Dark Matter et al.

Richard Jacobsson

<table>
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<th>Year</th>
<th>SUSY</th>
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<td>2020</td>
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</table>
13.7 billion years ago in a far gone place

We have also Dark Matter to thank for our existence!
Our dawn on Dark Matter

- Observation of cluster of “nebulae”: F. Zwicky (1933)
  
  *Die Rotverschiebung von extragalaktischen Nebeln*
  
  von F. Zwicky,
  
  (16. II. 33.)
  
  § 5. Bemerkungen zur Streuung der Geschwindigkeiten
  
  im Coma-Nebelhaufen.

  Rotverschiebung extragalaktischer Nebel.

  Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal größer sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete. Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel größerer Dichte vorhanden ist als leuchtende Materie.

- Galaxy rotation curves: V. Rubin (1970)


  ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

  Vera C. Rubin† and W. Kent Ford, Jr.
  Department of Terrestrial Magnetism, Carnegie Institution of Washington and
  Lowell Observatory, and Kitt Peak National Observatoryγ

- Dark Matter is non-interacting!

  In order to obtain, as observed, a medium-sized Doppler effect of 1000 km/s or more, the average density in the Coma system would have to be at least 400 times greater than that derived on the basis of observations of luminous matter [A. Einstein and W. De Sitter, Proc. of the Nat. Acad. Sci. Vol. 18, S.213, 1932]. If this should be verified, it would lead to the surprising result that dark matter exists in much greater density than luminous matter.
Establishing Dark Matter – direct observation

- Tracing DM: Gravitational lensing confirms previous observations (2003)
  - Bullet galaxy clusters (2003)
  - Galaxy cluster Cl 0024+17 (ZwCl 0024+1652)

 Collision between two galaxy clusters
  - In red, X-ray emitting plasma = dominant baryonic mass (5-15%)
  - In blue, reconstruction of total mass distribution from lensing
  - Dark Matter remains around galaxy clusters (1-2% of mass) undisturbed
  ➔ Almost collisionless

 ➔ Very different density profile and dynamics from ordinary matter!
 Why does it form a halo?

 ➔ Independent limits on Dark Matter self-interaction, and interaction with ordinary matter
DM evidence from Cosmic Microwave Background (CMB) (2003)

- Thermal photons decouple from matter at \( T \approx 3000 \) K at an age of 380,000 years
  - Universe gets transparent to light
  - The CMB carries a snapshot of the seeds to structure formation ("acoustic peaks")

Gravity turns primordial density fluctuations into structures

- Distance scale over which mass collapse and form structures ("Jeans' instability")

\[
\text{Distance scale} \propto \frac{\text{temperature}}{\text{particle mass}} \times \text{matter density} \quad \text{for ordinary matter}
\]

- Gravity and electromagnetism collaborate to form gas clouds, stars and galaxies
- With no self-coupling there is no energy transfer or "sticking" between DM particles
  - DM distribution becomes "halo-like"
DM can contribute in two ways:

- Increasing mass density (increasing Jeans' scale for gravitational collapse)
- Damping clustering of (too) small structures due to free-streaming $d_{FS} \propto \frac{\text{velocity}}{\sqrt{\text{mass density}}}$
  
  $\Rightarrow$ Depends on "velocity" (relativistic=radiation/non-relativistic)

DM could produce a drop-off in the power spectrum of structures as a function of the scale

- Wash out of structures with sizes in the range $10^6 – 10^8$ solar masses
- How to measure?
  - Structures of $<10^8$ solar masses are very unlikely to have formed stars!
1. Gravitational lensing sensitive sub-structures $\mathcal{O}(10^7)$ solar masses

2. “Lyman-α forest” measured by spectroscopic telescopes – intergalactic hydrogen clumping
Not everything is singing and dancing:

“Missing satellite” or “too-big-to-fail problem”

Simulated halos retain many DM substructures from initial collapse (“sub-halos”)

Only ~10 satellites strongly visible around Milky Way

Jury is still out on this

- An option is self-interacting Dark Matter (SIDM), non-gravitational “Dark Interaction”?
  - How was Dark Matter created, how was the abundance regulated?
  - Is there some dynamics, DM stable/decay? ➔ particle physics questions!

