Inverno Astrofísico

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Lecture 1

Indications of the existence of dark energy

SNIa, CMB, BAO

Lecture 2

The cosmological constant problem
Effects of the cosmological constant

Lecture 3

Models of dark energy…?

Luminosity distance

Photons move on null geodesics

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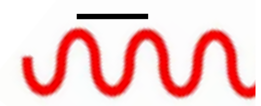

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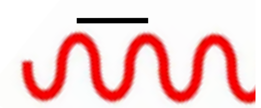

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We define the redshift as

$$z = \frac{\lambda_{rec} - \lambda_{em}}{\lambda_{em}} = \frac{a(t_{rec})}{a(t_{em})} - 1$$

$$1 + z = \frac{a(t_{rec})}{a(t_{em})} \equiv \frac{1}{a(t)}$$

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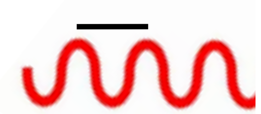

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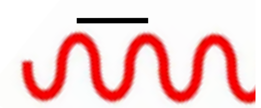

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$$1 + z = \frac{\lambda_{rec}}{\lambda_{em}} = \frac{\delta t_{rec}}{\delta t_{em}} = \frac{E_{em}}{E_{rec}} \qquad \boxed{\begin{aligned} E_{em} &= (1+z)E_{rec} \\ \delta t_{rec} &= (1+z)\delta t_{em} \end{aligned}}$$

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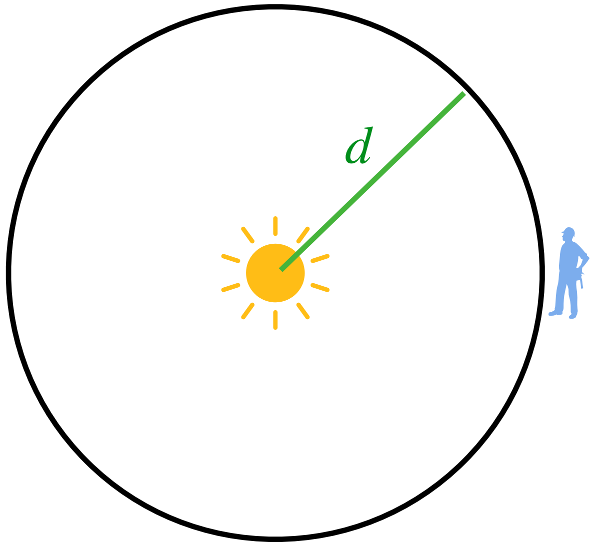
Luminosity distance



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Apparent luminosity (ℓ): power per unit area (flux density)

$$\ell = \frac{L}{4\pi d^2}$$

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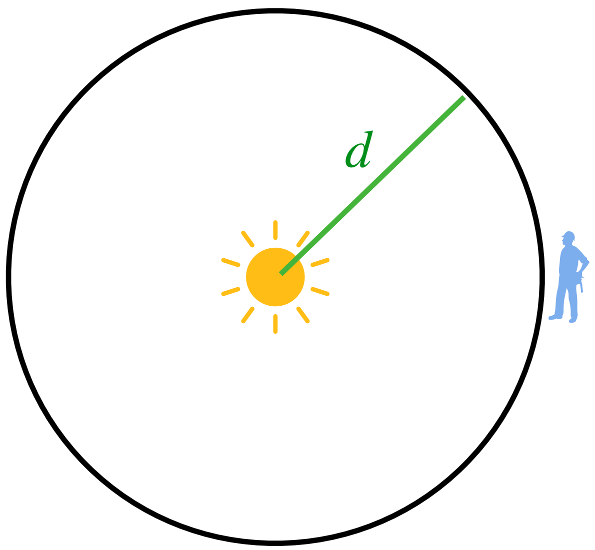

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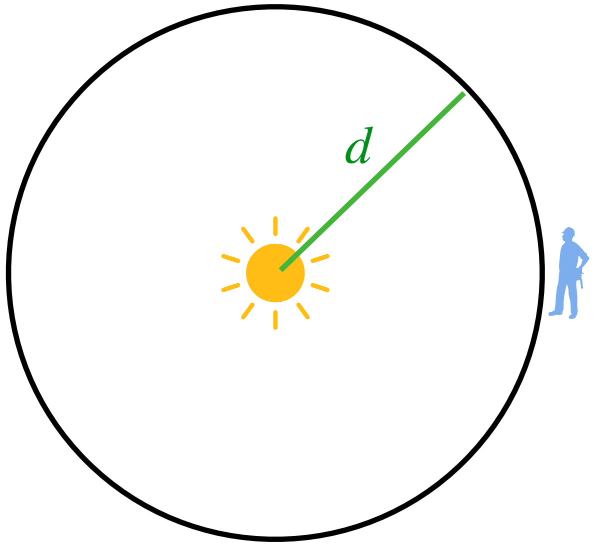

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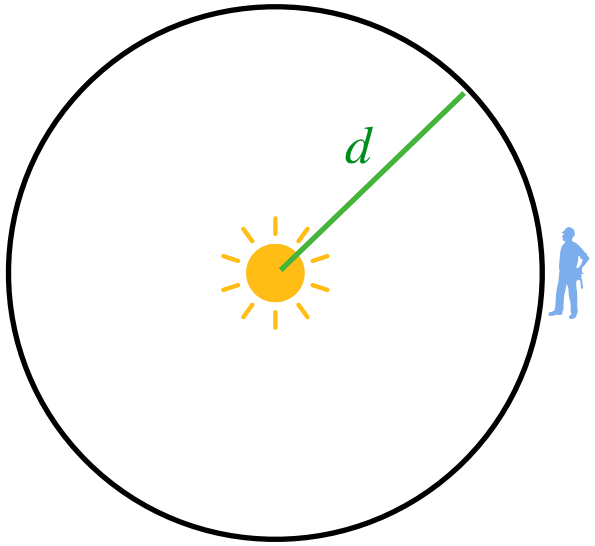

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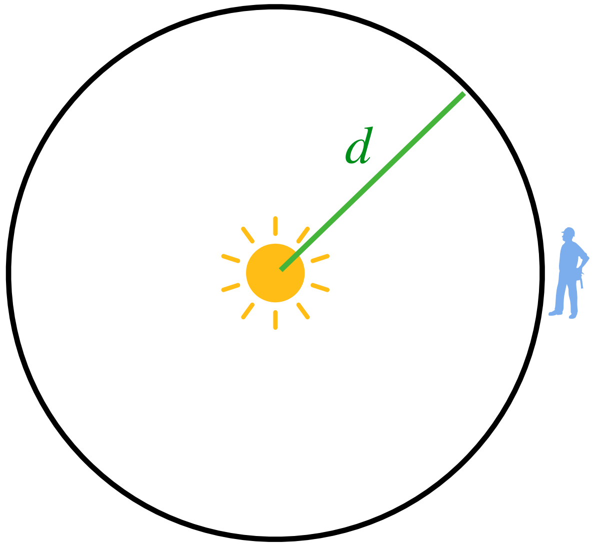

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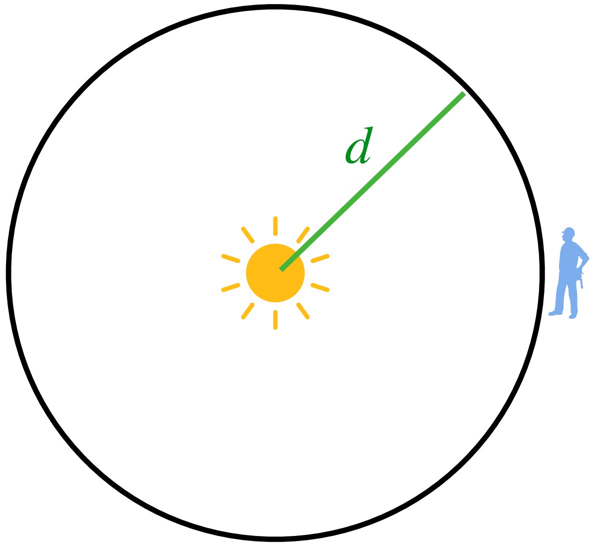

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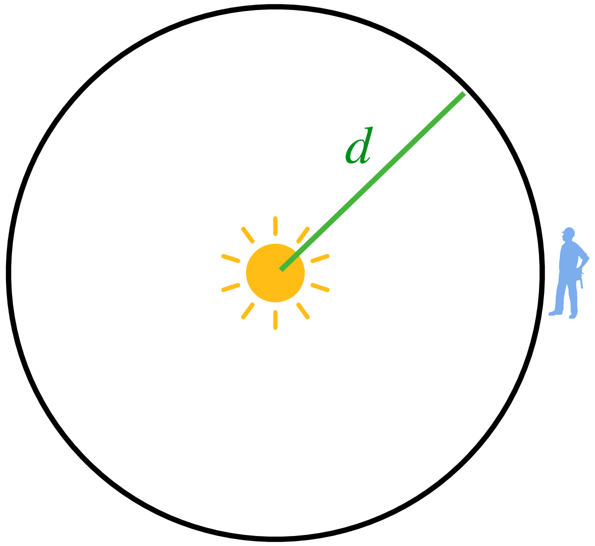

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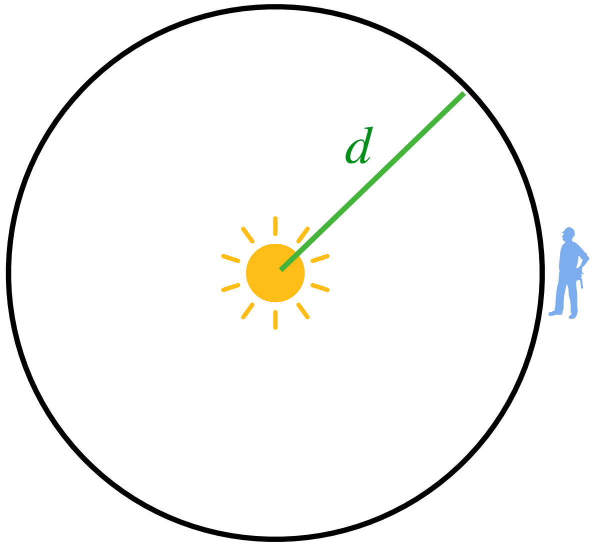

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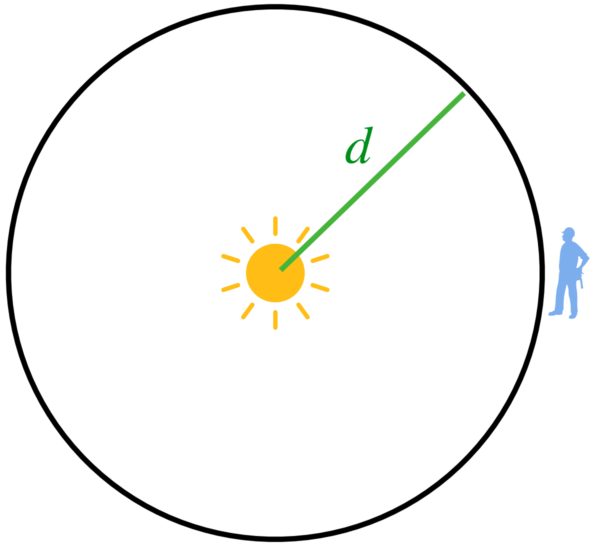

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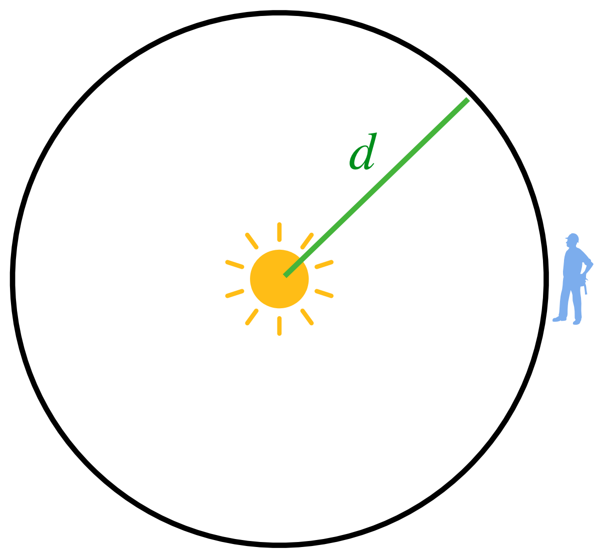

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Luminosity distance

How to calculate the superficie A … from the metric

$$ds^2 = -c^2dt^2 + a(t)^2dr^2 + a(t)^2r^2\left(d\theta^2 + \sin^2\theta d\phi^2\right)$$

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Luminosity distance

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$$r = c\int_0^z \frac{dz}{H(z)}$$

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How to calculate the superficie A ... from the metric

$$ds^2 = -c^2dt^2 + a(t)^2dr^2 + \underline{a(t)^2r^2\left(d\theta^2 + \sin^2\theta d\phi^2\right)}$$

$$A = 4\pi r^2 a(t) = 4\pi r^2$$

today

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Luminosity distance

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Luminosity distance

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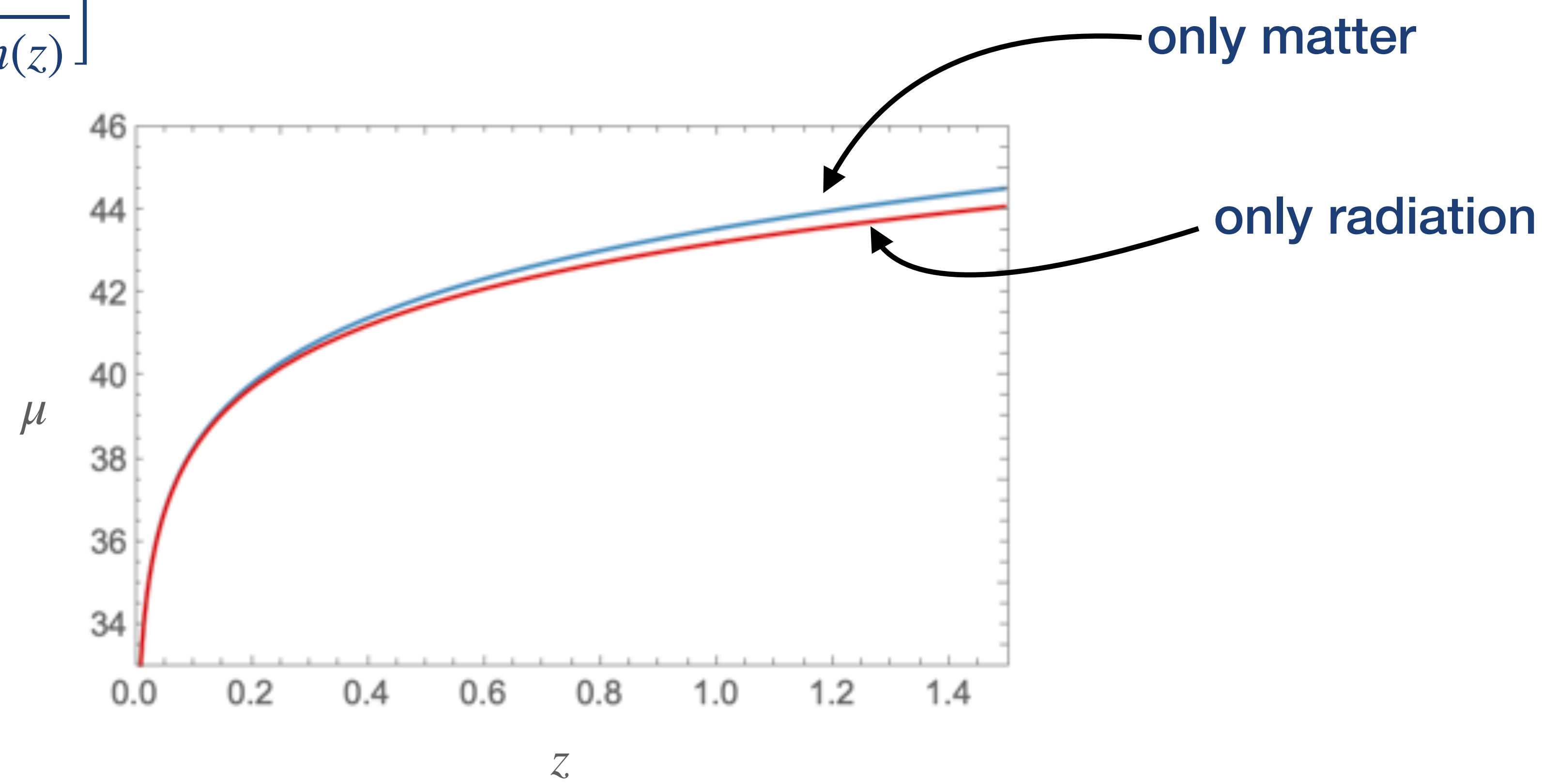

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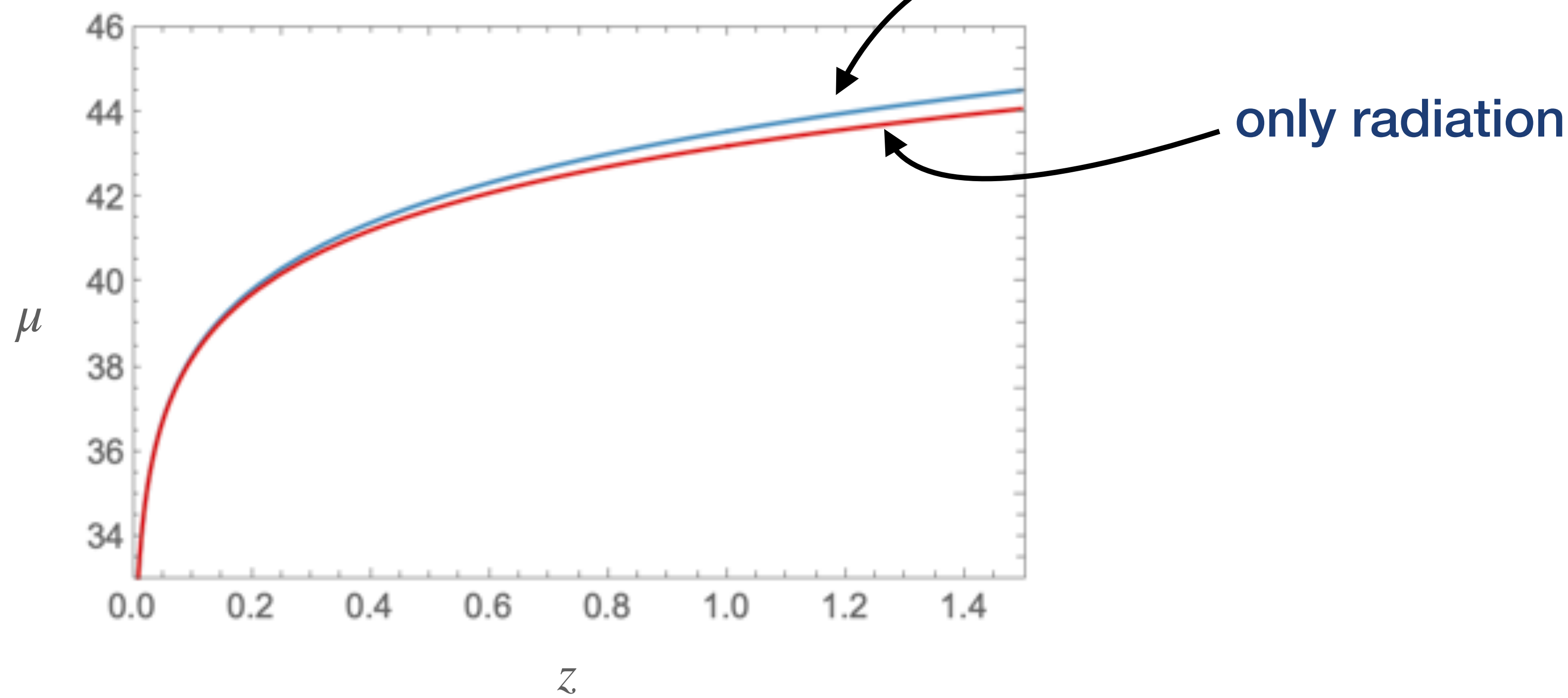

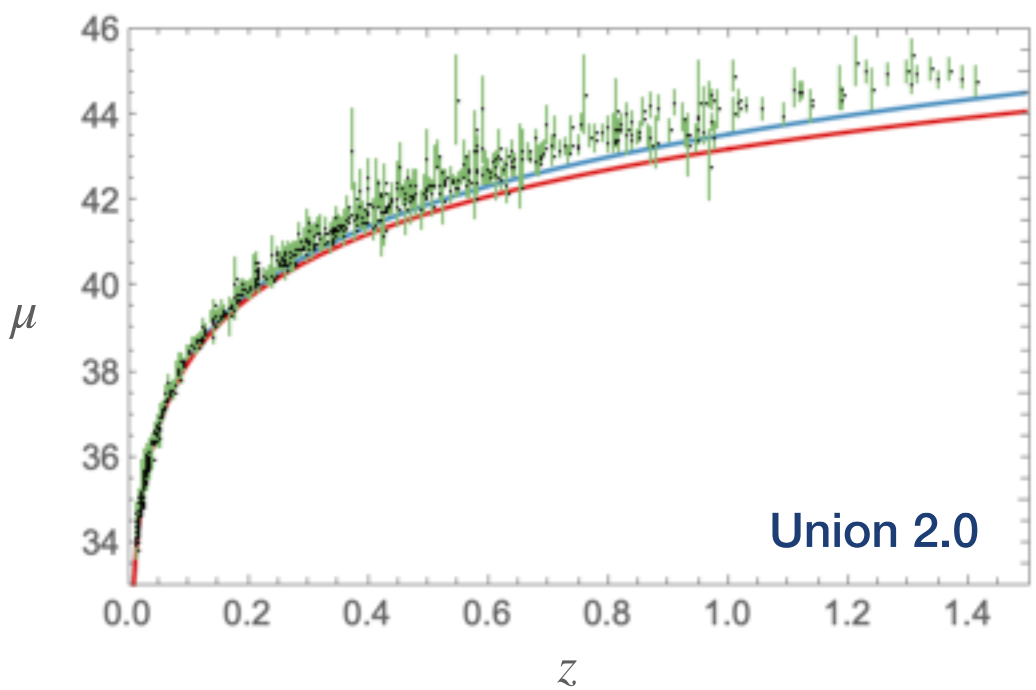

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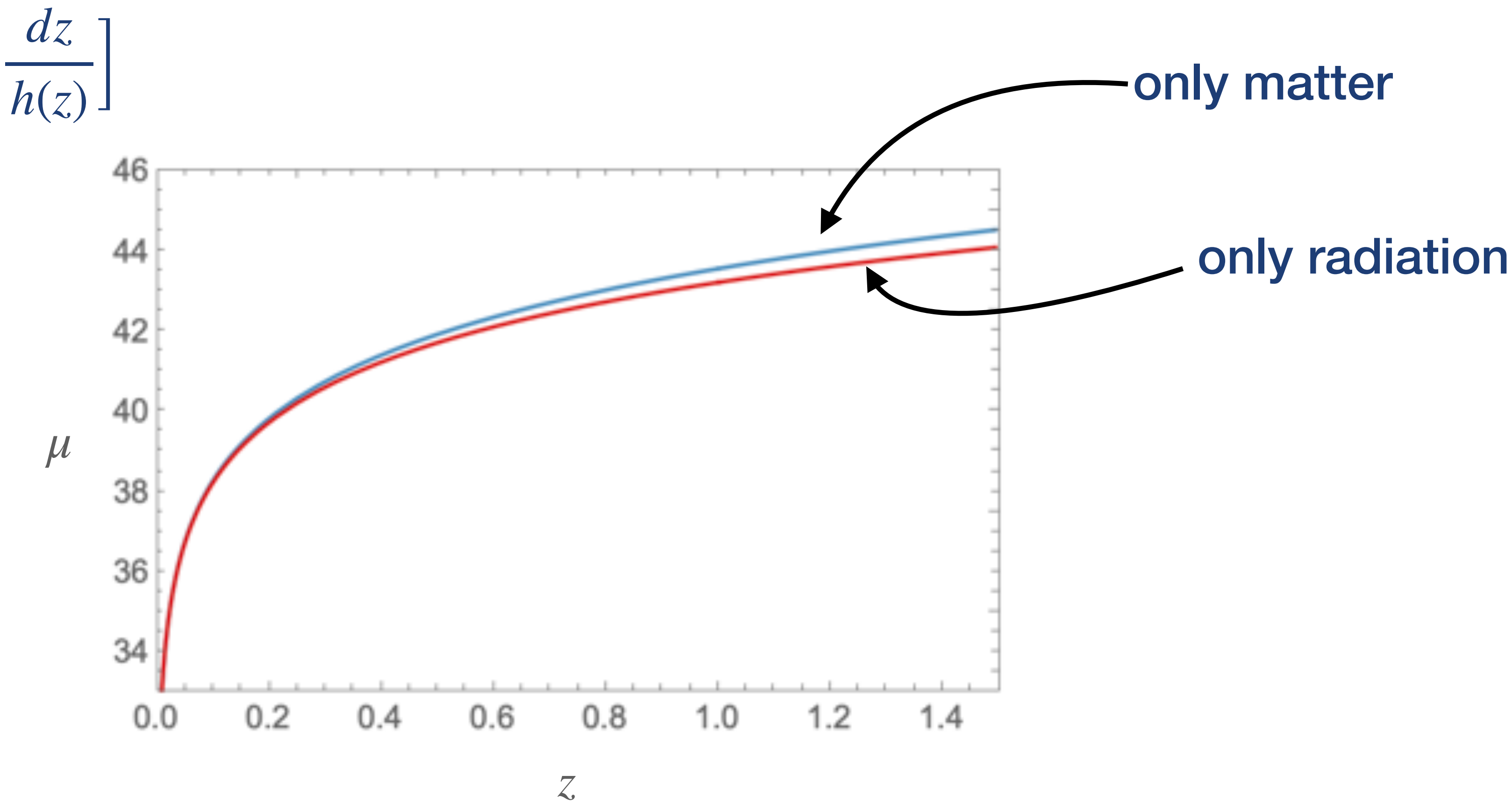

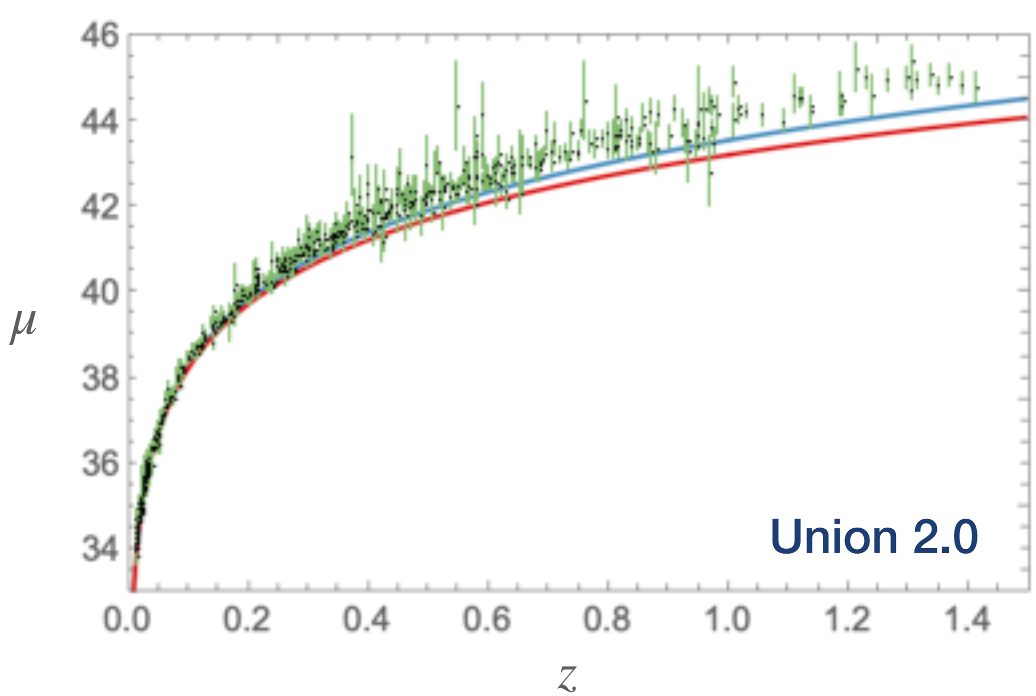

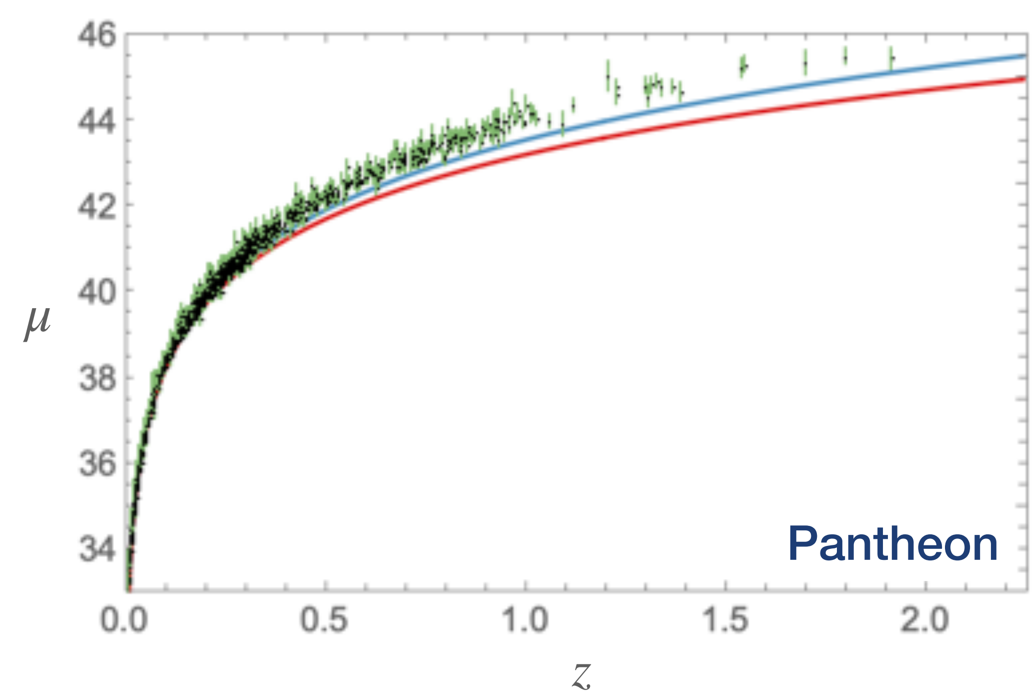

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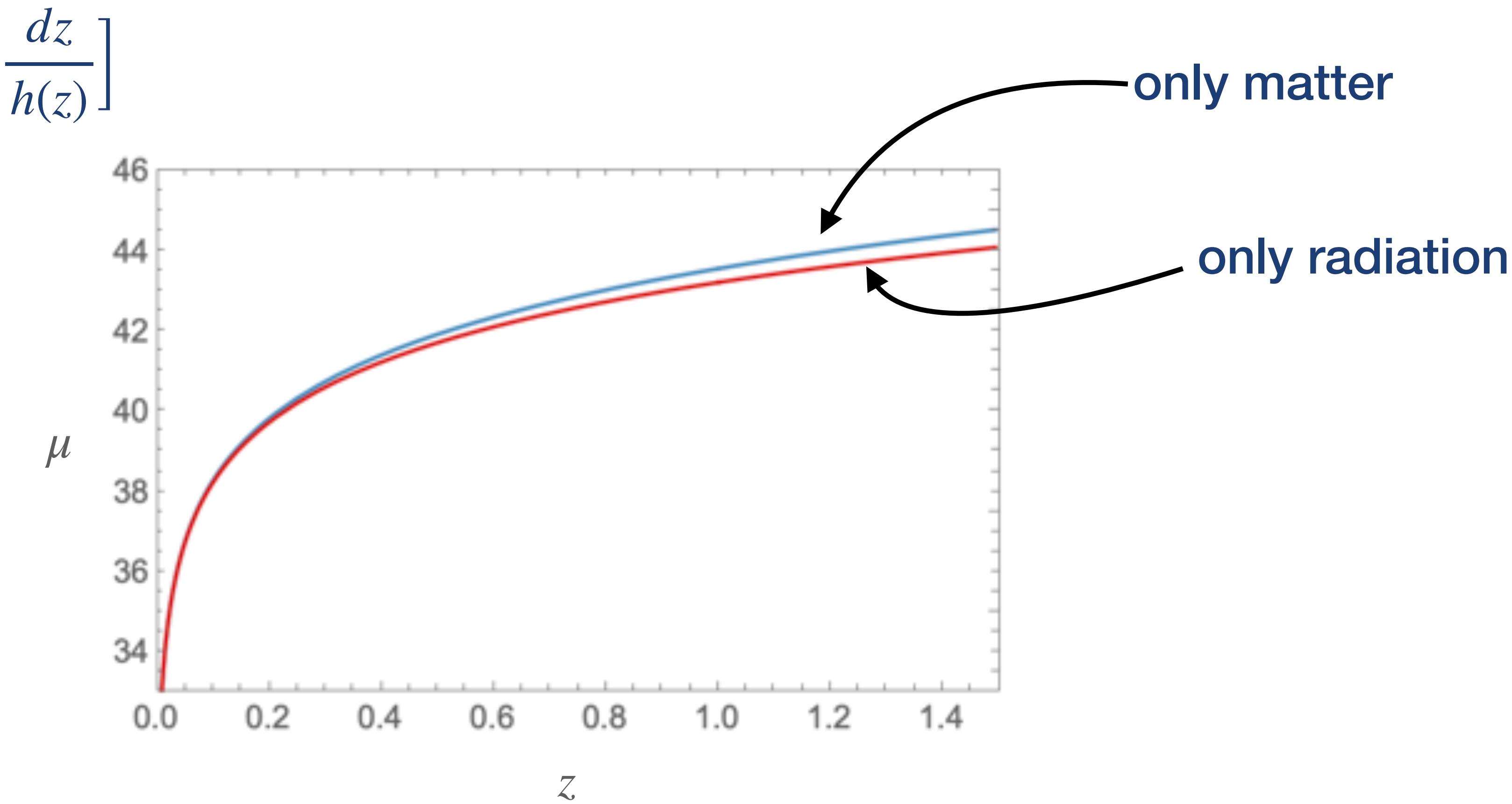
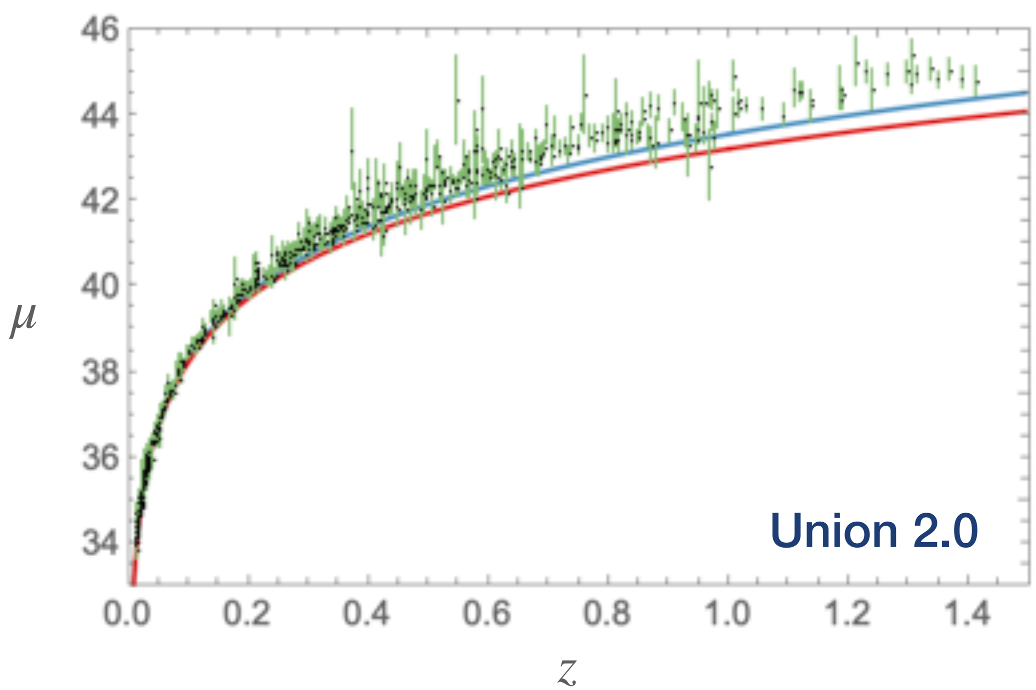
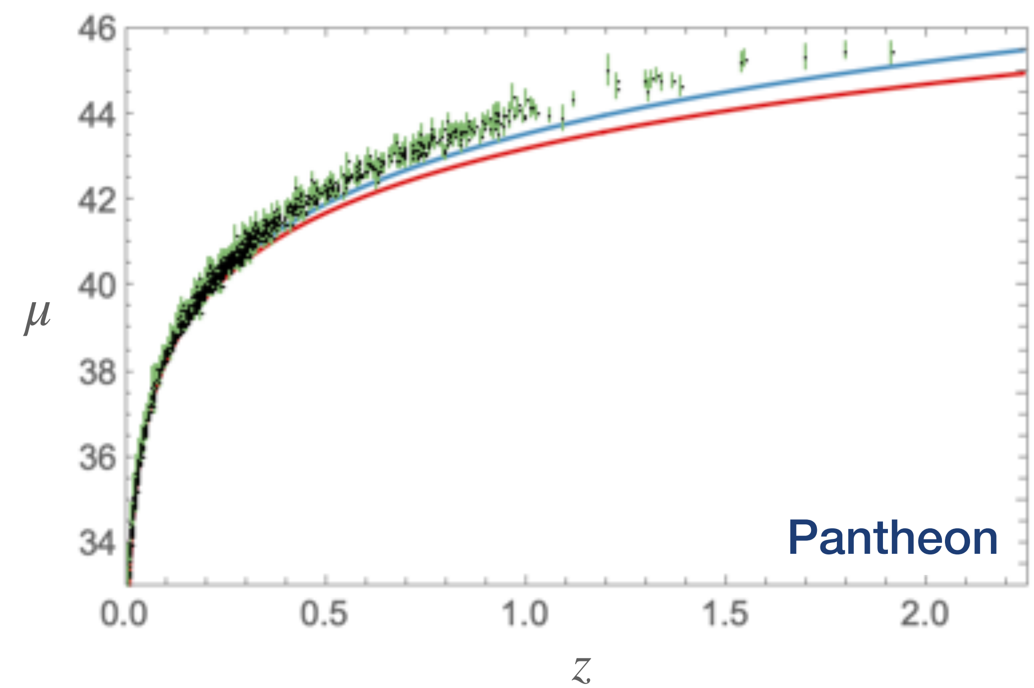






What are these data?

