Astroparticle Physics

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- Composition of Universe ?
- Evolution?
- Extreme phenomena ?
1) What is Astroparticle Physics?
   Cosmic Microwave Background
   Dark energy

2) Dark matter

3) High energy astrophysics
Today’s HE universe

Astroparticle → high energy phenomena, cosmic accelerators

Gamma rays

3rd EGRET catalog

Unidentified sources

Unidentified sources

Cosmic rays

Primary cosmic ray

Neutrinos

many astrophysical sources (sun, galactic center, AGN…)

⇒ Lecture 3
Content of the universe

A2218

Dark matter

Lecture 2

Lecture 1

Dark energy

(as seen from Hubble Space Telescope)

Difference

3 Weeks Before

Supernova Discovery
Evolution of the Universe
Lecture outline

1) What is Astroparticle Physics?
   - Cosmic Microwave Background
   - Dark energy

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3) High energy astrophysics
End of opaque Universe

Multiple scatterings of $\gamma$ on $e^-$ produces "thermal" spectrum at $T = 3000$ K ($z \sim 1100 = a_0 / a_{\text{rec}}$)
$t = 380,000$ yrs

"Uniform" background at $T_0 = 2.7$ K
Discovery

Discovered in 1965 as “excess noise” (Nobel Prize in 1978)

Bell Labs

Wilson Penzias

(+ Robert Dicke)

25 years later

COBE 1992
COBE sky maps

$T = 2.7 \, \text{K}$

$\Delta T = 3.4 \, \text{mK}$
(after subtraction of constant emission)

$\Delta T = 3.368 \, \text{mK}$

$\Delta T = 18 \, \mu\text{K}$
(after subtraction of dipole)
COBE sky maps

scale 0-4 K: very homogeneous → cosmological origin

Yet, regions > 1° apart never in causal contact

\[ \theta_{\text{LSS}} \sim \frac{10^3 \times 3 \times 10^5}{14 \times 10^9} \text{ rad} \sim 1° \]

Inflation?
COBE sky maps

Doppler effect due to motion of Earth w.r.t. CMB
\((v = 370 \text{ km/s towards Virgo})\)

Anisotropies: potential wells
Early gravitational seeds for structure formation?
\((+\text{ foregrounds})\)
Anisotropies

- Before recombination, Universe = plasma of free e\(^{-}\) and protons
- Oscillations due to opposite effects of
  - gravity
  - pressure
  As far out as the sound horizon at recombination

- Presented as a power spectrum
  multipole \( \ell \)
  amplitude \( a_{\ell m} \)
  power \( \sim |a_{\ell m}|^2 \sim C_\ell \)

\[ (\ell - 1)C_\ell \approx 200/\theta \text{ (deg)} \]
Sound horizon at recombination

Limited by causality → maximum scale

Max scale relates to curvature $\Omega_k$ of the universe
2nd generation satellite

COBE
(7 degree resolution)

(\ell < 20)

WMAP
(0.25 degree resolution)

(\ell < 700)
WMAP

• Very low temperature signal ⇒ Need shielding from Sun, Earth, Moon, (Jupiter)

• Lagrange point L2: position of co-rotation with Earth ⇒ Stability of conditions

• 5 frequency channels Foreground removal (<90 GHz)

Launch: Jun. 2001
First results: 2003
“Concordance model”

Curvature of the Universe (95% CL)

**WMAP5 only:**
- $-0.063 < \Omega_\kappa < 0.017$

**WMAP5 + SN + BAO:**
- $-0.018 < \Omega_\kappa < 0.009$

H$_0$: present expansion rate of Universe
H$_0$ from HST = 72 ± 8 km/s/Mpc

Dunkley et al., astro-ph/0803.0586v1

Komatsu et al., astro-ph/0803.0547v1
"Concordance model"

\[ \Omega_i = \rho_i / \rho_c \]
\[ \Omega_{\text{tot}} = 1 \text{ for } \Omega_k = 0 \]

**WMAP alone**  
(flattened \( \Lambda \)CDM model)

- \( H_0 = 0.74 \pm 0.03 \)
- \( \Omega_b = 0.044 \pm 0.003 \)
- \( \Omega_m = 0.26 \pm 0.01 \)
- \( \Omega_\Lambda = 72 \pm 3 \text{ km/s/Mpc} \)
- \( \ldots \) \ldots

compatible w/ \( H_0 \) from HST  
(72 +/- 8 km/s/Mpc)

factor 2 improvement when combining with SN & BAO

Komatsu et al, astro-ph/0803.0547v1

Beyond WMAP

- More frequency channels
- Improved resolution
- Polarization

Probe of inflation (10^{-35} s after Big Bang)
(gravity wave-induced polarization)

Planck mission

2 instruments LFI & HFI

HEMTS  Bolometers

Freq coverage from 30 to 850 GHz
(9 channels)
Polarization sensitive

Launch successful (June 2009)
1) What is Astroparticle Physics?
   - Cosmic Microwave Background
   - Dark energy
   - Supernovae searches
   - Baryon acoustic oscillations

