Dark Matter Phenomenology using computational tools

I. Dark matter introduction, basic tools and how to install them

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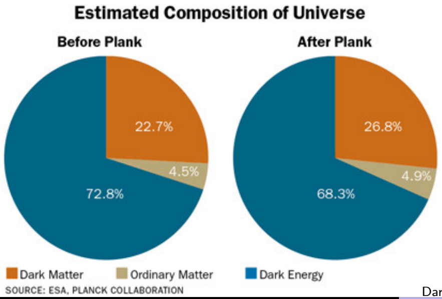
Guideline

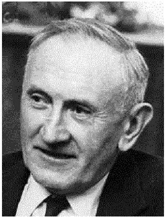
Dark Matter 101

What is Dark Matter?

We called Dark Matter (DM) to the matter that is not visible directly because it doesn't emit or absorb radiation, and the only visible effect is its gravitational effect over celestial objects.

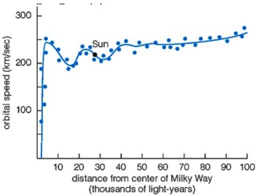
Identify the nature of DM is one of the most interesting problems in modern physics.



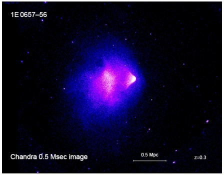


Evidence

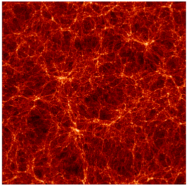
(a) Coma cluster



(b) Rotation curves



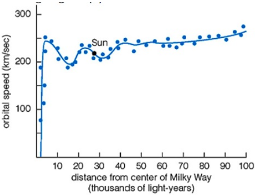
(c) Bullet cluster



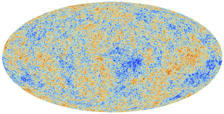
(d) Simulations

Evidence

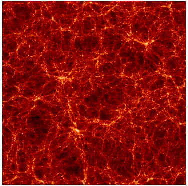
(a) Coma cluster



(b) Rotation curves

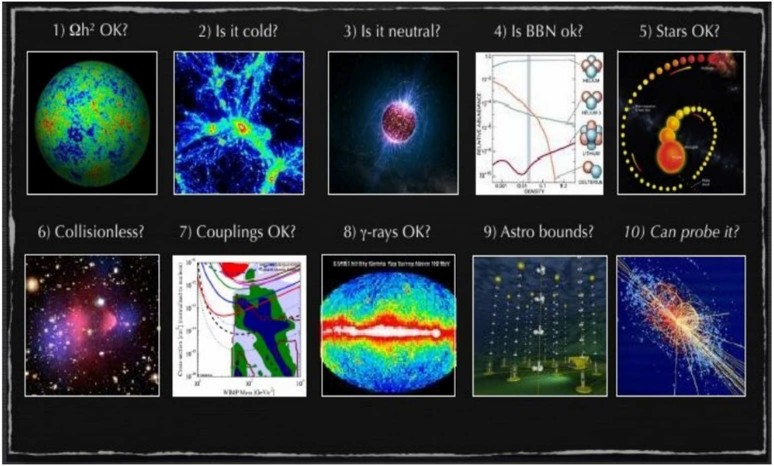


(c) Cosmic Microwave Background



(d) Simulations

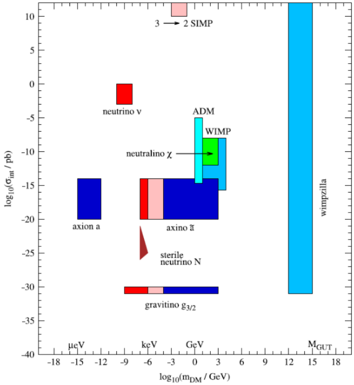
10 Questions for a DM candidate



Gianfranco Bertone, arXiv:0711.4996

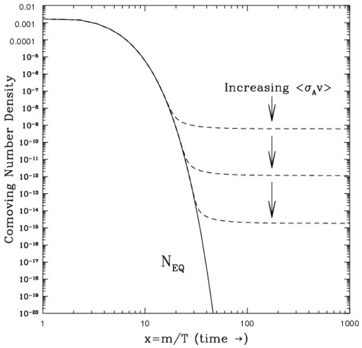
DM Candidates

The possible connection with new physics beyond the SM has stimulated the proliferation of dark matter candidates.



