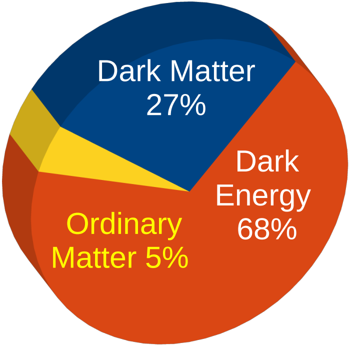
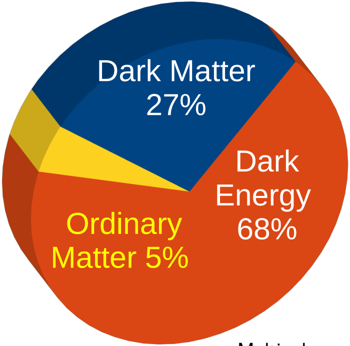
Scalar Dark Matter

Laura Lopez Honorez

Mini-workshop on scalar sector in Belgium

What is the Universe made of ?


Dark Matter
27%
Dark
Energy
68%
Ordinary
Matter 5%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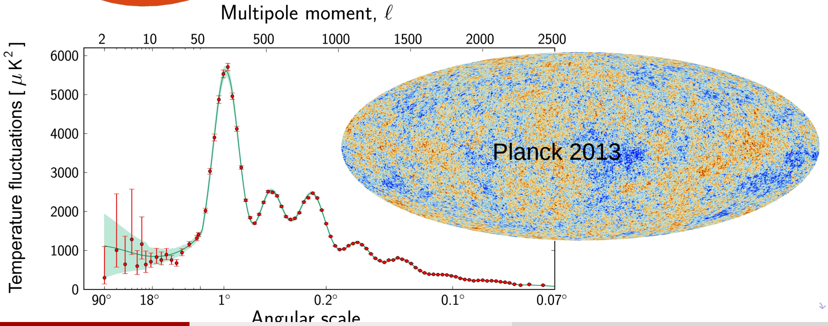
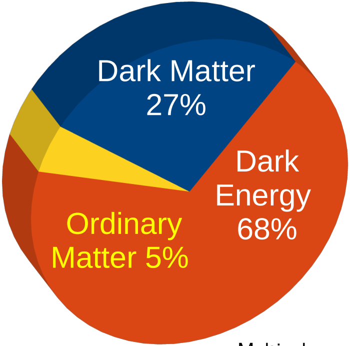
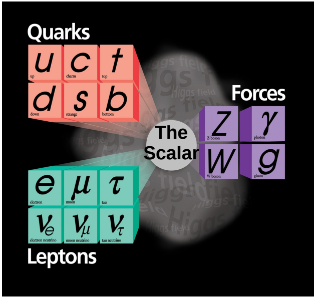
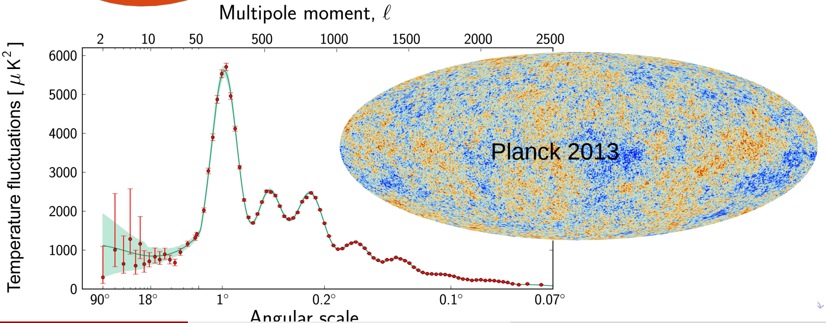
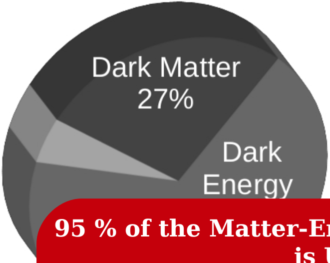

Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
Temperature fluctuations [μK²]
6000
5000
4000
3000
2000
1000
0
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale
Planck 2013



NO GOOD DM CANDIDATE!!







GOOD DM
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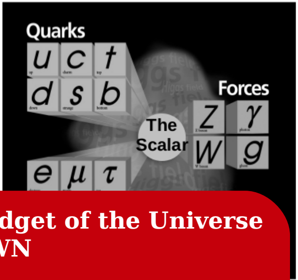
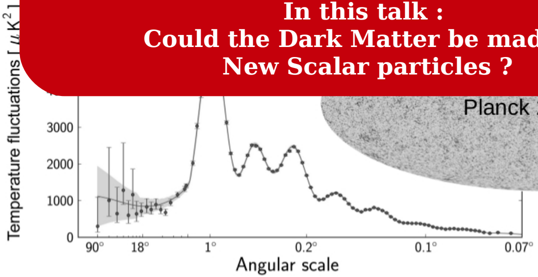


95 % of the Matter-Energy budget of the Universe is UNKNOWN

~84 % of the Matter Content is made of Dark Matter

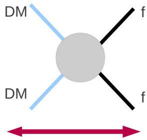
In this talk :
Could the Dark Matter be made of New Scalar particles ?



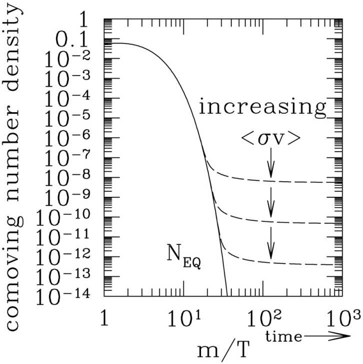
Focus on WIMPs

Weakly Interacting Massive Particles

- WIMP relic abundance is driven by :



Freeze-out mechanism :
$\rightsquigarrow \Omega h^2 \propto 1/\langle \sigma v \rangle$



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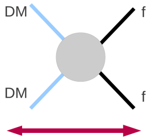
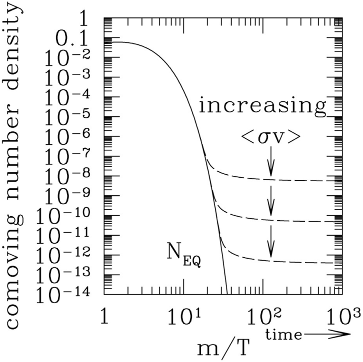


