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Quantum gravity effects on dark matter and gravitational waves

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Based on:

PRD 109 (2024) 2, 024057

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Higgs Discovery

The New York Times

Physicists Find Elusive Particle Seen as Key to Universe

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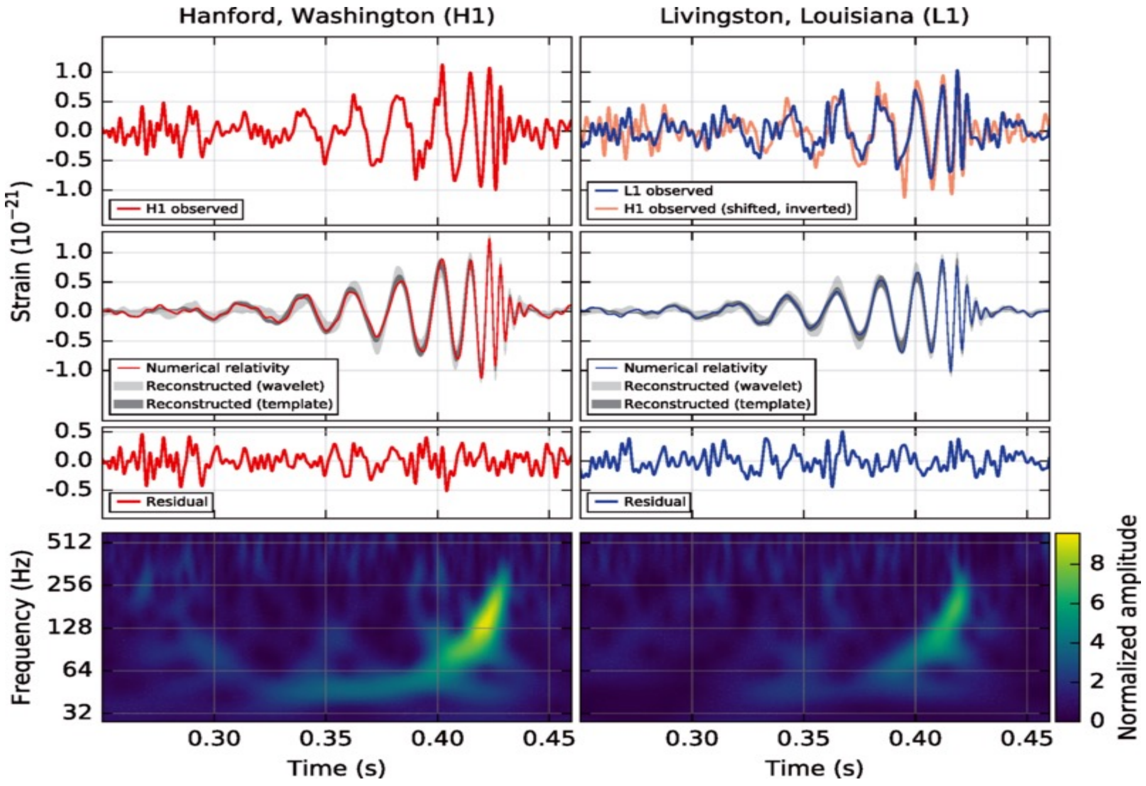
Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson. Pool photo by Denis Balibouse

GWs 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


The New York Times

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The Cosmos Is Thrumming With Gravitational Waves, Astronomers Find

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.

