University of Southampton
THE ROYAL SOCIETY
ICHEP 2024

Quantum Gravity Effects on Dark Matter and Gravitational Waves

Xin Wang

University of Southampton

Prague · Czech Republic

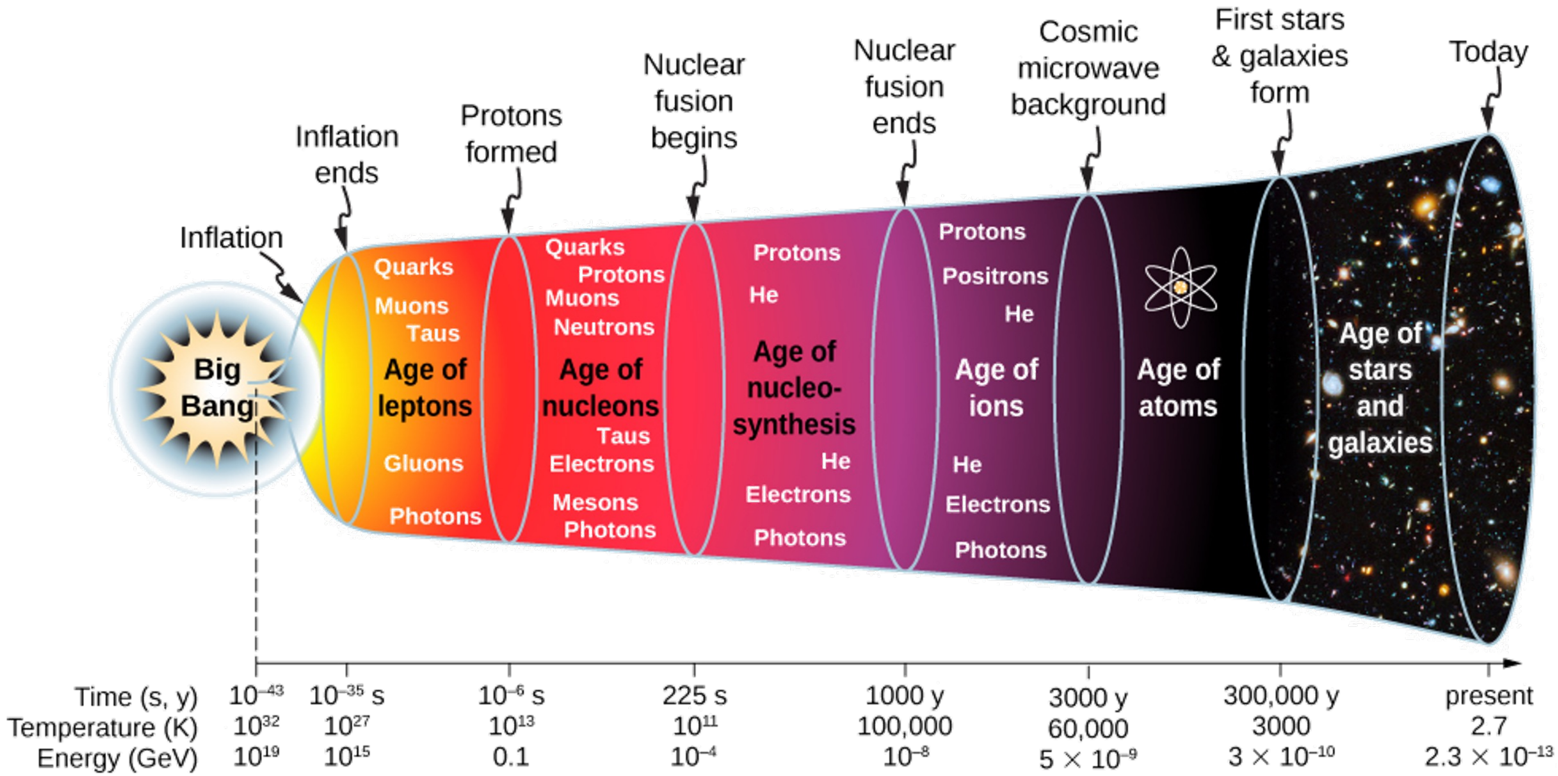
2024/07/19

Based on: PRD 109 (2024) 2, 024057 [2308.03724],
JCAP 05 (2024) 071 [2311.12487],
2407.XXXXX

In collaboration with:

Stephen F. King, Rishav Roshan, Graham White, Masahito Yamazaki
(+ Yann Gouttenoire)

Quantum gravity as a UV completion?



Quantum mechanics + Gravity?

UV completion

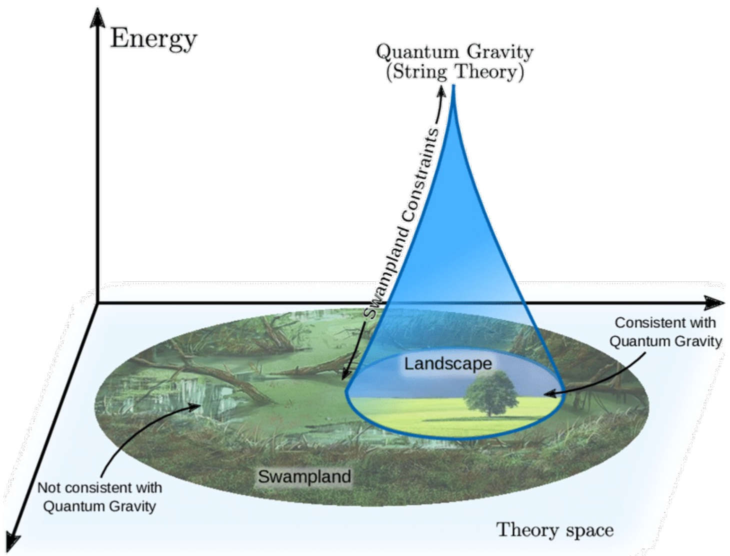
Standard Model

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

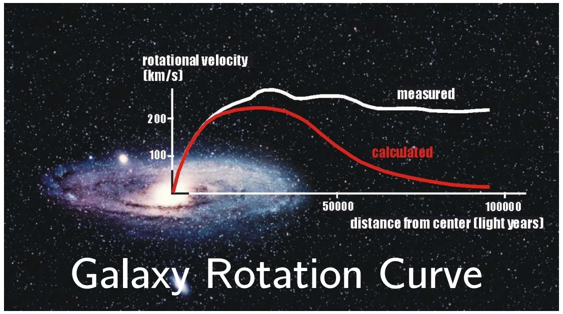
$$\mathcal{L}_{\not{Z}_2} = \frac{1}{\Lambda_{\rm QG}}\mathcal{O}_5 + \cdots$$

Any observational effects that can constrain $\Lambda_{\rm QG}$?

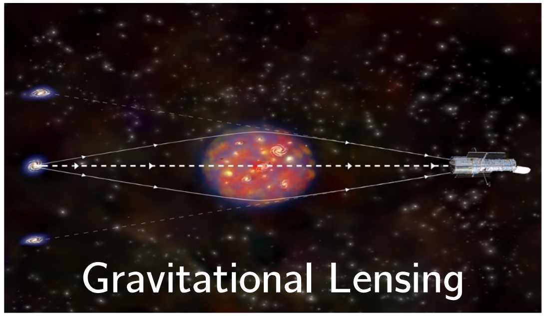
Motivation and background

Dark matter

Gravitational presence of Dark Matter



Galaxy Rotation Curve

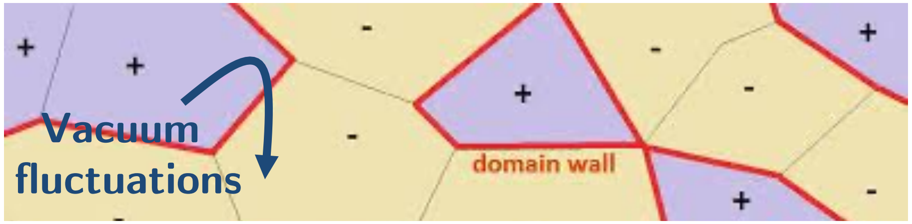

Gravitational Lensing


Bullet Cluster

Z_2 symmetry ➡ DM stability

Cosmological domain walls

Originate from the spontaneous breaking of discrete symmetries.



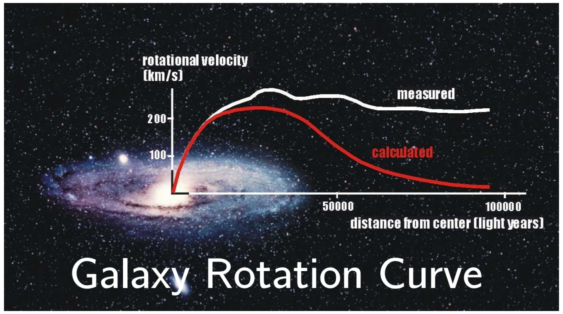
The energy density of domain walls soon dominates the total energy budget of the Universe.