“Core-cusp problem”

Central density profile: $\rho(r) \propto r^{-\alpha}$

- Simulation with CDM: $\alpha = 1 - 1.5$ ("Cuspy")
- Observed profile closer to $\alpha \sim 0$ ("Core")

Supernovae outflows drive flattening of DM profile?
Standard Model is not enough!

“Visible sector responsible for everything beyond structure formation?”

~95% of energy content in Universe today is Unknown!
Two types of evidence for New Physics:

**Experimental evidence for New Physics**
1. Neutrino masses and oscillations
2. Matter/antimatter asymmetry of the Universe, BBN and CMB $\eta = \frac{n_B}{n_Y} \bigg|_{T=3K} \sim 6 \times 10^{-10}$
3. Dark Matter
4. Dark Energy
   ➔ *No prejudice on mass/energy scale of the “new physics” required to solve these!*

**Theoretical “evidence” for New Physics – “prejudice”**
1. Hierarchy problem and stability of Higgs mass – Naturalness/Fine-tuning
2. Flavour structure of Standard Model
3. Strong CP problem (why CP violation is suppressed in strong interactions?)
4. Unification of interactions
5. Gravity
6. Inflation
7. …..
   ➔ *Preference for high mass/energy scales….*
So far, most experimental efforts have been focusing on searching for particles with masses just above the electroweak scale and with sizeable couplings to SM particles.
Why still SUSY searches in 2040++?

Indeed, even if fine-tuned, it makes our universe more likely

“SUSY anywhere is better than SUSY nowhere”
What are the alternatives? “New particles” can hide in two ways:

- Very massive OR very weakly coupled

DM tells us there could be a “very weakly interacting” scale
W. Pauli (1930) about the neutrino: "I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do."

What should/can we concentrate on in particle physics?
Room for searches below 10 GeV/c²

Many reasons MeV – GeV region is particularly interesting...
1. We know this mass scale exists !...
2. Absence of hints for new particles at higher energies
3. Cosmologically interesting
4. Largely unexplored territory
5. And because we can!
   (...test many very reasonable and far-reaching theoretical models!)

- Log₁₀ m [GeV]
- QCD axion
- Right Handed Neutrinos
- Particles required for baryogenesis
- Particles required for Higgs mass stability

Space for heavy WIMPs closing

LHC Operations Workshop, Evian, 31 January 2019
Another “prejudice”: SM not only successful, we discovered everything it predicted

Extending SM with a “Hidden Sector” using the same successful formalism
  • Lagrangian equation of motion + wave function + relativity + quantization + symmetries ↔ conservation + renormalizability, …
  • Lagrangian $\mathcal{L} \equiv [\text{Kinetic terms}] - [\text{Potential energy}] \Rightarrow [\text{Freemoving particles}] - [\text{Interactions}]$

Toy example
Another “prejudice”: SM not only successful, we discovered everything it predicted, so…

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- Lagrangian $\mathcal{L} \equiv [\text{Kinetic terms}] - [\text{Potential energy}] \implies [\text{Freemoving particles}] - [\text{Interactions}]

Toy example

$$\mathcal{L}_{u(1)}^{u'(1)} = \begin{bmatrix} i\bar{\psi}\gamma^\mu \partial_\mu \psi - m\bar{\psi}\psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - ie\bar{\psi}\gamma^\mu A_\mu \psi \end{bmatrix}$$

- Free fermion
- Fermion mass
- Free photon
- Interaction fermion-photon $\gamma$
- $f$
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Toy example (Higgs in the “…”)
Building a dynamic model of Hidden Sector

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Toy example

$$\mathcal{L}_{U(1)}^{U'(1)} = i \bar{\psi} \gamma^\mu \partial_\mu \psi - m \bar{\psi} \psi - \frac{i}{4} F_{\mu\nu} F^{\mu\nu} - i e \bar{\psi} \gamma^\mu A_\mu \psi - \frac{1}{4} \varepsilon F_{\mu\nu} V^{\mu\nu} + i \bar{\chi} \gamma^\mu \partial_\mu \chi - m \bar{\chi} \chi - \frac{1}{4} V_{\mu\nu} V^{\mu\nu} - i e \bar{\chi} \gamma^\mu A'_\mu \chi \ldots$$

One more fully valid term possible!

