Dark Matter: Overview

IEINSCHAFT

Allianz für Astroteilchenphysik

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Dark Matter:

- > Why ?
- > What ?
- > Where and how ?

Space - The Final Frontier What's out there?



What we claim to understand is only 5%!

Some questions for your generation

 >80% of matter is dark → true? what's behind this? > is there a variant of **Super-Symmetry**? > are there more than 3 spatial dimensions ? Is the 125 GeV particle the only Higgs boson ? • Why is there matter but no (primordial) antimatter ? • Why is the matter/antimatter asymmetry so crazily small: $\frac{N(baryons)}{N(photons)} \approx 6 \times 10^{-10}$

Understanding dark matter may be the golden key!



Why

do we think there is dark matter

?

a)

Gravitational Dynamics

Graviational Dynamics (1): Galaxy Clusters

spread in redshift → kinetic energy

virial theorem \rightarrow gravitational energy

Clusters are several hundred times more massive than what we see

Fritz Zwicky (1898 – 1974) Coma Cluster, 1933

Coma Cluster APOD, 2.5.2010, Dean Rowe

Graviational Dynamics (2): Galaxy Rotation



 $\rho_{\rm DM} \simeq 0.3 \, {\rm GeV} \, / \, {\rm cm}^3$

Fig. 11.4 Rotational velocities as a function of nuclear distance determined from emission line spectra for several galaxies (adapted from Rubin and Ford 1980; courtesy Professor Rubin and the *Astrophysical Journal*, published by the University of Chicago Press).

Weak Gravitational Lensing: Bullet Cluster

gravitating mass (inferred from weak lensing)

galaxies in visible light

hot gas (X rays)

NASA/CXC/CfA/STScl

b)

Cosmology

Standard Big Bang Cosmology tells us:

$$\Omega_{\rm photons} << \Omega_{\rm baryons} << \Omega_{\rm cold\, dark\, matter} << \Omega_{\rm dark\, energy}$$

\Rightarrow the Standard Model stuff is not enough!

Derived from a cocktail of cosmological probes:

- Cosmic Microwave Background (CMB)
- Supernovae Ia (and other standard candles)
- Galaxy surveys, large scale structure and Baryon Acoustic Oscillation (BAO)
- weak lensing (cosmic shear) as tracer for mass distribution
- Lyman α forest as tracer for intergalactic hydrogen
- X ray luminosity of galaxy clusters as tracer for total mass

CMB (1):

Cosmic Microwave Background Spectrum from COBE



perfect black body spectrum, T = 2.725 K

$$\Rightarrow n_{\gamma} \approx 411 \text{cm}^{-3}, \quad \Omega_{\gamma} < 10^{-4} \text{ negligible}$$

CMB (2): Temperature Anisotropies (10⁻⁵ level) $t \approx 380000 \text{ y}$

ESA and the Planck Collaboration

- from primordial quantum-fluctuations, stretched out by inflation
- tracer of initial mass distribution at time of decoupling
- matter dominated by gravity from then on

Expansion in Y_{lm}:

- >power spectrum of Tfluctuation vs. scale ℓ
- ➤representing intensities of matterlight oscillations
- very sensitive to (some) cosmological parameters...
- …in particular to baryon/dark matter ratio



Parameter sensitivity of the CMB power spectrum:



Parameter degeneracies exist \Rightarrow combined fits using complementary probes



An independent path: Big Bang Nucleosynthesis (BBN)

- Light elements formed in the primordial plasma (1s < t < 200s)
- Tricky to measure (from places "free" of contributions from stars)
- the coctail:
 - n / p freeze-out from weak
 interaction equilibrium at t ≈ 1s
 - fusion of nucleons/nuclei
 - photons → nuclear fission
 - neutrons decay
- hence sensitive to photon and nucleon (→baryon) density
- pretty consistent picture for

$$\eta \equiv \frac{n_b}{n_{\gamma}} \approx 6 \times 10^{-10}$$



Agrees with cosmological parameter fits (CMB & other probes)



What

(the hell) is dark matter

7

Assume it is some sort of particles:

- stable on cosmological time scales (or they would be gone)
- no electromagnetic radiation
- hence electrically neutral
- no strong interaction either or we would feel them





- they feel gravity
- and probably (hopefully) other weak interactions
- in any case they were driving the large scale structure formation



The DM particles must have been slow (v c) already at time of decoupling, because...



