Introduction to Cosmology I

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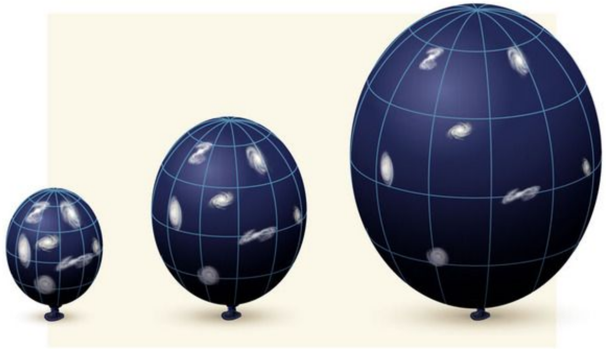
Almost invisibles in the Universe

Goals of today's lecture

- Understand the Universe across time, intuitively and as described with equations
- Understand the impact of *almost invisibles* on that system: neutrinos, dark matter, dark energy, even more hypothetical fields
- Get a sense of how we can measure the evolution of the Universe, and what that has told us so far
- Set foundation for lectures this week



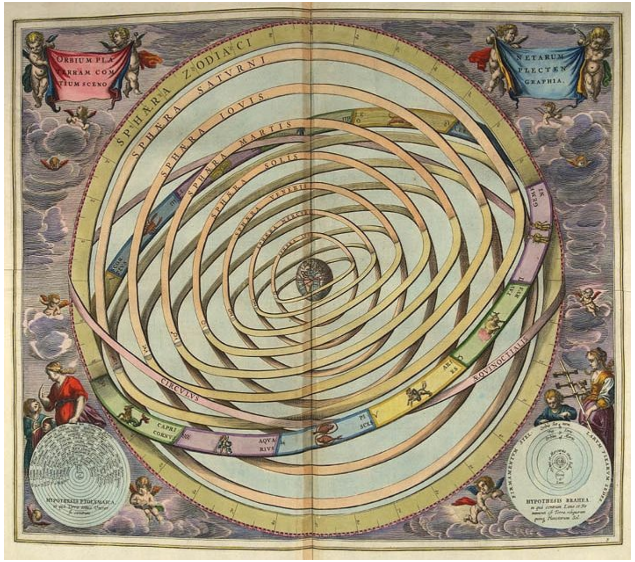
Future CMB Programs	Direct DM Searches (I)	Direct DM Searches (II)	View Ahead
Zeeshan Ahmed	Jodi Cooley	Jodi Cooley	Renee Hlozek

Indirect DM Exp (I)	Indirect DM Exp (II)	Axion-like Particle Searches	What Could Dark Energy Be?	DE & Hubble Tension
Tracy Slatyer	Tracy Slatyer	Gianpaolo Carosi	Mark Trodden	Adam Riess

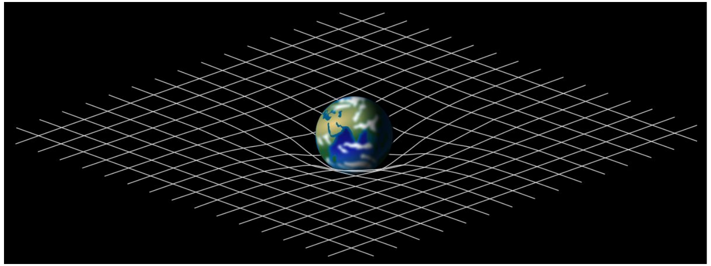
GW: Inflation & Phase Transitions (T)	Cosmic Neutrino Properties	Dark Matter / Dark Sector Theory (I)	Dark Matter / Dark Sector Theory (II)	Dark Matter / Dark Sector Theory (III)	Present & Future Probes of DE (I)	Present & Future Probes of DE (II)
Geraldine Servant	Scott Dodelson	Tim Tait	Tim Tait	Tim Tait	Aaron Roodman	Aaron Roodman

