Quantum Gravity Effects on Dark Matter and Gravitational Waves

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Based on *2308.03724, 2311.12487*

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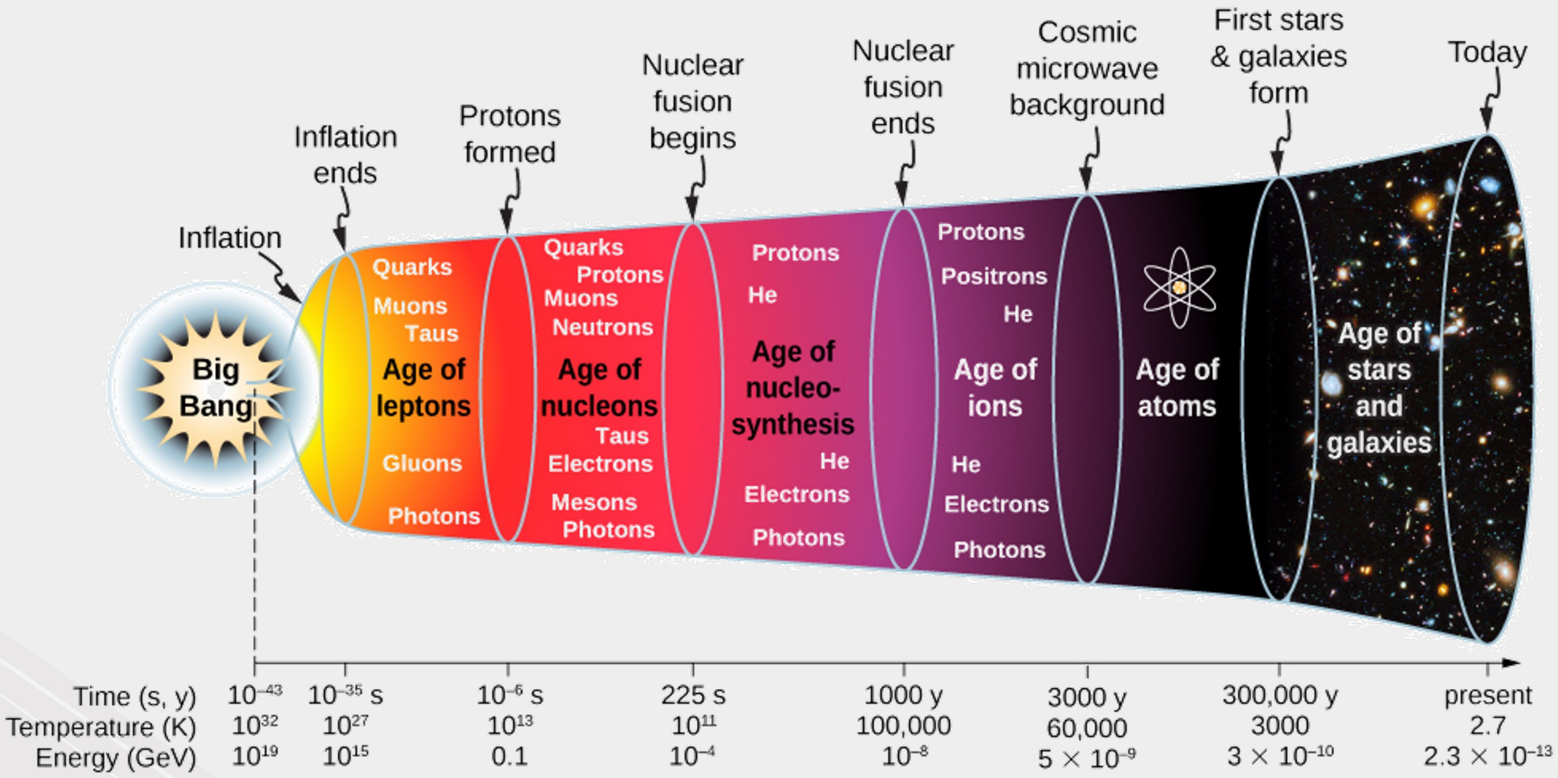
Motivation and background

Quantum gravity as a UV completion?



Quantum mechanics + Gravity? ← **Standard Model**

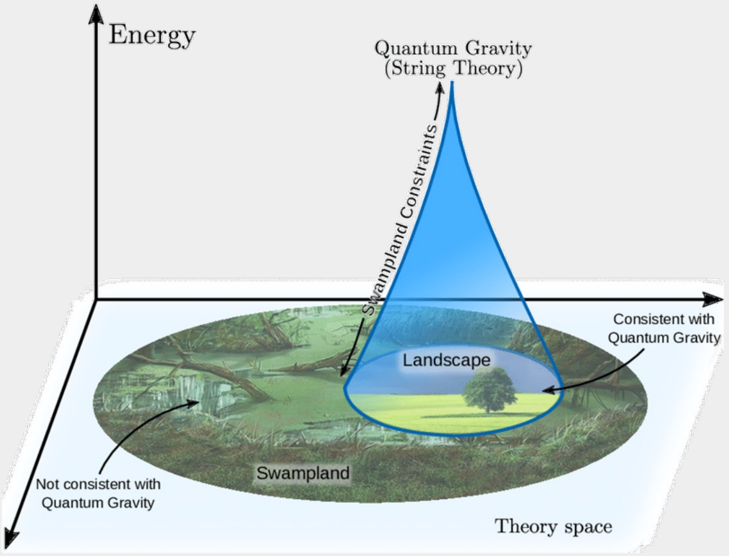
UV completion

Low-energy effective theory

Motivation and background

Quantum gravity as a UV completion?

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



Swampland conjectures

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

Swampland is in fact much larger than the string theory **landscape**.

- ☐ 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.

Original motivation: **Black-hole physics**

“no-hair” theorems

Hawking radiation

Rai & Senjanovic, PRD 49, 2729 (1994)

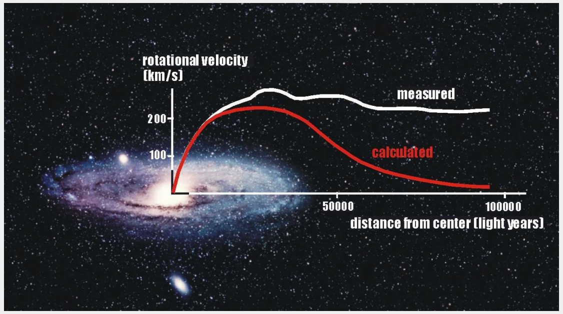
Global symmetries in low-energy EFTs are broken by

$$\mathcal{L}_{\cancel{\mathbb{Z}_2}} = \frac{1}{\Lambda_{\mathrm{QG}}}\mathcal{O}_5 + \cdots$$

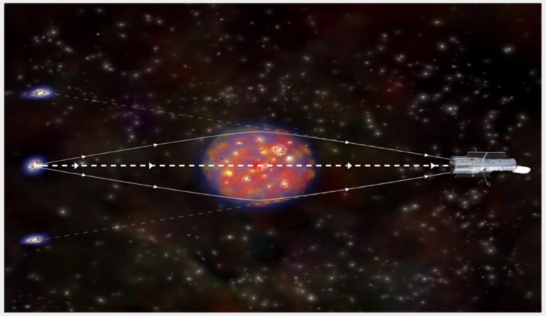
Any observational effects that can constrain Λ_{QG}?

