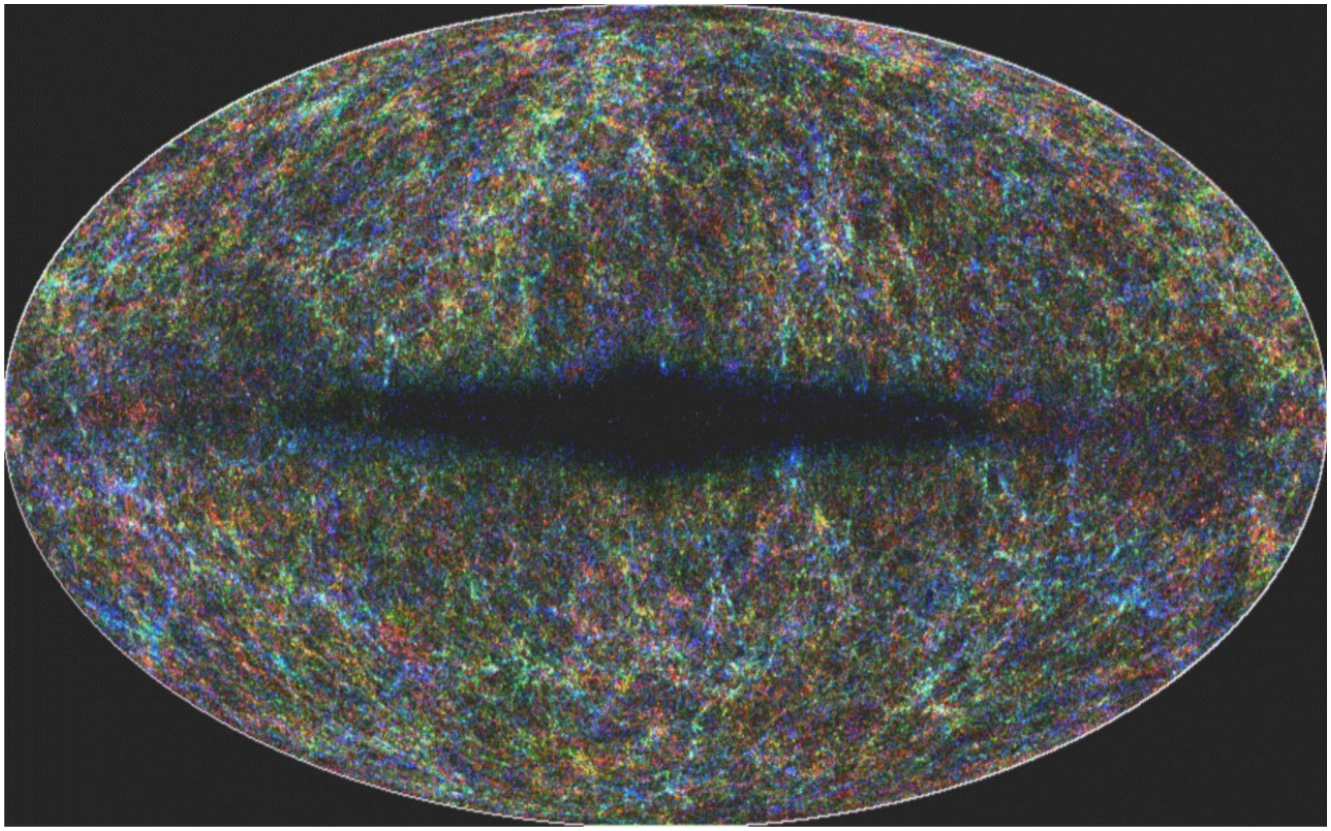
# The vacuum, the Higgs field, and modern cosmology

John Peacock



# Some big questions in cosmology:

**Why is the universe expanding?**

**What happened before the big bang?**

# The modern answer: because the vacuum has weight

- Given different names:

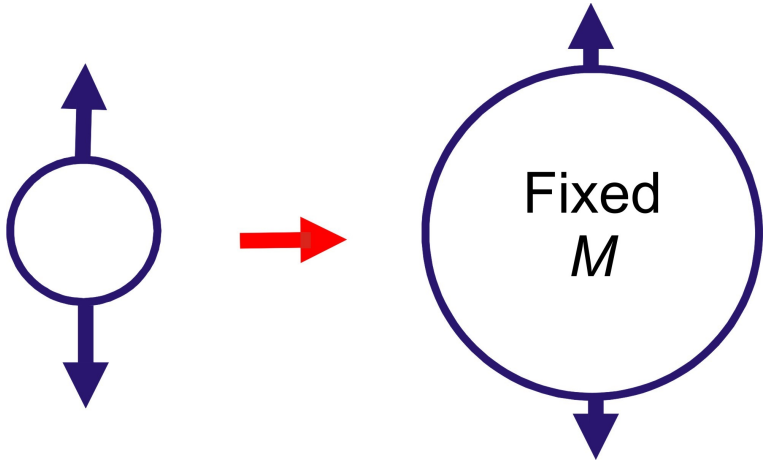
cosmological constant

vacuum energy

dark energy

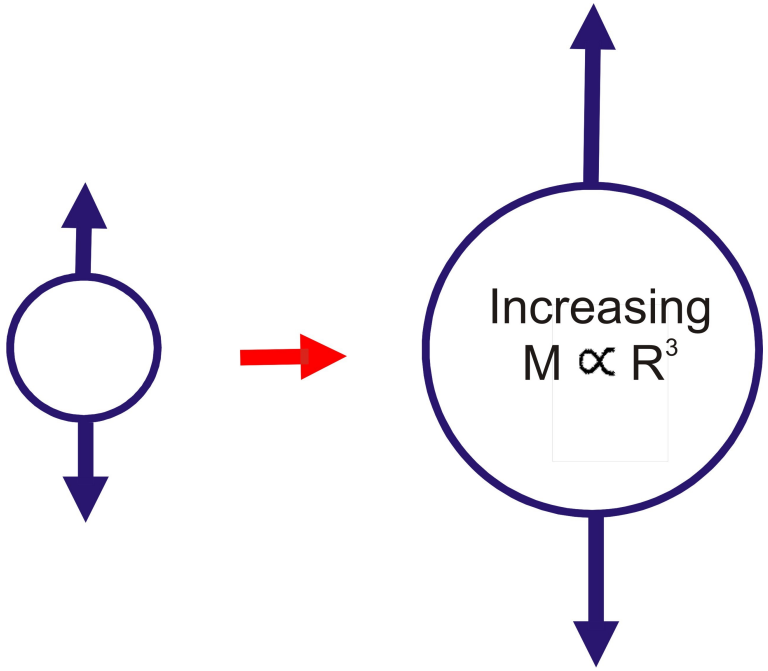
# Empty space has antigravity

Ordinary matter: expansion slows as it expands, since gravitational energy is less




$V = GM/R$
$\propto 1/R$

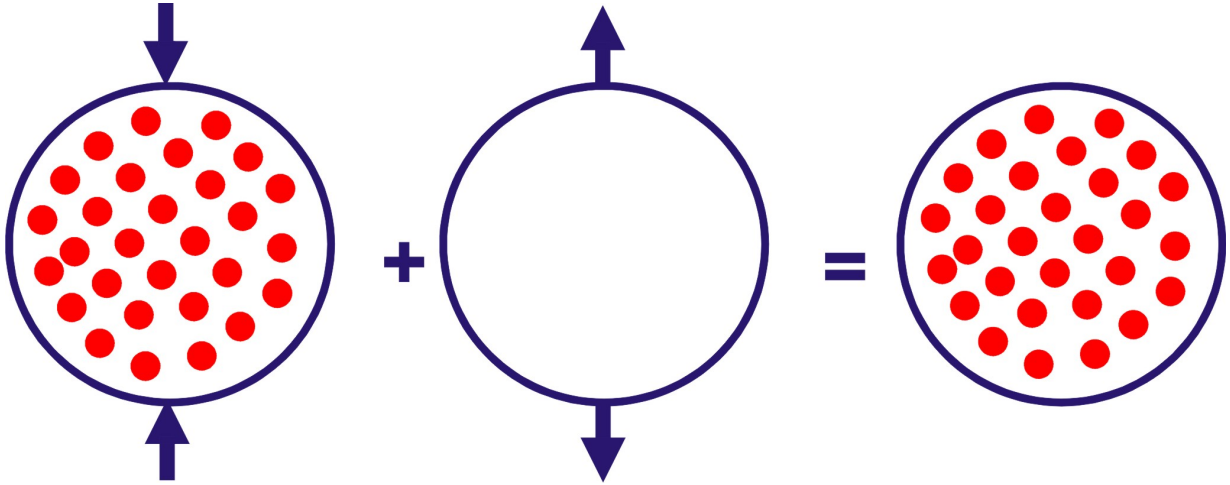
A sphere of vacuum increases mass as it expands, so gravitational energy goes up