Two principles we'll use

- There is no special place in the Universe - it is homogeneous and isotropic

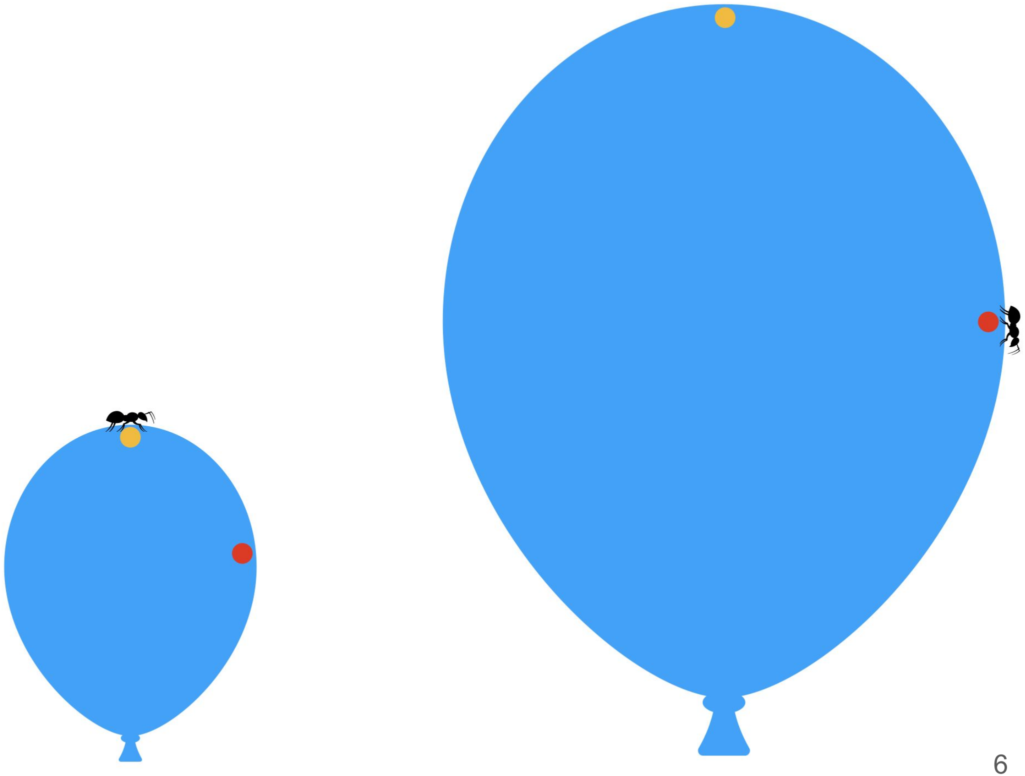


- Gravity is described by General Relativity



A General Relativity balloon

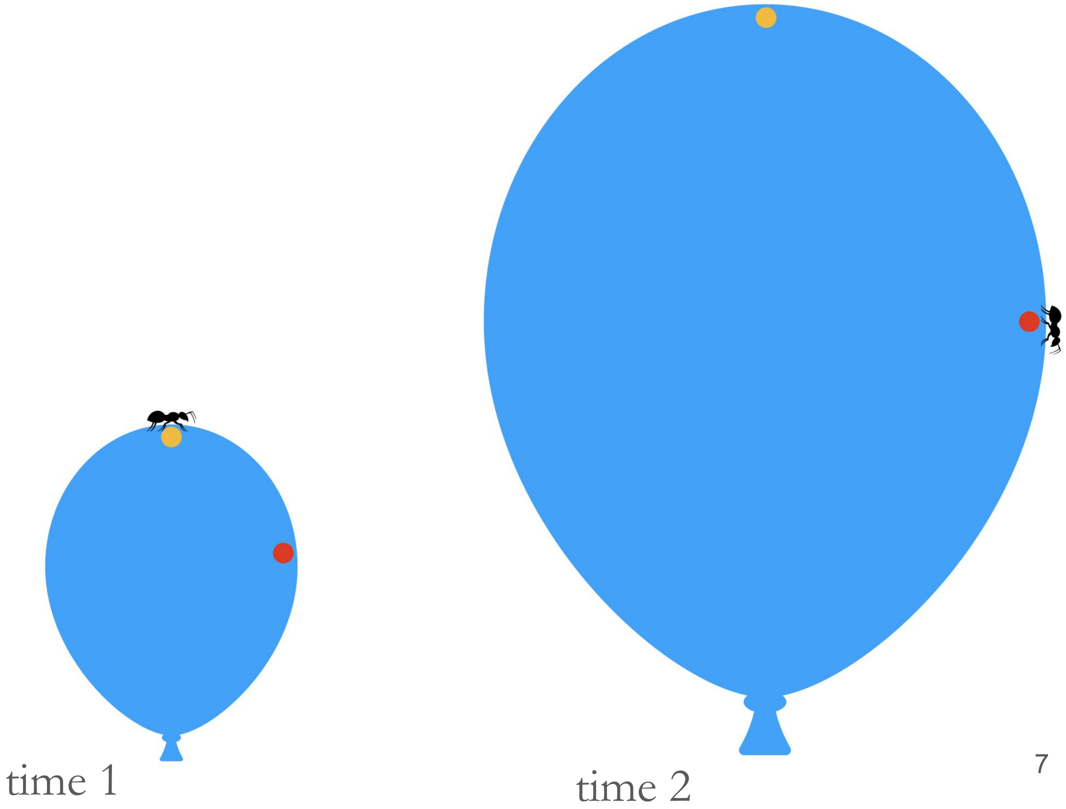
How could you describe the time evolution of the balloon?



A General Relativity balloon

How could you describe the time evolution of the balloon?

By the steps an ant could take!



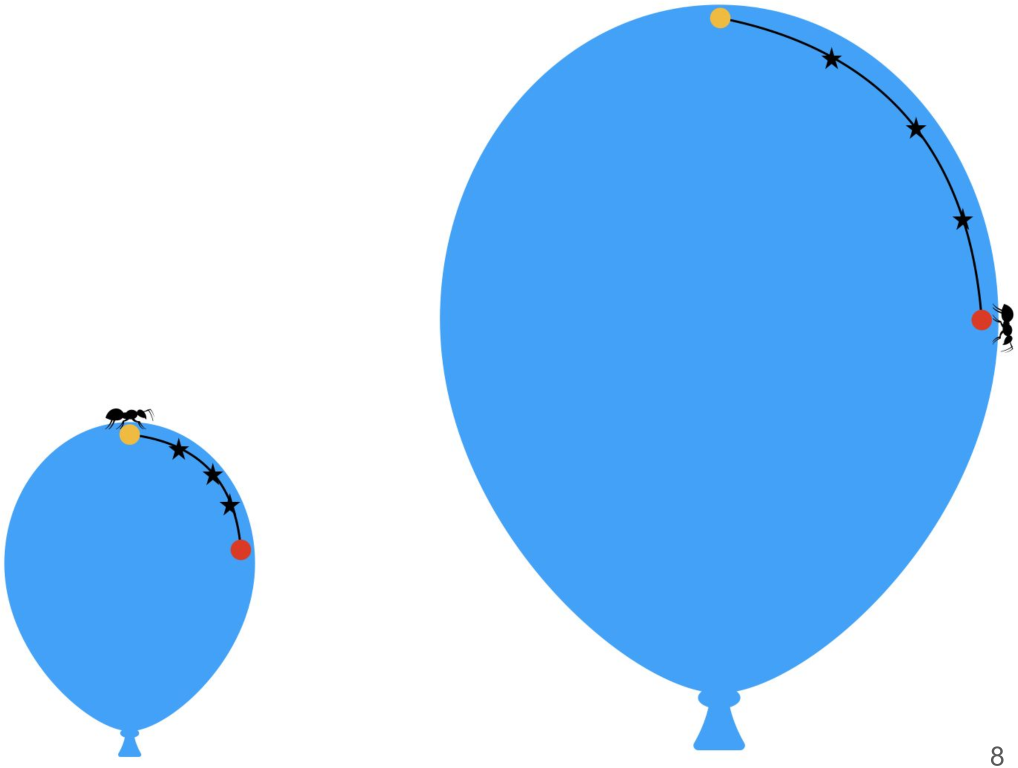
A General Relativity balloon

How could you describe the time evolution of the balloon?

By the steps an ant could take!

Printing a coordinate system x on the balloon,

$$v_{\mathrm{ant}}\,\mathrm{d}t = a(t)\,|\mathrm{d}x|$$



A General Relativity balloon

How could you describe the time evolution of the balloon?

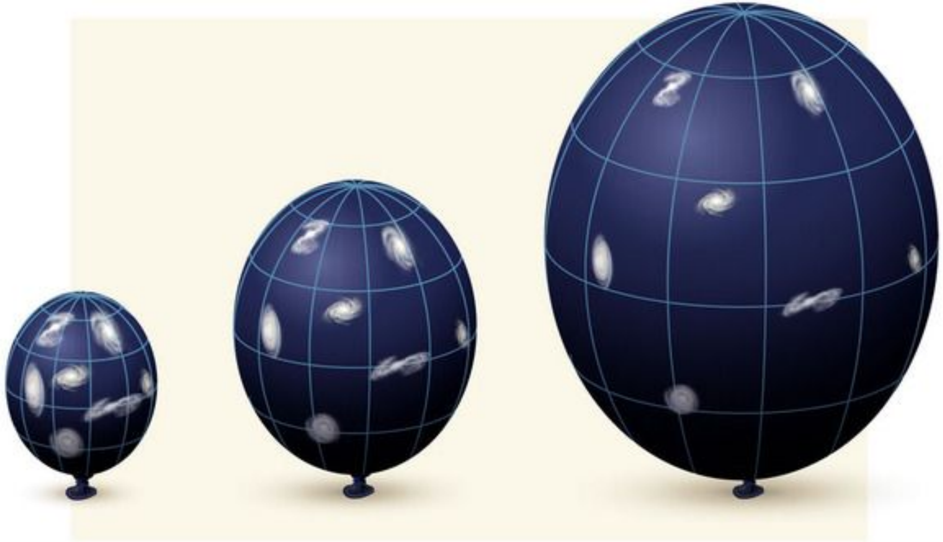
By the steps an ant could take!

Printing a coordinate system x on the balloon,

$$v_{\mathrm{ant}}\ \mathrm{d}t = a(t)\,|\mathrm{d}x|$$

Printing a coordinate system on the universe and using photons for ants,

$$c\ \mathrm{d}t = a(t)\,|\mathrm{d}\boldsymbol{x}|$$



Friedman-Lemaître-Robertson-Walker Metric

$$\mathrm{d}s^2 = \sum_{i,j=0}^{3} \underbrace{g_{ij}}_{\text{metric tensor}} \mathrm{d}x^i \mathrm{d}x^j = 0$$ for light, with coordinates $x^0 = t, x^{1,2,3}$

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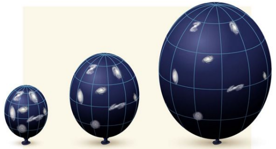
metric tensor