Motivation and background

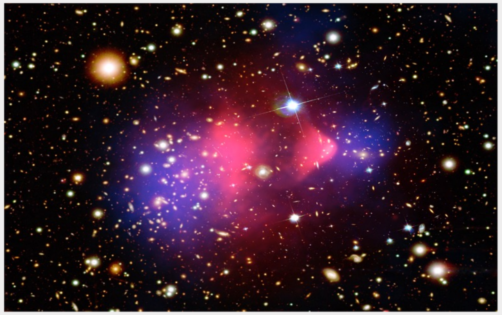
Dark matter



Galaxy Rotation Curve



Gravitational Lensing



Bullet Cluster

We have felt the gravitational presence of Dark Matter!

What we know :

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

What we don’t know:

- ☐ Nature of DM
- ☐ Interaction
- ☐ Production mechanism

Z_2 symmetry protects DM stability. Breaking of Z_2 symmetry allows DM to decay.

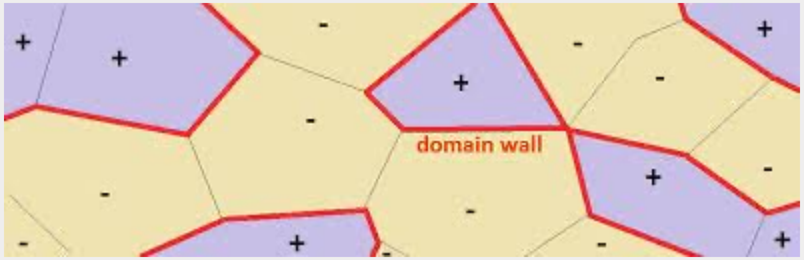
Motivation and background

Cosmological domain walls

Originate from the spontaneous breaking of discrete symmetries.

Domain wall problem

- Vacuum fluctuations of the scalar field allow it to jump into other domains, leading to the formation of domain walls.
- The energy density of domain walls soon dominates the total energy density of the universe, which conflicts with the present observational results.

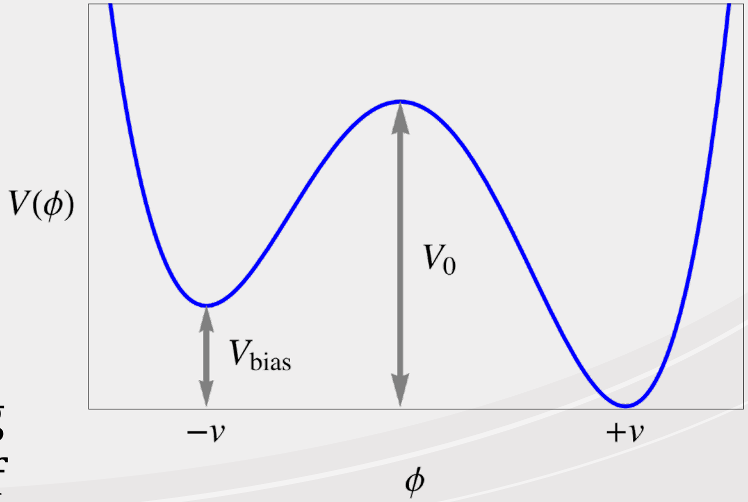


Zeldovich et al., Zh. Eksp. Teor. Fiz 67, 3 (1974)

