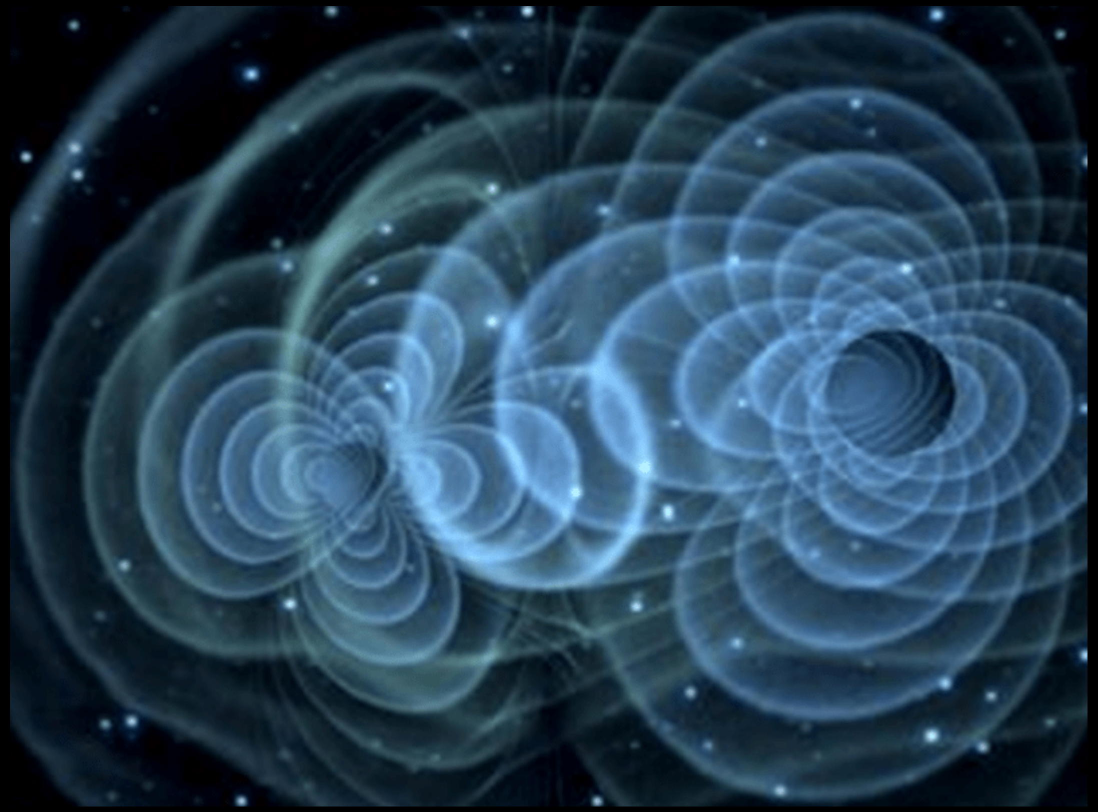
UNIVERSITY OF Southampton
School of Physics and Astronomy

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Gravitational Waves as Probes of New Physics

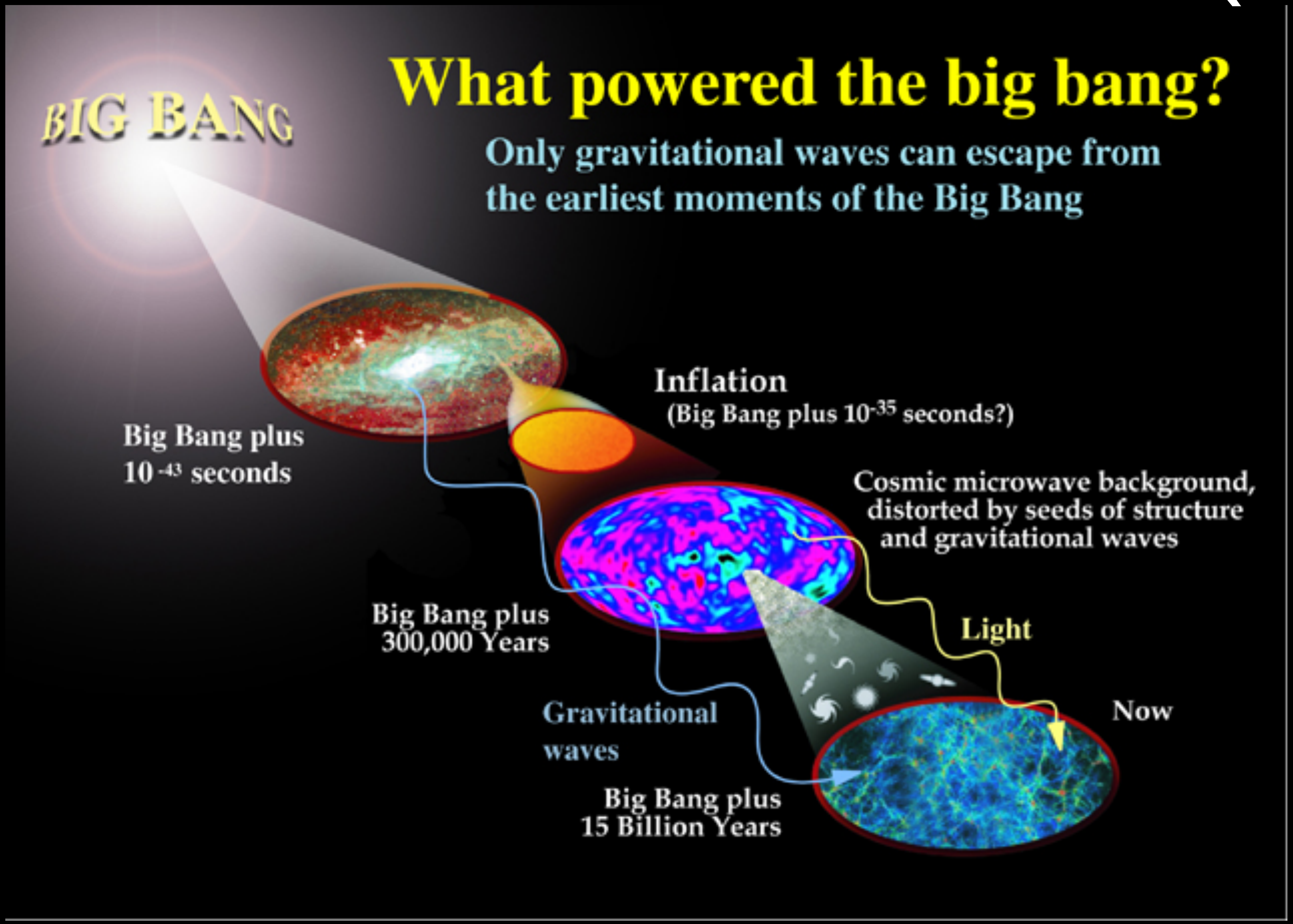


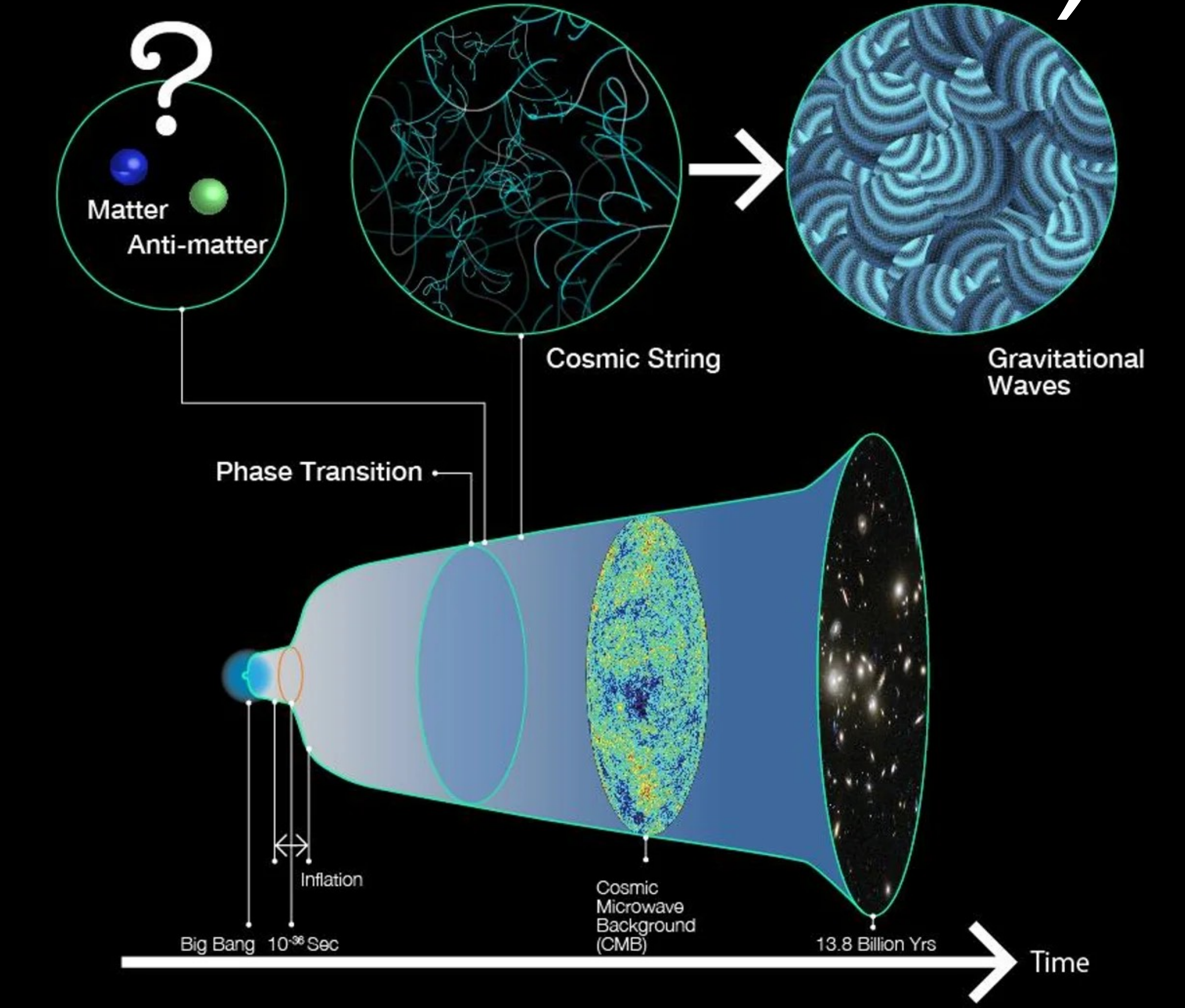
STEVE KING 08/09/24

Dark Side of the Universe

Corfu Summer Institute
Hellenic School and Workshops on Elementary Particle Physics and Gravity
Corfu, Greece

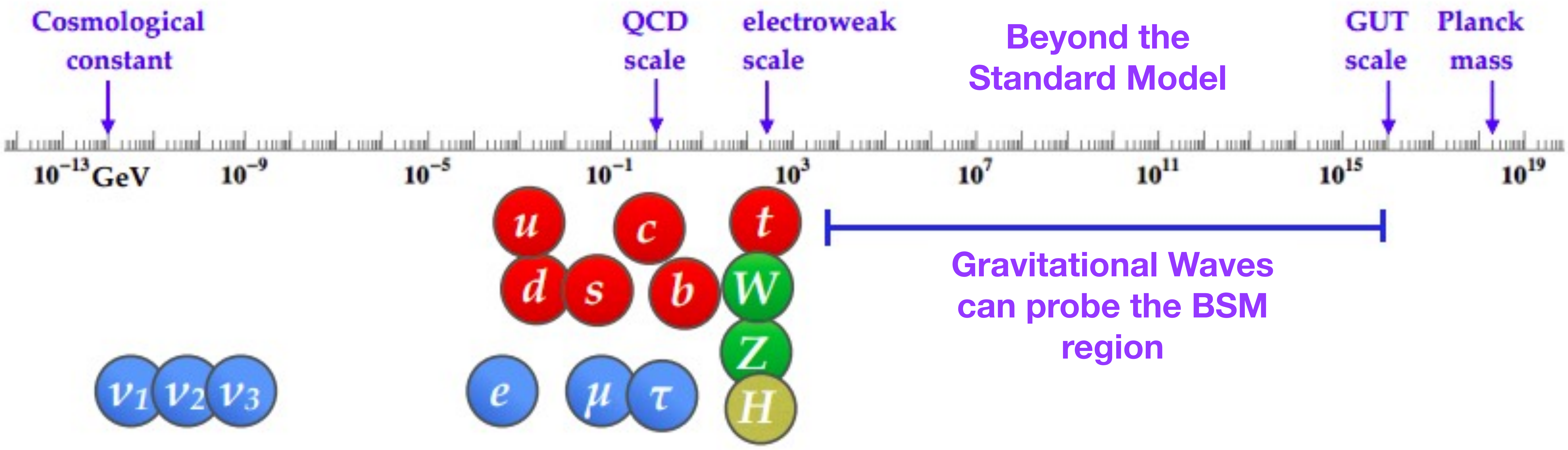
Gravitational Waves enable us to look back to the earliest moments of the Universe (back to Inflation)



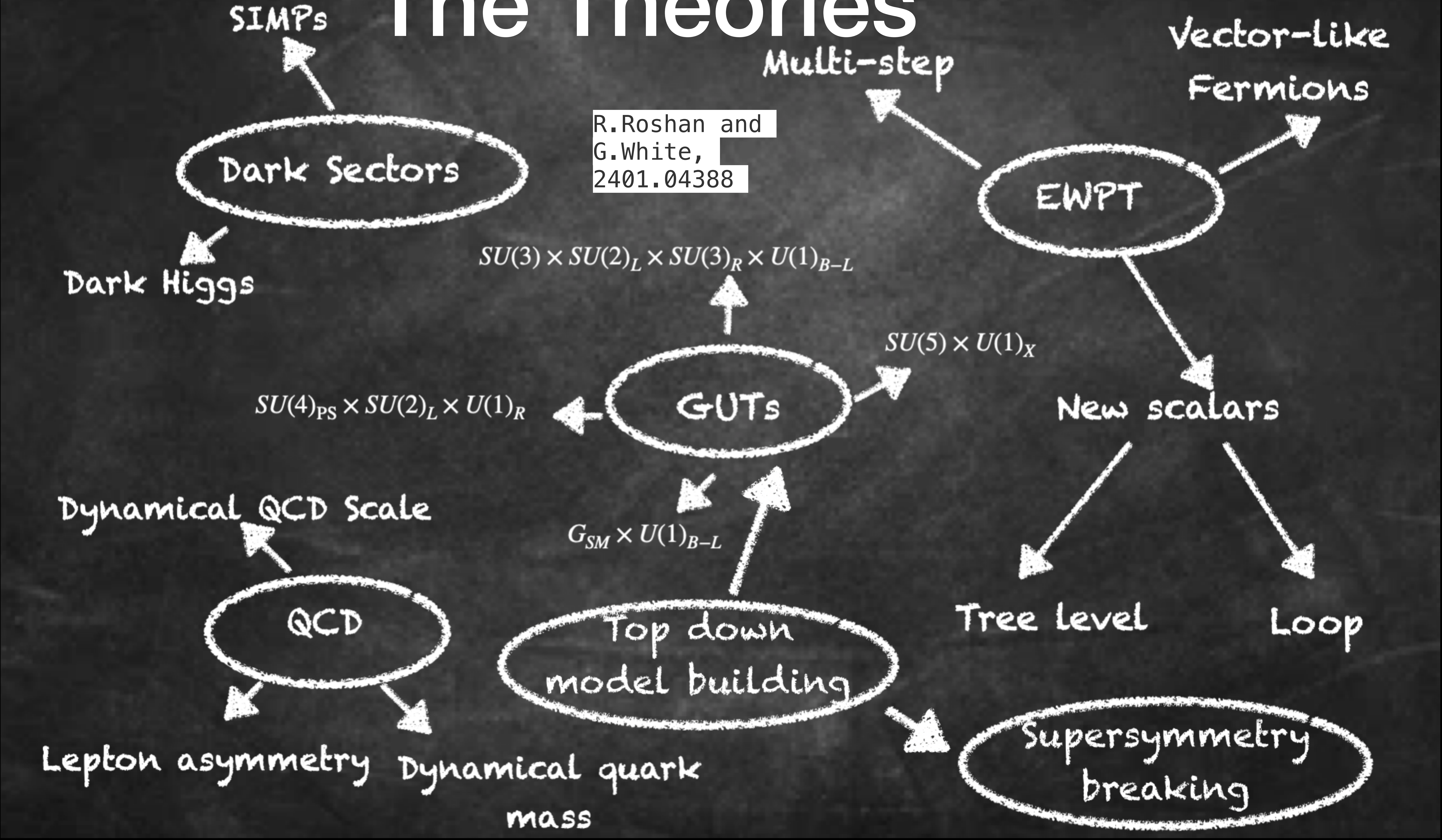



Inflationary expansion
Quarks+Gluons
Hadrons
Primordial nucleosynthesis
Creation of hydrogen and helium atoms
The dark time
Formation of first stars and galaxies
The present universe
Heat death
Big Bang
Singularity ?
„t=0“
≈ Size of universe
→ ∞
~10^50 ly
5x10^10 ly
10^7 ly
10 ly
150 km
10 cm
0
(ly = light year)
X, Y Leptoquarks
Quarks
Gluons
Quark-gluon plasma
Leptons
Photons
Quarks + Gluons
Protons, Neutrons
Photons
Leptons
Nuclei
Protons + Neutrons
Deuterium
Helium
Photons
Hydrogen
Helium
Atoms
galaxy
stars
galaxy
Blact holes
quantum eevaporation
Diluted radiation
Big rip ?
Hadronic era
Expansion
Expansion
Accelerated expansion
Gravitational Waves can probe this entire region
CMB
300,000 years
CMB region
t
Time: 10^-43 s 10^-35 s 10^-6 s 10 s 3000 years 2x10^8 years 14x10^9 years 10^60 years
Temperature: 10^32 10^27 °K 10^13 5x10^9 3000 °K 30 °K 2,7 °K 10^-10 °K
Energy: 10^19 10^15 GeV 100 MeV 200 keV 0,4 eV 0,1 eV 10^-4 eV ≈ 0

