# Using Gravitational Waves to see the Early Universe


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**School of Physics and Astronomy,**
**University of Southampton**


Based on: **2401.04388, PRD 109 (2024) 2, 024057, Nucl.Phys.B 1002 (2024) 116528 and Phys.Rev.D 107 (2023) 9, 095002**

**Collaborators:**

**Stephen F. King, Qaisar Shafi, George Lazarides, Graham White, Masahito Yamazaki, Debasish Borah, Xin Wang, Suruj Jyoti Das, Basabendu Barman and Rinku Maji**

# Plan of the talk

1. **A brief introduction to high-scale physics:**
   a. Dark Matter
   b. Matter-Antimatter asymmetry
   c. Scale of Quantum Gravity
   d. Primordial Black Holes

2. **Gravitational Wave Physics**
   a. Theory
   b. Sources
   c. Detectors
   d. Recent Discoveries

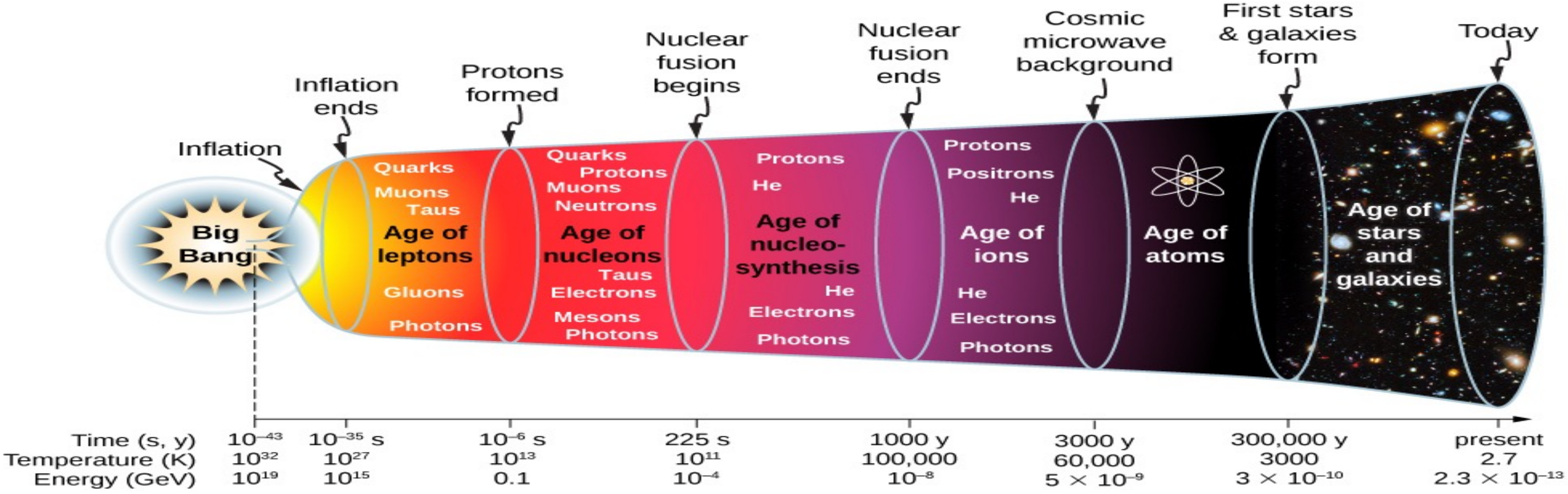
3. **GWs from Domain Walls and its applications**

4. **GWs from Cosmic Strings and its applications**

5. **GWs from PBH and its applications**

6. **Summary and Conclusion**

# The Early Universe




**Cosmological Puzzles**

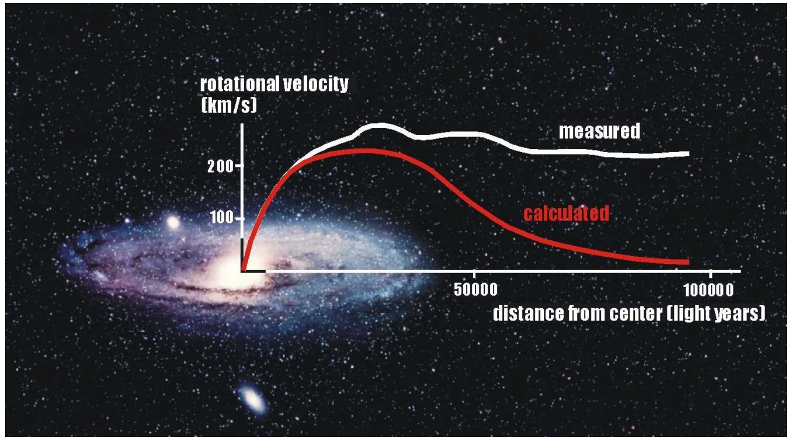
1. Inflation
2. Dark Matter
3. Matter-Antimatter asymmetry
4. Scale of Quantum Gravity
5. PBH

**A. Motivation to look for BSM Physics**

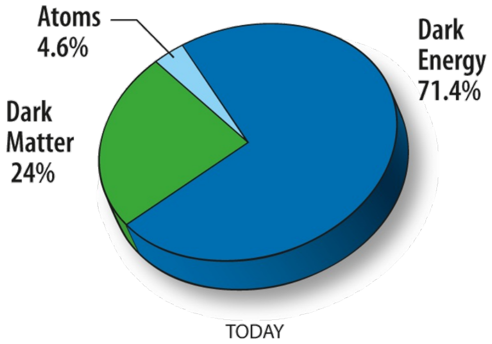
**B. High-Scale Physics**

**C. Cosmological Observations: a powerful investigative tool**

# Dark Matter




Evidence of DM : Galaxy Rotation Curve




**What we know :**

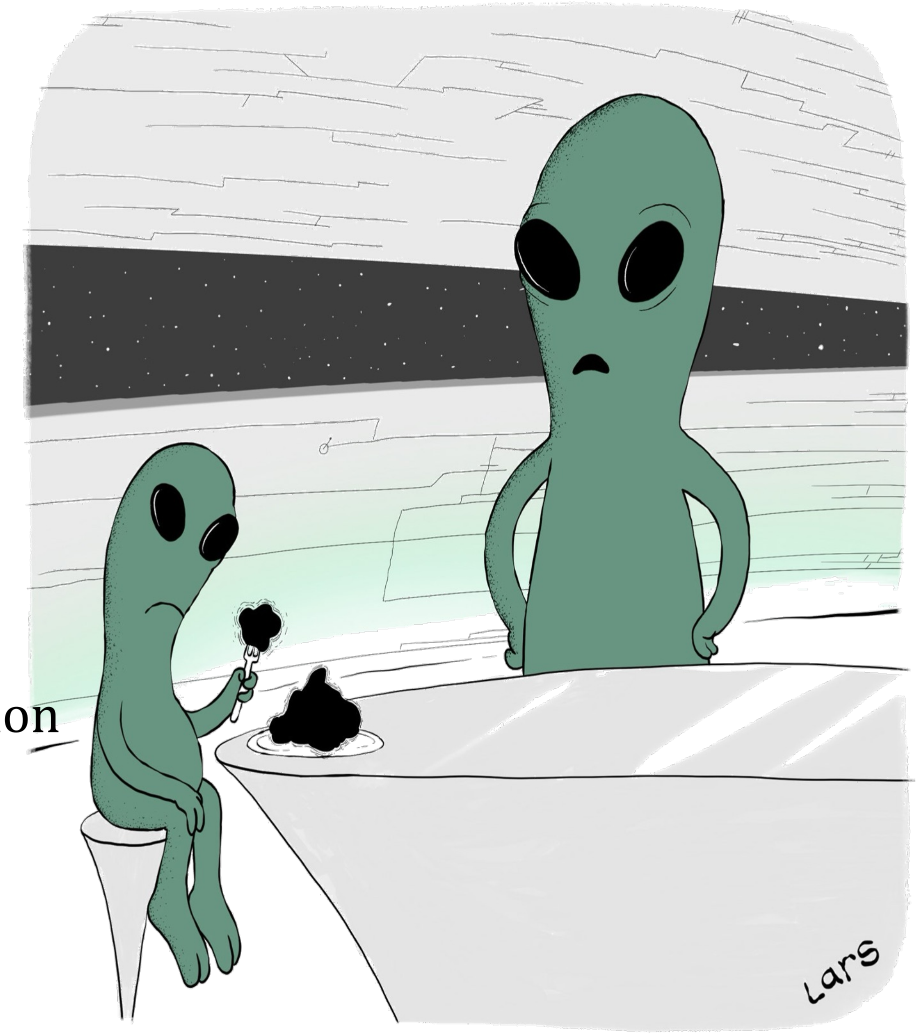
- ❑ Relic density
- ❑ Massive
- ❑ Stable object
- ❑ No or very weak interaction

**What we don't know:**

- ❑ Nature of DM
- ❑ Interaction
- ❑ Production mechanism

**How massive? How to probe?**

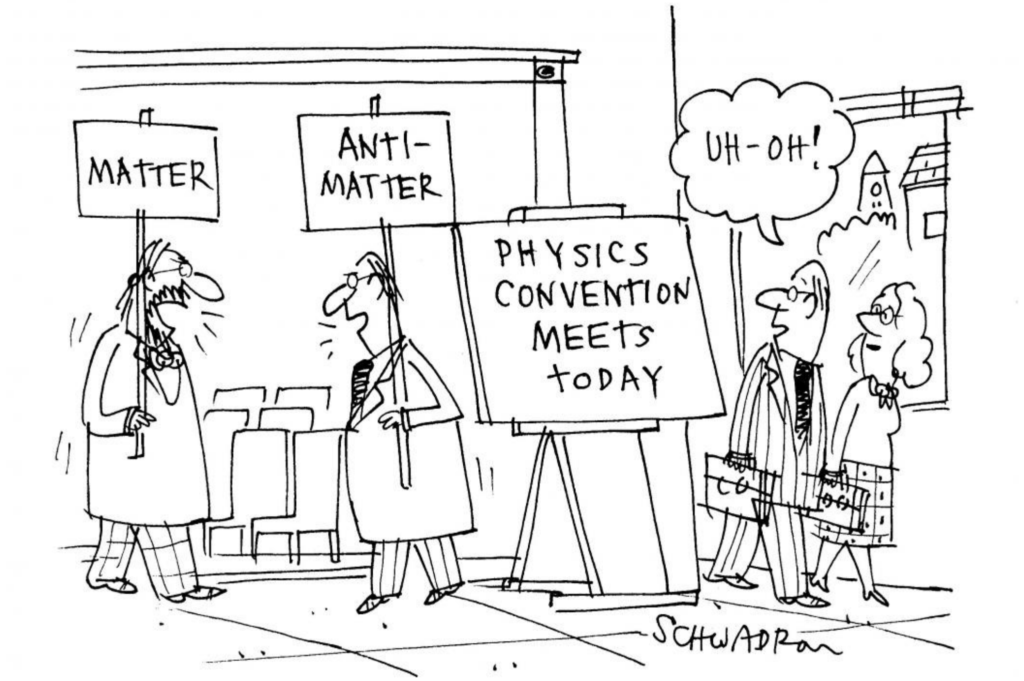
**Detecting particle nature of DM:**


"No dessert until you finish your dark matter."

# Matter-Antimatter asymmetry

**Every particle has its counterpart, called an antiparticle.**
**Antiparticle is identical to its particle counterpart in all respects except charge.**





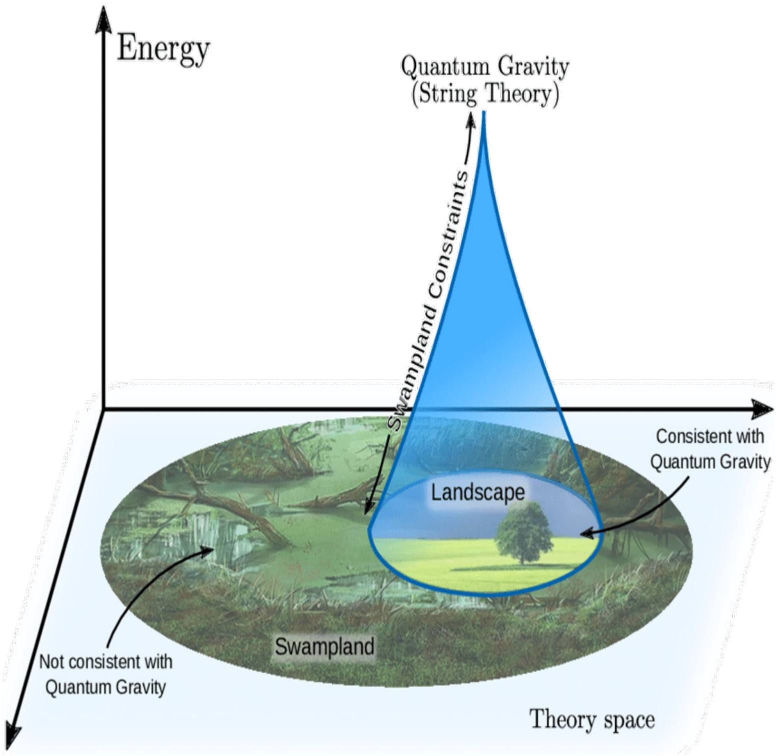
$$Y_B = \frac{n_B - n_{\bar{B}}}{s} = (8.70 - 8.73) \times 10^{-11}$$

**Most explanations consider very high-energy scales, can we test such scales?**

# 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
- ❑ 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**

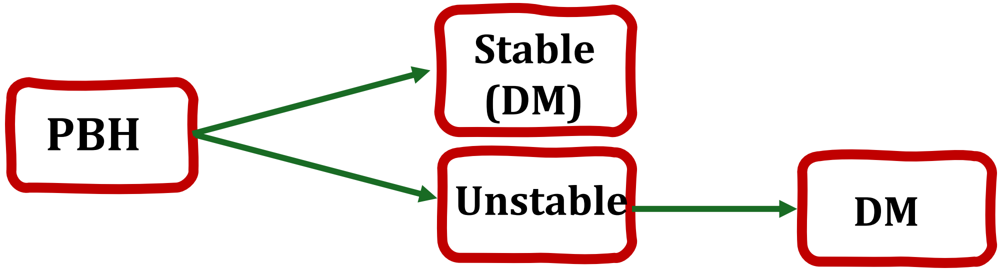
- ❑ No global symmetry conjecture
- ❑ Weak gravity conjecture
- ❑ Distance conjecture

