Cosmological phase transitions and the swampland

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Motivation

Applying swampland constraints to the cosmology of our universe is of phenomenological interest

This means caring about de Sitter / accelerated expansion, but also more than just pure de Sitter:

Reheating, EW Phase transition, (GUT phase transition),..

I will start by reviewing the Festina Lente swampland constraint [Montero, Van Riet, GV '19] and then extend this bound to finite temperatures to apply it to cosmological phase transitions

Festina Lente

[Montero, Van Riet, GV ’19; Montero, Vafa, Van Riet, GV ’21;..]

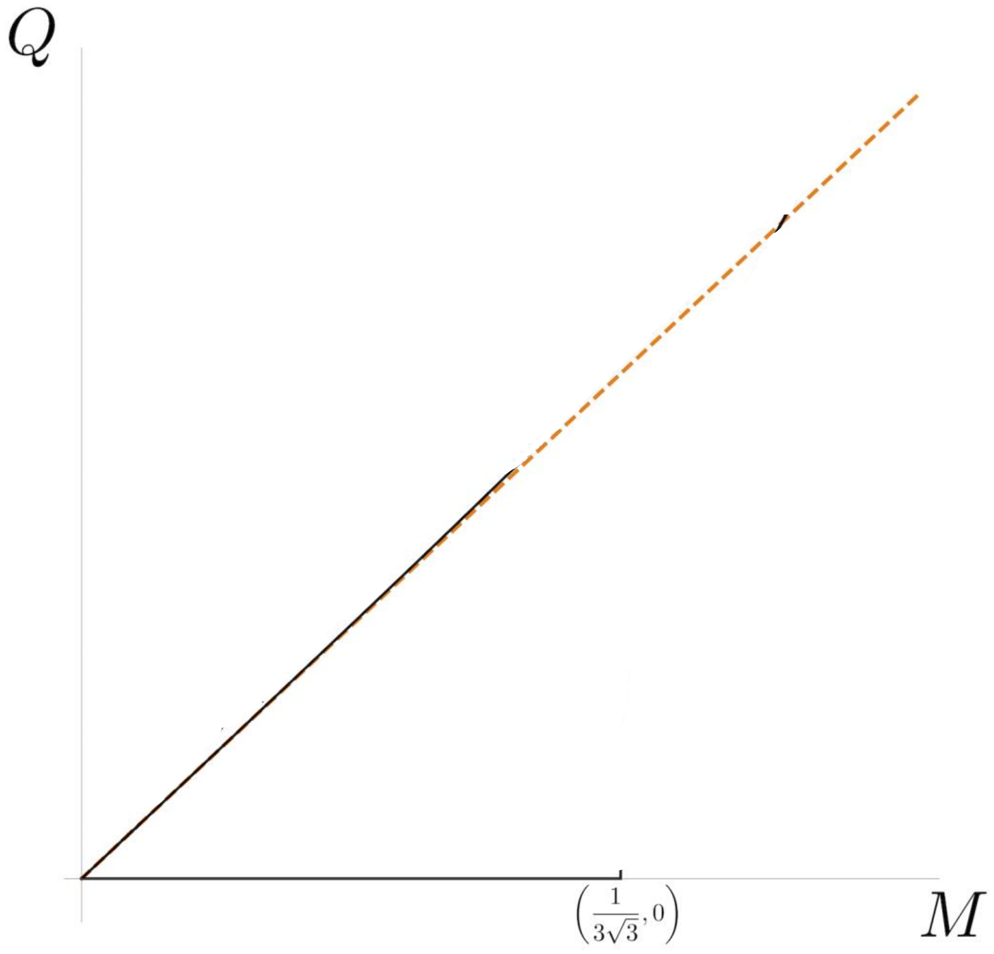
Festina Lente

Everyone seems to love the Weak Gravity Conjecture

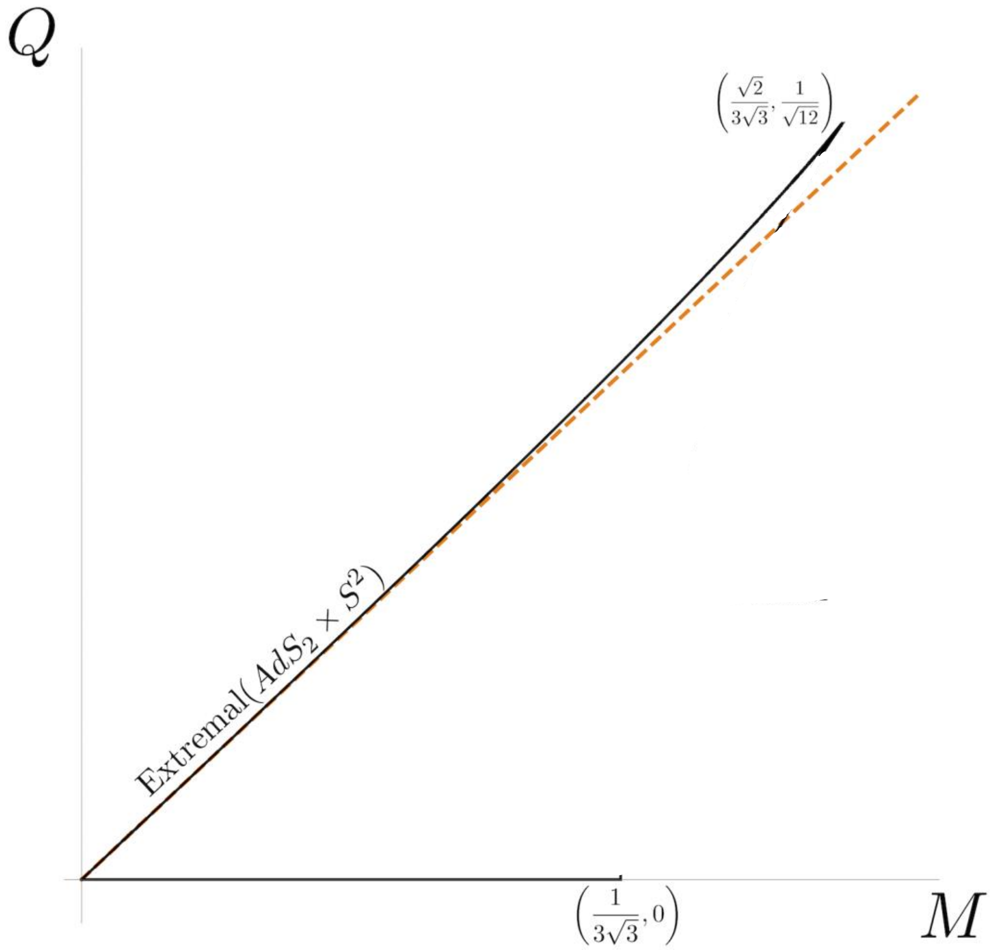
WGC follows from demanding charged black holes decay ‘nicely’ in flat space

Let’s go through the logic of charged black hole evaporation again but now in de Sitter space

