(A theorist’s view of)
The physics of rare events

Marco Cirelli
(CNRS LPTHE Jussieu Paris)
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$\text{DM DD}$  $\nu\nu\beta\beta$

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Dark Matter factsheet

DM exists
DM exists

- galactic rotation curves
- weak lensing (e.g. in clusters)
- ‘precision cosmology’ (CMB, LSS)
Dark Matter factsheet

- DM exists
- it’s a **new, unknown corpuscule**

\[ \text{dilutes as } \frac{1}{a^3} \text{ with universe expansion} \]
Dark Matter factsheet

- DM exists
- it’s a new, unknown particle

No SM particle can fulfill

dilutes as $1/a^3$ with universe expansion
Dark Matter factsheet

- DM exists
- It's a new, unknown particle
- Makes up 26% of total energy
- 82% of total matter

\[ \Omega_{DM} h^2 = 0.1199 \pm 0.0027 \]  

(Notice error!)

[Planck 2015, 1502.01589]

No SM particle can fulfill dilutes as \( 1/a^3 \) with universe expansion.
Dark Matter factsheet

- DM exists
- it’s a **new, unknown particle**
- makes up **26%** of total energy
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- neutral particle ‘dark’...

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- $\Omega_{DM} h^2 = 0.1199 \pm 0.0027$
  (notice error!)
- $p/m << 1$ at CMB formation
DM exists
it’s a new, unknown particle
makes up 26% of total energy
82% of total matter
neutral particle ‘dark’...
cold or not too warm
very feebly interacting

no SM particle can fulfill
dilutes as $1/a^3$ with universe expansion

$\Omega_{DM} h^2 = 0.1199 \pm 0.0027$
(notice error!)

$p/m << 1$ at CMB formation
-with itself
-with ordinary matter
(‘collisionless’)

(Dark Matter factsheet)
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- stable or very long lived

\[ \Omega_{DM} h^2 = 0.1199 \pm 0.0027 \] (notice error!)

\[ \tau_{DM} \gg 10^{17} \text{sec} \]
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- Possibly a relic from the EU

\[ \Omega_{\text{DM}} h^2 = 0.1199 \pm 0.0027 \]

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- Searched for by...

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- No SM particle can fulfill
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\[ \tau_{\text{DM}} \gg 10^{17} \text{ sec} \]

\[ p/m < < 1 \text{ at CMB formation} \]
- With itself
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\( h = 0.7199 \pm 0.0027 \)
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\[
\Omega_{\text{DM}} h^2 = 0.1199 \pm 0.0027 \\
\text{(notice error!)}
\]

\[\tau_{\text{DM}} \gg 10^{17}\text{ sec}\]

Direct Detection

DM

\[\text{DM} \rightarrow \text{DM}\]

SM

\[\text{SM} \rightarrow \text{SM}\]
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- **Direct Detection**
  - DM → DM
  - SM → SM

- **Indirect Detection**
  - DM → SM
  - SM → SM

Note: no SM particle can fulfill the role of DM.
DM dilutes as $1/a^3$ with universe expansion.

$\Omega_{DM} h^2 = 0.1199 \pm 0.0027$
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$p/m << 1$ at CMB formation
- with itself
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$\tau_{DM} \gg 10^{17}$ sec
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- **Direct Detection**
  - DM \(\rightarrow\) DM
  - SM \(\rightarrow\) SM

- **Indirect Detection**
  - DM \(\rightarrow\) SM
  - SM \(\rightarrow\) DM

- **Collider**
  - SM \(\rightarrow\) DM

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$$\Omega_{\text{DM}} h^2 = 0.1199 \pm 0.0027$$
(notice error!)

