



Using Gravitational Waves to see the Early Universe

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University of Southampton

Based on:

Rev.Mod.Phys. 97 (2025) 1, 015001, PRD 109 (2024) 2, 024057 and Phys.Rev.D 108 (2023) 2, 023531

Collaborators:

Stephen F. King, Graham White, Masahito Yamazaki, Xin Wang, Debasish Borah, Rome Samanta and Surujjyoti Das

About Me:



Plan of the talk

1. A brief introduction to high-scale physics:

- a. Dark Matter
- b. Scale of Quantum Gravity
- c. Primordial Black Holes

2. Gravitational Wave Physics

- a. Theory
- b. Recent Discoveries
- c. Detectors
- d. Sources

3. GWs from Domain Walls and its application

4. GWs from Cosmic Strings and its application

5. Final Remarks

6. Ongoing Works and Future Directions

The Standard Model

Fermions

	Quarks	Leptons
1st	u Up	e Electron ν_e Electron neutrino
2nd	c Charm	μ Muon ν_μ Muon neutrino
3rd	t Top	τ Tau ν_τ Tau neutrino

Bosons

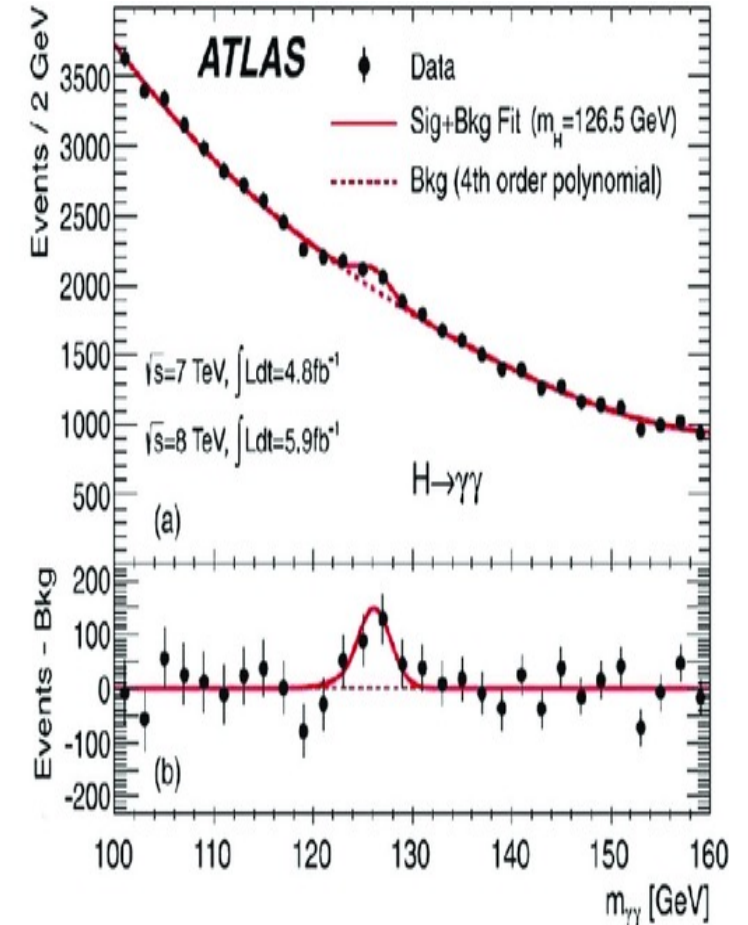
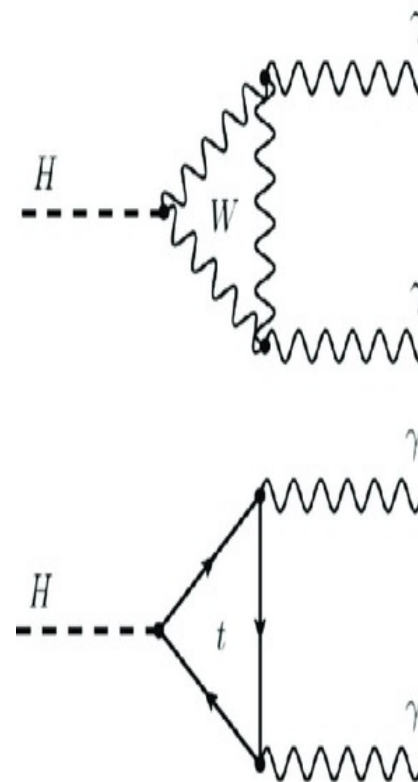
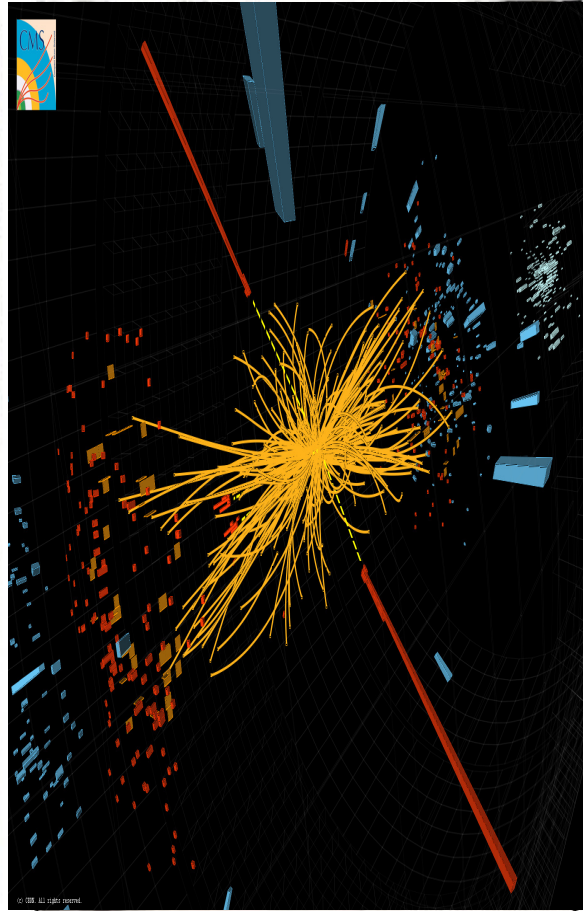
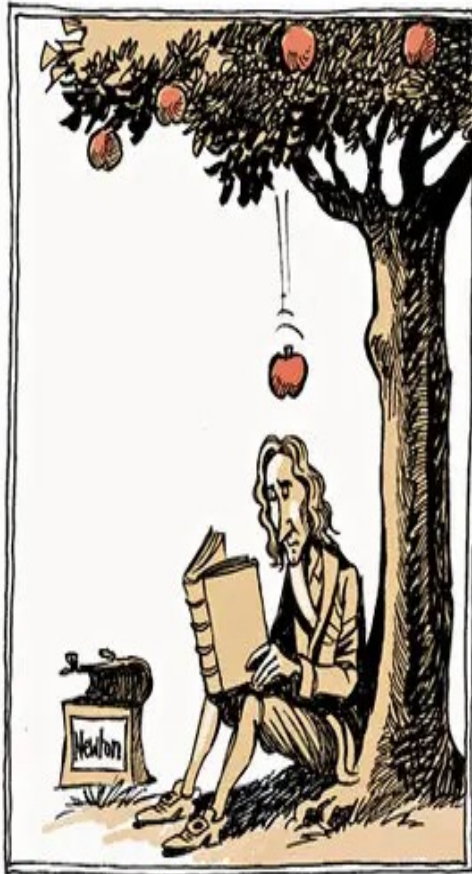
Gauge bosons

γ Photon	g Gluon
$W^\pm$ W boson	Z^0 Z boson



Higgs Discovery

Collisions That Changed The World



The Early Universe

Cosmological Puzzles

1. Dark Energy
2. Dark Matter
3. Matter-Antimatter asymmetry
4. Origin of large-scale structures

Some of the high scale physics

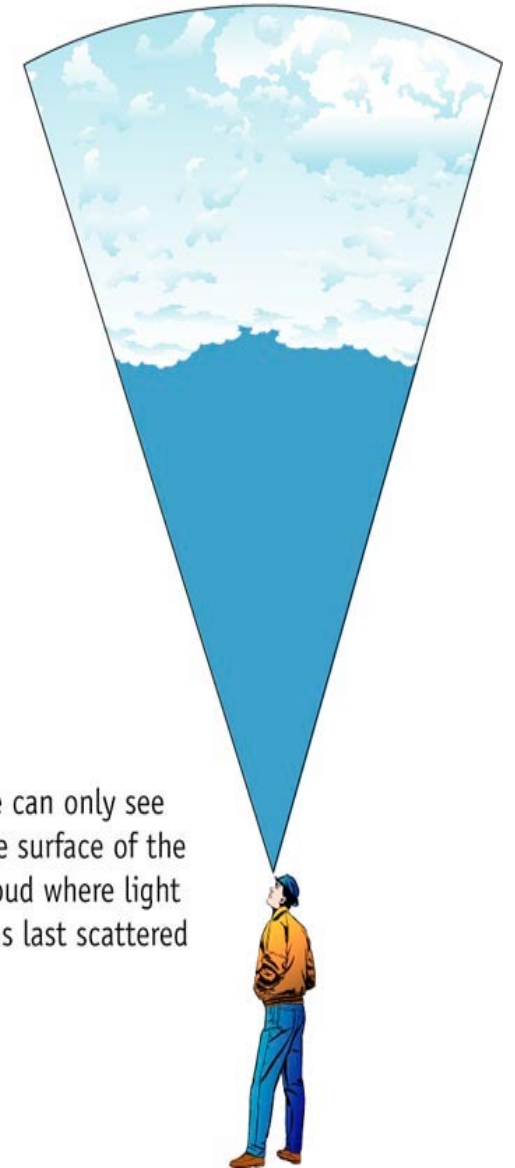
1. Inflation
2. Scale of Quantum Gravity
3. PBH

Cosmological Tools

1. Gravitational Waves
2. Cosmic Microwave Background
3. Neutrinos

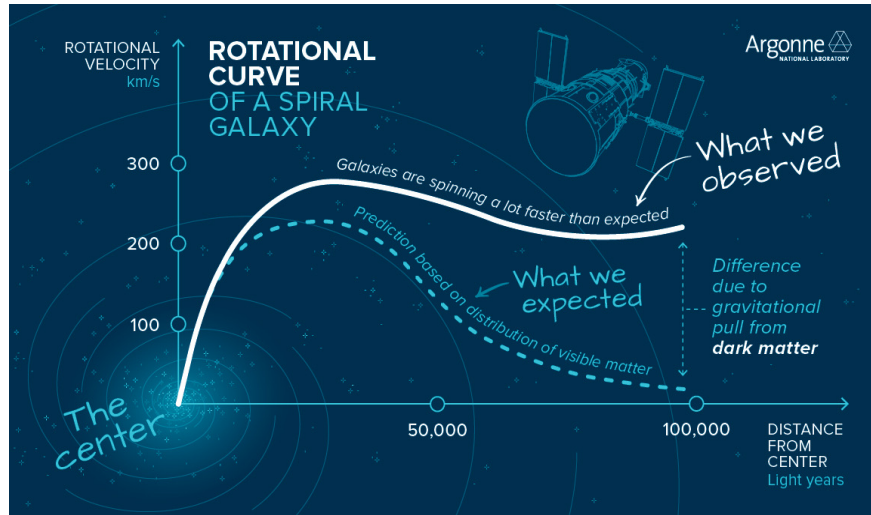


The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



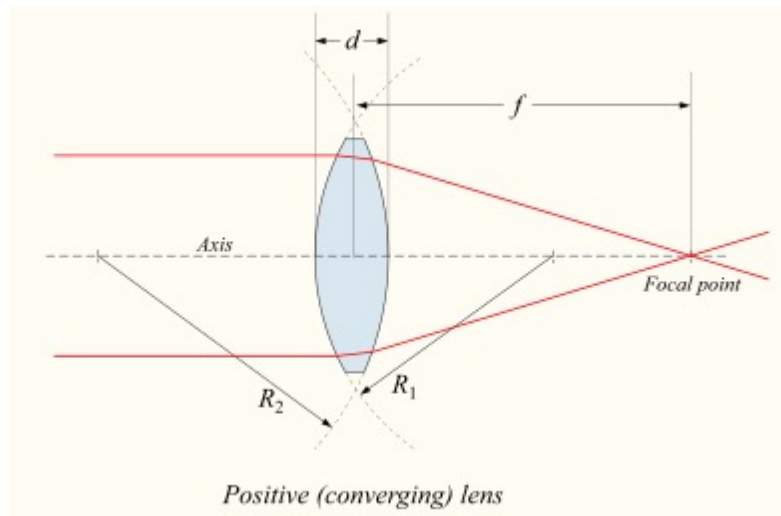
Dark Matter, a cosmic glue

Evidence of DM : Galaxy Rotation Curve



$$v = \sqrt{\frac{GM(r)}{r}}$$

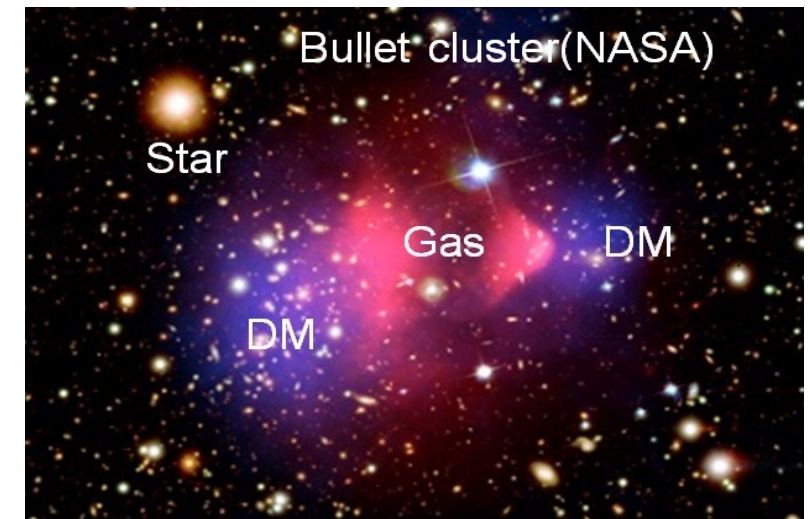
- ❑ Inside the galactic disk: $M(r) \sim \rho r^3$ (assumption: ρ const.)
- ❑ Outside the disk: $v \propto r^{-1/2}$ (expectation!)
- ❑ Observed: v is independent of $r \rightarrow \rho \sim r^{-2}$



Optical Lensing

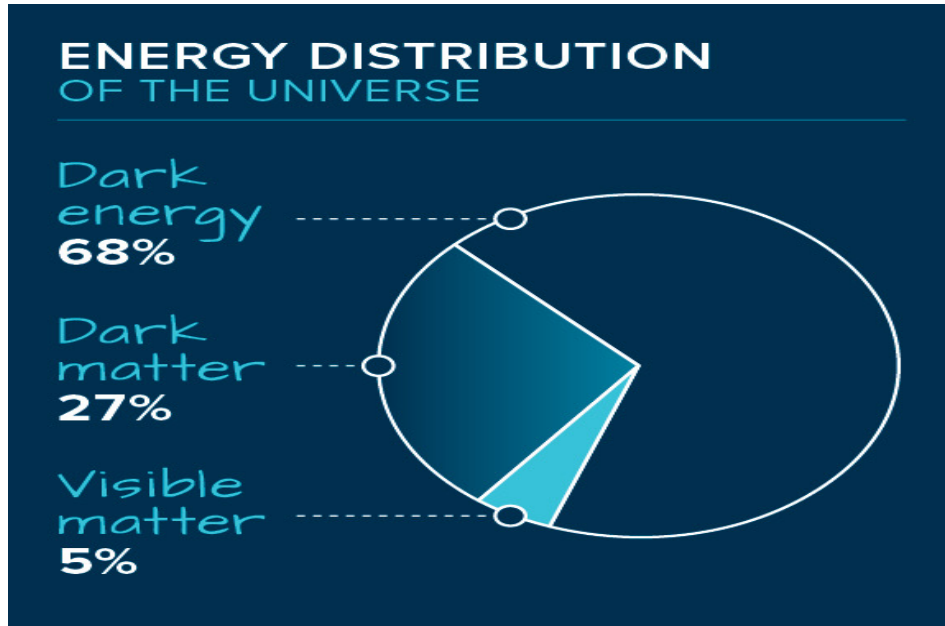


Gravitational Lensing



Evidence of DM II: Bullet Cluster

Dark Matter, a cosmic glue



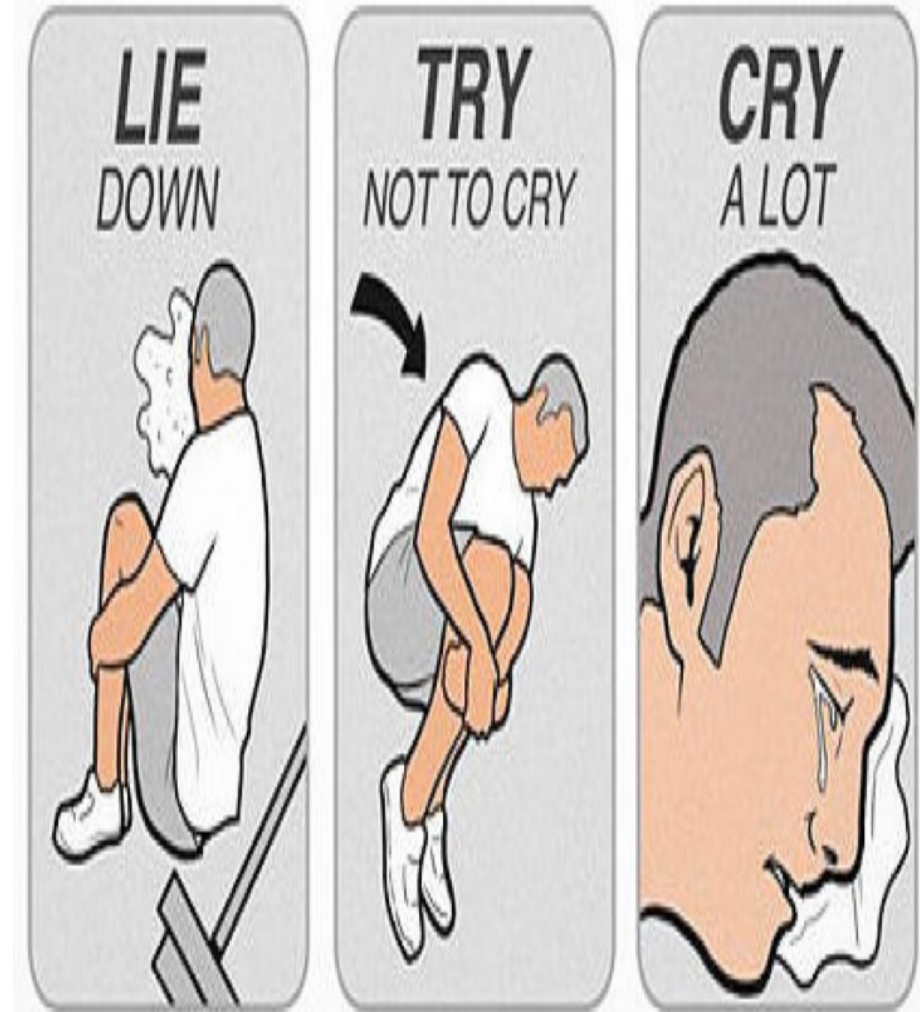
What we know :