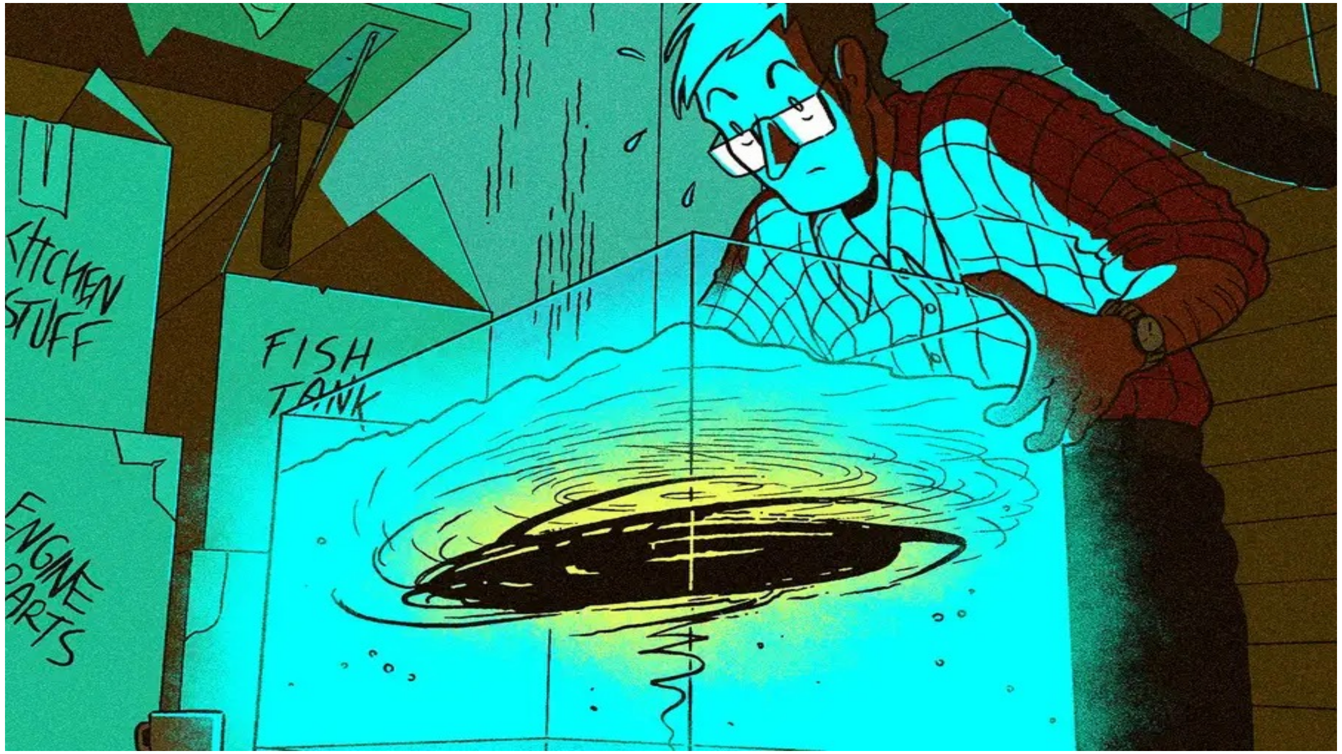
**No global symmetry conjecture**

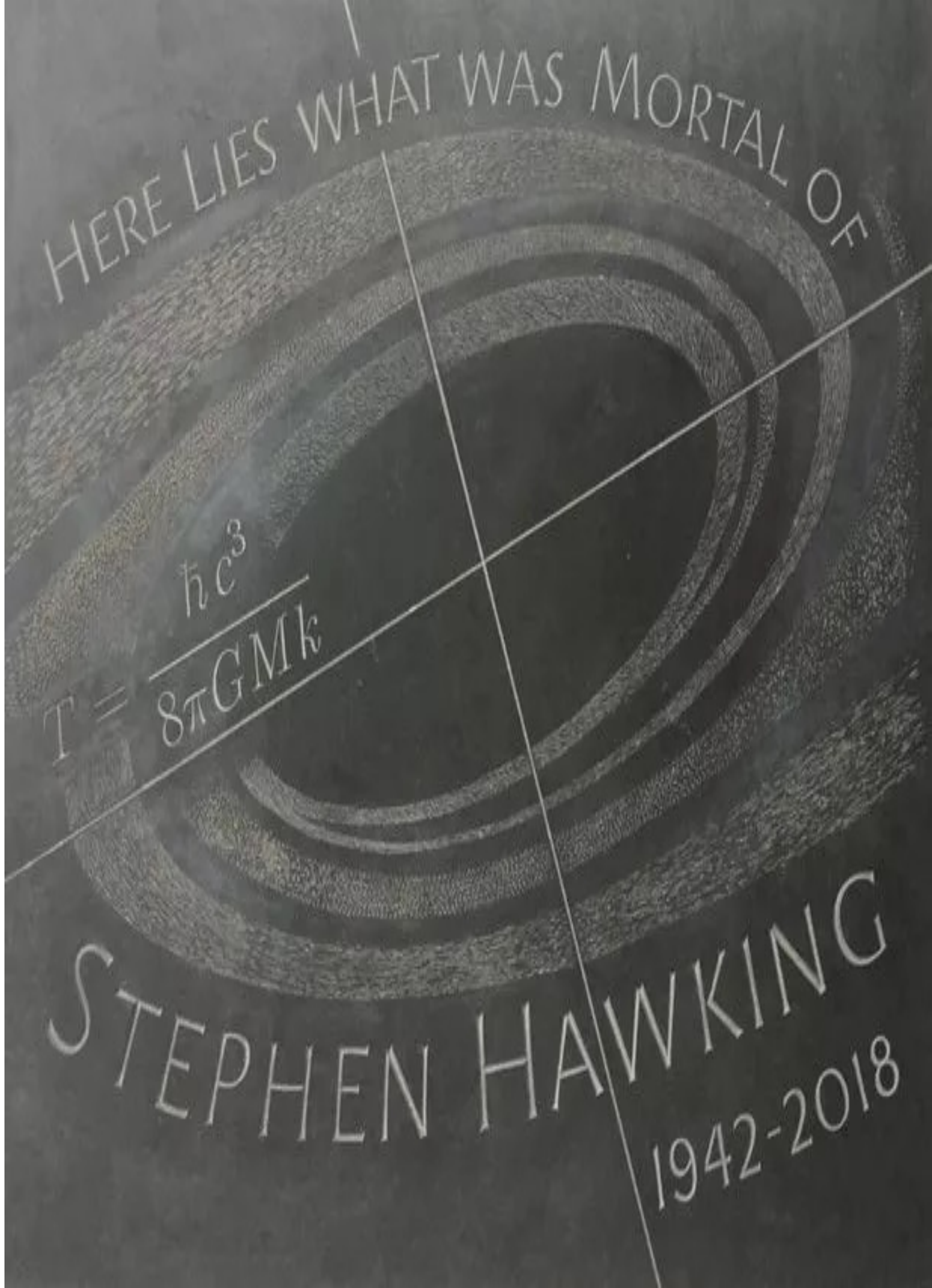
There exists no exact (continuous or discrete) global symmetry in quantum gravity theories. → Global symmetries in low-energy EFTs are broken by

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

# Primordial Black Holes



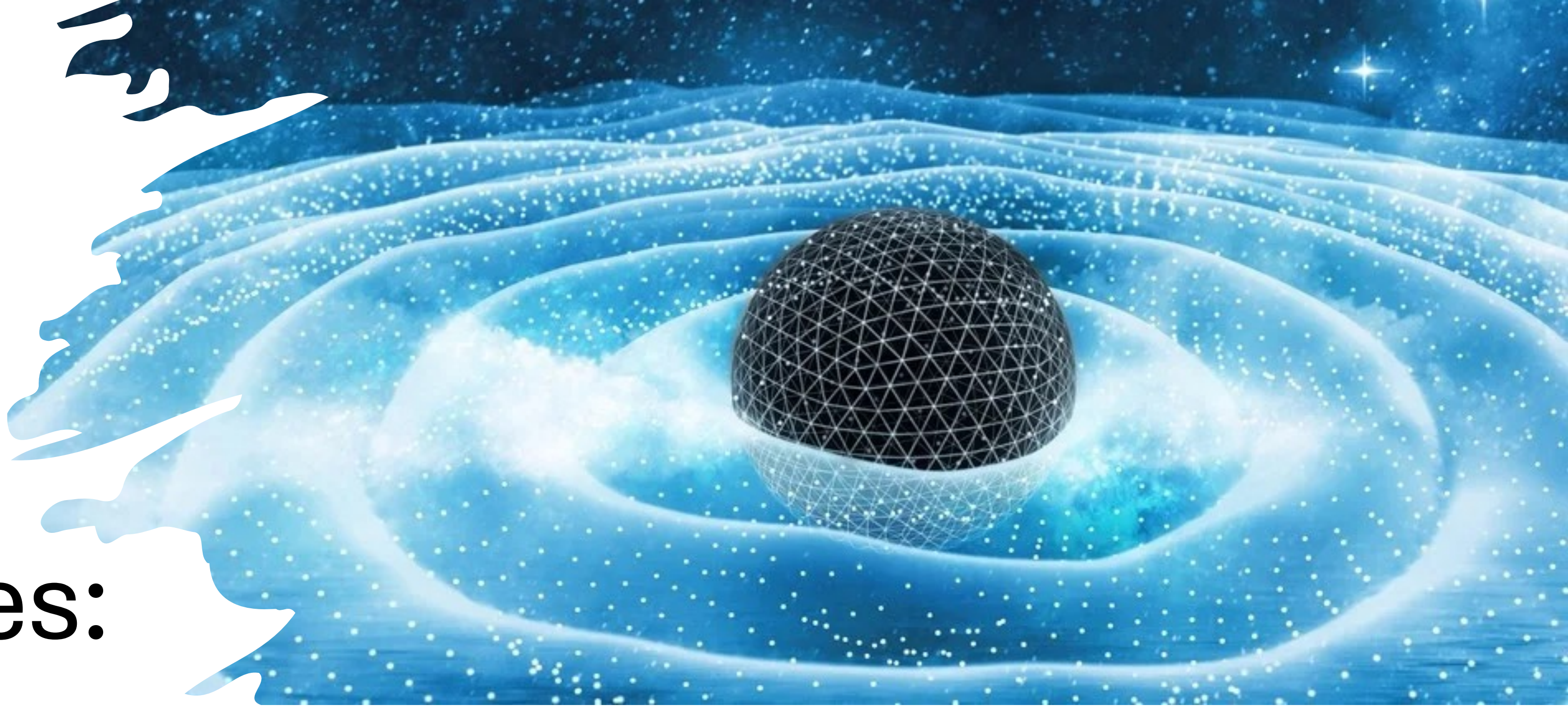




**Any observational effects of such PBHs?**

# 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 :**

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

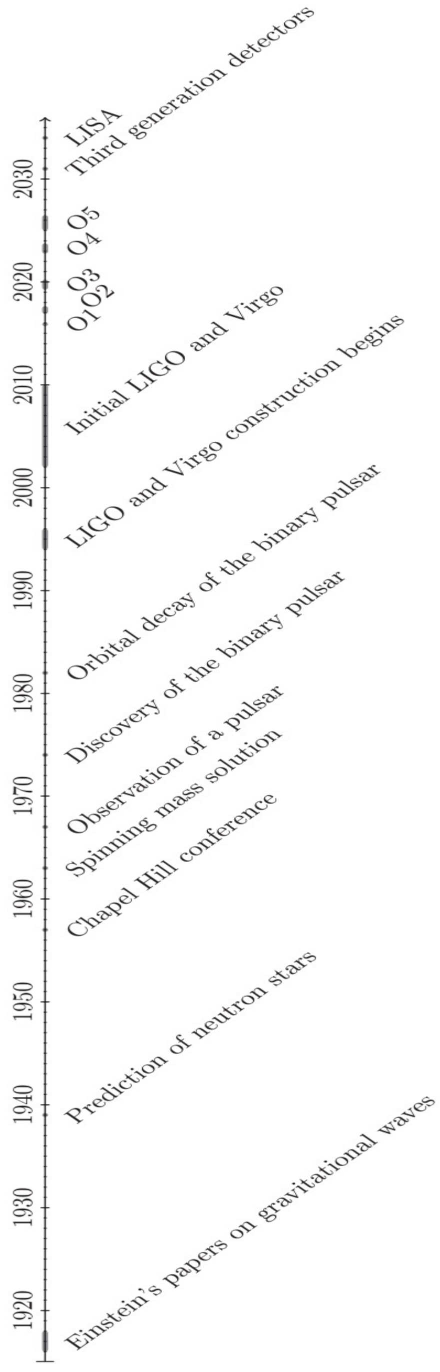
$T_{\mu\nu}$ → **Source term of GW**

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

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

$\ddot{Q}_{ij}$ → **Second time derivative of Quadrupole Moment**

**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:**

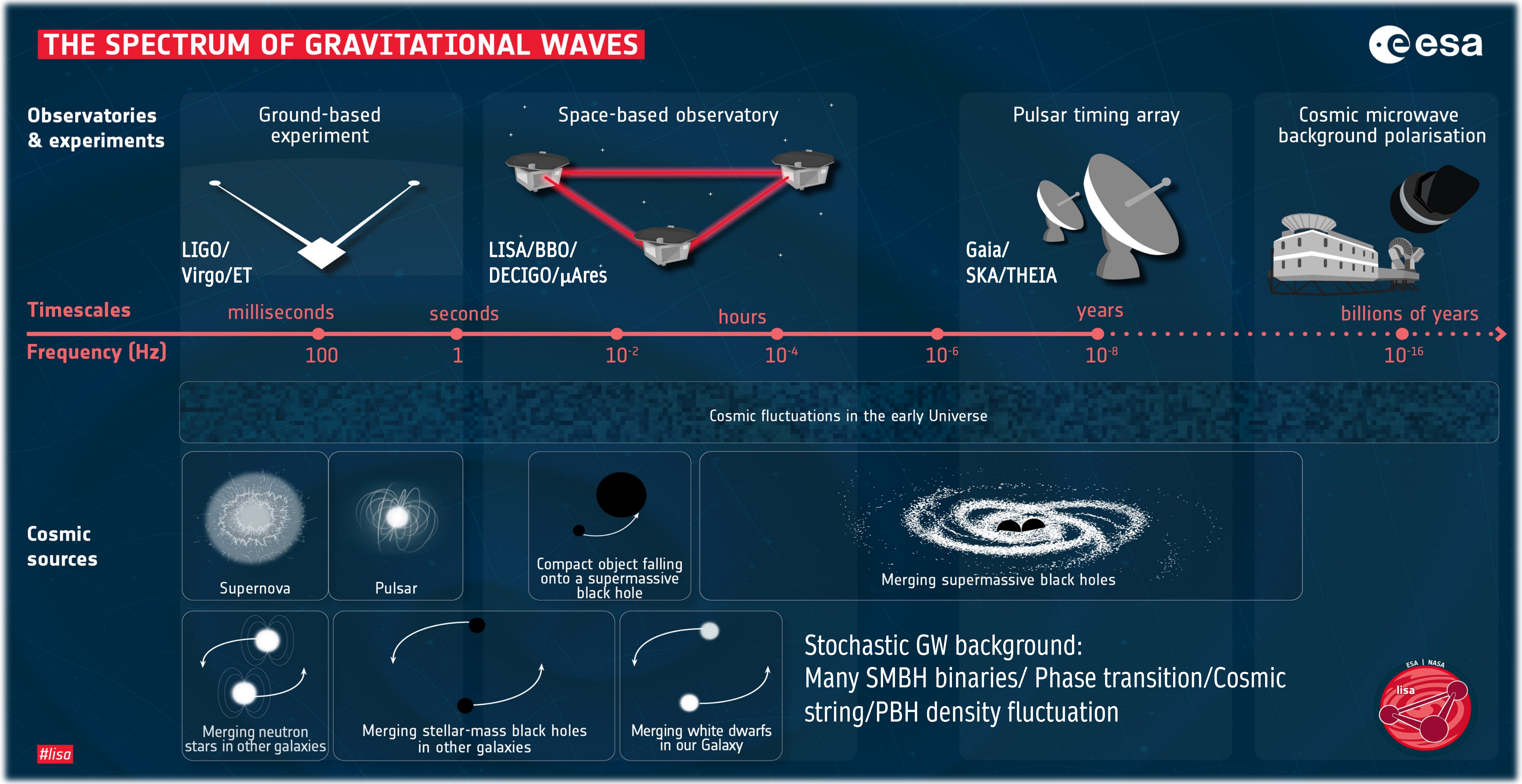
1. Inflation
2. Phase Transition
3. Topological Defects
4. Primordial Black Holes

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

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

**Can we use GW to TEST/PROBE these high-energy scales?**

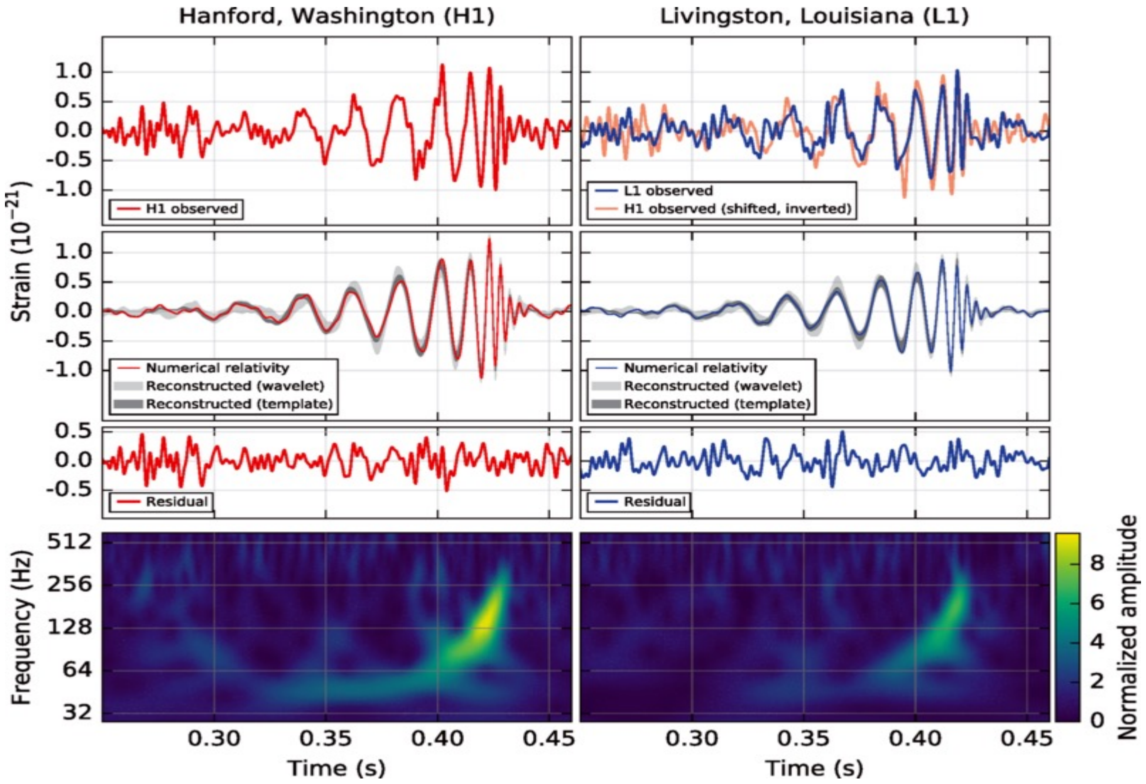
# GW Detections




Credit to ESA

# Recent 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

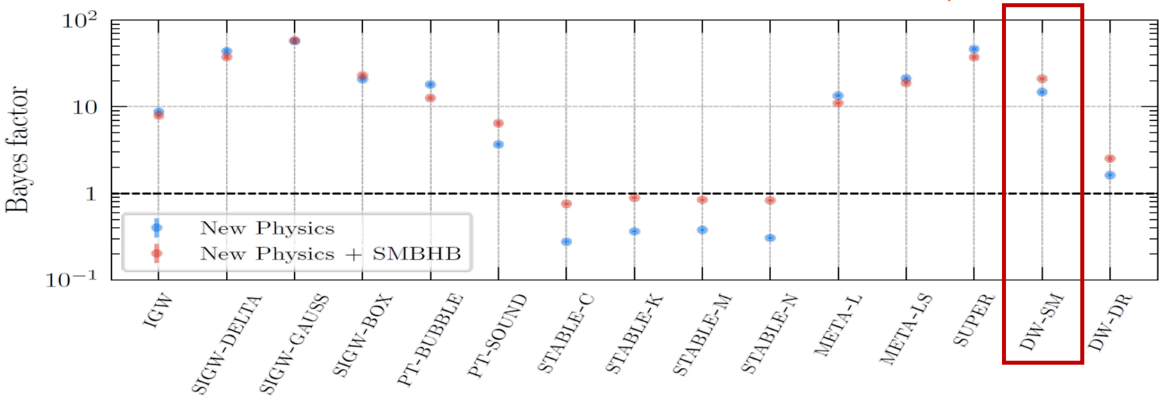
NEW YORK, THURSDAY, JUNE 29, 2023

*The Cosmos Is Thrumming With Gravitational Waves, Astronomers Find*

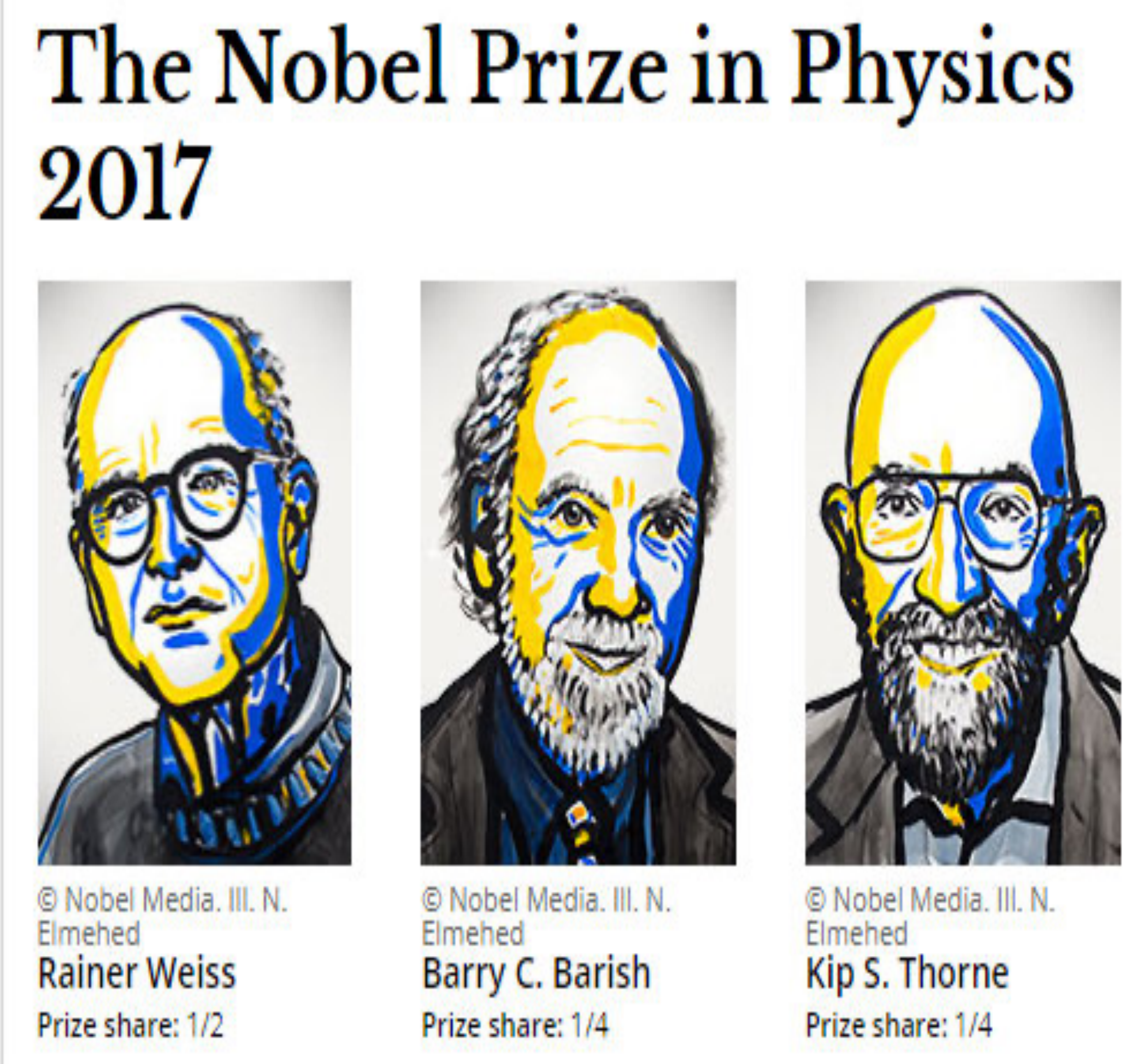
Several PTA projects have reported positive evidence of a stochastic gravitational wave background.

