Cosmology in this decade: new insights into fundamental physics

Raul Jimenez
ICREA
ICC University of Barcelona
icc.ub.edu/~jimenez

Courtesy of Planck and SKA teams
In cosmology one can actually perform ultimate experiments, i.e. those which contain ALL information available for measurement in the sky. The first one of its kind will be Planck (in Temperature) and in this decade we will also have such experiments mapping the galaxy field. Question is: how much can we learn about fundamental physics, if any, from such experiments?

Below are a few examples:

1. Dark energy
2. Nature of the initial conditions and perturbations
3. Neutrinos
4. Beyond the Standard Model physics
5. Inflation
Extremely successful model

State of the art of data then... (~1992)

~14 Gyr

(DMR)COBE
CMB
380,000 yr
(a posteriori information)
Avalanche of data

And it still holds!
Flatness problem

Horizon problem

Structure Problem
CMB, status

WMAP 5 + ground

Planck

Ground-based

- First galaxies
- Universe is reionized
- Ostriker-Vishniac/kSZ
  - weak lensing
  - Sunyaev-Zel’dovich (SZ) clusters
  - Diffuse thermal SZ
  - Kinetic SZ
  - Rees-Sciama/ISW
Planck will be the ultimate experiment for primary temperature

The next frontier is the polarization signal: “Smoking gun” of inflation

(CM)BPol Delayed to ????
Major projects of particular interest

Euclid 1.2m telescope at L2, competing for “cosmic vision”
ESA mission program 2015-2025

LSST

Both offer two probes: galaxy clustering and weak lensing

Shorter timescale (and closer to home) SDSSIII, BOSS, LAMOST

remember weak lensing
What surveys aim to measure

Cosmic microwave background

Galaxies

But there is much more cosmological information
What surveys aim to measure

Cosmic microwave background

Galaxies

But there is much more cosmological information
Large-scale structure $P(k)$

- WMAP almost fixes* the expected $P_{\text{lin}}(k)$ in $\text{Mpc}^{-1}$ through $\Omega_c h^2 (6\%)$ and $\Omega_b h^2 (3\%)$, independent of $\theta_{\text{CMB}}$

* ignoring the effect of massive neutrinos, fixing $N_{\text{rel}} = 3.046$

- Independent probe of the matter transfer function and primordial power spectrum: $\Omega_m h^2$, $n_s$
- Excellent probe for deviations from standard LCDM

Want (and can) measure both!
Turn over:
Matter-radiation equality

During radiation domination
Pressure support means
large Jeans length so sub-horizon
perturbations cannot grow

Slope: inflation seeding
primordial perturbations
Inflaton shape

Plus other subtle effects...
Large-scale structure $P(k)$ in equations

$$P_{\text{gal}}(k, \mu, a) = k^n T^2(k) D^2(a) [b(a) + f(a) \mu^2]^2$$

- $k$ = comoving wavenumber
- $\mu$ = $\cos$(angle to line-of-sight)
- $a$ = cosmological scale factor
- $b$ = galaxy bias factor
- $D$ = linear growth rate
- $f$ = $\frac{d\ln D}{d\ln a}$

Information from geometry
- Galaxy clustering as a standard ruler
- BAO or full power spectrum
- Alcock-Paczynski effect

Information from structure growth
- amplitude of power spectrum
- redshift-space distortions

Information from power spectrum shape
- Matter density
- Baryon Acoustic Oscillations
- Neutrino mass
- Inflation fluctuation spectrum
- $f_{\text{NL}}$

Slide: courtesy of W. Percival
Large-scale structure $P(k)$ in equations

$$P_{\text{gal}}(k, \mu, a) = k^n T^2(k) D^2(a) \left[ \mu^2 \right]^2$$

- **k** = comoving wavenumber
- **$\mu$** = cos(angle to line-of-sight)
- **a** = cosmological scale factor
- **b** = galaxy bias factor
- **D** = linear growth rate
- **f** = $d\ln D/d\ln a$

**Information from geometry**
- Galaxy clustering as a standard ruler
- BAO or full power spectrum
- Alcock-Paczynski effect

**Information from structure growth**
- Amplitude of power spectrum
- Redshift-space distortions

**Information from power spectrum shape**
- Matter density
- Baryon Acoustic Oscillations
- Neutrino mass
- Inflation fluctuation spectrum
- $f_{\text{NL}}$

Slide: courtesy of W. Percival
Most fundamental question in $\nu$

Are neutrinos Dirac or Majorana?

