Cosmic Ray Probes of Classicalization

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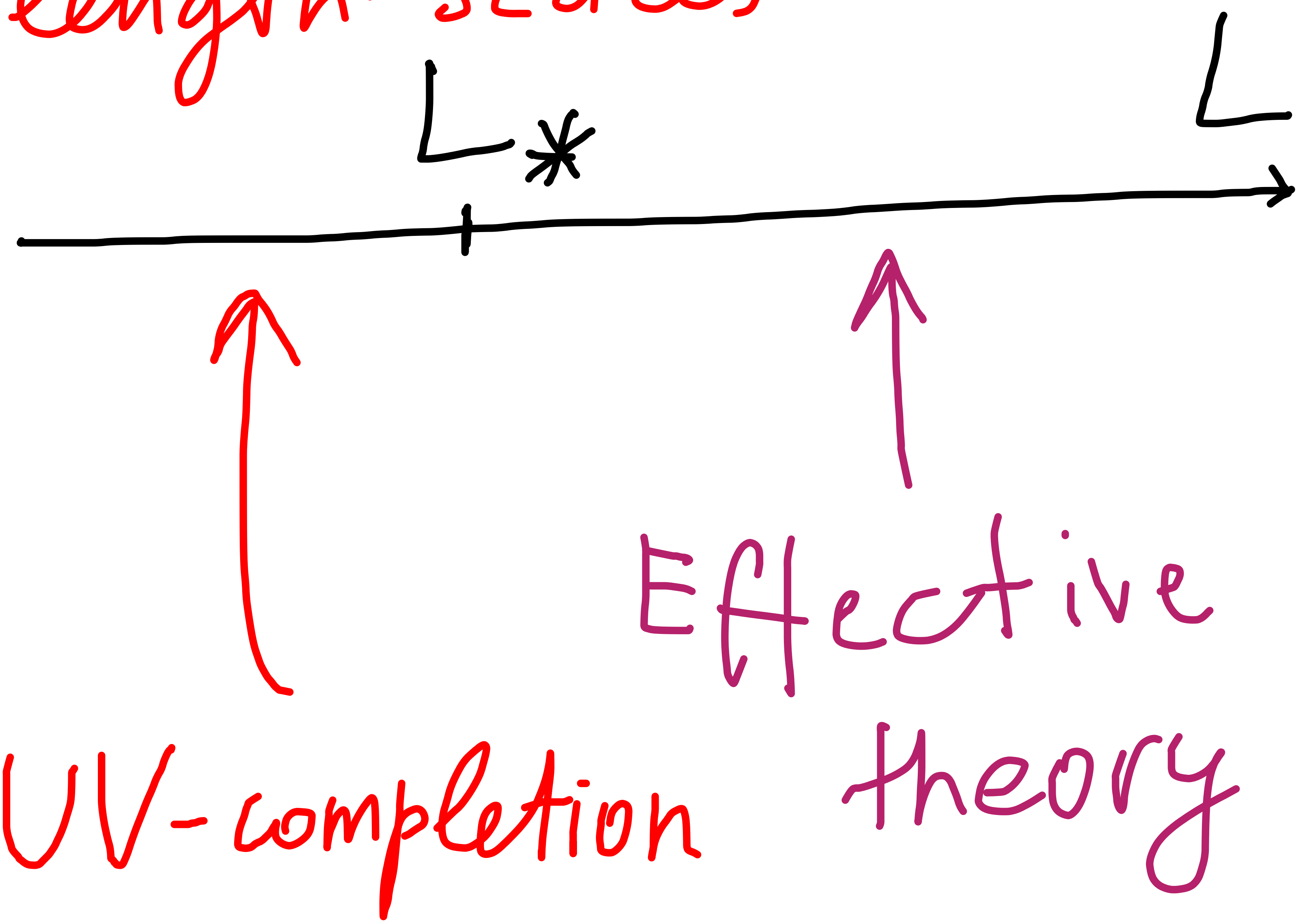
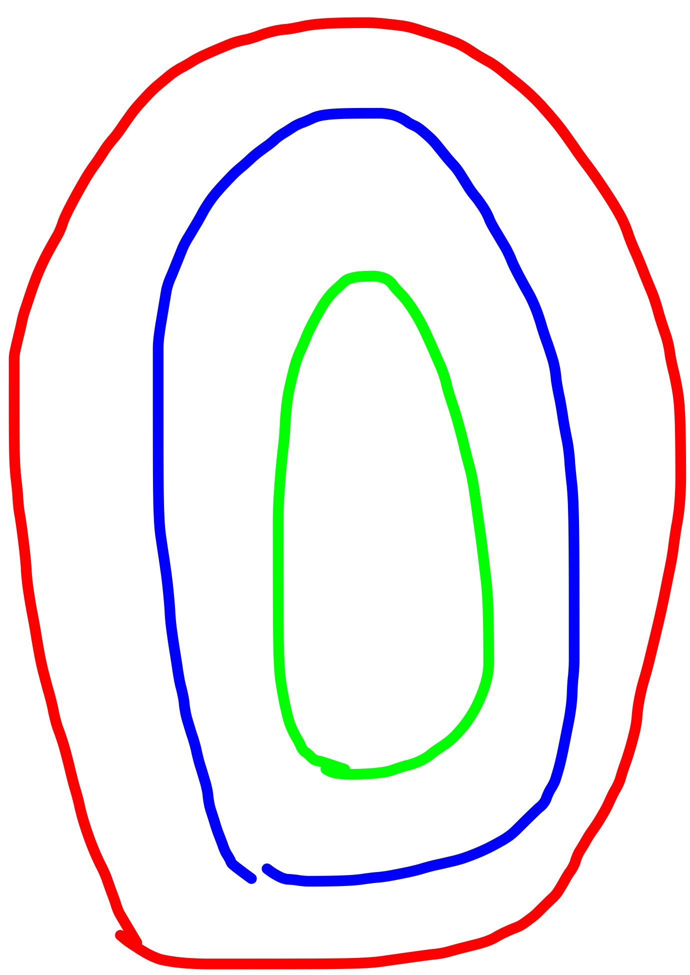
Fundamental physics is about understanding nature at different length-scales



