HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

# Macroscopic Dark Matter from dark confining phase transition

C. Gross, GL, A. Strumia, D. Teresi
arXiv [2105.02840]

**Giacomo Landini**

**Invisibles22 Workshop - Orsay**

21/06/2022

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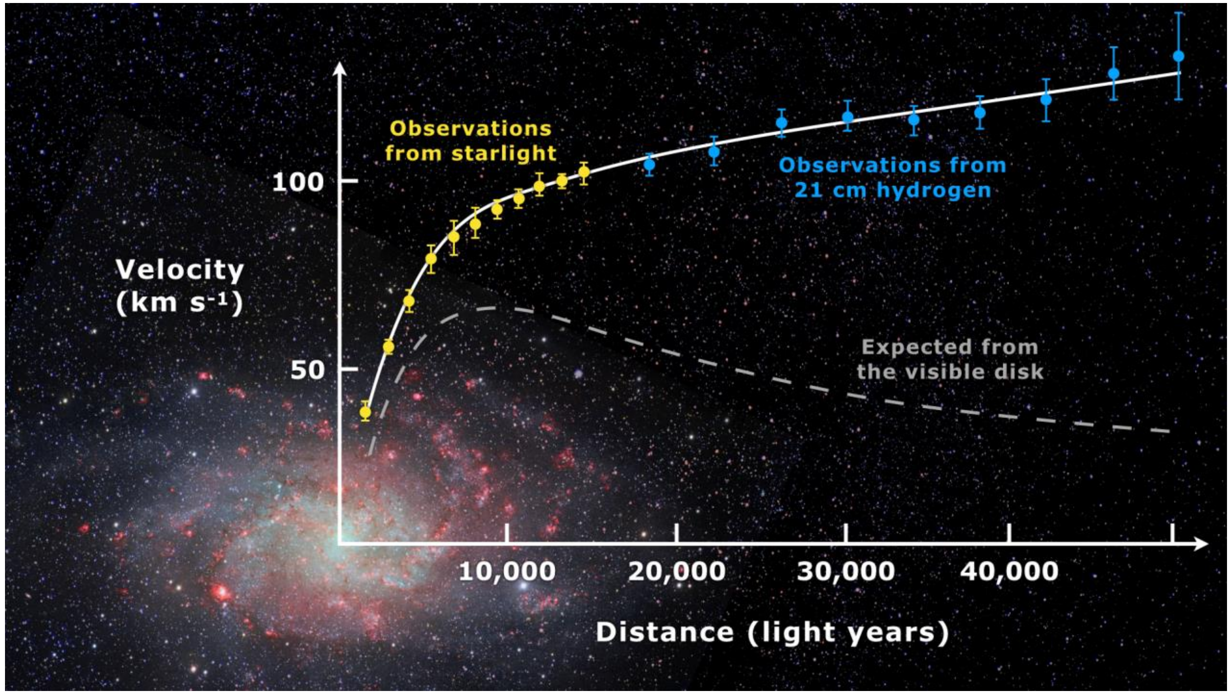
INSTITUT DE FÍSICA CORPUSCULAR

VNIVERSITAT DE VALÈNCIA

# Introduction

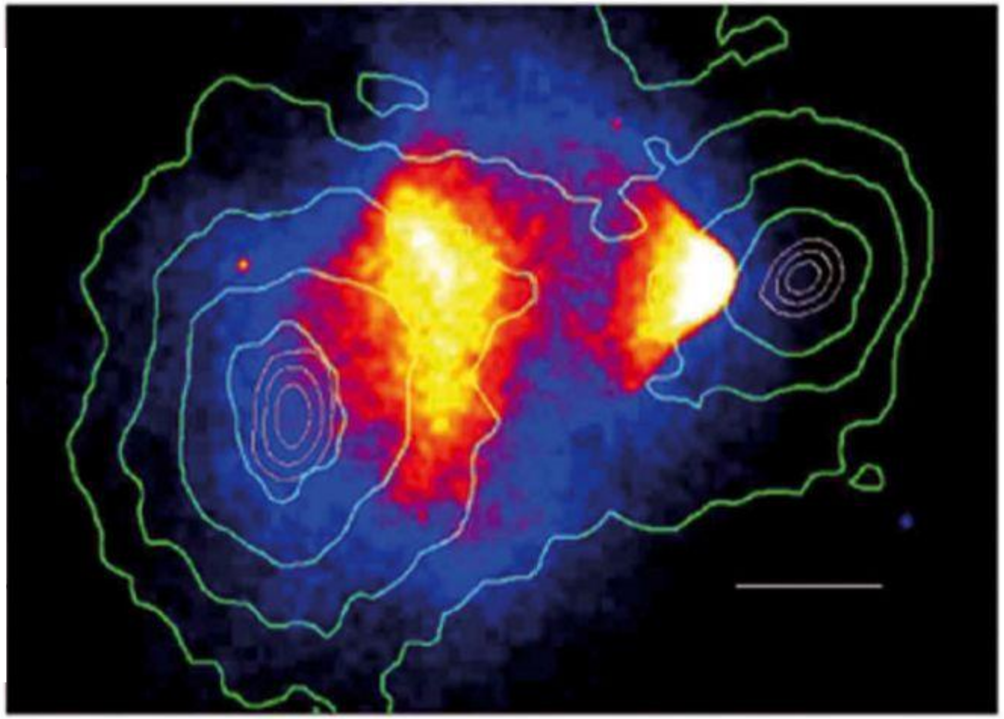
Dark Matter existence is supported by astrophysics and cosmology




Rotation curves of spiral galaxies flatten at large distances

# Introduction

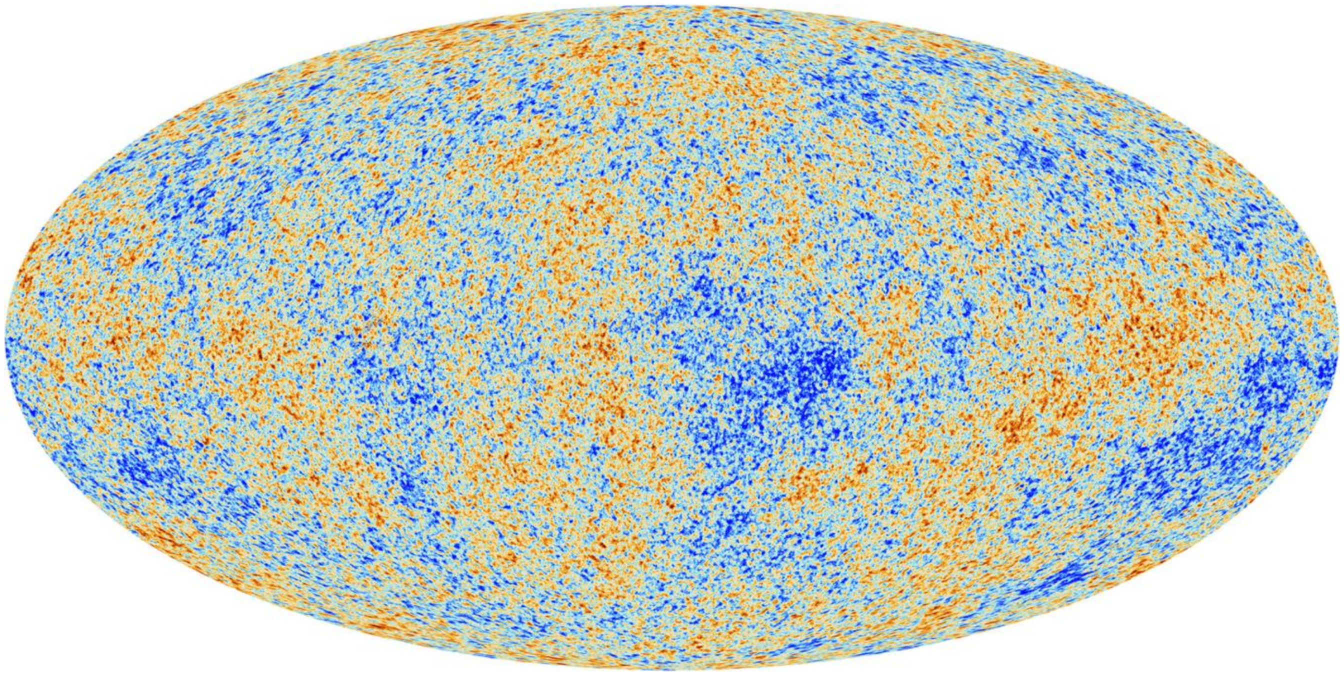
Dark Matter existence is supported by astrophysics and cosmology



Visible and total matter have different distributions in galaxy clusters

# Introduction

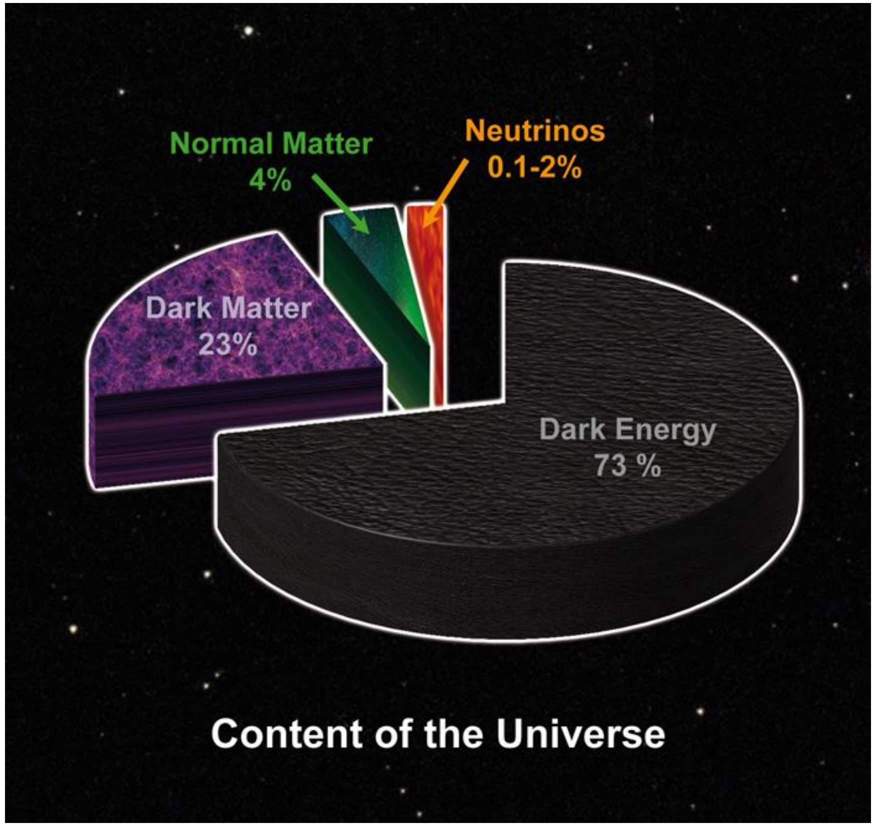
Dark Matter existence is supported by astrophysics and cosmology



