QUANTUM GRAVITY EFFECTS ON DARK MATTER AND GRAVITATIONAL WAVES

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In collaboration with:

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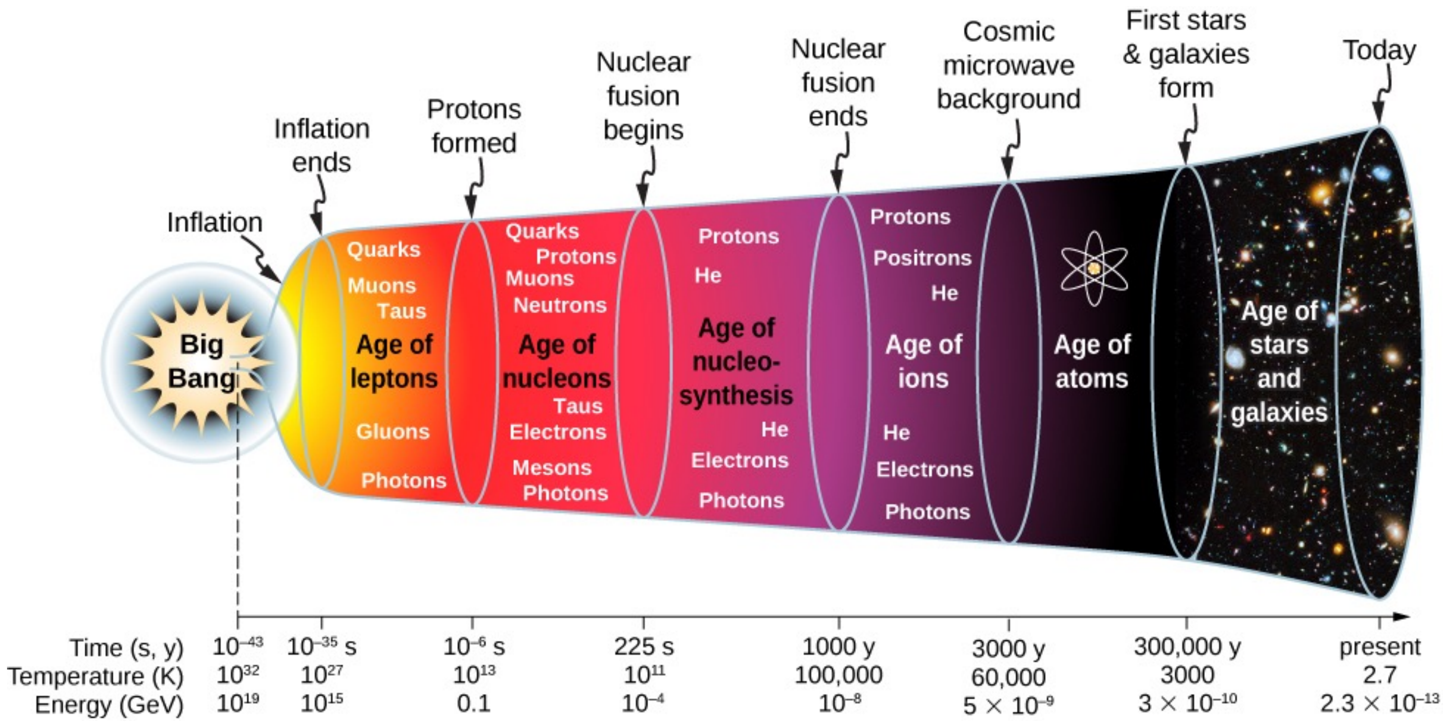
BACKGROUND

- DM
- Quantum Gravity
- Probing Early Universe



Cosmological Puzzles

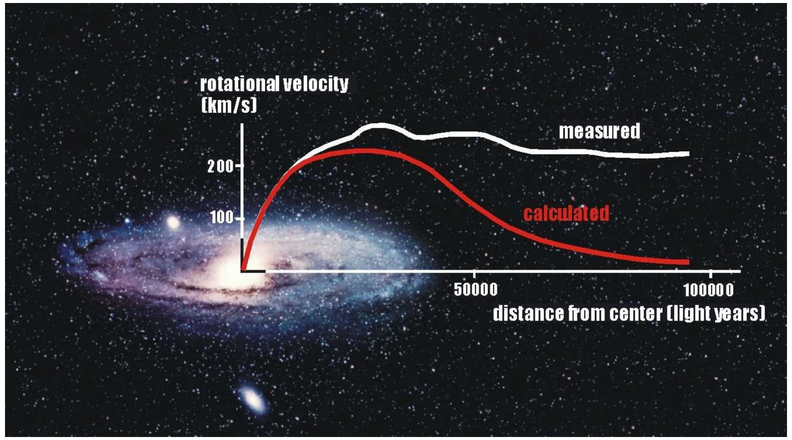
1. Dark Matter
2. Neutrino masses
3. Matter-Antimatter asymmetry