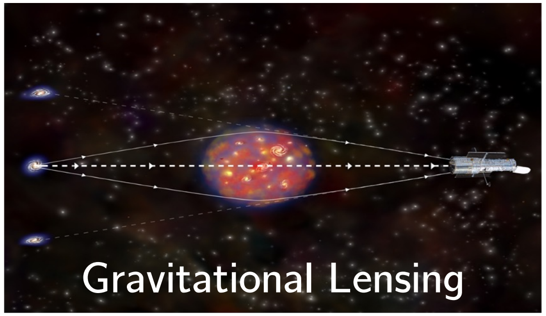
Vilenkin & Shellard (Cambridge University Press, 2000)

Motivation and background

Dark matter

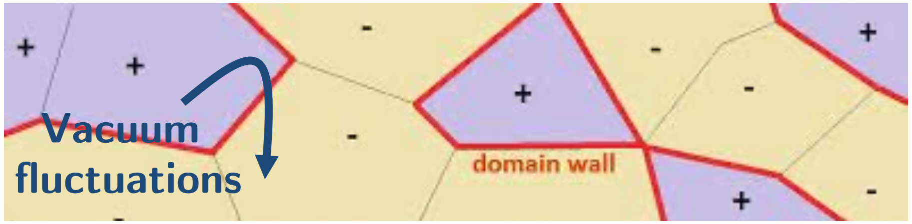
Gravitational presence of Dark Matter



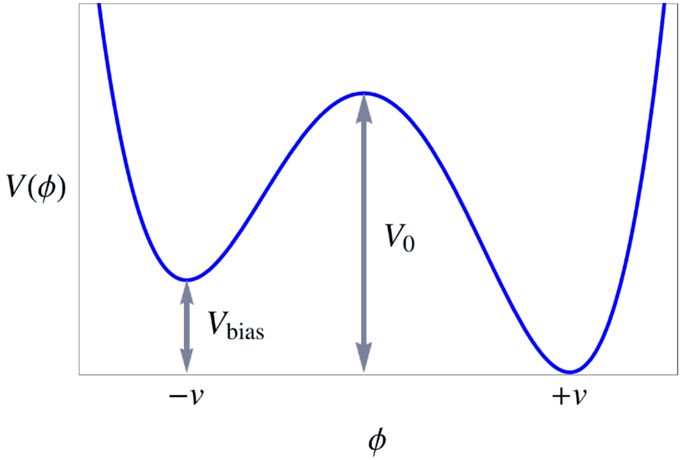


Z_2 symmetry → DM stability

Cosmological domain walls



Zeldovich et al., 1974, Kibble, 1976, Vilenkin, 1981, ...



Solution: metastable domain walls

Discrete symmetry is explicitly broken

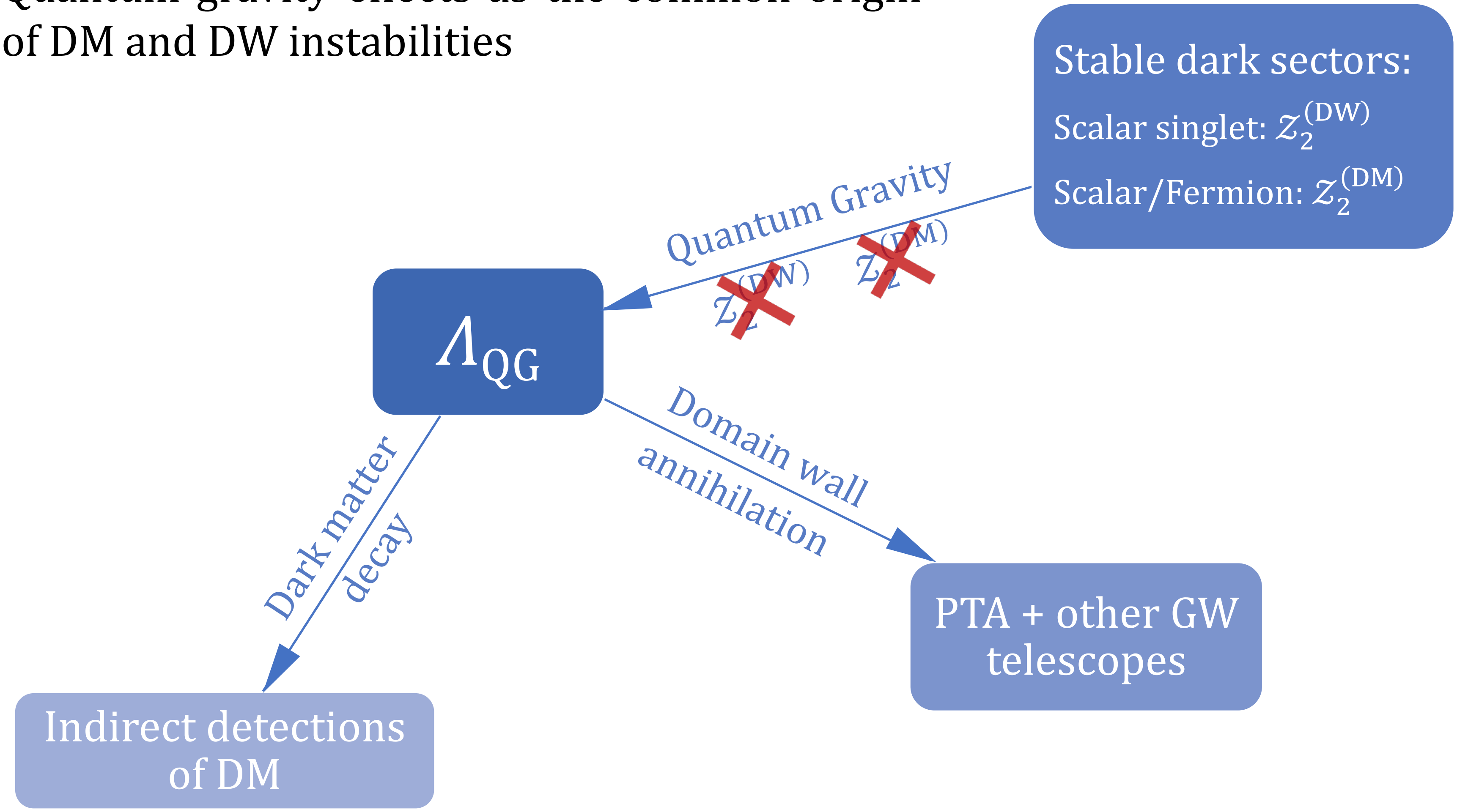
→ **Bias term** → **DWs annihilate**

Gravitational waves can be produced during the evolution of domain walls.

Saikawa, Universe 3, 40 (2017)

