Complementary probes of multi-component Dark Matter

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IRISH RESEARCH COUNCIL
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EISA
European Institute for Sciences and Their Applications

Corfu Summer Institute
Hellenic School and Workshops on Elementary Particle Physics and Gravity
Corfu, Greece

In collaboration with S. Moretti, D. Sokolowska, D. Rojas, J. Hernandez

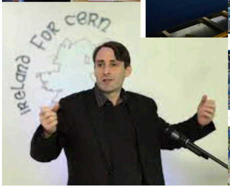
30.08.2023

Ireland is finally joining CERN

Trinity academics call on Ireland to join CERN

by Leigh Mc Gowran

3 OCT 2022 SAVE ARTICLE



THE IRISH TIMES

Oireachtas

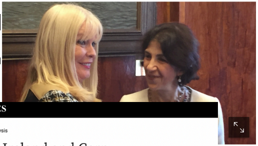
Harris say benefits of joining Cern 'significant' as department prepar submission

Minister tells Dáil he has Taoiseach's full support in bid to join nuclear research agency

Expand

Ireland could join CERN by 2018 - Gianotti

Updated / Friday, 4 Nov 2016 14:46



THE IRISH TIMES

Science Analysis

A happy new year for Ireland and Cern

Irish scientists could at last participate in 'big science' experiments and work with the best in the world

Expand

THE IRISH TIMES

Ireland should join Cern, says Oireachtas committee

Membership of organisation is critical to becoming 'a global innovation leader'

Thu Nov 14 2019 - 11:03

Why is Ireland not a member of Cern?

State has rich history in particle physics but will not cough up €1m Cern membership fee

Thu Jun 14 2018 - 01:00

Government to consider Cern membership

Review will study benefits and costs of joining the European nuclear reserach lab

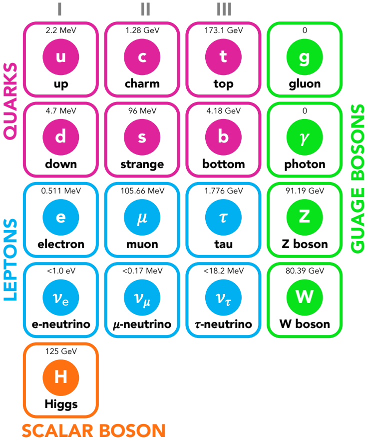
Thu Jan 30 2014 - 22:29

You are cordially invited to ...

The Standard Model

Its current formulation was finalised in the 70's and predicted:

- the W & Z bosons
  discovered in 1983
- the top quark
  discovered in 1995
- the tau neutrino
  discovered in 2000
- the Brout-Englert-Higgs mechanism
  a scalar boson discovered in 2012



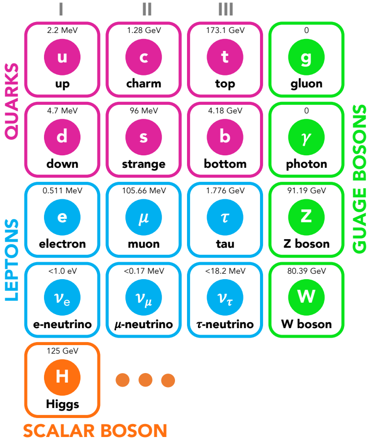
· · · and the need to go beyond

What is missing:

- a suitable Dark Matter candidate link
- a successful baryogenesis mechanism
  - strong first order phase transition
  - sufficient amount of CP violation link
- a natural inflation framework link
- an explanation for the fermion mass hierarchy link
- a stable electroweak vacuum link

$\Rightarrow$ beyond the Standard Model

$\Rightarrow$ **scalar extensions of the SM**



Scalar extensions of the SM

SM + scalar singlets

- Dark Matter severely constrained
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2HDM: SM + a doublet

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- Dark Matter many exotic possibilities
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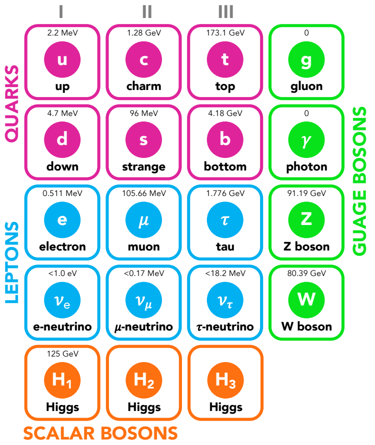
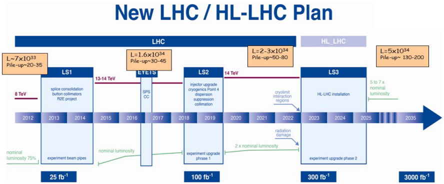
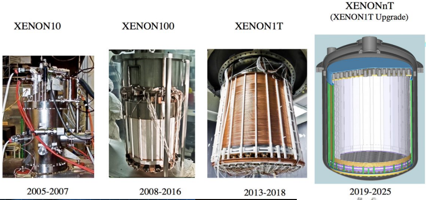
- Strong first order EWPT easily achieved
- Bonus: fermion mass hierarchy explanation

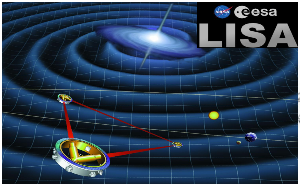


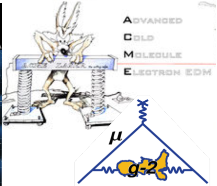
Complementary experimental probes of scalar extensions

- Collider experiments
  - LHC-RUN-III
  - HL-LHC
  - CEPC
- DM experiments
  - XENONnT
  - CTA
- GW experiments
  - DECIGO
  - LISA mission
- Precision experiments
  - $(g-2)_\mu$
  - Advanced ACME









How do we know Dark Matter exists?

