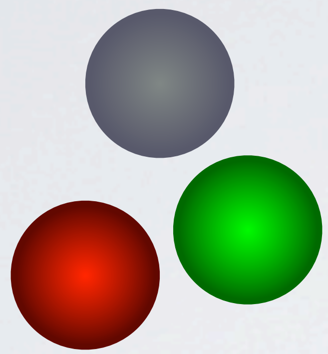
PARTICLE COSMOLOGY

David Seery

University of Sussex

STFC Introductory School in Astronomy, 2012

What lies beyond the Standard Model?



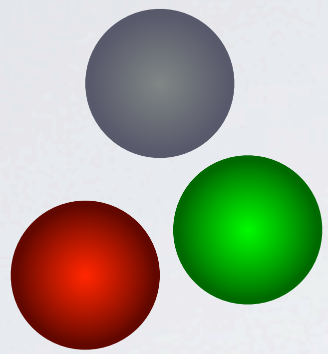
forces [$W^{\pm}$, Z, γ

matter [$e^{\pm}$, $\nu \times 3$ generations

quarks × 3 generations

probably at least one Higgs

What lies beyond the Standard Model?



forces [$W^\pm$, Z, γ

matter [$e\pm$, $\nu \times 3$ generations
quarks $\times$ 3 generations

probably at least one Higgs

- Why these particles? Why these gauge groups?
- Why are there three generations of the leptons? (anomalies)
- What determines the masses and how they couple?

What lies beyond the Standard Model?

Most people expect the Standard Model to be part of a larger structure

What lies beyond the Standard Model?

Most people expect the Standard Model to be part of a larger structure

1000 GeV the frontier

What lies beyond the Standard Model?

Most people expect the Standard Model to be part of a larger structure

1000 GeV	the frontier
175 GeV	top quark
125 GeV	probable Higgs boson
90 GeV	$W^{\pm}$, Z bosons
4 GeV	bottom quark

What lies beyond the Standard Model?

Most people expect the Standard Model to be part of a larger structure

1000 GeV the frontier

175 GeV top quark

125 GeV probable Higgs boson

90 GeV $W^{\pm}$, Z bosons

The $W^{\pm}$, Z want to be like photons.
They don't like having mass, and
misbehave at high energy.
More stuff comes out than goes in.

4 GeV bottom quark

What lies beyond the Standard Model?

Most people expect the Standard Model to be part of a larger structure

1000 GeV the frontier

175 GeV top quark

125 GeV probable Higgs boson

90 GeV $W^{\pm}$, Z bosons

4 GeV bottom quark

Can we repeat this kind of argument in cosmology?

The $W^{\pm}$, Z want to be like photons.
They don't like having mass, and misbehave at high energy.
More stuff comes out than goes in.

The $5bn argument for building the LHC was that something had to fix this.

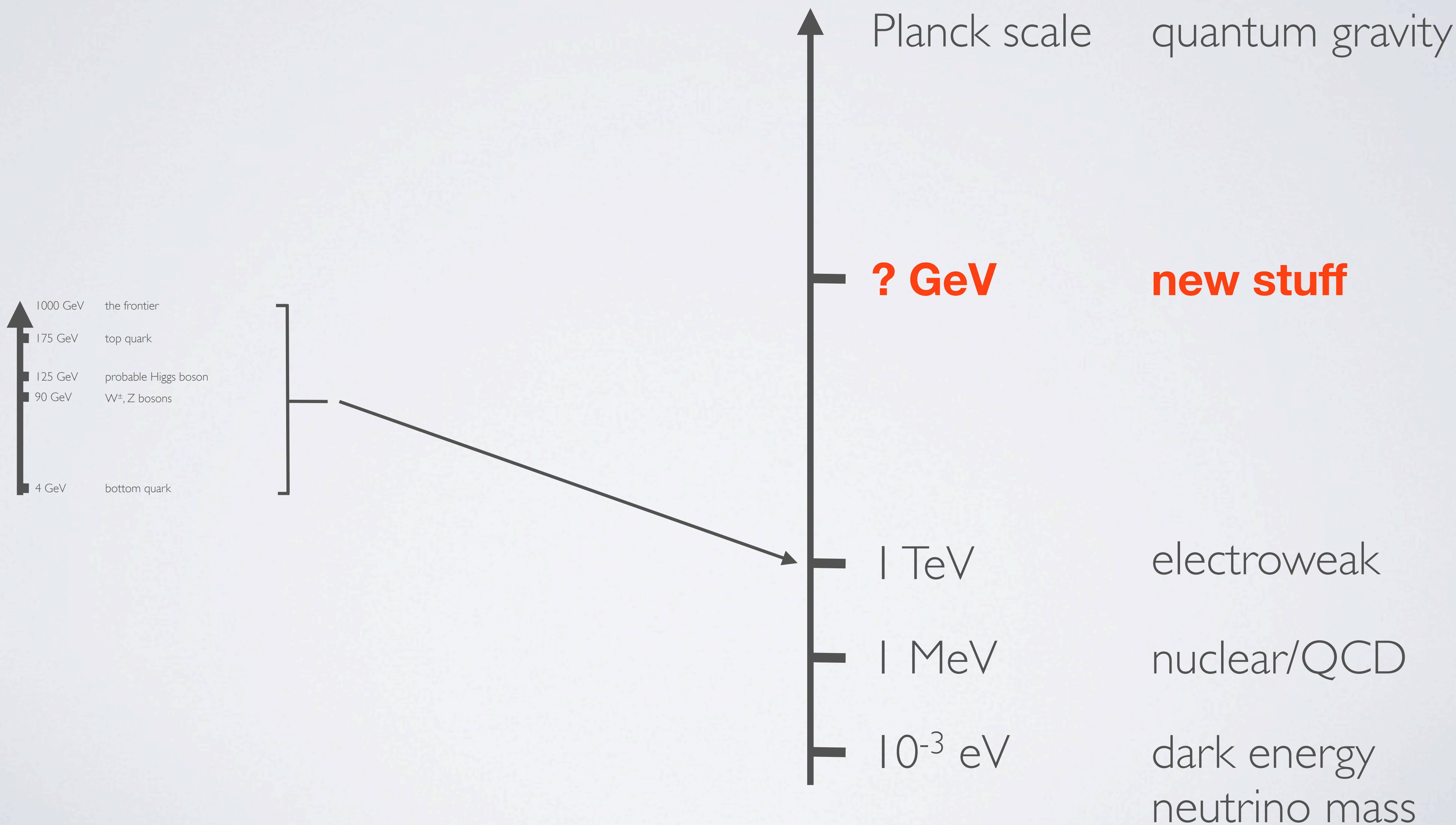
What lies beyond the Standard Model?

Most people expect the Standard Model to be part of a larger structure

1000 GeV	the frontier
175 GeV	top quark
125 GeV	probable Higgs boson
90 GeV	$W^{\pm}$, Z bosons
4 GeV	bottom quark

What lies beyond the Standard Model?

Most people expect the Standard Model to be part of a larger structure



That's as far as this argument gets us

We have no idea where this new physics might live,
or what it might look like

But you often hear words like

grand unified theories

supergravity

string theory

loop quantum gravity

causal set theory

Grand unified theories

This is the least ambitious suggestion for what might happen in the UV

usually we think of the electroweak gauge bosons as being separate

for example, they have different masses

Grand unified theories

This is the least ambitious suggestion for what might happen in the UV

80 GeV 90 GeV 0 GeV

$W^{\pm}$ Z γ

usually we think of the electroweak gauge bosons as being separate

for example, they have different masses

at high energy

~~80 GeV~~ ~~90 GeV~~ ~~0 GeV~~

$W^{\pm}$ Z γ

they all look massless

$$E^2 = p^2c^2 + m^2c^4$$

Grand unified theories

This is the least ambitious suggestion for what might happen in the UV

80 GeV 90 GeV 0 GeV

$W^{\pm}$ Z γ

usually we think of the electroweak gauge bosons as being separate

for example, they have different masses

at high energy

~~80 GeV~~ ~~90 GeV~~ ~~0 GeV~~

$W^{\pm}$ Z γ

we can package them all as the gauge bosons of SU(2) × U(1)

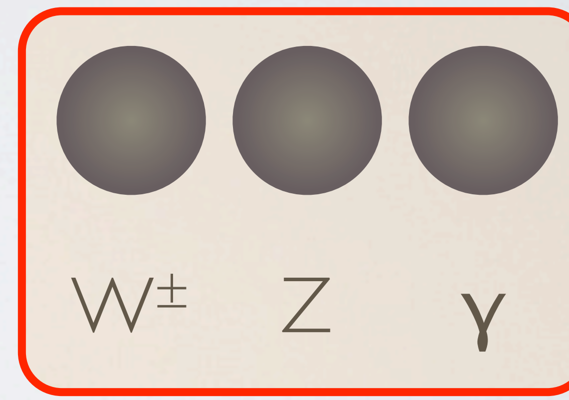
they all look massless

$$E^2 = p^2c^2 + m^2c^4$$

Grand unified theories

This is the least ambitious suggestion for what might happen in the UV

~~80 GeV~~ ~~90 GeV~~ ~~0 GeV~~



we can package them all as the gauge bosons of SU(2) × U(1)

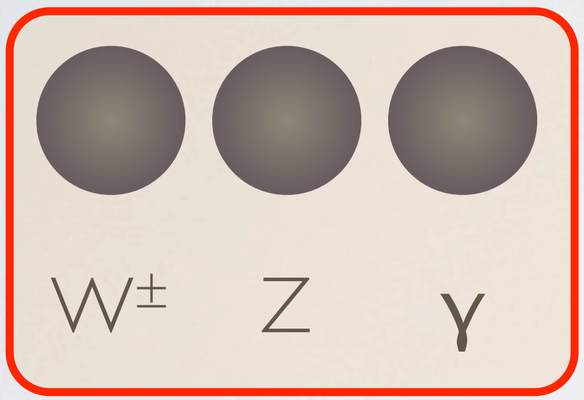
they all look massless

Grand unified theories

This is the least ambitious suggestion for what might happen in the UV

~100 GeV

~~80 GeV~~ ~~90 GeV~~ ~~0 GeV~~



we can package them
all as the gauge bosons
of SU(2) × U(1)

they all look massless

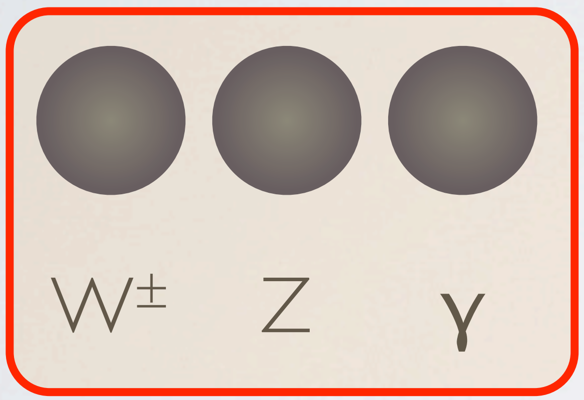
Grand unified theories

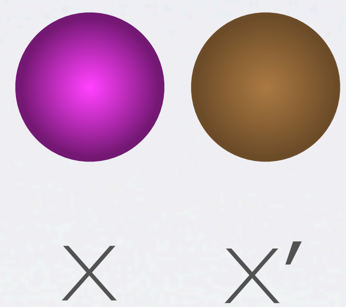
This is the least ambitious suggestion for what might happen in the UV

~100 GeV

~~80 GeV~~ ~~90 GeV~~ ~~0 GeV~~

M_{GUT} GeV





we can package them
all as the gauge bosons
of SU(2) × U(1)

maybe there
are other particles
with larger masses

they all look massless

Grand unified theories

This is the least ambitious suggestion for what might happen in the UV

~100 GeV

~~80 GeV~~ ~~90 GeV~~ ~~0 GeV~~ M_{GUT} GeV

$W^{\pm}$ Z γ X X′

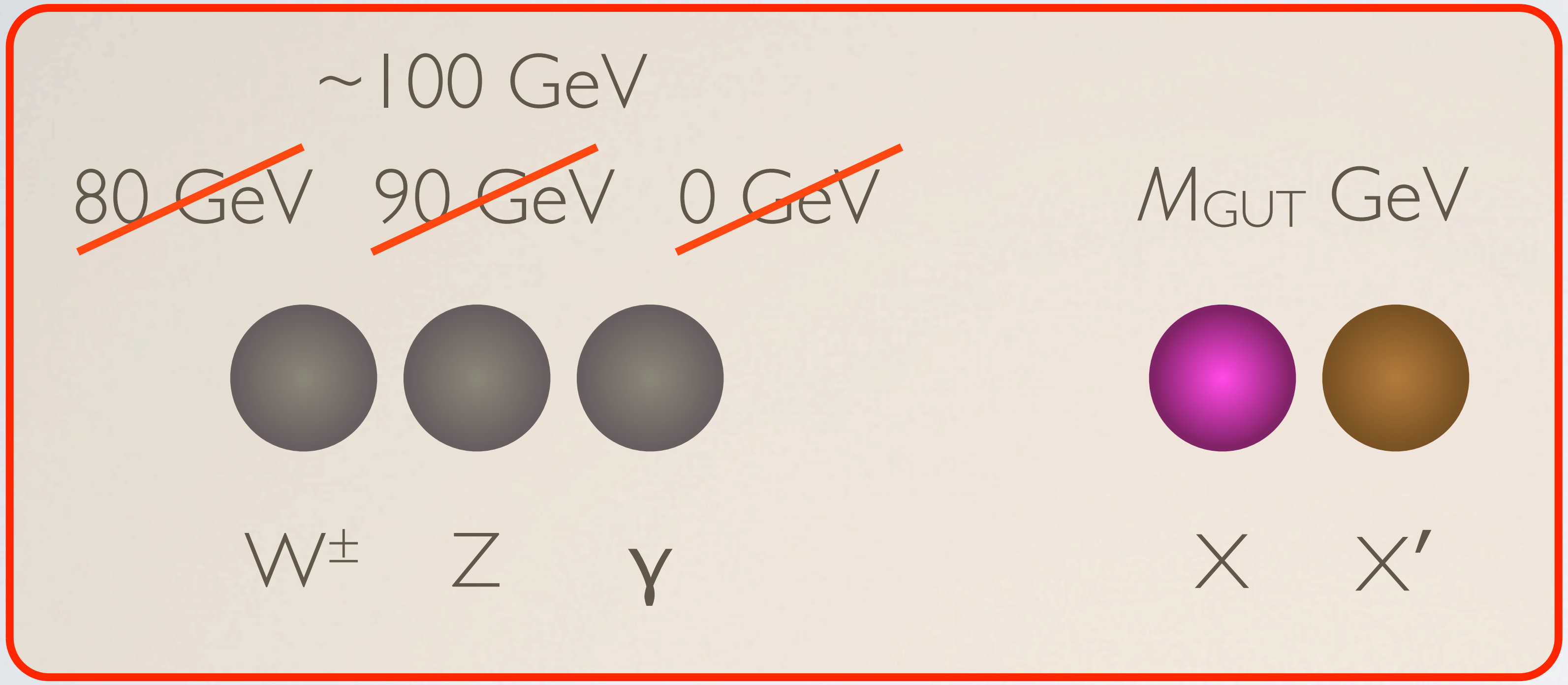
we can package them all as the gauge bosons of SU(2) × U(1)

maybe there are other particles with larger masses

they all look massless

Grand unified theories

This is the least ambitious suggestion for what might happen in the UV



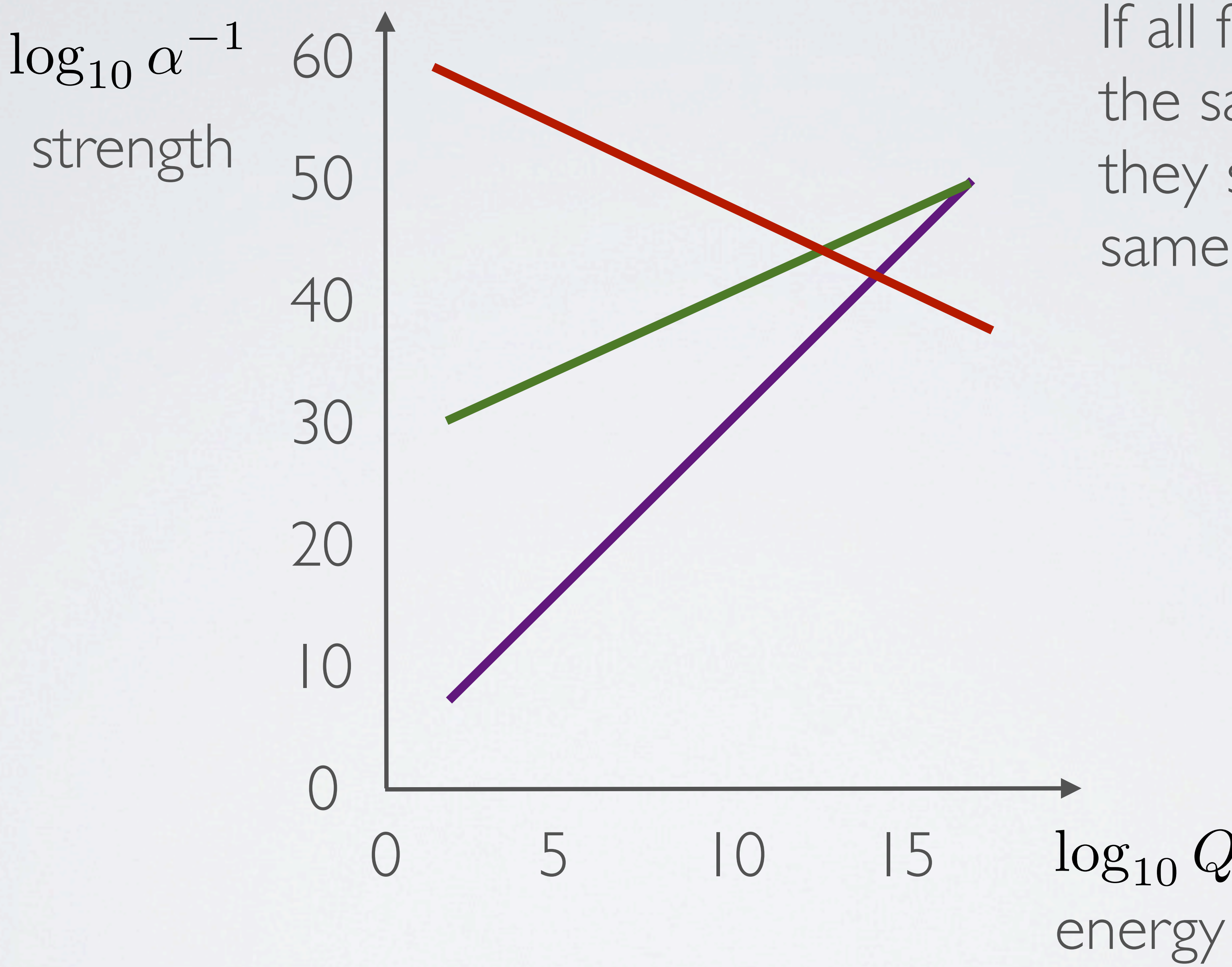
at energies larger than M_{GUT}, these could be packaged as the bosons of a larger gauge group

we can package them all as the gauge bosons of SU(2) × U(1)

