



**Class 1: Introduction | Observable universe & Dark energy**

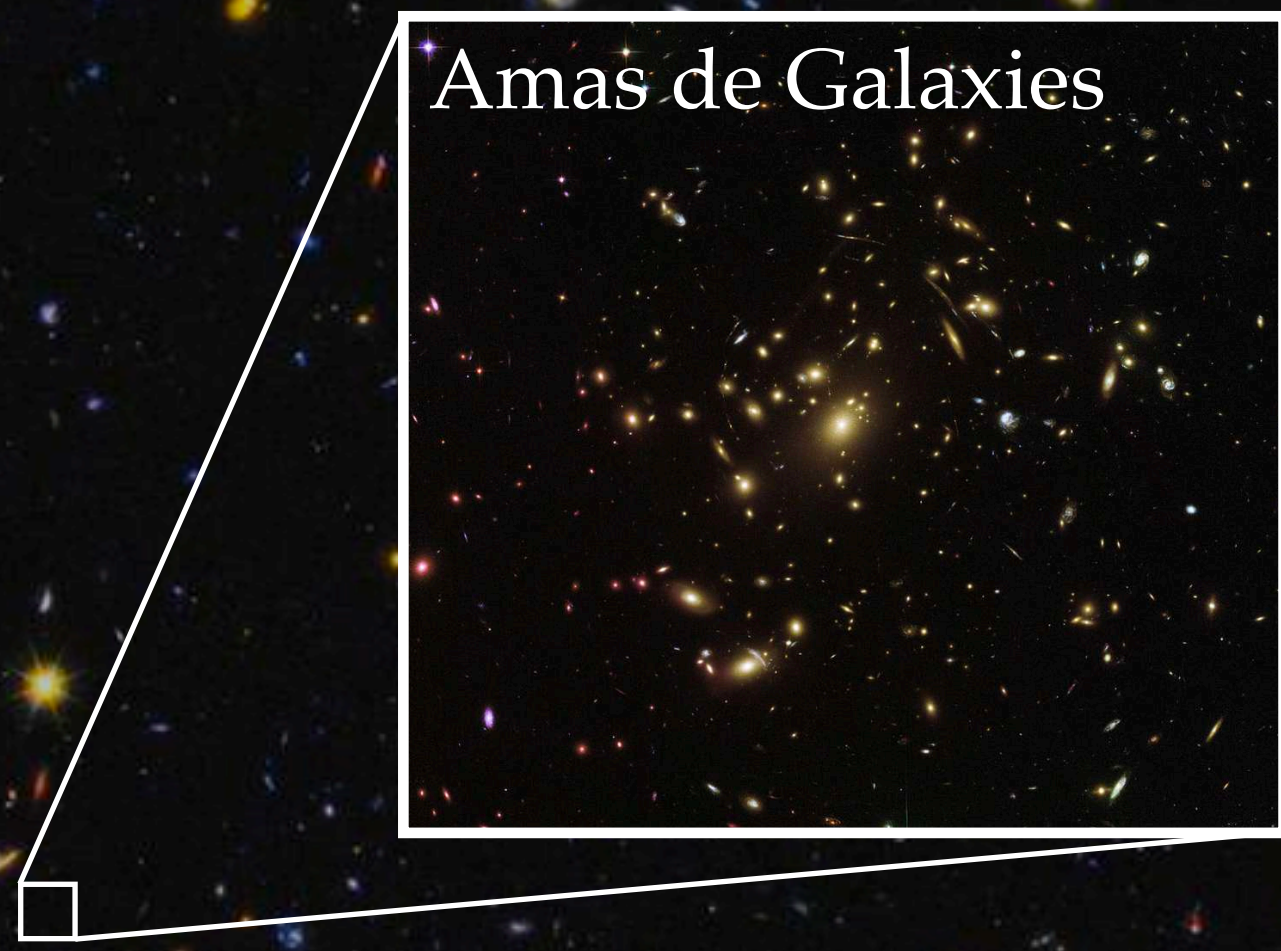
**Class 2: Details on Type Ia Supernova cosmology**

**Class 3: The Hubble Constant tension**

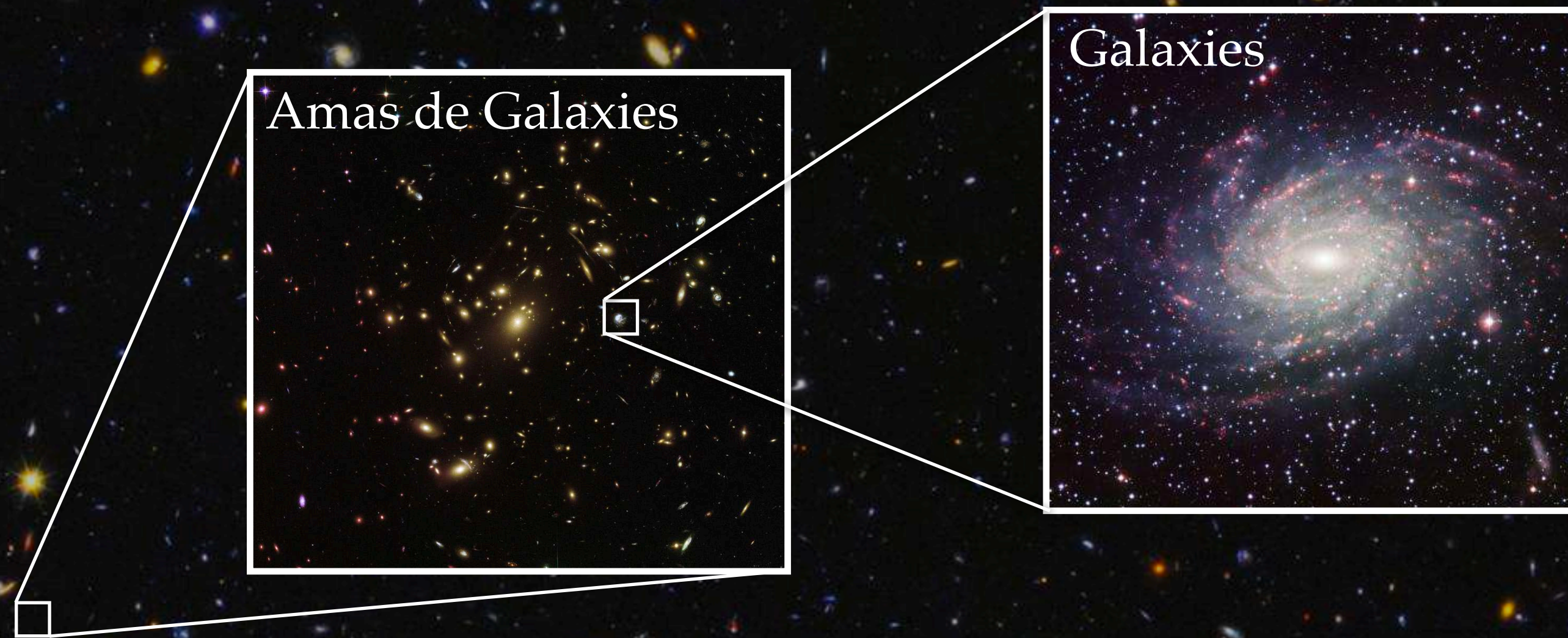


Class 1: Introduction

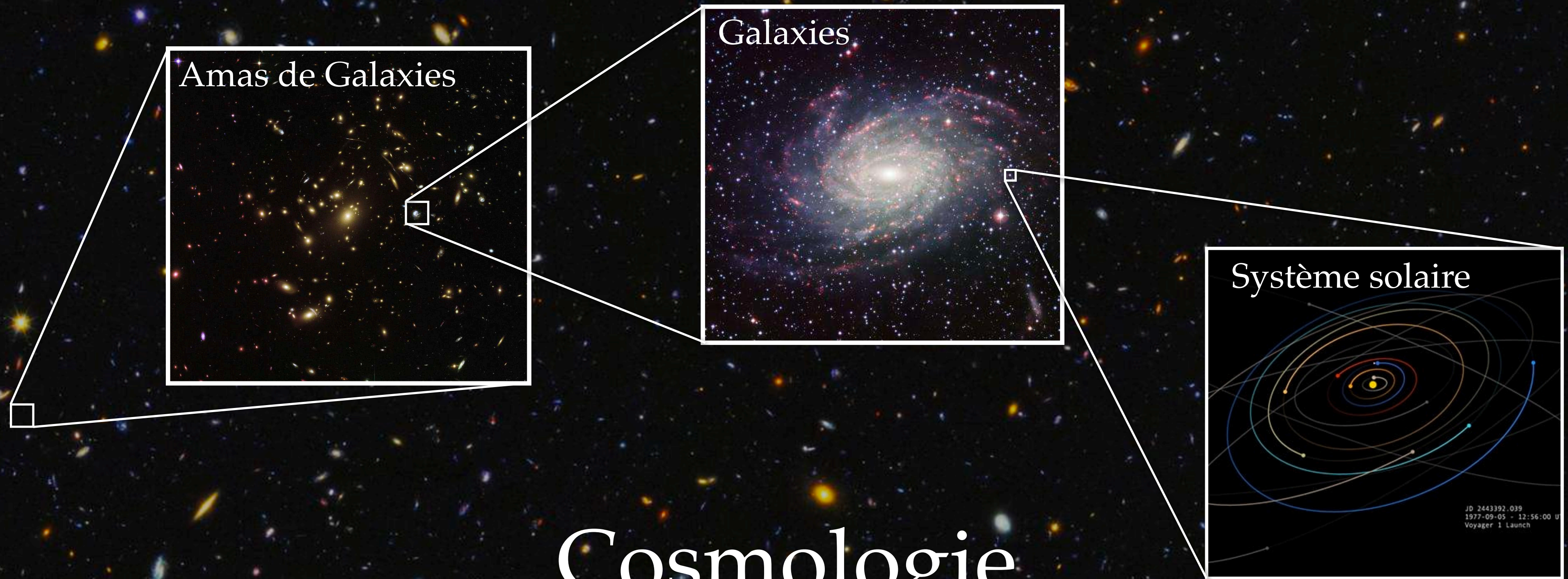
Cosmologie  
Observationnelle



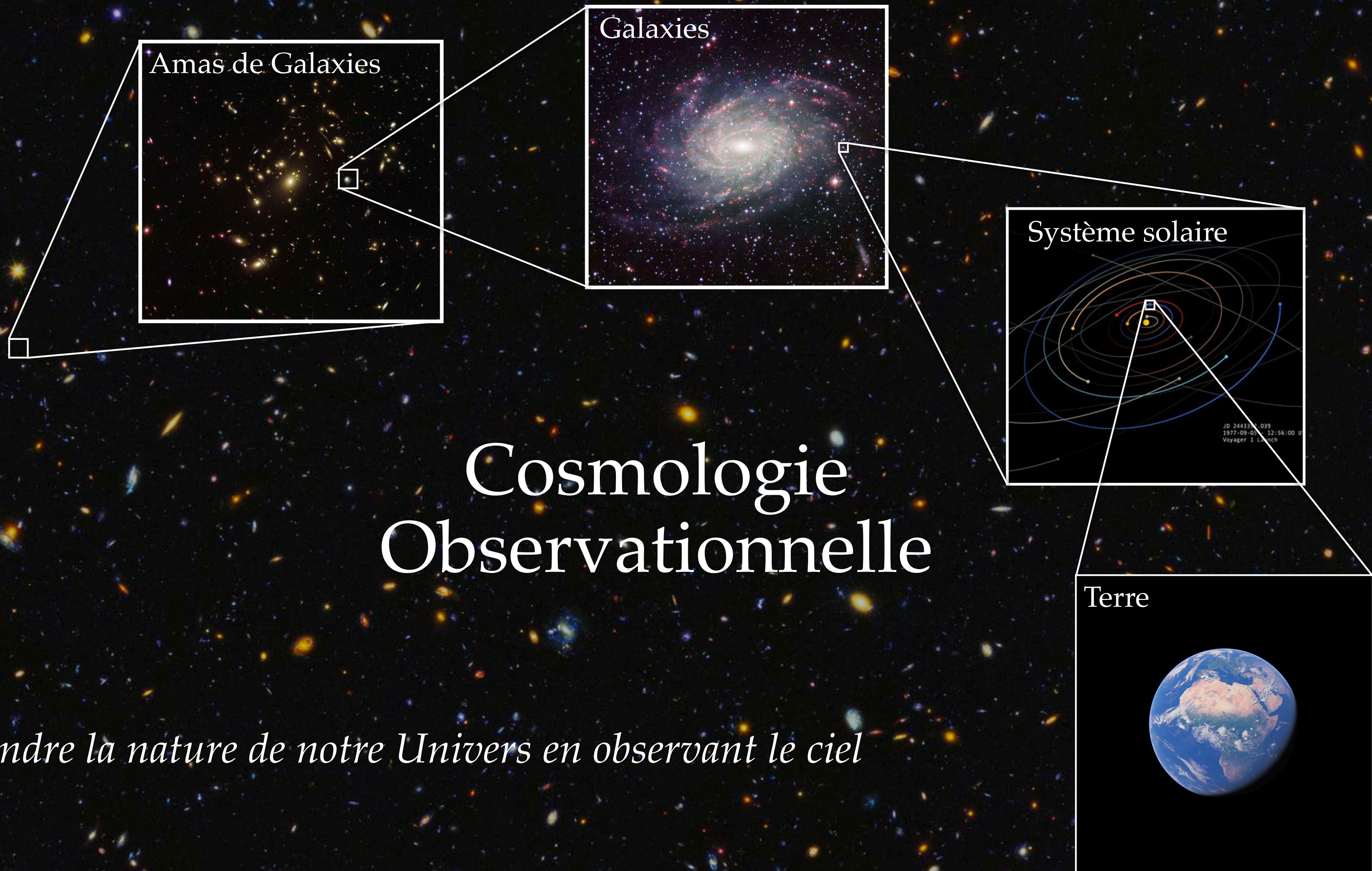
# Cosmologie Observationnelle



# Cosmologie Observationnelle



# Cosmologie Observationnelle

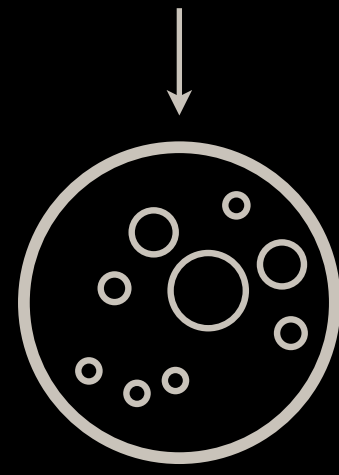


# Cosmologie Observationnelle

*Comprendre la nature de notre Univers en observant le ciel*



Lune



Terre



Distance pas à l'échelle



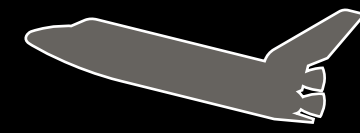
Lune



Terre



Lune



10h

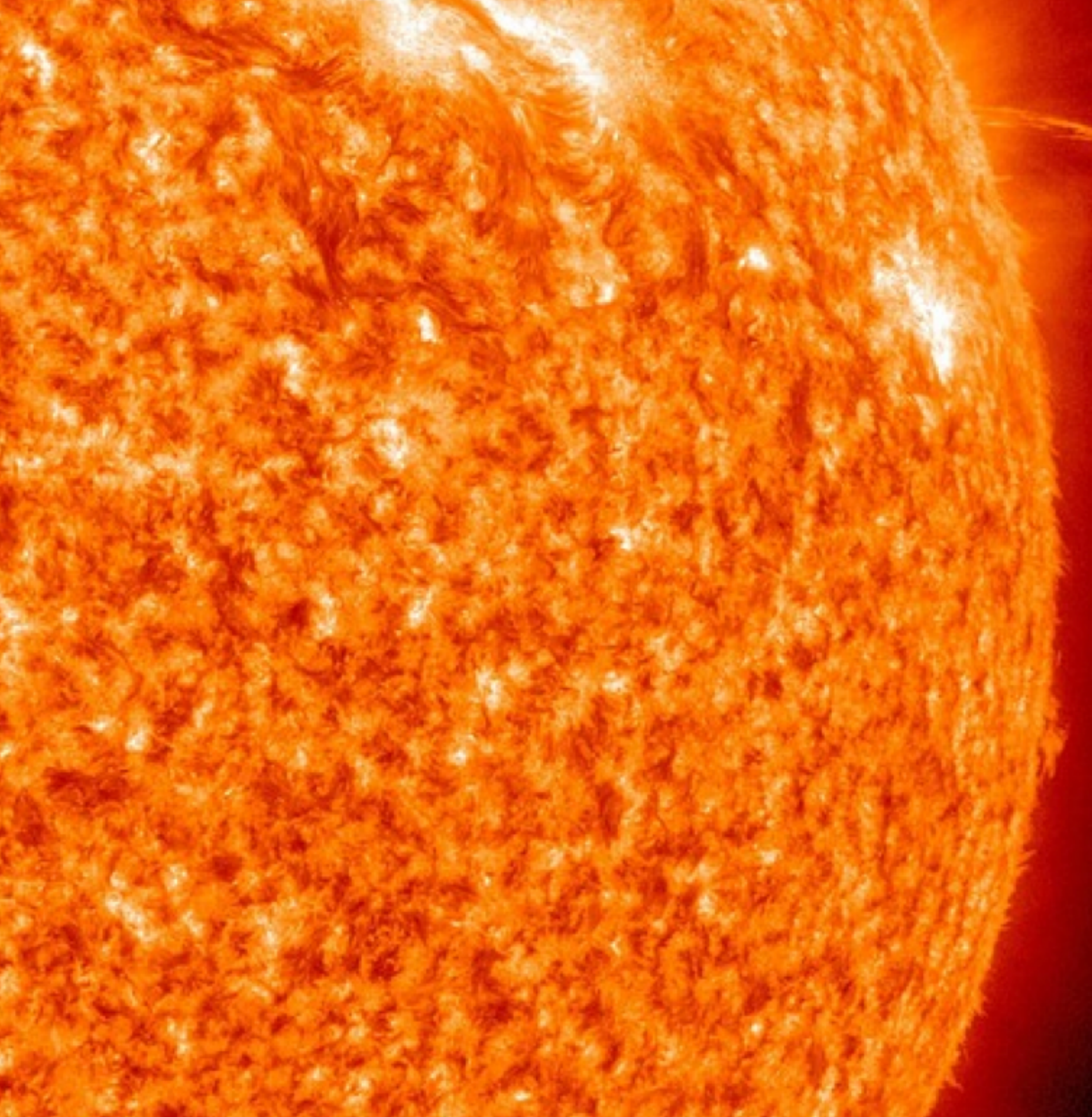


1 seconde

385 000 km

Terre





Soleil

Terre



(1 / 109)

Distance pas à l'échelle



Soleil



Mercure



Venus



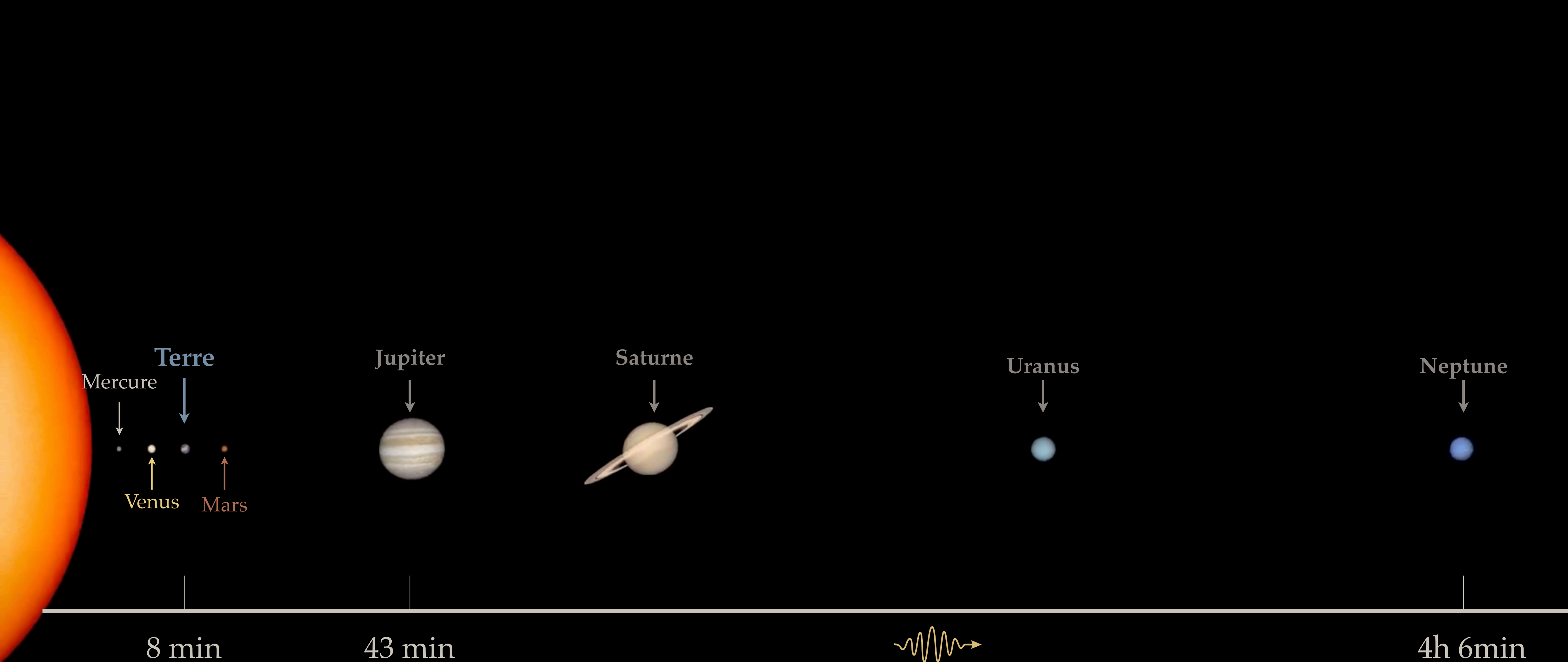
Terre



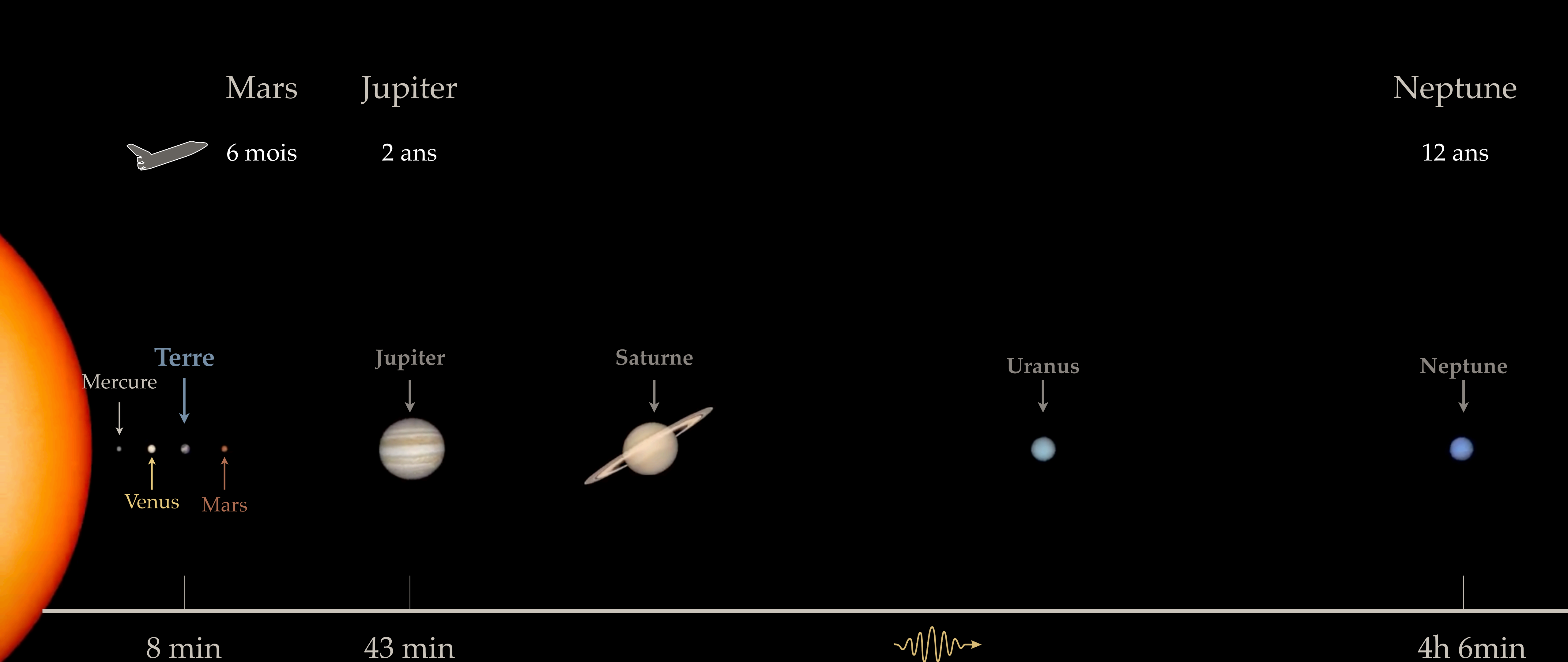
8 min

150 000 000 km

Diamètre de la terre: 13 000 km



Distance-taille ratio pas respecté



Distance-taille ratio pas respecté







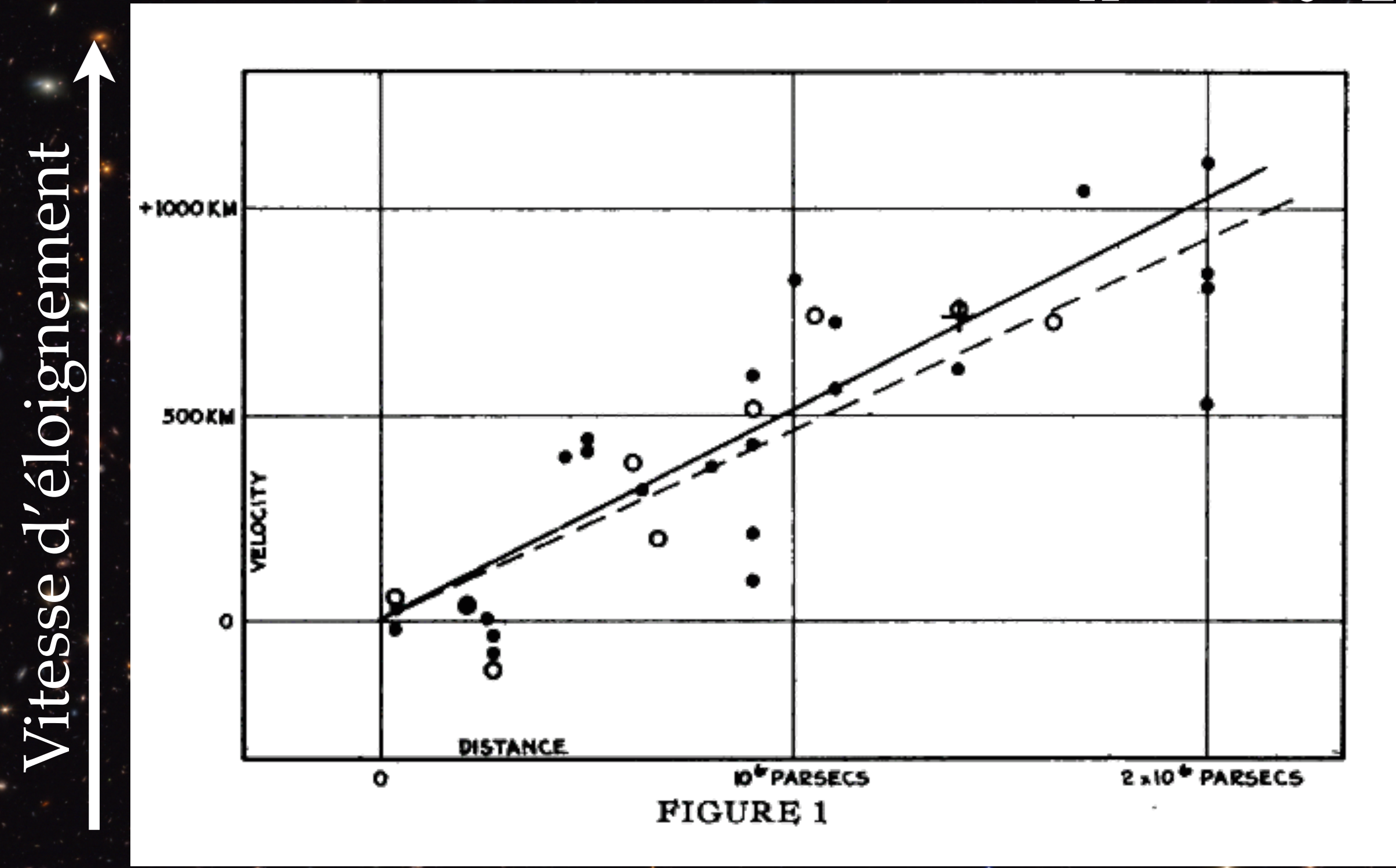




Hubble 11.3 jours

Webb 0.83 jours

$$v_H = H_0 d_L$$

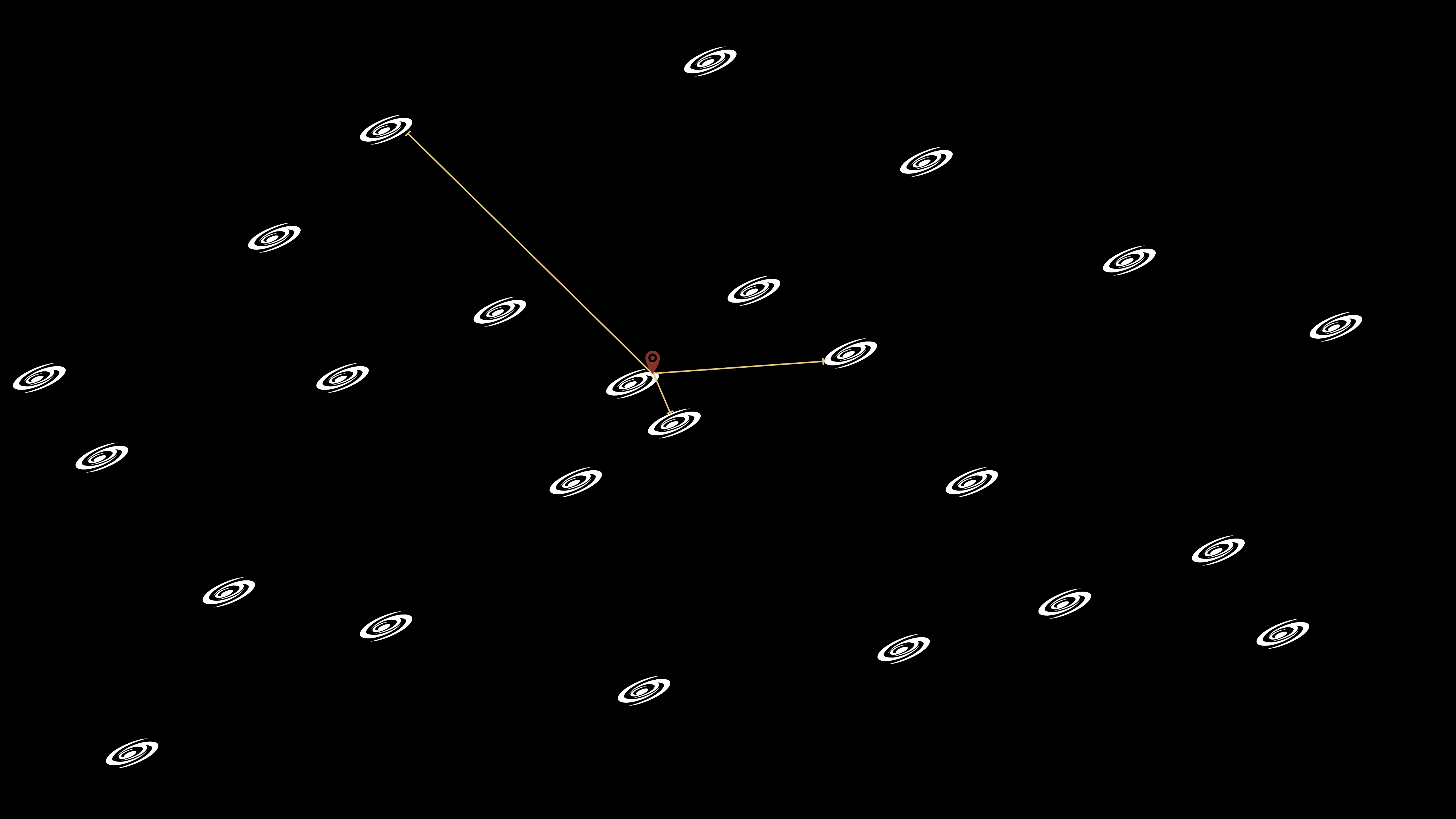


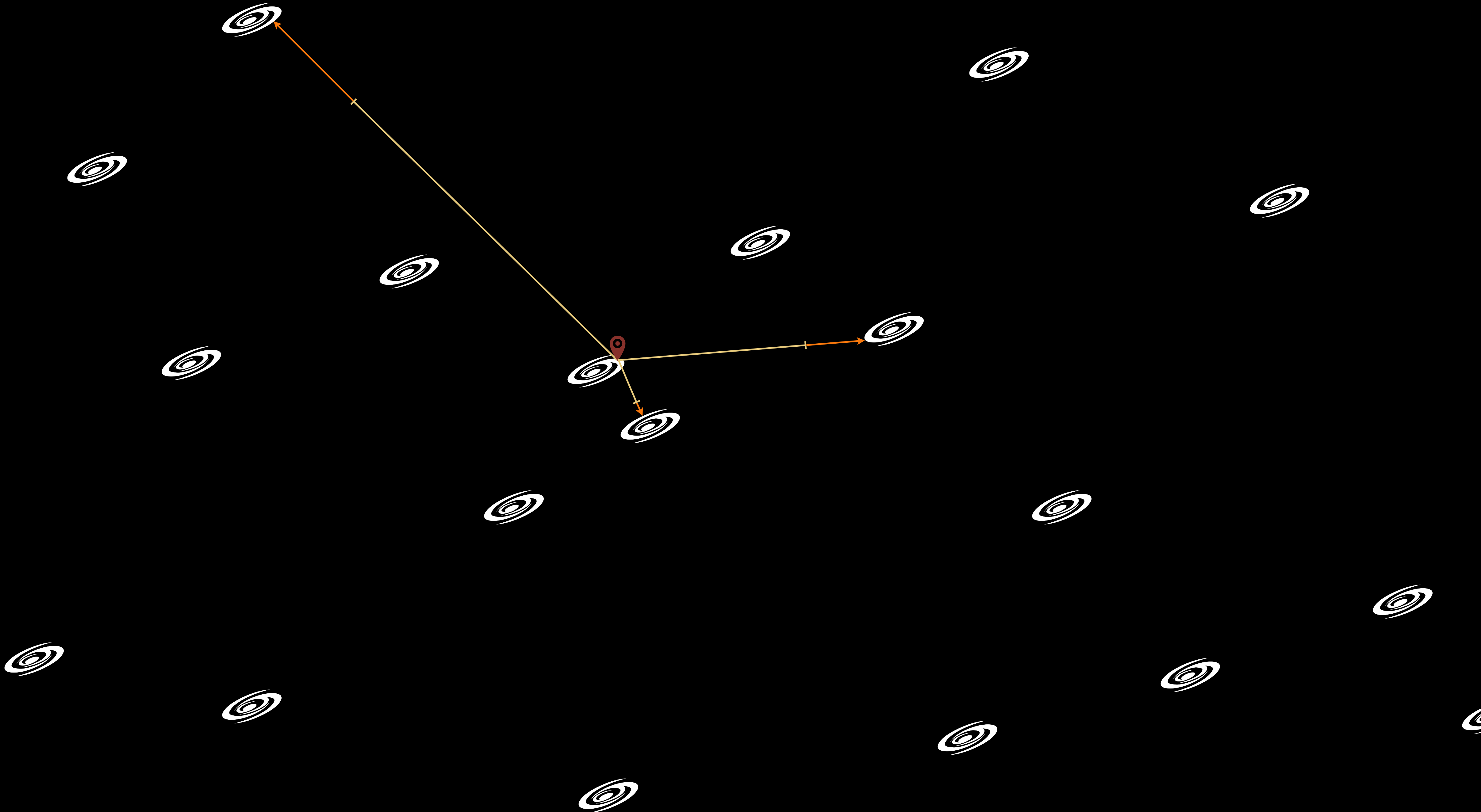
Vitesse d'éloignement

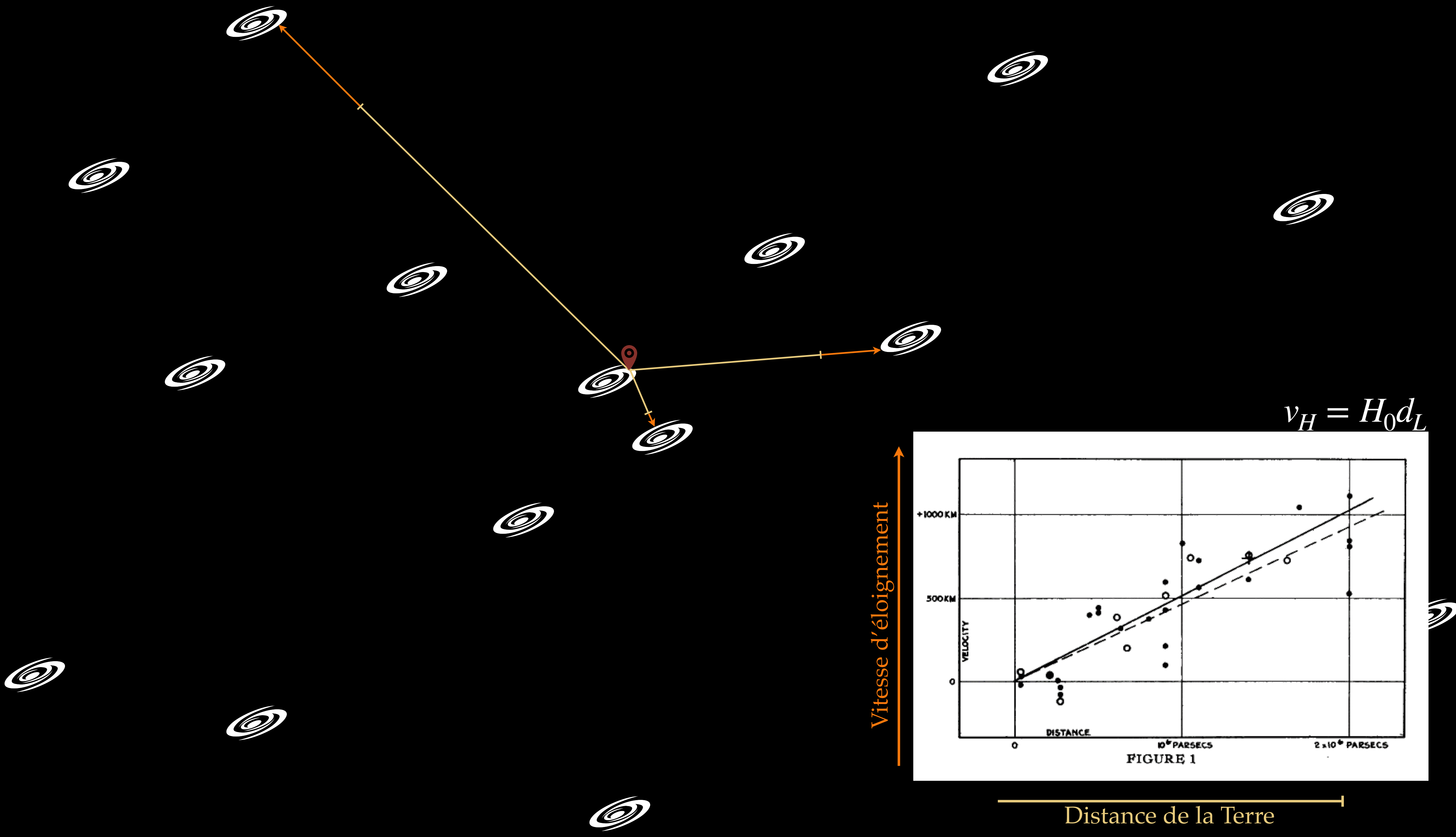
Distance de la Terre

Lemaître 1927

Hubble 1929







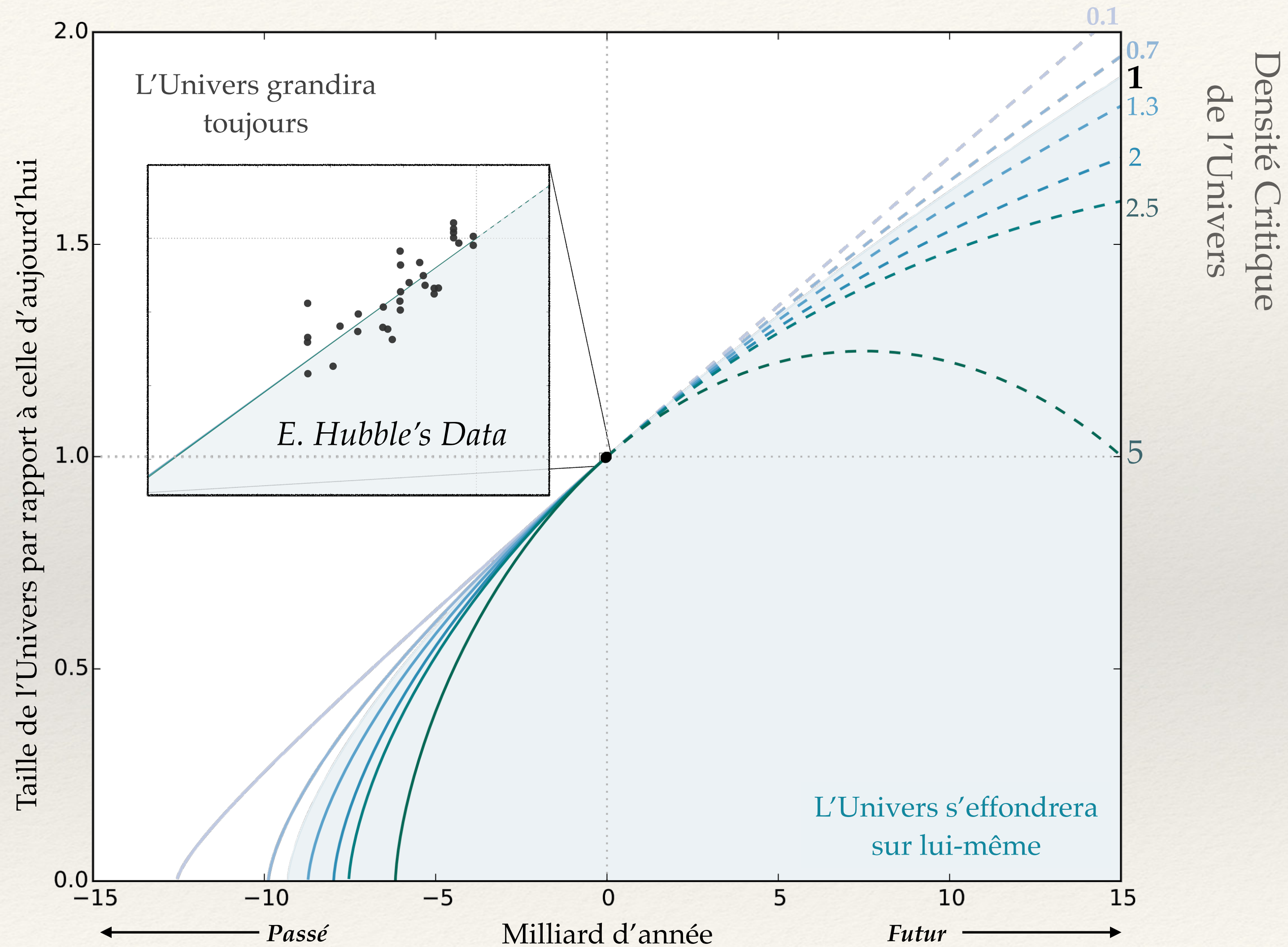
Vitesse d'éloignement

Distance de la Terre

$$v_H = H_0 d_L$$

FIGURE 1

# Prévoir du destin de l'Univers





Expansion rate of the Universe

$$H^2(z) = \frac{8\pi G}{3} \rho_m + \frac{8\pi G}{3} \rho_r - \frac{kc^2}{a^2}$$

