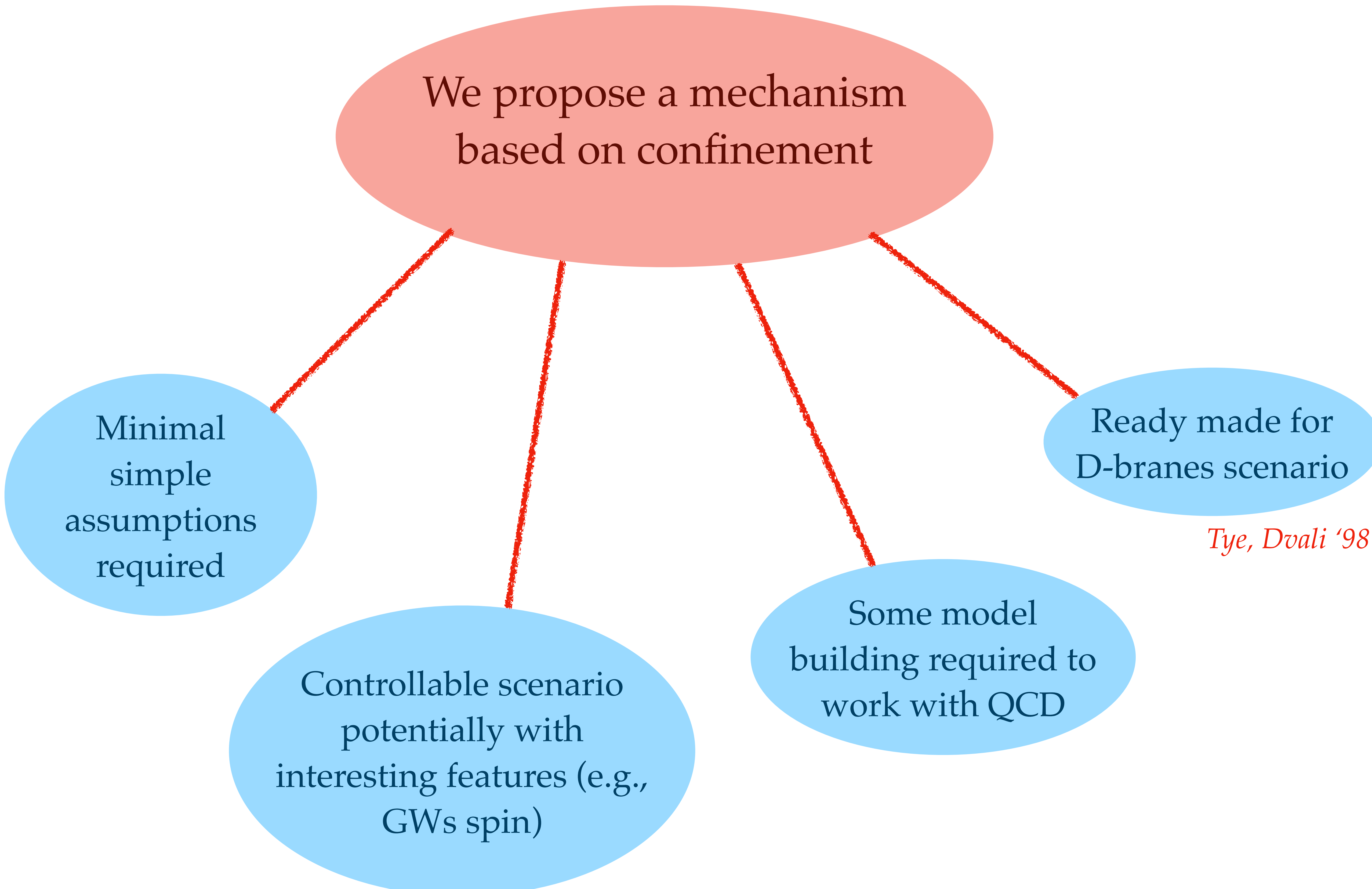
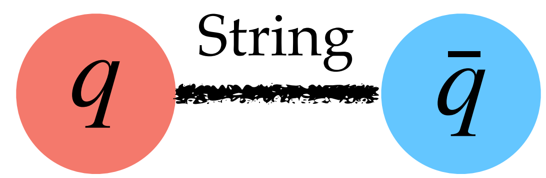
# Primordial black holes from confinement

Michael Zantedeschi
Tsung-Dao Lee Institute & Shanghai University, Shanghai
NEHOP 2023

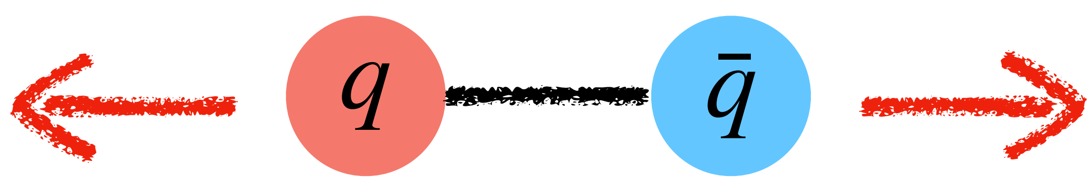
G. Dvali, F. Kühnel, MZ arXiv:2108.09471

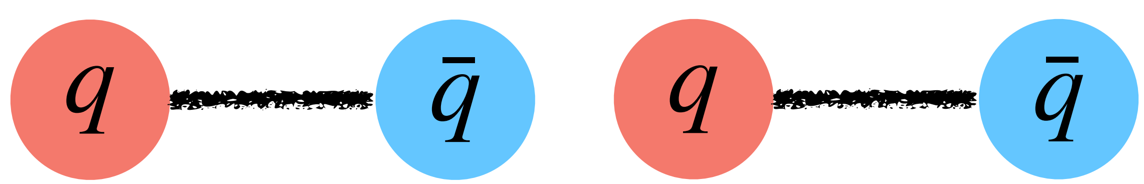


# Confinement




- Colour-charged particles (quarks and gluons) cannot be isolated. States are colourless
- Flux tubes of colour (strings) connect quarks
- Property of gauge theories (e.g., QCD)
- Separating quarks → nucleation of pairs




$P_{\text{tunnel}} \propto e^{-\pi \left( M_{\text{q}} / \Lambda_{\text{c}} \right)^2}$ → if $M_{\text{q}} > \Lambda_{\text{c}}$ it would not break!

# Confinement

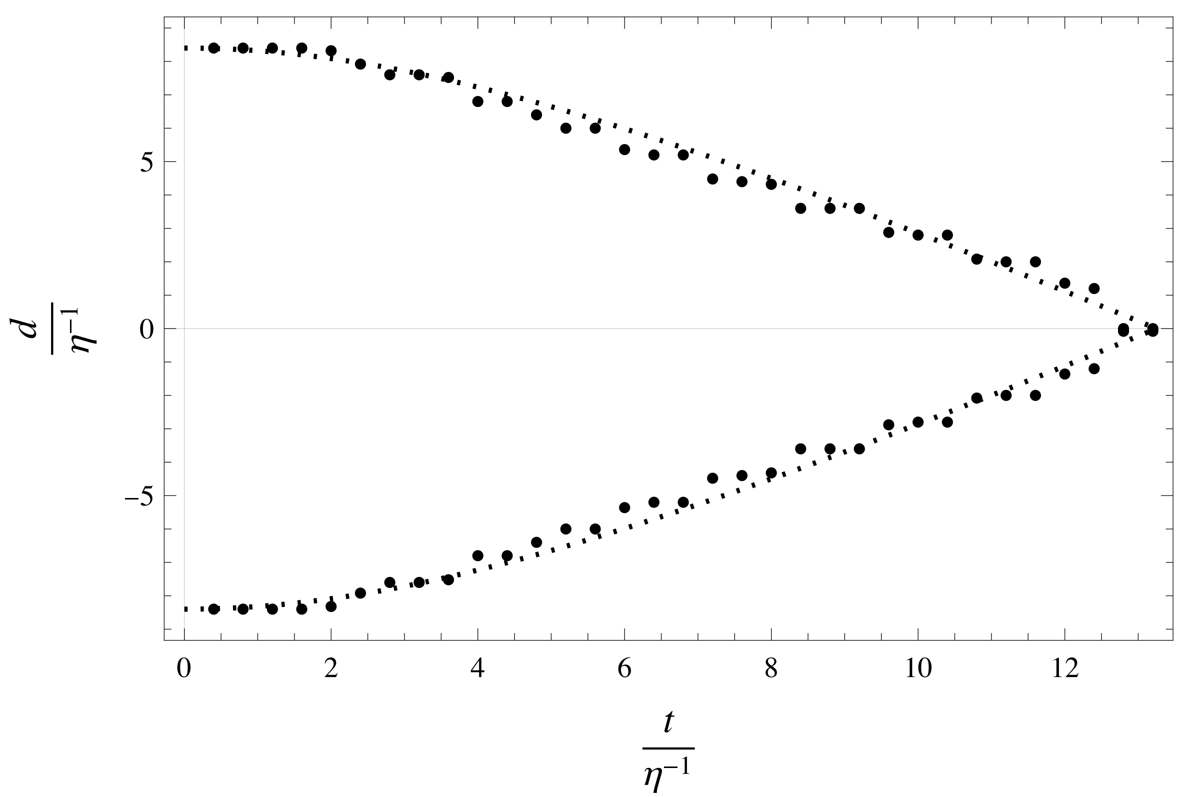
G. Dvali, J. S. Bermudez, MZ arXiv:2210:14947