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

What we **don't** know :

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

Detecting particle nature of DM:



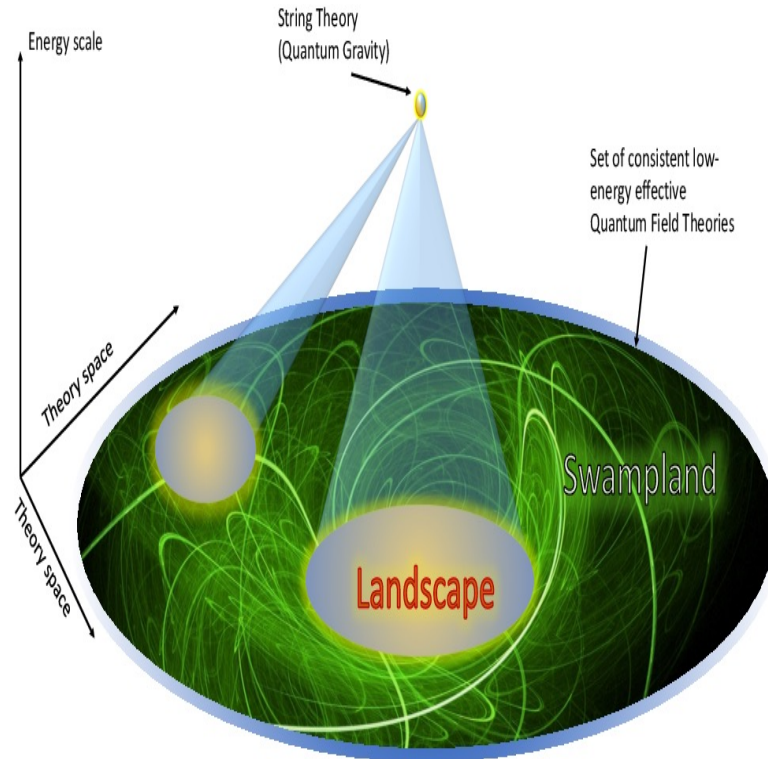
How massive? How to probe?

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

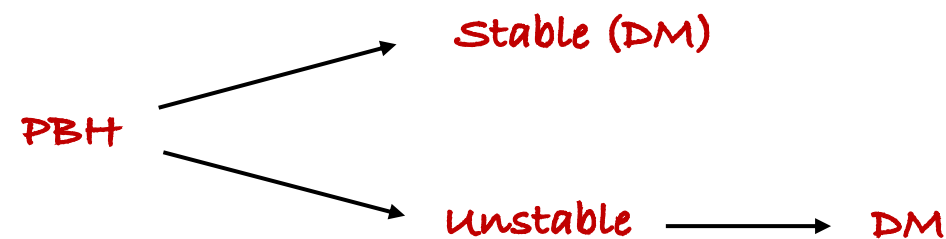
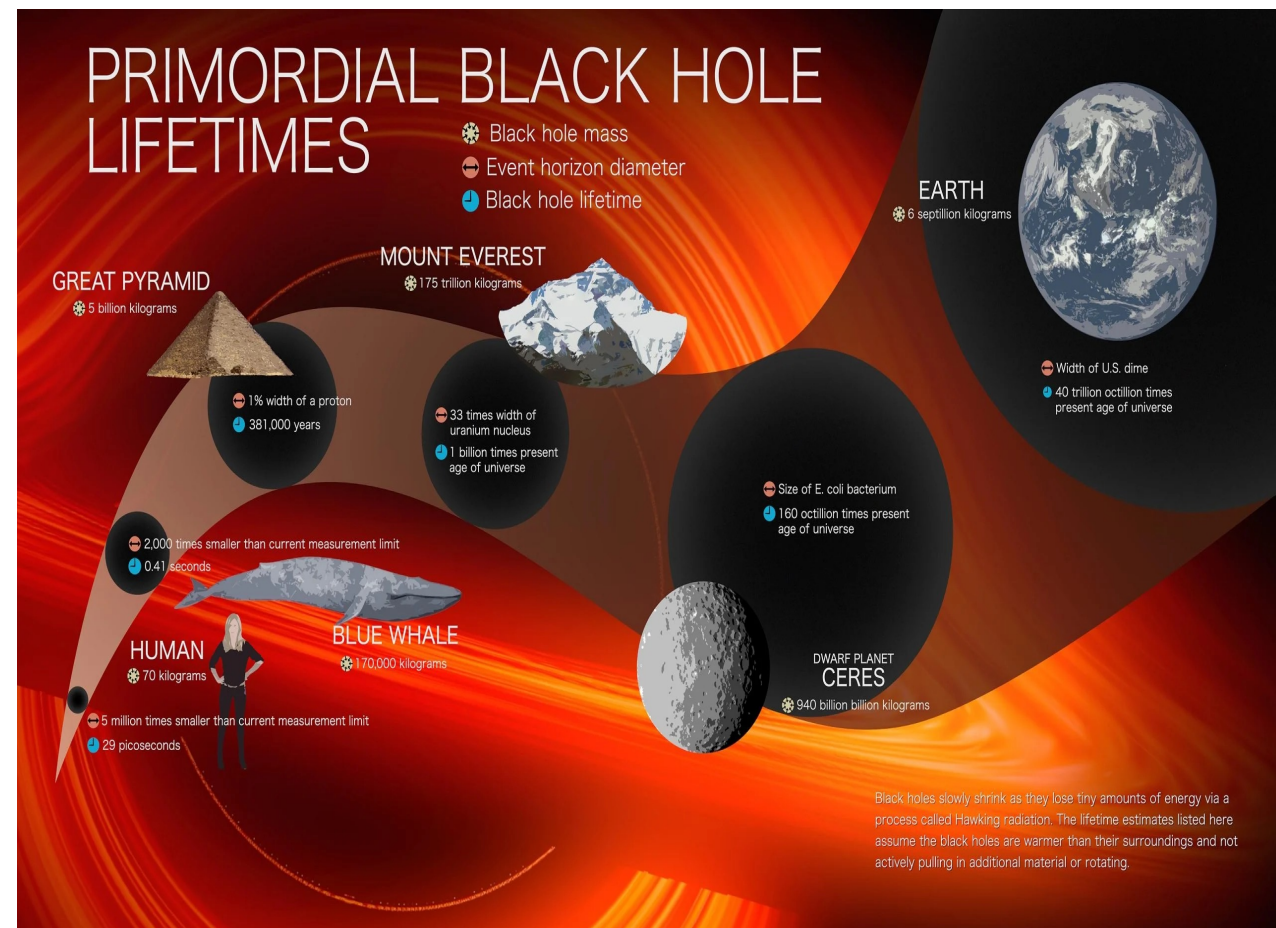
There exists no exact (continuous or discrete) global symmetry in quantum gravity theories.



Global symmetries in low-energy EFTs are broken by QG!

Any observational effects that can constrain Λ_{QG} ?

Primordial Black Holes



Any observational effects of such PBHs?

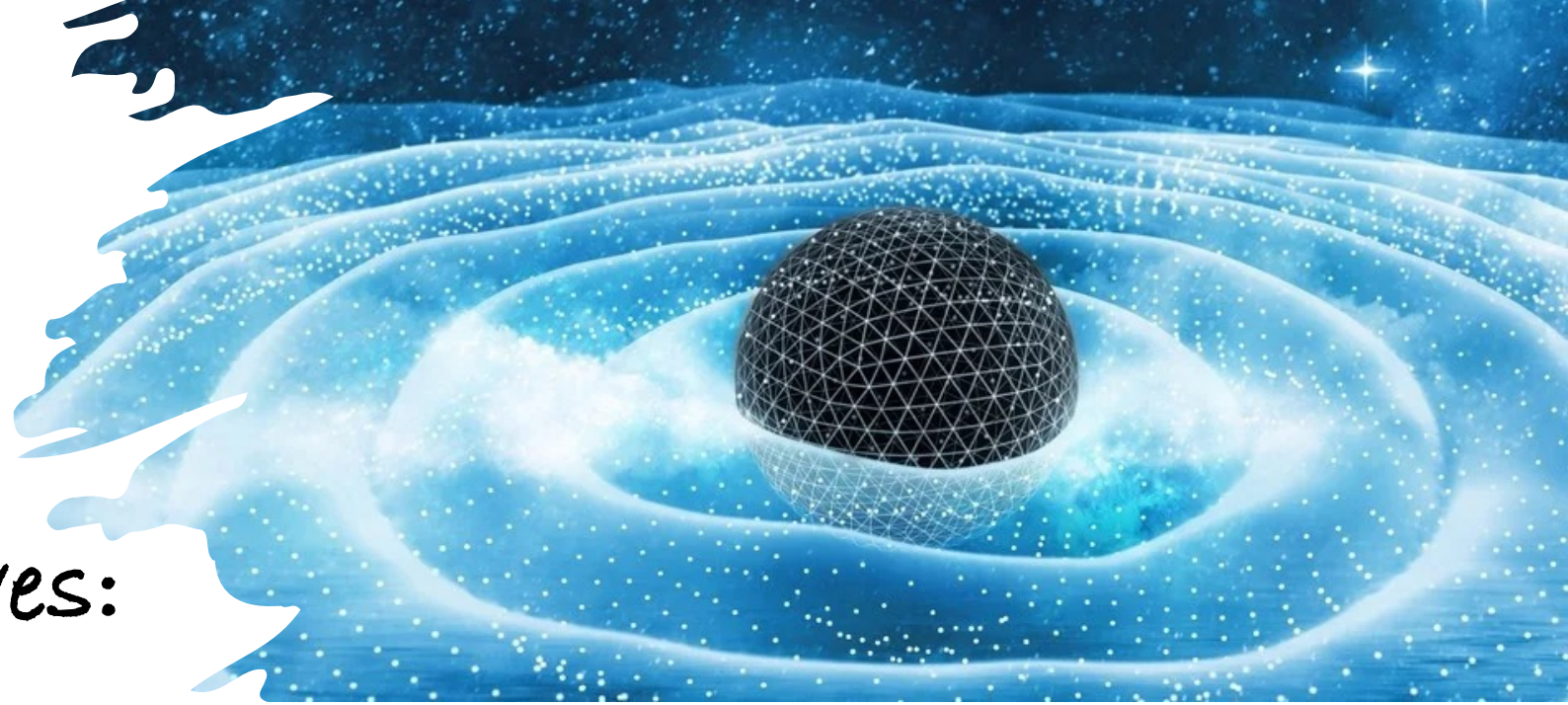
**THE LIGHT AT THE END
OF THE TUNNEL**



**IS JUST THE LIGHT OF AN
ONCOMING**

Gravitational waves:

Ripples in the fabric of spacetime



Gravitational waves: Theory

Einstein's Equation:

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

Space-time determines the trajectories of all object



Massive object curve space-time

Considering a small perturbation around the metric tensor:

$$g_{\mu\nu} = \underbrace{\eta_{\mu\nu}}_{\text{Flat space-time}} + \underbrace{h_{\mu\nu}}_{\text{Small deviation in flat space-time}}, \quad |h_{\mu\nu}| \ll 1$$

Propagation of GW in vacuum :

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

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

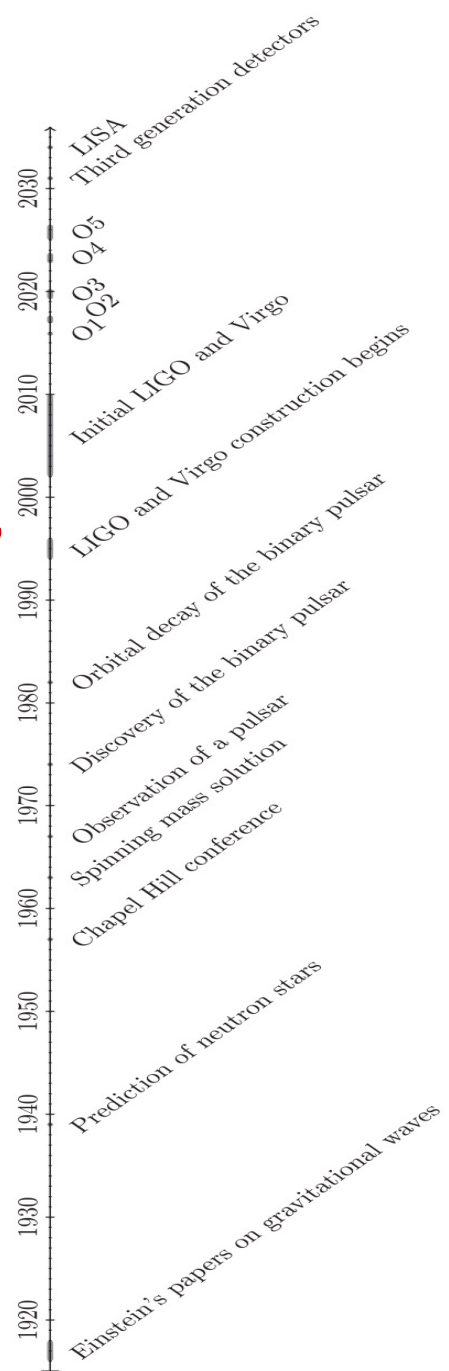
$$h_{ij} \simeq \frac{2G}{r} \ddot{Q}_{ij}(t_{Ret})$$

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

Power Emitted:

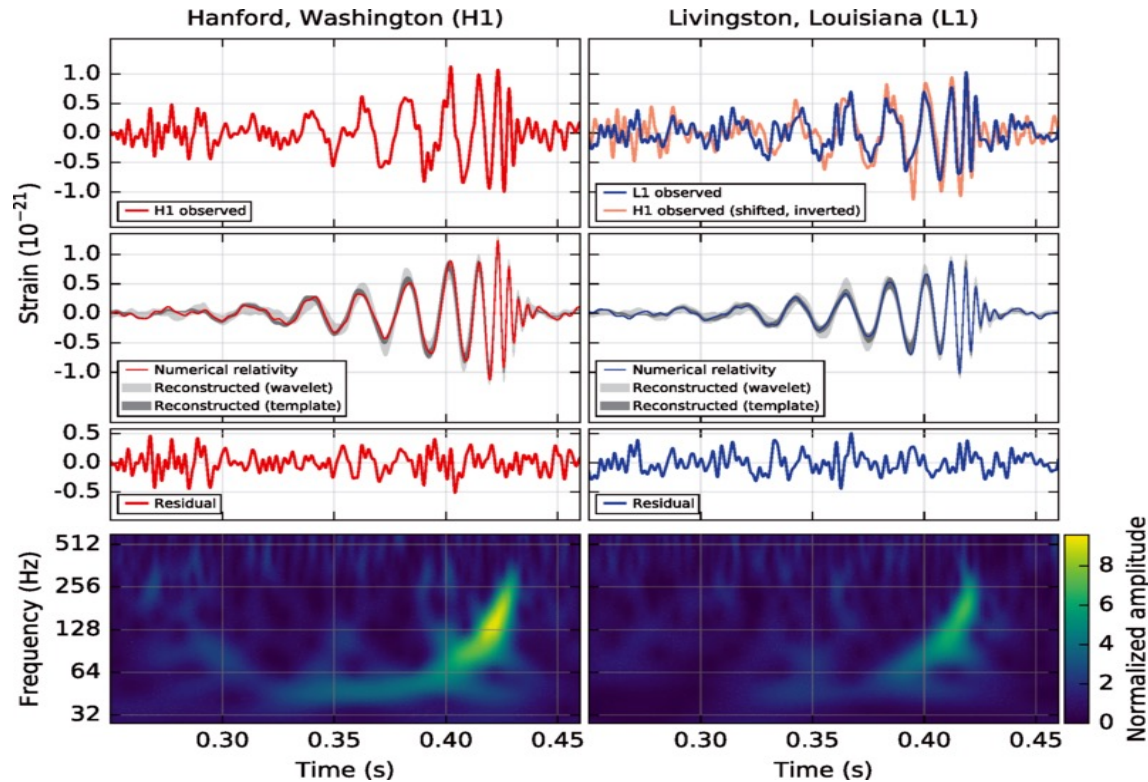
$$P_{GW} \simeq \frac{G}{45} \sum_{i,j} \langle \ddot{Q}_{ij} \ddot{Q}_{ij} \rangle$$

Timeline of significant events in the history of gravitational waves



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

© 2023 The New York Times Company 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.

