Big open questions in Cosmology (and how to get into research to answer them)

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UNIVERSITY OF CAMBRIDGE

Outline

1. A brief history of the Universe
2. 10 big open questions in cosmology
3. How to get into research (with tips based on personal experience)

D'où venons-nous? Que sommes-nous ? Où allons-nous?

Credits: Paul Gaugin

The oldest questions...

- *Where do we come from*?
- *What are we made of*?
- *Where are we going*?

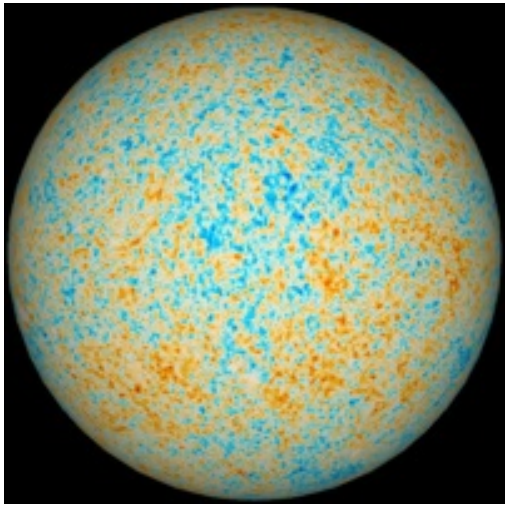
...and the modern versions of these questions

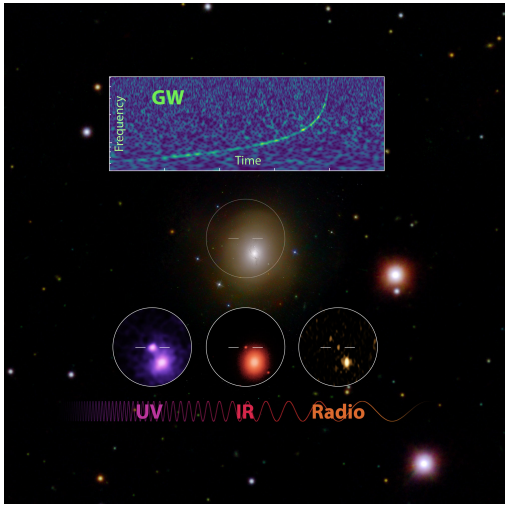
- *Where do we come from*?
- *What are we made of*?
- *Where are we going*?

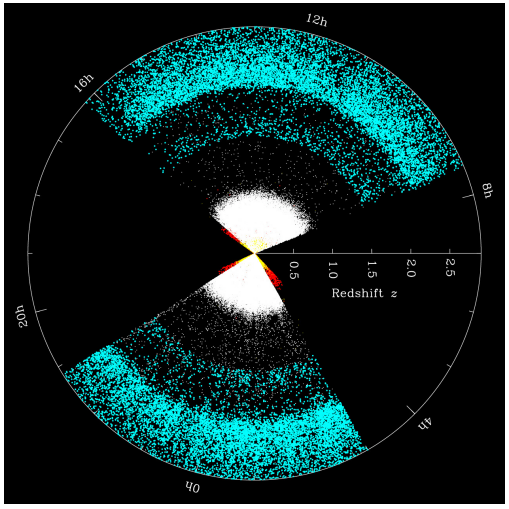
$\longrightarrow$

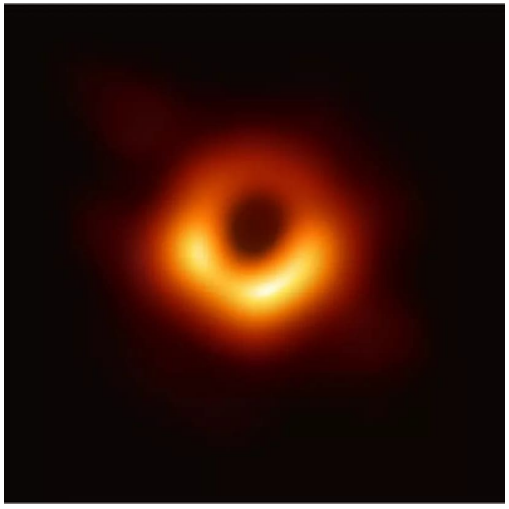
- *What were the Universe's initial conditions*?
- *What is the Universe made of*?
- *How will the Universe evolve*?

Lots of astrophysical and cosmological data to test theories for the origin/composition/fate of the Universe:

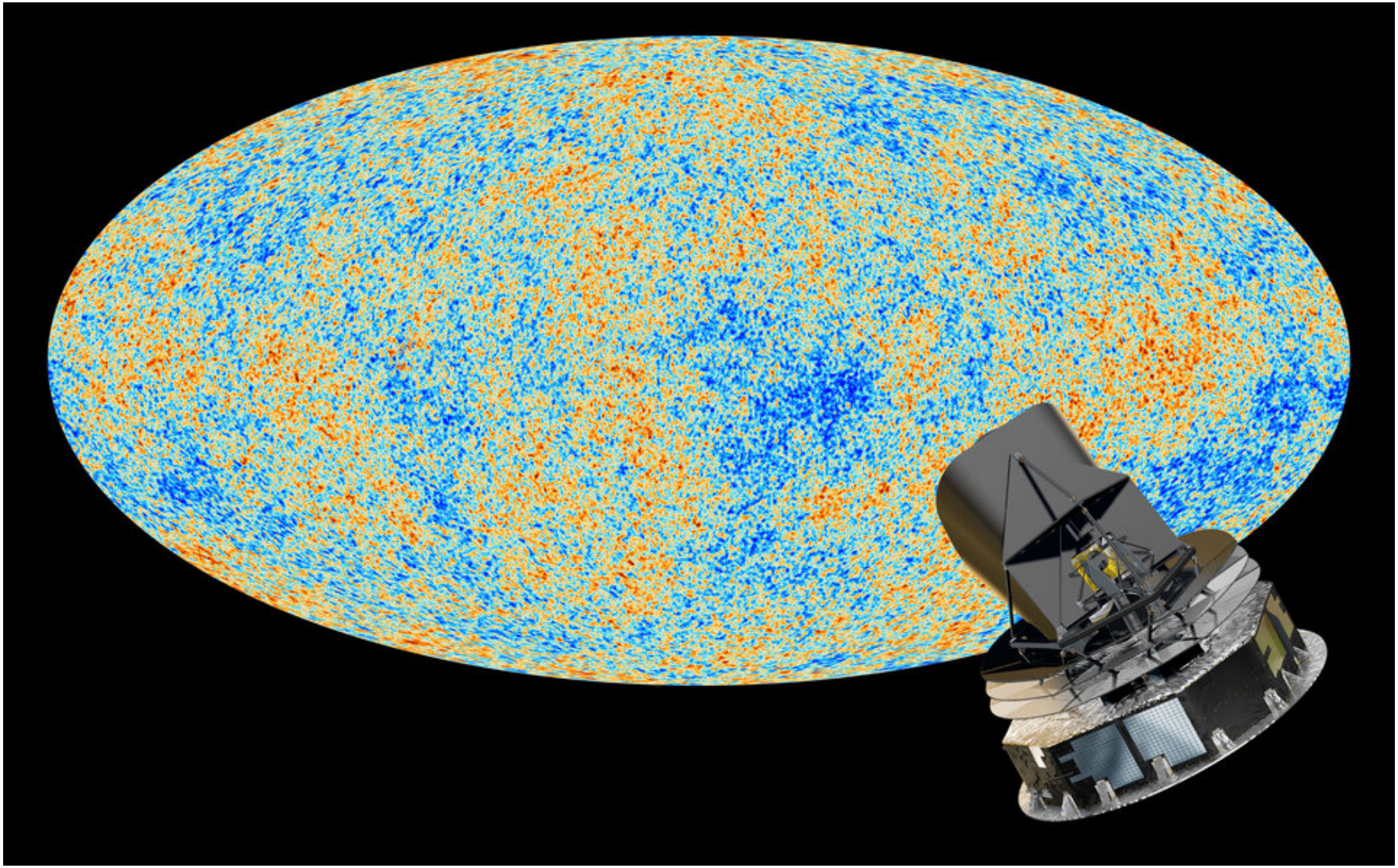






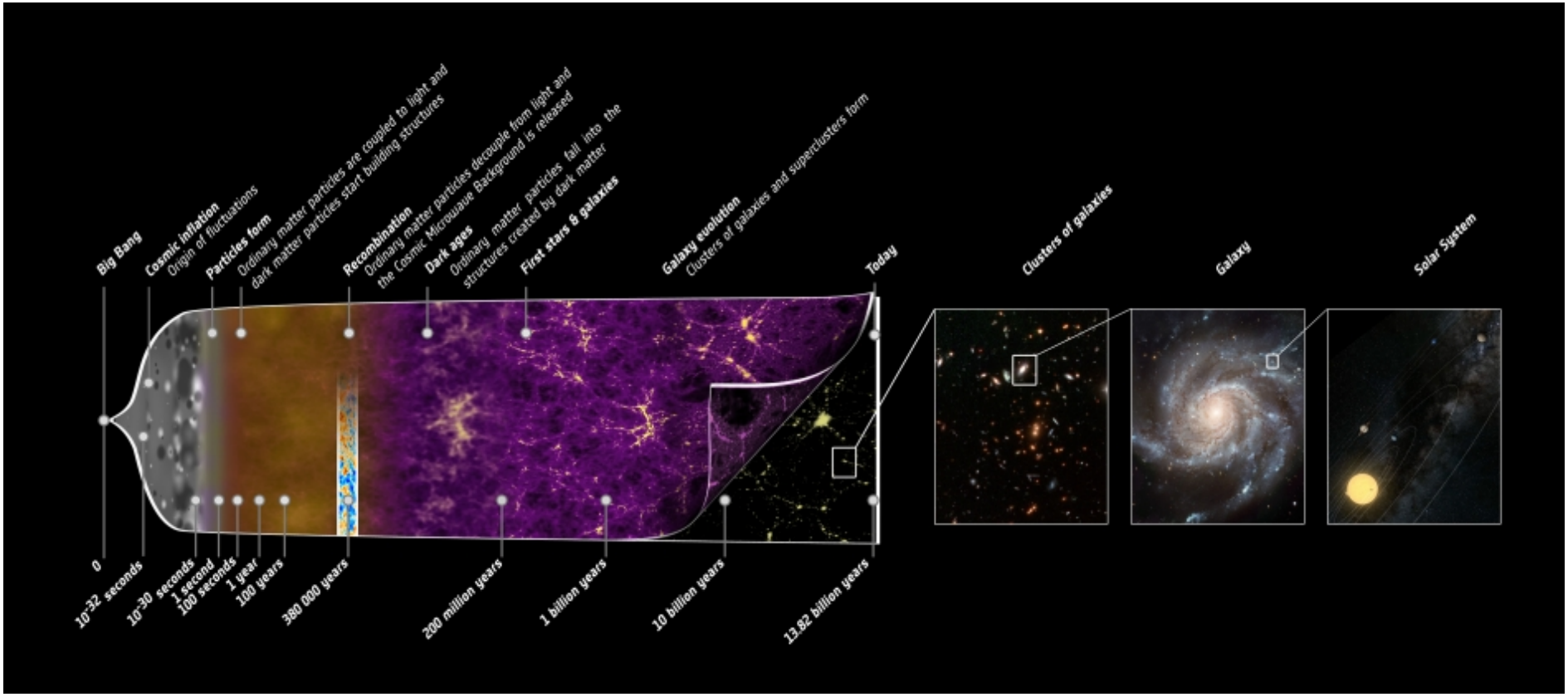


The CMB



Credits: *Planck* collaboration and ESA

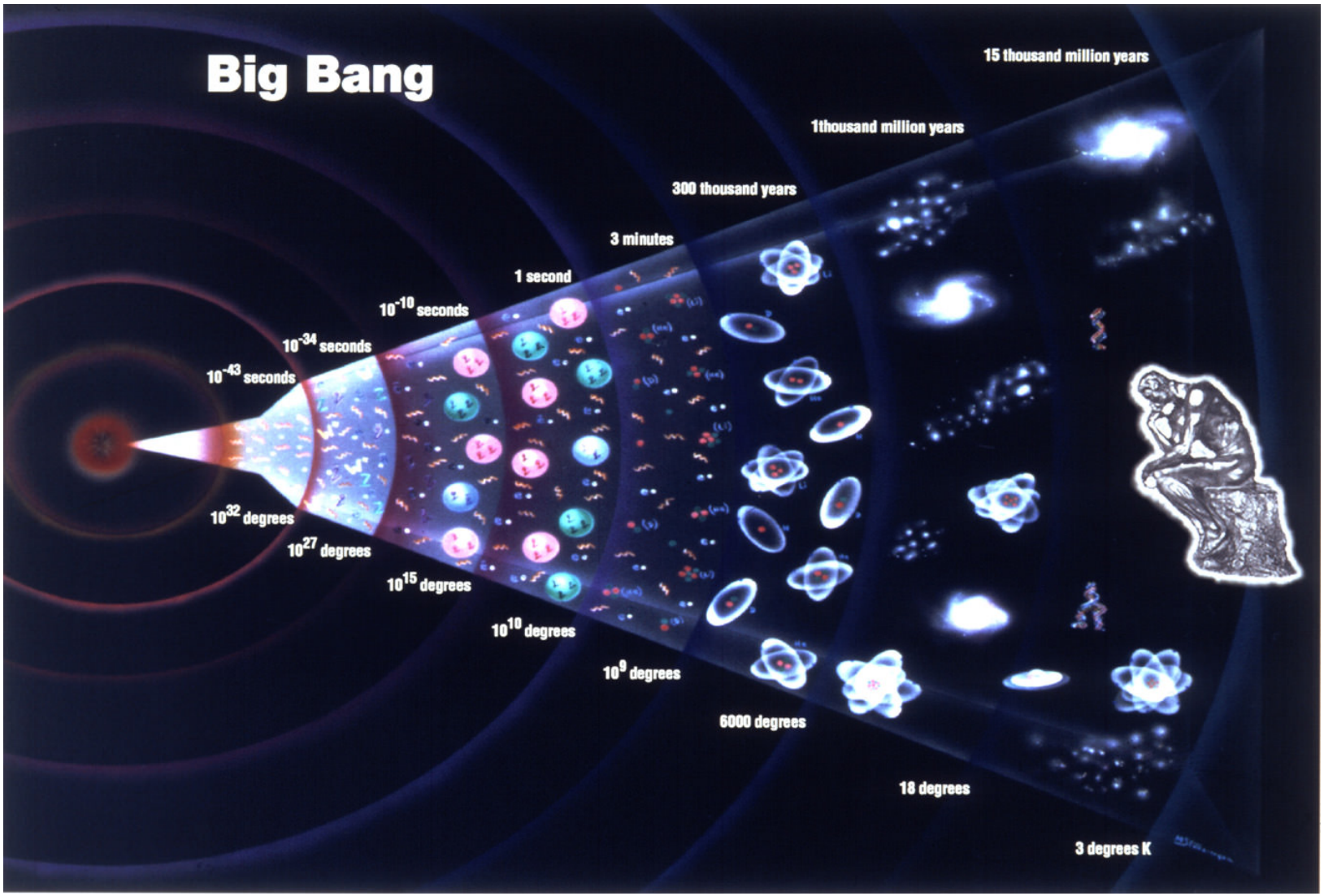
A brief history of the Universe



