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

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University of Chicago

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**

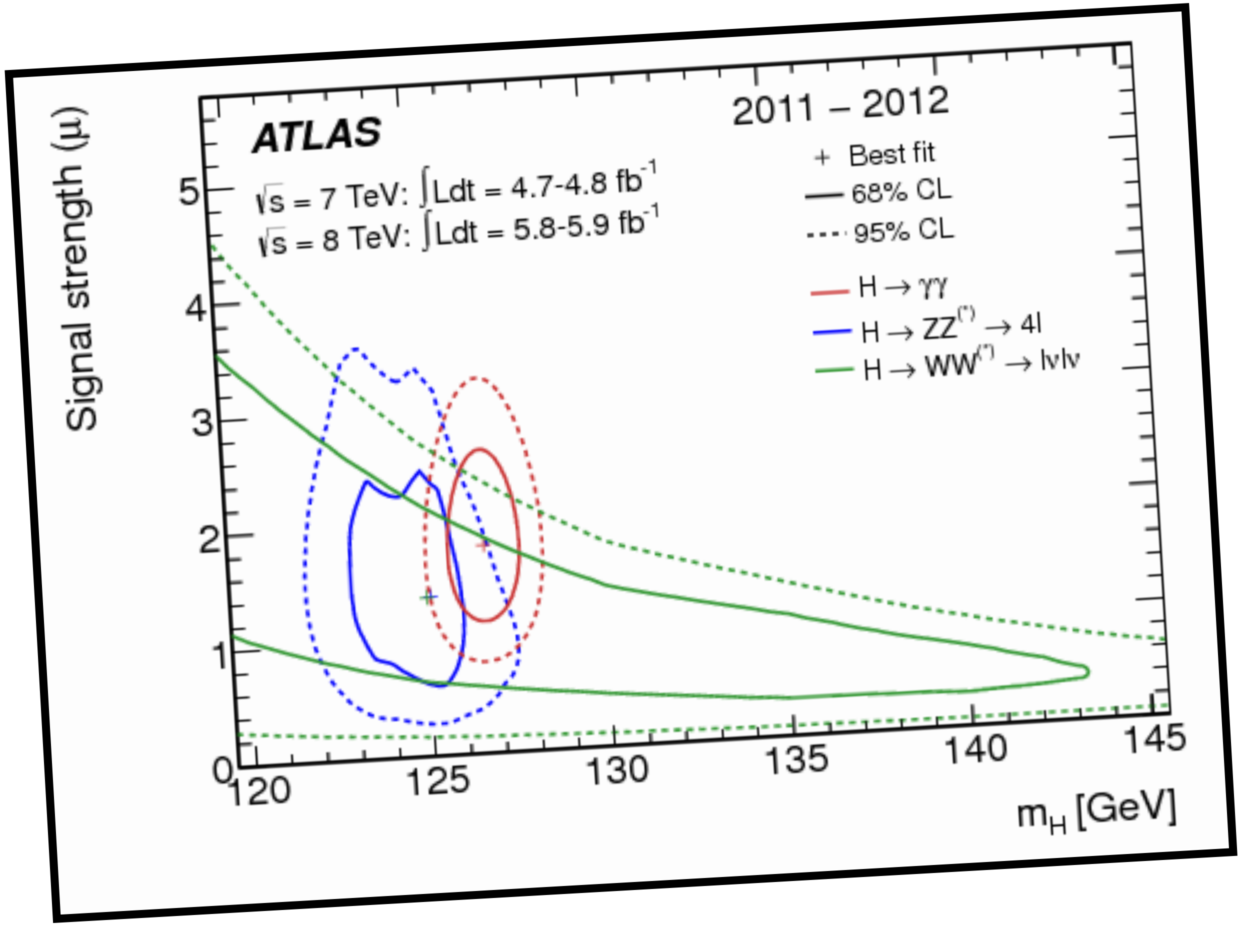
May 20th: ***Problems with the Standard Model***

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



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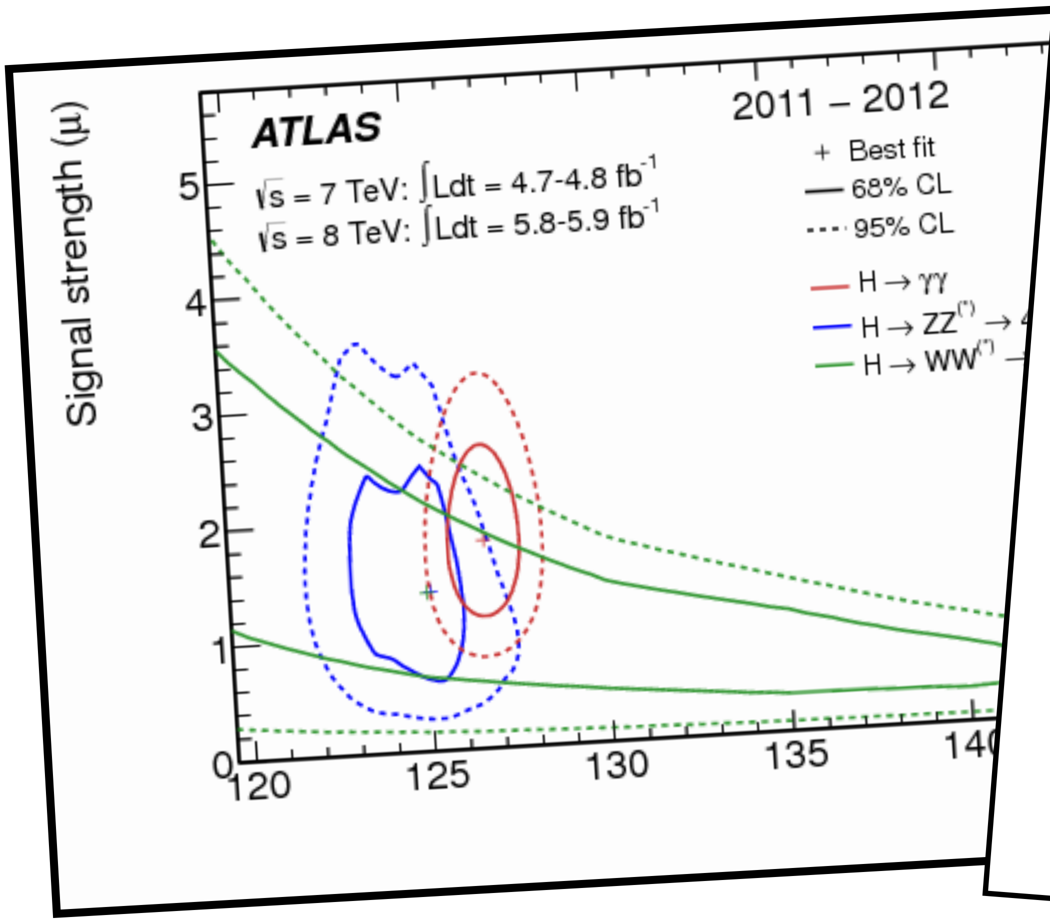

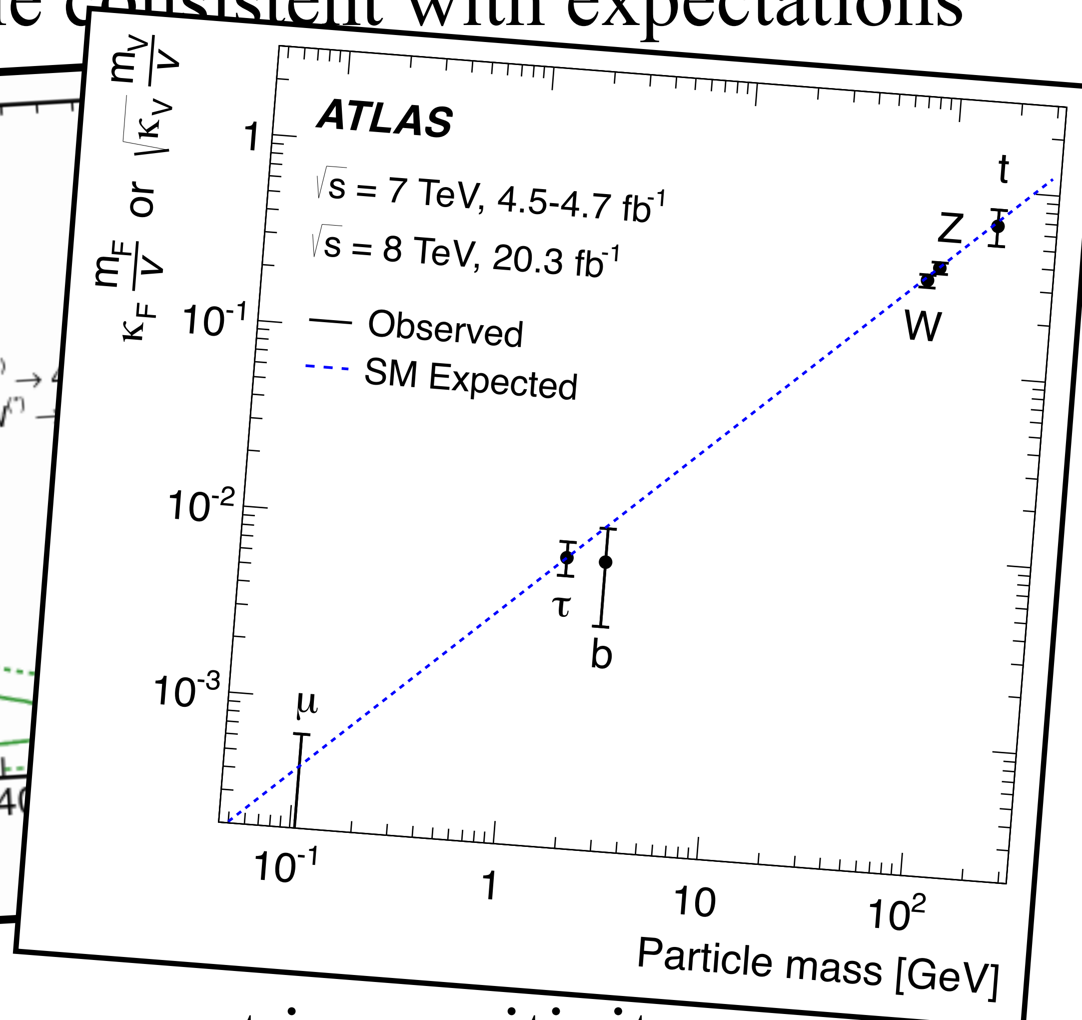

Since then: Significant improvement in sensitivity

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 extremes to find it ?
Why look for the Higgs boson in the first place ?
Are we done now that we have found it ?

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

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

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Focus of last two lectures

Today's Lecture

Problems with the Standard Model

Length Scales

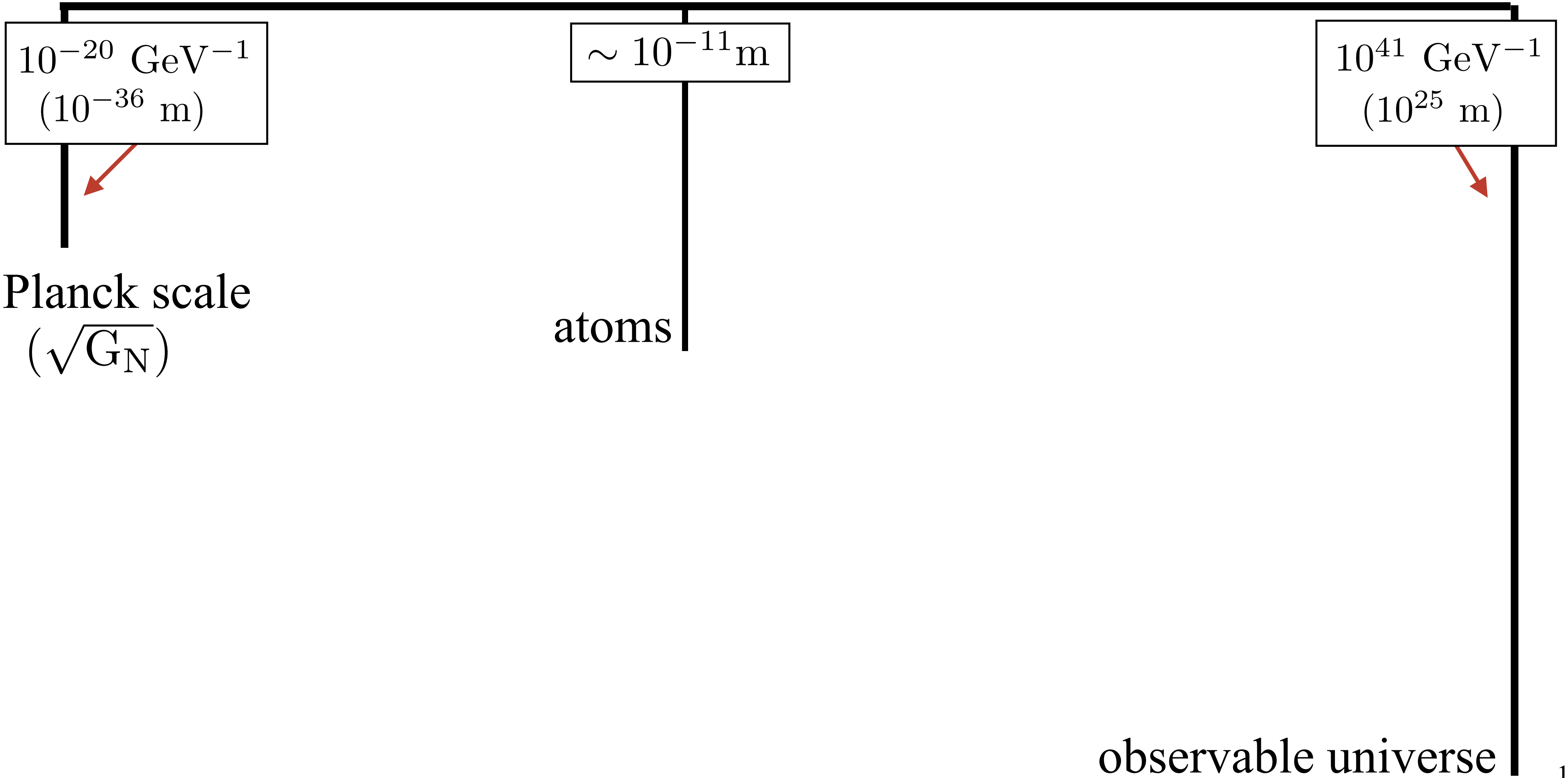
10^{-20} GeV^{-1}
(10^{-36} m)

10^{41} GeV^{-1}
(10^{25} m)

Planck scale
($\sqrt{G_N}$)

observable universe

Length Scales



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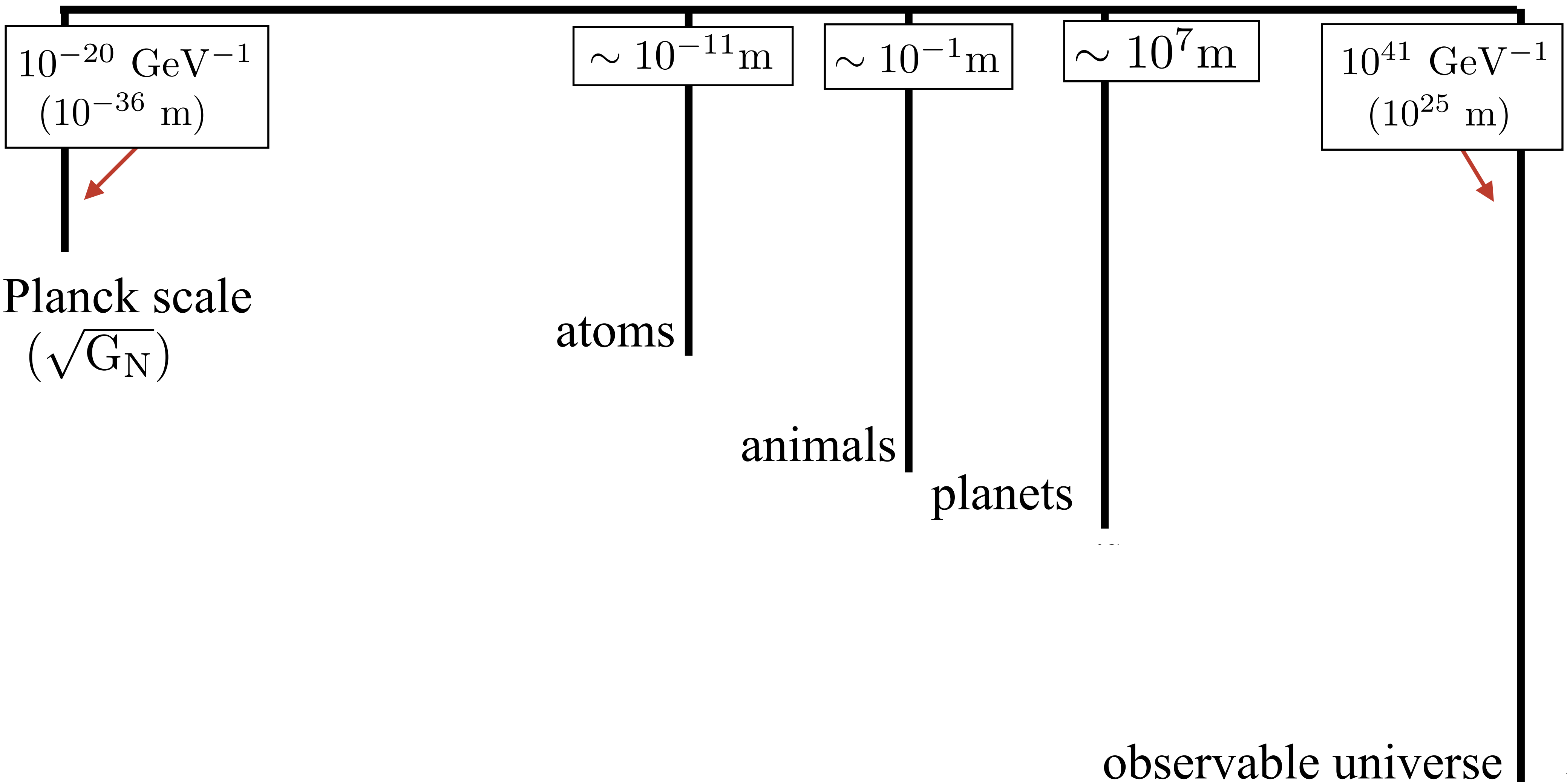

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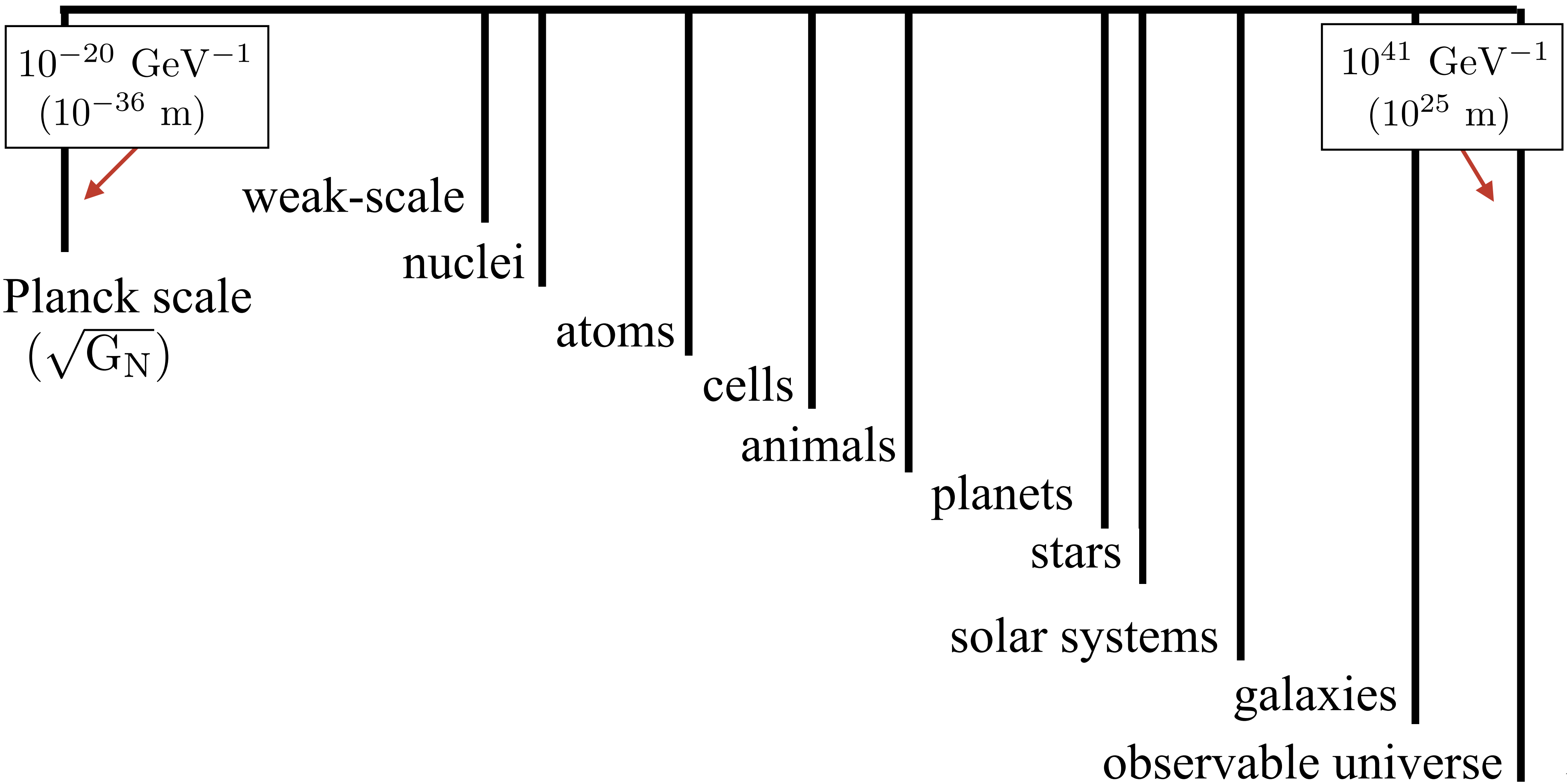

