DARK ENERGY :

A COSMOLOGICAL CONSTANT

OR SOMETHING ELSE ?

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Friedmann-Lemaître Models (1922-1931)

- Homogeneity & Isotropy ➔ space of constant curvature *k*

➔ Line element: $ds^2 = -c^2dt^2 + R^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right]$

- Scale factor R(t) obeys FL equations :

$$\frac{\dot{R}^2}{R^2} = \frac{8\pi G}{3}\rho + \frac{\Lambda c^2}{3} - \frac{kc^2}{R^2} \quad (1) \qquad \frac{\ddot{R}}{R} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3} \quad (2)$$

- cosmological constant Λ
- matter density ρ (t)
- pressure $p = w\rho c^2$

dust : w=0
radiation: w=1/3
repulsive energy : w <0

Cosmological Parameters

$$H(t) \equiv \frac{\dot{R}(t)}{R(t)}$$ Hubble-Lemaître parameter

$$\Omega_m = \frac{8\pi G\rho_m}{3H^2}$$ Matter density parameter

$$\Omega_\Lambda = \frac{\Lambda c^2}{3H^2}$$ c. c. energy density parameter

$$\Omega \equiv \Omega_m + \Omega_\Lambda$$ Total energy-density parameter

$$(1) \Rightarrow \Omega = 1 + \frac{kc^2}{R^2H^2}$$

$\Omega = 1 \Leftrightarrow k = 0$ (Euclidean space)

$\Omega < 1 \Leftrightarrow k < 0$ (hyperbolic space)

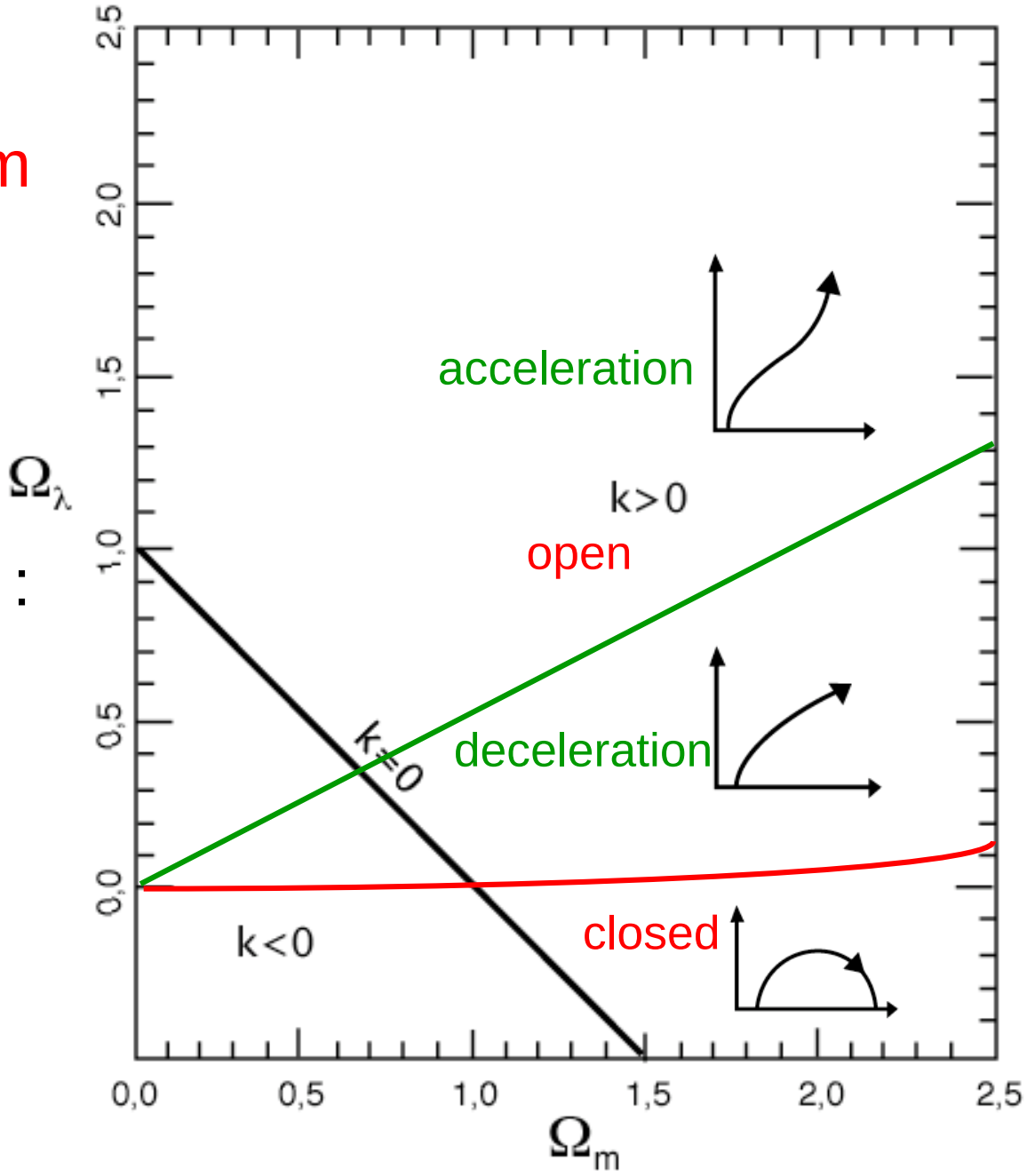
$\Omega > 1 \Leftrightarrow k > 0$ (spherical space)