Credits: NASA

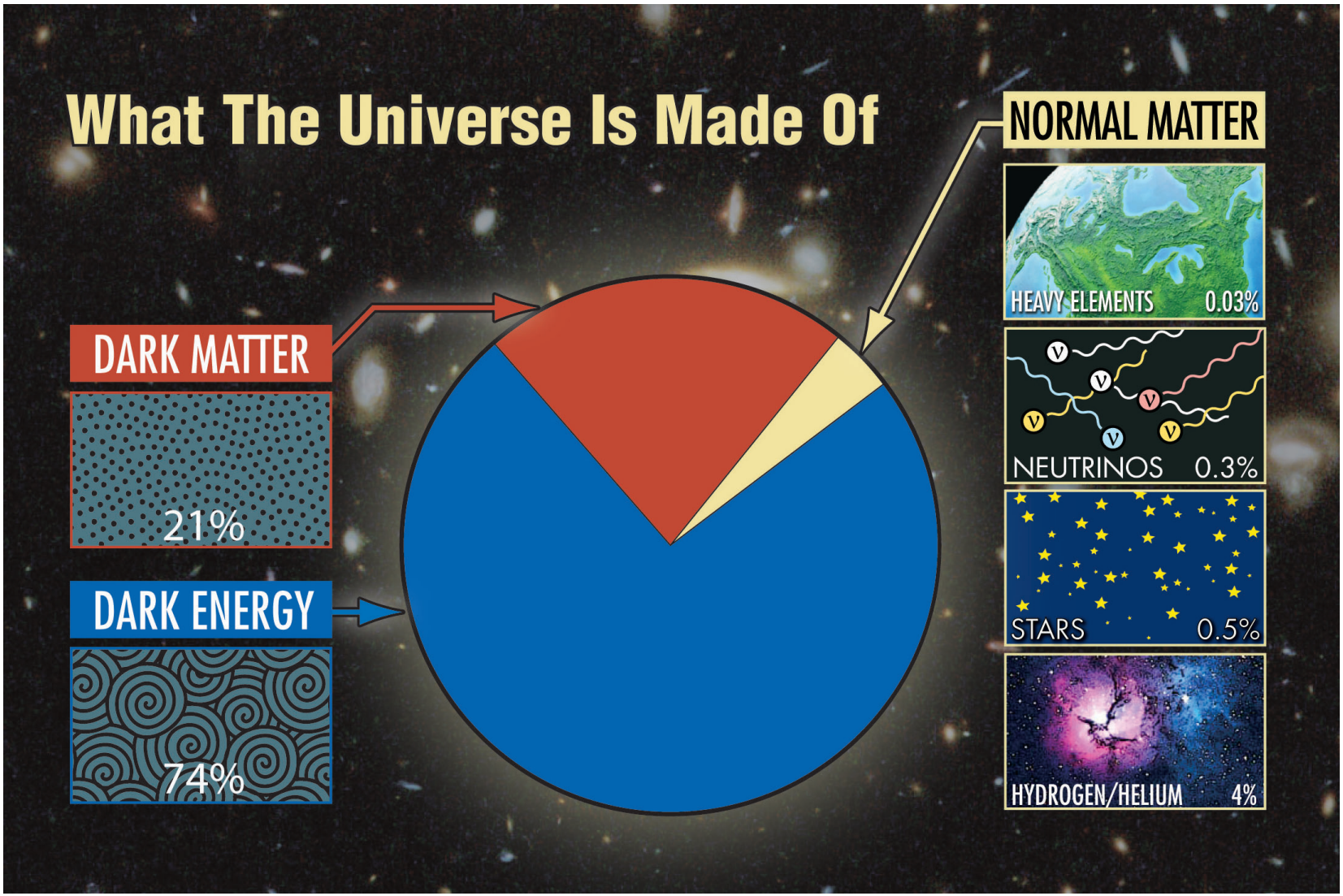
Where do we come from?

Cosmic inflation aka *(Hot) Big Bang*?



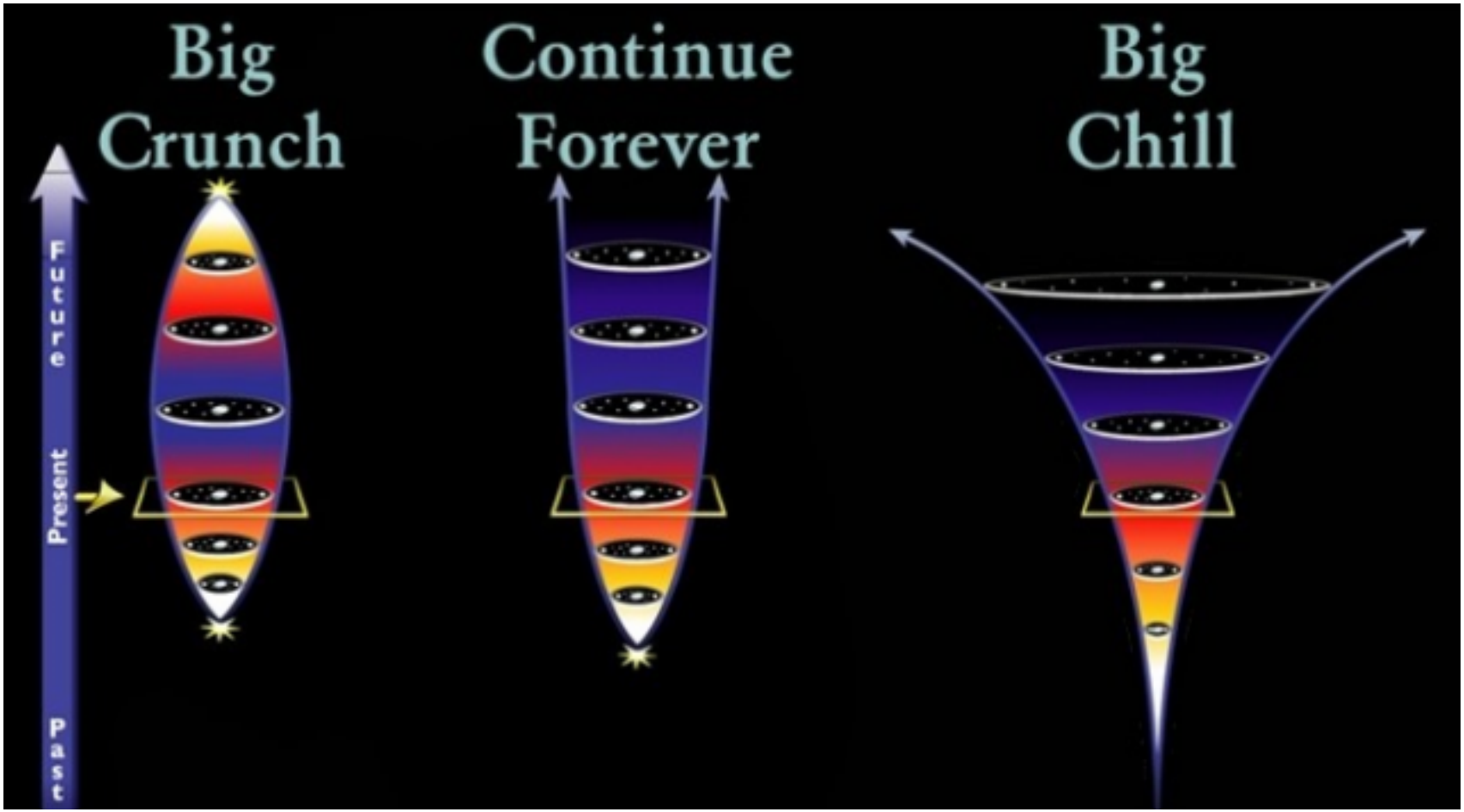
What are we made of?