maybe there are other particles with larger masses

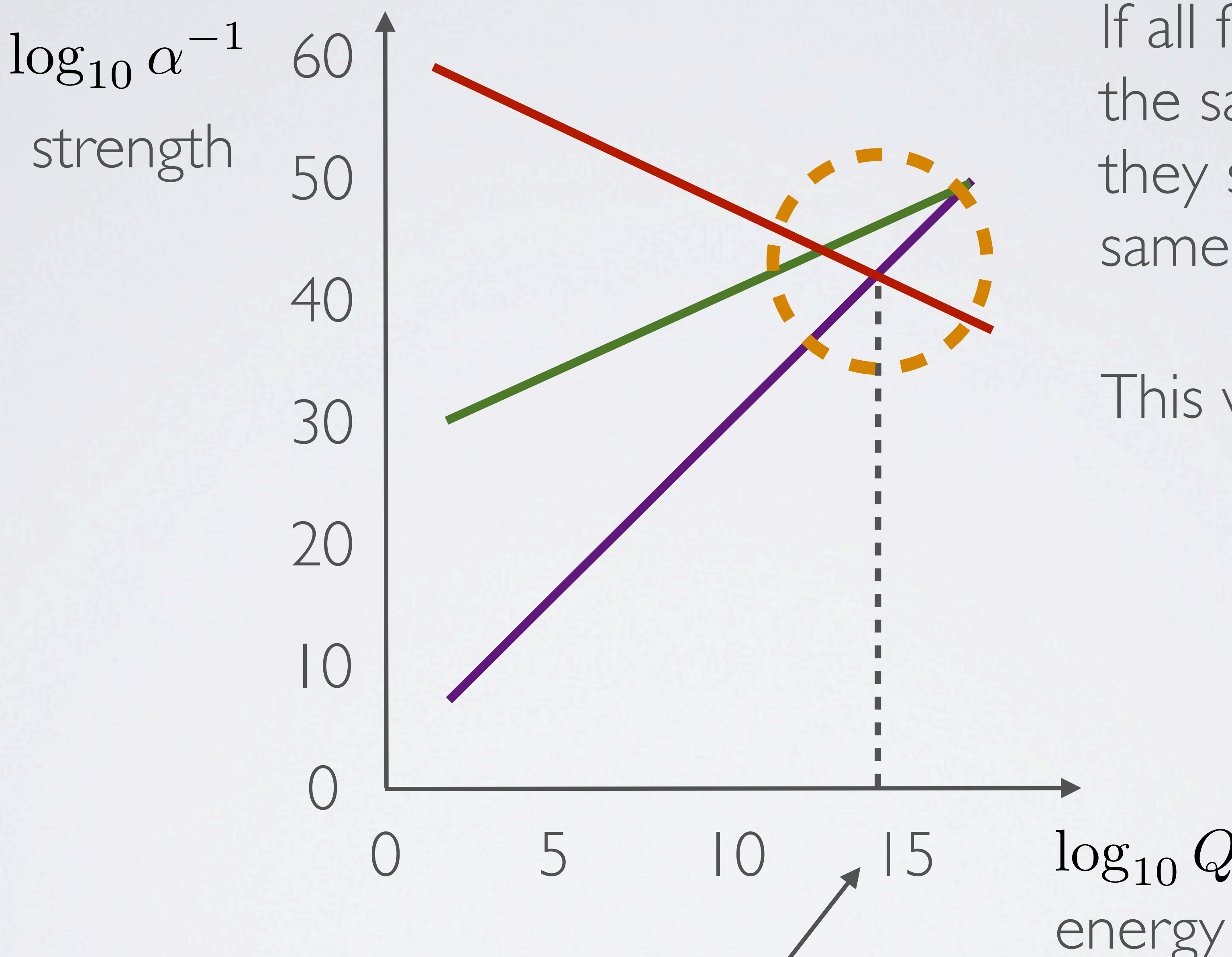
they all look massless

Grand unified theories



If all forces did behave the same at high energy, they should have the same strength.

Grand unified theories



If all forces did behave the same at high energy, they should have the same strength.

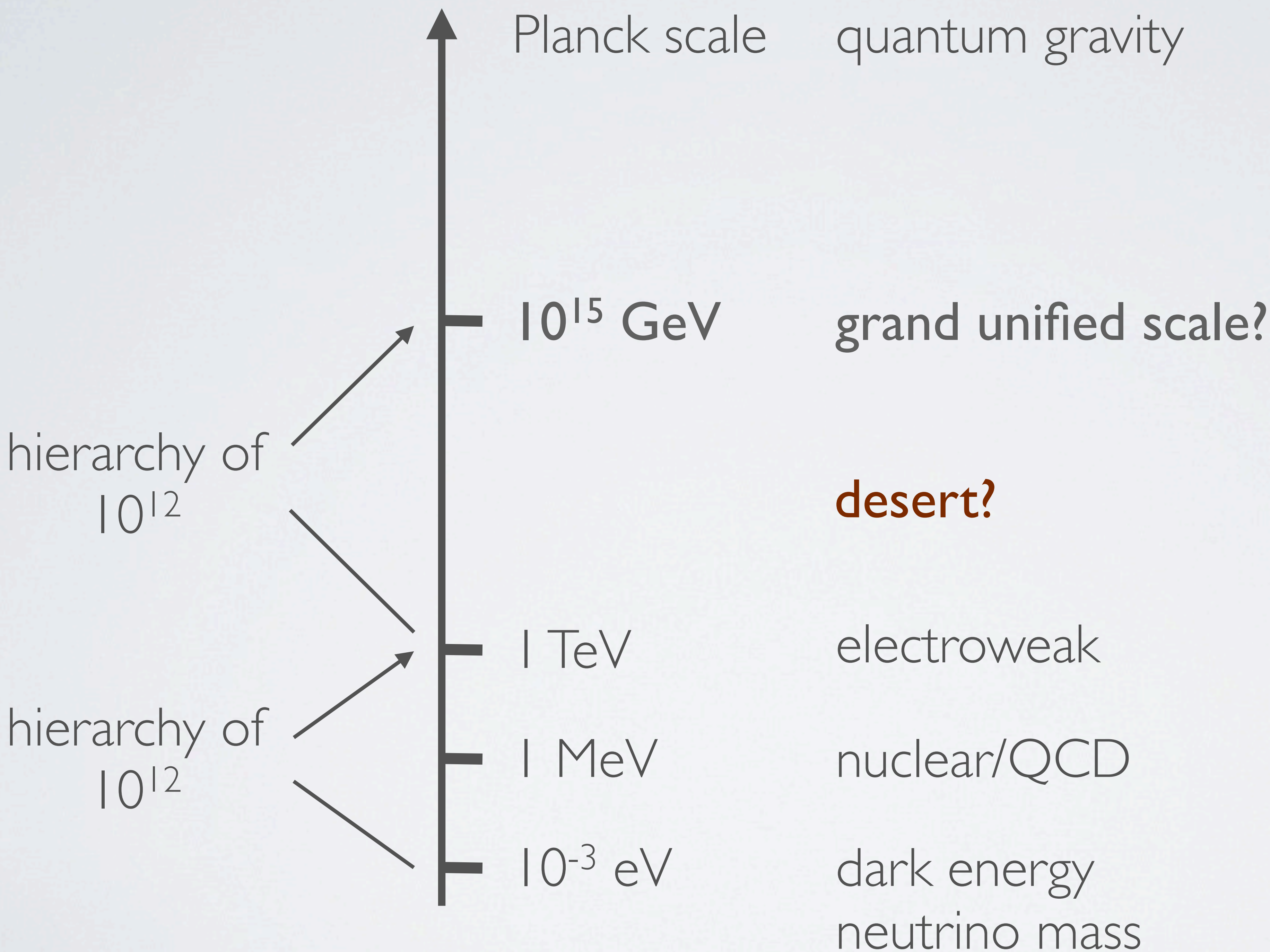
This very nearly happens

The unification point is near 10^{15} GeV

Grand unified theories

Planck scale	quantum gravity
10^{15} GeV	**grand unified scale?**
1 TeV	electroweak
1 MeV	nuclear/QCD
10^{-3} eV	dark energy neutrino mass

Grand unified theories



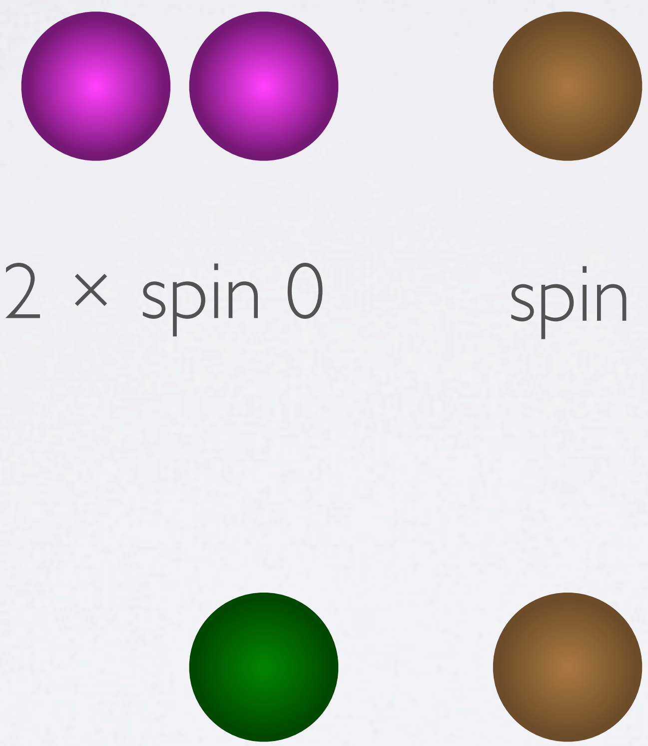
Supersymmetry and supergravity

The problem with this type of approach is that the new theory seems just as arbitrary as the old one.

Supersymmetry and supergravity

The problem with this type of approach is that the new theory seems just as arbitrary as the old one.

How does good behaviour come about?



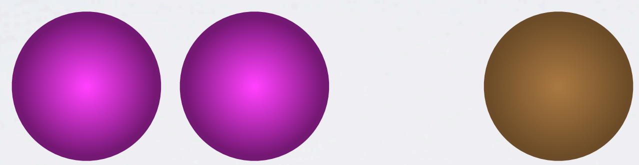
2 × spin 0   spin ½ ↑,↓

spin 1, two polarizations ⟳,⟲   spin ½ ↑,↓

Supersymmetry and supergravity

The problem with this type of approach is that the new theory seems just as arbitrary as the old one.

How does good behaviour come about?

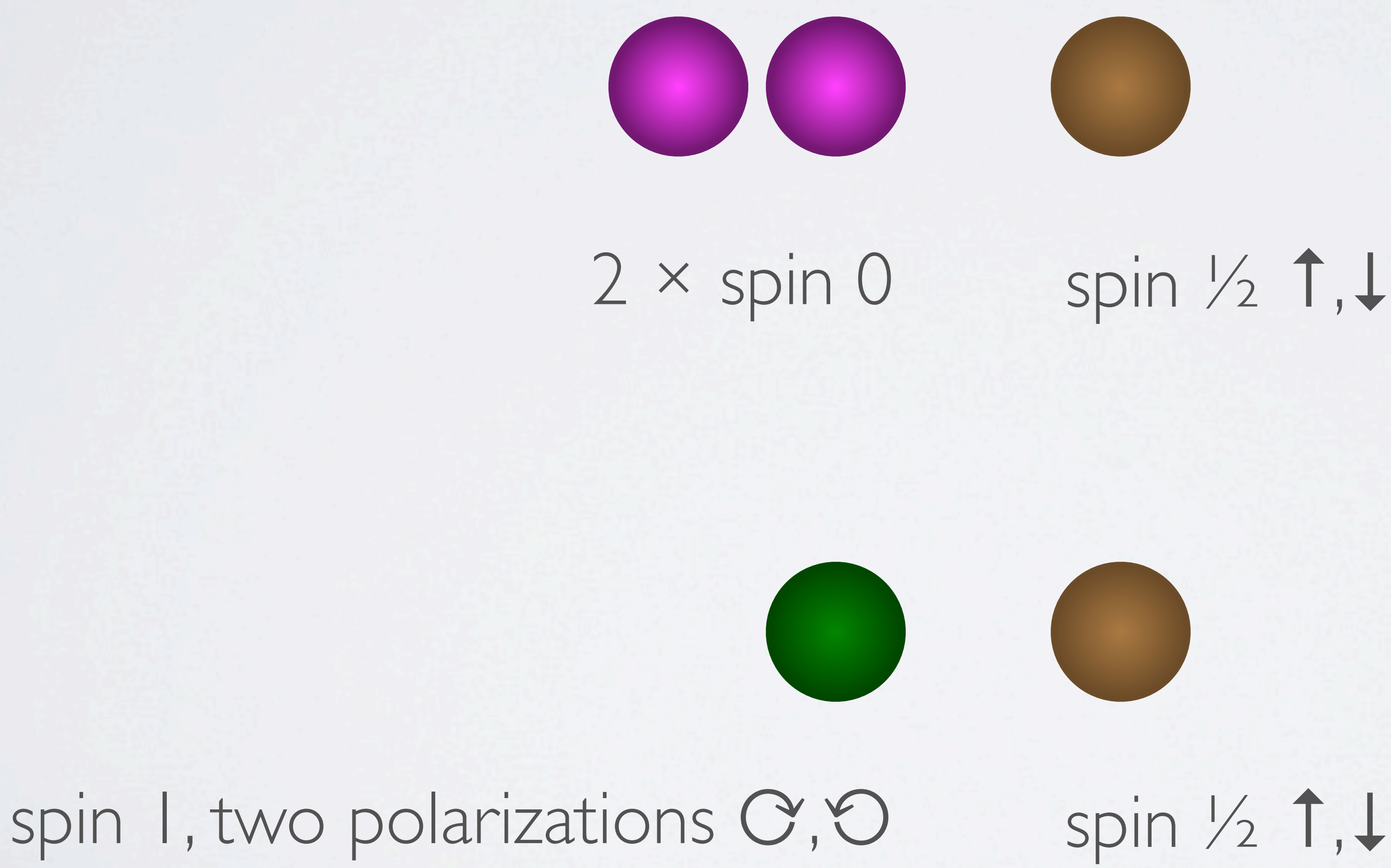


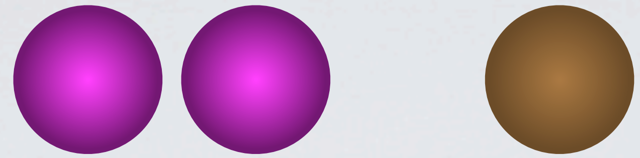
2 × spin 0 spin ½ ↑,↓

bad behaviour cancels

spin 1, two polarizations ⟳,⟲ spin ½ ↑,↓

bad behaviour cancels


2 × spin 0
spin ½ ↑,↓
spin 1, two polarizations ↻,↺
spin ½ ↑,↓

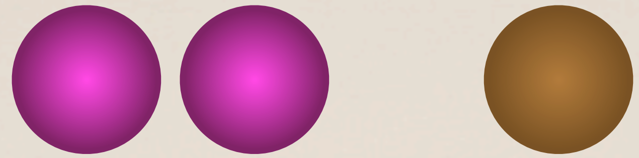


2 × spin 0

spin ½ ↑,↓

spin 1, two polarizations ⟳,⟲

spin ½ ↑,↓



chiral superfield

2 × spin 0

spin ½ ↑,↓

electron + selectron
neutrino + sneutrino

vector superfield

spin 1, two polarizations ↻,↺

spin ½ ↑,↓

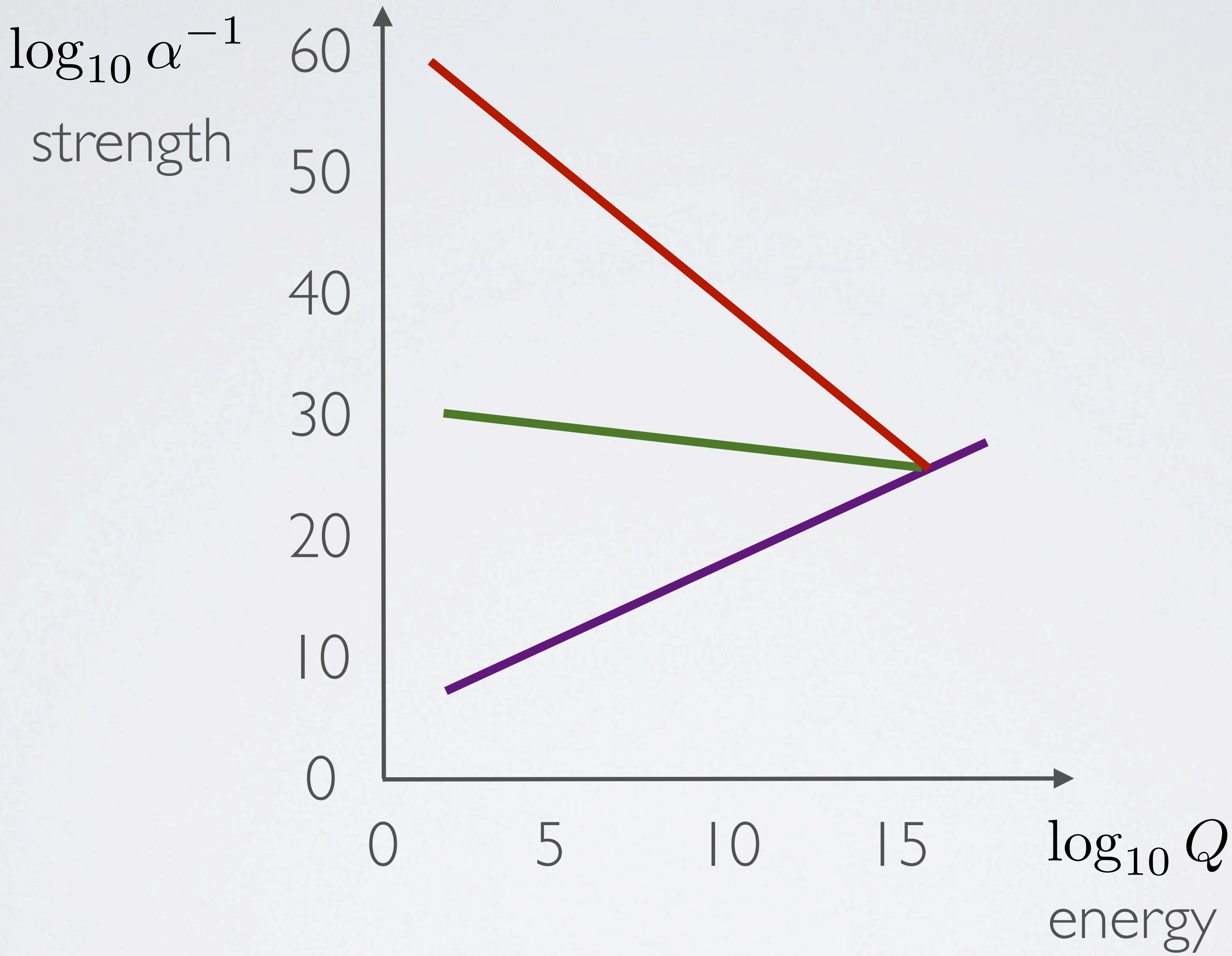
photon + photino
W + wino

If we build our theories out of packages of fields, with each package adjusted to behave nicely, we end up with a nice theory