The ΛCDM Universal Diagram

Theory

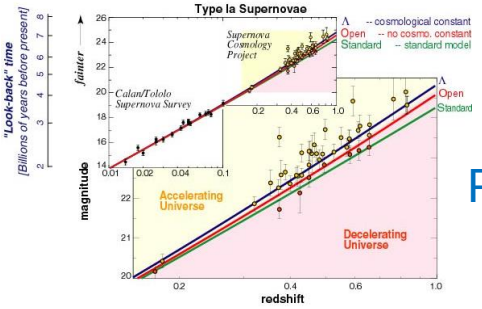
Key parameters :

W_m , W_L



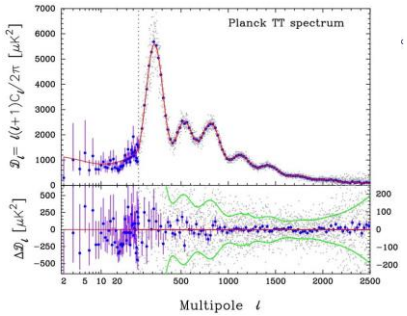
Clues for Accelerated Expansion

- Observations of SNIa



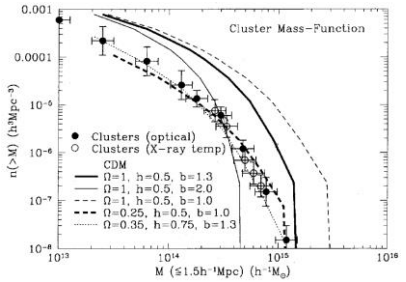
Perlmutter, Riess, Schmidt 1998 (Nobel Prize 2011)