Mostly dark stuff (and a bit of neutrinos)



Where are we going?

Depends on what dark energy is?



What we (think we) know about the Universe

- Most of it is dark:
  - Dark matter helps structure to come together ("cluster")
  - Dark energy makes Universe accelerate at late times
- An early accelerated epoch presumably set the initial conditions for the subsequent evolution
- Einstein's General Relativity seems to work quite well on all scales
- The current expansion rate of the Universe is $H_0 \approx 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$
  - *i.e.* every $3.086 \times 10^{19}\,\mathrm{km}$ out there you move, the apparent speed at which the Universe is expanding is $70\,\mathrm{km\,s^{-1}}$ faster

So we've figured out everything?

(and don't need researchers anymore)

10 big open questions

Color coding:

I have worked on this (obviously without finding an answer)

I have not directly worked on this but would know my way around

I honestly have no clue how to get around answering this

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10 big open questions

1. What makes up the dark matter?
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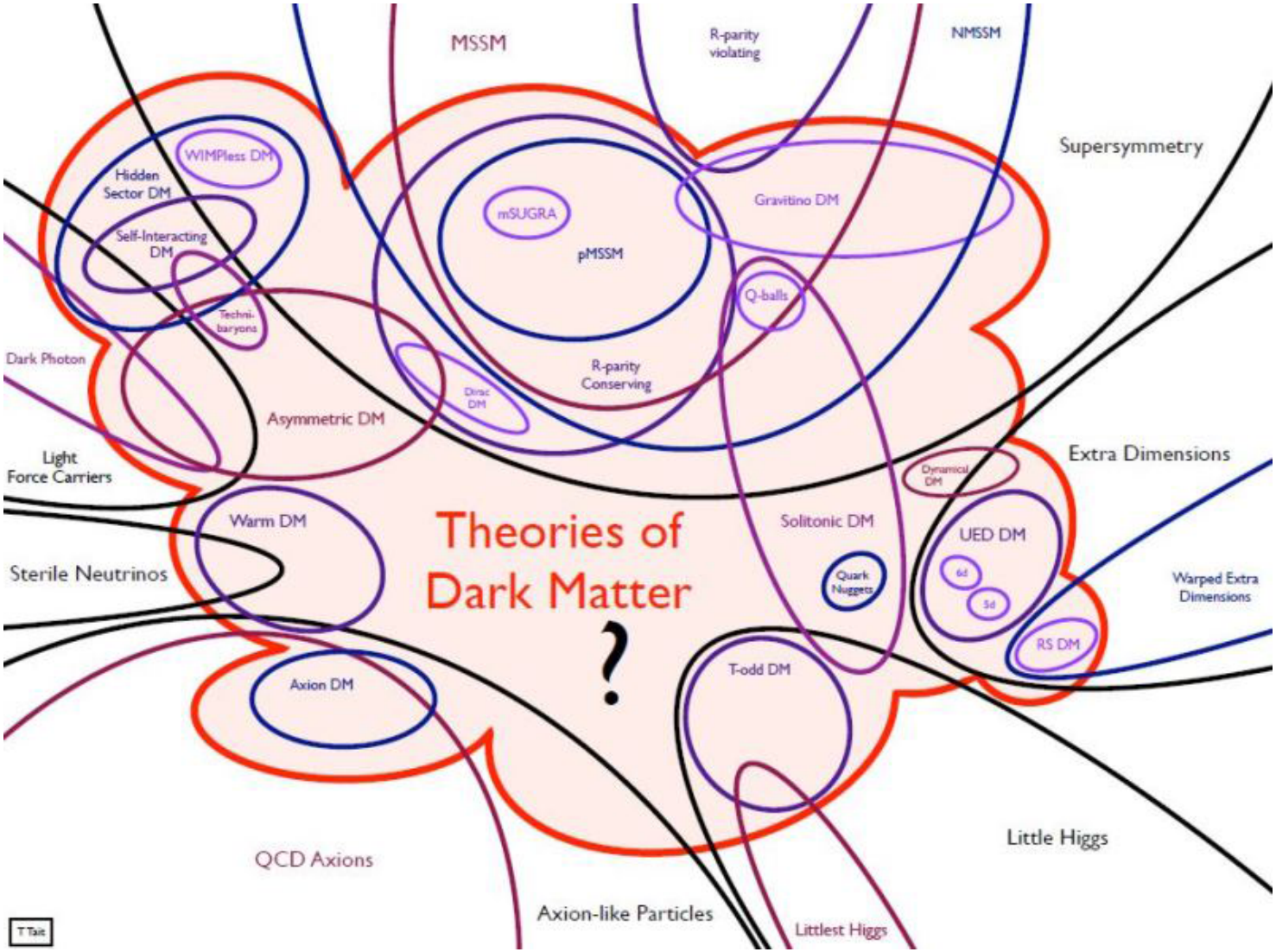
10. Why is there anything at all?

Question 1

What makes up the dark matter?

Question 1



Credits: Tim Tait

Question 2

What makes up the dark energy?

Question 2

- Cosmological constant
- Quintessence
- Modifications to Einstein's General Relativity (modified gravity)
- Fluids with funny equations of state
- Evaporating primordial black holes
- Dark energy doesn't exist (it's all backreaction)
- ...