How to fit them with a better model?

What are these data?

They come from supernovae of type Ia

There are two very different mechanisms leading to SN explosions:

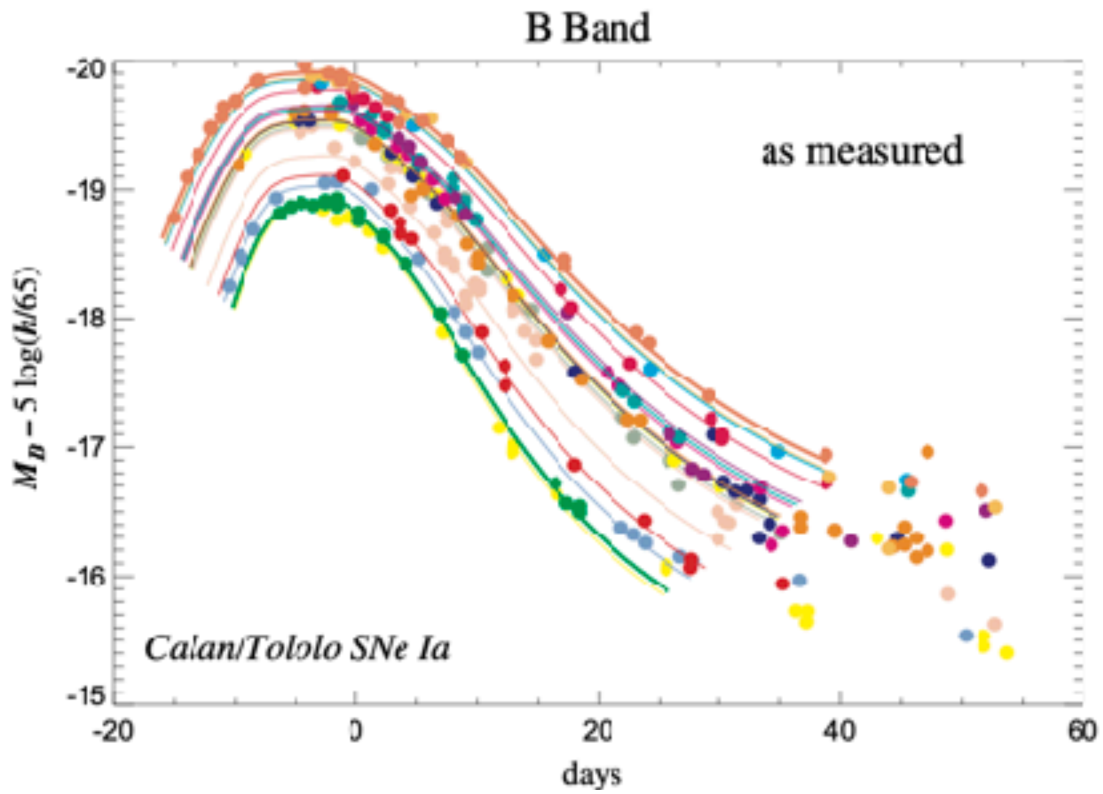
The gravitational collapse of the core of a star, once the nuclear fuel that feeds the thermonuclear reactions inside the core is exhausted. Depending on the properties of the progenitor, this leads to events classified as type Ib, Ic or type II SNe, and leaves behind a compact remnant, usually a neutron star or possibly a black hole

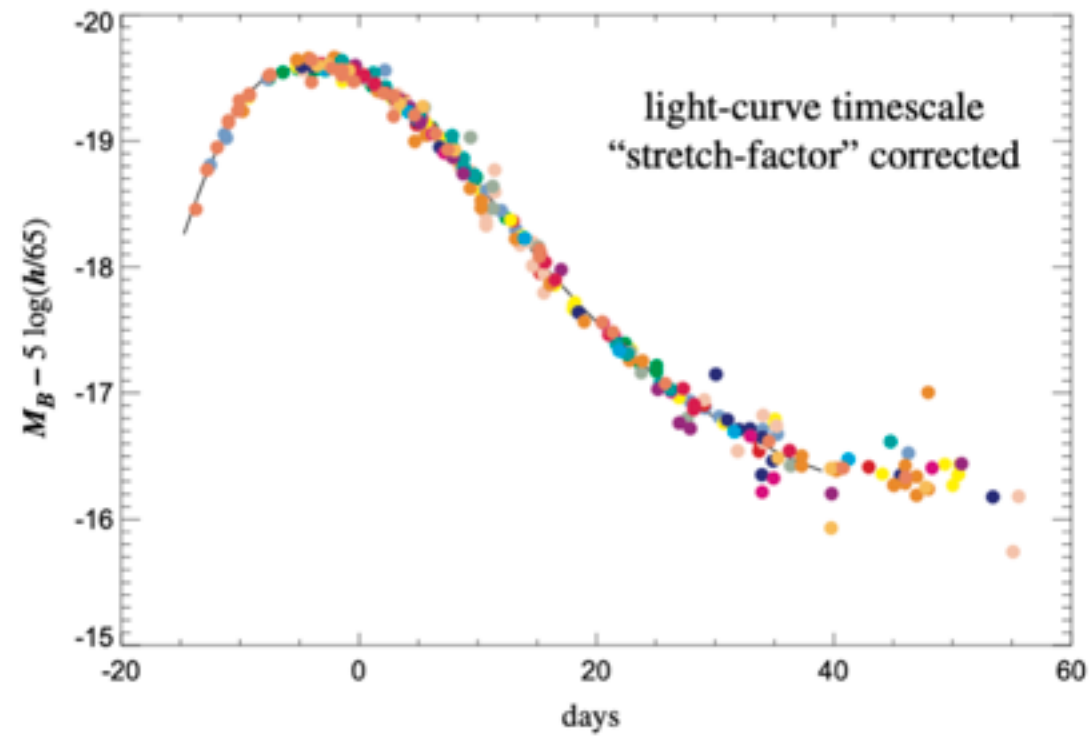
The thermonuclear explosion of a white dwarf that accretes mass from a companion, going beyond its Chandrasekhar limit (in reality it never reaches it, but we have increase of temperature in the core, which leads to carbon fusion leading to an explosion). This gives rise to type Ia SNe. In this case the star that explodes is dispersed in space and its remnant is not a compact object.

Release an energy ~ 10^{56} GeV
99% are neutrinos
1% goes into kinetic energy of the ejected material
less than 0.01%, i.e. about 10^{52} GeV, is released in photons

The corresponding peak luminosity in photons can be of order a few times $10^9 L_\odot$ or higher. Thus, a typical core-collapse SN at its peak has an optical luminosity that rivals the cumulative light emitted by all the stars in its host galaxy

SNIa





SNIa at small distance, so their relative distance can be found from redshift, so the relative brightness

They don't really have the same luminosity

Because of different composition

Because of intergalactic medium

But we see that they look the same, some stretch factor should correct it

The Pskovskii–Phillips relation

$$(M_B)_{peak} = -21.727 + 2.698\Delta m_{15}(B)$$ with similar relations in V- and I- bands

because of composition: more ^{56}Ni, implies higher peak, so higher temperature and opacity, therefore a slower decline of the light curve

+ some other corrections, we can make them standard candles

Therefore after corrections, we can know their absolute magnitude M, we measure m and redshift (z) so we obtain $\mu(z)$

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Very luminous, they reach an absolute magnitude of $M \simeq -19$ corresponding to $10^{10} M_{\odot}$

Relative small dispersion of the peak absolute magnitude

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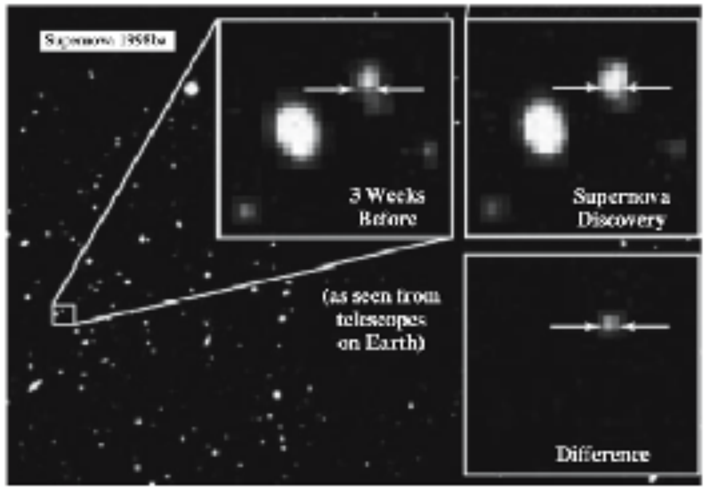
So we need a better strategy than luck to find them

Observe a large part of the sky

Observe it again $\simeq 3$ weeks after

Do the difference between images and follow the differences which are supernovae



Perlmutter et al. 1997

They found 7 SNIa for $0.35 < z < 0.65$

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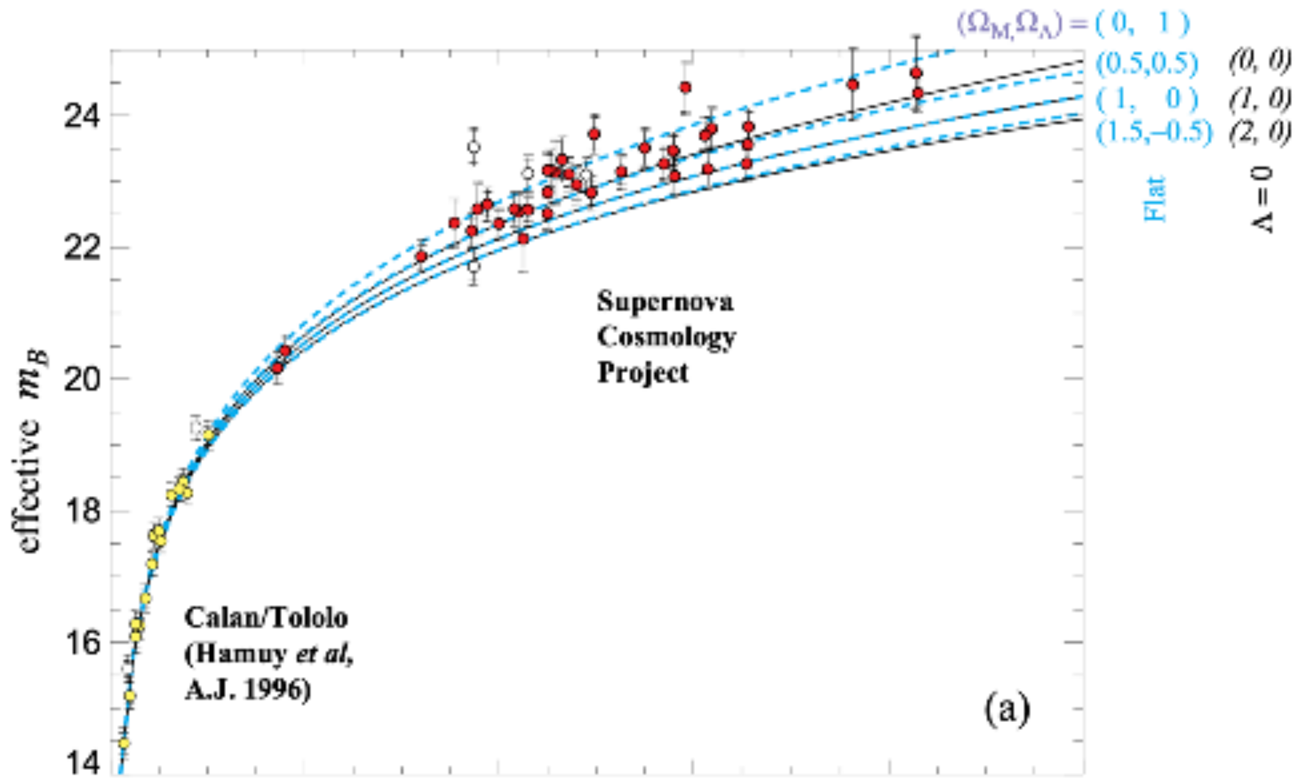

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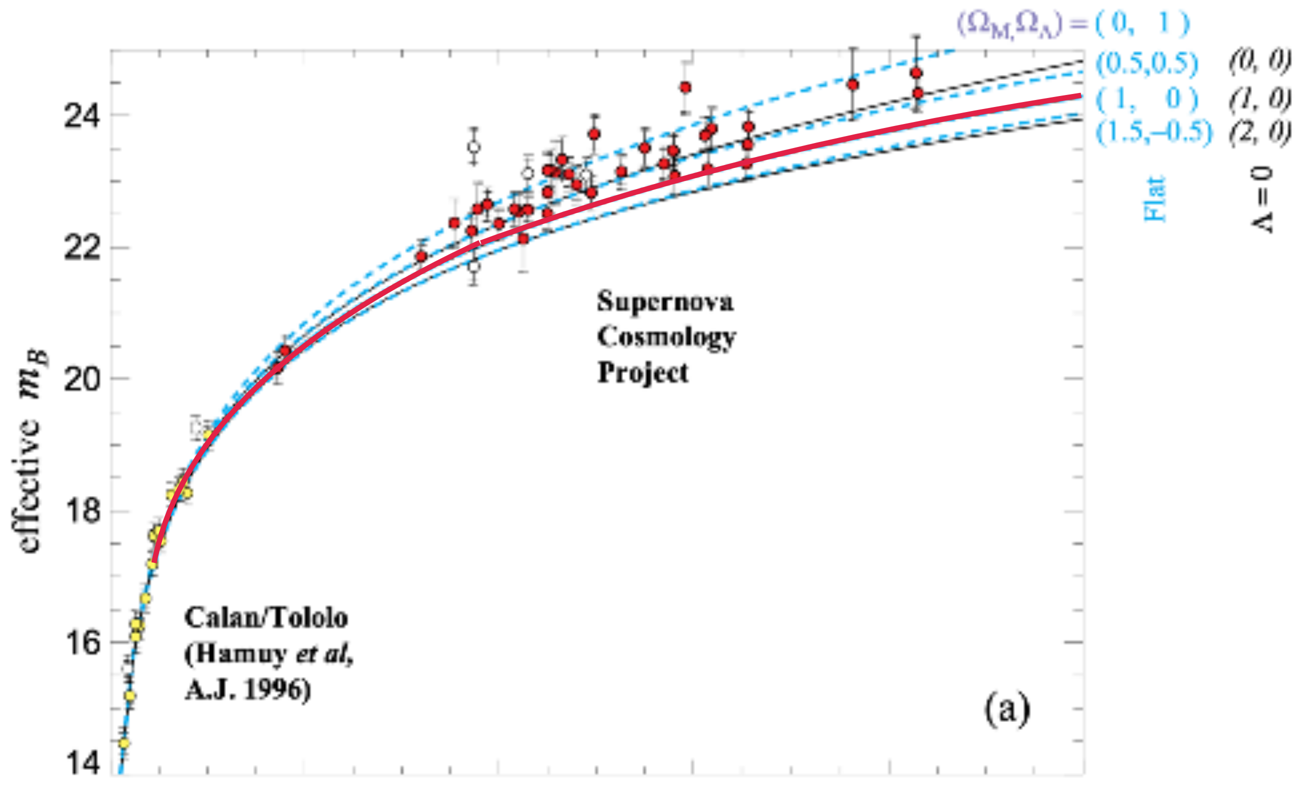

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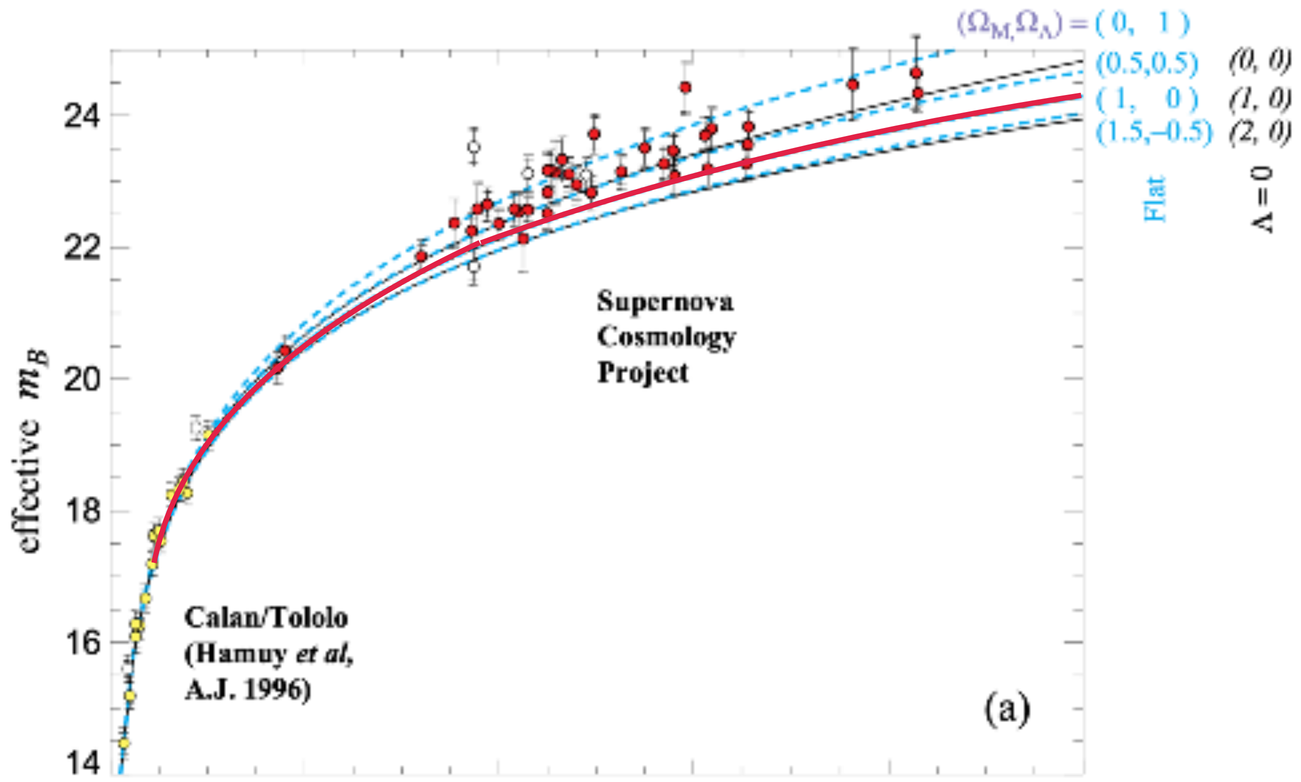

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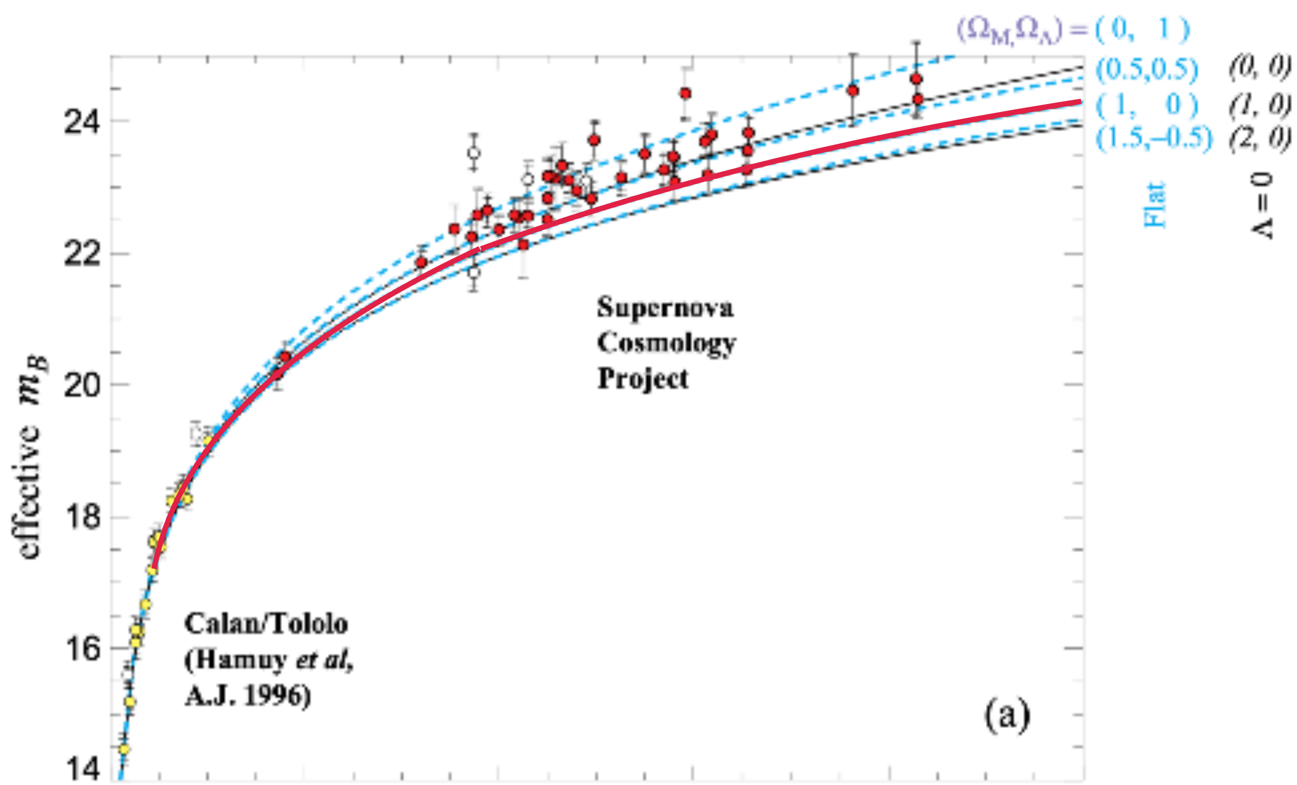

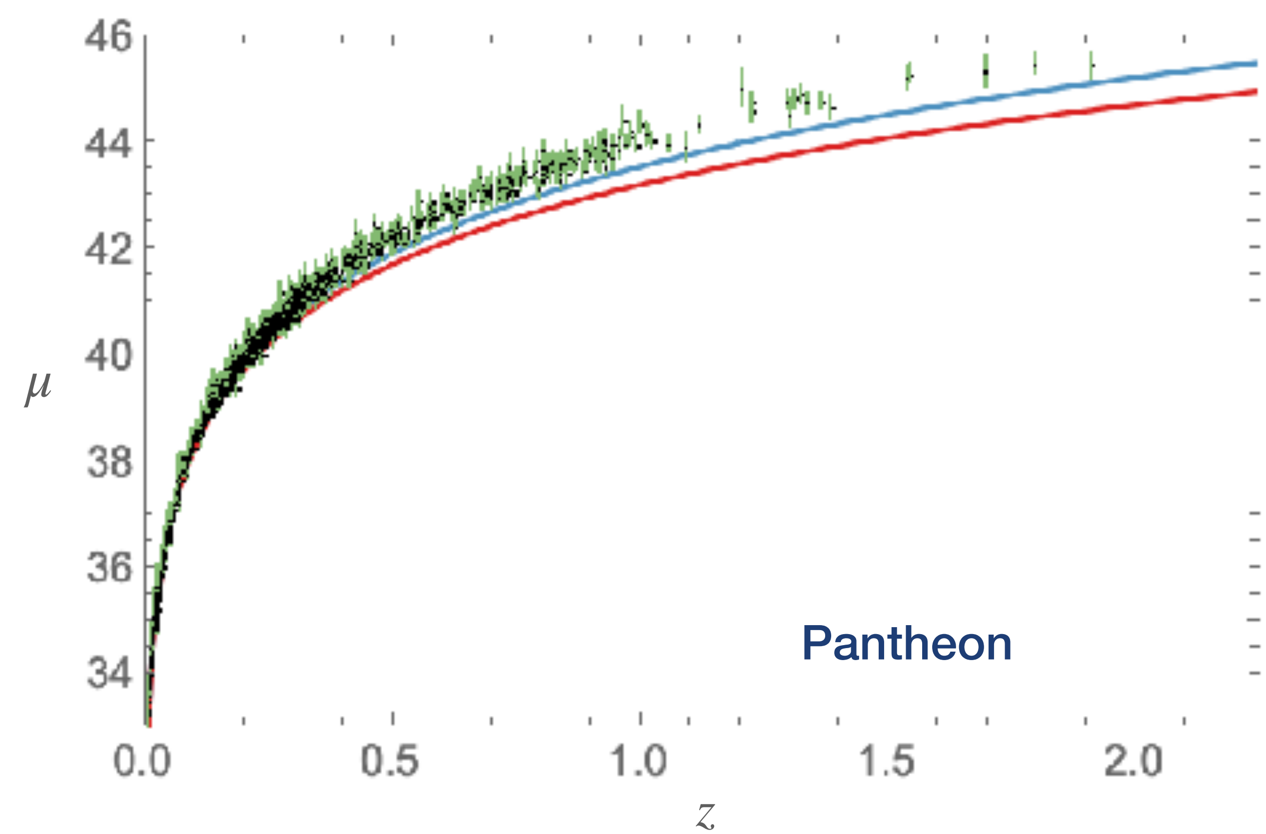

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$$\Omega_{m,0} + \Omega_{r,0} = 1$$

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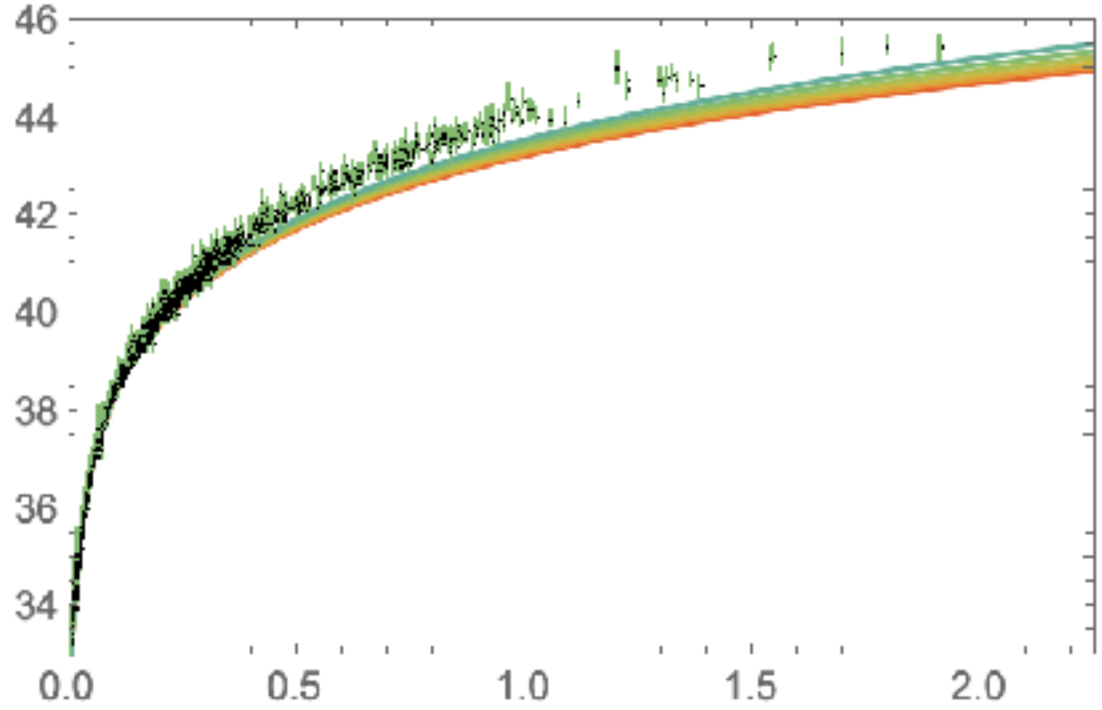

$\Omega_{m,0} = 1 \quad \Omega_{r,0} = 0$

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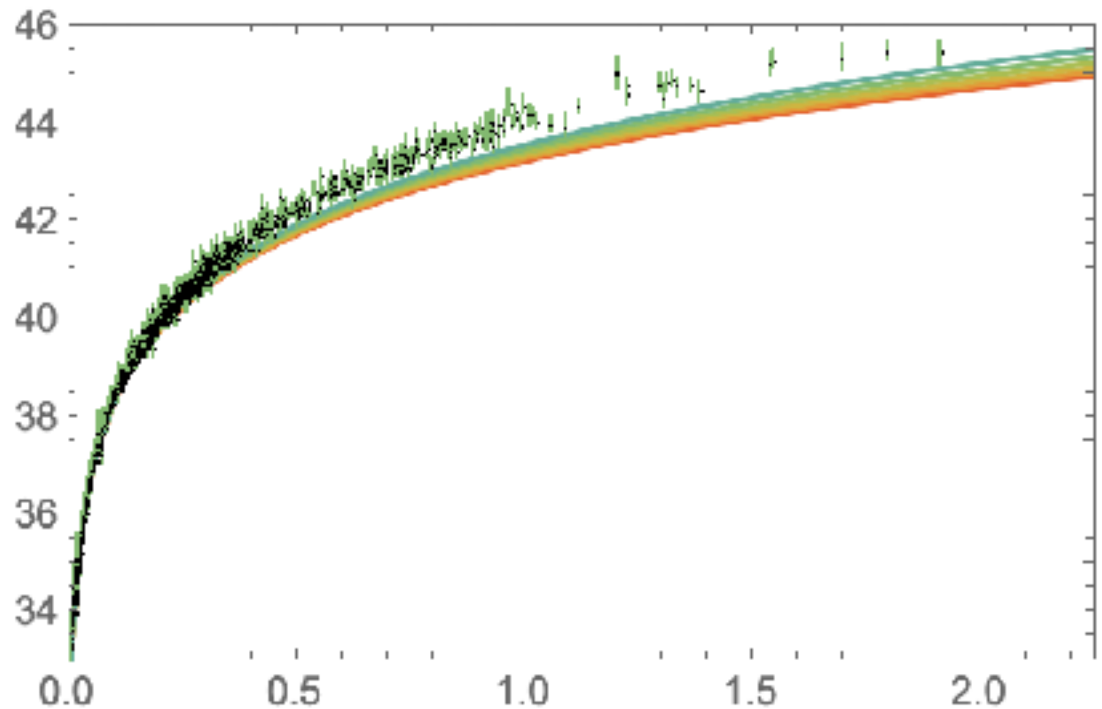

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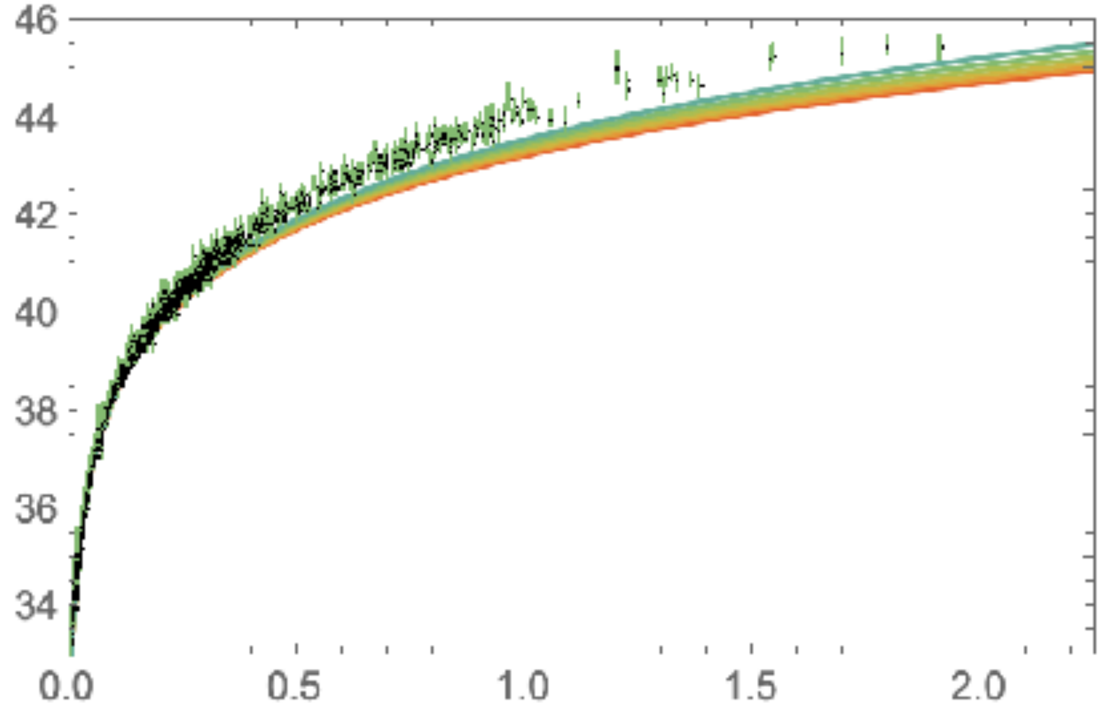