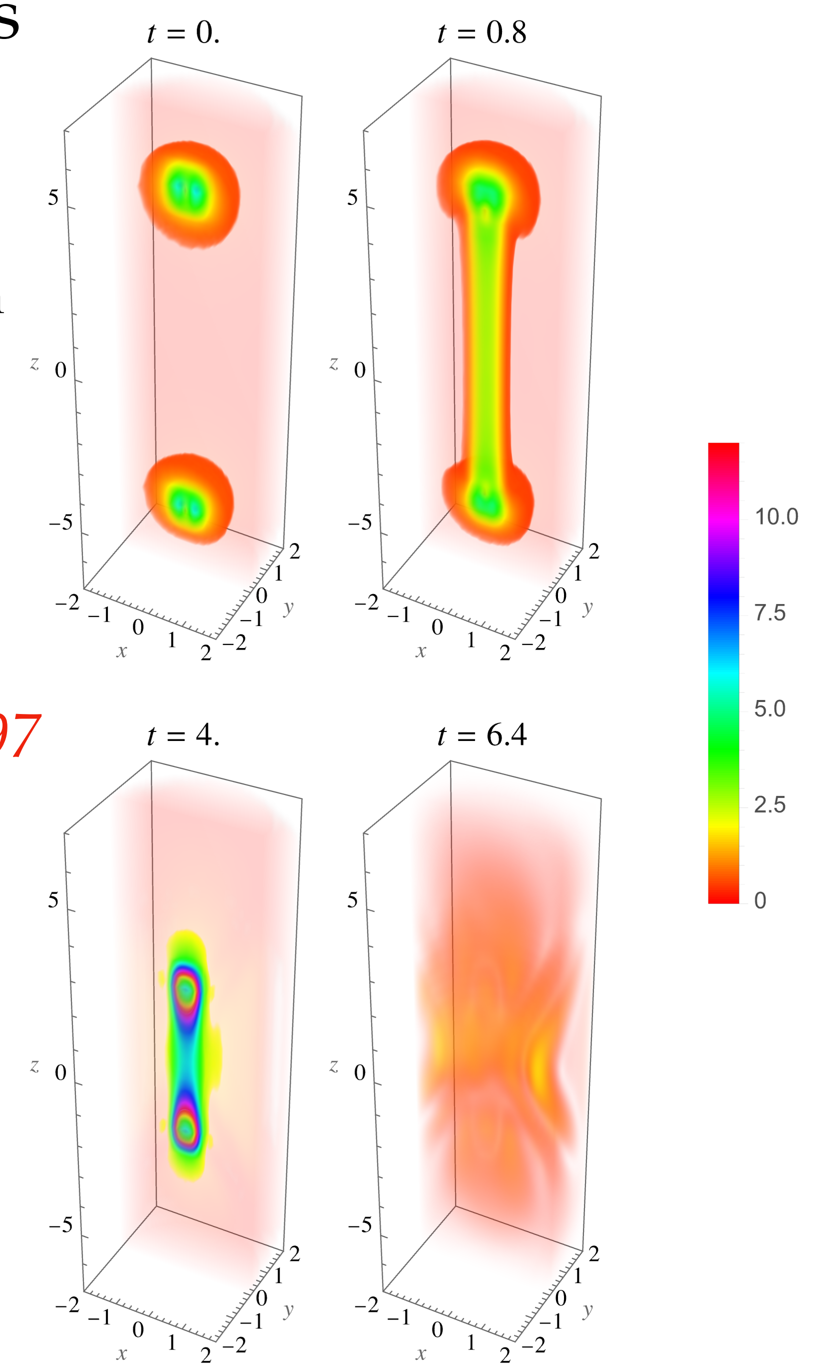
Example: Confinement of 't Hooft Polyakov Monopoles

- Relativistic acceleration of the monopoles $a = \Lambda_c^2 / m_m$
- Properly reproduced by point-like result

$$x(t) = \pm \frac{\mathrm{sgn}(t-t_0)}{a}\left(\gamma_0 - \sqrt{1 + (\gamma_0 v_0 - a\,|\,t - t_0\,|\,)^2}\right)$$

*Martin, Vilenkin '97*



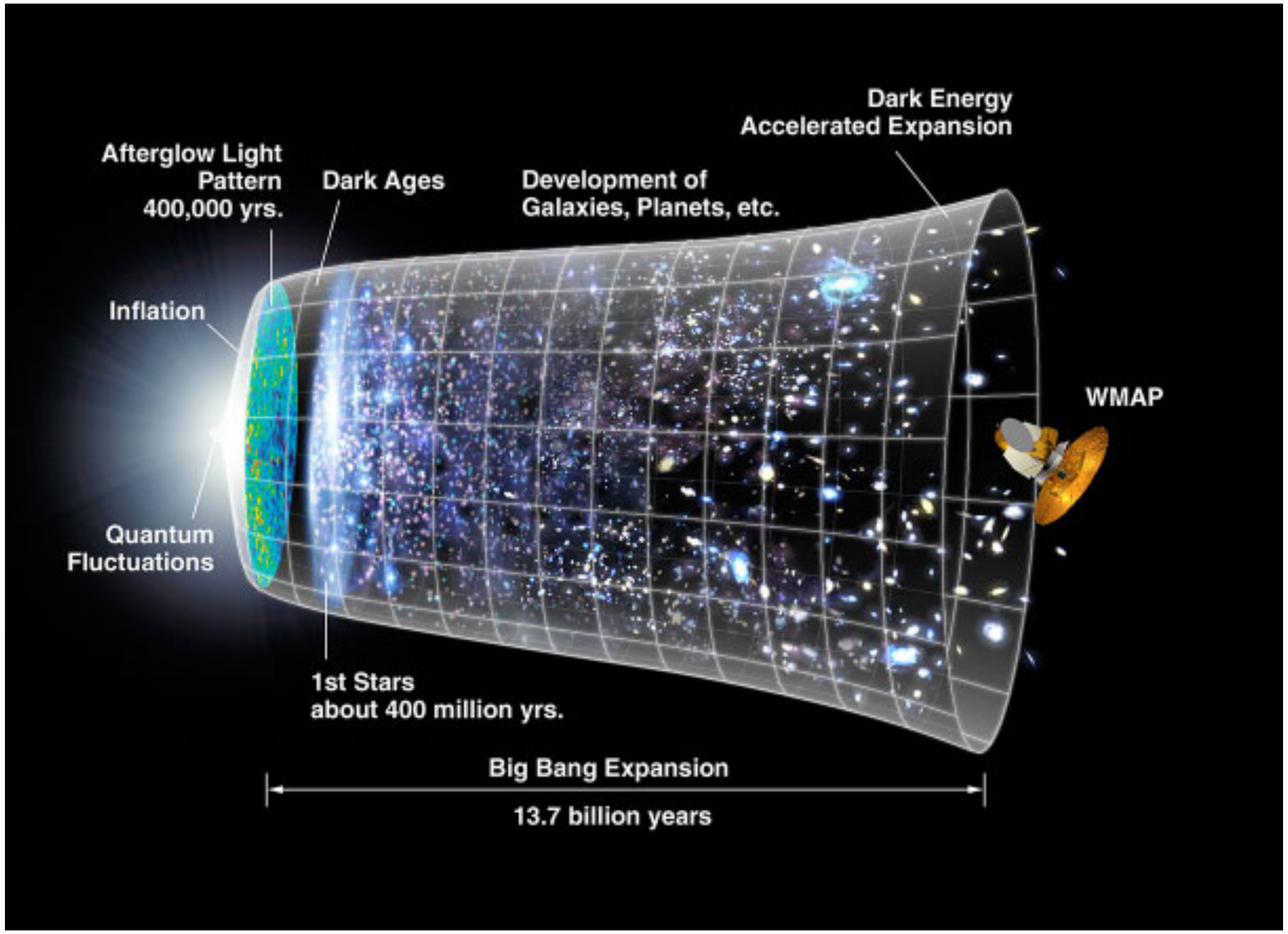



# Inflation

Period of exponential expansion

$$a(t) = a_0\, e^{H_{\rm i}\, t}, \quad H_{\rm i} \approx \text{const}$$

Introduced by Guth to address the flatness, horizon and monopole problem




Credit NASA

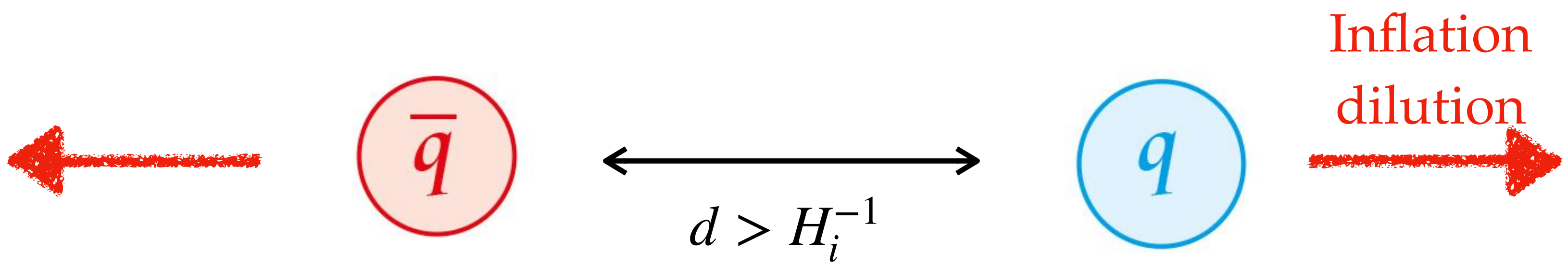
Fields fluctuate due to quasi-de-Sitter spacetime and particles are produced e.g.,

$$P \propto e^{-2\pi \frac{m}{H_{\rm i}}} = e^{-\frac{m}{T_{\rm H}}}, \quad H_{\rm i} < m$$

