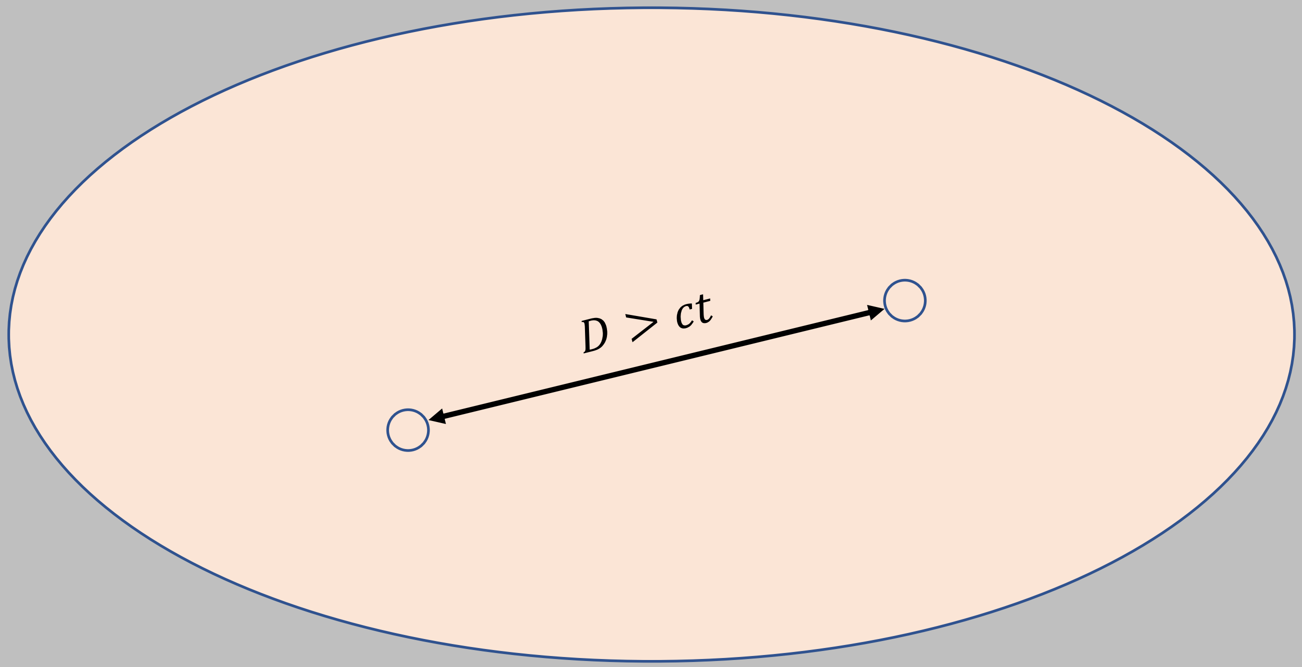
1970s – 80s: The rise of the flat matter-dominated Universe

Cosmologists were faced with several problems, two of which were particularly difficult

The Smoothness Problem: **The fact that the temperature of the CMB is so uniform ($\Delta T/T \approx 10^{-5}$) violates causality.**

Two widely seperated patches of the CMB were too far apart – even when the Universe was much smaller – to be causally connected at that time: $D > ct$

So how would they know to have precisely the same temperature?



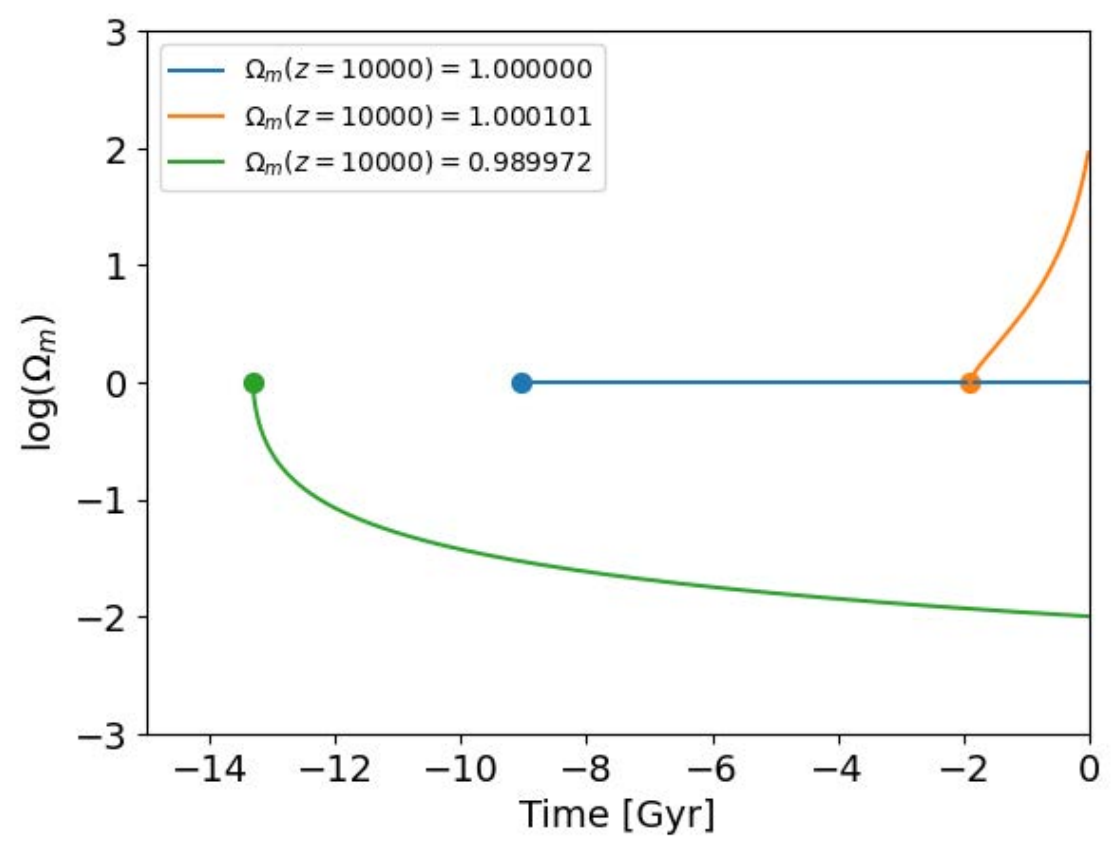
1970s – 80s: The rise of the flat matter-dominated Universe

Cosmologists were faced with several problems, two of which were particularly difficult

The Flatness Problem: The Friedmann equation tells us that Ω_m changes with time as the Universe expands. The only universe that doesn't happen in is an $\Omega_m = 1$ universe.

If Ω_m was *slightly* different from 1 in the early universe, it would be *wildly* different now:

Ω_m @ $z = 10000$	Ω_m today
1.000000	1.0000
1.000101	100
0.989972	0.01



Observational estimates of Ω_m were in the range of 0.3 – 0.8.

The only likely way the Universe would have Ω_m so close to 1 today is for it to have been precisely = 1 at early times.

Why would that be? Why would the universe be so precisely flat?

1970s – 80s: The rise of the flat matter-dominated Universe

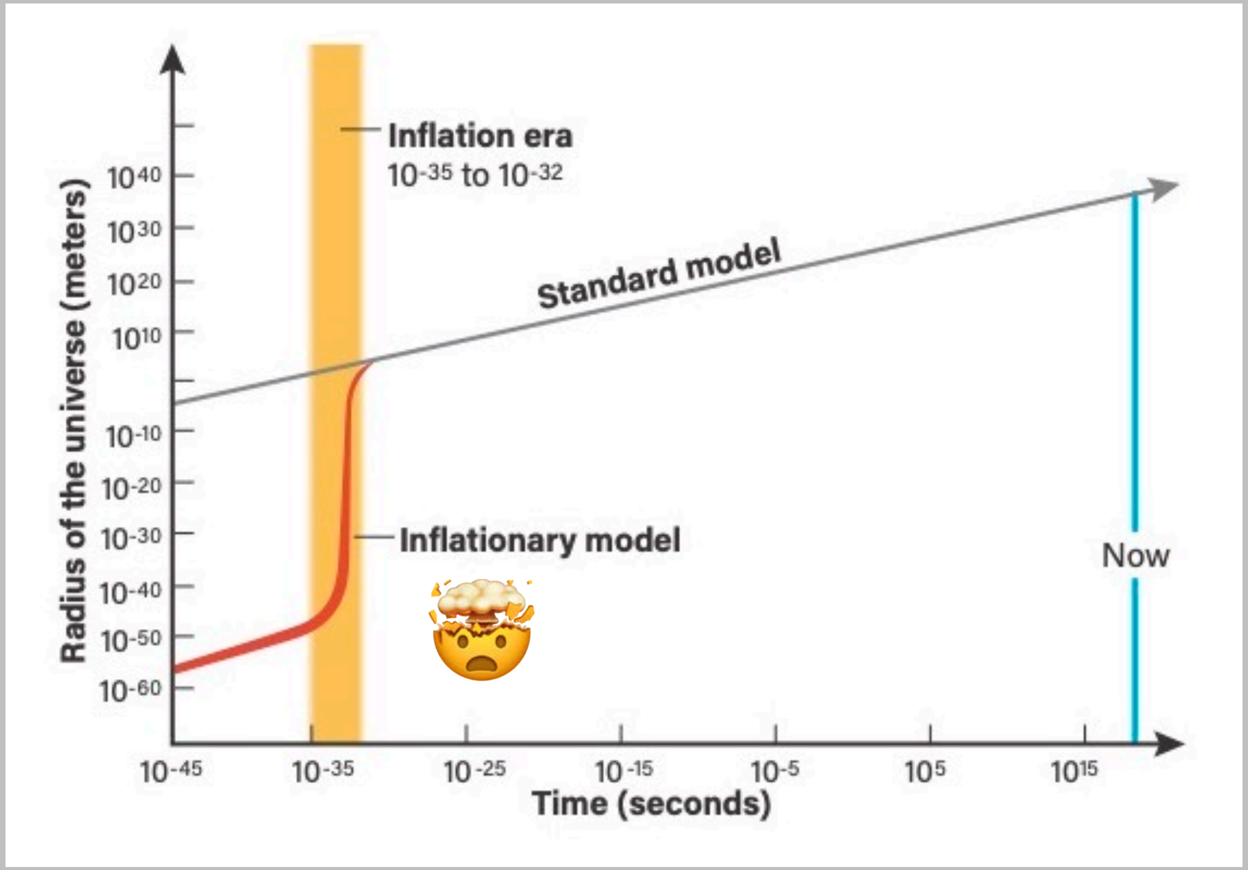
To fix the flat/smooth problems, in the late 1970s the **theory of inflation** was proposed.

In the very early universe, the universe was much smaller than the Friedmann Equation would predict. It was so small that the entire Universe was in causal contact at early times. The entire Universe was homogeneous and smooth.

Then, magically, the Universe inflated at an incredible rate! Those regions that were in causal contact were suddenly inflated so far apart that they are no longer in causal contact.

When? How fast? At $t = 10^{-35}$ seconds, the early Universe inflated by a factor of $\approx 10^{50}$ on a timescale of $\approx 10^{-34}$ seconds.