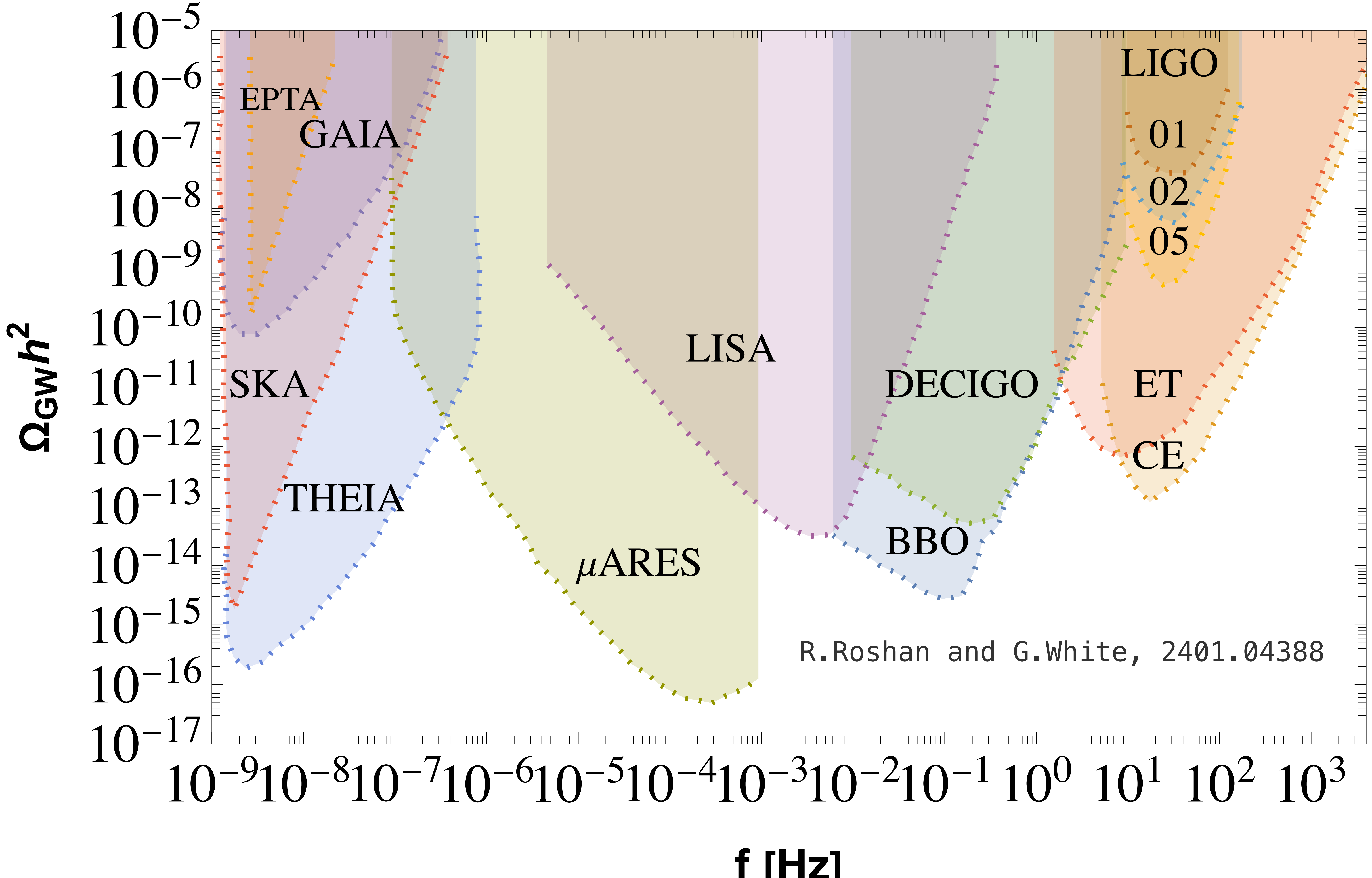
Gravitational Waves are sensitive to scales up to the Planck scale (well beyond the reach of colliders)



The Theories



The Detectors



Current observations are from LIGO 01-03

The stage is set for a bonanza of new results

Gravitational Waves are sensitive to :

- First Order Phase transitions FOPT (e.g. QCD)
- Cosmic Strings CS (e.g. U(1) sym breaking)
- Domain Walls DW (e.g. Z_2 sym breaking)

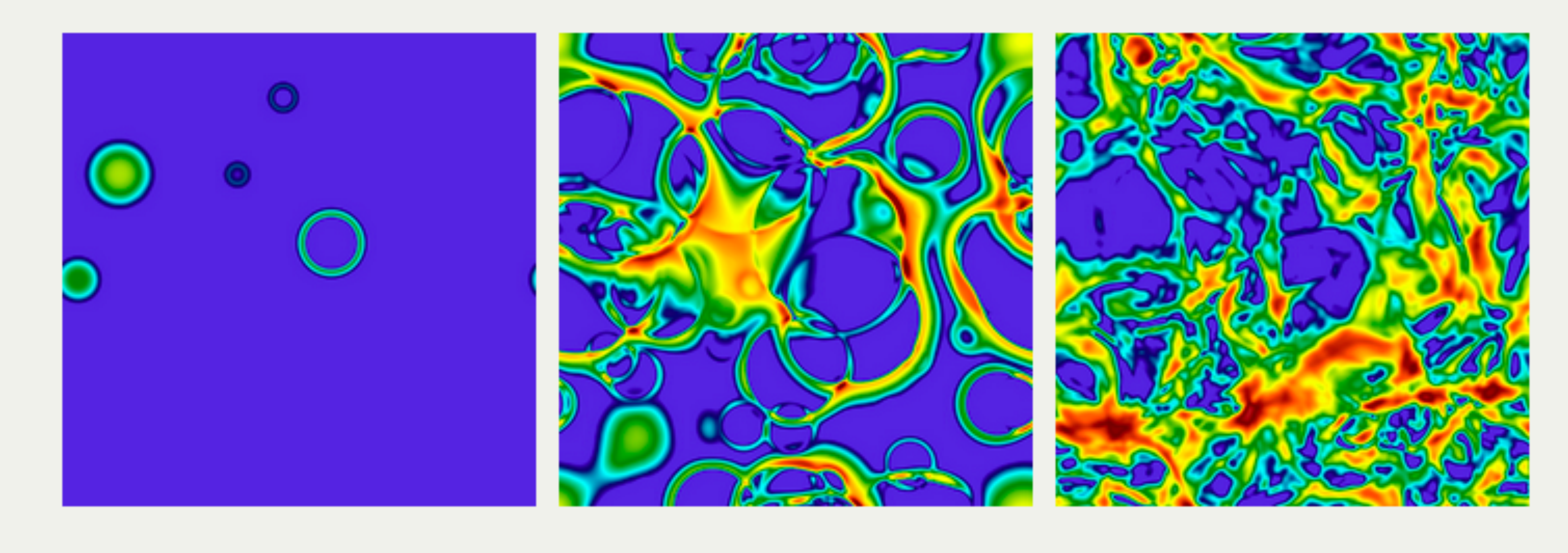
In this talk we are interested in a few BSM examples

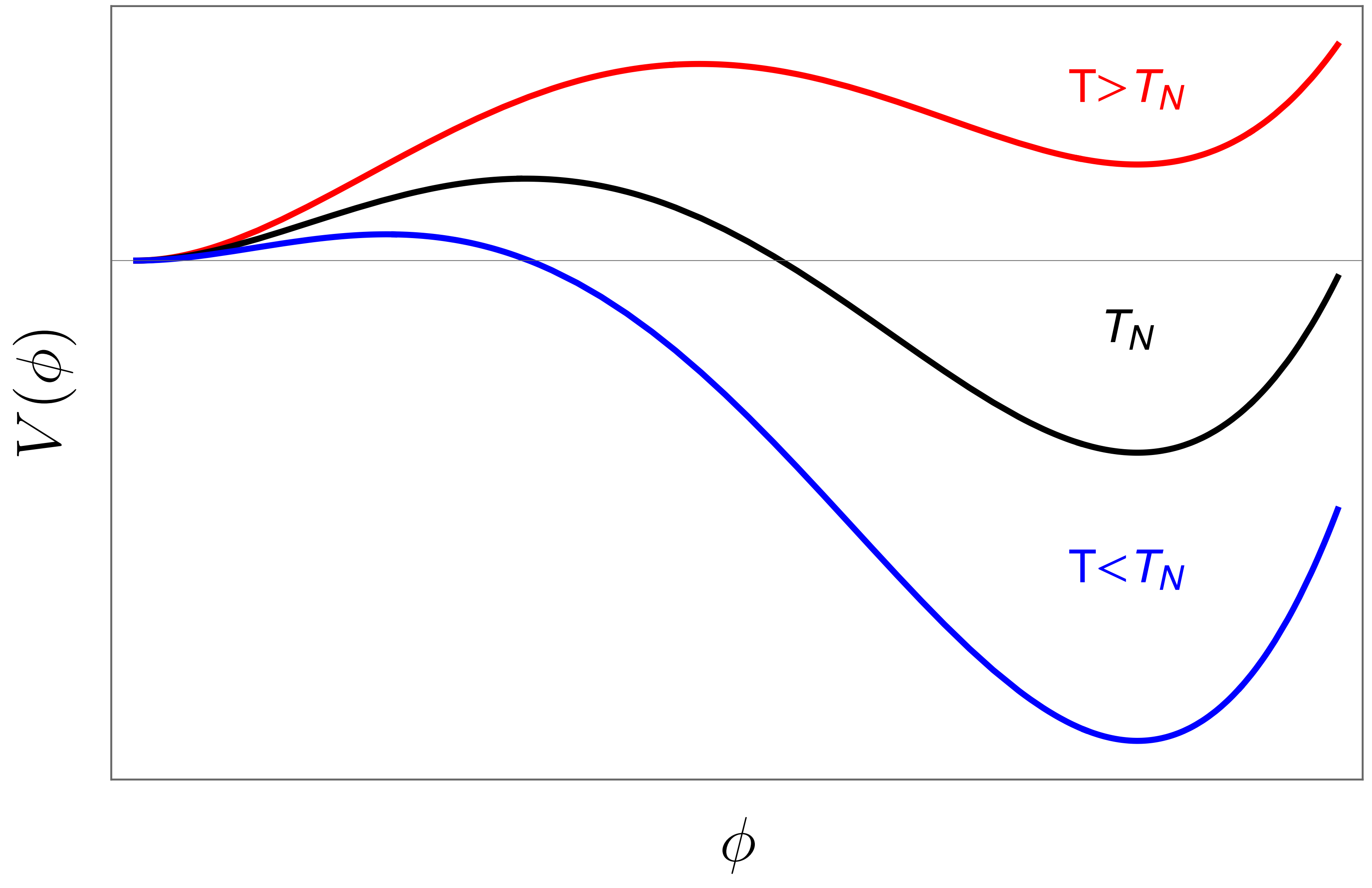
- Inflation (e.g. with a kink or hybrid)
- Many other effects (e.g. PBHs,…)
- See other talks: Wang; Avgoustidis; Vikman; Papanikolaou; Goshal; Balazs; Zhou; Ota; Khalil; Mahapatra…

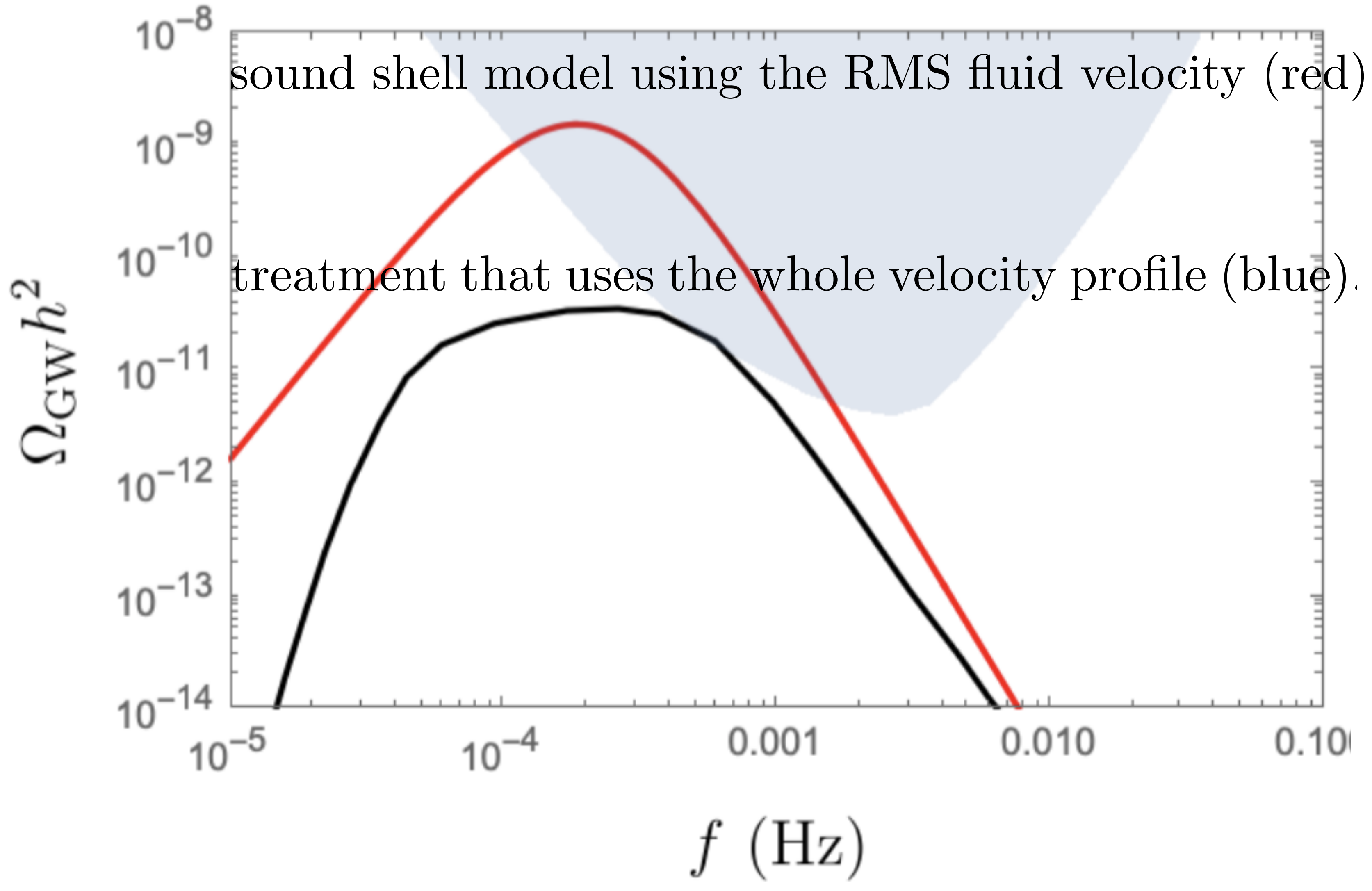
Gravitational Waves from First Order Phase Transitions

Phase Transitions:

- Bubbles nucleate and grow.
- Expand in plasma.
- Bubbles and fronts collide - - violent process.
- Sound Waves left behind in thermal plasma.
- Turbulence, damping.







$$\Omega_{\rm tot}(f) = \Omega_{\rm coll}(f) + \Omega_{\rm sw}(f) + \Omega_{\rm turb}(f)$$