*Basu, Guth, Vilenkin, '91*

# Formation Mechanism:

**Step 1:** de Sitter fluctuations produce quarks during inflation

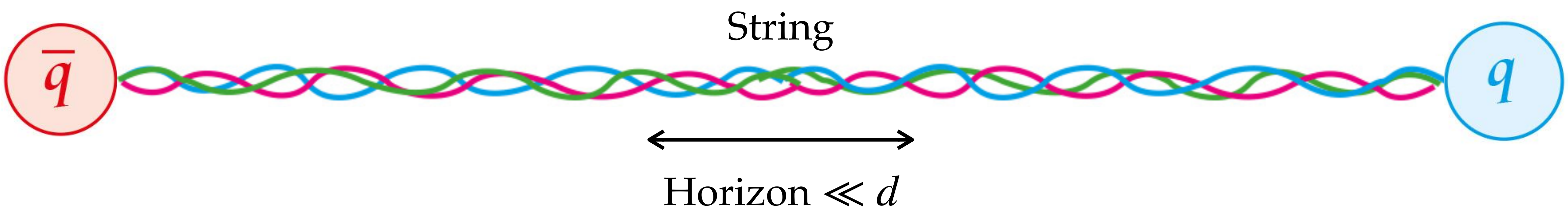



- Focus on a simple pair case (more complicated configurations possible)
- Constant production rate $\lambda$
- Depends on the relative mass scales
- Interested in distribution of quarks at super horizon distances
- Distance grows as $d \propto e^{N_e}$

See T Matsuda arXiv:hep-ph/0509061.

# Formation Mechanism:

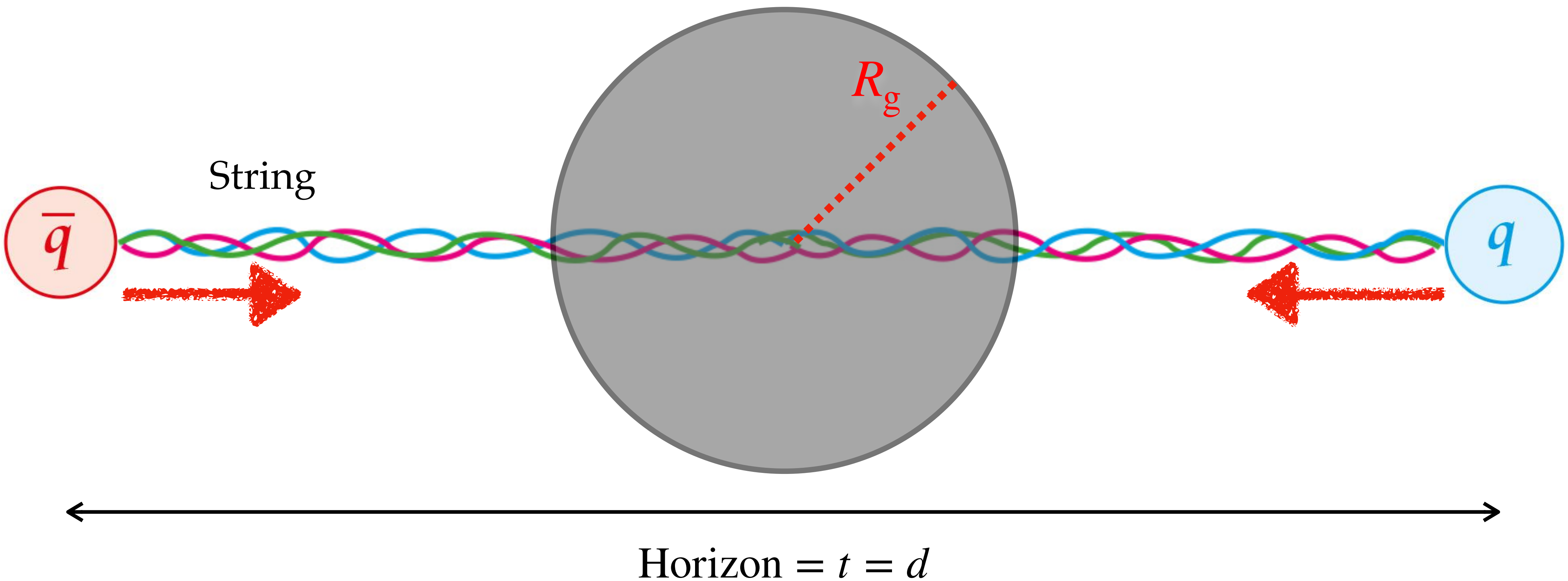
**Step 2:** Confinement at energy scale $\Lambda_c$, $M_q/\Lambda_c \gg 1$




- Flux tubes form connecting quark/anti-quark pairs
- The system cannot collapse as long as $d \gg$ Horizon
- String breaking into quarks pair: $P_{\text{tunnel}} \propto e^{-\pi\left(M_q/\Lambda_c\right)^2}$ suppressed as long as $M_q/\Lambda_c \gg 1$
- This condition should hold for the lightest confined quark
- Confinement can take place during inflationary period or in the late Universe

# Formation Mechanism:

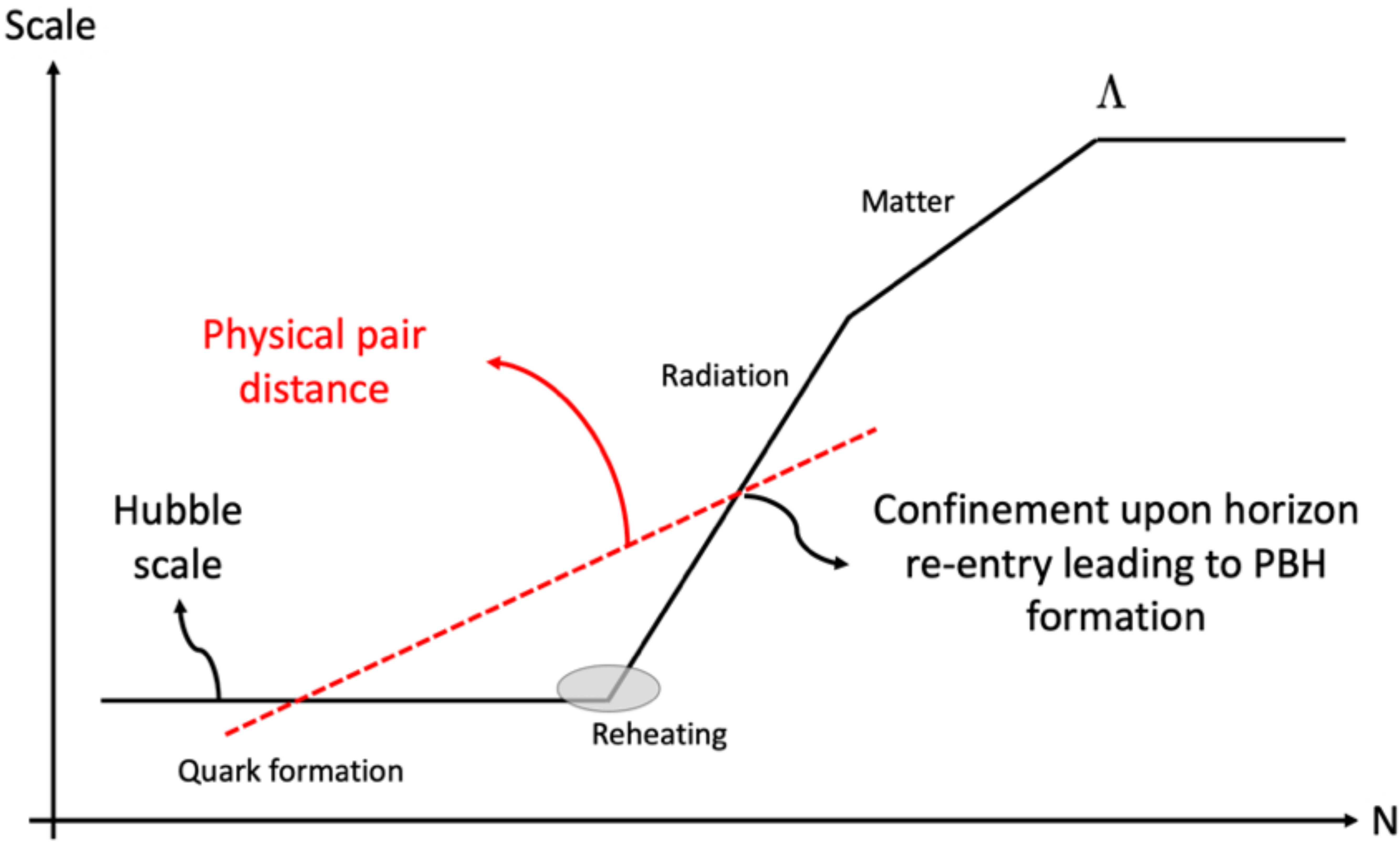
**Step 3:** As they re-enter horizon, collapse leads to BH formation