Theories describing nature at different length-scales are embedded in one another like Russian dolls



In usual (Wilsonian) UV-completion one integrates in some new weakly coupled physics at distances $L < L_*$

Examples:

weakly-coupled Higgs, SUSY, ...

Characteristic property of such Wilsonian UV-completion is that high energy scattering cross section diminishes

$$\sigma \sim \frac{\alpha^2}{s} \equiv r_*^2(s)$$

$r_*(s) \equiv$ scattering radius

In weakly-coupled theories $r_*(s)$ diminishes at high $\sqrt{s}$.

This makes extremely hard to probe such UV-completions in high energy experiments at low luminosity, such as high energy cosmic rays.

We have understood recently that there exists a new class of UV-completions, which we call

Non-Wilsonian UV-completion by Classicalization

In such a theory

$$\sigma(s) \propto s^{\gamma}$$

$$\gamma > 0$$

In the rest of my talk I shall try to explain physics behind this phenomenon and prospects for high energy cosmic ray experiments.

What is classicalization?

We need a bosonic field ϕ sourced by energy-density

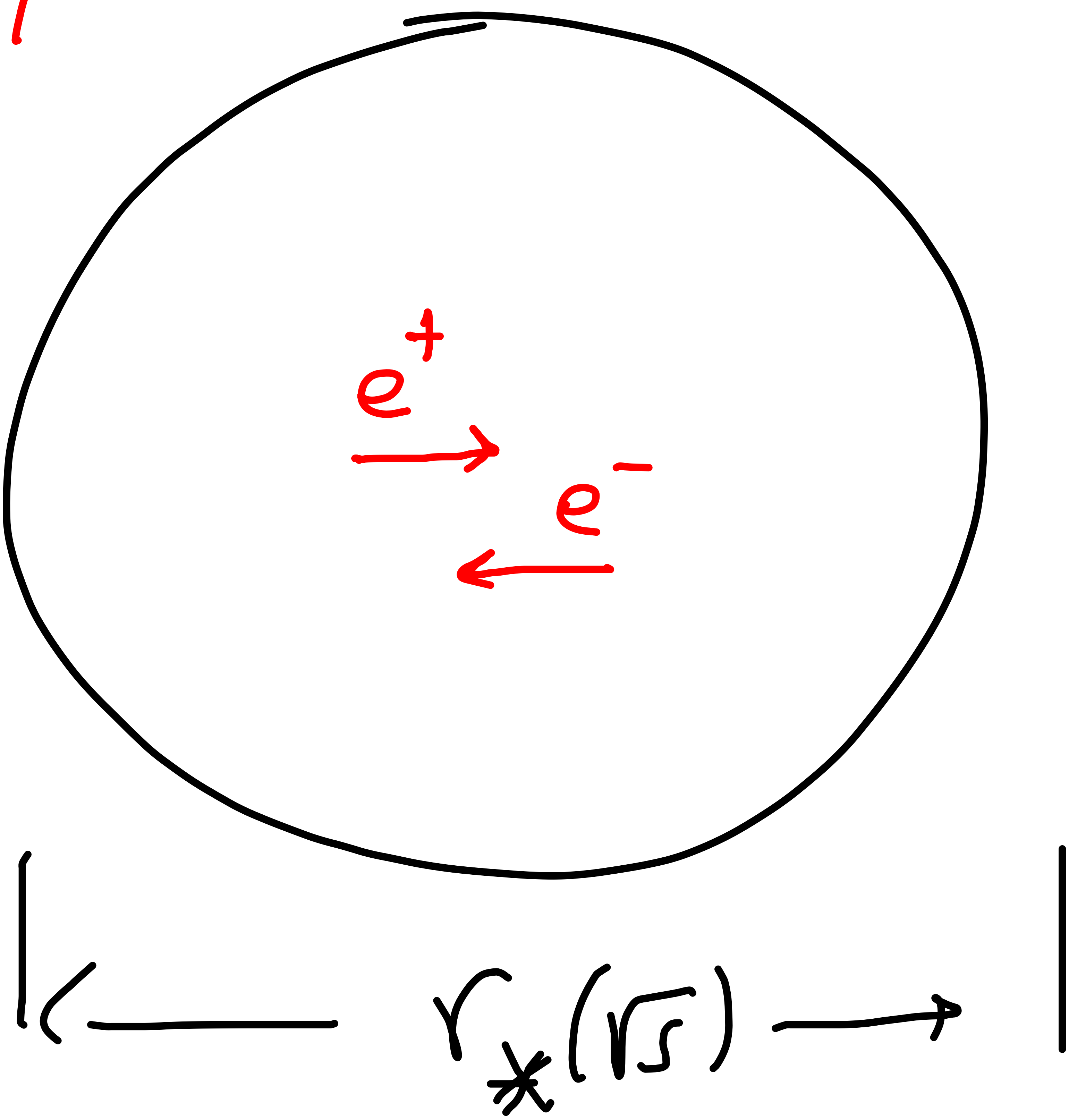
$$\mathcal{L} = \phi \frac{\rho}{M_*} + \ldots$$