NANOGrav, 2306.16219

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

GWs: Important Scientific Milestones



The Nobel Prize in Physics 2017



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Elmehed
Rainer Weiss
Prize share: 1/2



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Elmehed
Barry C. Barish
Prize share: 1/4



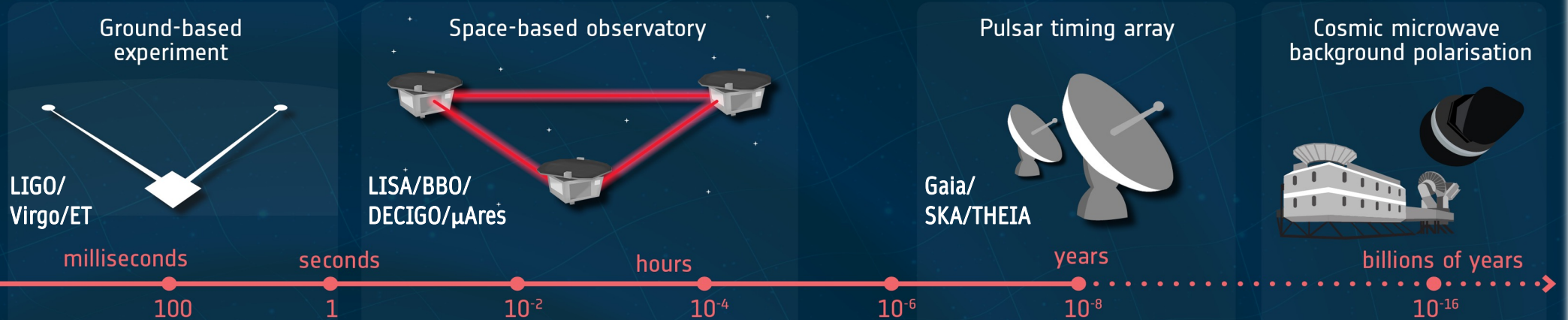
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Elmehed
Kip S. Thorne
Prize share: 1/4

GW Detections

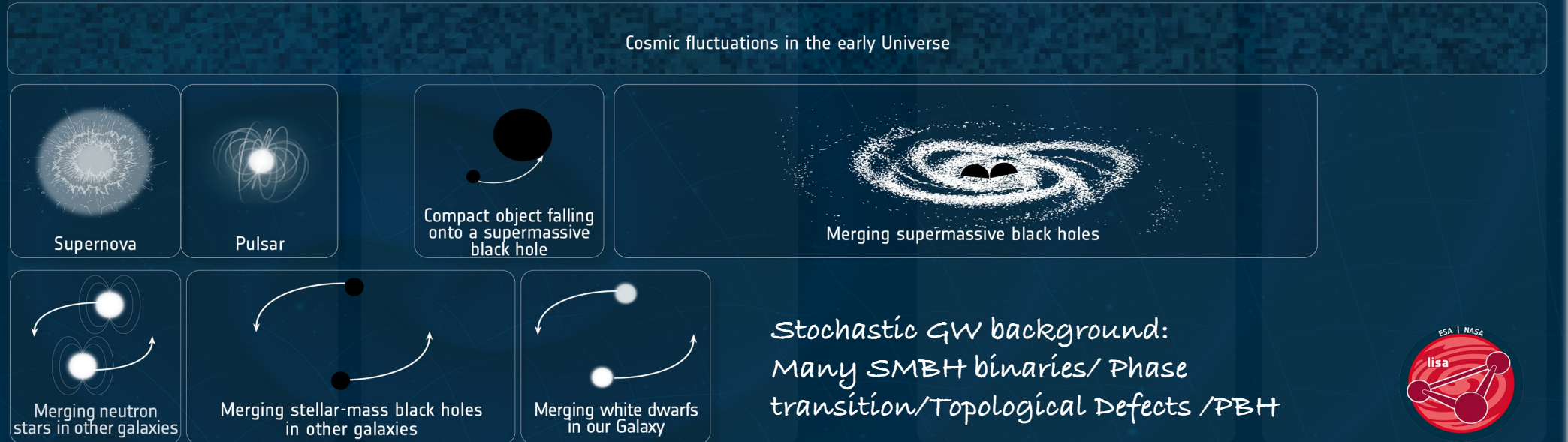
THE SPECTRUM OF GRAVITATIONAL WAVES



Observatories & experiments



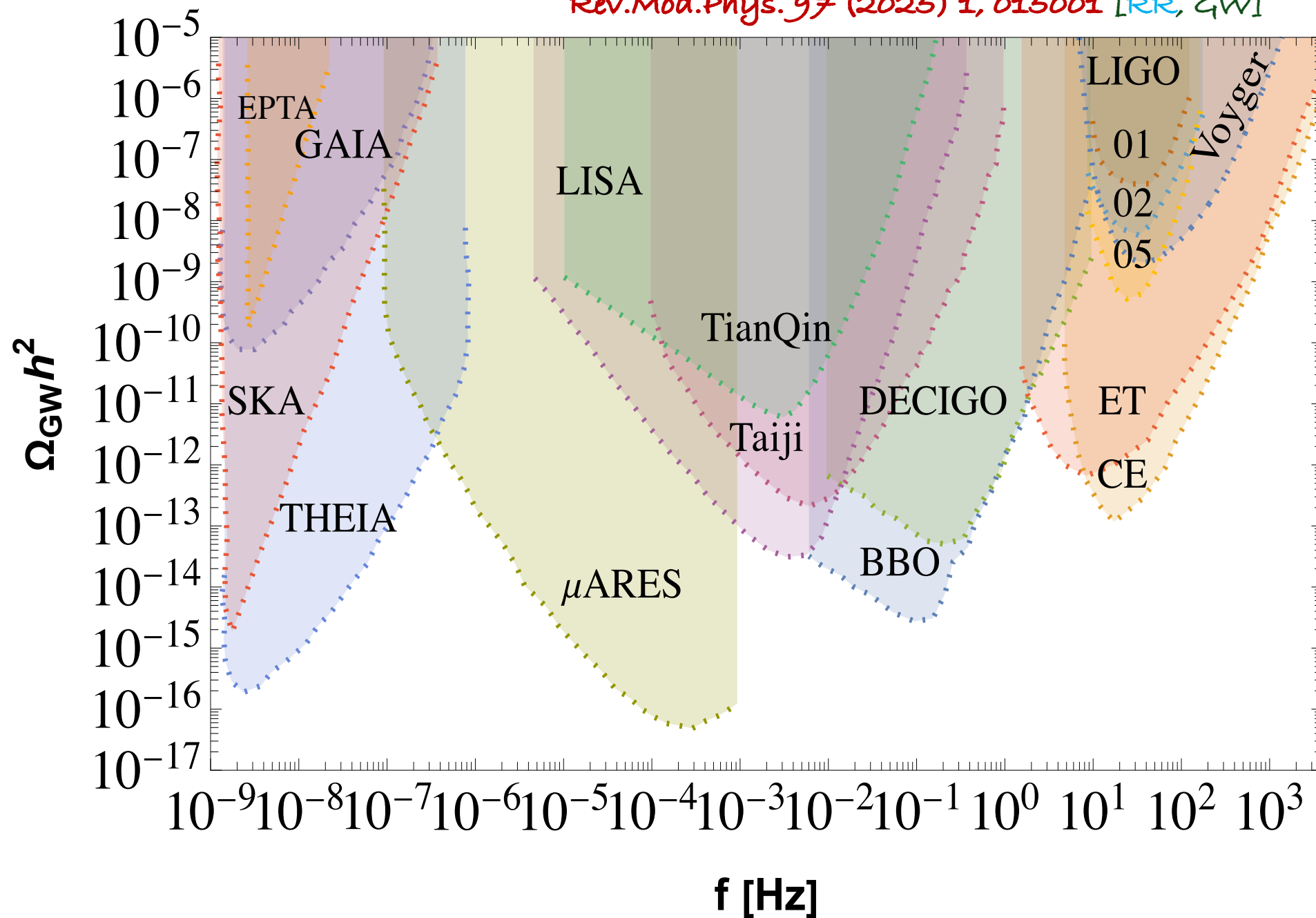
Cosmic sources



#lisa



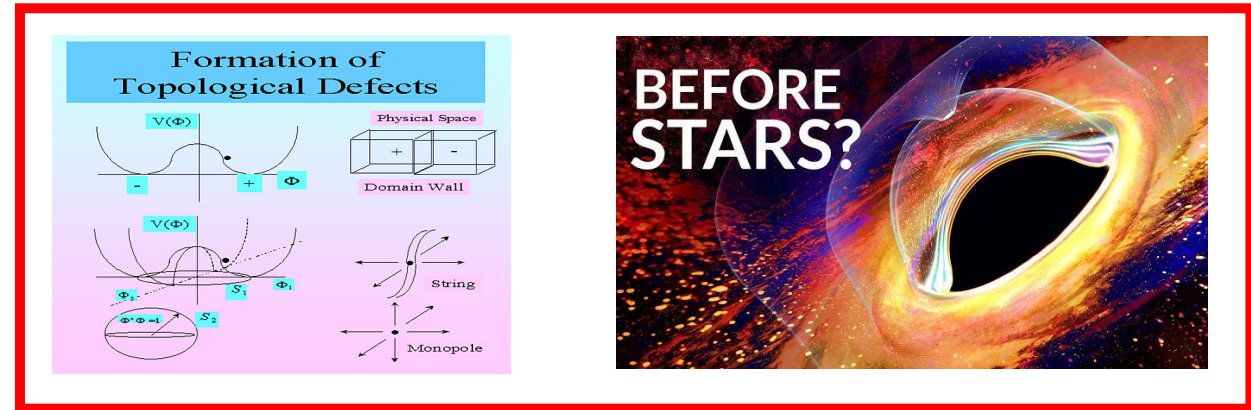
Credit to ESA



Possible sources of GW in the early universe

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

Possible Sources:



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

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

Gravitational waves from Domain Walls

My recent works on GWs from Domain Walls

Observable gravitational waves and ΔN_{eff} with global lepton number symmetry and dark matter

#5

Debasish Borah (Indian Inst. Tech., Guwahati), Nayan Das (Indian Inst. Tech., Guwahati), Rishav Roshan (Southampton U.) (Jun 6, 2024)

Published in: *Phys.Rev.D* 110 (2024) 7, 075042 • e-Print: [2406.04404](#) [hep-ph]

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 reference search  3 citations

Using gravitational waves to see the first second of the Universe

#7

Rishav Roshan (Southampton U.), Graham White (Southampton U.) (Jan 9, 2024)

Published in: *Rev.Mod.Phys.* 97 (2025) 1, 015001 • e-Print: [2401.04388](#) [hep-ph]

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 reference search  49 citations

Leptogenesis, dark matter and gravitational waves from discrete symmetry breaking

#8

Subhaditya Bhattacharya (Indian Inst. Tech., Guwahati), Niloy Mondal (Indian Inst. Tech., Guwahati), Rishav Roshan (Southampton U.), Drona Vatsyayan (Valencia U. and Valencia U., IFIC) (Dec 22, 2023)

Published in: *JCAP* 06 (2024) 029 • e-Print: [2312.15053](#) [hep-ph]

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 reference search  8 citations

Quantum gravity effects on fermionic dark matter and gravitational waves

#10

Stephen F. King (Southampton U.), Rishav Roshan (Southampton U.), Xin Wang (Southampton U.), Graham White (Southampton U.), Masahito Yamazaki (Tokyo U., IPMU and Nihon U., IQS) (Nov 21, 2023)

Published in: *JCAP* 05 (2024) 071 • e-Print: [2311.12487](#) [hep-ph]

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 reference search  7 citations

Quantum gravity effects on dark matter and gravitational waves

#11

Stephen F. King (Southampton U.), Rishav Roshan (Southampton U.), Xin Wang (Southampton U.), Graham White (Southampton U.), Masahito Yamazaki (Tokyo U., IPMU and Nihon U., IQS) (Aug 7, 2023)

Published in: *Phys.Rev.D* 109 (2024) 2, 024057 • e-Print: [2308.03724](#) [hep-ph]

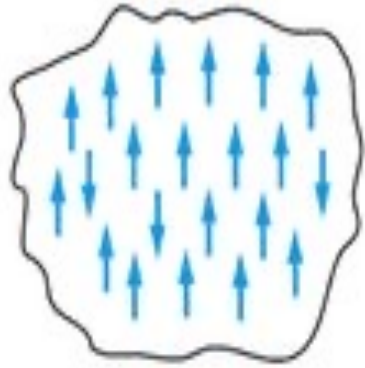
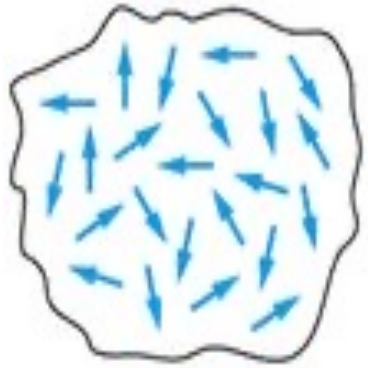
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 reference search  23 citations

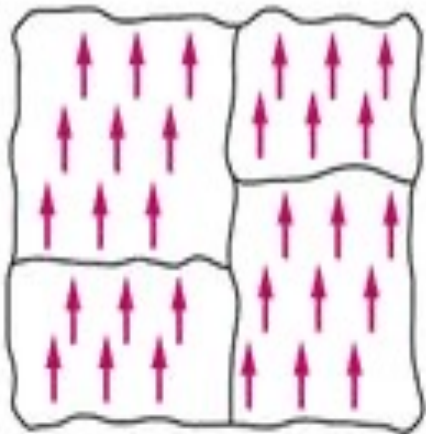
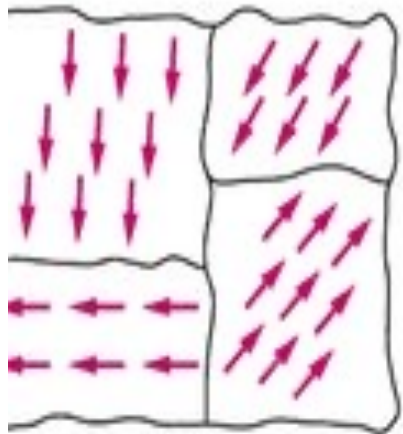
Domain Walls: Para and Ferromagnetism