Why? Who knows? One possibility: this is the moment when strong nuclear force seperated from the electroweak force. This phase transition released energy that drove inflation. But there are other theories, we don't know for sure. *Go ask the physicists.....*



courtesy Astronomy magazine

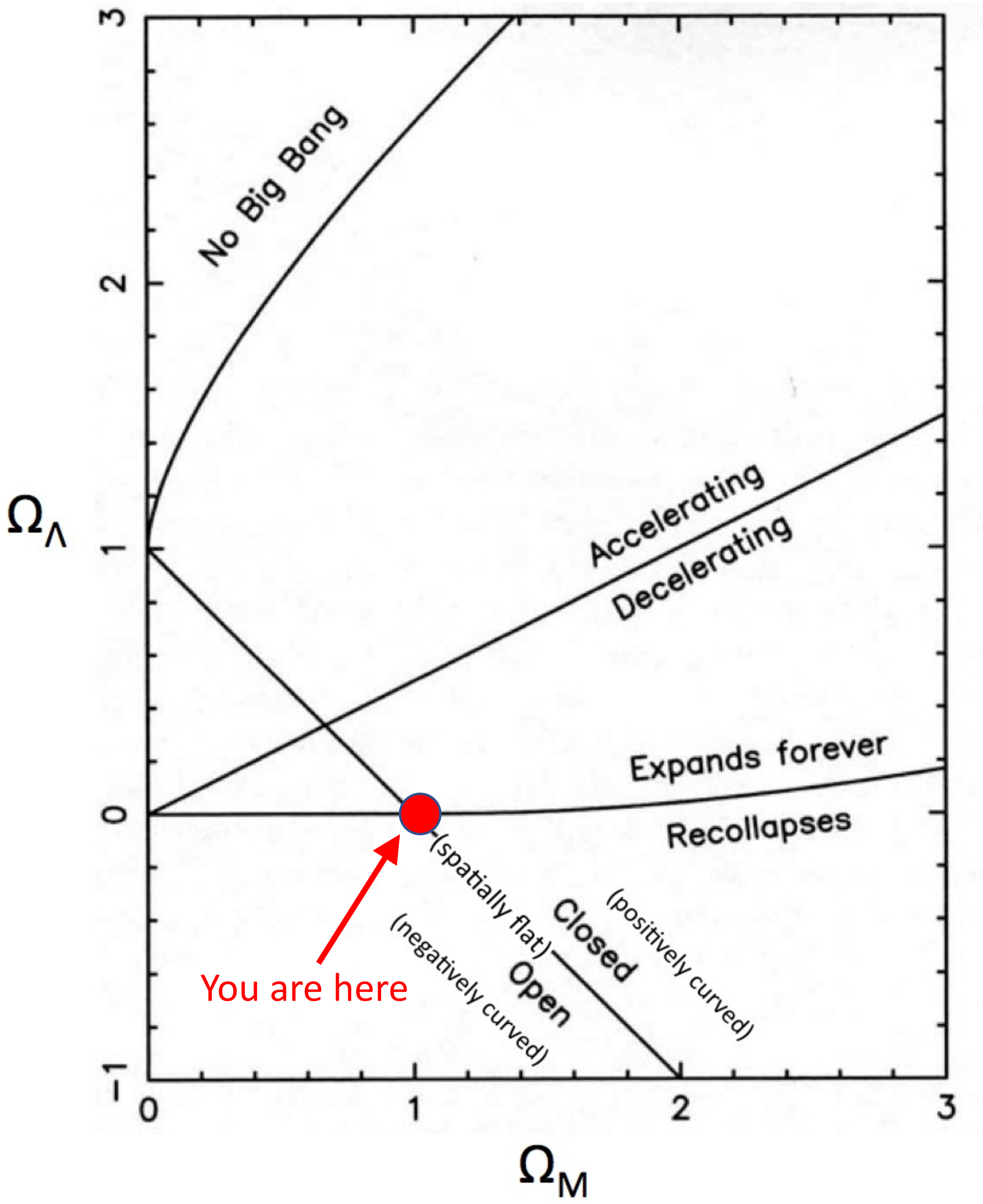
1970s – 80s: The rise of the flat matter-dominated Universe

Inflation fixes many problems:

- **Smoothness**: the early universe was much smaller before inflation, and everything was in causal contact. So no surprise that the CMB has almoste exactly the same temperature everywhere.
- **Flatness**: The inflationary expansion was so big (a factor of 10^{50}) that any curvature is essentially flattened out.

So the natural and expected cosological model was the **Standard Cold Dark Matter** (SCDM) model, as follows:

- The Universe is flat
- The Hubble constant was $H_0 = 70 \pm 20$ km/s/Mpc
- There wasn't much normal matter : $\Omega_b \approx 0.05$ or so
- We knew dark matter existed (galaxy rotation curves, galaxy cluster dynamics, etc), and plausibly would provide enough "missing mass" to get $\Omega_m = 1.0$
- So no need for any crazy cosmological constant: $\Omega_\Lambda = 0.0$

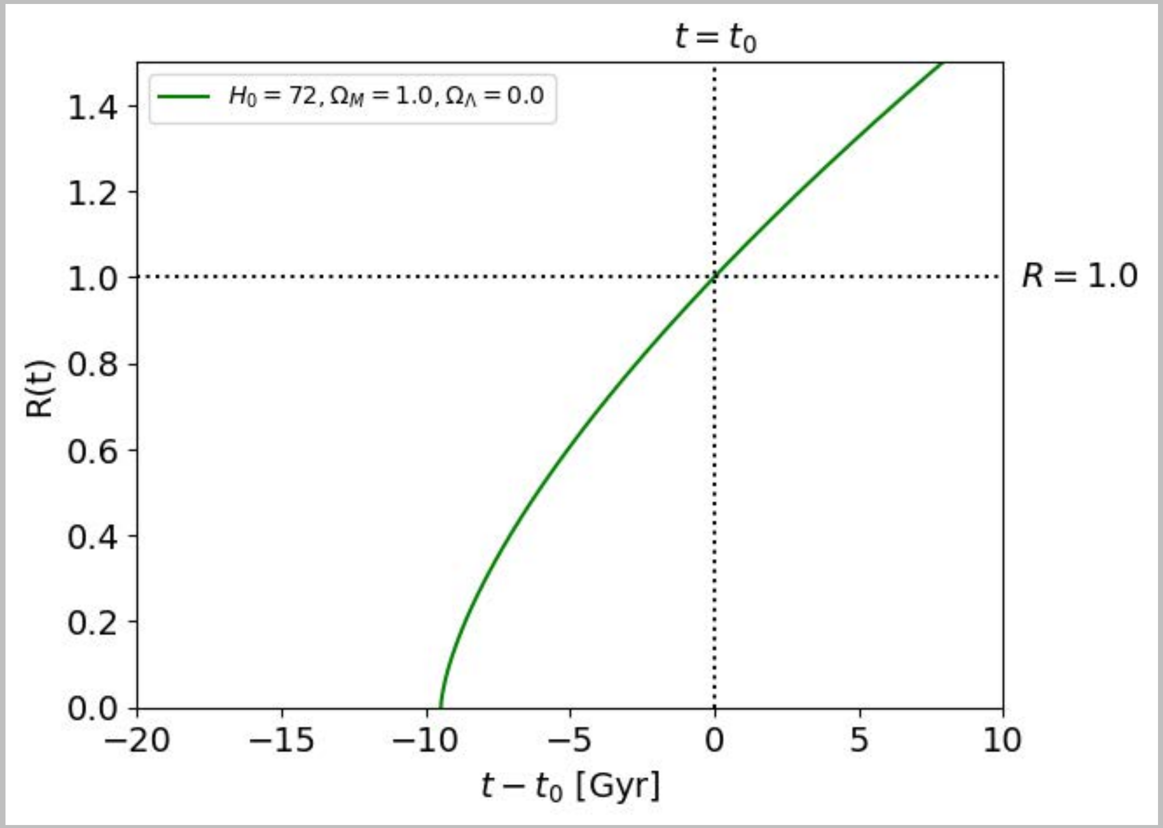


The age of the flat matter dominated universe

Using the Friedmann Equation, we can integrate R(t) for any combination of $H_0, \Omega_m, \Omega_\Lambda$ to work out the age of the Universe. Depending on these parameters, the math can be messy or non-analytic.

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

There is one case in which it is simple – a flat ($k = 0$), matter-only universe: $\Omega_m = 1.0, \Omega_\Lambda = 0.0$



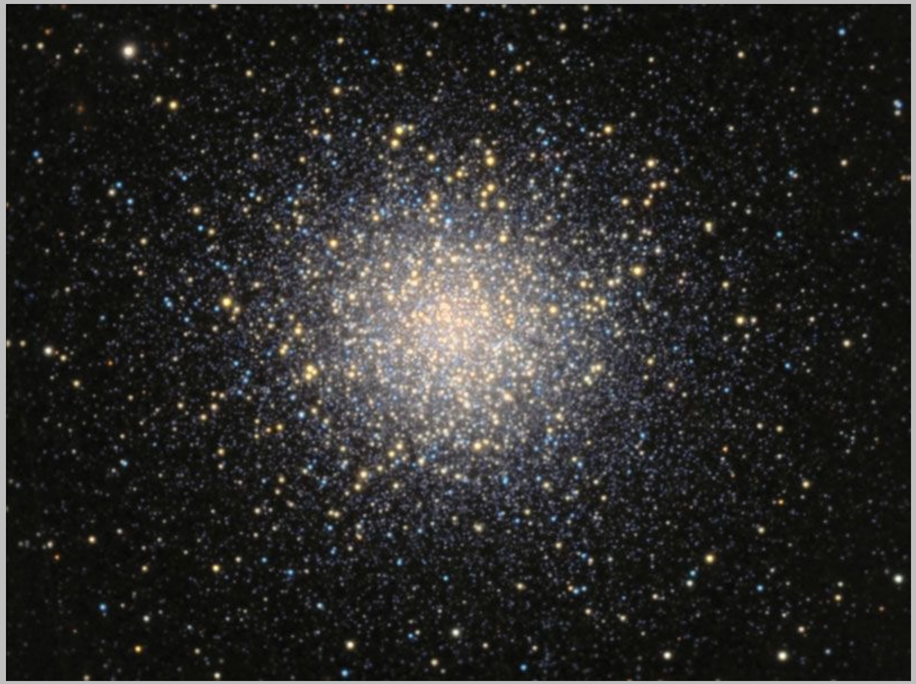
This integrates to

$$R(t) = (6\pi G\rho_c)^{1/3} t^{2/3}$$

Which you can (and will!) solve to get

$$t_0 = \frac{2}{3}\frac{1}{H_0} = 9.3\ Gyr$$

The "Cosmological Crisis" of the early 1990s



By the late 1980s, age estimates for globular clusters were becoming more and more secure: 9 − 12 billion years old.

But the age of a flat, matter-only universe is 9.3 billion years.
How can globular clusters be older than the Universe?

Possibilities to fix this crisis:

- *(Ignore the result)* ***Maybe globular cluster ages are wrong***

- *(Blame someone else)* ***Maybe our estimate of the Hubble constant is wrong***
  If $H_0 = 50$ km/s/Mpc, $t_0 = 13$ billion years.

- *(Believe the astronomical data)* ***Maybe there's less mass*** ($\Omega_\mathrm{m} < 1.0$)
  - If $\Omega_\mathrm{m} = 0.3$, $t_0 = 11.5$ billion years *(barely, maybe works)*
  - If $\Omega_\mathrm{m} = 0.0$, $t_0 = 14.0$ billion years *(ok, that works, but.... no matter of any type?)*
  - *And – ack – the Universe wouldn't be flat!*

- *(Get wild)* ***Maybe we have to consider adding a cosmological constant*** ($\Omega_\Lambda > 0.0$)
  An accelerating Universe is older

