# Cosmology from decaying dark energy, primordial at the Planck scale

- Why is the dark-energy density similar to the universe's?
- Why does it differ from the Planck energy density by 122 orders of magitude?

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# Contents

# The cosmological constant

- Introduced by Seeliger and Neumann in the 1890's to create a static universe

$$GM\frac{1}{r} \rightarrow GM\frac{e^{-\Lambda r}}{r}$$

- Applied to general relativity by Einstein in 1919

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R - \Lambda g_{\mu\nu} = 8\pi T_{\mu\nu}$$

- Zeldovich associated it to the quantum vacuum in 1967

$$\rho_{\Lambda P} = \frac{1}{(2\pi)^3}\int^{M_P} d^3k\sqrt{k^2+m^2}$$

$$T^i_{\mu\nu} = (\rho_\Lambda, p_\Lambda, p_\Lambda, p_\Lambda) = (\rho_\Lambda, -\rho_\Lambda, -\rho_\Lambda, -\rho_\Lambda) = \Lambda g_{\mu\nu}$$

# Coincidence problem

Today: dark energy $\Omega_{\Lambda 0} = \rho_{\Lambda 0}/\rho_{c0} \simeq .73$

dark matter $\Omega_{dm0} = \rho_{dm0}/\rho_{c0} \simeq .22$

baryonic matter $\Omega_{b0} \simeq .044$

# Fine-tuning problem

Today: critical density

$$\rho_{\Lambda 0} \simeq 4\times 10^{-6}\ \mathrm{GeV/cm^3}$$

Planck time: Planck density

$$\rho_{\Lambda P} = \frac{1}{(2\pi)^3}\int^{M_P} d^3k\sqrt{k^2+m^2} \simeq 3\times 10^{114}\ \frac{\mathrm{GeV}}{\mathrm{cm^3}}$$

# Standard cosmological equations

.General relativity $$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R - \Lambda g_{\mu\nu} = 8\pi T_{\mu\nu}$$

.FRW metric (isotropy) $$ds^2 = dt^2 - R^2(t)(dx^2 + dy^2 + dz^2)$$

.Flat universe $$\sum \Omega_i = 1$$

.Perfect fluid at rest $$T^i_{\mu\nu} = (\rho_i, p_i, p_i, p_i)$$

-00 component of Einstein equations

$$H^2 = \frac{8\pi}{3}\rho_c = \frac{8\pi}{3}(\rho_\Lambda + \rho_r + \rho_m)$$

Hubble constant $H = \dot{R}/R$

-contraction of Einstein equations: energy conservation

within and expanding volume $V \sim R^3$

$$\sum_i d(\rho_i V) = -\sum_i p_i dV$$

Parametric dependence on V,*t*,*R*,*T*, etc.

# Independent components

GR Energy conservation → $d(\rho_i V) = -p_i dV$ ← Thermodynamics

generalization

$$d(\rho_i V) = -p_i dV + \mu_i dN_i + T_i dS_i$$

| | | | |
|---|---|---|---|
| Matter | $p=0$ | $T=0$ | $dN=0$ ?? |
| radiation | $p=(1/3)\rho$ | $T=(\rho/a)^{1/3}$ | $\mu=0$ |
| dark-energy | $p=w\rho$ | $dS=0$ | ?? |

generalization

# Dark-energy equation of state

$p=w\rho$ ⇒ $E=cV^{-w}$  $c$-constant

- Extensiveness: Need such a thermodynamic quantity

- Presence of quanta

⇒ $N$ dependence

# Dark-energy's chemical potential

$p = w\rho$

Extensiveness $$s = \frac{1}{T}(\rho + p - n\mu)$$

Zero-temperature $$s = 0$$

$$\rho_{\Lambda w} = c_w n^{1+w} \qquad n\mu_{\Lambda w} = (1+w)\rho$$

Radiation-like $$\mu = 0$$

$$s_{rw} = c_{rw}\rho^{\frac{1}{1+w}}$$

## Intermediate case

$$n\mu_{w\chi} = (1 + w + \chi)\rho$$

$$s_{w\chi} = n\left(\frac{\rho}{c_w n^{1+w}}\right)^{-\frac{1}{\chi}}$$

$$T_{w\chi} = -\frac{\chi\rho}{n}\left(\frac{\rho}{c_w n^{1+w}}\right)^{\frac{1}{\chi}}$$

