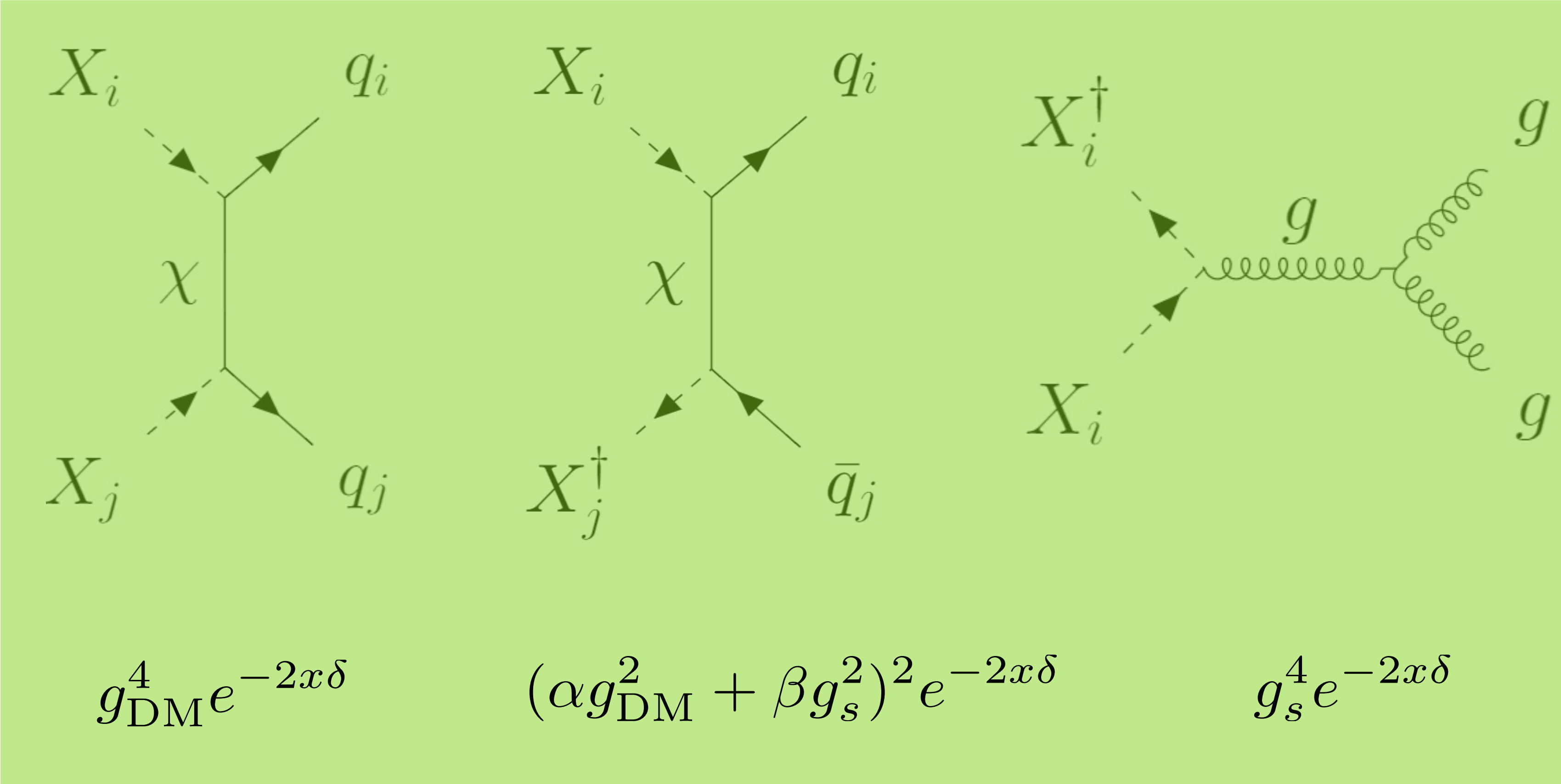

Small mass gap, additional coannihilation channels become relevant

$$\frac{dn}{dt} + 3Hn = -\langle \sigma_{\rm eff} v \rangle (n^2 - n^2_{\rm eq})$$

$$\langle \sigma_{\rm eff} v_{\rm rel} \rangle = \sum_{ij} \langle \sigma_{ij} v_{ij} \rangle \frac{n_{{\rm eq},i}}{n_{\rm eq}} \frac{n_{{\rm eq},j}}{n_{\rm eq}}$$

Coannihilating channels in Boltzmann equations

Coannihilations, Radiative and Non-Perturbative Effects in Relic Density Calculation

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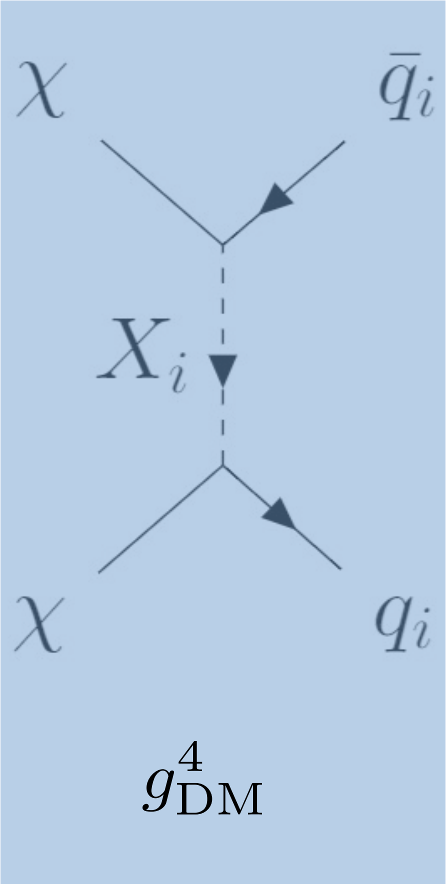

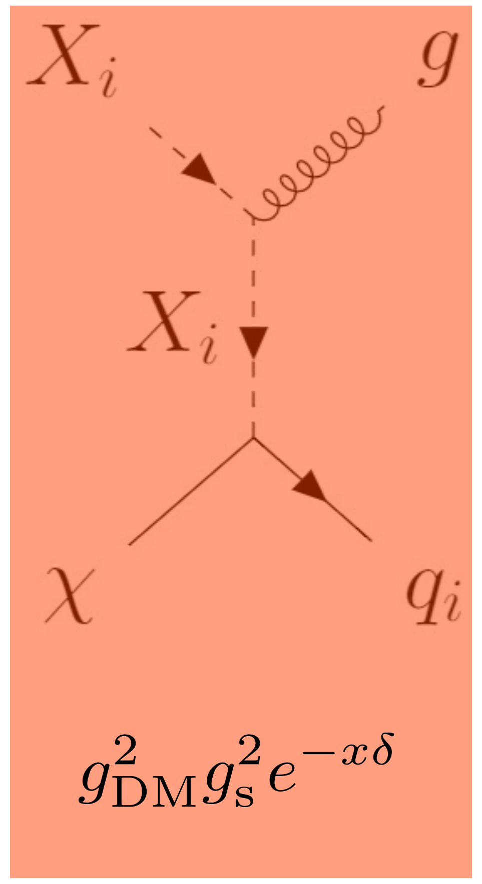

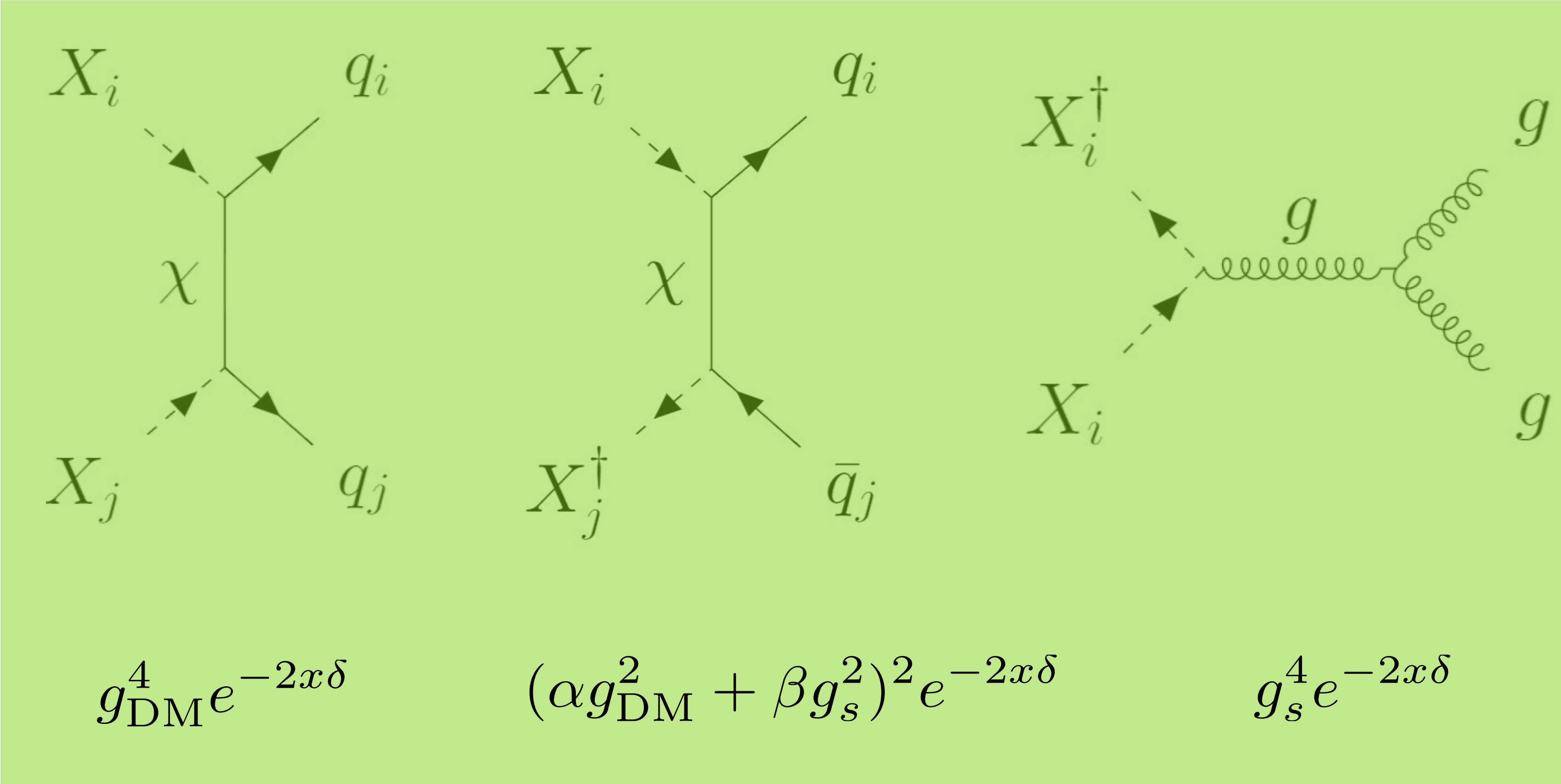

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Large mass gap, only relevant process

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Coannihilating channels in Boltzmann equations

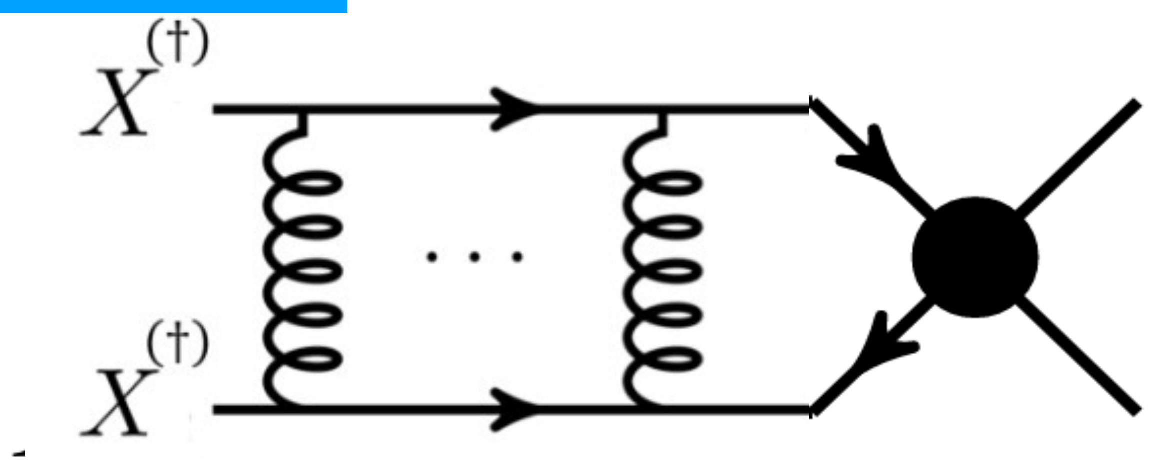
Assumptions:

- Coannihilating particle will later decay into DM $n = \sum_{i=1}^{N} n_i$
- Coannihilating particle in thermal equilibrium with DM particle $\Gamma(X + SM \longleftrightarrow \chi + SM) >> H$

Two further novel effects can affect the velocity averaged cross section

Sommerfeld Enhancement and Bound State Formation in relic abundance

Sommerfeld Enhancement



$$\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{1} \oplus \mathbf{8}$$

$$\mathbf{3} \otimes \mathbf{3} = \bar{\mathbf{3}} \oplus \mathbf{6}$$

- Relevant for $\alpha \sim v_{\rm rel}$
- Exchange of n gluons lead to $\left(\frac{\alpha}{v_{\rm rel}}\right)^n \sim 1$, which requires resummation

