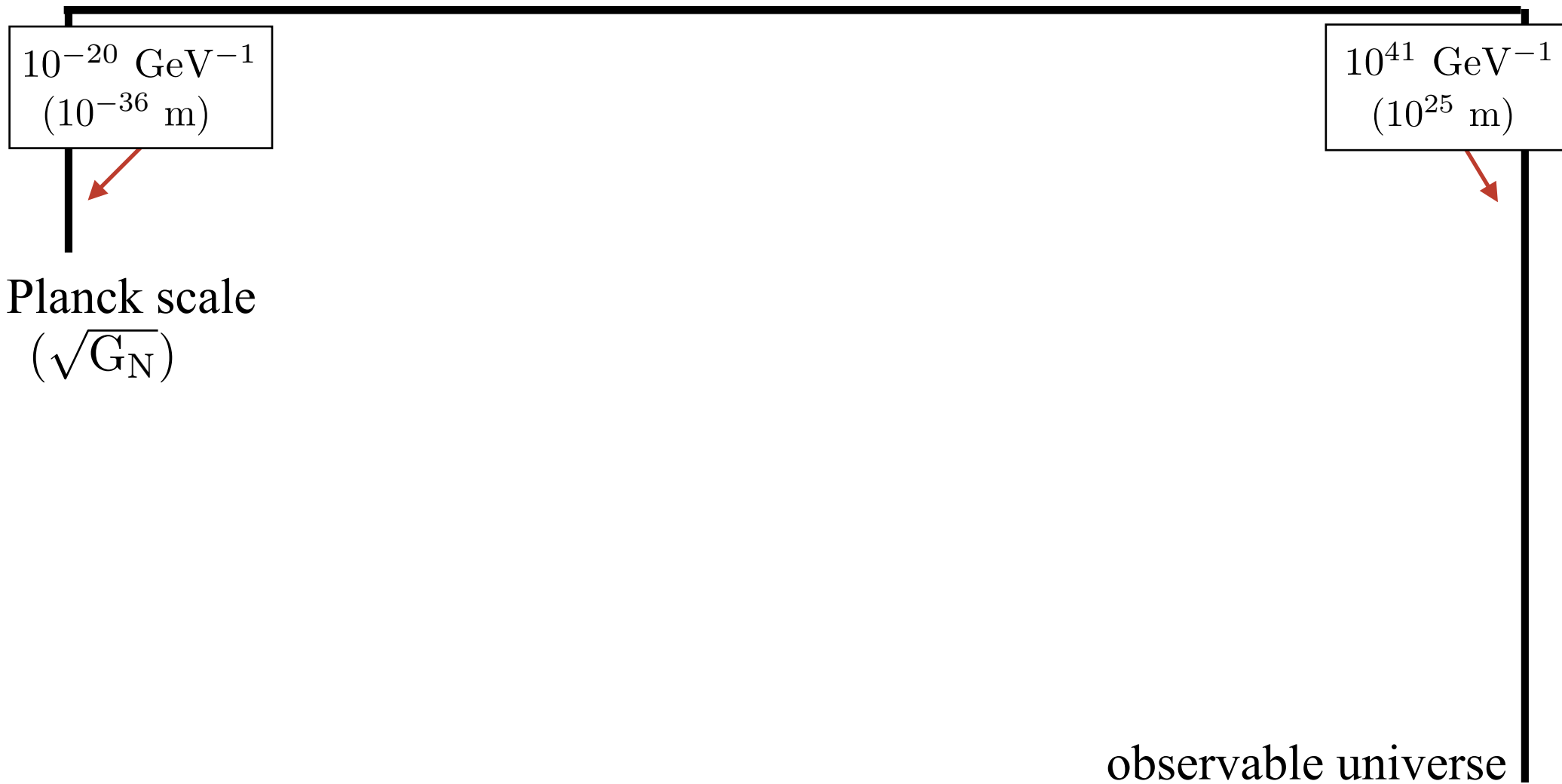