Consequence (1):

Dark Matter particles are either

 cold ↔ massive (i.e. non-relativistic when decoupling from thermal equilibrium)

⇒ Weakly Interacting Massive Particles

non-thermally produced and slow and possibly light

Consequence (2):

Standard (light!) neutrinos are excluded:

 $\Omega_v < 0.0062 / h^2$ negligible

Consequence (2) in different words:

dark matter standard neutrinos have to be heavy!

But:



What remains:

There could be (massive) sterile neutrinos...

a)

WIMPs Some Candidates



freeze out point: annihilation rate falls below expansion rate H

The WIMP miracle



Is this really a miracle???

Anyway, keep in mind:

$$\langle \sigma v \rangle \approx 3 \times 10^{-26} \, \mathrm{cm}^3 \, / \, \mathrm{s}$$



Neutralino annihilation to fermions:



- → heaviest energetically allowed quark dominates final state
- → internal bremsstrahlung is very important for final state gamma rays with $E_{\gamma} \rightarrow m_{\gamma}$ $\gamma \sim f$

this can avoid helicity suppression at cost $~lpha/\pi$

Neutralino annihilation to bosons:

If χ has large mixing with SU(2)_L-partners (Wino, Higgsino)



important sources of

- → prompt (⇒ high energy) electrons/positrons
- \rightarrow prompt (\Rightarrow high energy) neutrinos

Candidate 2: Extra Dimensions (Kaluza Klein excitations)



WIMP = lightest (neutral, stable) Kaluza Klein excitation (stable due to a conserved KK parity)

Most popular KK dark matter WIMP:



Remember the physical neutral gauge bosons in the SM:



B⁽¹⁾ annihilation to fermions:





Many other WIMP candidates...

- other KK states (Z, H, neutrino, graviton,...)
- Little Higgs dark matter
- technicolor states
- mirror dark matter

and subtleties affecting $\langle \sigma v \rangle_{today}$

- (near) mass degeneracies and co-annihilation
- resonance effects
- threshold effects

ask our theorists if you want to know more about this! 😳

b)

Axions

a non-thermally produced light DM candidate

 $10^{-6} \mathrm{eV} \leq m_a \leq 10^{-3} \mathrm{eV}$

Rich experimental program (for axions & axion-like particles)



tunable high Q microwave cavity



LHC magnet pointing at the sun



laser shining through a wall in a magnet



direct searches can look for e-recoils, e.g. EDELWEISS-II, arXiv:1307.1488 [astro-ph.CO]
Part III

HOW to look for DM experimentally

Where to search in the Universe

WIMP detection - the threefold way



a)



Direct Searches

sit down and wait



Direct WIMP Searches in the World



Example 1: Cryo detector CRESST (Gran Sasso)



Detection: supraconducting thermomenters



supraconducting phase-transitiontungsten-thermometer (SPT) detector moduls at < 10 mK

Example 2: Nobel gas detector XENON (Gran Sasso)



The latest exclusion limits (spin independent x-section)



Spin dependent x-section limits much weaker



b)



LHC

make your own dark matter

LHC collides gluons/quarks

 $p + p \rightarrow$ new strongly interacting states \rightarrow decay chain \rightarrow WIMPs







Run Number: 183391, Event Number: 618161 Date: 2011-06-12 05:50:25 CEST





The name of the game: Understand the backgrounds very well!

...so SUSY, where are you?