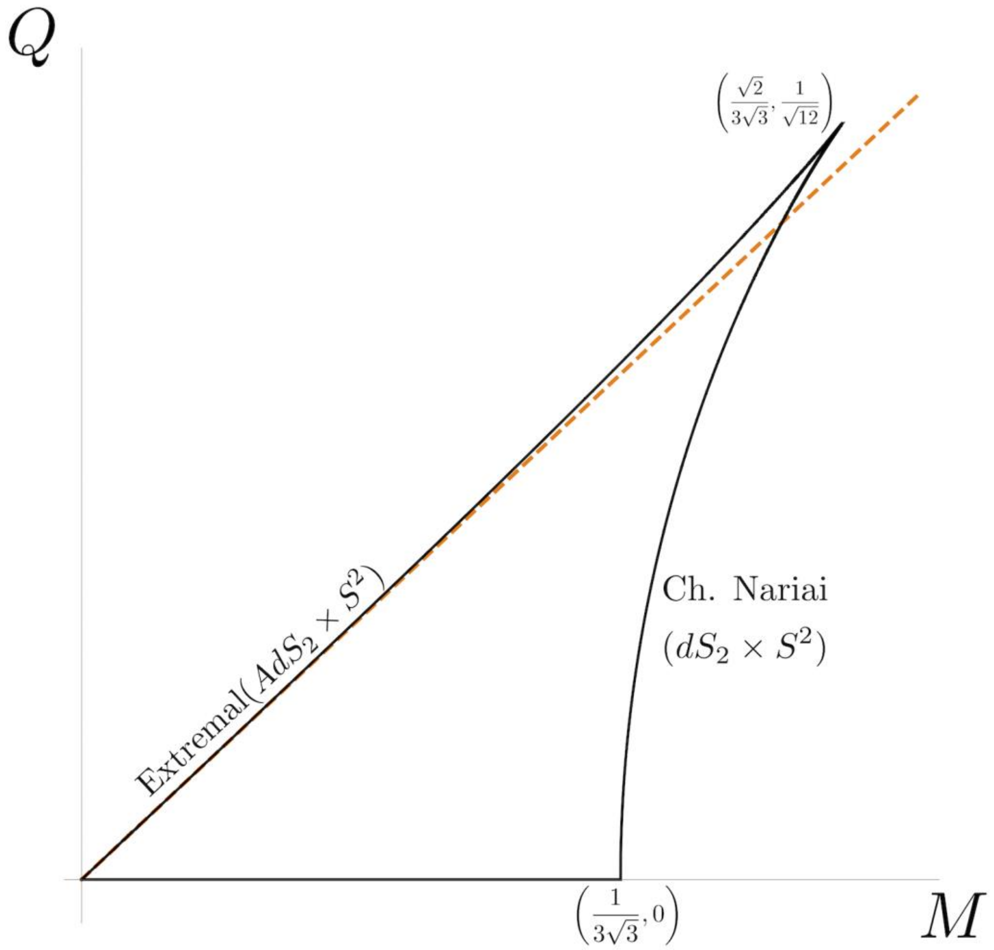
Black holes in de Sitter space



Black holes in de Sitter space



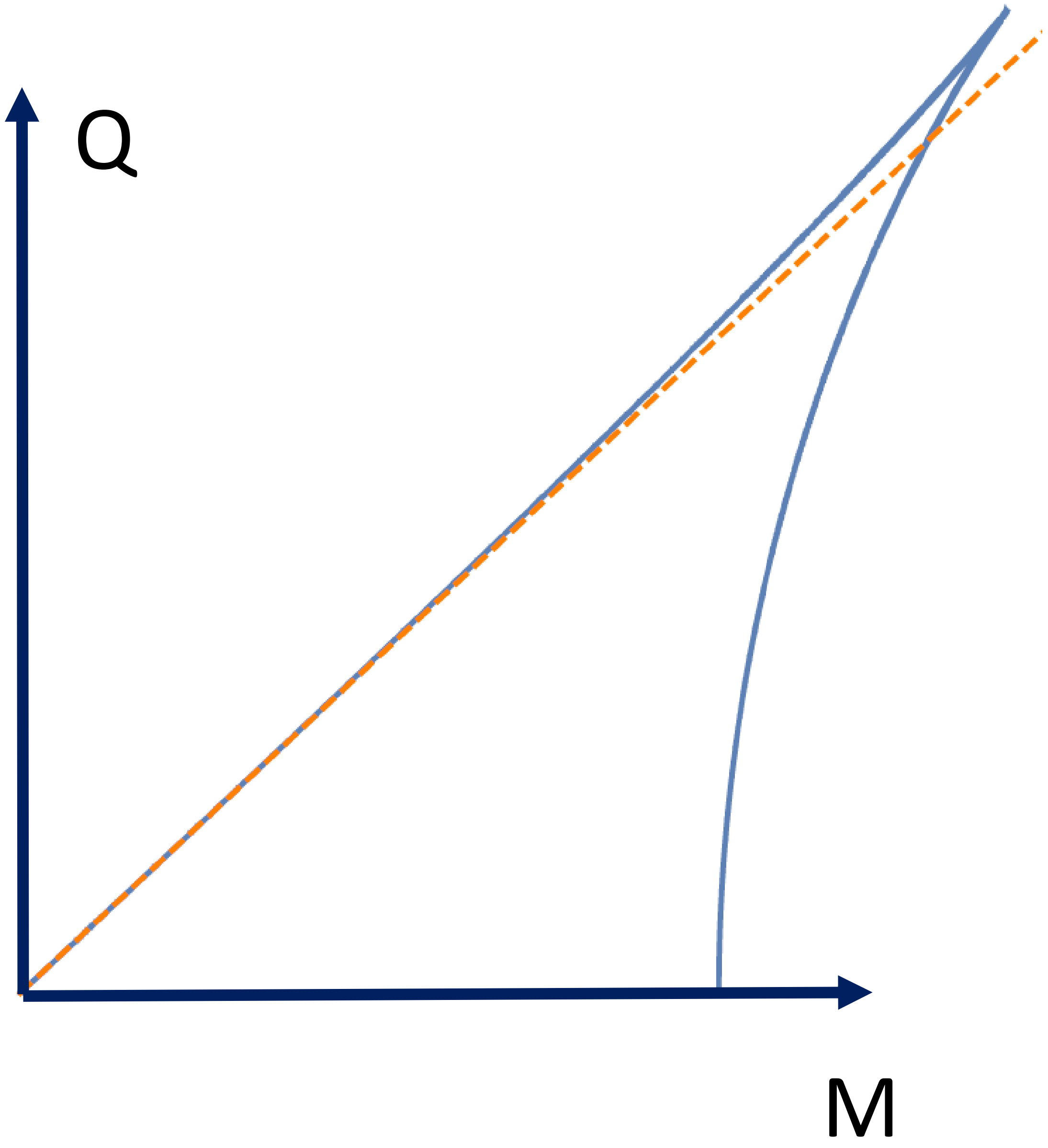
Black holes in de Sitter space



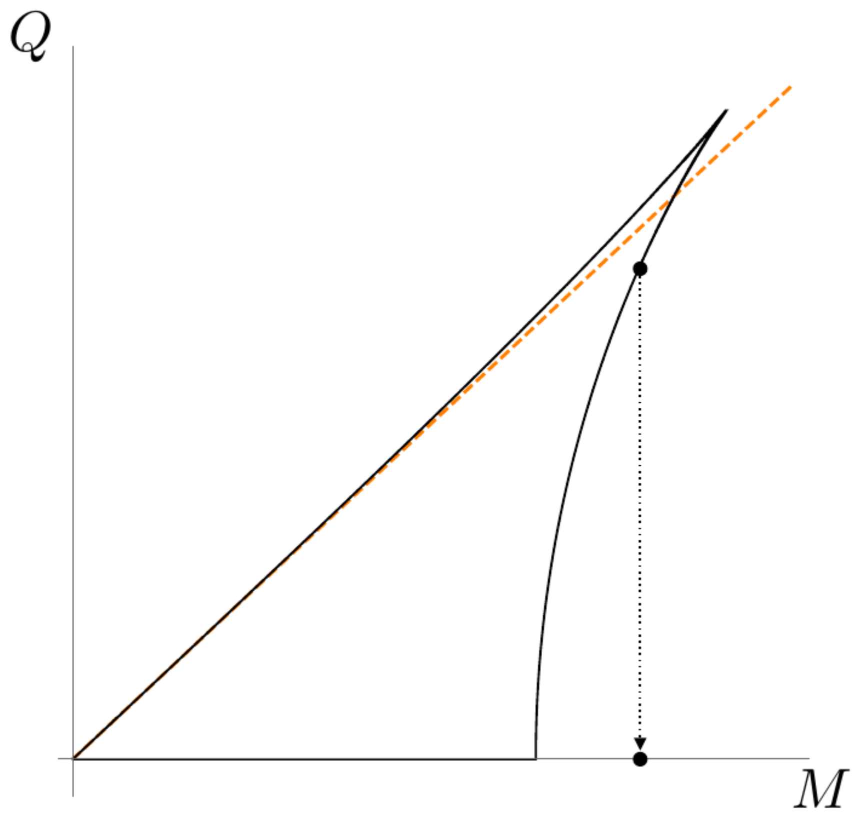
Weak gravity analogue in de sitter?

Consider particle of charge m and mass q,
See how BH decay depends on m and q

Two guiding principles:
-Expect to evaporate to empty de Sitter based on entropy
-Expect should not become superextremal based on cosmic censorship



Rapid regime $m^2 \ll qE$



For charged Nariai near tip: $E \sim g M_p H$

$$m^2 \gtrsim q\, g M_P H$$

Real world electromagnetism $\sqrt{g M_P H} \sim 10^{-3}\, eV$

Electron m=0,5MeV so satisfies this bound

All particles must obey this bound.

FL and Non-Abelian gauge fields [Montero, Vafa, Van Riet, Venken '21]

SU(N) gauge theory:

Non-Abelian vector fields themselves charged under U(1) subgroup SU(N)

$$m^2 \gtrsim q\, g M_P H$$

Would violate our bound if long-range nonabelian gauge fields massless!

SU(N) gauge theories must always be either confined or Higgsed, with characteristic scale above Hubble scale