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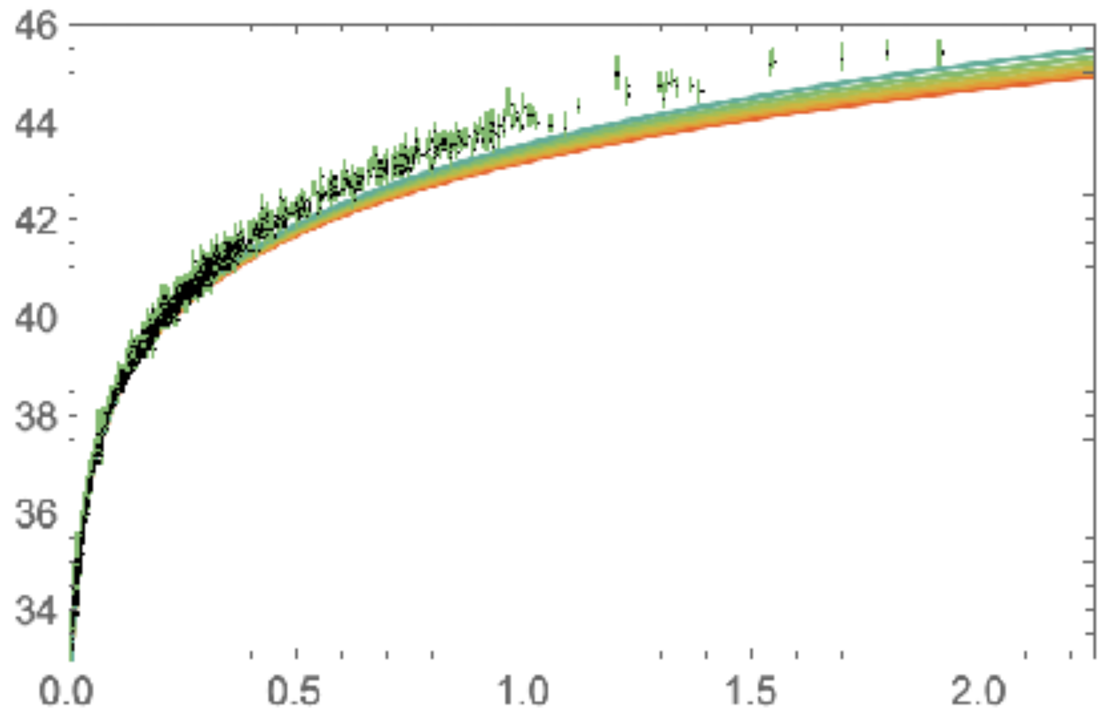

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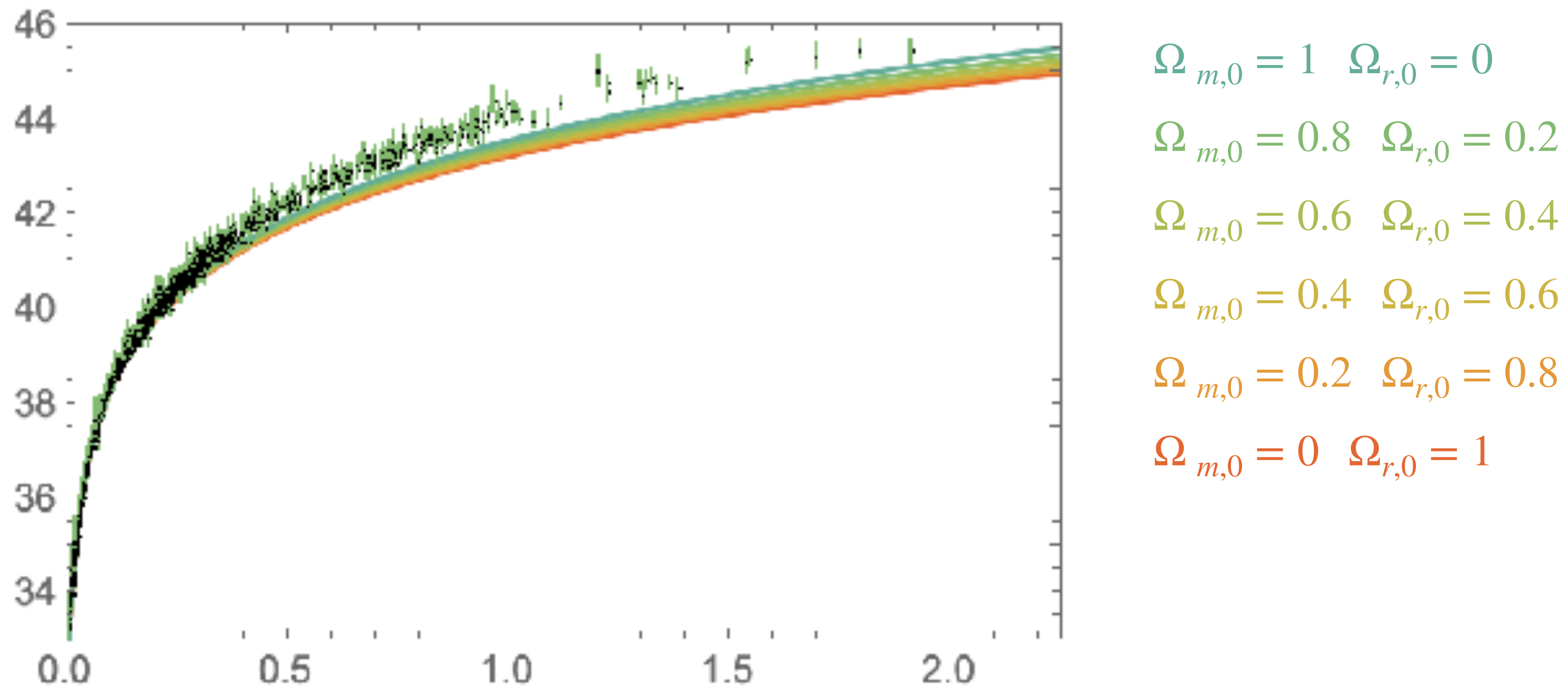

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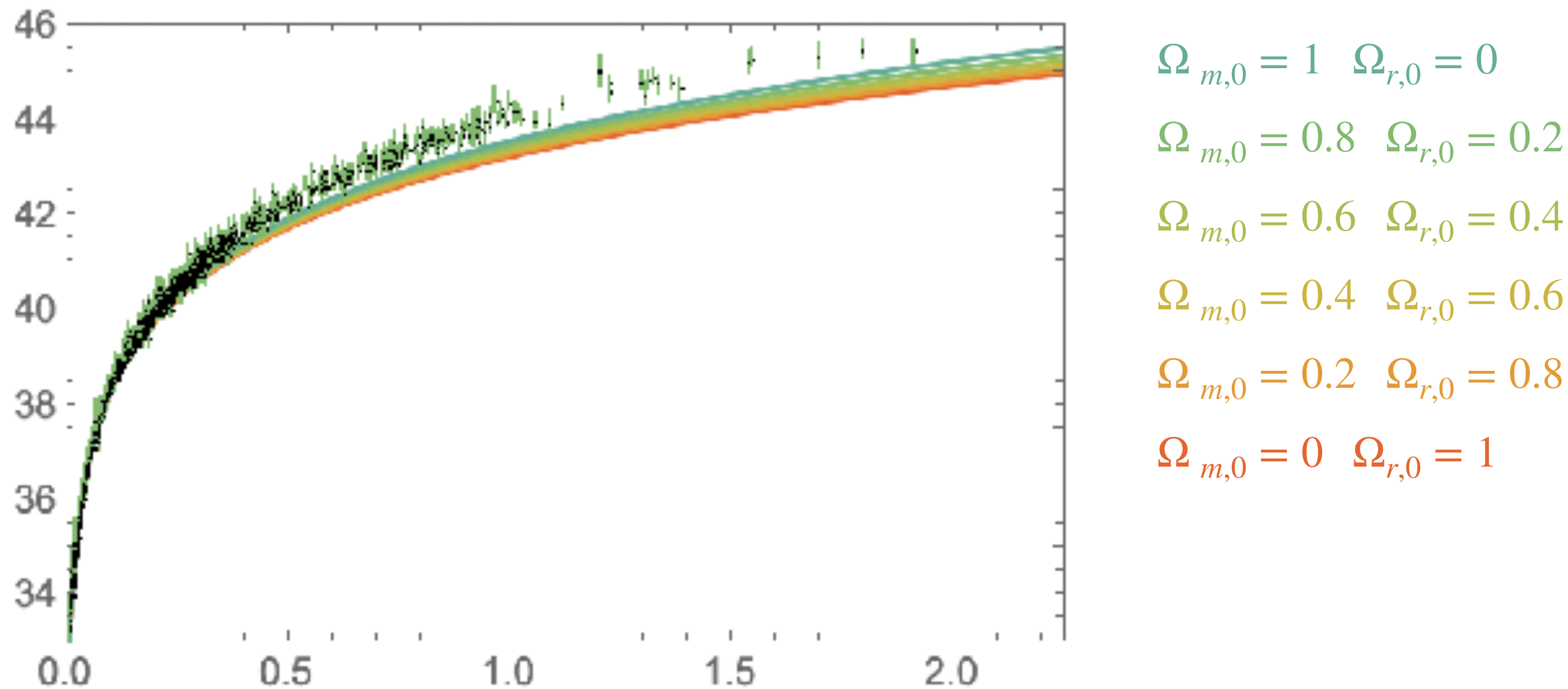

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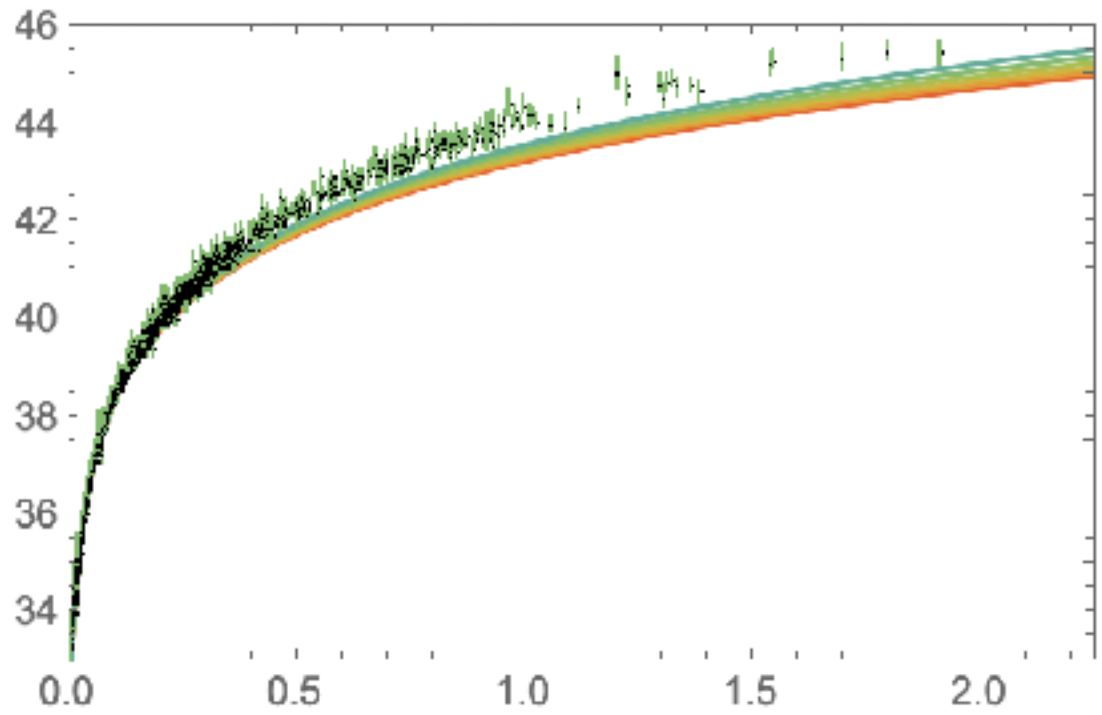

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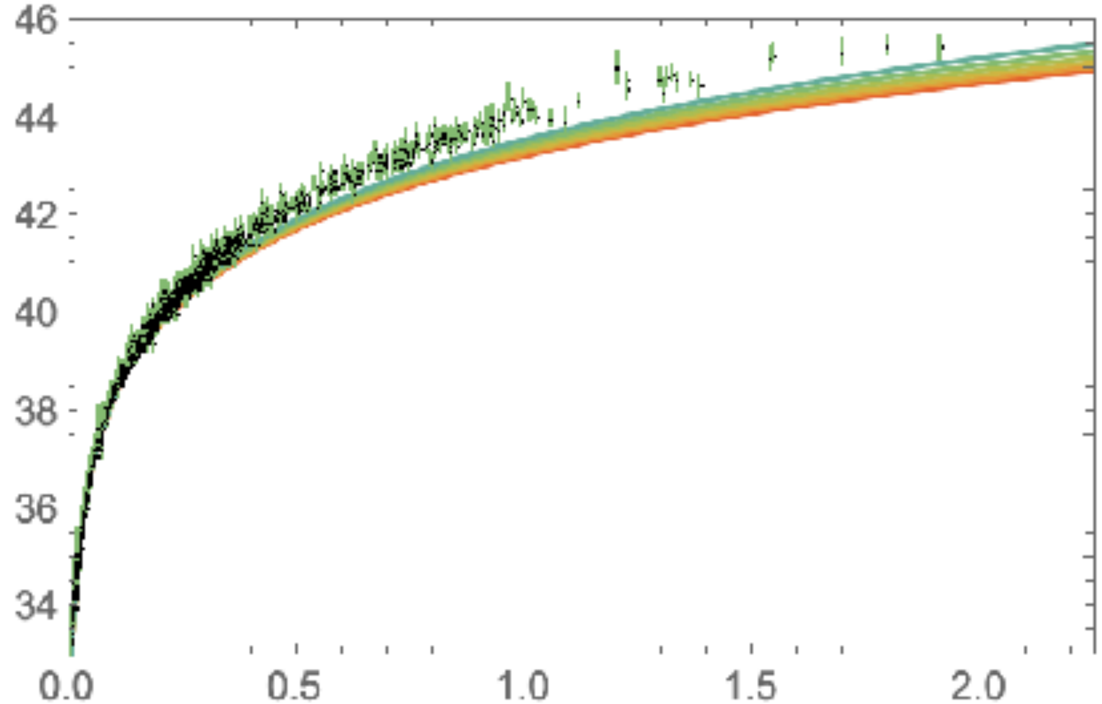

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Let's neglect radiation for simplicity

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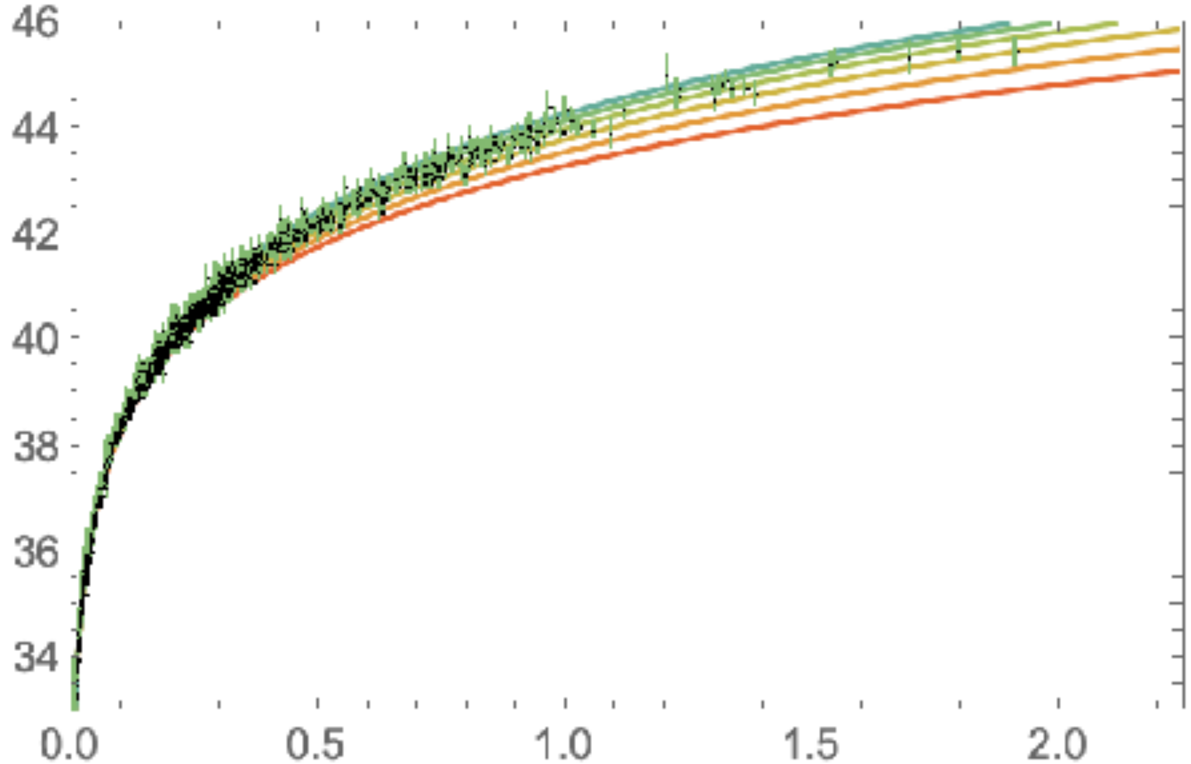

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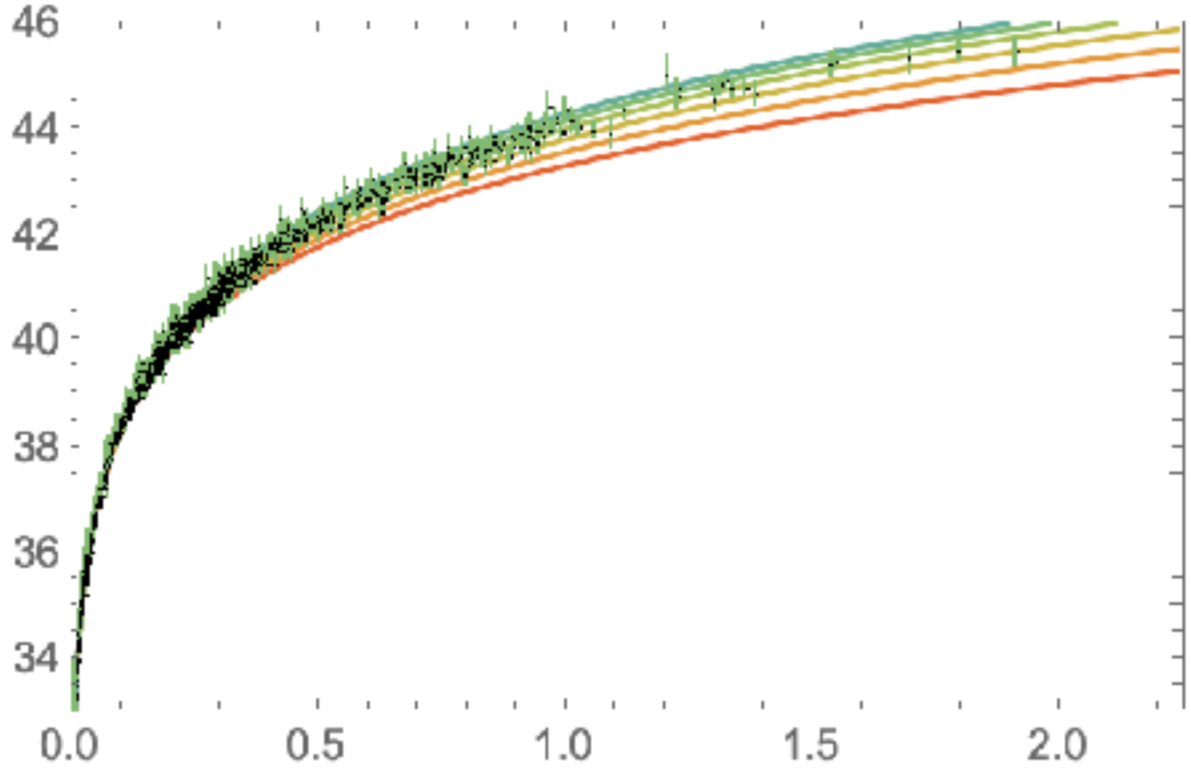

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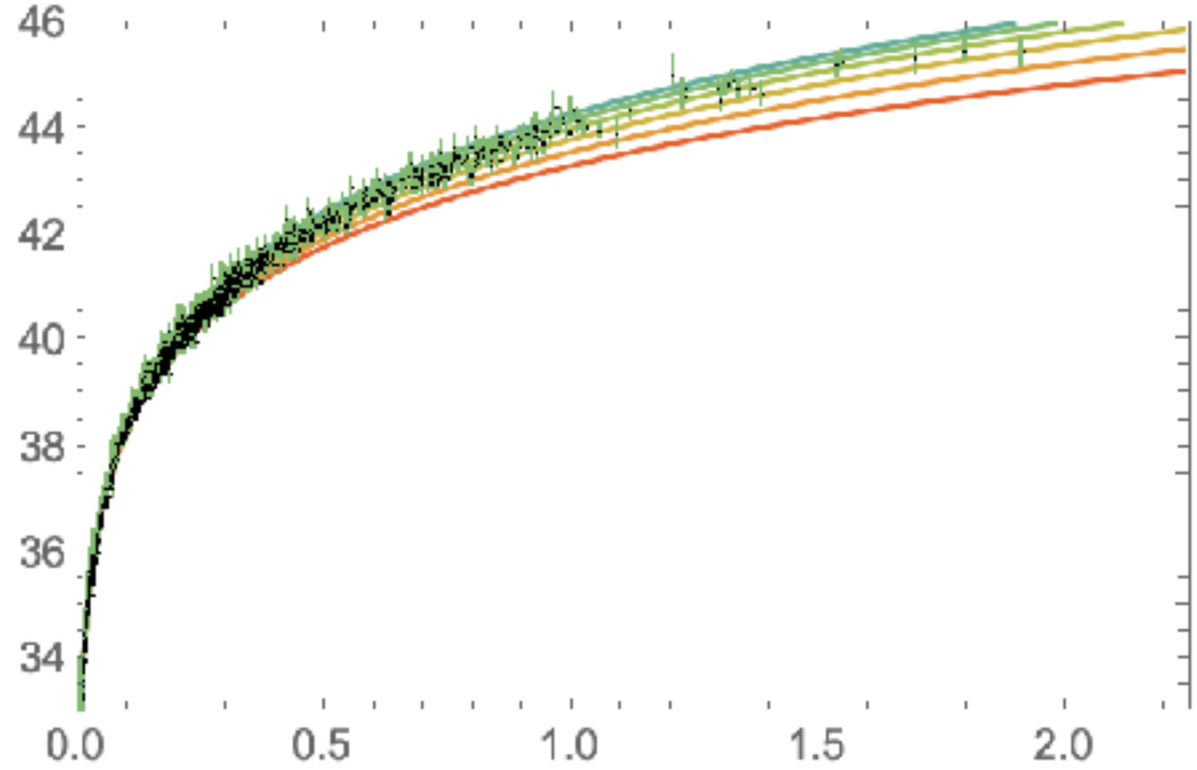

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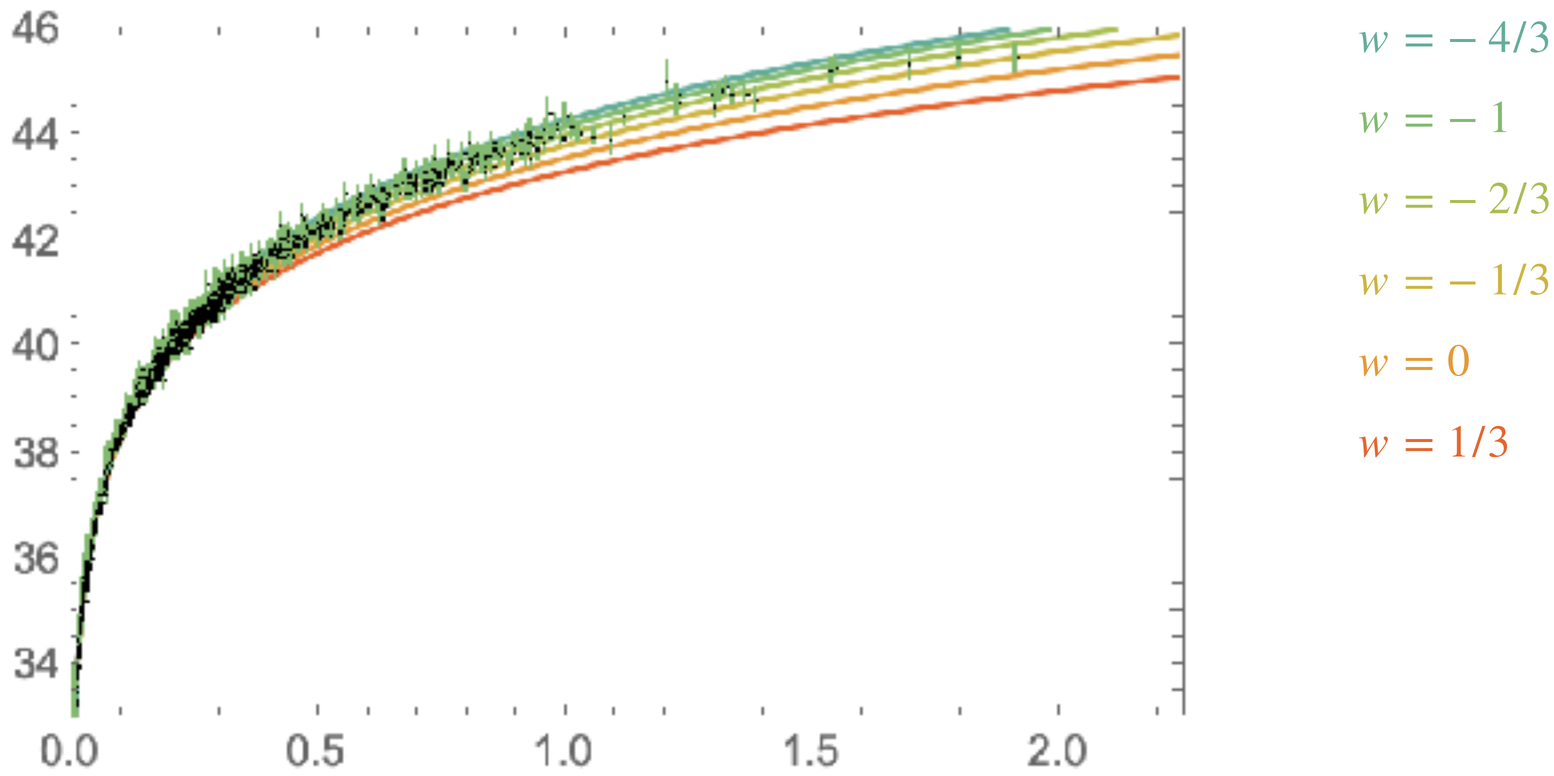

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X is known as the cosmological constant, and we write it Λ (instead of X)

A brief history of the Universe

	Time	Energy	
Planck Epoch?	$< 10^{-43}$ s	10^{18} GeV	
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Matter-Radiation Equality	10^4 yrs	1 eV	10^4
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Dark Ages	$10^5 - 10^8$ yrs		> 25
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Due to the phase transition, a huge amount of energy was released in the Universe

The release of the energy of the vacuum transformed the virtual particles, into real particles

In Linde's inflation, the expansion is produced by the decay of the potential energy of a field called inflaton

In all cases, we end this period with a hot Universe filled with interacting particles

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The Universe contained plasma, an incandescent and opaque soup of photons, protons and electrons

Because of these continuous reactions, light underwent continuous deviations and reflections and was therefore trapped in the plasma

The Universe was opaque and dark but its temperature continues to decrease

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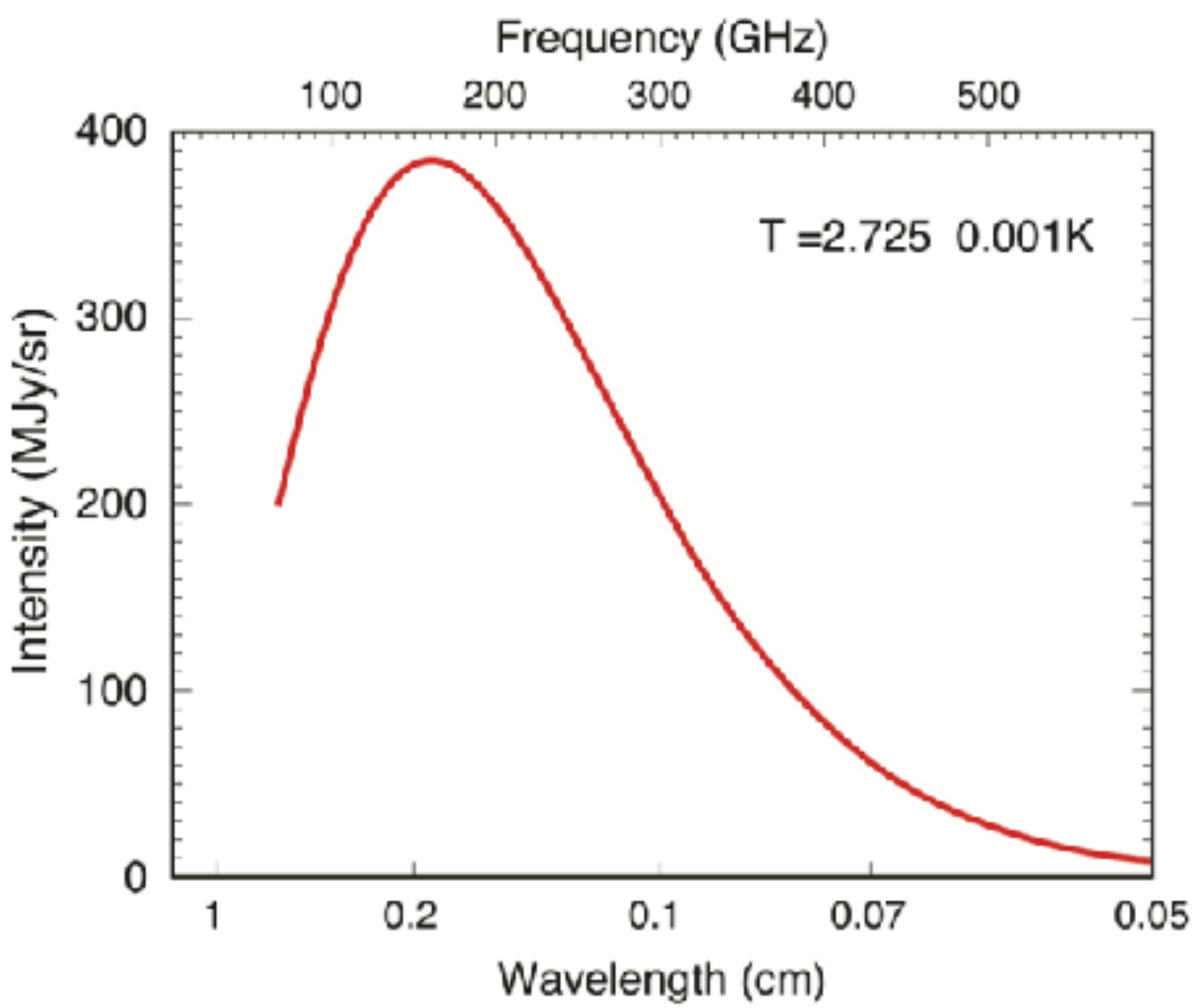

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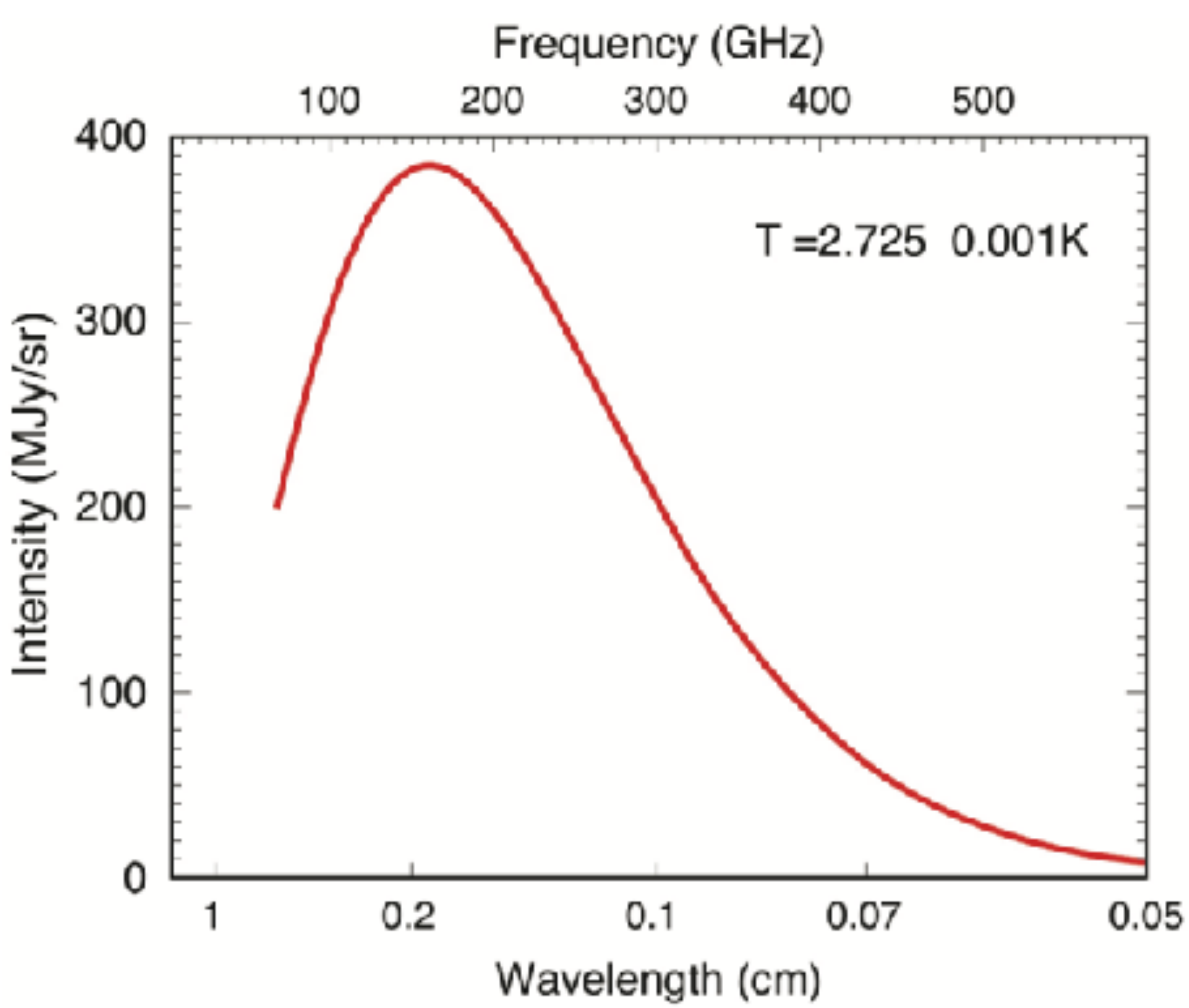
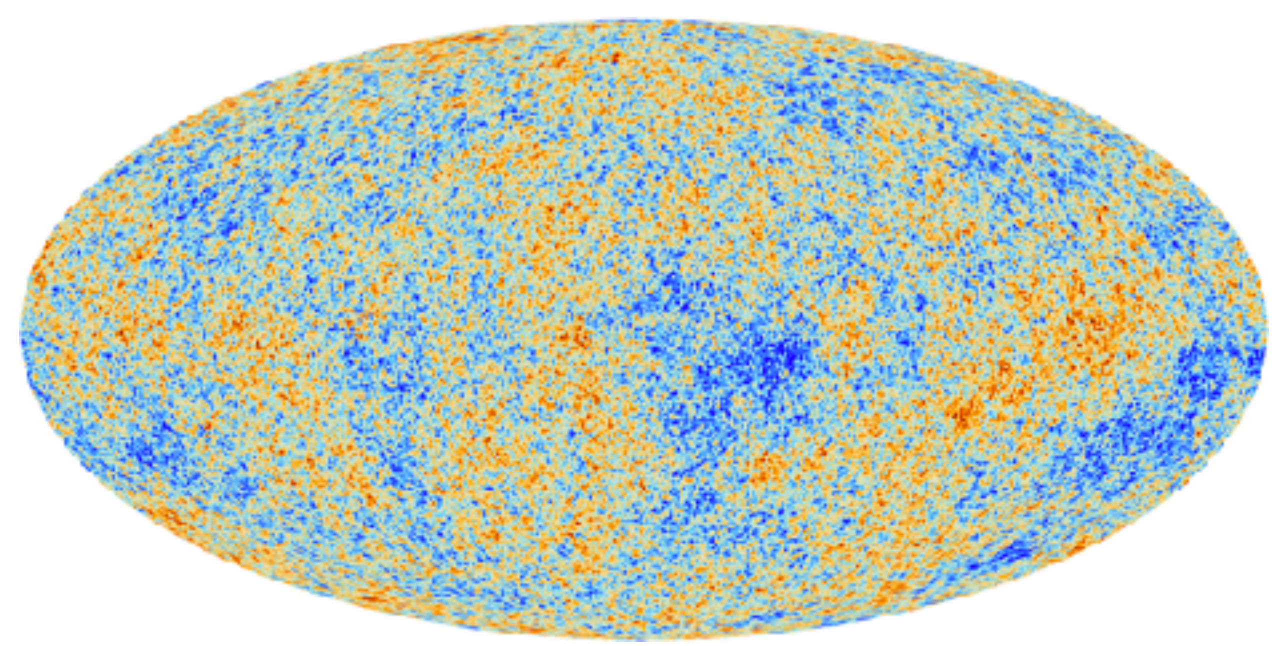


with very small fluctuations



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Where do the fluctuations come from?

