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ICTP-AP
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国际理论物理中心-亚太地区

Electroweak Phase Transition and Baryogenesis

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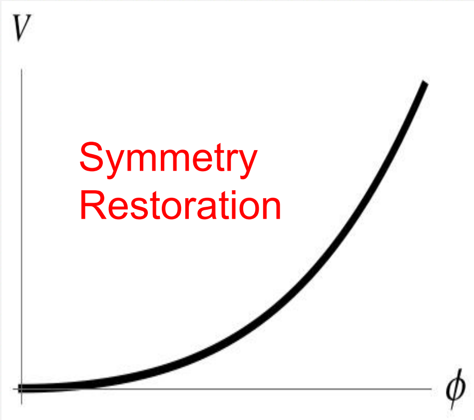
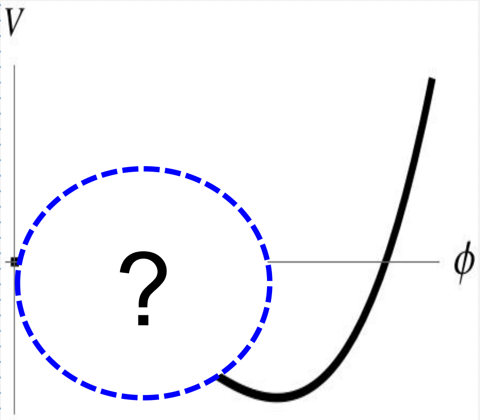
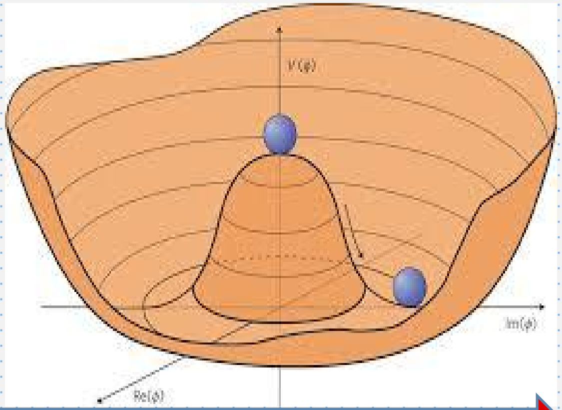
Sun Yat-sen University Zhuhai Campus

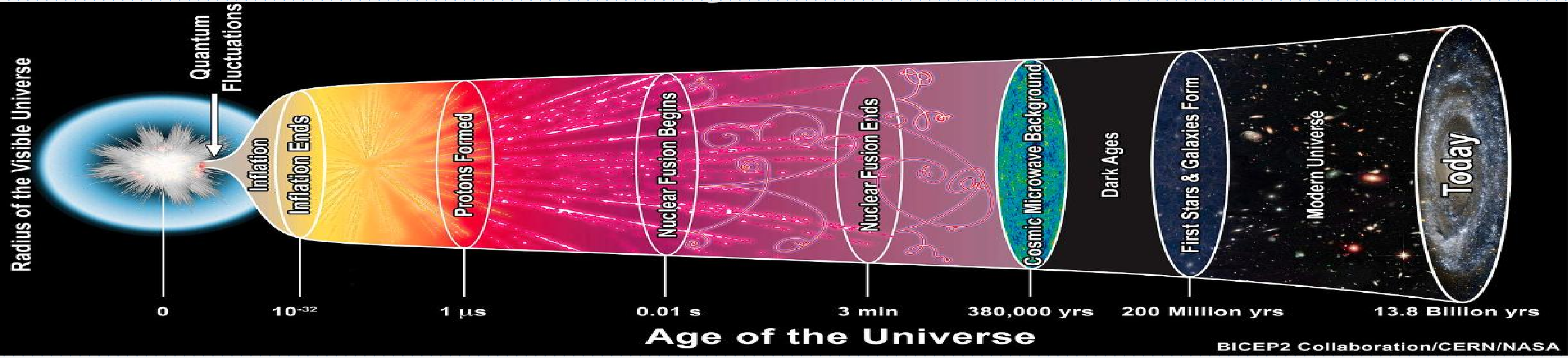
Electroweak Phase Transition



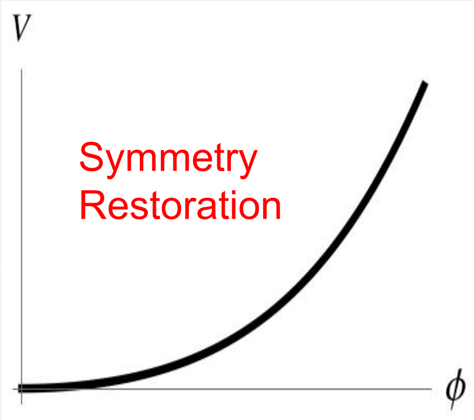


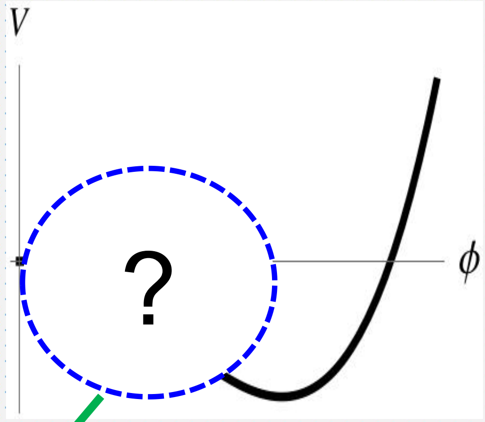


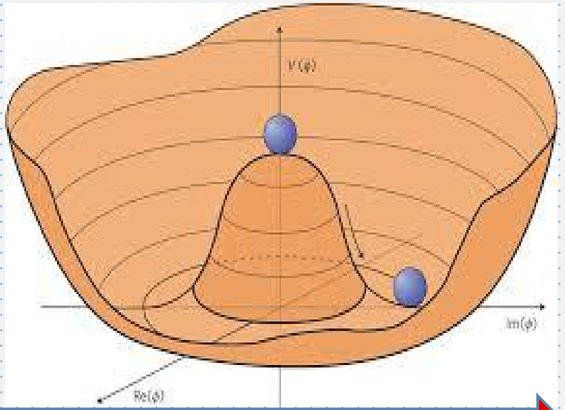
Temperature drops



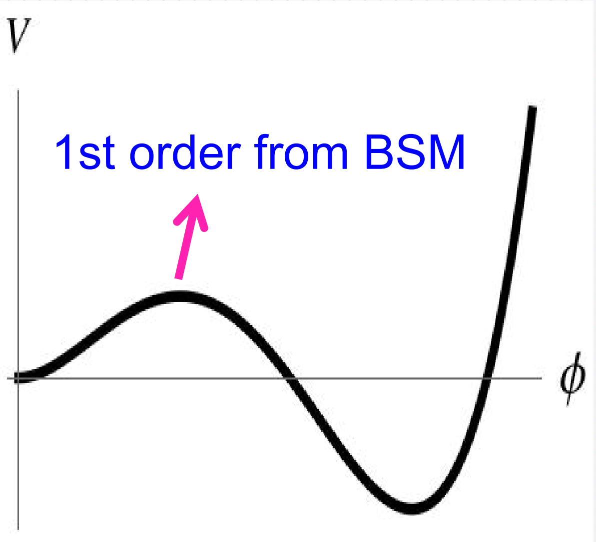
Electroweak Phase Transition



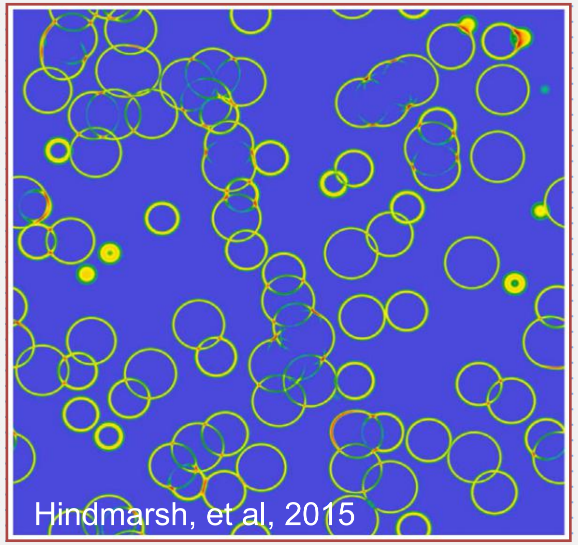




Temperature drops



bubbles, plasma, MHD

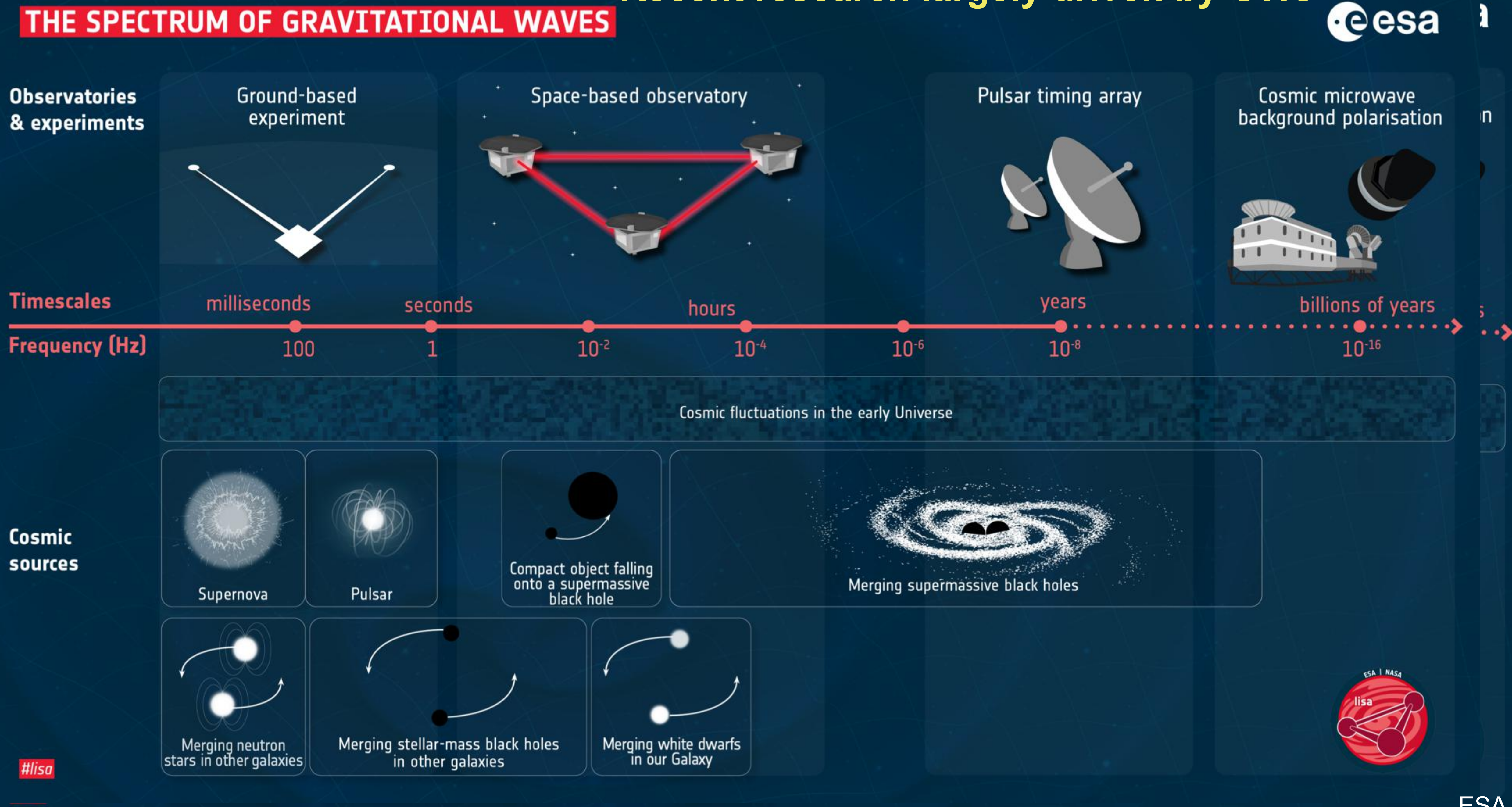


Electroweak Baryogenesis

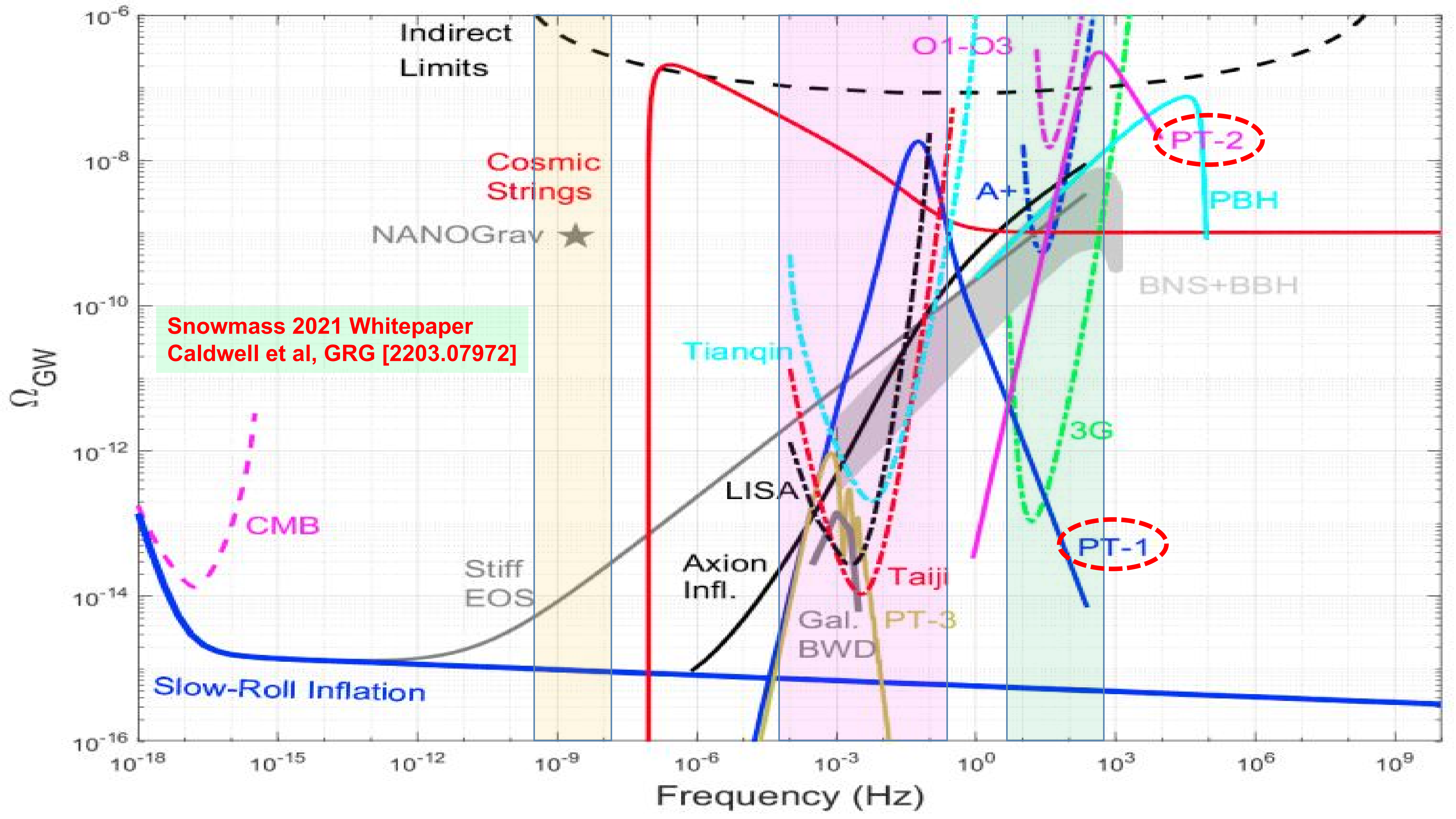
- Modified Higgs potential (Higgs physics, GW)
- Extra CP-violation (EDM, LHC)
- B-violation: Sphaleron process (LHC, GW)