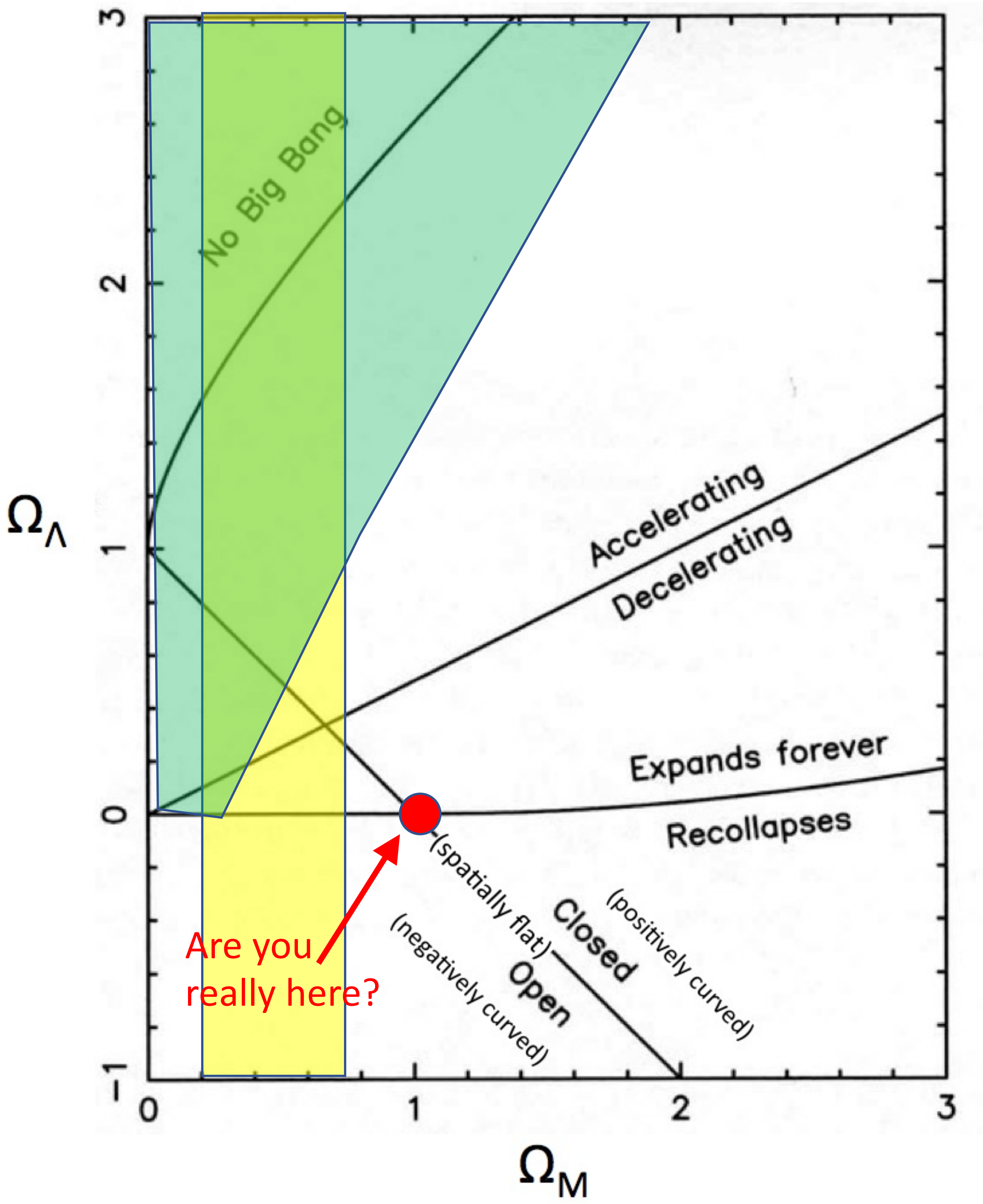
Cosmological parameter constraints

Estimates of H_0 are getting quite accurate, ruling out the low H_0 arguments. Since globular cluster ages are still old

$$\Omega_m \ll 1, \text{ or } \Omega_\Lambda > 0$$

The surveys for matter suggest the universe is less dense than needed to flatten the universe ($\rho > \rho_{crit}$):

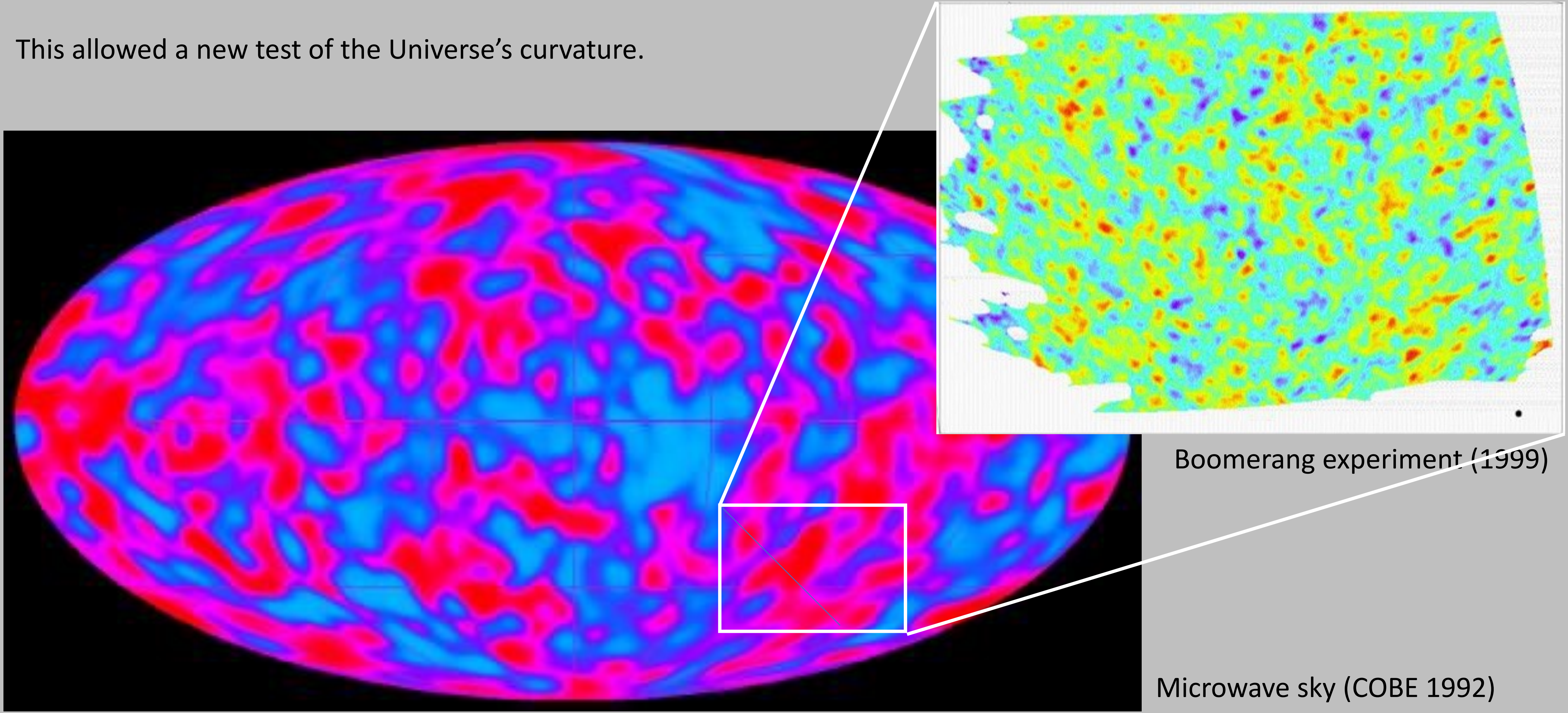
$$\Omega_m \approx 0.2 - 0.7$$



Meanwhile, better data began coming in for the cosmic microwave background (CMB)

Microwave observatories (ground and balloon) began getting images of the microwave background at higher resolution, seeing the temperature fluctuations on smaller scales.

This allowed a new test of the Universe's curvature.



Boomerang experiment (1999)

Microwave sky (COBE 1992)

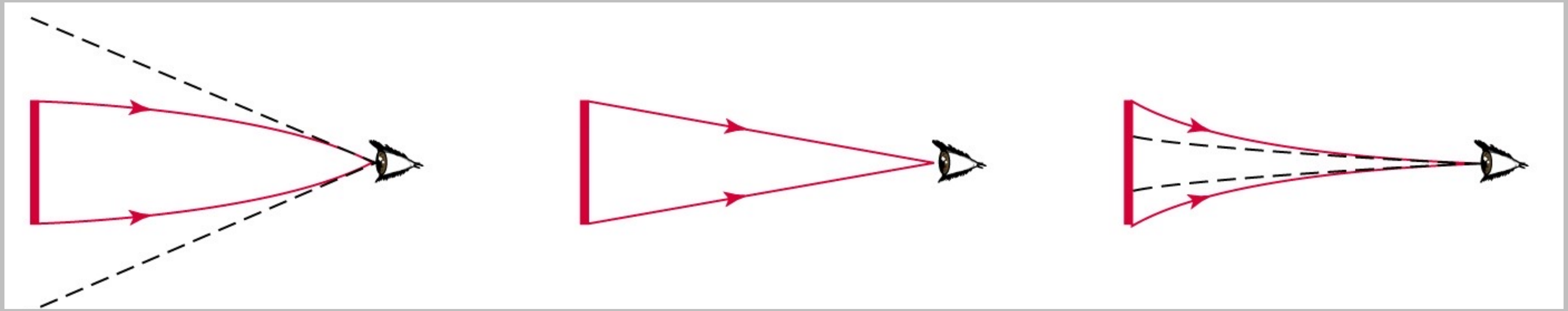
Using the CMB to probe the curvature of the Universe

Imagine looking at an object of fixed physical size (a “standard rod”) under different spatial geometries. Since straight lines curve differently under different spatial geometries, an object of fixed physical size will have different angular sizes under different geometries.

positive curvature, larger angular size

spatially flat

negative curvature, smaller angular size



So if you know the physical size of the object, you can predict the different angular sizes for different types of curvature.

In a hot dense medium (like the early universe) pressure waves that grow the overdensities of mass move at the sound speed, which only depends on density and temperature. So the lumps in the CMD will have a characteristic size given by $d = c_s \times t_{CMB} \approx 65$ Mpc in any universe. A standard rod!

c_s : sound speed

t_{CMB} : age of the universe at the time of the CMB

Using the CMB to probe the curvature of the Universe

The observed CMB matches the expectation for a spatially flat Universe!

Spatially flat: $\Omega_\mathrm{m} + \Omega_\Lambda = 1$

So the CMB insists the Universe is flat.

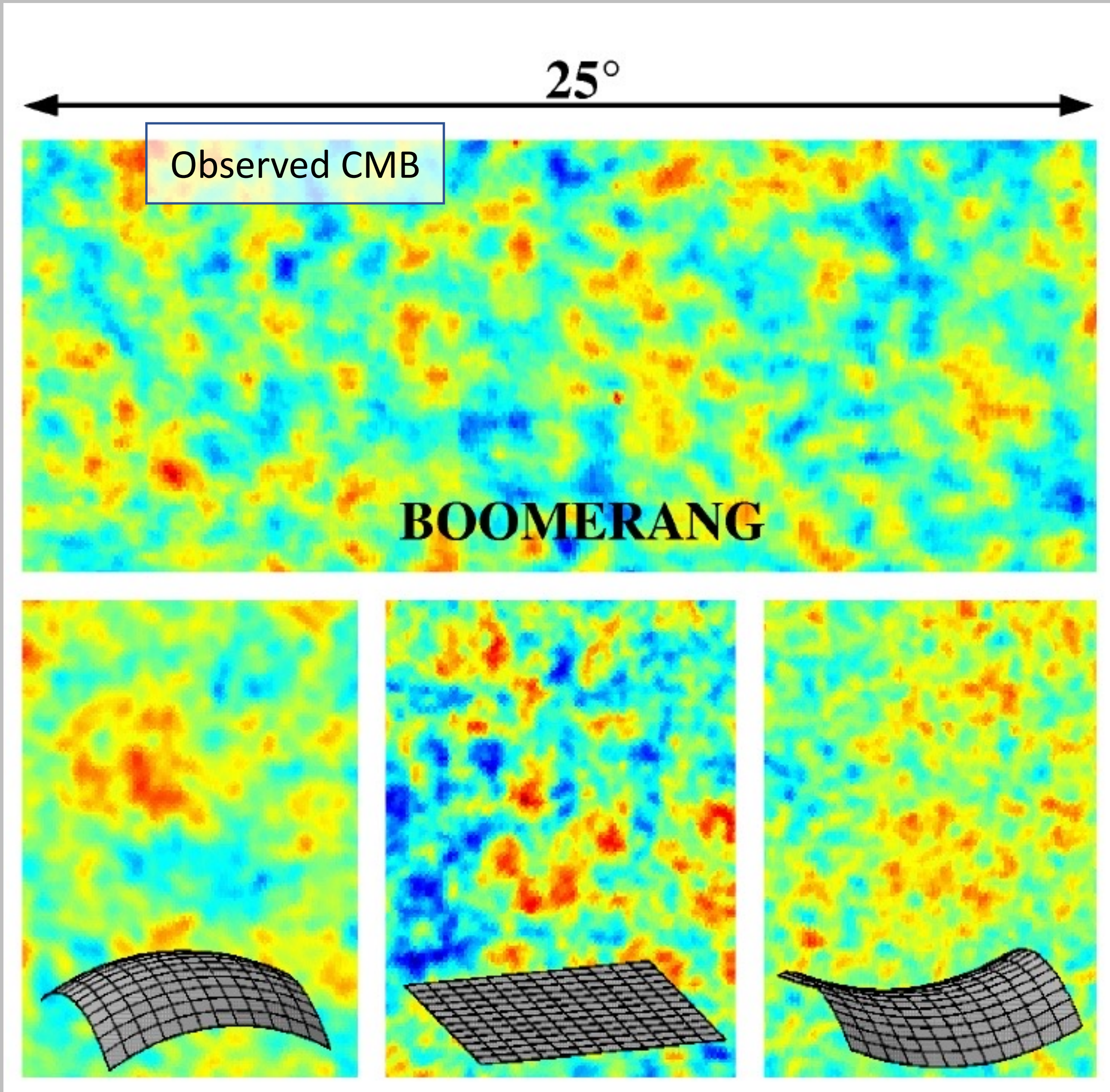
Globular clusters insist the Universe is old.

