Simplified Models of Dark Matter & Experimental Complementarity

Miguel Campos

based on **arXiv:1708.00890**
& *JCAP* **1707** (2017) no.07, 016

Max-Planck-Institut für Kernphysik &
Heidelberg Universität

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MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

MANITOP
Massive Neutrinos: Investigating their Theoretical Origin and Phenomenology

INTERNATIONAL MAX PLANCK RESEARCH SCHOOL PT FS

FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

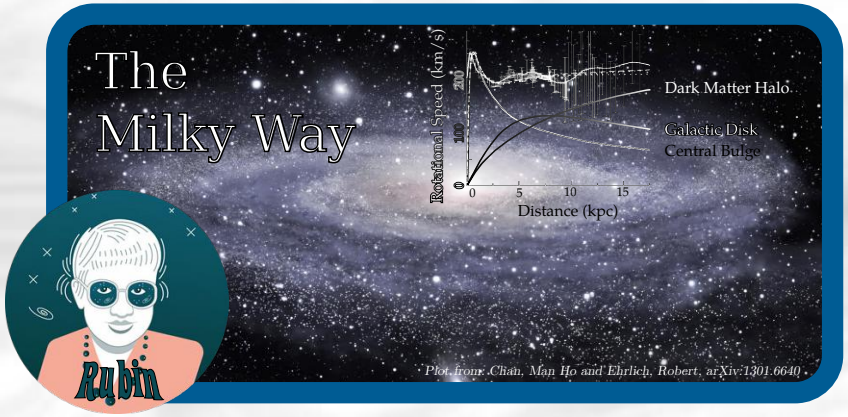
Introduction

Dark Matter

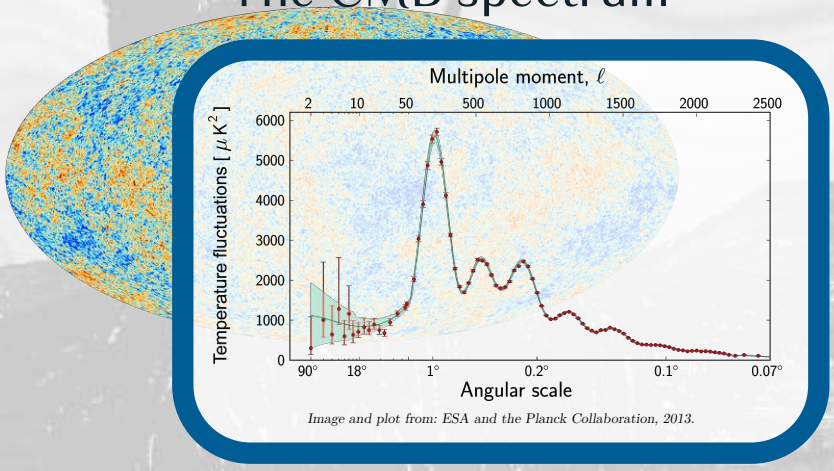
Evidence

The Coma Cluster

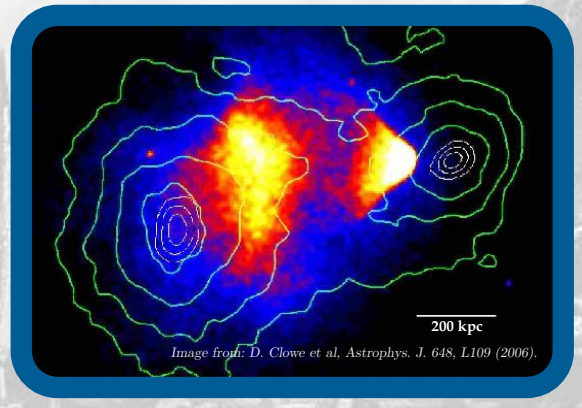
Galactic rotation curves



The CMB spectrum



The Bullet cluster

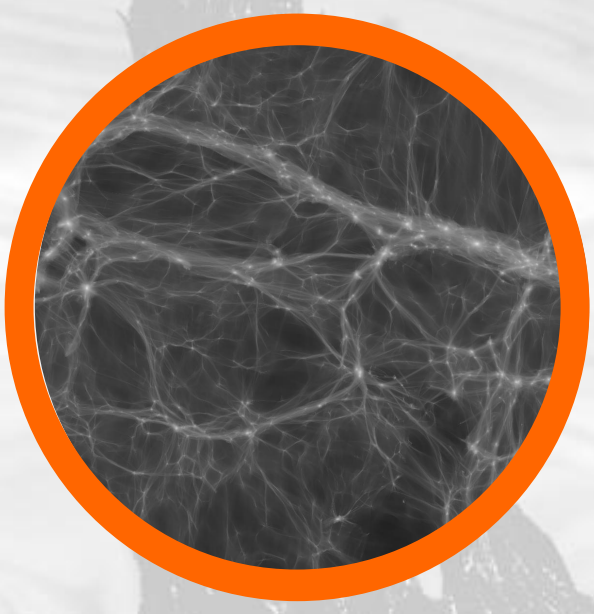


Introduction

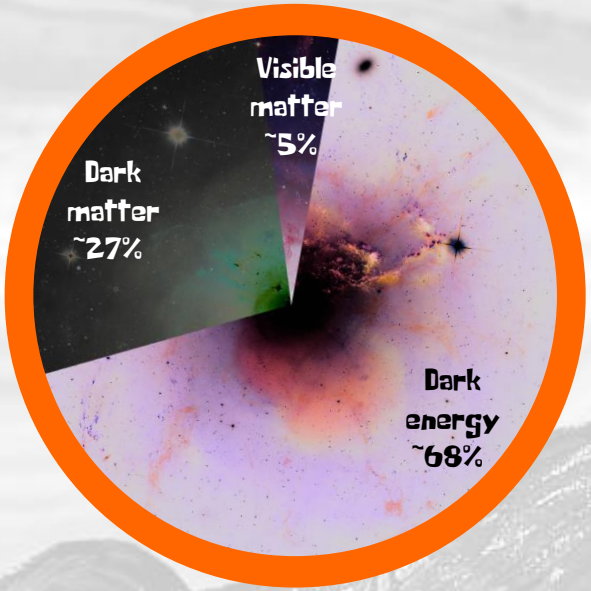
Dark Matter

What we know so far:

It is essential for galaxy formation



Its approximate abundance.



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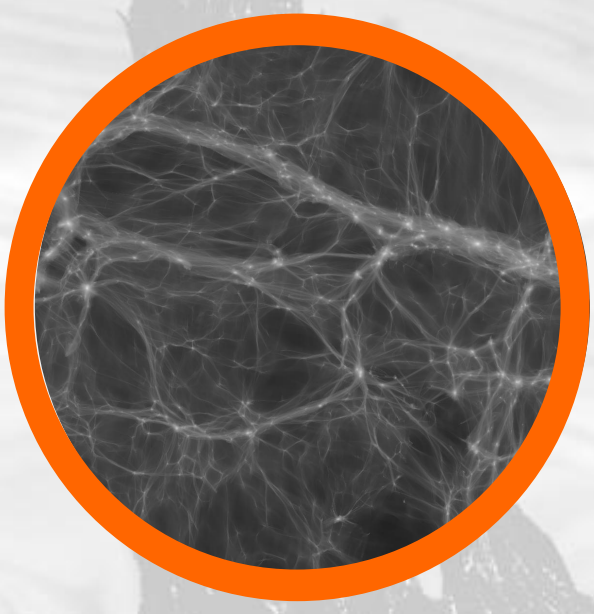

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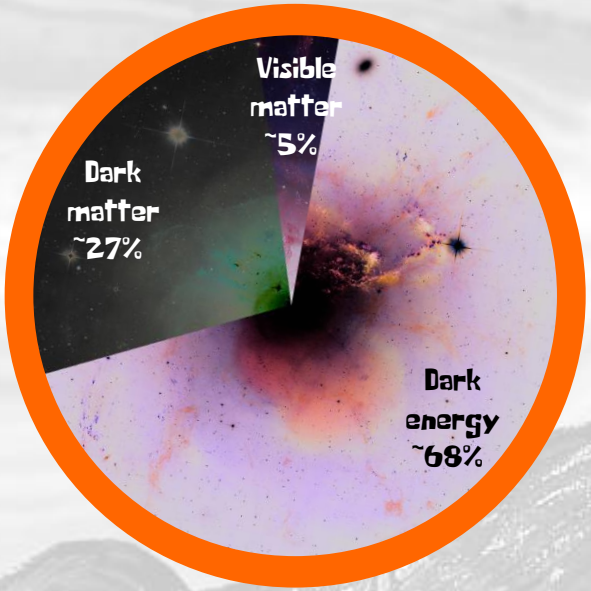
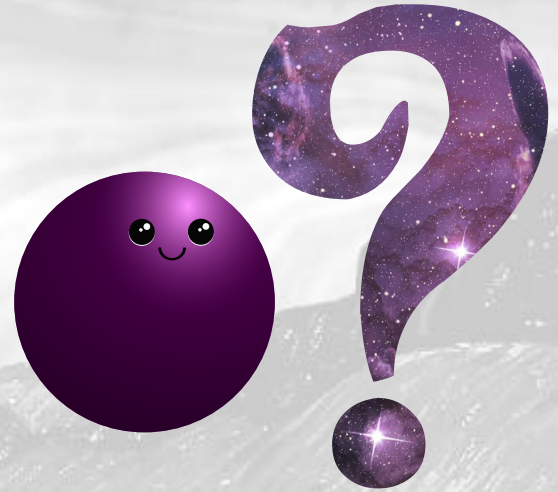


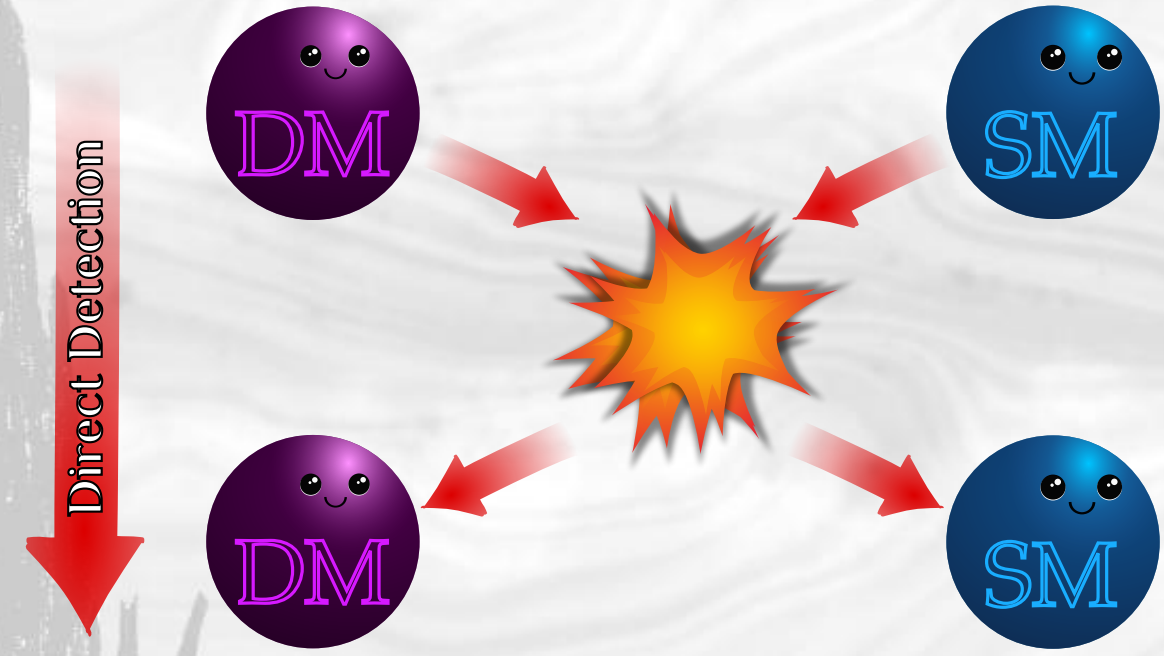
What we don't know:

What it actually is!