Morrissey,Ramsey-Musolf, NJP [1206.2942]

Recent research largely driven by GWs



ESA



Indirect Limits
Cosmic Strings
NANOGrav
O1-O3
A+
PT-2
PBH
BNS+BBH
Snowmass 2021 Whitepaper
Caldwell et al, GRG [2203.07972]
Tianqin
3G
LISA
CMB
PT-1
Axion Infl.
Taiji
Stiff EOS
Gal. BWD
PT-3
Slow-Roll Inflation
Ω_{GW}
Frequency (Hz)
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-15}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}

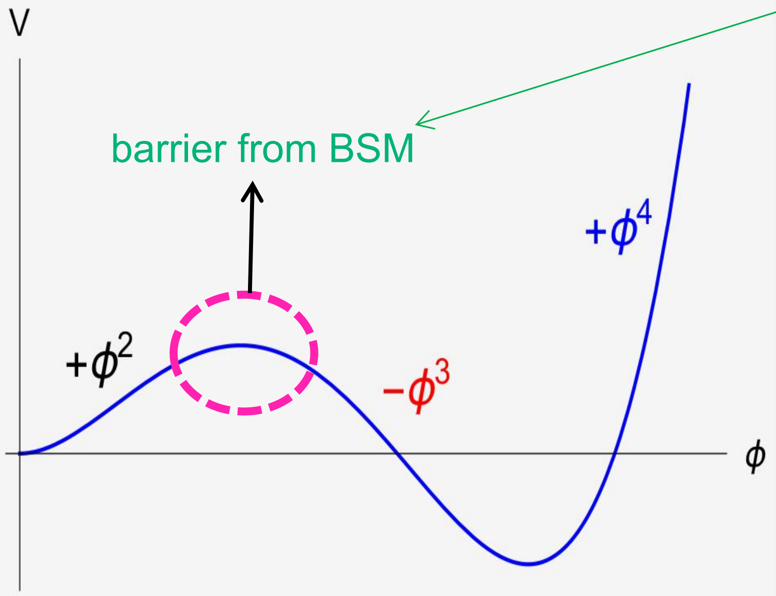
Finite Temperature Effective Potential: Perturbative Method

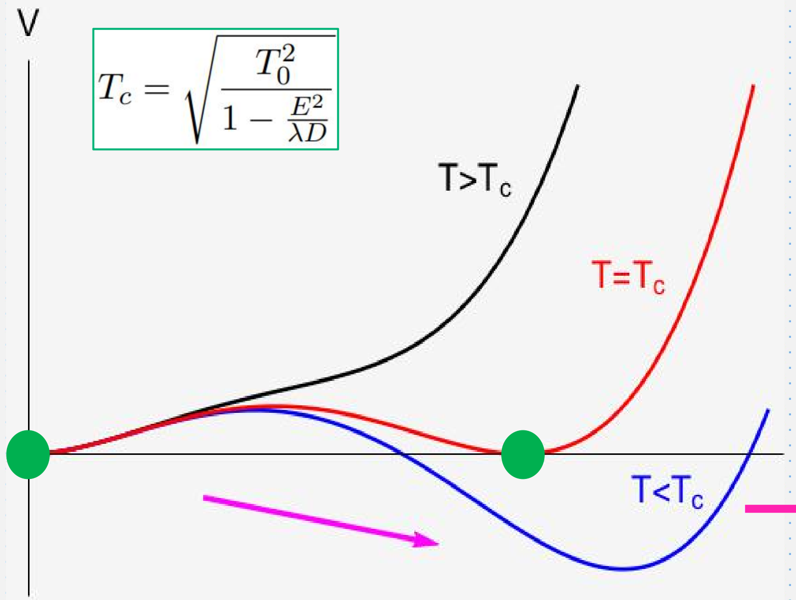
The commonly adopted approach:

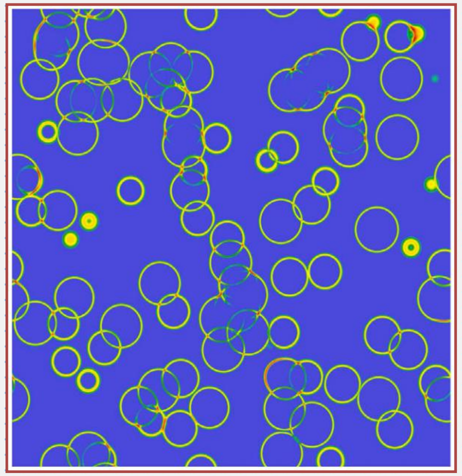
(see, e.g., Morrissey,Ramsey-Musolf, NJP [1206.2942])

$$V_T = V_{\rm tree} + V_{\rm CW} + \frac{T^2}{24}\sum_i c_i M_i^2(\phi) - \frac{T}{12\pi}\sum_j d_j \left[M_j^2(\phi)\right]^{3/2}$$

$$V(\phi,T) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda}{4}\phi^4$$







Hindmarsh et al, 2015

Nucleation rate

$$p = p_0 \exp\left[-\frac{S_{3,b}(T)}{T}\right]$$

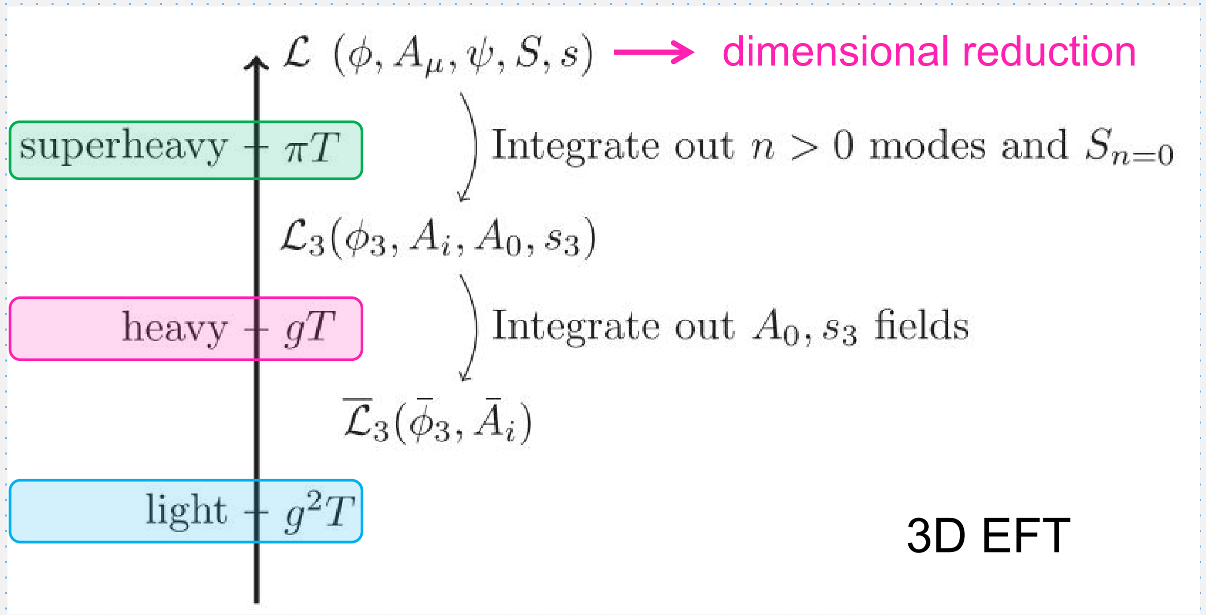
fluctuations

critical bubble

Non-Perturbative Method and Applications to BSMs

- Infrared problem (Linde, 1980)
- Gauge dependence
  (see, e.g., Patel,Ramsey-Musolf, JHEP [1101.4665])

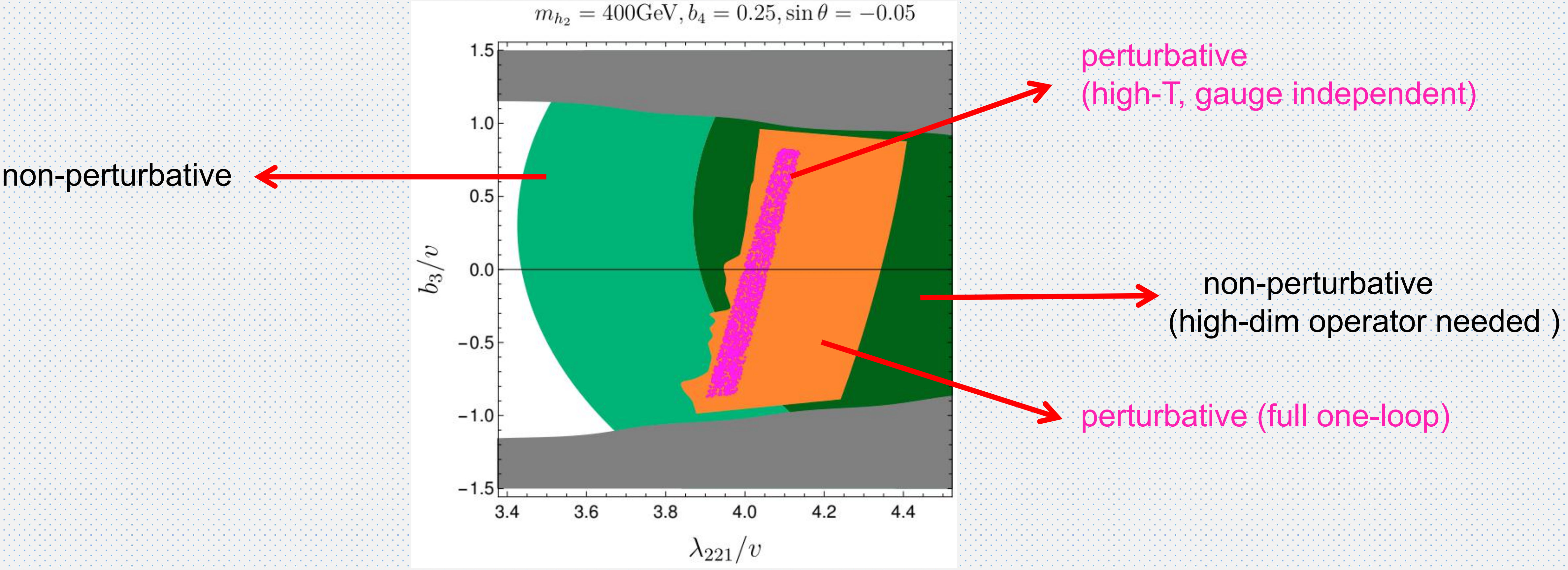
- Non-perturbative method overcomes these problems
- But yet quite limited in BSM studies



Gould,Kozaczuk,Niemi,Ramsey-Musolf,Tenkanen,Weir, PRD [1903.11604]

Dimensional Reduction (Status)		
SM	√	Farakos,Kajantie,Rummukainen,Shaposhnikov (1994)
MSSM	√	Cline,Kainulainen(1996), Losada(1996), Laine (1996)
xSM (SM + Singlet)	√	Brauner,Tenkanen,Tranberg,Vuorinen,Weir, JHEP [1609.06230]
ΣSM (SM + Triplet)	√	Niemi,Patel,Ramsey-Musolf,Tenkanen,Weir, PRD [1802.10500]
2HDM	√	Gorda,Helset,Niemi,Tenkanena,Weir, JHEP [1802.05056]

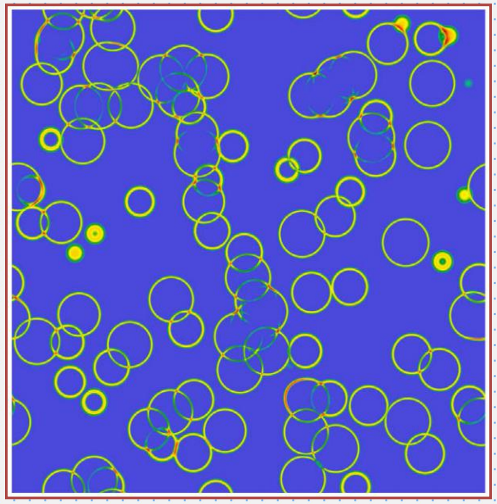
Perturbative vs Non-Perturbative: xSM



Alves,Goncalves,Ghosh,HG,Sinha, JHEP [1909.05268]

Precise Determination of Kinematics

Minkowski spacetime: Hindmarsh,Hijazi, JCAP [1909.10040]
Expanding universe: HG,Sinha,Vagie,White, JCAP [2007.08537]



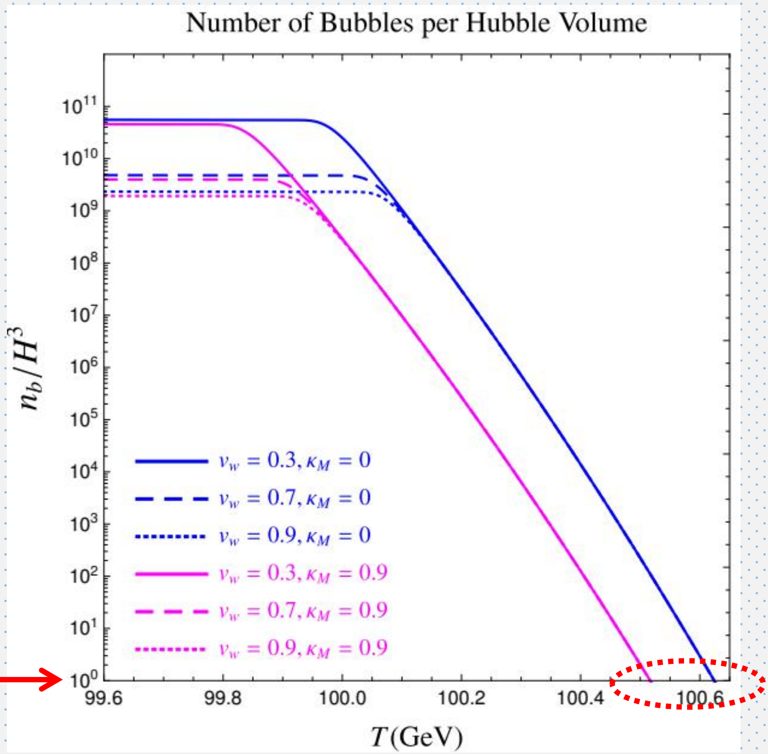
Hindmarsh et al, 2015

Statistical properties

- Bubble Nucleation Rate
- False Vacuum Fraction
- Unbroken Wall Area
- Bubble Lifetime Distribution
- Bubble Number Density and Mean Bubble Separation(R*)

