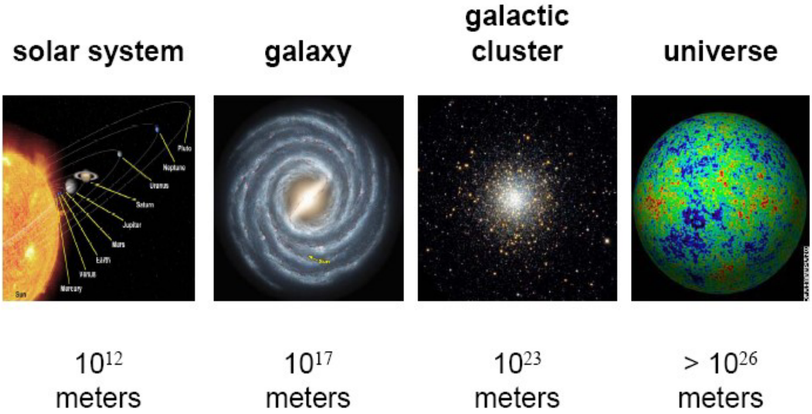
Dark Matter Working Group

Fawzi BOUDJEMA for the DM Working Group

boudjema@lapth.cnrs.fr

DM “seen" on many different scales

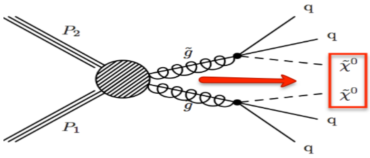


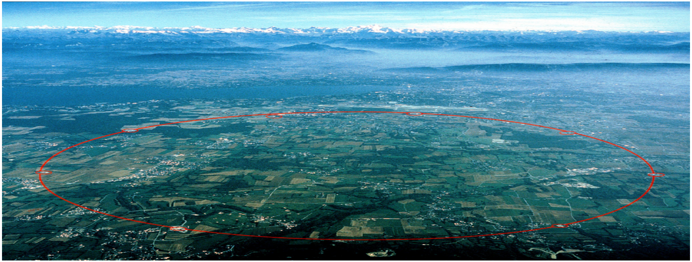
In our neighbourhood, search: Direct Detection

Galaxy, extragalactic: in indirect detection

Universe: relic density

And may be created at the LHC





DM: What is it? Properties

Microscopic Level: interaction, couplings, masses $\Longrightarrow$ We don't know

Macroscopic level: How is it distributed? $\Longrightarrow$ We don't know *really*, but we somehow know

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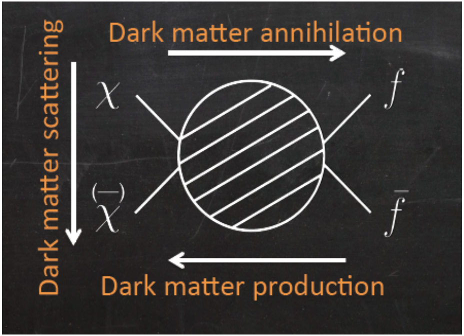
Apart from being

- NEUTRAL
- STABLE
- other properties, see later

Searches for DM, f any standard model particle



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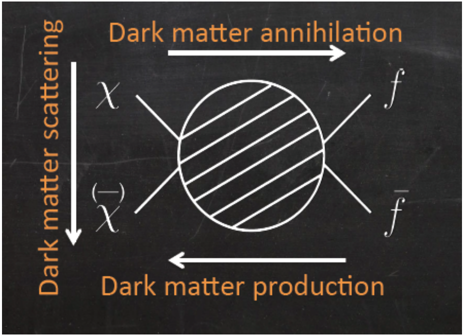

What do we need to know, to predict these observables?

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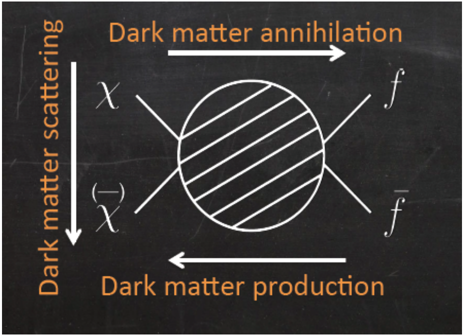

σv

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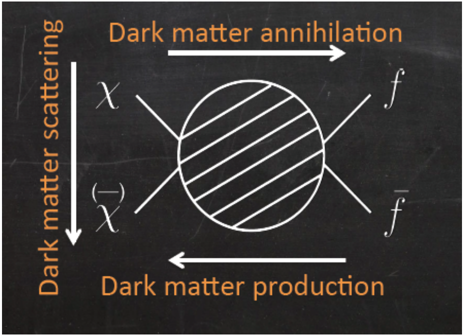
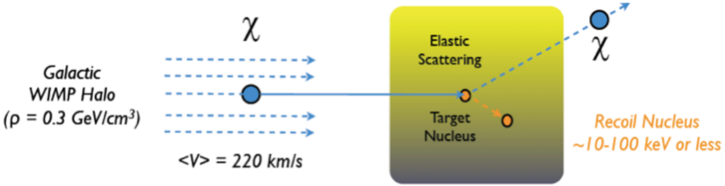


density of these DM: flux

Direct Detection: What is it and what's at stake, 1



Elastic Scattering of WIMPs off nuclei in a large underground detector

Measure nuclear recoil energy E_R

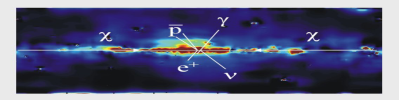
Need to go from $\chi q(g) \to \chi q(g)$ **TO** $\chi N \to \chi N$ **TO** $\chi \mathcal{N} \to \chi \mathcal{N}$