Finite temperature

2311.04955 [GV ‘23]

Finite temperature and FL

At high temperature (for example, during reheating), Higgsing and confinement are undone by effective thermal terms in Lagrangian.

Does this violate Festine Lente?

First need to know when we can apply FL at finite T

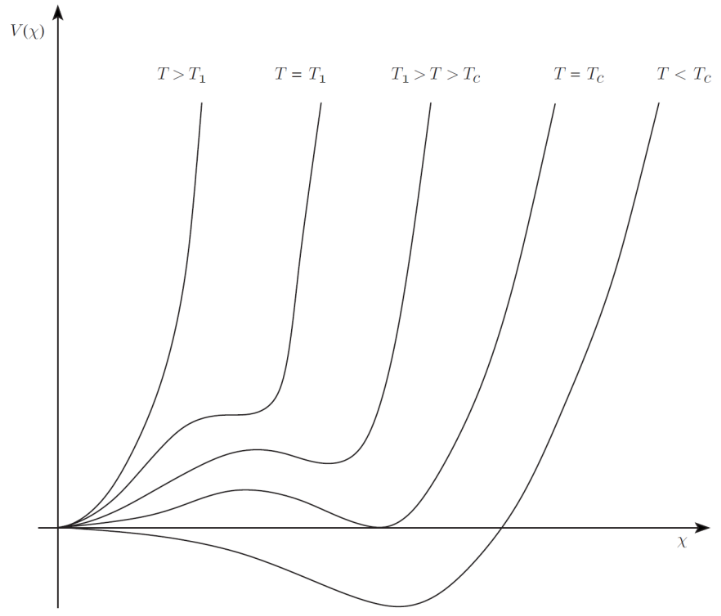


Image:Mukhanov

Note: reheating is the inspiration, but we want to make sure the physics is OK for any initial temperature where the EFT should be controlled

Applicability FL at finite T

Need Nariai BH -> Need a cosmic horizon / quasi de Sitter

Energy density radiation $$\rho_R = \sigma T^d$$

with $\sigma \sim N_T$ # particle species in thermal equilibrium

Vacuum energy density $$\rho_V = V$$

So need $$\frac{\rho_R}{\rho_V} \leq c \implies T \leq \left(\frac{cV}{\sigma}\right)^{1/d}$$

With c an order one constant (c=1 if demand accelerated expansion)

Higgsing

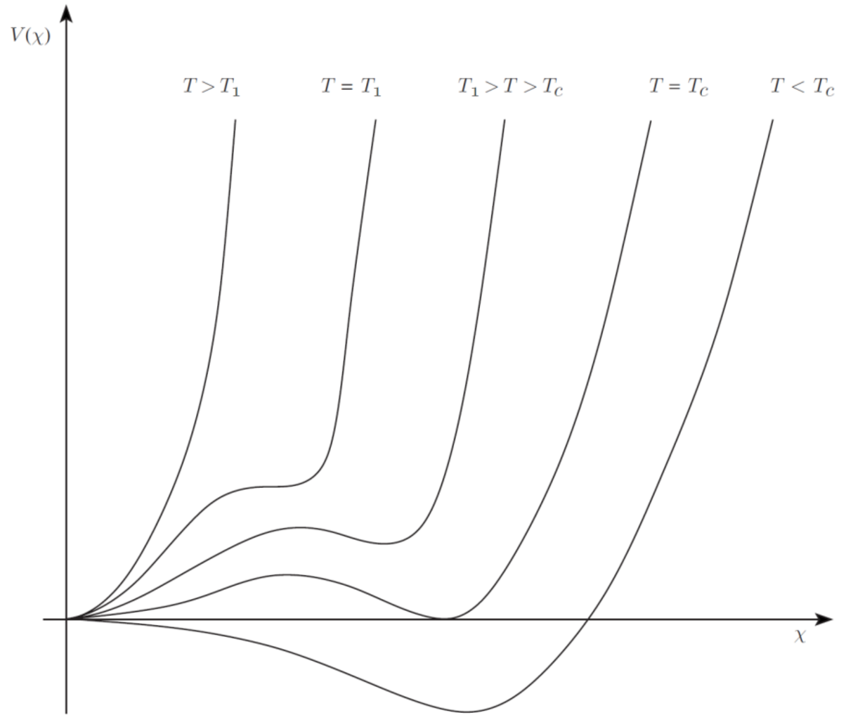
Quartic Higgs

$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4 + \frac{\mu^4}{4\lambda}$$