The common misinformation:

For the first time, Fritz Zwicky in 1933: "The Coma cluster moves too fast for its apparent gravitational pull (due to its luminous matter) to stay together."

$\Rightarrow$ Dark Matter within the cluster

How do we know Dark Matter exists?

The common misinformation:

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$\Rightarrow$ Dark Matter within the cluster

The correct information:

Three years prior, Knut Lundmark in 1930 had already found evidence for Dark Matter and coined the term.

How do we know Dark Matter exists?

Knut Lundmark, Lund Medd. No125 (1930) 1 – 10 (Thanks to D.Dravins and A. L'Huillier, Lund University for digging out the original paper, in German, my translation):

"Under the condition that the mass-luminosity relation is valid for all stellar systems, the mass for the investigated systems can be computed using the total absolute magnitude M_{tot} which can be found when the distance is known and the total apparent m_{tot} is observed. The mass computed in this way, the luminous mass, does understandably not include the mass of the dark objects of the system (extinguished stars, dark clouds, meteors, comets, and so on). To determine the total mass or the gravitational mass, we need to rely on the five cases where one has detected an effect of rotation by spectrographical means. … A comparison between the two kinds of masses gives an estimate of the ratio of luminous and dark matter for some stellar systems (Table 4)."

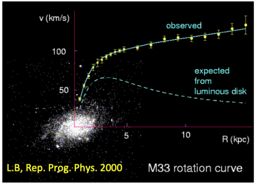


Tabelle 4.

Objekt	Ratio: $\frac{\text{Luminous + Dark Matter}}{\text{Luminous Matter}}$
Messier 81	100 : 1 (?)
N. G. C. 4594	30 : 1
Andromedanebel	20 : 1
Messier 51	10 : 1
Milchstraßensystem	10 : 1
Messier 33	6 : 1

From Lars Bergstrom's talk (modified) at the Workshop on Off-the-Beaten-Track Dark Matter and Astrophysical Probes of Fundamental Physics (April 2015) see also

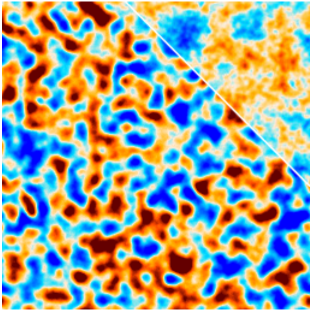
How do we know Dark Matter exists?

Patterns in the Cosmic Microwave Background (CMB):

Competition between

- the force of gravity causing matter to fall inward
- an outward pressure exerted by photons

Dark Matter feels the gravity but not the pressure from photons.

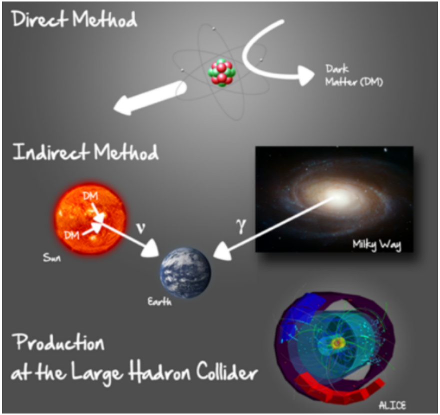


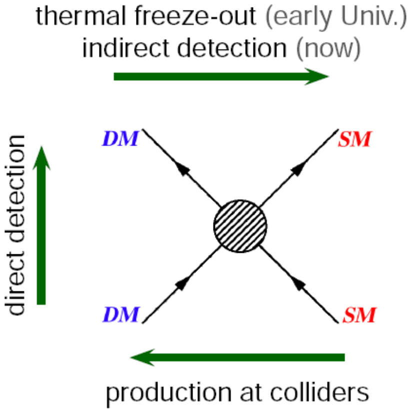
Planck CMB simulator

The total relic density by the Planck data: $\Omega_{\rm DM} h^2 = 0.1200 \pm 0.0012$

N. Aghanim et al. [Planck], Astron. Astrophys. 641, A6 (2020)

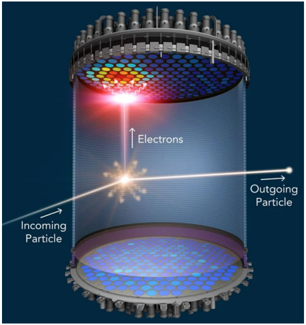
How do we look for Dark Matter?