**Matter (non-relativistics)**  
baryons / dark matter

**Radiation (relativistics)**  
photons / neutrinos

Curvature of the Universe

$$\rho_M \propto a^{-3}$$

Pure dilution ( $N/V$ )

$$\rho_R \propto a^{-4}$$

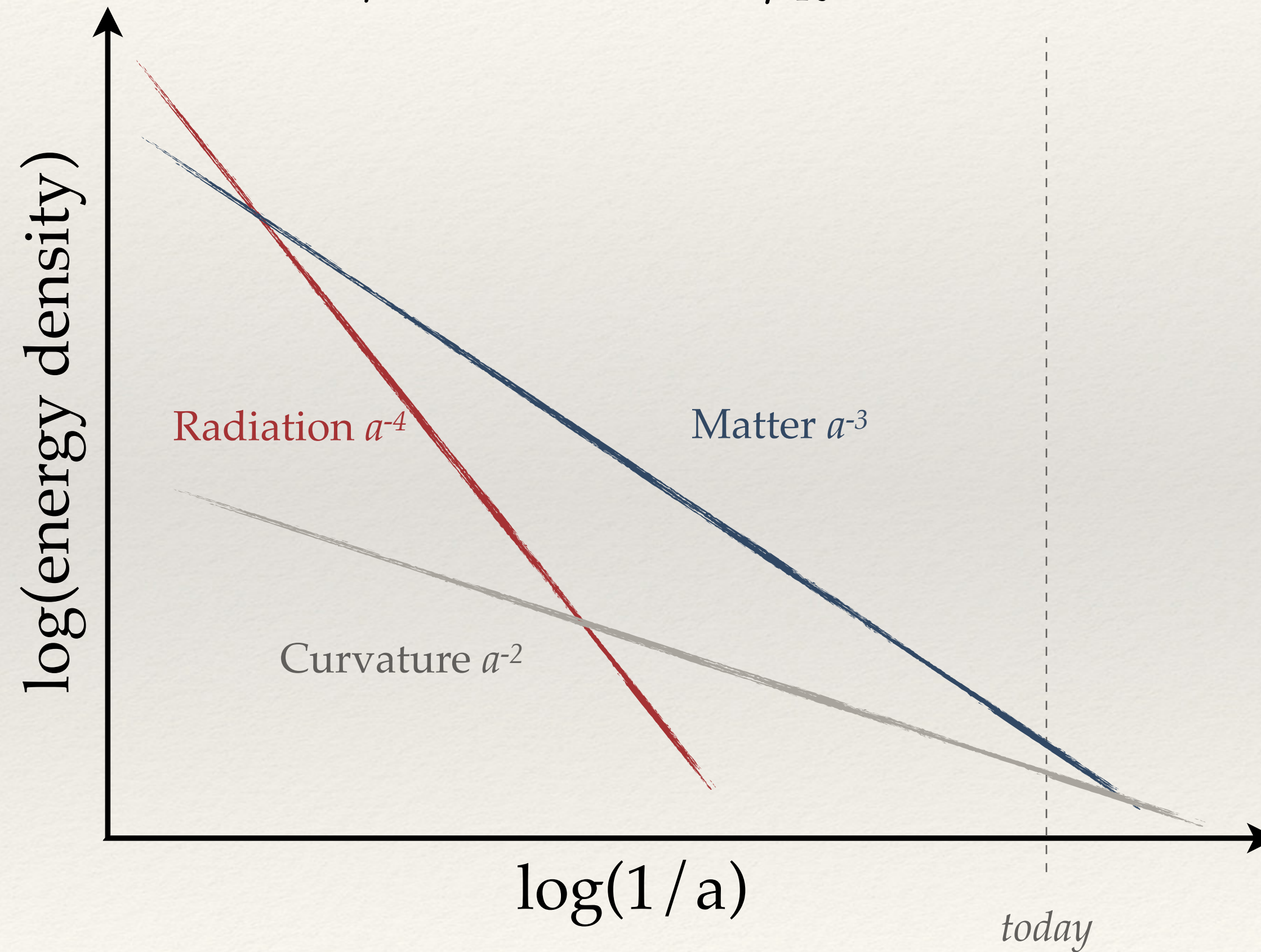
dilution of particles ( $N/V$ )  
& of energy ( $E=hv$ )

$$\propto a^{-2}$$

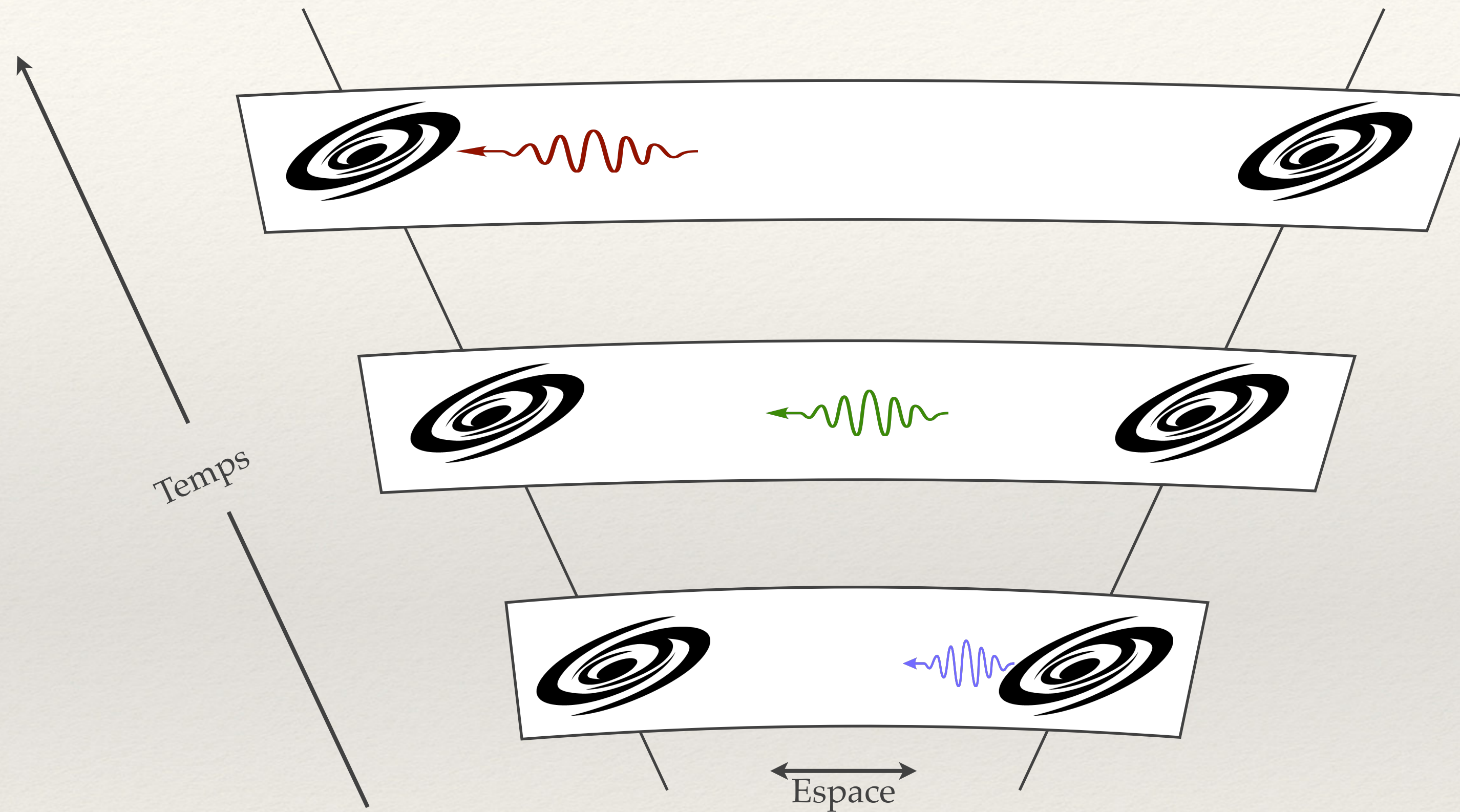
## Expansion rate of the Universe

$$H^2(z) = \frac{8\pi G}{3} \rho_m + \frac{8\pi G}{3} \rho_r - \frac{kc^2}{a^2}$$

$\rho_M \propto a^{-3}$        $\rho_R \propto a^{-4}$        $\propto a^{-2}$



# Le “Redshift” trace l’expansion de l’Univers



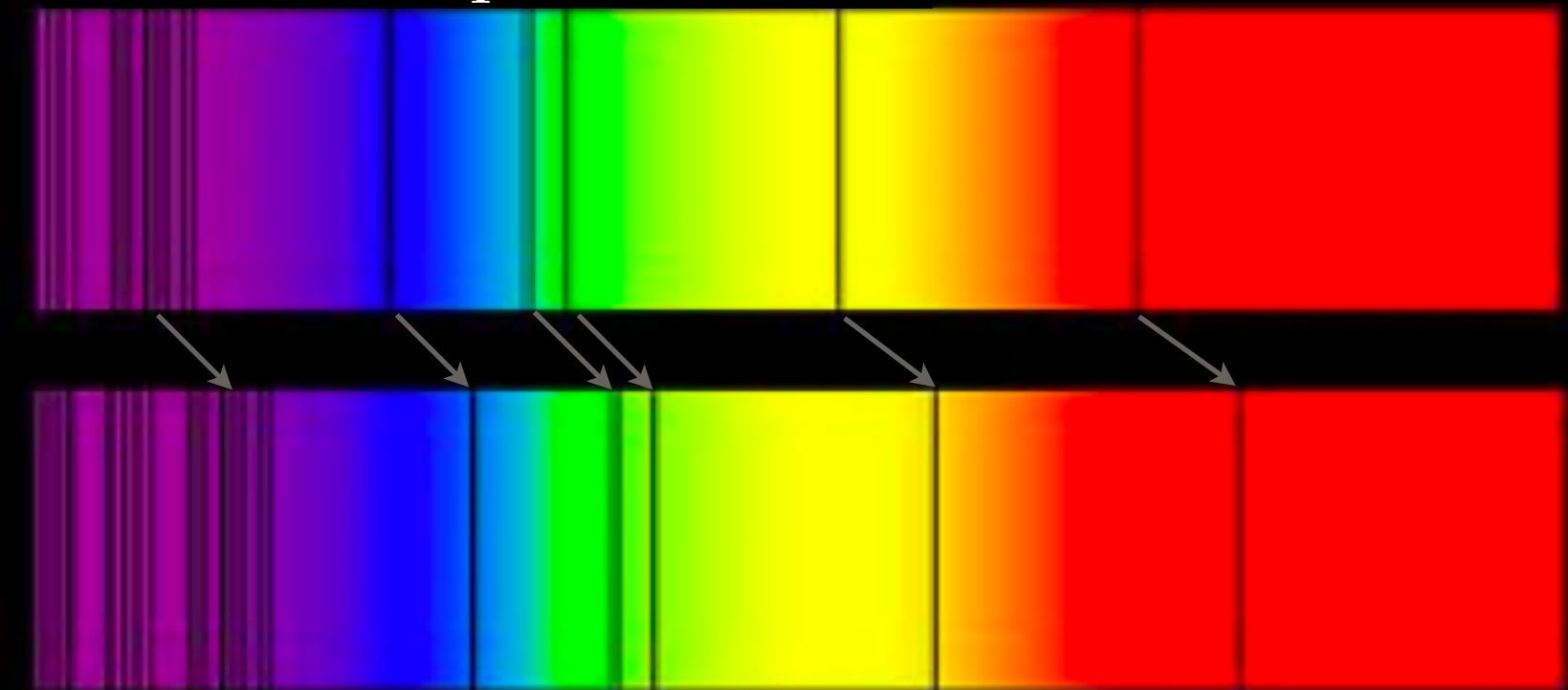
*L’expansion géométrique de l’Univers étire les photons*



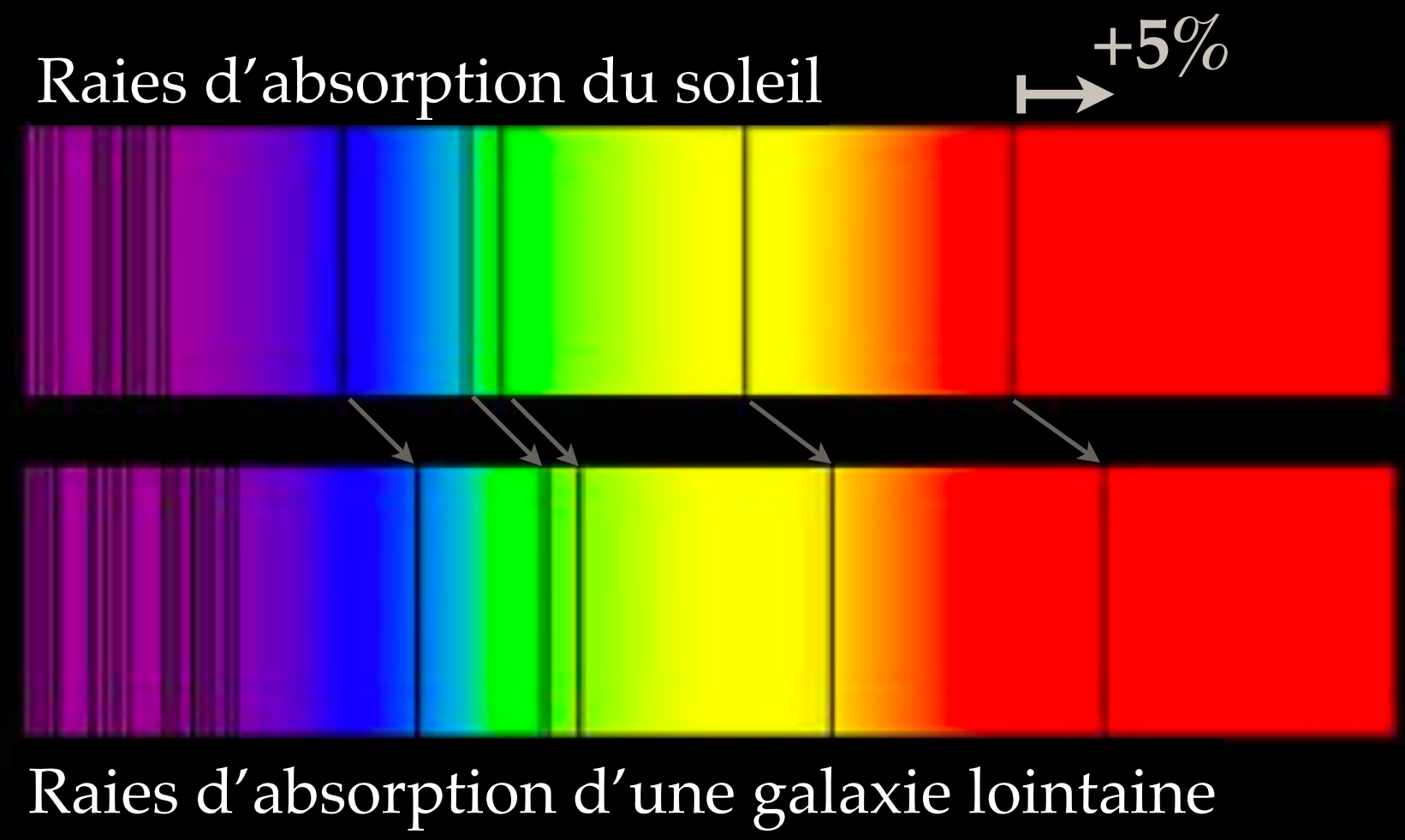
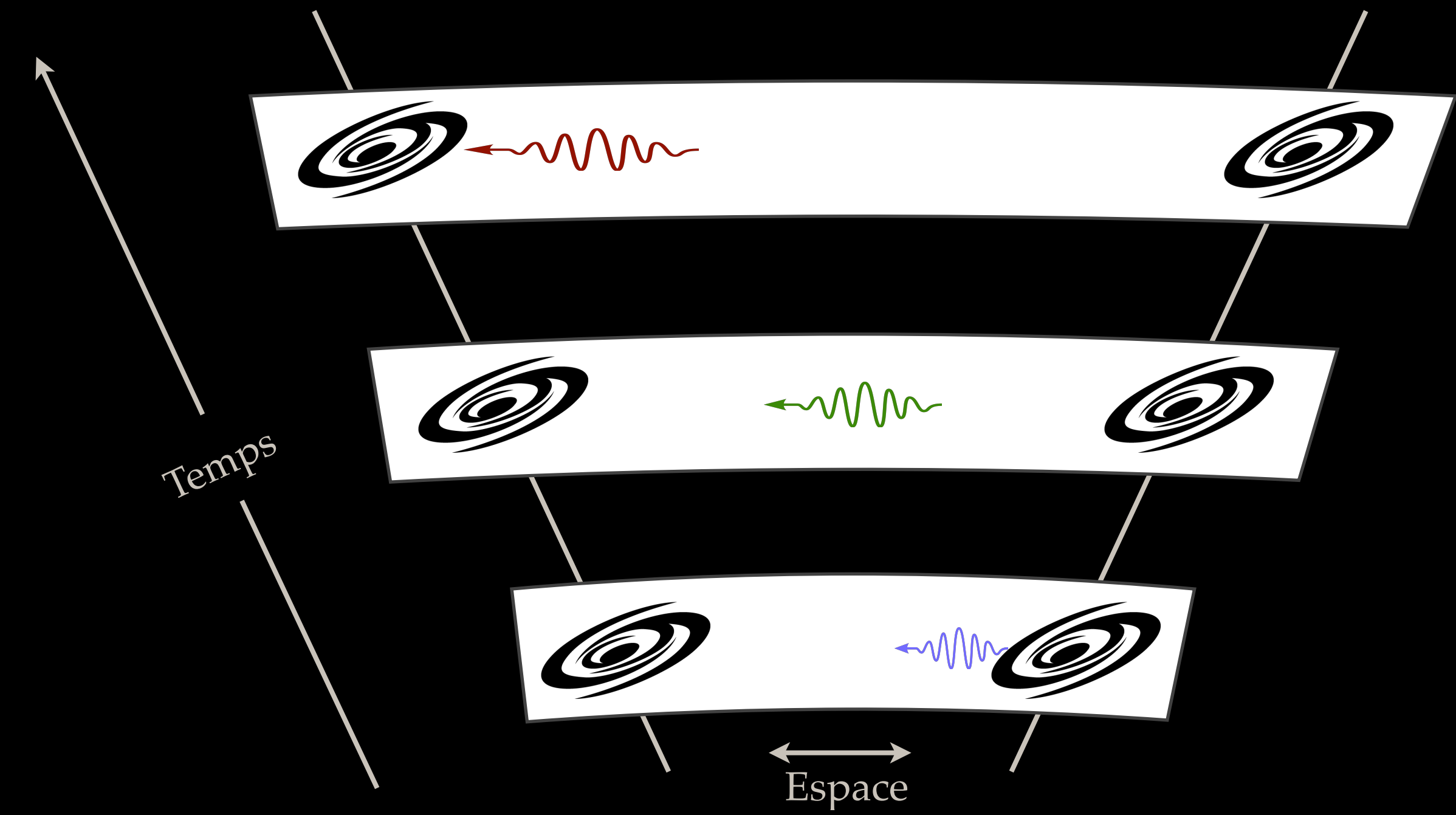
E. Hubble



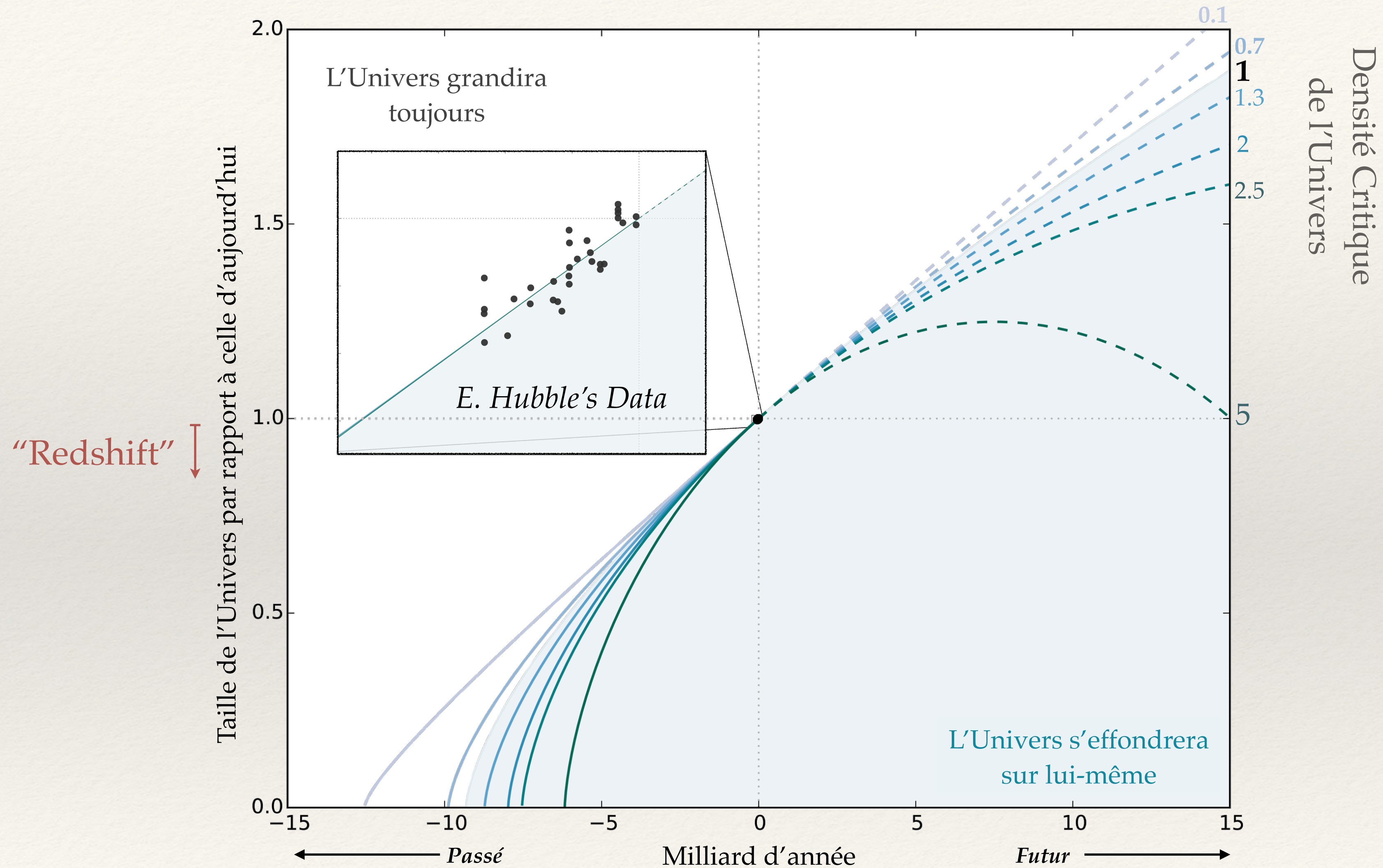
Raies d'absorption du soleil



Raies d'absorption d'une galaxie lointaine



# Prévoir du destin de l'Univers



# Chandelle Standard

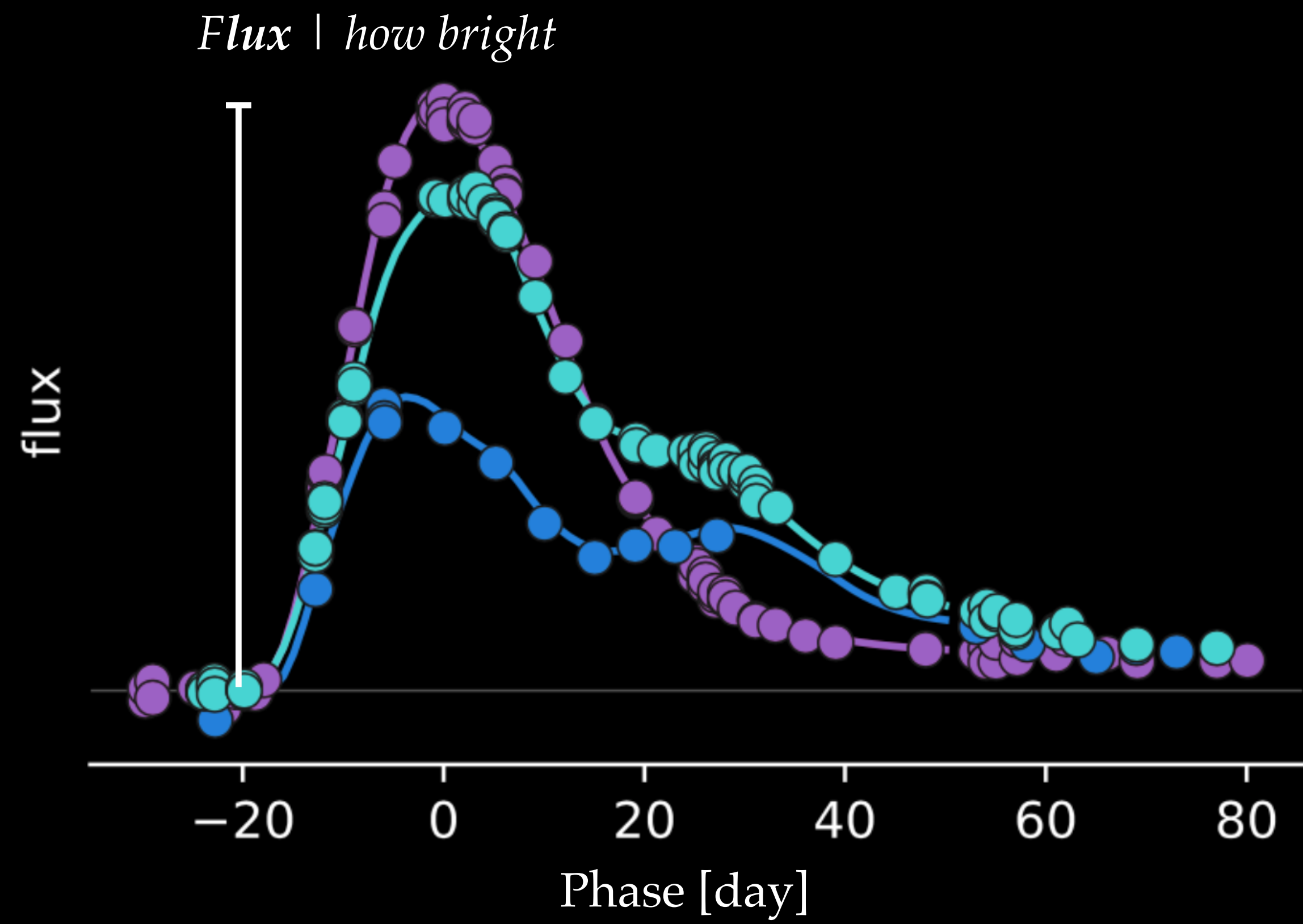
*Flux*  $\Leftrightarrow$  *Distance*  $f = \frac{L}{4\pi d_L^2}$



Supernova de Type Ia  
*aussi brillante qu'une galaxie*





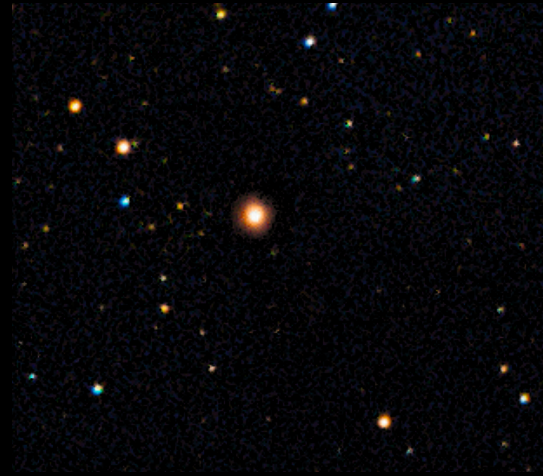


# Le Soleil



8 minutes

# L'étoile la plus proche



4 ans

# La galaxie la plus proche



150 000 ans

# Le groupe de galaxies le plus proche



60 millions d'années

# Les galaxies lointaines

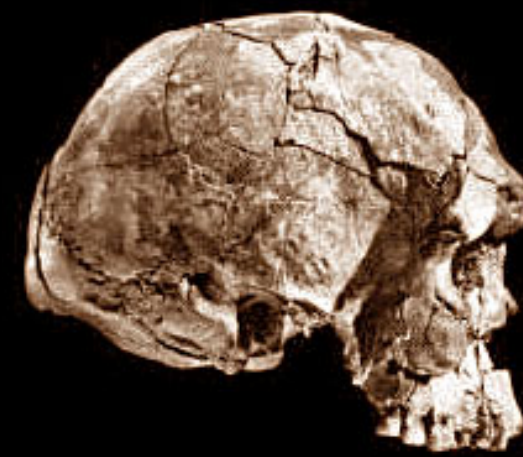
SCP15C03



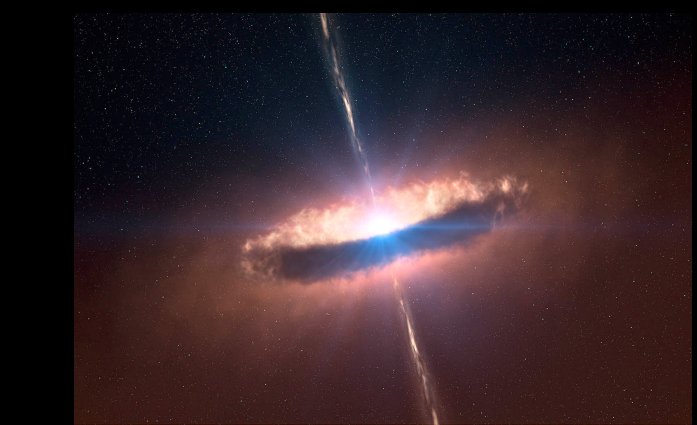
z~1.24

8 milliards d'années

*Mai 2020:*  
Levé progressive du confinement (11 / 05 / 202)  
UK sorti de l'UE



*Homo-sapiens*

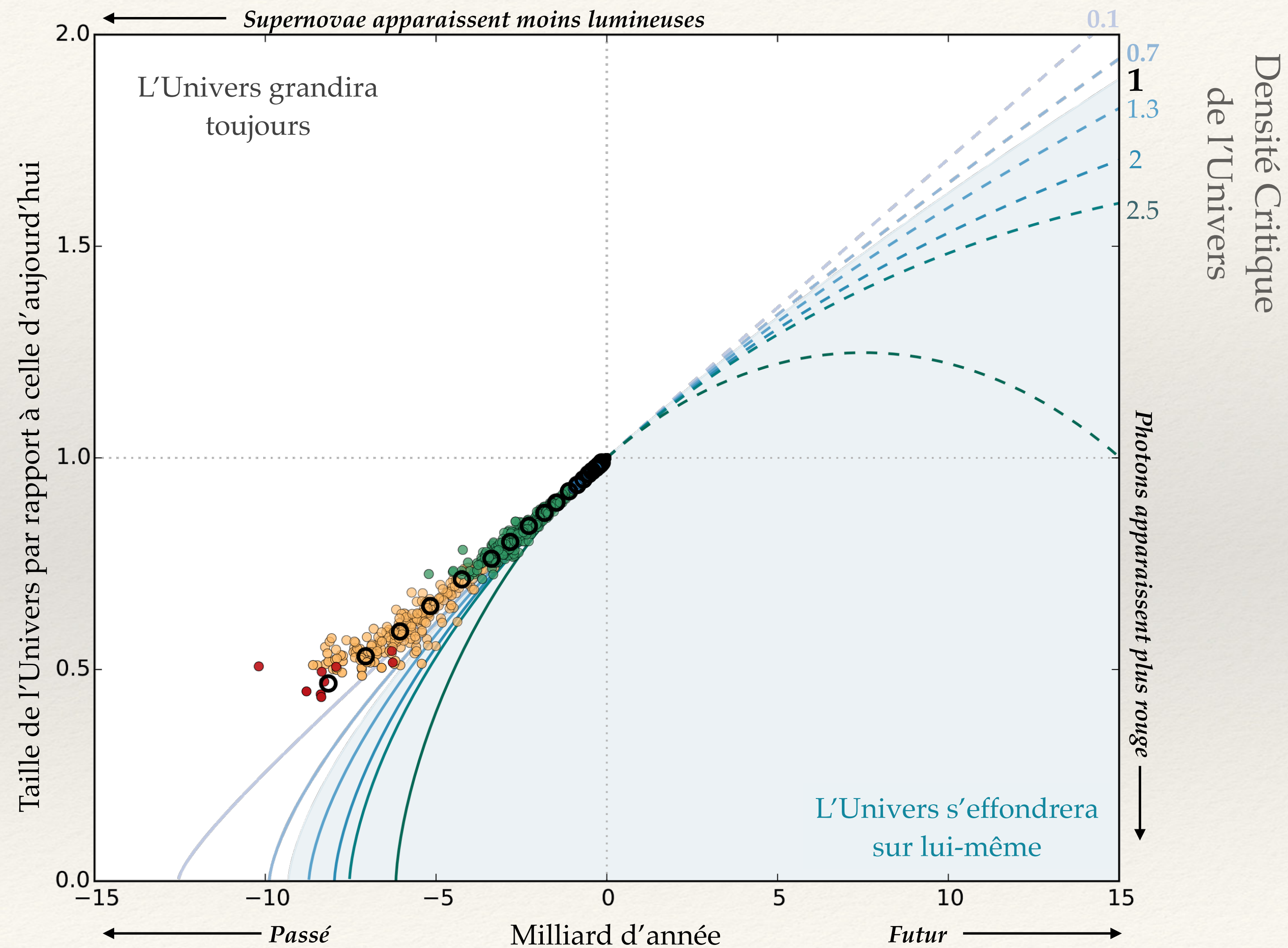


*Formation système solaire*



**Artist's Concept**

# Mais quelque chose ne marche pas...



*Einstein's equation*

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

the divergence of  $g_{\mu\nu}$  is also null :  $\frac{\partial g_{\mu\nu}}{\partial x^\mu} = 0$

*Einstein's equation*

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

Which is equivalent to:  $R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu} - \Lambda g_{\mu\nu}$

the divergence of  $g_{\mu\nu}$  is also null :  $\frac{\partial g_{\mu\nu}}{\partial x^\mu} = 0$

*Einstein's equation*

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

This works, but it affects the Newtonian limit:

$$\vec{F}_g = -\frac{GM}{r^2}\vec{u}_r + \frac{\Lambda c^2 r}{3}\vec{u}_r$$

*Repulsive force increasing  
with distance never  
observed in  
Newtonian gravitation*