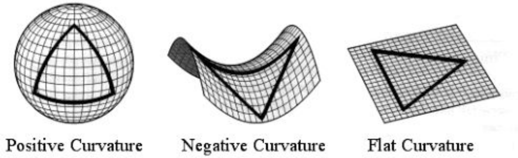
$$\mathrm{d}s^2 = c^2\mathrm{d}t^2 - a^2(t)\left[\mathrm{d}r^2 + f_K^2(r)(\mathrm{d}\theta^2 + \sin^2\theta\mathrm{d}\phi^2)\right]$$

is the most general metric that is homogeneous / isotropic

Friedman-Lemaître-Robertson-Walker Metric

$$f_K(r) = \begin{cases} r, & K = 0 \\ 1/K \sin(Kr), & K > 0 \\ 1/|K| \sinh(|K|r), & K < 0 \end{cases}$$





$$\mathrm{d}s^2 = c^2\mathrm{d}t^2 - \underbrace{a^2(t)}_{\text{time-dependent expansion}} \overbrace{\left[\mathrm{d}r^2 + f_K^2(r)(\mathrm{d}\theta^2 + \sin^2\theta\mathrm{d}\phi^2)\right]}^{\text{spatial coordinate system}}$$

is the most general metric that is homogeneous / isotropic

FLRW Metric + Einstein Equations: The dynamics of a Universe

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

homogeneous fluids filling the universe

Einstein Equations $$R_{ij} - \frac{1}{2} g_{ij} R = \frac{8\pi G}{c^4} T_{ij}$$

$$\Rightarrow \quad \frac{\ddot{a}}{a} = -\frac{4}{3}\pi G \left(\rho + \frac{3p}{c^2}\right)$$

The dynamics of a Universe with a cosmological constant

- A positive cosmological constant causes a positive acceleration
- A fluid with equation of state $p = -c^2\rho$ has the same effect

- Λ takes over if density and pressure of all else in the universe are small enough

cosmological constant Λ

$$R_{ij} - \frac{1}{2}g_{ij}R - \Lambda g_{ij} = \frac{8\pi G}{c^4}T_{ij}$$

$$\frac{\ddot{a}}{a} = -\frac{4}{3}\pi G\left(\rho + \frac{3p}{c^2}\right) + \Lambda\frac{c^2}{3}$$

The density of a Universe with a bunch of stuff

- A general fluid is described by its equation of state $p = w\rho c^2$
- Some fluids we know:
  - (cold) matter: *w=0*
  - radiation, relativistic matter: *w=⅓*
  - cosmological constant: *w=-1*
  - curvature: *w=-⅓*
  - a fluid you have designed: *w=w(t* or *a* or *ϱ)*
- Density changes with the expansion of the Universe as

$$\rho(t) = \rho_0 a^{-3(1+w)}(t)$$

The dynamics of a Universe with a bunch of stuff

- Given the current expansion rate $H_0 = \left.\frac{\dot{a}}{a}\right|_{\text{now}}$, there is a "critical density" that makes for a flat universe.

  Critical density = the density of Λ for an otherwise empty universe

$$\rho_{\mathrm{c}} = \frac{3H_0^2}{8\pi G} \, .$$

$$\Omega_{\mathrm{m}} = \frac{\rho_{\mathrm{m}}}{\rho_{\mathrm{c}}} \qquad \Omega_{\mathrm{r}} = \frac{\rho_{\mathrm{r}}}{\rho_{\mathrm{c}}}$$

matter radiation

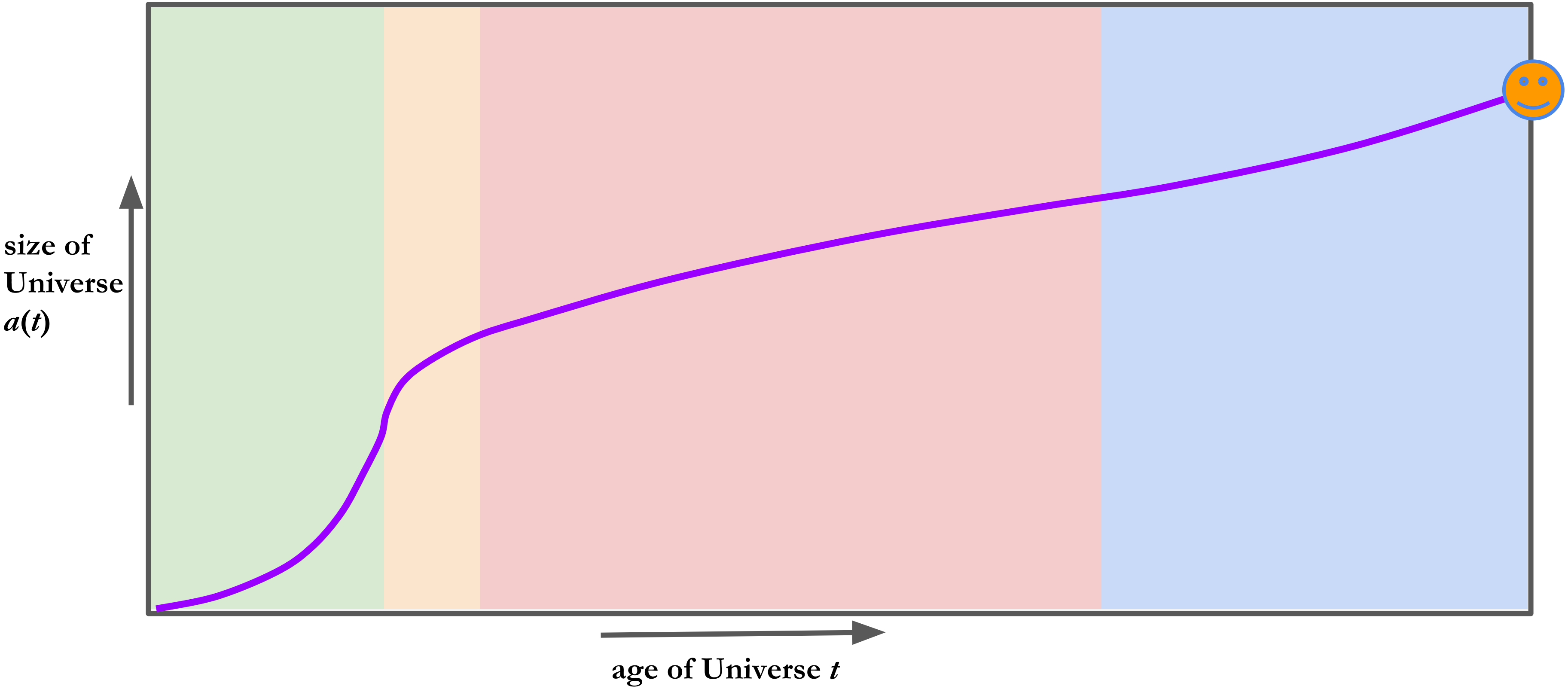
vacuum energy $\Omega_\Lambda = \frac{\Lambda c^2}{8\pi G\rho_{\mathrm{c}}}$

- Expressing each component as a fraction of ϱ_{c} and integrating leads to the useful equation:

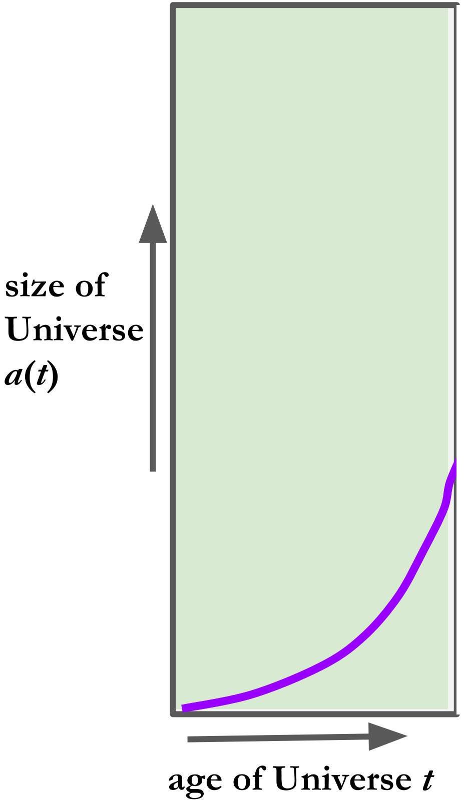
$$\Omega_{\mathrm{k}} = 1 - \Omega_{\mathrm{m}} - \Omega_{\mathrm{r}} - \Omega_\Lambda$$

$$H^2(t) = H_0^2\left(\Omega_{r,0}a^{-4}(t) + \Omega_{m,0}a^{-3}(t) + \Omega_{k,0}a^{-2}(t) + \Omega_{\Lambda,0}\right) = H_0^2\sum_i \Omega_{i,0}a^{-3(1+w_i)}$$

