# A cancellation mechanism for dark matter-nucleon interaction: non-Abelian case


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*In collaboration with:*


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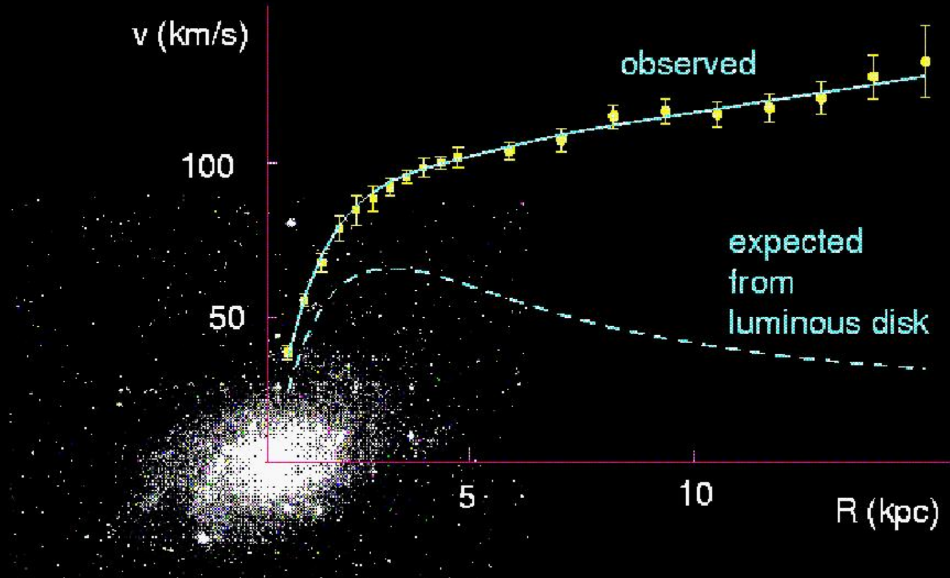
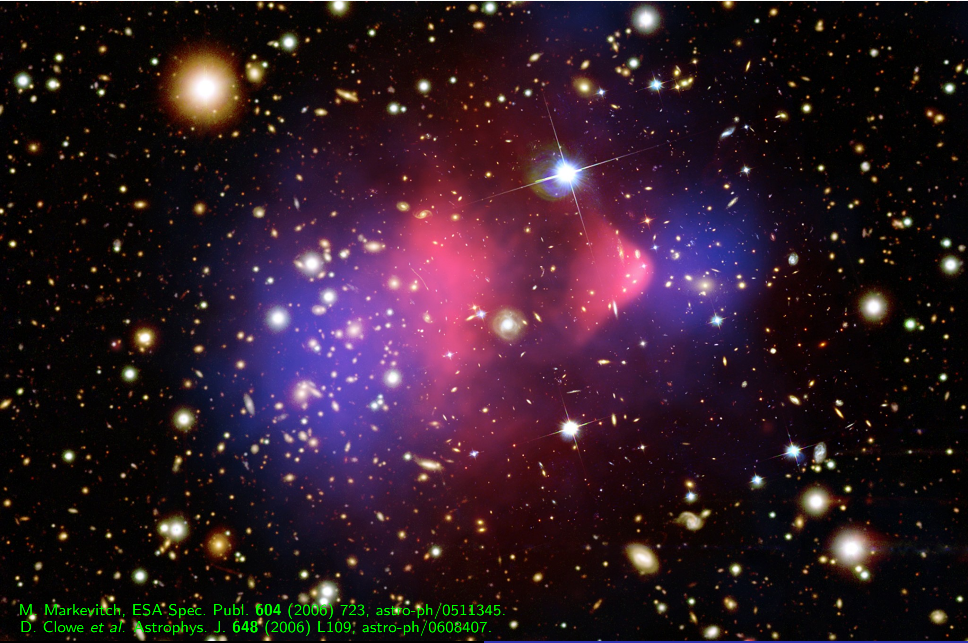
# Introduction

