DM-Stat: Statistical Challenges in the Search for Dark Matter

## **OVERVIEW: Dark Matter**



Bradley J. Kavanagh GRAPPA Institute, University of Amsterdam





DM-Stat: Statistical Challenges in the Search for Dark Matter

# Dark Matter: Episode I The Prequel Talk





Bradley J. Kavanagh GRAPPA Institute, University of Amsterdam





DM-Stat: Statistical Challenges in the Search for Dark Matter

# An Introduction to Dark Matter



Illustris simulation



Xenon1T detector



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WHAT IS DARK MATTER?

Nobody knows :(

Particles, or objects, or maybe something more diffuse

We've only ever identified it's gravitational interactions

It's everywhere in the Universe (to varying degrees...)



Dark Matter (DM) is everywhere, even in this room... but how much?

In 'ordinary' units:

In 'particle physics' units:

In 'astronomy' units:

 $\rho_{\chi} \sim 5 \times 10^{-25} \,\mathrm{g/cm^3}$ 

 $\rho_{\chi} \sim 0.3 \, {\rm GeV/cm^3}$ 

 $\rho_{\chi} \sim 0.008 \, M_{\odot}/\mathrm{pc}^3$ 

In 'British' units: 1 DMPPP



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In 'British' units: 1 DMPPP = 1 **D**ark **M**atter **P**article **P**er **P**int



## *Evidence:* How do we know Dark Matter is everywhere?

# *Theory:* What is Dark Matter?

## Searches: How can we make it not-so-Dark Matter?

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Evidence:

How do we know Dark Matter is everywhere?

# *Theory:* What is Dark Matter?

## Searches: How can we make it not-so-Dark Matter?

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#### TIMELINE OF THE UNIVERSE



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Dark Matter Overview



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#### Abell 370 Galaxy Cluster



#### NGC 4414 Spiral Galaxy

#### [astro-ph/0006397]

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DMStat, Banff - 26th Feb 2018

[Rubin et al. (1980)]

#### STRUCTURE FORMATION WITH DARK MATTER

Dark matter has become an integral part of our understanding of how Galaxies form - seed for structure growth



Cosmological simulations can now produce realistic (and beautiful) Galaxies

But Galaxy formation is messy and non-linear and still not fully understood

> [arXiv:1609.05917 vs. arXiv:1610.07663]

[Illustris simulation - arXiv:1405.2921]

#### [Alyson Brooks - Tuesday]

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#### TIMELINE OF THE UNIVERSE



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#### COSMIC MICROWAVE BACKGROUND (CMB)

## PLANCK (2009 - 2013)



[arXiv:1502.01589]

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#### A HOT MESS!



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#### A HOT MESS + DARK MATTER!



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#### CHANGING COSMOLOGICAL PARAMETERS

Changing amount of baryons (i.e protons and neutrons)



Changing total amount of matter (DM + baryons)



#### http://background.uchicago.edu/~whu/animbut/anim1.html

#### [astro-ph/0110414]

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Dark Matter Overview

## ENERGY BUDGET OF THE UNIVERSE



Anything you propose instead of Dark Matter still has to fit the CMB. So it will end up looking almost exactly the same as Dark Matter...

[E.g. Skordis - https://tinyurl.com/DM-and-CMB]

## Evidence:

## How do we know Dark Matter is everywhere?

*Theory:* What is Dark Matter?

## Searches:

## How can we make it not-so-Dark Matter?

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Dark Matter Shopping List

\* Non-baryoníc

\* 'Cold' (i.e. slow moving)

\* 'Neutral'

\* Produced in sufficient
amounts

[arXiv:0711.4996]

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## STANDARD MODEL (SM) OF PARTICLE PHYSICS



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#### STANDARD MODEL (SM) OF PARTICLE PHYSICS



Some Dark Matter but not nearly enough...