CMB measurements predict a huge amount of Dark Matter

# Introduction

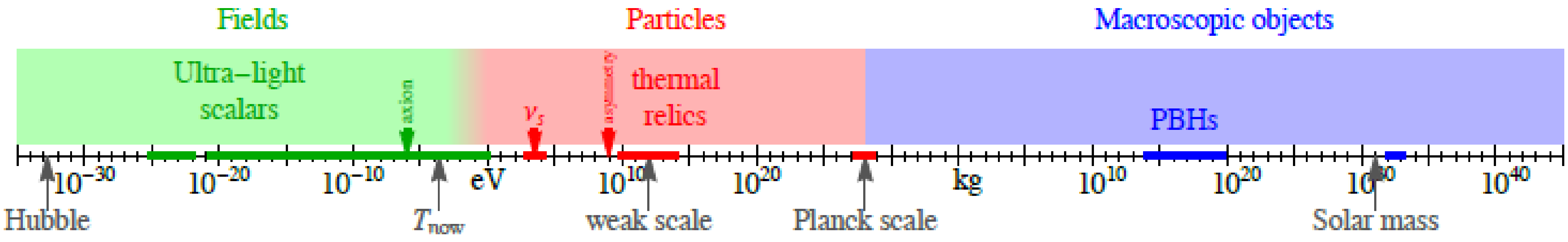
Today most of the Universe is dark!




Dark Matter fills the 84% of the matter content of the Universe

# Dark Matter candidates

The mass range of DM candidates spans over 80 order of magnitudes




Axions/ALPs
Fuzzy DM

WIMPs
Warm DM/Sterile $\nu$

PBHs
Boson stars

# General idea

1) First order cosmological phase transitions

2) Strongly coupled gauge dynamics

3) A new *heavy* particle carrying *dark color*

$\Downarrow$

Dark Matter as a macroscopic object made of dark particles

# Setup

SU(N) dark gauge group (*dark QCD*) + 1 *heavy* dark quark

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}\mathcal{G}^a_{\mu\nu}\mathcal{G}^{\mu\nu}_a + \bar{q}(i\gamma_\mu D^\mu - m)q \qquad m \gg \Lambda_{\rm DC}$$

The SM and the dark sector are only gravitationally coupled

$$T_{\rm dark} \neq T_{\rm SM} \qquad\qquad r \equiv \rho_{\rm dark}/\rho$$

**Assumption**: the dark quark abundance is dominated by an *asymmetry*

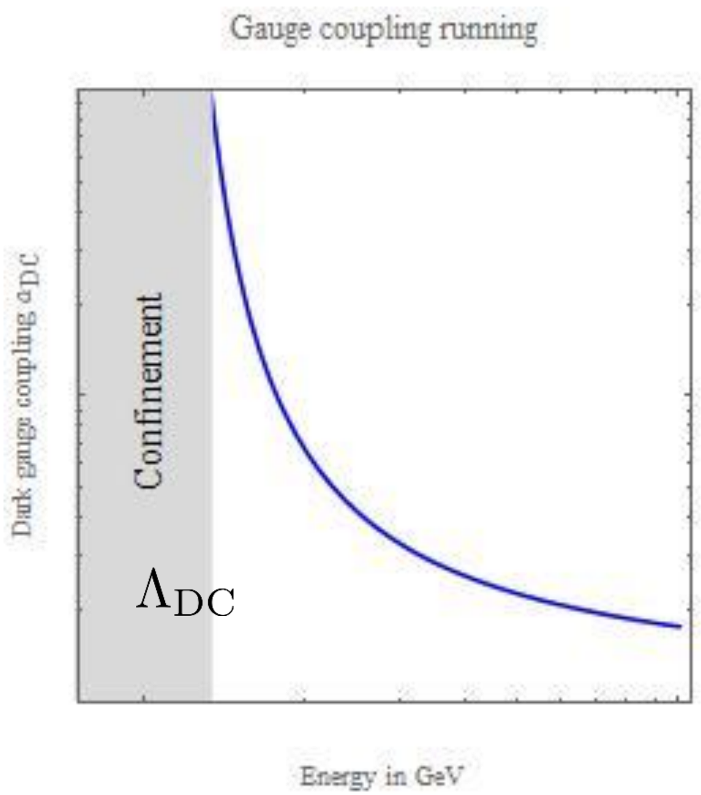
$$n_q = sY \sim T^3_{\rm SM} Y$$

# Gauge Confinement

The dark gauge coupling grows at low energy and the theory confines

$$\alpha_{\rm DC} \approx \frac{6\pi}{11N}\frac{1}{\ln \mu/\Lambda_{\rm DC}}$$

$$\Lambda_{\rm DC} \ll m$$




The d.o.f. of the theory must combine into *gauge-invariant bound states*: ***dark baryons*** and ***dark glue-balls***!

# Dark Glue-balls

Gauge-invariant bound states of dark gluons $m_{\rm DG} \approx \Lambda_{\rm DC}$

