High1 Workshop on String, Particle and Cosmology

Constraints to the inert doublet model of dark matter with very high-energy gamma-rays observatories



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Ref: LRJ, Aion Viana, Clarissa Siqueira arXiv:2411.05909v1 [hep-ph]

South Korea, Jan 18th, 2024
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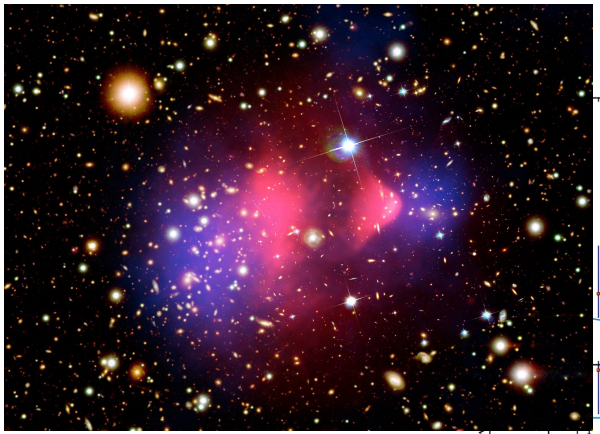
Research interests

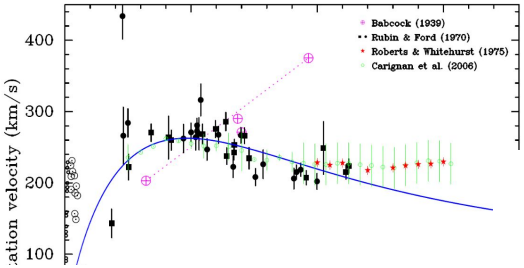
- **Dark matter phenomenology**
  - Experimental bounds: indirect detection, direct detection, collider.
  - Production mechanisms: freeze-out, freeze-in, gravitational production, etc.
- **Neutrinos phenomenology**
  - Neutrino mass problem.
  - Models that address both neutrino mass and dark matter problems.
- Other cosmology/particle physics topics: inflation, phase transitions in the early universe, baryon asymmetry, etc.

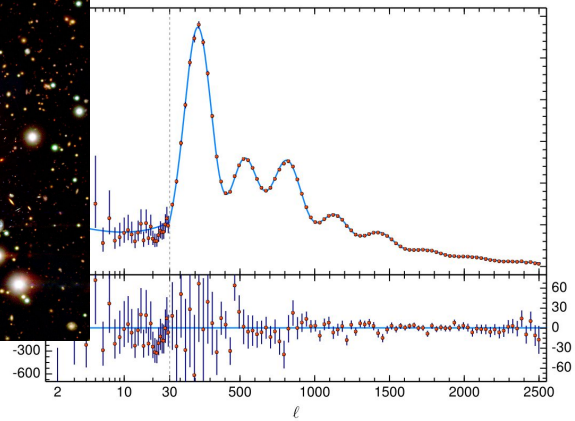
INDIRECT DARK MATTER DETECTION

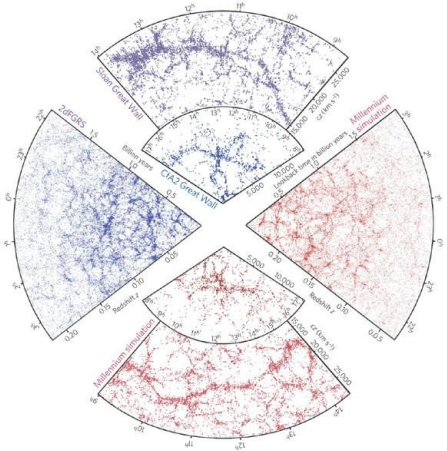
Introduction: evidences for dark matter

A lot of evidences point out to the “missing mass problem” in the Universe…

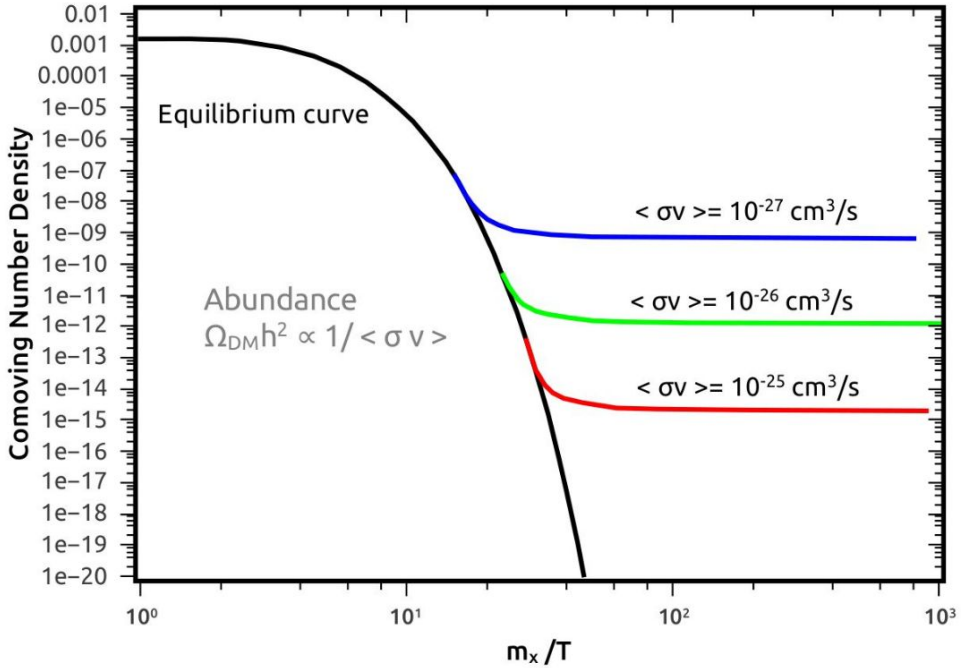








Freeze-out and the WIMP miracle



Solution of the Boltzmann equation for different annihilation cross sections. Source: Arcadi et al.

- **FREEZE-OUT** $\Gamma_{eq} \approx H$:

$$Y(x) \approx \begin{cases} Y_{eq}(x) & x \ll x_f \\ Y_{eq}(x_f) & x \gg x_f \end{cases}$$

- With some assumptions, the **cold relic abundance** is

$$Y_\infty = \frac{3.79\,(n+1)\,x_f}{\left(g_{*S}/g_*^{1/2}\right) m_{PL} m \langle \sigma\, v \rangle}$$

where $\langle \sigma\, v \rangle \sim x^{-n}$.

Indirect detection

- Process: **WIMP self-annihilation in astrophysical objects** $DM\,DM \rightarrow SM\,SM$
- Discovery: excess of cosmic messengers

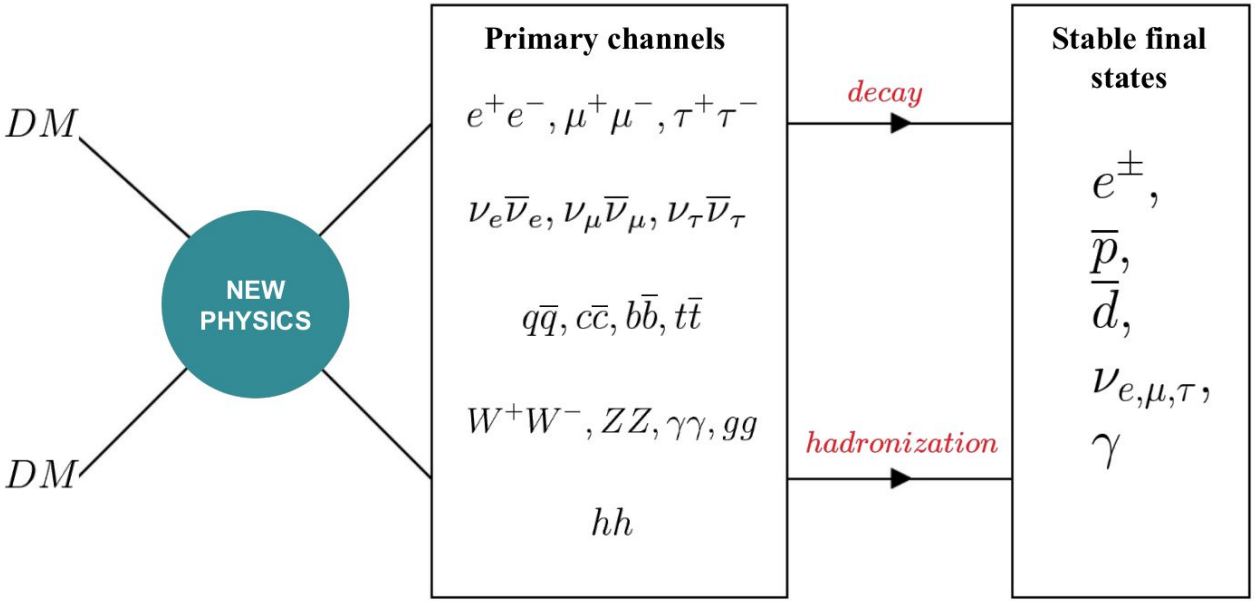
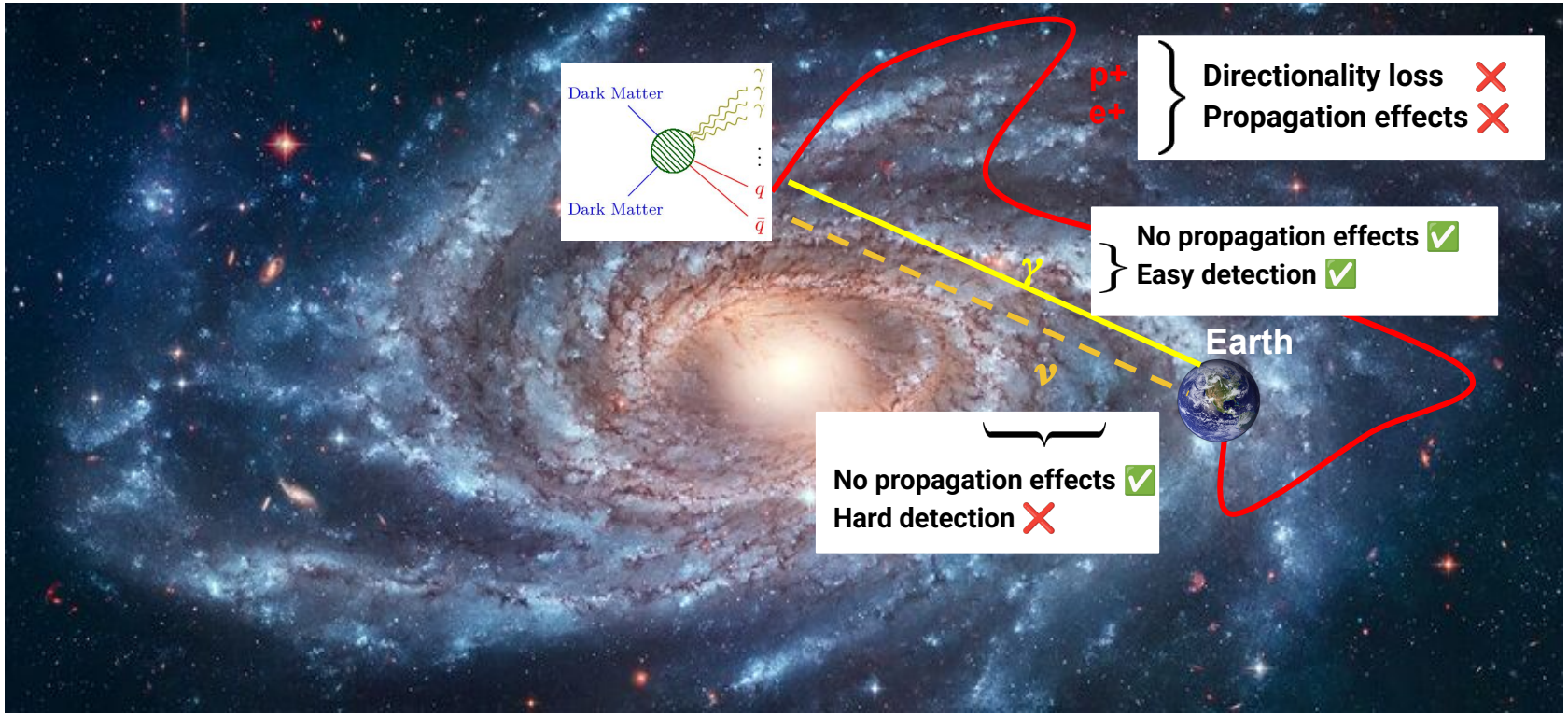