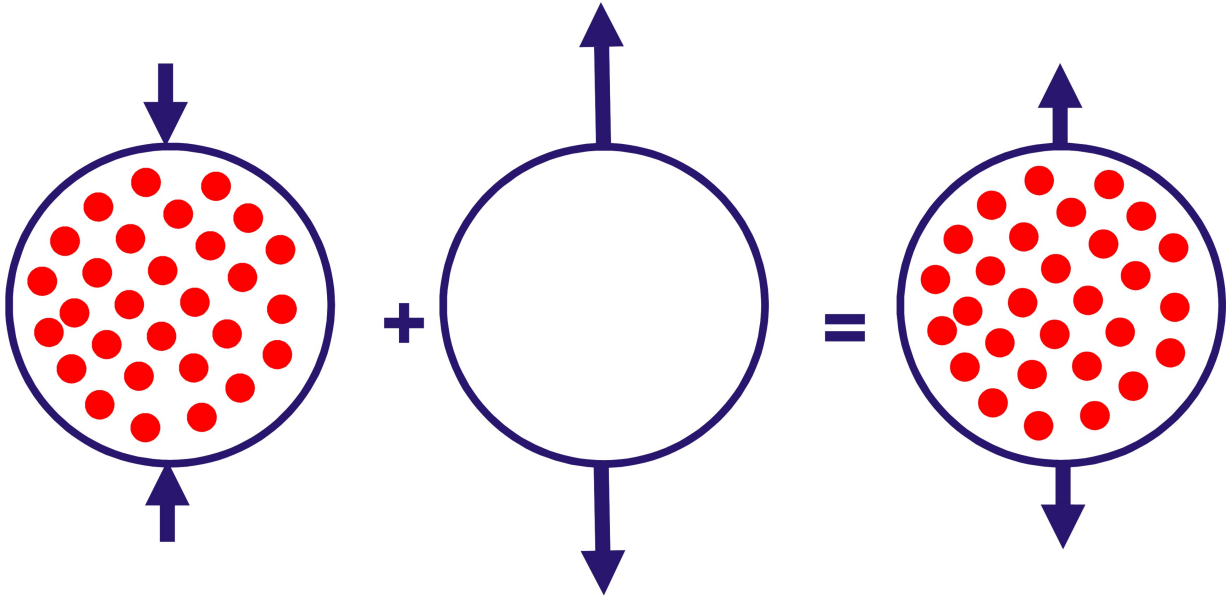

$V = GM/R$
$\propto R^2$

# Vacuum energy: Einstein's missed chance

1917: Einstein's static universe balanced gravity and repulsion from cosmological constant - abandoned after Hubble



Now: **'Dark Energy'** can cause the expansion of the universe to accelerate



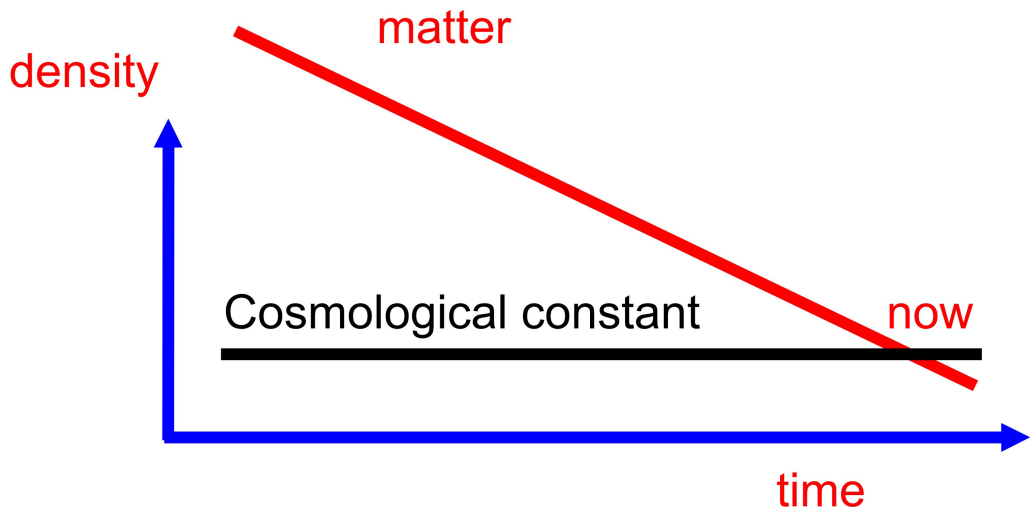
# The observed vacuum density

This accelerating expansion is seen in astronomical data (2011 Nobel Prize):