Freeze-out mechanism :
$\rightsquigarrow \Omega h^2 \propto 1/\langle\sigma v\rangle$

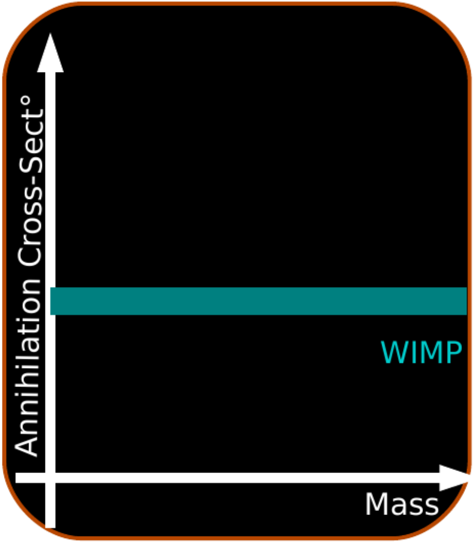
- Cosmo observations ($\Omega h^2 \sim 0.11$) can be interpreted as

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

$\rightsquigarrow$ target value for detection experiments
looking for annihilation products of WIMPs



WIMP tests



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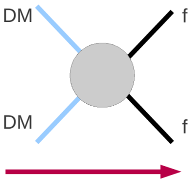
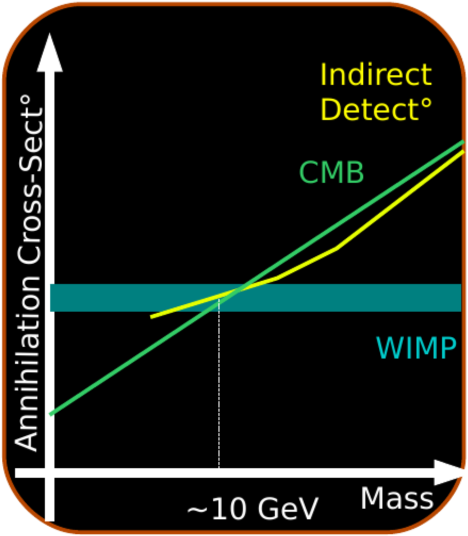
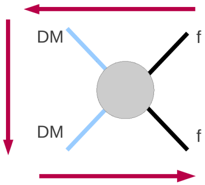
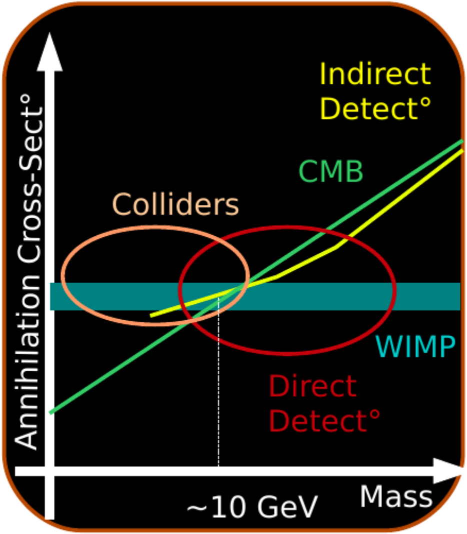

DM
DM
f
f


Annihilation Cross-Sect°
Indirect
Detect°
CMB
WIMP
~10 GeV
Mass

WIMP tests


DM
DM
f
f


Indirect
Detect°
CMB
Colliders
WIMP
Direct
Detect°
Annihilation Cross-Sect°
~10 GeV
Mass

Worked Examples with SMS Portal

$(H^\dagger H)$- dark sector operators drive the SM-DM interactions

[Silveira & Zee'85 ; McDonald'94 ; Burgess, Pospelov& ter Veldhuis'00 ; Patt & Wilczek'06 ; Barger et al'08 ; Andreas, Hambye, Tytgat'08,...]

Scalar Singlet of $SU(2)_L \times U(1)$

SMS portal with singlet scalar DM

DM = SM singlet scalar S :

- DM stability : Z_2 symmetry
- sms-DM interactions : $\lambda_S S^2 (H^\dagger H)$

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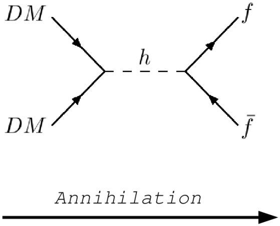
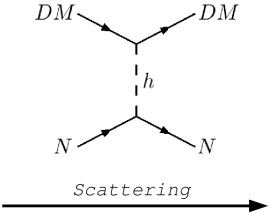
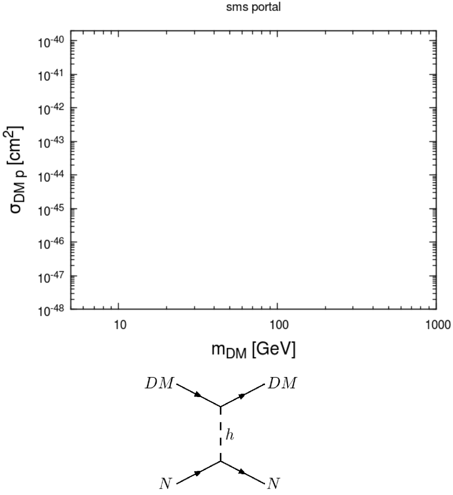
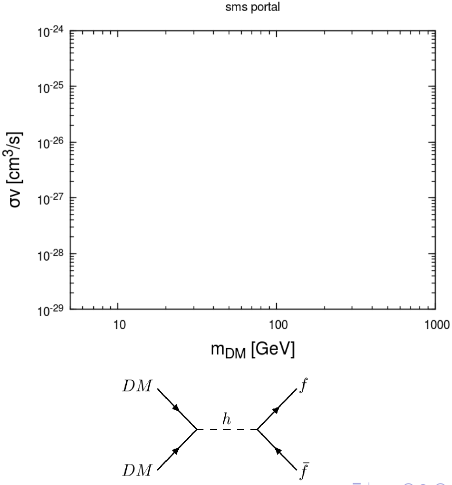




