# THE UNIVERSE BEYOND THE HORIZON

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*The multiverse picture that has emerged from inflationary cosmology.*

- Remote regions beyond our horizon are strikingly different from what we observe here.
- How can we test this theory?
- Theoretical study of the multiverse may explain some features of the visible universe.
- Beginning of the universe (if time permits).

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**INFLATION** *– super-fast, accelerated expansion of the universe.* *Guth (1981)*

*The key role is played by "false vacuum".*

# Properties of false vacuum

- Large energy density:

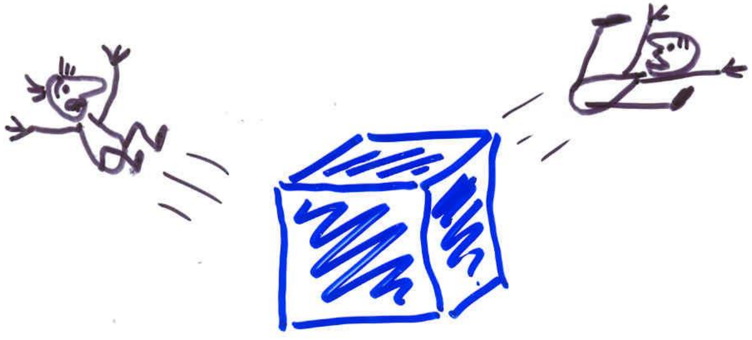
$$E = \rho_v V, \qquad \rho_v = const.$$

- Large negative pressure:

$$P = -\frac{\partial E}{\partial V} = -\rho_v.$$

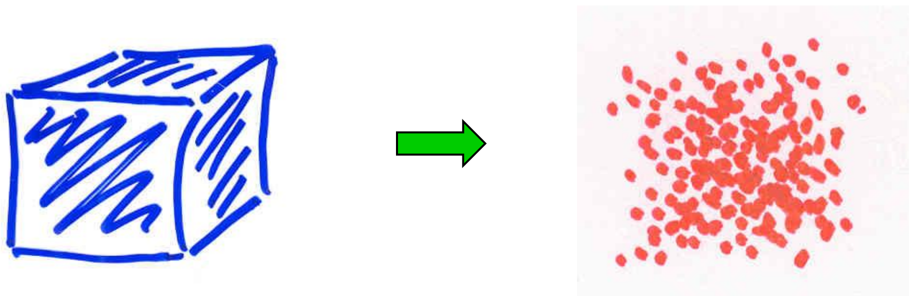
- Repulsive gravity:

$$\nabla^2 \Phi = 4\pi G(\rho_v + 3P_v) \Rightarrow$$



# Properties of false vacuum

- Decays into true vacuum + a hot fireball of particles:

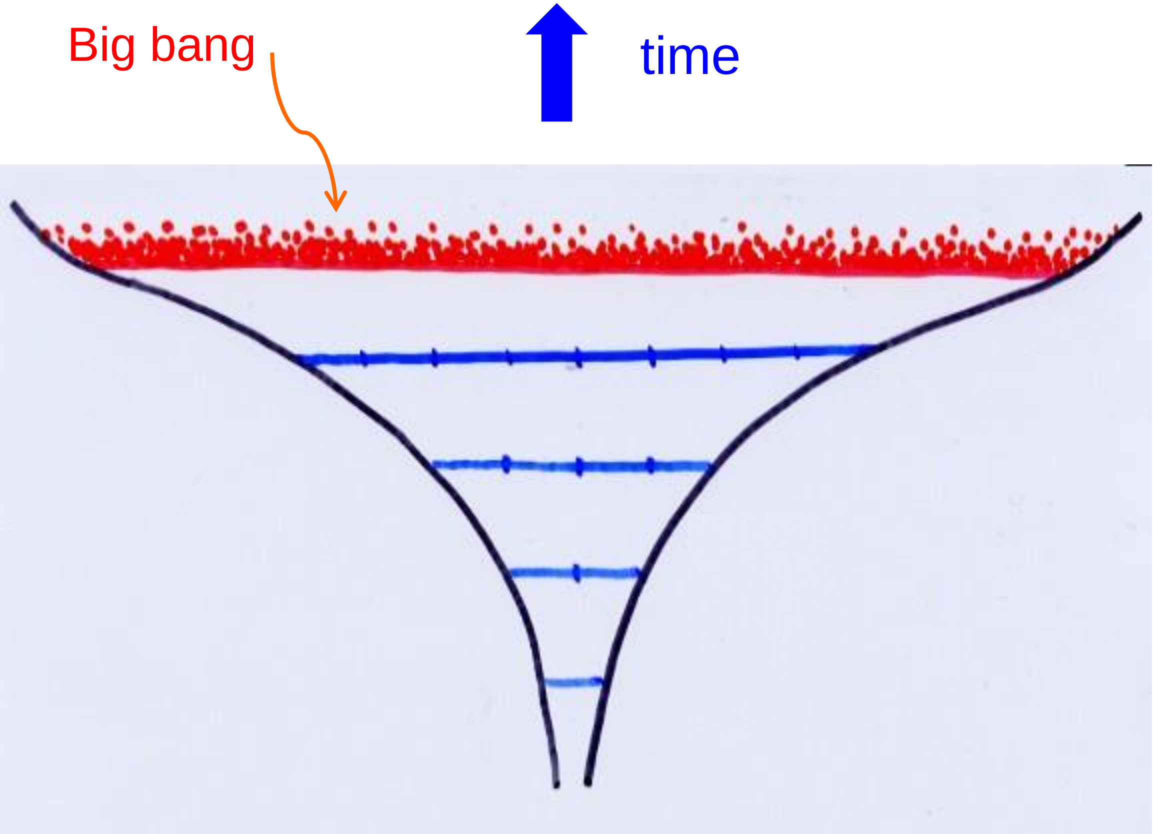


# Cosmic inflation

*Guth (1981)*

*Linde (1982)*

*Albrecht & Steinhardt (1982)*




$$R(t) \propto e^{Ht}$$

$$H = (8\pi G\rho_v / 3)^{1/2}$$

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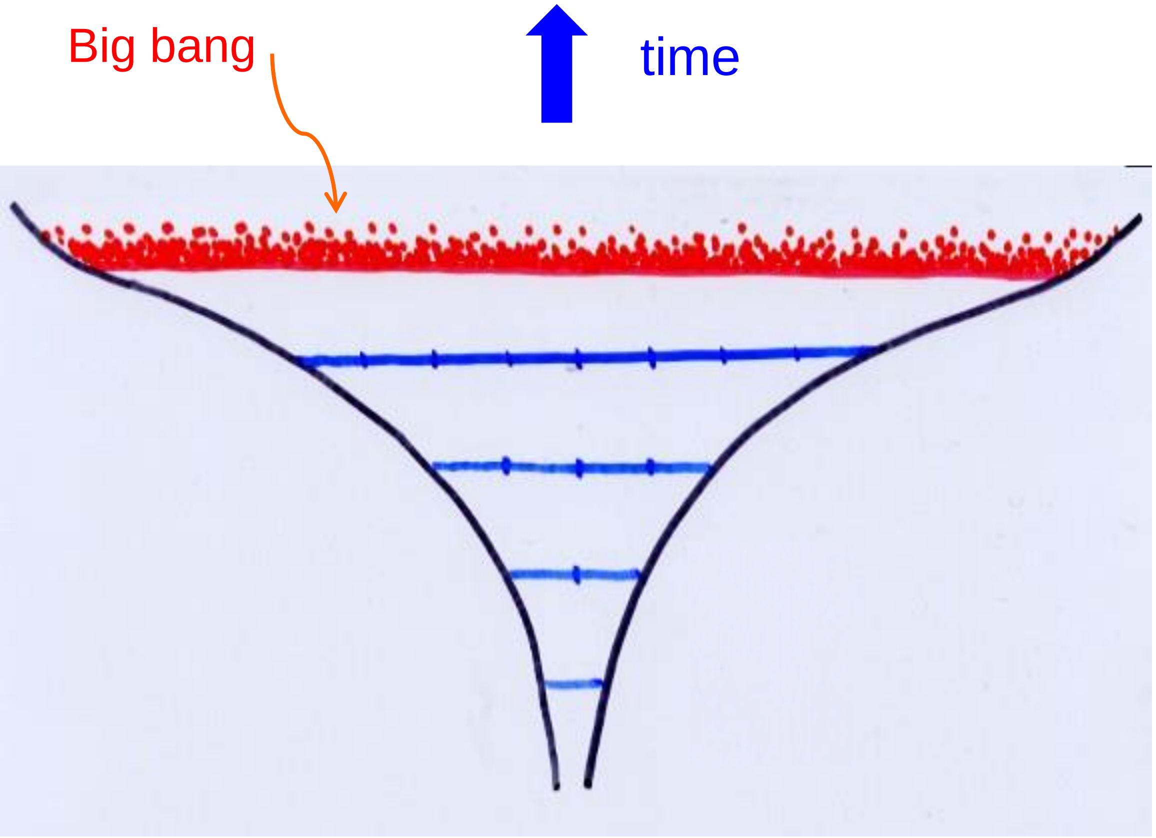
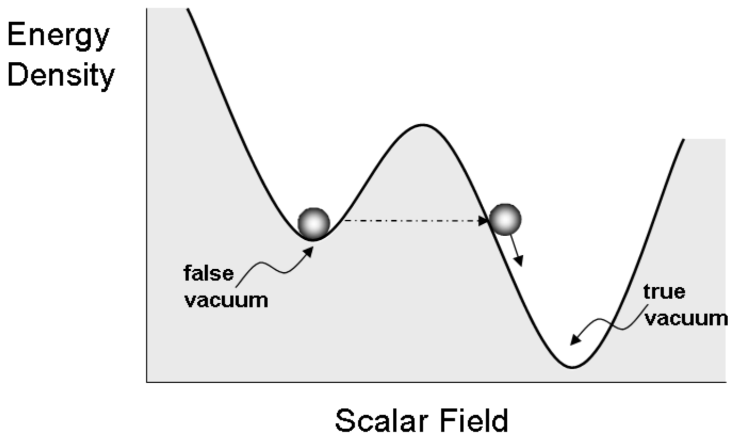