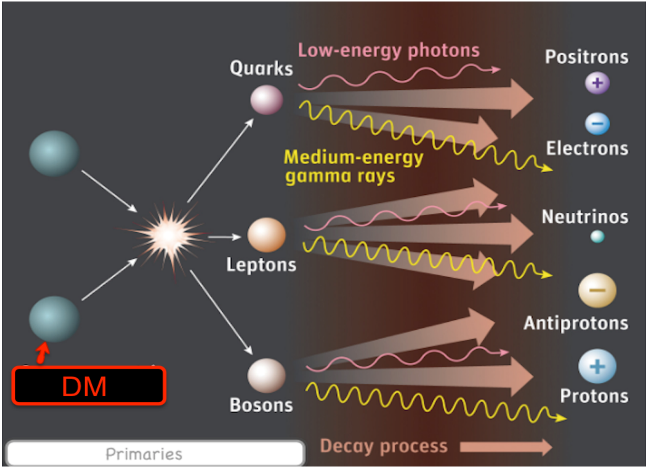
Interaction Rate

(Counts/keV/kg/day)

$$\frac{dR}{dE_R} = \underbrace{\frac{\sigma_{\chi N}}{m_\chi}}_{\text{particle theory}} \times \underbrace{\frac{F^2(E_R)}{\mu^2_{\chi\mathcal{N}}}}_{\text{Nuclear}} \times \underbrace{\frac{\rho_0 T(E_R)}{v\sqrt{\pi}}}_{\text{Properties of DM halo}}$$

Indirect Detection



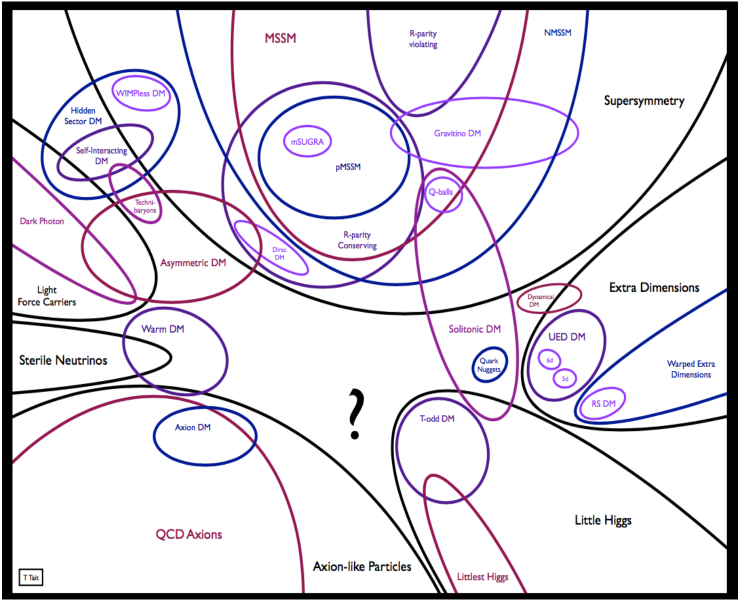


At Colliders

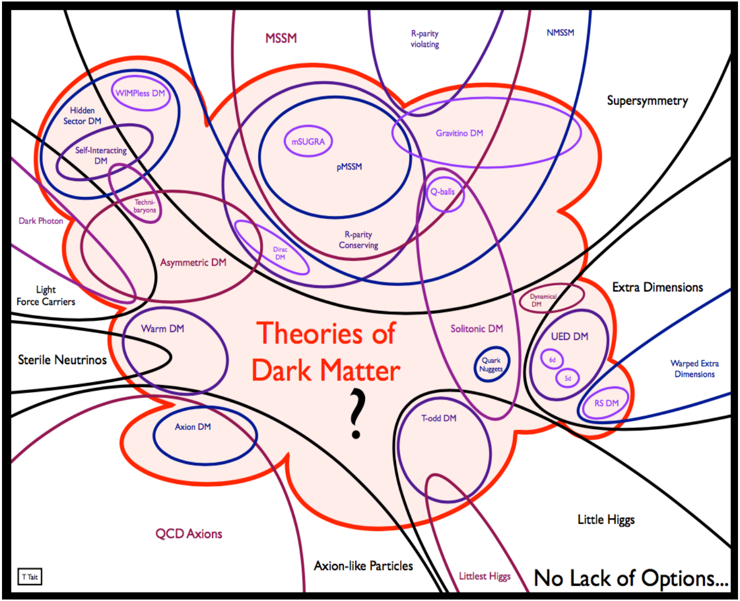
We are more in control !

provided we know

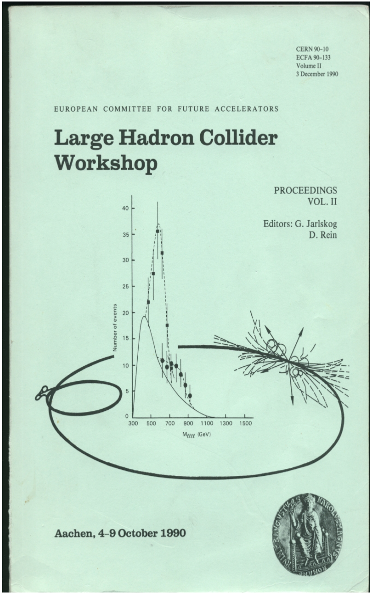
The other big unknown! New Physics Models from Tim Tait

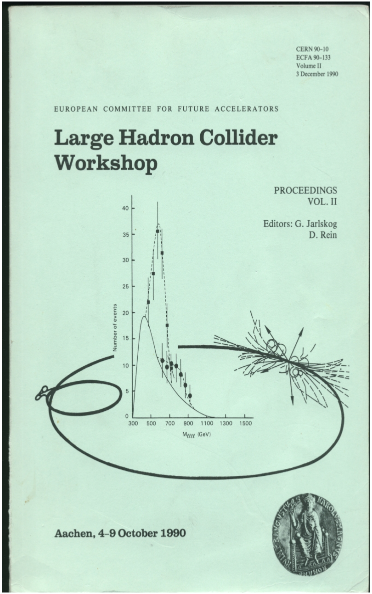


New Physics Models/DM from Tm Tait



LHC Dark Matter Connection is new: The new paradigm the Aachen Proceedings





- No mention of a connection between the LHC and Dark Matter, despite a SUSY WG.