$\mathcal{L} \supset -\lambda\, v\, h\, S S$





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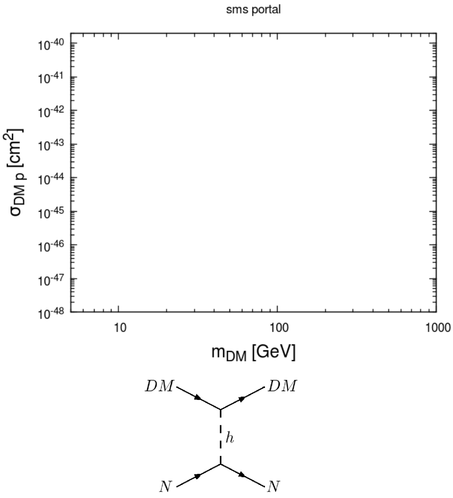

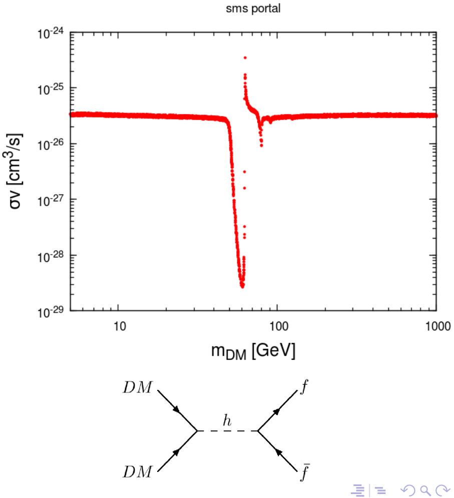

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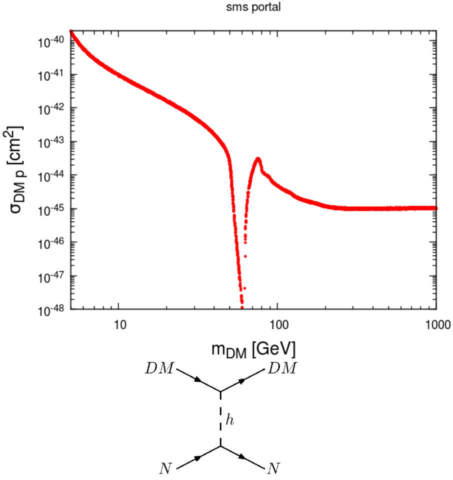

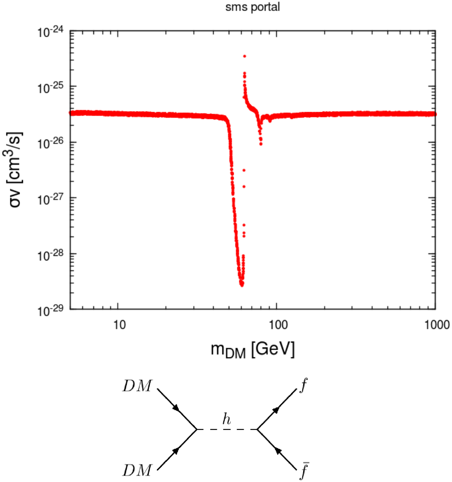

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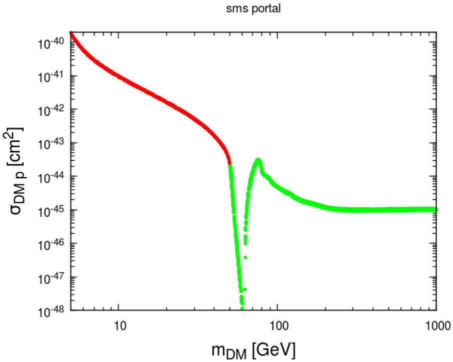
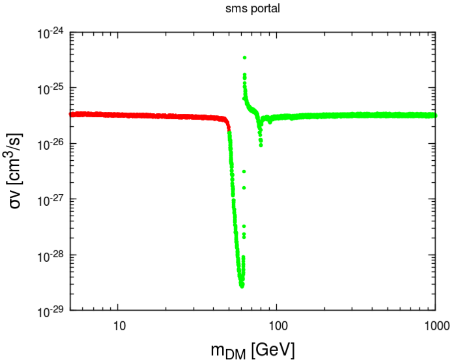
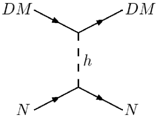
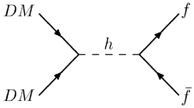
- Constraints from Colliders : restricted $\Gamma(h \to SS)$







Scattering



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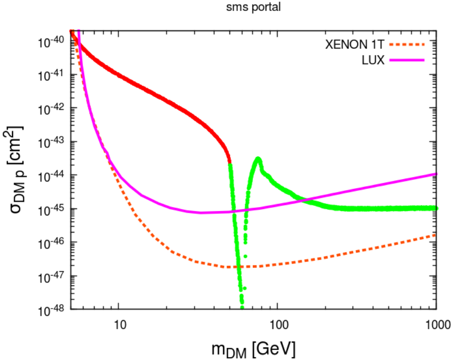
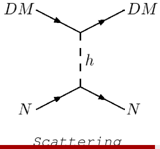
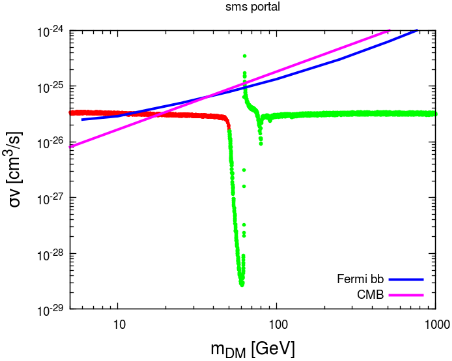
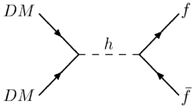
- Constraints from Colliders : restricted $\Gamma(h \to SS)$
- from Direct detection