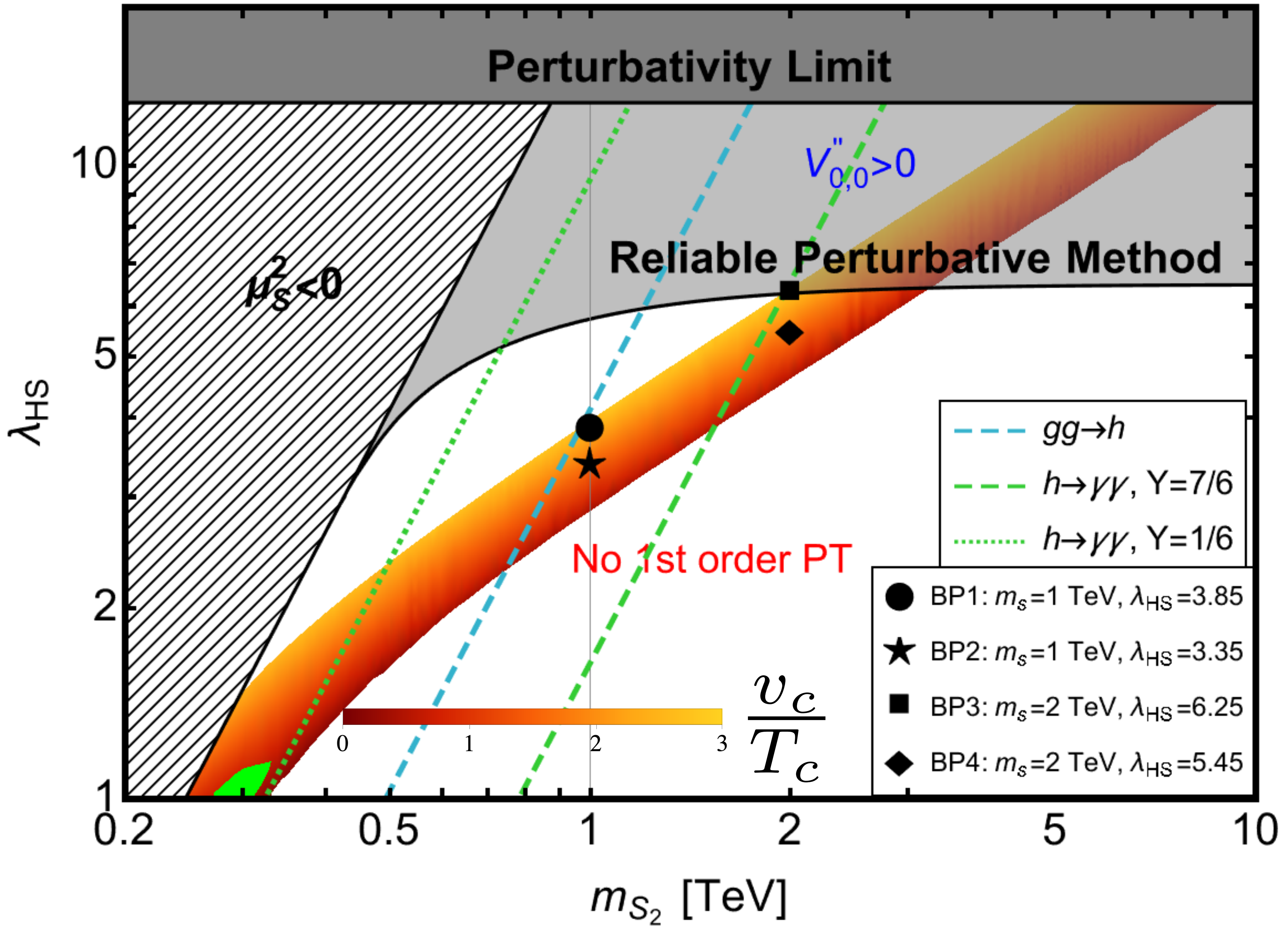
B.Fu and S.F.K., 2209.14605

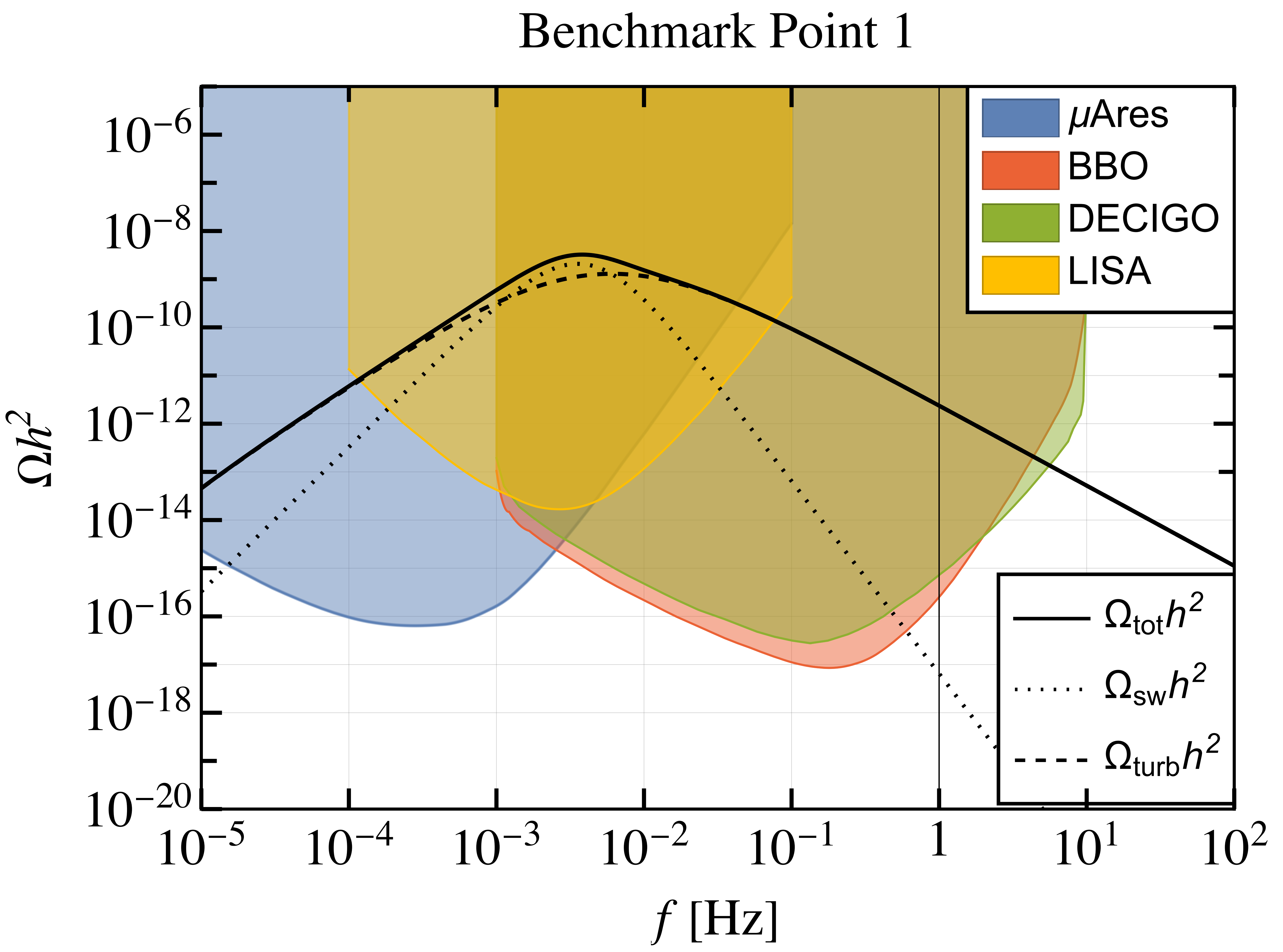
GW from leptoquark induced FOPT

$$V_0 = -\mu^2|H|^2 + \lambda_H|H|^4 + \mu_S^2|S_a|^2 + \lambda_S|S_a|^4 + 2\lambda_{HS}|H|^2|S_a|^2$$

$$V_{\rm eff}(h,T) = V_0 + \Delta V_0^{1-\rm loop}(h) + \Delta V_T^{1-\rm loop}(h,T)$$