			ATLAS SUSY Searches* - 95% CL Lower Limits (es* - 95% CL Lower Limits (Status: March 26, 2013)		
inos		$ \begin{array}{l} MSUGRA/CMSSM: 0 \ lep + j's + E_{\tau,miss} \\ MSUGRA/CMSSM: 1 \ lep + j's + E_{\tau,miss} \end{array} $	L=5.8 fb ⁻¹ .8 TeV (ATLAS-CONF-2012-109) 1.50 TeV $\widetilde{q} = \widetilde{g}$ L=5.8 fb ⁻¹ .8 TeV (ATLAS-CONF-2012-104) 1.24 TeV $\widetilde{q} = \widetilde{g}$ ma	mass ^{SS}		
-E	es	Pheno model : 0 lep + j's + $E_{T,miss}$	L=5.8 fb ⁻¹ .8 TeV [ATLAS-CONF-2012-109] 1.18 TeV g mass	$(m(\tilde{q}) < 2 \text{ TeV, light } \tilde{\chi}_{1}^{*})$ AILAS		
SU	rch	Gluing mod \tilde{x}^{\pm} ($\tilde{a} \rightarrow a \overline{a} \tilde{x}^{\pm}$) : 1 log $\pm i's \pm F$	L=5.8 tb 1,8 TeV [ATLAS-CONF-2012-109] 1.38 TeV [41LAS-CONF-2012-109] 1.38 TeV [41LAS-CONF-2012-109] 000 GeV 0 mass (m ⁰)	$(m(g) < 2 \text{ lev, light } \chi_1)$ Fremminary		
8	ea.	GMSR (INI SP) : 2 log (OS) + i's + E GMSR (INI SP) : 2 log (OS) + i's + E	(m(x, 10, 110, 110, 100, 100, 100, 100, 100	$(\tan \theta \le 15)$		
	0	GMSB ($\tilde{\tau}$ NLSP) : 1-2 τ + j's + E	L=20.7 fb ⁻¹ , 8 TeV [1210.1314] 1.40 TeV [12 mass	$S (\tan \beta > 18)$		
ĽŽ –	ISIV	GGM (bino NLSP) : $\gamma\gamma + E_{T,miss}^{T,miss}$	L=4.8 fb ⁻¹ , 7 TeV [1209.0753] 1.07 TeV [0] MASS (n	1(2 ⁰) > 50 GeV)		
H	ICIL	GGM (wino NLSP) : γ + lep + $E_{T_{relevent}}$	L=4.8 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-144] 619 GeV g mass	$Ldt = (4.4 - 20.7) \text{ fb}^{-1}$		
ñ	4	GGM (higgsino-bino NLSP) : $\gamma + b + E_{T niss}^{T niss}$	L=4.8 fb ⁻¹ , 7 TeV [1211.1167] 900 GeV g mass (mg ⁰ _c)	> 220 GeV)		
6		GGM (higgsino NLSP) : Z + jets + E T.miss	L=5.8 fb ⁻¹ , 8 TeV (ATLAS-CONF-2012-152) 690 GeV \widetilde{g}_{mass} (m(H) > 200	GeV) IS - 7, o lev		
\mathbf{v}		Gravitino LSP : 'monojet' + E T.miss	L=10.5 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-147] 645 GeV F ^{-1/2} scale (m(G) >	10 ⁻⁴ eV)		
ı squarks	3rd gen. gluino mediated	$\tilde{g} \rightarrow bb\tilde{\chi}'_{1}$: 0 lep + 3 b-j's + $E_{\tau,miss}$	L=12.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-145] 1.24 TeV g mass	$(m(\tilde{\chi}_1^0) \le 200 \text{ GeV})$		
		$\tilde{g} \rightarrow tt \tilde{\chi}_1^\circ$: 2 SS-lep + (0-3b-)j's + $E_{T,miss}$	L=20.7 fb ⁻¹ , 8 TeV [ATLAS-CONF-2013-007] 900 GeV g mass (any n			
		$g \rightarrow tt \chi_1^-: 0$ lep + multi-j's + $E_{T,miss}$	L=5.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-103] 1.00 TeV [g mass (m)	λ ₁ < 300 GeV) 8 TeV, partial 2012 data		