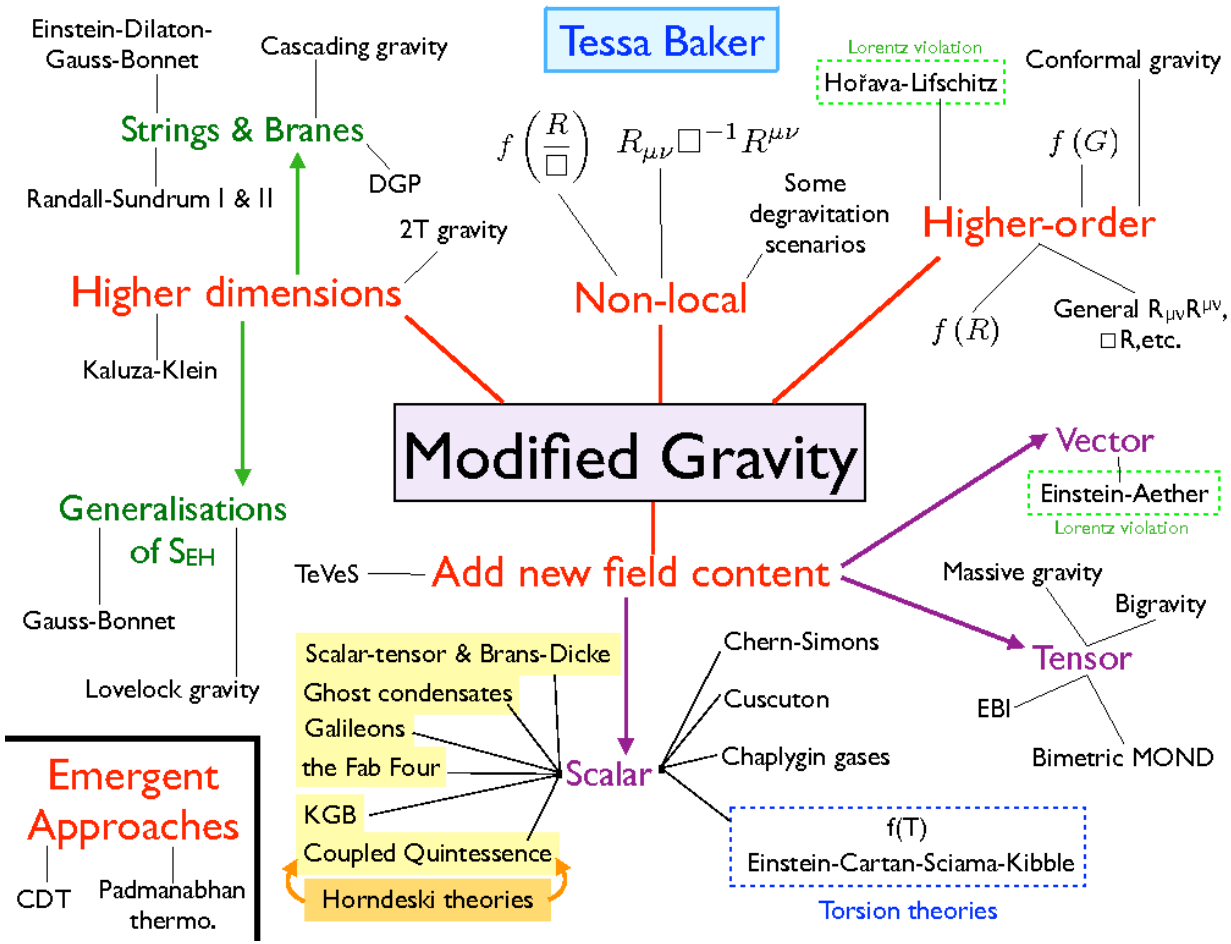
Credits: Tessa Baker

Question 3

Is General Relativity valid on the largest scales?

Question 3

So far approximately yes! Hints for deviations from GR on extremely large scales, future data with improved sensitivity will be able to tell us more



Credits: Tessa Baker

Question 4

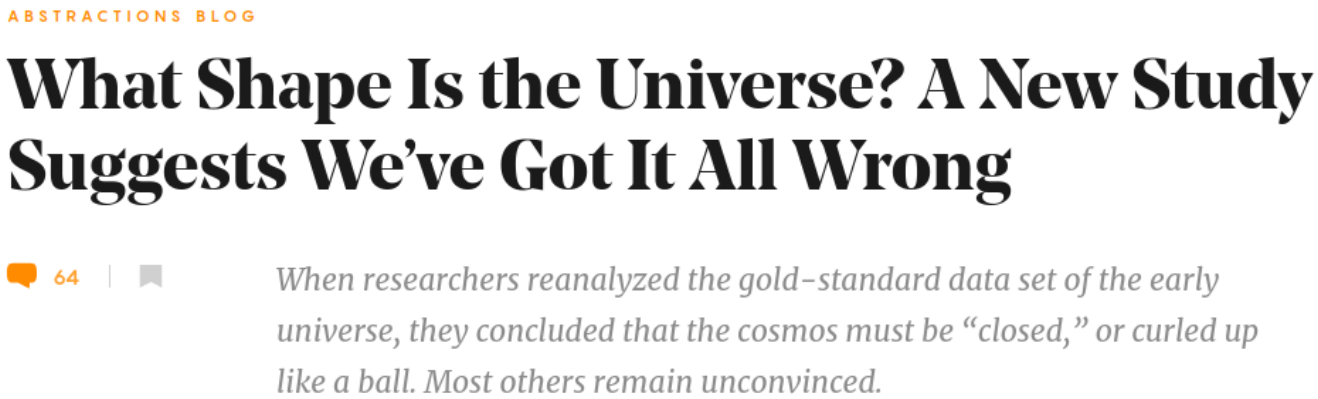
What is the shape of the Universe?

Question 4

Two aspects to this question:

- Local geometry $\rightarrow$ spatial curvature of the Universe
- Global geometry $\rightarrow$ topology of the Universe: finite or infinite? With or without boundary? Simply or multiply connected?

Cosmology can mostly answer the first question (and even then we do not have a clear answer at the moment)



ABSTRACTIONS BLOG

What Shape Is the Universe? A New Study Suggests We've Got It All Wrong

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When researchers reanalyzed the gold-standard data set of the early universe, they concluded that the cosmos must be "closed," or curled up like a ball. Most others remain unconvinced.