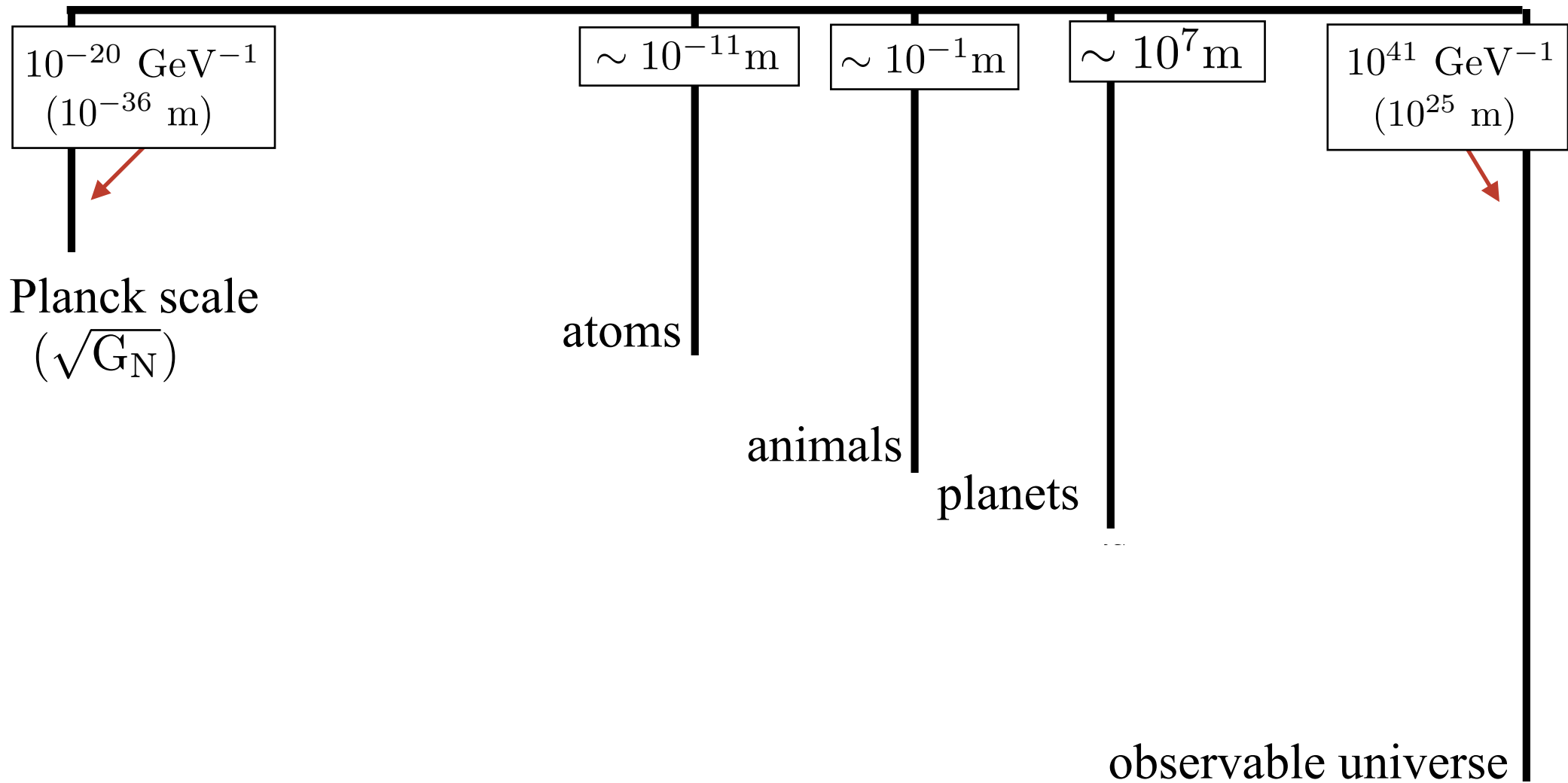


