Quantum Gravity improved black holes

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GOETHE UNIVERSITÄT FRANKFURT AM MAIN

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FIAS Frankfurt Institute for Advanced Studies

Outline

1. **Quantum effects at the BH core**
   Schwarzschild singularity
   Particle compression

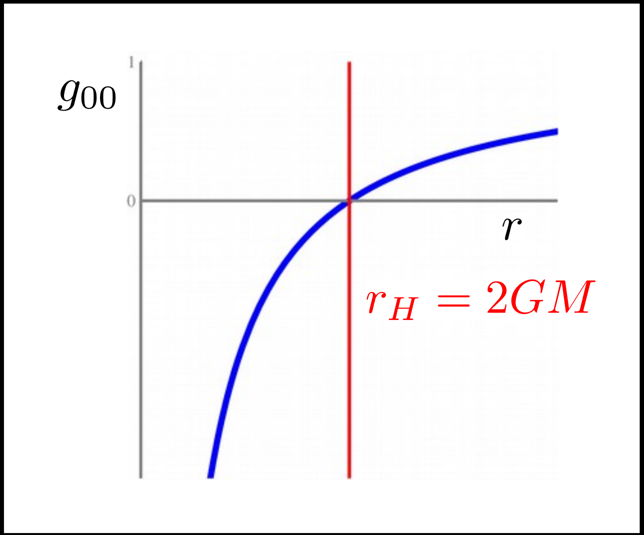
2. **Minimal resolution approach: GUP**
   Gravity as nonlocal field theory
   Geometry and properties of the GUP BH
   Features

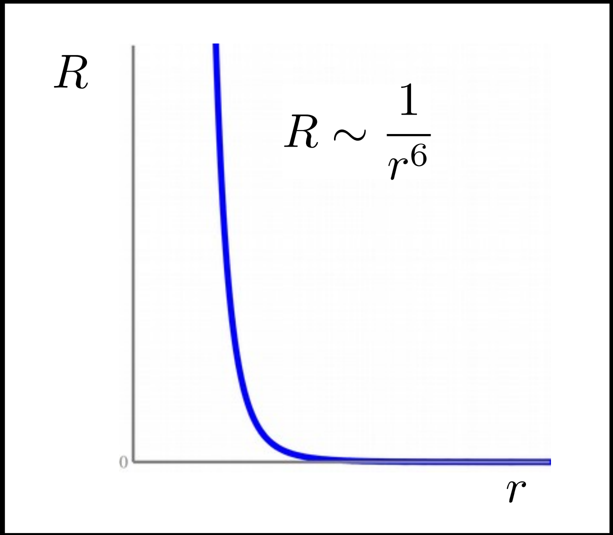
3. **What's next**
   Large extradimensional scenario
   Other BH core models
   Experimental evidence

Schwarzschild BHs exhibit problems

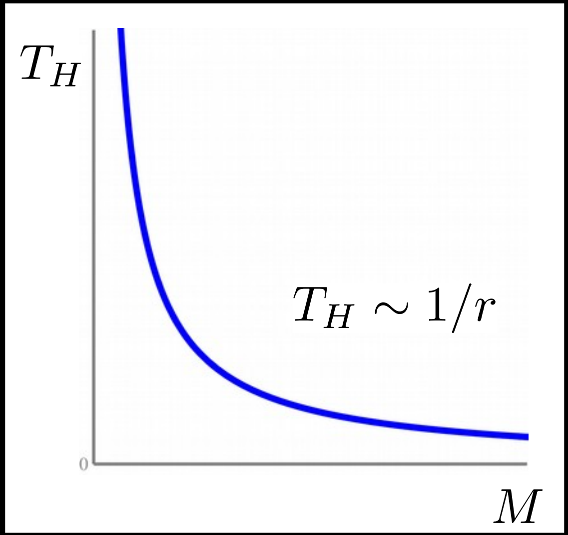
The Schwarzschild black hole is not suitable to describe „smallest distances“:

$$ds^2 = -\left(1 - \frac{2GM}{r}\right)dt^2 + \frac{1}{1-\frac{2GM}{r}}dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2$$





Curvature singularity

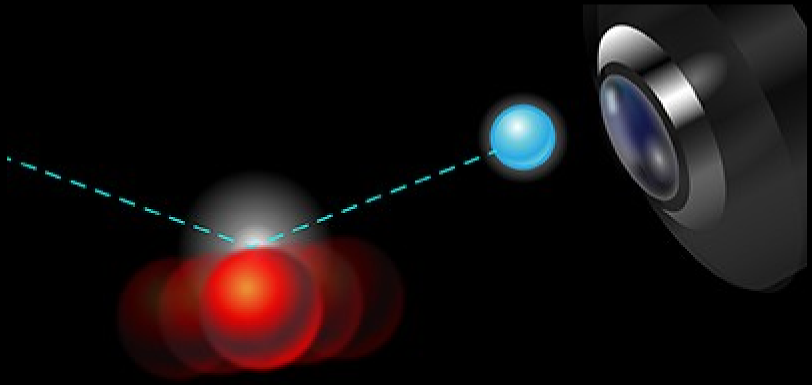


ill defined thermodynamics

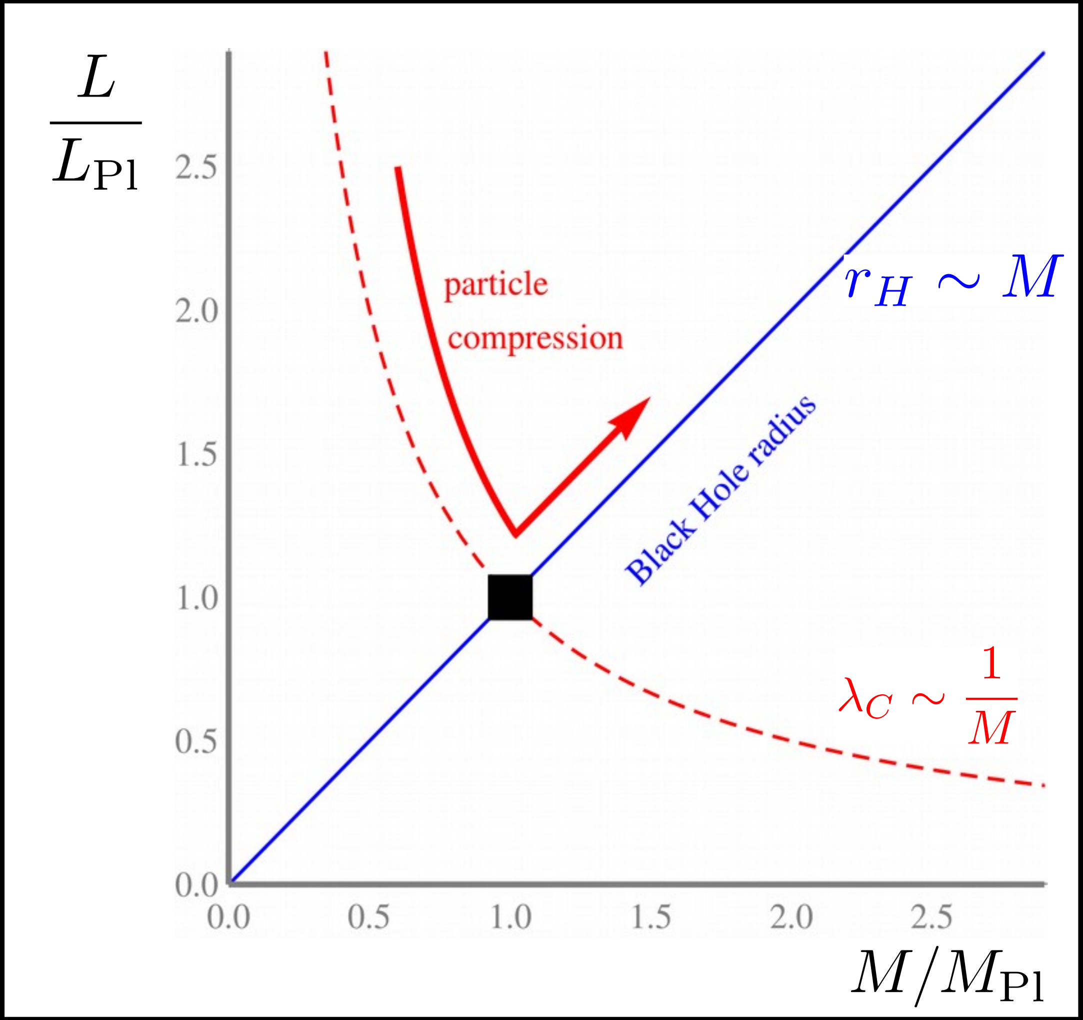
Incooperating gravitational effects in quantum mechanics

