Fundamental physics from Planck

Silvia Galli
KICP-UChicago
On behalf of the Planck collaboration

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The $\Lambda$CDM model: understanding the differences between WMAP and Planck, e.g.:

- Hubble parameter
  - Planck $67.31 \pm 0.96$
  - WMAP $69.7 \pm 2.1$

Extensions of $\Lambda$CDM: results on dark matter annihilation.

This talk will cover only a very small part of the Planck 2015 results, mostly in the Cosmological Parameters and Likelihood papers (Planck 2015 results XI, XIII).
Temperature power spectrum cosmic variance limited till $\ell \sim 1600$, on 40-70% of the sky.
Other experiments

WMAP cosmic variance limited till $l \sim 400$ (data points till $l \sim 1200$)

ACT and SPT use $< 5\%$ of the sky VS 40-70\% in Planck. Sample variance more than 3 times larger than Planck!
Planck TT power spectrum
See also Hannestad 03, Shafieloo 03, Bennet et al. 2011, Mortonson et al. 2009 and many others.
• WMAP and Planck parameters differ by ~1 sigma.
• WMAP errors factor 2 larger than Planck.
• $n_s$ and $H_0$ are larger in WMAP, while $\Omega_c h^2$ is smaller.

(NB: For Planck, we use TT only at high-l and TT and pol at low-l. For WMAP, we use all the TT and pol data available)

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**Scalar spectral index $n_s$**

- **Planck**: $0.9655 \pm 0.0062$
- **WMAP**: $0.974 \pm 0.013$

**Dark Matter density**

- **Planck**: $0.1197 \pm 0.0022$
- **WMAP**: $0.1137 \pm 0.0045$

**Hubble parameter (derived)**

- **Planck**: $67.31 \pm 0.96$
- **WMAP**: $69.7 \pm 2.1$
• If we cut Planck data at $l_{\text{max}}=800$, $n_s$ and $H_0$ increase and $\Omega_c h^2$ decreases, in good agreement with WMAP.

• Cutting $l_{\text{max}}=800$ makes Planck more sensitive to the $l \sim 20$ deficit, similarly to what happens with WMAP.
• When we cut at $l_{\text{max}}=800$, degeneracies in parameters are large. One can increase $n_s$ to better fit the $l=20$ deficit

\[ P_R(k) = A_s \left( \frac{k}{k_0} \right)^{n_s-1} \]

• Since a larger $n_s$ decreases the first peak, one can compensate by decreasing the value of $\Omega_c h^2$.

• A smaller $\Omega_c h^2$ requires a larger $H_0$ in order to keep the position of the peaks (e.g. the angular distance to last scattering) fixed.
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- Cutting the TT $l<30$, we recover the full Planck cosmology both with Planck $l_{\text{max}}=800$ and with WMAP.

- (NB: we cut here both the TT and pol data at low-$l$. We use a prior on $\tau$ to break degeneracies)
Summary

• Planck and WMAP cosmologies are in very good agreement, in particular when cutting Planck at l_{\text{max}}=800.

• The WMAP and Planck l_{\text{max}}=800 cosmologies are affected by the $l\sim20$ feature: $n_s$ is large to better fit the low-$l$, $\Omega_c h^2$ is low to compensate for large $n_s$ on the first peak, $H_0$ increases to keep the position of the peaks (angular diameter distance to last scattering surface) fixed.

• If we cut the $l<30$, the WMAP and Planck l_{\text{max}}=800 cosmologies are in very good agreement with the full Planck one.

• The full Planck cosmology is less affected by the $l\sim20$ deficit thanks to the longer lever arm. However, this deficit still impacts parameters at some level (e.g. Neff, $A_{\text{lens}}$)
Constraints on dark matter annihilation
Indirect search anomalies: Dark matter annihilation?

Cosmic rays excesses in PAMELA/FERMI/AMS-02
- Leptonic ann. chan.,
- Mass $\sim$ TeV,
- Large cross-section required ($\sim 10^{-23}\text{cm}^3$/s).
- Need broken power law in electrons.