Motivation for BSM Physics

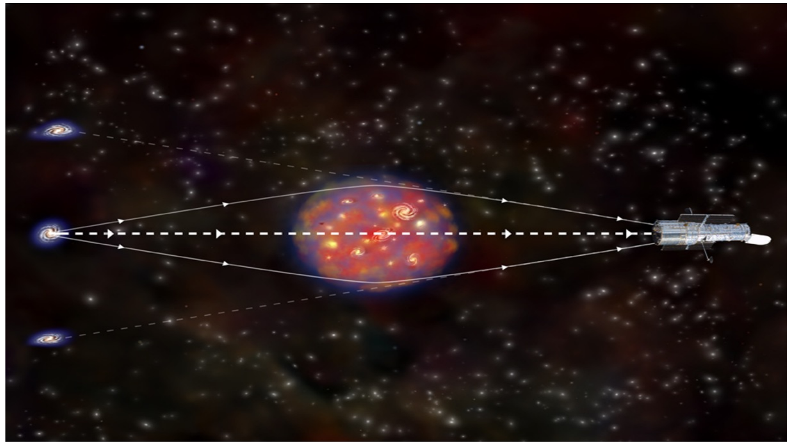
Cosmological Observations: a powerful investigative tool

BACKGROUND

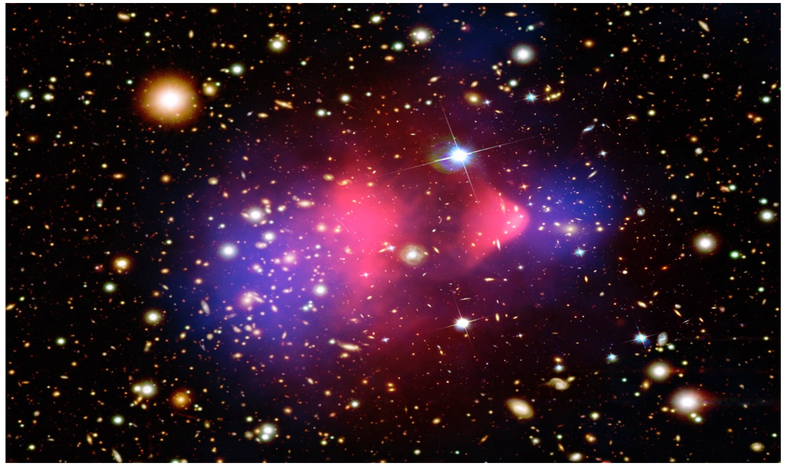
Dark matter



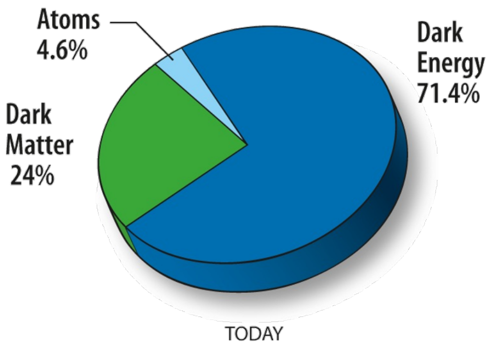
Evidence of DM I: Galaxy Rotation Curve



Evidence of DM II: Gravitational Lensing



Evidence of DM III: Bullet Cluster



We have felt the gravitational presence of Dark Matter!

BACKGROUND

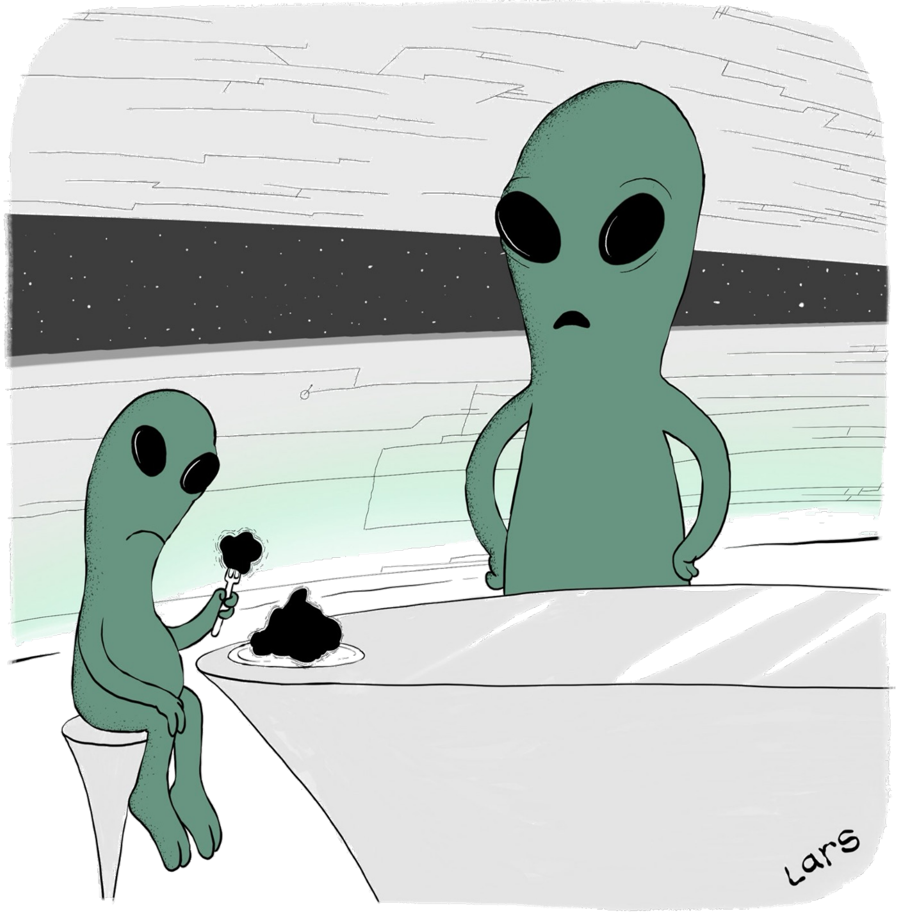
Dark matter

What we know :