Length Scales



Length Scales



Length Scales

(In principle)

Standard Model (After Higgs Discovery)

Standard Model (Before Higgs Discovery)

Failure WW scattering



~unexplored

LHC

Directly Probed Experimentally

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

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

weak-scale

nuclei

atoms

cells

animals

planets

stars

solar systems

galaxies

observable universe

Length Scales

(In principle)

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All intermediate scales directly set by basic fundamental physical parameters (*Seen explicit examples of some of these*)

Fundamental Length Scales

(In principle)

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~unexplored

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$$10^{-20} \text{ GeV}^{-1}$$

$$(10^{-36} \text{ m})$$

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$$(10^{-19} \text{ m})$$

$$10^{41} \text{ GeV}^{-1}$$

$$(10^{25} \text{ m})$$

Planck scale
($\sqrt{G_N}$)

weak scale

observable universe

Fundamental Length Scales

(In principle)

Standard Model (After Higgs Discovery)

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Failure WW scattering



~unexplored

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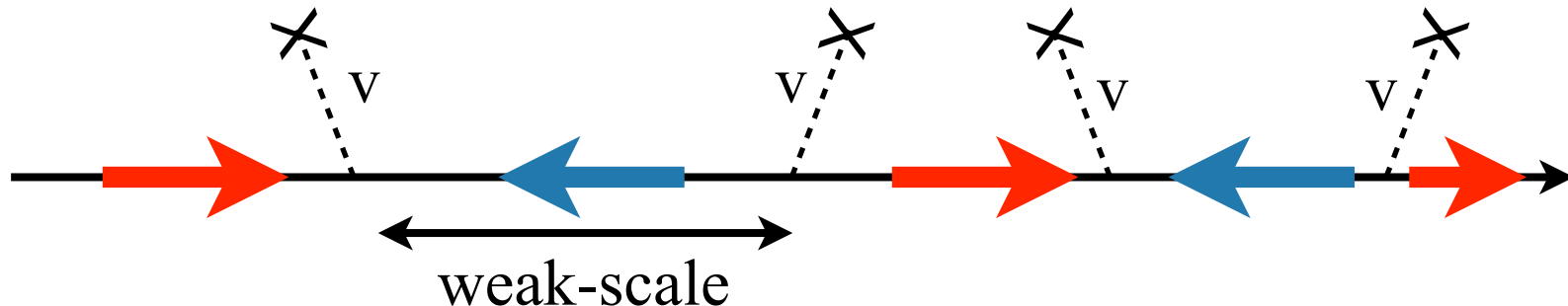
Planck scale

weak scale

observable universe

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

(In principle)

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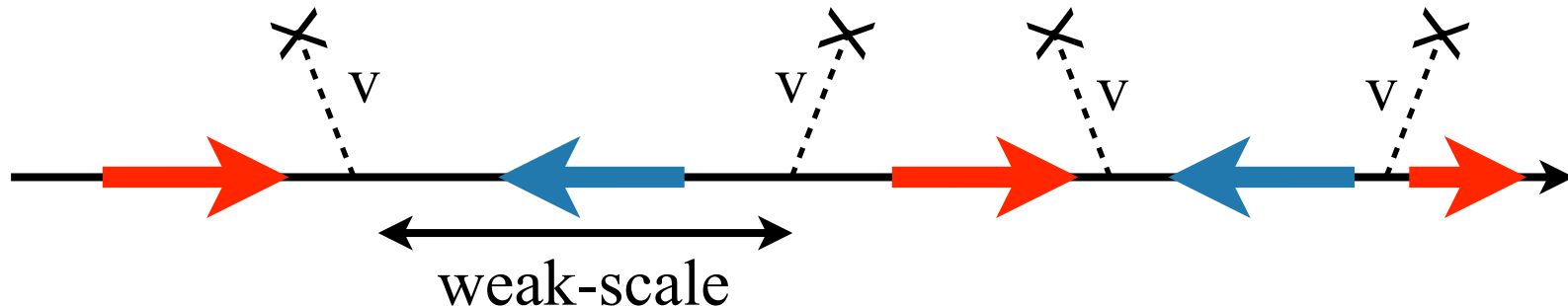
LHC exciting both because:
- it is the frontier **but also**
- exploring fundamental scale of nature