- Baryon acoustic oscillations



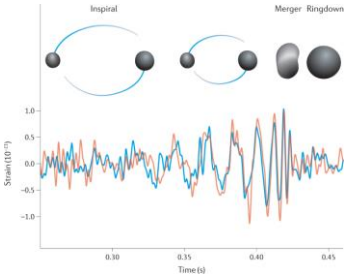
Eiseinstein et al. 2005

- Mass functions of galaxy clusters
- Age of the universe



Pain & Astier 2012

- Gravitational waves as standard sirens



Rosado et al. 2016

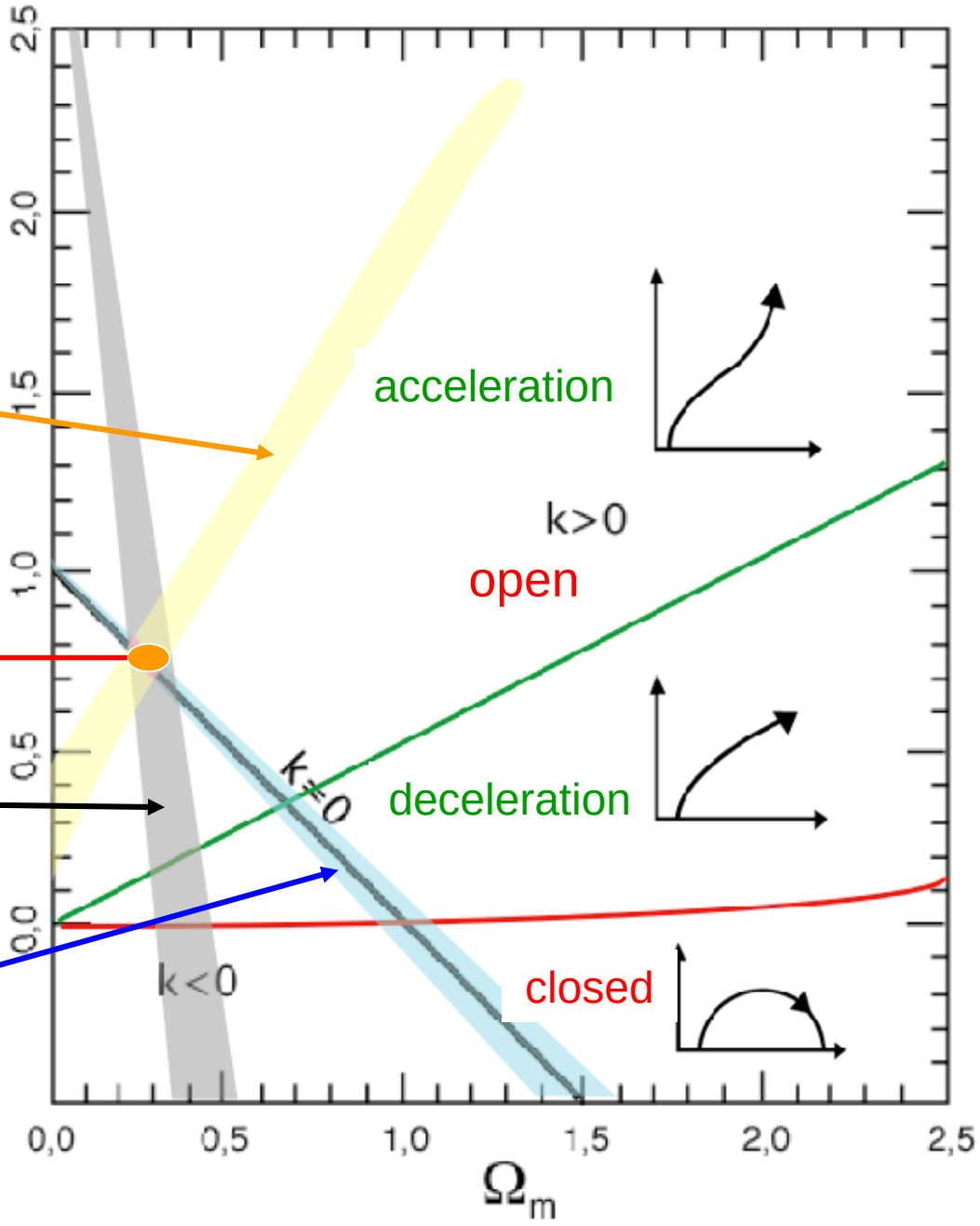
The ΛCDM Universal Diagram
Observations

Supernovae

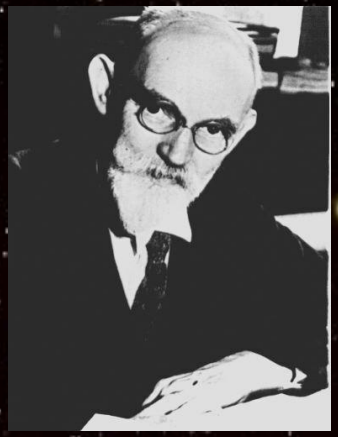
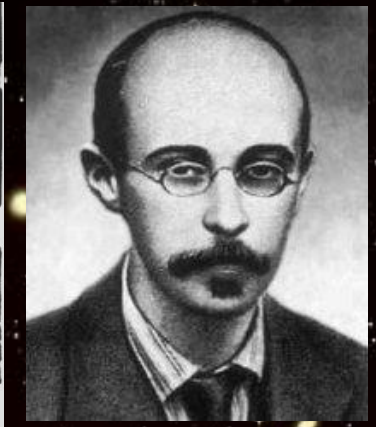
$(W_m, W_l) \approx (0.32, 0.68)$

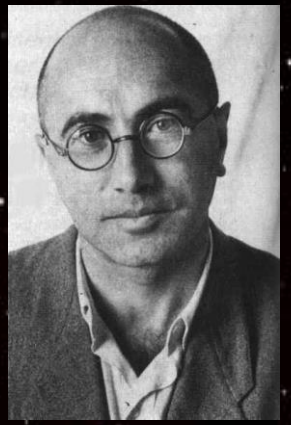
Galaxy clusters
Gravitational lenses

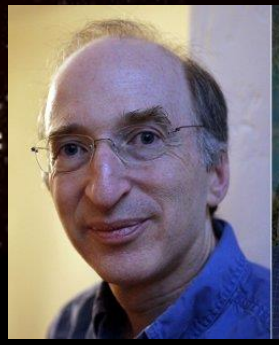
CMB anisotropies

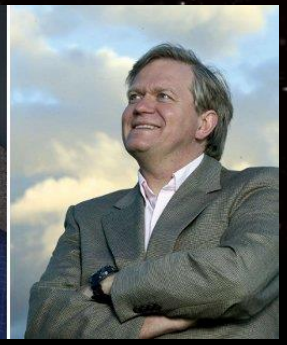


Go back to History…







• 1917 : Einstein introduces a repulsive « cosmological constant » Λ to ensure static equilibirum