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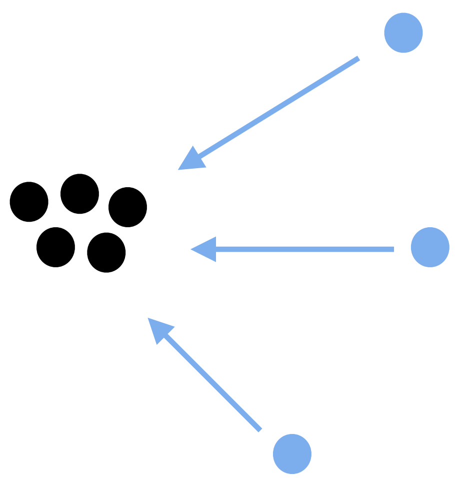

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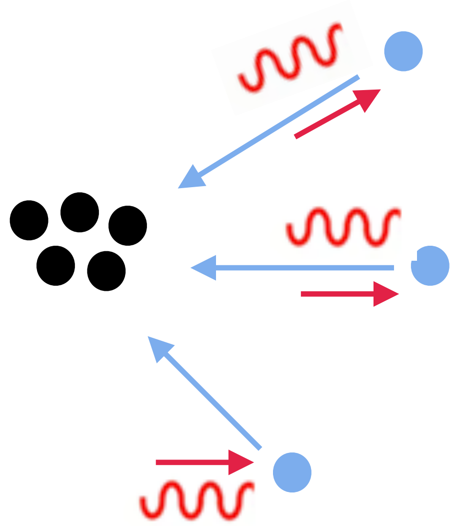

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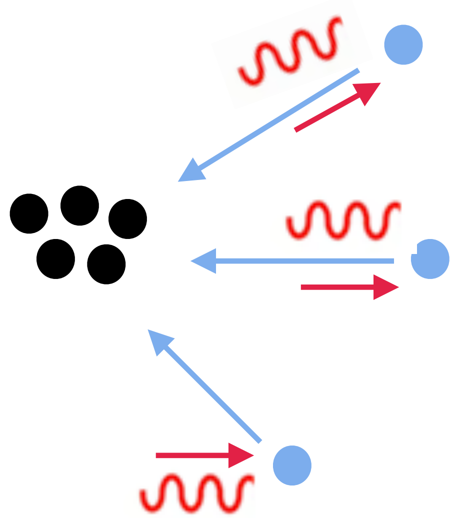

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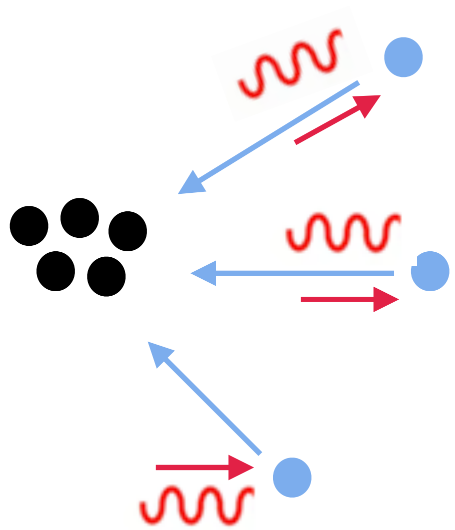

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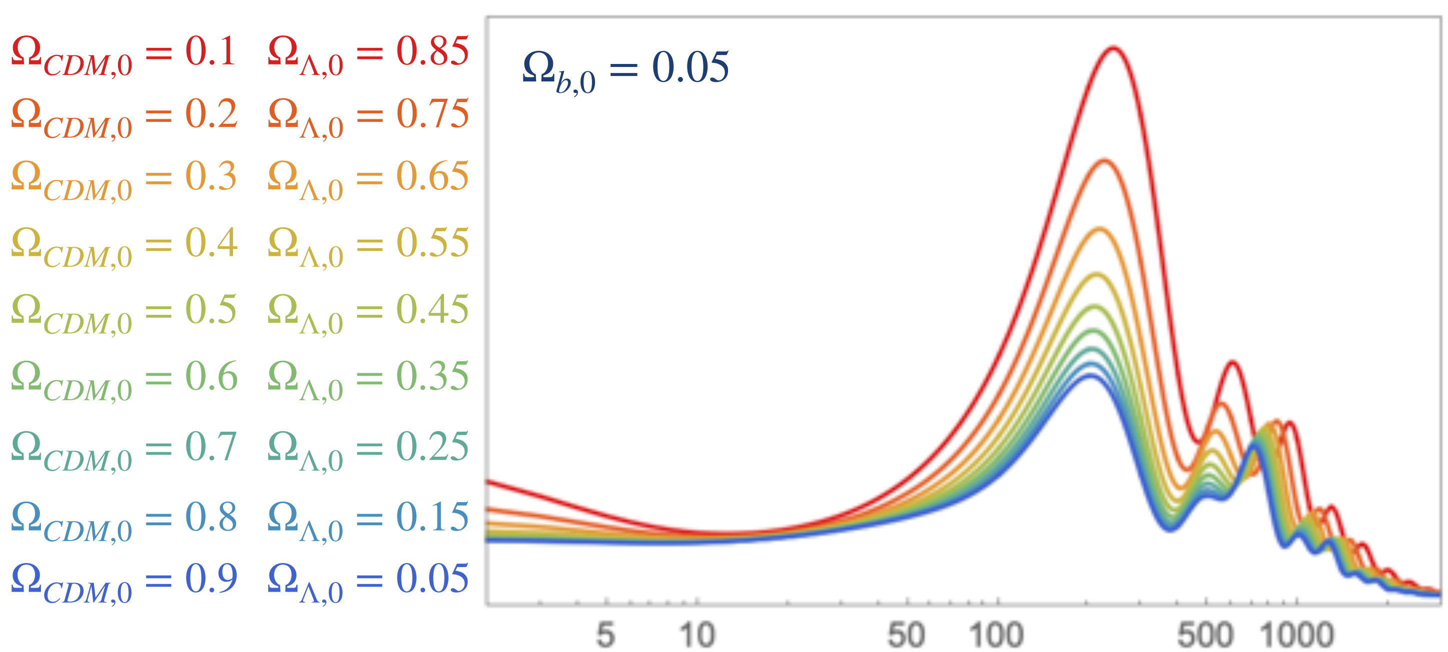

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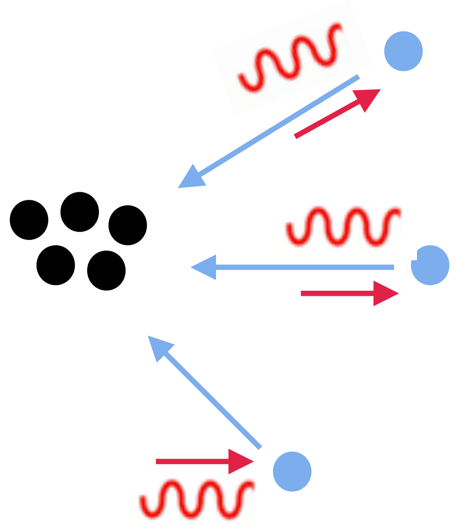

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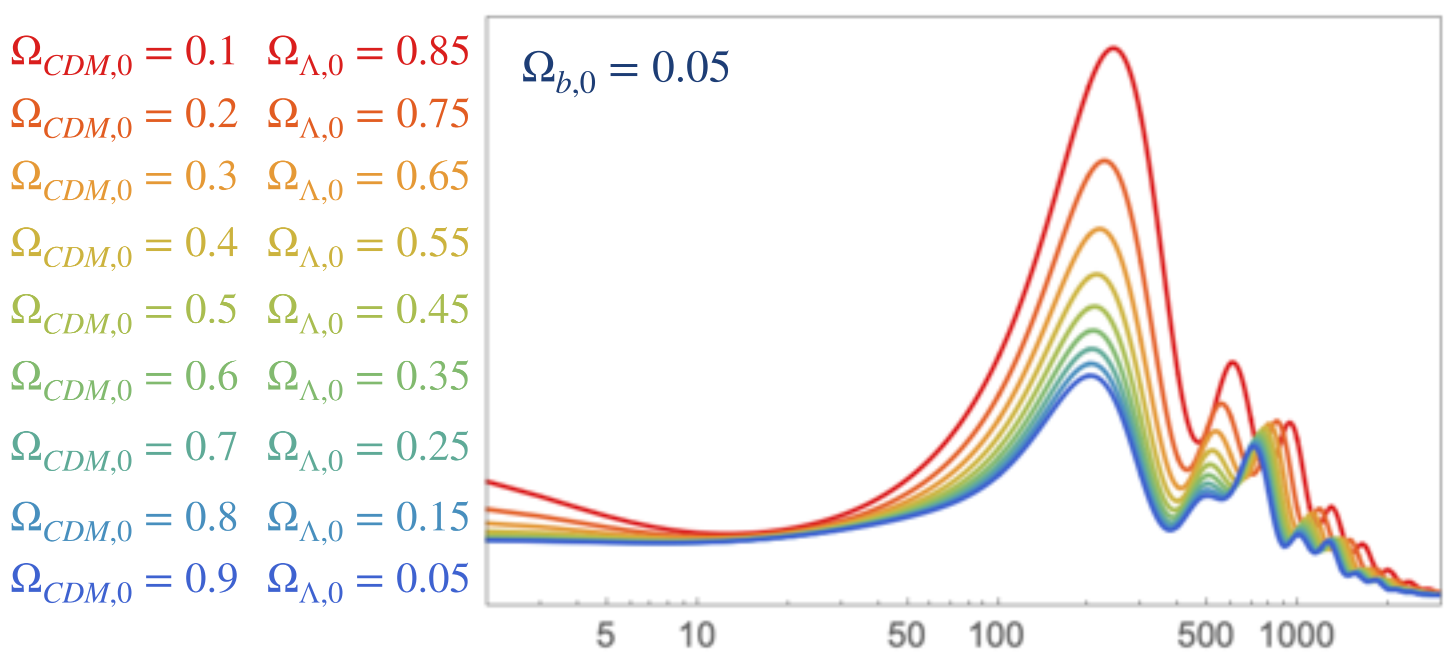

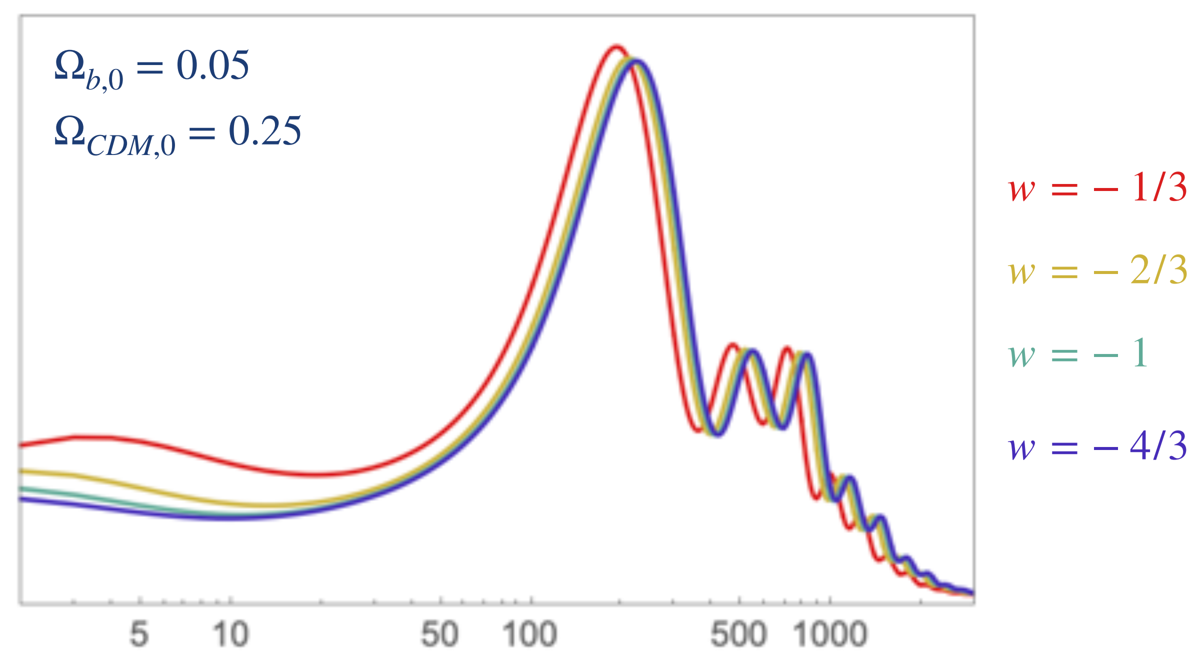

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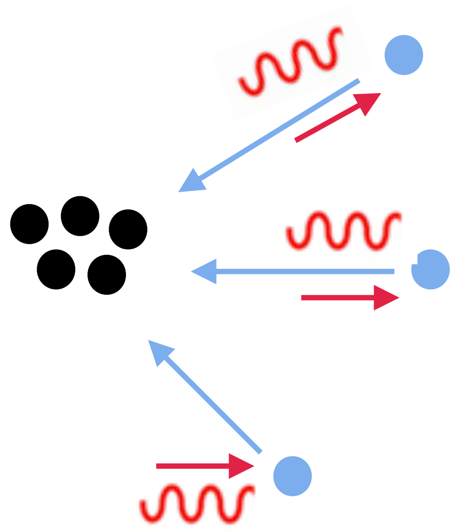

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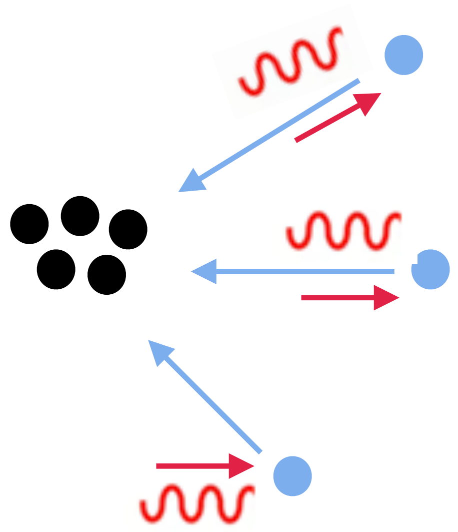

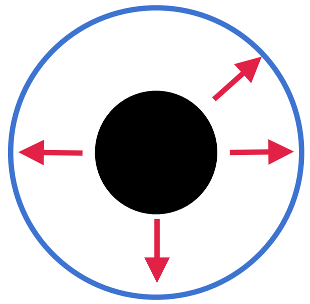

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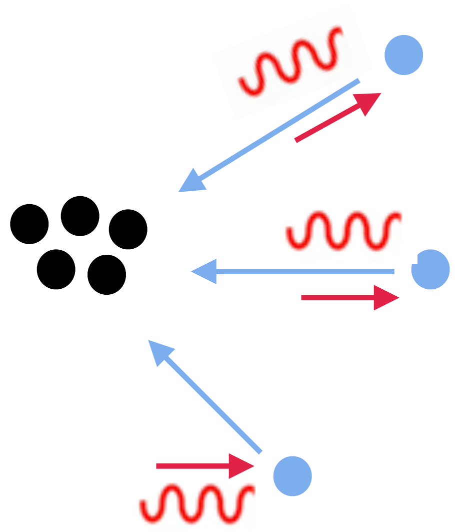
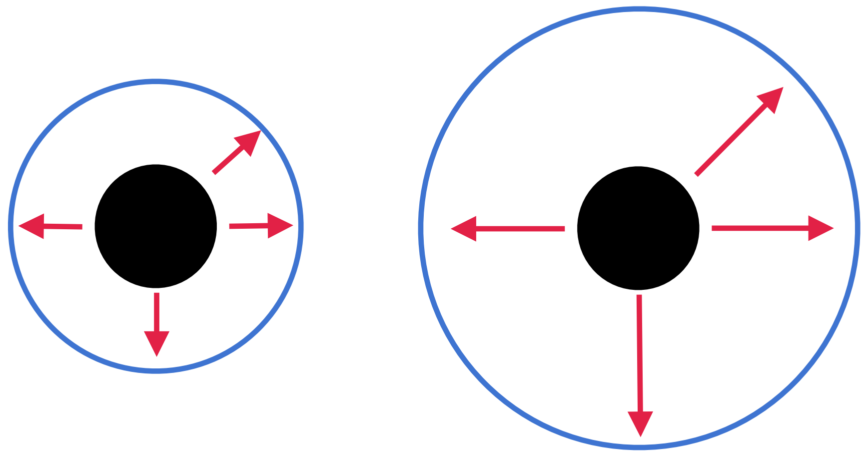
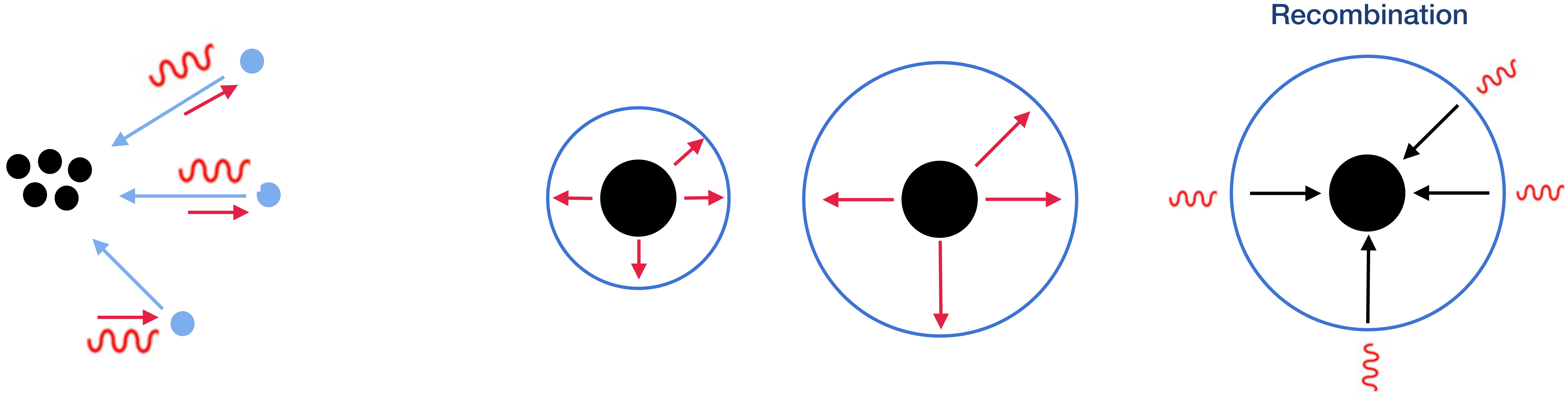




What is the Baryon Acoustic Oscillation?



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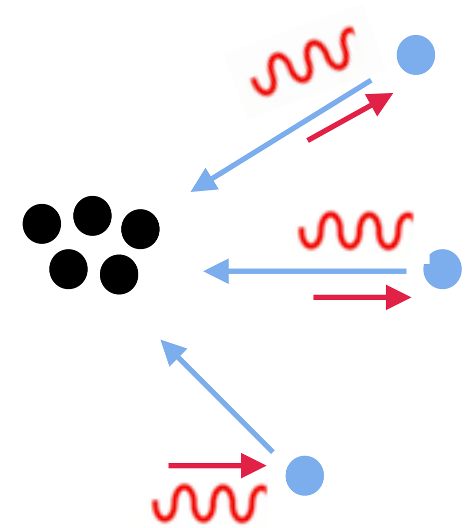
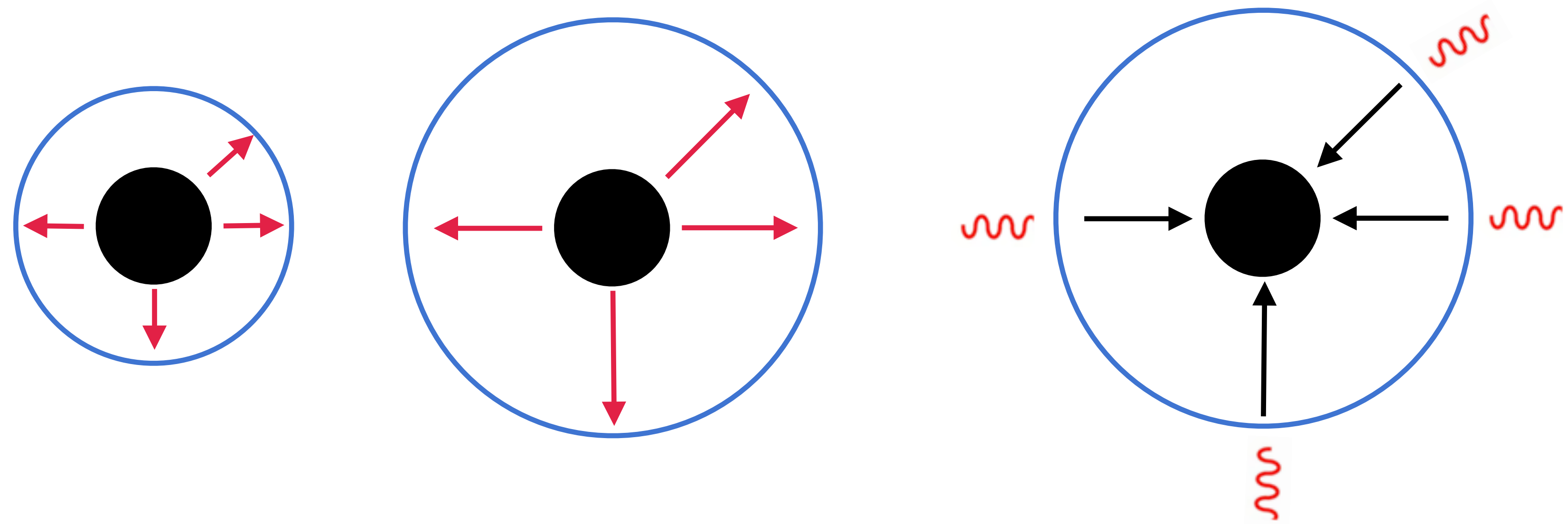
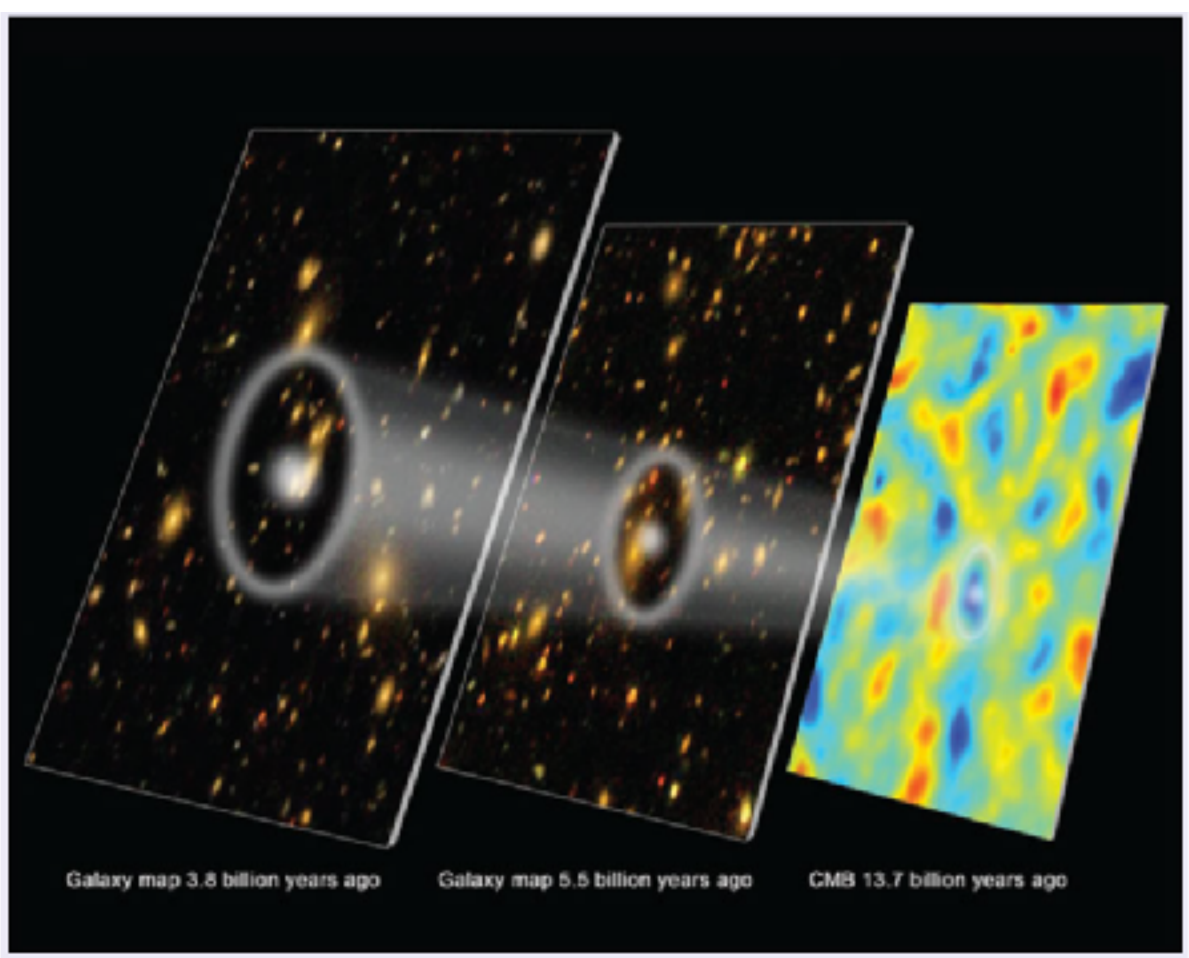


Recombination

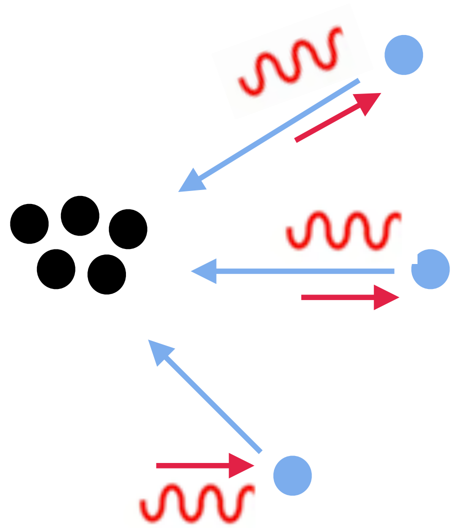


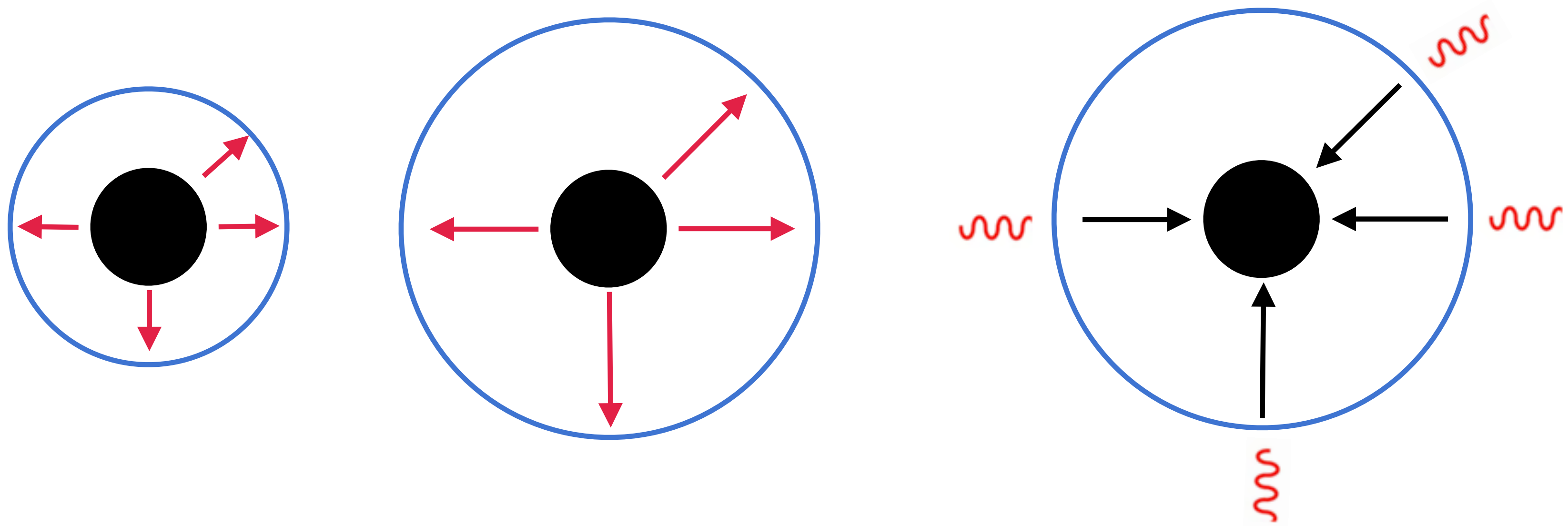


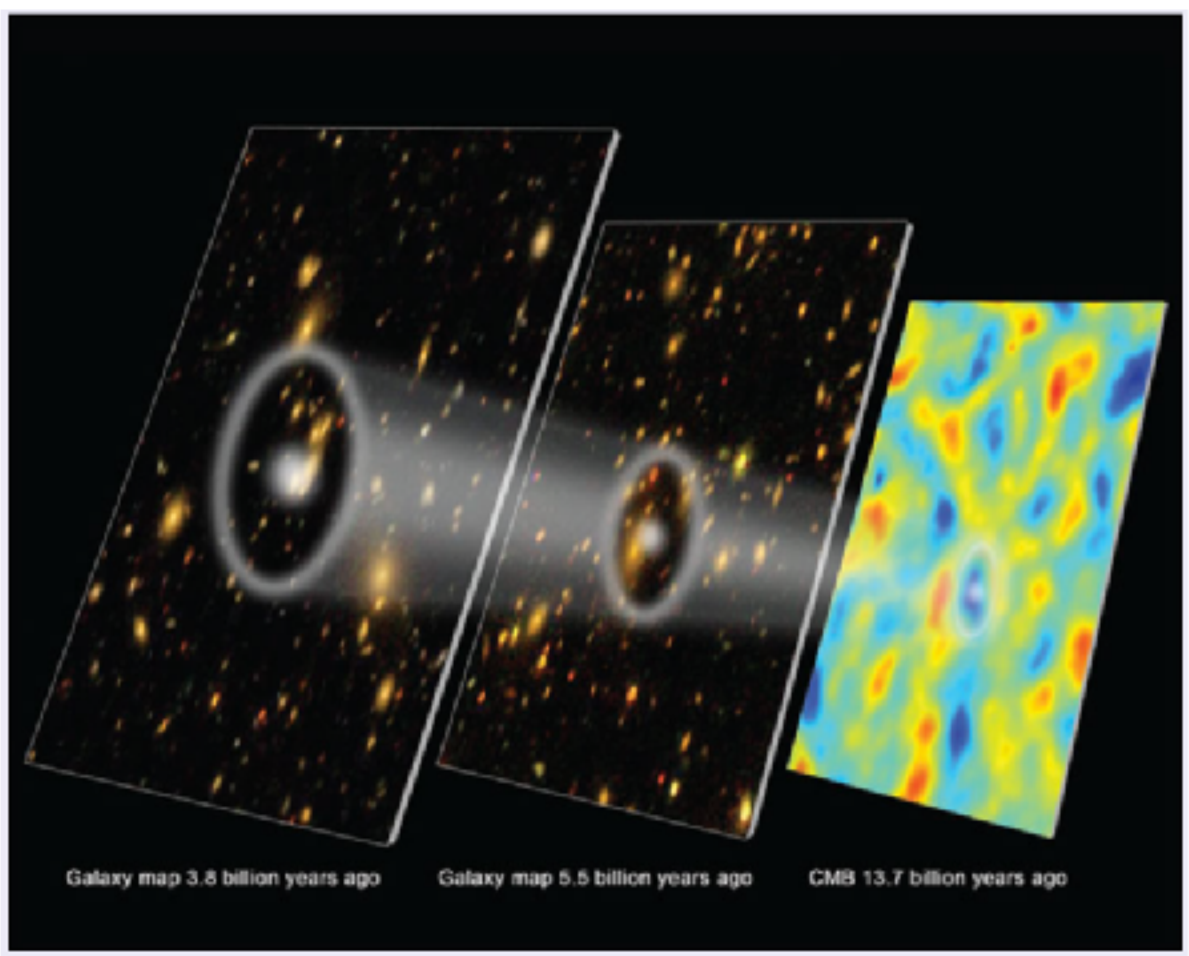
Credit: SDSS-III, South Pole Telescope

BAO

What is the Baryon Acoustic Oscillation?