The framework

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

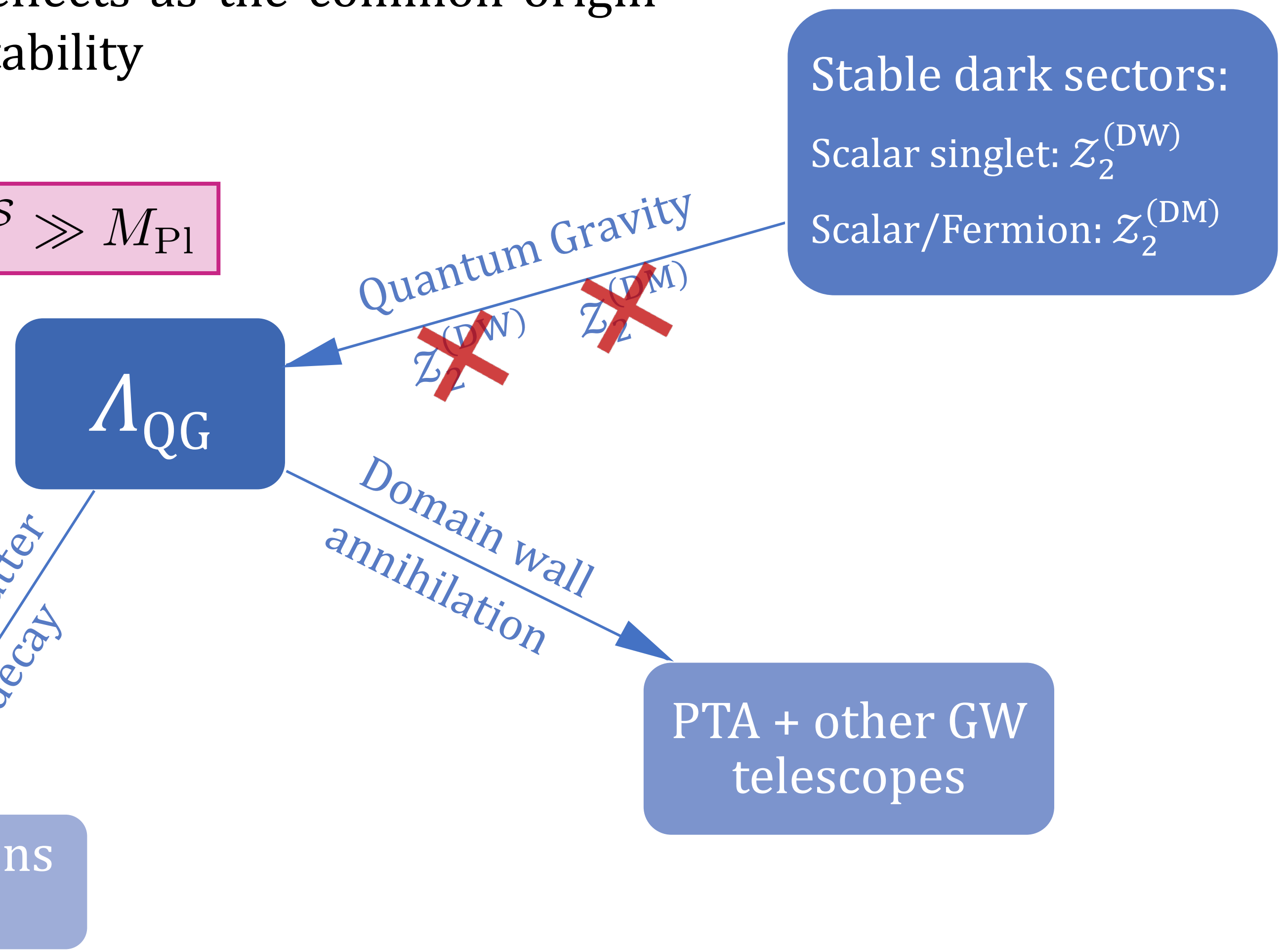


The framework

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

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

- Planck scale
- Non perturbative instanton effects



A minimalistic model with two singlet scalars

The model

Two scalars

S_1: Z_2^{DW}; S_2: Z_2^{DM}

Z_2-conserving:
$$V = \mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + H^\dagger H(\lambda_{hs1} S_1^2 + \lambda_{hs2} S_2^2) + \lambda_{s12} S_1^2 S_2^2 + \mu_2^2 S_2^2 + \frac{\lambda_2}{4} S_2^4 + \frac{\lambda_1}{4}(S_1^2 - v_1^2)^2$$

Z_2-violating:
$$\Delta V = \frac{1}{\Lambda_{\mathrm{QG}}} \sum_{i=1}^{2} (\alpha_{1i} S_i^5 + \alpha_{2i} S_i^3 H^2 + \alpha_{3i} S_i H^4) + \frac{1}{\Lambda_{\mathrm{QG}}} \sum_{j=1}^{4} c_j S_1^j S_2^{5-j}$$

A minimalistic model with two singlet scalars

The model

Z_2-conserving: $$V = \mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + H^\dagger H(\lambda_{hs1} S_1^2 + \lambda_{hs2} S_2^2) + \lambda_{s12} S_1^2 S_2^2 + \mu_2^2 S_2^2 + \frac{\lambda_2}{4} S_2^4 + \frac{\lambda_1}{4}(S_1^2 - v_1^2)^2$$

Two scalars

S_1: Z_2^{DW}; S_2: Z_2^{DM}

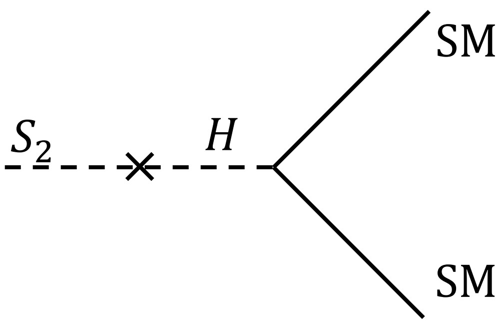
Z_2-violating: $$\Delta V = \frac{1}{\Lambda_{\mathrm{QG}}} \sum_{i=1}^{2} (\alpha_{1i} S_i^5 + \alpha_{2i} S_i^3 H^2 + \alpha_{3i} S_i H^4) + \frac{1}{\Lambda_{\mathrm{QG}}} \sum_{j=1}^{4} c_j S_1^j S_2^{5-j}$$

SF, RR, GW, **XW**, MY, PRD 109 (2024) 2, 024057

Decay of Dark Matter (S_2)

$\Delta V \supset S_2 H^4 / \Lambda_{\mathrm{QG}}$ → Electroweak symmetry breaking → $\sin\theta = \dfrac{v_h^3}{(m_h^2 - m_{\mathrm{DM}}^2)\Lambda_{\mathrm{QG}}}$

Decay via the Higgs portal



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

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

Spira, Prog.Part.Nucl.Phys. 95, 98 (2017)

Indirect detection

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

- CMB power spectrum: $\tau_{\mathrm{DM}} \gtrsim 10^{25}$ s
- SKA radio telescope: $\Gamma_{\mathrm{DM}} \gtrsim 10^{-30}\ \mathrm{s}^{-1}$

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

(To be tested)

A minimalistic model with two singlet scalars

The model

Z_2-conserving: $$V = \mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + H^\dagger H(\lambda_{hs1} S_1^2 + \lambda_{hs2} S_2^2) + \lambda_{s12} S_1^2 S_2^2 + \mu_2^2 S_2^2 + \frac{\lambda_2}{4} S_2^4 + \frac{\lambda_1}{4}(S_1^2 - v_1^2)^2$$

Two scalars

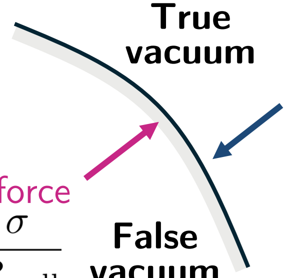
S_1: $Z_2^{\rm DW}$; S_2: $Z_2^{\rm DM}$

Z_2-violating: $$\Delta V = \frac{1}{\Lambda_{\rm QG}} \sum_{i=1}^{2} (\alpha_{1i} S_i^5 + \alpha_{2i} S_i^3 H^2 + \alpha_{3i} S_i H^4) + \frac{1}{\Lambda_{\rm QG}} \sum_{j=1}^{4} c_j S_1^j S_2^{5-j}$$

SF, RR, GW, **XW**, MY, PRD 109 (2024) 2, 024057

Biased domain wall (S_1)

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



$p_V \sim p_T$ gives the annihilation time

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

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

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

Surface energy density $\quad \sigma = \frac{4}{3}\frac{\sqrt{\lambda_1}}{2} v_1^3$

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

Peak frequency:

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

Peak energy density:

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

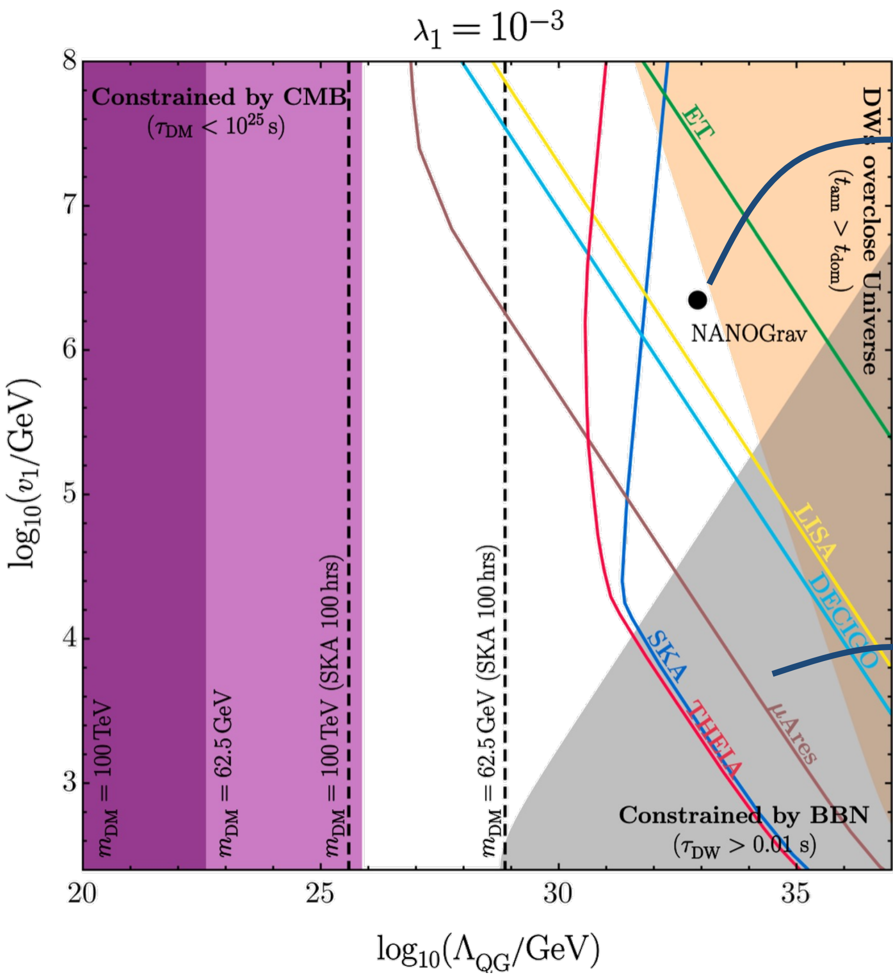
SGWB spectrum: $\quad a = 3, b \simeq c \simeq 1$