Solution: metastable domain walls

Discrete symmetry is explicitly broken

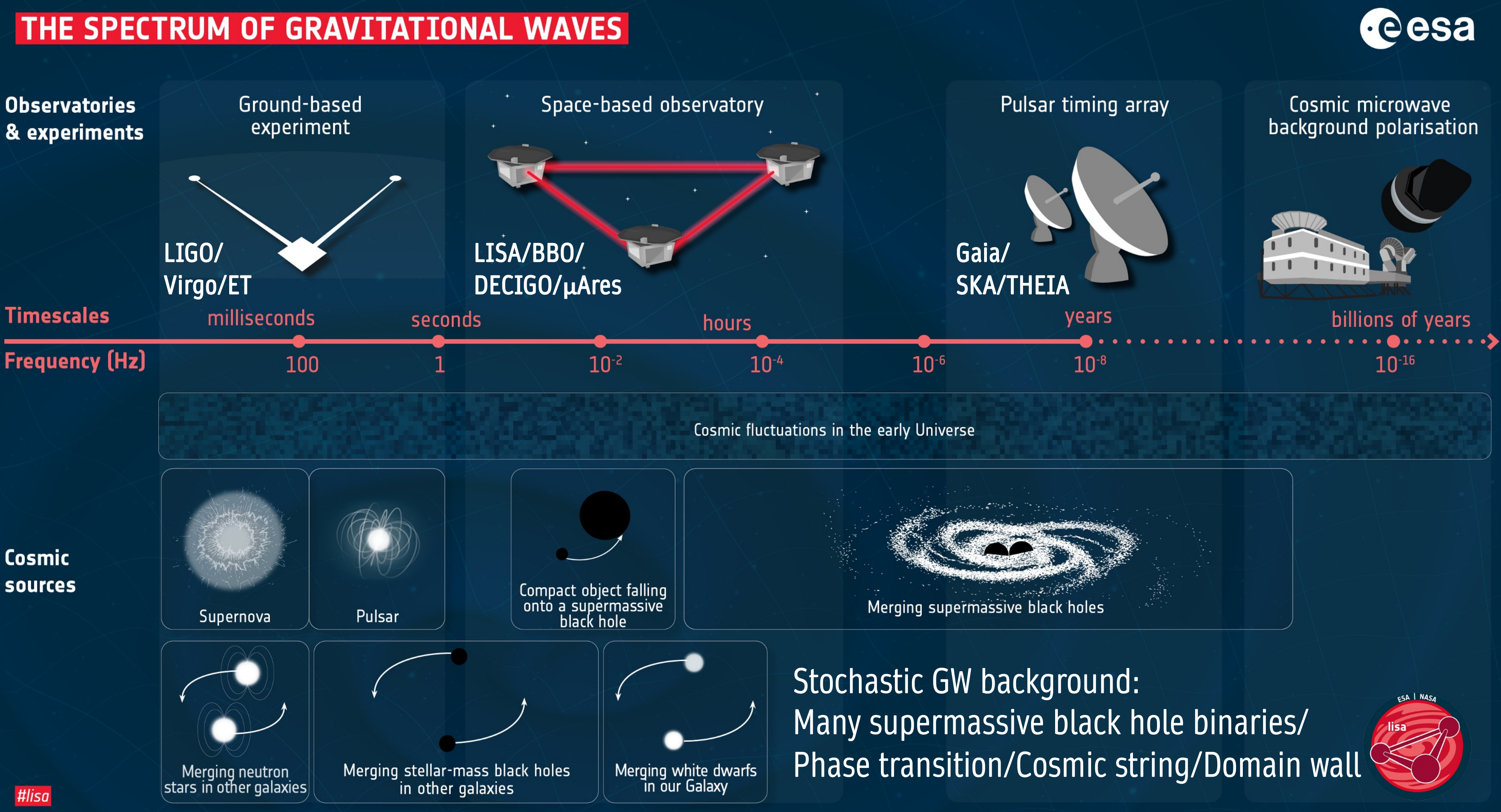
➡ **Bias term**



Saikawa, Universe 3, 40 (2017)

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

Motivation and background



Stochastic GW background:
Many supermassive black hole binaries/
Phase transition/Cosmic string/Domain wall

Credit to ESA

Gravitational Waves: a probe to the early Universe!

Motivation and background

NANOGrav, 2306.16213
EPTA, 2306.16214
PPTA, 2306.16215
CPTA, 2306.16216

Recent results reported by PTA projects

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

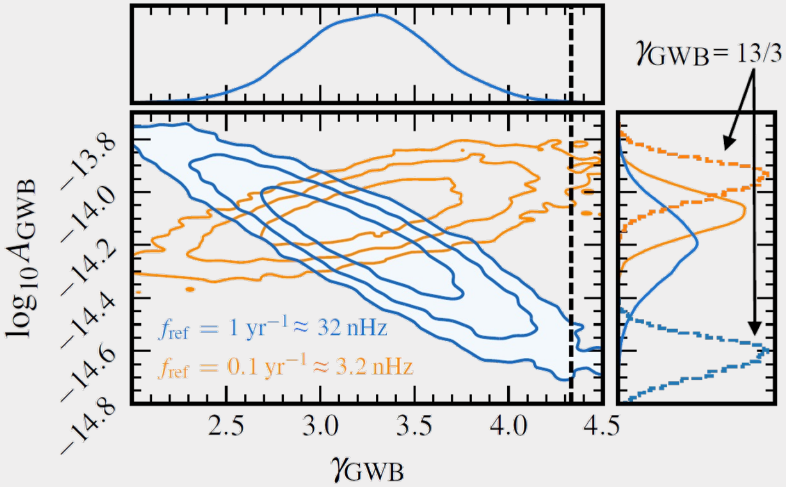
Nanograv ($f_{\rm rev} = 1\ {\rm yr}^{-1}$):

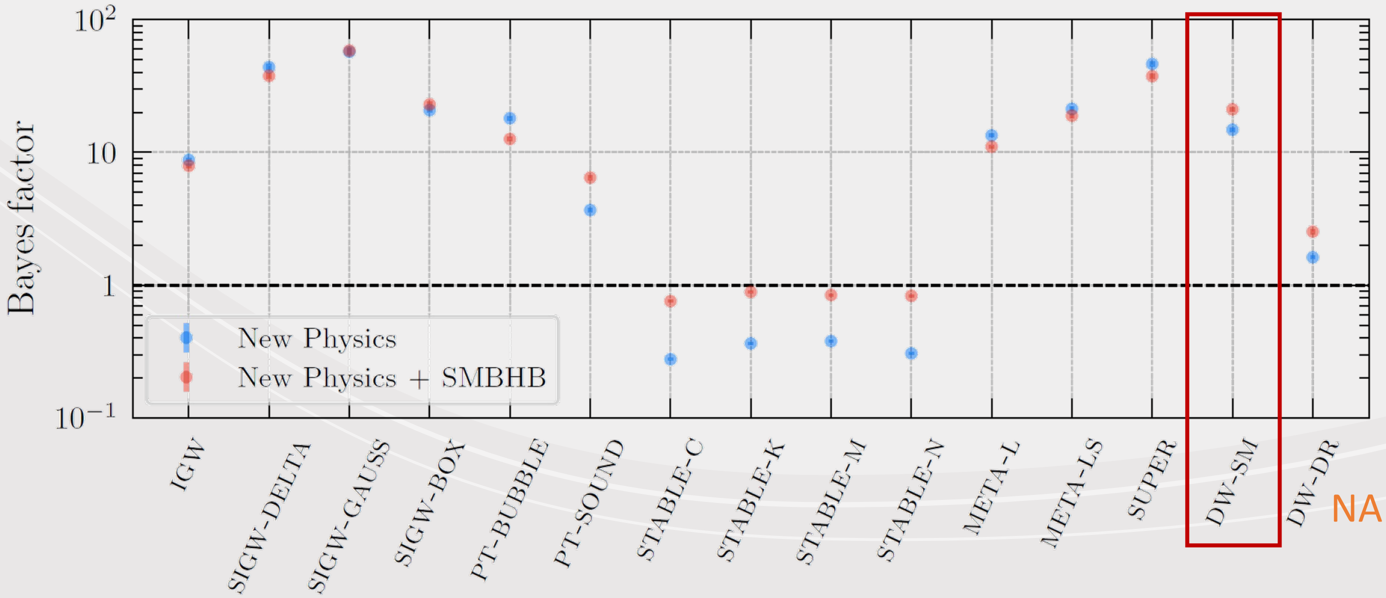
SMBHBs: $\gamma_{\rm GW} = 13/3, A_{\rm GW} \sim 2.4\times10^{-15}$