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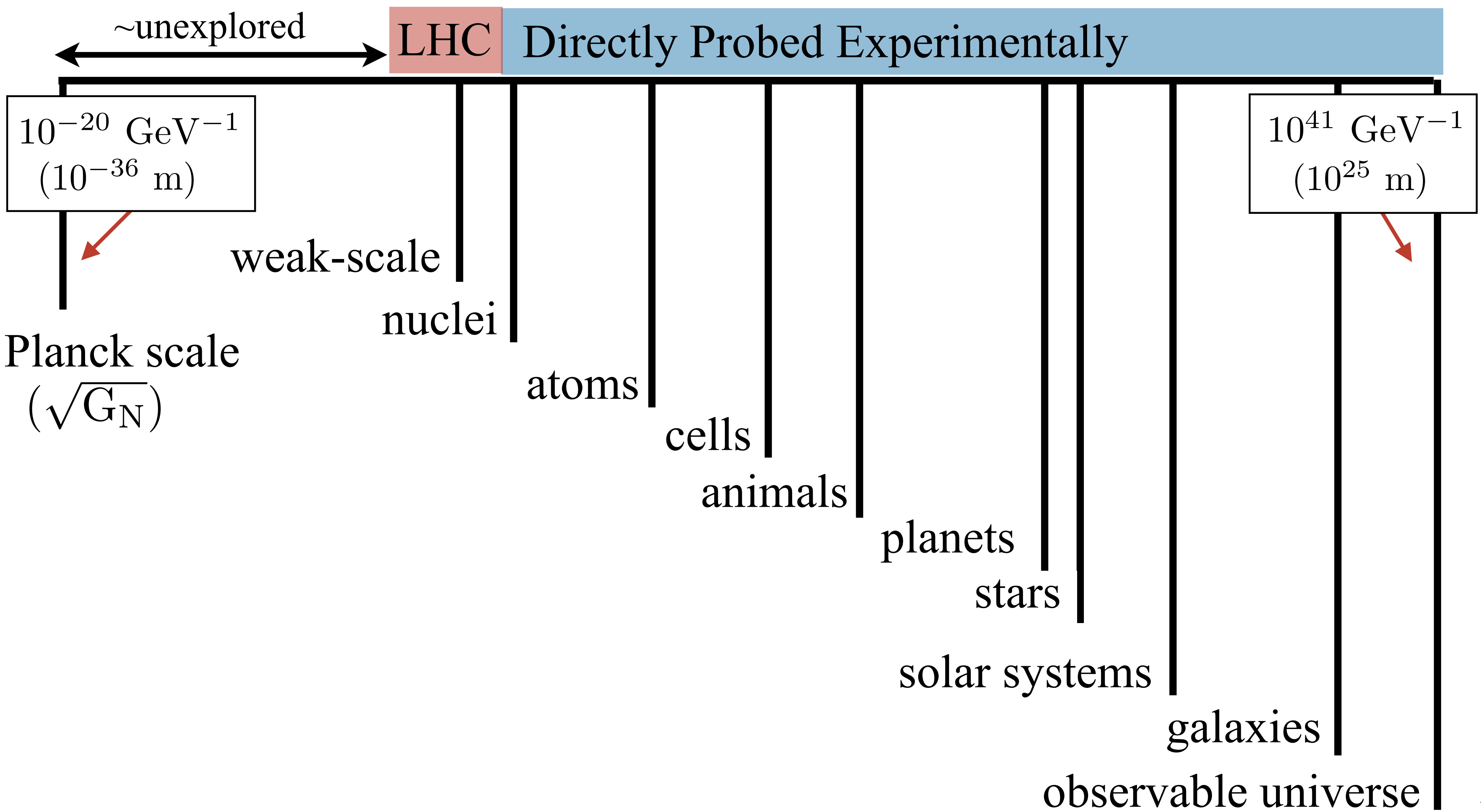

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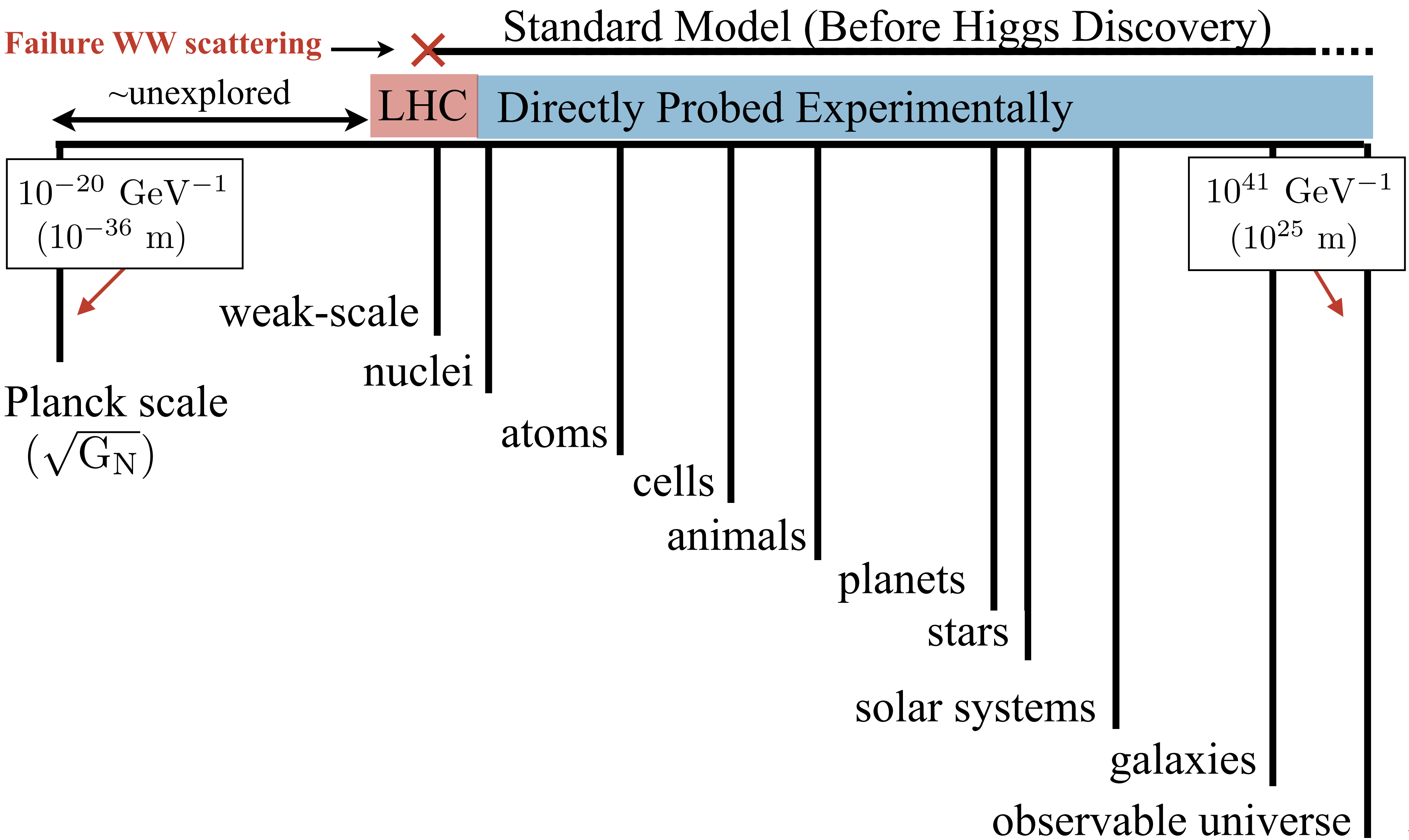

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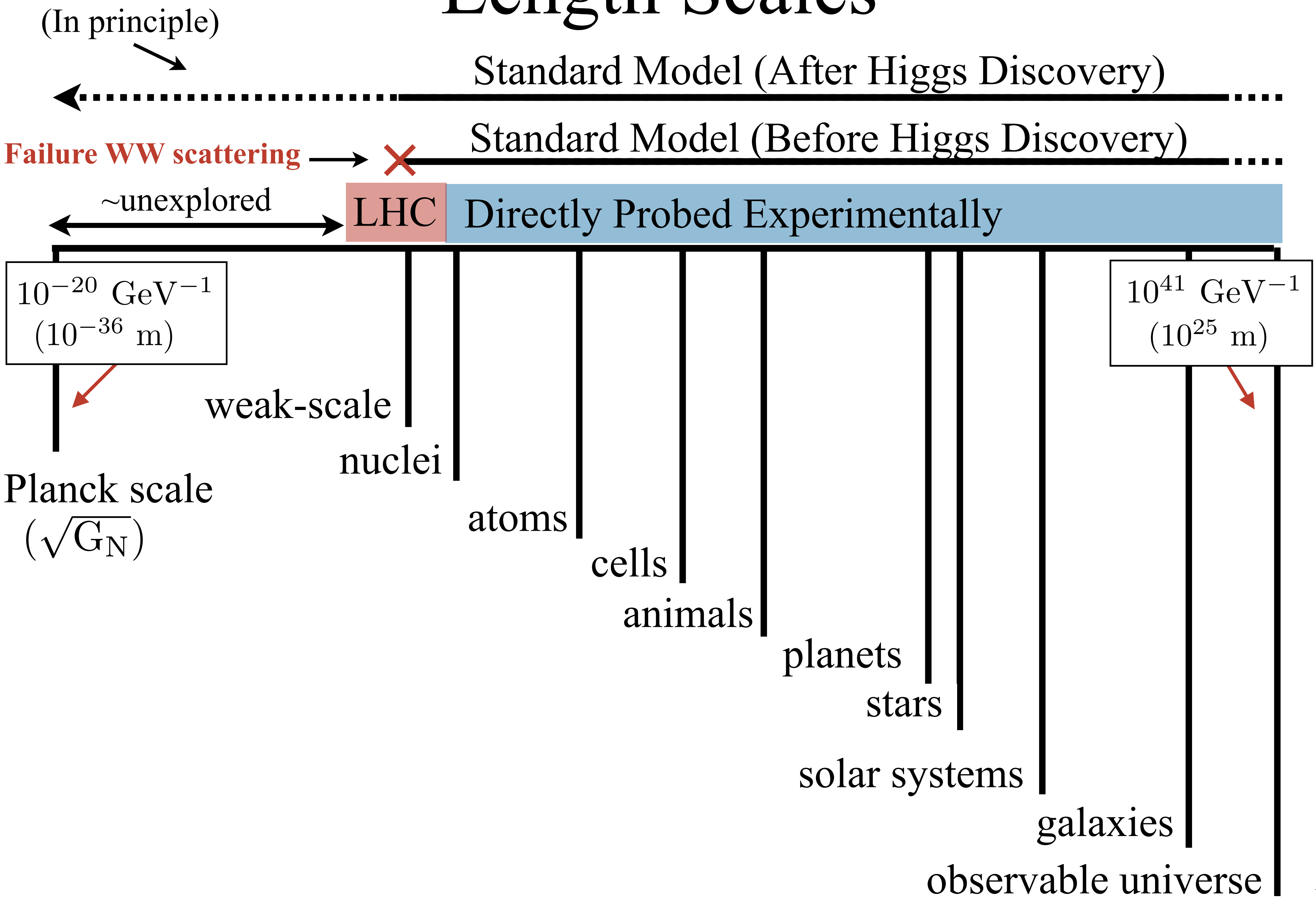

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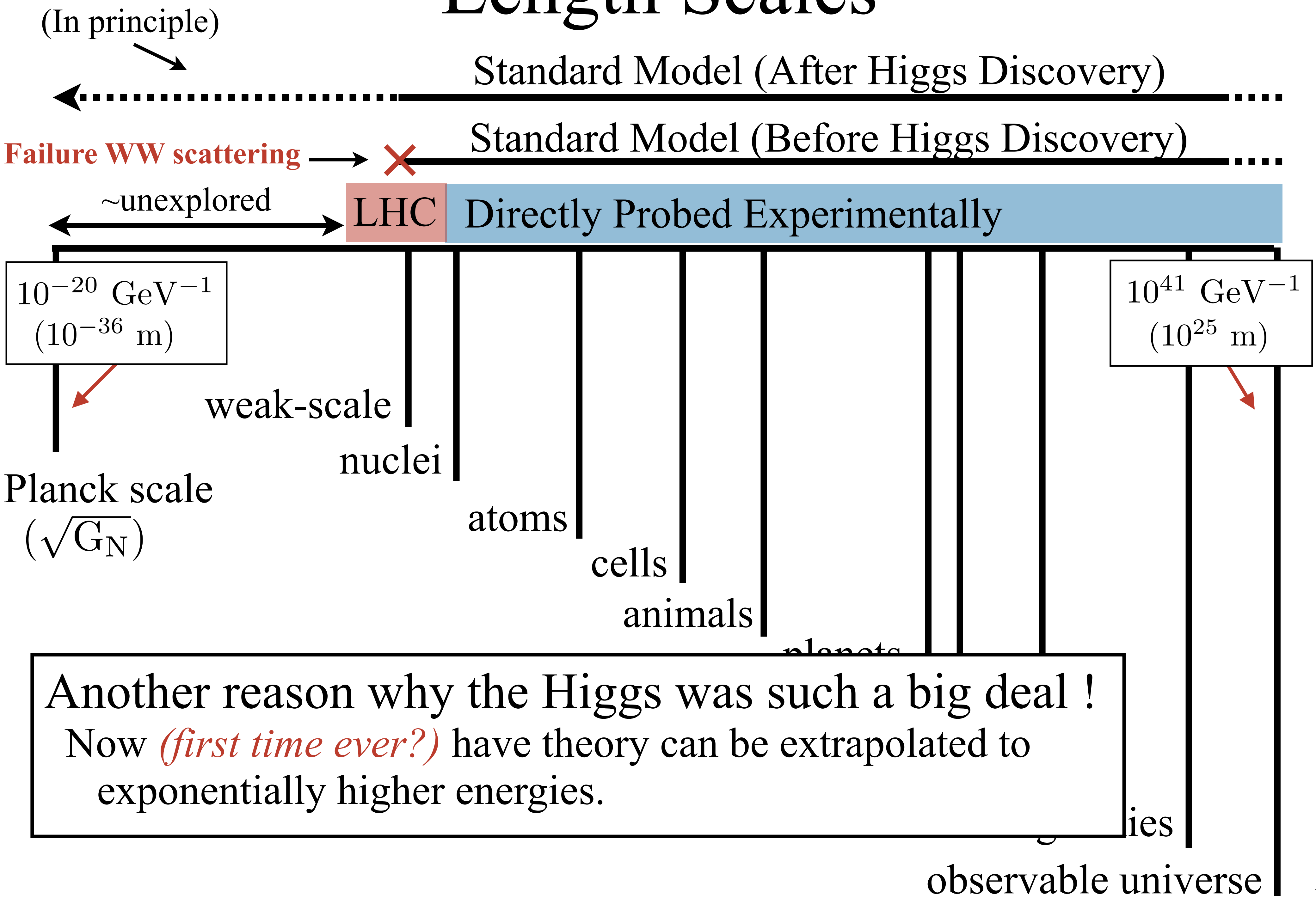
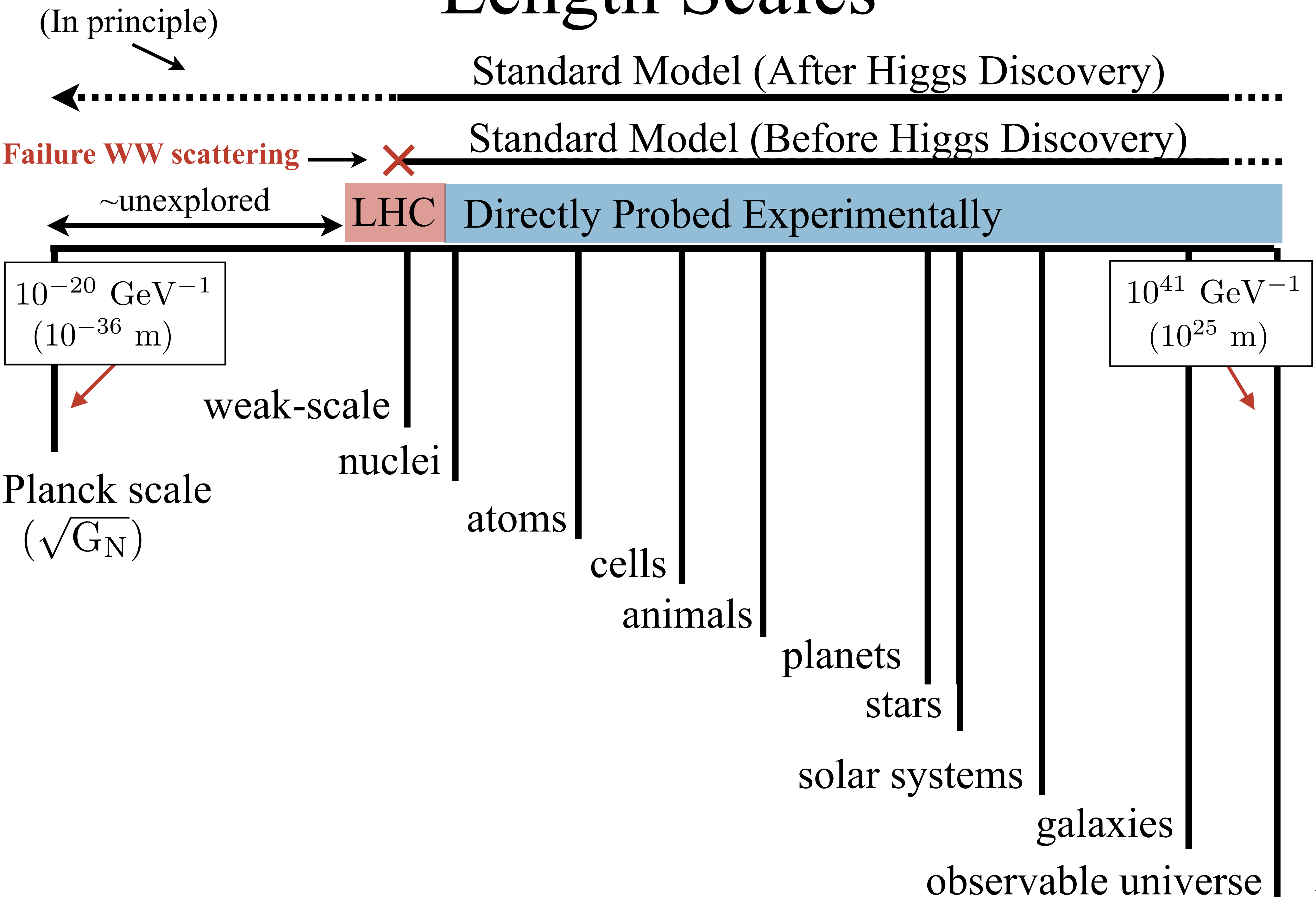


Another reason why the Higgs was such a big deal !

Now *(first time ever?)* have theory can be extrapolated to exponentially higher energies.

Length Scales



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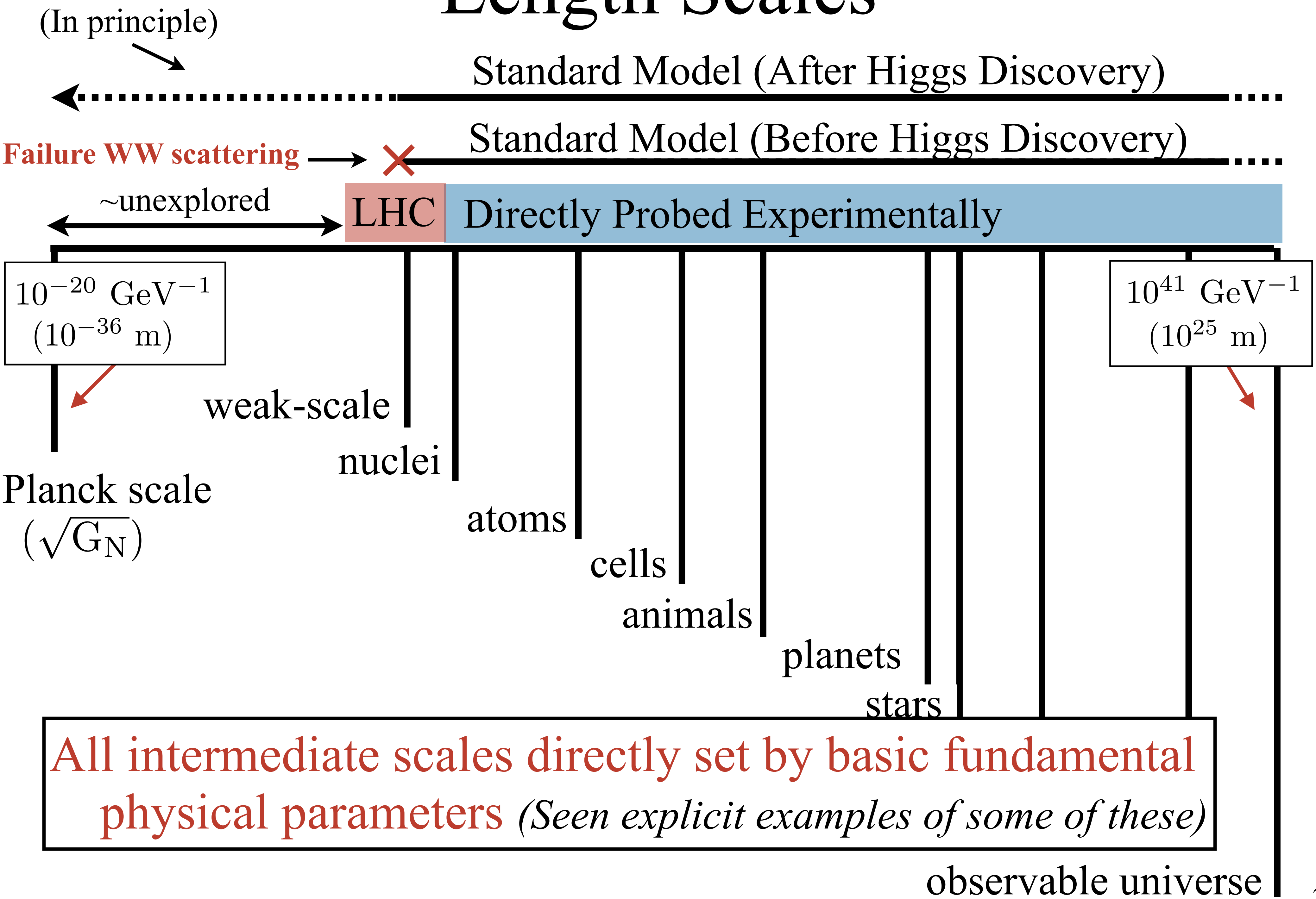
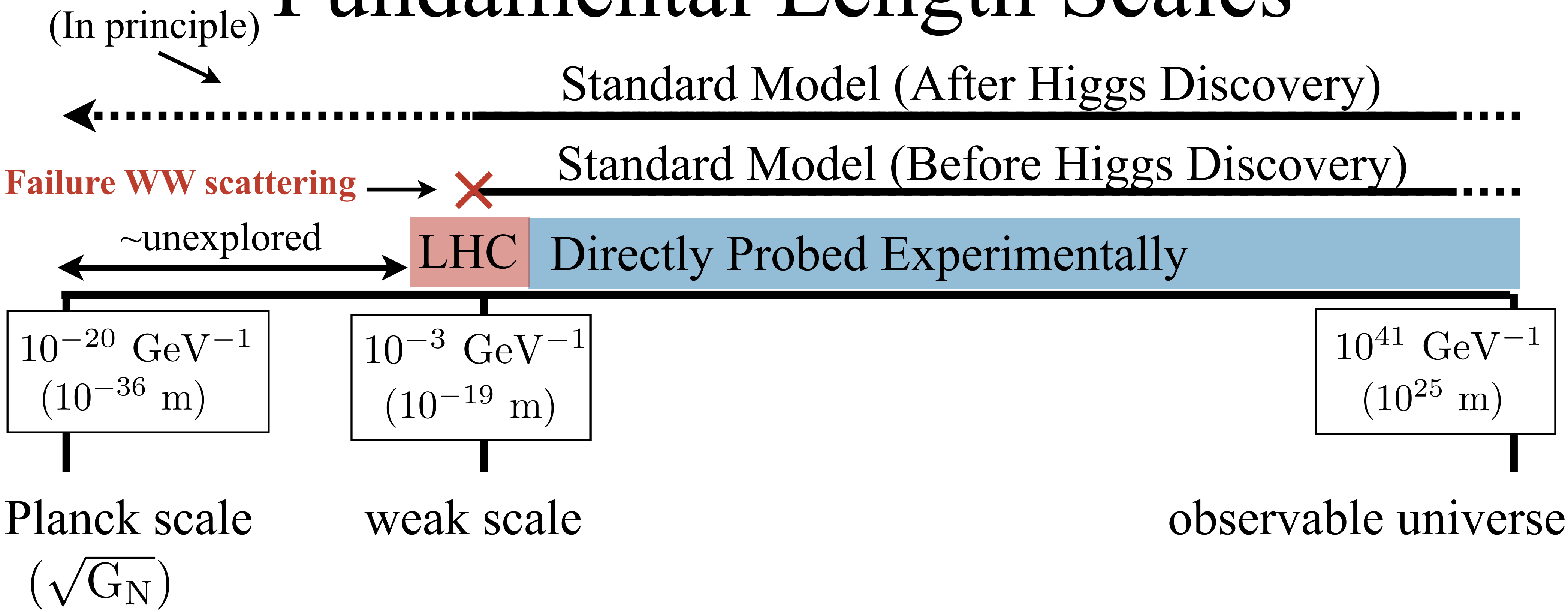