Diagram of dark matter annihilation through primary channels and further hadronization or decay, producing stable SM particles, also known as final states. Source: By the author.

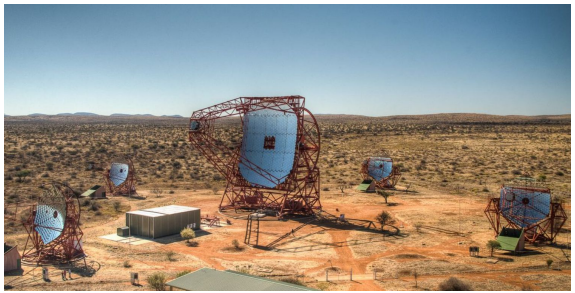
Indirect detection: cosmic messengers



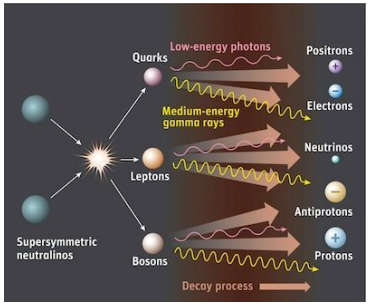
The gamma-ray flux from dark matter annihilation

$$\frac{d\Phi_{\rm ann}}{dE}(E,\Delta\Omega) = \frac{\langle\sigma v\rangle}{8\pi m_{DM}^2}\frac{dN}{dE} \int_{\Delta\Omega} d\Omega \int_{\rm l.o.s.} ds \rho_{DM}^2$$

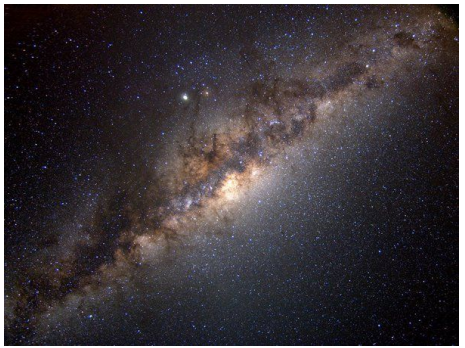
Gamma-ray Flux



Particle Physics

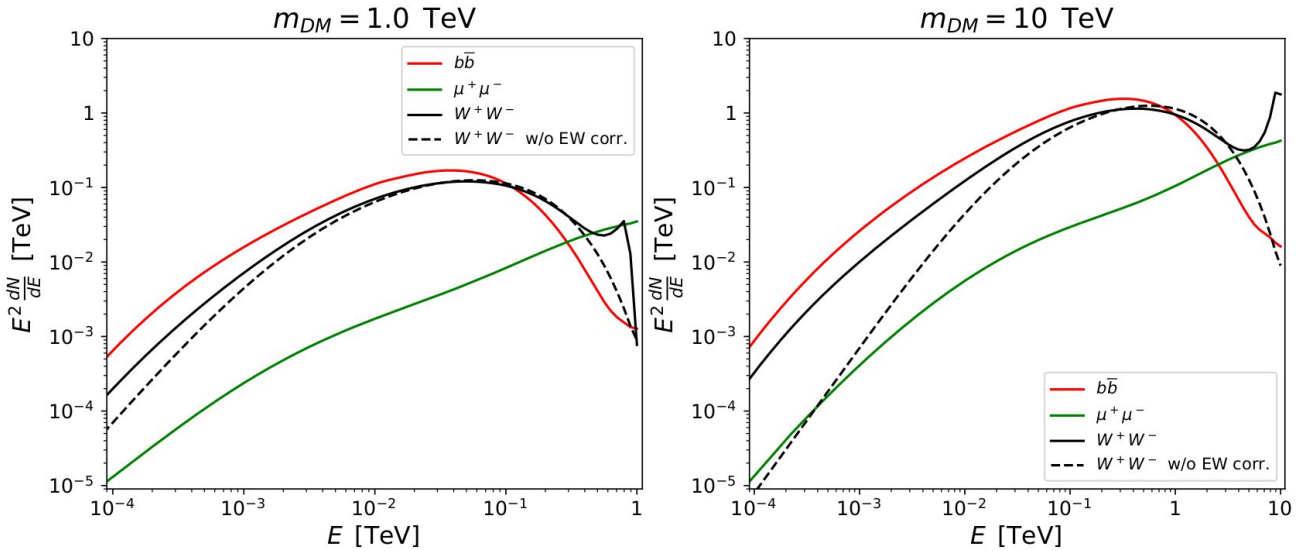


DM Distribution (astrophysics)



Gamma-ray spectra from dark matter annihilation

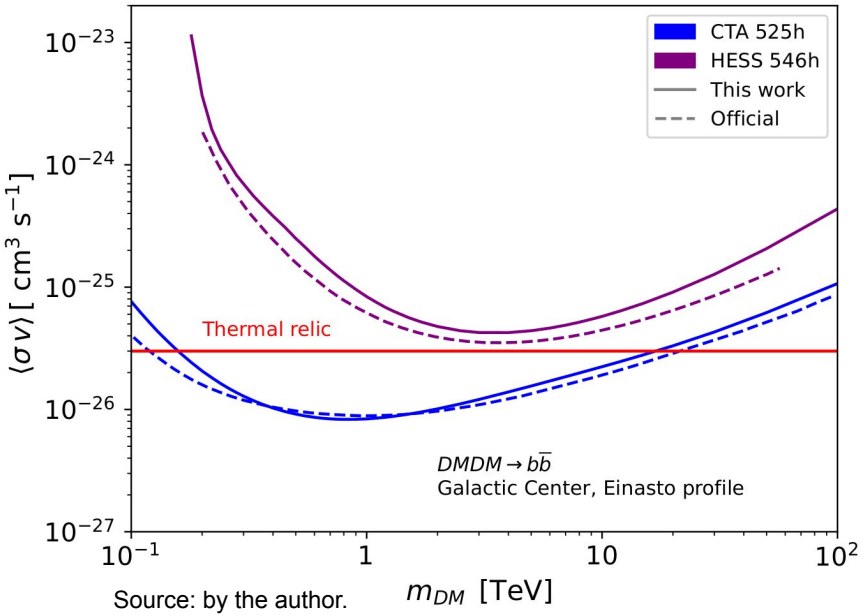
Gamma-ray annihilation spectrum can be divided into the **primary channels**: $\frac{dN}{dE} = \sum_i B_i \frac{dN_i}{dE}$



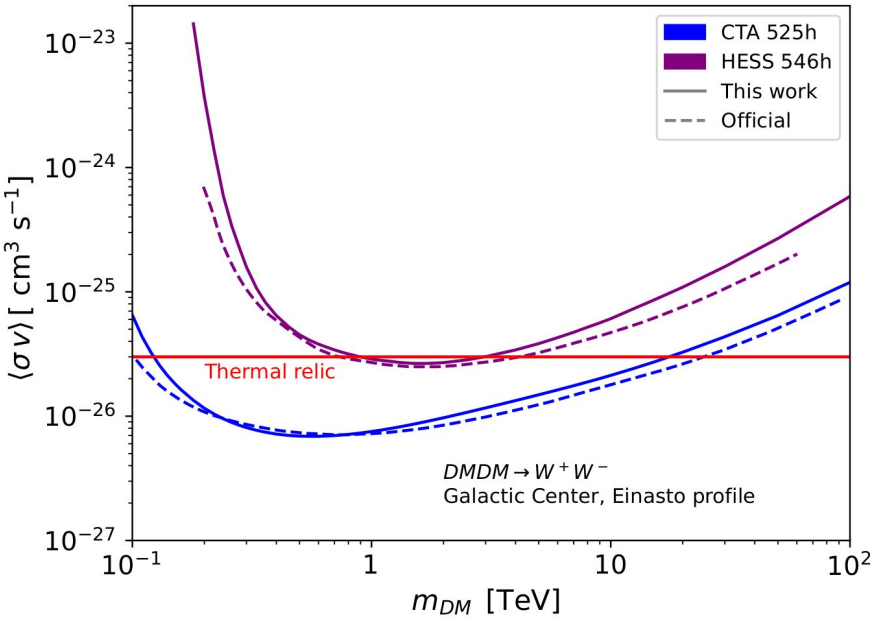
Dark matter annihilation gamma-ray spectra for the channels bb (red line), μ+μ− (green line) and W +W − with (dashed black line) and without (solid black line) EW corrections. Source: Adapted from CIRELLI et al.