↳ $\Omega_{\rm GW} \sim 9.3\times10^{-9}$

Generic: $\gamma_{\rm GW} \sim 3.2, A_{\rm GW} \sim 6.4\times10^{-15}$

Bayes: 3σ
Frequentist: 3.5-4σ





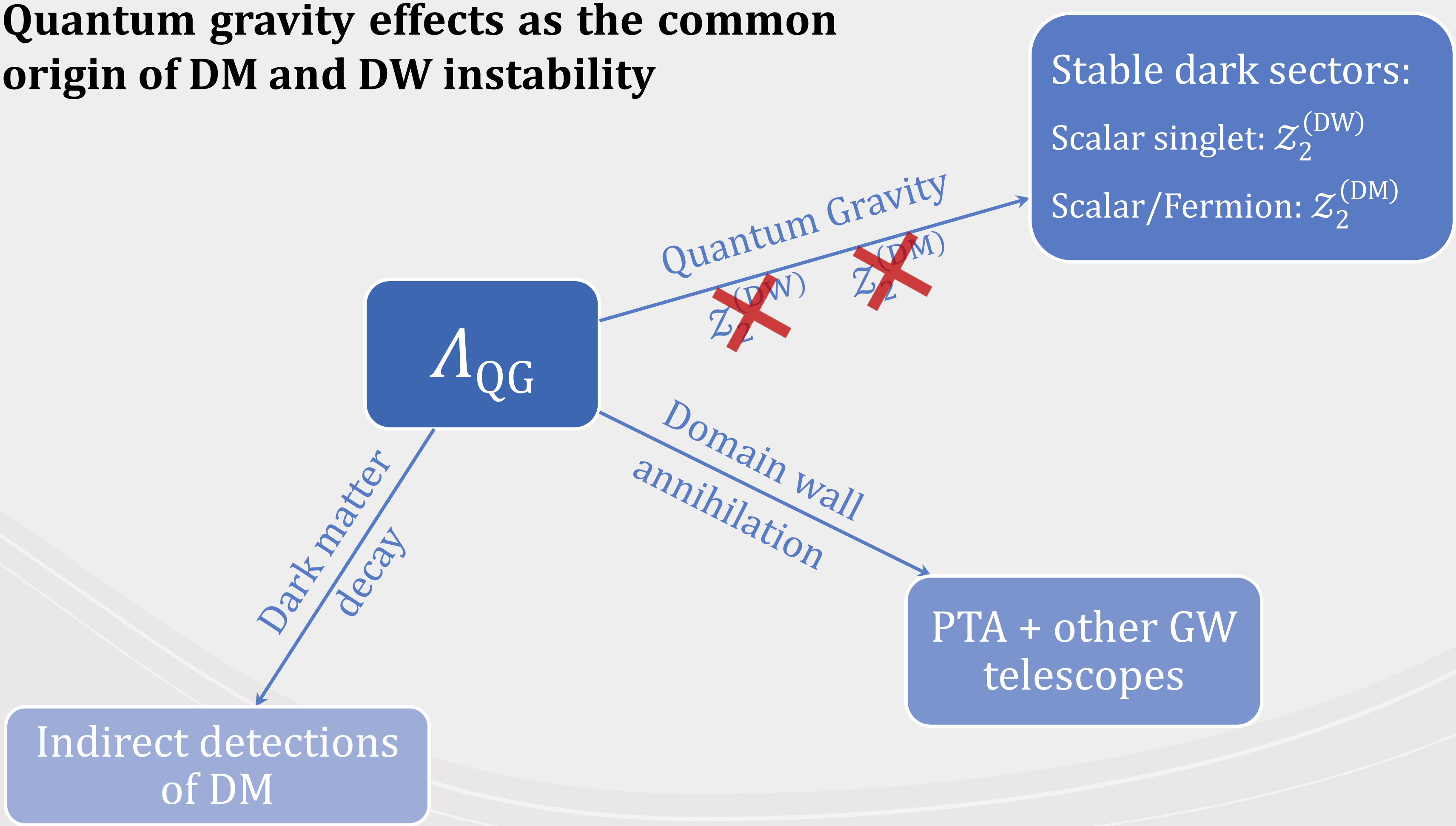
New physics explanations

NANOGrav, 2306.16219

Motivation and background

The framework

Quantum gravity effects as the common origin of DM and DW instability



Λ_{QG}

Quantum Gravity

$\cancel{\mathcal{Z}_2^{(\mathrm{DW})}}$ $\cancel{\mathcal{Z}_2^{(\mathrm{DM})}}$

Stable dark sectors:

Scalar singlet: $\mathcal{Z}_2^{(\mathrm{DW})}$

Scalar/Fermion: $\mathcal{Z}_2^{(\mathrm{DM})}$

Domain wall annihilation

PTA + other GW telescopes

Dark matter decay

Indirect detections of DM

The scale of quantum gravity

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

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

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

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

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

Extremely large!

- U(1) Peccei-Quinn symmetry breaking: $\mathcal{S} \gtrsim 190$ → $\Lambda_{\rm QG} \sim 10^{100}\ {\rm GeV}$
- Discrete Z_2 symmetry we are considering:

The size of the instanton action is $\mathcal{S} \sim \mathcal{O}(M_{\rm Pl}^2/\Lambda_{\rm UV}^2)$

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

→ $\mathcal{S} \sim \mathcal{O}(10)$

The range of the scale we are considering is $\Lambda_{\rm QG} \sim (10^{20} \cdots 10^{35})\ {\rm GeV}$

Corresponding to $\mathcal{S} \sim (4 \cdots 38)$

More realistic!

A minimalistic model with two singlet scalars

Two scalars

$\boldsymbol{S_1}$: associated with Z_2^{DW}; $\boldsymbol{S_2}$: 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)

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

Assume a common scale for the breaking of all global symmetries

- The number of tunable parameters of EFT is finite in string theory
- $\Lambda_{\mathrm{QG}} \sim \Lambda_{\mathrm{max}}$ gives the best attainable quality of global symmetry in a class of string compactification

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

A minimalistic model with two singlet scalars

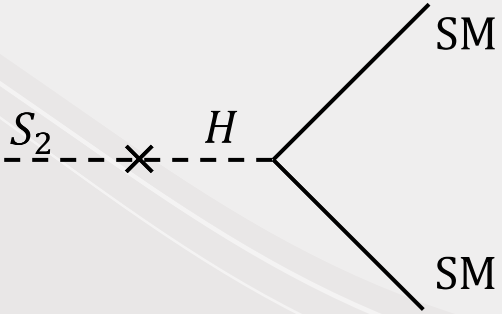
Decay of dark matter

$$\Delta V \supset S_2 H^4/\Lambda_{\mathrm{QG}} \xrightarrow{\text{Electroweak symmetry breaking}} \text{Mixing between } S_2 \text{ and } H$$

The mixing angle is given by

$$\sin\theta = \frac{v_h^3}{(m_h^2 - m_{\mathrm{DM}}^2)\Lambda_{\mathrm{QG}}}$$

Dark matter can decay into SM particles via the Higgs portal



The decay width

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

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

From Spira, Prog.Part.Nucl.Phys. 95, 98 (2017), adopt leading-order approximation.

A minimalistic model with two singlet scalars

Indirect detection of dark matter

CMB power spectrum

If the DM decay happens during or after the era of recombination, the energy injected can reionize the intergalactic medium and modify the CMB power spectrum.