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

NANOGrav, 2306.16219



# GWs: Important Scientific Milestones

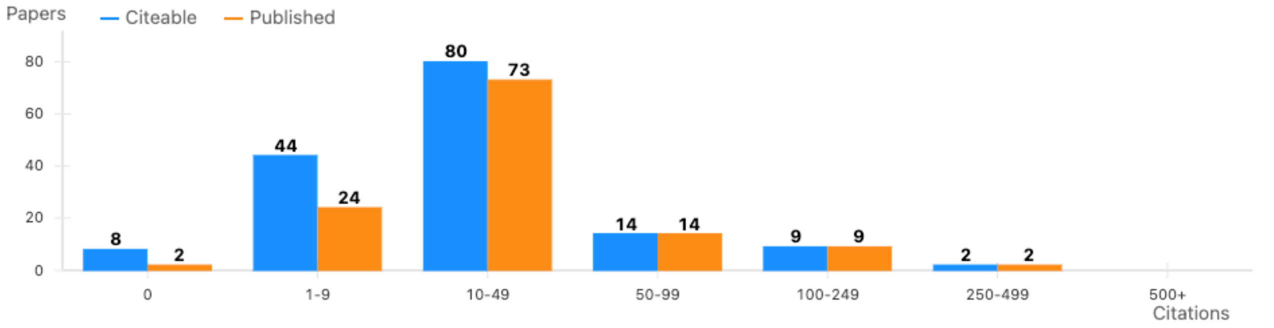



# Some recent works on GW from Domain Walls

**Citation Summary**

☐ Exclude self-citations ⓘ

| | Citeable ⓘ | Published ⓘ |
|---|---|---|
| Papers | 157 | 124 |
| Citations | 4,975 | 4,786 |
| h-index ⓘ | 36 | 36 |
| Citations/paper (avg) | 31.7 | 38.6 |




**Type-I two-Higgs-doublet model and gravitational waves from domain walls bounded by strings** #1

Bowen Fu (Shanghai Jiao Tong U.), Anish Ghoshal (Warsaw U.), Stephen F. King (Southampton U.), Moinul Hossain Rahat (Valencia U., IFIC) (Apr 25, 2024)

e-Print: 2404.16931 [hep-ph]

pdf · cite · claim · reference search · 0 citations

**Stochastic gravitational wave background generated by domain wall networks** #2

D. Grüber, L. Sousa, P.P. Avelino (Mar 14, 2024)

e-Print: 2403.09816 [gr-qc]

pdf · cite · claim · reference search · 0 citations

**The NANOGrav 15 yr Data Set: Search for Signals from New Physics** #1

NANOGrav Collaboration • Adeela Afzal (Munster U. and Quaid-i-Azam U.) et al. (Jun 28, 2023)

Published in: *Astrophys.J.Lett.* 951 (2023) 1, L11 • e-Print: 2306.16219 [astro-ph.HE]

pdf · links · DOI · cite · claim · reference search · 367 citations

**A review of gravitational waves from cosmic domain walls** #3

Ken'ichi Saikawa (DESY) (Mar 7, 2017)

Published in: *Universe* 3 (2017) 2, 40 • e-Print: 1703.02576 [hep-ph]

pdf · DOI · cite · claim · reference search · 134 citations

**On the estimation of gravitational wave spectrum from cosmic domain walls** #6

Takashi Hiramatsu (Kyoto U., Yukawa Inst., Kyoto), Masahiro Kawasaki (Tokyo U., ICRR and Tokyo U., IPMU), Ken'ichi Saikawa (Tokyo Inst. Tech.) (Sep 19, 2013)

Published in: *JCAP* 02 (2014) 031 • e-Print: 1309.5001 [astro-ph.CO]

pdf · DOI · cite · claim · reference search · 139 citations

**Axion cosmology with long-lived domain walls** #8

Takashi Hiramatsu (Kyoto U., Yukawa Inst., Kyoto), Masahiro Kawasaki (Tokyo U., IPMU and Tokyo U., ICRR), Ken'ichi Saikawa (Tokyo U., ICRR), Toyokazu Sekiguchi (Nagoya U.) (Jul, 2012)

Published in: *JCAP* 01 (2013) 001 • e-Print: 1207.3166 [hep-ph]

pdf · DOI · cite · claim · reference search · 175 citations

**Gravitational Waves from Collapsing Domain Walls** #13

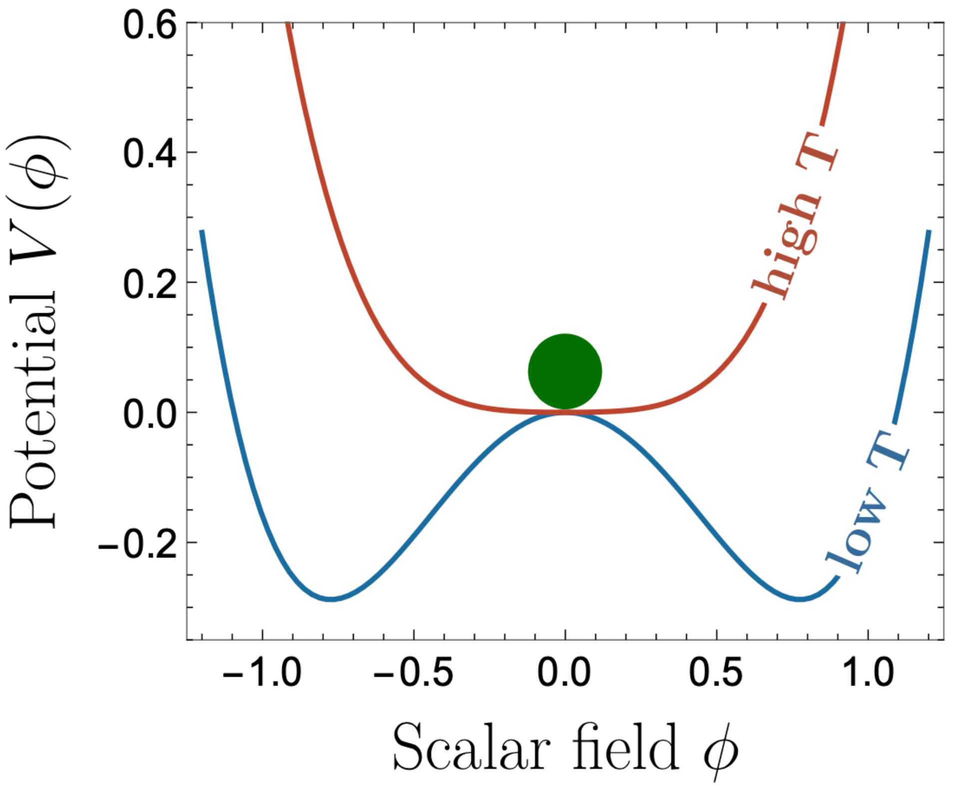
Takashi Hiramatsu (Tokyo U., ICRR), Masahiro Kawasaki (Tokyo U., ICRR and Tokyo U., IPMU), Ken'ichi Saikawa (Tokyo U., ICRR) (Feb, 2010)

Published in: *JCAP* 05 (2010) 032 • e-Print: 1002.1555 [astro-ph.CO]

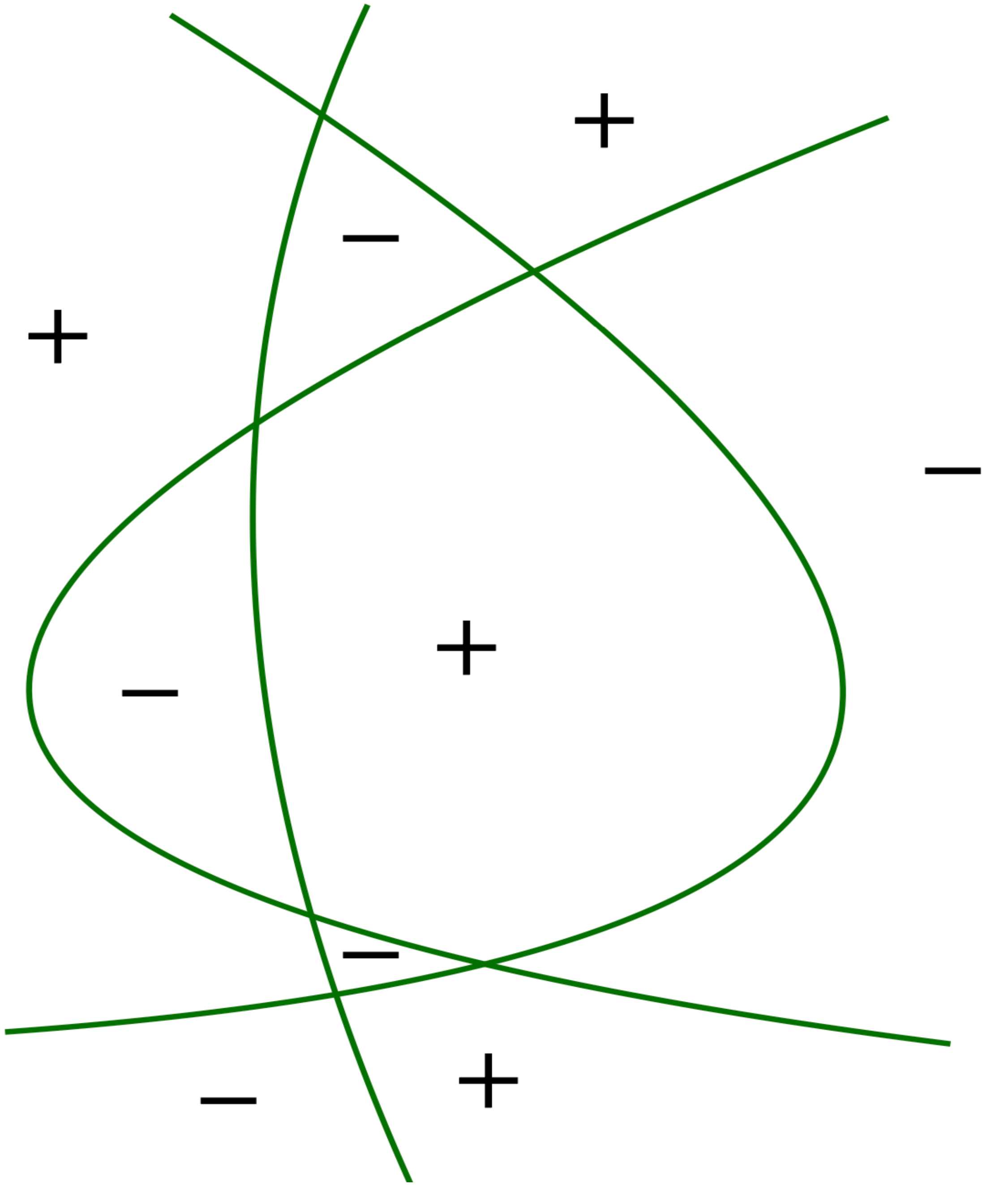
pdf · DOI · cite · claim · reference search · 81 citations