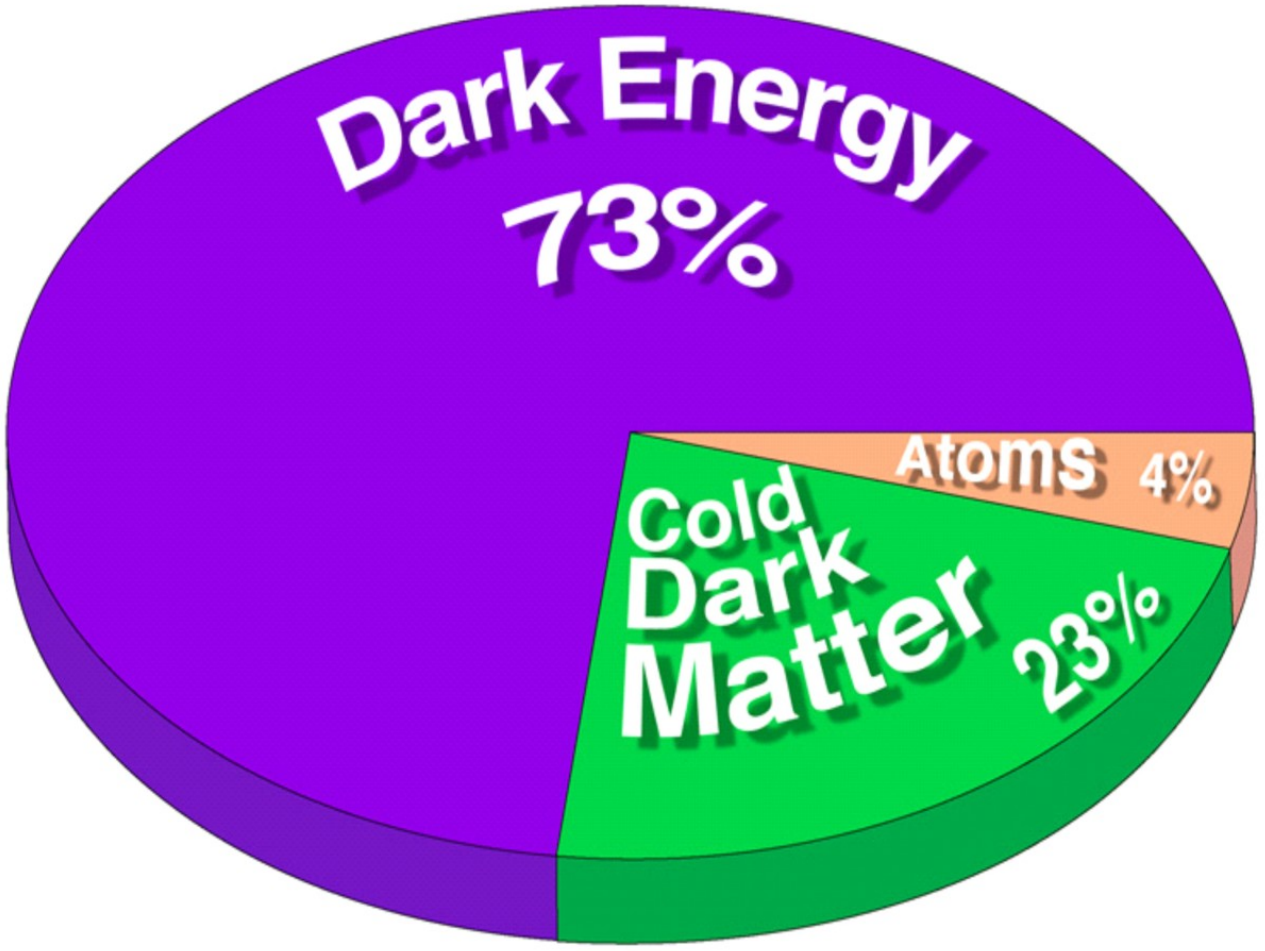
Observed vacuum density $= 6 \times 10^{-27}\,\mathrm{kg\,m^{-3}}$

Acceleration only recent as vacuum density was negligible in the past

The 'why now' problem:

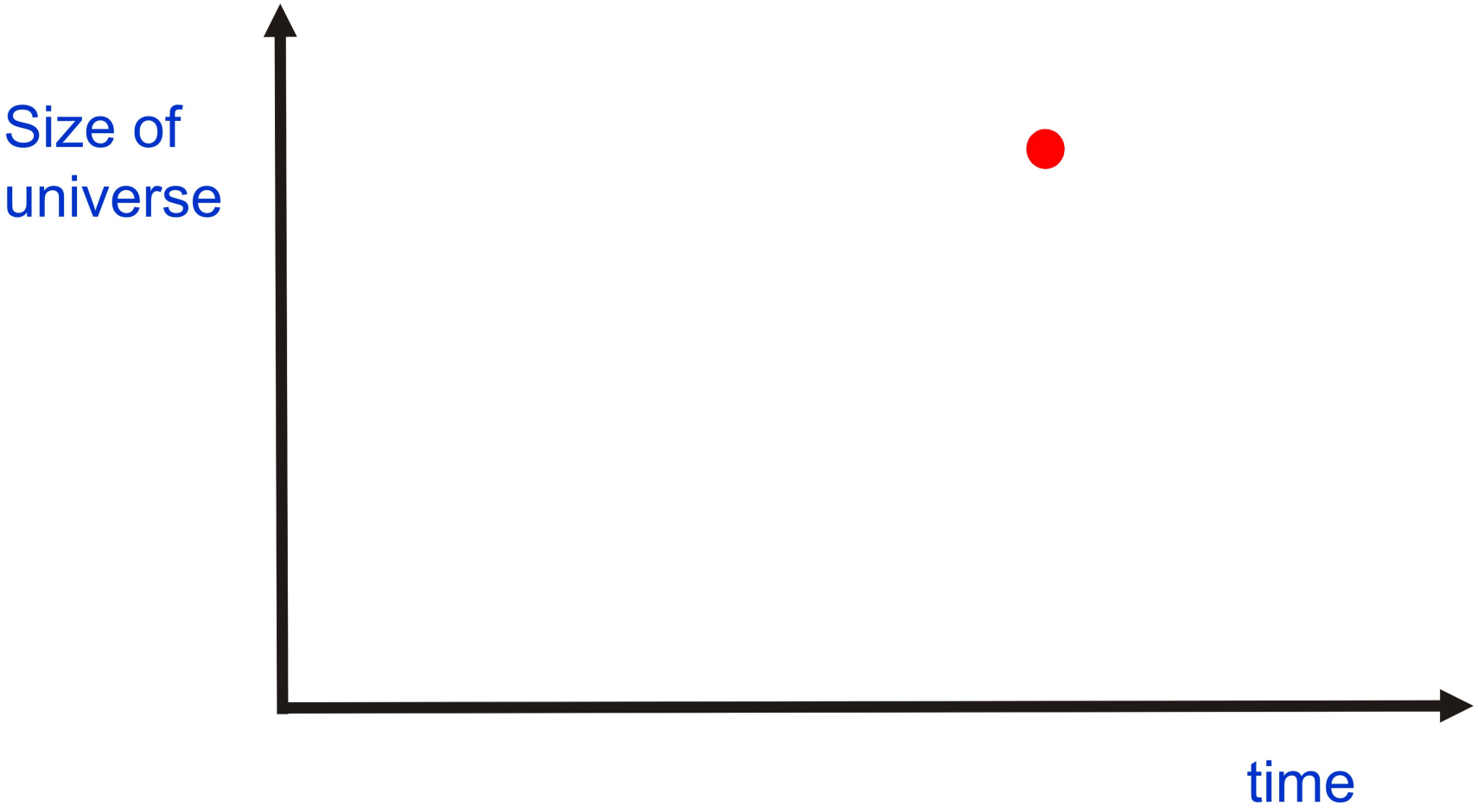


# The puzzling universe




Plus about 0.01% radiation: more important in the past

# The Big Bang and cosmic