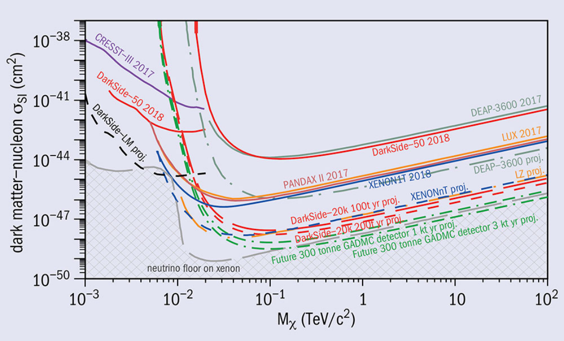




Direct Detection searches

In deep underground gigantic tanks of liquid gas



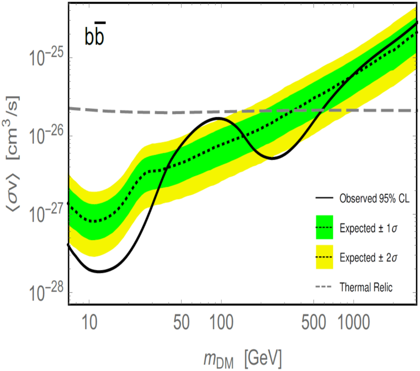


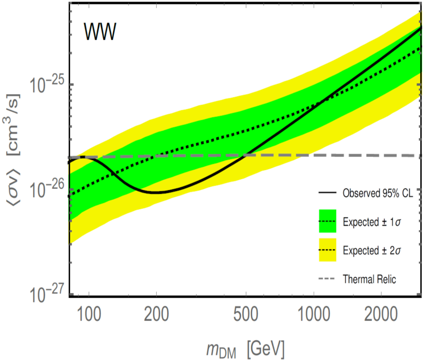
Constrain the spin-independent scattering cross section of DM off of nuclei

E. Aprile et al. [XENON], Phys. Rev. Lett. 121, no.11, 111302 (2018)

Indirect Detection observations

In dense regions of sky with telescopes in orbit $\mathrm{DM\,DM} \to bb/\tau\tau/WW$

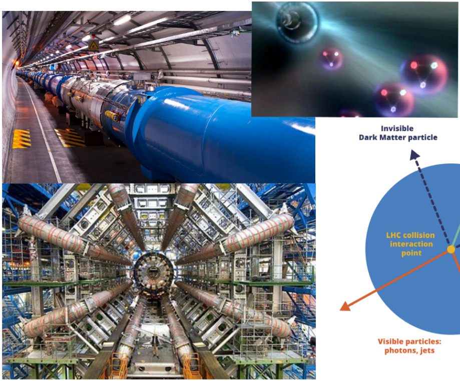


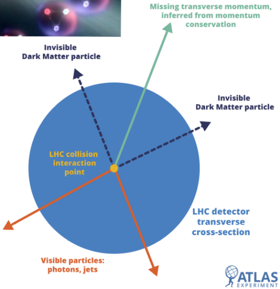


[M. Ackermann et al. [Fermi-LAT], Phys. Rev. Lett. 115, no.23, 231301 (2015)], [M. Cirelli and G. Giesen, JCAP 04, 015 (2013)], [Symmetry 2020, 12(10), 1648]

High energy collider experiments

Pair-producing it in high energy collider experiments

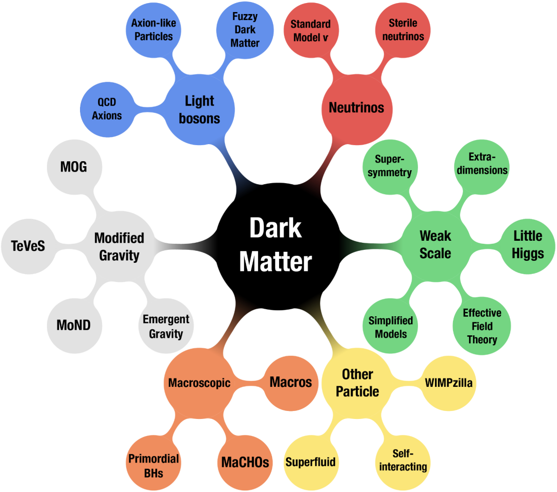




Looking for events with MET + model dependent objects

$$pp \to \text{jets/leptons}/\gamma/\text{W/Z/h} + \not{E}_T$$

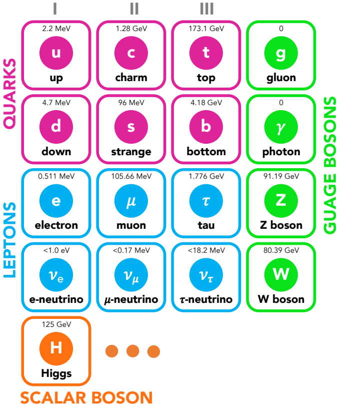
What is Dark Matter?



(Image: G. Bertone and T. M. P. Tait)

Higgs portal models and extra scalars

Scalar extensions are a common characteristic of almost all BSM scenarios.



The scalar sector is the least understood and experimentally least constrained sector.

