WHAT CAN WE LEARN ABOUT FUNDAMENTAL PHYSICS FROM ASTROPARTICLE PHYSICS?

Antonio Masiero
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and
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Gravity?

The Standard Model

Leptons Quarks

Leptons I II III
Three Generations of Matter

Quarks

Force Carriers

Higgs boson

Gravity?
The Energy Frontier

Origin of Mass

Matter/Anti-matter Asymmetry

Origin of Universe

Unification of Forces

New Physics Beyond the Standard Model

Neutrino Physics

Proton Decay

Dark Matter

Dark Energy

The Intensity Frontier

The Cosmic Frontier
MICRO
PARTICLE PHYSICS
GWS STANDARD MODEL

MACRO
COSMOLOGY
HOT BIG BANG STANDARD MODEL

HAPPY MARRIAGE
Ex: NUCLEOSYNTHESIS

BUT ALSO
POINTS OF FRICTION

- COSMIC MATTER-ANTIMATTER ASYMMETRY
- INFLATION
- DARK MATTER + DARK ENERGY

“OBSERVATIONAL” EVIDENCE FOR NEW PHYSICS BEYOND THE (PARTICLE PHYSICS) STANDARD MODEL
SM FAILS TO GIVE RISE TO A SUITABLE COSMIC MATTER-ANTIMATTER ASYMMETRY

• NOT ENOUGH CP VIOLATION IN THE SM

Need for **New Sources of CPV in Addition to the Phase Present in the CKM Mixing Matrix**

• For $M_{Higgs} > 80$ GeV the ELW. Phase Transition of the SM is a Smooth Crossover

**Need New Physics Beyond SM.** In particular, fascinating possibility: The entire matter in the universe originates from the same mechanism responsible for the extreme smallness of neutrino masses
INFLATION

SEVERE COSMOGICAL PROBLEMS

- CAUSALITY (isotropy of CMBR)
- FLATNESS ($\Omega$ close to 1 today)
- AGE OF THE UNIV.
- PRIMORDIAL MONOPOLES

COMMON SOLUTION FOR THESE PROBLEMS

VERY FAST (EXPONENTIAL) EXPANSION IN THE UNIV.

$V(\phi)$ - VACUUM ENERGY

TRUE VACUUM

$\Omega$ dominated by vacuum en.

NO WAY TO GET AN “INFLATIONARY SCALAR POTENTIAL” IN THE STANDARD MODEL
NO ROOM IN THE PARTICLE PHYSICS STANDARD MODEL FOR INFLATION

\[ V = \mu^2 \phi^2 + \lambda \phi^4 \rightarrow \text{no inflation} \]

Need to extend the SM scalar potential

Ex: GUT’s, SUSY GUT’s,…

ENERGY SCALE OF “INFLATONARY PHYSICS”:

LIKELY TO BE \( \gg M_w \)

DIFFICULT BUT NOT IMPOSSIBLE TO OBTAIN ELECTROWEAK INFLATION IN SM EXTENSIONS

For some inflationary models \( \rightarrow \) large amount of primordial gravitational waves
Present “Observational” Evidence for New Physics

- NEUTRINO MASSES ★★★
- DARK MATTER ★★★★★
- MATTER-ANTIMATTER ASYMMETRY ★★★
- INFLATION ★
The Energy Scale from the “Observational” New Physics

- neutrino masses
- dark matter
- baryogenesis
- inflation

NO NEED FOR THE NP SCALE TO BE CLOSE TO THE ELW. SCALE

The Energy Scale from the “Theoretical” New Physics

- Stabilization of the electroweak symmetry breaking at \( M_W \) calls for an ULTRAVIOLET COMPLETION of the SM already at the TeV scale

- CORRECT GRAND UNIFICATION “CALLS” FOR NEW PARTICLES AT THE ELW. SCALE
On the Energetic Budget of the Universe