Planck scale

weak scale

Weak scale: Fundamental scale in physics

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Fundamental Length Scales

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$$10^{41} \text{ GeV}^{-1}$$

$$(10^{25} \text{ m})$$

Planck scale

weak scale

Hubble scale

$$(\sqrt{G_N})$$

- 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

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

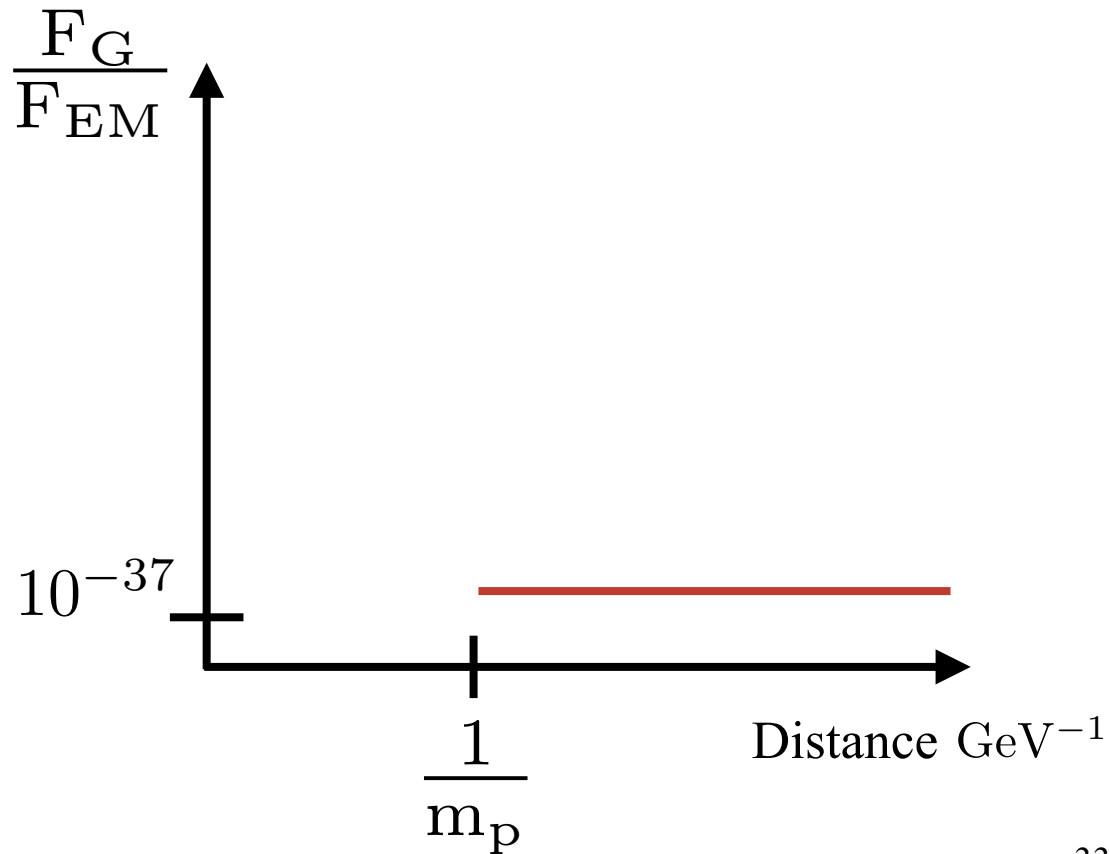
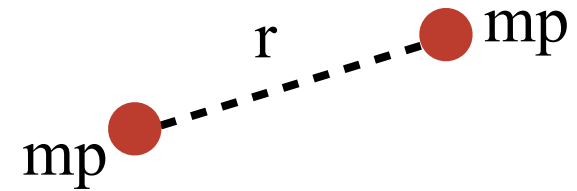
Pure number: α

Gravitational Interaction

$$F_{\text{G}} = \underbrace{G_{\text{N}}}_{\text{Dimensionful number}} \frac{m_{\text{p}}^2}{r^2}$$