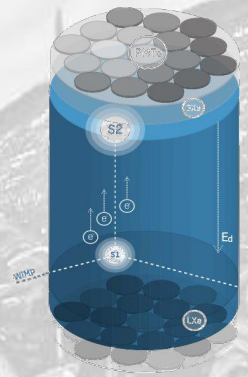


Introduction

Methods of Detection



Scattering



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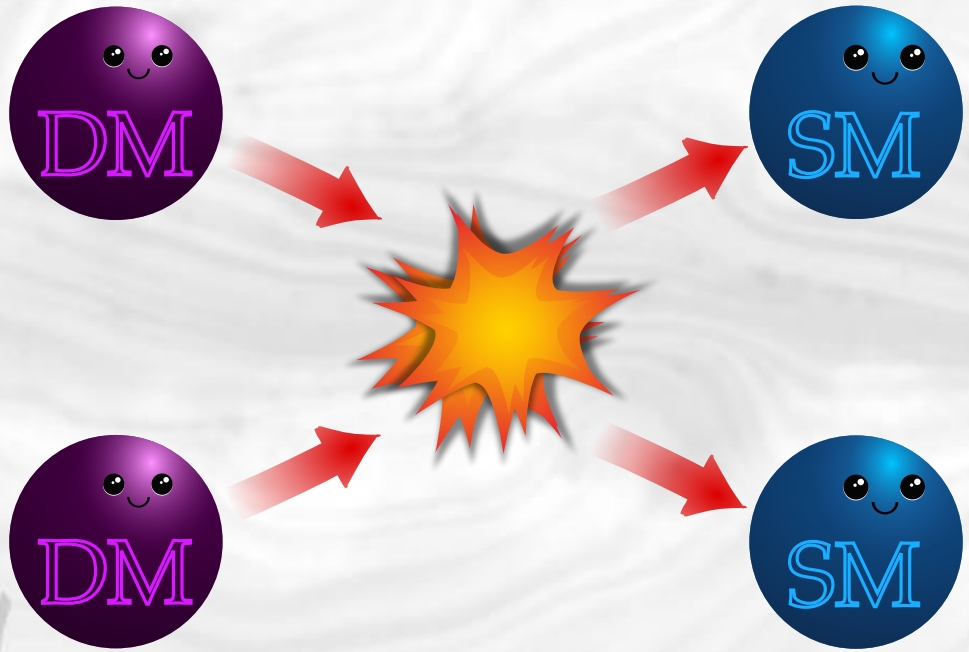
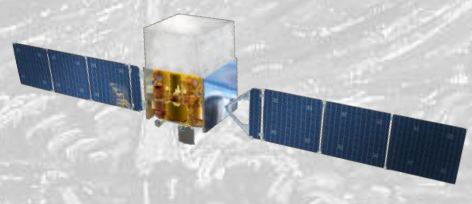


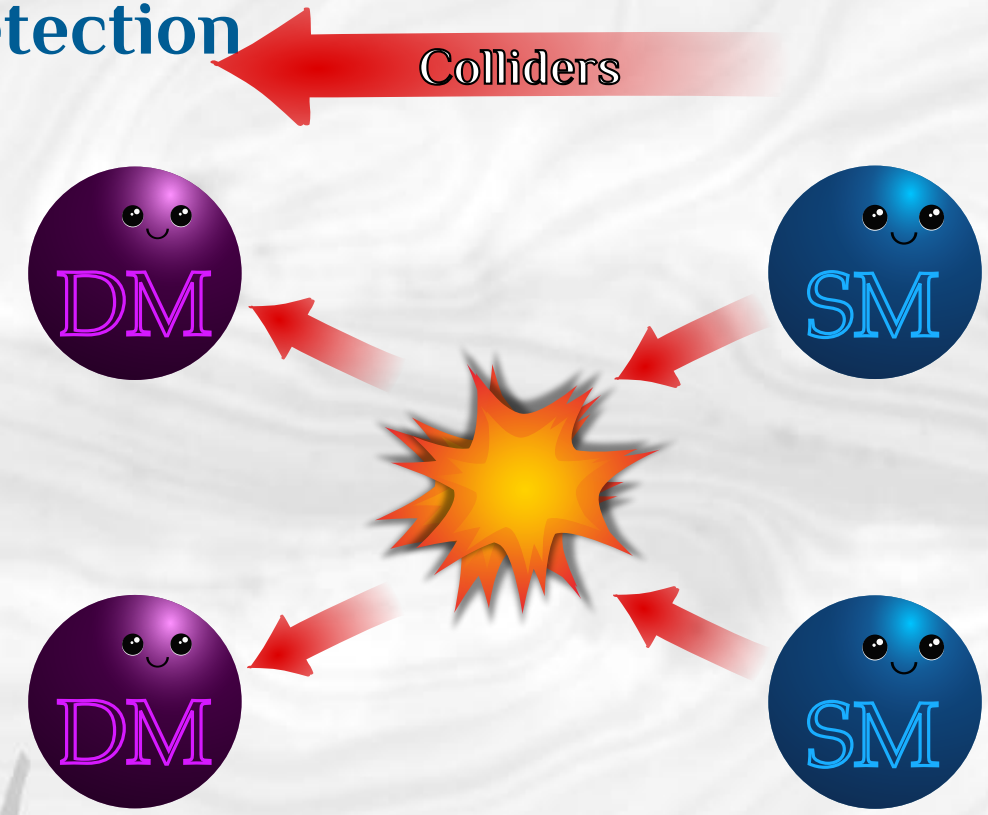
Indirect Detection



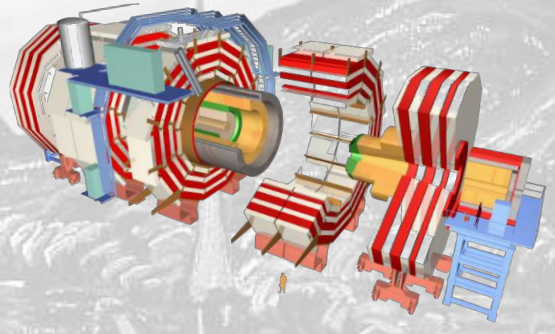
Annihilation

Introduction

Methods of Detection



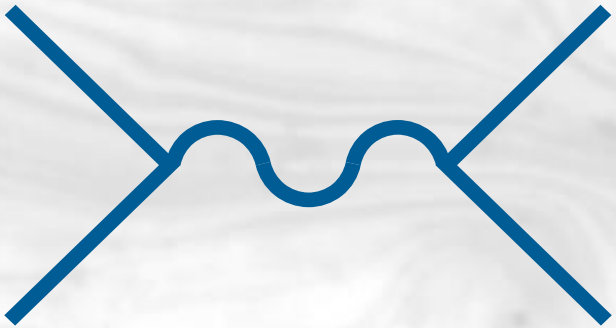
Production



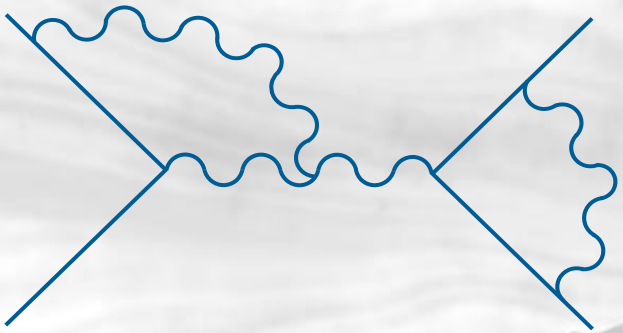
Introduction

Theoretical Approaches

Effective Field Theories



Simplified Models



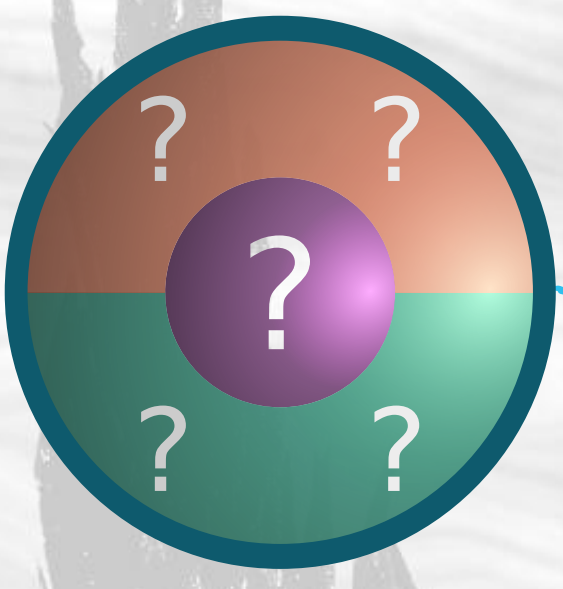
UV Complete Models

Introduction

Simplified Models

Dark Sector

Visible Sector



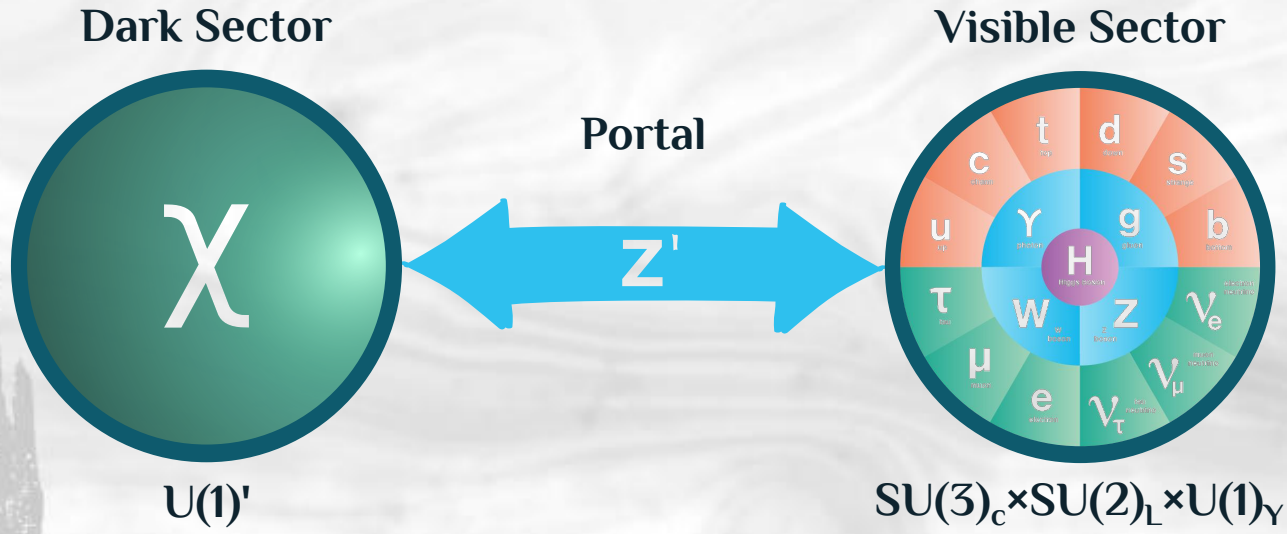
Portal

New Gauge Symmetries

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

1st Case of Study

The Dark Sequential Z' Portal



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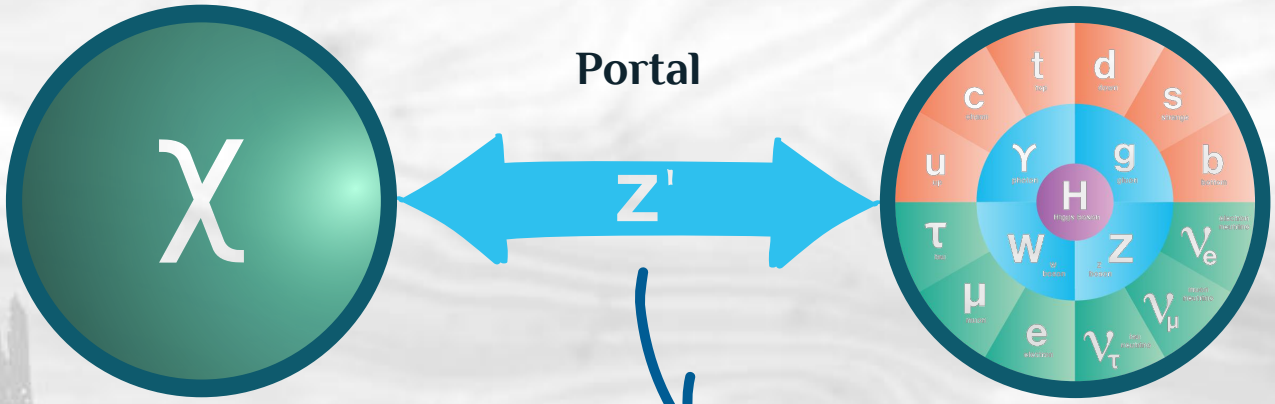

Majorana fermion

U(1)'

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

Natural consequence of a symmetry breaking chain in GUTs and other extended groups.

If the SM Higgs is not charged under **U(1)'**, there is no mass mixing and Z' is the only ***portal***. Here, Z' couples to the SM exactly as Z does, hence ***Sequential***.