acceleration



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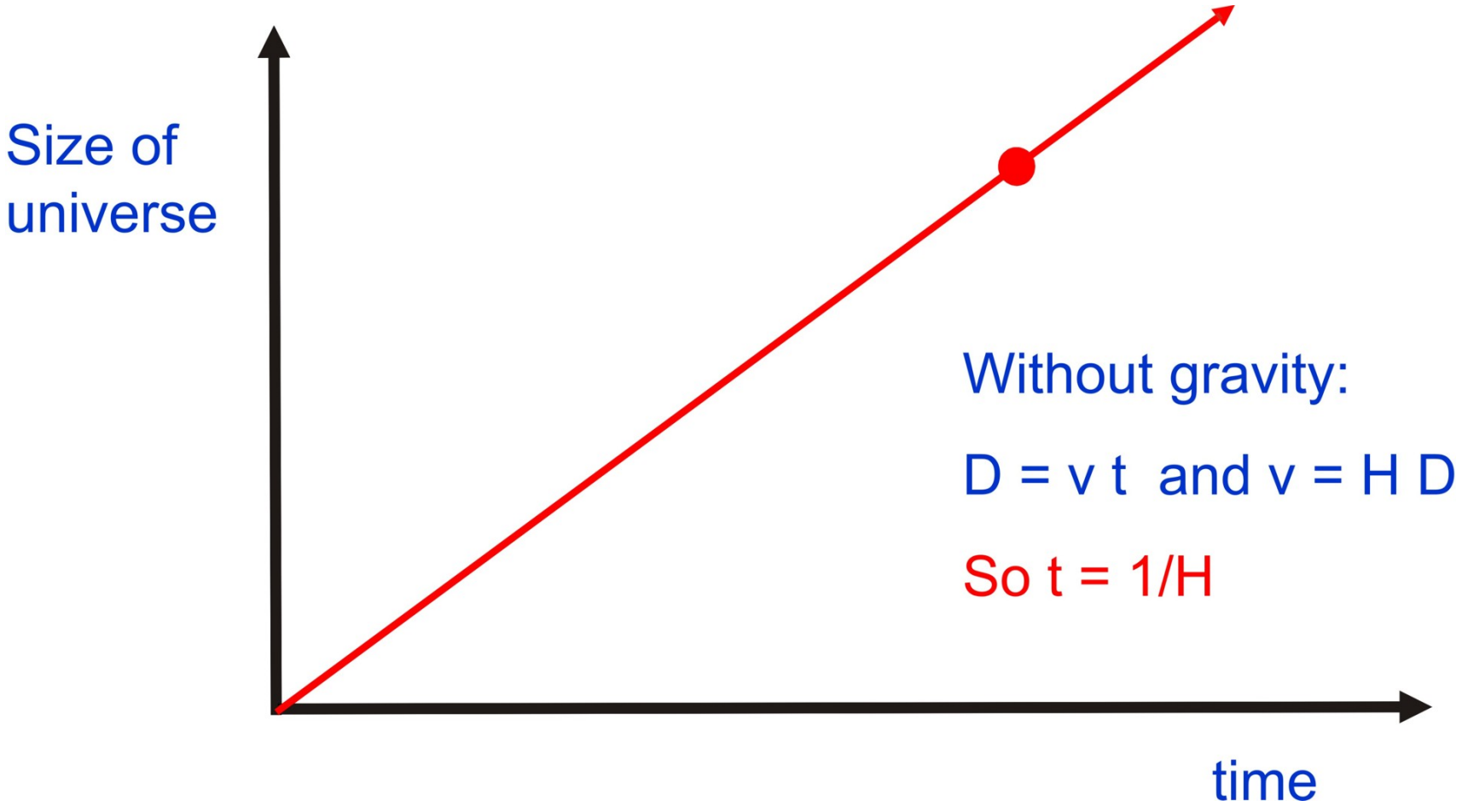
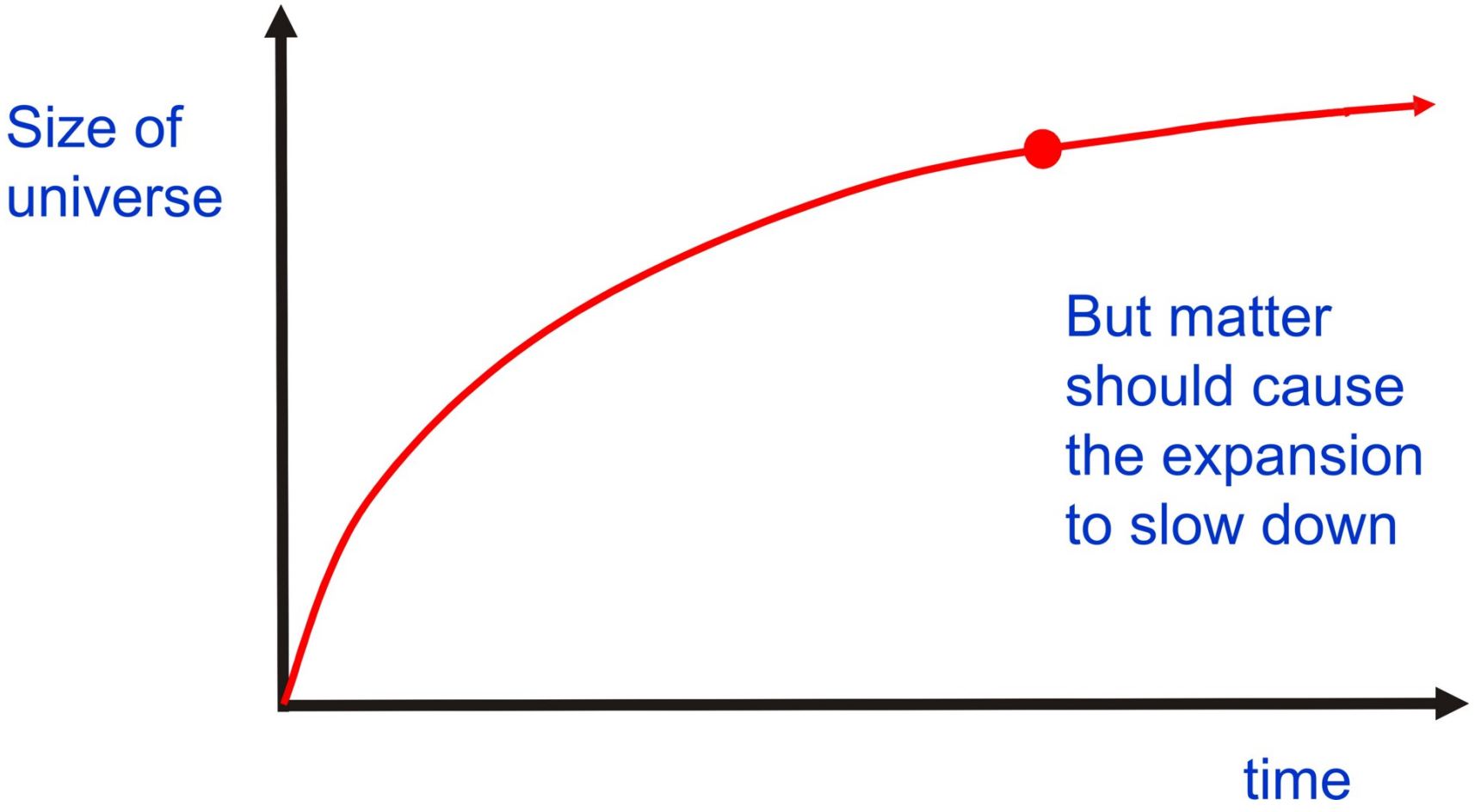