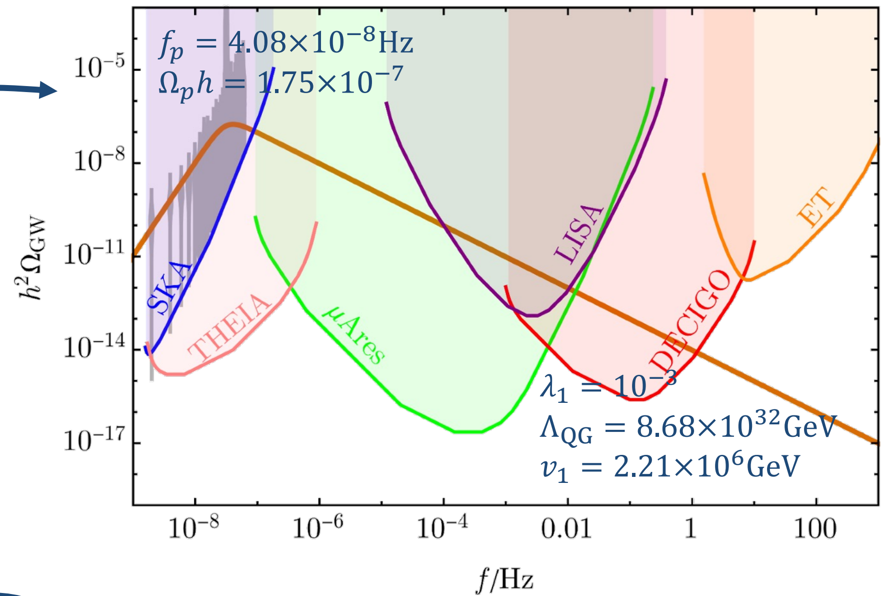
$$h^2 \Omega_{\rm GW} = h^2 \Omega_p \frac{(a+b)^c}{\left(b x^{-a/c} + a x^{b/c}\right)^c}$$

NANOGrav, Astrophys.J.Lett. 951 (2023) 1, L11

A minimalistic model with two singlet scalars

Combined constraints on quantum gravity scale





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

Take the $\varrho = 10$ as threshold

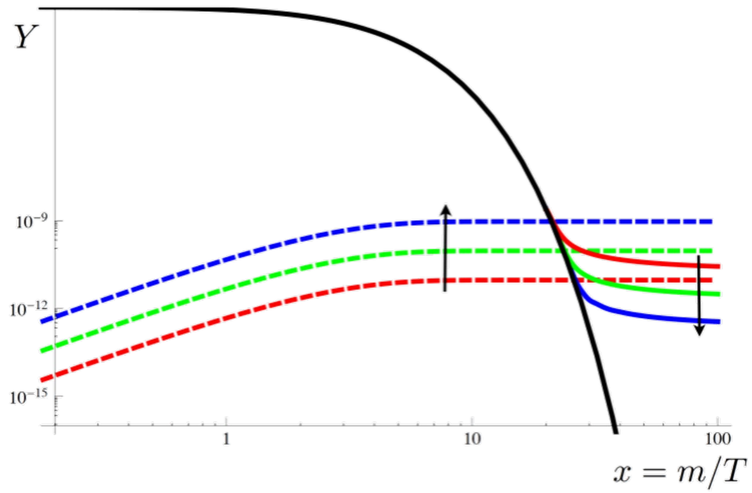
SF, RR, GW, **XW**, MY, PRD 109 (2024) 2, 024057

Freeze-in or freeze-out?

Consider fermionic FIMP Dark Matter

- DM never enters thermal equilibrium
- The initial abundance is negligible
- DM abundance slowly freeze-in

Bernal et al., Int. J. Mod. Phys. A 32 (2017) 1730023;
Fatemeh et al., JHEP 03, 048 (2015)



The model

SF, RR, GW, **XW**, MY, JCAP 05 (2024) 071

One scalar + one fermion   ***S***: associated with $Z_2^{\rm DW}$; ***χ***: associated with $Z_2^{\rm DM}$

@ Dimension 5

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

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

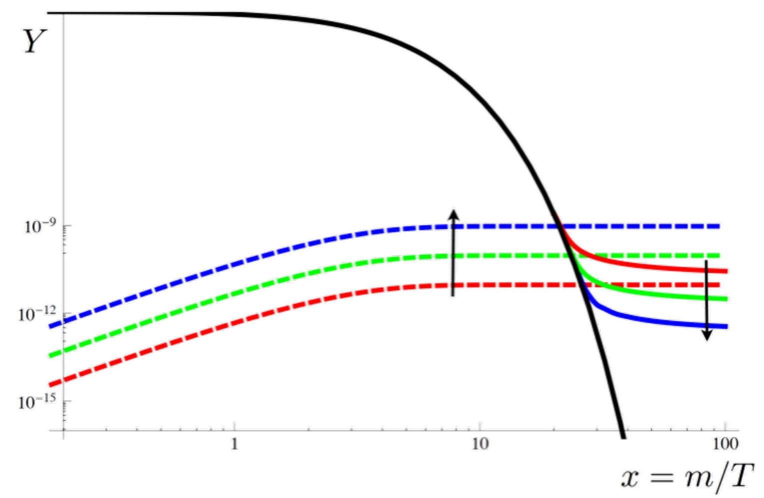
The fermionic dark matter case

Freeze-in or freeze-out?

Consider fermionic FIMP Dark Matter

- DM never enters thermal equilibrium
- The initial abundance is negligible
- DM abundance slowly freeze-in

Bernal et al., Int. J. Mod. Phys. A 32 (2017) 1730023;
Fatemeh et al., JHEP 03, 048 (2015)



The model

SF, RR, GW, **XW**, MY, JCAP 05 (2024) 071

One scalar + one fermion ***S***: associated with $Z_2^{\rm DW}$; ***χ***: associated with $Z_2^{\rm DM}$

@ Dimension 5

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

Z_2 conserving

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

Freeze-in scenario

$$Y_{\rm DM}^{\rm UV} \simeq 3\frac{180}{1.66\times(2\pi)^7 g_\star^S\sqrt{g_\star^\rho}}\left(\frac{T_{\rm RH}M_{\rm Pl}}{\Lambda_{\rm FI}^2}\right)$$

$$Y_{\rm DM}^{\rm IR} \simeq \frac{135 M_{\rm Pl}}{1.66\times 8\pi^3 g_\star^S\sqrt{g_\star^\rho}}\left(\frac{\Gamma_{s\to\chi\chi}}{m_s^2}+\frac{\Gamma_{h\to\chi\chi}}{m_h^2}\right)$$

→ Relic abundance

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

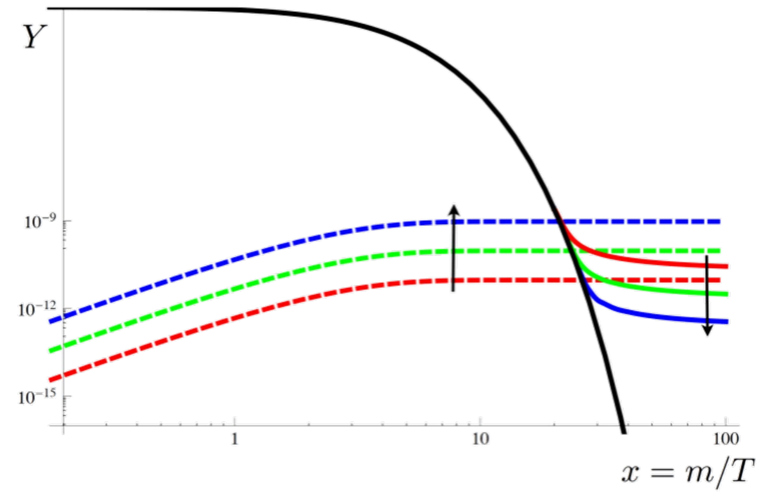
The fermionic dark matter case

Freeze-in or freeze-out?