- Quarks accelerate towards each other $a = \Lambda_c^2/m_q$ and become relativistic

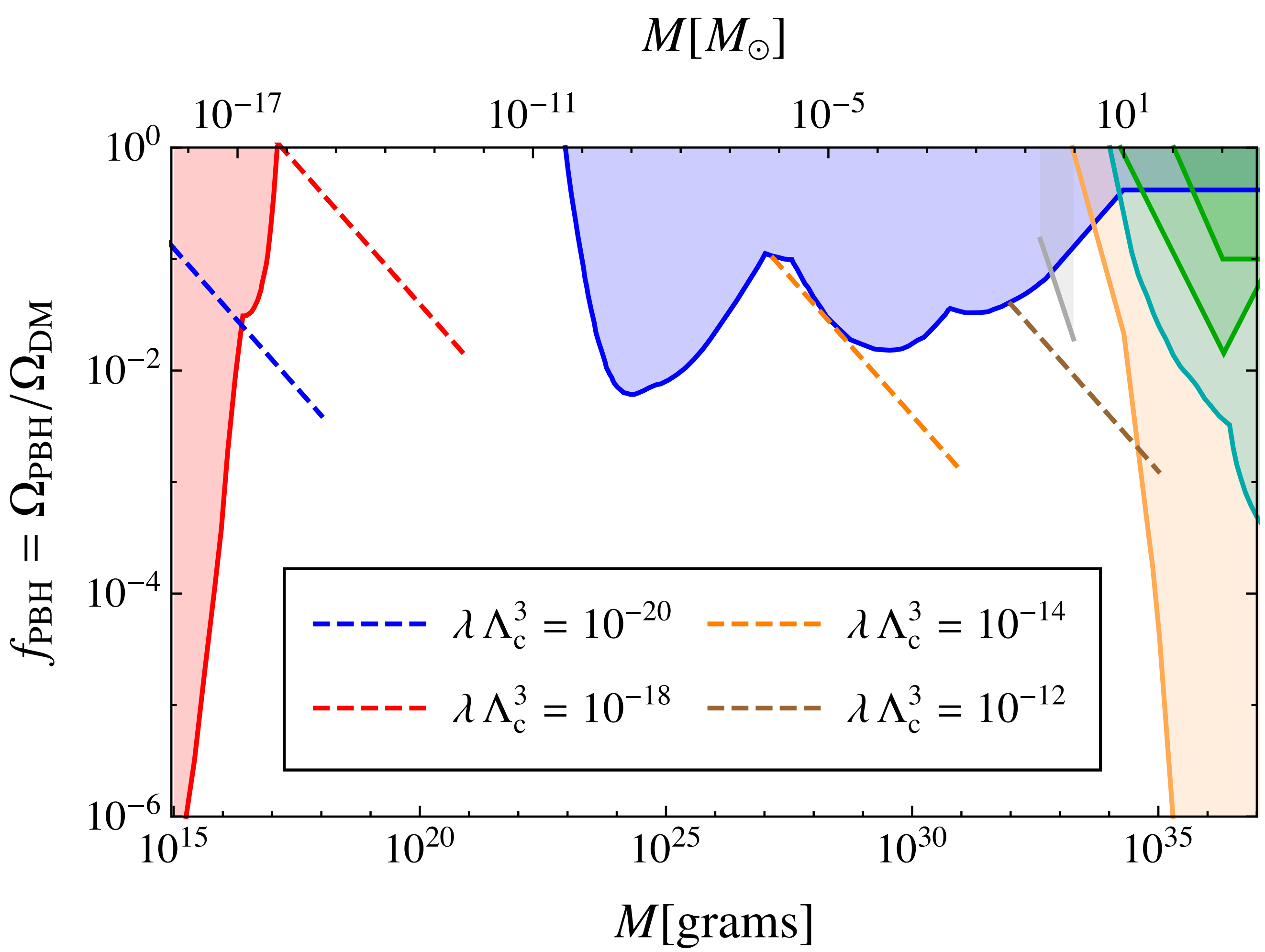
$$E \simeq \Lambda_c^2 t \simeq M_{\rm PBH}, \quad R_g \gg \Lambda_c^{-1}$$

- The connecting string is not *exactly straight*
- Primordial BHs due to overdensities are heavier $M_{\rm PBH}^{\rm over} \sim t$



Scale
Λ
Matter
Physical pair
distance
Radiation
Hubble
scale
Confinement upon horizon
re-entry leading to PBH
formation
Reheating
Quark formation
N

# Dark matter




## Monochromatic spectrum

$$f_{\rm PBH} = \frac{\rho_{\rm PBH}}{\rho_{\rm DM}} \propto \lambda\Lambda_c^3 M_{\rm PBH}^{-1/2}$$

$\longrightarrow$ Filled areas are phenomenological constraints (evaporation, dynamical,...)

The scaling holds for radiation domimated universe

$\longrightarrow$ Seeds for supermassive black holes in the galactic centres

$\longrightarrow$ Maximally rotating sub-solar PBHs production

$\longrightarrow$ Possible embedding with known QCD as long as $\Lambda_c < m_q$ (assumption required)

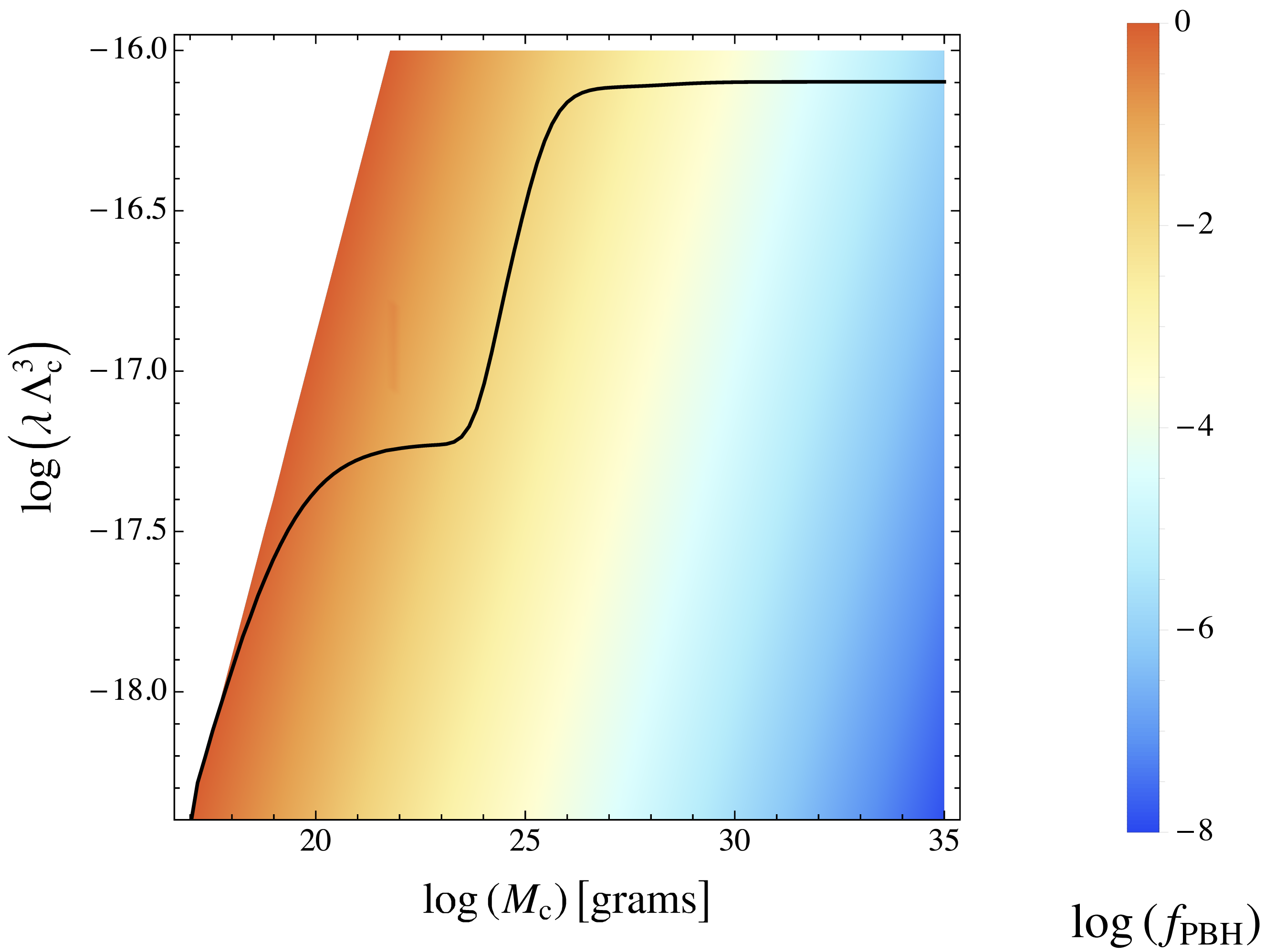
$\longrightarrow$ Interesting stochastic background with flat $\Omega_{\rm GW}$ (relevant for NANOGrav, LISA,...)