- $\tau_{\text{DM}} \gg 10^{17} \text{sec}$

- Mass??
- Charge??
- Interactions??
Candidates

A matter of perspective: plausible mass ranges

‘only’ 90 orders of magnitude!
Candidates

A matter of perspective: plausible mass ranges

thermal particles

weak scale (1 TeV)
Candidates

A matter of perspective: plausible cross sections

- cosmology: $\sigma \approx 1/T_0 M_{Pl}$
- vector: $\sigma \approx \alpha^2 m_{N}^2 / M_{Z}^4$
- Higgs: $\sigma \approx \alpha^2 m_{N}^4 / m_{h}^6$
- loop: $\sigma \approx \alpha^4 m_{N}^4 / (4\pi)^2 M_{W}^6$
- atmospheric $\nu$ background
Candidates

WIMPs
Candidates

new physics at the TeV scale

thermal freeze-out

WIMPs
Candidates

WIMPs

new physics at the TeV scale

LHC

Indirect Detection

Direct Detection

thermal freeze-out
DM as a thermal relic from the Early Universe

Boltzmann equation in the Early Universe:

\[ \Omega_X \approx \frac{6 \times 10^{-27} \text{cm}^3 \text{s}^{-1}}{\langle \sigma_{\text{ann}} v \rangle} \]

Relic \( \Omega_{\text{DM}} \approx 0.23 \) for \( \langle \sigma_{\text{ann}} v \rangle = 3 \times 10^{-26} \text{cm}^3/\text{sec} \)

Weak cross section:

\[ \langle \sigma_{\text{ann}} v \rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{1 \text{ TeV}^2} \Rightarrow \Omega_X \sim \mathcal{O}(\text{few } 0.1) \quad \text{(WIMP)} \]
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Candidates

new physics at the TeV scale

Direct Detection

Indirect Detection

LHC

thermal freeze-out

WIMPs
Candidates

new physics at the TeV scale

LHC

Indirect Detection

WIMPs

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thermal freeze-out
Candidates

new physics at the TeV scale

thermal freeze-out

LHC

Indirect Detection

Direct Detection

1. even without a larger framework, WIMPs are still appealing
2.
Candidates

new physics at the TeV scale

thermal freeze-out

LHC

Indirect Detection

Direct Detection

WIMPs

1. even without a larger framework, WIMPs are still appealing
2. the three search strategies are complementary
WIMP DD: ‘theory’
SM weak scale SI interactions
WIMP DD: ‘theory’

SM weak scale SI interactions

tree level, vector

\[ \sigma_{SI} \sim \frac{\alpha^2 m_N^2}{M_Z^4} \]
WIMP DD: ‘theory’

SM weak scale SI interactions

tree level, vector
WIMP DD: ‘theory’

SM weak scale SI interactions

tree level, vector

Escudero, Berlin, Hooper, Lin 1609.09079
WIMP DD: ‘theory’

SM weak scale SI interactions

\[ \sigma_{SI} \sim \frac{\alpha^2 m_N^2}{M_Z^4} \]

tree level, vector

\[ \sigma_{SI} \sim \frac{\alpha^2 m_N^4}{M_h^6} \]

tree level, scalar
WIMP DD: ‘theory’

SM weak scale SI interactions

tree level, vector

tree level, scalar
WIMP DD: ‘theory’

SM weak scale SI interactions

Tree level, vector

Tree level, scalar

Escudero, Berlin, Hooper, Lin 1609.09079
WIMP DD: ‘theory’

SM weak scale SI interactions

- **Tree level, vector**
  \[ \sigma_{SI} \sim \frac{\alpha^2 m_N^2}{M_Z^4} \]

- **Tree level, scalar**
  \[ \sigma_{SI} \sim \frac{\alpha^2 m_N^4}{M_h^6} \]

- **One loop**
  \[ \sigma_{SI} \sim \frac{\alpha^4 m_N^4}{M_W^6} \]
WIMP DD: ‘theory’

SM weak scale SI interactions

- Tree level, vector
- Tree level, scalar
- One loop

[Diagram showing various interactions and limits on dark matter scattering cross-sections against mass.]

WIMP limit plotter created by Tarek Saab, University of Florida and Enectali Figueroa, Northwestern University
Disable watermark in settings.
WIMP DD: ‘theory’

SM weak scale SI interactions

tree level, vector

tree level, scalar

one loop

Cirelli, Fornengo, Strumia hep-ph/0512090
WIMP DD: ‘theory’

SM weak scale SI interactions

**tree level, vector**

Still viable under which conditions?

