Accidentally Stable Dark Matter in a Parity Symmetric Theory

Matthew J. Baldwin

University of Chicago

PHENO 2026

Based on: 2606.xxxxx *M. Baldwin, K. Harigaya, I. Wang, Accidentally Stable Dark Matter in a Parity Solution to the Strong CP Problem*

Parity Symmetric Left-Right Models

Left-right models are extensions of the SM gauge group with an additional $SU(2)_R$

$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X$$

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Left-right models have **parity (P) symmetry** if we associate $SU(2)_R$ charged partners for each $SU(2)_L$ charged particle

SM quarks, leptons

$q(3,1,2,1/6)$

$l(1,1,2,-1/2)$

$$\xleftrightarrow{\quad P \quad}$$

Parity partners

$\bar{q}(\bar{3},2,1,-1/6)$

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Left-right models with Parity symmetry can provide **solutions to BSM problems:**

1) Solution to the strong CP problem
2) Connection to scale of Higgs quartic coupling vanishing [1]
3) Neutrino masses
4) Possible to unify into GUT gauge groups, e.g. $SO(10)$ [2]
5) **WIMP dark matter** models can be constructed— this talk

[1] *L. Hall, K. Harigaya*, Higgs Parity Grand Unification (2019)
[2] *M.J. Baldwin, K. Harigaya*, Electroweak-Charged Dark Matter and SO(10) Unification with Parity (2024)

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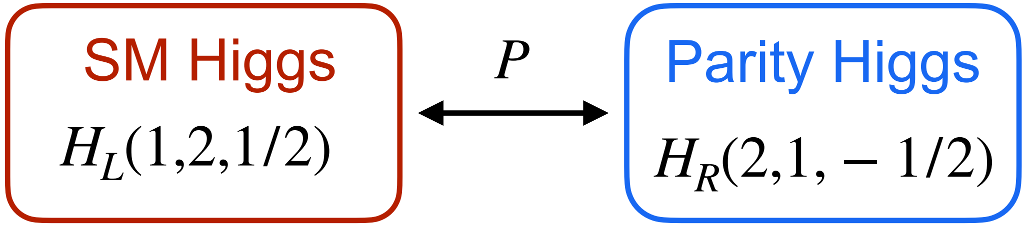

SM Higgs

$H_L(1,2,1/2)$

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$H_R(2,1,-1/2)$

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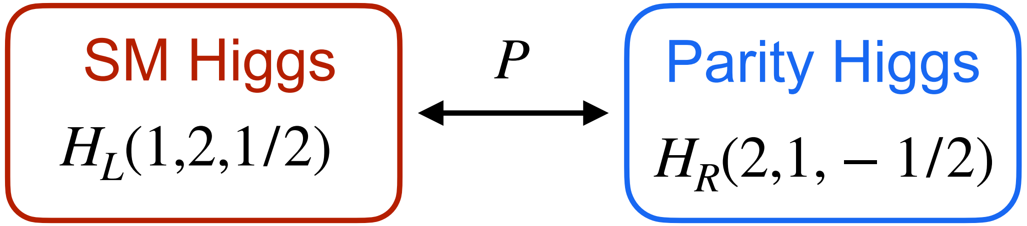

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Parity breaking scale

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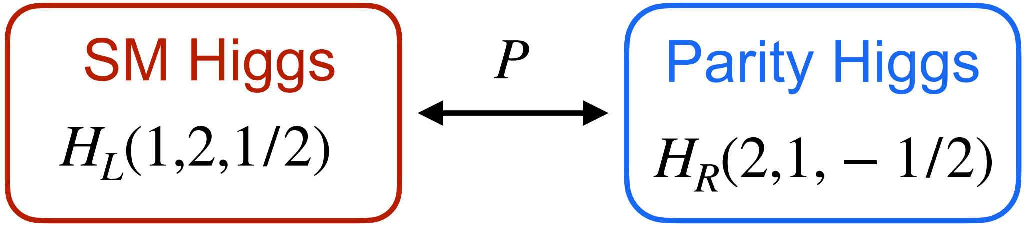
This results in **heavy gauge bosons** $W_R^{\pm}$ and Z_R



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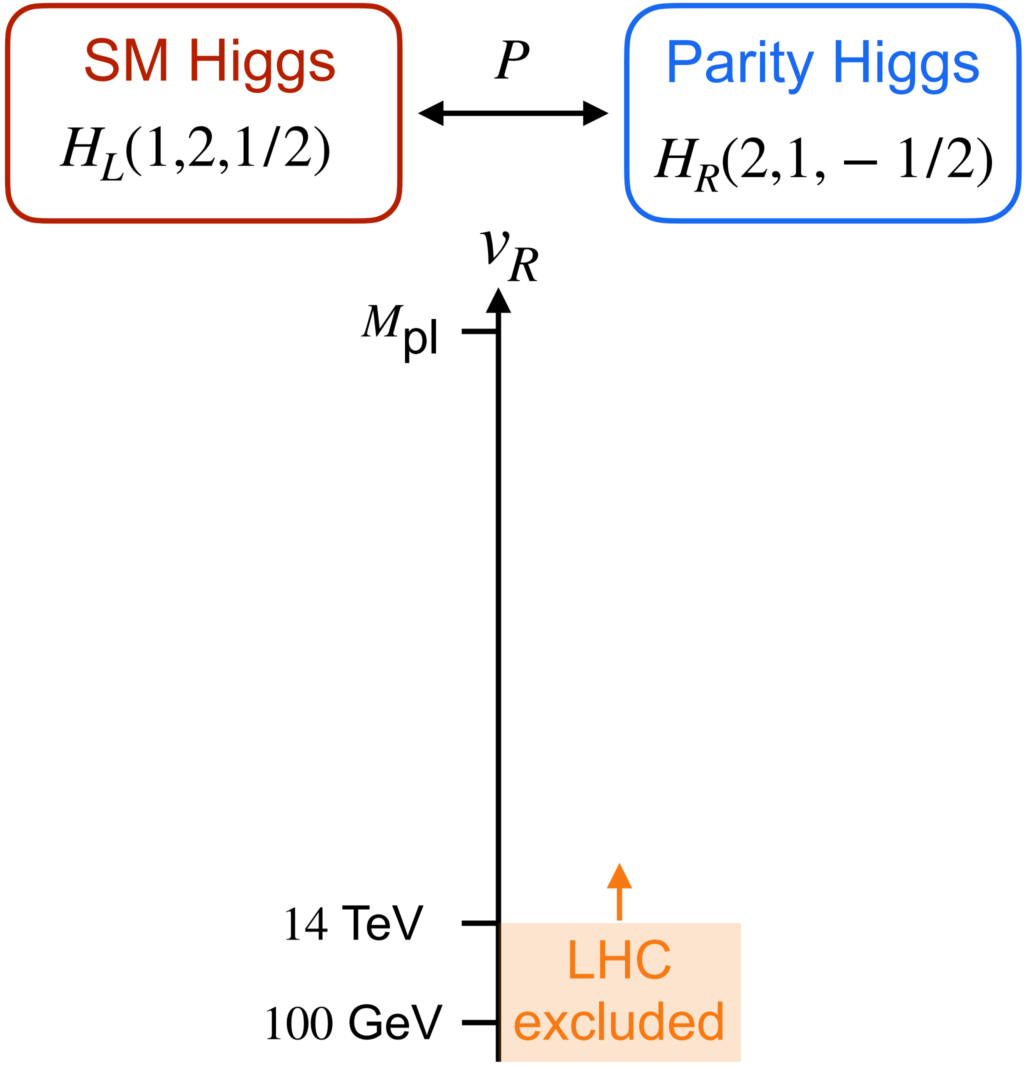
LHC searches for $W_R^{\pm}$ provide **lower bound** on v_R [3]

$$6 \text{ TeV} \lesssim M_{W_R} = \frac{1}{\sqrt{2}} g v_R \longrightarrow v_R \gtrsim 14 \text{ TeV}$$



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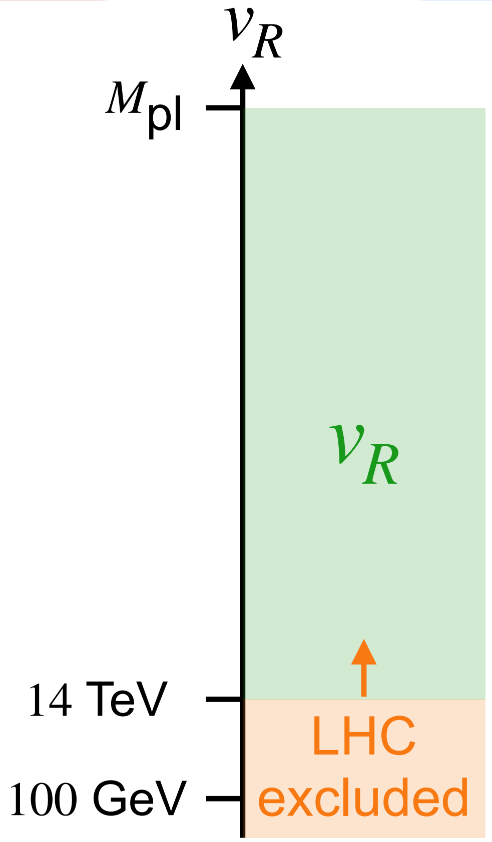
Without upper bound[1], v_R could be as large as $M_{\rm pl}$



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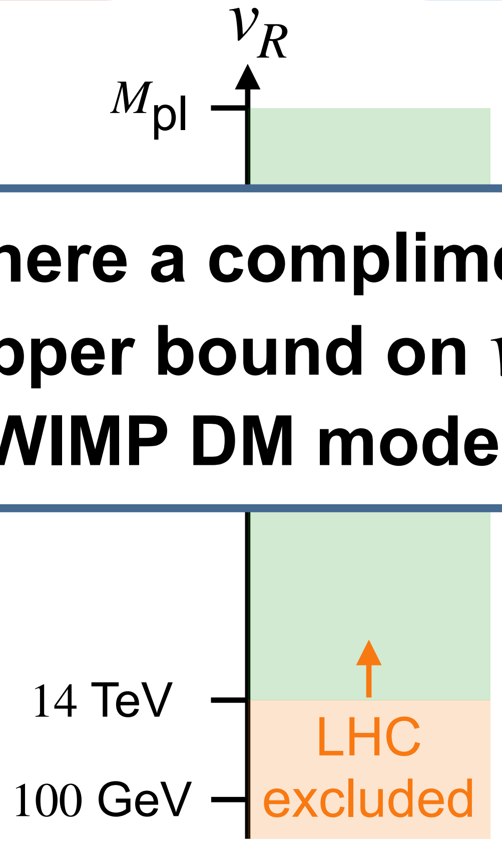

Is there a complimentary upper bound on v_R in WIMP DM models?

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WIMP dark matter embeds into Parity symmetric Left-right models

Doublet pair

$\psi_r(1,2,1,-1/2)$

$\psi_l(1,1,2,-1/2)$

Smallest representation

Bi-doublet

$\psi(1,2,2,0)$

Excluded in minimal model

Upper bounds on v_R in these models studied in 2507:22113

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Goal: 1) Compute DM mass M_{χ^0} and parity breaking scale v_R that give correct **relic abundance**

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Goal: 1) Compute DM mass M_{χ^0} and parity breaking scale v_R that give correct **relic abundance**

2) Obtain **constraints** on the $(M_{\chi^0},\ v_R)$ parameter space

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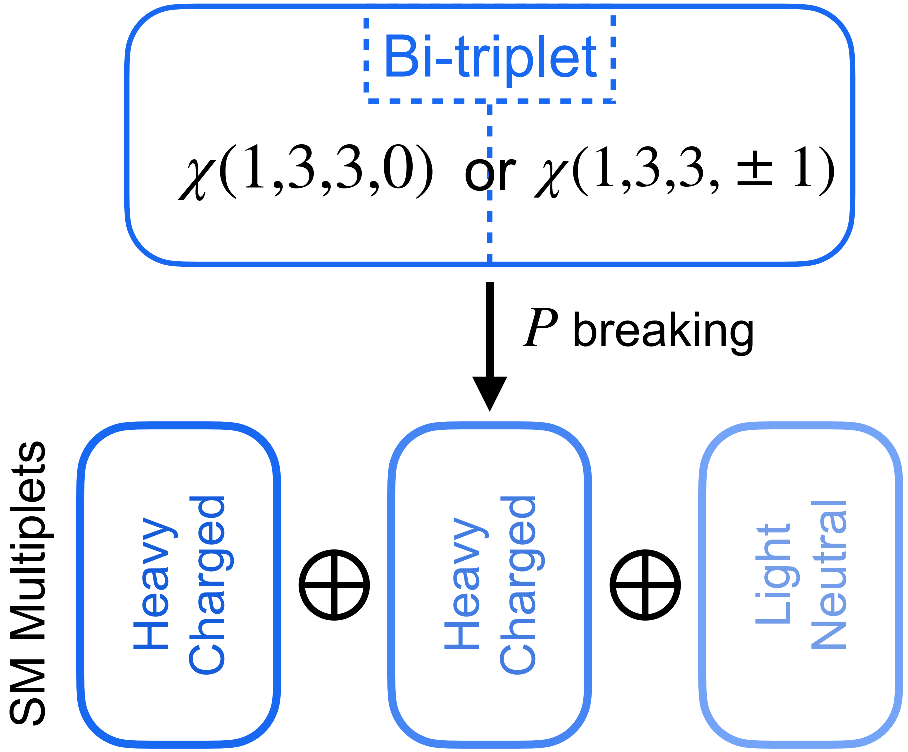

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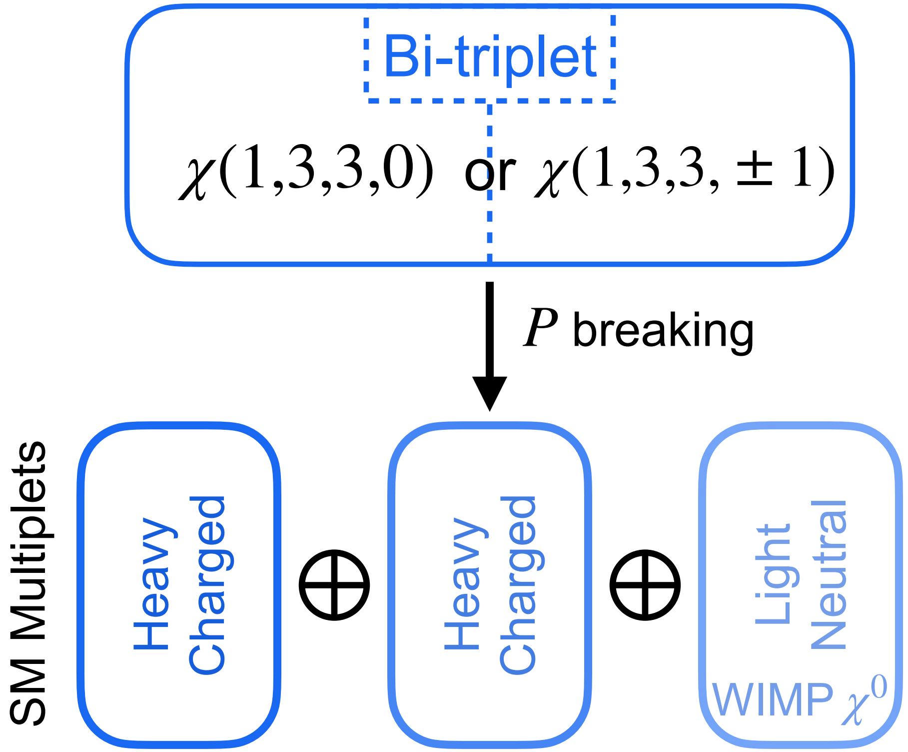

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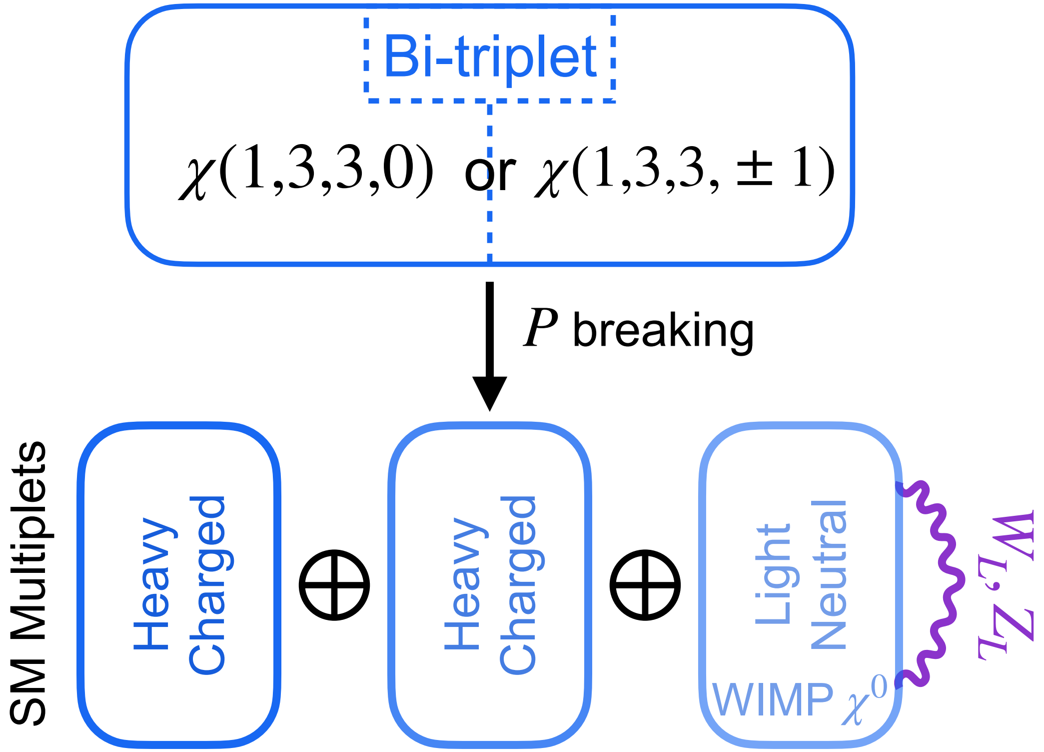

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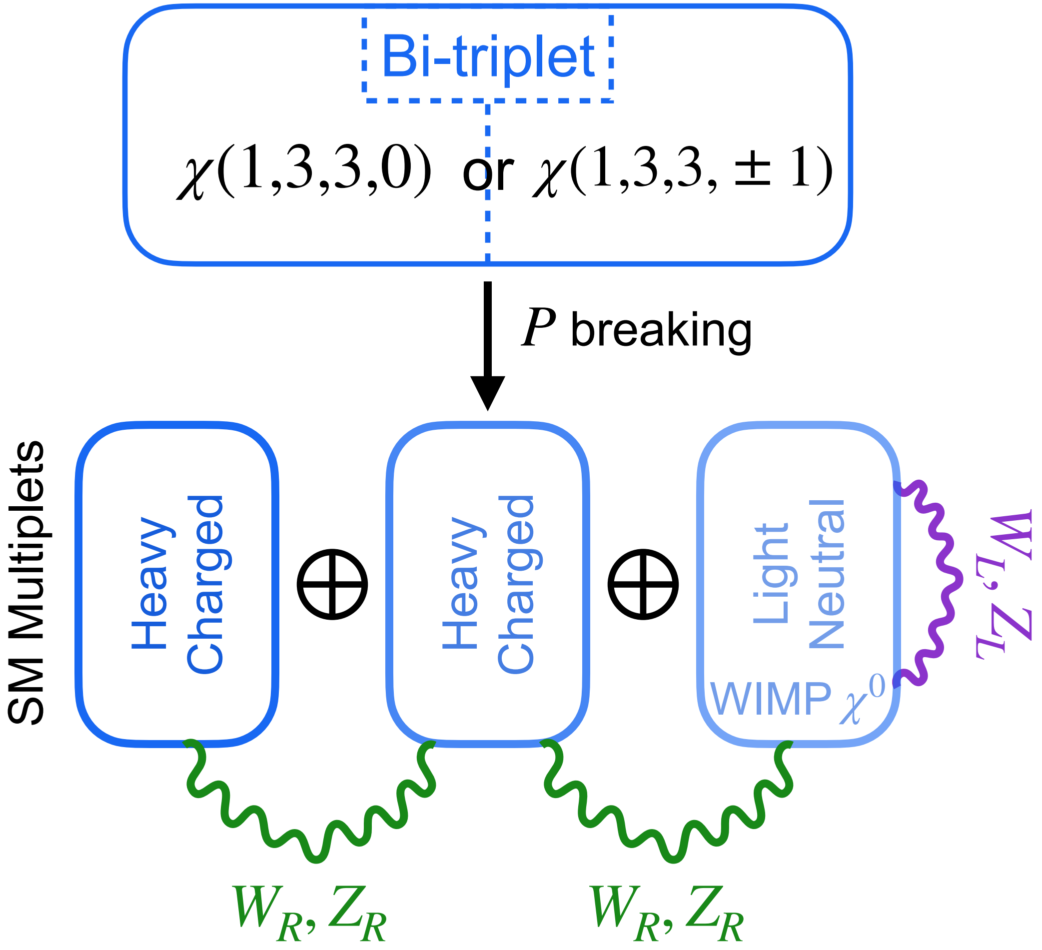

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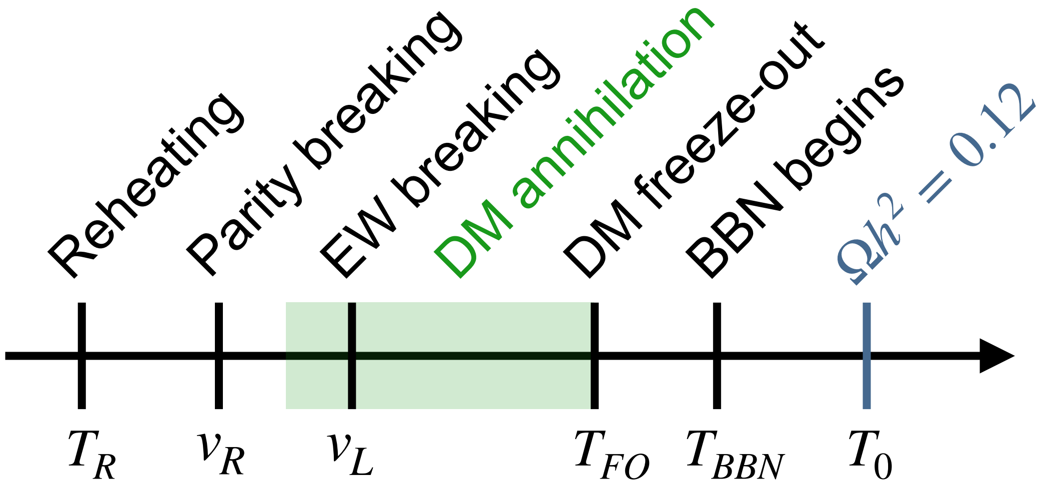