There is a widespread belief in a minimal spatial resolution in nature: Planck scale

Example Gedankenexperiments:
Heisenberg Microscope



Shrinking a volume of matter:



The Planck scale

$$M_{\rm Pl} = \sqrt{\frac{c^3}{\hbar G}} \approx 10^{-8}\text{kg}$$
$$L_{\rm Pl} = 1/M_{\rm Pl} \approx 10^{-35}\text{m}$$
$$T_{\rm Pl} = L_{\rm Pl}/c \approx 10^{-44}\text{s}$$

Incooperating gravitational effects in quantum mechanics

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Generalized Uncertainty Principle (GUP)

$$\Delta x \Delta p \geq \frac{\hbar}{2}(1+\beta p^2)$$

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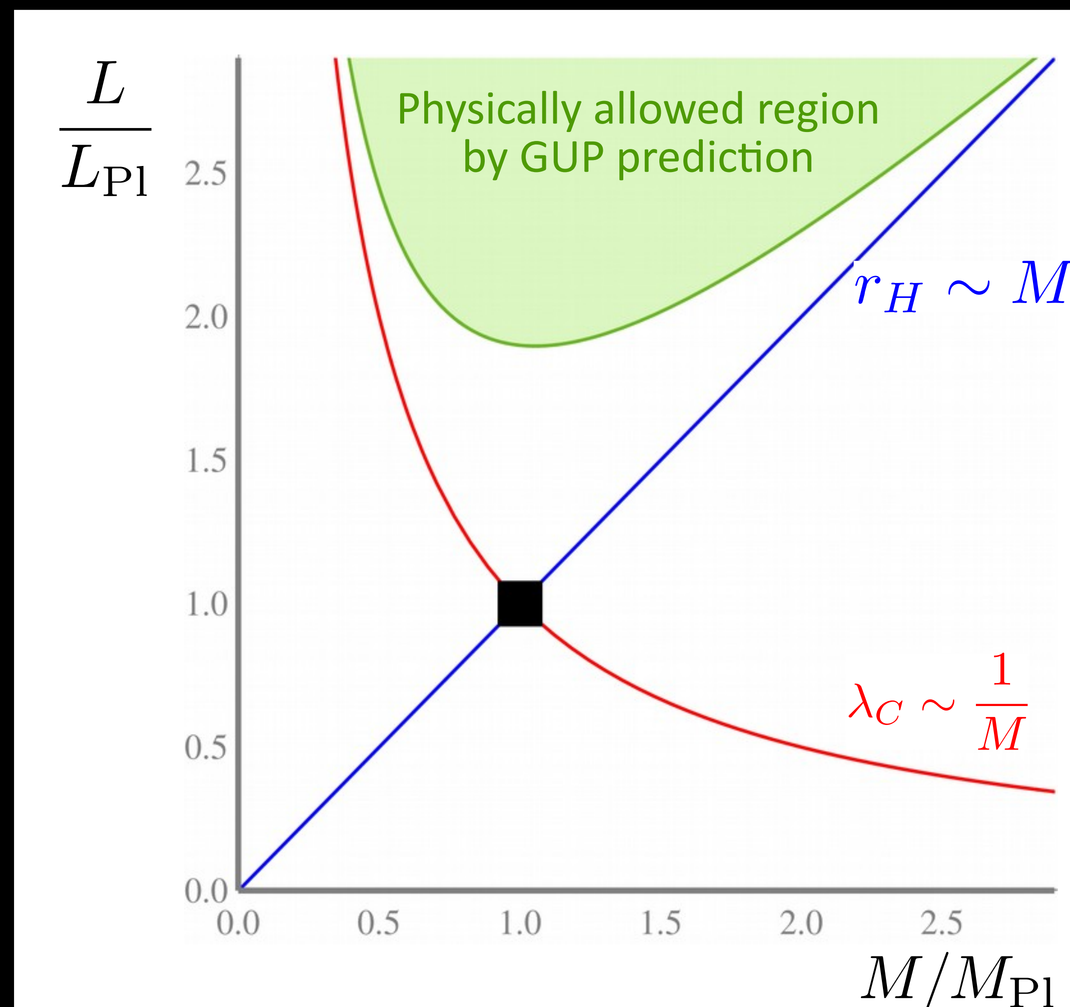

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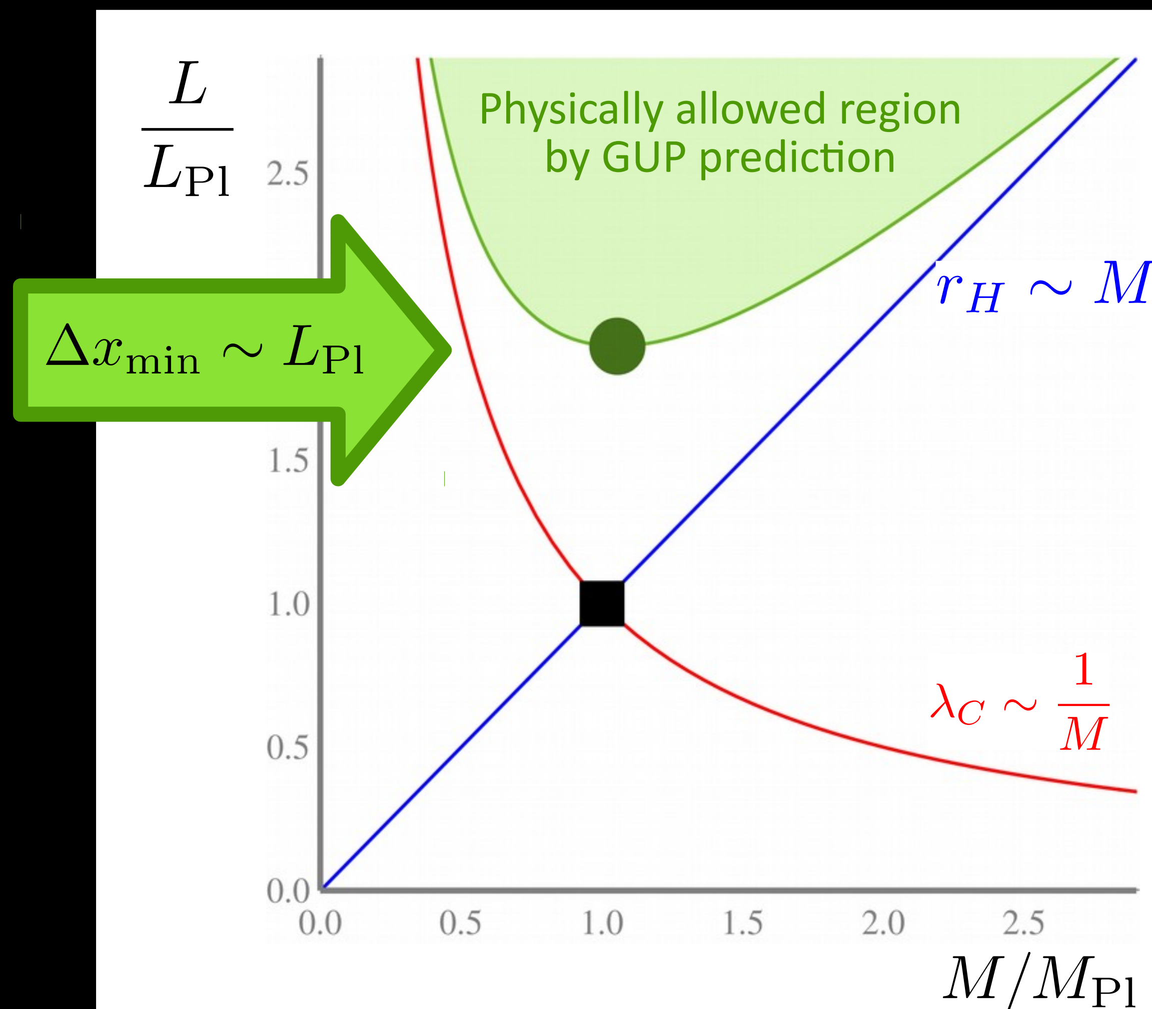