**tree level, scalar**

**one loop**
WIMP DD: ‘theory’

SM weak scale SI interactions

- tree level, vector
- tree level, scalar
- one loop

Still viable under which conditions?

- real particle
  (Majorana fermion, real scalar)
WIMP DD: ‘theory’

SM weak scale SI interactions

Still viable under which conditions?
- real particle (Majorana fermion, real scalar)
- hypercharge $Y = 0$

one loop
WIMP DD: ‘theory’

SM weak scale SI interactions

- tree level, vector
- tree level, scalar
- one loop

Still viable under which conditions?
- real particle (Majorana fermion, real scalar)
- hypercharge $Y = 0$
- SD interactions only
- inelastic scattering
1. even without a larger framework, WIMPs are still appealing
2. the three search strategies are complementary
Candidates

A matter of perspective: plausible mass ranges

Sub-GeV DM?

‘only’ 90 orders of magnitude!
Candidates

A matter of perspective: plausible mass ranges

Sub-GeV DM?

Why not!

‘only’ 90 orders of magnitude!
Neutrinos exist
Neutrinos exist

massive, oscillating neutrinos are a window to BSM
Neutrinos exist

massive, oscillating neutrinos are a window to BSM progress in the past 2 decades:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>best-fit</th>
<th>3σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m^2_{21}$ [10^{-5} eV^2]</td>
<td>7.37</td>
<td>6.93 – 7.96</td>
</tr>
<tr>
<td>$\Delta m^2_{31(23)}$ [10^{-3} eV^2]</td>
<td>2.56 (2.54)</td>
<td>2.45 – 2.69 (2.42 – 2.66)</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>0.297</td>
<td>0.250 – 0.354</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$, $\Delta m^2_{31(32)} &gt; 0$</td>
<td>0.425</td>
<td>0.381 – 0.615</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$, $\Delta m^2_{32(31)} &lt; 0$</td>
<td>0.589</td>
<td>0.384 – 0.636</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$, $\Delta m^2_{31(32)} &gt; 0$</td>
<td>0.0215</td>
<td>0.0190 – 0.0240</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$, $\Delta m^2_{32(31)} &lt; 0$</td>
<td>0.0216</td>
<td>0.0190 – 0.0242</td>
</tr>
</tbody>
</table>

Nakamura & Petcov, PDG 2018
Neutrinos exist

massive, oscillating neutrinos are a window to BSM progress in the past 2 decades:

open questions:

- Majorana or Dirac?
- absolute mass scale?
- mass ordering?
Neutrinos exist

massive, oscillating neutrinos are a window to BSM progress in the past 2 decades:

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Neutrinos factsheet

\( \nu \beta \beta \)
If neutrinos are Majorana, $0
\nu\beta\beta$ can happen

$$(A, Z) \rightarrow (A, Z + 2) + 2e^-$$
If neutrinos are **Majorana**, $0\nu\beta\beta$ can happen

$$(A, Z) \rightarrow (A, Z + 2) + 2e^-$$

$0\nu\beta\beta$ violates the (total) **lepton number** BSM!
Effective Majorana mass $m_{\beta\beta}$

$$m_{\beta\beta} = \sum_{i=1,2,3} U_{ei}^2 m_i$$

$$\nu_{\ell} = \sum_{i=1,2,3} U_{\ell i} \nu_i$$
Effective Majorana mass $m_{\beta\beta}$ is connected to absolute mass and ordering.

\[ m_{\beta\beta} = \left| \sum_{i=1,2,3} U_{ei}^2 m_i \right| \]

\[ \nu_\ell = \sum_{i=1,2,3} U_{\ell i} \nu_i \]
Conclusions

The physics of rare events (DM DD and $\nu\beta\beta$) is in an experiment driven phase.

Theory can (does) point to preferred directions, but actually too many...