Phys. Rept. 2015, 555, 1

Relic Density

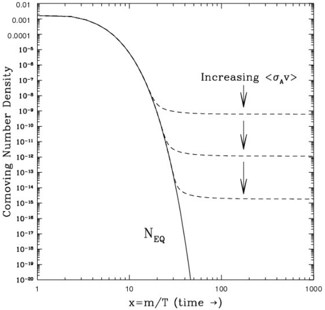


- When the interaction rate of a specie of particles falls down the expansion rate of the Universe, the particle decouple.
- The relic density is the quantity of a certain specie of particles that remains present as a remnant of the Big Bang.

Boltzmann Equation

$$\frac{dn_X}{dt} = -3Hn_X - \langle \sigma v \rangle (n_X^2 - n_{X,eq}^2).$$

Relic Density



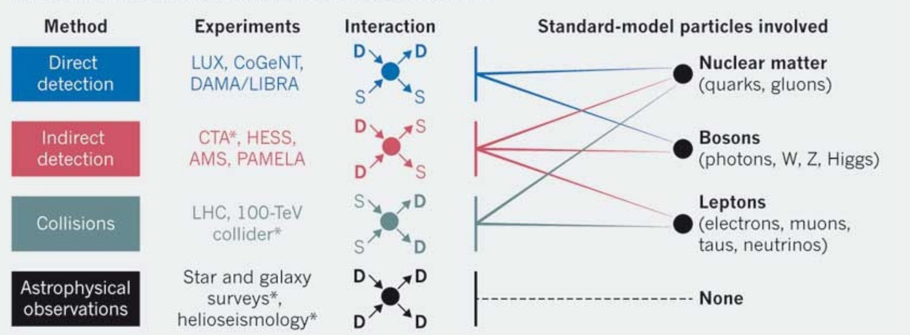
- When the interaction rate of a specie of particles falls down the expansion rate o the Universe, the particle decouple.
- The relic density is the quantity of a certain specie of particle that remains present as a remnant of the Big Bang.

$$\Omega_X h^2 \approx \frac{3\times 10^{-27} cm^3 s^{-1}}{\langle \sigma v \rangle}$$

$$\mathbf{\Omega_X h^2 = 0{,}1198 \pm 0{,}0012}$$

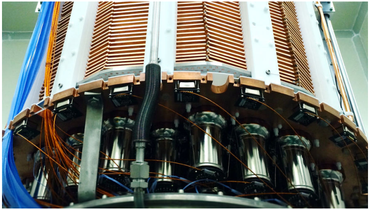
Planck 2018 Results, arXiv:1807.06209

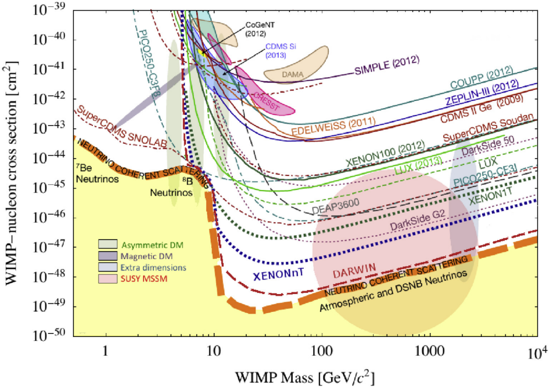
Detection of DM



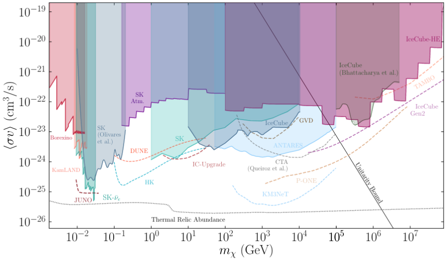
LUX, Large Underground Xenon experiment; CoGeNT, Coherent Germanium Neutrino Technology Dark Matter Experiment; CTA, Cherenkov Telescope Array; HESS, High Energy Stereoscopic System; AMS, Alpha Magnetic Spectrometer; PAMELA, Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics; LHC, Large Hadron Collider. *Planned experiment or observations.