A weak “interaction” between the visible sector and the dark sector, and a dark matter self-interaction!
Another “prejudice”: SM not only successful, we discovered everything it predicted, so…

Extending SM with a “Hidden Sector” using the same successful formalism
- Lagrangian equation of motion + wave function + relativity + quantization + symmetries ↔ conservation + renormalizability, …
- Lagrangian $\mathcal{L} \equiv [\text{Kinetic terms}] - [\text{Potential energy}] \implies [\text{Freemoving particles}] - [\text{Interactions}]

Toy example

\[
\mathcal{L}_{U(1)} = i\bar{\psi} \gamma^\mu \partial_\mu \psi - m\bar{\psi} \psi - \frac{1}{4} F_{\mu \nu} F^{\mu \nu} - ie\bar{\psi} \gamma^\mu A_\mu \psi + \frac{1}{4} \varepsilon F_{\mu \nu} V^{\mu \nu},
\]

One more fully valid term possible!

Kinetic mixing between ordinary photon and dark photon (can be massive)!

“Vector portal” → Coupling extremely week

Dark versions can be considered for all (neutral) SM features!
Dynamics of Hidden Sector may drive dynamics of Visible Sector!

- Dark Matter (trivial!) – fermionic or scalar
- Neutrino oscillations
- Baryon asymmetry
- Higgs mass
- Dark Energy
- Inflaton
- ……

Simple extension and no new energy scale!
Composite operators as “portals”:

- **Vector portal ($\gamma/Z^0$) (aka “Dark photons”)**
  - Motivated in part by idea of “mirror world” restoring L/R symmetry, dark matter, g-2 anomaly, …

- **Scalar portal ($H^0$) (aka “Dark Higgses”)**
  - Mass mixing with dark singlet scalar $\chi$: $(g\chi + \lambda\chi^2)H^\dagger H$
  - Mass to Higgs boson and mass generation in dark sector, inflaton, dark phase transitions BAU, dark matter,…
"Neutrino portal" (aka “sterile neutrinos")
- Mixing with right-handed neutrino N (Heavy Neutral Lepton): $Y_{1\ell} H^\dagger \bar{N}_1 L_\ell$
  ➔ Neutrino oscillation and mass, baryon asymmetry, dark matter

E.g. vMSM (Shaposhnikov et al.)

$N_1$: O(keV/c^2) mass HNL as decaying dark matter
$N_{2,3}$: Mass in range 100 MeV/c^2 – 100 GeV/c^2, origin of neutrino oscillations/mass and baryon asymmetry

"Axion portal" (not strong CP axion) (aka axion-like particles ALPs)
- Mixing with Axion Like Particles, pseudo-scalars pNGB: $\frac{a}{F} G_{\mu\nu} \bar{G}^{\mu\nu}, \frac{\partial a}{F} \bar{\psi} \gamma_5 \psi, \text{etc}$
  ➔ Arise in spontaneous breaking of approximate symmetries at a high mass scale F
  ➔ Extended Higgs, SUSY breaking, dark matter, possibility of inflaton,…

➔ Or combinations thereof!!
“Neutrino portal”

- Mixing with right-handed neutrino $N$ (Heavy Neutral Lepton): $Y_{i\ell} H^\dagger N_l L_\ell$
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“Axion portal” (not strong CP axion)

- Mixing with Axion Like Particles, pseudo-scalars $pNGB$: $\frac{a}{F} G_{\mu\nu} G^{\mu\nu}, \frac{a}{F} \bar{\psi} \gamma \mu \gamma_5 \psi$, etc
- Arise in spontaneous breaking of approximate symmetries at a high mass scale $F$
- Extended Higgs, SUSY breaking, dark matter, possibility of inflaton,…

Or combinations thereof!!

Rich variety and phenomenology requires generic and complementary search!
Production and principal sources

- **Dark vectors (“Dark Photons”)**
  - Loads of photons! – Bremsstrahlung, light neutral meson decays, quark annihilation
  - Sources: electron fixed target beams, electron colliders, proton fixed heavy target

- **Dark scalars (“Dark Higgses”)**
  - Loads of Higgses (real) or in Penguin decays of K, D, B mesons
  - Proton colliders, proton fixed heavy target, electron colliders (H factory)

- **Heavy neutral leptons (“sterile neutrinos”)**
  - Loads of weak decays of hadrons, W, Z
  - Sources: proton fixed heavy target, proton colliders, electron colliders (W, Z)

- **Axion-like particles (“ALPs”)**
  - Possible couplings to photons, gluons and fermions, loads of interactions!
  - Proton colliders, proton heavy fixed target, space

- **(Light) Dark Matter direct detection (“vWIMPs”)**
  - Through one of the portals or Space!