# Domain Wall Formation

$$V(\phi) = \frac{\lambda}{4}(\phi^2 - v^2)^2$$



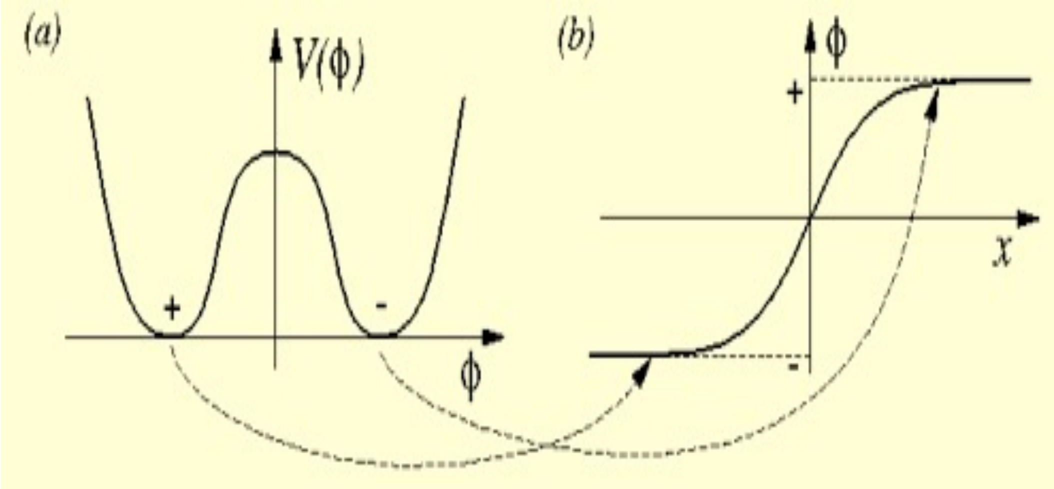

**Spontaneous breaking of $\mathbb{Z}_2$**

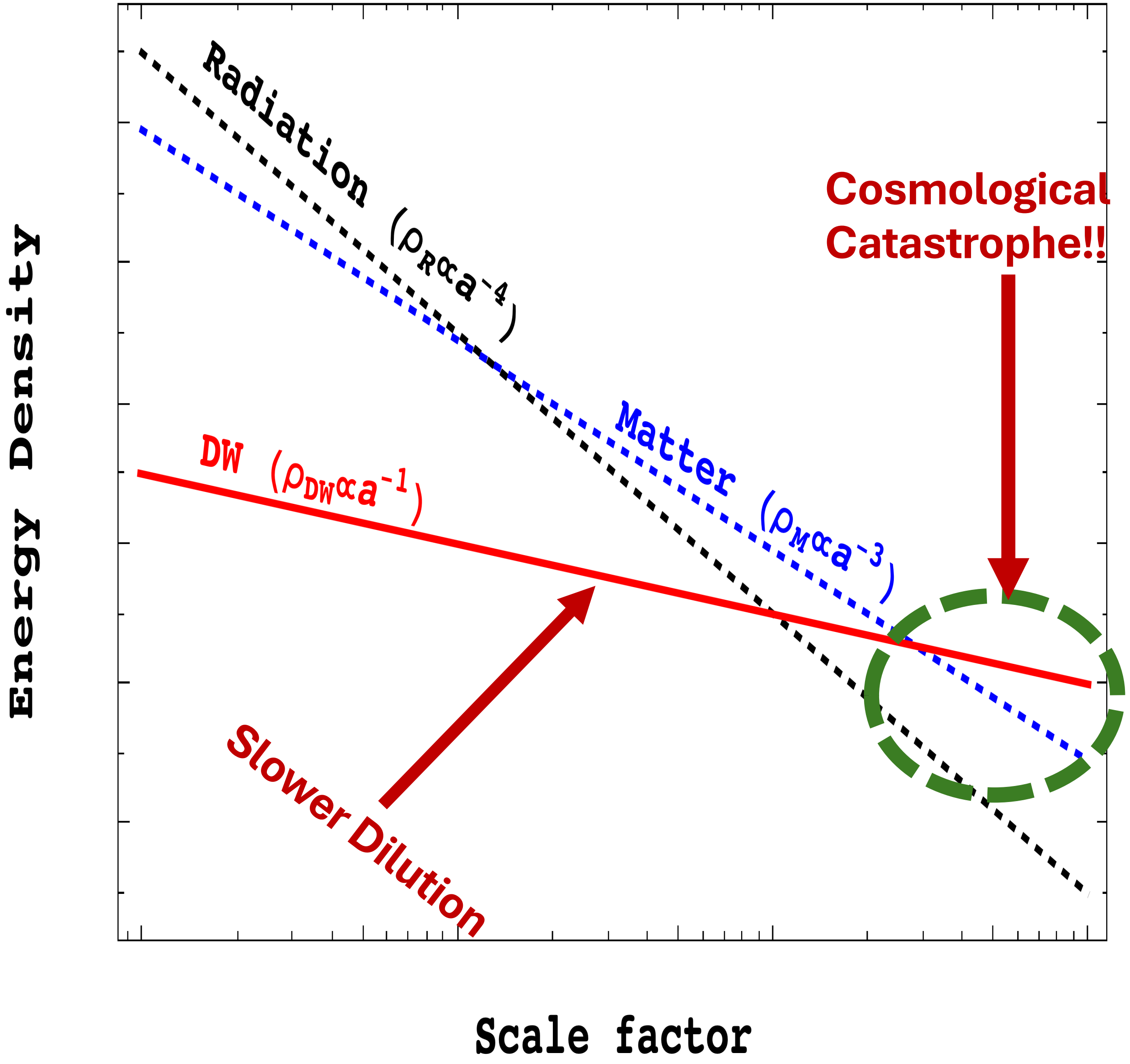



From Yann Gouttenoire's SHEP seminar

# Domain Wall: Fact-Sheet

$$\phi(x) = v \tanh\left(\sqrt{\frac{\lambda}{2}} v x\right)$$




**Surface Tension**

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

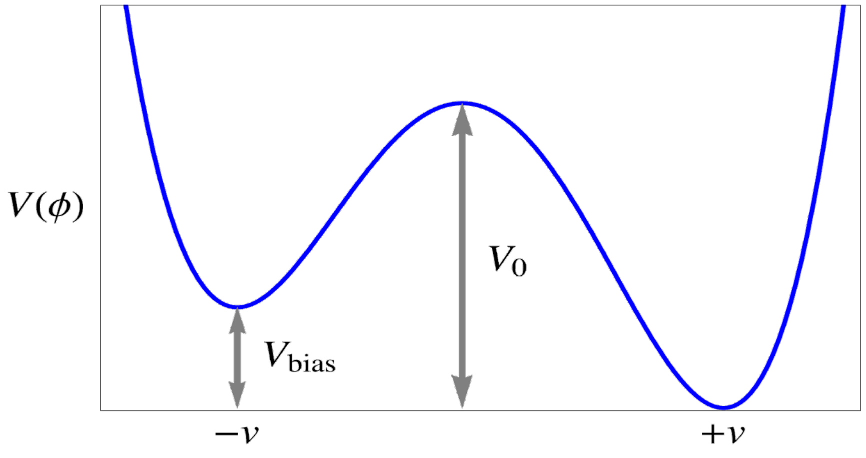
**Energy Density**

$$\rho_{\rm DW} \propto a^{-1}$$

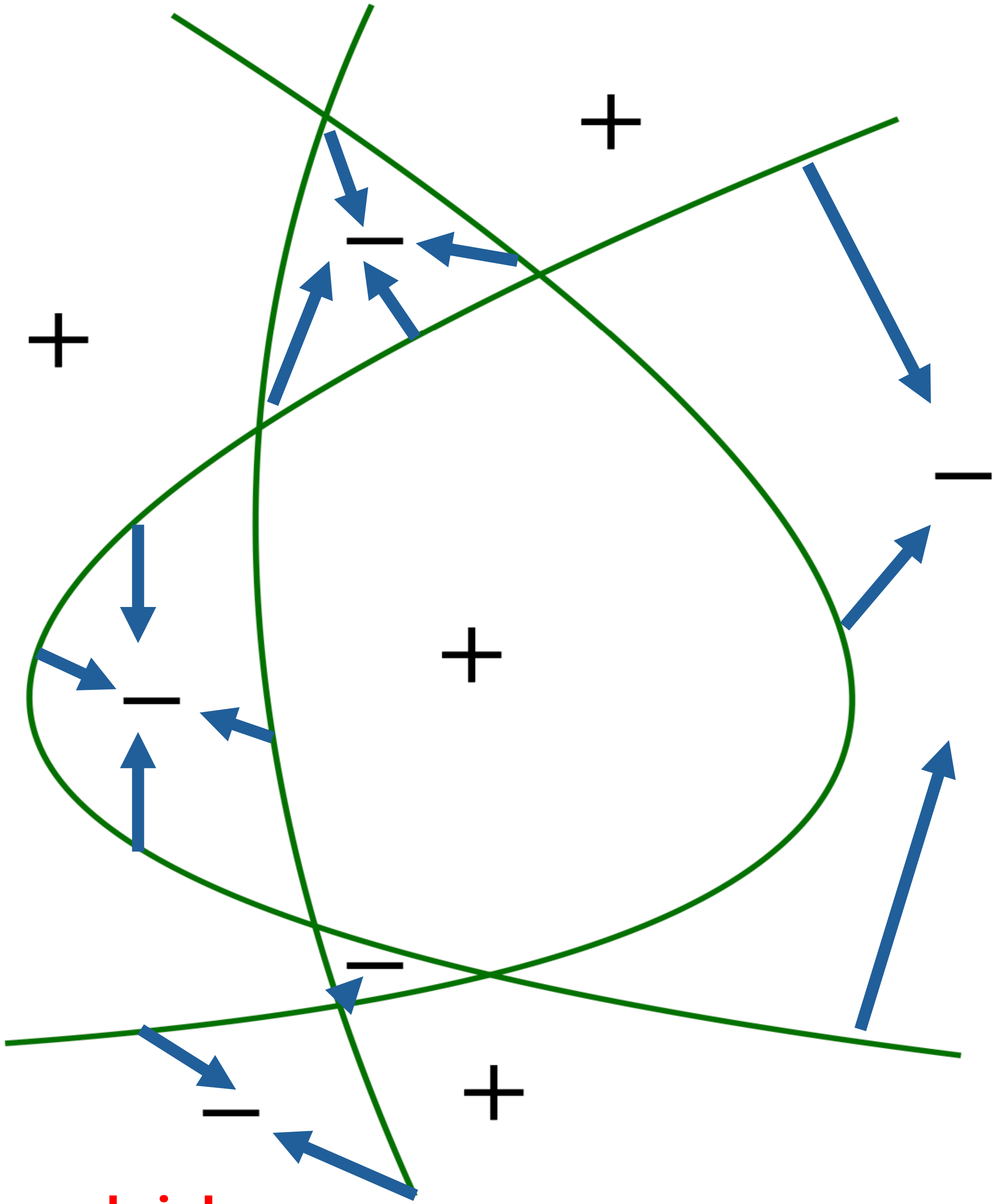
(Dilutes much slower than radiation and matter)

# Possible Solutions

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



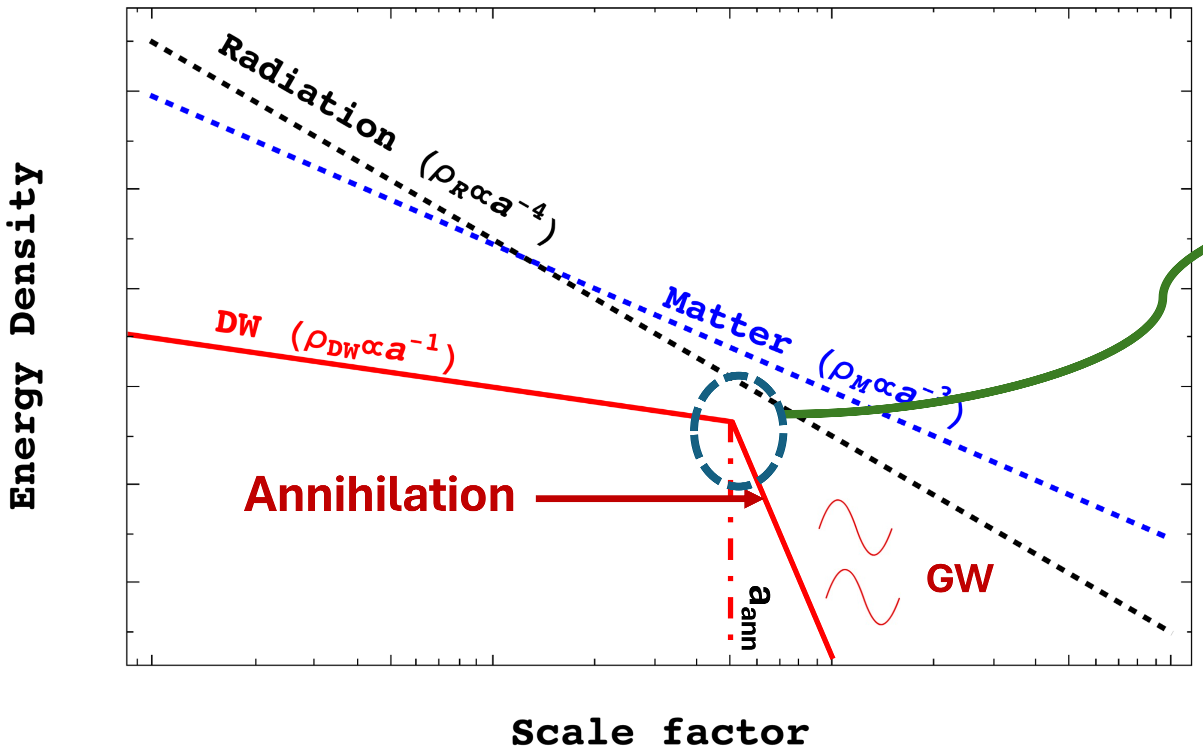

Saikawa, Universe 3, 40 (2017)

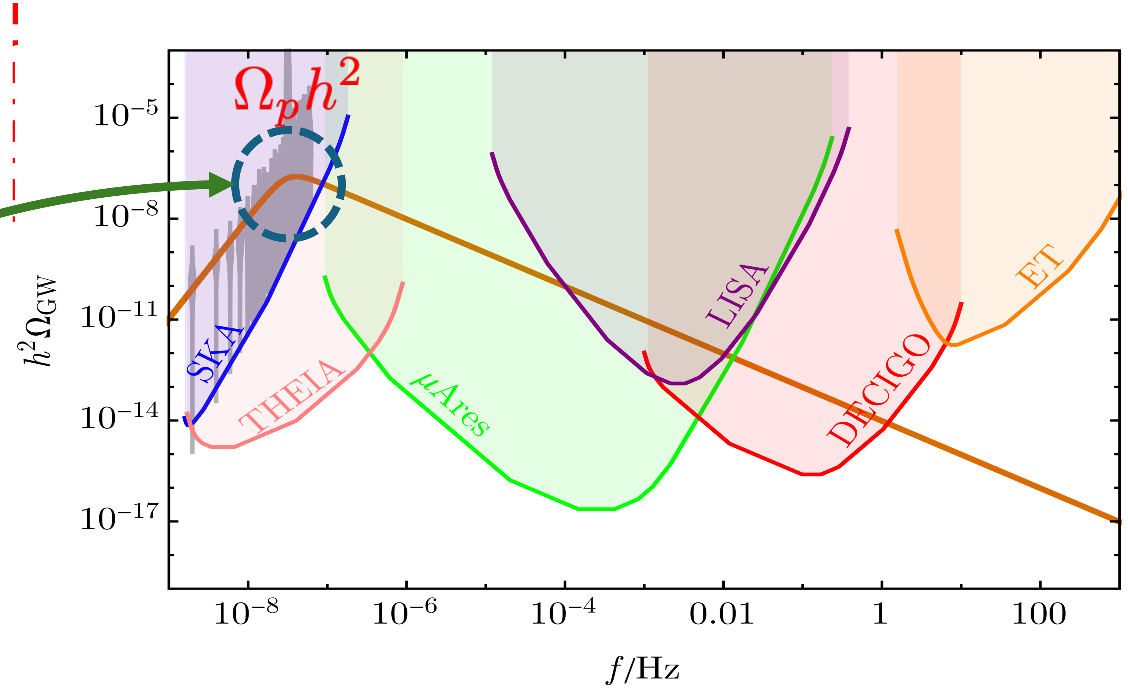



$$p_V \sim V_{\rm bias},\ \ p_T \sim \sigma\frac{\mathcal{A}}{t}$$

$V_{\rm bias} \Longrightarrow p_V > p_T \Longrightarrow$ **False vacuum shrinks**

# Gravitational Waves from Domain Walls




**GW spectrum:**

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

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

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

**Broken power law**

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

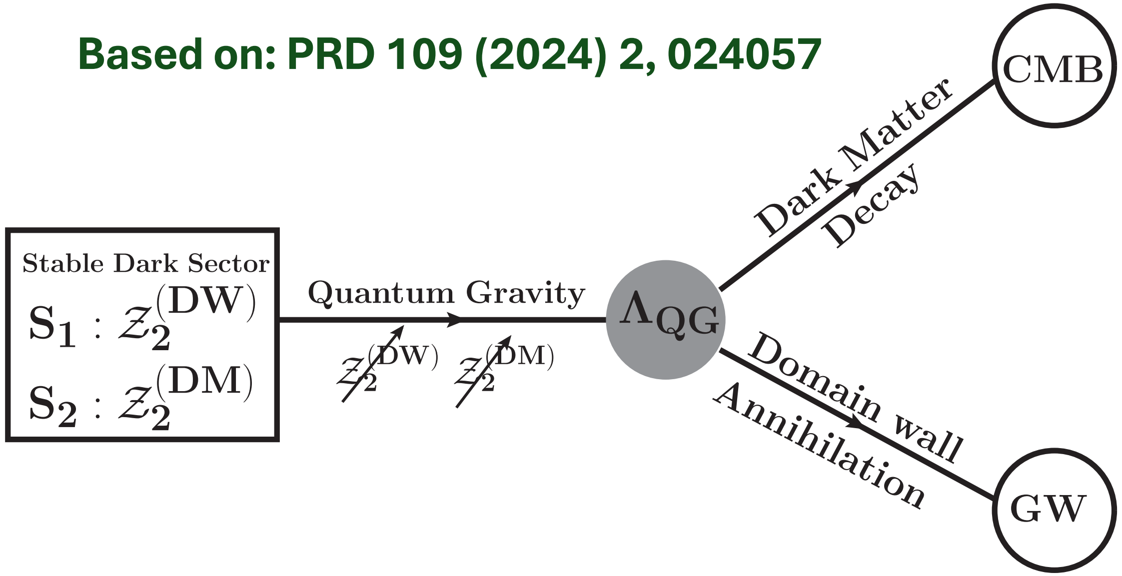
$x = f/f_p$

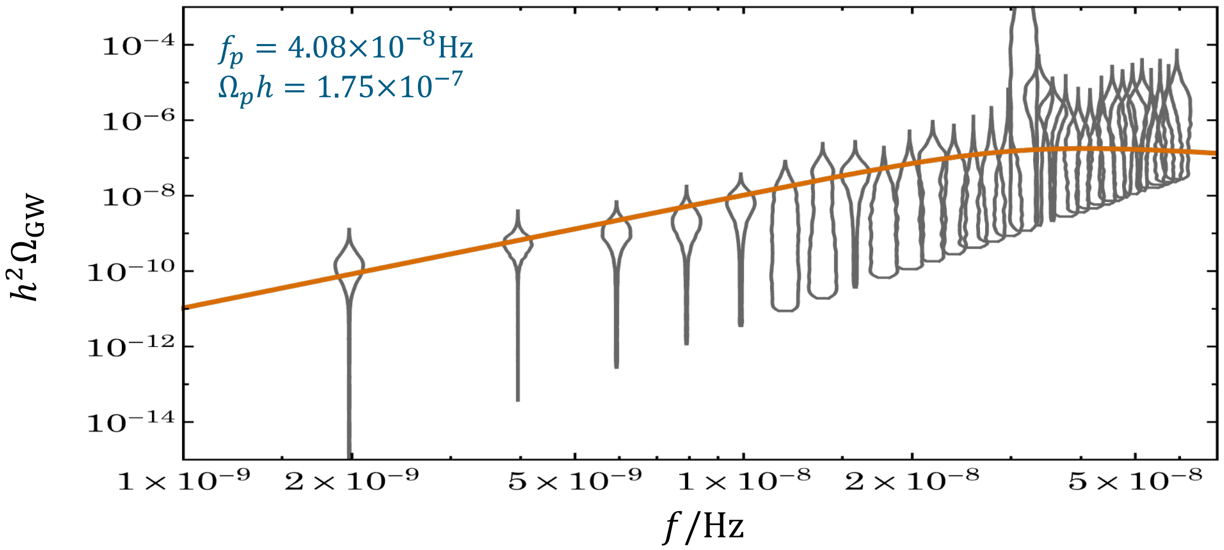
$a = 3$ by causality

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

# Applications: GW from DW

Based on: PRD 109 (2024) 2, 024057




## 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)

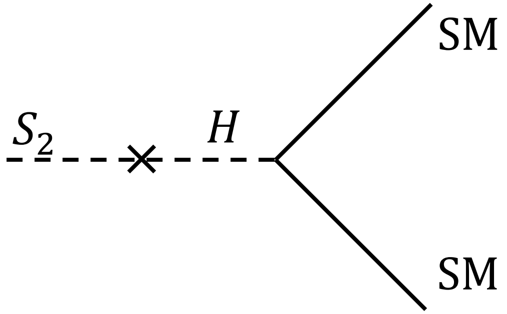
$$\Delta V = \frac{1}{\Lambda_{QG}}\sum_{i=1}^{2}(\alpha_{1i}S_i^5 + \alpha_{2i}S_i^3 H^2 + \alpha_{3i}S_i H^4) + \frac{1}{\Lambda_{QG}}\sum_{j=1}^{4} c_j S_1^j S_2^{5-j}$$

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

# DM Decay:

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

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

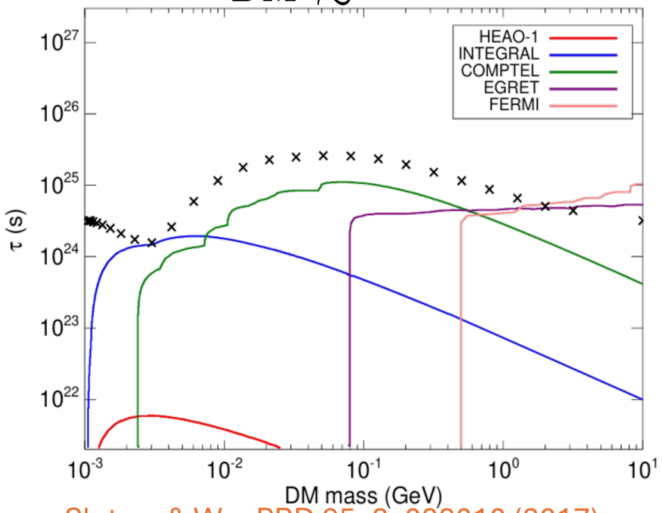



$S_2 \rightarrow \mathrm{SMSM} \rightarrow e\bar{e}, \gamma\bar{\gamma}, \nu\bar{\nu}$

