How and Why to go Beyond the Discovery of the Higgs Boson

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http://hep.uchicago.edu/~johnda/ComptonLectures.html

Lecture Outline

April 1st: **Newton's dream & 20th Century Revolution**

April 8th: **Mission Barely Possible: QM + SR**

April 15th: **The Standard Model**

April 22nd: **Importance of the Higgs**

April 29th: **Guest Lecture**

May 6th: **The Cannon and the Camera**

May 13th: **The Discovery of the Higgs Boson**

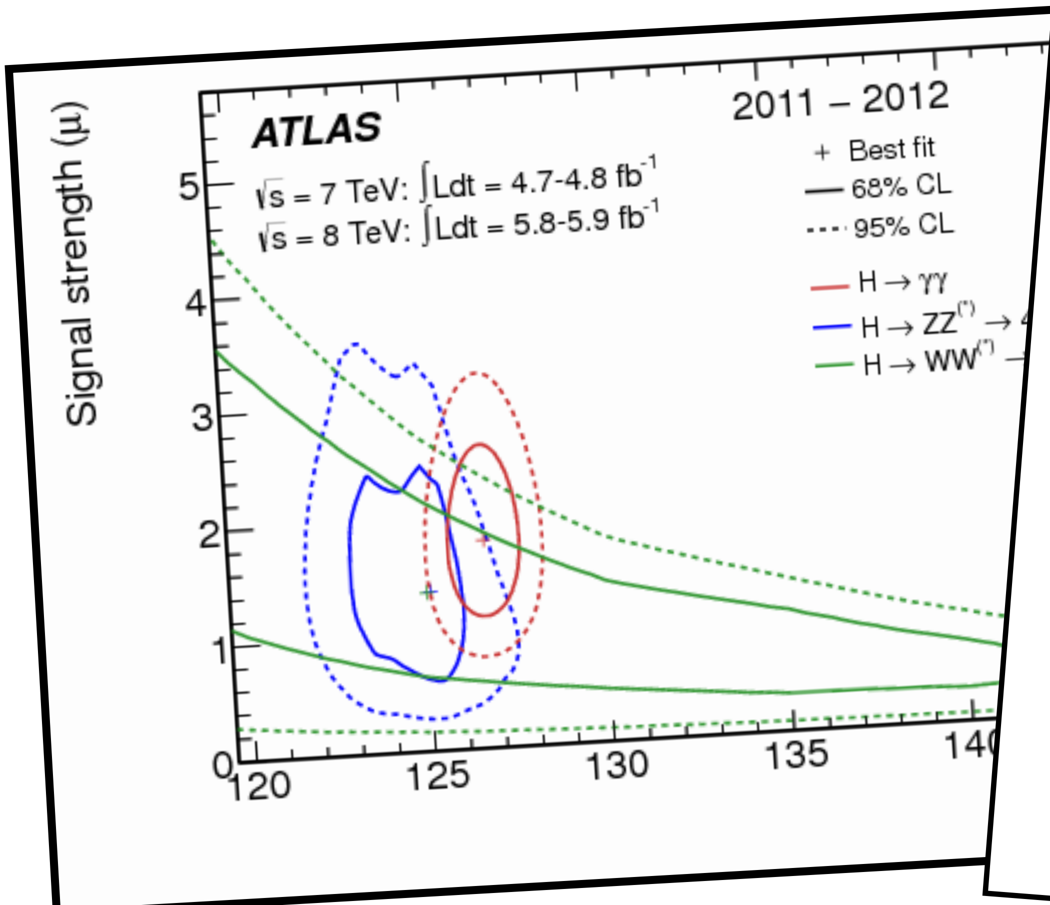
May 20th: ***Problems with the Standard Model***

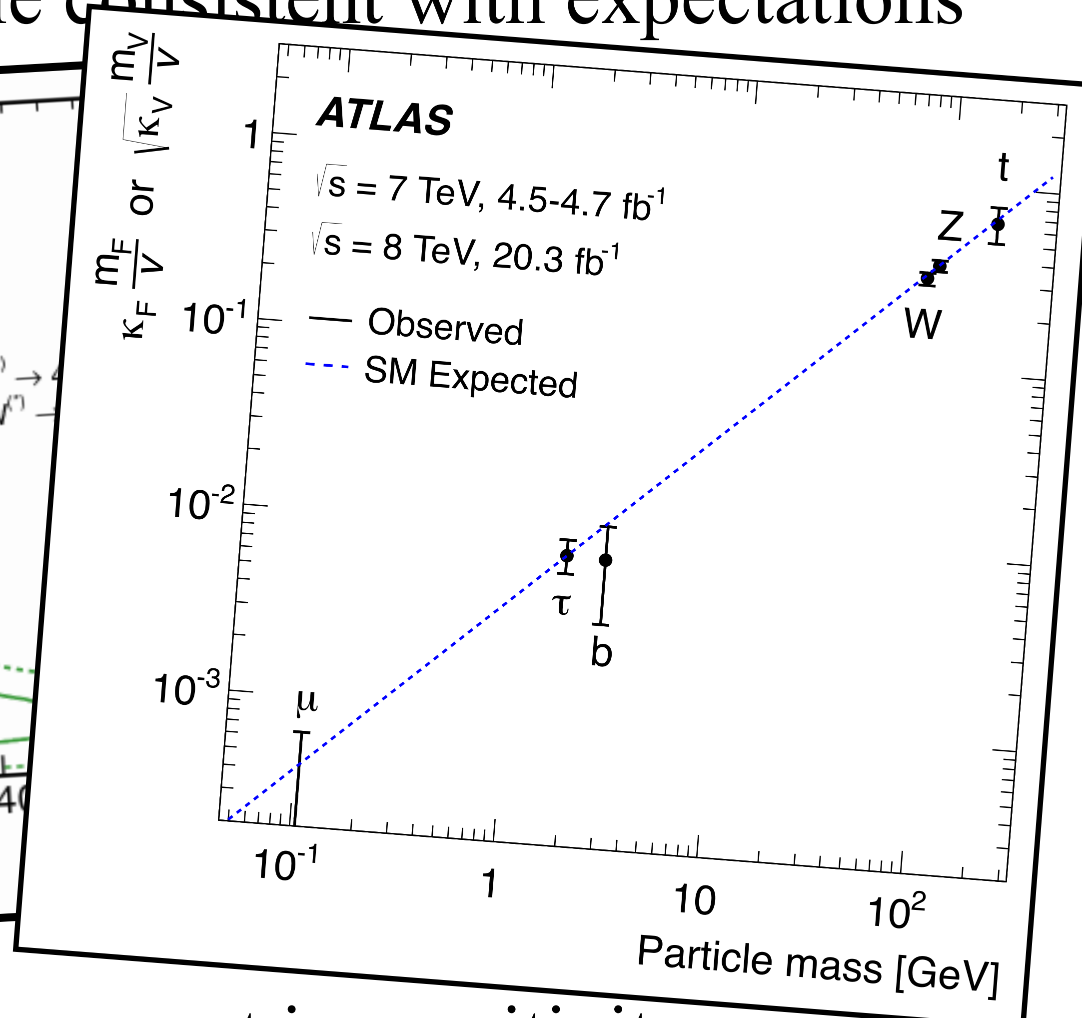
May 27th: **Memorial Day: No Lecture**

June 3rd: **Going beyond the Higgs: What comes next ?**

Reminder: Last Week

2012: Discovered new particle consistent with expectations





Since then: Significant improvement in sensitivity
Agreement with Higgs interpretation ~20% level
No sign of any deviations

What it Took: In Numbers

- **>10,000** scientists and engineers from **85** countries
- **27 kilometer** particle accelerator
- Protons moving at **99.9999993%** the speed of light
- **~1 billion** proton collisions / second (for 2 years)
- Total budget: **~10 billions dollars**
- Detectors - size of apartment buildings - operating at **40 MHz**
- Generate **80 TB/s** (~10 × size of library of congress)
- (Salary of physicist) << (Salary of banker or engineer)

~~What is the Higgs boson~~ ?!?