The resulting limits on the DM lifetime tend to be much larger than the age of the Universe

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

SKA radio telescope

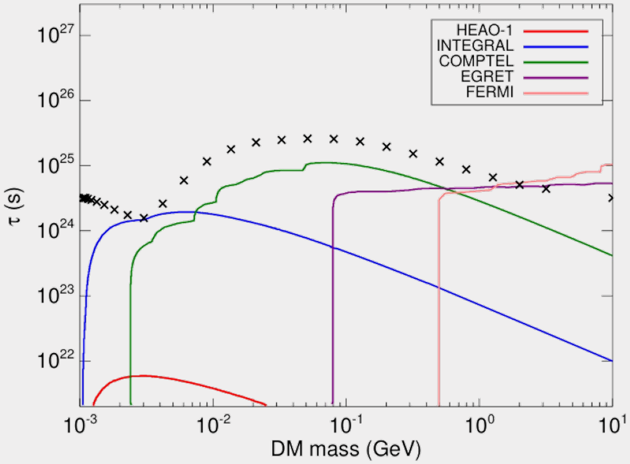
e^+e^- pairs produced by DM decays can undergo energy loss via electromagnetic interactions.

Such radio signals can then be observed by radio telescopes like SKA.

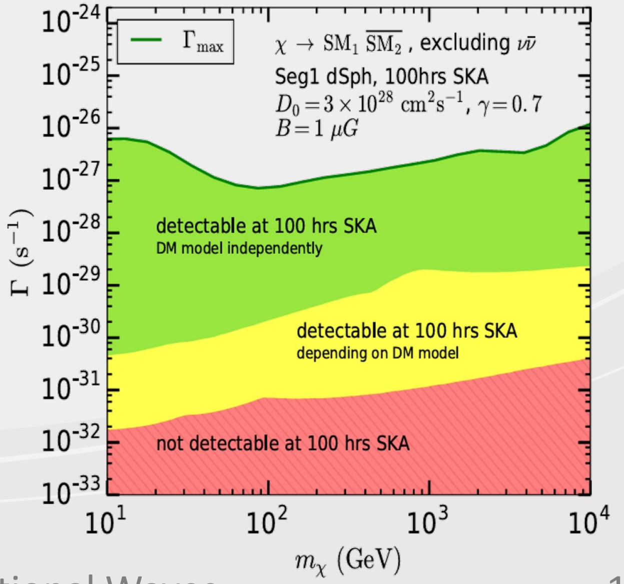
A better probe for DM decay width

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

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



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



A minimalistic model with two singlet scalars

Solving the domain wall problem – Biased domain wall

Introduce a bias term which breaks vacua degeneracy

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

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

- False vacuum region tends to shrink ➡ Volume pressure force $p_V \sim V_{\rm bias}$
- The tension force $p_T \sim \frac{\sigma}{\boxed{R_{\rm wall}}}$

Surface energy density $\sigma = \frac{4}{3}\frac{\sqrt{\lambda}}{2} v_1^3$

Typical curvature radius $R_{\rm wall} \sim vt \sim \frac{\sqrt{\sigma t^3}}{M_{\rm Pl}}$

$p_V \sim p_T$ gives the annihilation time

$$t_{\rm ann} = C_{\rm ann} \frac{\mathcal{A}\sigma}{V_{\rm bias}} = 6.58 \times 10^{-4}\,{\rm s}\, C_{\rm ann} \mathcal{A} \hat{\sigma} \hat{V}_{\rm bias}^{-1}$$

Temperature ➡

$$T_{\rm ann} = 3.41 \times 10^{-2} {\rm GeV} \times C_{\rm ann}^{-1/2} \mathcal{A}^{-1/2} \left(\frac{g_*(T_{\rm ann})}{10} \right)^{-1/4} \hat{\sigma}^{-1/2} \hat{V}_{\rm bias}^{1/2}$$

$\hat{\sigma} = \sigma / {\rm TeV}^3$

$\hat{V}_{\rm bias} = V_{\rm bias} / {\rm MeV}^4$

$C_{\rm ann} \simeq 2$

Area parameter $\mathcal{A} \simeq 0.8 \pm 0.1$

Annihilate before BBN $t_{\rm ann} < 0.01$s: $\boxed{V_{\rm bias}^{1/4} \gtrsim 5.07 \times 10^{-4}\ {\rm GeV}\ C_{\rm ann}^{1/4} \mathcal{A}^{1/4} \hat{\sigma}^{1/4}}$

A minimalistic model with two singlet scalars

Gravitational waves from domain wall annihilation

NANOGrav, 2306.16219

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 $t\sim t_{\rm ann}$

$$\Omega_p h^2\simeq 5.3\times10^{-20}\,\boxed{\widetilde{\epsilon}}\,\mathcal{A}^4 C_{\rm ann}^2\,\widehat{\sigma}^4\,\widehat{V}_{\rm bias}^{-2}$$

Effective parameter ~0.7

The corresponding peak frequency

$$f_p\simeq 3.75\times10^{-9}\ {\rm Hz}\ C_{\rm ann}^{-1/2}\mathcal{A}^{-1/2}\widehat{\sigma}^{-1/2}\widehat{V}_{\rm bias}^{1/2}$$

$f_p\propto T_{\rm ann}$ ➡

High annihilation temperature results in high peak frequency

$$T_{\rm ann}\sim 10{\rm MeV}\rightarrow f_p\sim 10^{-9}{\rm Hz}$$

Broken power law

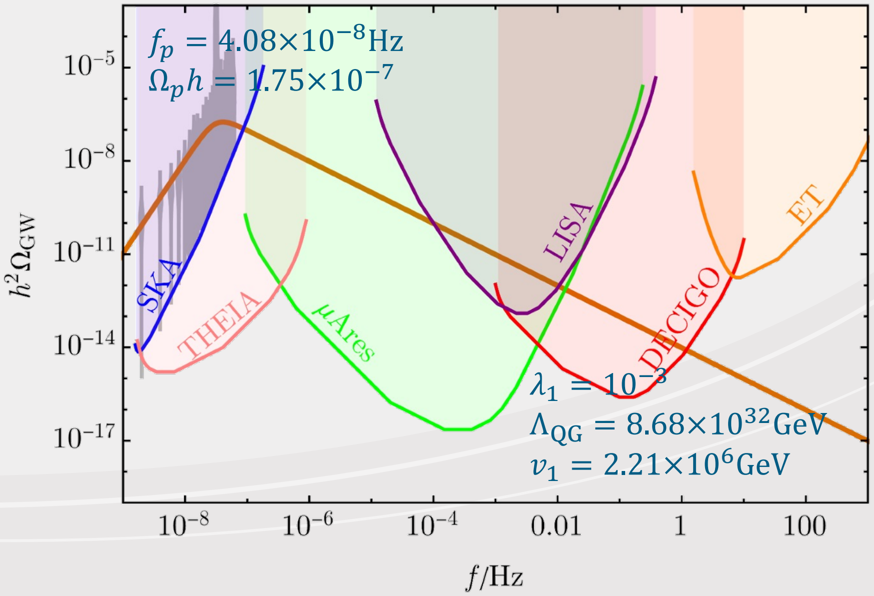
$$h^2\Omega_{\rm GW}=h^2\Omega_p\frac{(a+b)^c}{\left(bx^{-a/c}+ax^{b/c}\right)^c}$$