# Dark matter

Extended spectrum

$$\int_{M_1}^{M_2} \mathrm{d}\ln M_{\mathrm{PBH}} \, \frac{\mathrm{d} f_{\mathrm{PBH}}(M_{\mathrm{PBH}})}{\mathrm{d}\ln M_{\mathrm{PBH}}} \frac{1}{f_{\max}(M_{\mathrm{PBH}})} \overset{!}{\leq} 1$$

*Carr, Raidal, Tenkanen, Vaskonen, Veermäe '17*




Compatibility with observations below the black line

$\boxed{\text{100\% of dark matter}}$

# Super massive black holes as a bonus

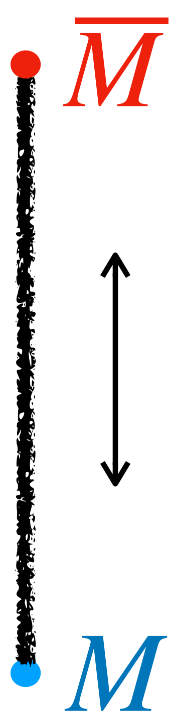
- These are black holes in the galactic centres which might be too heavy to be explained by accretion of stellar black holes
- They have masses $\geq 10^9 M_\odot$
- Primordial BHs of masses $M_{\rm PBH} \geq 10^4 M_\odot$ can explain them due to accretion
- $f_{\rm PBH}^{constain}(M \gtrsim 10^4\, M_\odot) \lesssim 10^{-9}$ , which is satisfied

$$f_{\rm PBH}^{\rm heavy} \equiv \int_{10^4\, M_\odot} \mathrm{d}\ln M_{\rm PBH} \, \frac{\mathrm{d} f_{\rm PBH}(M_{\rm PBH})}{\mathrm{d}\ln M_{\rm PBH}} \approx 10^{-10}$$

Correct value to obtain SMBHs via accretion *Serpico, Poulin, Inman, Kohri '20*

# Gravitational Waves

$\longrightarrow$ System dual to monopole/antimonopole pair connected by string




Point-like limit previously studied by *Martin, Vilenkin '97*

- Two solutions studied: oscillatory and rotating system
- Both of them give radiated gravitational power scaling as

$$P_{\mathrm{n}} \sim \frac{\Lambda_{\mathrm{c}}^4}{n}, \quad \omega_{\mathrm{n}} = 2\pi n/d,$$

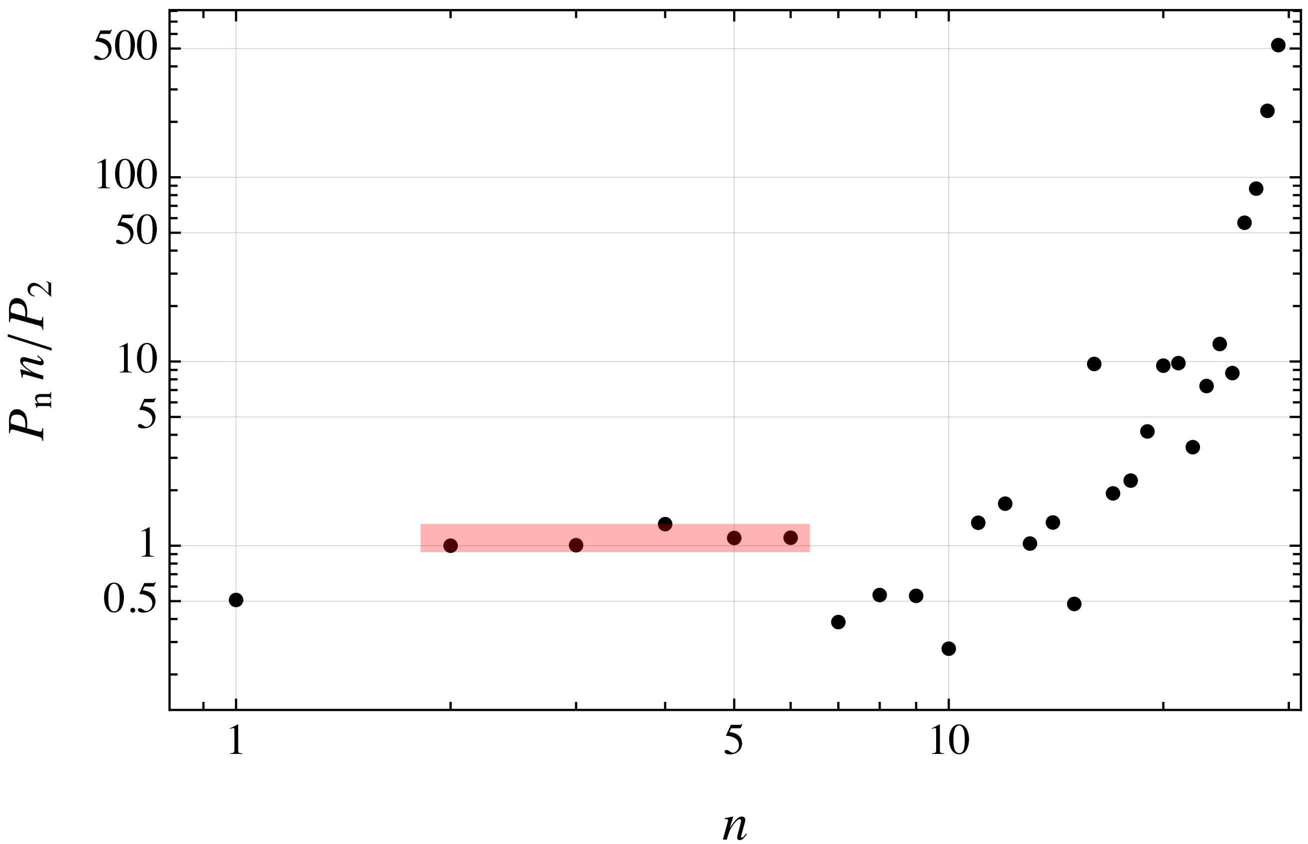
for large range of frequencies

- Use these results to estimate $\Omega_{\mathrm{GW}}$ due to the proposed mechanism

See eg *Leblond, Shlaer, Siemens '09*

# Gravitational Waves

The point-like case properly reproduces the GW spectrum of the numerical simulation with 't Hooft Polyakov monopoles

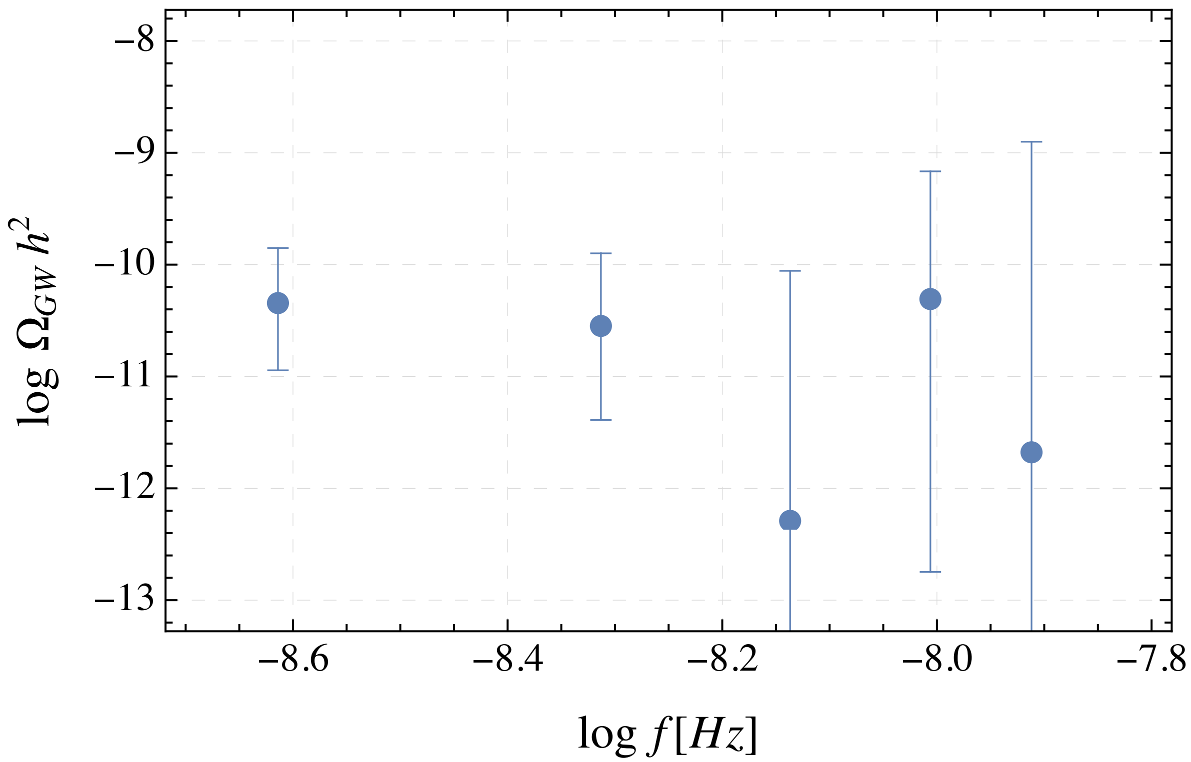



- $\dfrac{dP_n}{d\Omega} = \dfrac{G\,\omega_n^2}{\pi}\left(T^*_{\mu\nu}(\omega_n, \mathrm{k})T^{\mu\nu}(\omega_n, \mathrm{k}) - \dfrac{1}{2}\,|\,T^{\mu}_{\mu}(\omega_n, \mathrm{k})\,|^2\right)$
- Properly reproduced by point-like case on low frequencies i.e., $P_n \propto n^{-1}$
- Finite width corrections

