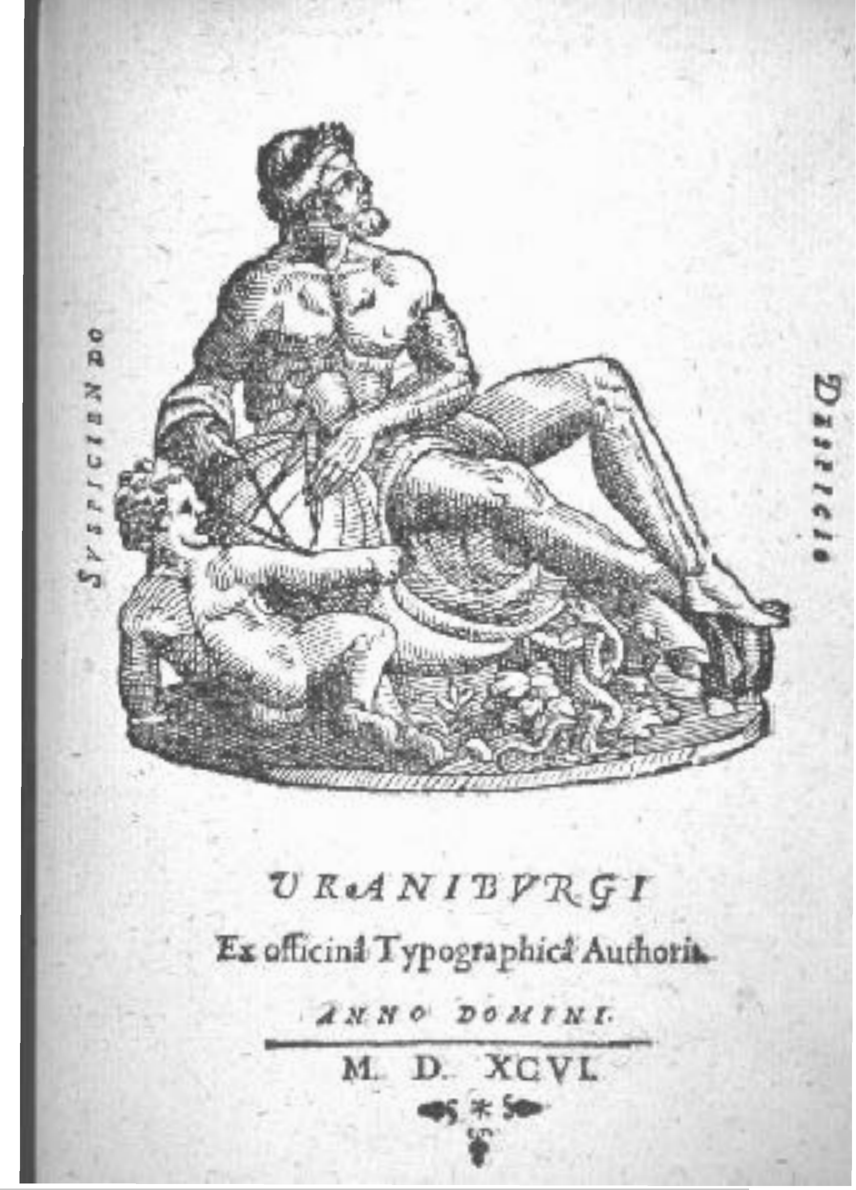
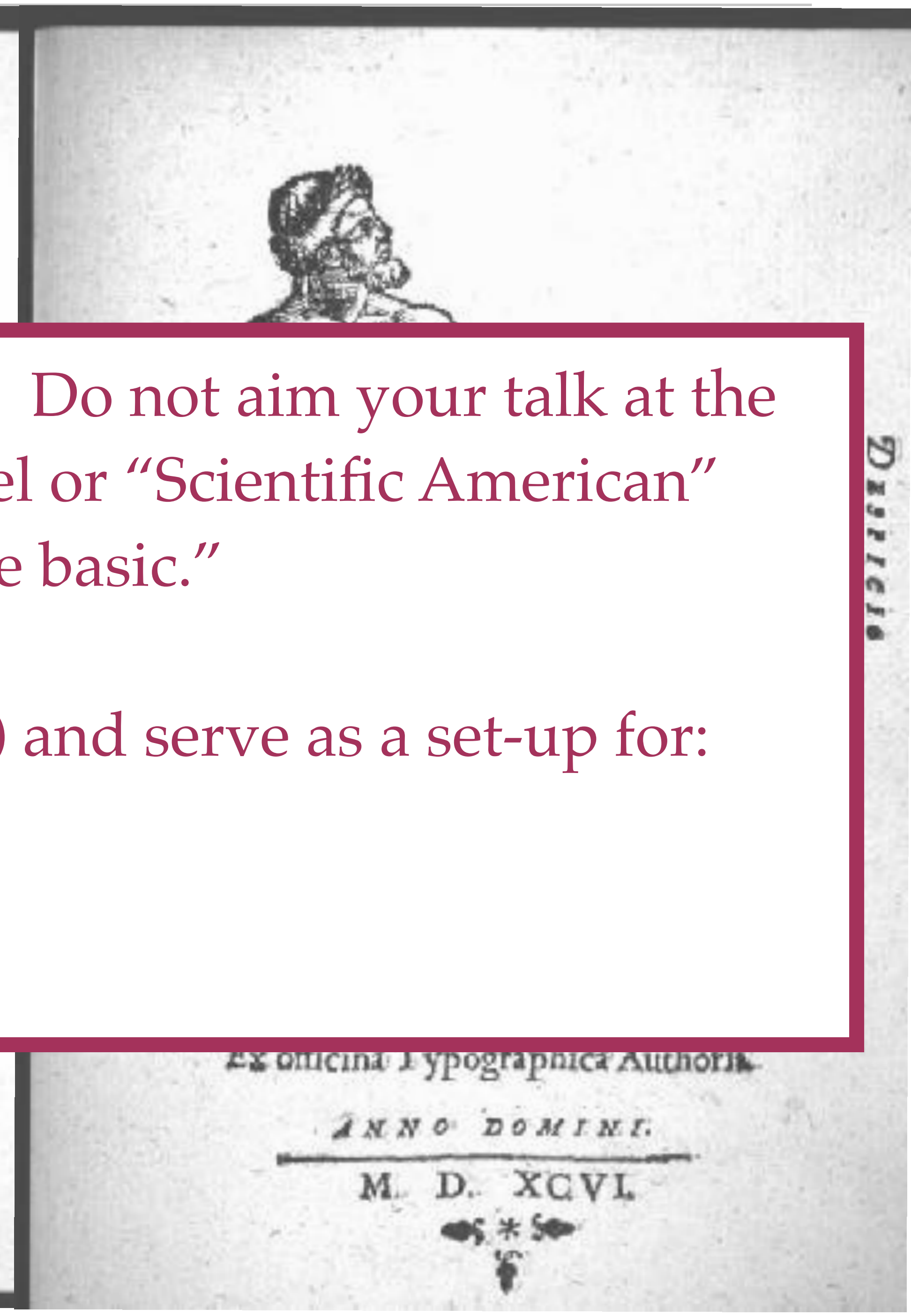


Cosmology: Theory Overview

Mark Trodden
University of Pennsylvania

ICFA Seminar, November 7, 2017

Tycho Brahe's personal emblems from the front and back of his *Astronomical Letters* (1596)



"…the audience will contain a broad range of people…. Do not aim your talk at the experts… Sometimes we speak about "colloquium" level or "Scientific American" level, but in fact, much of your talk should be even more basic."

I'll mostly try to follow this (starting very basic indeed!) and serve as a set-up for:

Ofer Lava (Dark Energy) and
Suzanne Staggs (CMB).

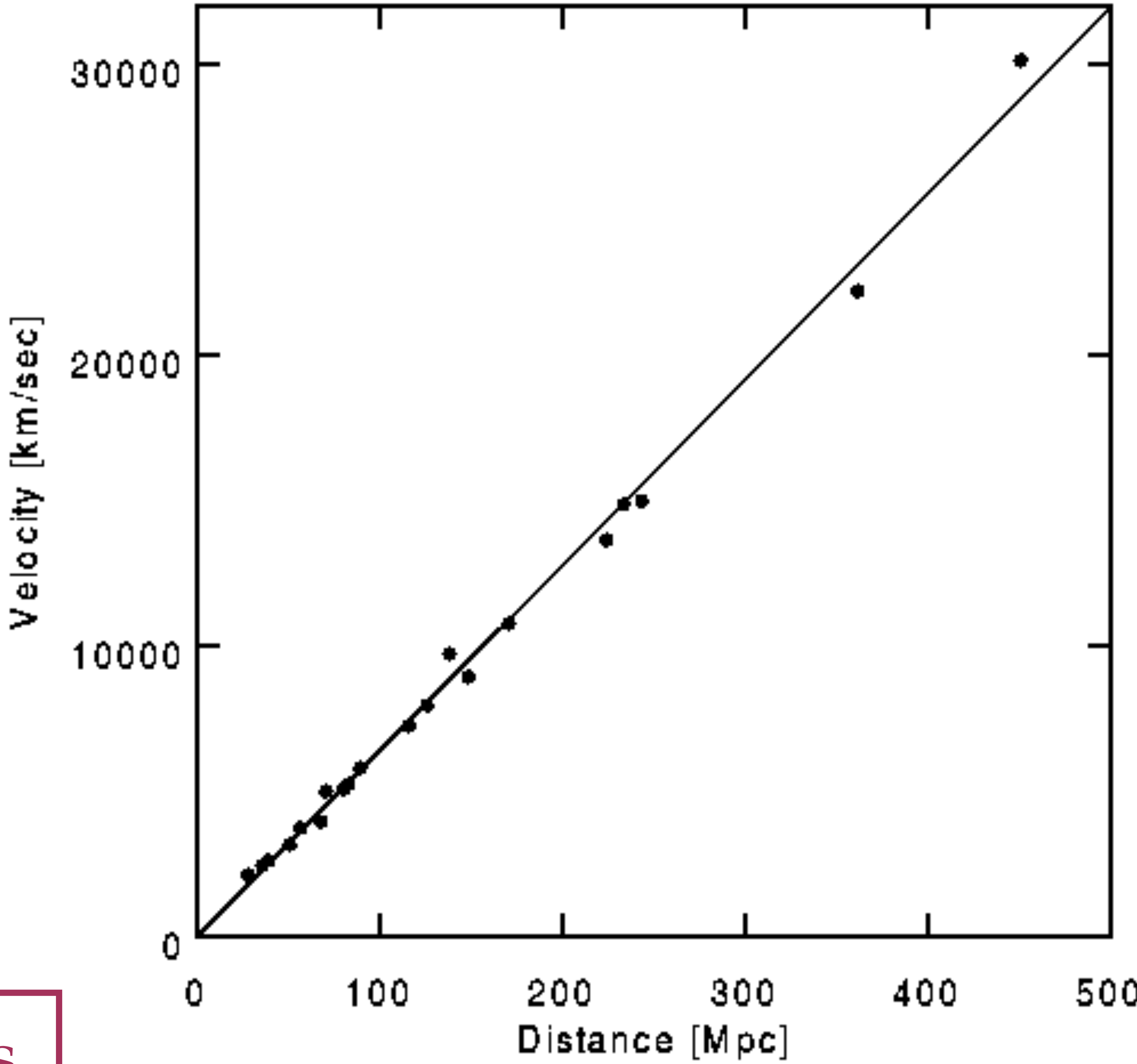
"Despiciendo, Suspicio"
("By looking down I see what is above")

"Suspiciendo, Despicio"
("By looking up I see what is below")

Using alchemy and astronomy to illuminate each other

[Courtesy of Peter Barker (University of Oklahoma)]