☐ Relic density (~24 % of the Universe)
☐ Massive
☐ Stable object
☐ No or very weak interaction

What we don't know:

☐ Nature of DM
☐ Interaction
☐ Production mechanism in the early Universe



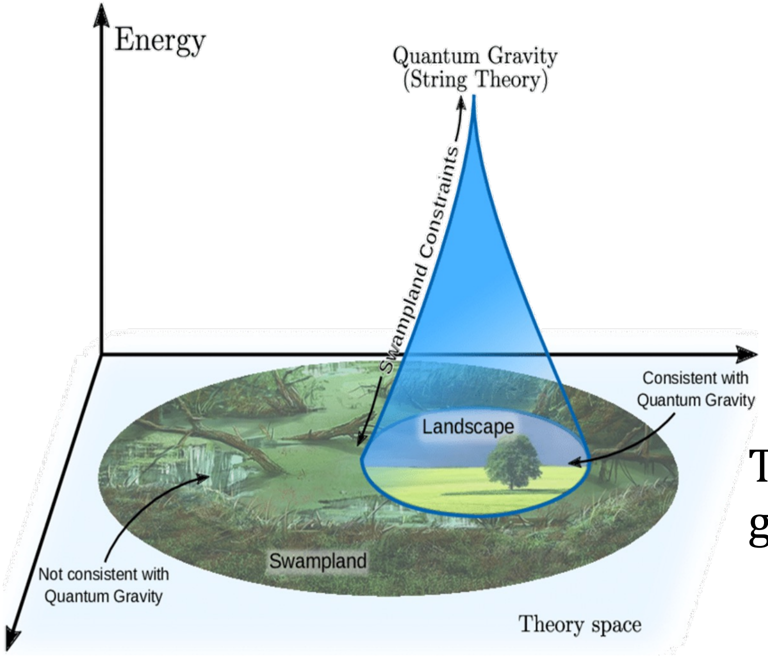
"No dessert until you finish your dark matter."

BACKGROUND

Quantum gravity as a UV completion?

Vafa, hep-th/0509212
Ooguri & Vafa, NPB 766, 21 (2007)

- ❑ For decades **EFT has played a vital role** in Particle physics
- ❑ It has **guided physicists** looking for the signatures of new physics
- ❑ However, it has limitations: **The situation becomes different once we include gravity and demand that the EFT in question is valid at all energies in suitable QG theory**



Swampland

Refers to low-energy EFTs which are not compatible with quantum gravity.

Swampland conjectures

- ❑ No global symmetry conjecture
- ❑ Weak gravity conjecture
- ❑ Distance conjecture

No global symmetry conjecture

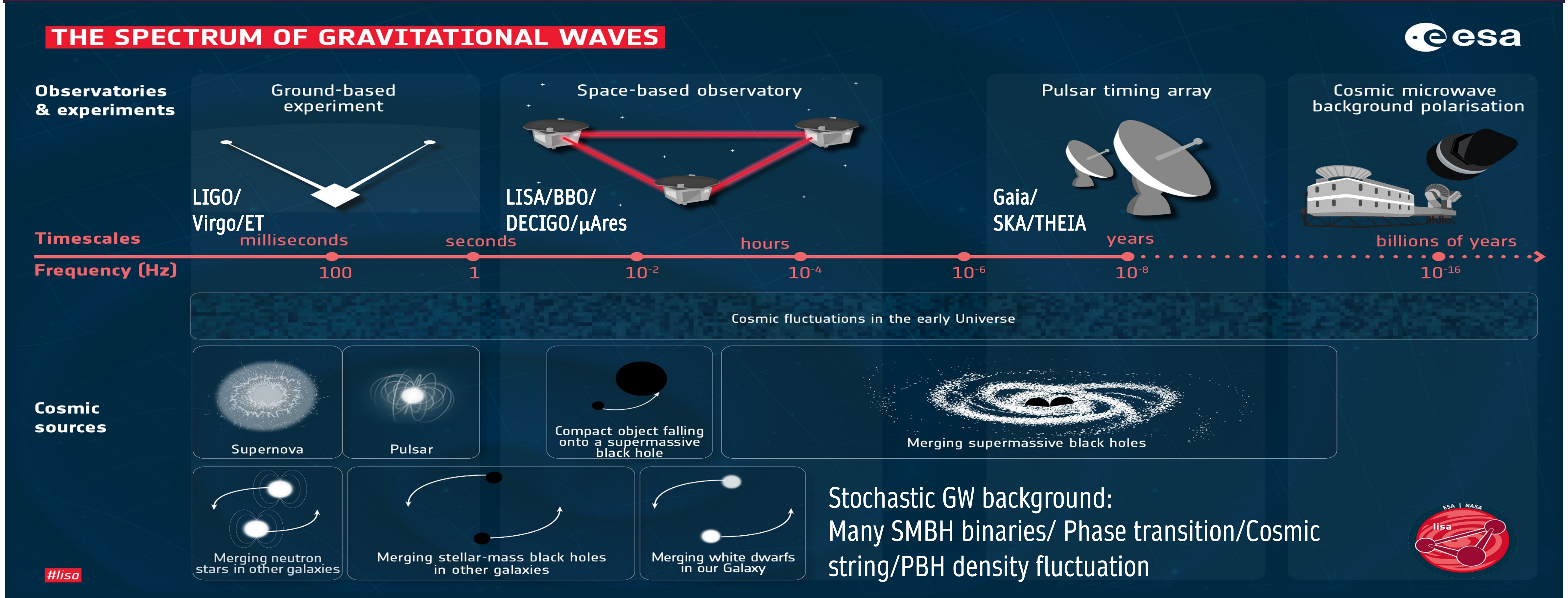
There exists no exact (continuous or discrete) global symmetry in quantum gravity theories.