(In absence of a SM portal) they are stable and contribute to DM

The abundance is set by $3 \to 2$ cannibalistic processes

$$\Omega_{\rm DG} \propto \left(\frac{T_{\rm dark}}{T_{\rm SM}}\right)^3$$

DG contribution to DM is *negligible* for very *cold dark sectors*

$$T_{\rm dark} \ll T_{\rm SM} \qquad r \ll 1$$

# Dark Baryons

Gauge-invariant bound states of N dark quarks $m_B \approx Nm$

Baryon formation is a step-by-step process

$$q + q \to qq$$
$$qq + q \to qqq$$
$$\dots$$

Typical scattering energy scale
$m \gg \Lambda_{\rm DC}$

Cross sections must be evaluated at $\alpha_{\rm DC}(m) \ll 1$

Energy in dark baryons = observed energy in DM fixes the asymmetry parameter

$$Y \approx {\rm eV}/m$$

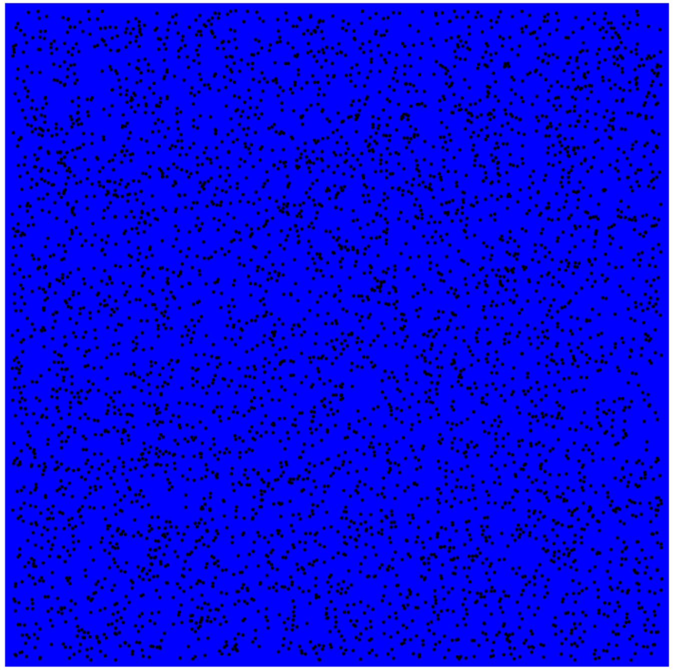
if they make ***all*** the DM

*Baryons will be the constituents of our macroscopic bound states*

# Phases of the theory

$$T_{\mathrm{dark}} \gg \Lambda_{\mathrm{DC}}$$

*Deconfined phase*

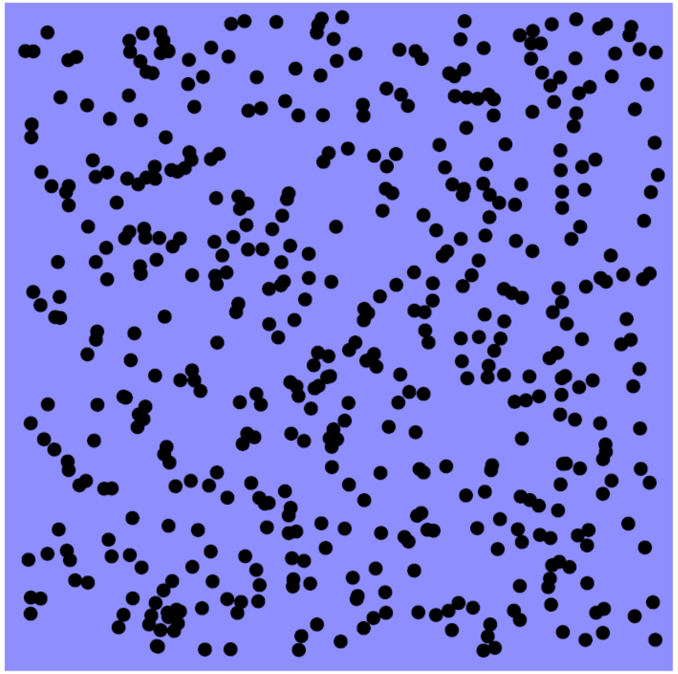


dark quark-gluon plasma

dark quarks and dark gluons
are free and weakly-interacting

$$T_{\mathrm{dark}} \leq \Lambda_{\mathrm{DC}}$$

*Confined phase*



Hadronic phase

dark quarks and dark gluons combine into
gauge-invariant bound states

# Confining phase transition

Early Universe $T_{\rm dark} \gg \Lambda_{\rm DC}$

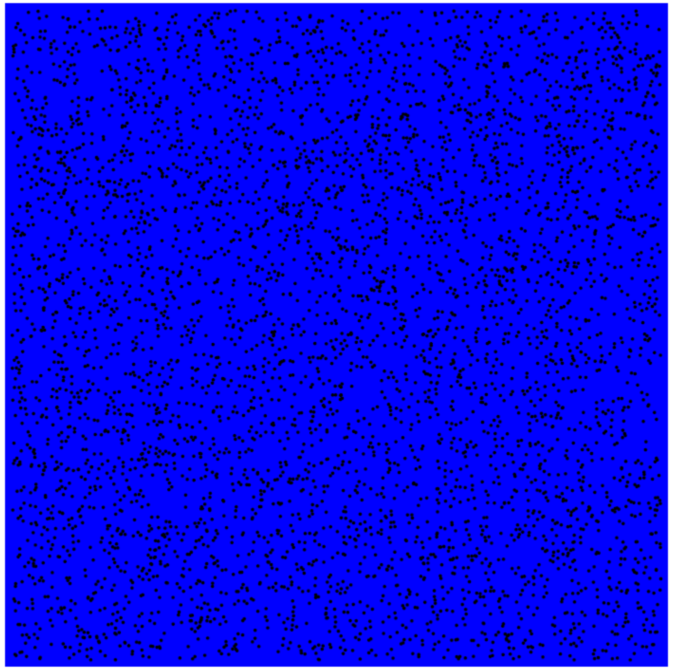
When $T_{\rm dark} \simeq \Lambda_{\rm DC} \equiv T_{\rm cr}$