Thermal corrections e.g. $\sim\alpha T^2|\phi|^2$ with α dependent on couplings

ϕ=0 symmtertic vacuum stabilized at temperature above

$$\alpha T_c^2 = \mu^2$$



Higgsing

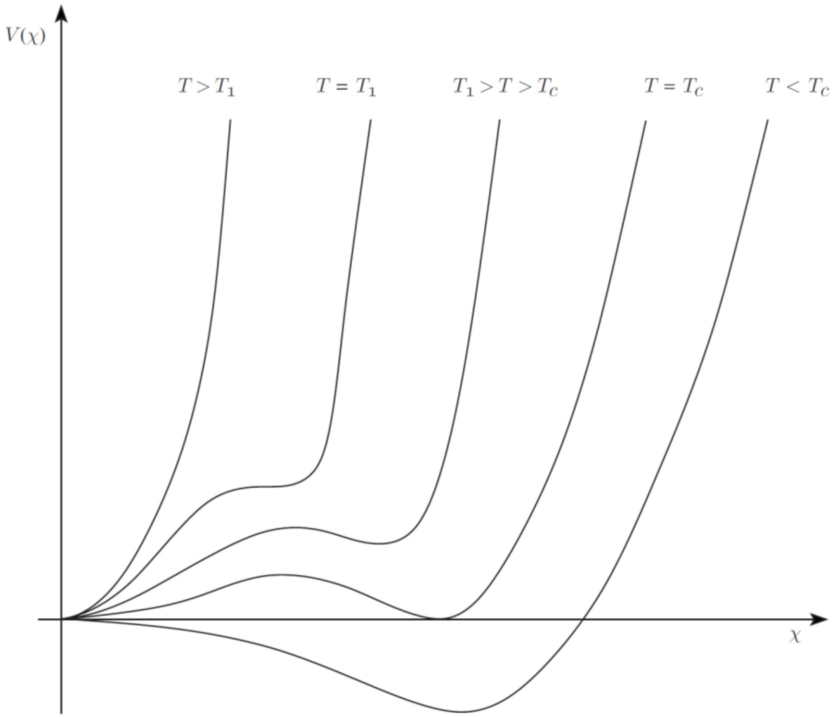
When $T \leq \left(\frac{cV}{\sigma}\right)^{1/d}$ FL can be applied,

When FL applies theory must be Higgsed

so T_c must be hotter than this bound

Implies

$$\lambda > \frac{c\alpha^2}{4\sigma}$$



Higgsing

Higgs VEV in symm breaking vacuum sets electroweak scale

$E_{EW} = \langle \phi \rangle = \mu / \sqrt{2\lambda}$

μ sets the mass of the Higgs m_H

So $\lambda > \frac{c\alpha^2}{4\sigma}$ is equivalent to

$$\frac{E_{EW}}{|m_H|} \approx \frac{1}{\lambda^{1/2}} < \left(\frac{4\sigma}{c\alpha^2} \right)^{1/2}$$

Higgsing

$$\frac{E_{EW}}{|m_H|} \approx \frac{1}{\lambda^{1/2}} < \left(\frac{4\sigma}{c\alpha^2}\right)^{1/2}$$

Preference for a heavy Higgs relative to the Electroweak scale

➔Preference for a higher-order phase transition (though does not fully exclude first-order)

Filling in SM values $3.08 > c^{1/4}$, so bound obey for reasonable c

Called the scale electroweak, but of course applies to any Higgsed theory (e.g. GUT)

Higgsing: first-order phase transition

$$\frac{E_{EW}}{|m_H|} \approx \frac{1}{\lambda^{1/2}} < \left(\frac{4\sigma}{c\alpha^2}\right)^{1/2}$$

First-order phase transition in GUT interesting as a source of Baryogenesis, source gravitational waves

Increasing $\langle\phi\rangle/|\mu|$ increases strength GW signal

This is precisely what we bound from above. Upper bound on GW/baryogenesis from GUT

Confinement

When $T \leq \left(\frac{cV}{\sigma}\right)^{1/d}$ FL can be applied

In order to obey FL, the theory must remain confined whenever the temperature obeys this bound, so

$$\Lambda_{QCD} > \left(\frac{cV}{\sigma}\right)^{1/d}$$

Essentially, confinement scale must be above vacuum energy. Obeyed in real world, but much stronger than constrain from just FL without thermal effects.

Inflation

So far considered bound with present-day vacuum energy in mind, but what about inflation? Would imply e.g.

$$\Lambda_{QCD} > \left(\frac{cV_{inf}}{\sigma}\right)^{1/d}$$

Such low scale inflation seems like a tall order!

One options: running couplings.

Another option: $\sigma \sim N_T$ # particle species in thermal equilibrium

Increase N_T during inflation to obey the bound

Inflation

Increase N_T during inflation to obey the bound

$$c\left(\frac{\Lambda_{inf}}{\Lambda_{QCD}}\right)^d \lesssim N_T$$

Also $N_T \leq N_{sp}$ with N_{sp} the total # particle species in the EFT

In QG one has the species scale [Dvali '07; Dvali, Lust '09] providing a UV cut-off for any EFT

$$\Lambda_{sp} \sim \frac{M_p}{N_{sp}^{1/(d-2)}} \qquad \Rightarrow \qquad \Lambda_{sp} \lesssim c^{-1/(d-2)}\left(\frac{\Lambda_{QCD}}{\Lambda_{inf}}\right)^{d/(d-2)} M_P$$

Inflation

If we want our EFT to be able to describe inflation (perhaps not necessary?) then require $\Lambda_{inf} \ll \Lambda_{sp}$. Combining with previous

$$\Lambda_{inf} \ll \Lambda_{QCD}^{d/(2d-2)} M_P^{(d-2)/(2d-2)}$$

Real-world values:

$$\Lambda_{\text{inf}} \ll 10^5 \text{ GeV}$$

Very low scale inflation, but perhaps not a bad thing? Helps with e.g. moduli problem in stringy inflation [German, Ross, Sarkar '01]

Summary

Festina Lente bound: $m^2 \geq \sqrt{6} g q M_p H$

Also requires Higgsing/confinement nonabelian gauge theories

Constraints strengthened in the presence of thermal radiation, also interplay with bound on inflation

Not discussed due to time:

These swampland constraints have been checked in controlled string theory set-ups (the KS throat) and are obeyed there

Extra Slides

Extensions [Montero, Vafa, Van Riet, Venken ‘21]

-Multiple U(1) gauge fields

-Multiple charged particle species / towers speed up discharge

-> strengthen bound

-Rolling quintessence scalar instead of pure de Sitter

-Magnetic version FL

..