~~Why did we need such extreme~~ ... ~~find it~~ ?

~~Why look for the Higgs boson in the~~ ... ?

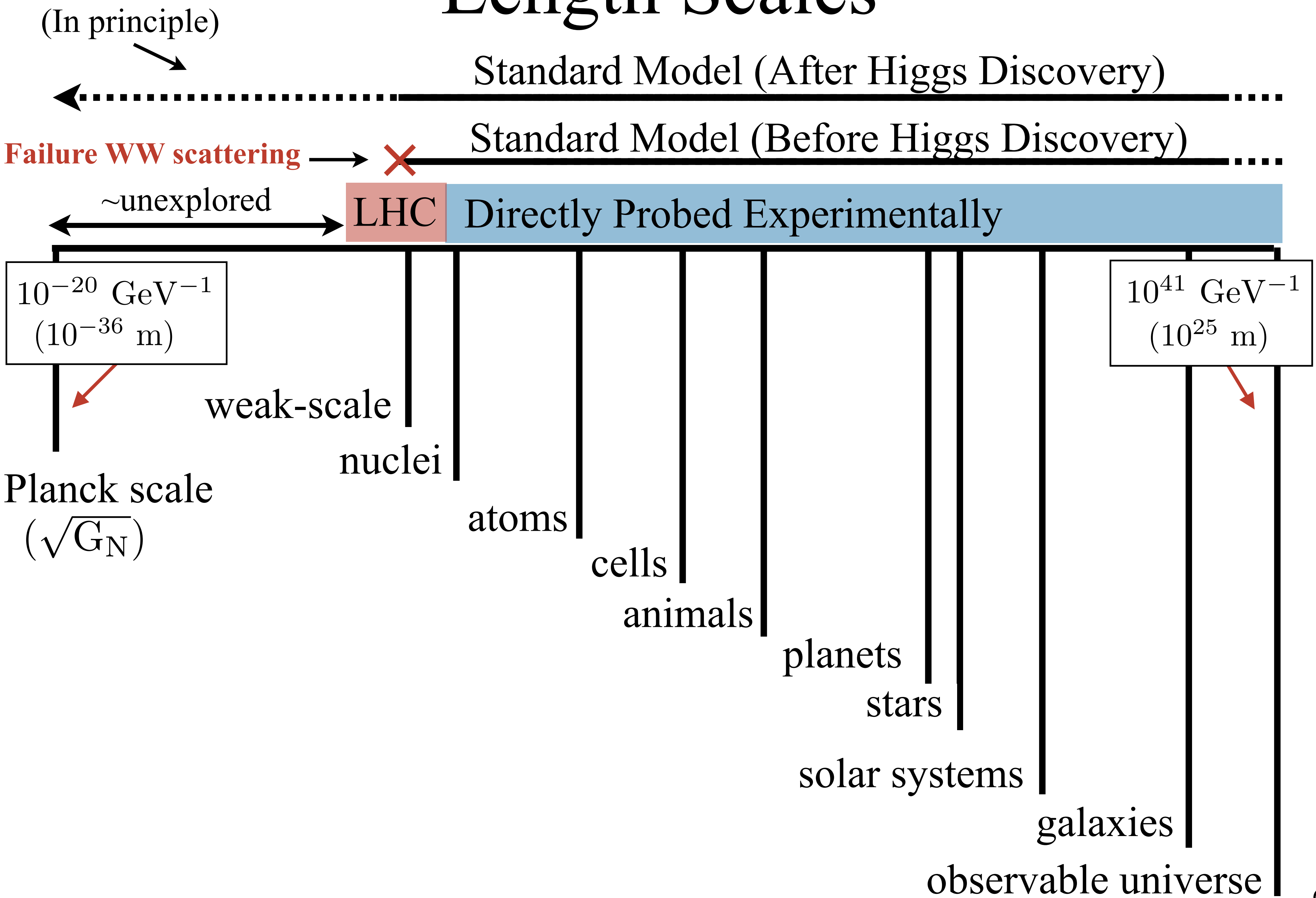
Are we done now that we have found it ?