		$g \rightarrow tt \chi$: 0 lep + 3 b-j's + $E_{T,miss}$	L=12.8 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-145] 1.15 TeV g mass	(m(X ₁) < 200 GeV)		
	3rd gen. squarks direct production	$\overrightarrow{DD}, \overrightarrow{D}, \overrightarrow{DD}, \overrightarrow$	L=12.8 fb : 8 TeV [ATLAS-CONF-2012-165] E20 GeV D IIIdSS $(m(\chi_1) < 120 \text{ G})$ L=22 7 fb : 8 TeV [ATLAS-CONF-2012-165] D IIIdSS $(m(\chi_1) < 120 \text{ G})$	iv) / rev, all 2011 data		
		$t_{\text{T,miss}}$	$(m(\chi_1) = 2m(\chi_1))$			
5		tt (medium), $t \rightarrow b\tilde{\gamma}^{\pm}$: 1 lep + b-iet + E	L=20.7 fb ⁻¹ , 8 TeV [ATLAS-CONF-2013-037] 160-410 GeV \tilde{t} mass $(m(\tilde{y}^2) = 0 \text{ GeV}, m(\tilde{y}^2) = 1$	50 GeV)		
ã		$\tilde{t}\tilde{t}$ (medium), $\tilde{t} \rightarrow b\tilde{\chi}^{\pm}$: 2 lep + E_{τ} miss	L=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-167] 160-440 GeV T Mass (m(2)) = 0 GeV, m(t)-m(ž [*]) = 10 GeV)		
q		$\tilde{t}t$ (heavy), $\tilde{t} \rightarrow t\tilde{\chi}^0$: 1 lep + b-jet + E_{τ}	L=20.7 fb ⁻¹ , 8 TeV [ATLAS-CONF-2013-037] 200-610 GeV T MASS (m($\tilde{\chi}_{1}^{0}) = 0$)			
ä		$\tilde{t}\tilde{t}$ (heavy), $\tilde{t} \rightarrow t\tilde{\chi}^{0}$: 0 lep + 6(2b-)jets + $E_{T miss}$	L=20.5 fb ⁻¹ , 8 TeV [ATLAS-CONF-2013-024] 320-660 GeV \tilde{t} mass $(m(\tilde{\chi}^0) = 0)$			
C I		tt (natural GMSB) : Z(→II) + b-jet + E	L=20.7 fb ⁻¹ , 8 TeV [ATLAS-CONF-2013-025] 500 GeV t mass (m($\tilde{\chi}_1^0$) > 150 GeV)			
		$t_2t_2, t_2 \rightarrow t_1 + Z : Z(\rightarrow II) + 1 \text{ lep } + b \text{-jet } + E$	L=20.7 fb ⁻¹ , 8 TeV [ATLAS-CONF-2013-025] 520 GeV t_2 mass $(m(\tilde{t}_1) = m(\tilde{\chi}_1^2) + 10)$	30 GeV)		
\geq	<i>EW</i> direct	$[l_1,] \rightarrow l_{\chi_1}^{\infty}$: 2 lep + $E_{\tau, miss}$	L=4.7 fb ⁻¹ , 7 TeV [1208.2884] 85-195 GeV I MASS (m($\tilde{\chi}_1^{*}) = 0$)			
		$\tilde{\chi}, \tilde{\chi}, \tilde{\chi}, \tilde{\chi} \rightarrow \text{lv}(\text{IV}): 2 \text{ lep } + E_{\tau,\text{miss}}$	L=4.7 fb ⁻¹ , 7 TeV [1208.2884] 110-340 GeV χ^{-1} mass $(m(\bar{\chi}) < 10 \text{ GeV}, m(\bar{\chi}) = 0$	$(m(\tilde{\chi}_{1}^{2}) + m(\tilde{\chi}_{2}^{2})))$		
Ē1		$\chi, \chi, \chi \rightarrow tV(tV): 2t + E_{T,miss}$	L=20.7 fb ⁻¹ , 8 TeV [ATLAS-CONF-2013-028] 180-330 GeV χ_1 mass $\langle m(\chi_1) < 10 \text{ GeV}, m(\chi_2) < \frac{1}{2}$	$(m(\chi_{1}) + m(\chi_{2})))$		
	-	$\chi_1 \chi_2 \rightarrow \chi_1 \chi_1 (vv), v \chi_1 (vv) : 3 \text{ lep } + E^{T,\text{miss}}$	L=20.7 fb ⁻¹ , 8 TeV [ATLAS-CONF-2013-035] 600 GeV χ_1 [mass $(m(\chi_1) = m(\chi_1) = $	$_{2}$, $m(\chi_{1}) = 0$, $m(l, v)$ as above)		