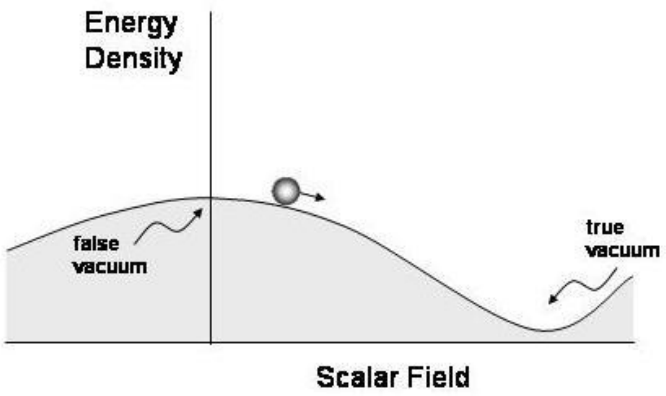

*Explains some puzzling features of the big bang:*

- High temperature
- Expansion
- Homogeneity and flatness
- Small inhomogeneities

*Mukhanov & Chibisov (1981)*

# Variety of models

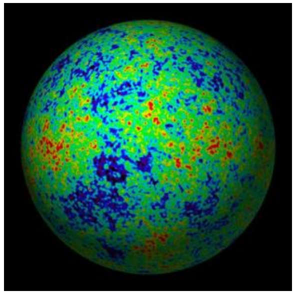


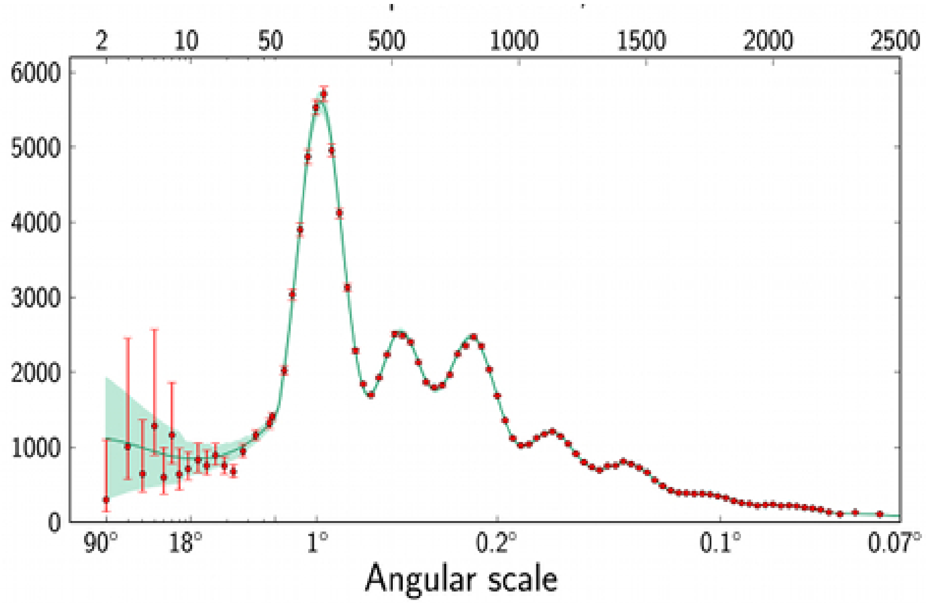

The key predictions are robust.

# Evidence for inflation:

CMB



*WMAP, Planck*




- Nearly scale-invariant spectrum of density fluctuations.
- Flat large-scale geometry (at ~1% accuracy).