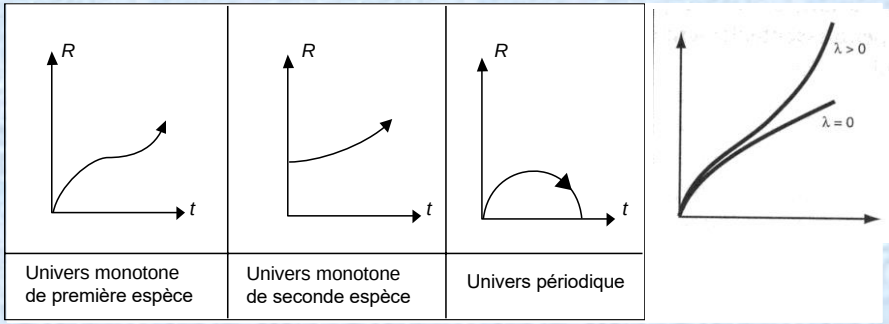
$$G_{ij} = k T_{ij}$$

$$\Downarrow$$

$$G_{ij} + \Lambda g_{ij} = k T_{ij}$$

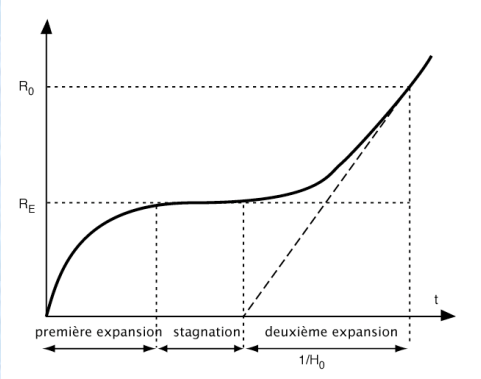
• 1922 : Cartan proves that the Einstein field tensor with Λ is the most general tensor in Riemannian geometry having zero divergence (like the energy momentum tensor)

• 1922-1924 : Friedmann calculates dynamical solutions with or without Λ

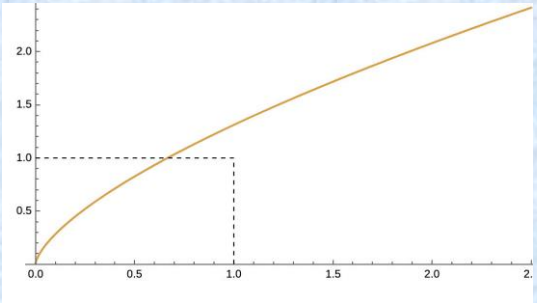


• 1931 : Lemaître proposes a model with accelerated expansion due to Λ

(solves the age problem and allows galaxy formation)

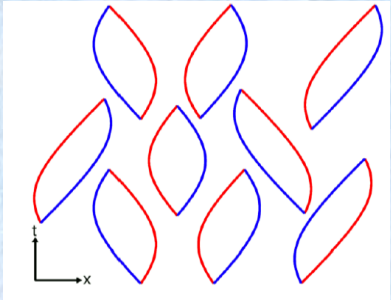


• 1932 : Einstein-de Sitter drop Λ (and curvature): ($\Omega_m = 1, \Omega_\Lambda = 0$)
Standard model until 1980's



• 1934 : Lemaître interprets Λ as the quantum vacuum energy with

$p = \rho_{vac}c^2 = -\Lambda c^4/4\pi G$

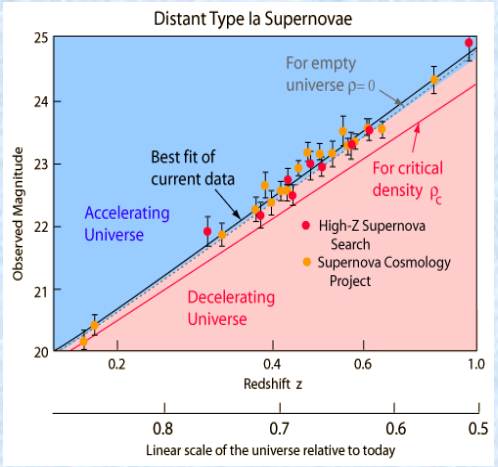


• 1964 : Zeldovich calculates the vacuum energy with QFT in Minkowski space and finds a huge value

• 1984 : Peebles reintroduces Λ (and dark matter) constrained by inflation theory ($\Omega_{tot} \approx 1$) and structure formation (Ω_m low)

→ **The ΛCDM standard model**

• 1998 : Experimental discovery of cosmic acceleration interpreted as due to **Repulsive « Dark Energy »**



Repulsive because:

Variation of space scale factor : $R\ddot{}/R = -(\rho_{tot}+3p/c^2)$

→ Acceleration if $R\ddot{}/R > 0 \rightarrow (\rho_{tot}+3p/c^2) < 0$

But equation of state : $p = w\rho c^2$

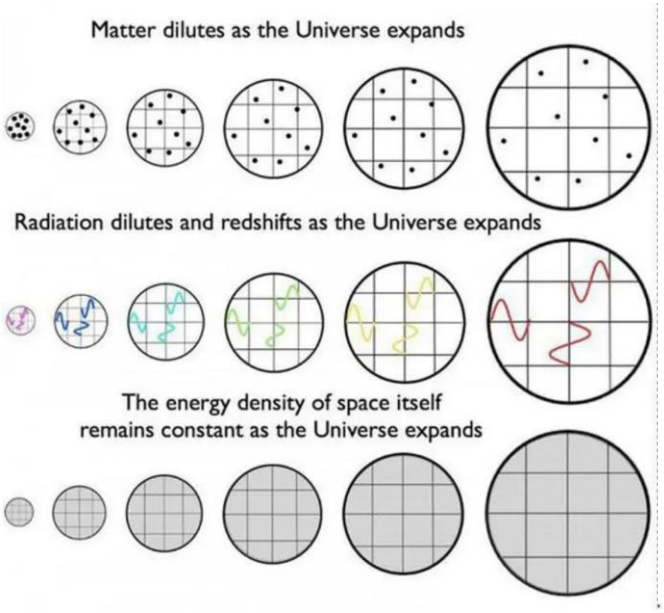
→ Acceleration if $w < -1/3$

Nature of Dark Energy depends on its equation of state $p = w\rho c^2$

1. Cosmological Constant : $w = -1$
2. New force field variable with time (Quintessence models) $: -1 < w < -1/3$
3. Phantom Energy $: w < -1$
4. Artefact : necessity of DE could disappear in inhomogenous cosmologies, modified theories of gravity, dark gravity, etc.