## Indirect detection of dark matter

**CMB power spectrum**

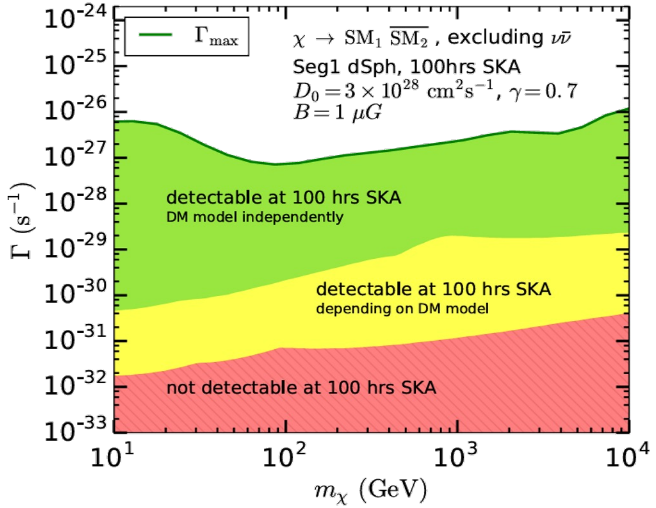
$\tau_{\rm DM} \gtrsim 10^{25}$ s



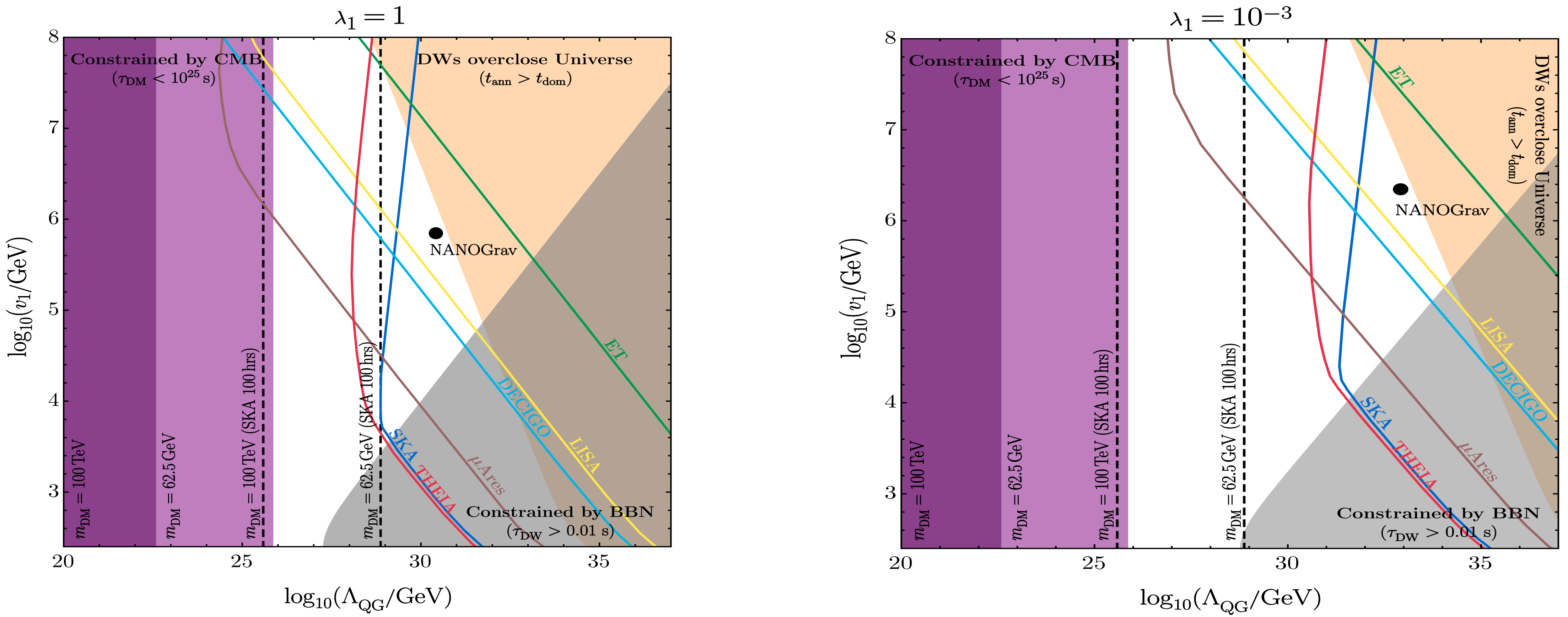

Slatyer & Wu, PRD 95, 2, 023010 (2017)

**SKA radio telescope**

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



# GW from DW: Testing the scale of Quantum Gravity

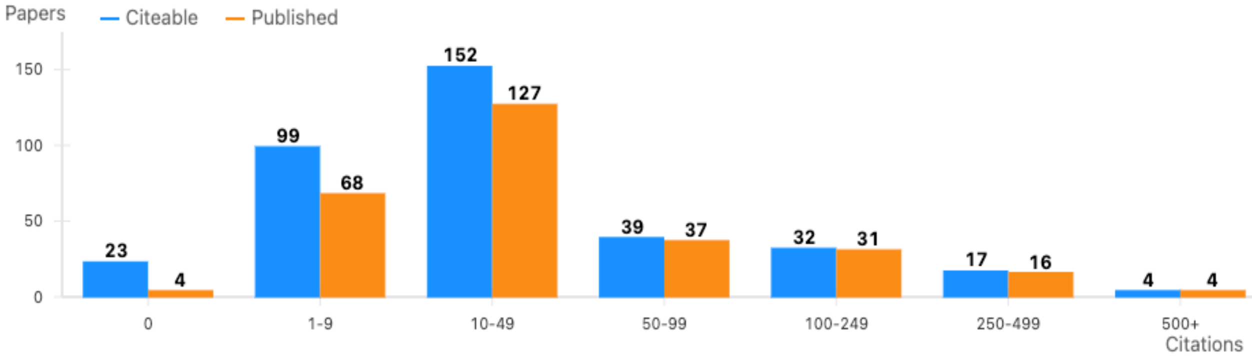


# Some recent works on GW from Cosmic Strings

### Citation Summary

Exclude self-citations

| | Citeable | Published |
|---|---|---|
| Papers | 366 | 287 |
| Citations | 20,526 | 19,271 |
| h-index | 69 | 67 |
| Citations/paper (avg) | 56.1 | 67.1 |




**Type-I two-Higgs-doublet model and gravitational waves from domain walls bounded by strings** #1
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e-Print: 2404.16931 [hep-ph]
pdf cite claim reference search 0 citations

**Ultra-high frequency gravitational waves from cosmic strings with friction** #2
S. Mukovnikov, L. Sousa (Apr 19, 2024)
e-Print: 2404.13213 [astro-ph.CO]
pdf cite claim reference search 0 citations

**The NANOGrav 15 yr Data Set: Search for Signals from New Physics** #1
NANOGrav Collaboration • Adeela Afzal (Munster U. and Quaid-i-Azam U.) et al. (Jun 28, 2023)
Published in: *Astrophys.J.Lett.* 951 (2023) 1, L11 • e-Print: 2306.16219 [astro-ph.HE]
pdf links DOI cite claim reference search 367 citations

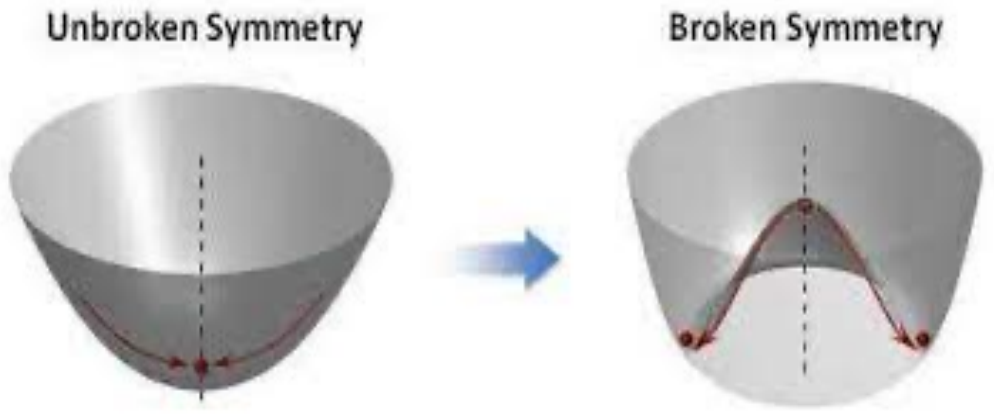
**The number of cosmic string loops** #8
Jose J. Blanco-Pillado (Tufts U., Inst. of Cosmology and Basque U., Bilbao and IKERBASQUE, Bilbao), Ken D. Olum (Tufts U., Inst. of Cosmology), Benjamin Shlaer (Tufts U., Inst. of Cosmology) (Sep 25, 2013)
Published in: *Phys.Rev.D* 89 (2014) 2, 023512 • e-Print: 1309.6637 [astro-ph.CO]
pdf DOI cite claim reference search 266 citations

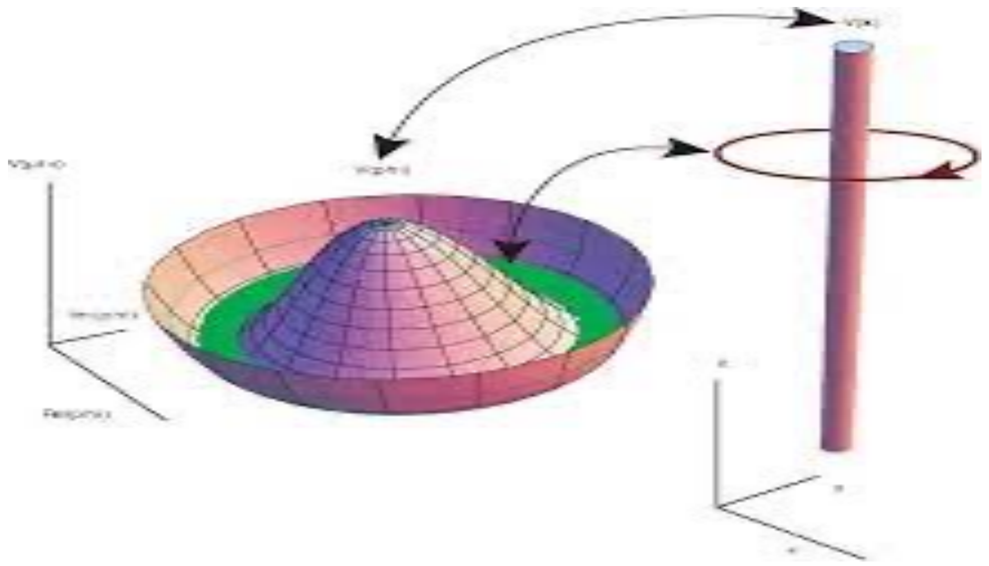
**Cosmological Backgrounds of Gravitational Waves and eLISA/NGO: Phase Transitions, Cosmic Strings and Other Sources** #9
Pierre Binetruy (APC, Paris), Alejandro Bohe (Paris, Inst. Astrophys.), Chiara Caprini (Saclay, SPhT), Jean-Francois Dufaux (APC, Paris) (Jan, 2012)
Published in: *JCAP* 06 (2012) 027 • e-Print: 1201.0983 [gr-qc]
pdf DOI cite claim reference search 294 citations

**Gravitational wave bursts from cusps and kinks on cosmic strings** #14
Thibault Damour (IHES, Bures-sur-Yvette), Alexander Vilenkin (Tufts U.) (Apr, 2001)
Published in: *Phys.Rev.D* 64 (2001) 064008 • e-Print: gr-qc/0104026 [gr-qc]
pdf DOI cite claim reference search 364 citations

**Gravitational wave bursts from cosmic strings** #15
Thibault Damour (IHES, Bures-sur-Yvette), Alexander Vilenkin (Tufts U.) (Apr, 2000)
Published in: *Phys.Rev.Lett.* 85 (2000) 3761-3764 • e-Print: gr-qc/0004075 [gr-qc]
pdf DOI cite claim reference search 377 citations

# Cosmic String Formation



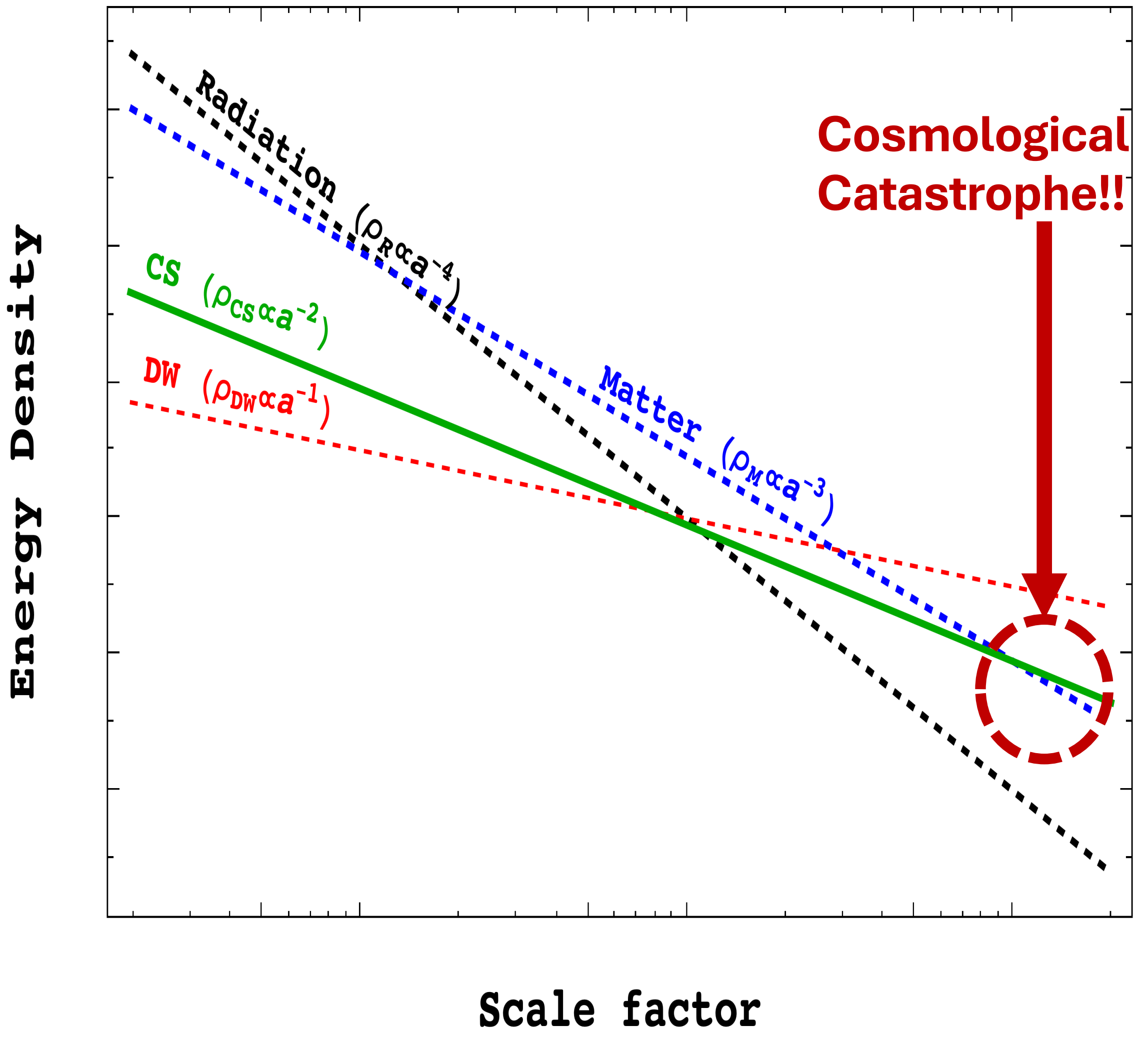
**Cosmic Strings**

CS is a 1-d defect originating from SSB of U(1) symmetry.

a. Breaking of global U(1) symmetry: **Global string**
b. Breaking of local U(1) symmetry: **Local string**

# Cosmic Strings: Fact-Sheet

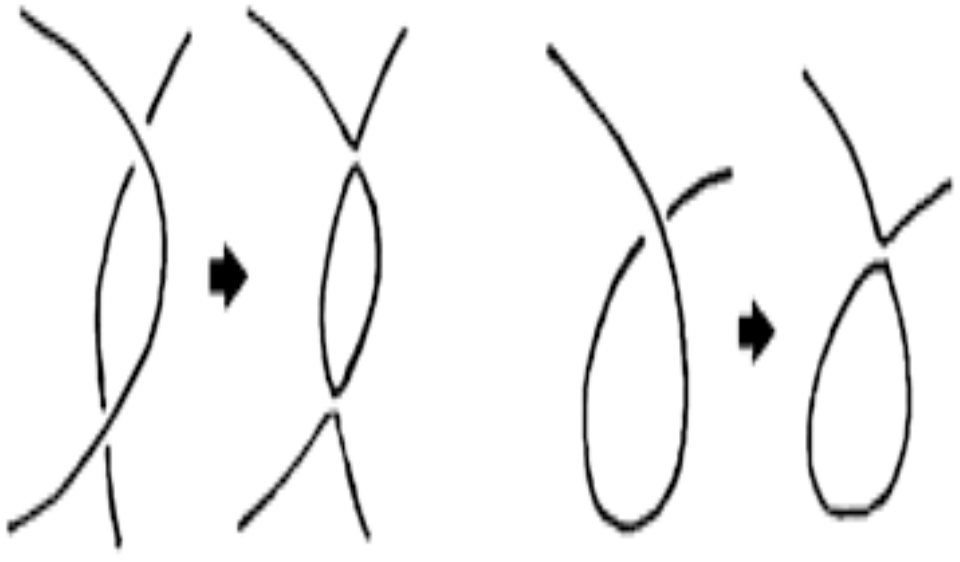
$\rho_{\text{CS}} \propto a^{-2}$ (Dilutes much slower than radiation and matter but faster than DW)




**The evolution of CS network is much more complicated:**

a. Intercommutation of intersecting strings leads to the formation of loops of different sizes.

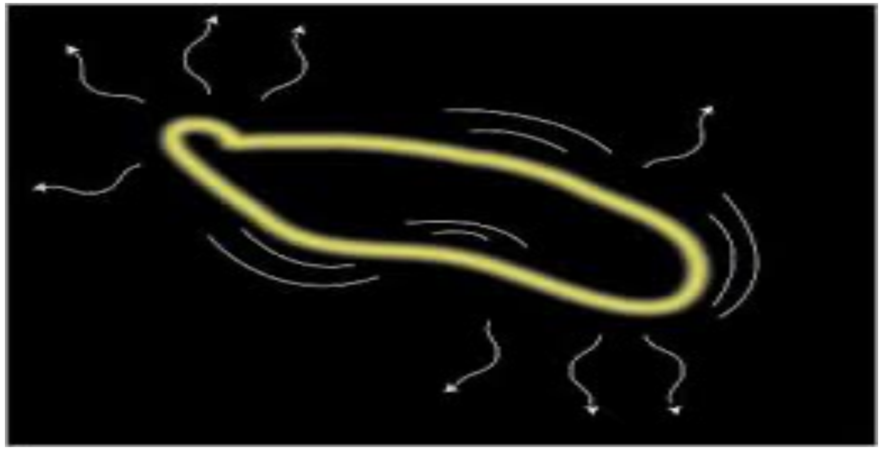
b. Smaller loops decay by radiating GW.