*Inflation has now become*
*the leading cosmological paradigm.*

# BEYOND THE HORIZON

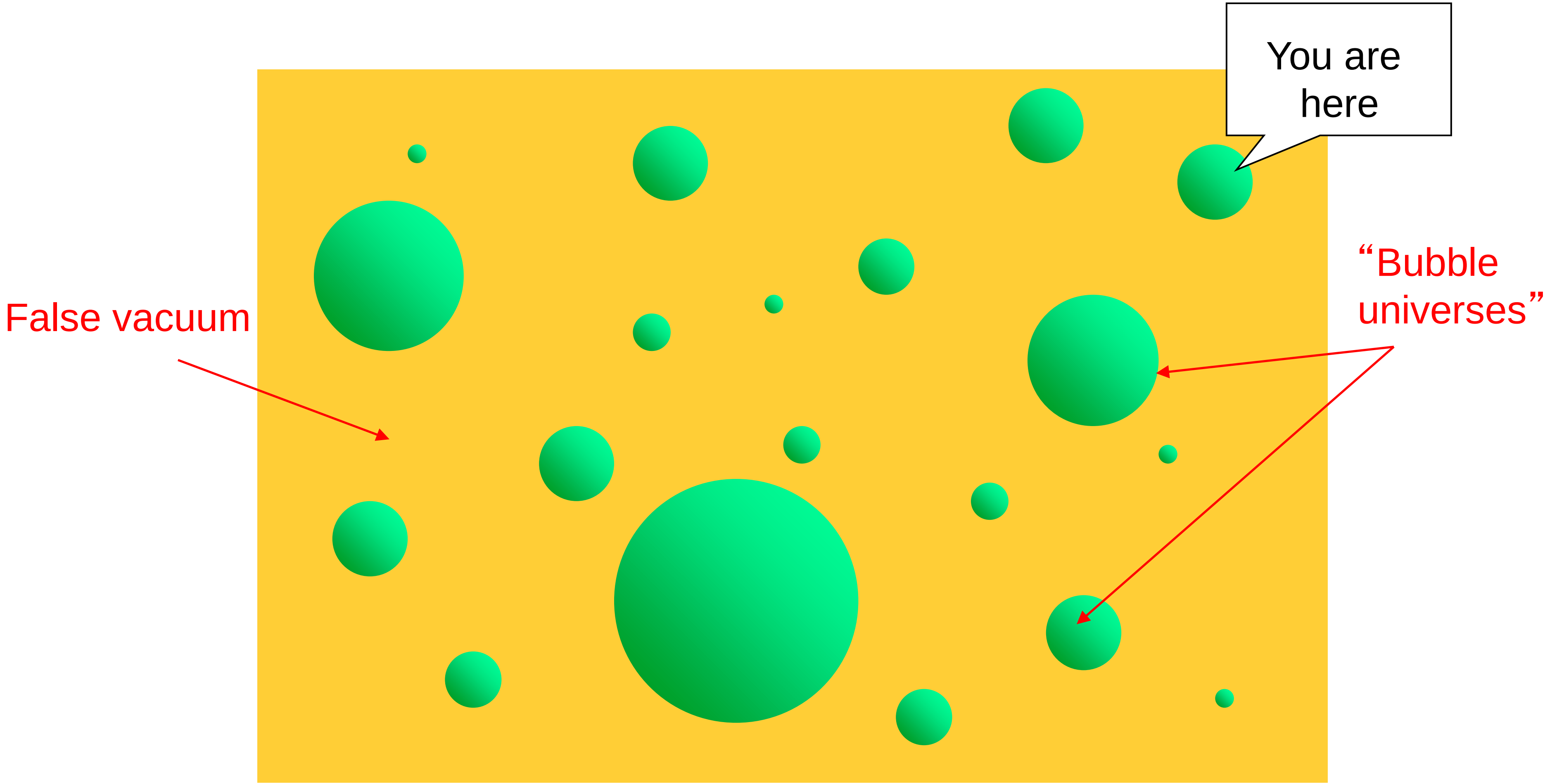
Inflation ended in our local region, but it still continues in distant parts of the universe.

*A.V. (1983)*

*A. Linde (1986)*

***Inflation is generically eternal.***

# False vacuum decays through bubble nucleation

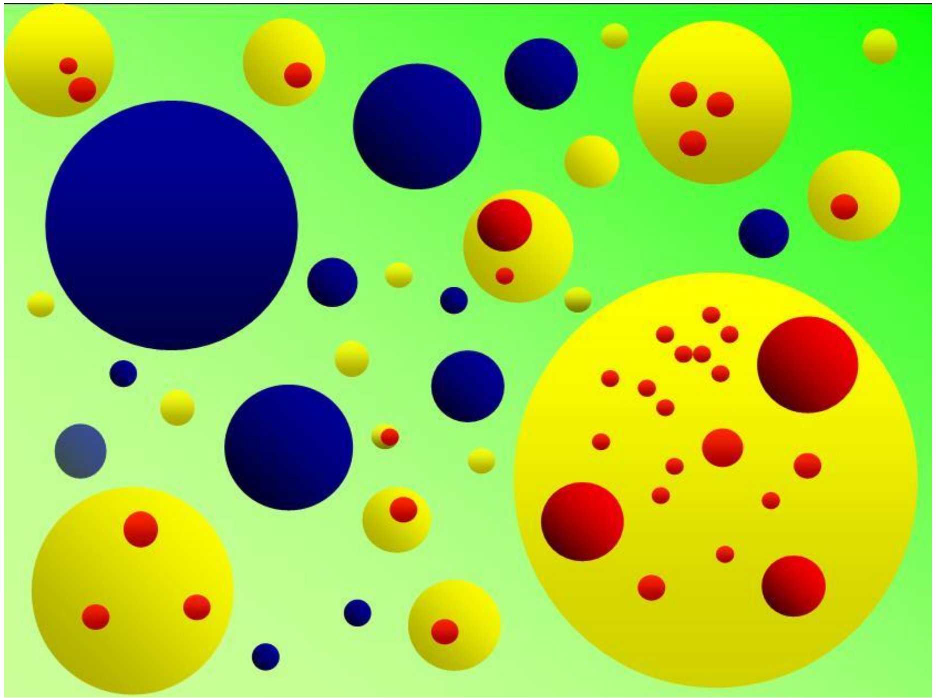



An unlimited number of bubbles will be formed in the course of eternal inflation.

Particle physics models typically predict a number of vacua with different low-energy constants of nature.

Bubbles of all types will be produced in the course of eternal inflation.