Focus of last two lectures

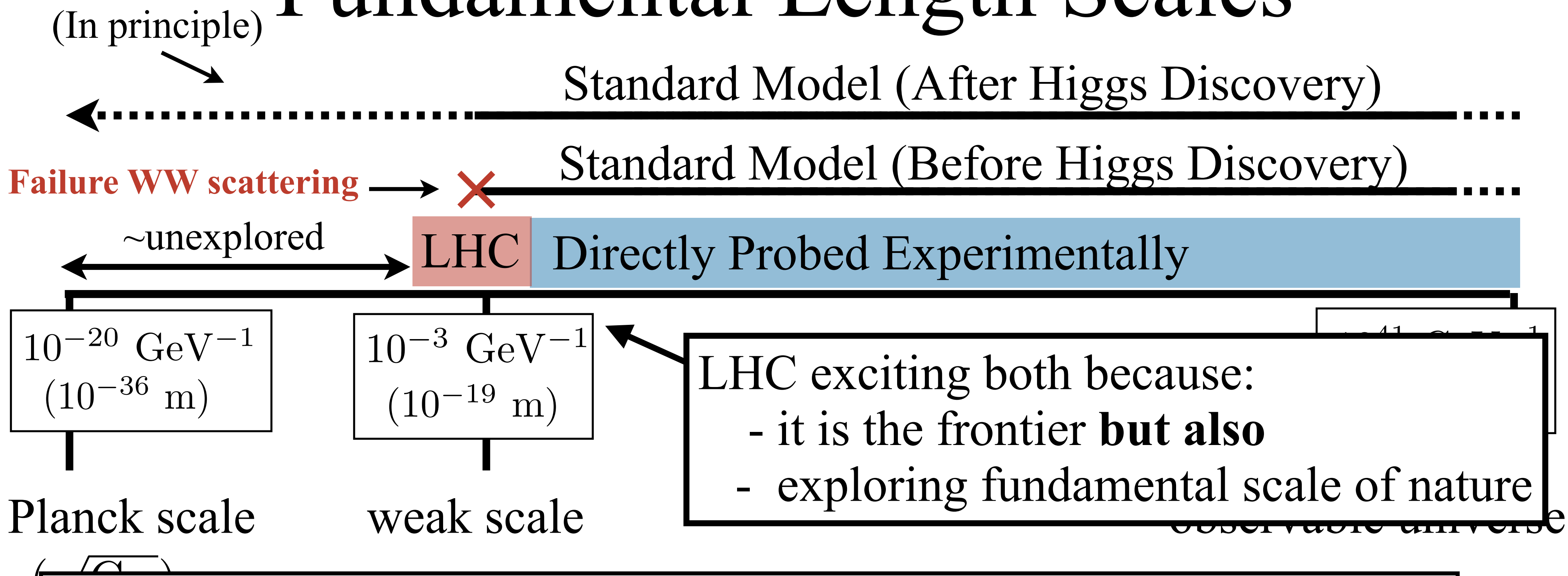
Today's Lecture

Problems with the Standard Model

Length Scales

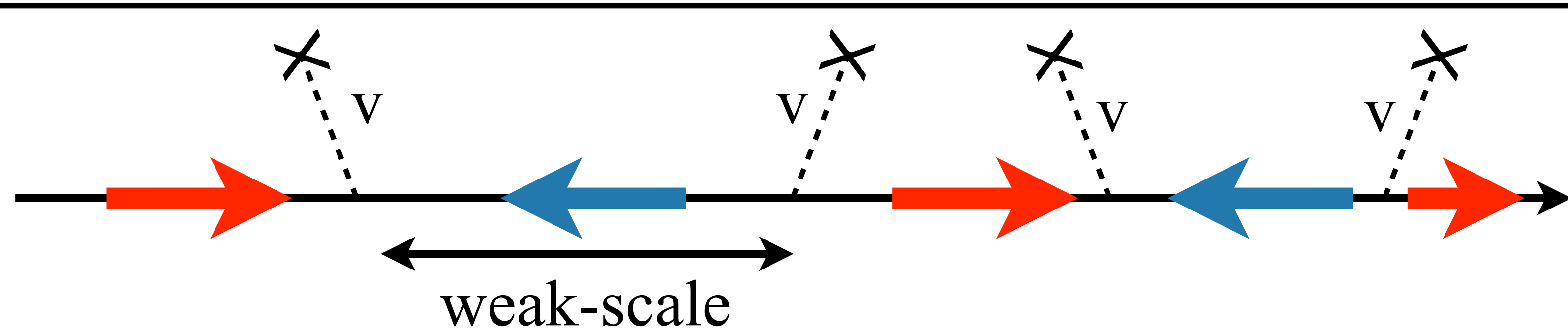


Fundamental Length Scales

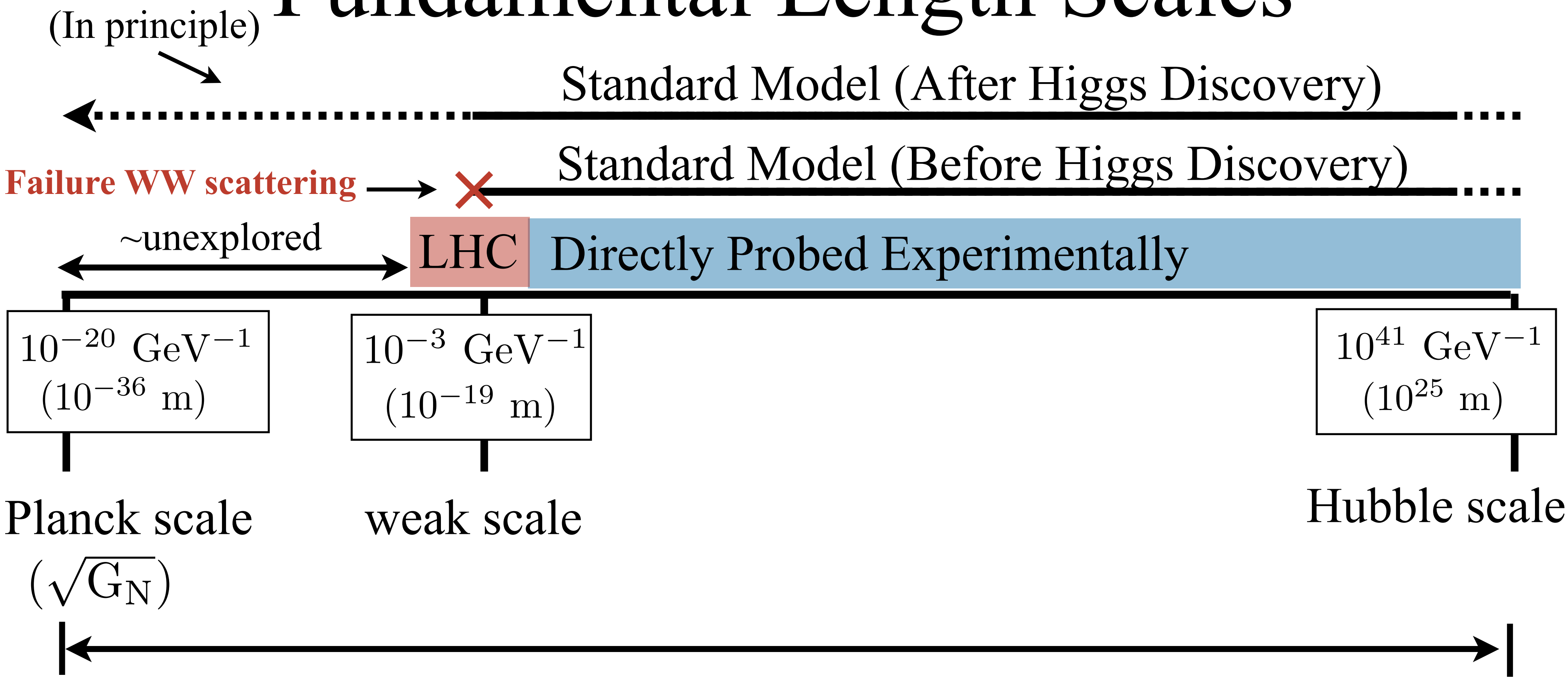


Weak scale: Fundamental scale in physics

- Scale associated with fundamental particle masses
- Typical at which massive particles interact with Higgs field
- The first time start seeing the forces have same underlying structure



Fundamental Length Scales



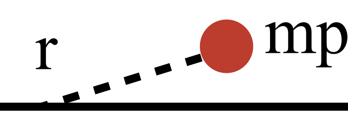
- Large range, but not infinite.
- Claim: Everything we know, ***and can possibly know***, within this range
- Upper bound set by finite upper speed limit (finite age of universe)
- Talk about lower bound, next. Believed to really be hard lower bound
- Deep mysteries/problems with SM directly associated with each fundamental scale

Problem with the Planck Scale

Relative Strength of Gravity

Electromagnetic Interaction

$$F_{EM} = e^2 \quad 1$$



At short distances, (comparable to ℓ_{Pl}) gravitational interaction dominates
- ℓ_{PL} the scale at which gravity is becoming strong