(in other words, origin of neutrino mass: Higgs mechanism or beyond the SM mechanism?)
Cosmic Neutrino Background

56 cm$^{-3}$ at 1.95 K (0.17 meV)

Possible mechanical effect: torque of order $G_F$ if target and neutrino background are polarized (Stodolsky effect) and net neutrino-antineutrino asymmetry

End of tritium beta decay: high resolution

Still far from observability, awaiting for future technology
Neutrino mass eigenstates are not the same as flavor

- Oscillations indicate neutrinos have mass:
  \[ \Delta m_{21}^2 \equiv \Delta m_{32}^2 = 8.0^{+0.6}_{-0.4} \cdot 10^{-5} \text{eV}^2 \]
  \[ |\Delta m_{31}^2| \approx |\Delta m_{32}^2| \equiv \Delta m_{\text{atm}}^2 = 2.4^{+0.6}_{-0.5} \cdot 10^{-3} \text{eV}^2 \]
- Three possible hierarchies

- Physics beyond the standard model!
- The standard model has 3 neutrino species, but...
Outlook towards the future

Can the hierarchy be determined?
Are neutrino Majorana or Dirac?

Neutrinos....
Cosmology is key in determining the absolute mass scale.

The problem is systematic errors.

Neutrino properties
Physical effects

Total mass $\sim 1$ eV become non relativistic before recombination.

Total mass $<\sim 1$ eV become non relativistic after recombination: alters matter-radn equality but effect can be “cancelled” by other parameters.

After recombination

Finite neutrino masses suppress the matter power spectrum on scales smaller than the free-streaming length.

\[ P(k)/P(k,\Sigma m=0) \]

- $\Sigma m = 0$ eV
- $\Sigma m = 0.3$ eV
- $\Sigma m = 1$ eV
From the literature

<table>
<thead>
<tr>
<th>model</th>
<th>base dataset</th>
<th>U.L. (eV)</th>
<th>sys. errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda$CDM</td>
<td>WMAP5</td>
<td>1.3</td>
<td>[27]</td>
</tr>
<tr>
<td>$w$CDM</td>
<td>WMAP5</td>
<td>1.5</td>
<td>[27]</td>
</tr>
<tr>
<td>$\Lambda$CDM</td>
<td>WMAP5+BAO+SN</td>
<td>0.67</td>
<td>-</td>
</tr>
<tr>
<td>$w$CDM</td>
<td>WMAP5+BAO+SN</td>
<td>0.80</td>
<td>-</td>
</tr>
<tr>
<td>$\Lambda$CDM</td>
<td>WMAP5+$P_{halo}(k)$</td>
<td>0.62</td>
<td>marginalized</td>
</tr>
<tr>
<td>$w$CDM</td>
<td>WMAP5+BAO+SN+ Chandra Clusters</td>
<td>0.33</td>
<td>±0.1</td>
</tr>
<tr>
<td>$\Lambda$CDM</td>
<td>WMAP3+WL mass function</td>
<td>1.43</td>
<td>-</td>
</tr>
<tr>
<td>$\Lambda$CDM</td>
<td>WMAP3+Ly-$\alpha$+CMB small +BAO+SN+SDSS &amp; 2dF $P(k)$</td>
<td>0.17</td>
<td>IGM [33]</td>
</tr>
<tr>
<td>$\Lambda$CDM</td>
<td>WMAP5+Ly-$\alpha$+CMB small +$H_0$ 2001 [45]</td>
<td>0.28</td>
<td>IGM [33]</td>
</tr>
<tr>
<td>$\Lambda$CDM</td>
<td>WMAP3+$H_0+H(z)$</td>
<td>0.50</td>
<td>-</td>
</tr>
<tr>
<td>$\Lambda$CDM</td>
<td>WMAP5+SN+BAO+WL</td>
<td>0.54</td>
<td>+0.04</td>
</tr>
<tr>
<td>$\Lambda$CDM</td>
<td>WMAP5+$b(L)+P_{LRG}(k)$ 2006</td>
<td>0.28</td>
<td>bias modeling</td>
</tr>
<tr>
<td>$w$CDM</td>
<td>WMAP5+$b(L)+P_{LRG}(k)$ 2006</td>
<td>0.59</td>
<td>bias modeling</td>
</tr>
</tbody>
</table>
Robust neutrino constraints...