The multiverse



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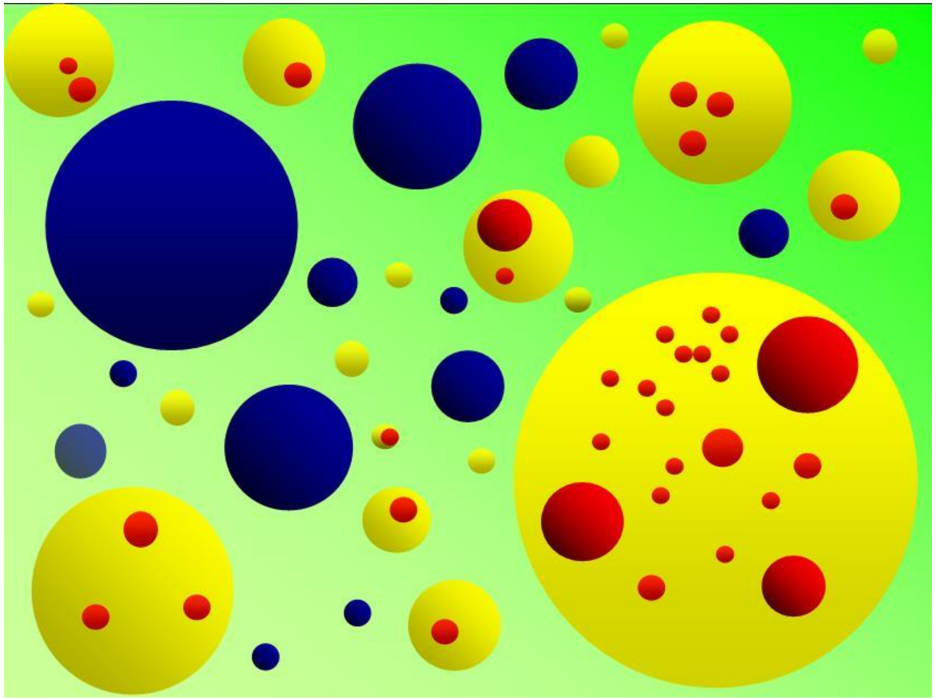

Particle theories with extra dimensions (including string theory) predict a vast landscape of vacua:

$$N \sim 10^{500}$$

*Bousso & Polchinski (2000)*

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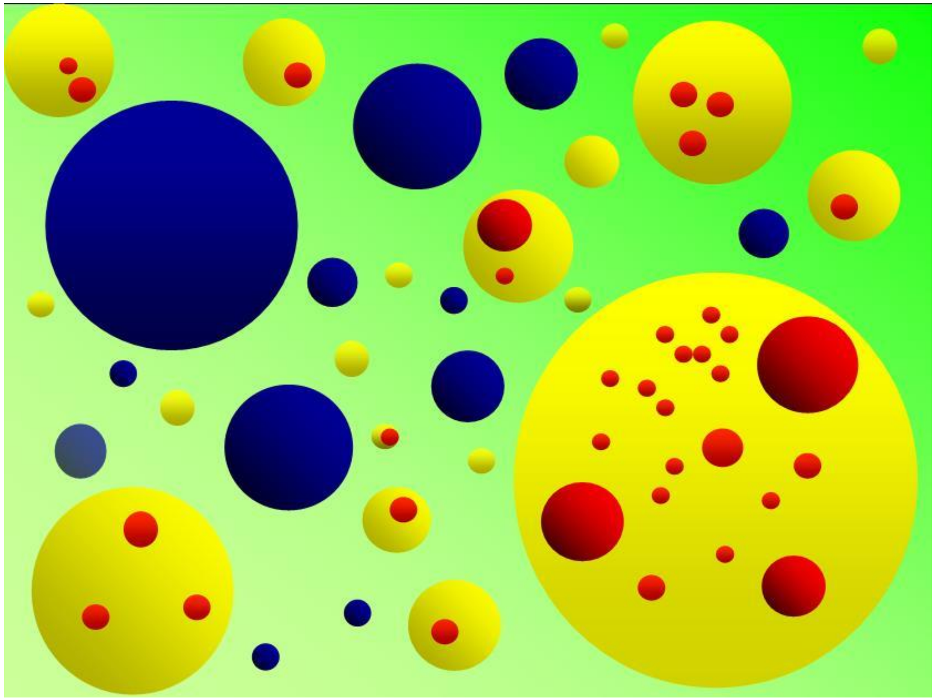

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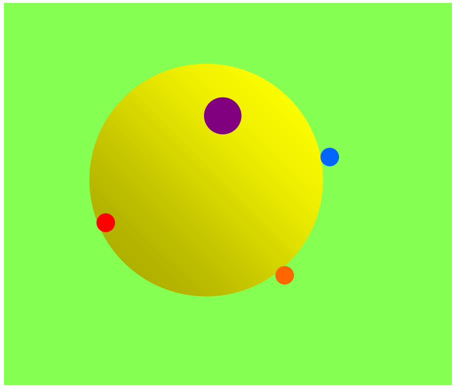
*Controversial !*

# How can we test multiverse models?



Bubble collisions can leave an imprint on the cosmic background radiation.

*Chang, Kleban & Levi (2008)*

This would be a direct evidence for the multiverse.