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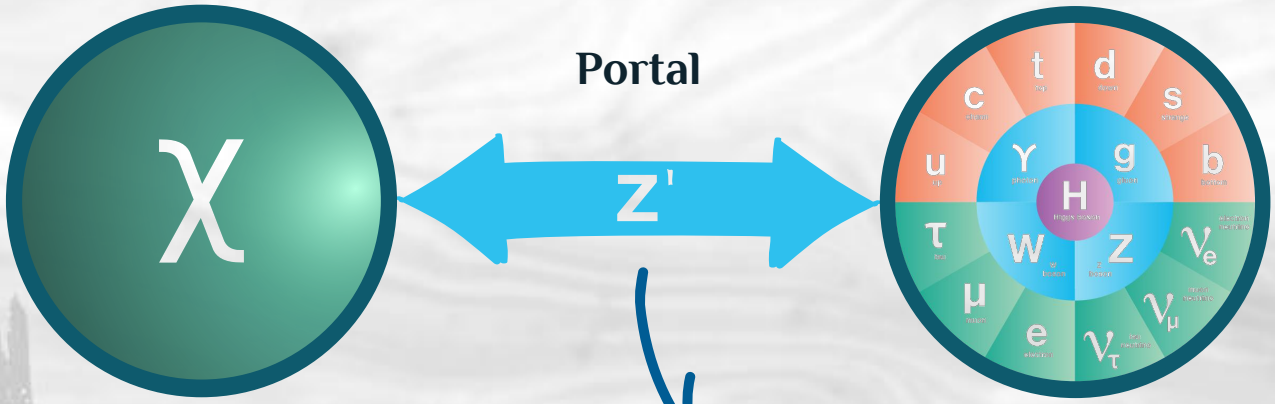

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$$\mathcal{L} \supset \left[g_\chi \chi \gamma^\mu \gamma^5 \chi + \sum_{f \in \mathrm{SM}} \bar{f} \gamma^\mu (g_{fv} + g_{fa} \gamma^5) f \right] Z'_\mu$$

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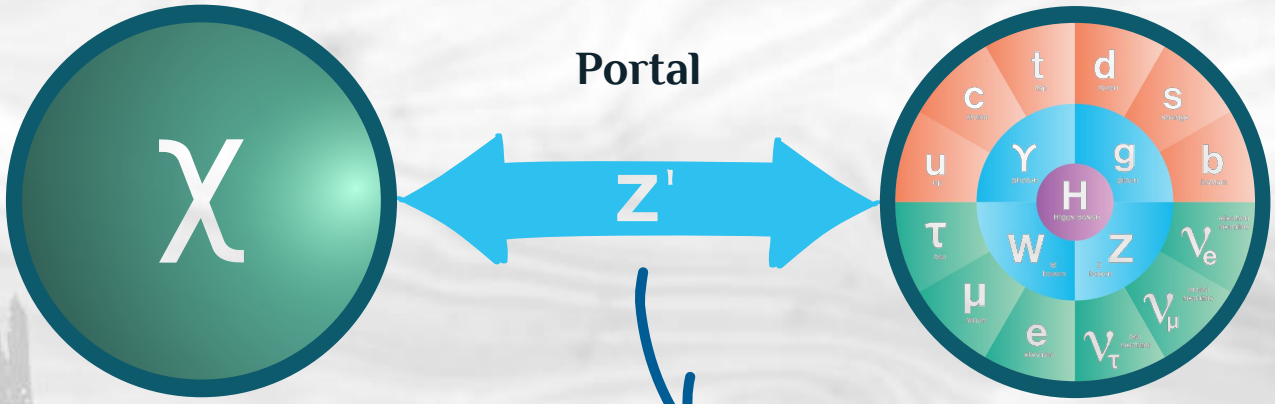

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$\bar{f}\gamma^\mu f \chi \gamma_\mu \gamma_5 \chi$ → SI —velocity suppressed→ ✗

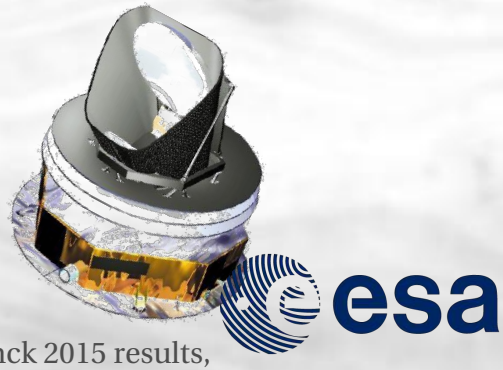
$\bar{f}\gamma^\mu \gamma_5 f \chi \gamma_\mu \gamma_5 \chi$ → SD → ✓

Constraints

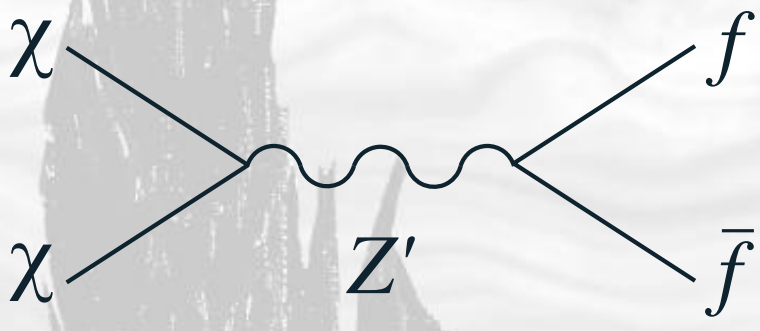
Relic Density

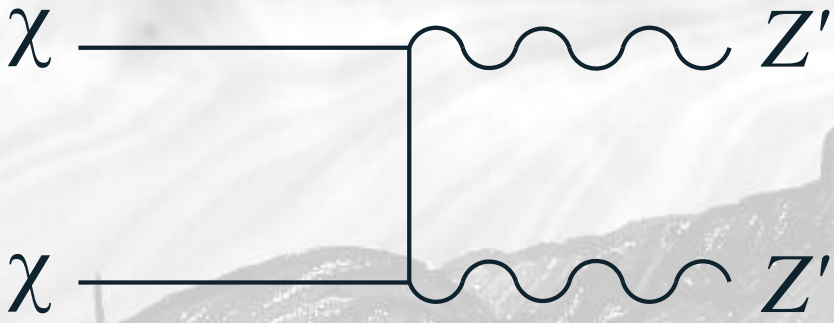
$$\Omega h^2 = 0.1199 \pm 0.012$$

(through thermal production)



[Planck 2015 results,
Astron. Astrophys. 594 (2016) A13]





Calculated using `MicrOmegas 4.3.2`.

Constraints

Direct Detection

$$\sigma^{\mathrm{SD}}_{\chi N} = \frac{12\mu^2_{\chi N}}{\pi}\frac{g^2_\chi}{M^4_{Z'}}\left[g_{ua}\Delta^N_u + g_{da}\left(\Delta^N_d + \Delta^N_s\right)\right]^2, \;\; N = p, n$$

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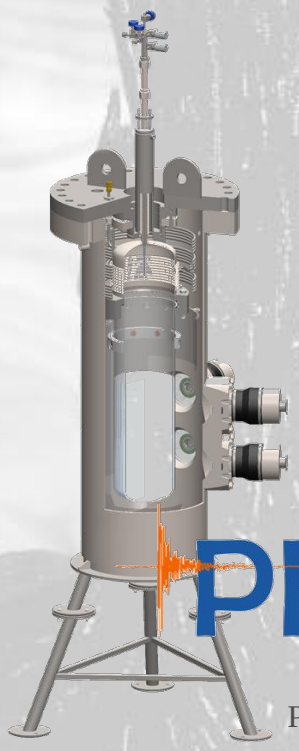
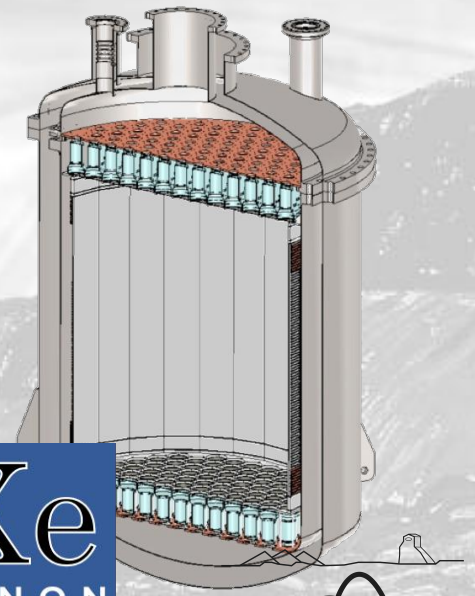
SD_p

SD_n





(One unpaired proton in C_3F_8)

(One unpaired neutron in Xe)

PICO

[PICO Collaboration, Phys. Rev. Lett. 118, 251301 (2017)]

[XENON Collaboration, arXiv:1705.06655]

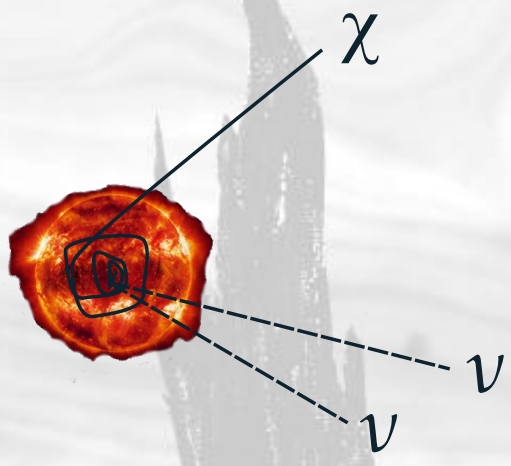
[XENON Collaboration, JCAP 1604 (2016) no.04, 027]

[LUX Collaboration, Phys. Rev. Lett. 118, 251302 (2017)]

Xe XENON Dark Matter Project + LUX

Constraints

Direct Detection 2



- Neutrino flux is connected to DM capture and annihilation.
- Once the equilibrium is reached the annihilation can be removed and limits can be imposed on the capture rate.

Constraints

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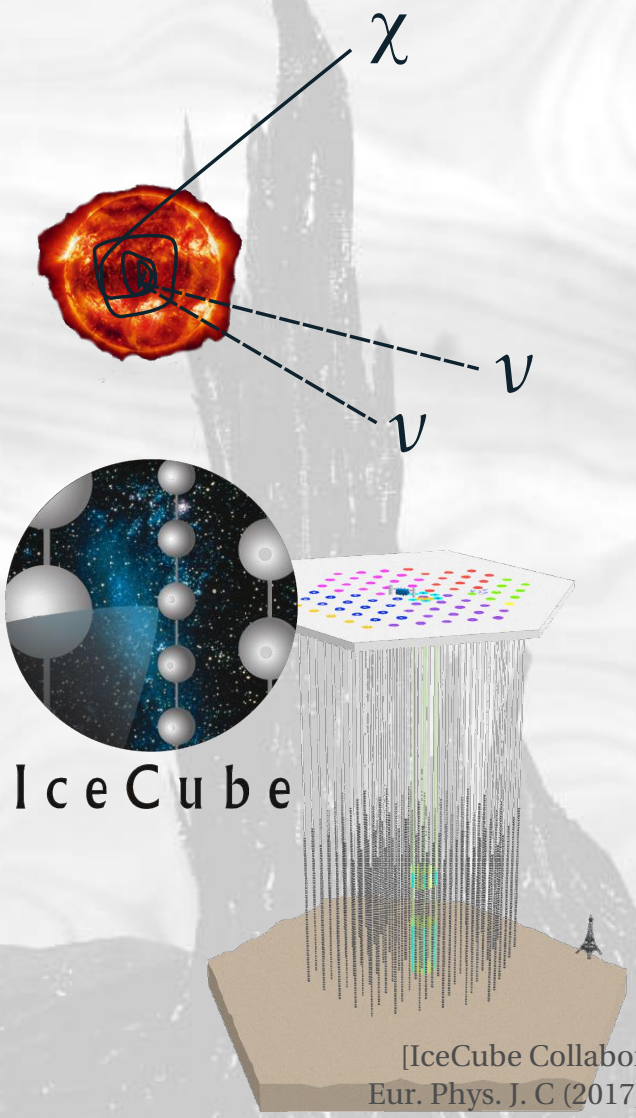

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$$C_{\mathrm{DM}} = 10^{20} s^{-1} \left(\frac{1\ \mathrm{TeV}}{m_\chi} \right)^2 \frac{2.77\, \sigma_{SD_p} + 4270\, \sigma_{SI_p}}{10^{-40} cm^{-2}}$$

[IceCube Collaboration, Eur. Phys. J. C (2017) 77: 146]