The Big Bang: zero size and infinite density $1/H = 14$ billion years ago

# The Big Bang and cosmic acceleration



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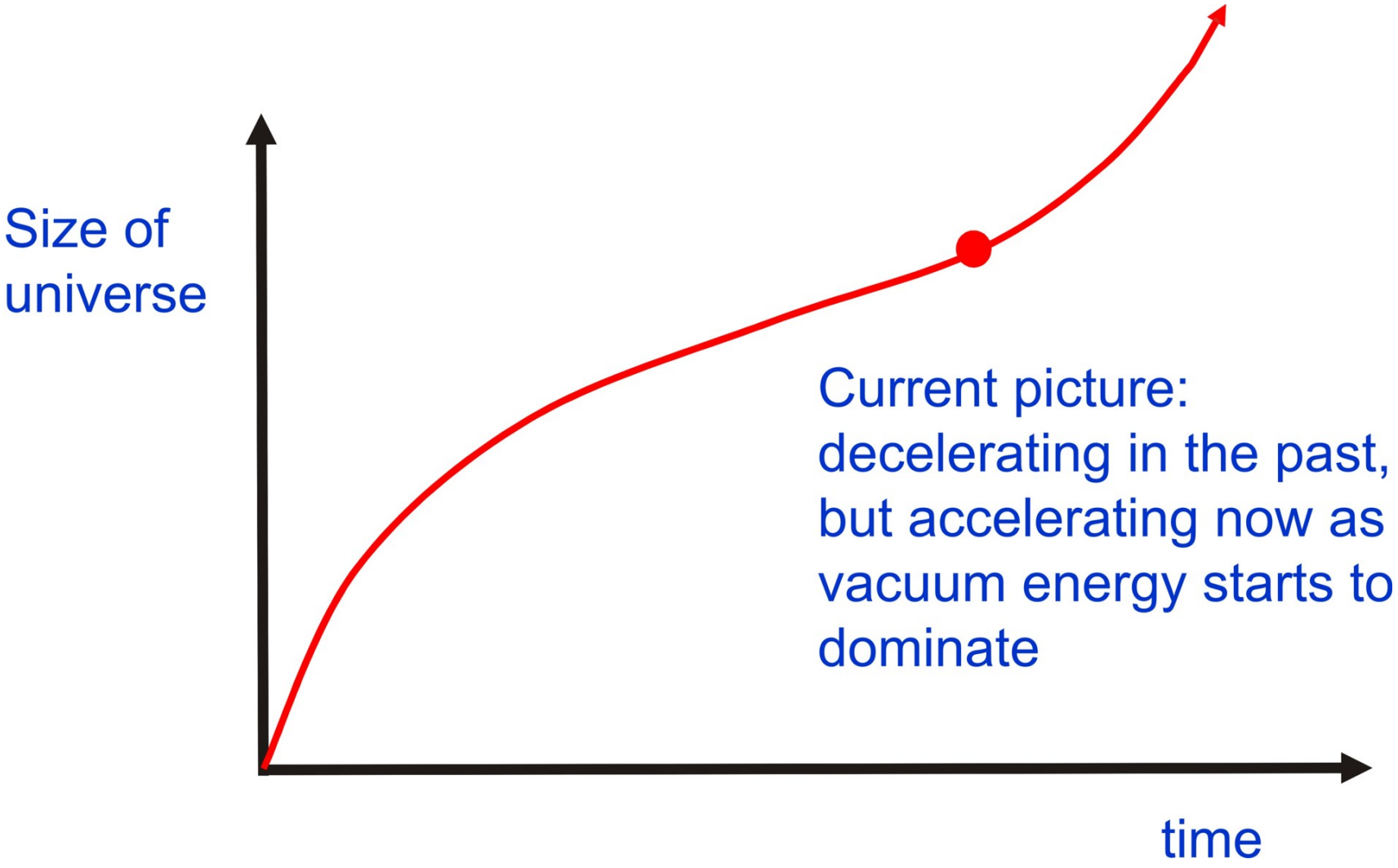

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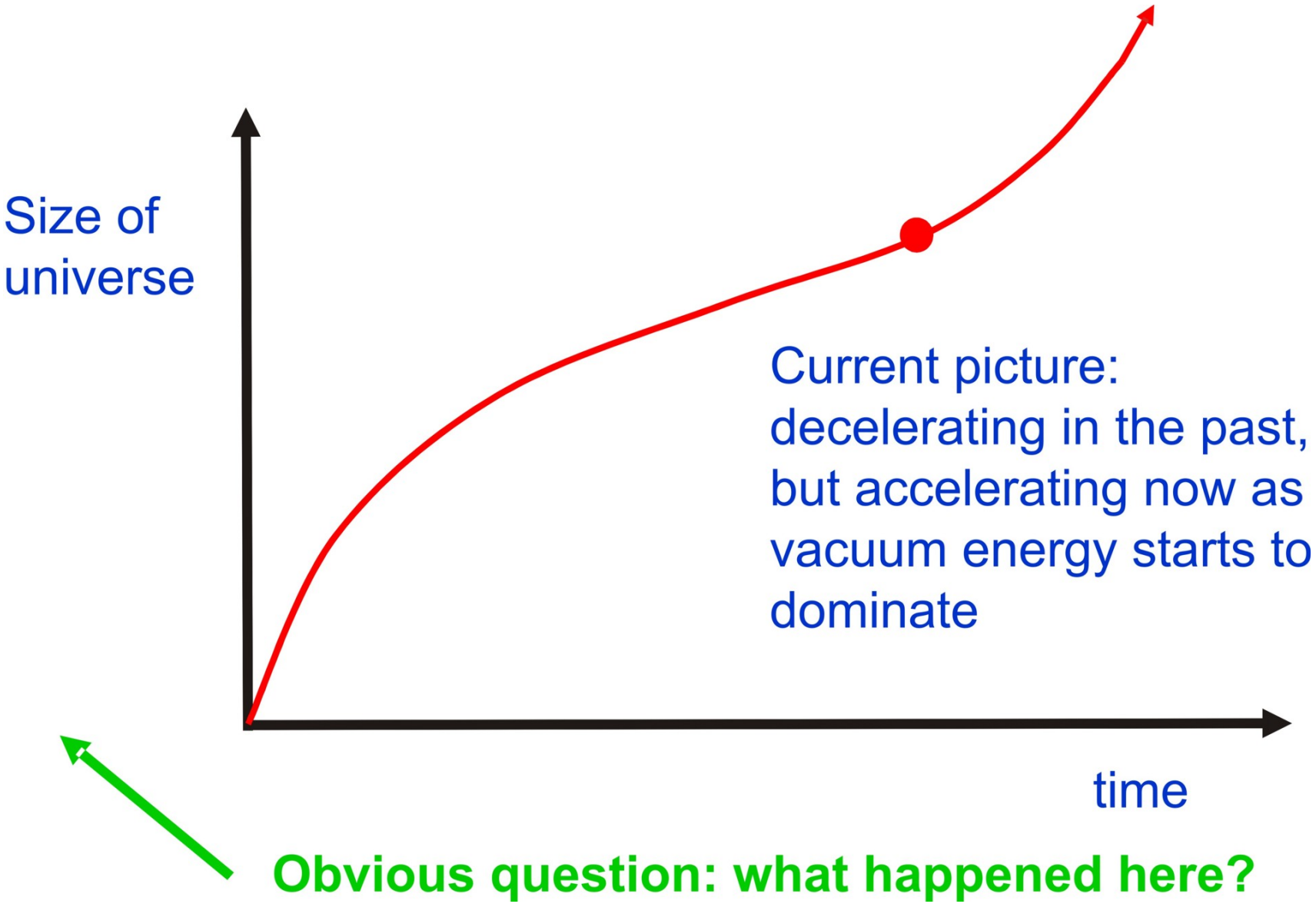