- from Indirect detection & CMB





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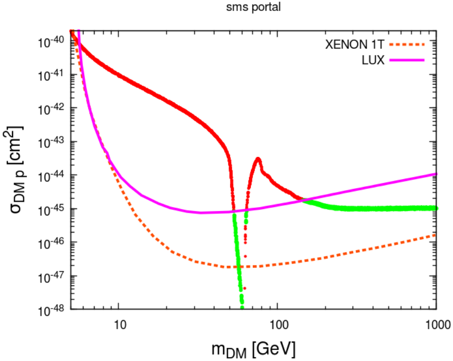

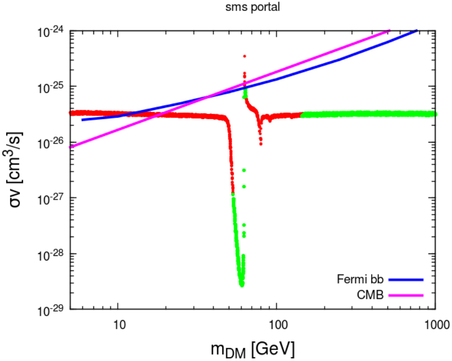

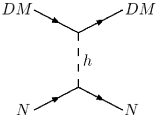

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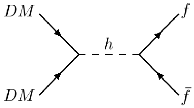

Scalar n-plet of $SU(2)_L \times U(1)$

Scalar DM model

- Extra n-uplet case ($n > 2$) :
  - only one coupling to the Higgs $\lambda_3 |H_1|^2 |H_n|^2$
  - no mass splittings between H_n^0 and $H_n^{\pm(\ldots\pm)}$

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- Particular case : $n = 2 \equiv$ IDM
  - three couplings to the Higgs.

$$\lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + h.c.\right]$$

  - non zero mass splittings :

$$H_2 = \begin{pmatrix} iH^+ \\ \frac{(H_0 - iA_0)}{\sqrt{2}} \end{pmatrix} \quad H_1 = \begin{pmatrix} 0 \\ \frac{(h+v_0)}{\sqrt{2}} \end{pmatrix}$$

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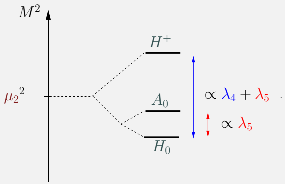
$${m_\chi}^2 = \mu_2^2 + \lambda_\chi v_0^2$$



$$\lambda_{H_c} \equiv \lambda_3/2$$

$$\lambda_{H_0,A_0} \equiv (\lambda_3 + \lambda_4 \pm \lambda_5)/2$$

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$\rightsquigarrow$ viable mass ranges $m_{H_0} \sim$ GeV-TeV range

We will refer to $H_0 - h$ coupling as $\lambda_{H_0} = \lambda_L$

Free parameters : $m_{H_0}, \lambda_L, \Delta m_{A^0}, \Delta m_{H^+}$

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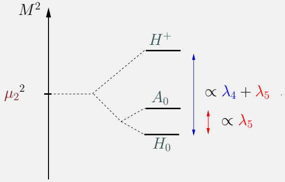

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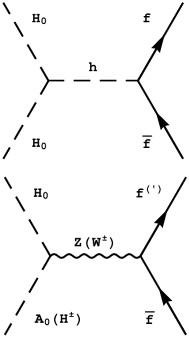
Inert doublet model parameter space

- $m_{H_0} \lesssim m_W$: GeV range

$$H_0 H_0 \to h^* \to \bar{f} f \text{ and } H_0 A_0 \to Z^* \to \bar{f} f$$

Barbieri PRD06, LLH JCAP06,Gustafsson PRL07, Cao PRD07, Andreas JCAP08,...



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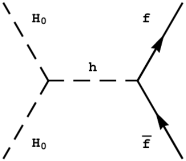
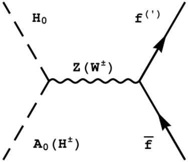
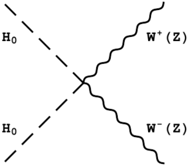




- $m_{H_0} \gg m_W$: TeV range

  $H_0 H_0 \to ZZ, WW, hh$ and coannihil into bosons

  Cirelli NPB06, Hambye, Ling,LLH & Rocher JHEP09



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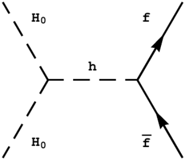
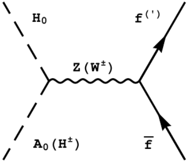
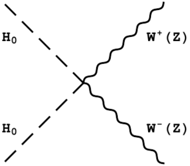




LARGE MASS GAP DUE TO EFFICIENT *WW* AND *ZZ* ANNIHILATION



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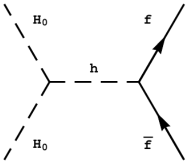
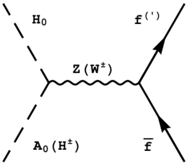
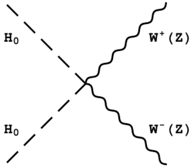




- Above W-threshold : cancellations

  $H_0 H_0 \to WW$ vs $H_0 H_0 \to h \to WW$ LLH & Yaguna JCAP11

LARGE MASS GAP DUE TO EFFICIENT WW AND ZZ ANNIHILATION



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  $H_0 H_0 \to h^* \to \bar{f} f$ and $H_0 A_0 \to Z^* \to \bar{f} f$

  Barbieri PRD06, LLH JCAP06,Gustafsson PRL07, Cao PRD07, Andreas JCAP08,...