Scalar extensions of the SM

SM + scalar singlets link

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- CP-violation not possible

2HDM: SM + a doublet link

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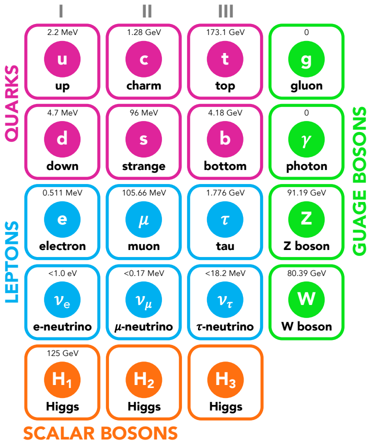


3-Higgs doublet models (3HDMs)

2 scalar doublets + the SM Higgs doublet

$\phi_1, \phi_2 \qquad\qquad \phi_3$

$$\phi_1 = \begin{pmatrix} H_1^+ \\ \frac{H_1+iA_1}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} H_2^+ \\ \frac{H_2+iA_2}{\sqrt{2}} \end{pmatrix}, \qquad \phi_3 = \begin{pmatrix} G^+ \\ \frac{h+iG^0}{\sqrt{2}} \end{pmatrix}$$

3HDM with a $Z_2 \times Z_2'$ symmetry

DM protected by a Z_2 symmetry $(-,+,+)$, and Z_2' symmetry $(+,-,+)$

$$\phi_1 \to -\phi_1, \quad \phi_2 \to -\phi_2, \quad \text{SM fields} \to \text{SM fields}, \quad \phi_3 \to \phi_3$$

Z_2 symmetry respected by the vacuum $(0, 0, v)$:

$$\phi_1 = \begin{pmatrix} H_1^+ \\ \frac{H_1 + iA_1}{\sqrt{2}} \end{pmatrix}, \qquad \phi_2 = \begin{pmatrix} H_2^+ \\ \frac{H_2 + iA_2}{\sqrt{2}} \end{pmatrix}, \qquad \phi_3 = \begin{pmatrix} G^+ \\ \frac{v + h + iG^0}{\sqrt{2}} \end{pmatrix}$$

The lightest neutral field from each doublet is a viable DM candidate.

Z_2 symmetry: only ϕ_3 couples to fermions $\phi_u = \phi_d = \phi_e = \phi_3$

$$-\mathcal{L}_{Yukawa} = Y_u \bar{Q}_L' i\sigma_2 \phi_u^* u_R' + Y_d \bar{Q}_L' \phi_d d_R' + Y_e \bar{L}_L' \phi_e e_R' + \text{h.c.}$$

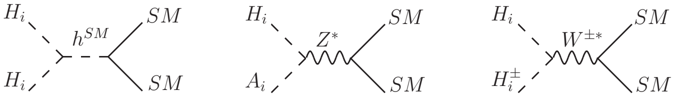
No FCNCs

J. Hernandez, V. Keus, S. Moretti, D. Rojas, D. Sokolowska, [JHEP 03, 045 (2023)] and [arXiv:2012.11621]

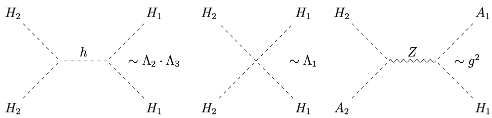
Two-component Dark Matter: H_1, H_2

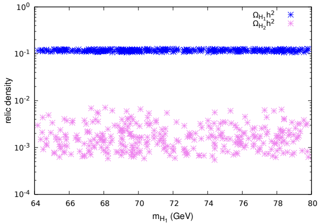
The lightest neutral field from each doublet is a viable DM candidate:

$$m_{H_1} < m_{A_1} < m_{H_1^\pm} \qquad m_{H_2} < m_{A_2} < m_{H_2^\pm}$$



The conversion processes play an important role in DM production.

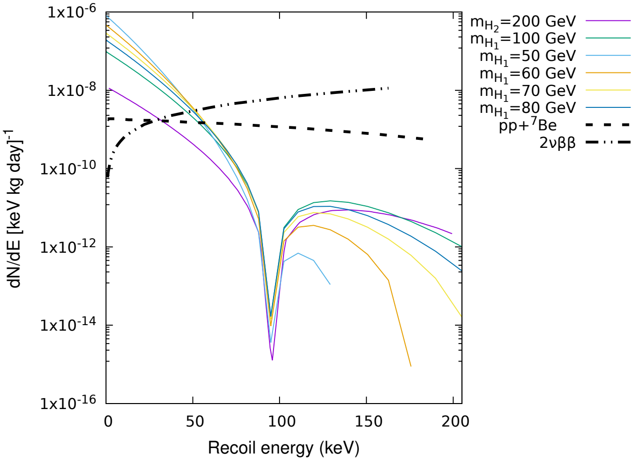




J. Hernandez, V. Keus, S. Moretti, D. Rojas, D. Sokolowska, [JHEP 03, 045 (2023)] and [arXiv:2012.11621]

Astrophysical probes: Direct detection XENONnT/LZ

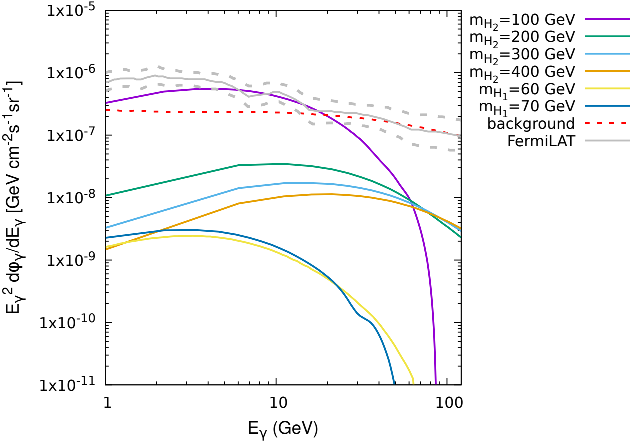
Light DM H_1: probed in the nuclear recoil energy event rate