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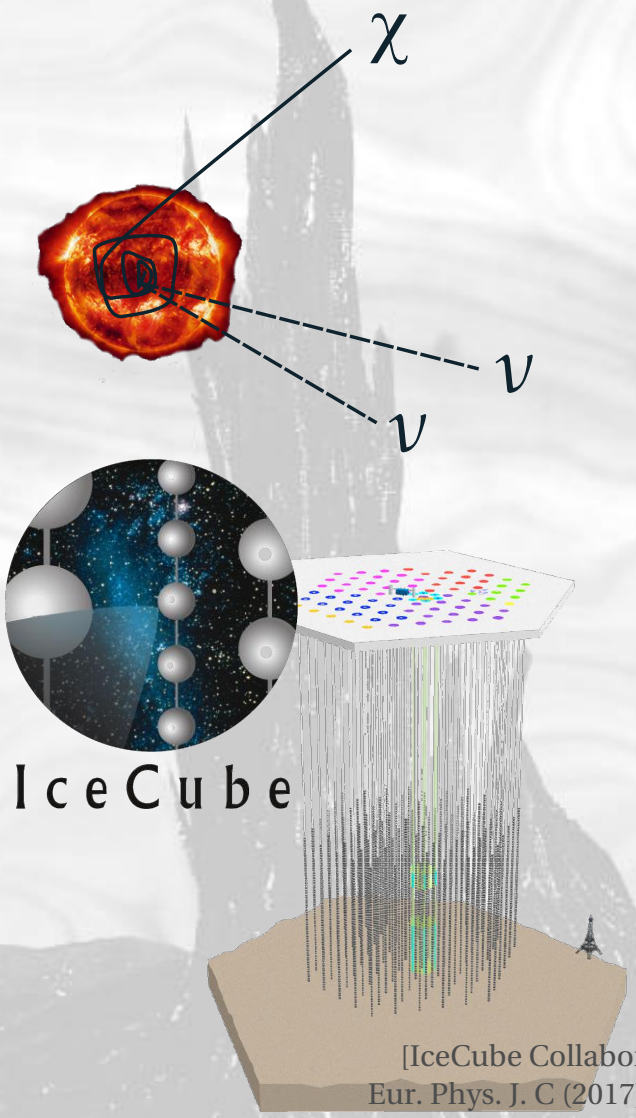

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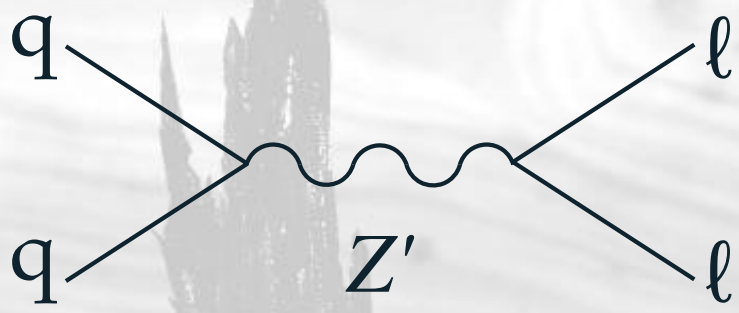
Subdominant, but limits closer to those of DD Experiments (PICO-60).

Dominant, but limits coming from DD Experiments (XENON1T, LUX) are several orders of magnitude stronger.

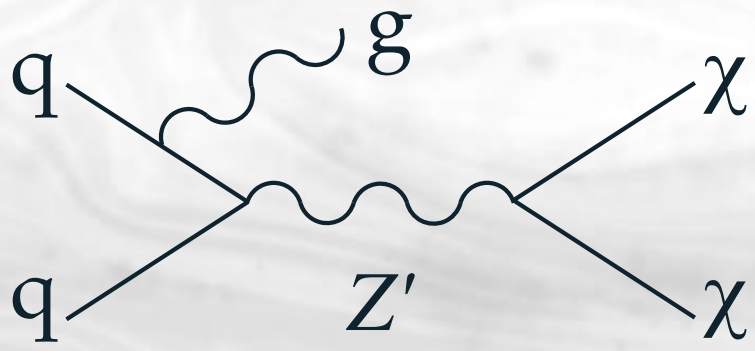
Constraints

Colliders

Dileptons



Monojet



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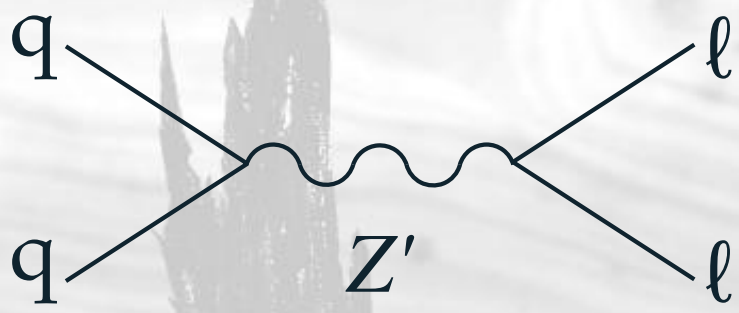

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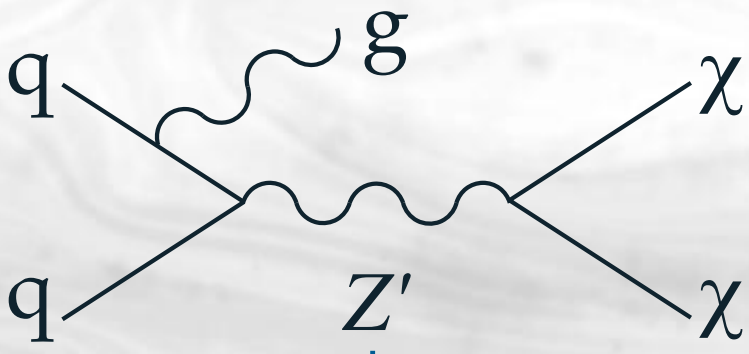


Monojet searches are based on events with missing energy peaking at DM pairs, hence the limits are for $M_\chi < M_{Z'}/2$

For 13 TeV and 36.1 fb^{-1}, it roughly excludes $M_{Z'} \approx 4$ TeV.

The limit weakens for $M_\chi < M_{Z'}$

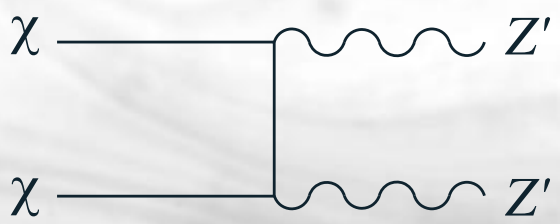
$$\frac{\Gamma(Z' \to \ell\ell)}{\Gamma(Z' \to ff)} \Rightarrow \mathrm{Br}(Z'_{\mathrm{SSM}} \to \ell\ell)\,[1 - \mathrm{Br}(Z' \to \chi\chi)]$$

[ATLAS Collaboration, arXiv:1707.02424]

Constraints

Perturbativity

As this is ***not*** a UV complete theory, the model exhibits an odd behavior in the process $\chi\chi \to Z'Z'$



$$\sigma(\chi\chi \to Z'Z') \propto \frac{\sqrt{s}M_\chi}{M_{Z'}}$$

This is due to the contribution from Z'_L to the diagram. Unitarity can be restored once the scalar that breaks **U(1)'** is introduced.

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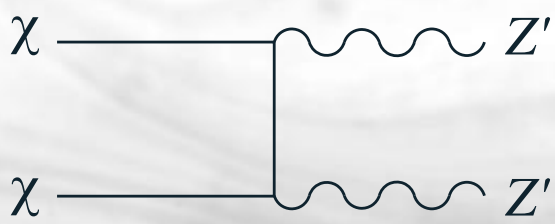

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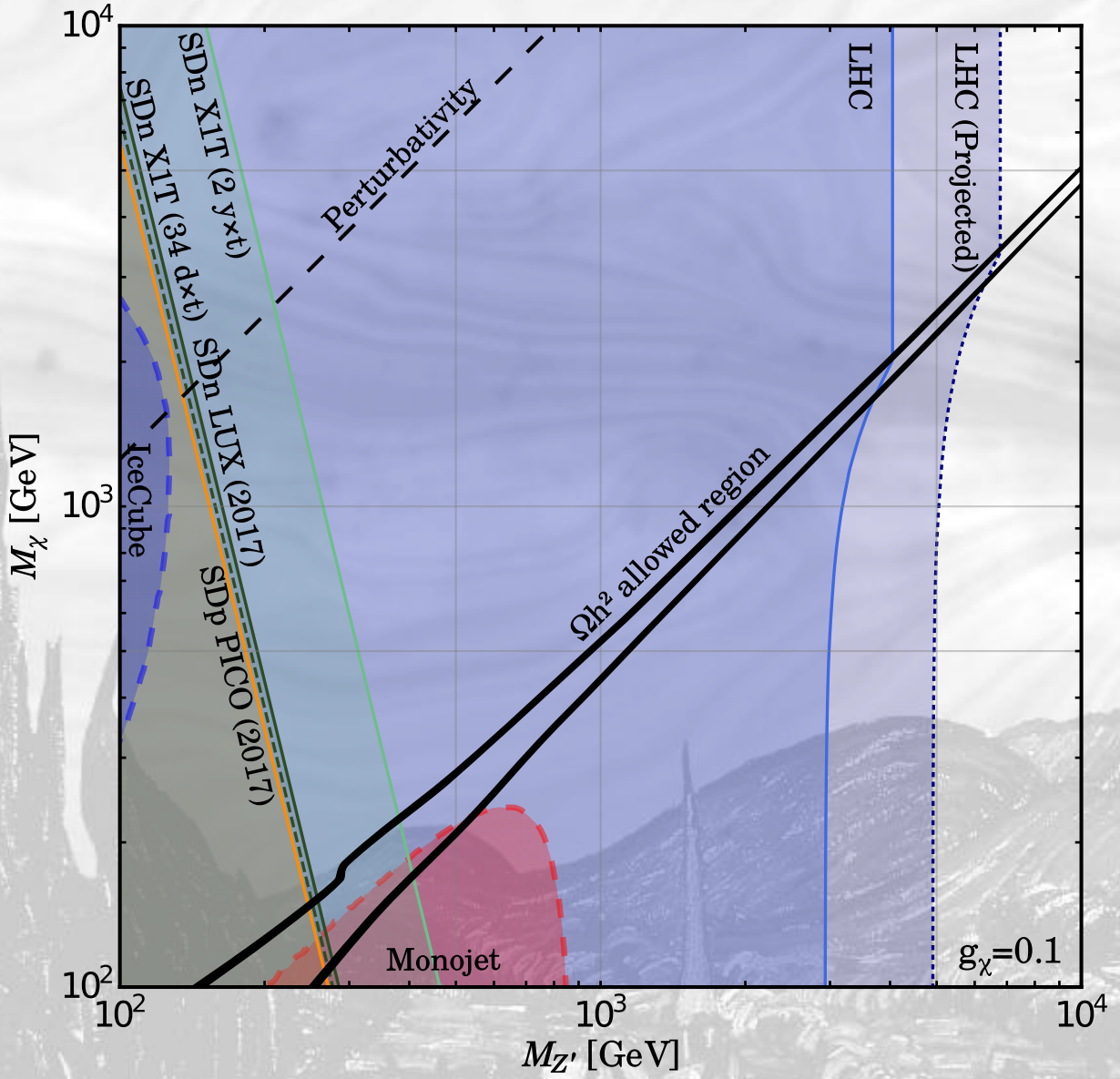
Hence, a limit on the validity of our results can be translated as

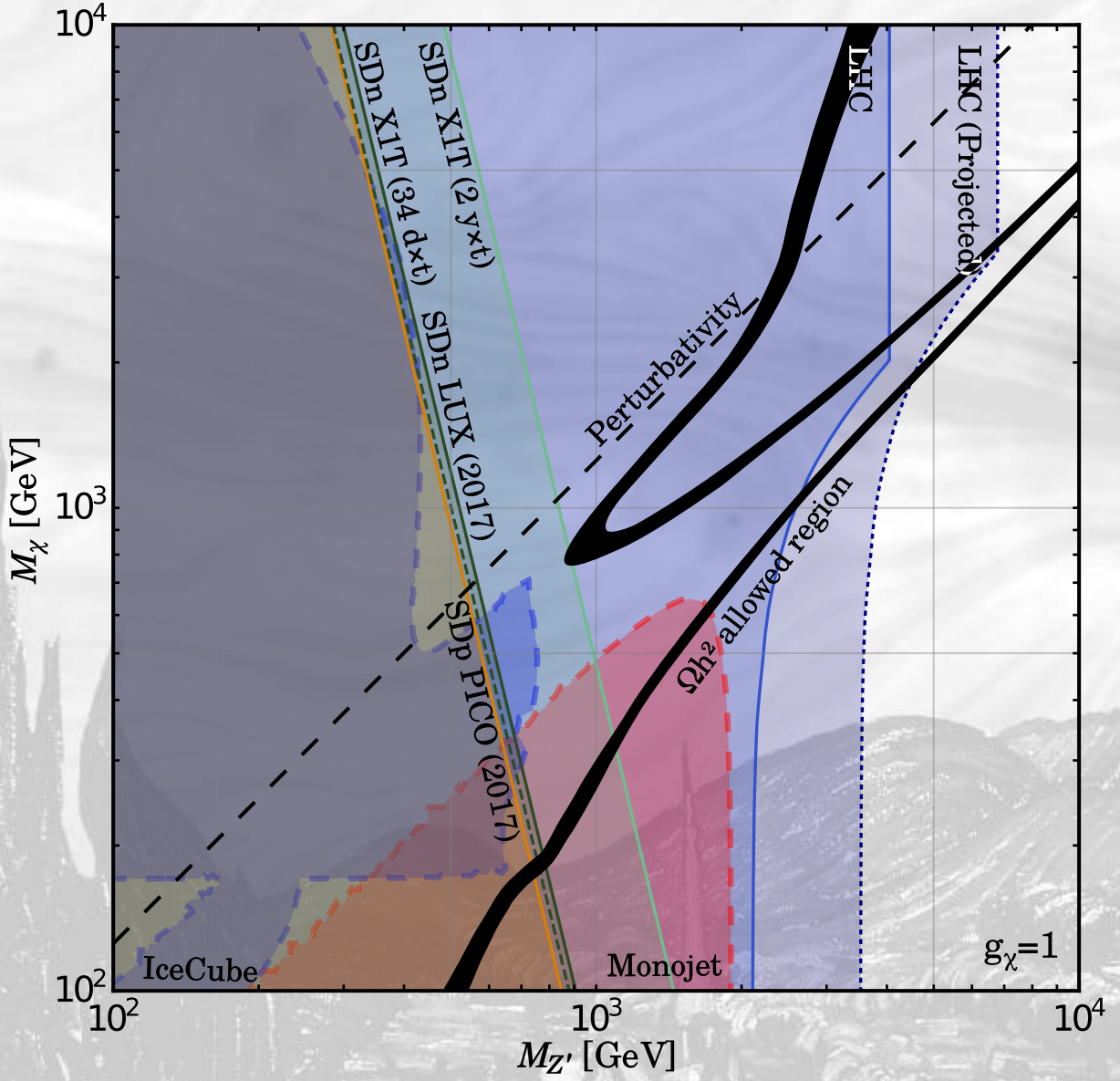
$$M_\chi > \sqrt{\frac{\pi M_{Z'}}{2g_\chi^2}}$$