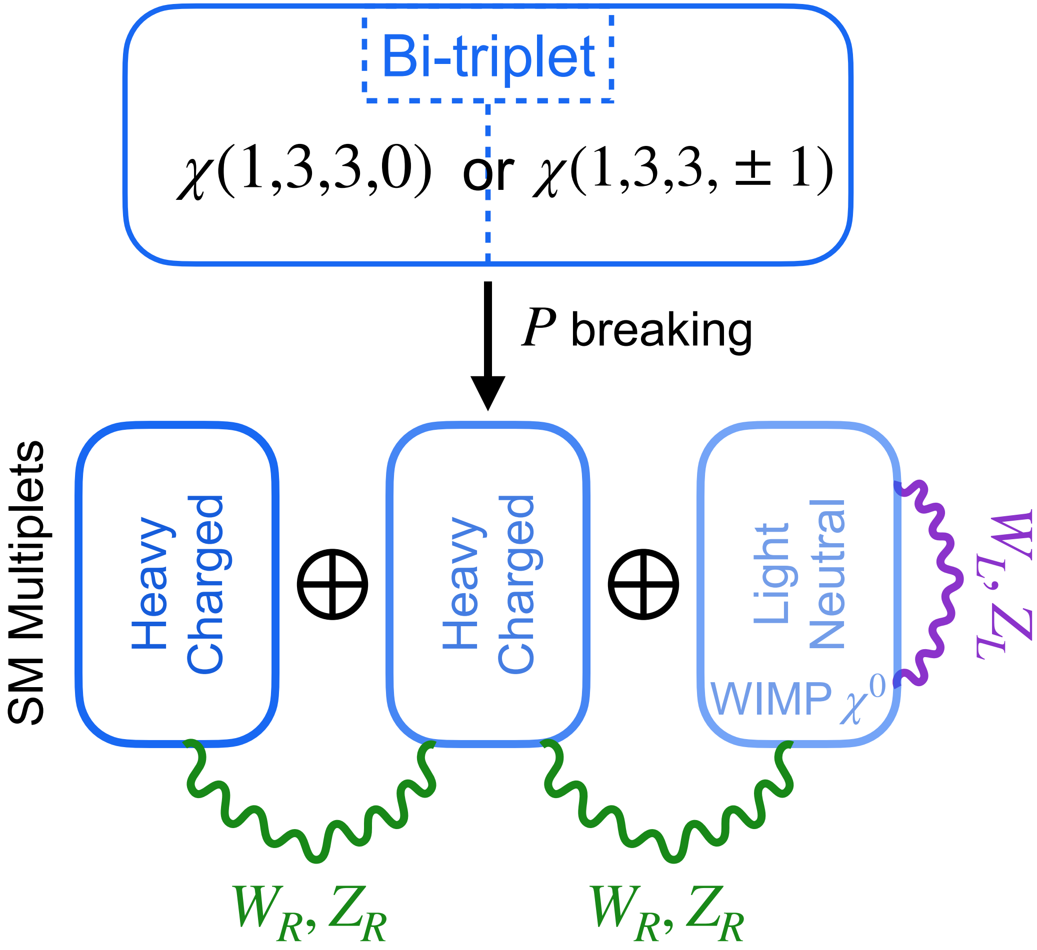

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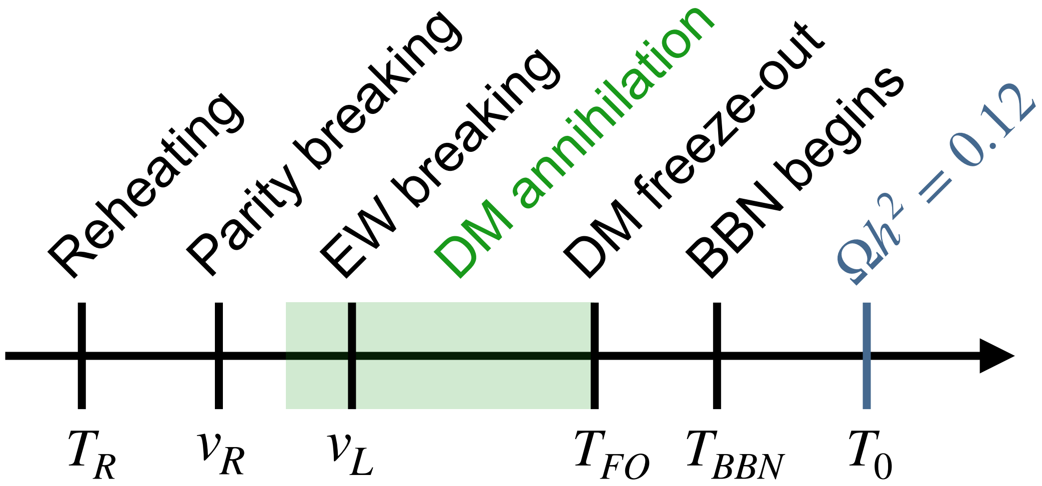
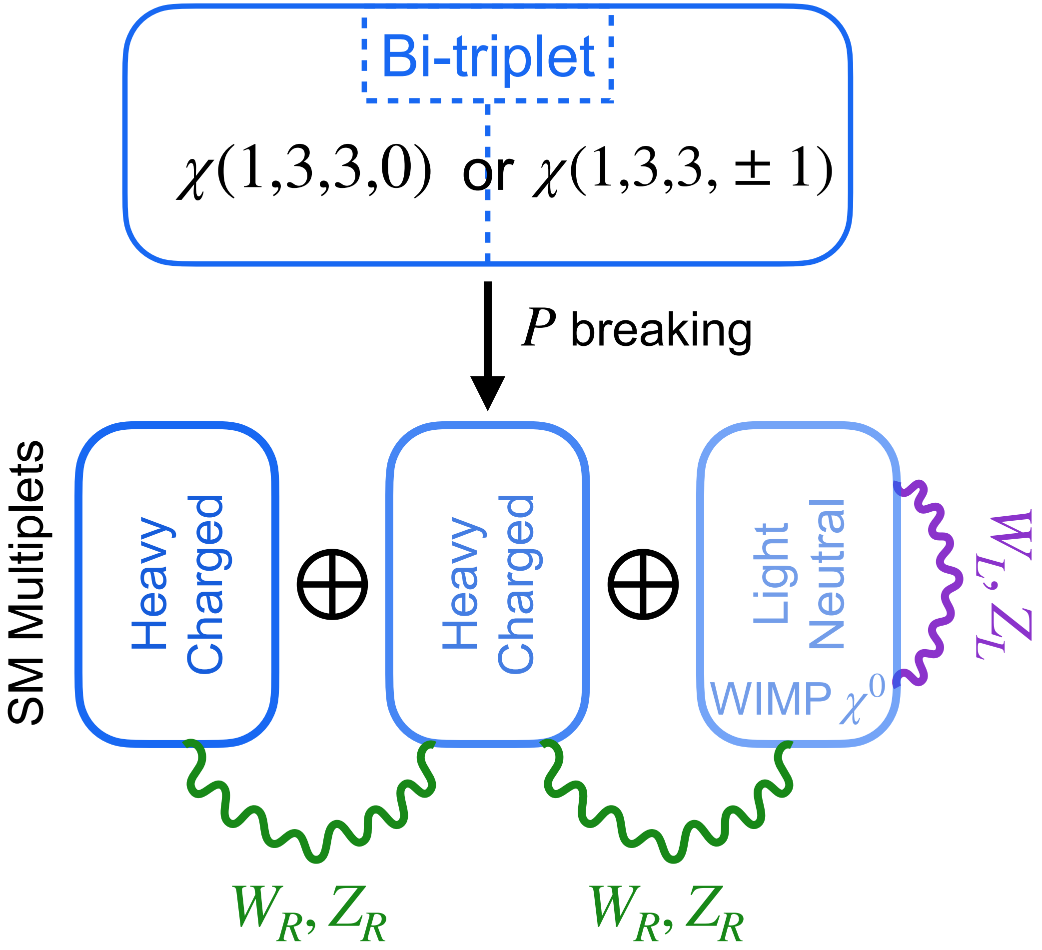
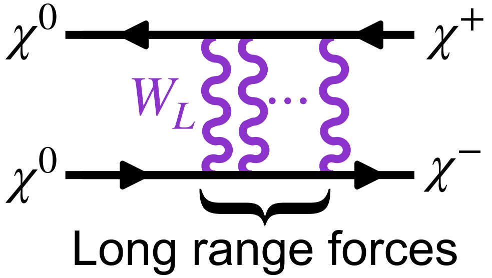




Abundance computed from Boltzmann equation using annihilation cross-sections modified by

1) **Sommerfeld effect**



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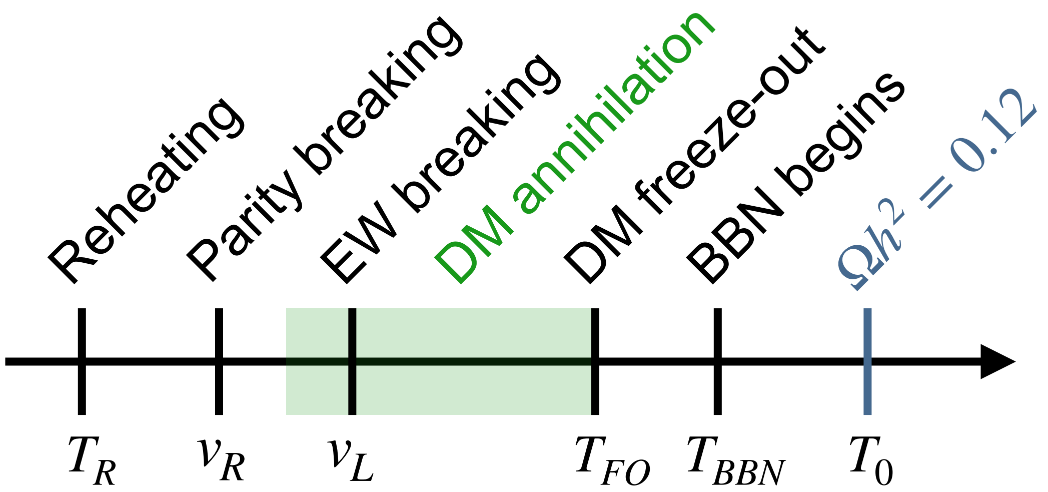

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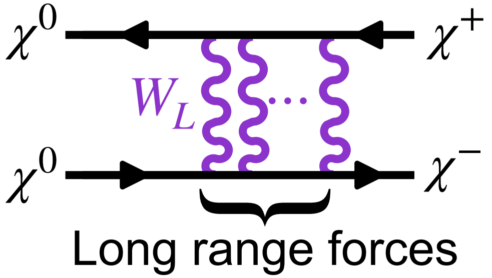
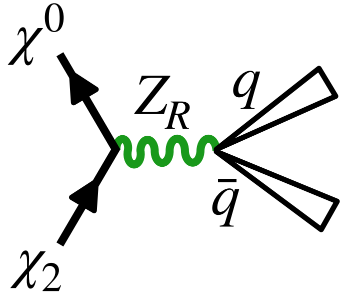
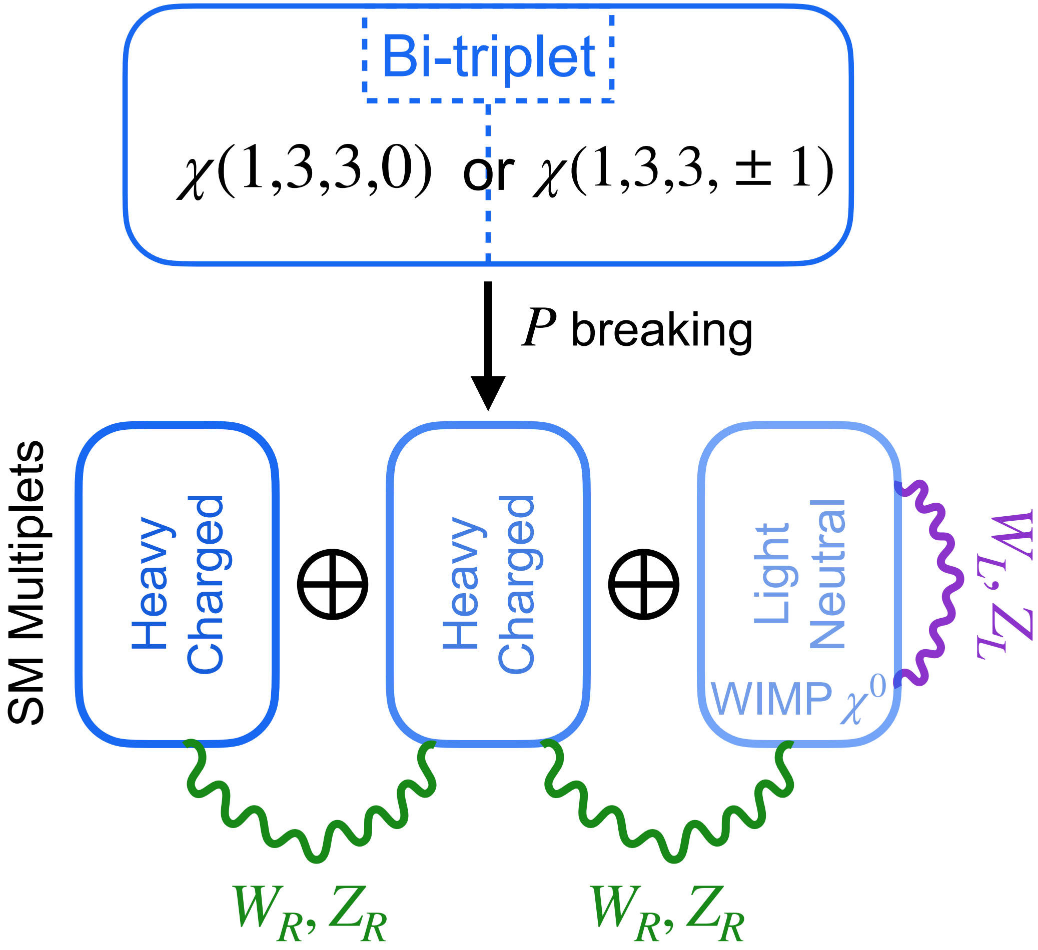


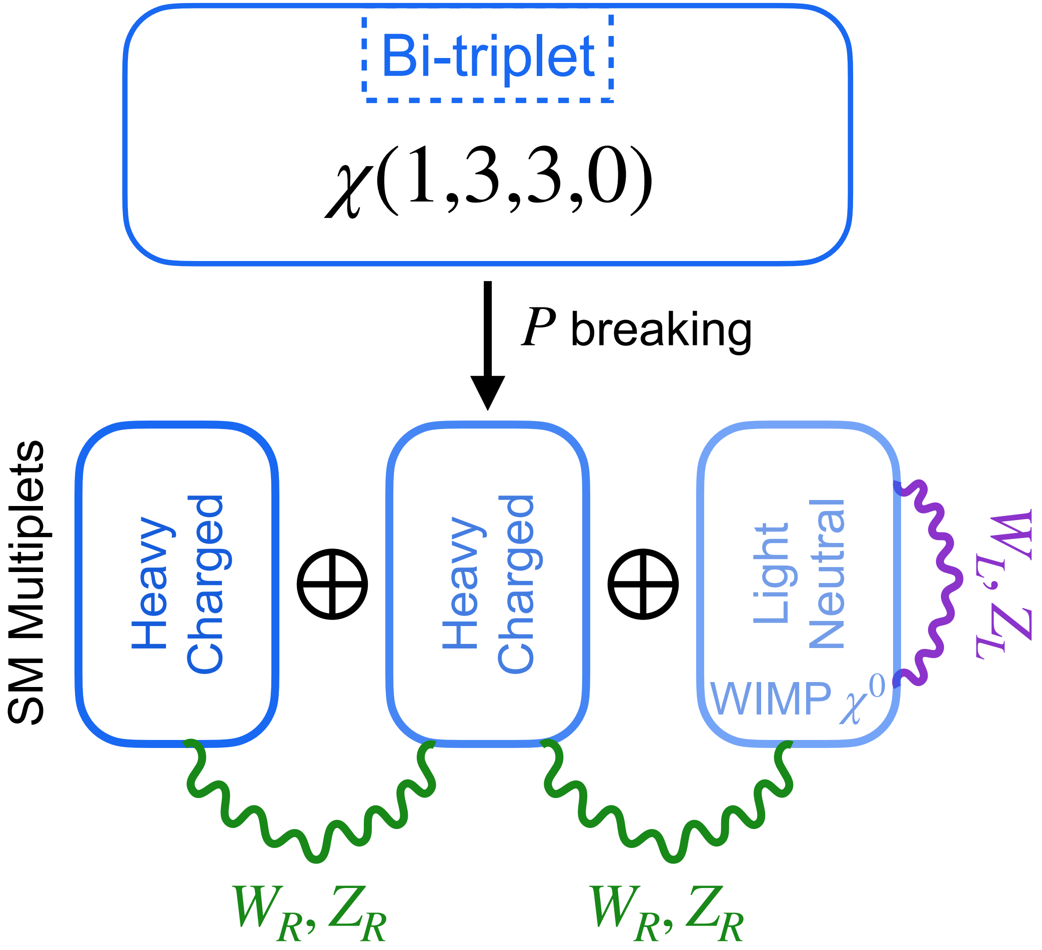
2) W_R **and** Z_R **resonance**





Thermal Relic Abundance

Example: $(1,3,3,0)$, $v_R = 40$ TeV



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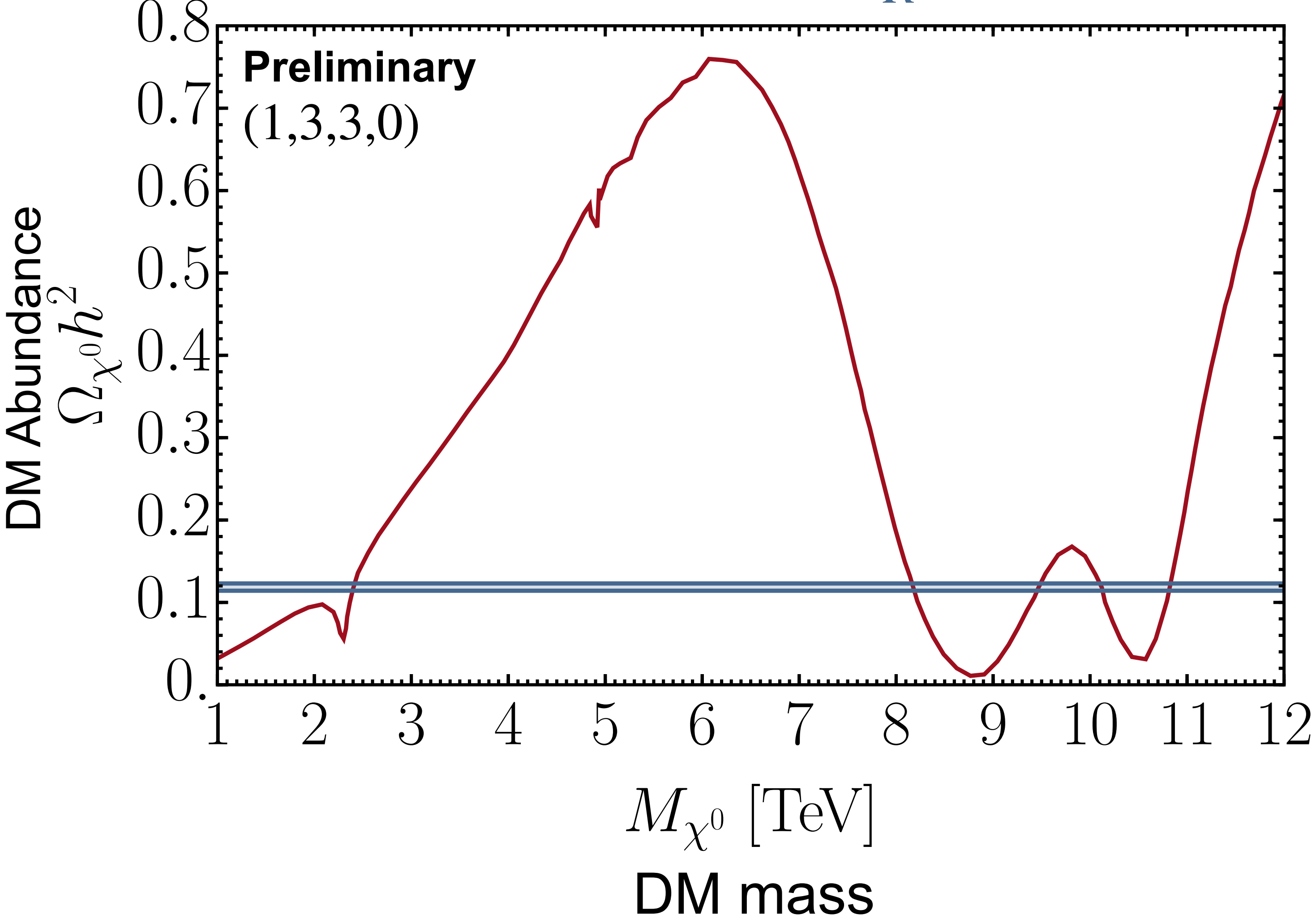

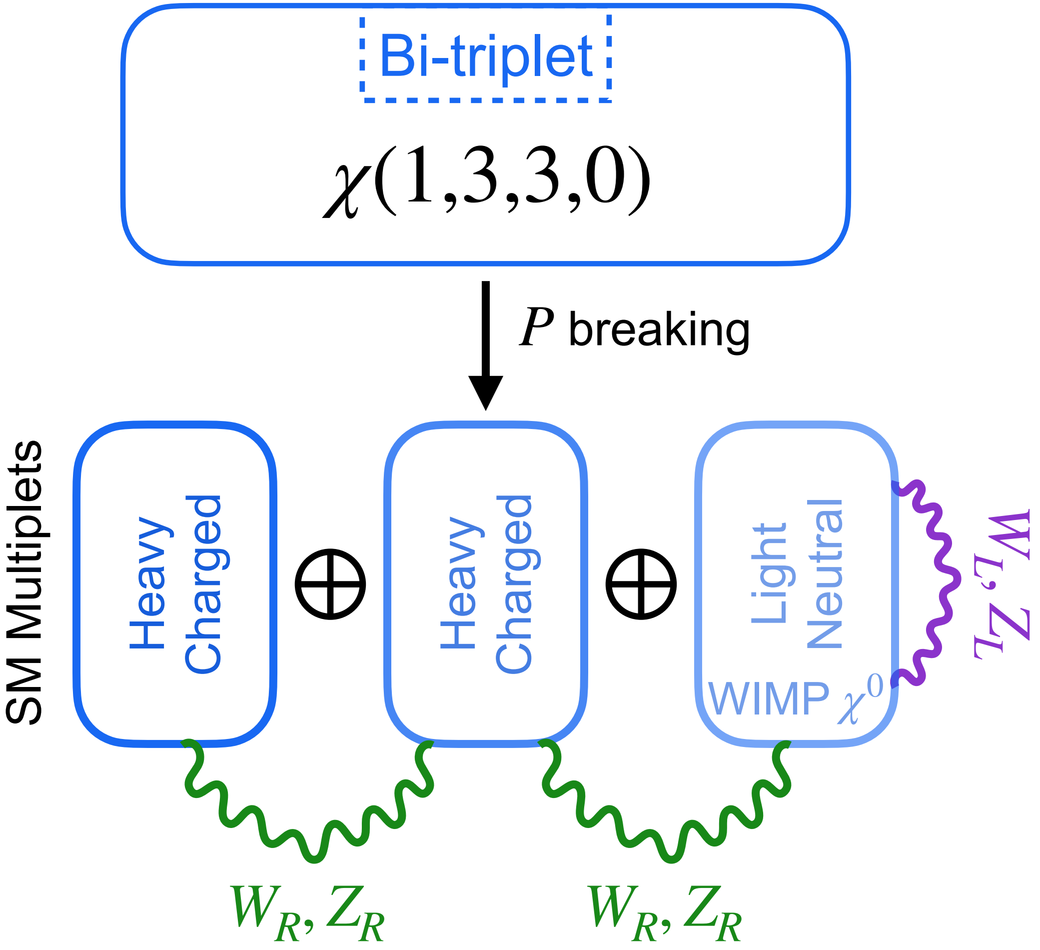

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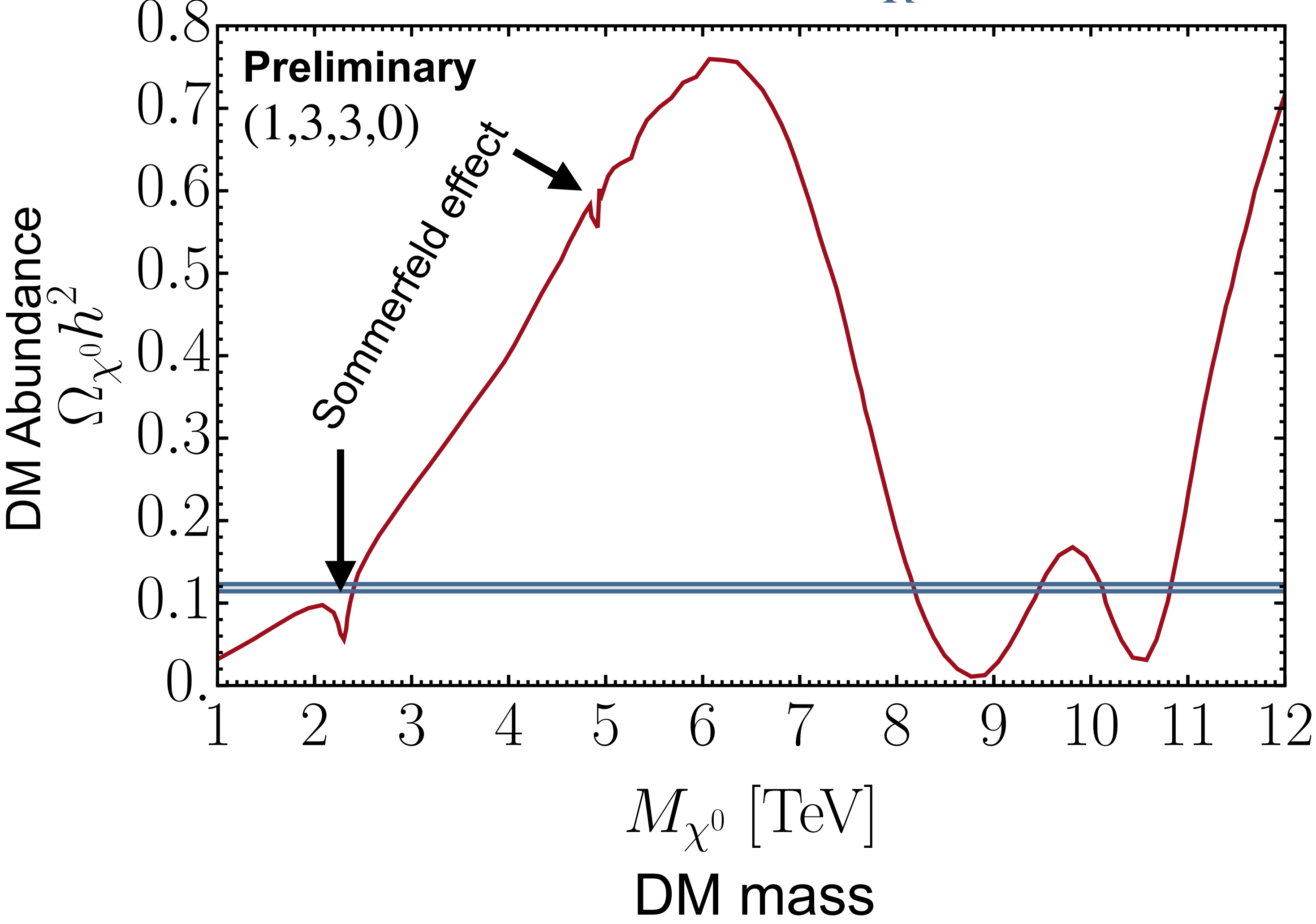