Direct Detection

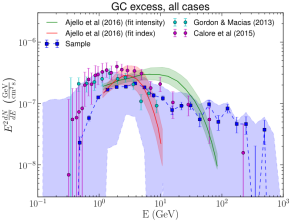


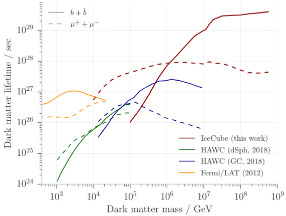


Indirect Detection



arXiv:1912.09486





C. Pérez de los Heros (2020)

Colliders

ATLAS EXPERIMENT

ATLAS NOTE

ATLAS-CONF-2016-070

4th August 2016

CERN

Search for new light resonances decaying to jet pairs and produced in association with a photon or a jet in proton-proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS Collaboration

Abstract

This note describes a search for new resonances decaying to pairs of jets in 15.5 fb^{-1} of proton-proton collisions with a centre-of-mass energy of $\sqrt{s}$ = 13 TeV recorded during 2015 and 2016 by the ATLAS detector at the Large Hadron Collider. The search requires the new resonance to be produced in association with a high-p_T photon or jet, such as those radiated from the colliding partons, in order to efficiently trigger on events containing light resonances. The distribution of the invariant mass of the pair of jets is examined for local excesses above a data-derived estimate of the smoothly falling background. No evidence of anomalous phenomena is observed in the data, which are used to exclude effective cross-sections of processes with Gaussian-shaped contributions to the observed dijet mass distribution and regions of the parameter space of a lepto-phobic axial-vector Z' benchmark model. These results extend limits on light dijet resonances obtained by ATLAS with 2015 data.

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

CERN

Submitted to: Eur. Phys. J. C

CERN-EP-2020-184
19th November 2020

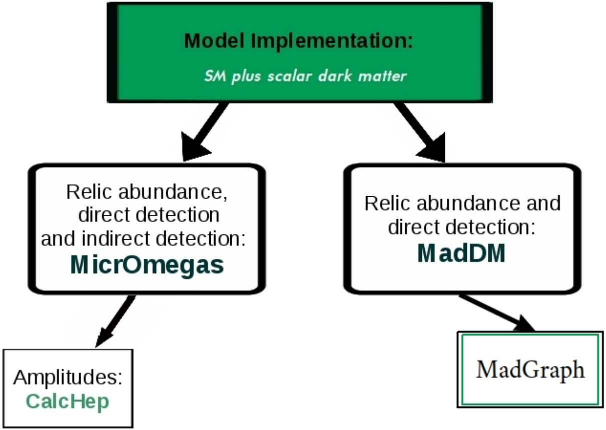
Search for dark matter produced in association with a single top quark in $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector

The ATLAS Collaboration

This paper presents a search for dark matter in the context of a two-Higgs-doublet model together with an additional pseudoscalar mediator, a, which decays into the dark-matter particles. Processes where the pseudoscalar mediator is produced in association with a single top quark in the 2HDM+a model are explored for the first time at the LHC. Several final states which include either one or two charged leptons (electrons or muons) and a significant amount of missing transverse momentum are considered. The analysis is based on proton–proton collision data collected with the ATLAS experiment at $\sqrt{s}$ = 13 TeV during LHC Run 2 (2015–2018), corresponding to an integrated luminosity of 139 fb^{-1}. No significant excess above the Standard Model predictions is found. The results are expressed as 95% confidence-level limits on the parameters of the signal models considered.

Computational Tools

Tools


Model Implementation:
SM plus scalar dark matter
Relic abundance, direct detection and indirect detection:
MicrOmegas
Relic abundance and direct detection:
MadDM
Amplitudes:
CalcHep
MadGraph

Model Implementation

SARAH | FEYNRULES | LANHEP

- FeynRules is a Mathematica package that allows the calculation of Feynman rules.
- The user provide FeynRules with the minimal information required to describe the new model.
- The Feynman rules calculated by the package can be used to implement the NP model into other existing tools as MicrOmegas.