Limits

Zero-temperature $\rho \sim \rho_{w\Lambda}$ for $\chi \rightarrow 0$

Radiation-like $s_{w\chi} = s_{rw}$ for $\chi = -w - 1$

## Polytropic gas

$$s_{hw} = (n/w)\mathrm{Log}[\rho/(c_w n^{1+w})]$$

$$n\mu_{hw} = \rho\{1 + w - \mathrm{Log}[\rho/(c_w n^{1+w})]\}$$

# Dark-energy chemical potential contribution

$$\mu_\Lambda dN = \mu_\Lambda(n_\Lambda dV + V dn_\Lambda)$$

(1) (2)

Using, $dV = d(R^3) = 3R^2\dot{R}\,dt$

Part $(1)\ N\Gamma_1 dt = n_\Lambda \mu_\Lambda dV = (1 + w_\Lambda + \chi)\rho_\Lambda dV$

$$\partial N_\Lambda / \partial V = n_\Lambda$$

$$H \sim \rho_\Lambda^{1/2} \qquad n_\Lambda \Gamma_1 = 3(1 + w_\Lambda + \chi) H \rho_\Lambda \sim \rho_\Lambda^{3/2}$$

Part (2) $N\Gamma_2 dt = \mu_\Lambda V dn_\Lambda$

$$T = 0,\ \Gamma_2 \sim \sigma n_\Lambda v \sim (1/M_P^4) n_\Lambda \rho_\Lambda^{1/2}$$

$$\sigma \sim (1/M_P^4)\rho_\Lambda^{1/2}$$

Zero-temperature $n_\Lambda \Gamma_2 \sim \rho_\Lambda^{-\frac{2}{w_\Lambda+1}+1/2}$ $\rho_\Lambda \rightarrow 0$

$$-3 < w_\Lambda < -1,\ \Gamma_2 \ll \Gamma_1$$

Small temperature $\sigma \sim (1/M_P^4)T^2$, and $\rho_\Lambda \sim \rho_{w\Lambda}$

# Two-component model

1) Dark-energy conservation $d(\rho_\Lambda V) = -p_\Lambda dV + \mu_\Lambda dN_\Lambda$

$$\mu_\Lambda dN = \mu_\Lambda(n_\Lambda dV + V dn_\Lambda) \quad (1) \quad N\Gamma_1 dt = n_\Lambda \mu_\Lambda dV = (1 + w_\Lambda + \chi)\rho_\Lambda dV$$

$$n_\Lambda \Gamma_1 = 3(1 + w_\Lambda + \chi) H \rho_\Lambda \qquad n\mu_{w\chi} = (1 + w + \chi)\rho$$

$$\boxed{\dot{\rho}_\Lambda + 3(w_\Lambda + 1) H \rho_\Lambda = 3[(w_\Lambda + 1) + \chi] H \rho_\Lambda}$$

2) Total energy conservation $\sum_i d(\rho_i V) = \sum_i (-p_i dV + \mu_i dN_i + T_i dS_i)$

$$\boxed{\dot{\rho}_i + 3(w_i + 1) H \rho_i = -3[(w_\Lambda + 1) + \chi] H \rho_\Lambda}$$