See also e.g. [Guidetti, Righi, GV, Westphal ’22; Montero, Muñoz, Obied ‘22; Mishra ‘22] for further extensions

Wat to do

Consider Einstein gravity in de Sitter space

+ U(1) gauge field

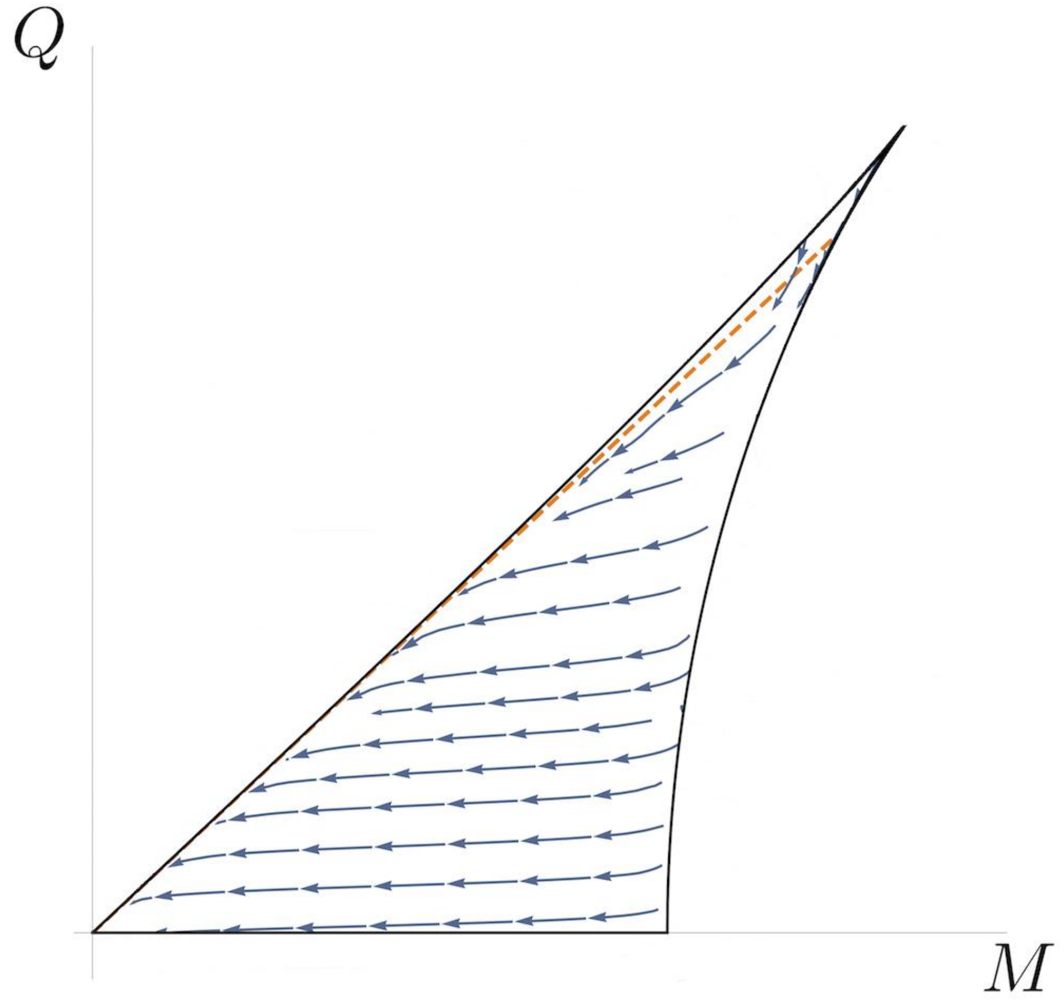
+ charged particle mass m charge q

See how black hole evolution depends on m, q

Schwinger effect for electric field E:

$$\Gamma = \frac{(qE)^2}{4\pi^3} \exp\left(-\frac{\pi m^2}{qE}\right)$$

Quasistatic $m^2 \gg qE$



$$\frac{dM}{dQ} = \frac{\dot{M}}{\dot{Q}} = G\sqrt{U(r_g)}\frac{\mathscr{T}}{\mathscr{J}} + \frac{Q}{r_g}$$