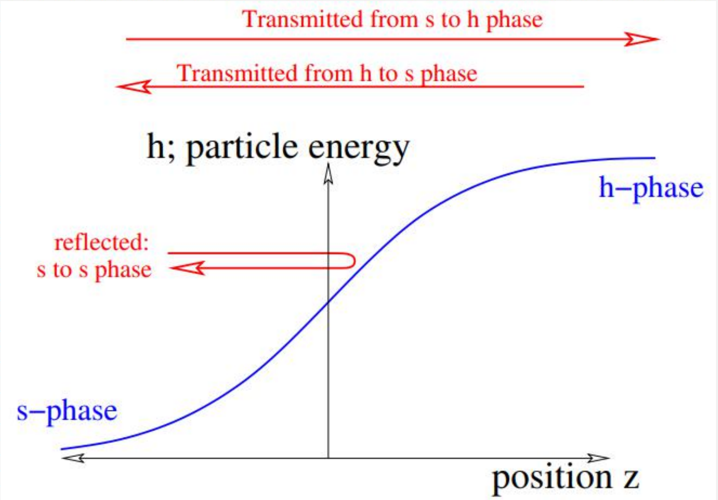
Useful for modelling of the process

Important inputs for GW (or other observables) calculations



1 bubble per Hubble volume
(nucleation temperature Tn)

Wall Velocity: vw



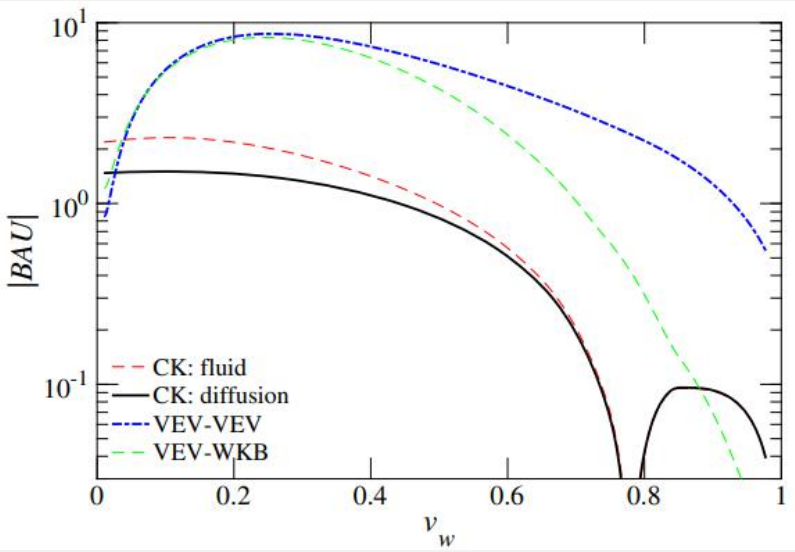
Bodeker,Moore, JCAP [1703.08215]

Usually chosen as given fixed value in EWBG and GW studies

But, significant advances in recent years (driven by GW studies)

$$\Box\phi + V_T'(\phi) + \sum \frac{dm^2}{d\phi} \int \frac{d^3p}{(2\pi)^3 2E} \delta f(p,x) = 0$$

- Friction from out-of-equilibrium (Moore,Prokopec, PRL [9503296]; PRD [9506475])
- Transition radiation (Bodeker,Moore, JCAP [1703.08215])
- All orders resummation (Höche et al, JCAP [2007.10343])
- Lineared distribution or not (Laurent,Cline, PRD [2007.10935]; PRD[2204.13120])
- Singularity or not (Dorsch,Huberb,Konstandin, JCAP [2112.12548], Laurent,Cline)

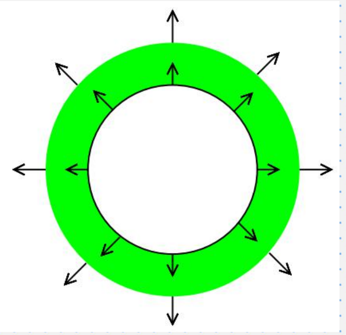


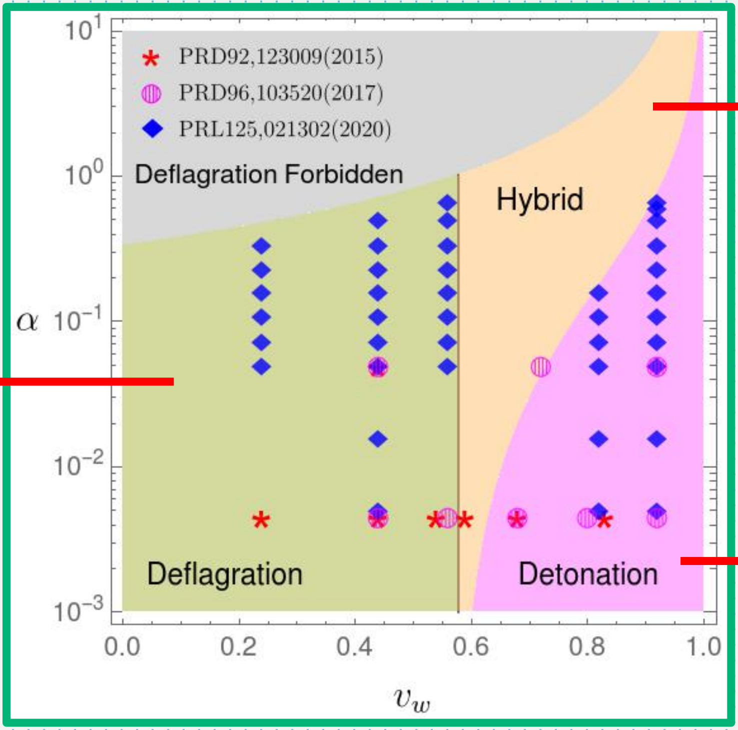
- EWBG generally requires small vw
- Might be possible at relatively large vw, Cline,Kainulainen, PRD [2001.00568]

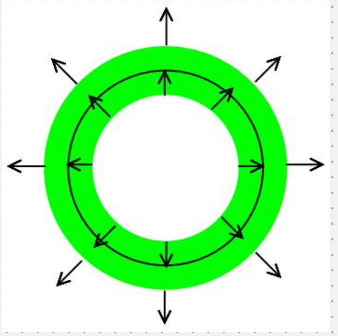
Cline,Kainulainen, PRD [2001.00568]

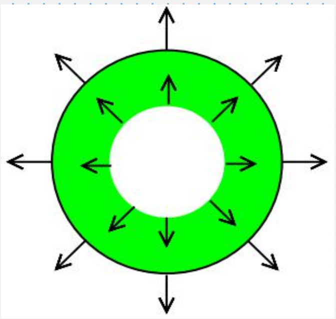
Relativistic Combustion and Simulations

Combined analysis: Espinosa,Konstandin,No,Servant JCAP [1004.4187]









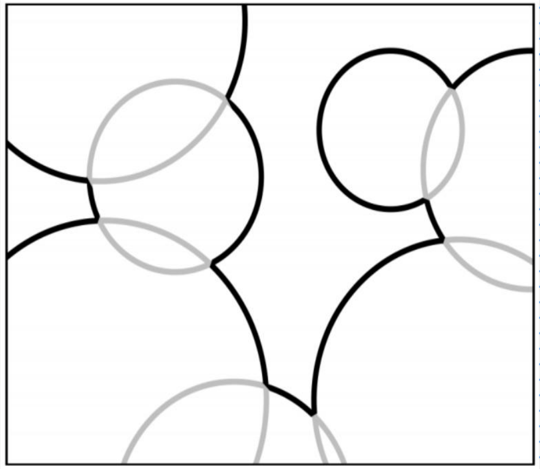
Alves,Goncalves,Ghosh,HG,Sinha, JHEP [1909.05268]

Simulations present clearer picture, and reveal possible new phenomena

Gravitational Wave Sources

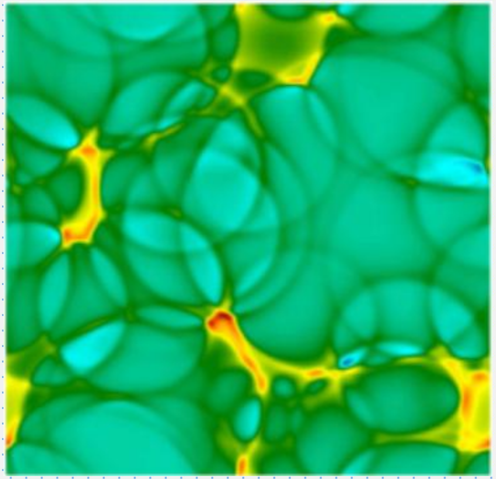
A clearer picture of the PT has been gained from GW studies

Bubble Collisions



energy concentrated at walls

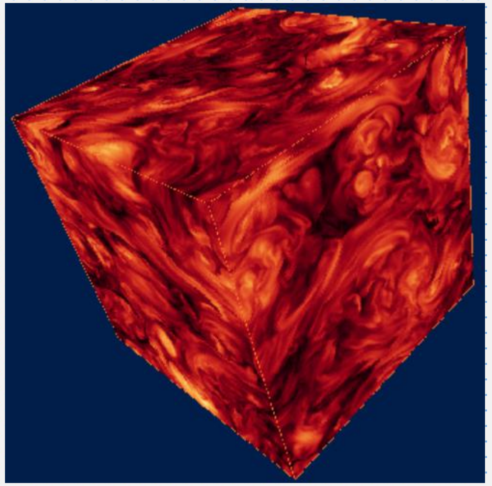
Sound Waves



Hindmarsh, et al,PRL112,041301(2013)

acoustic production

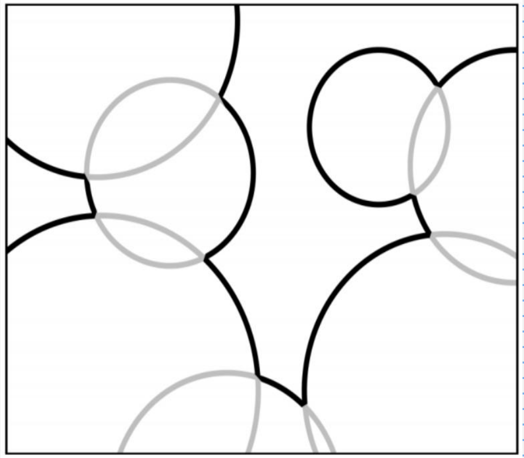
MagnetoHydrodynamic Turbulence



https://home.mpcdf.mpg.de/~wcm/projects/homog-mhd/mhd.html

turbulent motion

Bubble Collisions



Envelope Approximation

Simulations:
Kosowsky, Turner, Watkins, Kamionkowski, PRL69,2026(1992), PRD45,4514(1992), PRD47,4372(1993), PRD49,2837(1994), Huber, Konstandin, JCAP09(2008)022
Analytical Modelling:
Jinno, Takimoto, PRD95,024009(2017)

Beyond the Envelope Approximation

Bulk flow model: Konstandin, JCAP03(2018)047, Jinno, Takimoto, JCAP01(2019)060
Direct large scalar lattice simulations: Cutting, Escartin, Hindmarsh, Weir, PRD97,123513(2018), arXiv:2005.13537

Expanding Universe: Zhong, Gong, Qiu, JHEP02(2022)077

New Phenomena

Di, Wang, Zhou, Bian, Cai, Liu, Phys.Rev.Lett. 126 (2021) 25, 251102
Lewicki, Vaskonen, EPJC 80,1003(2020)
Zhao, Di, Bian, Cai, arxiv:2204.04427

$$\Omega_{\rm coll}(f)h^2 = 1.67\times 10^{-5}\Delta\left(\frac{H_{\rm pt}}{\beta}\right)^2\left(\frac{\kappa_\phi\alpha}{1+\alpha}\right)^2 \times\left(\frac{100}{g_*}\right)^{1/3} S_{\rm env}(f),$$

$$f_{\rm env} = 16.5\left(\frac{f_{\rm bc}}{\beta}\right)\left(\frac{\beta}{H_{\rm pt}}\right)\left(\frac{T_{\rm pt}}{100\ {\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6}\ \mu{\rm Hz},$$

Sound Waves

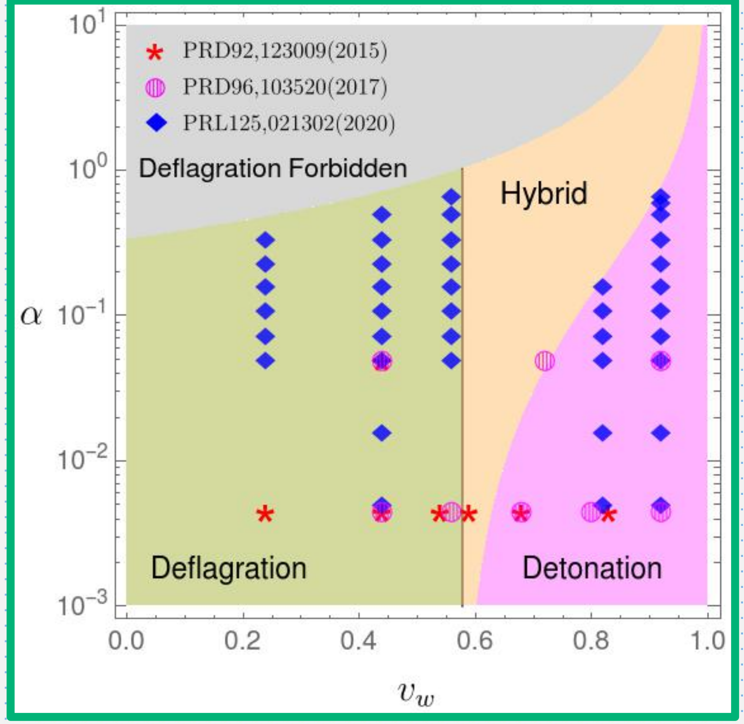
Numerical Simulations:

Hindmarsh, Huber, Rummukainen, Weir,
PRL112, 041301 (2014), PRD92, 123009 (2015), PRD96, 103520 (2017)

Analytical Modelling(sound shell model)