What Hubble Saw



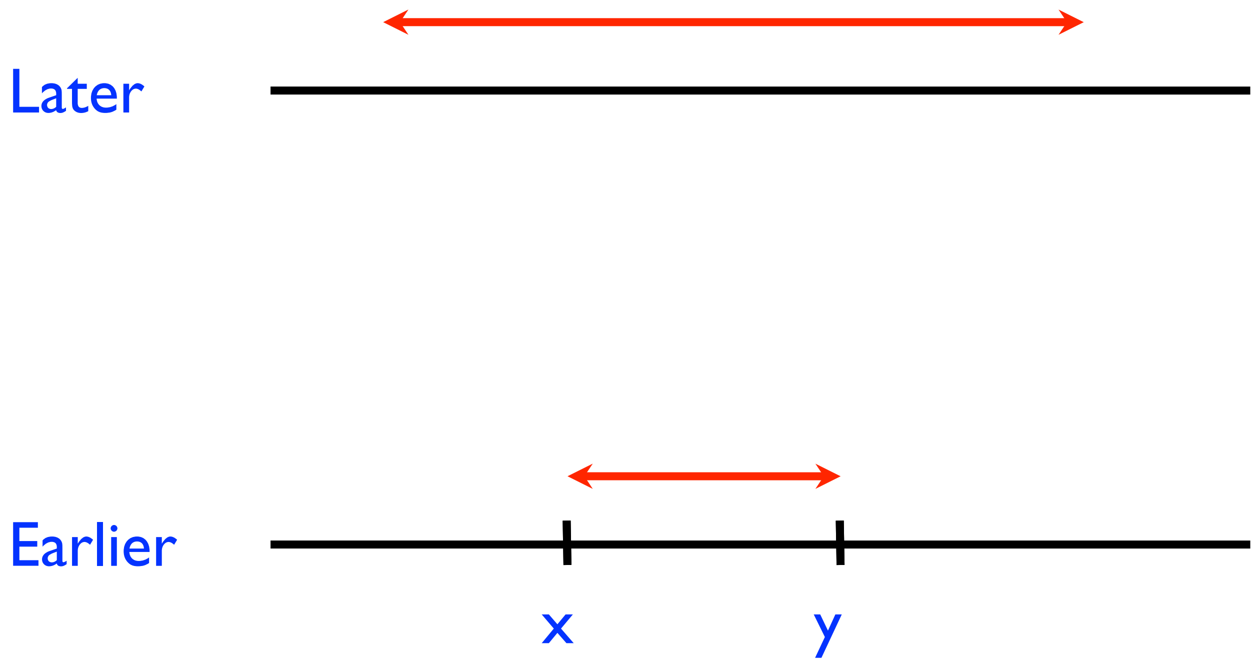
All distant galaxies recede - speeds proportional to distances

The universe is expanding!

Why is this Happening?

General Relativity: Gravity = Matter warping space and time.

Evolution of universe dependent on matter in it and vice versa.



Expansion rate depends on how much matter, radiation, weird stuff, ... there is in the universe! Fantastically successful theory and fact about the world!

But ... Poses its own Problems!

What is causing cosmic acceleration

What is the nature of dark matter?

You have already heard a great deal about this, and how it connects cosmology to fundamental physics

Origins:

- Why is the universe so flat?
- Why is the universe so almost-homogeneous?
- Why did galaxies form?

Our Main Story

Turn to the most important thing in the universe you live in right now.

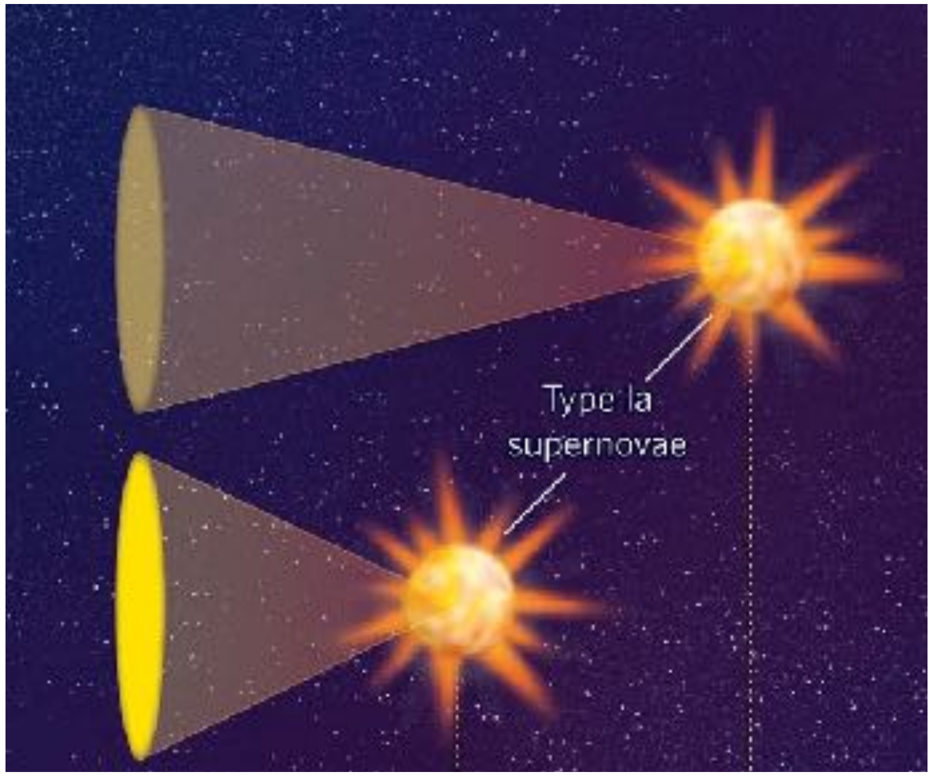
What is causing cosmic acceleration

What is the nature of dark matter?

Remember Hubble? Let's look even further away, and even earlier back in time.

Hubble on Steroids

Construct a Hubble diagram using objects with a known brightness. The dimmer they are, the further away



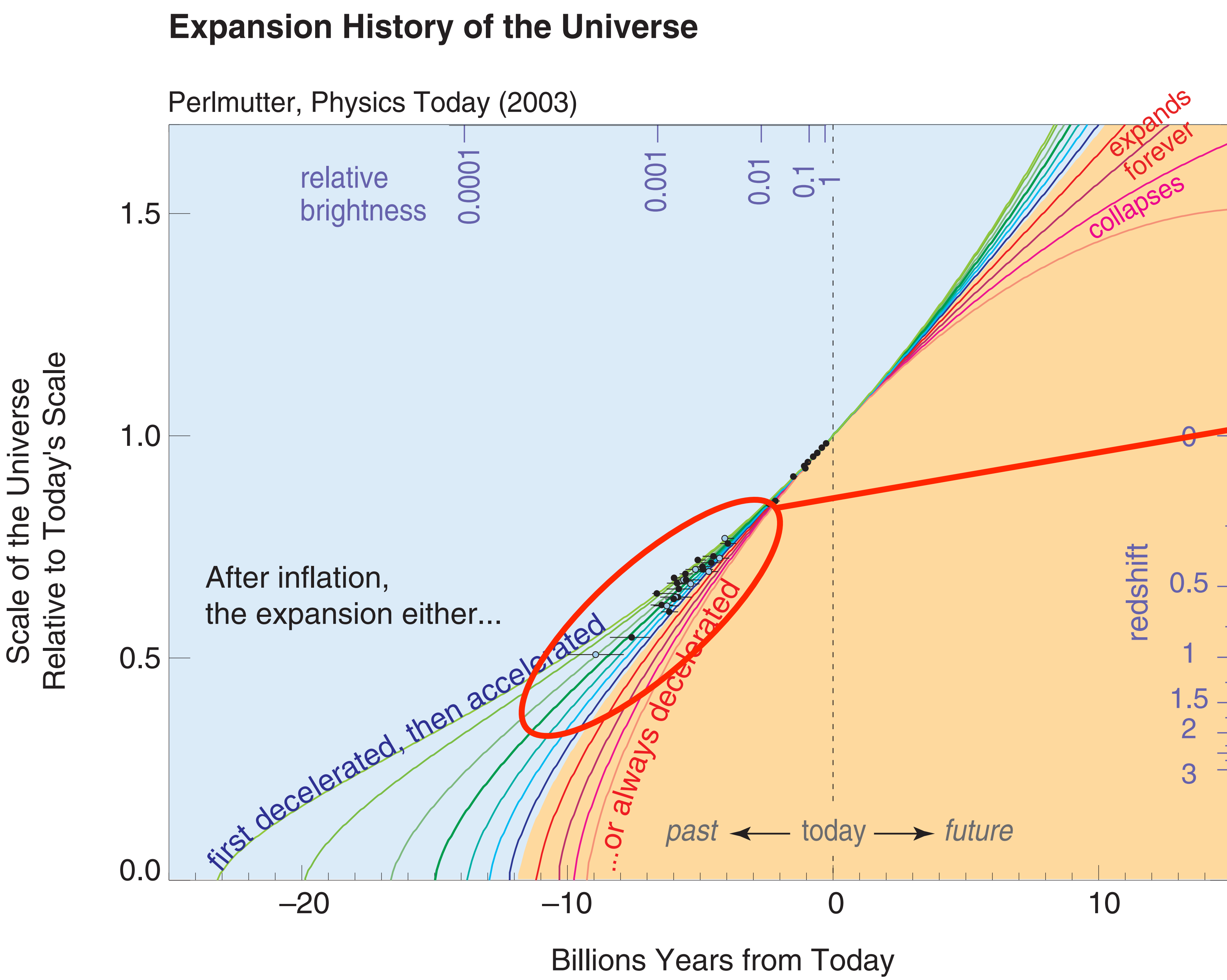
R. Caldwell & M. Kamionkowski, *Nature* **458**, 587-589 (2009)

Type Ia supernovae turn out to be just right for this job

Measuring their distances, and getting their velocities allows us to reconstruct the history of the size of the universe.

The Cosmic Expansion History

So what does astronomy tell us about cosmic history?

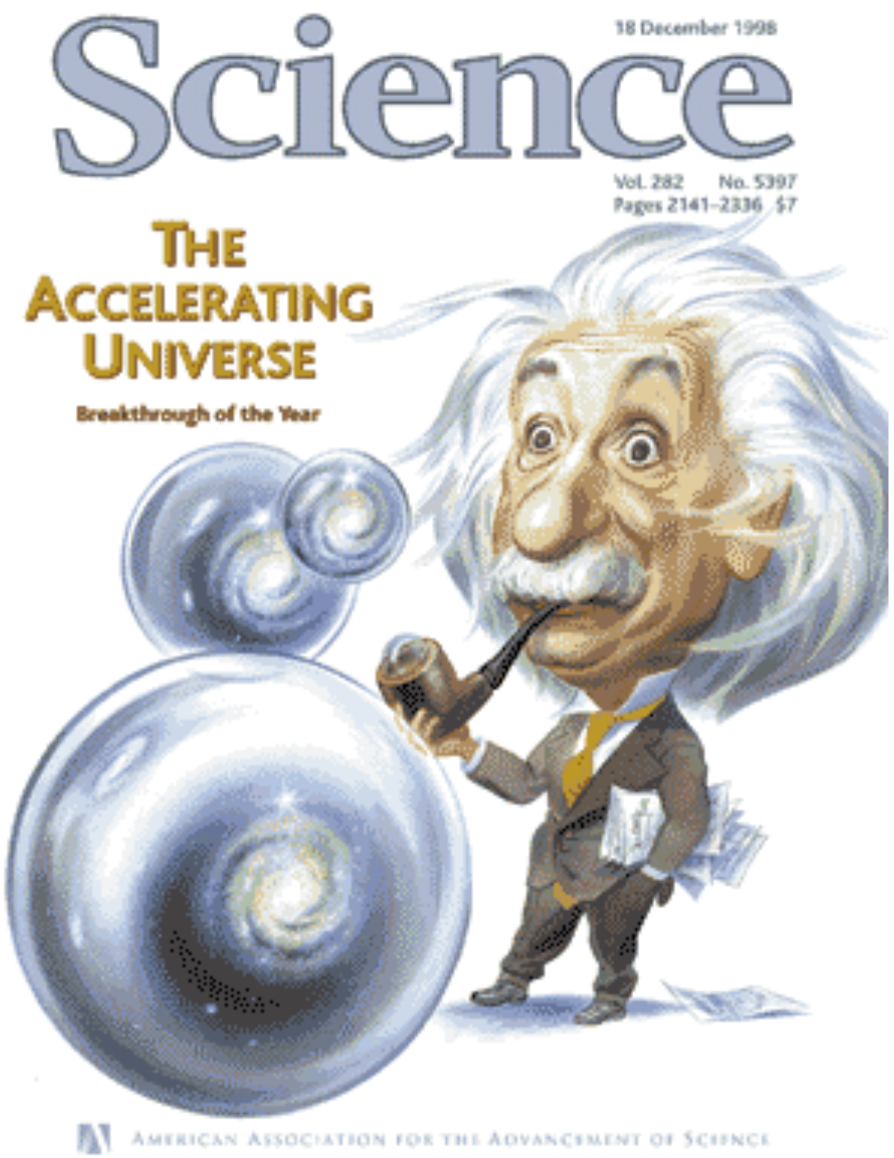


We now know, partly through this data, that the universe is not only expanding ...