# Theory

Expansion rate of the Universe

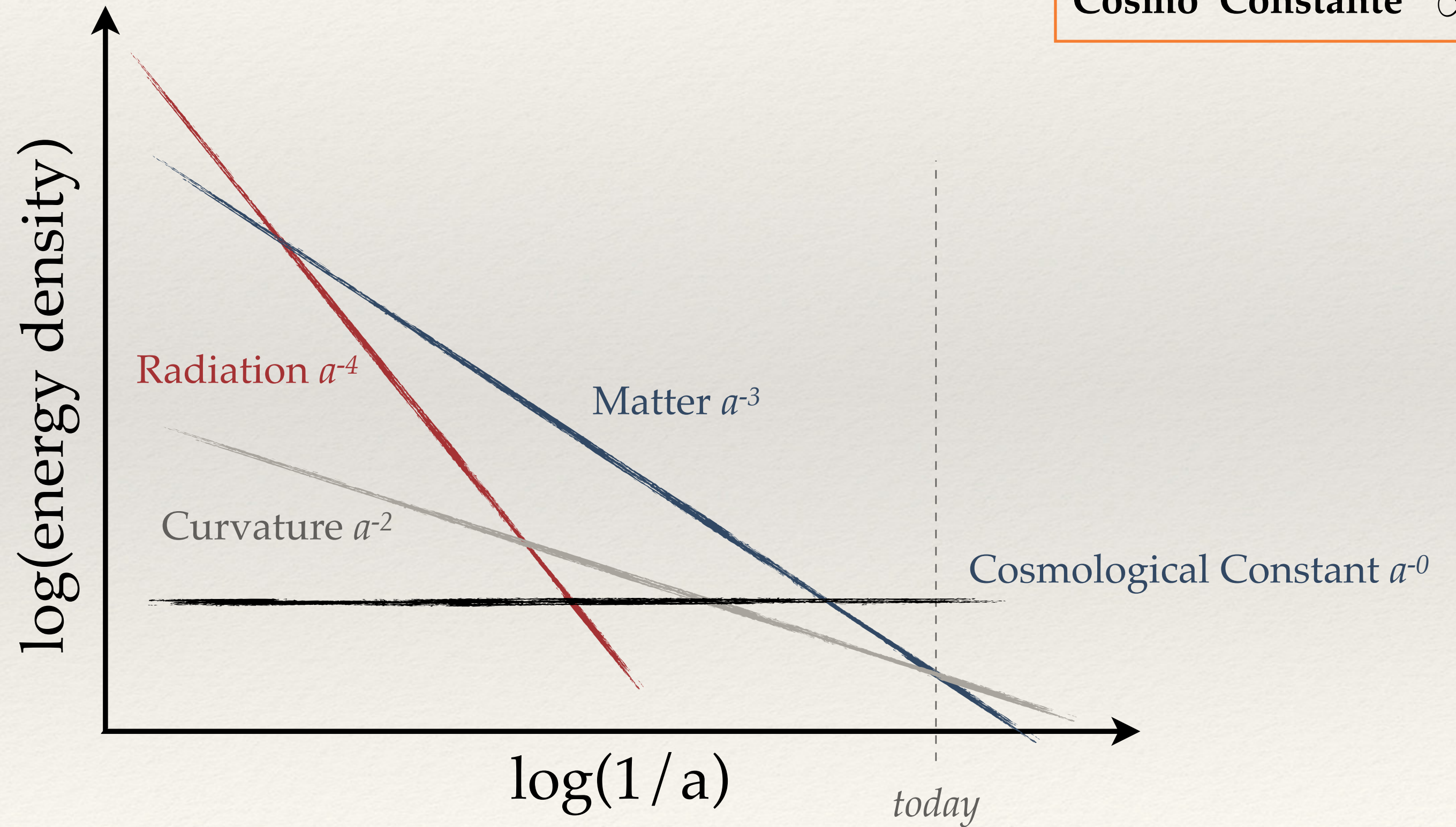
$$H^2(z) = \frac{8\pi G}{3}\rho_m + \frac{8\pi G}{3}\rho_r - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

$$\rho_M \propto a^{-3}$$

$$\rho_R \propto a^{-4}$$

$$\propto a^{-2}$$

$$\text{Cosmo Constante } \propto a^0$$





# Theory

Expansion rate of the Universe

$$\rho_M \propto a^{-3}$$

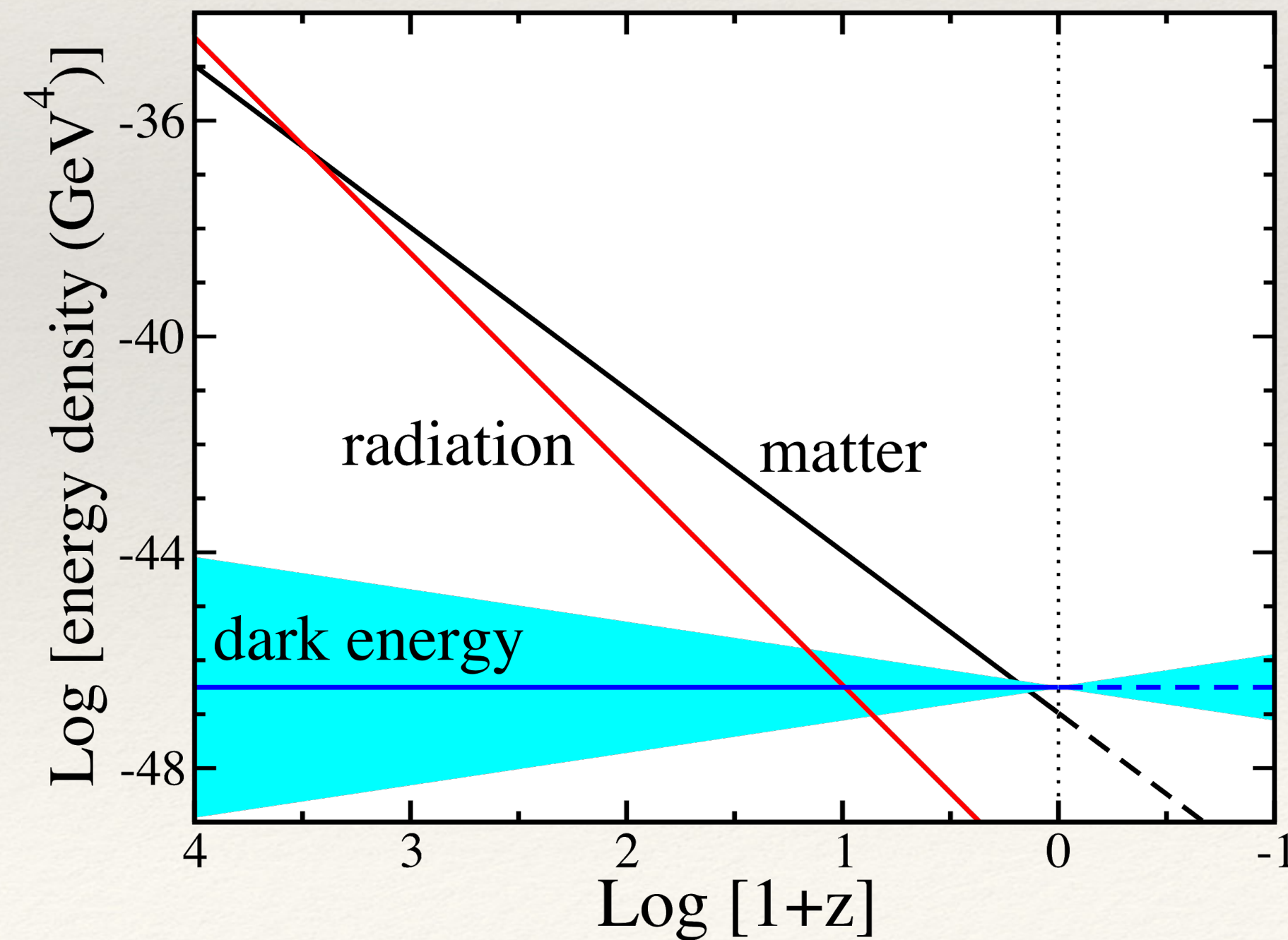
$$\rho_R \propto a^{-4}$$

$$\propto a^{-2}$$

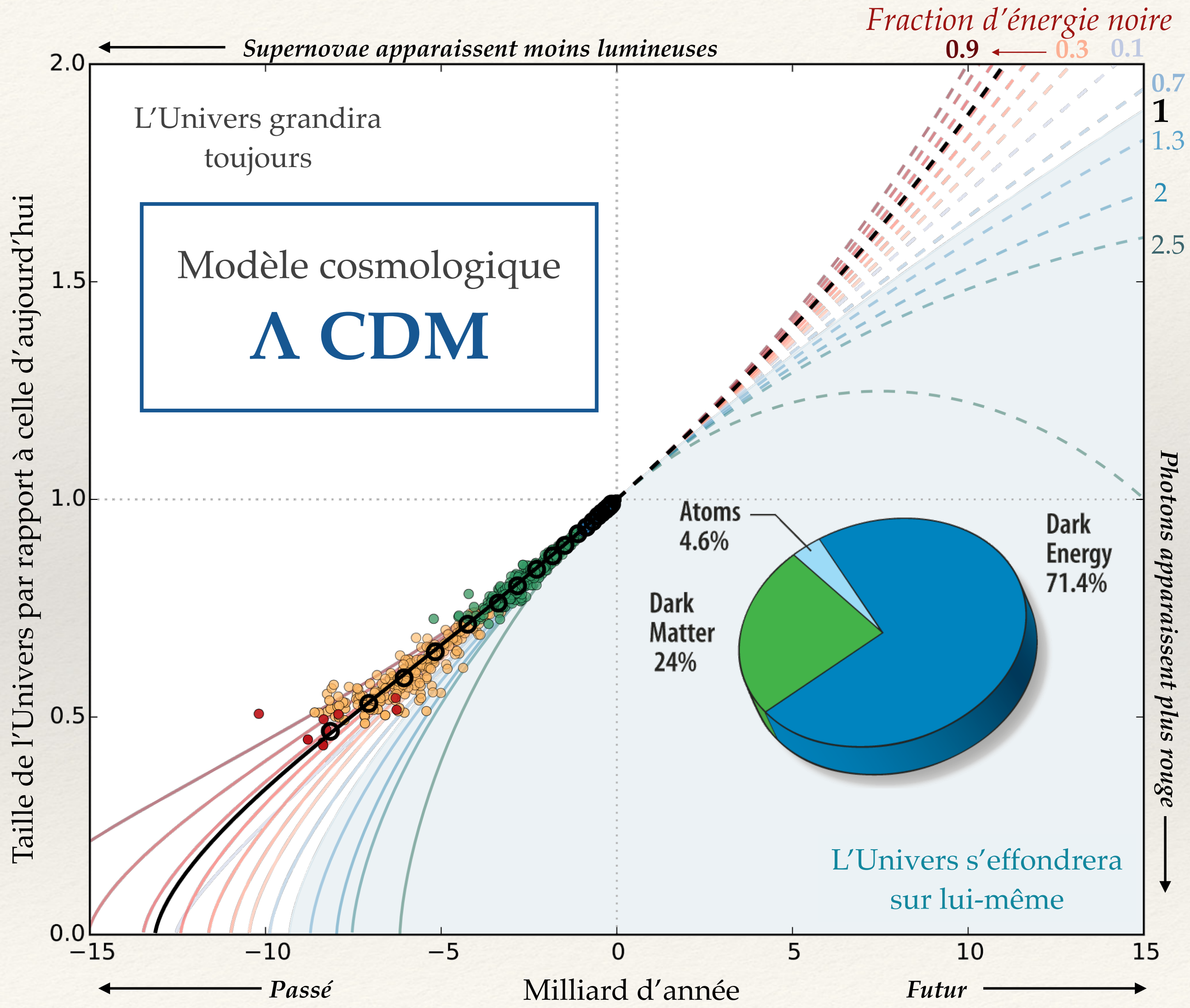
$$\text{Cosmo Constante } \propto a^0$$

$$H^2(z) = \frac{8\pi G}{3} \rho_m + \frac{8\pi G}{3} \rho_r - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

$$H(z) = H_0 \times \sqrt{\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)}}$$



# Découverte de l'énergie noire | 70% de l'Univers



Densité Critique de l'Univers



Prix Nobel 2011

# Le fond diffus cosmologique

*Discovered by chance in 1965*



Prix Nobel 1978



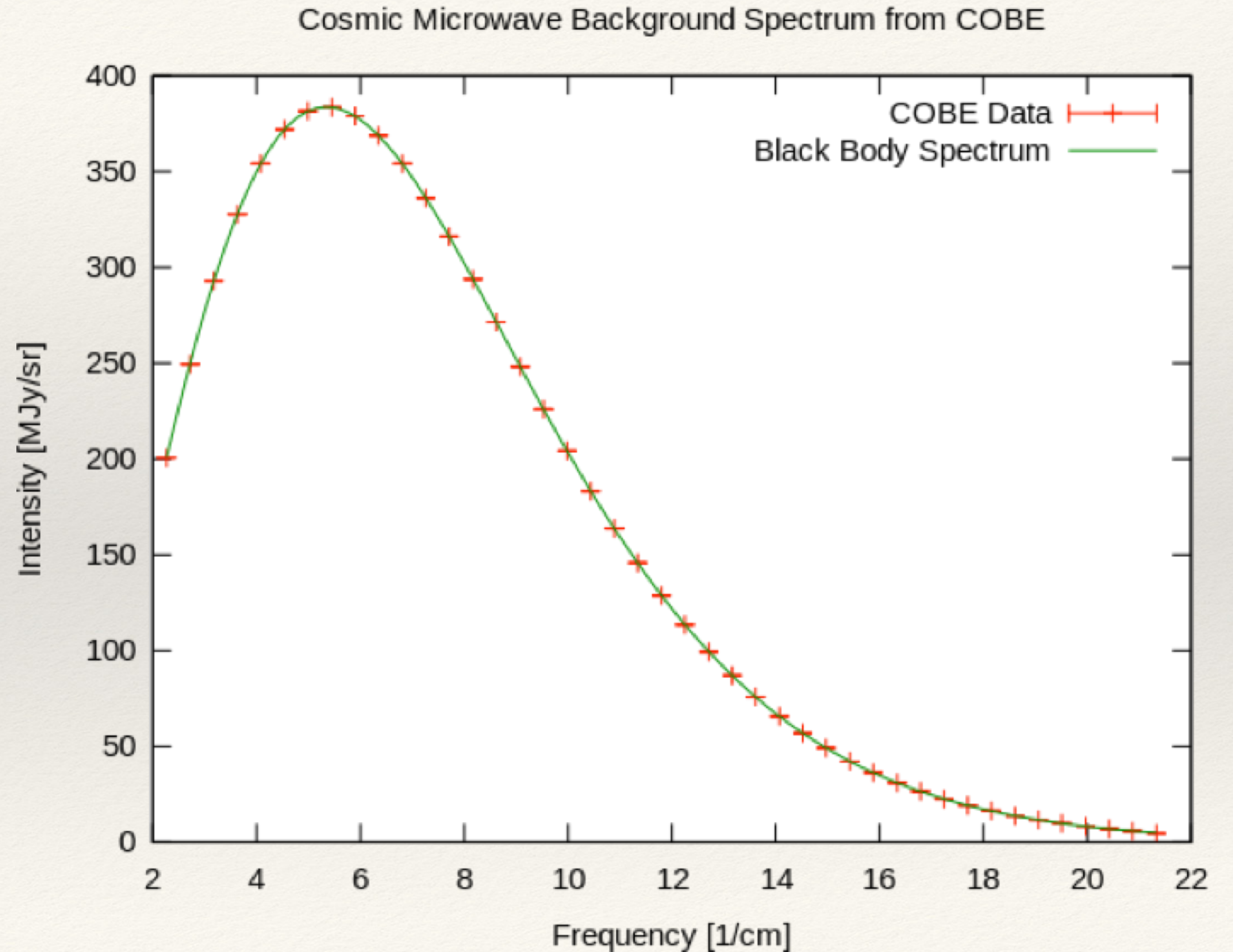
*Un signal quasi-uniforme  
Correspondant à un corps noir à 3 degré Kelvin  
(3000 K  $\Rightarrow$  3K à cause de l'expansion de l'Univers)*

# Cosmic Microwave Background

Discovered by chance in 1965 | Nobel 1978



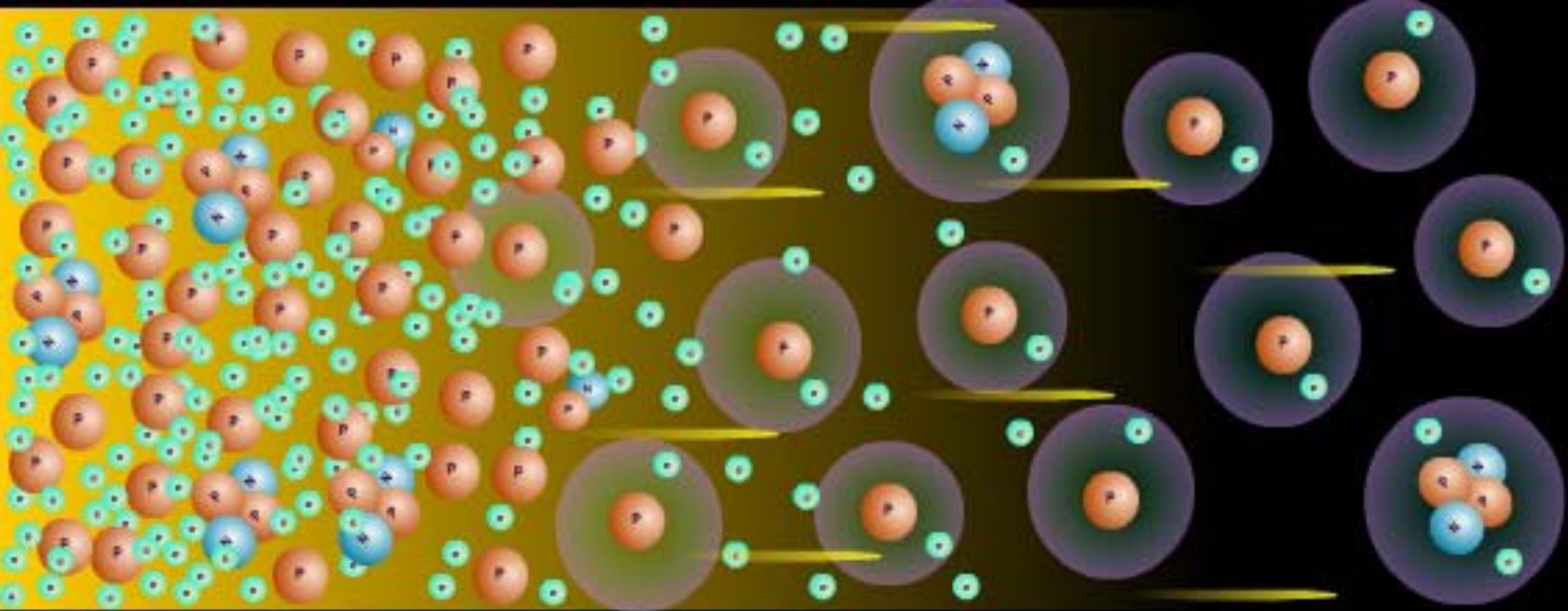
*Almost Uniform signal  
Corresponding to a 3k black body*



Ionized

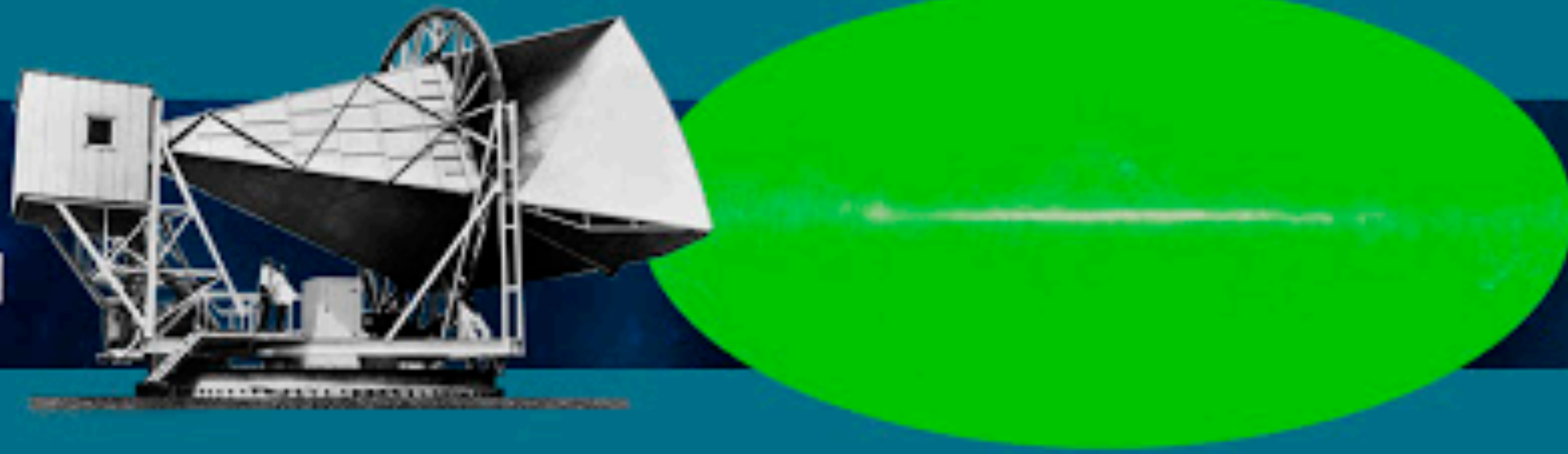
Recombination  
 $z \sim 1\,000$   
( $\sim 400\,000$  years)