Beth Reid, LV, R. Jimenez, Olga Mena, (JCAP 2010)  arXiv:0910.0008

DATA:

WMAP5

H0 from Riess et al 2009 $h=0.74\pm0.036$

MaxBCG 

$$\sigma_8(\Omega_m/0.25)^{0.41} = 0.832 \pm 0.033.$$

Rozo et al 09, Koester et al 07, Johnston et al 07

SDSS DR7 halo $P(k)$
Physical effects cnt’

WMAP $M_\nu=0$

WMAP  

Constant $\Sigma m_\nu$

WMAP+maxBCG+$H_0$

WMAP+BAO+SNe $M_\nu=0$

WMAP+BAO+SNe  

Constant $\Sigma m_\nu$

+maxBCG+$H_0$

Neutrino properties
So far extending parameter space was relaxing $\Sigma m_\nu$ constraints

DM-DE coupling!

Not even in this case....

CMB+H0+Phalo+SN
+maxBCG
<table>
<thead>
<tr>
<th>model</th>
<th>base dataset</th>
<th>(-)</th>
<th>+maxBCG</th>
<th>+(H_0)</th>
<th>+maxBCG+(H_0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Lambda CD)M</td>
<td>WMAP5</td>
<td>1.3</td>
<td>1.1</td>
<td>0.59</td>
<td>0.40</td>
</tr>
<tr>
<td>(\Lambda CD)M</td>
<td>WMAP5+BAO+SN</td>
<td>0.67</td>
<td>0.35</td>
<td>0.59</td>
<td>0.31</td>
</tr>
<tr>
<td>(\Lambda CD)M +(\alpha)</td>
<td>WMAP5</td>
<td>1.34</td>
<td>1.25</td>
<td>0.54</td>
<td>0.39</td>
</tr>
<tr>
<td>(\Lambda CD)M +(r)</td>
<td>WMAP5</td>
<td>1.36</td>
<td>1.18</td>
<td>0.83</td>
<td>0.40</td>
</tr>
<tr>
<td>(wCD)M</td>
<td>WMAP5+BAO+SN</td>
<td>0.80</td>
<td>0.52</td>
<td>0.72</td>
<td>0.47</td>
</tr>
<tr>
<td>dark coupling</td>
<td>WMAP5+(P_{halo}(k)+SN)</td>
<td>-</td>
<td>-</td>
<td>0.51</td>
<td>-</td>
</tr>
<tr>
<td>(\Lambda CD)M</td>
<td>WMAP5</td>
<td>1.3</td>
<td>1.0</td>
<td>0.57</td>
<td>0.41</td>
</tr>
<tr>
<td>(\Lambda CD)M</td>
<td>WMAP5+BAO+SN</td>
<td>0.71</td>
<td>0.41</td>
<td>0.61</td>
<td>0.30</td>
</tr>
<tr>
<td>(\Lambda CD)M +(\alpha)</td>
<td>WMAP5</td>
<td>1.28</td>
<td>1.17</td>
<td>0.63</td>
<td>0.43</td>
</tr>
<tr>
<td>(\Lambda CD)M +(r)</td>
<td>WMAP5</td>
<td>1.23</td>
<td>0.86</td>
<td>0.72</td>
<td>0.30</td>
</tr>
<tr>
<td>(wCD)M</td>
<td>WMAP5+BAO+SN</td>
<td>0.82</td>
<td>0.46</td>
<td>0.74</td>
<td>0.44</td>
</tr>
<tr>
<td>dark coupling</td>
<td>WMAP5+(P_{halo}(k)+SN)</td>
<td>-</td>
<td>-</td>
<td>0.56</td>
<td>-</td>
</tr>
</tbody>
</table>