Leptoquark singlet S_1, doublet S_2 or triplet S_3





- NANOGrav Collaboration, arXiv:2306.16213

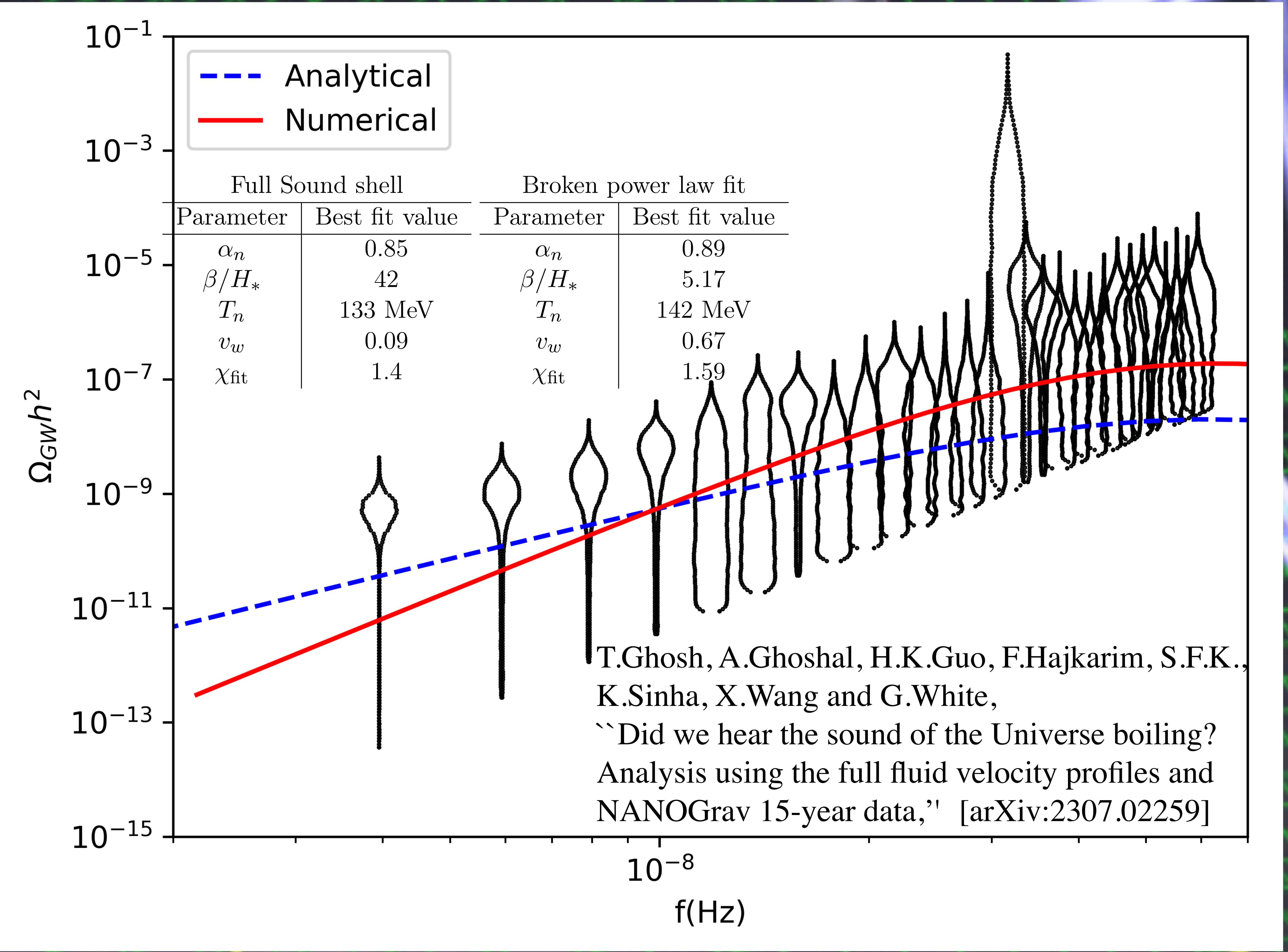
Pulsar Timing Arrays

first observation of stochastic GW background

- NANOGrav Collaboration, arXiv:2306.16213

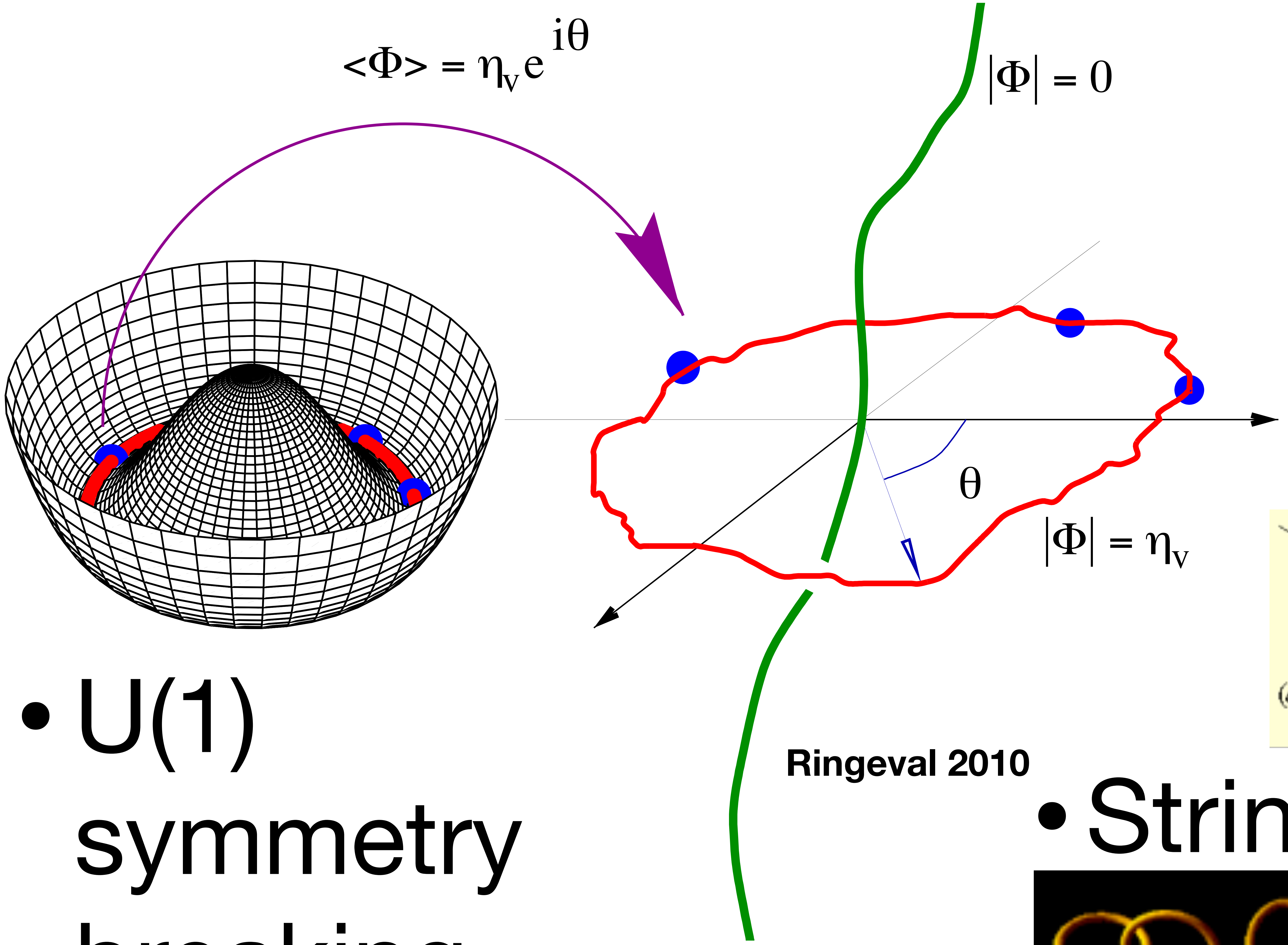
Pulsar Timing Arrays

first observation of stochastic GW background



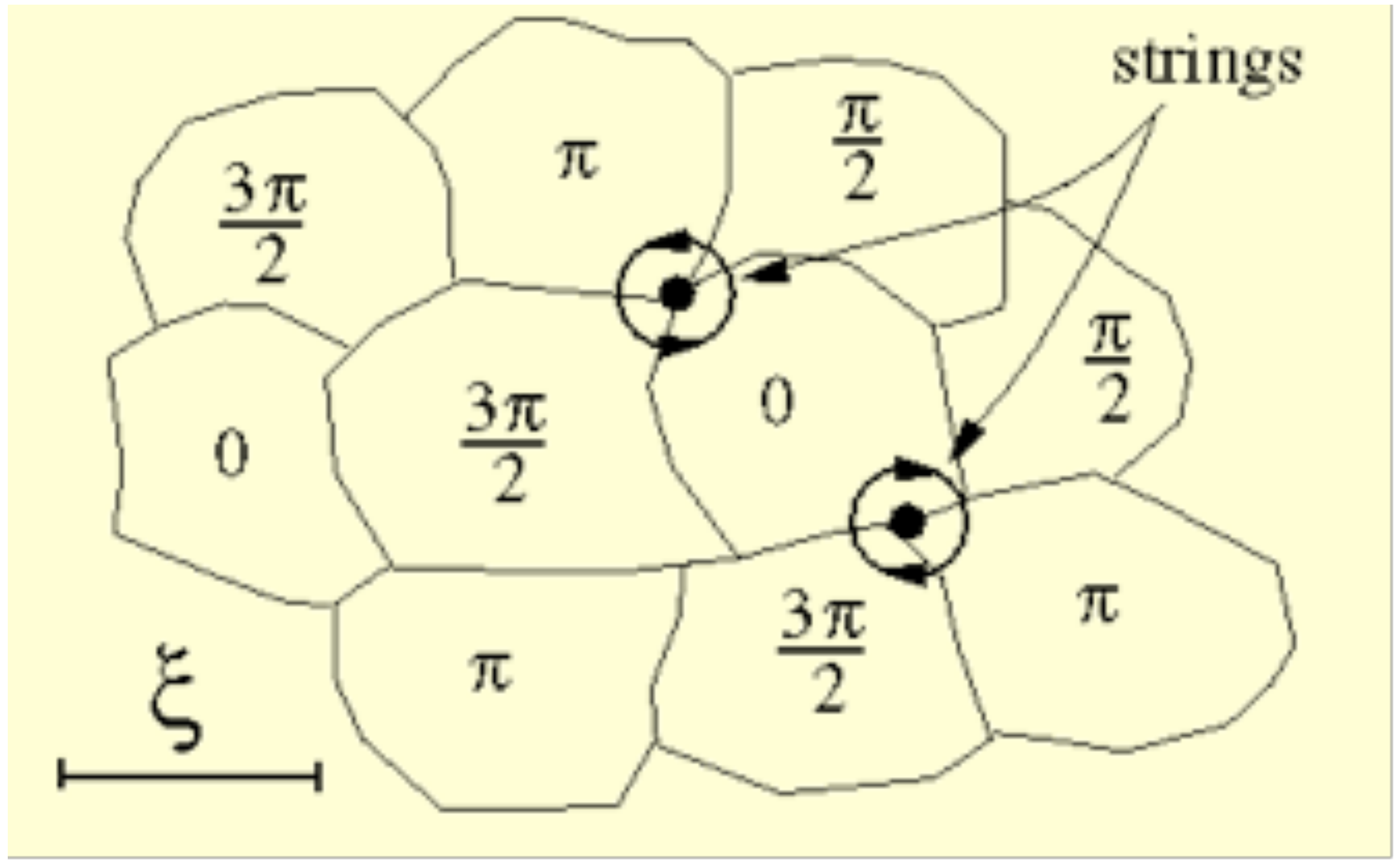
Full Sound shell		Broken power law fit	
Parameter	Best fit value	Parameter	Best fit value
α_n	0.85	α_n	0.89
β/H_*	42	β/H_*	5.17
T_n	133 MeV	T_n	142 MeV
v_w	0.09	v_w	0.67
$\chi_{\rm fit}$	1.4	$\chi_{\rm fit}$	1.59

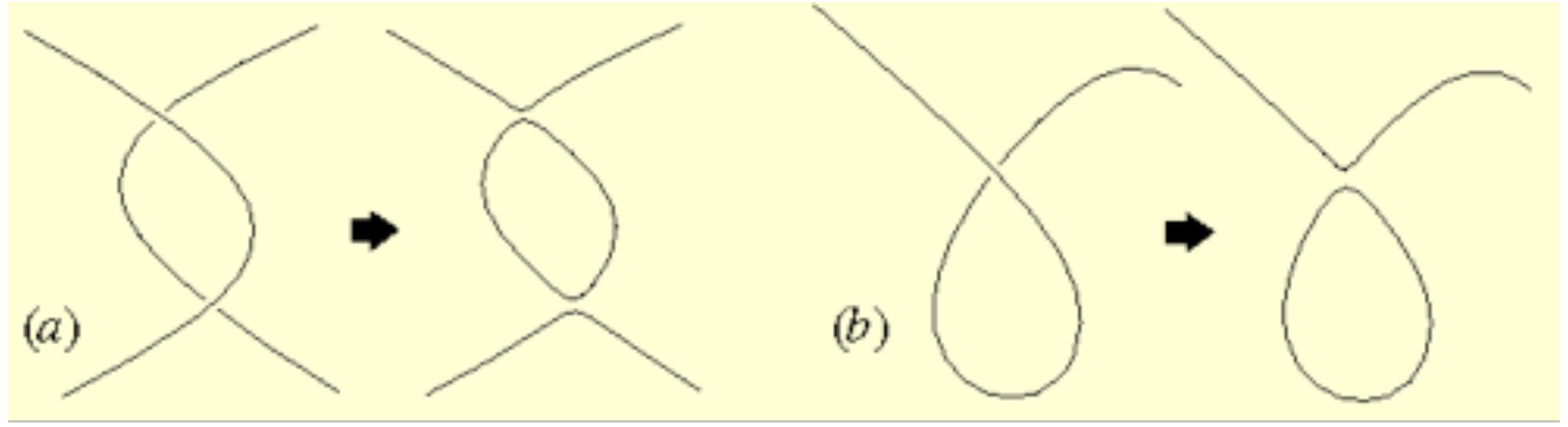
Gravitational Waves from Cosmic Strings



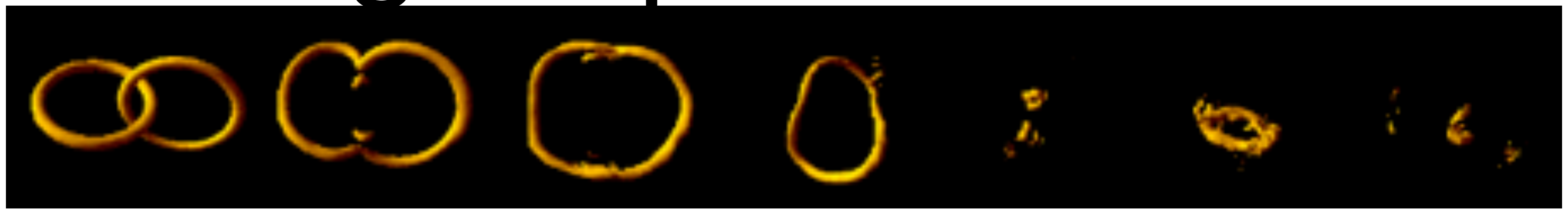
Ringeval 2010

- U(1) symmetry breaking



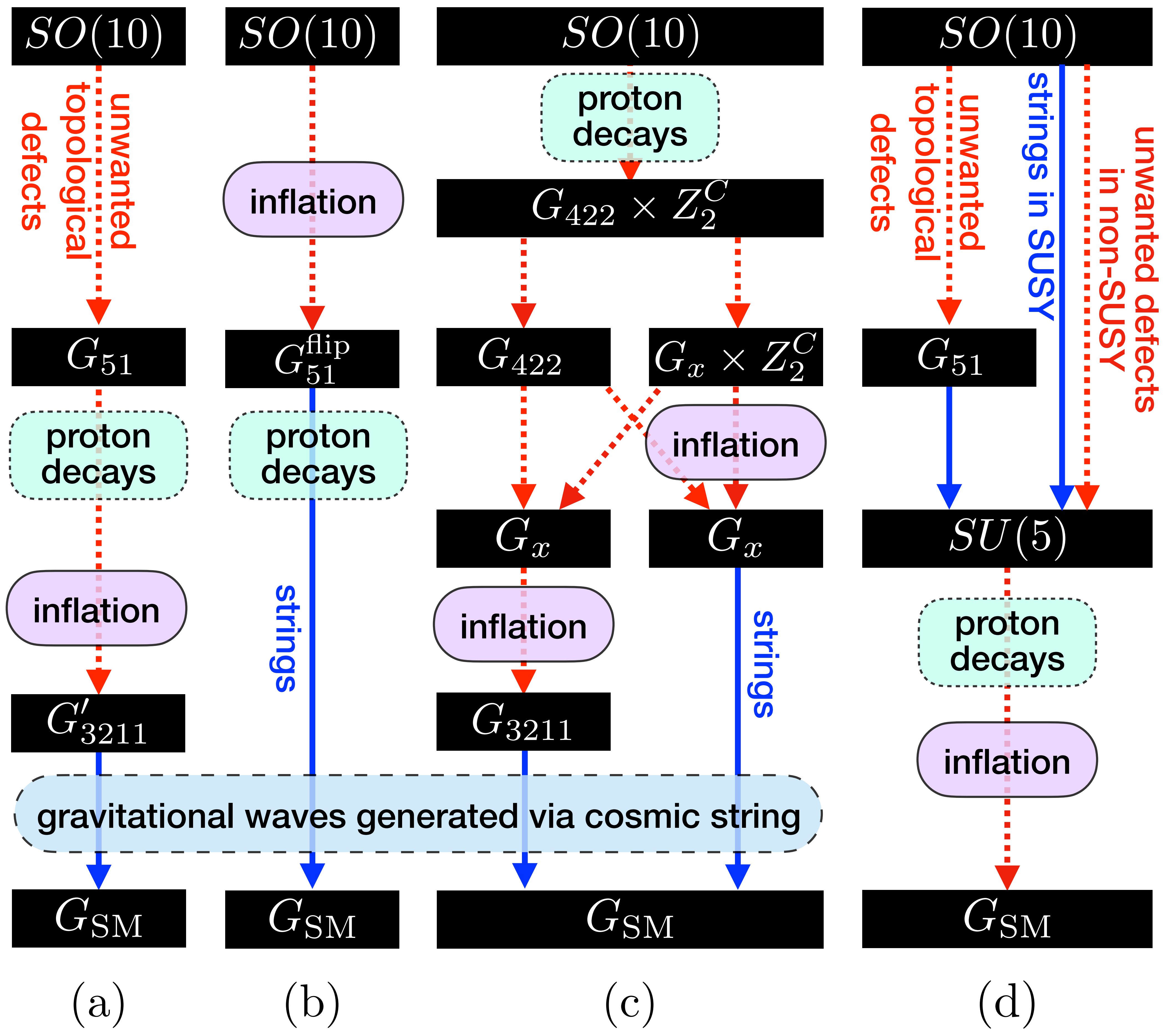


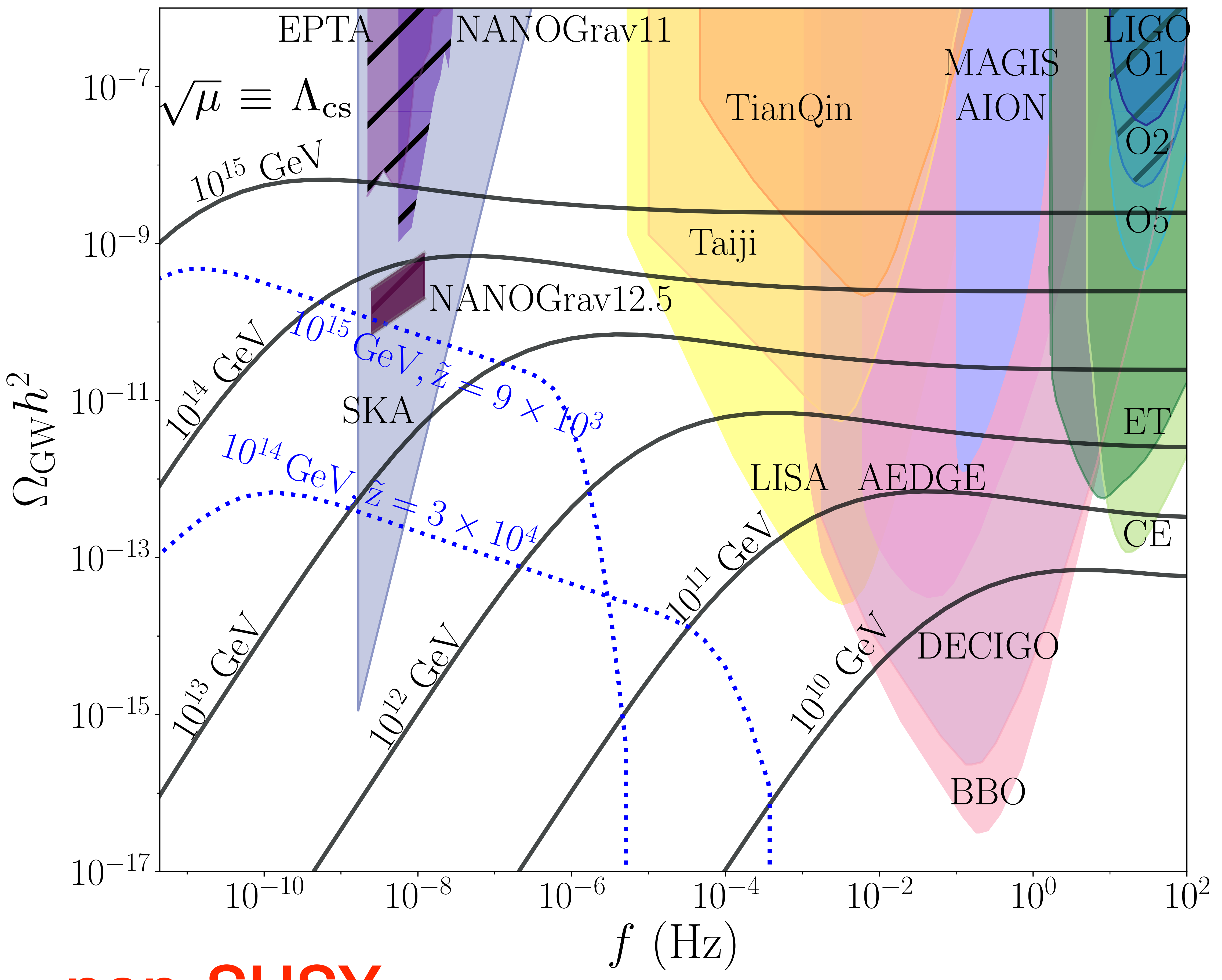
- String loops radiate GWs



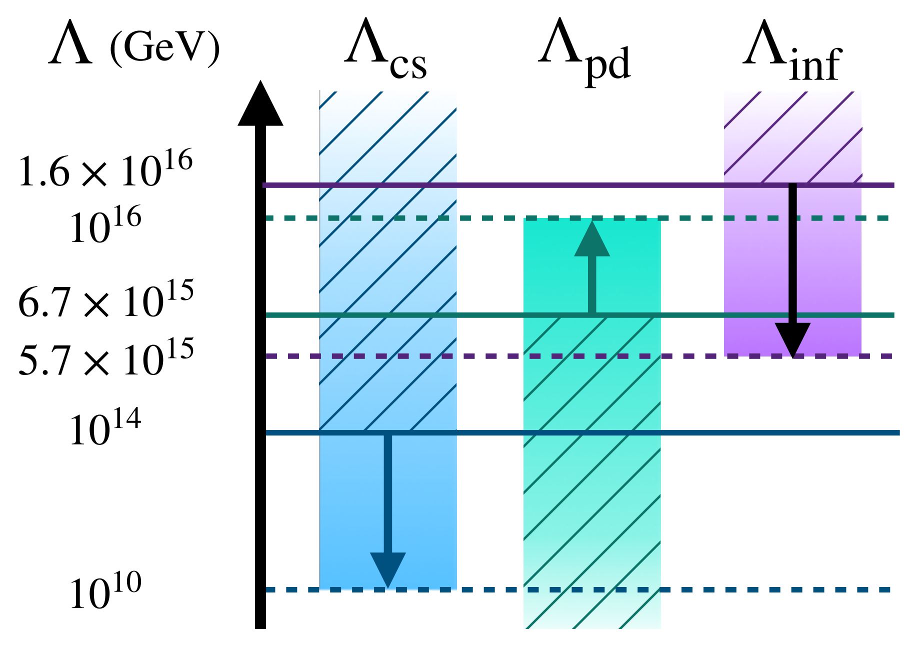
GWs via CSs from gauged $U(1)_{B-L}$ in SO(10) GUTs

S.F.K., S.Pascoli, J.Turner and Y.L.Zhou, 2005.13549; 2106.15634; w/ Marsili 2209.00021; 2308.05799





