Beyond Standard Model Theories

Yonit Hochberg
New Ideas for Old Puzzles

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Outline

Dark matter & Naturalness
Setting the Stage
Dark Matter

What is the dark matter (DM) of our universe?

- Rotation Curves
- Gravitational Lensing
- Bullet Cluster
- CMB

![Graph showing rotation curves of NGC 6503](image)

![Image of gravitational lensing](image)

![Image of the Bullet Cluster](image)

![Image of CMB temperature fluctuations](image)

Pie chart showing the composition of the universe:
- Dark energy: 68%
- Dark matter: 27%
- Atoms: 5%
Classic Solution*

Correct thermal relic abundance:

\[ m_{\text{DM}} \sim \alpha \times 30 \ \text{TeV} \]

For weak coupling, weak scale emerges.

**WIMP = Weakly Interacting Massive Particle**

\[ \langle \sigma_{\text{ann}} v \rangle = \frac{\alpha^2}{m_{\text{DM}}^2} \]

*of course also axion*
Experimental Status

E.g. Direct Detection

[website: supercdms.slac.stanford.edu/dark-matter-limit-plotter]
(Similarly strengthening limits for direct production and indirect detection)

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Naturalness

Why is the Higgs mass so light compared to the scale of gravity?

$H^0$

$J = 0$

Mass $m = 125.10 \pm 0.14$ GeV
Classic Solutions

Supersymmetry?

Composite Higgs?

Extra dimensions?

Standard particles

SUSY particles

Extra dimension

weak brane

gravity brane

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Experimental status

*E.g.* supersymmetry

(Similarly strengthening limits in other channels)

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Dominant ideas are being challenged.

Great opportunity for creativity!
Dark Matter
New Ideas Abundant

- ..... 
- Weakly coupled WIMPs [Pospelov, Ritz, Voloshin 2007; Feng, Kumar 2008] 
- Asymmetric dark matter [Kaplan, Luty, Zurek, 2009] 
- Freeze-in dark matter [Hall, Jedamzik, March-Russell, West, 2009] 
- ELDERs [Kuflik, Perelstein, Rey-Le Lorier, Tsai, 2016 & 2017] 
- Forbidden dark matter [Griest, Seckall, 1991; D’Agnolo, Ruderman, 2015] 
- Co-decaying dark matter [Dror, Kuflik, Ng, 2016] 
- Co-scattering dark matter [D’Agnolo, Pappadopulo, Ruderman, 2017] 
- .....
Ex. #1: Forbidden Channels

Forbidden @ T=0; Boltzmann suppressed @ finite T

\[ m_{DM} \sim \alpha \times (30 \text{ TeV}) \times e^{-x_F\Delta} \]

\[ 2m_{DM} < m_{\text{thing}_1} + m_{\text{thing}_2} \]

[Griest, Seckel, 1991; D’Agnolo, Ruderman, 2015]
Ex. #2: SIMPs

What if dark matter mostly interacted with itself?

\[ \langle \sigma v^2 \rangle_{3 \to 2} \equiv \frac{\alpha^3}{m_{DM}^5} \]

\[ m_{DM} \sim \alpha \times 100 \text{ MeV} \]

3 \to 2 self-annihilations

For strong coupling, the strong scale emerges.

SIMP = Strongly (self) Interacting Massive Particle

[Carlson, Hall, Machacek, 1992; \textbf{YH}, Kuflik, Volansky, Wacker, 2014]
Ex. #2: SIMPs

Pumps heat into the system: need to shed the heat

3 $\rightarrow$ 2 self-annihilations

[entropy]

thermalize with light SM species (active during freeze-out)

[YH, Kuflik, Volansky, Wacker, 2014]
Ex. #2: SIMPs

What if the order was reversed?

decouples 1\textsuperscript{st} 
Determines DM relic density 

decouples 2\textsuperscript{nd}
Ex. #3: ELDERs

ELastically DEcoupling Relic (ELDER)

decouples 2\textsuperscript{nd} decouples 1\textsuperscript{st}

Determines DM relic density

DM relic abundance \( \propto e^{-\langle \sigma v \rangle_{el#}} \)