Non-relativistic enhancement of cross section due to an attractive potential

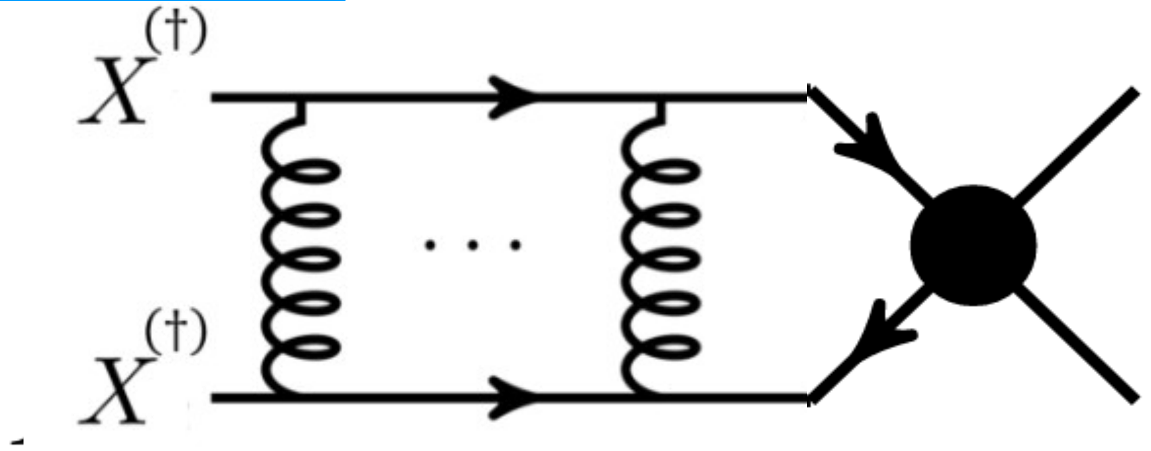
$$V(r)_{\mathbf{3}\otimes\bar{\mathbf{3}}} = \begin{cases} -\frac{4}{3}\frac{\alpha_s^S}{r} & [\mathbf{1}] \quad \textbf{attractive} \\ +\frac{1}{6}\frac{\alpha_s^S}{r} & [\mathbf{8}] \quad \textbf{repulsive} \end{cases}$$

$$\sigma_{\rm SE} = S_0\left(\frac{\alpha_s^S C_{[\hat{\mathbf{R}}]}}{v_{\rm rel}}\right)\sigma_0$$

Enhancement for attractive potential

Sommerfeld Enhancement and Bound State Formation in relic abundance

Sommerfeld Enhancement



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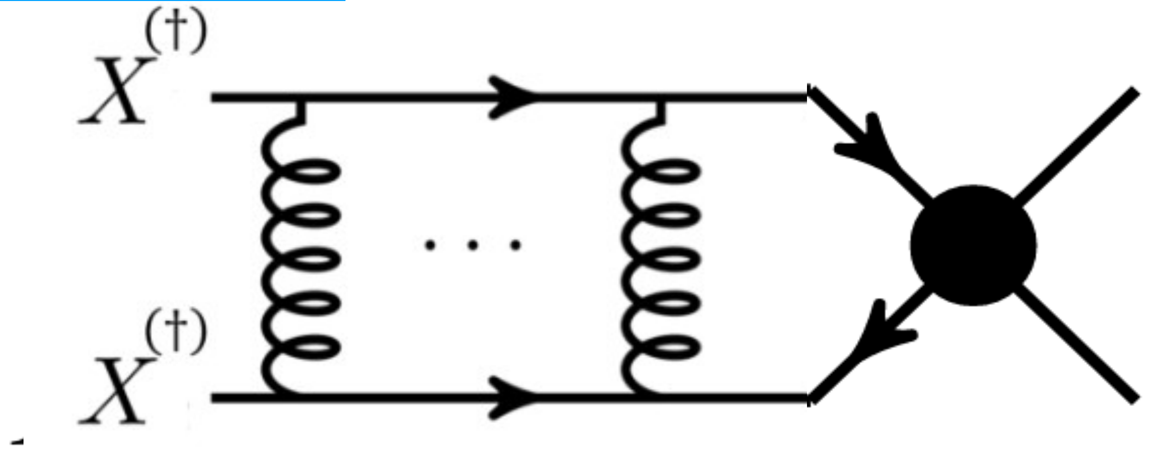
Enhancement for attractive potential

Bound State Formation

Sommerfeld Enhancement and Bound State Formation in relic abundance

Sommerfeld Enhancement



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- Exchange of n gluons lead to $\left(\frac{\alpha}{v_{\text{rel}}}\right)^n \sim 1$, which requires resummation

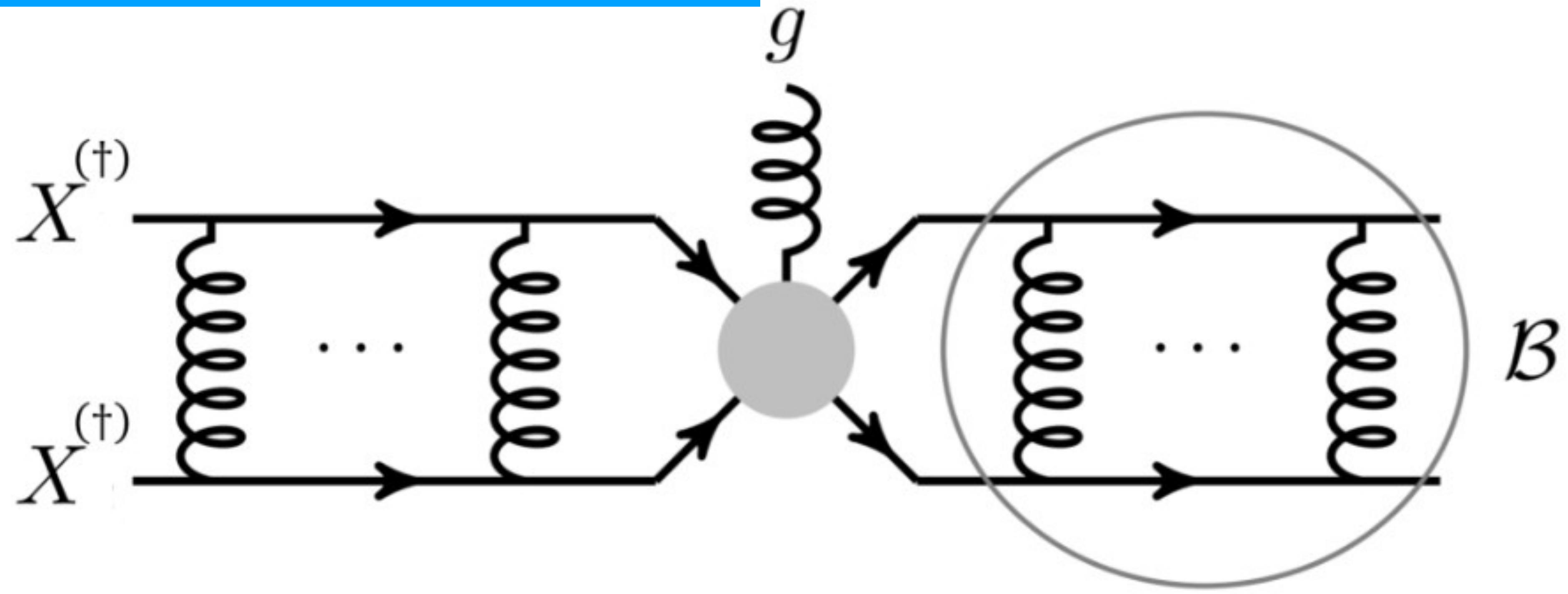
Non-relativistic enhancement of cross section due to an attractive potential

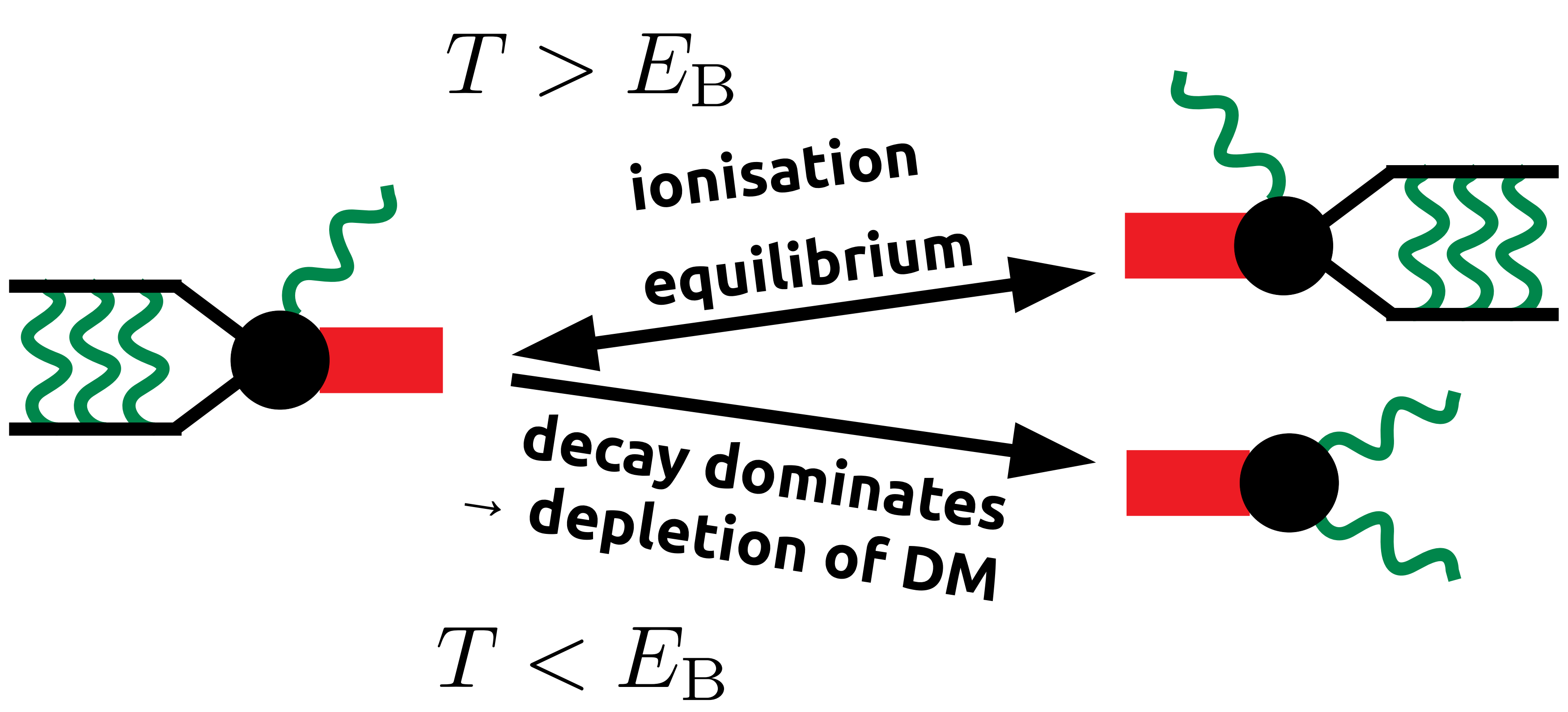
$$V(r)_{\mathbf{3}\otimes\bar{\mathbf{3}}} = \begin{cases} -\frac{4}{3}\frac{\alpha_s^S}{r} & [\mathbf{1}] \quad \textbf{attractive} \\ +\frac{1}{6}\frac{\alpha_s^S}{r} & [\mathbf{8}] \quad \textbf{repulsive} \end{cases}$$

$$\sigma_{\text{SE}} = S_0\left(\frac{\alpha_s^S C_{[\hat{\mathbf{R}}]}}{v_{\text{rel}}}\right)\sigma_0$$

Enhancement for attractive potential

Bound State Formation





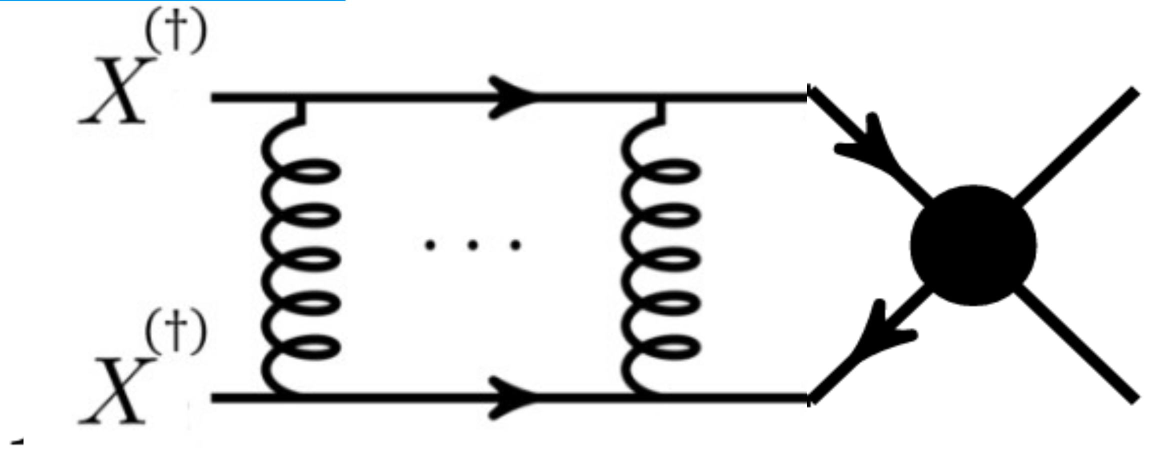
bound state formation

bound state ionisation

bound state decay

Sommerfeld Enhancement and Bound State Formation in relic abundance

Sommerfeld Enhancement



$$\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{1} \oplus \mathbf{8}$$

$$\mathbf{3} \otimes \mathbf{3} = \bar{\mathbf{3}} \oplus \mathbf{6}$$

- Relevant for $\alpha \sim v_{\rm rel}$
- Exchange of n gluons lead to $\left(\frac{\alpha}{v_{\rm rel}}\right)^n \sim 1$, which requires resummation