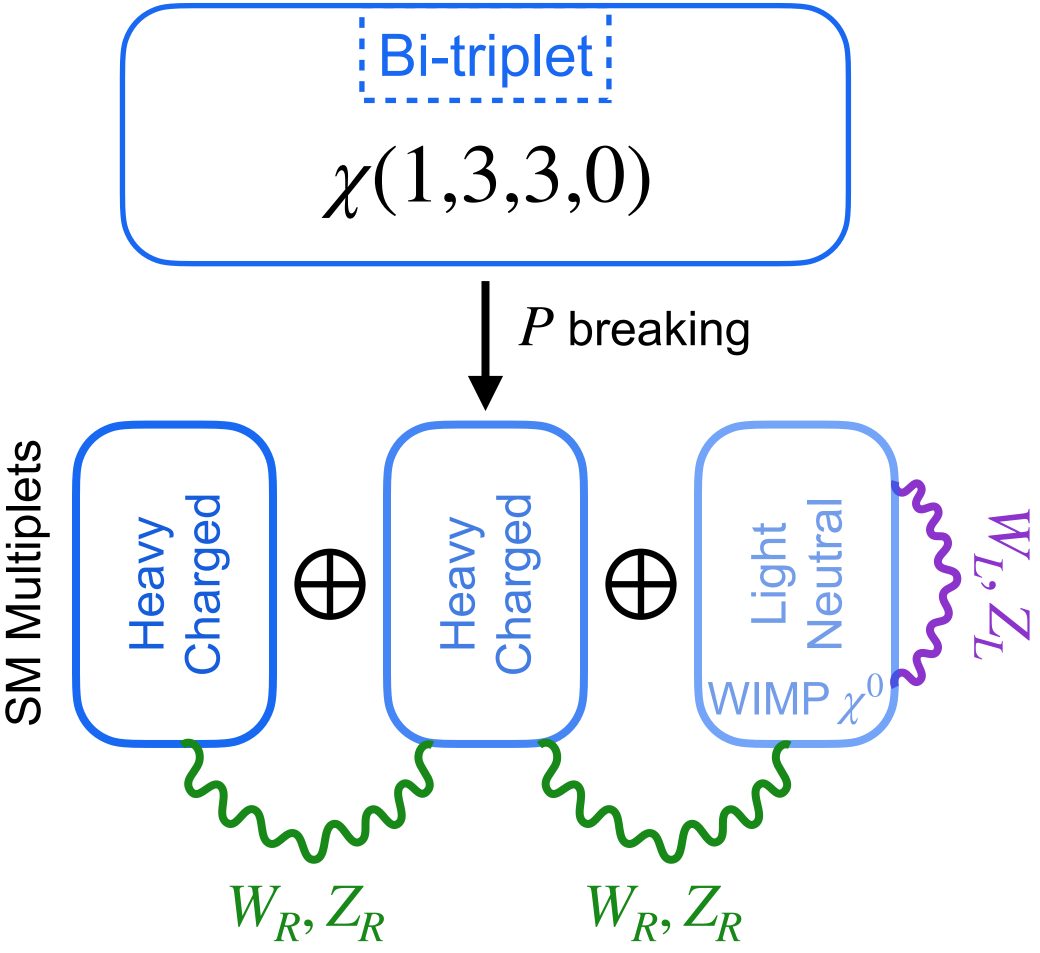

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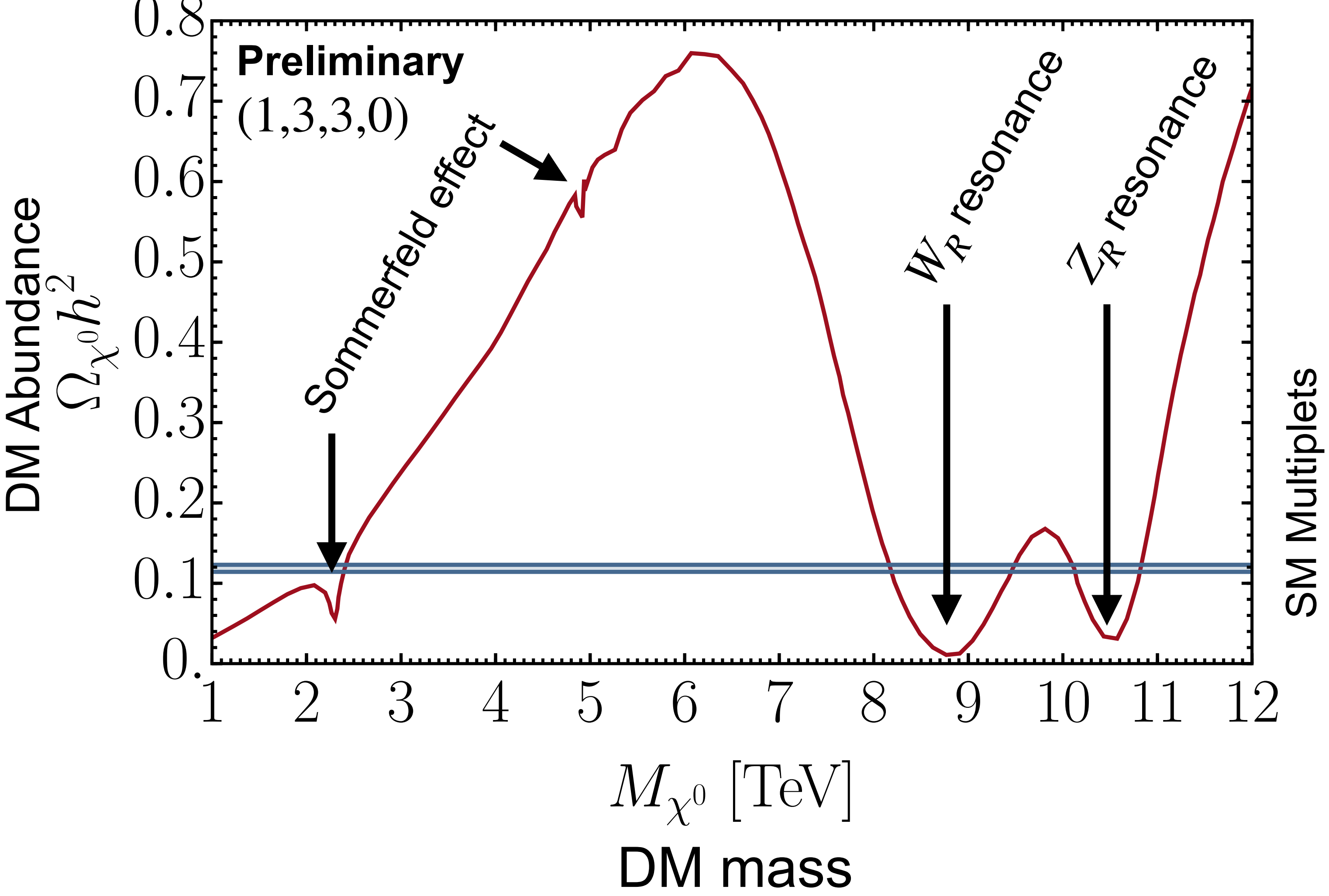

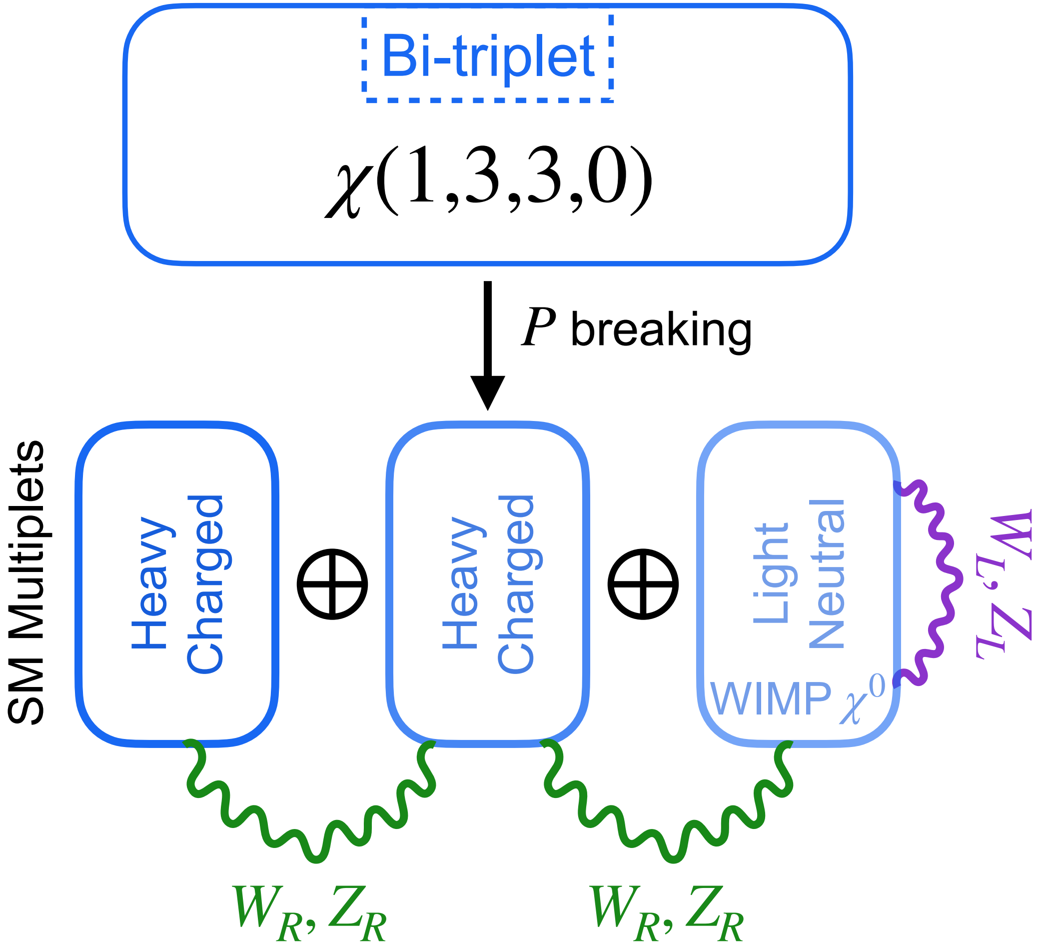

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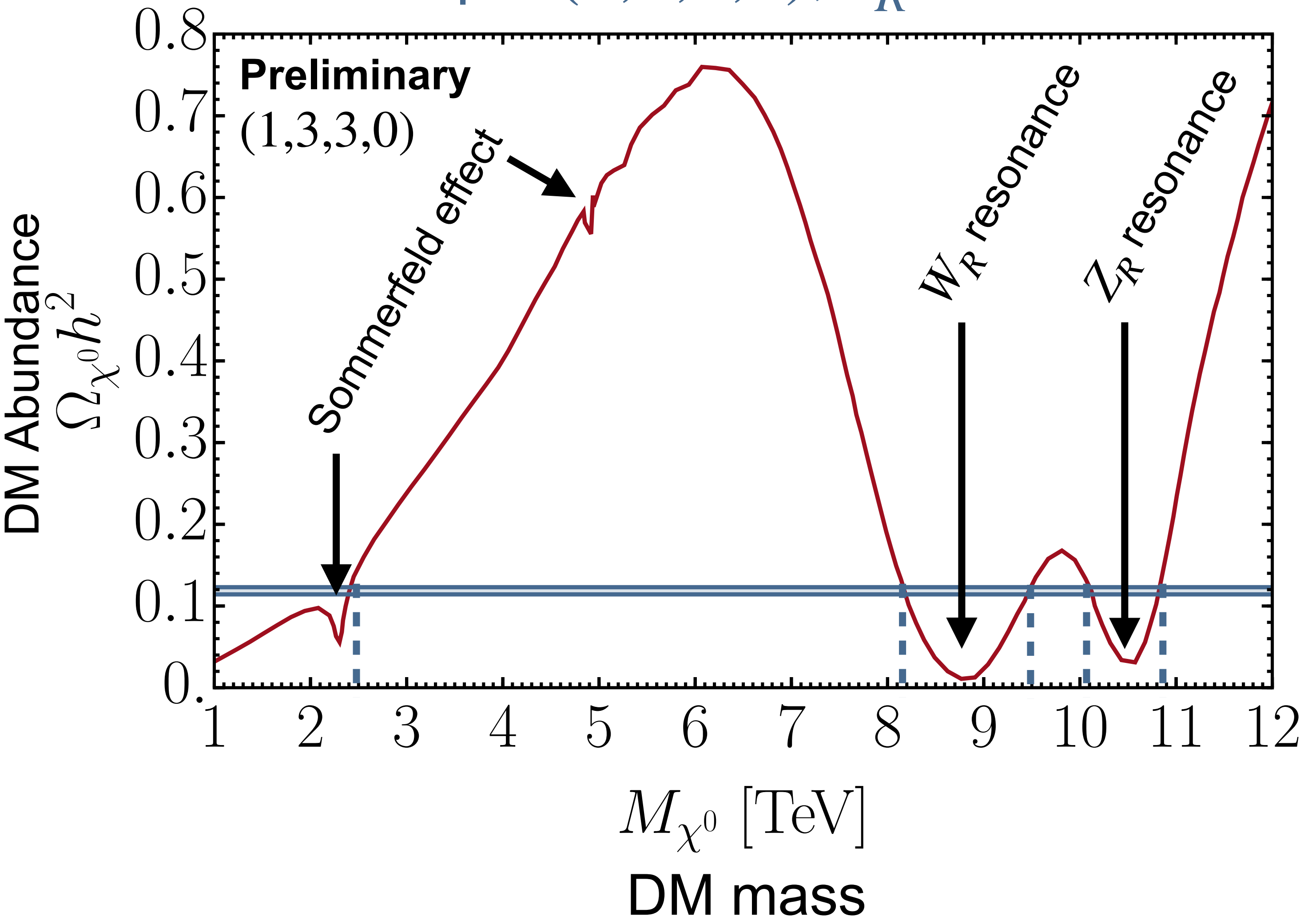

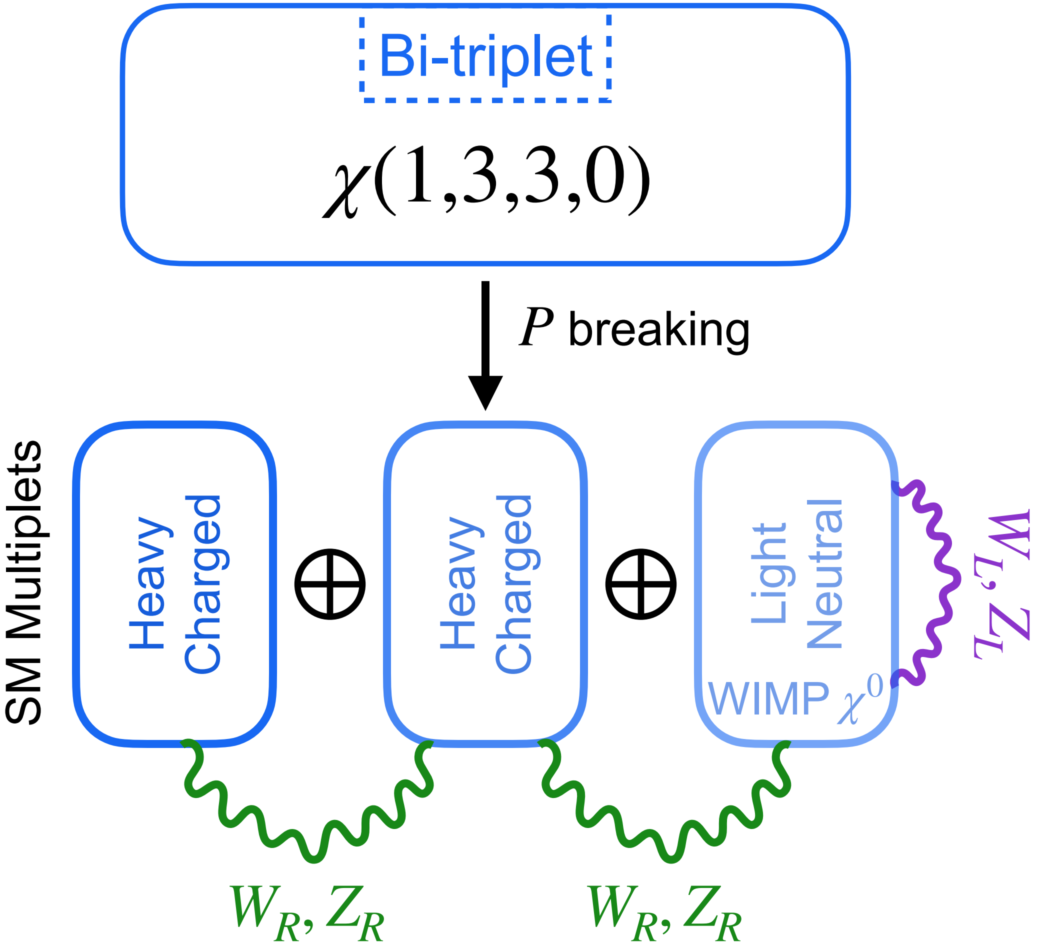

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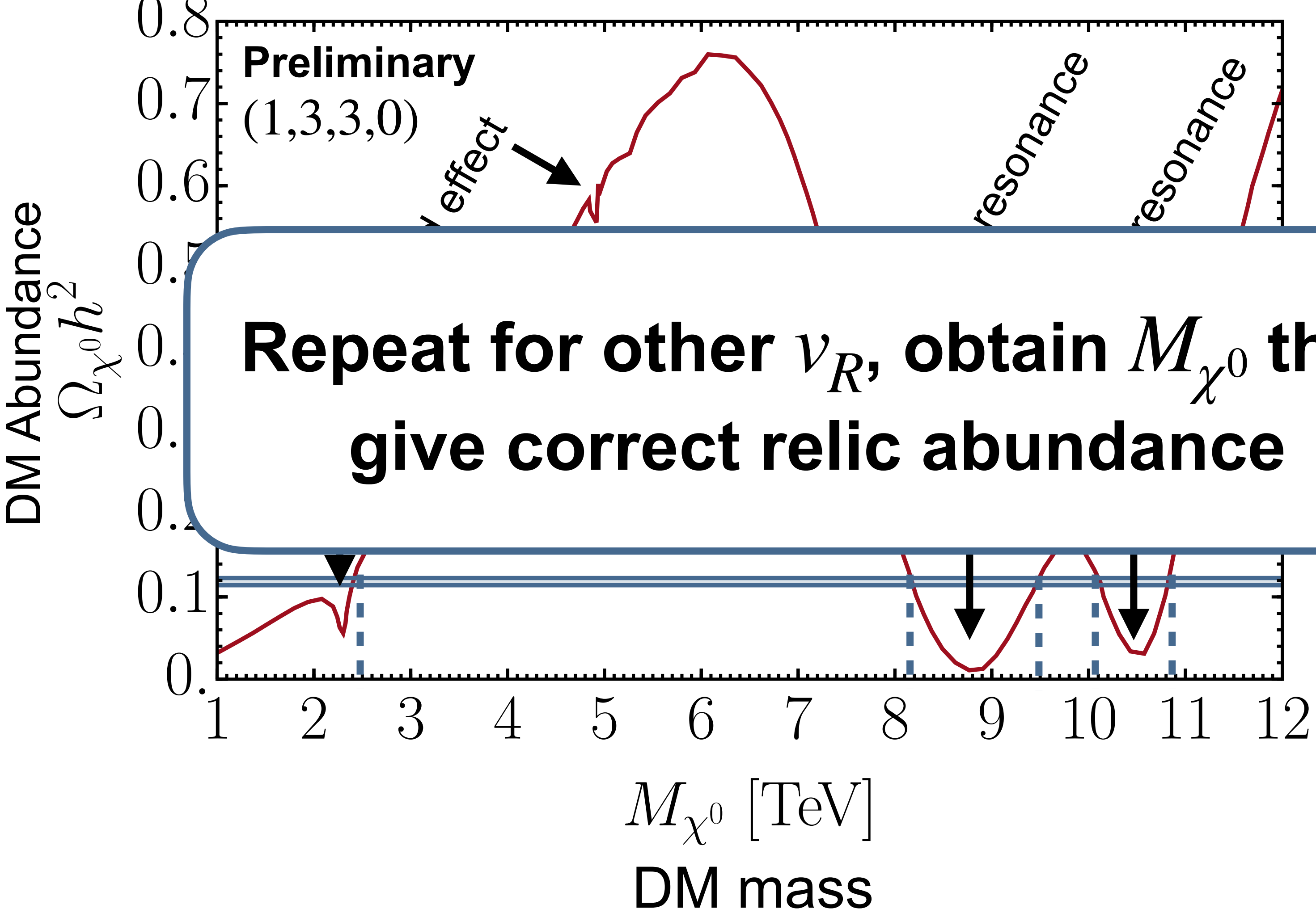
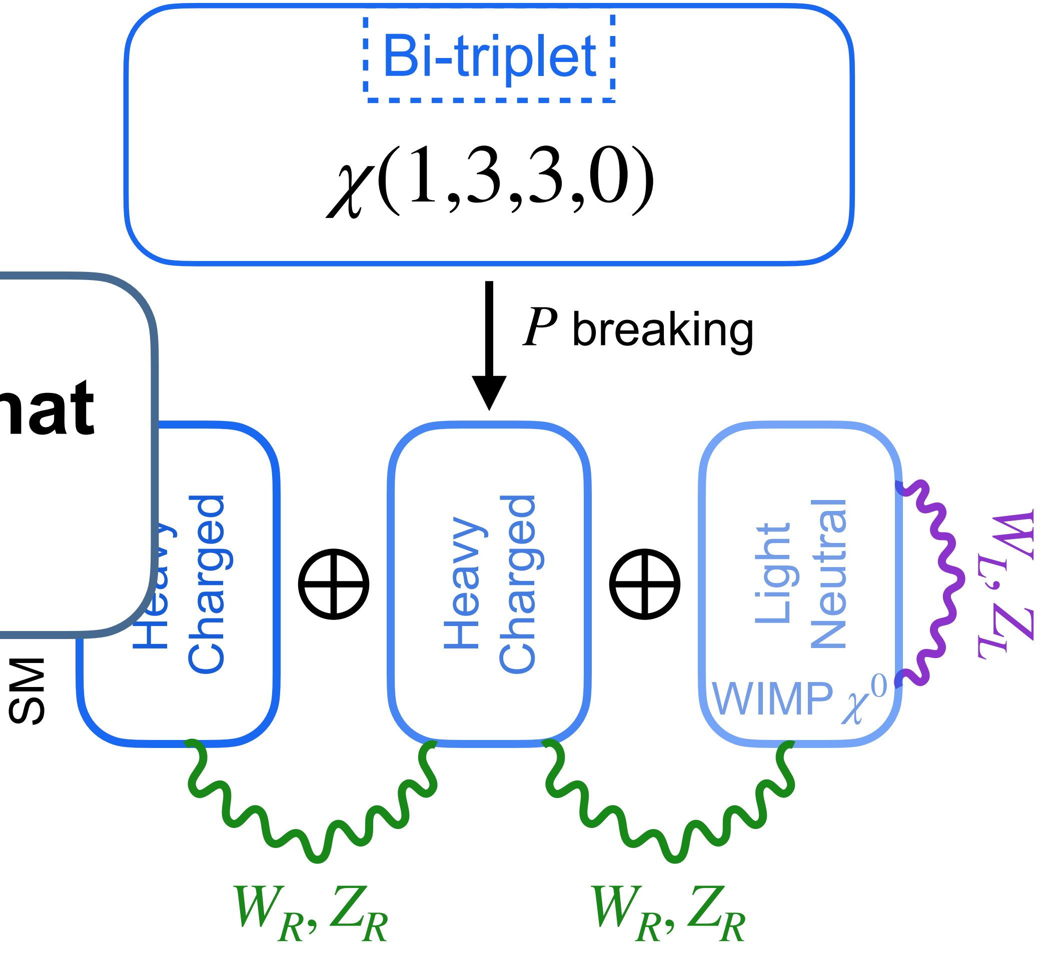