➡ *Confining phase transition*

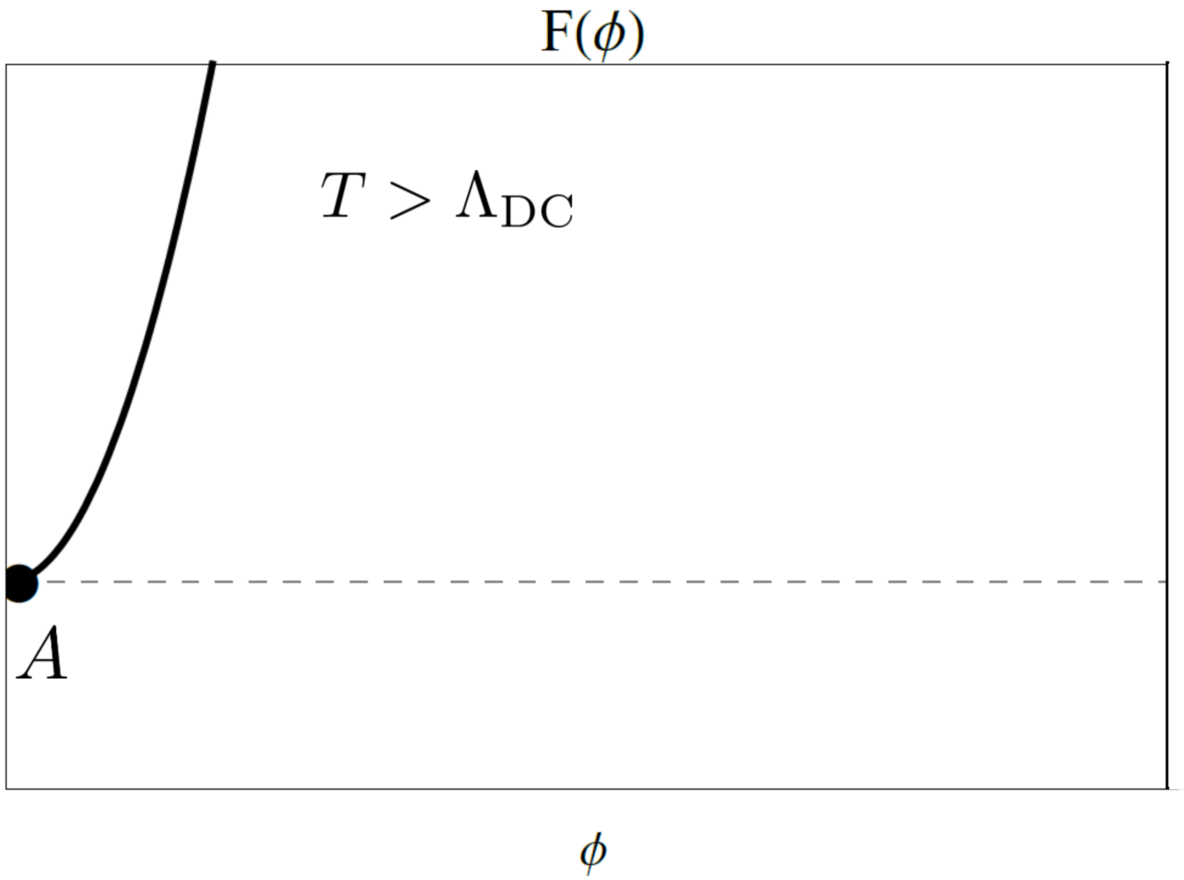
Our model: 1 heavy + 0 light quarks

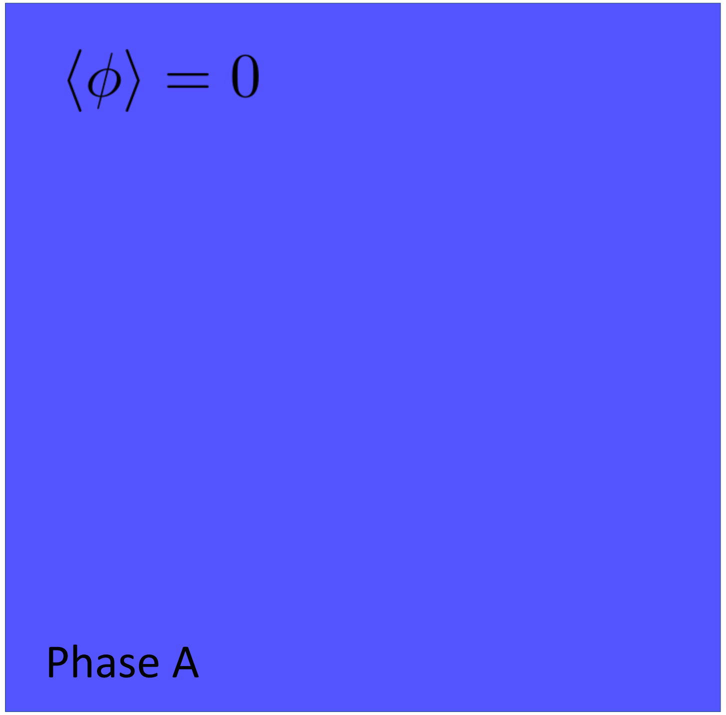
➡ *First order phase transition*

*Deconfined phase*



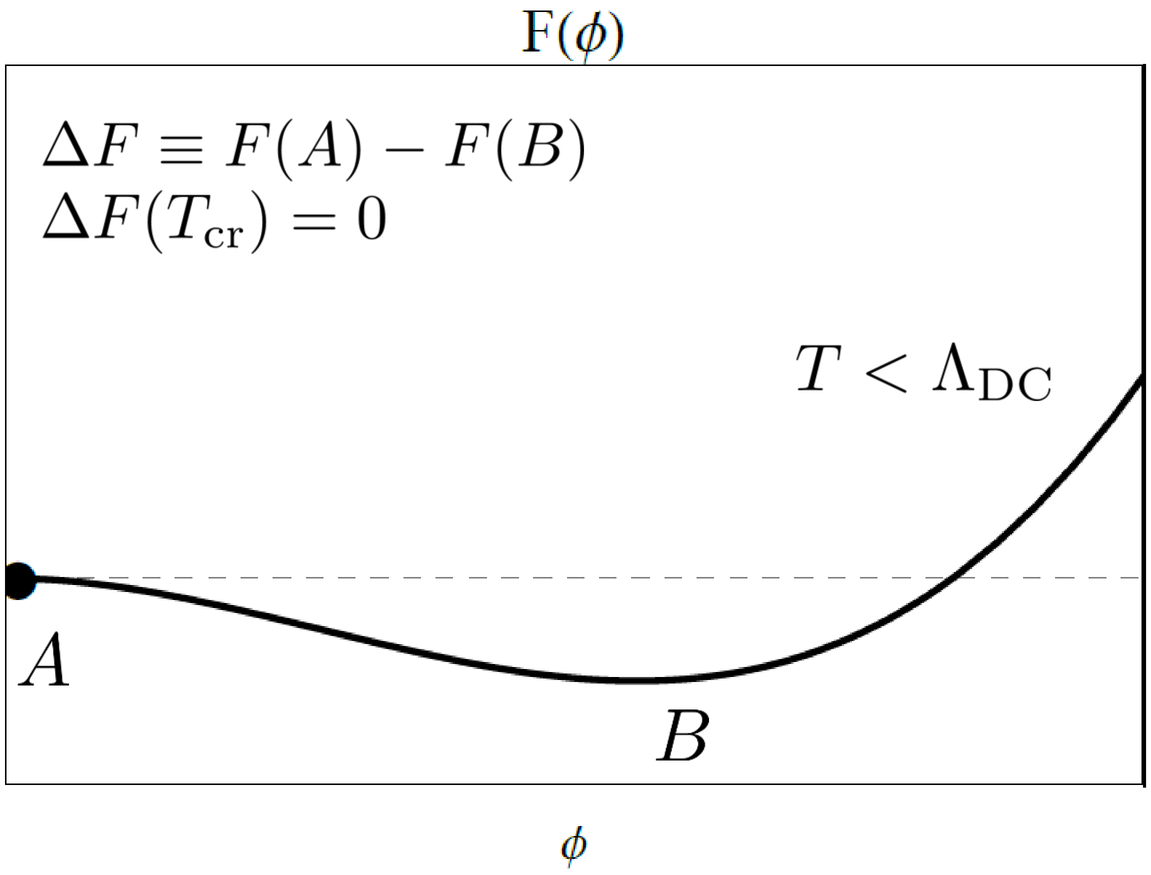
# First order phase transitions

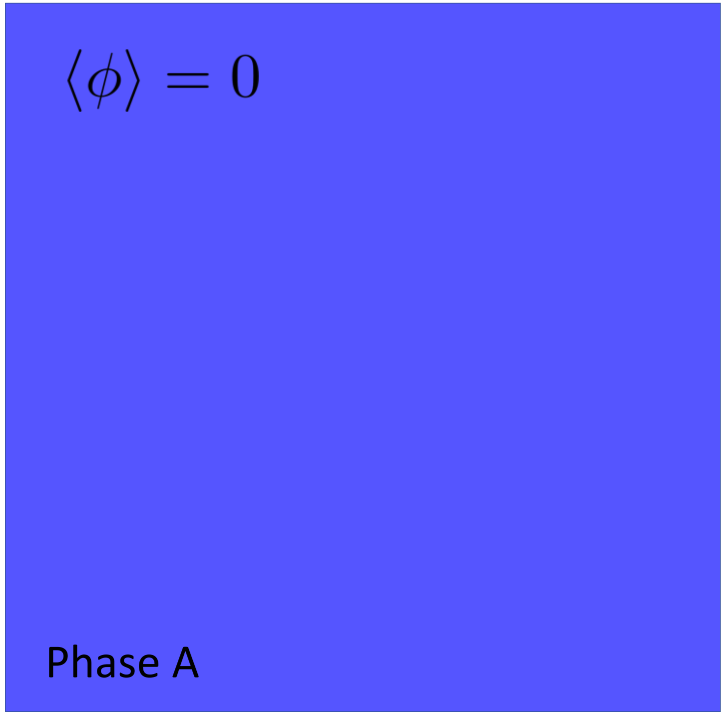



A = deconfined phase

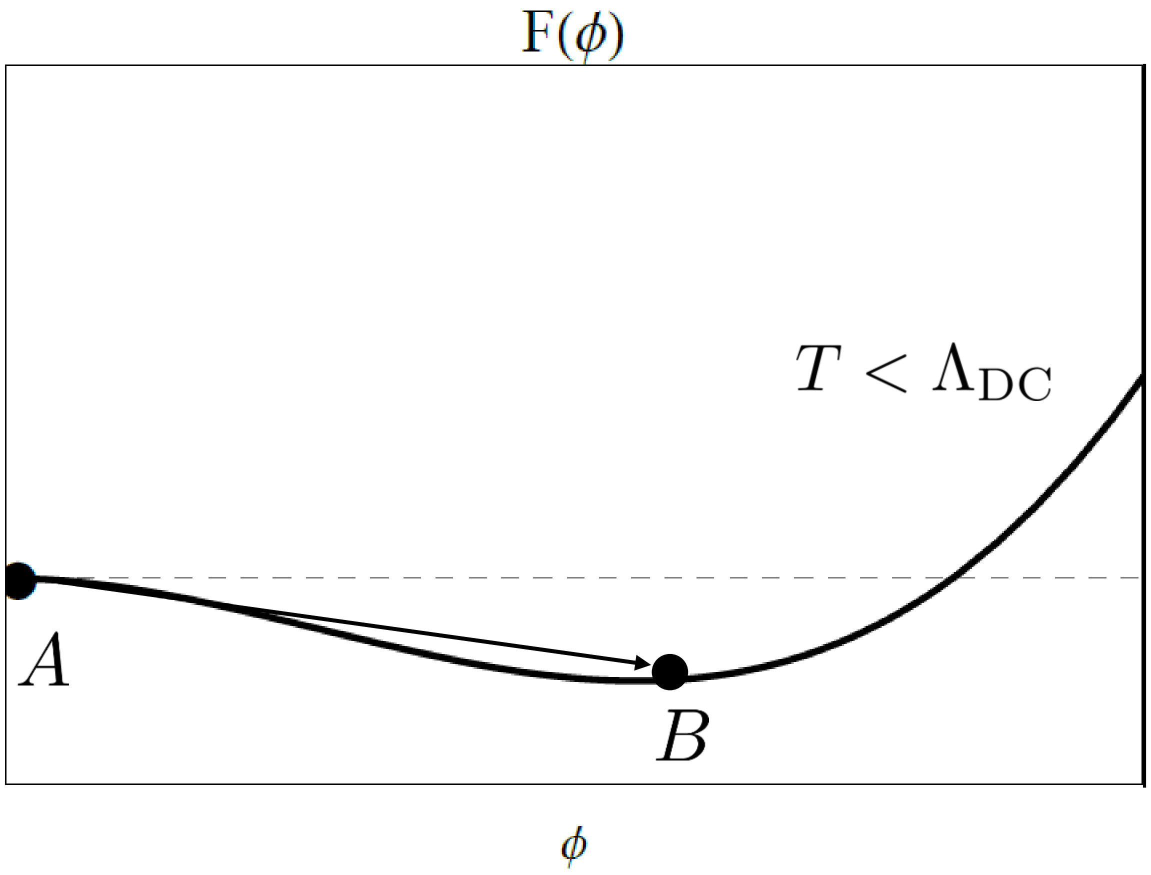
# First order phase transitions

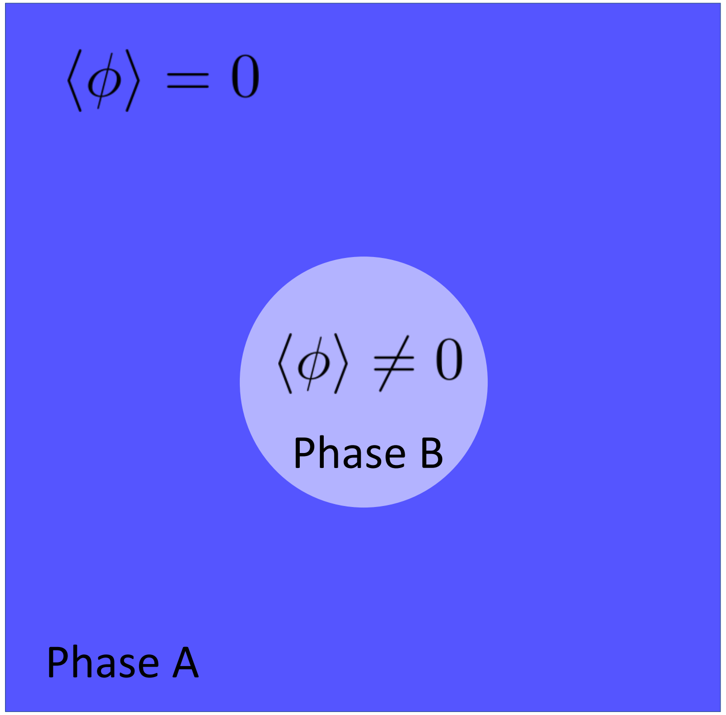



A = deconfined phase
B = confined phase

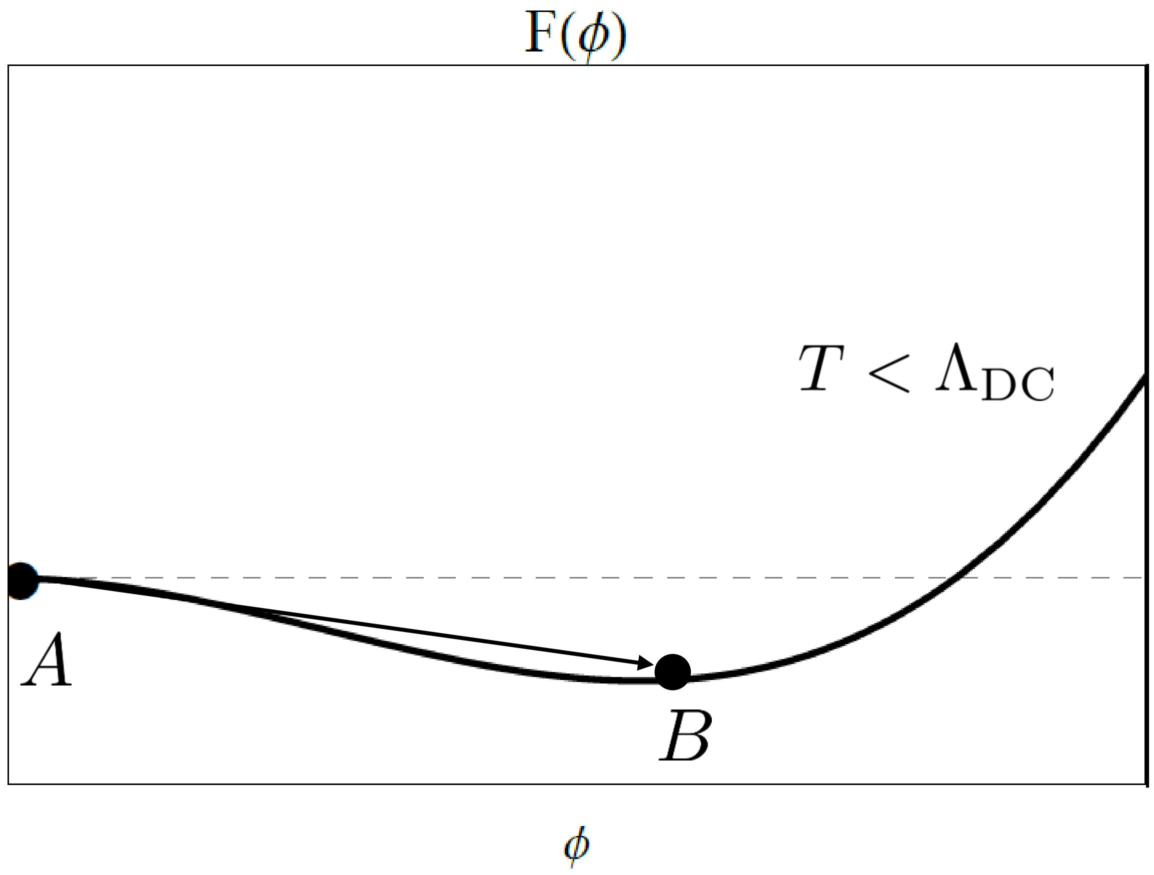
# First order phase transitions

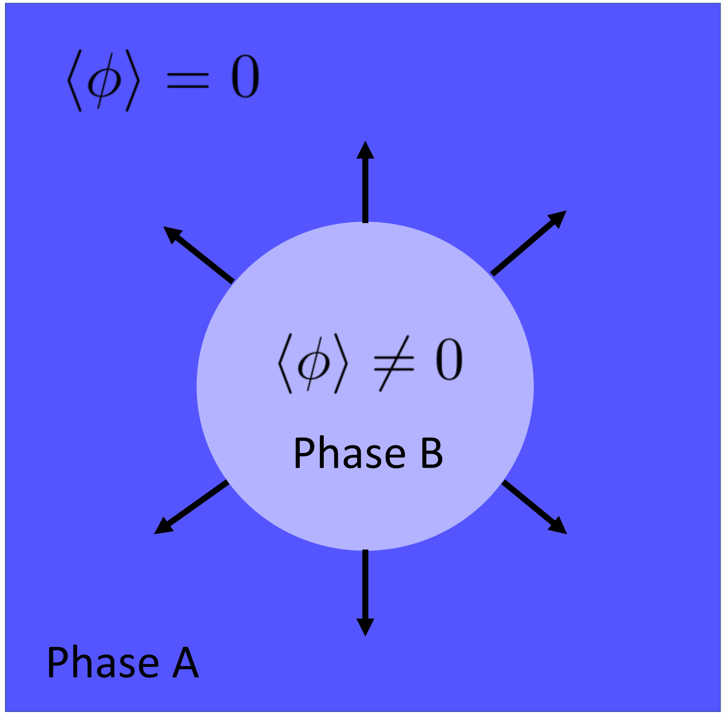



Bubbles of confined phase **nucleate**, expand and fill the Universe

# First order phase transitions

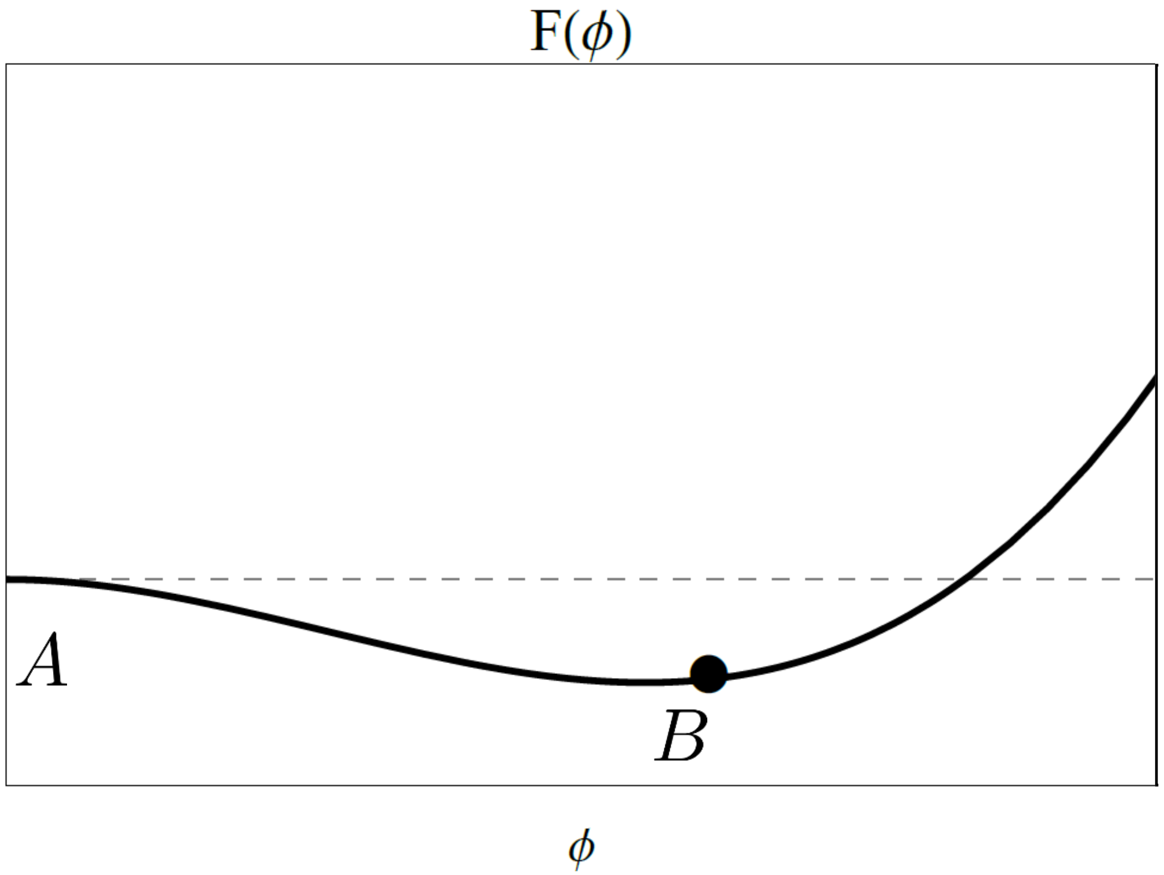


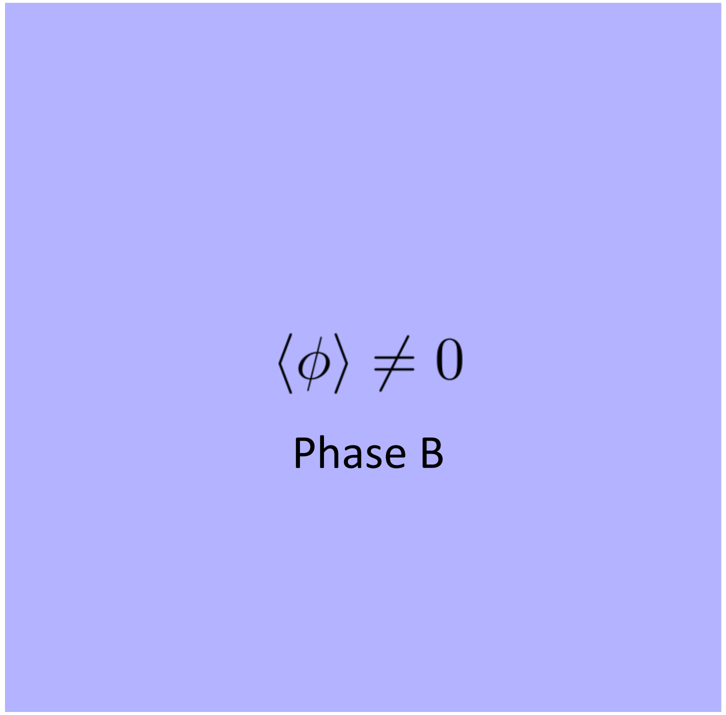




$$\Delta P = -\Delta F$$

Bubbles of confined phase nucleate, **expand** and fill the Universe

# First order phase transitions

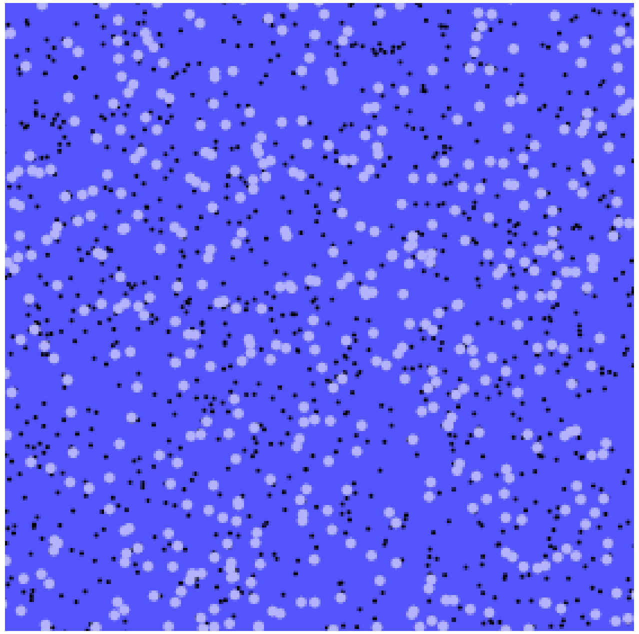



Bubbles of confined phase nucleate, expand and **fill the Universe**

# Confining phase transition

$a)$ Nucleation, $x \approx 0.1$