Incooperating gravitational effects in quantum mechanics

There is a widespread belief in a minimal spatial resolution in nature: Planck scale

Generalized Uncertainty Principle (GUP)

$$\Delta x \Delta p \geq \frac{\hbar}{2}(1+\beta p^2) \qquad \Rightarrow \qquad [\hat{x}^i, \hat{p}_j] = i\hbar\delta^i_j\left(1+\beta\ \hat{\vec{p}}^{\,2}\right)$$

→ maximal localized momentum states and

$$1 = \int_{-\infty}^{\infty} \frac{\mathrm{d}^3 p}{1+\beta \vec{p}^2} |p\rangle\langle p|$$

→ gives us a momentum space cutoff. Use Cutoff to determine sharpest possible object in GUP:

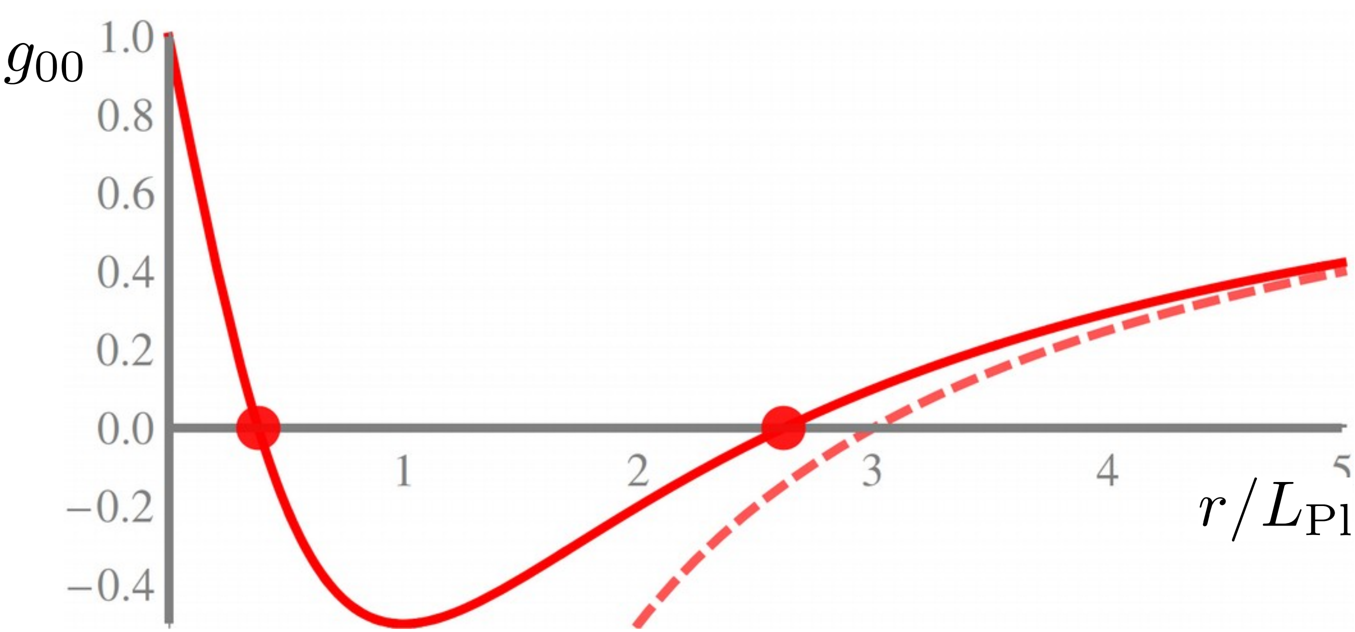
$$\mathcal{T}^0_0 \sim M \int_{-\infty}^{\infty} \frac{\mathrm{d}^3 p}{1+\beta \vec{p}^2} e^{i\vec{p}\cdot\vec{r}}$$

Fourier Transformation in coordinate frame of a freely infalling observer

The GUP-inspired black hole

$$\mathcal{T}_0^0 \sim M\mathcal{A}^{-2}(\Box)\delta(\vec{r}) \sim \frac{M}{\beta}\frac{e^{-r/\sqrt{\beta}}}{4\pi r}$$

$$\mathrm{d}s^2 = -\left(1 - \frac{2GM}{r}\gamma(2; r/\sqrt{\beta})\right)\mathrm{d}t^2 + \left(1 - \frac{2GM}{r}\gamma(2; r/\sqrt{\beta})\right)^{-1}\mathrm{d}r^2 + r^2\mathrm{d}\Omega^2$$



Big masses:
Classical Schwarzschild behaviour

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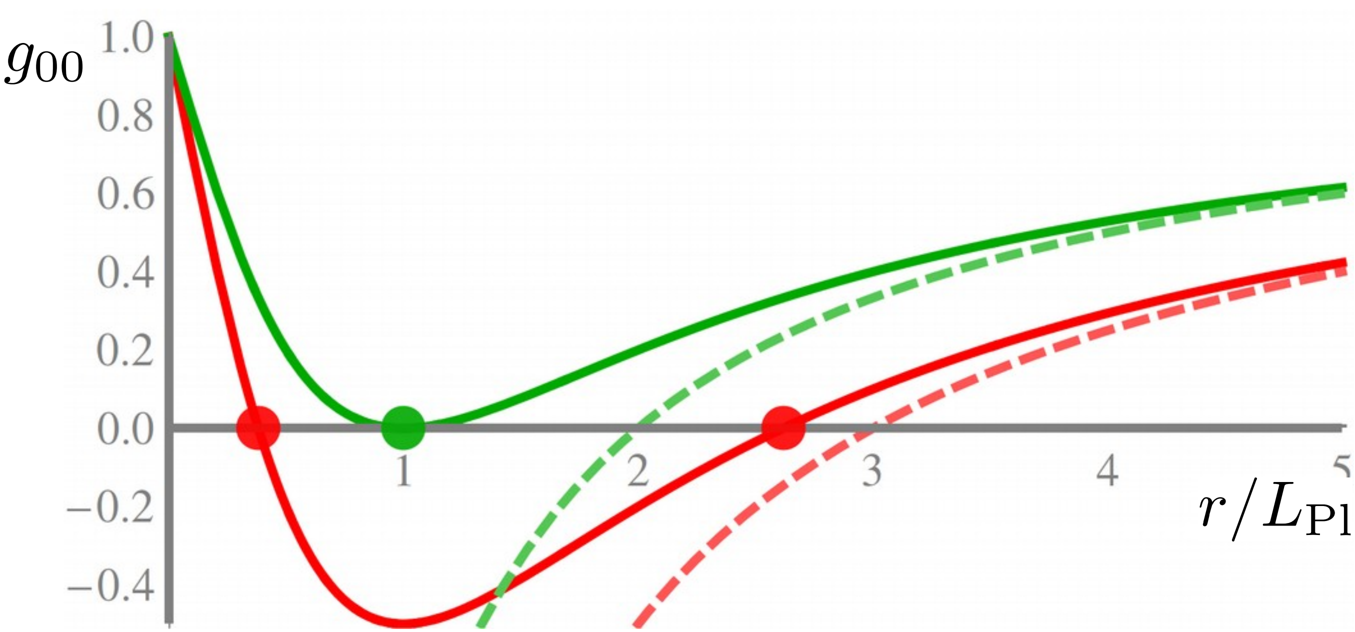