... but is accelerating!!

If we trust Einstein's theory, then we infer that the universe must contain some new strange stuff, which we call **dark energy!**

Perhaps the Biggest Question in Modern Cosmology



Discovery, 1998

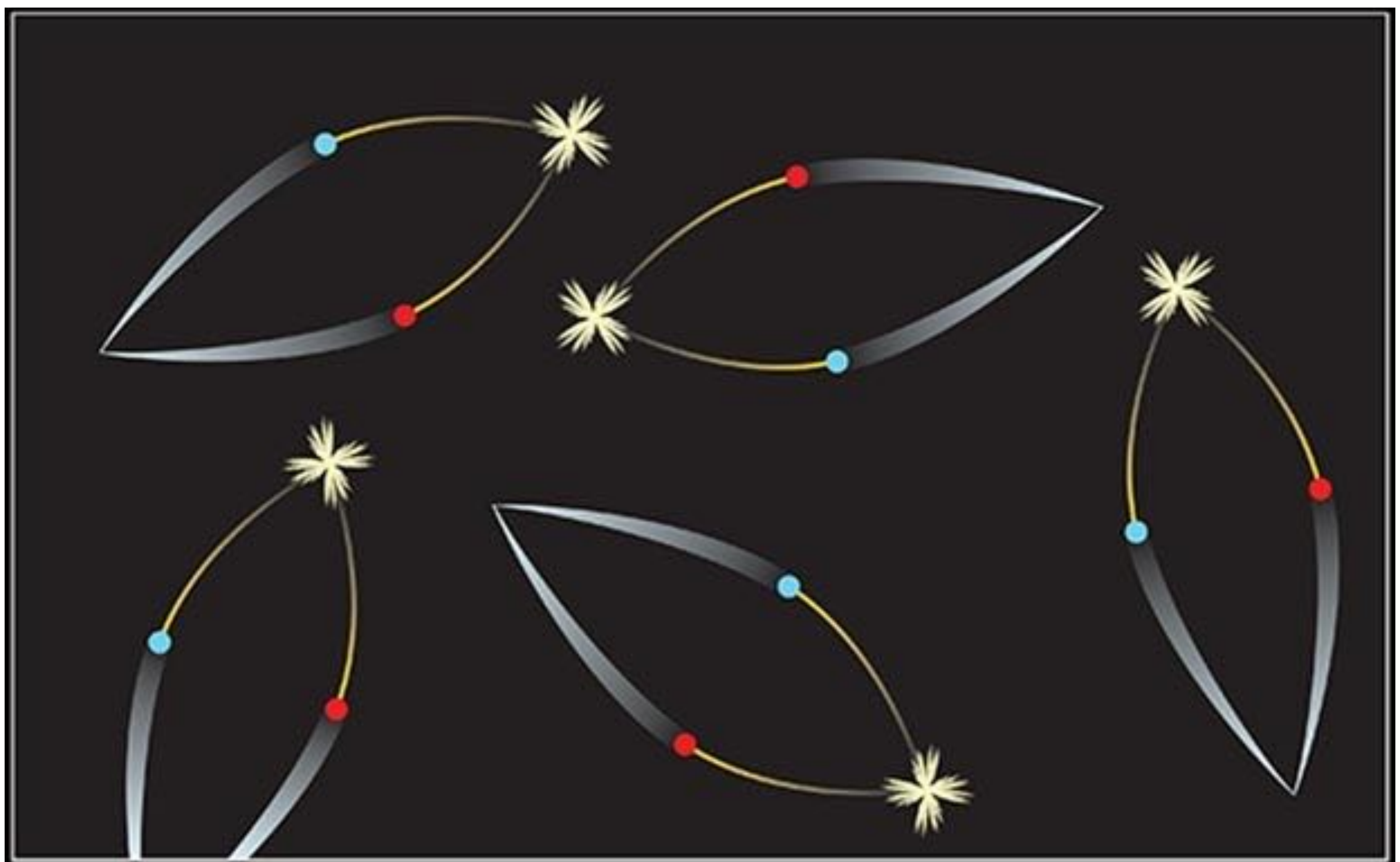
Nobel Prize 2011

What Does this Have to do with Tiny Physics?

Is this phenomenon in the same class as dark matter: observe something through gravity, and infer presence of a new type of energy bending space and time?

If so, we could be measuring the weight of nothingness!

Quantum mechanics: pretty much anything happens if you wait long enough:



Some things are complicated, large scale & take a long time

But on the small scale, for simple things, this happens all the time!!

On tiny scales the universe is a bubbly and energetic place to be!!

Einstein's Cosmological Constant Reborn

Remember Einstein? How do these quantum fluctuations affect the universe?

They have exactly the right properties to make the universe accelerate and hence could be the dark energy if they are of the right magnitude!

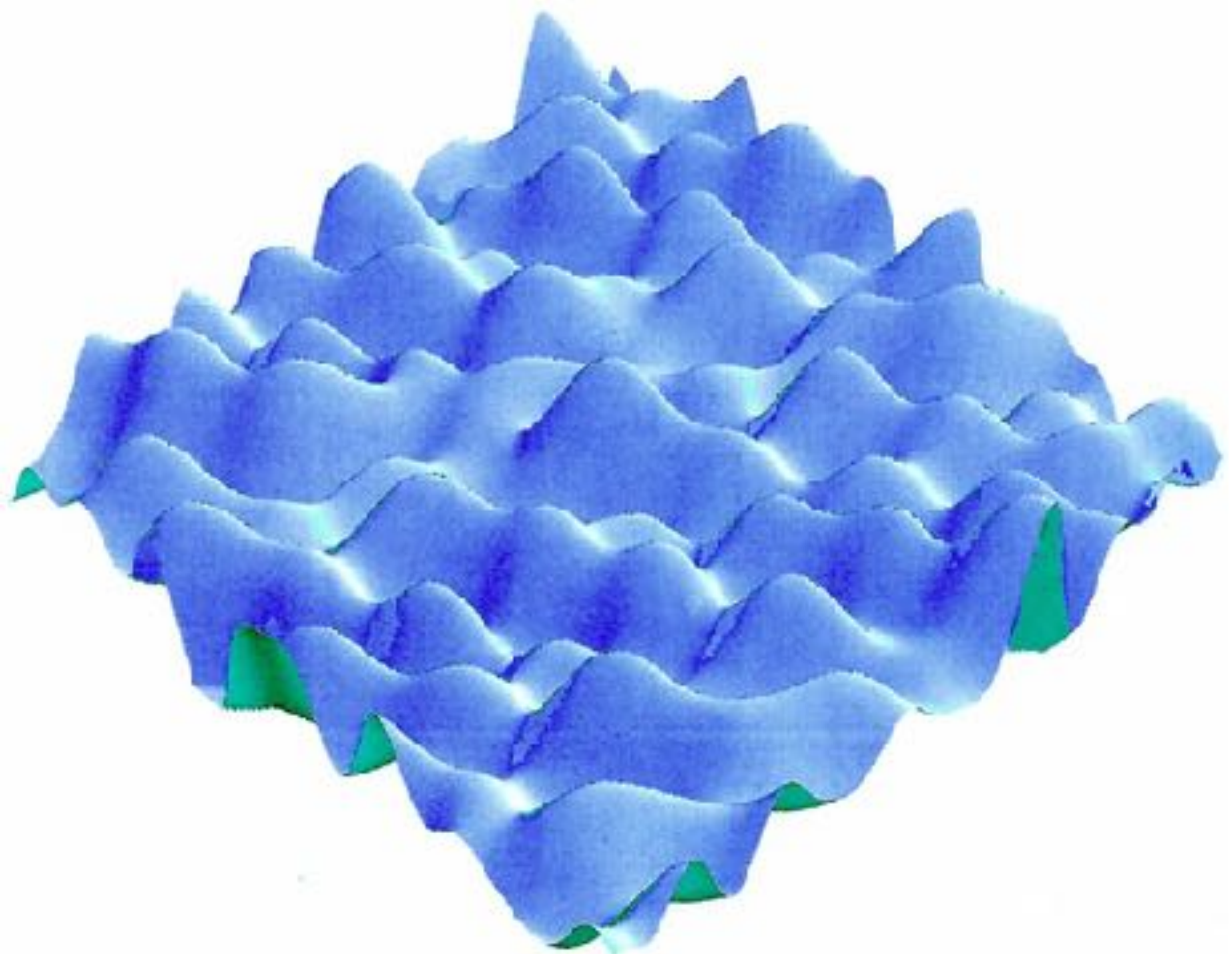
This describes a *cosmological constant*.

Given our current understanding of particle physics we expect size of these to be at least 10^{60} too large! (OK, we know, not something to brag about)

Must try harder!

Lambda, the Landscape & the Multiverse

Anthropics provide a logical possibility to explain this, but a necessary (not sufficient) requirement is a way to realize and populate many values. The string landscape, with eternal inflation, may provide a way to do this.



[Image: SLIM FILMS. Looking for Life in the Multiverse, A. Jenkins & G. Perez, Scientific American, December 2009]

An important step is understanding how to compute probabilities in such a spacetime

No currently accepted answer, but quite a bit of serious work going on. Too early to know if can make sense of this.

How to Think of This (or, at least, how I do)

A completely logical possibility - should be studied. Present interest relies on

- String theory (which may not be the correct theory)
- The string landscape (which might not be there)
- Eternal inflation in that landscape (which might not work)
- Perhaps a solution of the measure problem (which we do not have yet)

If dynamical understanding of CC is found, would be hard to accept this.

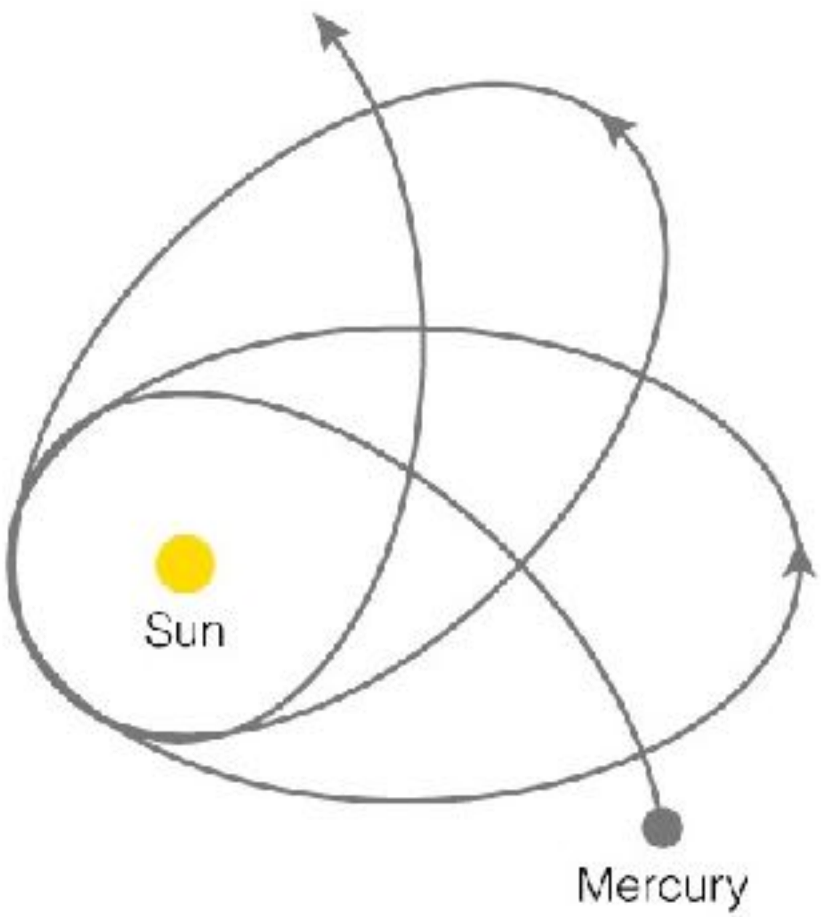
If DE is time or space dependent, would be hard to explain this way.

Worthwhile mapping out the space of alternative ideas. Even though there are no compelling models yet, there is already theoretical progress and surprises.

Furthermore - the CC problem alone is an important motivating factor in quite a lot of theoretical work on these issues.