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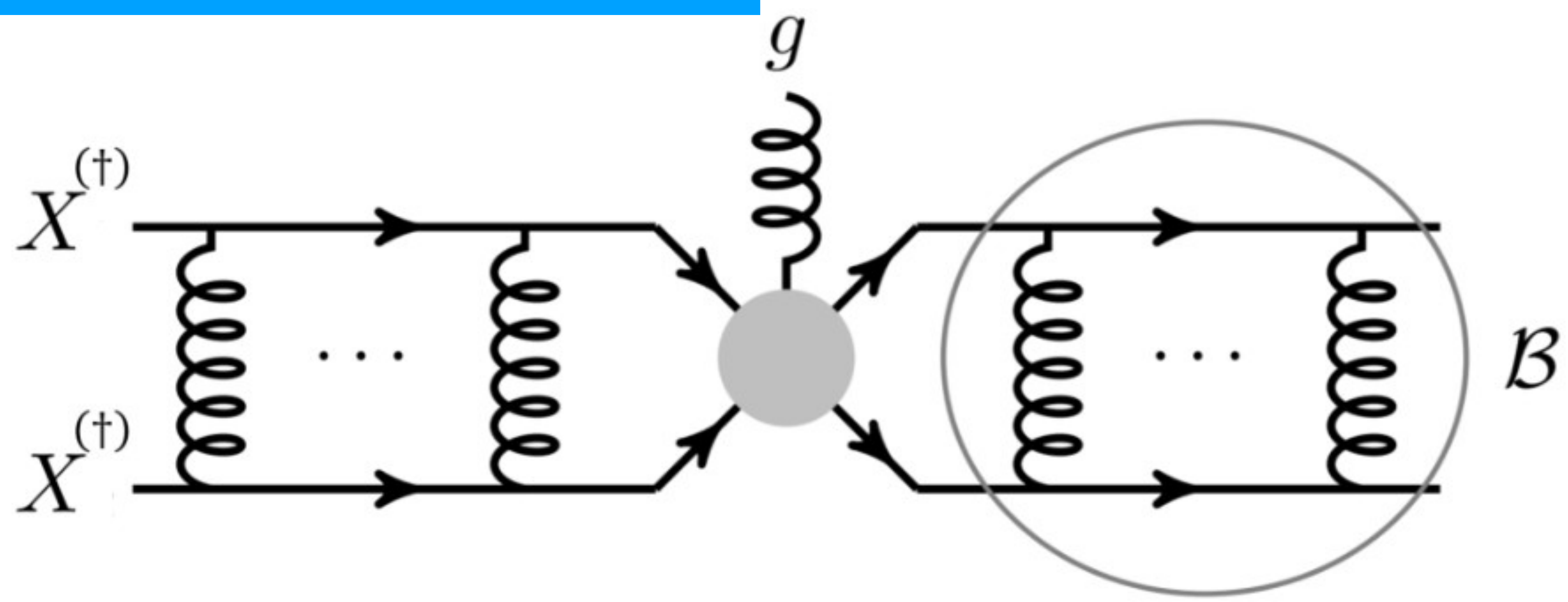
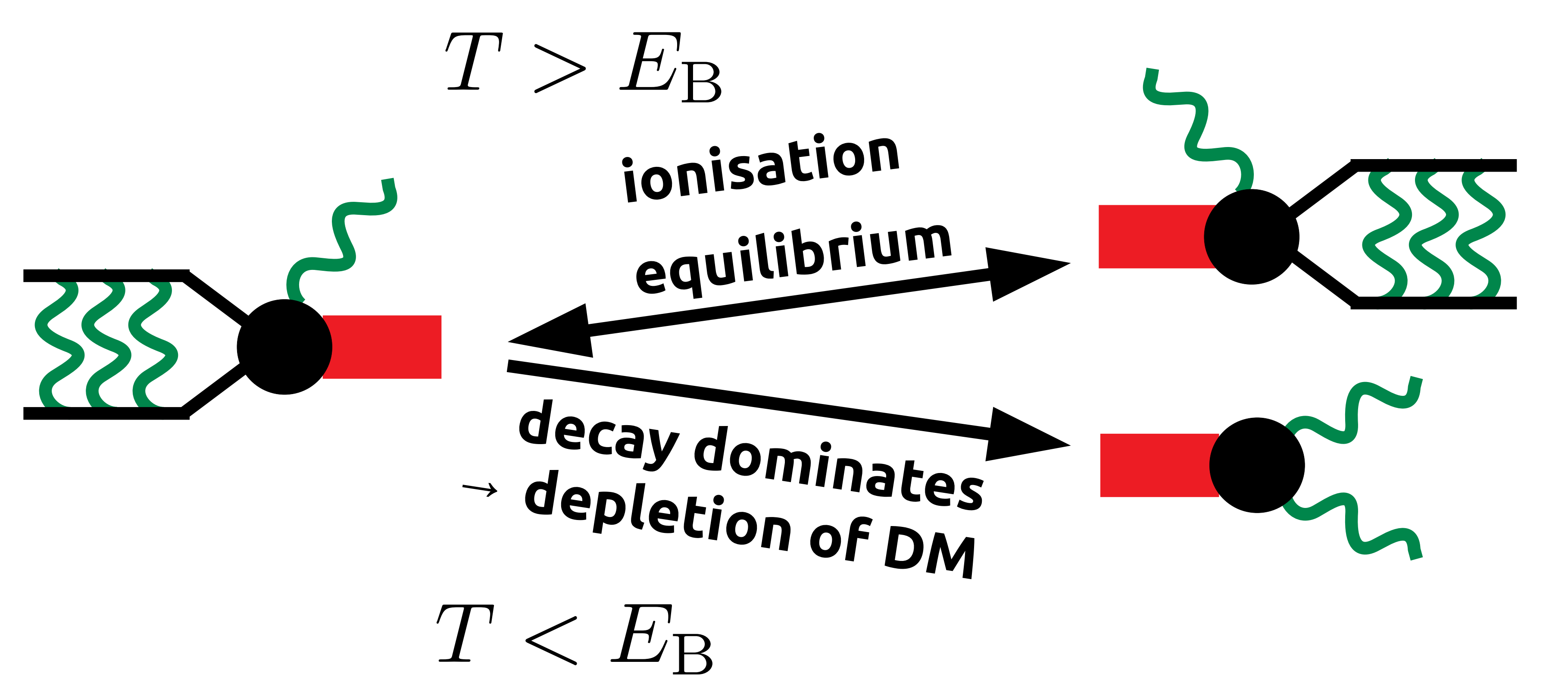




bound state formation

bound state ionisation

bound state decay

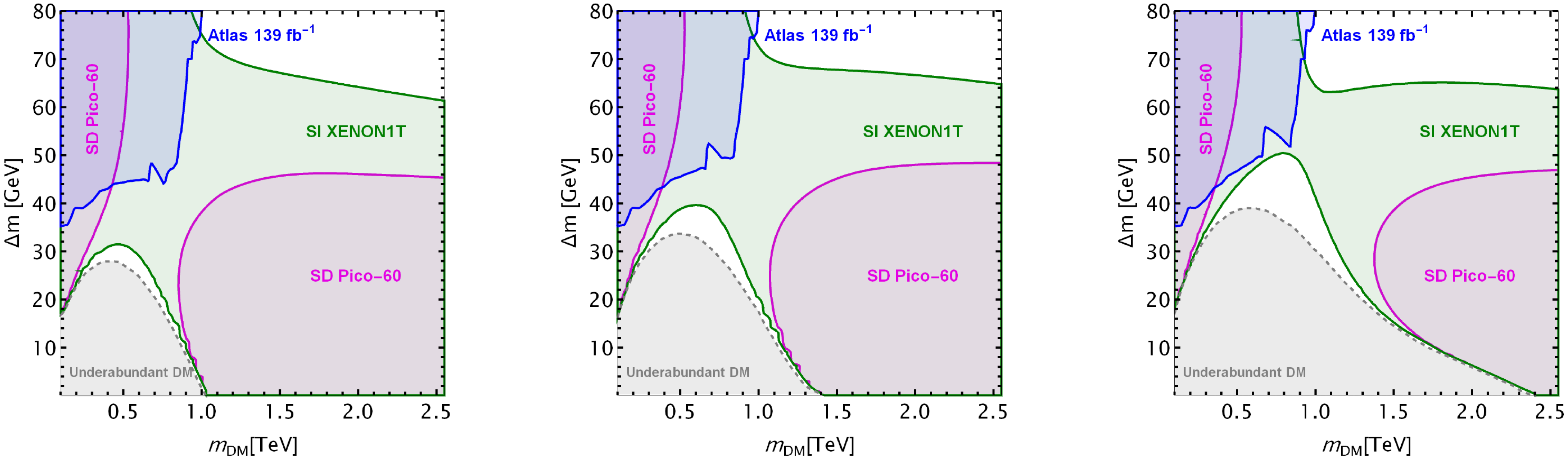
$$\langle\sigma_{\rm eff} v_{\rm rel}\rangle = \sum_{ij}\langle S\left(\frac{\alpha}{v_{ij}}\right)\cdot\sigma_{ij}v_{ij}\rangle\frac{n_{{\rm eq},i}}{n_{\rm eq}}\frac{n_{{\rm eq},j}}{n_{\rm eq}} + \langle\sigma_{\rm BSF}v_{\rm rel}\rangle_{\rm eff}\left(\frac{n_{{\rm eq},X}}{n_{\rm eq}}\right)^2$$

M. Becker, E. Copello, J. Harz K. Mohan, **DS**. JHEP08(2022) 145

Also see J. Harz, K. Petraki JHEP2018, Klasen, Harz, Wiggering,Sassi PRD2023

Impact of Sommerfeld Enhancement and bound states

perturbative only **+ Sommerfeld effect** **+ bound states**



- DD and LHC searches set upper bound on g_{DM}
- Requirement of non-overproduction sets lower bound on g_{DM}
  - → **Correction on g_{DM} due to SE and BSF lead to altered exclusion limits**
  - → **opens up parameter space that was previously thought to be excluded**

1. The model tightly constrained by Direct Detection,
2. Model parameters then relaxed by SE + BSF.

The package is now implemented in MicrOmegas Dark Matter Tool

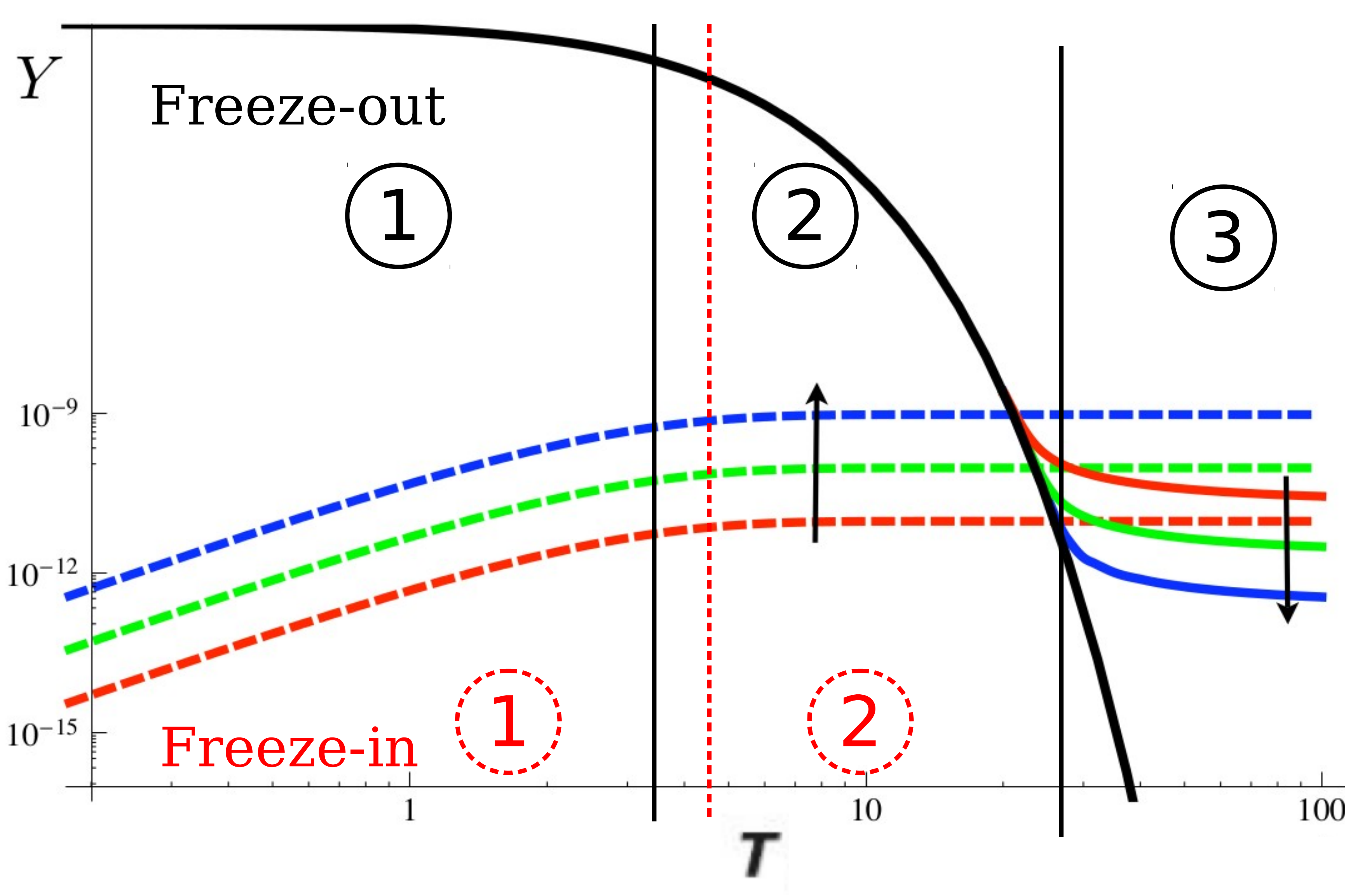
M. Becker, E. Copello, J. Harz K. Mohan, DS. JHEP08(2022) 145