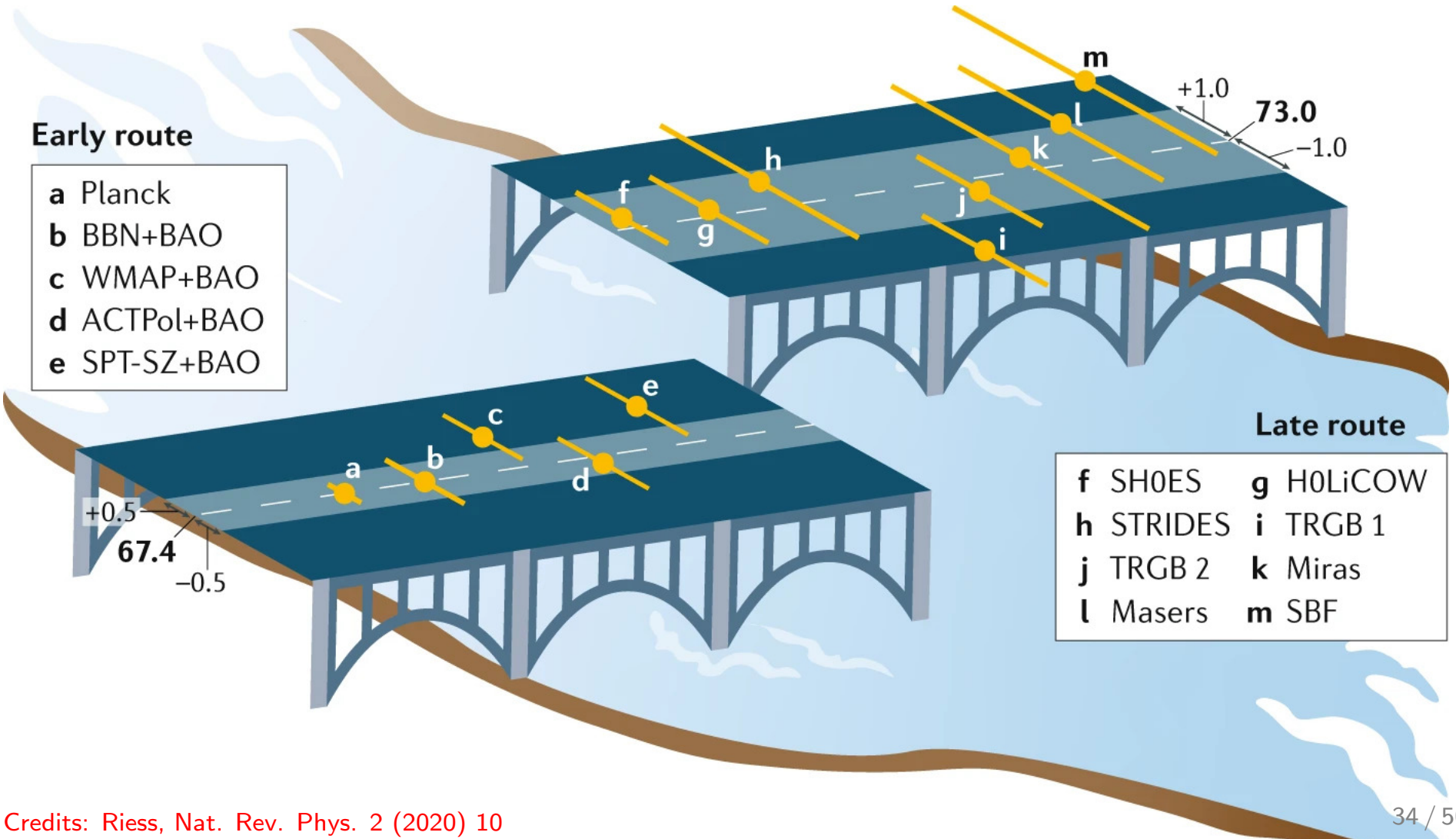
Credits: Quanta Magazine

Question 5

What is the expansion rate of the Universe (H_0)?

Question 5

No clear solution to the H_0 tension yet, but indications that it requires something funny to occur before the CMB formed



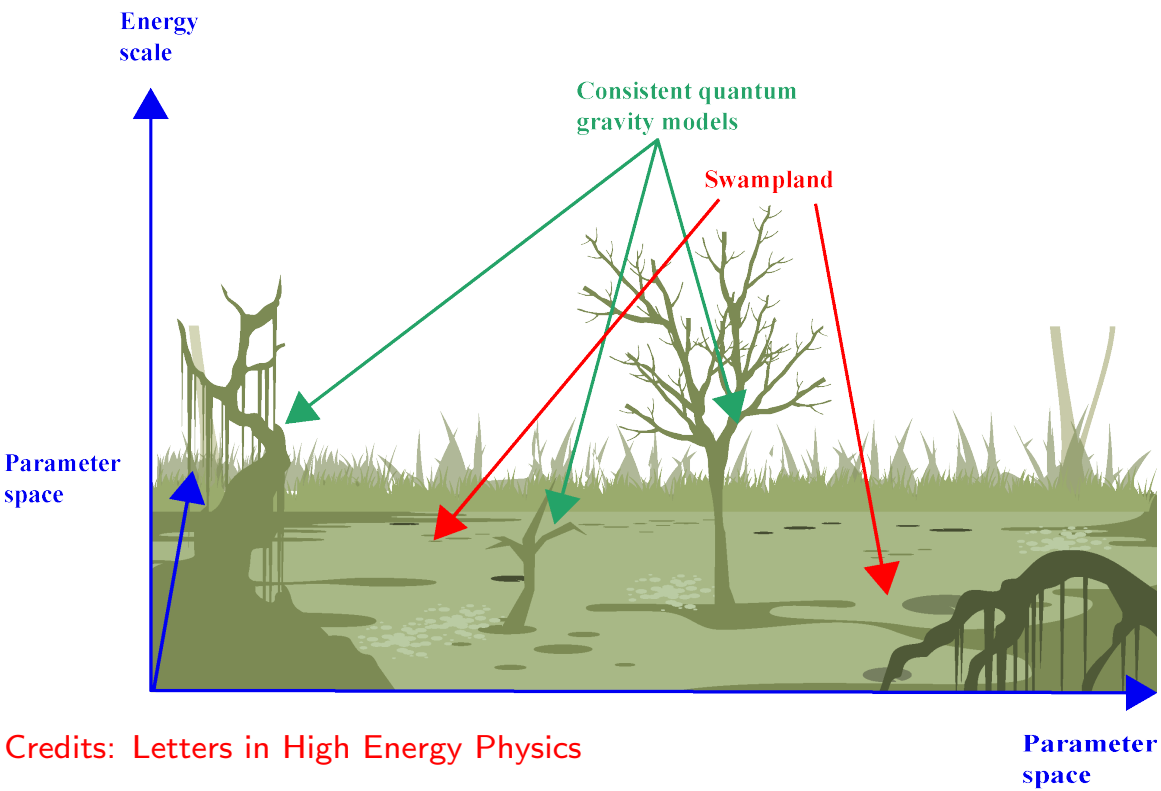
Credits: Riess, Nat. Rev. Phys. 2 (2020) 10

Question 6

Is our standard cosmological model compatible with string theory?

Question 6

Hints that the answer might be “No” (in relation to the “swampland” program)



Credits: Letters in High Energy Physics

Question 7

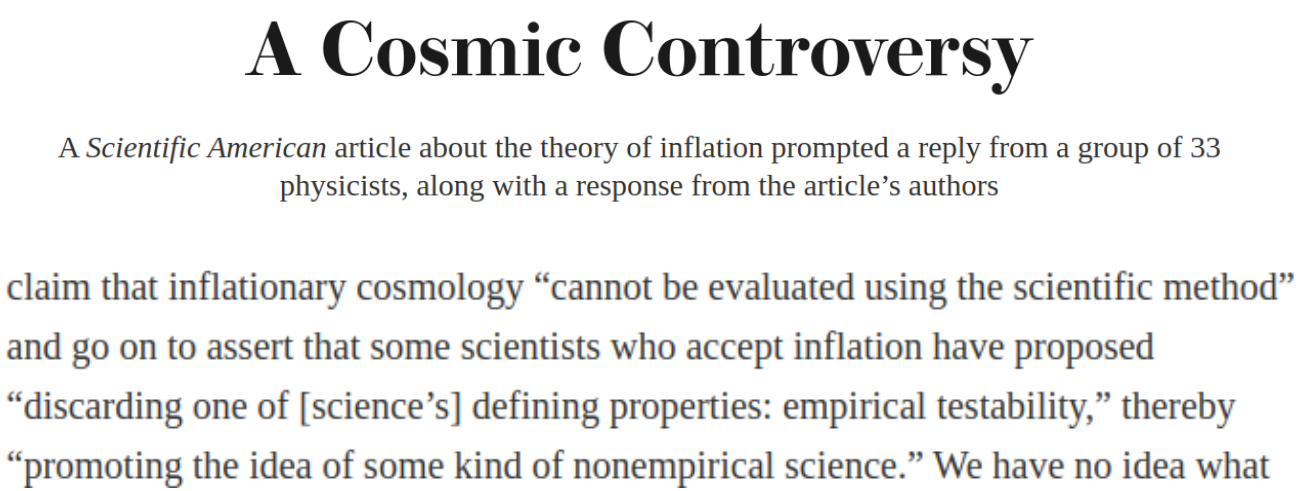
What set the initial conditions for the Hot Big Bang expansion?