So, what is Dark Energy ?

Since matter and radiation dilute as the Universe expands, the behaviour of the scale factor depends on the balance between matter, radiation and dark energy

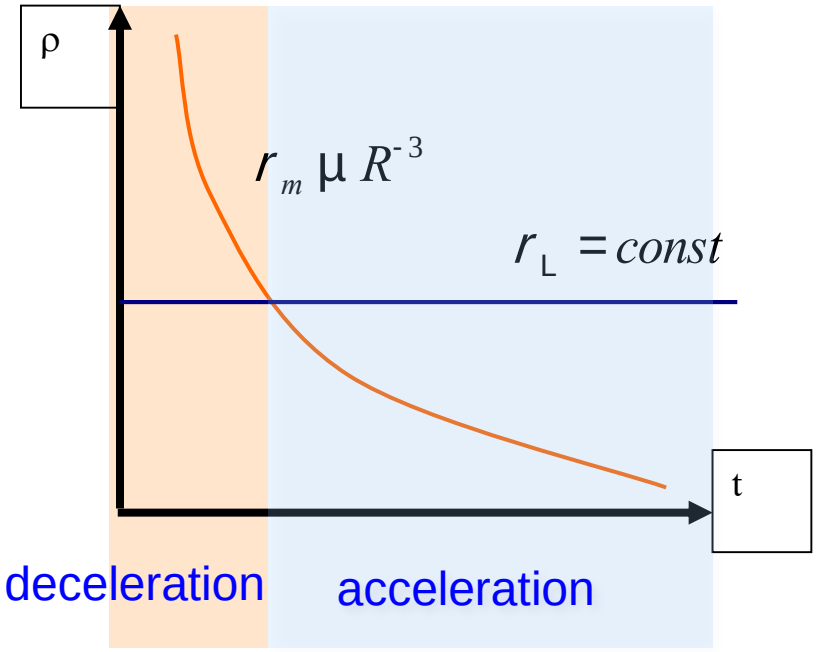


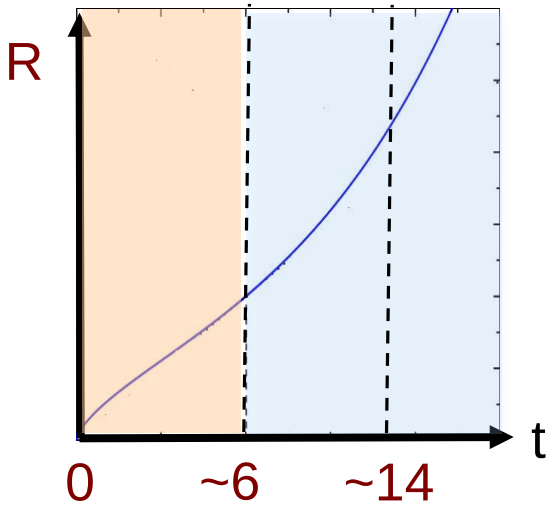
$\rho_m \propto R^{-3}$

$\rho_{rad} \propto R^{-4}$

ρ_Λ ?

For instance, if ρ_Λ = const (c.c.):





At late times:

$r_L >> r_m \Rightarrow R \mu e^{Ht}$

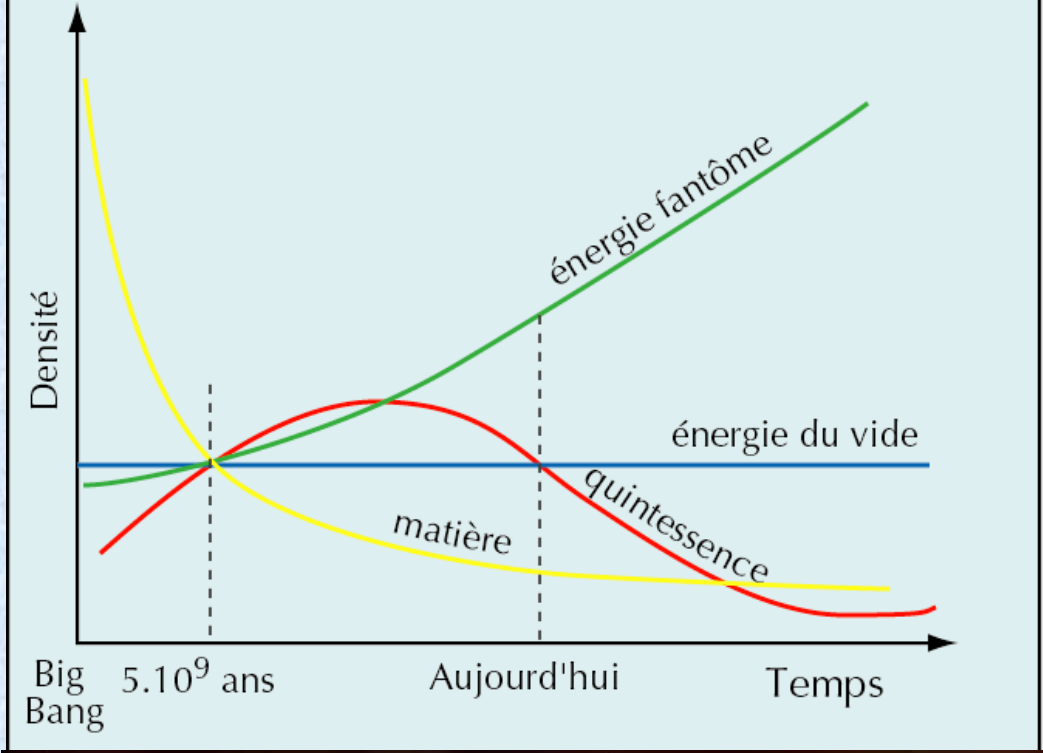
In all cases :

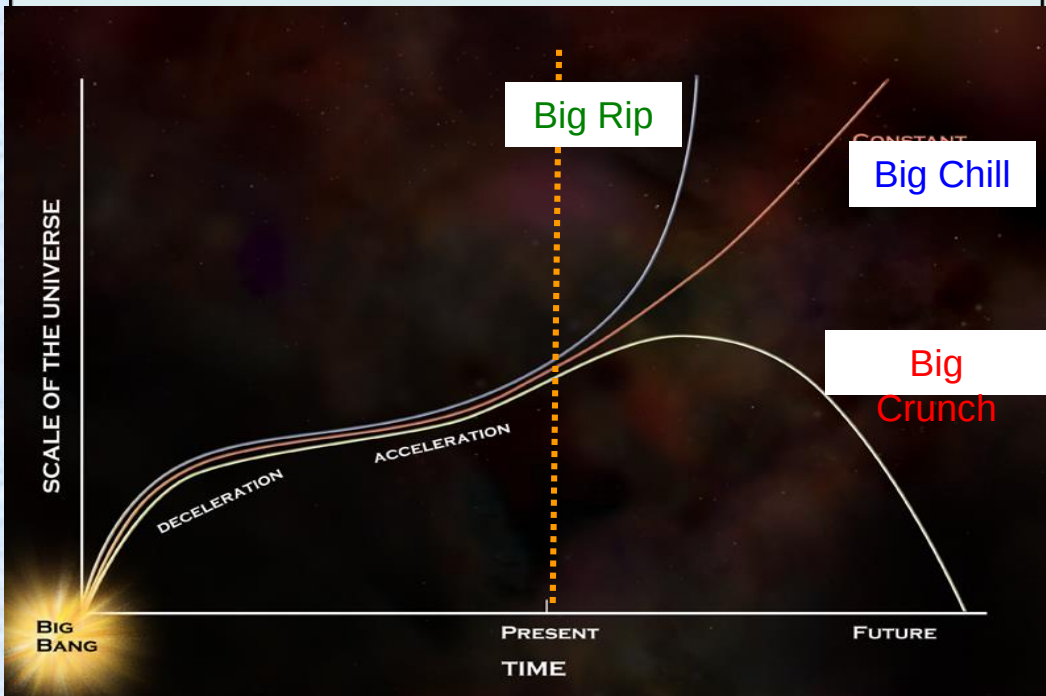
The Evolution of the Universe depends on the equation of state $p = w\rho c^2$ for Dark Energy

Planck Collaboration (2018)
$w = -1.028 \pm 0.032$

⬇

D.E. ≈ C.C. !





Fallacious reasonings against the c.c.

1) A Coincidence Problem ?

- There is only a very short phase of cosmological time during which the matter density is of comparable magnitude to the vacuum energy density.
- We are thus living in a very unlikely moment in the history of the universe
- This violates the cosmological principle (no privileged position in the universe, neither in space nor in time)

➔ Fine-tuning ?

➔ Anthropic solution? (philosophy, string landscape…)

➔ Time-varying forms of dark energy

Fallacious reasonings against the c.c.

2) The Cosmological Constant « Problem »

•Using naive naturalness arguments in quantum field theory, one expects that the theoretical vacuum energy density is

$\rho_{vac} \sim 10^{91}\ g/cm^3 \Rightarrow \Lambda_{th} \sim 10^{66}\ cm^{-2}$

•The cosmologically observed value is

$\rho_{\Lambda} \sim 6 \times 10^{-30}\ g/cm^3 \Rightarrow \Lambda_{obs} \sim 10^{-56}\ cm^{-2}$

A discrepancy by 122 orders of magnitude !