[F. Kahlhoefer, K. Schmidt-Hoberg, T. Schwetz, and S. Vogl, *JHEP* **02** (2016) 016]

Results


SDn X1T (2 y×t)
SDn X1T (34 d×t)
SDn LUX (2017)
SDp PICO (2017)
IceCube
Perturbativity
LHC
LHC (Projected)
Ωh² allowed region
Monojet
g_χ=0.1
M_χ [GeV]
M_Z' [GeV]
10^2
10^3
10^4

Results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LHC
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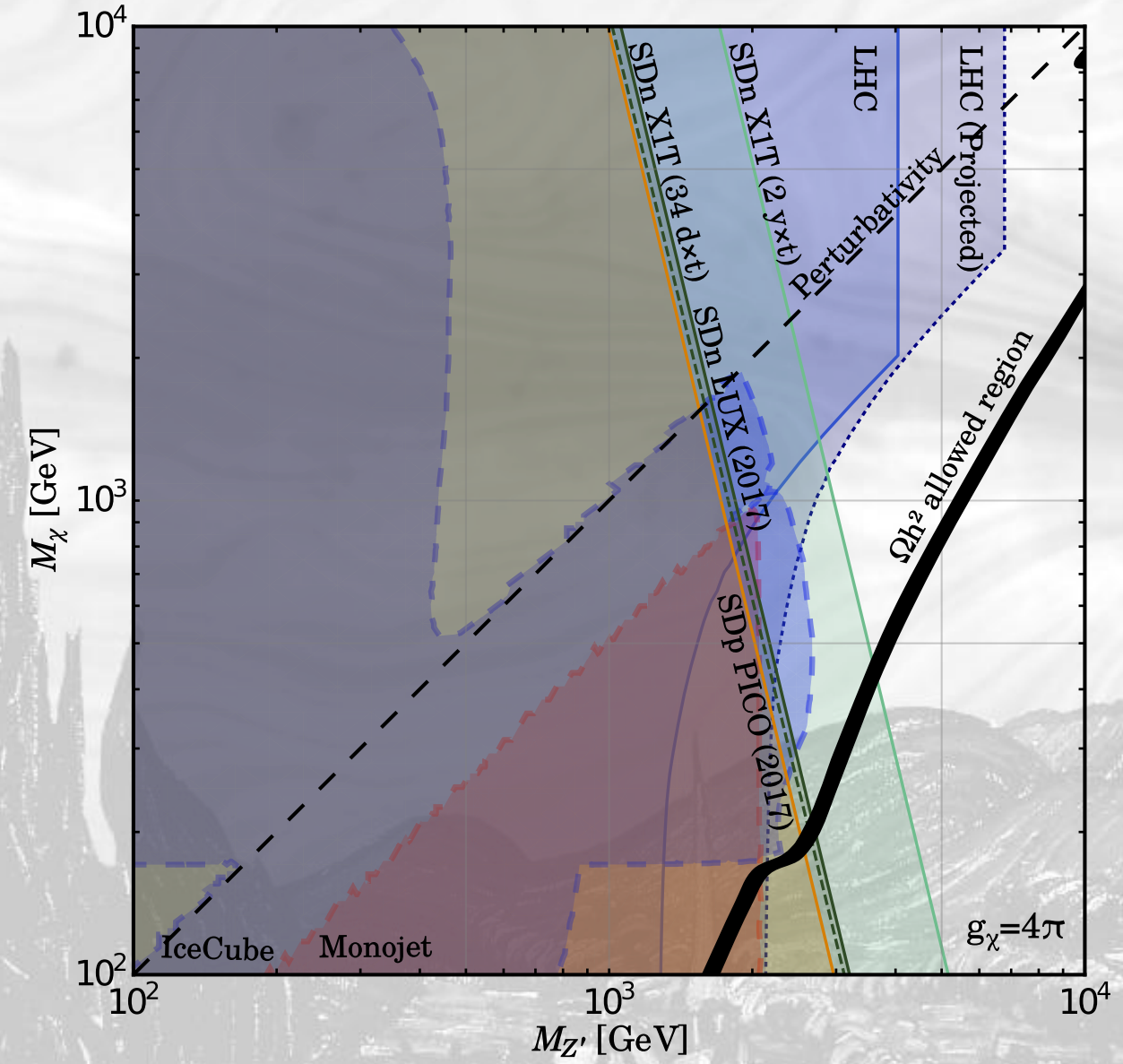
IceCube
Monojet
gχ=1
Mχ [GeV]
MZ' [GeV]
10²
10³
10⁴

Results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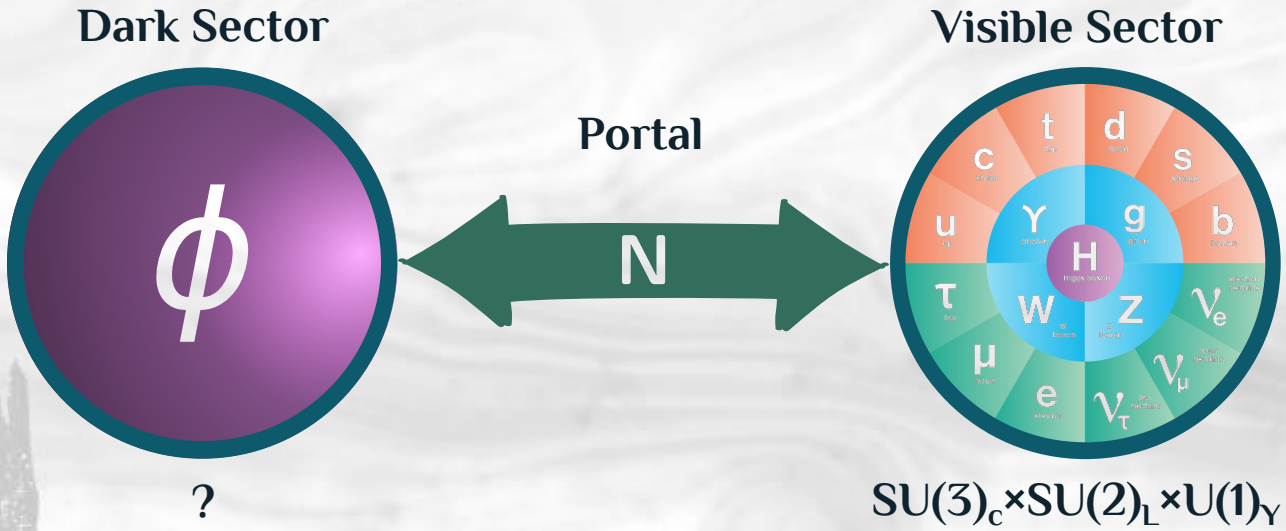
IceCube
Monojet
g_χ=4π
M_χ [GeV]
M_Z' [GeV]
10^2
10^3
10^4

2nd Case of Study

The Neutrino Portal



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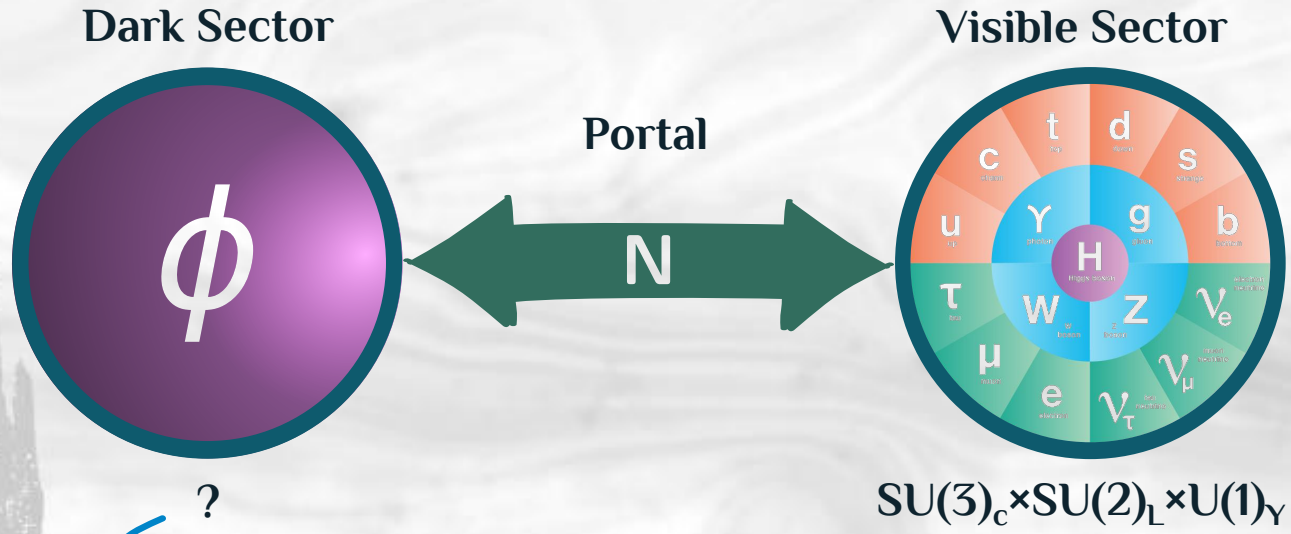
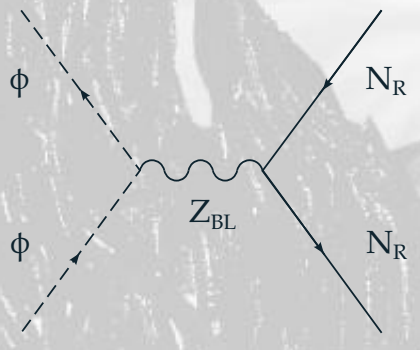


For example $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ with 3 right handed neutrinos to avoid anomalies



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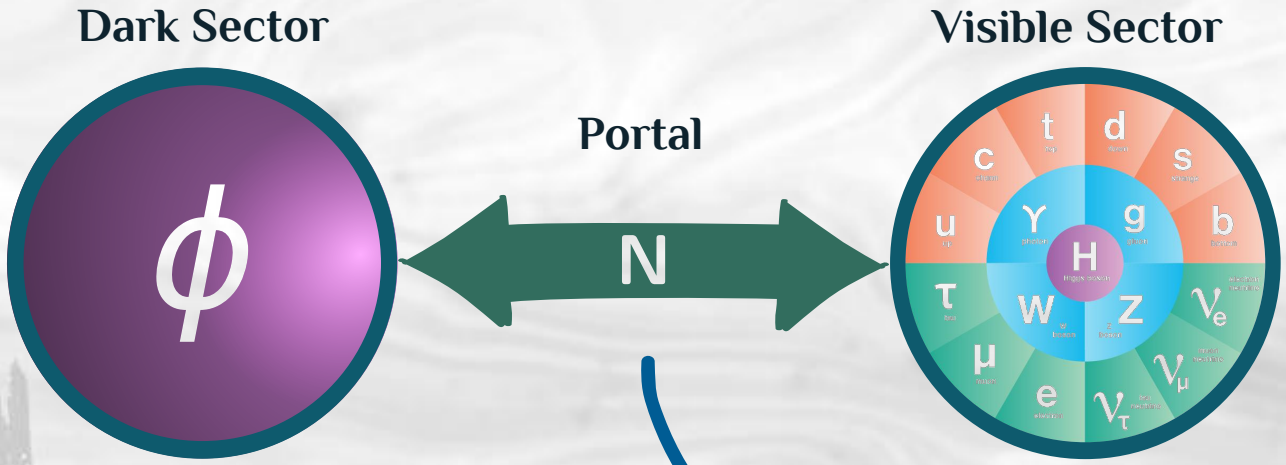
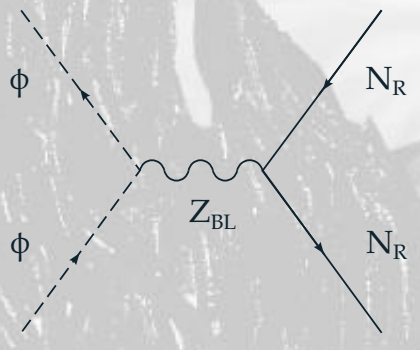
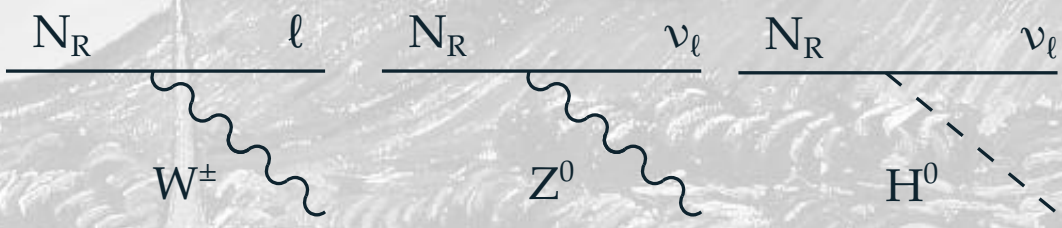


For example $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ with 3 right handed neutrinos to avoid anomalies

⚠ Assumption: Dark matter interacts only with sterile neutrinos, that have seesaw I interactions.