- Stars and galaxies are only \(\sim 0.5\%\)
- Neutrinos are \(\sim 0.1-1.5\%\)
- Rest of ordinary matter
  (electrons, protons & neutrons) are 4.4%
- Dark Matter 23%
- Dark Energy 73%
- Anti-Matter 0%
- Higgs Bose-Einstein condensate
  \(\sim 10^{62}\%??\)

Courtesy of H. Murayama
Equazione del Campo di Gravitazione

\[ R_{jk} - \frac{1}{2} g_j R + \Lambda g_k = \frac{8 \pi G}{c^4} T_{jk} \]

Costante Cosmologica

1916.

ANNALEN DER PHYSIK.
VIERTE FOLGE. BAND 49.

1. Die Grundlage
der allgemeinen Relativitätstheorie;
von A. Einstein.

Die im nachfolgenden dargelegte Theorie bildet die denk-
bar weitgehendste Verallgemeinerung der heute allgemein als
"Relativitätstheorie"
ich im folgenden zu
Relativitätstheorie" Verallgemeinerung
leichtert durch die
theorie durch Mix
matiker zuerst die

IS THE COSMOLOGICAL CONSTANT THE SOURCE OF
THE DARK ENERGY OF THE UNIVERSE AND THE
CAUSE OF ITS ACCELERATED EXPANSION?
DM → NEW PHYSICS BEYOND THE
( PARTICLE PHYSICS ) SM - if Newton is right
at scales > size of the Solar System

• \( \Omega_{\text{DM}} = 0.233 \pm 0.013 \) *

• \( \Omega_{\text{baryons}} = 0.0462 \pm 0.0015 \) **

*from CMB (5 yrs. of WMAP) + Type I Supernovae + Baryon Acoustic Oscillations (BAO)

**CMB + Type I SN + BAO in agreement with Nucleosynthesis (BBN)
The **BULLET CLUSTER**: two colliding clusters of galaxies

Stars, galaxies and putative DM behave differently during collision, allowing for them to be studied separately. In **MOND** the lensing is expected to follow the baryonic matter, i.e. the X-ray gas. However the lensing is strongest in two separated regions near the visible galaxies ➔ **most of the mass in the cluster pair is in the form of collisionless DM**.

![Chandra 0.5 Msec Image](1E 0657–56)
DM: the most impressive evidence at the "quantitative" and "qualitative" levels of New Physics beyond SM

- **QUANTITATIVE**: Taking into account the latest WMAP data which in combination with LSS data provide stringent bounds on $\Omega_{\text{DM}}$ and $\Omega_{\text{B}}$ EVIDENCE FOR NON-BARYONIC DM AT MORE THAN 10 STANDARD DEVIATIONS!! THE SM DOES NOT PROVIDE ANY CANDIDATE FOR SUCH NON-BARYONIC DM

- **QUALITATIVE**: it is NOT enough to provide a mass to neutrinos to obtain a valid DM candidate; LSS formation requires DM to be COLD NEW PARTICLES NOT INCLUDED IN THE SPECTRUM OF THE FUNDAMENTAL BUILDING BLOCKS OF THE SM!
Cosmological Bounds on the sum of the masses of the 3 neutrinos from increasingly rich samples of data sets

<table>
<thead>
<tr>
<th>Case</th>
<th>Cosmological data set</th>
<th>Σ bound (2σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>WMAP</td>
<td>&lt; 2.3 eV</td>
</tr>
<tr>
<td>2</td>
<td>WMAP + SDSS</td>
<td>&lt; 1.2 eV</td>
</tr>
<tr>
<td>3</td>
<td>WMAP + SDSS + SN\textsubscript{Riess} + HST + BBN</td>
<td>&lt; 0.78 eV</td>
</tr>
<tr>
<td>4</td>
<td>CMB + LSS + SN\textsubscript{Astier}</td>
<td>&lt; 0.75 eV</td>
</tr>
<tr>
<td>5</td>
<td>CMB + LSS + SN\textsubscript{Astier} + BAO</td>
<td>&lt; 0.58 eV</td>
</tr>
<tr>
<td>6</td>
<td>CMB + LSS + SN\textsubscript{Astier} + Ly-α</td>
<td>&lt; 0.21 eV</td>
</tr>
<tr>
<td>7</td>
<td>CMB + LSS + SN\textsubscript{Astier} + BAO + Ly-α</td>
<td>&lt; 0.17 eV</td>
</tr>
</tbody>
</table>