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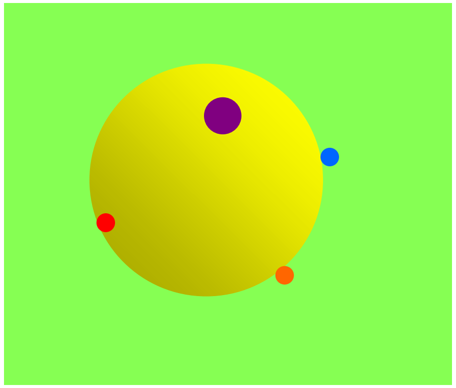

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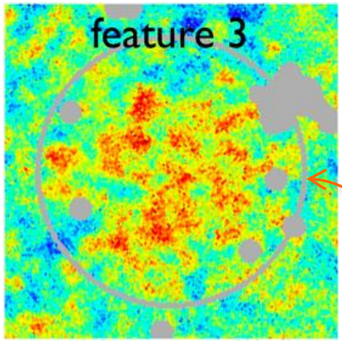


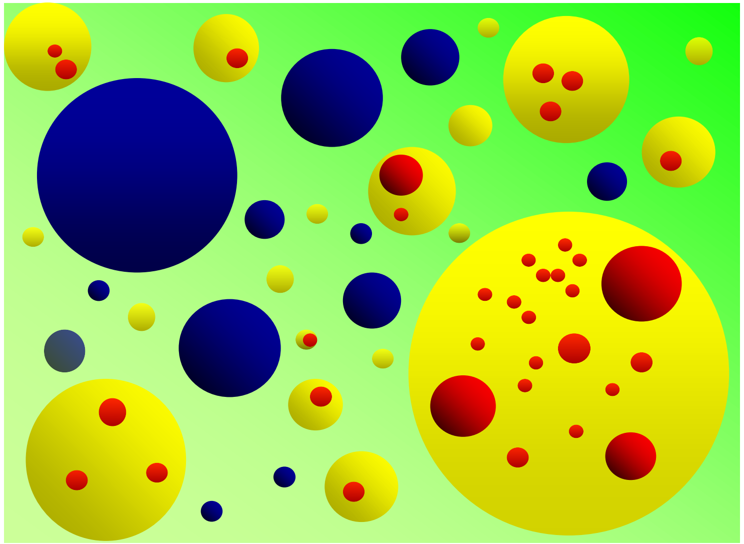

Search in the CMB data

*Feeney, Johnson, Mortlock & Peiris (2010)*

**A 7$^{o}$ hot spot consistent with a bubble collision.**

*No guarantee of detectable bubble collisions within our horizon.*

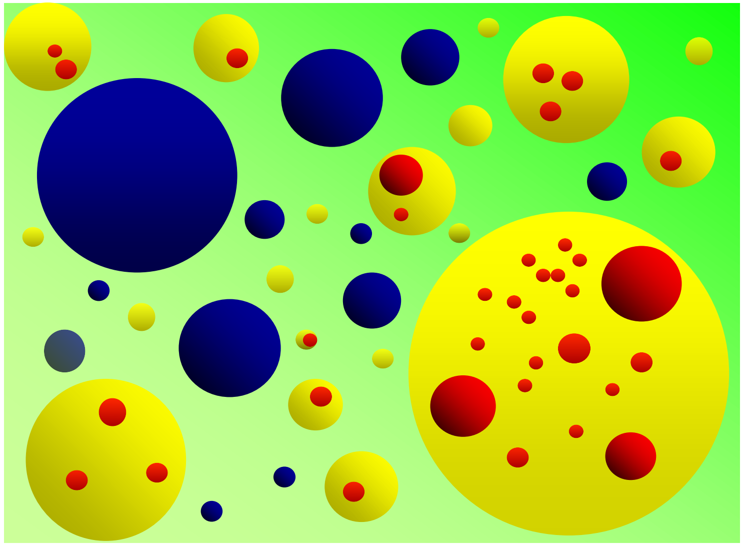
⇨ ***Indirect tests***



*Anthropic principle:* *Carter (1973)*

We can live only in bio-friendly bubbles. *This explains the fine-tuning of the constants.*

We can try to turn this into testable (statistical) predictions.



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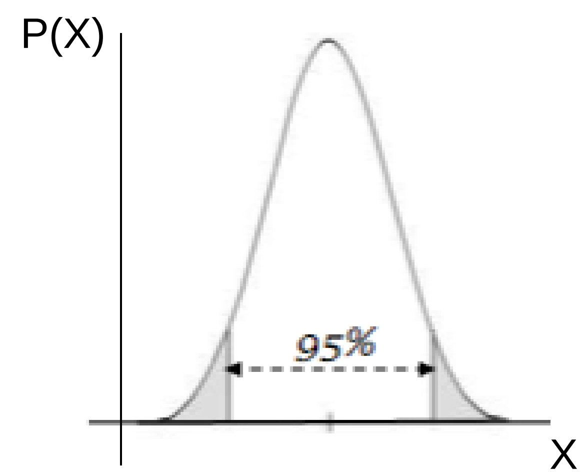
*Strategy:*

- Find the probability distribution for the values of some parameter *X* measured by a randomly picked observer.
- Make a prediction for a range of *X* at a specified confidence level.
- This assumes we are typical observers.