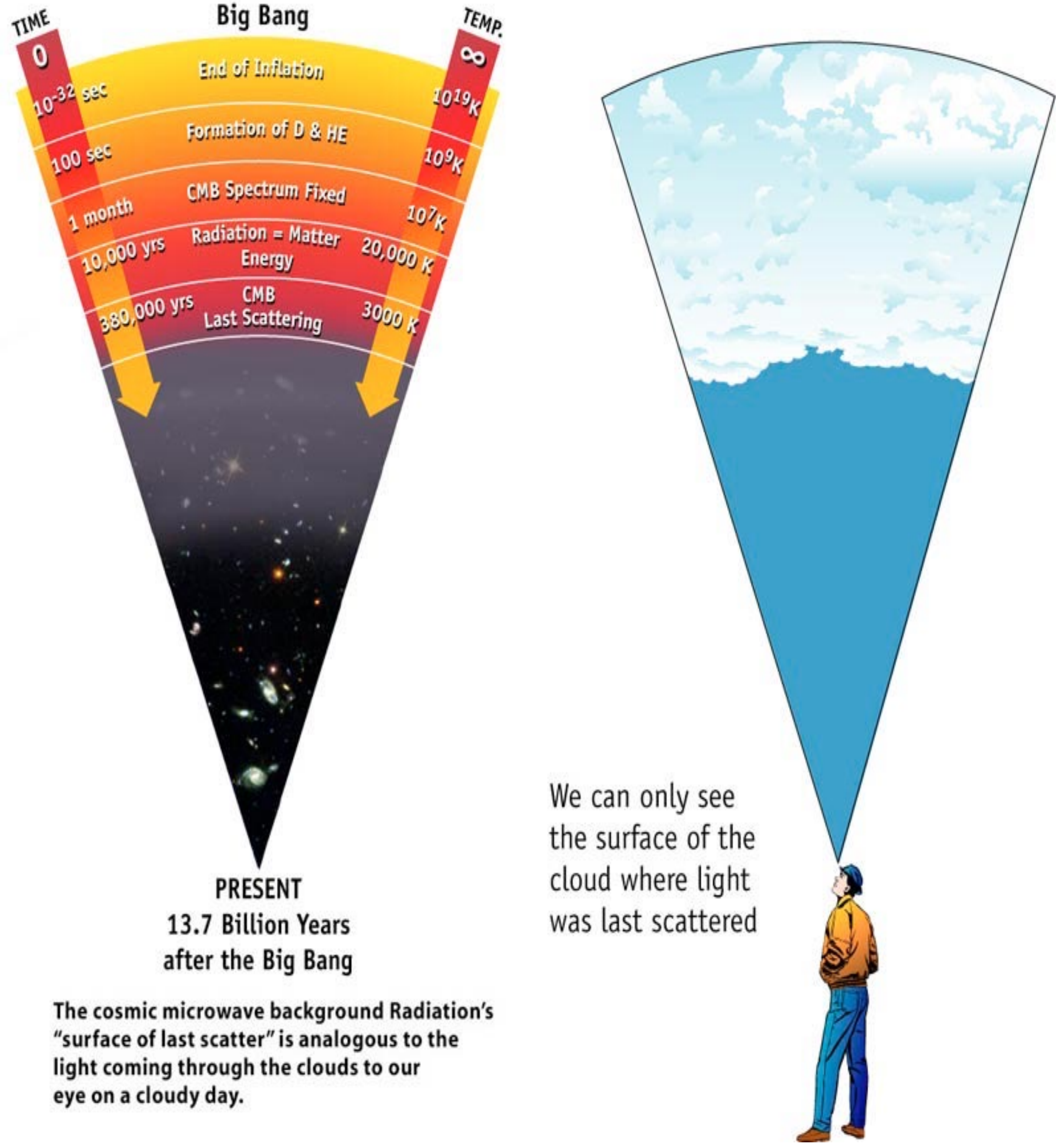
The Early Universe

Cosmological Puzzles

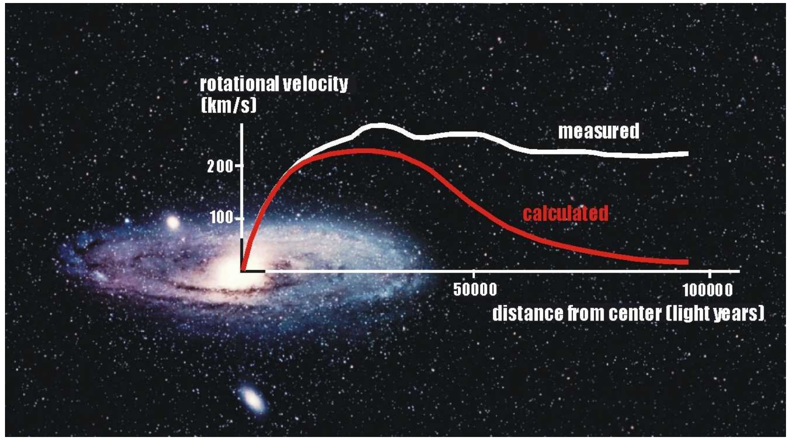
1. Inflation
2. Dark Matter
3. Matter-Antimatter asymmetry
4. Scale of Quantum Gravity
5. PBH

Tools

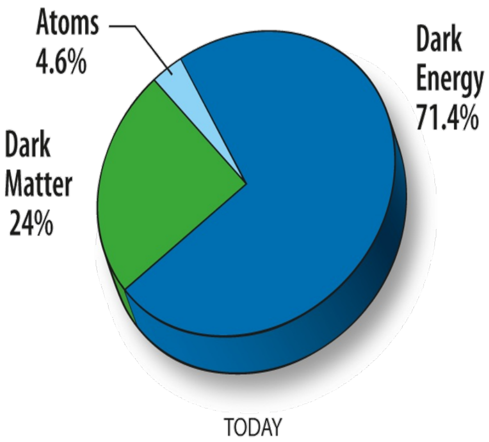
1. Gravitational Waves
2. Cosmic Microwave Background
3. Neutrinos
4. Collider Searches



Dark Matter, a cosmic glue



Evidence of DM : Galaxy Rotation Curve



Detecting particle nature of DM:

What we know :

- ❑ Relic density
- ❑ Massive
- ❑ Stable object
- ❑ No or very weak interaction

What we don't know :

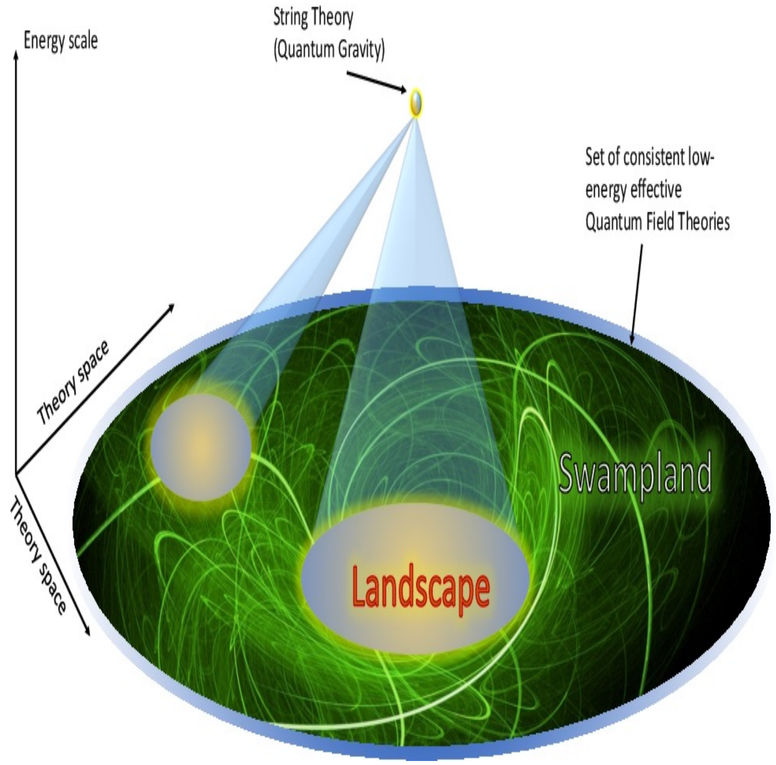
- ❑ Particle Nature
- ❑ Interaction
- ❑ How Massive
- ❑ Production Mechanism

How massive? How to probe?

Scale of Quantum Gravity

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

- For decades **EFT has played a vital role** in Particle 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

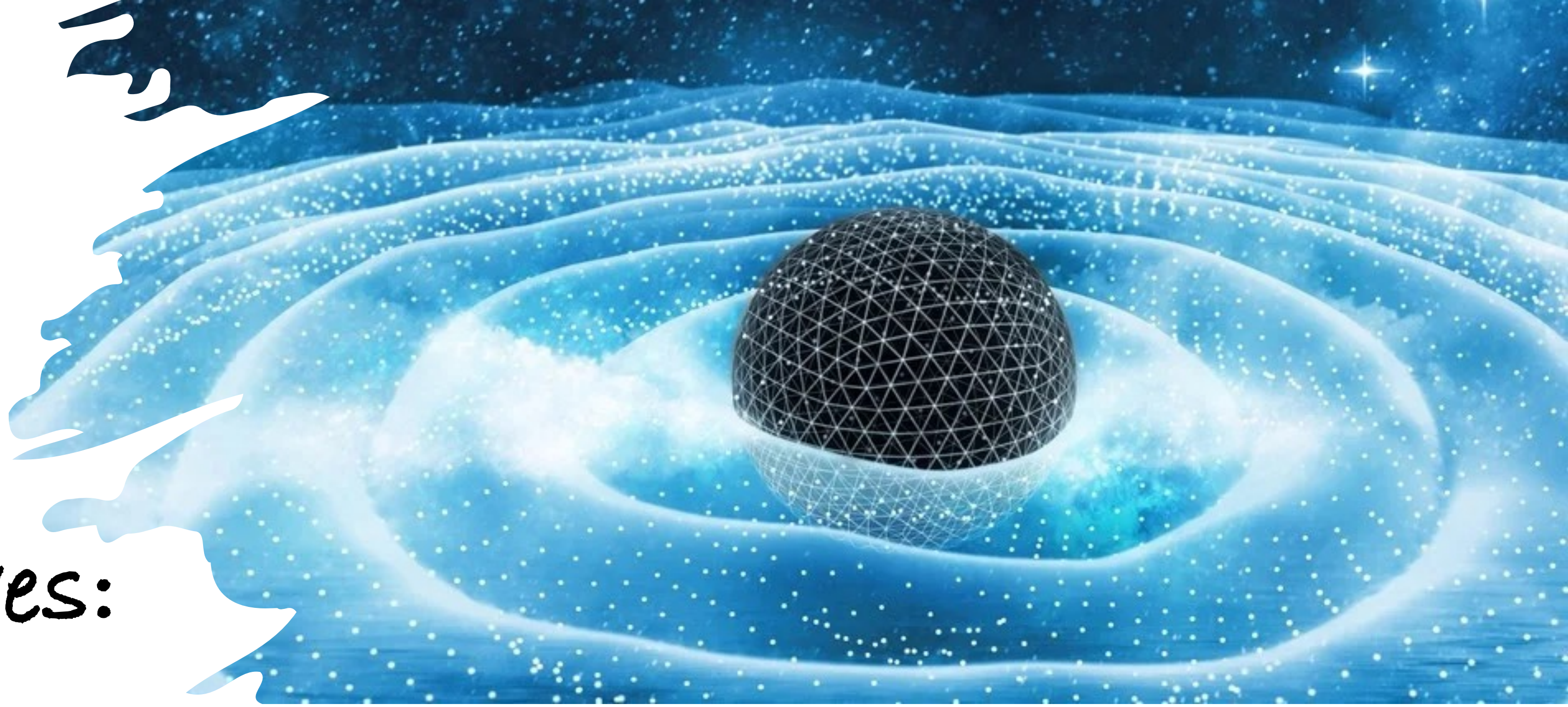
There exists no exact (continuous or discrete) global symmetry in quantum gravity theories. → Global symmetries in low-energy EFTs are broken by QG!