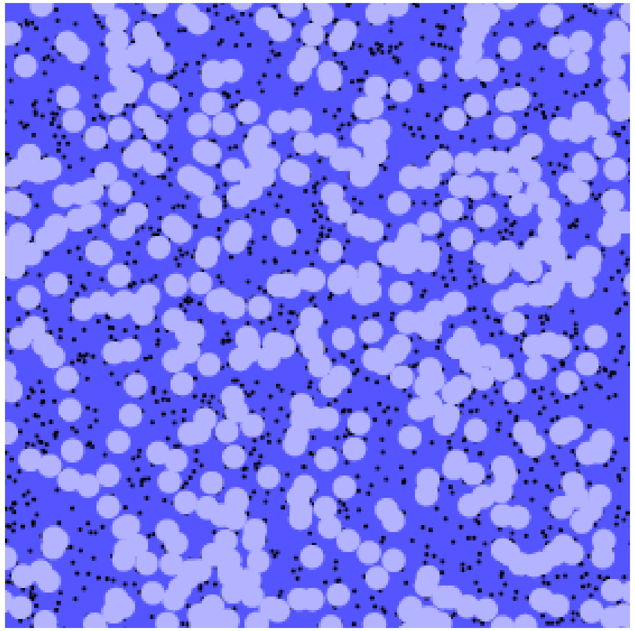


Nucleation temperature: bubbles of confined phase start nucleating

$$T_{\rm dark} \lesssim \Lambda_{\rm DC}$$

# Confining phase transition

$b$) Percolation, $x \approx 1/2$

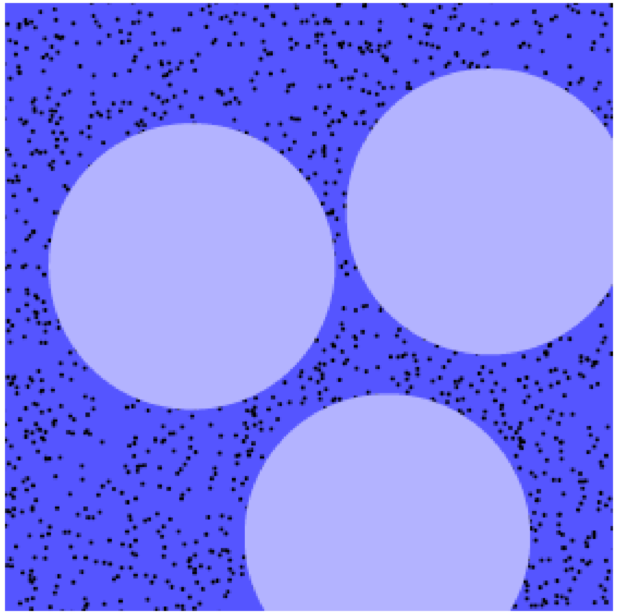


Slow and isothermal bubble expansion + coalescence

$$T_{\rm dark} \approx \Lambda_{\rm DC}$$

# Confining phase transition

c) Coalescence, $x \approx 1/2$



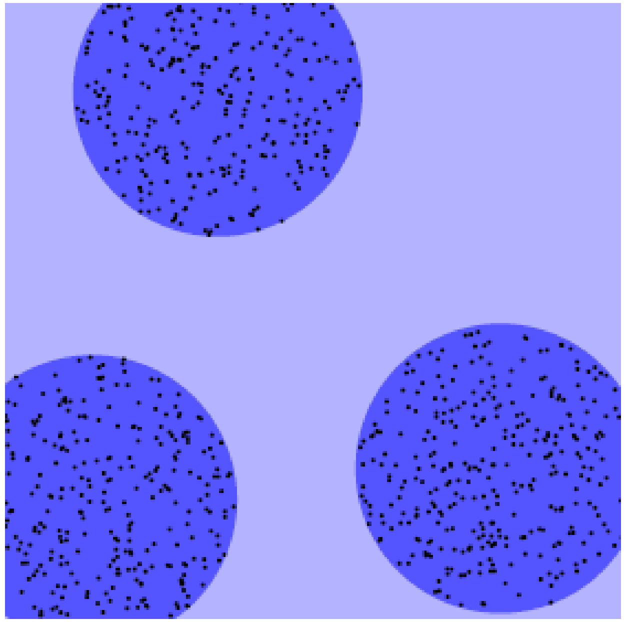
Slow and isothermal bubble expansion + coalescence

$$T_{\rm dark} \approx \Lambda_{\rm DC}$$

# Confining phase transition

Universe: mostly in the confined phase + *pockets* of deconfined phase

$c'$) Coalescence, $x \approx 1/2$



The heavy dark quarks are *trapped inside* the pockets

# Dark Baryon formation (1)

Baryon formation is a step-by step process

$$q + q \to qq$$
$$qq + q \to qqq$$
$$\cdots$$

We can estimate the *collision time-scale* for baryon formation processes

$$\tau_{\rm coll} \sim \frac{1}{n_q \sigma v_{BF}} \sim \frac{m^2 R^3}{\alpha^3_{\rm dark} Q}$$