  Significantly affected by 3bdy annihilation :
  $H_0 H_0 \to W W^* \to W \bar{f} f'$ LLH & Yaguna JHEP10

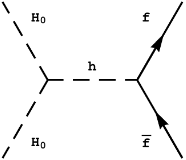
- Above W-threshold : cancellations

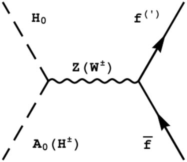
  $H_0 H_0 \to WW$ vs $H_0 H_0 \to h \to WW$ LLH & Yaguna JCAP11

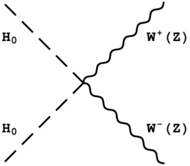
LARGE MASS GAP DUE TO EFFICIENT WW AND ZZ ANNIHILATION

- $m_{H_0} \gg m_W$: TeV range
  $H_0 H_0 \to ZZ, WW, hh$ and coannihil into bosons

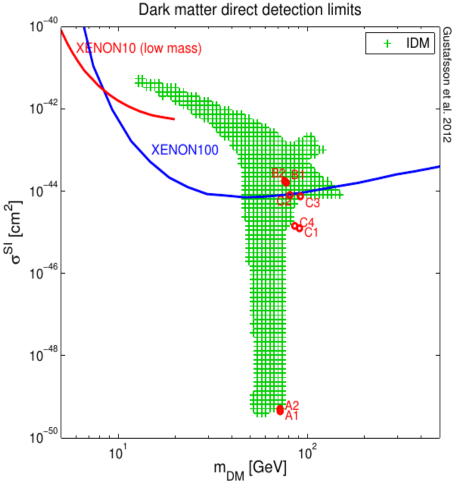
  Cirelli NPB06, Hambye, Ling,LLH & Rocher JHEP09





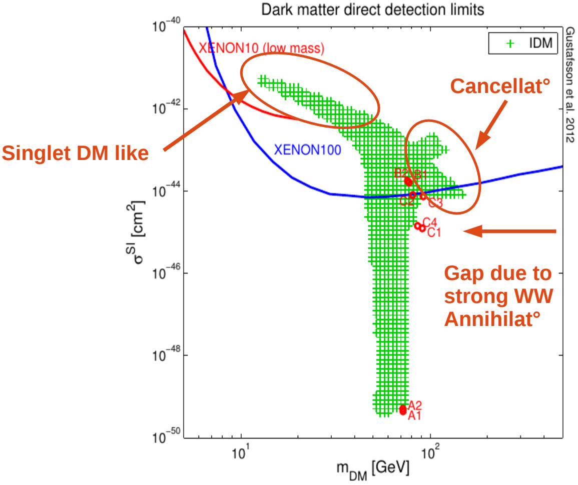


Inert doublet model : viable parameter space



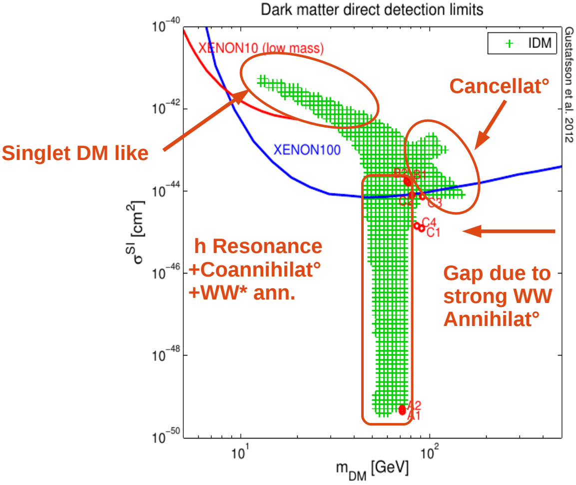
[Gustafsson, Rydbeck,LLH,Lundstrom PRD'12]

Inert doublet model : viable parameter space



[Gustafsson, Rydbeck,LLH,Lundstrom PRD'12]

Inert doublet model : viable parameter space



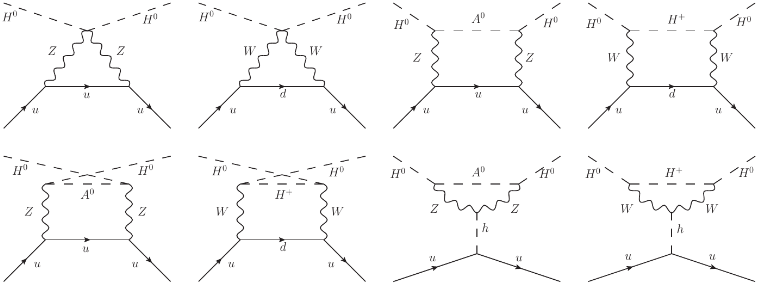
[Gustafsson, Rydbeck,LLH,Lundstrom PRD'12]

Loop Corrections in the IDM

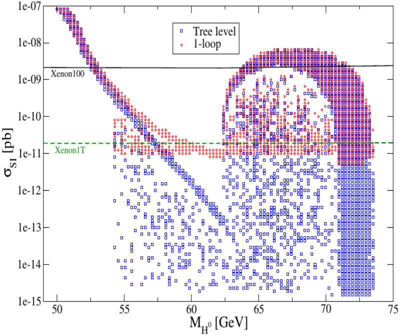
based on : arXiv :1302.1657, Yaguna et al.

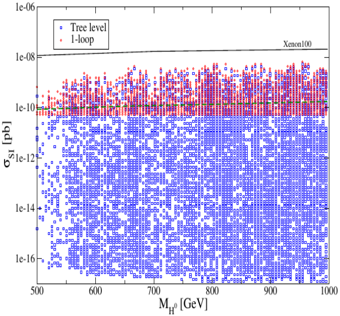
Important loop corrections due to gauge processes

$$V = \mu_1^2|H_1|^2 + \mu_2^2|H_2^2| + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + \text{h.c.}\right],$$