Magnetic field absent

In presence of magnetic field

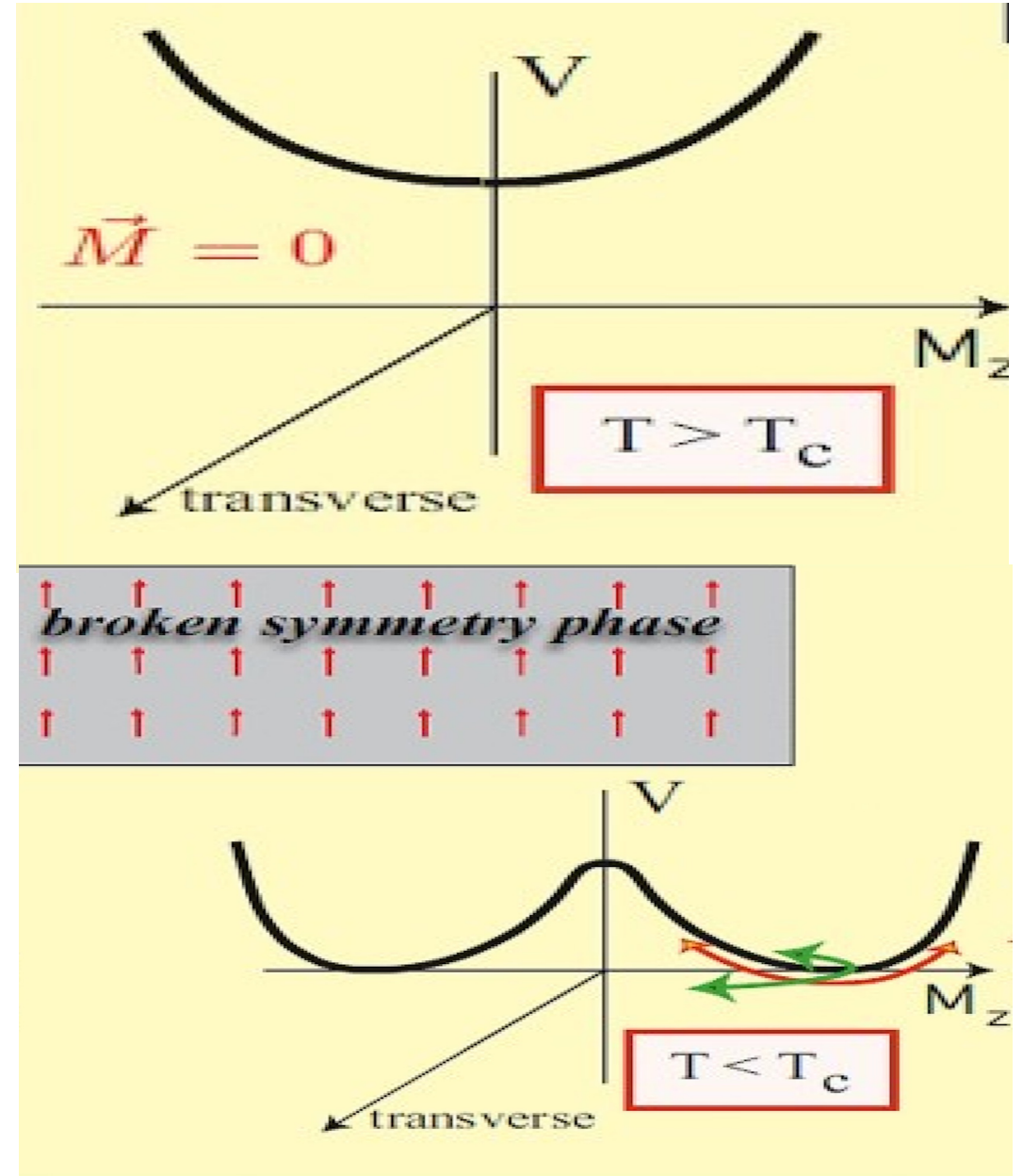


Paramagnetism



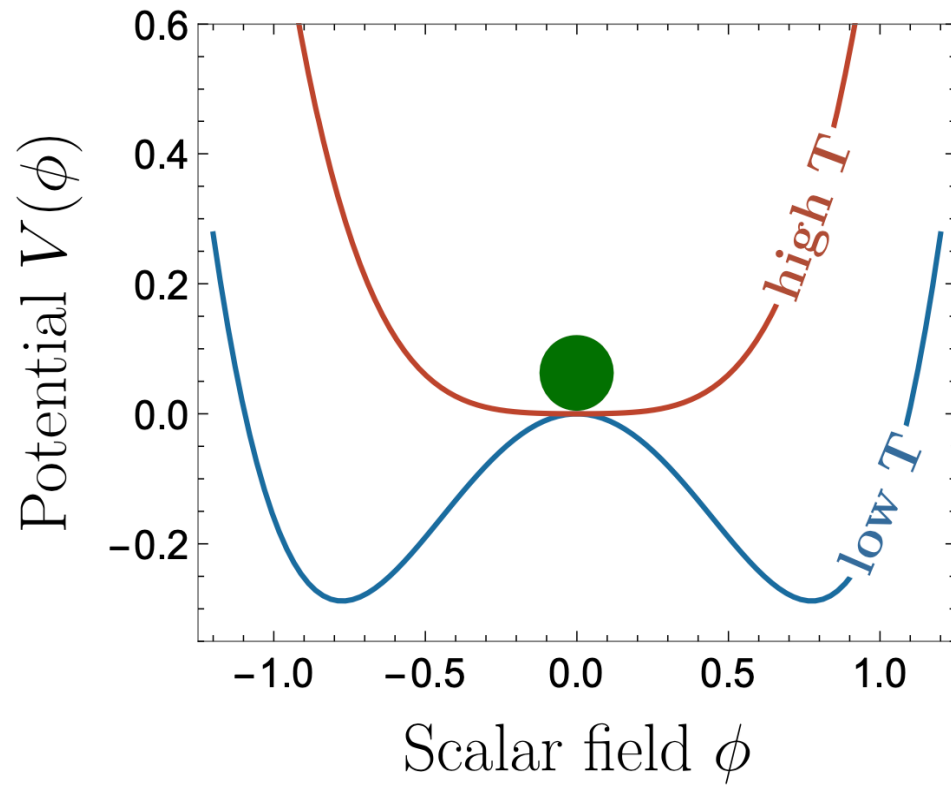
Ferromagnetism

Temperature

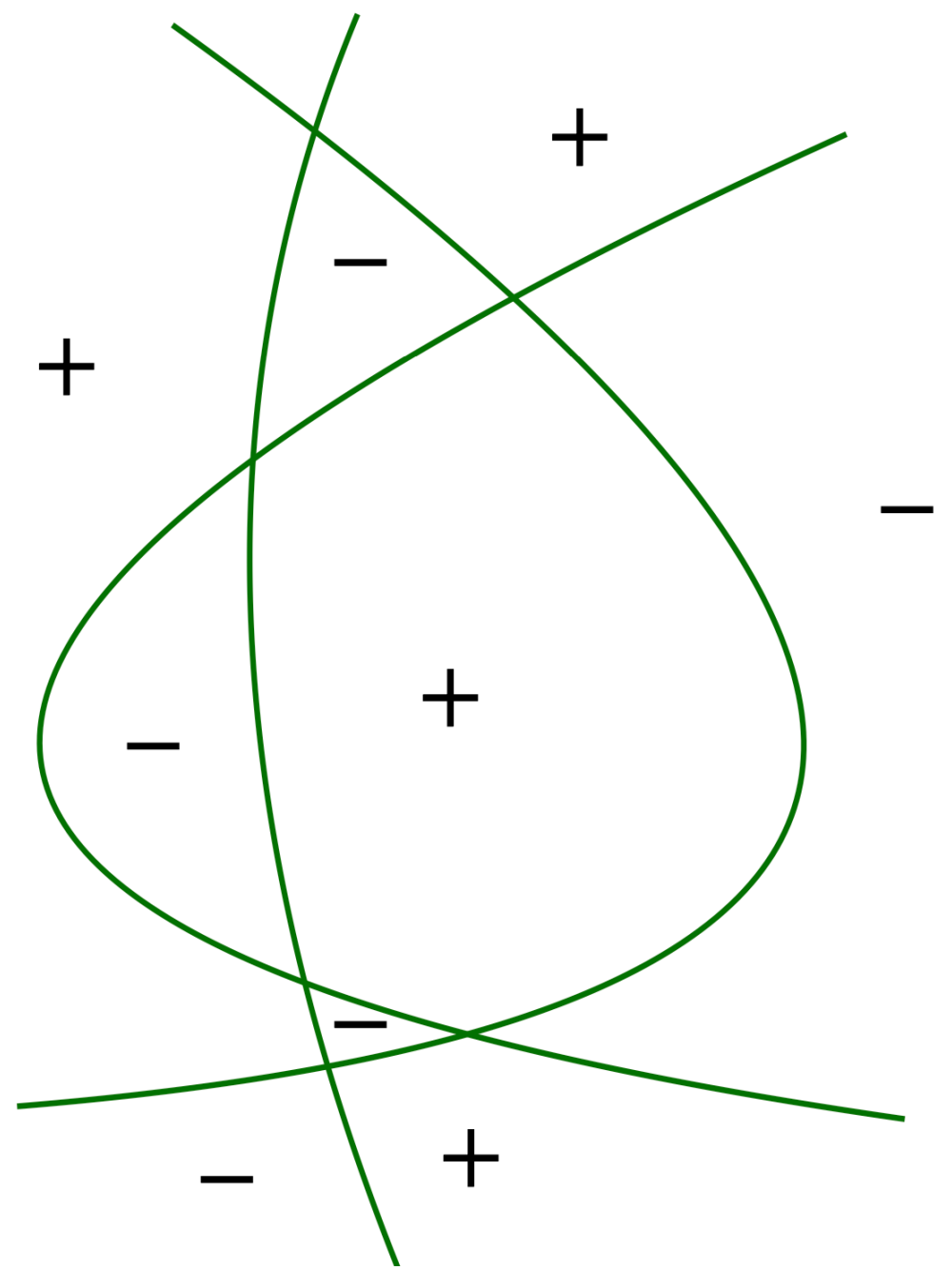


Domain Wall Formation

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

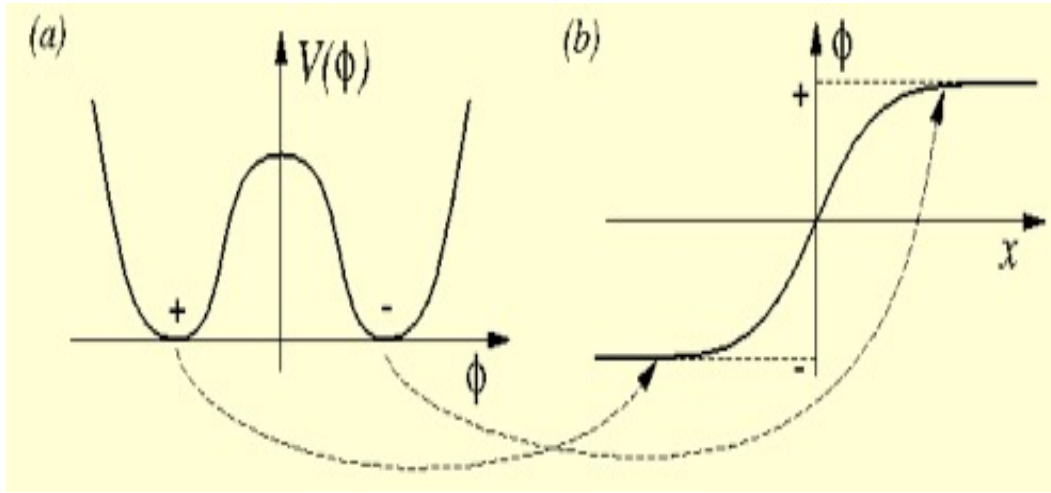


Spontaneous breaking of $\mathbb{Z}_2$



Domain Wall: Fact-Sheet

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



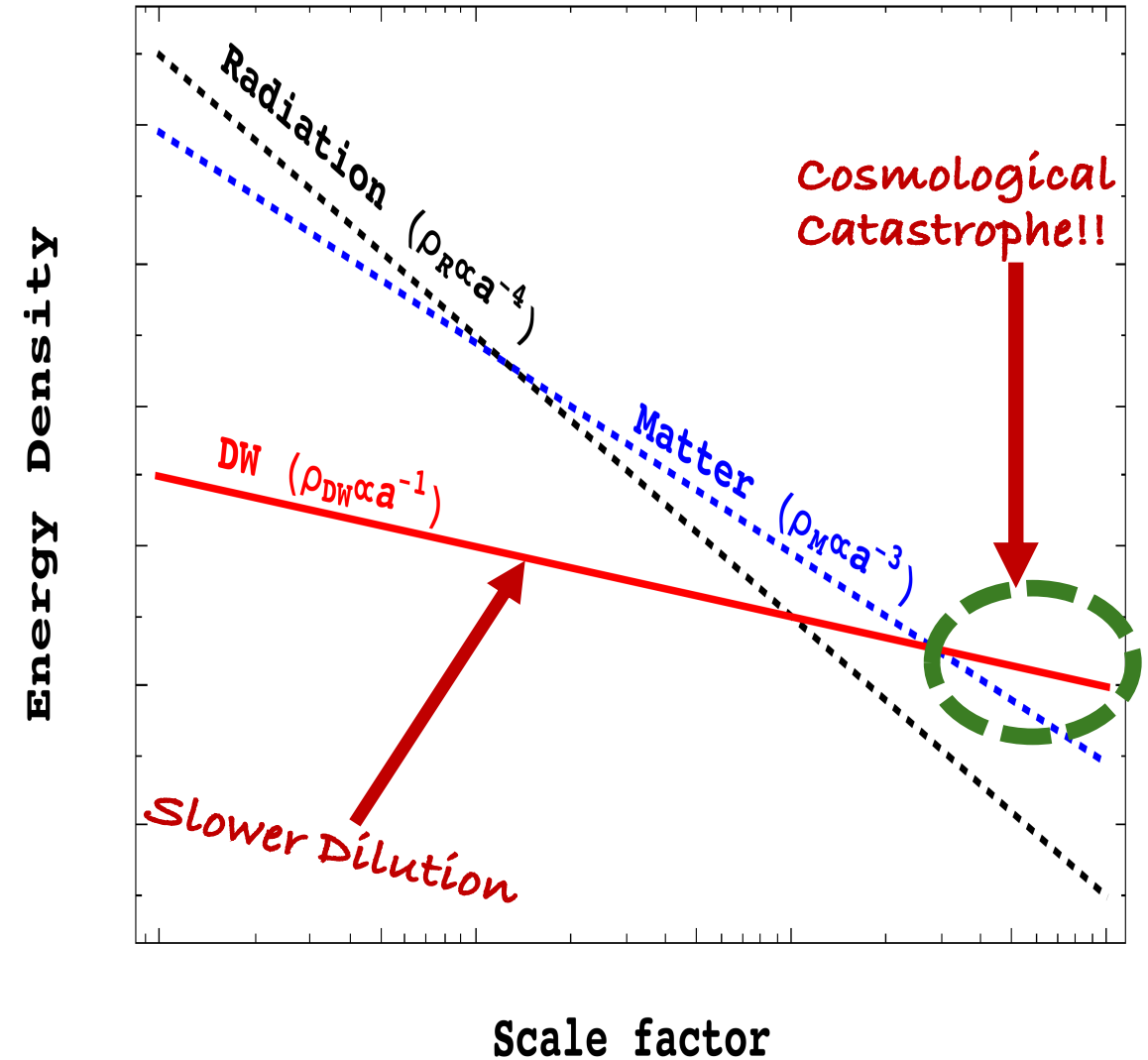
Surface Tension

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

Energy Density: $\rho_{\text{DW}} \propto a^{-1}$

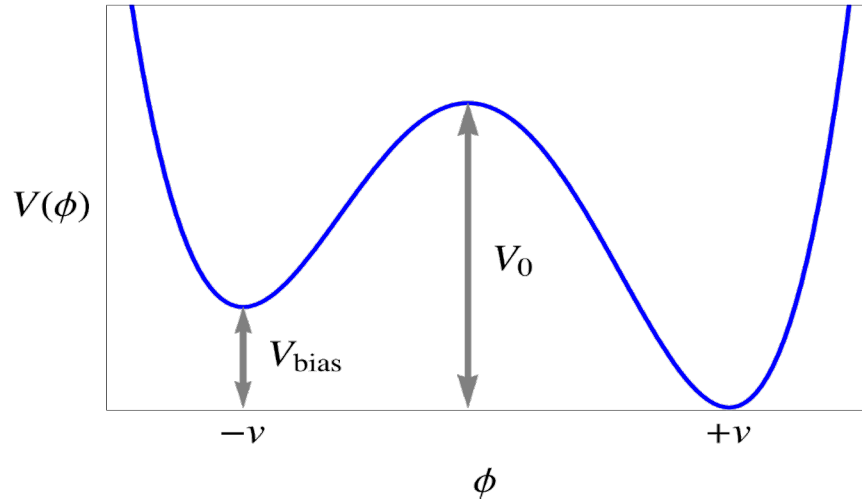
$$\rho_{\text{DW}} \propto t^{-1} \text{ (Scaling Regime)}$$

(Dilutes much slower than radiation and matter)



Possible Solutions

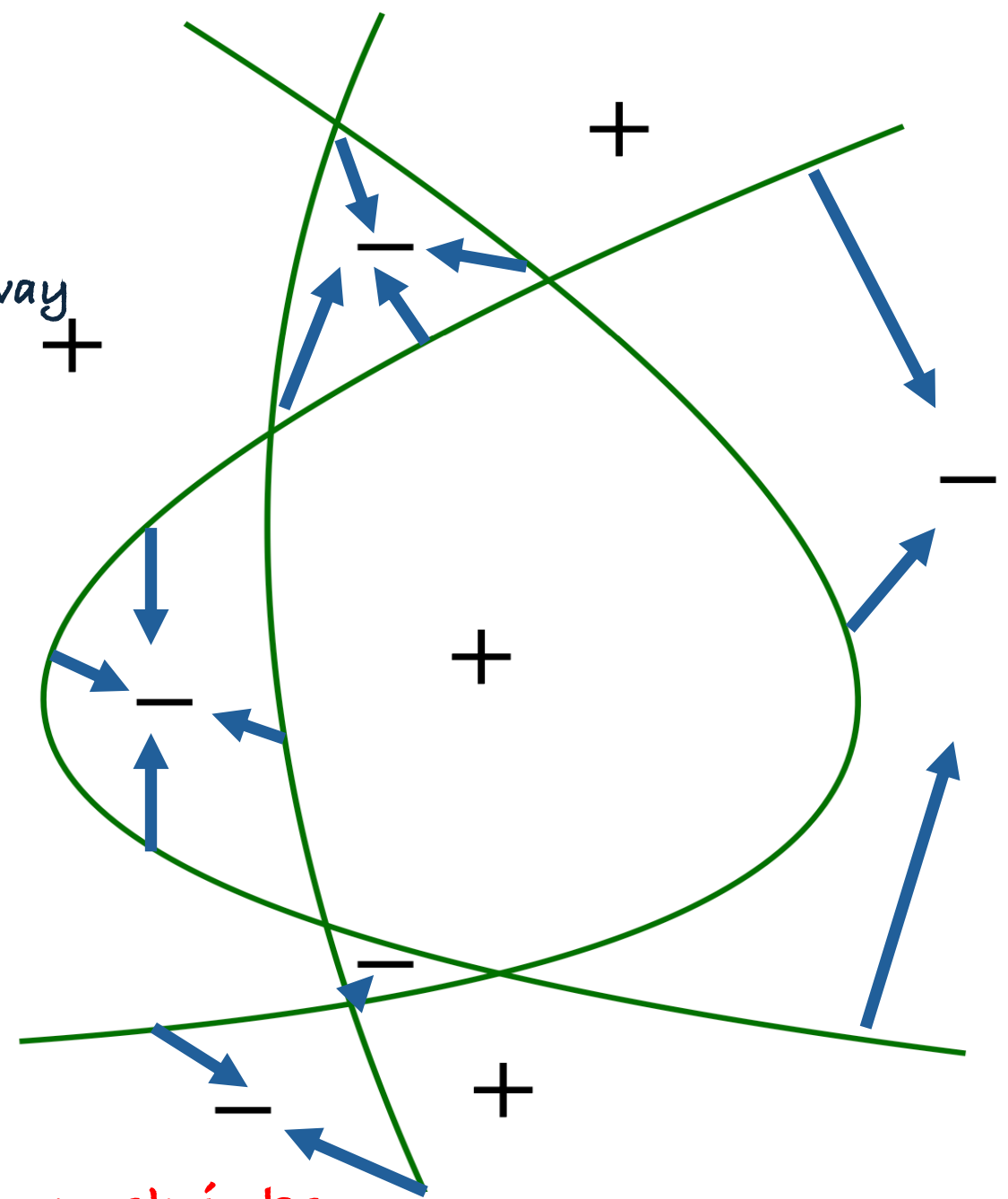
1. If formed before inflation, they can be inflated away
2. Symmetry restoration at some temperature
3. Metastable Domain Walls