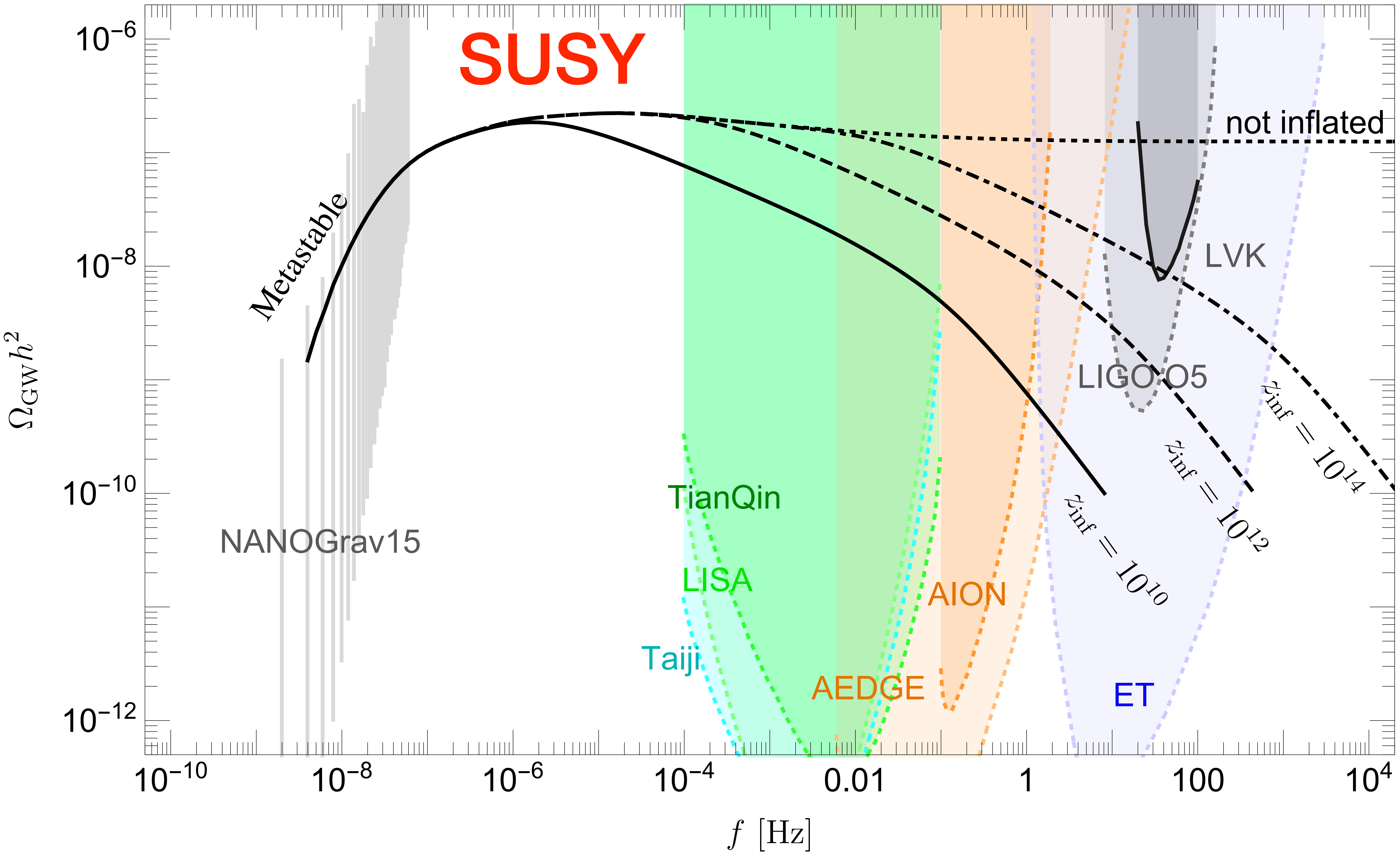
non-SUSY



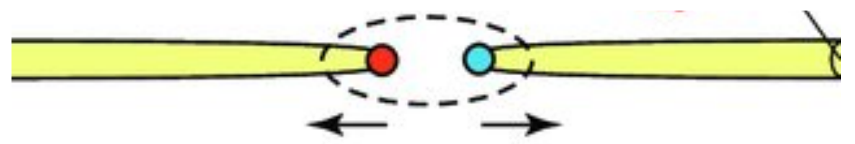
Observables		**Proton decays**
		$p \to \pi^0 e^+$ observed ⇒ non-SUSY contribution indicated
GWs	Observed	• types (a) and (c) favoured • types (b) and (d) excluded
	Marginal	• types (a) and (c) favoured • type (d) excluded • type (b) allowed if $p \to K^+ \bar{\nu}$ not observed and $\Lambda_{pd} \sim \Lambda_{cs}$

Flipped SU(5): unification, proton decay, fermion masses and gravitational waves

S.F.K., G.K.Leontaris and Y.L.Zhou, 2311.11857



Metastable cosmic strings



SUSY GUTs with metastable cosmic strings and inflation dilution can fit NANOGrav 15 year data

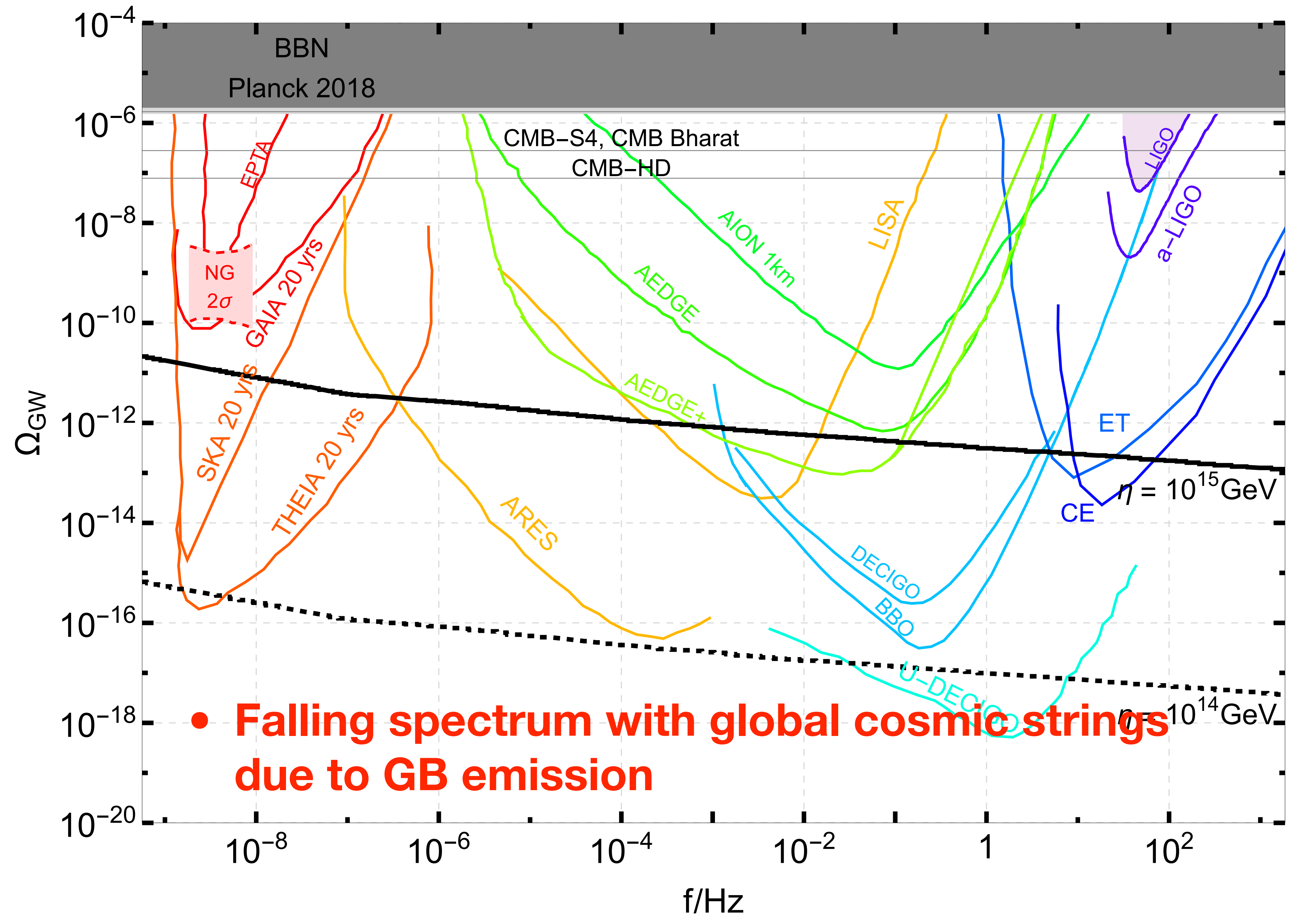
B.Fu, A.Ghoshal and S.F.K.2306.07334

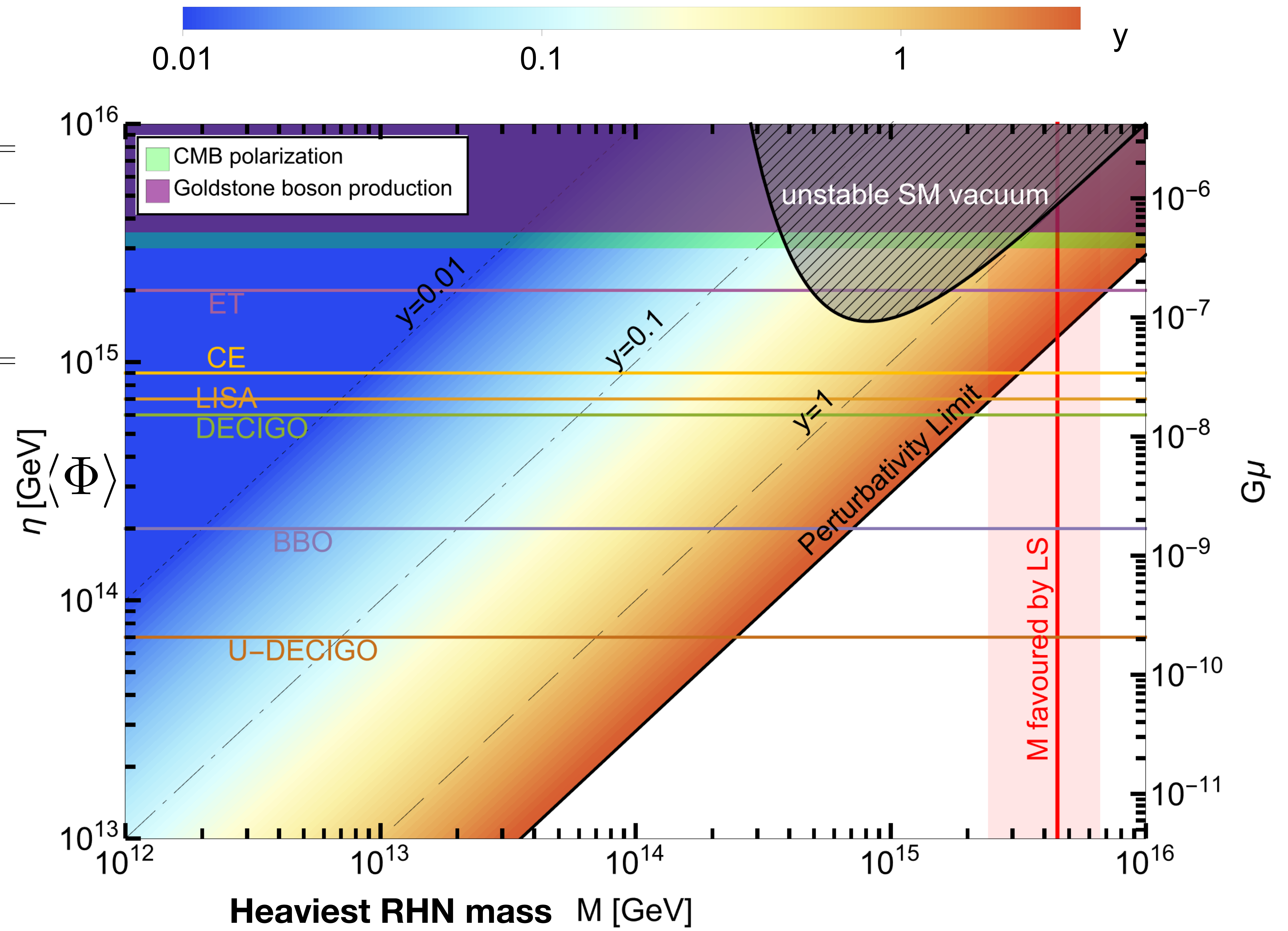
Cosmic string gravitational waves from global $U(1)_{B-L}$ symmetry breaking as a probe of the type I seesaw scale

Majoron breaks $U(1)_{B-L}$

$$Y_{\alpha i}\overline{L_\alpha}\tilde{H}N_i + \frac{1}{2}y_i\Phi\overline{N_i^c}N_i + h.c.$$

	Q	u_R	d_R	L	e_R	H	N	Φ
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**2**	**1**	**1**
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	$-\frac{1}{2}$	0	0
$U(1)_{B-L}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	-1	-1	0	-1	2



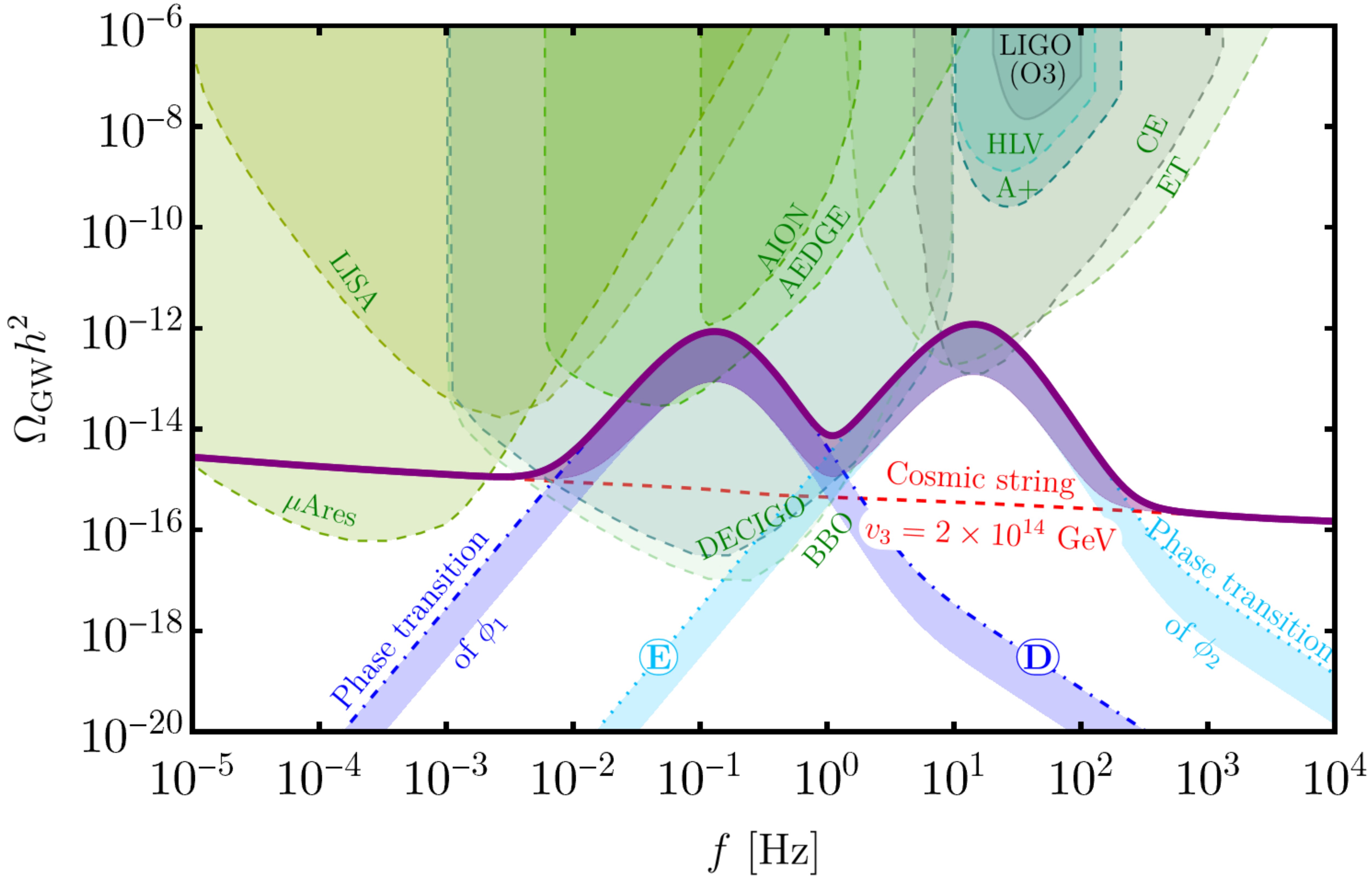


P.Di Bari, S.F.K. and M.H.Rahat, 2306.04680

Gravitational waves from phase transitions and cosmic strings in neutrino mass models with multiple Majorons

$$U(1)_{L_1} \times U(1)_{L_2} \times U(1)_{L_3}$$

$$\left(\overline{L_a} h_{aI} H N_I + \frac{y_1}{2}\phi_1 \overline{N_1^c} N_1 + \frac{y_2}{2}\phi_2 \overline{N_2^c} N_2 + \frac{y_3}{2}\phi_3 \overline{N_3^c} N_3 + \text{h.c.}\right) + V_0(\phi_1, \phi_2, \phi_3)$$