There is a mention of LSP to be stable/neutral because of cosmo reason, but no attempt at identifying it or **weighing the universe at the LHC**

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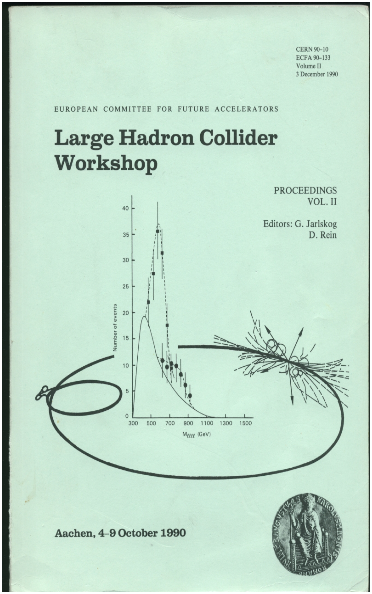

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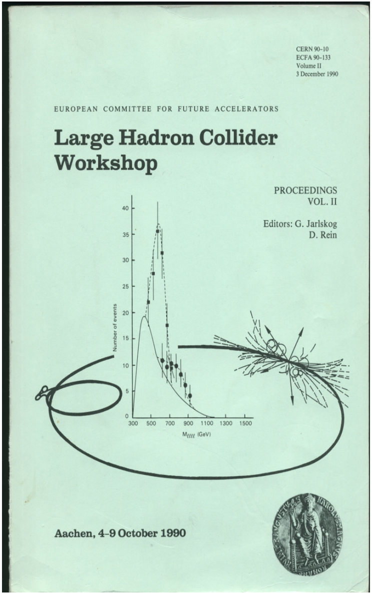

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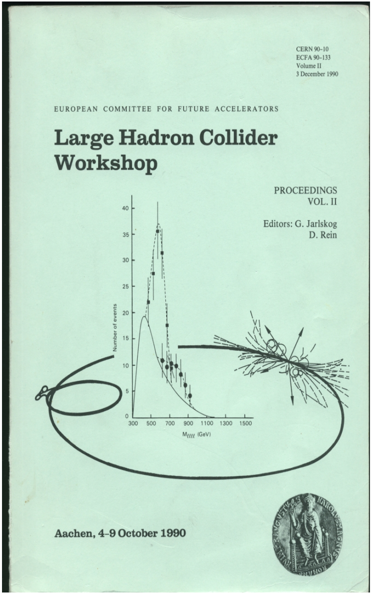

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• New Paradigm, Particle Physics to match the precision of recent cosmological measurements

A somehow new shift in the paradigm, after the LHC results and Higgs discovery

Murayama 2017

sociology

- Particle physicists used to think
  - need to solve problems with the SM
  - hierarchy problem, strong CP, etc
  - it is great if a solution also gives dark matter candidate as an *option*
  - big ideas: supersymmetry, extra dim
  - probably because dark matter problem was not so established in 80's

A somehow new shift in the paradigm, after the LHC results

recent thinking

- dark matter definitely exists
  - hierarchy problem may be optional?
- need to explain dark matter on its own
- perhaps we should decouple these two
- do we really need big ideas like SUSY?
- perhaps we can solve it with ideas more familiar to us?

Warm *vs* Cold DM: Kinetic decoupling, seeds of matter

- After the number of DM particles has frozen up, there is no longer any equilibrium in the number density but $\chi f \to \chi f$ can still occur and DM velocity distribution is still in Equilibrium with that of the plasma.

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- For WDM kinetic decoupling occurs earlier characterised by larger thermal velocities, inhibiting the clumping of DM on mass scales of dwarf galaxies.

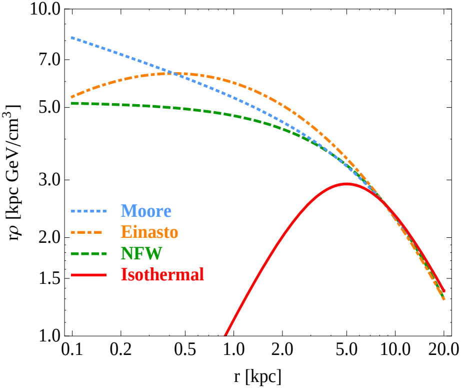
DM seeds structure. And we need the right amount

Simulations tend to favour CDM

Some discrepancies however for small scales (see later)

But in all cases DM seeds structure

N-body simulations: DM Halo Profiles (MW)



$$\rho(r) = \rho_o \left(\frac{r_o}{r}\right)^{\gamma} \left(\frac{1+(r_o/a)}{1+(r/a)}\right)^{\left(\frac{\beta-\gamma}{\alpha}\right)}$$

$(\alpha, \beta, \gamma, a(kpc)) = (2, 2, 0, 4)$ Isothermal

$(\alpha, \beta, \gamma, a(kpc)) = (1, 3, 1, 20)$ NFW cusped

$(\alpha, \beta, \gamma, a(kpc)) = (1.5, 3, 1.5, 28)$ Moore, cusped

Cusped: ρ diverges for $r \to 0$

$\rho_o \sim 0.3 GeV/cm^3$ at $r_o = 8.5 kpc$

Pics halo profile. Cusp vs Core

It may be that the inner profile is more cored (flatter slope) . NFW prefer steeper inner slopes.

$$\textit{Burkert} \longrightarrow \rho_{\rm Burk}(r) = \frac{\bar{\rho}_0}{(1 + r/r_s)(1 + (r/r_s)^2)}, r_s \quad \text{is the core radius}$$

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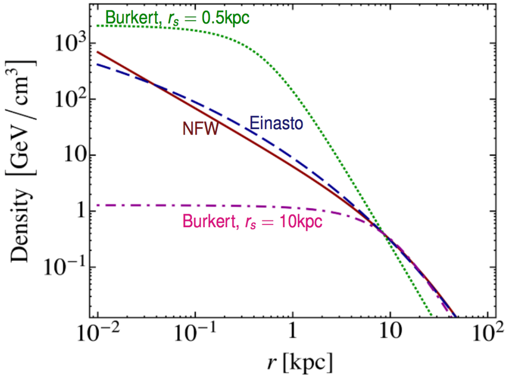
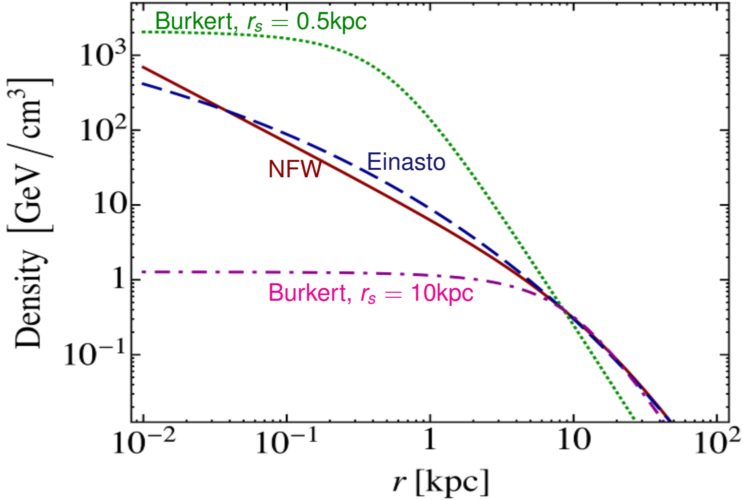


Cusp/Core



Burkert, $r_s = 0.5$kpc
NFW
Einasto
Burkert, $r_s = 10$kpc
Density [GeV/cm^3]
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-1}
1
10
10^2
r [kpc]

Challenges and Open Questions: ΛCDM

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- more sophisticated simulations (influence of baryons,..) needed and could perhaps do the job.