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#### SUPERSYMMETRY (SUSY)

An example of a self-consistent high energy theory, which also gives you a DM particle



#### [hep-ph/9506380]

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#### SUPERSYMMETRY (SUSY)

An example of a self-consistent high energy theory, which also gives you a DM particle



#### [hep-ph/9506380]

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#### SUPERSYMMETRY CONSTRAINTS

#### Falling out of favour - we haven't seen any of these new particles (yet)

Nodel $e_1/4$ , $r_2$ , $r_2$ Just, $e_2/4$ , $r_4/4$ ,	ATLAS SUSY Sea December 2017	rches*	- 95%	% CI	L Lov	ver Limits		ATLAS Preliminary $\sqrt{s} = 7, 8, 13 \text{ TeV}$
Bit	Model	$e, \mu, \tau, \gamma$	Jets	$E_{T}^{miss}$	∫£ dı[ħ	-*) Mass limit	√s = 7,8 TeV √s = 13 TeV	Reference
Bit Mit Strate     0     3.8     Yes     5.1     2     Provide Strate     P	$\begin{array}{c} \tilde{q}\tilde{q}, \tilde{q} \rightarrow q \tilde{k}_{1}^{0} \\ \tilde{q}\tilde{q}, \tilde{q} \rightarrow q \tilde{k}_{1}^{0} (compressed) \\ \tilde{q}\tilde{q}, \tilde{q} \rightarrow q \tilde{k}_{1}^{0} (compressed) \\ \tilde{g}\tilde{q}, \tilde{g} \rightarrow q \tilde{k}_{1}^{0} (compressed) \\ \tilde{g}\tilde{q}, \tilde{g} \rightarrow q \tilde{q} \tilde{k}_{1}^{0} \rightarrow q q \tilde{k}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q \tilde{k}_{1}^{0} \rightarrow q q \tilde{k}_{1}^{0} \\ \tilde{g}\tilde{g}\tilde{g}\tilde{g}\tilde{g}\tilde{g}\tilde{g}\tilde{g}\tilde{g}\tilde{g}$	0 mono-jet 0 0 <i>ec.,yy</i> 3 <i>e.,y</i> 0 1.2 <i>e</i> +0.1 <i>l</i> 2 <i>y</i> <i>y</i> 0	2-6 jets 1-3 jets 2-6 jets 2-6 jets 2-6 jets 2-6 jets 2-jets - - 2 jets - - 2 jets - - - - - - - - - - - - -	Yes Yes Yes Yes Yes Yes Yes Yes	36.1 36.1 36.1 14.7 36.1 36.1 3.2 36.1 36.1 20.3	4 4 710 GeV 2 2 2 2 2 2 2 2 2 2 2 2 2	1.57 TeV     m(l <sup>2</sup> <sub>1</sub> )<200 GeV, m(l <sup>∞</sup> ges. 2)+m(2 <sup>er</sup> ges. 2) m(2)+m(2))>5 GeV       2.02 TeV     m(l <sup>2</sup> <sub>1</sub> )<5 GeV	1712.02332 1711.03301 1712.02332 1712.02332 1611.05791 1706.02794 1607.06079 ATLAS-CONF-2017-060 ATLAS-CONF-2017-060 1502.01518