Question 7

Single-field slow-roll inflation or alternatives? Examples:

- Multi-field inflation
- Modified gravity
- Ekpyrotic phase (slow contraction) followed by bounce
- String gas cosmology
- ...

Recent debate (even in popular science outlets) as to whether inflation even qualifies as a "good" testable theory



A Cosmic Controversy

A *Scientific American* article about the theory of inflation prompted a reply from a group of 33 physicists, along with a response from the article's authors

claim that inflationary cosmology "cannot be evaluated using the scientific method" and go on to assert that some scientists who accept inflation have proposed "discarding one of [science's] defining properties: empirical testability," thereby "promoting the idea of some kind of nonempirical science." We have no idea what

Credits: Scientific American

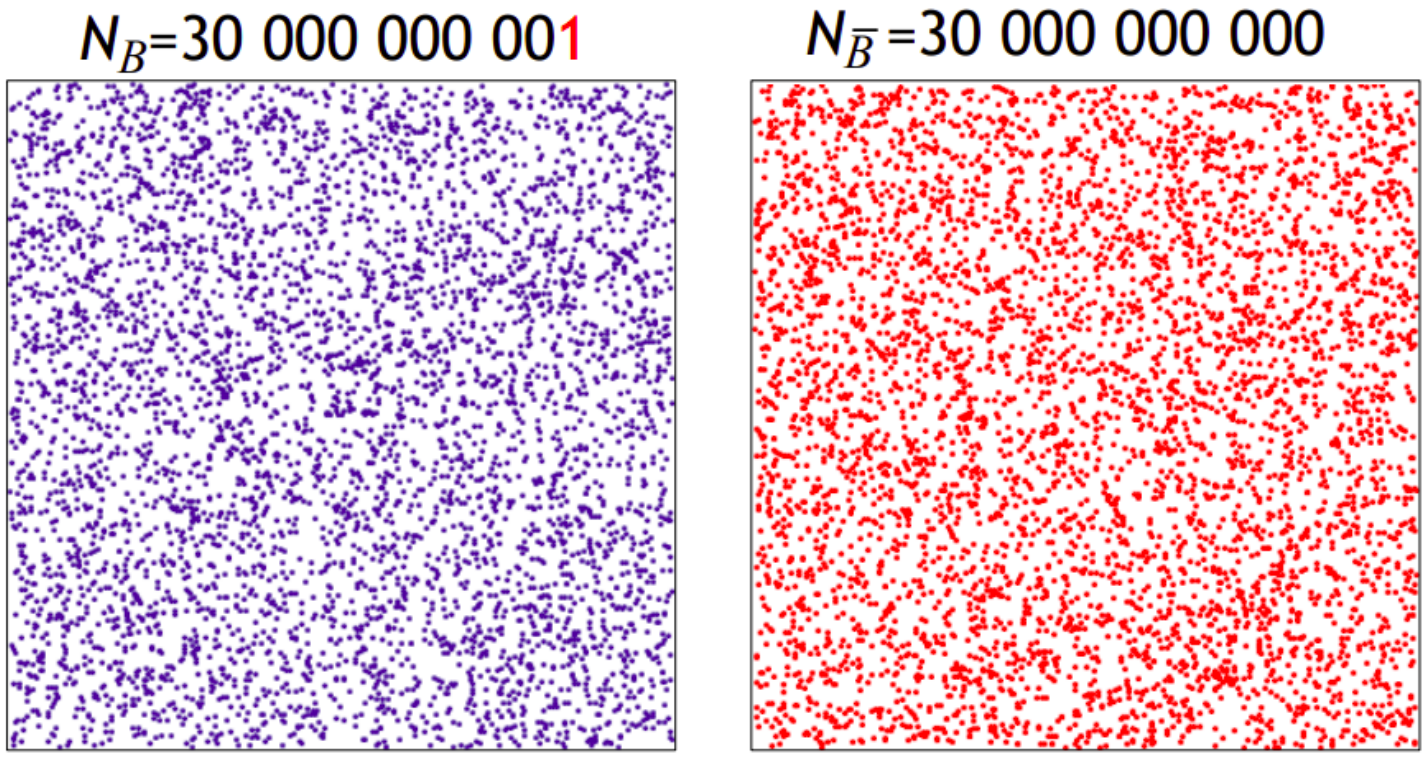
Question 8

Where did all the antimatter go?

Question 8

Baryogenesis!

$t \lesssim 10^{-6}$ s



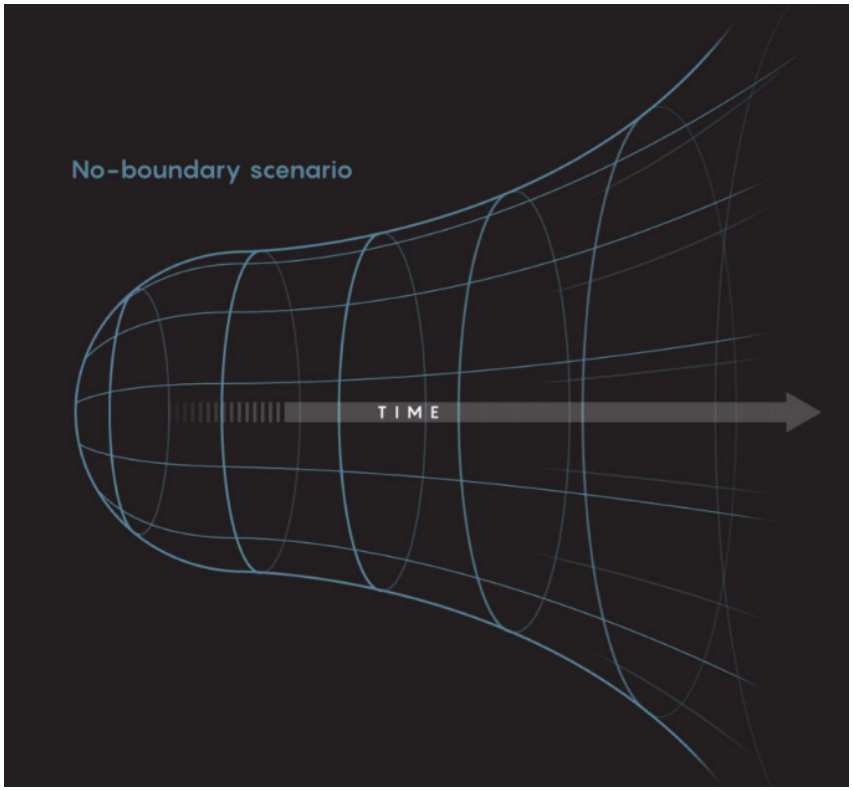
Many realistic particle physics models for baryogenesis, with connections to neutrino masses, dark matter, inflation and so on, but none convincingly seen in experiments

Question 9

What came before the Big Bang?