Any observational effects that can constrain Λ_{QG}?


THE LIGHT AT THE END
OF THE TUNNEL
GW
IS JUST THE LIGHT OF AN
ONCOMING TRAIN.

Gravitational Waves:

Ripples in the fabric of spacetime



Gravitational Waves: Theory

Einstein's Equation:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} \mathcal{R} = 8\pi G T_{\mu\nu}$$

Space-time determines the trajectories of all object

Massive object curve space-time

Considering a small perturbation around the metric tensor:

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \qquad |h_{\mu\nu}| << 1$$

$\eta_{\mu\nu}$: Flat space-time

$h_{\mu\nu}$: Small deviation in flat space-time

Propagation of GW in vacuum :

$$(\partial_t^2 - \partial_x^2) h_{\mu\nu} = 16\pi G T_{\mu\nu}$$

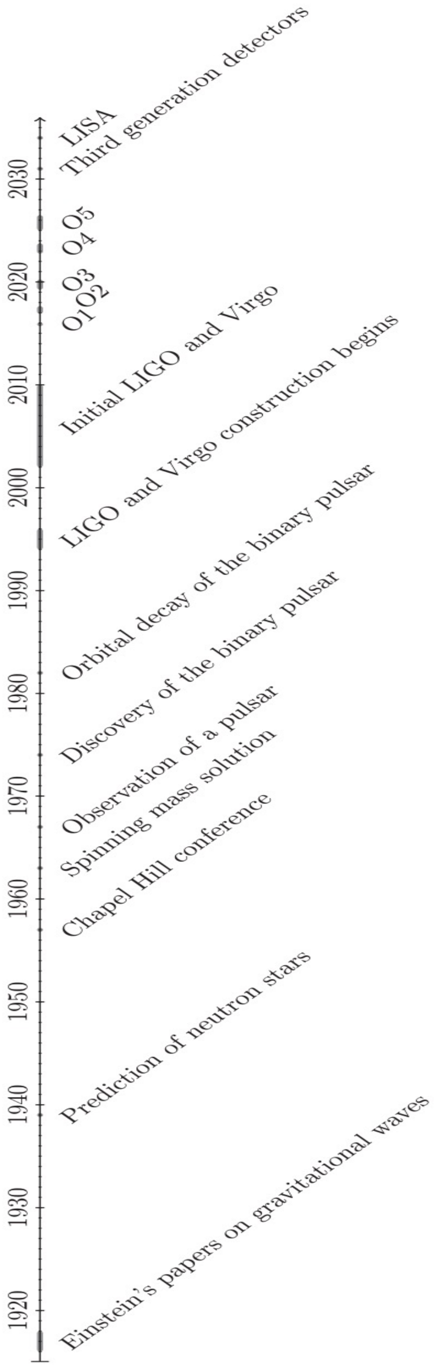
In the far-field regime, the amplitude can be approximated as,

$$h_{ij} \simeq \frac{2G}{r} \ddot{Q}_{ij}(t_{Ret})$$

- Need a Quadrupole Moment
- Derivative suggests that the source cannot be static
- Decreases with the distance

Power Emitted:

$$P_{GW} \simeq \frac{G}{45} \sum_{i,j} \langle \dddot{Q}_{ij} \dddot{Q}_{ij} \rangle$$



Timeline of significant events in the history of gravitational waves

RevModPhys.94.025001

Possible sources of GW in the early Universe

- GW propagates freely once generated
- Carry unique information about the processes that produced them