Repeat for other v_R, obtain M_{χ^0} that give correct relic abundance



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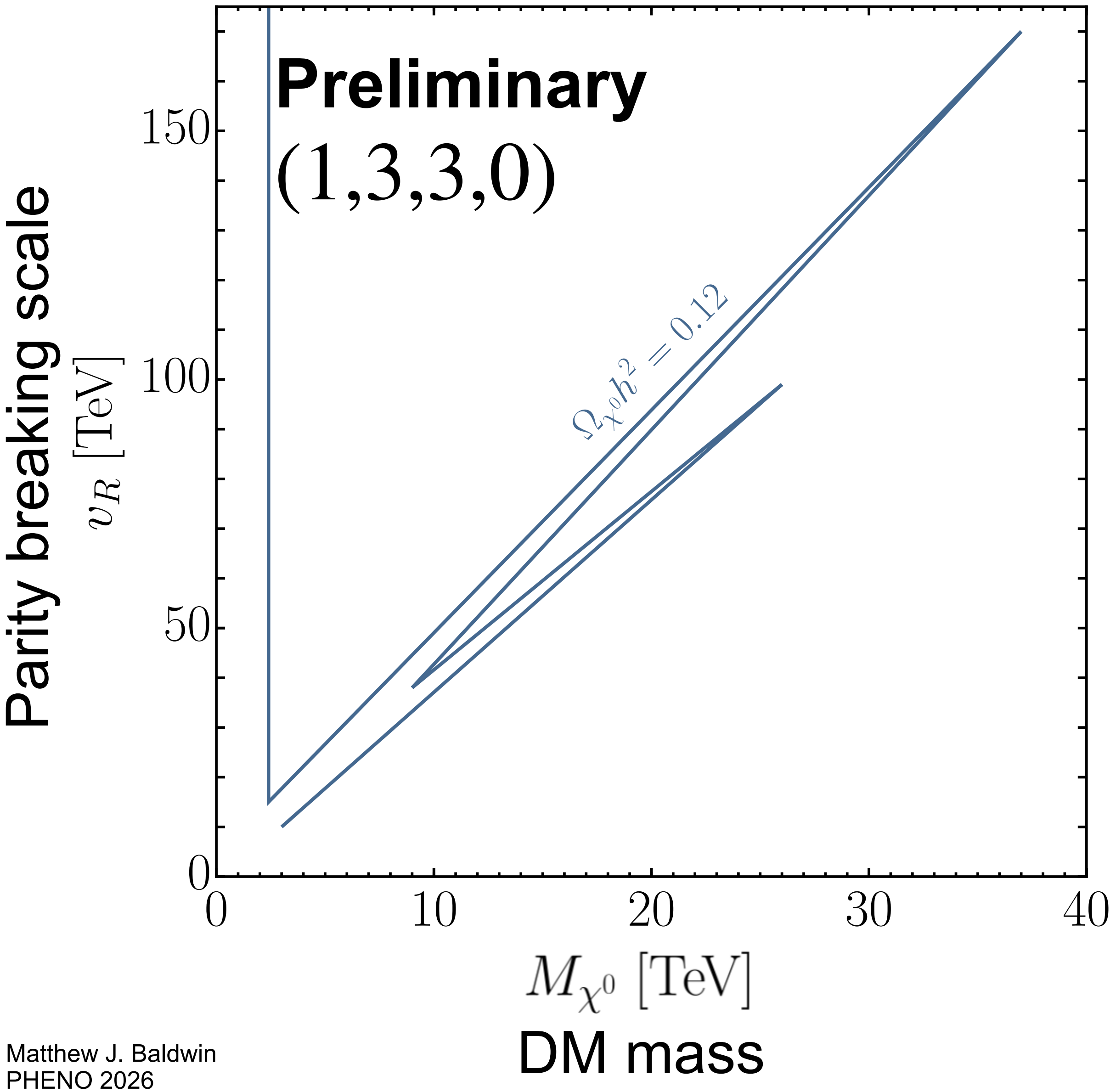
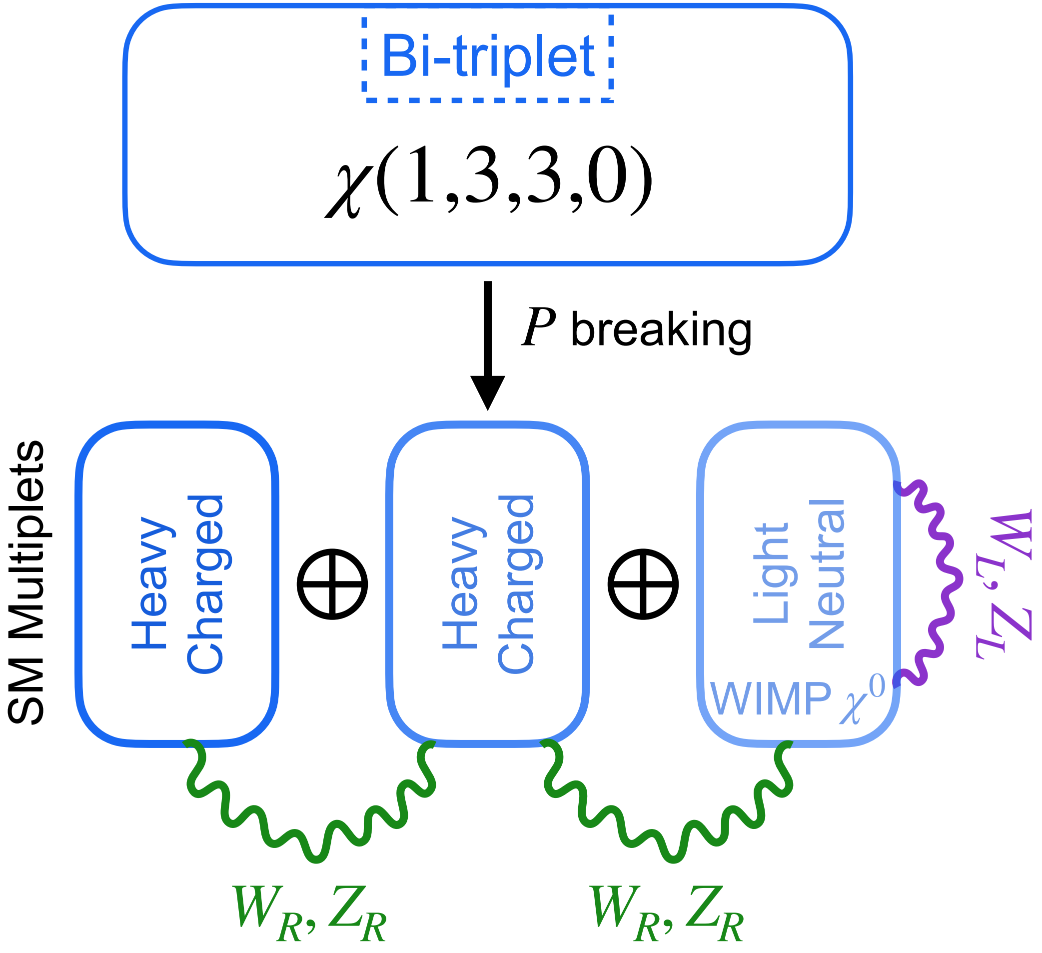
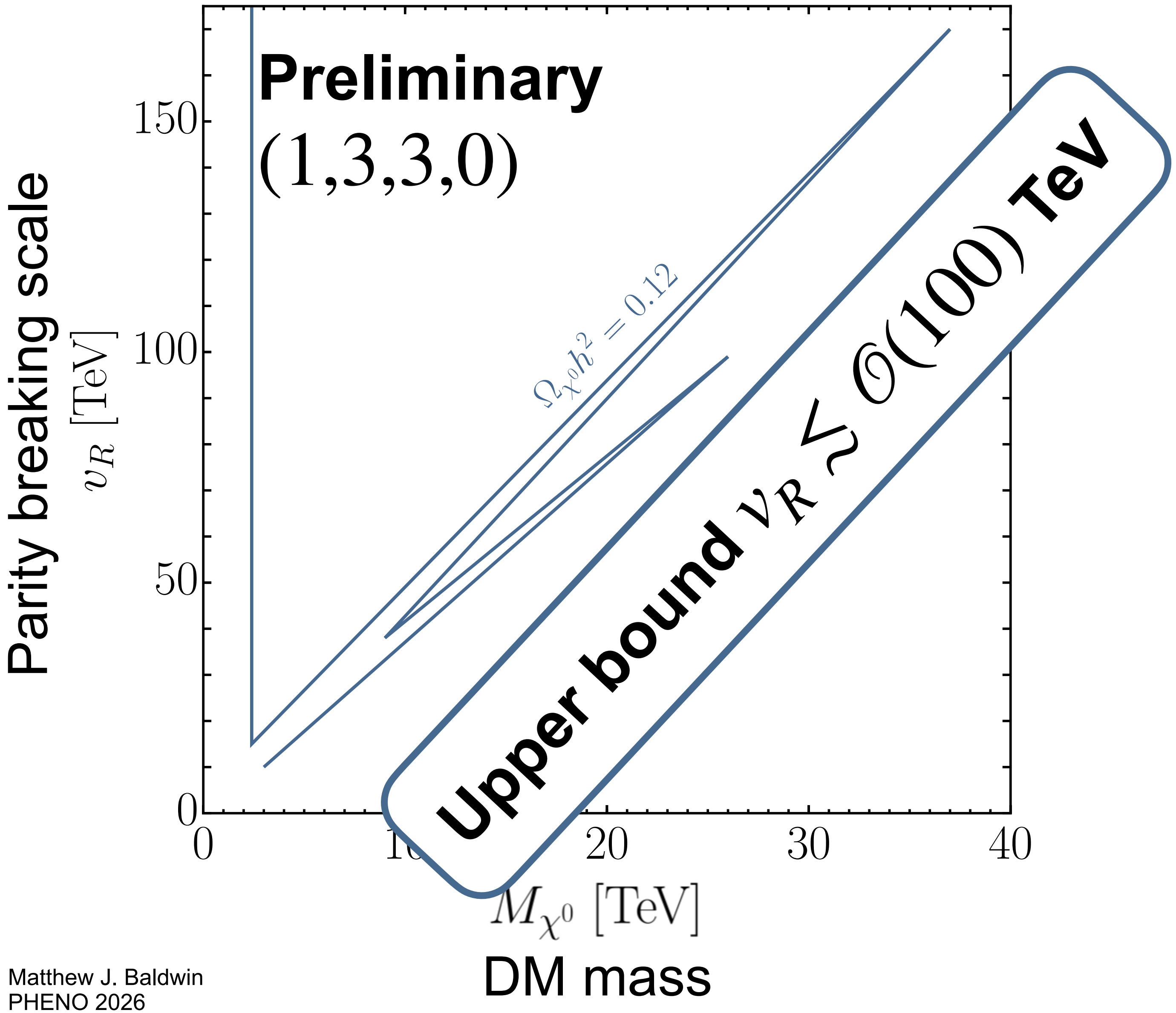
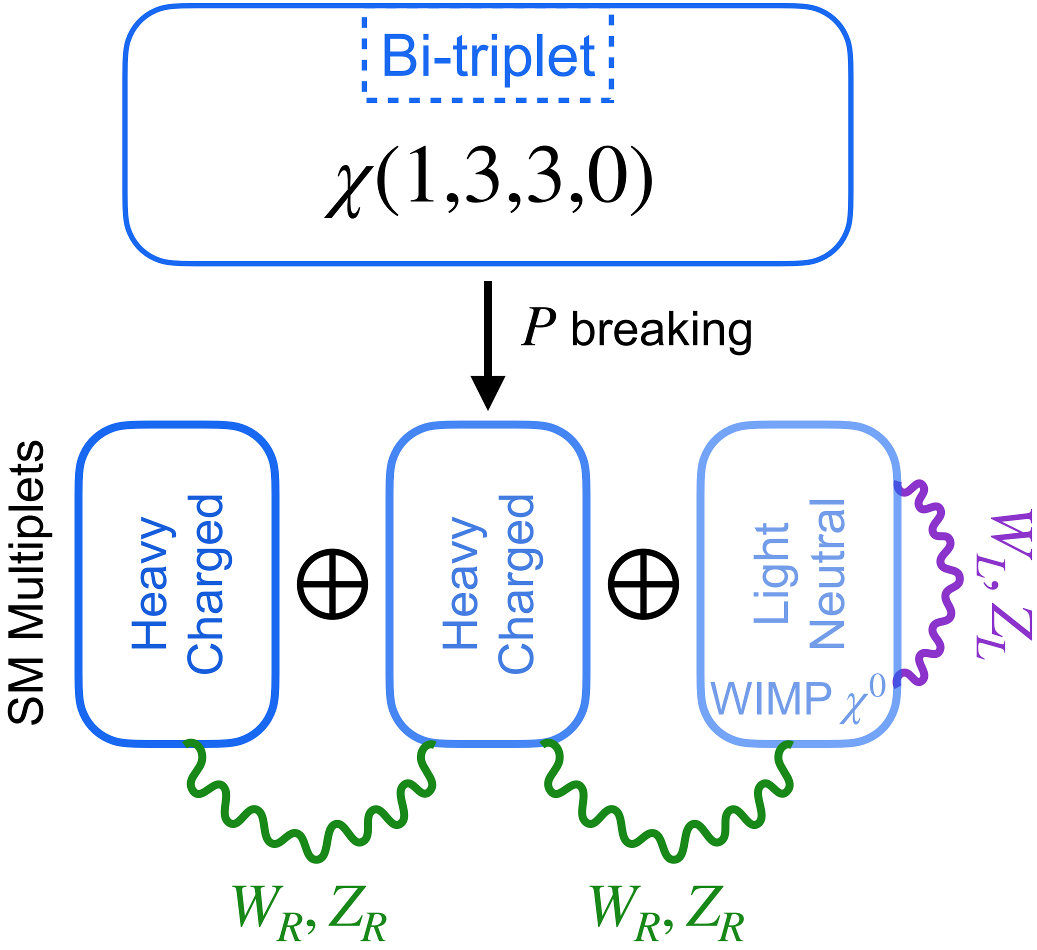




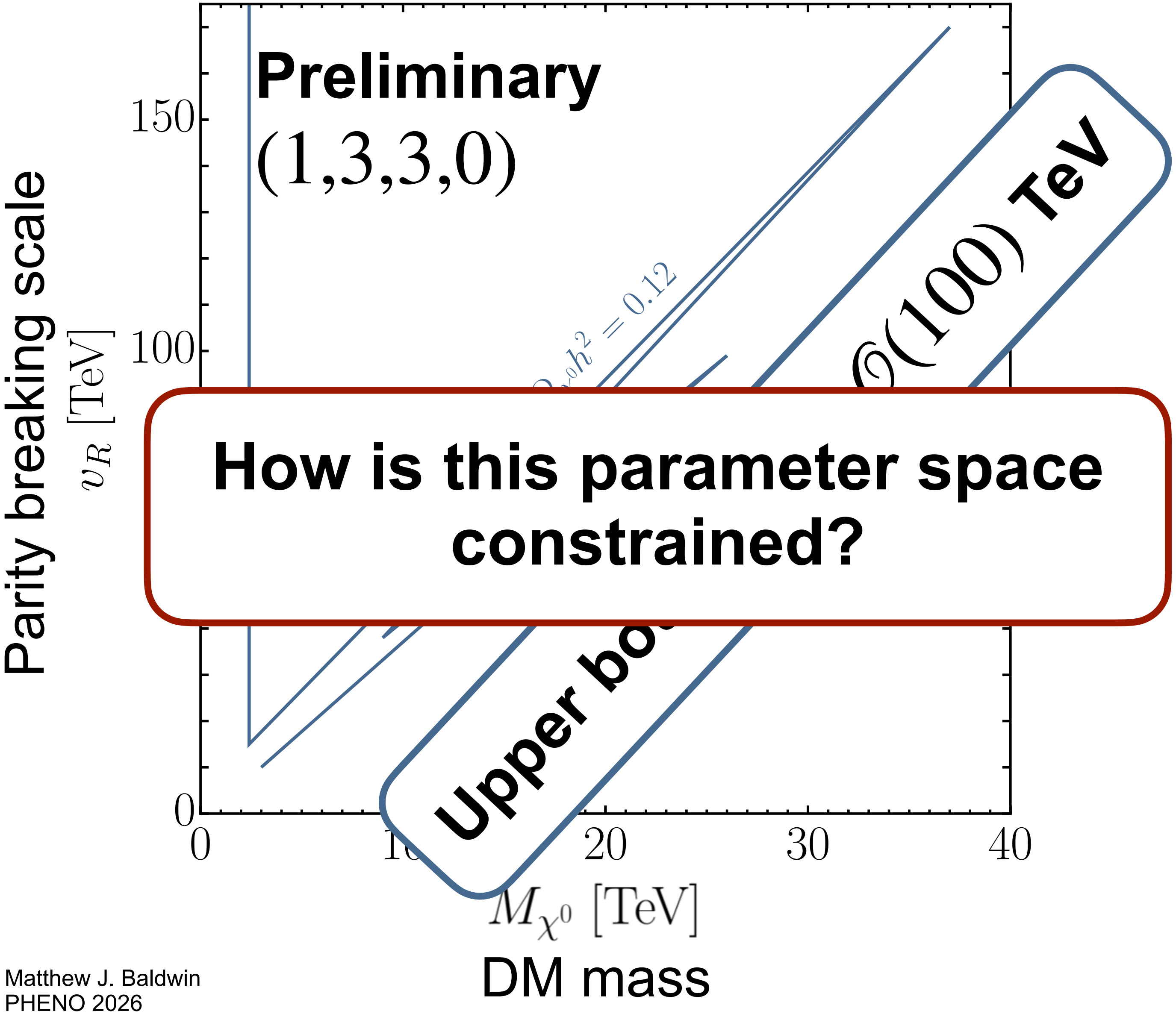
Thermal Relic Abundance



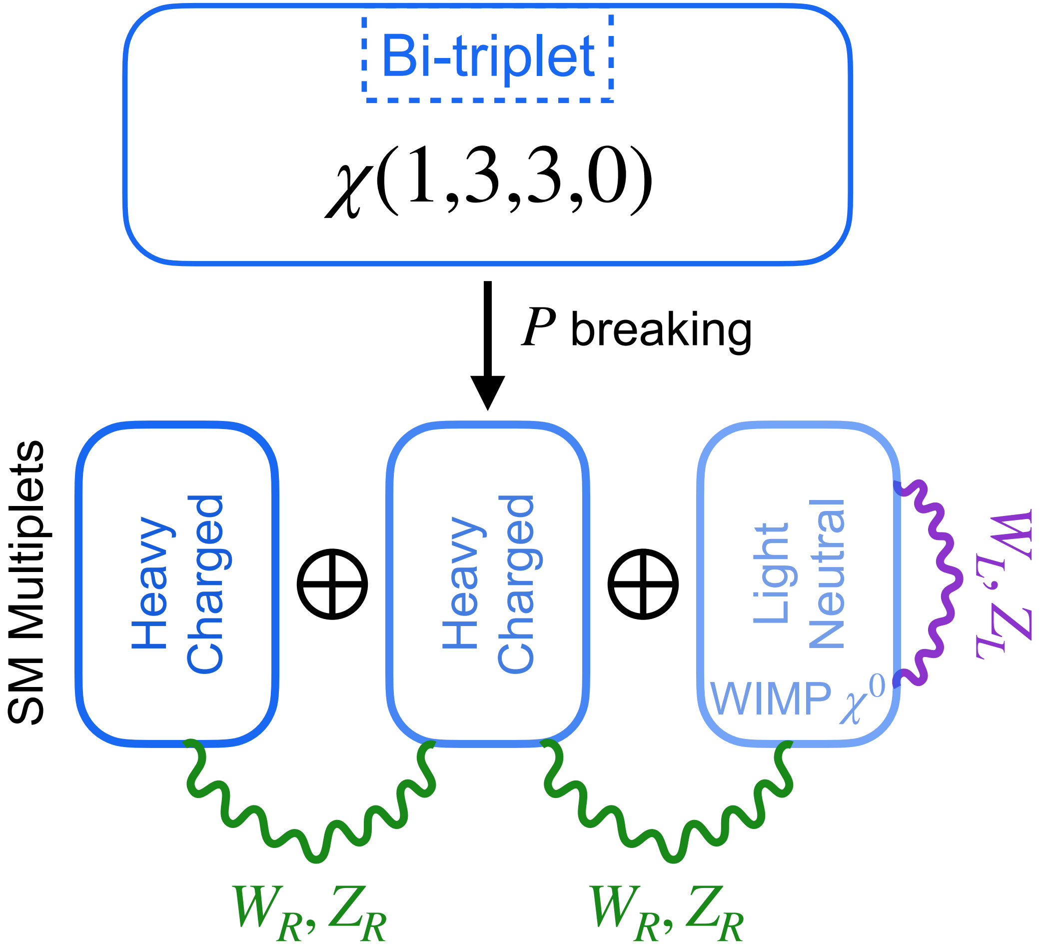
Upper bound $v_R \lesssim \mathcal{O}(100)$ TeV



Thermal Relic Abundance



How is this parameter space constrained?