Effect on Spin Independent scattering cross-section





Conclusion

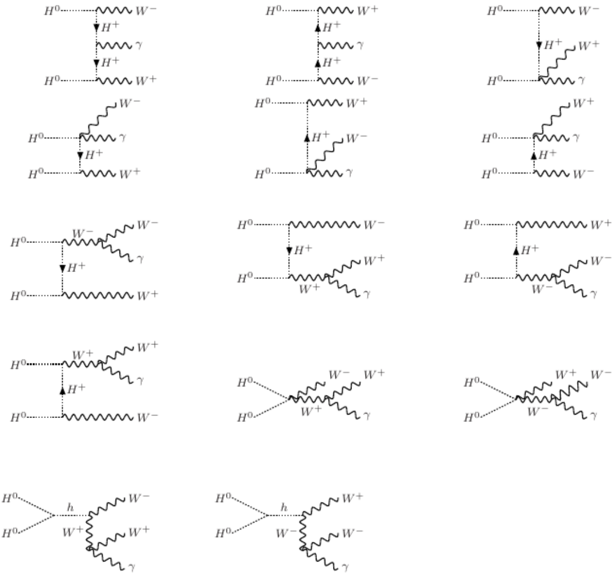
- Cosmo : Compiling cosmological probes tell us that 95% of the Universe content is unknown. Dark matter would make 84% of the matter content but its true nature still obscure.
- Particle : Up to now no convincing evidence for a given given candidate BUT DM searches are now seriously digging into the viable WIMP DM parameter space.
- SMS portal a worked example :
  - Low mass dark matter ($5 \lesssim m_{DM} \lesssim 40$ GeV) is now excluded by the combination of Direct, Indirect and Collider searches
  - Middle mass regime ($40 \lesssim m_{DM} \lesssim 100$ GeV) is seriously threatened by direct detection searches a part for resonant annihilation or coannihilations
  - Large mass regime will be tested up to $\sim$ TeV range by future Direct detection experiments

Thank you for your attention ! ! !

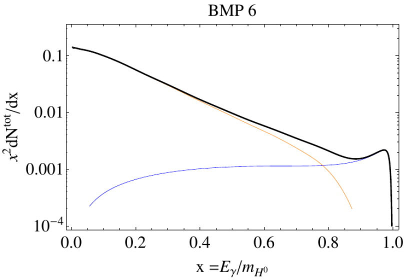
Backup

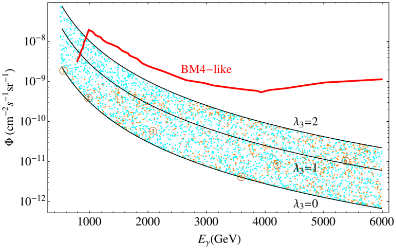
Detection & Constraints

spectral features with Bremsstrahlung (Garcia-Cely ’13)



spectral features with Bremsstrahlung (Garcia-Cely '13)





Gamma ray lines in the IDM

«Significant gamma-ray line from Inert Doublet»

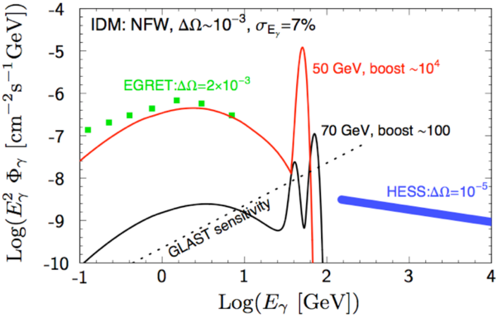


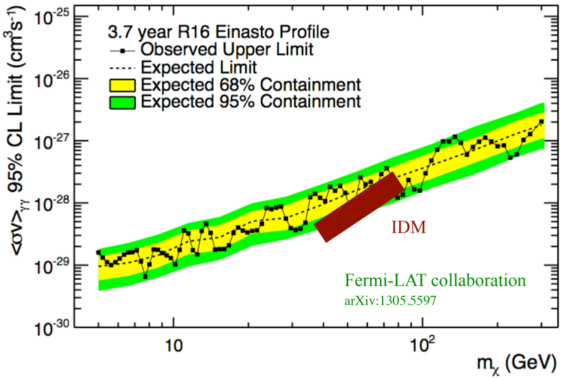
TABLE II: *IDM benchmark model results.*

Model	$v\sigma_{tot}^{v\to 0}$ $[\mathrm{cm}^3\mathrm{s}^{-1}]$	Branching ratios [%]: $\gamma\gamma$	$Z\gamma$	$b\bar{b}$	$c\bar{c}$	$\tau^+\tau^-$	$\Omega_{\mathrm{CDM}}h^2$
I	1.6×10^{-28}	36	33	26	2	3	0.10
II	8.2×10^{-29}	29	0.6	60	4	7	0.10
III	8.7×10^{-27}	2	2	81	5	9	0.12
IV	1.9×10^{-26}	0.04	0.1	85	5	10	0.11

Gustafsson, Bergstrom, Lundstrom & Edsjo
Phys.Rev.Lett. 99 (2007) 041301

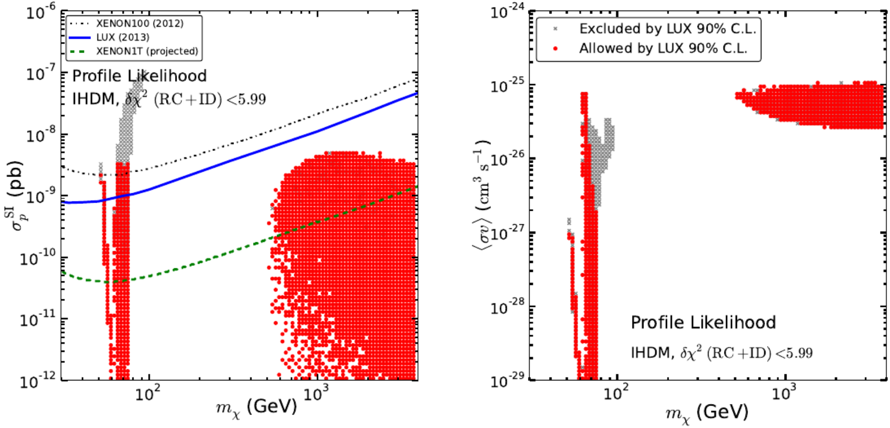
$M_{\mathrm{higgs}} \sim$ 500 GeV

CURRENT EXPERIMENTAL LIMITS



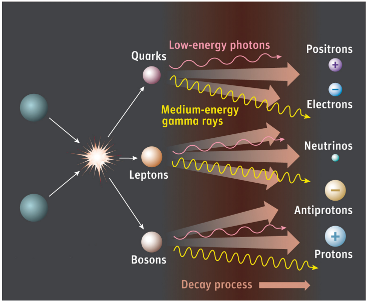
Fermi-LAT limits on gamma ray lines

Latest analysis of the IDM- Tsai '13



Making use of dark matter annihilation

DM annihilation driving the relic abundance also give rize to $\gamma, \nu, p^{\pm}, e^{\pm}$ production that is constrained :