➡ Global symmetries in low-energy EFTs are broken by

Any observational effects that can constrain Λ_{QG}?

Background

Gravitational Waves: a probe to the early Universe



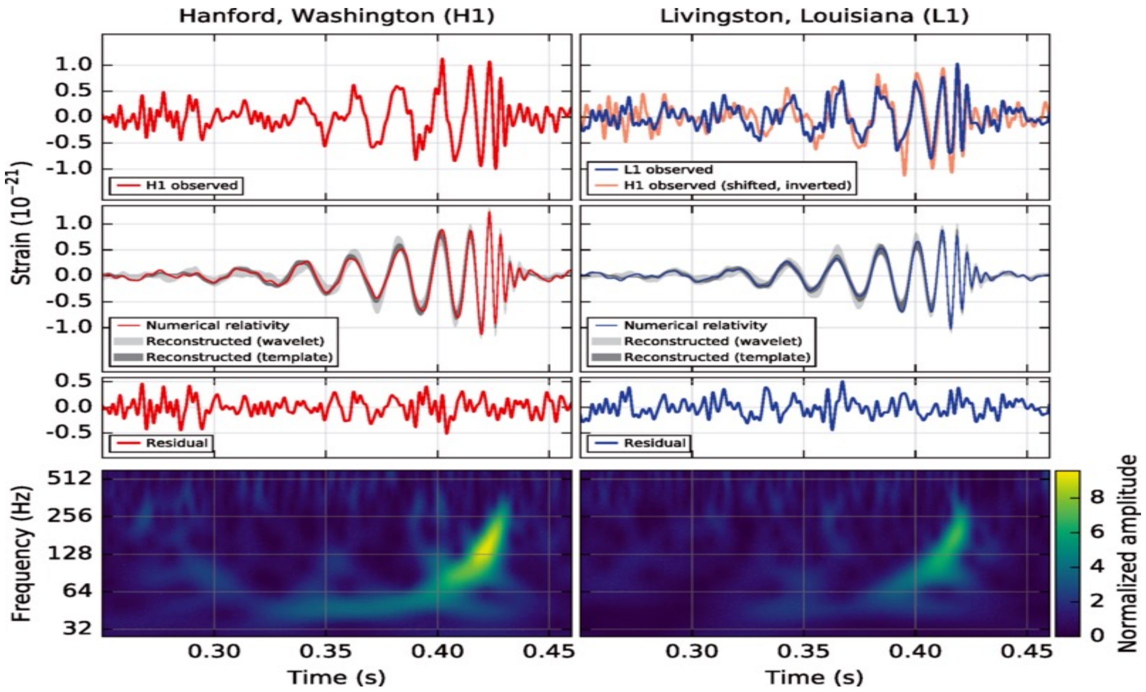
Stochastic GW background:
Many SMBH binaries/ Phase transition/Cosmic string/PBH density fluctuation

Credit to ESA

Gravitational Waves: a probe to the early Universe!

RECENT GW DISCOVERIES

Discovery of GW by LIGO-VIRGO Col.



PRL 116, 061102 (2016)

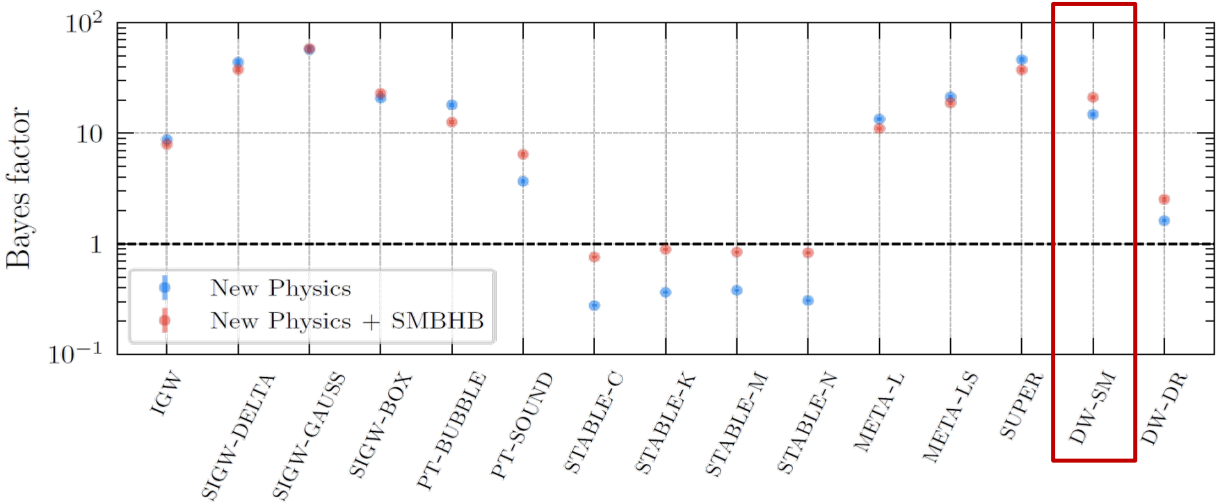
Source of GW: Merging of pair of BHs at z = 0.09

Recent results reported by PTA projects

Several PTA projects have reported positive evidence of a stochastic gravitational wave background.