Neutral

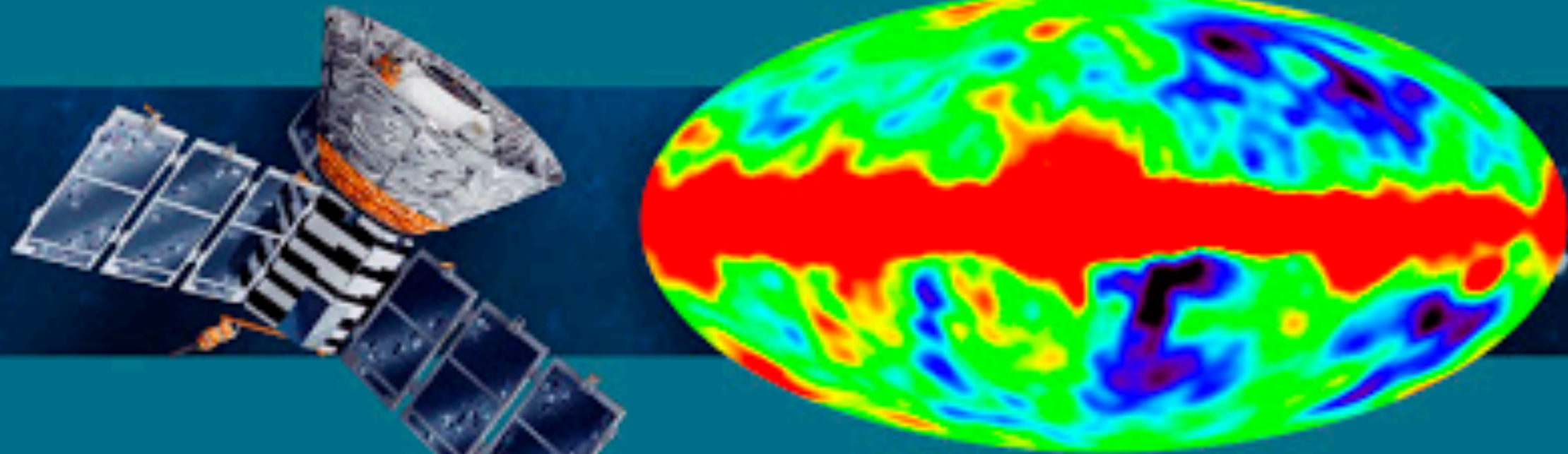


Time

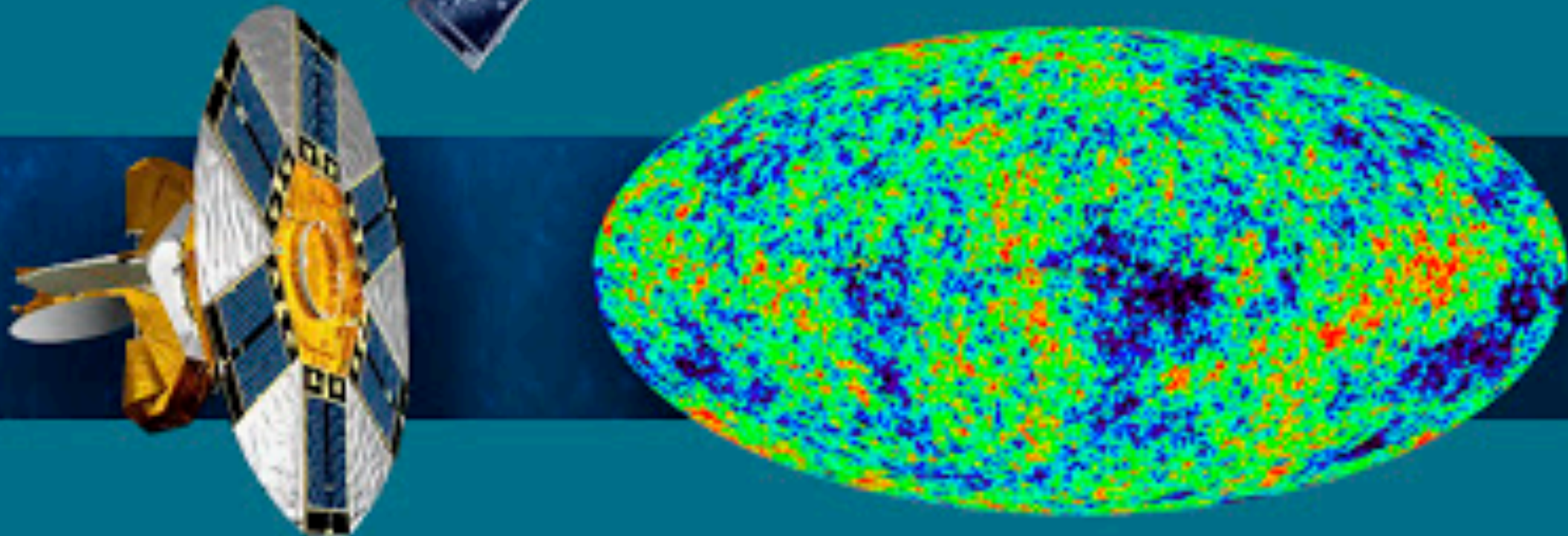
1962  
PENZIAS & WILSON



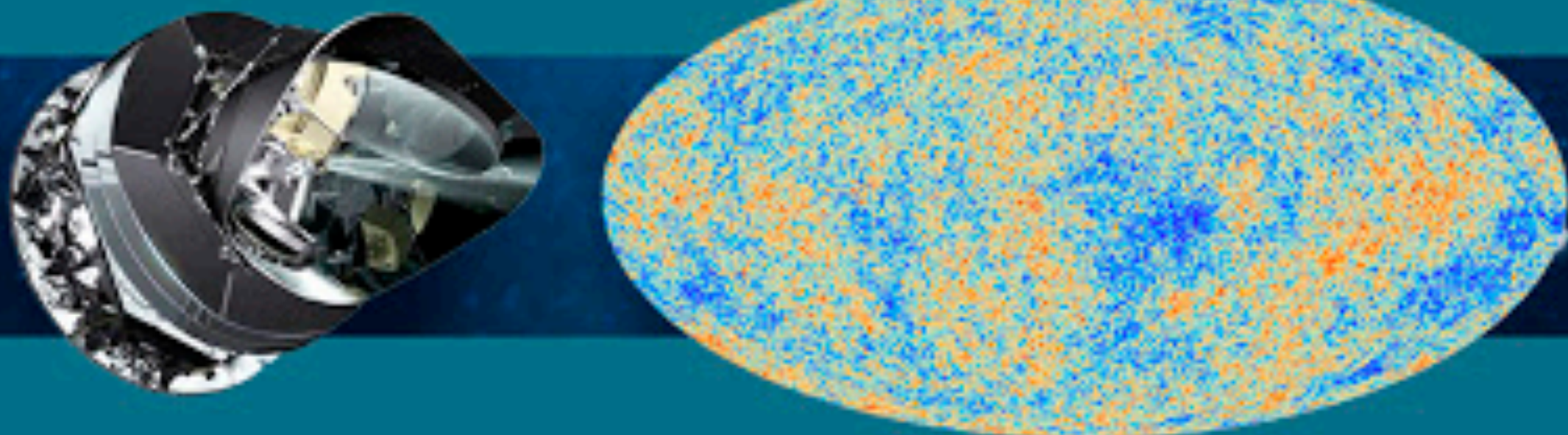
1989-1993  
COBE



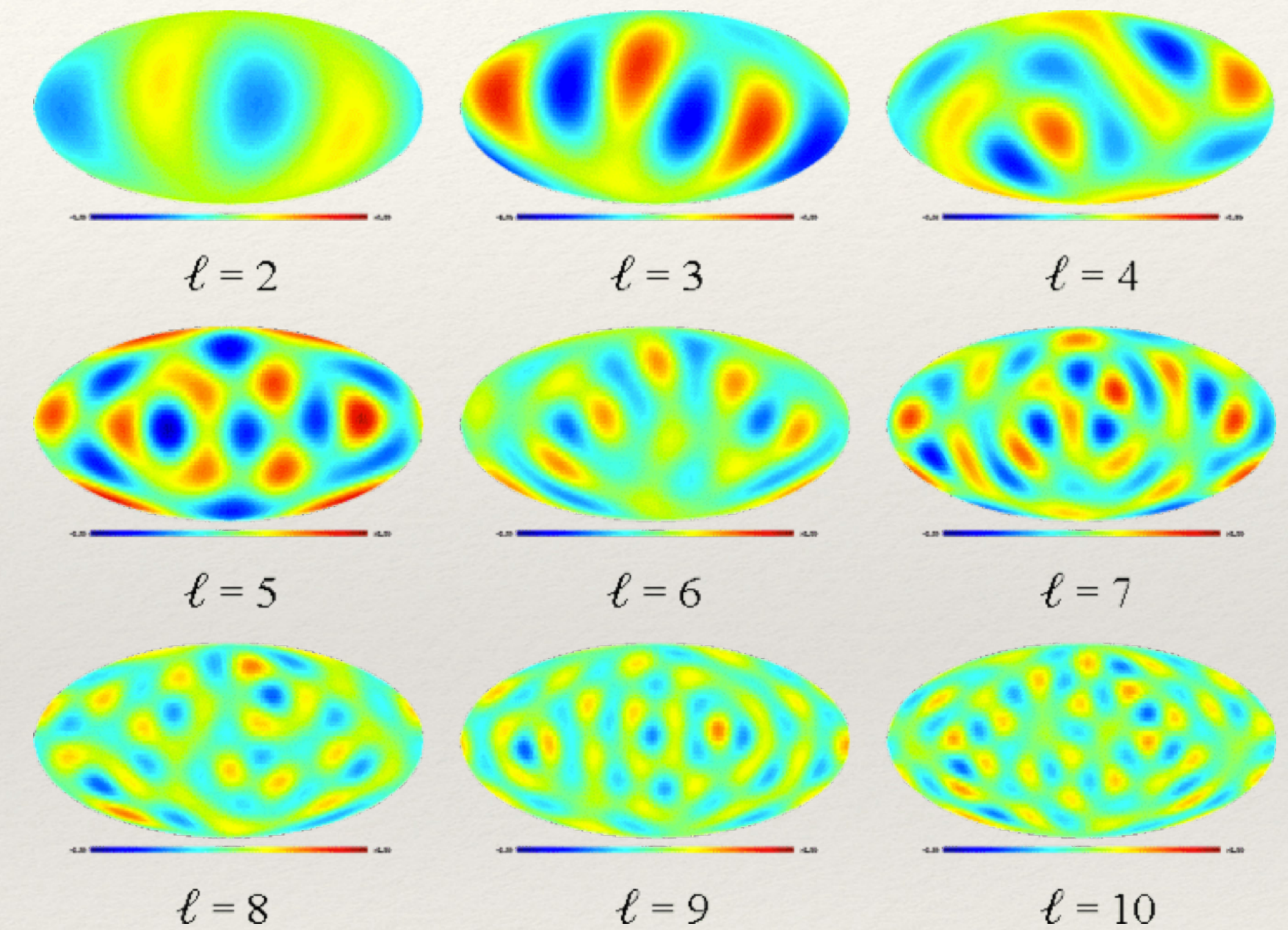
2001-2010  
WMAP



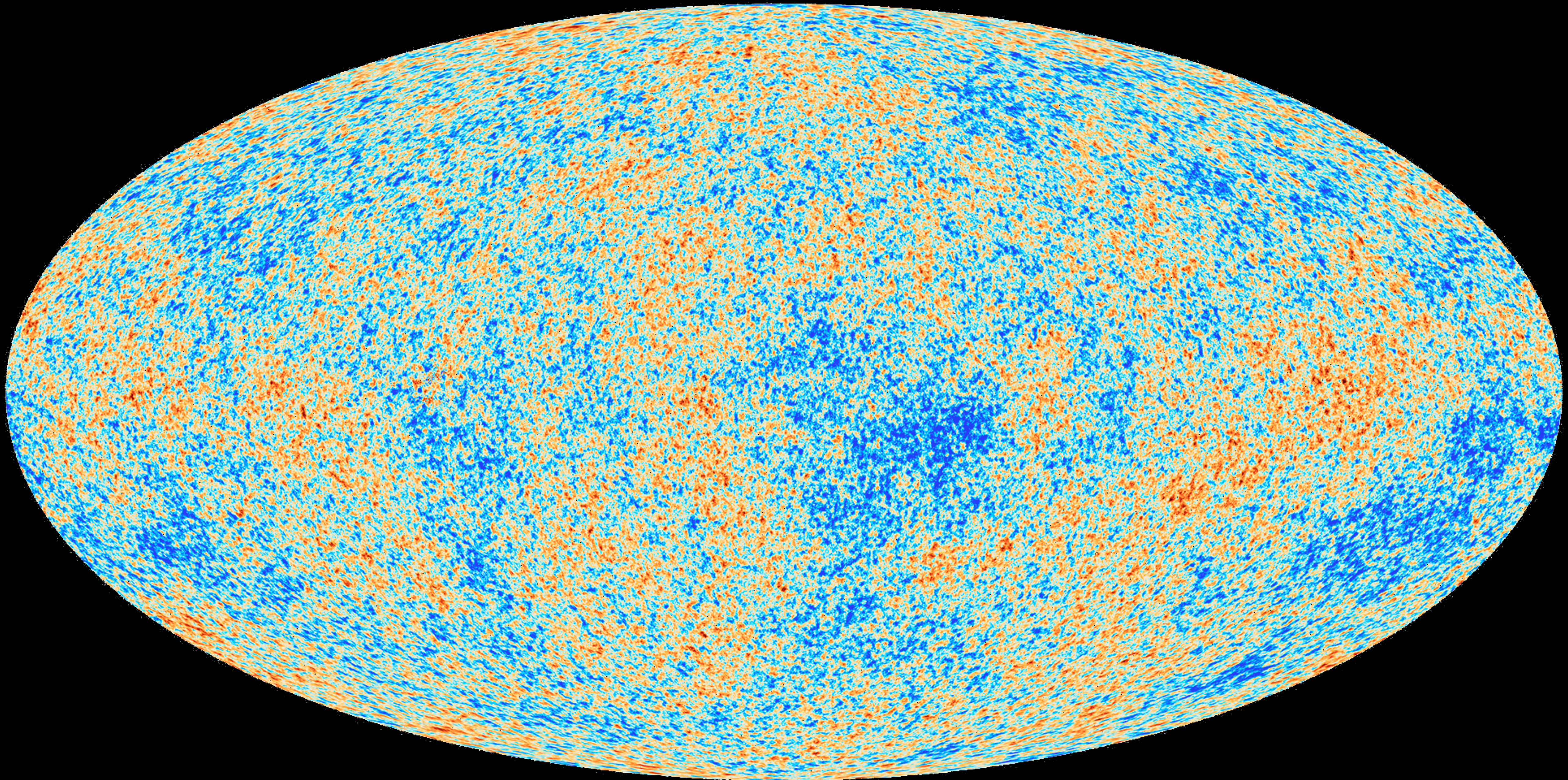
2009-2013  
PLANK

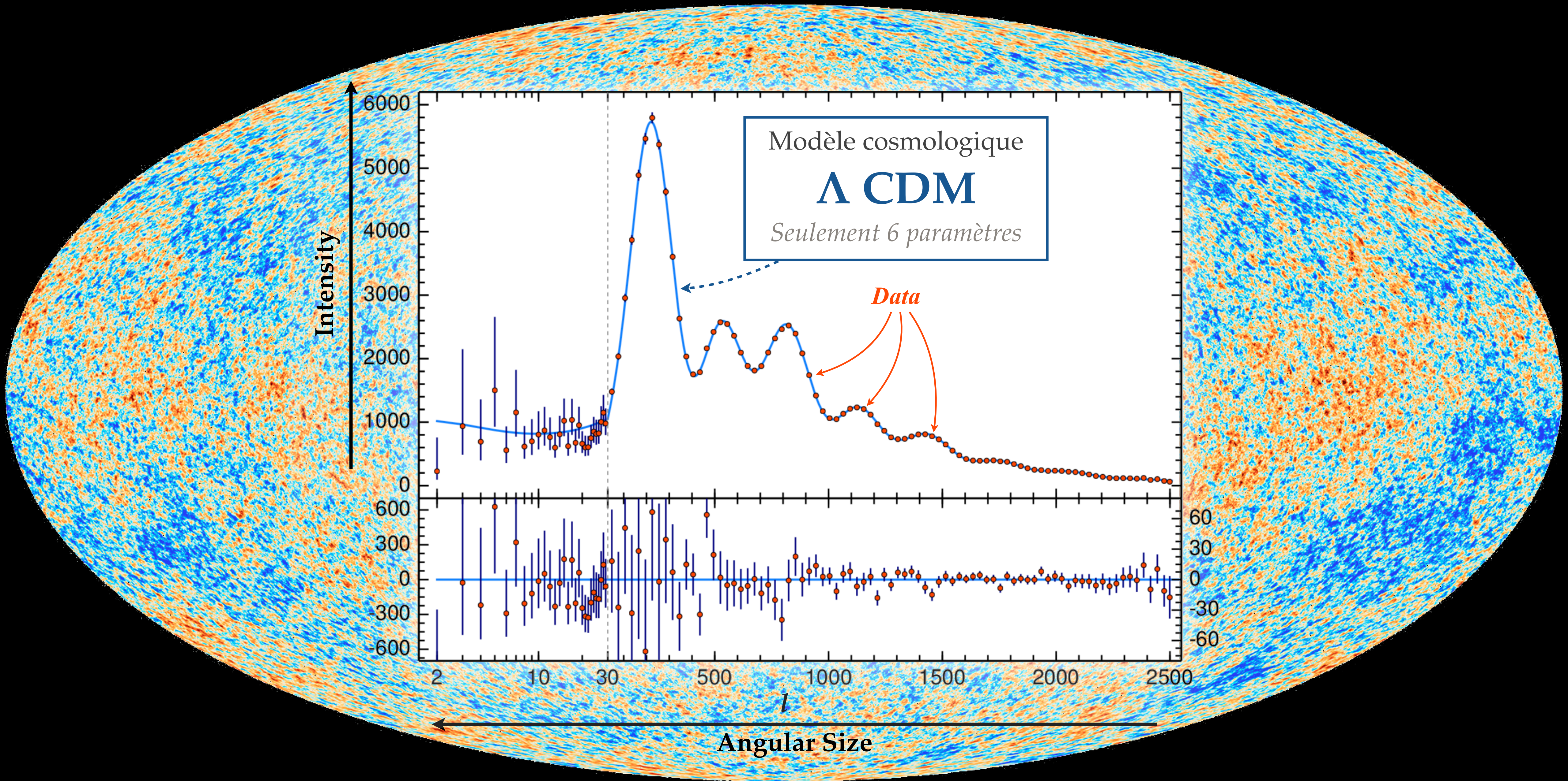


# Analyses des Anisotropies du Fond diffus cosmologique



*Spherical Harmonics Decomposition*

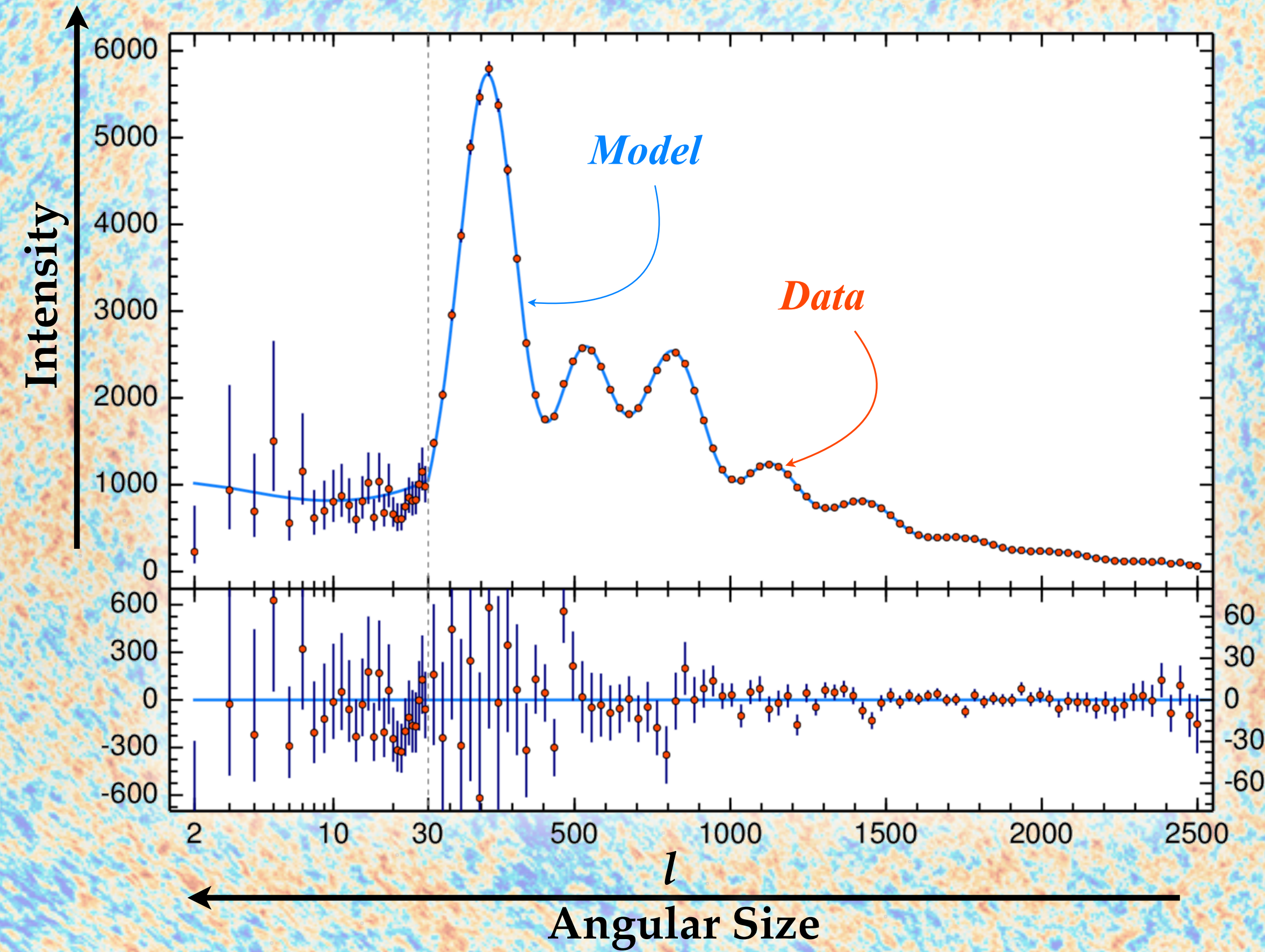




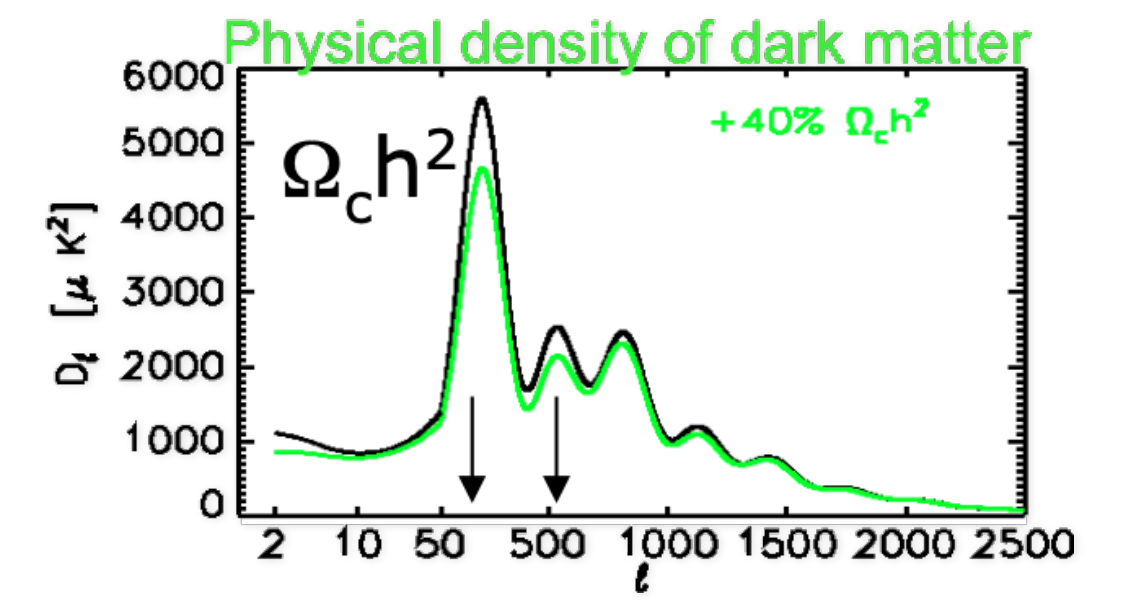
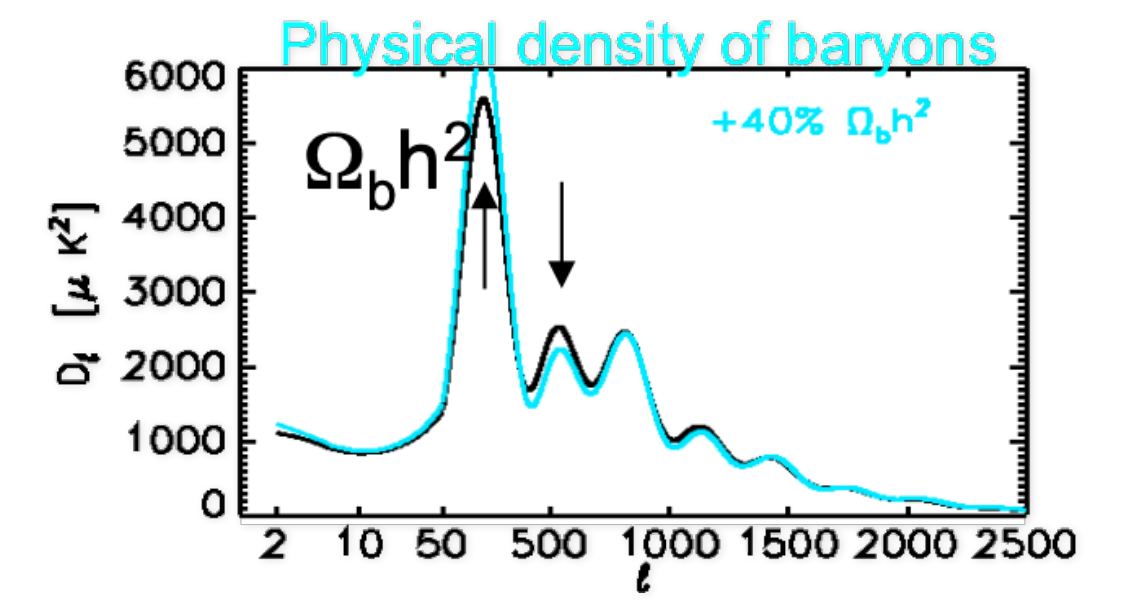
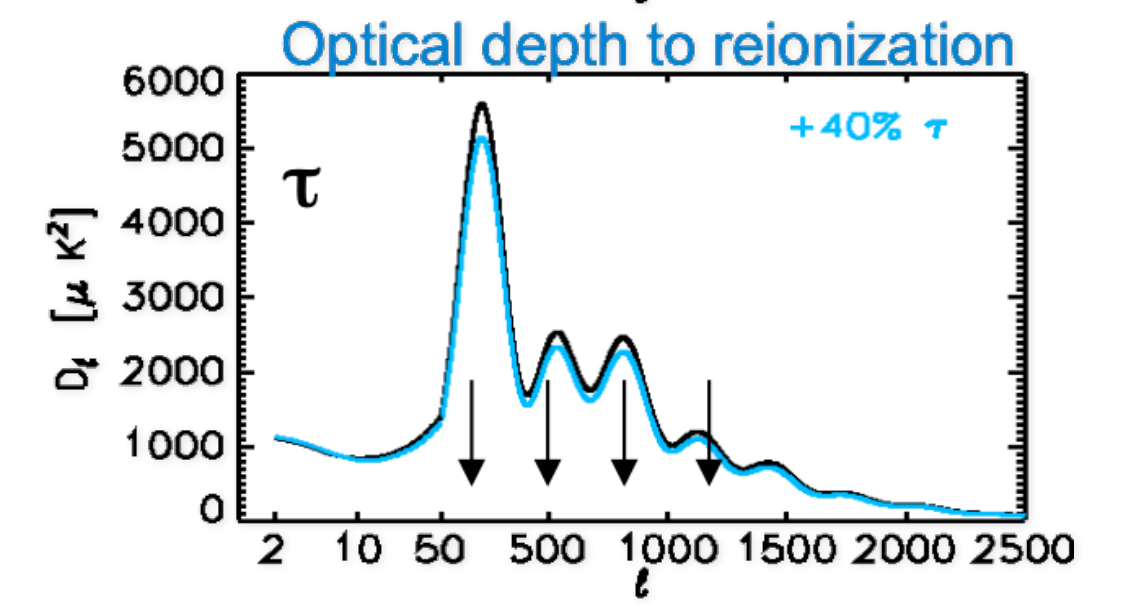
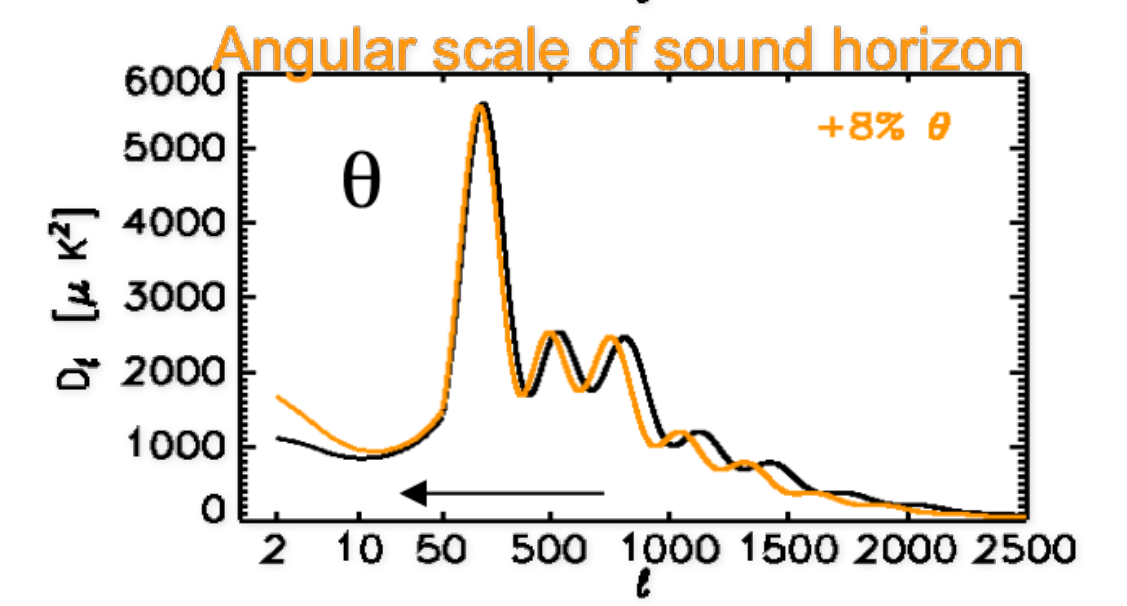
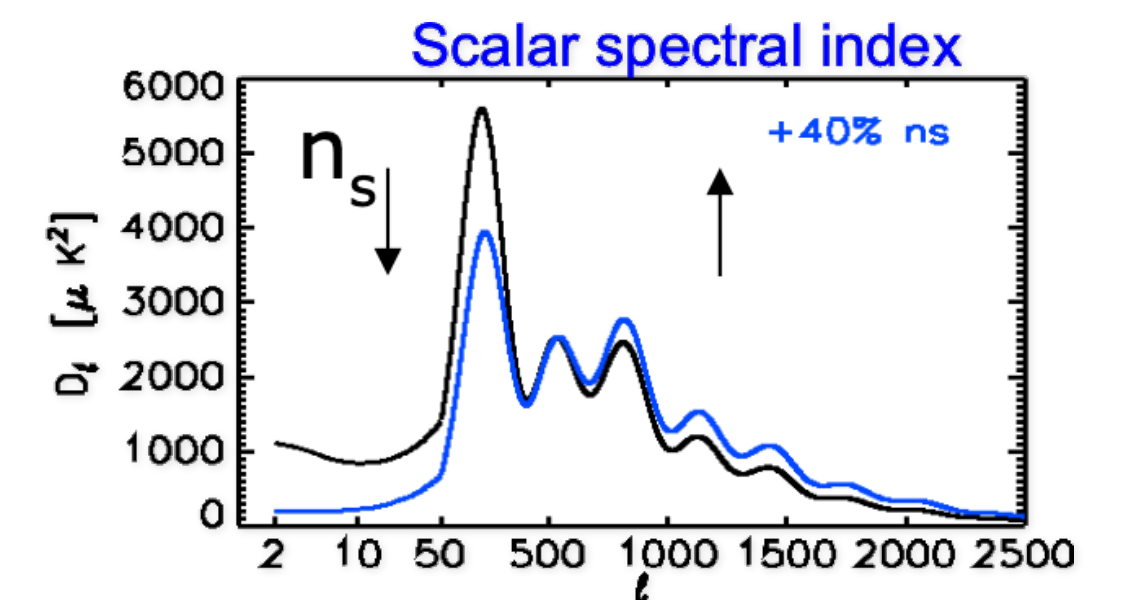
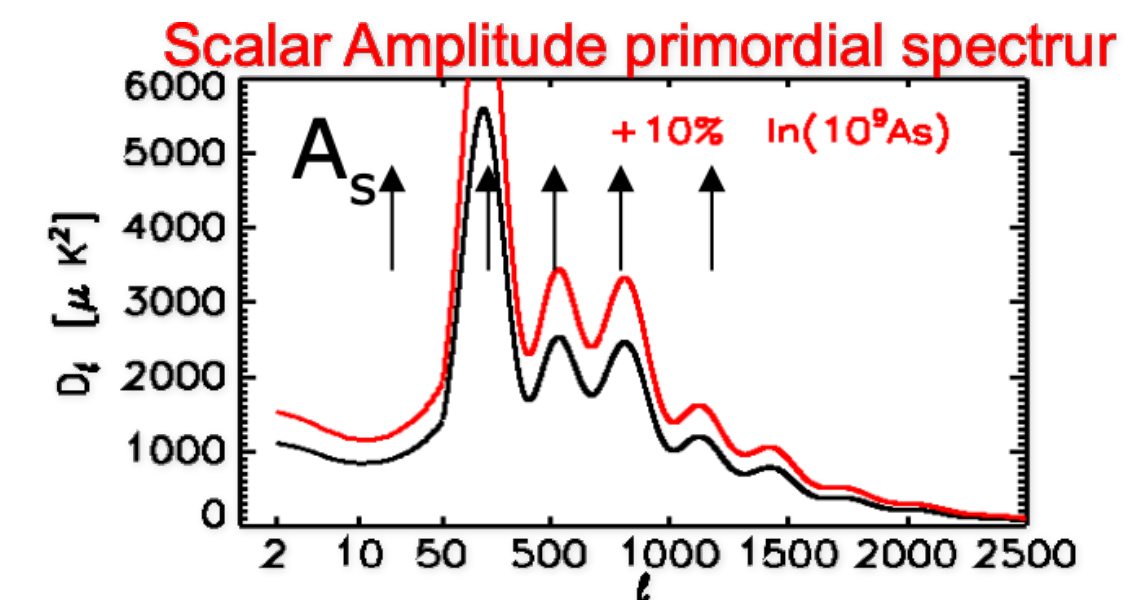


# Planck Results | 6 $\Lambda$ CDM Parameters

Credit: S. Galli | Planck Collaboration

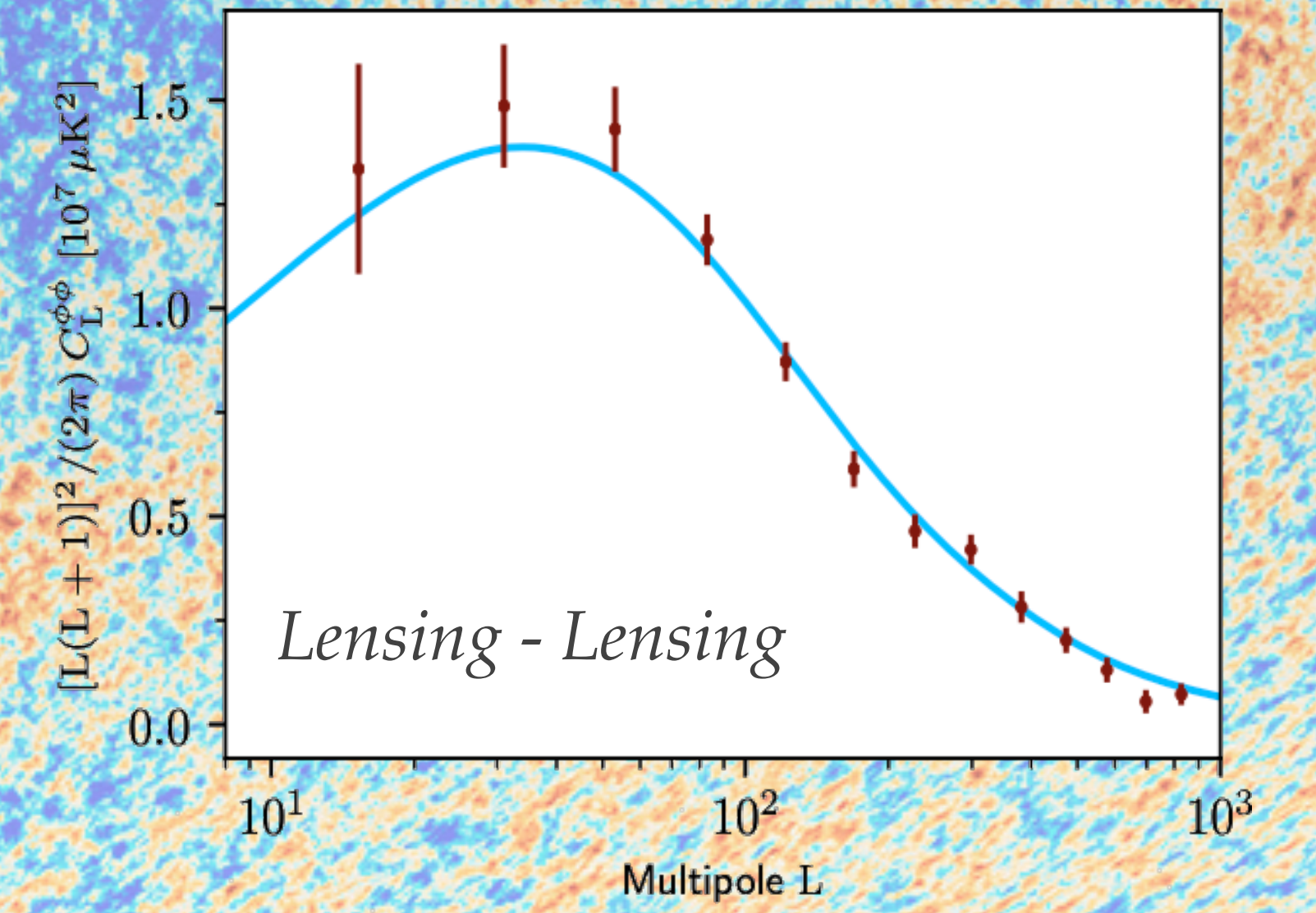
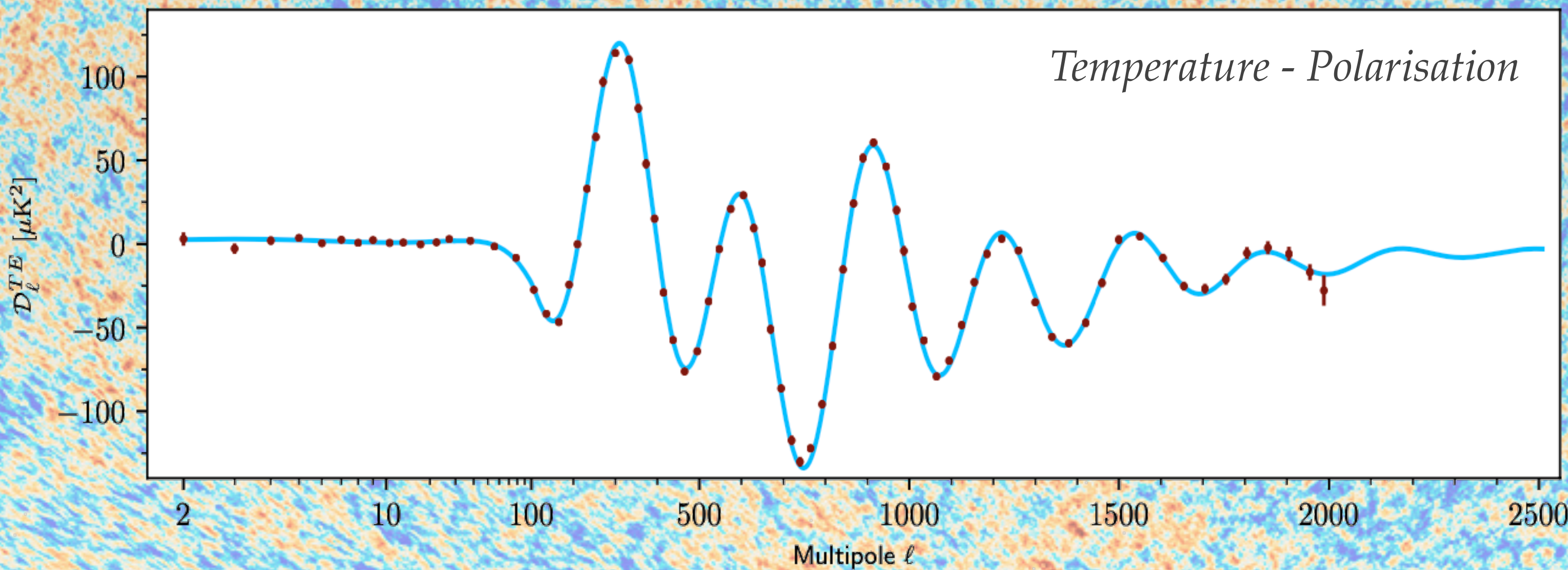
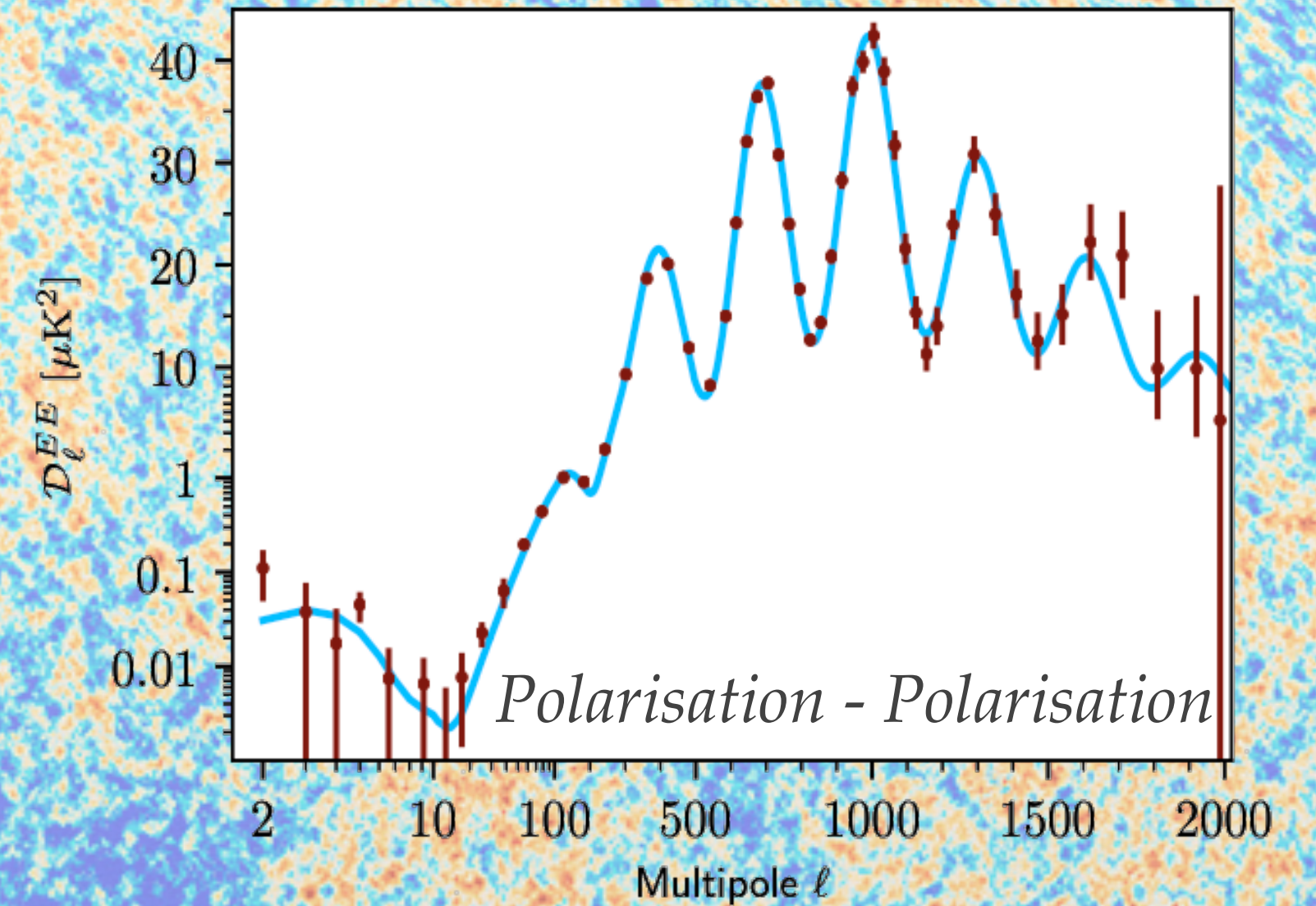
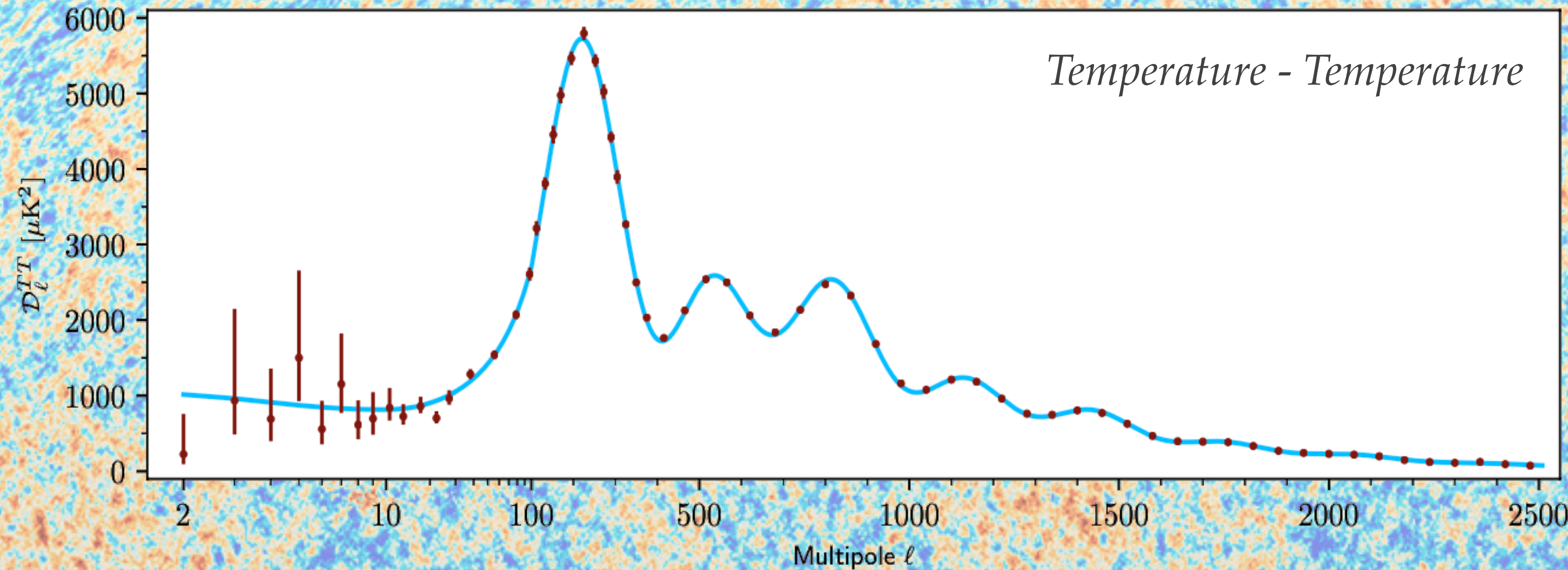


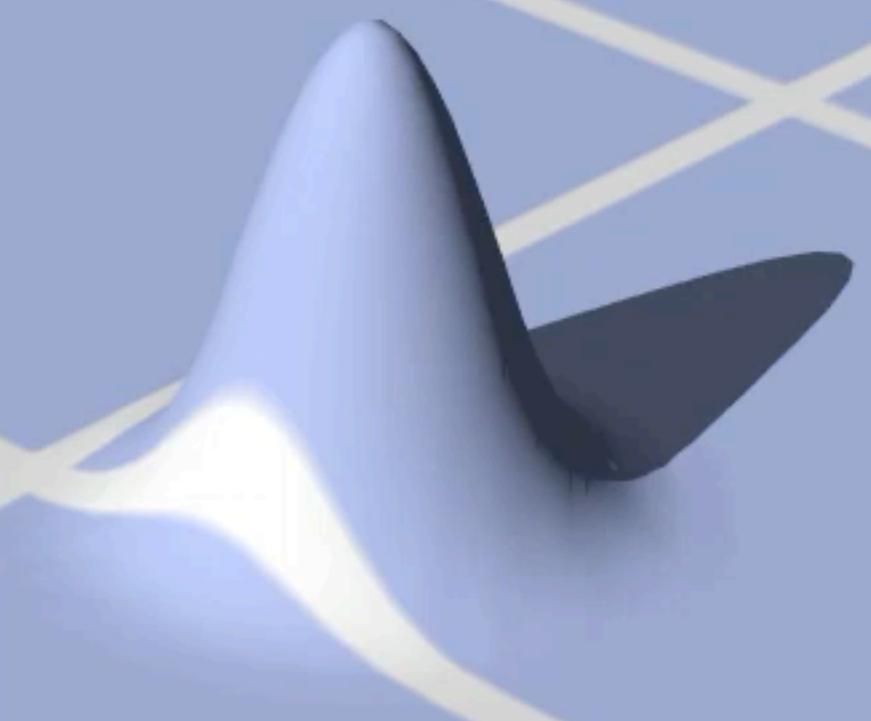
## Change the model

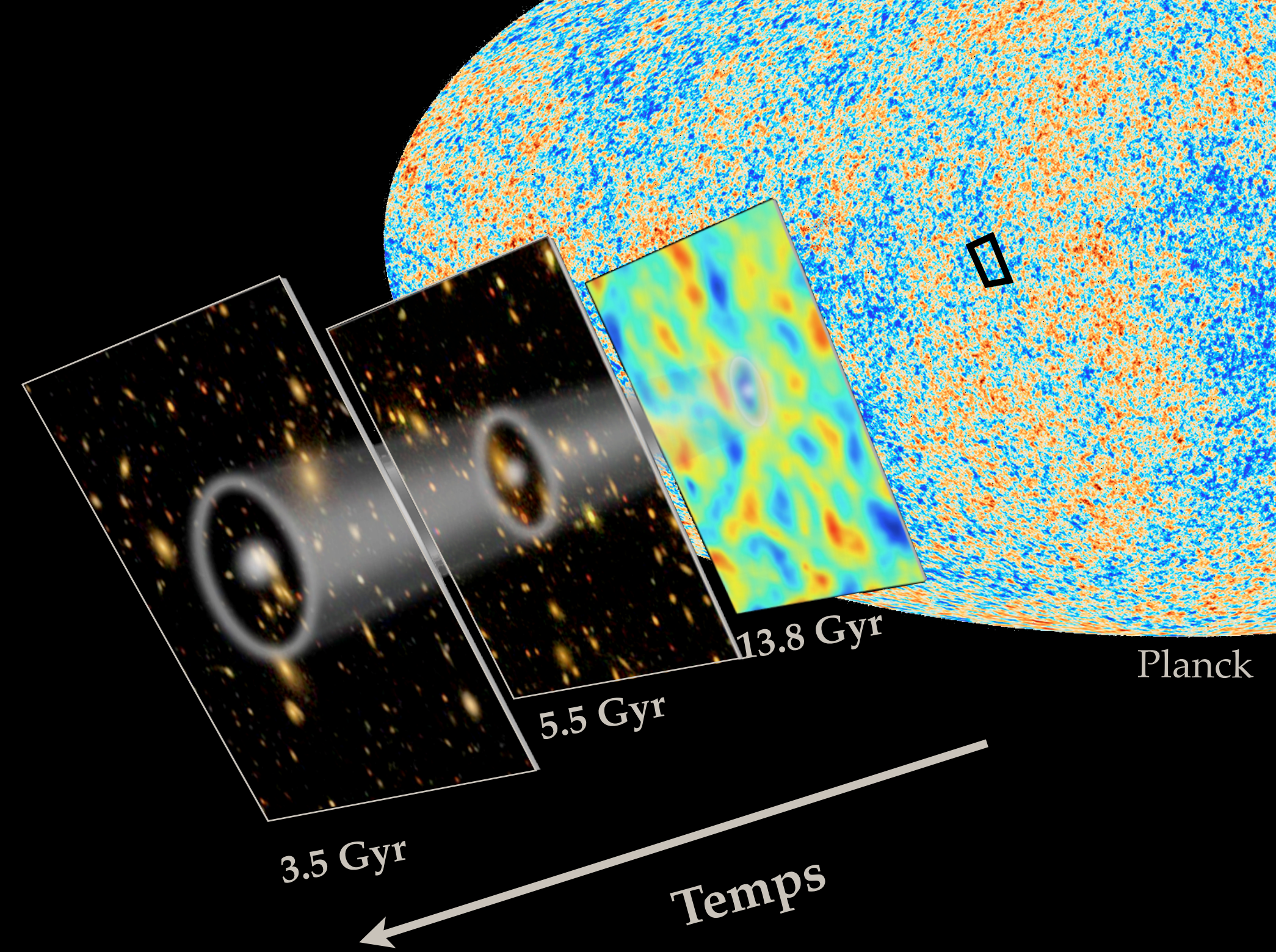
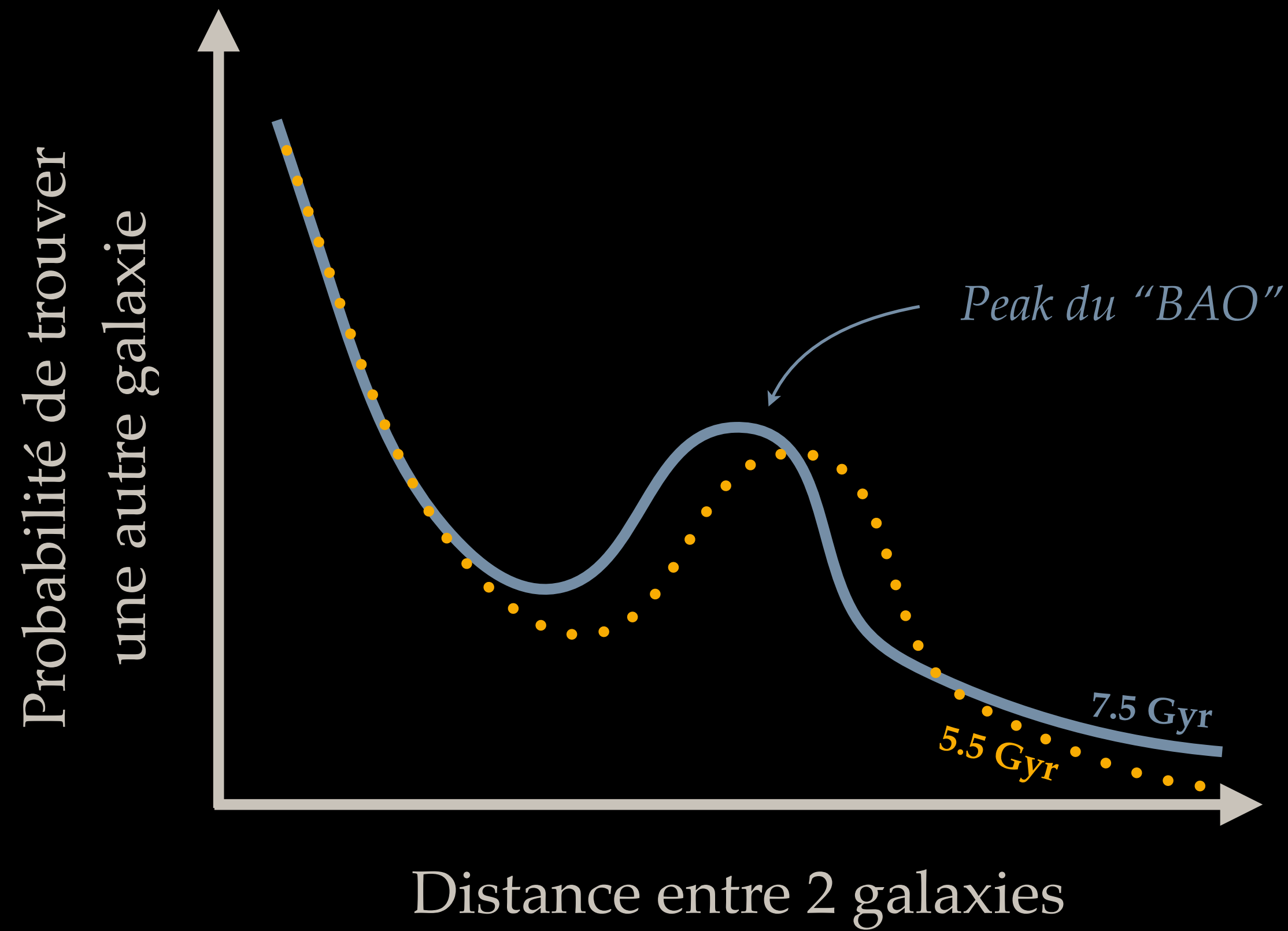


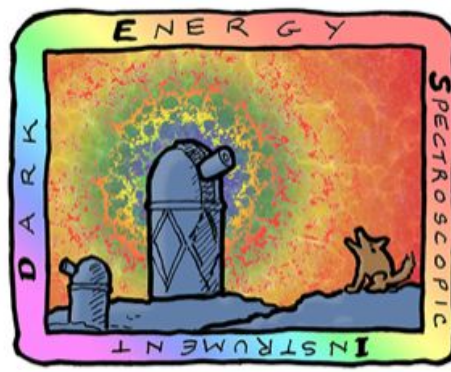
# Planck Data | *Temperature, lensing, polarisation*

Planck et al. 2020









DARK ENERGY  
SPECTROSCOPIC  
INSTRUMENT

U.S. Department of Energy Office of Science

# Tracers of the matter distribution

Five target classes  
40 million redshifts  
in 5 years

DESI (2021-2026)