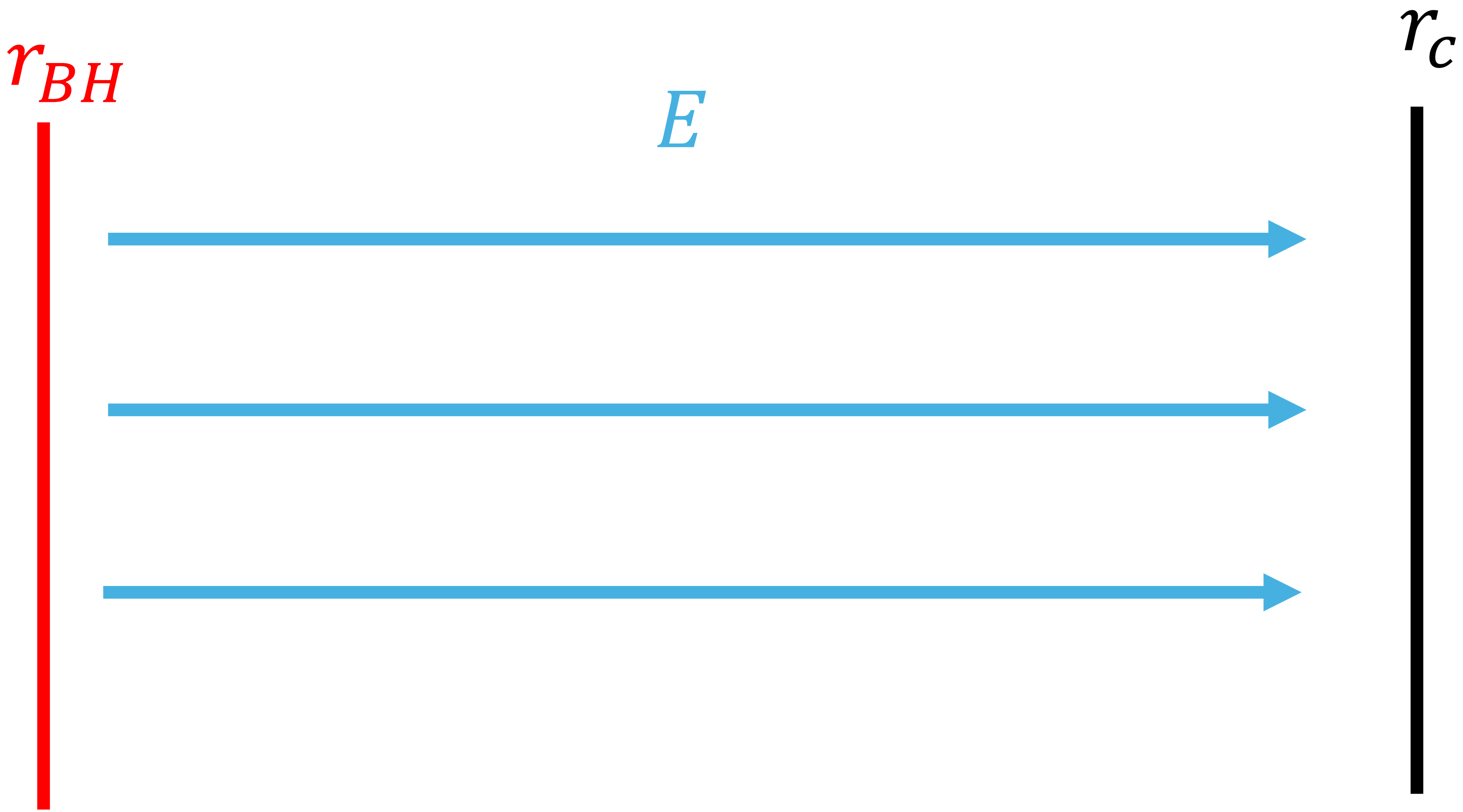
Rapid discharge

For massless charged particles electric field discharges on timescale $t_{disch.} \sim (q\, E)^{-1/2}$

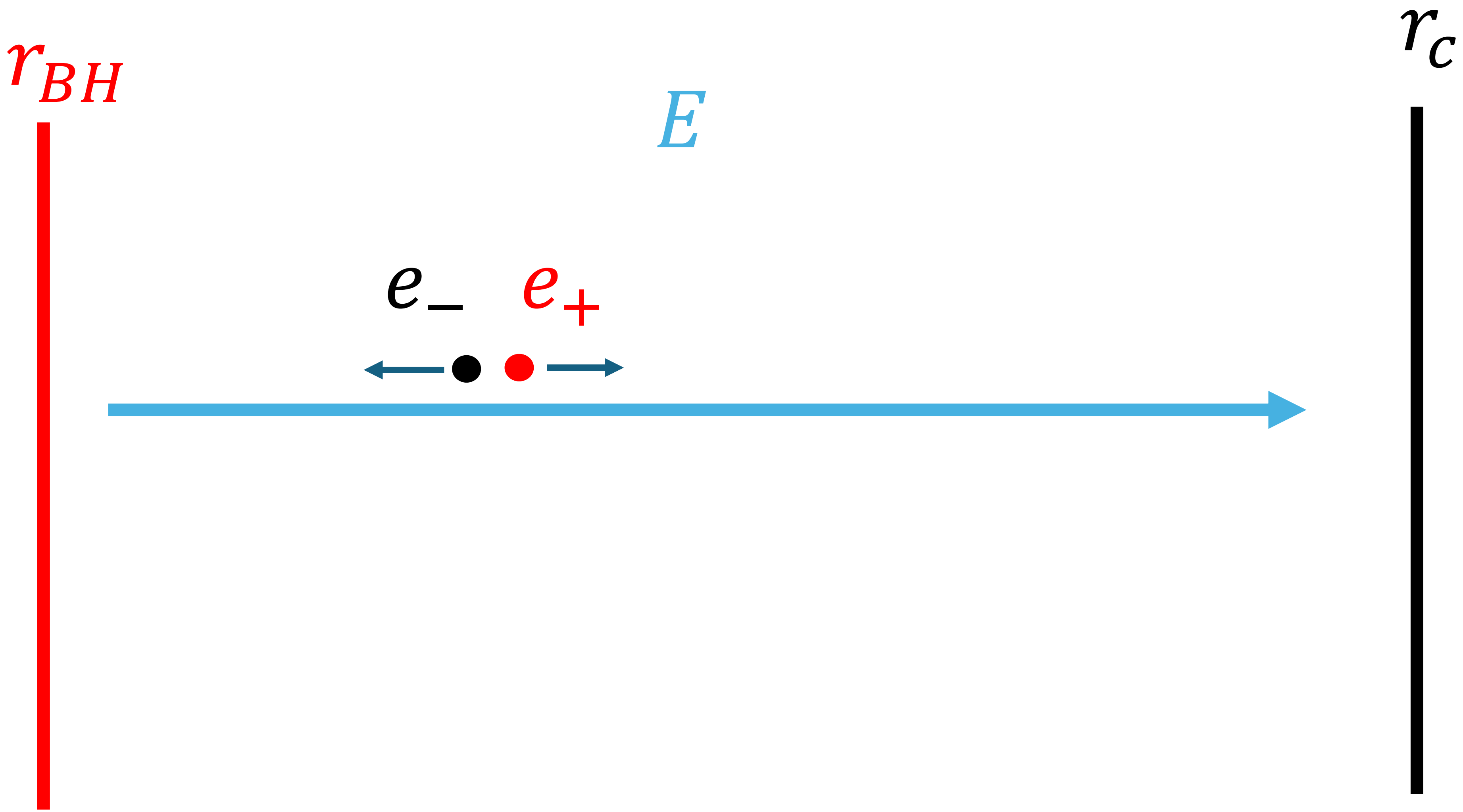
As $E \sim g M_p H$ one has $t_{disch.} \sim (gq)^{-1/2} V^{-1/4}$, so significantly more rapid than a Hubble time