Source of SGWB: Merging of SMBH Binaries/Cosmological origin/combination of Both.

NANOGrav, 2306.16219



Cosmological domain wall

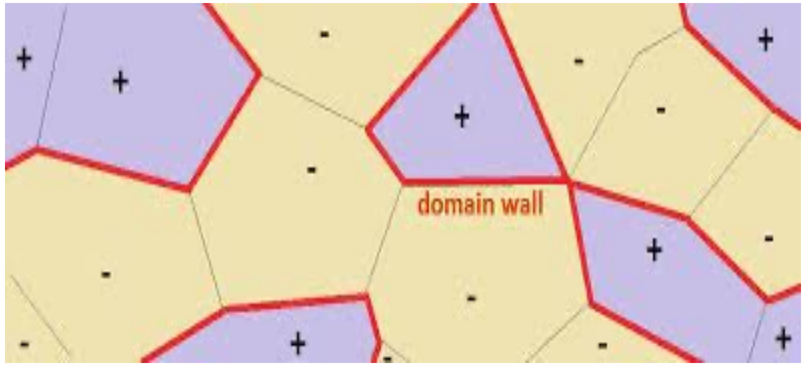
Spontaneous Symmetry breaking and topological defects

U(1) gauge theory → Cosmic string

Discrete symmetry → Domain wall

Chiral symmetry to U(1) → Monopole

Zeldovich et al., Zh. Eksp. Teor. Fiz 67, 3 (1974)



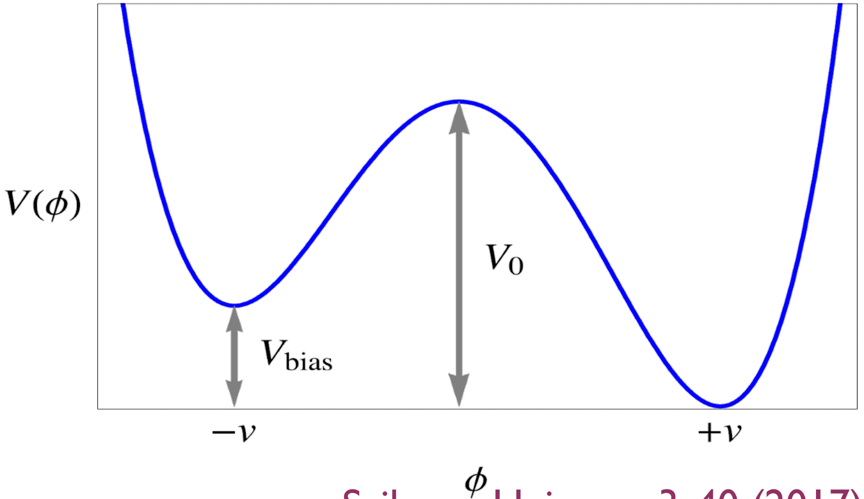
Domain wall problem

The energy density of domain walls soon dominates the total energy density of the universe, which conflicts with the present observational results.

Solution: metastable domain walls

Discrete symmetry is explicitly broken

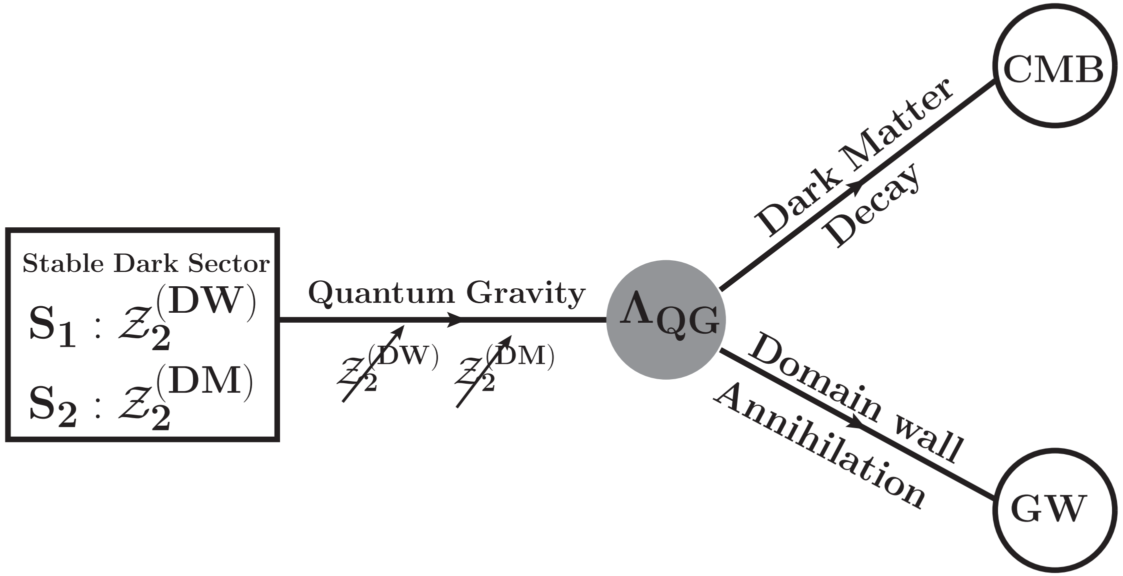
→ **Bias term**



Saikawa, Universe 3, 40 (2017)

Gravitational waves can be produced during the process of collisions and annihilations of domain walls.

THE FRAMEWORKS



THE SCALE OF QUANTUM GRAVITY

Global symmetry can be broken by non-perturbative instanton effects.