$Q$ #Quarks in a pocket

$R$ Radius of the pocket

Baryon formation is negligible during the Phase Transition if

$$\tau_{\rm coll} \gg \tau_{\rm PT} \sim \frac{1}{g_{\rm dark} H}$$

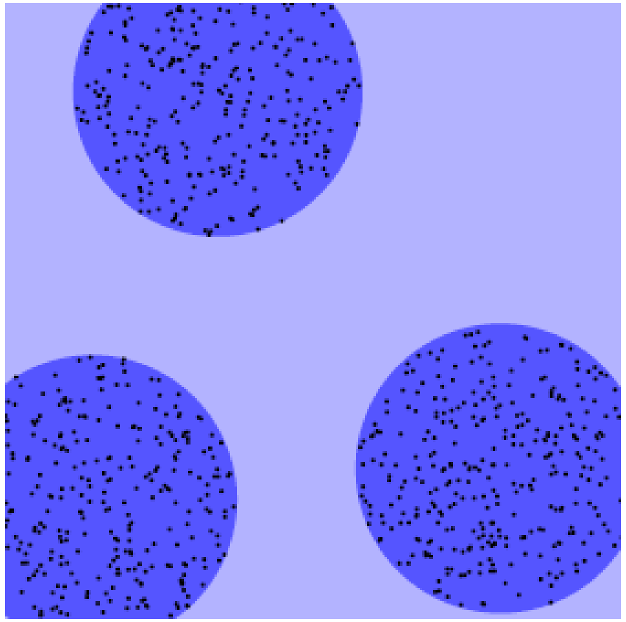
It is crucial that

$$\frac{m}{\Lambda_{\rm DC}} \gg \frac{M_{\rm Pl}}{m}$$

# Confining phase transition

Universe: mostly in the confined phase + *pockets* of deconfined phase

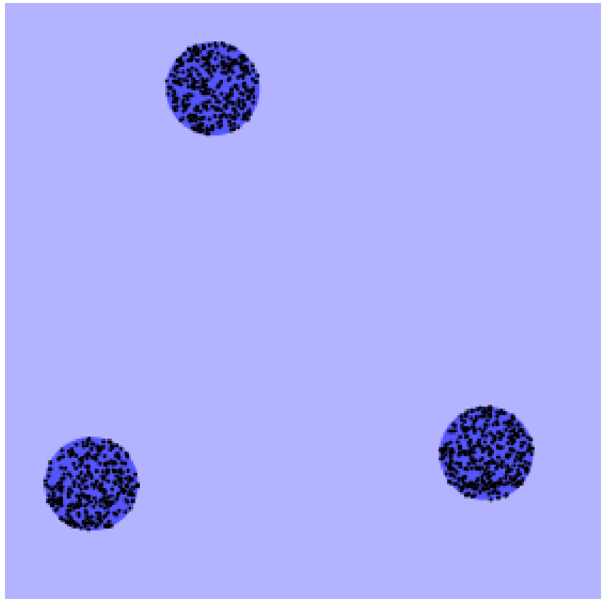
$c'$) Coalescence, $x \approx 1/2$



The heavy dark quarks are *trapped inside* the pockets
(baryon formation inside the pockets is negligible during the PT)

# Confining phase transition

$\partial$) Compression, $x \approx 1$

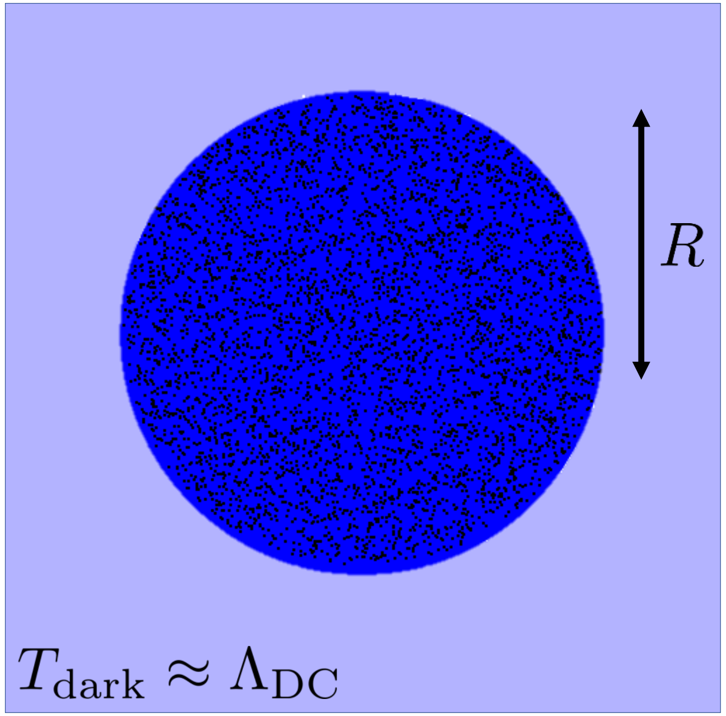


Slow and isothermal compression of pockets and quarks inside

$$T_{\rm dark} \approx \Lambda_{\rm DC}$$

# Pockets dynamics: pressures

Pockets compression as the phase transition goes on

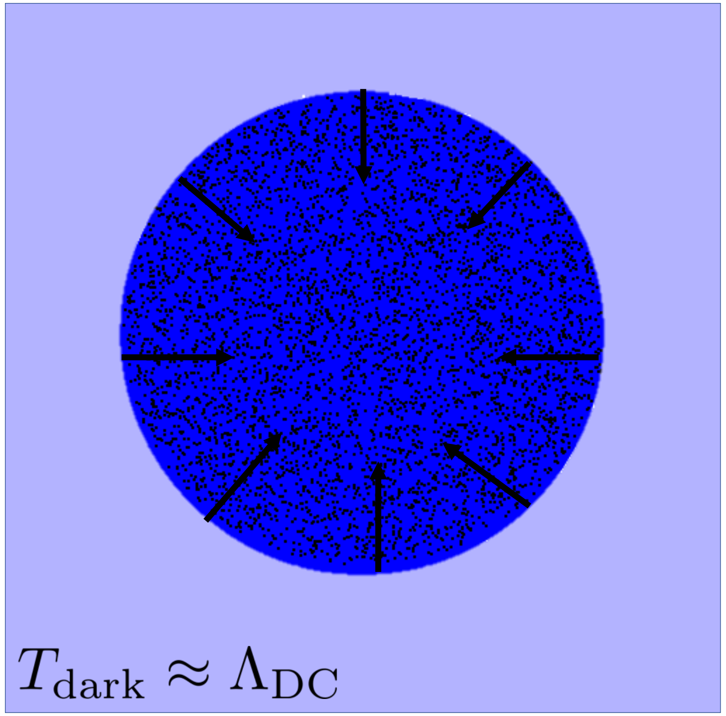



Pockets contain a gas of dark quarks with negligible interactions

New contributions to the *pressure on the wall of the pockets* as $R$ gets smaller