Minkowski: Hindmarsh, 120, 071301 (2018)
Hindmarsh, Hijazi, JCAP12(2019)062

FLRW: HG,Sinha,Vagie,White,JCAP 01 (2021) 001



$$\Omega_{\rm sw}(f)h^2 = 2.65\times10^{-6}\left(\frac{H_{\rm pt}}{\beta}\right)\left(\frac{\kappa_{\rm sw}\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{1/3} \times v_w\left(\frac{f}{f_{\rm sw}}\right)^3\left(\frac{7}{4+3(f/f_{\rm sw})^2}\right)^{7/2}\Upsilon(\tau_{\rm sw}),$$

$$\Upsilon = 1-(1+2\tau_{\rm sw}H_{\rm pt})^{-1/2} \quad \text{(RD)}$$

HG,Sinha,Vagie,White,JCAP 01 (2021) 001

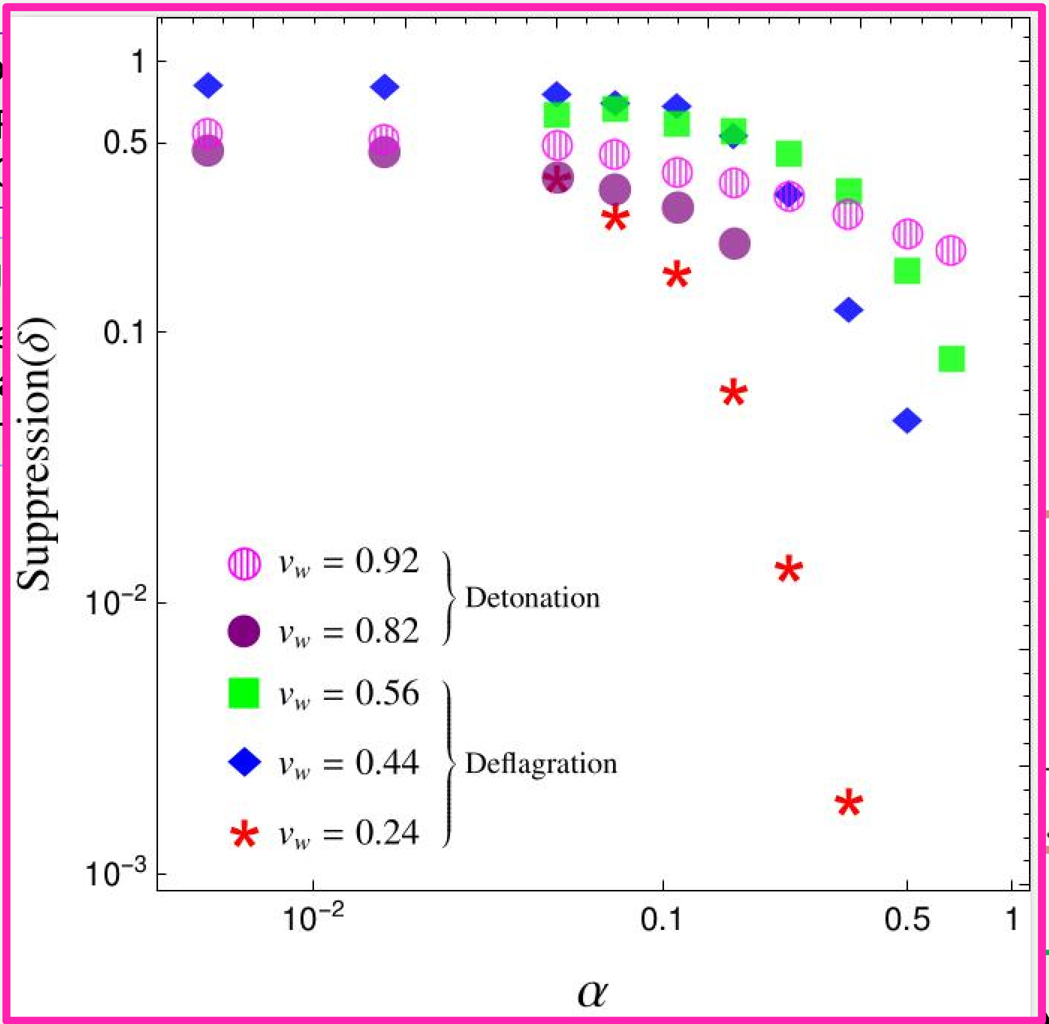
Previous formula enforces an infinite lifetime.

Usually the dominant source for a thermal plasma.

Sound Waves

Numerical Simulatio
Hindmarsh, Huber, I
PRL112, 041301 (20

Analytical Modelling
Minkowski: Hindma
Hindma
FLRW: HG,Sir



- Solve the fluid velocity profile

  modes: detonation, deflagration, hybrid

  Espinosa, Konstandin, No, Servant (JCAP06,028)

- Reduction found for alpha~1 and small vw

  Cutting, Hindmarsh, Weir, PRL125, 021302 (2020)

$$\left(\frac{\kappa_{sw}\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{1/3}$$

$$\left(\frac{7}{\ldots f/f_{sw})^2}\right)^{7/2}\Upsilon(\tau_{sw}),$$

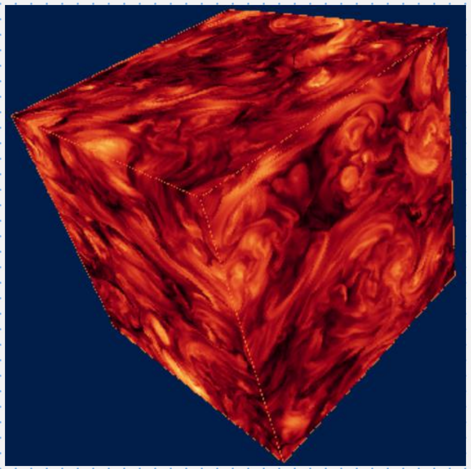
$$\Upsilon = 1-(1+2\tau_{sw}H_{pt})^{-1/2} \quad \text{(RD)}$$

HG,Sinha,Vagie,White,JCAP 01 (2021) 001

Previous formula enforces an infinite lifetime.

The dominant source for a FOPT in a thermal plasma.

Magnetohydrodynamic Turbulence



https://home.mpcdf.mpg.de/~wcm/projects/homog-mhd/mhd.html

Analytical Modelling

Kolmogorov spectrum:
Kosowsky, Mack,Kahniashvili, PRD66,024030(2002)
Gogoberidze, Kahniashvili, Kosowsky, PRD76,083002(2007)
Caprini, Durrer, Servant, JCAP12(2009)024

5%~10% but uncertain

$$h^2\Omega_{\rm turb}(f) = 3.35 \times 10^{-4} \left(\frac{H_*}{\beta}\right) \left(\frac{\kappa_{\rm turb}\,\alpha}{1+\alpha}\right)^{\frac{3}{2}} \left(\frac{100}{g_*}\right)^{1/3} v_w\, S_{\rm turb}(f)$$

Caprini, Durrer, Servant, JCAP12(2009)024 (adopted by the LISA Cosmology Working group, JCAP04(2016)001)

$$S_{\rm turb}(f) = \frac{(f/f_{\rm turb})^3}{[1+(f/f_{\rm turb})]^{\frac{11}{3}}\,(1+8\pi f/h_*)}$$

$$h_* = 16.5 \times 10^{-3}\,{\rm mHz} \left(\frac{T_*}{100\,{\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{\frac{1}{6}}$$

$$f_{\rm turb} = 2.7 \times 10^{-2}\,{\rm mHz}\,\frac{1}{v_w}\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{100\,{\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{\frac{1}{6}}$$

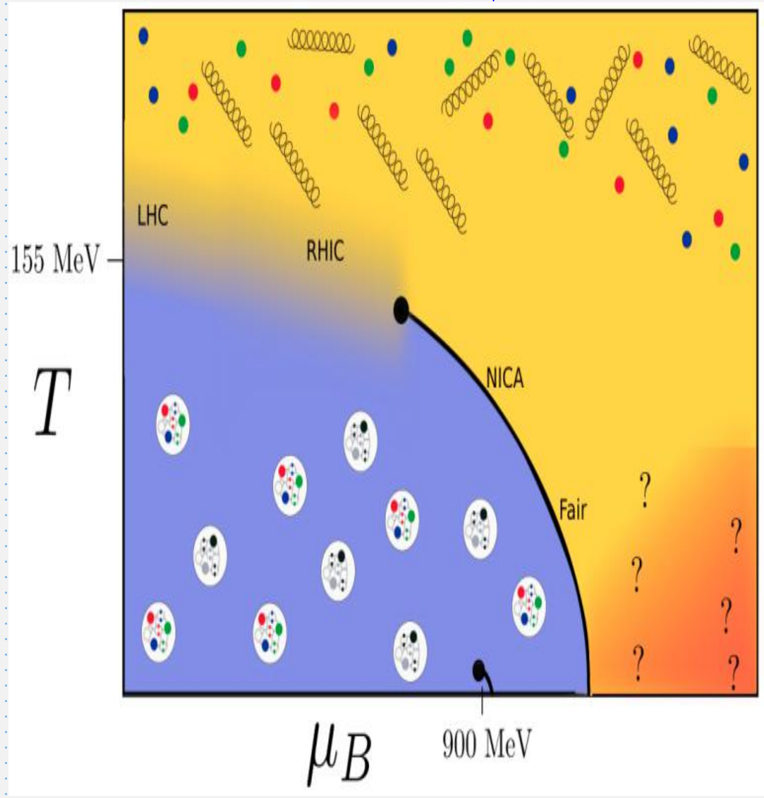
New result: Pol et al, PRD 102, 083512 (2020)

Generic Features

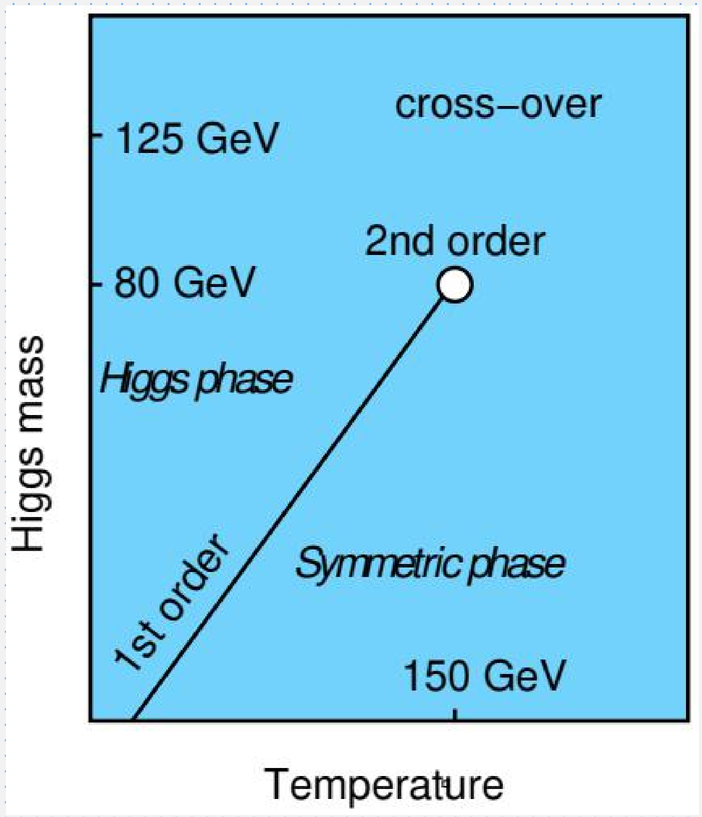
- LIGO (~100Hz) : (~PeV - EeV)
- LISA, Taiji, Tianqin: ~mHz : (~100GeV)
- PTA: nHz (~100MeV)

EWPT

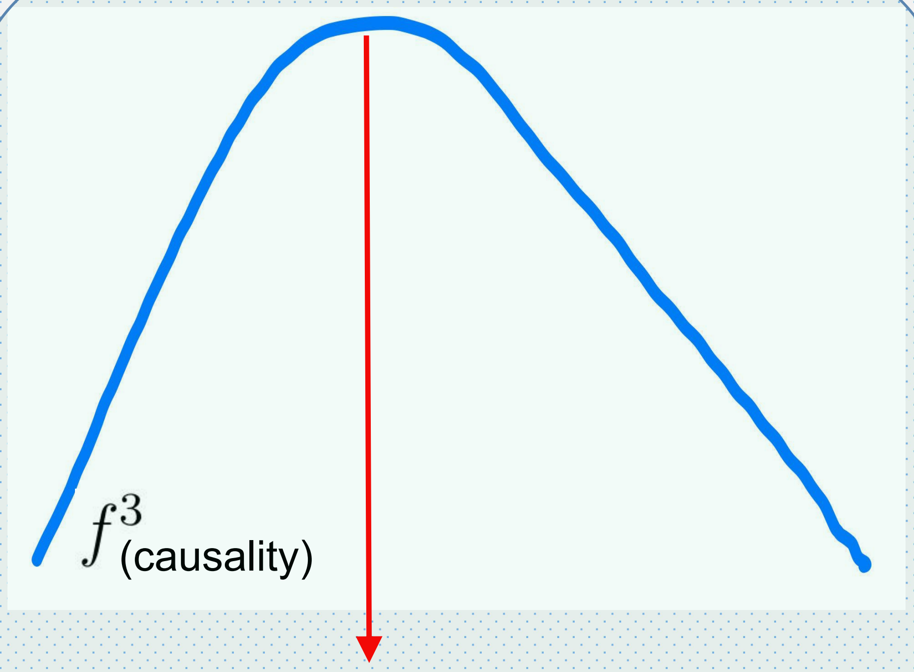
QCD PT



Guenther, arxiv: 2010.15503



Hindmarsh et al SciPost Phys.Lect.Notes 24 (2021)



$$f_{\rm peak} \sim 10^{-3}{\rm Hz} \left(\frac{g_s(T_*)}{100}\right)^{1/6} \left(\frac{T}{100{\rm GeV}}\right)$$

typical length scale

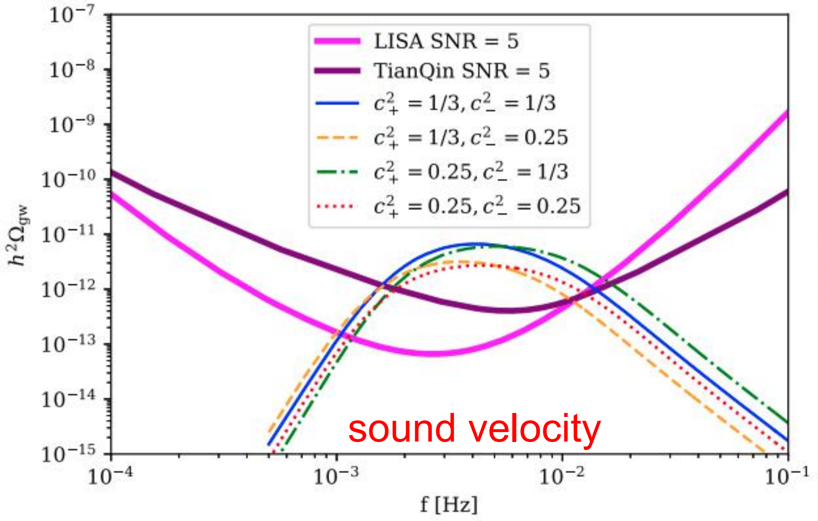
tells PT temperature
(symmetry breaking scale)

Uncertainties

- Finite T effective potential calculations
- Phase transition parameter calculations (vw)
- GW spectra calculations (simulations, modellings)
- Possibly new phenomena

$\Delta\Omega_{\rm GW}/\Omega_{\rm GW}$	4d approach	3d approach
RG scale dependence	$\mathcal{O}(10^2 - 10^3)$	$\mathcal{O}(10^0 - 10^1)$
Gauge dependence	$\mathcal{O}(10^1)$	$\mathcal{O}(10^{-3})$
High-T approximation	$\mathcal{O}(10^{-1} - 10^0)$	$\mathcal{O}(10^0 - 10^2)$
Higher loop orders	unknown	$\mathcal{O}(10^0 - 10^1)$
Nucleation corrections	unknown	$\mathcal{O}(10^{-1} - 10^0)$
Nonperturbative corrections	unknown	unknown

Croon,Gould,Schicho,Tenkanen,White, JHEP [2009.10080]



Wang,Huang,Li, PRD [2112.14650]

Effect(fixed wall velocity)	Range of error (medium)	Range of error (low)	Type of error
Transition temperature	$\mathcal{O}(10^{-4}\text{–}10^1)$	$\mathcal{O}(10^{-1}\text{–}10^0)$	Random
Mean bubble separation	$\mathcal{O}(0\text{–}10^{-1})$	$\mathcal{O}(10^{-1}\text{–}10^0)$	Suppression
Fluid velocity	$\mathcal{O}(10^{-2}\text{–}10^0)$	$\mathcal{O}(10^{-2}\text{–}10^0)$	Random
Finite lifetime	$\mathcal{O}(10^{-3}\text{–}10^{-1})$	$\mathcal{O}(10^1\text{–}10^3)$	Enhancement
Vorticity effects	$\mathcal{O}(10^{-1}\text{–}10^0)$	–	Random