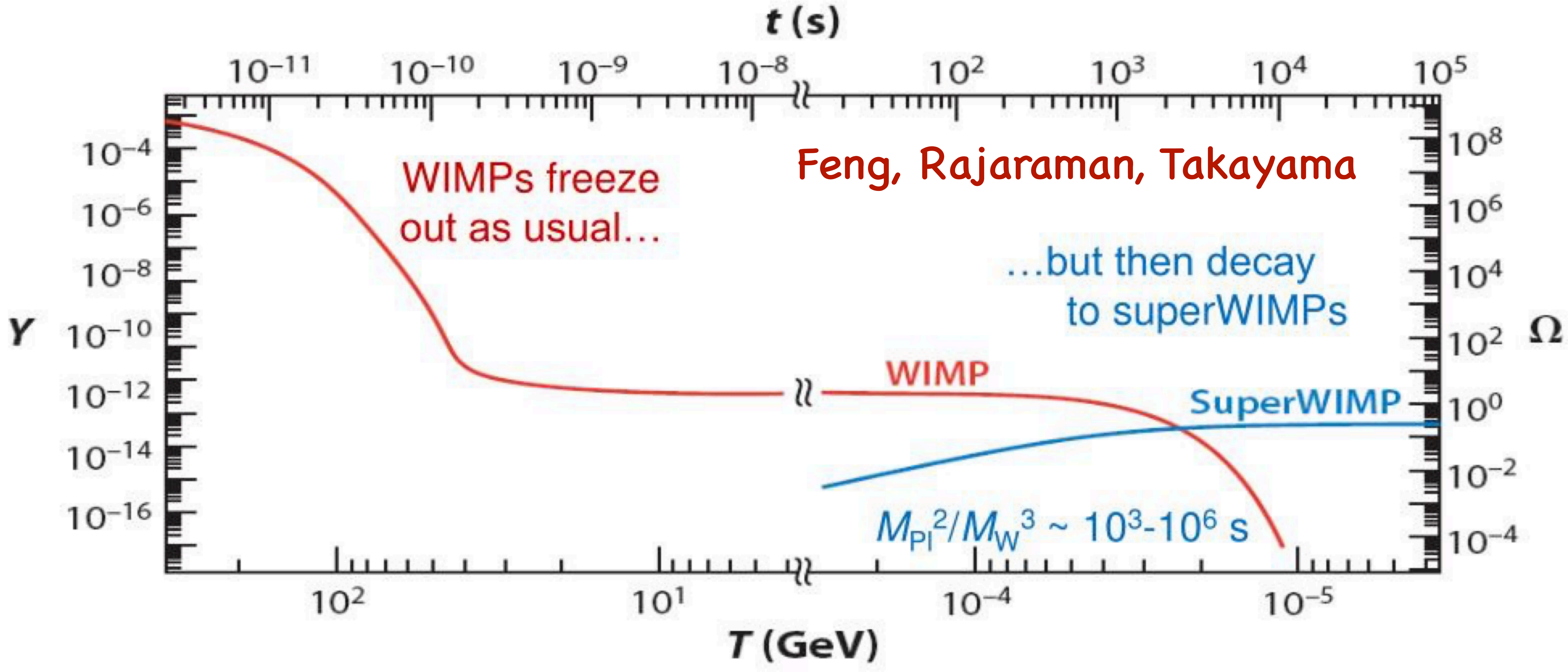
Alternative Mechanisms of Dark Matter Production

(Non-) Thermal mechanisms

- **Freeze-In**
- **Super WIMPS**

Tweaked from arXiv:0911.1120





Both set ups characterised by extremely weakly interacting particles

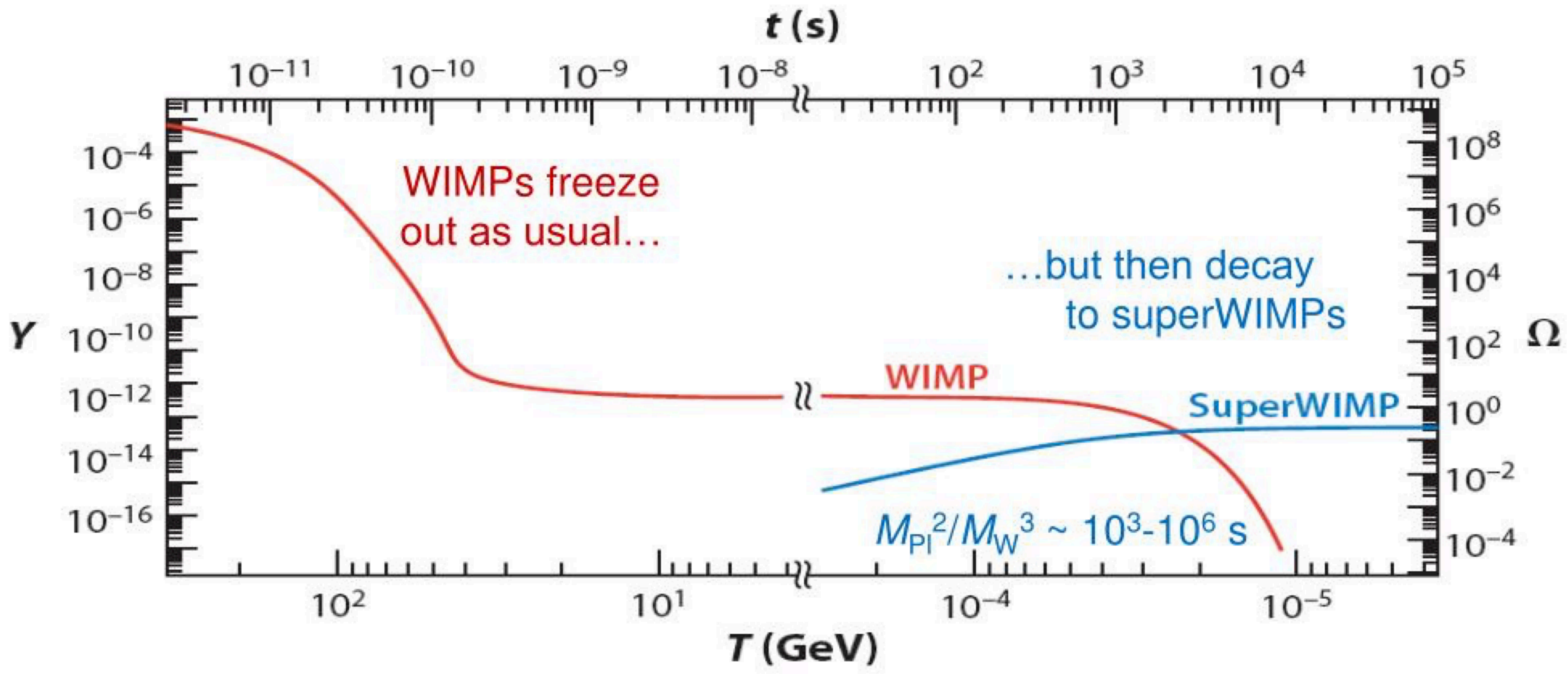
Cosmological Probes of SuperWIMP Dark Matter

What if Neutralinos are not the Lightest SUSY particle, but next to lightest?

- In Supergravity inspired Supersymmetry scenarios, the gravitino can be the lightest particle, and very very weakly coupled to the neutralino, leading to a long lived neutralino (decaying to a gravitino + a Photon).
- The neutralino (a WIMP) can Freeze-out, and long afterwards decay to gravitino (**SuperWIMP**).
- Being extremely long lived it will escape the detector without a trace (No prompt searches).
- However it will leave definite signatures in Cosmology due to energy dump as photon.

Feng, Rajaraman, Takayama hep-ph/0306204

The gravitino mass is a free parameter related to the SUSY breaking scale F



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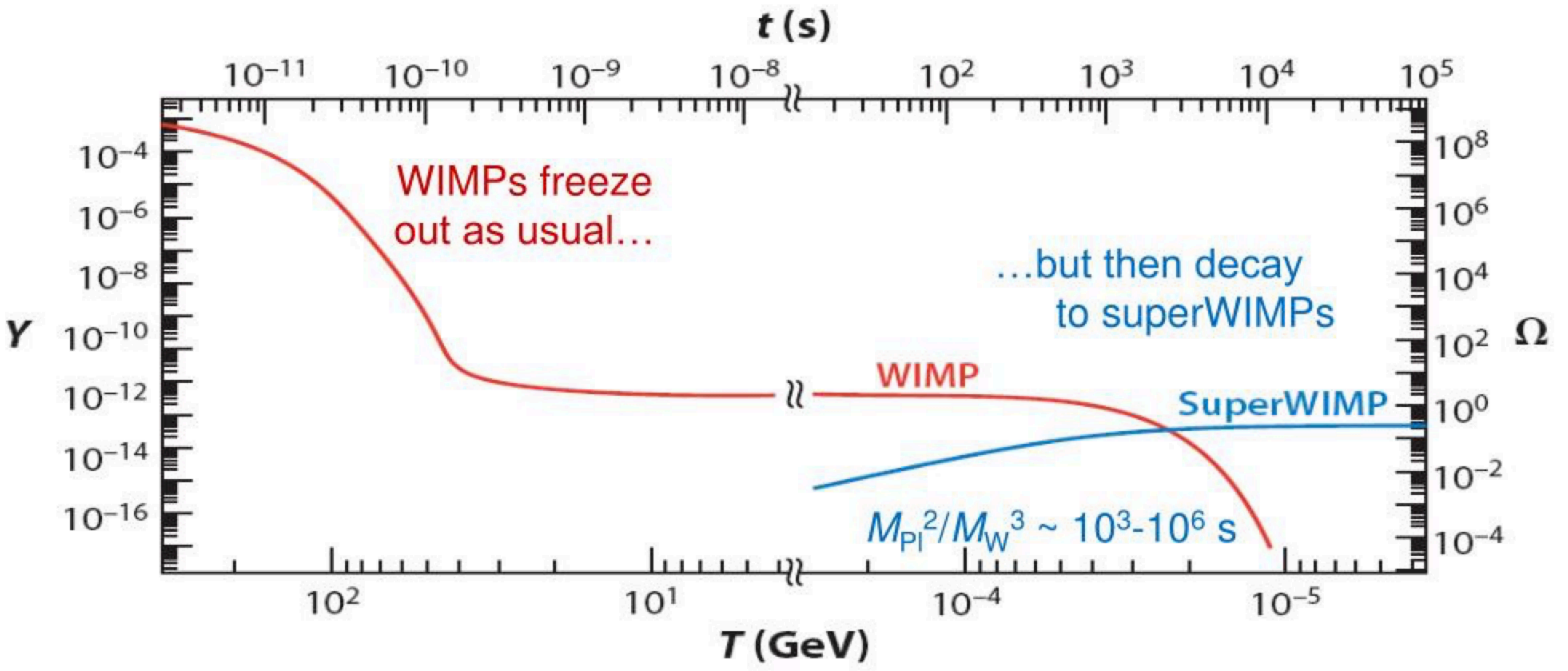
The gravitino mass is a free parameter related to the SUSY breaking scale F

$$m_{\tilde{G}} \simeq \langle F \rangle / m_{\rm pl}$$

$$\begin{aligned}\Gamma(\chi_1^0 \to \tilde{G}\gamma) &= \frac{m_{\chi_1^0}^5 \cos^2\theta_W}{6\pi m_{\rm Pl}^2 m_{\tilde{G}}^2} \epsilon_{\rm SM}^3 \left(1 + 3\frac{m_{\tilde{G}}^2}{m_{\chi_1^0}^2}\right) \\ &\simeq 1.1 \times 10^{-14}\ {\rm s}^{-1}\, \epsilon_{\rm SM}^3 \left(1 + 3\frac{m_{\tilde{G}}^2}{m_{\chi_1^0}^2}\right) \\ &\times \left(\frac{m_{\chi_1^0}}{\rm GeV}\right)^5 \left(\frac{\rm GeV}{m_{\tilde{G}}}\right)^2 ,\end{aligned}$$