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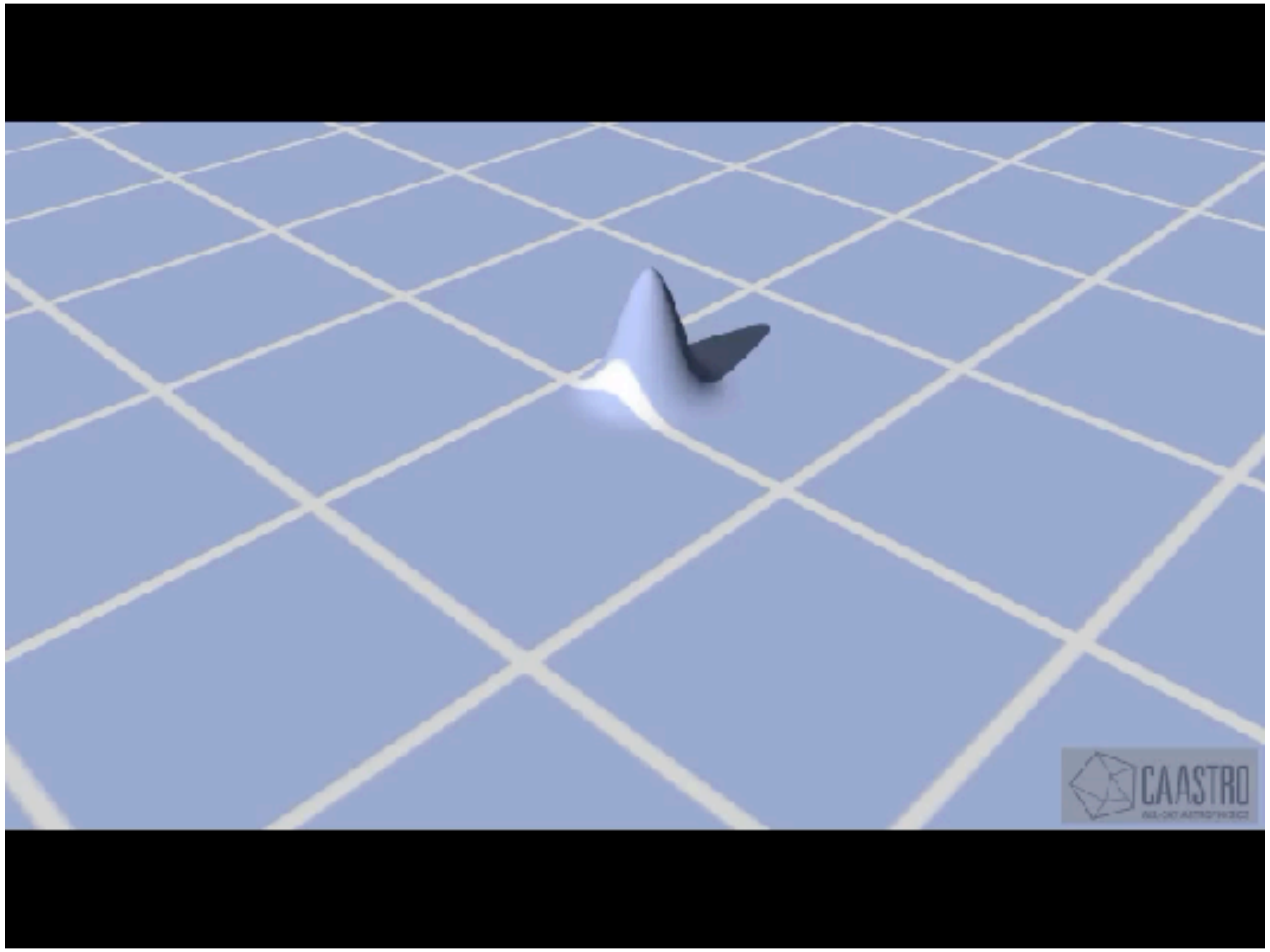
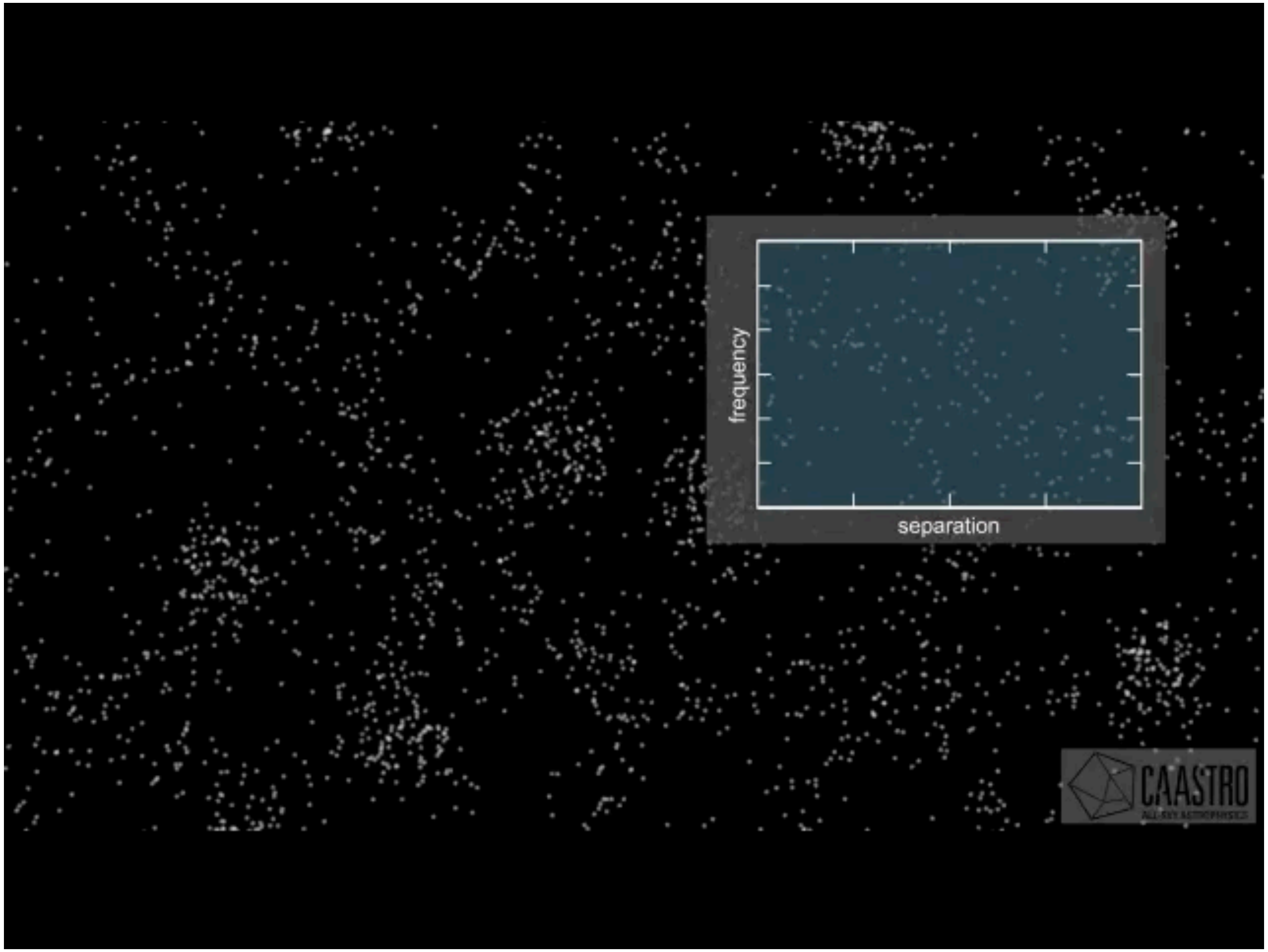


Credit: http://caastro.org/

How do we measure BAO?



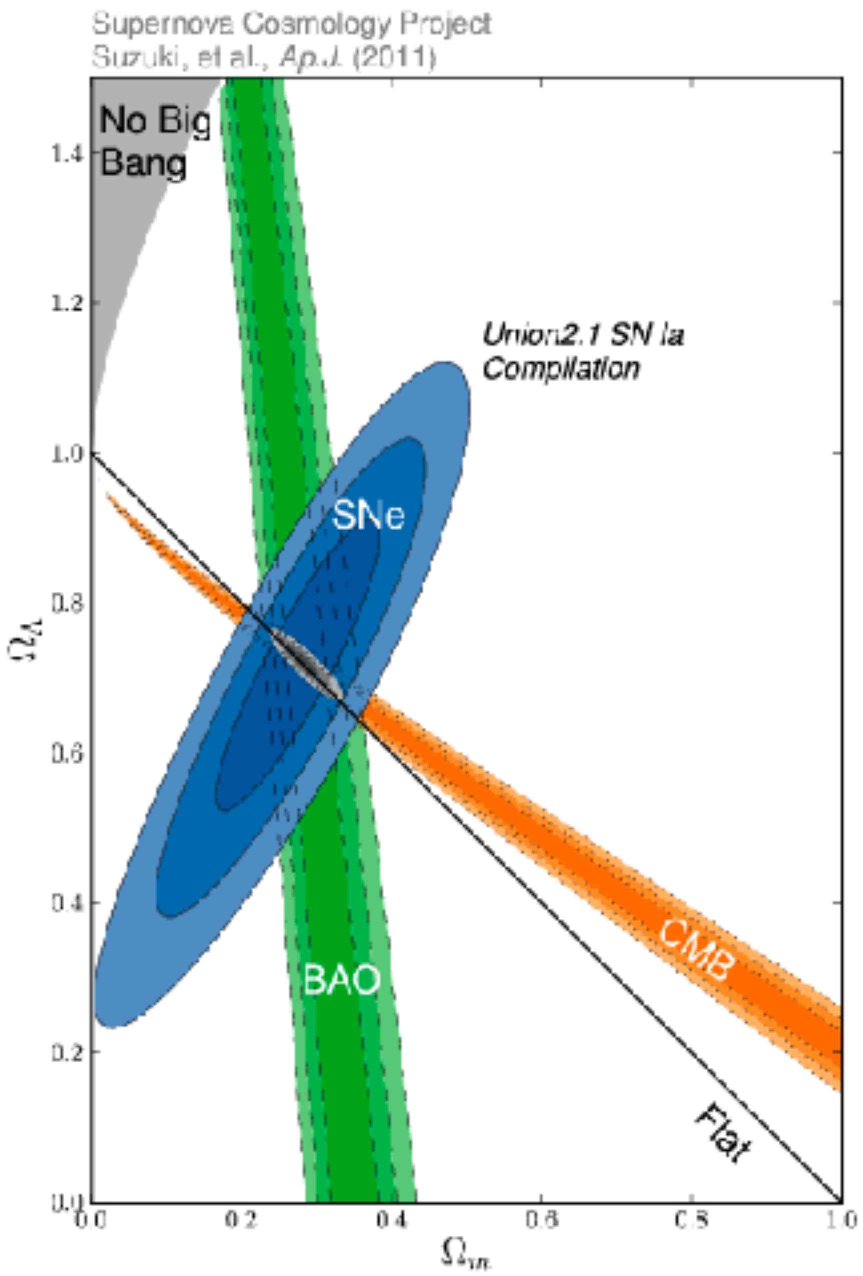
Credit: http://caastro.org/

The BAO can be measured at a given redshift and it will depend on the cosmological model

All observations

Considering all observations, and if we assume $w = -1$, we find

$$\Omega_{m,0} \simeq 0.31 \quad \Omega_{\Lambda,0} \simeq 0.69$$



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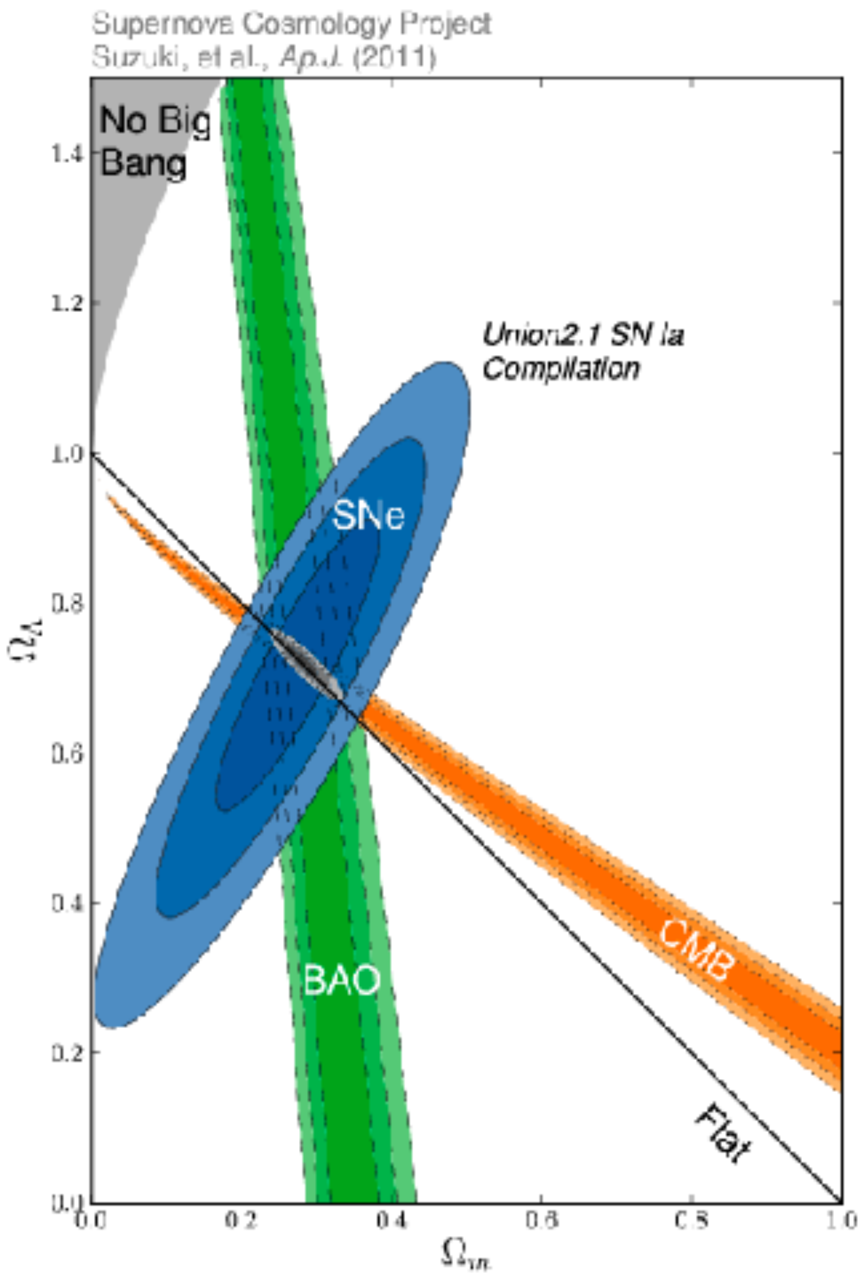

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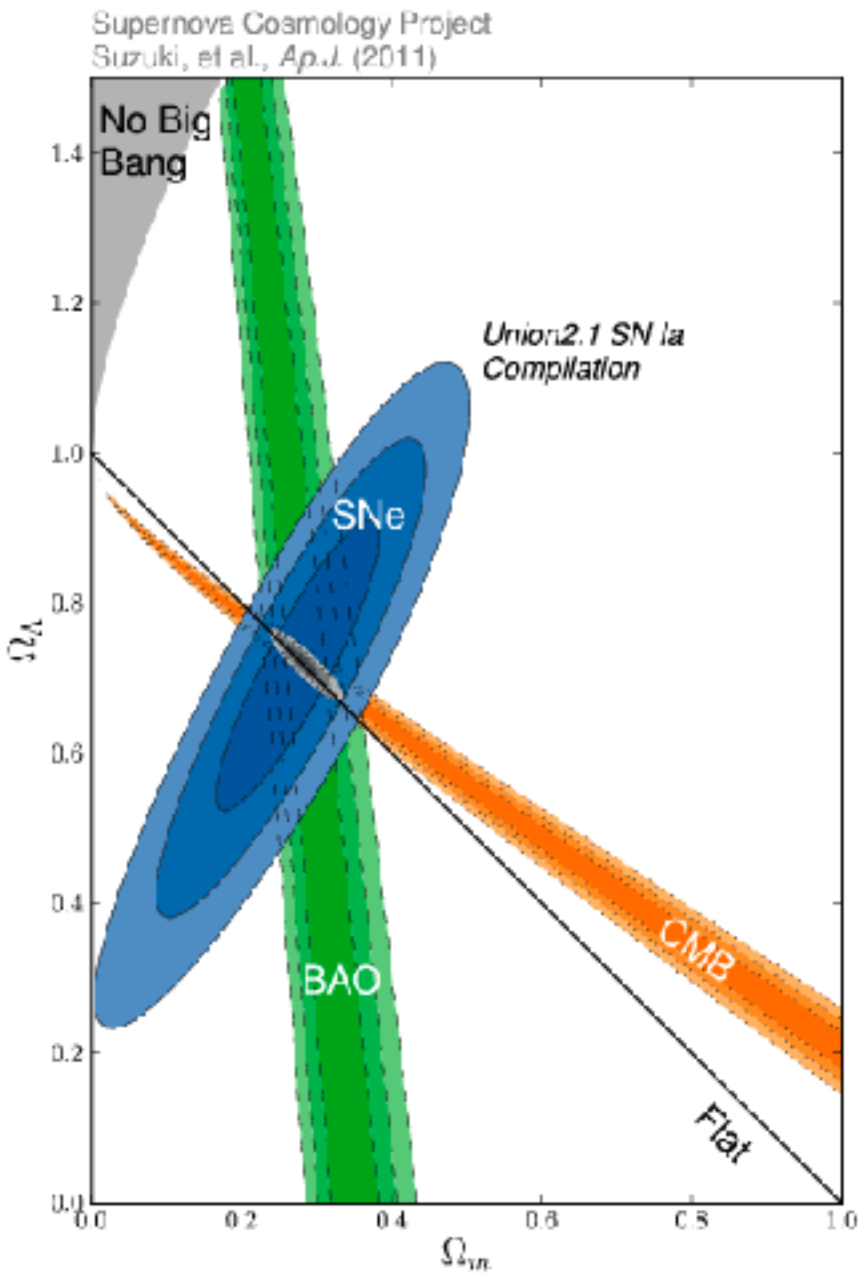

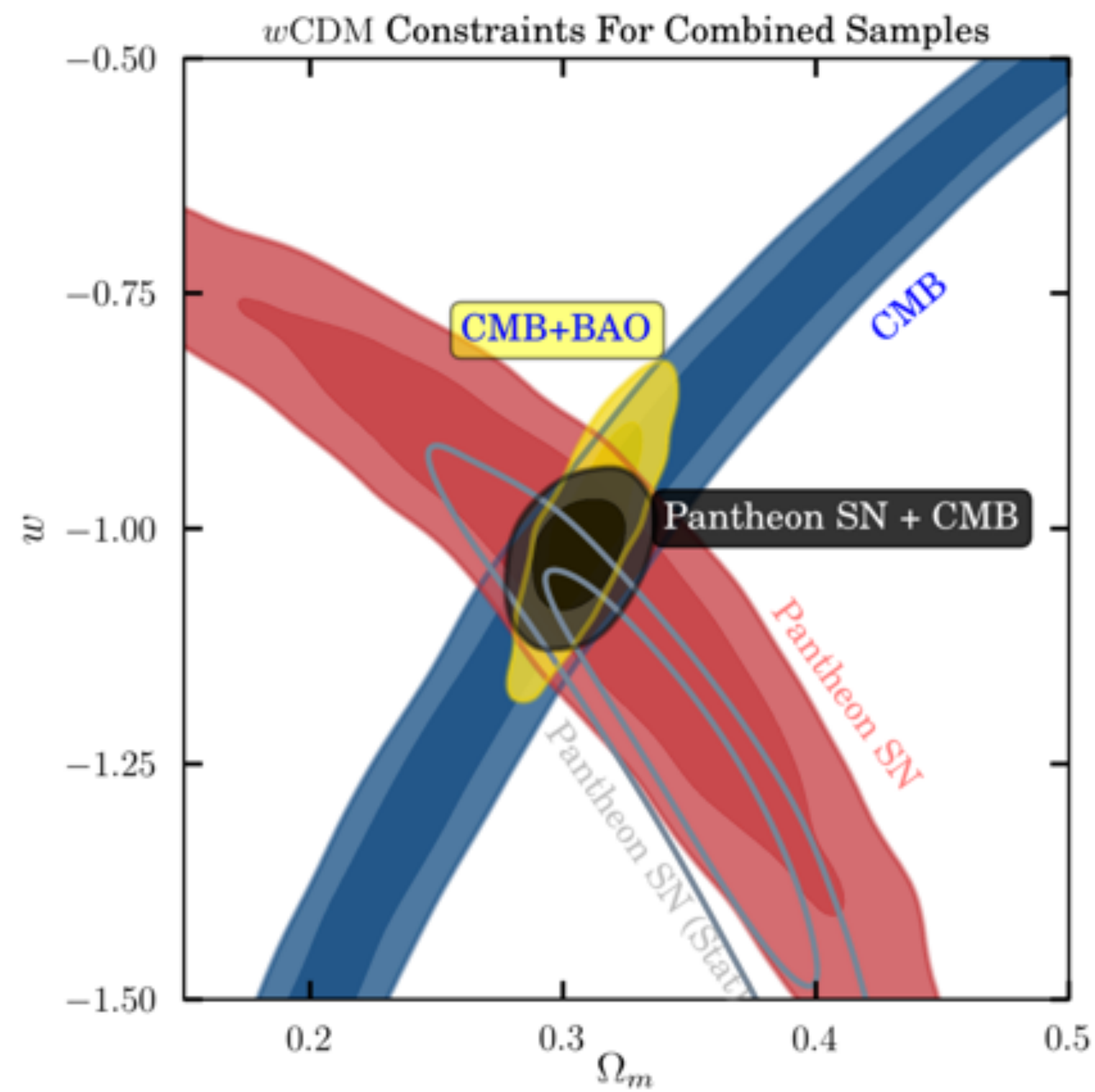

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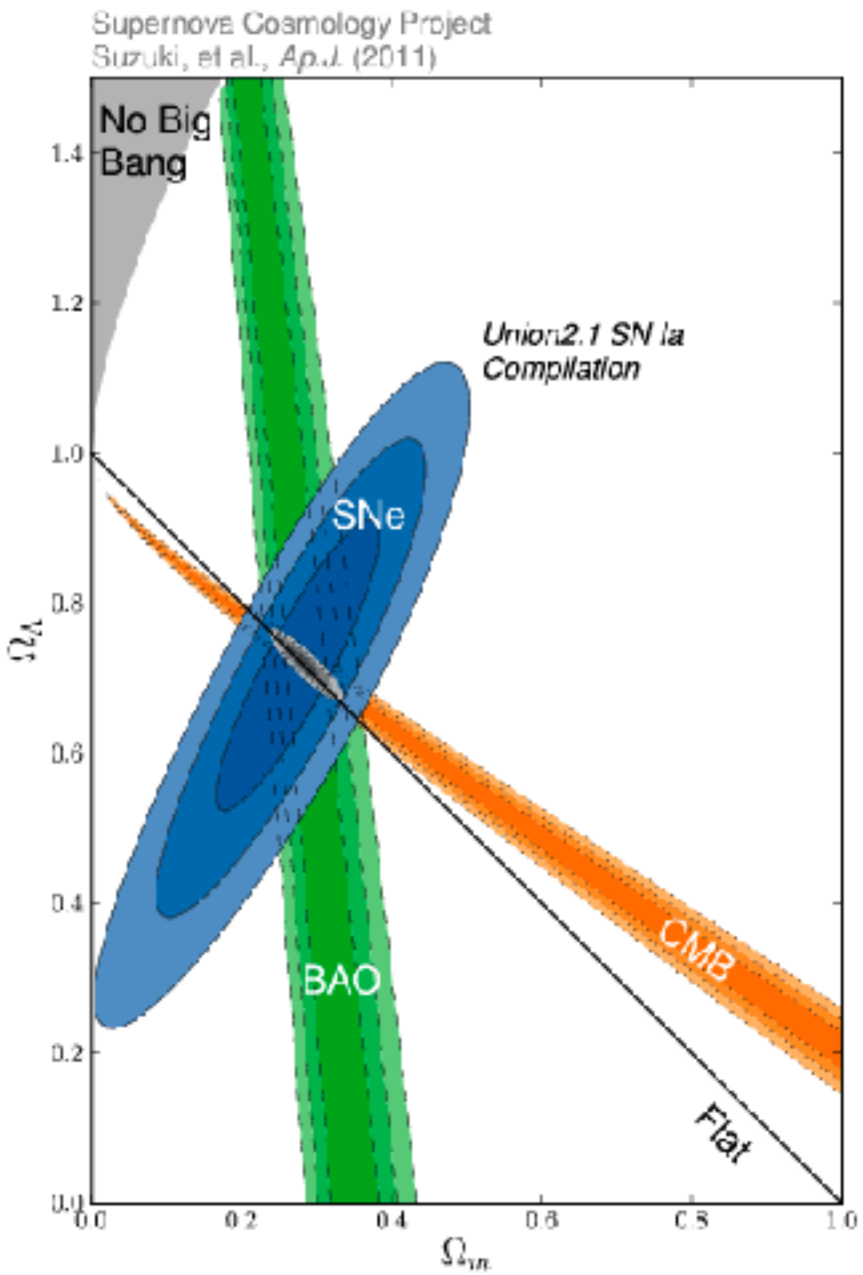

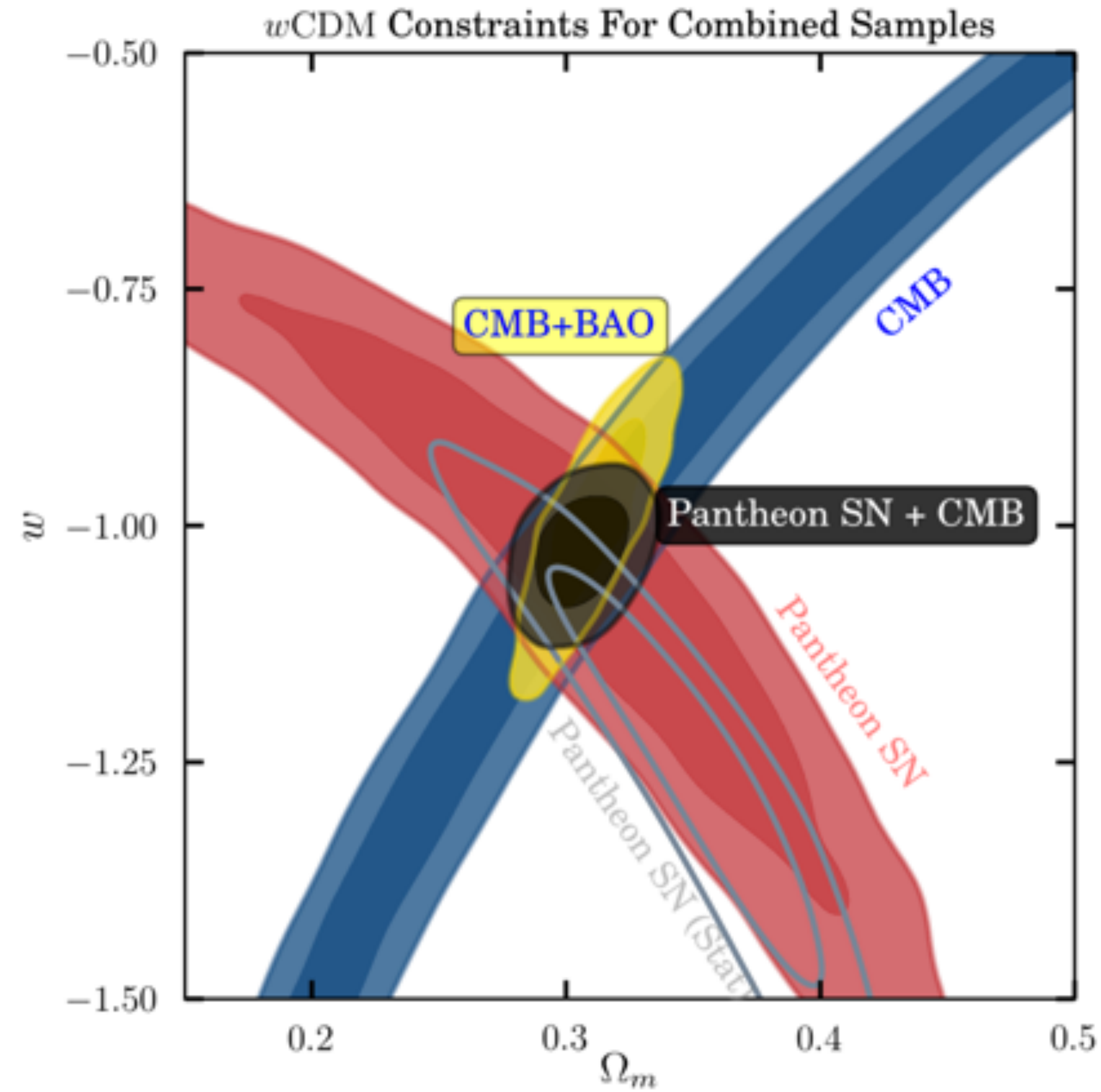

If we assume w constant

It is possible that the "X" known as dark energy is the cosmological constant but not sure

Effects of the cosmological constant

Cosmological effects

Accelerate the Universe

$$H \equiv \frac{\dot{a}}{a} = H_0 \sqrt{\Omega_{r,0}(1+z)^4 + \Omega_{m,0}(1+z)^3 + \Omega_{\Lambda,0}}$$

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$$H = H_0\sqrt{\Omega_{r,0}(1+z)^4 + \Omega_{m,0}(1+z)^3 + \Omega_{\Lambda,0}}$$

The Universe started accelerating $6{,}1\ 10^9$ years ago (depends a lot on H_0)

Effects of the cosmological constant

Cosmological effects

Modification of the age of the Universe

$$dt = -\frac{dz}{(1+z)H(z)}$$

$$\text{Age of the Universe} = \int_0^{t_0} dt = -\int_\infty^0 \frac{dz}{(1+z)H(z)} = \int_0^\infty \frac{dz}{(1+z)H(z)}$$

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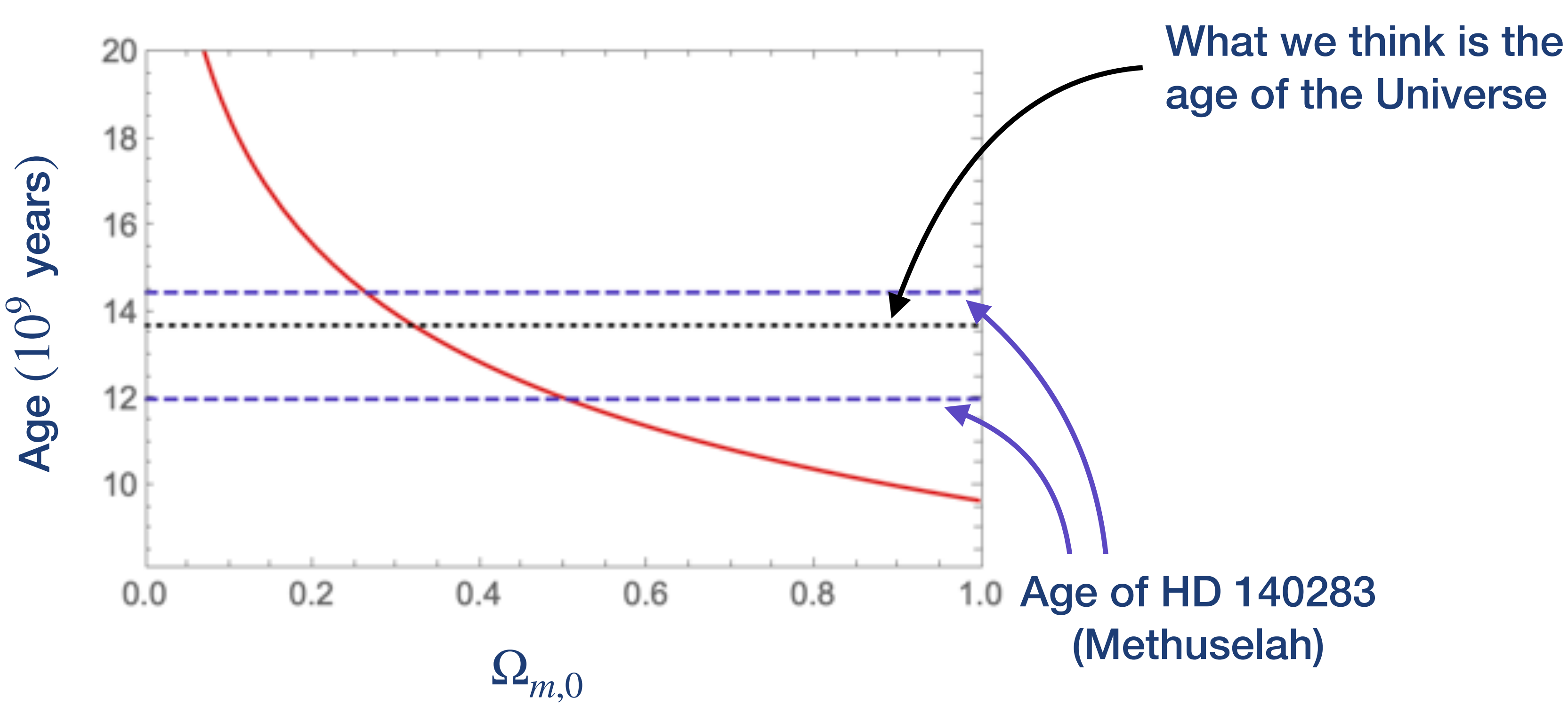