Saikawa, Universe 3, 40 (2017)

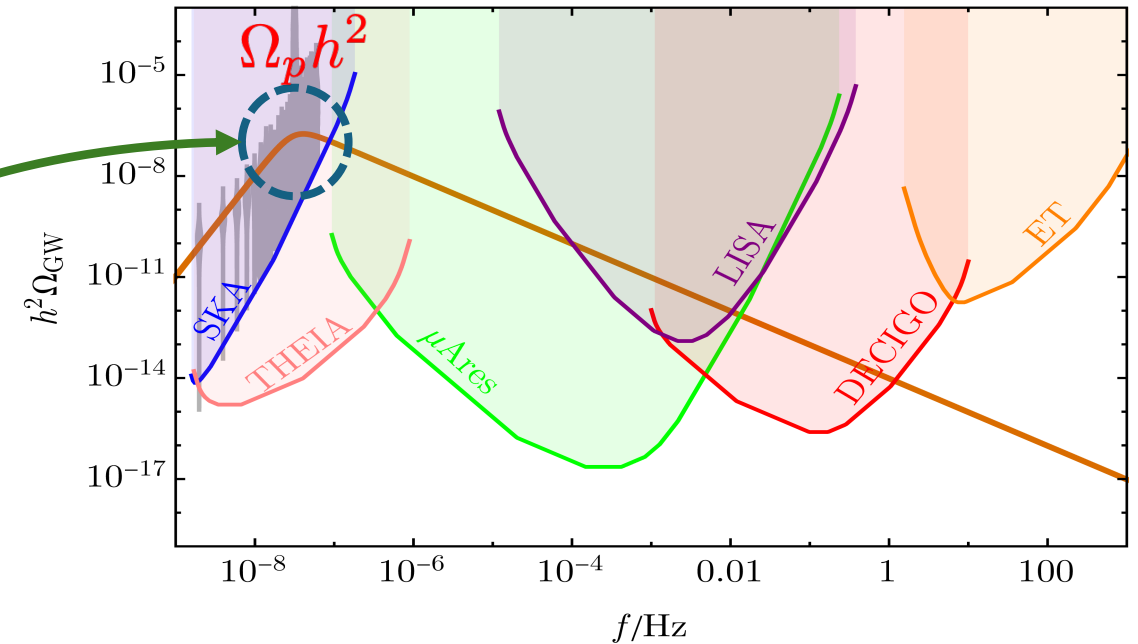
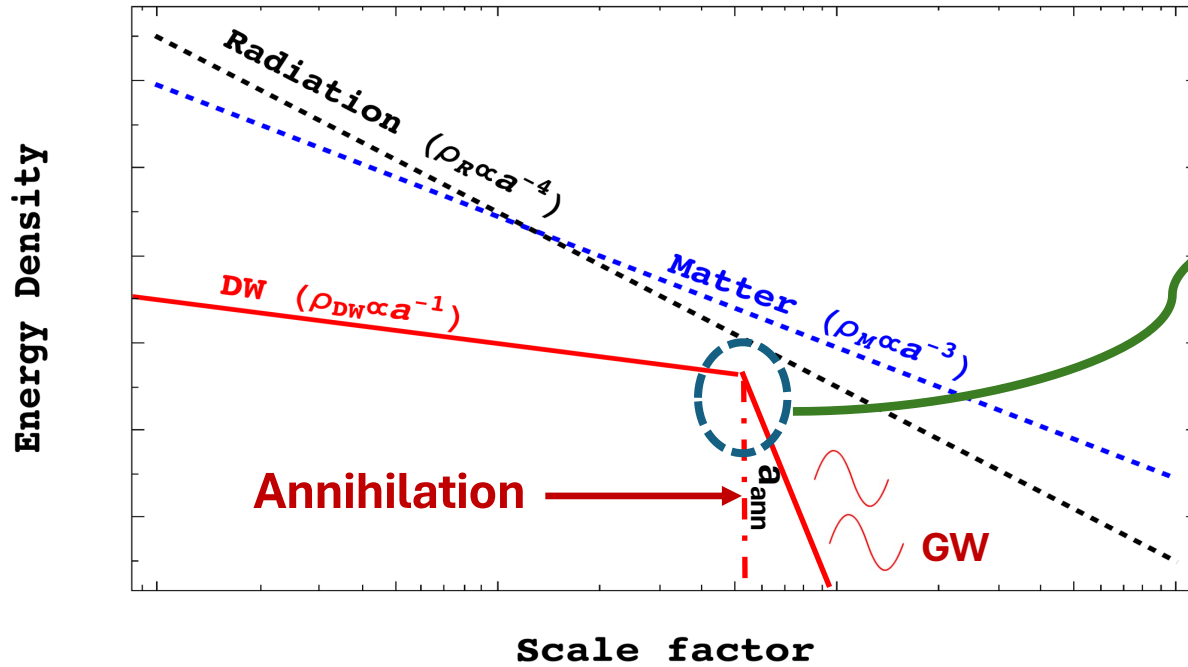
$$p_V \sim V_{\text{bias}}, \quad p_T \sim \sigma \frac{\mathcal{A}}{t}$$

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



Gravitational waves from Domain Walls

JCAP 05 (2024) 071 [SFK,RR,XW,GW,MY]



$$P_{\text{GW}} \simeq \frac{G}{45} \sum_{i,j} \langle \ddot{Q}_{ij} \ddot{Q}_{ij} \rangle \sim \sigma^2 \mathcal{A}^2 t^2$$

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

Broken power law

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

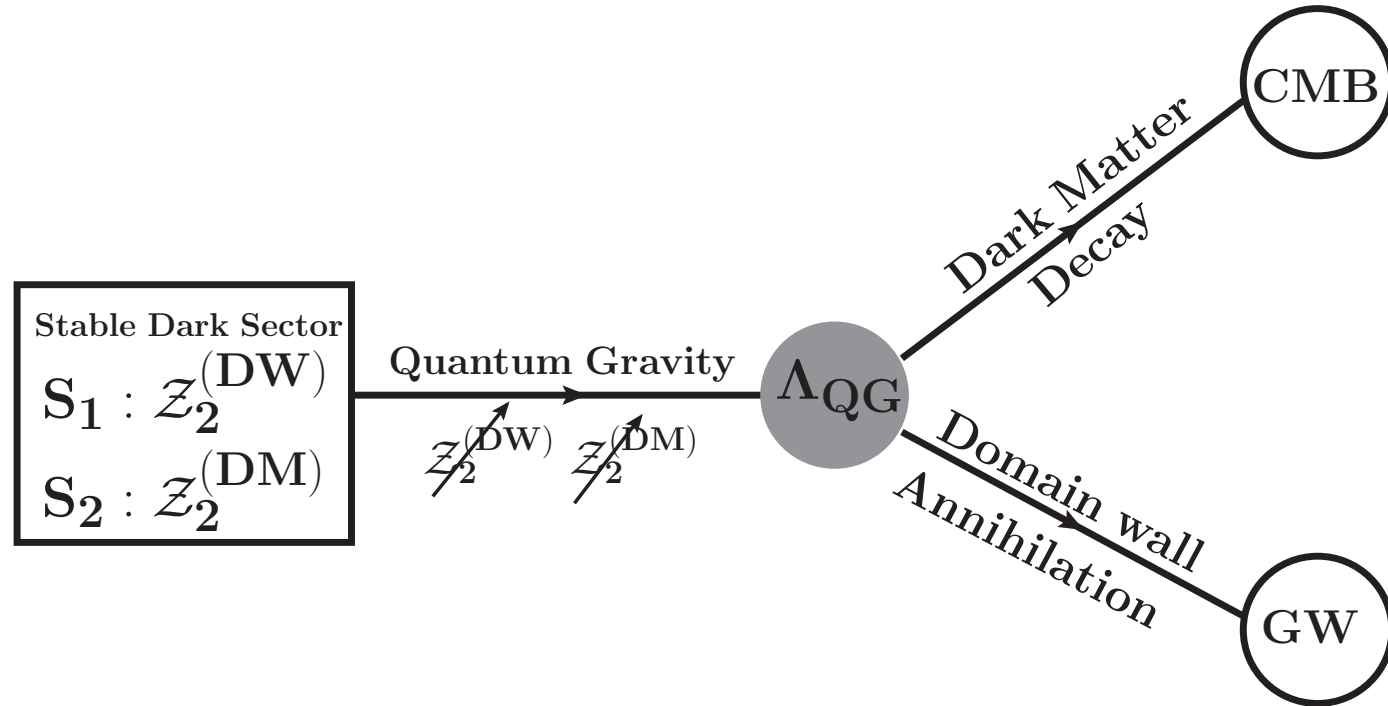
$$\Omega_{\text{GW}} h^2 \propto f^{-1} \text{ for } f > f_p$$

The peak amplitude and frequency appear when $t \sim t_{\text{ann}}$

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

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

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
 $\mathcal{O}_5/\Lambda_{\text{QG}}$ is suppressed by e^{-S}

Effective quantum gravity scale

$$\Lambda_{\text{QG}} \sim M_{\text{Pl}} e^S \gg M_{\text{Pl}}$$

Generally, a global symmetry-breaking scale can be much higher than the Planck scale.

❖ U(1) Peccei-Quinn symmetry breaking: $S \gtrsim 190 \longrightarrow \Lambda_{\text{QG}} \sim 10^{100} \text{ GeV}$ **Extremely large!**

❖ Discrete Z_2 symmetry we are considering: $S \sim \mathcal{O}(M_{\text{Pl}}^2/\Lambda_{\text{UV}}^2) \longrightarrow S \sim \mathcal{O}(10)$

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

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

The setup

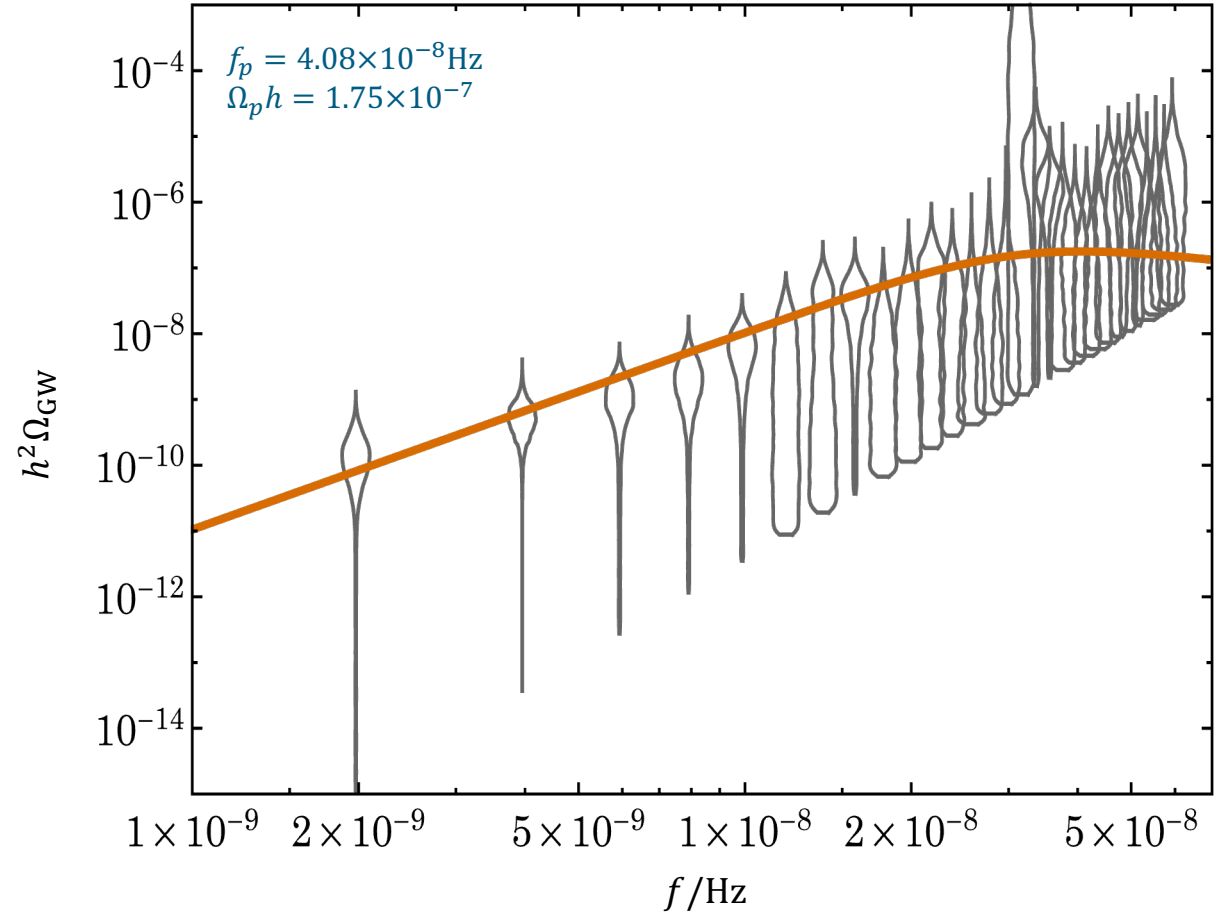
The renormalizable potential (Z_2 -conserving)

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

Dimension-five potential (Z_2 -breaking)

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

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

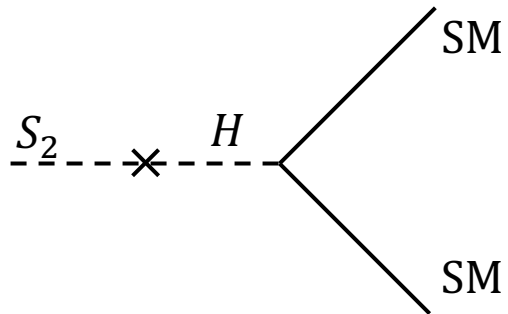


PRD 109 (2024) 2, 024057 [SFK,RR,XW,GW,MY]

DM Decay:

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

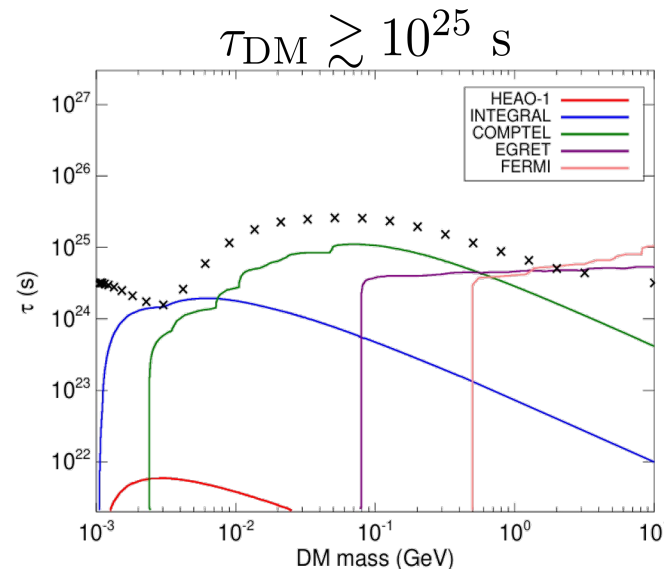
$$\Gamma_{\text{DM}} = \frac{1}{16\pi} \frac{\sin^2 \theta}{m_{\text{DM}}} |M|_{h \rightarrow \text{SMSM}}^2$$