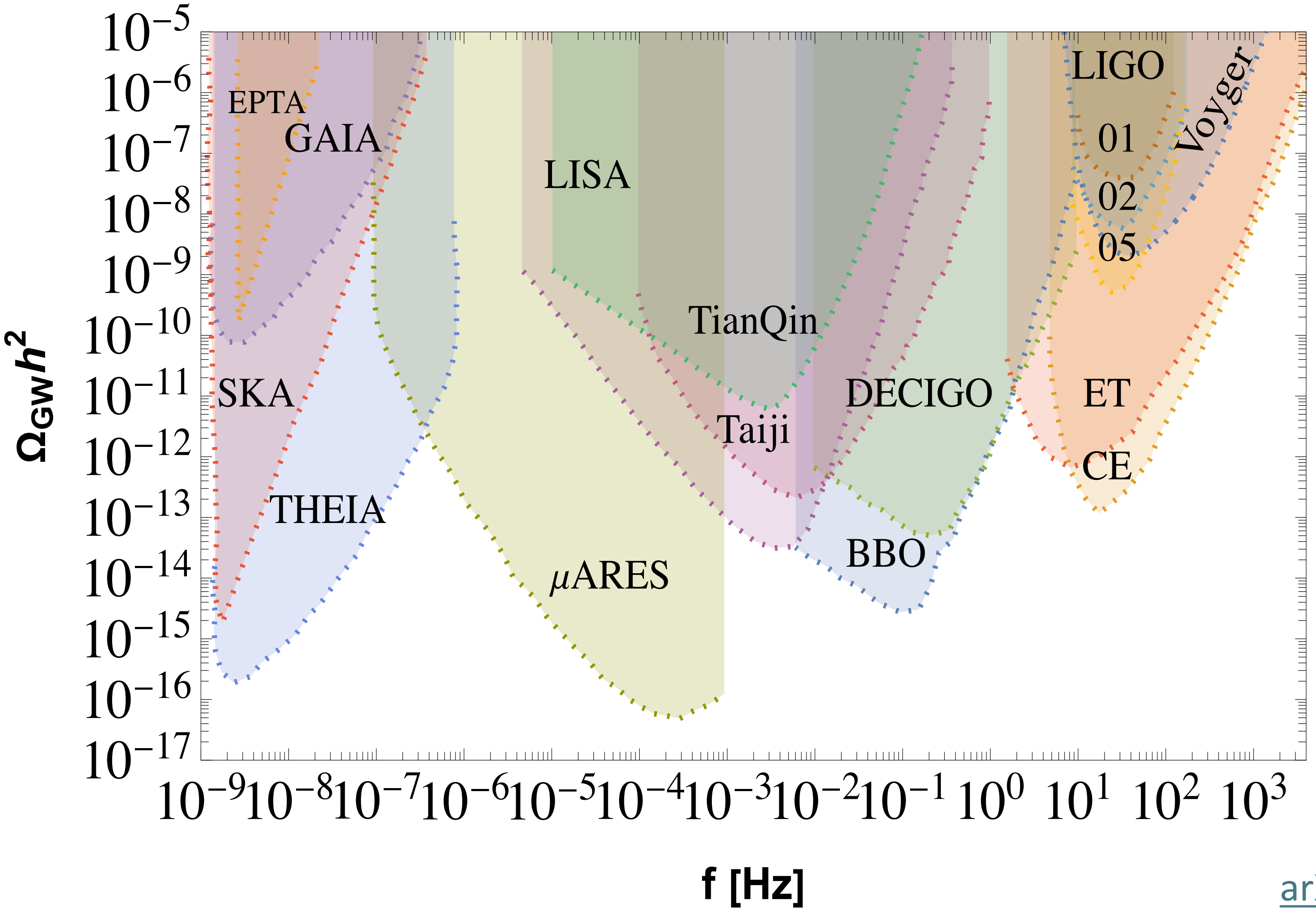
Possible Sources:

1. Inflation
2. Phase Transition
3. Topological Defects
4. Primordial Black Holes

These sources might also be the origin of some of the Cosmological Puzzles:

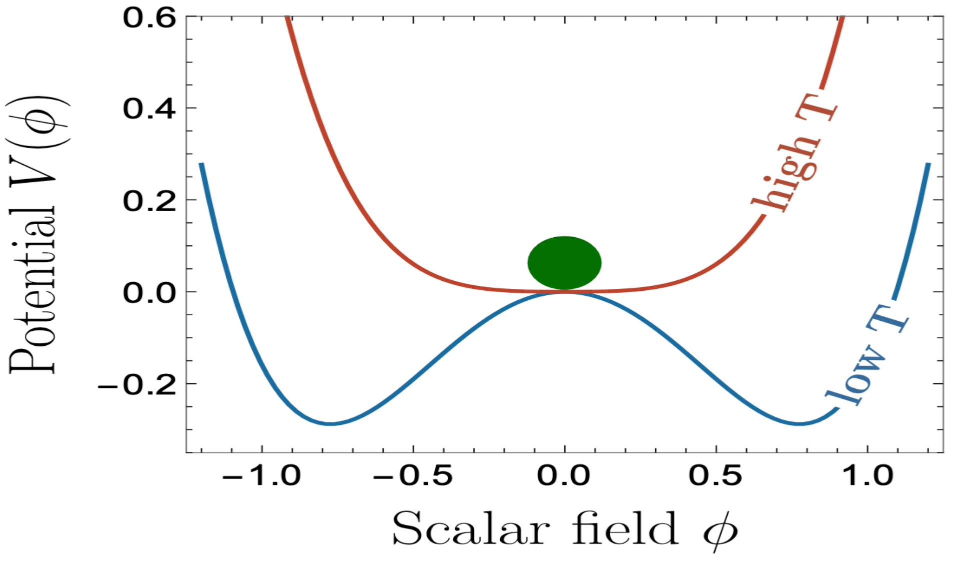
1. Dark Matter
2. Matter-Antimatter asymmetry
3. Primordial Black Holes