Surveys of matter in the universe insist $\Omega_\mathrm{m} < 1$.

The cosmological constant is crazy talk.

Something has to give.....

Simulated CMBs under different spatial curvatures ⇒



positive curvature

flat space

negative curvature

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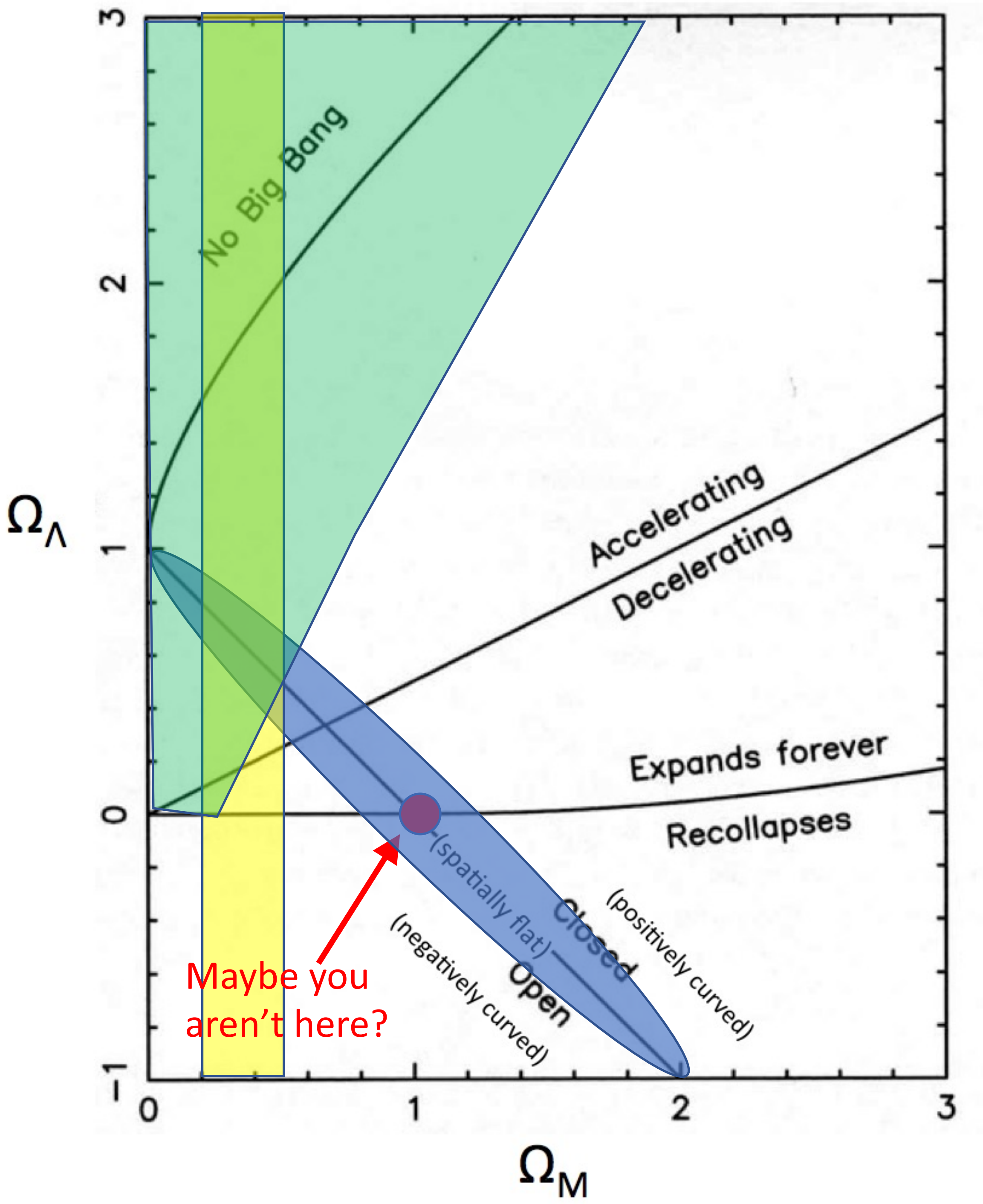
$$\Omega_m \ll 1, \text{ or } \Omega_\Lambda > 0$$

The surveys for matter are getting better, and continue to support a low density universe

$$\Omega_m \approx 0.2 - 0.5$$

The fluctuations in the CMB continue to demand a flat universe

$$\Omega_m + \Omega_\Lambda = 1$$



Measuring the shape of space: the "Redshift-Distance Test"

The apparent brightness of high-redshift objects is different in different cosmologies, due to:

- The curvature of space (the $1/d^2$ effect depends on curvature)
- The expansion history of the Universe (affects how $z \longrightarrow d$)

These can be calculated for difference universes to work out the effective distance modulus.

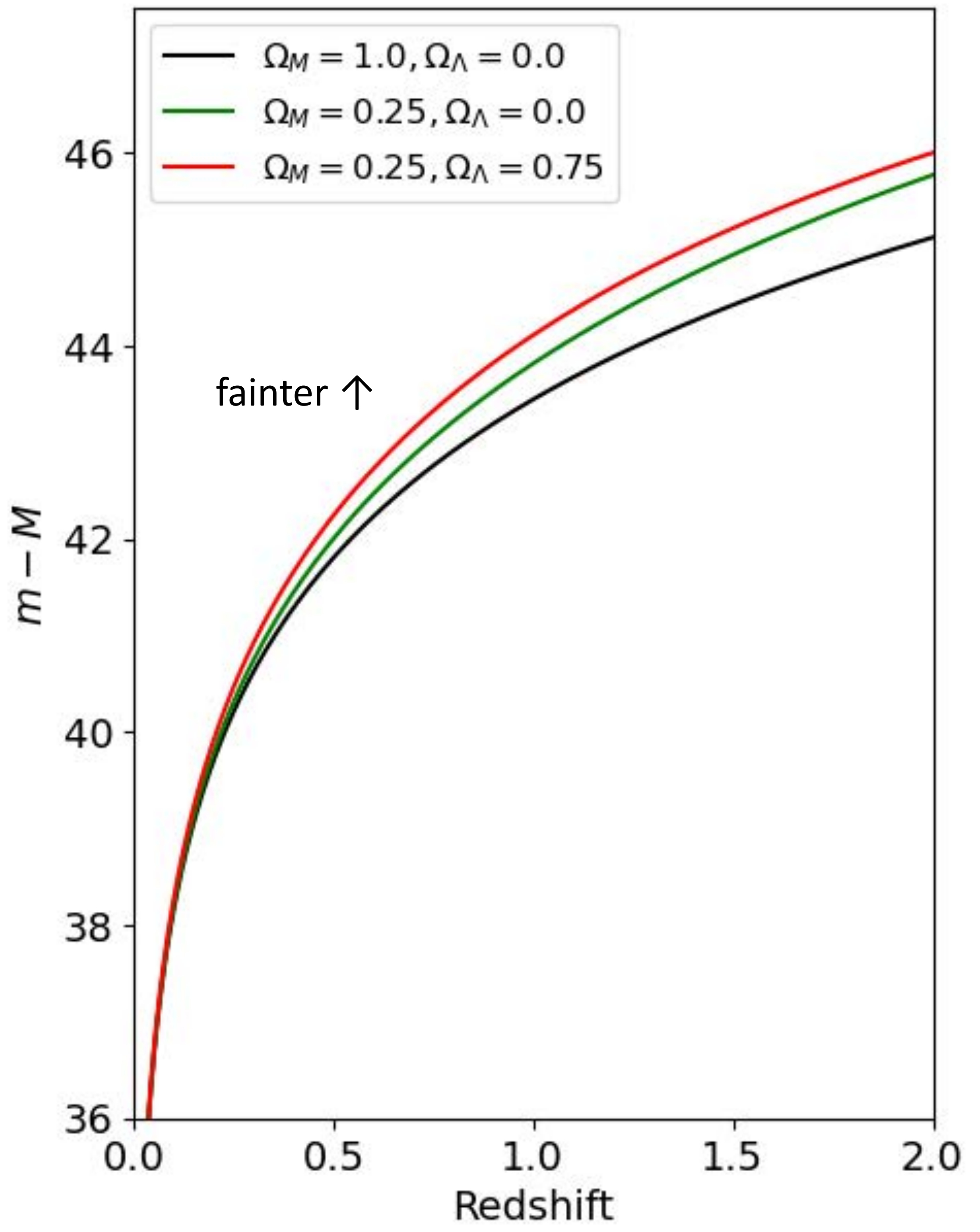
- **locally**, we had: $m - M = 5 \log d - 5$
- **cosmologically** we have: $m - M = 5 \log D_L - 5$
  where we define Luminosity distance:

$$D_L = f(z, H_0, \Omega_m, \Omega_\Lambda)$$

So if we have a type of object with a fixed, known luminosity (a "standard candle") we can measure its apparent magnitude at different redshifts and see which line it falls on.

Requirements for our standard candle:

- Needs to be a bright object
- Needs to be a precise, fixed luminosity



Type Ia supernovae as standard candles

Remember Type Ia SNe: accreting white dwarfs that detonate when they hit the Chandrasekhar mass of $\approx 1.4\ M_{\odot}$. Their peak magnitude should be similar in all cases.

Host	SN	$M^0_{B,i}$
M101	2011fe	−19.389
N1015	2009ig	−19.047
N1309	2002fk	−19.331
N1365	2012fr	−19.390
N1448	2001el	−19.111
N2442	2015F	−19.236
N3021	1995al	−19.535
N3370	1994ae	−19.161
N3447	2012ht	−19.207
N3972	2011by	−19.103
N3982	1998aq	−19.507
N4038	2007sr	−19.058
N4424	2012cg	−19.534
N4536	1981B	−19.293
N4639	1990N	−19.113
N5584	2007af	−19.085
N5917	2005cf	−19.255
N7250	2013dy	−19.196
U9391	2003du	−19.449

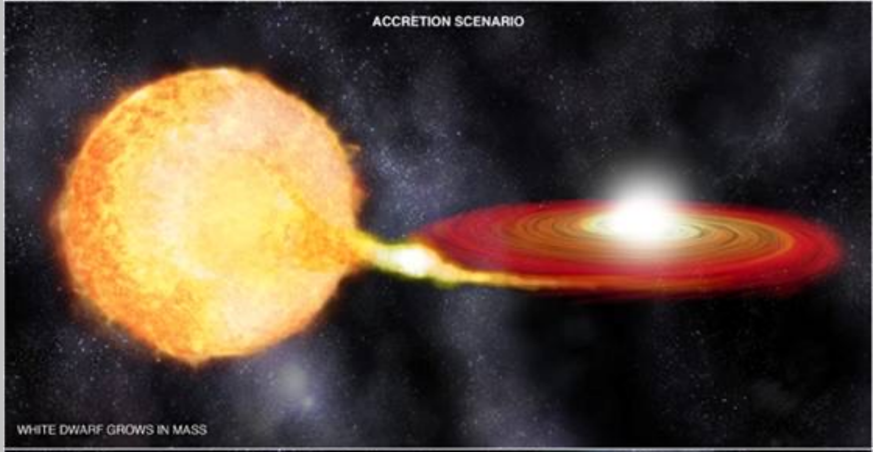
Are they "standard" enough?