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

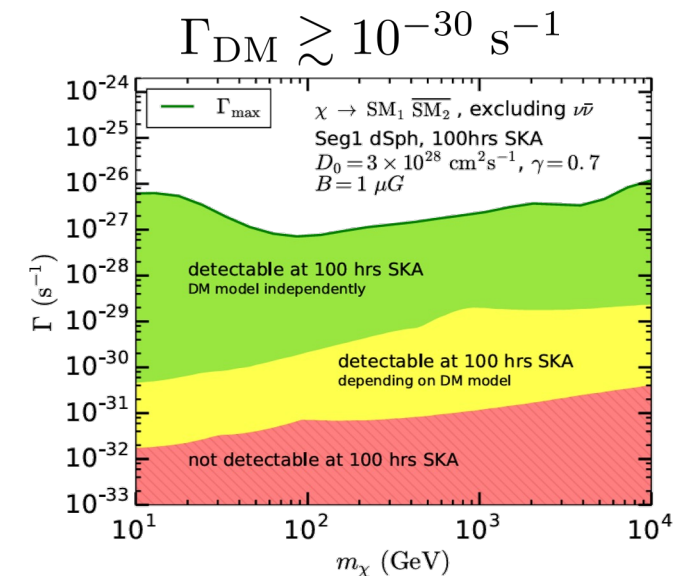
Indirect detection of dark matter

CMB power spectrum

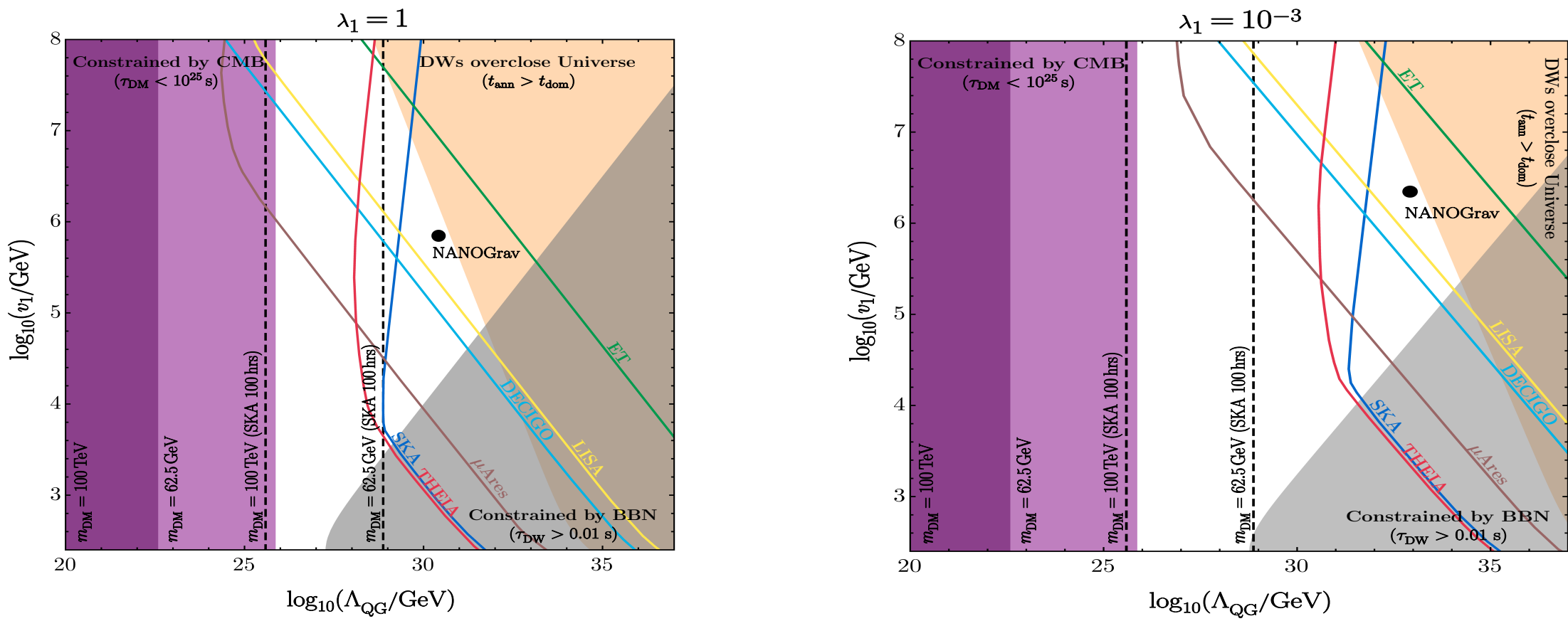


Slatyer & Wu, PRD 95, 2, 023010 (2017)

SKA radio telescope



GW from DW: Testing the scale of Quantum Gravity



My recent works on GW from Cosmic Strings

Using gravitational waves to see the first second of the Universe

#7

Rishav Roshan (Southampton U.), Graham White (Southampton U.) (Jan 9, 2024)

Published in: *Rev.Mod.Phys.* 97 (2025) 1, 015001 • e-Print: [2401.04388](#) [hep-ph]

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 reference search  49 citations

Imprint of PBH domination on gravitational waves generated by cosmic strings

#13

Debasish Borah (Indian Inst. Tech., Guwahati), Suruj Jyoti Das (Indian Inst. Tech., Guwahati), Rishav Roshan (Kyungpook Natl. U. and Chonnam Natl. U.), Rome Samanta (Prague, Inst. Phys.) (Apr 24, 2023)

Published in: *Phys.Rev.D* 108 (2023) 2, 023531 • e-Print: [2304.11844](#) [hep-ph]

 pdf  DOI  cite  claim

 reference search  13 citations

Gravitational wave signatures of a PBH-generated baryon-dark matter coincidence

#15

Basabendu Barman (Warsaw U.), Debasish Borah (Indian Inst. Tech., Guwahati), Suruj Jyoti Das (Indian Inst. Tech., Guwahati), Rishav Roshan (Kyungpook Natl. U.) (Nov 30, 2022)

Published in: *Phys.Rev.D* 107 (2023) 9, 095002 • e-Print: [2212.00052](#) [hep-ph]

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 reference search  31 citations

A predictive SO(10) model

#16

George Lazarides (Aristotle U., Thessaloniki), Rinku Maji (Ahmedabad, Phys. Res. Lab), Rishav Roshan (Kyungpook Natl. U.), Qaisar Shafi (Delaware U., Bartol Inst.) (Oct 7, 2022)

Published in: *JCAP* 12 (2022) 009 • e-Print: [2210.03710](#) [hep-ph]

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 reference search  18 citations

Probing high scale seesaw and PBH generated dark matter via gravitational waves with multiple tilts

#17

Debasish Borah (Indian Inst. Tech., Guwahati), Suruj Jyoti Das (Indian Inst. Tech., Guwahati), Rishav Roshan (Kyungpook Natl. U.) (Aug 9, 2022)

Published in: *Nucl.Phys.B* 1002 (2024) 116528 • e-Print: [2208.04965](#) [hep-ph]

 pdf  DOI  cite  claim

 reference search  17 citations

Heavier W boson, dark matter, and gravitational waves from strings in an SO(10) axion model

#21

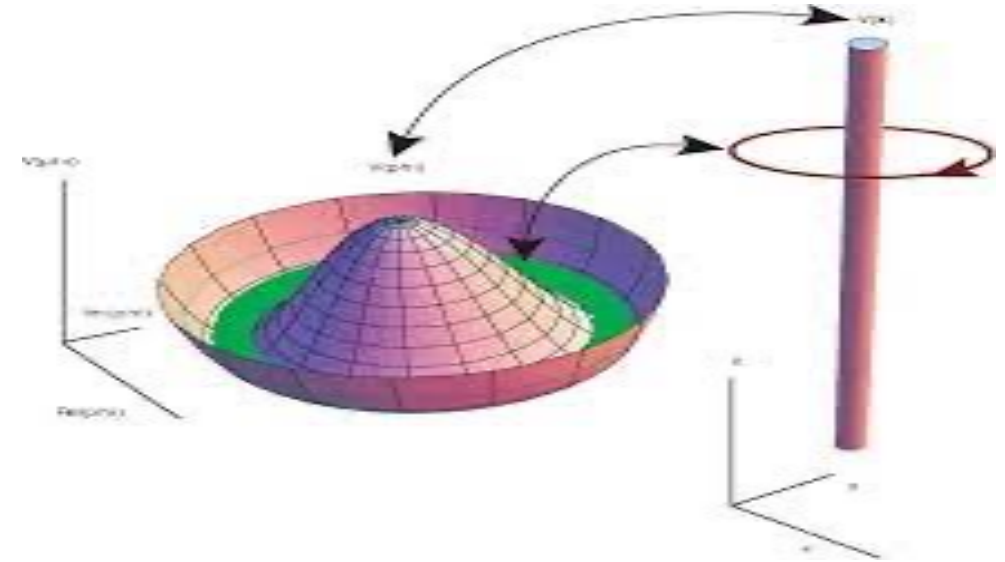
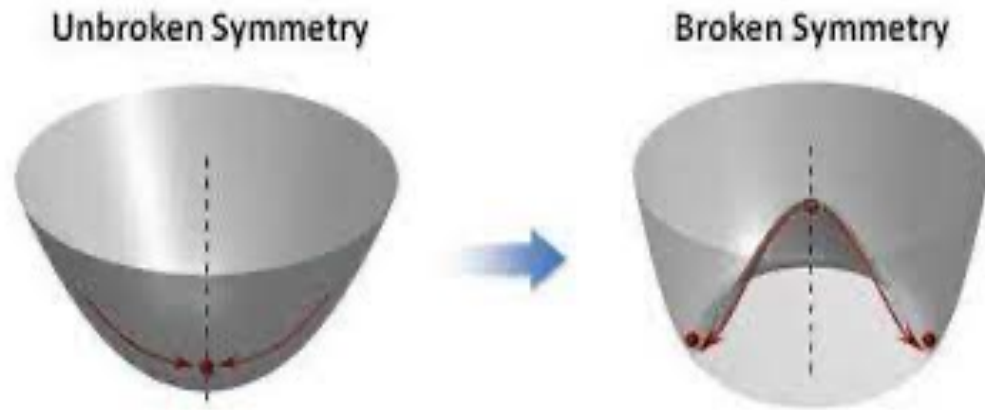
George Lazarides (Aristotle U., Thessaloniki), Rinku Maji (Ahmedabad, Phys. Res. Lab), Rishav Roshan (Kyungpook Natl. U.), Qaisar Shafi (Delaware U., Bartol Inst.) (May 10, 2022)

Published in: *Phys.Rev.D* 106 (2022) 5, 055009 • e-Print: [2205.04824](#) [hep-ph]

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 reference search  31 citations

Cosmic String Formation



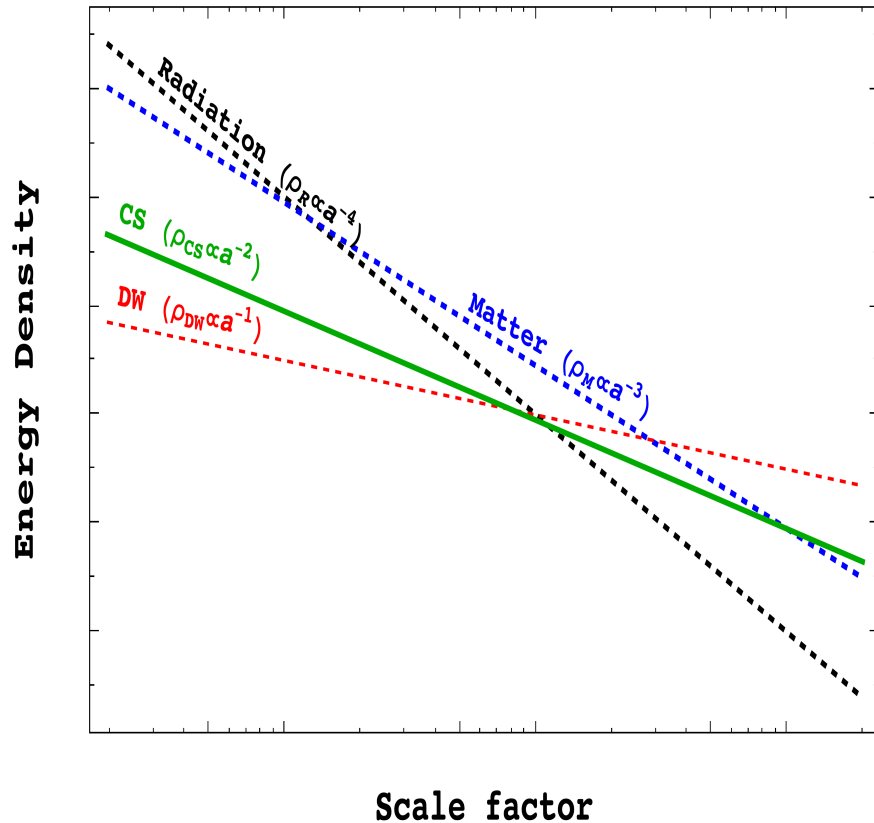
Cosmic Strings

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

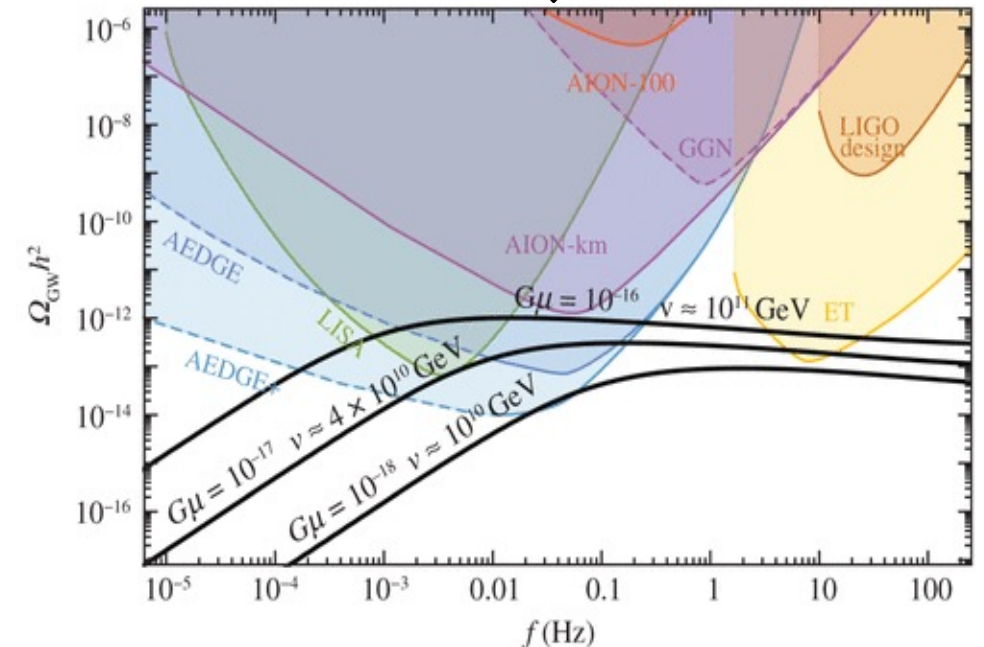
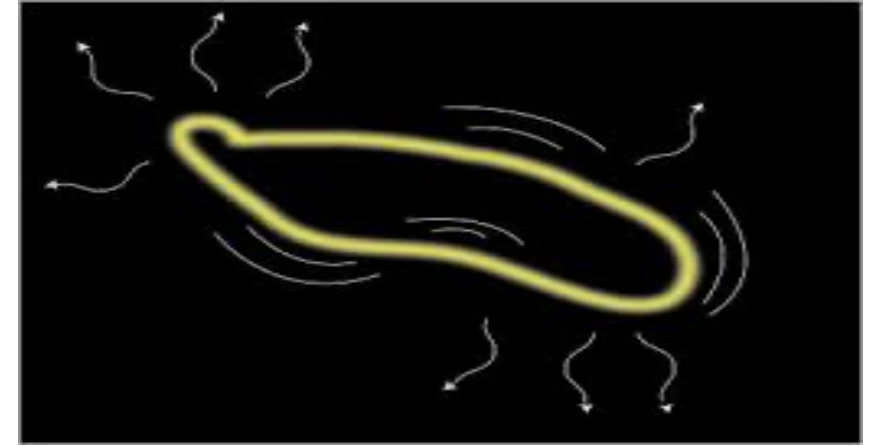


Gravitational waves from Cosmic Strings



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

$$\sim G\mu$$

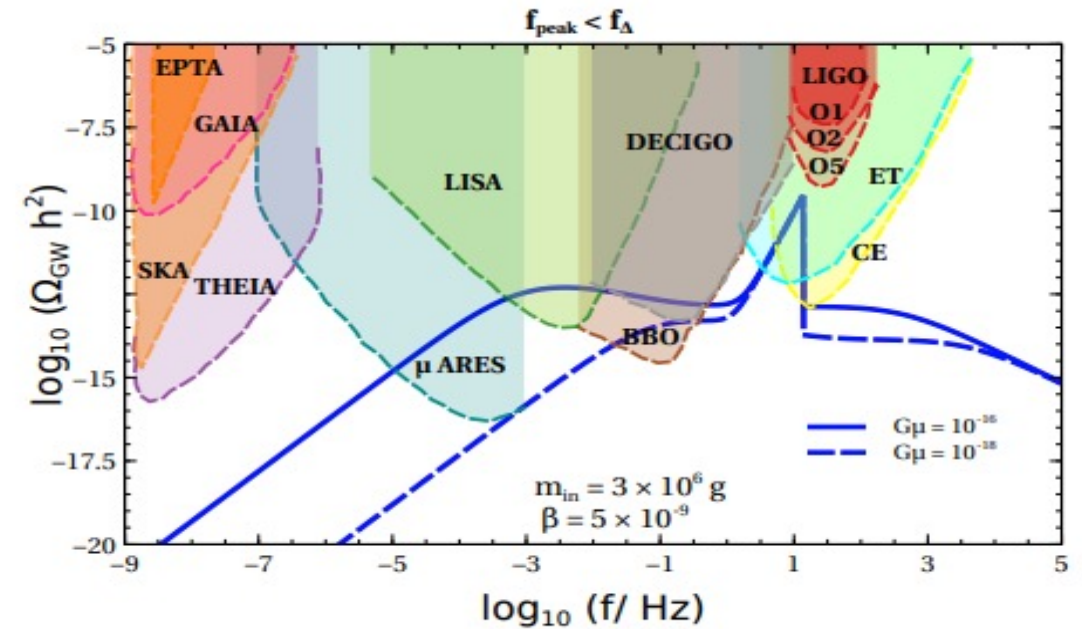
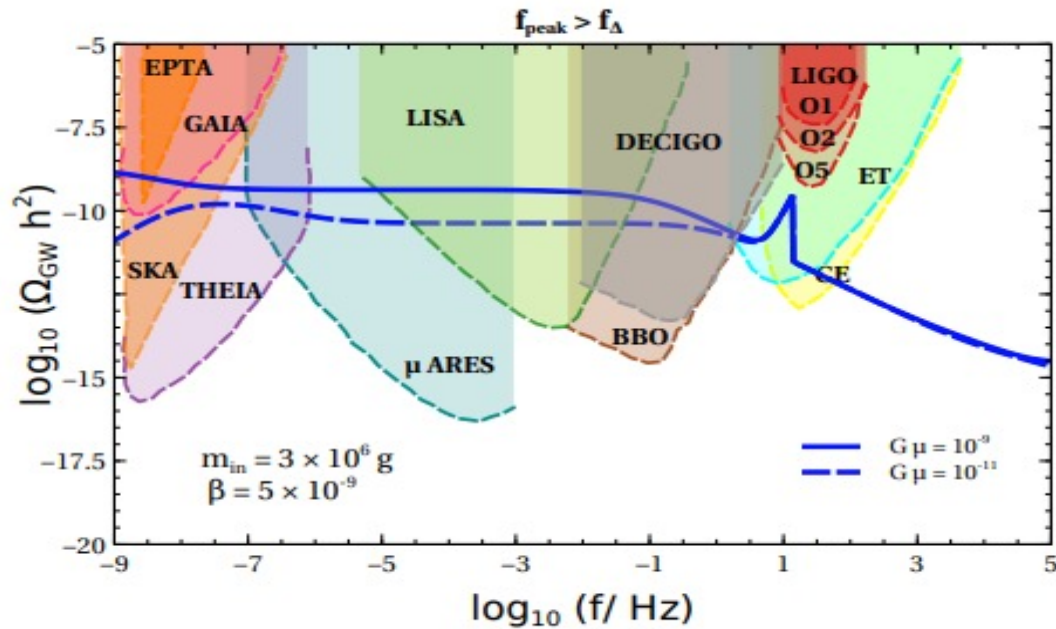


The evolution of CS network is much more complicated:

- Intercommutation of intersecting strings leads to the formation of loops of different sizes.
- Smaller loops decay by radiating GW.