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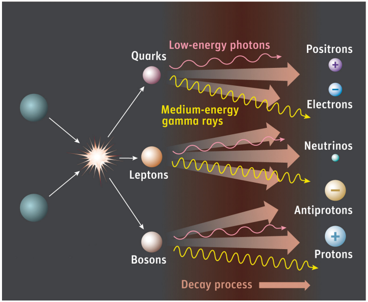

- *today* by Indirect detection searches :
  ⇝ Among the latter Fermi-Lat limits for gamma rays from dwarf spheroidal galaxies are the most constraining

Making use of dark matter annihilation

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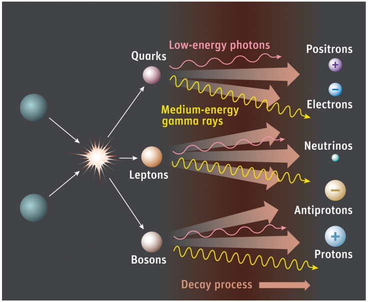
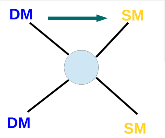
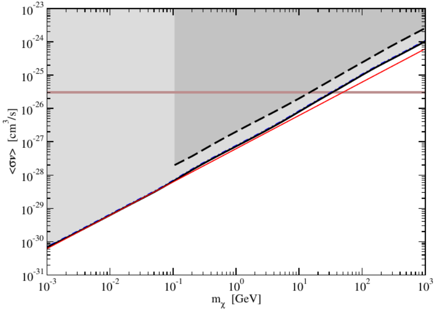


- *today* by Indirect detection searches :
  $\rightsquigarrow$ Among the latter Fermi-Lat limits for gamma rays from dwarf spheroidal galaxies are the most constraining
- *at early times* (z=1000) by CMB :
  $\rightsquigarrow$ Energy losses in the IGM at epoch of recombination
  $\rightsquigarrow$ affects recombination history
  $\rightsquigarrow$ impact on CMB anisotropy spectrum at high multipoles.

Making use of dark matter annihilation



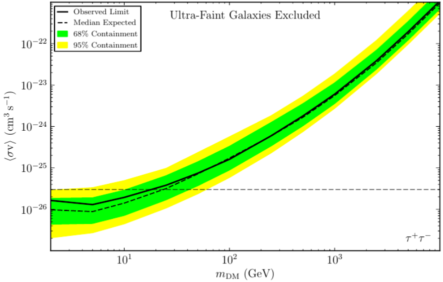
Constraints from CMB



upper bounds using WMAP9+SPT/ACT 12+HST+BAO

[LLH, Mena, Palomares-Ruiz, Vincent ’13]

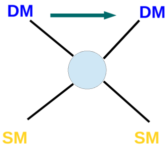
Constraints from Fermi-Lat



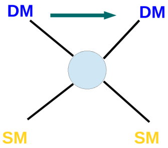
upper bound using 20 dwarfs and 200 MeV-100 GeV gamma rays

[Fermi-LAT Collaboration PRL ’13]

Direct Detection

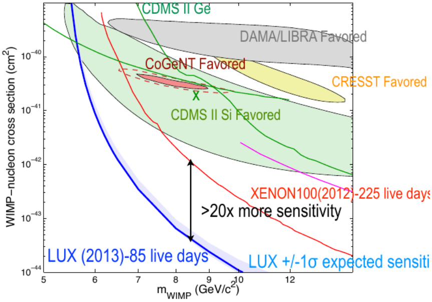


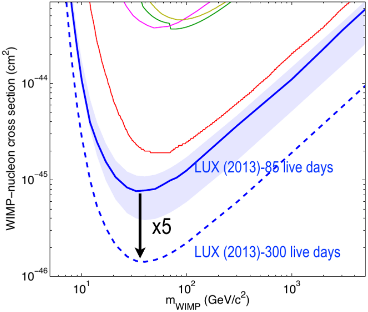
Direct Detection



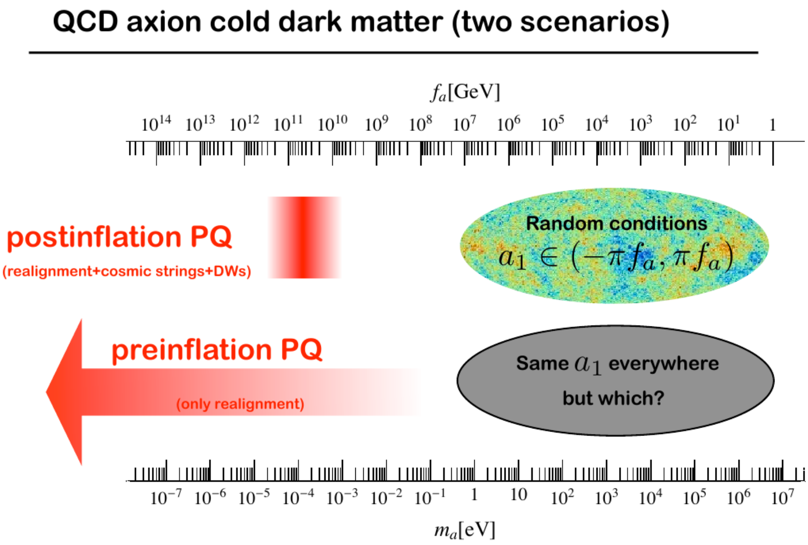
Upper bound on the DM scattering cross-section on Nucleons in Underground detectors

[Akerib et al '13]