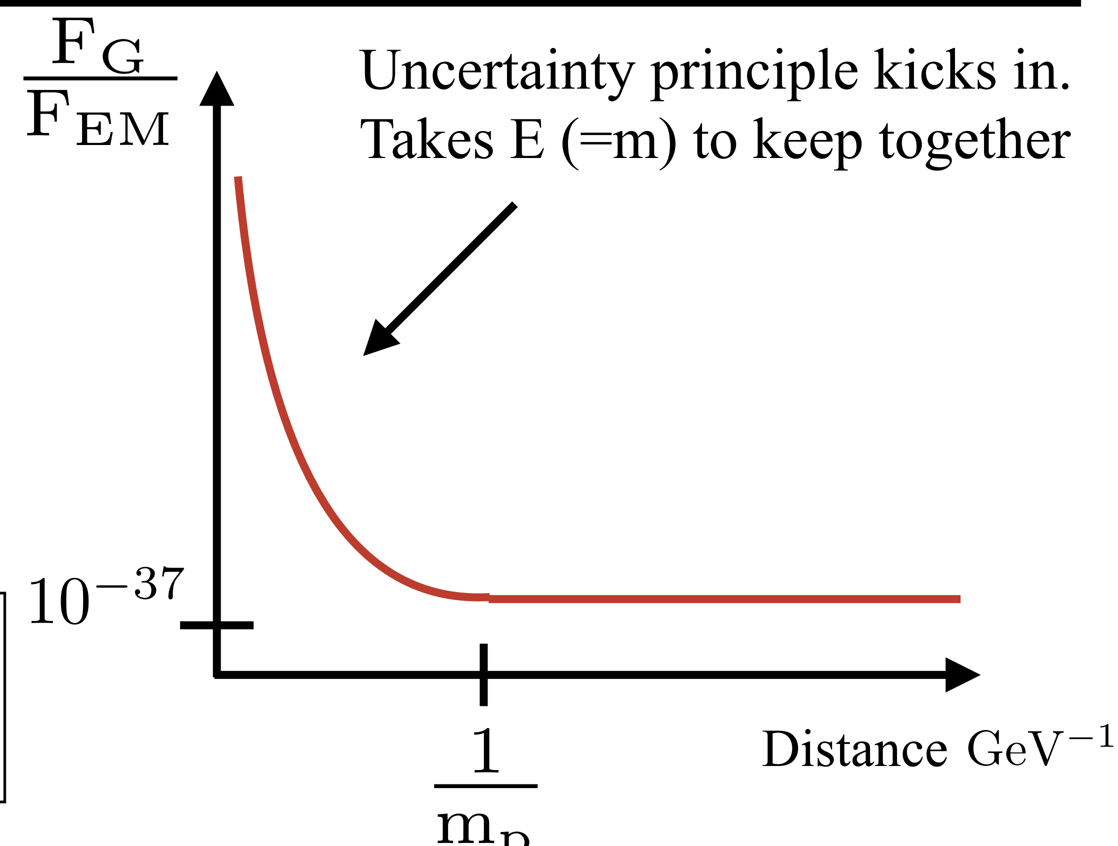
Pure number: α

Gravitational Interaction

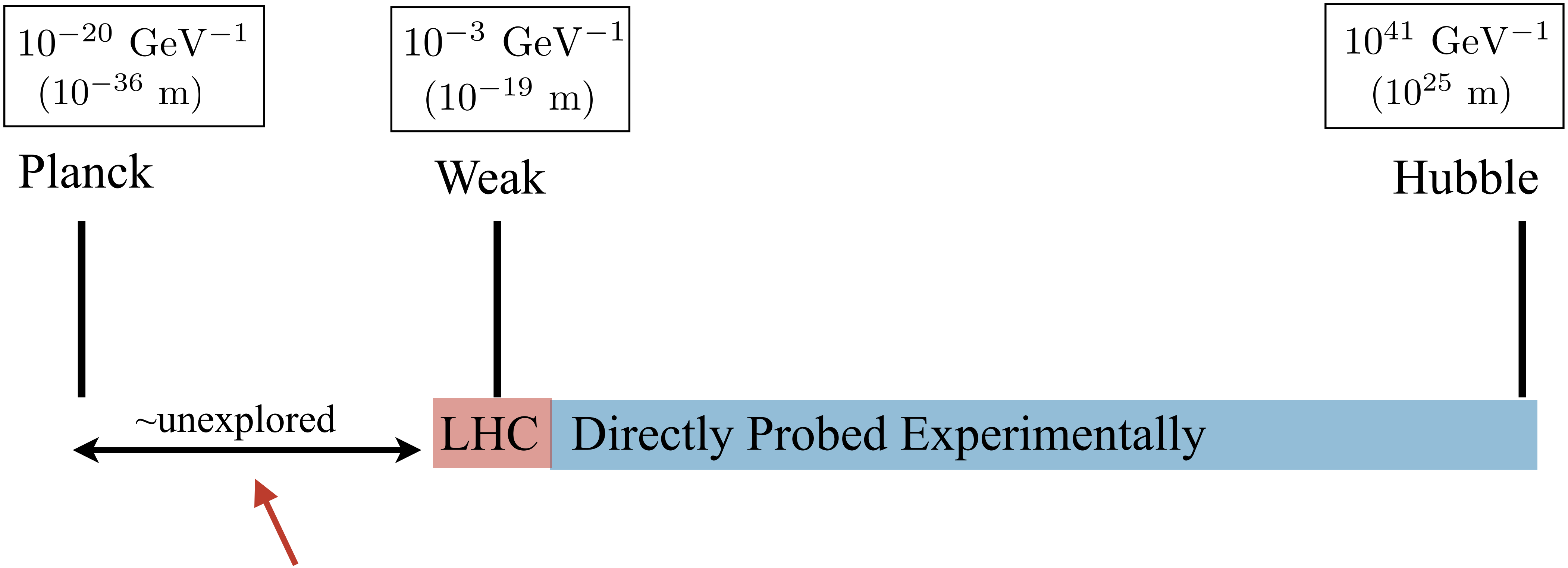
$$F_G = \underbrace{G_N}\frac{m_p^2}{r^2}$$

Dimensionful number

$G_N \sim (l_{Pl})^2 \sim (10^{-20}\ \mathrm{GeV}^{-1})^2$



Probing Smaller Distance Scales



- Say we decided to probe smaller and smaller distance scales
- Build collider, go to higher and higher energies
- Eventually reach point where gravitational interaction dominates
- Continue to smaller distance … then something new happens…

Create Black Holes !

Some point put so much energy into collisions that you create black hole

Estimate scale when this happens:

$$G_N \frac{m^2}{r} \sim mc^2$$

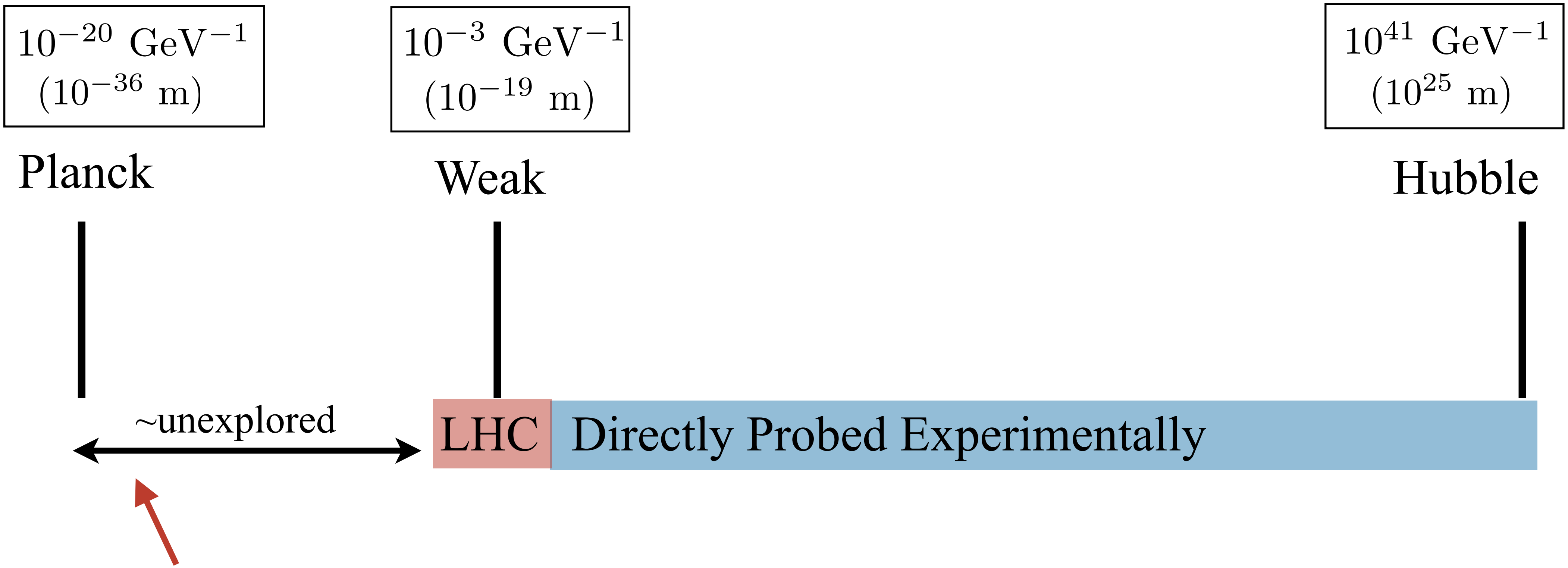
At high energies, mass dominated by E associated w/uncertainty principle