Extremal mass:
One degenerate horizon

Big masses:
Classical Schwarzschild behaviour

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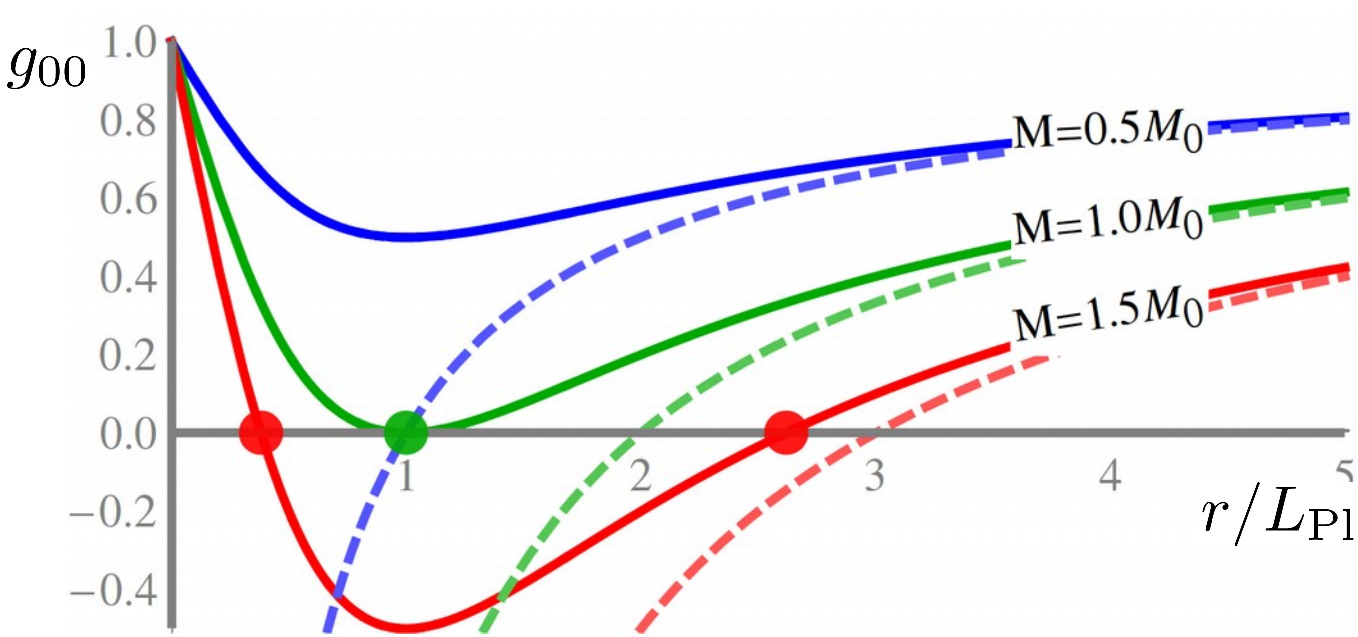


Too light mass:
no black hole (*G-Lump*)

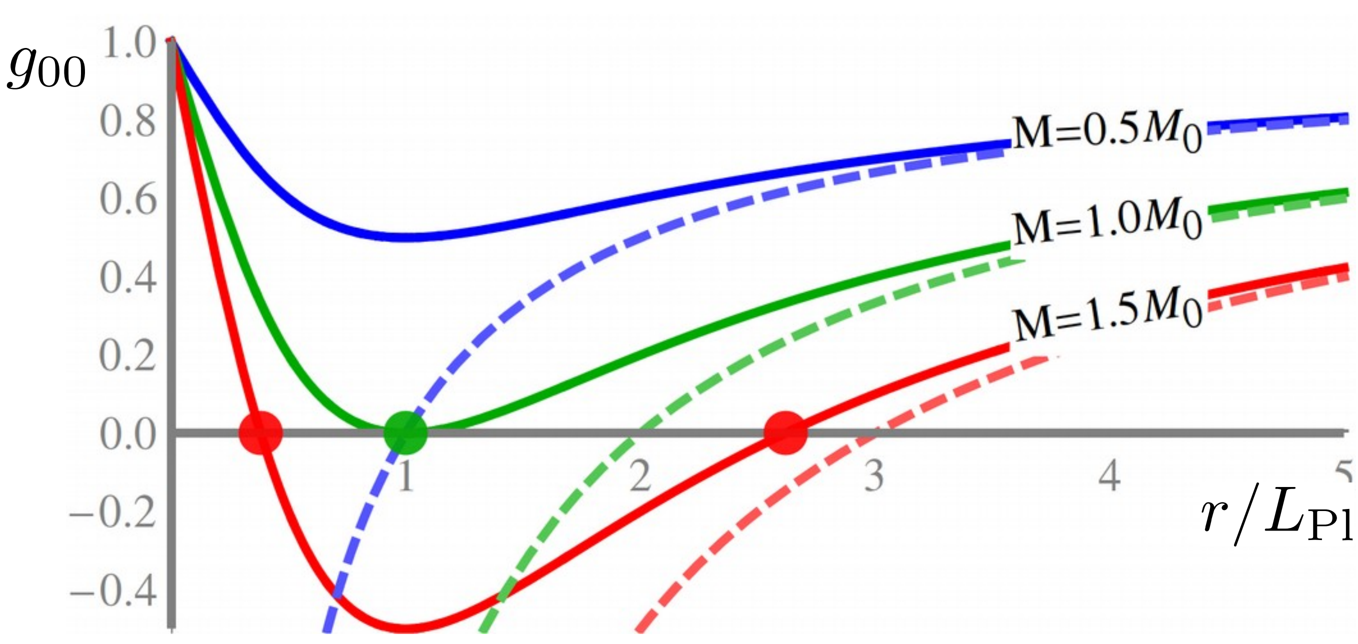
Extremal mass:
One degenerate horizon

Big masses:
Classical Schwarzschild behaviour

The GUP-inspired black hole

Features:

- Schwarzschild at large distances
- String theory motivated modification at Planck scale
- Still left: Curvature singularity at origin



Too light mass:
no black hole (*G-Lump*)

Extremal mass:
One degenerate horizon

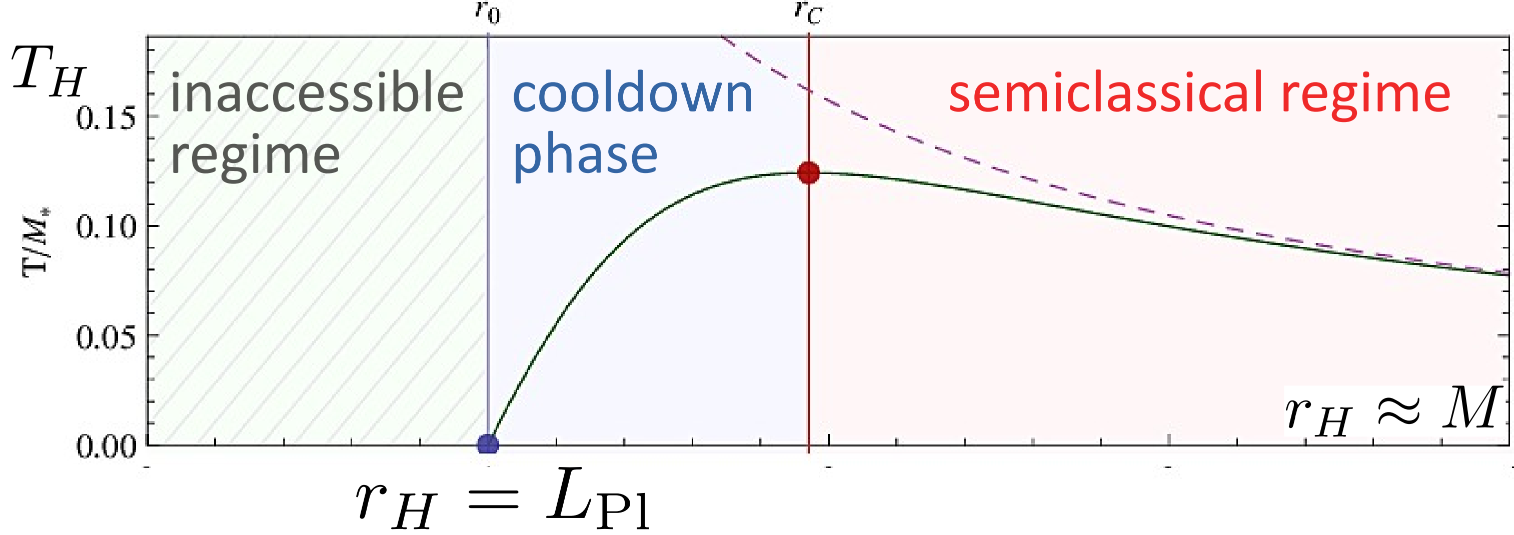
Big masses:
Classical Schwarzschild behaviour