Application: probing early MD eras

$\text{SM} \times \text{U}(1) \xrightarrow{\text{Gauged}} \text{Cosmic String} \longrightarrow \text{GW}$



Early Matter Dominated era results from PBH dominated universe

Final Remarks

1. Some high-scale physics: **DM, understanding the scale of QG, PBH etc.**
2. How to test/probe these scales? **Primordial Gravitational Waves?**
3. GW can have **cosmological origins: Topological defects, PBHs, etc.**
4. The same sources might also **produce particles** responsible for all the above cosmological puzzles.
4. This suggests that primordial **GW** can help us **understand, test, and 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.**

Ongoing Works

1. Neutrino mass and GWs from Electroweak Phase transitions. [RR, JV]
2. Asymmetric dark Matter and GWs from Phase Transition. [DB, AD, RR, IS]
3. Minimal scale invariant WIMP dark matter and GWs [AB, RR, AZ]
2. Quantum Gravity origin of PBH dark matter and GWs [YG, SFK, RR, XW, GW, MY]
5. Effect of PBH mass distribution on GW production during reheating [MG, YM, MO, RR]
6. Electroweak Phase transitions and Electroweak vacuum stability with VLQ [DB, RR, AS]

Future Directions

1. Gravitational waves from **monopoles and textures**.
2. Gravitational waves from **Hybrid Defects**.
3. Gravitational waves from **Phase Transition** and its connection to early universe physics **like PBH formation**.
4. **Bridge the gap** between the **community** working on **PBH formation and evaporation**.
5. Both the formation and evaporation of PBH are **effective sources of Gravitational Waves**

Image generated by ChatGPT that I fail to understand!

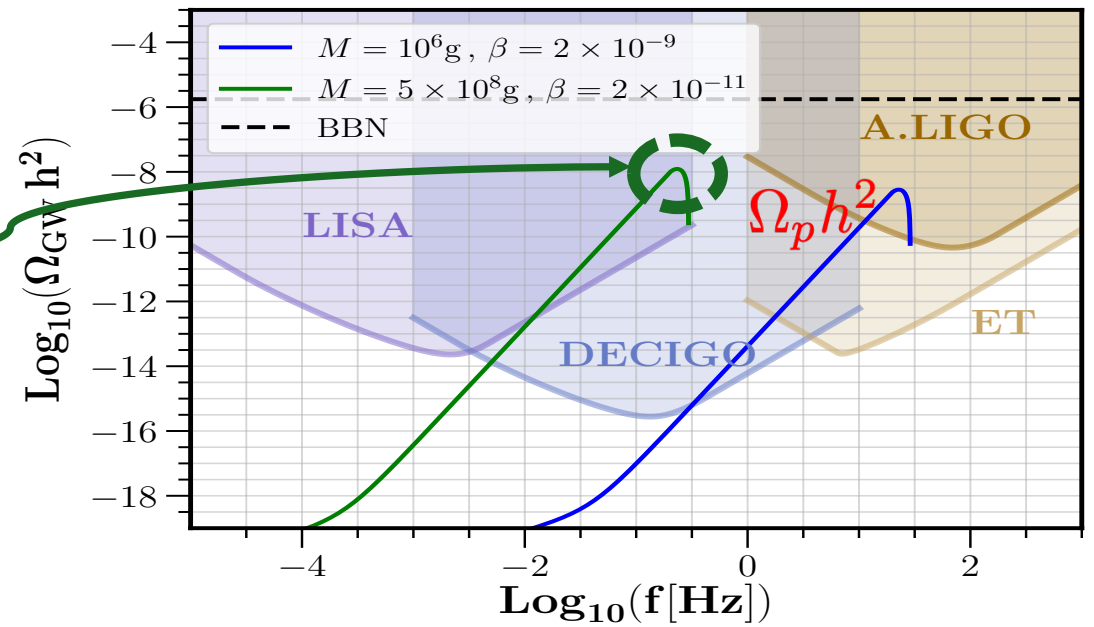
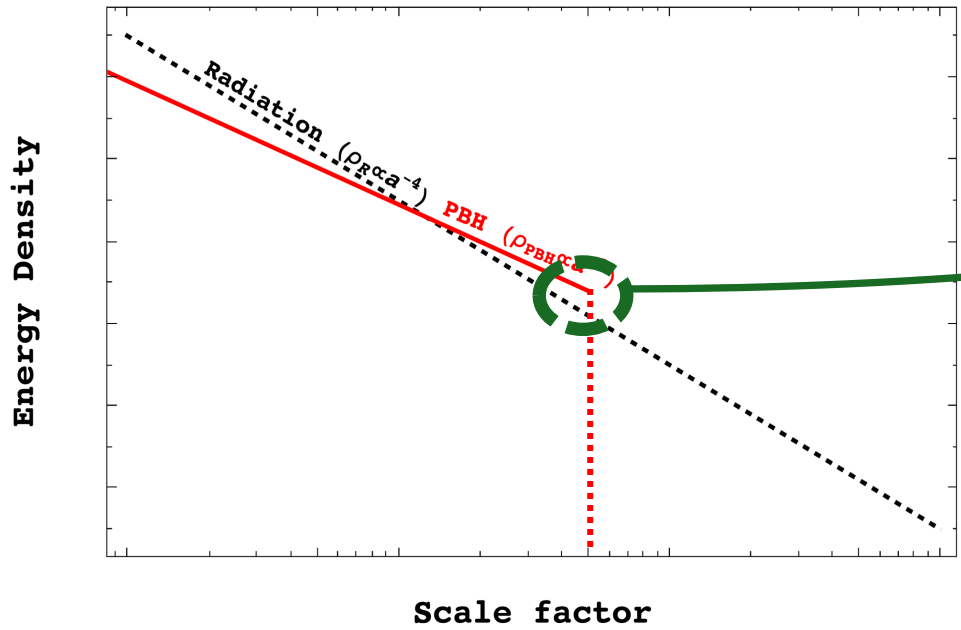


Thank you!

Backup

Gravitational waves from PBH

JCAP04(2021)062



Inhomogeneity in the distribution of the PBH $\longrightarrow$ Induces GW at second order when PBH dominates

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

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

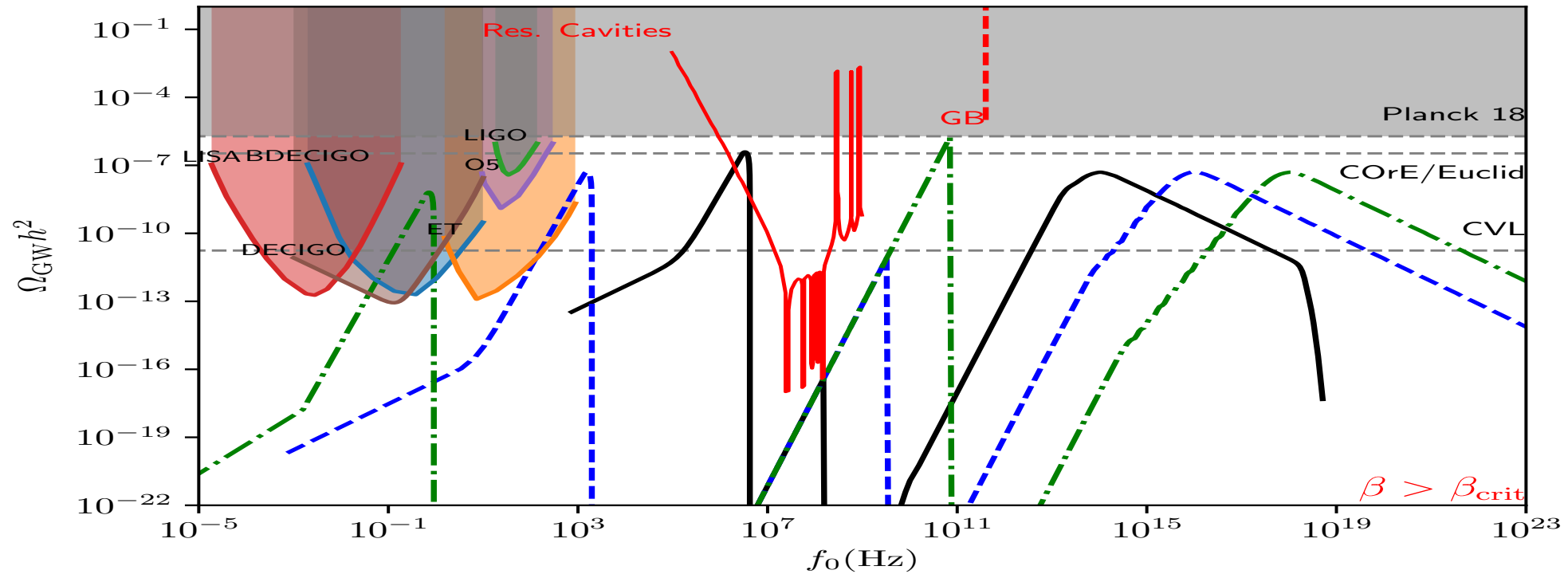
$$\Omega_{\text{GW}}^{\text{peak}} \approx \mathcal{P}_{\Phi}^2(k = k_{\text{UV}}) S_{\Phi}^4(k/k_{\text{RH}}) \left(\frac{k_{\text{UV}}}{k_{\text{RH}}} \right)^7$$

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

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

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

Application: GW Production During Reheating



arXiv: 2411.04189

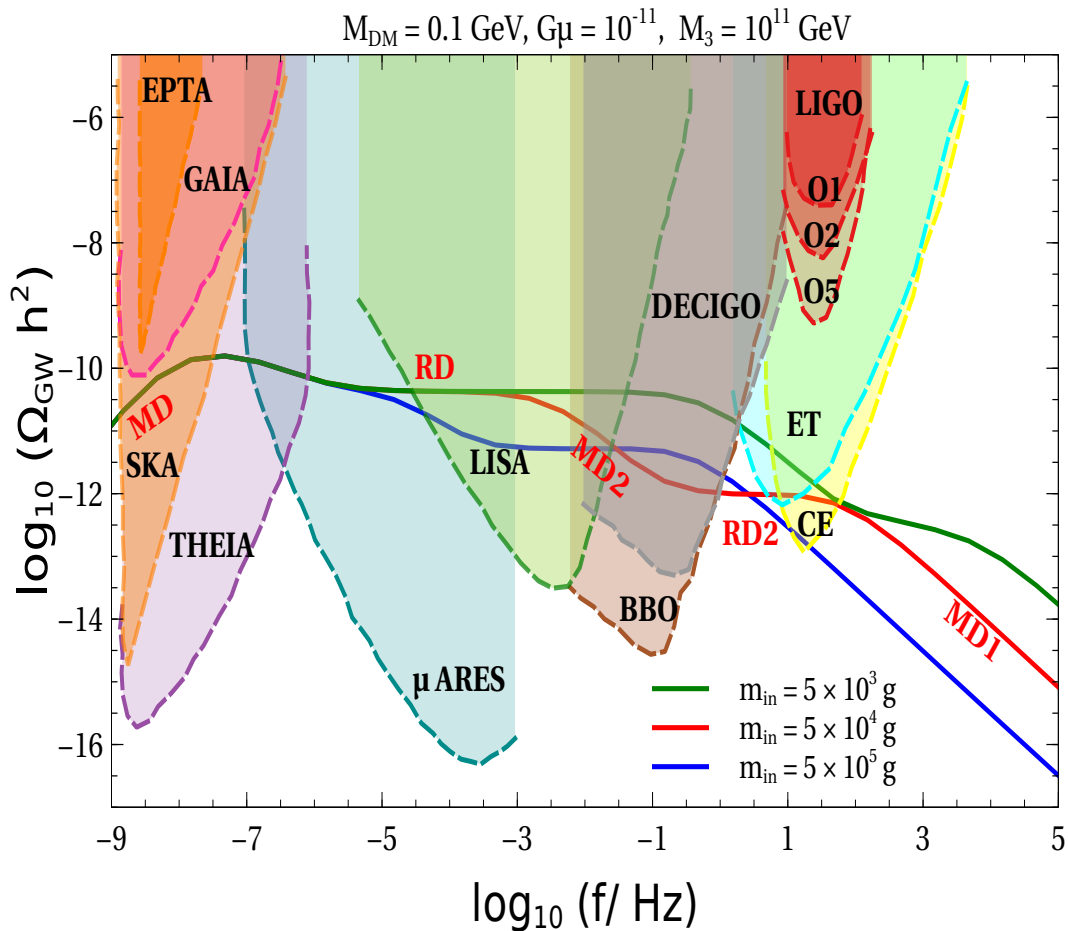
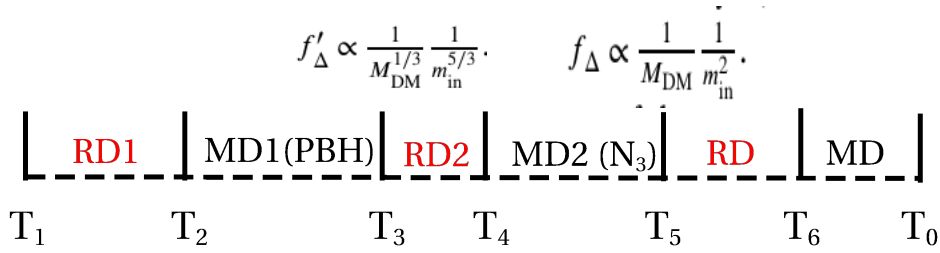
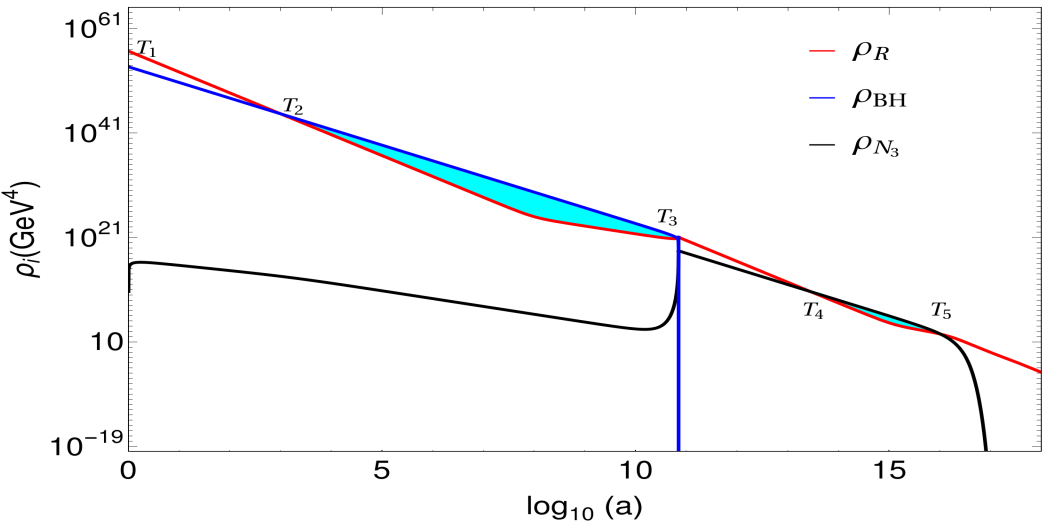
Application: probing multiple MD eras

SM $\times$ U(1) $\xrightarrow{\text{Gauged}}$ **Cosmic String** $\longrightarrow$ **GW**

$$-\mathcal{L} \supset \sum_{\alpha,i} Y_{\alpha i} \bar{L}_{\alpha} \tilde{H} N_i + \frac{1}{2} \sum_{i,j=1,2} h_{ij} S \bar{N}_i^c N_j + \frac{1}{2} M_3 \bar{N}_3^c N_3 + \frac{m_{\text{DM}}^2}{2} \phi^2.$$

Multiple Matter Dominated era resulting from:

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



Neutrinos, an elusive particle

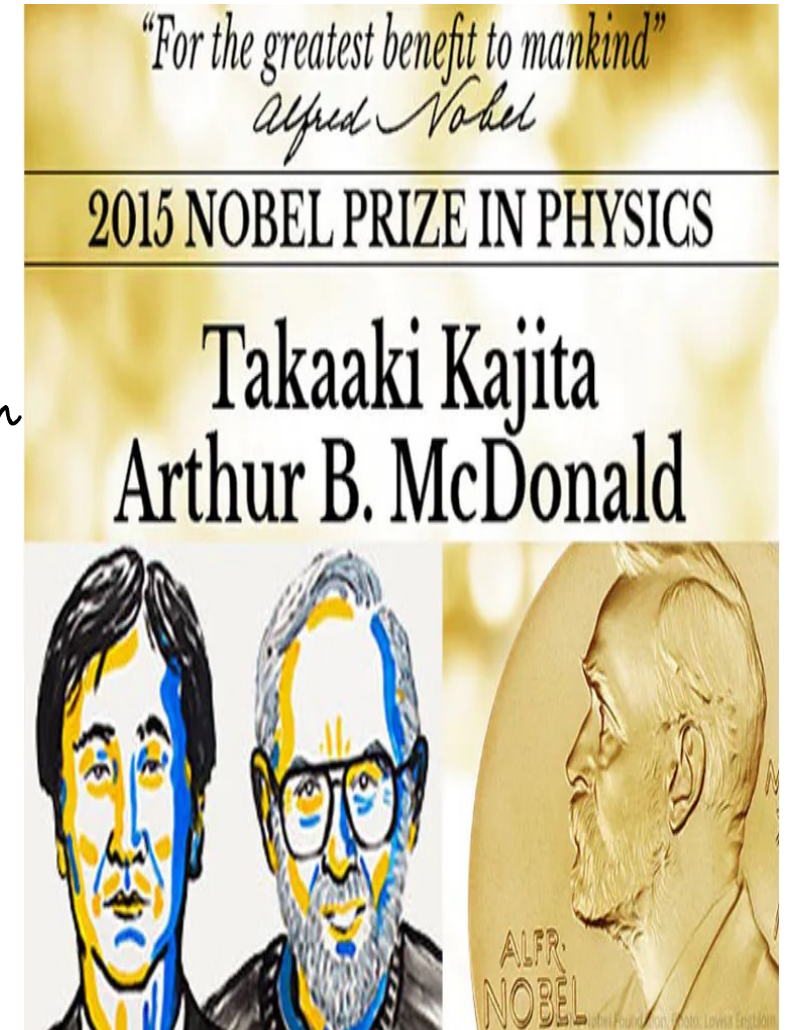


What we know :

- ☐ 3 types of neutrinos
- ☐ They oscillate
- ☐ Tiny but unknown masses
- ☐ Participates in weak interaction

What we **don't** know :

- ☐ Origin of neutrino mass
- ☐ Nature [Dirac/Majorana]
- ☐ Absolute neutrino mass



Neutrino mass might involve heavy scales origin: how to test such scales?