		$\chi \chi \rightarrow W \chi \chi \chi$, 5 lep + $E_{T, miss}$ Direct \tilde{x}^{\pm} pair prod. (AMSB) : long-lived \tilde{x}^{\pm}	$\frac{1}{2} \frac{1}{2} \frac{1}$	(ptons decoupled)		
0.	es se	Stable a R-badrons : low & By	L=4.7 fb ⁻¹ 7 TeV [1211 1597] 220 080 X ₁ mass (1 < 0, 7 < 10 ms) 985 GeV 0 mass			
	7-liv	GMSB, stable $\tilde{\tau}$: low β	L=4.7 fb ⁻¹ 7 TeV (1211 1597) 300 GeV τ Mass (5 s tan8 s 20)			
	art	GMSB, $\tilde{\gamma}^0 \rightarrow \gamma \tilde{G}$; non-pointing photons	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2013-016] 230 GeV $\tilde{\chi}^0$ mass $(0.4 < \tau(\tilde{\chi}^0) < 2 \text{ ns})$			
Γ	PLC	$\tilde{\chi}^0 \rightarrow qq\mu (RPV)^1: \mu + heavy displaced vertex$	L=4.4 fb ⁻¹ , 7 TeV [1210.7451] 700 GeV [1210.7451] 700 GeV	1 m, ĝ decoupled)		
		LFV : pp→ṽ,+X, ṽ,→e+µ resonance	L=4.6 fb ⁻¹ , 7 TeV [1212.1272] 1.61 TeV [\widetilde{V}_{τ} [1	iass (λ ₃₁₁ =0.10, λ ₁₃₂ =0.05)		
>	RPV	LFV : $pp \rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e(\mu) + \tau$ resonance	L=4.6 fb ⁻¹ , 7 TeV [1212.1272] 1.10 TeV V ₁ MASS	$(\lambda'_{311}=0.10, \lambda_{1(2)32}=0.05)$		
		Bilinear RPV CMSSM : 1 lep + 7 j's + E _{T,miss}	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-140] 1.2 TeV $\tilde{q} = \tilde{g}$ mas	$S = (c\tau_{LSP} \le 1 \text{ mm})$		
D		$\tilde{\chi}_1 \tilde{\chi}_1, \tilde{\chi}_1 \to W \tilde{\chi}_1, \tilde{\chi}_1 \to eev_{\mu}, e\mu v_e : 4 lep + E_{\tau, miss}$	L=20.7 fb ⁻¹ , 8 TeV [ATLAS-CONF-2013-036] 760 GeV χ_1 mass (mQ)) > 300 GeV, $\lambda_{121} > 0$)		
R		$\chi_1 \chi_1,, \chi_1 \rightarrow \tau \tau v_e, e \tau v_\tau : 3 \text{ lep } + 1 \tau + E_{\tau, miss}$	L=20.7 fb ⁻¹ , 8 TeV [ATLAS-CONF-2013-036] 350 GeV χ_1 mass $(m(\tilde{\chi}_1) > 80 \text{ GeV}, \lambda_{133} > 0$	1		
		$g \rightarrow qqq$: 3-jet resonance pair	L=4.6 fb ⁻¹ , 7 TeV [1210.4813] 666 GeV g mass	ā.		
Н	$g \rightarrow it_1 (- bs : 2 \ s - ie p + (0 \cdot 3b -)) s + \epsilon_{T,nigs}$ Scalar gluon : 2-jet resonance pair WIMP interaction (D5, Dirac χ) : 'monojet' + ϵ_{-}		L=20.7 fb , 8 feV [ATLAS-CONF-2013-007] 880 GeV 9 [11:dSS (any m L=4.6 fb ⁻¹ 7 TeV (1310-4838) 997 GeV SOLUOD MOSS (and Unit from 1110-2803)	(1)		
Je			(#10.5 lb ⁻¹ 8 TeV [2210.4626] (#10.2012.147] 704 GeV M [*] 9Cale (m. < 80)	GeV limit of s 687 GeV for D8)		
E		T,miss		sev, initial 4 dos dev la bay		
\bigcirc			10 ⁻¹ 1	10		
	Maga apple					
	*Only a	selection of the available mass limits on new st	tes or phenomena shown. al cross section uncertainty	wass scale [TeV]		