J. Hernandez, V. Keus, S. Moretti, D. Rojas, D. Sokolowska, [JHEP 03, 045 (2023)] and [arXiv:2012.11621]

Astrophysical probes: Indirect detection Fermi-LAT

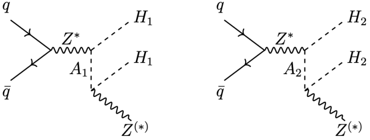
Heavy DM H_2: contributes to the photon flux from the galactic center

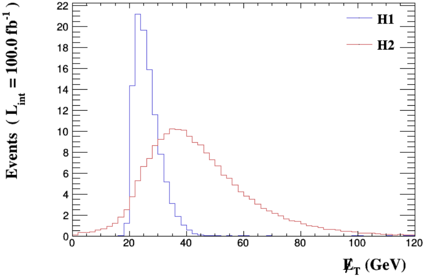


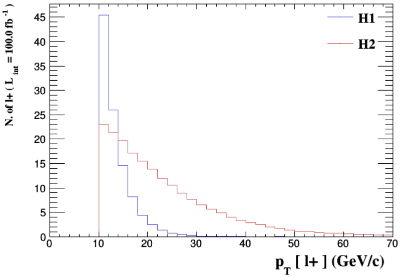
J. Hernandez, V. Keus, S. Moretti, D. Rojas, D. Sokolowska, [JHEP 03, 045 (2023)] and [arXiv:2012.11621]

Collider probes: distributions of observables

$m_{H_2} - m_{H_1} > \not{E}_T$ resolution $\Rightarrow$ visible effect in different distributions







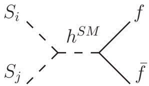
Missing transverse energy and transverse momentum of either lepton

J. Hernandez, V. Keus, S. Moretti, D. Rojas, D. Sokolowska, [JHEP 03, 045 (2023)] and [arXiv:2012.11621]

Purely scalar extensions as DM models:

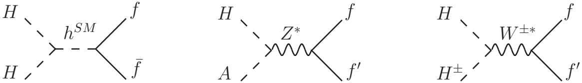
SM + singlet(s):

- $\phi_{SM}, S \Rightarrow$ DM
- $\phi_{SM}, S_{1,2} \Rightarrow$ DM



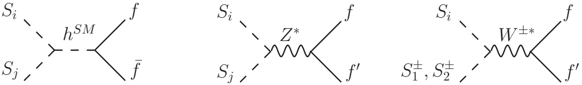
2HDMs:

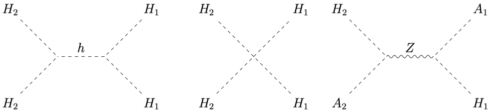
- $\phi_1, \phi_2 \Rightarrow$ DM



3HDMs:

- $\phi_1, \phi_2, \phi_3 \Rightarrow$ DM
- $\phi_1, \phi_2, \phi_3 \Rightarrow$ DM, CPV
- $\phi_1, \phi_2, \phi_3 \Rightarrow$ DM, DM





Complementary collider and astrophysical probes of both components of DM H_1 and H_2

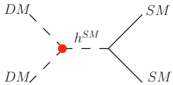
BACKUP SLIDES

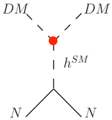
Purely scalar extensions w/o a Z_2 symmetry:

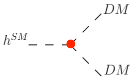
Relic density / Indirect detection — Direct detection — Collider experiments

SM + singlet(s):

- $\phi_{SM}, S \Rightarrow$ DM, ~~CPV~~
- $\phi_{SM}, S_{1,2} \Rightarrow$ DM, ~~CPV~~

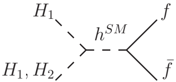


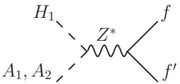


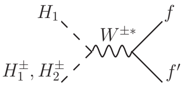


2HDMs:

- $\phi_1, \phi_2 \Rightarrow$ ~~DM~~, CPV
- $\phi_1, \phi_2 \Rightarrow$ DM, ~~CPV~~







2HDM + singlet:

- $\phi_1, \phi_2, S \Rightarrow$ ~~DM~~, CPV
- $\phi_1, \phi_2, S \Rightarrow$ DM, ~~CPV~~
- $\phi_1, \phi_2, S \Rightarrow$ DM, CPV

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- $\phi_1, \phi_2, \phi_3 \Rightarrow$ ~~DM~~, CPV
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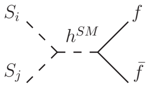
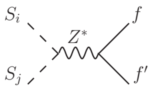
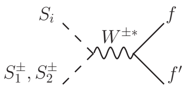


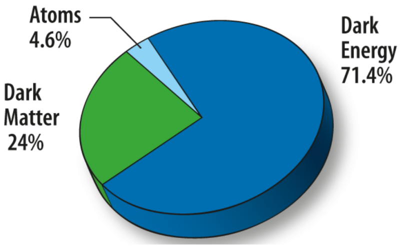




Dark Matter

Characteristics:

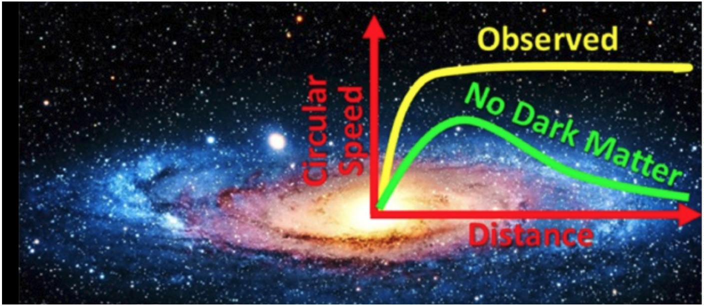
- Cold (non-relativistic at the onset of galaxy formation)
- Non-baryonic
- Neutral & weakly interacting
- Stable due to a discrete symmetry

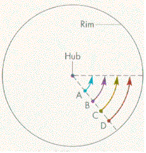


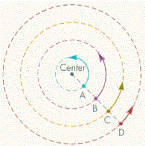
$$\underbrace{\mathrm{DM\ DM} \to \mathrm{SM\ SM},}_{\text{pair annihilation}} \quad \underbrace{\mathrm{DM} \not\to \mathrm{SM}, \ldots}_{\text{stable}}$$

back

Galactic rotation curves







Expectation: stars velocity to fall towards the edges.

Observation: stars velocity stays constant towards the edges.

$\Rightarrow$ a spread of Dark Matter throughout the galaxy

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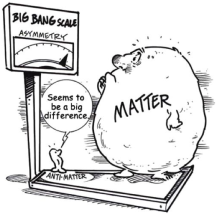
Baryon asymmetry in the universe

Sakharov's conditions for a successful baryogenesis mechanism:

- B-violation
- C & CP-violation
- Departure from thermal equilibrium

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{ub} \neq V_{ub}^{*} ; V_{td} \neq V_{td}^{*} \Rightarrow \text{CPV}$$



Observation $\frac{N(B)}{N(\gamma)} \approx 10^{-9} \quad \gg \quad 10^{-20}$ provided by the SM

$\Rightarrow$ New sources of CPV needed.

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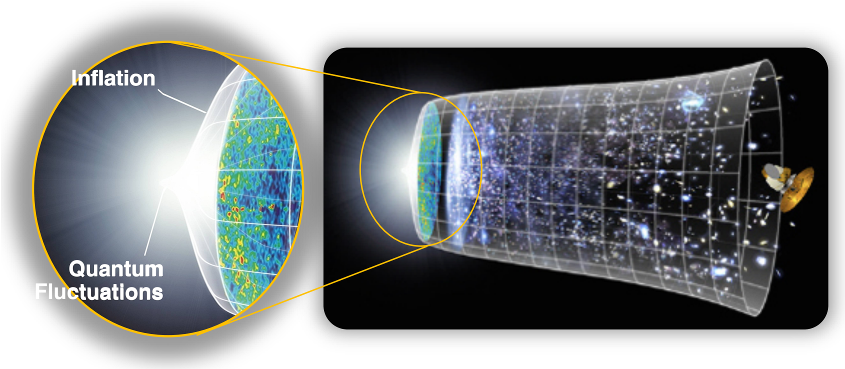
Inflation: an exponential expansion in the early universe



Explains: generation of primordial density fluctuations seeding structure formation, the flatness, homogeneity and isotropy of the universe

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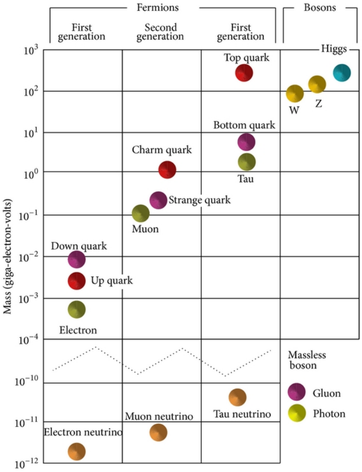
Fermion mass hierarchy in the SM

No explanation for

- $m_t/m_e \approx 10^6$
- $m_t/m_\nu \approx 10^{11}$



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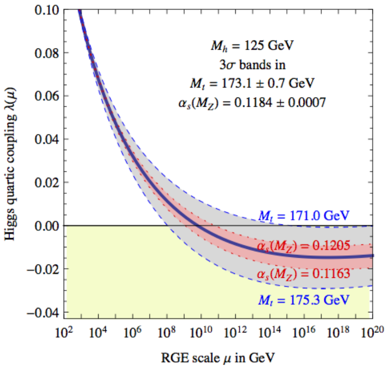
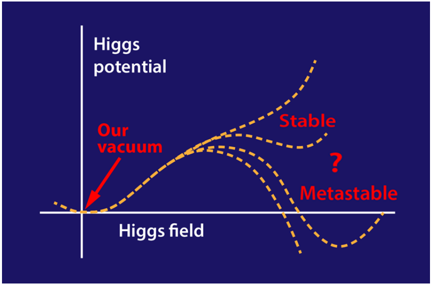
The SM electroweak vacuum is not stable





$$V = -\mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$

$\Rightarrow$ Scalar extensions can stabilise the EW vacuum.

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Who discovered the expansion of the universe?

Common lore: Edwin Hubble discovered the expansion of the Universe, in 1929. Fritz Zwicky discovered Dark Matter, in 1933.