*Principle of mediocrity* A.V. (1995)




*Example: cosmological constant* Weinberg (1987)

# Cosmological constant problems

Cosmological constant = energy density of *our* vacuum

$$\Lambda = \frac{1}{V}\sum \frac{1}{2}\hbar\omega$$

Cutoff at $M_p \sim 10^{19}\,\mathrm{GeV}$ ➡ $\Lambda \sim 10^{120}\rho_m$

average density of matter

*Observations:* $\Lambda \sim 2\rho_m$

*Riess et. al. (1998)*
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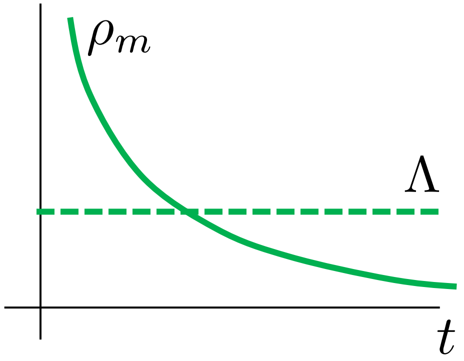
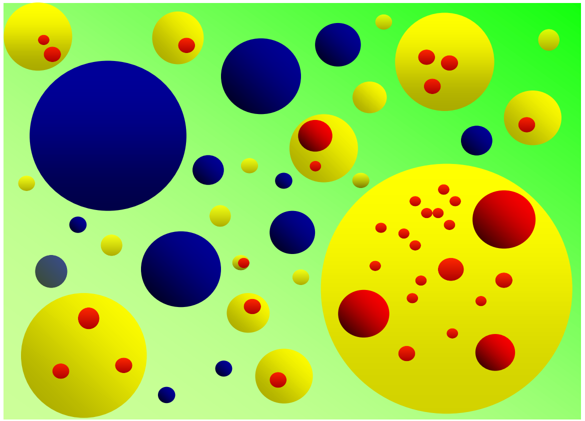
- *Why is* $\Lambda$ *so small? – The cosmological constant problem.*

  Fermions and bosons contribute with opposite signs,
  but we need cancellation up to 120th decimal point!

- *Why is* $L \sim r_m$*? – The coincidence problem.*



# In the multiverse:

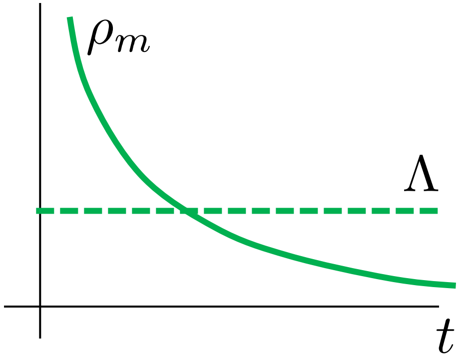


- $\Lambda$ takes different values in different bubbles.

$$|\Lambda| \lesssim 10^{120} \rho_m$$

(Focus on bubbles where other parameters are the same)

- Structure formation stops when $\Lambda$ starts dominating. High $\Lambda$ means no galaxies.




- Anthropic range: $-20\rho_m < \Lambda < 1000\rho_m$

*Weinberg (1987)*

# Probability distribution for a randomly picked observer

$$P(\Lambda) \propto P^{(vol)}(\Lambda) f^{(selec)}(\Lambda)$$

Fraction of volume (from particle physics and theory of inflation).

Number of observers per unit volume

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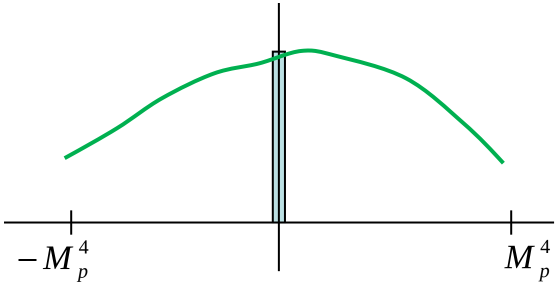
- The anthropic range is tiny compared to the full range of variation of $\Lambda$.



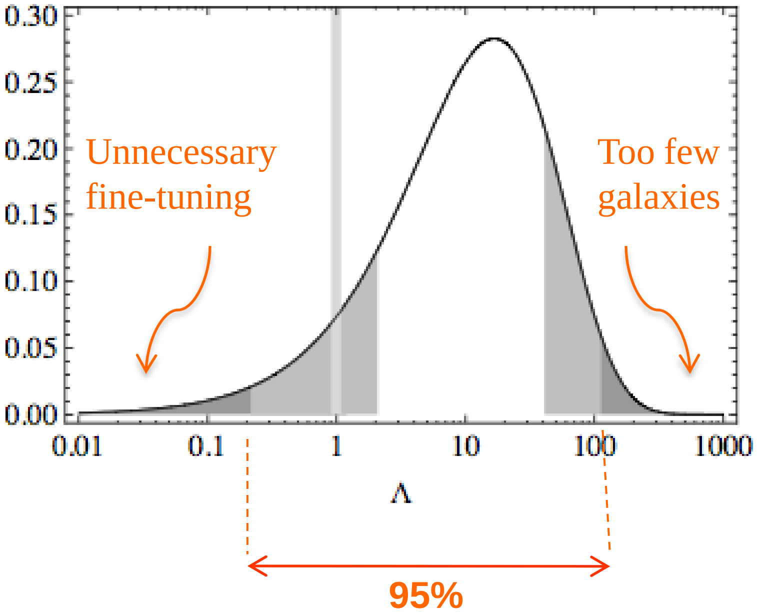

$$P^{(vol)}(\Lambda) \approx \text{const}$$

(in the range of interest).