3) 00 component of Einstein equations

$$\boxed{H^2 = \frac{8\pi}{3}\rho_c = \frac{8\pi}{3}(\rho_\Lambda + \rho_i)}$$

# Scale-factor dependence

Dark energy $\rho_\Lambda \sim R^{3\chi}$

other dominant component $\rho_i \sim R^{3\chi}$

baryonic matter $\rho_b \sim 1/R^3$

Asymptotic limit

$$\lim_{\rho_\Lambda \to 0} \frac{\rho_\Lambda}{\rho_c} = \frac{d_i + 3\chi}{d_i - 3(w_\Lambda + 1)}$$

$$d_i = 3(w_i + 1)$$

$$-d_i/3 < \chi < 0$$

# Time relations

Planck time

general equation of state $p_i = w_i \rho_i$

standard cosmology $\rho_c \sim 1/(6\pi t^2)$

decaying dark-energy $\rho_c \sim 1/(6\pi \chi^2 t^2)$

$\Rightarrow$ $\rho_0 \sim \rho_P (t_P/t_0)^2$

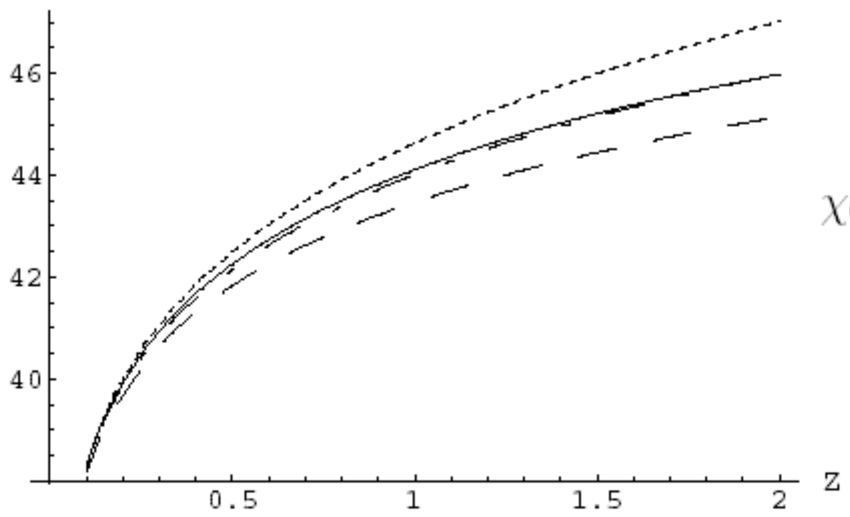
can explain fine tunning!

# Supernova data

distance-redshift relation

$$d_L = H_0^{-1}(1+z)\int_0^z dz'[\Omega_{b0}(1+z')^3 + (1-\Omega_{b0})(1+z')^{-3\chi_0}]^{-1/2}$$

$\mu = 5\mathrm{Log}_{10}(d_L) + 25$




$w_\Lambda = -1$

$\Omega_{m0} = 0,\ \Omega_{\Lambda 0} = 1$ (dotted)

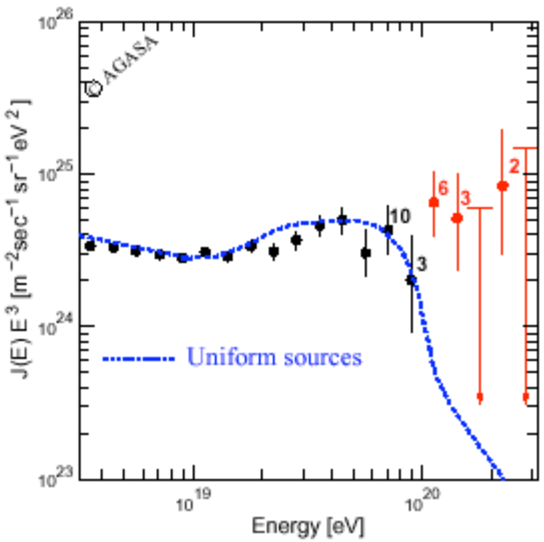
$\Omega_{m0} = .27,\ \Omega_{\Lambda 0} = .73$ (line)

$\Omega_{m0} = 1,\ \Omega_{\Lambda 0} = 0$ (dashed)

$\chi_0 = -.48$

$\Omega_{b0} = .044$ (dot- dashed)