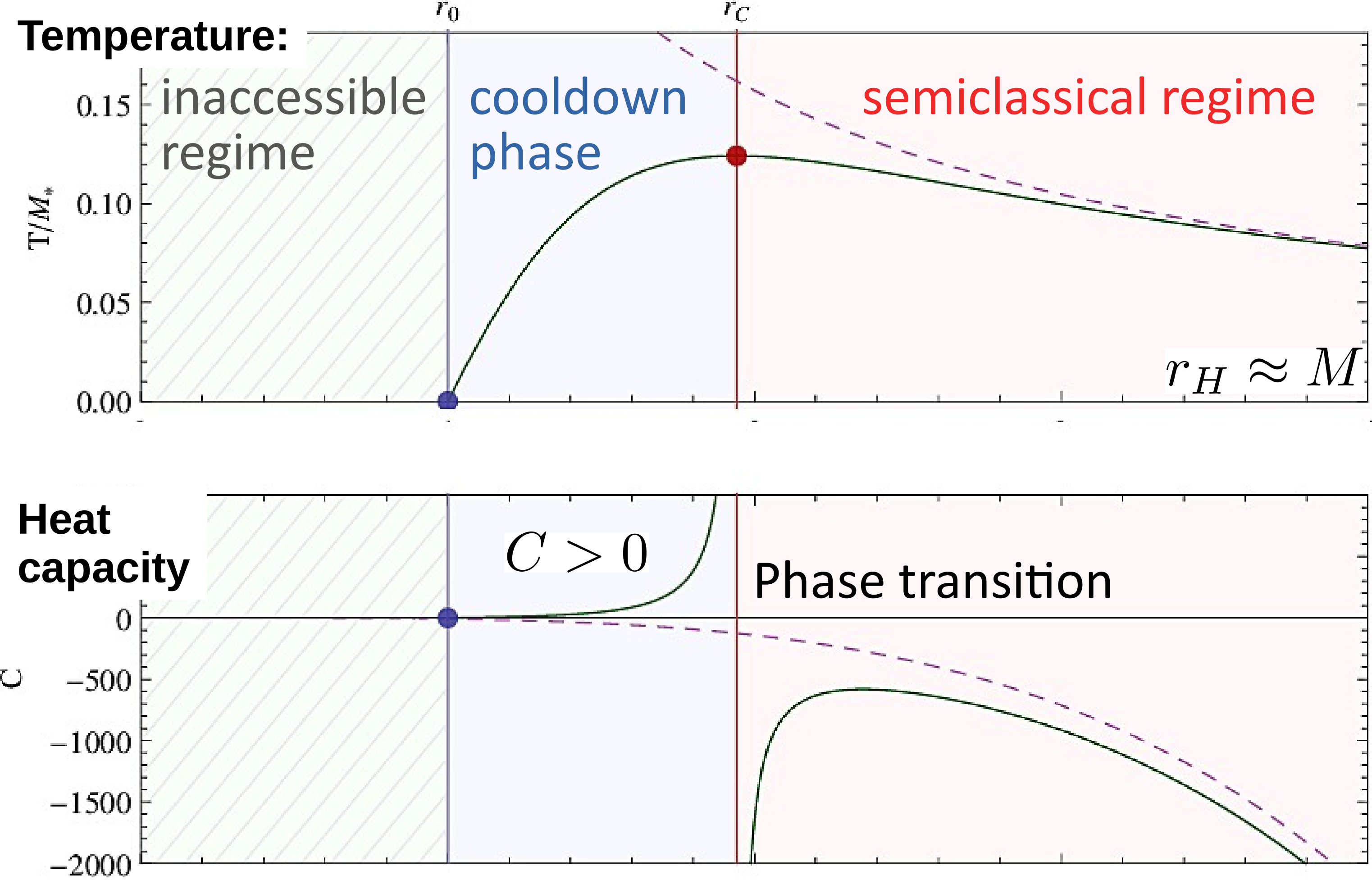
The GUP-inspired black hole

Further features:

- Regular thermodynamics
- The existance of a remnant
- Self-completeness of gravity