Another Possibility

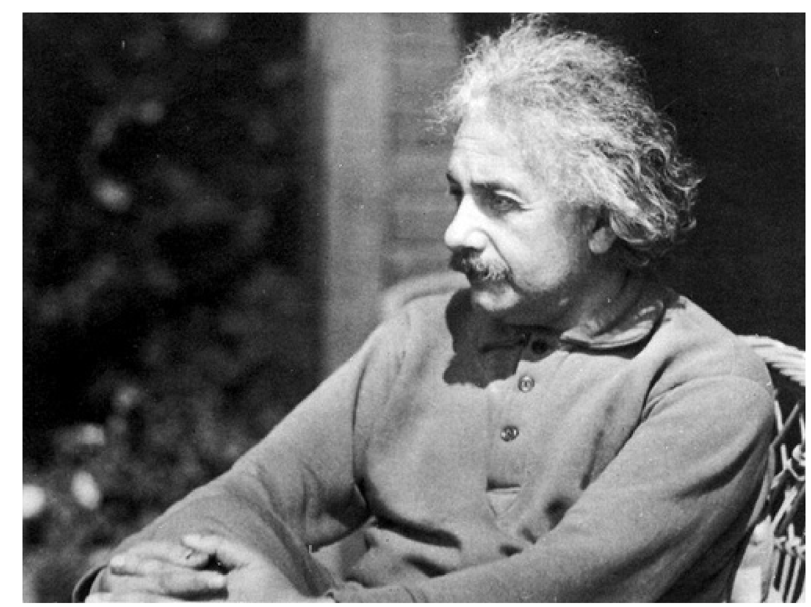
A related tale played out over 50 years over a century ago



Annales de l'Observatoire Impérial de Paris. Publiées par U. J. Leverrier, Directeur de l'Observatoire, tom. v. 4to, Paris, 1859.

This volume contains the theory and tables of *Mercury* by M. Leverrier; the discrepancy as regards the secular motion of the perihelion which is found to exist between theory and observation, led, as is well known, to the suggestion by M. Leverrier of the existence of a planet or group of small planets interior to *Mercury*. The volume contains also a memoir by M. Foucault, on the "Construction of Telescopes with Silvered

"[General Relativity] explains ... quantitatively ... the secular rotation of the orbit of Mercury, discovered by Le Verrier, ... without the need of any special hypothesis.", **SPAW, Nov 18, 1915**



This leads to a big open question:

Could a similar story be unfolding today, with cosmic acceleration the canary in the mine, warning of the breakdown of gravity?

A common Language - EFT

How do theorists think about all this? In fact, whether dark energy or modified gravity, ultimately, around a background, it consists of a set of interacting fields in a Lagrangian. The Lagrangian contains 3 types of terms:

- Kinetic Terms: e.g.

$$\partial_\mu\phi\partial^\mu\phi \qquad F_{\mu\nu}F^{\mu\nu} \qquad i\bar{\psi}\gamma^\mu\partial_\mu\psi \qquad h_{\mu\nu}\mathcal{E}^{\mu\nu;\alpha\beta}h_{\alpha\beta} \qquad K(\partial_\mu\phi\partial^\mu\phi)$$

- Self Interac

$V(\phi)$ … ν ν

- Interactio

$\Phi\bar{\psi}\psi$ A … $\dfrac{1}{M_p}\pi T^\mu_\mu$

Possibly useful reference for the details of all this:

Beyond the Cosmological Standard Model
B. Jain, A. Joyce, J. Khoury and MT
Phys.Rept. **568** 1-98 (2015), *[arXiv:1407.0059]*

Depending on the background, such terms might have functions in front of them that depend on time and/or space.

Most of the state-of-the-art work (which you don't want to see here), and many of the general concerns of theorists can be expressed in this language.

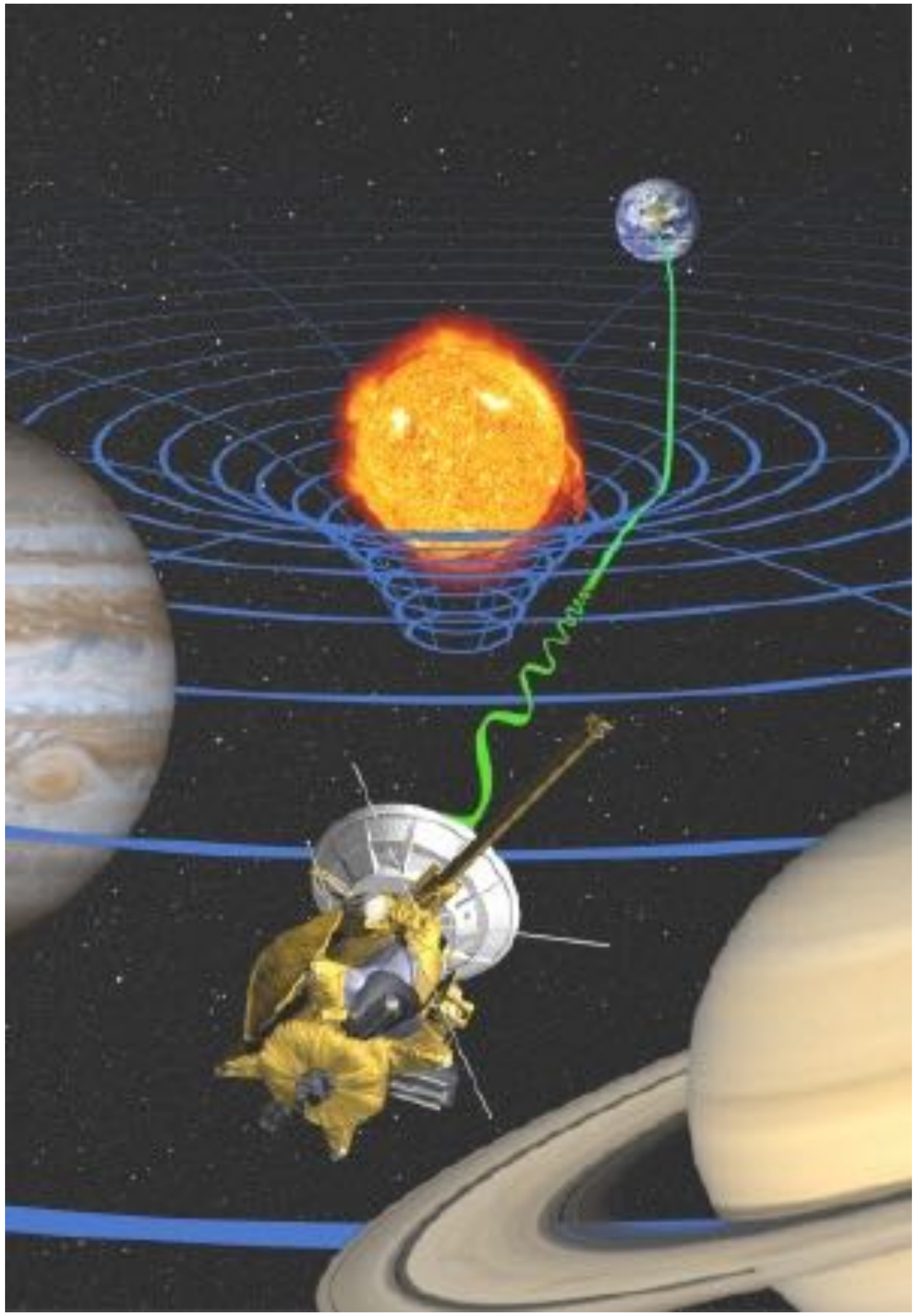
General Comment - Screening

- New forces (scalar, e.g.) of gravitational strength, are extremely tightly constrained by Solar System (and other) tests of gravity.

- Successful models exhibit "screening mechanisms". Dynamics of new degrees of freedom rendered irrelevant in UV, and only become free at large distances (or in regions of low density, more precisely).

- EFT of excitations around a nontrivial background is not the naive one.

- Protects against local tests of gravity. But makes calculations and observational constraints very tricky to extract.



Many Theories Have Very Effective Screening

Massive gravity, e.g., uses something called the "Vainshtein Effect".
Makes theory almost exactly like GR to large distance around sources

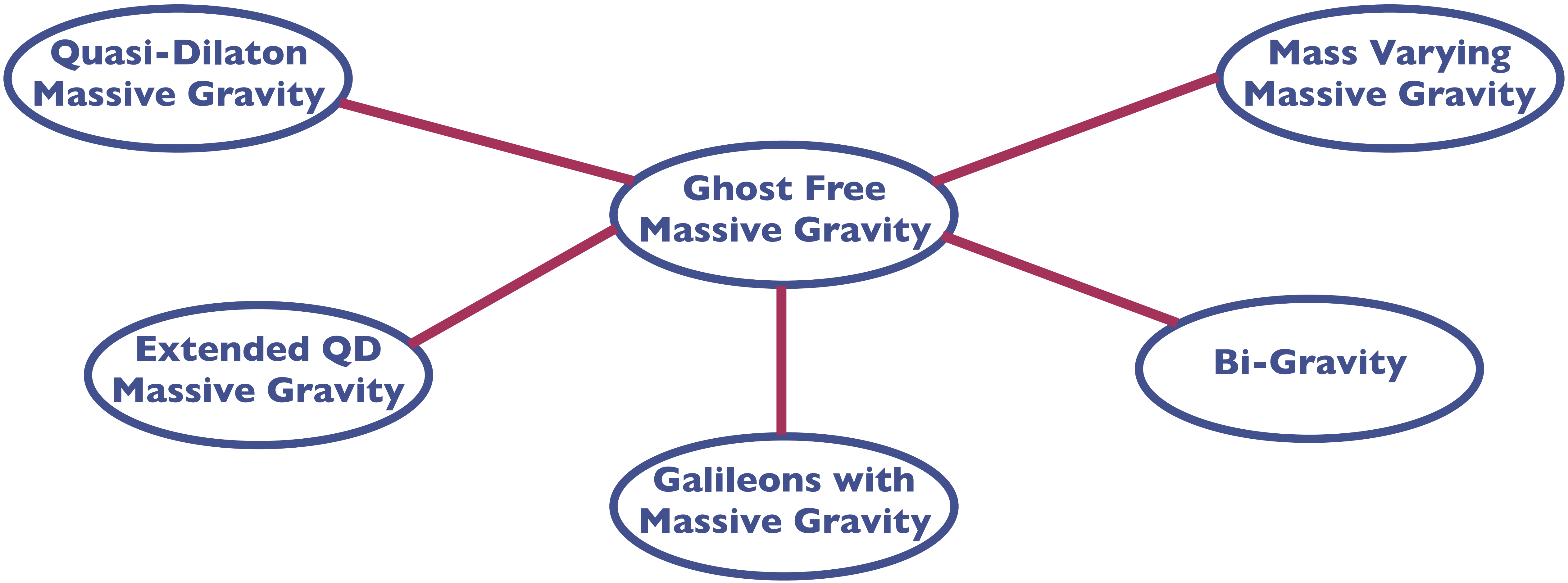
→ ~0.1 kpc = 10^7 AU

→ ~Mpc ~ 30 galactic radii

→ ~10 Mpc ~ 10 virial radii

What are People doing, and Can we Test it?

- Many attempts to implement this idea - but Einstein is stubborn!
- Has yielded a number of fresh insights into fundamental theory.
- Just e.g., none of these strangely-named ideas existed before recent breakthroughs.



- A theoretically fertile but difficult area - lots of ongoing work. No definitive model yet in which all calculations are under control. Ripe for theoretical/observational progress in the coming years.