HG,Sinha,Vagie,White, JHEP [2103.06933]

BSM studies

Chung,Long,Wang, PRD [1209.1819]

- Large cubic term from thermal correrctions (loop level)
- Add new scalars (tree level)
- Including non-renormalizable operators

More general EFT approach: Cai,Hashino,Wang,Yu [2202.08295]

Classification according to the symmetries

Classification according to the problems

Models	Strong 1^{st} order phase transition	GW signal	Cold DM	Dark Radiation and small scale structure
SM charged				
Triplet [20–22]	✓	✓	✓	✗
complex and real Triplet [23] (Georgi-Machacek model)	✓	✓	✓	✗
Multiplet [24]	✓	✓	✓	
2HDM [25–30]	✓	✓		✗
MLRSM [31]	✓	✓	✗	✗
NMSSM [32–36]	✓	✓	✓	✗
SM uncharged				
S_r (xSM) [37–49]	✓	✓	✗	✗
2 S_r's [50]	✓	✓	✓	✗
S_c (cxSM) [49, 51–54]	✓	✓	✓	✗
$U(1)_D$ (no interaction with SM) [55]	✓	✓	✓	✗
$U(1)_D$ (Higgs Portal) [56]	✓	✓	✓	
$U(1)_D$ (Kinetic Mixing) [57]	✓	✓	✓	
Composite $SU(7)/SU(6)$ [58]	✓	✓	✓	
$U(1)_L$ [59]	✓	✓	✓	✗
$SU(2)_D \to$ global $SO(3)$ by a doublet [60–62]			✓	✗
$SU(2)_D \to U(1)_D$ by a triplet [63–65]			✓	✓
$SU(2)_D \to Z_2$ by two triplets [66]			✓	✗
$SU(2)_D \to Z_3$ by a quadruplet [67, 68]			✓	✗
$SU(2)_D \times U(1)_{B-L} \to Z_2 \times Z_2$ by a quintuplet and a S_c [69]			✓	✗
$SU(2)_D$ with two dark Higgs doublets [70]	✓	✓	✗	✗
$SU(3)_D \to Z_2 \times Z_2$ by two triplets [62, 71]			✓	✗
$SU(3)_D$ (dark QCD) (Higgs Portal) [72, 73]	✓	✓	✓	
$G_{SM} \times G_{D,SM} \times Z_2$ [74]	✓	✓	✓	
$G_{SM} \times G_{D,SM} \times G_{D,SM} \cdots$ [75]	✓	✓	✓	
Current work				
$SU(2)_D \to U(1)_D$ (see the text)	✓	✓	✓	✓

Ghosh,HG,Han,Liu, JHEP [2012.09758]

EWPT and Related Physics

The electroweak phase transition: a collider target

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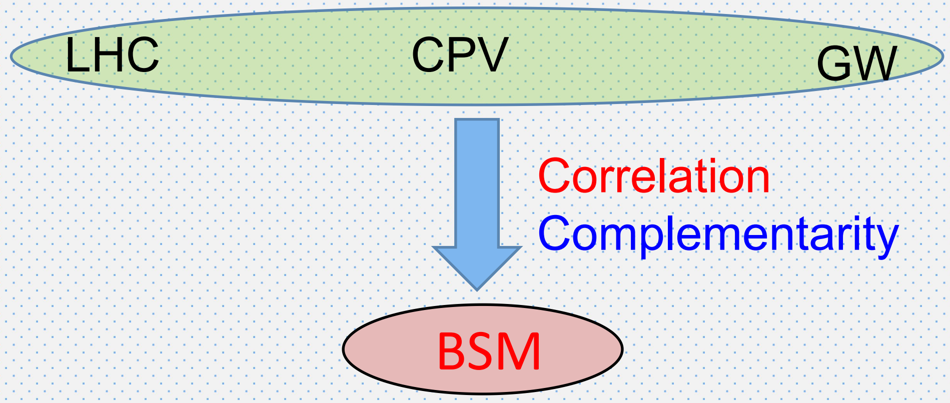
- Modified Higgs potential (Higgs physics, GW)
- Extra CP-violation (EDM, LHC)
- B-violation: Sphaleron process (LHC, GW)

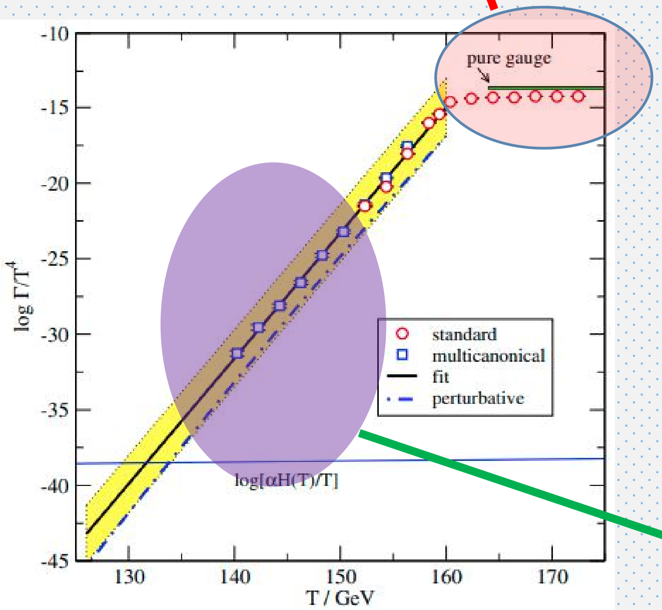


Electroweak Baryogenesis

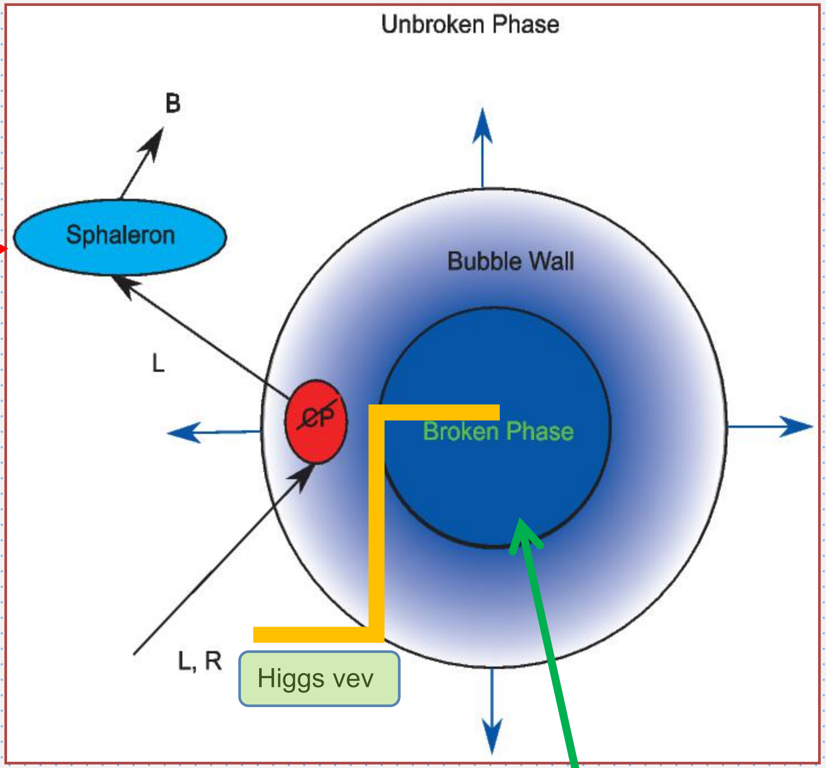
Kuzmin,Rubakov,Shaposhnikov (1985)
Shaposhnikov (1986)
Cohen,Kaplan,Nelson (1990, 1991)

symmetric phase

$$\Gamma^{\rm sym} \approx 6 \times (18 \pm 3)\alpha_W^5 T^4$$

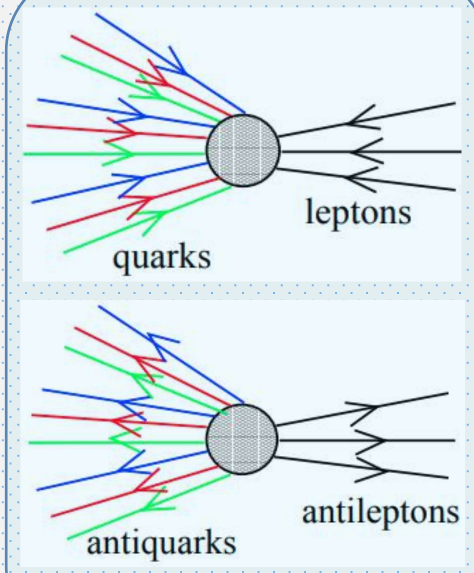


D'Onofrio et al, PRL [1404.3565]



$$\log \frac{\Gamma_{\rm Broken}}{T^4} = (0.83 \pm 0.01)\,\frac{T}{\rm GeV} - (147.7 \pm 1.9)$$

broken phase (should be suppressed)



Cline [0609145]

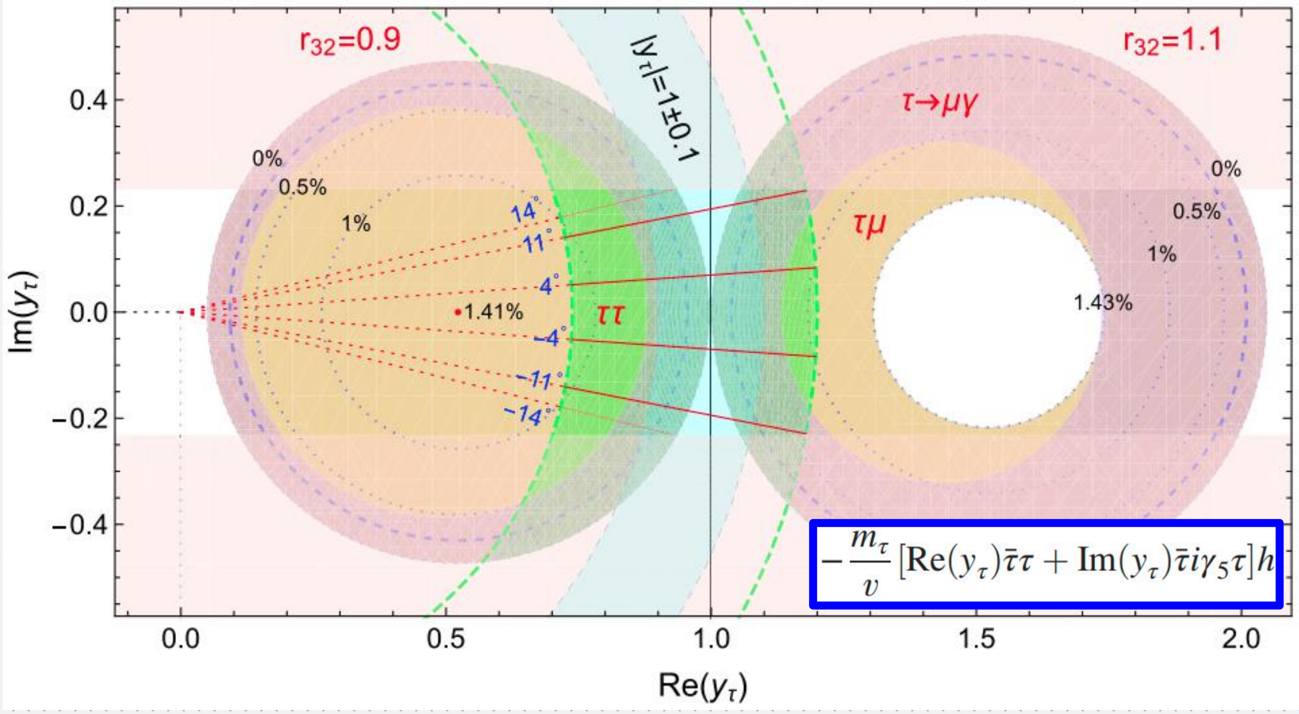
Lepton-flavored Electroweak Baryogenesis

- CP-violation is generally small, decoupled from GW analysis
- Lepton-flavored EWBG is effective for baryon asymmetry generation

Many studies since then:

De Vries,Postma, van de Vis, JHEP [1811.11104]
Modak,Senaha, PRD [1811.08088]
Fuyuto,Hou,Senaha, PLB [1705.05034]
and more...

HG,Li,Liu,Ramsey-Musolf,Shu, PRD [1609.09849]



Type III 2HDM

$$\mathcal{L}_{\rm Yukawa}^{\rm Lepton} = -\overline{L^i}[Y_{1,ij}\Phi_1 + Y_{2,ij}\Phi_2]e_R^j + \text{H.c.}$$

Jarlskog-like invariant

$$J_A = \frac{1}{v^2\mu_{12}^{\rm HB}}\sum_{a,b,c=1}^{2} v_a v_b^* \mu_{bc}\,\mathrm{Tr}[Y_c Y_a^\dagger]$$

$$\mathrm{Im}(J_A) = \begin{cases} \text{Gauge Basis:} \; -Y_{2,\tau\mu}^E \mathrm{Im} Y_{2,\tau\mu}^E & \Rightarrow \quad \text{Baryon Asymmetry} \\ \\ \text{Mass Basis:} \;\; 2m_\tau \mathrm{Im} N_{\tau\tau}^E/v^2 & \Rightarrow \quad \text{CP-violating } h\bar{\tau}\tau \end{cases}$$

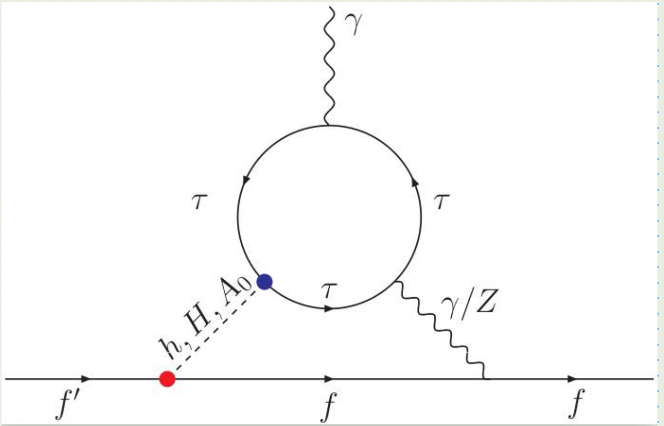
Lepton-flavored Electroweak Baryogenesis: Higgs CPV

$$-\frac{m_\tau}{v}\left[\mathrm{Re}(y_\tau)\bar{\tau}\tau + \mathrm{Im}(y_\tau)\bar{\tau}i\gamma_5\tau\right]h$$

OK

discovery or exclusion?