(a) Intersection (b) self-intersection

# Gravitational Waves from Cosmic Strings

At a later time, the size of a loop's initial length $l_i = \alpha t_i$ can be expressed as: $l(t) \simeq \alpha t_i - \Gamma G\mu(t - t_i).$



$G\mu$ : String Tension $\quad \Gamma = 50$

Set of normal mode oscillation with frequency $f_k = 2k/l$

$$\Omega_{\rm GW}(t_0, f) = \sum_k \Omega_{\rm GW}^{(k)}(t_0, f) \qquad f \equiv f(t_0) = f_k a(t_0)/a(t)$$

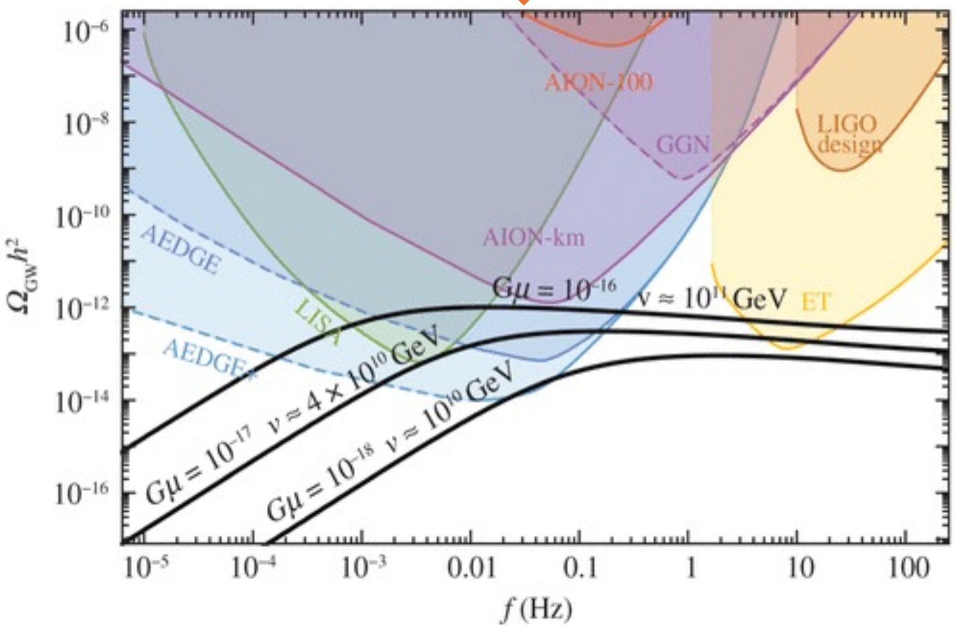
GW energy density at present:

$$\Omega_{\rm GW}^{(k)}(f) = \frac{1}{\rho_c}\frac{2k}{f}\frac{\mathcal{F}_\alpha \Gamma^{(k)} G\mu^2}{\alpha(\alpha+\Gamma G\mu)}\int_{t_F}^{t_0} d\tilde{t}\,\frac{C_{\rm eff}(t_i^{(k)})}{t_i^{(k)\,4}}\left[\frac{a(\tilde{t})}{a(t_0)}\right]^5\left[\frac{a(t_i^{(k)})}{a(\tilde{t})}\right]^3\Theta(t_i^{(k)} - t_F),$$

Typical feature:

$$\Omega_{\rm GW}^{(k=1),\rm plateau}(f) = \frac{128\pi G\mu}{9\zeta(\delta)}\frac{A_r}{\epsilon_r}\Omega_r\left[(1+\epsilon_r)^{3/2} - 1\right]$$

$$\epsilon_r = \alpha/\Gamma G\mu \qquad \Omega_r \simeq 9\times 10^{-5} \qquad A_r = 5.4$$




Phil.Trans.Roy.Soc.Lond.A 380 (2022) 20210060

# Applications: GW from Cosmic Strings

**Example I:** JHEP 11 (2021) 175 (Ligong Bian, Xuewen Liu and Ke-Pan Xie )

**The relevant symmetry:** $\mathrm{SM} \times \mathrm{Z}_2 \times \mathrm{U}(1)_{\mathrm{B-L}}$ —Gauged→ **Cosmic String** → **GW**

**The relevant Lagrangian:**

$$\mathcal{L}_{\mathrm{B-L}} = \sum_i \bar{\nu}_R^i i\not{\partial}\nu_R^i - \frac{1}{2}\sum_{i,j}\left(\lambda_R^{ij}\bar{\nu}_R^{i,c}\Phi\nu_R^j + \right) - \sum_{i,j}\left(\lambda_D^{ij}\bar{\ell}_L^i\tilde{H}\nu_R^j + \right) + D_\mu\Phi^\dagger D^\mu\Phi - \lambda_\phi\left(|\Phi|^2 - \frac{v_\phi^2}{2}\right)^2 - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu},$$

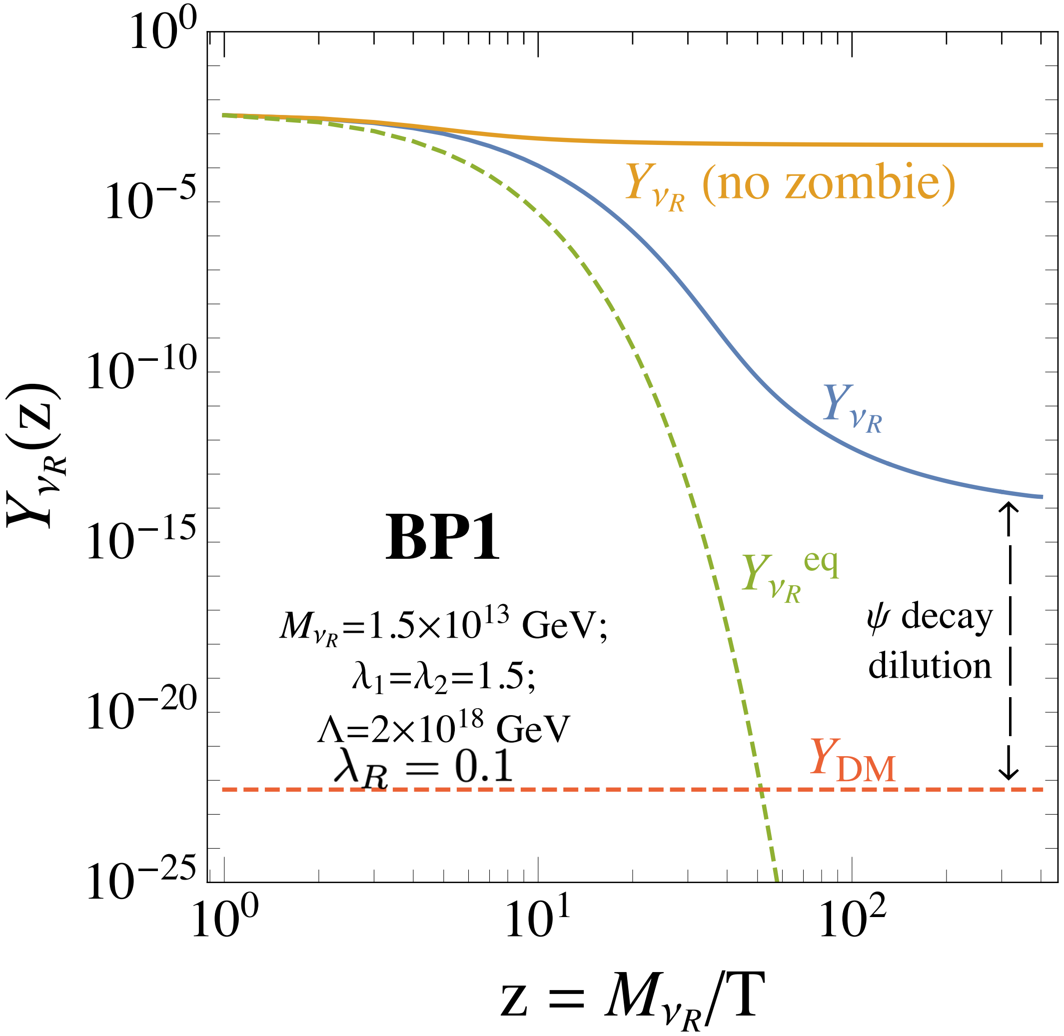
**The relevant Lagrangian for DM:**

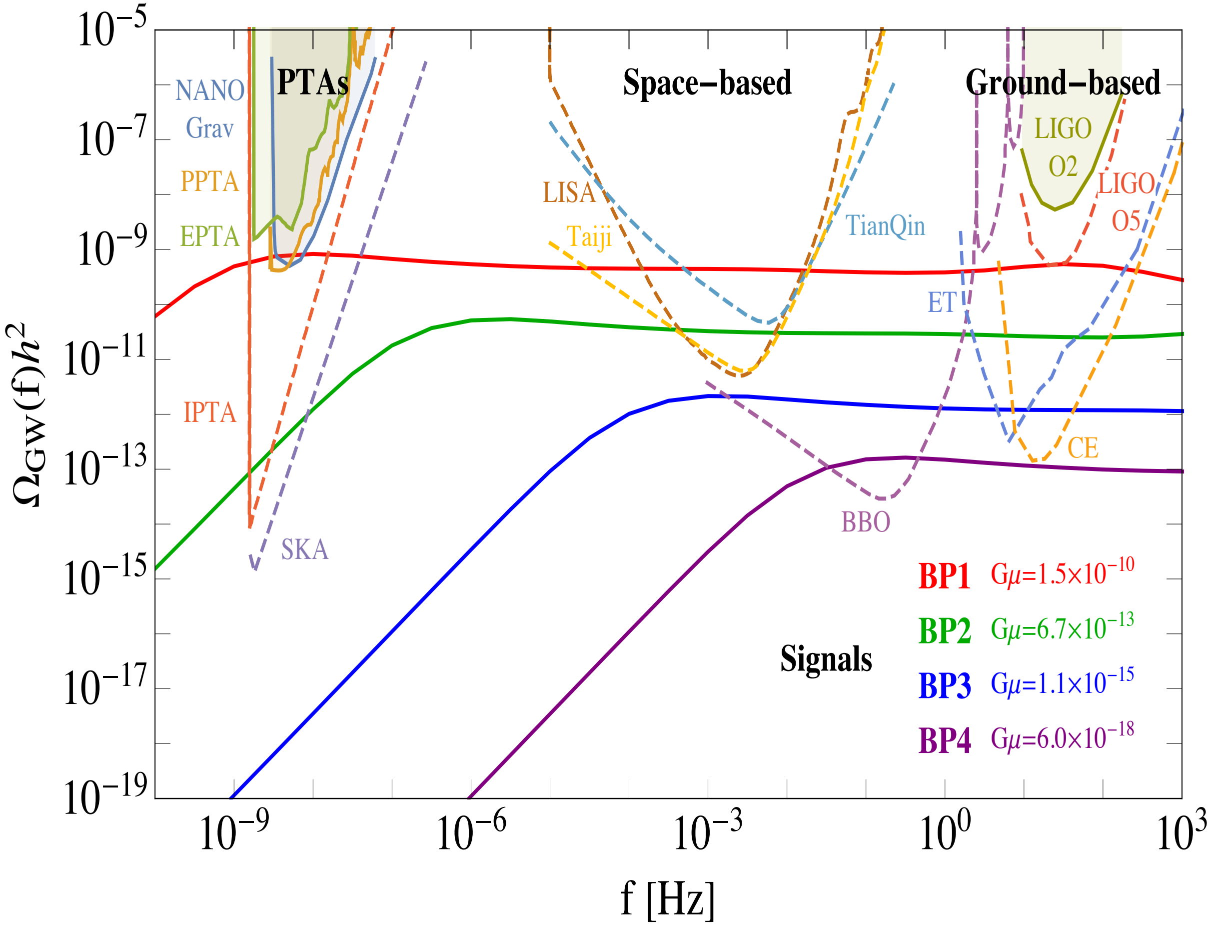
$$\mathcal{L}_{\mathrm{DM}} = \bar{\psi}\left(i\not{\partial} - M_\psi\right)\psi + \frac{1}{2}\partial_\mu S\partial^\mu S - \frac{1}{2}M_S^2 S^2 + (\lambda_1 S\bar{\psi}\nu_R + ) + \lambda_2 S\bar{\psi}\psi,$$

$$\mathcal{L}_6 = \frac{1}{\Lambda^2}\sum_{i,j,j'}(\bar{\psi}^c u_R^i)(\bar{d}_R^{j,c} d_R^{j'}) + \mathrm{h.c.},$$

**(Responsible for the slow decay)**

# GW from CS: As a probe to super-heavy DM




$$G\mu \sim \frac{v_\phi^2}{M_{\rm Pl}^2} \sim 10^{-10} \times \left(\frac{M_{\nu_R}/\lambda_R}{10^{14}\ {\rm GeV}}\right)^2$$

# Applications: GW from Cosmic Strings

**Example II:** Nucl.Phys.B 1002 (2024) 116528

**The relevant symmetry:** $\mathrm{SM} \times \mathrm{U}(1)$ → Gauged → Cosmic String → GW

**The relevant Lagrangian:**

$$-\mathcal{L} \supset \sum_{\alpha,i} Y_{\alpha i} \overline{L}_\alpha \tilde{H} N_i + \frac{1}{2} \sum_{i,j=1,2} h_{ij} S \overline{N_i^c} N_j + \frac{1}{2} M_3 \overline{N_3^c} N_3 + \frac{m_{\rm DM}^2}{2} \phi^2 .$$

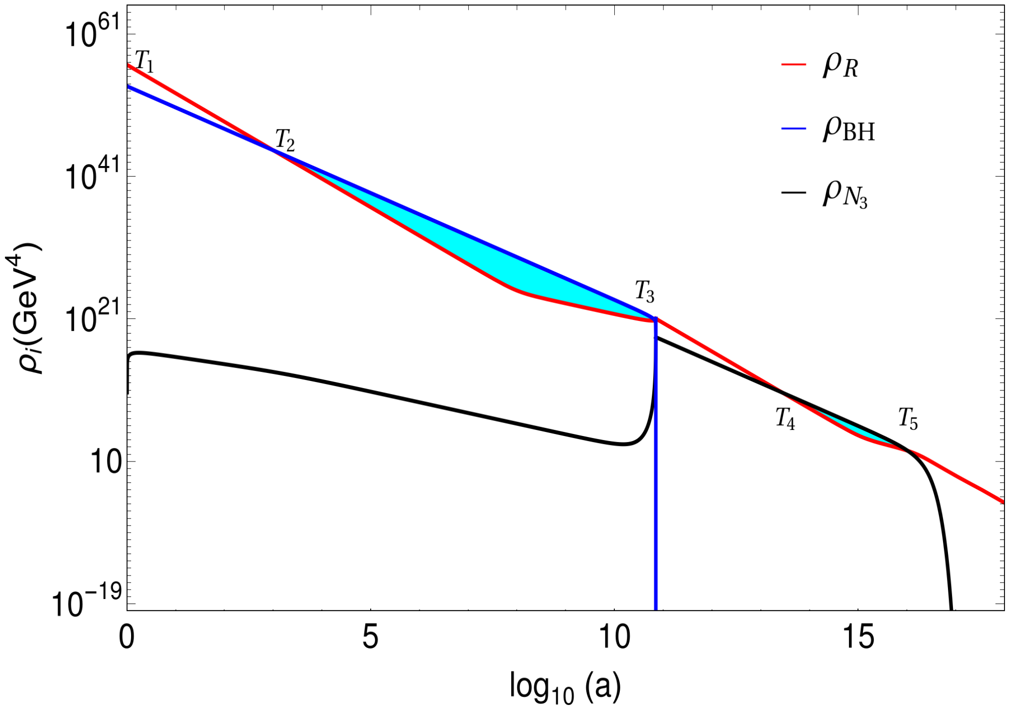
**Multiple Matter Dominated era resulting from:**

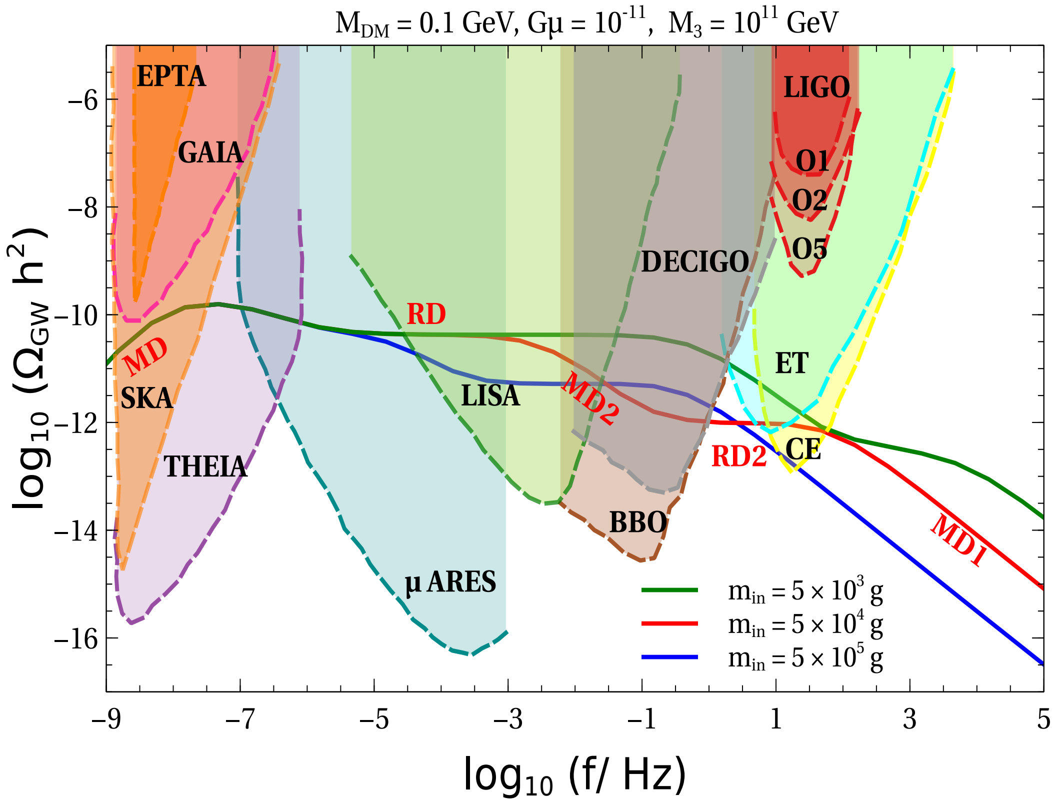
- **PBH dominated Universe**
- **Diluter ($N_3$) dominated universe**

# GW from CS: probing multiple MD eras

$f'_{\Delta} \propto \frac{1}{M_{\rm DM}^{1/3}} \frac{1}{m_{\rm in}^{5/3}}$.