Model Independent limit on the DM mass

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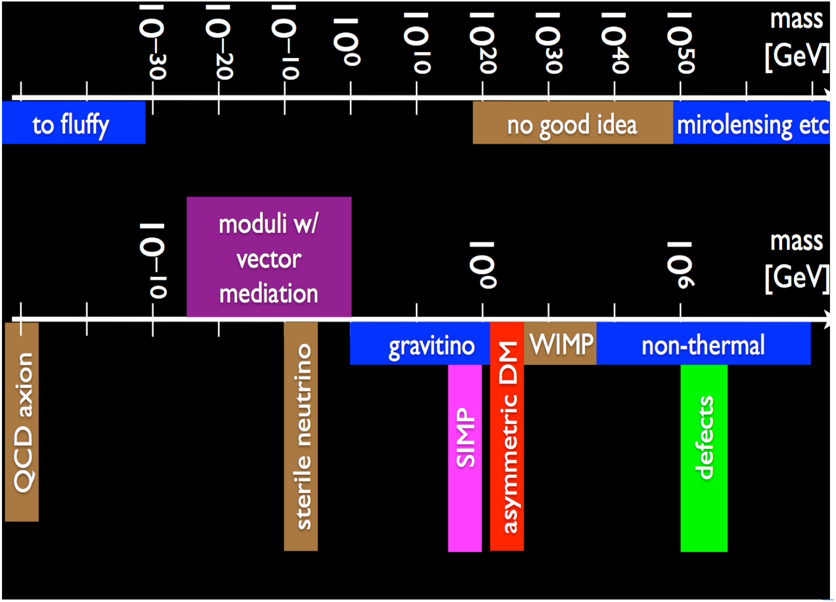
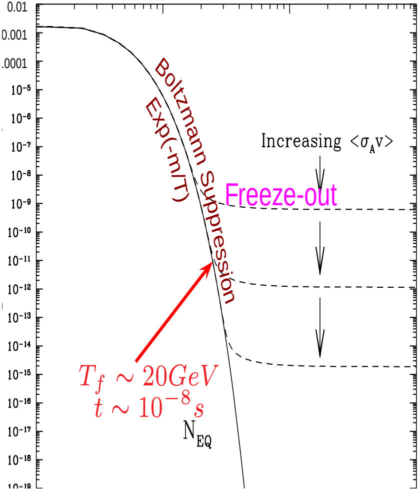
- Absence of lensing for the detection of MACHOS (MAssive Compact Halo Objects) $m > 10^{67}\text{eV}$

DM Mass Range



(Freeze-out) Relic Density: Boltzman transport equation (WIMP)



based on $\hat{L}[f] = \hat{C}[f]$

dilution due to expansion

$dn/dt = -3Hn - <\sigma v> (n^2 - n_{eq}^2)$

$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to X$

$X \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$

- at early times $\Gamma \gg H \to \sim n_{eq}$
- $T \sim m$ X not enough energy to give $X \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$ n drops and so does Γ

$T_f \simeq m/25$

$\Omega_{\tilde{\chi}_1^0} h^2 \propto 1/\sigma_{\tilde{\chi}_1^0}$

Relic and miracles

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$$\Omega_\chi h^2 \sim \frac{1}{\langle \sigma v \rangle / (10^{-26}{\rm cm}^3/{\rm s})} \sim 0.1 \left(\frac{0.01}{\alpha}\right)\left(\frac{m}{100{\rm GeV}}\right)^2$$

WIMP MIRACLE

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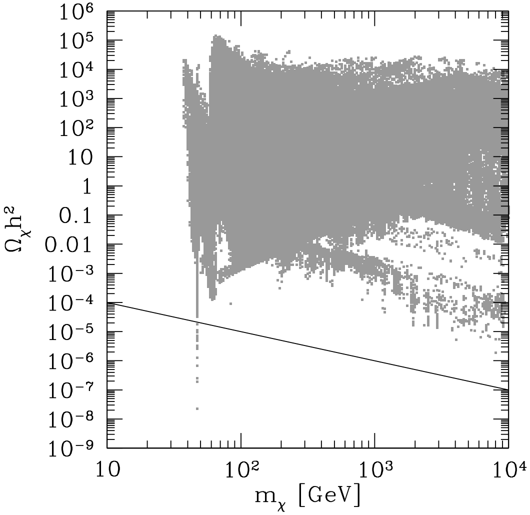
  WIMP MIRACLE
- MIRACLE all equal values of $(m/\alpha)^2$. Smaller m with smaller α will do also WIMPLESS DM

Relic Density constraint is a killer



even in a naive model like mSUGRA (dead now!!) orders of magnitude for the relic, DM cross sections orders of magnitude also
(same for direct and indirect detection)

- At early times Universe is radiation dominated: $H(T) \propto T^2$ ◀
- Expansion rate can be enhanced by some scalar field (kination), extra dimension $H^2 = 8\pi G/3\ \rho(1 + \rho/\rho_5)$, anisotropic cosmology,...
- Entropy conservation (entropy increase will reduce the relic abundance)
- Wimps (super Wimps) can be produced non thermally, or in addition produced in decays of some field (inflaton,....)