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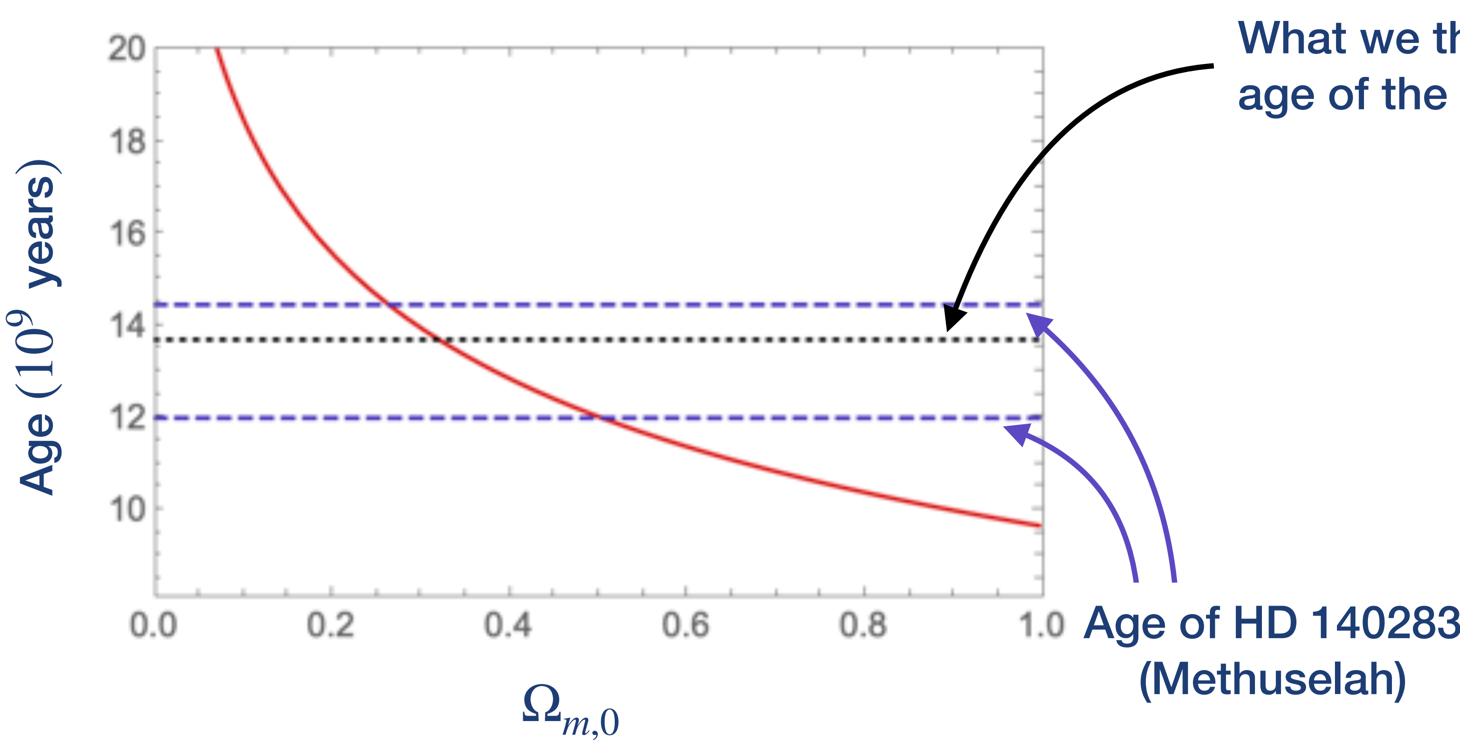
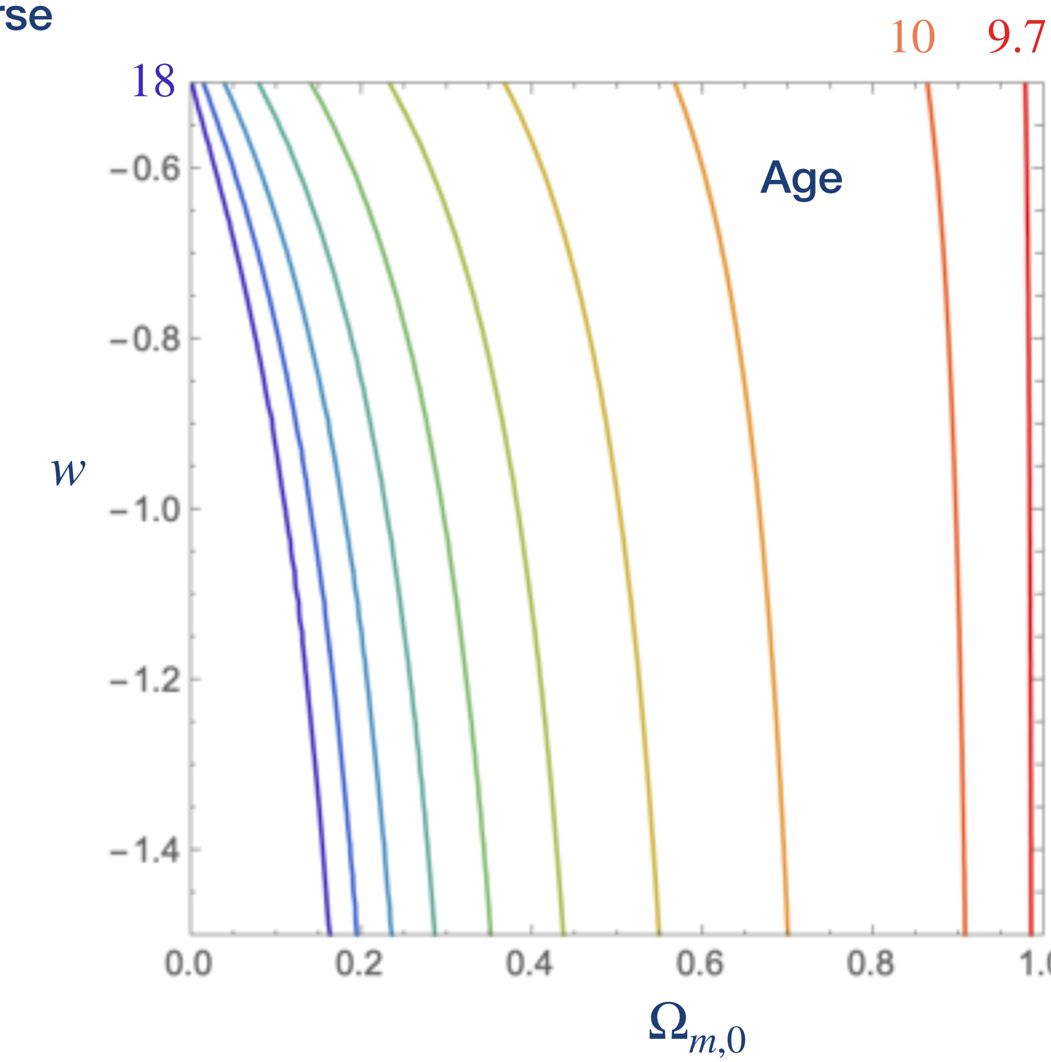
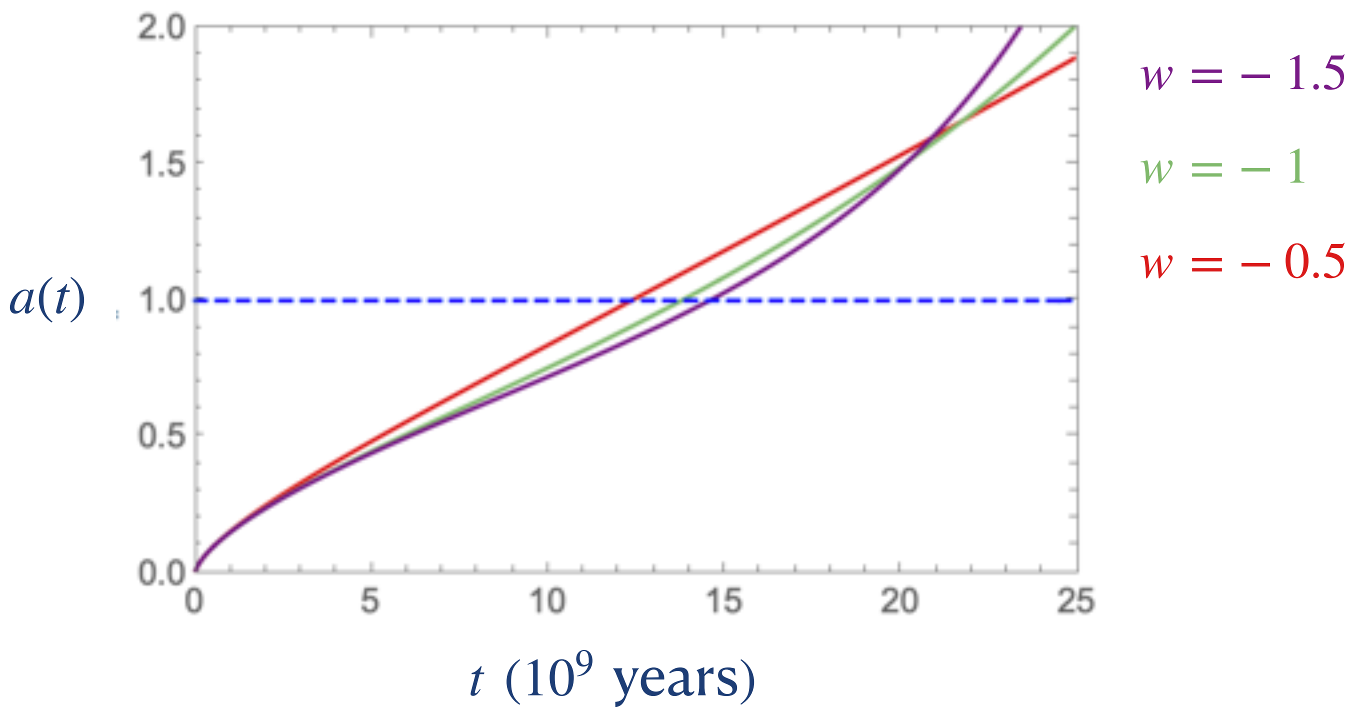




Effects of the cosmological constant

Cosmological effects

Evolution of the Universe



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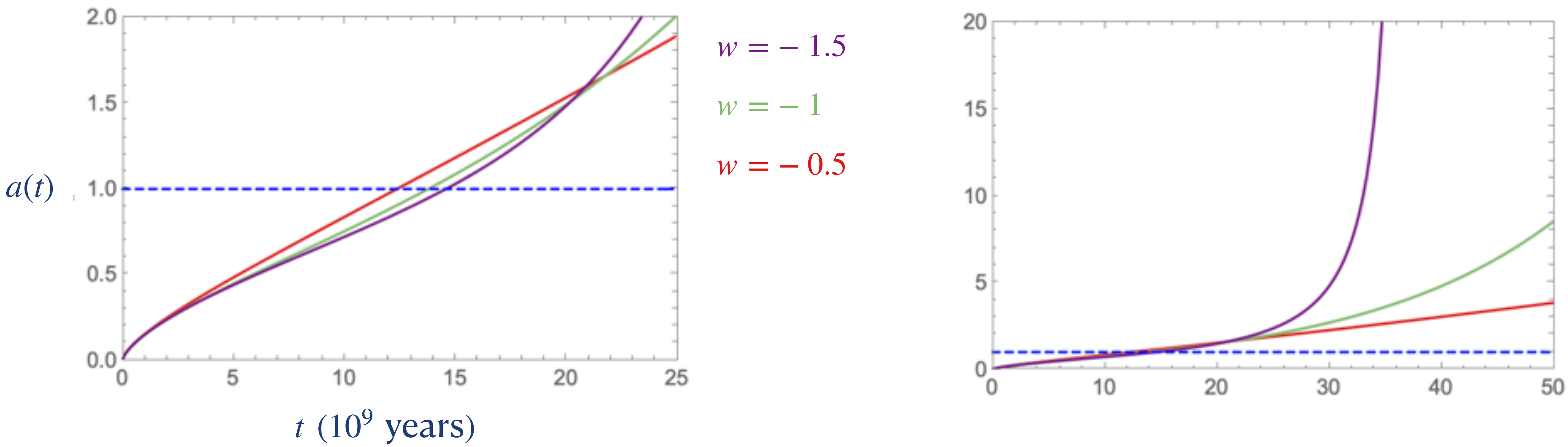

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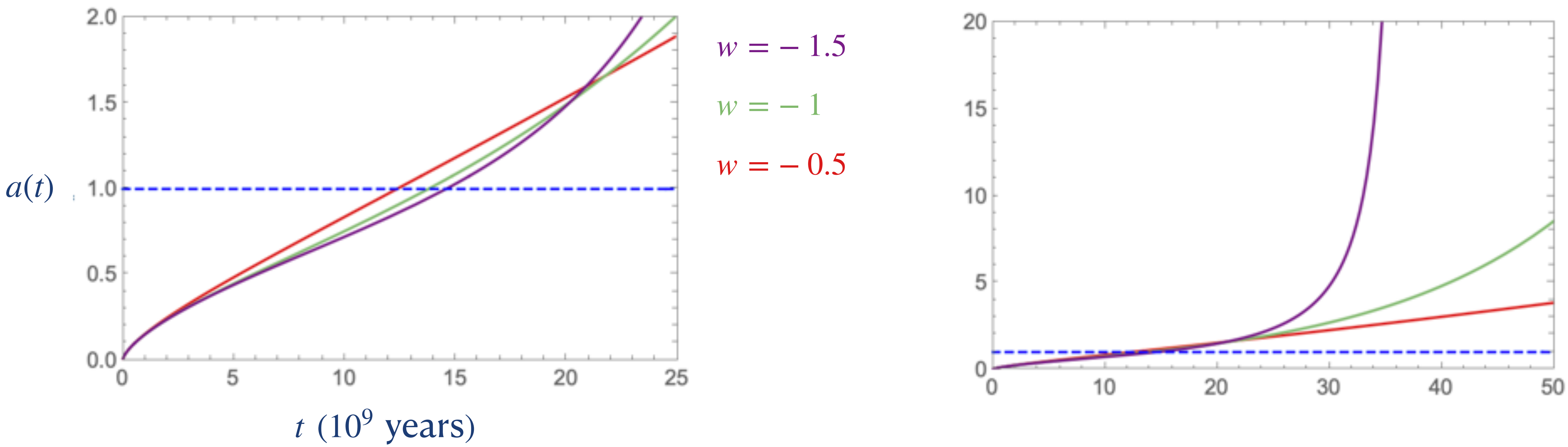

For a cosmological constant, the Universe expands exponentially in the future

Cosmological effects

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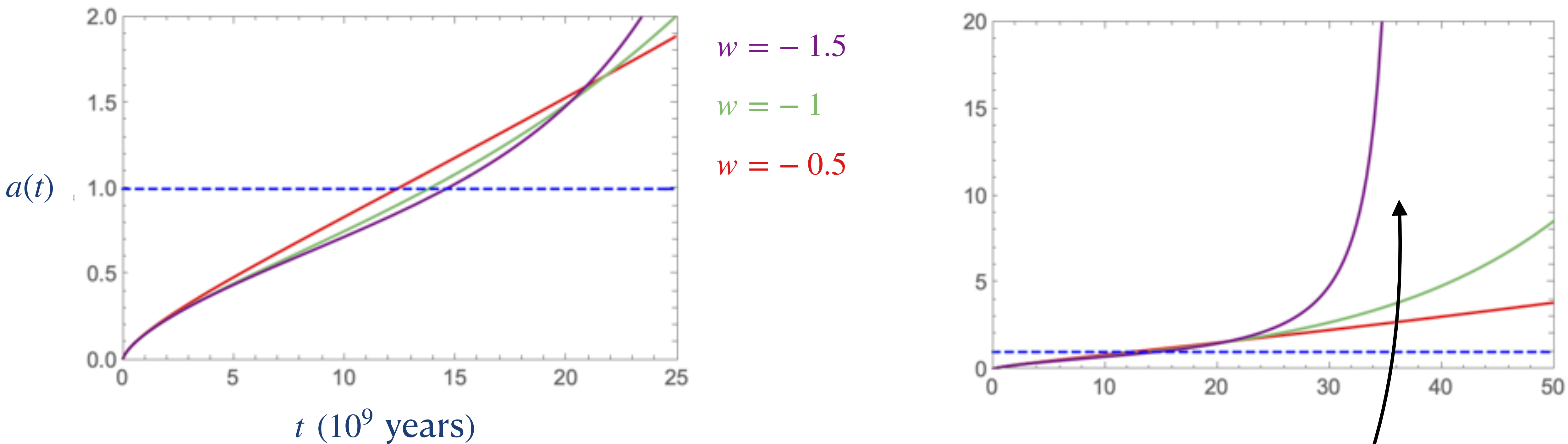

For a cosmological constant, the Universe expands exponentially in the future

For $w < -1$ (phantom energy), the scale factor diverges after a finite time (Big Rip)

Effects of the cosmological constant

Black hole effects

$$ds^2 = -\left(1 - \frac{2M}{r} - \frac{\Lambda}{3}r^2\right)dt^2 + \frac{dr^2}{1 - \frac{2M}{r} - \frac{\Lambda}{3}r^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

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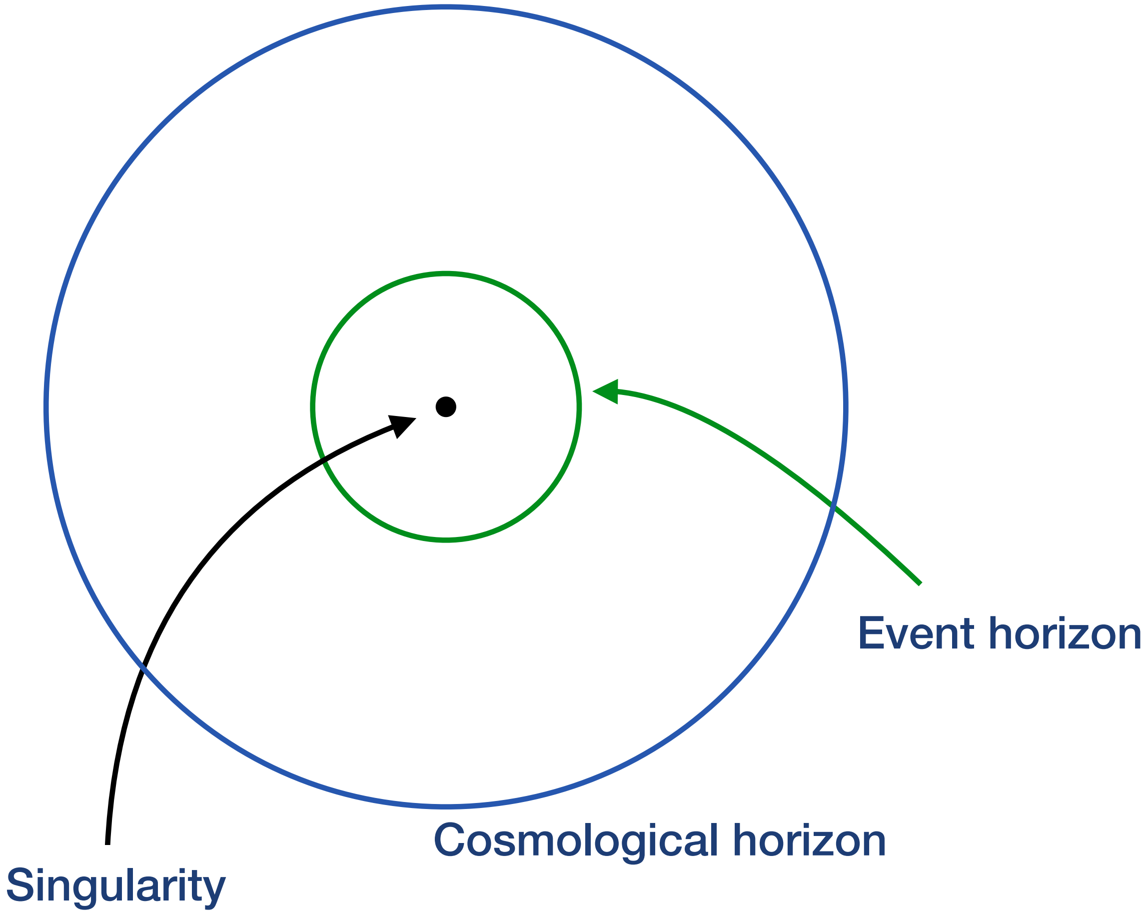
We have two horizons



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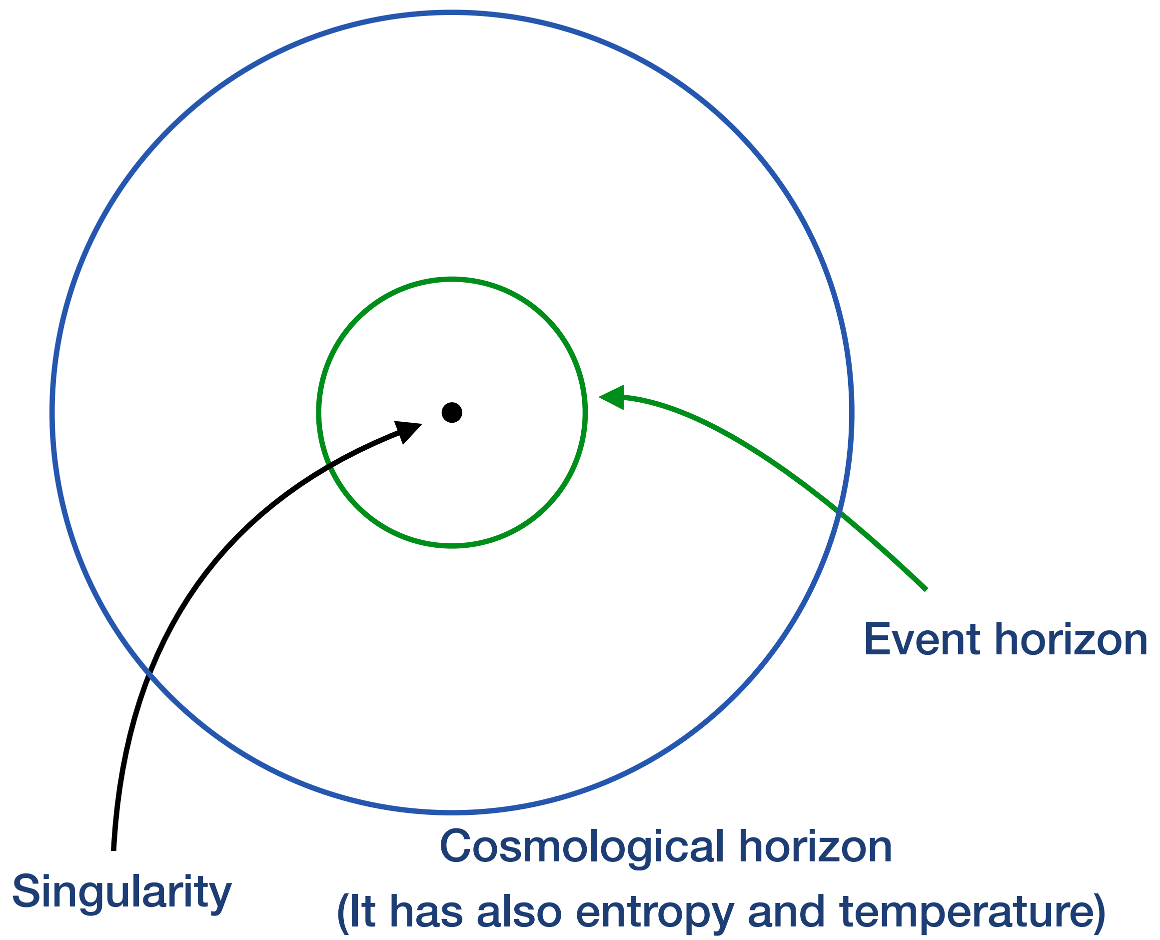

Even without mass we have a horizon, we can't see points at infinity

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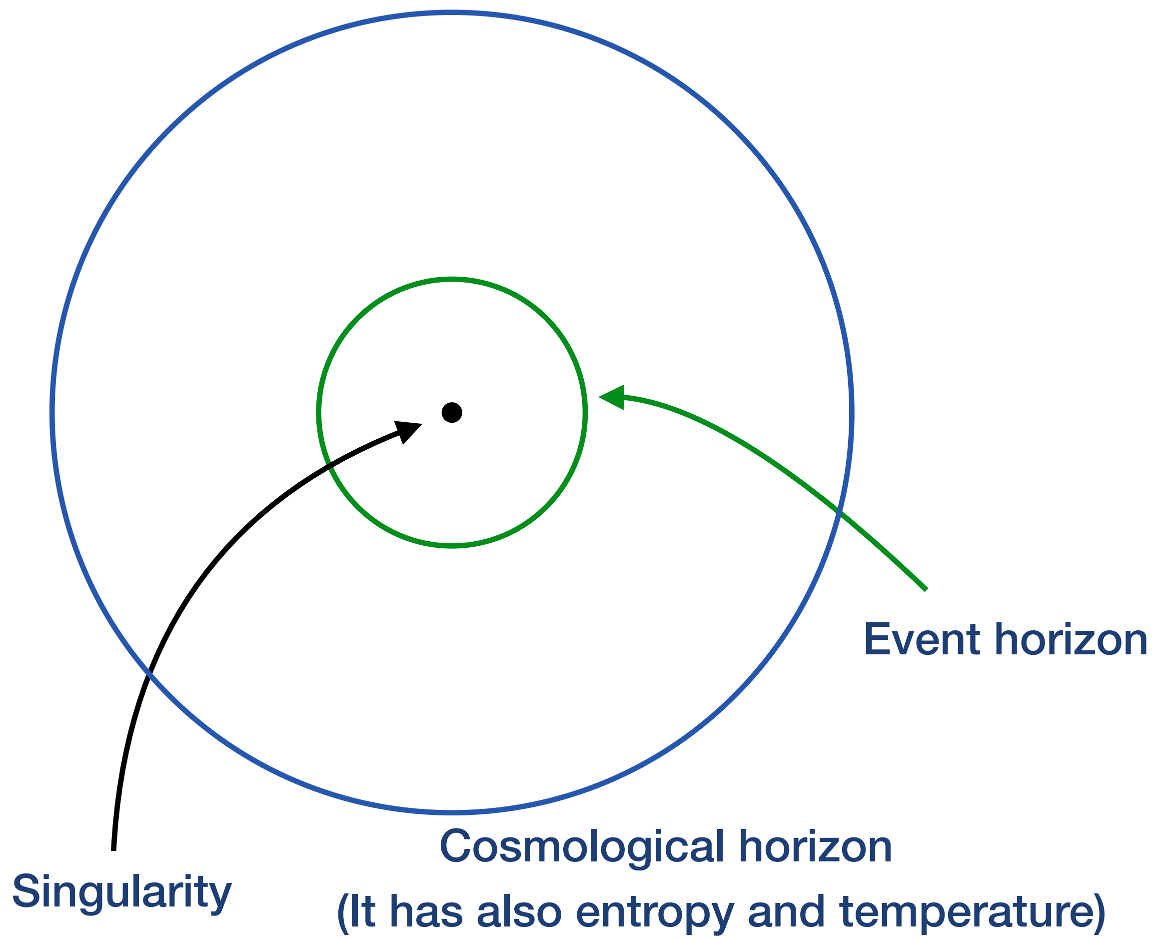


Newtonian limit

$$m\overrightarrow{a} = \left(\frac{m\Lambda}{3}r - \frac{GMn}{r^2}\right)\overrightarrow{e}_r$$

Repulsive force

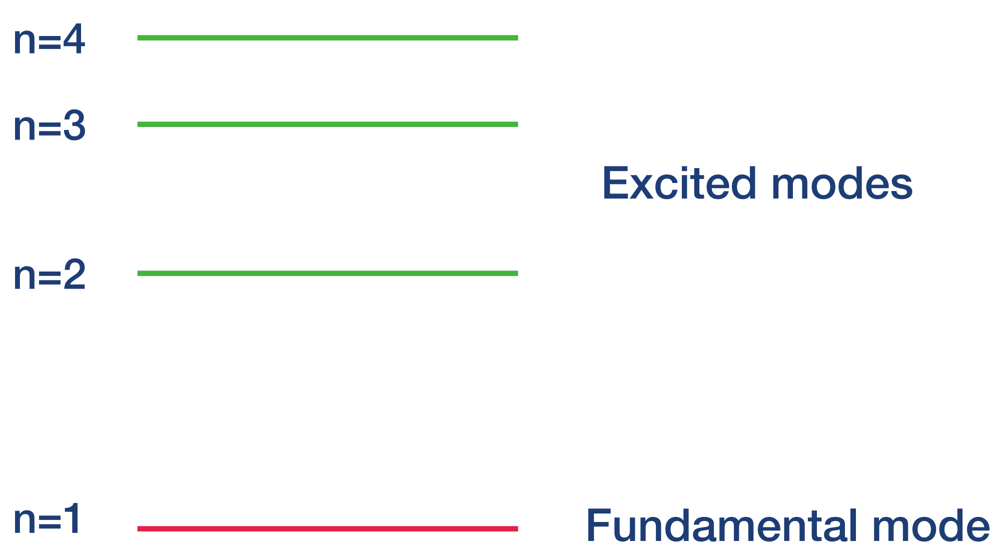
Dominant at large distances

Even without mass we have a horizon, we can't see points at infinity

Cosmological Constant Problem

Quantum mechanics

Electron of the hydrogen atom



Quantum mechanics

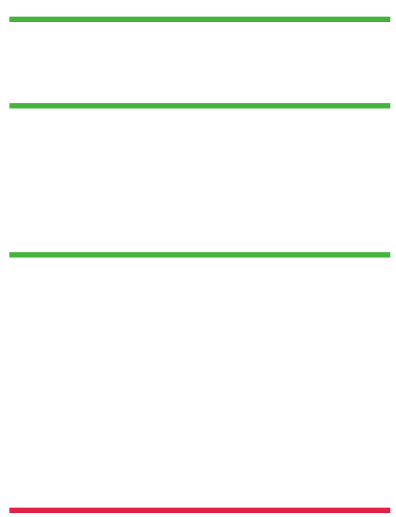
Electron of the hydrogen atom

n=4

n=3

n=2

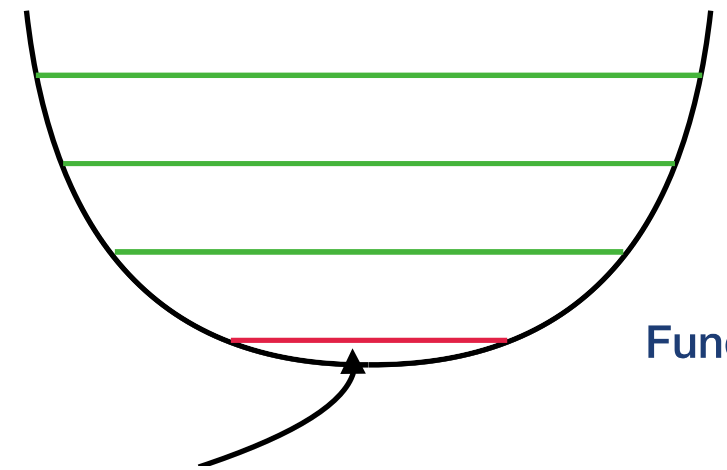
n=1



Excited modes

Fundamental mode

Harmonic oscillator



Excited modes

Fundamental mode

The energy is not zero because of the Heisenberg Principle

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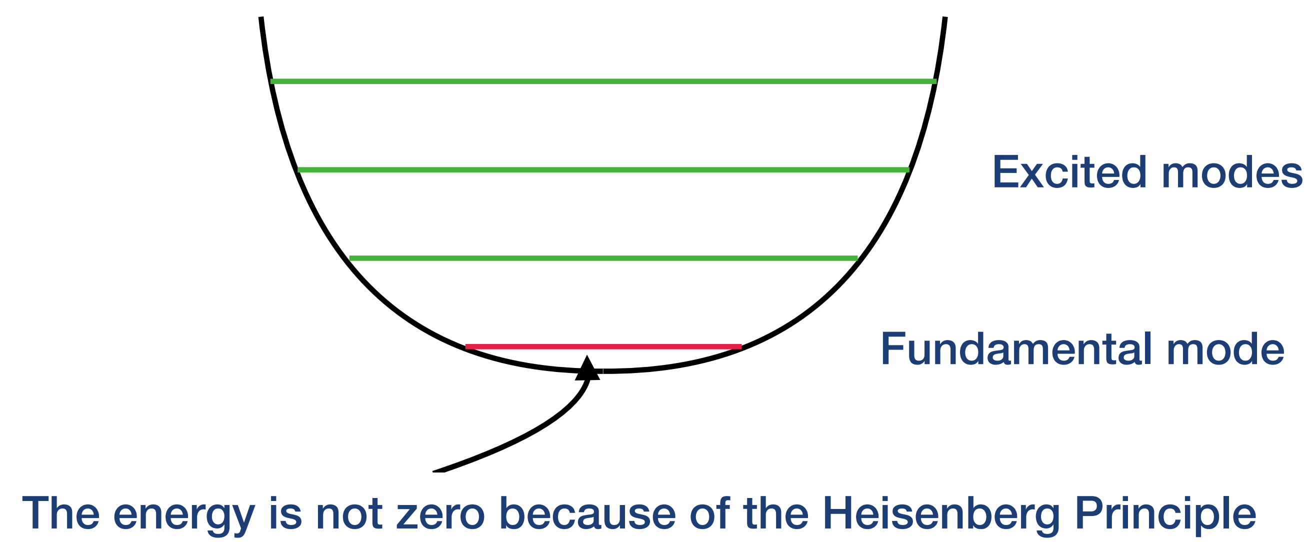

Quantum Field Theory

Cosmological Constant Problem

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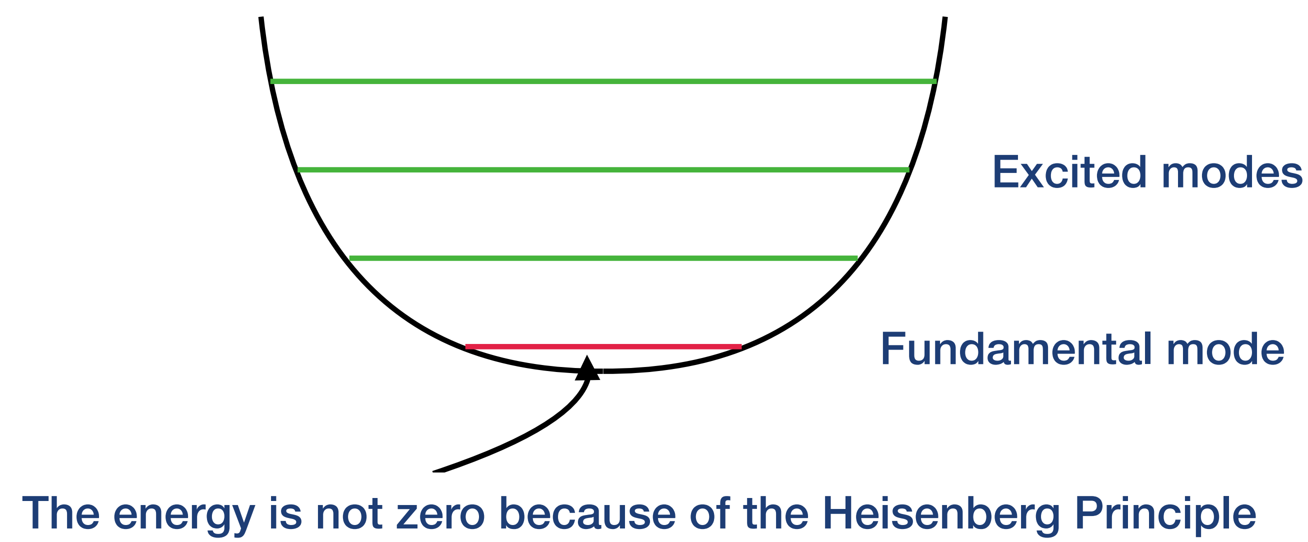

Quantum Field Theory

The number of particles is not fixed

We have a field which has a fundamental mode and excited states

Excited states represent the creation of particles

The fundamental mode is the absence of particles, known as vacuum and as quantum mechanics it has energy