Fundamental Length Scales



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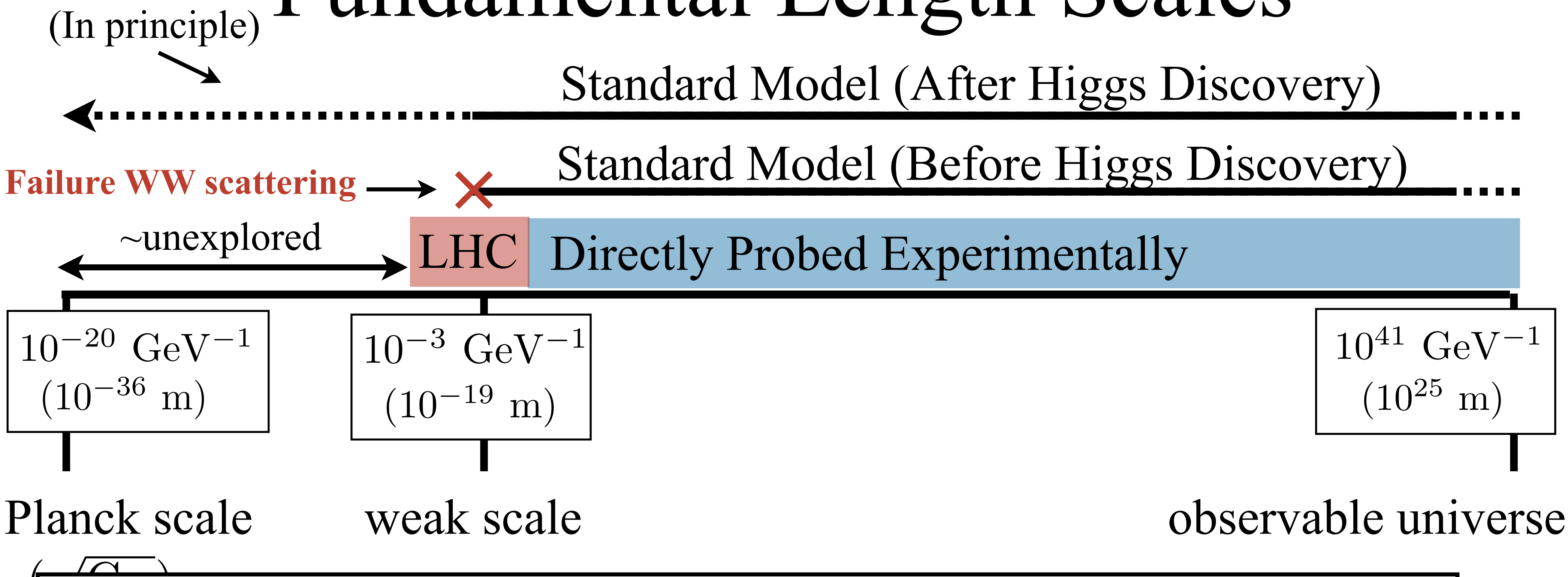
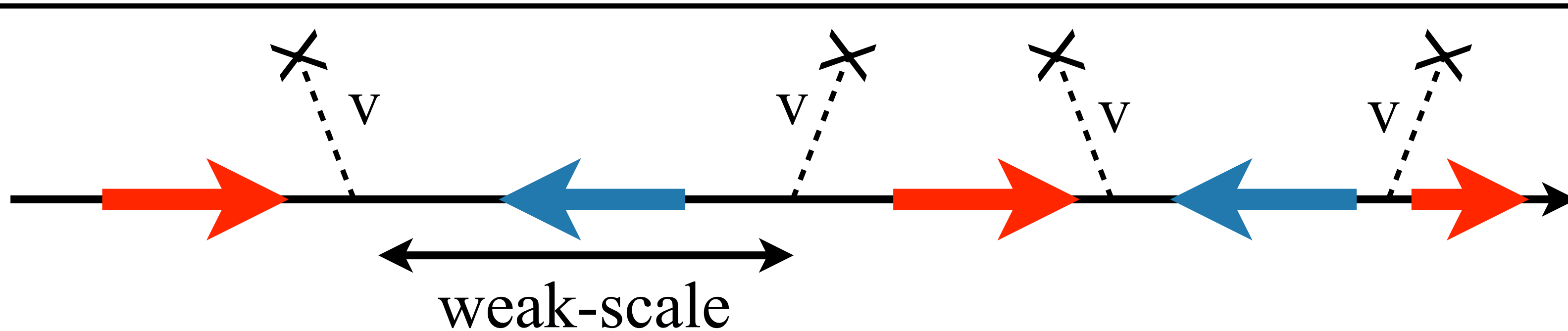


Weak scale: Fundamental scale in physics
- Scale associated with fundamental particle masses
- Typical at which massive particles interact with Higgs field
- The first time start seeing the forces have same underlying structure



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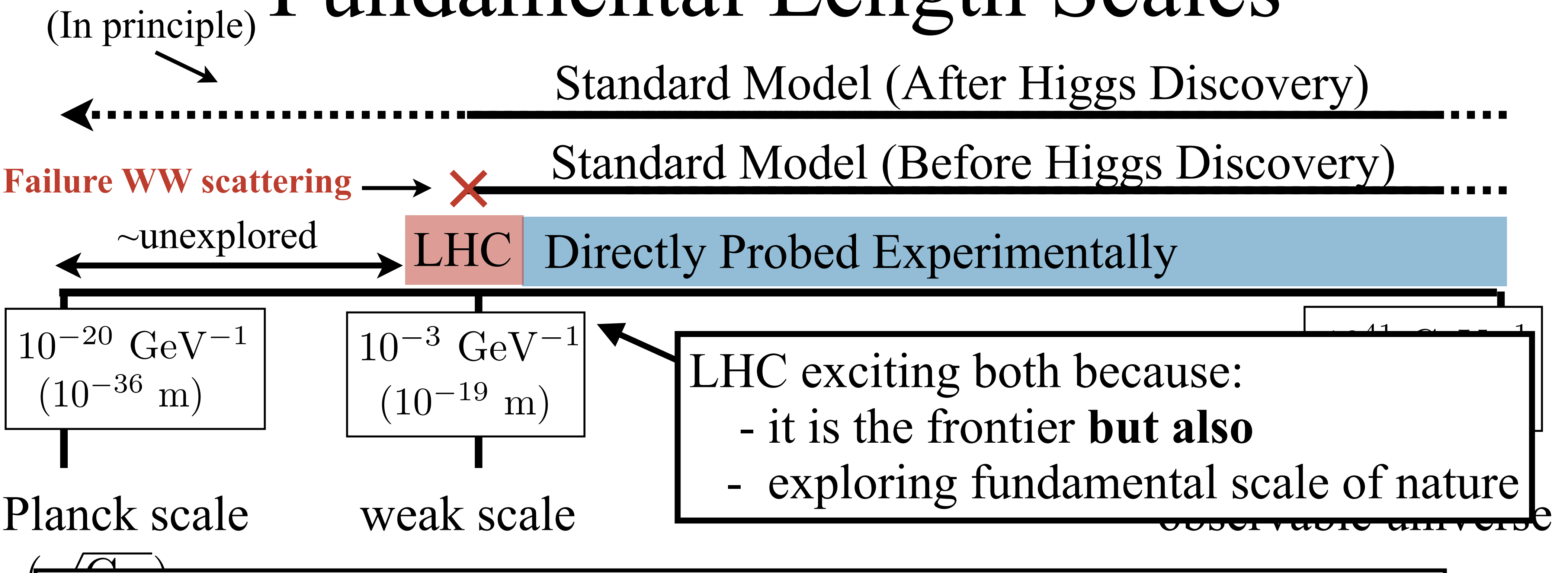

LHC exciting both because:
- it is the frontier **but also**
- exploring fundamental scale of nature

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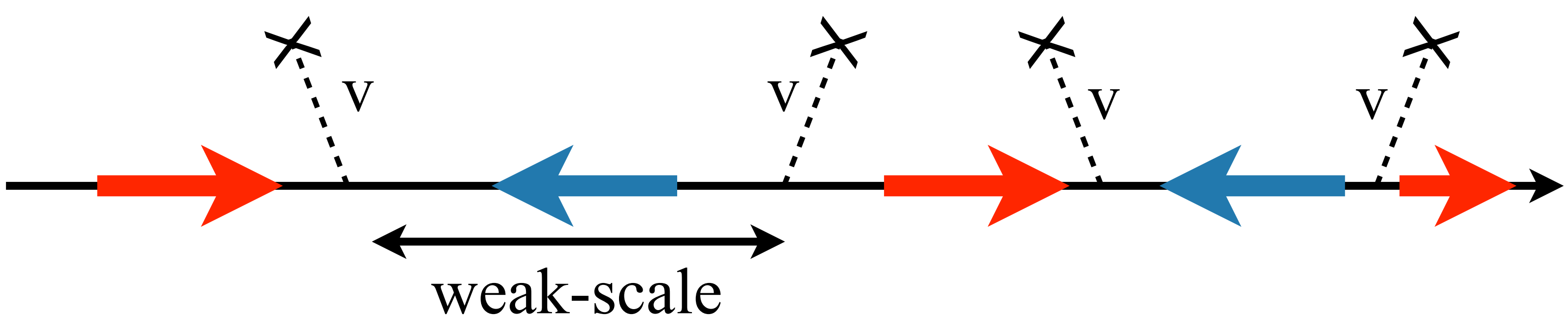

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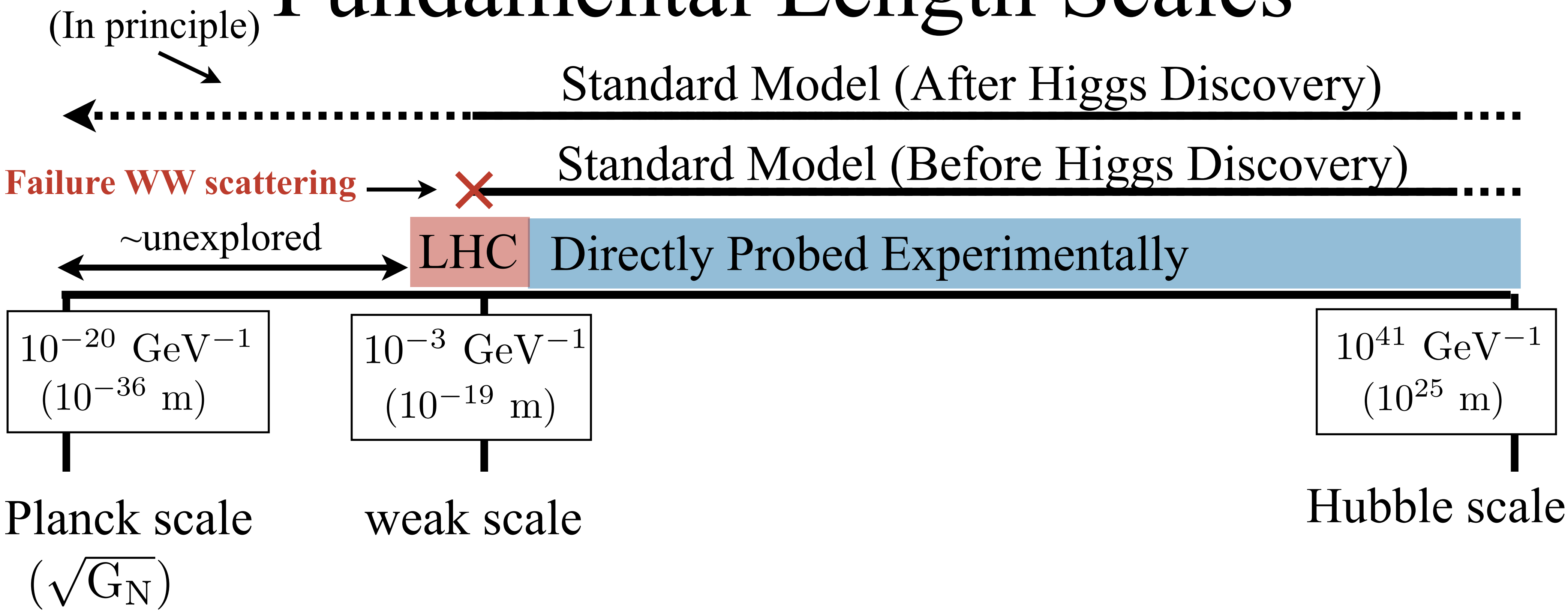

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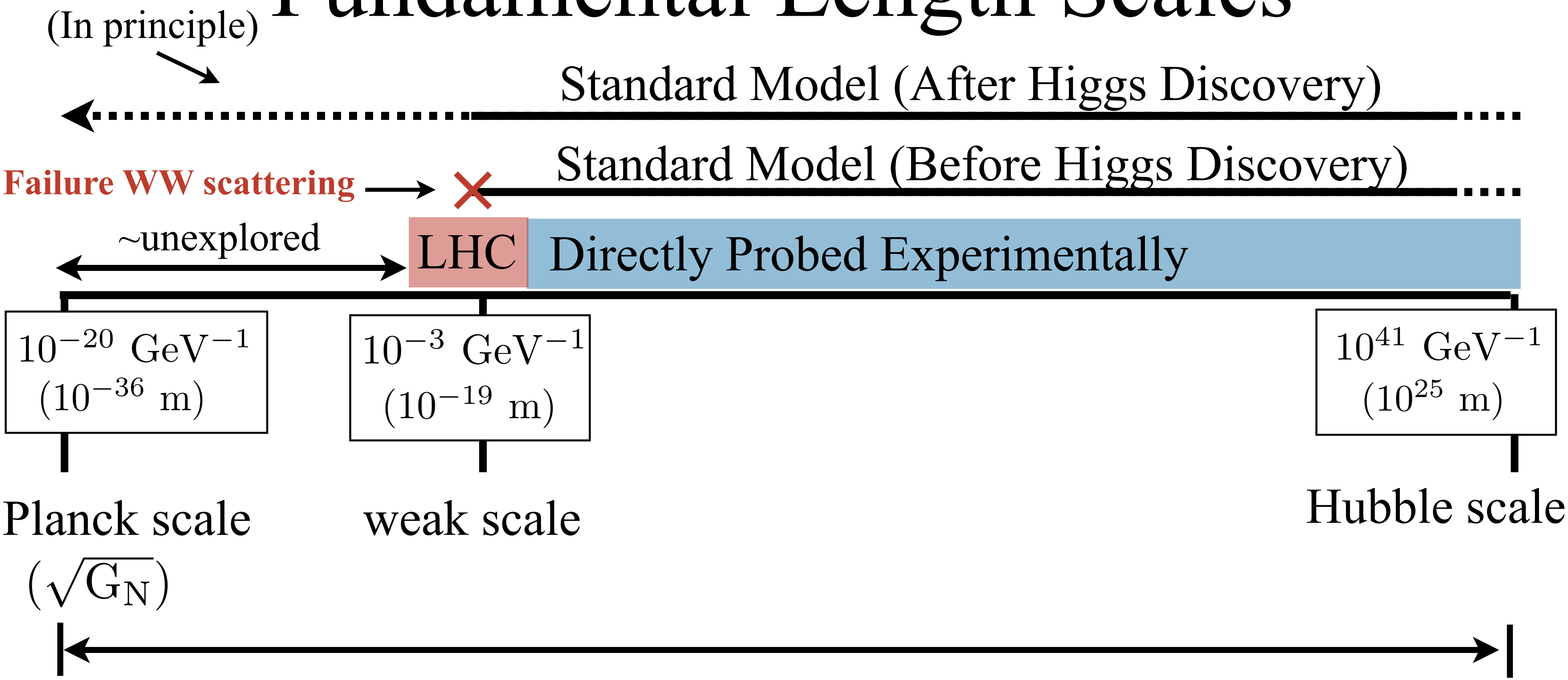

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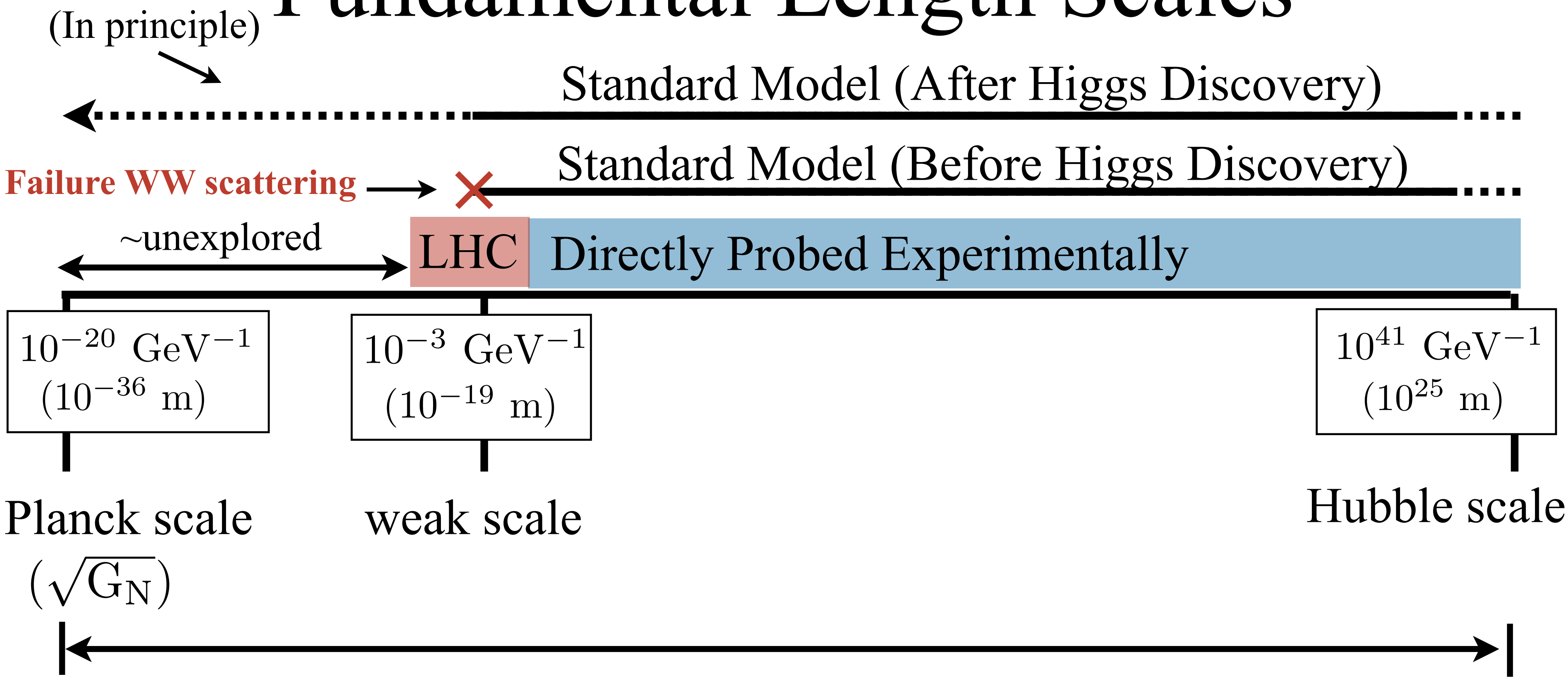
Fundamental Length Scales



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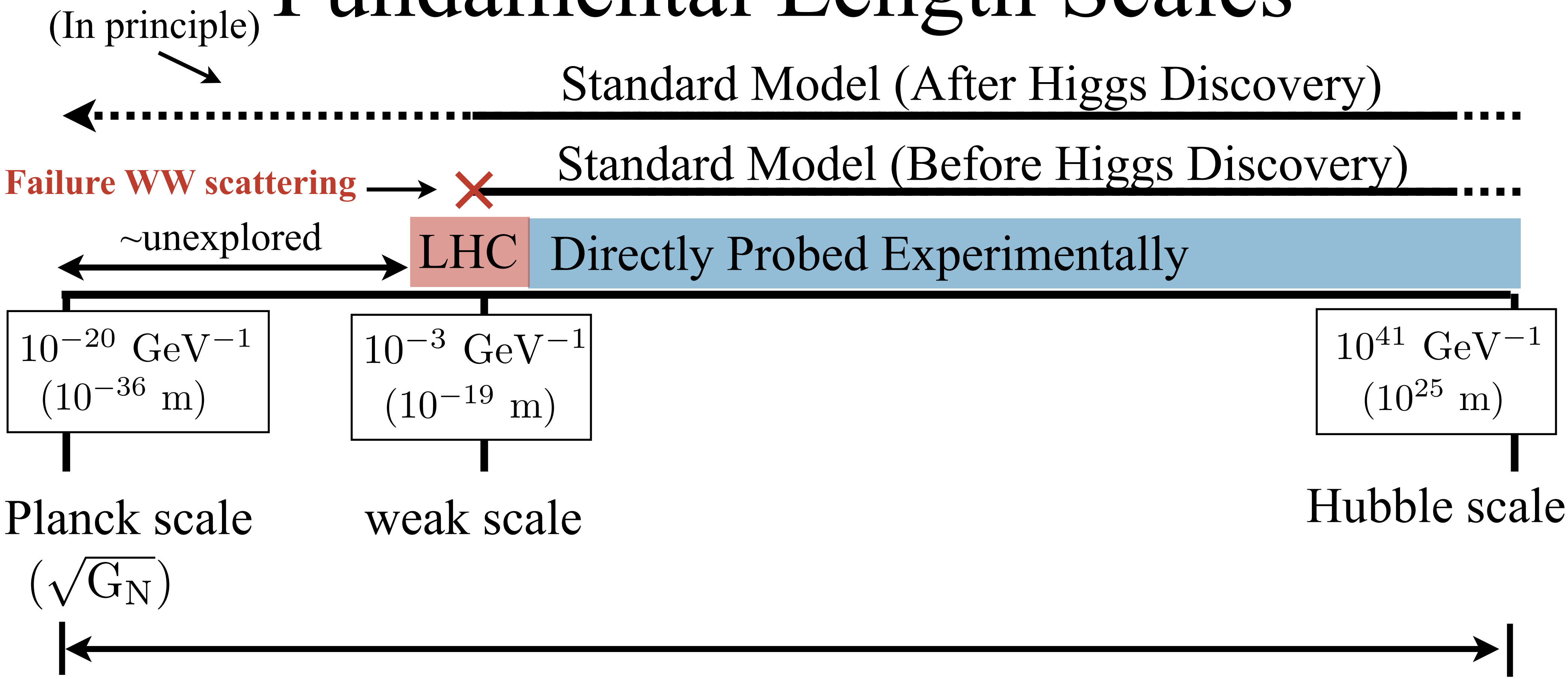