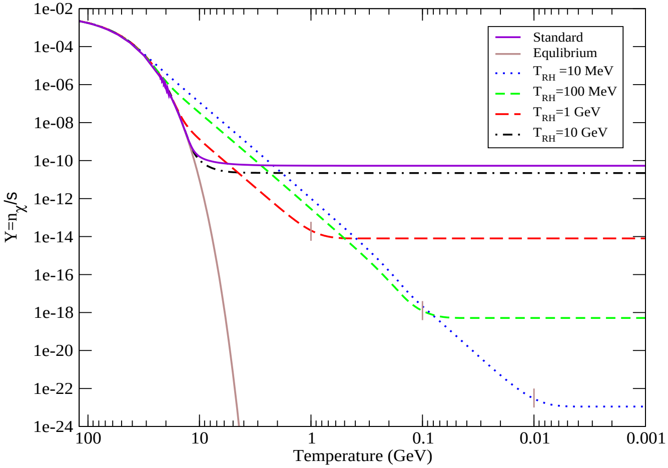
Prototype: A scalar field decaying not long before BBN (Giudice, Kolb; Gelmini and Gondolo, ...)

$$\frac{d\rho_\phi}{dt} = -3H\rho_\phi - \Gamma_\phi \rho_\phi$$
$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle (n^2 - n_{eq}^2) + \frac{b}{m_\phi}\Gamma_\phi \rho_\phi$$
$$\frac{ds}{dt} = -3Hs + \frac{\Gamma_\phi \rho_\phi}{T}$$

where m_ϕ, Γ_ϕ, and ρ_ϕ are respectively the mass, the decay width and the energy density of the scalar field, and b is the average number of (winps/sWIIMPs e.g neutralinos) produced per ϕ decay. Notice that b and m_ϕ enter into these equations only through the ratio b/m_ϕ ($\eta = b\,(100\,TeV/m_\phi)$ and not separately. Finally, the Hubble parameter, H, receives contributions from the scalar field, Standard Model particles, and (new physics, supersymmetric particles),

$$H^2 = \frac{8\pi}{3M_P^2}(\rho_\phi + \rho_{SM} + \rho_\chi)\,.$$
$$T_{RH} = 10MeV(m_\phi/100\,TeV)^{3/2}(M_P/\Lambda) \quad \Gamma_\phi \sim m_\phi^3/\Lambda^2$$

Non Standard Cosmo, Figs Gelmini and Gondolo: Low reheating only



mSUGRA parameters: $M_{1/2} = m_0 = 600\,\mathrm{GeV}$, $A_0 = 0$, $\tan\beta = 10$, and $\mu > 0$,
$\rightarrow m_\chi = 246\,\mathrm{GeV} \rightarrow T_{f.o} = 10 GeV$. $\Omega_{\rm std} h^2 \simeq 3.6$ ($\eta = 0$)

Freeze-in (new [2018] version of micrOMEGAs)

DM may be produced thermally but at early times its number density too small, as well as its cross sections with the SM particles, *i.e.* the bath. In this case. This is the case of FIMP (Feebly Interacting Massive Particles)

$$g_1 \int C[f_1]\, d\bar{p} \quad = \quad -\sum_{\text{spins}} \int \left(f_1 f_2 (1 \pm f_3)(1 \pm f_4) |\mathscr{M}_{12\to 34}|^2 - f_3 f_4 (1 \pm f_1)(1 \pm f_2) |\mathscr{M}_{34\to 12}|^2 \right)$$

$$\times (2\pi)^4 \delta^4 (p_1 + p_2 - p_3 - p_4)\, d\Pi_1\, d\Pi_2\, d\Pi_3\, d\Pi_4 \,, \quad d\Pi_i = \frac{d\bar{p}_i}{E_i}$$

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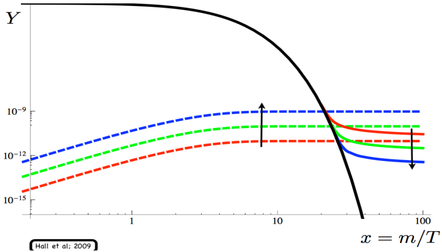
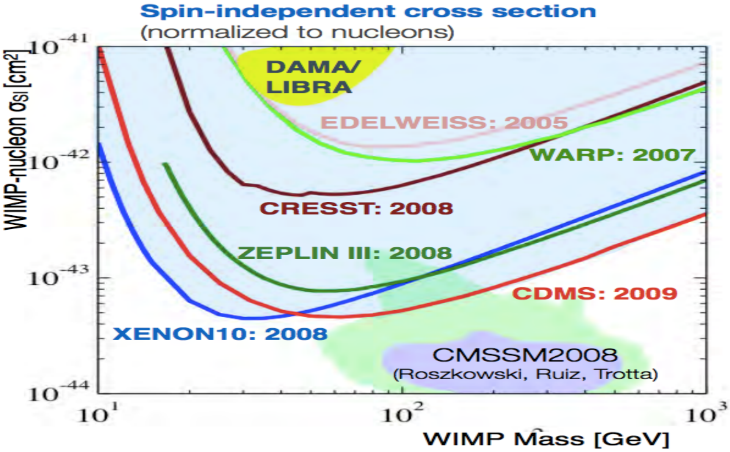
Annihilation term not present!

Correct relic density can still be obtained.



Some old limits first and interpretations: SI



The bell shape easily understood. Low masses penalised because of the threshold (E_R). Higher masses because of the flux $n \sim \rho/M_\chi$

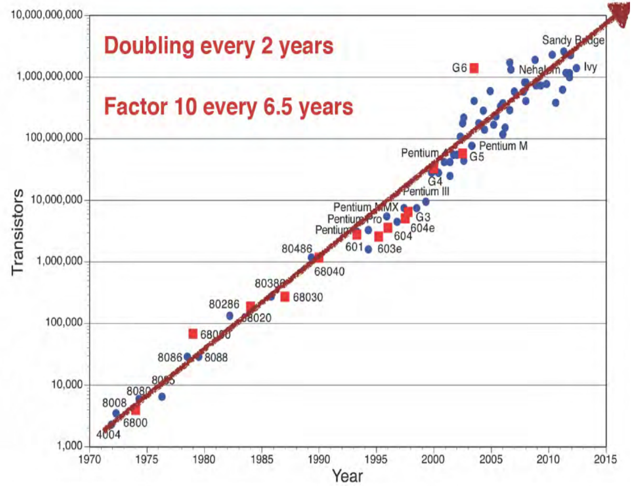
Tremendous Progress in Direct Detection Experiments R. Gaitskel

A Worldwide search, many detectors (noble gases)

Dark Matter Searches DM2016, UCLA, Feb 2016 Rick Gaitskell, Brown University, LUX / DOE