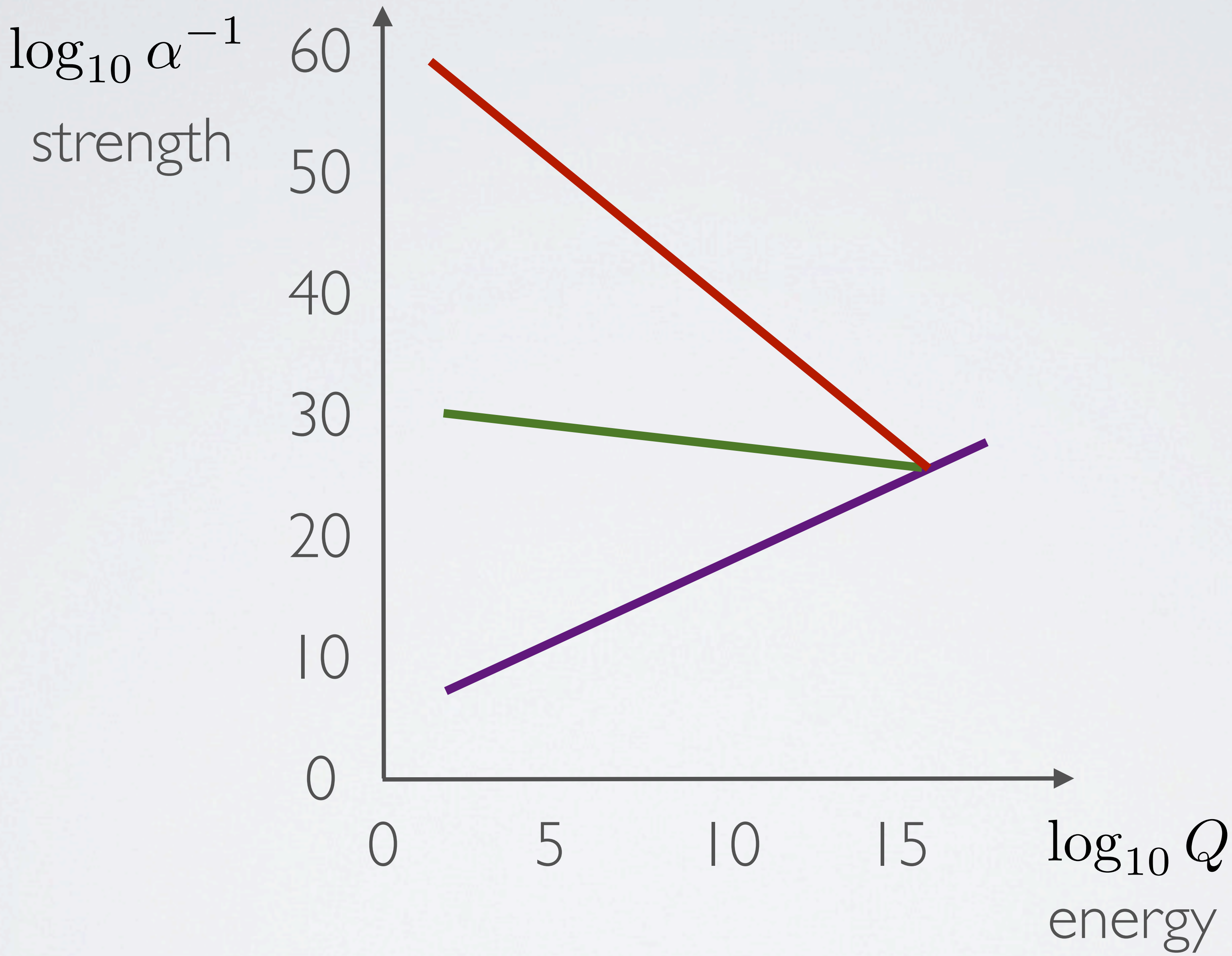
This is what happens in supersymmetry

Supergravity is what you get when you apply this idea to general relativity.
It has some nice features, but it is complicated

Supersymmetric grand unified theories



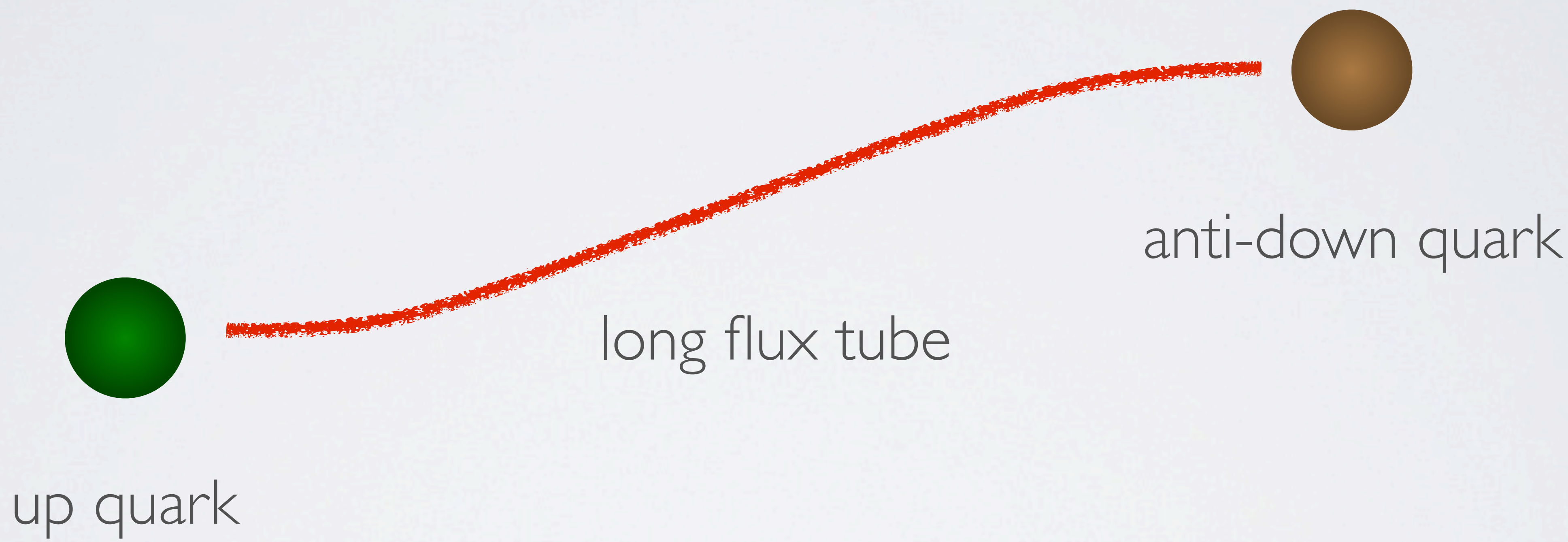
Supersymmetric grand unified theories



This time the unification is nearly exact.
This is one of the major reasons people like supersymmetry.

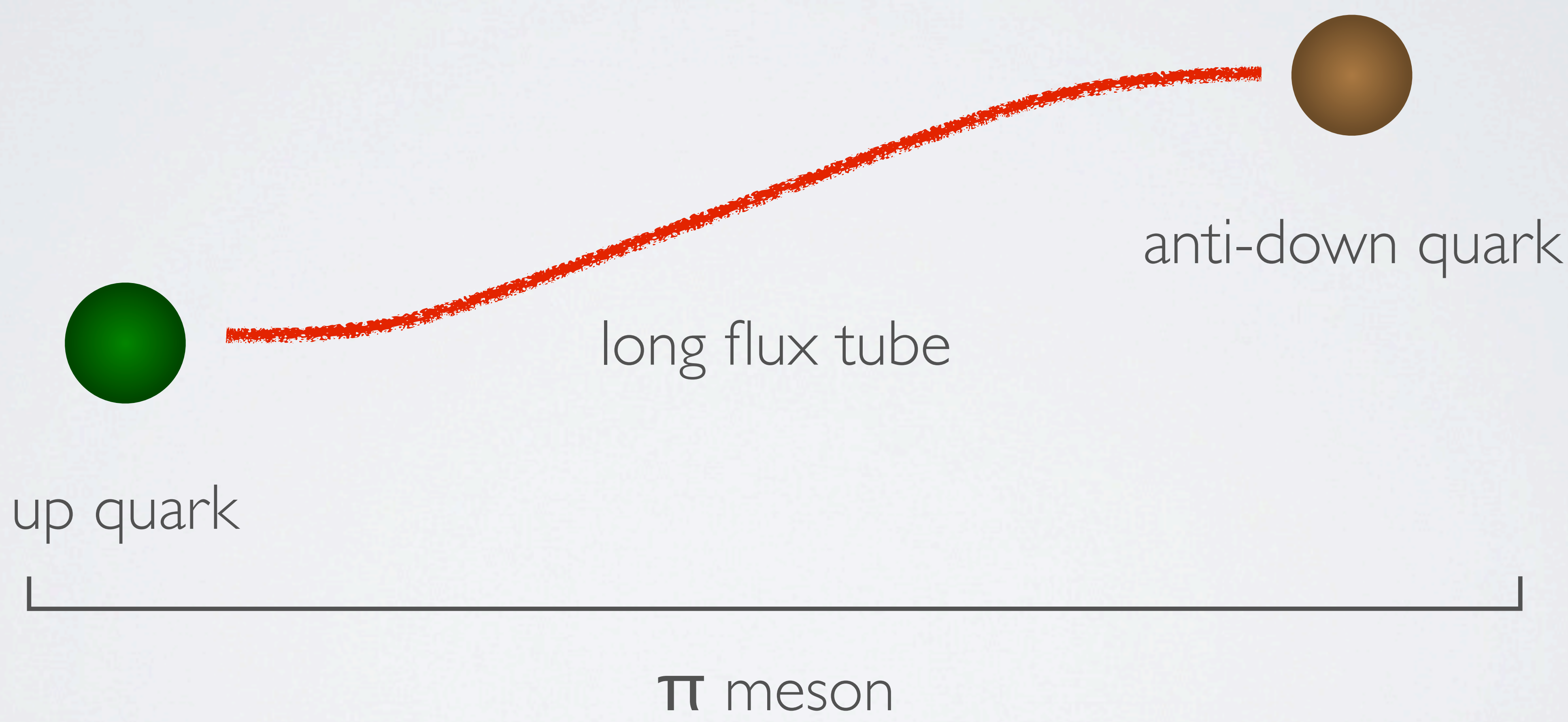
String theory

String theory is the most popular of the "ambitious" theories.
It began life as a theory of the strong interaction, but QCD killed it.



String theory

String theory is the most popular of the "ambitious" theories.
It began life as a theory of the strong interaction, but QCD killed it.

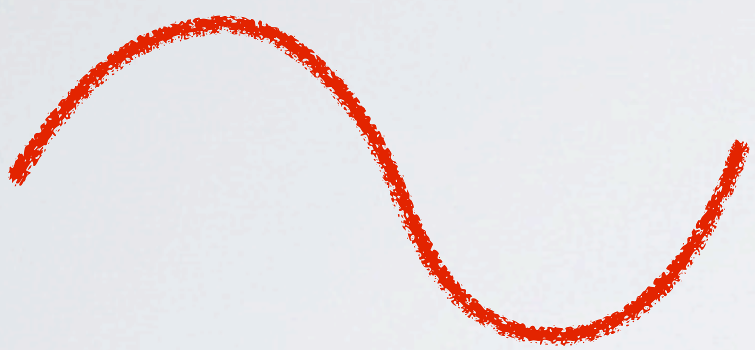


String theory

String theory is the most popular of the “ambitious” theories.
It began life as a theory of the strong interaction, but QCD killed it.

String theory

String theory is the most popular of the “ambitious” theories.
It began life as a theory of the strong interaction, but QCD killed it.

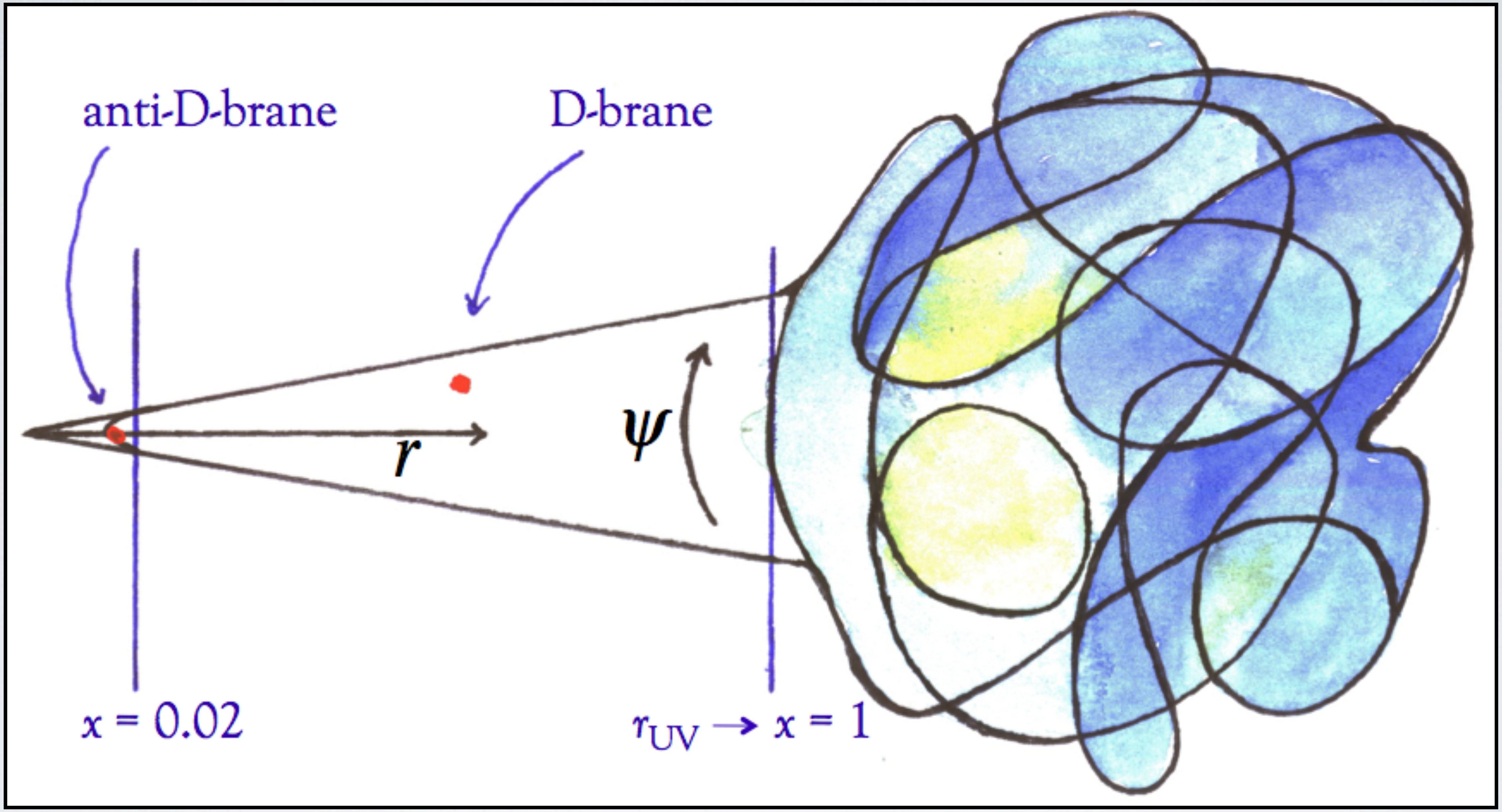


Fluctuations of open strings describe normal matter.

Fluctuations of closed strings describe gravity.

String theory turns out to produce these fields in supersymmetric packages
(This is how supersymmetry was first noticed)

Extradimensional scenarios



Credit: Dias, Frazer & Liddle arXiv:1203.3792

Particle cosmology

You can't just add lots of stuff and expect it not to change something.

Particle cosmology

You can't just add lots of stuff and expect it not to change something.

In the early universe, the temperature would have been high enough to make these new particles relevant.

Much of particle cosmology is concerned with this, although not exclusively (eg. nucleosynthesis, baryogenesis, leptogenesis, …)

Particle cosmology

CUSTOMERS

String theory,
Particle theorists

EARLY UNIVERSE
COSMOLOGISTS

Particle cosmology

CUSTOMERS

String theory,
Particle theorists

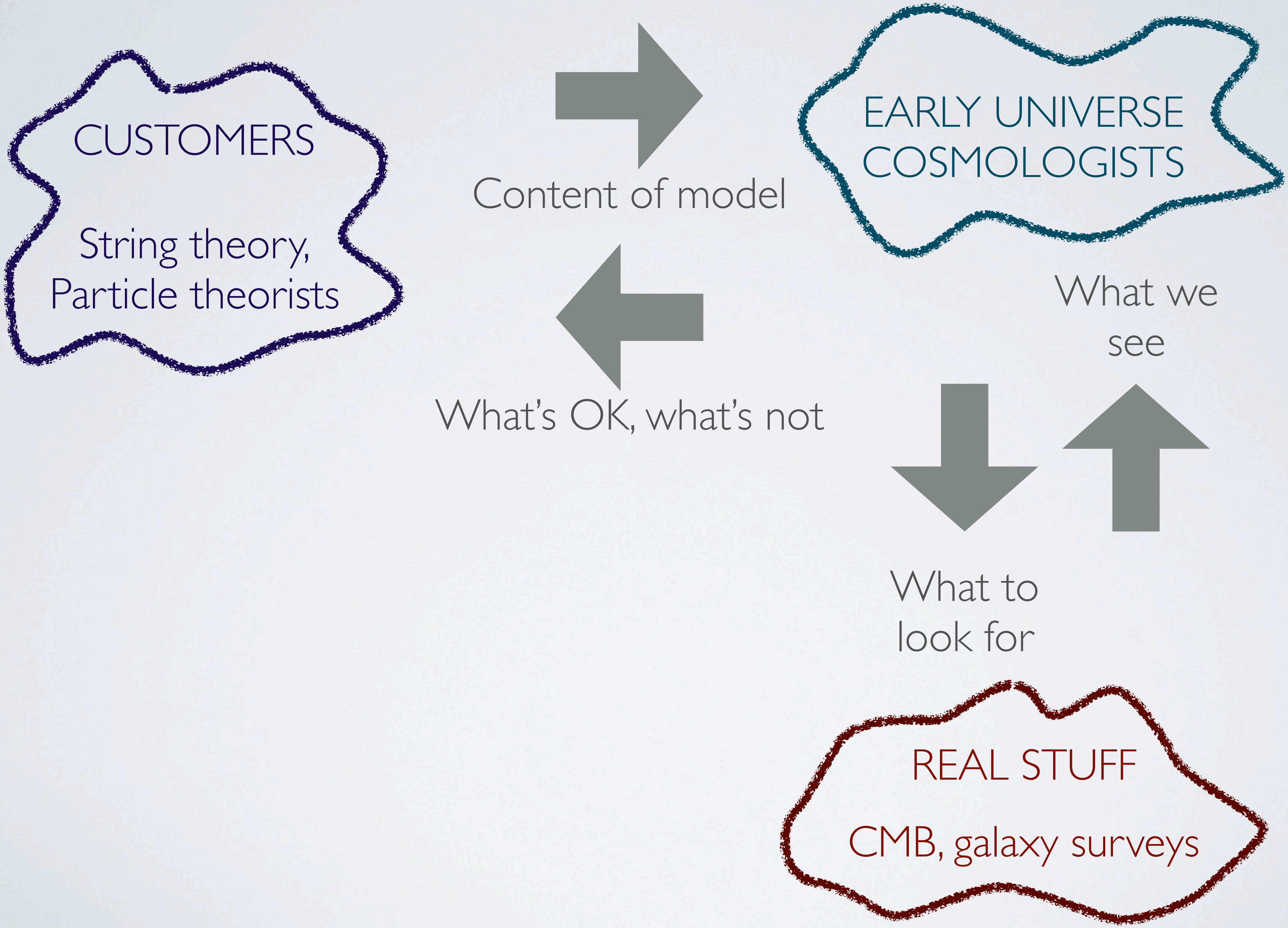
Content of model

EARLY UNIVERSE
COSMOLOGISTS

REAL STUFF

CMB, galaxy surveys

Particle cosmology



Particle cosmology

CUSTOMERS

String theory,
Particle theorists

Content of model

EARLY UNIVERSE
COSMOLOGISTS

What's OK, what's not

What we
see

What to
look for

REAL STUFF

CMB, galaxy surveys

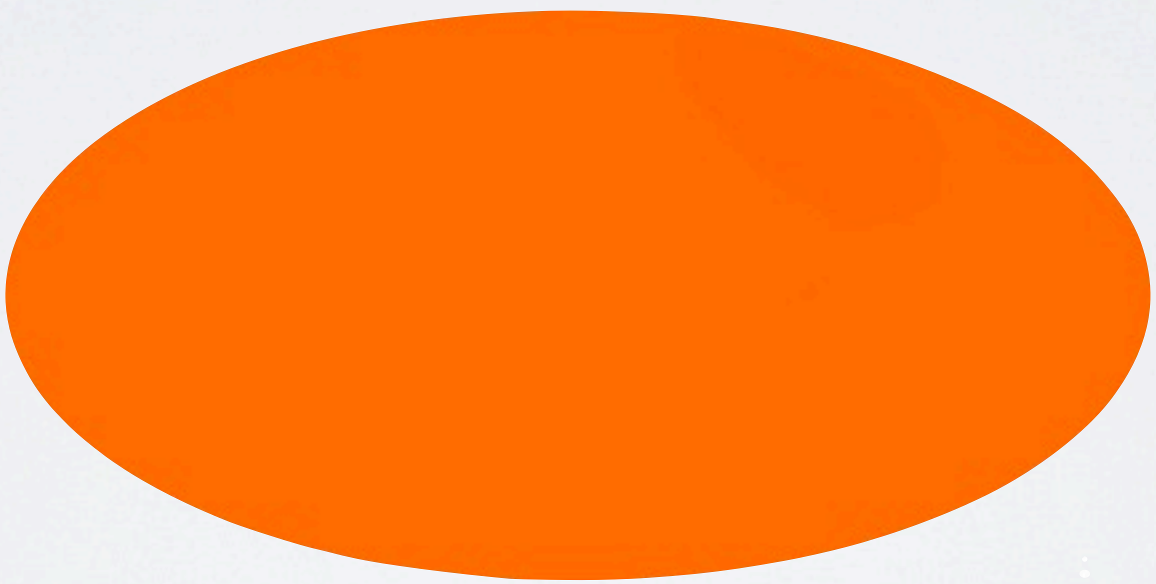
Observations are now so difficult that we will not see signatures of new physics unless we know what to look for.