SARAH

- SARAH is a Mathematica package for building and analyzing SUSY and non-SUSY models.
- It calculates all vertices, mass matrices, tadpoles equations, one-loop corrections for tadpoles and self-energies, and two-loop RGEs for a given model.
- SARAH writes model files for FeynArts, CalcHep/CompHep, which can also be used for dark matter studies using MicrOmegas, the UFO format which is supported by MadGraph 5 and for WHIZARD and OMEGA.
- The implementation of new models is efficient and straightforward as in the other model implementation options.

LanHEP

- The LanHEP is a program for Feynman rules generation in momentum representation.
- LanHEP is written on C programming language.
- It was developed since 1994 as a part of CompHEP project to help to create new physical models starting from the Lagrangian.
- LanHEP read input file which describes the physical model by the set of statements.
- THe physical model is defined by the tables of parameters, particles and interaction vertices with explicit Lorentz structure.
- Outputs: LaTeX, FeynArts, CompHEP

To install FeynRules

- VERSION: A INSTALAR: FeynRules 2.3
- AUTHORS: Adam Alloul, Neil D. Christensen, Celine Degrande, Claude Duhr, Benjamin Fuks
- PROGRAMMING LANGUAGE: Mathematica package
- DOWNLOAD: http://feynrules.irmp.ucl.ac.be/
- DATABASE: http://feynrules.irmp.ucl.ac.be/wiki/ModelDatabaseMainPage