G. Dvali, J. S. Bermudez, MZ arXiv:2210:14947

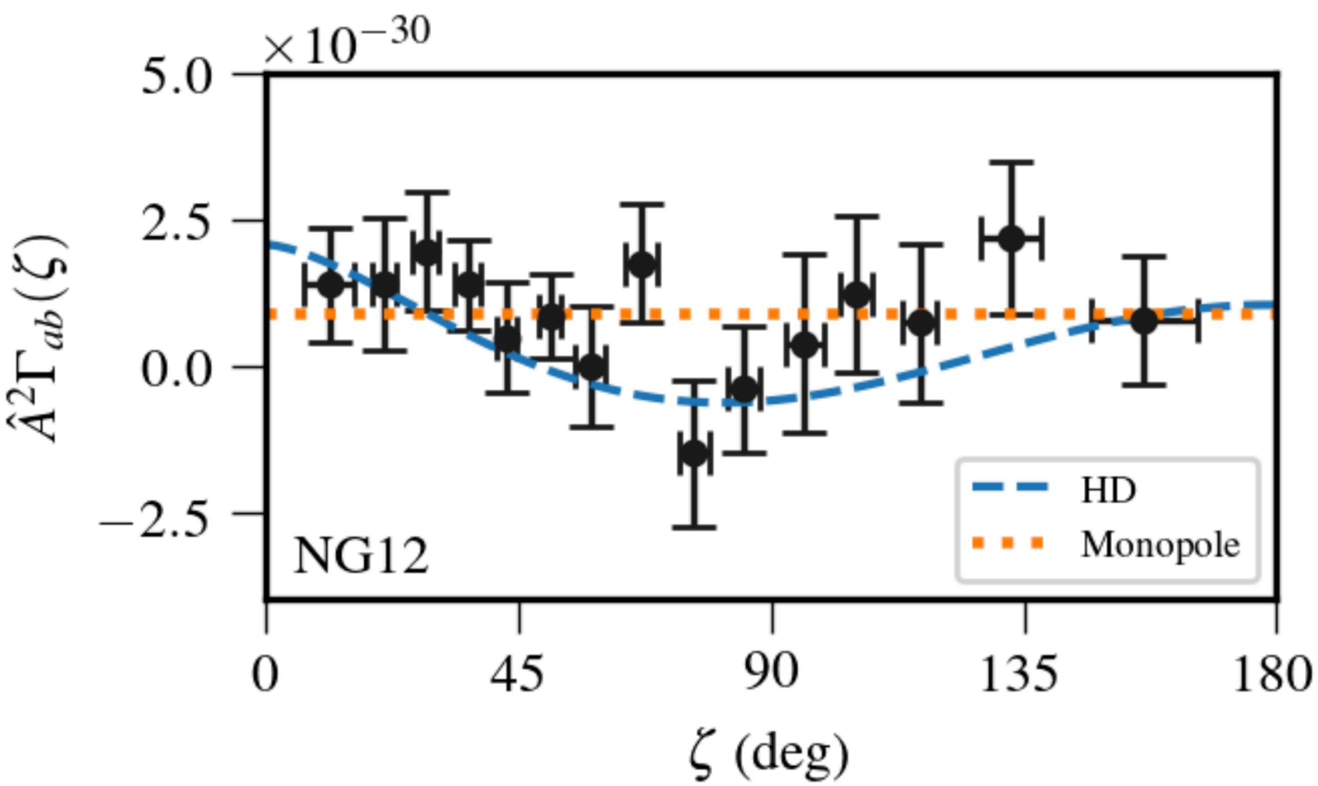
# Gravitational Waves

NANOGrav data pointing to a GW stochastic background




- Flat $\Omega_{\rm GW}$
- Relevant for NANOGrav

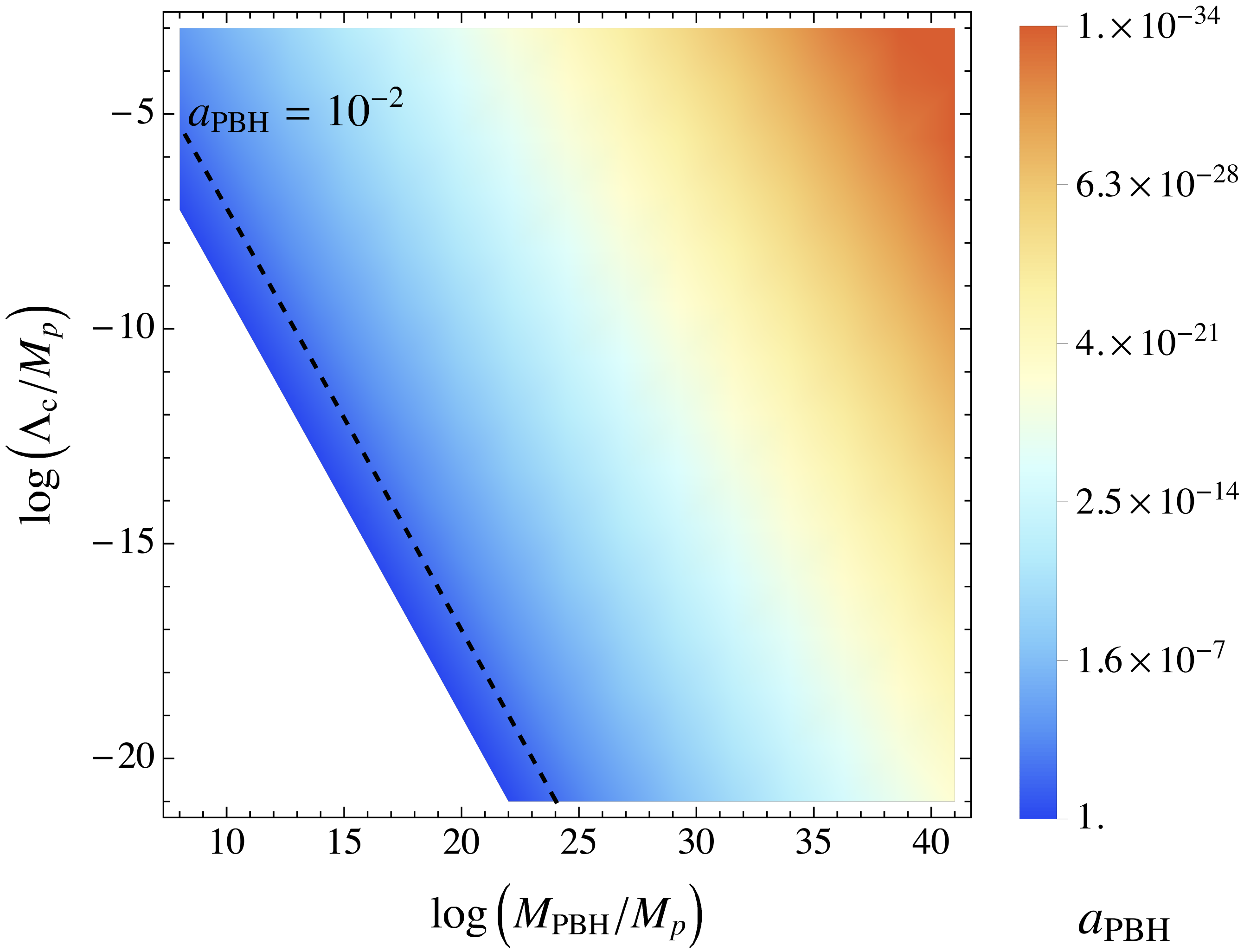
$$\Omega_{GW}^{NANO} \sim 10^{-10} \propto \lambda\,\Lambda_c^4$$

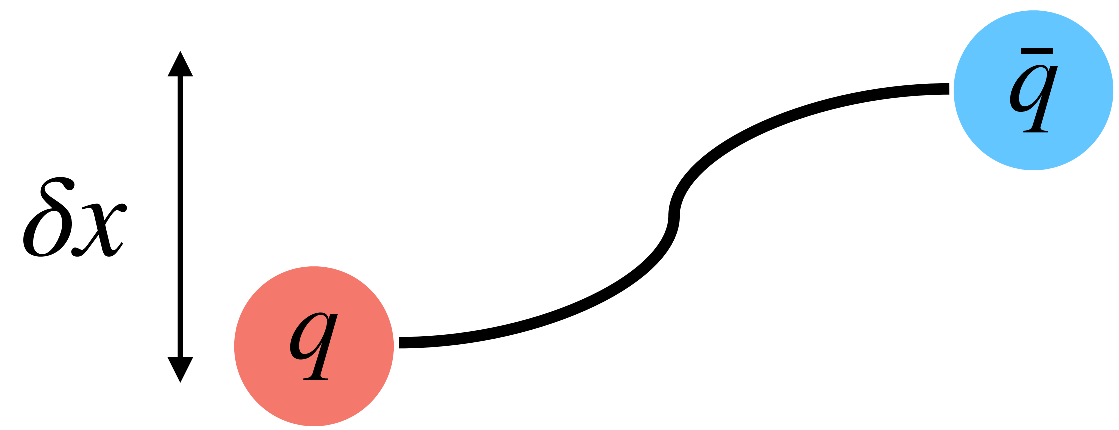



Lack of Hellings-Downs correlation?