Distance between cosmic and BH horizon of Hubble scale

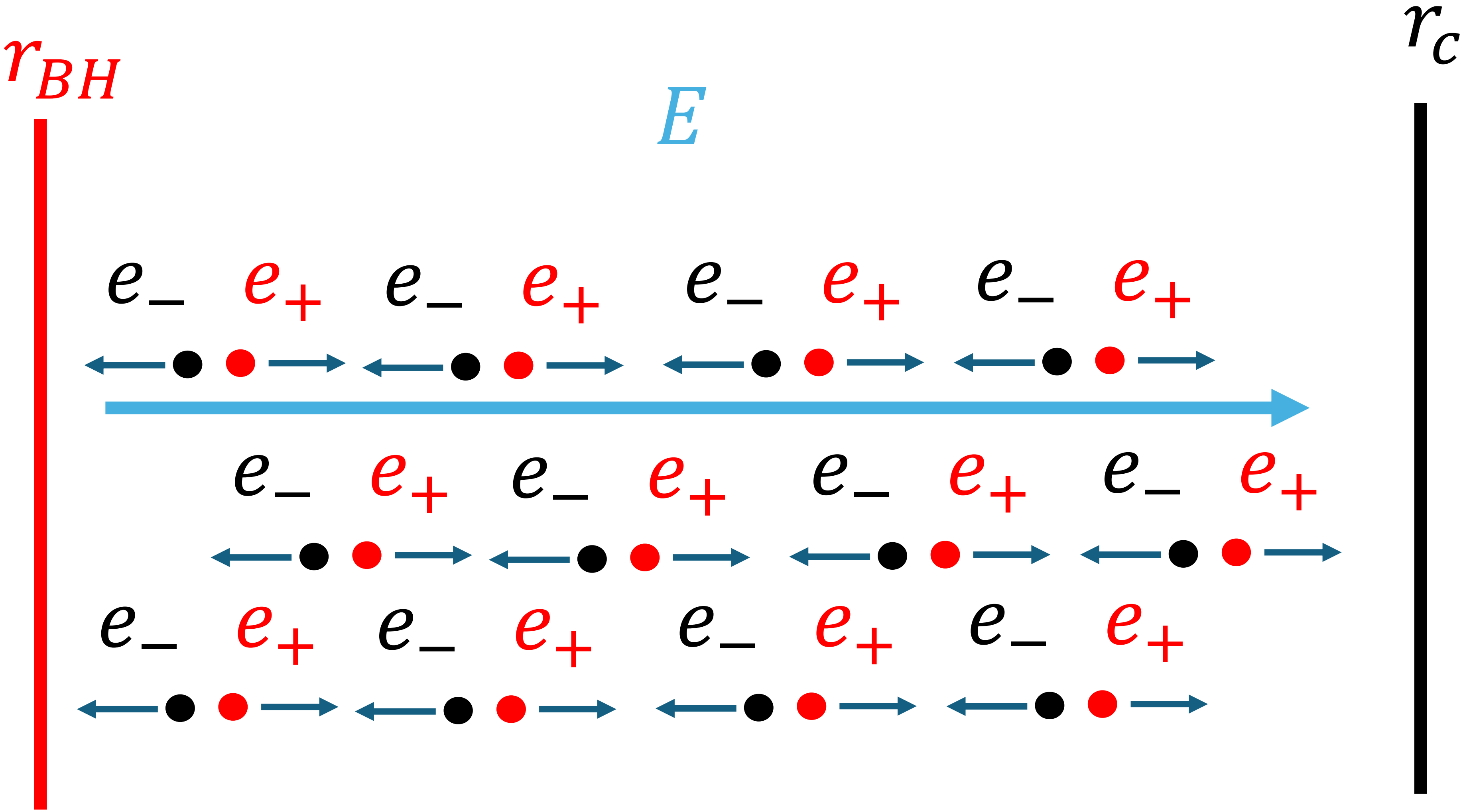
Rapid discharge

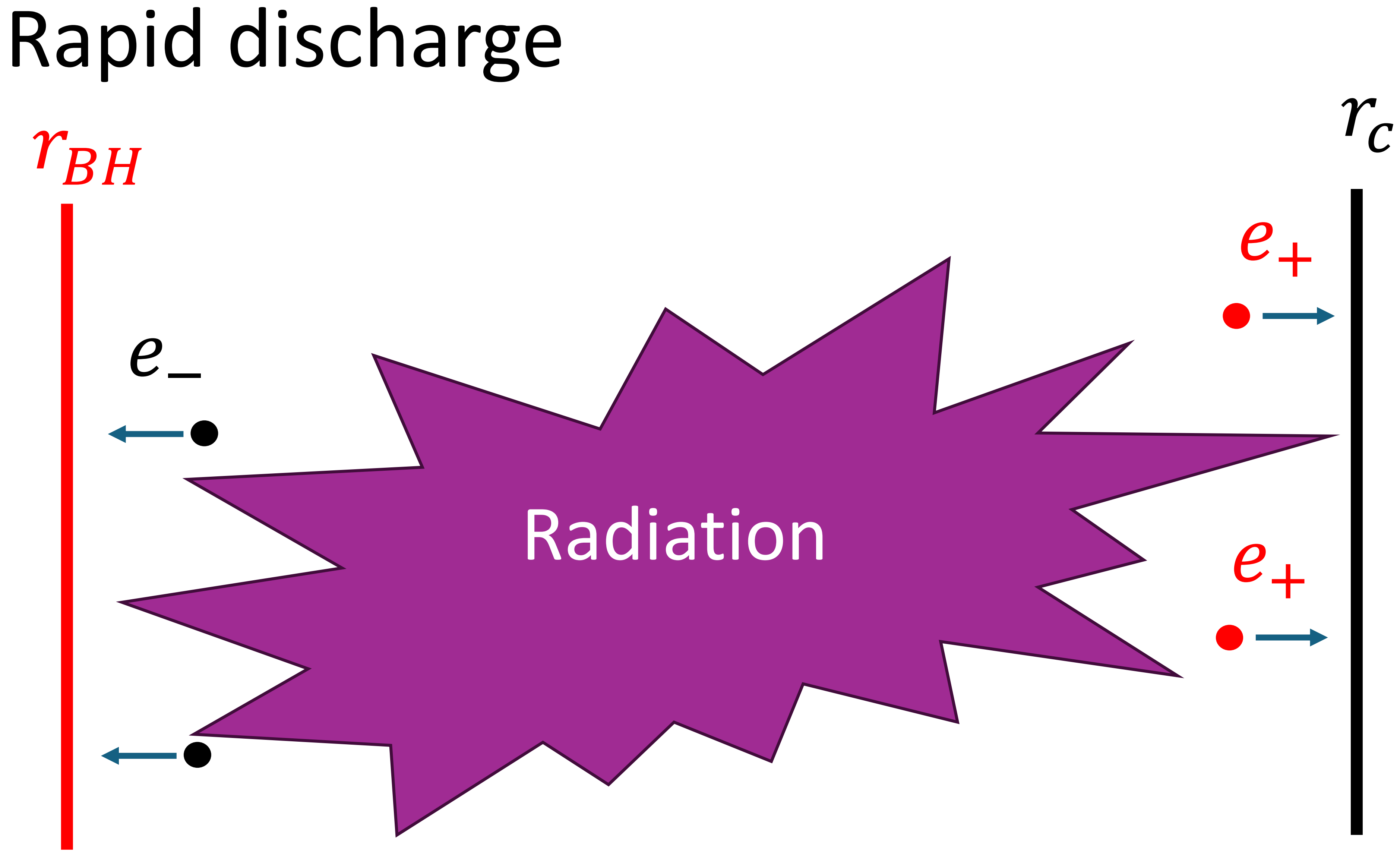


Rapid discharge



Rapid discharge




Rapid discharge
r_{BH}
r_c
e_+
e_-
Radiation
e_+

Festina Lente [Montero, Van Riet, Venken ‘19]

Demand charged black holes of cosmic size evaporate back to empty de Sitter space rather than crunching singularity:
All charged particles should obey

$$m^2 \gtrsim q\, g M_P H$$

Festina Lente (FL) bound:
Black holes should decay, but not too quickly

FL and string theory

Have given a heuristic black hole argument for FL

Can we also check FL explicitly in top-down models of quantum gravity (string theory)?

Problem: there is a long-running debate on to what extend de Sitter vacua are controlled in string theory.