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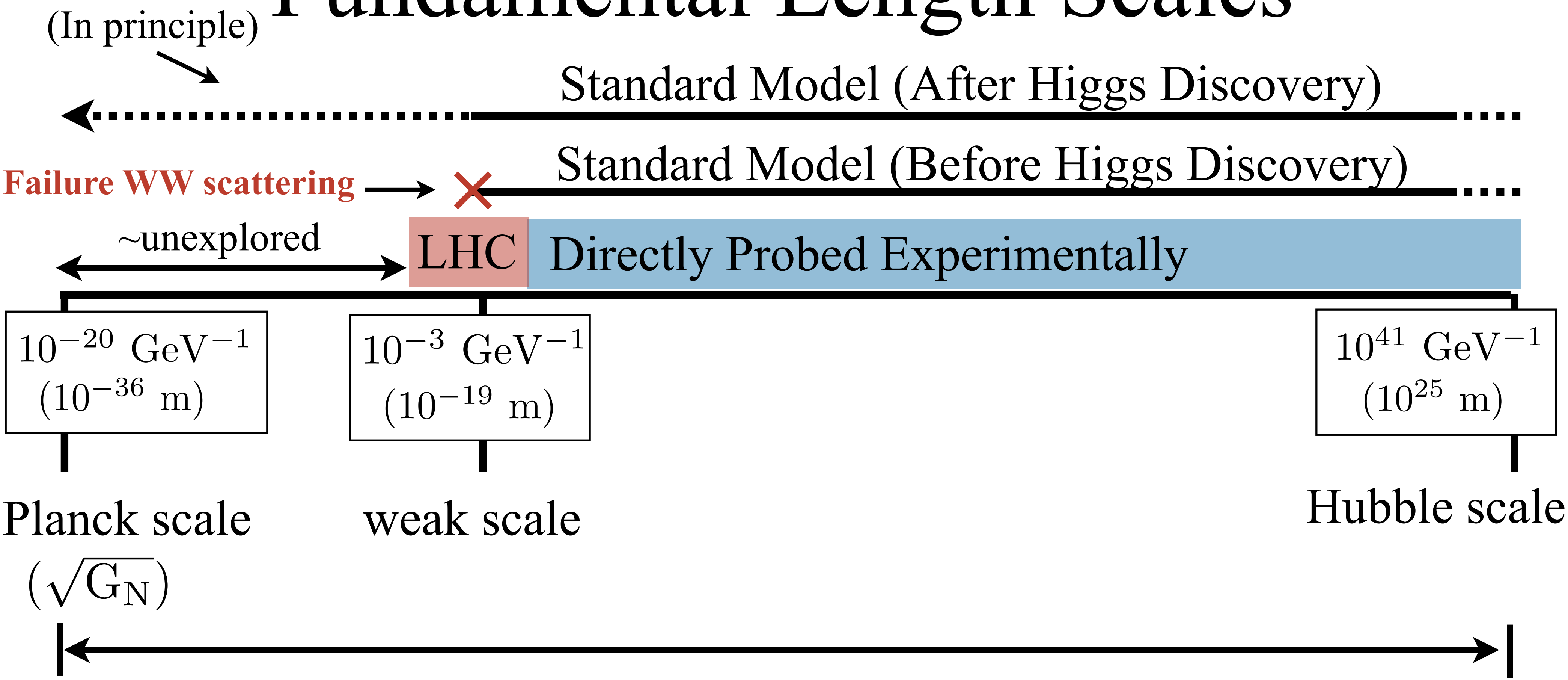

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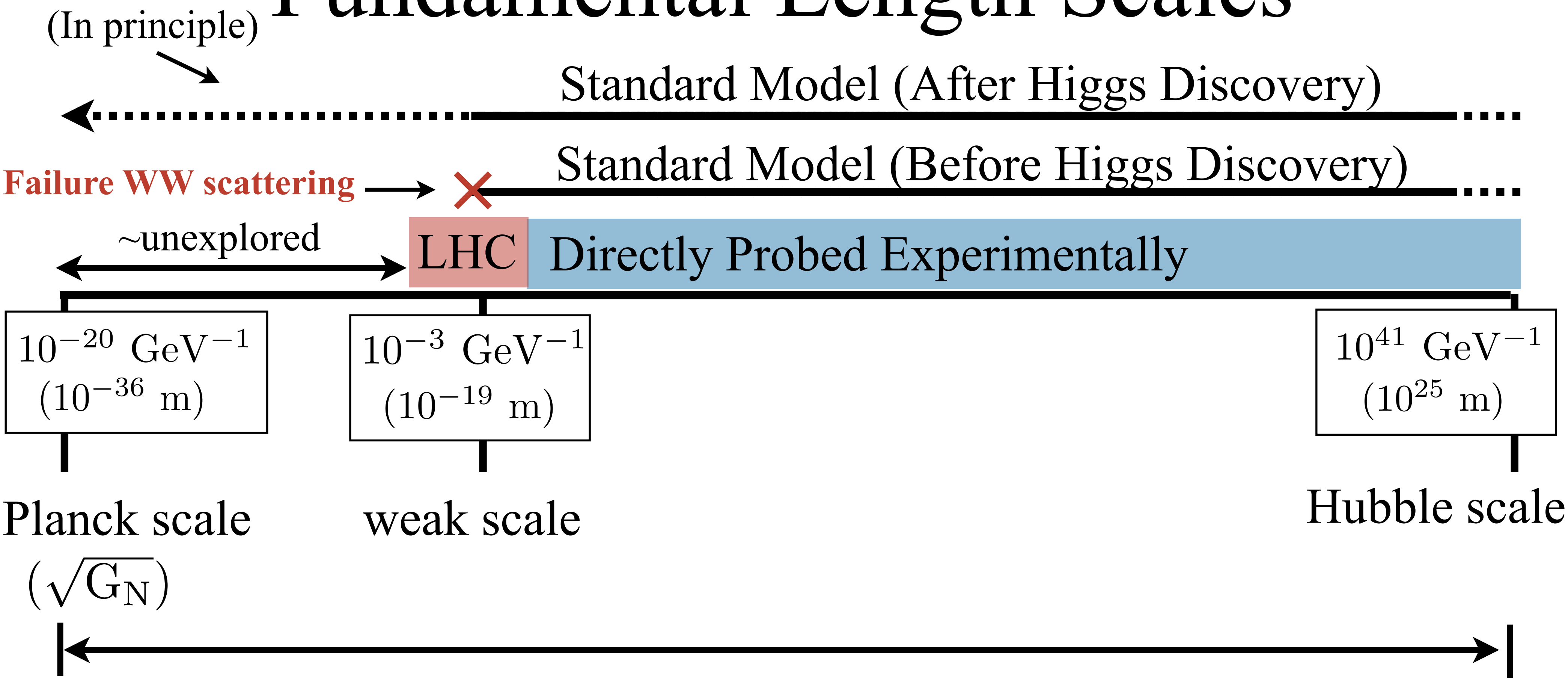

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- Deep mysteries/problems with SM directly associated with each fundamental scale

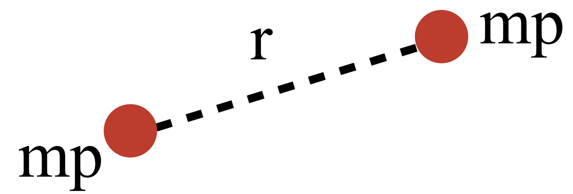
Problem with the Planck Scale

Relative Strength of Gravity

Electromagnetic Interaction

$$F_{EM} = \underbrace{\frac{e^2}{4\pi}}\frac{1}{r^2}$$

Pure number: α



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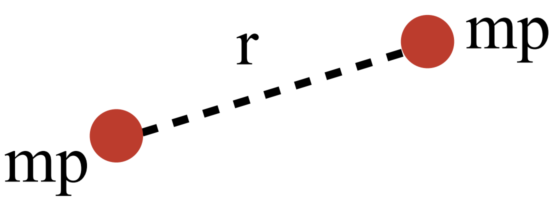

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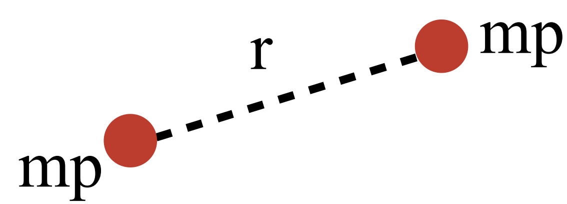

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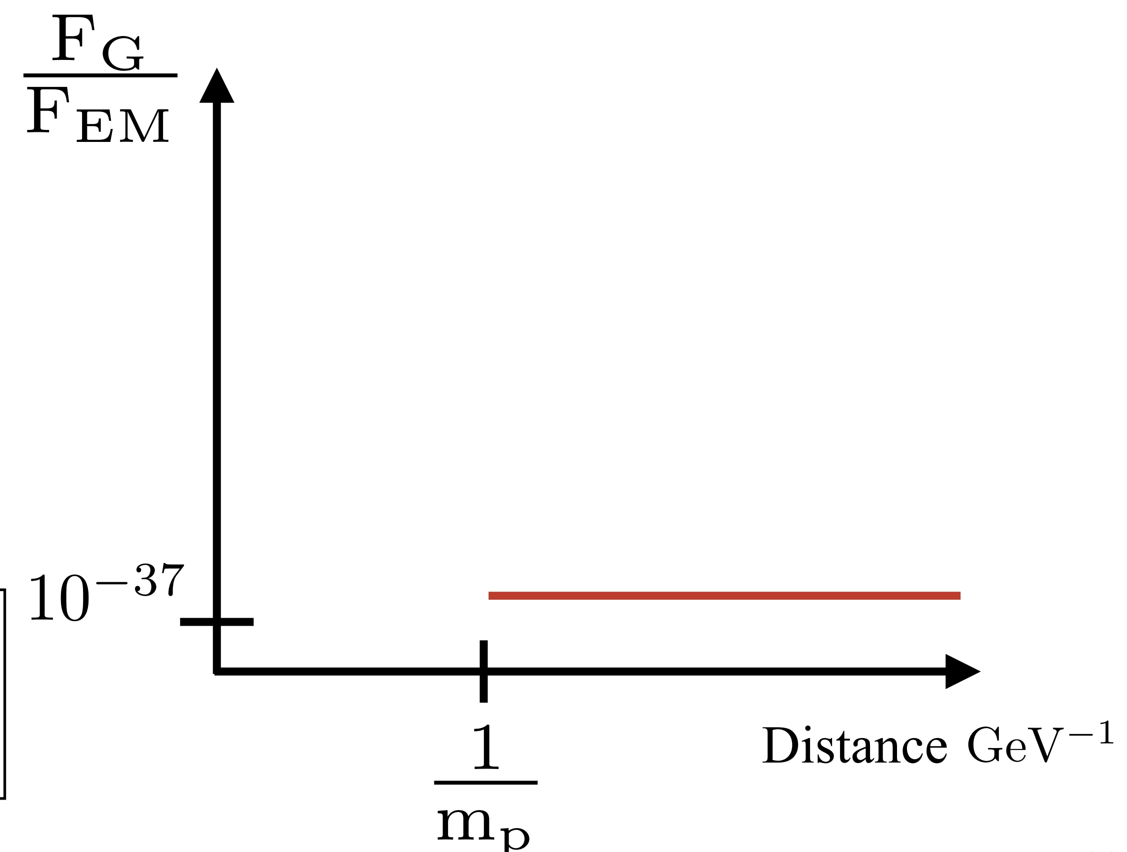

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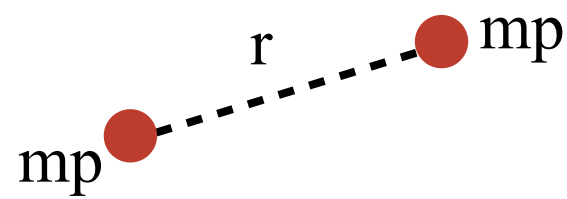

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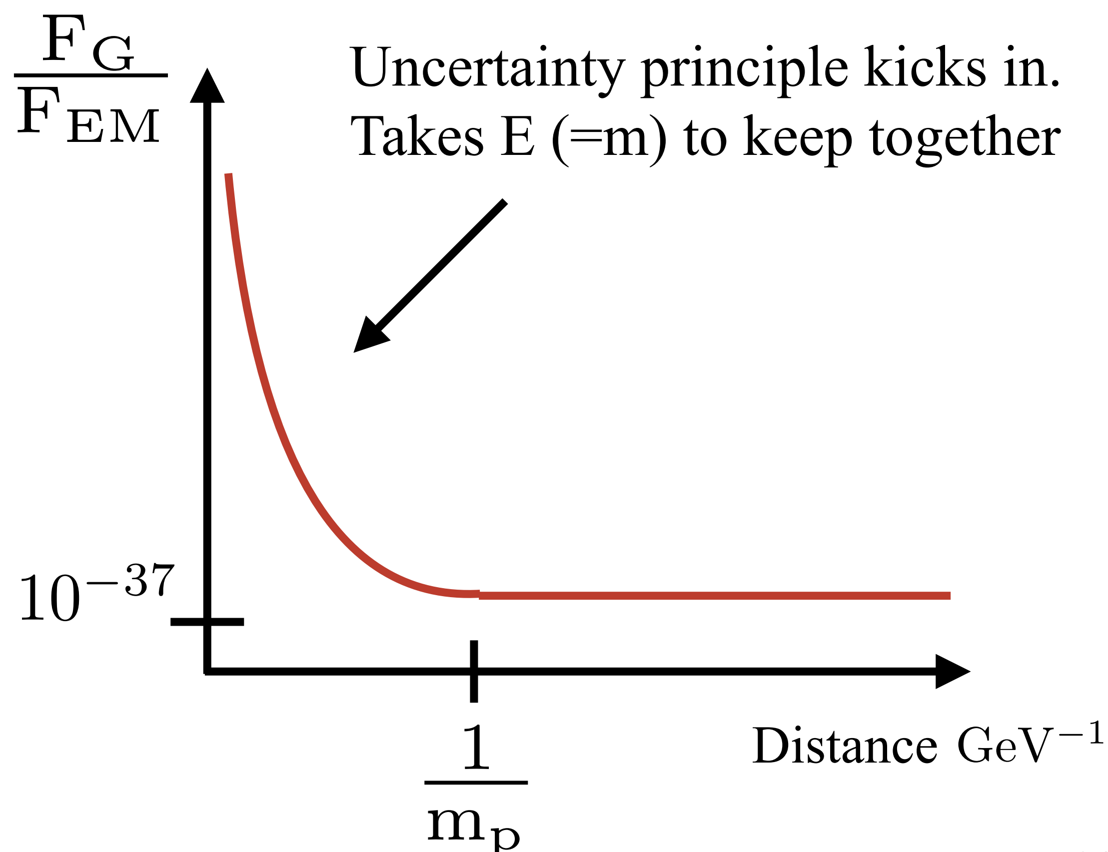

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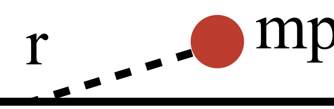
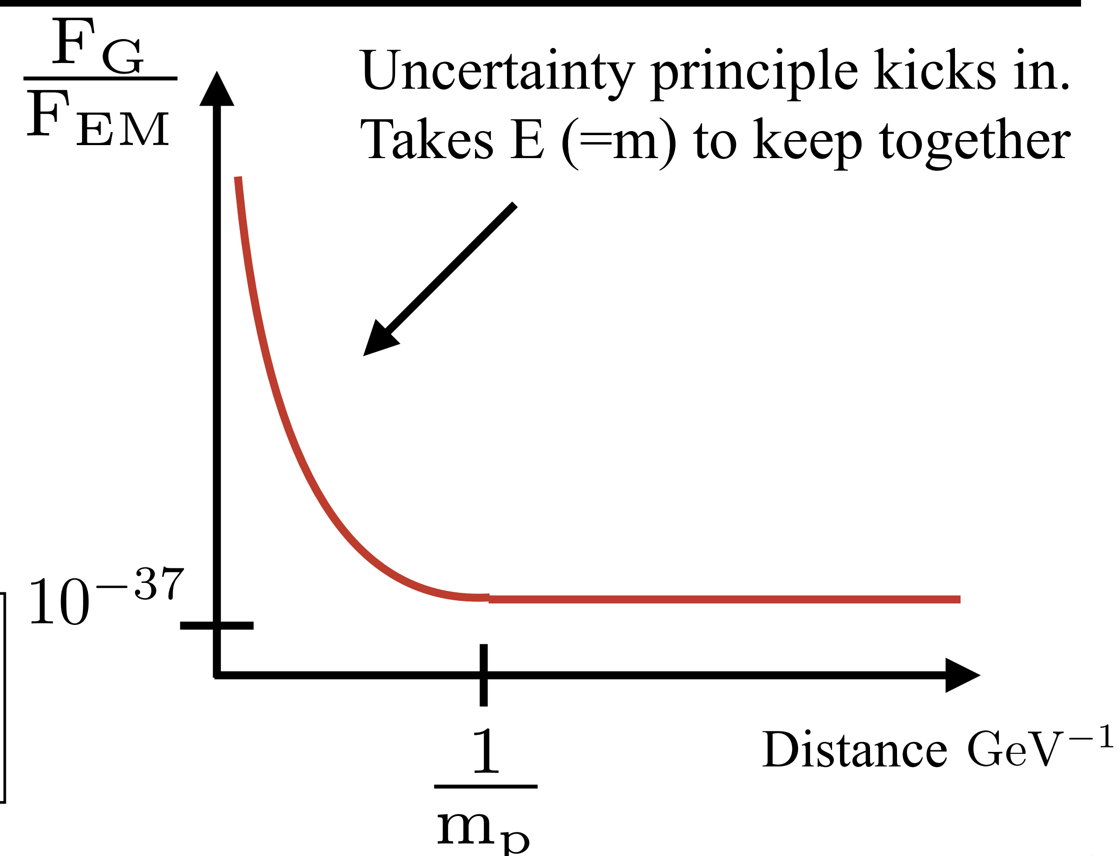


At short distances, (comparable to ℓ_{Pl}) gravitational interaction dominates
- ℓ_{PL} the scale at which gravity is becoming strong

Pure number: α



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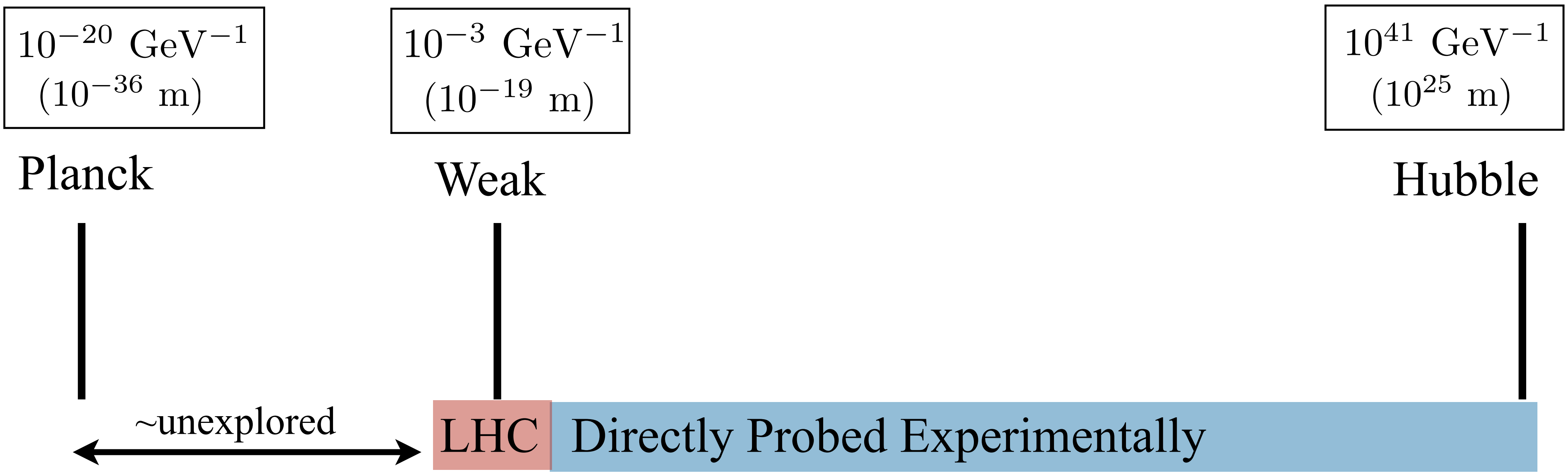
Probing Smaller Distance Scales



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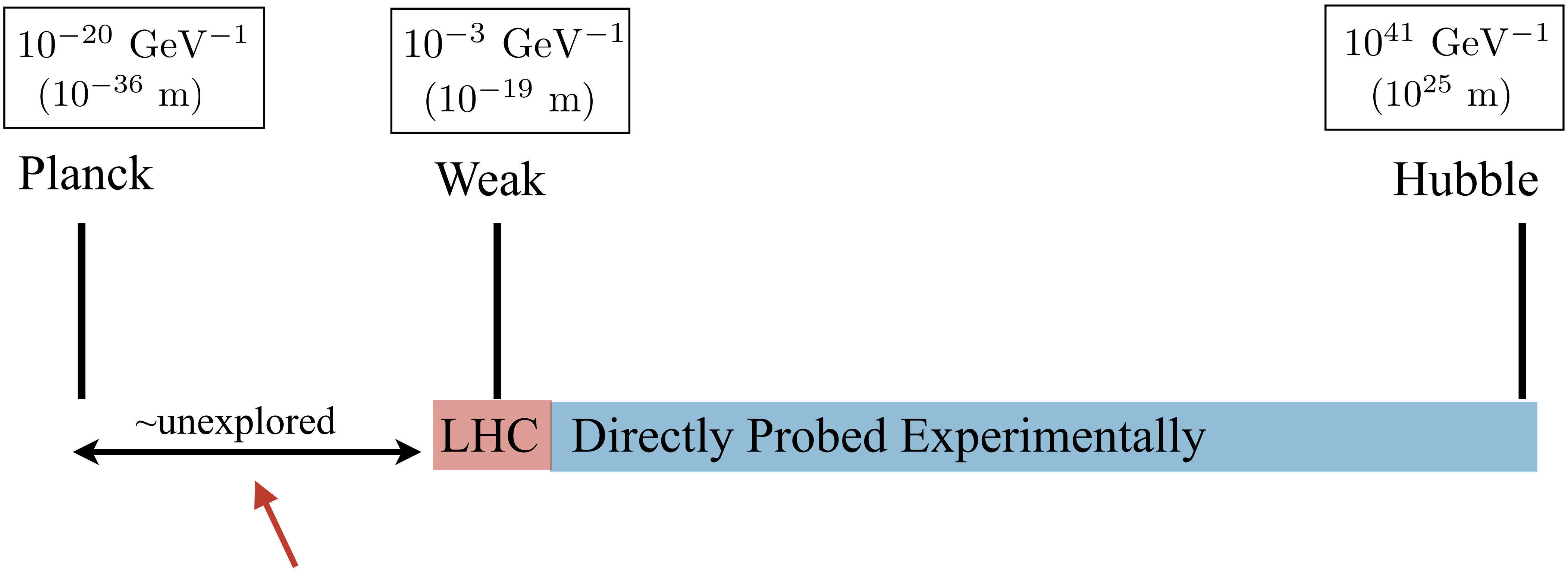

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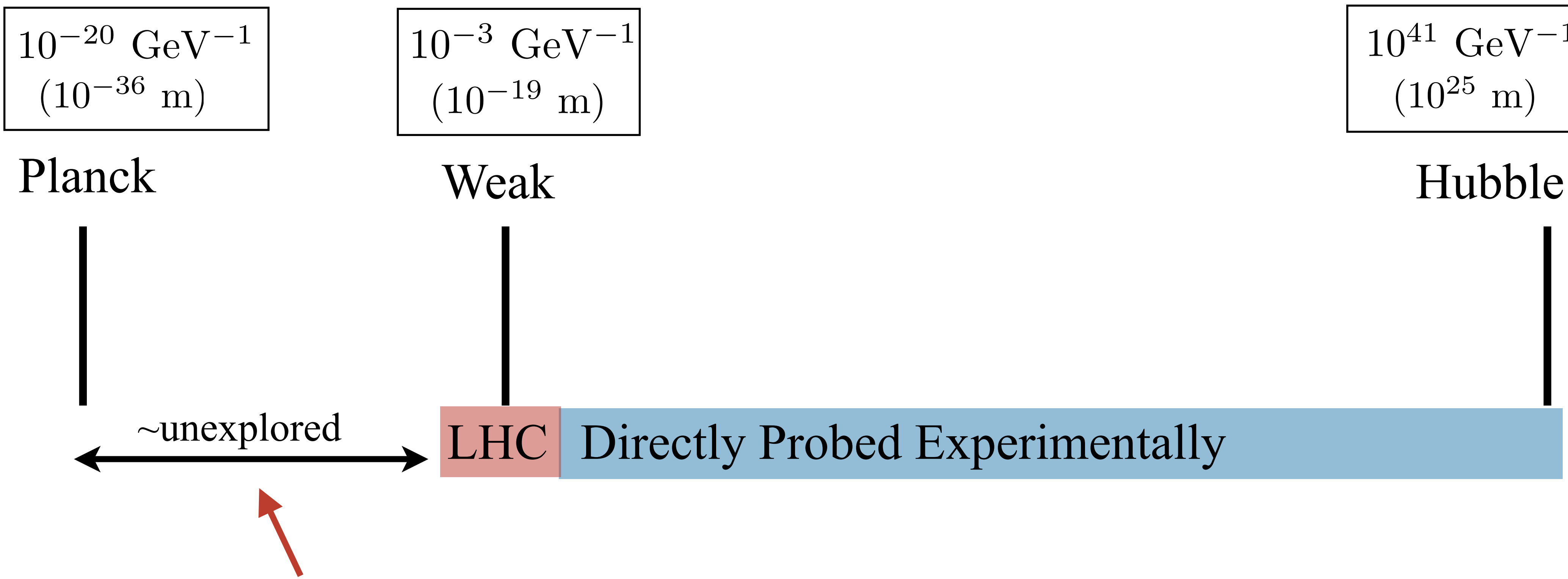