(We have the same problem with LHC)

Particle cosmology

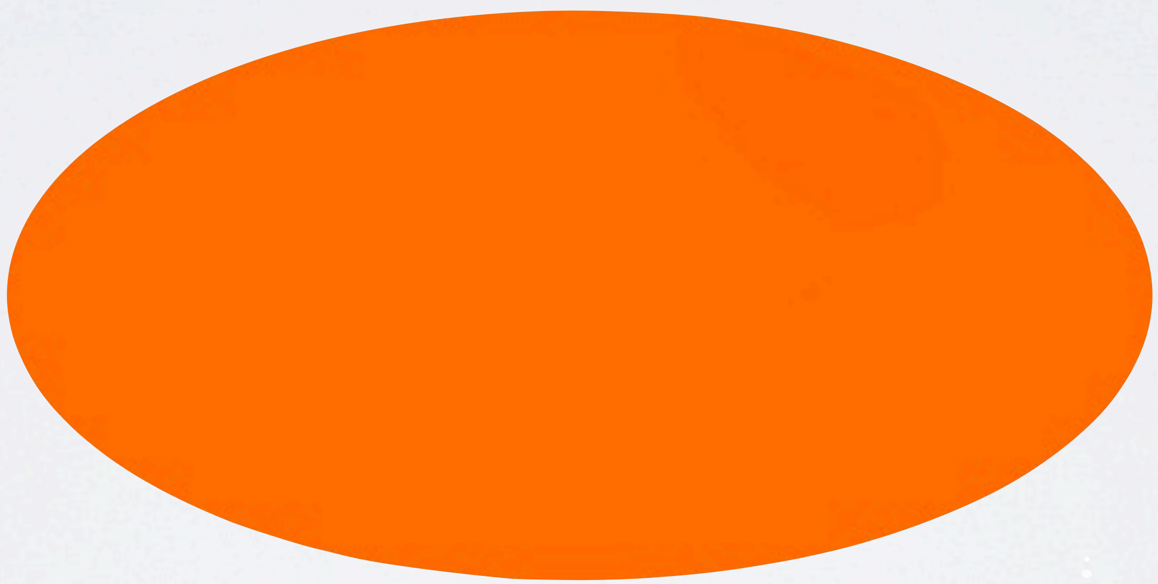
When people first thought seriously about what might happen, they realized that this extra stuff could be helpful

This is a measurement (yes, actual data) of what the universe looked like at redshift $z \sim 1100$



Particle cosmology

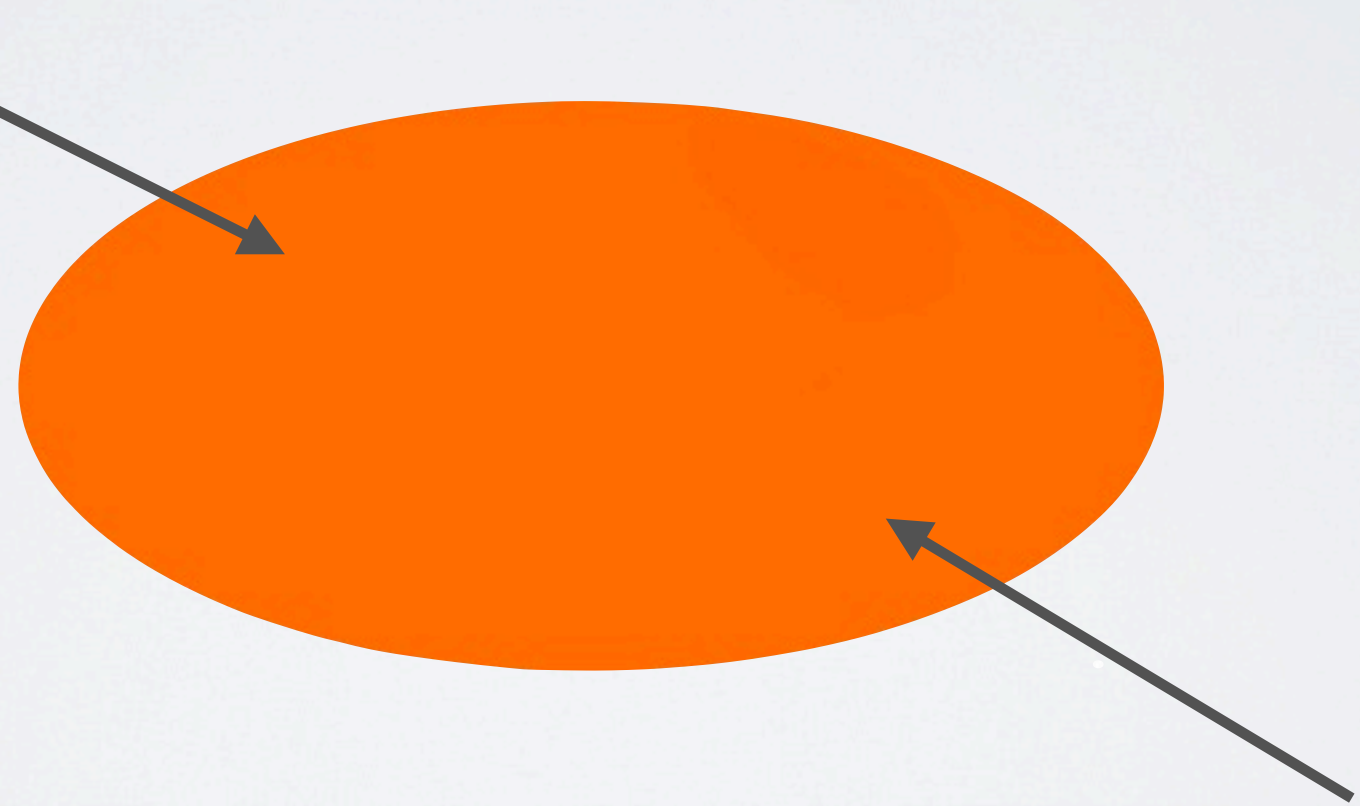
When people first thought seriously about what might happen, they realized that this extra stuff could be helpful



Particle cosmology

When people first thought seriously about what might happen, they realized that this extra stuff could be helpful

Pick a direction

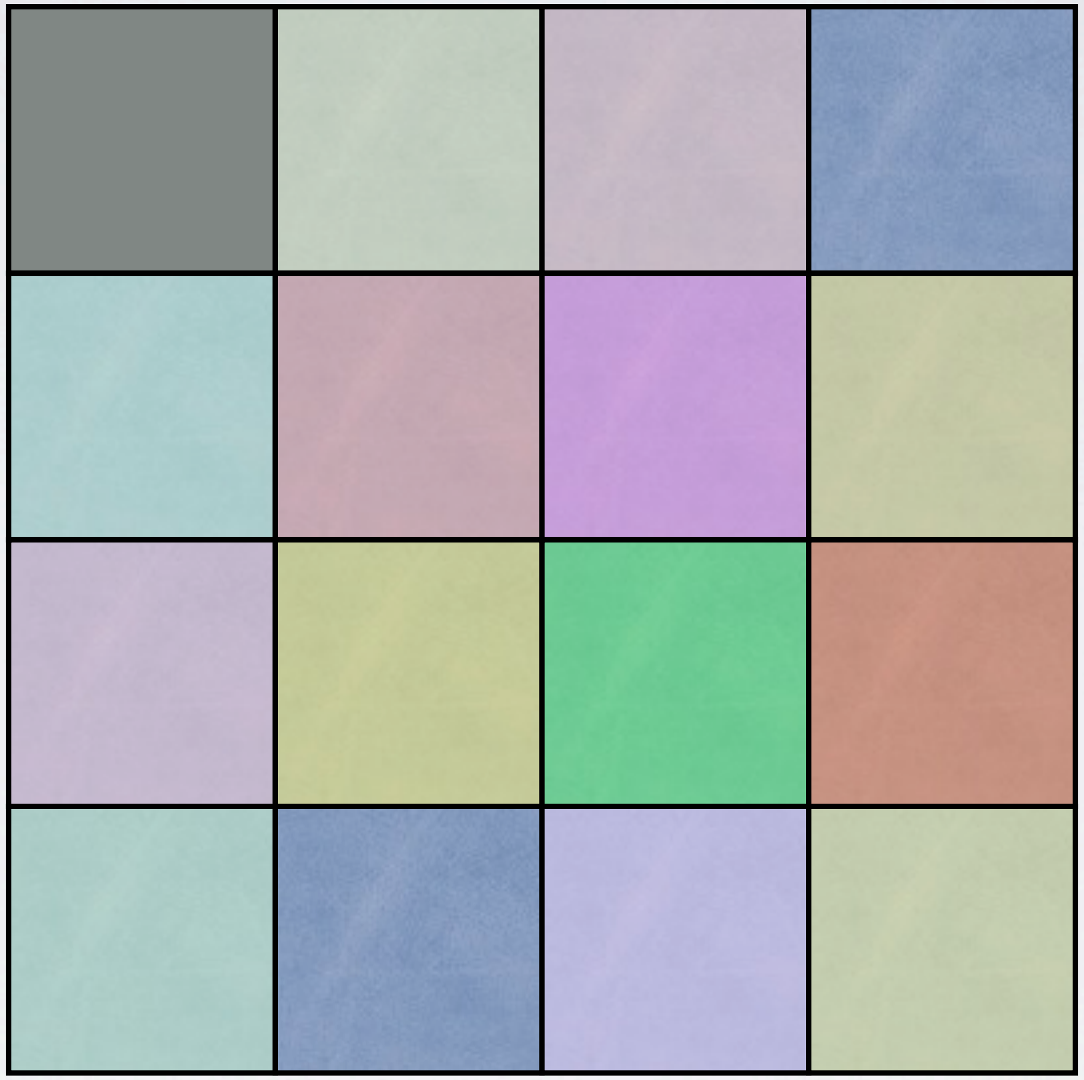


How do these photons know to have the same temperature?

"horizon problem"

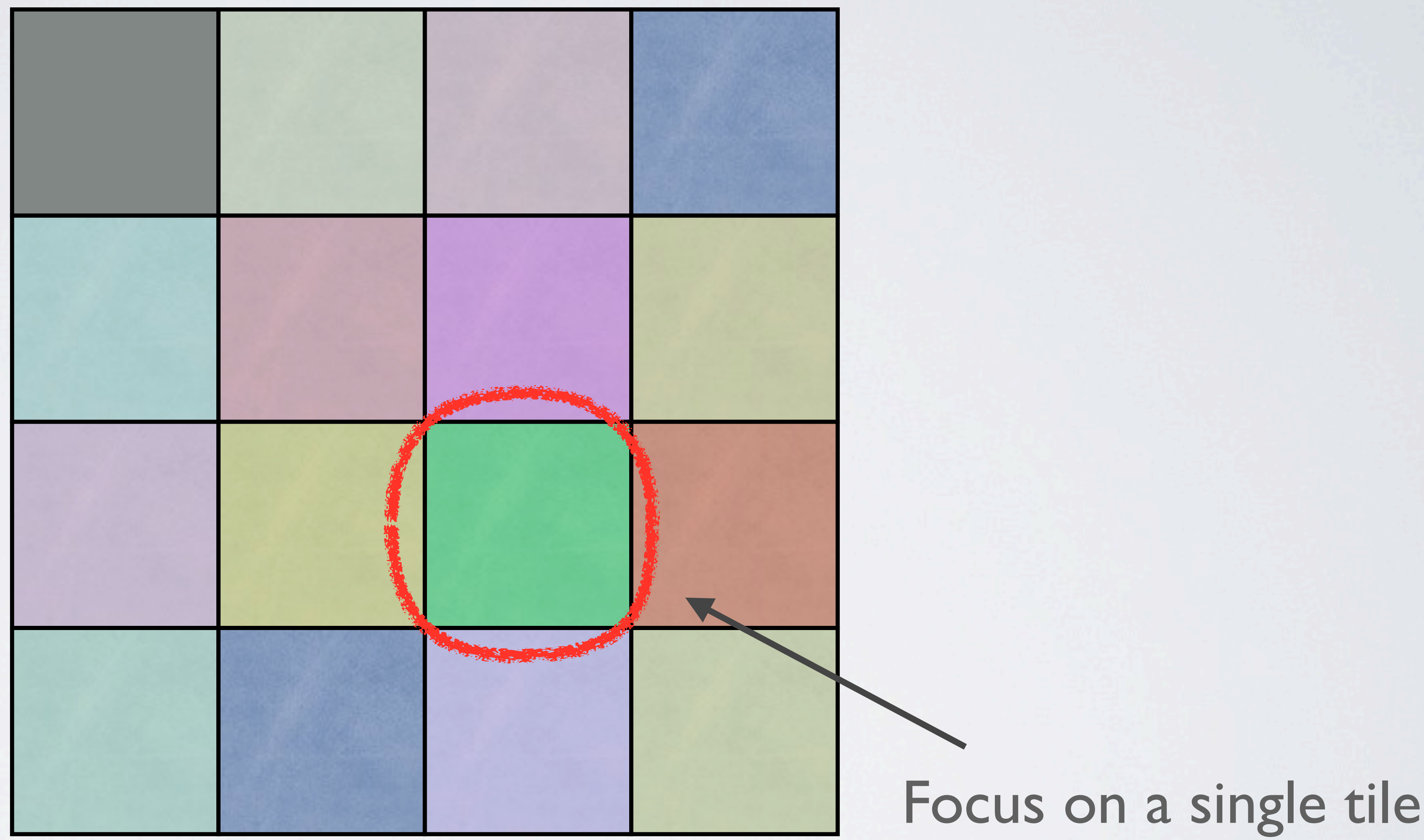
This is the antipodal direction

The early universe is probably a complicated place



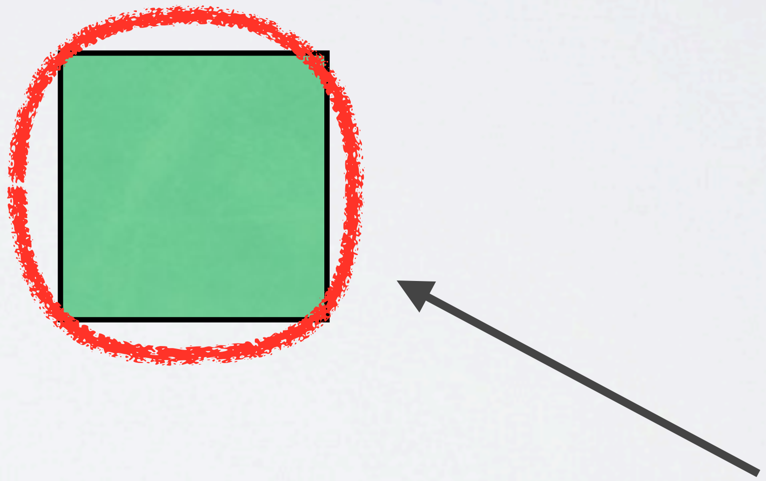
We can try to divide it up into regions where things are roughly homogeneous

The early universe is probably a complicated place



We can try to divide it up into regions where things are roughly homogeneous

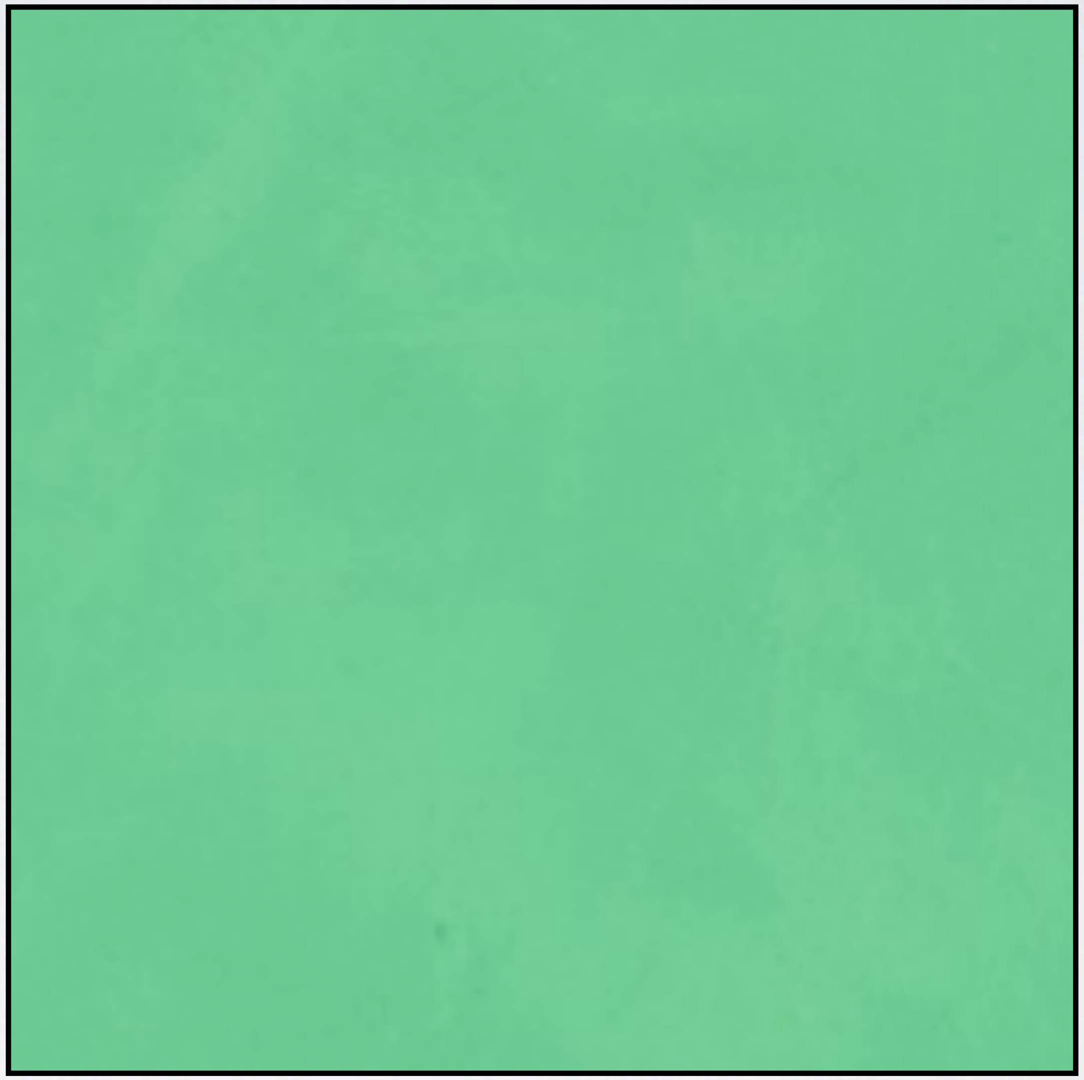
The early universe is probably a complicated place