Consider fermionic FIMP Dark Matter

- DM never enters thermal equilibrium
- The initial abundance is negligible
- DM abundance slowly freeze-in

Bernal et al., Int. J. Mod. Phys. A 32 (2017) 1730023;
Fatemeh et al., JHEP 03, 048 (2015)



The model

SF, RR, GW, **XW**, MY, JCAP 05 (2024) 071

One scalar + one fermion S: associated with $Z_2^{\rm DW}$; χ: associated with $Z_2^{\rm DM}$

@ Dimension 5

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

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

Z_2 violating

Active-sterile mixing and indirect detection

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

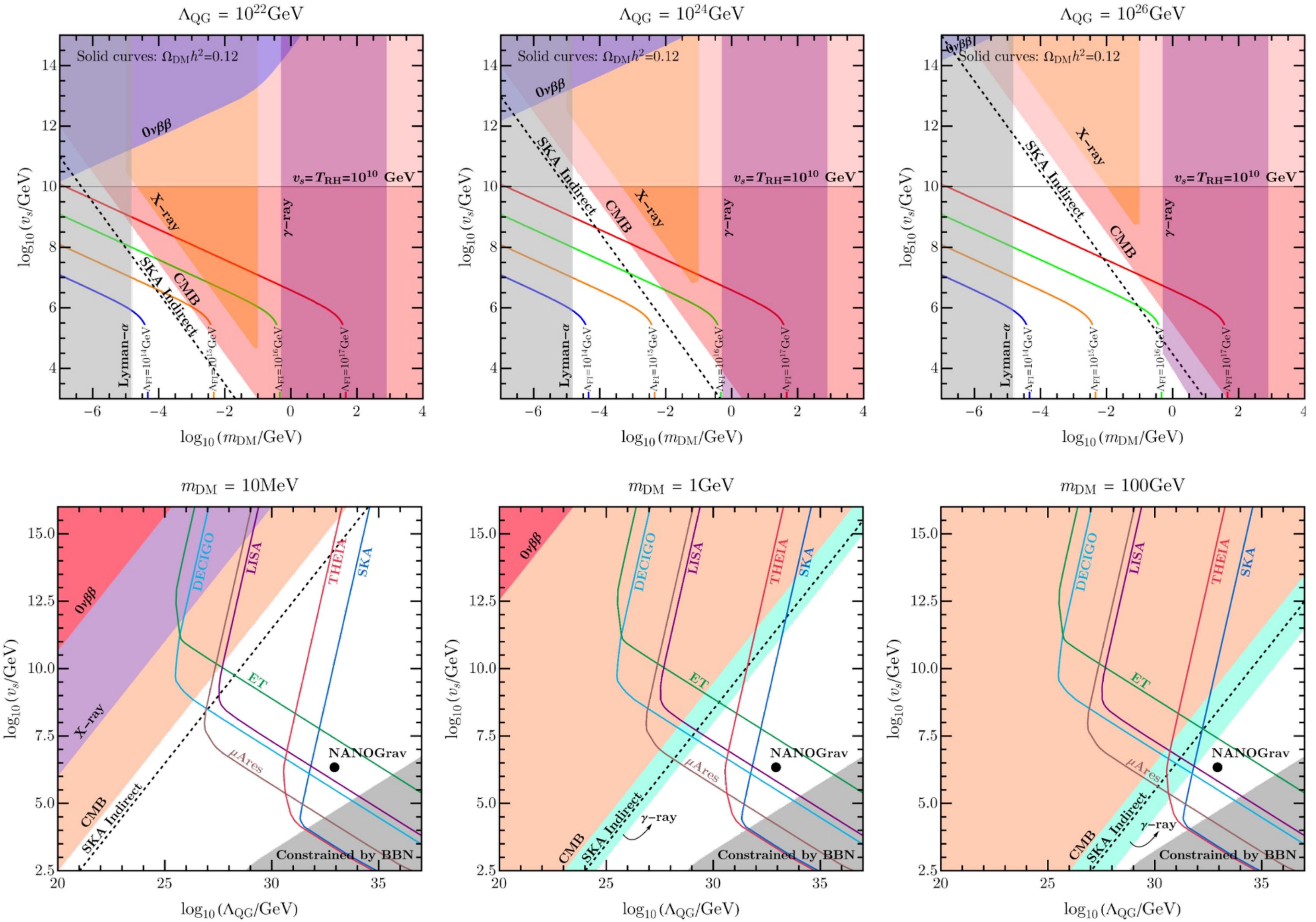
- ❑ X/γ-ray
- ❑ CMB
- ❑ SKA
- ❑ $0\nu\beta\beta$