[Kuflik, Perelstein, Rey-Le Lorier, Tsai, 2016 & 2017]
WIMP/SIMP/ELDER

Fixed DM mass

3→2 self interactions

DM-SM coupling

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[Image credit: Eric Kuflik]
Generic in complex rich dark sectors.
Zoo of particles w/structure
SU(3)_c x SU(2)_L x U(1)_Y

Why not in the dark sector too?
New gauge symmetries?
Dark Sectors

Think Standard Model!

Strongly coupled gauge theories

E.g. $SU(3)_{\text{dark}} \times U(1)_{\text{dark}}$

$Sp(N_c), SU(N_c), SO(N_c)$

Kinetically mixed hidden photon ($V$)

QCD-like theories, pions = dark matter

Many processes, many dark matter mechanisms.

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Dark Sectors

forbidden annihilations  3→2 annihilations  2→2 annihilations

2→2 annihilations  elastic scattering  semi-annihilations


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Dark Sectors

forbidden annihilations  3 → 2 annihilations  2 → 2 annihilations

2 → 2 annihilations  elastic scattering  semi-annihilations

3 → 2 dark glueballs:
E.g. Carelson, Hall, Machacek, 1992;
Soni, Zhang, 2016; Forestell,
Morrissey, Sigurdson, 2017

Dark nuclei:
E.g. Krnjaic, Sigurdson, 2014;
Detmold, Pochinsky, McCullough,
2015
Predictive.
Predictive

E.g. Kinetically Mixed U(1)

SU(2), $N_f = 2$
$\alpha_D = 1/4\pi$
$m_\pi = 300$ MeV

semi-annihilations contribute
non-thermalized with SM

ELDER

WIMP

coupling of $V$ to EM current
Experimental Probes

**E.g. Kinetically Mixed U(1)**

![Graph showing experimental probes](image)

[Plot: YH, Kuflik, Murayama, 2016]
Experimental Probes

E.g. Dark Spectroscopy @ Lepton Colliders

Mono-photon traces the resonance structure of the dark sector

\[ e^+e^- \rightarrow \gamma + \text{inv} : \]

\[ E_\gamma = \frac{\sqrt{s}}{2} \left( 1 - \frac{M_{\text{inv}}^2}{s} \right) \]

\[ \text{Belle II projection} \]
\[ \sqrt{s} = 10 \text{ GeV, } 50 \text{ ab}^{-1} \]
\[ \sigma_{E_\gamma}/E_\gamma = 1\% \]
\[ m_{\gamma_{\text{td}}} = 12 \text{ GeV, } \epsilon_\gamma = 10^{-2} \]

[YH, Kuflik and Murayama, 2016 & 2017]
Experimental Probes

*E.g.* Dark Showers @ LHC

[Schwaller, Stolarski, Weiler, 2015; CMS 2018]

*Emerging Jets*

[Cohen, Lisanti, Lou, 2015; + w/ Mishra-Sharma, 2017]

*Semi-visible Jets*

[Strassler, Zurek, 2006]

*Hidden Valleys*
Experimental Probes

E.g. Long Lived Particles

Long-Lived Particles at the Energy Frontier:
The MATHUSLA Physics Case

Editors:
David Curtin, Marco Drewes, Matthew McCullough, Patrick Meade, Rabindra N. Mohapatra, Jessie Shelton, Brian Shuve.