Focus on a single tile

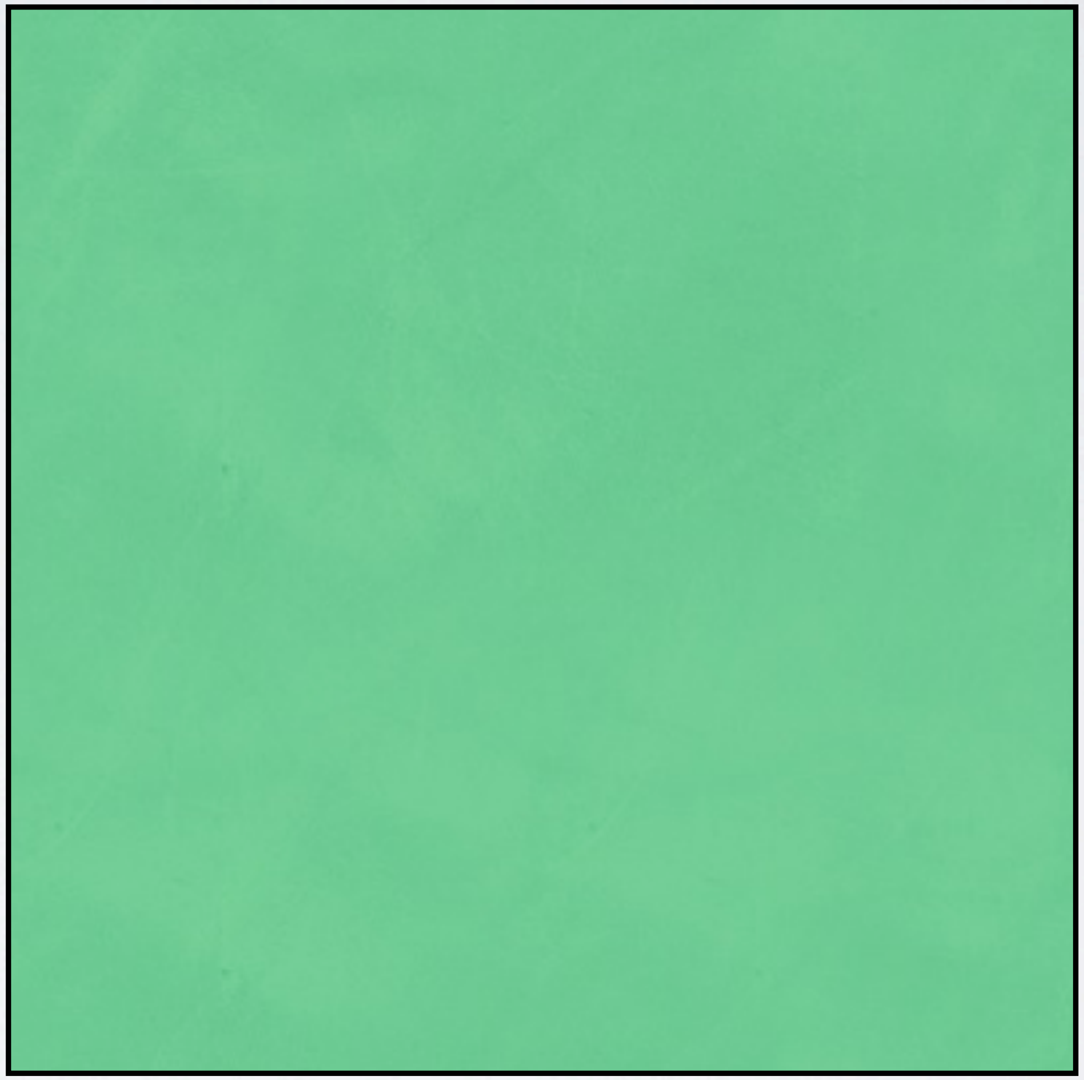
The early universe is probably a complicated place

The early universe is probably a complicated place



The early universe is probably a complicated place

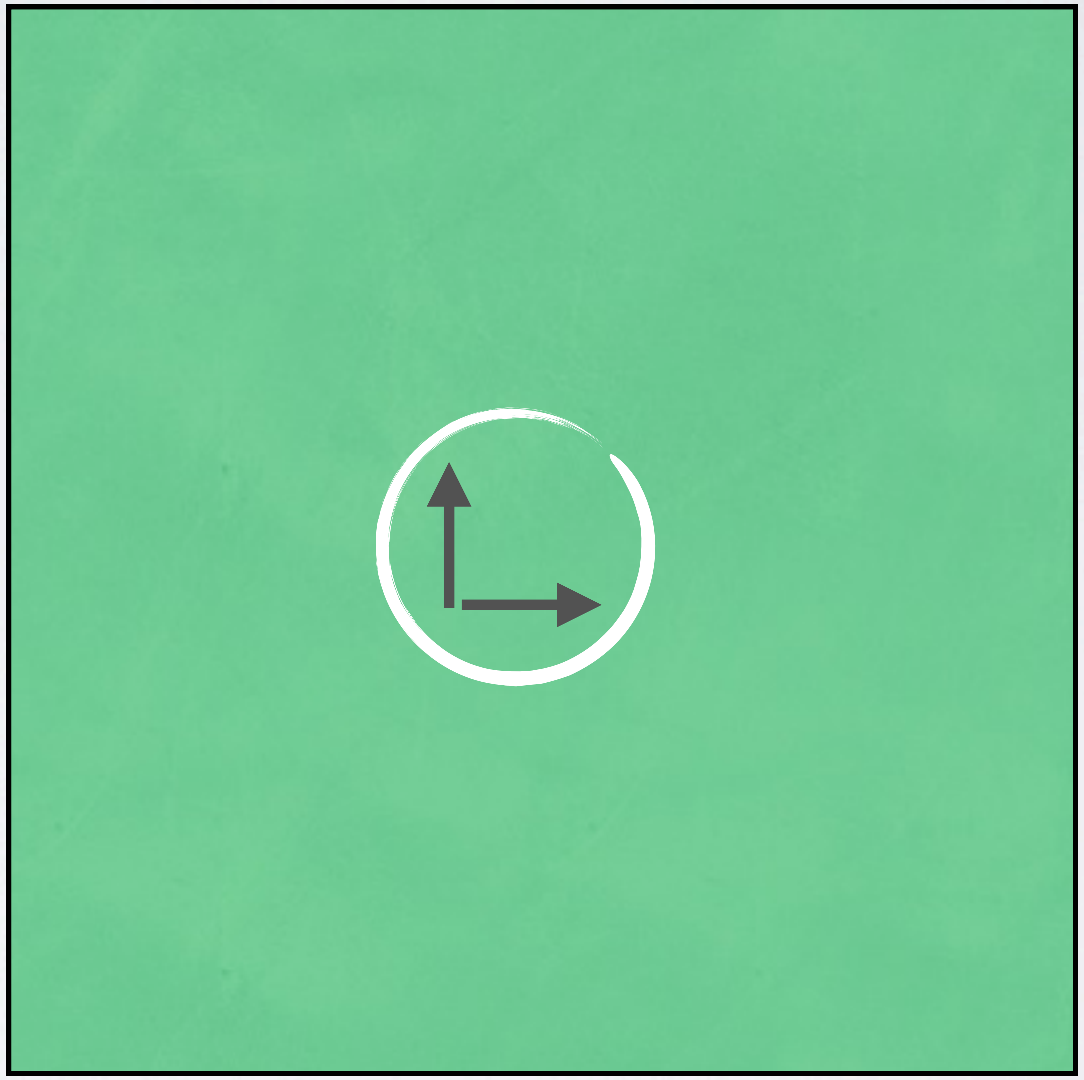
Around 1980, several people realized that new physics sometimes contained the right properties to expand one of the patches very rapidly



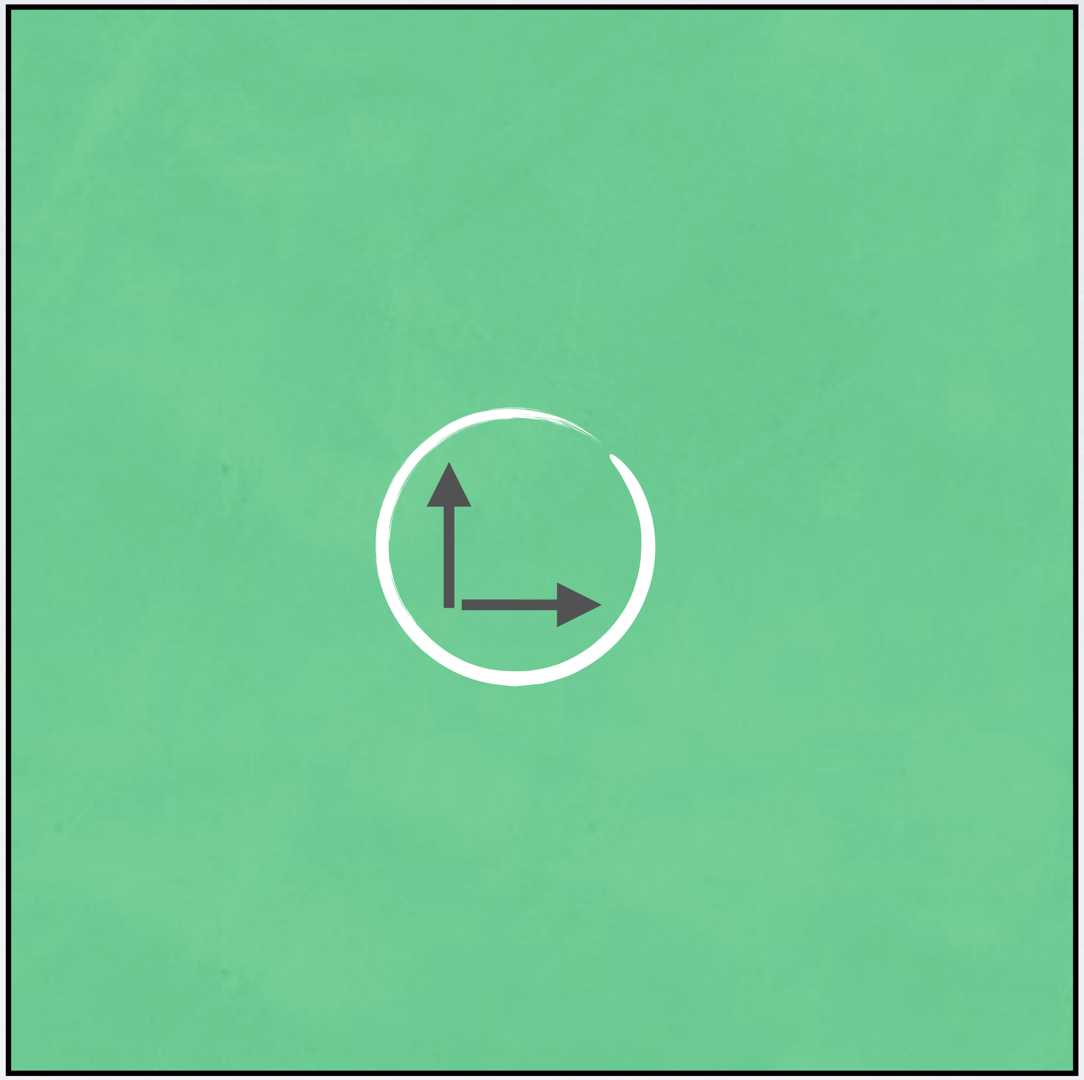
The early universe is probably a complicated place

To anyone making measurements far inside an expanded patch, it might not be so surprising that all directions look the same

Around 1980, several people realized that new physics sometimes contained the right properties to expand one of the patches very rapidly

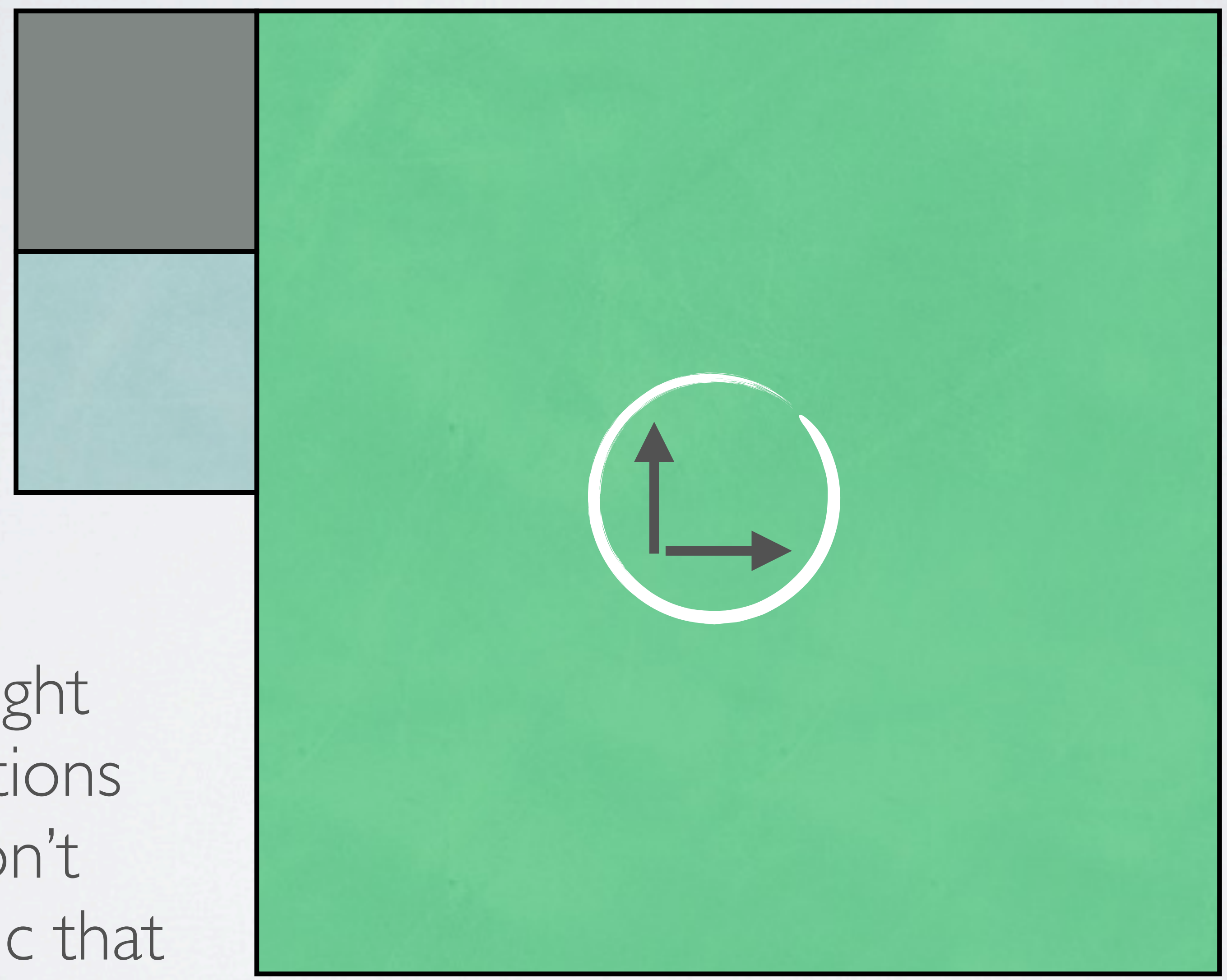


The early universe is probably a complicated place



The early universe is probably a complicated place

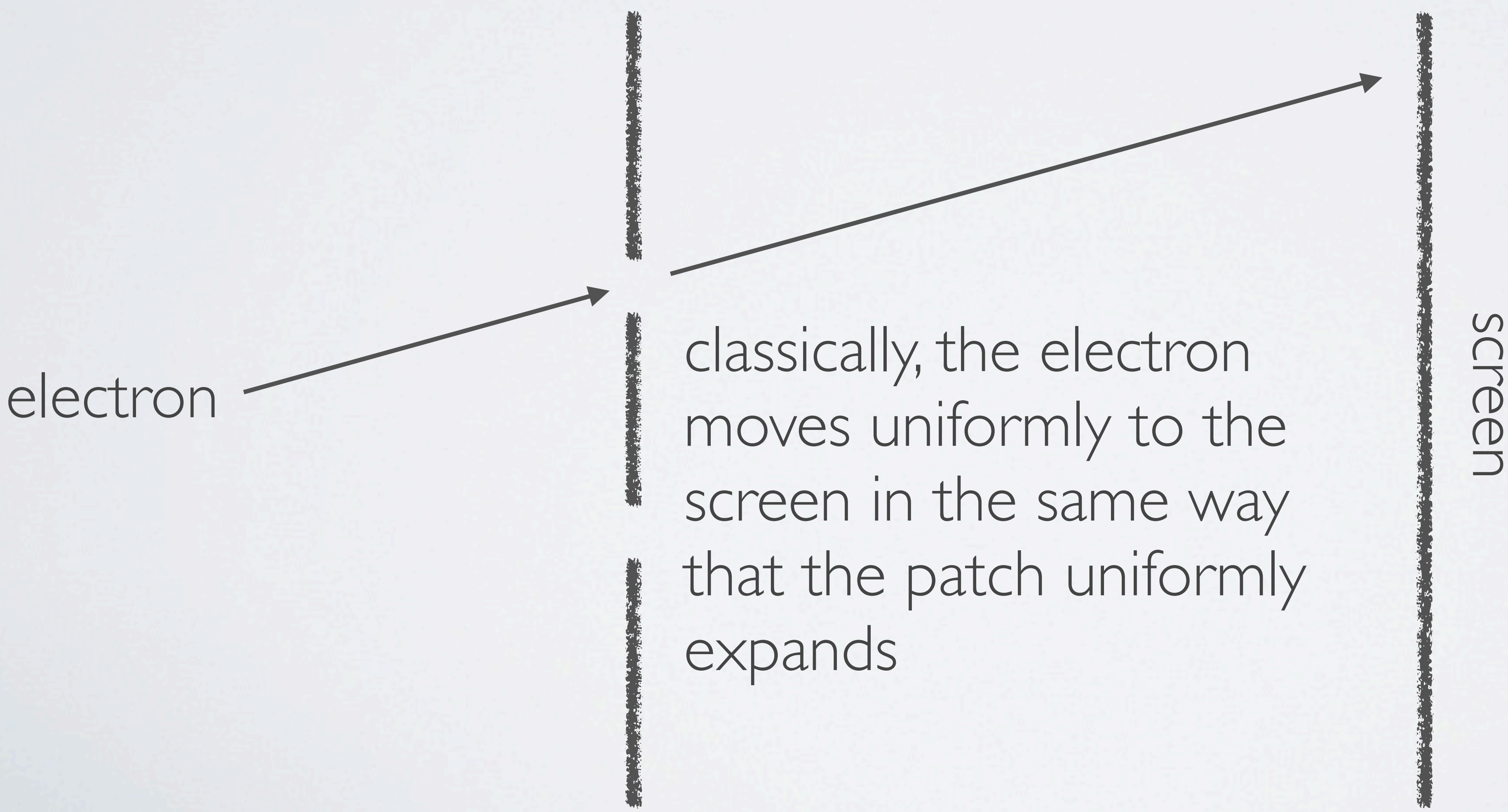
"Anthropic reasoning"



Not all patches might expand, but conditions near those that don't could be so chaotic that we could not live there.