Forgotten pioneer: Knut Lundmark, Sweden (1889 – 1958)

" … measurements by a Swedish astronomer, Knut Lundmark, were much more advanced than formerly appreciated. Lundmark was the first person to find observational evidence for expansion, in 1924 — three years before Lemaître and five years before Hubble. Lundmark's extragalactic distance estimates were far more accurate than Hubble's…"

Ian Steer, NASA/IPAC, Pasadena, arxiv:1212.1359; J. R. Astron. Soc. Can. 105 (2011) 18

From Lars Bergstrom's talk at the Workshop on Off-the-Beaten-Track Dark Matter and Astrophysical Probes of Fundamental Physics (April 2015) back

Scalar singlet extension of SM

the SM Higgs doublet + a scalar singlet

ϕ S

$$\phi = \begin{pmatrix} G^+ \\ \frac{h+iG^0}{\sqrt{2}} \end{pmatrix} \qquad S = \left(\frac{s}{\sqrt{2}}\right)$$

$$\underbrace{S\ S \to \mathrm{SM\ SM}}_{\text{pair annihilation}}, \qquad \underbrace{S \not\to \mathrm{SM\ SM}}_{\text{stable}}$$

back

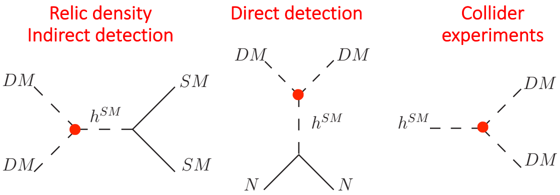
SM + scalar singlet

DM protected by a Z_2 symmetry $(+, -)$ from decaying to SM particles.

$$\text{SM fields} \to \text{SM fields}, \quad \phi \to \phi, \quad S \to -S$$

The Lagrangian and the vacuum are Z_2 symmetric: $\langle \phi \rangle = v$, $\langle S \rangle = 0$

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial S)^2 - m_s^2 S^2 - \lambda_s S^4 - \lambda_{hs} \phi^2 S^2$$



Tension: all relevant interactions are governed by the same coupling!

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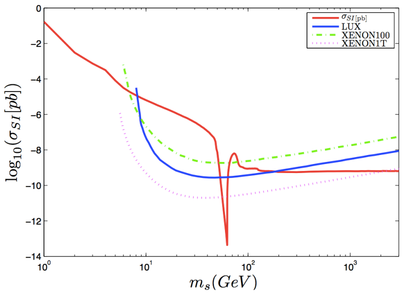
SM + scalar singlet

- Bounded from below potential:
  $h, s \to \infty \;\; \Rightarrow V > 0$
- Vacuum stability:
  $\tau_{v_{EW}} >$ age of the universe
- Perturbative unitarity:
  $|\lambda_i| \leq 4\pi, \;\; |\Lambda_i| \leq 8\pi$
- Higgs decays:
  $BR(h \to inv.) < 20\% \;\; \Rightarrow \lambda_{hs}$ small
- Relic density:
  λ_{hs} large
- Direct and indirect detection:
  λ_{hs} small



H. Han, S. Zheng, [JHEP 12 (2015) 044]

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2-Higgs doublet models (2HDMs)

the SM Higgs doublet + 1 scalar doublet

ϕ_1 ϕ_2

$$\phi_1 = \begin{pmatrix} G^+ \\ \frac{h+iG^0}{\sqrt{2}} \end{pmatrix} \qquad \phi_2 = \begin{pmatrix} H^+ \\ \frac{H+iA}{\sqrt{2}} \end{pmatrix}$$

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Higgs portal models: SM + 2 scalar doublets

DM is protected by a Z_2 symmetry $(+,-)$ from decaying to SM particles:

$$\text{SM fields} \to \text{SM fields}, \quad \phi_1 \to \phi_1, \quad \phi_2 \to -\phi_2$$

Z_2 symmetry: only ϕ_1 couples to fermions $\phi_u = \phi_d = \phi_e = \phi_1$

$$-\mathcal{L}_{Yukawa} = Y_u \bar{Q}'_L i\sigma_2 \phi_u^* u'_R + Y_d \bar{Q}'_L \phi_d d'_R + Y_e \bar{L}'_L \phi_e e'_R + \text{h.c.}$$

Z_2 symmetry respected by the vacuum: $\phi_1 = \begin{pmatrix} G^+ \\ \frac{v+h+iG^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} H^+ \\ \frac{H+iA}{\sqrt{2}} \end{pmatrix}$

DM candidate: the lightest neutral particle from the dark doublet

$$HH \to h \to \text{SM}, \quad HA \to Z \to \text{SM}, \quad HH^\pm \to W^\pm \to \text{SM}$$

Tension: all scalar interactions are governed by the same coupling!
Gauge couplings are fixed!