Big Org     O     2.8     Mode     Big Org     Big Org <td>88. 8→168° 1 28. 8→168°</td> <td>0 0-1 e.µ</td> <td>3.b 3.b</td> <td>Yes Yes</td> <td>36.1 36.1</td> <td>2</td> <td>1.92 TeV m(t<sup>2</sup>)-600 GeV 1.97 TeV m(t<sup>2</sup>)-200 GeV</td> <td>1711.01901 1711.01901</td>	88. 8→168° 1 28. 8→168°	0 0-1 e.µ	3.b 3.b	Yes Yes	36.1 36.1	2	1.92 TeV m(t <sup>2</sup> )-600 GeV 1.97 TeV m(t <sup>2</sup> )-200 GeV	1711.01901 1711.01901
$\frac{1}{4}\sum_{k=1}^{k}\sum_{i=1}^{k}(-i)\sum_{k=1}^{k}(-i)\sum$	$ \begin{array}{c} k_1 k_1, k_1 \rightarrow b k_1^0 \\ k_2 k_3 k_3, k_3 \rightarrow d k_1^0 \\ k_3 k_3, k_3 \rightarrow d k_1^0 \\ k_1 k_1, k_1 \rightarrow b k_1^0 \text{ or } k_1^0 \\ k_1 k_1, k_1 \rightarrow b k_1^0 \text{ or } k_1^0 \\ k_1 k_1, k_1 \rightarrow b k_1^0 \text{ or } k_1^0 \\ k_1 k_1, k_1 \rightarrow b k_1^0 \\ k_1 k_1, k_1 \rightarrow b k_1^0 \\ k_1 k_1 k_1 k_1 \rightarrow b k_1 \end{pmatrix} $	0 2 e, µ (SS) 0 - 2 e, µ 0 - 2 e, µ 0 2 e, µ (Z) 3 e, µ (Z) 1 - 2 e, µ	2.b 1.b 1.2.b 1.2.jets/1.2 mano-jet 1.b 1.b 4.b	Yes Yes Yes Yes Yes Yes Yes	36.1 36.1 4.7/13.3 20.3/36.1 36.1 20.3 36.1 36.1 36.1	\$     960 GeV       \$,     275-700 GeV       \$i,     117-179 GeV       \$i,     117-179 GeV       \$i,     90-196 GeV       \$i,     90-430 GeV	m(t <sup>2</sup> )=<420 GeV m(t <sup>2</sup> )=<200 GeV, m(t <sup>2</sup> )= m(t <sup>2</sup> )=100 GeV m(t <sup>2</sup> )=2m(t <sup>2</sup> ), m(t <sup>2</sup> )=<55 GeV m(t <sup>2</sup> )=1 GeV m(t <sup>2</sup> )=5 GeV m(t <sup>2</sup> )=5 GeV m(t <sup>2</sup> )=5 GeV m(t <sup>2</sup> )=0 GeV m(t <sup>2</sup> )=0 GeV	1708.09066 1706.03731 1209.2162, ATLAS-CONF-2016-077 1506.08616, 1709.04163, 1711.11520 1711.03001 1403.5222 1706.03966 1706.03966
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	$\begin{array}{c} \underbrace{ \tilde{I}_{L,R} \tilde{I}_{L,R}, \tilde{I}_{-} \leftarrow \tilde{I}_{1}^{0} } \\ \tilde{X}_{1}^{+} \tilde{X}_{1}^{+} \tilde{X}_{1}^{+} \leftarrow \tilde{I} \wedge (F) \\ \tilde{X}_{1}^{+} \tilde{X}_{1}^{+} \tilde{I}_{2}^{+} \tilde{X}_{1}^{+} \leftarrow \tilde{I} \times (F) \\ \tilde{X}_{1}^{+} \tilde{X}_{1}^{+} \tilde{J}_{2}^{+} \leftarrow \tilde{I}_{1} \tilde{I}_{1}^{+} (F) \\ \tilde{X}_{1}^{+} \tilde{X}_{1}^{+} \leftarrow \tilde{I}_{2} \tilde{I}_{1}^{+} (F) \\ \tilde{X}_{1}^{+} \tilde{X}_{1}^{+} \leftarrow \tilde{I}_{2} \tilde{I}_{1}^{+} \tilde{I}_{1}^{+} \tilde{I}_{1}^{+} h \rightarrow b \tilde{b} / W W / (TT / Y) \\ \tilde{X}_{1}^{+} \tilde{X}_{1}^{+} \tilde{X}_{1}^{+} \tilde{X}_{1}^{+} \tilde{I}_{1}^{+} h \rightarrow b \tilde{b} / W W / (TT / Y) \\ \tilde{X}_{1}^{+} \tilde{X}_{1}^{+} \tilde{X}_{1}^{+} \tilde{X}_{1}^{+} \tilde{I}_{1}^{+} h \rightarrow b \tilde{b} / W W / (TT / Y) \\ \tilde{X}_{1}^{+} \tilde{X}_{1}^{+} \tilde{X}_{1}^{+} \tilde{X}_{1}^{+} \tilde{I}_{1}^{+} h \rightarrow b \tilde{b} / W W / (TT / Y) \\ \tilde{G} GM (who NLSP) weak prod., \tilde{X}_{1}^{0} \rightarrow G GM (b ho NLSP) weak prod., \tilde{X}_{1}^{0} \rightarrow G GM (b ho NLSP) \\ \end{array}$	2 e.µ 2 e.µ 2 t 3 e.µ 2 3 e.µ e.µ.y 4 e.µ yG 1 e.µ + y yG 2 y	0 - 0-2 jets 0-2 b 0 -	Yes Yes Yes Yes Yes Yes Yes	36.1 36.1 36.1 36.1 20.3 20.3 20.3 20.3 36.1	2     90-500 GeV       \$\$\vec{k}_1^2\$     750 GeV       \$\$\vec{k}_1^2\$     760 GeV       \$\$\vec{k}_1^2\$     760 GeV       \$\$\vec{k}_1^2\$     550 GeV       \$\$\vec{k}_1^2\$     550 GeV       \$\$\vec{k}_1^2\$     550 GeV       \$\$\vec{k}_1^2\$     550 GeV       \$\$\vec{k}_1^2\$     635 GeV       \$\$\vec{k}_1\$     115-370 GeV       \$\$\vec{k}_2\$     1.06 TeV	$\begin{split} m(t_{1}^{2})=0 & m(t_{1}^{2})=0, m(t_{1}^{2})=0.5(m(t_{1}^{2})+m(t_{1}^{2})), \\ m(t_{1}^{2})=0, m(t_{1}^{2})=0.5(m(t_{1}^{2})+m(t_{1}^{2})), \\ m(t_{1}^{2})=m(t_{1}^{2})=0, m(t_{1}^{2})=0.5(m(t_{1}^{2})+m(t_{1}^{2})), \\ m(t_{1}^{2})=m(t_{1}^{2}), m(t_{1}^{2})=0, t_{1}^{2}$	ATLAS-CONF-2017-039 ATLAS-CONF-2017-039 1708.07875 ATLAS-CONF-2017-039 ATLAS-CONF-2017-039 1501.07110 1405.5086 1507.05493 ATLAS-CONF-2017-080
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	Direct: $\hat{t}^{\dagger}_{1}\hat{k}^{\dagger}_{1}$ prod., long-lived $\hat{t}^{\dagger}_{1}$ Direct: $\hat{t}^{\dagger}_{1}\hat{k}^{\dagger}_{1}$ prod., long-lived $\hat{t}^{\dagger}_{1}$ Stable, stopped $\hat{g}$ R-hadron Stable $\hat{g}$ R-hadron Metastable $\hat{g}$ R-hadron, $\hat{g}$ -hadron Metastable $\hat{g}$ R-hadron, $\hat{g}$ -hadron,	Disapp. trk dEldx trk 0 trk dEldx trk displ, vtx 1-2 µ 2 y displ, ev/ep/p	1 jet - 1-5 jets - - - - -	Yes Yes · · Yes · Yes ·	36.1 18.4 27.9 3.2 32.8 19.1 20.3 20.3	k*     460 GeV       k*     495 GeV       k     495 GeV       k     850 GeV       k     937 GeV       k     937 GeV       k     1.0 TeV	m(t <sup>2</sup> <sub>1</sub> )-m(t <sup>2</sup> <sub>1</sub> )160 MeV, r(t <sup>2</sup> <sub>1</sub> )0.2 ns m(t <sup>2</sup> <sub>1</sub> )-m(t <sup>2</sup> <sub>1</sub> )160 MeV, r(t <sup>2</sup> <sub>1</sub> )15 ns m(t <sup>2</sup> <sub>1</sub> )160 GeV, 10 µe-cr(2)-<1000 s <b>1.58 TeV</b> <b>1.57 TeV</b> m(t <sup>2</sup> <sub>1</sub> )100 GeV, 1>10 ns <b>2.37 TeV</b> r(t))0.17 ns, m(t <sup>2</sup> <sub>1</sub> ) = 100 GeV 10-ctar(t <sup>2</sup> <sub>1</sub> )<-20 11-r(t <sup>2</sup> <sub>1</sub> )<2 ns, SIPS8 model 7 <cr(t<sup>2<sub>1</sub>)&lt;2 ns, SIPS8 model 7 <cr(t<sup>2<sub>1</sub>)&lt;2 70 mm, m(t<sup>2</sup><sub>1</sub>)-1.3 TeV</cr(t<sup></cr(t<sup>	1712.02118 1506.05332 1310.8584 1606.05129 1604.04520 1710.04801 1411.8785 1409.5542 1504.05182
Other Scalar charm, $\bar{c} \rightarrow c\bar{k}_1^0$ 0 2 $\epsilon$ Yes 20.3 2 510 GeV m( $\bar{k}_1^0 \times 200 \text{GeV}$ 1501.01325   'Only a selection of the available mass limits on new states or	$ \begin{array}{c} LFV pp{\rightarrow} \hat{v}_r + X, \hat{v}_r \rightarrow e\mu/e\pi/\mu\pi\\ Birrear \ RPV \ CMSSM\\ \hat{X}_1^+ \hat{x}_1^-, \hat{X}_1^+ \rightarrow W \hat{x}_1^+, \hat{x}_1^0 \rightarrow eev, epv, \mu\mu\nu\\ \hat{X}_1^+ \hat{x}_1^-, \hat{X}_1^+ \rightarrow W \hat{x}_1^0, \hat{x}_1^0 \rightarrow eev, epv, \mu\mu\nu\\ \hat{X}_2^+ \hat{X}_1^-, \hat{X}_1^+ \rightarrow W \hat{x}_1^0, \hat{x}_1^0 \rightarrow epq\\ \hat{X}_3^+ \hat{X}_1 \rightarrow Q \hat{x}_1^0, \hat{x}_1^0 \rightarrow epq\\ \hat{X}_3^+ \hat{X}_1 \rightarrow d \hat{x}_1^- \hat{x}_1 \rightarrow d \mu\\ \hat{X}_1^+ \hat{x}_1^-, \hat{x}_1^- \rightarrow d \mu\\ \hat{I}_1 \hat{I}_1, \hat{I}_1 \rightarrow d \mu\\ \hat{I}_1 \hat{I}_1, \hat{I}_1 \rightarrow d \mu \end{array}$	eμ.er.μr 2 e.μ (SS) 4 e.μ + r 0 4 1 e.μ 8 1 e.μ 8 0 2 e.μ	0-3 b 5 large-it jo 10 jots/0-4 10 jots/0-4 2 jots + 2 b 2 b	· Yes Yes ets · 1.5 · 1.5 ·	3.2 20.3 13.3 20.3 36.1 36.1 36.1 36.7 36.7 36.1	F,     4.2       Å1     1.14 Tr       Å1     450 GeV       Å2     2       Å1     100-470 GeV       Å1     100-470 GeV       Å1     0.4	1.9 TeV     J <sub>211</sub> =0.11, J <sub>202110,010</sub> =0.67       1.45 TeV     m(k)=m(k), cr <sub>0,10</sub> <1 mm	1607.08079 1404.2500 ATLAS-CONF-2018-075 1405.5086 SUSY-2016-02 1704.08480 1704.08480 1704.08480 1710.05544
	Other Scalar charm, t→ct <sup>0</sup> Only a selection of the available ma	0 ss limits on r	2 c	Yes	20.3	2 510 GeV	m(8))+200 GeV	1501.01325