nothing yet; mostly sensitive to strongly interacting gluinos/squarks; mass sensitivity beyond 1 TeV

... if not SUSY, is anybody else around?

		ATLAS Exotics Searches* - 95% CL Lower Limits (Status: HCP 2012)						
	Large ED (ADD) : monoiet + E	(=4.7 /b ⁻¹ .7 To)/ (1210.4491)	4 37 ToV M (S=	2)				
	Large ED (ADD) : monophoton + $E_{T,miss}$	L=4.6 fb ⁻¹ , 7 TeV [1209.4625]	1.93 TeV M _D (δ=2)					
1S	Large ED (ADD) : diphoton & dilepton, m	L=4.7 fb ⁻¹ , 7 TeV [1211.1150]	4.18 TeV M _s (HL)	z δ=3, NLO) AILAS				
ioi	UED : diphoton + $E_{T,miss}$	L=4.8 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-072]	1.41 TeV Compact. scale R ⁻¹	Preliminary				
Sue	S ¹ /Z ₂ ED : dilepton, m _{il}	L=4.9-5.0 fb ⁻¹ , 7 TeV [1209.2535]	4.71 TeV Μ _{KK} ~	R ^{**}				
ime	RS1: dipnoton & dilepton, $m_{\gamma\gamma/1}$ RS1: 77 resonance m	L=4.7-5.0 fb ⁻¹ , 7 TeV [1210.8389]	2.23 TeV Graviton mass (k/M = 0.1)	$(M_{\rm Pl} = 0.1)$				
PE	RS1 : WW resonance, m _{T NN}	L=4.7 fb ⁻¹ , 7 TeV [1208.2880]	1.23 TeV Graviton mass $(k/M_{el} = 0.1)$	(1) $Ldt = (1.0 - 13.0) \text{ fb}^{-1}$				
<i>ctre</i>	RS $g_{KK} \rightarrow tt$ (BR=0.925) : $tt \rightarrow l+jets, m_{theoreted}$	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-136]	1.9 TeV g _{kk} mass	J E-ZOTY				
ŵ	ADD BH (M _{TH} /M _D =3) : SS dimuon, N _{ch_part}	L=1.3 fb ⁻¹ , 7 TeV [1111.0080]	1.25 TeV $M_D(\delta=\hat{6})$	s = 7, 8 lev				
	ADD BH $(M_{TH}/M_D=3)$: leptons + jets, Σp	L=1.0 fb ⁻¹ , 7 TeV [1204.4646]	1.5 TeV M _D (δ=6)					
	Quantum black hole : dijet, $F_{y}(m_{\parallel})$	L=4.7 fb ⁻¹ , 7 TeV [1210.1718]	4.11 TeV M _D (δ=6	5) A				
0	agent Cl : ee & uu. m	L=4.9-5.0 fb ⁻¹ , 7 TeV [1211.1150]	7.0 104	13.9 TeV A (constructive int.)				
0	uutt CI : SS dilepton + jets + E _{T miss}	L=1.0 fb ⁻¹ , 7 TeV [1202.5520]	1.7 TeV A					
	Z' (SSM) : m _{ee/µµ}	L=5.9-6.1 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-129]	2.49 TeV Z' mass					
	Z' (SSM) : m _{ee}	L=4.7 fb ⁻¹ , 7 TeV [1210.6604]	1.4 TeV Z' mass					
Ś	W' (SSM): $m_{T,e/\mu}$ W' (\rightarrow to $q = 1$): m	L=4.7 fb ⁻¹ , 7 TeV [1209.4446]	2.55 TeV W' mass					
	W'_{p} (\rightarrow tb, SSM); m	L=4.7 fb , 7 leV [1209.6593] 430 GeV L=1.0 fb ⁻¹ , 7 TeV [1205.1016]	1.13 TeV W' mass					
	W*: m _{Te/u}	L=4.7 fb ⁻¹ , 7 TeV [1209.4446]	2.42 TeV W* mass					
\sim	Scalar LQ pair (β =1) : kin. vars. in eejj, evjj	L=1.0 fb ⁻¹ , 7 TeV [1112.4828] 66	<mark>ø GeV</mark> 1 [€] gen. LQ mass					