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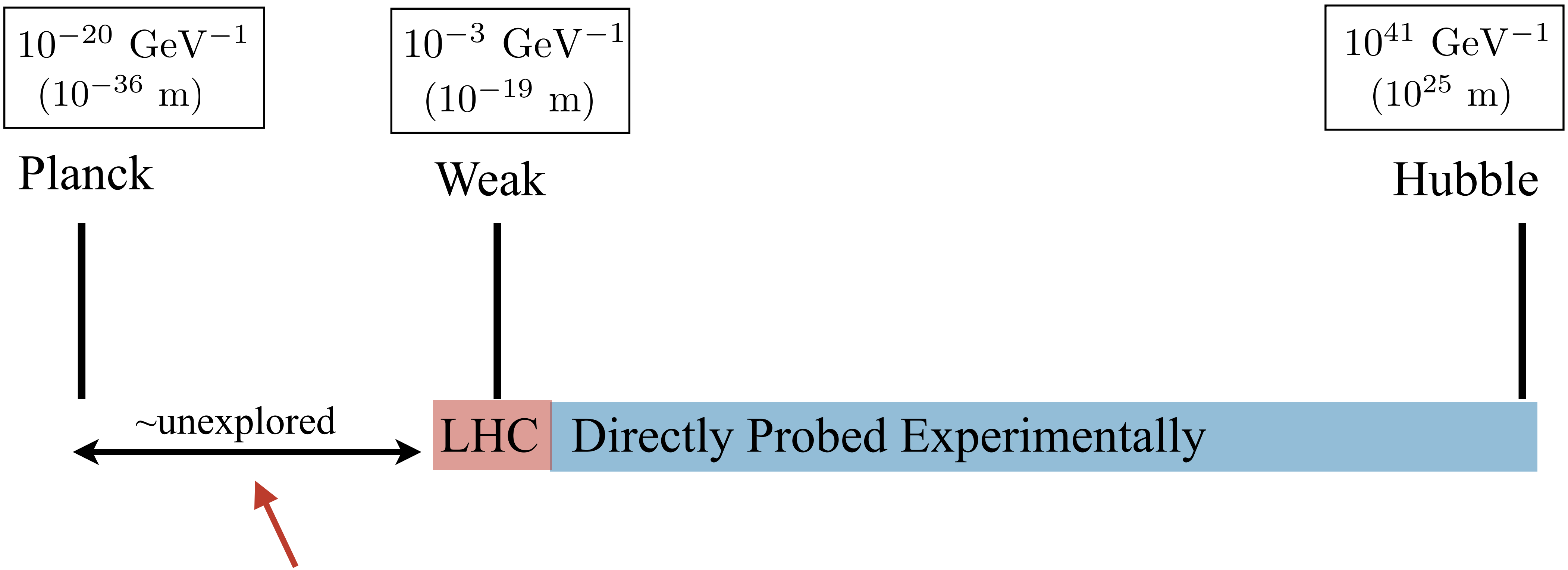

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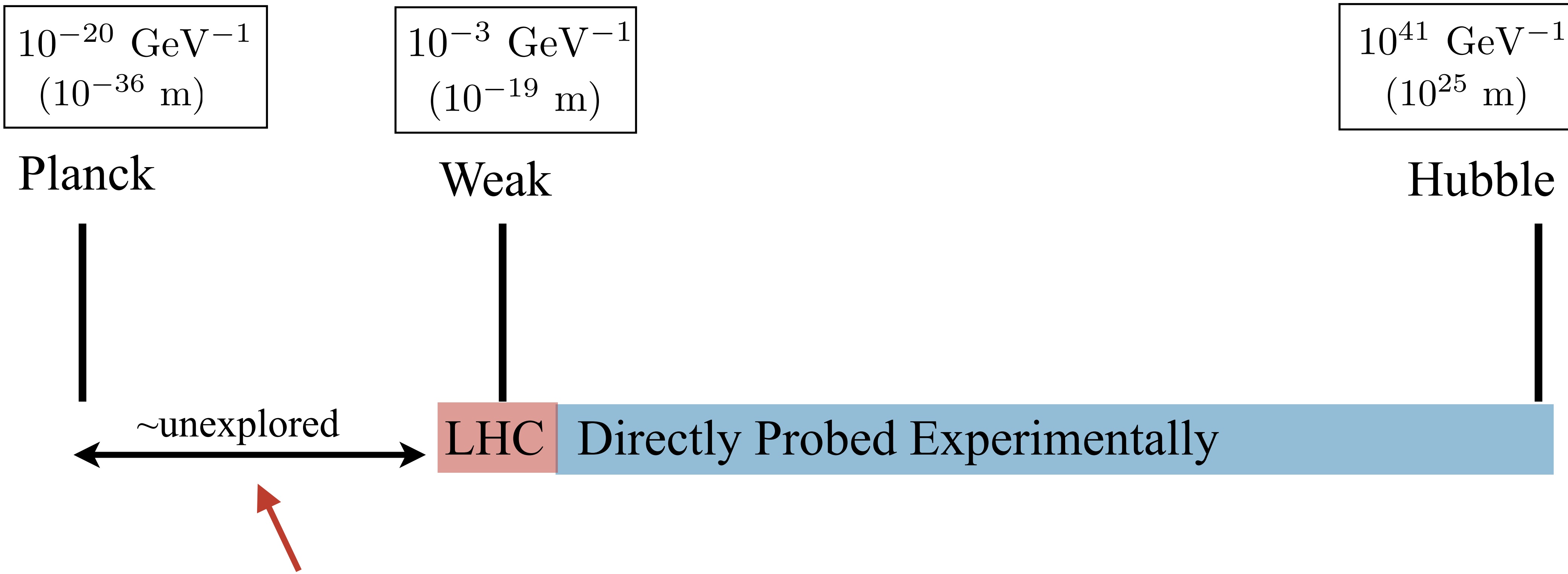

- Say we decided to probe smaller and smaller distance scales
- Build collider, go to higher and higher energies
- Eventually reach point where gravitational interaction dominates
- Continue to smaller distance … then something new happens…

Create Black Holes !

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

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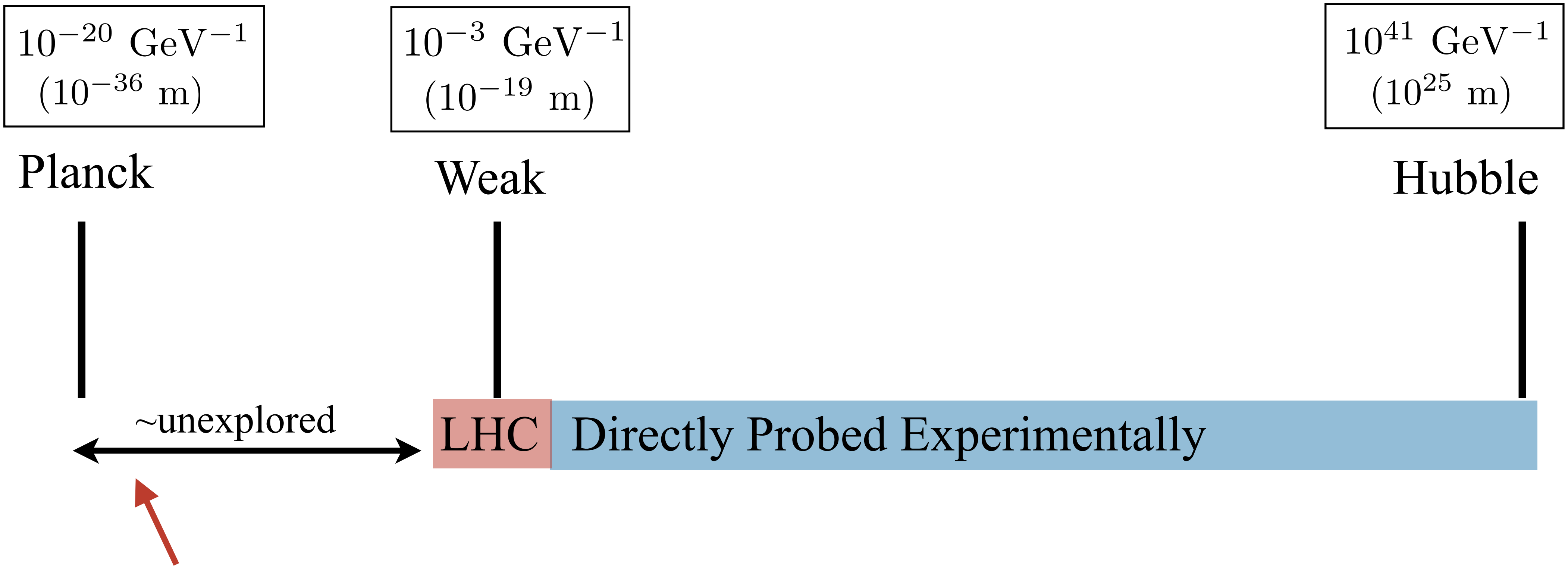
$$\mathrm{m} \sim \frac{1}{\mathrm{r}}$$

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

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

Probing Smaller Distance Scales



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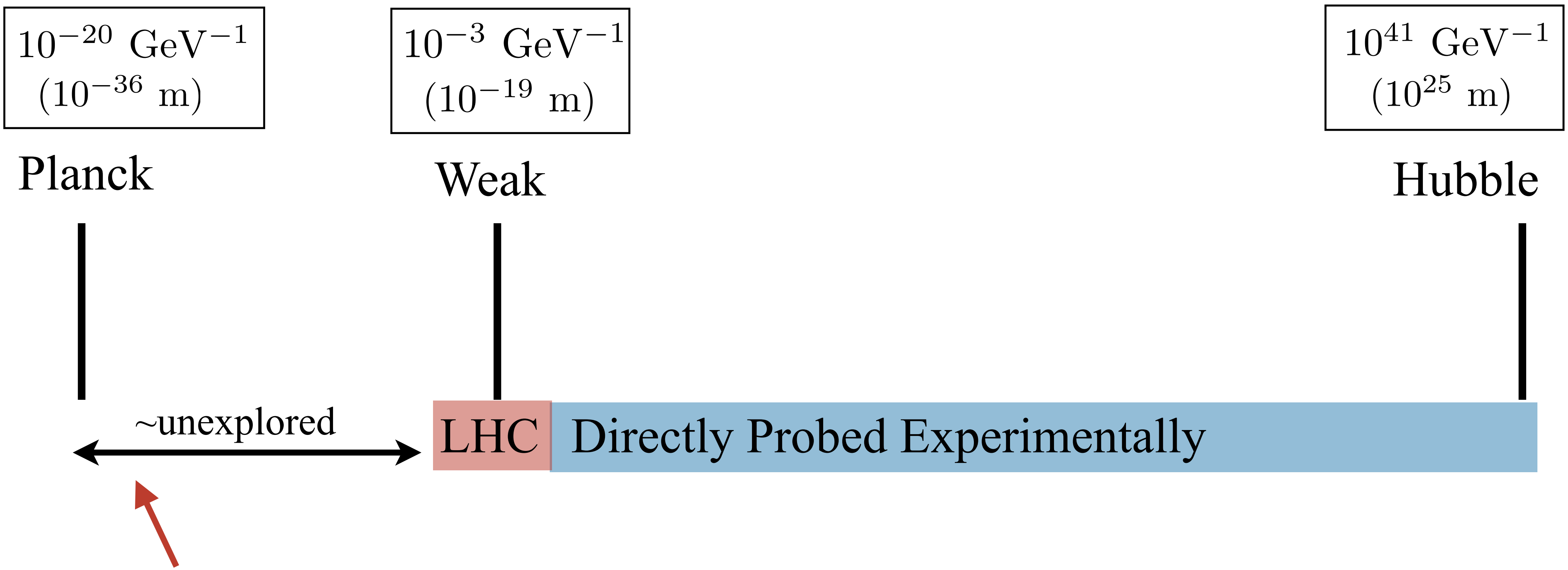

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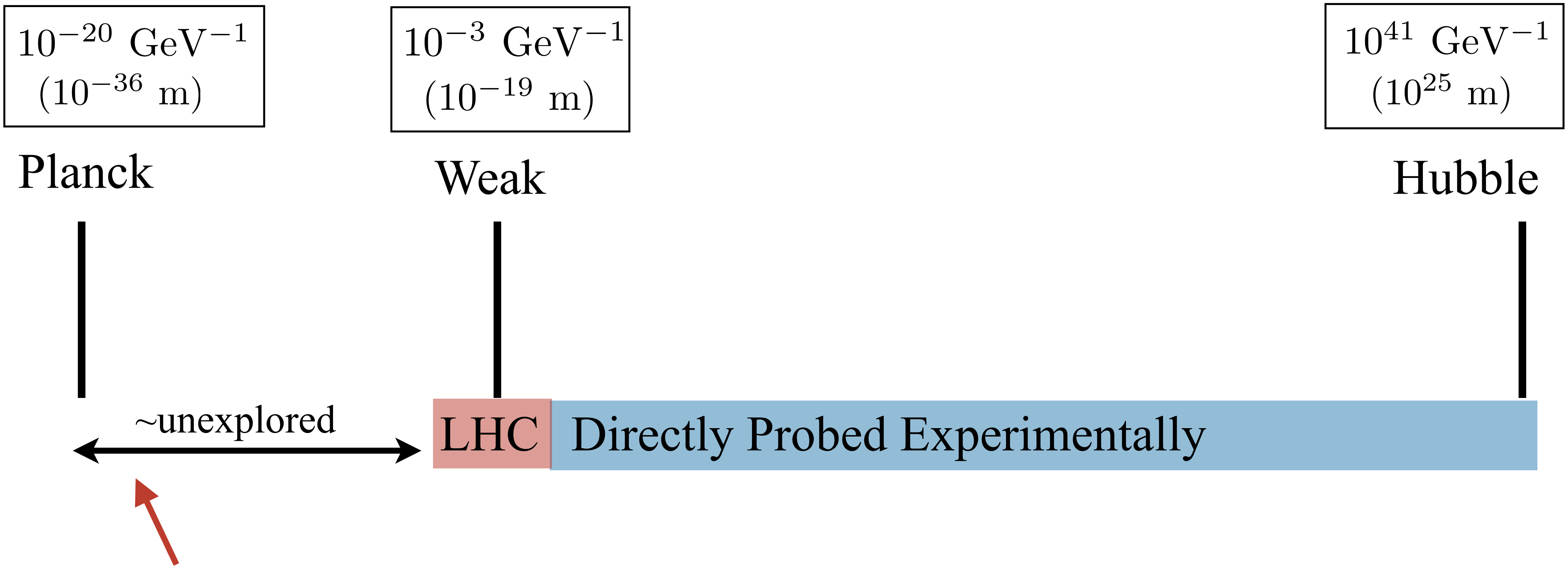

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    - *Physics telling us that smaller scales dont exist*

(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

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Problems associated with other two scales close related to one another
- Both come down to vacuum fluctuations

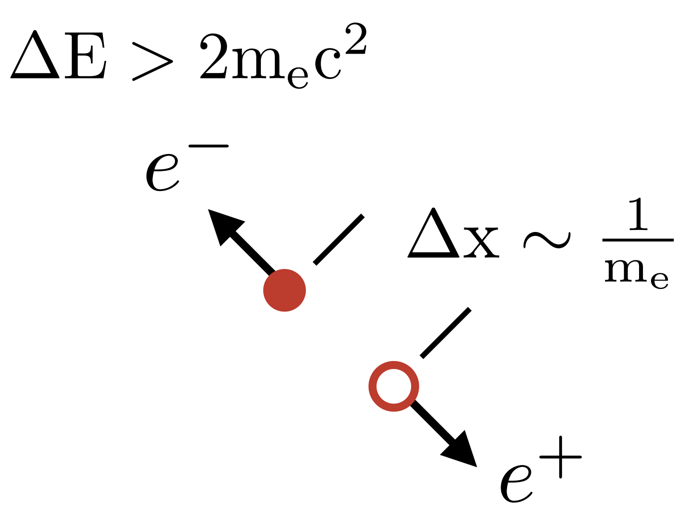
Problems with Weak and Hubble Scales

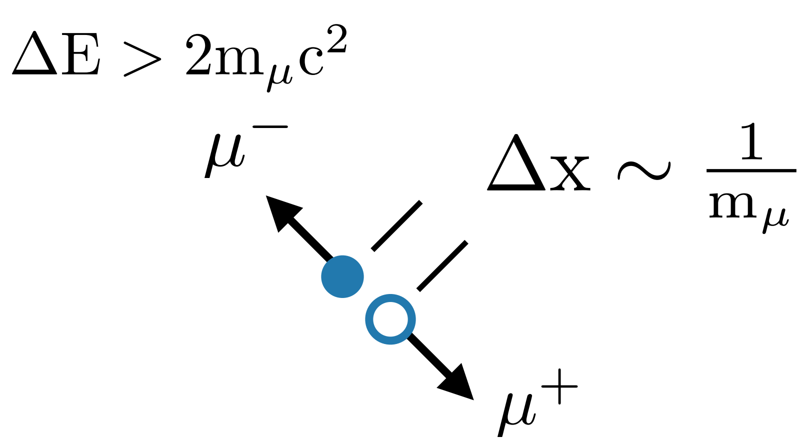
Lecture 2

Combining Relativity and Quantum Mechanics

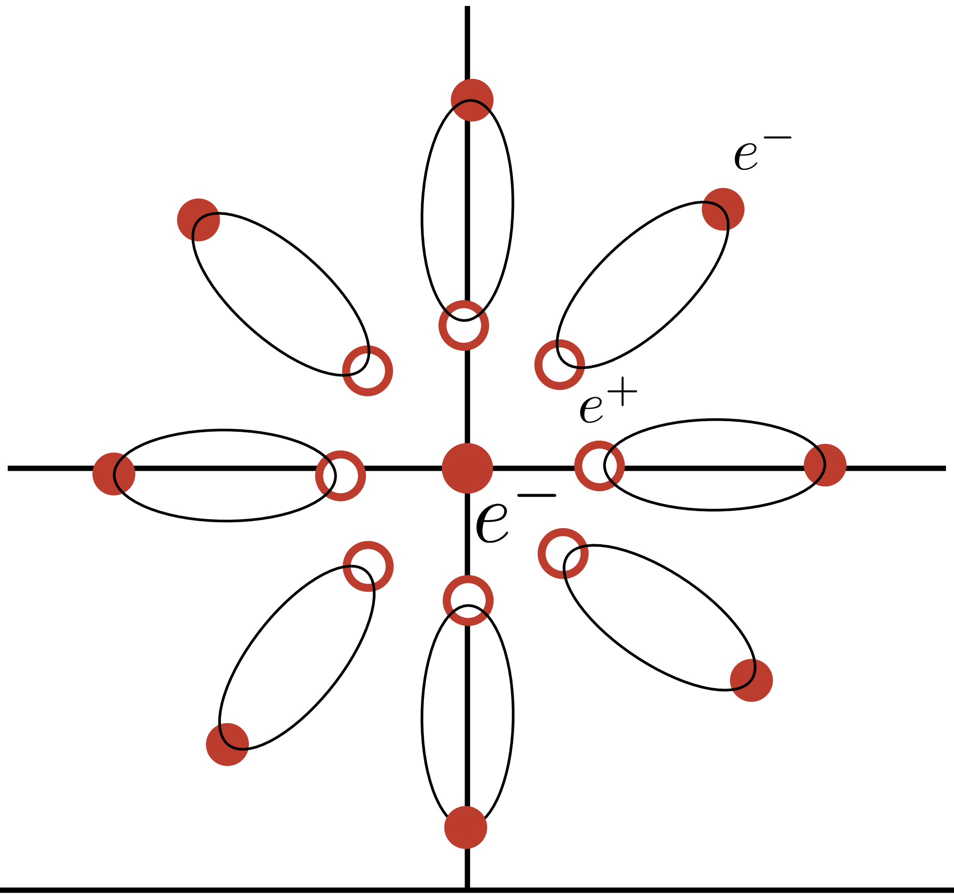
- To preserve causality needed to Anti-particle must exist

- In turn, major implications on the vacuum:





Vacuum Fluctuations ***ARE REAL !***



Precisely predict magnetic properties

g/2 = 1.0011596521809(8),

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

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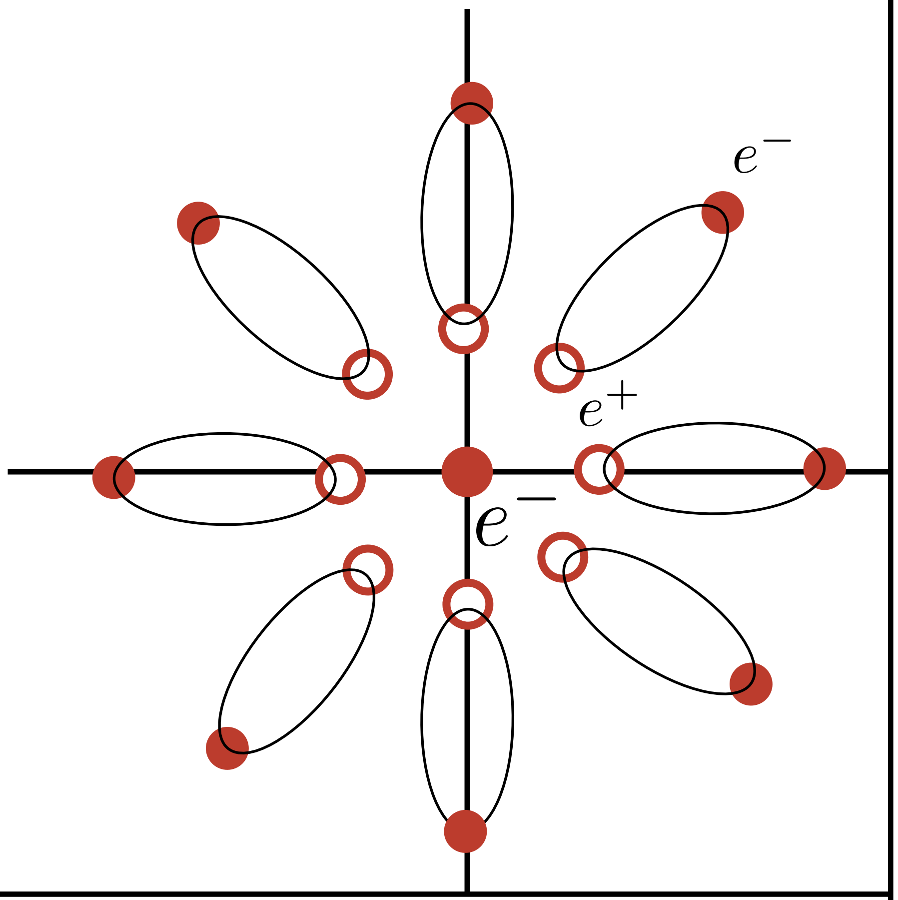