# Pockets dynamics: pressures

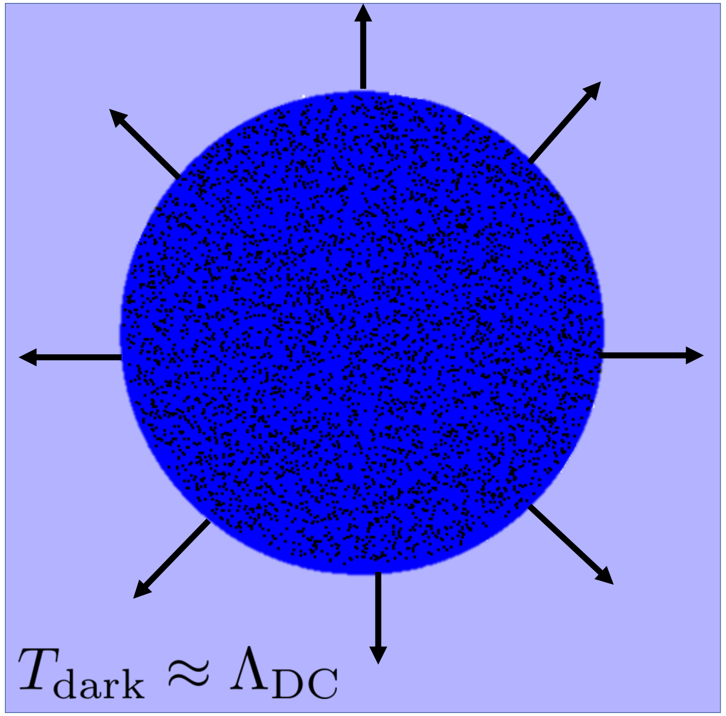
Vacuum energy = free energy difference between the two phases




$$p_V \propto R^0$$

# Pockets dynamics: pressures

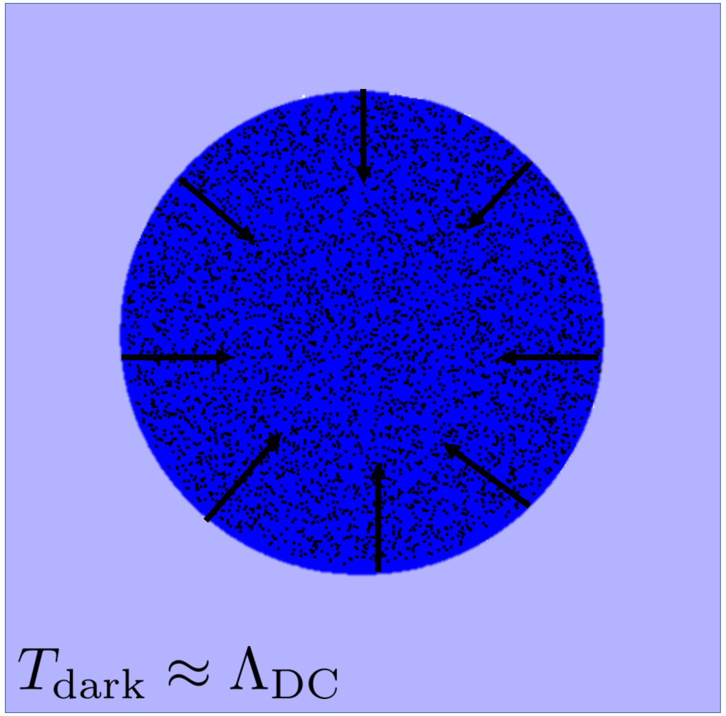
Thermal pressure of the dark quark gas




$$p_{\mathrm{gas}} \propto R^{-3}$$

# Pockets dynamics: pressures

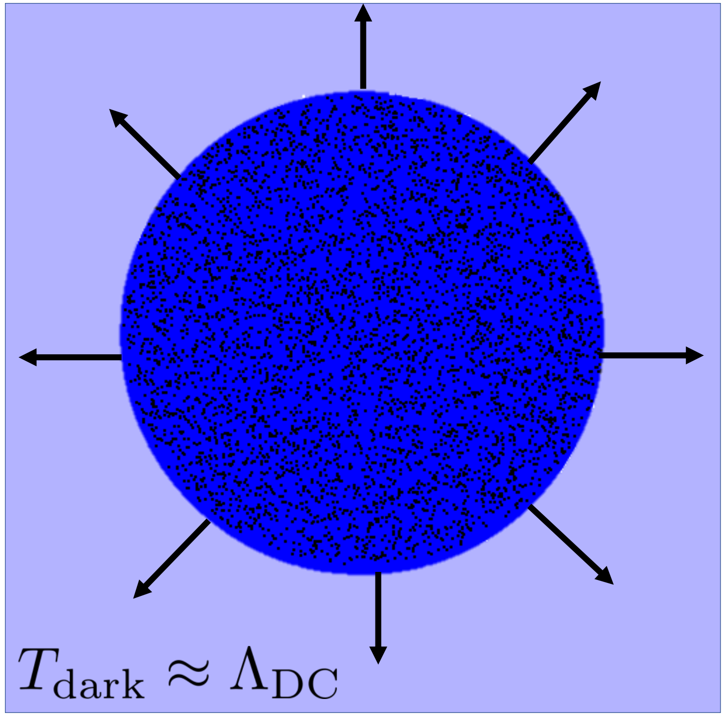
Pressure by *gravitational attraction* (quarks are very heavy!!)




$$p_{\mathrm{gravity}} \propto R^{-4}$$

# Pockets dynamics: pressures

Quantum Fermi pressure




$$p_F \propto R^{-5}$$

# Gravitational bound states

If pockets get compressed so much that

$$p_{\text{gravity}} \gtrsim p_{\text{gas}} = p_V$$

the system undergoes a *gravitational collapse*. This occurs if

$$Q \gtrsim Q_{\text{cr}} \approx 0.1 \left(\frac{M_{\text{Pl}}}{m}\right)^3 \frac{T^2}{T_{\text{cr}}^2}$$

$\Downarrow$

Number of quarks inside a pocket $\quad Q \approx Y(R_i \Lambda_{\text{DC}})^3$

$\Downarrow$

This sets a lower bound on the quark mass $\quad m \geq m_{\text{cr}}(\Lambda_{\text{DC}}, r)$

# Gravitational bound states

Two possible final states

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Two possible final states

**Dark dwarfs:** Fermi pressure stops the gravitational collapse

$$p_F = p_{\text{gravity}} \quad \Rightarrow \quad R_{\text{dwarf}} \approx \frac{M_{\text{Pl}}^2}{m^3 Q^{1/3}} \qquad M = Qm$$

# Gravitational bound states

Two possible final states

**Dark dwarfs:** Fermi pressure stops the gravitational collapse

$$R_{\rm dwarf} \approx \frac{M_{\rm Pl}^2}{m^3 Q^{1/3}} \qquad\qquad M = Qm$$

**Black Hole:** gravitational collapse

$$Q \gtrsim Q_{\rm BH} = \frac{0.44}{\sqrt{N}} \left(\frac{M_{\rm Pl}}{m}\right)^3 \qquad\qquad M = Qm$$

# Gravitational bound states

Two possible final states

**Dark dwarfs:** Fermi pressure stops the gravitational collapse

$$R_{\rm dwarf} \approx \frac{M_{\rm Pl}^2}{m^3 Q^{1/3}} \qquad\qquad M = Qm$$

**Black Hole:** gravitational collapse

$$Q \gtrsim Q_{\rm BH} = \frac{0.44}{\sqrt{N}} \left(\frac{M_{\rm Pl}}{m}\right)^3 \qquad\qquad M = Qm$$

*Dark Matter is a macroscopic object made of dark particles!!*

# Dark Baryon formation (2)

Baryon formation processes are characterized by the *collision time-scale*

$$\tau_{\rm coll} \sim \frac{1}{n_q \sigma v_{BF}} \sim \frac{m^2 R^3}{\alpha_{\rm dark}^3 Q} \qquad (1)$$

*New scale* in the problem: gravitational collapse occurs on a time-scale

$$\tau_G \sim \frac{M_{\rm Pl}}{\sqrt{m n_q}} \sim \frac{M_{\rm Pl} R^{3/2}}{\sqrt{mQ}} \qquad (2)$$

When (1) and (2) are comparable baryon formation processes become relevant

⬇

Formation of Dark Baryons starts during the gravitational collapse

# Dark Baryon formation (3)

Each formation process releases energy into the pocket

$$q + q + \ldots + q \to B + E_B$$

$$E_B \sim \alpha_{\rm DC}^2 m$$

If the total released energy is larger than the gravitational binding energy the bound state gets destroyed

$$E_B > U_{\rm grav} = Qm^2/RM_{\rm Pl}^2 \qquad (\alpha_{\rm DC} > v_{\rm esc})$$