The complete history of the Universe



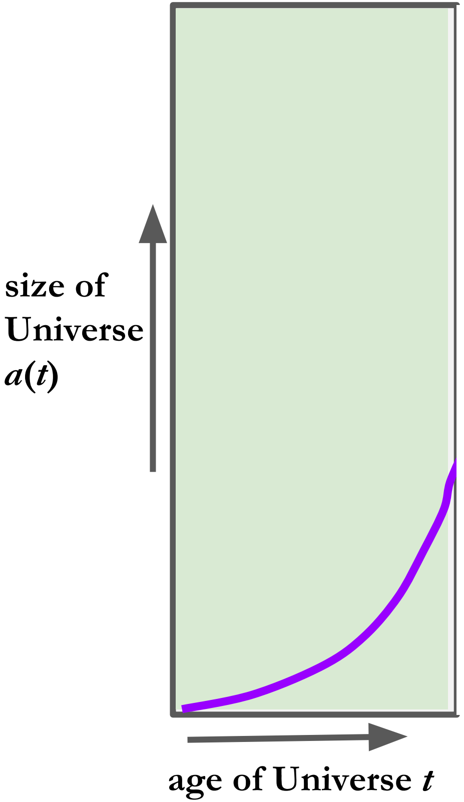
Understanding the history of the Universe: Inflation



- A phase of exponential growth, increasing the size of the Universe by a factor of ~10^{30} within t~10^{-32}s
  - How can you make that happen?

$$\frac{\ddot{a}}{a} = -\frac{4}{3}\pi G\left(\rho + \frac{3p}{c^2}\right) + \Lambda\frac{c^2}{3}$$

Understanding the history of the Universe: Inflation



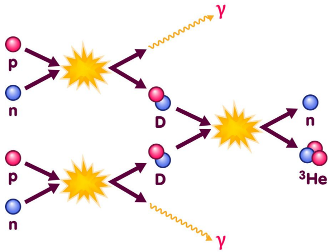
- A phase of exponential growth, increasing the size of the Universe by a factor of ~10^{30} within t~10^{-32}s
    - Need large vacuum energy density

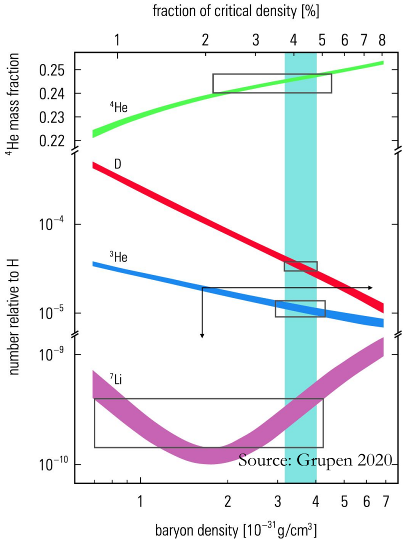
almost invisible

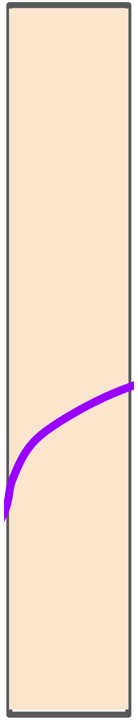
$$\frac{\ddot{a}}{a} = \cancel{-\frac{4}{3}\pi G\left(\rho + \frac{3p}{c^2}\right)} + \Lambda\frac{c^2}{3}$$

- Completely dilutes all other components of the Universe
- Perfectly nulls the curvature of the Universe
- Causally disconnects parts of the Universe

Understanding the history of the Universe: The hot universe







- *somehow* the vacuum energy must turn into radiation: reheating 10^{-32}s

  almost invisible

$$H^2(t) = H_0^2\left(\Omega_{r,0}a^{-4}(t) \cancel{+ \Omega_{m,0}a^{-3}(t) + \Omega_{k,0}a^{-2}(t) + \Omega_{\Lambda,0}}\right)$$

- *somehow* in this primordial plasma, the abundance of matter exceeded the abundance of antimatter 10^{-10}s

  almost invisible

- Neutrinos are initially coupled to this plasma, substantial share of energy density 1s

  almost invisible

- Expansion stops particle interactions: freeze out. The abundance of light nuclei today implies that the density of Baryons must be small. 100s

  almost invisible

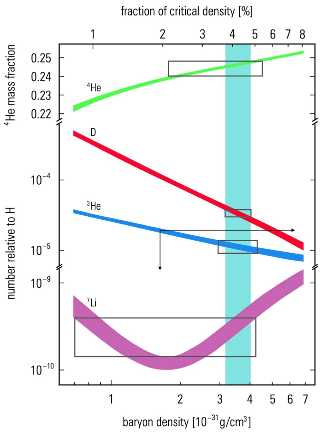
- Eventually the Universe becomes diffuse/cold/transparent: relic photons as Cosmic Microwave Background until today 380k years

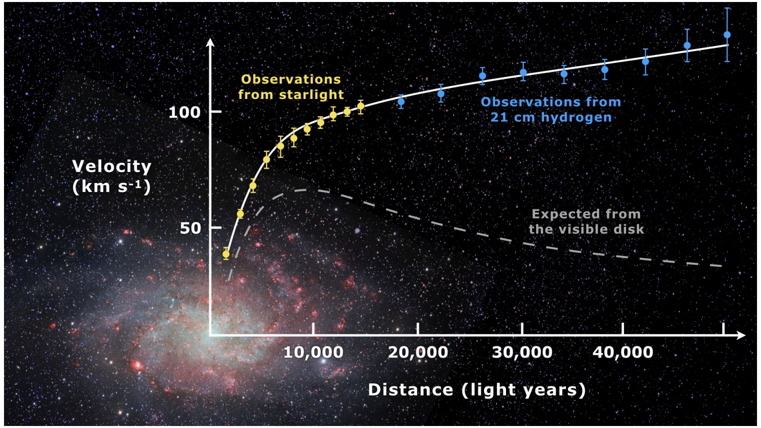
Dark Matter

Evidence:

certified almost invisible

- Low abundance of ‘regular’ matter implied by primordial nucleogenesis + presence of massive structures today = most matter must be non-Baryonic
- Rotation curves / motions of galaxies: most of their gravity not due to stars/gas
- Patterns in the CMB (see next time), expansion, and growth of structure imply that the total density of matter must be ~6x the density of Baryons





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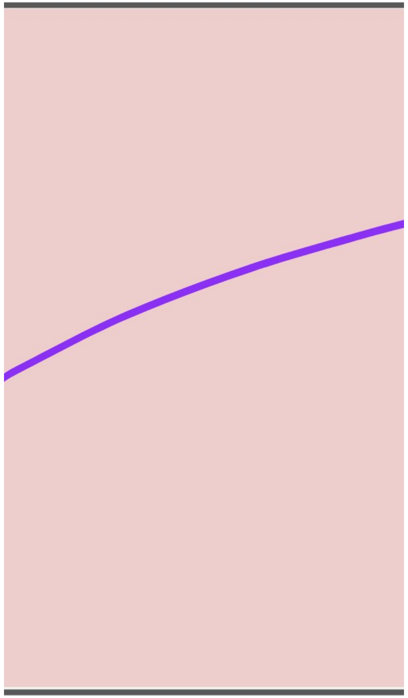
Dark Matter could be:

- One or more stable, massive (now non-relativistic) particles from the primordial plasma that do not affect the formation of elements
- One or more stable, light particles that are present at non-relativistic speeds *somehow*
- Standard model particles ruled out. Primordial black holes mostly ruled out.

