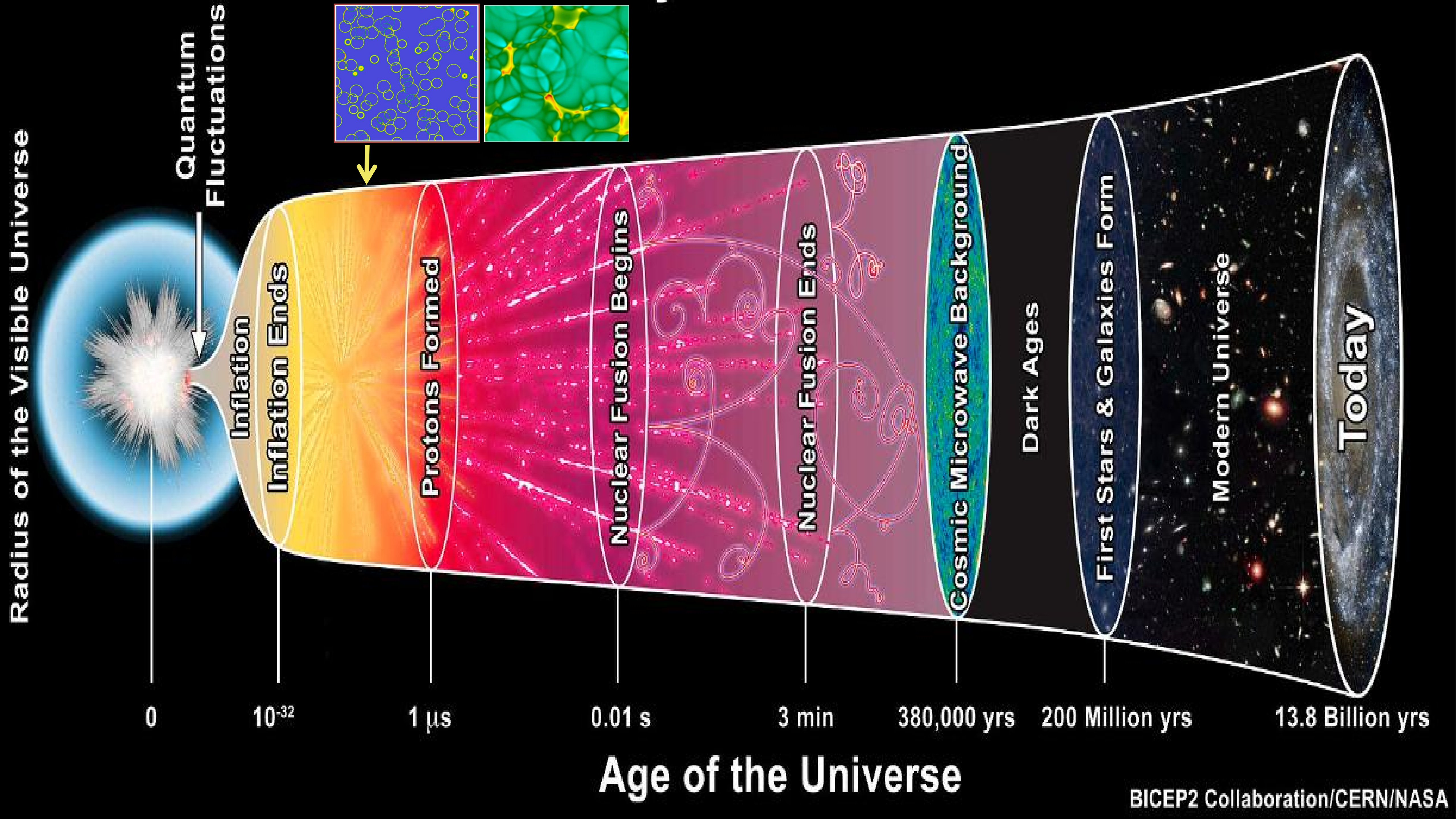
宇宙相变引力波理论和实验进展

郭怀珂

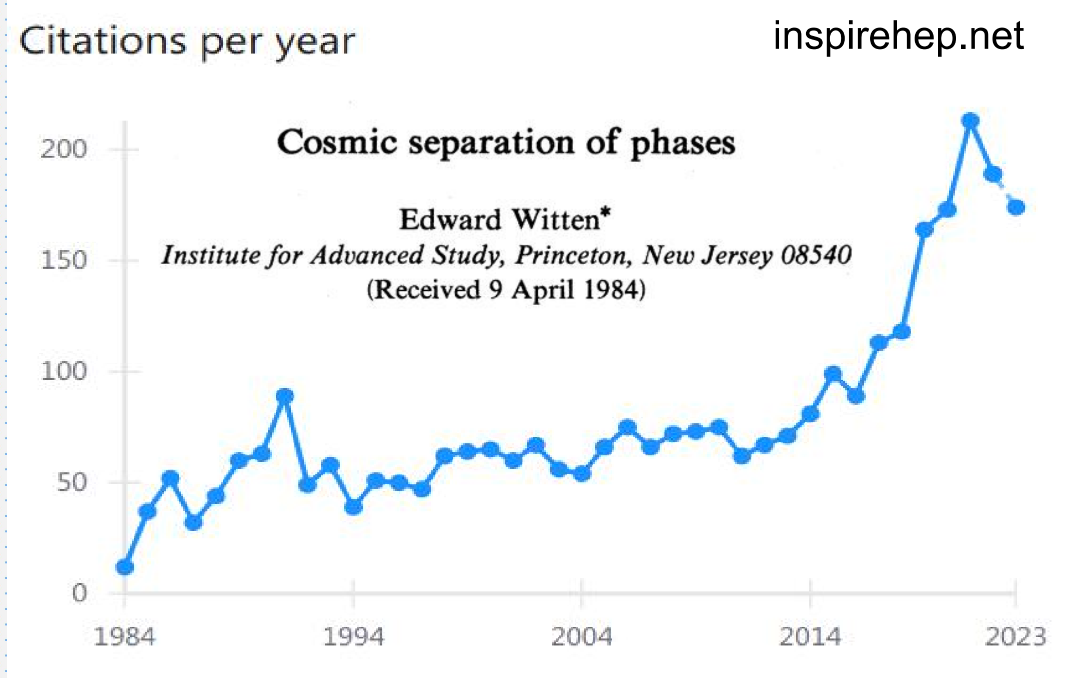
中国科学院大学
国际理论物理中心-亚太地区

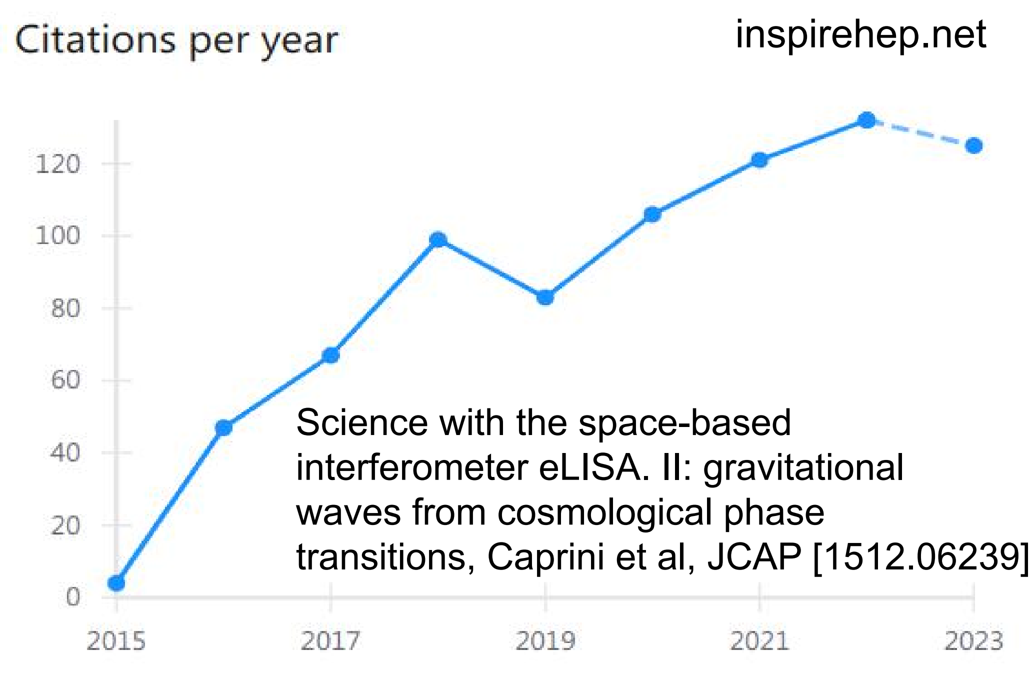
2023-12-17

第十七届TeV工作组学术研讨会



Radius of the Visible Universe
Quantum Fluctuations
Inflation
Inflation Ends
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Dark Ages
First Stars & Galaxies Form
Modern Universe
Today
0
10-32
1 μs
0.01 s
3 min
380,000 yrs
200 Million yrs
13.8 Billion yrs
Age of the Universe
BICEP2 Collaboration/CERN/NASA