THE DM ROAD TO NEW PHYSICS BEYOND THE SM: IS DM A PARTICLE OF THE NEW PHYSICS AT THE ELECTROWEAK ENERGY SCALE?
THE “WIMP MIRACLE”

Table 1. Properties of various Dark Matter Candidates

<table>
<thead>
<tr>
<th>Type</th>
<th>Particle Spin</th>
<th>Approximate Mass Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axion</td>
<td>0</td>
<td>$\mu$eV-meV</td>
</tr>
<tr>
<td>Inert Higgs Doublet</td>
<td>0</td>
<td>50 GeV</td>
</tr>
<tr>
<td>Sterile Neutrino</td>
<td>1/2</td>
<td>keV</td>
</tr>
<tr>
<td>Neutralino</td>
<td>1/2</td>
<td>10 GeV - 10 TeV</td>
</tr>
<tr>
<td>Kaluza-Klein UED</td>
<td>1</td>
<td>TeV</td>
</tr>
</tbody>
</table>

Many possibilities for DM candidates, but WIMPs are really special: peculiar coincidence between particle physics and cosmology parameters to provide a Viable DM Candidate at the ELW. Scale
WIMPS (Weakly Interacting Massive Particles)

\[ \#\chi \sim \#\gamma \]

\[ m_\chi \]  

\[ T_{\text{decoupl.}} \text{ typically } \sim \frac{m_\chi}{20} \]

\[ \Omega_\chi \text{ depends on particle physics (}\sigma_{\text{annih.}}\text{) and “cosmological” quantities (H, } T_0, \ldots) \]

\[ \Omega_\chi h^2 \sim \frac{10^{-3}}{<\sigma_{\text{annih.}} V_\chi > \text{ TeV}^2} \]

\[ \sim \frac{\alpha^2}{M^2_\chi} \]

\[ \Omega_\chi h^2 \text{ in the range } 10^{-2} - 10^{-1} \text{ to be cosmologically interesting (for DM)} \]

\[ m_\chi \sim 10^2 - 10^3 \text{ GeV (weak interaction)} \]

\[ \Omega_\chi h^2 \sim 10^{-2} - 10^{-1} !!! \]

THERMAL RELICS (WIMP in thermodynamics equilibrium with the plasma until } T_{\text{decoupl}}\)
## STABLE ELW. SCALE WIMPs from PARTICLE PHYSICS

### 1) ENLARGEMENT OF THE SM

<table>
<thead>
<tr>
<th>SUSY</th>
<th>EXTRA DIM.</th>
<th>LITTLE HIGGS.</th>
</tr>
</thead>
<tbody>
<tr>
<td>((x^{\mu}, \theta))</td>
<td>((x^{\mu}, j^i))</td>
<td>SM part + new part</td>
</tr>
</tbody>
</table>

Anticomm. Coord. \to New bosonic Coord. \to cancel \(\Lambda^2\) at 1-Loop

### 2) SELECTION RULE

<table>
<thead>
<tr>
<th>R-PARITY LSP</th>
<th>KK-PARITY LKP</th>
<th>T-PARITY LTP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutralino spin 1/2</td>
<td>spin 1</td>
<td>spin 0</td>
</tr>
</tbody>
</table>

\(\rightarrow\) DISCRETE SYMM.

\(\rightarrow\) STABLE NEW PART.