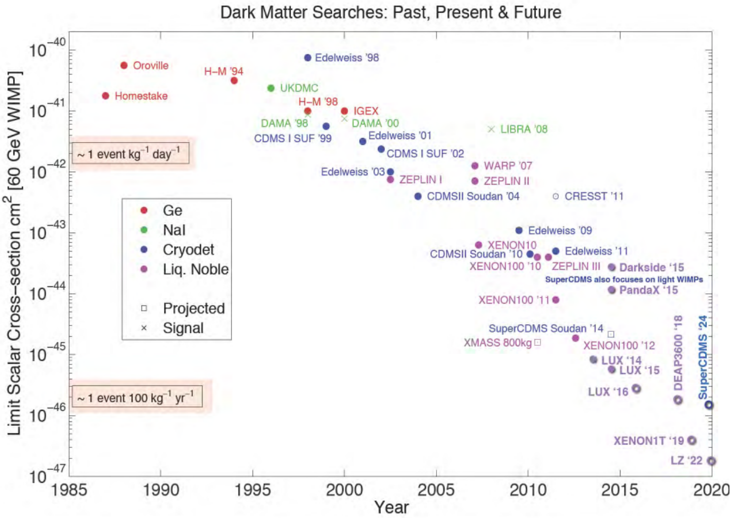
Tremendous Progress in Direct Detection Experiments

Compare to processors (Moore's law!)



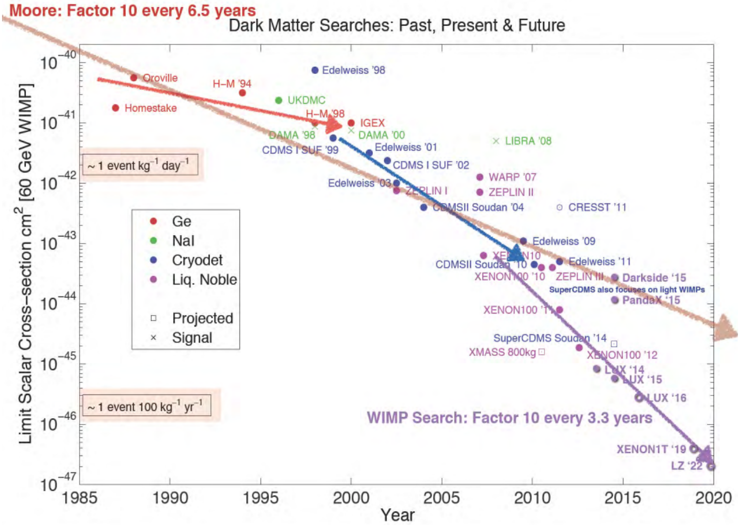
Tremendous Progress in Direct Detection Experiments R. Gaitskel

Progress



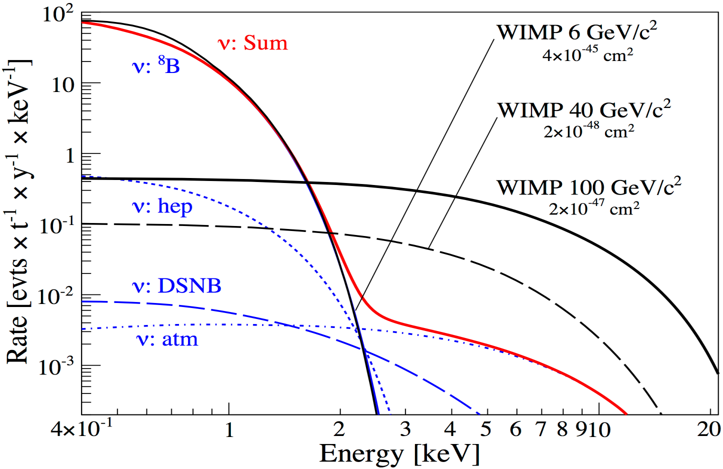
Tremendous Progress in Direct Detection Experiments

Progress

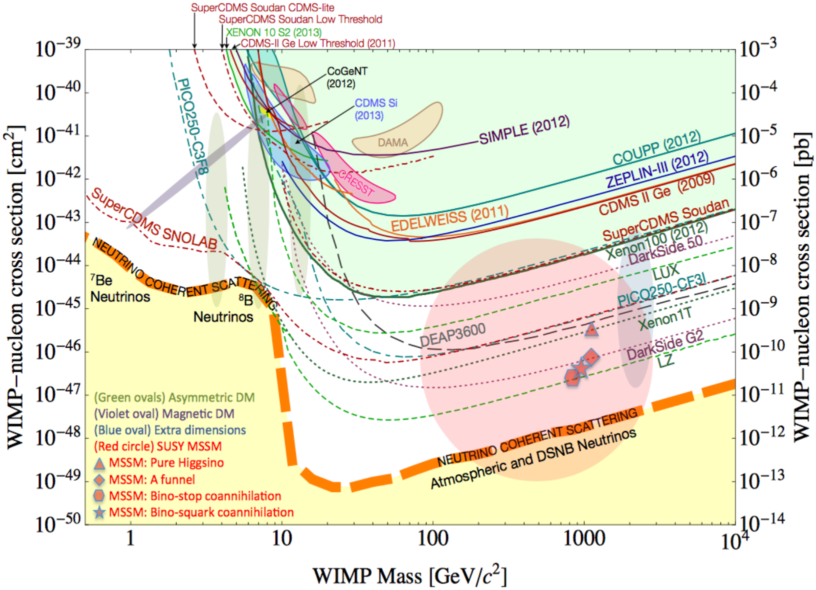


Direct Detection Experiments: Reaching the limit

νN scattering as an irreducible background (different sources of ν some with very large fluxes,... (Sun, the diffuse supernova background (DSNB), and the atmosphere (atm), L. Baudis)