# Cosmic Rays




Spectrum in the highest energy range

# Cosmic Rays

Galactic origin up to $E_{cr} \simeq 10^{11}$ GeV

Emissivity $10^{-9}\ \frac{\text{GeV}}{\text{cm}^2\text{sec}}$

Energy density $\rho_{cr} \simeq 4 \times 10^{-19} \frac{\text{GeV}}{\text{cm}^3}$

Dark energy decays to dark matter

$$(E_{cr}/M_P)^3 \rho_{\Lambda 0} H_0 = \Gamma_a \rho_{cr}$$

gravitational interaction $\Gamma_a \sim m_a^5 / M_P^4$

mass of intermediary particle $m_a \sim 10^4$ GeV

# Future work

-Structure formation
-Cosmic background radiation
-Inflation
-Microscopic basis of dark-energy **equation of state**

# Conclusions

-The model represents a departure from the zero-temperature cosmological constant.
-It maintains the results of the standard cosmology.
-Dark energy's coincidence with the critical density today is connected to the universe evolution.
-This favors contingency, rather than chance.
-Account of dark energy's quanta connects today's energy-density scale with Planck's, within classical general relativity and thermodynamics.
-The universe emerges as flat, interconnected, evolving deterministically, and in an inexorable process of accelerated expansion and decay.

| Cantidad | Símbolo | Valor |
| --- | --- | --- |
| Constante Gravitacional | $G$ | $6.673 \times 10^{-11}$ $m^{3}$ $kg^{-1}$ $seg^{-2}$ |
| Velocidad de la luz en el vacío | $c$ | 299,792,458 m $seg^{-1}$ |
| Constante de Planck | $h$ | $6.626 \times 10^{-34}$ m kg $seg^{-1}$ |

| Cantidad | Símbolo | Ecuación | Valor |
| --- | --- | --- | --- |
| Longitud de Planck | $l_P$ | $l_P = \sqrt{\frac{hG}{c^3}}$ | $4.051 \times 10^{-35}$ m |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# Early universe

Dark energy $\rho_\Lambda \sim R^{3\chi}$

Dark matter component $\rho_i \sim R^{3\chi}$

baryonic matter $\rho_b \sim 1/R^3$

radiation $\rho_r \sim 1/R^4$

## Matter domination:

structure formation: dark energy

$$\Omega_\Lambda \ll 1 \qquad \chi_0 = -.48$$

## Radiation domination:

nucleosynthesis: dark energy

$$\Omega_\Lambda \ll 1 \qquad \chi_r \sim -4/3$$

# Time constraints

| | |
|---|---|
| Radiation | $\chi_r \sim -4/3$ |
| Average | $|\chi_t| = \frac{1}{t_0(6\pi\rho_{c0})^{1/2}} \simeq .67$ |
| Recent | $\chi_0 = -.48$ |

⇨ $\chi_r < \chi_t < \chi_0$

Consistency: time of the universe until dark-energy baryon density equality

$$\int_0^{z_{\Lambda b}} dz'(1+z')^{-1}[\Omega_{b0}(1+z')^3 + (1-\Omega_{b0})(1+z')^{-3\chi_0}]^{-1/2} \simeq \ .9 < H_0 t_0 \simeq 1$$