### 3) FIND REGION (S) PARAM. SPACE WHERE THE “L” NEW PART. IS NEUTRAL + \(\Omega_L h^2\) OK

<table>
<thead>
<tr>
<th>(m_{\text{LSP}})</th>
<th>(m_{\text{LKP}})</th>
<th>(m_{\text{LTP}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(~100 - 200) GeV *</td>
<td>(~600 - 800) GeV</td>
<td>(~400 - 800) GeV</td>
</tr>
</tbody>
</table>

* But abandoning gaugino-masss unif. \(\rightarrow\) Possible to have \(m_{\text{LSP}}\) down to 7 GeV

Bottino, Donato, Fornengo, Scopel
SUSY & DM : a successful marriage

- Supersymmetrizing the SM does not lead necessarily to a stable SUSY particle to be a DM candidate.
- However, the mere SUSY version of the SM is known to lead to a too fast p-decay. Hence, necessarily, the SUSY version of the SM has to be supplemented with some additional (ad hoc?) symmetry to prevent the p-decay catastrophe.
- Certainly the simplest and maybe also the most attractive solution is to impose the discrete R-parity symmetry.
- MSSM + R PARITY LIGHTEST SUSY PARTICLE (LSP) IS STABLE.
- The LSP can constitute an interesting DM candidate in several interesting realizations of the MSSM (i.e., with different SUSY breaking mechanisms including gravity, gaugino, gauge, anomaly mediations, and in various regions of the parameter space).
**DM ↔ THE ORIGIN OF THE SUSY BREAKING**

**HIDDEN SECTOR SUSY BREAKING AT SCALE $\sqrt{F}$**

- **DM NEUTRALINO**
  - $F = M_W M_{Pl}$
  - $M_{gravitino} \sim F/M_{Pl} \sim (10^2 - 10^3)$ GeV

- **DM GRAVITINO**
  - $F = (10^5 - 10^6)$ GeV
  - $M_{gravitino} \sim F/M_{Pl} \sim (10^2 - 10^3)$ eV

**MESSengers**

**GRAVITY**

**OBSERVABLE SECTOR**

- SM + superpartners
- MSSM: minimal content of superfields
HUMAN PRODUCTION OF WIMPs

WIMPS HYPOTHESIS
DM made of particles with mass 10GeV - 1Tev
ELW scale
With WEAK INTERACT.

LHC, ILC may PRODUCE WIMPS
WIMPS escape the detector → MISSING ENERGY SIGNATURE

POSSIBILITY TO CREATE OURSELVES IN OUR ACCELERATORS THOSE DM PARTICLES WHICH ARE PART OF THE RELICS OF THE PRIMORDIAL PLASMA AND CONSTITUTE 1/4 OF THE WHOLE ENERGY IN THE UNIVERSE
Collider experiments do not distinguish between stable ($\tau > 10^{17}$ s) and long-lived ($\tau > 10^{-7}$ s) particle.

$$P' \rightarrow P \Rightarrow \Omega_{P'} = \frac{m_{P'}}{m_P} \Omega_P$$

Gravitino

Long-lived charged particle at the LHC ($\tilde{\tau} \rightarrow \tau \tilde{\gamma}$)

Hamaguchi-Kuno-Nakaya-Nojiri; Feng-Smith; Ellis-Raklev-Øye; Hamaguchi-Nojiri-de Roeck

Distinctive ToF and energy loss signatures

“Stopper”s in ATLAS/CMS caverns:

- Measure position and time of stopped $\tilde{\tau}$; time and energy of $\tau$
- Reconstruct susy scale and gravitational coupling

G. GIUDICE
PREDICTION OF $\Omega$ DM FROM LHC AND ILC FOR TWO DIFFERENT SUSY PARAMETER SETS

BALTZ, BATTAGLIA, PESKIN, WIZANSKY
HUNTING FOR DARK MATTER

DIRECT DM SEARCHES

INDIRECT DM SEARCHES
Model Independent Annual Modulation Result

DAMA/Nal (7 years) + DAMA/LIBRA (4 years)  
Total exposure: $300555 \text{ kg} \times \text{day} = 0.82 \text{ ton} \times \text{yr}$

Experimental single-hit residuals rate vs time and energy

The data favor the presence of a modulated behavior with proper features at $8.2\sigma$ C.L.