- **Fixed target luminosities not to be ignored**
  - “Primary” SPS FT luminosity for a long target (e.g. 1m+ Mo, $\rho_N$ nucleon density)
    - $S_{\text{SPS}} \int \Phi_0 \times \rho_N \times e^{-1/\lambda} \, dl = \Phi_0 \times \rho_N \times \lambda = 3.6 \times 10^{45} \, \text{cm}^{-2}$ (cascades not incl.)
  - HL-LHC luminosity: $L_{\text{int}}[\text{year}^{-1}] = 10^7 \, s \times 10^{35} \, \text{s}^{-1} \text{cm}^{-2} = 10^{42} \, \text{cm}^{-2}$
Weak couplings and light masses make HS particles “long-lived”

- Four generic cases for detection ($\epsilon \ll 1$):

**Production**

- **Direct**
  - $e, p \rightarrow \epsilon^2$ Hidden portal (long-lived) \rightarrow SM
  - $e, p \rightarrow \epsilon^2$ Hidden portal (not long-lived) \rightarrow SM
  - $e, p \rightarrow \epsilon^2$ Hidden portal (very long-lived, or very light) \rightarrow SM
  - $e, p \rightarrow \epsilon^2$ Hidden portal (not long-lived) \rightarrow SM

**Detection**

- **Decay signature (“displaced vertex) Allow identification of model**
  - Probability $\propto \epsilon^4$

- **Dark matter scattering Recoil against electron or nuclei**
  - Probability $\propto \epsilon^4$

- **Escape detector Missing energy/momentum/mass**
  - Probability $\propto \epsilon^2$

- **Cannot be distinguished**

If $m_{HP} > 2m_{DM}$

- Escape detector
- Missing energy/momentum/mass
- Probability $\propto \epsilon^2$
Weak couplings and light masses make HS particles “long-lived”

- Four generic cases for detection ($\epsilon \ll 1$):

Production

- **Direct**
  - $e, p$\n  - Hidden portal (long-lived)
  - SM

- **Indirect**
  - $e, p$\n  - Hidden portal (very long-lived, or very light)
  - SM

Detection

- **SM**
  - $e, p$\n  - Hidden portal (long-lived)
  - SM

- **Hidden portal**
  - $\epsilon^2$
  - Escape detector
  - Missing energy/momentum/mass
  - Probability $\propto \epsilon^2$

- **Hidden portal**
  - $\epsilon^2$
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- **Hidden portal**
  - $\epsilon^2$
  - If $m_{HP} > 2m_{DM}$
  - Escape detector
  - Missing energy/momentum/mass

Experimental challenge $\Rightarrow$ Intensity Frontier
Experimental techniques

- Direct search: visible decay to SM particles \((signal \propto \epsilon^4)\)

- "Fixed target mode setups":
  - NA62++@CERN (p@400, \(10^{18}\))
  - HPS, APEX, DarkLight@JLAB (e@1-10)
  - SHiP@CERN (p@400, \(2 \times 10^{20}\))
  - SeaQuest@FNAL (p@120, \(10^{18}-10^{20}\)) (LBNF@FNAL)

- "Collider mode setups":
  - ATLAS, CMS, LHCb @LHC (no absorbers)
  - BELLE2@sKEKB (no absorber)
  - FASER@LHC
  - MATHUSLA@LHC (no spectrometer)

- Assumes \(m_{HP} > 2m_e\), \(m_{HP} < 2m_\chi\) where \(\chi\) is DM particle
Experimental techniques

- Direct search: visible decay to SM particles \((signal \propto \epsilon^4)\)
  - Protons or electrons
  - Long high-Z/A target
  - (Absorber/sweeper)
  - Assumes \(m_{HP} > 2m_e\), \(m_{HP} < 2m_\chi\) where \(\chi\) is DM particle

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“Fixed target mode setups”:
- BDX@JLAB \((e@11, 10^{22})\), MiniBooNE@FNAL \((p@8.9, 10^{20})\), SHiP@CERN \((p@400, 2x10^{20})\) (interest for BDX-like experiments at LNF, Mainz (MESA), SLAC, Cornell…)}
**Direct search: visible decay to SM particles** \((signal \propto \epsilon^4)\)