Monopolar signal generated by a mild extension e.g., $g_q\,\phi\,\bar{q}q$ (relative coupling to SM weaker by $\epsilon \sim 10^{-3}$)

# High-spin sub-solar mass primordial black holes




$$\delta x \simeq \sqrt{N_{\rm e}}\, H_{\rm i}^{-1}$$

$$a_{\rm PBH} \simeq \frac{\delta x}{R_{\rm g}} \simeq \frac{1}{H_{\rm i} M_{\rm PBH}} \log\left(\frac{H_{\rm i} M_{\rm PBH}}{\Lambda_{\rm c}^2}\right)^{1/2}$$

N.B. Overdensity PBHs do not rotate (in radiation)

→This source of spin matters for lighter black holes

# Possible embedding with standard QCD

- Assumption required:

$$\Lambda_{\rm c} < M_{\rm q} \text{ from nucleation to collapse}$$

- At $T = 0$ QCD does exactly the opposite $\Lambda_{\rm c} > M_{\rm q}$, however,...
- It is natural for the confining and mass scales to change in the Early Universe

*Dvali '95*

- This is the case if couplings are expectation values of fields (moduli) with flat potentials
- For example, couplings between inflaton and standard model can achieve that

# Possible embedding with standard QCD

$$g_y \bar{\psi}_L \psi_R \phi \qquad\qquad \frac{1}{4g^2} F_{\mu\nu} F^{\mu\nu}$$

Couplings are expectation values of fields and can be very different in the early Universe

$$g_y = f_y\left(S_y/M_*\right), \quad \frac{1}{g^2} = f_F\left(S_F/M_*\right)$$

Expectation values of fields $\phi$, $S_y$ and $S_F$ change at non-zero temperature

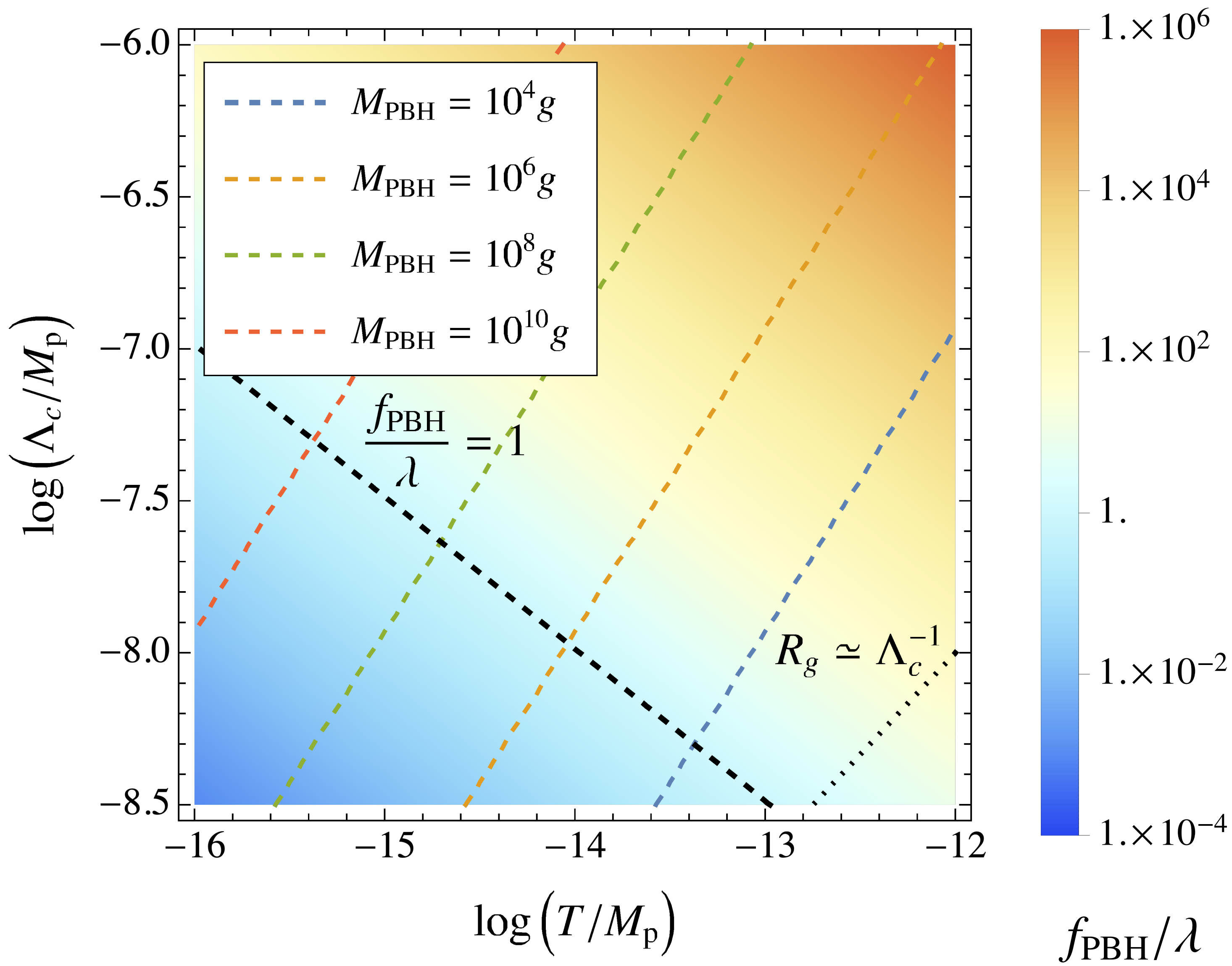
**Requirement**: Low temperature expectation value should set the right coupling values

This should happen before BBN$\rightarrow$ large room for PBH production

# Thank you!

# Dark matter

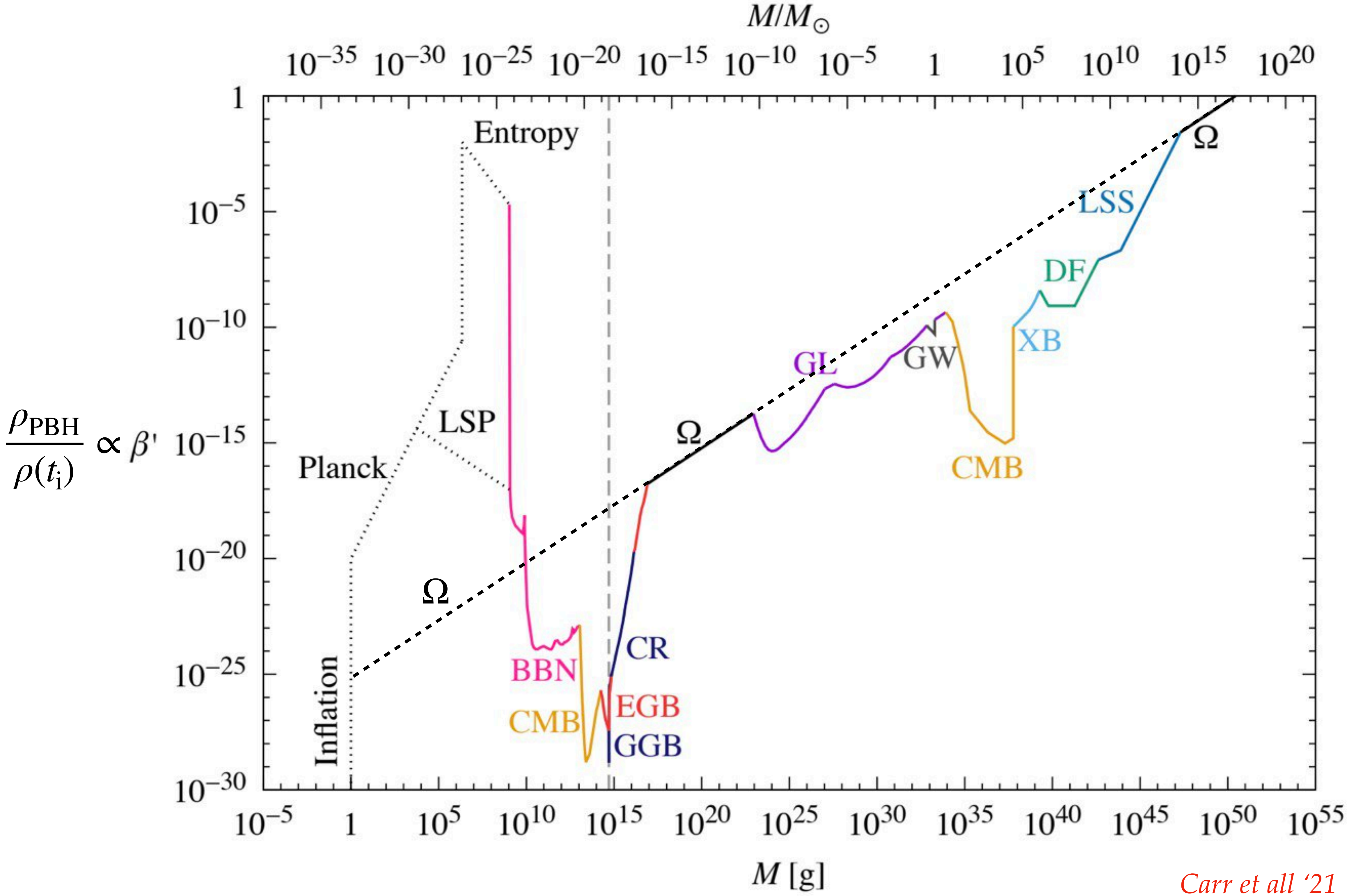
Recent studies show that black holes could live much longer than we thought due to ``*memory burden*'' (*Dvali, Eisemann, Michel, Zell '20*):




$$\tau(M_{\rm BH} = 10^{15}{\rm g}) \sim {\rm M}_{\rm BH}^3 \sim {\rm t}_0$$

$$\tau \to \tilde{\tau} \geq \tau S^2$$

- **Huge window** could open up for primordial black holes scenarios!
- Other constraints also should change!