Upper limits for primary channels

- **HESS** data: extrapolation to **546h** from **2004-2014 Galactic Center** data (arXiv:1607.08142v1). Comparison with **HESS 2022 results** (arXiv:2207.10471v1).
- **CTAO** projection: simulations of **Alpha Configuration** (South Array) for **525h in the GC** (**prod5 version v0.1**). Comparison with **CTA 2021 results** (arXiv:2007.16129v2).



Source: by the author.



THE INERT DOUBLET MODEL

The construction of the IDM

The lagrangian of the scalar sector is now

$$\mathcal{L}_S = (D_\mu H_1)^\dagger D^\mu H_1 + (D_\mu H_2)^\dagger D^\mu H_2 - V(H_1, H_2)$$

Kinetic term: EW covariant derivative

$$D_\mu = \partial_\mu + \frac{i}{2} g_W \sigma_j W_\mu^j + \frac{i}{2} g' Y B_\mu$$

ElectroWeak Symmetry: $SU_L(2) \otimes U_Y(1)$

→ **- COUPLINGS WITH THE VECTOR BOSONS**

Scalar potential

$$V(H_1, H_2) = \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 + \lambda_1 |H_1|^4 + \lambda_2 |H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1^\dagger H_2|^2 + \lambda_5 Re\left[\left(H_1^\dagger H_2\right)^2\right]$$

→ **- COUPLINGS WITH THE HIGGS BOSON**
- MASSES OF THE SCALAR SECTOR

IDM: Theoretical constraints

- **Electroweak vacuum stability** (Belyaev et al.):

$$\lambda_1 > 0,\ \lambda_2 > 0,\ \lambda_3 > -2\sqrt{\lambda_1\lambda_2},$$
$$\lambda_3 + \lambda_4 - |\lambda_5| > -2\sqrt{\lambda_1\lambda_2},\ \lambda_4 - |\lambda_5| < 0$$

- **Perturbative unitarity constraints** (Belyaev et al.): $|c_i| < 8\pi$

$$c_{1,2} = \lambda_3 \pm \lambda_4, \quad c_{3,4} = -3\left(\lambda_1 + \lambda_2\right) \pm \sqrt{9\left(\lambda_1 - \lambda_2\right)^2 + \left(2\lambda_3 + \lambda_4\right)^2},$$

$$c_{5,6} = \lambda_3 \pm \lambda_5, \quad c_{7,8} = -\left(\lambda_1 + \lambda_2\right) \pm \sqrt{\left(\lambda_1 - \lambda_2\right)^2 + \lambda_4^2},$$

$$c_{9,10} = \lambda_3 + 2\lambda_4 \pm 3\lambda_5, \qquad c_{11,12} = -\left(\lambda_1 + \lambda_2\right) \pm \sqrt{\left(\lambda_1 - \lambda_2\right)^2 + \lambda_5^2}$$

IDM: Collider constraints

Constraints from the **Large Electron-Positron Collider** (LEP) and the **Large Hadron Collider** (LHC):

- **Electroweak precision data (EWPD) from LEP** (kinetically forbidden decays):

$$m_H + m_{H^\pm} > m_{W^\pm}, \quad m_A + m_{H^\pm} > m_{W^\pm}$$
$$m_H + m_A > m_Z, \quad m_{H^\pm} > m_Z/2$$

- **Electroweak precision test** (loop contributions, Barbieri et al):

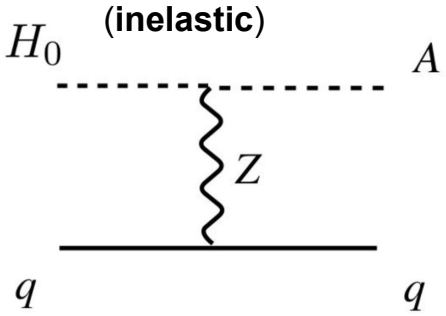
$$S = \frac{1}{72\pi\left(x_2^2 - x_1^2\right)^3}\left[x_2^6 f_a\left(x_2\right) - x_1^6 f_a\left(x_1\right) + 9x_2^2 x_1^2\left(x_2^2 f_b\left(x_2\right) - x_1^2 f_b\left(x_1\right)\right)\right]$$
$$T = \frac{1}{32\pi^2 \alpha v^2}\left[f_c\left(m_{H^\pm}^2, m_A^2\right) + f_c\left(m_{H^\pm}^2, m_H^2\right) - f_c\left(m_A^2, m_H^2\right)\right]$$
$$S = 0.06 \pm 0.09, \quad T = 0.10 \pm 0.07 (\text{Best fit})$$

- **LHC Higgs decay data**:

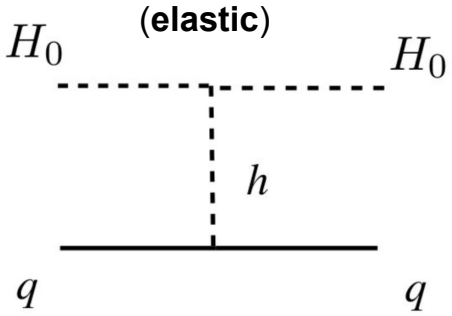
$$BR\left(h \to \text{invisible}\right) < 0.26$$

The IDM as dark matter: direct detection

DD experiments probe the IDM through two processes:



g^2



$\lambda_L y_f$

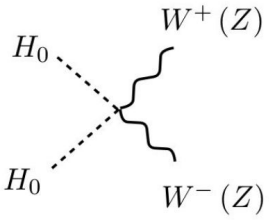
(**already excluded**, arXiv:hep-ph/0612275v2)

$$\sigma_{H-N} = \frac{\lambda_{345}^2 v^2}{m_h^4} \frac{f_N^2 m_N^2}{(m_H + m_N)^2}$$

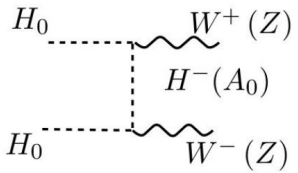
The IDM as dark matter: annihilation

Main kind of **annihilation in the IDM**:

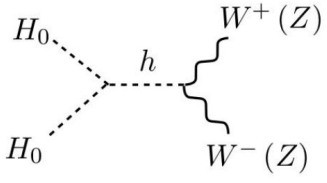
- 1) Vector bosons: HH → W +W −, HH → ZZ.



g^2



g^2



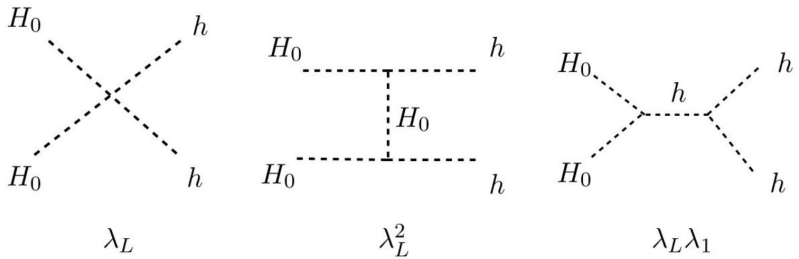
$\lambda_L g$

$$\langle \sigma\, v \rangle_{VV} = \frac{m_H^2}{2\,\delta_V \pi v^4} \left[\left(1 + \frac{\lambda_{345} v^2}{4m_H^2 - m_h^2}\right) \left(1 - r_V + \frac{3}{4} r_V^2\right) + \frac{4m_H^4}{\left(m_H^2 + m_{\phi_V}^2 - m_V^2\right)^2} (1 - r_V)^2 \right.$$
$$\left. - \frac{2m_H^2}{m_H^2 + m_{\phi_V}^2 - m_V^2} \left(1 + \frac{\lambda_{345} v^2}{4m_H^2 - m_h^2}\right) \left(2 - 3r_V + r_V^2\right) \right] \sqrt{1 - r_V}$$

The IDM as dark matter: annihilation

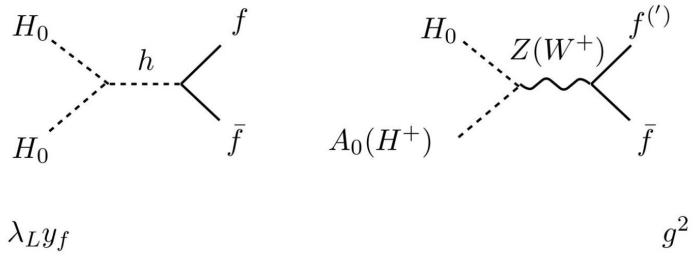
Main kind of **annihilation in the IDM**:

- 2) Higgs bosons: HH → hh



$$\langle \sigma\, v \rangle_{hh} = \frac{1}{64\pi} \frac{\lambda_{345}^2}{m_H^2} \left[1 + \frac{3m_h^2}{4m_H^2 - m_h^2} + \frac{2\,\lambda_{345} v^2}{m_h^2 - 2m_H^2} \right]^2 \sqrt{1 - r_h}$$