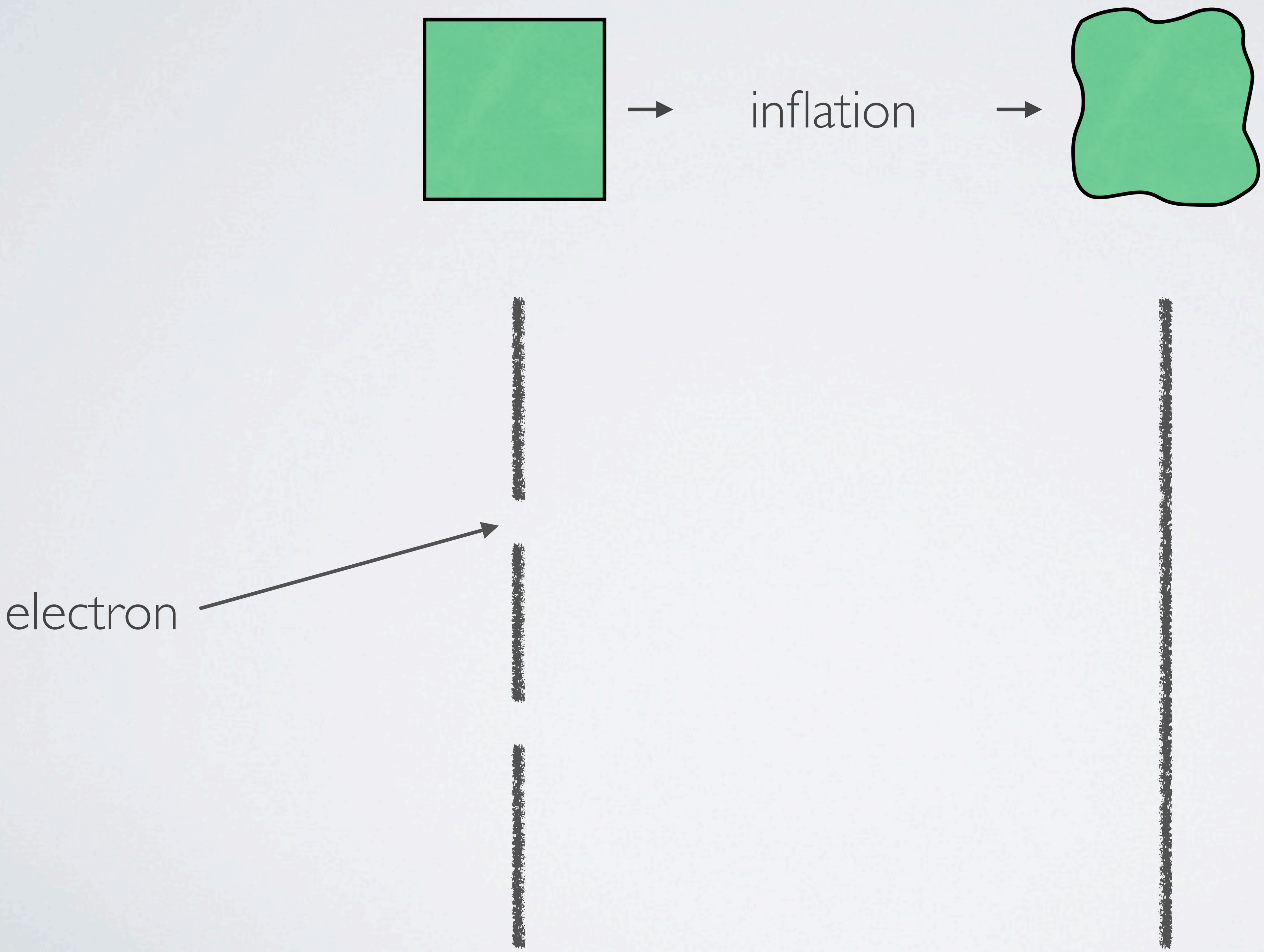
In a quantum theory, you can't insist that the patch follows a definite history

In a quantum theory, you can't insist that the patch follows a definite history

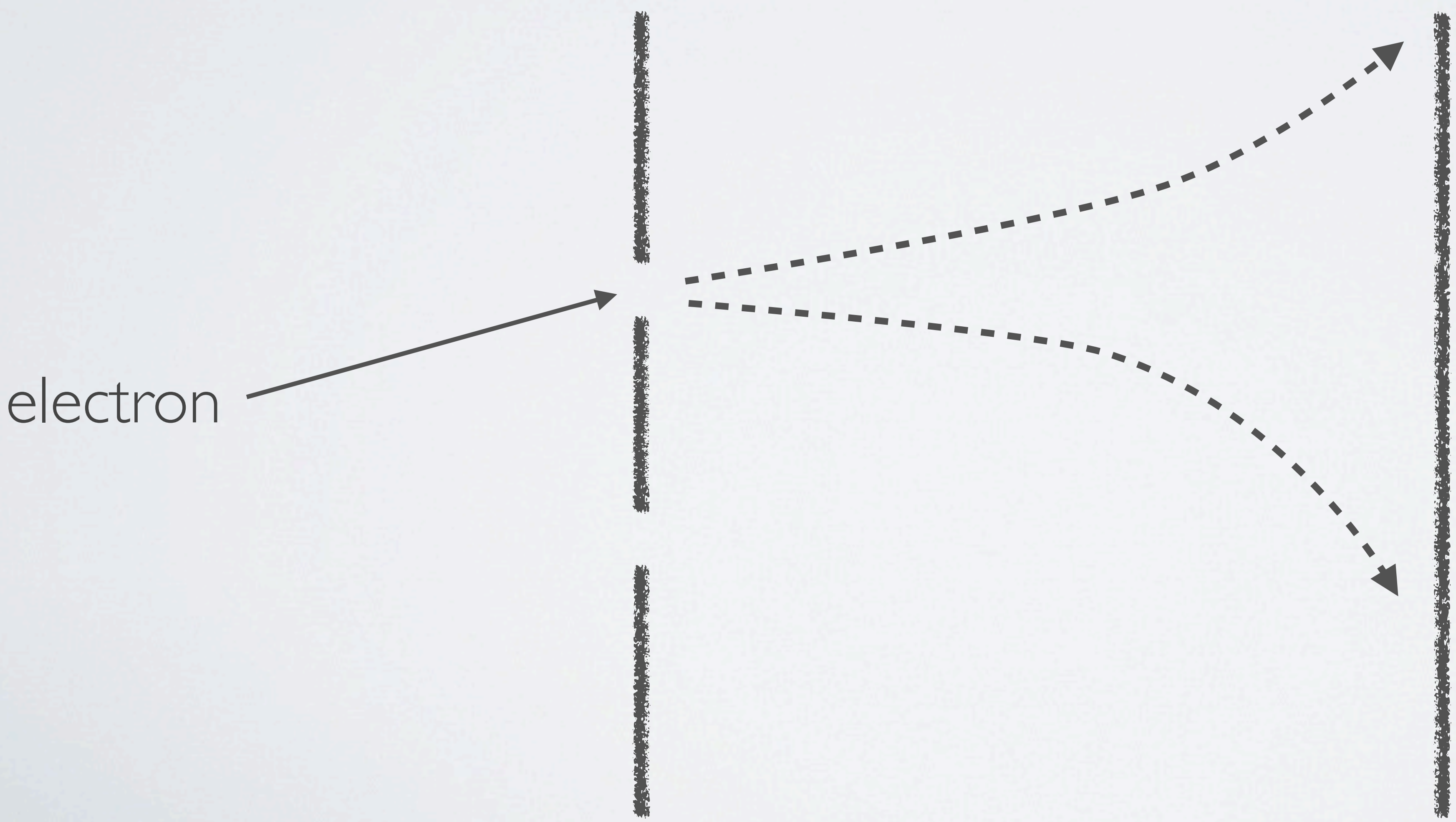


classically, the electron moves uniformly to the screen in the same way that the patch uniformly expands

In a quantum theory, you can't insist that the patch follows a definite history



In a quantum theory, you can't insist that the patch follows a definite history



In reality,
the electron may take any path to the screen.
Every time we try, we get a different position.
But some are more probable than others

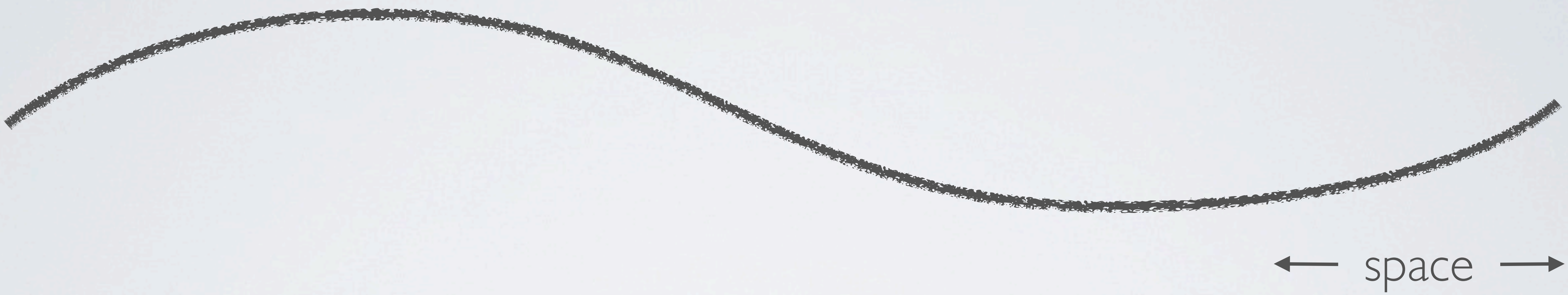
In a quantum theory, you can't insist that the patch follows a definite history

In a quantum theory, you can't insist that the patch follows a definite history

In the same way, every time a patch expands we get a slightly different result.

But some are more probable than others – those close to the configuration produced by a classical history

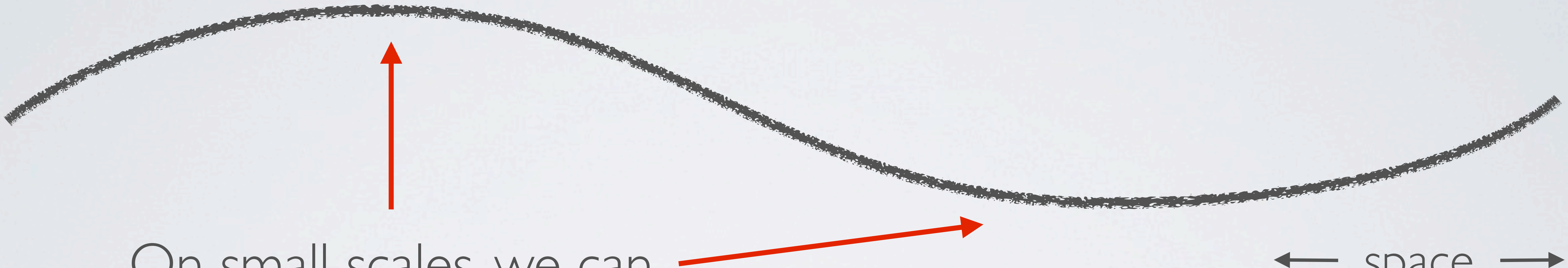
Think about an expanding patch



Think about an expanding patch

High density fluctuation

Low density fluctuation



On small scales, we can borrow energy

← space →

$$\Delta E \cdot \Gamma^{-1} \sim \hbar$$

Energetic fluctuations decay rapidly, at rate $\Gamma \sim \Delta E$

This exchange of energy is going on all the time, on all scales

Distant objects
recede rapidly

"Hubble scale"

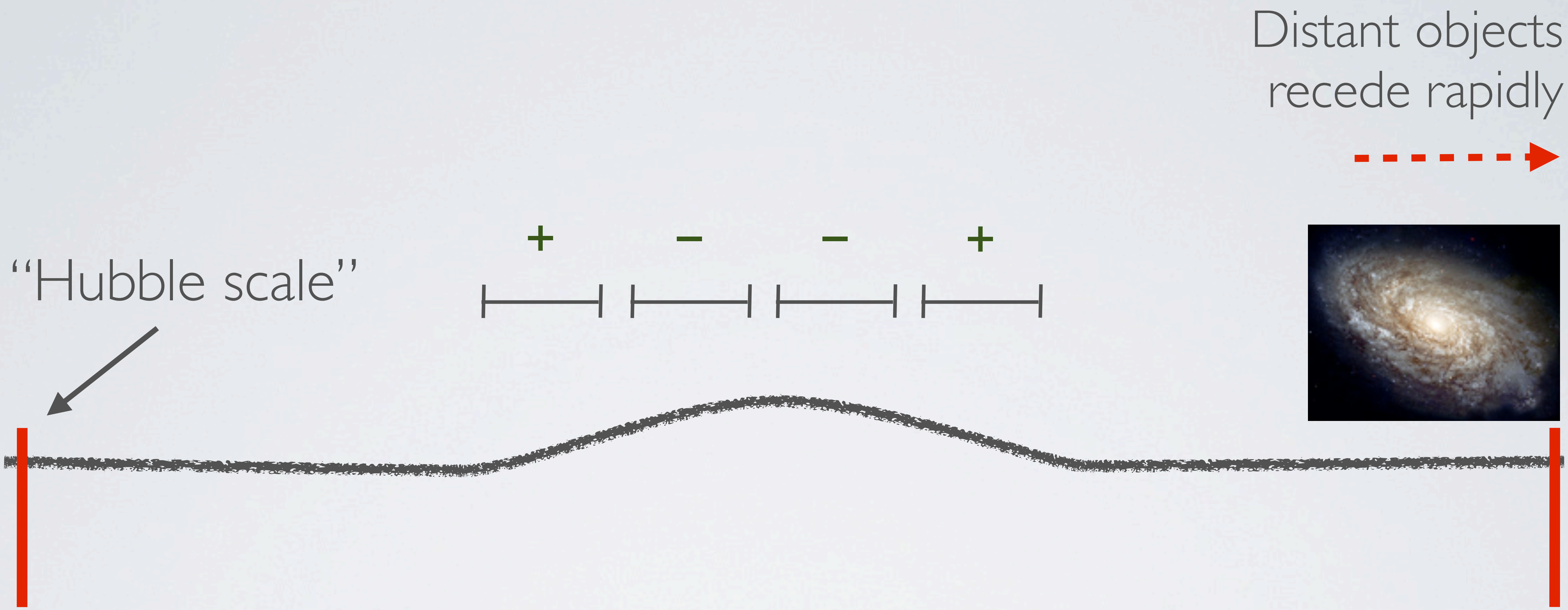
At large distances, objects recede so
rapidly that any photons I send cannot
catch them up

This exchange of energy is going on all the time, on all scales

Distant objects
recede rapidly

"Hubble scale"

This exchange of energy is going on all the time, on all scales



This does not matter for small-scale borrowing,
which carries on just like in this room.

This exchange of energy is going on all the time, on all scales

Distant objects
recede rapidly

“Hubble scale”

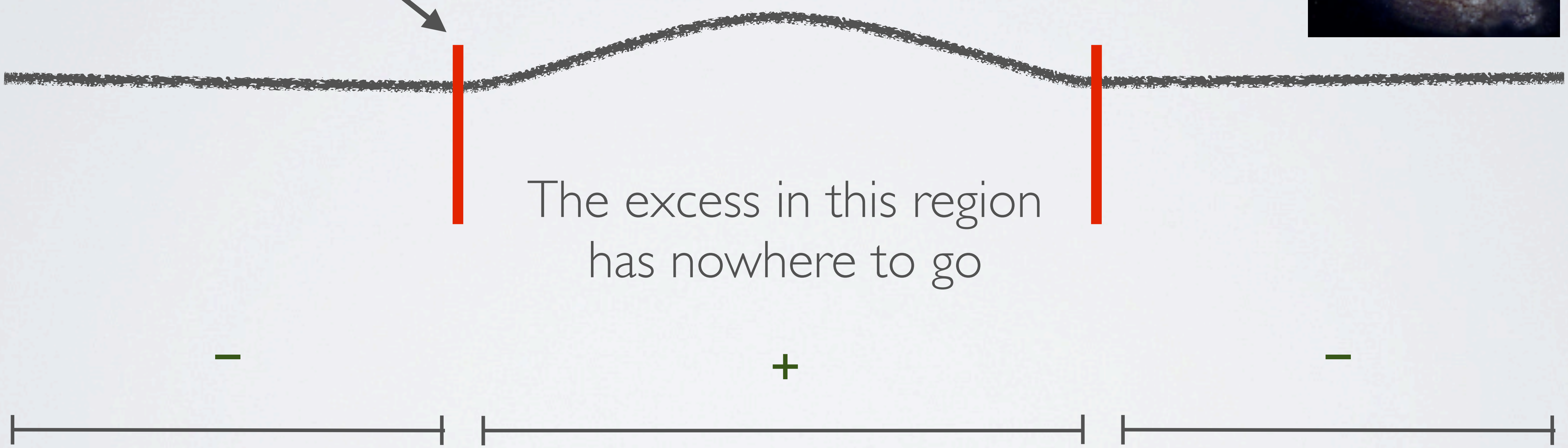
But the region we can talk to is always shrinking