3 million QSOs

**Lya**  $z > 2.1$

**Tracers**  $0.9 < z < 2.1$

16 million ELGs

$0.6 < z < 1.6$

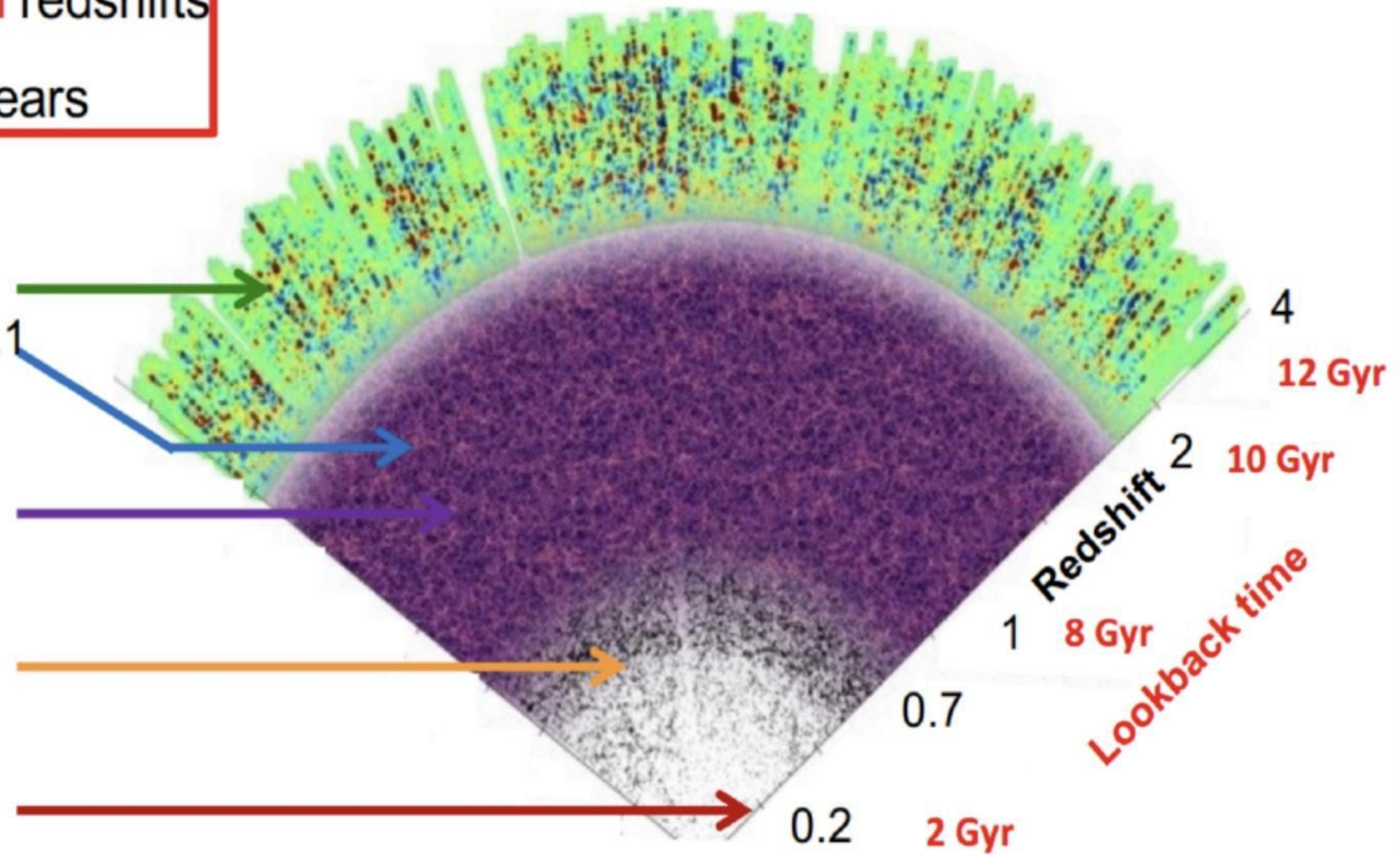
8 million LRGs

$0.4 < z < 1.0$

13.5 million

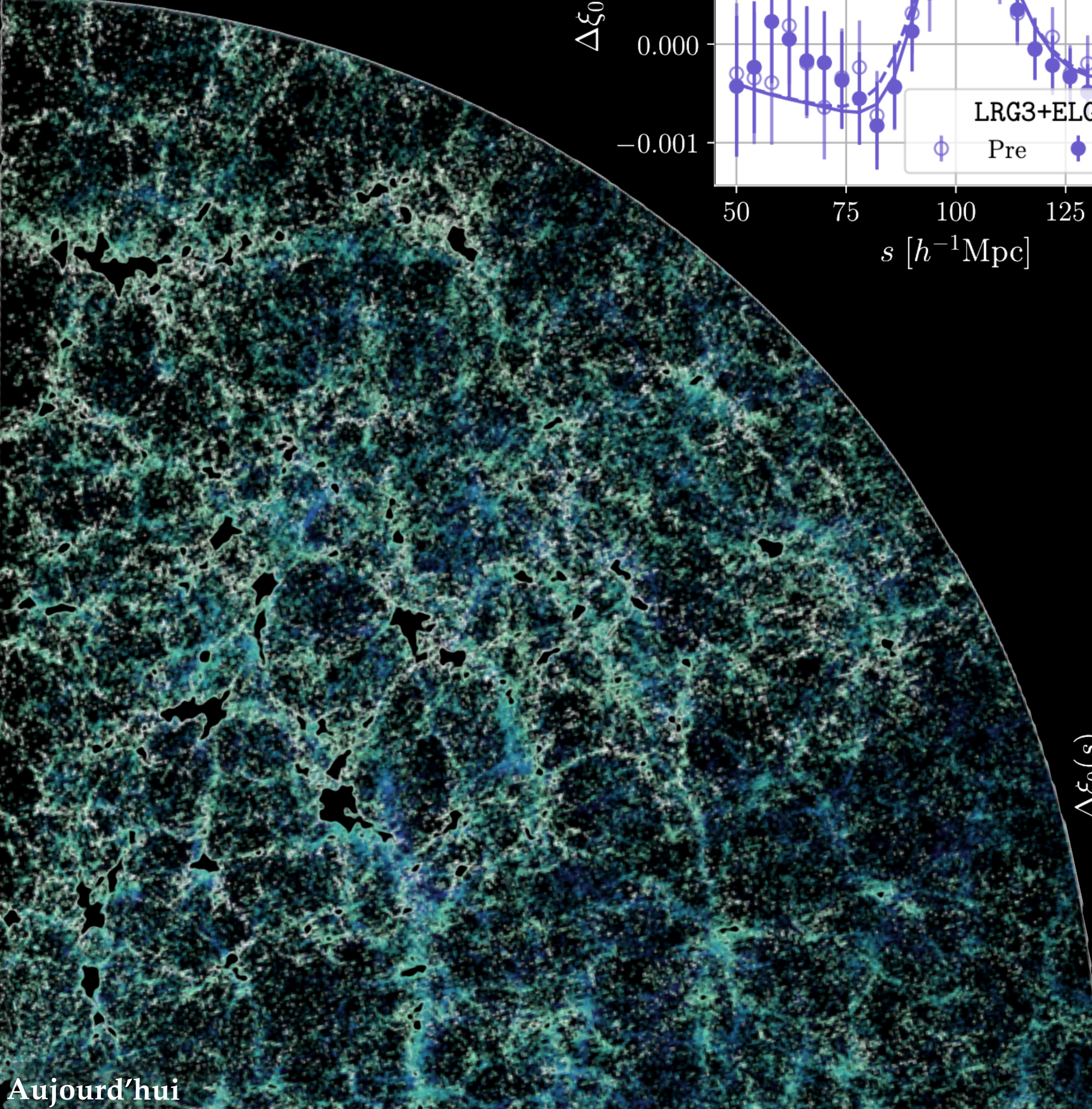
**Brightest galaxies**

$0.0 < z < 0.4$

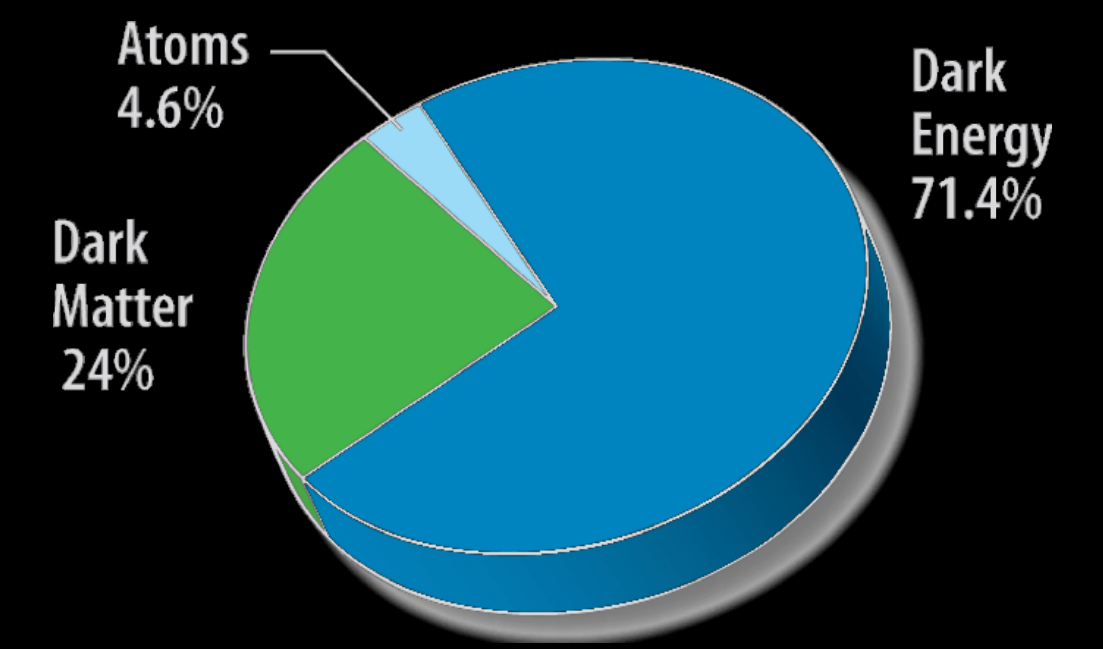
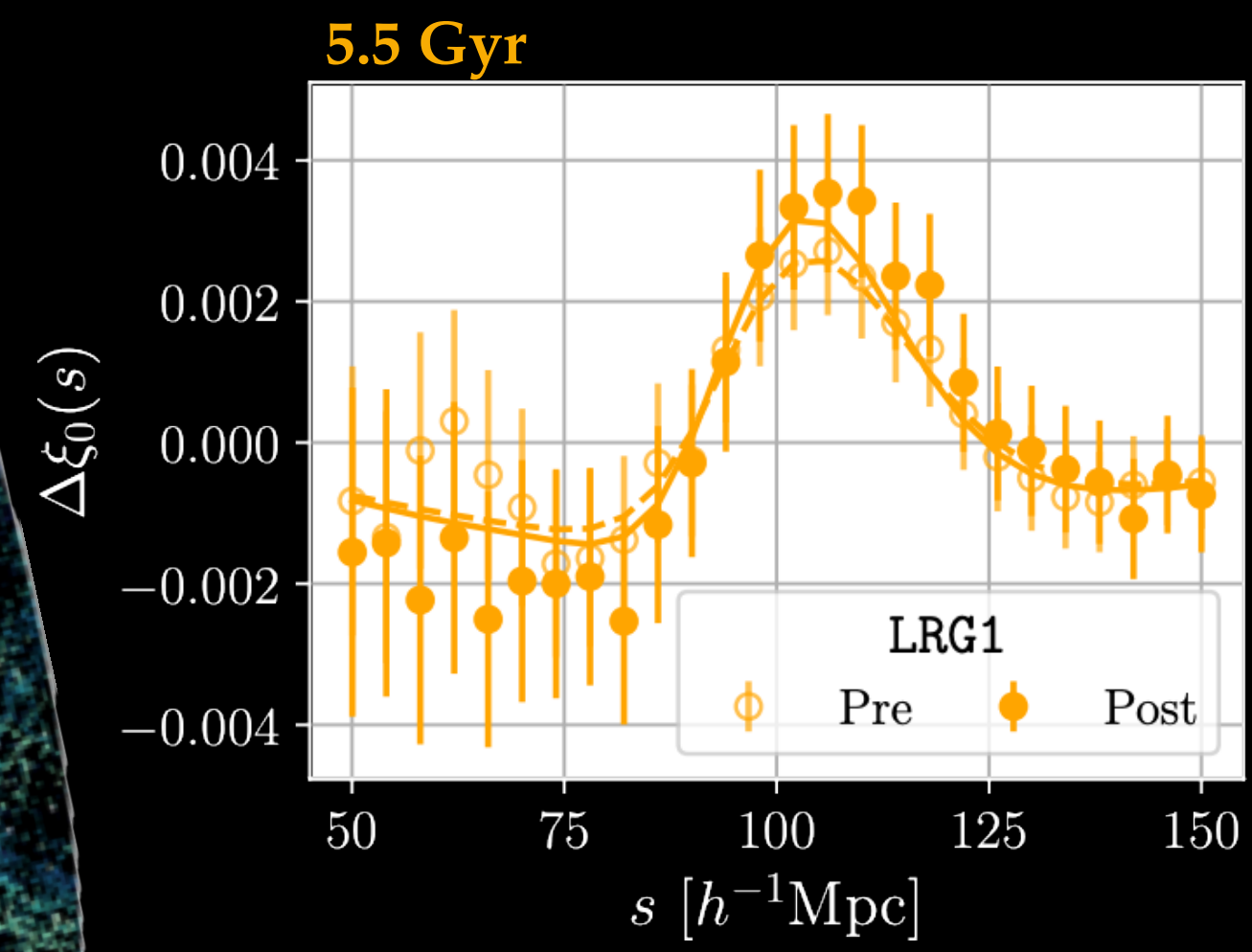
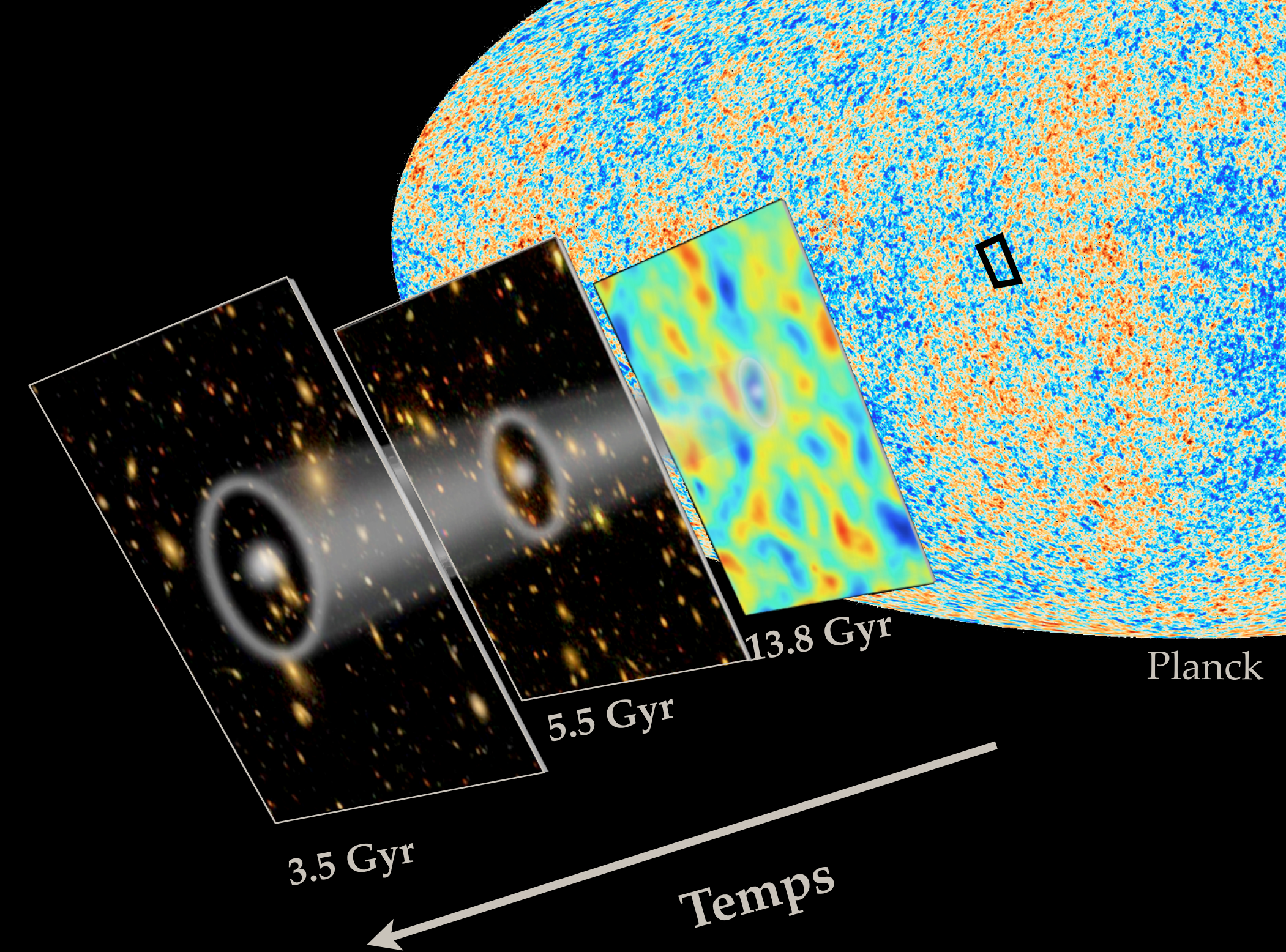
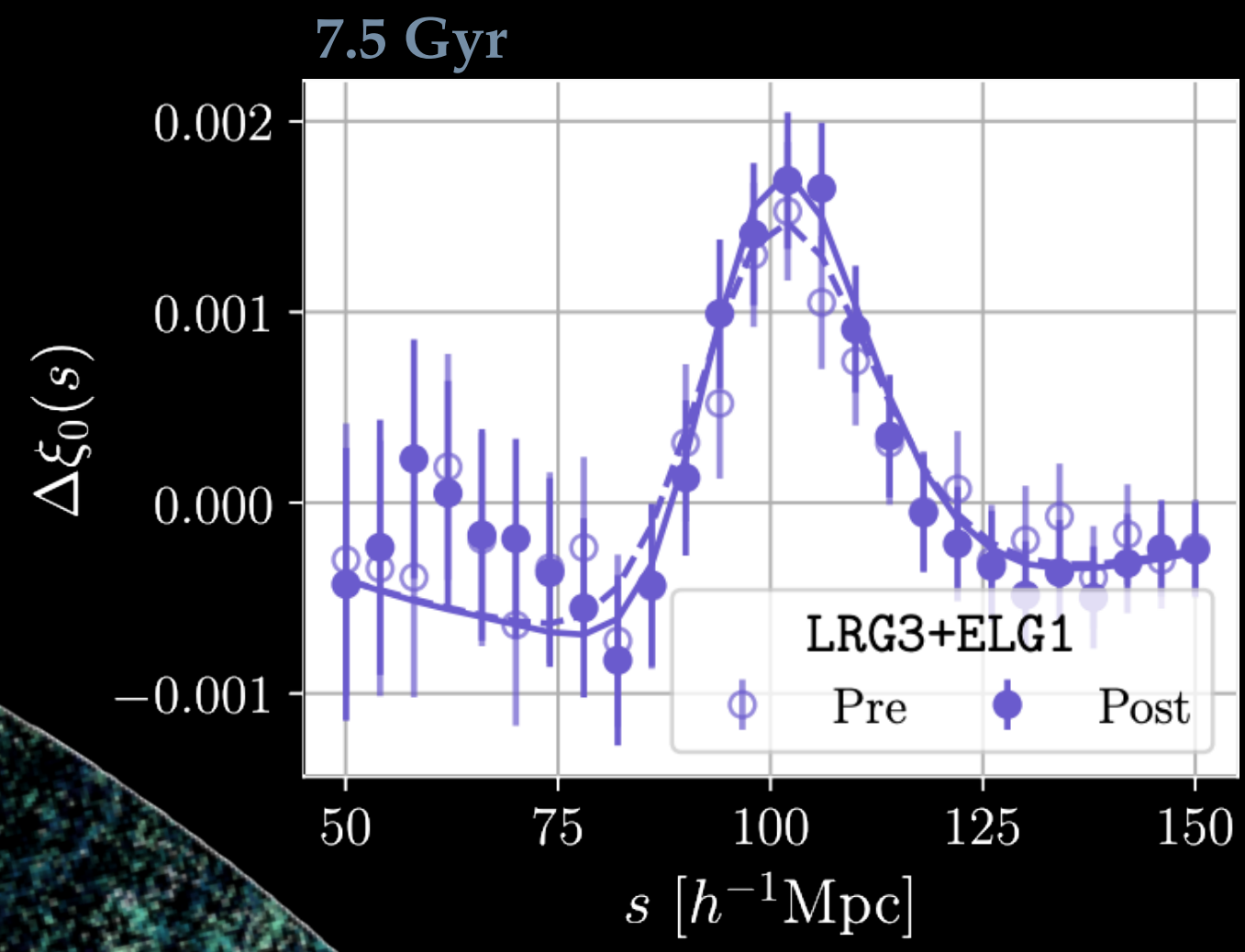


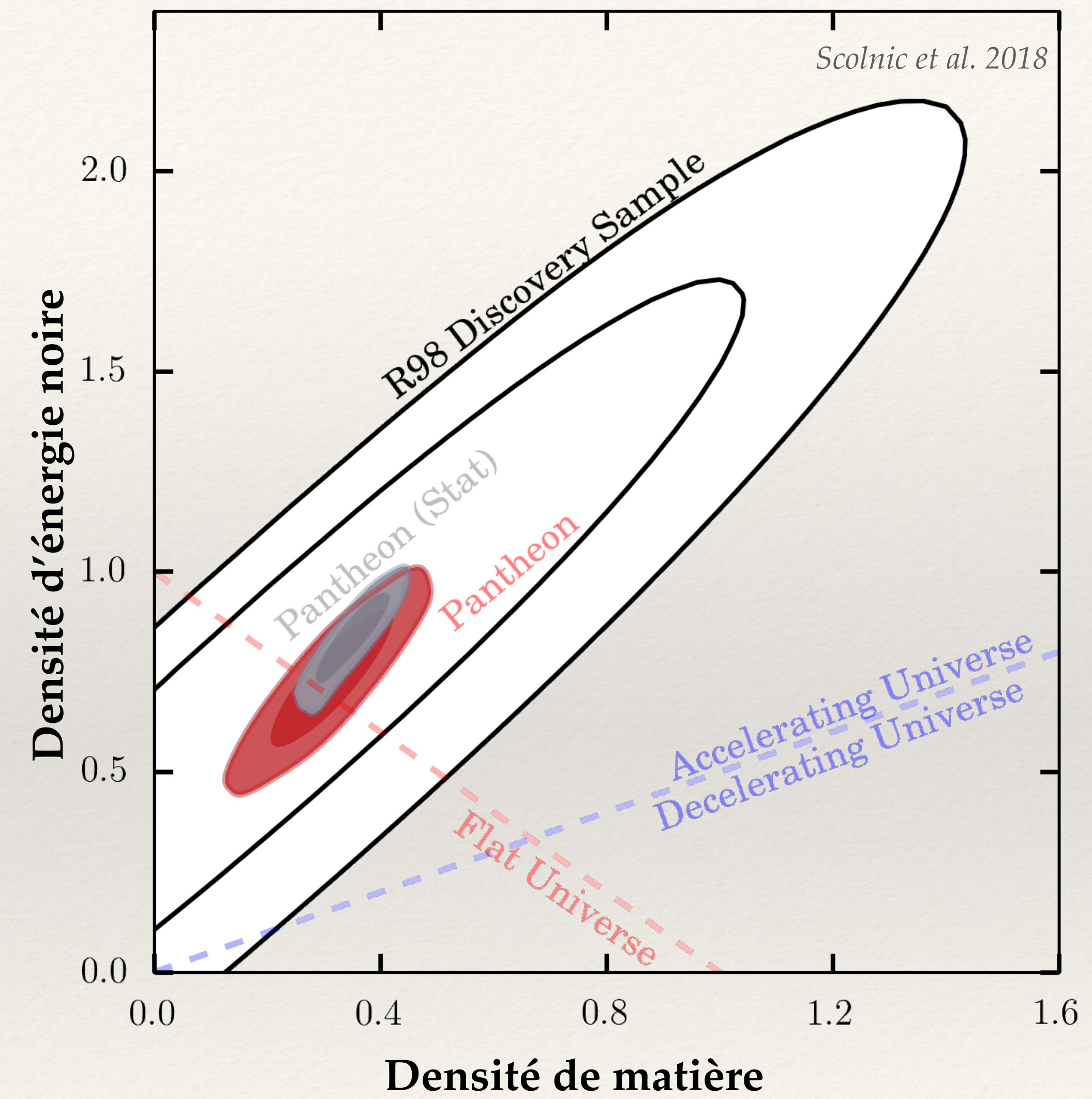
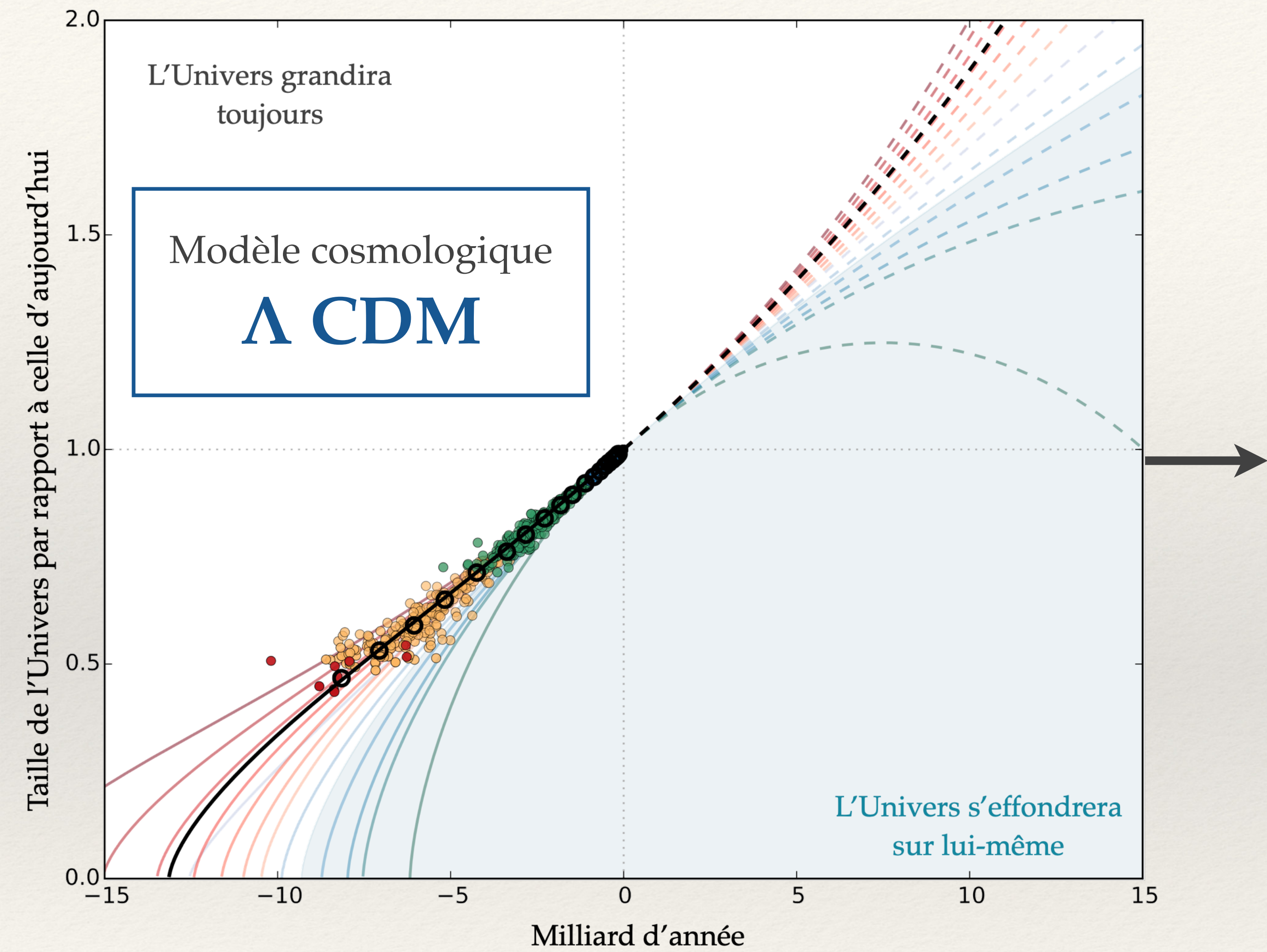
From: E. Burtin

DESI



Aujourd'hui

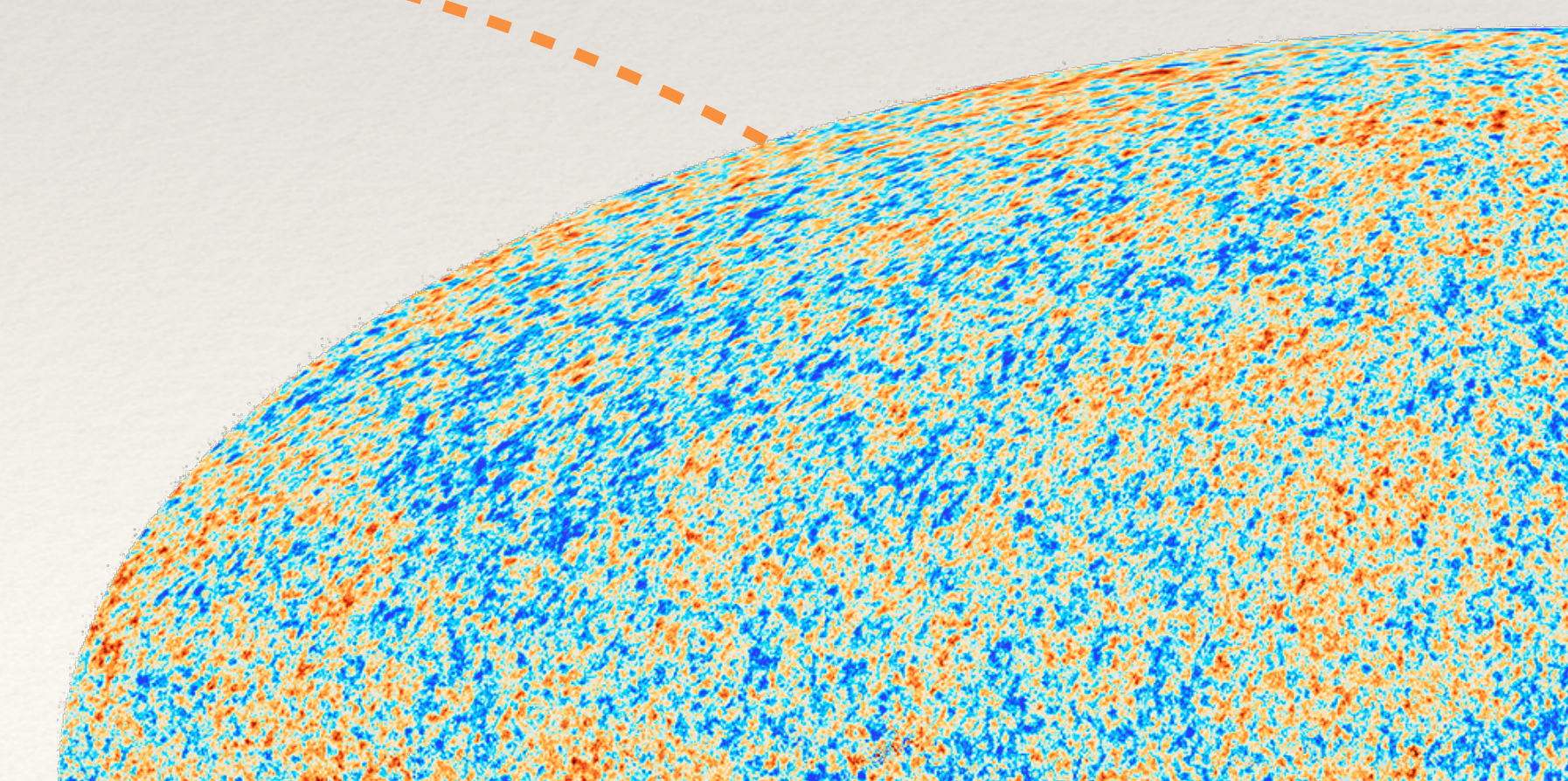
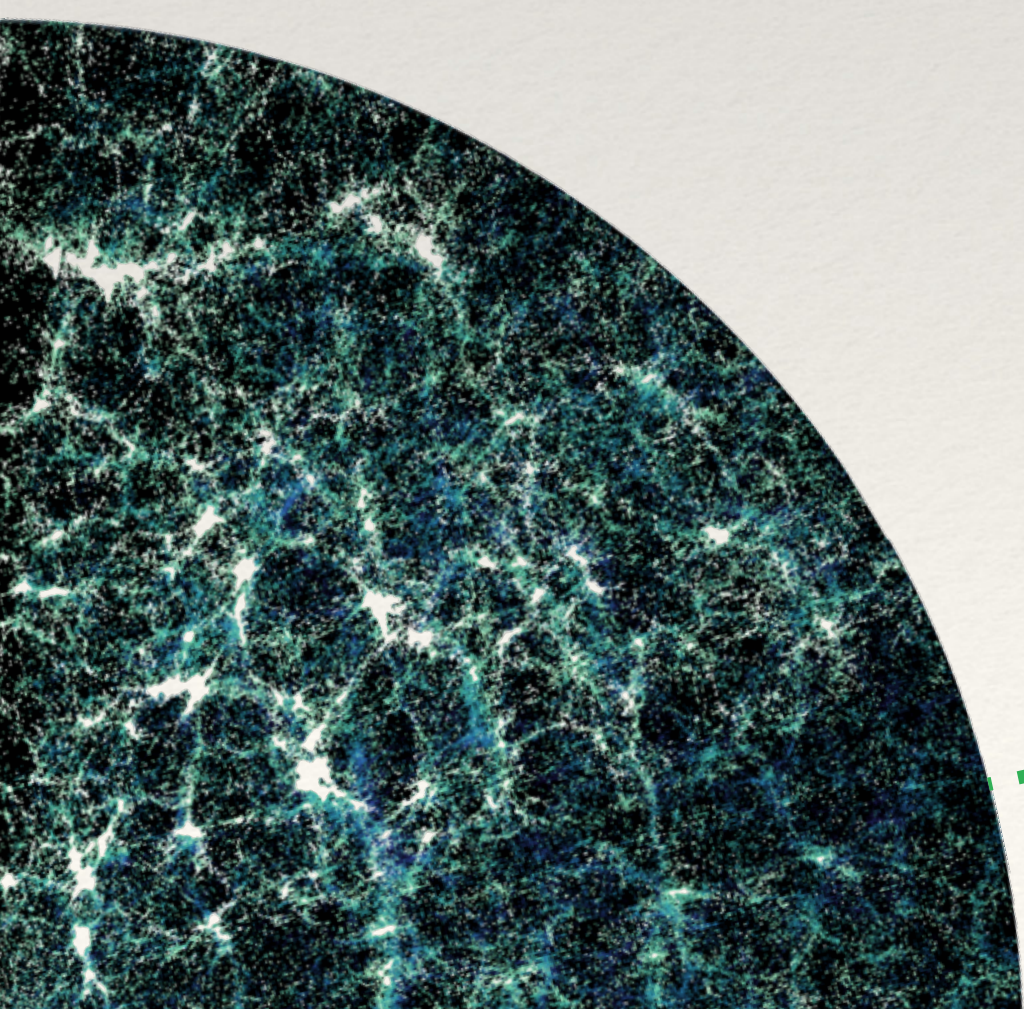
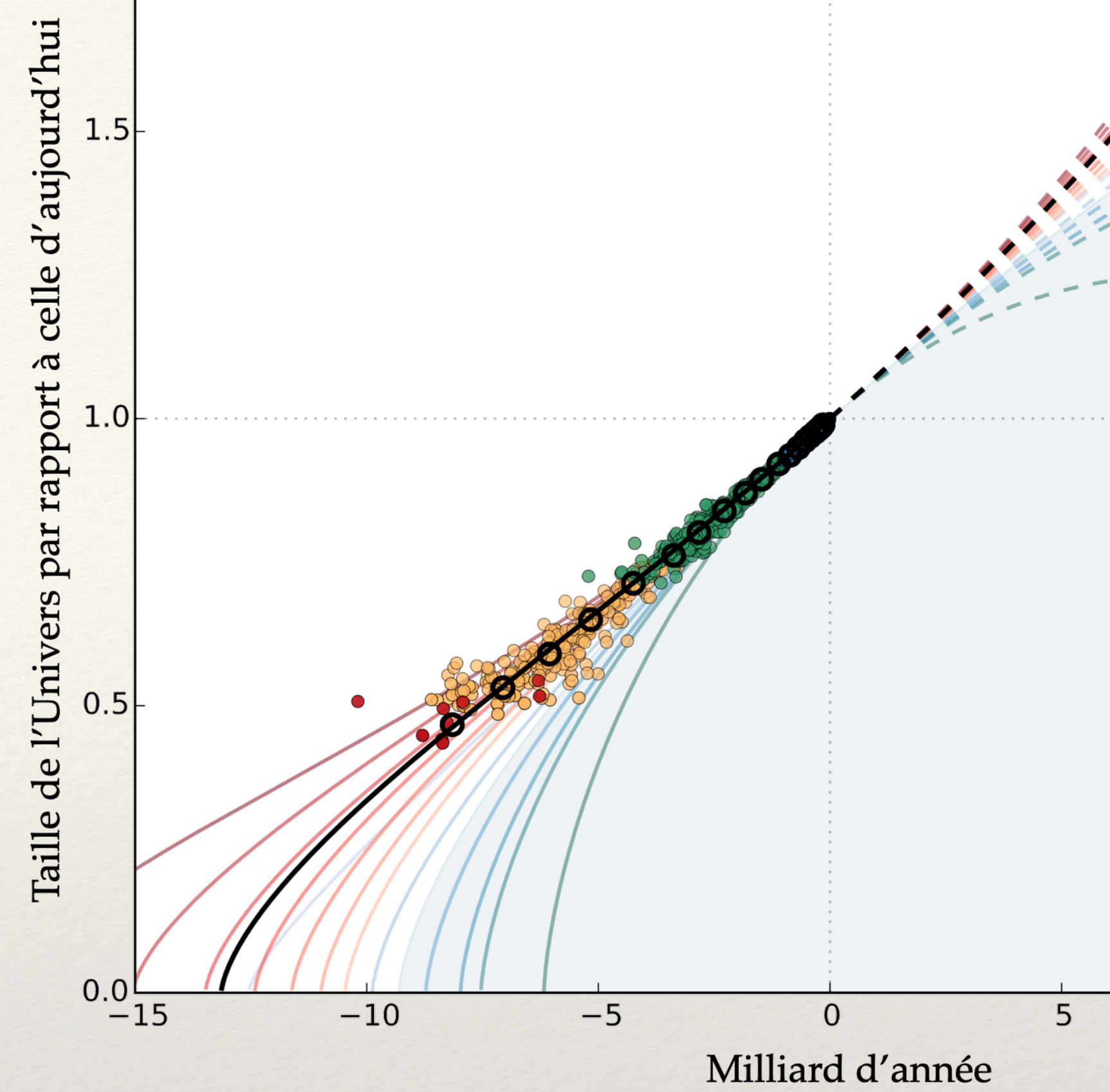
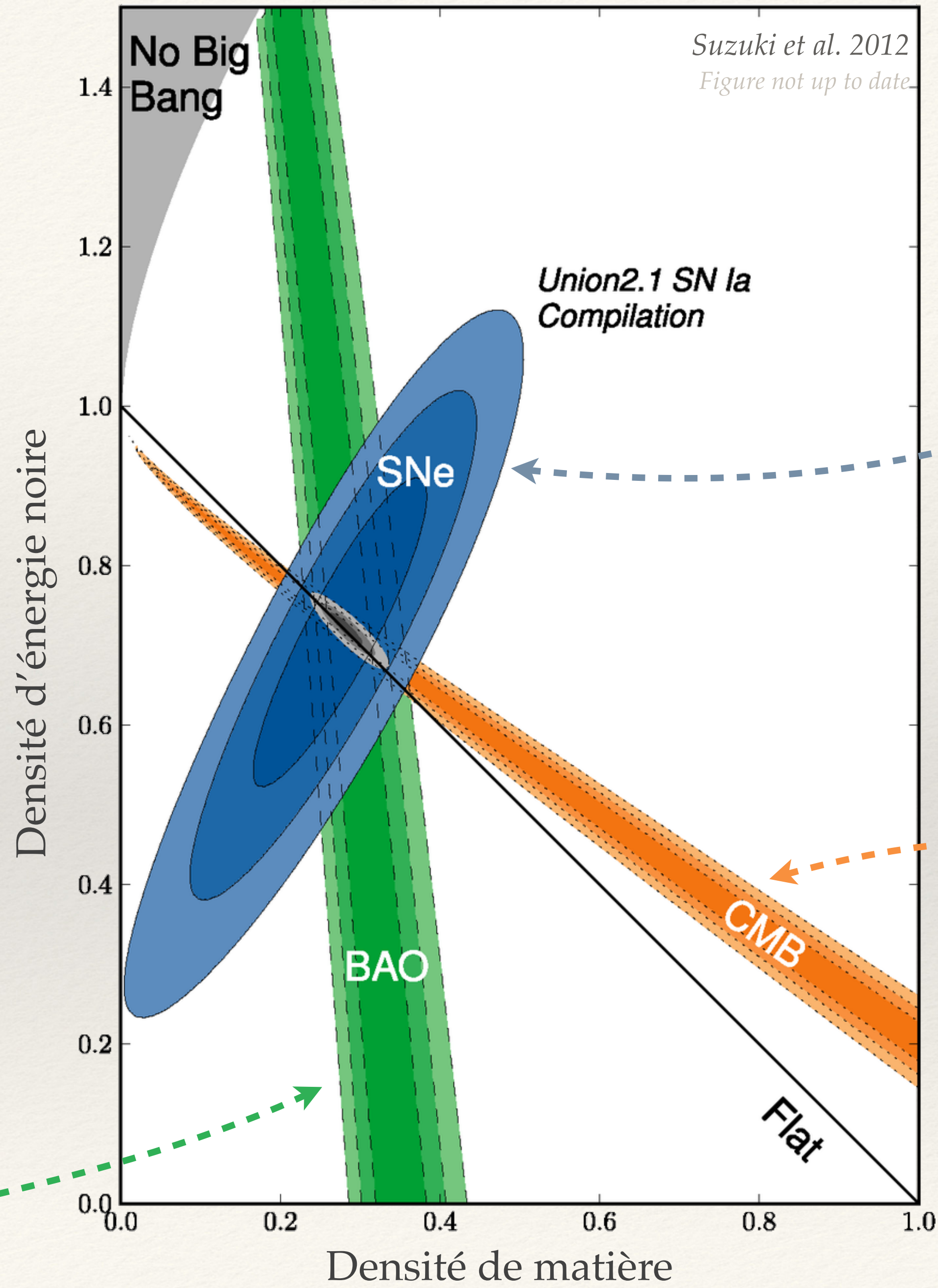