Unconstrained from EDM measurements



$$\left|\frac{d_e}{e}\right| \approx 1.87\times 10^{-29}|\mathrm{Im}y_\tau|$$

ACME 2014: $\left|\frac{d_e}{e}\right| < 8.7\times 10^{-29} e\cdot \mathrm{cm}$

Collider Sensitivities

Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000		125	125	≥ 500	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	20,000	250	350	500	1,000		250			
HZZ/HWW	$4\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.4\cdot10^{-4}$	$1.1\cdot10^{-4}$	$4\cdot10^{-5}$	$8\cdot10^{-6}$	✓	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$	–	0.50	✓	–	–	–	–	–	0.06	–	–	$< 10^{-2}$
$HZ\gamma$	–	~1	✓	–	–	–	–	–	–	–	–	$< 10^{-2}$
Hgg	0.12	0.011	✓	–	–	–	–	–	–	–	–	$< 10^{-2}$
$Ht\bar{t}$	0.24	0.05	✓	–	–	0.29	0.08	–	–	–	✓	$< 10^{-2}$
$H\tau\tau$	0.07	0.008	✓	0.01	0.01	0.02	0.06	–	✓	✓	✓	$< 10^{-2}$
$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

Snowmass White Paper: Gritsan et al [2205.07715]

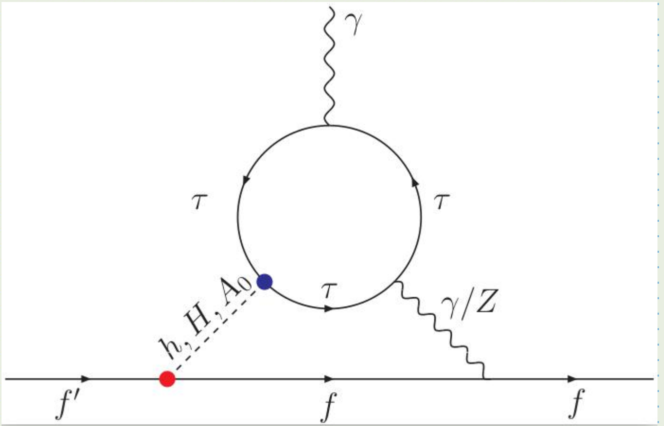
Lepton-flavored Electroweak Baryogenesis: Higgs CPV

$$-\frac{m_\tau}{v}\left[\mathrm{Re}(y_\tau)\bar{\tau}\tau + \mathrm{Im}(y_\tau)\bar{\tau}i\gamma_5\tau\right]h$$

OK

discovery or exclusion?

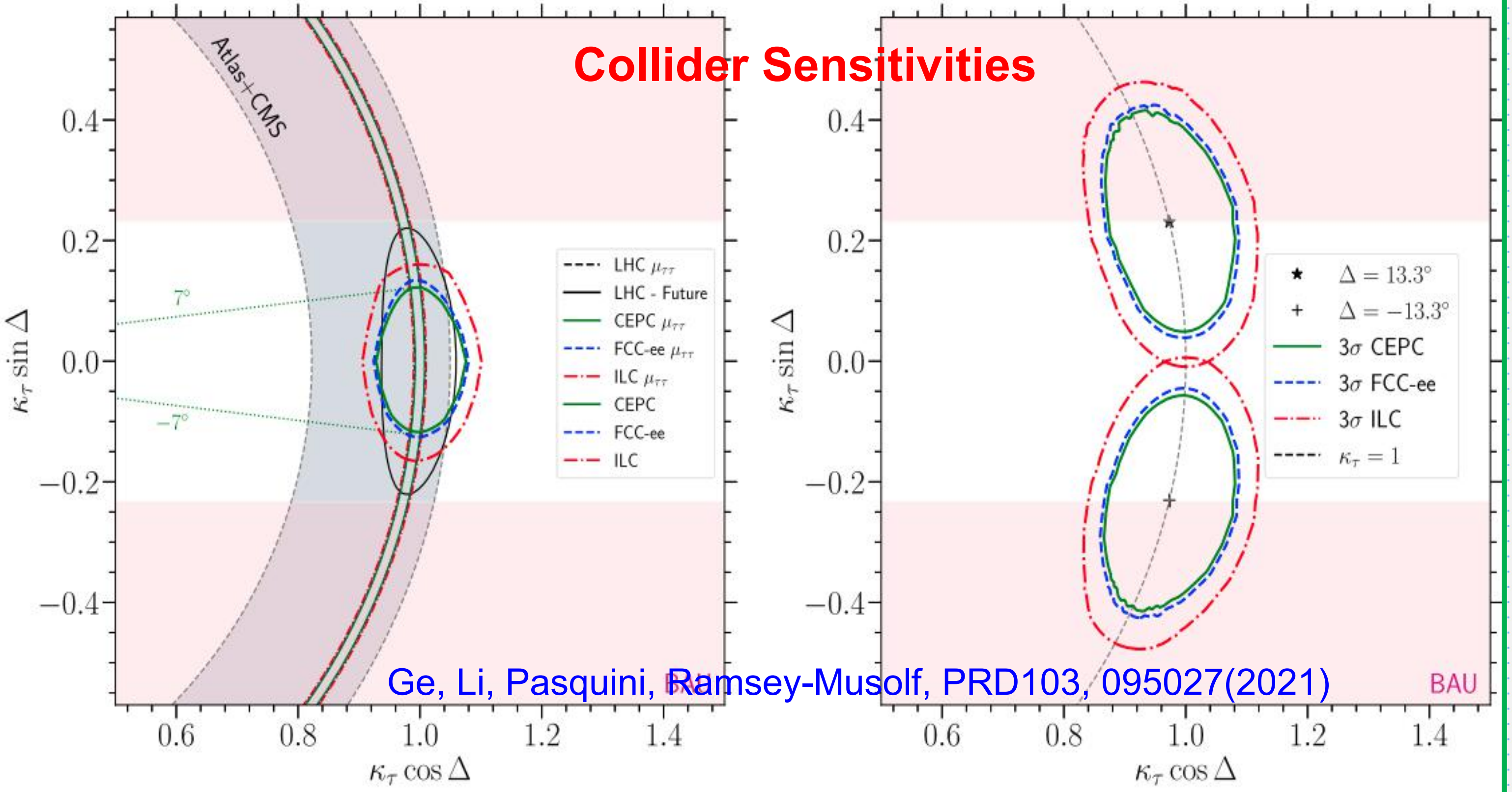
Unconstrained from EDM measurements



$$\left|\frac{d_e}{e}\right| \approx 1.87\times 10^{-29}|\mathrm{Im}y_\tau|$$

$$\text{ACME 2014:}\ \left|\frac{d_e}{e}\right| < 8.7\times 10^{-29} e\cdot\mathrm{cm}$$

Collider Sensitivities



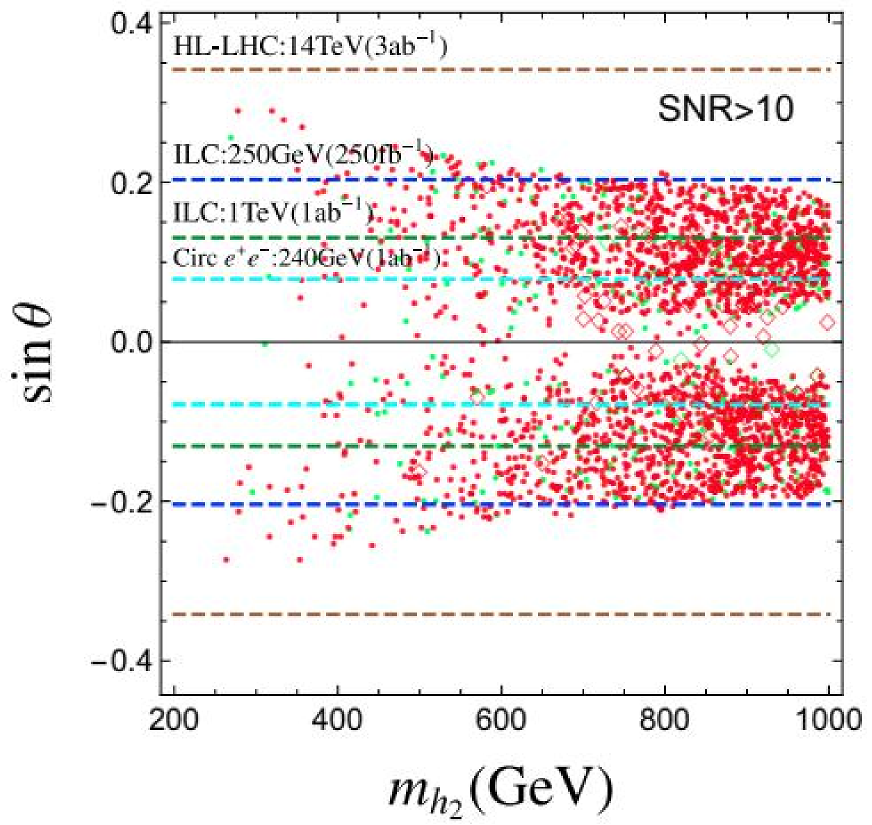
Ge, Li, Pasquini, Ramsey-Musolf, PRD103, 095027(2021)

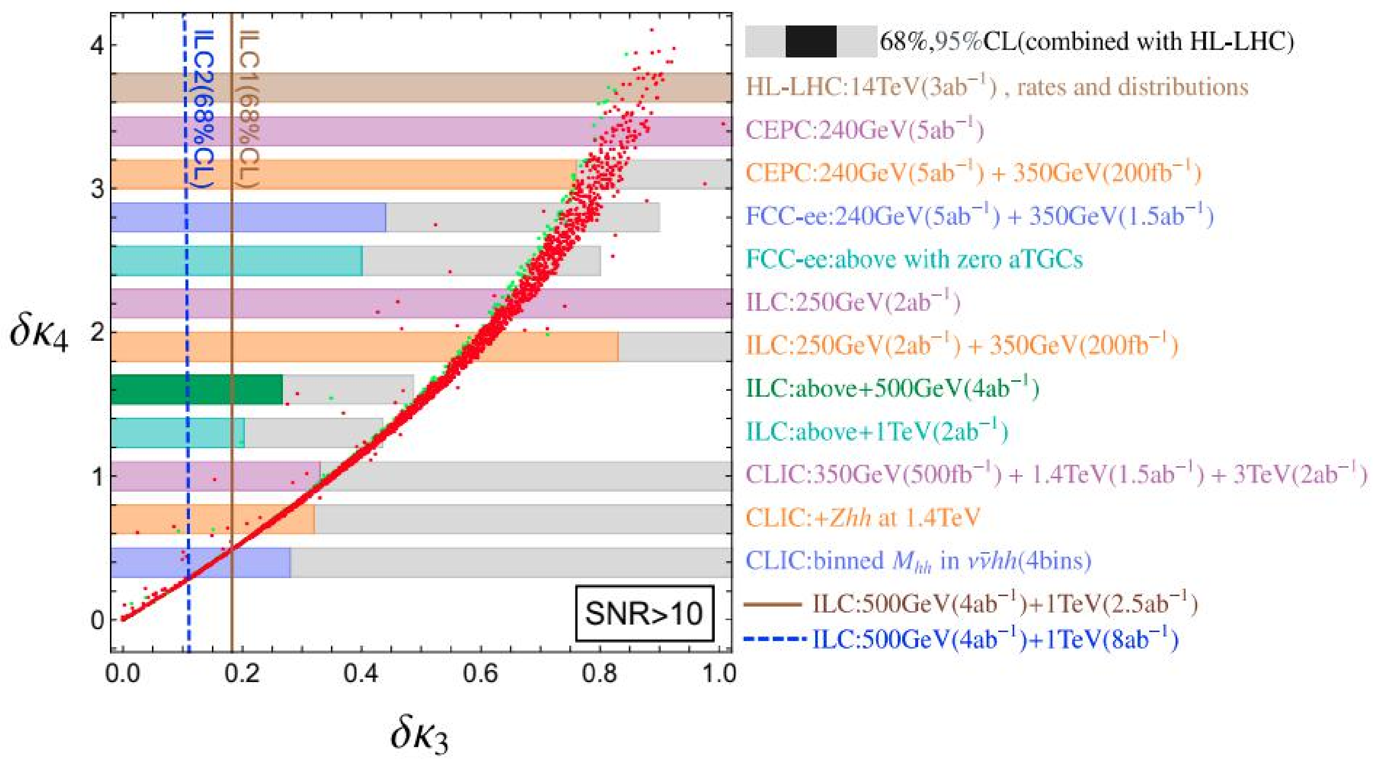
Higgs Precision Measurements

- First order EWPT achievable in simplest SM+Singlet model
- Correlation and complementarity between collider and GW probes

h1: the Higgs
h2: heavier scalar

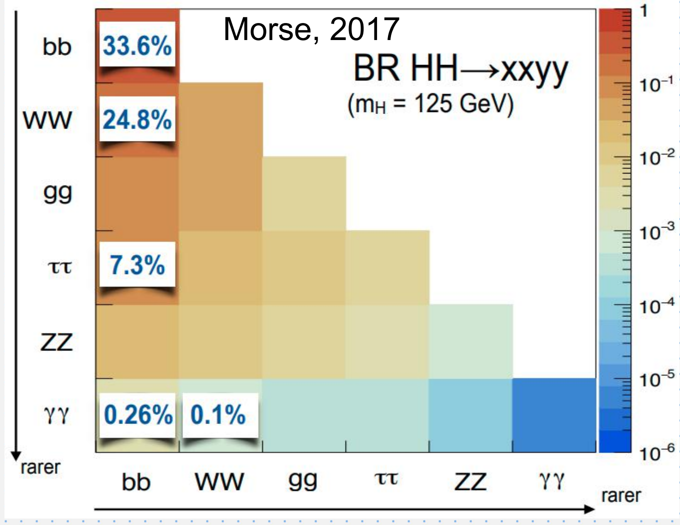
$$\Delta\mathcal{L} = -\frac{1}{2}\frac{m_{h_1}^2}{v}(1+\delta\kappa_3)h_1^3 - \frac{1}{8}\frac{m_{h_1}^2}{v^2}(1+\delta\kappa_4)h_1^4$$





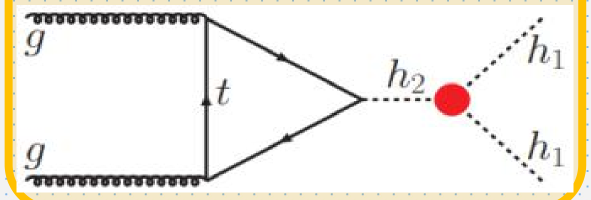
Alves,Ghosh,HG,Sinha,Vagie, JHEP [1812.09333]