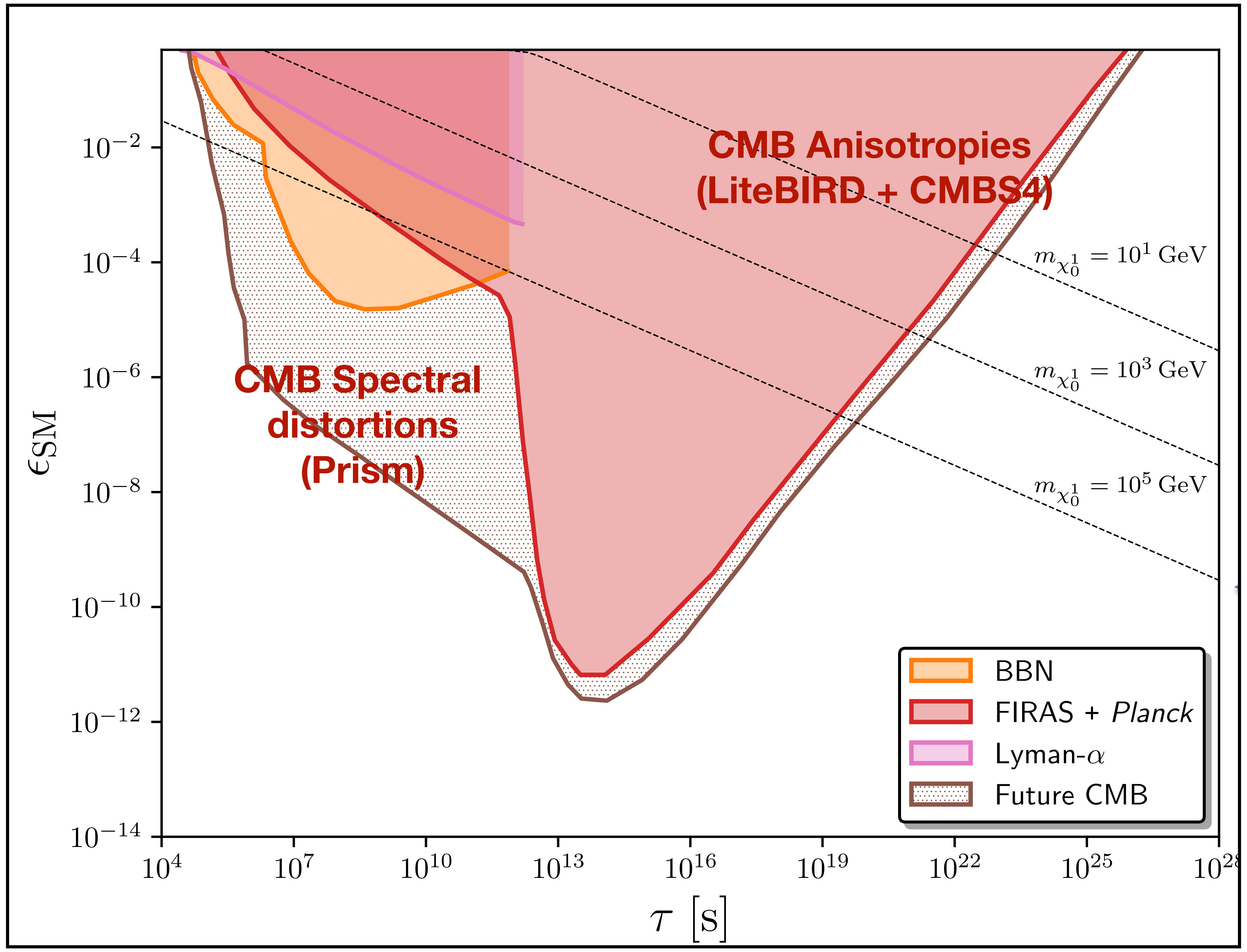


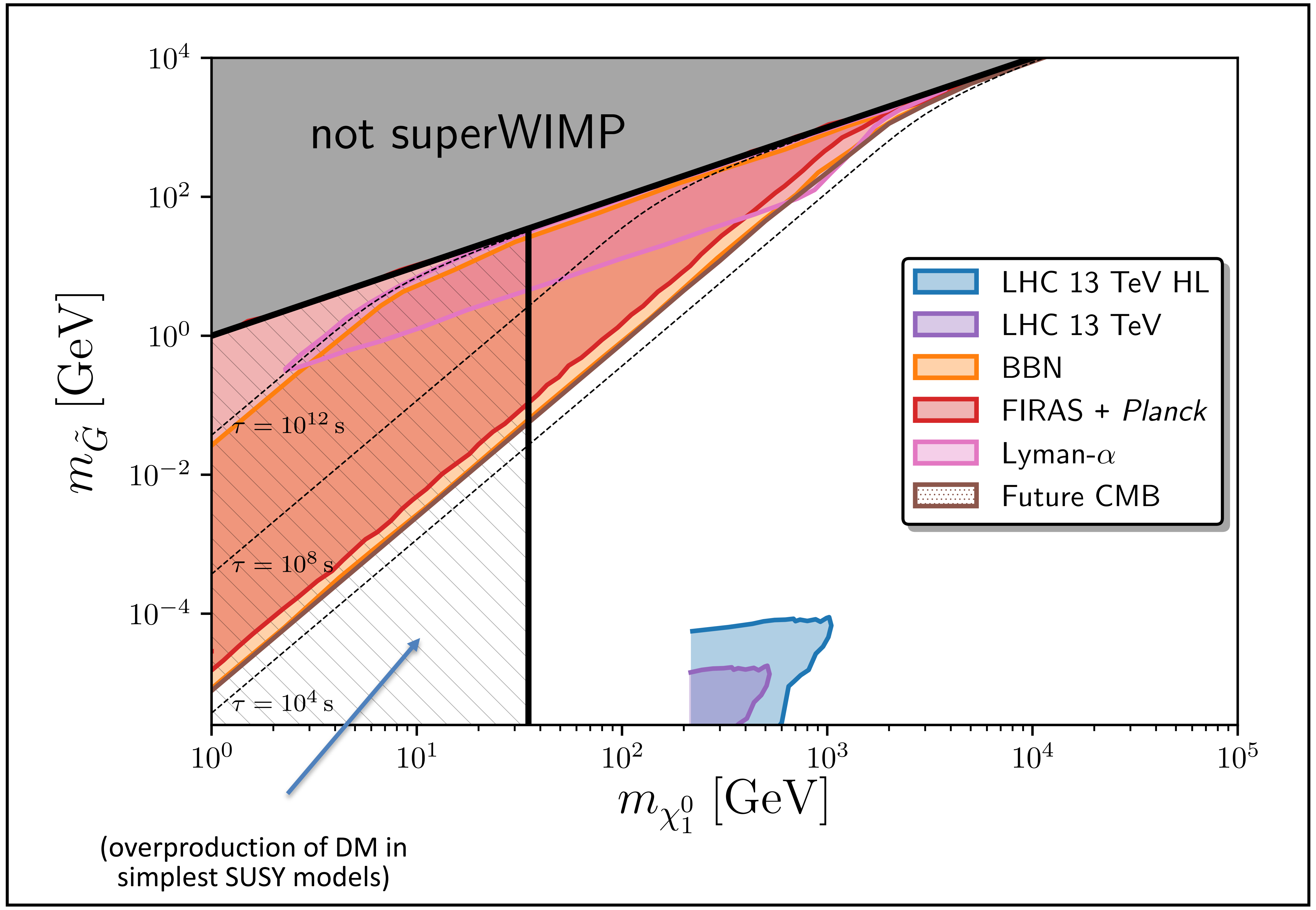
Extremely long lived

$$L = c\tau \simeq 2.8 \times 10^{22} \left(\frac{\rm GeV}{m_{\chi_1^0}}\right)^3 \frac{(1 - 2\epsilon_{SM})}{\epsilon_{SM}^3 (1 + 3(1 - 2\epsilon_{SM}))} m$$

$$\epsilon_{\rm SM} \equiv \frac{E_\gamma}{m_{\chi_1^0}} = \frac{m_{\chi_1^0}^2 - m_{\tilde{G}}^2}{2 m_{\chi_1^0}^2}$$

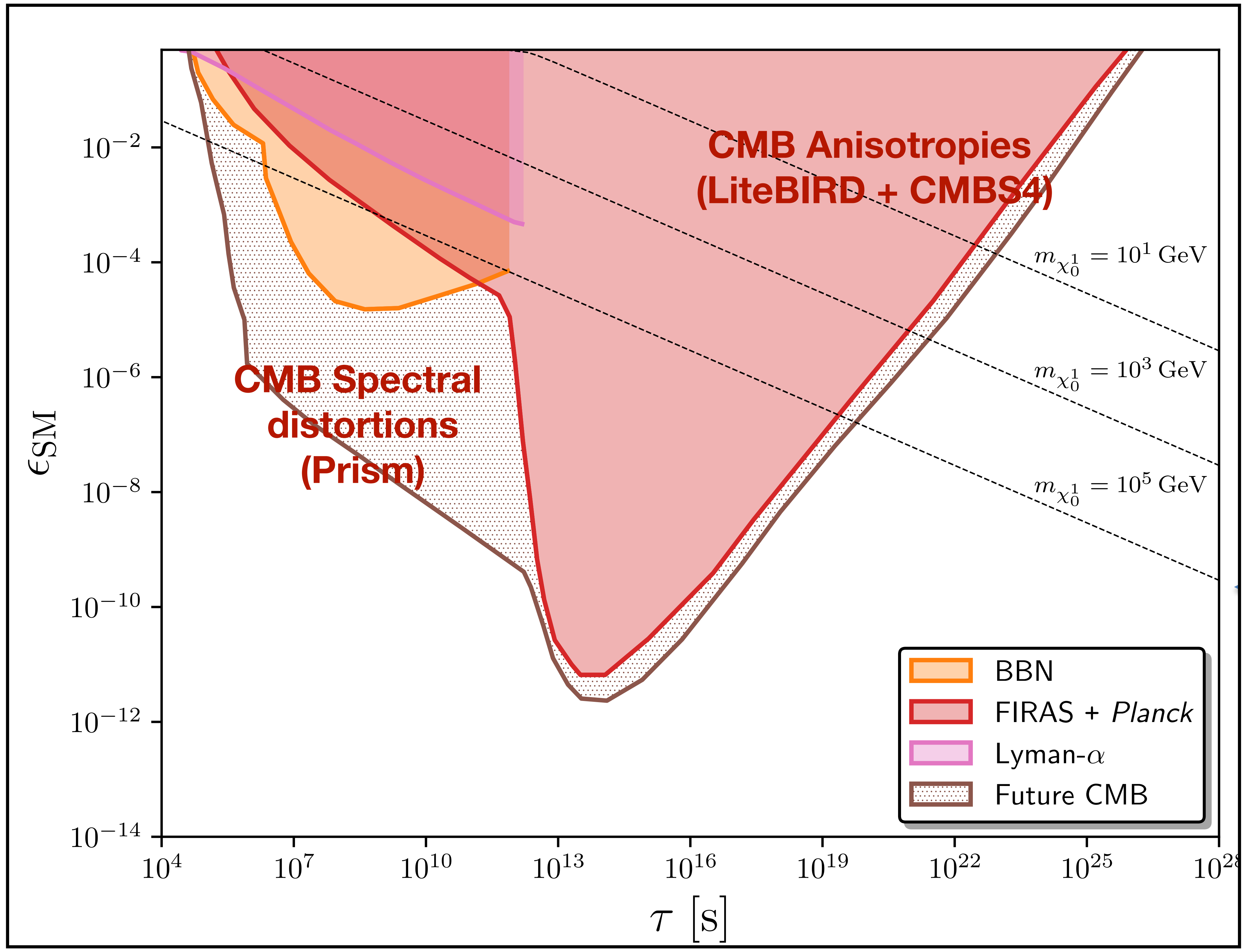
Cosmological Constraints on SuperWIMPs

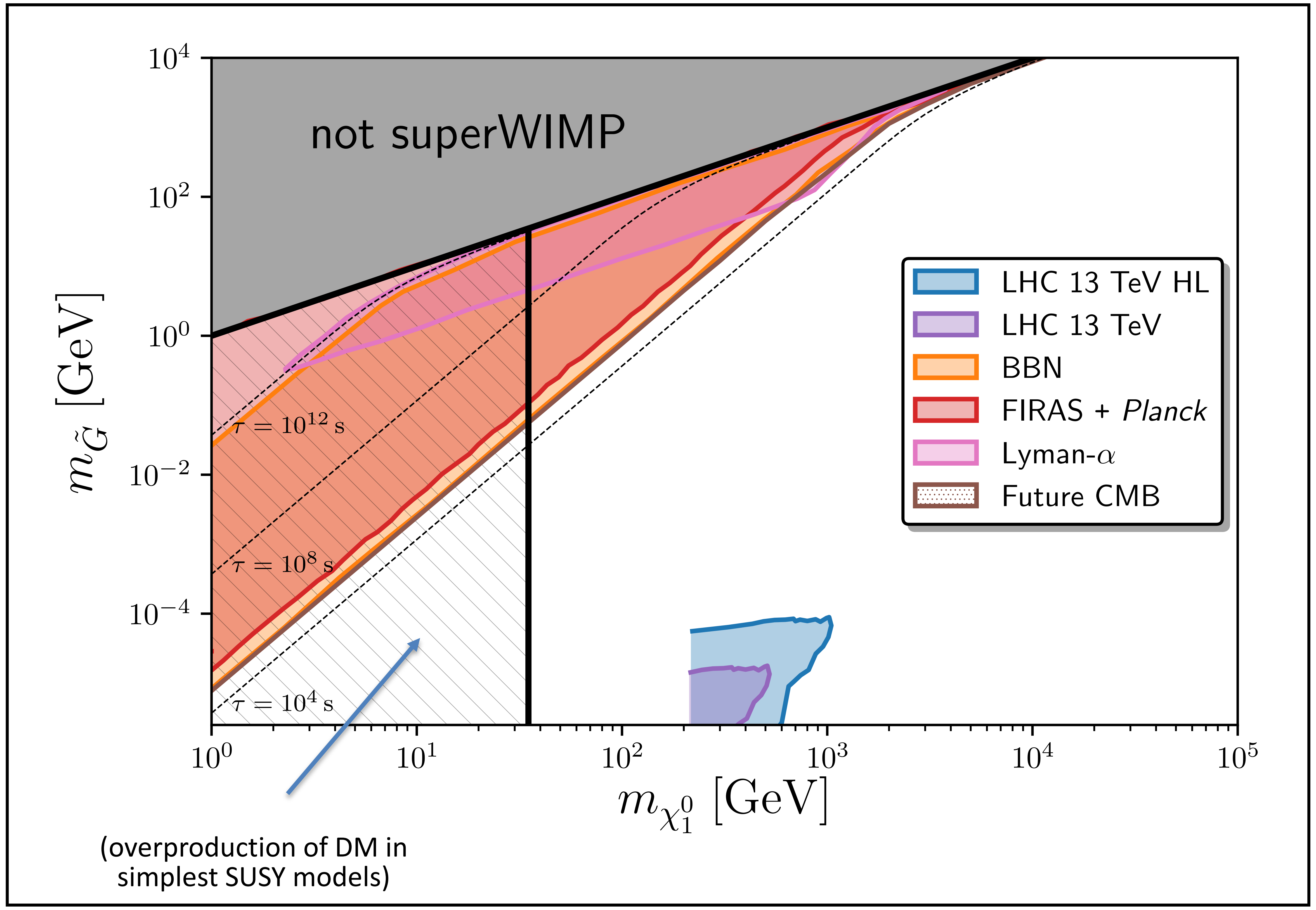




EPJCXXXX

Cosmological Constraints on SuperWIMPs





Cosmological constraints on Supersymmetric superWIMPs

Meera Deshpande[a], Jan Hamann[b], Dipan Sengupta[a],
Martin White[a], Anthony G. Williams[a], and Yvonne Y. Y. Wong[b]
[a] *ARC Centre of Excellence for Dark Matter Particle Physics, Department of Physics, The University of Adelaide, Adelaide SA 5005, Australia* and
[b] *Sydney Consortium for Particle Physics and Cosmology, School of Physics, The University of New South Wales, Sydney NSW 2052, Australia*