*Carr et all '21*

**Evaporation constraints to be revisited**

# Each transition has interesting soliton dynamics

$$SU(2) \longrightarrow U(1) \longrightarrow 1$$

- Massive "$W^{\pm}$"
- Monopoles
- Unconfined magnetic flux
- Coulomb-like interaction (almost)

- Massive "$A$"
- Strings
- Confined magnetic flux
- **Rapid annihilation of monopole pairs**

# The system

$$\mathcal{L} = \frac{1}{2} D_\mu \varphi^a D^\mu \varphi^a + (D_\mu \psi)^\dagger D_\mu \psi - \frac{1}{4} W^a{}_{\mu\nu} W^{a\,\mu\nu} - V(\psi, \varphi)$$

$$V(\varphi, \psi) = \frac{\lambda}{4}(\varphi^a \varphi^a - \eta^2)^2 + \frac{\tilde{\lambda}}{2}(\psi^\dagger \psi - v^2)^2 + c\varphi^a \varphi^a \psi^\dagger \psi$$

SU(2) adjoint

SU(2) doublet

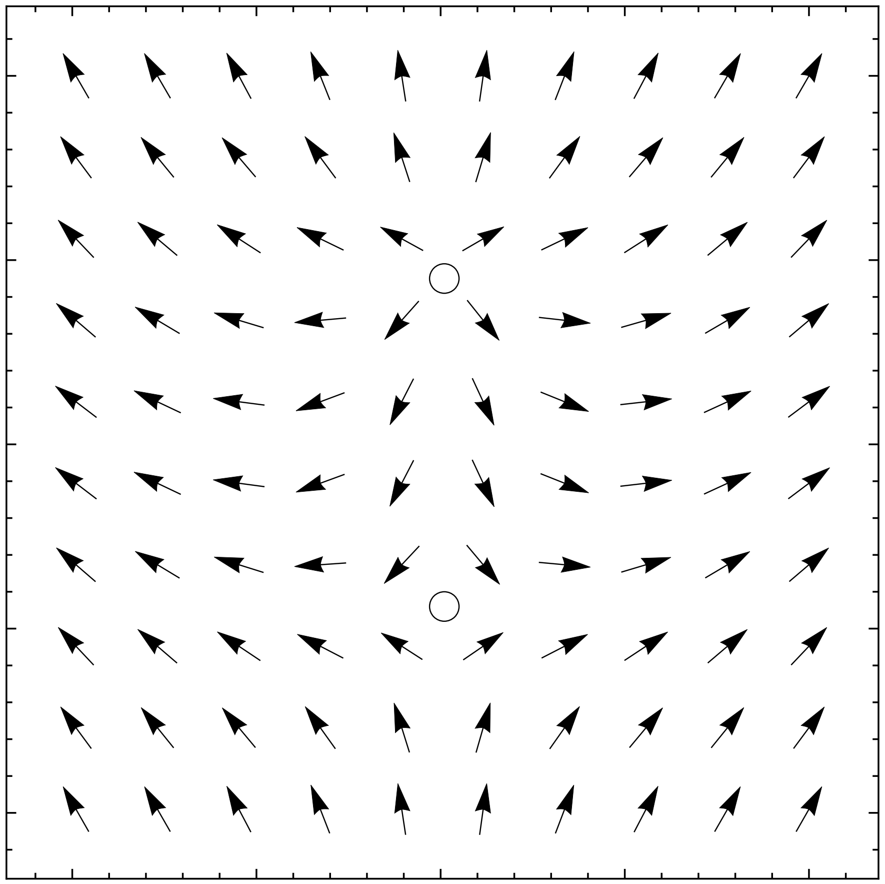
$$SU(2) \longrightarrow U(1) \longrightarrow 1$$

Massive "$W^\pm$"

Massive "$A$"

# Initial Conditions

$$\varphi^a = h(r_m)h(\bar{r}_m)\hat{\varphi}^a$$



$$D_\mu \hat{\varphi}\,|_{r\to\infty} = 0$$

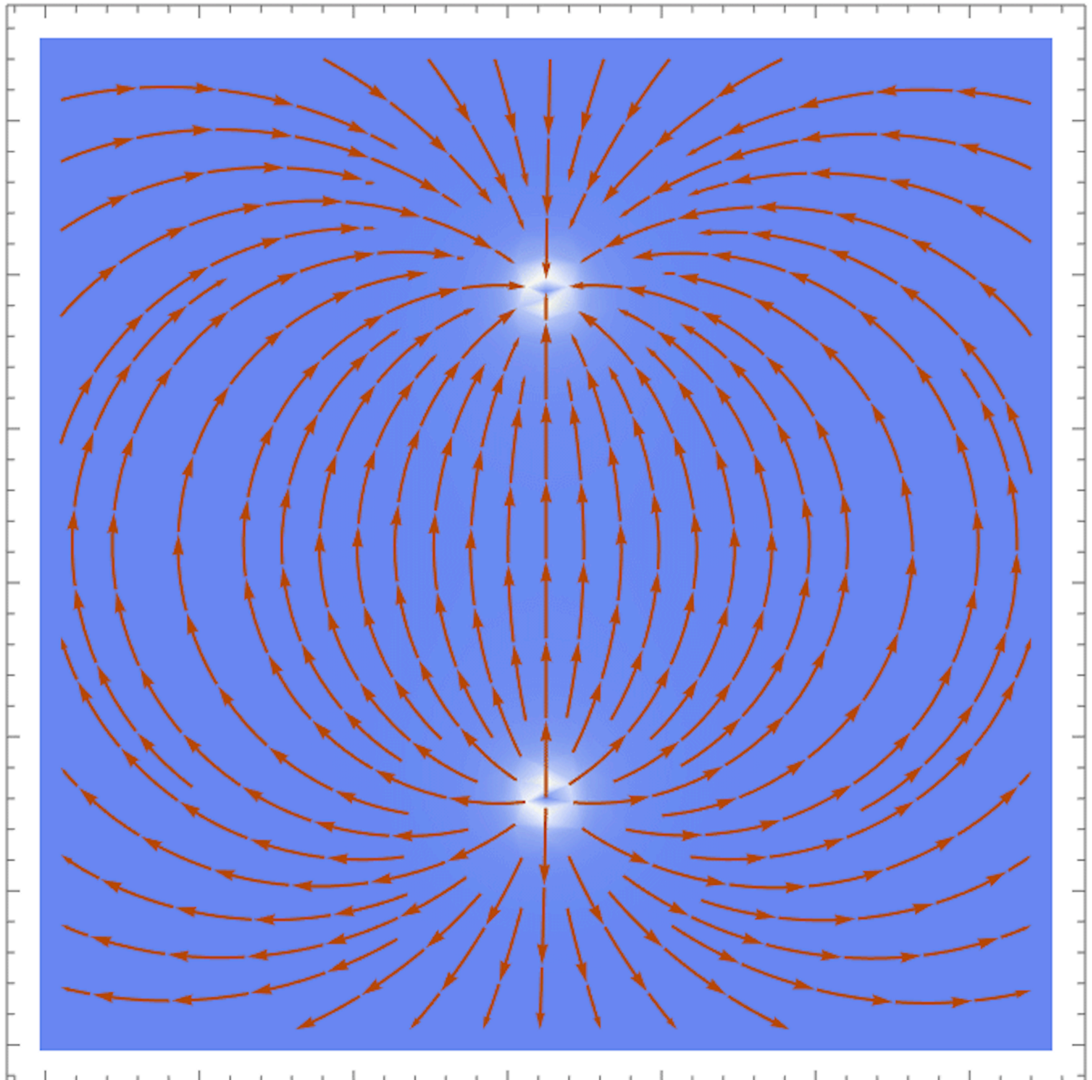
$$\downarrow$$

Saurabh, Vachaspati '18

$$W_\mu^a = -(1 - k(r_m))(1 - k(\bar{r}_m))\epsilon^{abc}\hat{\varphi}^b \partial_\mu \hat{\varphi}^c$$

$$F_{\mu\nu} = W_{\mu\nu}^a \hat{\varphi}^a - \epsilon^{abc}\hat{\varphi}^a D_\mu \hat{\varphi}^b D_\nu \hat{\varphi}^c$$

Magnetic field lines



$$\psi = v\, l(r_{xy}, z) \begin{pmatrix} \sin(\theta/2)\sin(\bar{\theta}/2)e^{i\gamma} + \cos(\theta/2)\cos(\bar{\theta}/2) \\ \sin(\theta/2)\cos(\bar{\theta}/2)e^{i\phi} + \cos(\theta/2)\sin(\bar{\theta}/2)e^{i(\phi-\gamma)} \end{pmatrix}$$

Vachaspati, Field '94

$\gamma$ = twist angle