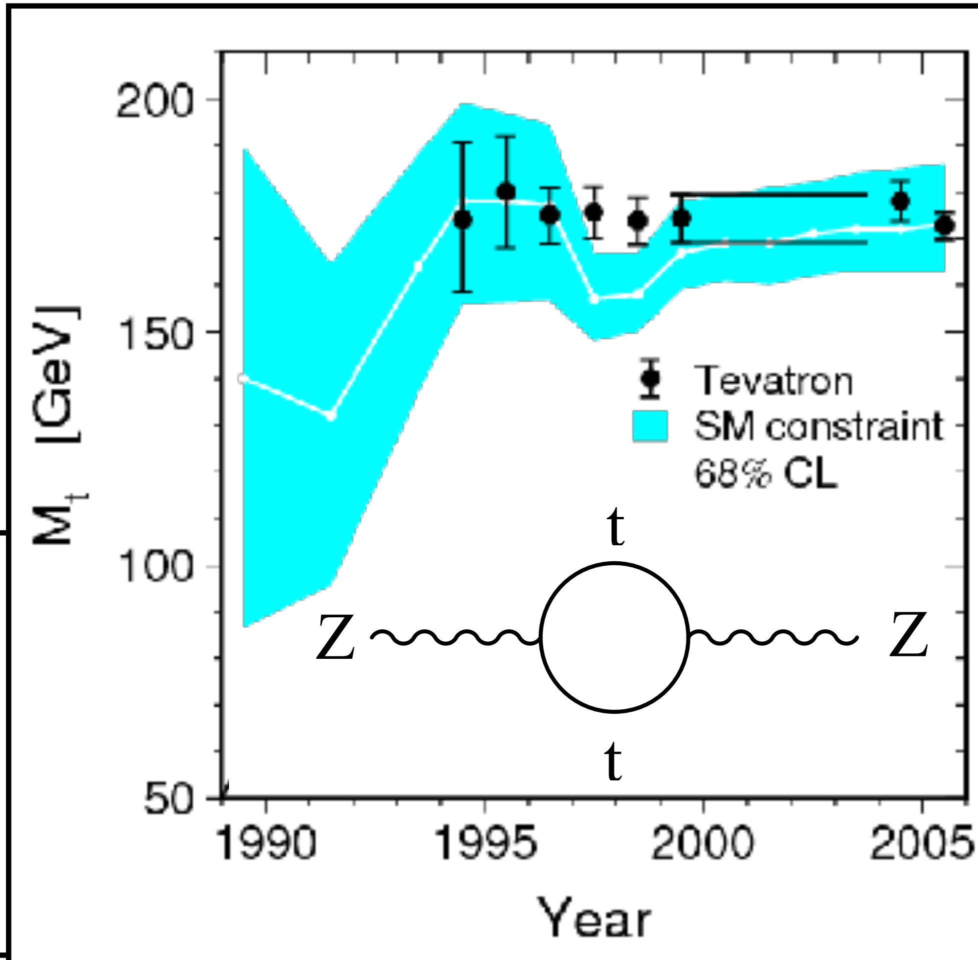

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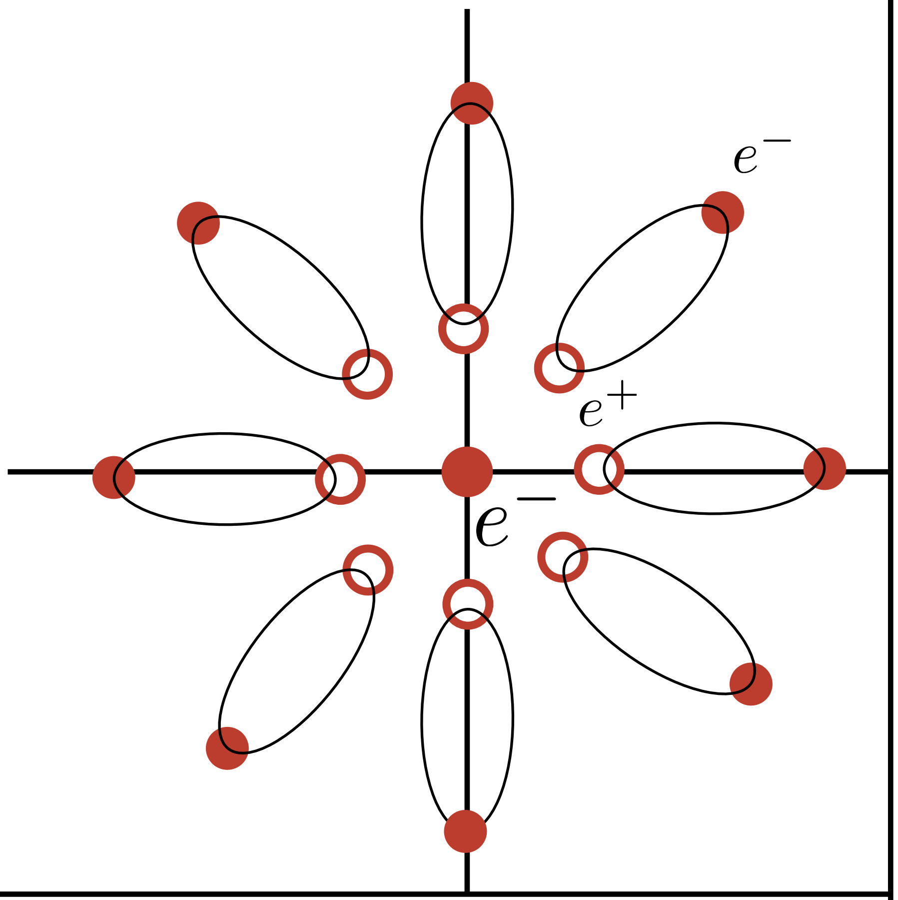
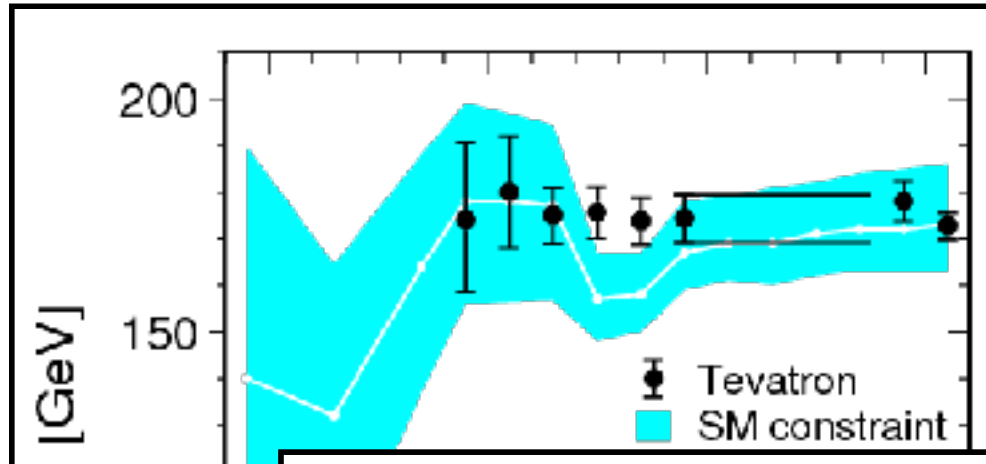
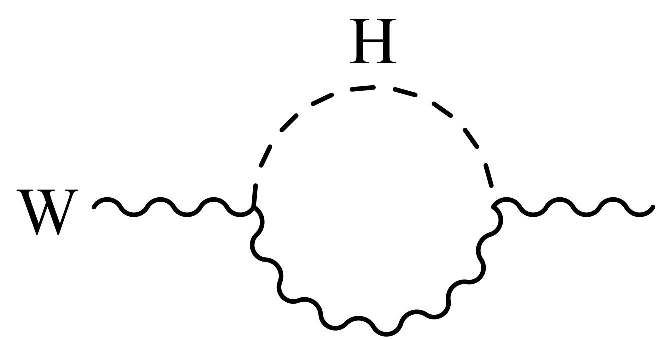




Precisely predict magnetic properties

g/2 = 1.0011596521809(8),

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



m_H

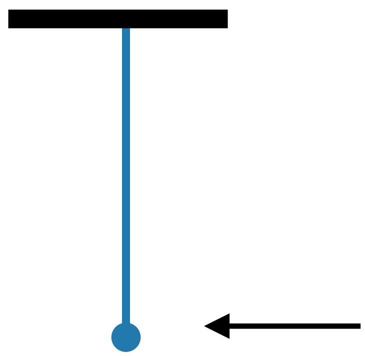
(Predicted)

50 —— 150 GeV

115 GeV (Discovered)

Vacuum Has Energy

Classically (w/o QM)



Lowest possible energy is 0

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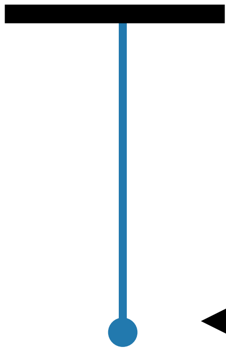

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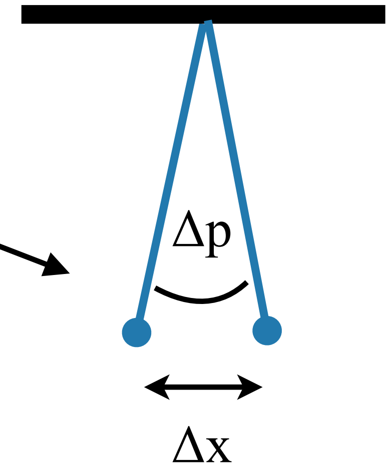
Quantum World

Minimum non-zero energy: E~hω



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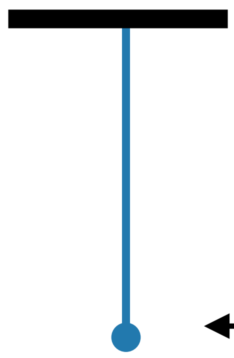

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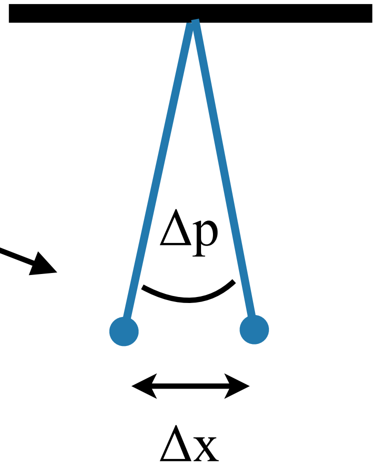

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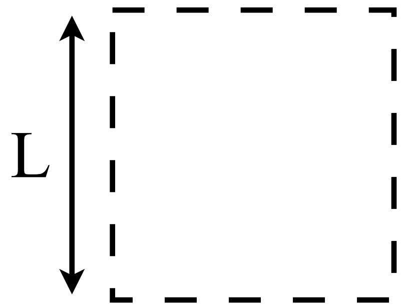
Estimate energy density in region of empty space: *Dimensional Analysis*



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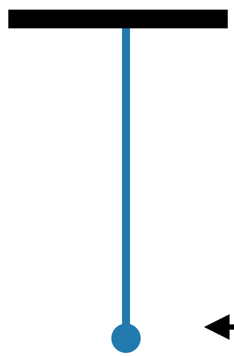

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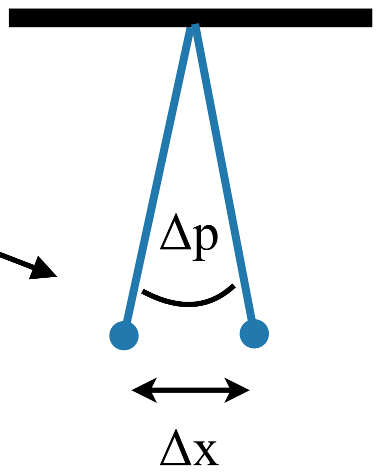

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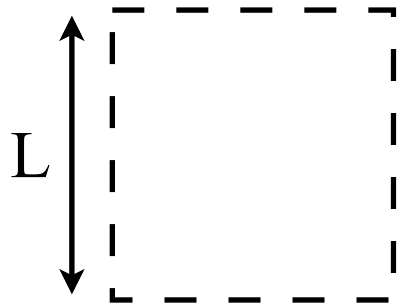

$$\Lambda \sim \frac{\mathrm{E}}{\mathrm{V}}$$

Vacuum Has Energy

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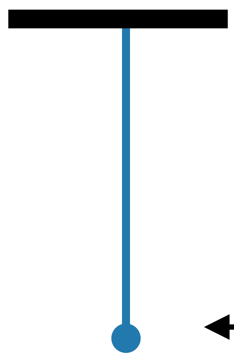
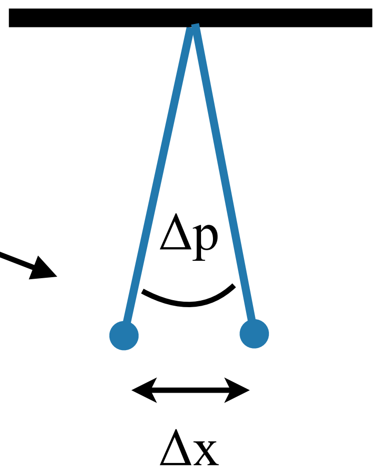


Quantum World



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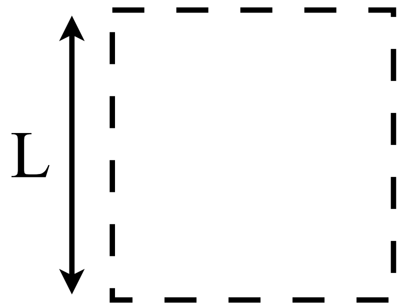

$$\Lambda \sim \frac{E}{V}$$

$(V \sim L^3)$

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

Vacuum Has Energy

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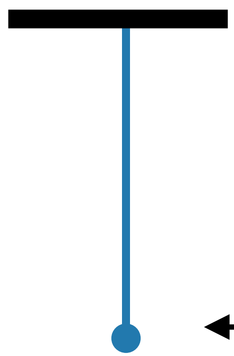

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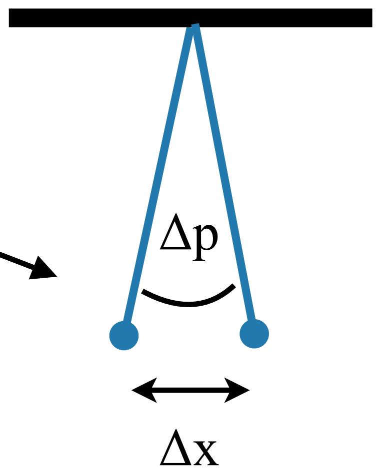

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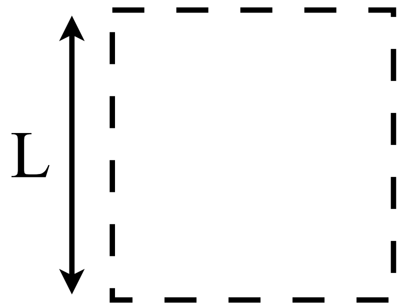

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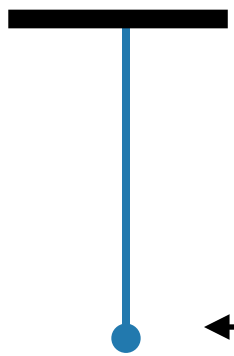

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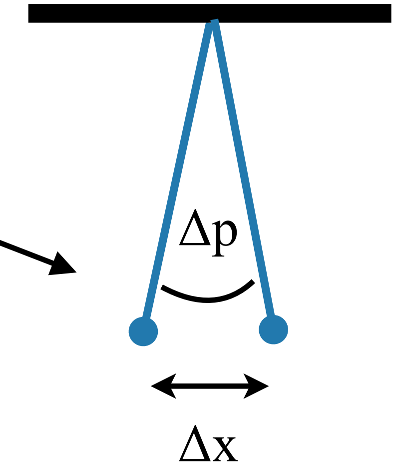

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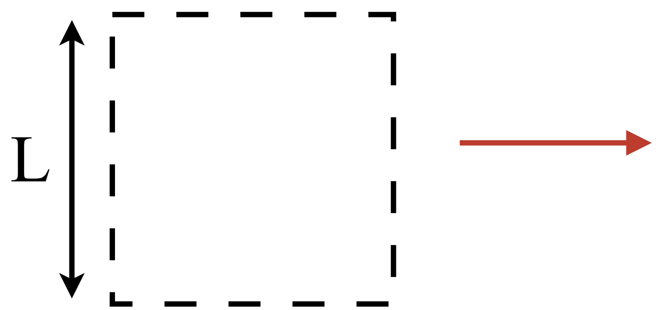
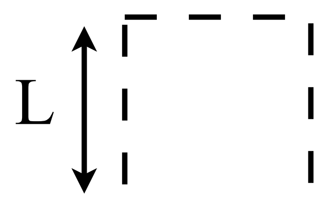


Smaller Box



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Λ much bigger

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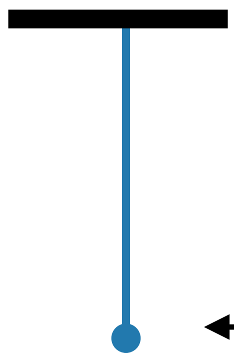

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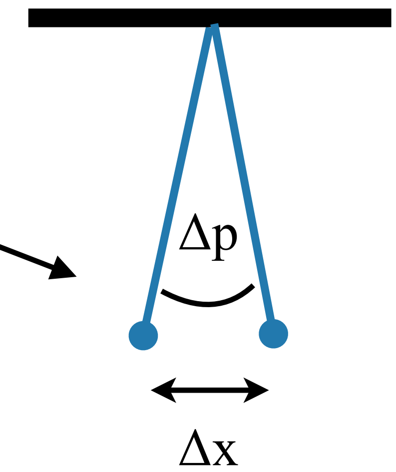

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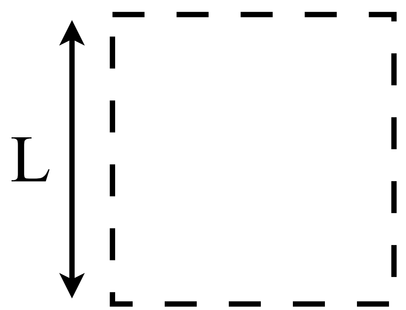

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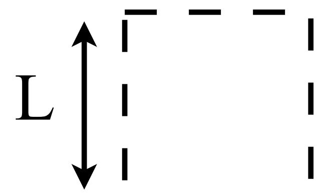
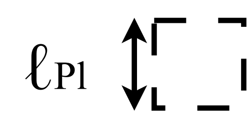


Λ much bigger

Reach: Cut-off



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

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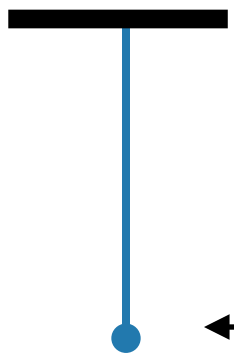

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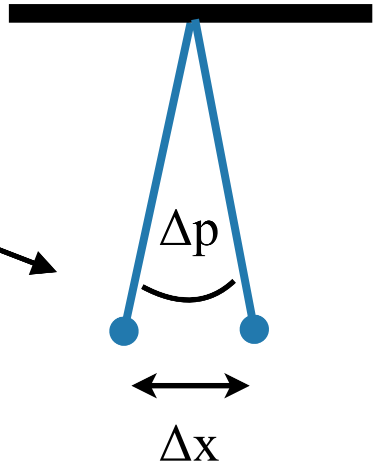

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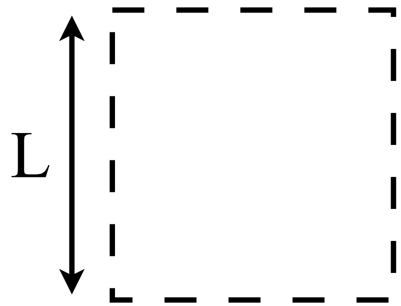

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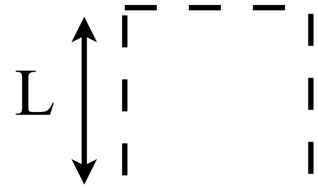

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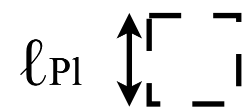

$\Lambda \sim \frac{1}{{\ell_{Pl}}^4}$

...this is a problem

Cosmological Constant Problem

Without gravity constant energies (Λ) can be ignored *(overall offset)*

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With gravity, constant energy warps space-time, interacts gravitationally

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

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

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Clearly something wrong !

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How do we deal with this in the current theory ?

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Constant.
Input parameter to theory

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

120 digits

Λ_{QM}

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$+$

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“Fine Tuning”

Λ $\Lambda_{\text{Classical}}$

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120 digits

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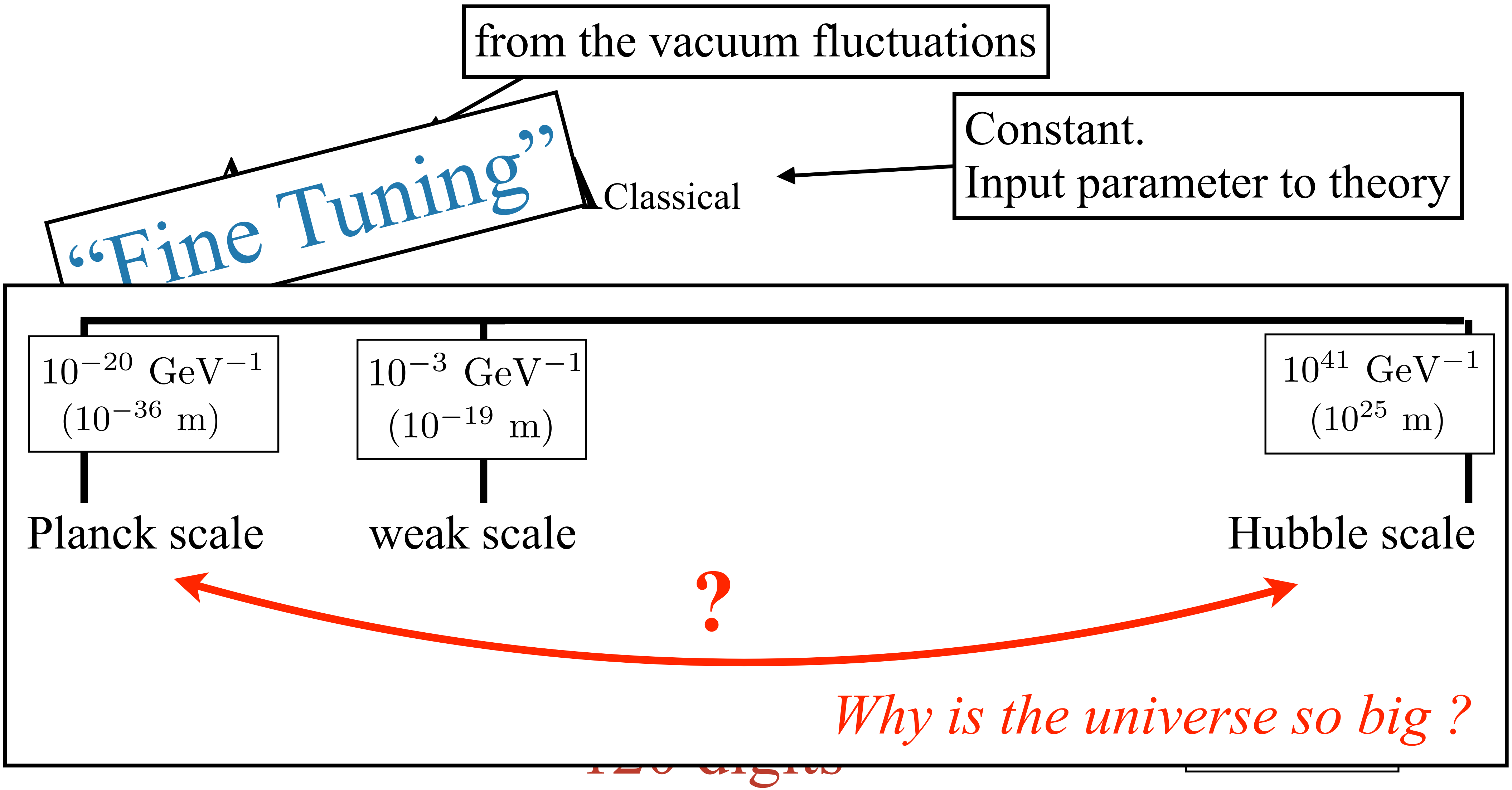