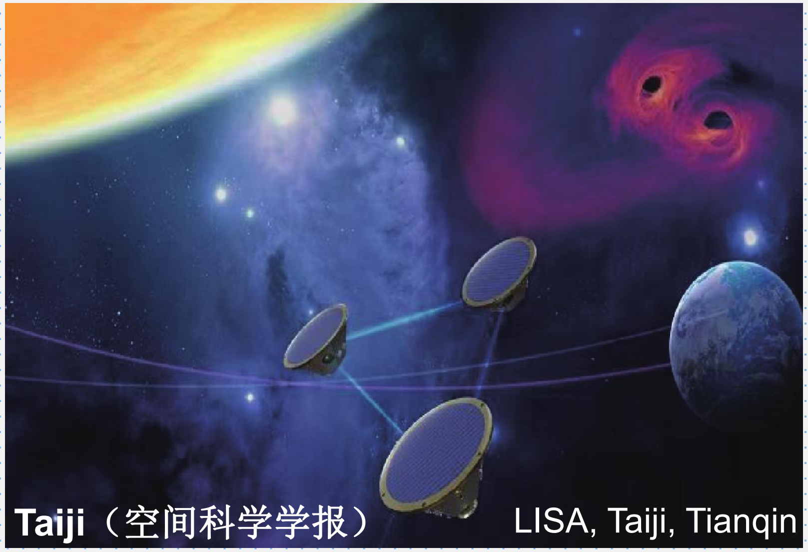
EPTA

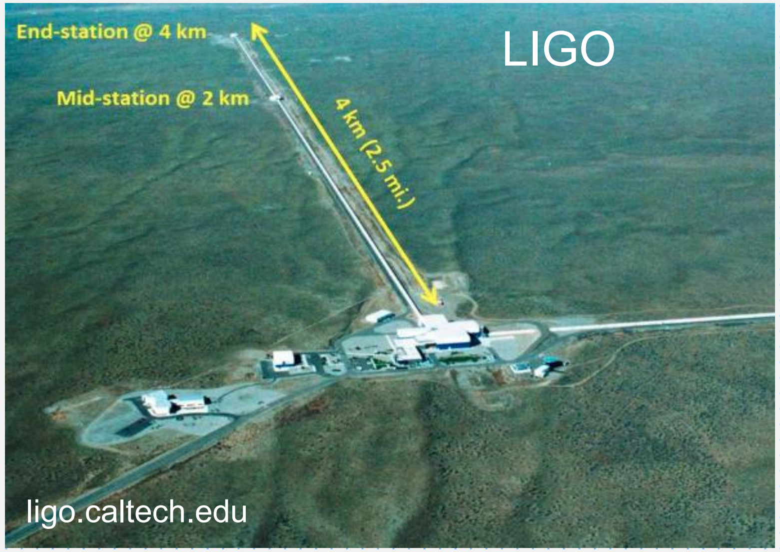
NANOGrav Physics Frontiers Center

PPTA

InPTA Indian Pulsar Timing Array

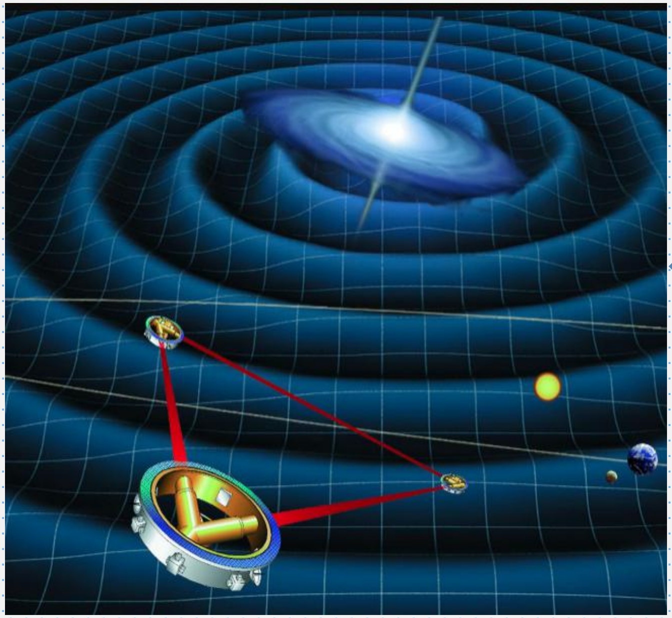
中国脉冲星测时阵列（**CPTA**）



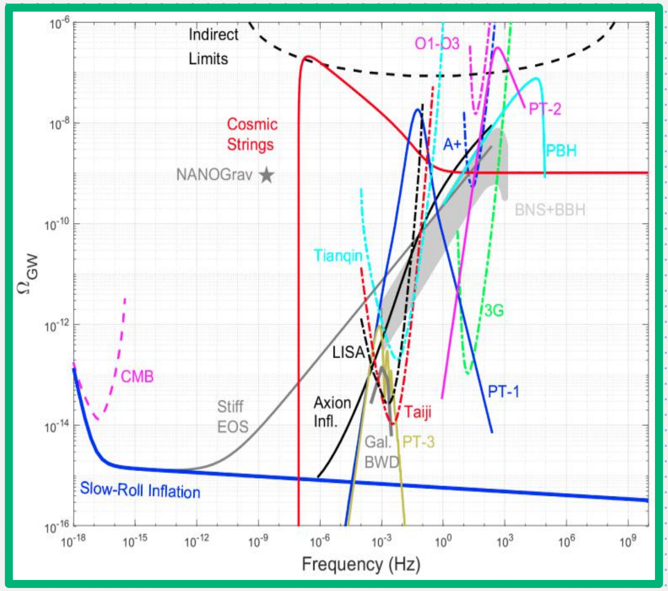


From Theory to Experiment

theorist