# Velocity distribution



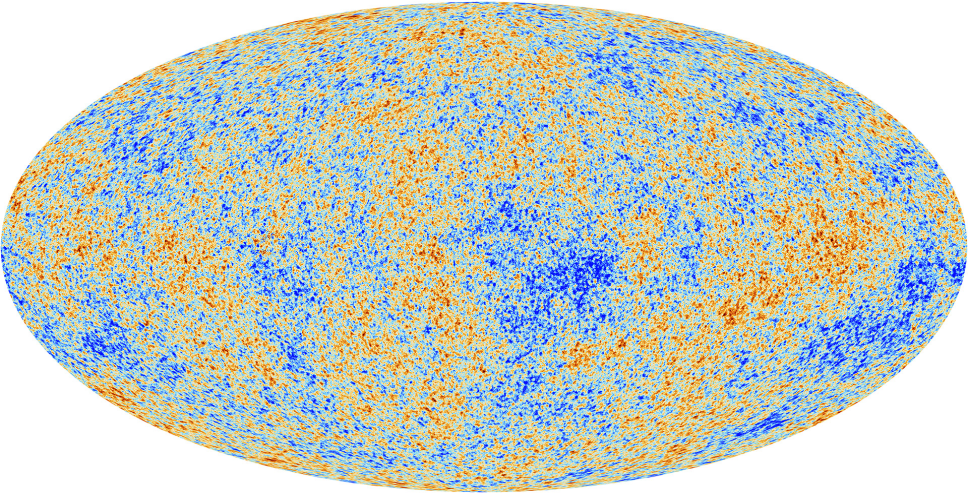

E. Corbelli and P. Salucci, *Mon. Not. Roy. Astron. Soc.* **311** *441* (2000), arXiv:astro-ph/9909252.

# Bullet Cluster



M. Markevitch, ESA Spec. Publ. **604** (2006) 723, astro-ph/0511345.
D. Clowe *et al.* Astrophys. J. **648** (2006) L109, astro-ph/0608407.

# Cosmic Microwave Background



**Dark Matter relic abundance**[1] $\Omega_{DM}h^2 \approx 0.12$**.**

[1] P. A. R. Ade *et al.* [Planck Collaboration] Astron. Astrophys. **594** (2016) A13, arXiv:1502.01589.

# Some general characteristics

- Stable or very slow decay rate.
- Electrically Neutral.
- Cold/Warm and non-relativistic today.
- Smaller allowed mass[2] $m_{DM} \gtrsim \mathcal{O}(1 - 10\ \mathrm{keV})$.
- Non-Baryonic.

[2] V. Iršič et al. Phys. Rev. D **96** (2017) no.2, 023522, arXiv:1702.01764.

# freeze-out mechanism – WIMPs

Three stages:

- Equilibrium (production $\leftrightarrow$ annihilation), $T \gtrsim m_{DM}$.
- Production stops, $T \lesssim m_{DM}$.
- Annihilation stops, $T = T_{FO} \approx \dfrac{m_{DM}}{25}$.

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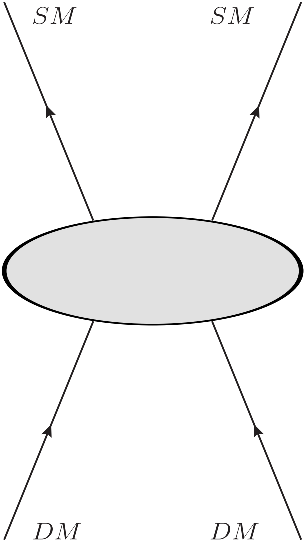
WIMP= Weakly Interacting Massive Particle.