Can look for signals in, e.g., cosmology

- Weak gravitational lensing
- CMB lensing and the ISW effect
- Redshift space galaxy power spectra
- Combining lensing and dynamical cross-correlations
- The halos of galaxies and galaxy clusters

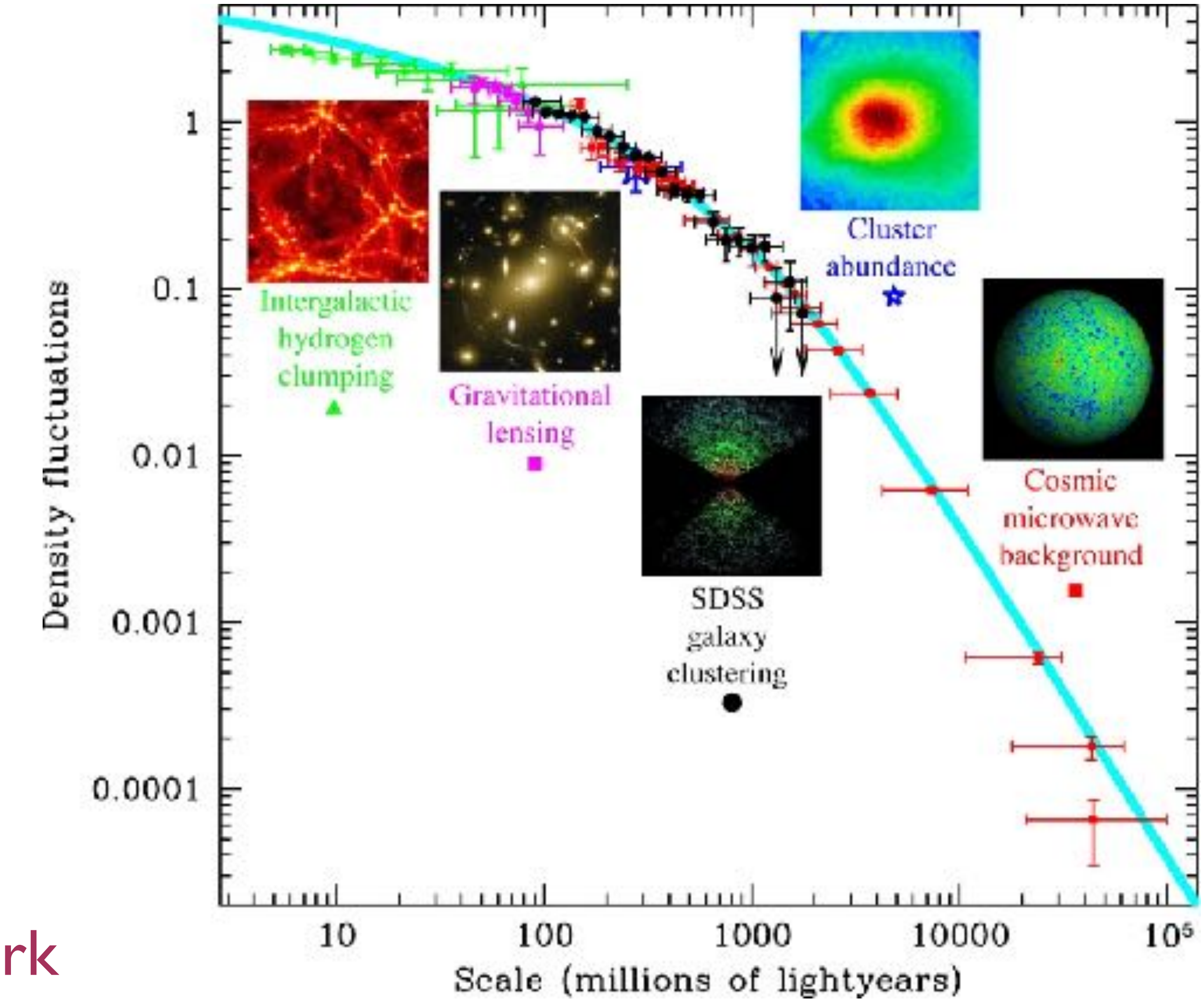
- Very broadly: Gravity is behind the expansion history of the universe

- But it is also behind how matter clumps up - potentially different.

- This could help distinguish a CC from dark energy from other possibilities

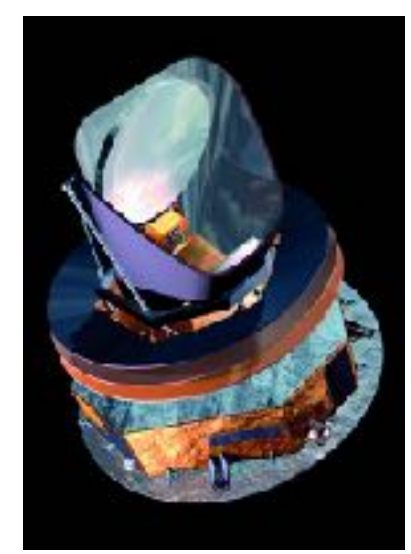
- Much work remains here!

See Ofer Lahav's talk



DARK ENERGY SURVEY

Large Synoptic Survey Telescope



Analogy with Particle Physics

Particle Physics

New physics discovery relies on:

- increasing energy of collisions,
  - Allows access to new events that don't appear at lower E.
- increasing accelerator luminosity
  - e.g. produce more Higgs, and measure decay modes more accurately.
  - Can allow very rare decays to be discovered at statistically significant level.

Survey Cosmology

New physics discovery relies on:

- increasing redshift of detection,
  - Allows access to new events and objects absent at lower z.
- increasing number of objects
  - detecting more objects, allows more precise measurements of inhomogeneities.
  - Can allow different signatures in shape of power spectrum to be discovered at statistically significant level.

All allow access to **a lot of** new physics! (See Ofer's talk)

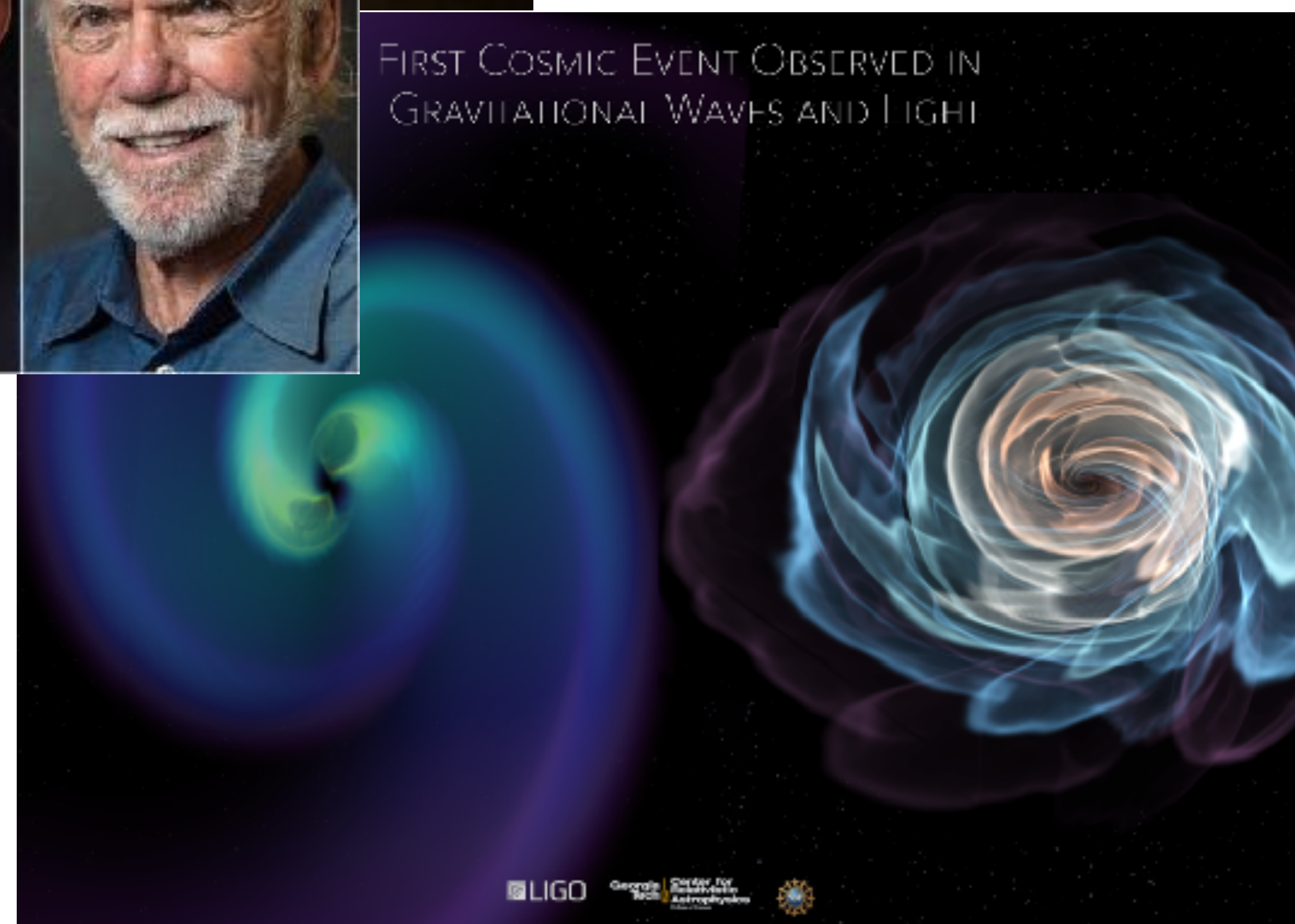
One of primary points from Cosmic Visions White Paper:
(S. Dodelson, K. Heitmann, C. Hirata, K. Honscheid, A. Roodman, U. Seljak, A. Slosar and M.T., "Cosmic Visions Dark Energy: Science,"arXiv:1604.07626 [astro-ph.CO].)

Now we also have New Tools!

LIGO/VIRGO +DES, etc. are already bounding many of these ideas!

Theory space is suddenly getting narrower. How much?

We need smart theorists, and support for them if we are to understand what these remarkable new tools can teach us about fundamental physics, such as cosmic acceleration.



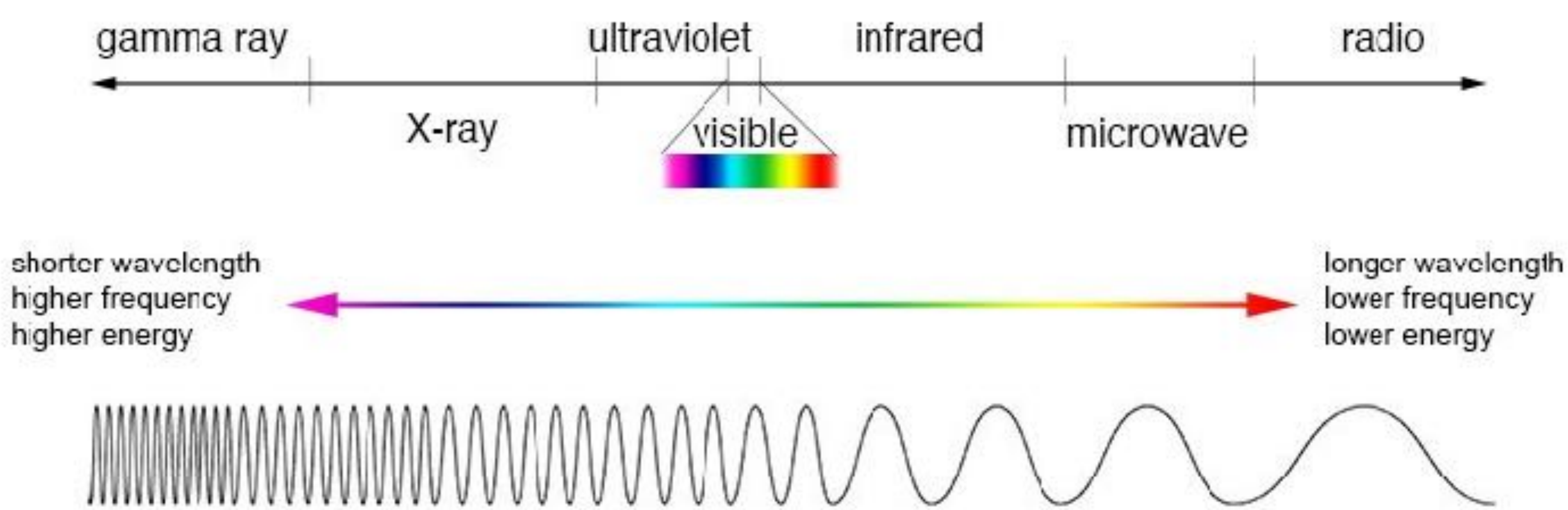
Back to the Beginning

- Dark matter played it's biggest role in the universe when galaxies were forming.
- And Cosmic Acceleration is an even later phenomenon.
- But what do we know about the earliest times, and what determined how galaxies formed?
- Let's go back even earlier - smaller distances, higher temperatures, higher energies! What might we learn there.