- $f^{(selec)}$ is (roughly) proportional to the fraction of matter clustered in galaxies.

Assumes that the number of observers per unit mass in galaxies is independent of $\Lambda$ .

# Probability distribution for a randomly picked observer




*Weinberg (1987), A.V. (1995), Efstathiou (1995), Martel, Shapiro & Weinberg (1998)*

*(Before measurement)*

- Explains the coincidence: $\Lambda$ is expected to dominate near the end of galaxy formation epoch.
- No alternative explanations.

*Our first evidence for the multiverse*

# Which other parameters may be predicted?

$\rho_{DM}$

*Linde (1998)*
*Tegmark, Aguirre, Rees & Wilczek (2006)*

*Axions: peak at observed value*

$m_\nu$

*Pogosian, Tegmark & A.V. (2006)*

*Peak at* $\sum m_\nu \sim 1\,\mathrm{eV}$

# The measure problem

- In the multiverse, anything that can happen will happen – an infinite number of times. This includes all possible measurement results.

- Probabilities can be defined at a certain time. But the results generally depend on the choice of time variable.

  It can be "proper time" measured by clocks, the "scale factor time", or any combination of the two.

  *Linde & Mezhlumian (1994)*

- Predictions for $\Lambda$ are not sensitive to this choice.

*May need new ideas.*

- *Measure form the fundamental theory?*

  Holographic ideas;
  Quantum cosmology.

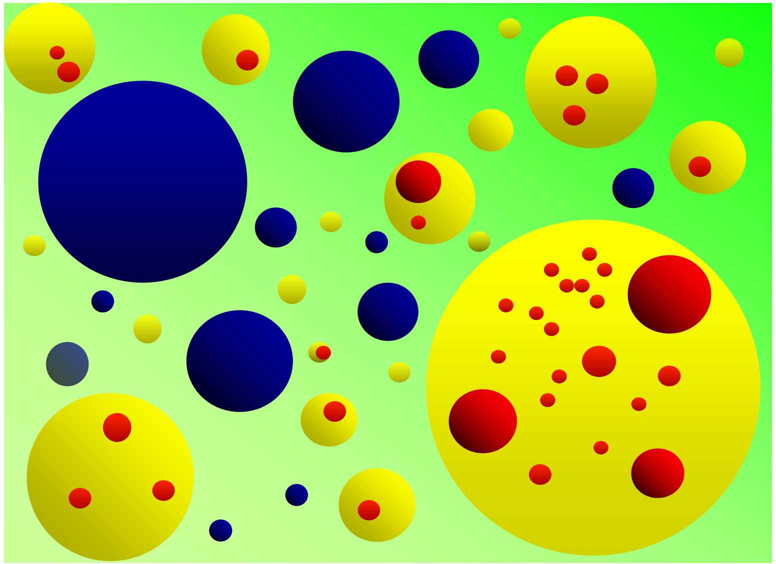
  *Garriga & A.V.*
  *Bousso, Freivogel et.al.*
  *Nomura*

  *Favor scale factor measure.*

# DID THE UNIVERSE HAVE A BEGINNING?

Inflation is generically eternal
to the future.

Could it have no beginning
in the past?



## ***Theorem:***

*A universe that is on average expanding is geodesically incomplete to the past.*

Does not rely on Einstein's equations.

*Borde, Guth & A.V. (2003)*

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⇨ Inflation cannot be eternal to the past.

*What happened before inflation?*

*And what happened before that?*

## Spontaneous creation of universes from "nothing".

A compact inflating universe can spontaneously nucleate out of "nothing".

A state with no classical space, time and matter.

*A.V. (1982), Hartle & Hawking (1983), Linde (1984), Rubakov (1984), Zel'dovich & Starobinsky (1984)*

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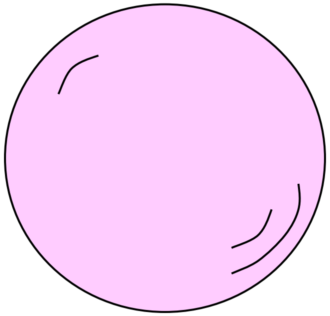

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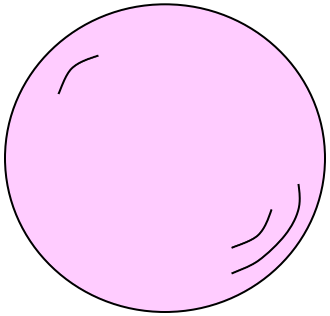

*Most probable initial state:*

a small closed universe filled with a high-energy false vacuum.

*No time before.*

*St. Augustine (398)*

# SUMMARY

- Inflation is a never-ending process, constantly producing new “bubble universes” with diverse properties.

- This multiverse picture can be tested using the principle of mediocrity.

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- Inflation is a never-ending process, constantly producing new "bubble universes" with diverse properties.
- This multiverse picture can be tested using the principle of mediocrity.
- The multiverse is eternal to the future, but it must have a beginning.
- Quantum cosmology may provide the probability distribution for the initial states.

# End of the world

- A negative energy bubble will eventually nucleate within our horizon.

- It will engulf the entire visible universe, turning all objects into some alien forms of matter.