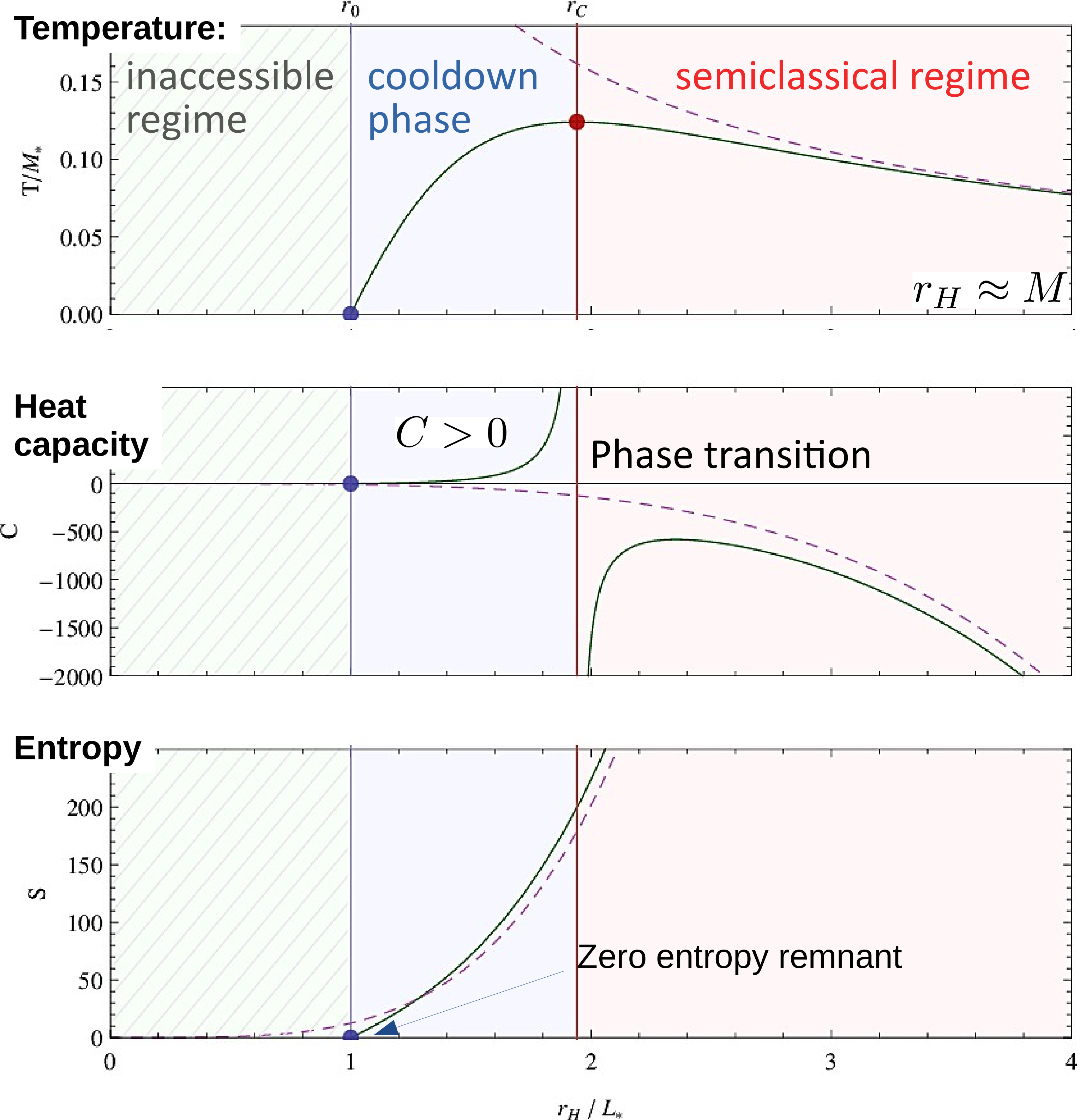
The black hole remnant: thermodynamics





The black hole remnant: thermodynamics

The black hole remnant: thermodynamics



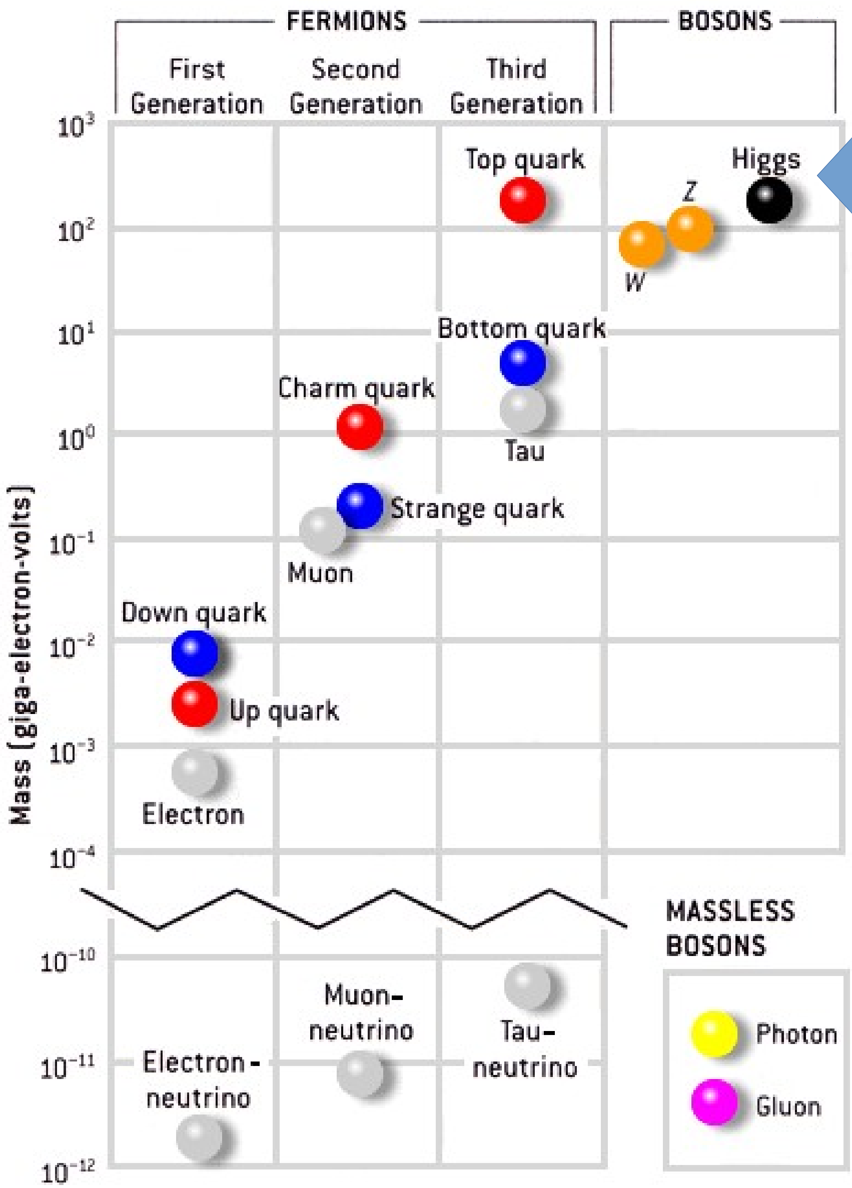
The remnant:

A cold stable evaporation endpoint

The GUP-inspired black hole

An ongoing project: Extending GUP black holes to extra dimensions.

The weak hierarchy problem of the Standard Model



Elektroweak scale

$\Lambda_{\mathrm{EW}} \sim 123\ \mathrm{GeV}$

vs.

Planck scale

$M_{\mathrm{Pl}} \sim 10^{19}\ \mathrm{GeV}$

Large Extra Dimensions

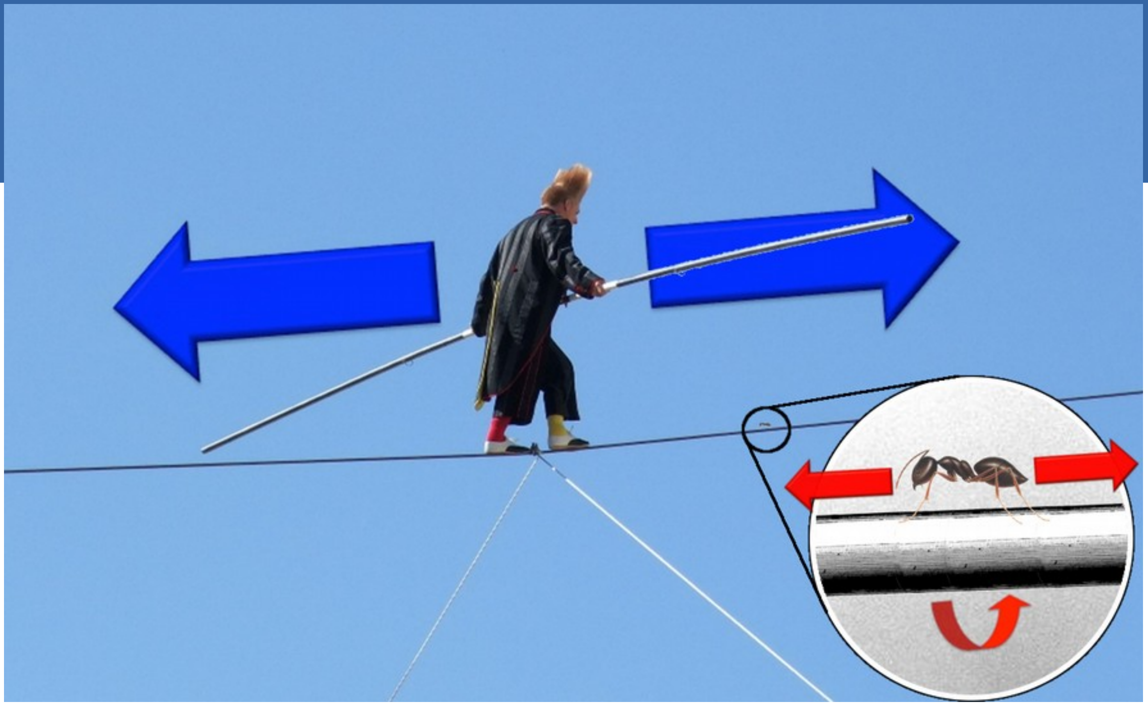
ADD scenario ← Arkani-Hamed, Dimopoulos, Dvali 1998