$$m \sim \frac{1}{r}$$

$$G_N \frac{1}{r^3} \sim \frac{1}{r}$$

$$r \sim \sqrt{G_N} \sim l_{Pl}$$

Probing Smaller Distance Scales



- Go to higher-higher energies… Gravity begins to dominate
- At ℓPl make blackhole / Cant tell whats happening in blackhole
- Even higher energies gives bigger blackhole
- Nothing can do (in principle) to get information about smaller scales
    - *Physics telling us that smaller scales dont exist*

(Seen kind of thing before in QM and Relativity)

Probing Smaller Distance Scales

Lower Limit to Spacetime

Notion of space-time breaking down ℓPl /Not clear what replaces it.

<u>Major issue:</u>

- Understanding of these short scales needed for:
  - Early universe: *What happened when universe curvature ℓPl*
  - Details of blackholes
- Physics is about what happens in space-time

Other hints that some dramatic need ("Holographic Principle")

- Black hole information scales like area
- Observables with QM can in principle perfectly predict
- Toy models where see space emerging
- …

(Seen kind of thing before in QM and Relativity)

Problems with Weak and Hubble Scales

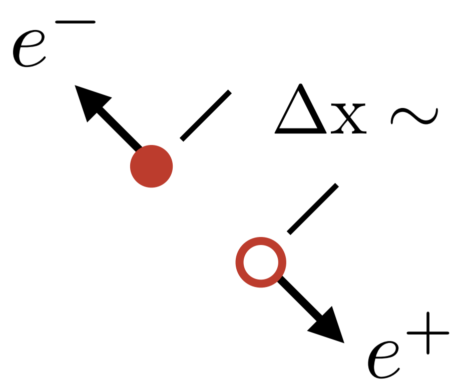
Lecture 2

Combining Relativity and Quantum Mechanics

- To preserve causality needed to Anti-particle must exist

- In turn, major implications on the vacuum:

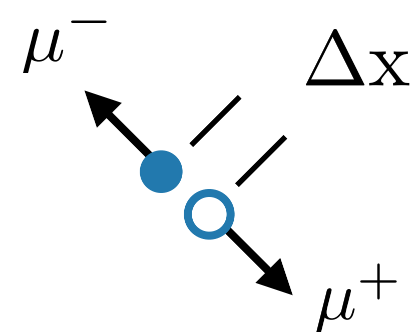
$\Delta \mathrm{E} > 2\mathrm{m_e c^2}$



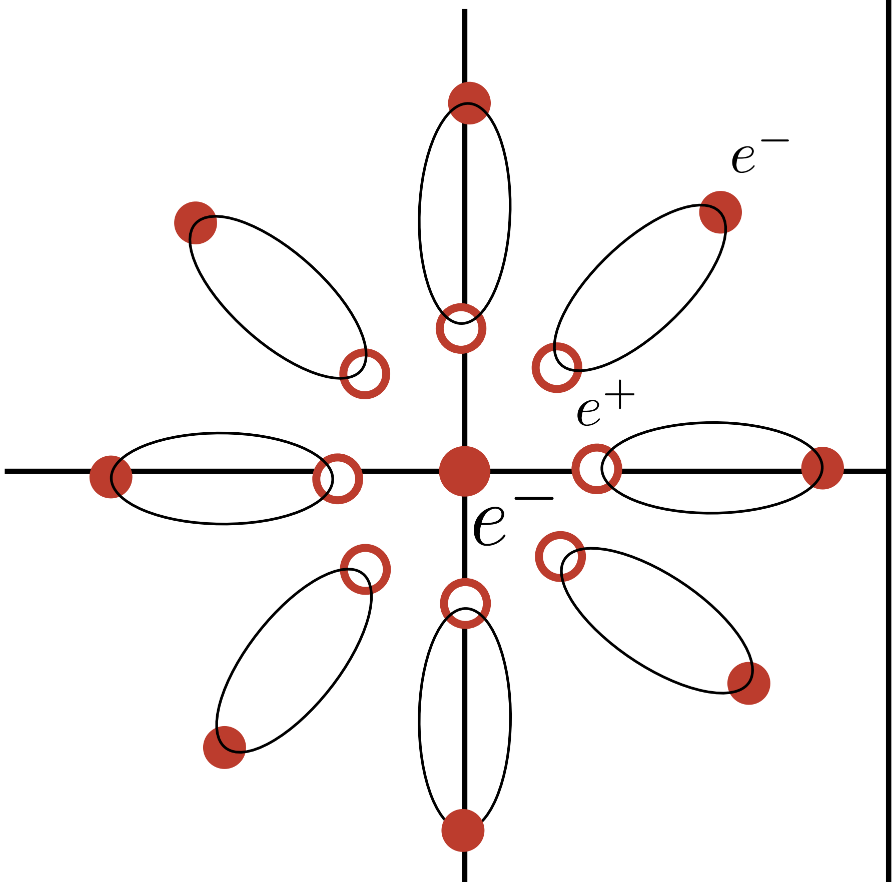
$\Delta \mathrm{x} \sim \frac{1}{\mathrm{m_e}}$

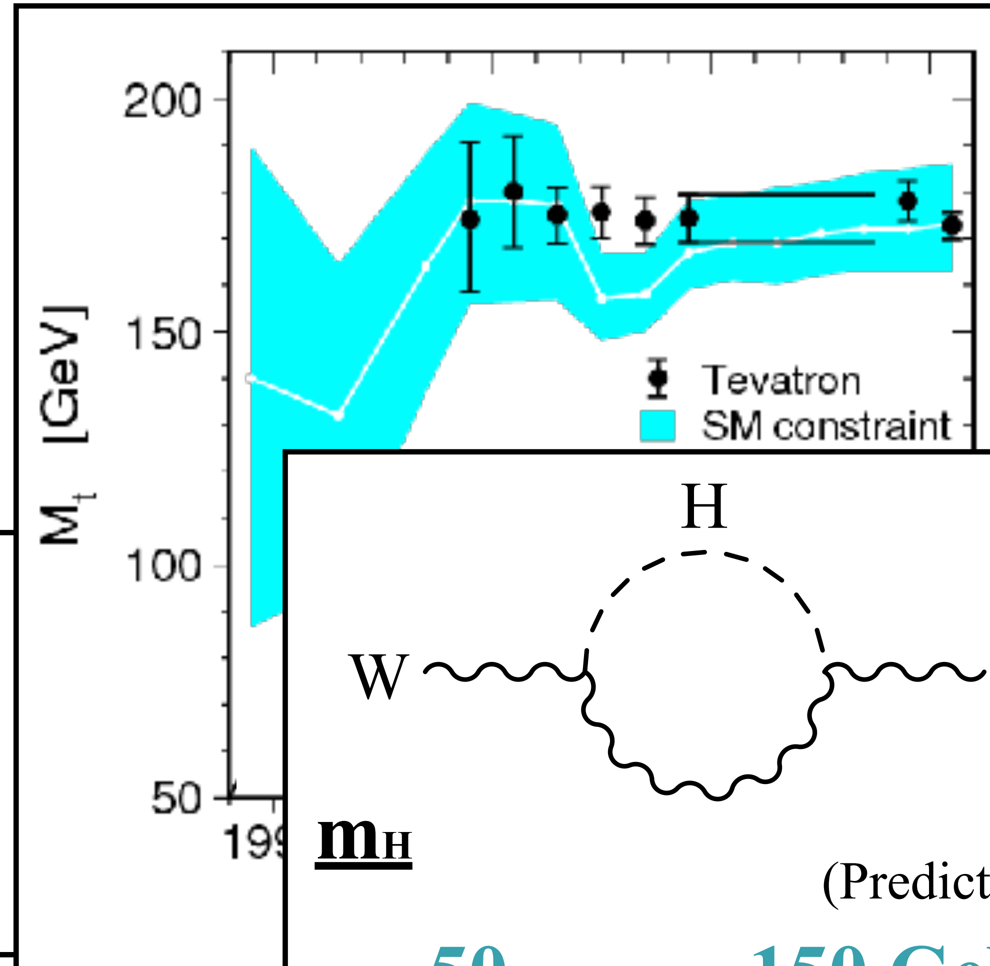
$\Delta \mathrm{E} > 2\mathrm{m_\mu c^2}$