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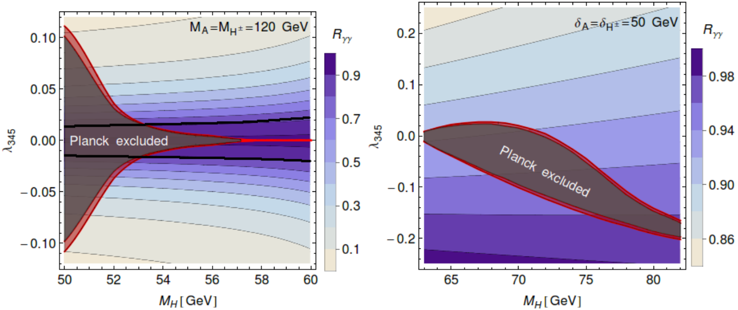
Higgs portal models: SM + 2 scalar doublets

More constraints:

Higgs invisible decays: $\mathrm{BR}(h \to S_i S_j) < 0.23 - 0.36$

$h \to \gamma\gamma$ signal strength: $\mu_{\gamma\gamma} = 1.16^{+0.20}_{-0.18}$



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M. Krawczyk, D. Sokolowska, P. Swaczyna and B. Swiezewsk, [JHEP 09 (2013) 055]

3-Higgs doublet models (3HDMs)

two scalar doublets + the SM Higgs doublet

ϕ_1, ϕ_2 ϕ_3

$$\phi_1 = \begin{pmatrix} H_1^+ \\ \frac{H_1+iA_1}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} H_2^+ \\ \frac{H_2+iA_2}{\sqrt{2}} \end{pmatrix}, \qquad \phi_3 = \begin{pmatrix} G^+ \\ \frac{h+iG^0}{\sqrt{2}} \end{pmatrix}$$

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Z_2-symmetric 3HDM with dark CPV

DM is protected by a Z_2 symmetry $(-,-,+)$:

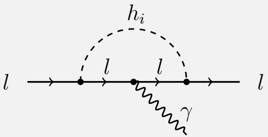
$$\phi_1 \to -\phi_1, \quad \phi_2 \to -\phi_2, \quad \text{SM fields} \to \text{SM fields}, \quad \phi_3 \to \phi_3$$

Z_2 symmetry respected by the vacuum $(0, 0, v)$:

$$\phi_1 = \begin{pmatrix} H_1^+ \\ \frac{H_1 + iA_1}{\sqrt{2}} \end{pmatrix}, \qquad \phi_2 = \begin{pmatrix} H_2^+ \\ \frac{H_2 + iA_2}{\sqrt{2}} \end{pmatrix}, \qquad \phi_3 = \begin{pmatrix} G^+ \\ \frac{v + h + iG^0}{\sqrt{2}} \end{pmatrix}$$

Only ϕ_3 can couple to fermions $\phi_u = \phi_d = \phi_e = \phi_3$ and $h_i = h$

$$\begin{aligned} -\mathcal{L}_{Yukawa} &= Y_u \bar{Q}'_L i\sigma_2 \phi_u^* u'_R \\ &+ Y_d \bar{Q}'_L \phi_d d'_R \\ &+ Y_e \bar{L}'_L \phi_e e'_R + \text{h.c.} \end{aligned}$$



No contributions to electric dipole moments (EDMs)

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V. Keus, [Phys. Rev. D 101, 073007 (2020)]

Z_2-symmetric 3HDM with dark CPV

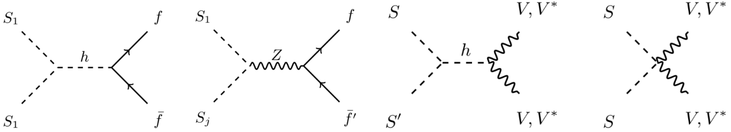
DM is protected by a Z_2 symmetry $(-,-,+)$:

$$\phi_1 \to -\phi_1, \quad \phi_2 \to -\phi_2, \quad \text{SM fields} \to \text{SM fields}, \quad \phi_3 \to \phi_3$$

Z_2 symmetry respected by the vacuum $(0, 0, v)$:

$$\phi_1 = \begin{pmatrix} H_1^+ \\ \frac{H_1+iA_1}{\sqrt{2}} \end{pmatrix}, \qquad \phi_2 = \begin{pmatrix} H_2^+ \\ \frac{H_2+iA_2}{\sqrt{2}} \end{pmatrix}, \qquad \phi_3 = \begin{pmatrix} G^+ \\ \frac{v+h+iG^0}{\sqrt{2}} \end{pmatrix}$$

DM candidate: the lightest CP-mixed state $S_{1,2,3,4}$ (mixtures of $H_{1,2}, A_{1,2}$)



Tension released: the extended dark sector allows for annihilations, co-annihilations and CP-violation!

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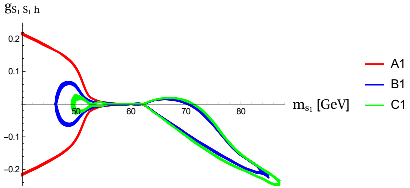
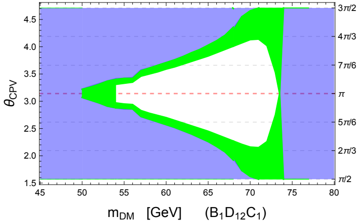
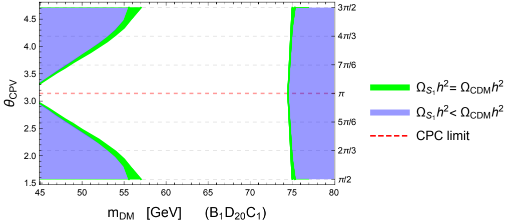
V. Keus, S. F. King, S. Moretti, D. Sokolowska, et al., [JHEP 12, 014 (2016)]

Z_2-symmetric 3HDM with dark CPV

Due to co-annihilation with other dark particles







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V. Keus, S. F. King, S. Moretti, D. Sokolowska, et al., [JHEP 12, 014 (2016)], V. Keus, [Phys. Rev. D 101, 073007 (2020)]