Beth Reid, LV, R. Jimenez, Olga Mena, arXiv:0910.0008
Profile likelihood ratio

\[ \ln \frac{L}{L_{\text{max}}} \]

- + WMAP
- * WMAP+maxBCG
- \(\triangle\) WMAP +H0
- \(\diamondsuit\) WMAP+H0+maxBCG

Beth Reid, LV, R. Jimenez, Olga Mena, arXiv:0910.0008

Neutrino properties
The data at $z>0$

Stern, RJ et al. JCAP 2011
Moresco et al. 2012

$$H(z) = -\frac{A}{1+z} \frac{dz}{dD4000_n}$$
Multiple uses of $H(z)$


WMAP+ACT+OHD+H0

WMAP+SPT+OHD+H0
Cosmology is key in determining the absolute mass scale.

![Graph showing neutrino properties](image)

- Inverted
- Degenerate
- Normal

Beth Reid, LV, R. Jimenez, Olga Mena, arXiv:0910.0008
Dirac or Majorana? ↔ hierarchy

Are neutrinos their own anti-particle? (are they Majorana or Dirac?)

0νββ (next generation)

Yes

Because Dirac OR because below threshold (still unknown)?

No

Majorana

Parameterization: $\Sigma, \Delta, sgn(\Delta)$

NH: $\Sigma = 2m + M$, $\Delta = (M - m)/\Sigma$
IH: $\Sigma = m + 2M$, $\Delta = (m - M)/\Sigma$

Examples:

(0.0, 0.009, 0.05) eV min NH
(0.0, 0.049, 0.05) eV min IH
(0.032, 0.033, 0.06) eV NH
(0.02, 0.054, 0.055) eV IH

Neglect solar splitting is a good approx.
Neutrinos of different masses have different transition redshifts from relativistic to non-relativistic behavior, and their individual masses and their mass splitting change the details of the radiation-domination to matter-domination regime.
Hierarchy effect on the shape of the power spectrum


A word of warning!
Can we see $\nu$-hierarchy in the sky?

Full sky, variance-dominated
Gal survey, 600 Gpc$^3$ ($z<2$)
21cm HI, 2000 Gpc$^3$ ($z<5$)

WL survey ($<z> < 3$)
50 gal / sq-arcmin

$n_s, \alpha_s, \Omega_\nu h^2, \Delta, Z, \Omega_b h^2, \Omega_c h^2, h, A_s$. 
Future surveys can help!

Are neutrinos their own anti-particle? (are they Majorana or Dirac?)

- Yes
- No

Because Dirac OR because below threshold (still unknown)?

COSMOLOGY

- $\Sigma < 0.1\text{eV}$
- $0.1\text{eV} < \Sigma < 0.15\text{eV}$
- $0.15\text{eV} < \Sigma < 0.25\text{eV}$
- $\Sigma > 0.25\text{eV}$

Determine $\Delta$

- Normal
- Inverted
- Degenerate

Majorana
unknown
Dirac
unknown
Things are better...

- When performing numerical simulations the non-linearities help!! (Wagner, Verde, Jimenez in arXiv this week)
...and current surveys could measure the hierarchy

From Fisher matrix (naïve though)
Summary

• Vast quantity of high quality cosmo data fast approaching: CMB, BAOs, Gravitational waves, 21cm, LAMOST

• Fruitful interplay between HEP/cosmo theory and cosmological observation: constraints on axions, neutrino masses, neutrino hierarchy, nature of the initial conditions...