Vacuum Fluctuations: Higgs Particle

Closely related problem

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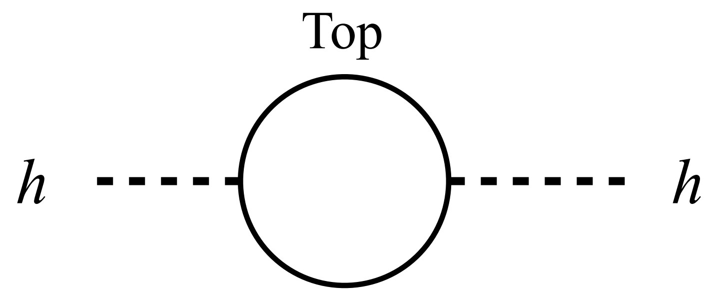

$\sim \Lambda^2$

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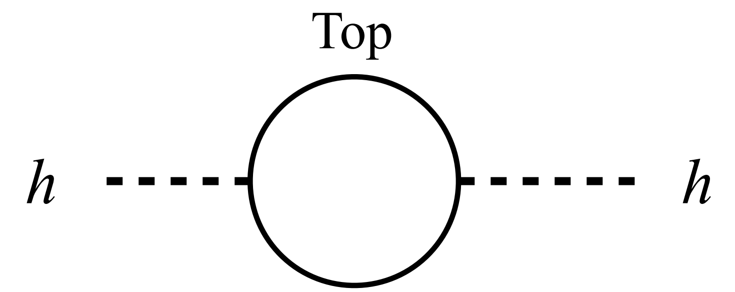

$\sim \Lambda^2 \;\Rightarrow\; \mathrm{mH} \sim 10^{20}\ \mathrm{GeV}$

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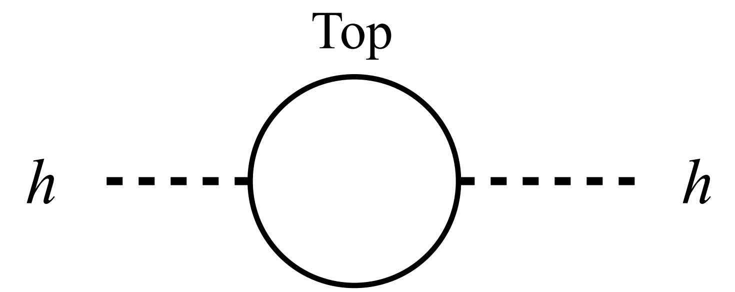
$$mH^2 = 2.569678321 \ldots 554 \ldots \times \ell_{\rm Pl}{}^2$$

60 digits



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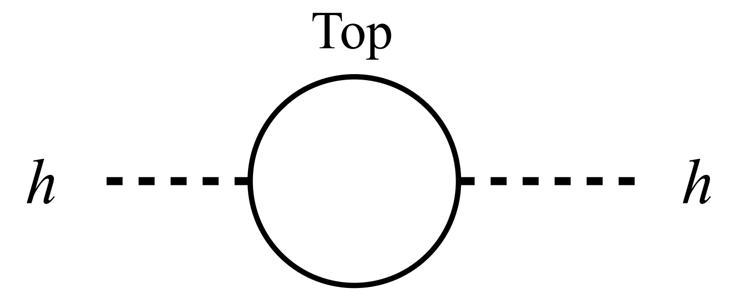

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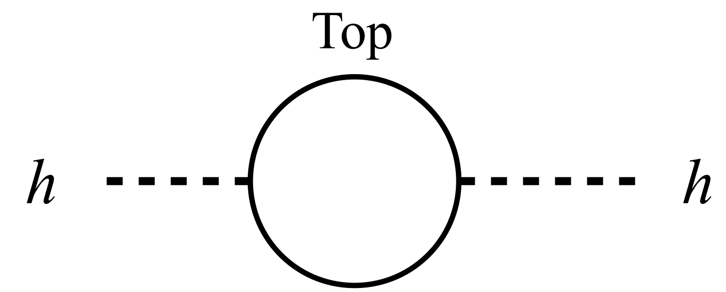

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- Estimated mass corrections unreasonably large

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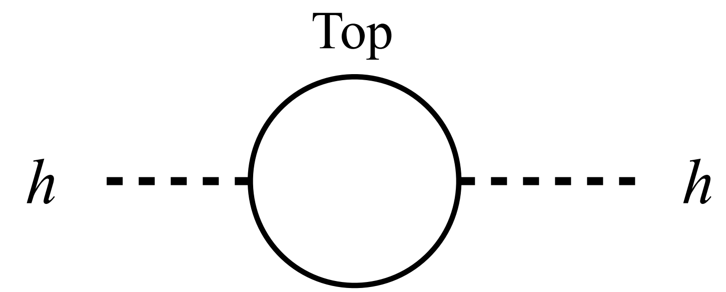
- Estimated mass corrections unreasonably large
- Instability of the Higgs mass



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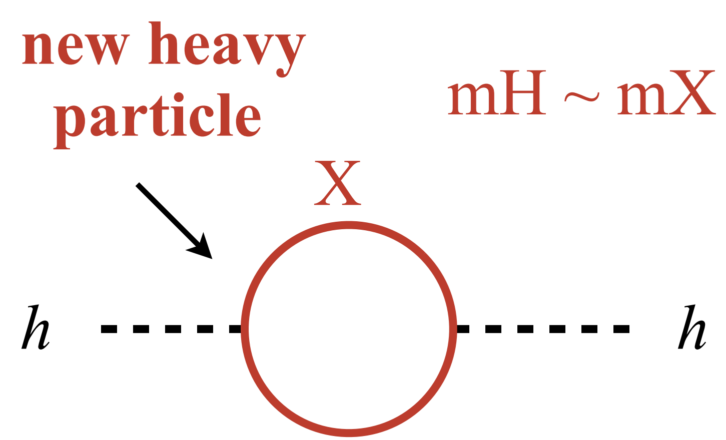

$mH \sim mX$

Vacuum Fluctuations: Higgs Particle

Closely related problem

Vacuum fluctuations of Higgs mass (m_H^2)

Top

h

eV

X

-

-

h

Vacuum Fluctuations: Higgs Particle

Closely related problem

Top

Vacuum fluctuations of Higgs mass (m_H^2)

Without "small scale" physics

(only gravity + pencil DoF)

- Bizarre, but stable
- Suggests fine tuning

h

eV

X

-

-

h

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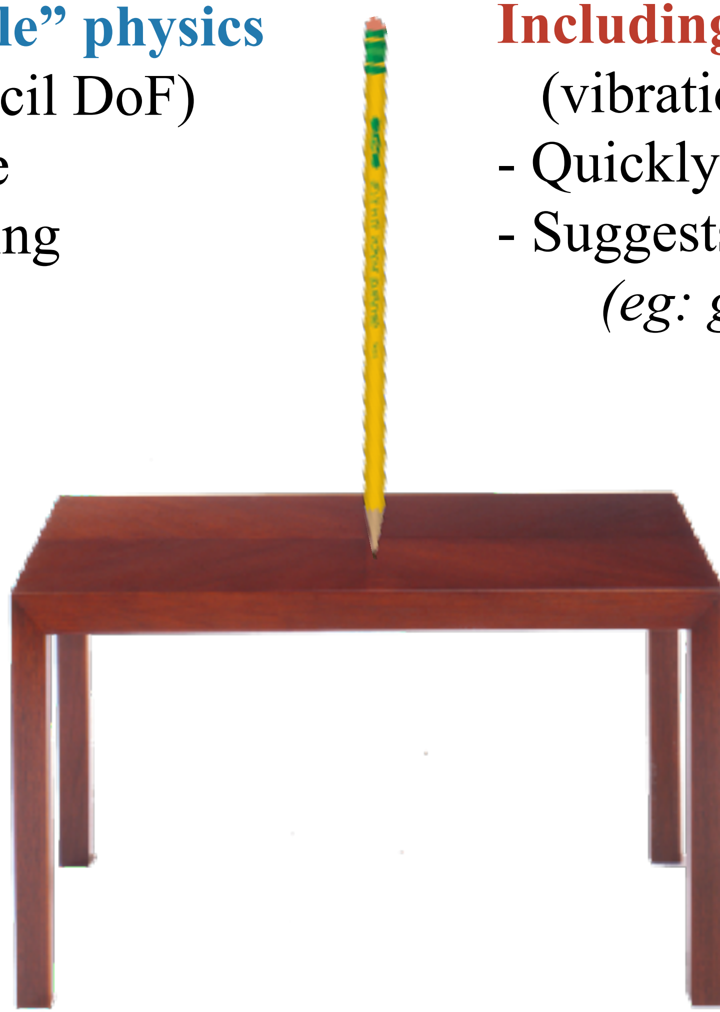

Including physics at smaller scales
(vibrations/ air molecules / atoms)
- Quickly lead to instability
- Suggests active mechanism
(eg: glue / string)

h

eV

X

h

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Top

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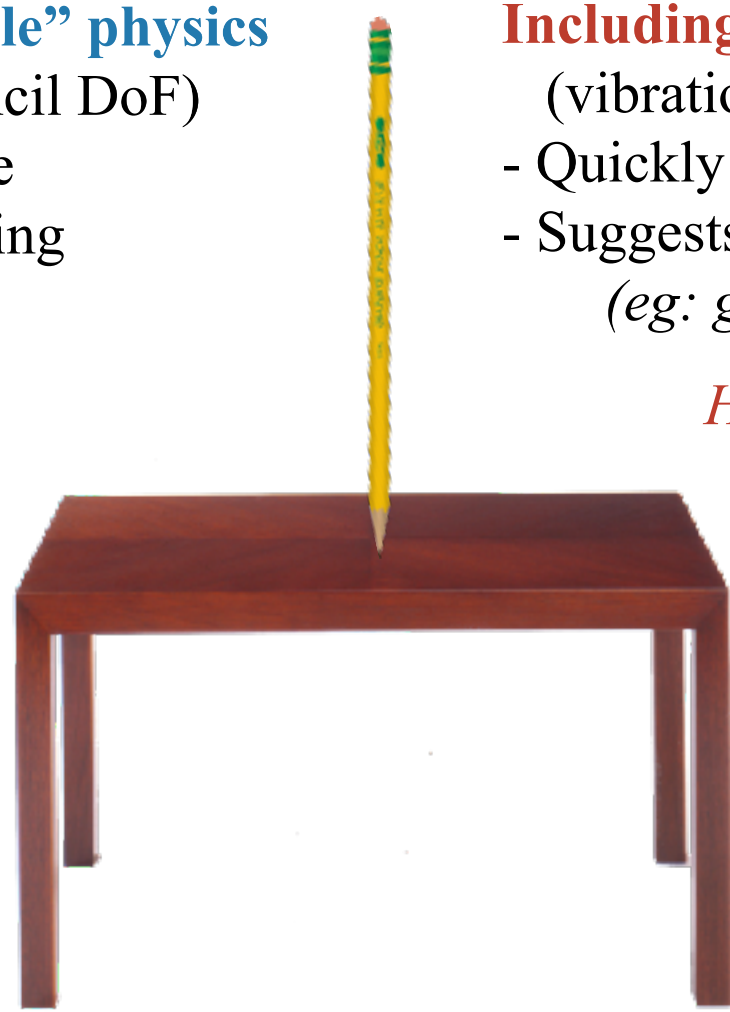
Higgs mass in SM



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  (eg: glue / string)

Higgs mass including new, high mass scale physics

h

eV

X

h

-

-

Vacuum Fluctuations: Higgs Particle

Closely related problem

Vacuum fluctuations of Higgs mass (m_H^2)

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

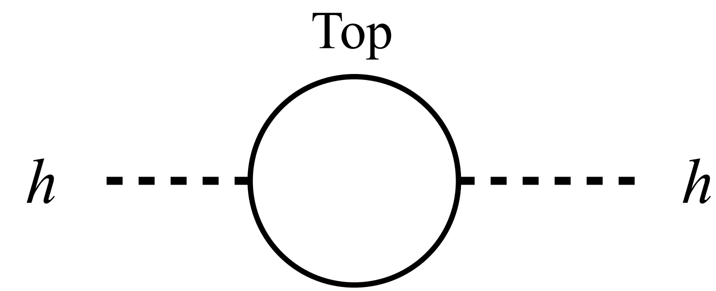
(60 digits)

$$+$$

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

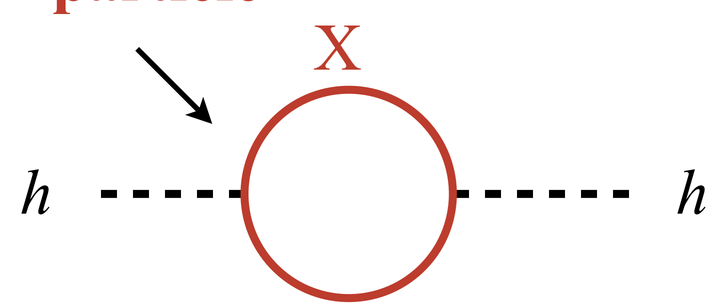
(60 digits)

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



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

$$mH \sim mX$$



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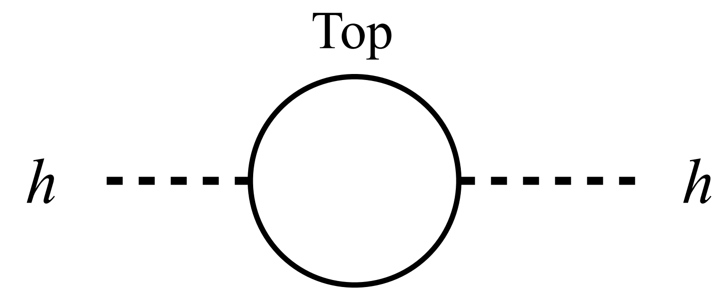

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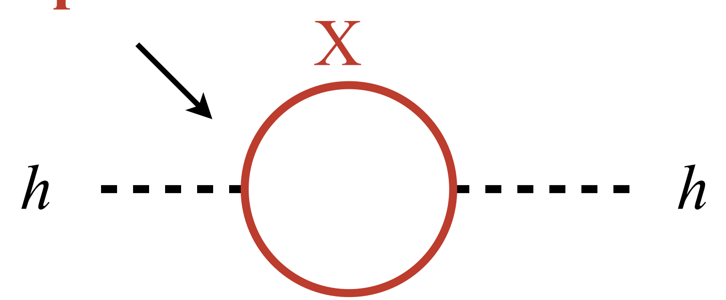
new heavy particle

$m_H \sim m_X$



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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 Field

Another way of talking about same problem

Can perform similar estimate for scale of interaction with condensate v

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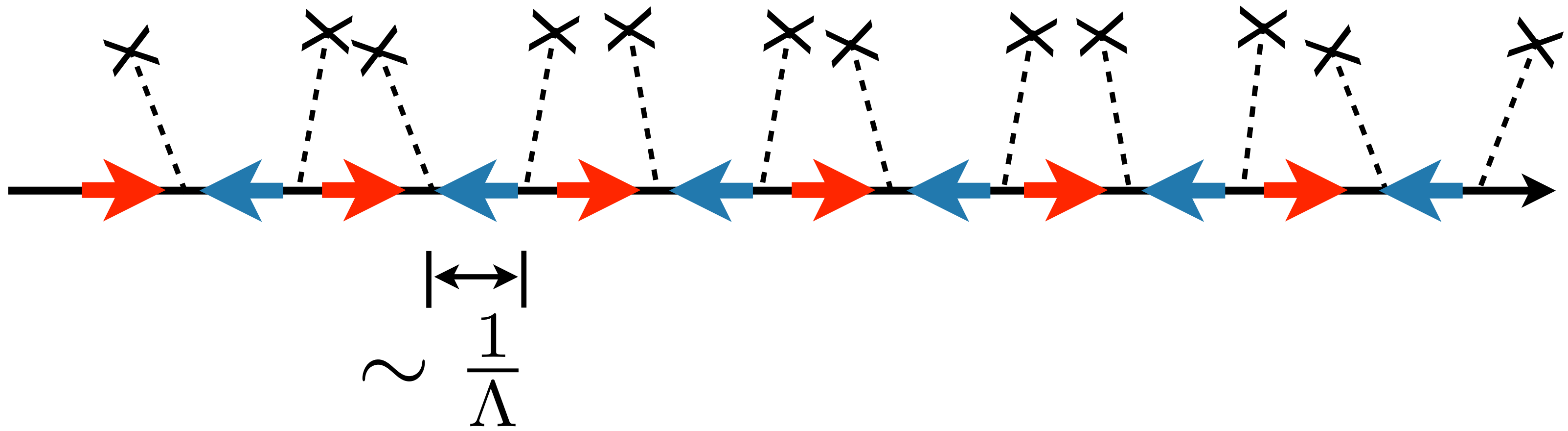

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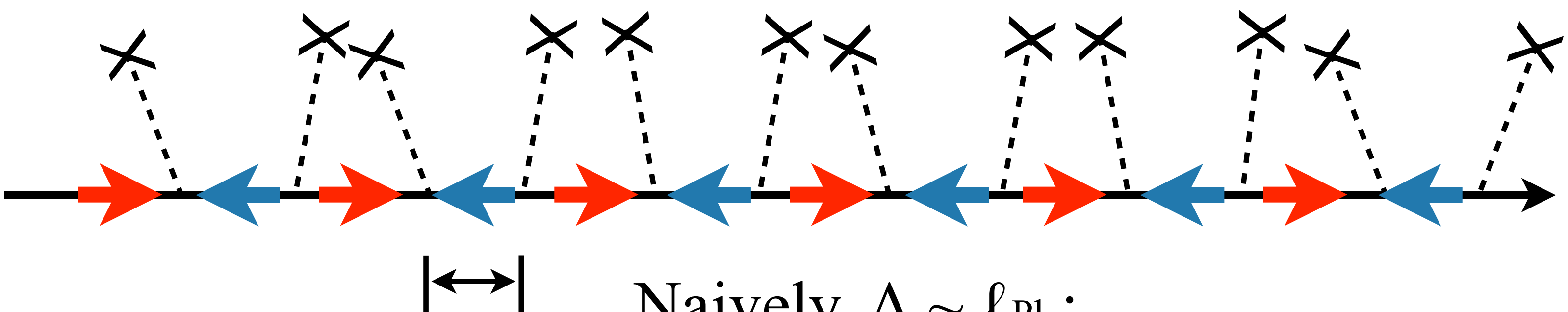

$$\sim \frac{1}{\Lambda}$$

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

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

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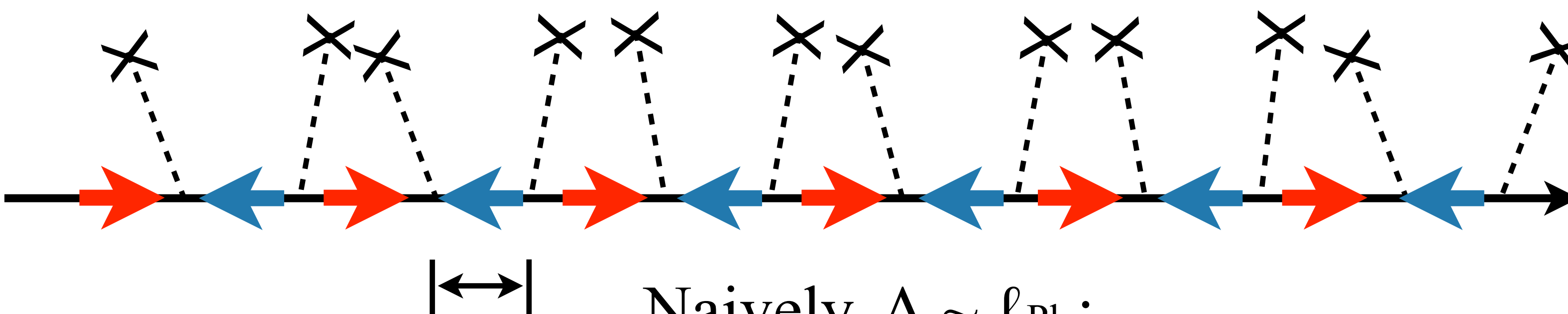

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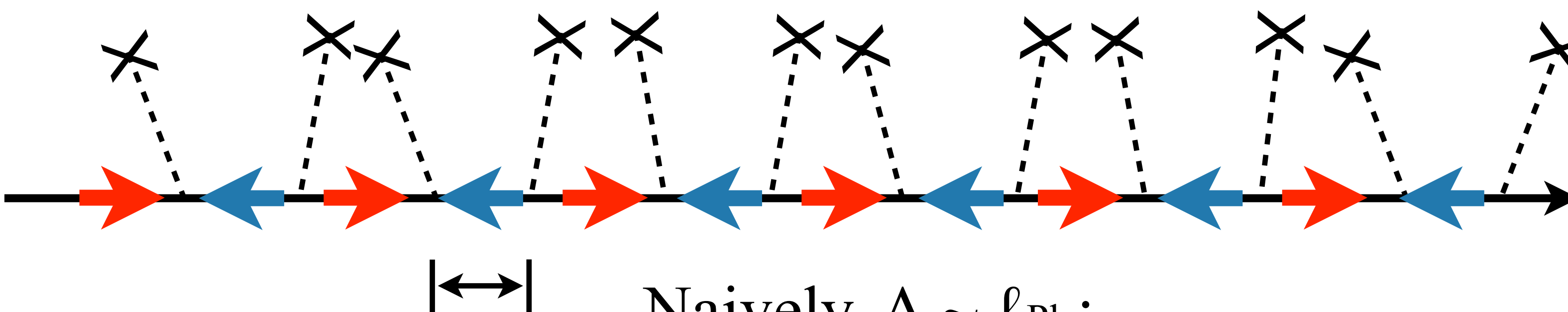

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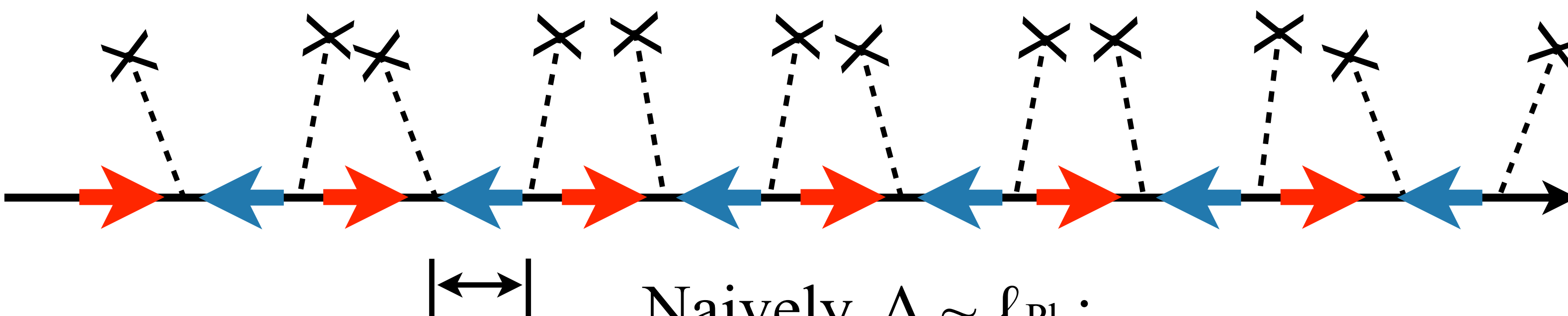