ΓC	Scalar LQ pair (β=1) : kin. vars. in μμjj, μvjj	L=1.0 fb ⁻¹ , 7 TeV [1203.3172] 6	ss Gev 2 nd gen. LQ mass					
10	Scalar LQ pair (β=1) : kin. vars. in ττj, τνj	L=4.7 fb ⁻¹ , 7 TeV [Preliminary] 538 G	eV 3° gen. LQ mass					
rks	4 generation : $tt \rightarrow VVVVD$ 4 th generation : b'b'(T T _{en}) $\rightarrow WtWt$	$L=4.7 \text{ fb}^{-1}$ 7 TeV [1210.5468] 03 (=4.7 fb^{-1} 7 TeV [ATI AS_CONE_2012_130] 6	Gev timass					
na	New quark b' : b'b ^{'3} → Zb+X, m _{zb}	L=2.0 fb ⁻¹ , 7 TeV [1204.1265] 400 GeV	b' mass					
V 9	Top partner : TT \rightarrow tt + A ₀ A ₀ (dilepton, M ₁₂)	L=4.7 fb ⁻¹ , 7 TeV [1209.4186] 483 Ge	T mass (m(A ₀) < 100 GeV)					
Vev	Vector-like quark : CC, mivg	L=4.6 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-137]	1.12 TeV VLQ mass (charge -1/3, co	supling $\kappa_{qQ} = v/m_Q$				
<	Excited quarks : v-let resonance m	L=4.6 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-137]	1.08 TeV VLQ mass (charge 2/3, cou	pling $\kappa_{qQ} = v/m_Q$)				
im.	Excited quarks : dijet resonance, m-	L=2.1 fb , 7 leV [1112.3580] (=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONE-2012-148]	2.46 TeV Q THASS					
θ	Excited lepton : I-y resonance, m	L=13.0 fb ⁻¹ , 8 TeV [ATLAS-CONF-2012-146]	2.2 TeV * mass (A = m(l*))				
T	Techni-hadrons (LSTC) : dilepton, mee/µµ	L=4.9-5.0 fb ⁻¹ , 7 TeV [1209.2535]	850 GeV ρ_{T}/ω_{T} mass $(m(\rho_{T}/\omega_{T}) - m(\pi_{T}) =$	M _w)				
leci	hni-hadrons (LSTC): WZ resonance (VIII), m	L=1.0 fb ⁻¹ , 7 TeV [1204.1548] 483 GeV ρ_{T} mass $(m(\rho_{T}) = m(\pi_{T}) + m_{W}, m(\alpha_{T}) = 1.1 m(\rho_{T}))$						
her	Major. neutr. (LRSM, no mixing) : 2-lep + jets	L=2.1 fb ⁻¹ , 7 TeV [1203.5420]	1.5 TeV N mass $(m(VV_R) = 2$ Te	(V) (< 1.4 TeV)				
Oth	H_{R}^{\pm} (DY prod., BR($H_{L}^{\pm} \rightarrow \parallel$)=1) : SS ee (µµ), m	L=4.7 fb ⁻¹ , 7 TeV [1210.5070] 409 GeV	$H_{\mu}^{\pm\pm}$ mass (limit at 398 GeV for $\mu\mu$)	< 1.4 lev)				
	H [±] _L (DY prod., BR(H [±] →eµ)=1) : SS eµ, m [∥] _{e1}	L=4.7 fb ⁻¹ , 7 TeV [1210.5070] 375 GeV	H ^{±±} mass					
	Color octet scalar : dijet resonance, m	L=4.8 fb ⁻¹ , 7 TeV [1210.1718]	1.86 TeV Scalar resonance n	nass				
		····		······································				
		10-'	1	10 102				
Mass scale [TeV]								
*Only a selection of the available mass limits on new states or phenomena shown								