$$M_* \equiv L_*^{-1}$$

Then a source with $\sqrt{s} \gg M_*$ creates a classical field ϕ of radius

$$r_*(\sqrt{s}) = \sqrt{s} / M_*^2$$

Such a source can be provided by two scattering quanta



Or equivalently high energy sources create a Bose-Einstein condensate of ϕ

of occupation number

$$N = \frac{s}{M_*^2}$$

and wave-length

$$r_*(\sqrt{s}) = \sqrt{s}/M_*^2$$

In such a theory there exist no single (or two) particle states of center of mass energy

$$\sqrt{s} \gg M_*$$

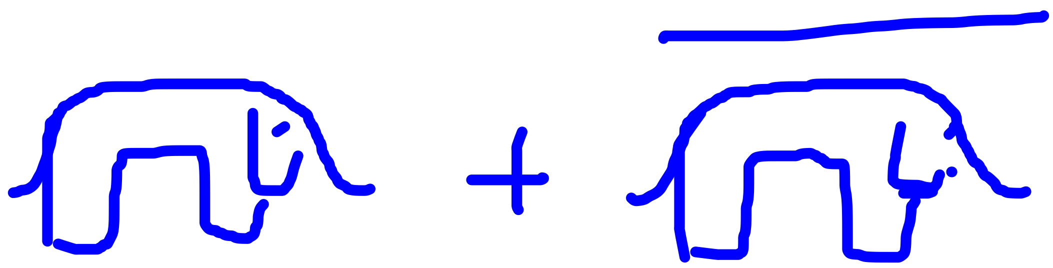
Instead, we only have multi-particle bound-states of occupation number $N = s/M_*^2$!

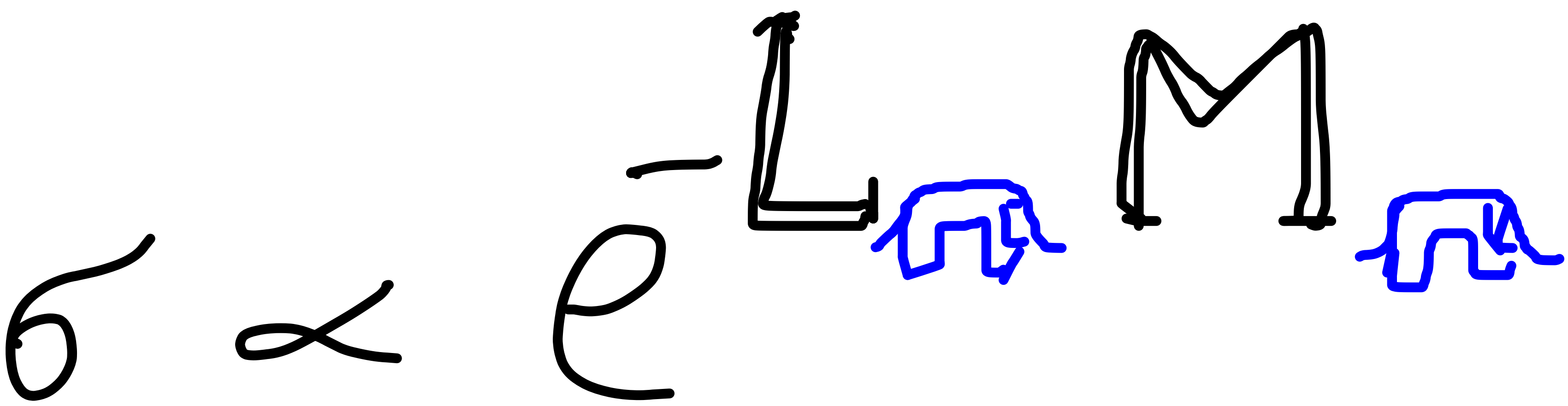
So above M_* theory classicalizes

Collective modes of Bose-Einstein condensate of soft ϕ - Bosons

Weakly-coupled quanta ϕ

How can a theory be UV-completed by classical objects?