Easy to understand : $\Lambda \propto L^{-2}$

QFT : $L \approx \ell_{Planck} \approx 10^{-33}$ cm

Astro : $L \approx \ell_{Univ} \approx 10^{28}$ cm

- A miscalculation ?

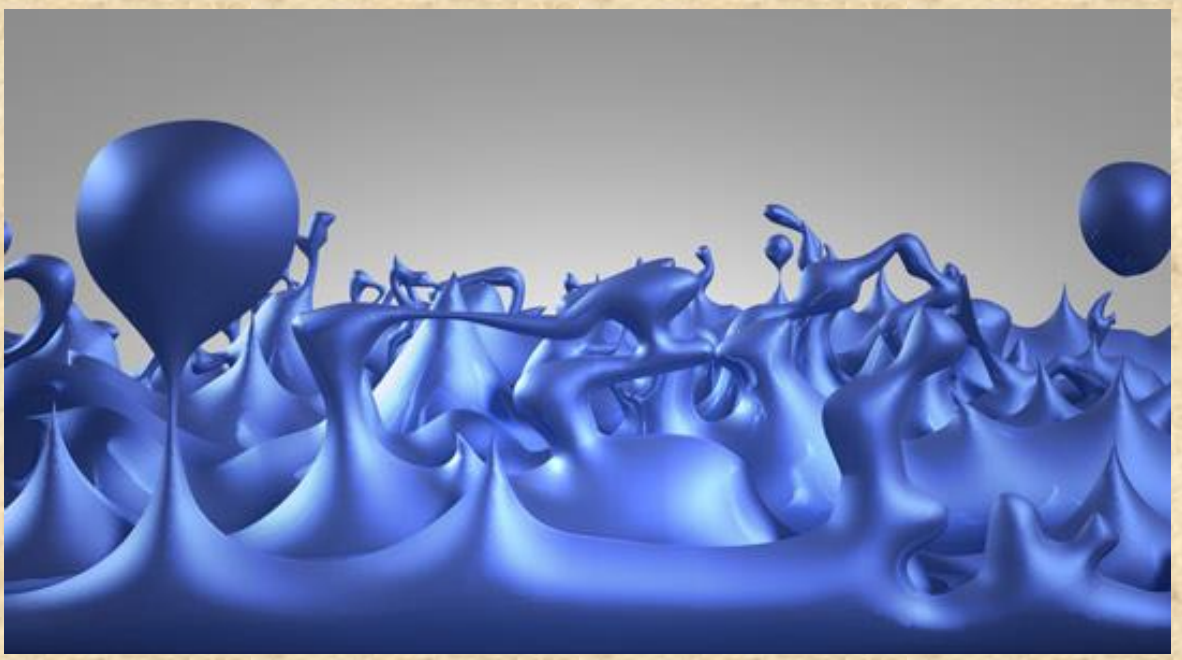
- The cosmological constant problem appears if one considers quantum matter fields on a zero-curvature, simply-connected spacetime background.

- But vacuum energy depends strongly of curvature and topology

- Can a realistic cosmological constant emerge from more realistic calculations?