Colors and Temperatures

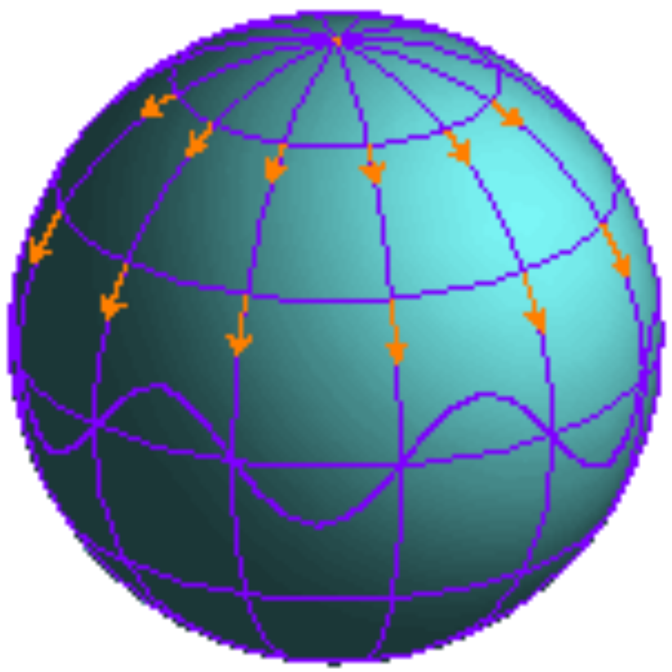
[image: www.freeimages.co.uk]

- Hot things glow!
- And even better, the colors they give off tell you their temperature!



- The early universe should be no exception.
- What does this imply?

Effects of Expansion on Light



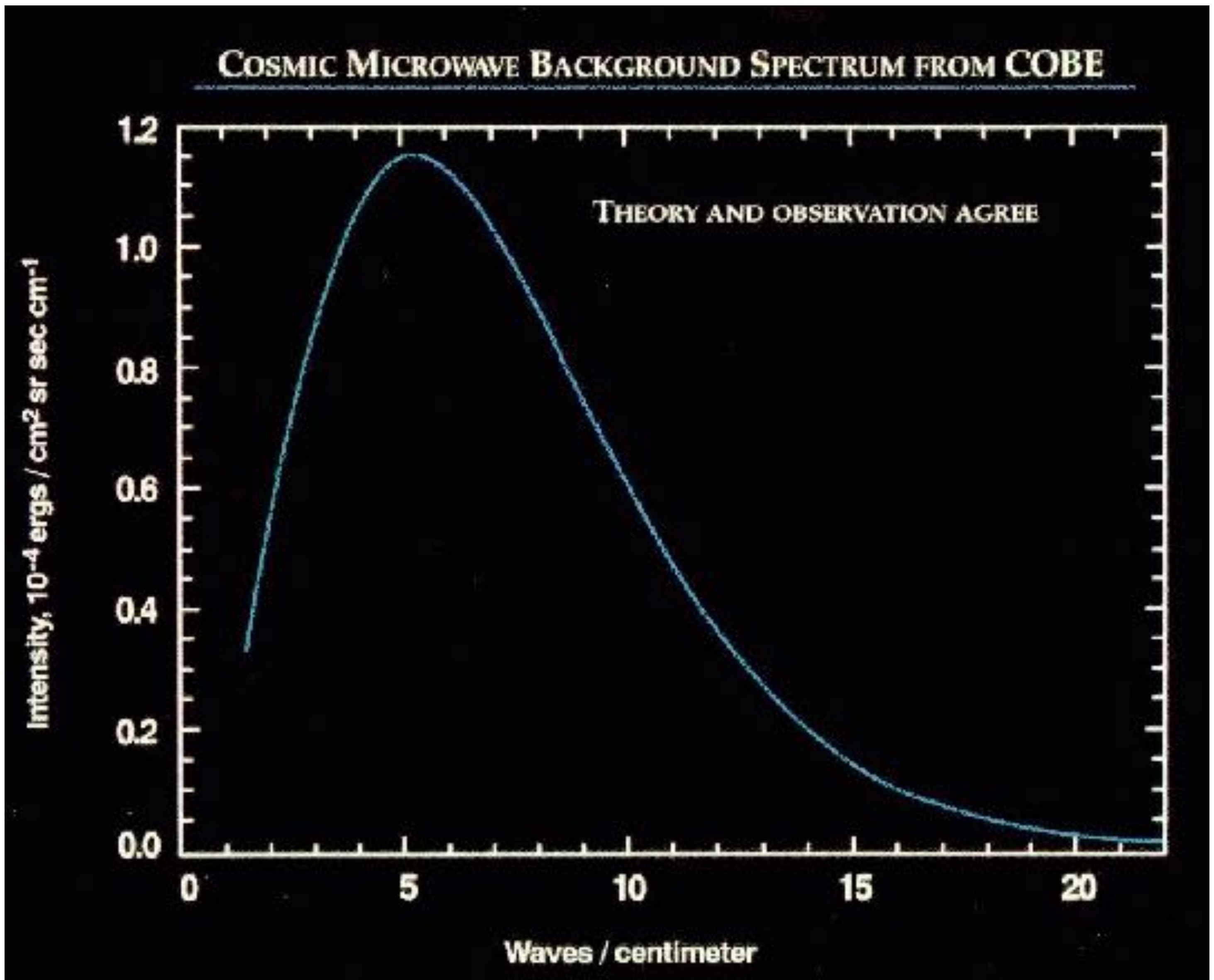
The effective temperature of the radiation decreases

If Big Bang Theory correct we should see this radiation with blackbody spectrum at temperature ~ 3 K !!

Cosmic Background Found!

Bell Labs 1964

Penzias & Wilson discover "noise" in radio equipment

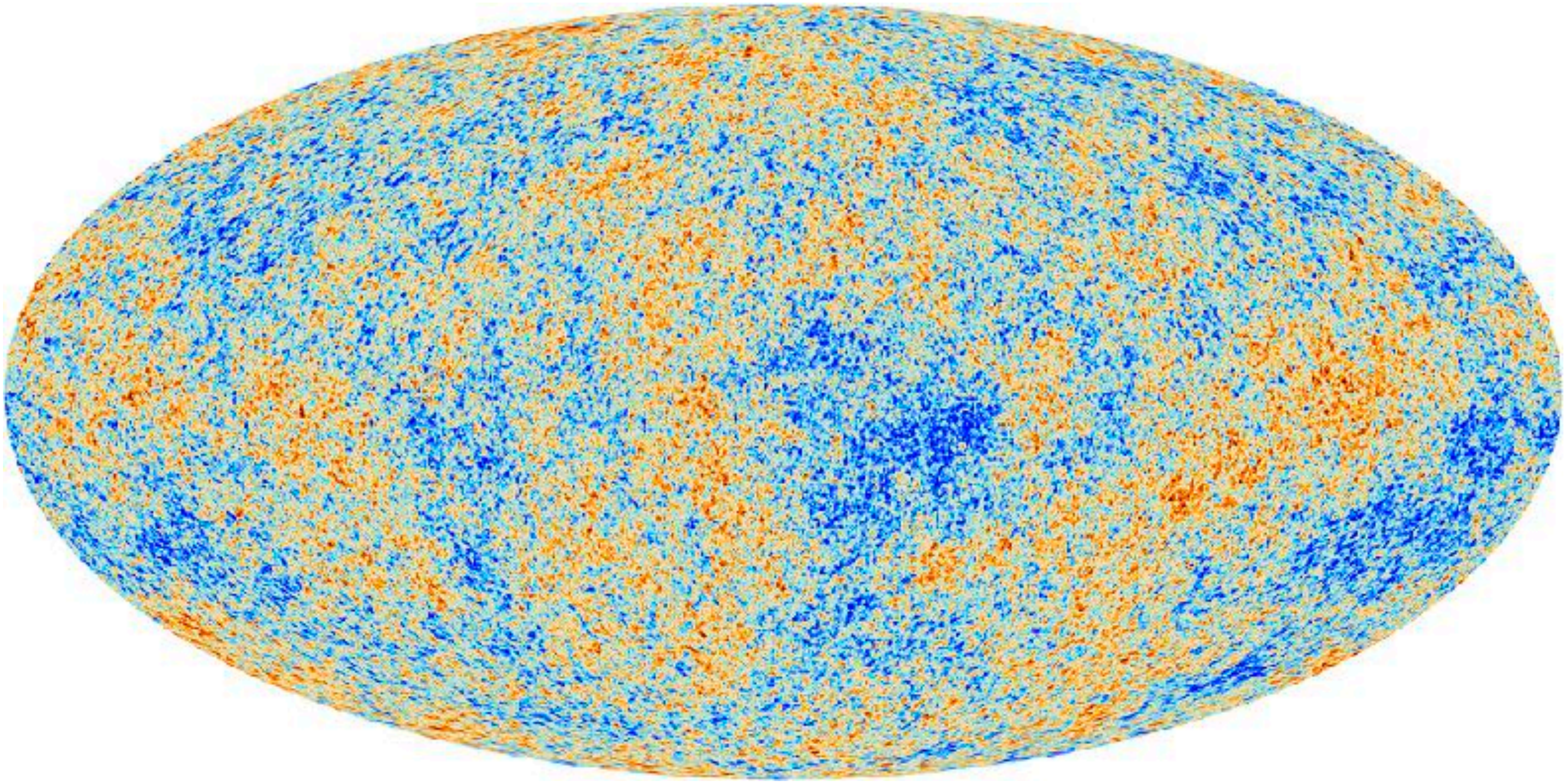


Noise is microwave radiation at temperature 3 K !!!!

The
Cosmic
Microwave
Background (CMB)

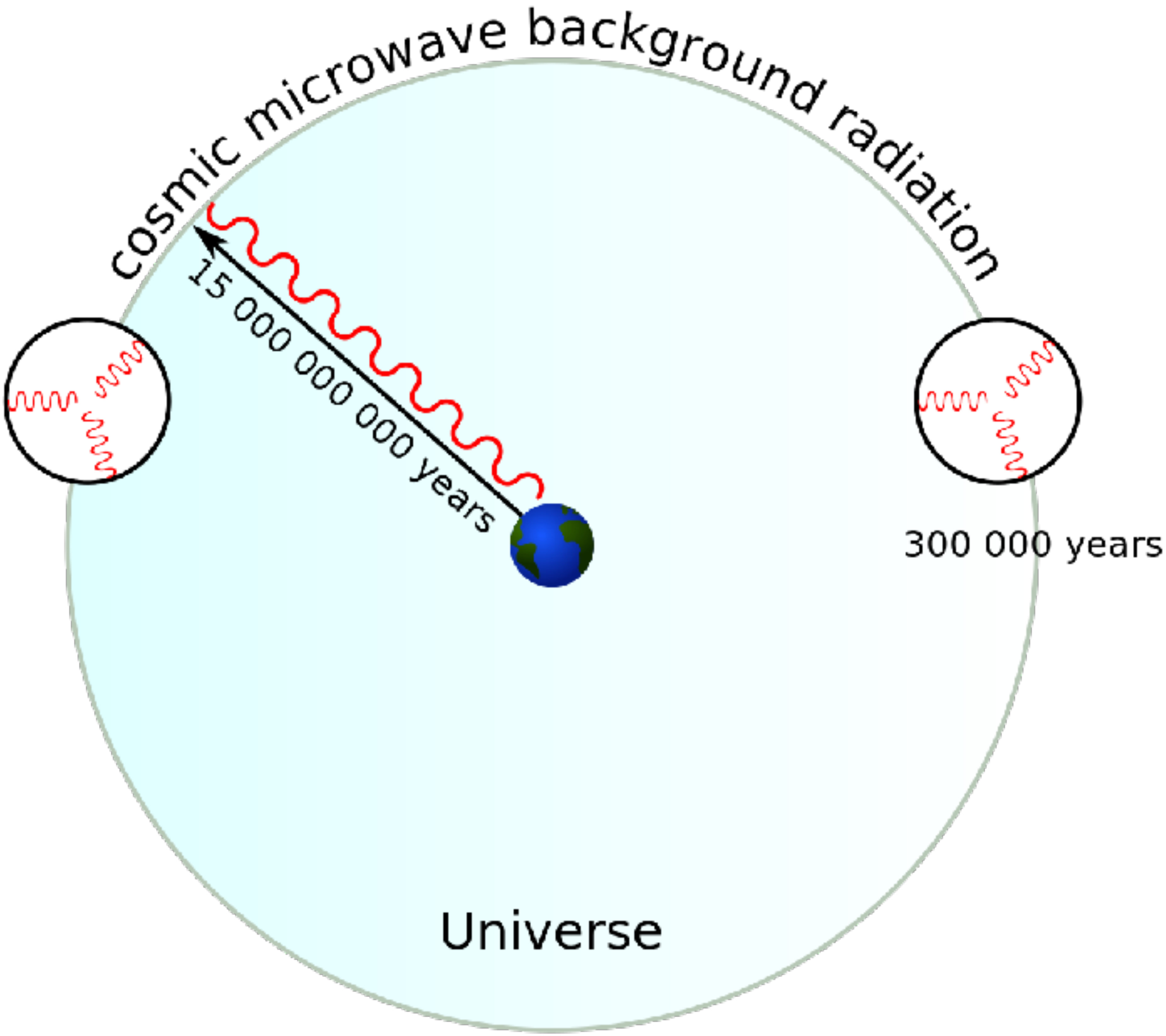
The CMB With Planck

Over the last half-century, has become one of our most important and pristine tools.