Calibration from Riess+16

$$\langle M_B \rangle = -19.26 \pm 0.16$$

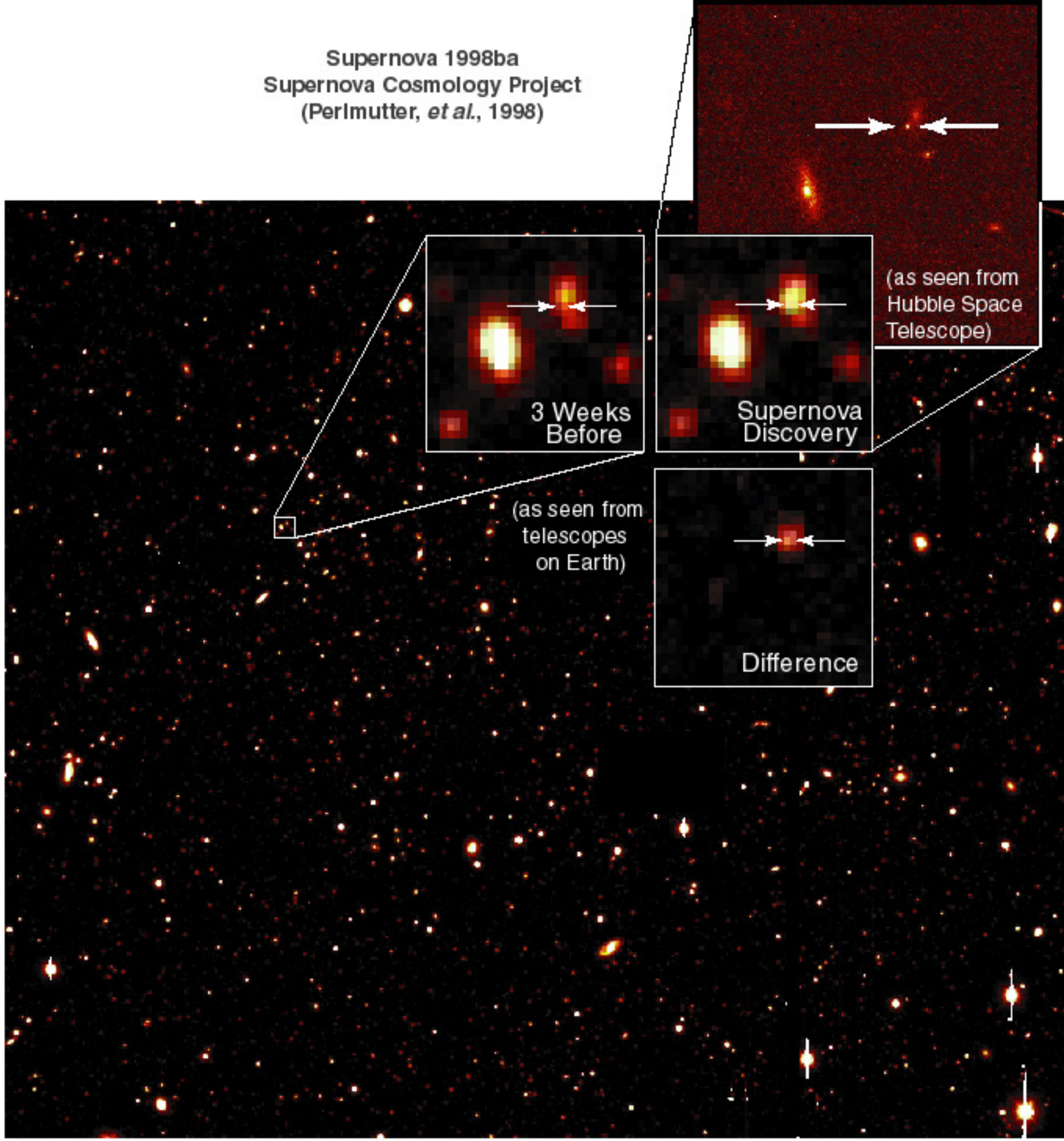
BUT

- Type Ia SNe are rare.
- You have to find them.
- You have to make sure they aren't a different type of SNe.
- And you have to hope Type Ia SNe at high redshift (in early universe) aren't different from the ones nearby!



Supernovae Cosmology Project

1. Take a deep, wide field image of a patch of sky, containing hundreds of galaxies.
2. Wait a few weeks, do it again. Look for differences: a possible supernova!
3. Take a spectrum of the supernova, make sure it actually is a Type Ia.
4. Take many images of the object over time to work out its light curve and derive its peak apparent magnitude.
5. Do this many times to build up the dataset.



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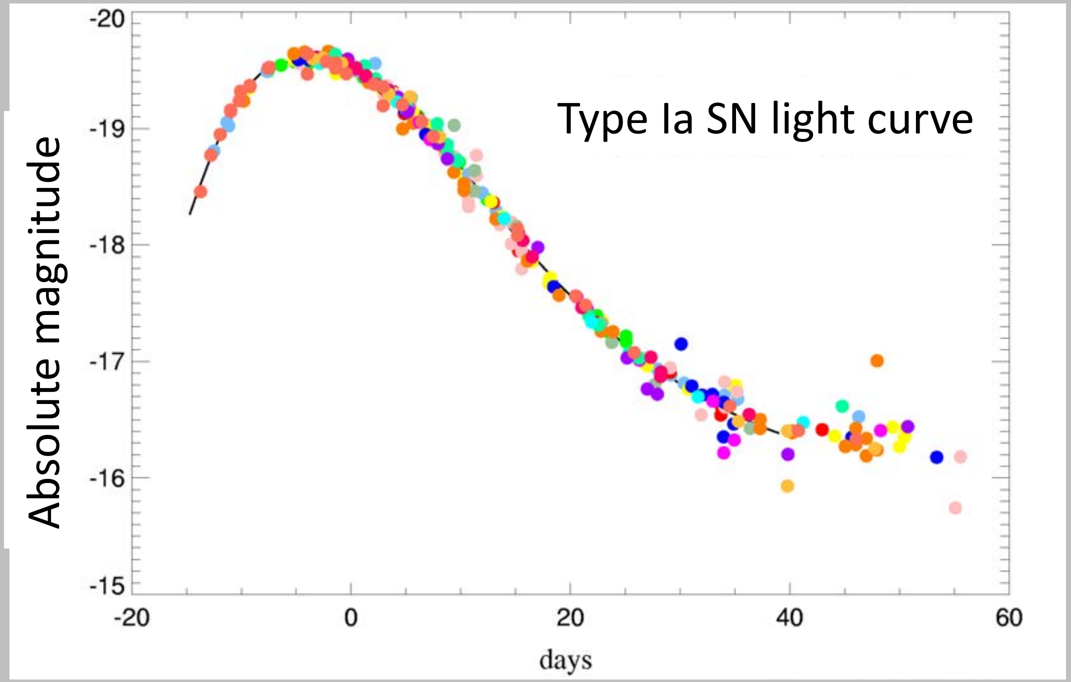
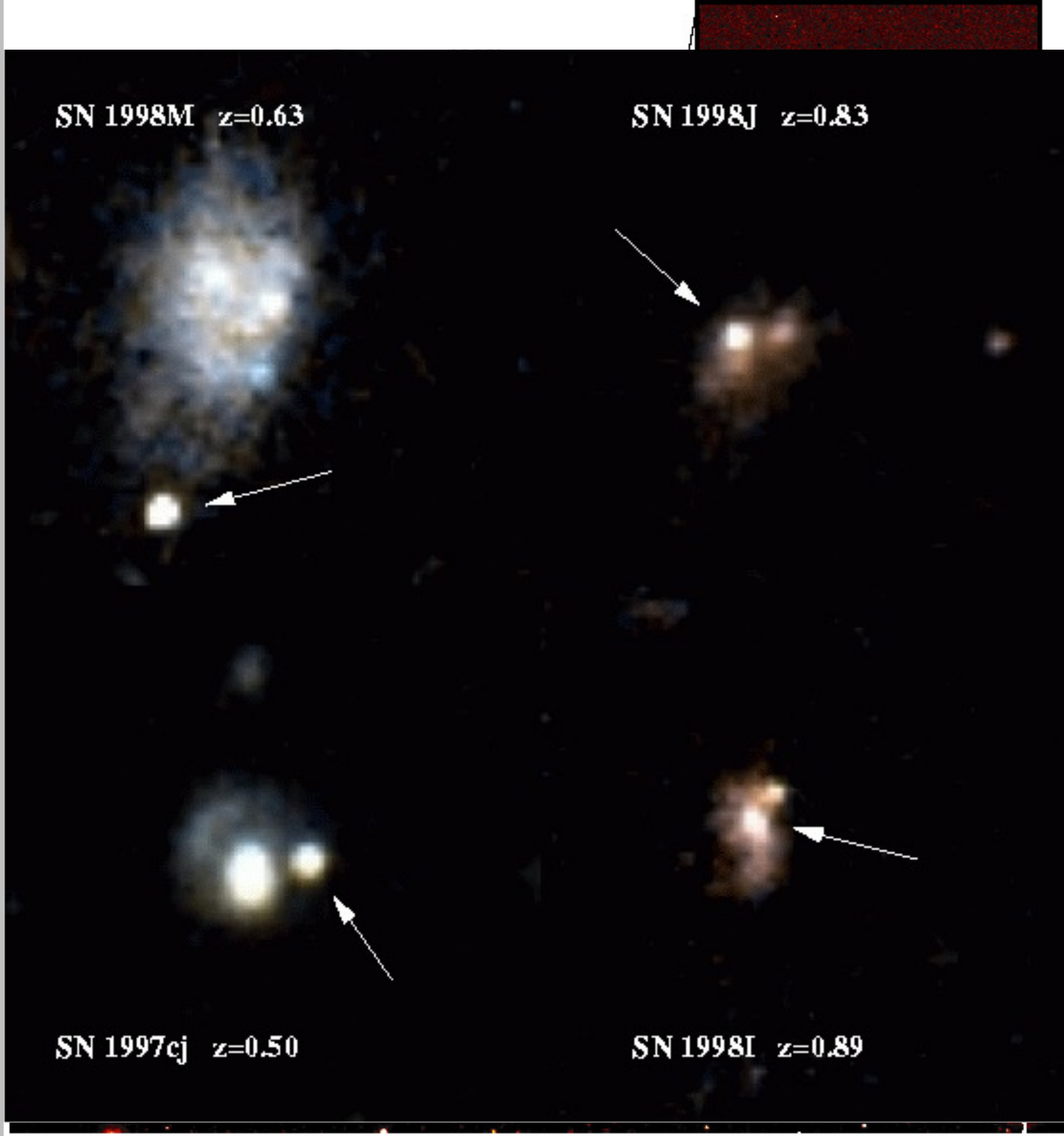