So vacuum of each field has energy… and it has pressure such that $P = -\rho$

Cosmological Constant Problem

They are various fields in Nature and each one has some vacuum energy

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- Fermion fields have a negative vacuum energy
- Boson fields have a positive vacuum energy

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We do not have in Nature, 1 boson for 1 fermion, so they do not cancel each other and we need to calculate it

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electron

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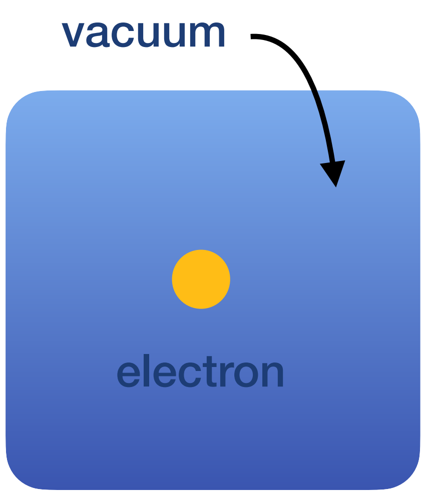

Electron interacts with the vacuum

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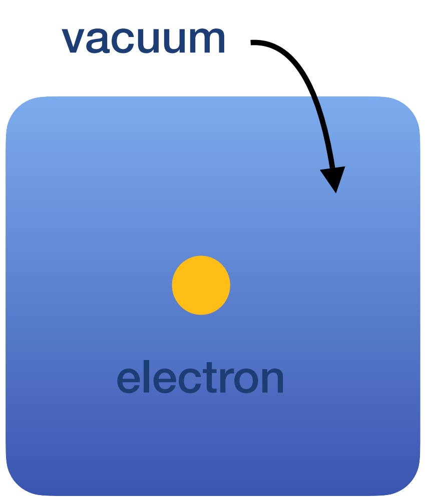

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Which modifies the “position” of the electron

And therefore its energy

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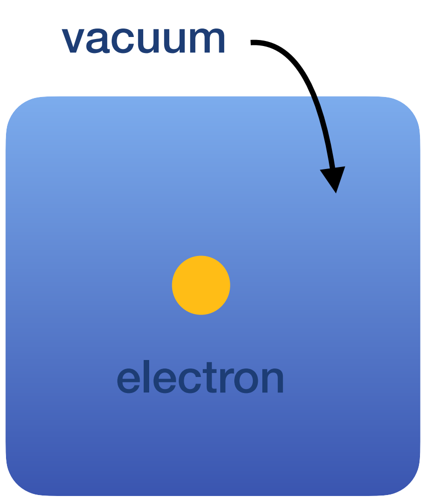

Electron interacts with the vacuum

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For the state $n = 2$ and $\ell = 0$
we have $\Delta E \simeq 2.8\ \mu eV$

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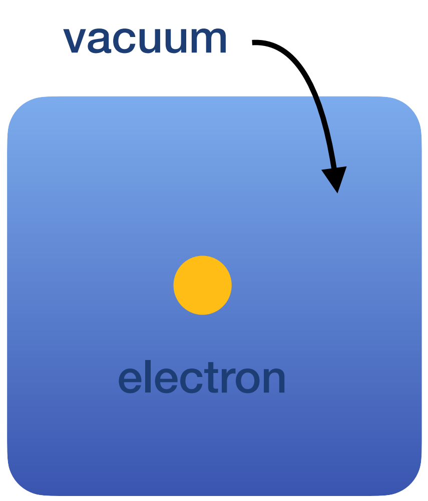
Do vacuum fluctuations really exist? Yes

Lamb Shift

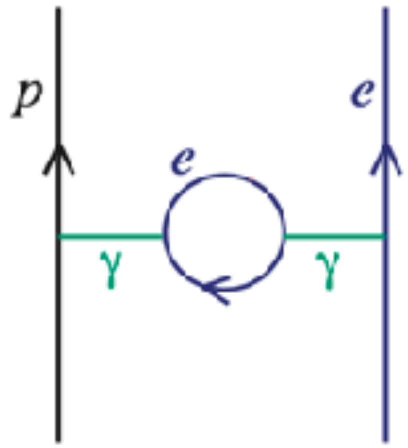


Electron interacts with the vacuum

Which modifies the “position” of the electron

And therefore its energy

For the state $n = 2$ and $\ell = 0$
we have $\Delta E \simeq 2.8\ \mu eV$



one-loop effect of
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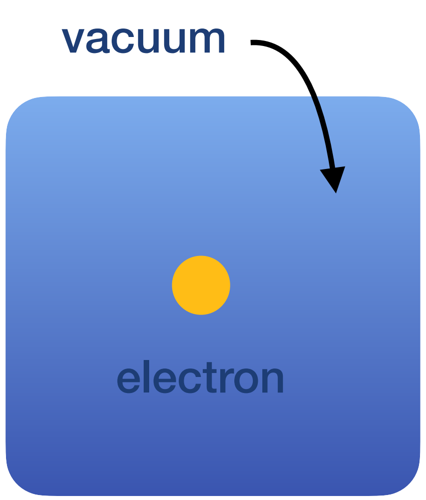

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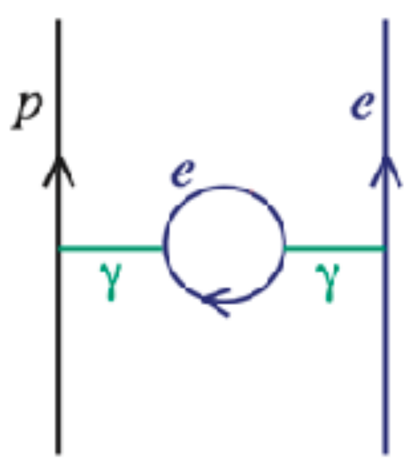

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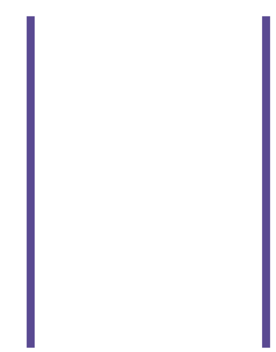

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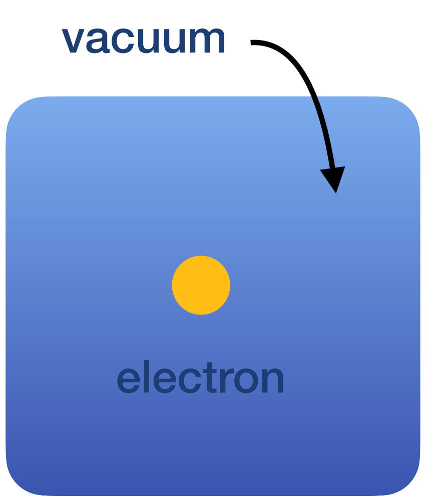

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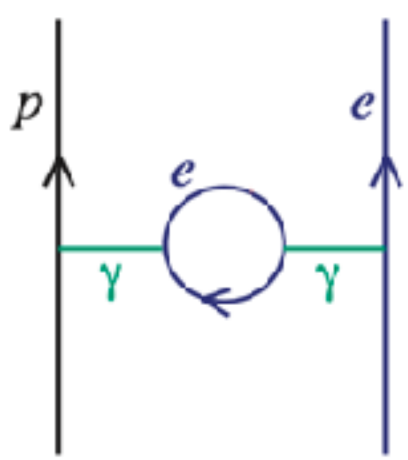

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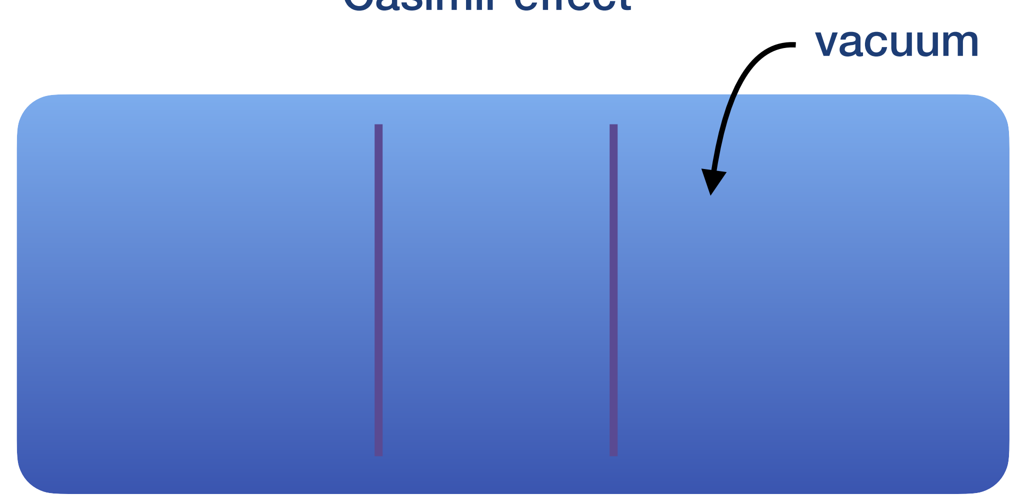

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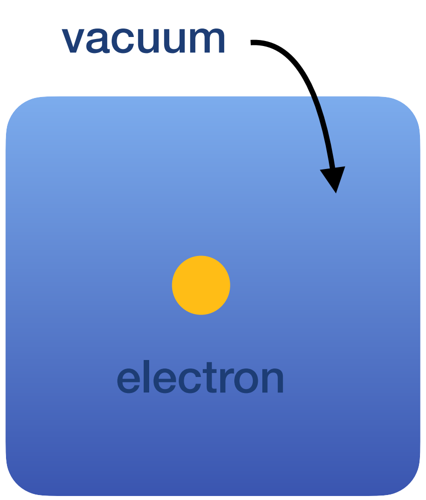

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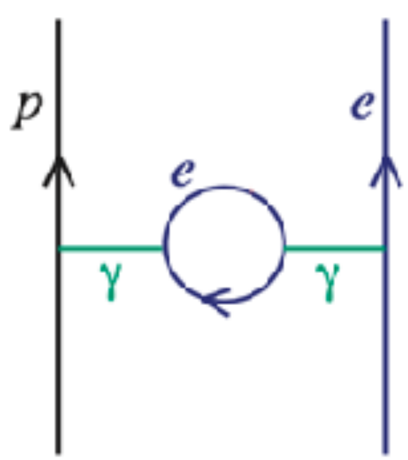

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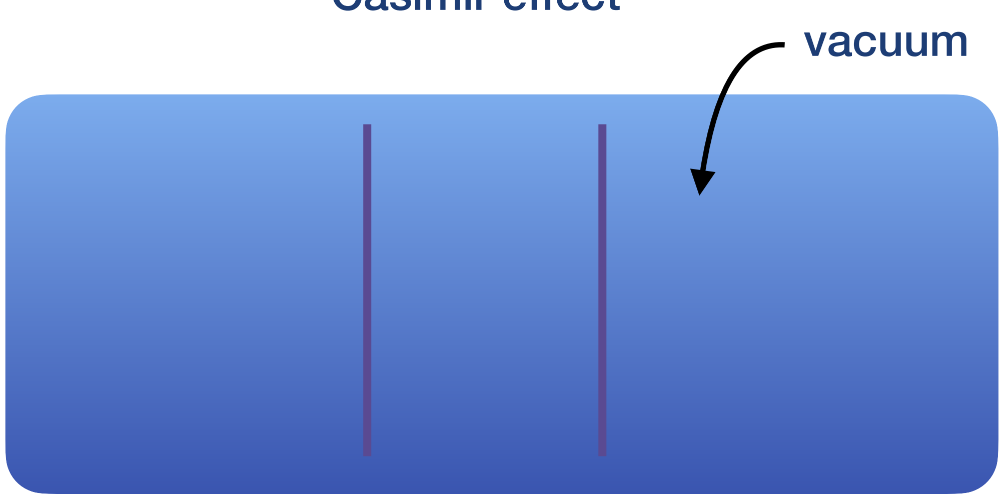

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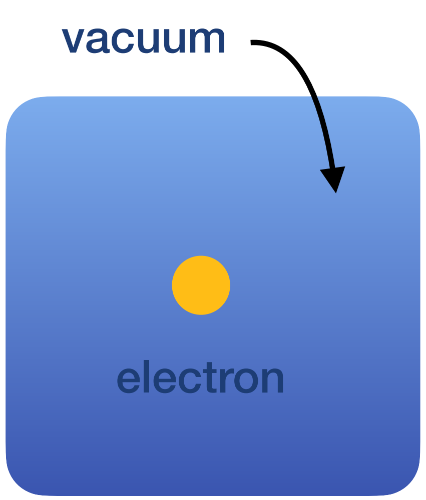

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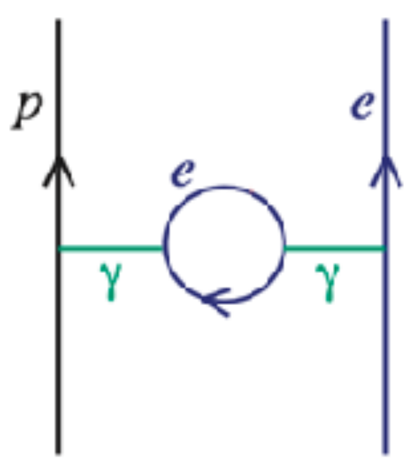

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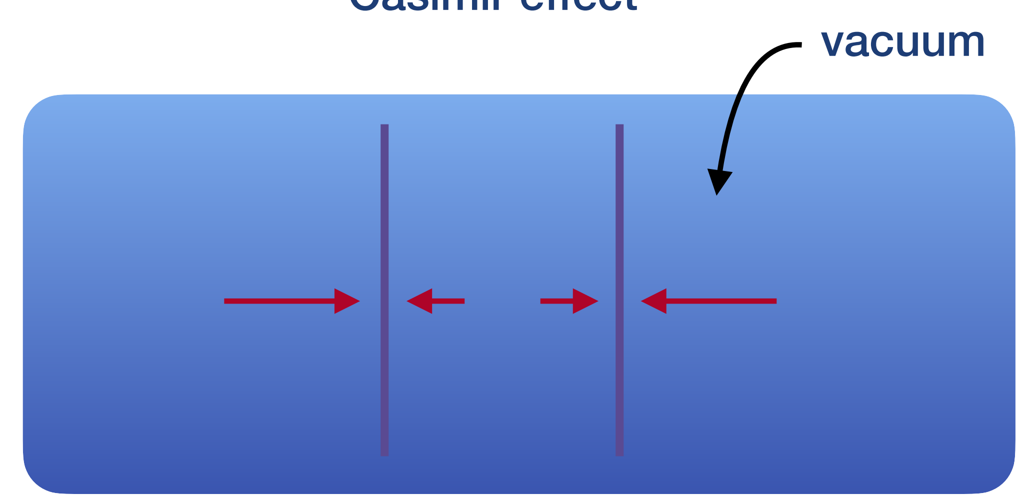

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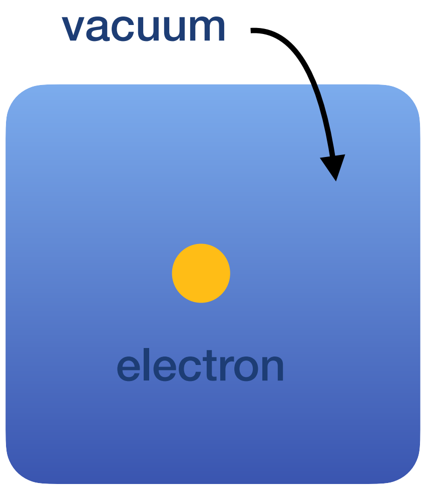

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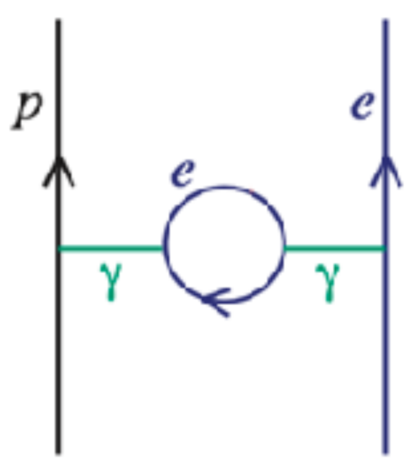

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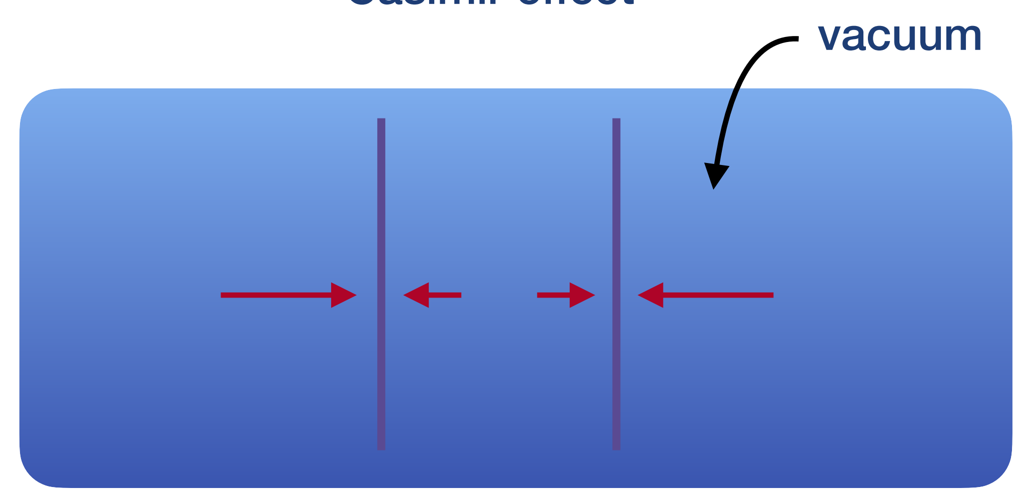

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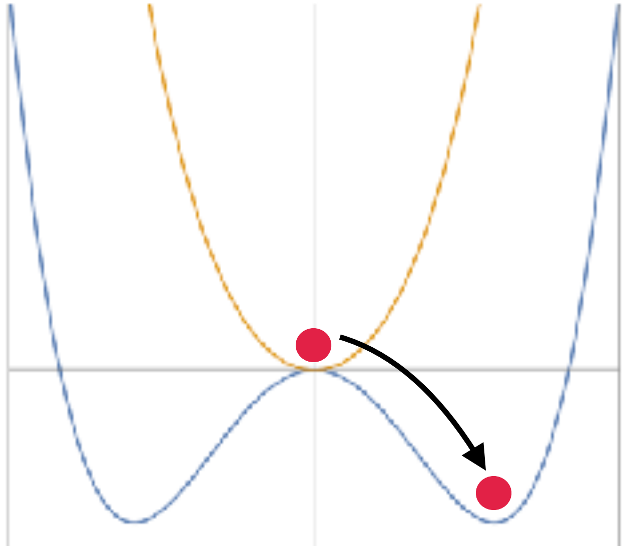

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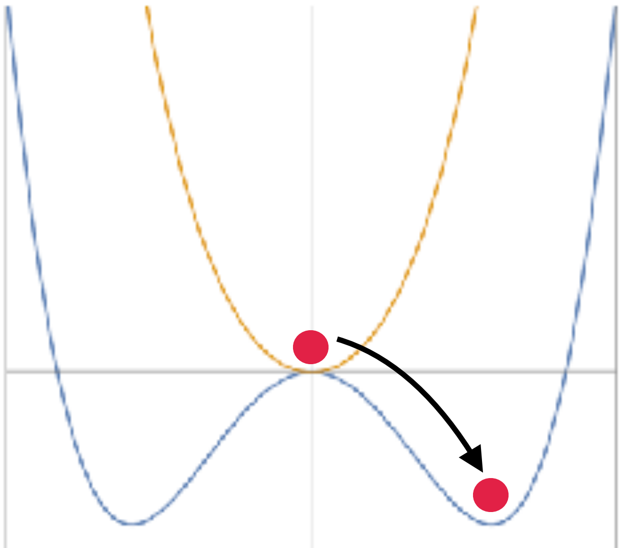

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Before electroweak phase transition

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If we remove 1 zero, the Universe accelerates too early and structures will not have time to form

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There is no positive cosmological constant in String Theory

- String Theory is a theory which is the best candidate for a theory describing all forces
- More than a theory, it is a consistent framework
- Therefore, any theory should be in the UV equivalent to some String Theory

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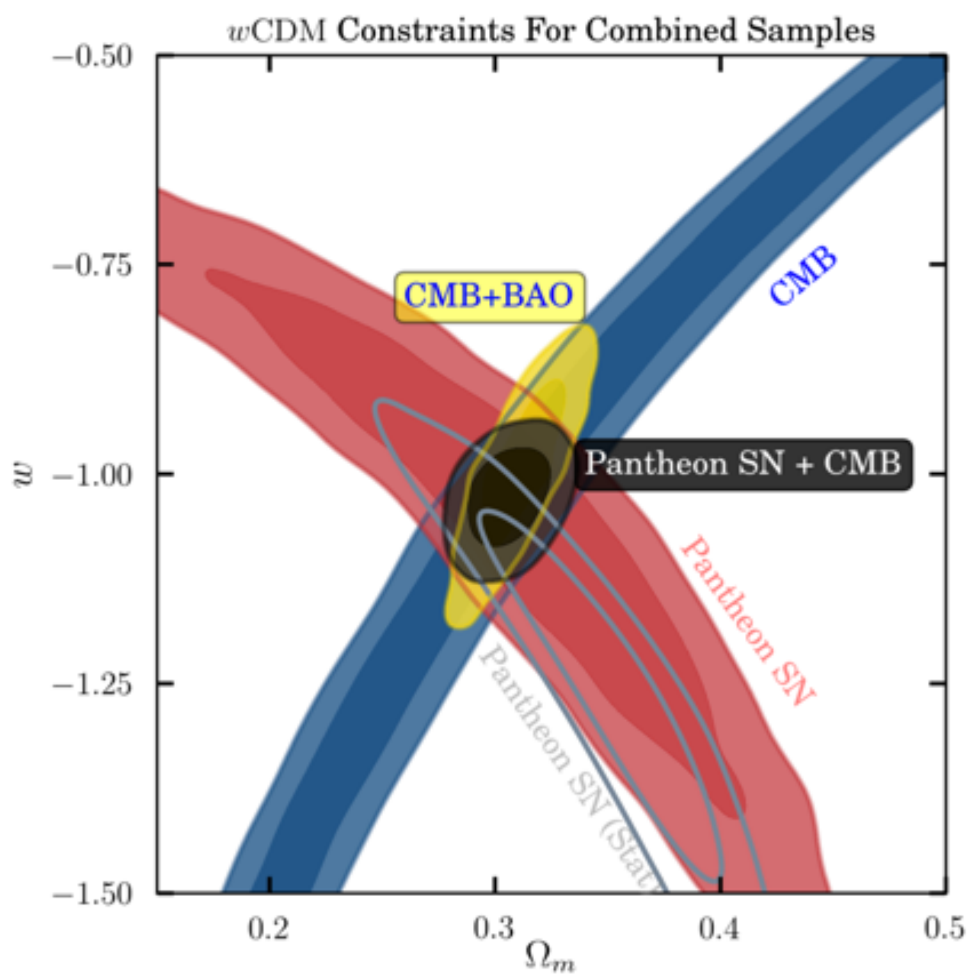

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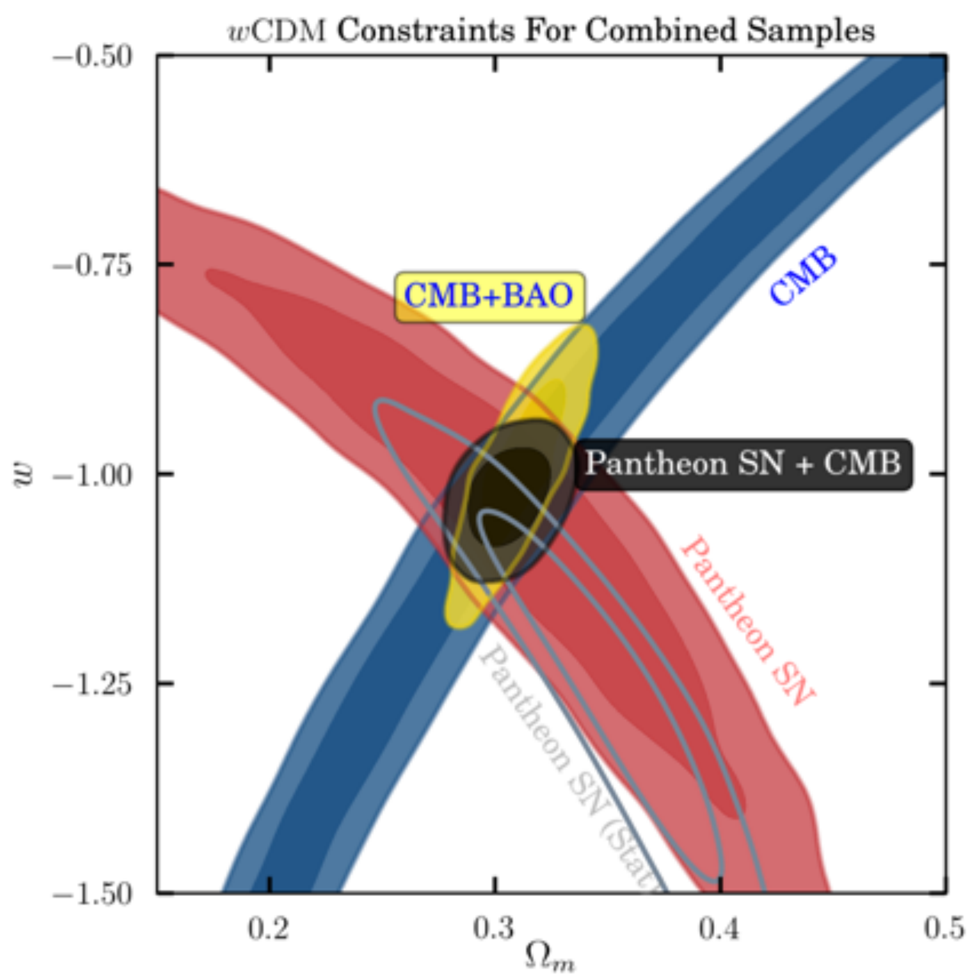

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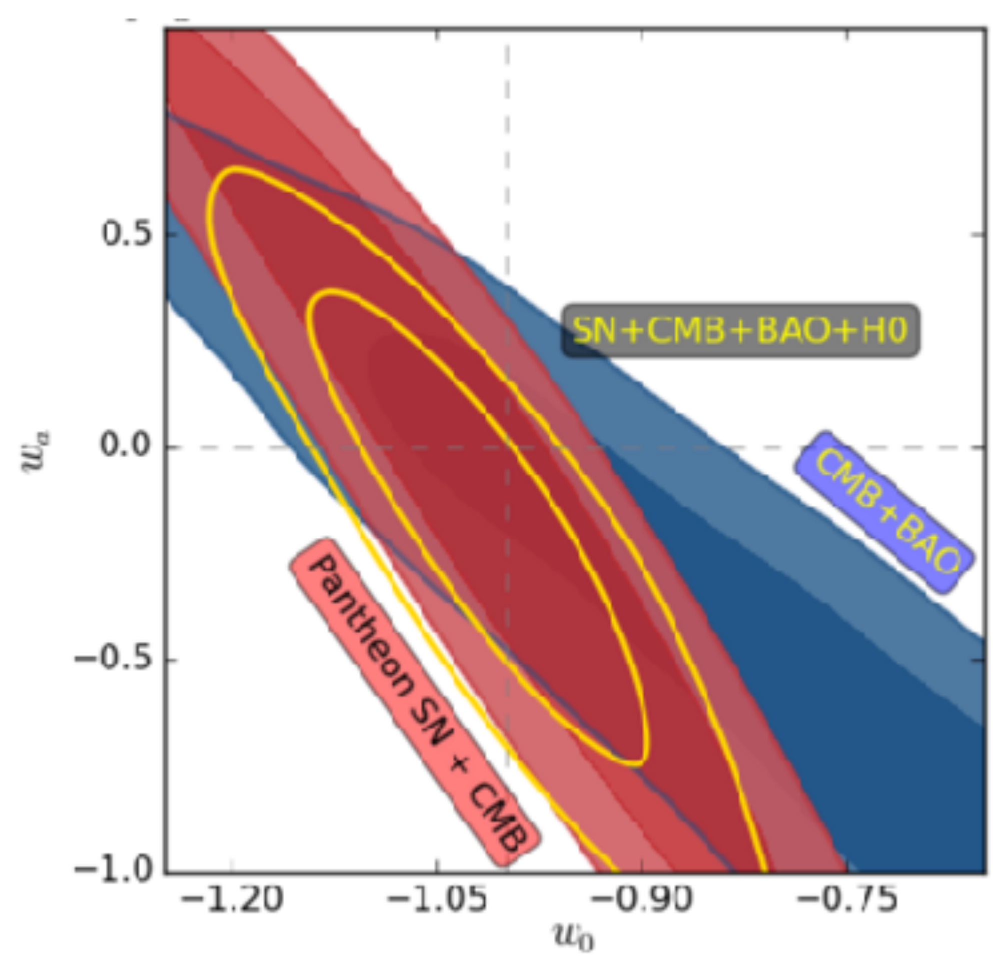


$$w(z) = w_0 + w_a \frac{z}{1+z}$$

It's called a parametrization

Two approaches

To assume that some physics cancels completely Λ because it is difficult to explain the value and because it is not included in String Theory

They are known as Dark Energy models

Or sometimes Modified Gravity

Two approaches

Cosmological Constant Problem

To assume that some physics cancels completely Λ because it is difficult to explain the value and because it is not included in String Theory

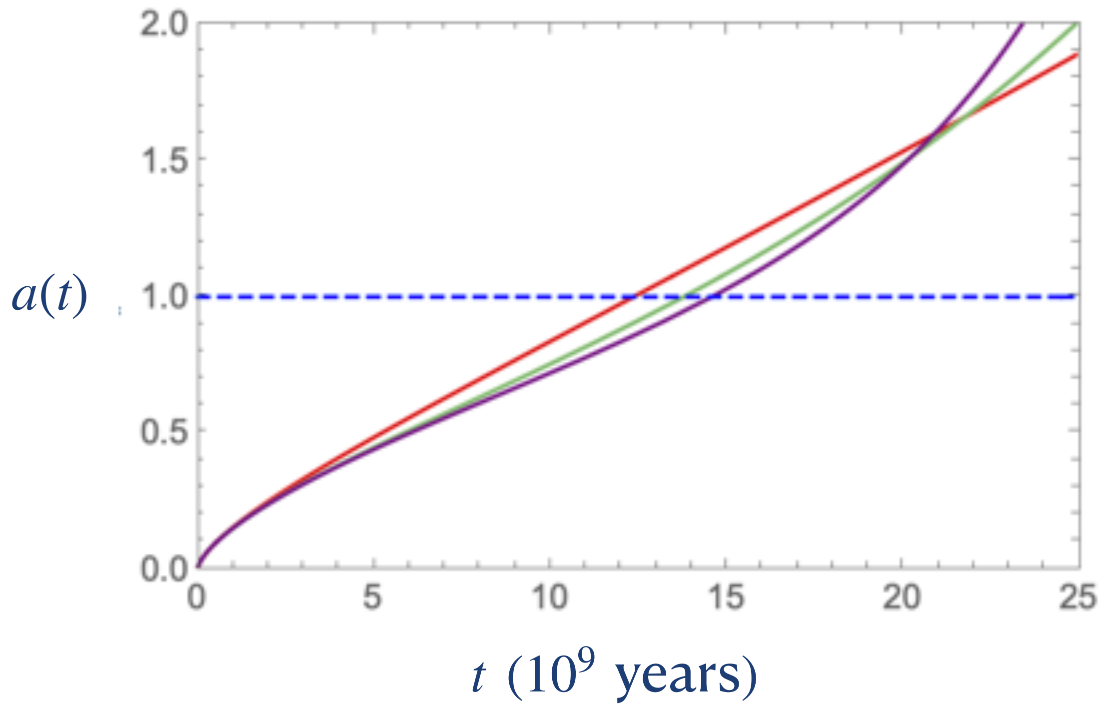
They are known as Dark Energy models

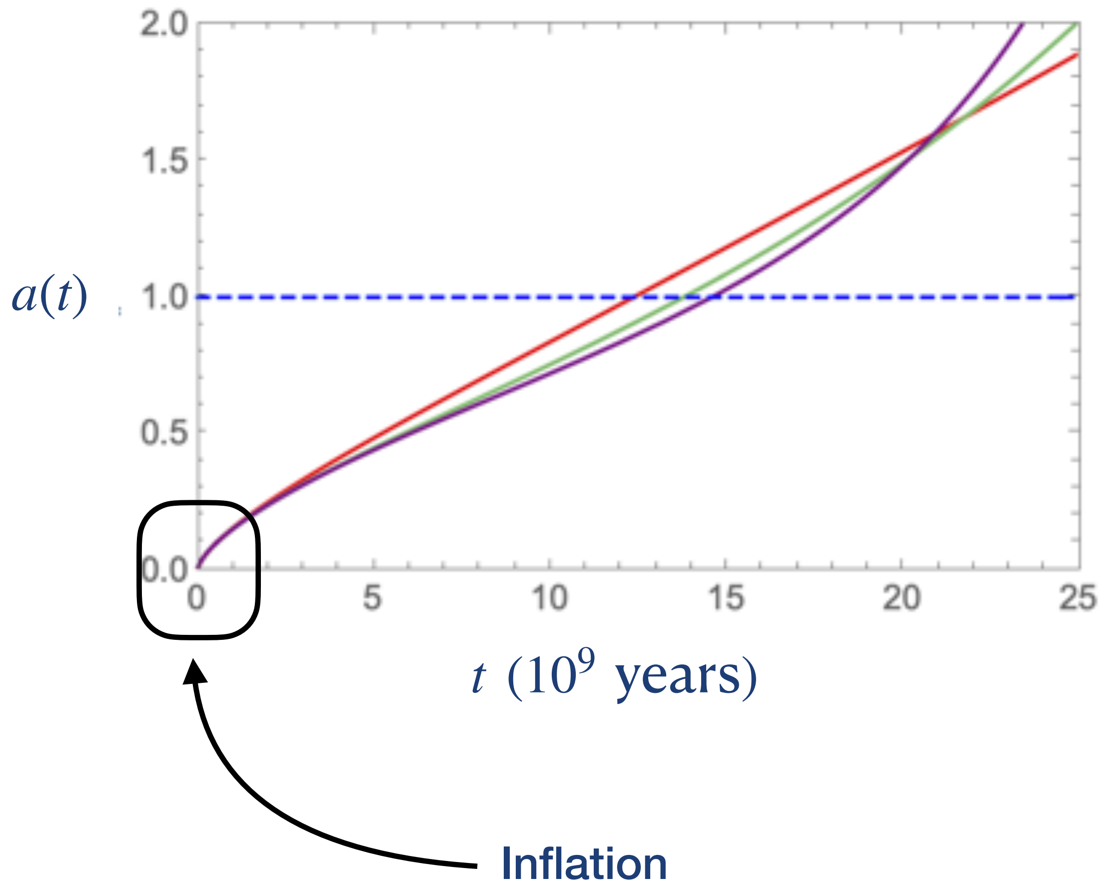
Or sometimes Modified Gravity

To try to find a mechanism which eliminates the vacuum energy for example a field which “eats” this vacuum in such a way that the cosmological constant doesn’t curve the spacetime