Combined results

SF, RR, GW, **XW**, MY, JCAP 05 (2024) 071

$m_{\rm DM} - v_s$

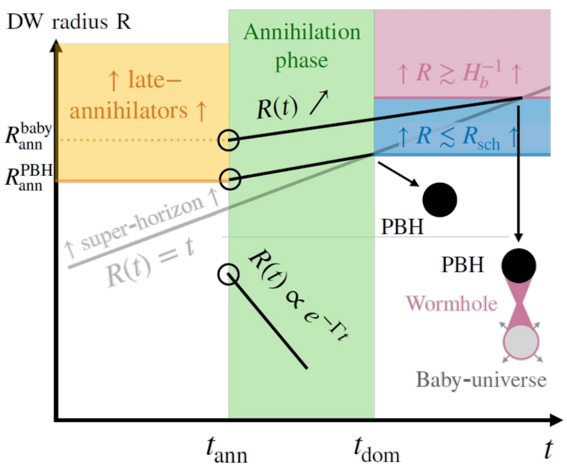
$\Lambda_{\rm QG} - v_s$

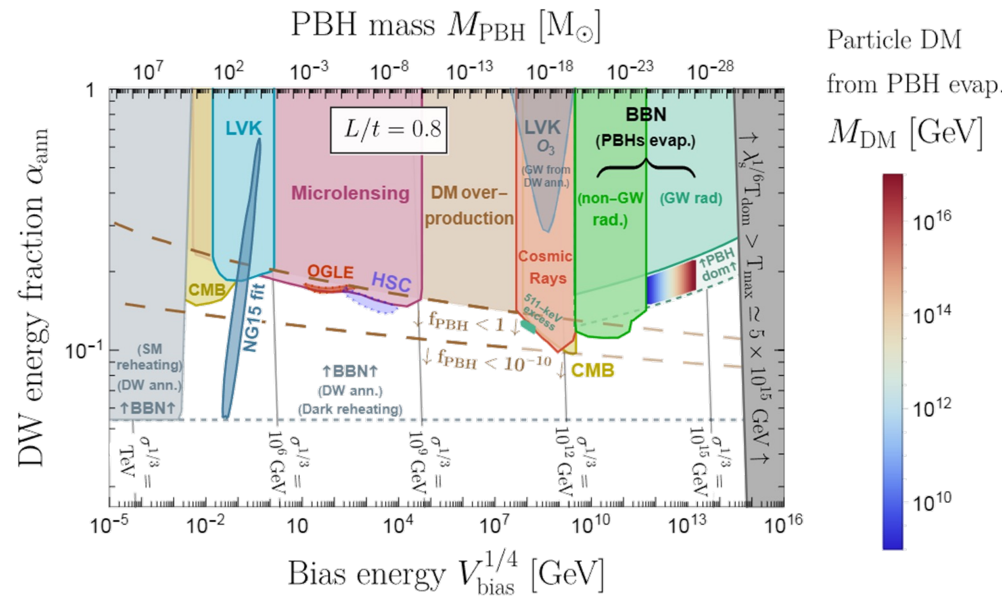


PBH from quantum gravity effects

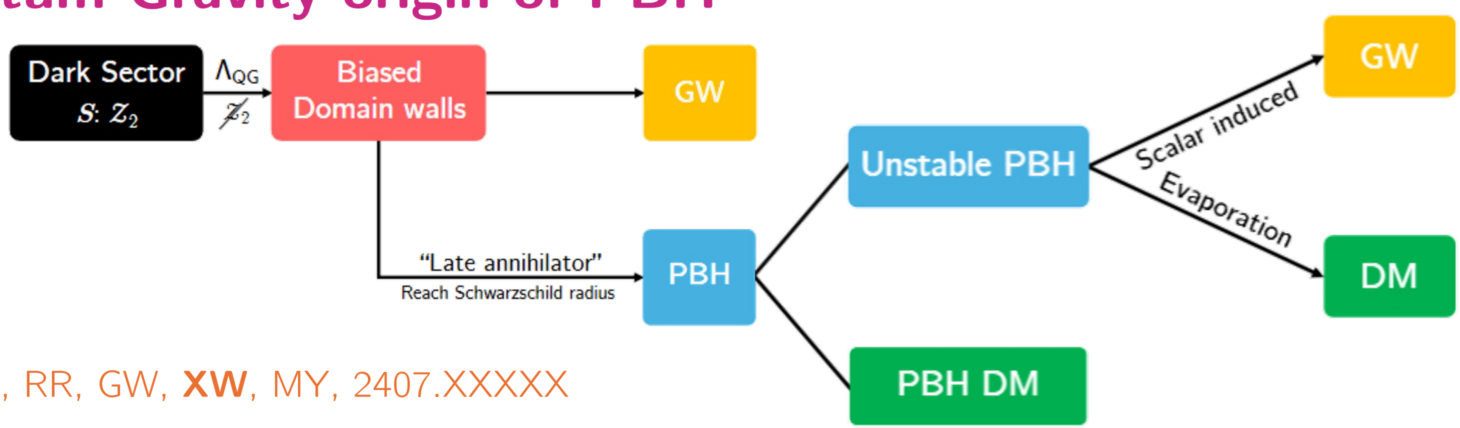
"Late annihilators" collapse into PBH

Yann & Edoardo, PRD 109, 12 (2024)





Quantum Gravity origin of PBH



YG, SF, RR, GW, **XW**, MY, 2407.XXXXX

A simple model with one singlet under Z_2

YG, SF, RR, GW, **XW**, MY,
2407.XXXXX

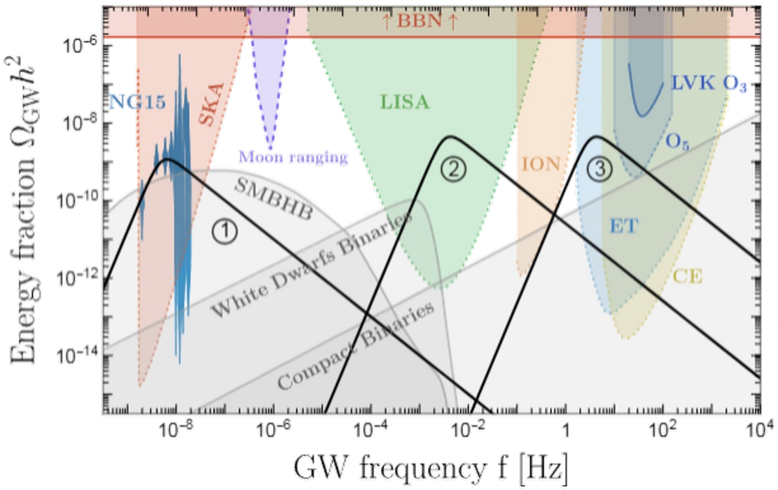
Renormalizable: $$V = \frac{\mu^2}{2} H^\dagger H + \frac{\lambda_h}{4}(H^\dagger H)^2 + \frac{\lambda_{hs}}{4} H^\dagger H S^2 + \frac{\lambda_s}{4}(S^2 - v_s^2)^2$$

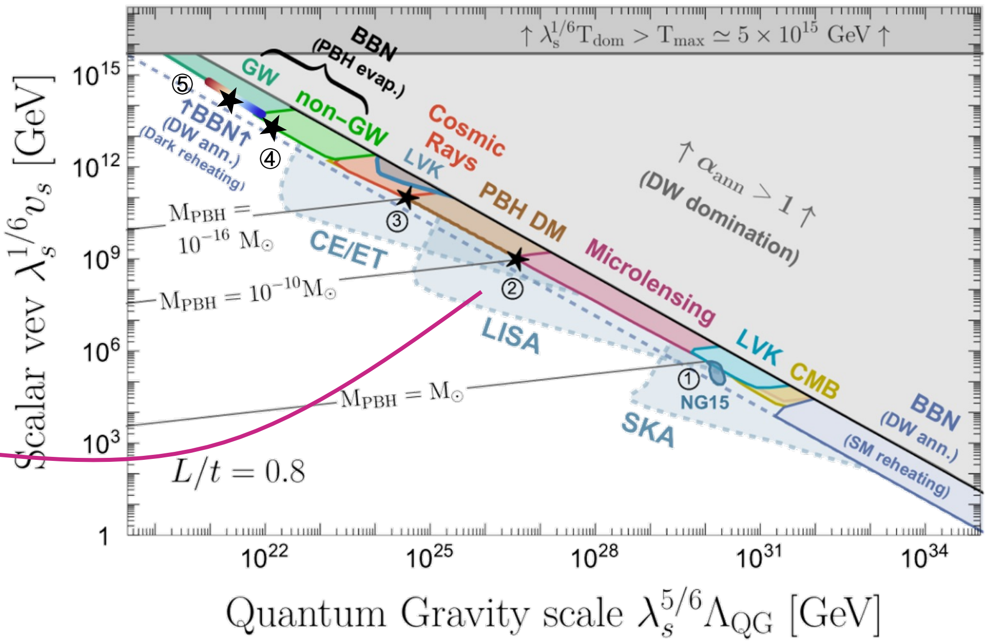
Dimension-5: $$\Delta V = \frac{1}{\Lambda_{\rm QG}}(\alpha_1 S^5 + \alpha_2 S^3 H^2 + \alpha_3 S H^4)$$

$$M = \underbrace{4\pi V_{\rm bias} R^3/3}_{\text{Volume } 25\%} + \underbrace{4\pi\sigma\gamma R^2}_{\text{Surface } 50\%} - \underbrace{8\pi^2 G \sigma^2 R^3}_{\text{Gravitational } 25\%}$$

Schwarzschild condition: $R_{\rm sc}(t_{\rm PBH}) = 2GM(t_{\rm PBH})$ → $$M_{\rm PBH} \simeq 14 M_\odot \left(\frac{100\ \mathrm{MeV}}{V_{\rm bias}^{1/4}}\right)^2$$

Results





A simple model with one singlet under Z_2

YG, SF, RR, GW, **XW**, MY,
2407.XXXXX

Renormalizable: $V = \frac{\mu^2}{2} H^\dagger H + \frac{\lambda_h}{4}(H^\dagger H)^2 + \frac{\lambda_{hs}}{4} H^\dagger H S^2 + \frac{\lambda_s}{4}(S^2 - v_s^2)^2$

Dimension-5: $\Delta V = \frac{1}{\Lambda_{\rm QG}}(\alpha_1 S^5 + \alpha_2 S^3 H^2 + \alpha_3 S H^4)$

$$M = \boxed{4\pi V_{\rm bias} R^3/3} + \boxed{4\pi\sigma\gamma R^2} - \boxed{8\pi^2 G\sigma^2 R^3}$$

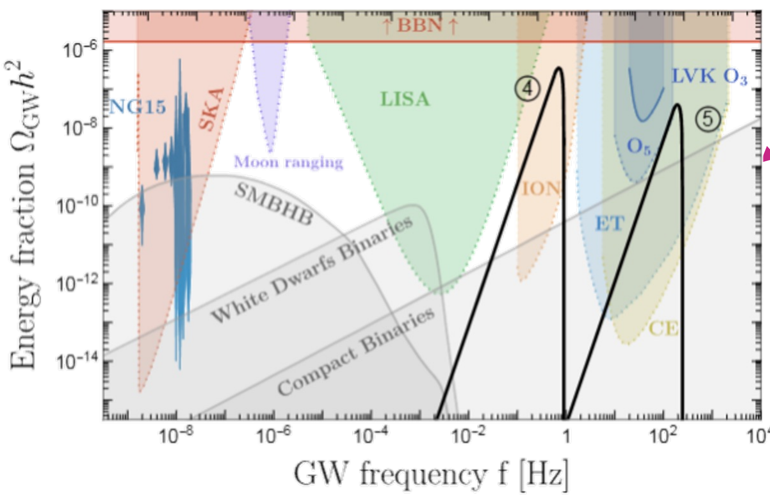
Volume 25% | Surface 50% | Gravitational 25%