$f_{\Delta} \propto \frac{1}{M_{\rm DM}} \frac{1}{m_{\rm in}^{2}}$.

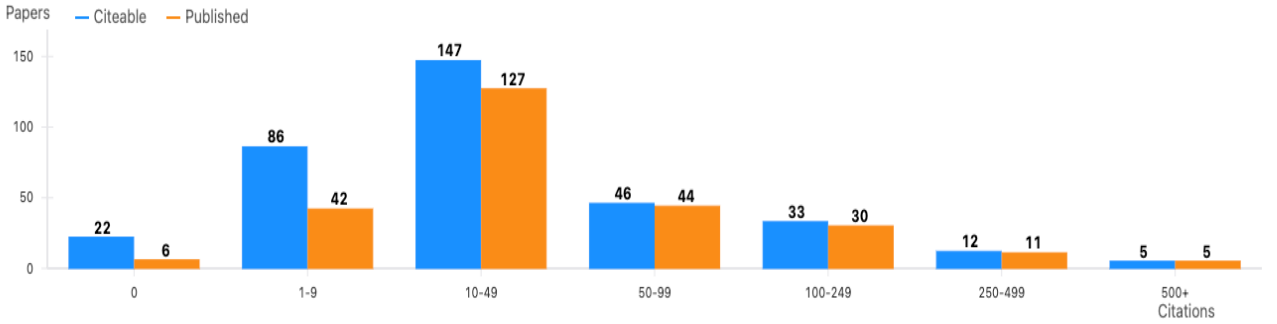



# Some recent works on GW from PBH

Citation Summary

☐ Exclude self-citations

| | Citeable | Published |
|---|---|---|
| Papers | 351 | 265 |
| Citations | 20,022 | 18,171 |
| h-index | 71 | 68 |
| Citations/paper (avg) | 57 | 68.6 |




The NANOGrav 15 yr Data Set: Search for Signals from New Physics #1
NANOGrav Collaboration • Adeela Afzal (Munster U. and Quaid-i-Azam U.) et al. (Jun 28, 2023)
Published in: *Astrophys.J.Lett.* 951 (2023) 1, L11 • e-Print: 2306.16219 [astro-ph.HE]
pdf links DOI cite claim reference search 367 citations

Non-Gaussianities in primordial black hole formation and induced gravitational waves #2
Shi Pi (Apr 9, 2024)
e-Print: 2404.06151 [astro-ph.CO]
pdf cite claim reference search 0 citations

Scalar Induced Gravitational Waves Review #3
Guillem Domènech (INFN, Padua) (Sep 3, 2021)
Published in: *Universe* 7 (2021) 11, 398 • e-Print: 2109.01398 [gr-qc]
pdf DOI cite claim reference search 280 citations

Primordial black holes—perspectives in gravitational wave astronomy #3
Misao Sasaki, Teruaki Suyama, Takahiro Tanaka, Shuichiro Yokoyama (Jan 16, 2018)
Published in: *Class.Quant.Grav.* 35 (2018) 6, 063001 • e-Print: 1801.05235 [astro-ph.CO]
pdf DOI cite claim reference search 744 citations

Primordial black holes and induced gravitational waves in non-singular matter bouncing cosmology #6
Theodoros Papanikolaou, Shreya Banerjee, Yi-Fu Cai, Salvatore Capozziello, Emmanuel N. Saridakis (Apr 4, 2024)
e-Print: 2404.03779 [gr-qc]
pdf cite claim reference search 0 citations

Gravitational Waves from Primordial Black Hole Mergers #9
Martti Raidal (NICPB, Tallinn), Ville Vaskonen (NICPB, Tallinn), Hardi Veermäe (NICPB, Tallinn) (Jul 5, 2017)
Published in: *JCAP* 09 (2017) 037 • e-Print: 1707.01480 [astro-ph.CO]
pdf DOI cite claim reference search 283 citations

Gravitational wave background as a probe of the primordial black hole abundance #11
Ryo Saito (Tokyo U. and Tokyo U., RESCEU), Jun'ichi Yokoyama (Tokyo U., RESCEU and Tokyo U., IPMU) (Dec, 2008)
Published in: *Phys.Rev.Lett.* 102 (2009) 161101, *Phys.Rev.Lett.* 107 (2011) 069901 (erratum) • e-Print: 0812.4339 [astro-ph]
pdf DOI cite claim reference search 359 citations

# Primordial Black Holes (PBH)

**PBH formation** → 
- **Collapse of large inhomogeneities**
- **Collapse of cosmic string loops**
- **Bubble collisions**

**PBH mass at formation:**

$$M_{\rm BH}(T_{\rm in}) = \frac{4}{3}\pi\gamma\left(\frac{1}{\mathcal{H}(T_{\rm in})}\right)^3 \rho_{\rm rad}(T_{\rm in})$$

**Black hole Temperature:**

$$T_{\rm BH} = \frac{1}{8\pi G M_{\rm BH}} \approx 1.06\left(\frac{10^{13}\,{\rm g}}{M_{\rm BH}}\right)\,{\rm GeV}$$

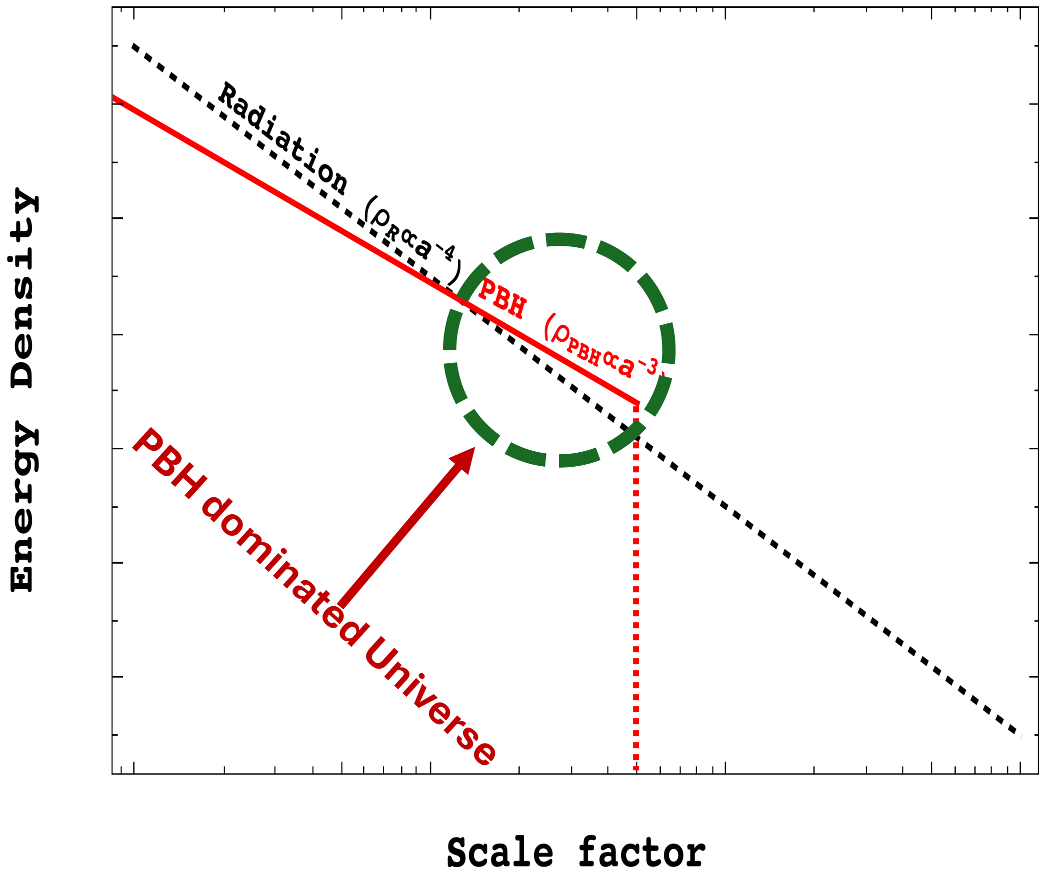
**Hawking evaporation:**

$$\frac{dm_{\rm BH}(t)}{dt} = -\frac{\mathcal{G}\,g_\star(T_{\rm BH})}{30720\,\pi}\frac{M_{\rm pl}^4}{m_{\rm in}(t)^2}$$

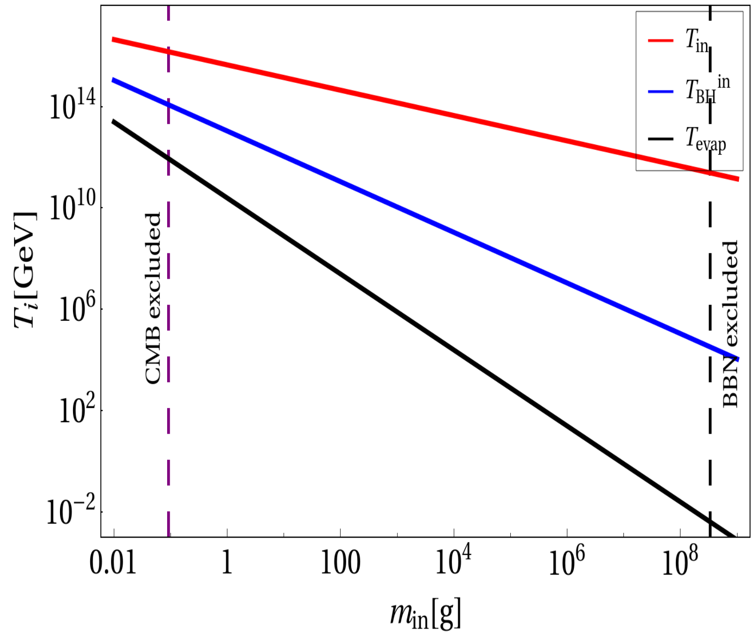
$$\beta \equiv \frac{\rho_{\rm BH}(T_{\rm in})}{\rho_{\rm rad}(T_{\rm in})}$$

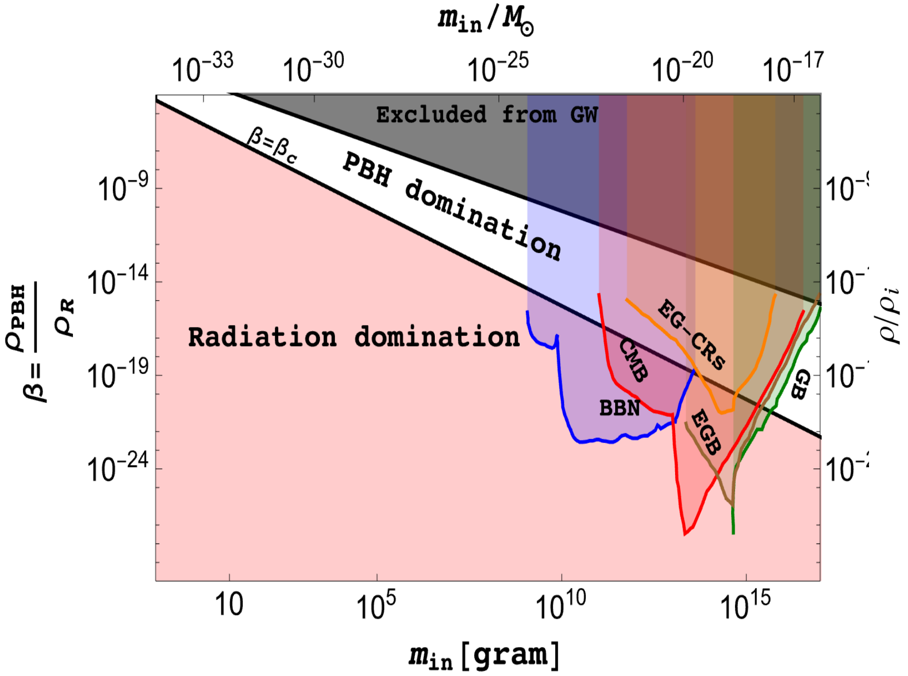
$$\beta < \beta_{\rm crit} \equiv \gamma^{-1/2}\sqrt{\frac{\mathcal{G}\,g_\star(T_{\rm BH})}{10640\,\pi}}\frac{M_{\rm pl}}{m_{\rm in}}$$

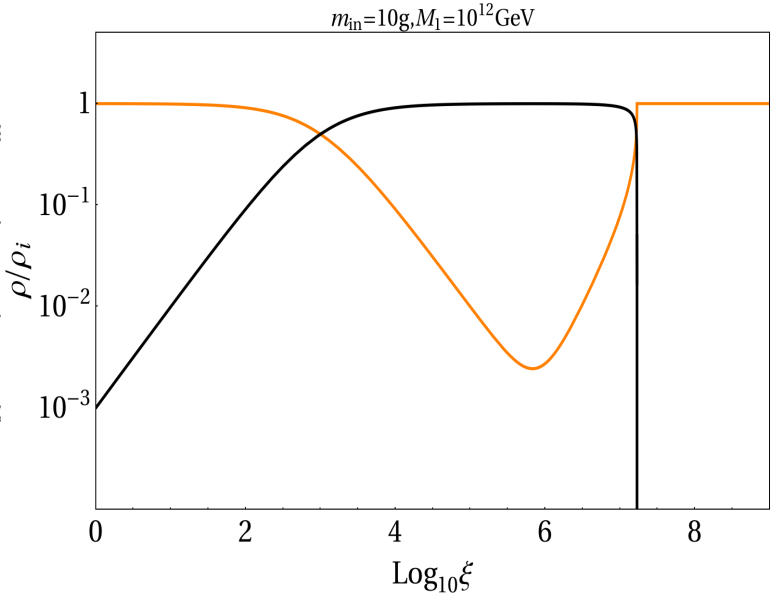
**Bound on PBH mass:** $0.1\,{\rm g} \lesssim m_{\rm in} \lesssim 3.4\times10^8\,{\rm g}$



# PBH: Fact-Sheet




$$T_{\rm in} = \left(\frac{45\,\gamma^2}{16\,\pi^3\,g_\star\,(T_{\rm in})}\right)^{1/4}\sqrt{\frac{M_{\rm pl}}{M_{\rm BH}(T_{\rm in})}}\,M_{\rm pl}$$

$$T_{\rm BH} = \frac{1}{8\pi\,G\,M_{\rm BH}} \approx 1.06\,\left(\frac{10^{13}\,{\rm g}}{M_{\rm BH}}\right)\,{\rm GeV}$$

$$T_{\rm evap} \equiv \left(\frac{45\,M_{\rm pl}^2}{16\,\pi^3\,g_\star\,(T_{\rm evap})\,\tau^2}\right)^{1/4}$$

# Particle production from PBH

$$\mathcal{N}_X = \frac{g_{X,H}}{g_{\star,H}(T_{\rm BH})} \begin{cases} \frac{4\,\pi}{3}\left(\frac{m_{\rm in}}{M_{\rm pl}}\right)^2 & \text{for } m_X < T_{\rm BH}^{\rm in}\,, \\ \frac{1}{48\,\pi}\left(\frac{M_{\rm pl}}{m_X}\right)^2 & \text{for } m_X > T_{\rm BH}^{\rm in}\,. \end{cases},$$

## Leptogenesis from PBH:

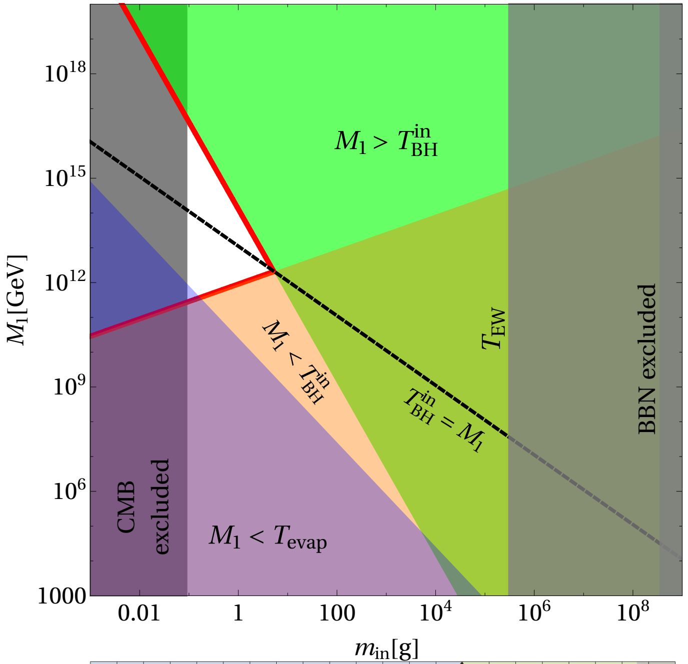
$$M_1 \begin{cases} > \frac{4\, g_{\star,H}(T_{\rm BH}^{\rm in})}{g_X\, a_{\rm sph}}\, \zeta\, \frac{Y_B^0}{Y_B^{\rm evap}}\, \frac{v^2\, M_{\rm pl}^2}{m_\nu\, m_{\rm in}^2} & \text{for } M_1 < T_{\rm BH}^{\rm in}\,; \\ < \frac{g_X\, a_{\rm sph}}{256\,\pi^2\, g_{\star,H}}\, \frac{1}{\zeta}\, \frac{Y_B^{\rm evap}}{Y_B^0}\, \frac{M_{\rm pl}^2\, m_\nu}{v^2} & \text{for } M_1 > T_{\rm BH}^{\rm in}\,, \end{cases}$$