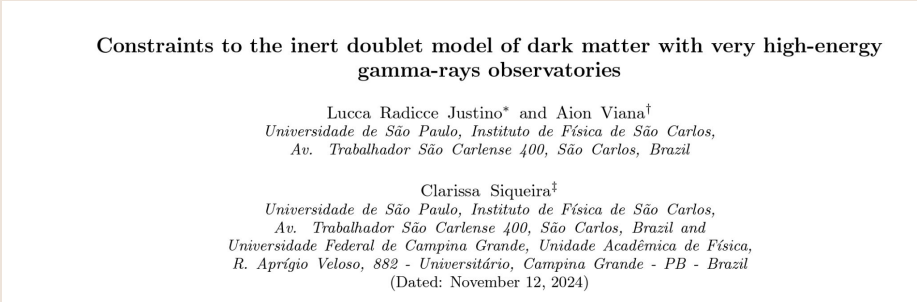
- 3) Fermions through the Higgs portal: HH → h → f f



$$\langle \sigma\, v \rangle_{f\bar{f}} = \frac{N_c}{4\pi} \frac{\lambda_{345} m_f^2}{\left(4m_H^2 - m_h^2\right)^2} \left(1 - r_f\right)^{\frac{3}{2}}$$

https://arxiv.org/abs/2411.05909

LIMITS TO THE INERT DOUBLET MODEL



Constraints to the inert doublet model of dark matter with very high-energy gamma-rays observatories

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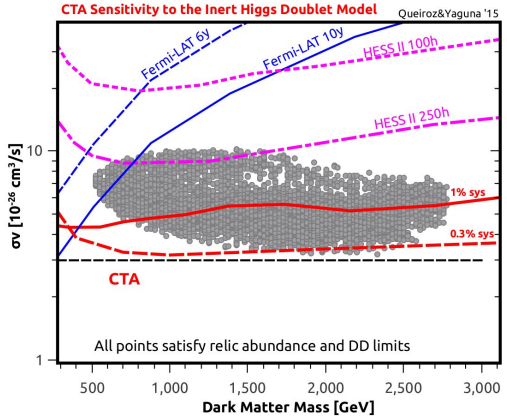
Clarissa Siqueira‡
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(Dated: November 12, 2024)

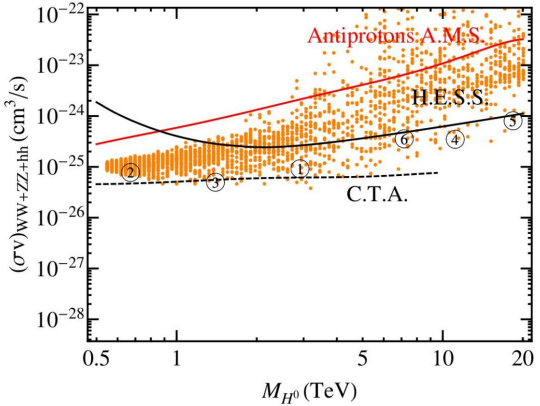
arXiv:2411.05909v1 [hep-ph]

Motivation

Previous results ⇒ potential of the CTA observatory to probe the Inert Doublet Model.



Fermi-LAT, HESS and CTA for the W +W−
Source: Queiroz & Yaguna.



HESS, CTA and antiprotons AMS (Sommerfeld enhancement).
Source: Garcia-Clay & Ibarra.

- IDM limits must be updated with the new experimental/computational results:

1) **CTA's IRFs**. 2) **HESS 546h** limits at the GC region. 3) **LUX-ZEPLIN** first results.

Methodology

Scan in the parameter space:

$$
\begin{aligned}
0 < \lambda_{345} < 2\pi, \\
300\,\mathrm{GeV} < m_H < 30,000\,\mathrm{GeV}, \\
0.5\,\mathrm{GeV} < \Delta_+ < 10\,\mathrm{GeV}, \\
0.5\,\mathrm{GeV} < \Delta_o < 10\,\mathrm{GeV}.
\end{aligned}
$$

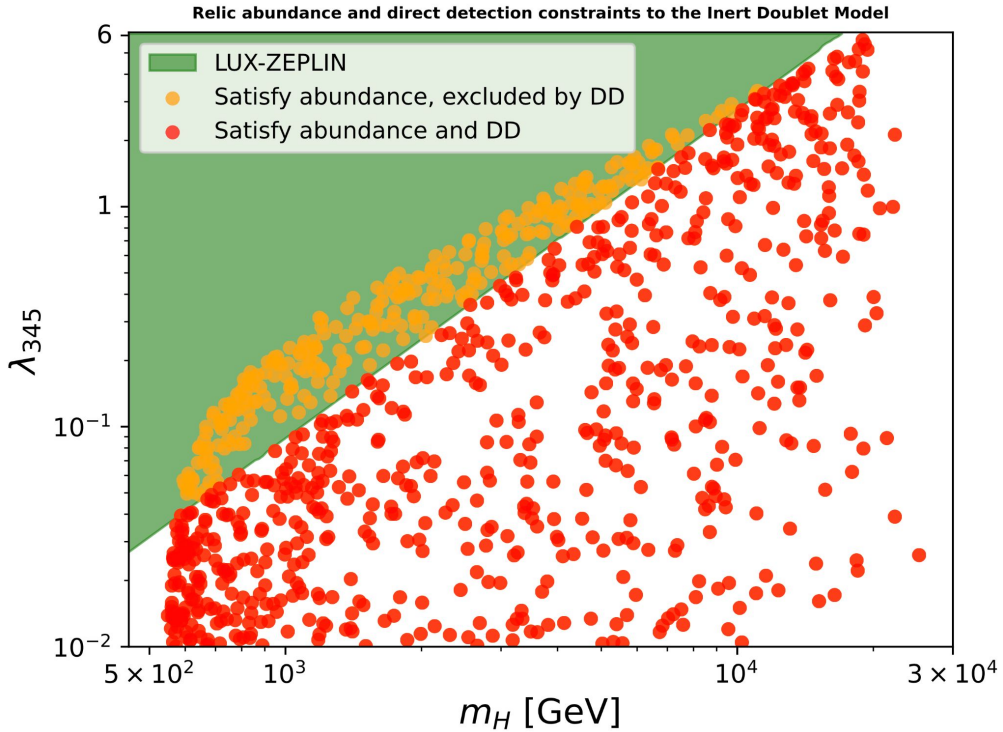
Cuts on the parameter space:

1. **Unitarity** and **inertness**, i.e., $\mu^2 = m_H^2 - \lambda_{345} v^2 > 0$;
2. **Relic abundance** (**PLANCK** satellite) $\Omega h^2 = 0.1200 \pm 0.0012$;
3. **LUX-ZEPLIN** upper limits (90% C.L.).

Two scans:

- **Random scan**: **Relic abundance+Direct detection+Colliders+Theoretical**.
- **Discrete scan**: **Indirect detection**. Mass-splittings: $\Delta_o, \Delta_+ = (0.5, 1.0, 5.0, 10.0)\ \mathrm{GeV}$

IDM: random scan



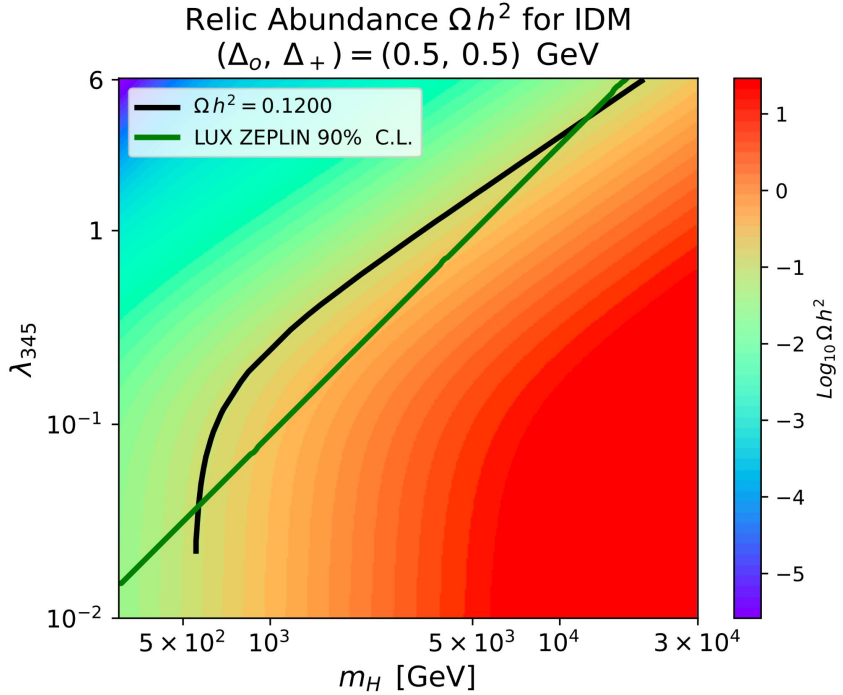
Color map of the relic abundance Ω h2 at logarithmic scale in the parameter space for the random scan. Abundance as exact limit. Source: by the author.

Relic abundance as exact bound.

- **Unitarity** and **relic abundance** constrain mDM to **500 GeV - ~ 25 TeV**.
- **DD** (orange) cuts **high couplings and low mDM** (**mH ≲5 TeV**)
- **~800 scenarios** (red points) satisfying all constraints (**except indirect detection**).

IDM: discrete scan

Relic abundance map for the 16 benchmarks ($\Delta_o, \Delta_+ = (0.5, 1.0, 5.0, 10.0)\ \mathrm{GeV}$).



Color map of the relic abundance Ωh2 at logarithmic scale in the $\lambda_{345} \times m_{DM}$ parameter space for a benchmark in the discrete scan.