MicrOmegas

- Compute the relic density of DM in a generic model of particle physics
- Computes the rates for dark matter direct and indirect detection

```
galletita@galleta: ~/Documents/ProgramasPhysics/micromegas_4.2.5/InerteFR
Dark matter candidate is '~H0' with spin=0/2 mass=5.00E+01

=== MASSES OF HIGGS AND ODD PARTICLES: ===
Higgs masses and widths
PROCESS: h->2*x
PROCESS: W+->2*x
PROCESS: Z->2*x
PROCESS: h->W-,E,ne
Delete diagrams with W+<1
PROCESS: h->Z,ne,Ne
Delete diagrams with Z<1
      h   120.00 1.01E+00

Masses of odd sector Particles:
~H0  : MH0   =    50.0 || ~A0  : MA0   =    60.0 || ~H+  : MHch  =    90.0


==== Calculation of relic density =====
PROCESS: ~H0,~H0->AllEven,1*x{ne,Ne,nm,Nm,nl,Nl,e,E,m,M,l,L,u,U,c,C,t,T,d,D,s,S,b,B,a,Z,W+,W-,g,h
PROCESS: ~H0,~H0->Z,ne,Ne
Delete diagrams with %Z+W<1
PROCESS: ~H0,~H0->W-,E,ne
Delete diagrams with %Z+W<1
PROCESS: ~H0,~A0->AllEven,1*x{ne,Ne,nm,Nm,nl,Nl,e,E,m,M,l,L,u,U,c,C,t,T,d,D,s,S,b,B,a,Z,W+,W-,g,h
PROCESS: ~A0,~A0->AllEven,1*x{ne,Ne,nm,Nm,nl,Nl,e,E,m,M,l,L,u,U,c,C,t,T,d,D,s,S,b,B,a,Z,W+,W-,g,h
Xf=2.71e+01 Omega=2.28e-03
# Channels which contribute to 1/(omega) more than 1%.
# Relative contributions in % are displayed
   86% ~H0 ~H0 ->b B
    7% ~H0 ~H0 ->c C
    5% ~H0 ~H0 ->l L
omega_h^2 = 2.28E-03

==== Indirect detection =======
    Channel          vcs[cm^3/s]
==================================
 annihilation cross section 1.05E-24 cm^3/s
 contribution of processes
  ~H0,~H0 -> b B        8.71E-01
  ~H0,~H0 -> c C        7.08E-02
  ~H0,~H0 -> l L        5.17E-02
  ~H0,~H0 -> W+ W-      5.44E-03
  ~H0,~H0 -> s S        4.92E-04
  ~H0,~H0 -> m M        1.83E-04
Photon flux  for angle of sight f=0.10[rad]
and spherical region described by cone with angle 0.10[rad]
Photon flux = 2.26E-11[cm^2 s GeV]^{-1} for E=25.0[GeV]
Positron flux  =  3.87E-09[cm^2 sr s GeV]^{-1} for E=25.0[GeV]
Antiproton flux  =  1.84E-08[cm^2 sr s GeV]^{-1} for E=25.0[GeV]
```

```
galletita@galleta: ~/Documents/ProgramasPhysics/micromegas_4.2.5/InerteFR
  ~H0,~H0 -> W+ W-      5.44E-03
  ~H0,~H0 -> s S        4.92E-04
  ~H0,~H0 -> m M        1.83E-04
Photon flux  for angle of sight f=0.10[rad]
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Antiproton flux  =  1.84E-08[cm^2 sr s GeV]^{-1} for E=25.0[GeV]

==== Calculation of CDM-nucleons amplitudes  =====
PROCESS: QUARKS,~H0->QUARKS,~H0{u,U,c,C,t,T,d,D,s,S,b,B
Delete diagrams with _S0_!=1,_V5_,a
CDM[antiCDM]-nucleon micrOMEGAs amplitudes for ~H0
proton:  SI  5.174E-08 [5.174E-08]  SD  0.000E+00 [0.000E+00]
neutron: SI  5.156E-08 [5.156E-08]  SD  0.000E+00 [0.000E+00]
CDM[antiCDM]-nucleon cross sections[pb]:
 proton  SI 1.128E-06 [1.128E-06] SD 0.000E+00 [0.000E+00]
 neutron SI 1.120E-06 [1.120E-06] SD 0.000E+00 [0.000E+00]

===============Neutrino Telescope=======  for  Sun
 E>1.0E+00 GeV neutrino flux       2.30E+12 [1/Year/km^2]
 E>1.0E+00 GeV anti-neutrino flux  2.18E+12 [1/Year/km^2]
 E>1.0E+00 GeV Upward muon flux    2.91E+02 [1/Year/km^2]
 E>1.0E+00 GeV Contained muon flux 1.33E+04 [1/Year/km^3]

h :   total width=1.005367E+00
 and Branchings:
5.197487E-05 h -> Z,Z
4.896016E-04 h -> W+,W-
8.752175E-07 h -> m,M
2.470423E-04 h -> l,L
3.382137E-04 h -> c,C
2.350107E-06 h -> s,S
4.173728E-03 h -> b,B
1.575421E-24 h -> g,g
9.946963E-01 h -> ~H0,~H0

W+ :   total width=2.013035E+00
 and Branchings:
1.109842E-01 W+ -> ne,E
1.109839E-01 W+ -> nm,M
1.109020E-01 W+ -> nl,L
3.160457E-01 W+ -> u,D
1.687810E-02 W+ -> c,D
1.690255E-02 W+ -> u,S
3.154001E-01 W+ -> c,S
1.354453E-05 W+ -> u,B
1.890064E-03 W+ -> c,B
galletita@galleta:~/Documents/ProgramasPhysics/micromegas_4.2.5/InerteFR$
```

arXiv:1407.6129

To install

- VERSION A INSTALAR: micromegas-5.2.7
- AUTHORS: Genevieve Belanger, Fawzi Boudjema, Alexander Pukhov y Andrei Semenov
- PROGRAMMING LANGUAGE: C y Fortran
- DOWNLOAD: https://lapth.cnrs.fr/micromegas/

MadDM

- MadDM is able to calculate the dark matter relic abundance in generic models which include a multi-component dark sector, resonance annihilation channels and co-annihilations.
- MadDM aims to bridge the gap between collider oriented event generators and dark matter physics tools.
- The direct detection module calculates spin independent and spin dependent dark matter-nucleon cross sections and differential recoil rates as a function of recoil energy, angle and time.
- Also provides a simplified simulation of detector effects for a wide range of target materials and volumes.