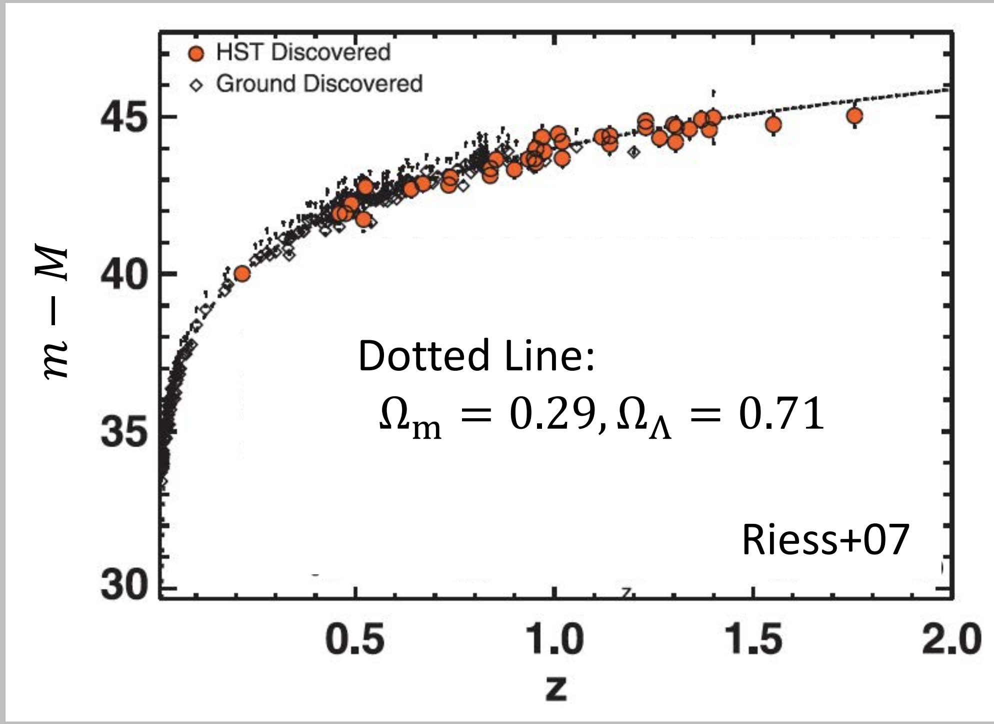


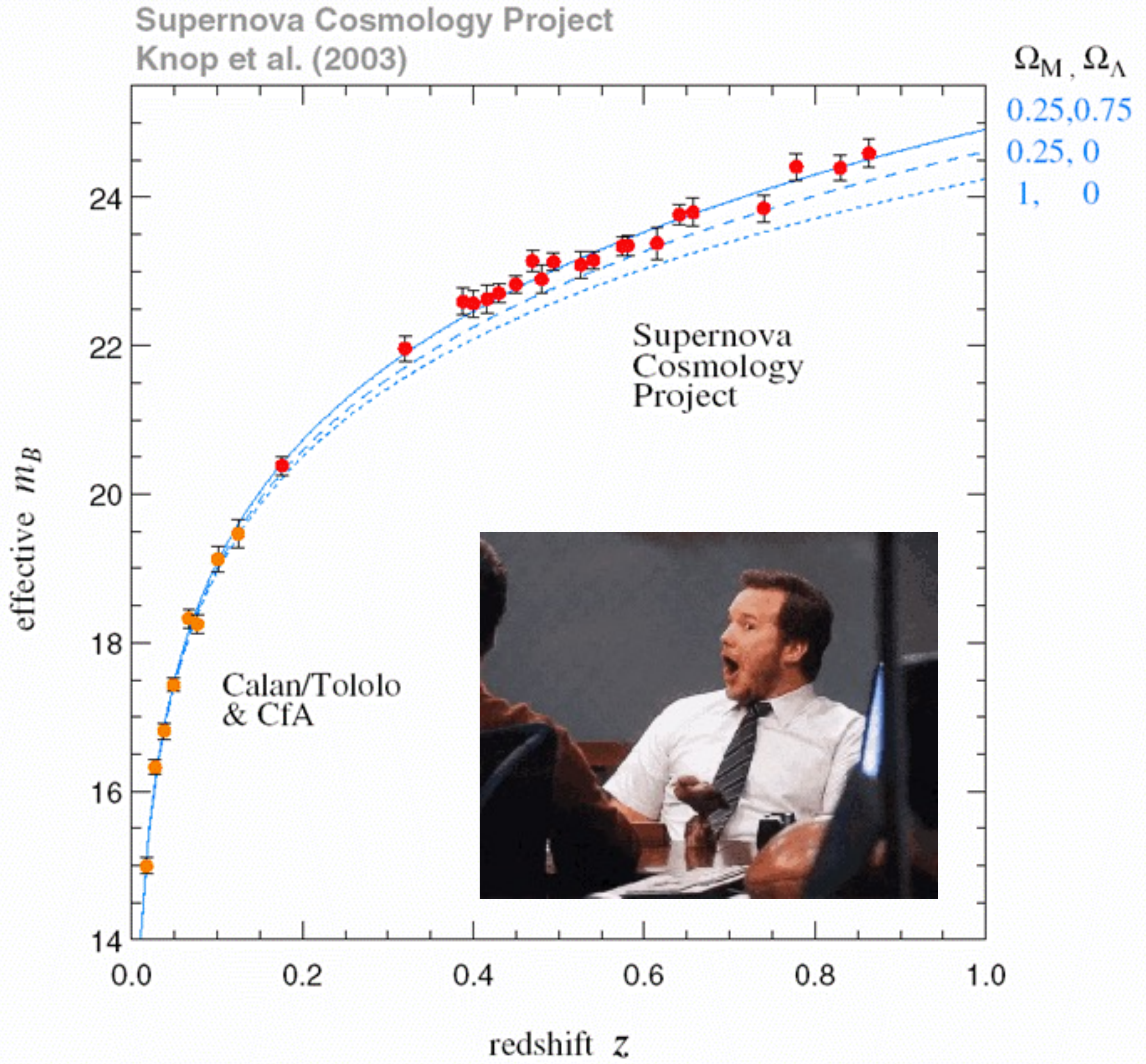
And the answer is.....

...not what people expected!

$$\Omega_m = 0.25, \Omega_\Lambda = 0.75$$

The same result was obtained seperately and nearly simultaneously by two different research groups, and has been subsequently verified by several others.





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$$\Omega_\mathrm{m} \approx 0.2 - 0.5$$

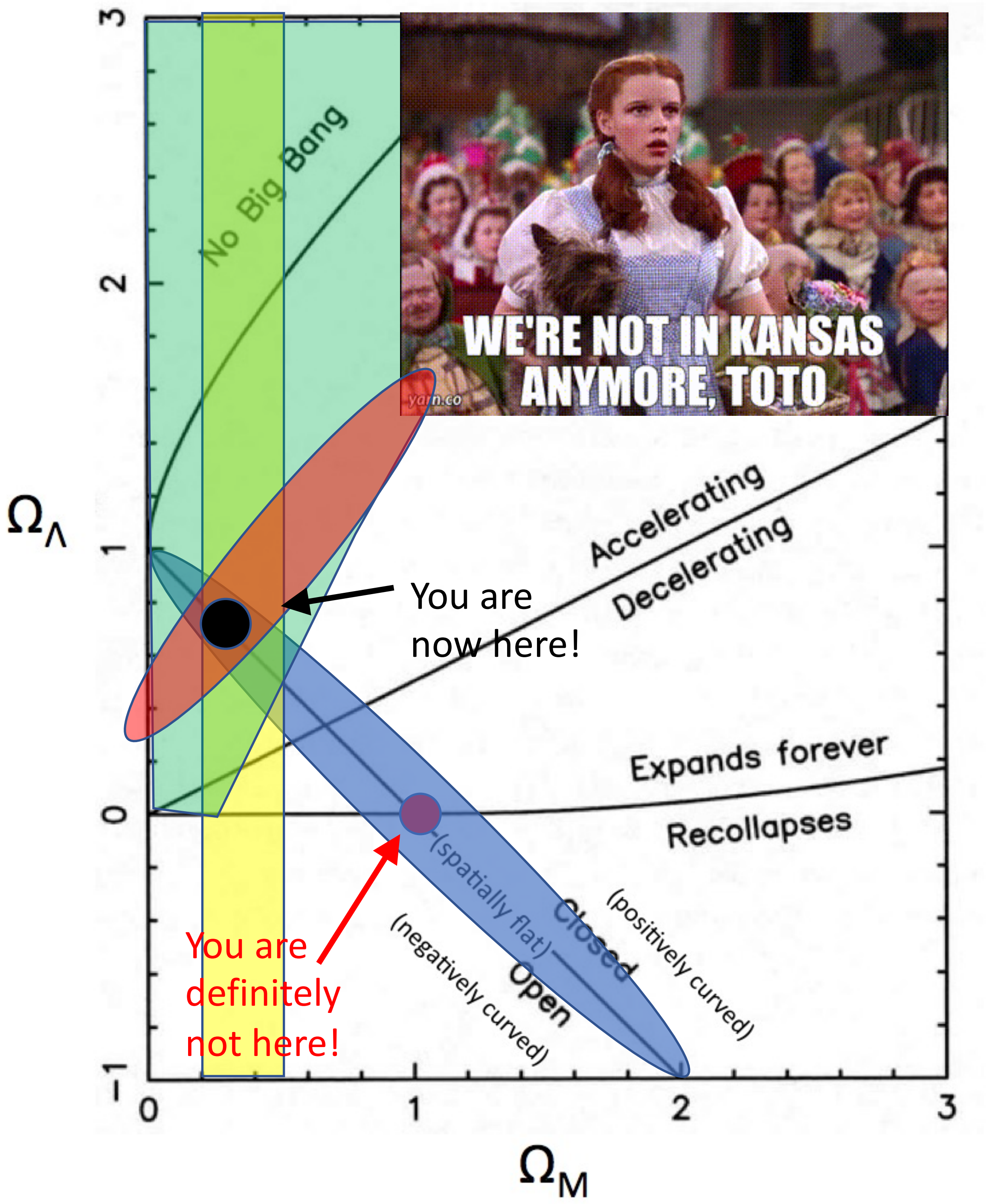
The fluctuations in the CMB continue to demand a flat universe

$$\Omega_\mathrm{m} + \Omega_\Lambda = 1$$

Supernovae cosmology shows acceleration:

$$\Omega_\Lambda - \Omega_\mathrm{m} \approx 0.4$$

Concordance cosmology: $\Omega_\mathrm{m} \approx 0.3,\ \Omega_\Lambda \approx 0.7$



The Cosmological Constant, Lambda, Dark Energy : time to take it seriously

Back to 1919: Einstein introduces the cosmological constant to keep the Universe static: But he threw it out once Hubble had demonstrated the Universe was not static. ***Now it's back.***

Dynamics Equation	Friedmann Equation
$\frac{\ddot{R}}{R} = -\frac{4\pi}{3}G\rho + \frac{1}{3}\Lambda c^2$	$\left(\frac{\dot{R}}{R}\right)^2 - \frac{8}{3}\pi G\rho - \frac{1}{3}\Lambda c^2 = -\frac{kc^2}{R^2}$
ρ decelerates the Universe Λ accelerates the Universe	ρ and Λ work together to set the shape of space.

The cosmological constant Λ acts like an energy (**"dark energy"**) providing an outwardly accelerating pressure, but working with matter to curve space.

(Remember Einstein: $E = mc^2$, so space responds to the matter-energy equivalency....)

But.... what is it?

Dark Energy: We really don't know what it is.

Simplest idea is that it is the **energy density of empty space**, perhaps due to virtual particles. As space expands, there is more space and so dark energy continues to grow in dominance compared to matter.

Virtual Particles from the Heisenberg Uncertainty Principle

Remember the Heisenberg Uncertainty Principle : $\Delta E \Delta t = \hbar$
And use $E = mc^2$ to rewrite it as $\Delta m \Delta t = \hbar / c^2$

On small enough scales, the amount of mass or energy in a vacuum is uncertain. Particles can pop in and out of existence, being created and then almost instantly annihilated, on length- and time-scales that are unobservable.

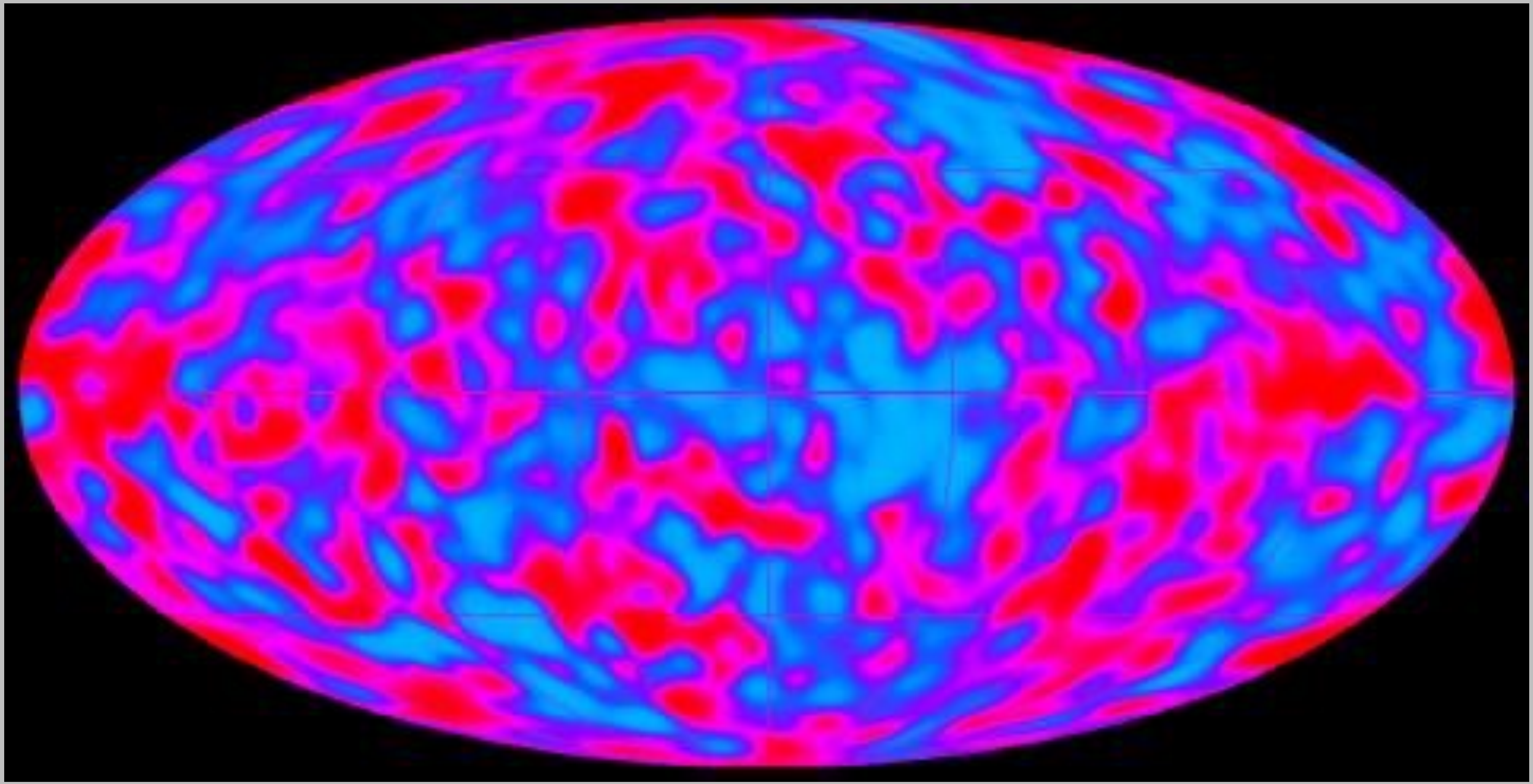
- Theoretical estimate of energy density due to "virtual particles": $\approx\approx\approx 10^{111}$ J m^{-3}
- Observational measurement of the energy density associated with $\Lambda := 6\times 10^{-10}$ J m^{-3}

Only off by 120 orders of magnitude!