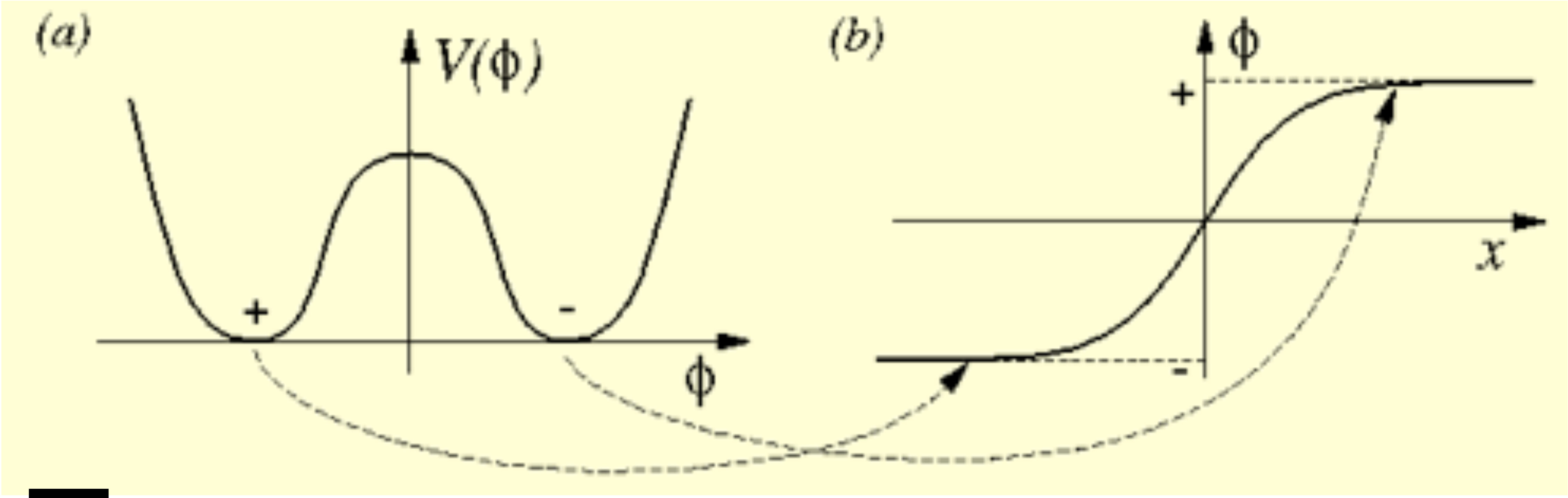


$$\sum_{I=1,2,3} \left[-\mu_I^2 \phi_I^* \phi_I + \lambda_I (\phi_I^* \phi_I)^2\right] + \sum_{I,J,I\neq J}^{1,2,3} \frac{\zeta_{IJ}}{2} (\phi_I^* \phi_I)(\phi_J^* \phi_J)$$

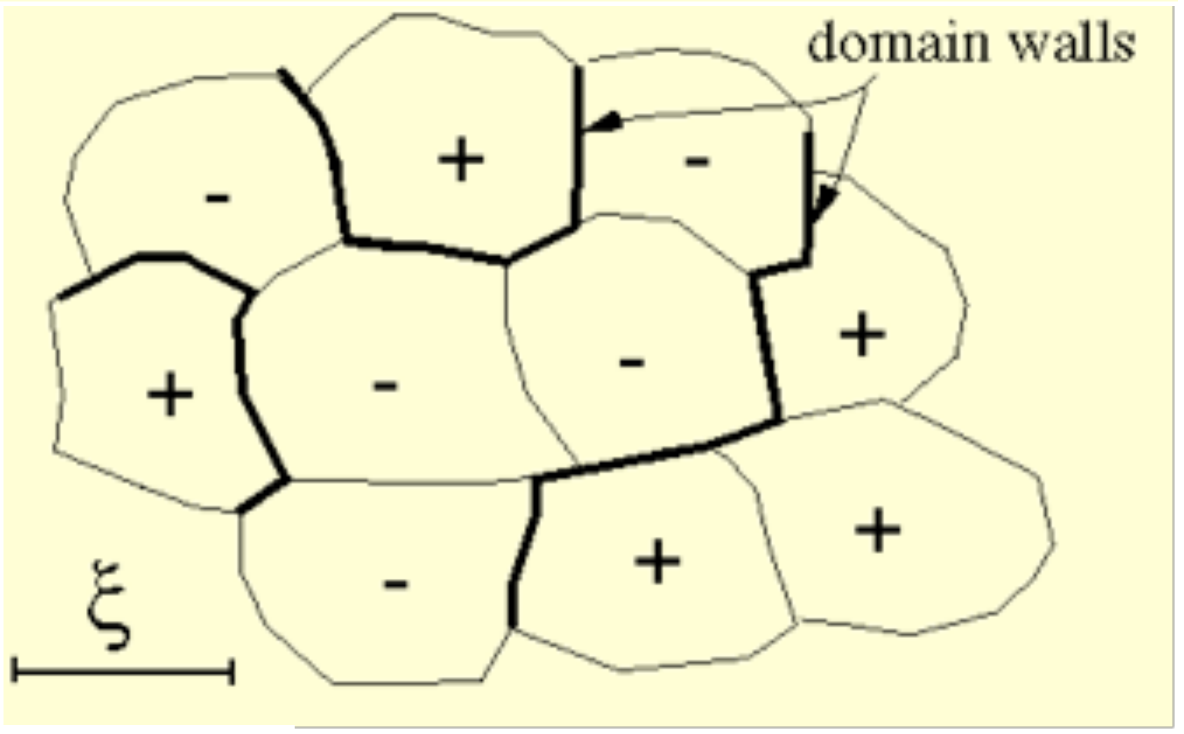
	λ_I	v_I [GeV]
Ⓓ	0.00027	1188.2
Ⓔ	0.00029	2.32×10^5

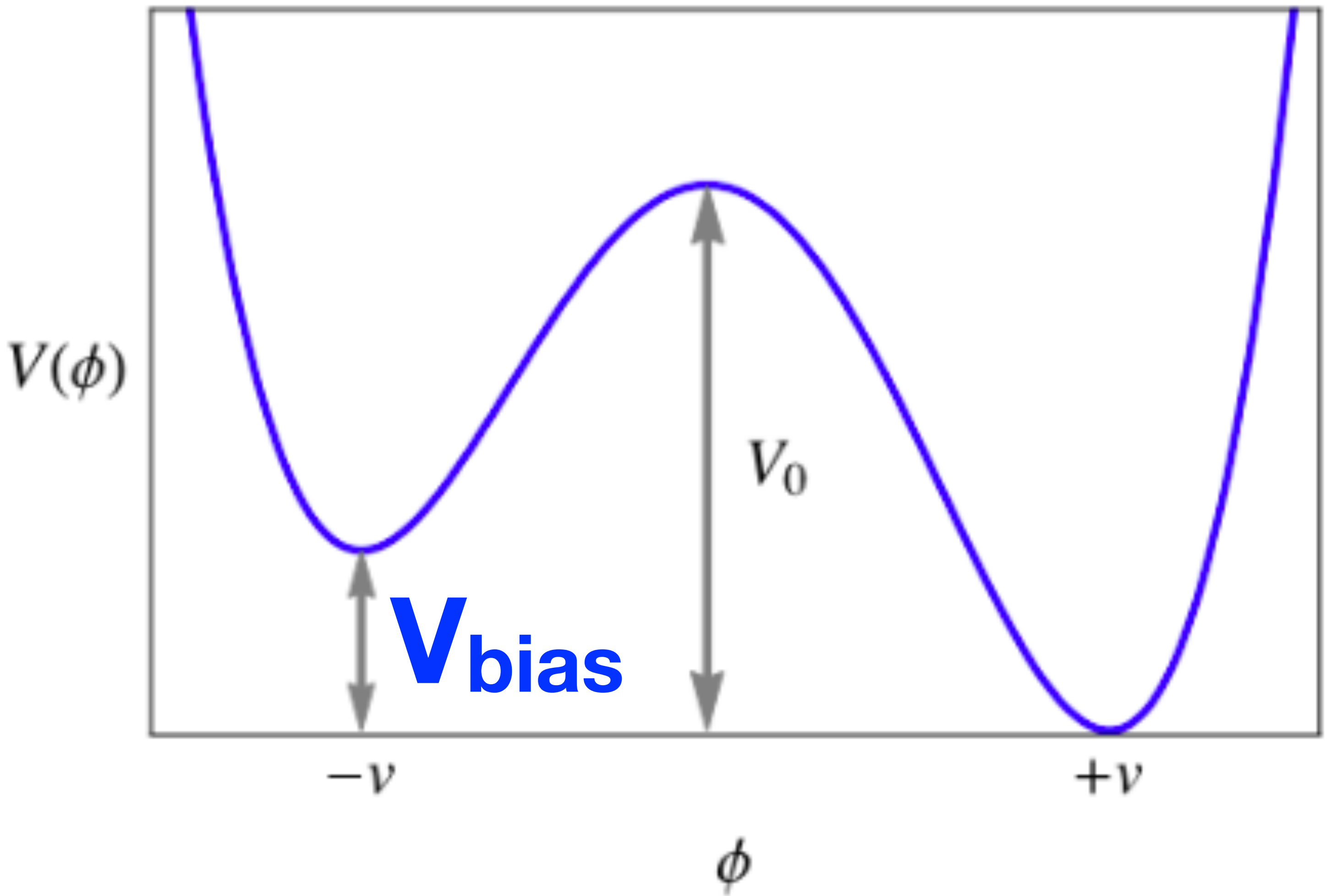
Phase transitions for Φ_1, Φ_2 enhanced by Φ_3

Gravitational Waves from Domain Walls

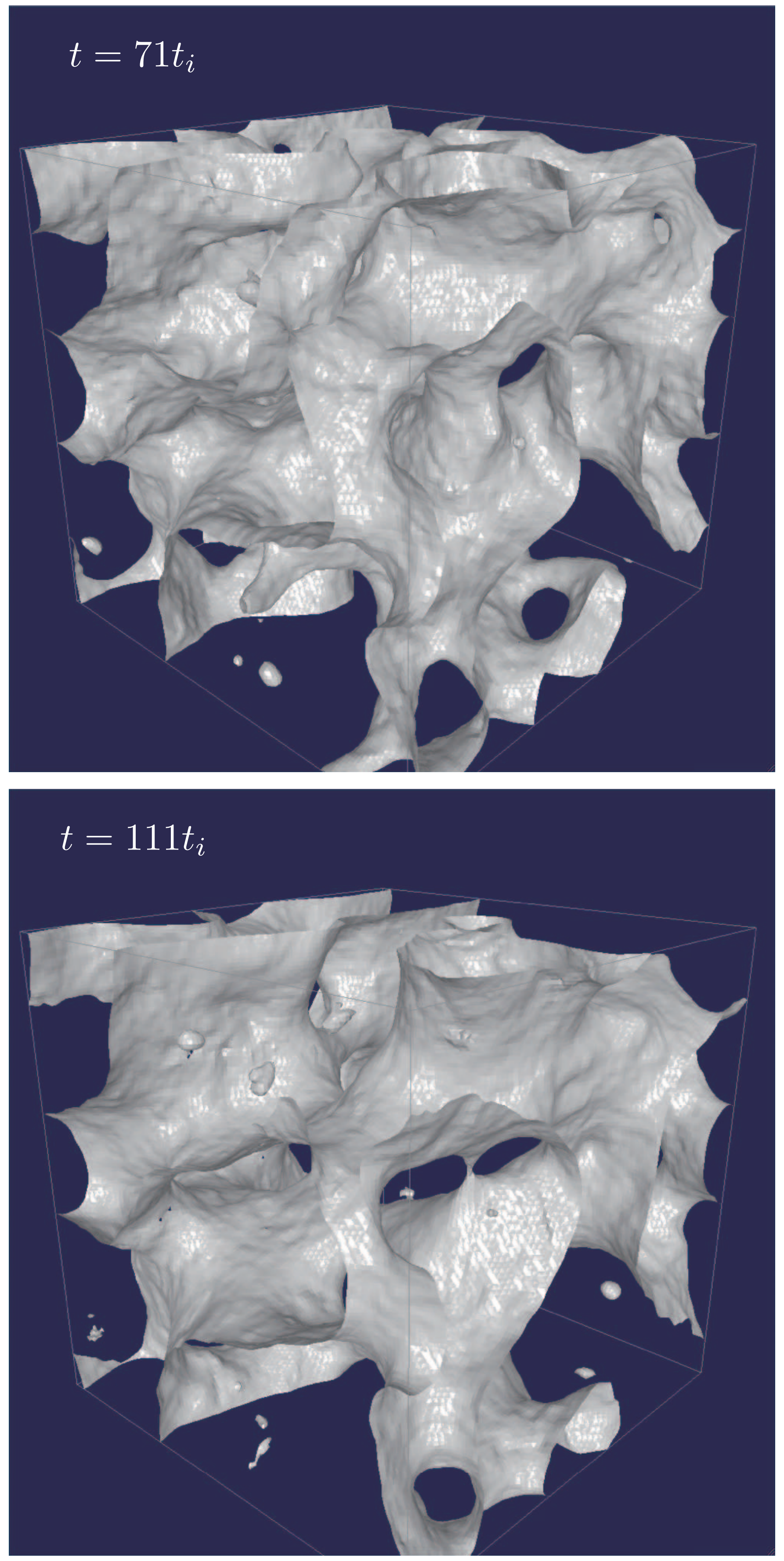


- Z_2 symmetry breaking

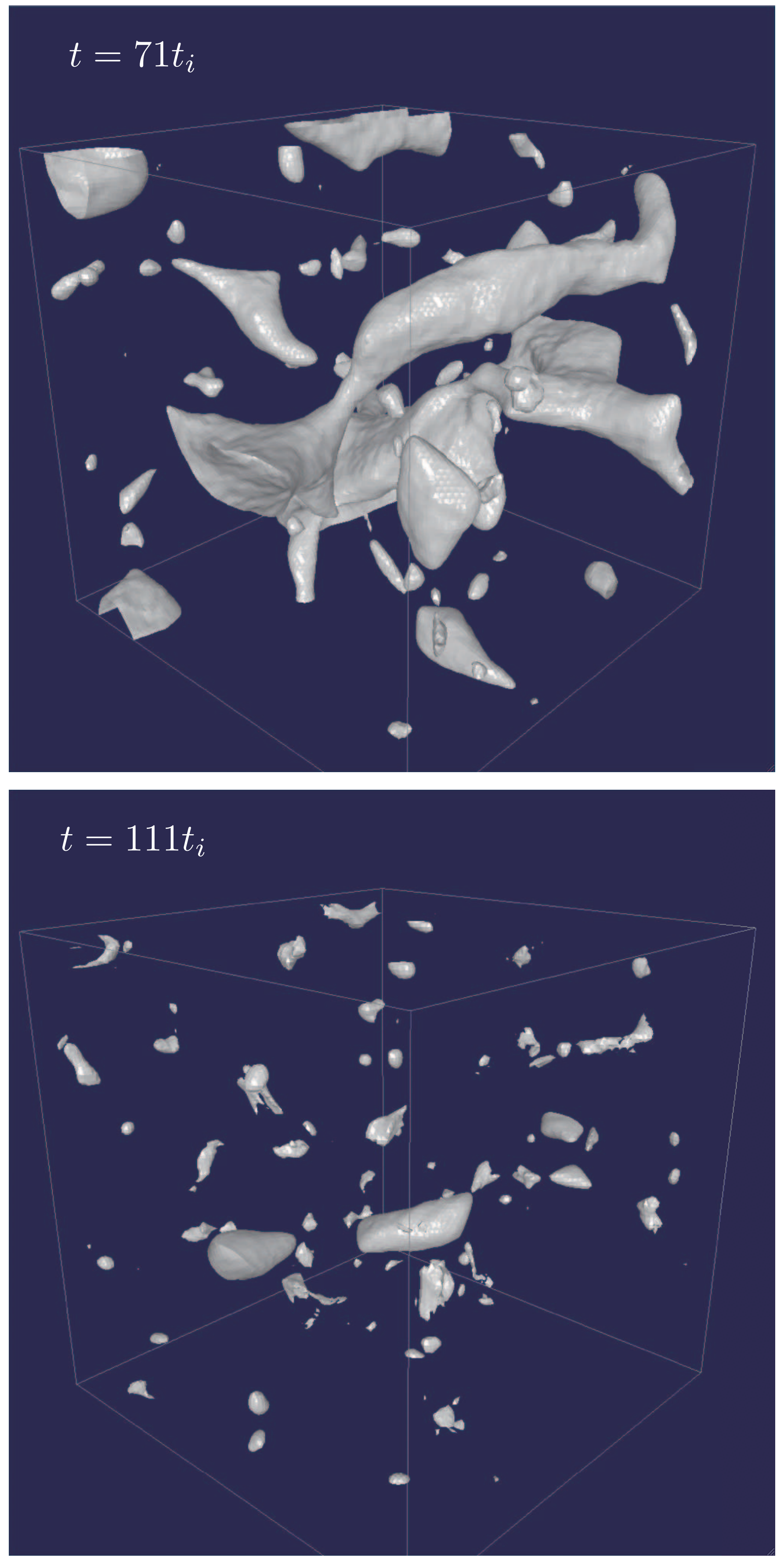




Introduce V_{bias} to allow domain walls to decay (otherwise dominate energy density of Universe)