This exchange of energy is going on all the time, on all scales

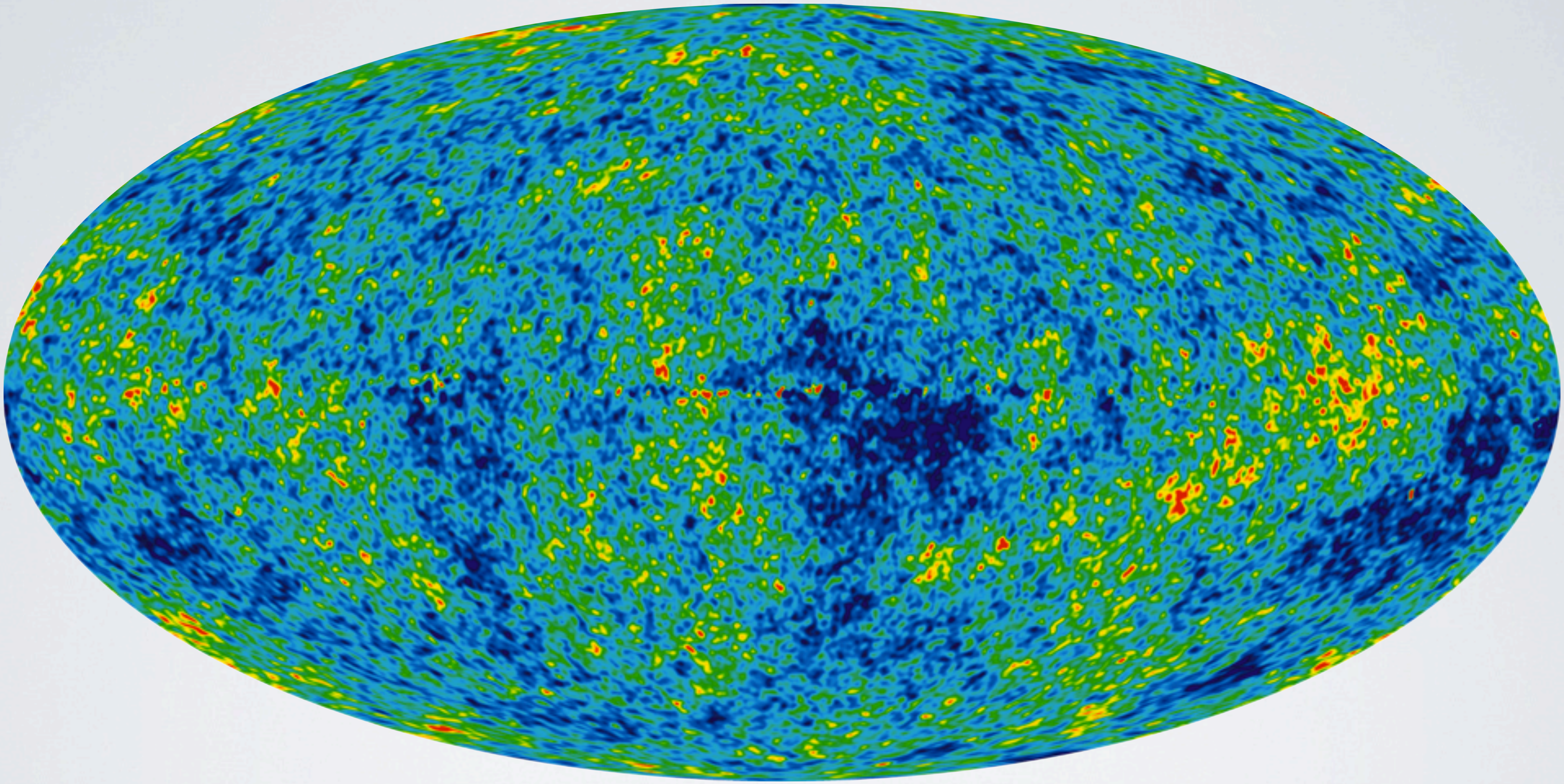
Distant objects recede rapidly

A fluctuation on the scale which has just become uncommunicable can't pay back its energy

"Hubble scale"

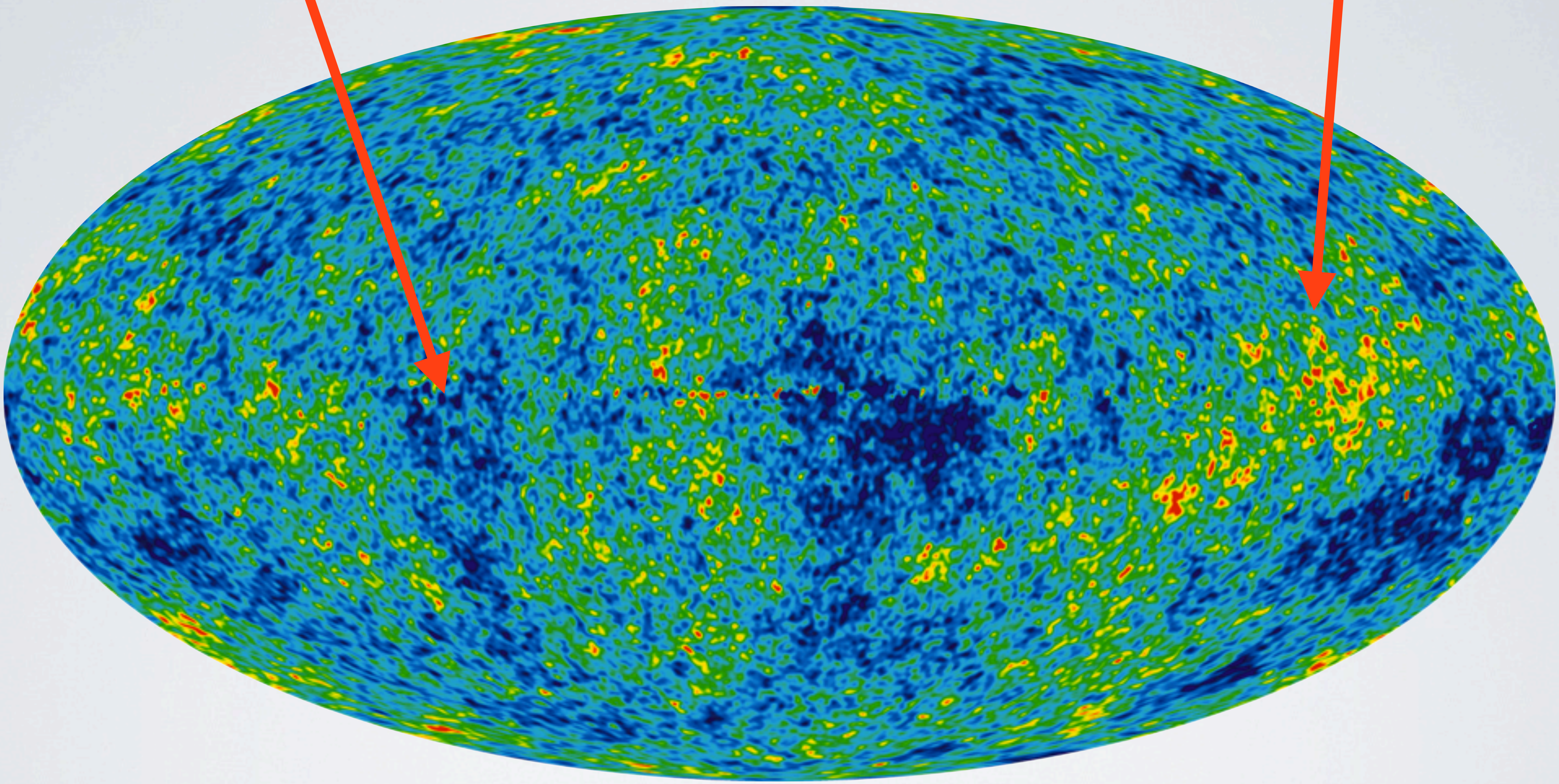


But the region we can talk to is always shrinking



When you subtract the uniform orange, this is what the CMB looks like slightly overexpanded region

slightly underexpanded region



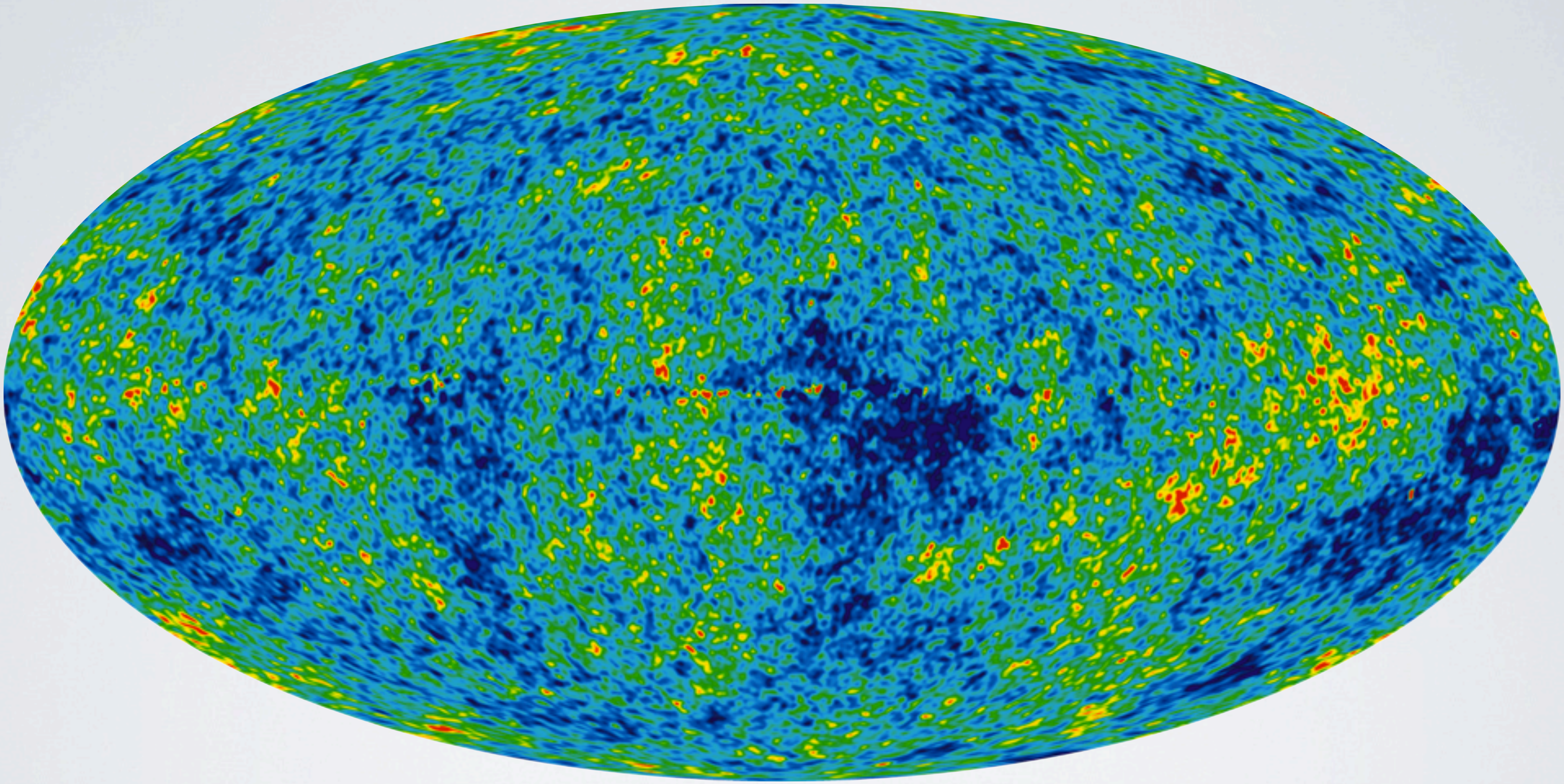
When you subtract the uniform orange, this is what the CMB looks like

Where are we now?

- Inflation can explain the surprising large-scale homogeneity and isotropy
- It can also explain why there are small fluctuations (CMB, galaxies)
- In the late 90s we learned that the present universe was accelerating. This made an era of early inflation seem much more likely
- Since then we have learned that fluctuations we see in the CMB and galaxies are compatible with an inflationary origin
- Most cosmologists consider inflation to be the probable source of the fluctuations
- By looking at the properties of the fluctuations, we can try to distinguish between different models

  Right now, there is a lot of effort here.

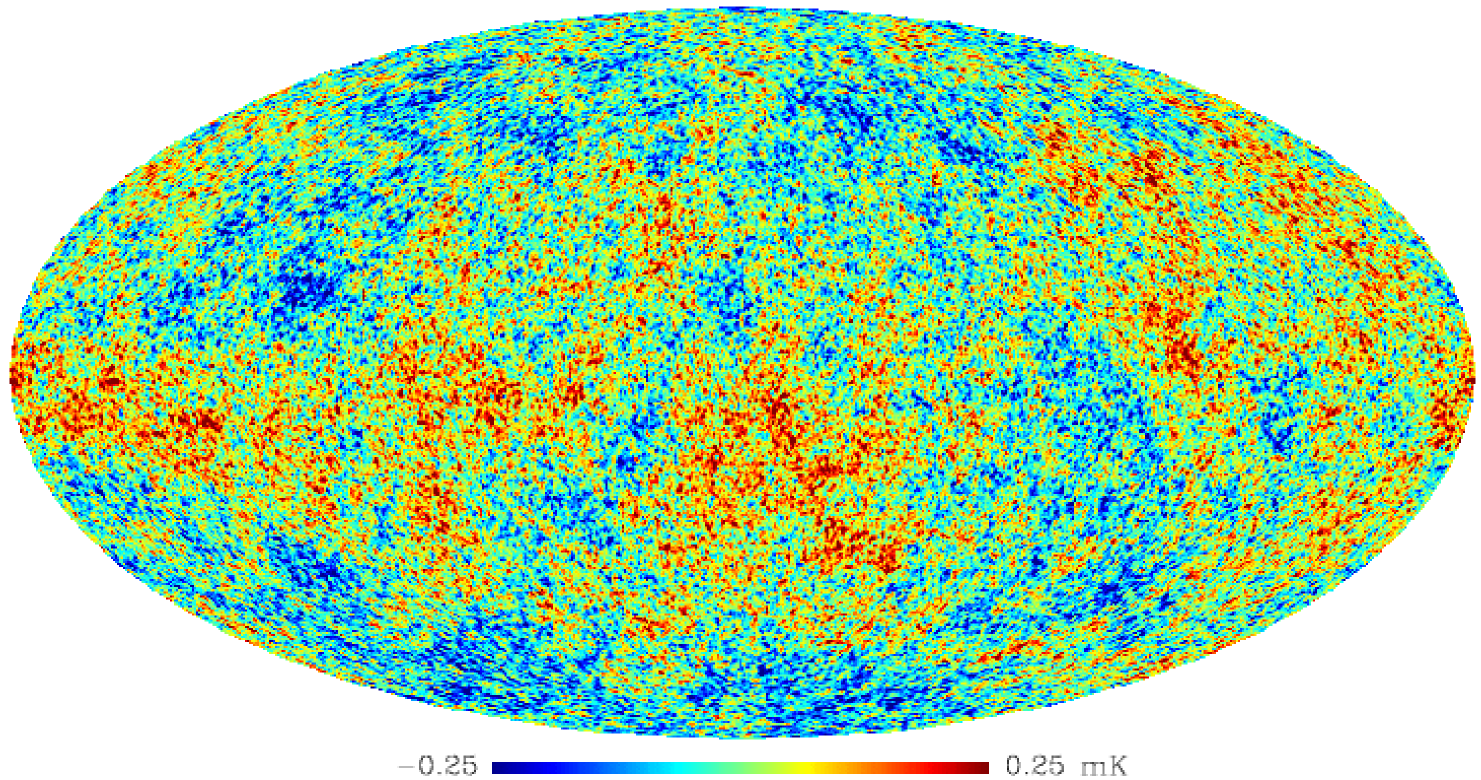
Inflationary nongaussianity



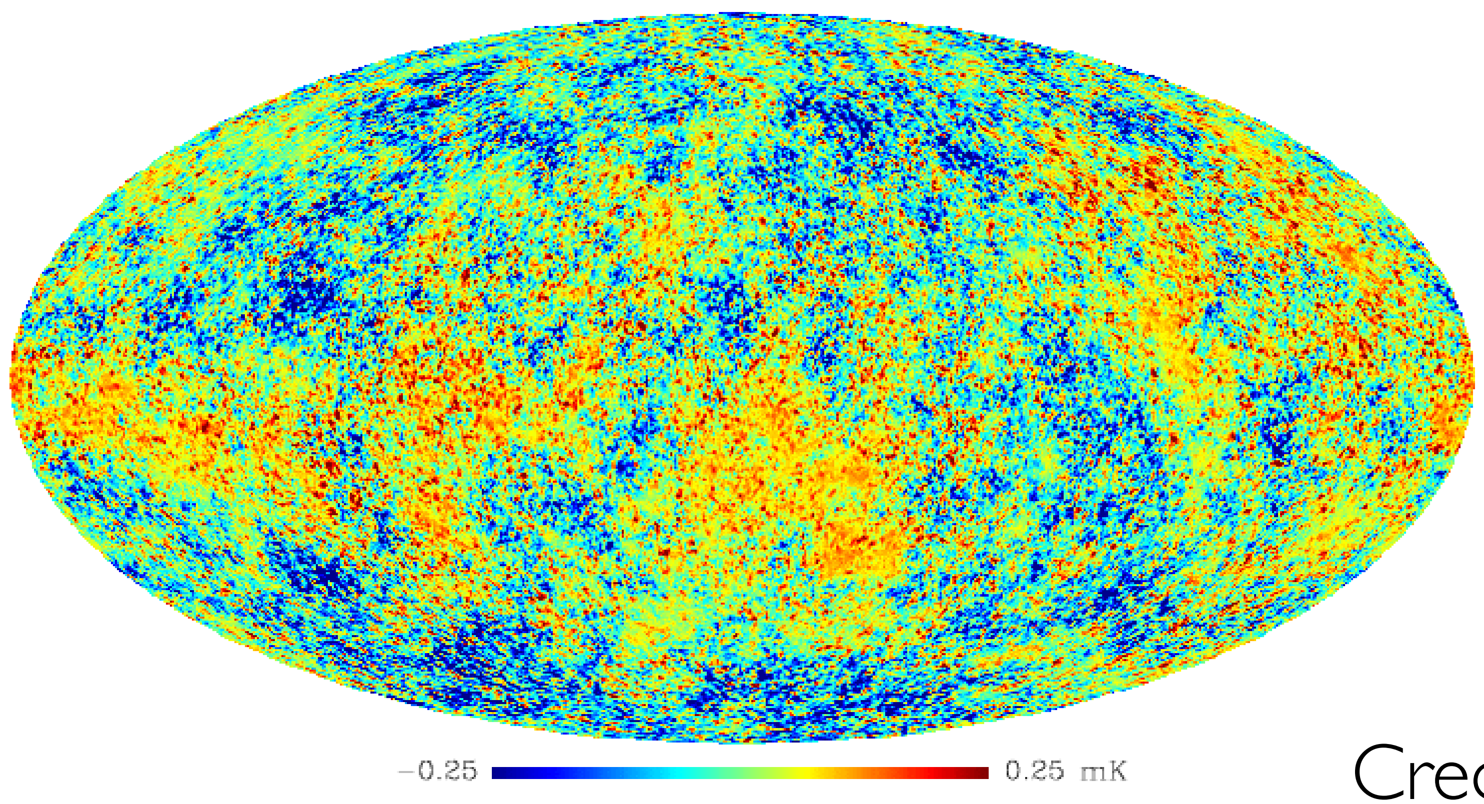
The details of borrowing depend on subtle particle physics.

Is a subpatch more or less likely to borrow if it already has borrowed energy?

Temperature, $f_{NL} = 0$



Temperature, $f_{NL} = 3000$



Credit: Michele Liguori

To prepare for the LHC, particle theorists had to refine their calculations significantly.

The same is true for upcoming CMB observations with *Planck*.

$$\left\langle \frac{\delta\rho}{\rho}(\boldsymbol{k}_1)\frac{\delta\rho}{\rho}(\boldsymbol{k}_2)\right\rangle = (2\pi)^3\delta(\boldsymbol{k}_1+\boldsymbol{k}_2)P(k_1)$$

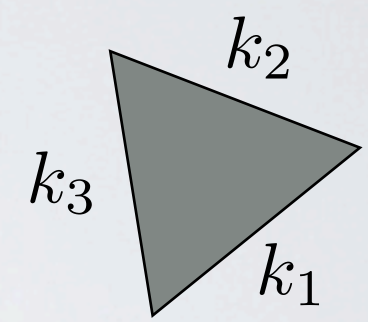
$$\left\langle \frac{\delta\rho}{\rho}(\boldsymbol{k}_1)\frac{\delta\rho}{\rho}(\boldsymbol{k}_2)\frac{\delta\rho}{\rho}(\boldsymbol{k}_3)\right\rangle = (2\pi)^3\delta(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3)B(k_1,k_2,k_3)$$

$$\left\langle \frac{\delta\rho}{\rho}(\boldsymbol{k}_1)\frac{\delta\rho}{\rho}(\boldsymbol{k}_2)\frac{\delta\rho}{\rho}(\boldsymbol{k}_3)\frac{\delta\rho}{\rho}(\boldsymbol{k}_4)\right\rangle = (2\pi)^3\delta(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3+\boldsymbol{k}_4)T(\cdots)$$

To prepare for the LHC, particle theorists had to refine their calculations significantly.