Question 9

- If inflation occurred, what happened before ($t \lesssim 10^{-32}\,\mathrm{s}$)? Or $t < 0$?
- Many would say this question is ill-posed
- Hard to answer without a theory of quantum gravity
- Hawking-Hartle no-boundary proposal ($t < 0$ ill-posed)
- Tunnelling out of nothing (Vilenkin-Linde)



Credits: Quanta Magazine

Question 10

Why is there anything at all?

Question 10

From cosmology to cosmogony/philosophy/religion, selection of (unsatisfying?) proposed answers:

- God/universal designer/supreme being or variations:
  - uncaused cause (Aristotle)
  - "a substance which [...] is a necessary being bearing the reason for its existence within itself" (Leibniz)
- A cause might not be necessary to form the Universe (Hume)
- Something exists necessarily rather than being caused (Leftow)
- I see that something exists, so that's it (Russell)
- Anthropic principle (Barrow/Tipler/Tegmark)
- "Nothing is unstable" (Wilczek)
- Nothing is impossible (Rundle)

How to get into research to answer these questions

Disclaimer: tips skewed and based upon my experience. Take everything with a grain of salt!

My path so far

- 2004-2009: High school in Southern Italy 
- 2009-2012: BSc in Physics @University of Trento, Italy 
- 2012-2013: Erasmus exchange student @Imperial College, UK 
- 2013-2014: MSc in Physics @University of Melbourne, Australia 
- 2014-2015: Visiting researcher @Niels Bohr Institute, Denmark 
- 2015-2019: PhD in Theoretical Physics @Stockholm University, Sweden (with Prof. Katherine Freese and Prof. Lars Bergström) 
- 2019-2022: Newton-Kavli Fellow @University of Cambridge, UK 
- 2022+: job insecurity 

General academic path: Bachelor, Master's, PhD (real hard-core research usually starts here, but can start earlier), (bottleneck here), postdoctoral research, (huge bottleneck here), lecturer/assistant professor, associate professor, full professor

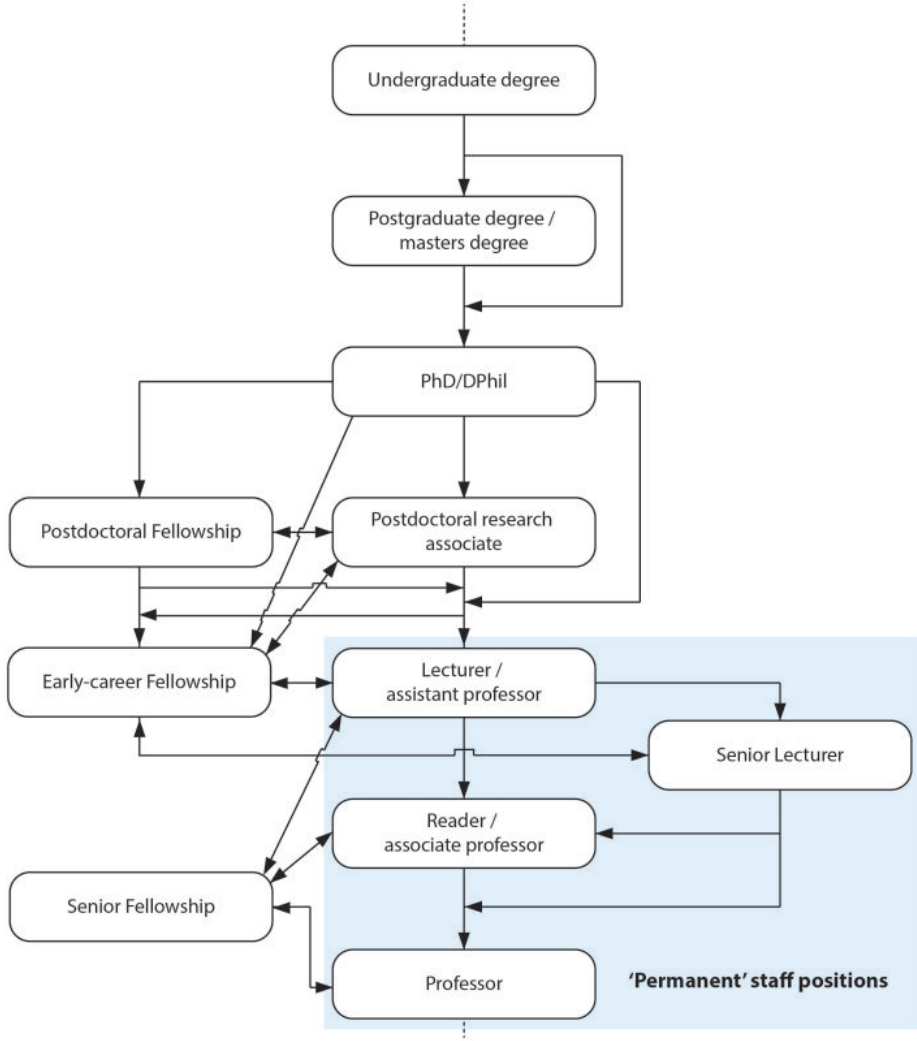
Debunking some myths

- You don't need to go to (say) MIT / Harvard / Princeton / Cambridge / Oxford to do good/great science
- Very good research is also done outside the "top" institutions (*e.g.* Netherlands produces $\approx$ half Hubble/Einstein fellows)
- You can start research well before your PhD (difficult part is finding a good/supportive mentor who has time for you $\rightarrow$ ask Oem how!)
- Do **NOT** look at University rankings, what is much more important is to find a supportive advisor you get along well with, in a stimulating environment, in a country you feel like you would thrive in
- Very few geniuses, lots of hard work, lots of luck/serendipity (being in the right place at the right time $\rightarrow$ CYWF?)

Of course, it's not all that simple...

Main difficulties:

- Lots of competition
- Can't go down the ladder
- Substantial job insecurity
- #available positions decreases by $\gtrsim \mathcal{O}(10)$ at each rung...
- ...so most eventually end up working in the private sector
- Need to be very flexible and change country often...
- ...often for short-term jobs



My personal advice if you are interested in cosmology

- **Take everything I said with a grain of salt**
- Get a **very strong** base in maths, statistics, and programming
- Get yourself a head start and start going through classic textbooks (Dodelson, Weinberg, Mukhanov) as soon as you have your base
- Read cosmology section of arXiv (arxiv.org/list/astro-ph.CO/recent) on a daily basis to get a feel for what's going on
- Learn how to use `INSPIRE-HEP` and `NASA-ADS` databases
- Something good came out of COVID: many free (recorded) webinars!
- If you come from developing countries: aim for Master's programs at ICTP hubs (Trieste, ICTP-SAIFR in Brazil, ICTP-EAIFR in Rwanda) or AIMS (South Africa, Ghana $\rightarrow$ NextEinstein Program)
- If you have some concrete research idea: contact someone expert on the subject (but don't necessarily expect an answer)
- Difficult: find which questions are worth tackling
- You will encounter many difficulties: don't give up!

Conclusions

- Cosmology is finally trying to quantitatively answer some of the most basic questions ever asked by humankind: *Where do we come from*?, *What are we made of*?, *Where are we going*?
- Many captivating open questions: what is the dark stuff made of? What is the shape of the Universe? Why is there anything at all?...
- Be tenacious and the next big discovery might come from you!