Bi-triplet

$\chi(1,3,3,0)$

P breaking

SM Multiplets

Heavy Charged $\oplus$ Heavy Charged $\oplus$ Light Neutral

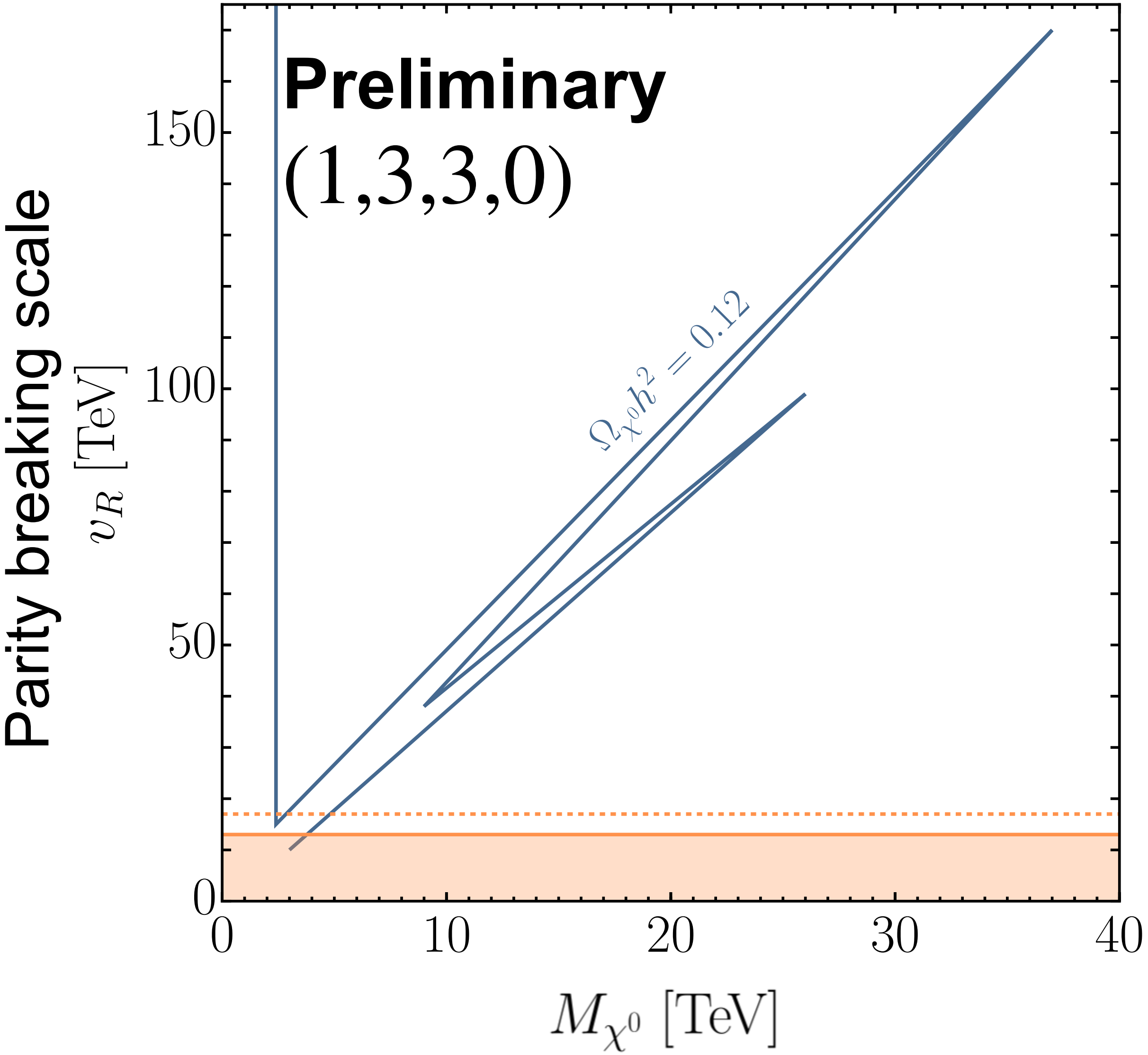
WIMP χ^0

W_L, Z_L

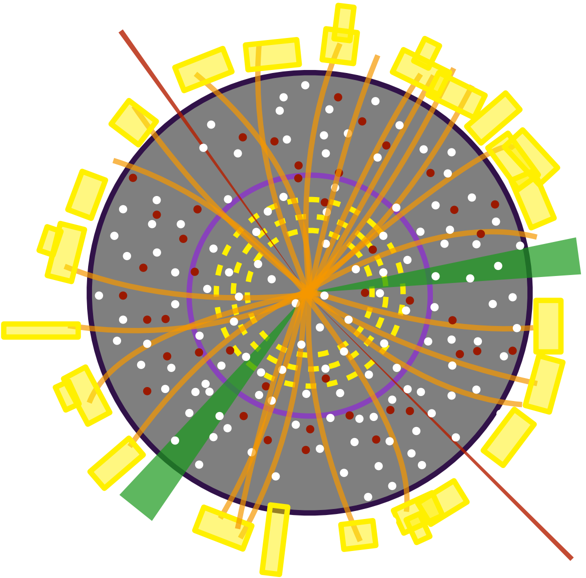
W_R, Z_R

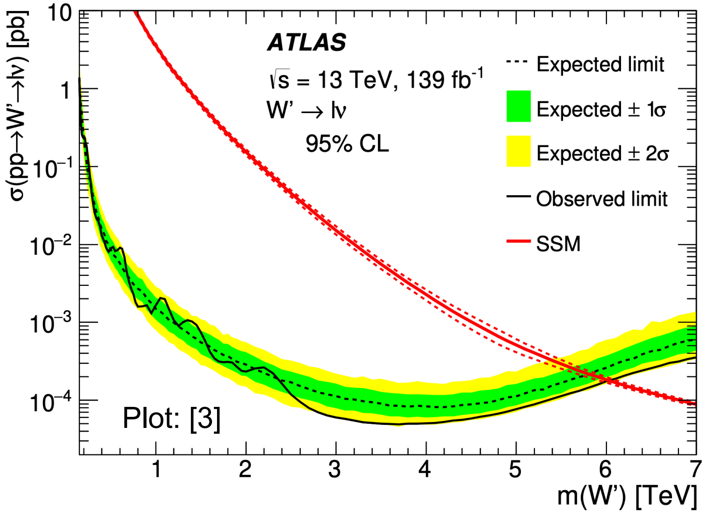
W_R, Z_R

Collider Constraints



Collider searches for $W_R^\pm$ provide **lower bound** on $m_{W_R} \propto v_R$



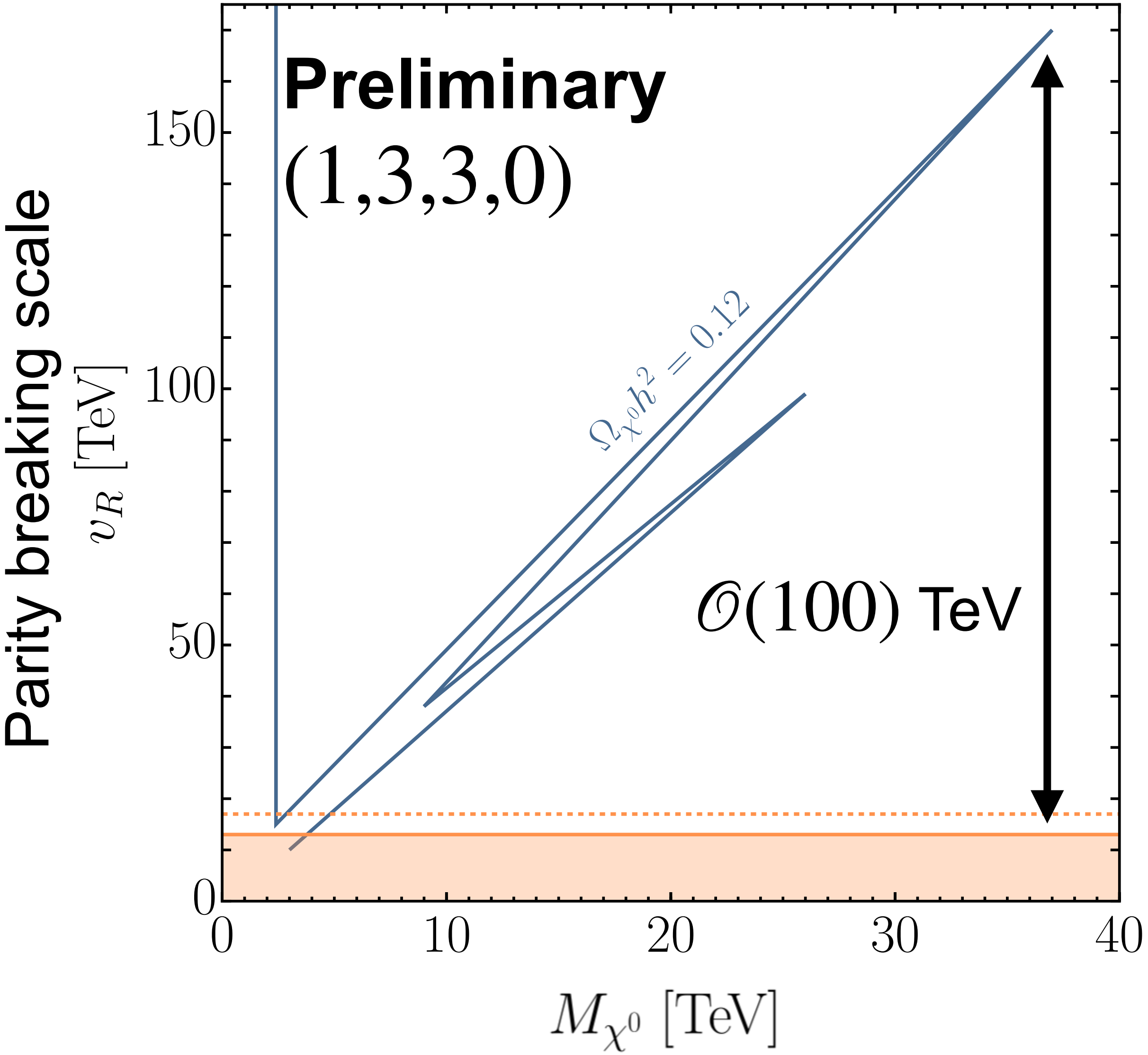


Plot: [3]

$$6 \text{ TeV} \lesssim M_{W_R} = \frac{1}{\sqrt{2}} g v_R \longrightarrow v_R \gtrsim 14 \text{ TeV}$$

[3] *ATLAS Collaboration, G. Aad et al.*, Search for a heavy charged boson in events with a charged lepton and missing transverse momentum from pp collisions at √s = 13 TeV with the ATLAS detector (2019)

Collider Constraints



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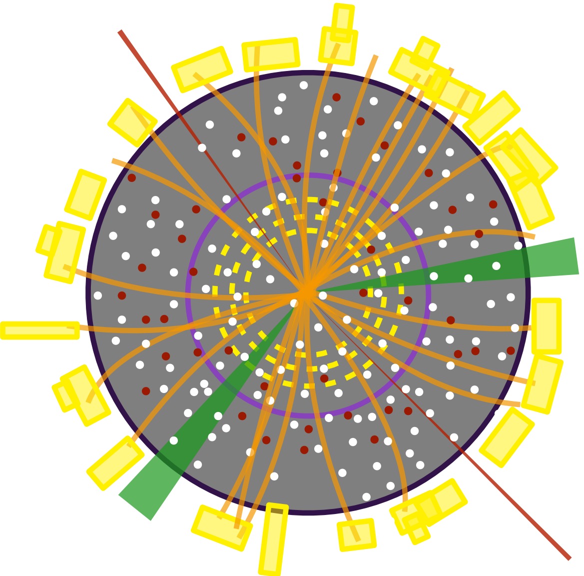

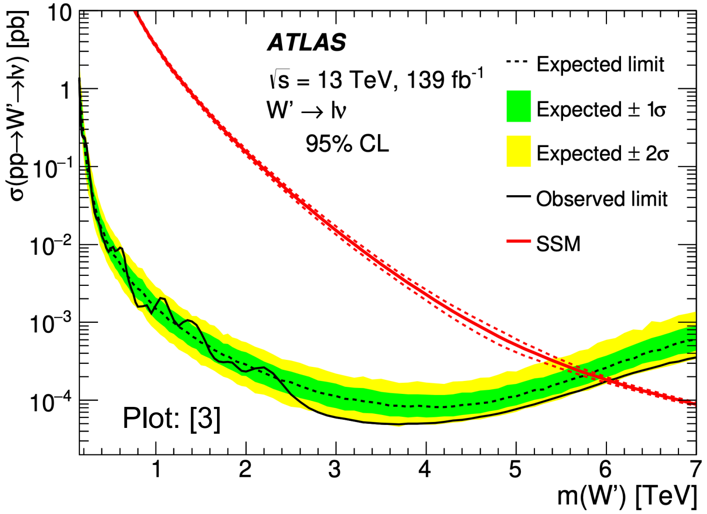

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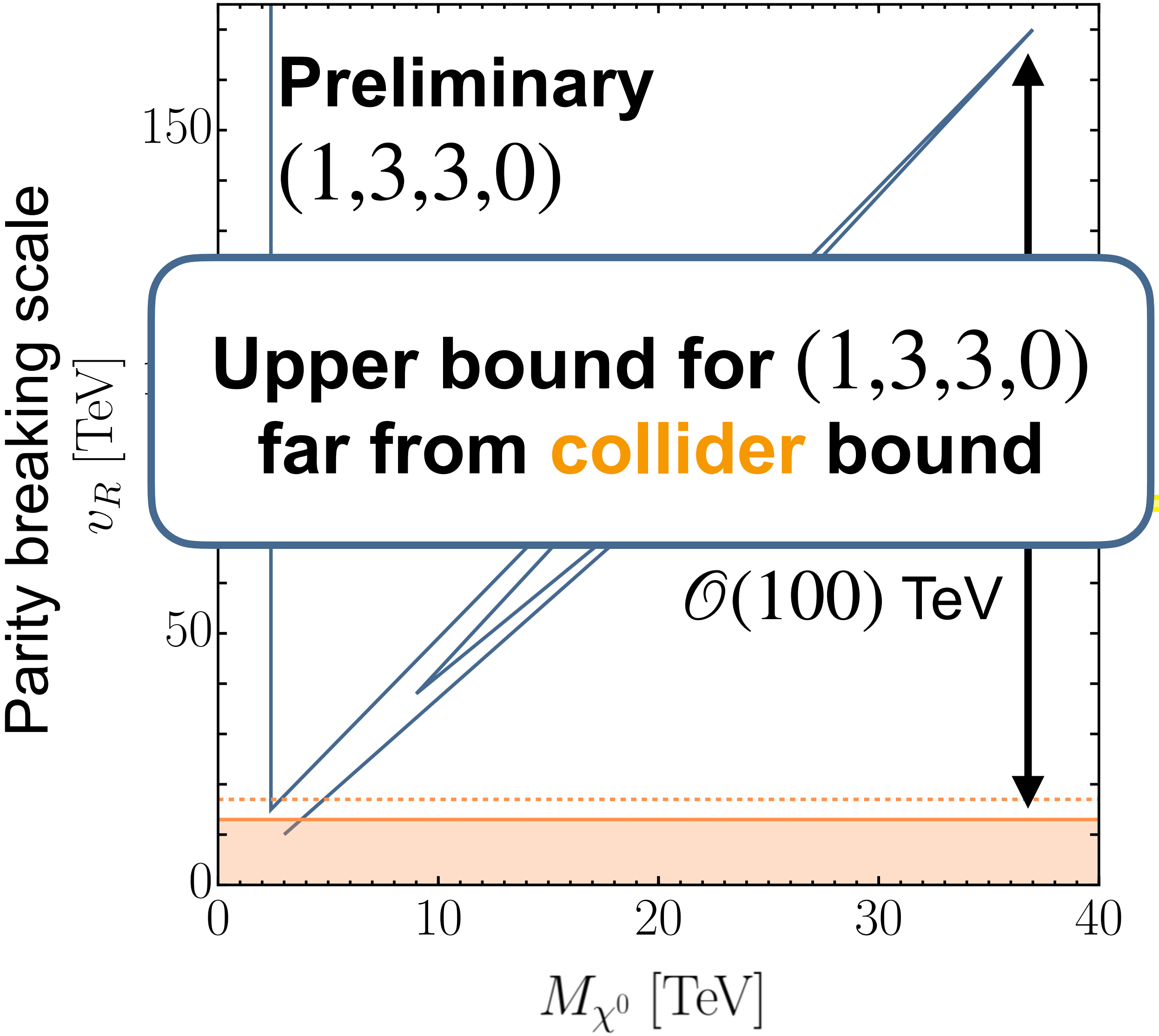
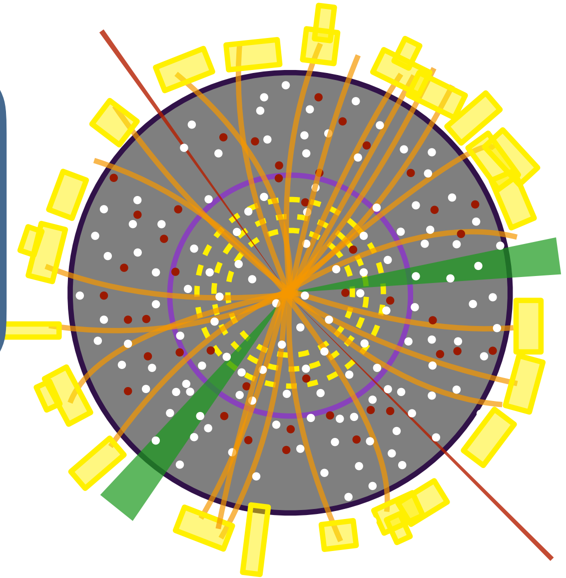
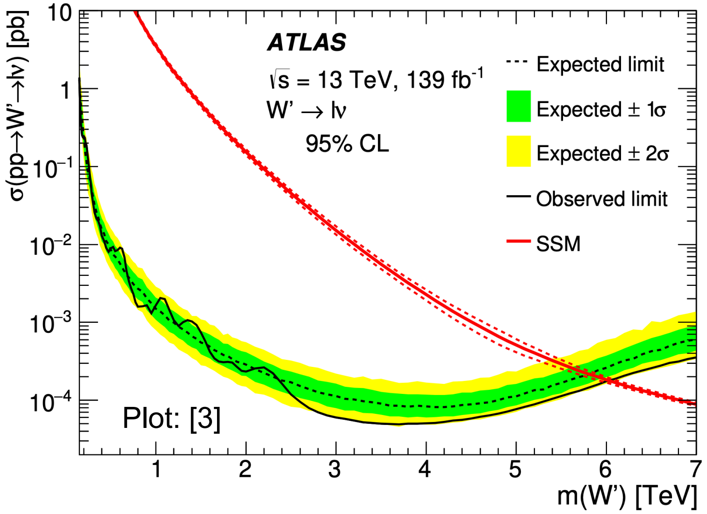


Upper bound for (1,3,3,0)
far from collider bound

Collider searches for $W_R^{\pm}$ provide **lower bound** on $m_{W_R} \propto v_R$





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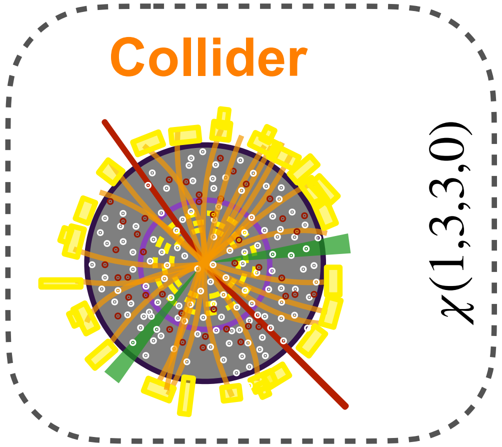
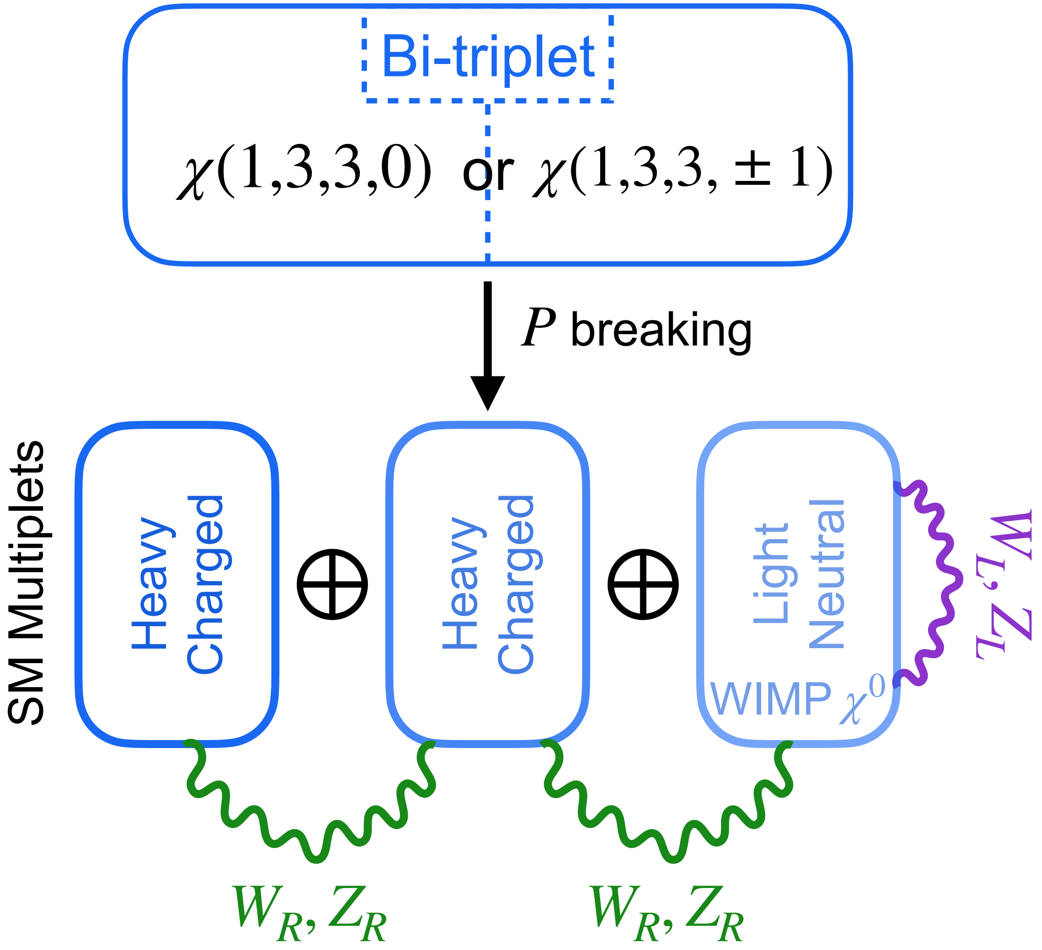
Direct Detection Constraints

Constraints:



Collider

$\chi(1,3,3,0)$



Bi-triplet

$\chi(1,3,3,0)$ or $\chi(1,3,3,\pm 1)$

P breaking

SM Multiplets

Heavy Charged $\oplus$ Heavy Charged $\oplus$ Light Neutral

WIMP χ^0

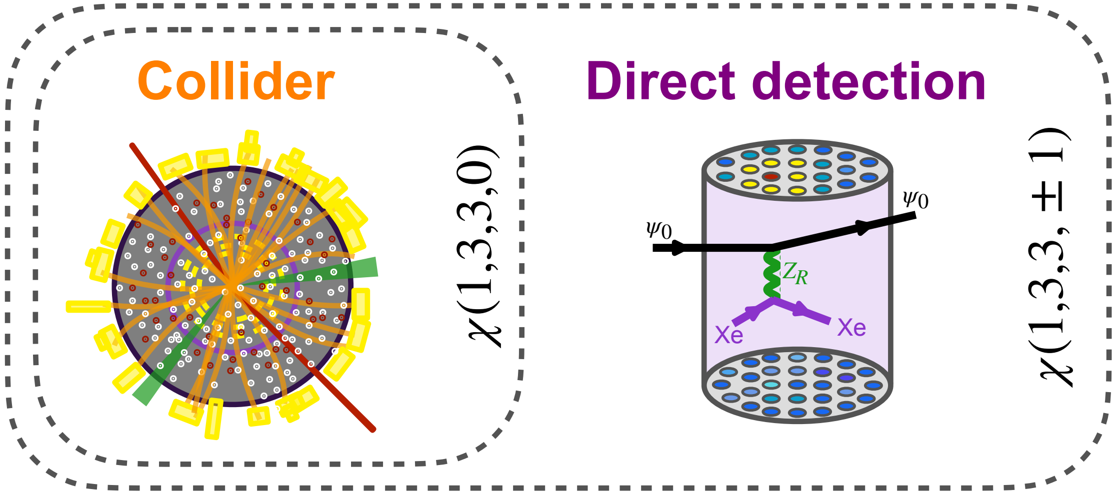
W_R, Z_R

W_R, Z_R

W_L, Z_L

Direct Detection Constraints

Constraints:

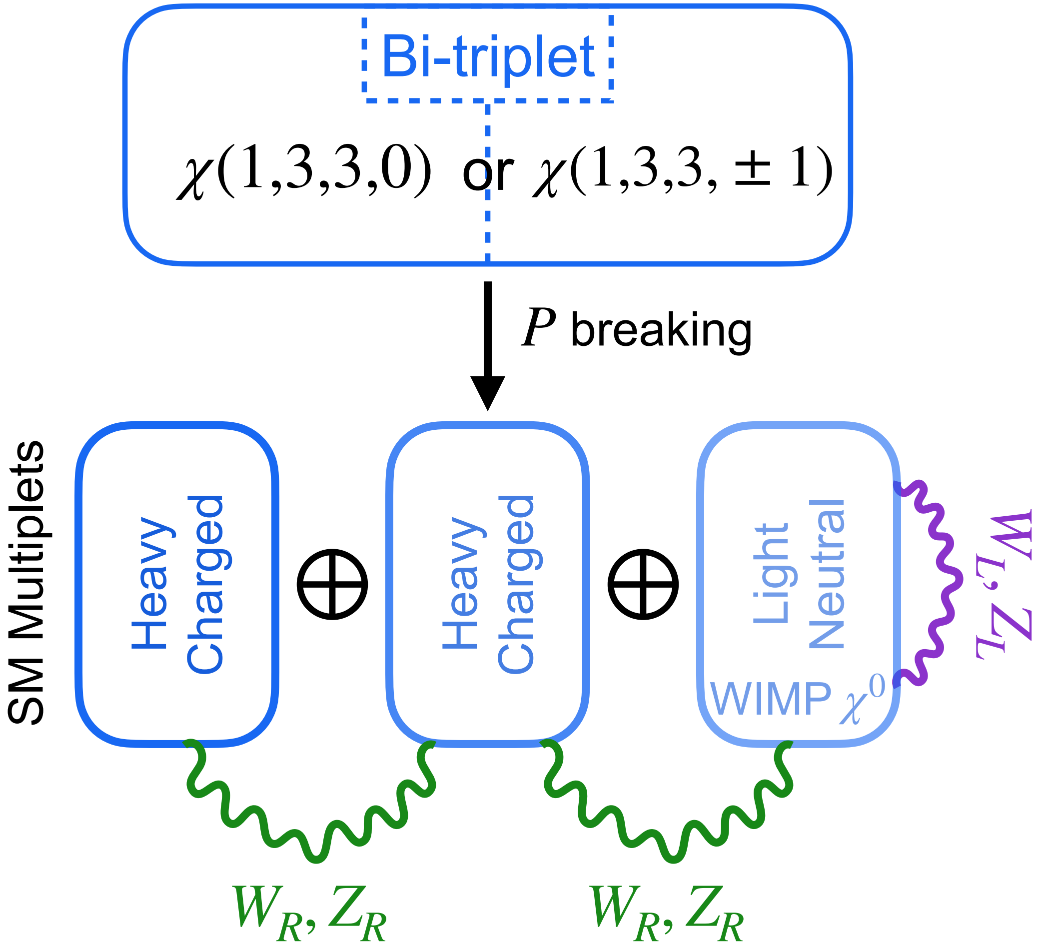


Collider

$\chi(1,3,3,0)$

Direct detection

$\chi(1,3,3,\pm 1)$



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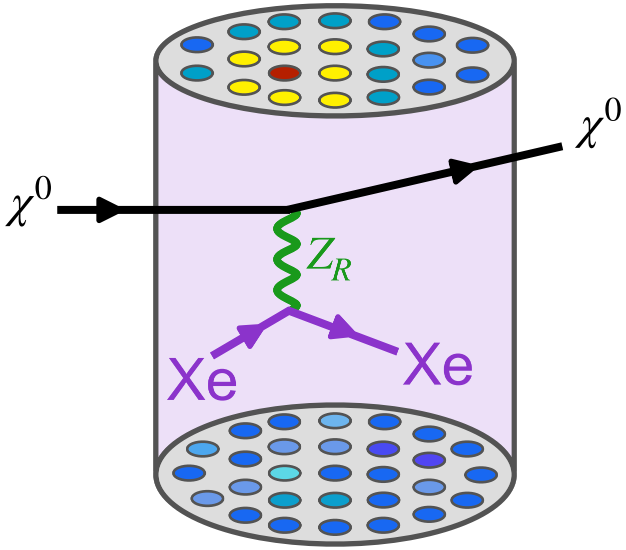
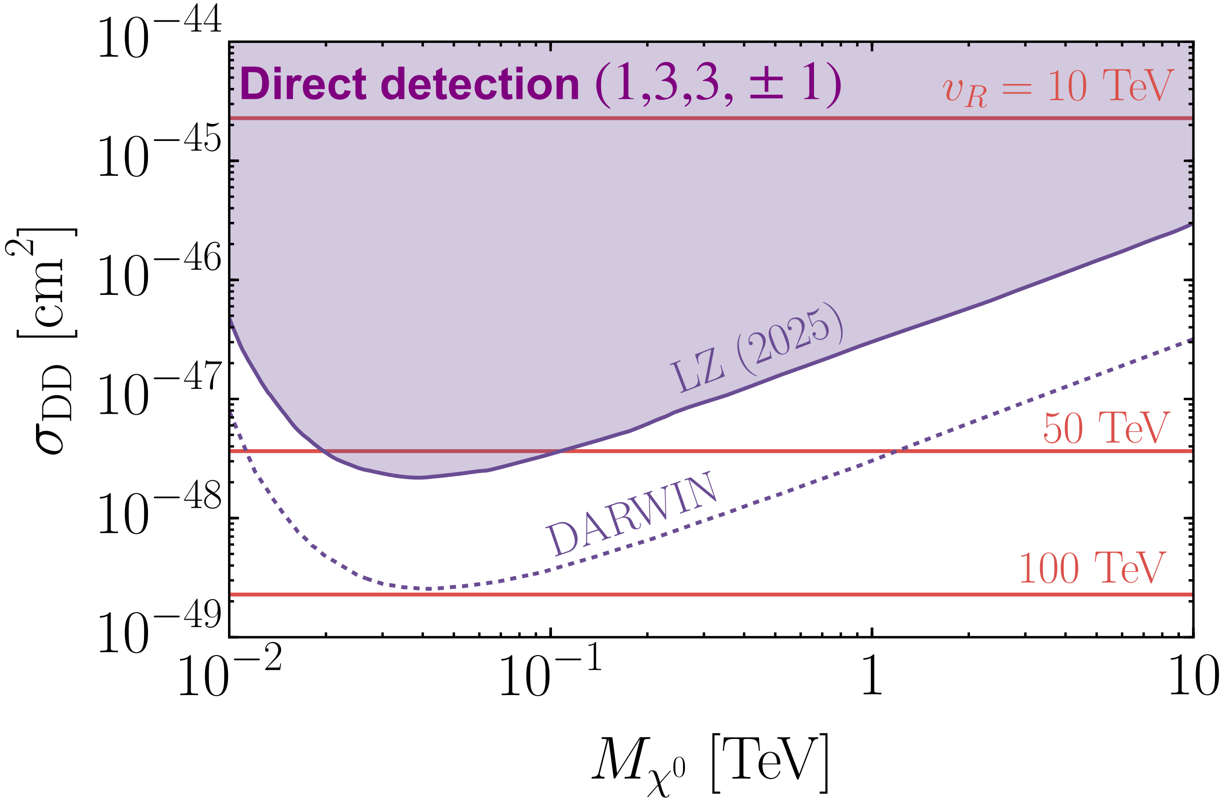
Direct Detection Constraints

Direct detection of WIMP-nucleon scattering in $(1,3,3,\pm 1)$ places lower bound on v_R

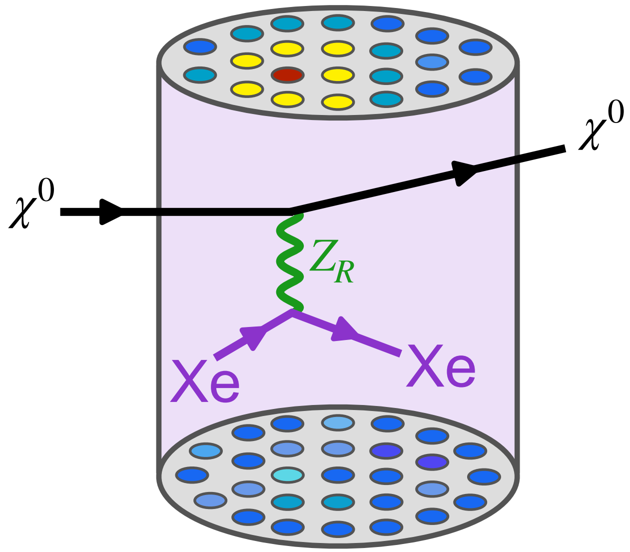


[5] *LZ Collaboration Collaboration, J. Aalbers et al.*, Dark Matter Search Results from 4.2 Tonne-Years of Exposure of the LUX-ZEPLIN (LZ) Experiment (2024)
[6] *DARWIN Collaboration, J. Aalbers et al.*, DARWIN: towards the ultimate dark matter detector (2016)

Direct Detection Constraints



Direct detection of WIMP-nucleon scattering in $(1,3,3,\pm 1)$ places lower bound on v_R



LZ— liquid Xe direct detection experiment searching for nucleon-DM scattering [5]

DARWIN— proposed liquid Xe direct detection experiment [6]

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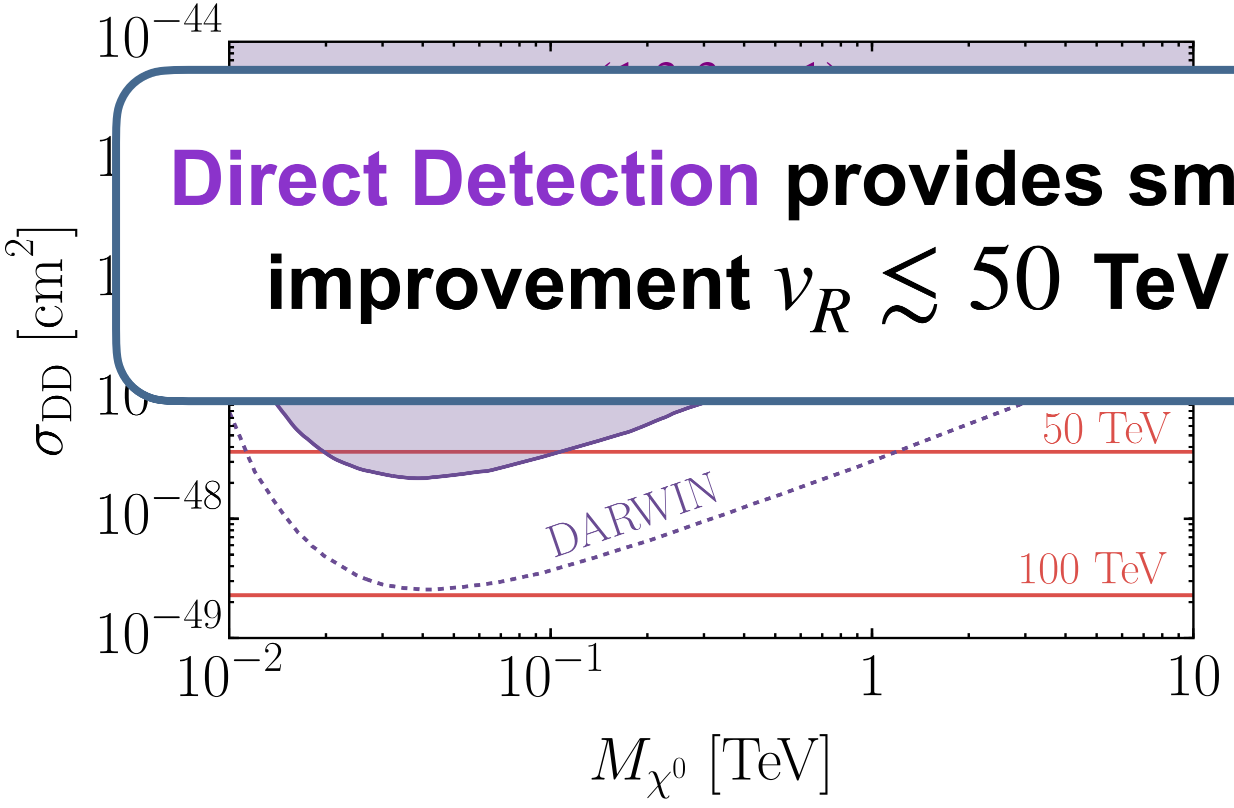
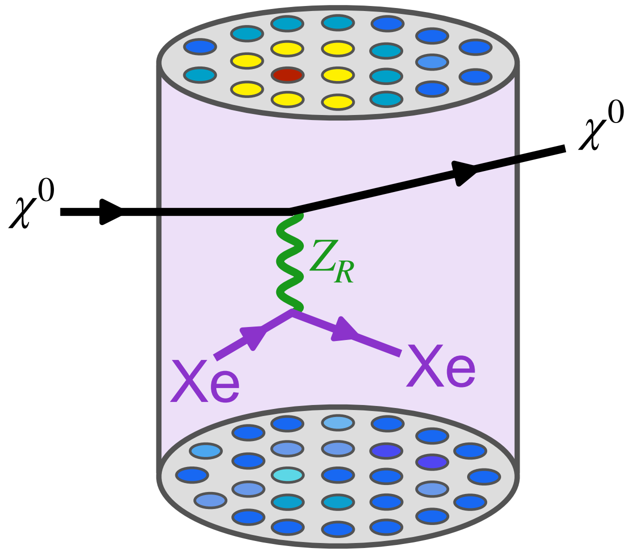


Direct Detection **provides small improvement $v_R \lesssim 50$ TeV**

Direct detection of WIMP-nucleon scattering in $(1,3,3,\pm 1)$ places lower bound on v_R



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Indirect Detection Constraints

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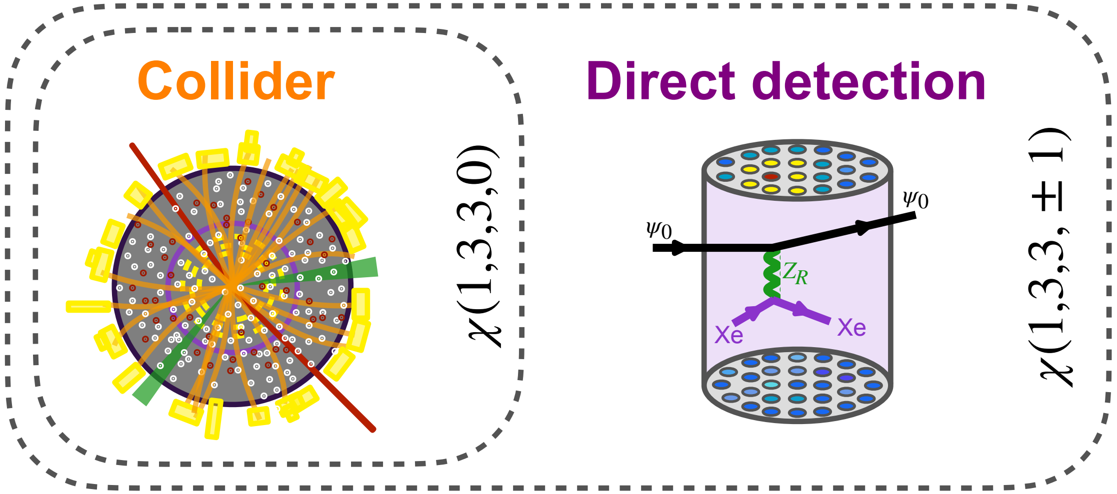

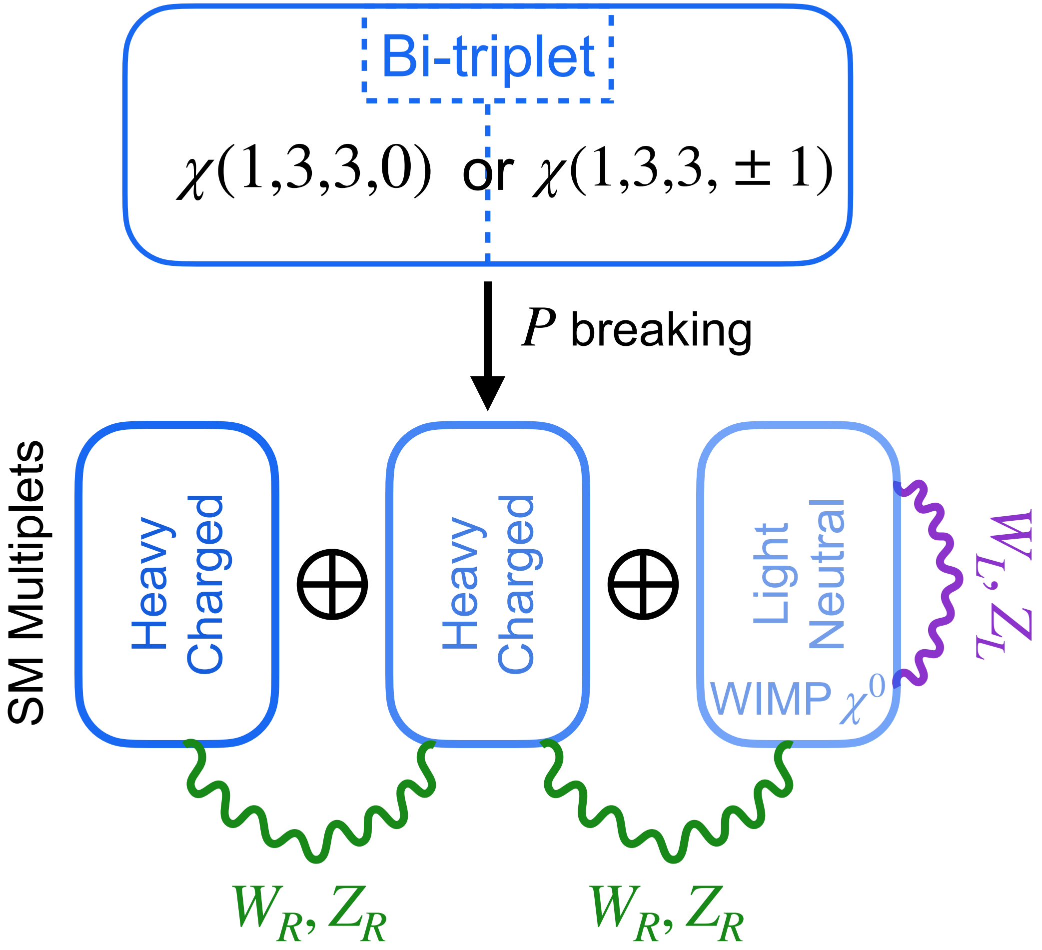

Indirect Detection Constraints

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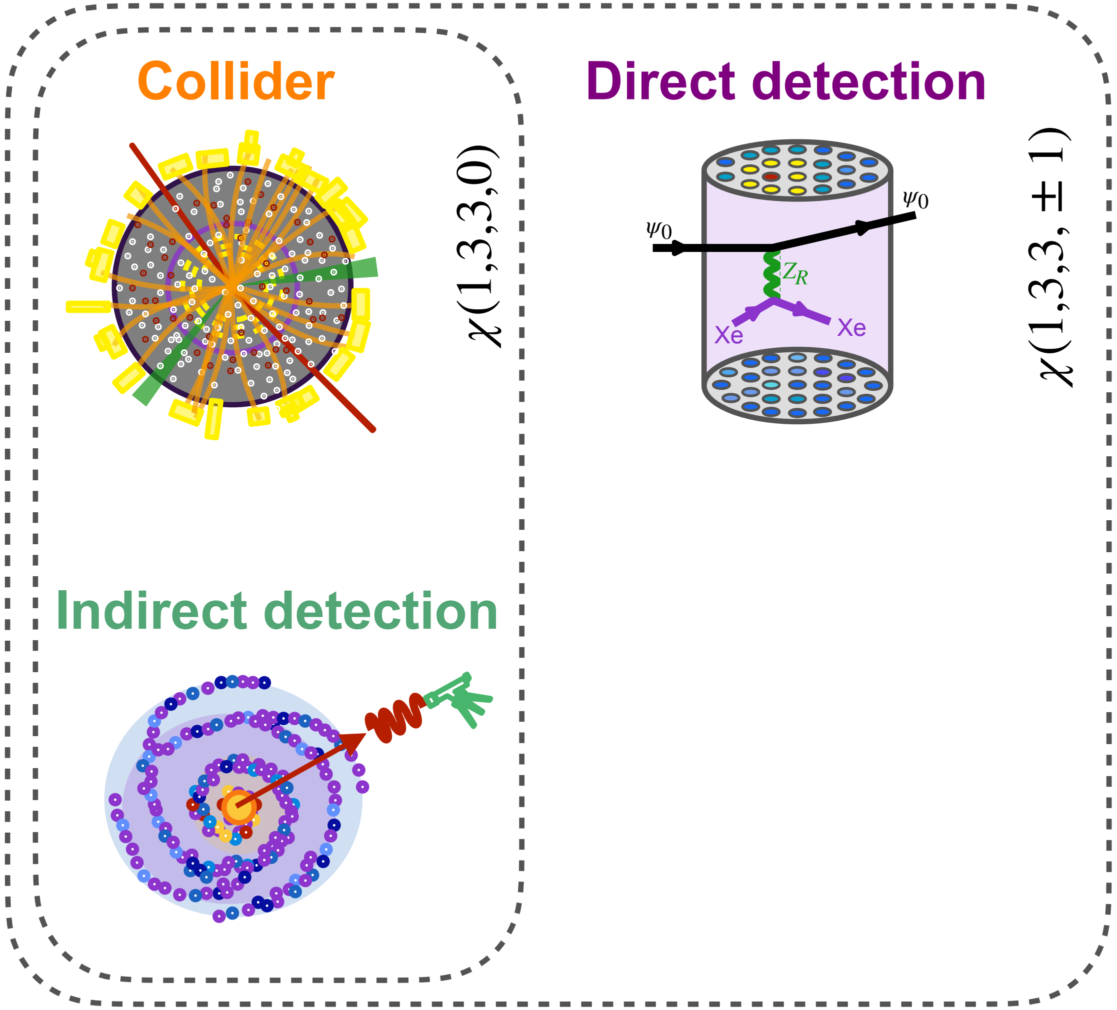


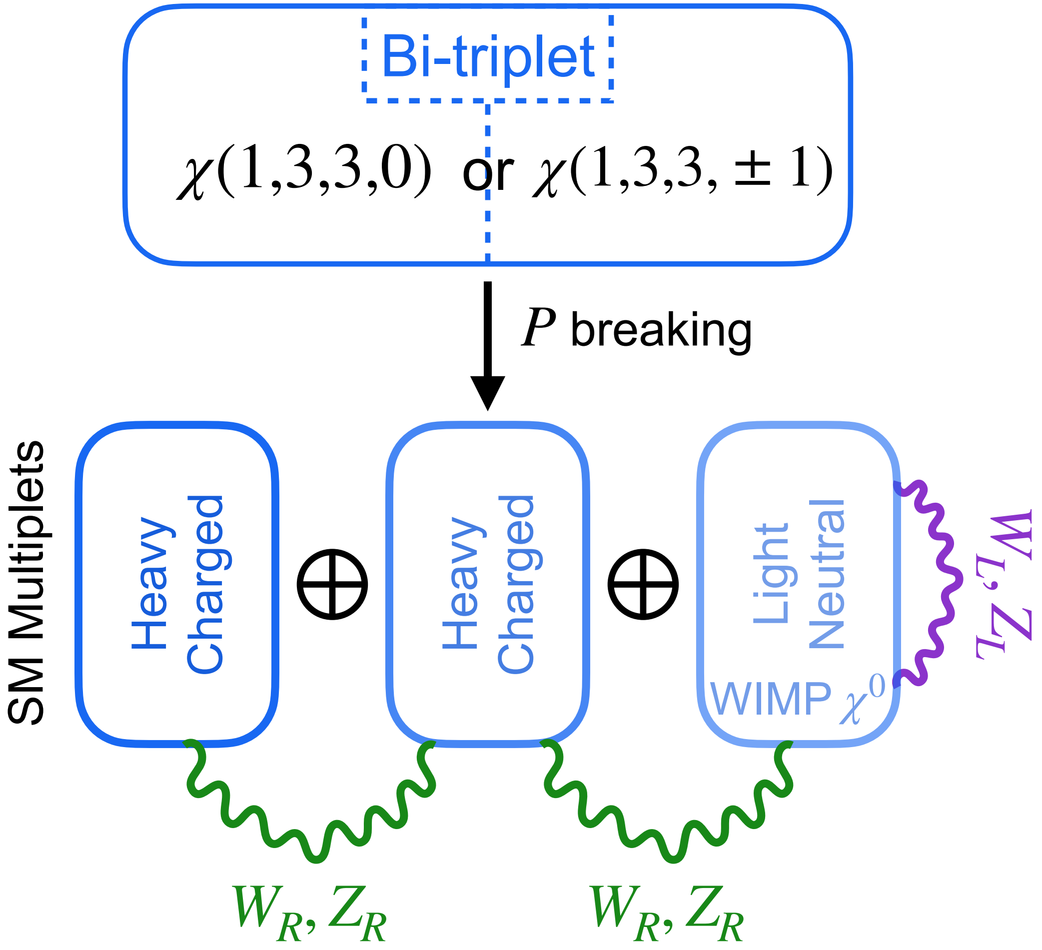
Collider

$\chi(1,3,3,0)$

Direct detection

$\chi(1,3,3,\pm 1)$

Indirect detection



Bi-triplet

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SM Multiplets

Heavy Charged $\oplus$ Heavy Charged $\oplus$ Light Neutral

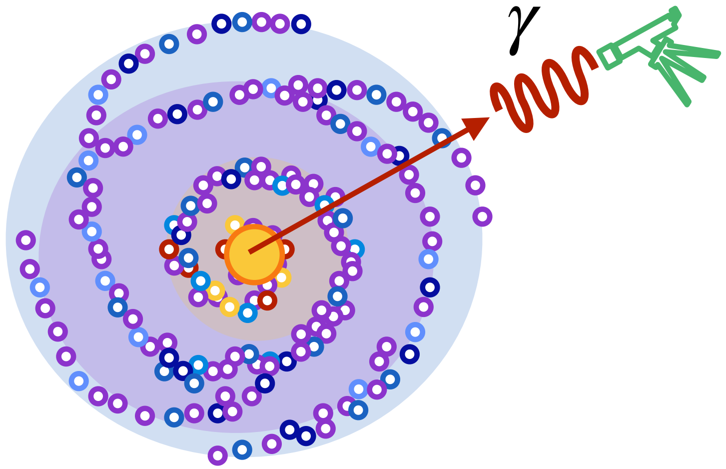
WIMP χ^0

W_L, Z_L

W_R, Z_R W_R, Z_R

Indirect Detection Constraints

Indirect detection [4] constrains photons from DM annihilation in galactic centre



[4] *C.T.A. Collaboration, A. Acharyya et al. Sensitivity of the Cherenkov Telescope Array to a dark matter signal from the Galactic centre (2021)*

Indirect Detection Constraints

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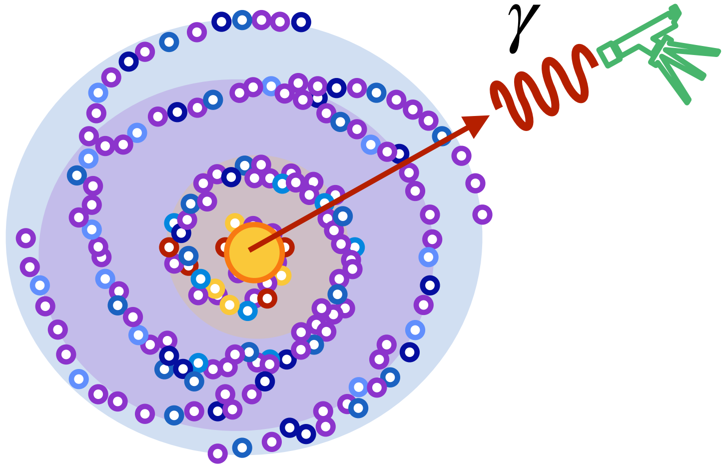

Annihilation via **Sommerfeld effect** produces:

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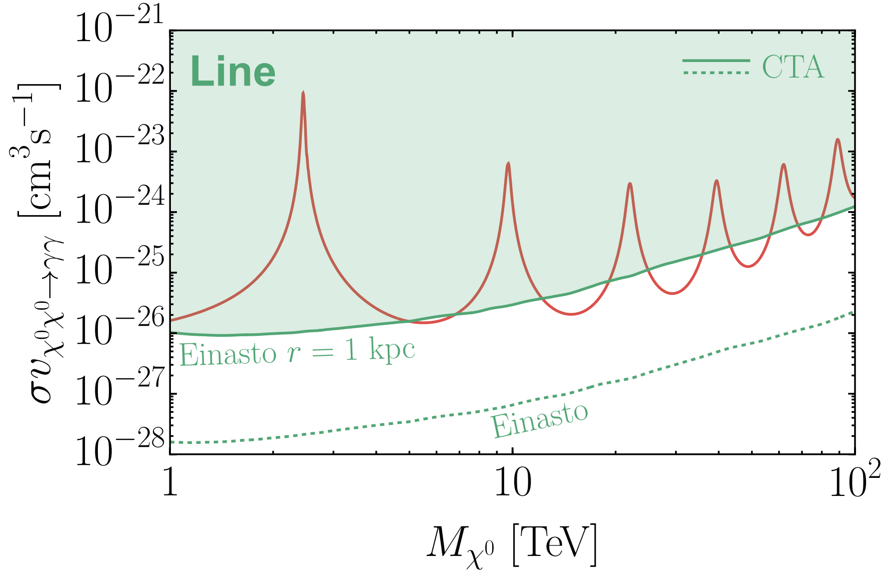
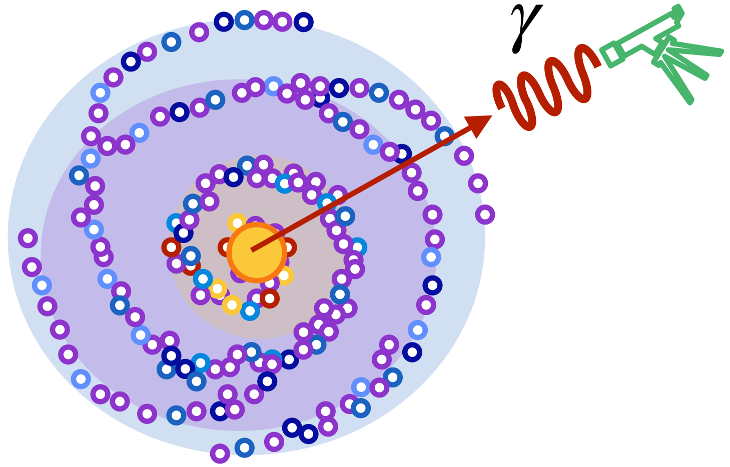
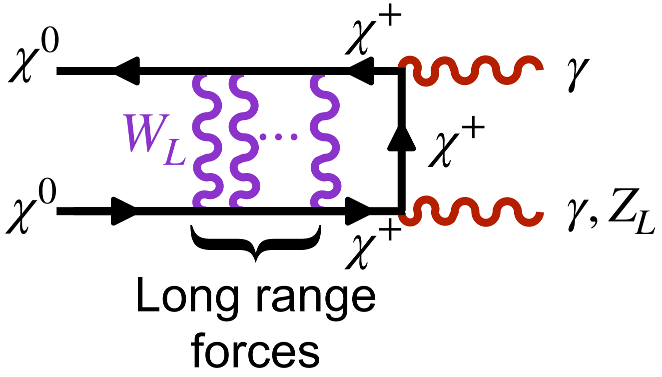
Indirect Detection Constraints



Indirect detection [4] constrains photons from DM annihilation in galactic centre



Annihilation via **Sommerfeld effect** produces:
1) **Lines** from photon final states



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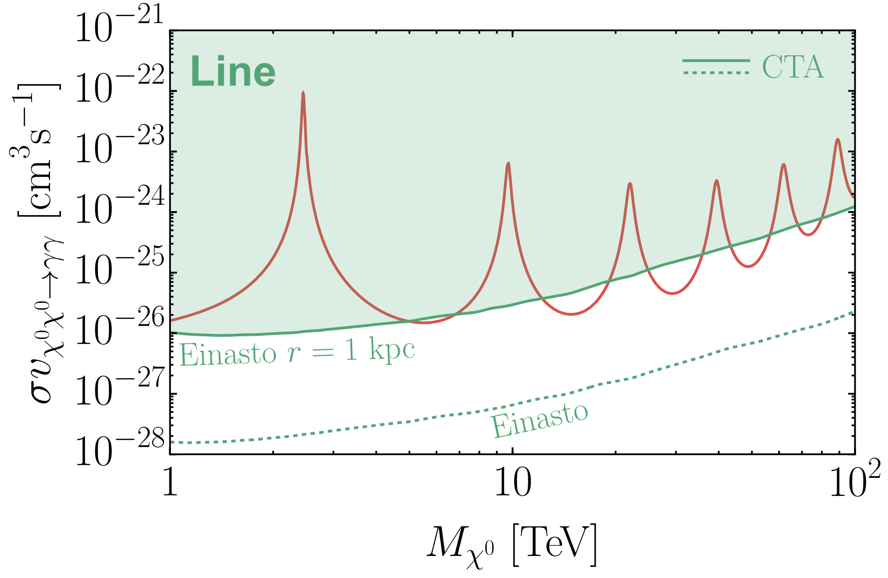
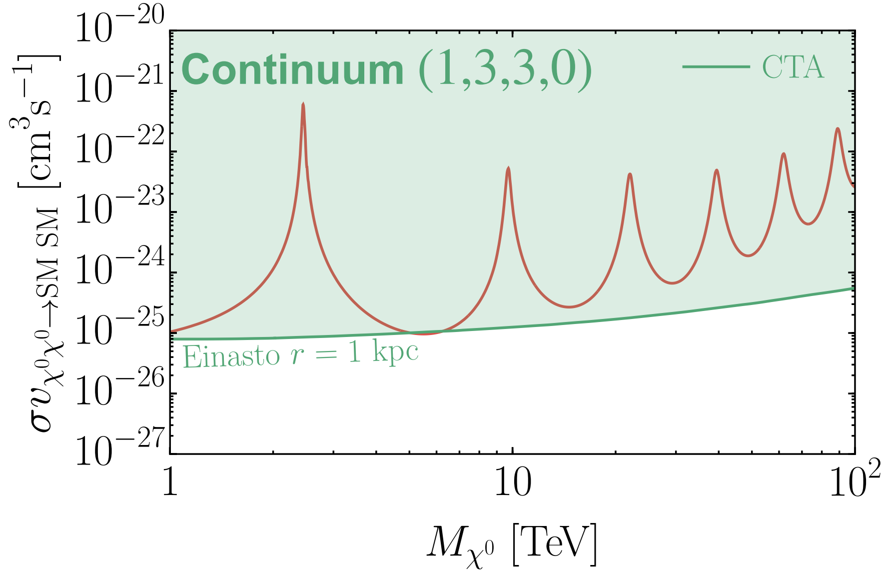
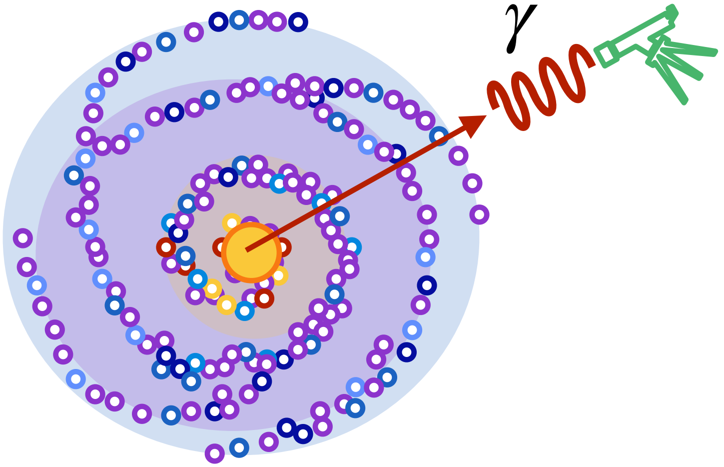
Indirect Detection Constraints

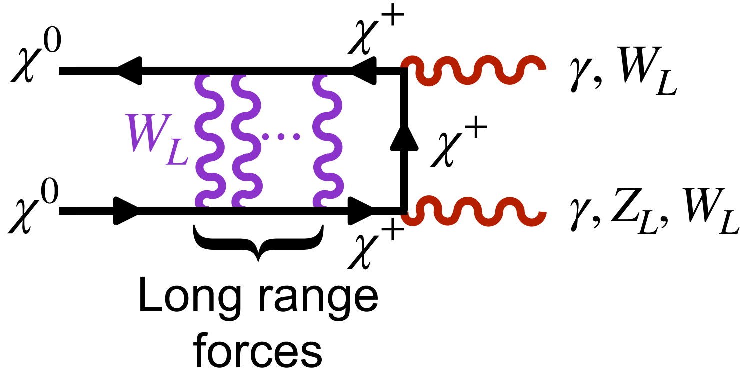




Indirect detection [4] constrains photons from DM annihilation in galactic centre



Annihilation via **Sommerfeld effect** produces:
1) **Lines** from photon final states
2) **Continuum** from other SM final states



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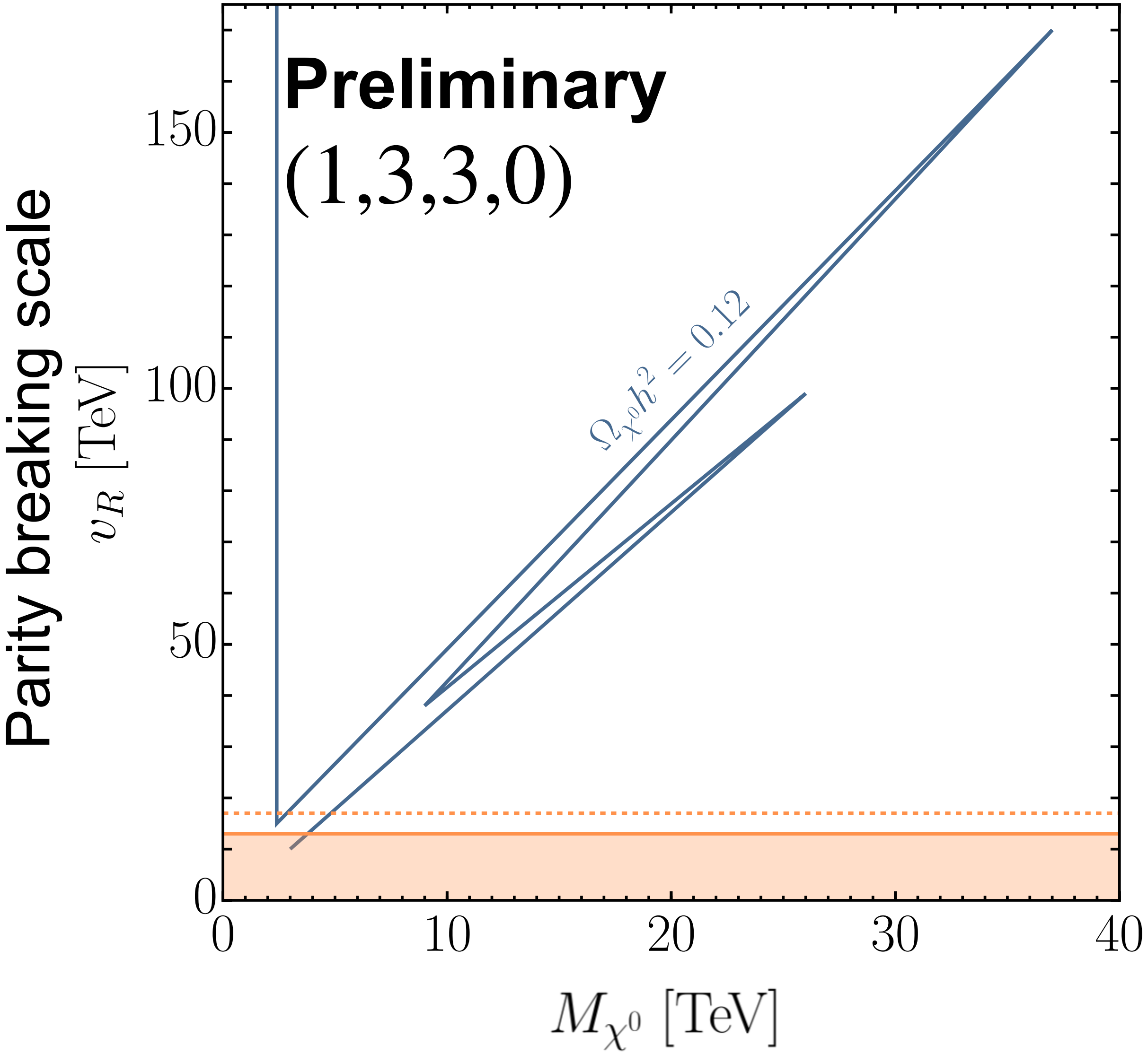
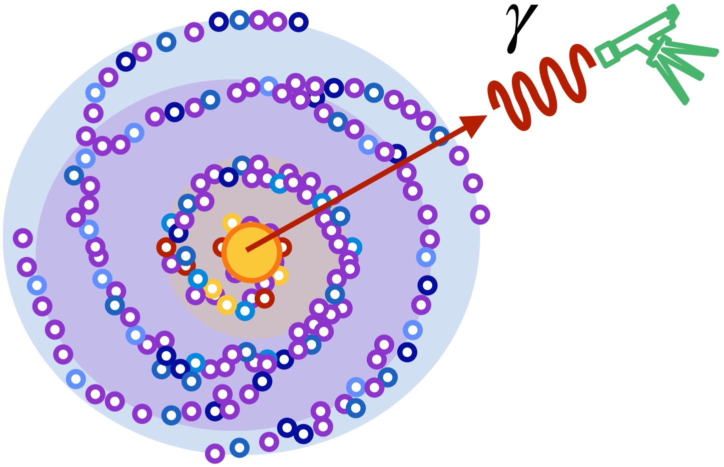
Indirect Detection Constraints



Indirect detection [4] constrains photons from DM annihilation in galactic centre



Upper bound out of reach of **direct detection** and **collider** searches— need **indirect detection**

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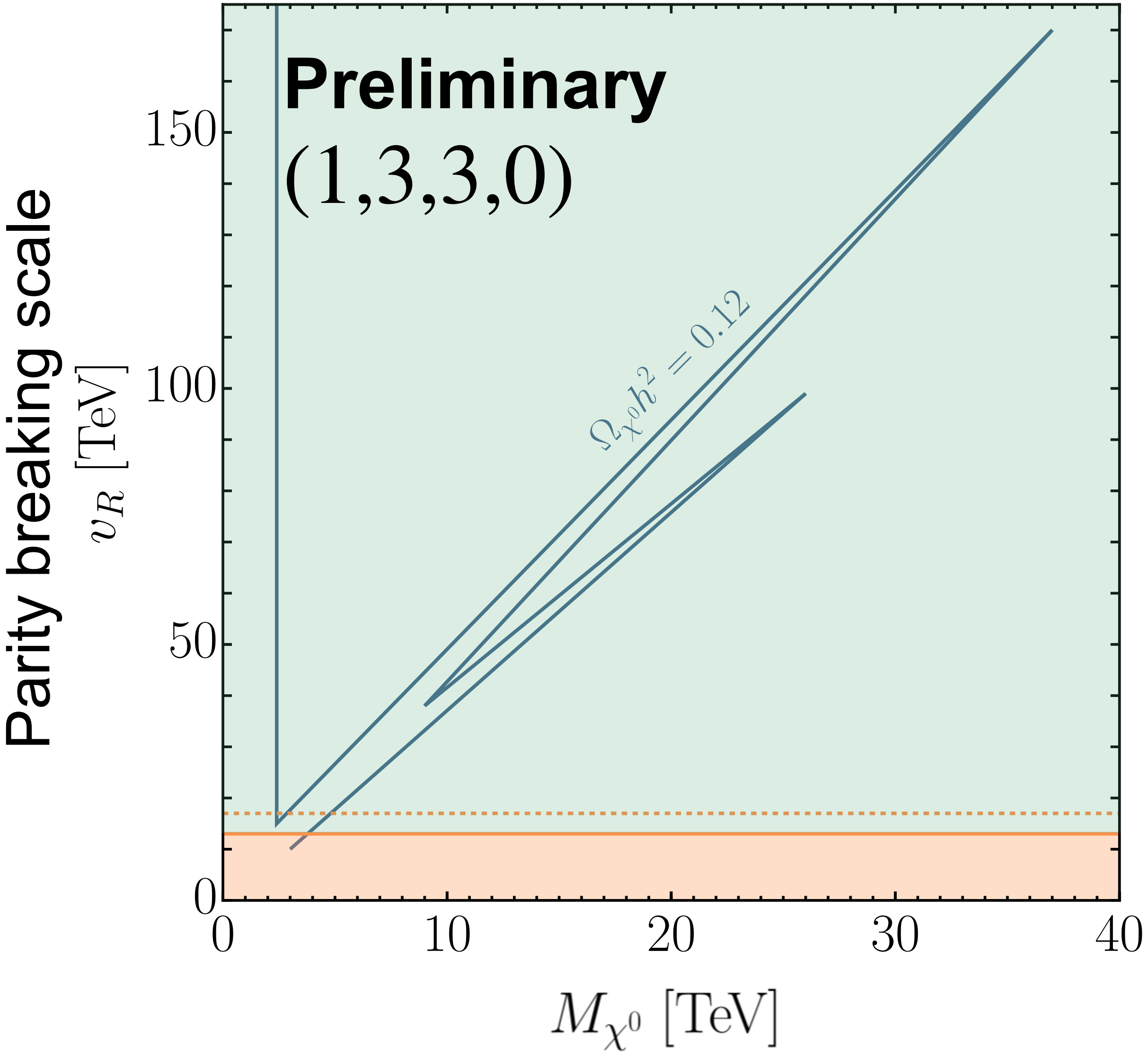
Indirect Detection Constraints



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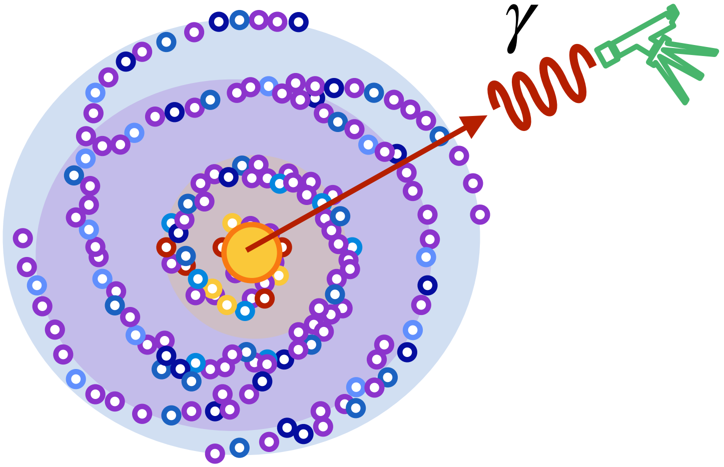

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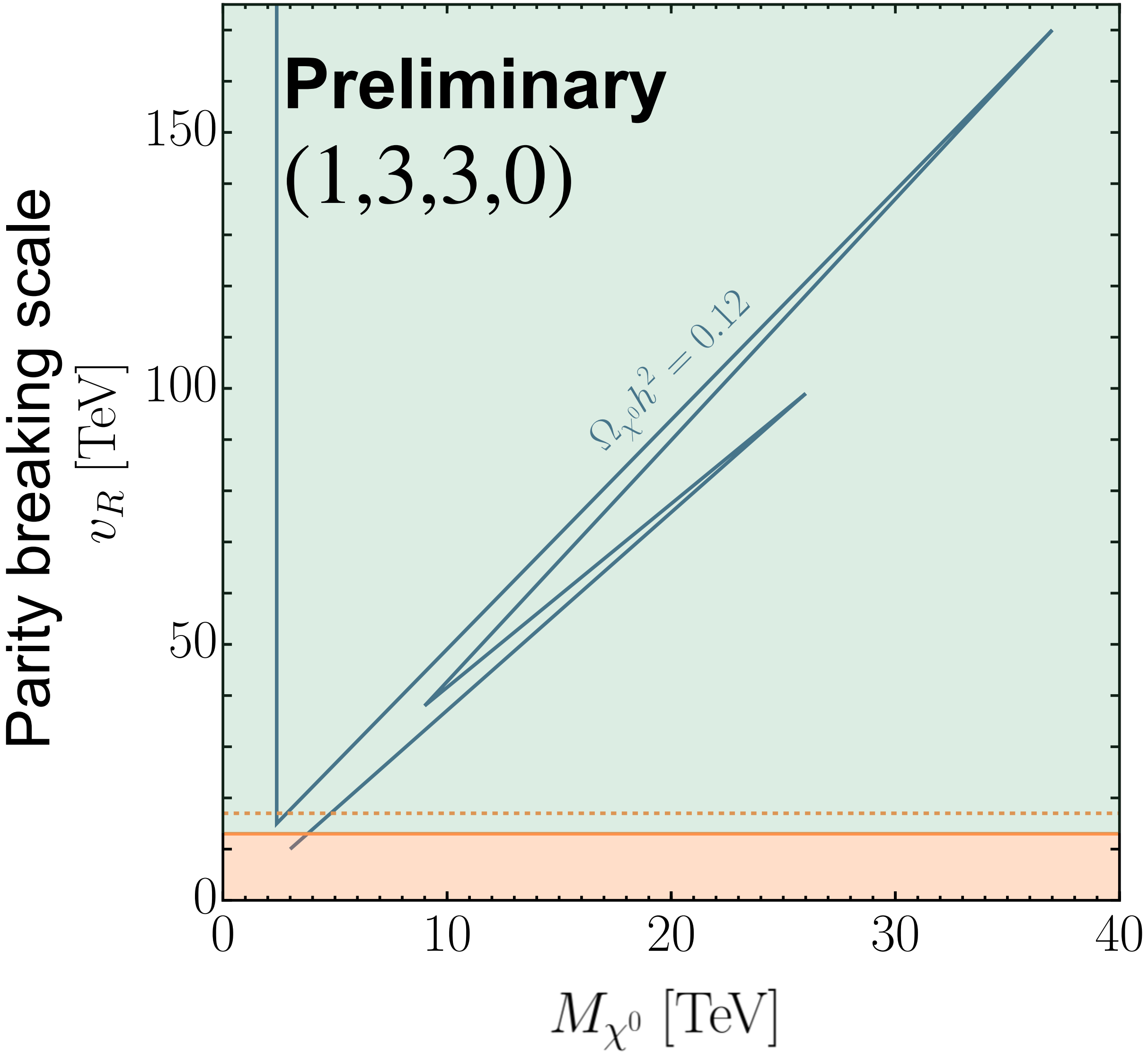
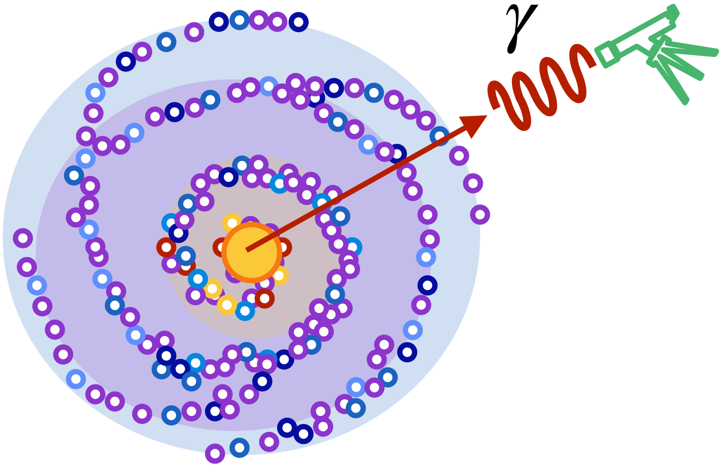


Indirect detection [4] constrains photons from DM annihilation in galactic centre



Upper bound out of reach of **direct detection** and **collider** searches— need **indirect detection**

C.T.A. constraint evaded by assuming different DM profile

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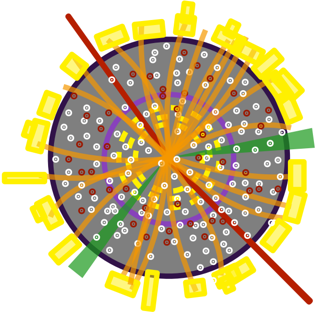
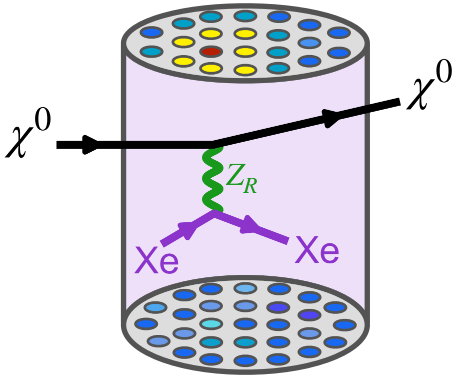
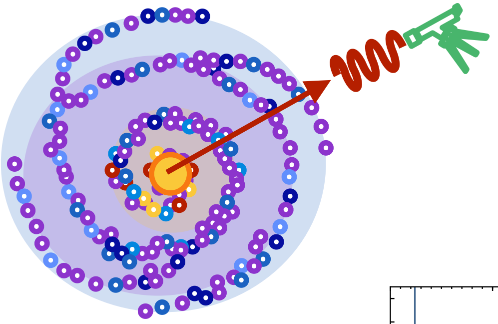
[4] *C.T.A. Collaboration, A. Acharyya et al. Sensitivity of the Cherenkov Telescope Array to a dark matter signal from the Galactic centre (2021)*