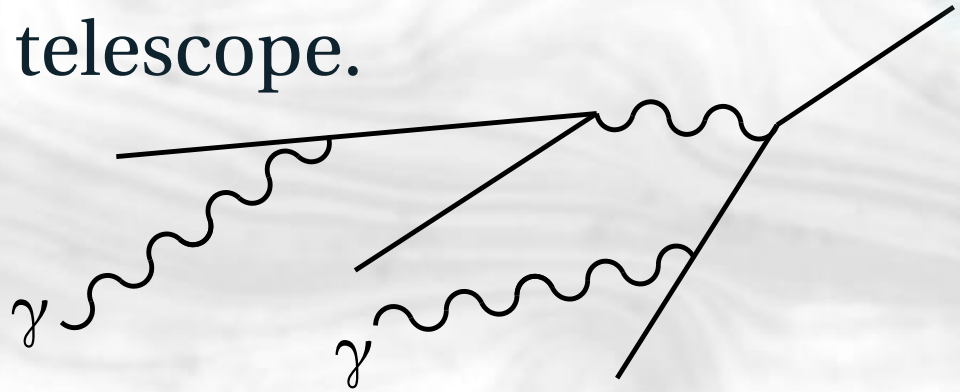




Constraints

Indirect Detection

Fermi-LAT:
Pair-conversion telescope.



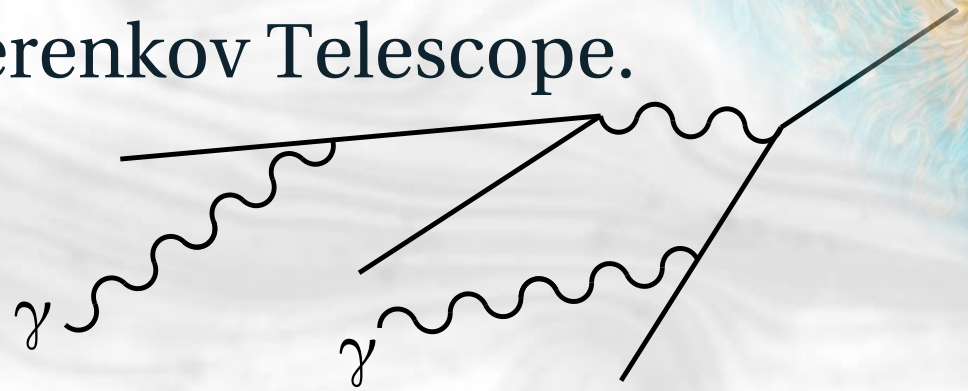
Characteristics:

- Energy range: 20 MeV - 300 GeV
- Effective area: ~ 1 m²
- Field of view: 2.4 sr
- Background: Terrestrial gamma rays, GRBs and solar flares.

Constraints

Indirect Detection

H.E.S.S:
Imaging Air Cherenkov Telescope.



Characteristics:

- Energy range: 200 GeV - 10 TeV
- Effective area: ~ 10^5 m^2
- Field of view: 5 deg
- Background: Cosmic rays, events from the inner band of the GC.

Method

The differential flix (the astro-particle connection)

$$\frac{d\Phi_\gamma(\Delta\Omega)}{dE}(E_\gamma) = \frac{1}{4\pi}\frac{\sigma v}{2M_{DM}^2}\frac{dN_\gamma}{dE_\gamma}\cdot J_{ann}$$

Method

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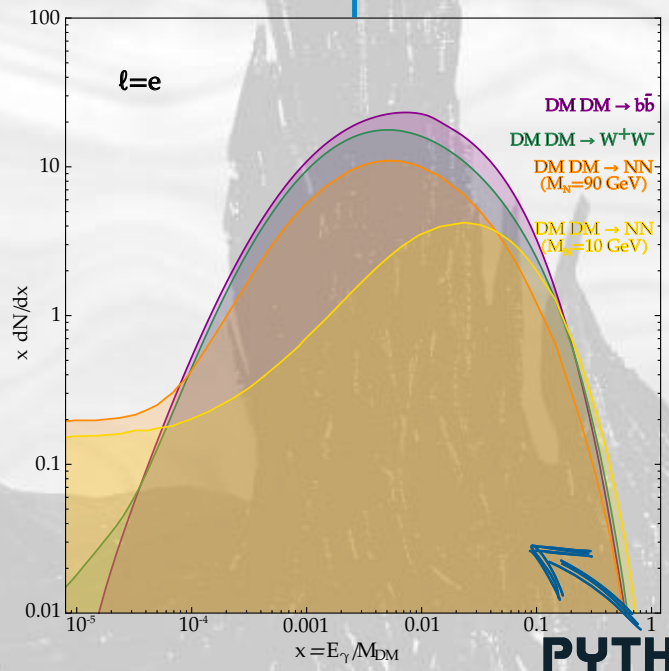
Particle physics



PYTHIA 8.219

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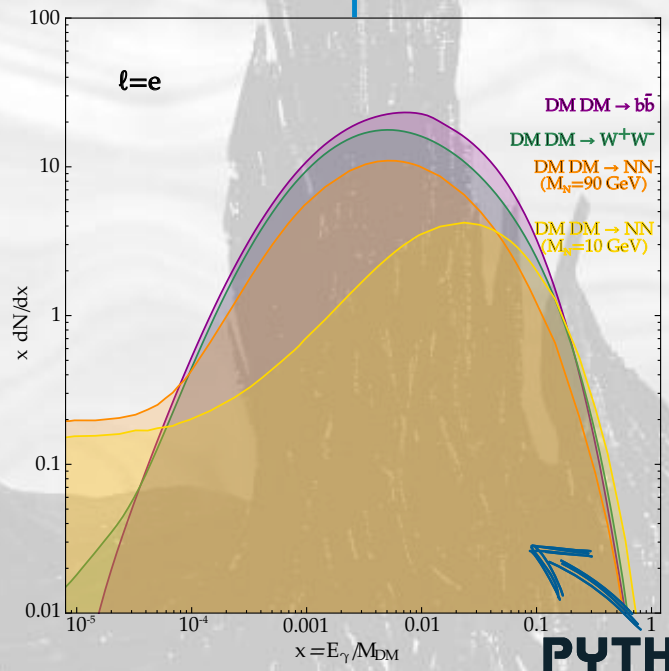
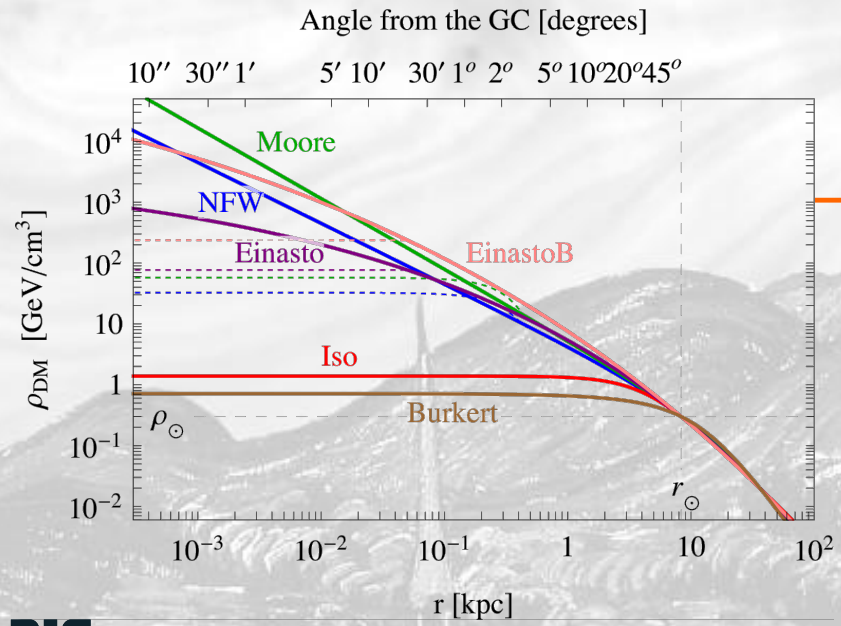
Particle physics