[But see e.g. arXiv:1507.07446]

#### EFFECTIVE FIELD THEORY (EFT)

Add a new particle and ask what kind of interactions it is allowed to have...



#### $(m_{\rm DM}, c_1, c_2, c_3, ...)$

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Dark Matter Overview

[arXiv:1008.1783]

#### SIMPLIFIED MODELS

#### Add extra particles which mediate the interactions



 $(m_{\rm DM}, m_{\rm med}, c_{\rm DM}, c_{\rm med})$ 

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DMStat, Banff - 26th Feb 2018

[arXiv:1506.03116]

#### DARK/HIDDEN SECTORS

#### Add lots of extra particles which are hidden from us



#### [arXiv:0808.2318]



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Focus is often on so-called WIMP Dark Matter (perhaps motivated by SUSY) (Very) loosely speaking:  $m_\chi \sim {\rm keV} - {\rm TeV} \sim [10^{-6}, 10^3] \, m_p$ 

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Perhaps the best 'prior' is whether or not you can come up with a sensible production mechanism.

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It turns out that particles with TeV-scale mass (~1000 proton masses) and "weak-scale" interactions gives just the right amount of DM today!

The WIMP Miracle!

Sadly, we haven't seen these 'weak-scale' particles yet. But not to worry...

[arXiv:0903.3381]

#### ALTERNATIVE PRODUCTION MECHANISMS

Freeze-Out [Kolb & Turner (1990)] Freeze-in [arXiv:0911.1120] Asymmetric Dark Matter [arXiv:1305.4939] Forbidden Dark Matter [arXiv:1505.07107] Secluded Dark Matter [arXiv:0711.4866] SIMP Dark Matter [arXiv:1402.5143] Self-interacting Dark Matter [arXiv:1510.08063] Misalignment Mechanism [arXiv:1105.2812] Gravitational production (WIMPzillas!) [hep-ph/9810361] Hidden sector freeze-out [arXiv:1712.03974] Early kinematic decoupling [arXiv:1706.07433] Elastically decoupling relics [arXiv:1706.05381] Semi-annihilating Dark Matter [arXiv:1611.09360]

## Necessity is the mother of invention!

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#### Look everywhere we can...

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## *Evidence:* How do we know Dark Matter is everywhere?

*Theory:* What is Dark Matter?

Searches:

How can we make it not-so-Dark Matter?

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### DARK MATTER INTERACTIONS



## DIRECT DETECTION

#### Look for the interaction of DM with nuclei:



Rare event searches with (sometimes) unknown BG... Hope to compare recoil energy spectra with DM predictions!

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## DIRECT DETECTION

#### Look for the interaction of DM with nuclei:



Rare event searches with (sometimes) unknown BG... Hope to compare recoil energy spectra with DM predictions!

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## **DIRECT DETECTION**

#### Look for the interaction of DM with nuclei:



Rare event searches with (sometimes) unknown BG... Hope to compare recoil energy spectra with DM predictions!

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#### XENON1T



[See e.g. <u>https://tinyurl.com/ycomgccl</u>]

#### 3.2 tons of liquid Xenon in a tank!

Deep underground - LNGS lab in Italy (3200 m.w.e.)

Low background, low threshold detector

[arXiv:1705.06655]

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Dark Matter Overview



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#### DIRECT DETECTION CONSTRAINTS



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Dark Matter Overview

#### DIRECT DETECTION CONSTRAINTS



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Dark Matter Overview

#### UNCERTAINTIES IN DIRECT DETECTION

#### Local distribution of Dark Matter is uncertain...



#### UNCERTAINTIES IN DIRECT DETECTION

Unknown form of the interaction...

Generalising, you could write down 30+ different interactions...



#### DARK MATTER ELECTRON SCATTERING

So far, we've only talked about DM-nucleus interactions. Could also look for DM interacting with electrons in your detector:



#### [arXiv:1703.00910]

#### **INDIRECT DETECTION**

Look for the products of DM annihilation





#### **INDIRECT DETECTION**

Look for the products of DM annihilation





#### The light travels in a straight line and we could observe it with telescopes

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Dark

#### **INDIRECT DETECTION**

Look for the products of DM annihilation





# Charged particles (cosmic rays) diffuse through the galaxy to get to us

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INDIRECT DETECTION (WITH LIGHT)