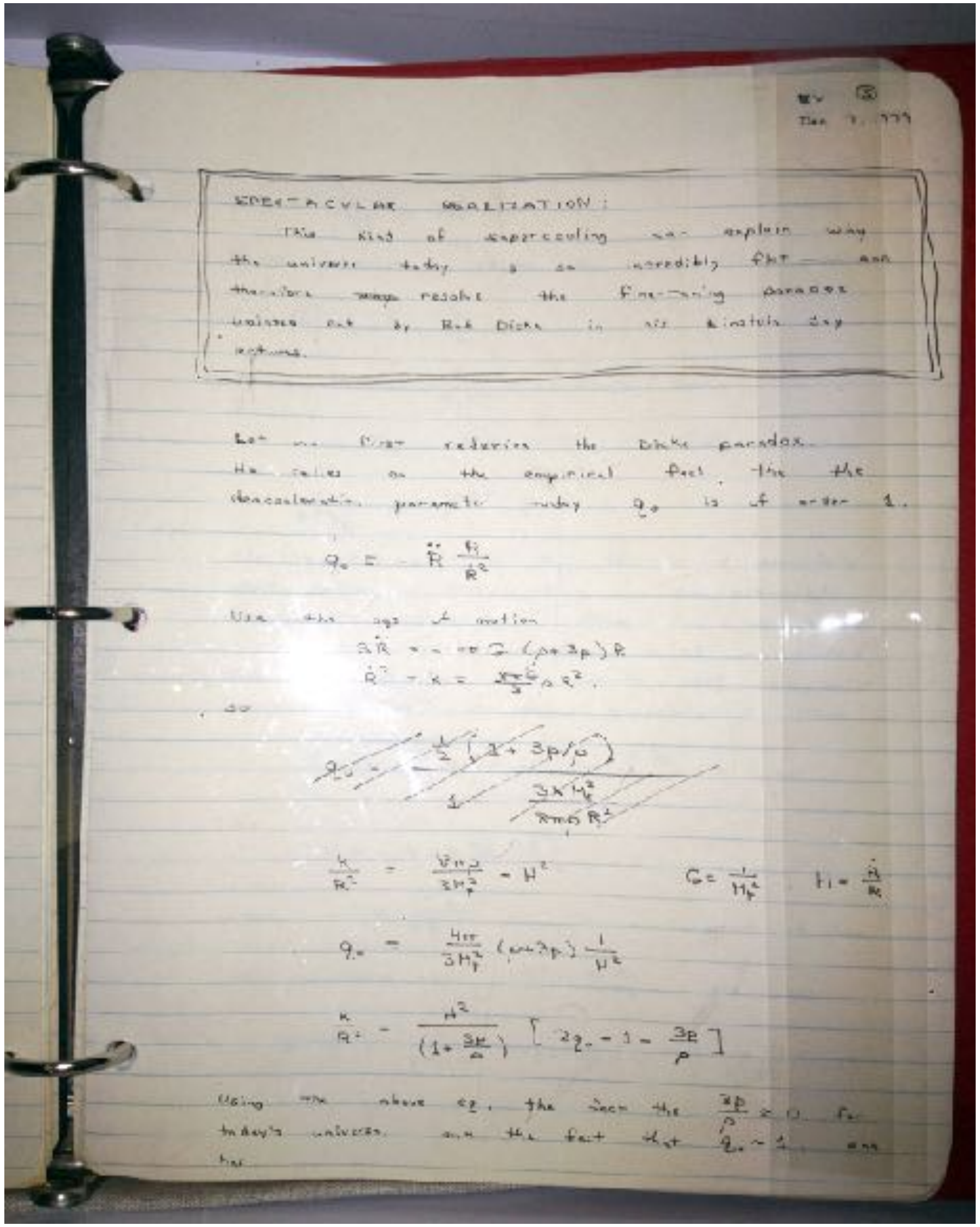


See Suzanne Staggs' talk

Reveals a big problem



The Leading Idea - Inflation



Makes the universe grow unimaginably large in a minuscule amount of time.

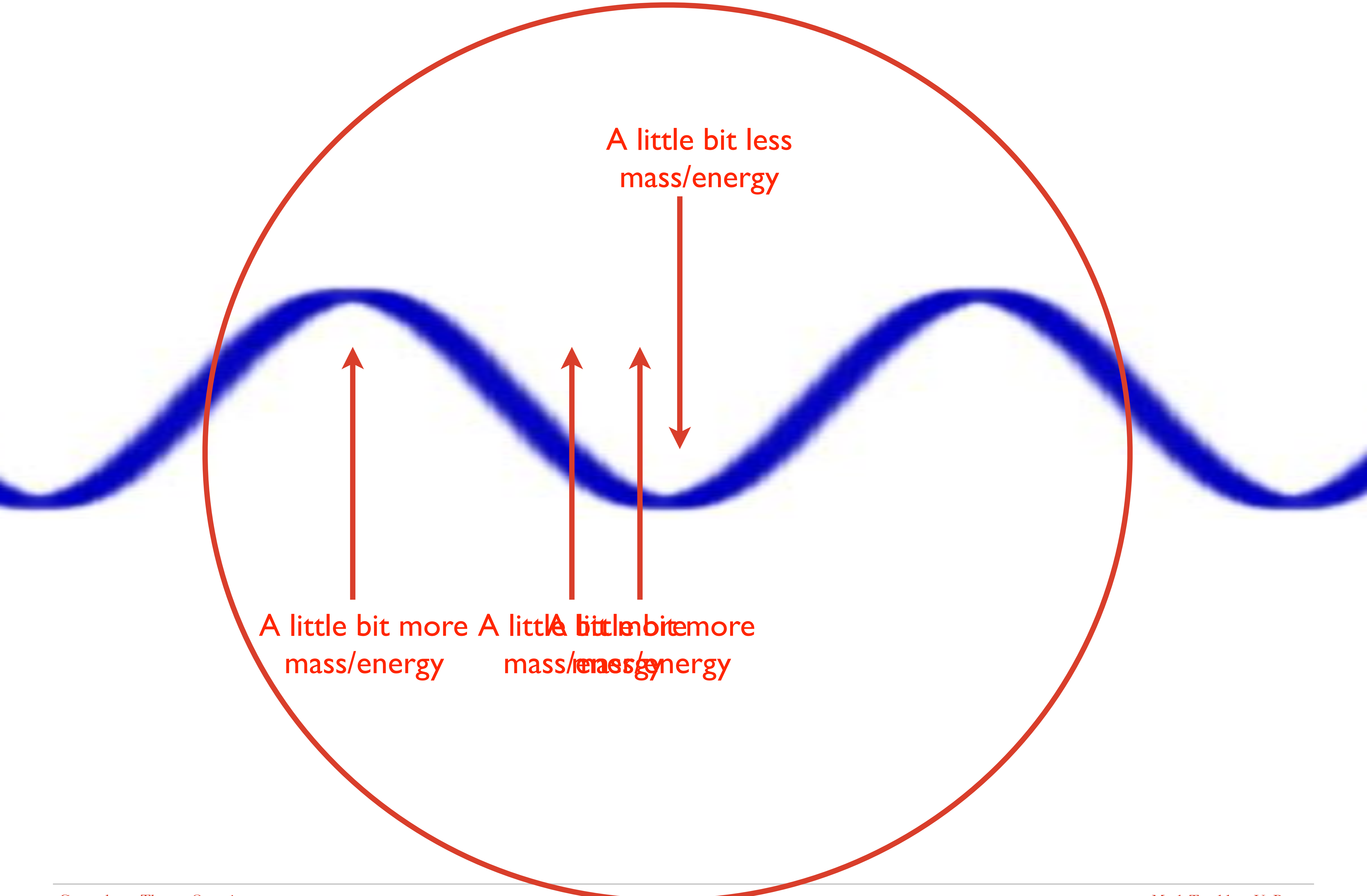
Our observable universe comes from such a tiny patch that it was all originally the same temperature.

Great! But wait a minute, where did those tiny variations come from.

That, of course, is the amazing story!

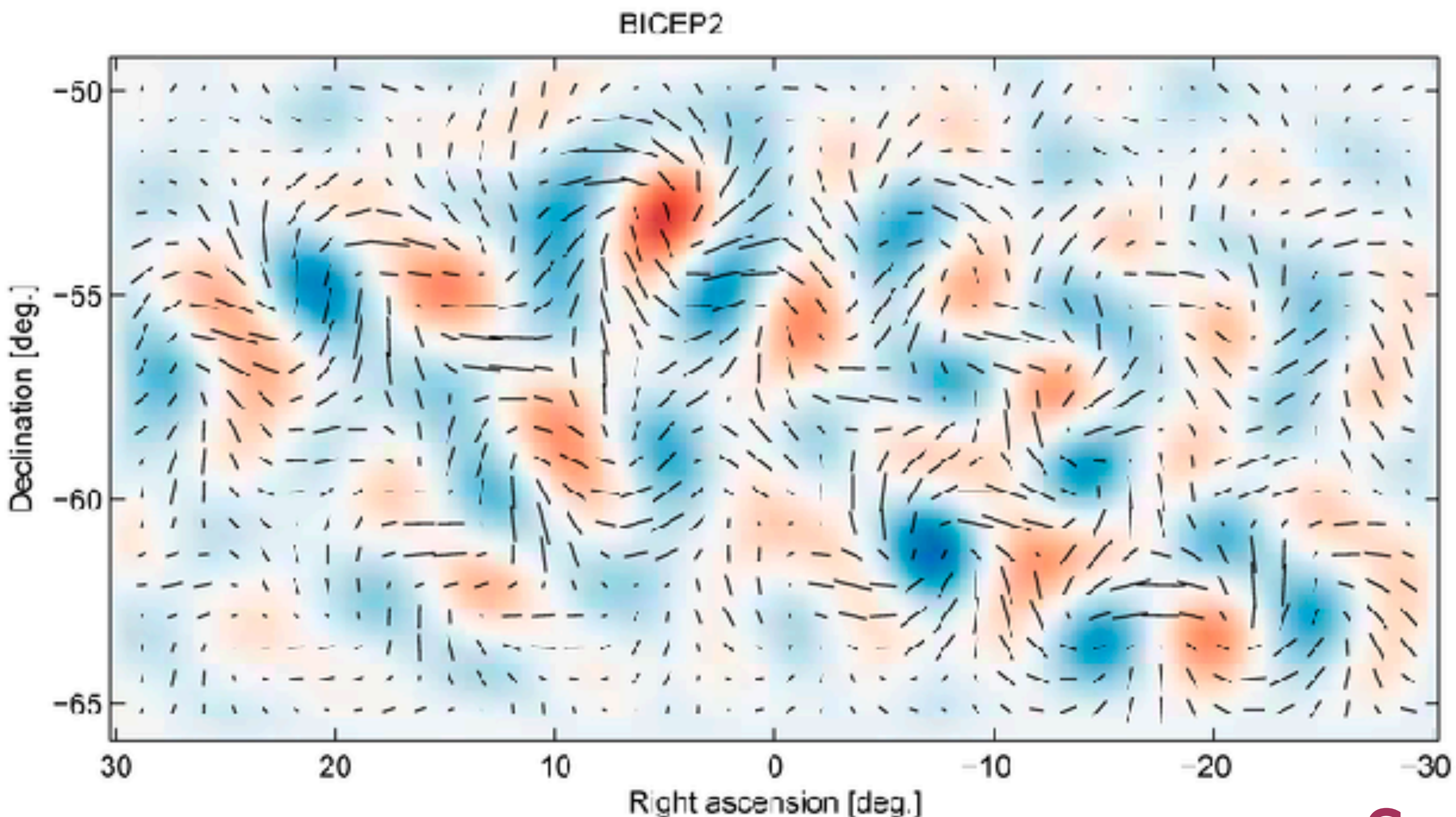
[Adler Planetarium; curated by the Adler's Webster Institute for the History of Astronomy.]