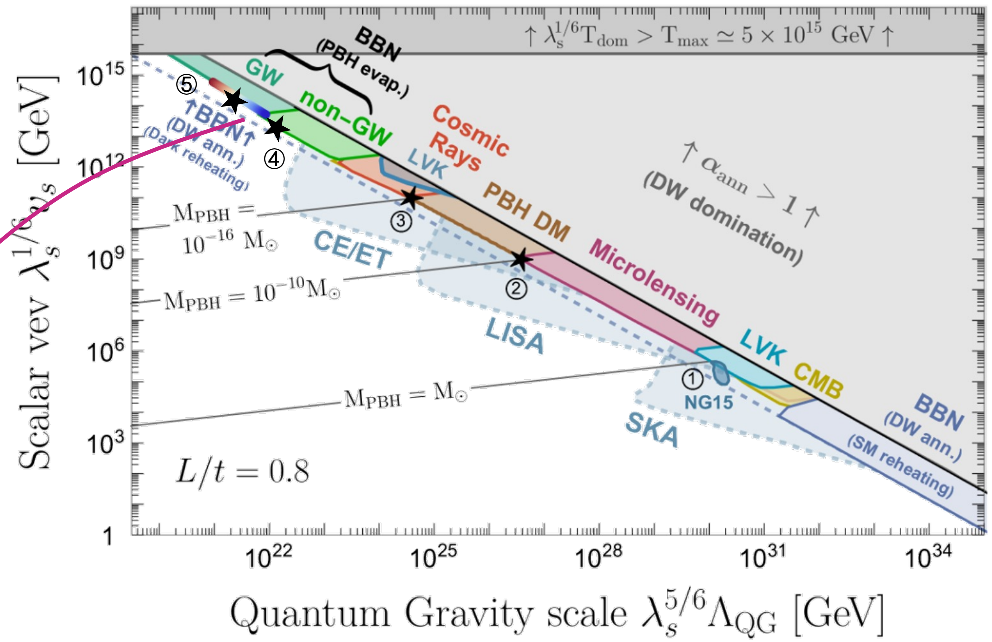
Schwarzschild condition

$R_{\rm sc}(t_{\rm PBH}) = 2GM(t_{\rm PBH})$

$$M_{\rm PBH} \simeq 14 M_\odot \left(\frac{100\ \rm MeV}{V_{\rm bias}^{1/4}}\right)^2$$

Results

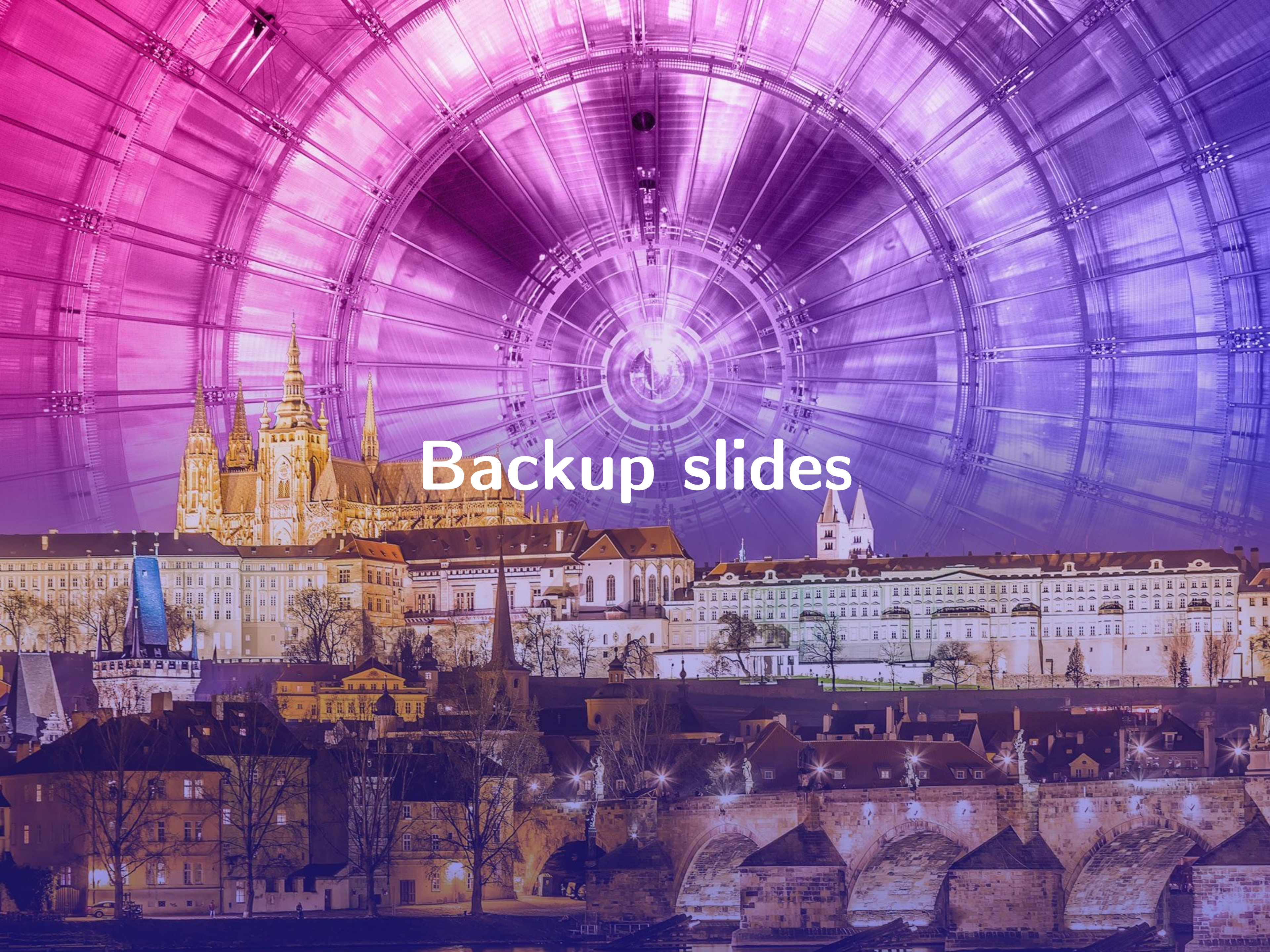




Summary

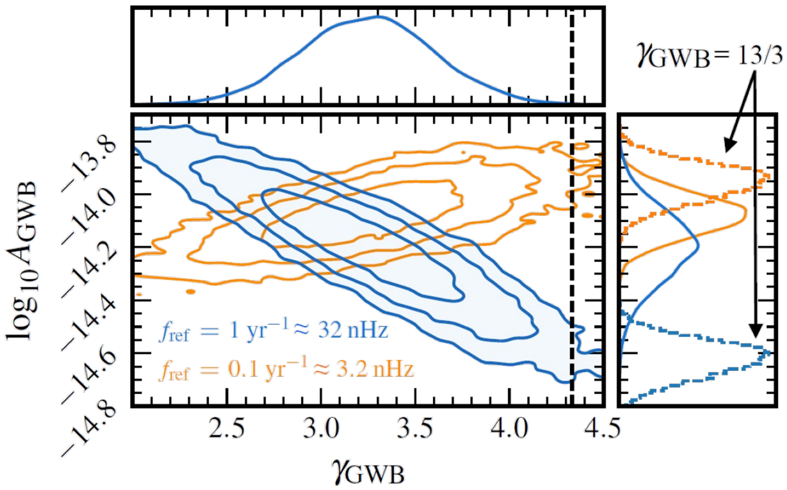
- Quantum gravity effects could be the common origin of dark matter, gravitational waves and primordial black holes.
- The quantum gravity scale considered here is the combination of Planck scale and the suppression from non-perturbative instanton effects.
- Dark matter indirect detections and gravitational 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.

Thank you!


