Energia Oscura
(Dark Energy)
How do we know that Dark Energy is out there?
The cosmic inventory

Most of the Universe is Dark

\[ \Omega_{\text{lum}} \sim 0.01 \]

\[ \Omega_L \approx 0.040 \pm 0.005 \]

\[ \Omega_{\text{DM}} \sim 0.23 \]

\[ \Omega_{\text{de}} \sim 0.72 \]
The cosmic inventory

‘Definition’ of Dark Energy:

72%
23%
4%
1%
The cosmic inventory

‘Definition’ of Dark Energy:

Einstein equations

$$\frac{\dot{a}}{a} = -\frac{4\pi G}{3} (\rho + 3p)$$

The 'size' of the Universe

72 %

23 %

1 %

4 %
The cosmic inventory

‘Definition’ of Dark Energy:

Einstein equations

\[ \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) \]

if \( \rho < -p/3 \) i.e. \( w := \frac{\rho}{p} < -\frac{1}{3} \)

\[ \Rightarrow \text{acceleration!} \]
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\[ \Rightarrow \text{acceleration!} \]

special case:

\[ \rho = -p \quad \text{i.e. } w = -1 \]

cosmological constant \( \Lambda \)

(constant as \( \rho_i \propto (1 + z)^{3(1+w_i)} \sim \text{const} \) )
1) Supernovae type Ia: ‘standard candles’

\[ L = 4\pi F d_L^2 \]

Luminosity distance (‘unknown’)
Flux (‘measured’)
Luminosity (‘known’)

The Evidence for DE

in a static Universe
1) Supernovae type Ia: ‘standard candles’

\[
\mathcal{L} = 4\pi F d_L^2 = 4\pi F \chi^2 (1 + z)^2
\]

- Luminosity (‘known’)
- Comoving distance (‘unknown’)

\((1 + z)\) due to redshift
\((1 + z)\) due to expansion

in an expanding Universe
1) Supernovae type Ia: ‘standard candles’

\[ \mathcal{L} = 4\pi F d_L^2 = 4\pi F \chi^2 (1 + z)^2 \]

\[ \chi(z) = \int_0^z \frac{dz'}{H(z)} = \int_0^z \frac{dz'}{H_0 \sqrt{\Omega_M (1 + z')^3 + \Omega_\Lambda}} \]

so \( \mathcal{L} \) as fnct of \( z \) and \( \Omega_M, \Omega_\Lambda \)
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Riess et al., 1998, Astron. J. 116

about 60 SNe
The Evidence for DE

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Well, they are not really standard, let’s standardize them

B Band

as measured

peak \( \propto \) duration of lightcurve

light-curve timescale “stretch-factor” corrected

Calan/Tololo SNe Ia
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1) Supernovae type Ia: ‘standard candles’

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Bottom line: distant SNe appear \textbf{dimmer} than predicted in a Universe without DE, the Universe has \textbf{accelerated} in the past 5 Gyr

about 600 SNe

dimmer \hspace{2cm} brighter

Suzuki et al., 1105.3470
2) Baryon Acoustic Oscillations: ‘standard ruler’

\[ L = \theta d_A \]

- Length ('known')
- Angular distance ('unknown')
- Angle ('measured')
The Evidence for DE

2) Baryon Acoustic Oscillations:

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\[ L = \theta d_A = \theta \frac{\chi}{1 + z} \]

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\( d_A \) comoving distance (‘unknown’)

\( \chi \) length (‘known’)

Length (‘known’)

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The Evidence for DE

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What is the ‘ruler’?

D Eisenstein, cmb.as.arizona.edu/~eisenste/acousticpeak/
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What is the ‘ruler’? A pinch in the galaxy distribution
The Evidence for DE

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Length (`known`)

`comoving distance` (`unknown`)

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What is the `ruler`? A **pinch** in the galaxy distribution

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**NB:** can actually do the same in \( z \) direction
The Evidence for DE

3) CMB:

In principle: another ‘standard ruler’ *:
the size of the sound horizon at $z \sim 1100$

$$r_s = \int c_s \, d\tau \quad c_s \simeq c/\sqrt{3}$$
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On the other hand: CMB fit gives

$$\Omega_{\text{tot}} \approx 1$$
$$\Omega_{\text{DM}} \approx 0.27$$
$$\Omega_{\Lambda} \approx 0.73$$

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Moreover, recently: using weak lensing of CMB light

$$\Omega_{\Lambda} = 0.61^{+0.14}_{-0.06}$$

* (actually, it’s the ‘same’ ruler as BAO!)

Sherwin et al., ACT Atacama Cosmology Telescope, 1105.0419
The Evidence for DE

- complementarity
- concordance

$\Omega_\Lambda = 0.725 \pm 0.016$
$\Omega_M = 0.274 \pm 0.007$

Other probes played / will play a role:
- cluster counts
- weak lensing...

Suzuki et al., 1105.3470
Komatsu et al., WMAP7, 1001.4538
What do we know of the (particle physics) properties of Dark Energy?
Nature of DE

\( \Lambda \) cosmological constant, \( w = -1 \)
Nature of DE

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measured value \( \rho_\Lambda = 2.5 \times 10^{-47} \text{ GeV}^4 \)
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estimate \[ \rho_{\text{vac}} = \frac{1}{2} \sum_{\text{particles}} g_i \int_0^{k_{\text{max}}} \frac{d^3 k}{(2\pi)^3} \sqrt{k^2 + m^2} \]

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if $k_{\text{max}} \sim M_{\text{Pl}}$  

$\rho_\Lambda \sim 10^{74}$ GeV$^4$
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121 orders of magnitude!!
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if SuSy \( k_{\text{max}} \sim 1 \text{ TeV} \) \( \rho_\Lambda \sim 10^{12} \text{ GeV}^4 \)

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The worst fine tuning problem. Ever.
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evolution in time

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Anthropism? Multiverse?
Nature of DE

$\Phi$ ‘quintessence’, $w > -1$
Nature of DE

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$$\rho_\Phi = \frac{1}{2} \dot{\Phi}^2 + V$$

$$p_\Phi = \frac{1}{2} \dot{\Phi}^2 - V$$

$$w_\Phi = -1 + \frac{\dot{\Phi}^2}{\dot{\Phi}^2 + 2V}$$

so if $\dot{\Phi} \ll V$ → Dark Energy
**Nature of DE**

\( \Phi \), 'quintessence', \( w > -1 \)

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Modified Gravity (\( f(R) \), DGP...)
Nature of DE

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Swiss cheese, local voids...
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Modified Gravity (f(R), DGP...)

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Conclusions (for today)

**Dark Matter exists**

**Dark Energy exists**

We have (almost) no clue of what they are, but many hints and many ideas.

The ‘era of data’ is now for DM.

The ‘era of data’ is coming for DE.

May you live in exciting times.