Stable DW on the left with V_{bias} =0

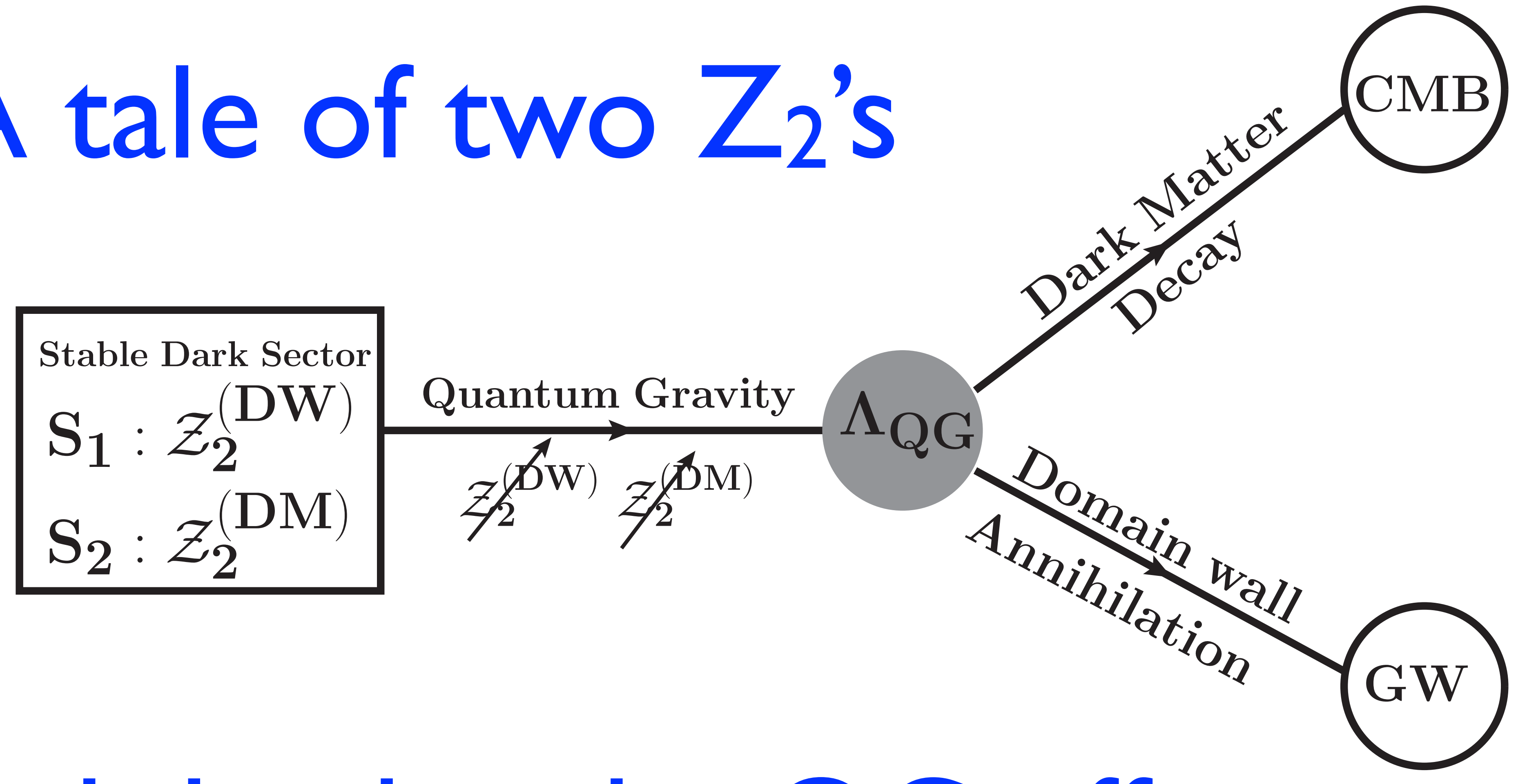


Unstable DW decay via GWs due to V_{bias}

S.F.K., R.Roshan, X.Wang, G.White and M.Yamazaki, 2308.03724; 2311.12487

Quantum gravity effects on dark matter and gravitational waves

A tale of two Z_2's



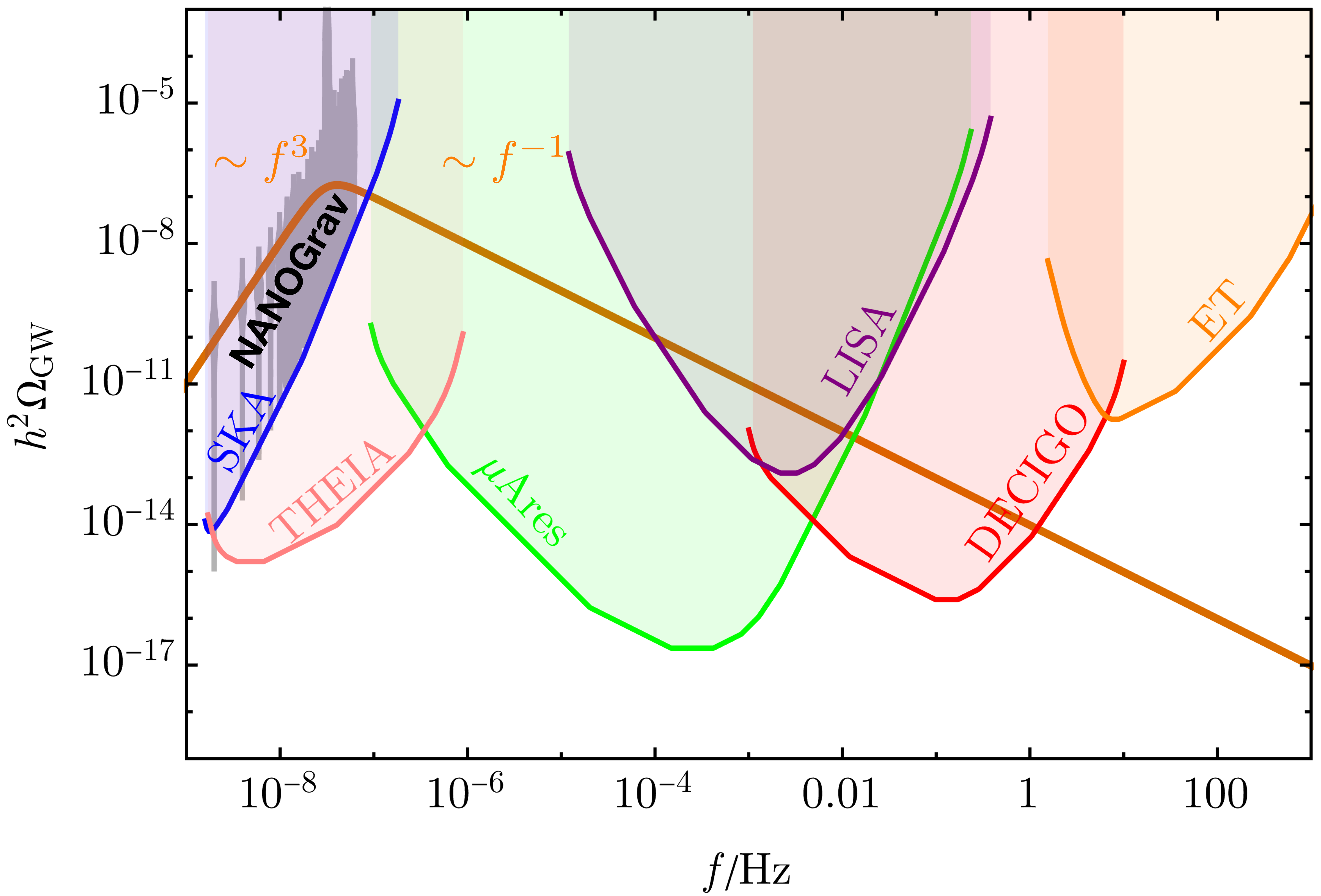
Both broken by QG effects

$$\mathcal{L}_{\not{\mathcal{Z}}_2} = \frac{1}{\Lambda_{QG}} \mathcal{O}_5 \rightarrow V_{bias}$$

Due to instanton effects

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

Peak occurs when volume pressure ~ V_{bias}

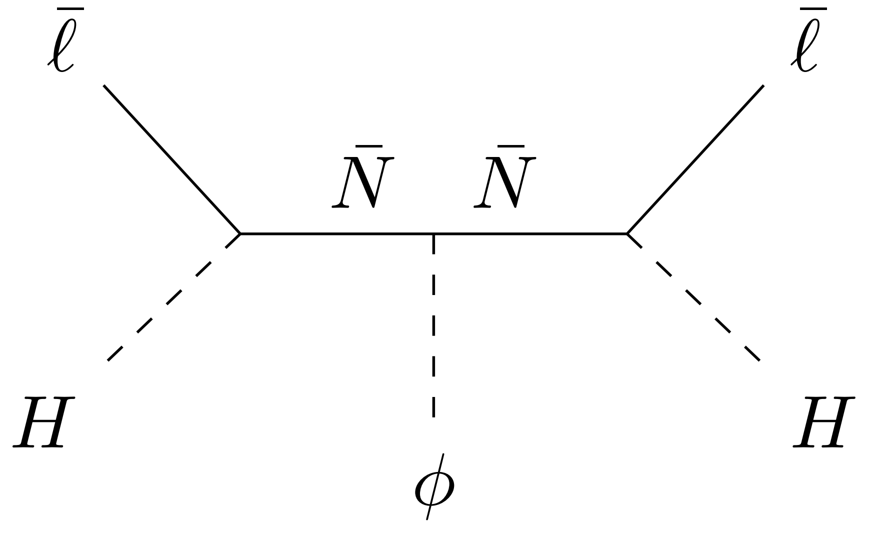


S.F.K., D.Marfatia and M.H.Rahat, 2306.05389

Toward distinguishing Dirac from Majorana neutrino mass with gravitational waves

Majorana seesaw

$$-\mathcal{L}_M \supset \mathcal{Y}\;\bar{\ell} H \bar{N} + \bar{N}\bar{N}^T\phi$$



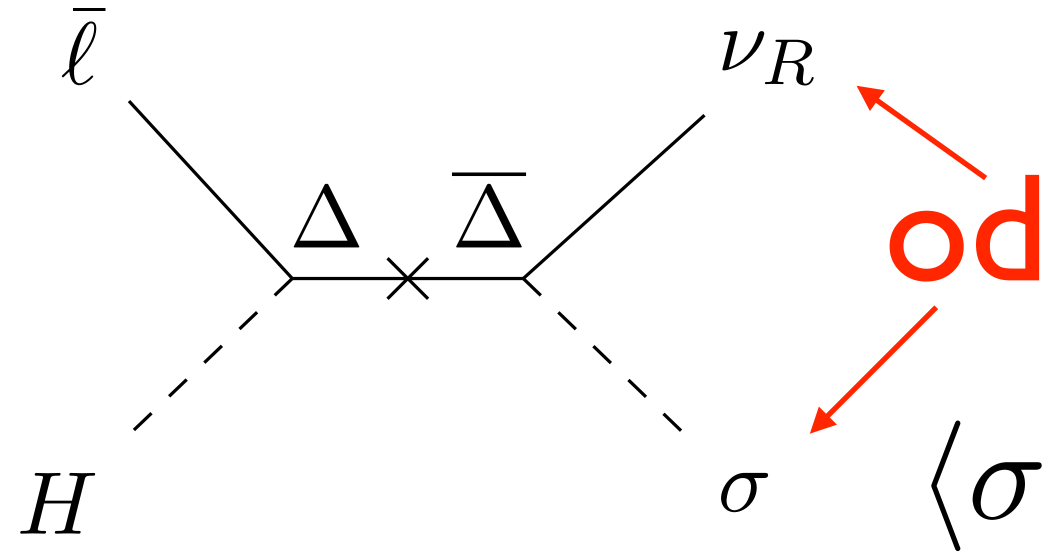
$$\mathcal{M}_M = \frac{1}{\sqrt{2}} v^2\;\mathcal{Y}\;\mathcal{M}_N^{-1}\;\mathcal{Y}^T$$

Gauged $U(1)_{B-L}$ broken

→Cosmic strings

Dirac seesaw

$$-\mathcal{L}_D \supset \mathcal{Y}_L \bar{\ell} H \Delta_R + \mathcal{Y}_R \overline{\Delta}_L \sigma \nu_R + \mathcal{M}_\Delta \overline{\Delta}\Delta$$



odd under Z_2

$\langle\sigma\rangle = u$ breaks Z_2

$$\mathcal{M}_D = \frac{1}{\sqrt{2}}\; v\; u\; \mathcal{Y}_L \mathcal{M}_\Delta^{-1} \mathcal{Y}_R$$