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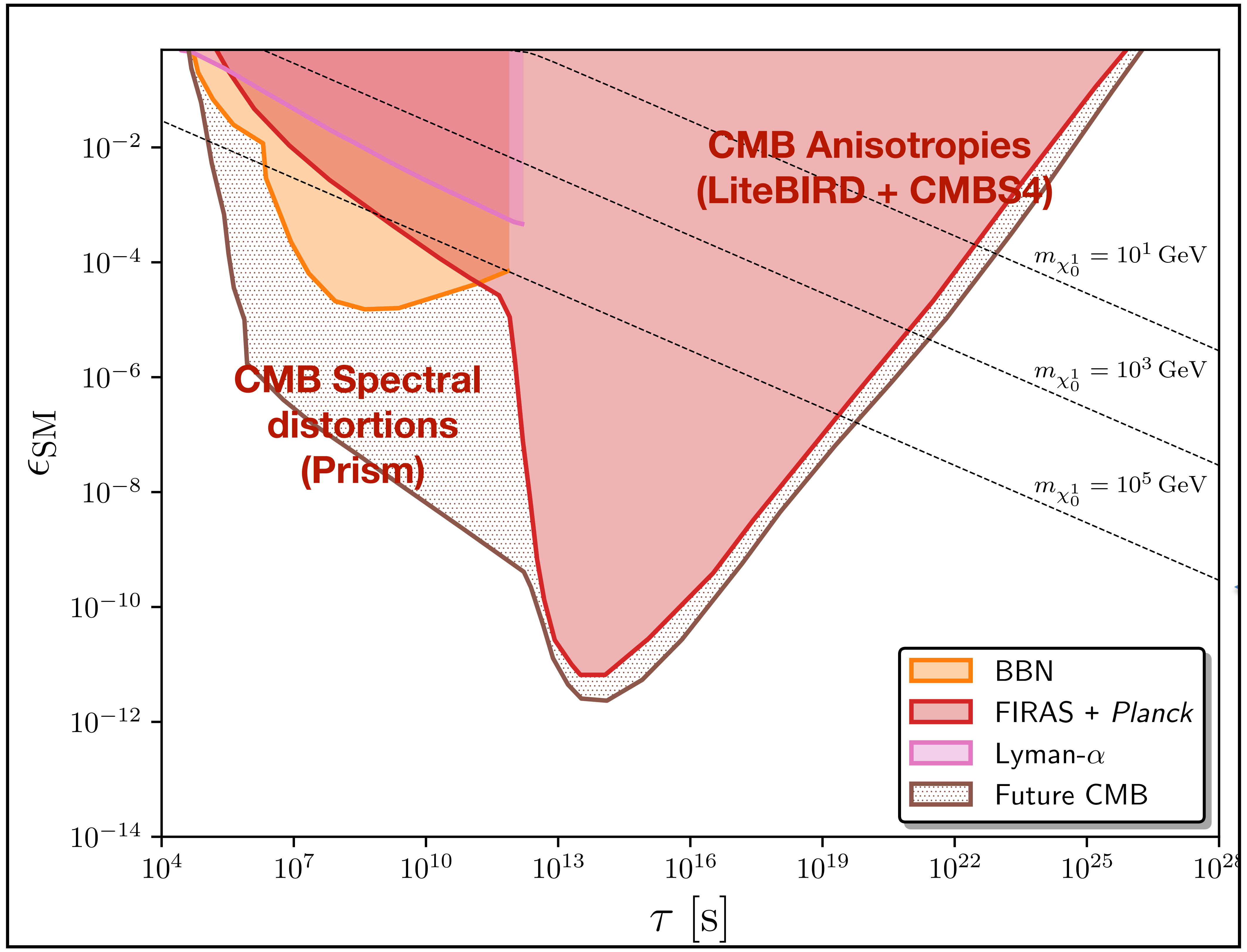

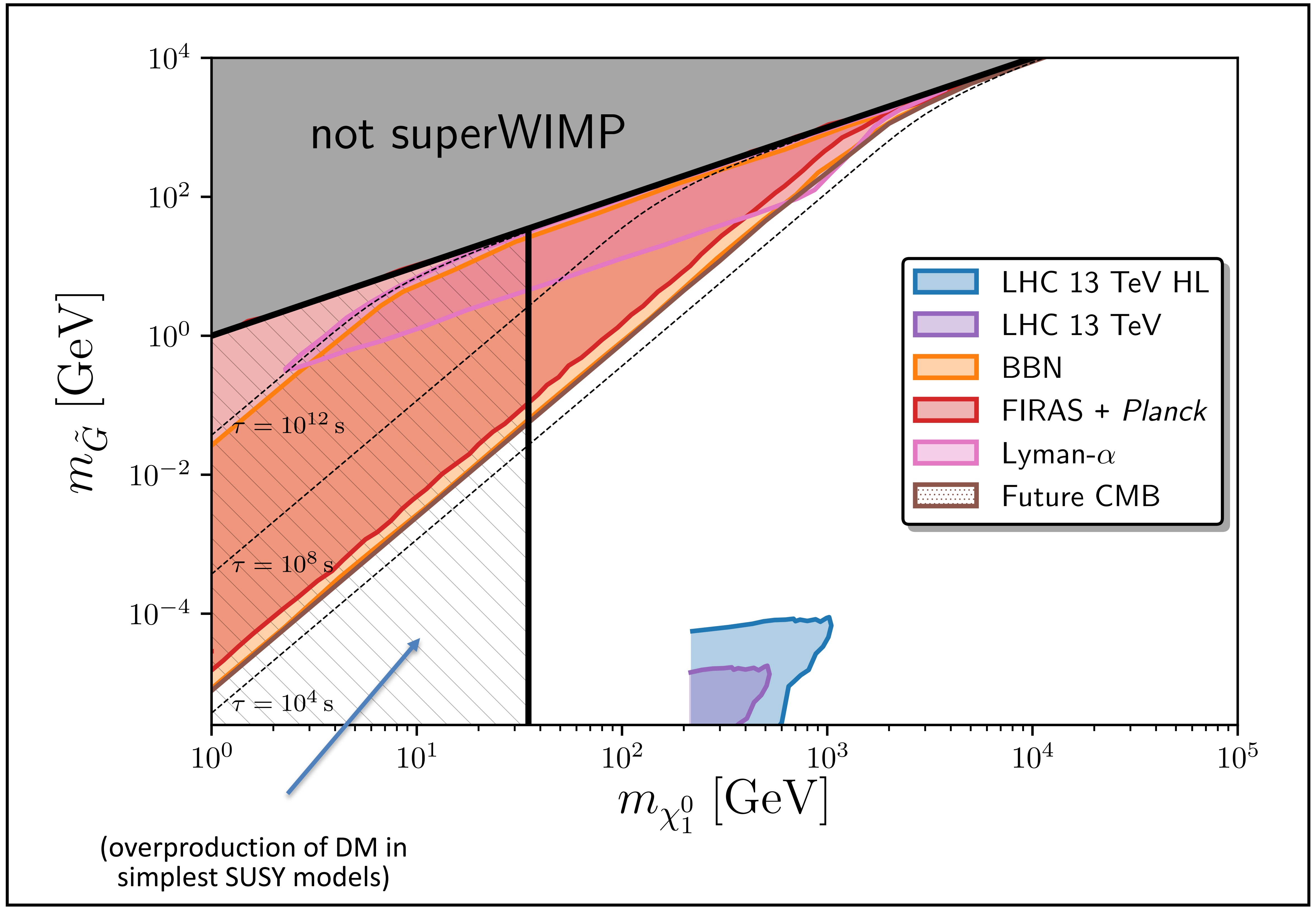

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EPJCXXXX

C. Arina, **DS,** et al. To appear soon

DARK MATTER VIA t-CHANNEL PRODUCTION
COSMOLOGY SECTION

A PREPRINT

LHC Dark Matter Working Group

A Simplified Freeze-in Model for LHC

Dark Matter populated through extremely weakly coupled systems is difficult to probe

Cosmology

- Primordial nucleosynthesis
- Lyman-α
- Spectral Distortions of CMB

Most promising

Collider

- Displaced objects
- HSCPs
- Mono-X
- Disappearing tracks

Some parts of the parameter space

Astro and Ground Based Detection

- Direct detection
- Indirect detection

Very difficult

A simplified Freeze-in Model for LHC

Consider an extension of the SM by a Z_2-odd real singlet scalar s (DM) along with a Z_2-odd vector-like SU(2)-singlet fermion F (parent).

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \partial_\mu s\,\partial^\mu s - \frac{\mu_s^2}{2} s^2 + \frac{\lambda_s}{4} s^4 + \lambda_{sh} s^2 \left(H^\dagger H\right)$$
$$+ \bar{F}\left(iD\right)F - m_F \bar{F} F - \sum_f y_s^f \left(s\bar{F}\left(\frac{1+\gamma^5}{2}\right) f + \text{h.c.}\right)$$

- $f = \{e,\mu,\tau\} \rightarrow F$ transforms as (**1, 1, -1**)
  "Heavy lepton"
- $f = \{u,c,t\} \rightarrow F$ transforms as (**3, 1, -2/3**)
  "Heavy *u*-quark"
- $f = \{d,s,b\} \rightarrow F$ transforms as (**3, 1, 1/3**)
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- $f = \{d,s,b\} \to F$ transforms as (**3, 1, 1/3**) "Heavy *d*-quark"

Assuming that DM is mostly populated by F decays, we can relate the relic abundance with the parent particle lifetime:

$$c\tau \approx 4.5\,\text{m}\,\xi g_F \left(\frac{0.12}{\Omega_s h^2}\right)\left(\frac{m_s}{100\text{keV}}\right)\left(\frac{200\text{GeV}}{m_F}\right)^2 \left(\frac{102}{g_*(m_F/3)}\right)^{3/2} \left[\frac{\int_{m_F/T_R}^{m_F/T_0} dx\, x^3 K_1(x)}{3\pi/2}\right]$$

Freeze-in favours long lifetimes, unless

- Dark matter is very light
- The reheating temperature is lov

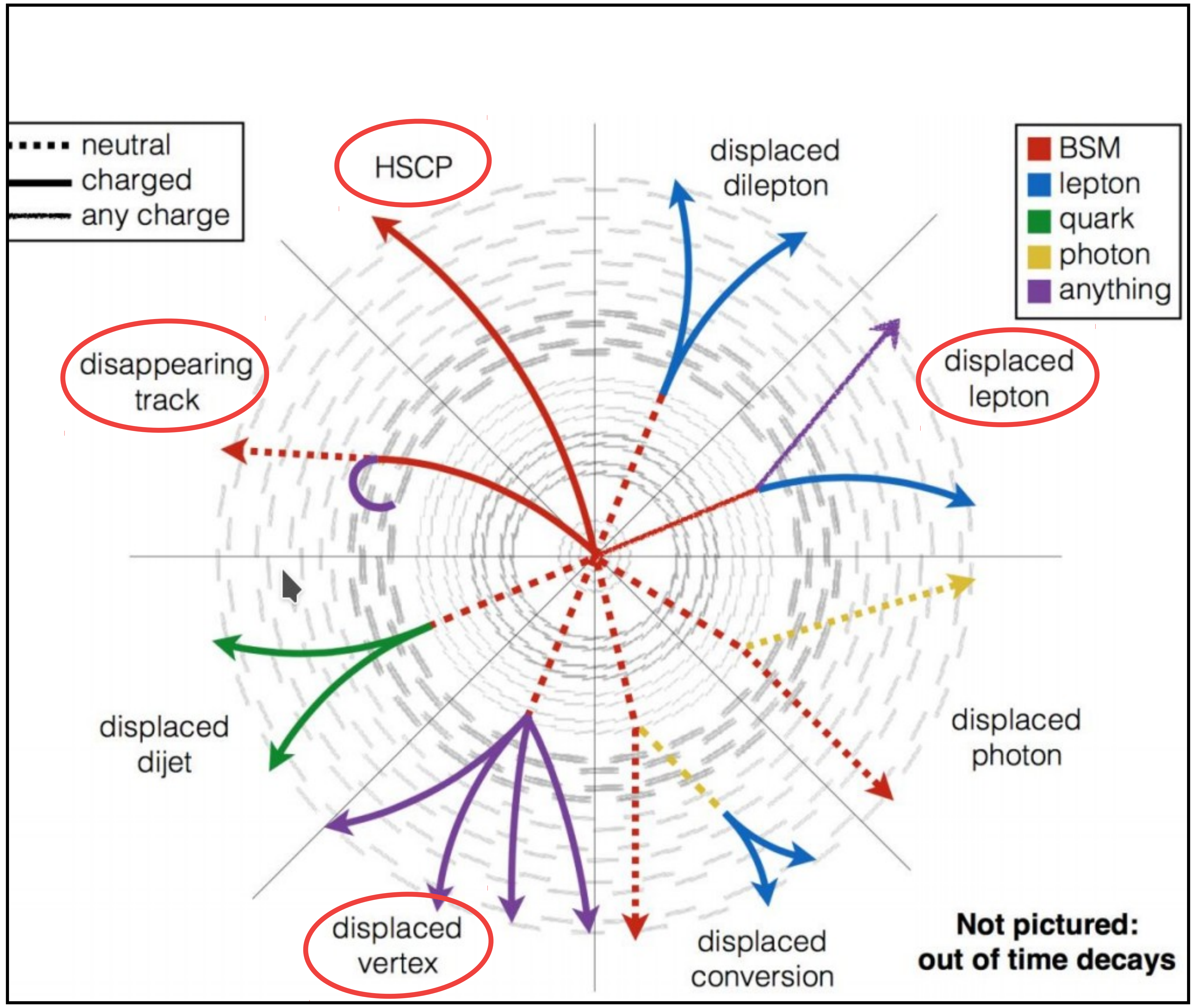
- **Big-Bang Nucleosynthesis**
  we consider 1cm < cτ < 10^4m → T~150 MeV
  → heavy fermions decay well before onset of BBN
- **Lyman-α forest**

$$m_{\rm DM} \gtrsim 12\ \text{keV} \left(\frac{\sum_i \text{BR}_i \Delta_i^\eta}{\sum_i \text{BR}_i}\right)^{1/\eta} \gtrsim 12\ \text{keV}$$