### 2-4 keV

$A=(0.0215\pm0.0026) \text{ cpd/kg/keV}$

$\chi^2/dof = 51.9/66$  
$8.3\sigma$ C.L.

Absence of modulation? No

$\chi^2/dof=117.7/67 \Rightarrow P(A=0) = 1.3 \times 10^{-4}$

### 2-5 keV

$A=(0.0176\pm0.0020) \text{ cpd/kg/keV}$

$\chi^2/dof = 39.6/66$  
$8.8\sigma$ C.L.

Absence of modulation? No

$\chi^2/dof=116.1/67 \Rightarrow P(A=0) = 1.9 \times 10^{-4}$

### 2-6 keV

$A=(0.0129\pm0.0016) \text{ cpd/kg/keV}$

$\chi^2/dof = 54.3/66$  
$8.2\sigma$ C.L.

Absence of modulation? No

$\chi^2/dof=116.4/67 \Rightarrow P(A=0) = 1.8 \times 10^{-4}$
Neutralino-nucleon scattering cross sections along the WMAP-allowed coannihilation strip for tan\(\beta=10\) and coannihilation/funnel strip for tan\(\beta=50\) using the hadronic parameters

\[
\begin{array}{ll}
\frac{m_u}{m_d} & 0.553 \pm 0.043 \\
\frac{m_d}{m_d} & 5 \pm 2 \text{ MeV} \\
\frac{m_s}{m_d} & 18.9 \pm 0.8 \\
m_c & 1.25 \pm 0.09 \text{ GeV} \\
m_b & 4.20 \pm 0.07 \text{ GeV} \\
m_t & 171.4 \pm 2.1 \text{ GeV} \\
\sigma_0 & 36 \pm 7 \text{ MeV} \\
\sum \pi_N & 64 \pm 8 \text{ MeV} \\
a_3^{(p)} & 1.2695 \pm 0.0029 \\
a_8^{(p)} & 0.585 \pm 0.025 \\
\Delta_s^{(p)} & -0.09 \pm 0.03 \\
\end{array}
\]

Ellis, Olive, Sandick

LHC Sensitivity
ultimately: “1 tonne” detectors:

\[ \sigma_p^{SI} \lesssim 10^{-10} \text{ pb} \]

will cover all 68\% region
DM INDIRECT DETECTION

WIMP-WIMP annihilation in the galactic halos may be detected through production of $\gamma$, neutrinos, anti-matter.
INDIRECT SEARCHES OF DM

- **WIMPs collected inside celestial bodies** (Earth, Sun): their annihilations produce energetic neutrinos
- **WIMPs in the DM halo**: WIMP annihilations can take place (in particular, their rate can be enhanced with there exists a CLUMPY distribution of DM as computer simulations of the DM distribution in the galaxies seem to suggest. From the WIMP annihilation:
  -- **energetic neutrinos** (under-ice, under-water exps: Amanda, Antares, Nemo, Nestor, …)
  -- photons in tens of GeV range (gamma astronomy on ground: Magic, Hess, … or in space: Agile, Glast…)
  -- antimatter: look for an excess of antimatter w.r.t. what is expected in cosmic rays (space exps: Pamela, AMS, …)
PAMELA excess: October 2008, stimulated enormous theoretical activity; note: statistical errors only! Fermi: feature observed by ATIC not confirmed

Strumia

EPS09

$\bar{p}$: consistent with bck  
$e^+/e^-$: excess  
$e^- + e^+$: feature?
Pulsars: Fermi & PAMELA

pulsar parameters “randomly” varied!