2) Dark matter

3) High energy astrophysics
Measurement of the geometry

\[ 1 - \Omega_k(t) = \sum \Omega_x(t) + \Omega_\Lambda(t) \]

Closed Universe

Flat Universe

Open Universe

AT A GIVEN DISTANCE

Known physical size

Known luminosity

angle depends on geometry

flux depends on geometry
White dwarfs in binary systems

Very luminous ($L \sim 10^{10} L_{\text{sun}}$)

→ out to high $z$

Fixed conditions ($1.4 M_{\text{sun}}$)

→ standard candle
Type Ia searches

3 steps
- discovery (differential photometry)
- identification (spectrum)
- photometric follow-up → light curve
Study of a supernova

Photometry
→ light-curve
→ max flux
→ distance

Spectrum
→ SNIa
→ redshift z
Hubble diagram

\[ m = -2.5 \log \Phi + \text{cst} \]

\[ \Phi \equiv \frac{L}{4\pi d_L^2} \]

where \( d_L(z, H_0, \Omega_M, \Omega_\Lambda, w, \ldots) \)

1 + \( z = \frac{a(t_{\text{obs}})}{a(t_{\text{em}})} \)

At a given \( z \)

Calan Tololo
Hamuy et al., A.J. 1996

Accelerated expansion

= smaller rate in the past
= more time to reach a given \( z \)
= larger distance of propagation of the photons
= smaller flux

\[ \Omega_\Lambda \]

Accelerated Constant expansion

\[ \Omega_M, \Omega_\Lambda, w, \ldots \]
SNLS 2006

Astier et al., A&A 447 (2006) 31A

\[ \Omega_M = 0.26 \]

for \( \Omega_T = 1 \)
Beyond $\Omega_\Lambda$...

- $\rho_v$ incompatible with a possible $\rho_v$ from particle physics
  - $\Omega_\Lambda = 0.7 \rightarrow \rho_v = \Omega_\Lambda \times \rho_c \sim 10^9$ eV m$^{-3}$
  - $\rho_v$ from quantum field theory: $\rho_v \sim M^4 / (hc)^3$
    taking $M = M_{pl} \rightarrow \rho_v \sim 10^{132}$ eV m$^{-3}$

- Coïncidence problem
  $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$ yet different evolution with time

- quintessence?

  $w = p/\rho$
  $\begin{cases} 
  w = 0 & \text{for matter} \\
  w = 1/3 & \text{for radiation} \\
  w = -1 & \text{for cosmological constant} \\
  w > -1 & \text{for "quintessence", dynamical DE}
  \end{cases}$
Equation of state of DE

Time evolution of dark energy density $\rho_{de}$ determined by $w$

$$w = \frac{p_{de}}{\rho_{de}} \quad \frac{1}{\rho_{de}} \frac{d\rho_{de}}{dt} = -3H(1 + w)$$

- $w = -1$ cosmological constant
- $w = 0$ matter
- $w = 1/3$ relativistic matter, radiation

No evidence so far for $w \neq -1$ (and no serious theory)

$w = -1.02 \pm 0.10$

Astier et al., A&A 447 (2006) 31A
Standard candles: supernovae
- evolution (variation of flux) and impact on cosmology?
- dust?

Standard rulers
- almost no systematics!

Sound horizon at recombination

Photon distribution (CMB)

Galaxy distribution (BAO)
Imprint on galaxies

Mass profile = \( \rho R^2 \quad R = \text{comoving radius} \)
Imprint on galaxies

ν's don’t interact → stream away

Gas hot & ionized → photon/e- plasma with huge pressure → expanding sound wave

CDM no pressure → sits still & accretes surroundings (overdense)

Mass profile = \( \rho R^2 \)
Imprint on galaxies

Mass profile = $\rho R^2$

Recombination $e^+e^-\rightarrow p$
(t = 380,000 yrs)

Photons stream past gas particles

Gas wave slows down
Mass profile = $\rho R^2$

**Imprint on galaxies**

- A CDM perturbation at center
- A gas perturbation 150 Mpc away

**Mass profile**

$\rho R^2$

**Graph**

- Dark Matter, Gas, Photon, Neutrino
- 1.45 Myrs
- $z=478$
Imprint on galaxies

Acoustic peak decreases relative to original because CDM outweighs gas 5 to 1

Mass profile = \( \rho R^2 \)
Imprint on galaxies

Mass profile = \( \rho R^2 \)

\[ \Rightarrow \text{small excess in galaxy-galaxy correlation function at 150 Mpc} \]
Position of acoustic peak:

\[ s \approx c_s \frac{t(z = 1100)(1 + z)}{H(z = 1100)} \]

\[ \propto \frac{1}{\sqrt{\Omega_M}} \]

SDSS (z ~ 0.3)


\[ \Omega_{\text{cdm}} + \Omega_b = 0.273 \pm 0.025 + 0.123(1+w) + 0.137(1-\Omega_T) \]
Conclusions

Energy content of the Universe
Concordance model

- Dark Energy (~72%)
- Non baryonic DM (~24%)
- Baryonic DM (~3%)
- Stars (~1%)