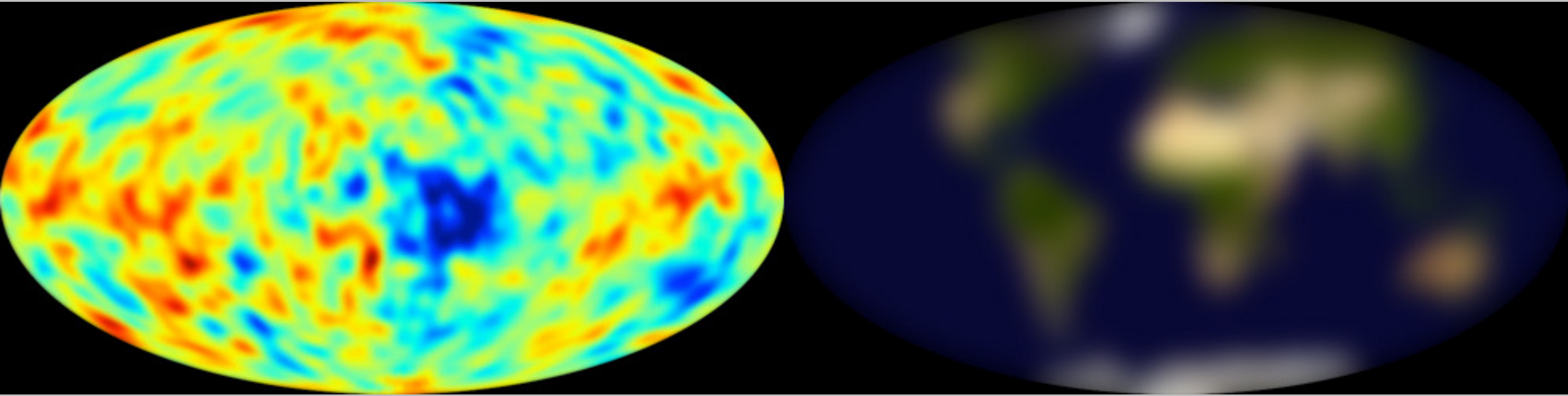
More work is needed.

Meanwhile, better data began coming in for the cosmic microwave background (CMB)

COBE all-sky microwave map (1992)

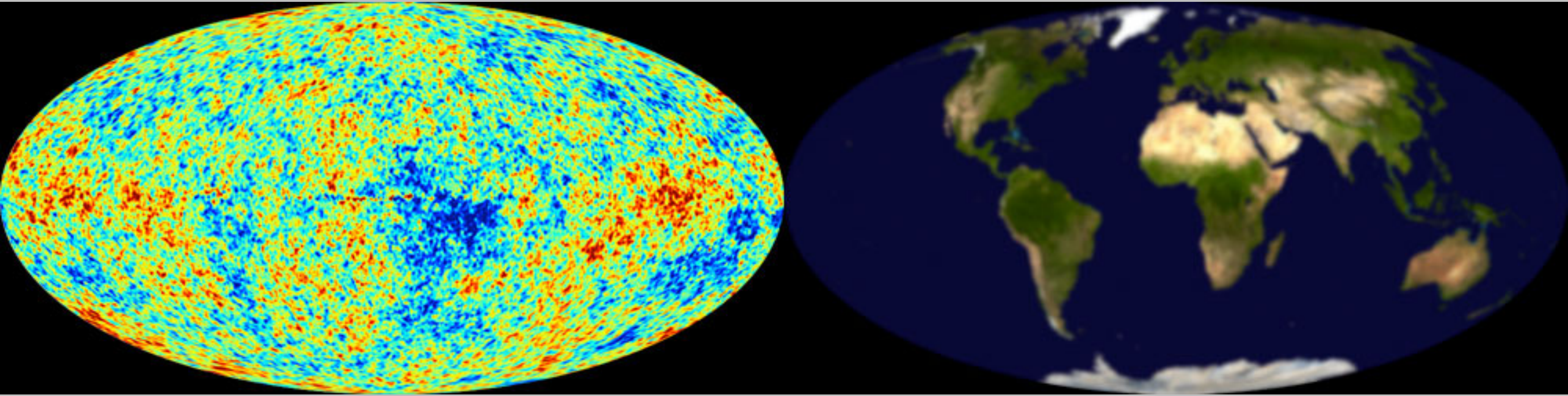


COBE all-sky CMB map (1992)



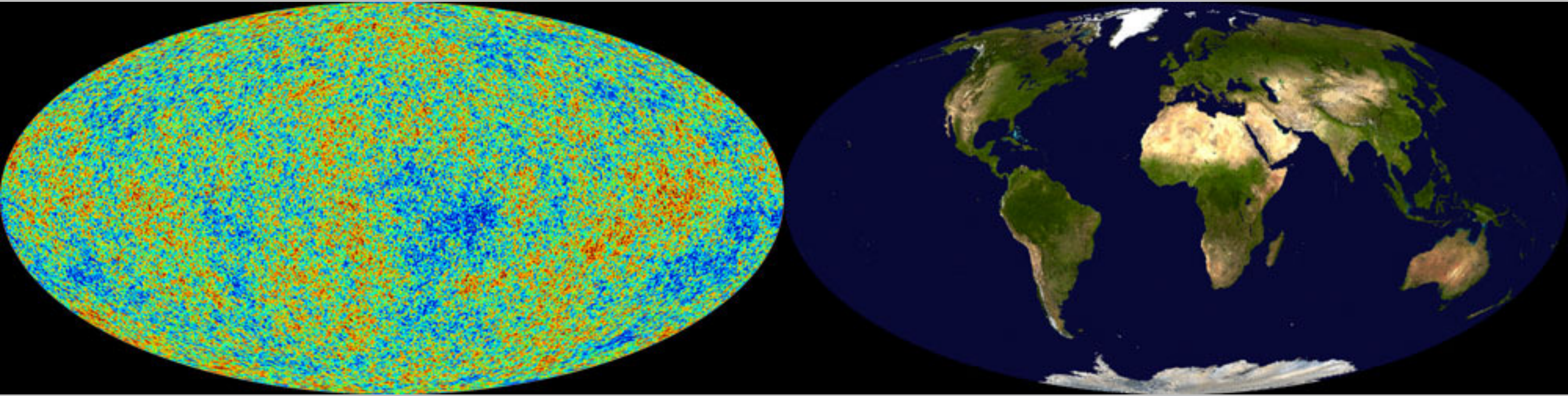
Graphics from New Scientist

WMAP all-sky CMB map (2003)



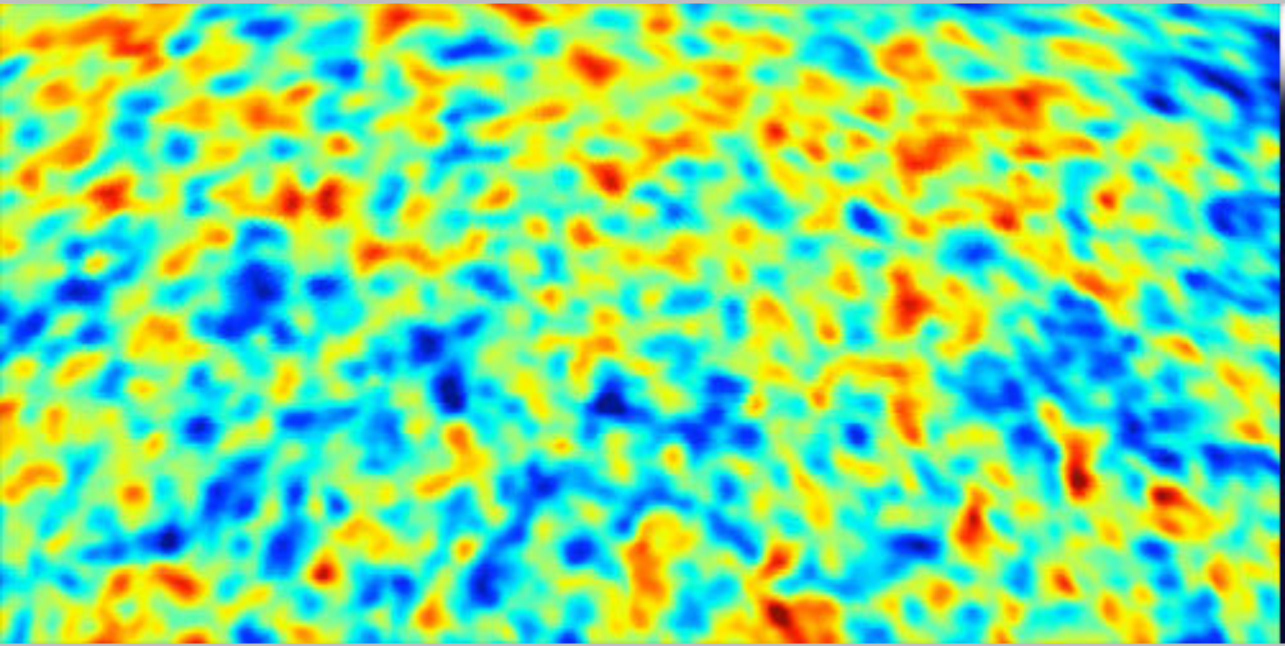
Graphics from New Scientist

Planck all-sky CMB map (2013)



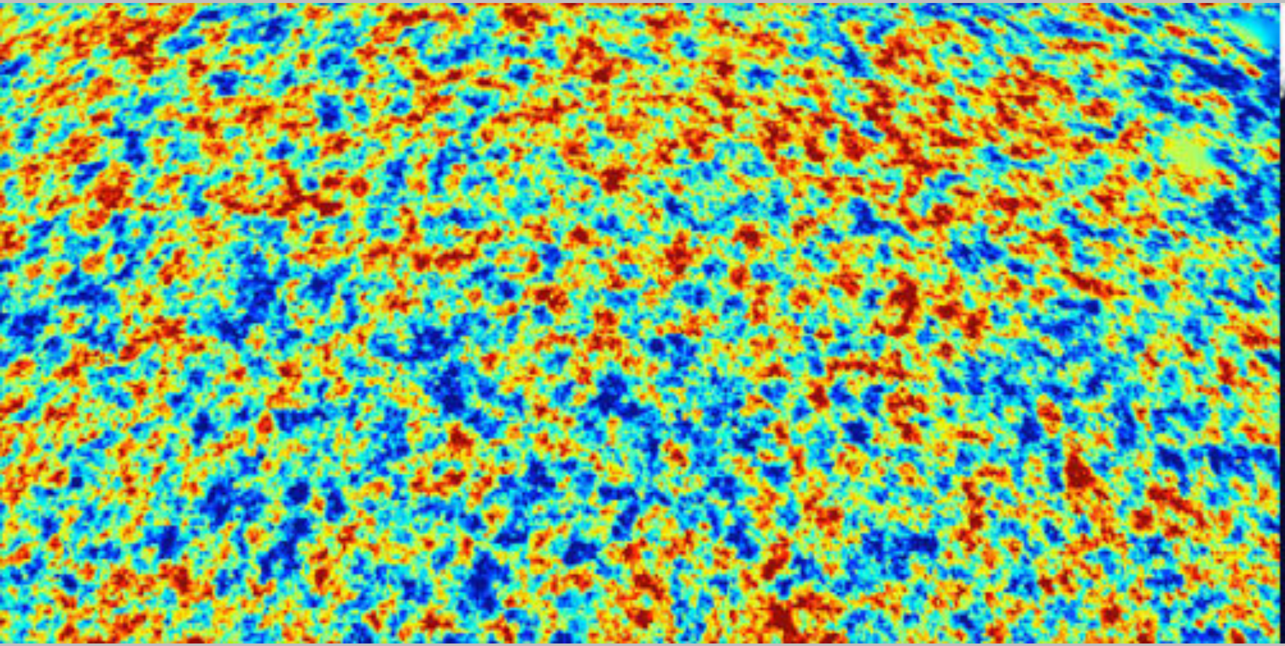
Graphics from New Scientist

WMAP zoomed in (2003)