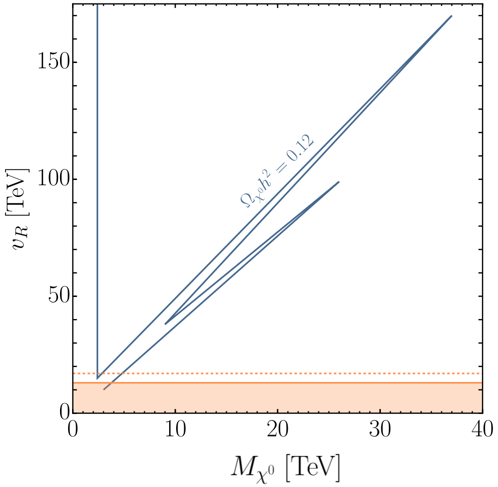
Conclusion

Parity symmetric Left-right models can solve many BSM problems





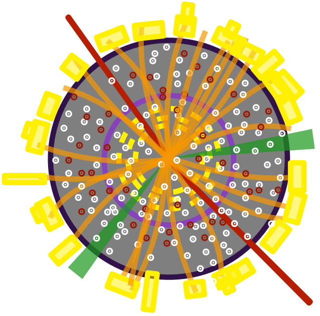


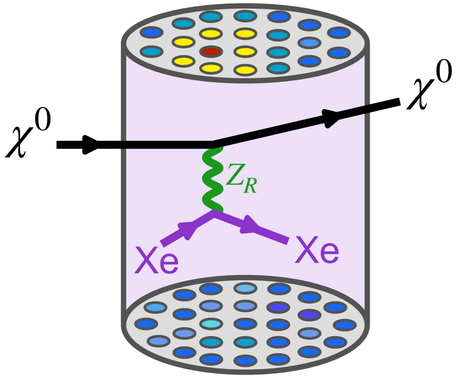


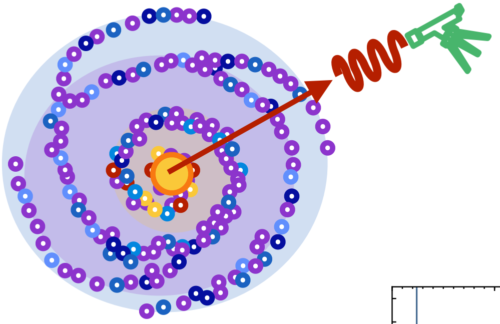
Conclusion

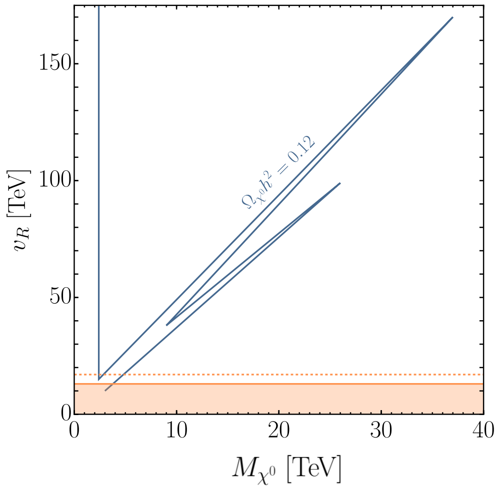
Parity symmetric Left-right models can solve many BSM problems

WIMP candidate embeds into Left-right models in various ways







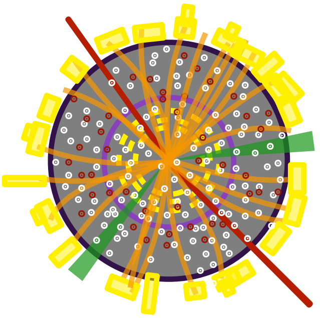


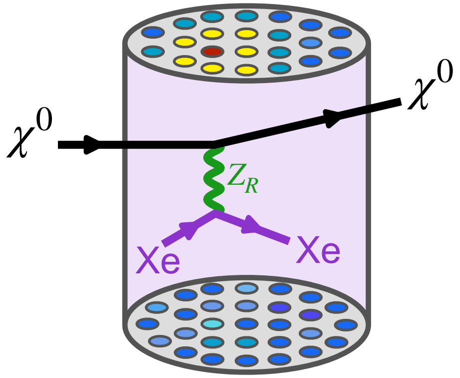
Conclusion

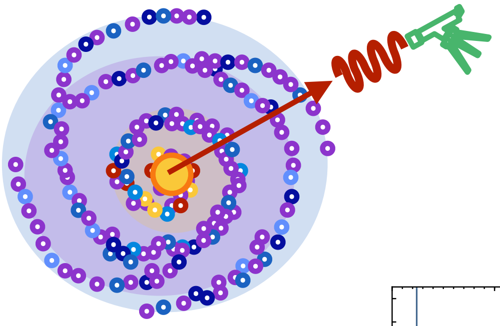
Parity symmetric Left-right models can solve many BSM problems

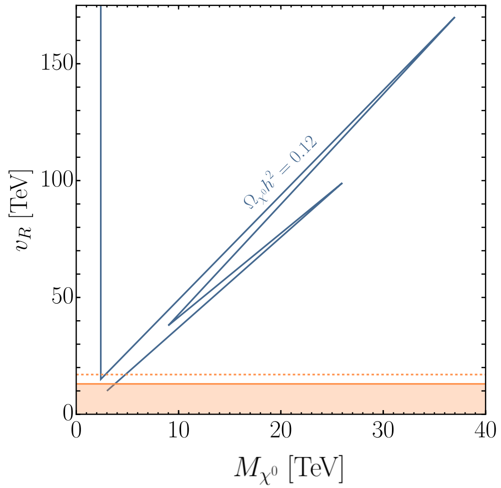
WIMP candidate embeds into Left-right models in various ways

Thermal relic abundance places **upper bound** on parity breaking scale for bi-triplet WIMP embedding

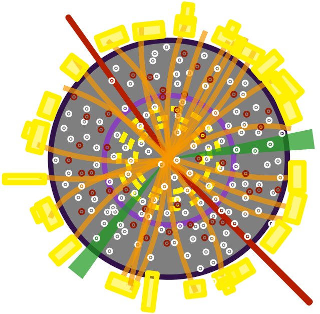


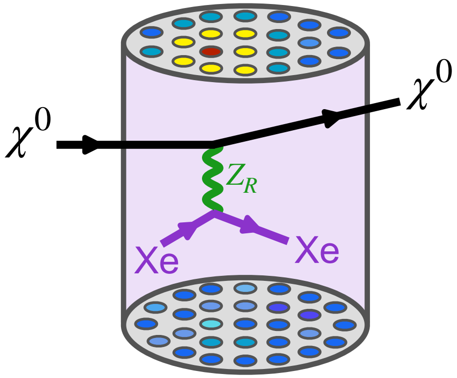






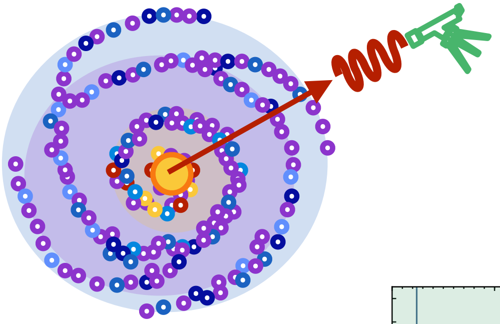
Conclusion





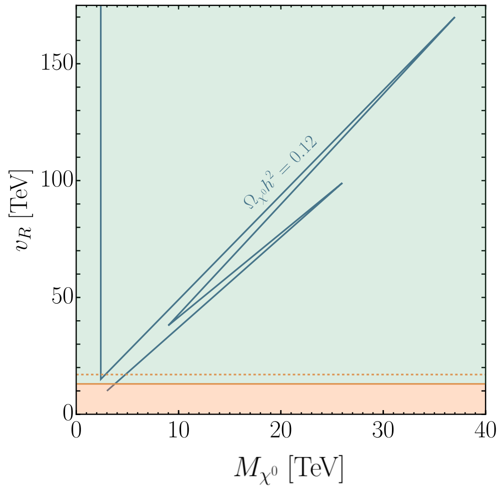
Parity symmetric Left-right models can solve many BSM problems

WIMP candidate embeds into Left-right models in various ways



Thermal relic abundance places **upper bound** on parity breaking scale for bi-triplet WIMP embedding

Collider and **direct detection** probe small parity breaking scale.
Indirect detection needed to probe full parameter space



Conclusion

Parity symmetric Left-right models can solve many BSM problems

WIMP candidate embeds into Left-right models in various ways

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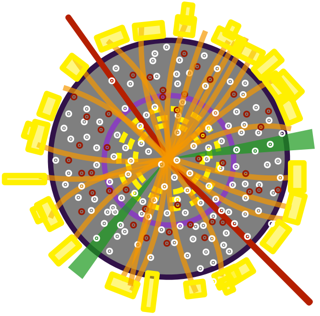
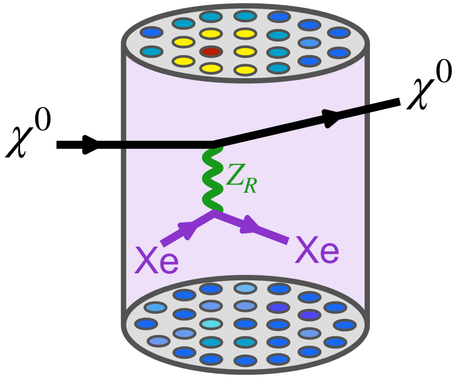
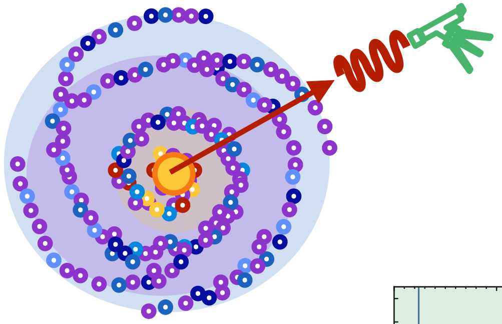
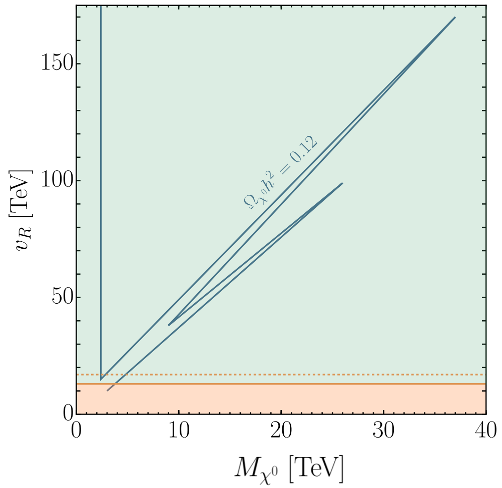
Next— rare processes e.g. $\mu \to e + \gamma$ probes of parity breaking scale.









Backup Slides

Lifetime of Accidentally Stable Dark Matter

For $(1,3,3,0)$ and $(1,3,3,\pm 1)$ lowest dimension operator generating DM decays are dim-6

$$\chi(1,3,3,0):\ \ \chi H_R H_R^* l H_L^*$$

$$\chi(1,3,3,\pm 1):\ \ \chi H_R^* H_R^* l H_L^*$$

If these operators are generated from scale Λ, these lead to a DM lifetime

$$\tau_\chi \sim 10^{28}\ \text{sec}\left(\frac{10\ \text{TeV}}{m_\chi}\right)\left(\frac{40\ \text{TeV}}{v_R}\right)^4\left(\frac{\Lambda}{M_{Pl}}\right)^4$$

Current ΛCMD large scale structure constraints require $\tau_\chi > 10^{19}$ sec

Quark Yukawa Generation in Next-to-minimal Model

Generating SM Yukawas requires additional fermions to be introduced in the Left-Right model

$$\mathscr{L}_y = \underbrace{\boxed{x_Q q\bar{Q}H_R + x_Q\bar{q}QH_L}}_{\text{u-type Yukawas}} + \underbrace{\boxed{x_D q\bar{D}H_L + x_D\bar{q}DH_R}}_{\text{d-type Yukawas}}$$

We use a next-to-minimal model in order to generate W_L—W_R mixing at 1-loop

$$\mathscr{L} = \mathscr{L}_y + \underbrace{\boxed{x_U q\bar{U}H_L + x_U\bar{q}UH_R}}_{\text{u-type Yukawas}}$$

Charge lepton Yukawas can be generated by $\Delta(\mathbf{1}, \mathbf{2}, \mathbf{2}, 0)$, but this generates dim-6 bi-triplet decays with UV scale $\Lambda \ll M_{Pl}$. We assume $\Delta(\mathbf{1}, \mathbf{2}, \mathbf{2}, 0)$ doesn't generate charged lepton Yukawas

Neutrino Sector

Neutrino masses can be generated via Radiative Singlet Model [8] by introduction of singlet S

$$\mathscr{L} = x_S S \left(l H_L + \bar{l} H_R \right) + \frac{1}{2} m_S S^2$$

Correlations between couplings of Left-right model Weinberg operators lead to zero mass at tree-level

Non-zero masses are generated at 1-loop level

Majorana or Pseudo-Dirac neutrinos possible for certain parameter choices in the model

[8] *L. Hall, K. Harigaya, Y. Shpilman*, Radiative Majorana Neutrino Masses in a Parity Solution to the Strong CP Problem (2023)

Indirect Detection and Galactic Centre DM Profile

Indirect detection differential gamma flux [9]:

Energy spectrum

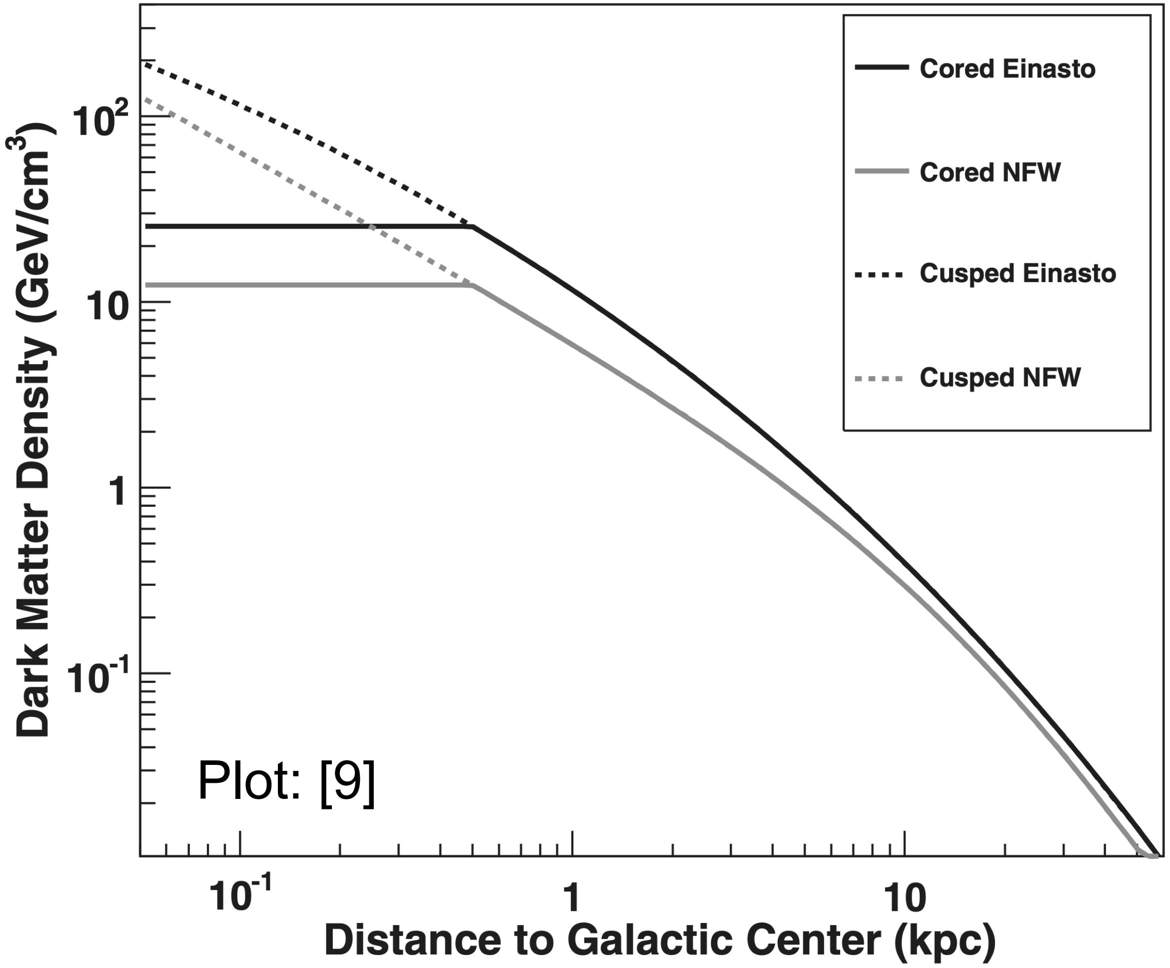
$$\frac{d\Phi}{d\Omega dE} = \boxed{\frac{\sigma v}{8\pi m_{DM}^2}} \times \boxed{\frac{dN}{dE}} \times \boxed{\int ds\ \rho_{DM}^2}$$

Annihilation cross section

Integral over line of sight DM density

Uncertainty in DM profile near galactic centre makes line of sight DM integral uncertain

Cored profiles can predict smaller fluxes compared to cuspy profiles



Plot: [9]

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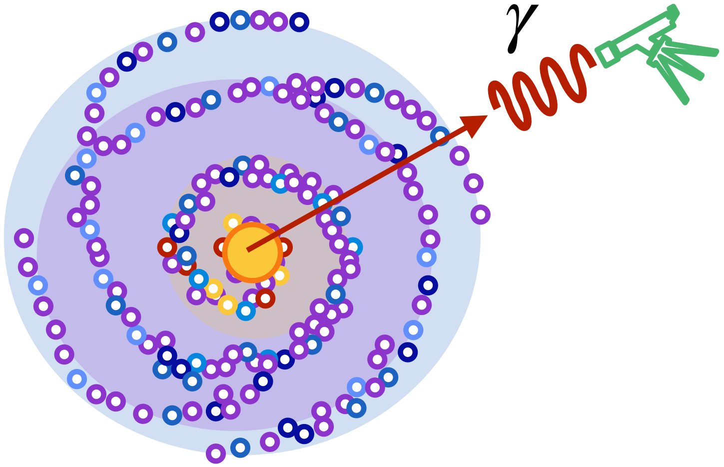
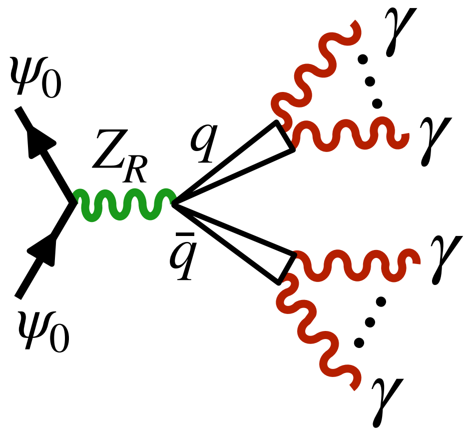
[9] *Arcadi et al.,* The Waning of the WIMP? A Review of Models, Searches, and Constraints (2017)
[10] *H.E.S.S. Collaboration,* Constraints on an Annihilation Signal from a Core of Constant Dark Matter Density around the Milky Way Center with H.E.S.S. (2015)

Indirect Detection Constraints

Continuum **indirect detection** signal can also be produced for $(1,3,3,\pm 1)$ from Z_R resonance





This signal allows C.T.A. [4] to probe the Z_R resonant branch

[4] *C.T.A. Collaboration, A. Acharyya et al. Sensitivity of the Cherenkov Telescope Array to a dark matter signal from the Galactic centre (2021)*

Upper Bound on v_R From Higher Dimensional Operators

Higher dimensional Parity symmetric operators can contribute a tree-level θ term, for example

$$\frac{1}{\Lambda^2}\left(|H_L|^2 - |H_R|^2\right) G\tilde{G}$$

After Parity breaking, to ensure the θ term is sufficiently small, v_R is bounded from above

$$v_R \lesssim 10^{13}\ \text{GeV}\left(\frac{\Lambda}{10^{18}\ \text{GeV}}\right)$$

This still leaves a large possible range for v_R if no other upper bounds constrain v_R

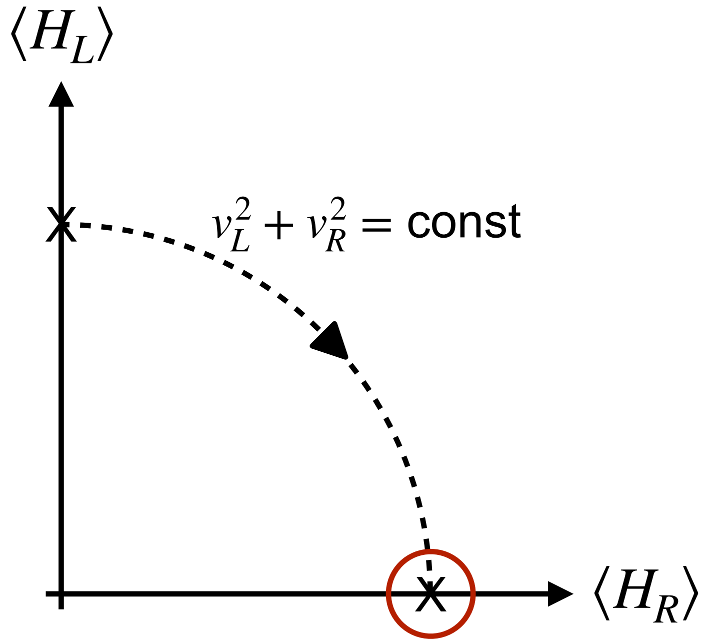
Domain Walls From Parity Breaking

To avoid a domain wall problem, Parity can be spontaneously broken via an additional $SU(N)$ pure Yang Mills sector with $\theta = \pi$.

$$\frac{G\tilde{G}}{M_{pl}^2}\left(|H_L|^2 - |H_R|^2\right)$$

$$\langle G\tilde{G}\rangle \sim \Lambda^4 \sim v_R^2 M_{pl}^2 \implies \Lambda \sim \sqrt{v_R M_{pl}} \approx 10^{11} \text{ GeV}$$

If temperature does not return above 10^{11} GeV after reheating, domain walls from Parity breaking inflated away

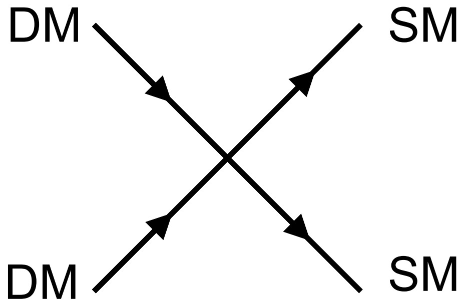


Matthew J. Baldwin
PHENO 2026

Cross-sections for Fixed Initial Spin

WIMP must obtain correct relic abundance to be dark matter

Abundance calculated with Boltzmann equation from annihilation cross-sections



Cross-sections are modified due to long range force effects—Sommerfeld effect

Spin-dependent cross-sections needed to compute this effect

Computation can be automated— automated code for $2 \rightarrow 2$ cross-sections has been developed

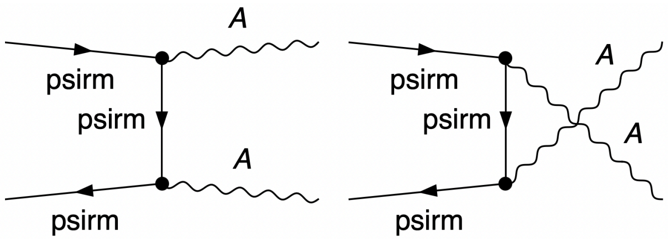
Function

`getCrossSection[0, ψrm, ψrmbar, γ, γ, doublets];`

Spin Particles Model

↓

Diagrams



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Cross section

Spin–0 σ for $\psi_r{}^- \overline{\psi_r{}^-} -> \gamma\gamma$

$$\frac{4\,\pi\,\alpha_2{}^2\,g_Y{}^4}{M_{\psi_r{}^-}{}^2\left(g^2+g_Y{}^2\right)^2}$$

Computation time $\mathcal{O}(1)$ sec per process