Backup slides

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

Bayes: 3σ
Frequentist: 3.5-4σ



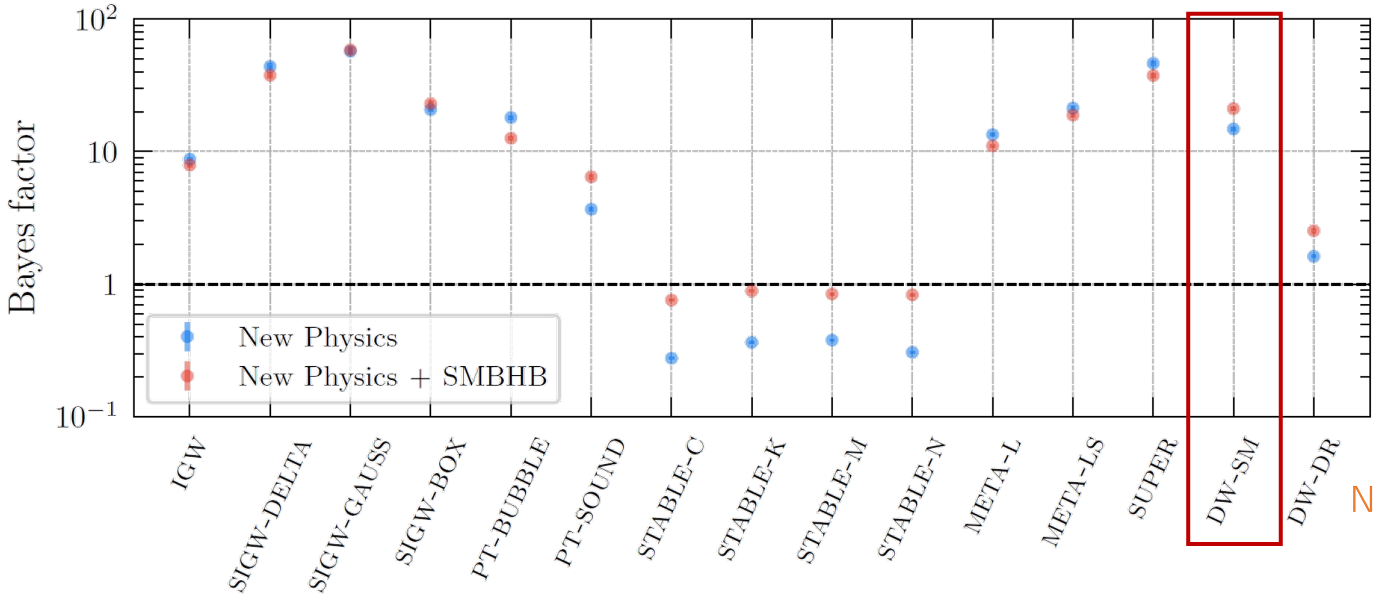
Several PTA projects have reported positive evidence of a stochastic gravitational wave background.

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



New physics explanations

NANOGrav, 2306.16219

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

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

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

Kamionkowski et al., PLB 282, 137 (1992)
Holman et al., PLB 282, 132 (1992)

For the discrete Z_2 symmetry we are considering:

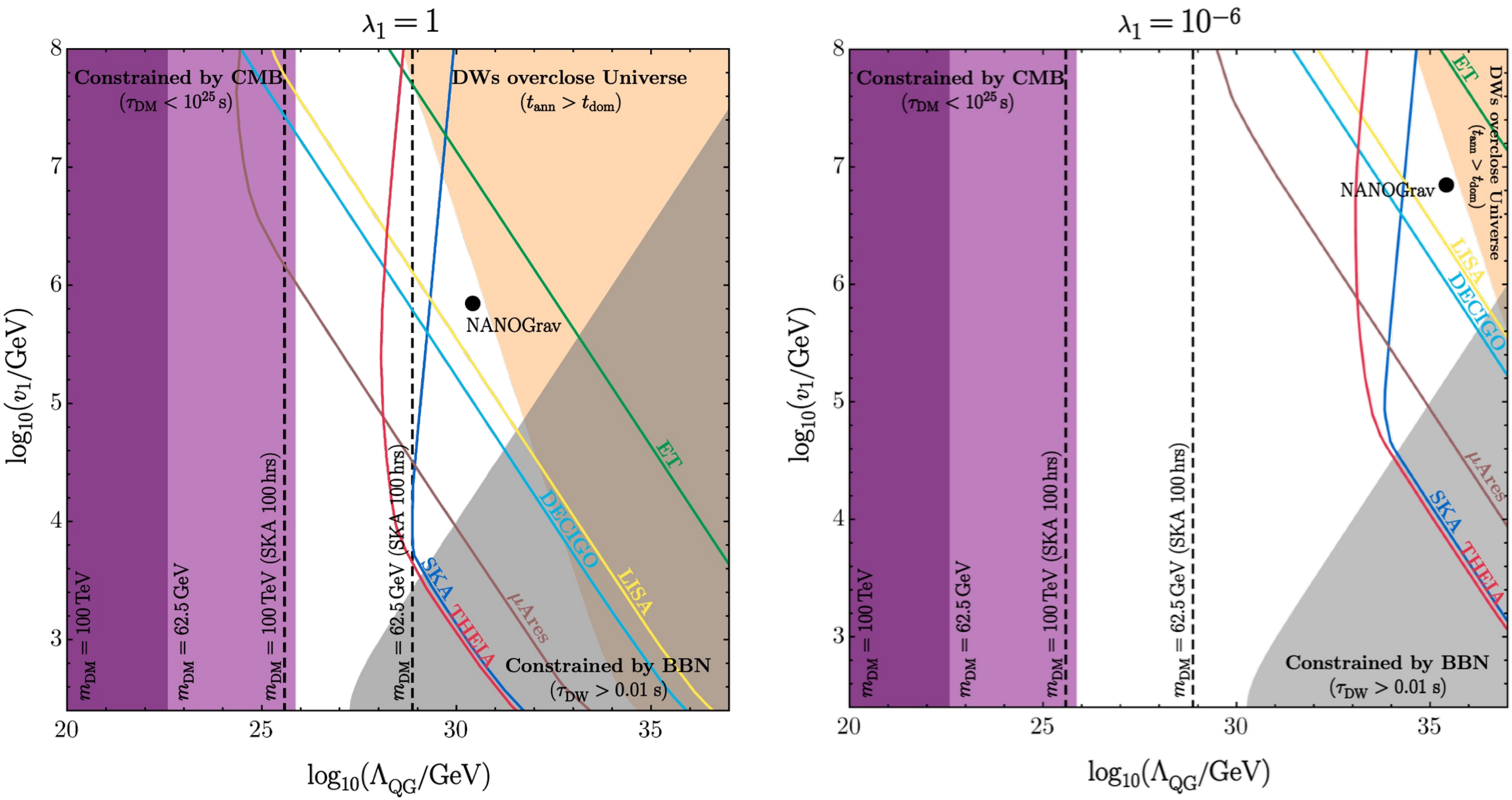
The size of the instanton action is $\mathcal{S} \sim \mathcal{O}(M_{\rm Pl}^2/\Lambda_{\rm UV}^2)$

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 $\Lambda_{\rm QG} \sim (10^{20} \cdots 10^{35})$ GeV

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

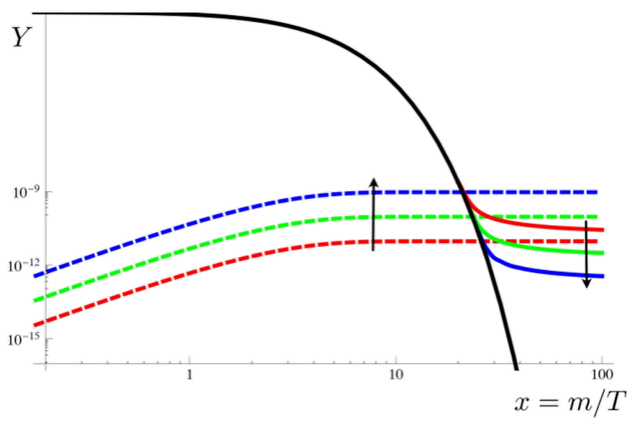
Different values of λ_1

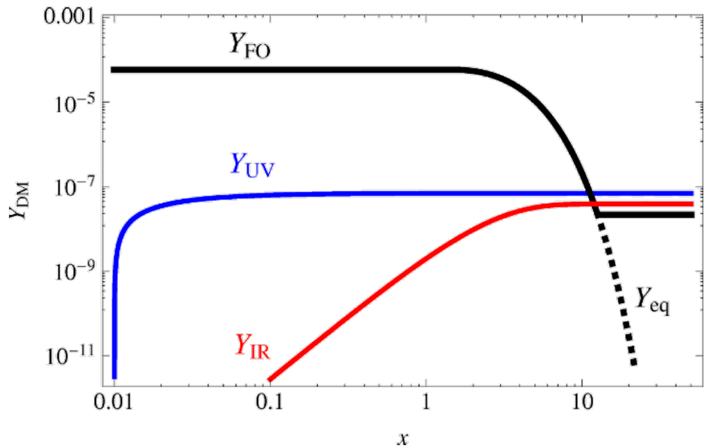


Freeze-in or freeze-out?

- 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)





Active-sterile mixing

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