$\Delta \mathrm{x} \sim \frac{1}{\mathrm{m_\mu}}$



Vacuum Fluctuations ***ARE REAL !***





m_H

(Predicted)

50 —— 150 GeV

115 GeV (Discovered)

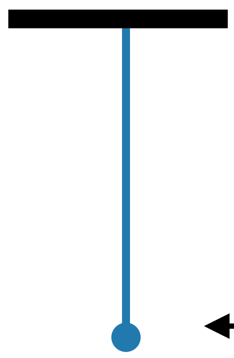
Precisely predict magnetic properties

g/2 = 1.0011596521809(8),

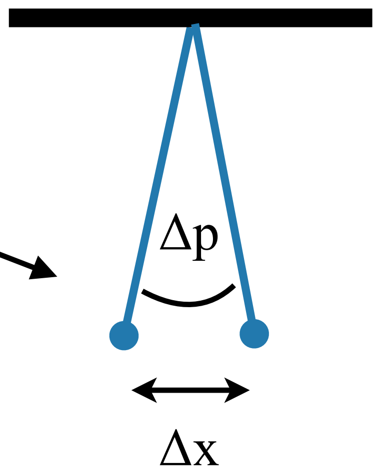
(Agree to better than one part in a trillion.)

Vacuum Has Energy

Classically (w/o QM)



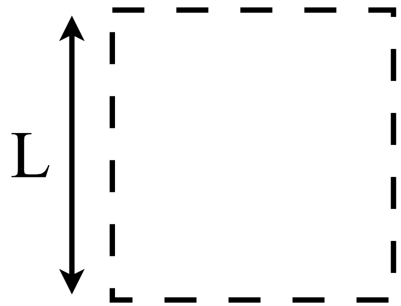
Quantum World



Minimum non-zero energy: E~hω

Lowest possible energy is 0

Estimate energy density in region of empty space: *Dimensional Analysis*

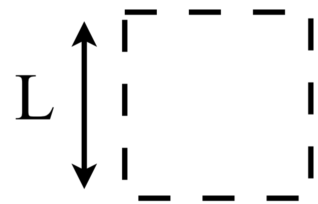


$\Lambda \sim \frac{E}{V} \sim \frac{1}{L^4}$

$(V \sim L^3)$

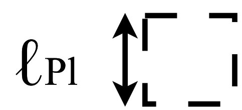
$(E \sim \frac{1}{L})$

Smaller Box



Λ much bigger

Reach: Cut-off



$\Lambda \sim \frac{1}{{\ell_{Pl}}^4}$

...this is a problem

Cosmological Constant Problem

Without gravity constant energies (Λ) can be ignored *(overall offset)*
With gravity, constant energy warps space-time, interacts gravitationally

Uniform matter/energy controls size/expansion of overall Universe

$$t_{\rm Double} \sim \frac{1}{\sqrt{G_N \Lambda}} \sim \frac{1}{\sqrt{{\ell_{\rm Pl}}^2 \Lambda}}$$

Clearly something wrong !

- Naive cut off at $\ell_{\rm Pl}$: $\Rightarrow$ $t_{\rm Double} \sim 10^{-43}$ s

(would be bad for atoms/planets/people…)

- Conservative cut-off at 100 GeV: $\Rightarrow$ $t_{\rm Double} \sim 10$ ns

(would be bad for atoms(?)/planets/people…)

Measured: $t_{\rm Double} \sim 10^{10}$ years $\Rightarrow$ cut off of 10μm !

Cosmological Constant Problem

How do we deal with this in the current theory ?

from the vacuum fluctuations

Constant.
Input parameter to theory

$$\Lambda = \Lambda_{\mathrm{QM}} + \Lambda_{\mathrm{Classical}}$$

$$= 3.\,342\,862\,210\,\ldots\,554\ldots \times {\ell_{\mathrm{Pl}}}^{-4}$$

120 digits

Λ_{QM}

$+$

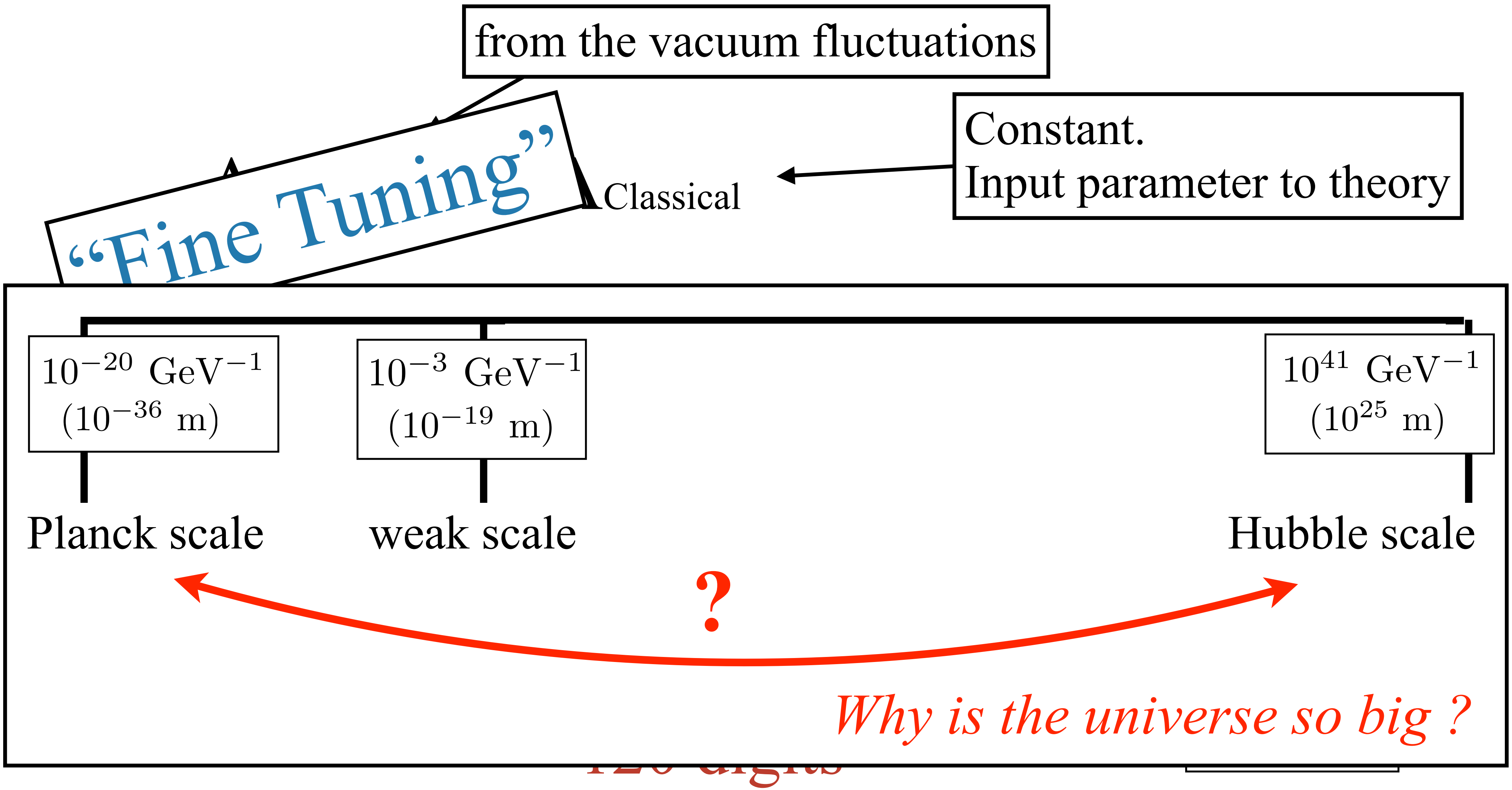
$$-\ 3.\,342\,862\,210\,\ldots\,541\ldots \times {\ell_{\mathrm{Pl}}}^{-4}$$