$e^+ + e^- \longrightarrow$ 



So what is special about classicalons?

First, what is classicality?

Nature is quantum $\hbar \neq 0$.

Classicality implies many particles.

For example, earth's gravitational field is classical because it contains $N \sim 10^{66}$ gravitons!

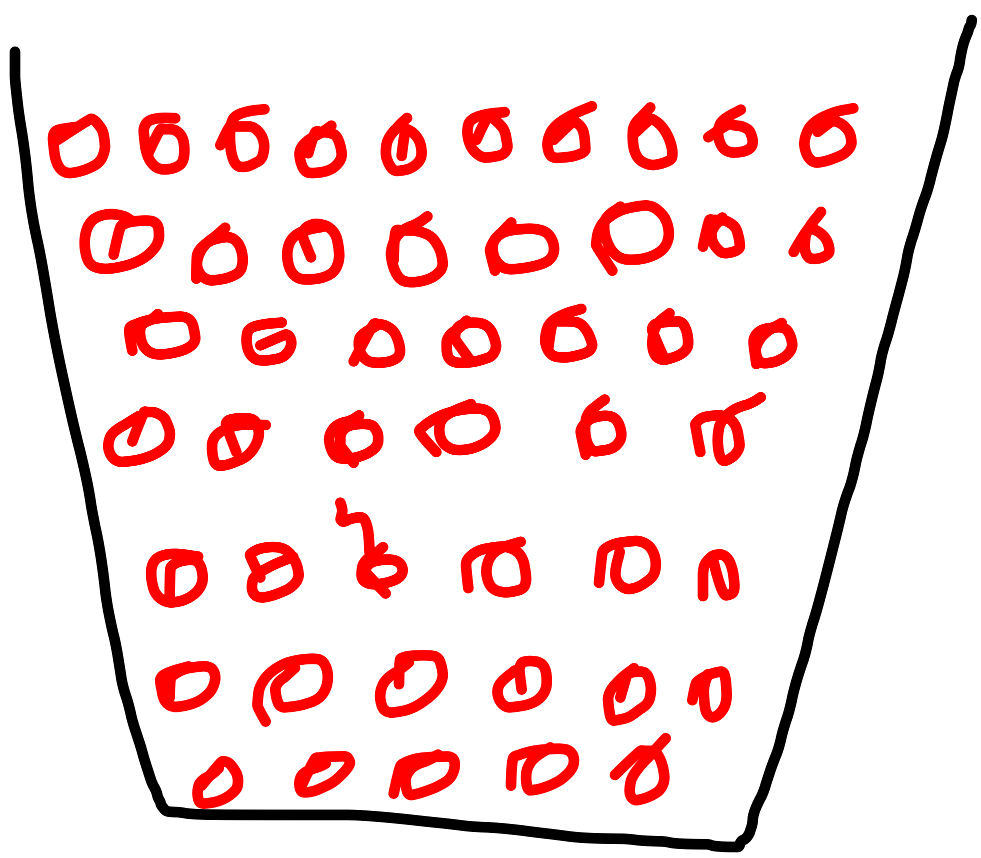
In contrast, gravitational field created by a single electron contains only

$$N \sim 10^{-44}$$

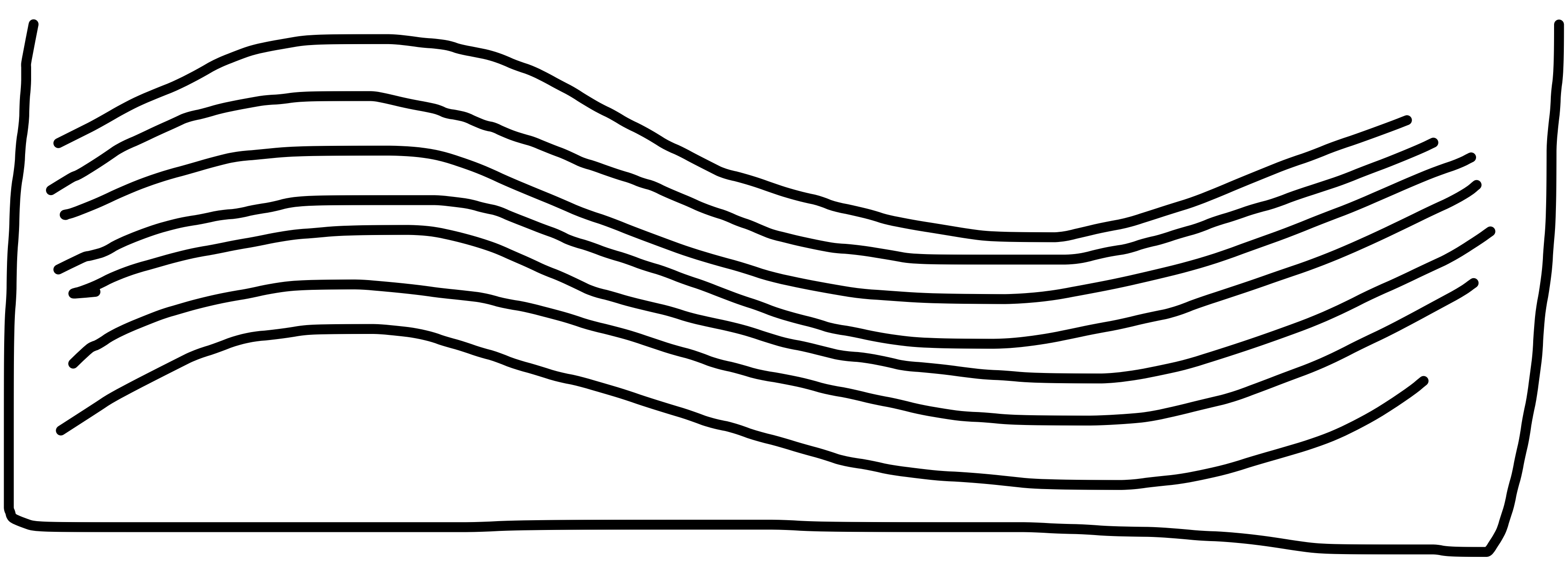
gravitons!