Understanding the history of the Universe: Matter domination



- Gravitation slows the expansion of the Universe

$$\frac{\ddot{a}}{a} = -\frac{4}{3}\pi G\left(\rho + \cancel{\frac{3p}{c^2}}\right)$$

- A lot of things that happen here are ***totally visible...***
  - Density fluctuations grow from $1/10^5$ to unity
  - Stars, galaxies, galaxy clusters form
  - Supermassive black holes grow at centers of galaxies
  - …
  - But: all of these are closely related to dark matter clustering

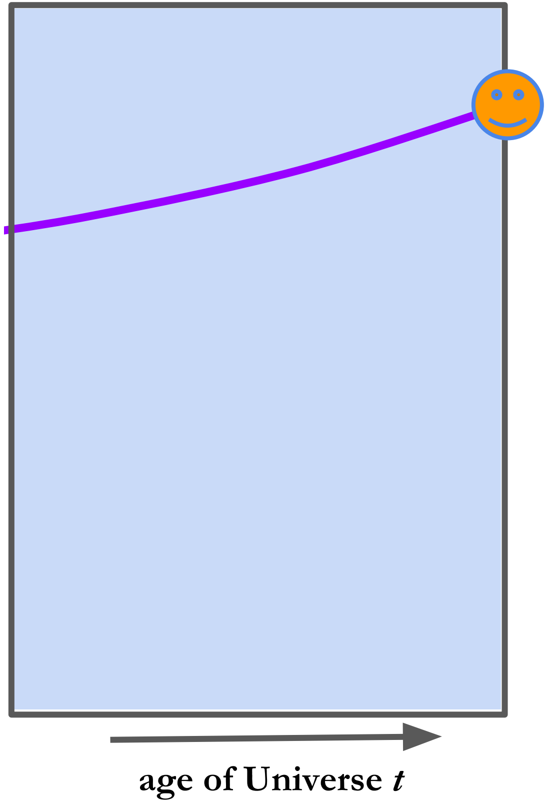
Understanding the history of the Universe: Dark Energy takes over

certified almost invisible

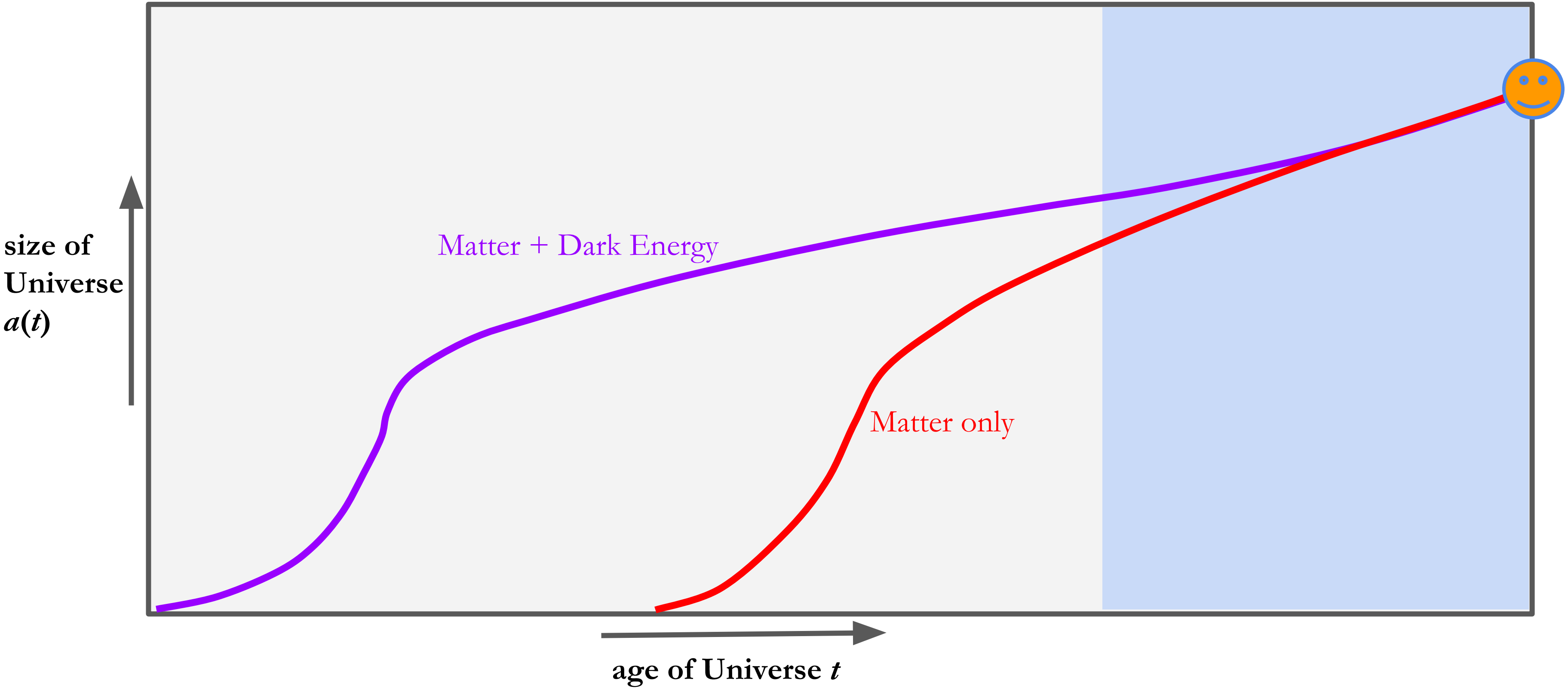
- $\frac{\ddot{a}}{a} = -\frac{4}{3}\pi G\left(\rho + \frac{3p}{c^2}\right) + \Lambda\frac{c^2}{3}$ > 0 once ϱ diluted enough, if there is a positive Λ

  The expansion is then accelerating!

- Requires about 70% or energy at present day to be in the form of vacuum energy density.
  - This is strangely close to the matter density.
  - This is ~a hundred orders of magnitude *less* than a naive calculation of vacuum energy suggests.
  - We do not have nearly as many clues to its nature as in the case of dark matter.



How do we know there is Dark Energy?