Graphics from New Scientist

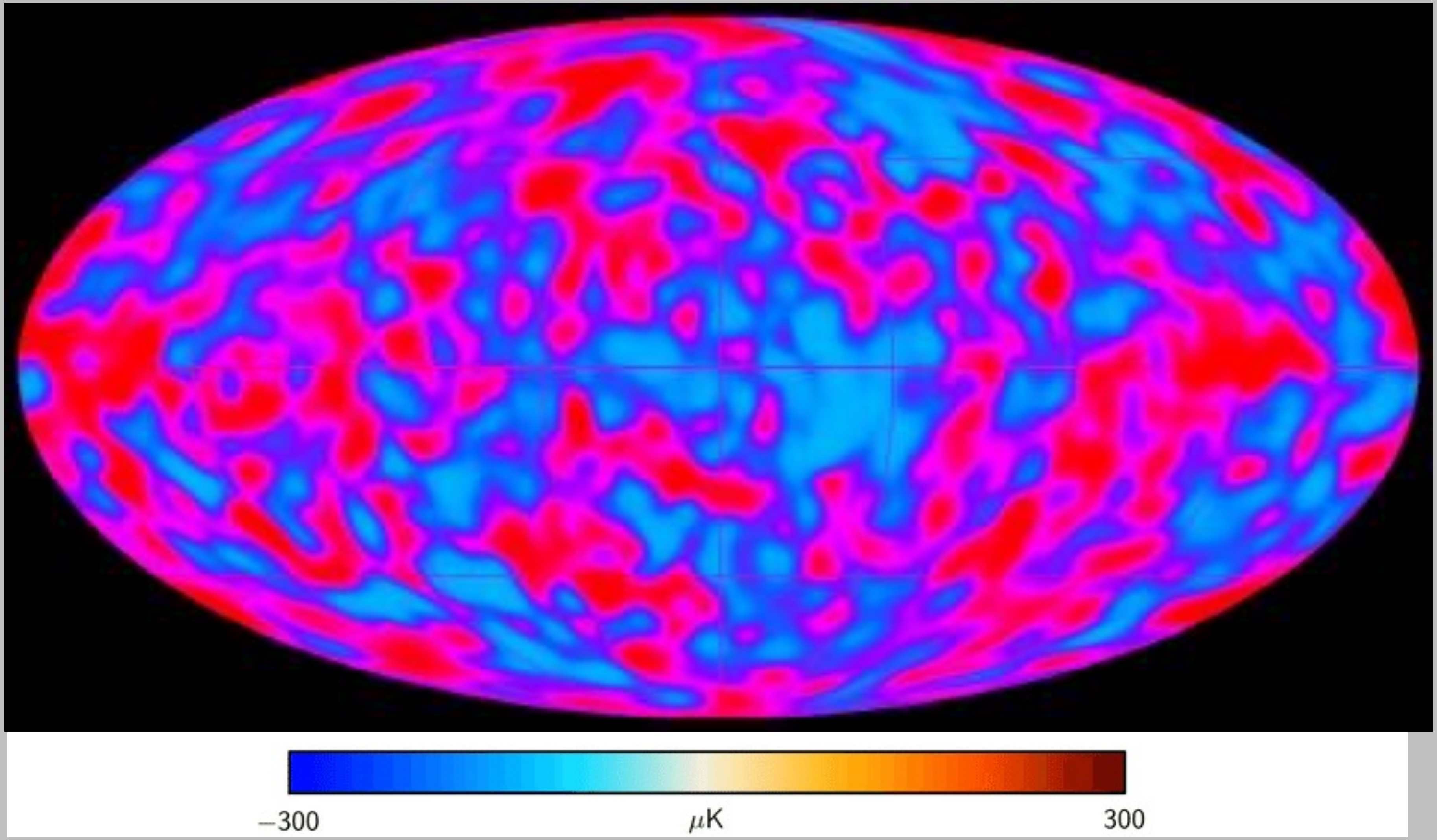
Planck zoomed in (2013)



Graphics from New Scientist

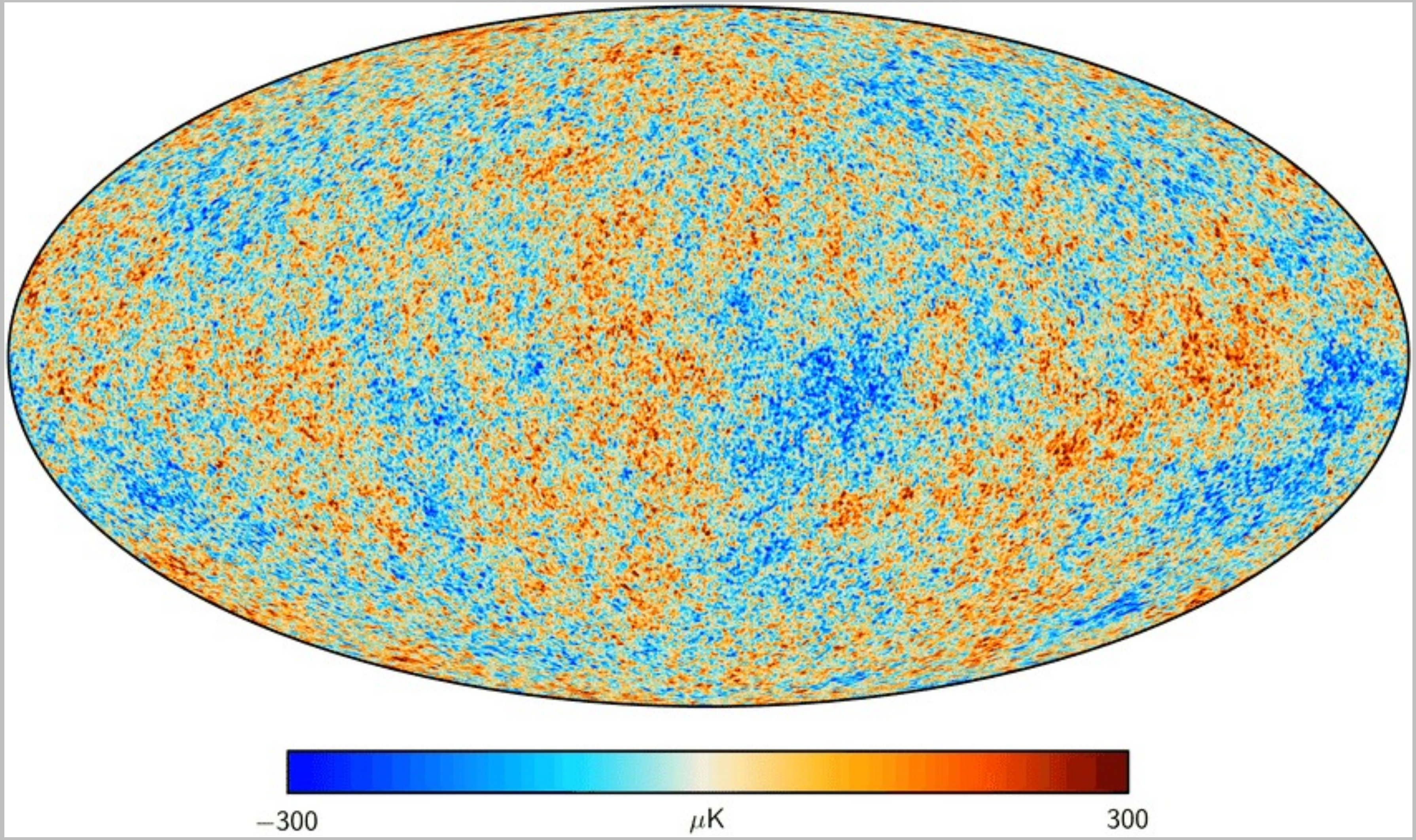
Satellite cosmic microwave background measurements: WMAP (mid 2000s) and Planck (mid 2010s)

COBE all-sky microwave map (1992)



Satellite cosmic microwave background measurements: WMAP (mid 2000s) and Planck (mid 2010s)

Planck all-sky microwave map (2018)



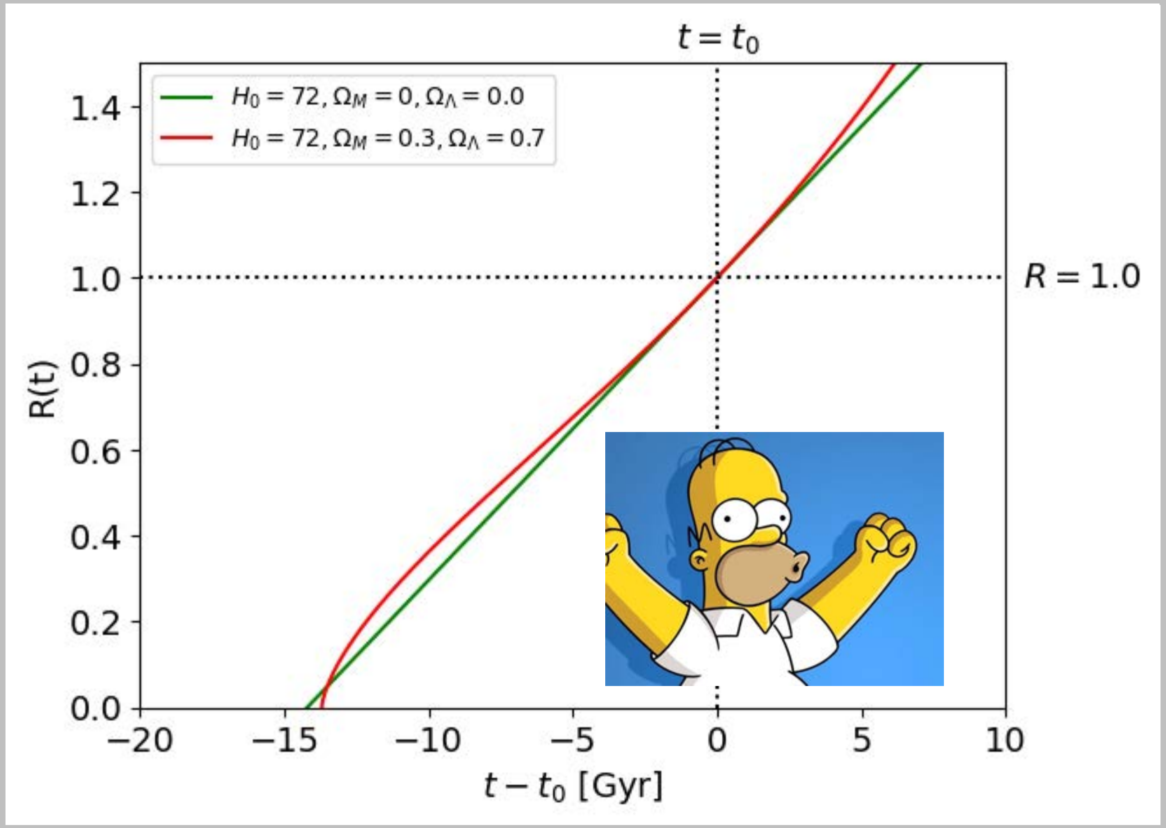
The structure of the CMB on smaller scales is sensitive to other cosmological parameters (H_0, Ω_m, Ω_Λ, Ω_{baryon}, ...).
(More on this in ASTR 328!)

The most recent estimates (Planck 2018) give:

Parameter	Value
H_0	67.7 km/s/Mpc
$\Omega_{m,0}$	0.31
$\Omega_{\Lambda,0}$	0.69
$\Omega_{baryon,0}$	0.049

The (Basic) Cosmological Parameters: Best estimates

$$H_0 \approx 72\, km/s\,/Mpc$$
$$\Omega_{m,0} \approx 0.3, \quad \Omega_{\Lambda,0} \approx 0.7 \quad \Big\} \; \Omega_0 = 1$$
$$\Big\} \; t_0 = 13.6 \text{ Gyr}$$



Remember, the parameters change with time as the Universe expandsΩ_m starts at 1 ("matter dominated"), but drops over as the Universe expands and the density drops.

Ω_Λ starts at 0 since matter dominates at early times, but rises over as the Universe expands and the density drops.

Total $\Omega = 1$ always: a spatially flat universe stays flat.