Want to be sure our computation is controlled when checking conjecture

FL and string theory

$m^2 \geq \sqrt{6} g q M_p H$ can be rewritten as

$m^4 \geq \sqrt{2} (gq)^2 V$ so remains nontrivial constraint in $M_p \to \infty$ limit

Need unambiguous V to apply in QFT

-SUSY fixes V=0, can then break dynamically, e.g. ISS. Seem to obey FL

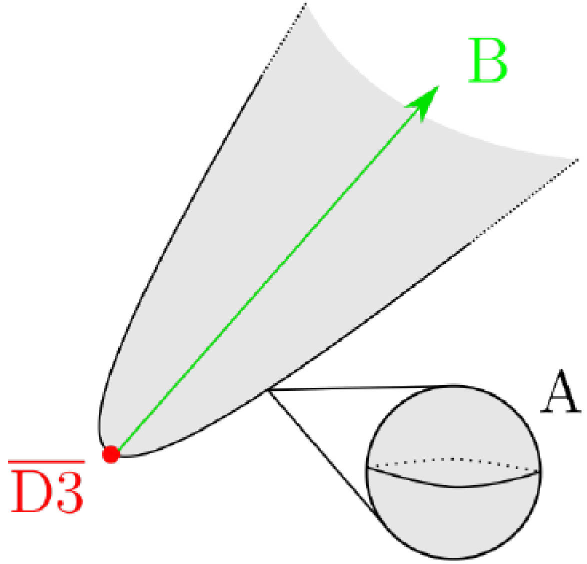
-Should also constrain QFTs constructed starting from quantum gravity (constructed such that value V not ambiguous)

Klebanov-Strassler throat [Klebanov, Strassler '00; Kachru, Pearson, Verlinde '02]

4 external direction+ 6 noncompact internal directions:

Klebanov-Strassler throat with anti-D3 at the tip provides a QFT with positive vacuum energy from a 4D perspective

6 internal dimensions: 3D A-cycle+ 3D B-cycle



$$V_{\overline{D3}} \sim \frac{g_s^3}{4\pi}\frac{e^{4A_0}}{\sigma_0^2}$$

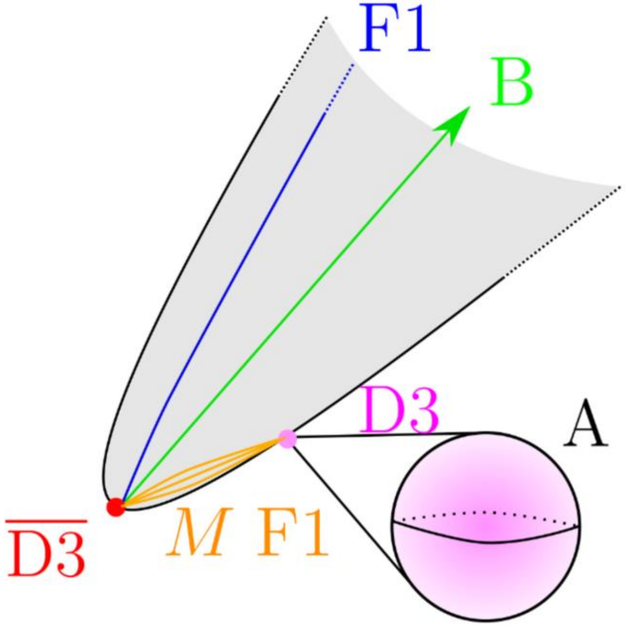
A(y) warping
y=0 tip of throat

M units of F_3 flux on A-cycle
K units of H_3 flux on B-cycle
Radius A-cycle at tip

$$r_0 = \sqrt{g_s M}\, l_s \,.$$

FL in the KS throat

D3-branes wrapping A-cycle pointlike in 4 external dimensions provide charged particles from 4D perspective



$$m^4 = e^{4A} T_{D3}^4 (\text{Vol}_A)^4 \gtrsim p M^2 g_s T_{D3} e^{4A}$$

$\rightarrow \quad g_s M^2 \gg \sqrt{p}$

This is also a necessary condition for the supergravity solution to be controlled
->FL provides known consistency conditions in controlled set-up

FL and string compactification

If we buy into FL we can apply it to proposed de Sitter compactifications of string theory (with gravity in the lower-dimensional de Sitter theory)

See [Montero, Vafa, Van Riet, Venken '21] for detailed discussion

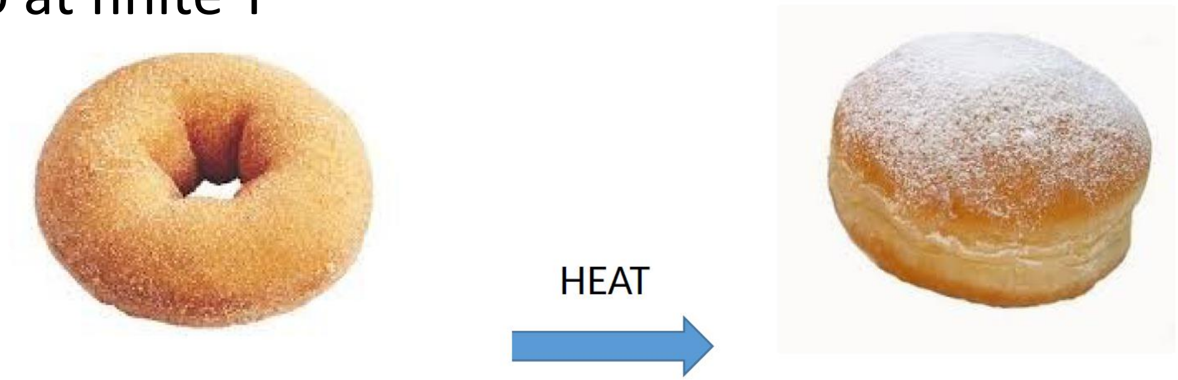
String theory

KS throat has confining gauge theory in holographic dual

What happens in the KS throat at finite temperature?

Series of papers analyzing this [Michel, Mintun, Polchinski, Puhm, Saad ,15; Polchinski ,15; Bena, Grana, Kuperstein, Massai ’15; Cohen-Maldonado, Diaz, Van Riet, Vercnocke ‘16; Bena, Blaback, Turton ’16; Cohen-Maldonado, Diaz, Gautason ,16; Armas, Nguyen, Niarchos, Obers, Van Riet ,19; Armas, Nguyen, Niarchos, Obers ‘19; Blaback, Gautason, Ruiperez, Van Riet ‘19; Nguyen ’20; Nguyen, Niarchos ‘22]

Recently reviewed in [Van Riet, Zoccarato ‘23] Doughnut-berliner transition: as heat up, the positive-energy vacuum destabilizes precisely when confinement would be lost, FL is obeyed also at finite T



META-STABLE UNSTABLE

Applicability FL at finite T

As universe expands, the temperature of the thermal radiation, lowers. If the analysis shows that the BH rapidly discharges to a big crunch, this should happen before the radiation has cooled significantly.

Rapid discharge happens within an e-fold unless

So except at extremely small coupling this is fine $g \lesssim H/M_p$

Then to check FL all we need to check is that whenever

$T \leq \left(\frac{cV}{\sigma}\right)^{1/d}$, FL is obeyed

Higgsing

Discussed quartic Higgs. Analogous bound generic Higgs potential

$$\frac{-V''(0)}{\sqrt{V(0)}} > \alpha\sqrt{\frac{c}{\sigma}}$$

If $\alpha/\sqrt{\sigma} > H/M_p$ implies (and stronger than) refined de Sitter conjecture at symmetry-restoring points