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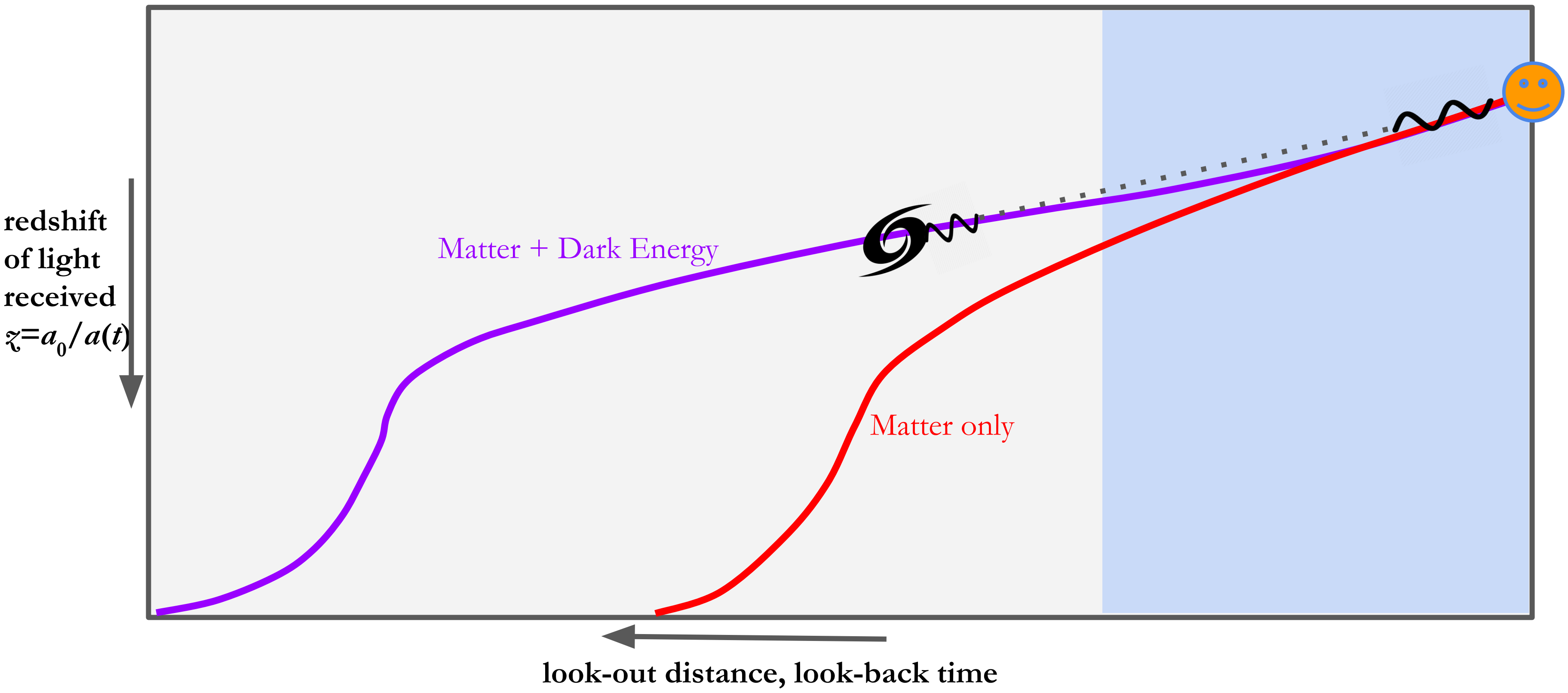

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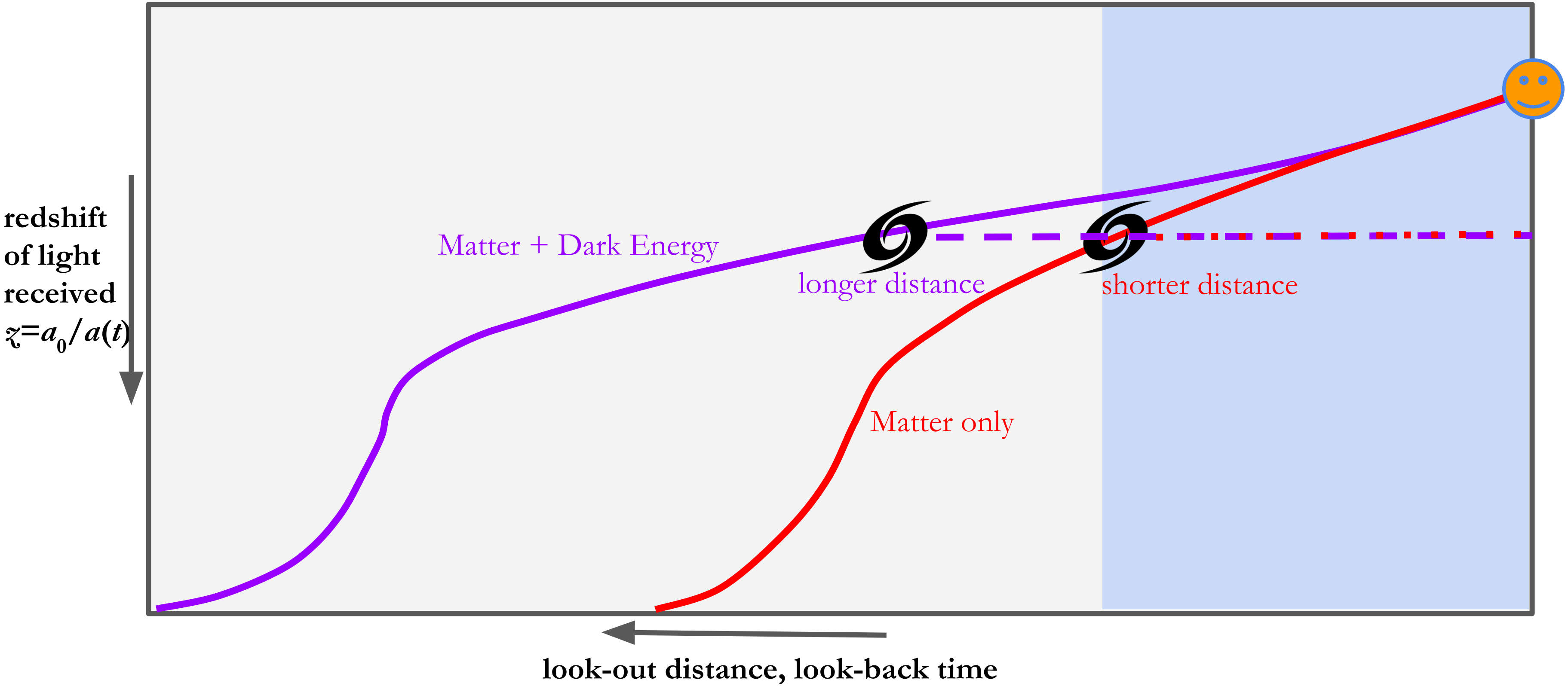

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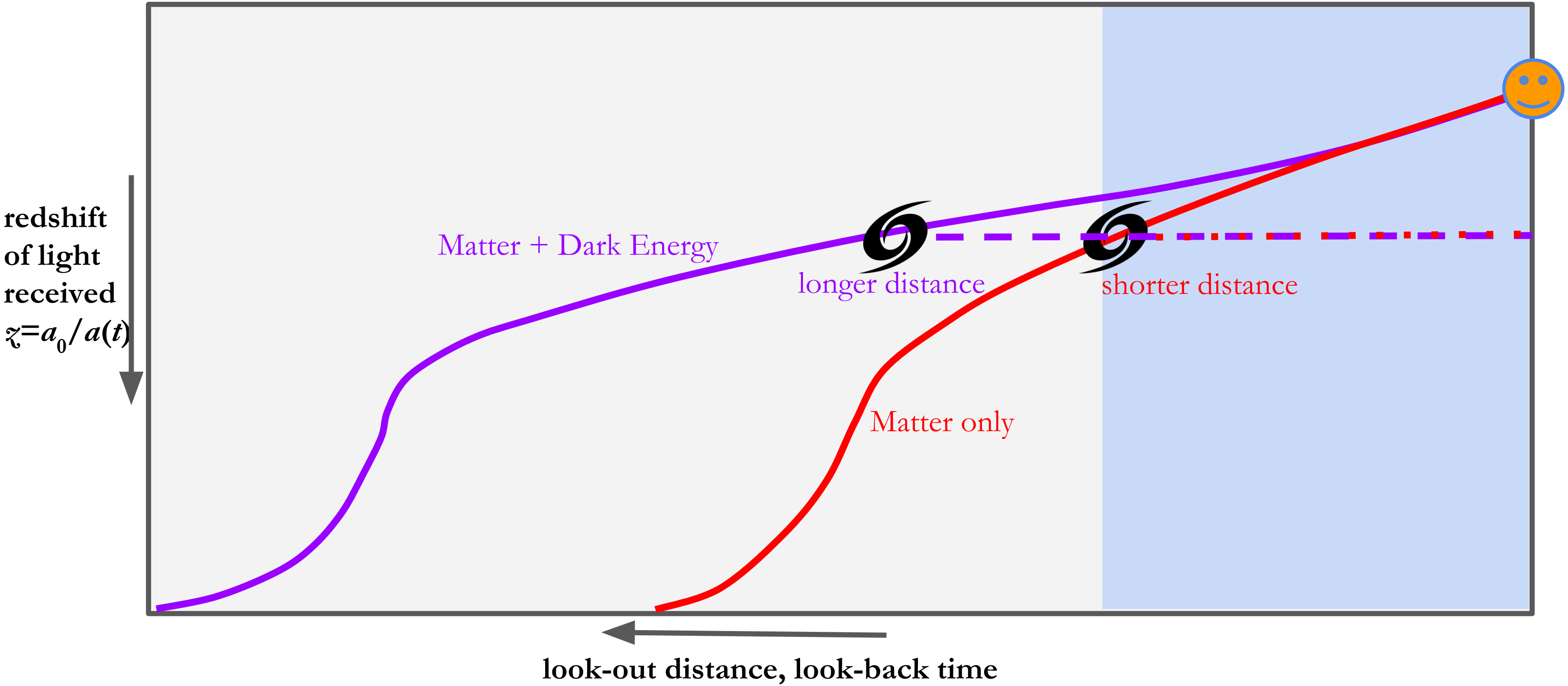