**But how can the vacuum weigh anything?**

**Isn't it empty by definition?**

# Physics of the subatomic realm:

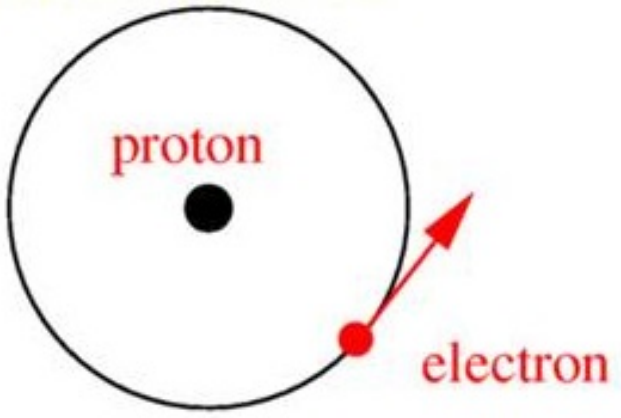
# The uncertainty principle (1927)

$$\boxed{\Delta(mv)\Delta(x) \gtrsim \hbar}$$

Precise knowledge of both position and speed is impossible

Werner Heisenberg (1901 - 1976)

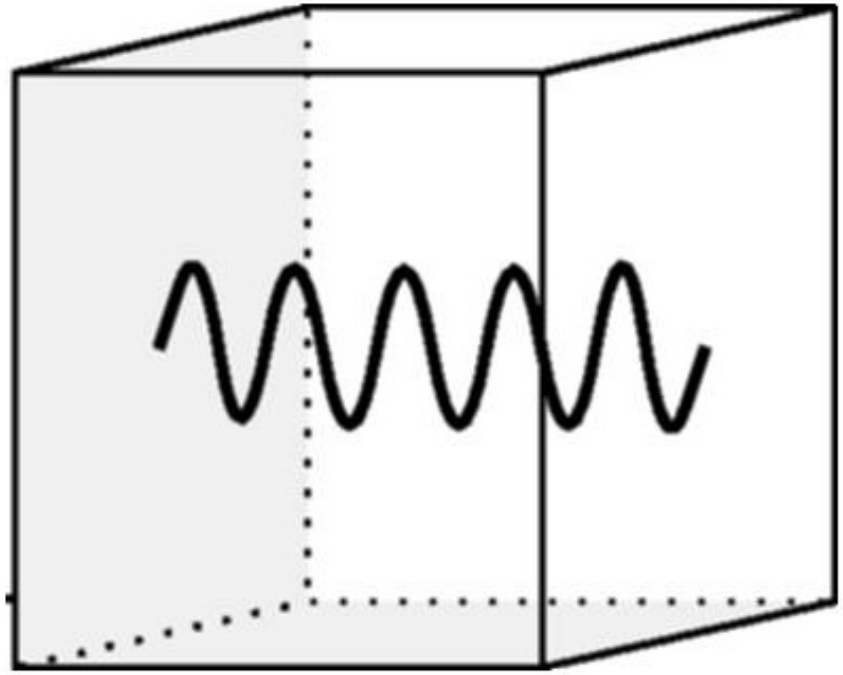
## Sizes of atoms




Uncertainty in speed of electrons
=speed of light
if size of atom = $10^{-12}$ m

# The vacuum of fields:

# zero-point energy



Energy in
electromagnetic wave
mode of frequency $\nu$
$= (n + 1/2)h\nu$
n photons and zero-point
energy (inevitable from
uncertainty principle)

- The vacuum is all n=0, so some energy remains

# The embarrassment of the vacuum density

Need to sum zero-point energy over all photon frequencies - but then the answer is infinite

Stop at some maximum photon energy (= new physics) and convert energy density to mass density via $E = Mc^2$

Predicted vacuum density $\sim 10^{36} (E_{\mathrm{max}}/10\,\mathrm{TeV})^4\,\mathrm{kg\,m}^{-3}$

Observed vacuum density $\sim 10^{-26}\,\mathrm{kg\ \ m}^{-3}$

So energy scale of new physics is $\sim 0.001$ eV??

Need some other contribution to cancel the zero-point energy