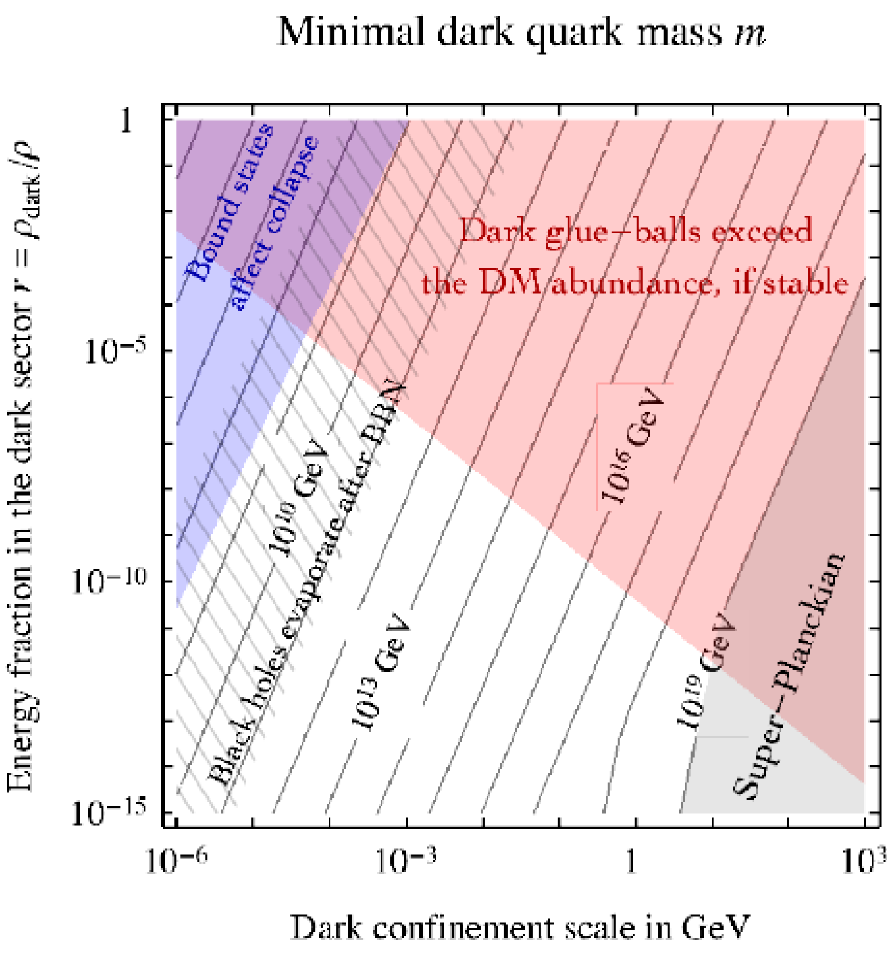
$$\Rightarrow \quad \alpha_{\rm DC} \gtrsim Q^{1/6}\left(\frac{m}{M_{\rm Pl}}\right)^{2/3} \gtrsim \left(\frac{m}{M_{\rm Pl}}\right)^{1/6}$$

$\downarrow$

Evaluated at $E \sim m$

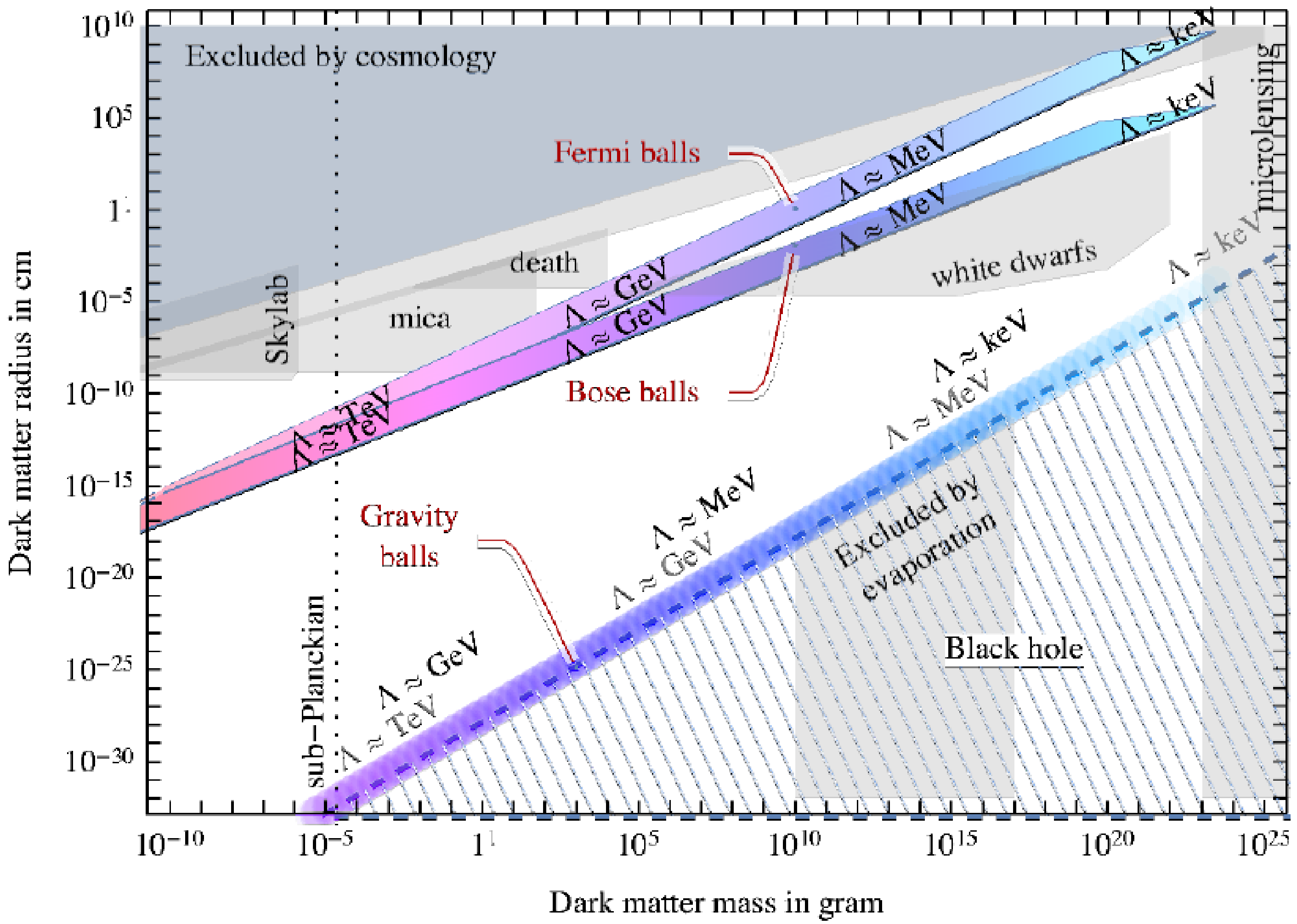
# Dark Baryons

Macroscopic Dark Matter is viable for super-heavy quark masses




In presence of a symmetric component $\bar{q}q$ annihilations would destroy the pockets

# Dark Matter parameter space




Dark dwarfs are viable DM candidates

Black Holes can be DM above the Hawking limit on evaporation

This project has received funding /support from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska -Curie grant agreement No 860881-HIDDeN

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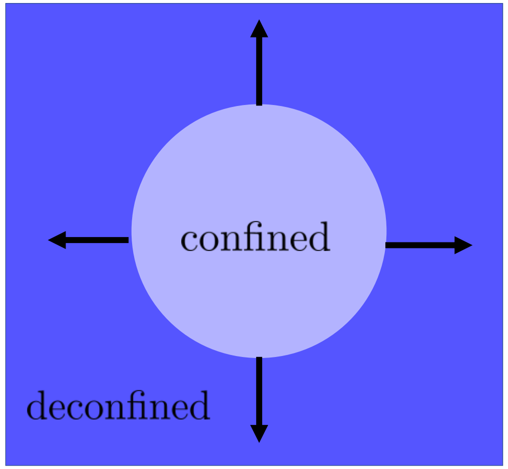
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

# Backup slides

# Bubble nucleation: thermodynamics




Free energy cost to increase a spherical bubble's surface area

$$\Delta F_{\rm surf} = 4\pi R^2 \sigma \qquad \sigma \sim T_C^3$$

Free energy decrease due to phase conversion in the bubble's volume

$$\Delta F_{\rm vol} = -\frac{4\pi}{3} R^3 \Delta f \qquad \Delta f = l\delta = l\left(1 - \frac{T_{\rm dark}}{T_{\rm C}}\right)$$

Latent heat $\quad l \equiv \Delta\rho(T_{\rm cr}) \sim T_{\rm cr}^4$

Large in a strongly-coupled theory

Heats the sorroundings of the bubble

Critical bubbles minimizes the free energy

$$R_c = \frac{2\sigma}{l\delta}$$

# Bubble nucleation: thermodynamics

Bubble nucleation becomes active when you can nucleate a bubble x Hubble volume

$$\gamma \approx T_C^4 \exp\left[-F_C/T_C\right] \approx H^4$$

$$\gamma \approx T_C^4 \exp\left[-\frac{k}{\delta^2}\right] \qquad k = \frac{16\pi}{3}\frac{\sigma^3}{l^2 T_C} \qquad k \approx 0.7 \times 10^{-4}$$

SU(3) lattice (small for general N)

$$\delta \equiv 1 - \frac{T_{\rm dark}}{T_{\rm cr}}$$

Bubble nucleate at nucleation temperature set by $\delta^2 \sim k$

The nucleation temperature is very closed to the critical temperature

# Bubble expansion

Competition between Hubble expansion (*cooling*) and latent heat (*heating*)

$$\frac{dT_{\rm dark}}{dt} \approx -HT_{\rm dark} + \frac{l\,dx/dt}{d\rho_{\rm dark}/dT_{\rm dark}} \approx -HT_{\rm dark} + \frac{T_C}{g_{\rm dark}}\frac{dx}{dt}$$

$$g_{\rm dark} = 2(N^2 - 1)$$

The system reaches a steady state

$$\frac{dT_{\rm dark}}{dt} \approx 0 \qquad \text{(cooling = heating)}$$

Bubble expansion is *slow* and *isothermal*

$$T \leq T_{\rm dark} \;\Rightarrow\; \Delta F = -\Delta P \to 0 \;\Rightarrow\; v_w \leq \delta$$

Time-scale of the phase transition $\tau_{\rm PT} \sim \frac{1}{g_{\rm dark} H}$

# Power emitted during compression

Does compression heat the pocket?

Heat exchange through dark gluons/glue-balls

$$W_{\rm rad} = \frac{4\pi R^2}{120}\pi^2(T_{\rm in}^4\epsilon_{\rm in} - T_{\rm out}^4\epsilon_{\rm out})$$

$$\epsilon_{\rm in} \sim \epsilon_{\rm out} \sim e^{-M_{\rm DG}/T}$$

in: gluons must convert into glue-balls

out: glue-balls abundance is suppressed

Temperatures above $\Lambda_{\rm DC}$ cool easily

Temperatures below $\Lambda_{\rm DC}$ need an exponentially slow time to cool

$$T \approx \Lambda_{\rm DC}$$

# Pressures equations

Pressure of a thermal gas

$$p_{\text{gas}} = QT/V$$

Gravity: uniform sphere of mass M = Q m

$$p_{\text{gravity}} \approx Q^2 m^2 / M_{\text{Pl}}^2 R^4$$

Fermi pressure (non-relativistic fermions)

$$p_F \approx Q^{5/3} / m R^5$$