Quantum gravity effect becomes relevant at Planck length →

Non-perturbative instanton effects $\mathcal{O}_5/\Lambda_{\rm QG}$ is suppressed by $e^{-\mathcal{S}}$ →

Effective quantum gravity scale

$$\boxed{\Lambda_{\rm QG} \sim M_{\rm Pl}\, e^{\mathcal{S}} \gg M_{\rm Pl}}$$

Giddings & Strominger, NPB 306, 890 (1988)
Blumenhagen et al., NPB 771, 113 (2007)
Florea et al., JHEP 05, 024 (2007)

In general, the scale of a global symmetry breaking can be much higher than the Planck scale.

- U(1) Peccei-Quinn symmetry breaking: $\mathcal{S} \gtrsim 190 \longrightarrow \Lambda_{\rm QG} \sim 10^{100}\ {\rm GeV}$ **Extremely large!**
- Discrete Z_2 symmetry we are considering: $\mathcal{S} \sim \mathcal{O}(M_{\rm Pl}^2/\Lambda_{\rm UV}^2) \longrightarrow \mathcal{S} \sim \mathcal{O}(10)$

  Weak gravity conjecture requires $\Lambda_{\rm UV} \lesssim M_{\rm Pl}$

More realistic!

The range of the scale we are considering is $\Lambda_{\rm QG} \sim (10^{20} \cdots 10^{35})\ {\rm GeV} \longrightarrow$ Corresponding to $\mathcal{S} \sim (4 \cdots 38)$

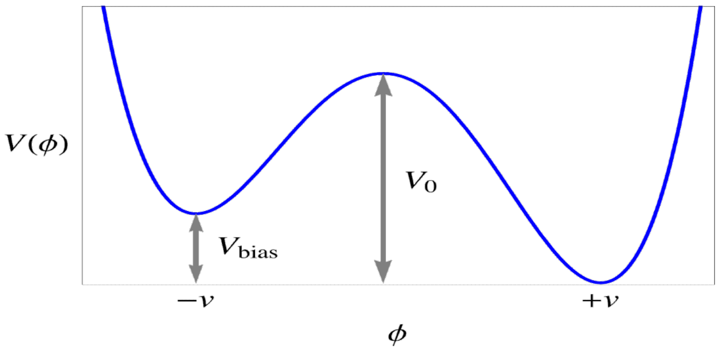
A MINIMALISTIC MODEL WITH TWO SINGLET SCALARS

Two scalars S_1: associated with Z_2^{DW}; S_2: associated with Z_2^{DM};

The renormalizable potential (Z_2-conserving)

$$V = \mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + H^\dagger H(\lambda_{hs1} S_1^2 + \lambda_{hs2} S_2^2) + \lambda_{s12} S_1^2 S_2^2 + \mu_2^2 S_2^2 + \frac{\lambda_2}{4} S_2^4 + \frac{\lambda_1}{4}(S_1^2 - v_1^2)^2$$

- S_1 acquires its vev v_1, S_2 doesn't
- λ_{hs1} is sufficiently small
- Bounded from below



Dimension-five potential (Z_2-breaking)

$$\Delta V = \frac{1}{\Lambda_{\rm QG}} \sum_{i=1}^{2} (\alpha_{1i} S_i^5 + \alpha_{2i} S_i^3 H^2 + \alpha_{3i} S_i H^4) + \frac{1}{\Lambda_{\rm QG}} \sum_{j=1}^{4} c_j S_1^j S_2^{5-j}$$

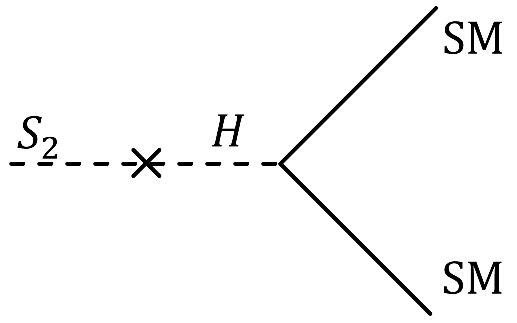
$$\rightarrow \quad V_{\rm bias} \simeq \frac{1}{\Lambda_{\rm QG}} \left(v_1^5 + \frac{v_1^3 v_h^2}{2} + \frac{v_1 v_h^4}{4} \right)$$

The number of SM-singlet moduli fields is ~ 100. The two-singlet model here is simplified but can still capture the qualitative features

DECAY OF SCALAR DM

$$\Delta V \supset S_2 H^4/\Lambda_{\mathrm{QG}} \xrightarrow{\text{Electroweak symmetry breaking}} \text{Mixing between } S_2 \text{ and } H\text{:} \quad \sin\theta = \frac{v_h^3}{(m_h^2 - m_{\mathrm{DM}}^2)\Lambda_{\mathrm{QG}}}$$

$$\Gamma_{\mathrm{DM}} = \frac{1}{16\pi}\frac{\sin^2\theta}{m_{\mathrm{DM}}}|M|^2_{h\to\mathrm{SMSM}}$$