(This is why the electron is not a black hole.)

Marcoscopic objects are characterized by number of constituents N, their coupling strength α, ...



However α has an universal meaning in the systems in which everybody talks to each other at a same strength, such as Bose-Einstein condensates.



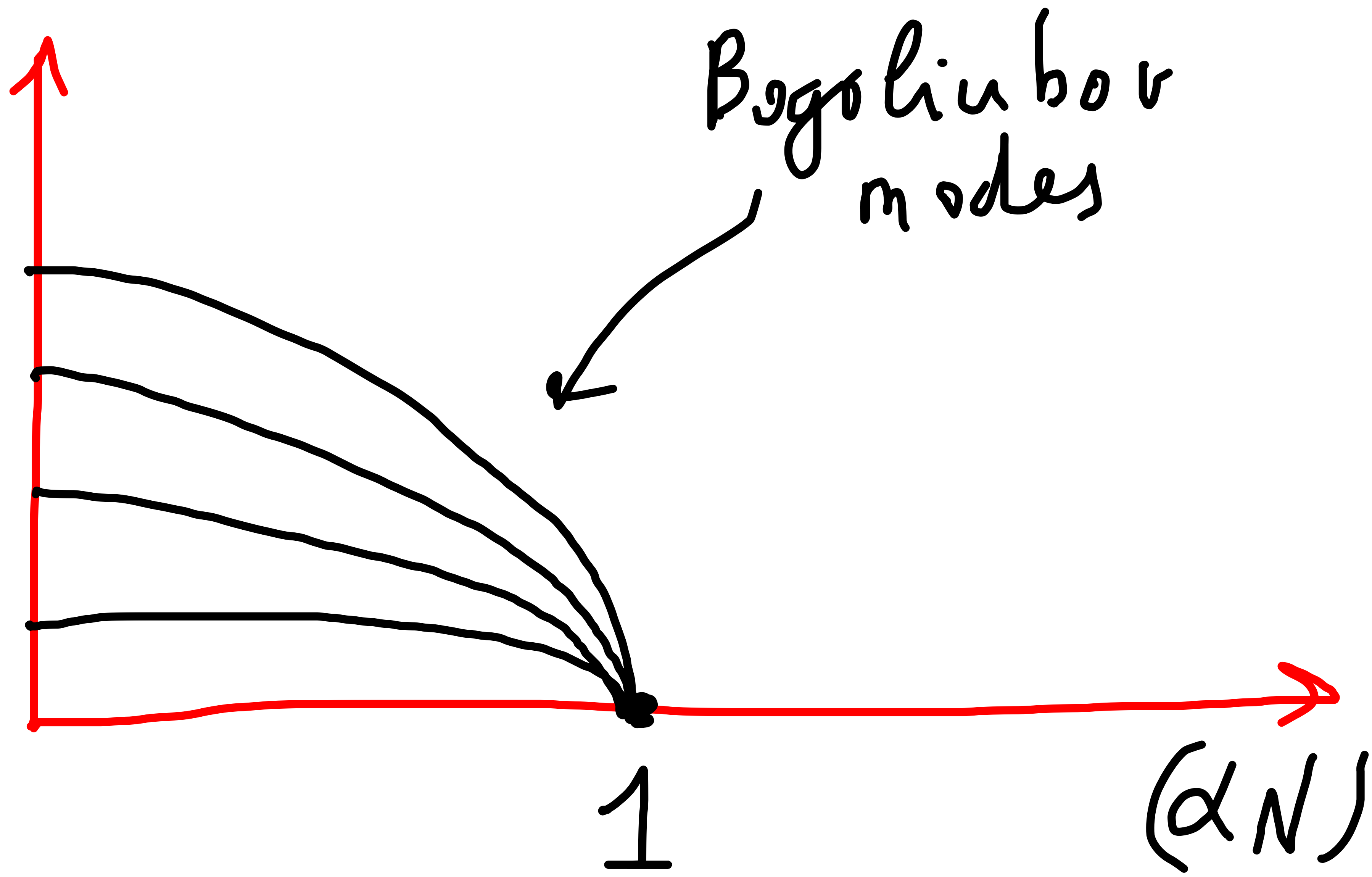
For such systems we can define a quantity