Look for excess light coming from promising sources (centre of the galaxy, Dwarf Spheroidal galaxies)

Fermi Large Area Telescope constraints from Dwarf Spheroidal Galaxies



**INDIRECT DETECTION (WITH LIGHT)** 

Look for excess light coming from promising sources (centre of the galaxy, Dwarf Spheroidal galaxies)

Not always clear which are the promising targets - efficient forecasting is important

[Tom Edwards - Thursday]

Not always clear how much Dark Matter there is:



#### GALACTIC CENTRE EXCESS

In recent years there was a promising 'excess' in the Galactic centre



Now generally accepted as a new population of point sources - owing the to the application of some new (for the DM community) statistical techniques

[Tracy Slatyer - Friday]

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Dark Matter Overview

[arXiv:1506.05104, arXiv:1506.05124]

#### GALACTIC CENTRE EXCESS

In recent years there was a promising 'excess' in the Galactic centre



Now generally accepted as a new population of point sources - owing the to the application of some new (for the DM community) statistical techniques

or "How Statistics killed Dark Matter"

[Tracy Slatyer - Wednesday]

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[arXiv:1506.05104, arXiv:1506.05124]

#### INDIRECT DETECTION (WITH CHARGED PARTICLES)

Charged particles diffuse through the galaxy under the influence of magnetic fields, Galactic winds, collisions...

Observe at (or near) Earth with detectors such as AMS-02



[arXiv:1504.04276, arXiv:1610.03071] INDIRECT DETECTION (WITH CHARGED PARTICLES)

Charged particles diffuse through the galaxy under the influence of magnetic fields, Galactic winds, collisions...

Many different uncertainties in this process...



#### INDIRECT DETECTION (WITH CHARGED PARTICLES)

Observed cosmic ray fluxes are not yet fully understood

Have to simultaneously fit diffusion parameters and possible DM signal (with pronounced degeneracies...)



#### Collider Searches



[arXiv:1702.02430]

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Dark Matter Overview

### COLLIDER SEARCHES (AT THE LHC)



Most common signature is 'something' + missing energy (which is carried away by the DM)

Complicated backgrounds...

Use a combination of Monte Carlo and control regions to fix background rates



#### COLLIDER SEARCHES (AT THE LHC)



Most common signature is 'something' + missing energy (which is carried away by the DM)



Jets + Missing energy search at ATLAS



## COLLIDER SEARCHES (AT THE LHC)

# In more 'complete' models (e.g. SUSY), you know exactly what to look for:



But with more complete models come more particles, more constraints - global fits are important! [e.g. GAMBIT - arXiv:1705.07908]

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SIMULATING COLLIDER SIGNALS

To constrain Dark Matter, we have to determine what the signal should look like in the detector

But detector simulation is very expensive for (complicated) collider experiments



Machine learning is already being used to accelerate detector simulation and parameter scans



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### DARK MATTER INTERACTIONS



#### "EXOTIC" SEARCHES

New ideas every day...

Fixed target experiments [arXiv:1702.02688] Impact of DM interactions on CMB [arXiv:1801.08609] Offsets between Galaxies and DM [arXiv:1504.06576] Novel Direct Detection targets [arXiv:1611.06228]

to name just a few...

...and this is only for WIMPy Dark Matter... We haven't even started talking about axions, PBHs,...

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Dark Matter Overview

#### STATISTICAL CHALLENGES IN THE SEARCH FOR DARK MATTER

How do we distinguish the faintest of signals from unknown backgrounds?

How do we obtain meaningful constraints on huge parameter spaces?

Which is the best target to look at or detector to build?

How do we accelerate the search for Dark Matter?



## STATISTICAL CHALLENGES IN THE SEARCH FOR DARK MATTER

How do we distinguish the faintest of signals from unknown backgrounds?

How do we obtain meaningful constraints on huge parameter spaces?

Which is the best target to look at or detector to build?

I CAN WORK WITH THE MEANS. UNIT OF A STATE OUT OF A

Prof. Wahlberg

How do we accelerate the search for Dark Matter?