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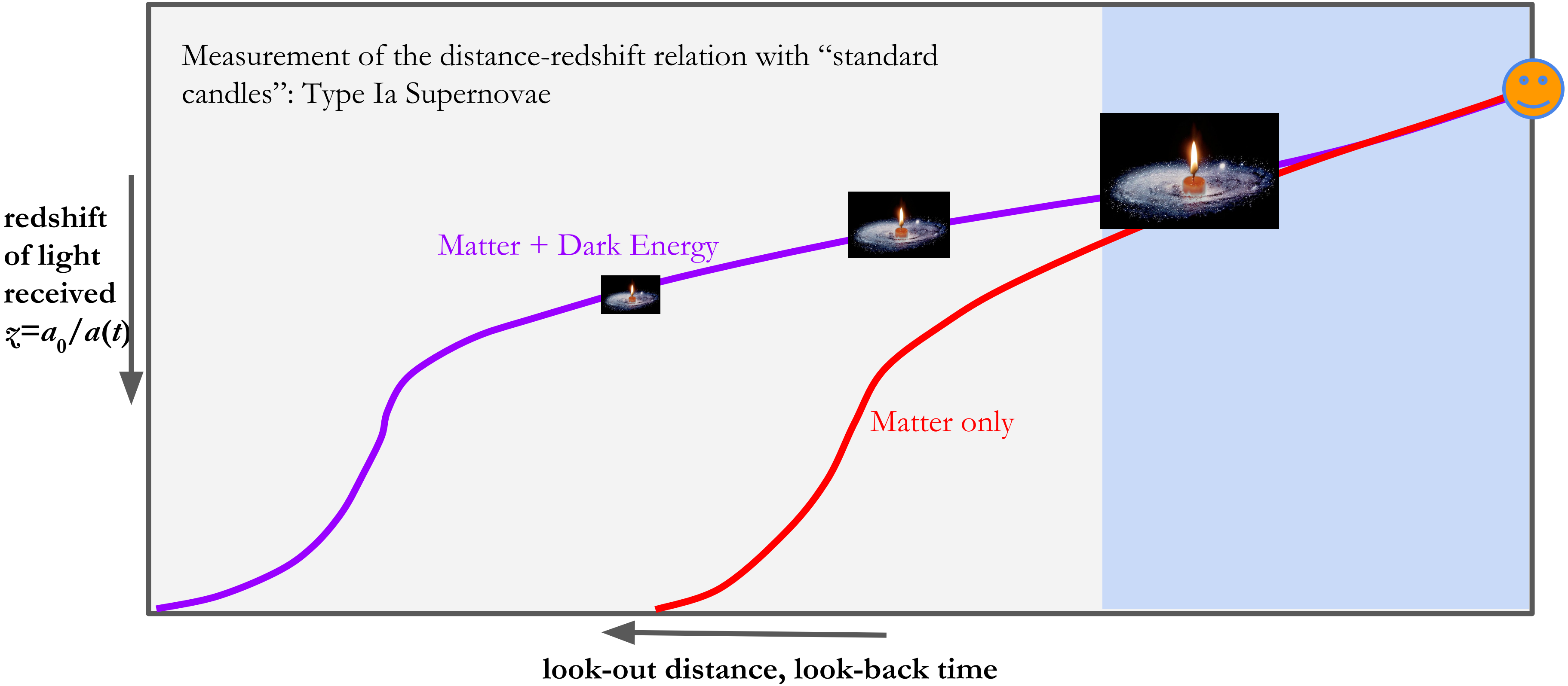

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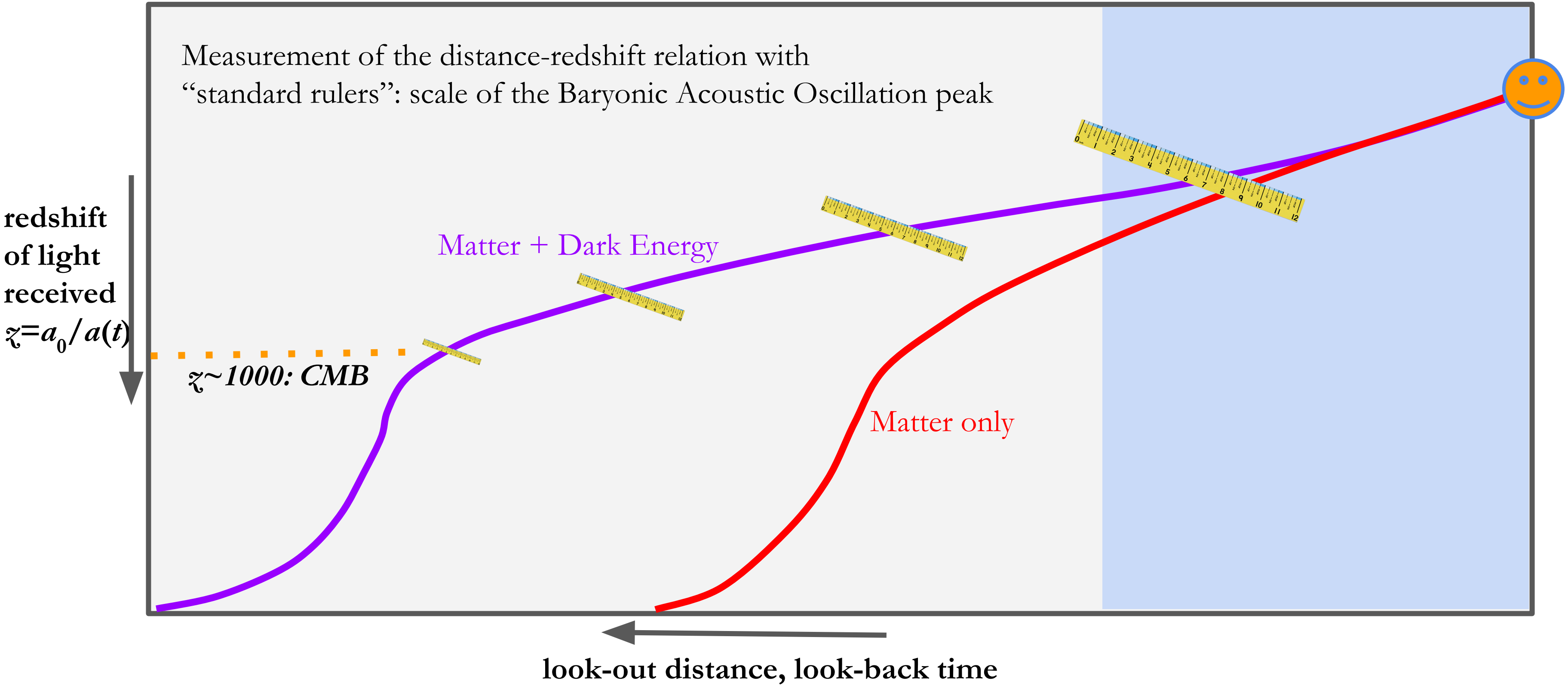
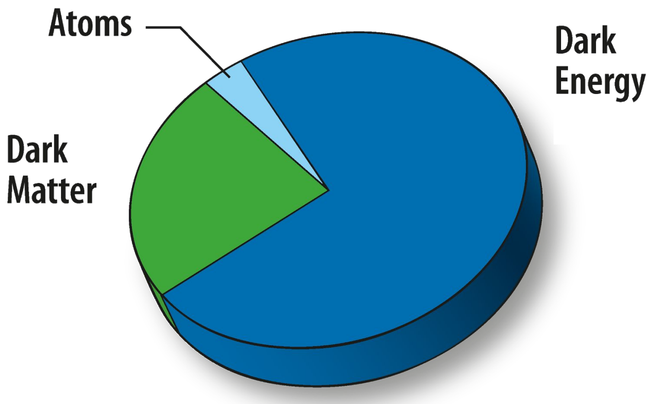
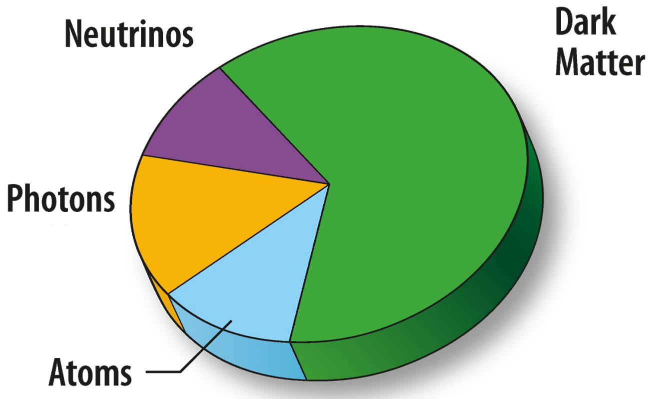