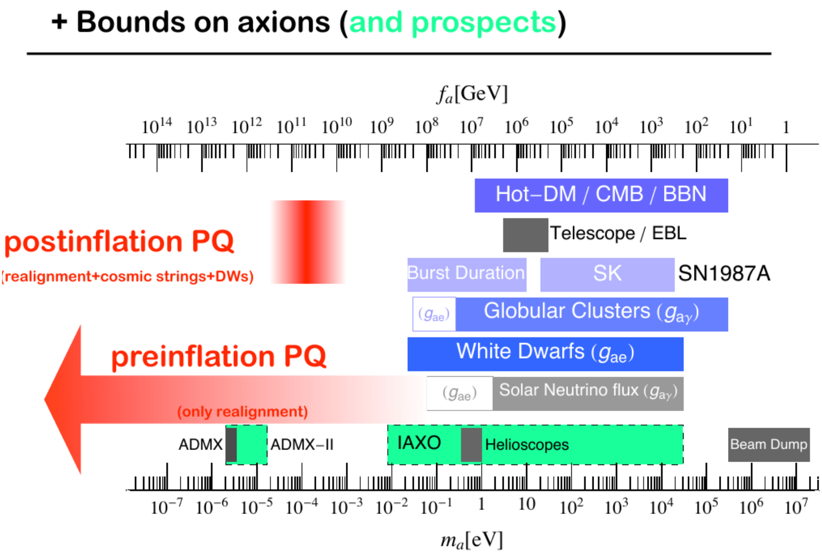




Axion DM (courtesy J. Redondo)



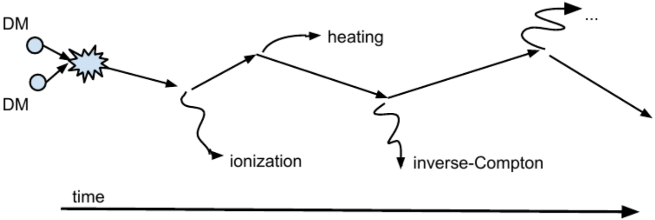
Axion DM (courtesy J. Redondo)



DM impact on CMB

Proper calculation of the deposition efficiency

1. At a given redshift z, calculate the final-state spectrum dN_i/dE_i for $i = \{e^+, e^-, \gamma\}$
2. Calculate the energy loss to (inverse) Compton scattering, Coulomb scattering, (photo) ionization or pair-production for each species.
3. Step forward to the next value of z, given the new $E_i = E_{i,0} - E(z)'dz$, including loss to IGM and to redshift.
4. Repeat.

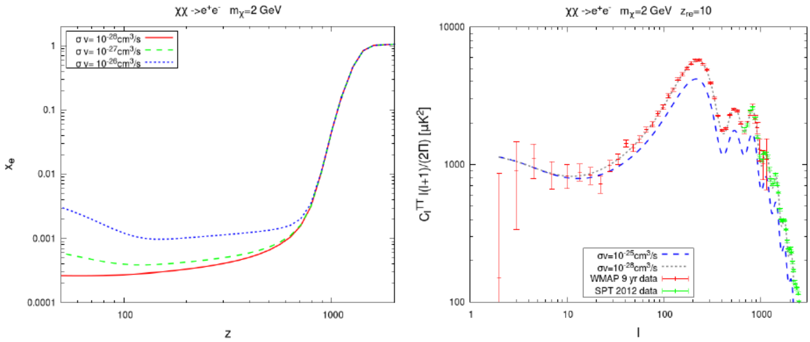


DM impact on CMB

- Dark matter annihilation rate is proportional to $(1+z)^6$, which leads to a dependence of
$$\sqrt{1+z} \quad (2)$$
for the heating and ionization rates. Therefore dominates in the early Universe. Around $z = 1100$, the extra energy injection has the effect of **delaying recombination**.
- This **broadens the last scattering surface**. This can be seen as a broadening of the CMB's "focal plane": you can still resolve large structures, but smaller details become blurred: $\Rightarrow$ **suppression of the correlations at high multipoles**.
- This is **degenerate** with a change in the scalar spectral index n_s.
- This can be disentangled by late-time effects.

courtesy of A. Vincent

DM impact on CMB



courtesy of A. Vincent

	Planck		Planck+lensing		Planck+WP	
Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.19^{+0.12}_{-0.14}$	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029	0.14094	0.1414 ± 0.0029	0.14305	0.1426 ± 0.0025
$\Omega_m h^3$	0.09597	0.09590 ± 0.00059	0.09603	0.09593 ± 0.00058	0.09591	0.09589 ± 0.00057
Y_P	0.247710	0.24771 ± 0.00014	0.247785	0.24775 ± 0.00014	0.247695	0.24770 ± 0.00012
Age/Gyr	13.819	13.813 ± 0.058	13.784	13.796 ± 0.058	13.8242	13.817 ± 0.048
z_*	1090.43	1090.37 ± 0.65	1090.01	1090.16 ± 0.65	1090.48	1090.43 ± 0.54
r_*	144.58	144.75 ± 0.66	145.02	144.96 ± 0.66	144.58	144.71 ± 0.60
$100\theta_*$	1.04139	1.04148 ± 0.00066	1.04164	1.04156 ± 0.00066	1.04136	1.04147 ± 0.00062
z_{drag}	1059.32	1059.29 ± 0.65	1059.59	1059.43 ± 0.64	1059.25	1059.25 ± 0.58
r_{drag}	147.34	147.53 ± 0.64	147.74	147.70 ± 0.63	147.36	147.49 ± 0.59
k_D	0.14026	0.14007 ± 0.00064	0.13998	0.13996 ± 0.00062	0.14022	0.14009 ± 0.00063
$100\theta_D$	0.161332	0.16137 ± 0.00037	0.161196	0.16129 ± 0.00036	0.161375	0.16140 ± 0.00034
z_{eq}	3402	3386 ± 69	3352	3362 ± 69	3403	3391 ± 60
$100\theta_{eq}$	0.8128	0.816 ± 0.013	0.8224	0.821 ± 0.013	0.8125	0.815 ± 0.011
$r_{drag}/D_V(0.57)$	0.07130	0.0716 ± 0.0011	0.07207	0.0719 ± 0.0011	0.07126	0.07147 ± 0.00091

able 2. Cosmological parameter values for the six-parameter base ΛCDM model. Columns 2 and 3 give results for the *Planck* emperature power spectrum data alone. Columns 4 and 5 combine the *Planck* temperature data with *Planck* lensing, and columns and 7 include *WMAP* polarization at low multipoles. We give best fit parameters as well as 68% confidence limits for constrained arameters. The first six parameters have flat priors. The remainder are derived parameters as discussed in Sect. 2. Beam, calibration

This is really the end