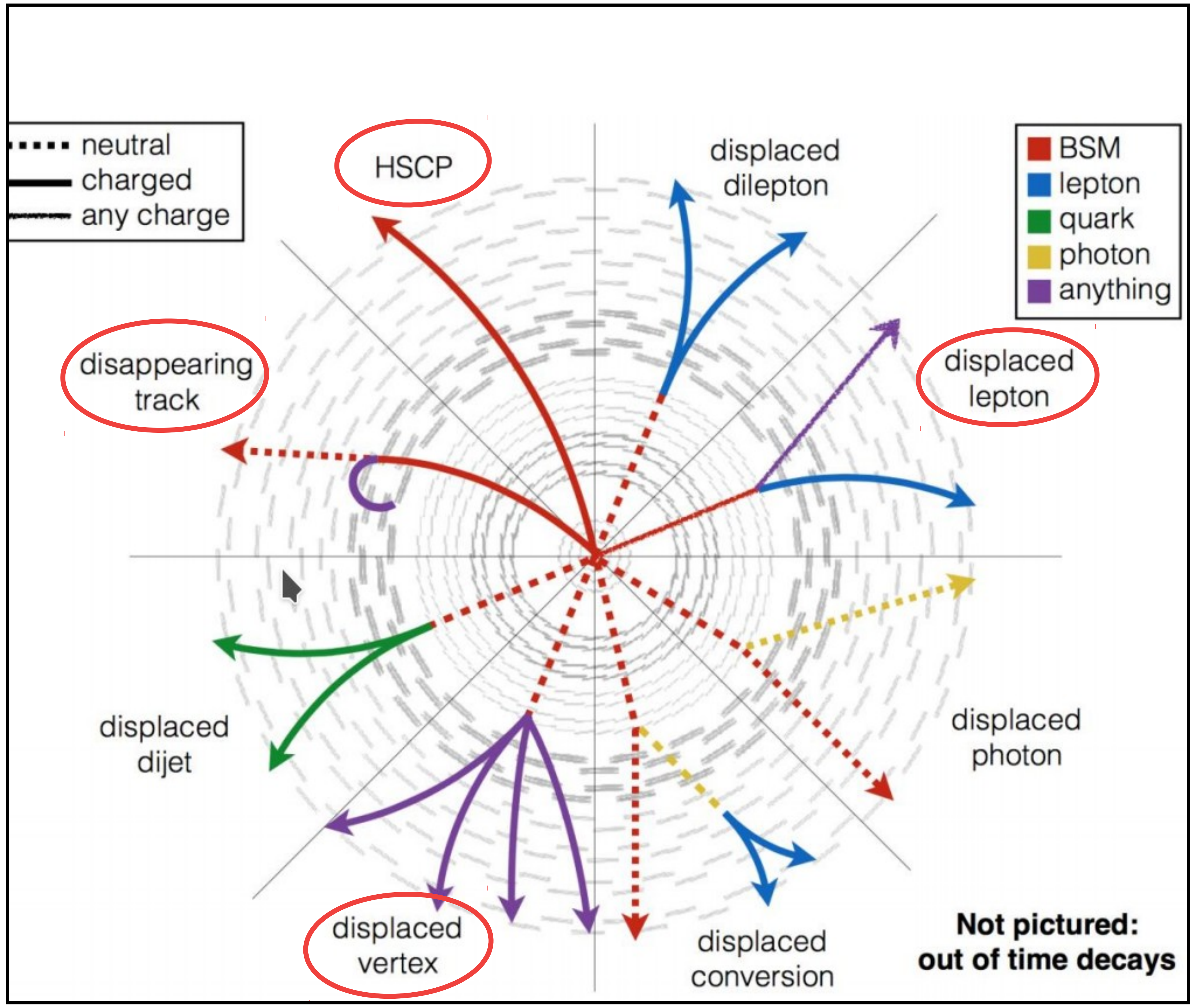
G. Belanger, J.Zurita, …, **DS**, JHEP 02 (2019) 186

A simplified Freeze-in Model for LHC

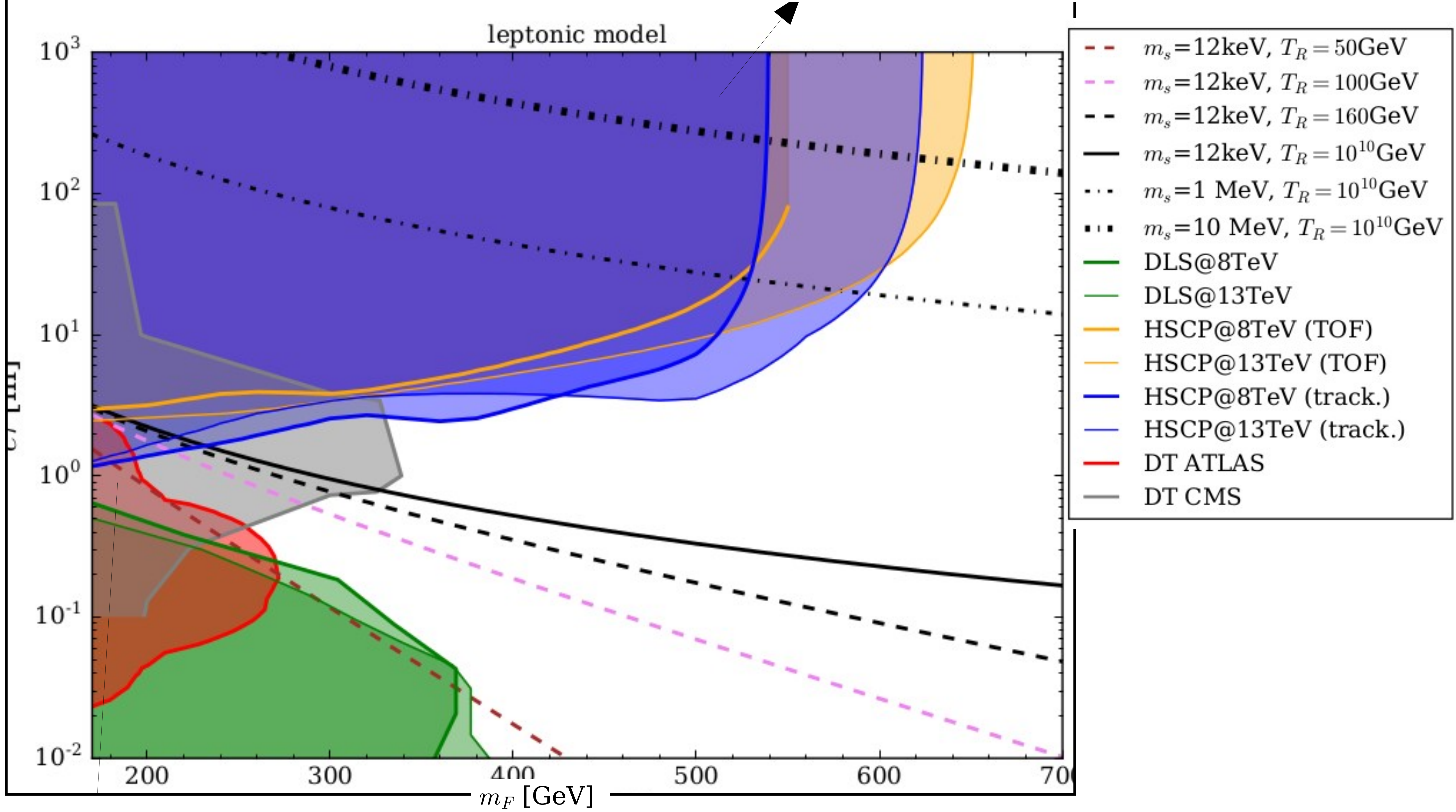
A simplified Freeze-in Model for LHC



A simplified Freeze-in Model for LHC



HSCP: Tracker + TOF analysis more powerful for larger lifetimes, tracker-only for shorter ones.



DT: Order-of-magnitude difference in peak sensitivity between ATLAS/CMS

G. Belanger, J. Zurita, **DS** … JHEP 02 (20

Conclusion

We are in uncharted territory,

But the ride is exciting

International Workshop

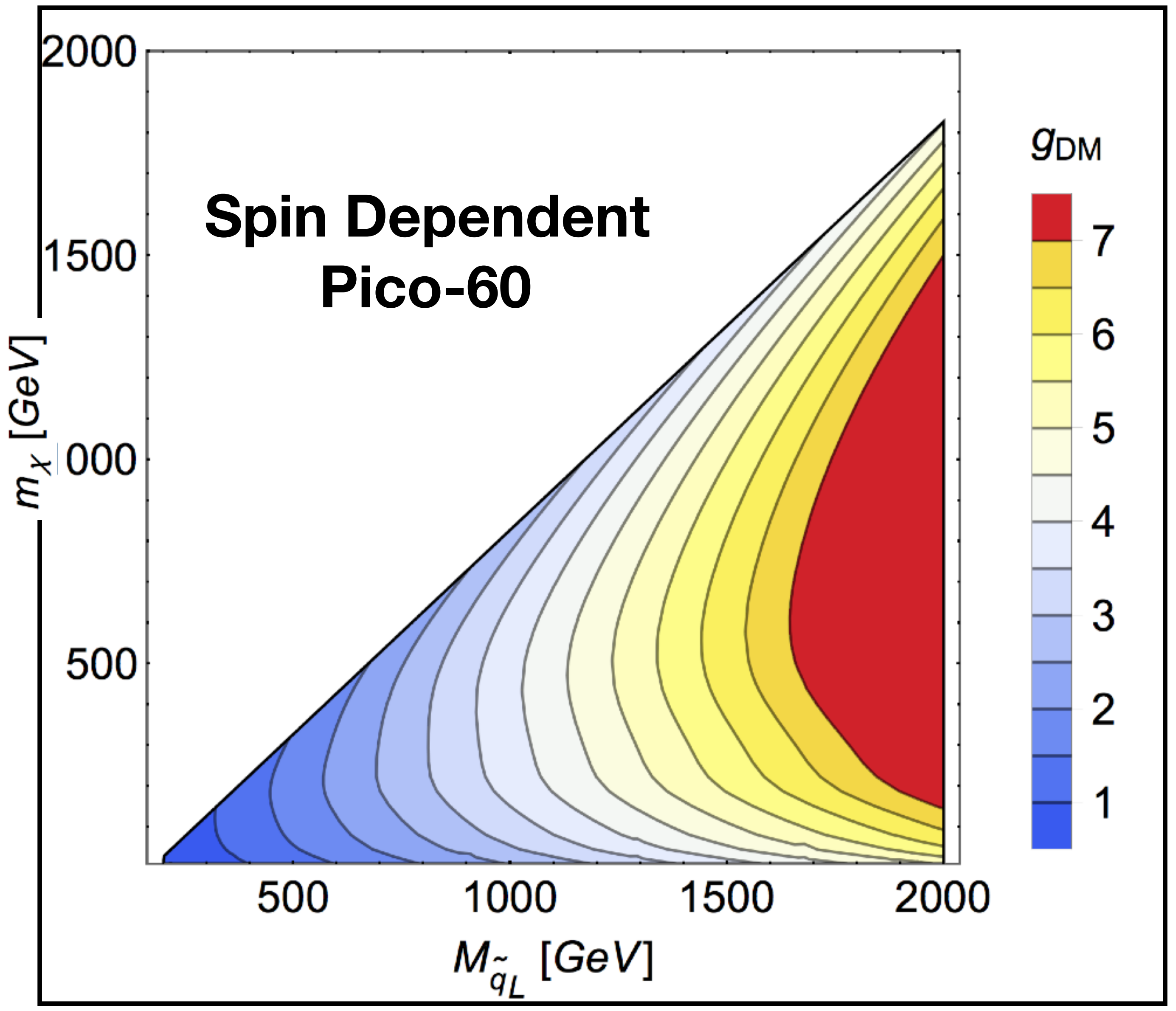
9–13 Dec 2024
Australia/Sydney timezone

Direct Detection at 1-loop

Is the spin-independent 1-loop more sensitive than the tree level spin-dependent direct detection limit?

$$\mathcal{L}_{SI}^{\rm eff} = \sum_{q=u,d,s} \mathcal{L}_q^{\rm eff} + \mathcal{L}_g^{\rm eff}$$