$x=f/f_p$

$a=3$ by causality

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

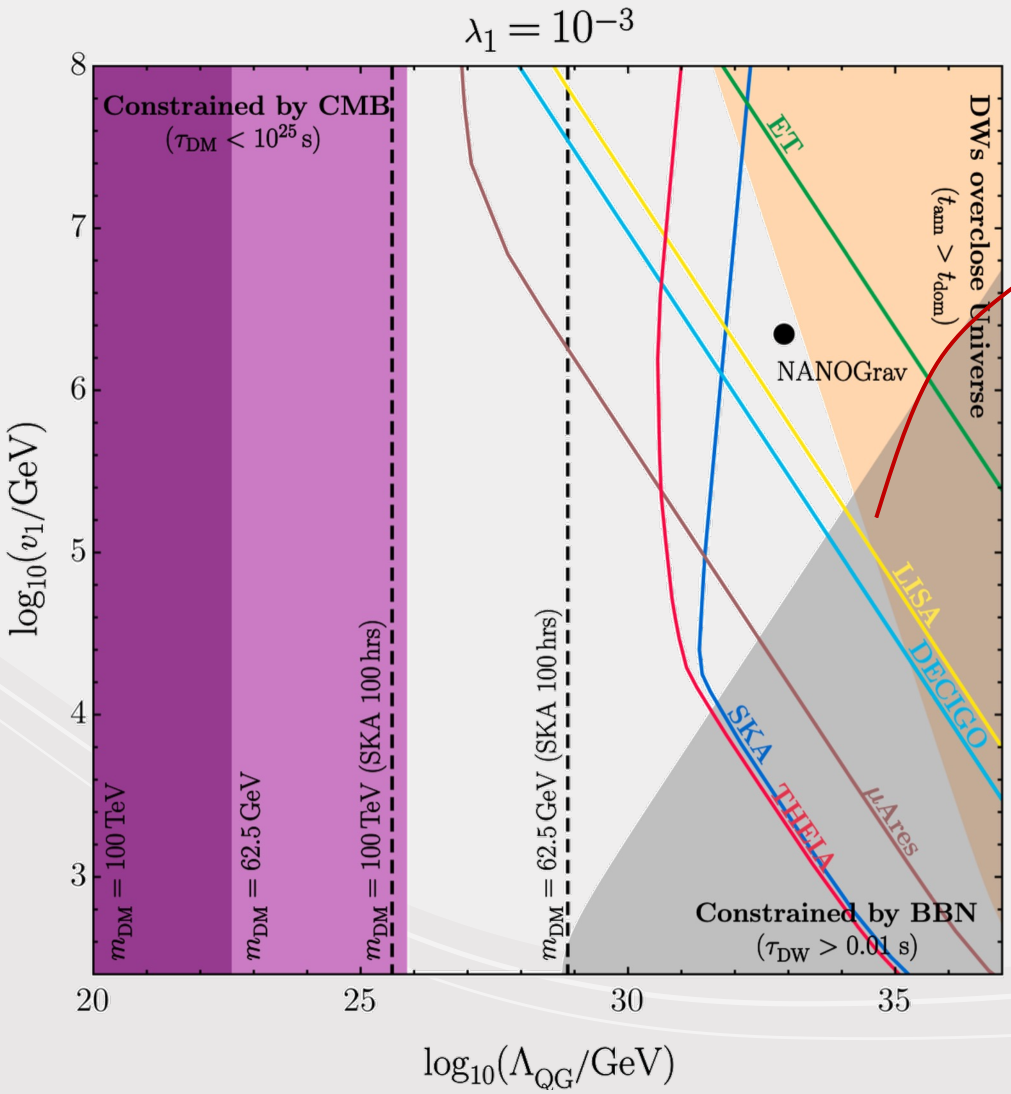
SF, RR, GW, **XW**, MY, 2311.12487



A minimalistic model with two singlet scalars

Combined constraints on quantum gravity scale

SF, RR, GW, **XW**, MY, 2308.03724



Signal-to-noise ratio

$$\varrho = \left[n_{\rm det} t_{\rm obs} \int_{f_{\rm min}}^{f_{\rm max}} df \left(\frac{\Omega_{\rm signal}\,(f)}{\Omega_{\rm noise}\,(f)} \right)^2 \right]^{1/2}$$

Take the $\varrho > 10$ as discovery

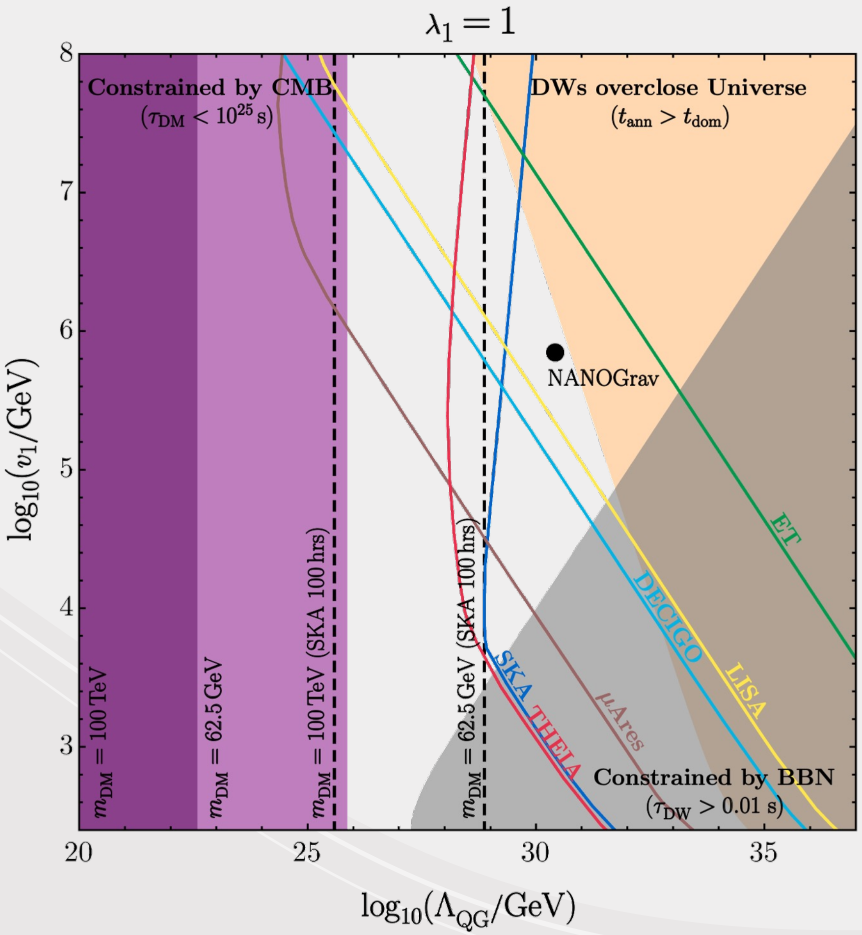
Two typical DM mass:

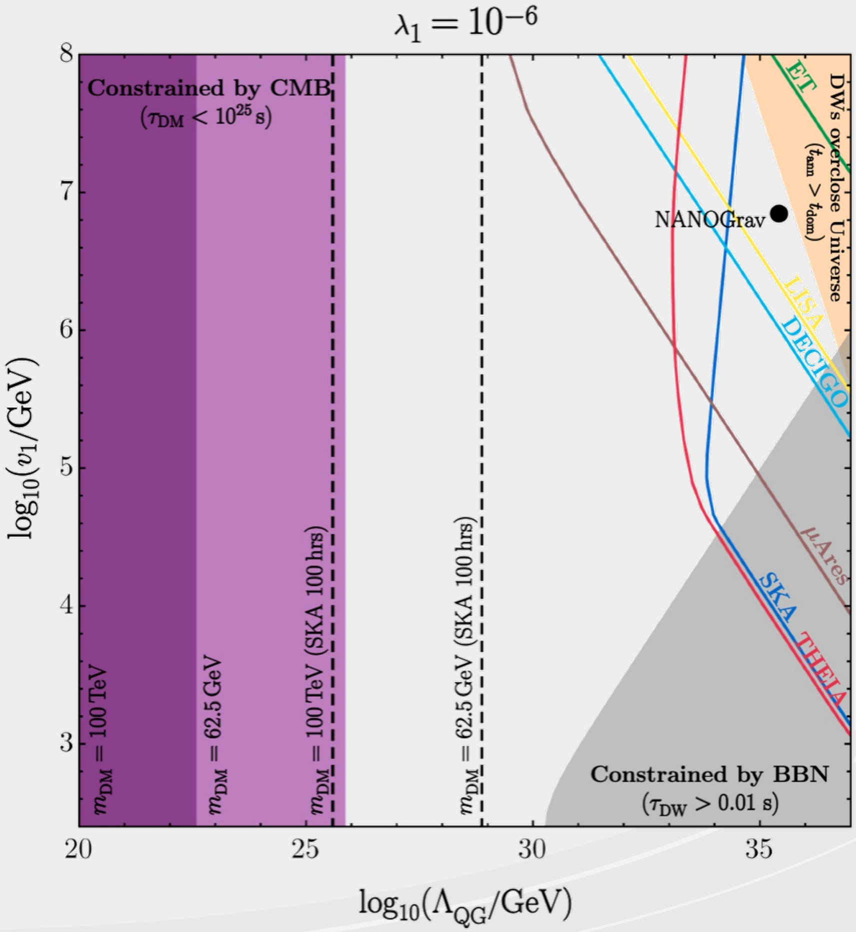
$m_{\rm DM} = 62.5{\rm GeV}$, Higgs resonance
$m_{\rm DM} = 100{\rm TeV}$, Unitarity bound

A minimalistic model with two singlet scalars

Combined constraints on quantum gravity scale

SF, RR, GW, **XW**, MY, 2308.03724



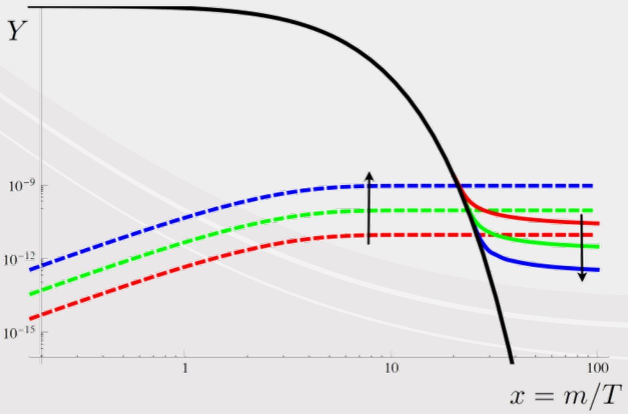


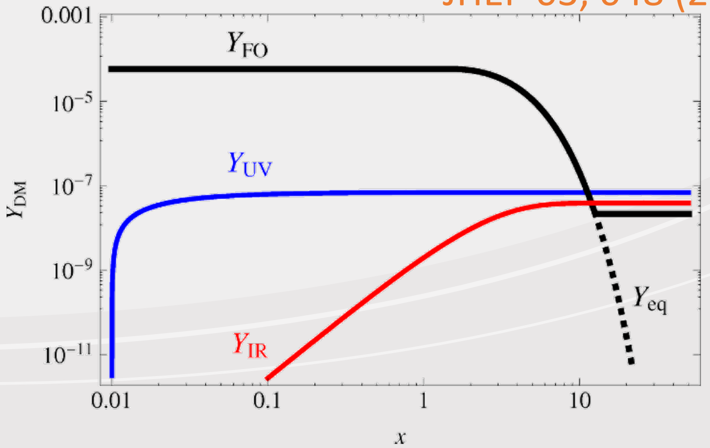
The fermionic dark matter case

Freeze-in or freeze-out?

- Severe problems with fermionic WIMP-type DM.
- An alternative is the feebly-interacting massive particle (FIMP).
  - DM never enters thermal equilibrium with the SM bath
  - The initial abundance is negligible
  - DM abundance slowly freeze-in
- Two types of freeze-in scenarios:
  - IR freeze-in: renormalizable interaction between FIMP and SM bath
  - UV freeze-in: only non-renormalizable interaction

Fatemeh et al., JHEP 03, 048 (2015)





The fermionic dark matter case

One singlet scalar + one singlet fermion

SF, RR, GW, **XW**, MY, 2311.12487

S: associated with Z_2^{DW}; χ: associated with Z_2^{DM};

The fermion sector

The only dimension-five operators that violate both Z_2^{DW} and Z_2^{DM}:

$$\mathcal{L}_{\mathrm{break}} = \frac{1}{\Lambda_{\mathrm{QG}}} S \overline{\ell_\alpha} \tilde{H} \underline{\chi}$$

Can be regarded as sterile neutrino

Dimension-five operators associated with Λ_{FI} that conserve Z_2 symmetry

$$\mathcal{L} = \frac{1}{\Lambda_{\mathrm{FI}}} \overline{\chi} \chi S^2 + \frac{1}{\Lambda_{\mathrm{FI}}} \overline{\chi} \chi H^\dagger H$$

Freeze-in scenario

Elahi et al., JHEP 03, 048 (2015)