- Protons or electrons
- Long high-Z/A target
- Assumes \(m_{HP} > 2m_e, \ m_{HP} < 2m_\chi\) where \(\chi\) is DM particle

**Direct search: Scattering off atomic electrons and nuclei** \((signal \propto \epsilon^4)\)

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**Operating with electrons** (production/detection) assumes vector portal
Some new options for CERN

- FASER
- SHiP
- MATHUSLA
- NA64++
- LDMX
- IAXO (solar)
Opportunities for CERN

- Summary of the Physics Beyond Collider working group:

<table>
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<tr>
<th>Proposal</th>
<th>Main Physics Cases</th>
<th>Beam Line</th>
<th>Beam Type</th>
<th>Beam Yield</th>
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<td><strong>sub-eV mass range:</strong></td>
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<td>axions from sun</td>
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<td>LHC-FT</td>
<td>charmed hadrons oEDMs</td>
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<td><strong>MeV-GeV mass range:</strong></td>
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<td>SHiP</td>
<td>ALPs, Dark Photons, Dark Scalars</td>
<td>BDF, SPS</td>
<td>400 GeV p</td>
<td>2 \cdot 10^{20}/5 years</td>
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<td>NA62++</td>
<td>LDM, HNLs, lepto-phobic DM, ..</td>
<td>K12, SPS</td>
<td>400 GeV p</td>
<td>up to 3 \cdot 10^{18}/year</td>
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<td>NA64++</td>
<td>ALPs, Dark Photons, Dark Scalars, HNLs</td>
<td>H4, SPS</td>
<td>100 GeV e^-</td>
<td>5 \cdot 10^{12} eot/year</td>
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<td>LDMX</td>
<td>+ L_μ – L_τ</td>
<td>M2, SPS</td>
<td>160 GeV μ</td>
<td>10^{12} – 10^{13} mot/year</td>
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<td>LDMX</td>
<td>+ CP, CPT, lepto-phobic DM</td>
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<td>5 \cdot 10^{12}/year</td>
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<td>AWAKE/NA64</td>
<td>Dark Photon, LDM, ALPs,...</td>
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<td>8 (SLAC) -16 (eSPS) GeV e^-</td>
<td>10^{16} – 10^{18} eot/year</td>
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<td>RedTop</td>
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<td>MATHUSLA200</td>
<td>Weak-scale LLPs, Dark Scalar,</td>
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<td>1.8 or 3.5 GeV</td>
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<td>LHCb IP</td>
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<td>300 fb^{-1}</td>
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**Access to higher masses**

- Includes also Dark Matter candidates from SUSY and Extra Dimensions models: Neutralino, sgoldstino, axino, saxion,…)

**Signatures:**

- Mono-jet + missing transverse energy
- Disappearing tracks
- Long-lived particle search with displaced vertices (leptons/jets)
- Invisible Higgs decays $pp \rightarrow Z(\rightarrow ll)H(\rightarrow \text{invisible})$

⇒ Very challenging with the increased pileup in the future
# Searches for Long-Lived Particles at LHC

**ATLAS Long-lived Particle Searches** - 95% CL Exclusion

**Status:** July 2018

<table>
<thead>
<tr>
<th>Model</th>
<th>Signature</th>
<th>$\mathcal{L} dt$ [fb$^{-1}$]</th>
<th>Lifetime limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPV $x_i \rightarrow e e v/\mu v/\mu v$</td>
<td>displaced lepton pair</td>
<td>20.3</td>
<td>$\tilde{x}_0$ lifetime: 7-740 mm</td>
</tr>
<tr>
<td>GGM $x_i \rightarrow Z \gamma$</td>
<td>displaced vtx + jets</td>
<td>20.3</td>
<td>$\tilde{x}_0$ lifetime: 6-480 mm</td>
</tr>
<tr>
<td>GGM $x_i \rightarrow Z \gamma$</td>
<td>displaced dimuon</td>
<td>32.9</td>
<td>$\tilde{x}_0$ lifetime: 0.029-16.8 mm</td>
</tr>
<tr>
<td>AMSG</td>
<td>non-pointing or delayed $y$</td>
<td>20.3</td>
<td>$\tilde{x}_0$ lifetime: 0.36-8.4 mm</td>
</tr>
<tr>
<td>AMSG $p p \rightarrow x_i x_i x_i x_i$</td>
<td>disappearing track</td>
<td>20.3</td>
<td>$\tilde{x}_0$ lifetime: 0.22-3.0 mm</td>
</tr>
<tr>
<td>AMSG $p p \rightarrow x_i x_i x_i x_i$</td>
<td>disappearing track</td>
<td>36.1</td>
<td>$\tilde{x}_0$ lifetime: 0.057-1.53 mm</td>
</tr>
<tr>
<td>Stealth SUSY</td>
<td>large pixel dE/dx</td>
<td>18.4</td>
<td>$\tilde{x}_0$ lifetime: 1.31-9.0 mm</td>
</tr>
<tr>
<td>Split SUSY</td>
<td>2 ID/MS vertices</td>
<td>19.5</td>
<td>$\tilde{x}_0$ lifetime: &gt; 0.9 mm</td>
</tr>
<tr>
<td>Split SUSY</td>
<td>large pixel dE/dx</td>
<td>36.1</td>
<td>$\tilde{x}_0$ lifetime: &lt; 0.03-13.2 mm</td>
</tr>
<tr>
<td>Split SUSY</td>
<td>displaced vtx + $E_T^{miss}$</td>
<td>32.8</td>
<td>$\tilde{x}_0$ lifetime: 0.0-2.1 m</td>
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</table>