Grasso et al
Standard Dark Matter best fit

DM with $M = 3 \text{ TeV}$ that annihilates into $\tau^+\tau^-$ with $\sigma v = 1.9 \times 10^{-22} \text{ cm}^3/\text{s}$

(Inverse Compton depends only on the $e^\pm$ spectrum)

Watch boost factor! DM particles too heavy for SUSY to be relevant for LHC
The "Why Now" Problem

- Why do we see matter and cosmological constant almost equal in amount?
- "Why Now" problem
- Actually a triple coincidence problem including the radiation
- If there is a deep reason for $\rho_\Lambda \sim ((\text{TeV})^2/M_{Pl})^4$, coincidence natural

Arkani-Hamed, Hall, Kolda, HM
DO THEY “KNOW” EACH OTHER?

DIRECT INTERACTION $\phi$ (quintessence) WITH DARK MATTER

DANGER: $\phi$ Very LIGHT

$m_{\phi} \sim H_0^{-1} \sim 10^{-33}$ eV

Threat of violation of the equivalence principle
constancy of the fundamental “constants”,…

INFLUENCE OF $\phi$ ON THE NATURE AND THE ABUNDANCE OF CDM

Modifications of the standard picture of WIMPs FREEZE - OUT

CDM CANDIDATES

CATENA, FORNENGO, A.M., PIETRONI, SCHELKE
\[ H = A(T)H_{\text{std}} \quad \text{at early times} \]
\[ H = H_{\text{std}} \quad \text{at later times} \]

\[ A(T) = 1 + \eta \left( \frac{T}{T_f} \right)^\nu \tanh \left( \frac{T - T_{\text{re}}}{T_{\text{re}}} \right) \]
NEUTRALINO RELIC ABUNDANCE IN GR AND S-T THEORIES OF GRAVITY
MICRO

STANDARD MODEL of PARTICLE PHYSICS

G-W-S MODEL

HAPPY MARRIAGE
EX: NUCLEOSYNTHESIS

BUT ALSO

FRICITION POINTS

MACRO

MODELLO STANDARD of COSMOLOGY

HOT BIG BANG

DARK MATTER AND DARK ENERGY

LHC → AN EXCEPTIONAL WINDOW TO EXPLORE THE UNIVERSE AND ITS ORIGIN, BUT...
NEW PHYSICS AT THE ELW SCALE

DM - FLAVOR
for DISCOVERY
and/or FUND. TH.
RECONSTRUCTION

A MAJOR LEAP AHEAD IS NEEDED

"LOW ENERGY" PRECISION PHYSICS

FCNC, CP ≠, (g-2), (ββ)_{0\nu\nu}

LEPTOGENESIS

LEPTONIC PHYSICS

GW INFLATION

NEUTRINO PHYSICS

m_\chi n_\chi \sigma_\chi \ldots

LINKED TO COSMOLOGICAL EVOLUTION
BACK-UP SLIDES
EVIDENCE FOR DM

Various astrophysical sources have confirmed the existence of Dark Matter (DM)

- Binding of Galaxies in Clusters (F. Zwicky, 1933)
- Rotation curves of Galaxies (V.C. Rubin and W.K. Ford, 1970)
- Bindings of hot gases in clusters
- Gravitational Lensing observations
- Large Scale Structure simulations
- High z - Supernovae
- Observations of colliding clusters of Galaxies

The most direct and accurate evidence comes from WMAP by measuring anisotropies of the CMB power spectrum

~ 73% DarkEnergy, ~ 23% DarkMatter, 4% Baryons
PROSPECTS FOR DISCOVERING THE CMSSM AT THE LHC IN LIGHT OF WMAP

RED: FULL SAMPLE OF CMSSM MODELS
BLUE: POINTS COMPATIBLE WITH WMAP
GREEN: POINTS ACCESSIBLE TO LHC
YELLOW: POINTS ACCESSIBLE TO PRESENT DIRECT DM SEARCHES