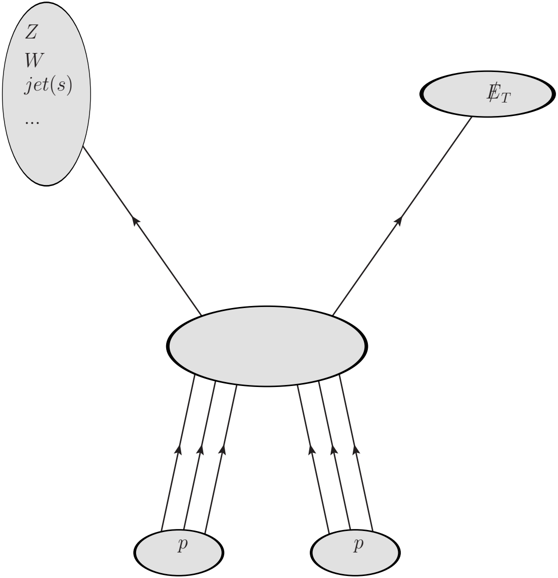
$$m_{DM} \sim 100 \text{ GeV} \Rightarrow \Omega_{MD} h^2 \sim 0.1 \, \frac{10^{-8} \text{ GeV}^{-2}}{\langle \sigma v \rangle} \, .$$

Typical mass scale of weak interactions $\leftrightarrow$ Typical cross section of weak interactions (*WIMP-miracle*).

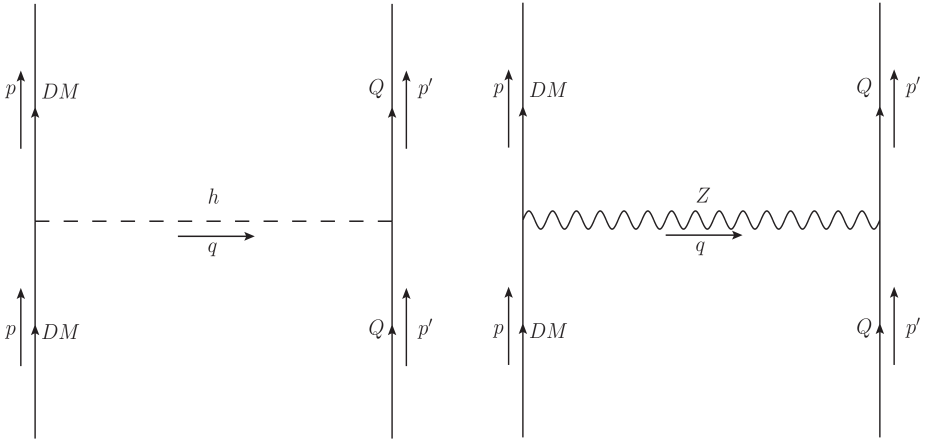
# Indirect detection



# LHC



# Direct detection



# XENON

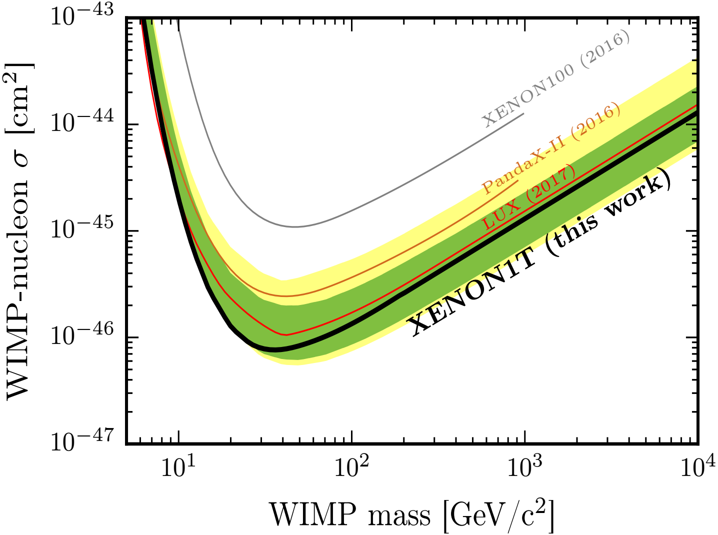



Figure : E. Aprile *et al.* [XENON Collaboration], Phys. Rev. Lett. **119**, no. 18, 181301 (2017), arXiv:1705.06655.