Dimensionful number

$$G_{\text{N}} \sim (l_{\text{Pl}})^2 \sim (10^{-20} \text{ GeV}^{-1})^2$$



Relative Strength of Gravity

Electromagnetic Interaction

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

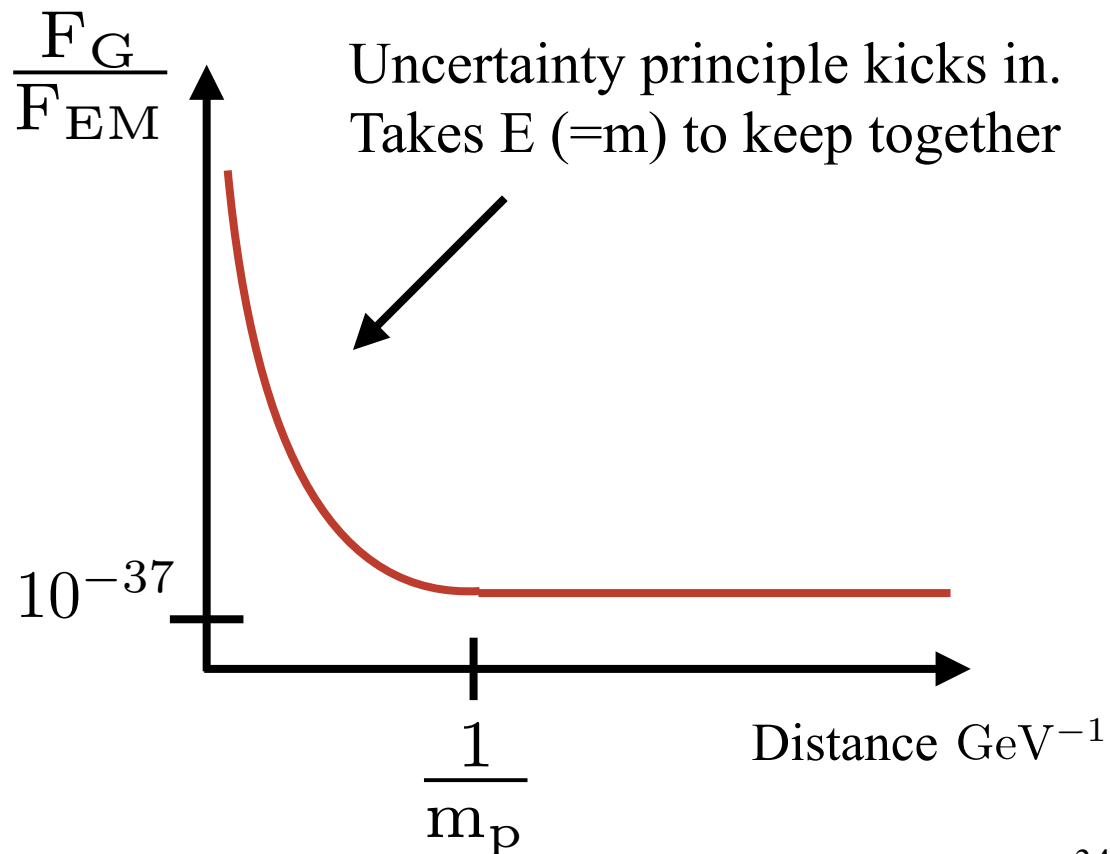
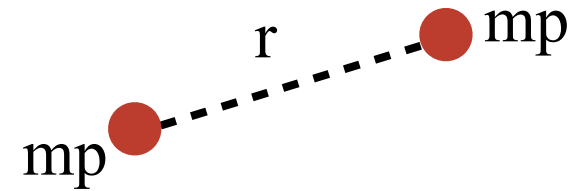
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Relative Strength of Gravity