The contents of *our* Universe

- Based on all observations, the universe is about 13.8 billion years old and today contains:
  - 70% vacuum energy
  - 25% dark matter
  - 5% baryons
- Time variations of dark energy equation of state are not well constrained
- Light new particles could influence early universe physics and expansion history



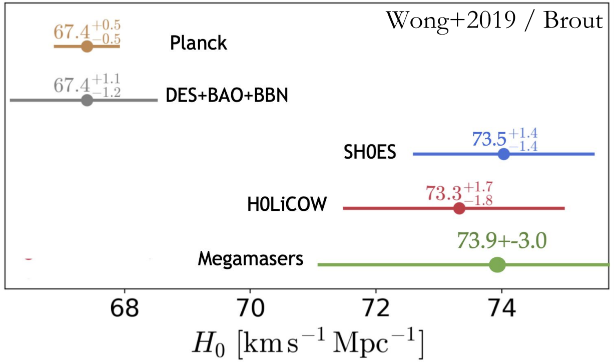
TODAY

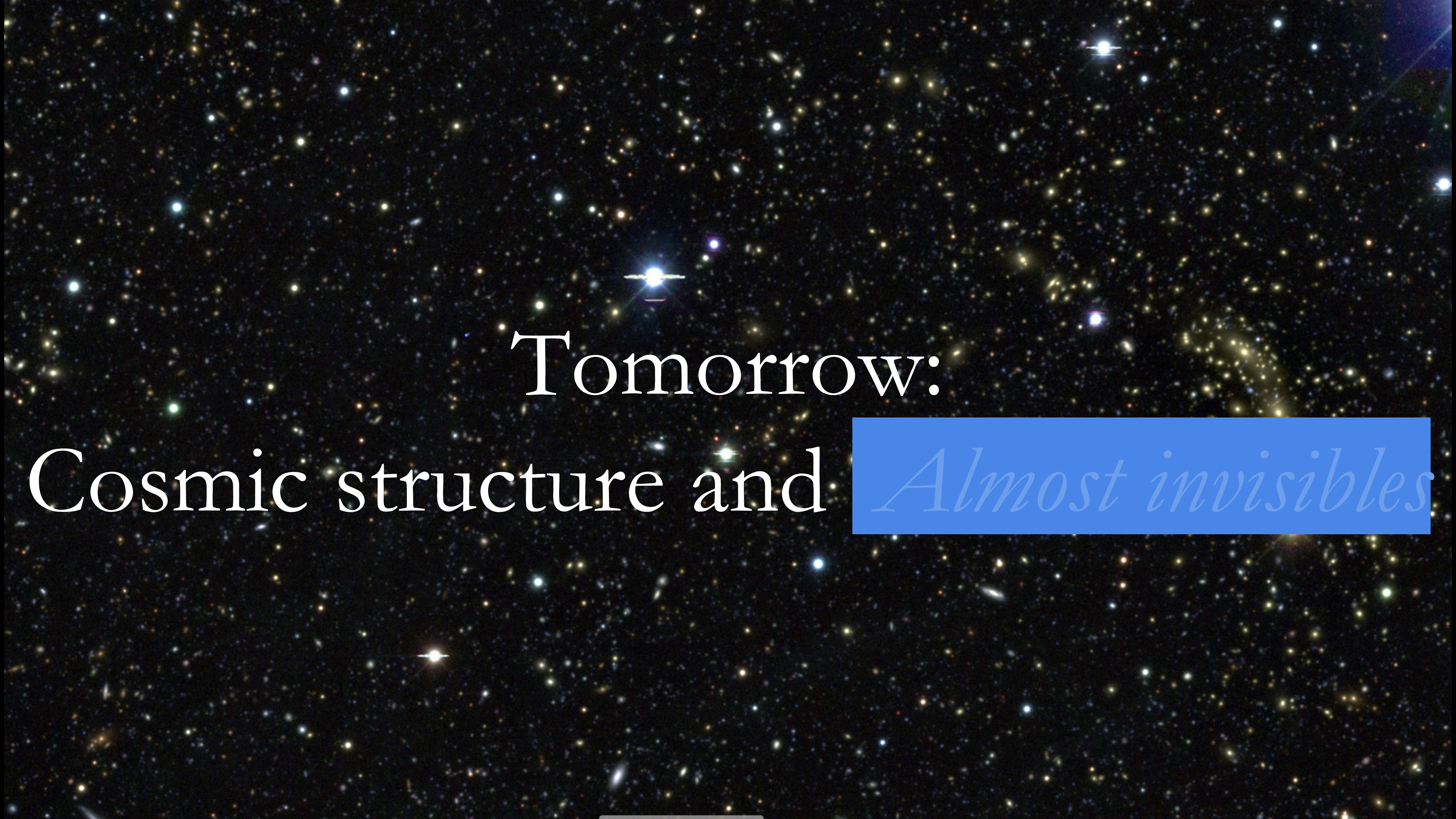


13.7 BILLION YEARS AGO
(Universe 380,000 years old)

Two tensions

- Measurements of *local* expansion rate H_0 disagree with the parameter needed to describe expansion *history* at >4σ
  - Could point at additional particle(s) / interactions in early Universe that change size of "standard ruler"
  - Could point at very recent additional acceleration
  - Could point at systematic errors
- Measurement of late-time density fluctuation amplitudes disagree with early-time fluctuation amplitude at ~2-3σ
  - Could point at additional particle(s) / interactions
  - Could point at modifications of gravity
  - Could point at statistical fluke or systematic errors




Tomorrow:
Cosmic structure and *Almost invisibles*