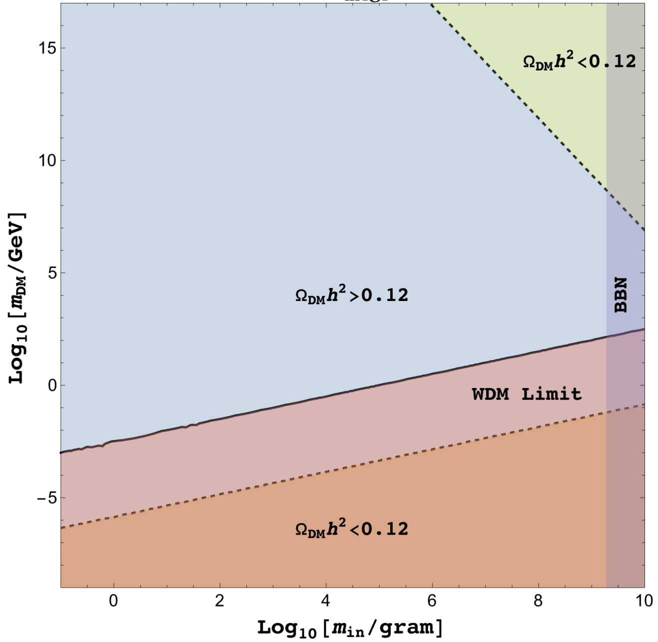
## DM from PBH:

$$\Omega_{\rm DM}\, h^2 = \mathbb{C}(T_{\rm ev}) \begin{cases} \frac{1}{\pi^2}\sqrt{\frac{M_{\rm pl}}{m_{\rm in}}}\, m_{\rm DM} & \text{for } m_{\rm DM} < T_{\rm BH}^{\rm in} \\ \frac{1}{64\,\pi^4}\left(\frac{M_{\rm pl}}{m_{\rm in}}\right)^{5/2} \frac{M_{\rm pl}^2}{m_{\rm DM}} & \text{for } m_{\rm DM} > T_{\rm BH}^{\rm in} \end{cases}$$

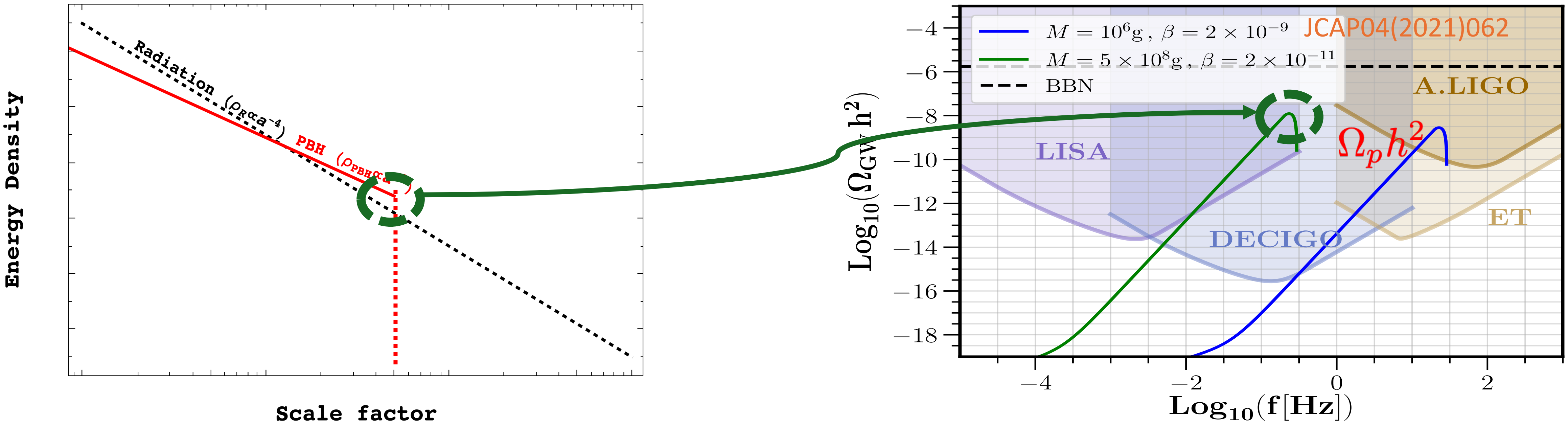
with

$$\mathbb{C}(T_{\rm ev}) = \frac{s_0}{\rho_c}\, \frac{1}{\zeta}\, \frac{g_{X,H}}{g_{\star,H}}\, \frac{5}{g_{\star s}(T_{\rm ev})} \left(\frac{\pi^3\, g_\star(T_{\rm ev})}{5}\right)^{3/4} \sqrt{\frac{\mathcal{G}\, g_{\star,H}}{10640\,\pi}}.$$



# Gravitational Waves from PBH




**Inhomogeneity in the distribution of the PBH** → **Induces GW at second order when PBH dominates**

$$\left\langle \frac{\delta\rho_{\rm BH}(k)}{\rho_{\rm BH}}\frac{\delta\rho_{\rm BH}(k')}{\rho_{\rm BH}} \right\rangle = \frac{4\pi}{3}\left(\frac{d}{a}\right)^3 \delta(k+k')$$

$$k_{\rm UV} = \frac{a_{\rm in}}{d_i} = \left(\frac{\beta}{\gamma}\right)^{\frac{1}{3}} k_i \,, \quad \mathcal{P}_{{\rm BH},i}(k) = \frac{2}{3\pi}\left(\frac{k}{k_{\rm UV}}\right)^3$$ **(Initial Isocurvature)**

$$\Omega_{\rm GW}^{\rm peak} \approx \mathcal{P}_\Phi^2(k=k_{\rm UV}) S_\Phi^4(k/k_{\rm RH}) \left(\frac{k_{\rm UV}}{k_{\rm RH}}\right)^7$$

$$S_\Phi\,(k/k_{\rm RH}) = \left(\sqrt{\frac{2}{3}}\frac{k}{k_{\rm RH}}\right)^{-1/3} , \quad \mathcal{P}_\Phi(k \gg k_{\rm BH}) = \mathcal{P}_{{\rm BH},i}\left(\frac{\sqrt{3}}{2}\frac{k_{\rm BH}}{k}\right)^4$$

$$\Omega_{\rm GW}(t_0, f) \simeq \Omega_{\rm GW}^{\rm peak}\left(\frac{f}{f_{\rm peak}}\right)^{11/3} \Theta\left(f_{\rm peak} - f\right)$$

$$\Omega_{\rm GW}^{\rm peak} \simeq 2\times 10^{-6}\left(\frac{\beta}{10^{-8}}\right)^{16/3}\left(\frac{m_{\rm in}}{10^7 {\rm g}}\right)^{34/9} \quad f_{\rm peak} \simeq 1.7\times 10^3\,{\rm Hz}\left(\frac{m_{\rm in}}{10^4{\rm g}}\right)^{-5/6}$$

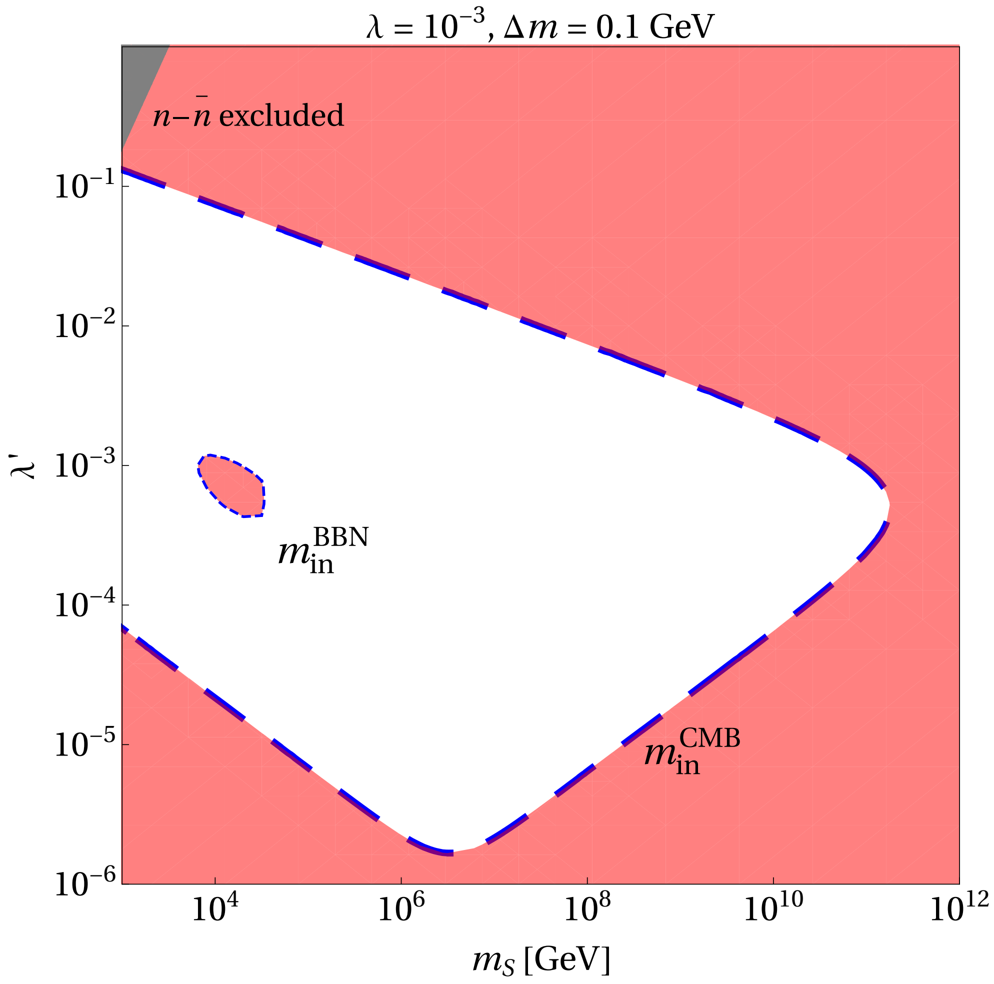
# Applications: GW from PBH

**Based on PRD 107 (2023) 9, 095002**

$$Y_B = \frac{n_B}{s} = \epsilon_1 \frac{n_{S_1}}{s} + \epsilon_2 \frac{n_{S_2}}{s}.$$

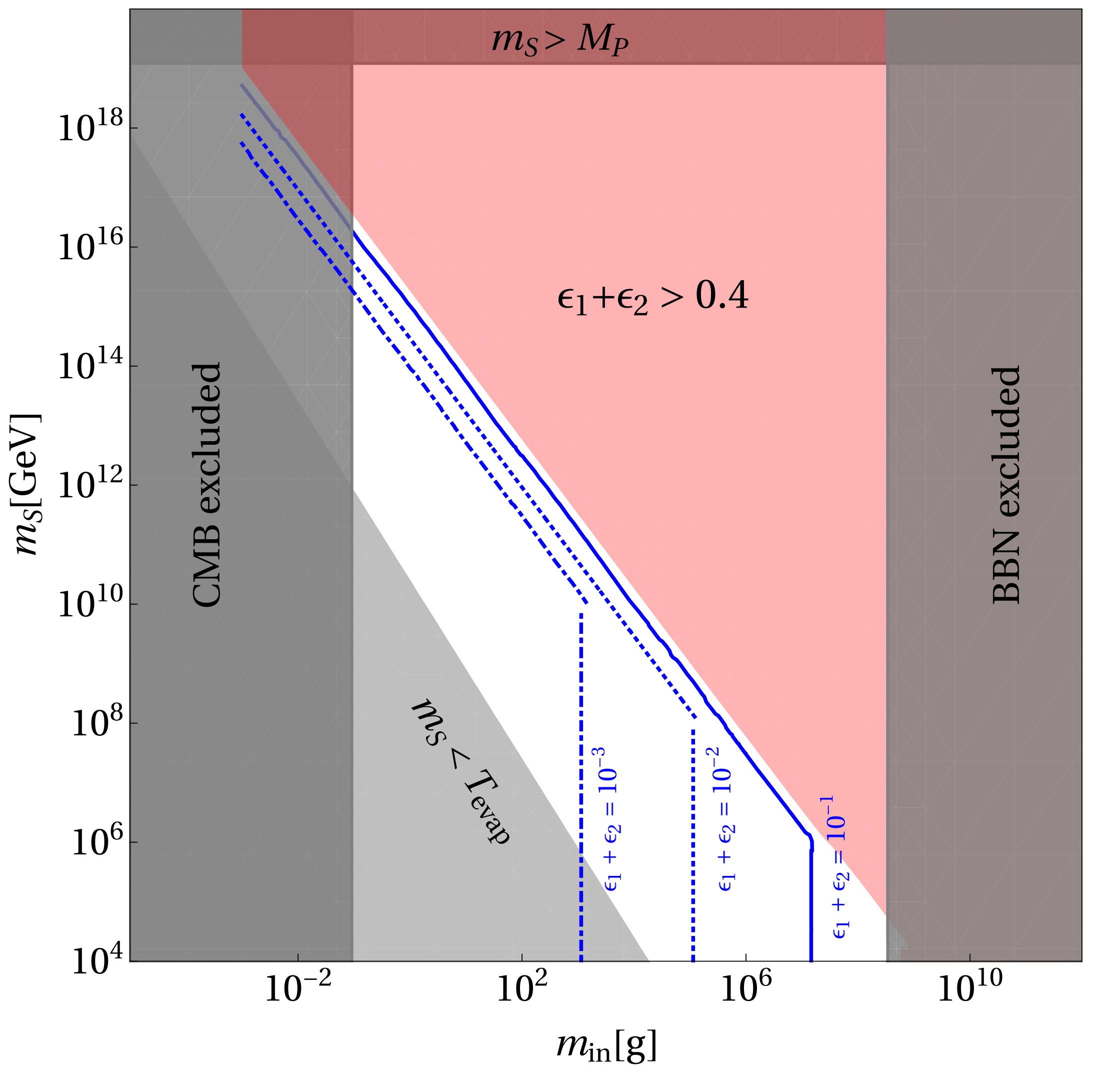
$$-\mathcal{L} \supset \lambda\, S\, \psi\, u^c + \lambda'\, S^\star\, d^c\, d^c + \frac{1}{2}\, m_\psi\, \overline{\psi^c}\, \psi + \text{h.c.}$$

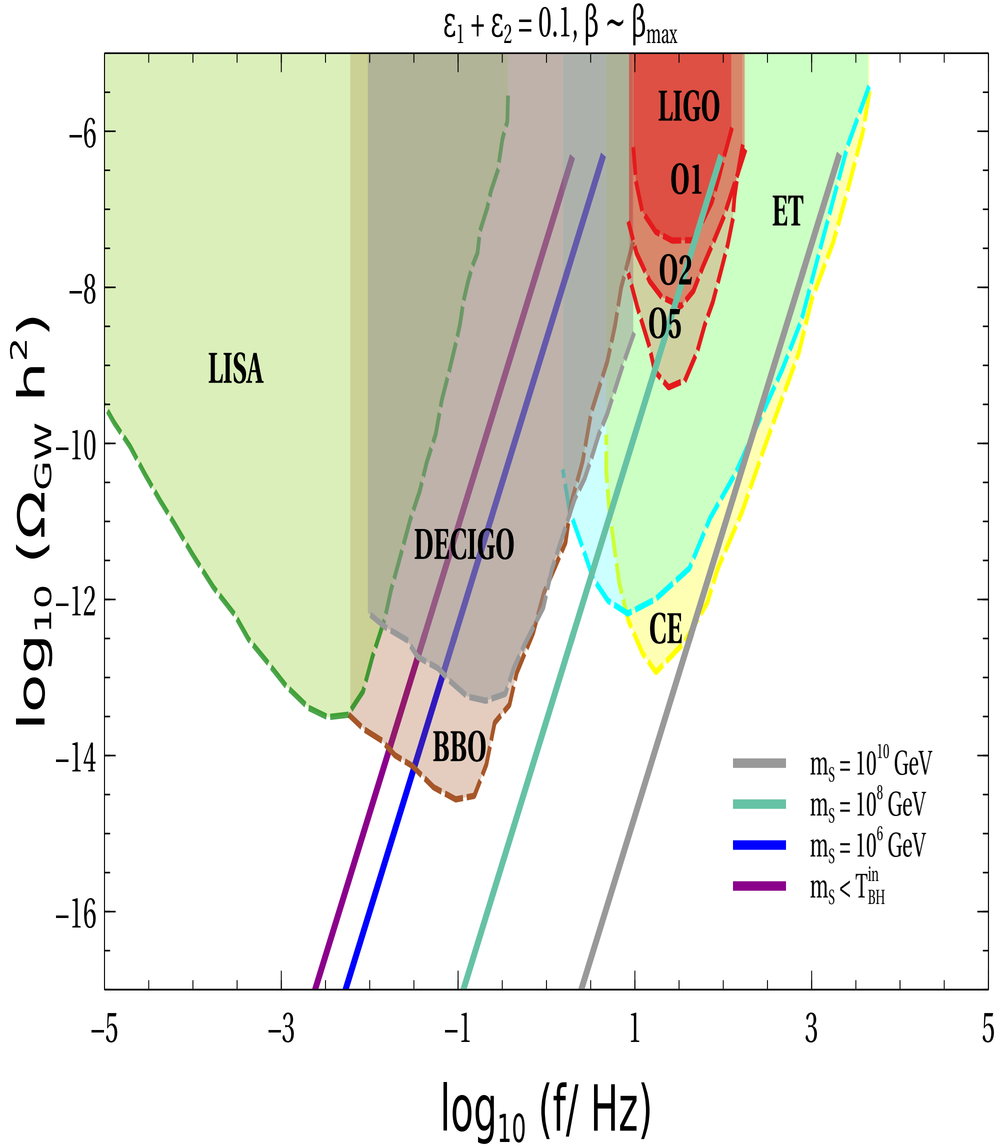
| Fields | $SU(3)_c$ | $SU(2)_L$ | $U(1)_Y$ |
|---|---|---|---|
| $u^c$ | 3 | 1 | $-4/3$ |
| $d^c$ | 3 | 1 | $+2/3$ |
| $S_i\ (i \in 1, 2)$ | 3 | 1 | $+4/3$ |
| $\psi$ | 1 | 1 | 0 |




$$\epsilon_\alpha = \frac{1}{8\,\pi} \frac{\sum_{i,j,k} \text{Im}\left(\lambda^*_{\alpha k} \lambda_{\beta k} \lambda'^*_{\alpha ij} \lambda'_{\beta ij}\right)}{\sum_{i,j} |\lambda'_{\alpha ij}|^2 + \sum_i |\lambda_{\alpha i}|^2} \times \frac{\left(m^2_{S_\alpha} - m^2_{S_\beta}\right) m_{S_\alpha} m_{S_\beta}}{\left(m^2_{S_\alpha} - m^2_{S_\beta}\right)^2 + m^2_{S_\alpha} \Gamma^2_{S_\beta}}$$

# GW from PBH: Probing Asymmetric Universe



# Summary and Conclusion

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

2. How to **test/probe** these scales? **Primordial 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.**