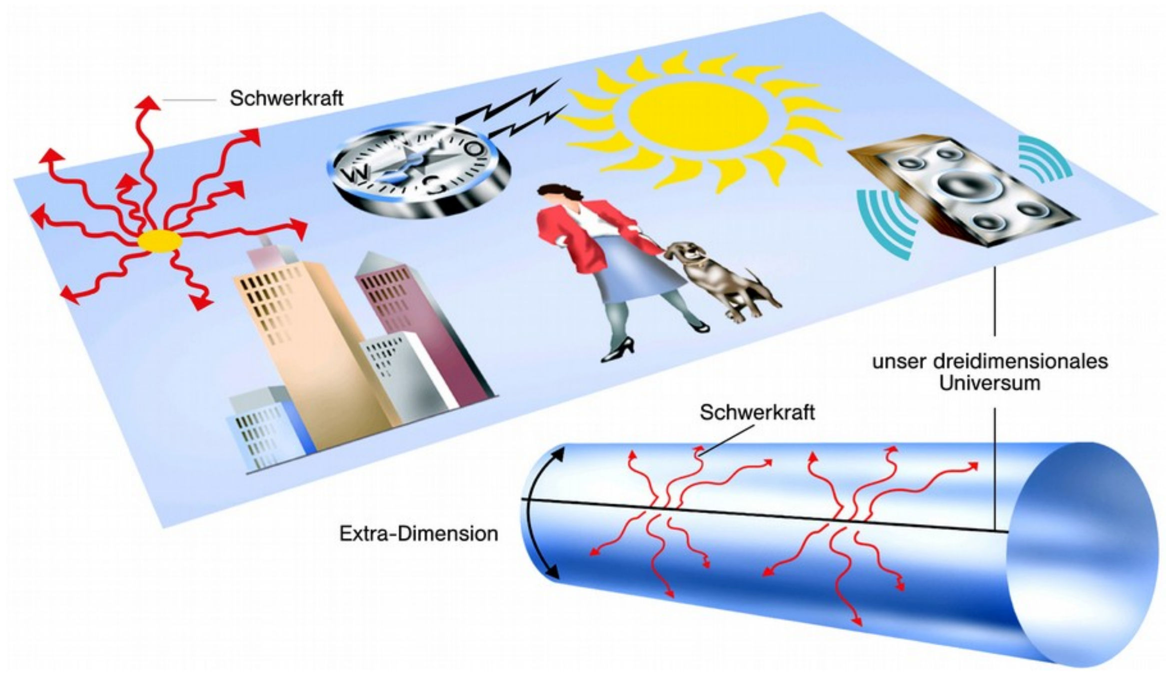
$$M_{\mathrm{Pl}}^2 = V_n M_*^{n+2}$$

Integrated huge Volume of extra dimensions

$$V_n = (2\pi R_c)^n$$

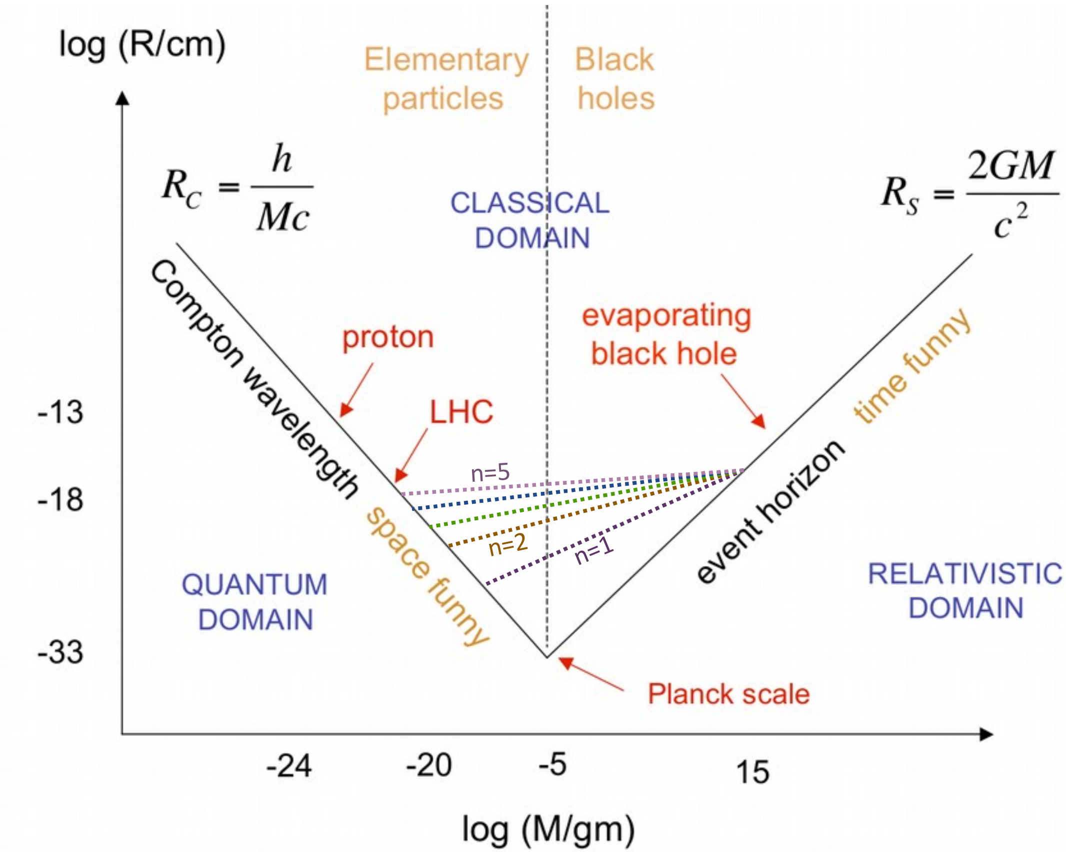
Large $\cong$ **µm** up to **mm**

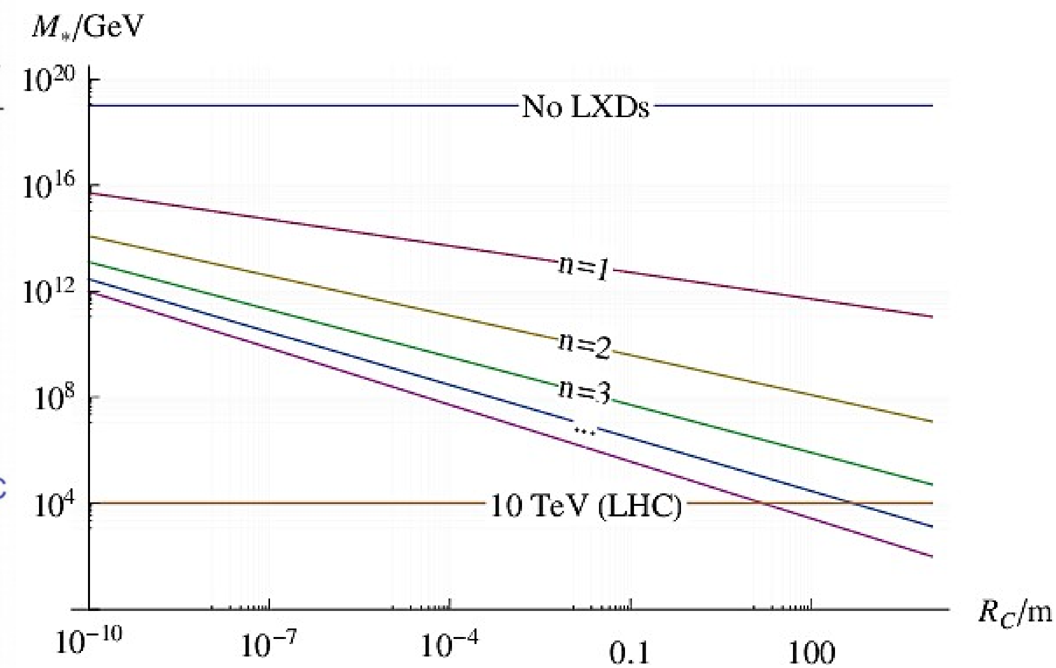




Large Extra Dimensions

$$M_{\rm Pl}^2 \sim {R_c}^n M_*^{n+2}$$





Maybe modify GUP for LXDs
ongoing work

$$\mathcal{T}_0^0 \sim M \int_{-\infty}^{\infty} \frac{\mathrm{d}^{3+n} p}{1+\beta \vec{p}^{2+n}} e^{i\vec{p}\cdot\vec{r}}$$

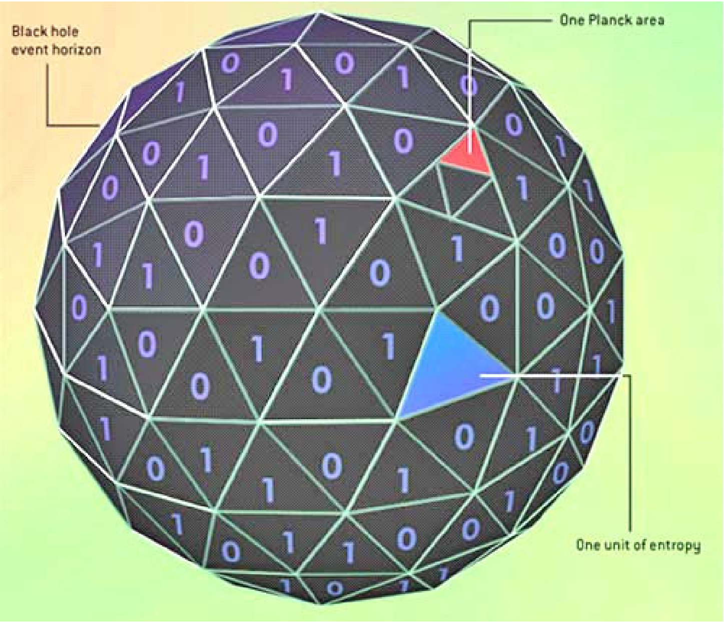
Outlook: Different metrics

The holographic metric:

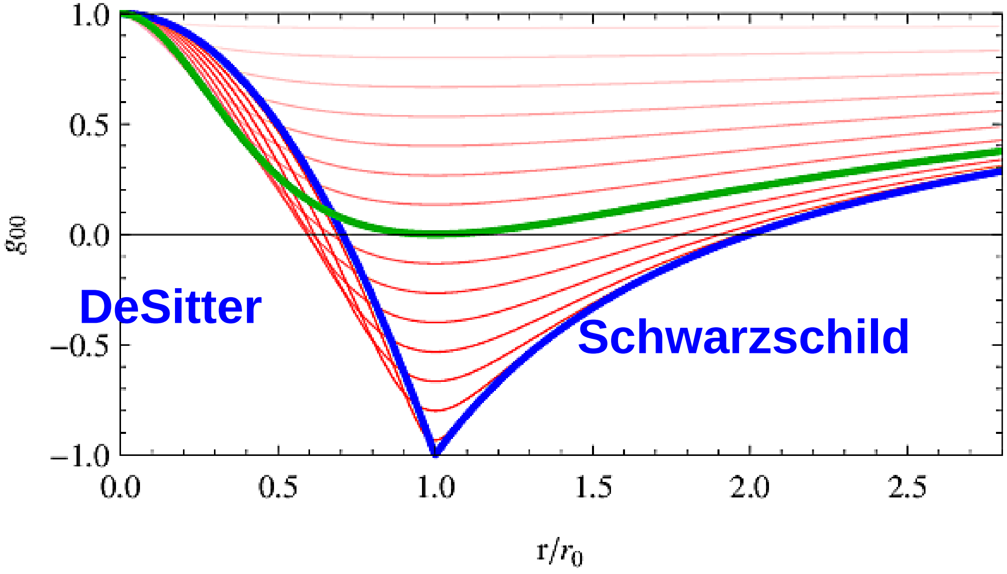
- Regular center? **No**
- Classical low-energy limit? **Yes**
- Self-encoding? **Yes**
- Holographic picture holds? **Yes**

The self-regular metric:

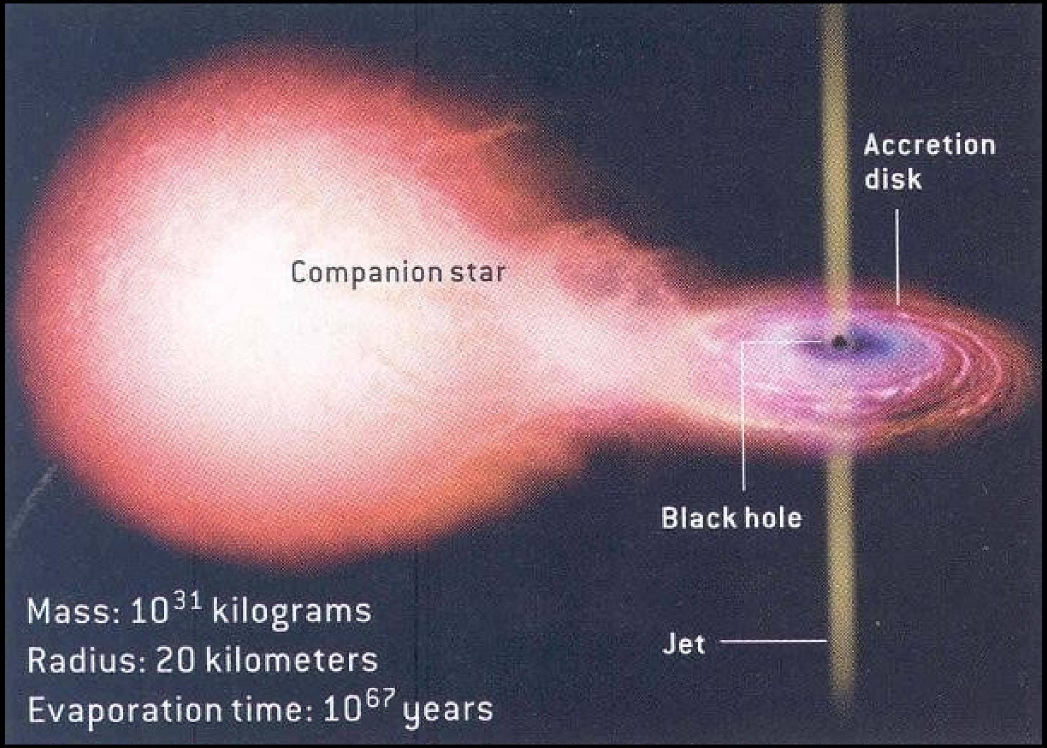
- Regular center? **Yes**
- Classical low-energy limit? **Yes**
- Self-encoding? **Yes**
- Holographic picture holds? **No**



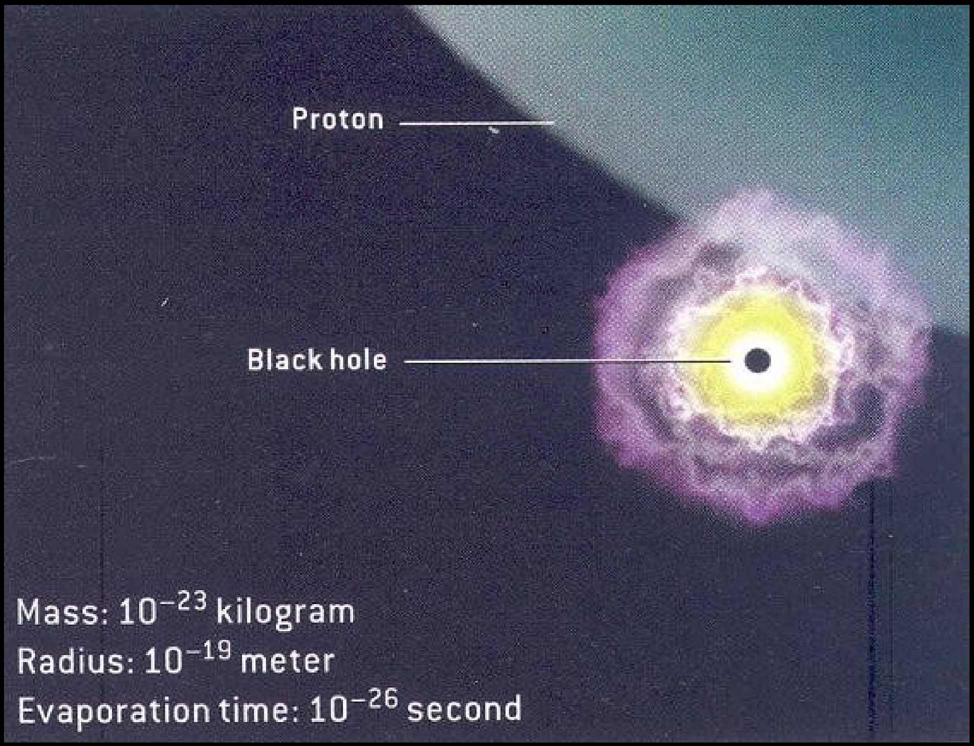
Regular De Sitter core:
Quantum outward pressure



Conclusion



Macroscopic



Microscopic

Literature

Nicolini, Spallucci
Holographic screens in UV self-complete QR
[arXiv:1210.0015]
Ongoing: Isi, Knipfer, Köppel, Mureika, Nicolini
Self-Completeness and the GUP in extradimensions
Ongoing: Bleicher, Dirkes, Frassino, Knipfer, Köppel, Nicolini
GUP and BHs – a paedagogical review

Picture Credits

Bernhard Carr [KSM 2012]
Bekenstein, Kamajian [Scientific American 2005]
SM particle chart: Phys. Today 65, 9, 12 (2012)