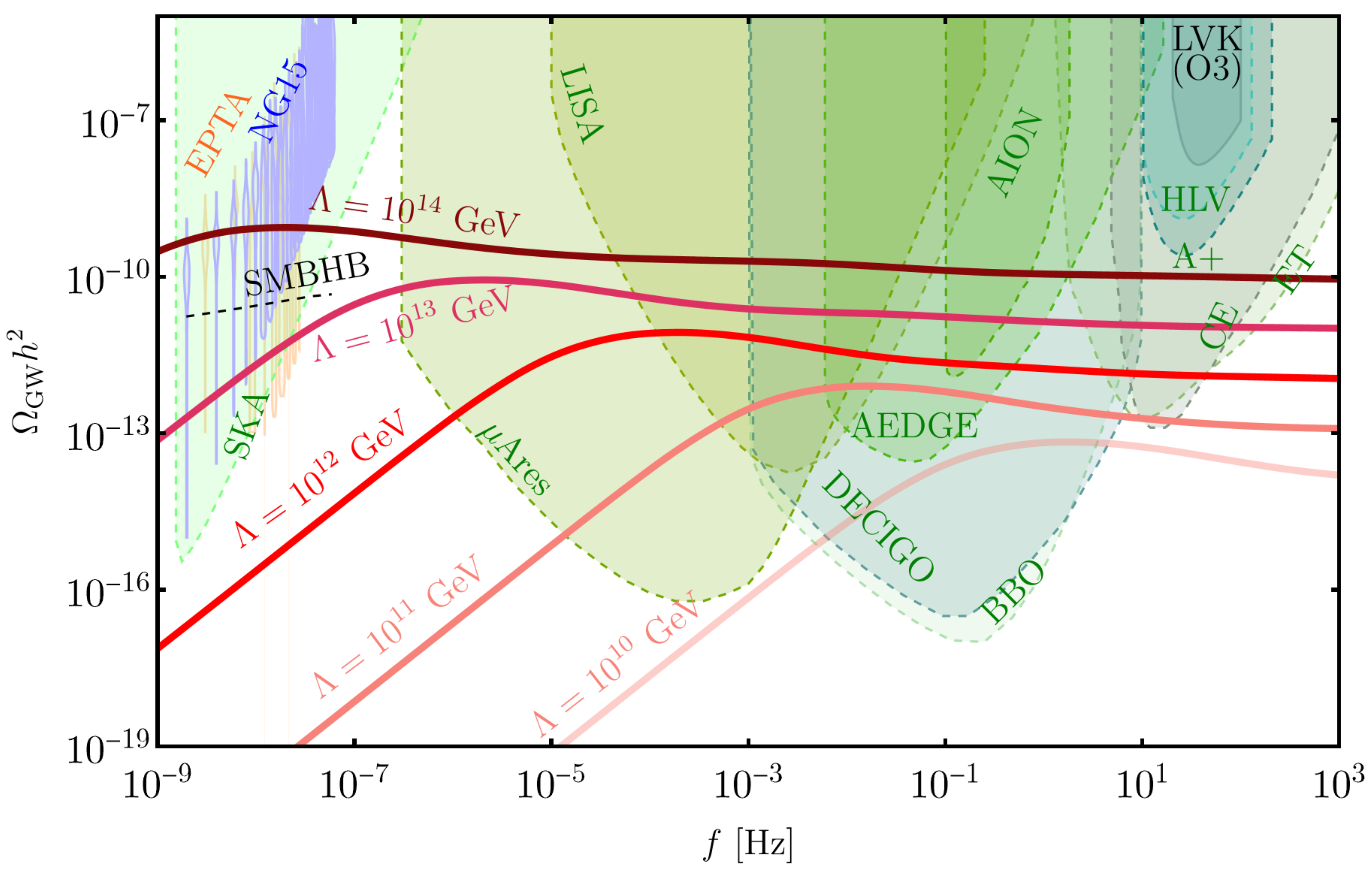
Global $U(1)_{B-L}$ preserved

Z_2 broken → Domain Walls

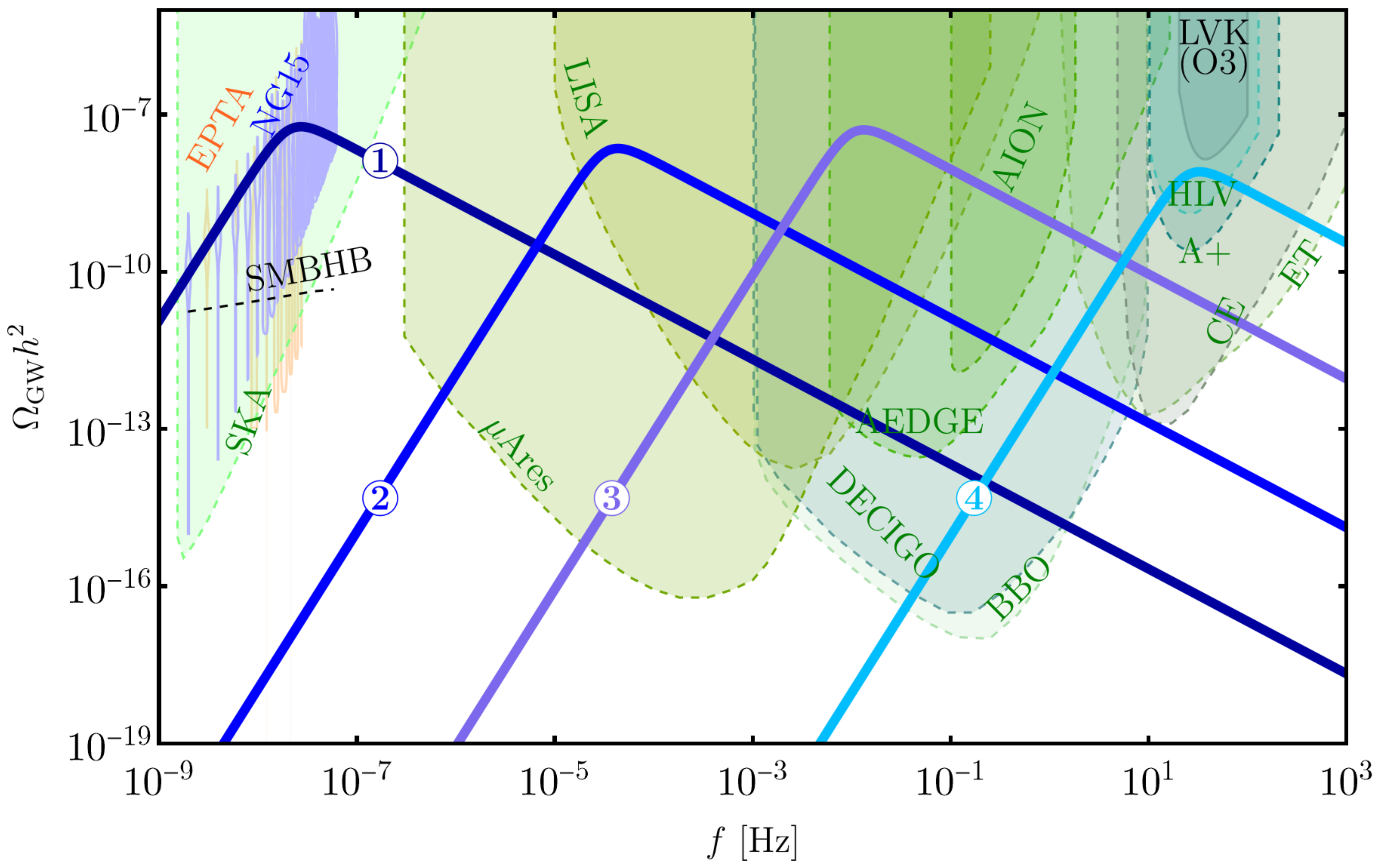
S.F.K., D.Marfatia and M.H.Rahat, 2306.05389

Toward distinguishing Dirac from Majorana neutrino mass with gravitational waves

Majorana seesaw



Dirac seesaw



Benchmark Point	u [GeV]	$V_{\rm bias}$ [GeV^4]	$y_{\rm max}(M_\Delta < M_{\rm Pl})$
①	10^5	10^{-5}	4.93
②	5.2×10^7	7.14×10^{10}	0.216
③	1.2×10^9	10^{19}	0.045
④	2×10^{11}	2.5×10^{32}	0.0035

$$V(\sigma) = \frac{\lambda}{4}(\sigma^2 - u^2)^2 \qquad \Delta V(\sigma) = \epsilon u \sigma \left(\frac{\sigma^2}{3} - u^2\right)$$

Majorana vs Dirac can be distinguished from shape of GW spectrum

- - Dirac is better fit to NANOGrav

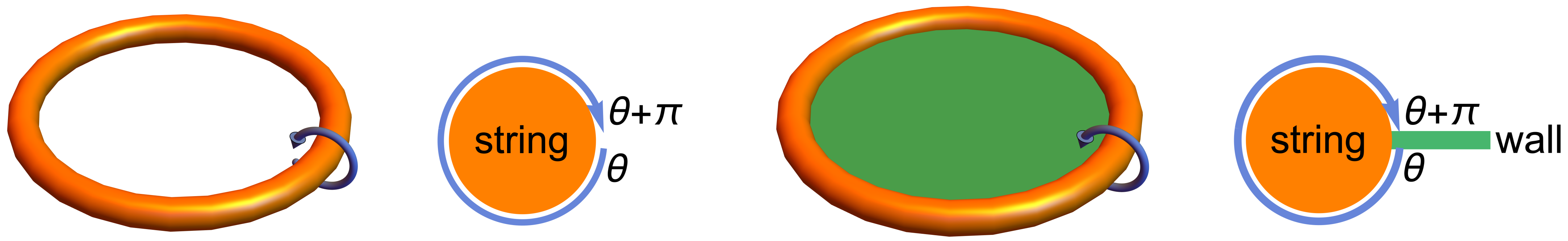
B.Fu, A.Ghoshal, S.F.K. and M.H.Rahat, 2404.16931

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

$$Y_u \overline{Q}\tilde{\Phi}_2 u_R + Y_d \overline{Q}\Phi_2 d_R + Y_e \overline{L}\Phi_2 e_R + Y_N \overline{L}\tilde{\Phi}_2 N_R + y_N \phi N_R N_R$$

	$u_{R\beta}$	$d_{R\beta}$	Q_α	L_α	$e_{R\beta}$	$N_{R\beta}$	Φ_2	Φ_1	ϕ
$SU(2)_L$	**1**	**1**	**2**	**2**	**1**	**1**	**2**	**2**	**1**
$U(1)_Y$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{6}$	$-\frac{1}{2}$	-1	0	$\frac{1}{2}$	$\frac{1}{2}$	0
$U(1)_R$	1	-1	0	0	-1	1	1	-1	-2
residual Z_2	$-$	$-$	$+$	$+$	$-$	$-$	$-$	$-$	$+$

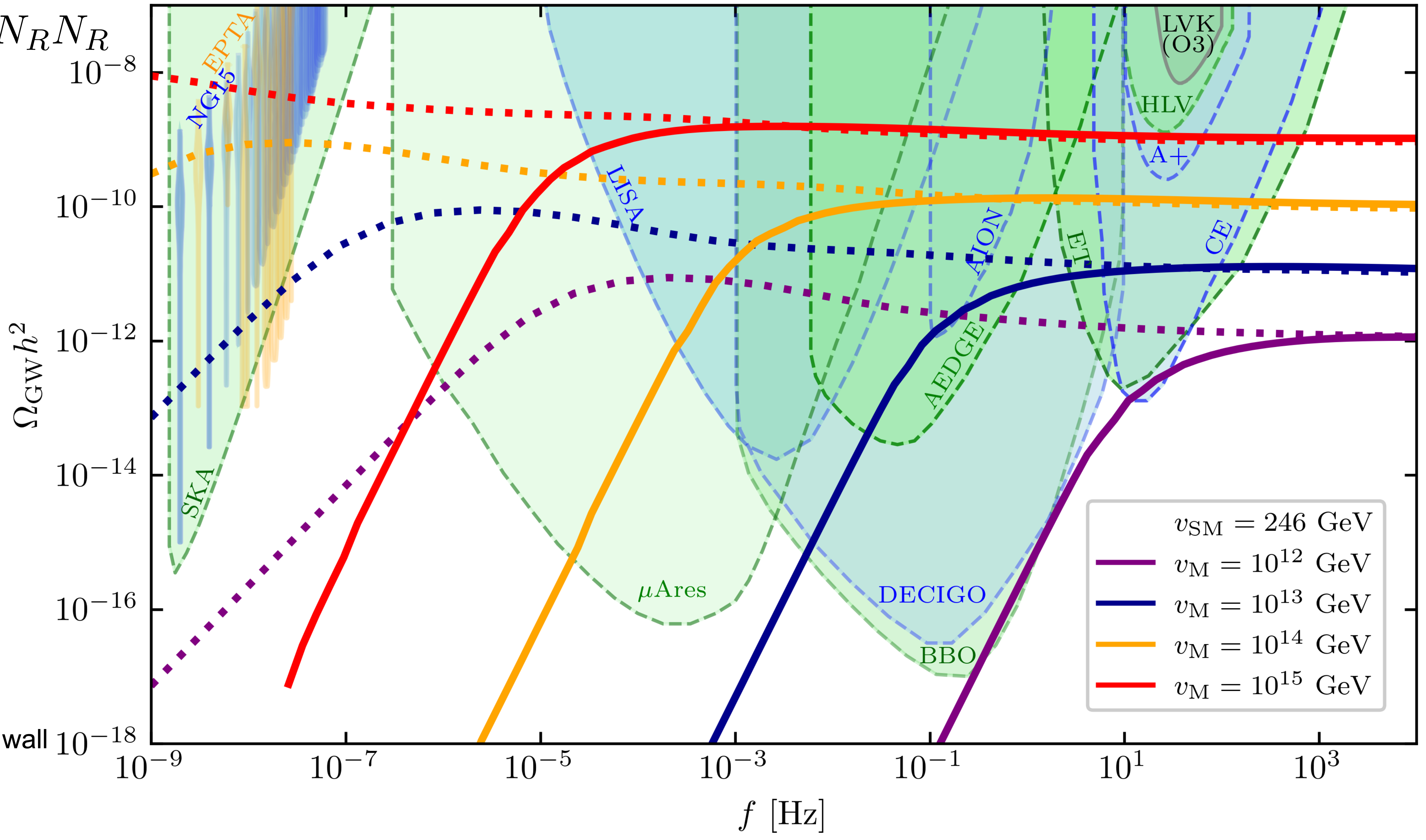
$$U(1)_R \xrightarrow{\langle\phi\rangle} Z_2 \xrightarrow{\langle\Phi_i\rangle} \text{nothing}$$



Vilenkin and Everett 1982

(a) Before Z_2 symmetry breaking.

(b) After Z_2 symmetry breaking.

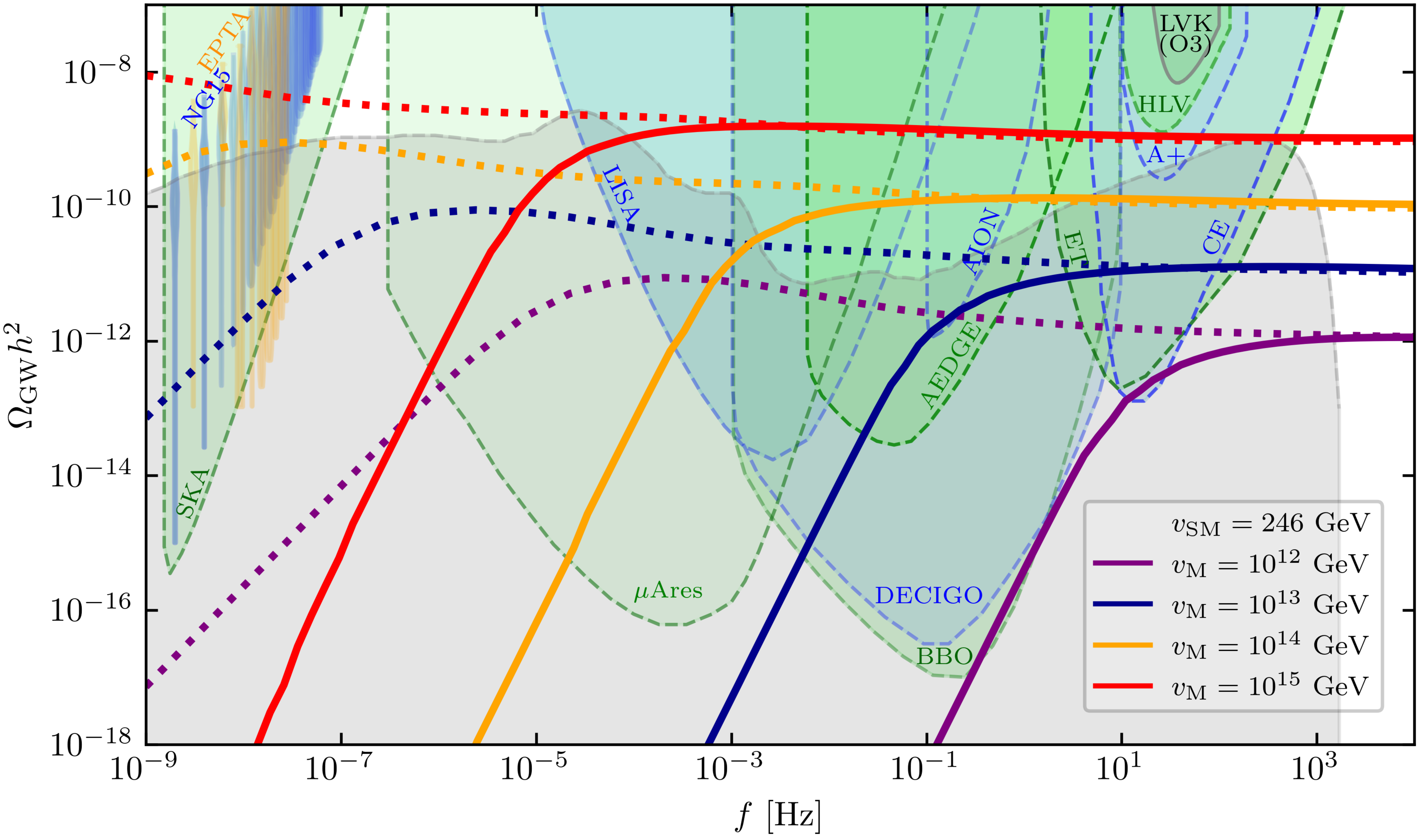


DW decay without $V_{\rm bias}$!

Surface tension in the walls causes the combined relic to decay earlier than strings

Conclusion

- GWs can probe new physics BSM at HE, only a few examples here: FOPT, CS, DW (+combos)
- FOPT at QCD scale can describe NANOGrav
- CS $U(1)_{B-L}$ gauged w/GUTs; global w/Majorons
- DW Z_2 w/QG bias; Majorana vs Dirac
- DW bounded by CS in 2HDM (type I)



$\Omega_{\rm GW} h^2$
f [Hz]
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^{1}
10^{3}
EPTA
NG15
SKA
LISA
μAres
DECIGO
BBO
AEDGE
AION
ET
CE
A+
HLV
LVK (O3)
$v_{\rm SM} = 246$ GeV
$v_{\rm M} = 10^{12}$ GeV
$v_{\rm M} = 10^{13}$ GeV
$v_{\rm M} = 10^{14}$ GeV
$v_{\rm M} = 10^{15}$ GeV