Modèle cosmologique

# $\Lambda$ CDM

Seulement 6 paramètres





# $\Lambda$ : Énergie noire

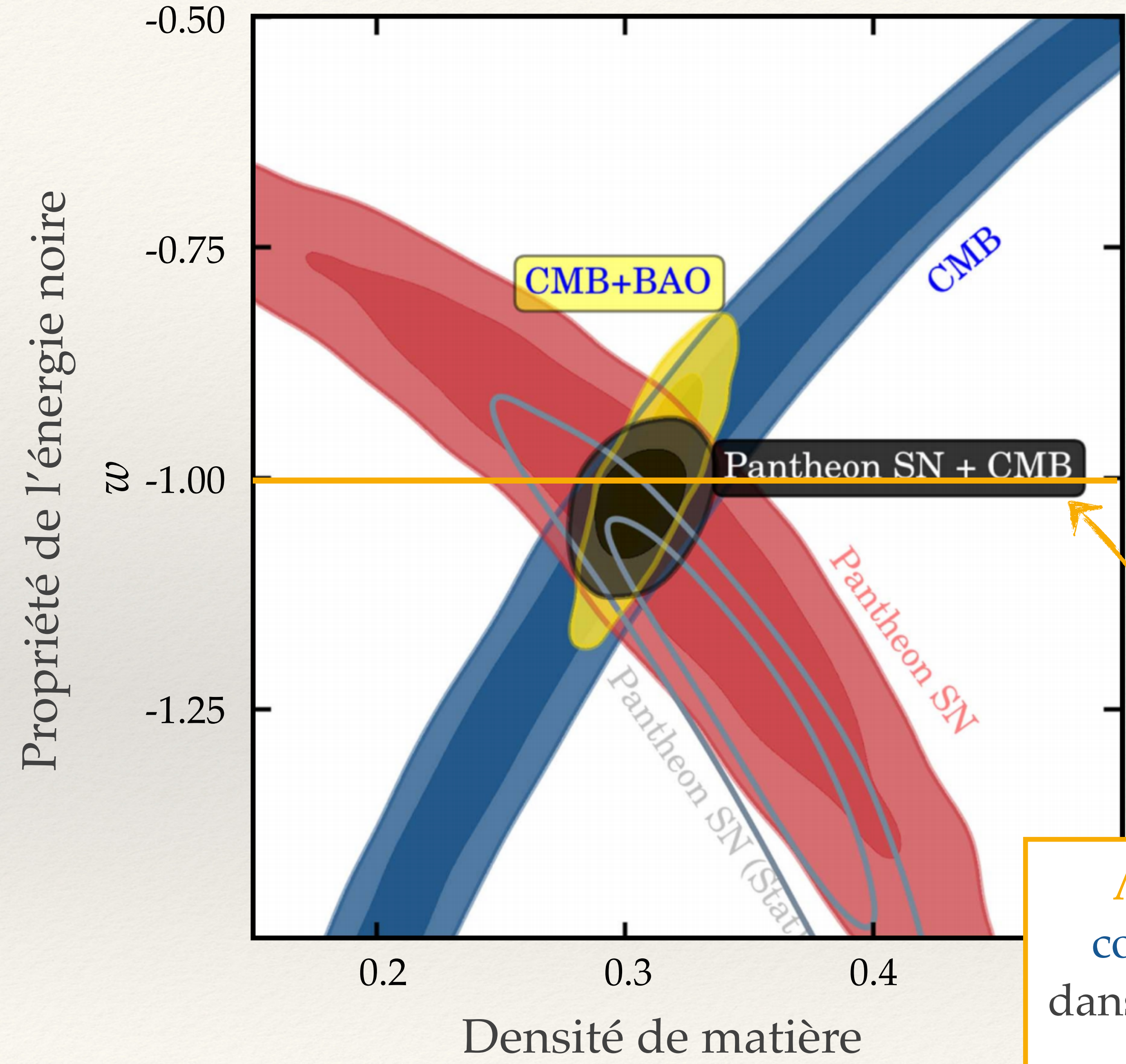
*Responsable de l'accélération de l'expansion de l'Univers*

$O(100\ 000 \sim 10\ 000\ 000)$  milliers d'années lumière

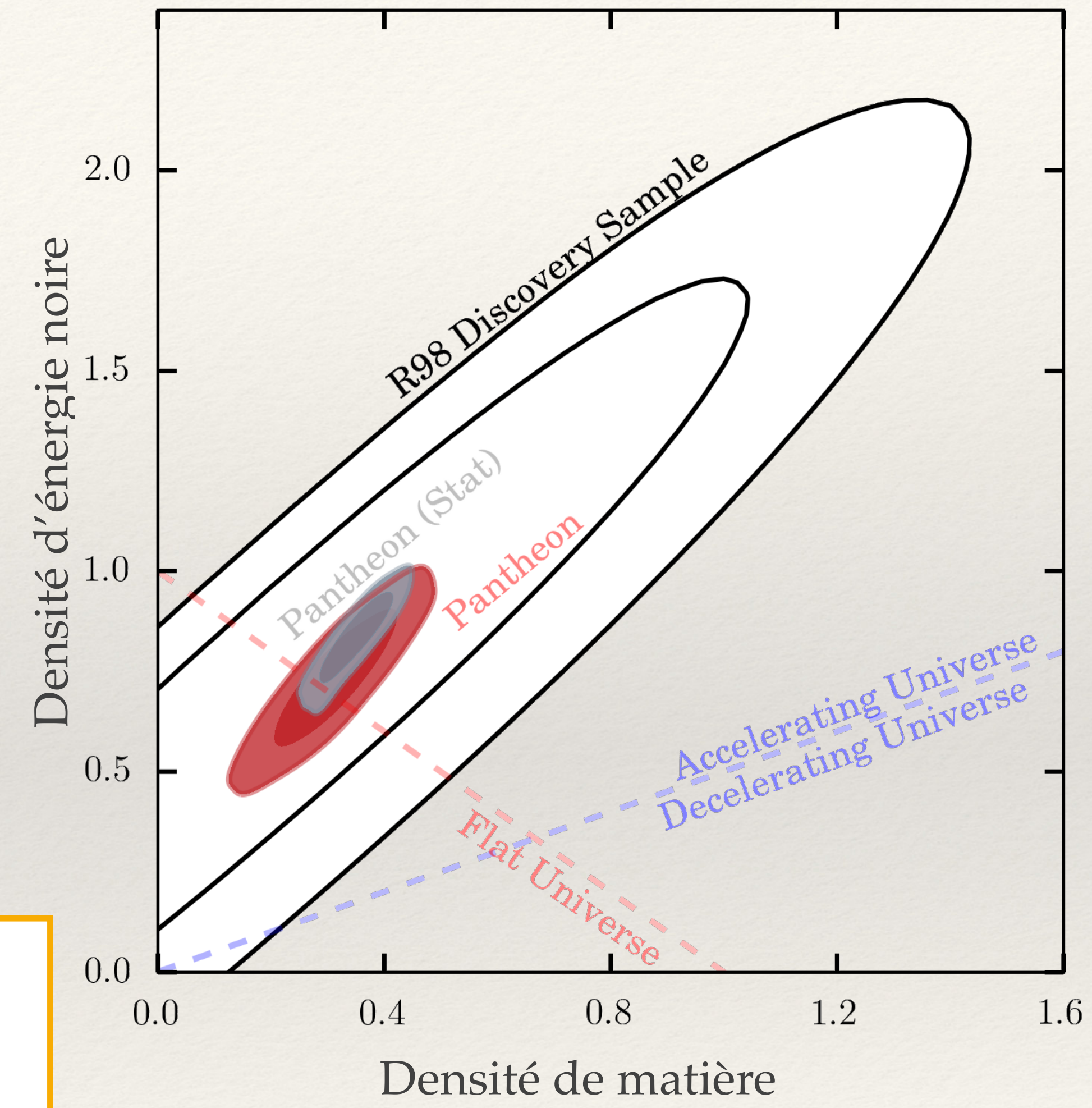
# *CDM*: Matière noire

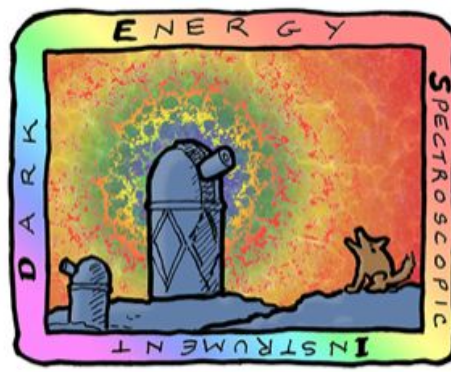
*"Particule" créant un excès d'attraction gravitationnelle*

$O(1 \sim 100)$  milliers d'années lumière



$\Lambda$  constante cosmologique dans les équations d'Einstein





DARK ENERGY  
SPECTROSCOPIC  
INSTRUMENT

U.S. Department of Energy Office of Science

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16 million ELGs

$0.6 < z < 1.6$

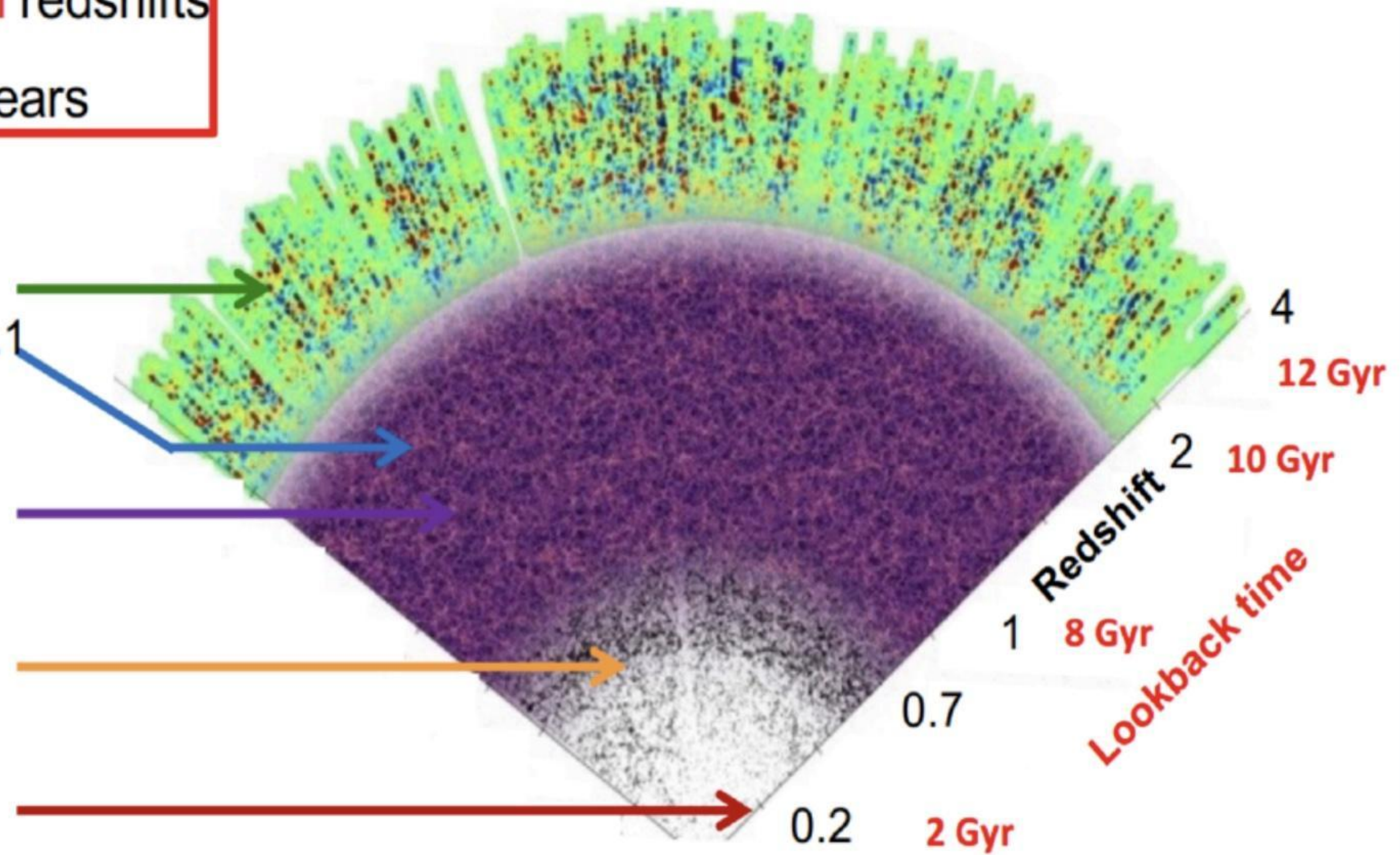
8 million LRGs

$0.4 < z < 1.0$

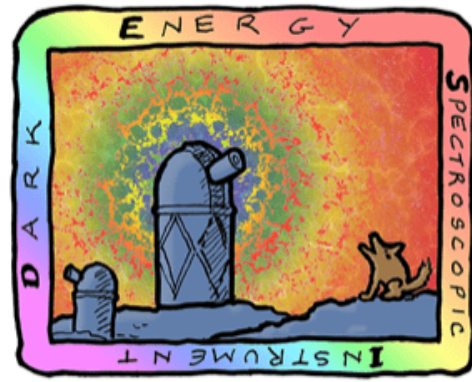
13.5 million

**Brightest galaxies**

$0.0 < z < 0.4$



From: E. Burtin

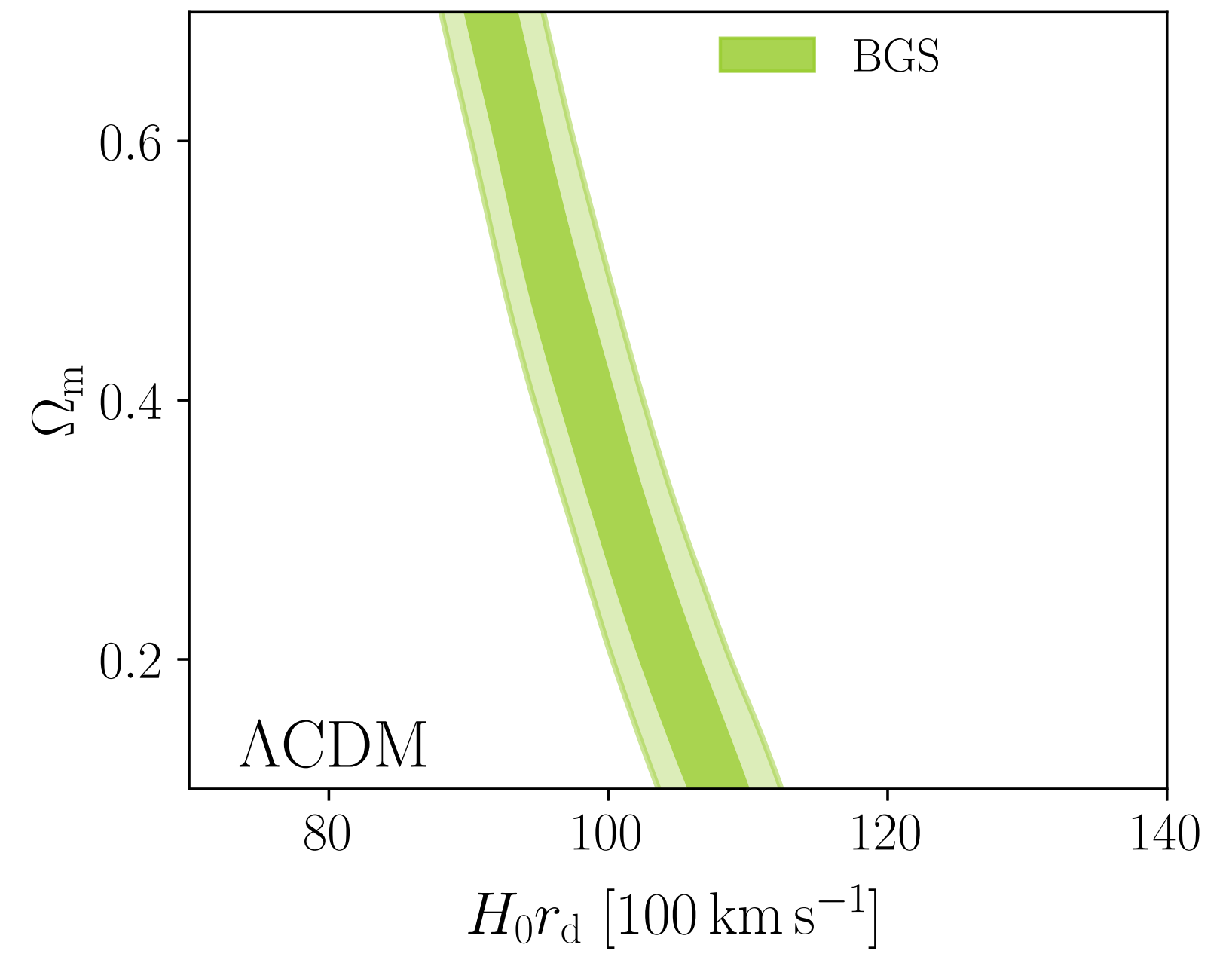
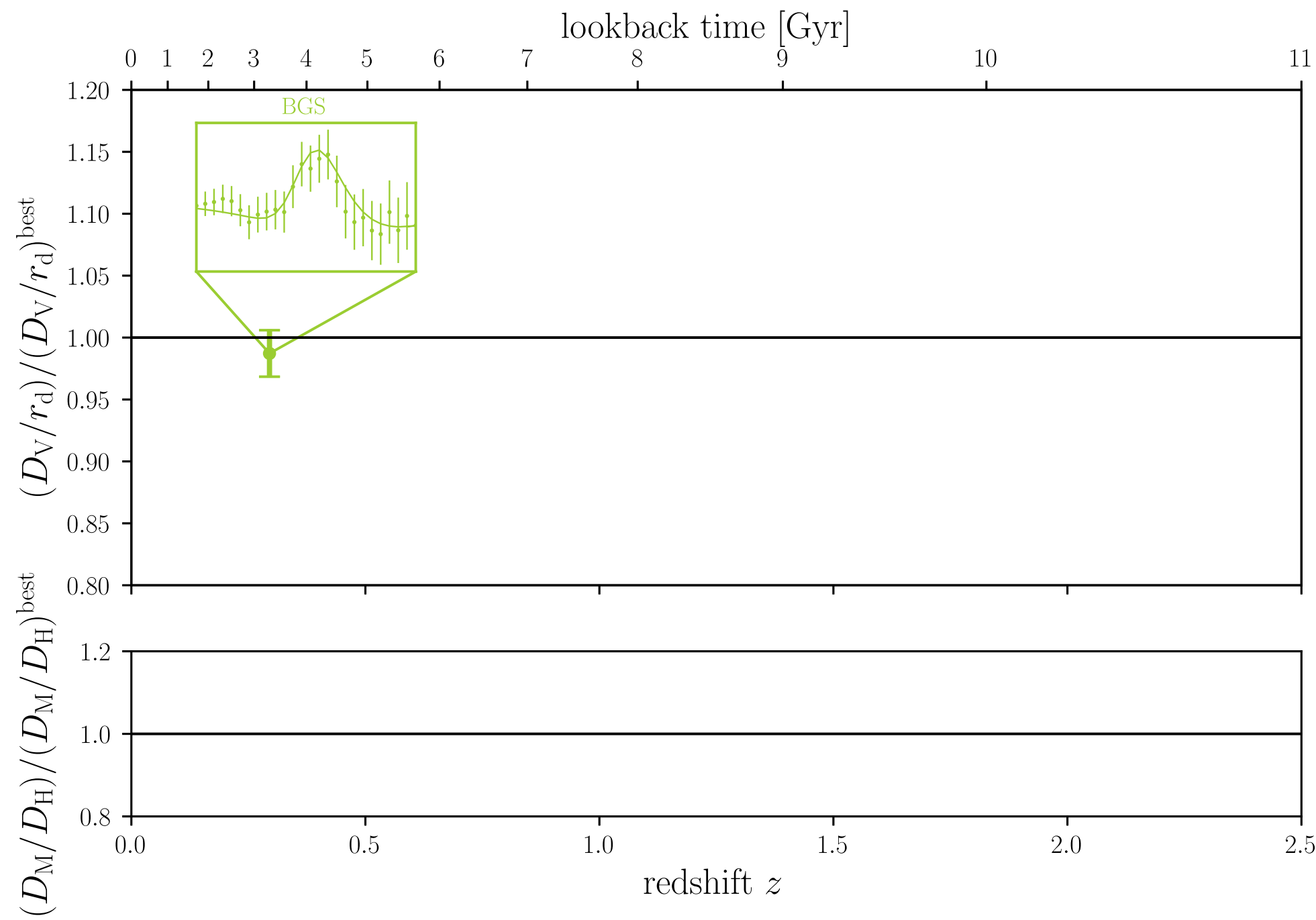


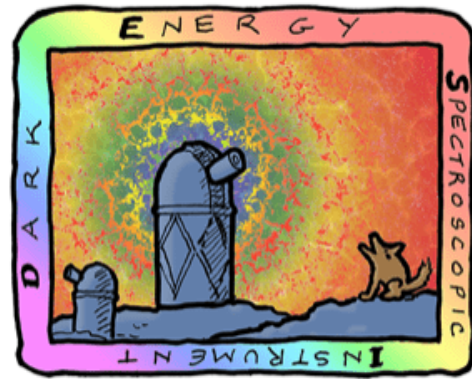
DARK ENERGY  
SPECTROSCOPIC  
INSTRUMENT

# DESI Y1 BAO

U.S. Department of Energy Office of Science

## DESI BAO measurements



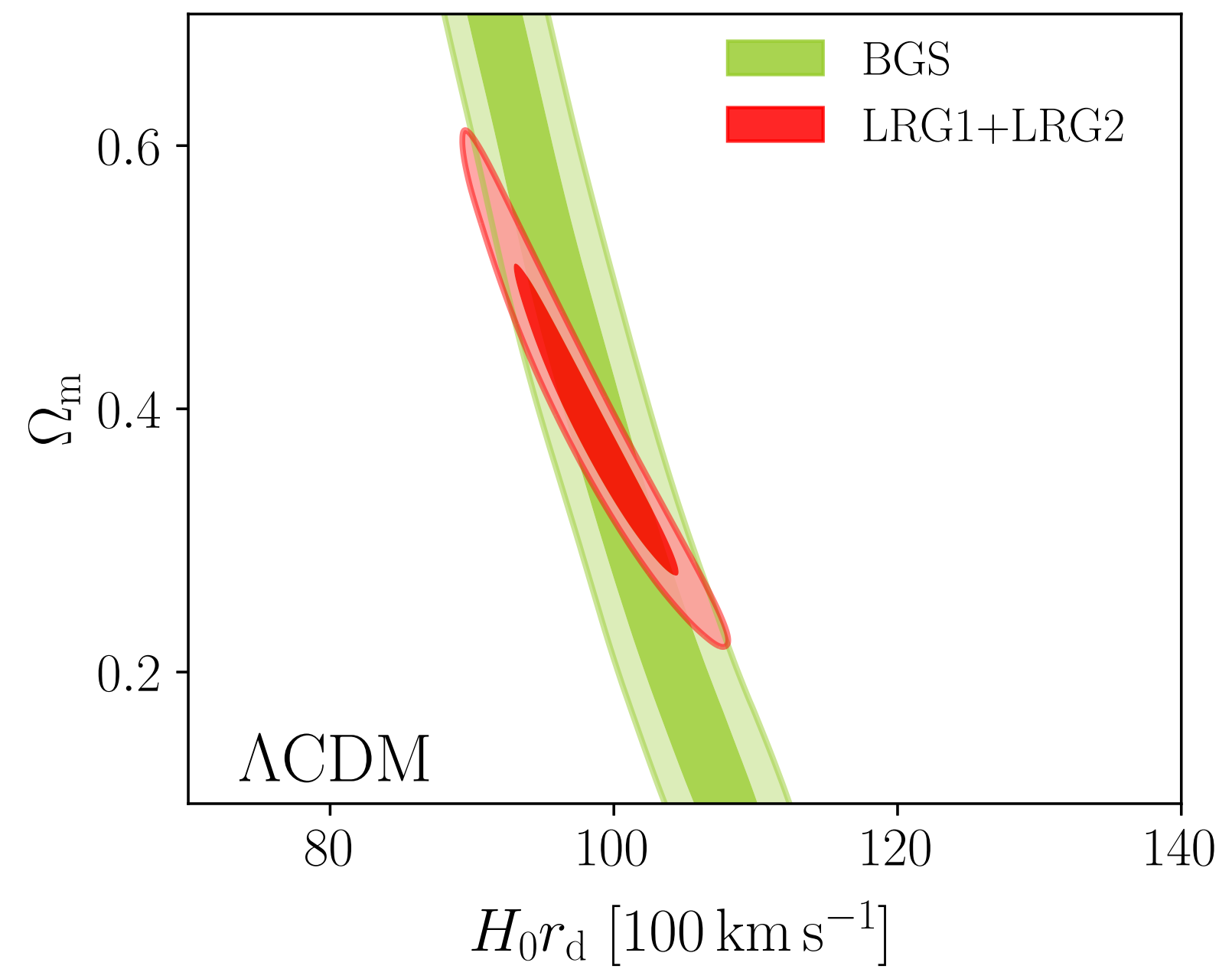
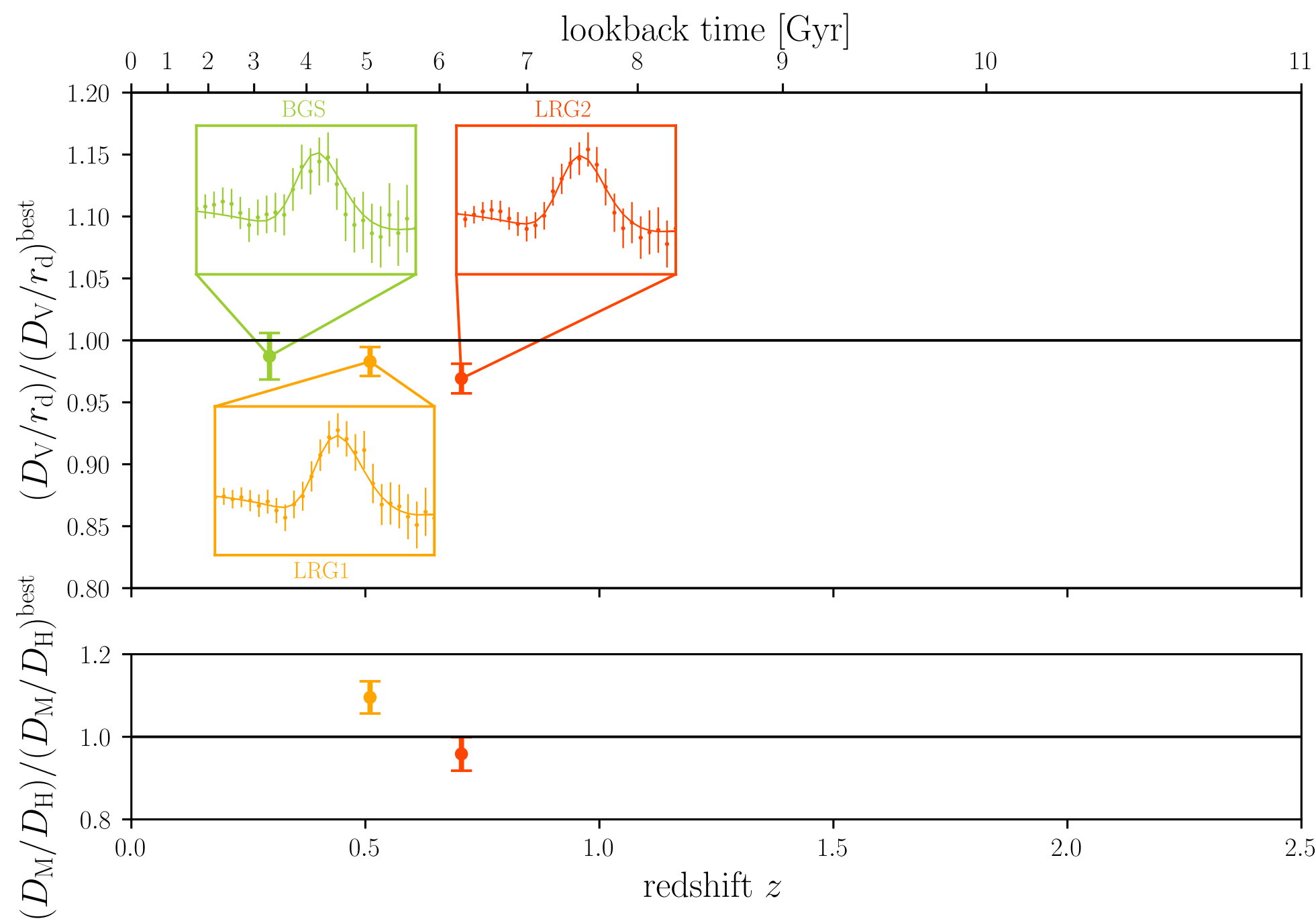


DARK ENERGY  
SPECTROSCOPIC  
INSTRUMENT

# DESI Y1 BAO

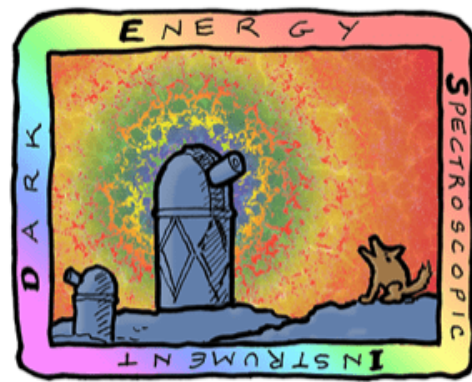
U.S. Department of Energy Office of Science

## DESI BAO measurements



10

From: A. De Mattia

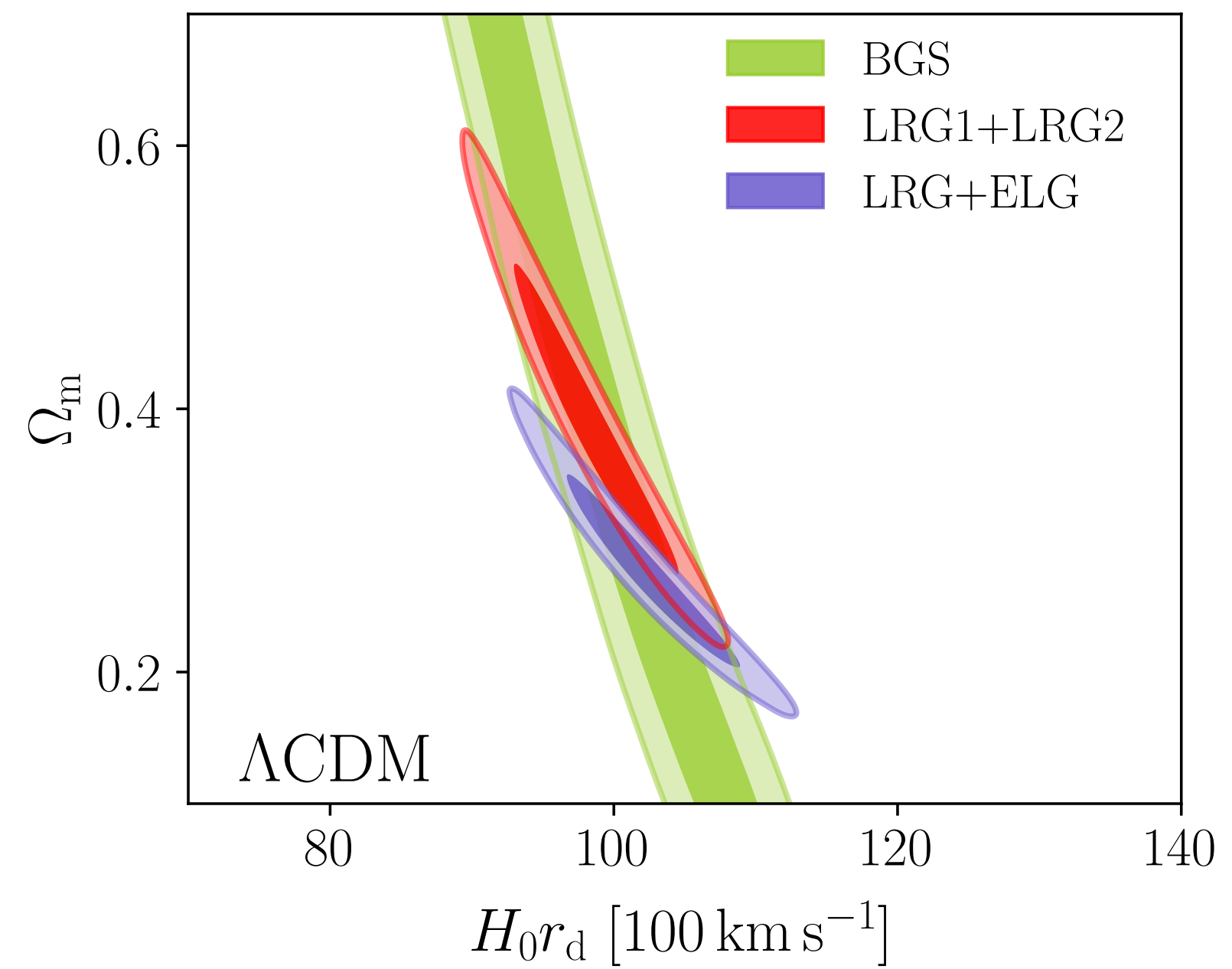
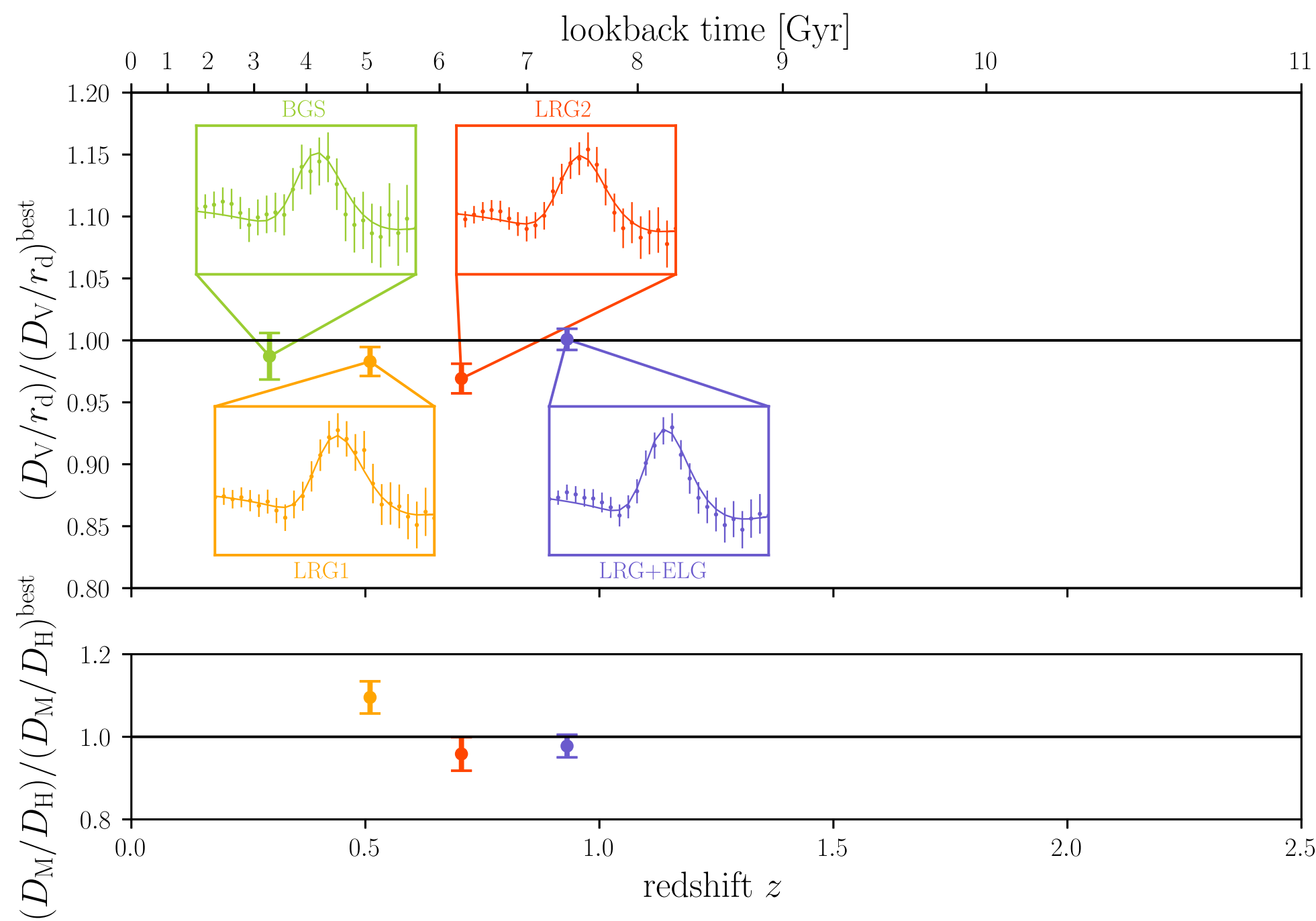


DARK ENERGY  
SPECTROSCOPIC  
INSTRUMENT

# DESI Y1 BAO

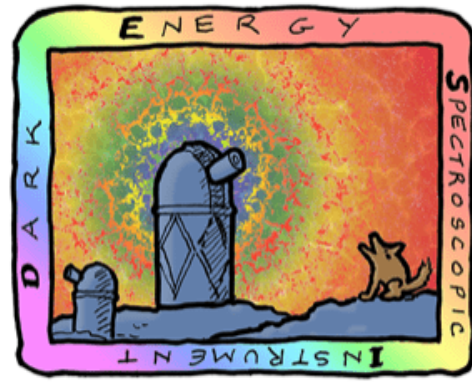
U.S. Department of Energy Office of Science

## DESI BAO measurements



11

From: A. De Mattia

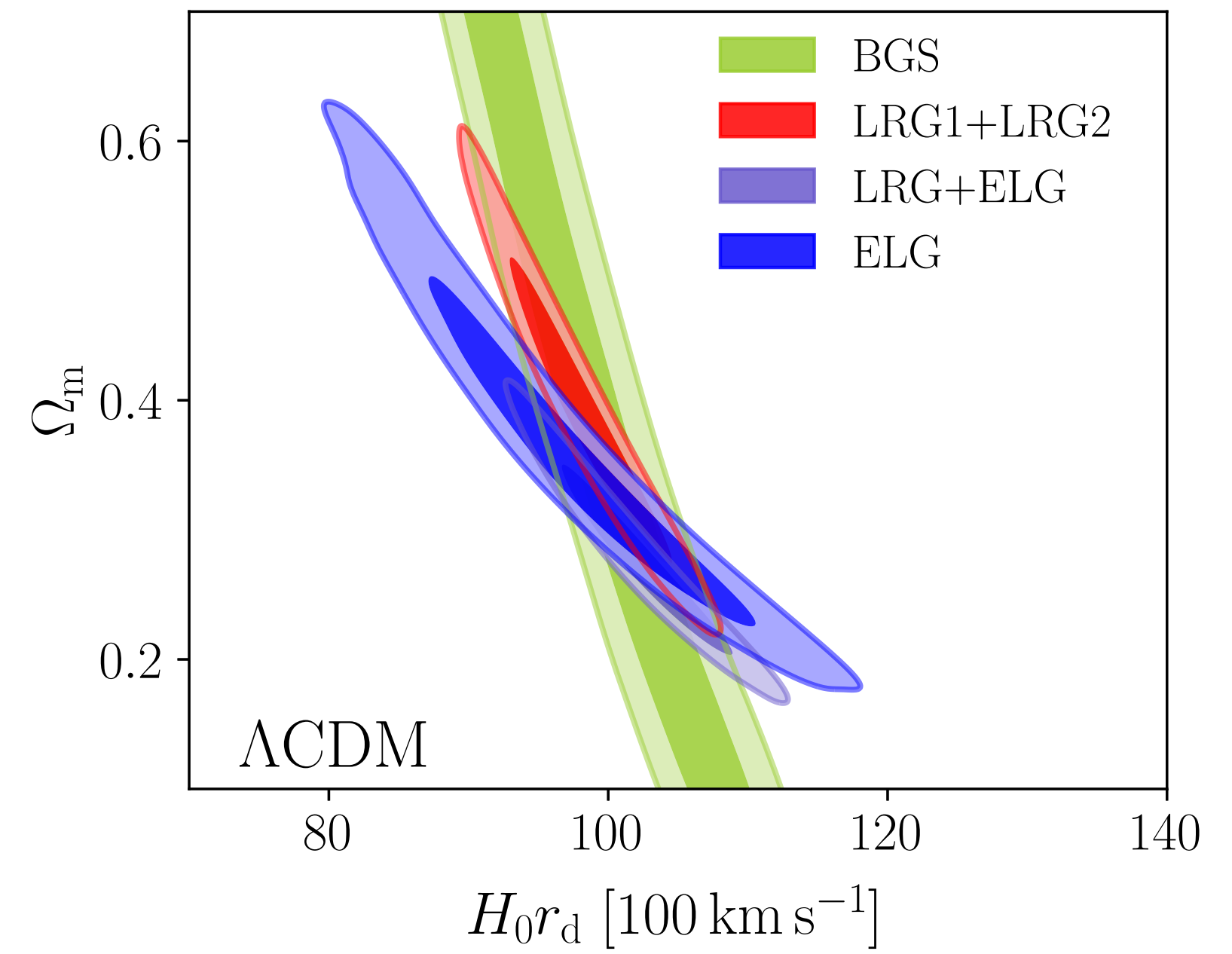
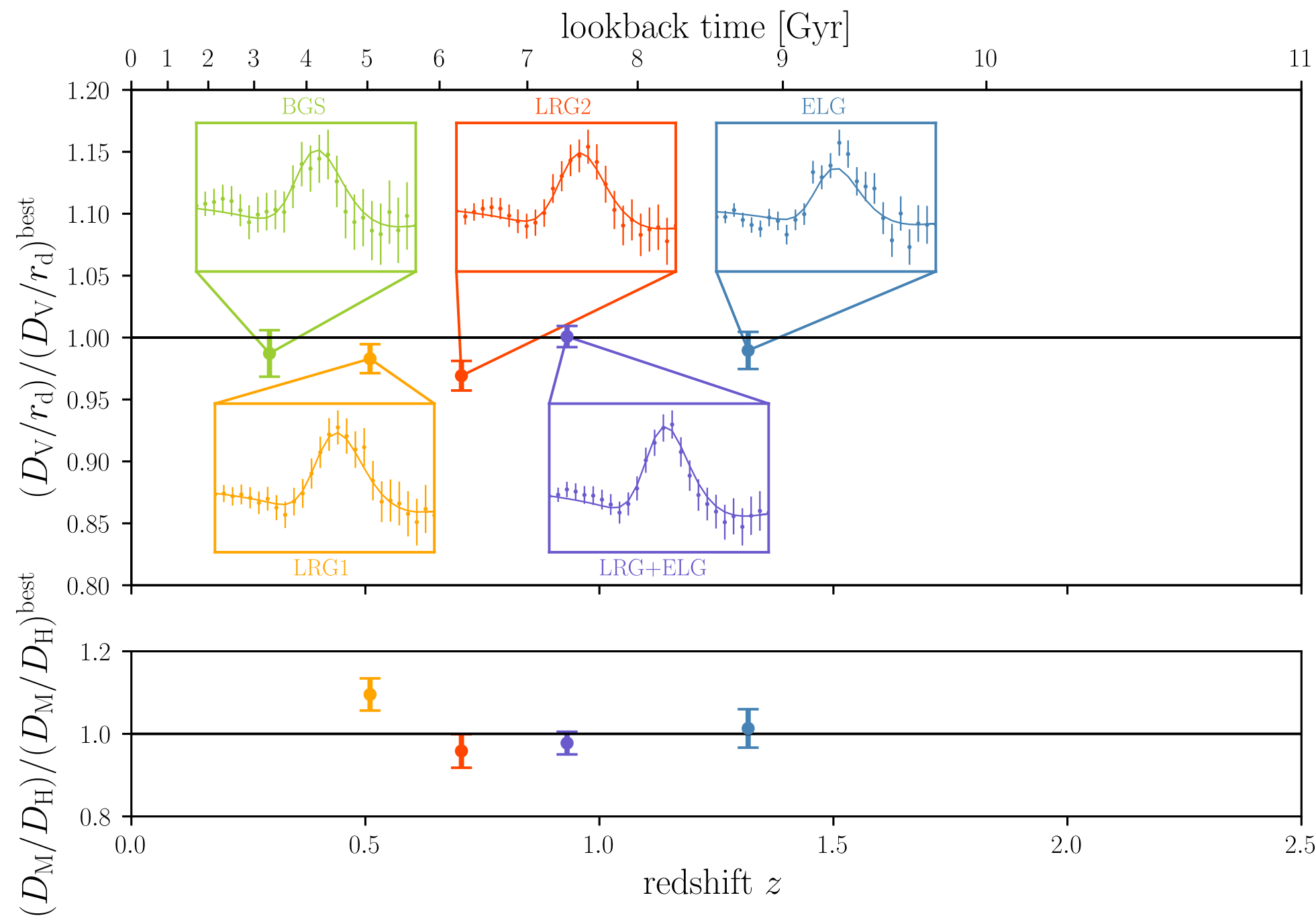