Ellis et al.
A.M., PROFUMO, ULLIO
WHY TO GO BEYOND THE SM

“OBSERVATIONAL” REASONS

• HIGH ENERGY PHYSICS
  NO (but $A_{FB}^{Z \rightarrow bb}$)
  • FCNC, CP ≠
  NO (but $b \rightarrow sqq$ penguin …)
  • HIGH PRECISION LOW-EN.
  NO (but $(g-2)_{\mu}$ …)

• NEUTRINO PHYSICS
  YES $m_\nu \neq 0$, $\theta_\nu \neq 0$

• COSMO - PARTICLE PHYSICS
  YES (DM, $\Delta B_{COSm}$, INFLAT., DE)

THEORETICAL REASONS

• INTRINSIC INCONSISTENCY OF SM AS QFT
  NO (spont. broken gauge theory without anomalies)

• NO ANSWER TO QUESTIONS THAT “WE” CONSIDER “FUNDAMENTAL” QUESTIONS TO BE ANSWERED BY “FUNDAMENTAL” THEORY
  YES (hierarchy, unification, flavor)
THEORETICAL REASONS TO GO BEYOND THE SM

- **FLAVOR PUZZLE** → RATIONALE FOR FERMION MASSES AND MIXINGS

- **UNIFICATION PROBLEM** → NO REAL UNIF. OF ELW. + STRONG INTERACTIONS + GRAVITY LEFT OUT OF THE GAME

- **HIERARCHY PROBLEM(S)** → ULTRAVIOLET COMPLETION OF THE SM TO (NATURALLY) STABILIZE THE ELW. BREAKING SCALE + TUNING OF THE COSMOLOGICAL CONSTANT
THE RISE AND FALL OF NEUTRINOS AS DARK MATTER

• Massive neutrinos: only candidates in the SM to account for DM. From here the “prejudice” of neutrinos of a few eV to correctly account for DM

• Neutrinos decouple at ~1 MeV; being their mass $<\text{decoupling temperature}$, neutrinos remain relativistic for a long time. Being very fast, they smooth out any possible growth of density fluctuation forbidding the formation of proto-structures.

• The “weight” of neutrinos in the DM budget is severely limited by the observations disfavoring scenarios where first superlarge structures arise and then galaxies originate from their fragmentation
LSS PATTERN AND NEUTRINO MASSES

(E.g., Ma 1996)
SPIN - INDEPENDENT NEUTRALINO - PROTON CROSS SECTION FOR ONE OF THE SUSY PARAM. FIXED AT 10 TEV

PROFUMO, A.M., ULLIO
Some final thoughts

• Very solid evidence of (a large amount of) NON-BARYONIC COLD DM
• In the SM NO CANDIDATE FOR COLD DM (ordinary neutrinos are hot DM; indeed, the best limit on neutrino masses comes from cosmology!)
• **WIMPS:** (very) appealing COSMO (HBB SM) – PARTICLE (GWS SM) “conspiracy” in providing the (quantitatively and qualitatively) right DM
• WIMPS can be part of the NEW PHYSICS at the ELW scale (link ultraviolet completion of the SM – DM constituents)
• Possibility of a joint cosmo – and particle – exploration of the TeV New Physics
• If WIMP is the DM: complementary hunting for TeV New Physics at LHC and in DIRECT and INDIRECT searches of DM
LHC and “LOW-ENERGY” NEW PHYSICS

- **LHC discovers NP**: difficult, if not impossible, to “reconstruct” the fundamental theory lying behind those signals of NP;

- **LHC does not see any signal of NP**: still a NP related to the stabilization of the elw. scale may be present, but with particles whose masses are in the multi-TeV range.
THE G-W-S STANDARD MODEL

[Diagram showing the G-W-S Standard Model with Elementary Particles and Force Carriers, including Quarks, Leptons, and bosons like photons (γ), gluons (g), and W and Z bosons.]