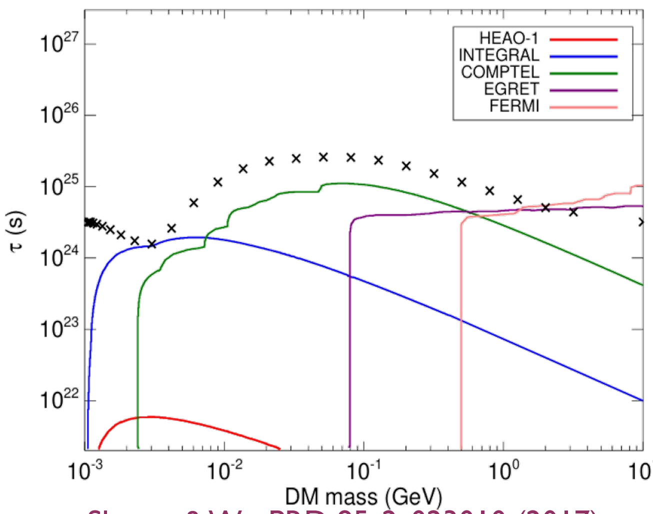


$S_2 \to \mathrm{SMSM} \to e\bar{e}, \gamma\bar{\gamma}, \nu\bar{\nu}$

Indirect detection of dark matter

CMB power spectrum

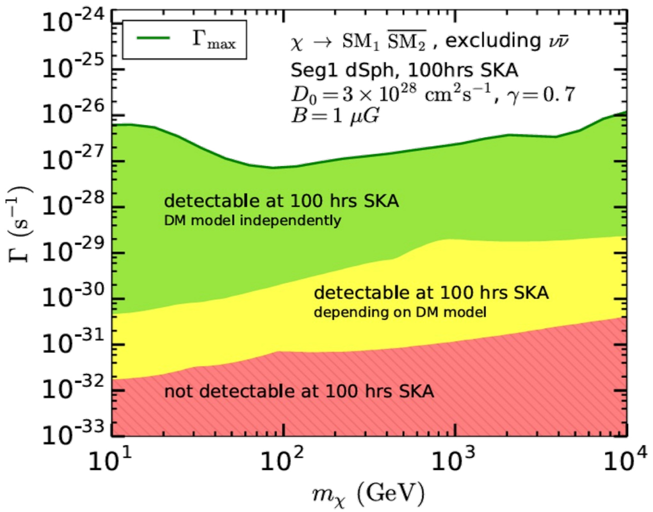
$$\tau_{\mathrm{DM}} \gtrsim 10^{25}\ \mathrm{s}$$



Slatyer & Wu, PRD 95, 2, 023010 (2017)

SKA radio telescope

$$\Gamma_{\mathrm{DM}} \gtrsim 10^{-30}\ \mathrm{s}^{-1}$$



Dutta et al., JCAP 09, 005 (2022)

GW FROM DOMAIN WALL ANNIHILATION

GWs can be produced during the collapsing of domain walls $\rho_{\rm GW} \sim G\mathcal{A}^2\sigma^2$

The spectrum of GWs is given by

$$\Omega_{\rm GW}(t,f) = \frac{1}{\rho_c(t)}\frac{{\rm d}\rho_{\rm GW}(t)}{{\rm d}\ln f}$$

The peak amplitude appears when $t \sim t_{\rm ann}$

$$\Omega_p h^2 \simeq 5.3\times 10^{-20}\,\tilde{\epsilon}\mathcal{A}^4 C_{\rm ann}^2 \hat{\sigma}^4 \hat{V}_{\rm bias}^{-2}$$

The corresponding peak frequency

$$f_p \simeq 3.75\times 10^{-9}\ {\rm Hz}\ C_{\rm ann}^{-1/2}\mathcal{A}^{-1/2}\hat{\sigma}^{-1/2}\hat{V}_{\rm bias}^{1/2}$$

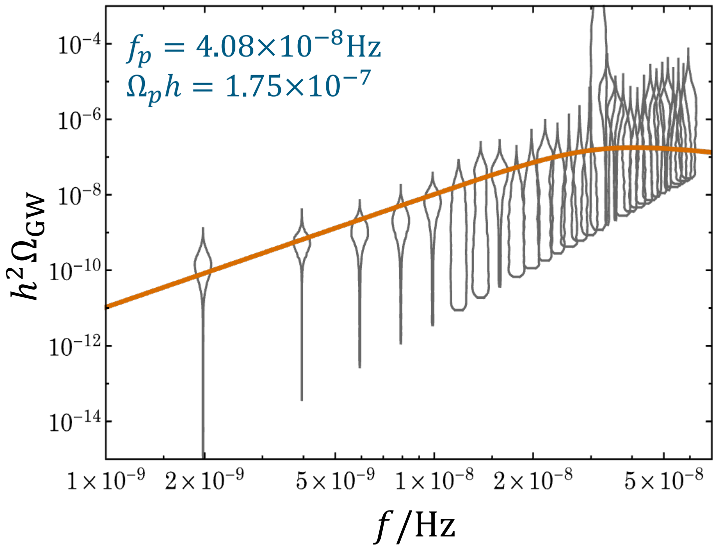
Broken power law

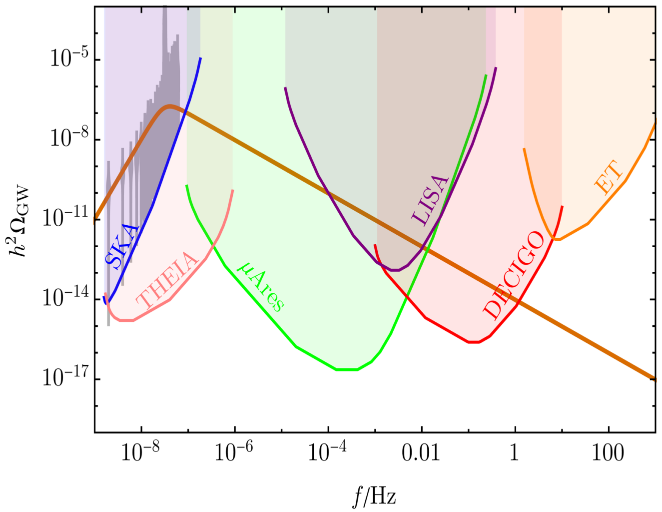
$$h^2\Omega_{\rm GW} = h^2\Omega_p \frac{(a+b)^c}{\left(bx^{-a/c} + ax^{b/c}\right)^c}$$