Nope! Multi-TeV sensitivities reached for many models



Indirect Searches

C)

watching the Universe

Some of the best places to look

gravitational centres with small astrophysical backgrounds

Galactic Centre

Dwarf Spheroidal Galaxies NASA

Sun Core





characteristic emission of high energy particles

- γ gamma rays
- $\nu, \overline{\nu}$ neutrinos
- $\overline{\mathbf{p}}, \mathbf{e}^+$ anti-matter

detectable on earth?

Anti-matter from the Universe

Alpha Magnetic Spectrometer on ISS



WIMP annihilation?

 Astrophysical source (close-by pulsar)?

Positron-Anomaly



Antiprotons



Compatible with cosmic ray propagation models

Neutrinos from dark matter annihilation Most sensitive for $m_{\gamma} \ge 100 \text{ GeV}$: IceCube / Deep Core (/ PINGU)



IceTop 80 stations, each with 2 IceTop Cerenkov detector tanks 2 optical sensors per tank 320 optical sensors

IceCube array 86 strings including 6 DeepCore strings 60 optical sensors on each string 5160 optical sensors

Amanda II array (precurser to IceCube)

DeepCore

6 strings-spacing optimized for lower energies, 360 optical sensors

Eiffel Tower 324 m (1063 ft) H. Kolanoski Humboldt University

Neutrino detection

Cherenkov light

detector in ice / water



interaction

neutrino

WIMP annihilation in the core of the der Sun

only neutrinos can escape





IceCube beats direct searches in high mass region for spin dependent proton WIMP scattering



Gamma Rays from dark matter annihilation



We are (un)lucky: the gamma ray sky is crowded; great astrophysics!

Look for regions with high DM density but low astrophysical gamma ray activity







Look for weird spectral shapes, cut-offs ...

...or look for the smoking gun: a line / a bump





E,



- Interaction volume "tested" in dt $dV = \sigma(v)v dt$
- Annihilation probability in dt in V

$$dp = \frac{dV}{V} = \sigma(v) v dt / V$$

Annihilation rate in V

$$\Gamma = \frac{dp}{dt} = \sigma(v)v / V$$

Total annihilation rate in V

$$\int_{\text{ot}} = \frac{1}{V} \times \sum_{\text{targets, projectiles}} \sigma(v) v = \frac{1}{V} C \langle \sigma v \rangle$$
target-projectile pairs



- Total annihilation rate in V $\Gamma_{tot} = \tfrac{1}{v} C \left< \sigma v \right>$
- Number of pairs

$$C = \begin{cases} N_t N_p = \frac{N^2}{4}, & \chi \neq \overline{\chi} \\ \frac{N(N-1)}{2} \approx \frac{N^2}{2}, & \chi = \overline{\chi} \end{cases}$$



• Use mass density $\rho = Nm_{\chi}/V$

$$\frac{d\Gamma}{dV} = \frac{\Gamma_{tot}}{V} = \frac{\rho^2}{\nu m_{\chi}^2} \langle \sigma v \rangle \quad \text{with} \quad \nu = \begin{cases} 4, & \chi \neq \overline{\chi} \\ 2, & \chi = \overline{\chi} \end{cases}$$



$$\frac{d\Gamma_{\gamma}}{dVdE} = \frac{\rho^2}{\nu m_{\chi}^2} \frac{dN_{\gamma}}{dE} \langle \sigma v \rangle$$

rate seen by detector

$$d\Gamma_{\rm det} = \frac{A}{4\pi s^2} d\Gamma_{\gamma}$$

detected gamma ray flux from dV

 $\frac{d\phi}{dE} = \frac{1}{A} \frac{d\Gamma_{det}}{dE} = \frac{1}{4\pi s^2} \frac{\rho^2}{\nu m_{\chi}^2} \frac{dN_{\gamma}}{dE} \langle \sigma v \rangle dV$

detector



Astrophysical Factor



- Units: $[J] = M_{\odot}^2 kpc^{-5} = 4.45 \, TeV^2 \, cm^{-5}$
- $\int d\Omega$: to be folded with angular resolution of detector (psf)
- Good targets have large J and small astrophysical backgr.
Candidate 1: Dwarf Galaxies (DG)



- ~25 DGs are known
- very old objects
- large mass/luminosity ratio
- dark matter dominated (little gas/dust, no star forming activity) $M_{DM} \sim 10^5 10^8 M_{\odot}$
- close-by (~ 10 kpc)
- compact (~ 1 kpc)
- DM density (⇒ J factors) from stellar kinematics (velocity spread)

Fermi result from stacking analysis



Candidate 2: Milky Way Halo



Milky Way Halo

Depends on assumed slope of DM density profile



Very competitive with DGs in high mass range:



Dark Matter:

- > Why ? Overwhelming evidence
- > What ? A WIMP the optimistic view
- > Where and how ? The threefold way

Good Luck!