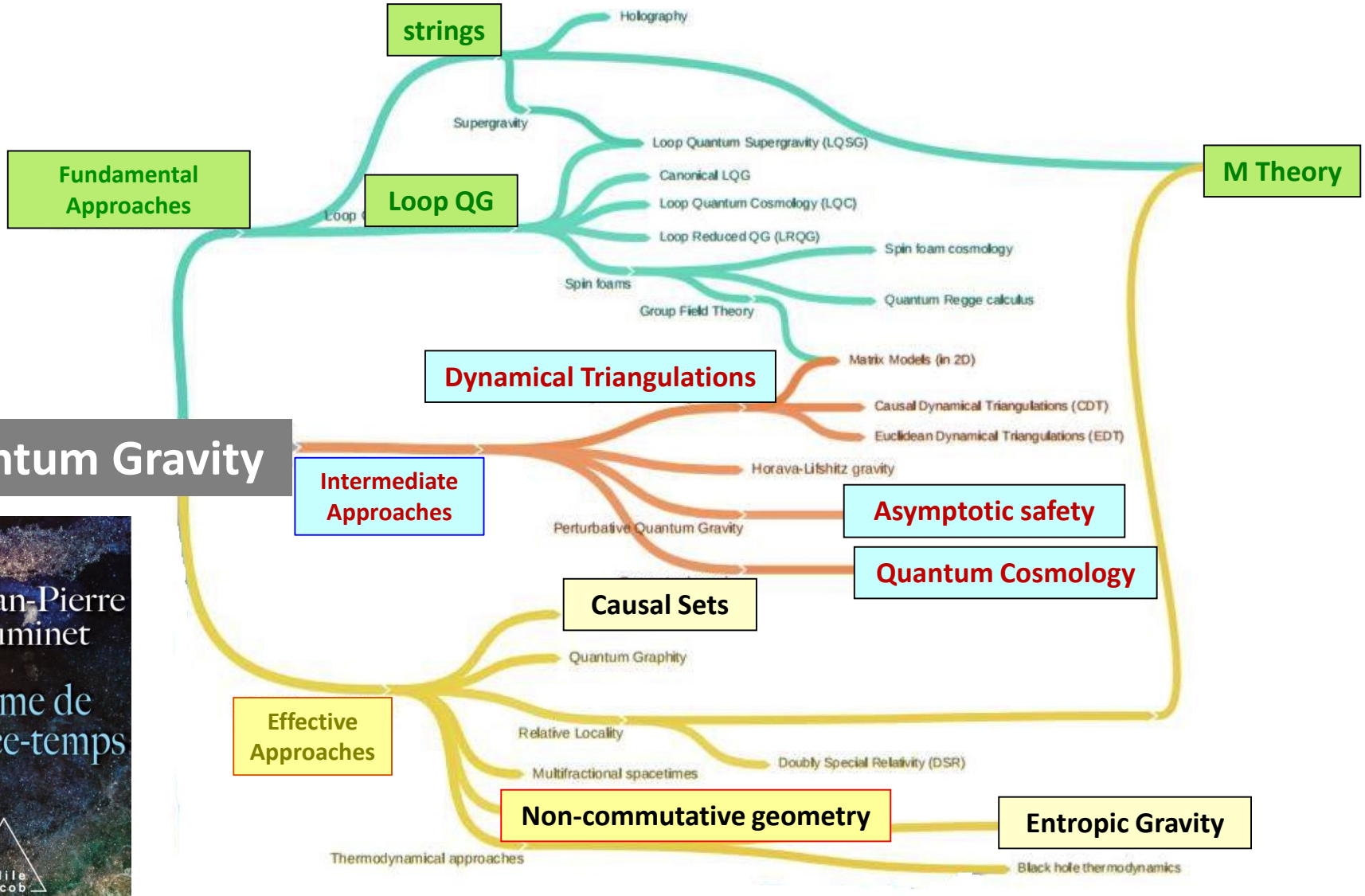
YES!

Example : Spacetime could be fundamentally made of “foam”, in which the curvature and topology of space constantly fluctuate on extremely small scales (Wheeler).



All this complicated topology would cancel out most of the impact of vacuum energy, making the cosmological constant huge at the Planck scale but very small at the local observable level (Carlip, 2020).

• What happens in quantum gravity theories and non-classical space-time ?



• String and Brane Theory : No reliable calculation.

Some argue Λ should be strictly zero

➔ Dark Energy would be something else, but what?

• Loop quantum gravity : seems OK for Λ (Zhang et al. 2021)

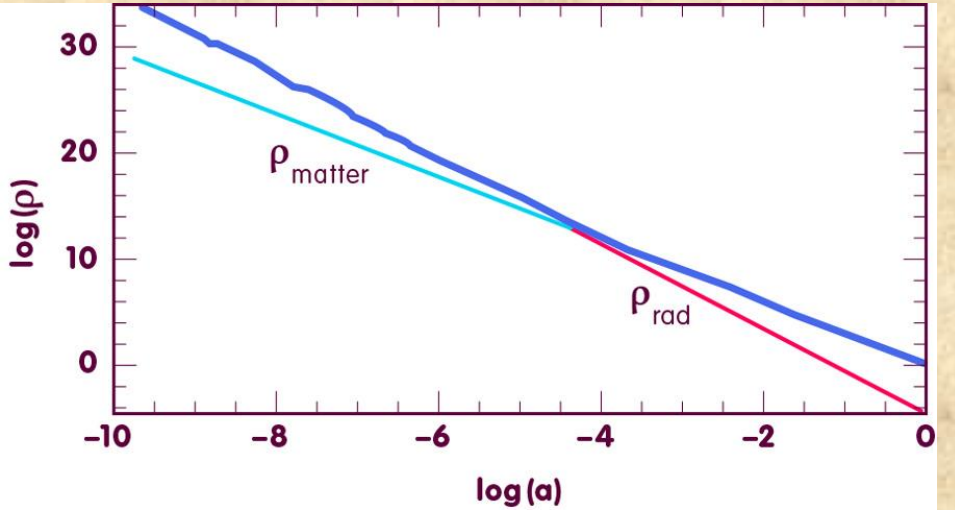
• Entropic gravity : seems OK for Λ (Díaz-Saldaña et al. 2018)

• Dynamical triangulations : predict correct emergent Λ (Ambjorn 2010)

• Non-commutative geometry : No reliable calculation

• Causel Sets : Fluctuating ρ_Λ always $\approx \rho_m + \rho_{rad}$ (Sorkin, 2006)

→ No coincidence problem



Conclusion

- Cosmology requires an accelerating factor

- The true Λ explains all cosmological data. Its value is not unnatural

- Alternative explanations require ad hoc theories with a lot of fine-tuning required

- Only if observational evidence gives $w \neq -1$ (not the case today), dark energy ≠ c. c. required.

Thank you

In reality, energy resides in the vacuum and the vacuum is nothing but energy.

Wang Fuzhi (17th century)