Fermi Galactic Center excess
- Many ann. chan. allowed.
- Mass $\sim$ few tens GeV,
- Thermal relic cross section ($\sim 10^{-26}\text{cm}^3$/s)
DM annihilation at the epoch of recombination

\[
\frac{dE}{dt} = \rho_c^2 c^2 \Omega_{DM}^2 (1 + z)^6 f_{\text{eff}} \frac{\langle \sigma v \rangle}{m_\chi} p_{\text{ann}}
\]

The injected energy ionizes, excites and heats the medium. This affects the evolution of the free electron fraction.
DM annihilation at the epoch of recombination

\[ \frac{dE}{dt} = \rho_c^2 c^2 \Omega_{DM}^2 (1 + z)^6 f_{\text{eff}} \frac{\langle \sigma v \rangle}{m_\chi} \]

- The injected energy ionizes, excites and heats the medium. This affects the evolution of the free electron fraction.
- Suppresses the peaks, but enhances polarization at large scales!
2015 Polarization power spectra

Pre-Planck measurements

Planck 2015

TE

EE

Planck 2015 measurements
Constraints on Dark Matter Annihilation

Most of parameter space preferred by AMS-02/Pamela/Fermi ruled out at 95%, under the assumption $<\sigma v>(z=1000)=<\sigma v>(z=0)$

Thermal Relic cross sections at $z\sim1000$ ruled out for:

- $m<40$ GeV ($e^-e^+$)
- $m<16$ GeV ($\mu^+\mu^-$)
- $m<10$ GeV ($\tau^+\tau^-$)

Only a small part of the parameter space preferred by Fermi GC is excluded

$f_{\text{eff}}$ from T. Slatyer (Madhavacheril et al. 2013)
Conclusions

• Planck 2015 data is powerful to constrain LCDM and extensions.
• Planck polarization improves spectacularly constraints on DM annihilation.
• Thermal Relic cross sections at $z \sim 1000$ ruled out for:

  \[ m \sim < 40 \text{ GeV} \ (e^-e^+) \]
  \[ m \sim < 16 \text{ GeV} \ (\mu^+\mu^-) \]
  \[ m \sim < 10 \text{ GeV} \ (\tau^+\tau^-). \]
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.
Thermal relic cross section excluded at:

- $ee \sim 15$ GeV
- $\mu\mu \sim 10$ GeV
- $\tau\tau \sim 80$ GeV

Fermi-lat collaboration
arXiv:1503.02641
Comparison with other datasets:

**BAO**

Cluster counts ($\sigma_8-\Omega_m$) vs. Weak Lensing ($\sigma_8-\Omega_m$) vs. Direct measurements $H_0$

**Supernovae ($\Omega_m$)**

$H_0=67.8\pm0.96$ (PlanckTT+lowP+lensing) vs $H_0=72.8\pm2.4$ [2σ tension] (Riess+11)

$H_0=70.6\pm3.3$ [1σ tension] (Efstathiou+14)

$H_0=74.3\pm2.6$ [2.5σ tension] (Freedman+12)

[in Km/s/Mpc]
Previous Constraints

Large degeneracies in TT only data.

Planck TT+WP 2013
WMAP9 (T+P)

\[ p_{\text{ann}} = f_{\text{eff}} \frac{<\sigma v>}{m_{\chi}} \]
Planck 2015 Constraints

Planck TT, TE, EE + lowP
PlanckTE + lowP
PlanckEE + lowP
PlanckTT + lowP
WMAP9

Polarization breaks degeneracies!

Planck TT, TE, EE set a constraint 5 times stronger than WMAP9, 4 times stronger than WMAP9 + SPT

\[
p_{\text{ann}} = f_{\text{eff}} \frac{\langle \sigma v \rangle}{m_\chi} \times 10^{-27}
\]
**Dataset**

- **Planck TT**: Planck TT $2 < \text{ell} < 2500$.
- **lowP**: low-l Planck **polarization** $2 < \text{ell} < 30$ (For 2013 results, this will indicate low-l WMAP polarization).
- **Planck TE, EE**: Planck TE and EE high-ell, $30 < \text{ell} < 2000$
  Small systematics in polarization might still be affecting the results.
- **Lensing**: Planck lensing potential $40 < \text{ell} < 400$ from 4-point correlation function
- **Ext**, external datasets:
  - **BAO** (6dFGS, SDSS-MGS, BOSS-LOWZ, CMASS DR11)
  - **JLA**: Type Ia Supernovae (SNLS +SDSS+low z Sne)
  - **H0**: Hubble constant ( Efstathiou 2014 reanalysis of Riess et al. 2011)

Whenever not specified, we assume
\[ \text{Neff}=3.046, \Sigma m_\nu=0.06\text{eV (1 massive, two massless)}. \]