Electromagnetic Interaction

$$F_{EM} = \frac{e^2}{r^2}$$

r  m_p

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

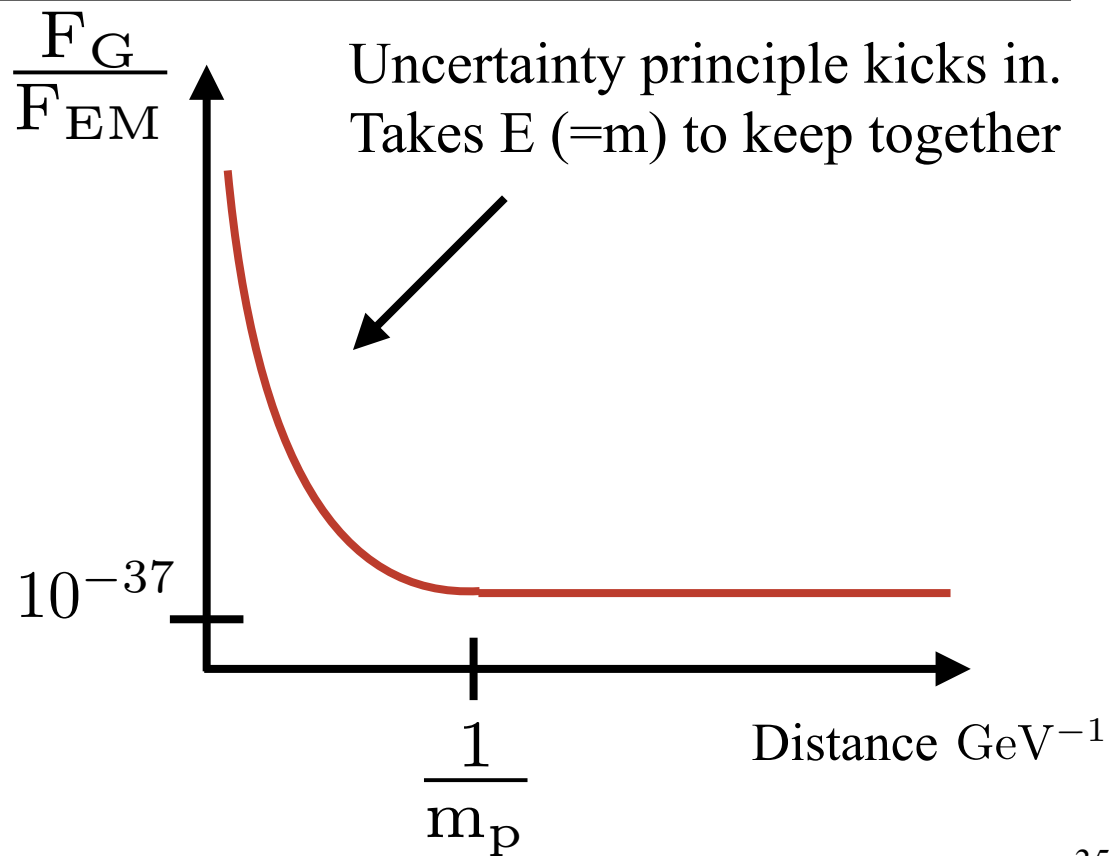
Pure number: α

Gravitational Interaction

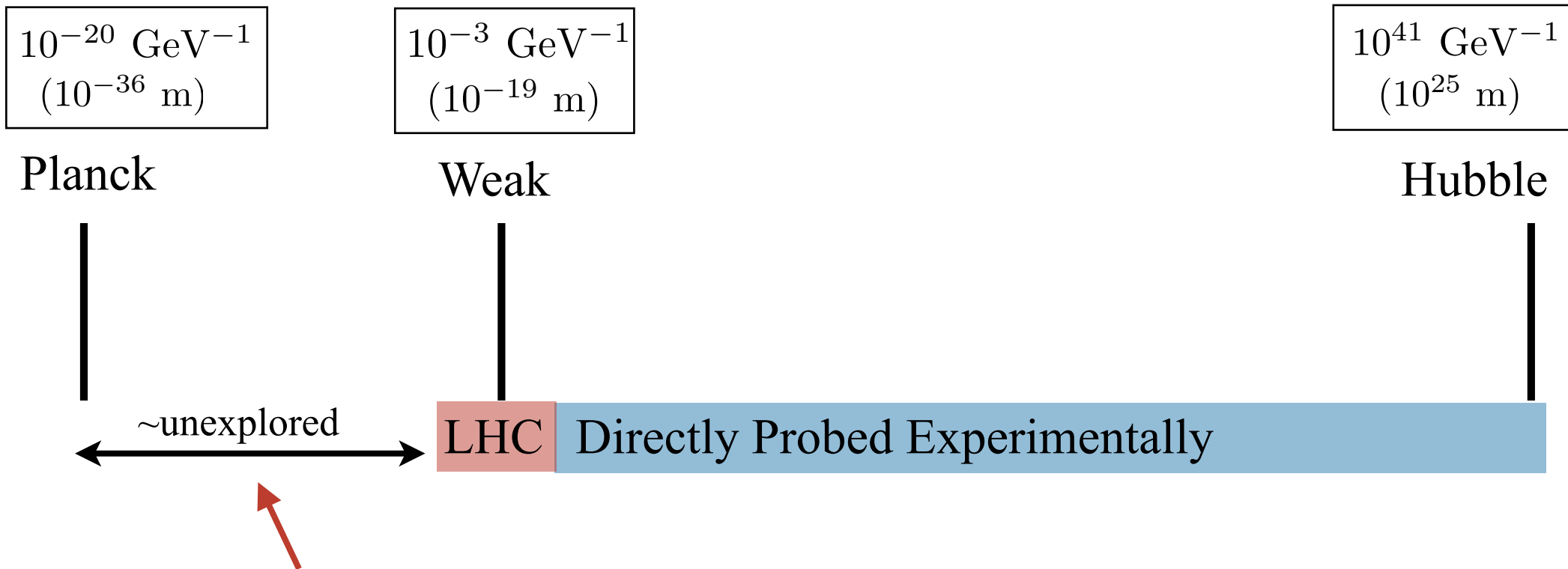
$$F_G = \underbrace{G_N}_{\text{Dimensionful}} \frac{m_p^2}{r^2}$$