GW Detections

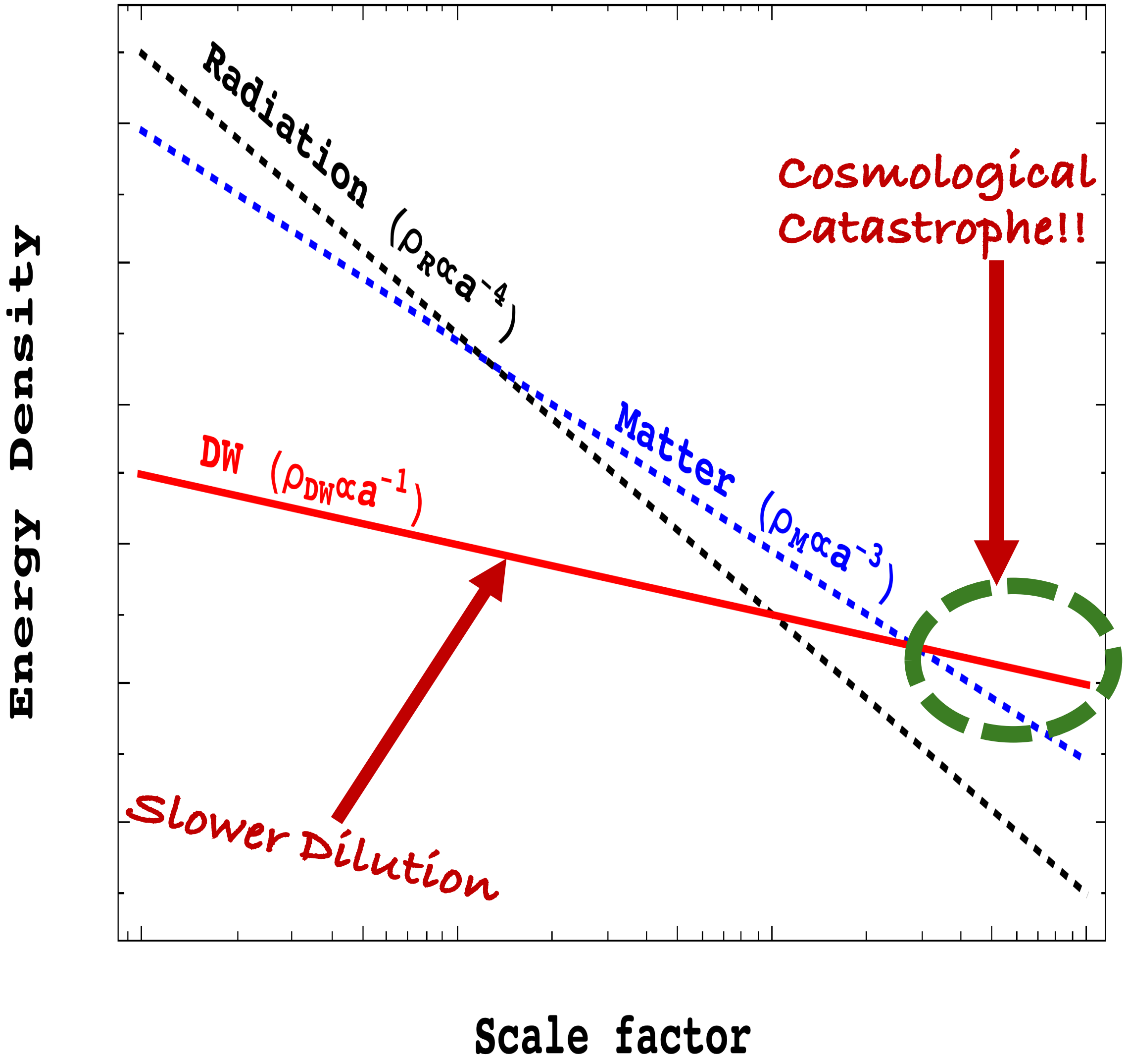


arXiv: 2401.04388

Domain Wall: Fact-Sheet



Spontaneous breaking of $\mathbb{Z}_2$



Surface Tension

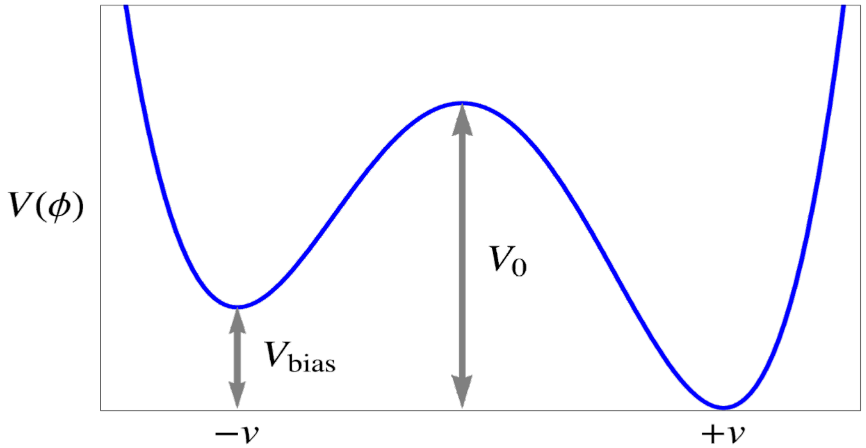
$$\sigma = \int_{-\infty}^{\infty} dx \left[\frac{1}{2}\left(\frac{\partial\phi(x)}{dx}\right)^2 + V(\phi(x))\right] = \sqrt{\frac{8\lambda}{9}} v^3$$

Energy Density

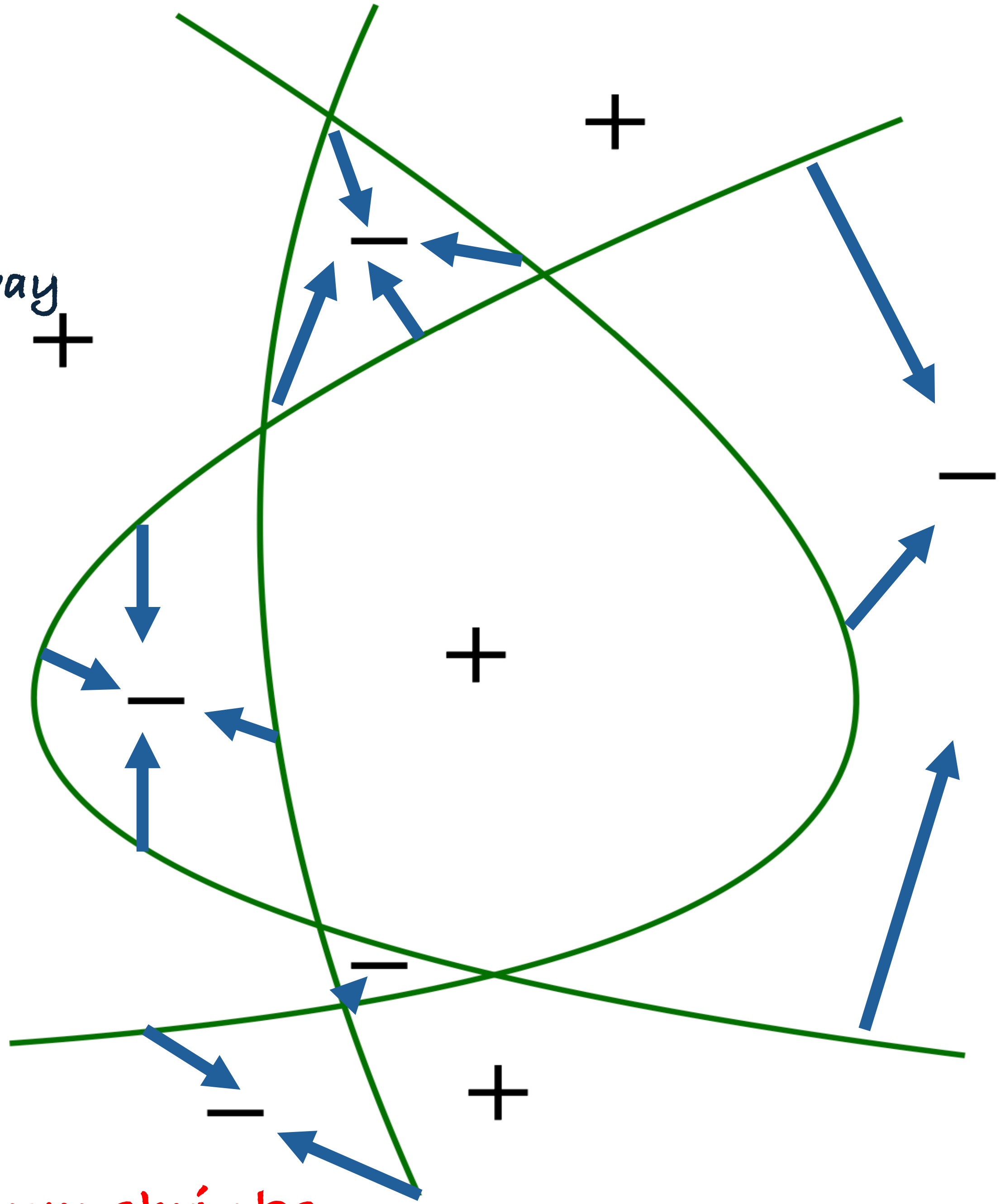
$\rho_{\mathrm{DW}} \propto a^{-1}$ (Dilutes much slower than radiation and matter)