Benchmark $(\Delta_o, \Delta_+) = (0.5, 0.5)\ \mathrm{GeV}$:

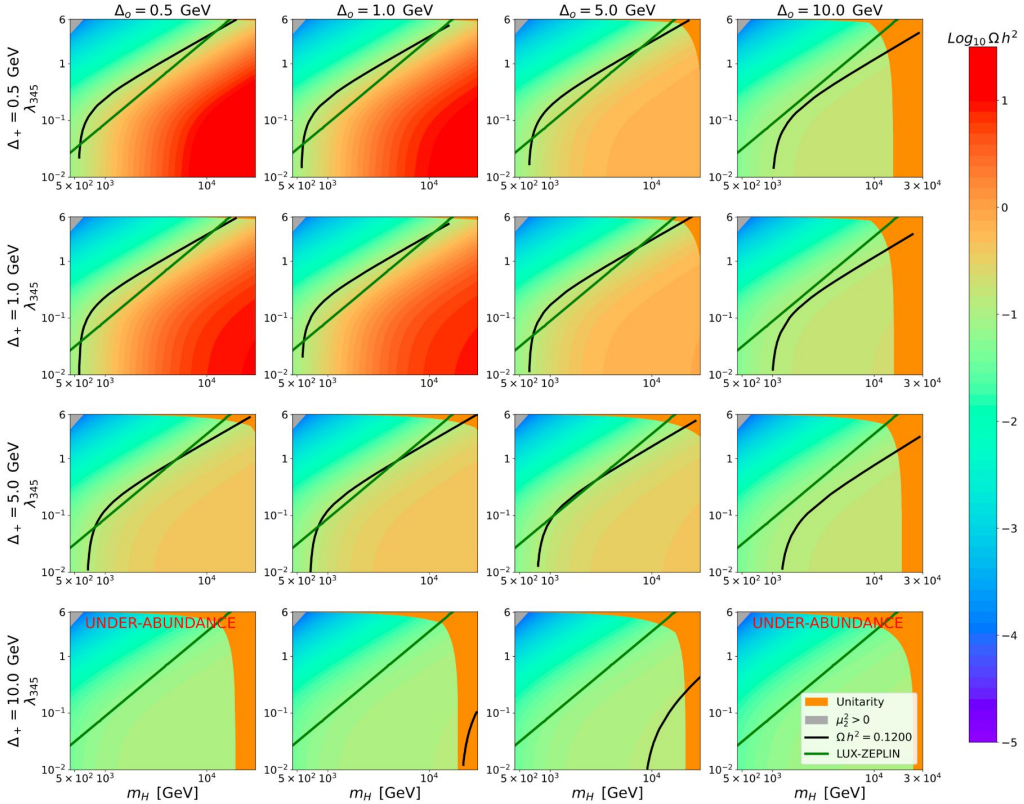
- Determining the spectra for the **right abundance curves**:

$$\left.\frac{dN}{dE}(m_H)\right|_{(\Delta_+,\Delta_o)} = \sum_i B_i\left(m_H, \Delta_+, \Delta_o, \lambda_{345}(m_H)\right)\frac{dN_i}{dE}$$

- The abundance curve is also mapped to the annihilation cross-section:

$$\lambda_{345} \times m_H \rightarrow \langle \sigma\, v \rangle \times m_H$$

IDM: discrete scan



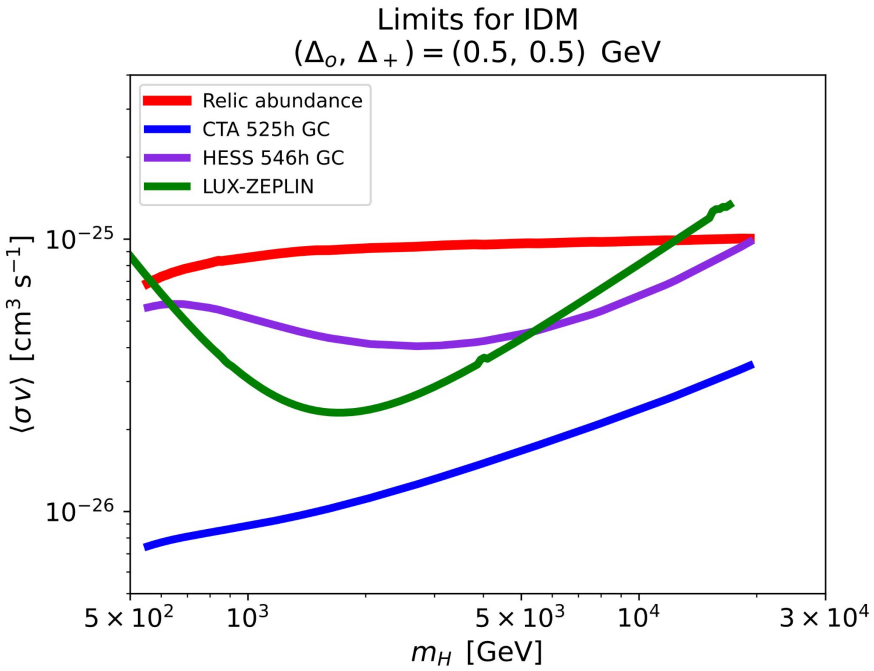
All benchmarks:

- **Co-annihilation**: $\Delta_o, \Delta_+ \lesssim 1\,\mathrm{GeV}$ enhance relic abundance.
- Complementary between **DD** and **relic abundance** in the 500 GeV - ~10 TeV energy range for .
- Unitarity: limits m_H up to **≈ 25 TeV**.

IDM: discrete scan

Benchmark $(\Delta_o, \Delta_+) = (0.5, 0.5)\ \mathrm{GeV}$

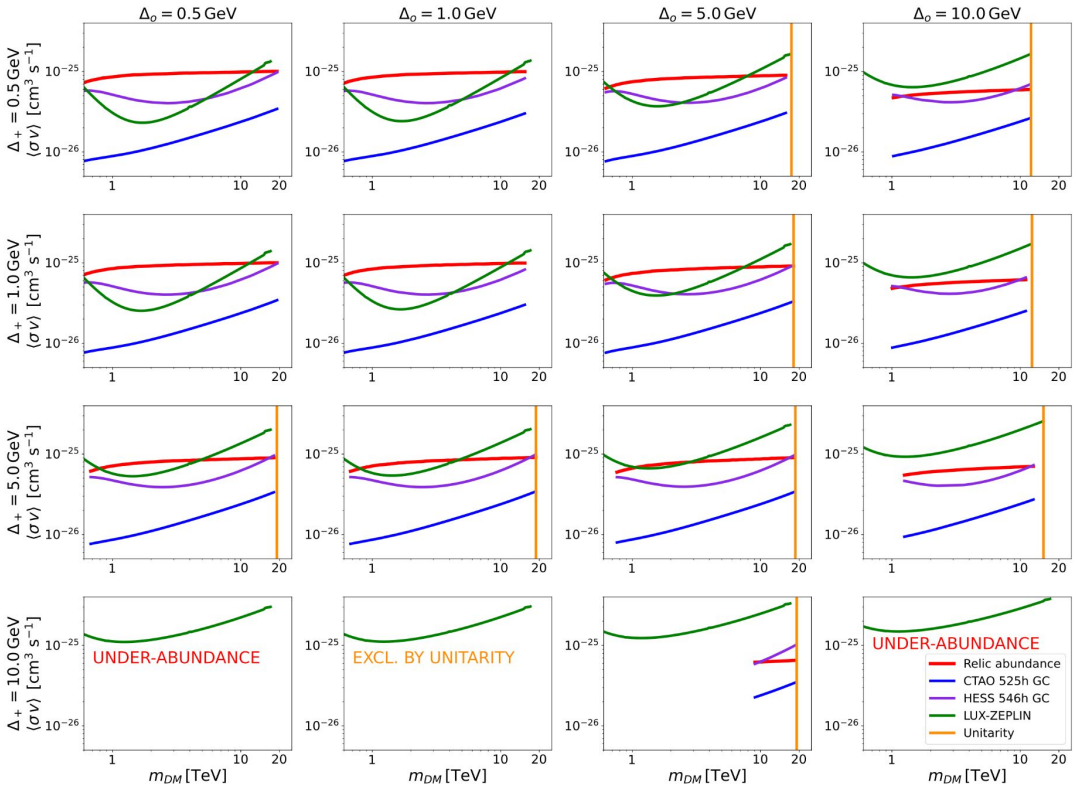
- Determining the **indirect detection limits.**
  - **CTA 525h GC**.
  - **HESS 546h GC.**
- Mapping DD and relic abundance to the $m_{DM} \times \langle \sigma\, v \rangle$ parameter space.
- Annihilation cross-section higher than the typical WIMP ($\langle \sigma\, v \rangle \sim 10^{-25}\,\mathrm{cm}^3.\mathrm{s}^{-1}$).



IDM: indirect detection limits

All benchmarks:

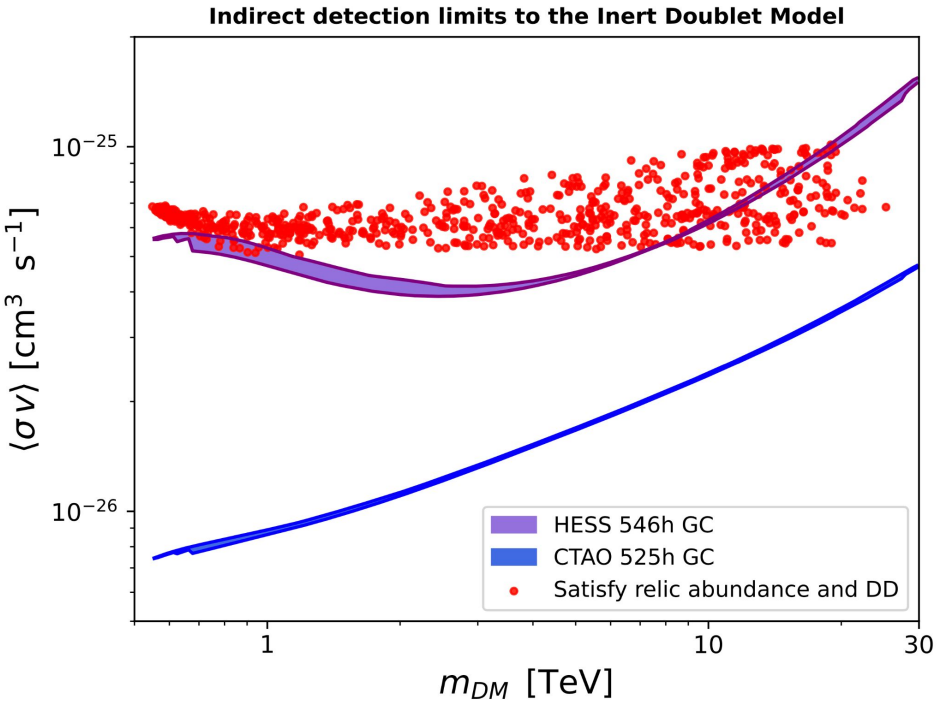
- **Projected CTA limits surpass the LUX-ZEPLIN and HESS limits** for all masses and benchmarks.