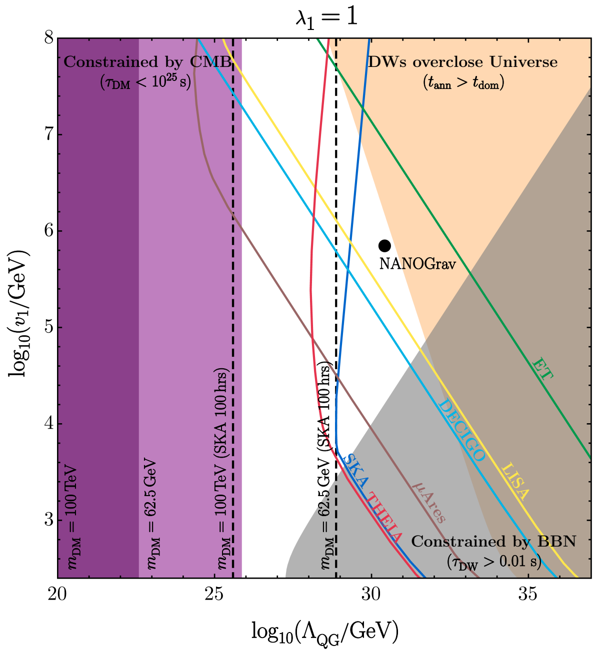
$x = f/f_p$

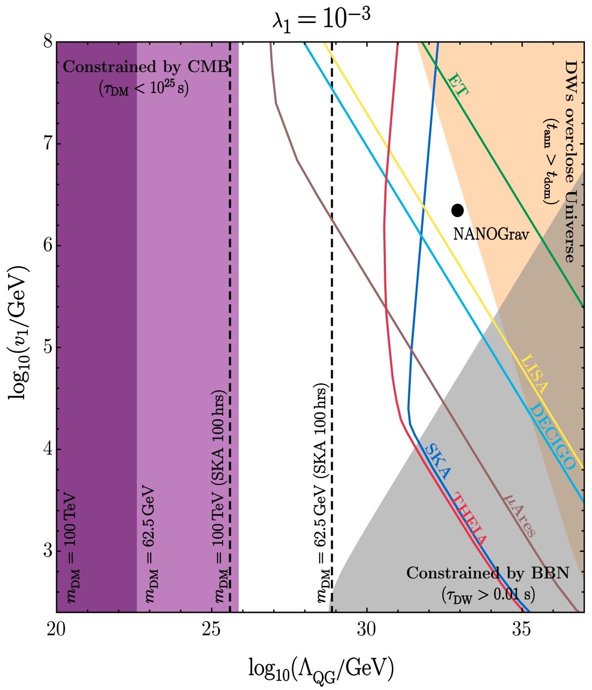
$a = 3$ by causality

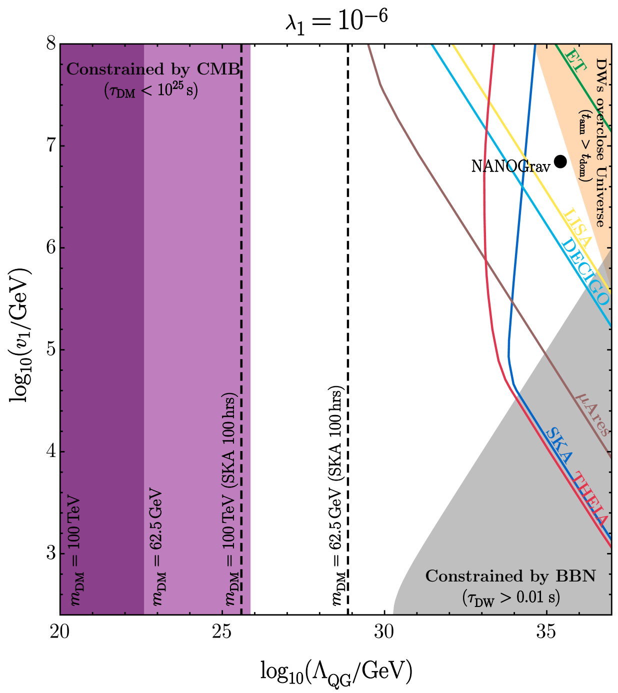
$b \simeq c \simeq 1$ by numerical simulation











COMBINED CONSTRAINTS

Summary

- ❑ We showed that our models have phenomenology that can plausibly lead us to measure the effective scale of QG.

- ❑ We have considered the low energy consequences of the swampland conjecture that global symmetries are broken by QG -- DM and DW can both become metastable as a result.

- ❑ If the phenomenology mentioned in these works is seen, it provides evidence for the paradigm of non-perturbative QG instantons breaking global symmetries.

- ❑ We show that the recent observations of a GW spectrum by PTA might have been produced by primordial metastable domain walls, and perhaps the GW spectrum is our first empirical information about QG.

Thank you!