arXiv:1308.4955

MadGraph

- MadGraph is very popular among theorists and experimentalists alike as it contains all the elements necessary for SM and BSM phenomenology, such as the computations of cross sections, the generation of hard events and their matching with event generators, and the use of a variety of tools relevant to event manipulation and analysis.
- New models with complex DM processes can be easily calculated in the MadGraph framework.
- The files needed to run a particular model are given by Feynrules.
- Cross check with other programs.

arXiv:1308.4955

To install: First MadGraph 5

- VERSION: MG5-3.2.0
- AUTHORS: J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torrielli, M. Zaro
- REQUIREMENTS: Python version 2.7 or 3.7 (or higher) and gfortran/gcc 4.6 or higher
- DOWNLOAD: http://madgraph.phys.ucl.ac.be/

To install MadDM

- VERSION: maddm-3.1
- AUTHORS: Mihailo Backovic, Kyoungchul Kong, Fabio Maltoni, Olivier Mattelaer, Antony Martini and Gopolang Mohlabeng
- PROGRAMMING LANGUAGE: Phyton and Fortran
- DOWNLOAD: https://launchpad.net/maddm

MadDM

```
=====================================================
|                  MadDM v2.0                       |
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Basics tutorial:  susy.phsx.ku.edu/~mihailo

Launchpad:  launchpad.net/maddm

arXiv:1308.4955
arXiv:1505.04190

Enter model name (press Enter to list the available models): InerteFR
Enter project name (InerteFR): ProjectOne
Calculate relic density? [y] (y/n)y
Calculate direct detection cross sections? [y] (y/n)n
Enter DM candidate (press Enter to automatically find the DM candidate):
 (Enter 'particles' to see a list of particles)
 *** Exclude particles via the standard MG "/" notation
```
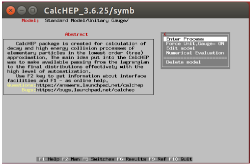
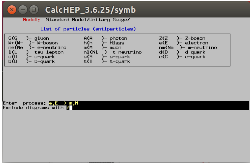
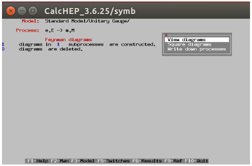

```
Would you like to edit the default param_card?[n] (y/n):
(or enter the location of param_card to be used)
n
------------------------------
DARK MATTER CANDIDATE:
------------------------------
{
    'name': '~H0',
    'antiname': '~H0',
    'spin': 1,
    'color': 1,
    'charge': 0.00,
    'mass': 'mdl_MH0',
    'width': 'mdl_WH0',
    'pdg_code': 35,
    'line': 'dashed',
    'propagator': '',
    'is_part': True,
    'self_antipart': True,
    'type': '',
    'counterterm': {}
}
Enter the coannihilation particles:
(press Enter to automatically find the coannihilation particles)
(Enter 'particles' to see a list of particles)

Enter the mass difference ratio desired for coannihilating particles [0.1]:
(Enter 0 for no coannihilating particles)

------ Generating Diagrams ------
Trying DM_particle1 DM_particle1 > fs_particles fs_particles QED=4 SIEFFS=0 SIEFFF=0 SIEFFV=0 SDEFFF=0 SDEFFV=0
 Done!
```

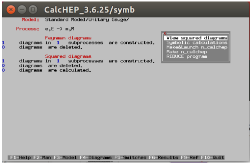
CalcHEP

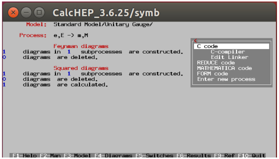
- This is a package for the automatic calculation of elementary particle collisions and decays in the lowest order of perturbation theory.
- Provides an interactive environment where the user can pass from the Lagrangian to the final distributions effectively with a high level of automation.