IDM: indirect detection limits

Jointing ID limits of all different benchmarks (bands of exclusion):

- Complementarity of relic abundance, direct and indirect limits for the IDM.
- **HESS excludes all masses between ~1 TeV - ~8 TeV**.
- **CTA will be able to probe all viable scenarios**, leading to a **total exclusion of model or a discovery**.



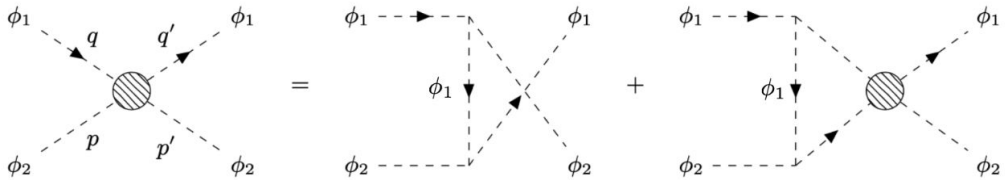
Summary and Conclusions

- A code for indirect detection limits was developed and it was validated by the comparison with the official limits.
- The IDM was scanned with the help of numerical calculations. The ID limits from **new data of HESS** and **projections of CTA** were evaluated and compared with relic abundance and DD constraints:
  - **HESS excludes all scenarios with masses in the 1 - 8 TeV**.
  - **CTA will be able to exclude all parameter space of the model or even make a discovery**.
- Some improvements (loop-corrections, Sommerfeld enhancement) can be made in the future.

Next project: Self-Resonance in the s-channel

- **Self-interacting DM** can explain **small scale problems** such as the cure-cusp, missing satellites, too-big-to-fail,etc.
- **Multi-component DM** can enhance both **DM self-scattering** and **annihilation** (without a light mediator).
- Former results (arXiv:2202.13717v3, SeongSik) found that the **u-channel** can lead to **Sommerfeld Enhancement** in semi-annihilation processes.
- Our (**Rojalin+Lucca+JunHo**) goal: make this analysis for the **s-channel** and apply it to other well motivated BSM particles such as **dark photon, singlet fermion etc**.

$$\mathcal{L} = |\partial_\mu \phi_1|^2 - m_1^2 |\phi_1|^2 + \frac{1}{2}(\partial_\mu \phi_2)^2 - \frac{1}{2} m_2^2 \phi_2^2 - 2 g m_1 \phi_2 |\phi_1|^2$$



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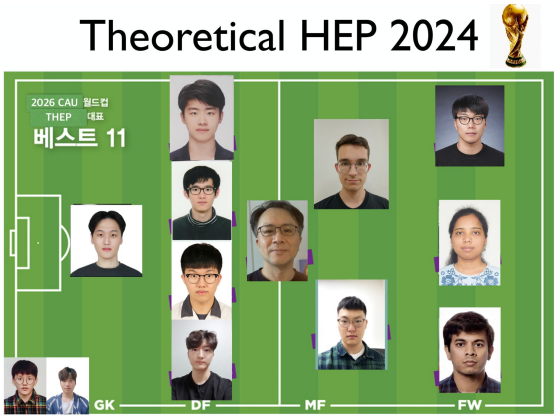
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ibs Institute for Basic Science

BACKUP

The construction of the IDM

- **Masses of scalar sector**:

$$m_h^2 = 2\lambda_1 v^2,\ m_H^2 = \mu_2^2 + \lambda_{345} v^2,$$
$$m_A^2 = \mu_2^2 + \bar{\lambda}_{345} v^2, m_{H^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2$$

- Physical couplings: $\lambda_{345} = \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)$, $\bar{\lambda}_{345} = \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5)$.

Scalar H Pseudo-scalar A

- Lightest particle among → **dark matter candidate**. Convention: H

The construction of the IDM

- **Reparameterization** to the **basis of physical couplings and mass splittings**

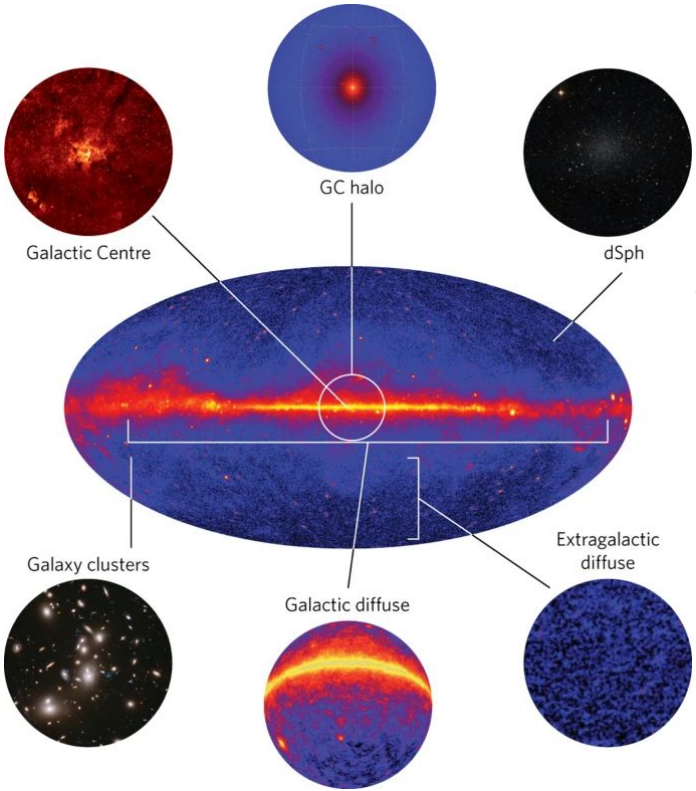
$$(\mu_2, \lambda_2, \lambda_3, \lambda_4, \lambda_5) \to (m_H, \Delta_+, \Delta_o, \lambda_{345}, \lambda_2): \quad \begin{cases} \Delta_+ = m_{H^+} - m_H \\ \Delta_o = m_A - m_H \end{cases}$$

$$\lambda_3 = 2\lambda_{345} + \frac{2\Delta_+ (2m_H + \Delta_+)}{v^2},$$
$$\lambda_4 = \frac{\Delta_o (2m_H + \Delta_o) - 2\Delta_+ (2m_H + \Delta_+)}{v^2},$$
$$\lambda_5 = -\frac{\Delta_0 (2m_H + \Delta_0)}{v^2},$$
$$\bar{\lambda}_{345} = \lambda_{345} + \frac{\Delta_0 (2m_H + \Delta_0)}{v^2}.$$

Indirect detection: astrophysical targets

- Galactic center:
  - **Strongest signal**
  - High background
  - Uncertainty on dark matter density

- Galaxy clusters:
  - Strong signal
  - Background may be important
  - Sub-halos can increase dark matter amount



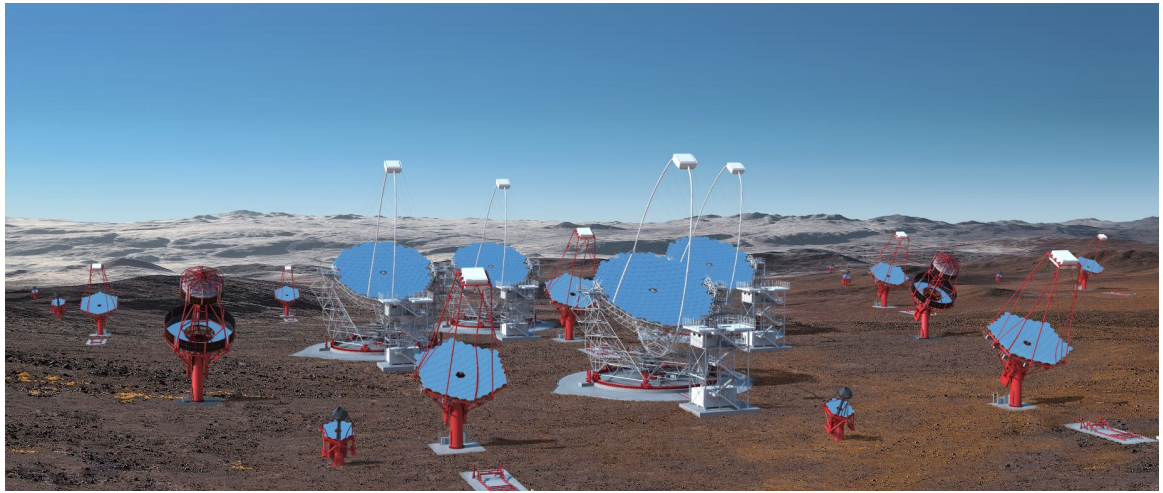
Targets for dark matter indirect detection searches. Source: Conrad & Reimer. DOI: 10.1038/NPHYS4049

- Dwarf Galaxies:
  - Lower signal
  - Clean background
  - Well-known dark matter distribution

The Cherenkov Telescope Array Observatory (CTAO)

- **Location**:
  - **North site**: Canary Islands (Spain)
  - **South site**: Paranal (Chile)
- **Telescopes**: SSTs, MSTs and LSTs
- **Energy resolution**: ~10% above 100 GeV
- **Aims**: increase **sensitivity**, **effective area** and **energy resolution**

Future IACT (under construction)



Artistic illustration of the CTA array. Image credit: Gabriel Pérez Diaz, IAC/Marc- André Besel, CTAO. Source: CTA CONSORTIUM.