Tremendous Progress in Direct Detection Experiments: Ultimate limits



Sub GeV DM, Direct Detection

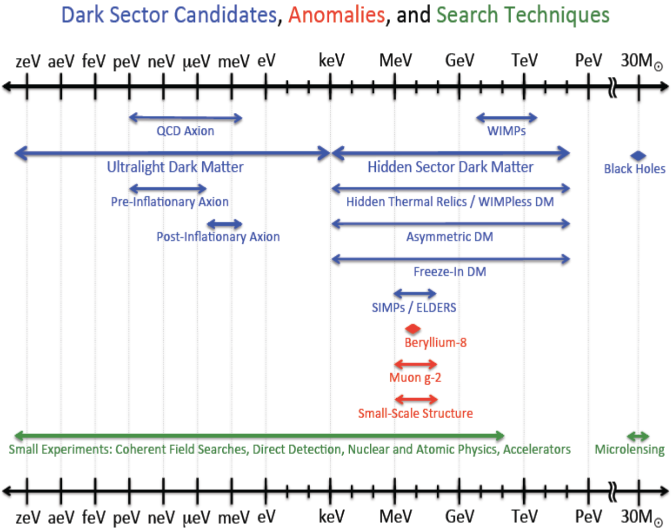
For such low masses, the threshold for the nuclear recoil energy for existing conventional detectors is far too small

$$E_R = E_{NR} \lesssim 100\text{eV}\left(\frac{m_\chi}{500\text{ MeV}}\right)^2\left(\frac{10\text{ GeV}}{m_N}\right)$$

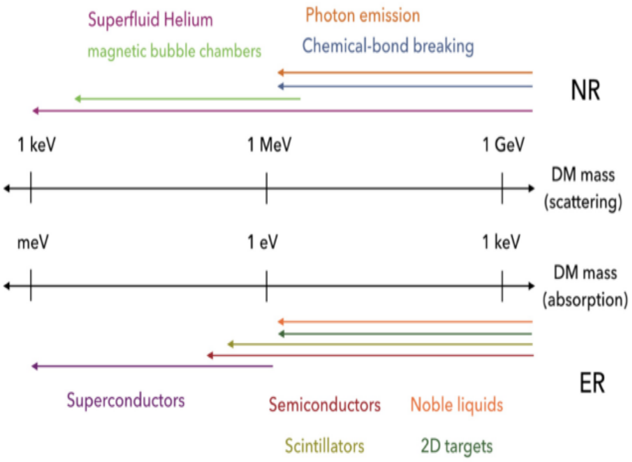
DM may excite the (bound) electron of the target more efficiently (e^- are excited from the valence band to the conduction band,...)

Smaller nuclei *He*, *O*, E_{NR} may be lowered

Sub-GeV Direct Detection. Scattering Off Electrons

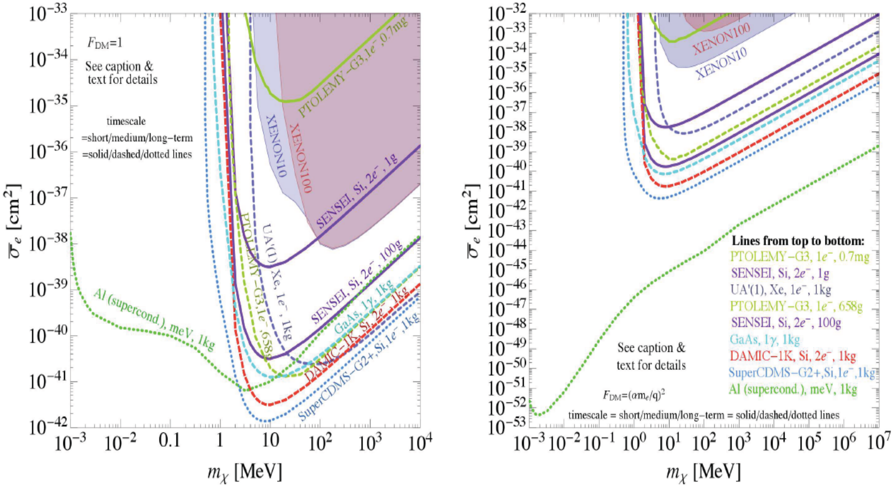


Sub-GeV Direct Detection. Scattering Off Electrons



Ideas to probe low-mass DM via scattering off, or absorption by, nuclei (NR) or electrons

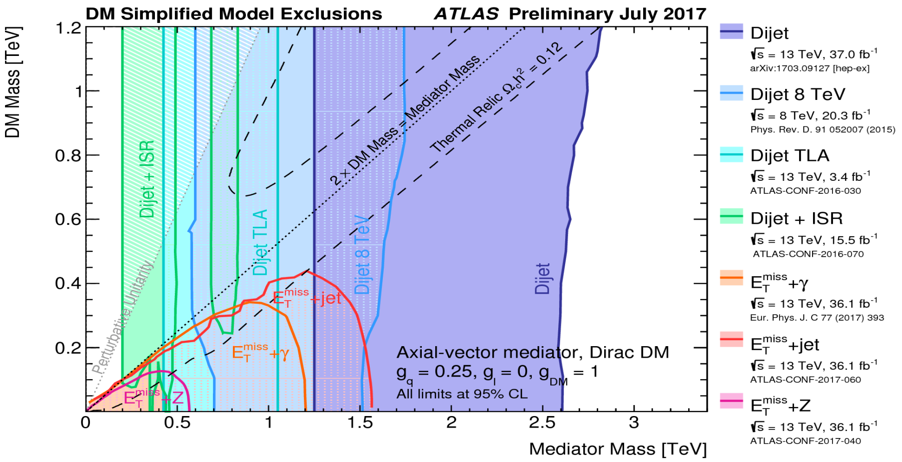
Sub-GeV Direct Detection. Scattering Off Electrons



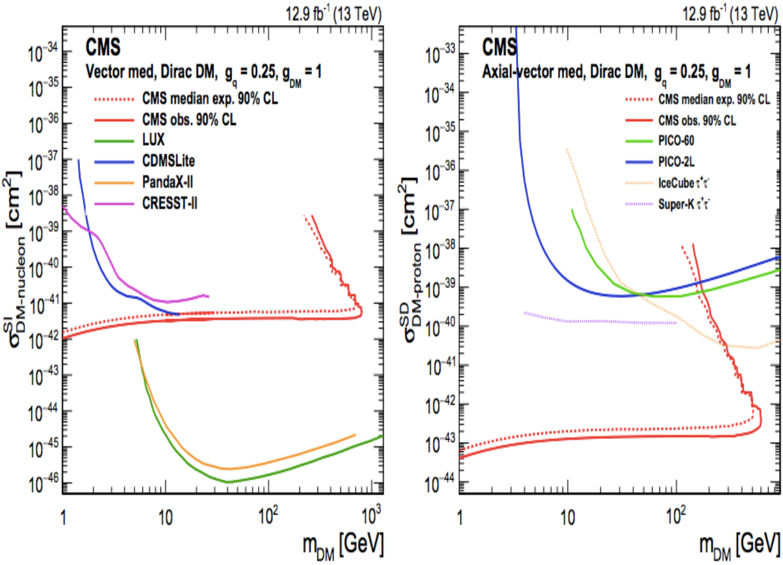
LHC Searches with (Most) Simplified Models

For example, the simplified models do not specify how the Z' boson acquires a mass nor does the formulation of the models explicitly require gauge invariance.