The DM abundance produced in a UV/IR freeze-in scenario is

$$Y_{\mathrm{DM}}^{\mathrm{UV}} \simeq 3 \frac{180}{1.66 \times (2\pi)^7 g_\star^S \sqrt{g_\star^\rho}} \left(\frac{T_{\mathrm{RH}} M_{\mathrm{Pl}}}{\Lambda_{\mathrm{FI}}^2} \right) \qquad Y_{\mathrm{DM}}^{\mathrm{IR}} \simeq \frac{135 M_{\mathrm{Pl}}}{1.66 \times 8\pi^3 g_\star^S \sqrt{g_\star^\rho}} \left(\frac{\Gamma_{s \to \chi\chi}}{m_s^2} + \frac{\Gamma_{h \to \chi\chi}}{m_h^2} \right)$$

The DM relic density

$$\Omega h^2 = 2.75 \times 10^8 \times \frac{m_{\mathrm{DM}}}{\mathrm{GeV}} \left(Y_{\mathrm{DM}}^{\mathrm{UV}} + Y_{\mathrm{DM}}^{\mathrm{IR}} \right)$$

The fermionic dark matter case

Active-sterile mixing and indirect detection

The DM can couple to the SM fields via active-sterile neutrino mixing

$$\mathcal{L}_{\rm break} = \frac{1}{\Lambda_{\rm QG}} S \overline{\ell_\alpha} \tilde{H} \chi$$ ➡ Give rise to Dirac mass terms

The mixing angle is approximately given by

$$\theta \simeq \sum_{i=1,2,3} \left(\frac{m_{D_i}}{m_{\rm DM}} \right) = \left(\frac{3 v_s v_h}{\sqrt{2} \Lambda_{\rm QG}} \right) \frac{1}{m_{\rm DM}}$$

Shrock, NPB 206, 359 (1982)
Essig et al., JHEP 11, 193 (2013)

The two-body radiative decay $\chi \to \nu\gamma$

$$\tau_{\chi \to \nu\gamma} \simeq \left(\frac{9 \alpha_{\rm EM} \sin^2\theta}{1024 \pi^4} G_F^2 m_{\rm DM}^5 \right)^{-1} \simeq 1.8 \times 10^{17}\ {\rm s} \left(\frac{10 {\rm MeV}}{m_{\rm DM}} \right)^5 \left(\frac{\sin\theta}{10^{-8}} \right)^{-2}$$

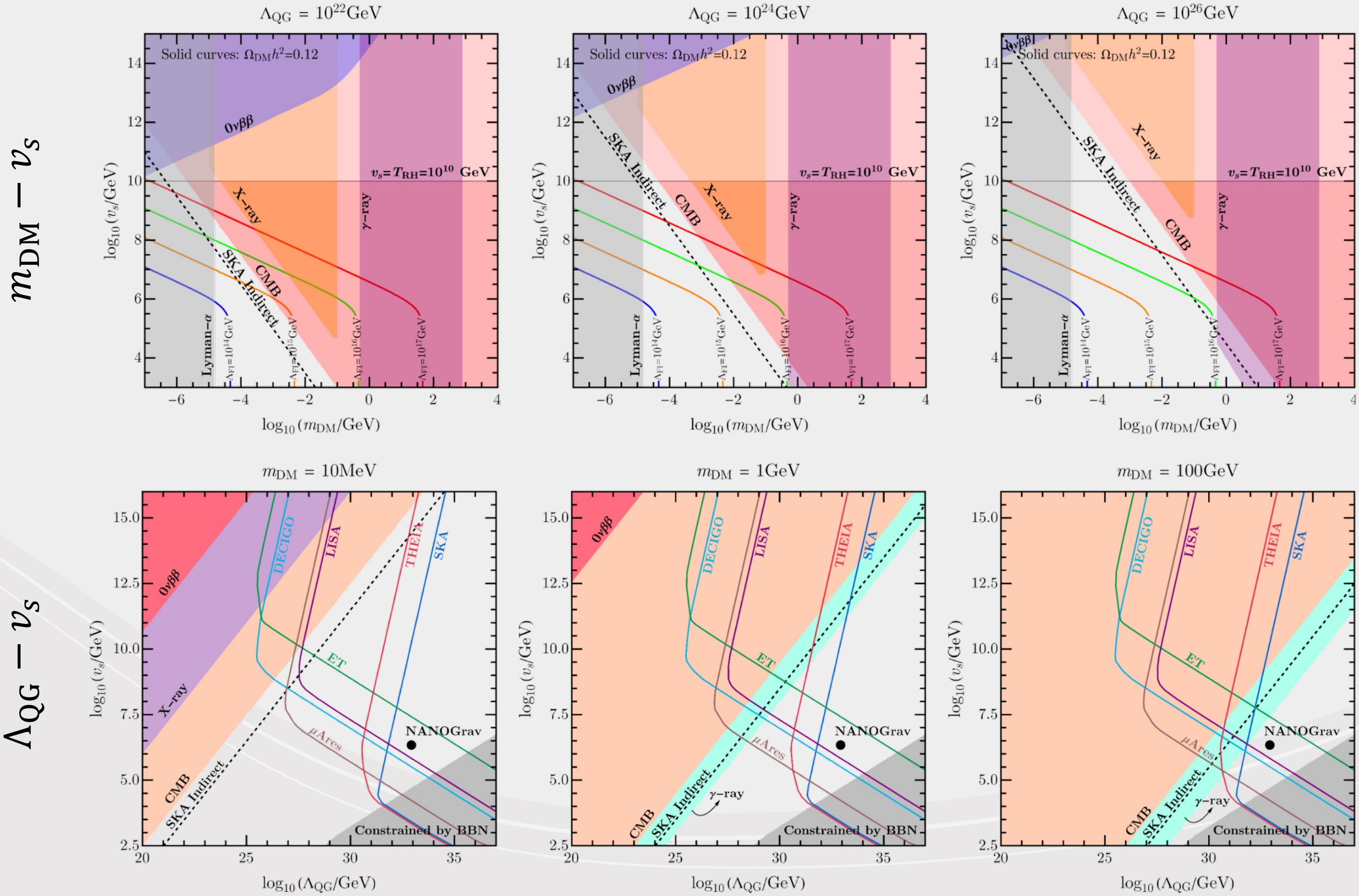
Indirect detection

- ☐ X/γ-ray: Null detection of characteristic line can lead to a constraint
- ☐ CMB: Constraint from the observation of CMB power spectrum
- ☐ SKA: Detection of the radio signals
- ☐ $0\nu\beta\beta$: via the active-sterile mixing

The fermionic dark matter case

Combined results

SF, RR, GW, **XW**, MY, 2311.12487



Summary

- ☐ Quantum gravity effects could be the common origin of dark matter and domain wall instabilities.
- ☐ The quantum gravity scale considered here is the combination of Planck scale and the suppression from non-perturbative instanton effects.
- ☐ Dark matter indirect detections and gravitational wave observations can be used to test the quantum gravity scale. The recent observations of a gravitational wave spectrum by PTA might be our first empirical information about quantum gravity.

Merci!