It is often part of what is called Modified Gravity

Two approaches


a(t)
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
25
t (10^9 years)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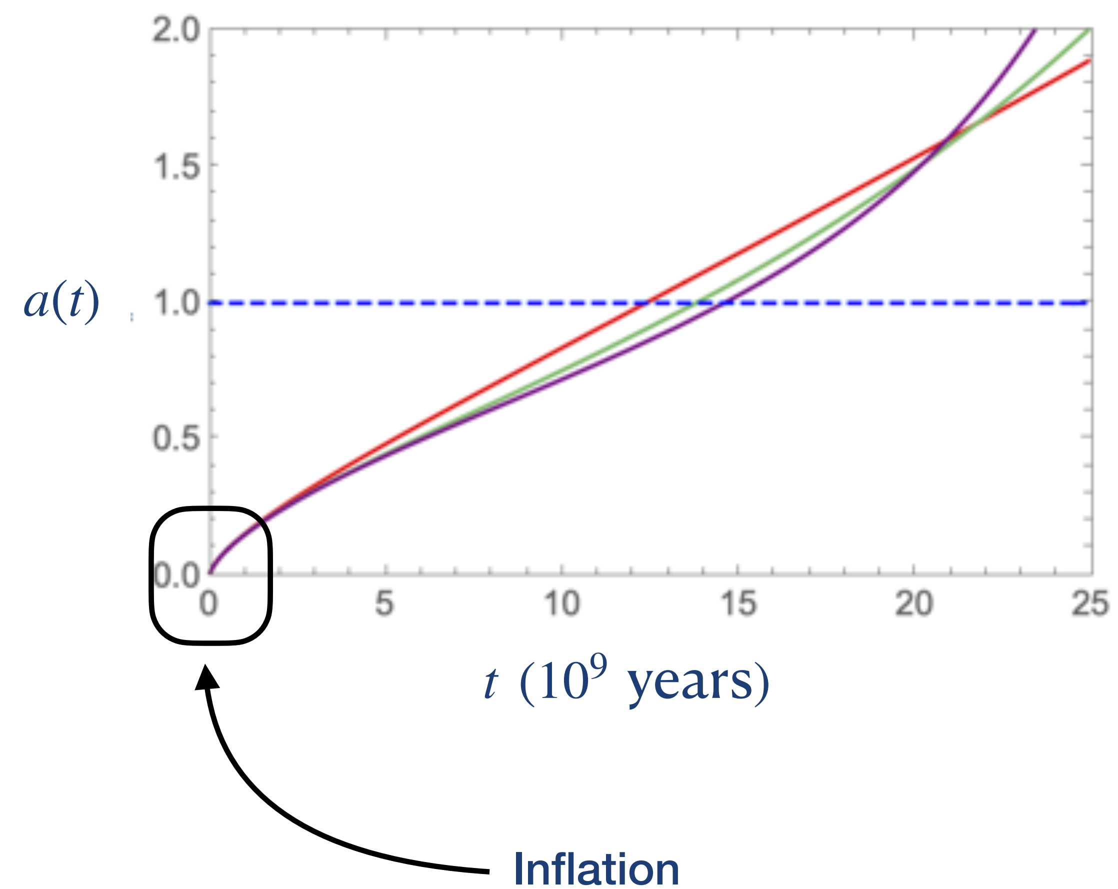
Inflation

Beyond ΛCDM



Scale invariant problem

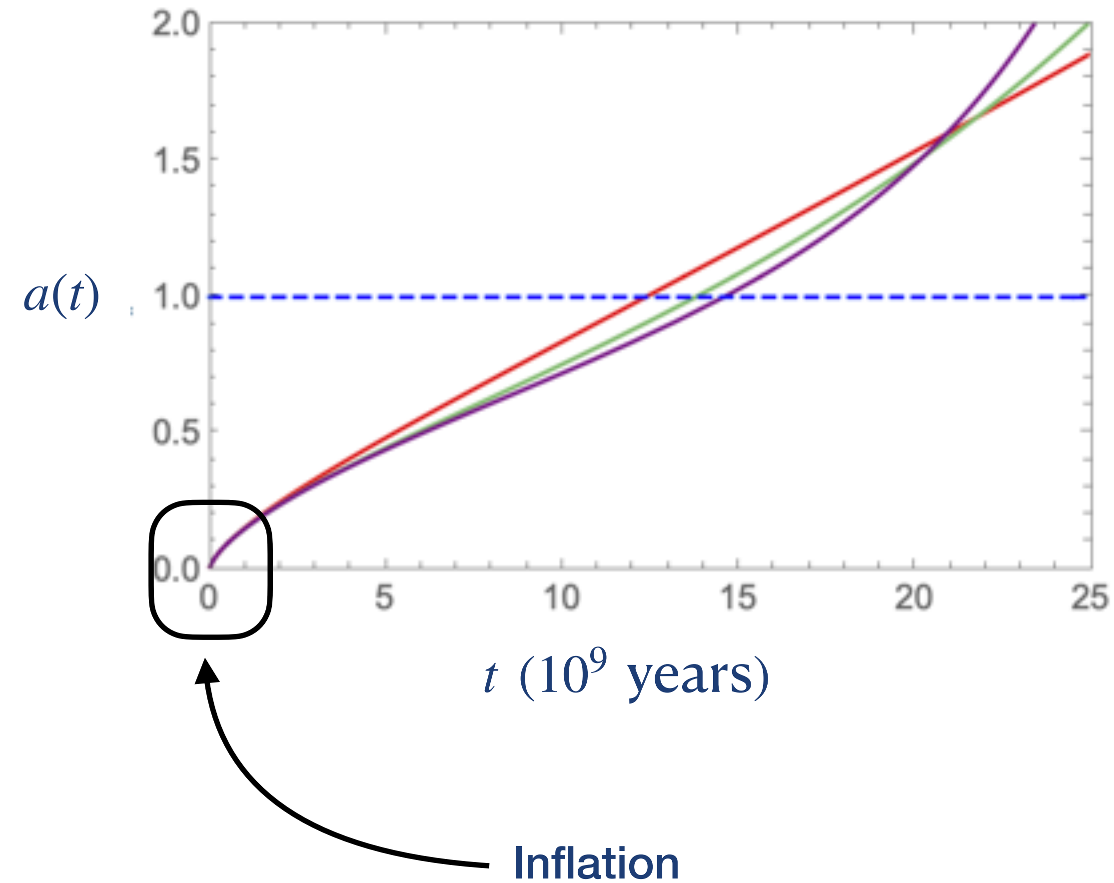
Amplitude of perturbations observed is approximately ($4\,\%$) the same at all scales (10^4 Mpc to 10 Mpc)

Origin? Quasi de Sitter Universe

$$ds^2 = \frac{1}{t^2 H^2}(-dt^2 + d\vec{x}^2)$$

It is scale invariant

$$t \to \lambda t \quad \vec{x} \to \lambda \vec{x}$$



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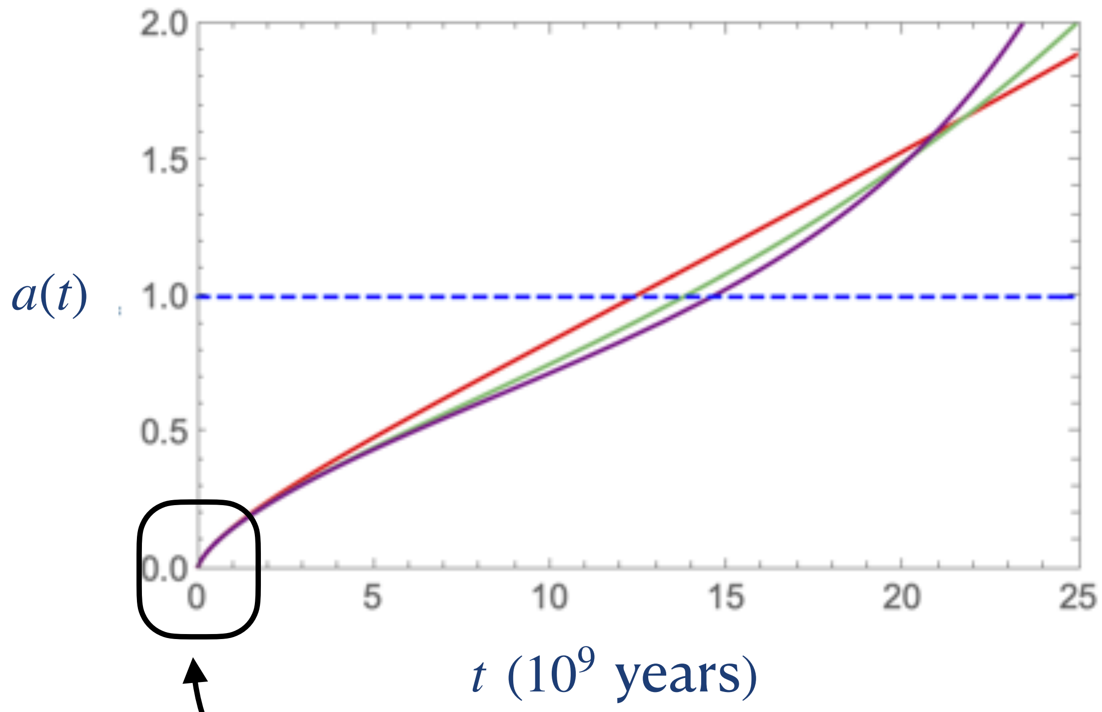

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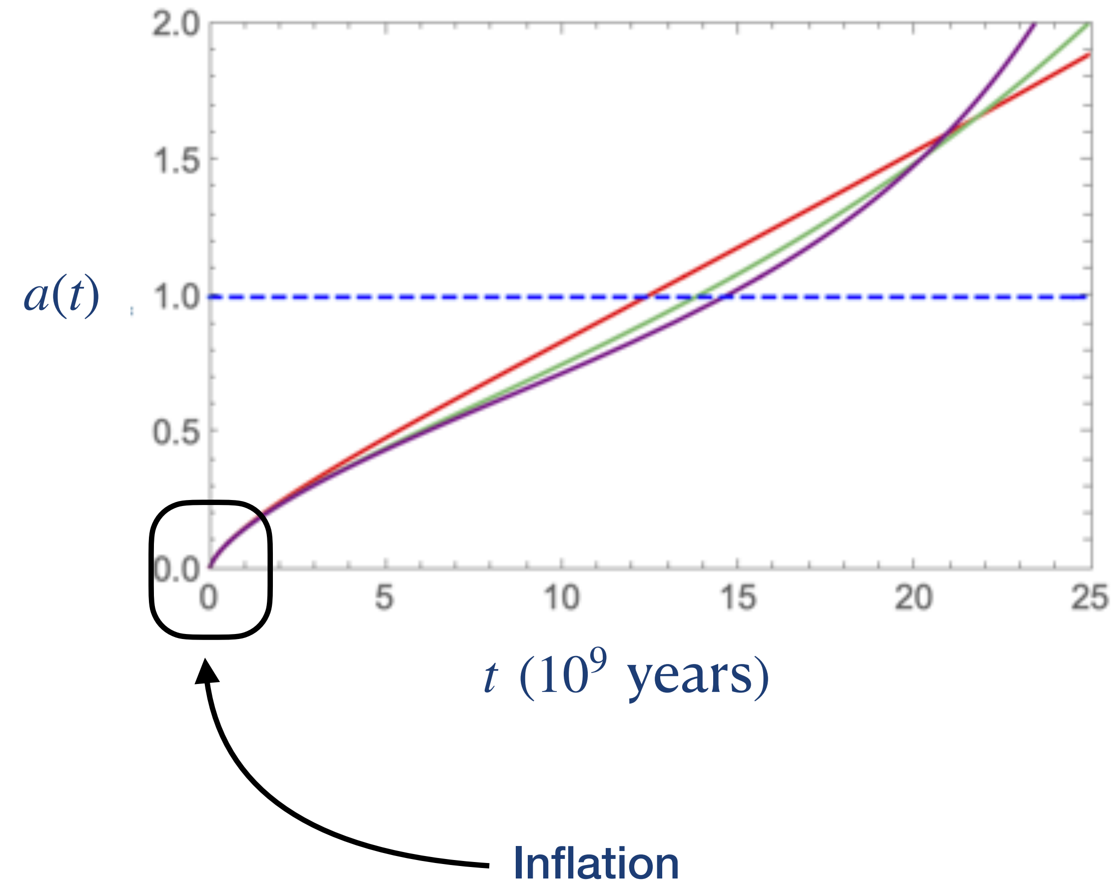

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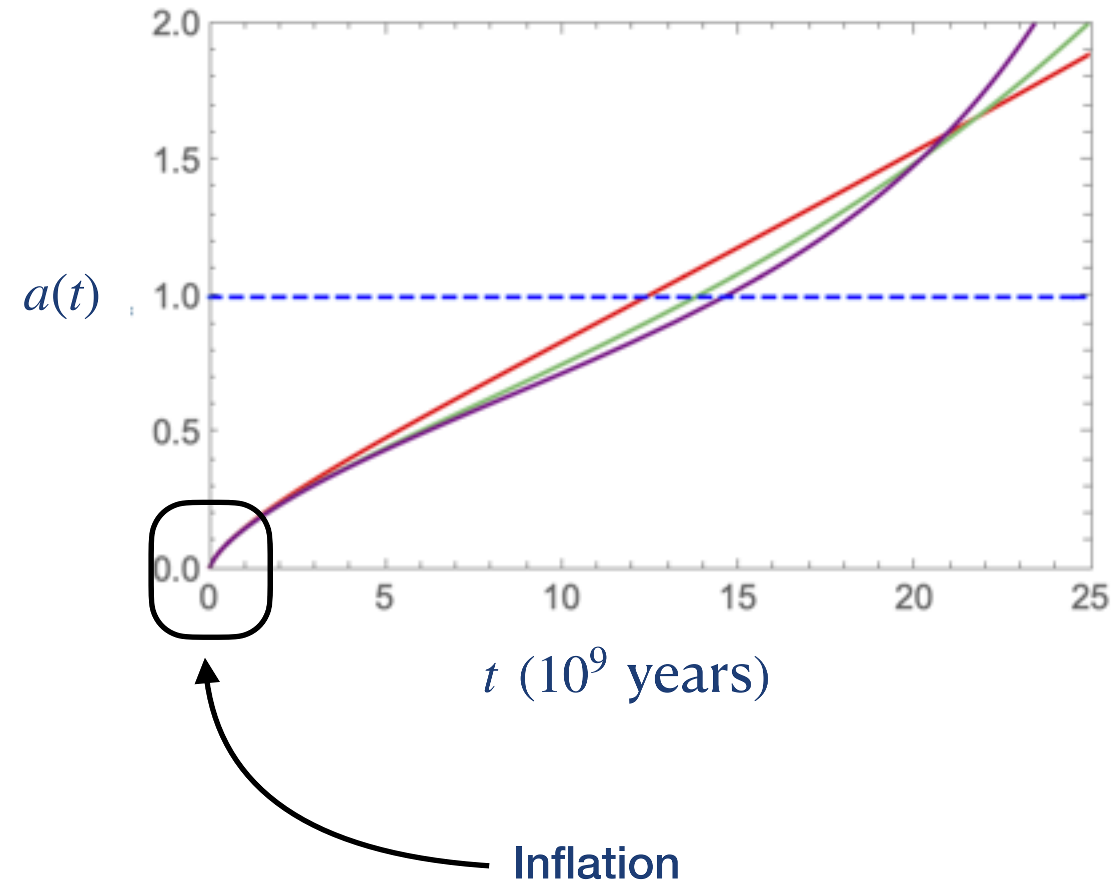

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Why not something similar today

It is not Λ

because of inflation

because Λ is problematic

As we said Λ is not a solution so we need something to accelerate the Universe

We need a fluid X with $w < -1/3$ to get an acceleration so we need negative pressure

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con materia

$$\rho \simeq \sqrt{A + Ba^{-6}}$$

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$$\rho \simeq \sqrt{A + Ba^{-6}} \longrightarrow \rho \simeq \sqrt{B}a^{-3} \quad \text{Early Universe}$$

$$\rho \simeq \sqrt{A + Ba^{-6}} \longrightarrow \rho \simeq \sqrt{A} \quad \text{Late Universe}$$

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$$\rho \simeq \sqrt{A + Ba^{-6}} \rightarrow \begin{cases} \rho \simeq \sqrt{Ba^{-3}} & \text{Early Universe} \\ \rho \simeq \sqrt{A} & \text{Late Universe} \end{cases}$$

Generalized chaplygin gas

$$P = -\frac{A}{\rho^{\alpha}}$$

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Viscosidad

$$T_{\mu\nu} = \rho u_\mu u_\nu + P(g_{\mu\nu} + u_\mu u_\nu) \qquad T_{\mu\nu} = \rho u_\mu u_\nu + (P - 3H\zeta)(g_{\mu\nu} + u_\mu u_\nu)$$

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$$T_{\mu\nu} = \rho u_\mu u_\nu + (P - 3H\zeta)(g_{\mu\nu} + u_\mu u_\nu)$$

$$\frac{\ddot{a}}{a} = 12\pi G H\zeta - \frac{1+3w}{2}H^2$$

Acceleration if $\zeta > 0$

Quintessence

A scalar field $\phi(t, x, y, z)$

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The scalar field has kinetic energy and potential energy

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Pressure $P = \frac{1}{2}\dot{\phi}^2 - V(\phi)$

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+ generalizations K-essence, Horndeski…

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Modified gravity modifies how matter and radiation curve spacetime

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f(R)-gravity

f(T)-gravity f(T)-gravity

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f(P)-gravity

f(Q)-gravity

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f(R)-gravity

f(T)-gravity f(T)-gravity

Starobinsky model produces inflation

f(G)-gravity

Why not dark energy

f(P)-gravity

f(Q)-gravity

Fab Four

$$L_{John} = V_{John}(\phi) G^{\mu\nu} \partial_\mu \phi \partial_\nu \phi$$

$$L_{Paul} = V_{Paul}(\phi) P^{\mu\nu\alpha\beta} \partial_\mu \phi \partial_\alpha \phi \nabla_{\nu\beta} \phi$$

$$L_{Georges} = V_{Georges}(\phi) R$$

$$L_{Ringo} = V_{Ringo}(\phi) \left(R^2 - 4 R_{\mu\nu} R^{\mu\nu} + R_{\mu\nu\alpha\beta} R^{\mu\nu\alpha\beta} \right)$$

Fab Four

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Self-tuning solution

Admit a Minkowski vacuum for any value of the cosmological constant

Remains true before and after any phase transition where the cosmological constant jumps instantaneously by a finite amount

Extra dimensions could be the solution

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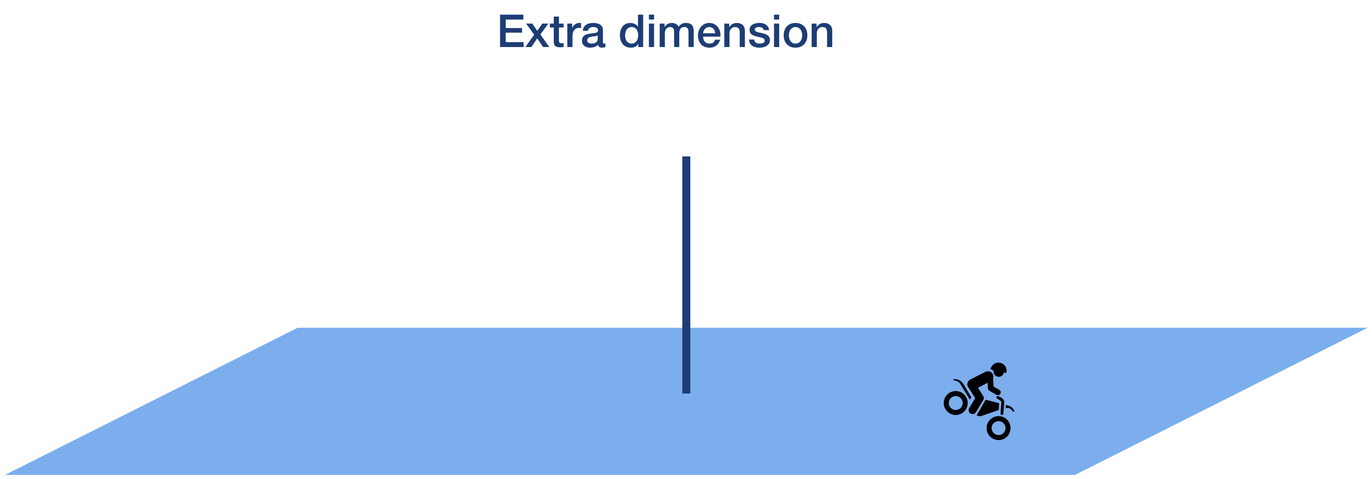
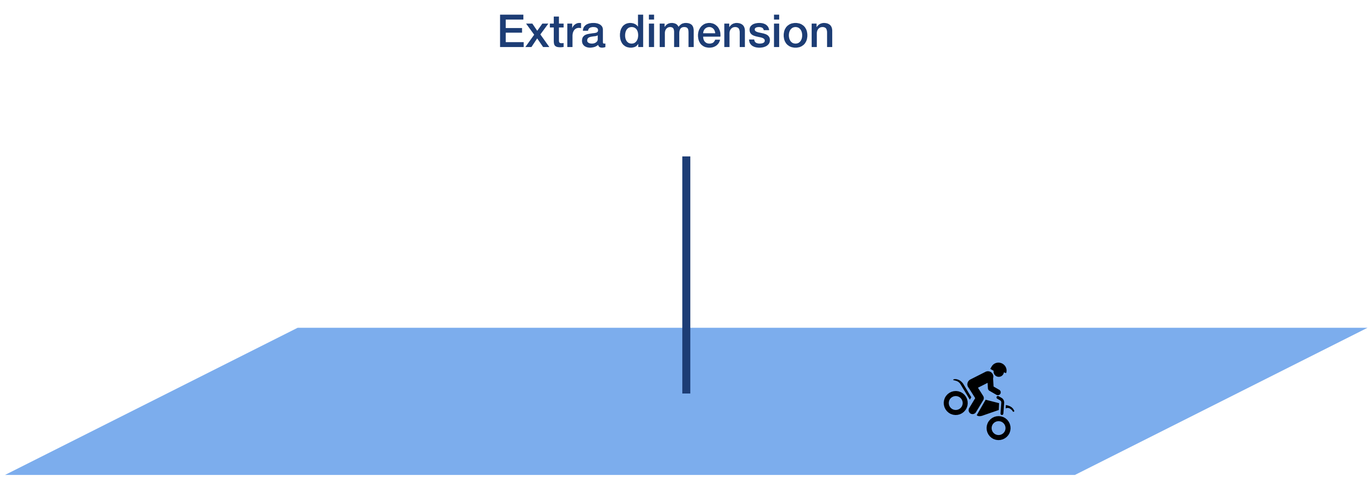


Degravitation

Extra dimensions could be the solution



Λ curves also the extra dimension

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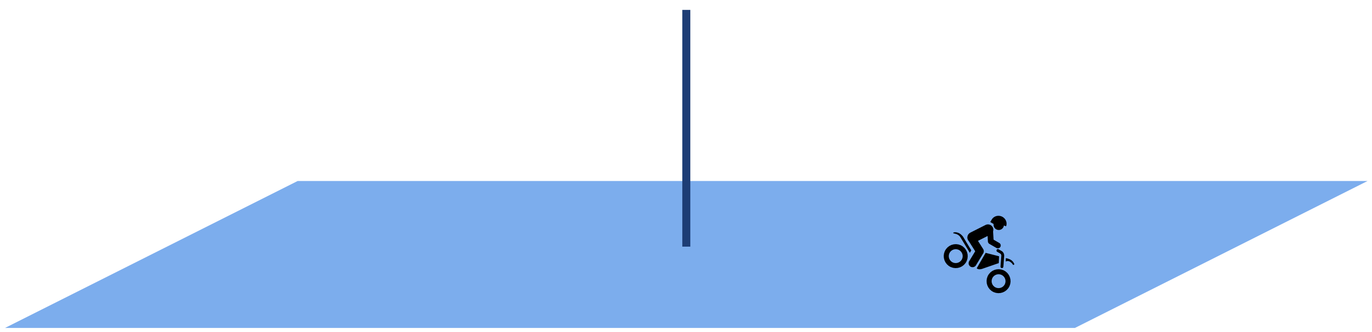

Λ curves also the extra dimension

With D dimensions

$$F \propto \frac{1}{r^{D-2}}$$

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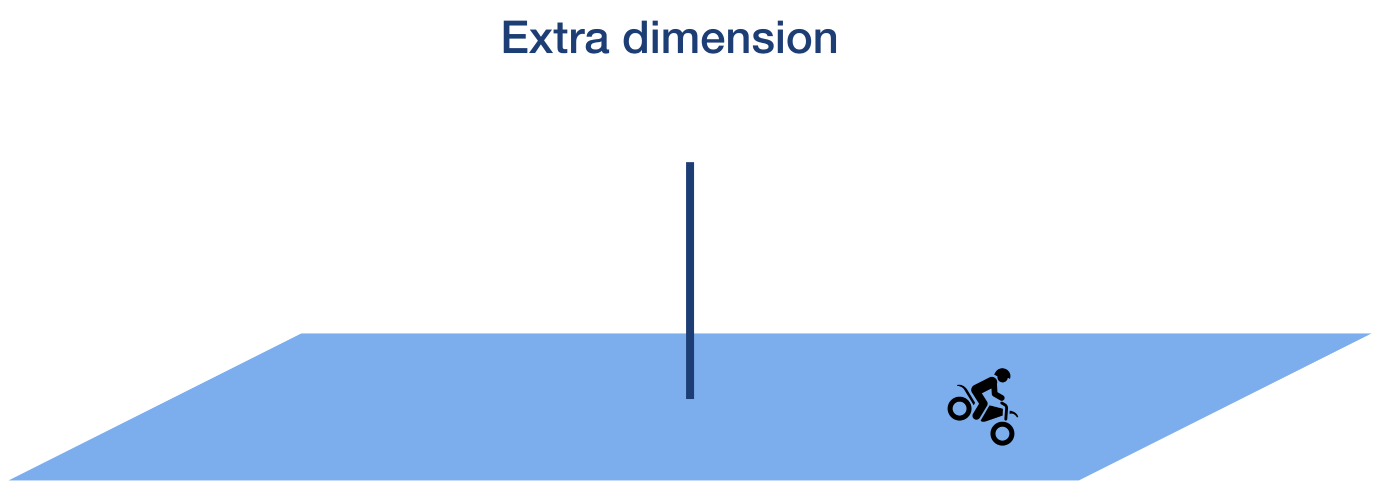

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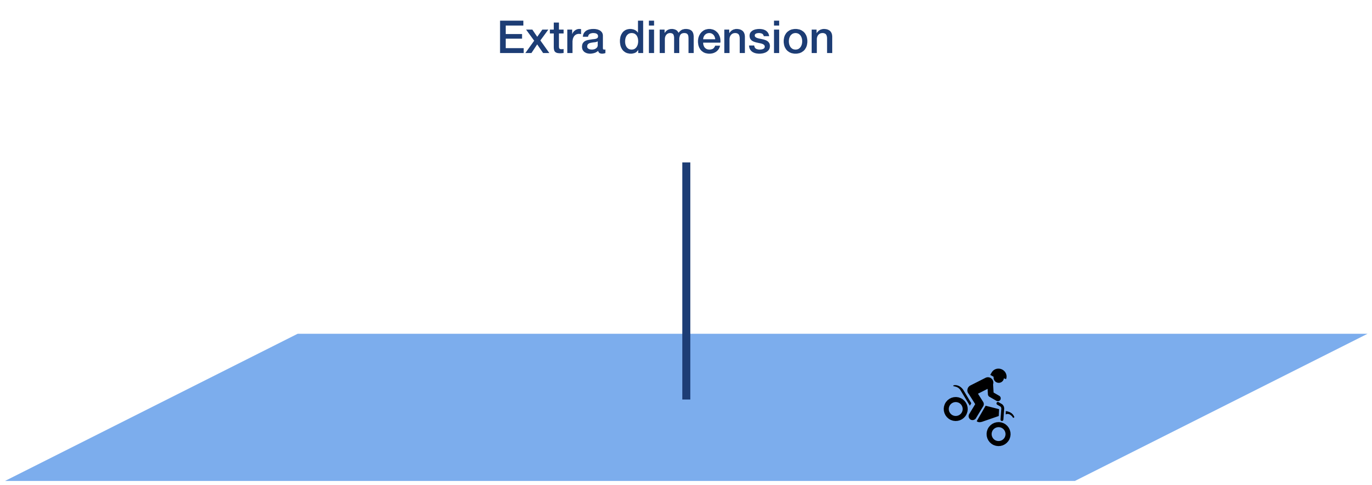

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At large distances, we do see the extra dimension $\quad F \propto \dfrac{1}{r^{D-2}}$

That is because the 4D graviton acquires a mass

Let’s consider the case of a uniform source in electromagnetism

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De-electrifying

It is similar to give a mass to the photons

$$L = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + A^{\mu}J_{\mu}$$

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Stueckelberg

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Variation wrt ϕ

$$\Box\phi + m\partial^{\mu}B_{\mu} = 0 \qquad \phi = -\frac{m}{\Box}\partial^{\mu}B_{\mu}$$

Variation wrt B^{μ}

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$$-\frac{m^2}{\Box}\partial^\mu(\partial_\mu B_\nu) \qquad\qquad \frac{m^2}{\Box}\partial^\mu(\partial_\nu B_\mu) \qquad\qquad = -\frac{m^2}{\Box}\partial^\mu F_{\mu\nu}$$

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$$\left(1 - \frac{m^2}{\Box}\right)\partial_\mu F^\mu{}_\nu = -J_\nu$$

What about non-linearities $$L = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m^2 A_\mu A^\mu + A^\mu J_\mu - \frac{\lambda}{4}(A_\mu A^\mu)^2$$

It does not spoil the de-electrification

We have the solution $\vec{E} = \vec{0}$ with $A_\mu = a\ \delta_\mu^0$ $m^2 a + \lambda a^3 = \Lambda$

The non-linearities shift A_μ without changing the electric field

We want the same for gravity which is a non-linear theory with a cosmological constant Λ

We would like gravity to be ignorant of Λ: degravitation

For that we need a massive gravity theory

Let us look to the linear theory

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = -\Lambda g_{\mu\nu}$$

$$\Box h_{\mu\nu} - \partial_\lambda\partial_\mu h^\lambda{}_\nu - \partial_\lambda\partial_\nu h^\lambda{}_\mu + \eta_{\mu\nu}\partial_\lambda\partial_\sigma h^{\lambda\sigma} + \partial_\mu\partial_\nu h - \eta_{\mu\nu}\Box h = \Lambda\eta_{\mu\nu}$$

Massive gravity $$\Box h_{\mu\nu} - \partial_\lambda\partial_\mu h^\lambda{}_\nu - \partial_\lambda\partial_\nu h^\lambda{}_\mu + \eta_{\mu\nu}\partial_\lambda\partial_\sigma h^{\lambda\sigma} + \partial_\mu\partial_\nu h - \eta_{\mu\nu}\Box h - m^2(h_{\mu\nu} - \eta_{\mu\nu}h) = \Lambda\eta_{\mu\nu}$$

Massive gravity

$$\Box h_{\mu\nu} - \partial_\lambda \partial_\mu h^\lambda{}_\nu - \partial_\lambda \partial_\nu h^\lambda{}_\mu + \eta_{\mu\nu} \partial_\lambda \partial_\sigma h^{\lambda\sigma} + \partial_\mu \partial_\nu h - \eta_{\mu\nu} \Box h - m^2 (h_{\mu\nu} - \eta_{\mu\nu} h) = \Lambda \eta_{\mu\nu}$$

$$h_{\mu\nu} = \frac{\Lambda}{3m^2} \eta_{\mu\nu}$$

It shifts the usual $h_{\mu\nu} = 0$ Minkowski vacuum to a new one but which is also flat

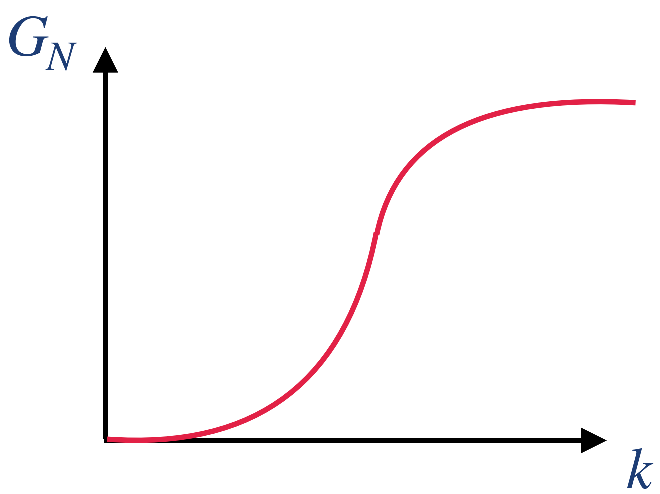
$$\Box h_{\mu\nu} - \partial_\lambda \partial_\mu h^\lambda{}_\nu - \partial_\lambda \partial_\nu h^\lambda{}_\mu + \eta_{\mu\nu} \partial_\lambda \partial_\sigma h^{\lambda\sigma} + \partial_\mu \partial_\nu h - \eta_{\mu\nu} \Box h - m^2 (h_{\mu\nu} - \eta_{\mu\nu} h) = \Lambda \eta_{\mu\nu}$$

$$\mathcal{O}_{\mu\nu}{}^{\alpha\beta} h_{\alpha\beta}$$

$$\mathcal{O}_{\mu\nu}{}^{\alpha\beta} h_{\alpha\beta} - m^2 (h_{\mu\nu} - \eta_{\mu\nu} h) = \Lambda \eta_{\mu\nu} \qquad \left(1 - \frac{m^2}{\Box}\right) \mathcal{O}_{\mu\nu}{}^{\alpha\beta} h_{\alpha\beta} = \Lambda \eta_{\mu\nu}$$

We need a theory which gives this type of behavior in the linear regime

$$G_N^{-1} G_{\mu\nu} = 8\pi T_{\mu\nu} \qquad G_N^{-1} \left(\frac{m^2}{\Box}\right) G_{\mu\nu} = 8\pi T_{\mu\nu}$$



A gravitational constant which filters long wavelengths

Copernican Principle: Humans do not occupy a privileged position in the Universe

B. Carter: *Although our situation is not necessarily central, it is inevitably privileged to some extent*

Very strong anthropic principle: everything in our universe has something to do with humankind

Very weak anthropic principle: takes the very existence of humankind as a piece of experimental data. For example, in order not to kill a person with the products of radio-decay, the life-time of a proton must be at least 10^{16} years

Weak anthropic principle: there are many regions in the universe, a multiverse. In these regions physical laws are in different forms. It just happens that in the region we are dwelling all physical laws, physical constants and cosmological parameters are such that clusters of galaxies, galaxies and our solar system can form, and humankind can appear.

Seesaw mechanism

Used for example in neutrino physics to explain their small non-zero mass

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$$M_\Lambda = \rho_\Lambda^{1/4} \simeq 10^{-12} GeV$$

$$M_{Pl} \simeq 10^{19} GeV$$

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Let’s consider 2 coupled Universes with 2 cosmological constants

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$$\Lambda_1 \simeq (10\ TeV)^4$$

$$\Lambda_- \simeq 10^{-46} GeV^4$$

$$\Lambda_2 \simeq M_{Pl}^4$$

Obrigado