Di-Higgs Production

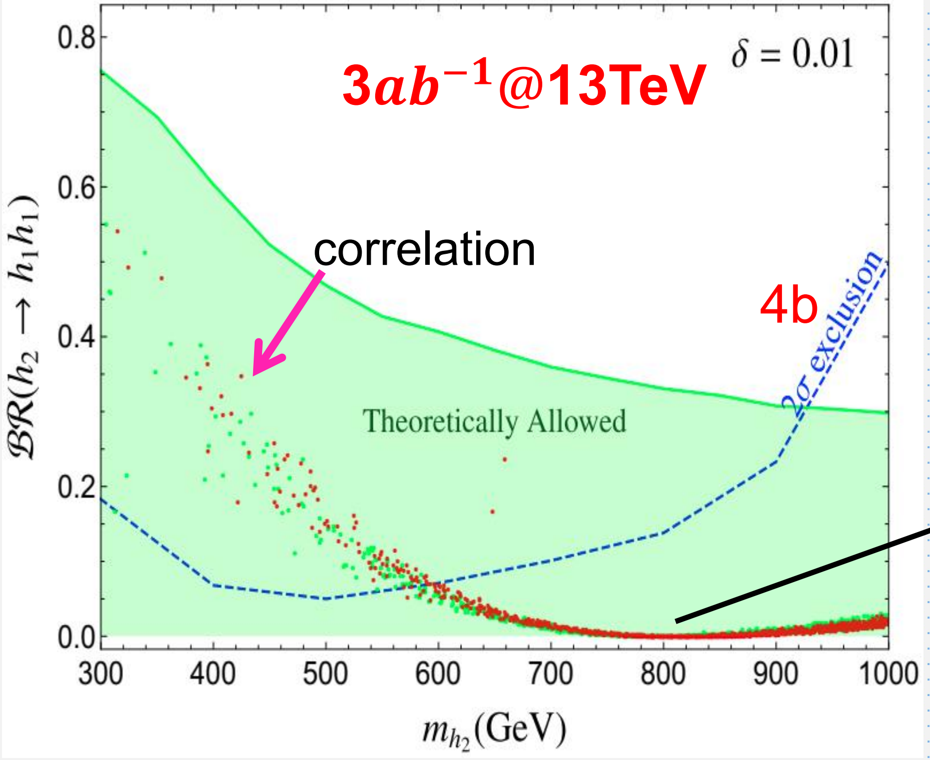


- Enhanced (resonant) di-Higgs production

Resonant Production

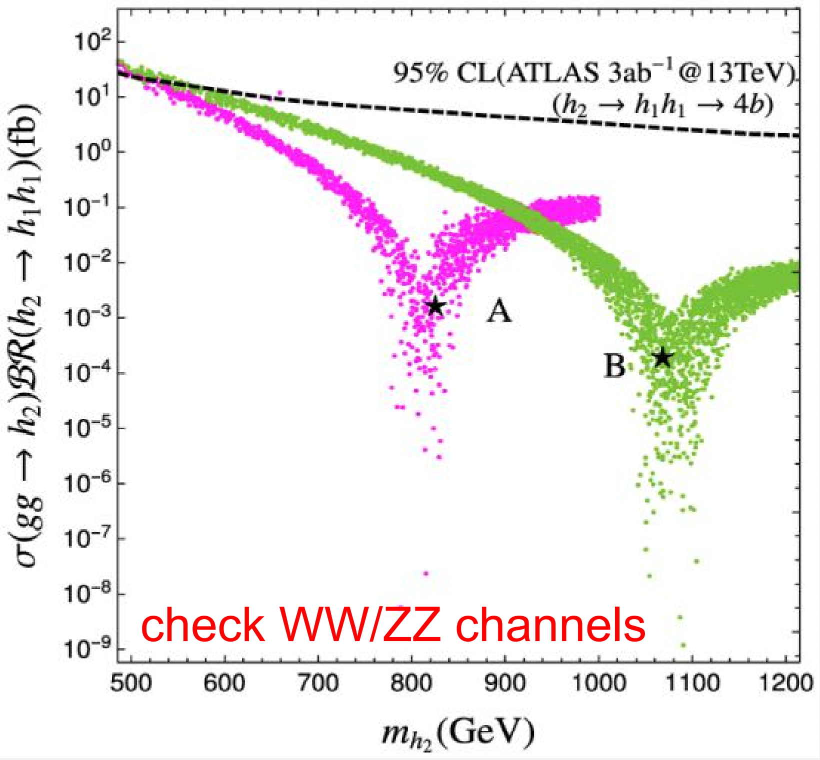


See also:
No,Ramsey-Musolf, PRD [1310.6035]
Li,Ramsey-Musolf,Willocq, JHEP [1906.05289]
Huang,No,Pernie,Ramsey-Musolf,Safonov, PRD [1701.04442]
Zhang,Li,Liu,Ramsey-Musolf,Zeng,Arunasalam [2303.03612]
and more...



di-Higgs blindspot

complementarity



Alves,Gonçalves,Ghosh,HG,Sinha, JHEP [1909.05268]

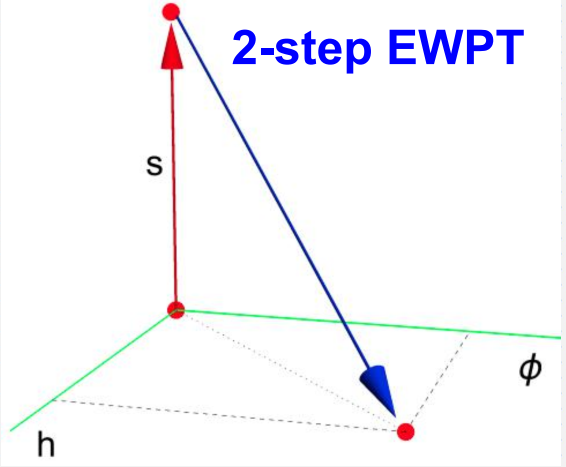
Alves,Gonçalves,Ghosh,HG,Sinha, PLB [2007.15654]

WIMP affecting EWPT

- WIMP naturally plays a role during EWPT

$$V_0 = -\frac{1}{2}\mu_\Phi^2\Phi^2 + \frac{1}{4}\lambda_\Phi\Phi^4 - \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_S S^4 \\ -\mu^2 H^\dagger H + \lambda\left(H^\dagger H\right)^2 + \lambda_1 S^2 H^\dagger H + \lambda_2 \Phi^2 H^\dagger H \\ +\lambda_3 S^2\Phi^2,$$

Chao,HG,Shu, JCAP [1702.02698]

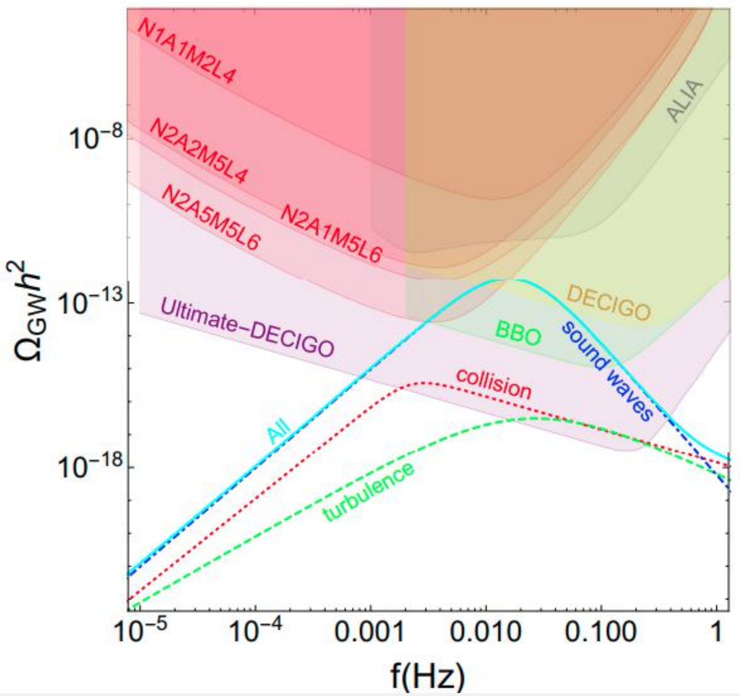


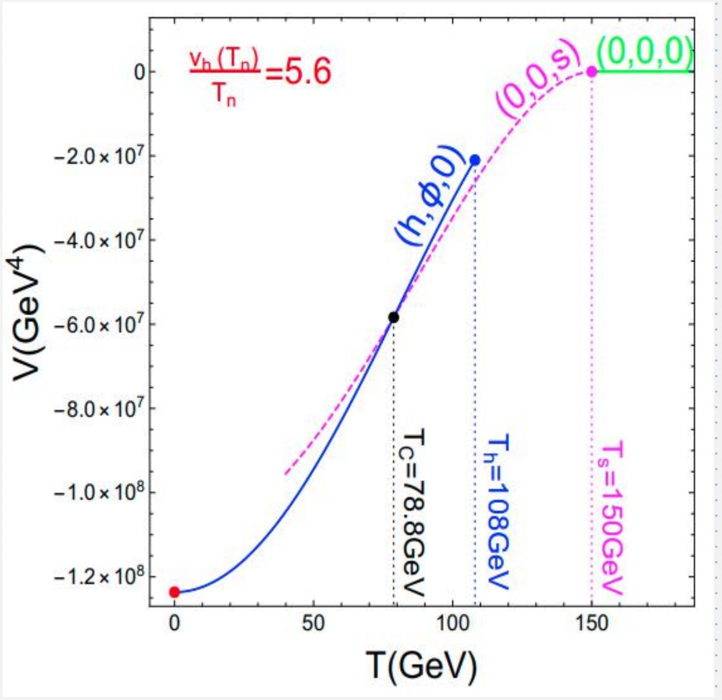
Direct detection limits

$$\sigma_n = \frac{\mu^2 m_n^2}{\pi v_{\rm EW}^2 m_S^2}\left|\frac{c_\theta a_{\hat h}}{m_{\hat h}^2} - \frac{s_\theta a_{\hat\phi}}{m_{\hat\phi}^2}\right|^2 \left(\frac{2}{9} + \frac{7}{9}\sum_{q=u,d,s} f_{T_q}^n\right)^2$$

vanishes

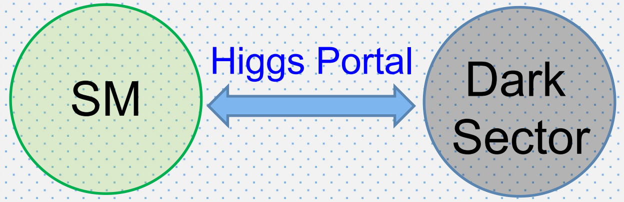
$$\lambda_3 = \frac{v_{\rm EW}\lambda_1\left(m_{\hat h}^2\tan\theta + m_{\hat\phi}^2\cot\theta\right)}{2v_\Phi\left(m_{\hat h}^2 - m_{\hat\phi}^2\right)}$$





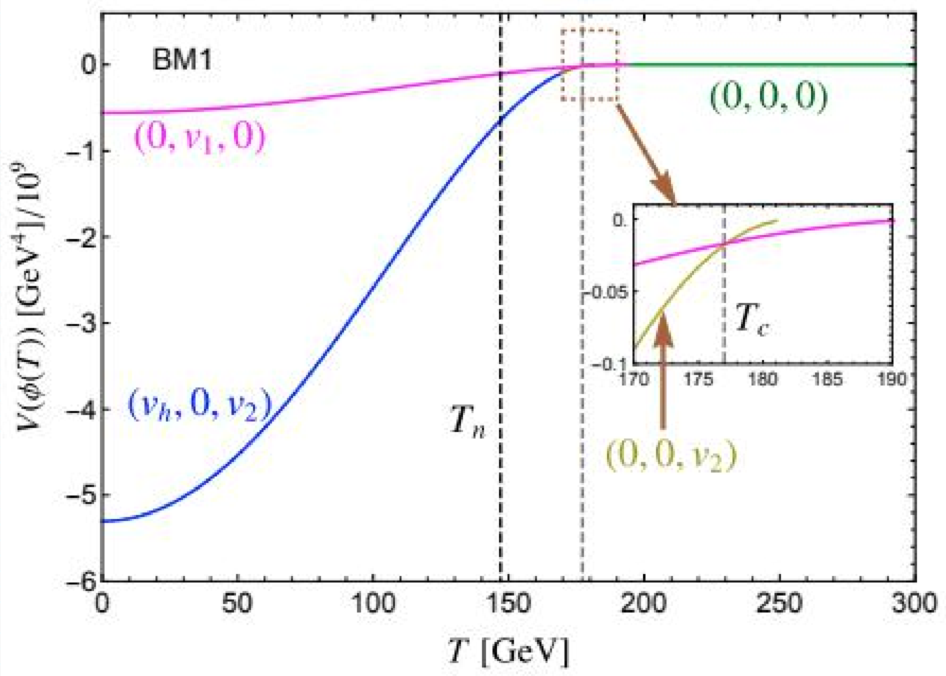
Dark Sector affecting EWPT

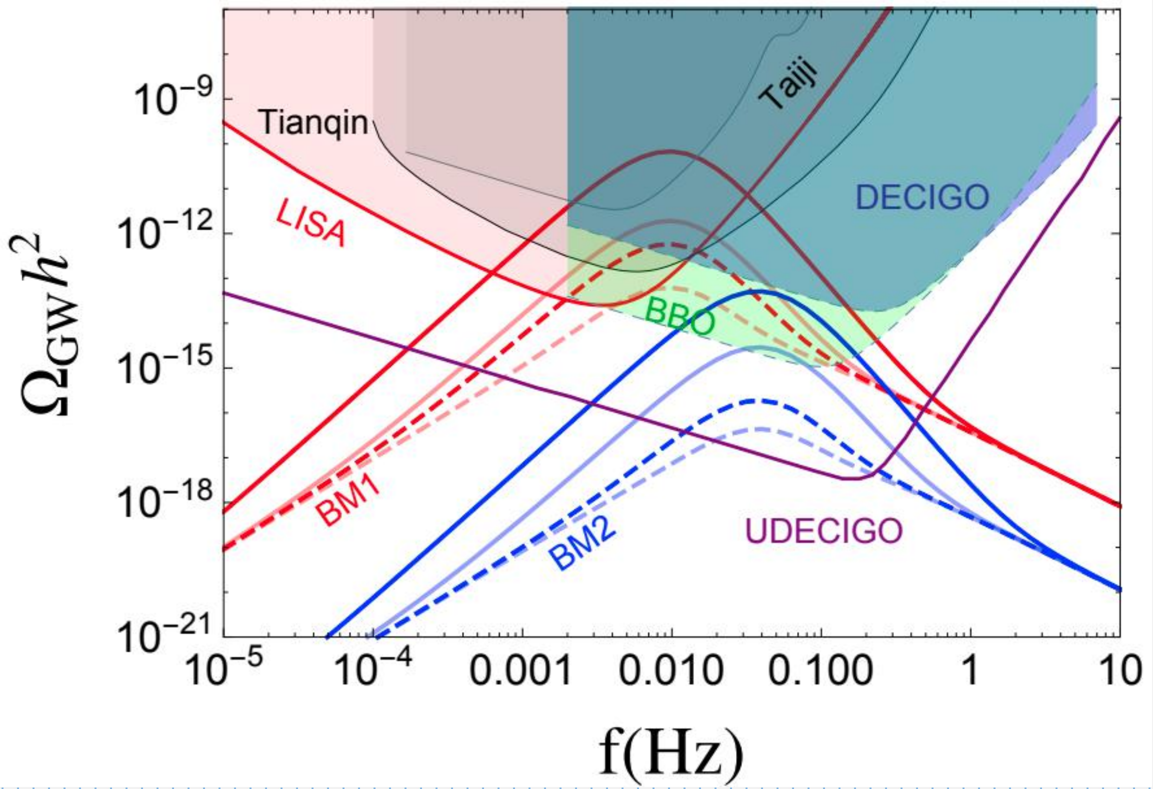
- Dark sector with a Higgs portal interaction with the SM sector