$$(N\alpha)$$

Something very special takes place at

$$N\alpha = 1$$

Critical point of quatum phase transition.



Such a system although multi-particle in reality is fully quantum.

Classicalons (including black holes) are at the critical point:

$$\alpha = \frac{L_*^2}{r_*^2} = \frac{M_*^2}{S} = \frac{1}{N}$$

There exist no quantum elephants but there exist quantum classicalons!

The efficiency of the cross-section growth is model-dependent.

An example of efficient classicalization by spin-2 fields.

$$m = 20\ \mathrm{MeV}$$

$$\alpha = 10^{32} \times \alpha_{\mathrm{Einstein}}$$

A prototype minimal scenario contains two (in general free) parameters:

Strength of Φ-coupling to energy:

$$M_*^{-2} \equiv L_*^2$$

and

Compton wave-length of Φ-S:

$$m^{-1}$$

Solution to the hierarchy problem fixes:

$$\bar{M}_*^{-2} \sim (\mathrm{TeV})^{-2}.$$

On m we can provide a phenomenological lower bound (comes from supernova cooling):

$$m \gtrsim 20\ \mathrm{MeV}.$$

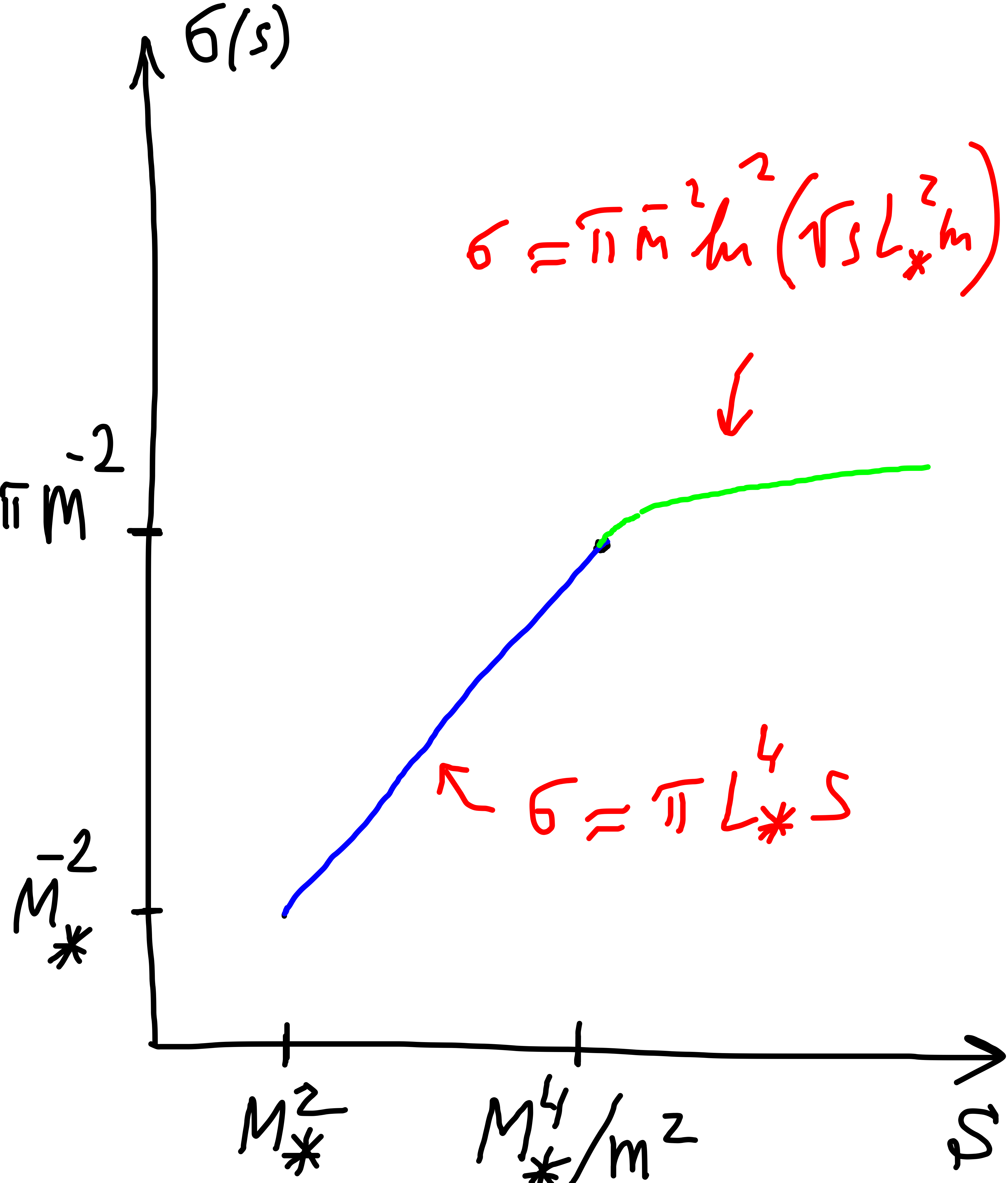
s-dependence of the cross section

$$\sigma(s) = \pi m^{-2} \ln^2\left(\frac{\sqrt{s}\,L_*^2}{\sqrt{\sigma(s)/\pi}}\right)$$

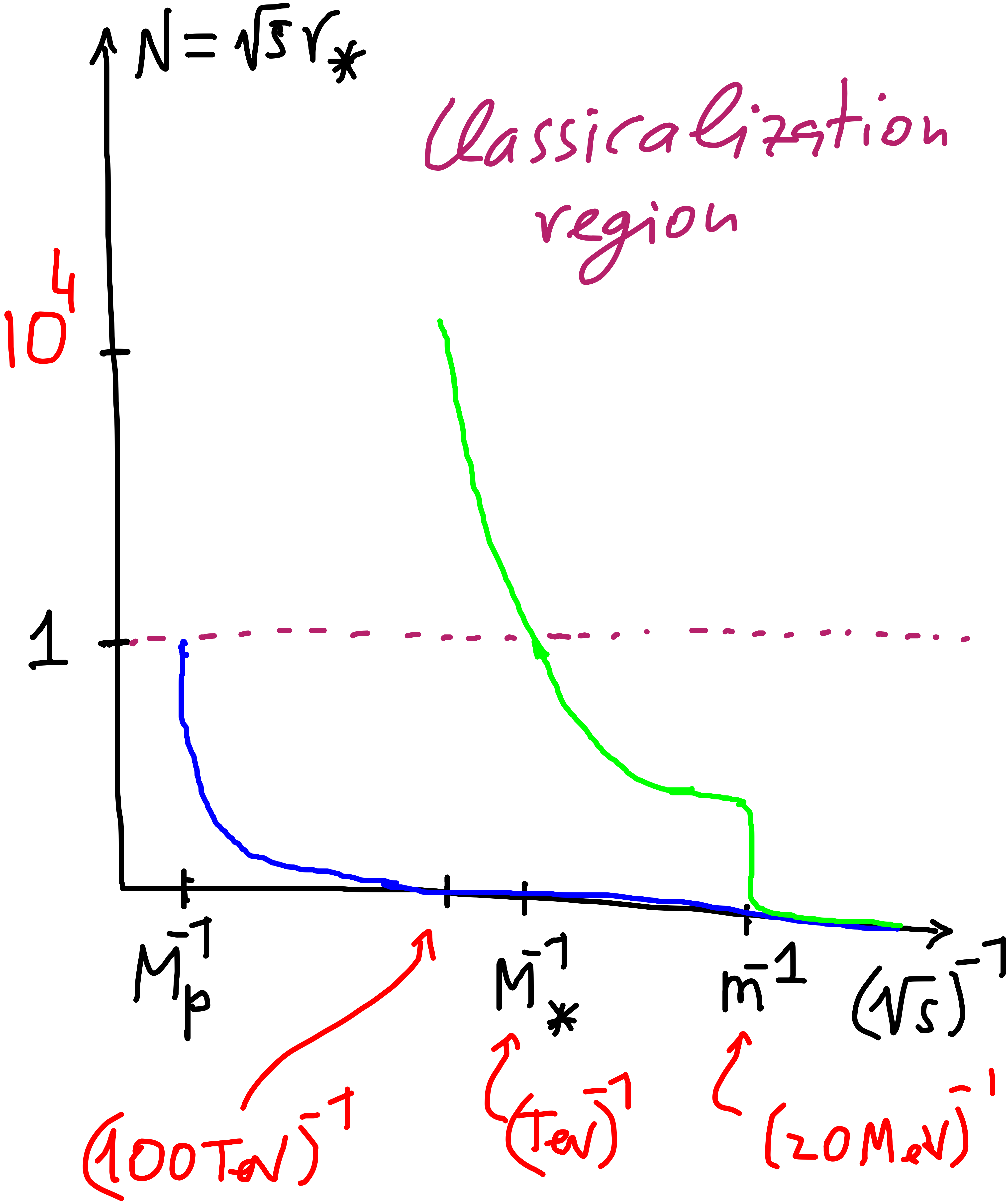
$$\Downarrow$$

$$\sqrt{s} < \frac{M_*^2}{m} \longrightarrow \sigma(s) \simeq \pi s L_*^4$$

$$\sqrt{s} > \frac{M_*^2}{m} \longrightarrow \sigma(s) \simeq \pi m^{-2} \ln^2\left(\sqrt{s}\,L_*^2 m\right)$$