**Higgs BR = 10**%

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<tbody>
<tr>
<td>$H \rightarrow ss$</td>
<td>2 low-EMF trackless jets</td>
<td>20.3</td>
<td>$\tilde{s}$ lifetime: 0.41-5.75 m</td>
</tr>
<tr>
<td>$H \rightarrow ss$</td>
<td>2 ID/MS vertices</td>
<td>19.5</td>
<td>$\tilde{s}$ lifetime: 0.31-25.4 m</td>
</tr>
<tr>
<td>FRVZ $H \rightarrow 2\gamma + X$</td>
<td>2 $e^-\mu^+$-jets</td>
<td>20.3</td>
<td>$\gamma_\gamma$ lifetime: 0-3 mm</td>
</tr>
<tr>
<td>FRVZ $H \rightarrow 2\gamma + X$</td>
<td>2 $e^-\mu^+$-jets</td>
<td>3.4</td>
<td>$\gamma_\gamma$ lifetime: 0.022-1.113 m</td>
</tr>
<tr>
<td>FRVZ $H \rightarrow 4\gamma + X$</td>
<td>2 $e^-\mu^+$-jets</td>
<td>3.4</td>
<td>$\gamma_\gamma$ lifetime: 0.038-1.63 m</td>
</tr>
<tr>
<td>$H \rightarrow Z_d Z_d$</td>
<td>displaced dimuon</td>
<td>32.9</td>
<td>$Z_d$ lifetime: 0.009-24.0 m</td>
</tr>
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</table>

**Scalar**

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</tr>
</thead>
<tbody>
<tr>
<td>$\Phi(300 \text{ GeV}) \rightarrow ss$</td>
<td>2 low-EMF trackless jets</td>
<td>20.3</td>
<td>$\tilde{s}$ lifetime: 0.26-7.9 m</td>
</tr>
<tr>
<td>$\Phi(300 \text{ GeV}) \rightarrow ss$</td>
<td>2 ID/MS vertices</td>
<td>19.5</td>
<td>$\tilde{s}$ lifetime: 0.19-31.9 m</td>
</tr>
<tr>
<td>$\Phi(600 \text{ GeV}) \rightarrow ss$</td>
<td>2 low-EMF trackless jets</td>
<td>3.2</td>
<td>$\tilde{s}$ lifetime: 0.09-2.7 m</td>
</tr>
<tr>
<td>$\Phi(900 \text{ GeV}) \rightarrow ss$</td>
<td>2 low-EMF trackless jets</td>
<td>20.3</td>
<td>$\tilde{s}$ lifetime: 0.15-4.1 m</td>
</tr>
<tr>
<td>$\Phi(1 \text{ TeV}) \rightarrow ss$</td>
<td>2 ID/MS vertices</td>
<td>19.5</td>
<td>$\tilde{s}$ lifetime: 0.11-16.3 m</td>
</tr>
<tr>
<td>$\Phi(1 \text{ TeV}) \rightarrow ss$</td>
<td>2 low-EMF trackless jets</td>
<td>3.2</td>
<td>$\tilde{s}$ lifetime: 0.78-16.0 m</td>
</tr>
</tbody>
</table>