The interactive session of CalcHEP enables the user to:

- Load a model and calculate its dependent parameters
- Choose between Feynman and unitary gauge and calculate decay widths and branching ratios by specifying the incoming and out-going particles, allowing us to remove particular diagrams from the calculation
- Generate and display Feynman diagrams and the squared ones and also the Latex output for them
- Calculate analytic expressions for the squared diagrams using the built-in symbolic calculator and export the results to different formats for further symbolic manipulations in those packages

arXiv:hep-ph/9908288

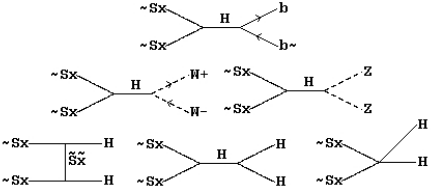
To install

- VERSION: calchep-3.8.10
- AUTHORS: Alexander Pukhov, Alexander Belyaev, Neil Christensen
- PROGRAMMING LANGUAGE: C and Fortran
- DOWNLOAD: http://theory.sinp.msu.ru/ pukhov/calchep.html

Simplest Model

Model: SM plus extra DM scalar

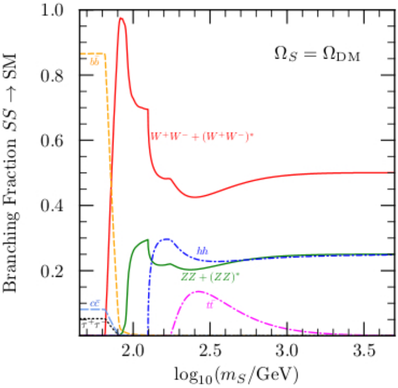
The most simple SM extension. It is called the Higgs Portal due to all annihilation processes of DM particle involve a Higgs boson.

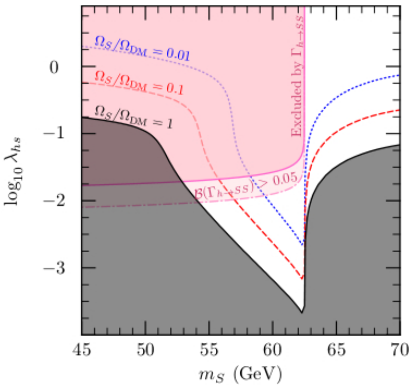


The Lagrangian with symmetry Z_2 that warranties the stability of the DM candidate is

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\mu_S^2 S^2 - \lambda_p S^2 H^\dagger H - \frac{1}{2}\lambda_S S^4$$

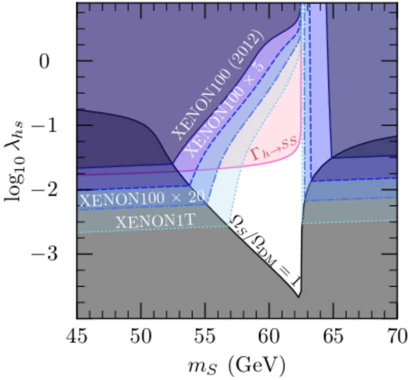
What do we want to reproduce in a first exercise?

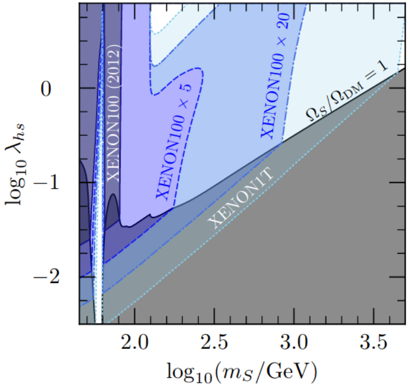




Cline and Scott, arXiv:1306.4710

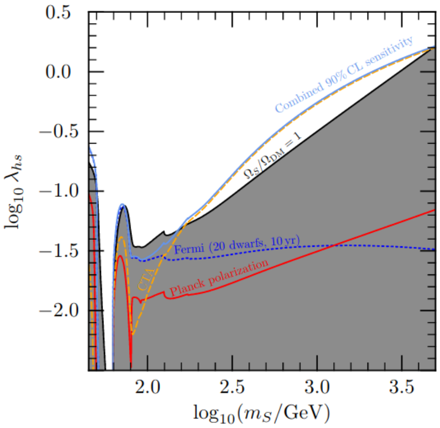
Direct Detection





Cline and Scott, arXiv:1306.4710

Indirect Detection



Cline and Scott, arXiv:1306.4710

Thank you for your attention.