Direct detection: spin (in)dependent

$$\frac{d\sigma_{DM-N}}{dE_R} = \left(\frac{d\sigma_{DM-N}}{dE_R}\right)_{SI} + \left(\frac{d\sigma_{DM-N}}{dE_R}\right)_{SD}$$

$$\left(\frac{d\sigma}{dE_R}\right)_{SI} \sim A^2 \qquad \left(\frac{d\sigma}{dE_R}\right)_{SD} \sim J\left(J+1\right)$$

Statistical analysis: log-likelihood method

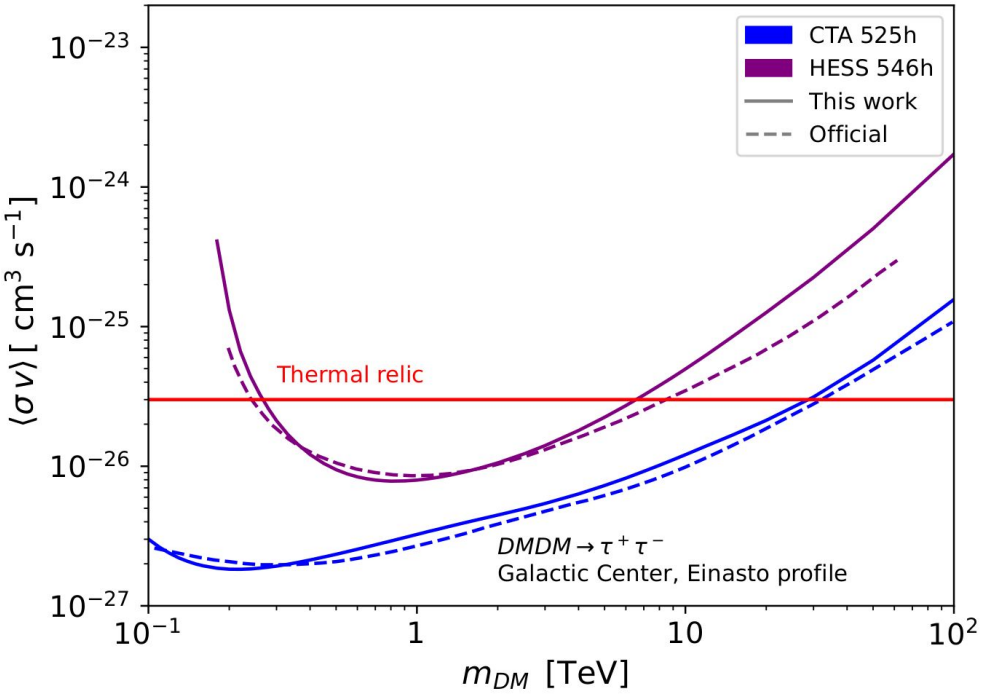
A source on gamma-ray astronomy or a hypothesis in high-energy physics can be tested only statistically. We rely on Wilks' theorem which gives a **test statistic** for comparing two hypothesis (new vs null):

$$TS \equiv -2 \ln \left[\frac{\mathcal{L}\left(\mathbf{x}|\lambda_o, \hat{\hat{\mu}}_o\right)}{\mathcal{L}\left(\mathbf{x}|\hat{\lambda}, \hat{\mu}\right)} \right] ,$$

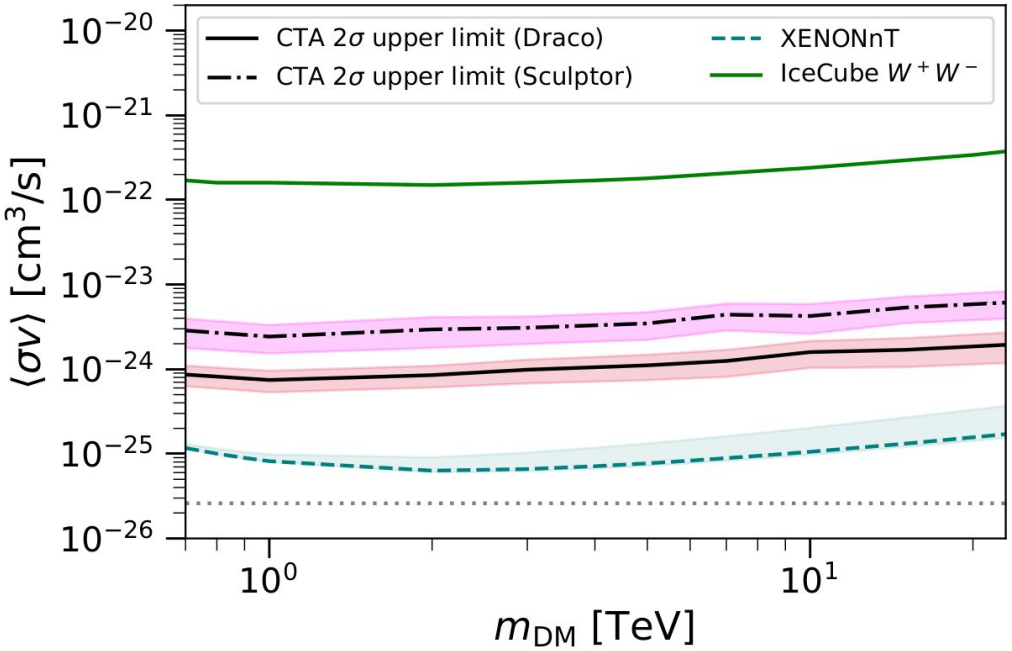
where $\mathcal{L}$ is the maximum likelihood associated to each hypothesis. The conditional maximum at the null hypothesis is $\left(\lambda_o, \hat{\hat{\mu}}_o\right)$ while the global maximization is obtained at $\left(\hat{\lambda}, \hat{\mu}\right)$.

Wilks' theorem shows that, for a large dataset, $TS \sim \chi^2(r)$, which enables us to define **confidence levels** (CL).

Indirect detection limits: primary channels



IDM limits from dwarf galaxies

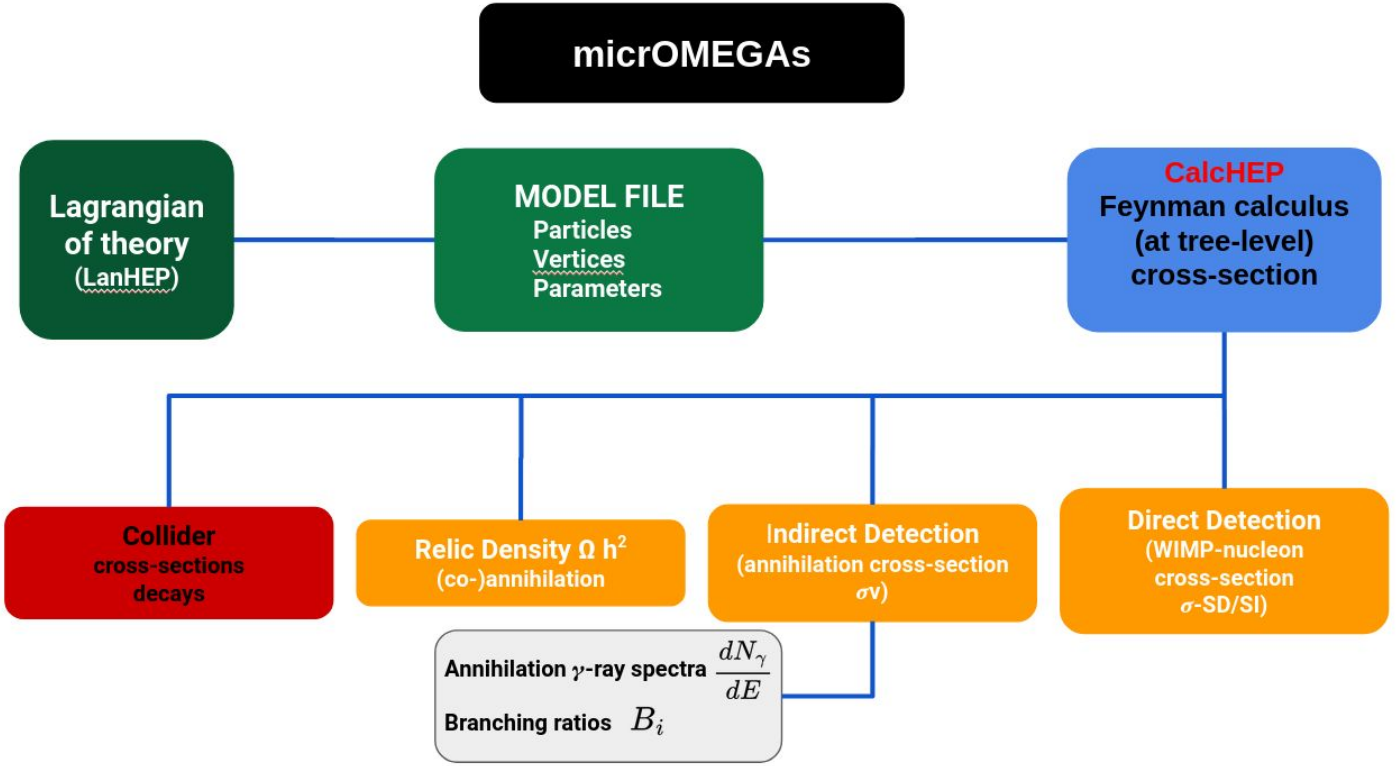


Complementary limits in terms of annihilation cross-section ⟨σ v⟩ from the projected CTA sensitivity at the dwarf galaxies Draco and Sculptor compared with projected XENONnT and IceCube. Source: Duangchan et al.