→ **Describe the one loop effective interaction for direct detection**



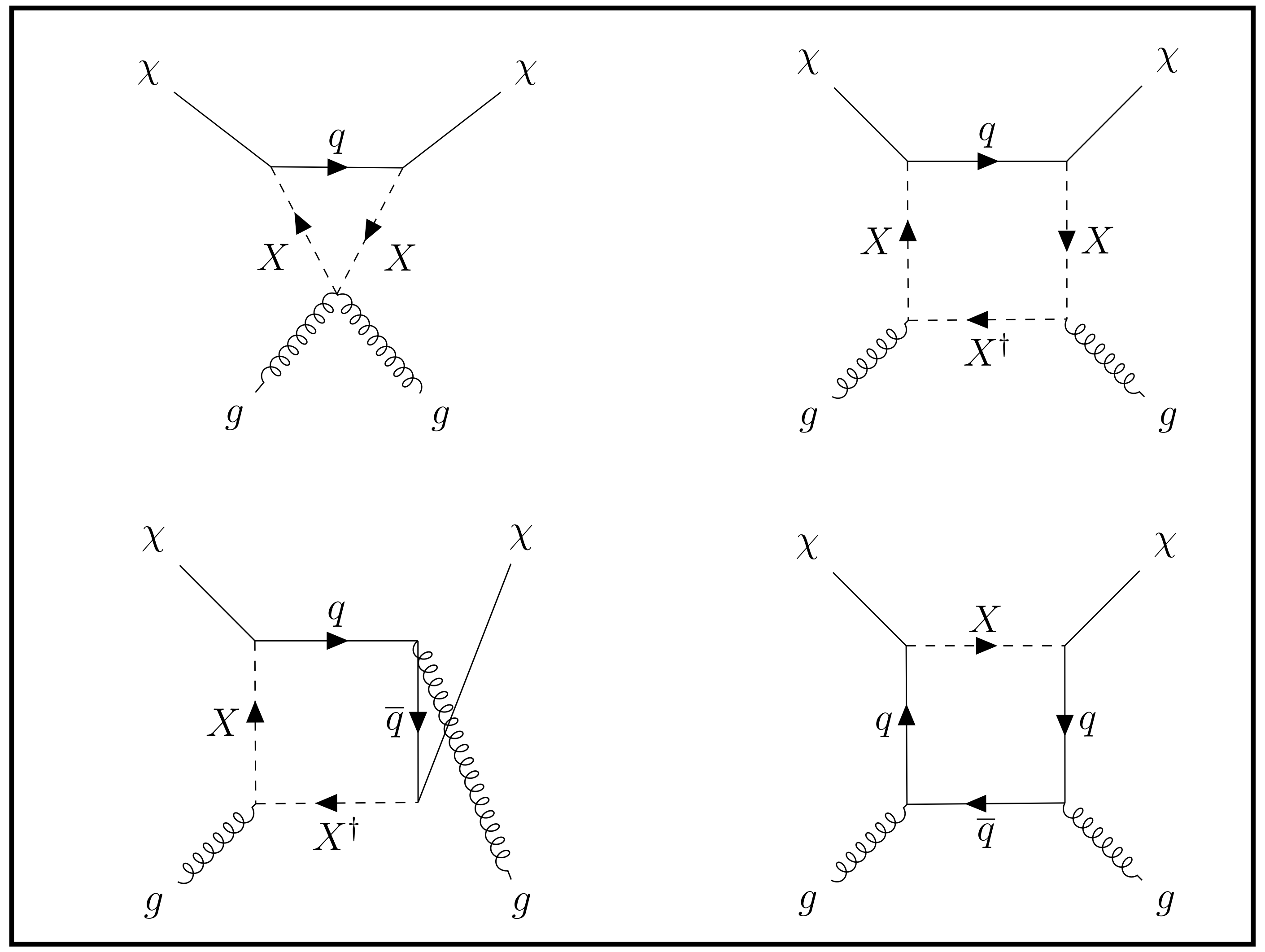
Determine Wilson Coefficients for effective operators

$$\mathcal{L}_q^{\rm eff} = f_q m_q\, \bar{\tilde{\chi}}\tilde{\chi}\, \bar{q}q + \frac{g_q^{(1)}}{m_\chi}\, \bar{\tilde{\chi}} i\partial^\mu\gamma^\nu\tilde{\chi}\, \mathcal{O}^q_{\mu\nu} + \frac{g_q^{(2)}}{m_\chi^2}\, \bar{\tilde{\chi}}(i\partial^\mu)(i\partial^\nu)\tilde{\chi}\, \mathcal{O}^q_{\mu\nu}\,,$$

$$\mathcal{L}_g^{\rm eff} = f_G\, \bar{\tilde{\chi}}\tilde{\chi} G^a_{\mu\nu}G^{a\mu\nu} + \frac{g_G^{(1)}}{m_\chi}\, \bar{\tilde{\chi}} i\partial^\mu\gamma^\nu\tilde{\chi}\, \mathcal{O}^g_{\mu\nu} + \frac{g_G^{(2)}}{m_\chi^2}\, \bar{\tilde{\chi}}(i\partial^\mu)(i\partial^\nu)\tilde{\chi}\, \mathcal{O}^g_{\mu\nu}\,.$$

Spin 0

Spin-2 Operators



See K. Mohan, DS, T. Tait, B.Yan, C.P Yuan. JHEP 05 (2019) 115

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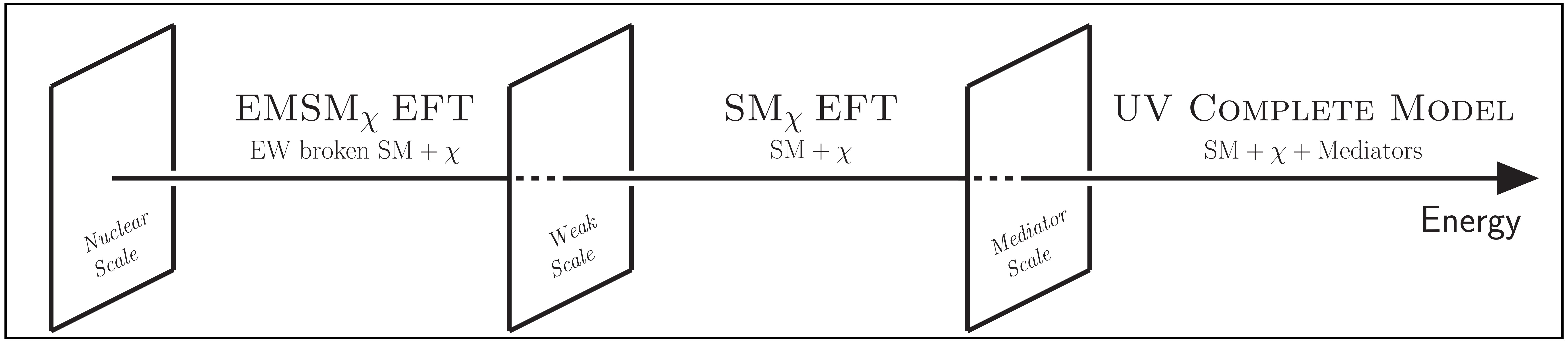

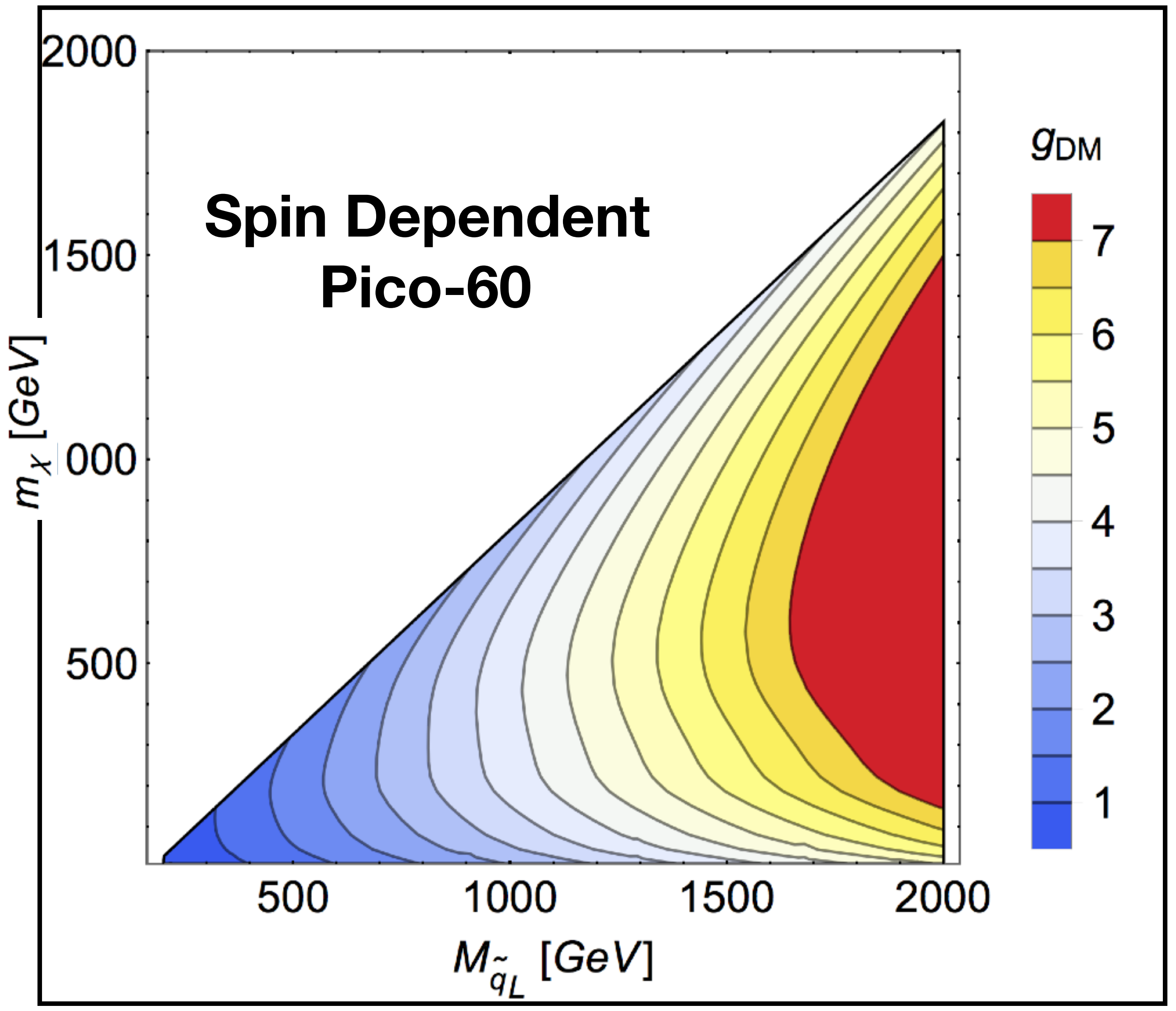

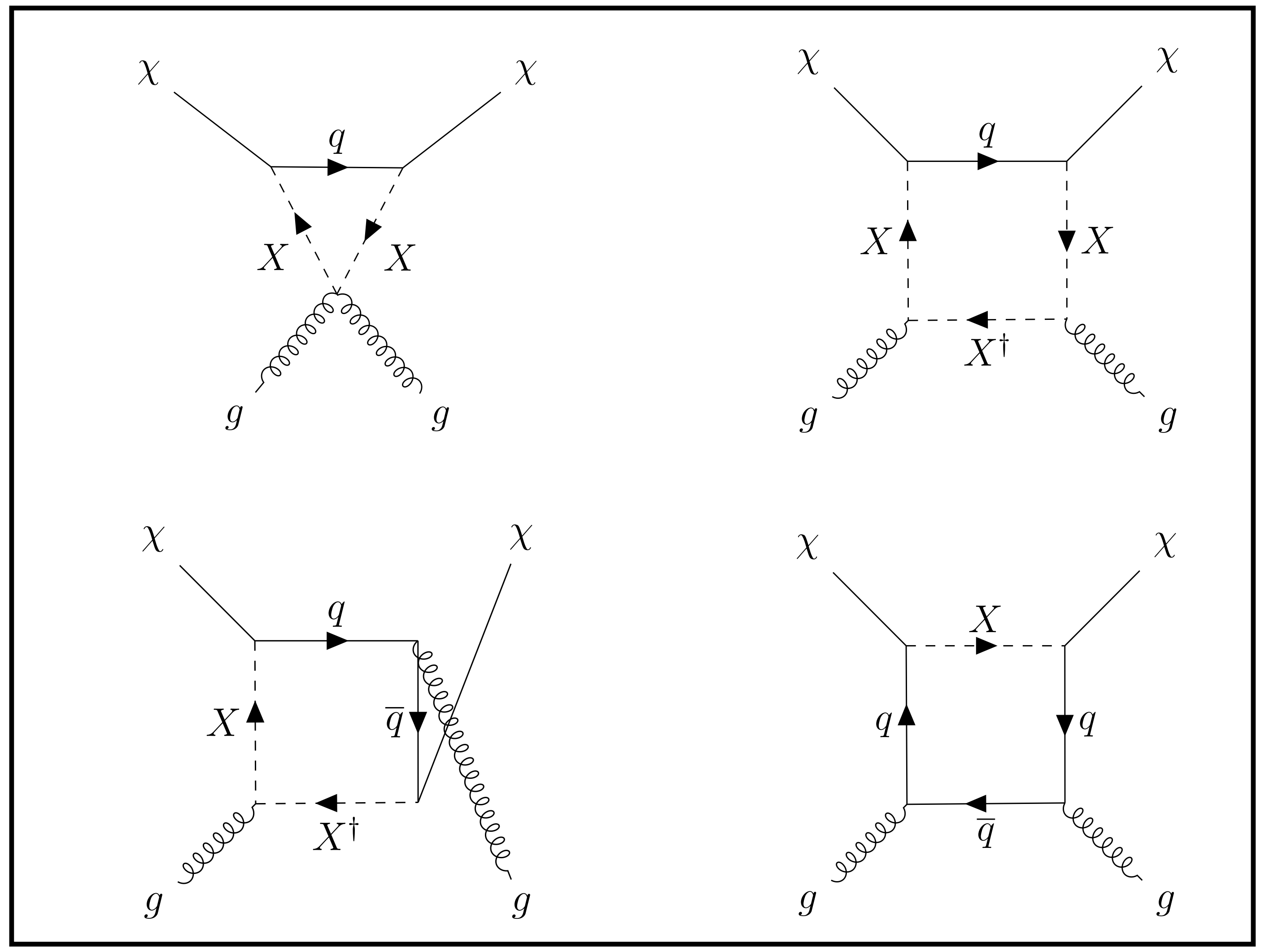

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