120 digits

$\Lambda_{\mathrm{Classical}}$

Cosmological Constant Problem

How do we deal with this in the current theory ?



Vacuum Fluctuations: Higgs Particle

Closely related problem

Vacuum fluctuations of Higgs mass (m_H^2)

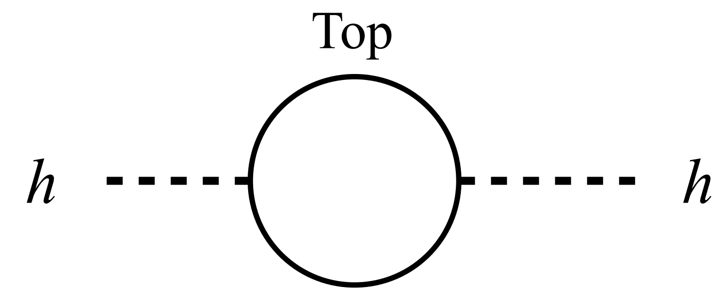
$$mH^2 = 2.569678321\ \ldots\ 554\ldots \times \ell_{Pl}^{\,2}$$

60 digits

$$+$$

$$-\ 2.569678321\ \ldots\ 453\ldots \times \ell_{Pl}^{\,2}$$

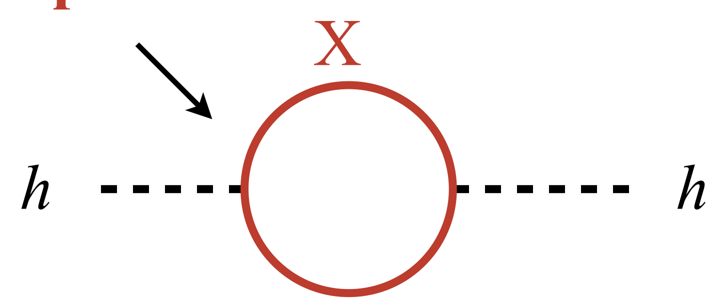
60 digits



$\sim \Lambda^2 \Rightarrow mH \sim 10^{20}$ GeV

new heavy particle

$mH \sim mX$



- Estimated mass corrections unreasonably large
- Instability of the Higgs mass

Particular to Spin-0 particles

- Spin 1/2 Protected by charge conservation.
  Need interactions with v to get their mass
- Spin 1, 3/2, 2: need needed the extra particles ω/Ω-from

Vacuum Fluctuations: Higgs Particle

Closely related problem

Vacuum fluctuations of Higgs mass (m_H^2)

Without "small scale" physics

(only gravity + pencil DoF)

- Bizarre, but stable
- Suggests fine tuning

Higgs mass in SM

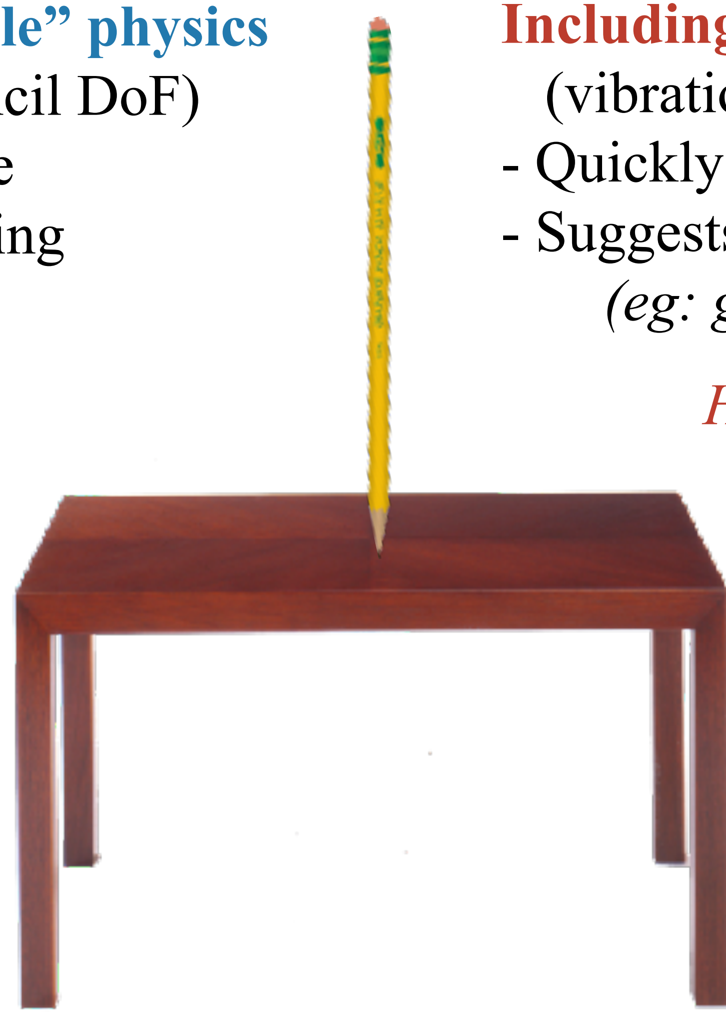
Including physics at smaller scales

(vibrations/ air molecules / atoms)

- Quickly lead to instability
- Suggests active mechanism

(eg: glue / string)