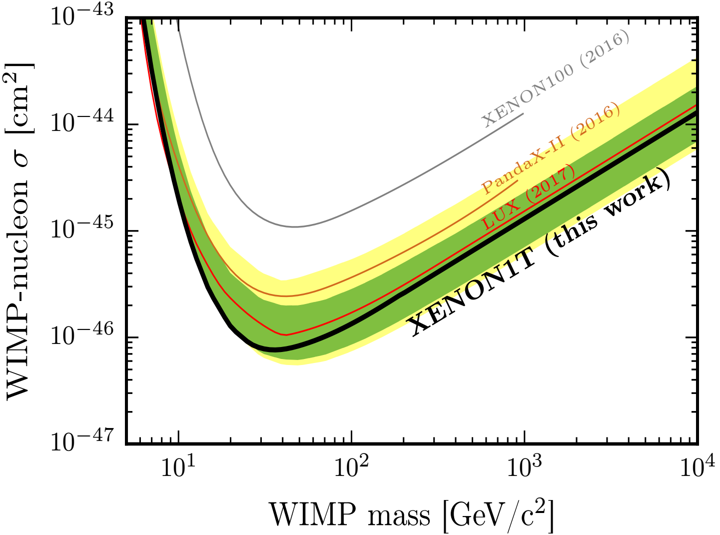



Figure : E. Aprile *et al.* [XENON Collaboration], Phys. Rev. Lett. **119**, no. 18, 181301 (2017), arXiv:1705.06655.

**Where are all the WIMPs?**

# Direct detection vanishing mechanism: The Abelian case

# The minimal model

Extension of the SM scalar sector by a scalar $S$:[3]

- Singlet under the $G_{\mathrm{SM}}$.
- Charged under a global, softly broken $U(1)$ symmetry.

Invariant potential:

$$V_0 = -\frac{\mu_H^2}{2}|H|^2 + \frac{\lambda_H^2}{2}|H|^4 - \frac{\mu_S^2}{2}|S|^2 + \frac{\lambda_S}{2}|S|^4 + \lambda_{HS}|H|^2|S|^2 \, .$$

Softly breaking term:

$$V_{\mathrm{soft}} = -\frac{\mu_S'^2}{4} S^2 + \mathrm{h.c.}$$

**Observation:**

There is one phase that can be absorbed in $S$ $\rightarrow$ *CP–invariance!*

[3] C. Gross, O. Lebedev and T. Toma, Phys. Rev. Lett. **119** (2017) no.19, 191801 doi:10.1103/PhysRevLett.119.191801 arXiv:1708.02253 [hep-ph].

# Naturally stable DM

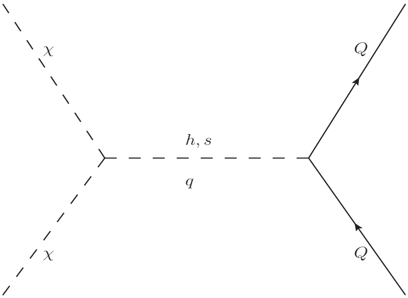
The scalars develop VEVs:

$$S = \frac{1}{\sqrt{2}}(v_S + s + i\,\chi)\;,$$
$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h \end{pmatrix}\;.$$

**Observation:**

CP–invariance $\rightarrow \chi$ is stable!