Matter-Antimatter asymmetry



Quantum Psychic



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

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

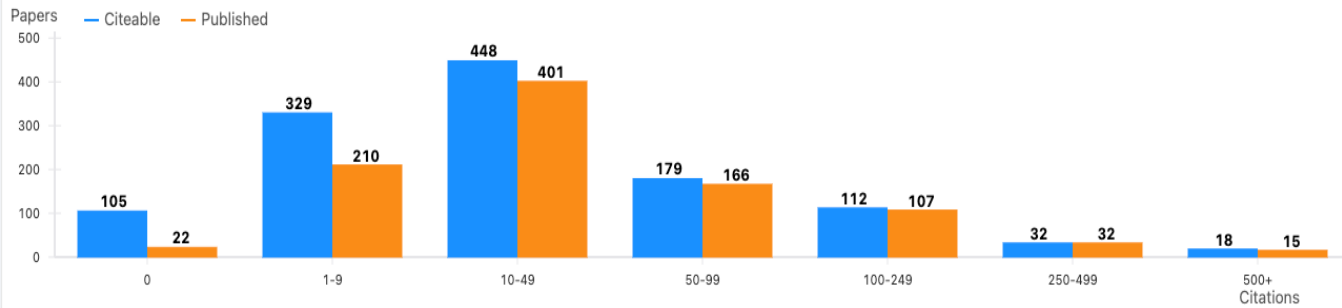
Gravitational waves from Phase Transition

Some recent works on GW from Phase transition

Citation Summary

☐ Exclude self-citations [?](#)

	Citeable ?	Published ?
Papers	1,223	953
Citations	67,602	60,888
h-index ?	125	122
Citations/paper (avg)	55.3	63.9



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](#)

Using gravitational waves to see the first second of the Universe #6

Rishav Roshan (Southampton U.), Graham White (Southampton U.) (Jan 9, 2024)

Published in: *Rev.Mod.Phys.* 97 (2025) 1, 015001 • e-Print: [2401.04388](#) [hep-ph]

[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [49 citations](#)

Theoretical uncertainties for cosmological first-order phase transitions #3

Djuna Croon (TRIUMF), Oliver Gould (Helsinki Inst. of Phys.), Philipp Schicho (Helsinki Inst. of Phys. and Bern U.), Tuomas V.I. Tenkanen (Bern U.), Graham White (TRIUMF and Tokyo U., IPMU) (Sep 21, 2020)

Published in: *JHEP* 04 (2021) 055 • e-Print: [2009.10080](#) [hep-ph]

[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [210 citations](#)

Review of cosmic phase transitions: their significance and experimental signatures #4

Anupam Mazumdar (Groningen U.), Graham White (TRIUMF) (Nov 5, 2018)

Published in: *Rept.Prog.Phys.* 82 (2019) 7, 076901 • e-Print: [1811.01948](#) [hep-ph]

[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [218 citations](#)

Detecting gravitational waves from cosmological phase transitions with LISA: an update #1

Chiara Caprini (APC, Paris), Mikael Chala (Durham U., IPPP and CAFPE, Granada and Granada U., Theor. Phys. Astrophys.), Glauber C. Dorsch (Caltech and Espirito Santo U.), Mark Hindmarsh (Helsinki Inst. of Phys. and Sussex U.), Stephan J. Huber (Sussex U.) et al. (Oct 29, 2019)

Published in: *JCAP* 03 (2020) 024 • e-Print: [1910.13125](#) [astro-ph.CO]

[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [657 citations](#)

Numerical simulations of acoustically generated gravitational waves at a first order phase transition #2

Mark Hindmarsh (Sussex U. and Helsinki Inst. of Phys.), Stephan J. Huber (Sussex U.), Kari Rummukainen (Helsinki Inst. of Phys. and Helsinki U.), David J. Weir (Stavanger U.) (Apr 13, 2015)

Published in: *Phys.Rev.D* 92 (2015) 12, 123009 • e-Print: [1504.03291](#) [astro-ph.CO]

[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [513 citations](#)

Energy Budget of Cosmological First-order Phase Transitions #10

Jose R. Espinosa (ICREA, Barcelona and Barcelona, IFAE and CERN), Thomas Konstandin (CERN), Jose M. No (Saclay, SPHT), Geraldine Servant (CERN and Saclay, SPHT) (Apr, 2010)

Published in: *JCAP* 06 (2010) 028 • e-Print: [1004.4187](#) [hep-ph]

[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [559 citations](#)

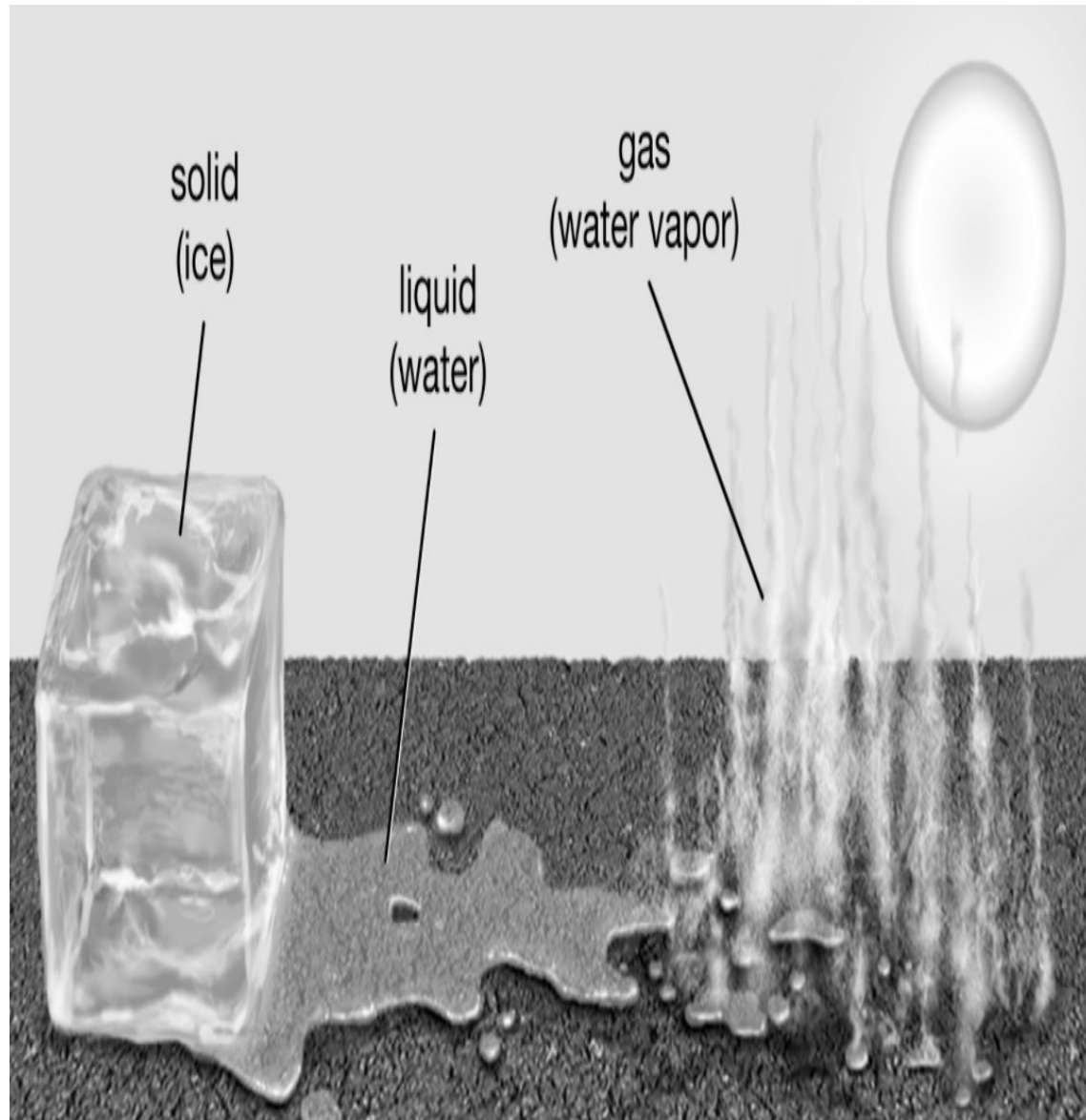
Gravitational Wave Production by Collisions: More Bubbles #11

Stephan J. Huber (Sussex U.), Thomas Konstandin (Barcelona, IFAE) (Jun, 2008)

Published in: *JCAP* 09 (2008) 022 • e-Print: [0806.1828](#) [hep-ph]

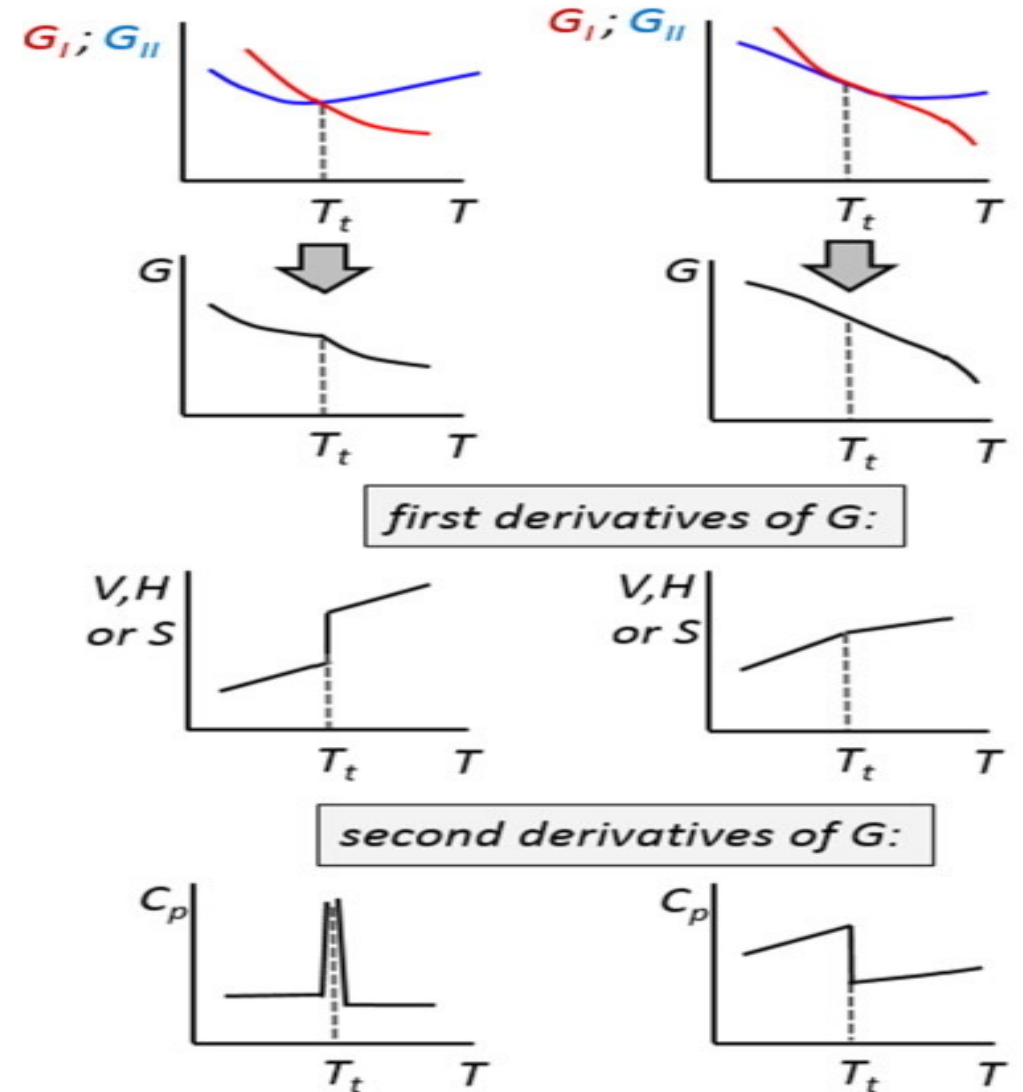
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Phase Transition

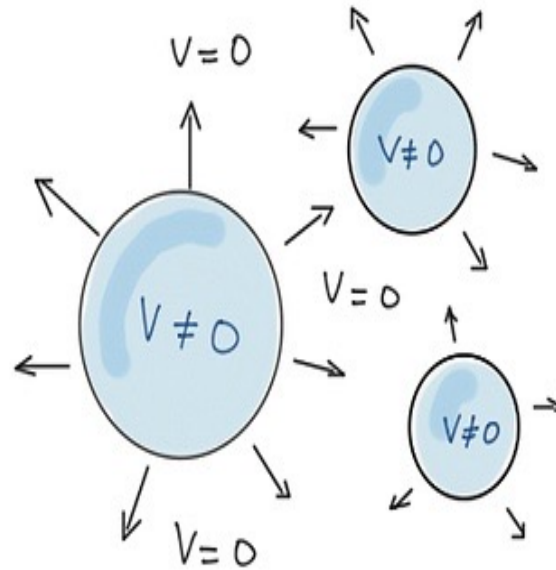
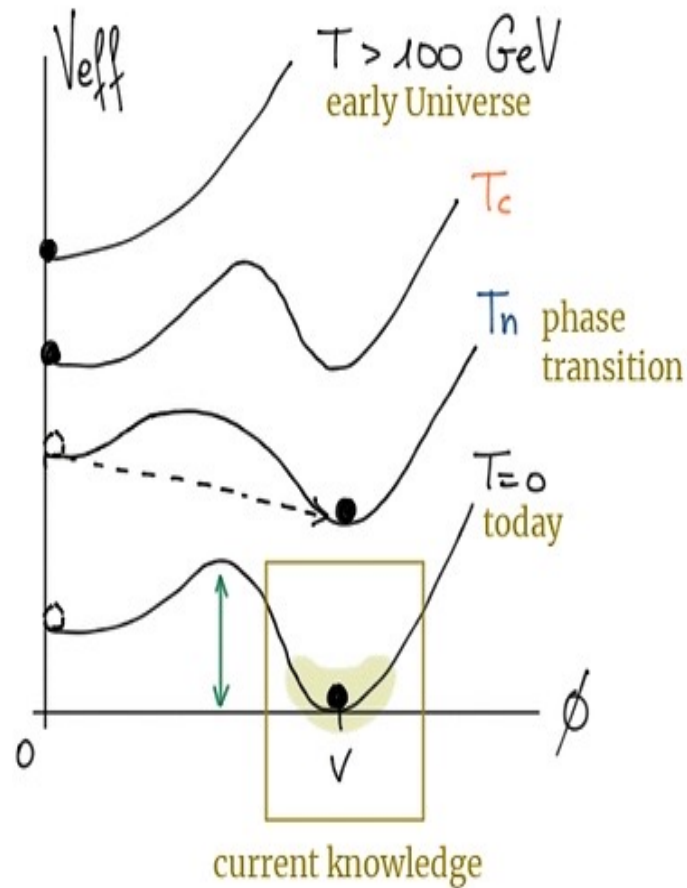


(a) First order

(b) Second order



GWs from First-Order Phase Transition



Sources of GWs:

- ☐ Bubble collision
- ☐ Sound waves
- ☐ Turbulence