IDM expanded scalar potential

$$
\begin{aligned}
V(H_1, H_2) = V(h) + \left(\mu_2^2 + \frac{\lambda_3}{2} v^2\right) H^+ H^- + \\
\frac{1}{2}\left(\mu_2^2 + \lambda_{345} v^2\right) H^2 + \frac{1}{2}\left(\mu_2^2 + \bar{\lambda}_{345} v^2\right) A^2 \\
+ \lambda_2 \left(H^+ H^-\right)^2 + \lambda_2 \frac{H^4 + A^4}{4} + \lambda_2 H^+ H^- H^2 + \\
\lambda_2 H^+ H^- A^2 + \lambda_2 \frac{H^2 A^2}{2} \\
+ \lambda_3 v h H^+ H^- + \lambda_{345} v h H^2 + \bar{\lambda}_{345} v h A^2 \\
+ \frac{\lambda_{345}}{2} h^2 H^2 + \frac{\bar{\lambda}_{345}}{2} h^2 A^2 + \frac{\lambda_3}{2} h^2 H^+ H^-
\end{aligned}
$$

Numerical methods



Flow chart of micrOMEGAS framework with the auxiliary packages and modules. Source: adapted from BELANGER et al.

J-factor

DM Distribution ⇒ J-factor

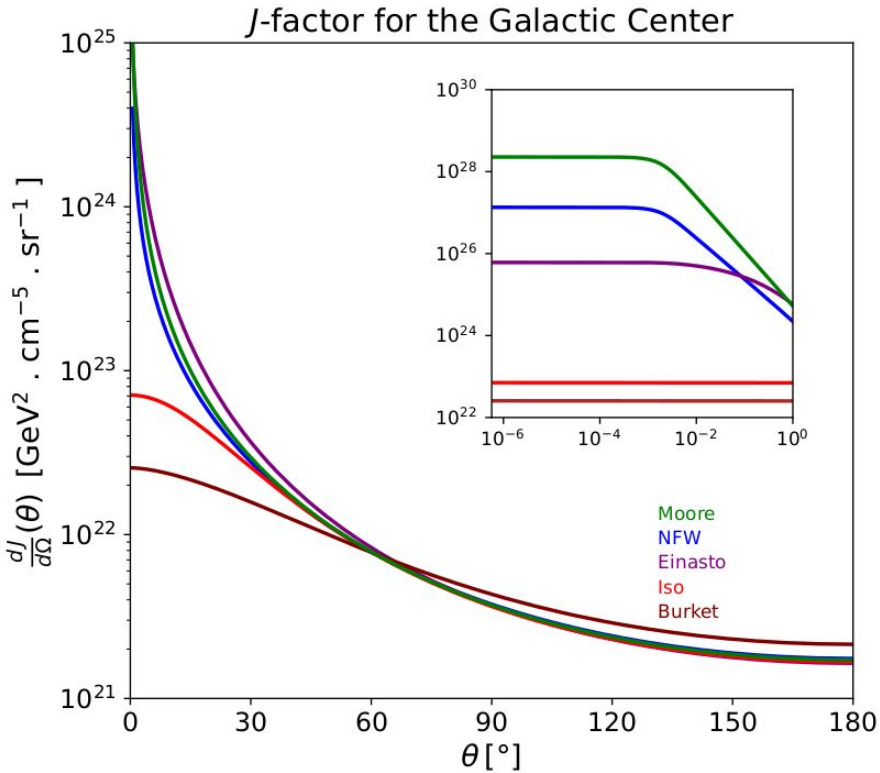
$$J\left(\Delta\Omega\right) = \int_{\Delta\Omega} d\Omega \int_{\text{l.o.s.}} ds \rho^2_{DM}\left(r\left(s,\Omega\right)\right)$$

- Cuspy vs Cored profiles on GC ⇒

  high difference between models ⇒

  high uncertainty on J-factor.

- Solution: consider extreme cases.
- This work: **Einasto profile considered for comparison with official results**.



Differential astrophysical factor in Milky Way in function of the opening angle θ from the Galactic Center. Source: adapted from Cirelli et al.

The IDM as dark matter: co-annihilation

Models of **dark sectors**: many models beyond the SM (**the lightest particle among them the dark matter candidate)**.

Co-annihilation processes:

$$\chi_1\chi_2 \leftrightarrow SMSM$$
$$\chi_2\chi_2 \leftrightarrow SMSM$$

CO-ANNIHILATION REGIME

$m_1 \approx m_2 \approx \ldots$
$\Rightarrow$
decaying after x_f

$$n = \sum_i n_i$$
(relevant abundance)

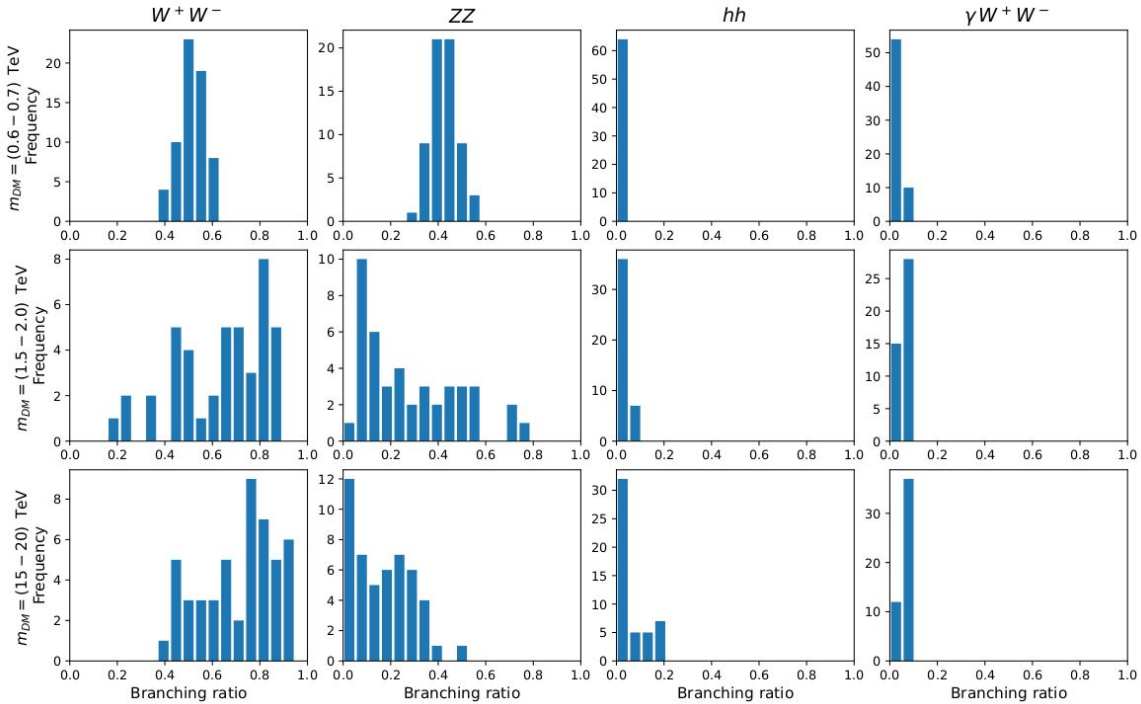
$$\frac{dn}{dt} = -3Hn - \langle \sigma_{\text{eff}}\, v \rangle \left(n^2 - n_{eq}^2\right)$$
Effective Boltzmann equation

Effective annihilation cross-section is

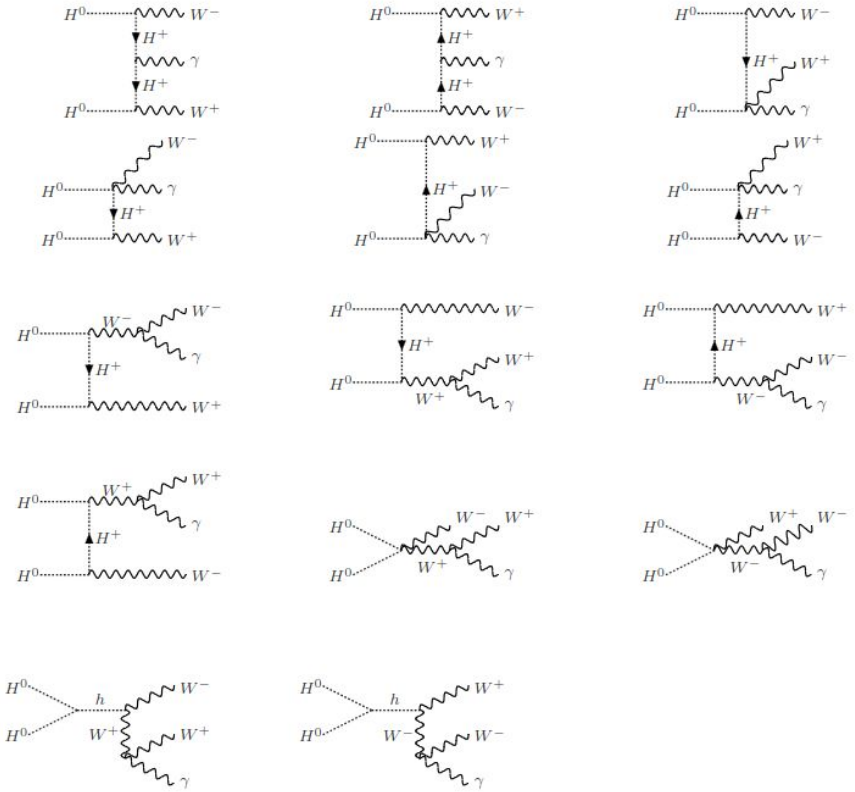
$$\sigma_{\text{eff}} = \sum_{ij} \sigma_{ij} \frac{g_i g_j}{g_{\text{eff}}^2} \left(1 + \frac{\Delta m_i}{m_1}\right)^{3/2} \left(1 + \frac{\Delta m_j}{m_1}\right)^{3/2} e^{-\frac{\Delta m_i + \Delta m_j}{T}}$$

Boltzmann attenuation → Coannihilation dominates for small mass-splitting

IDM: Branching ratios distribution



Spectral lines in the IDM



IDM: indirect detection limits