Contributors:

[arXiv:1806.07396]
Experimental Probes

E.g. Direct Detection, such as

- Atomic ionization [Essig et al, 2012]
- Color centers [Budnik et al, 2018]
- Semi-metals [YH et al, 2017]
- Superconductors [YH et al, 2015 x 2, 2019]
- Scintillators [Derenzo et al, 2016]
- 2D targets (graphene) [YH et al, 2016; Cavoto et al, 2018]
- Polar materials [Griffin et al, 2018]
- Semiconductors [Essig et al, 2012; SuperCDMS & SENSEI 2018; Kurinsky et al, 2019]
- Superfluid helium [Schutz, Zurek, 2016; Hertel et al 2018; Acanfora et al 2019]
Naturalness
Cosmological Dynamics

The Relaxion

[147x458]Graham, Kaplan, Rajendran,
“Cosmological relaxation of the weak scale”, PRL 2015

The Fluctuon

[522x224]Geller, YH, Kuflik,
“Inflating to the weak scale”, PRL 2019

N-naturalness

[Arkani-Hamed, Cohen, D’Agnolo, Hook, Kim, Pinner,
“Solving the Hierarchy Problem at Reheating with a Large Number of Degrees of Freedom”, PRL 2016]
Cosmological Dynamics

The Relaxion

[Graham, Kaplan, Rajendran, “Cosmological relaxation of the weak scale”, PRL 2015]

The Fluctuon

[Geller, YH, Kuflik, “Inflating to the weak scale”, PRL 2019]

N-naturalness

Basic Idea

The Higgs mass is at observed value because such a patch inflates the most in the early universe.
Basic Idea

\[ V \supset -m_h(\phi)^2|\phi|^2 + \lambda|\phi|^4 \]

e.g. \[ m_h^2(\phi) = (M^2 - \phi^2) \]

\[ M \gg \text{weak scale} \]
During inflation, $\phi$ has a very flat potential.

$\phi$ fluctuates $\Rightarrow$ spread in Higgs mass in the universe
During inflation, $\phi$ has a very flat potential.

$\phi$ fluctuates $\rightarrow$ spread in Higgs mass in the universe

*universe not drawn to scale
Why do we live in a seemingly unlikely patch of small Higgs mass?
Basic Idea

During inflation
Volume $\propto e^{\text{PE}(\phi) \times t}$

If PE is max when $m_h$ is small
→ the universe will be filled with small $m_h$

*universe not drawn to scale
Basic Idea

During inflation
Volume $\propto e^{\text{PE}(\phi) \times t}$

If PE is max when $m_h$ is small
$\rightarrow$ the universe will be filled with small $m_h$

$\text{Inflating to the weak scale}$

Potential Energy (PE)

$\text{the universe}$

*universe not drawn to scale*
Toy Model

Fields: $\phi$ fluctuation (axion-like PNGB)
$\alpha$ axion
$\tilde{h}$ Higgs

Parameters: $M$ cutoff
$y$ spurion

\[ V = M^3 y \phi + M^2 y^2 \phi^2 + \ldots \]
\[ (M^2 + y M \phi + \ldots) h^2 + \lambda h^4 \]
\[ \frac{a}{f} G \tilde{G} + \Lambda_P^4 \cos \frac{a}{F} \]

$V$ \(\sim\) large
$V(\phi) \sim v_{EW}$

$V_{\text{max}} @ v_{EW}$

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Ideas still in Infancy

• Possible pheno’:
  – Dark matter  [e.g. Banerjee, Kim, Perez, 2018]
  – Higgs-mixing  [e.g. Flacke, Frugiuele, Fuchs, Gupta, Perez, 2016]
  – Spatial and temporal changes in Higgs mass
  – ....

• Model building just at a start
  [e.g. Gupta, Komargodski, Perez, 2015; Espinosa et al, 2015; McAllister et al, 2016; Hook, Marquese-Tavares, 2016; and many more...]
  [e.g. Cheung, Saraswat, 2019]
Summary

• Experimental progress sourcing creativity in theoryland

  Innovative new ideas for the driving puzzles of the field

  Naturalness & dark matter

• Exciting time for particle physics

• Only just begun :-)
Thanks!
Backup
Requirements

- Inflaton drives inflation
- Axion moves fast and classically down the potential once barriers released
- Fluctuon fluctuates (up the potential)
- Most of the universe is filled with EW scale
- Things stay the same after inflation