Dimensionful number

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



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:

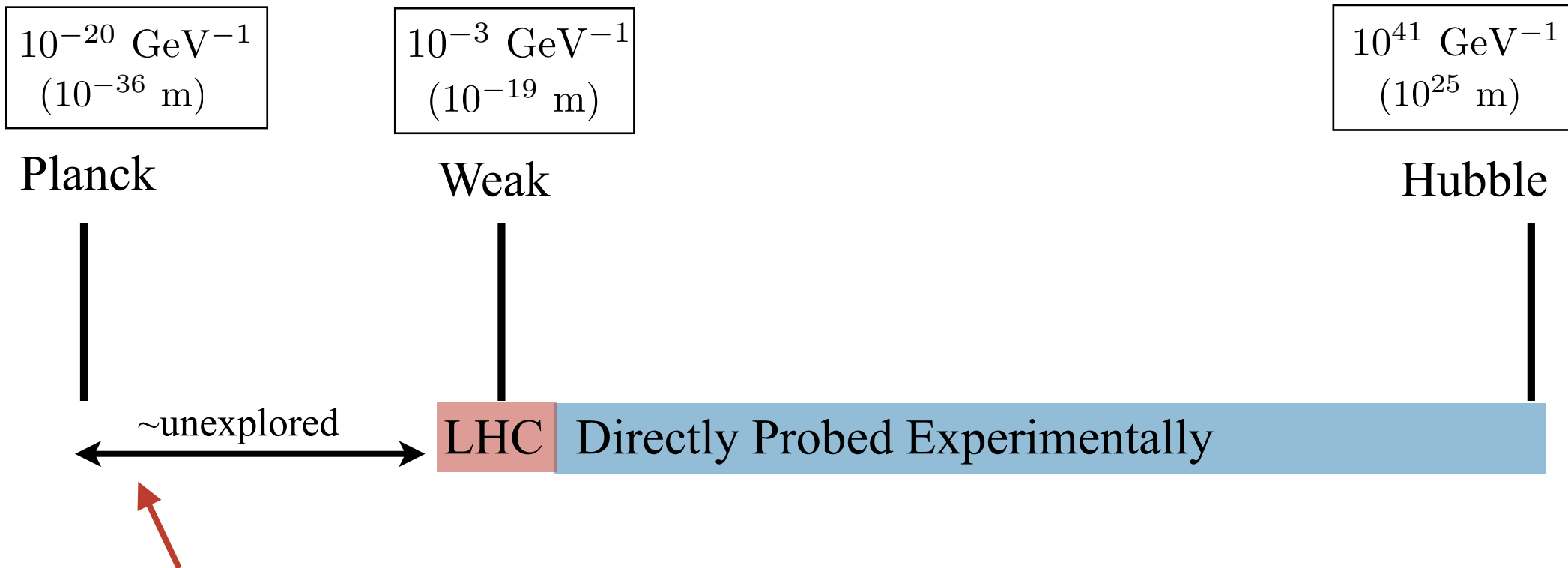
$$G_N \frac{m^2}{r} \sim mc^2 \quad \text{At high energies, mass dominated by } E \text{ associated w/uncertainty principle}$$

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

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

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

Probing Smaller Distance Scales



- Go to higher-higher energies... Gravity begins to dominate
- At ℓ_{Pl} 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 ℓ_{Pl} / Not clear what replaces it.

Major issue:

- Understanding of these short scales needed for:
 - Early universe: *What happened when universe curvature ℓ_{Pl}*
 - 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)