**Other**

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<tbody>
<tr>
<td>HV $Z^0(1 \text{ TeV}) \rightarrow q \bar{q}_v$</td>
<td>2 ID/MS vertices</td>
<td>20.3</td>
<td>$\tilde{s}$ lifetime: 0.1-4.9 m</td>
</tr>
<tr>
<td>HV $Z^0(2 \text{ TeV}) \rightarrow q \bar{q}_v$</td>
<td>2 ID/MS vertices</td>
<td>20.3</td>
<td>$\tilde{s}$ lifetime: 0.1-4.9 m</td>
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$\sqrt{s} = 8 \text{ TeV}$ $\sqrt{s} = 13 \text{ TeV}$
**Space prospects - Indirect detection**

- **Weak gravitational lensing to identify and characterize DM structures – Wide area sky surveys**
  - Ongoing: Dark Energy Survey (DES), Kilo-Degree Survey, Hyper Suprime-Cam, Pan-STARRS,
  - Future: Large Synoptic Survey Telescope (LSST), start 2022

  Survey of 30 billion objects expected in 10 years
  - 8.4 m diameter primary mirror
  - 3.2 gigapixel camera
  - Full-sky scan in 3 nights
  - 15 terabyte data/night

- **Small scale clustering at large redshift ("Lyman-α forest")**
  - Dark Energy Spectroscopic Instrument (DESI), start 2019

  - 5000 fibers in robotic actuators
  - 10 fiber cable bundles
  - 3.2 deg. field of view optics
  - 10 spectrographs
Space prospects - indirect detection

- Observation of decay/annihilation or decay products of cosmological WIMPs

- Gamma-rays
- Neutrinos
- Anti-matter
- Fermi-LAT.
- Cherenkov Telescopes (IACTs)
- IceCube, Antares...
- AMS-02, DAMPE, CALET...
Indirect detection – interesting hints?

- Hint of decaying Dark Matter?

- More data to confirm/reject was expected from Astro-H/Hitomi X-ray telescope which was lost few weeks after launch on February 17, 2016

- Waiting for a new high-resolution telescope, observation has been substantiated with data from NuSTAR (11σ) and Chandra (3σ)

What next?

- New telescope from JAXA?
- Large ESA X-ray Athena+ mission 2028
- Or discovery of HNLs at accelerators!...

E.g. 7 keV sterile neutrino

\[ E_\gamma = \frac{M_N c^2}{2} \]

\[ \tau \sim 10^{28} \text{ years} \]
Observation of cosmological Dark Matter by WIMP-nucleus/electron collision

- Crystals (NaI, Ge, Si)
- Cryogenic Detectors
- Liquid Noble Gases

- Tracking: DRIFT, DMTPC
  MIMAC, NEWS
  NEWAGE

- Superheated Liquids: PICO
  SIMPLE

- CoGeNT
- CDEX
- Malbek
- DAMIC
- NEWS (gas)

+ Axion searches (IAXO, JURA)

Space prospects – direct detection (WIMP)
Observation of cosmological Dark Matter by WIMP-nucleus/electron collision

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Axions/ALPs
- solar neutrinos
- 0νββ
- SN neutrinos
- CNNS
- +more rare processes

CoGeNT
CDEX
Malbek
DAMIC
NEWS (gas)

ArDM, Panda-X
DarkSide, DARWIN

+ Axion searches (IAXO, JURA)
Back to Earth again!
Experimenting with Dark Sector

“If all else fails - it makes a great frothy latte.”

Any resemblance to actual experiment, living or dead, is purely coincidental
Conclusions

We worried/y about finding just a Standard Model Higgs….
Conclusions

We worried/y about finding just a Standard Model Higgs…. 

…but taking all experimental results together with the remarkable progress in cosmological observations and theory makes the situation even more intriguing!

In addition to searches at the high energy frontier, future lies in a wide and complementary physics program of precision measurements and models with very weak couplings:

- W, Z, Higgs, top precision measurements
- Flavour physics
- Dark Matter and complex Hidden Sectors searches
- Neutrino physics

Interest and effort in HS physics has been increasing rapidly in the last few years!

The implications of a discovery is very difficult to overestimate…. 

Thanks to the superb operation of the accelerators, and collaboration with all departments on developing the future in this domain!
"I can't tell you what's in the dark matter sandwich. No one knows what's in the dark matter sandwich."