DARK ENERGY  
SPECTROSCOPIC  
INSTRUMENT

# DESI Y1 BAO

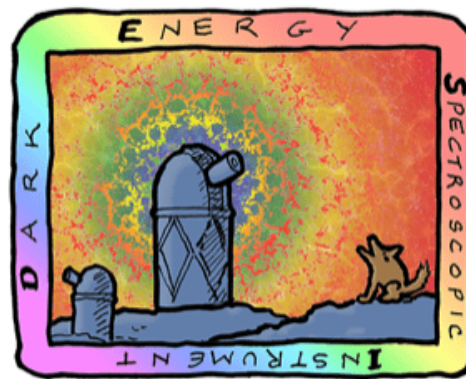
U.S. Department of Energy Office of Science

## DESI BAO measurements



12

From: A. De Mattia

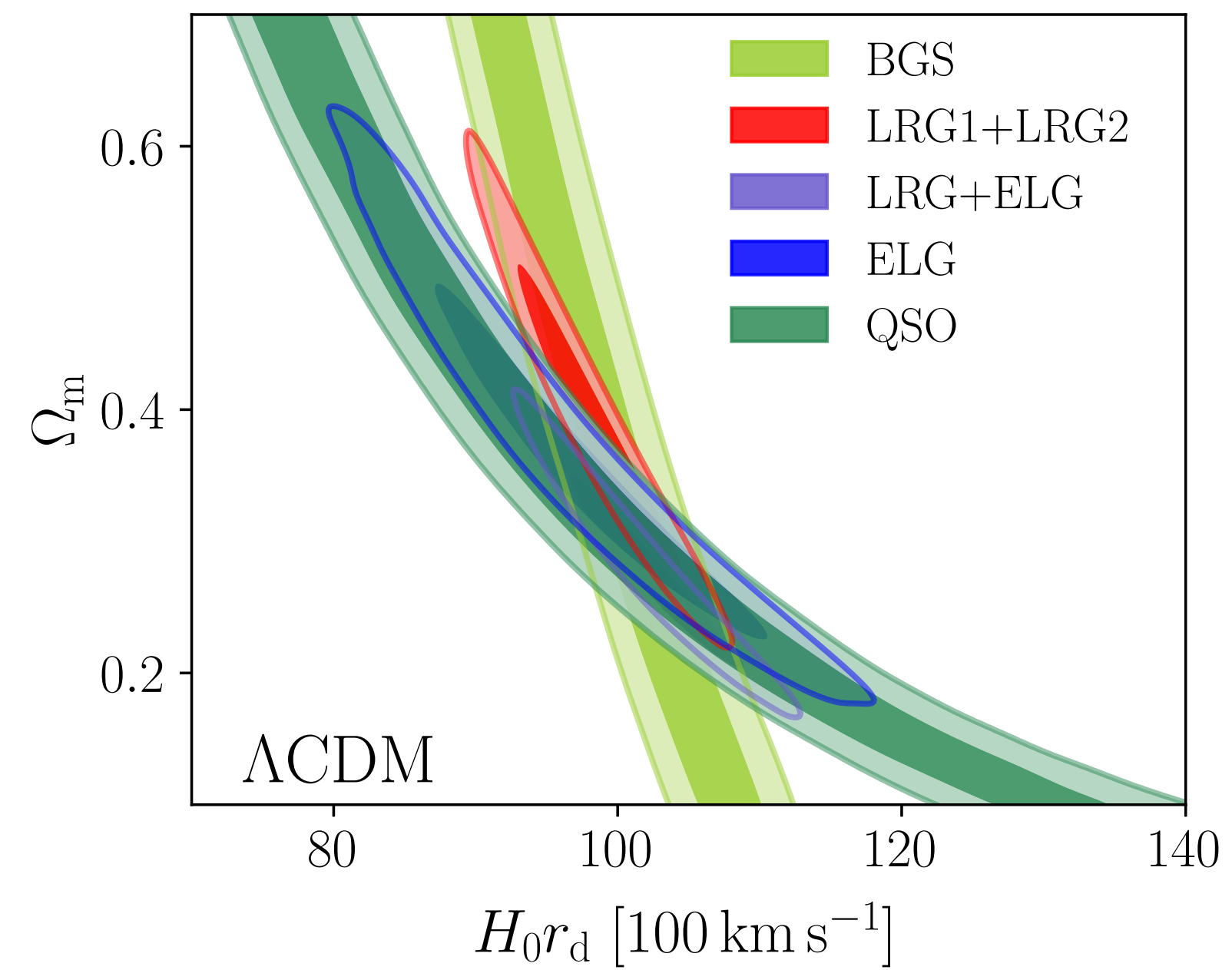
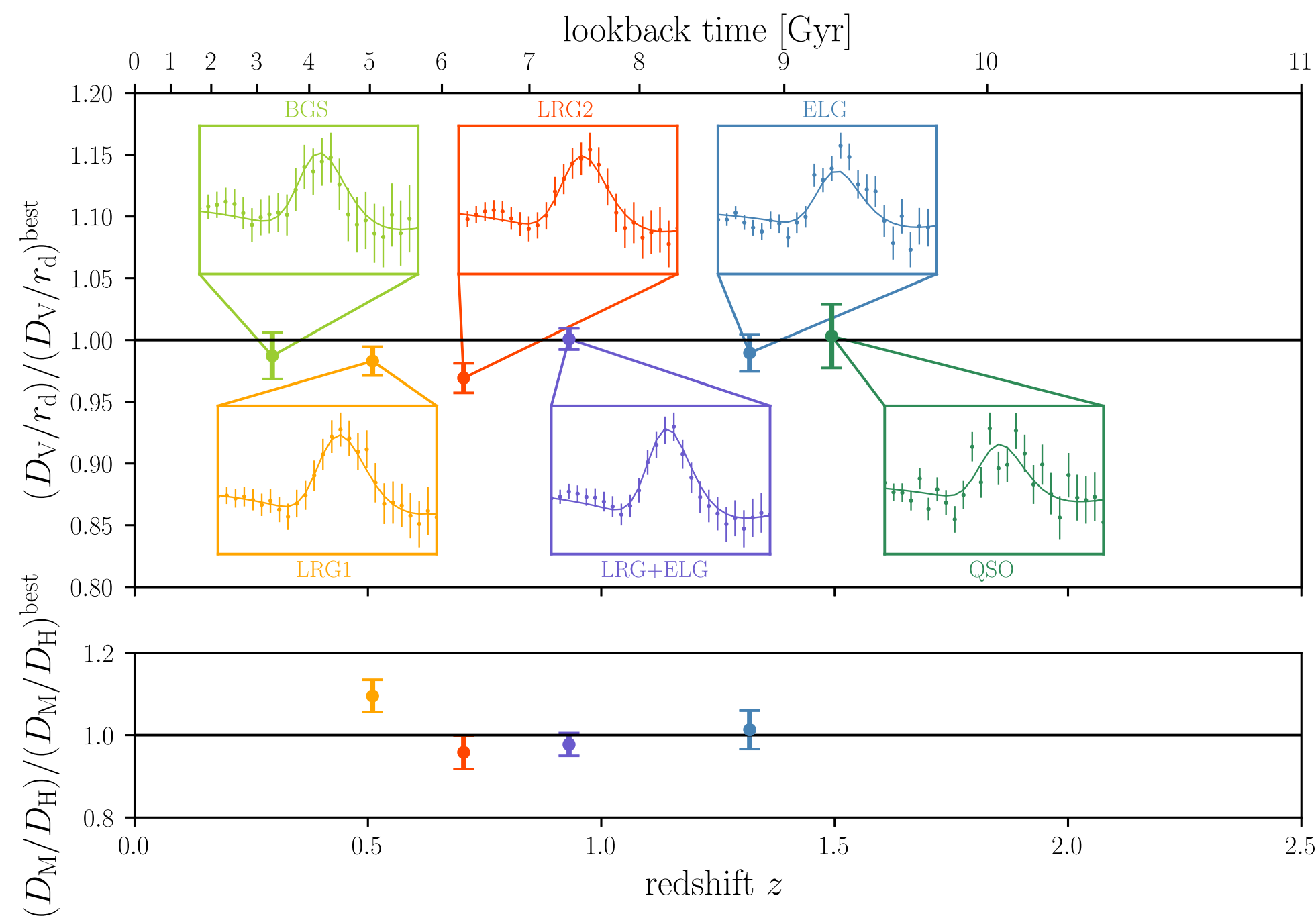


DARK ENERGY  
SPECTROSCOPIC  
INSTRUMENT

# DESI Y1 BAO

U.S. Department of Energy Office of Science

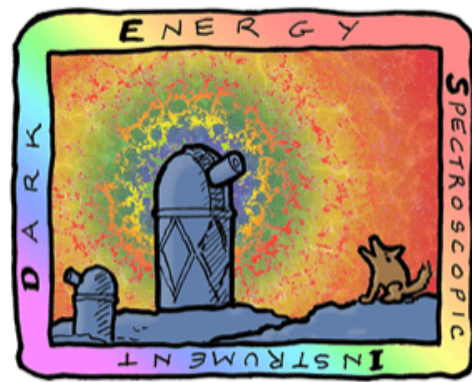
## DESI BAO measurements



13

From: A. De Mattia



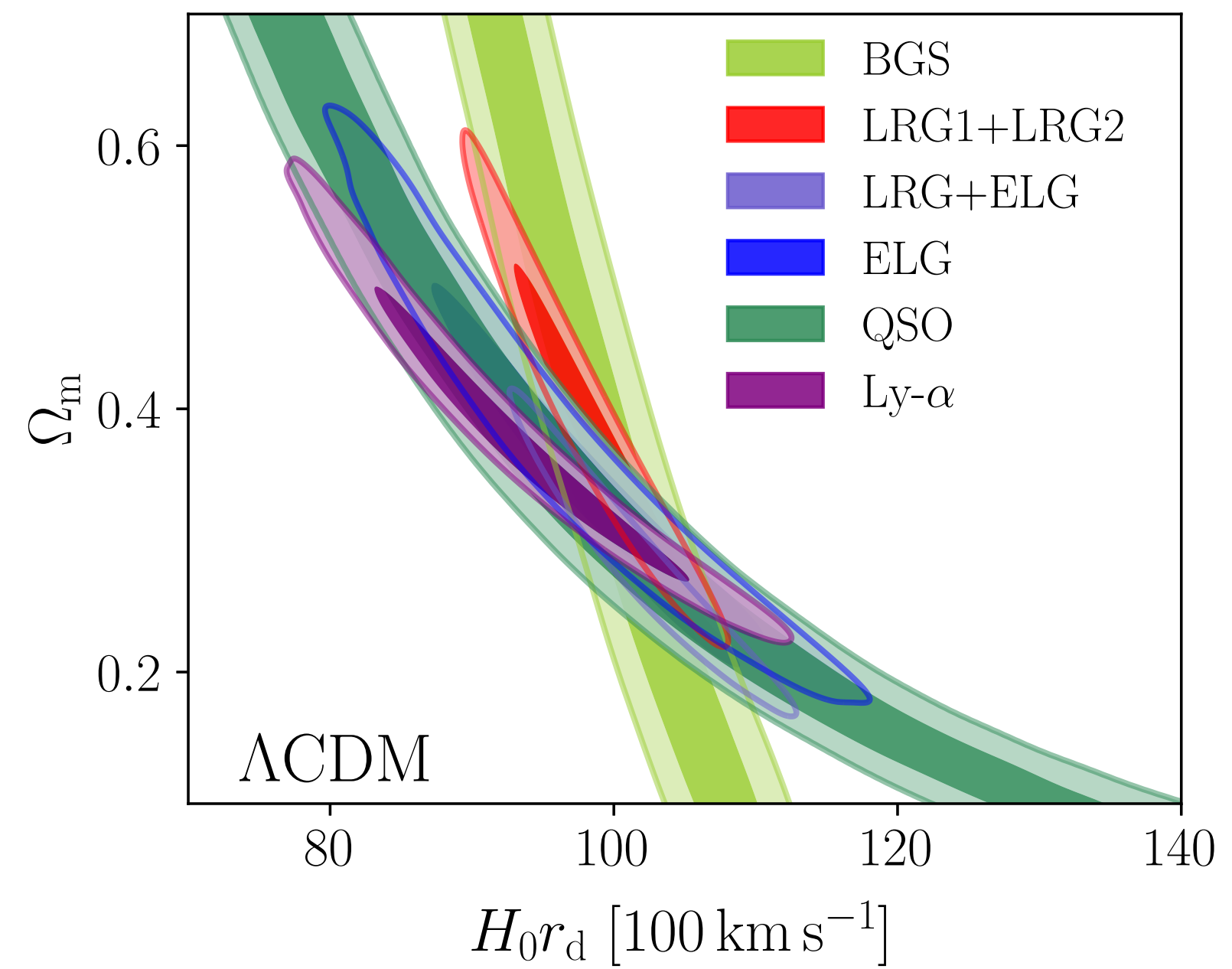
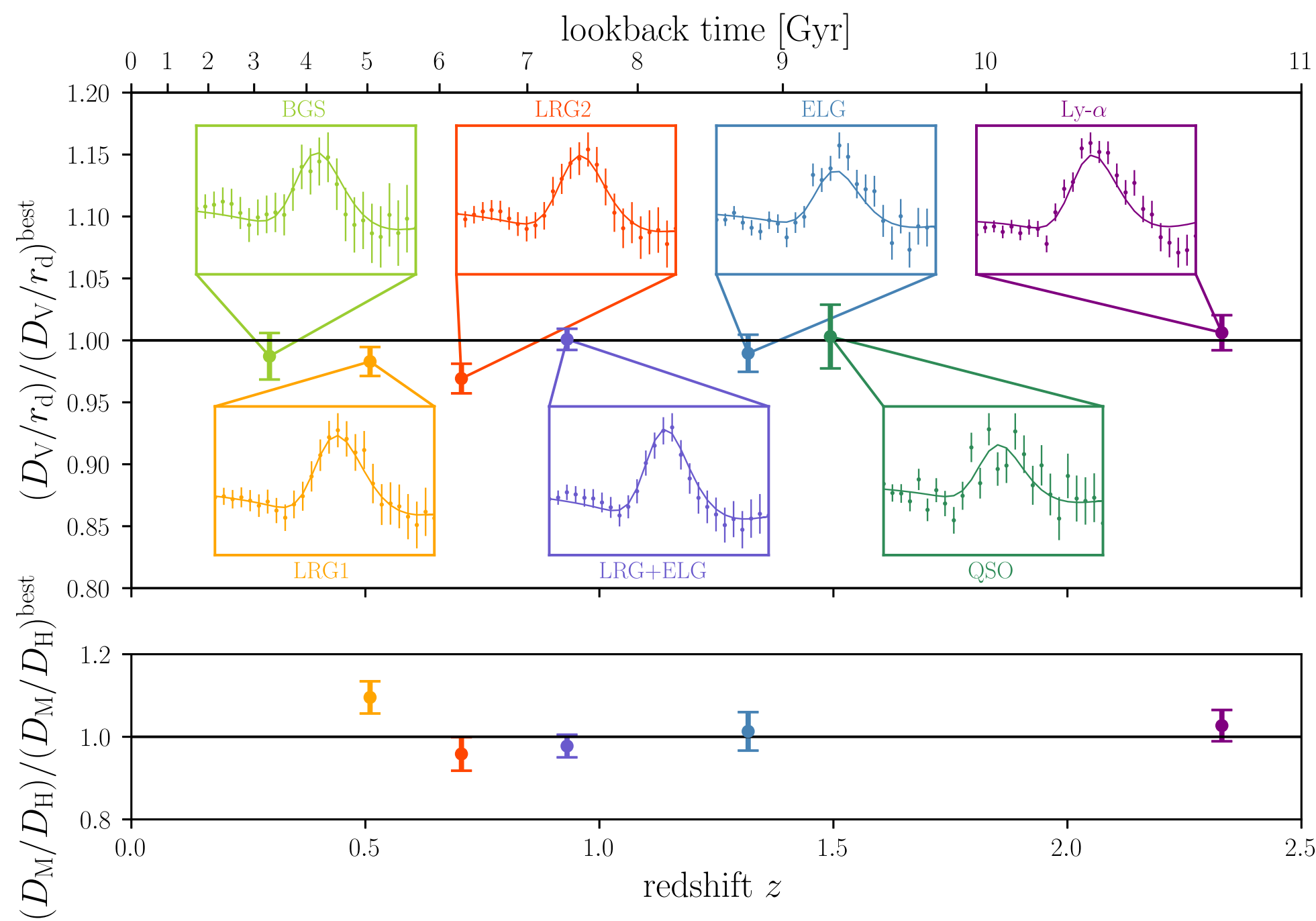


DARK ENERGY  
SPECTROSCOPIC  
INSTRUMENT

# DESI Y1 BAO

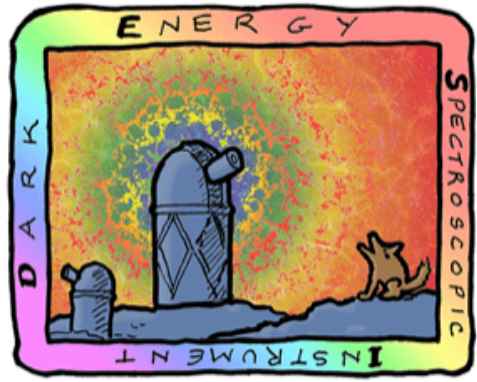
U.S. Department of Energy Office of Science

## DESI BAO measurements



14

From: A. De Mattia



DARK ENERGY  
SPECTROSCOPIC  
INSTRUMENT

# DESI Y1 BAO

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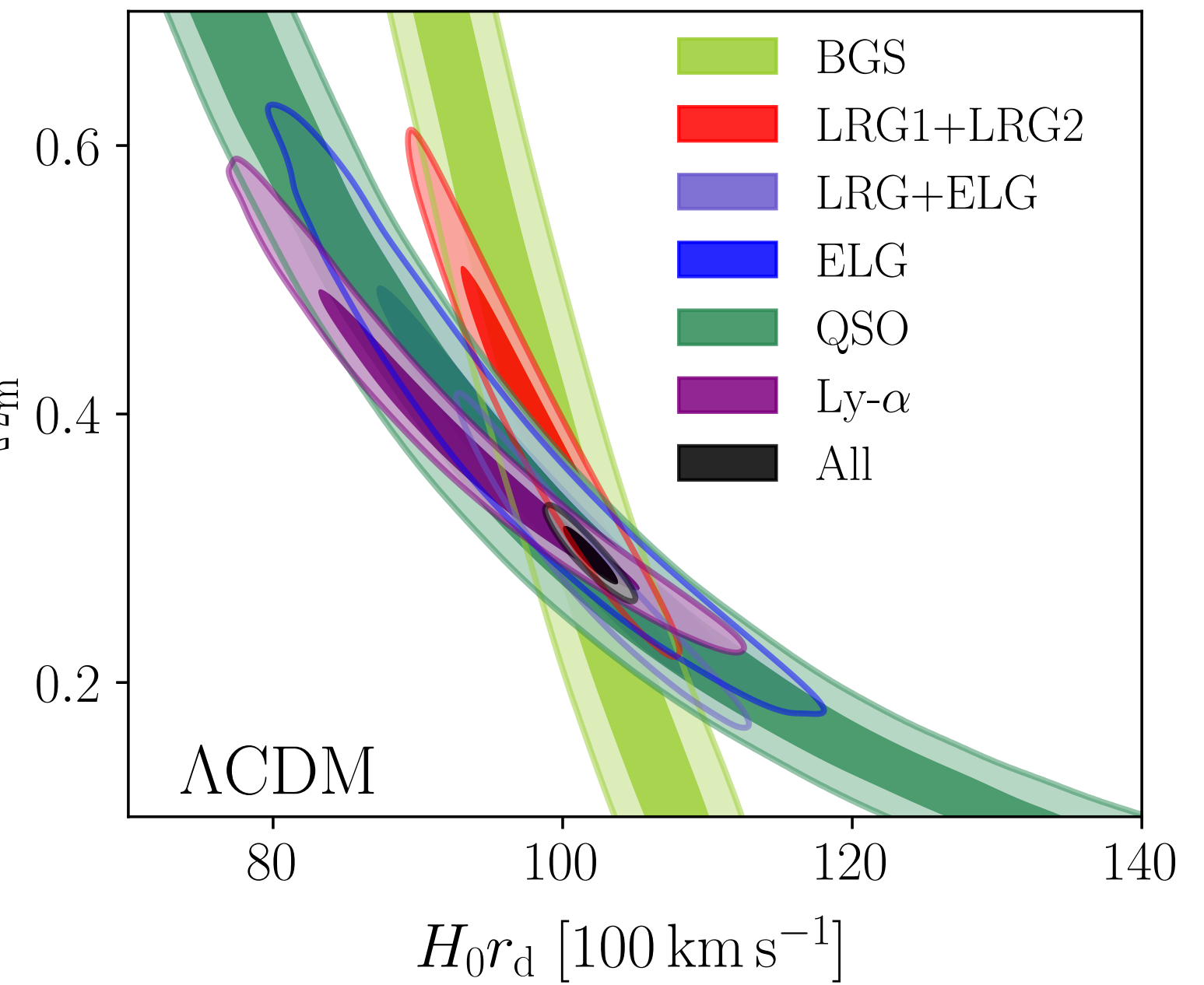
## DESI BAO measurements

Consistent with each other,  
and complementary

$$\Omega_m = 0.295 \pm 0.015 \quad (5.1\%)$$

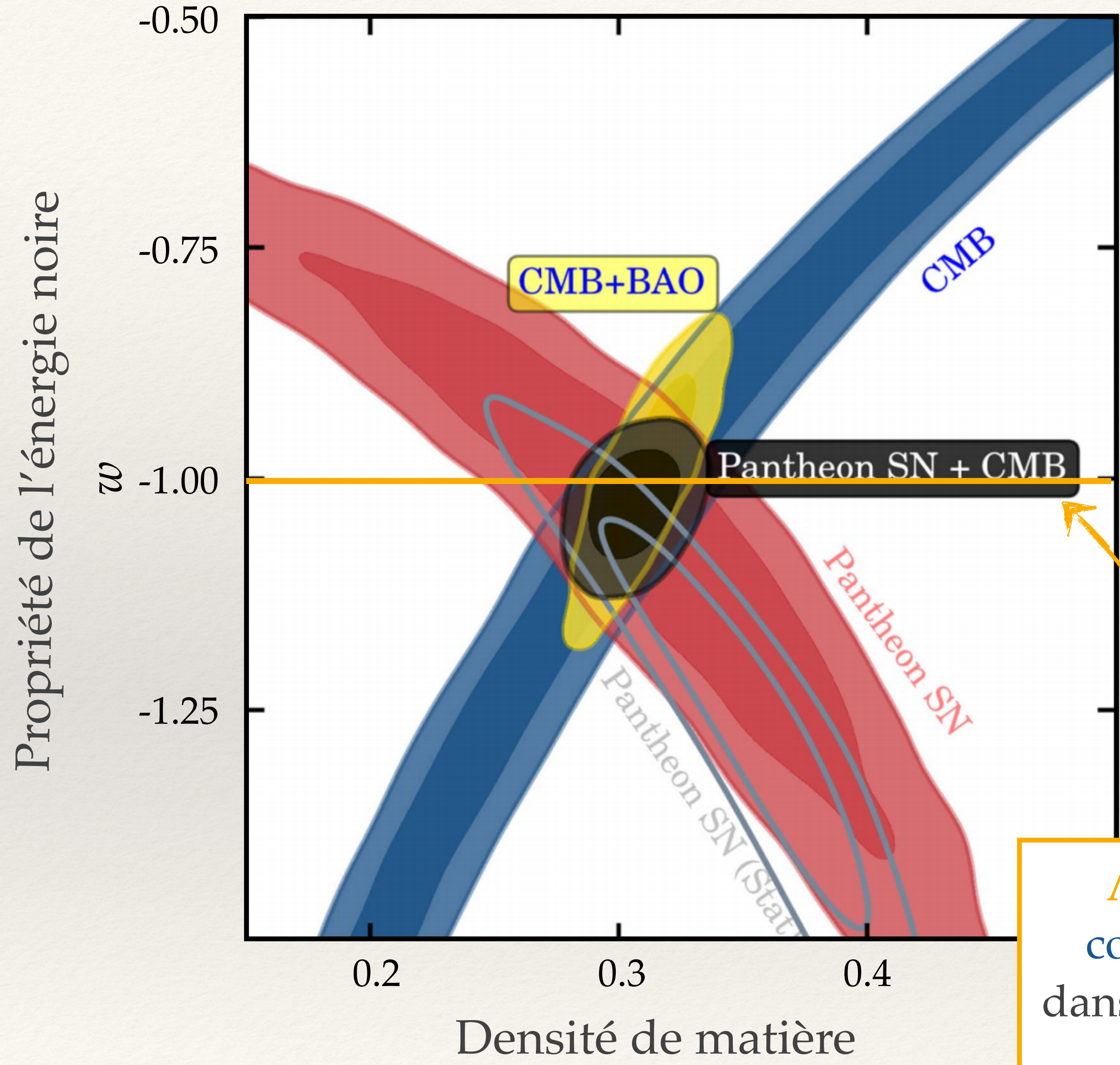
$$H_0 r_d = (101.8 \pm 1.3) [100 \text{ km s}^{-1}] \quad (1.3\%)$$

DESI

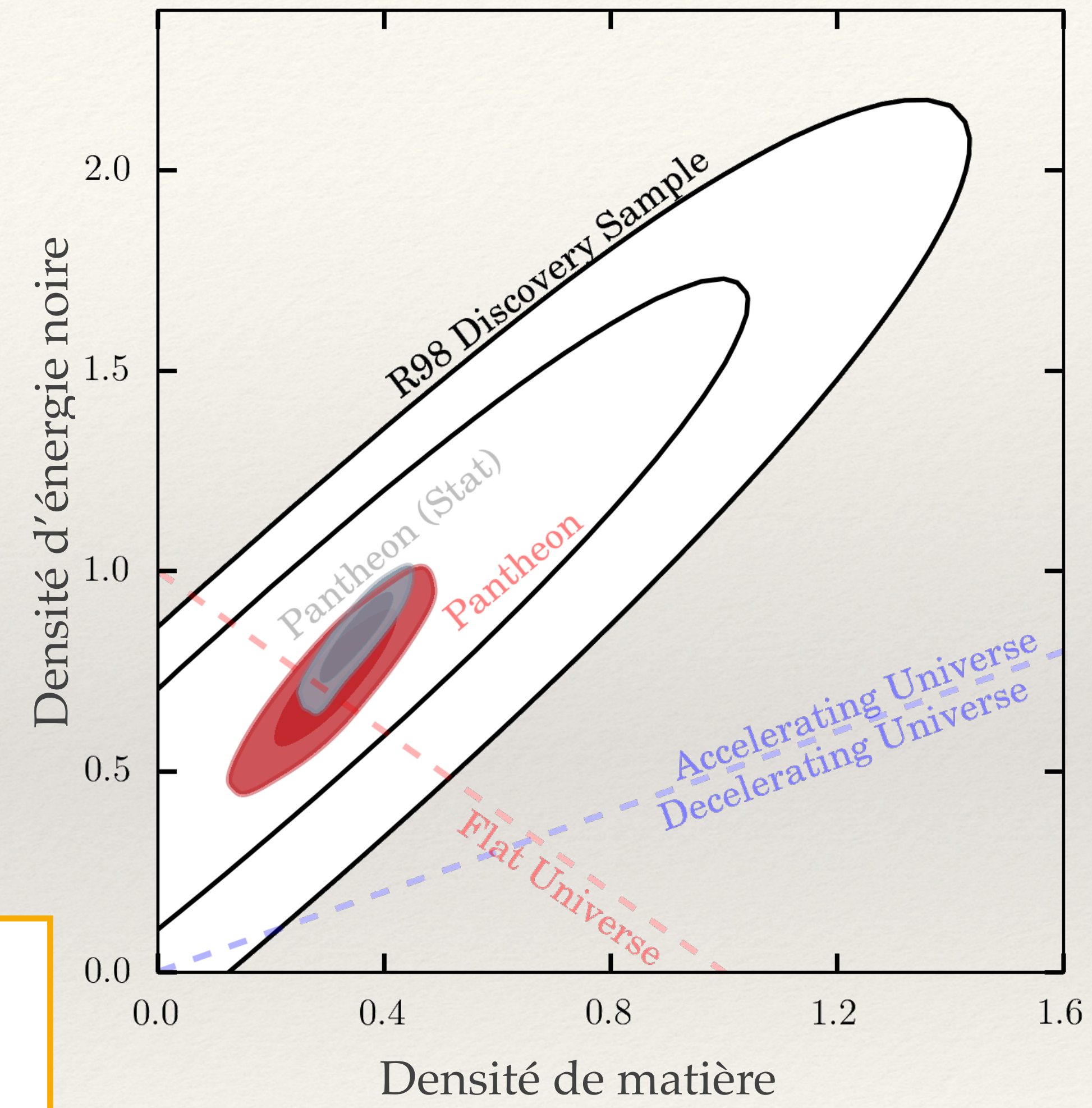


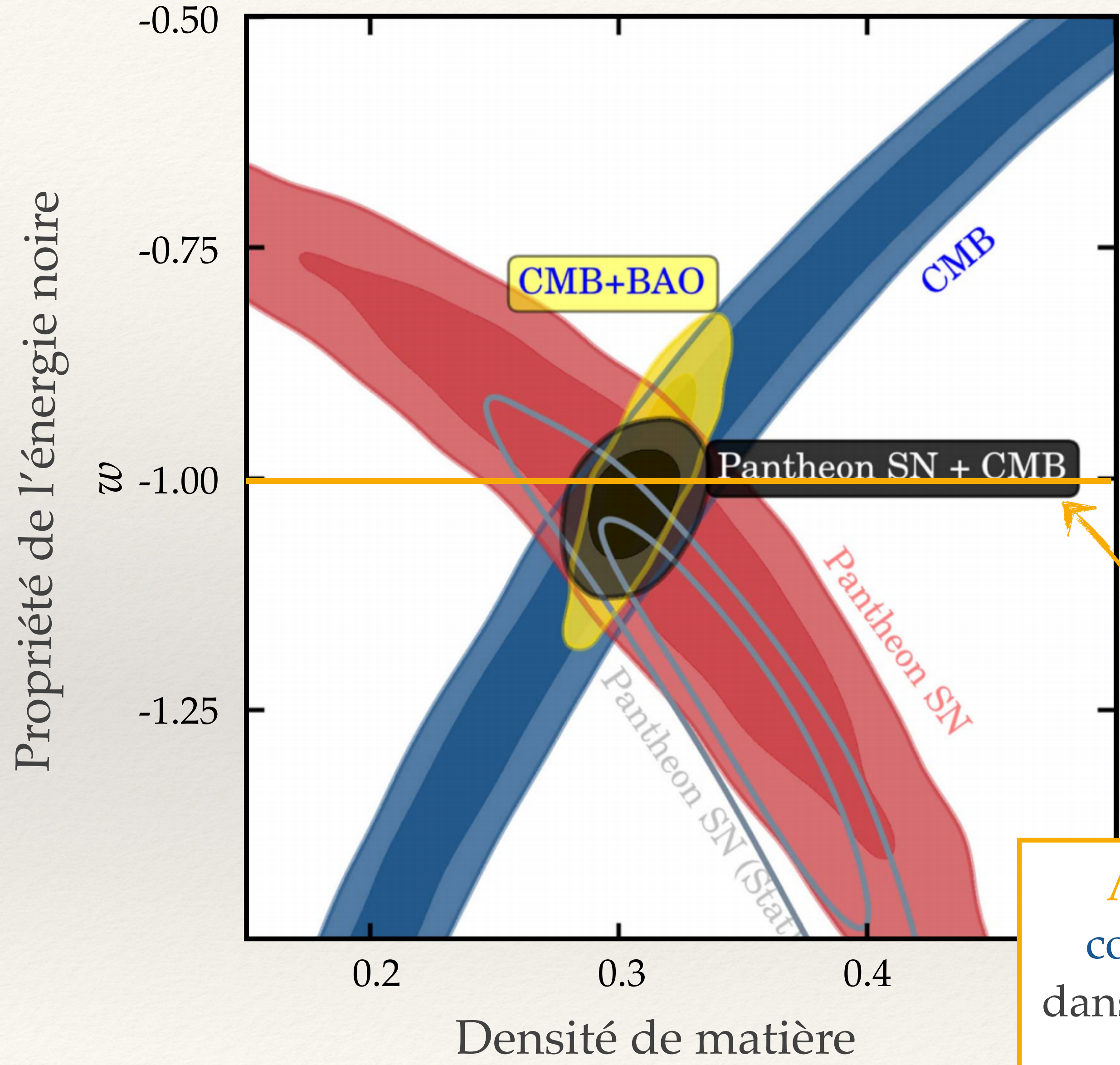
15

From: A. De Mattia

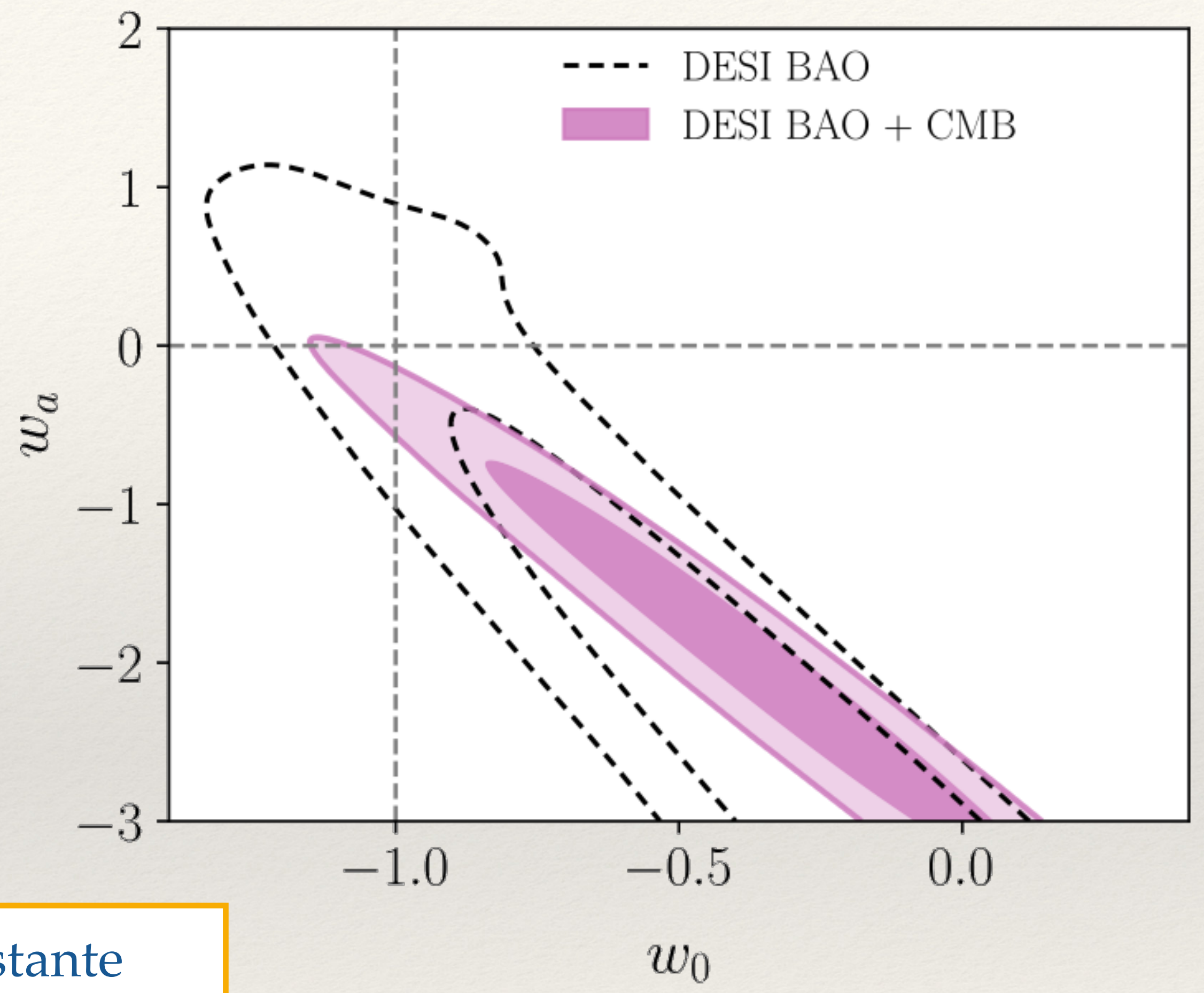


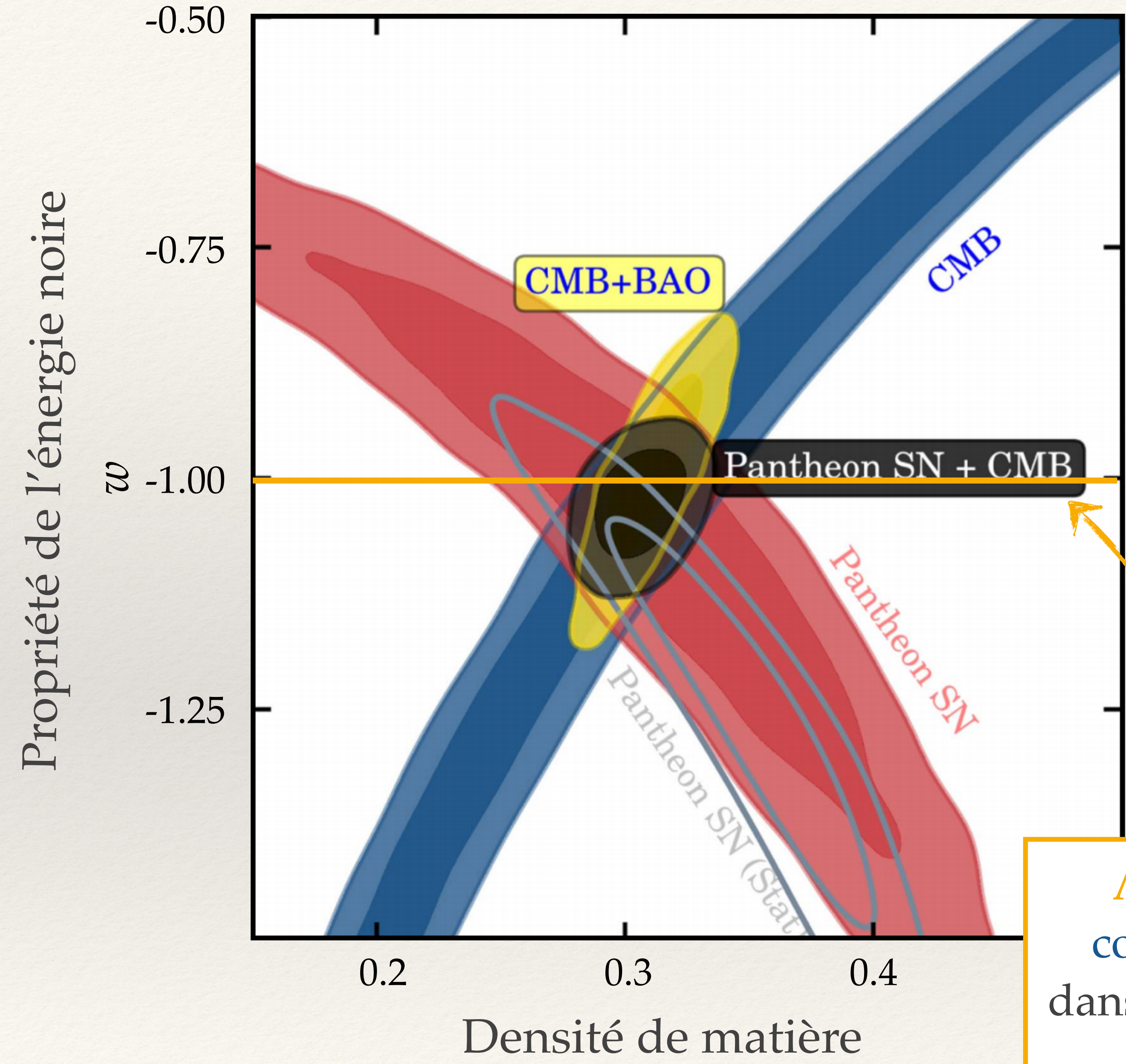
$\Lambda$  constante cosmologique dans les équations d'Einstein