# Nature's constants

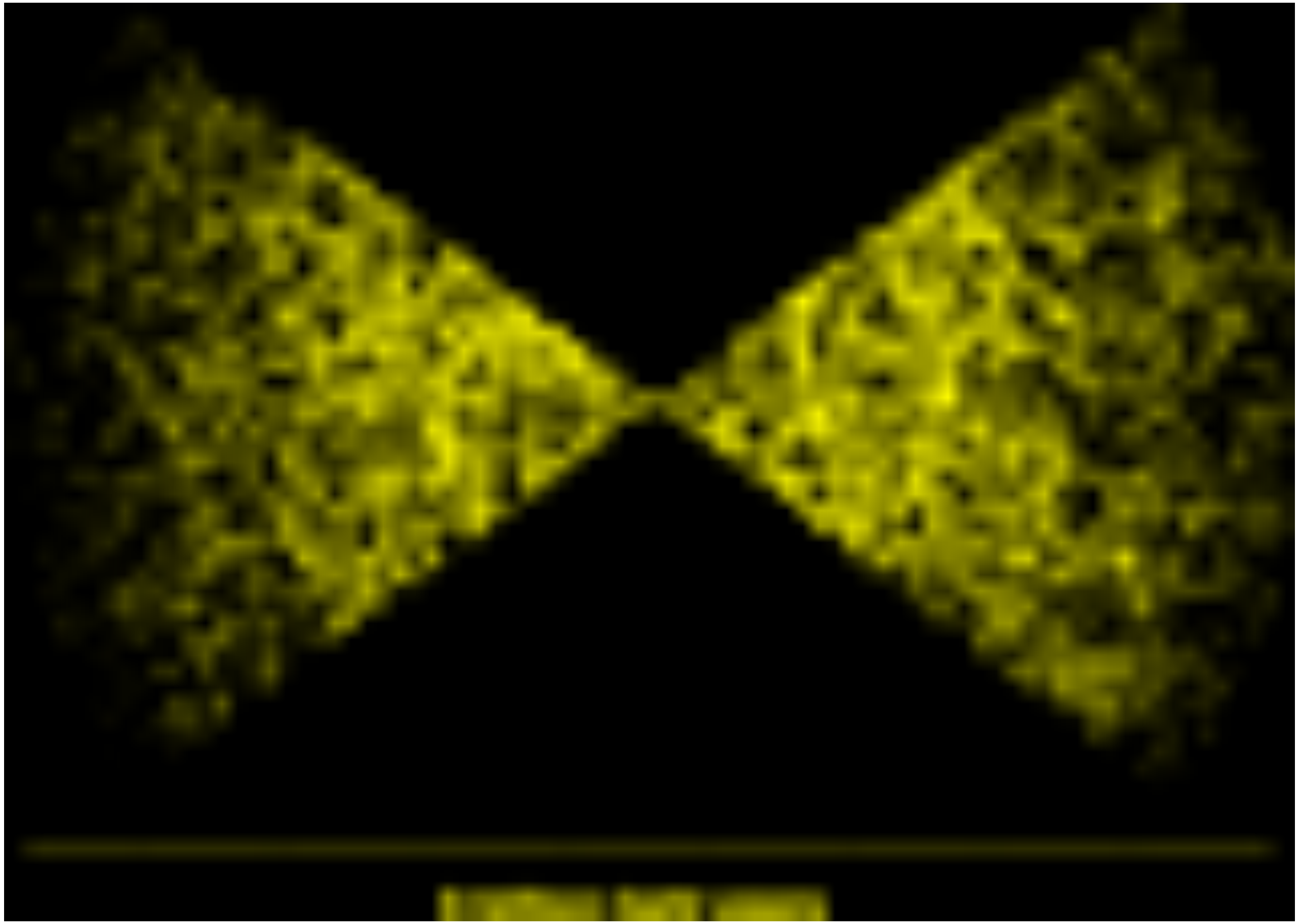
| Cantidad | Símbolo | Valor |
|---|---|---|
| Constante Gravitacional | G | $6.673 \times 10^{-11}\ m^{3}\ kg^{-1}\ seg^{2}$ |
| Velocidad de la luz en el vacío | c | $299{,}792{,}458\ m^{1}\ seg$ |
| Constante de Planck | h | $6.626 \times 10^{-34}\ m\ kg\ seg^{1}$ |