Possible Solutions

1. If formed before inflation, they can be inflated away
2. Symmetry restoration at some temperature
3. Metastable Domain Walls



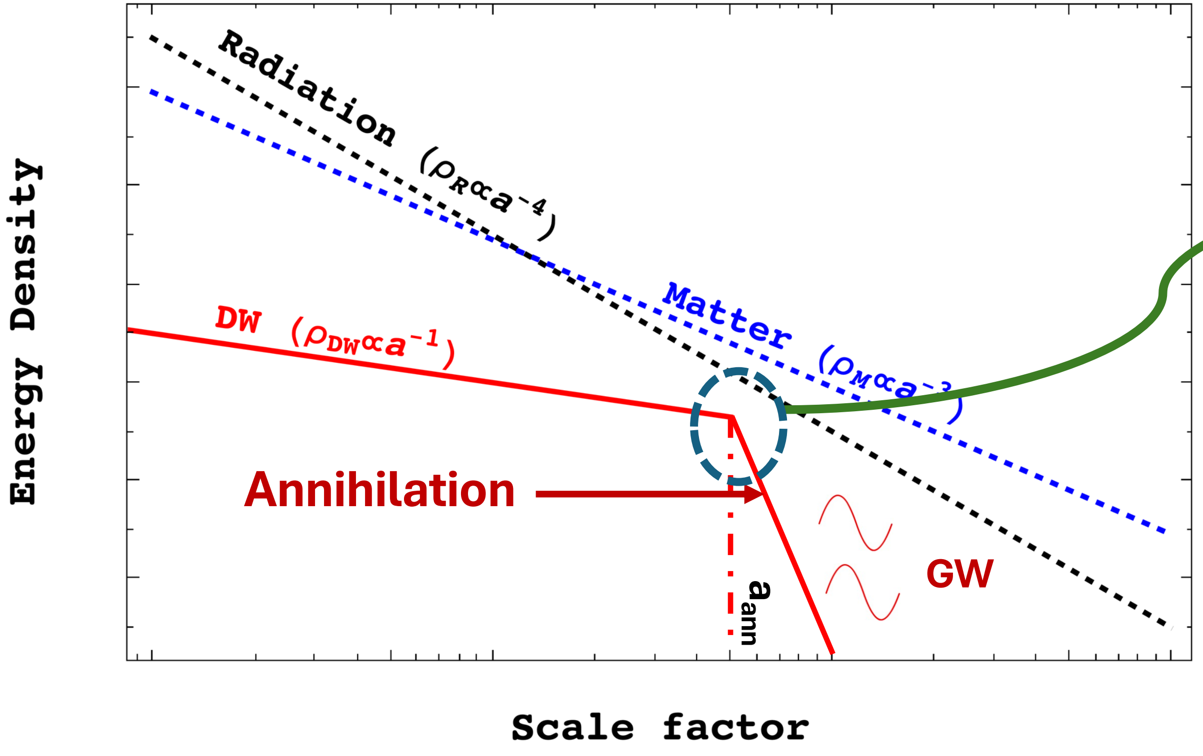
Saikawa, Universe 3, 40 (2017)



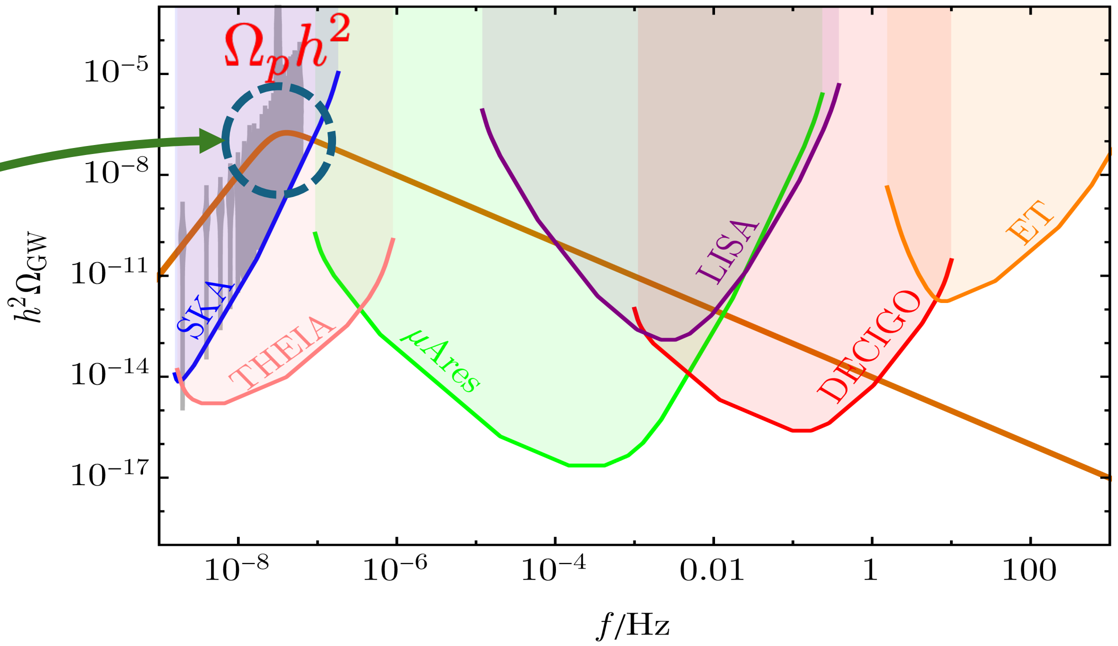
$$p_V \sim V_{\text{bias}}, \;\; p_T \sim \sigma \frac{\mathcal{A}}{t}$$

$V_{\text{bias}} \longrightarrow p_V > p_T \longrightarrow$ False vacuum shrinks

Gravitational Waves from Domain Walls



JCAP 05 (2024) 071



GW spectrum:

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

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

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

The corresponding peak frequency

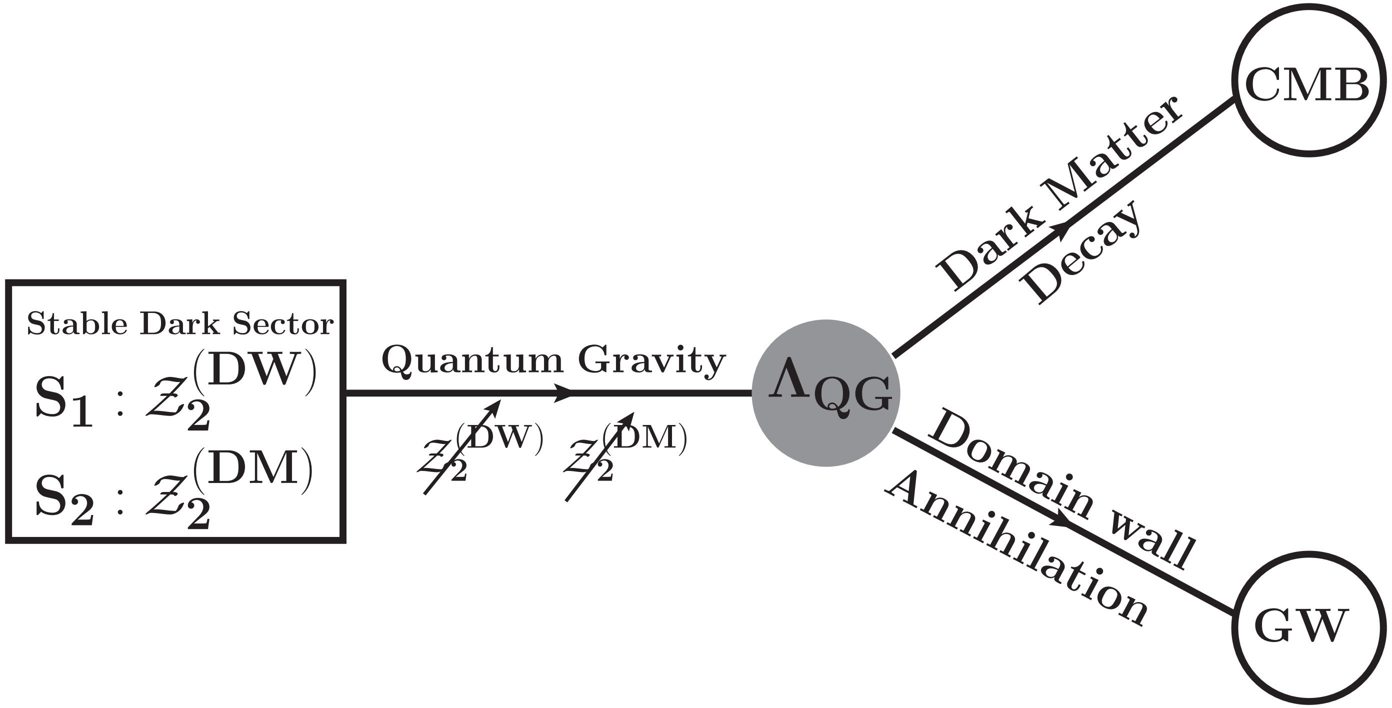
$$f_p \simeq 3.75 \times 10^{-9}\ \mathrm{Hz}\ C_{ann}^{-1/2}\mathcal{A}^{-1/2}\hat{\sigma}^{-1/2}\hat{V}_{bias}^{1/2}$$

Broken power law

$$\Omega_{GW} h^2 \propto f^3 \text{ for } \mathrm{f} < \mathrm{f_p}$$

$$\Omega_{GW} h^2 \propto f^{-1} \text{ for } \mathrm{f} > \mathrm{f_p}$$

Applications: GW from DW



Based on: PRD 109 (2024) 2, 024057

The scale of Quantum Gravity

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

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

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

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

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

The range of the scale we are considering is $\Lambda_{\rm QG} \sim (10^{20} \cdots 10^{35})\ {\rm GeV}$ ⟶ $\mathcal{S} \sim (4 \cdots 38)$ **More realistic!**

The setup

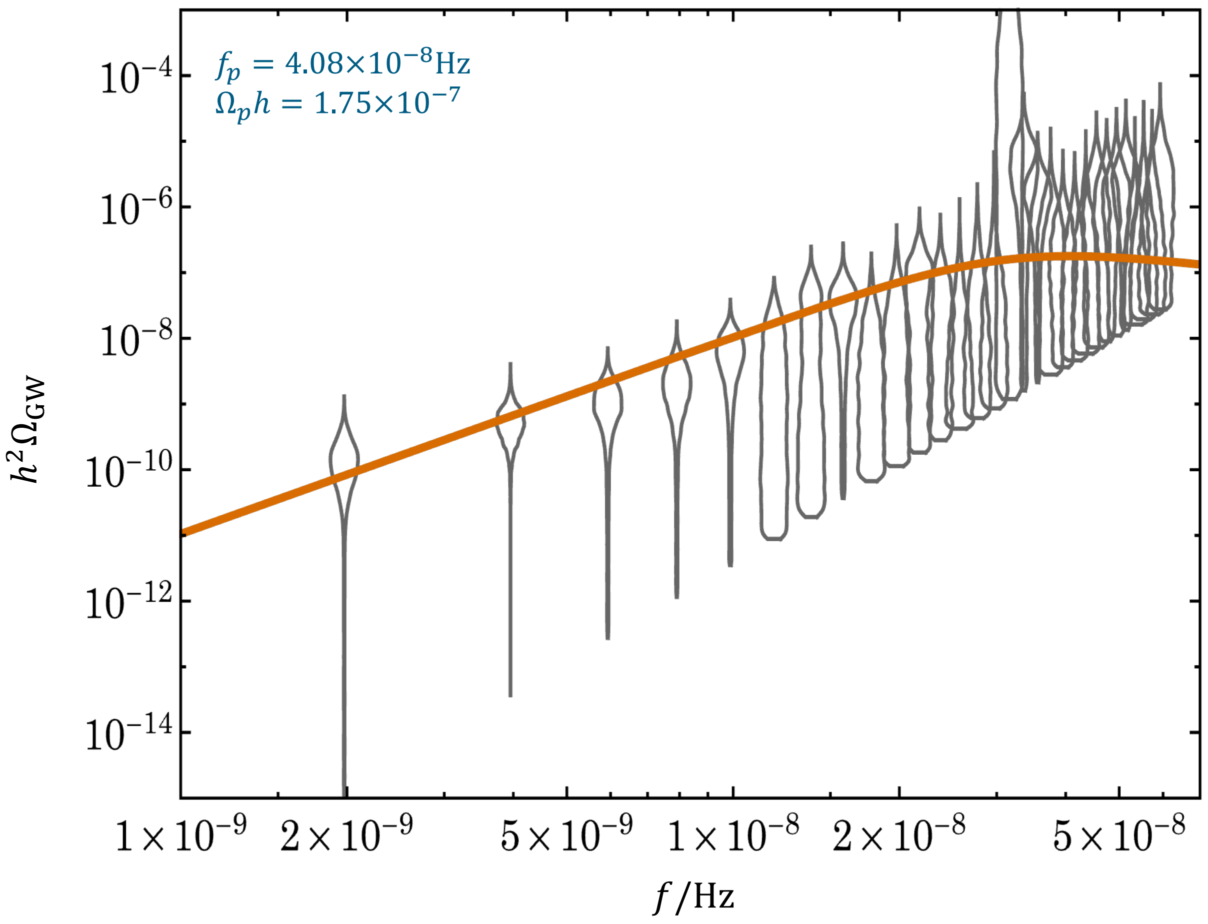
The renormalizable potential (Z_2-conserving)

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

Dimension-five potential (Z_2-breaking)