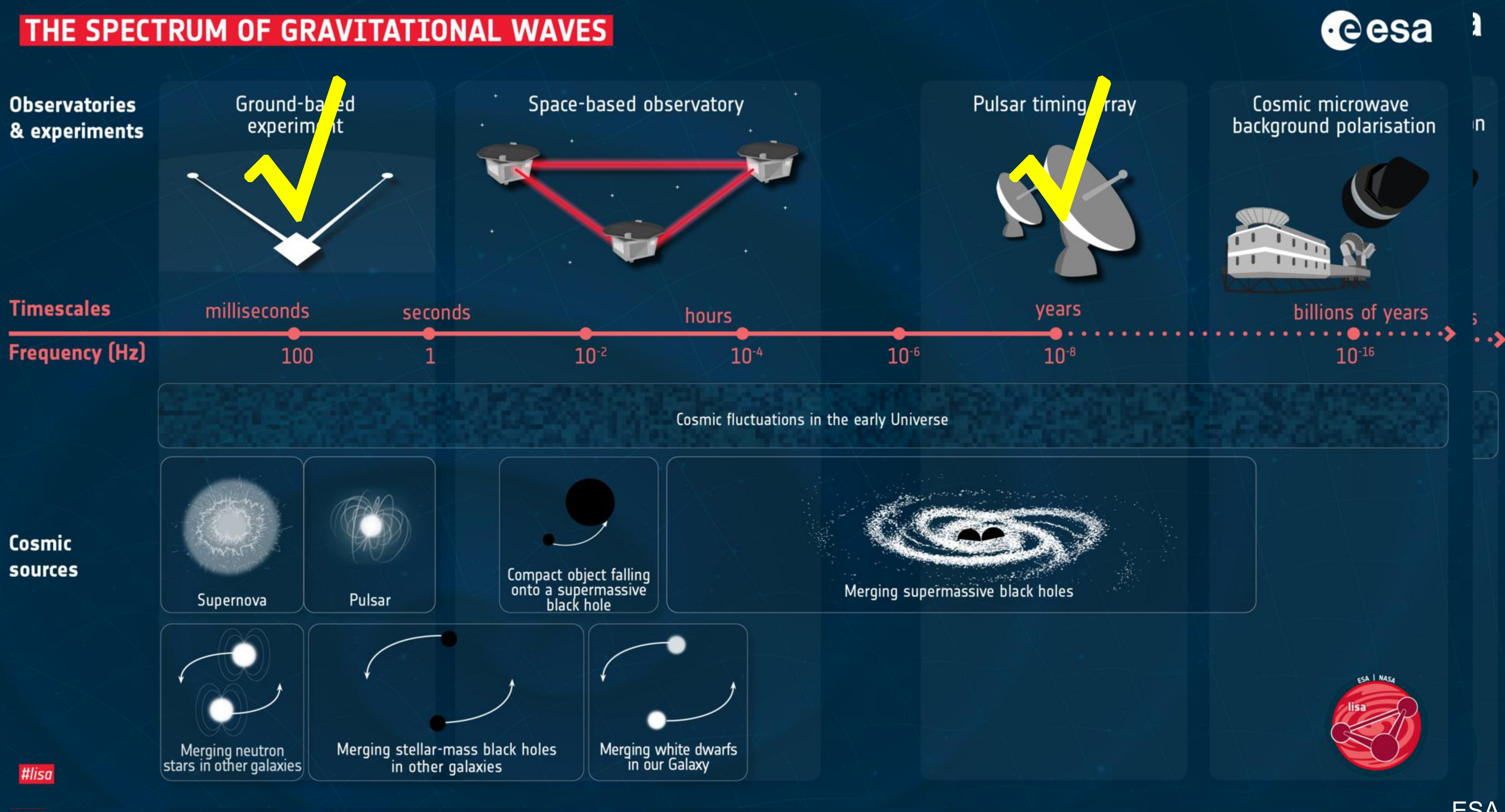
$$\mathscr{L} = \mathscr{L}_{\rm SM} + \mathscr{L}_{\rm portal} + \mathscr{L}_{\rm DS},$$
$$-\mathscr{L}_{\rm SM} \supset V_{\rm SM} = m_H^2|H|^2 + \frac{\lambda_H}{2}|H|^4,$$
$$-\mathscr{L}_{\rm portal} \supset V_{\rm portal} = \lambda_{H11}|H|^2|\Phi_1|^2 + \lambda_{H22}|H|^2|\Phi_2|^2,$$
$$\mathscr{L}_{\rm DS} = -\frac{1}{4}\tilde{W}^a_{\mu\nu}\tilde{W}^{a\mu\nu} + |D_\mu\Phi_1|^2 + |D_\mu\Phi_2|^2 - V_{\rm DS}$$

Ghosh, HG, Han, Liu, JHEP [2012.09758]





THE SPECTRUM OF GRAVITATIONAL WAVES



ESA

high-scale PT

LIGO Search Result

O1+O2+O3@LIGO (H1, L1), Virgo

- No Evidence for Broken Power Law Signal
- No Evidence for Bubble Collision Domination Signal
- No Evidence for Sound Waves Domination Signal

Broken Power Law

95% CL UL (CBC+BPL)

$$\Omega_{\rm ref} = 6.1 \times 10^{-9}$$

$$\Omega_{*} = 5.6 \times 10^{-7}$$

$$\Omega_{\rm BPL}(25\ \text{Hz}) = 4.4 \times 10^{-9}$$

Bubble Collision

95% CL UL with fixed Tpt and beta/Hpt

Phenomenological model (bubble collisions)

$\Omega^{95\%}_{\rm coll}(25\ \text{Hz})$

$\beta/H_{\rm pt} \backslash T_{\rm pt}$	10^7 GeV	10^8 GeV	10^9 GeV	10^{10} GeV
0.1	9.2×10^{-9}	8.8×10^{-9}	1.0×10^{-8}	7.2×10^{-9}
1	1.0×10^{-8}	8.4×10^{-9}	5.0×10^{-9}	…
10	4.0×10^{-9}	6.3×10^{-9}	…	…

no sensitivity

Sound Waves

95% CL UL

$$\Omega_{\rm sw}(25\ \text{Hz}) \quad 5.9 \times 10^{-9}$$

$$\beta/H_{\rm pt} < 1 \text{ and } T_{\rm pt} > 10^8\ \text{GeV}$$

First result from gravitational wave data!

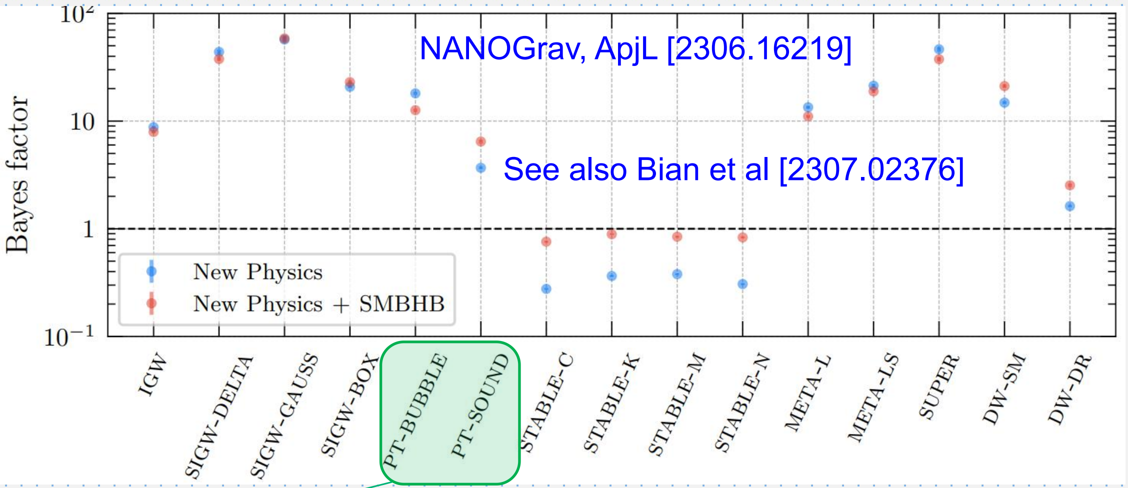
Romero, Martinovic, Callister, HG, Martínez, Sakellariadou, Yang, Zhao, PRL [2102.01714]

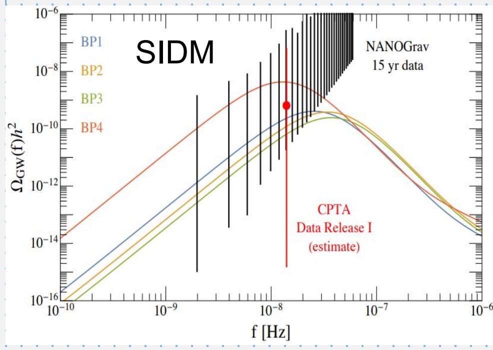
QCD-scale PT

What possible PTA discovery implies?

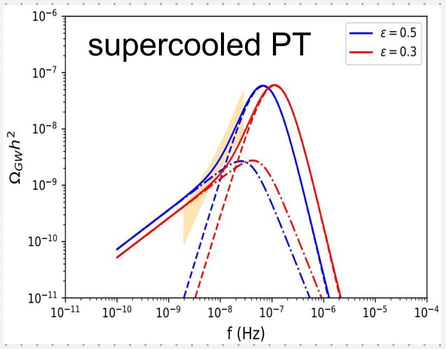
- Once discovered, firstly needs to know its origin
- Can be the next “CMB” (spectral shape, anisotropy, etc)
- Can be from first order QCD-scale PT

PPTA: Xue et al, PRL [2110.03096]
NANOGrav (12.5-year): Arzoumanian et al, PRL [2104.13930]
...

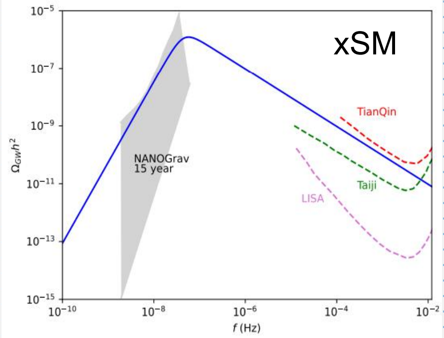




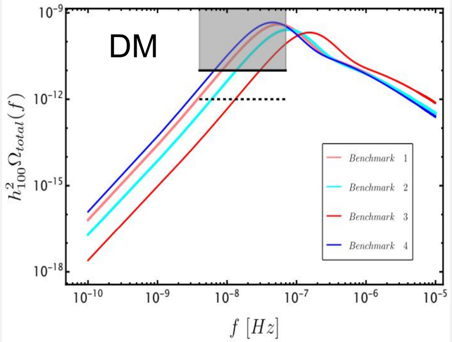
Han,Xie,Yang,Zhang [2306.16966]



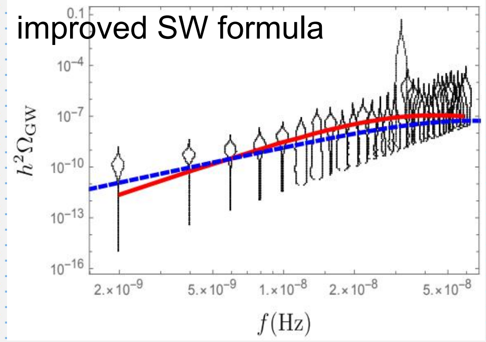
Zu,Zhang,Li,Gu,Tsai,Fan [2306.17239]



Xiao,Yang,Zhang [2307.01072]



Yang,Ma,Jiang,Huang [2306.17827]

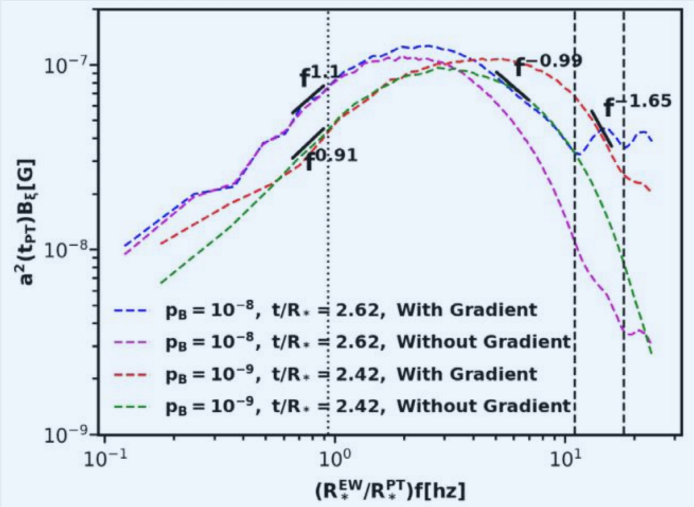


Ghosh et al [2307.02259]

and more...

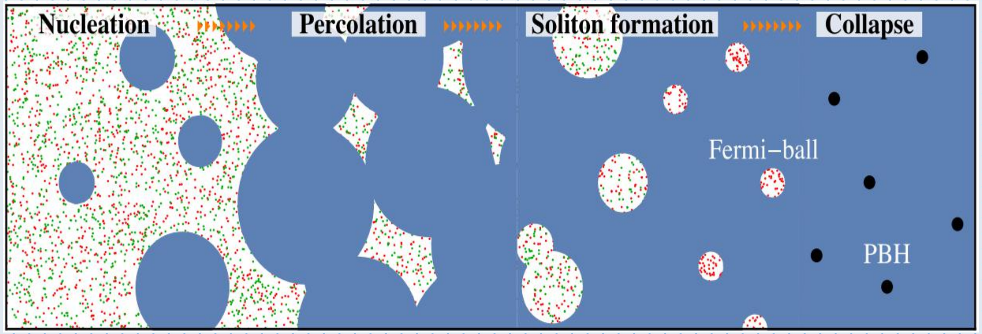
New Observables

Primordial magnetic field



Di,Wang,Zhou,Bian,Cai, PRL [2012.15625]
Yang,Bian,PRD [2102.01398]

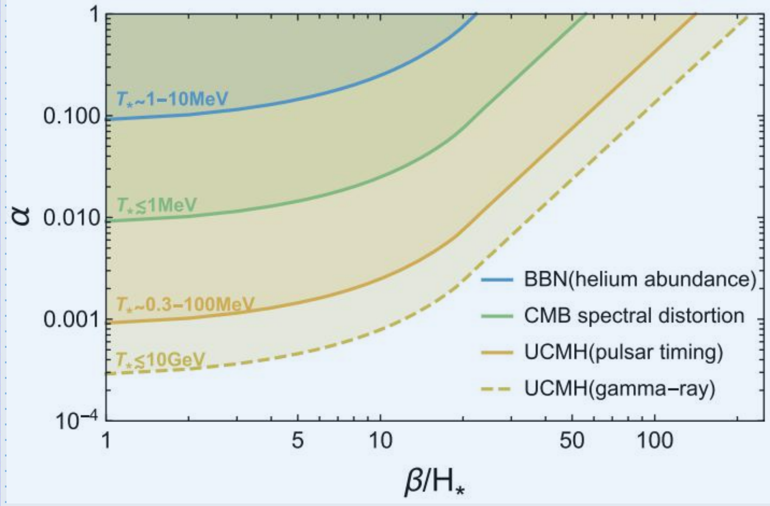
Primordial black holes



Kawana,Xie,PLB [2106.00111]

and more...

Curvature perturbations



Liu,Bian,Cai,Guo,Wang,PRL[2208.14086]

Summary

- Rapid experimental progresses (LIGO-Virgo-KAGRA, LISA/Taiji/Tianqin, PTA)
- A much clearer picture of a first order EWPT (simulations, analytical insights)
- More robost calculations (dimensional reduction, non-perturbative methods)
- More accurate predictions for GWs
- New observables (PBHs, curvature perturbations, magnetic fields, etc)
- Extensive phenomenological studies

Since LIGO's first direct detection of GWs (announced in 2016)

The 2023 Shanghai Symposium on Particle Physics and Cosmology:
Phase Transitions, Gravitational Waves, and Colliders (SPCS 2023)

Organizing Committee

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- Fa Peng Huang (Sun Yat-Sen University)
- Shu Li (Shanghai Jiao Tong University, Tsung-Dao Lee Institute)
- Kun Liu (Shanghai Jiao Tong University, Tsung-Dao Lee Institute)
- Lei Zhang (Nanjing University)

Website: https://indico-tdli.sjtu.edu.cn/event/1741/