The same is true for upcoming CMB observations with *Planck*.

$$\left\langle \frac{\delta\rho}{\rho}(\boldsymbol{k}_1)\frac{\delta\rho}{\rho}(\boldsymbol{k}_2)\right\rangle = (2\pi)^3\delta(\boldsymbol{k}_1+\boldsymbol{k}_2)P(k_1)$$



$$\left\langle \frac{\delta\rho}{\rho}(\boldsymbol{k}_1)\frac{\delta\rho}{\rho}(\boldsymbol{k}_2)\frac{\delta\rho}{\rho}(\boldsymbol{k}_3)\right\rangle = (2\pi)^3\delta(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3)\boxed{B(k_1,k_2,k_3)}$$

"Bispectrum"

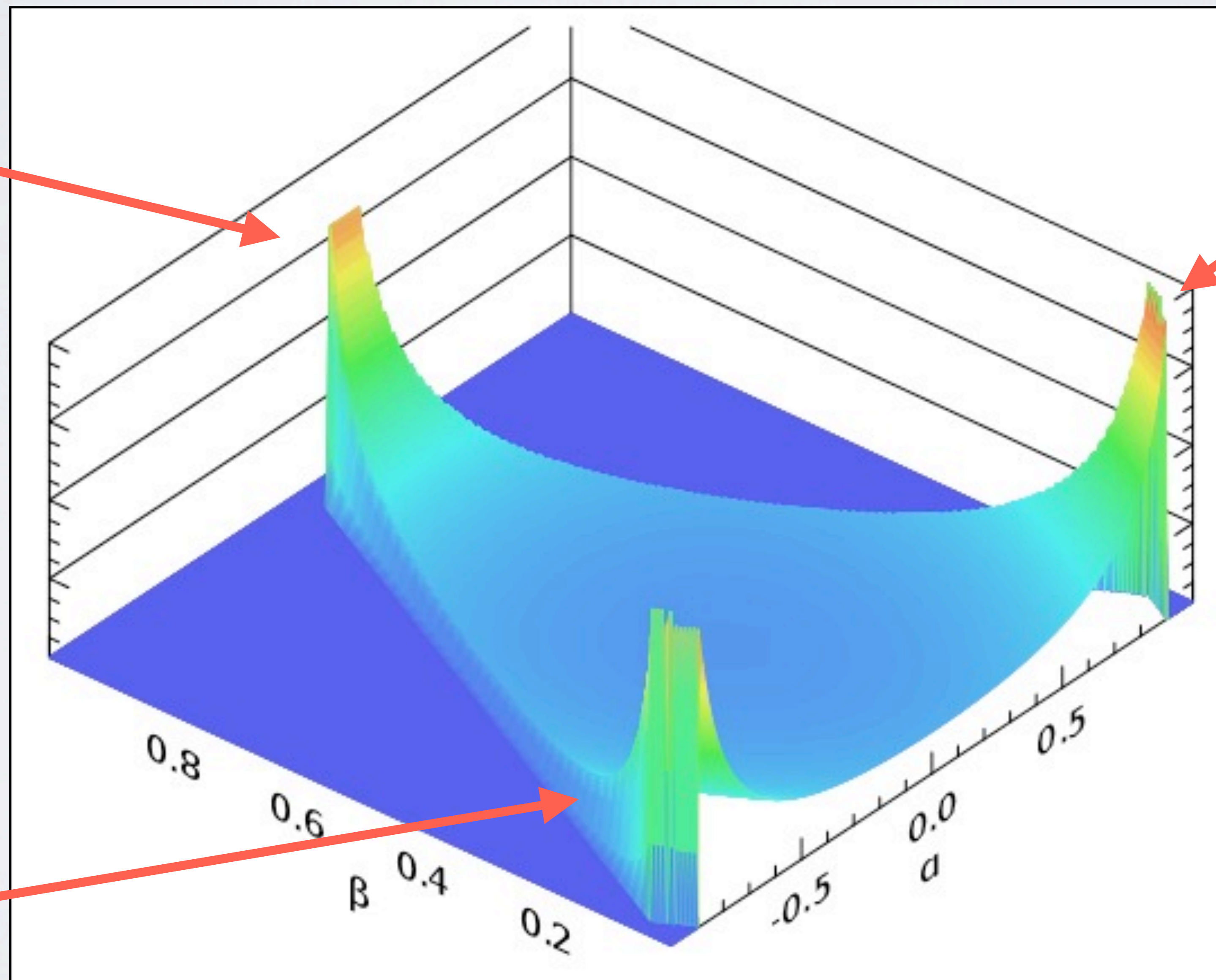
$$\left\langle \frac{\delta\rho}{\rho}(\boldsymbol{k}_1)\frac{\delta\rho}{\rho}(\boldsymbol{k}_2)\frac{\delta\rho}{\rho}(\boldsymbol{k}_3)\frac{\delta\rho}{\rho}(\boldsymbol{k}_4)\right\rangle = (2\pi)^3\delta(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3+\boldsymbol{k}_4)T(\cdots)$$

The bispectrum

This is a complicated function of the scales k_i
It turns out to be quite hard to calculate

$k_3 \to 0$

$k_2 \to 0$



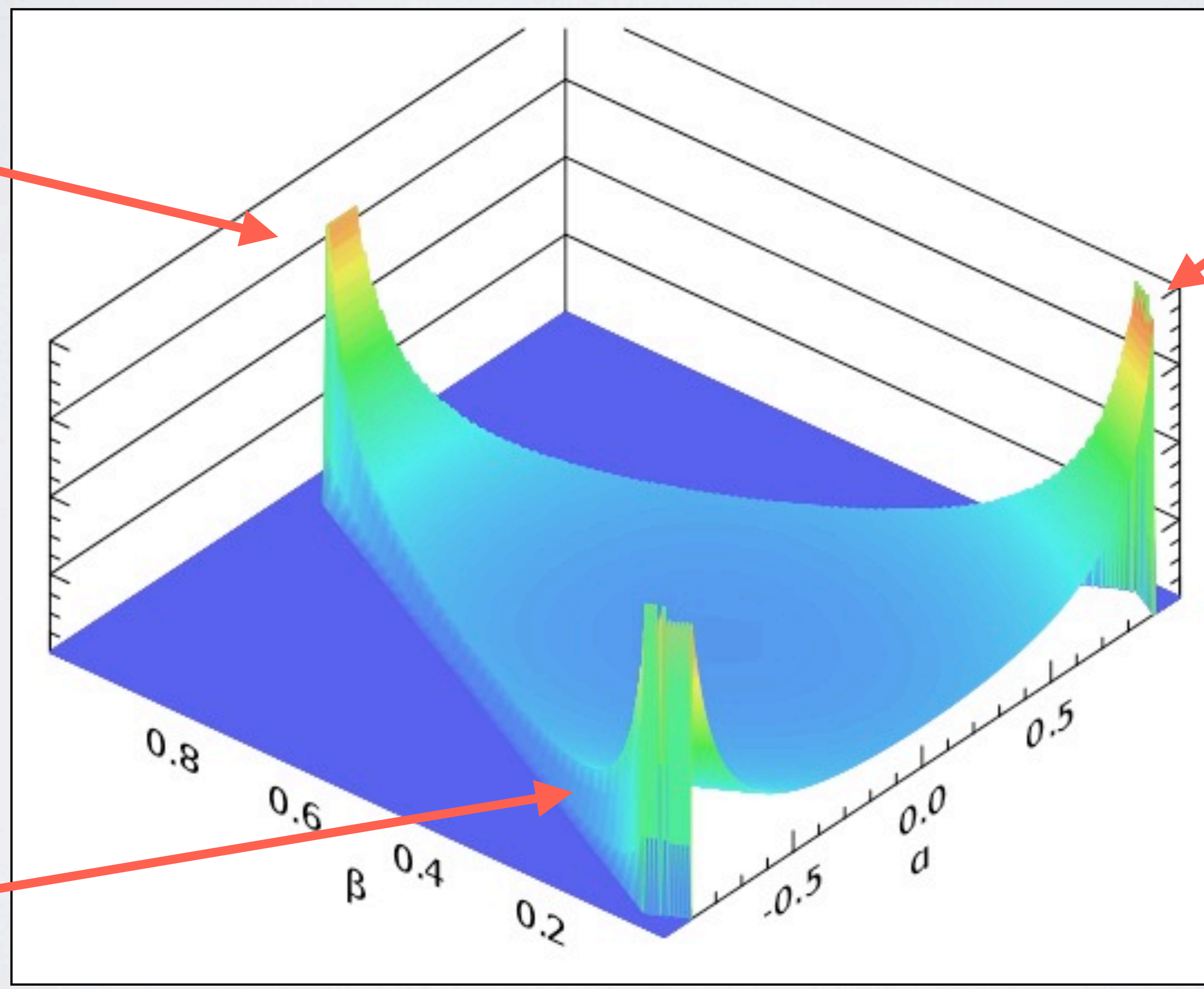
$k_1 \to 0$

The bispectrum

This is a complicated function of the scales k_i
It turns out to be quite hard to calculate

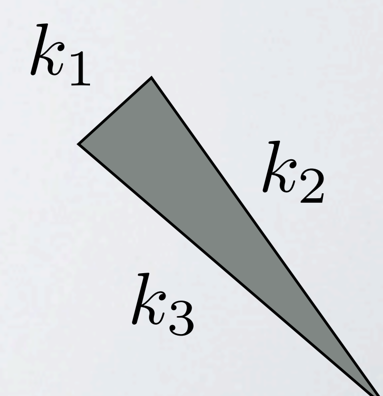
$k_3 \to 0$

$k_2 \to 0$



$k_1 \to 0$

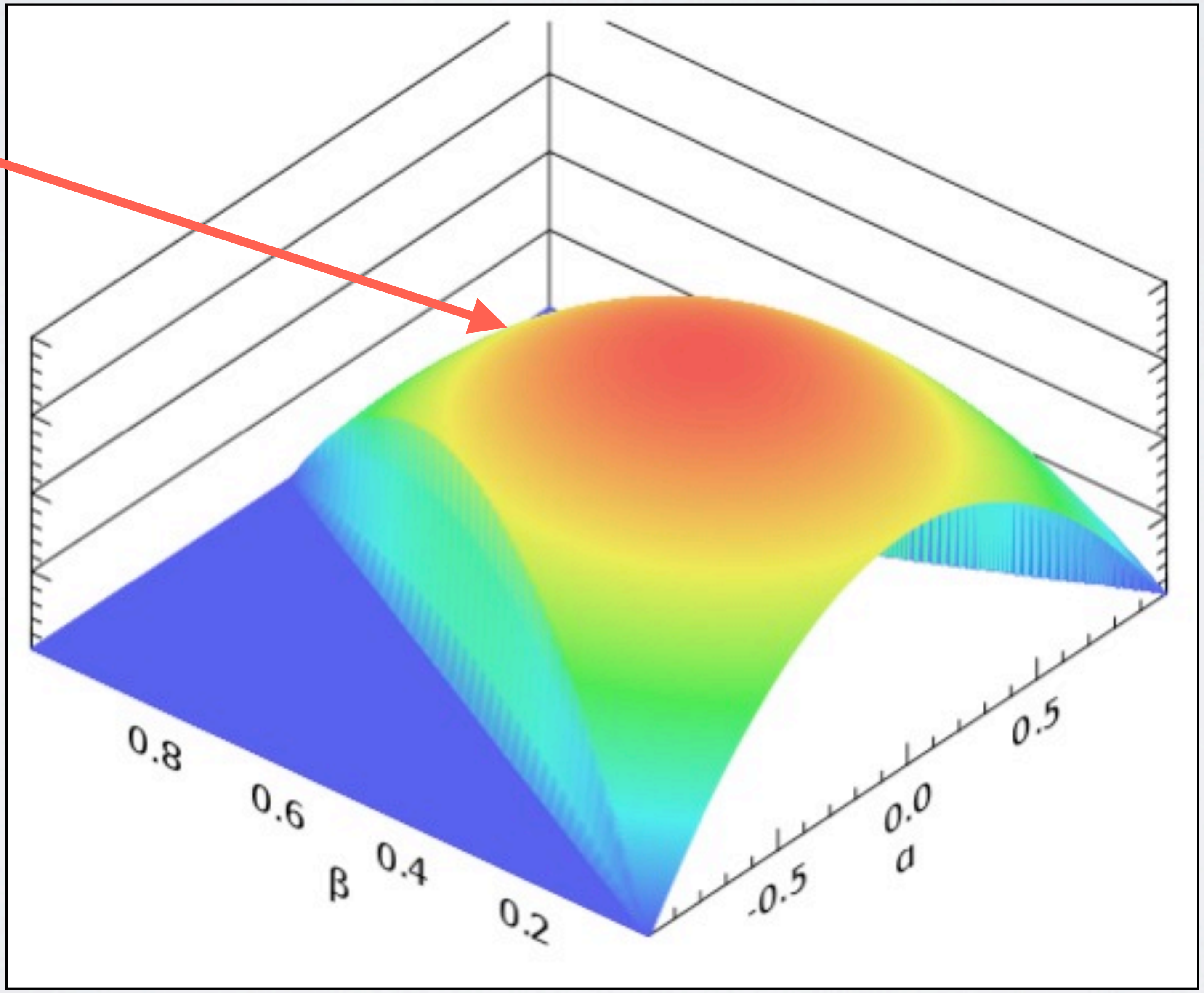
squeezed



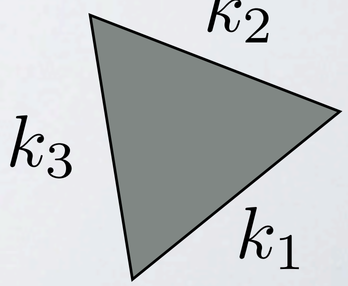
The bispectrum

This is a complicated function of the scales k_i
It turns out to be quite hard to calculate

$k_1 \approx k_2 \approx k_3$

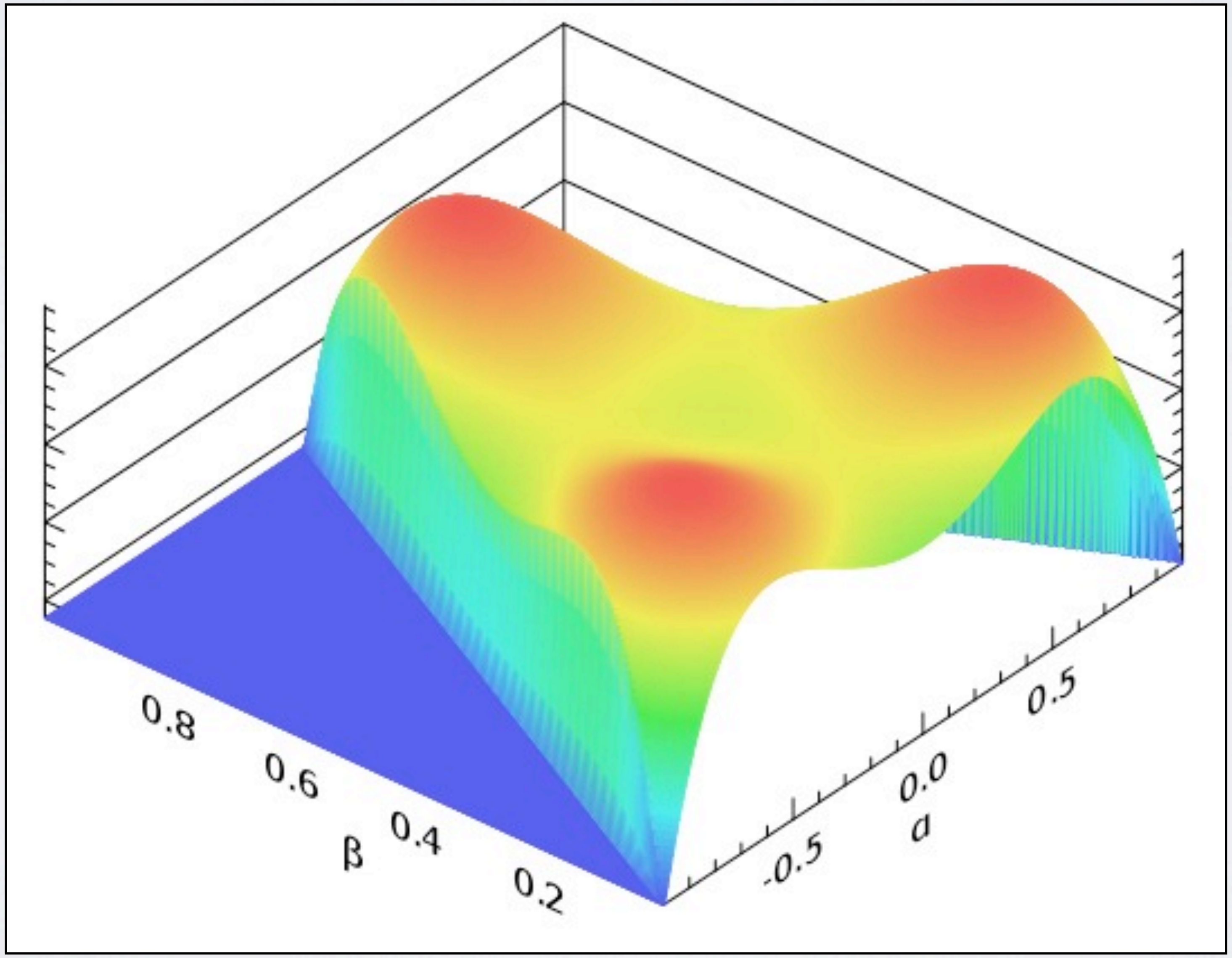


equilateral



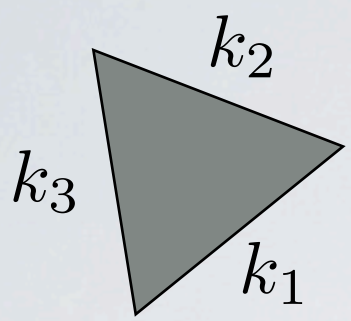
The bispectrum

This is a complicated function of the scales k_i
It turns out to be quite hard to calculate

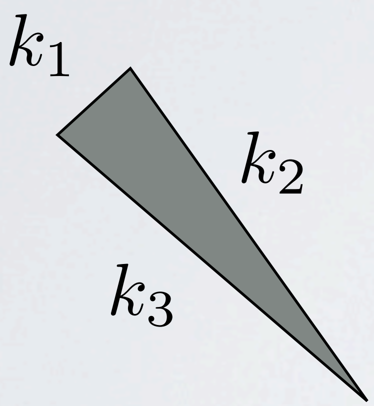


weird

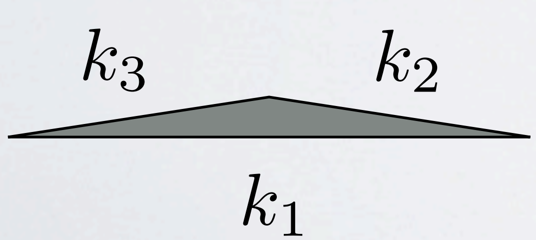
(mix of triangles)



Equilateral. Indicates that the fluctuations have exotic structure, such as nontrivial kinetic energy. Favours stringy or supergravity scenarios.



Squeezed. Indicates that the fluctuations have time evolution. Since that is forbidden in single-field models, this implies multiple light modes.



Folded. Indicates a near zero-energy "resonance" between positive and negative energy modes. Favours non-vacuum initial conditions.