Astrophysics



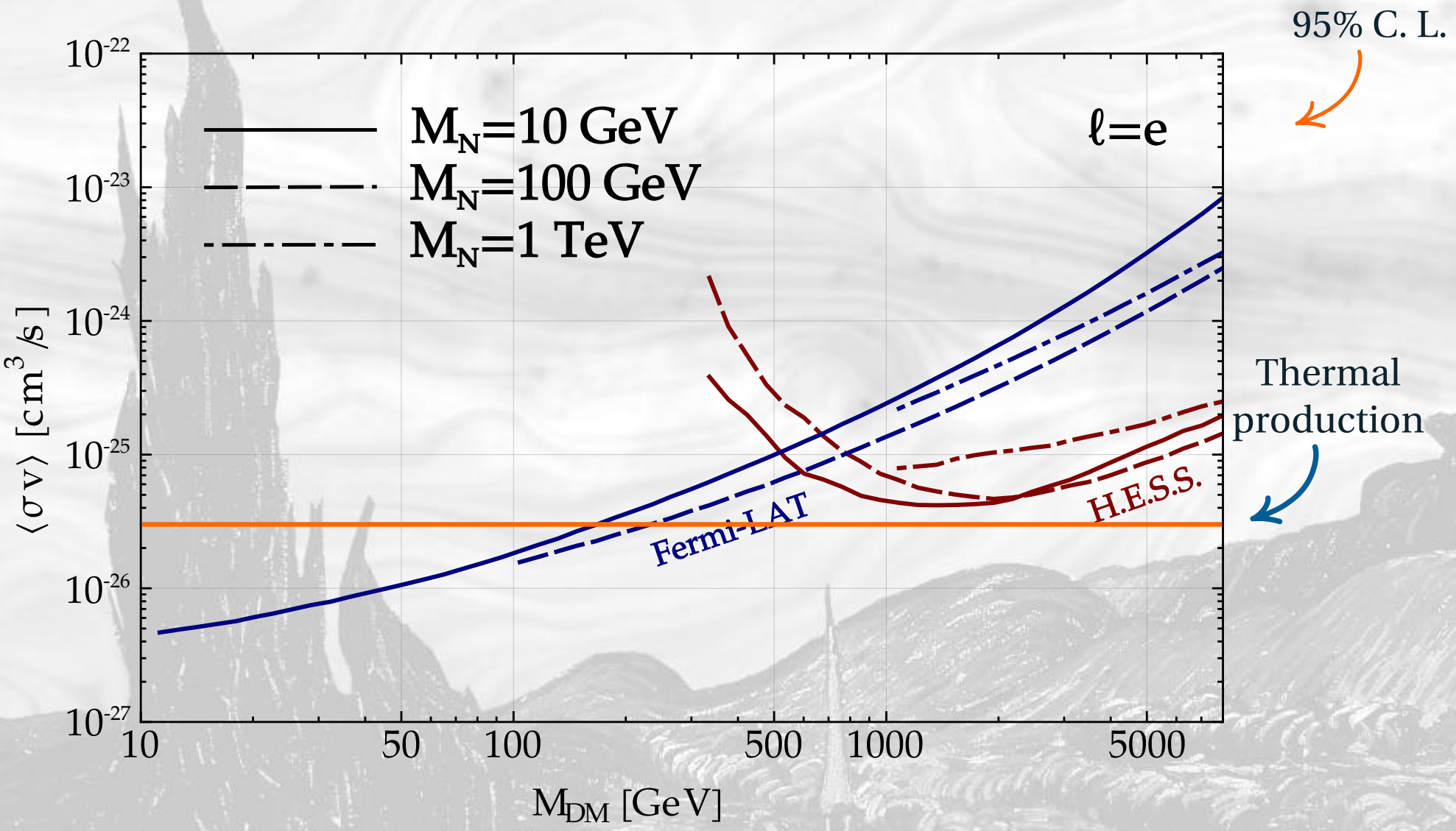
PYTHIA 8.219



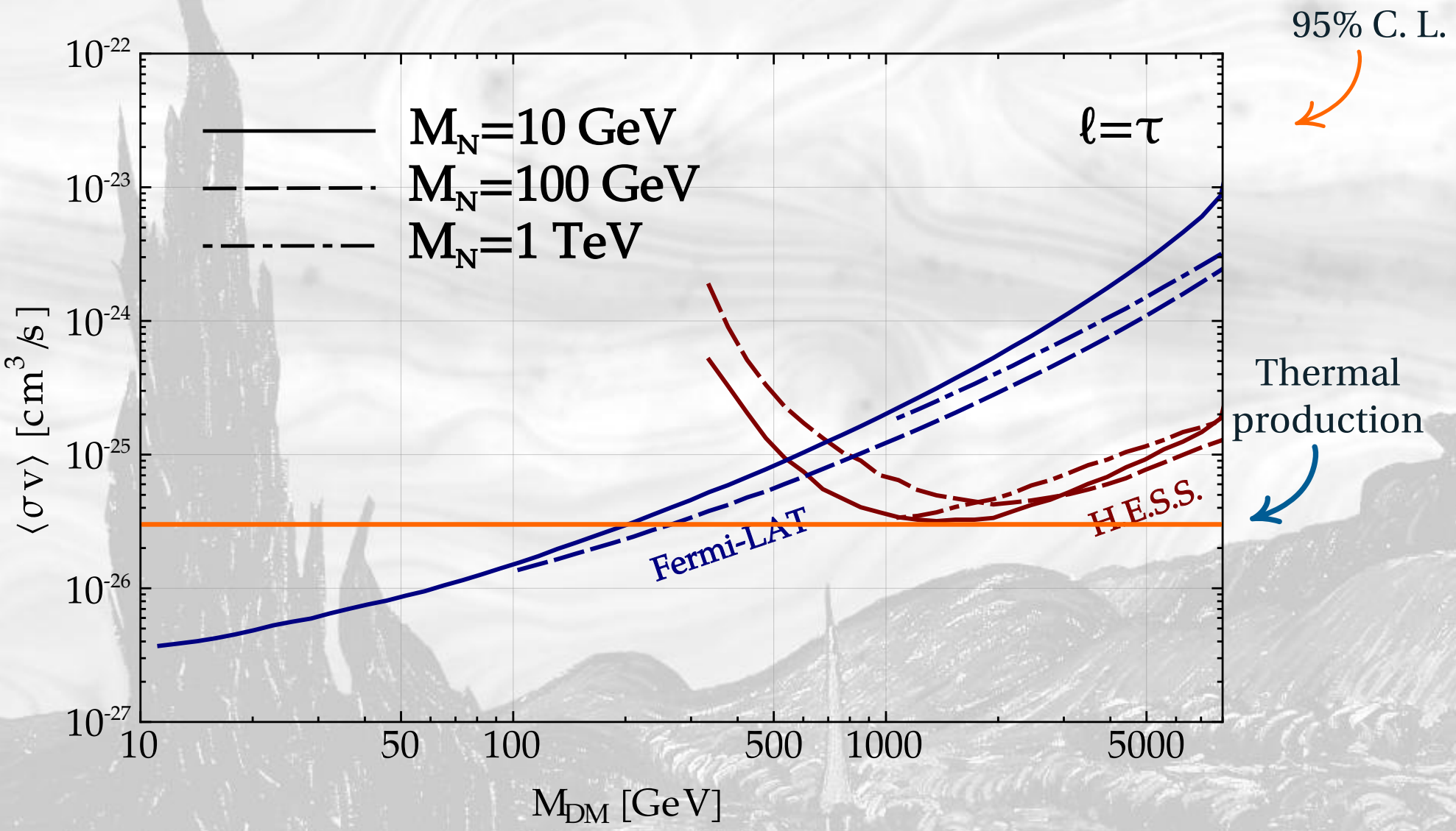
$$J_{ann} = \int_{\Delta\Omega} d\Omega \int \rho_{DM}^2(s)ds$$

[Cirelli, Marco, arXiv:1511.02031v3]

Results


95% C. L.
M_N=10 GeV
M_N=100 GeV
M_N=1 TeV
ℓ=e
Thermal production
Fermi-LAT
H.E.S.S.
$\langle \sigma v \rangle$ [cm^3/s]
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10
50
100
500
1000
5000
M_{DM} [GeV]

Results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Conclusions

We have investigated two different simplified models of dark matter and their phenomenological implications.

The complementarity among the different probes has been assessed, noticing that depending on the characteristics of the model, not all dark matter experiments have the same impact.

In the *Dark Sequential Z' Portal* model we revisited the status of a Majorana fermion as a dark matter particle, and by doing a full experimental scan we outlined the parameter space where this is a successful candidate.

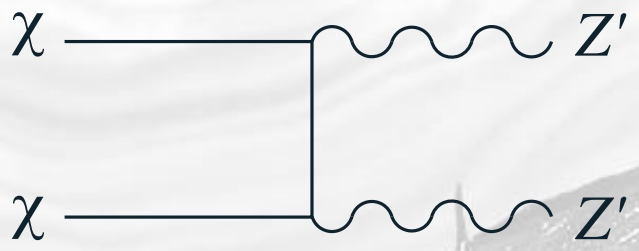
In the *Neutrino Portal* model we concluded that, despite experimentally challenging small mixing angles of the heavy neutrinos, interesting limits can be imposed using indirect detection, ruling out masses up to ~200 GeV for thermally produced dark matter.


Thank you!

Backup Slides

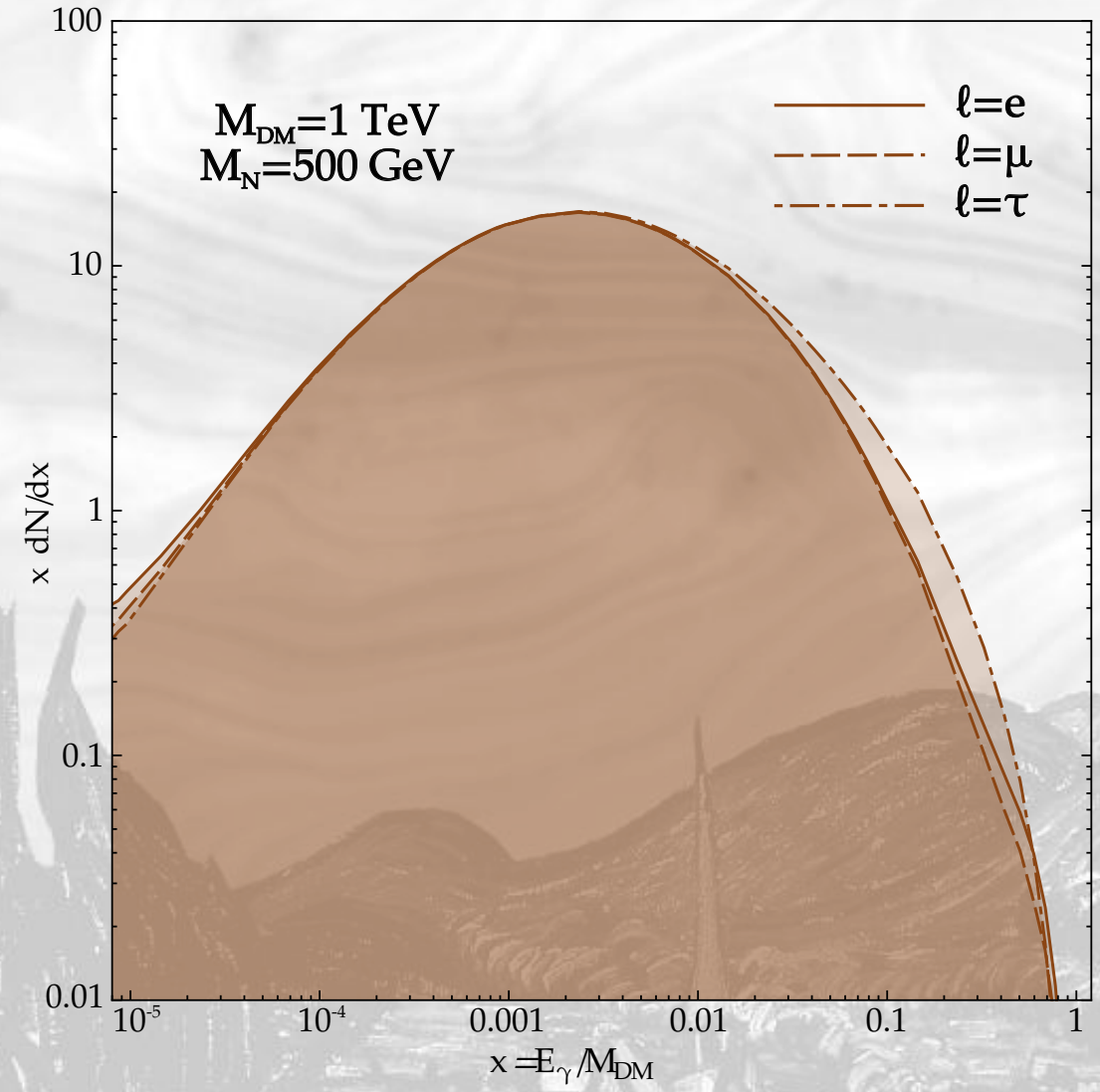
Dark Matter Decay Channels

$$\langle \sigma v \rangle_{Z'Z'} = \frac{g_\chi^4}{\pi m_\chi^2}\left(1-\frac{M_{Z'}^2}{m_\chi^2}\right)^{\frac{3}{2}}\left(1-\frac{M_{Z'}^2}{2m_\chi^2}\right)^{-2}$$
$$+\frac{g_\chi^4 v^2}{3\pi m_\chi^2}\sqrt{1-\frac{M_{Z'}^2}{m_\chi^2}}\left(1-\frac{M_{Z'}^2}{2m_\chi^2}\right)^{-4}\left(\frac{23}{16}\frac{M_{Z'}^6}{m_\chi^6}-\frac{59}{8}\frac{M_{Z'}^4}{m_\chi^4}+\frac{43}{4}\frac{M_{Z'}^2}{m_\chi^2}+2-12\frac{m_\chi^2}{M_{Z'}^2}+8\frac{m_\chi^4}{M_{Z'}^4}\right).$$



Backup Slides

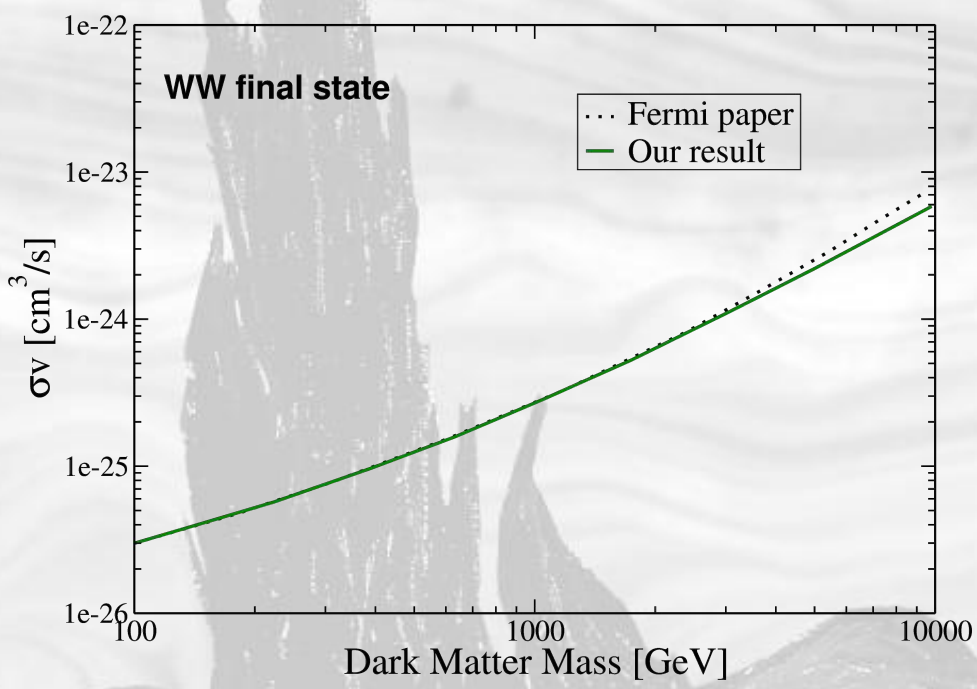
Energy spectrum for different final state leptons