Resolving the effective operator through a mediator exchange.



Most Simplified models: Vector Mediator. CMS limits



Embed effective operators within “Portals" scenarios

Dark Matter interacts only through the Portal Mediator.

Find “Singlet Operators"of the SM

$\varepsilon B^{\mu\nu} F'_{\mu\nu}$	$U(1)$vector portal	dark photon, minimally coupled to DM
$\lvert H\rvert^2 \left(\mu_s S + \lambda_s S^2\right)$	Higgs portal	
$y_N (LH) N$	neutrino portal	
$\frac{a}{f_a} F^{\mu\nu} \tilde{F}_{\mu\nu}$	axion portal	

Conclusions from Collider-DM

- Discovery of a signal of DM at LHC (missing E_T) or through production and study of it siblings could offer great opportunity to reconstruct the properties of DM.

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Conclusions from Collider-DM

- Discovery of a signal of DM at LHC (missing E_T) or through production and study of it siblings could offer great opportunity to reconstruct the properties of DM.
- with the data from LHC so far this does not look too promising especially from the point of view of naturalness
- indirect studies (very indirect) are not competitive with SI DD experiments

List of contributions on DM 2017

- **MSSM with Multiple Hidden Sectors**
  Priyanka Lamba
- **Renormalisation of the Inert Doublet Model and application to Relic Density Beyond Tree-level**
  Shankha Banerjee(Now Durham), F. Boudjema (LAPTh), G. Chalons(LPSc) and N. Chakrabarty(Now Taiwan).
- **Long-lived stau, sneutrino dark matter and right slepton spectrum**
  Shankha Banerjee, Genevieve Belanger, Avirup Ghosh and Biswarup Mukhopadhyaya
- **Probing the CP of a spin-0 mediator in its associated production with a top quark.**
  G. Belanger, Charanjit Khosa, S. D. Rindani
- **Cornering pseudoscalar-mediated dark matter with the LHC and cosmology**
  S. Banerjee, D. Barducci, G. Belanger, B. Fuks, A. Goudelis, B. Zaldivar; arXiv:1705.02327
- **Invisible decay of the Higgs boson in the context of a thermal and nonthermal relic in MSSM**
  R. K. Barman, G. Belanger, B. Bhattacherjee, R. Godbole, G. Mendiratta and D. Sengu
  Physical Review D 95, 2017, 095018.

Renormalisation of the Inert Doublet Model and application to Relic Density Beyond Tree-level

Shankha Banerjee(Now Durham), F. Boudjema (LAPTh), G. Chalons(LPSc) and N. Chakrabarty(Now Taiwan)

- SM+ an extra Scalar Doublet (Φ_2 with no v.e.v). The new doublet couples to the bosons of the SM but not to the fermions.
- Endowed with a $\mathbb{Z}_2$ symmetry. One of the neutral (scalar) components (scalar or pseudo-scalar) is a potential DM candidate
- The model has a non-decoupling limit, that give large corrections to the SM Higgs self-coupling. Could help trigger EW phase transition and could be measurable at LHC
- However if the scalar is a DM, this property is ruled out because of limit on Direct Detection

The model

$$V = \mu_1^2\Phi_1^\dagger\Phi_1 + \mu_2^2\Phi_2^\dagger\Phi_2 + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2$$
$$+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_2^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \left(\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right)$$

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG) \end{pmatrix} \text{ and } \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H + iA) \end{pmatrix}$$

$$m_h^2 = \lambda_1 v^2 \quad m_{H\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2 \quad m_H^2 = \mu_2^2 + \frac{1}{2}\lambda_L v^2 \quad m_A^2 = \mu_2^2 + \frac{1}{2}\lambda_A v^2$$

Masses can be taken as input parameters *in lieu* of $\lambda' s$. OS (On-Shel) renormalisation. Need extra-input (one self-coupling, or decay of Higgs or scattering of Higgses if all OS or combination of OS+$\bar{DR}$

Full renormalisation of the model is completed

2 Benchmarks

Benchmark 1 (Light scalars scenario)

```
 (MH, MA,MH+,Mh)= 57.5, 113.0,123 GeV
mu^2 =3261.5   G(GeV)^2 ;    lambda_2=0.01
==== Calculation of relic density =====
Xf=2.38e+01 Omega h^2=1.18e-01
# Channels which contribute to 1/(omega) more than 1%.
# Relative contributions in % are displayed
  72% ~X ~X ->b B
  15% ~X ~X ->W+ W- ==> OFF SHELL W (2->3 process !!!)
   7% ~X ~X ->c C
   3% ~X ~X ->l L
   2% ~X ~X ->Z Z
```

$\chi\chi \to W f \bar{f}$ $\chi = H, A$ Extremely challenging!

2 Benchmarks

Benchmark 2 (Heavy scalars scenario)

```
 (MH, MA,MH+,Mh)= 550, 551,552,125 GeV
mu^2 =301895.3 (GeV)^2 ;    lambda_2=0.01
==== Calculation of relic density =====
Xf=2.61e+01 Omega h^2=1.18e-01
# Channels which contribute to 1/(omega) more than 1%.
# Relative contributions in % are displayed
  18% ~X ~X ->W+ W-
  14% ~X ~X ->Z Z
  13% ~Hp ~Hm ->W+ W-
  9% ~H3 ~H3 ->W+ W-
  8% ~Hp ~X ->A W+
  7% ~H3 ~H3 ->Z Z
  5% ~Hp ~Hm ->A A
  5% ~Hp ~Hm ->A Z
  3% ~Hp ~X ->Z W+
  3% ~H3 ~Hp ->Z W+
  2% ~Hp ~Hm ->Z Z
```