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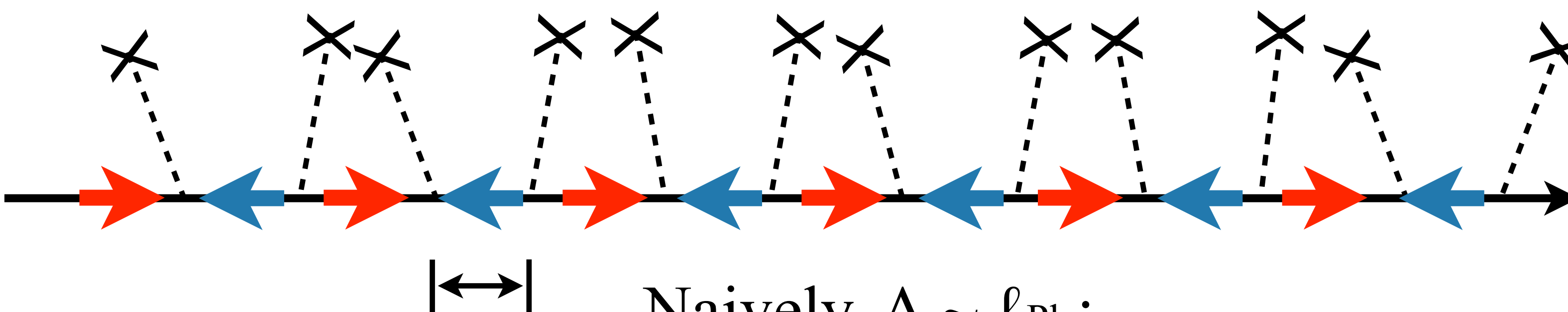

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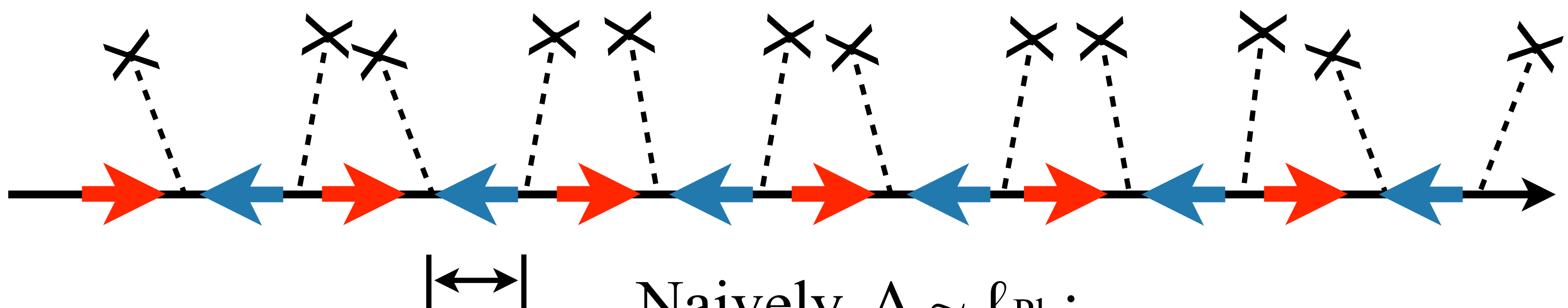

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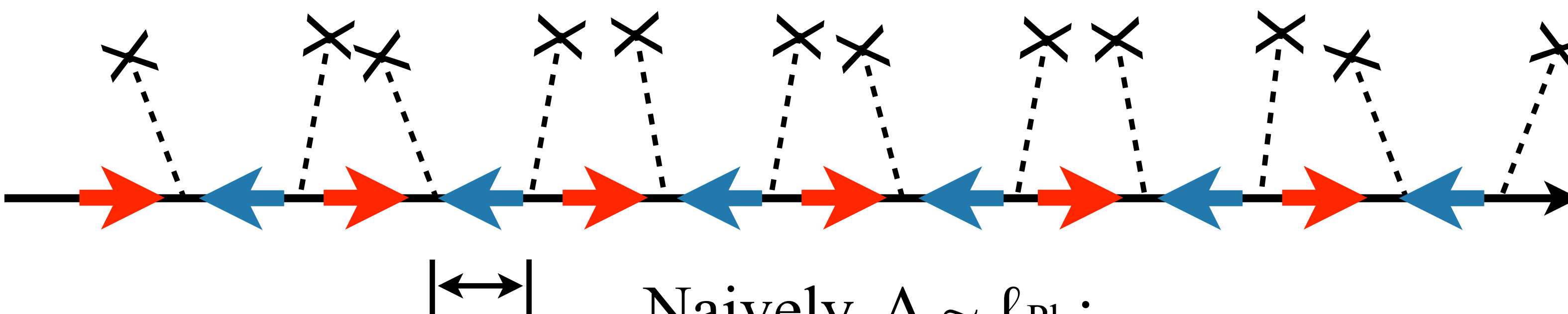

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Vacuum Fluctuations: Higgs Field

Another way of talking about same problem

Weakness of gravity directly responsible
~ all structure around us

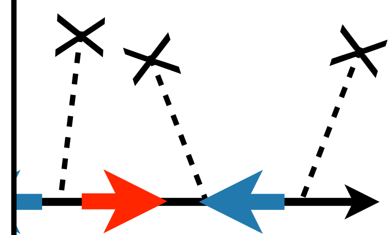
$$R_{\text{Planet}} \sim \sqrt{\frac{\alpha}{\alpha_G}} \times r_{\text{atom}}$$

$$R_{\text{Animal}} \sim \left(\frac{\alpha}{\alpha_G}\right)^{\frac{1}{4}} \times r_{\text{atom}}$$

(Stars ...)

C... n with condensate v

...n the theory



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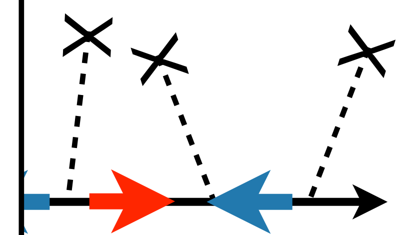
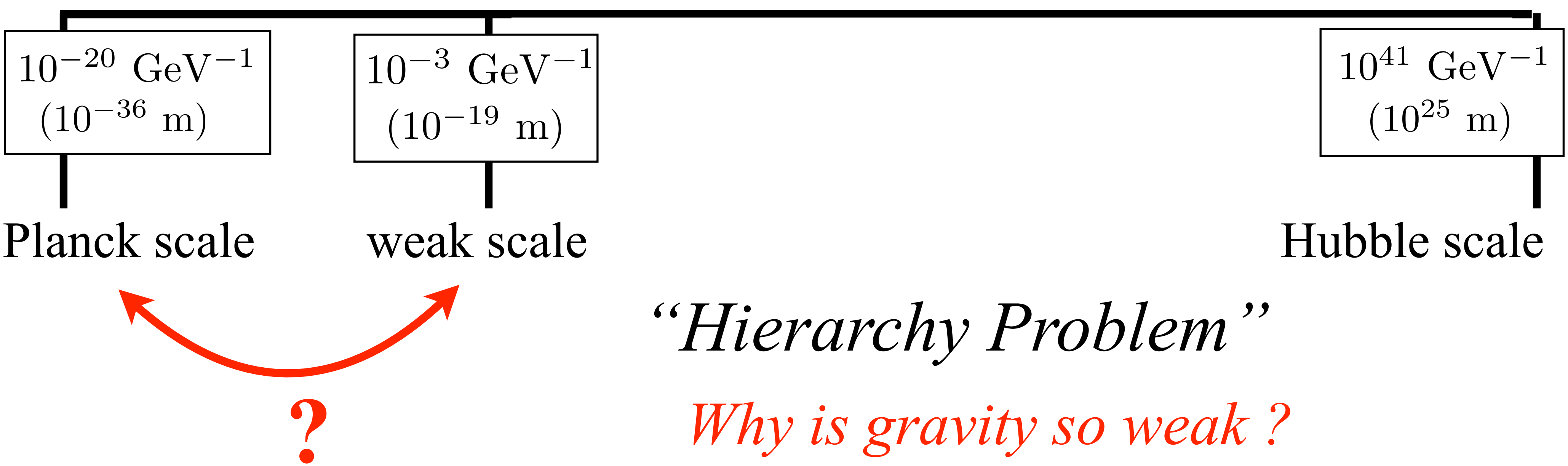




"Hierarchy Problem"

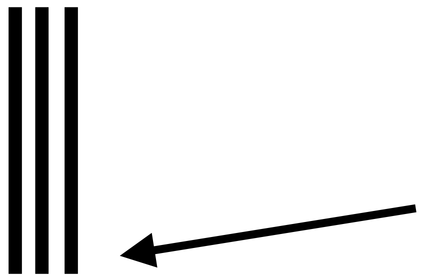
Why is gravity so weak ?

EM

Observe: ~ 10

Length Scales

Quantum Mechanics + Space-time leads us to expect:



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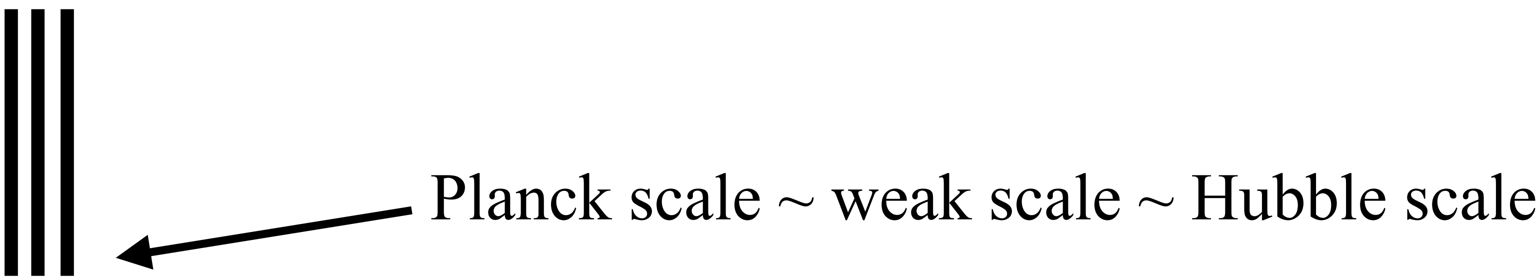

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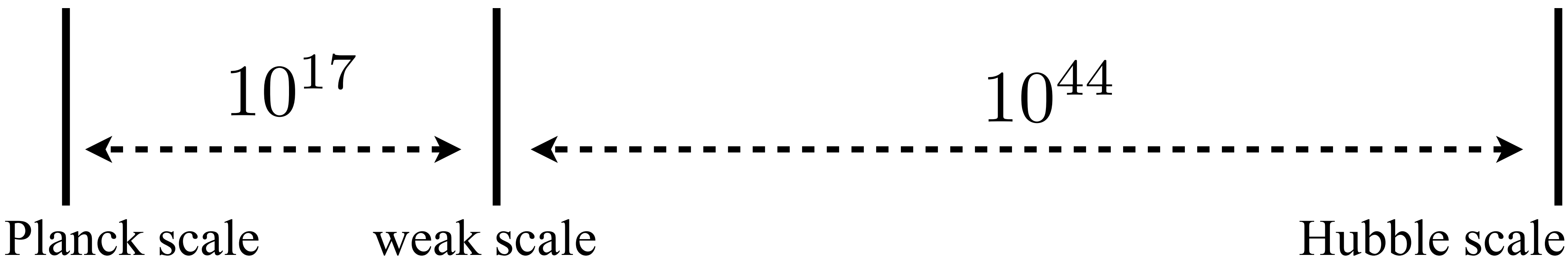

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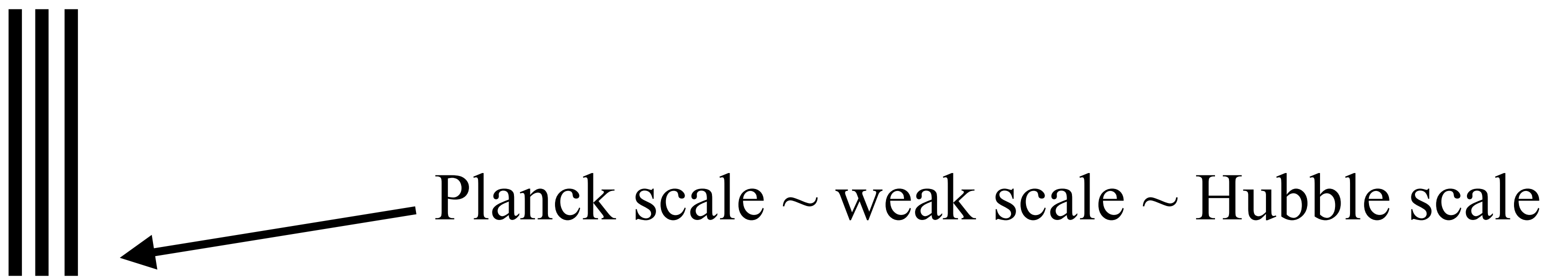

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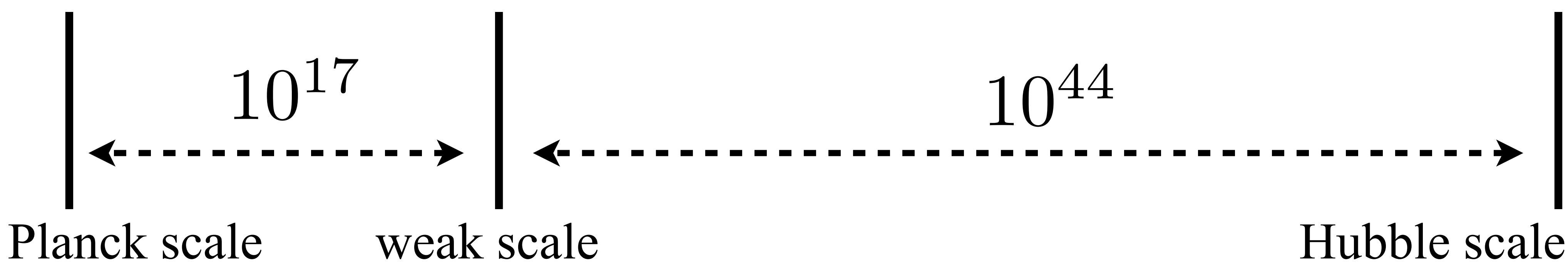

Current theory accounts for huge difference w/implausible cancellation

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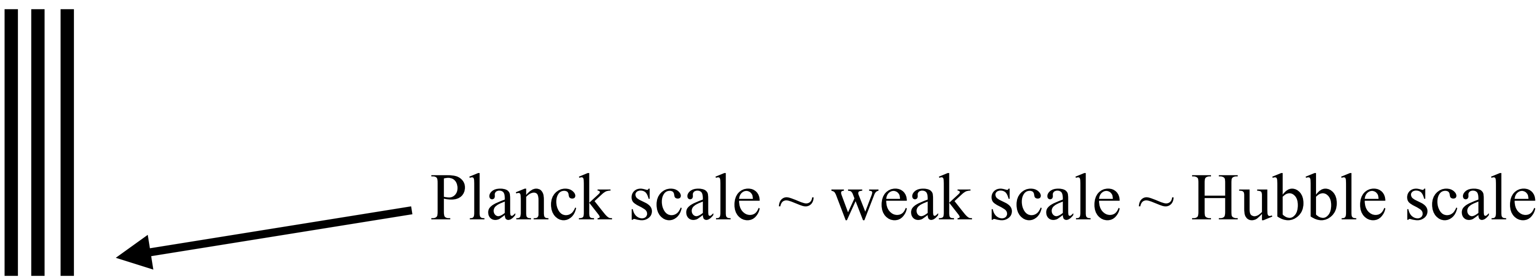

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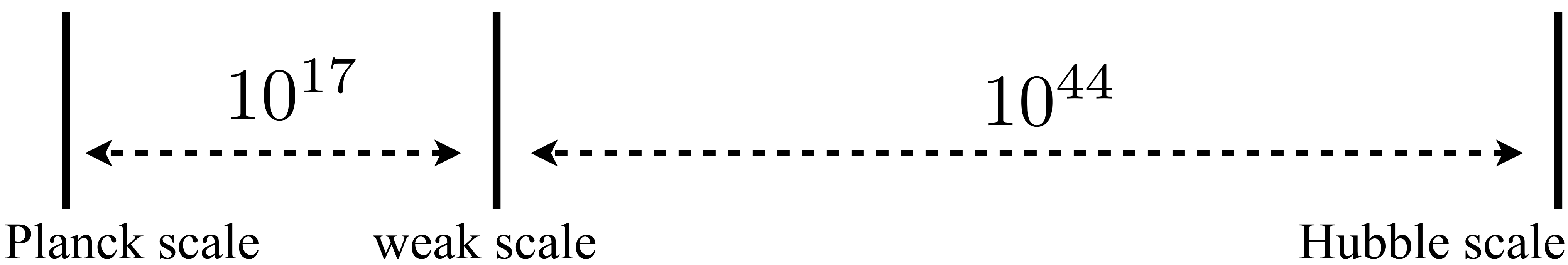
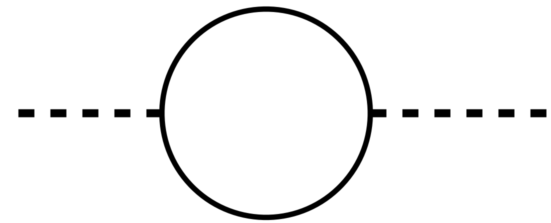


Current theory accounts for huge difference w/implausible cancellation

Need modifications QM or Space-time to avoid fine tuning

What scale do we need Modification?

m_H = + 

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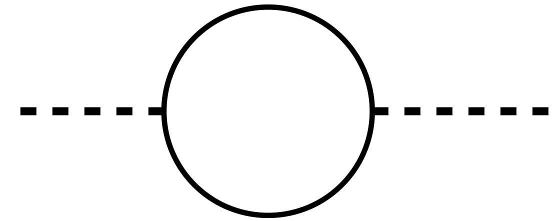
m_H = + 

~ weak-scale $\qquad m_{H\,Classical} \qquad \sim \Lambda^2$

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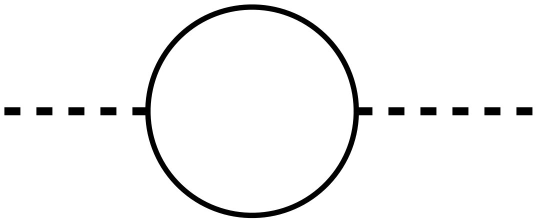
m_H = + 

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

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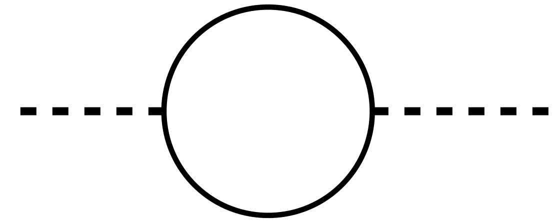
m_H = + 

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Need changes to stop vacuum fluctuations below: $10^{-3}\ \mathrm{GeV}^{-1}$
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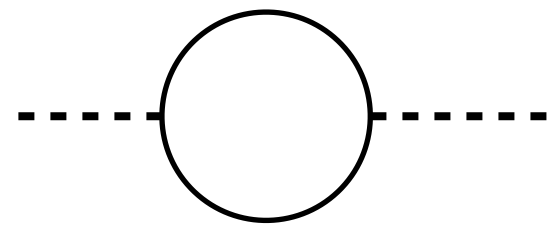
mH = + 

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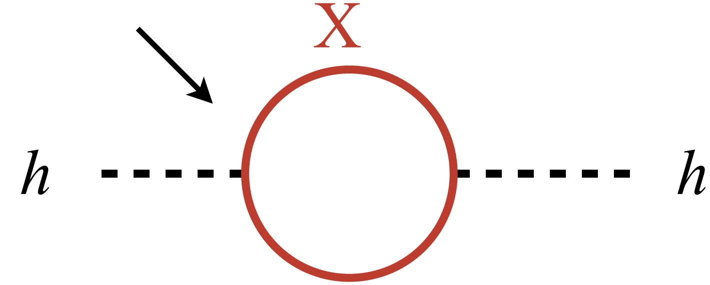
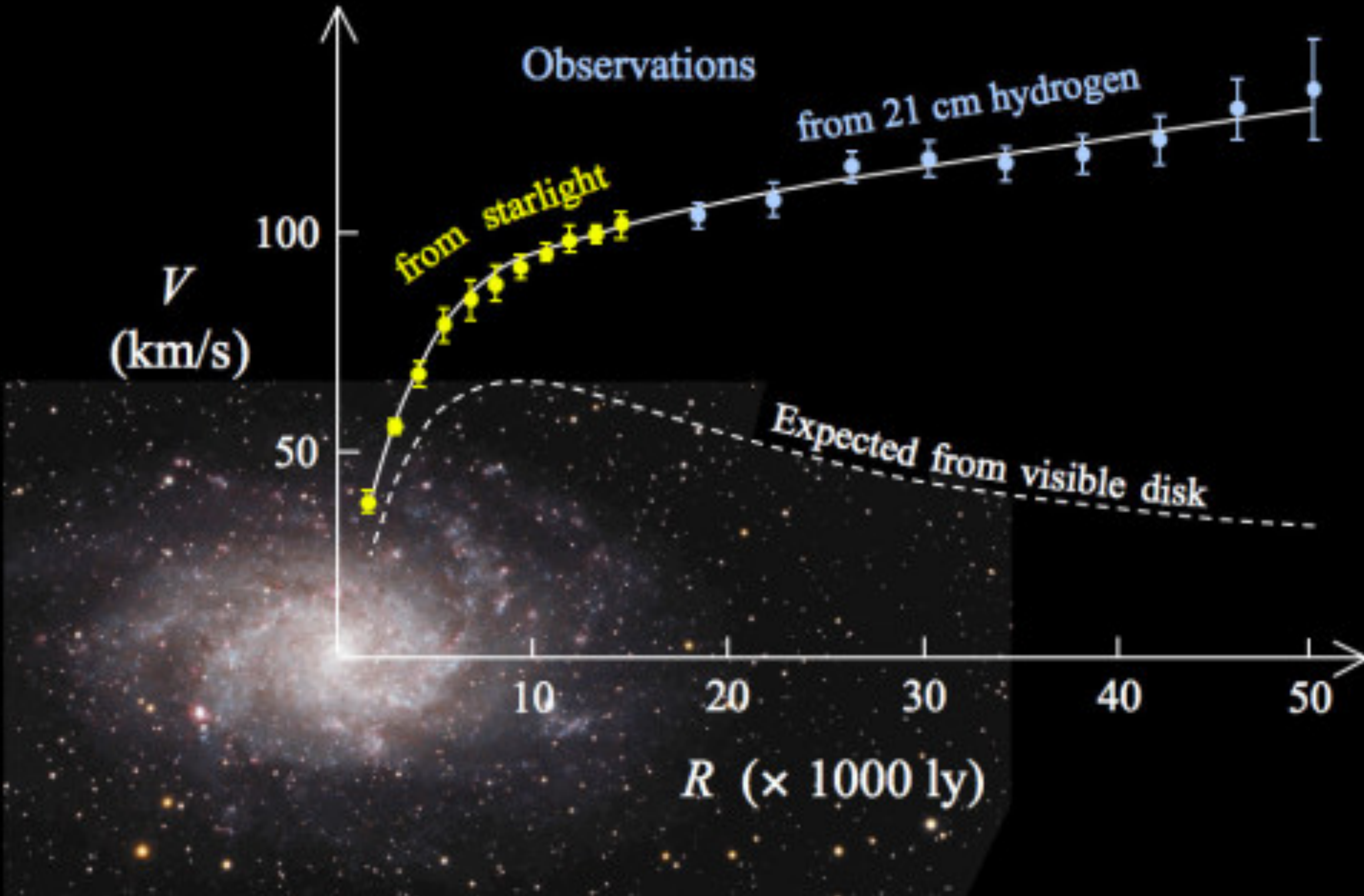
new particle   mX ~ 1000 GeV



Dark Matter



Observations
from 21 cm hydrogen
from starlight
100
50
V
(km/s)
Expected from visible disk
10
20
30
40
50
R (× 1000 ly)

Dark Matter

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