# Natural units of length, time, mass

*Planck length* $4.051 \times 10^{-35}$ *m*

*Planck time* $1.351 \times 10^{-43}$ *seg*

*Planck mass* $5.456 \times 10^{-8}$ *kg*



# Solutions and asymptotic behavior

$$\rho_i = -\rho_\Lambda + \frac{\dot{\rho}_\Lambda^2}{24\pi\chi^2\rho_\Lambda^2}$$

$$6\,\chi\,\rho_\Lambda\,\ddot{\rho}_\Lambda + (d_i - 6\,\chi)\;\dot{\rho}_\Lambda^2 - 24\,\pi\,[d_i - 3\;(1 + w_\Lambda)]\,\chi^2\,{\rho_\Lambda}^3 = 0$$

Exact solution

$$t - t_i = \int_{\rho_\Lambda}^{\rho_{\Lambda_i}} d\rho \left( \frac{d_i + 3\chi}{24\chi^2\pi[d_i - 3(w_\Lambda + 1)]\rho^3 + 3(d_i + 3\chi)\chi\, C\rho^{2-\frac{d_i}{3\chi}}} \right)^{\frac{1}{2}}$$

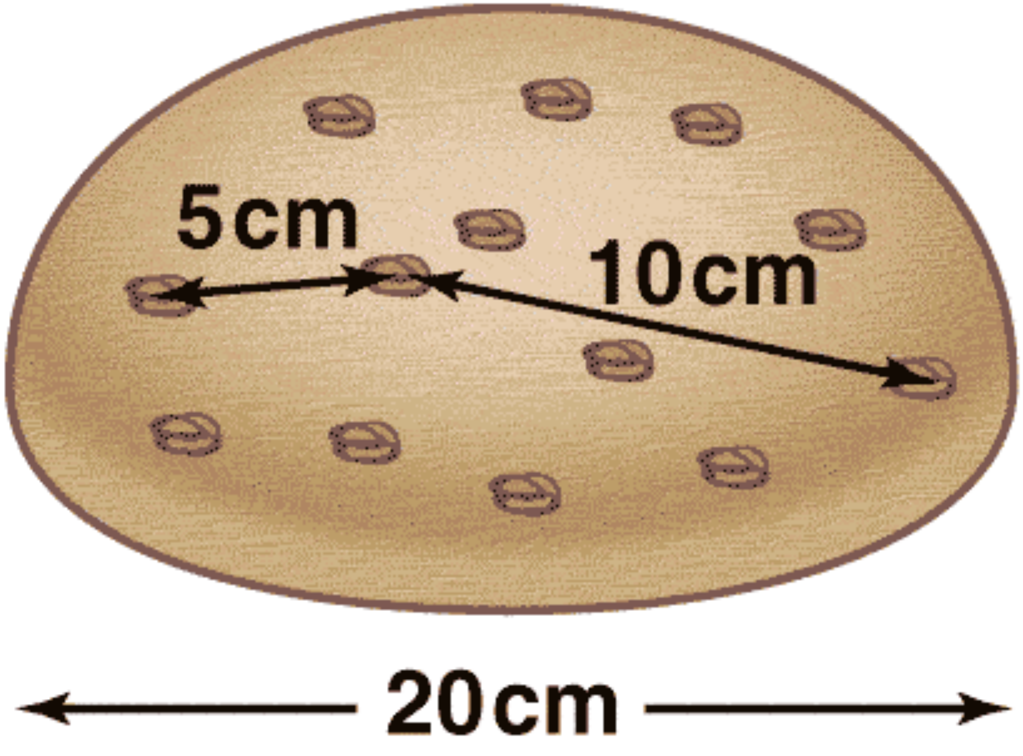
$$\rho_c \approx \frac{24\chi^2\pi[d_i - 3(w_\Lambda + 1)]\rho_\Lambda + (d_i + 3\chi)3\,\chi\,C{\rho_\Lambda}^{-\frac{d_i}{3\chi}}}{24\pi\chi^2(d_i + 3\chi)}$$

Asymptotic limit

$$\boxed{\lim_{\rho_\Lambda \to 0} \frac{\rho_\Lambda}{\rho_c} = \frac{d_i + 3\chi}{d_i - 3(w_\Lambda + 1)}}$$

$$d_i = 3(w_i + 1)$$

$$-d_i/3 < \chi < 0$$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