Higgs mass including new, high mass scale physics

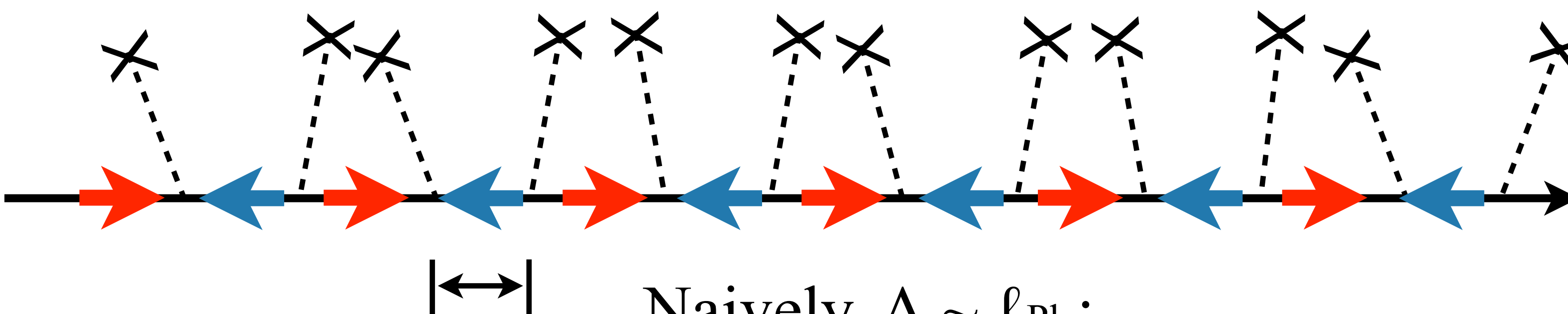


Vacuum Fluctuations: Higgs Field

Another way of talking about same problem

Can perform similar estimate for scale of interaction with condensate v

Same logic $\Rightarrow$ *Scale should be set by the cut-off in the theory*



$\sim \frac{1}{\Lambda}$

Naively, $\Lambda \sim \ell_{\rm Pl}$:

$$\sim \frac{1}{\ell_{\rm Pl}} \sim 10^{-20}\ \text{GeV}^{-1} \sim 10^{-36}\ \text{m}$$

Measured scale of: $\sim 10^{-3}\ \text{GeV}^{-1} \sim 10^{-19}\ \text{m}$

$\Lambda \sim \ell_{\rm Pl}$ would be bad for atoms/planets/ … all blackholes

Why is gravity so weak ?

$$\frac{F_G}{F_{EM}} \sim ({\ell_{\rm Pl}}^2 \Lambda^2)$$

Expect: ~ 1

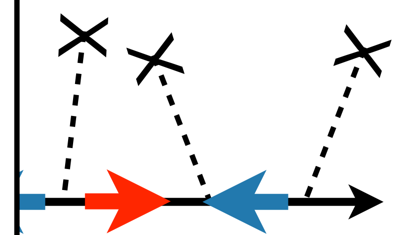
Observe: $\sim 10^{-34}$

Vacuum Fluctuations: Higgs Field

Another way of talking about same problem

C ... n with condensate v

... n the theory



Weakness of gravity directly responsible
~ all structure around us

$$R_{\text{Planet}} \sim \sqrt{\frac{\alpha}{\alpha_G}} \times r_{\text{atom}}$$

Planck scale	weak scale	Hubble scale
$10^{-20}\ \text{GeV}^{-1}$ (10^{-36} m)	$10^{-3}\ \text{GeV}^{-1}$ (10^{-19} m)	$10^{41}\ \text{GeV}^{-1}$ (10^{25} m)

?

"Hierarchy Problem"

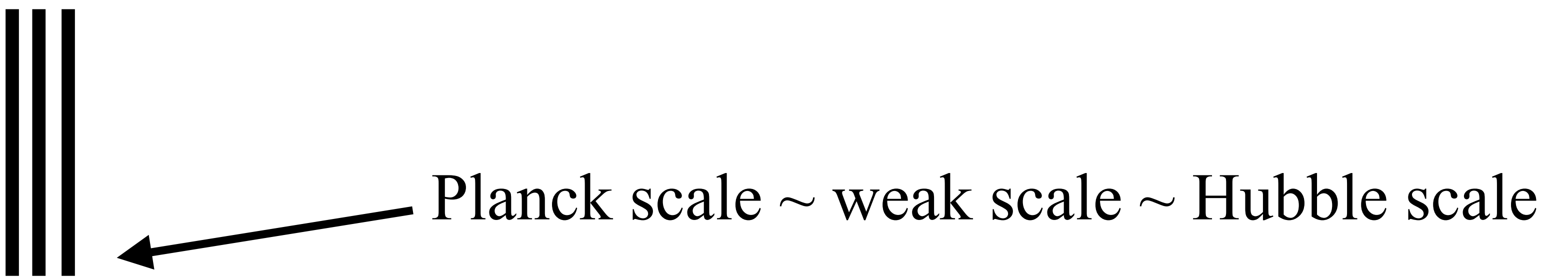
Why is gravity so weak ?

EM

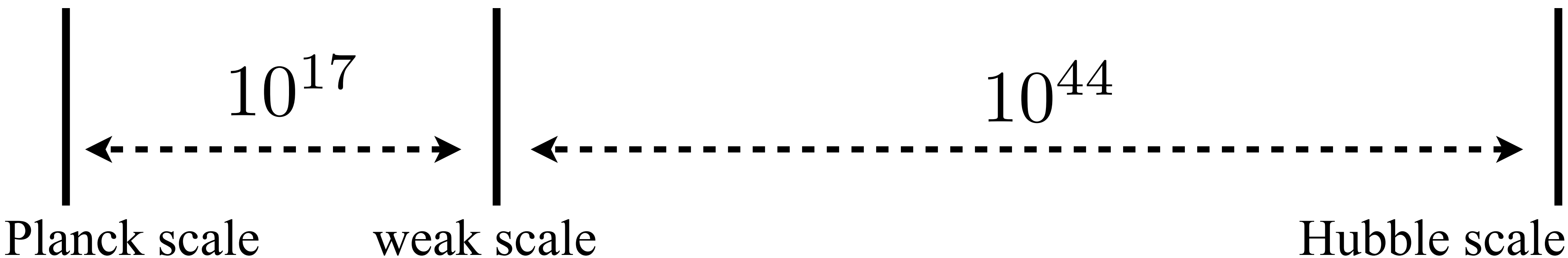
Observe: ~ 10

Length Scales

Quantum Mechanics + Space-time leads us to expect:



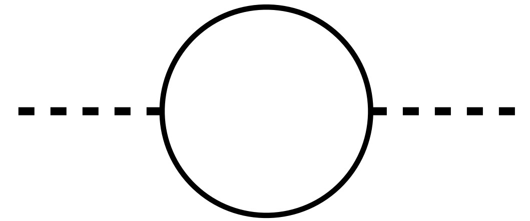
We observe:



Current theory accounts for huge difference w/implausible cancellation

Need modifications QM or Space-time to avoid fine tuning

What scale do we need Modification?

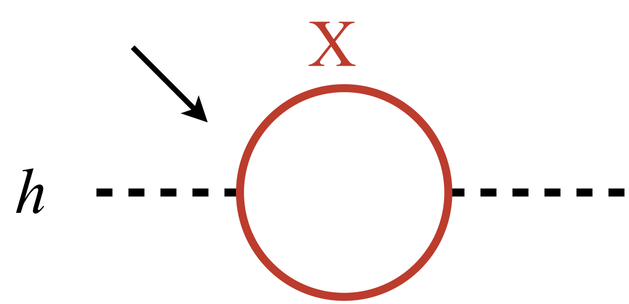
mH = + 

~ weak-scale $m_{H_{Classical}}$ $\sim \Lambda^2$

Can avoid need for fine tuning only if Λ ~ weak-scale.

Need changes to stop vacuum fluctuations below: 10^{-3} GeV^{-1} (10^{-19} m)

new particle $m_X \sim 1000$ GeV



Dark Matter

Most natural explanation requires new physics at $10^{-3}\ \text{GeV}^{-1}$ $(10^{-19}\ \text{m})$