σ(s)
πm^-2
M_*^-2
σ = π m^-2 ln^2 (√s L_*^2 m)
σ = π L_*^4 s
M_*^2
M_*^4/m^2
s



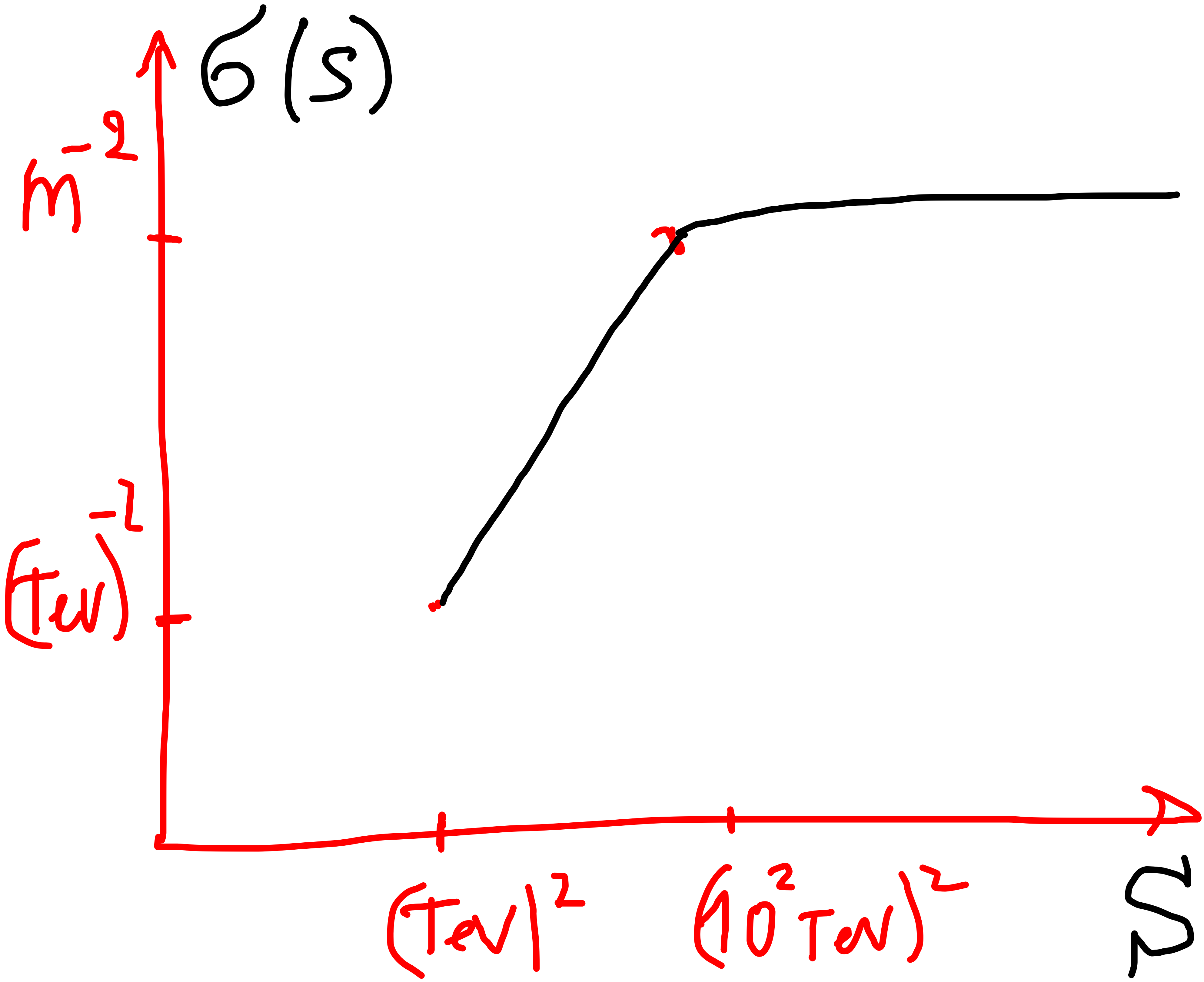
$N = \sqrt{s}\, r_*$
Classicalization region
10^4
1
M_p^{-1}
M_*^{-1}
m^{-1}
$(\sqrt{s})^{-1}$
$(100\,\text{TeV})^{-1}$
$(\text{TeV})^{-1}$
$(20\,\text{MeV})^{-1}$

Outlook

There exist a class of theories that are UV-complete in a non-Wilsonian way via classicalization.

Characteristic property of such completion is a sharp growth of the high energy cross-section due to production of states with high occupation number N.

High energy cosmic rays are natural probes for such theories.


σ(s)
m^-2
(TeV)^-1
(TeV)^2
(10^2 TeV)^2
S