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

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



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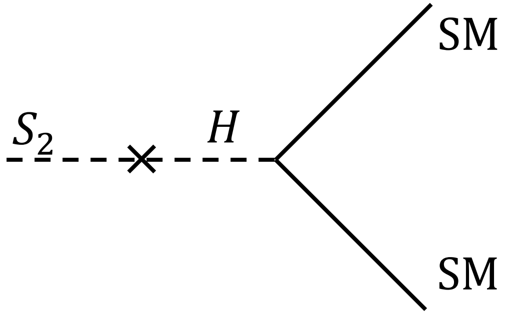
DM Decay:

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

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

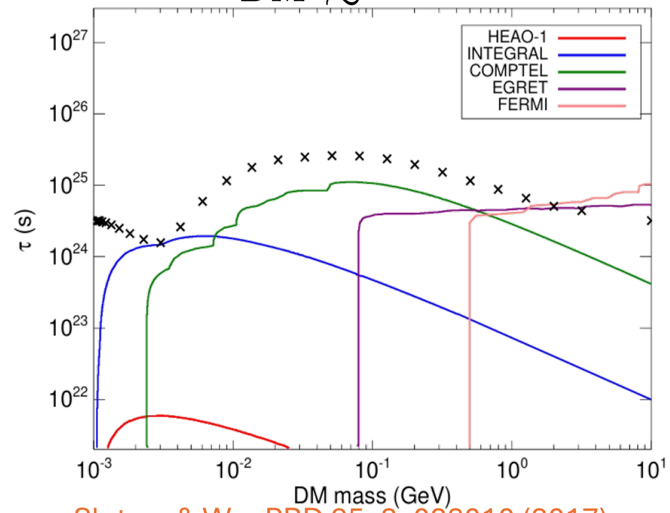


$S_2 \to \mathrm{SMSM} \to e\bar{e}, \gamma\bar{\gamma}, \nu\bar{\nu}$

Indirect detection of dark matter

CMB power spectrum

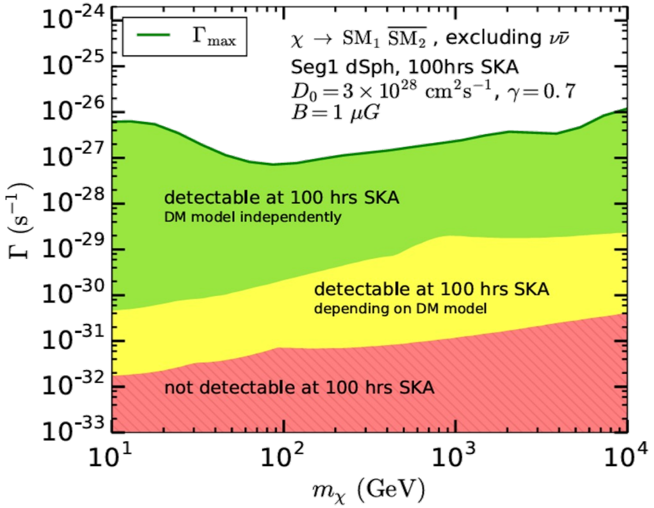
$\tau_{DM} \gtrsim 10^{25}$ s



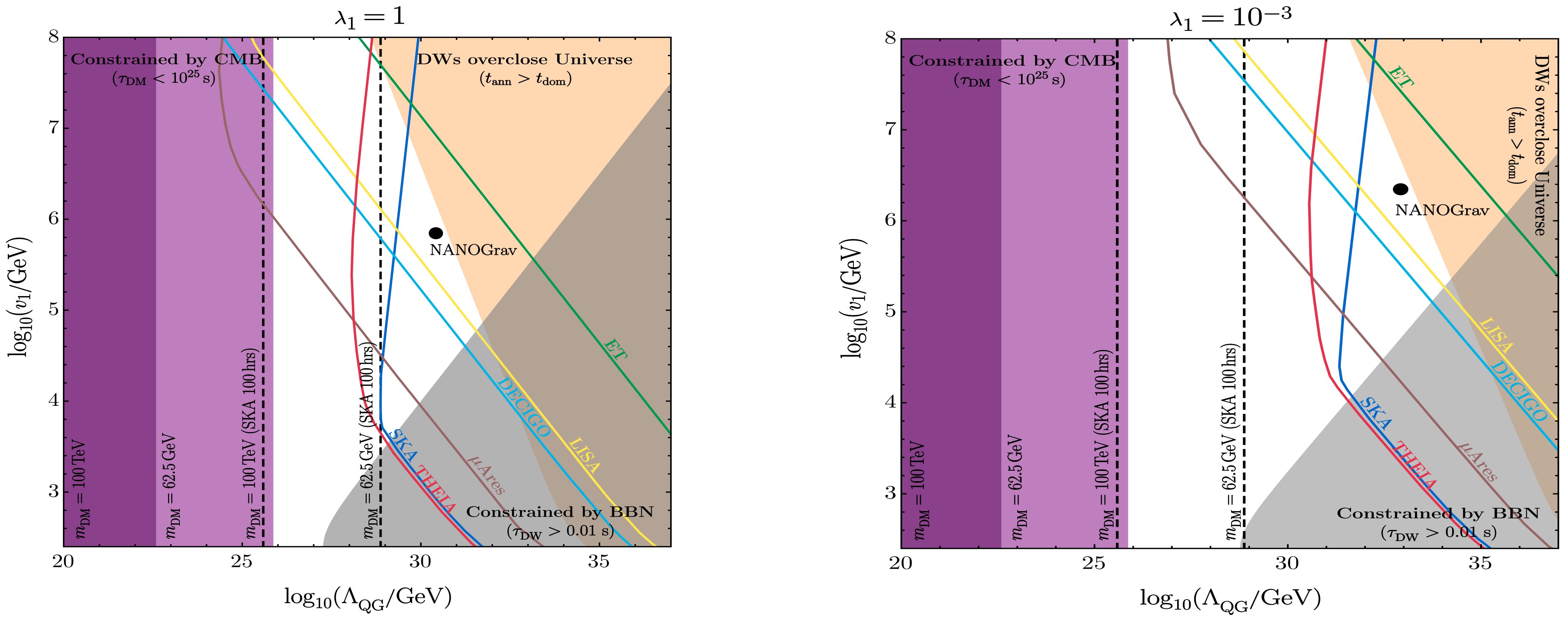
Slatyer & Wu, PRD 95, 2, 023010 (2017)

SKA radio telescope

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



GW from DW: Testing the scale of Quantum Gravity



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Final Remarks

1. **Some high-scale issues: DM, baryon asymmetric Universe**, the **scale of QG**.

2. How to **test/probe** these scales? **Gravitational Waves?**

3. **GW** can have **cosmological origins:** Phase transition, **Topological defects**, **PBHs**, etc.

4. The **same sources** might also **produce particles responsible for** all the **cosmological puzzles** discussed above.

4. **This suggests** that primordial **GW can help us understand/test/probe these scales because** they might have a **common origin**.

5. **Gravitational wave cosmology is one of the most promising avenues for discovering physics beyond the Standard Model.**

Thank You