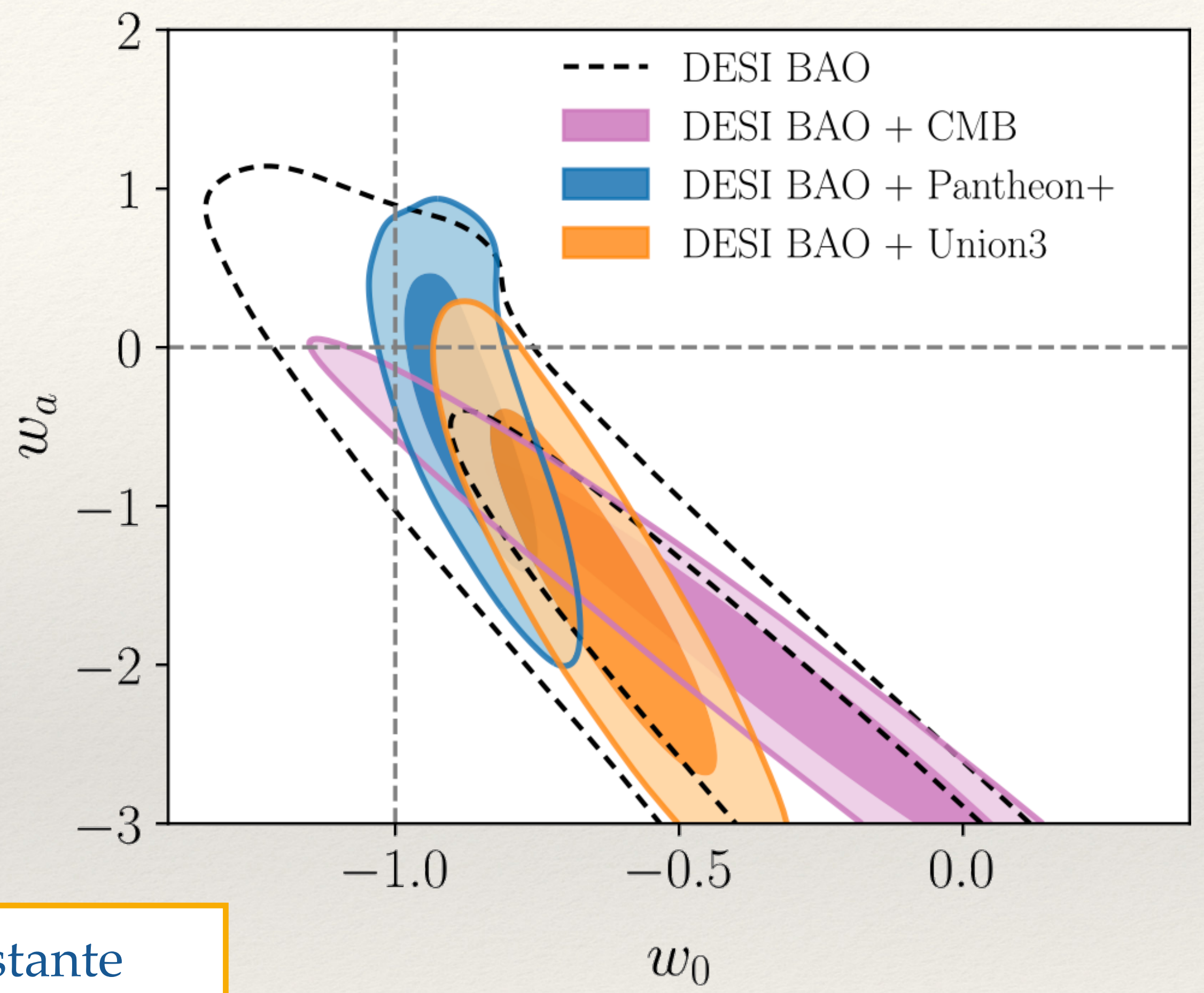


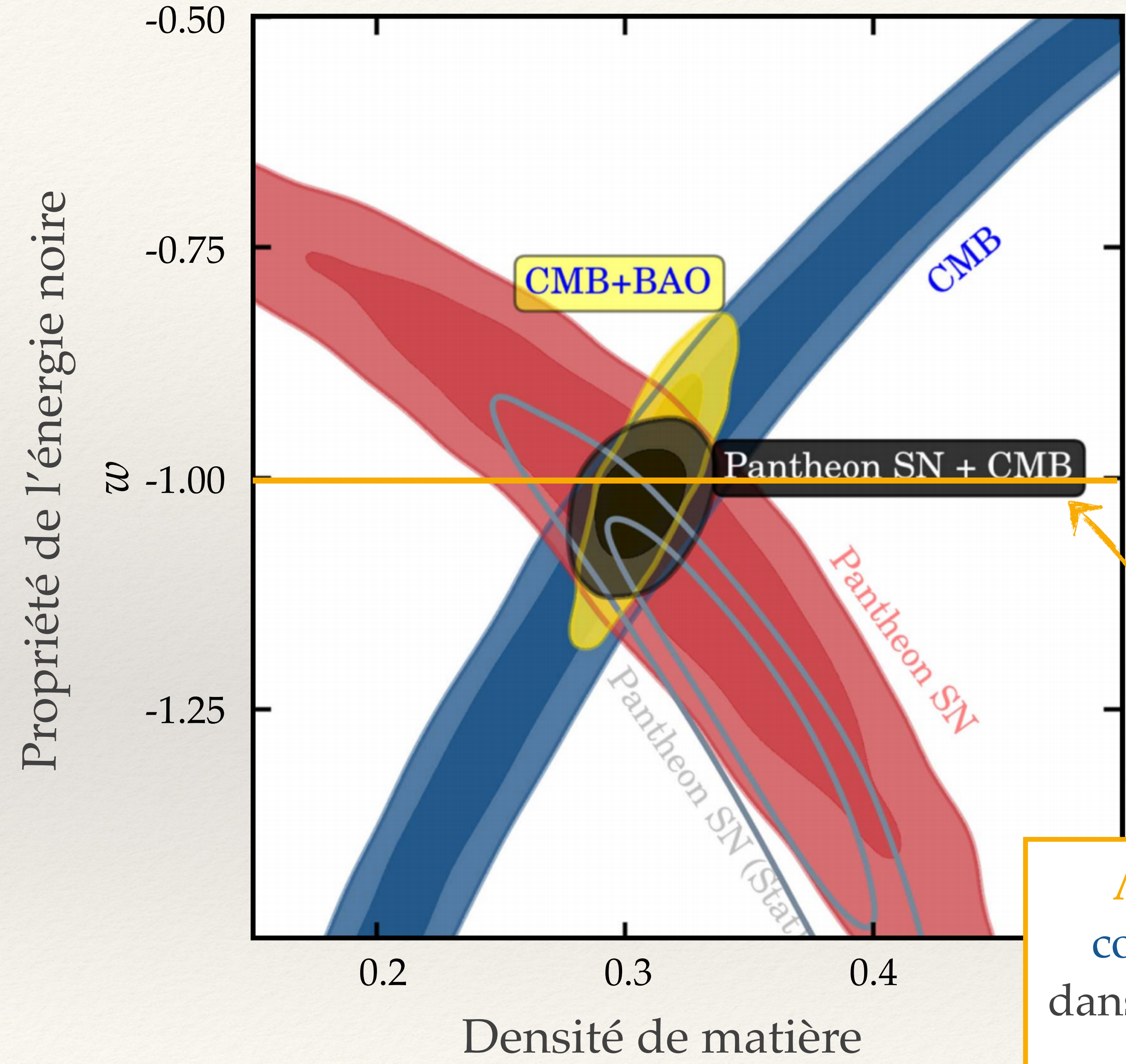
$\Lambda$  constante cosmologique dans les équations d'Einstein



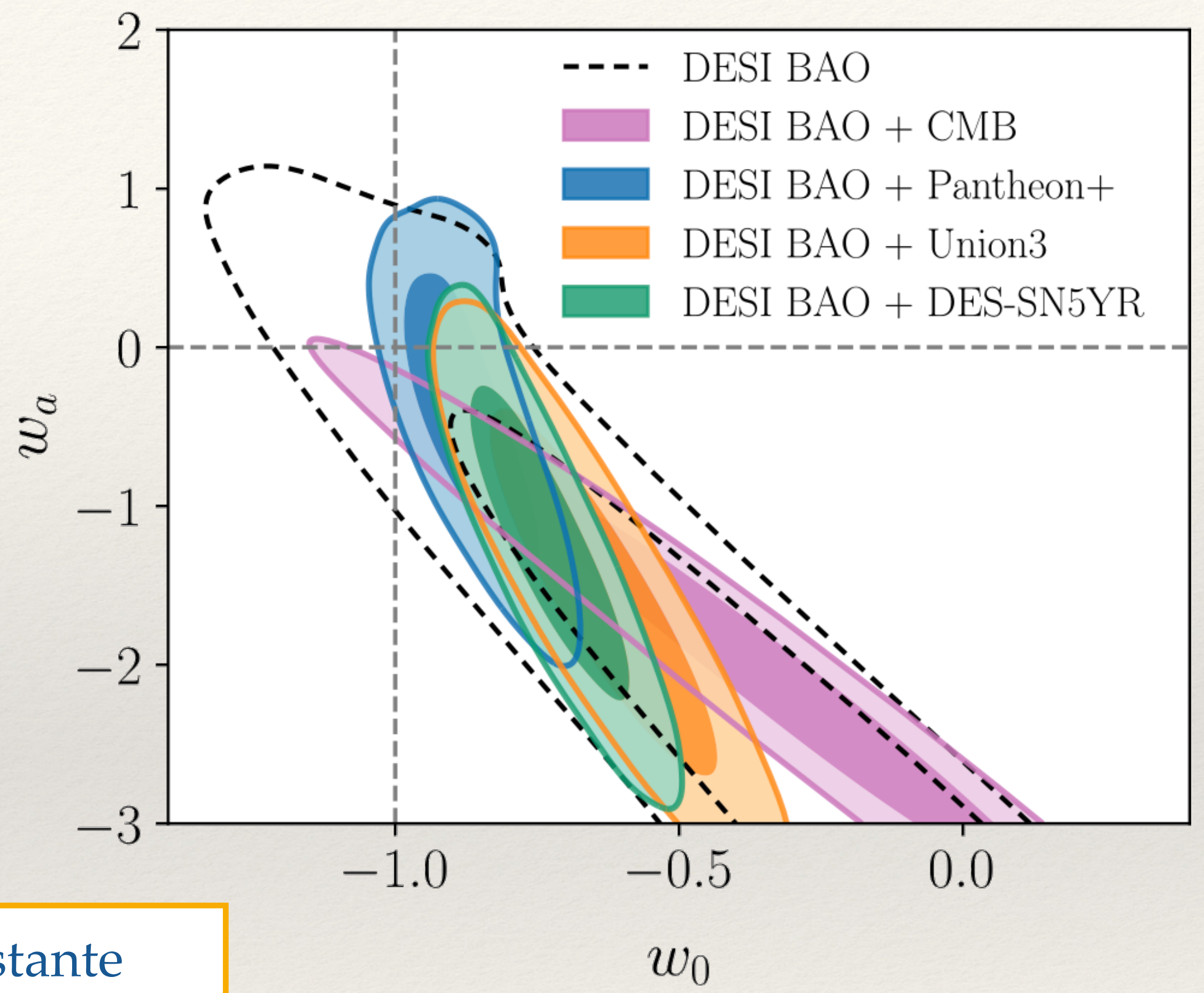


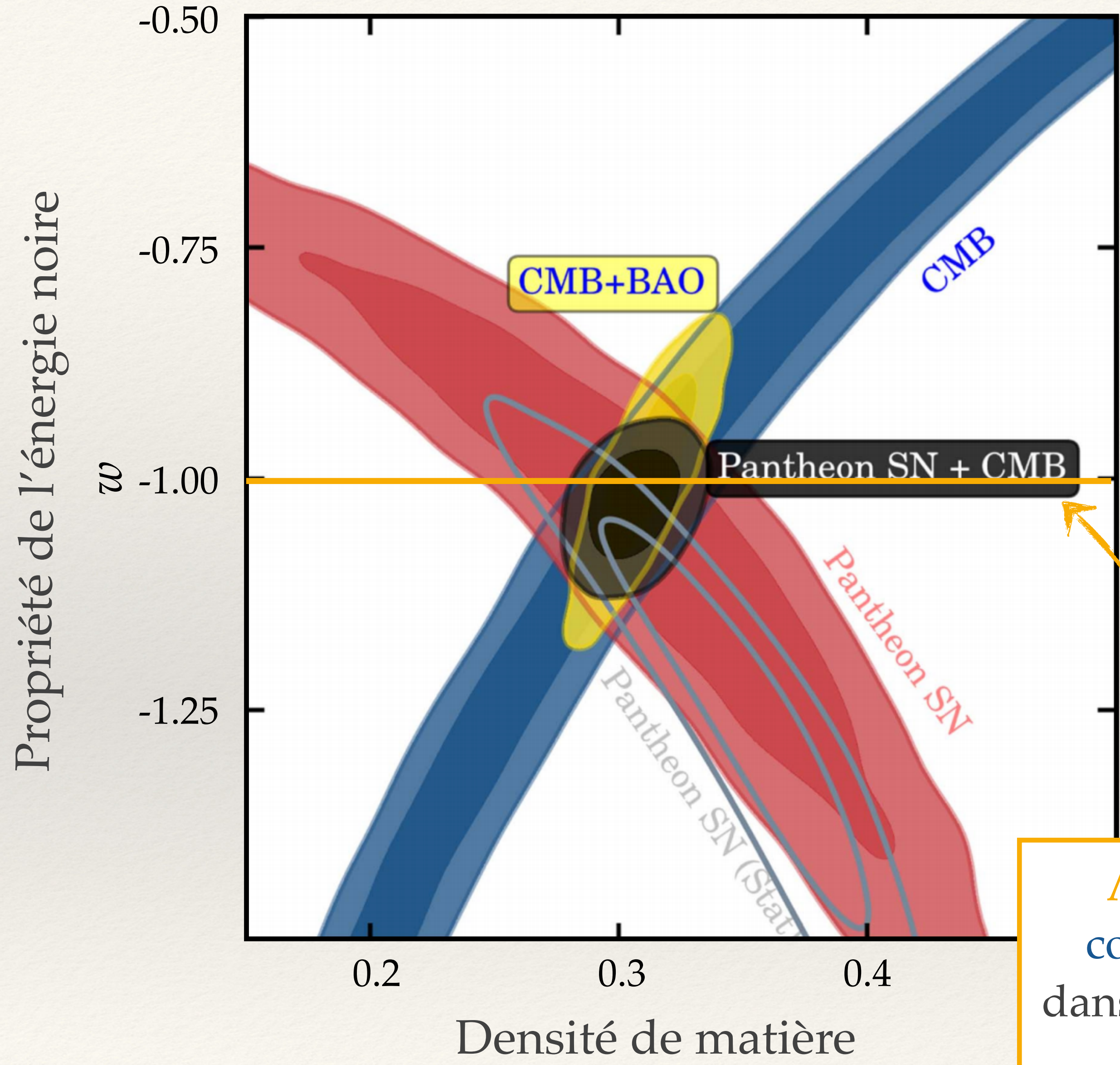
$\Lambda$  constante cosmologique dans les équations d'Einstein



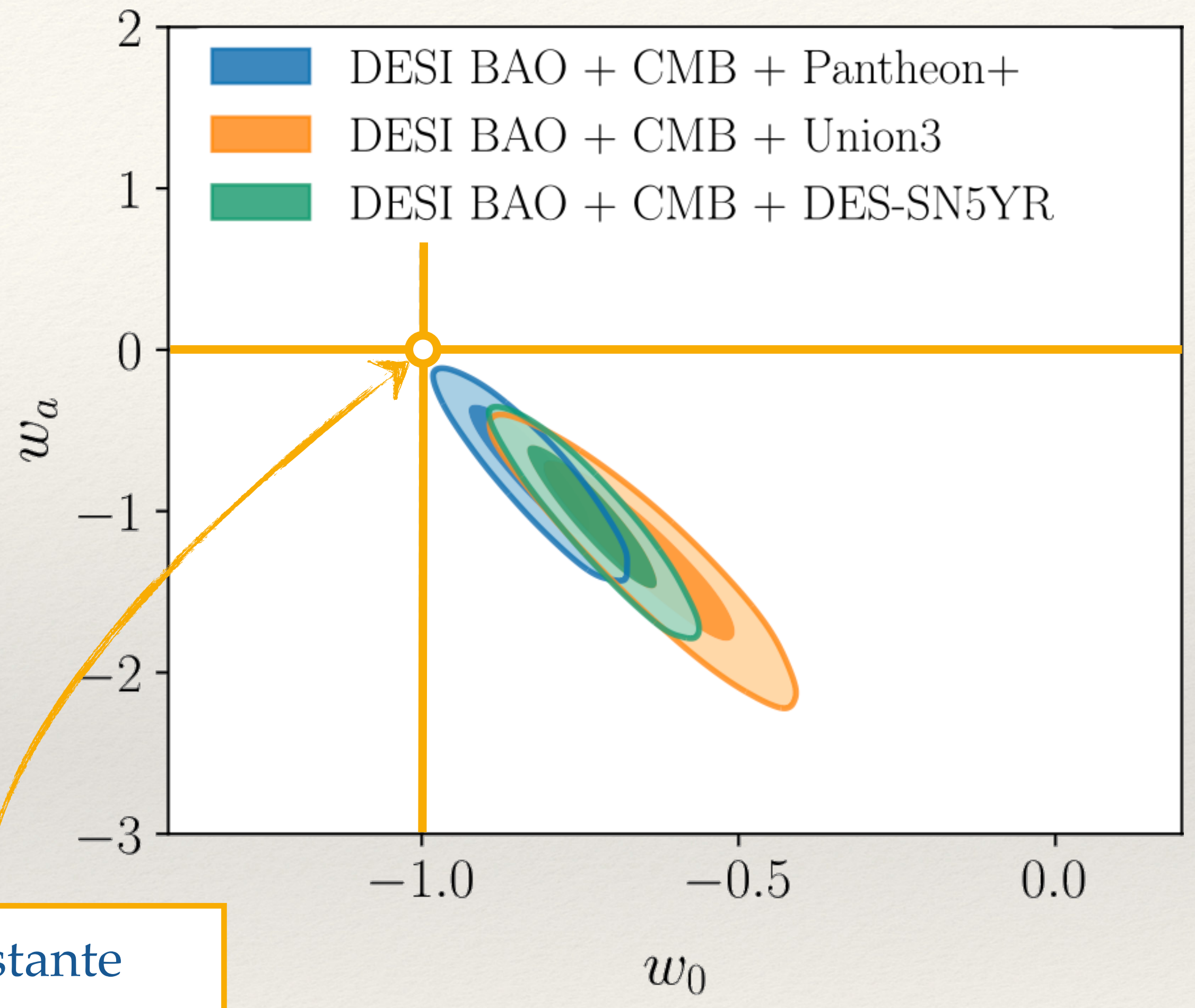


$\Lambda$  constante cosmologique dans les équations d'Einstein





$\Lambda$  constante cosmologique dans les équations d'Einstein



# Modern Cosmology | $H_0$ Direct vs. Indirect Measurements

$$H_0 = d_l / v_h$$

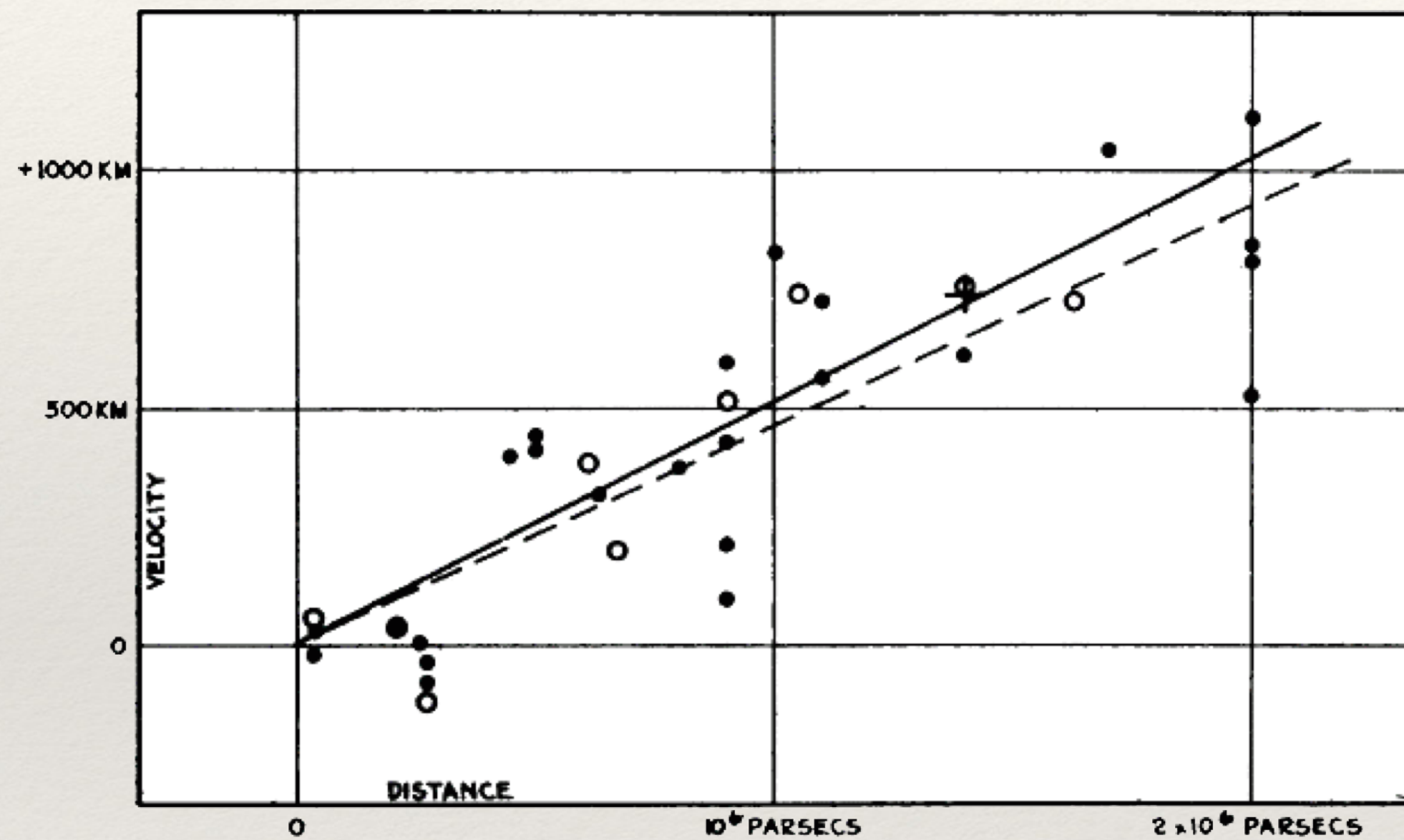
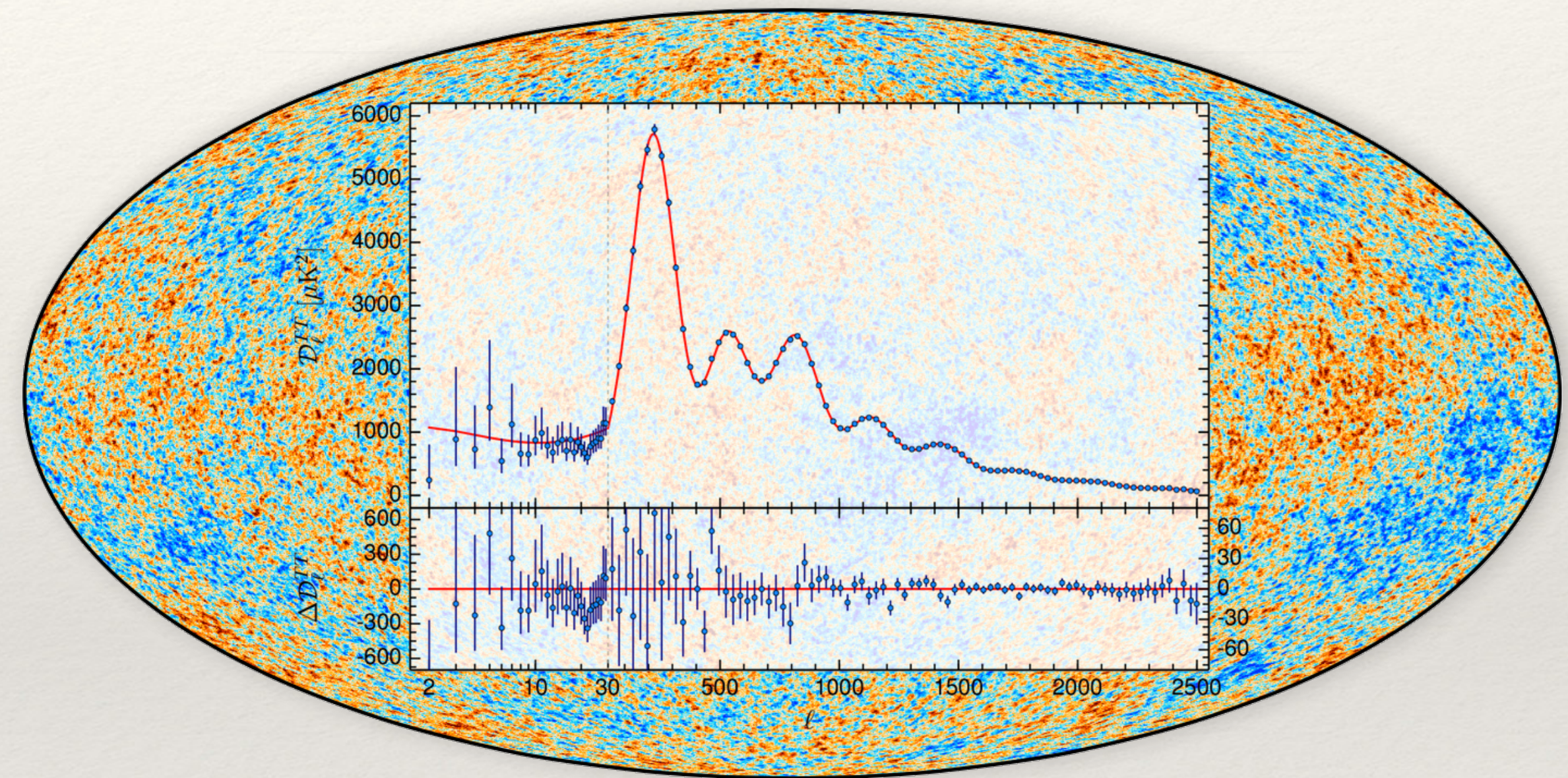


FIGURE 1

*Careful with peculiar velocities*

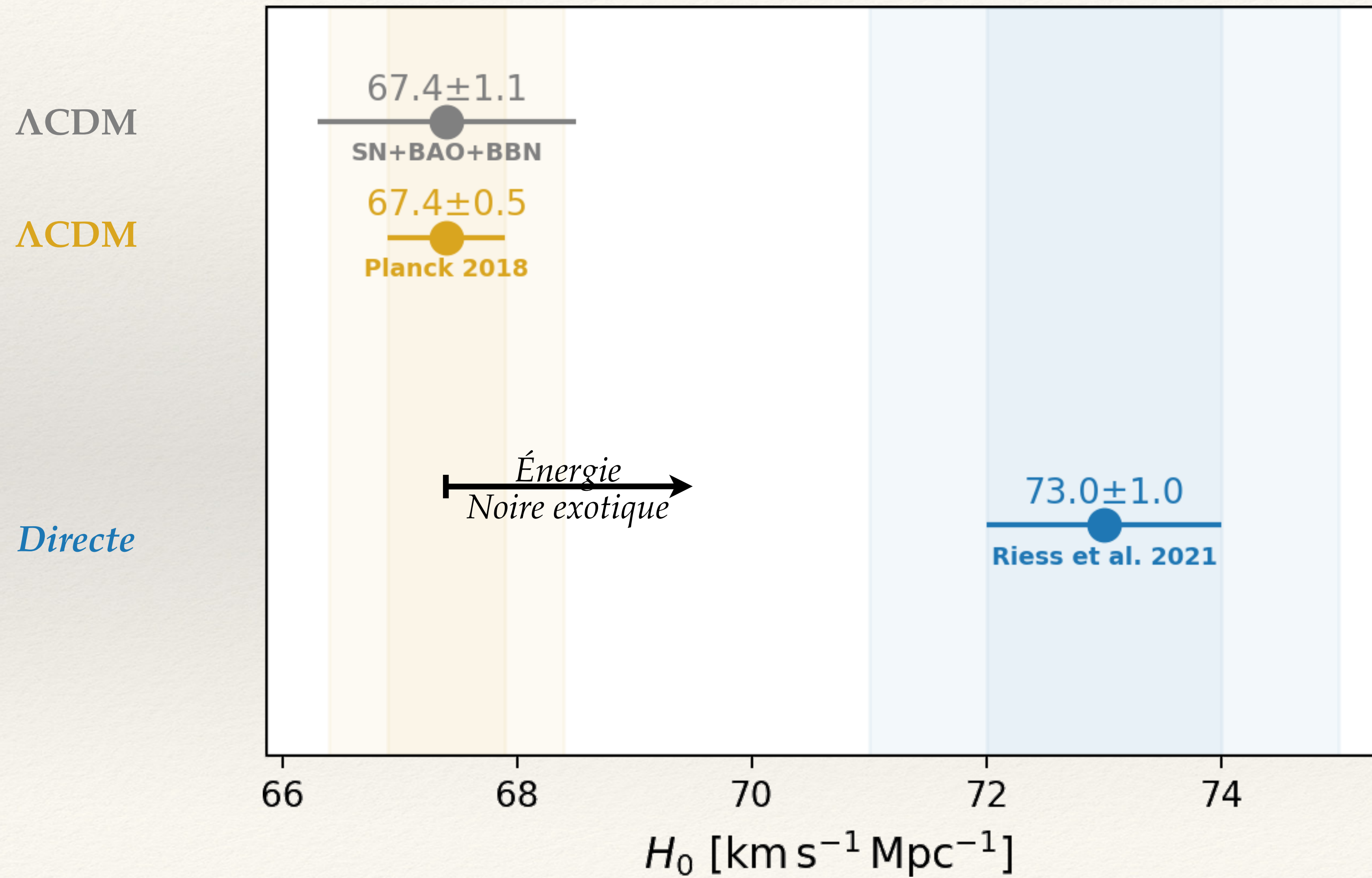
$$H(\underline{z}) = H_0 \times \sqrt{\Omega_r(1 + \underline{z})^4 + \Omega_m(1 + \underline{z})^3 + \Omega_\Lambda(1 + \underline{z})^{3(1+w)}}$$



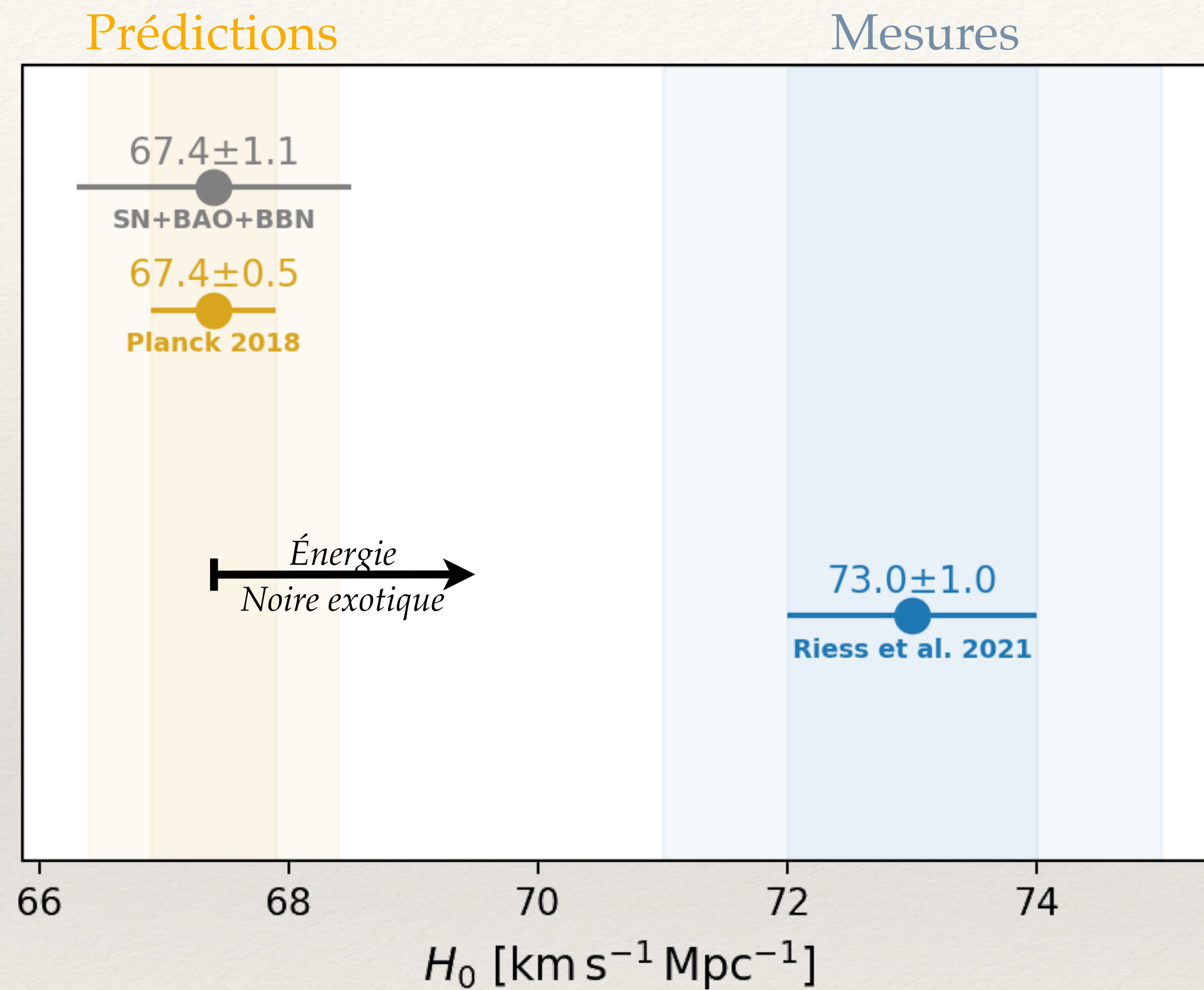
*Model dependent*



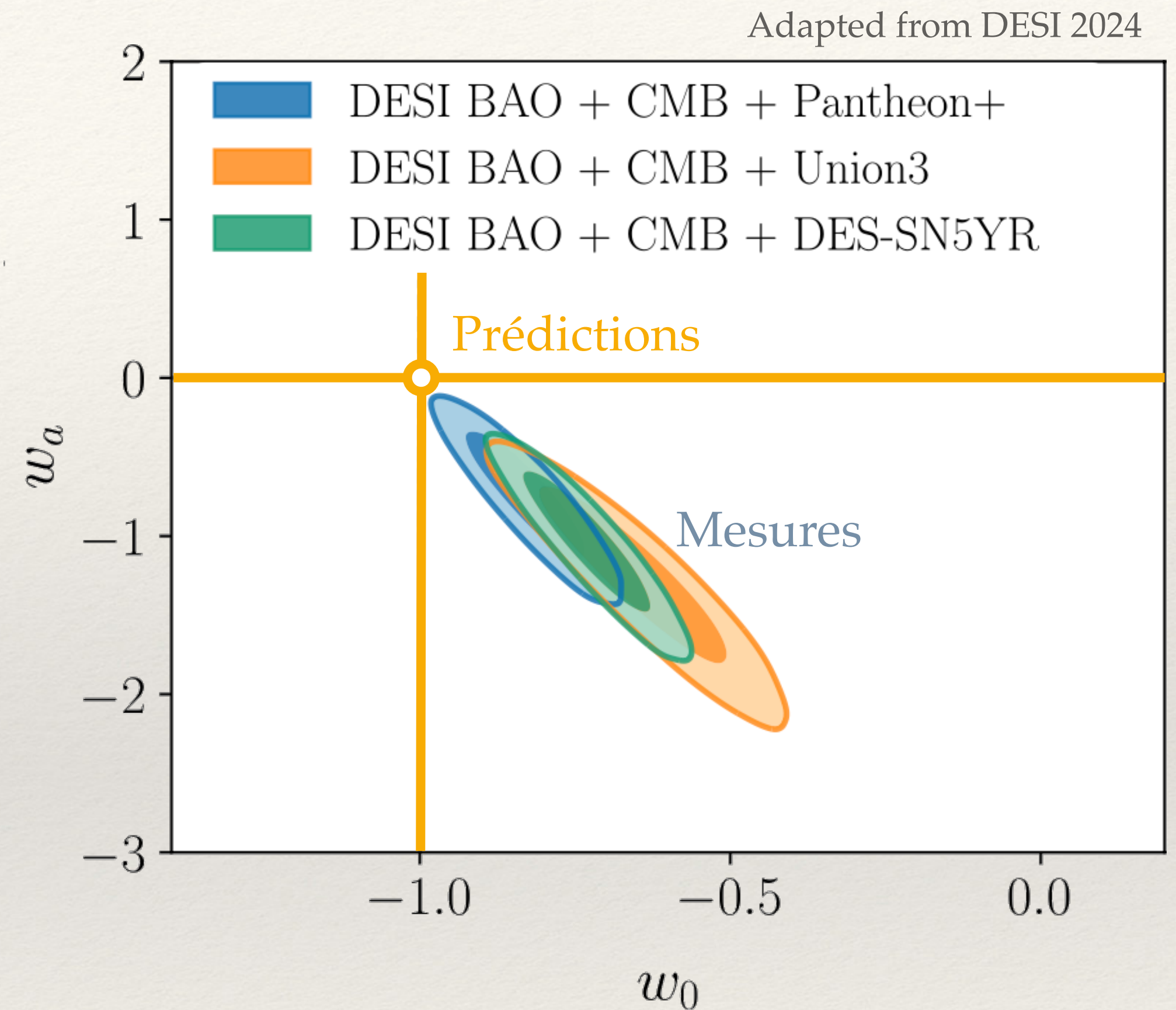
# Extension du modèle standard



# Trouble dans la Cosmologie



Constante de Hubble-Lemaître



Propriétés de l'énergie noire