Quantum Mechanics Writ Large!



What More Can We Learn from This?

- Many opportunities to learn about the details of comic evolution
- But, for me, the most exciting possibility is that we may learn about grand unification or, even better - quantum gravity!

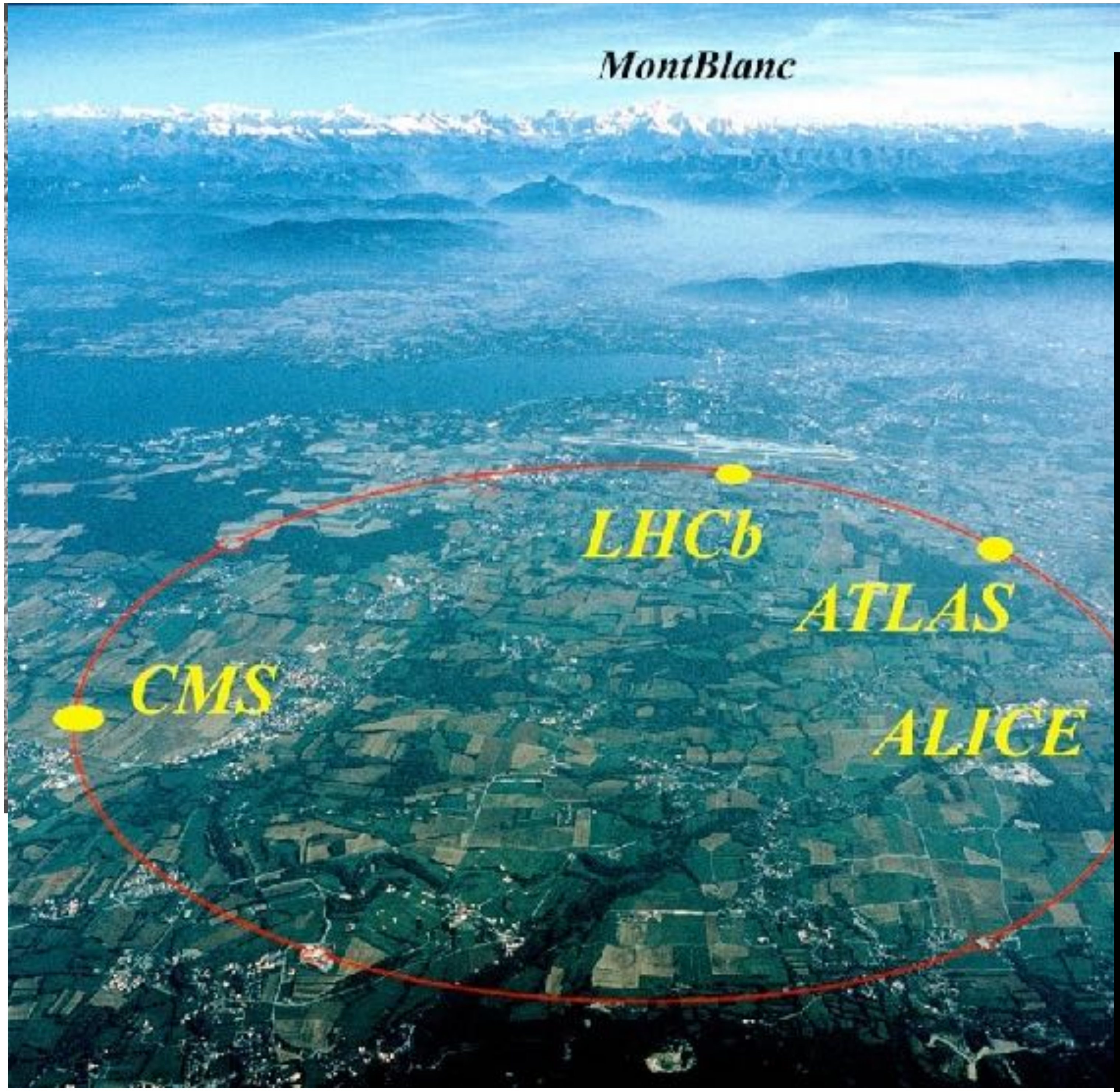


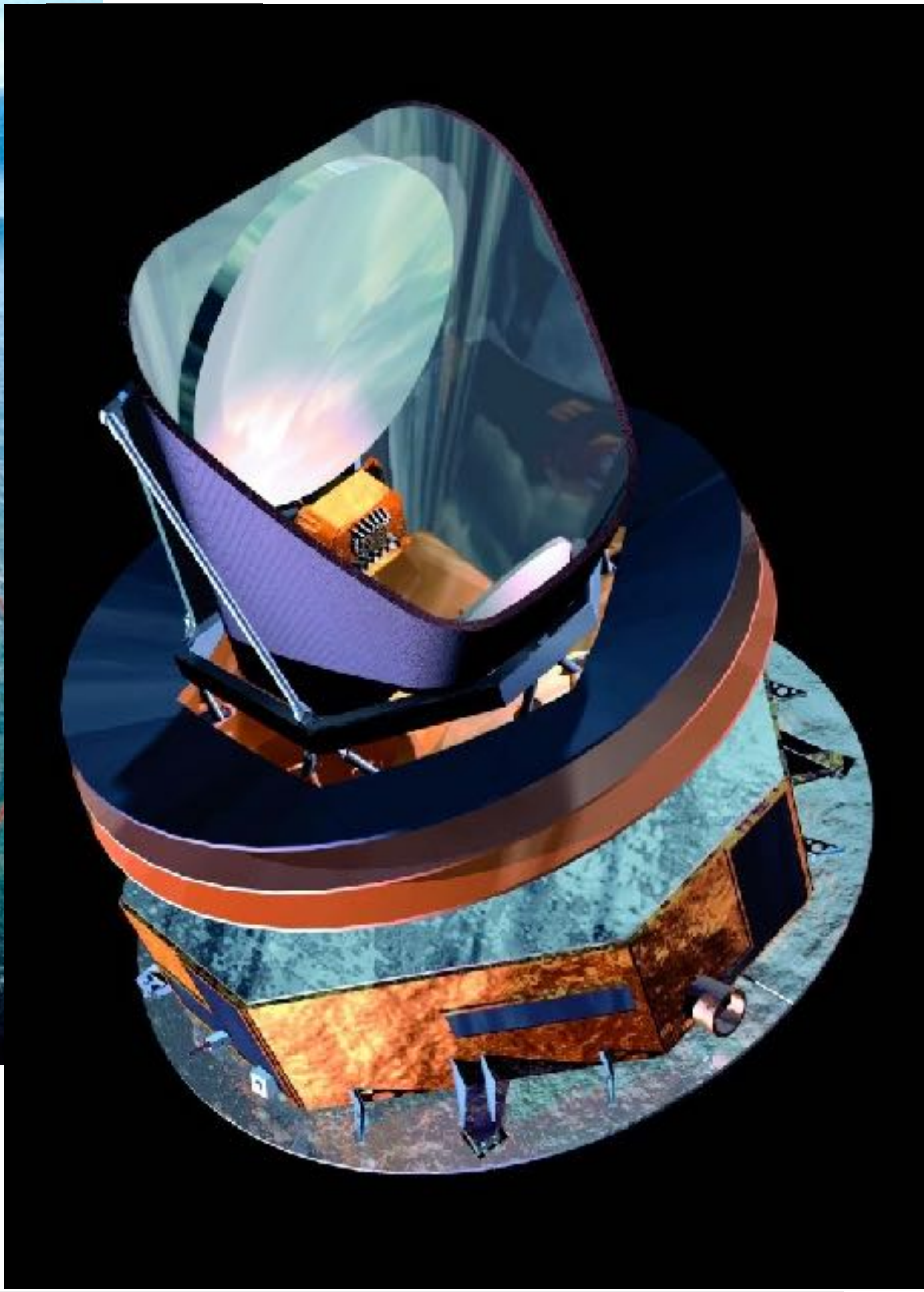
- Inflation fluctuates the CMB temperature.
- Tied up with the dynamics of inflation.
- But the metric (spacetime) also fluctuates!

See Suzanne's talk

- This can be measured with the polarization of the CMB.
- If inflation is right, and we do this, we will be directly confirming that gravity is quantum mechanical, for the first time in history!

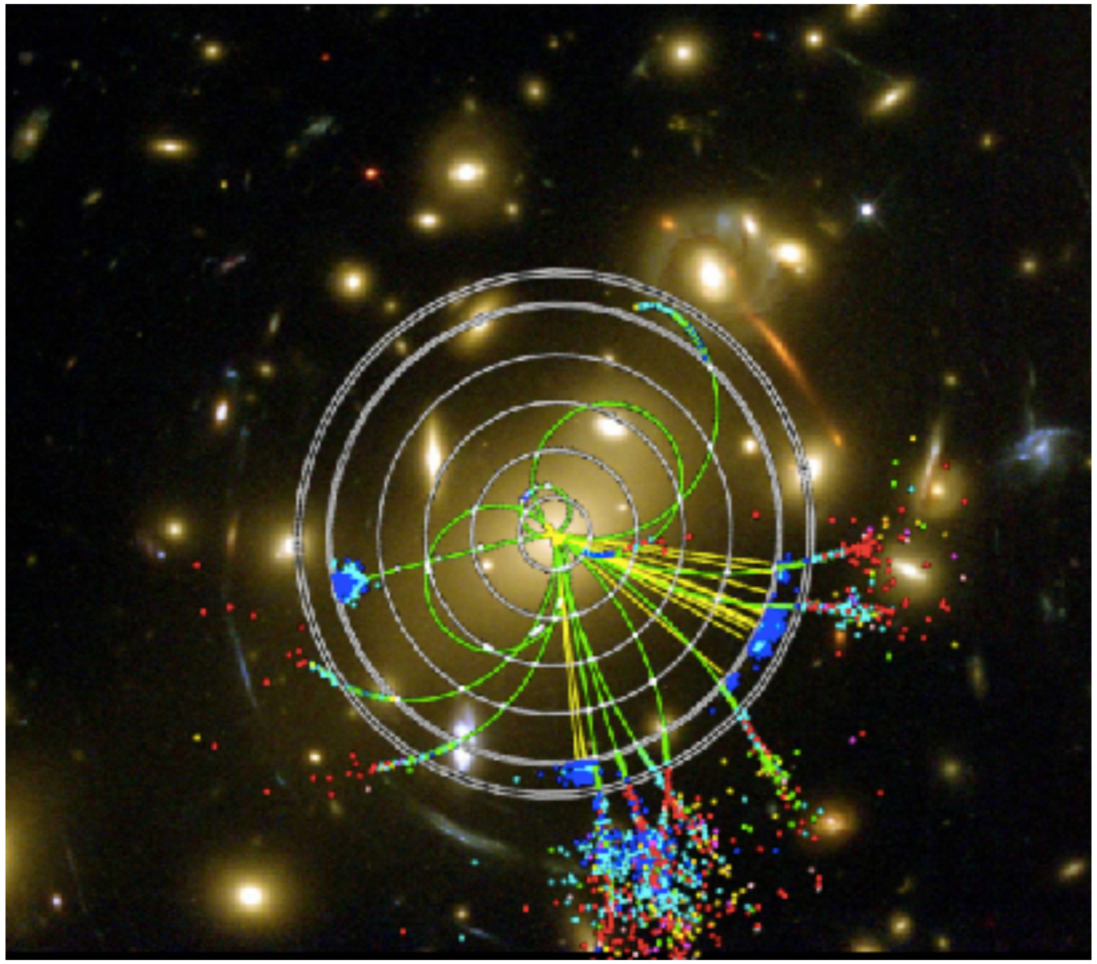
What Have We Learned?





Common to All these Questions …

- The secrets to how the universe looks lie in the subatomic world. Cosmos is a one-time expt. - a unique window into the laws of physics at smallest scales.
- This works because the power of the expansion of the universe causes the secrets of the atom to be scrawled across the night sky.



- Particle physics and cosmology are complementary tools, allowing us to attack fundamental physics from multiple angles.
- Most remarkably; over the time since my grandfather was born, humankind has been able to figure this out.
- Last ~20 years: details of CMB; cosmic acceleration; neutrino masses; the Higgs; gravitational waves; and much more …
- Just imagine what we might understand in another 5, 10, or 100 years!
- **We need patience and resolve, but should be excited and optimistic!**

Thank You!