# The cancellation mechanism




Propagator (at $q^2 \approx 0$) is proportional to the inverse of the CP-even mass matrix. So, the direct detection matrix element ($A_{DD}$) becomes

$$A_{\rm DD} \sim (\lambda_{HS} v,\, \lambda_S v_S) \begin{pmatrix} \lambda_S v_S^2 & -\lambda_{HS} v v_S \\ -\lambda_{HS} v v_S & \lambda_H v^2 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} = 0\,.$$

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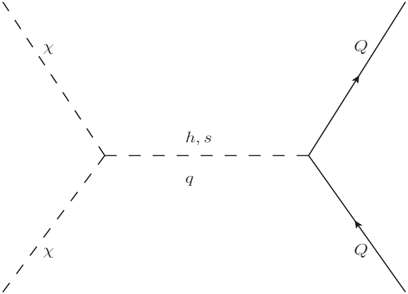


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*Goldstone bosons couple proportionally to the momentum (but some cancellations still have to occur).*

# Motivation

The minimal model:

- Natural explanation for the missing DM signal.
- Natural emergence of a WIMP stabilizing symmetry.
- The origin of the softly broken term can be explained (gauged $U(1)$).
- WIMP at low masses ($\sim 10 - 10^4\ \mathrm{GeV}$).

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**Generalization?**

# A simple Generalization

# $U(1) \times S_N$

- $N$ scalars ($S_i$).
- Transforming as $S_i \rightarrow e^{-ia} S_i$.
- Symmetry: $U(1) \times S_N$.
- All $S_i$ acquire VEV with all VEVs equal ($S_N$ symmetric choice).

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This results to a pseudo-Goldstone:

$$\xi = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} \chi_i \to S_N\text{-symmetric state.}$$

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Large number of phases $\to$ no naturally stable particle.

| $N$ | #phases |
|---|---|
| 1 | 1 |
| 2 | 3 |
| $\geq 3$ | $3 + \frac{1}{2}N(N-1)$ |

# Non-Abelian Generalization

# $SU(2)$

A more attractive/simple case:

- One scalar, $\Phi$.
- Doublet under a softly broken $SU(2)$.
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$$V_{\mathrm{soft}} = \sum_{i=1}^{2}\sum_{j=1}^{2}\left[(m_{\Phi\,ij}^{2}\Phi_i\Phi_j + \mathrm{h.c.}) + m'^{2}_{\Phi\,ij}\Phi_i^{\dagger}\Phi_j\right],$$

where $SU(2)$ is restored for $m_{\Phi\,ij} = m'_{\Phi\,ij} = 0$ and $m'_{\Phi\,ii} = \frac{\mu_\Phi}{2}$.

# $SU(2)$

The doublet $\Phi$ acquires a VEV:

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi + i\, s \\ \rho + i\, \chi + v_\Phi \end{pmatrix} \, ,$$

resulting to mixing between the $\rho$ and $h$.

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resulting to mixing between the $\rho$ and $h$.
DM content:

- Three pseudo-Goldstone bosons.
- No CP-invariance (as in the minimal case), but emergence of a $Z_2$.
- The interaction terms are invariant under orthogonal transformations $\rightarrow$ All pseudo-Goldstone bosons are stable $(Z_2^{(1)} \times Z_2^{(2)} \times Z_2^{(3)})$.
- The $h - \rho$ mass matrix is similar to the minimal $U(1)$ case $\rightarrow$ vanishing of the direct detection cross section for all DM particles!

# $SU(N)$

The results of the $SU(2)$ case hold also for the $SU(N)$, at least for $\Phi$ in the fundamental representation.

$SU(N)$ generalization:

- There are $2N-1$ pseudo-Goldstone bosons.
- The discrete symmetry is $Z_2^{(1)} \times Z_2^{(2)} \times Z_2^{(3)} \times \cdots \times Z_2^{(2N-1)}$ ($2N-1$ DM particles).

# Conclusion

- There are models that can explain the missing WIMP signal.
- Naturally stable DM particles.
- It seems to be fairly easy to find such models (WIMP paradigm is still alive).
- No fine tuning.

# Open questions

- What happens if $\Phi$ is in another representation of $SU(2)$ (*e.g.* $SU(2)$-triplet)?
- Phenomenological analysis (*e.g.* LHC detectability).
- Loop corrections to the scalar potential (also important for direct detection).
- The origin of the soft breaking terms.
- Any other models with the desirable attributes?

**Thank you!**