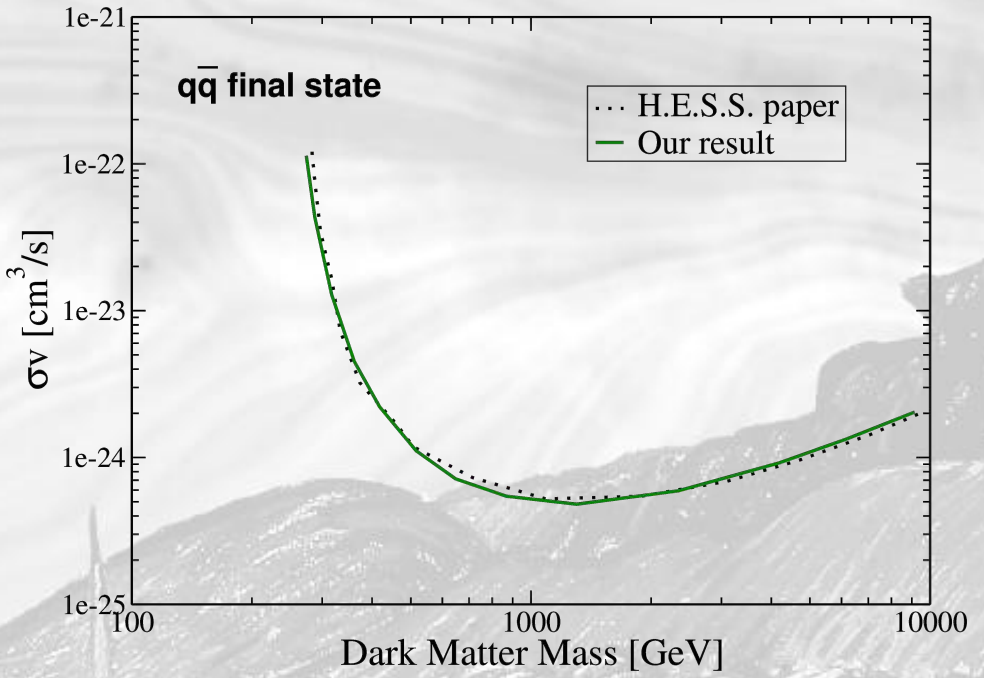
Backup Slides

Reproducing previous results

Fermi-LAT



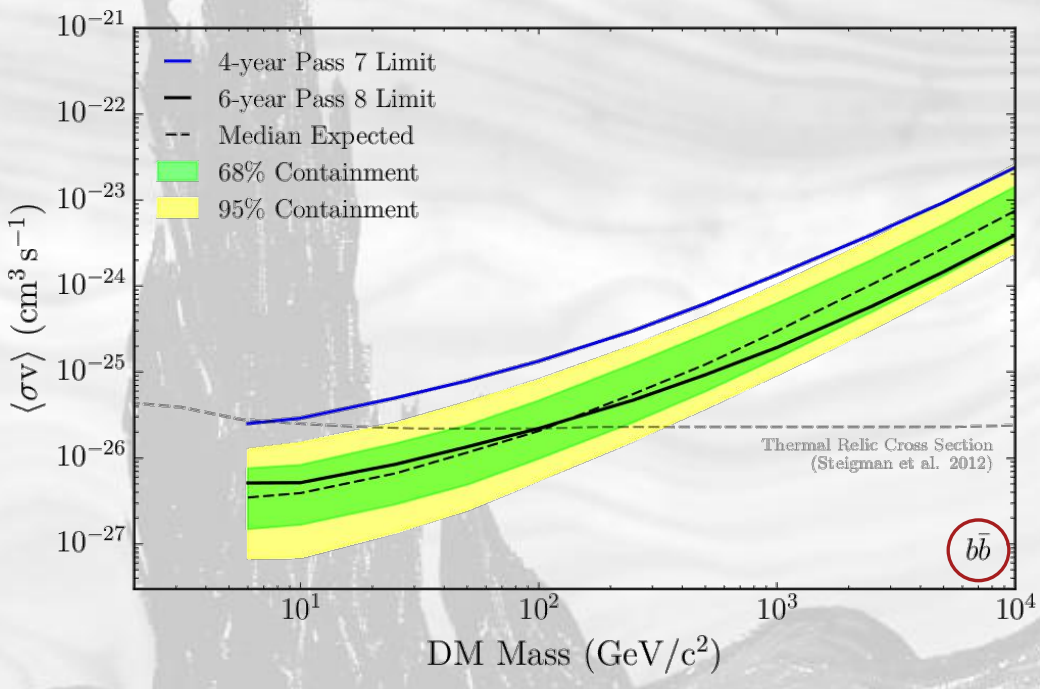
H.E.S.S.



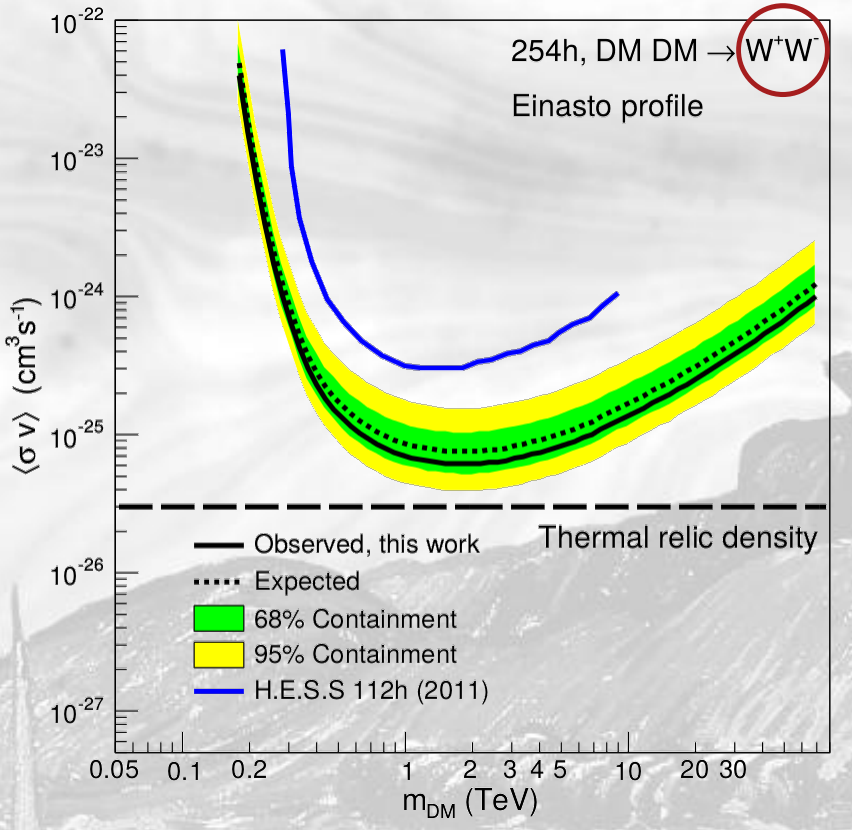
Backup Slides

Comparison with previous results

Fermi-LAT



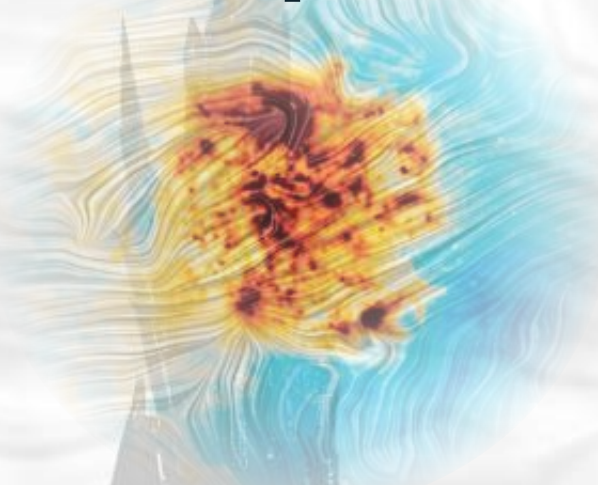
H.E.S.S.



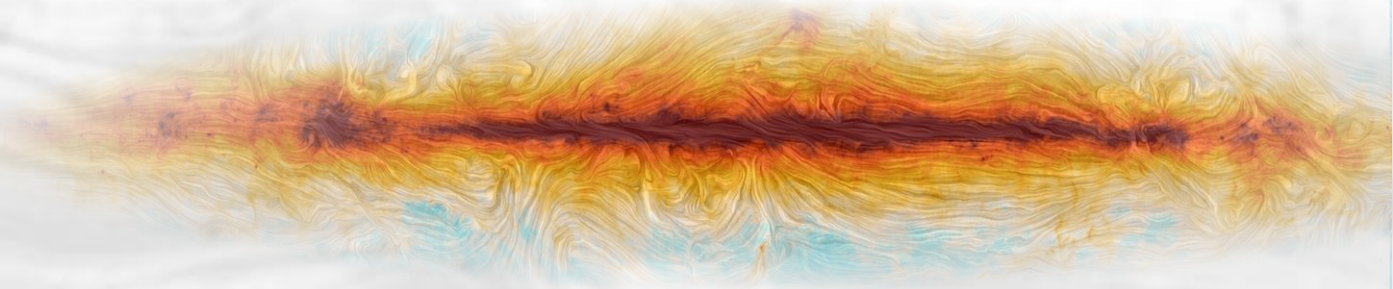
Backup Slides

Comparison between sources

dSphs



GC



Characteristics:

- J-factors ~ 10^{19} GeV^2 cm^{-5}
- Lack of non-thermal astrophysical processes.
- Probe the low-M_{DM} parameter space.

Characteristics:

- J-factors ~ 10^{21} GeV^2 cm^{-5}
- Gamma-ray emission from non-thermal processes makes a bright background.

Backup Slides

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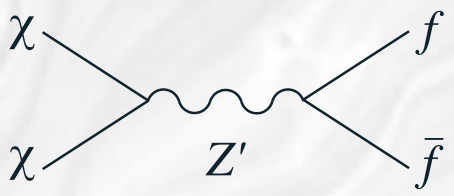
Small Digression

Why not Indirect Detection?



$$\langle \sigma v \rangle_{ff} = \sum_f n_c^f \frac{2\sqrt{m_\chi^2 - m_f^2}}{\pi m_\chi M_{Z'}^4 \left(M_{Z'}^2 - 4m_\chi^2\right)^2} \left[(g_{fa})^2 g_\chi^2 m_f^2 \left(M_{Z'}^2 - 4m_\chi^2\right)^2 \right]$$

$$- \frac{v^2}{6\pi m_\chi M_{Z'}^4 \sqrt{m_\chi^2 - m_f^2} \left(M_{Z'}^2 - 4m_\chi^2\right)^3} \Big[(g_{fa})^2 \left\{ -g_\chi^2 \left(M_{Z'}^2 - 4m_\chi^2\right) \right.$$

$$\times \left(23 m_f^4 M_{Z'}^4 - 192 m_f^2 m_\chi^6 - 4 m_f^2 m_\chi^2 M_{Z'}^2 \left(30 m_f^2 + 7 M_{Z'}^2\right) \right.$$

$$\left. \left. + 8 m_\chi^4 \left(30 m_f^4 + 12 m_f^2 M_{Z'}^2 + M_{Z'}^4\right)\right)\right\}$$

$$+ M_{Z'}^4 (g_{fv})^2 \left\{ 4 g_\chi^2 \left(m_f^4 + m_f^2 m_\chi^2 - 2 m_\chi^4\right) \left(M_{Z'}^2 - 4 m_\chi^2\right) \right\} \Big]$$

Small Digression

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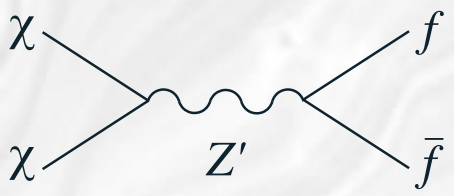

helicity suppressed $\propto \frac{m_f^2}{M_{Z'}^4}$

$$\langle \sigma v \rangle_{ff} = \sum_f n_c^f \frac{2\sqrt{m_\chi^2 - m_f^2}}{\pi m_\chi M_{Z'}^4 \left(M_{Z'}^2 - 4m_\chi^2\right)^2} \left[(g_{fa})^2 g_\chi^2 m_f^2 \left(M_{Z'}^2 - 4m_\chi^2\right)^2 \right]$$

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$$\left. \left. + 8 m_\chi^4 \left(30 m_f^4 + 12 m_f^2 M_{Z'}^2 + M_{Z'}^4\right)\right)\right\}$$
$$+ M_{Z'}^4 (g_{fv})^2 \left\{ 4 g_\chi^2 \left(m_f^4 + m_f^2 m_\chi^2 - 2 m_\chi^4\right) \left(M_{Z'}^2 - 4 m_\chi^2\right) \right\} \Big]$$

velocity suppressed $\propto v^2$