LIGO, LISA/Taiji/Tianqin, PTA, ...



Gravitational Wave Spectrum

α

β

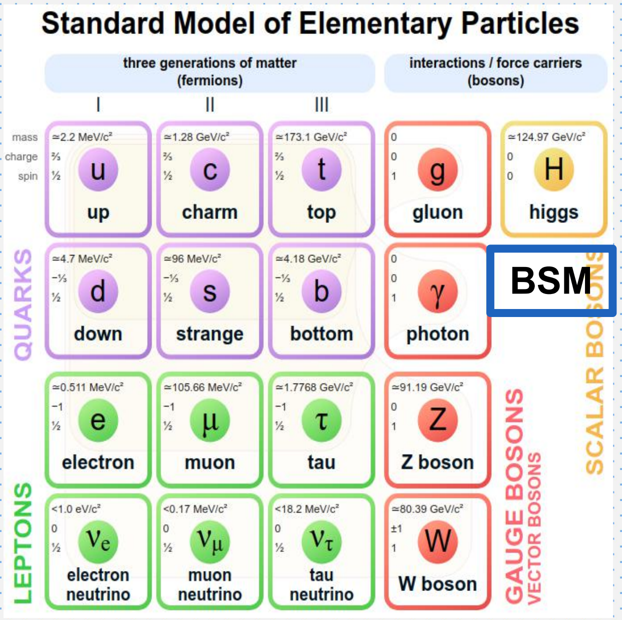
v_w

T_*

g_s

$\ldots$

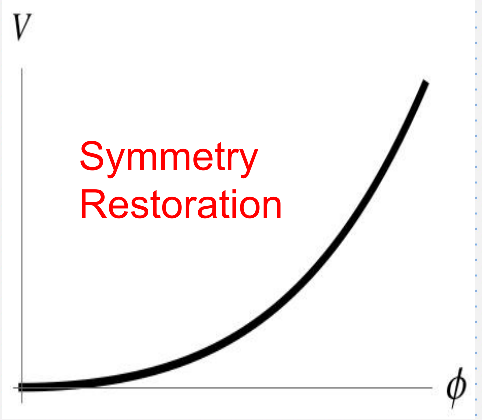
Phase Transition Parameters

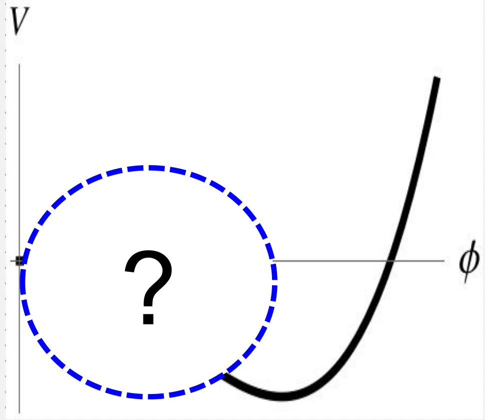


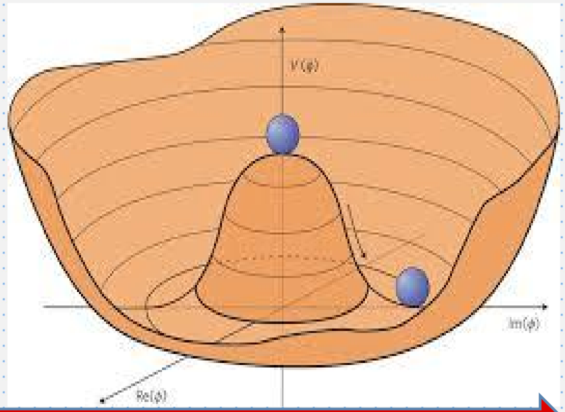
Particle Physics Model

experimentalist

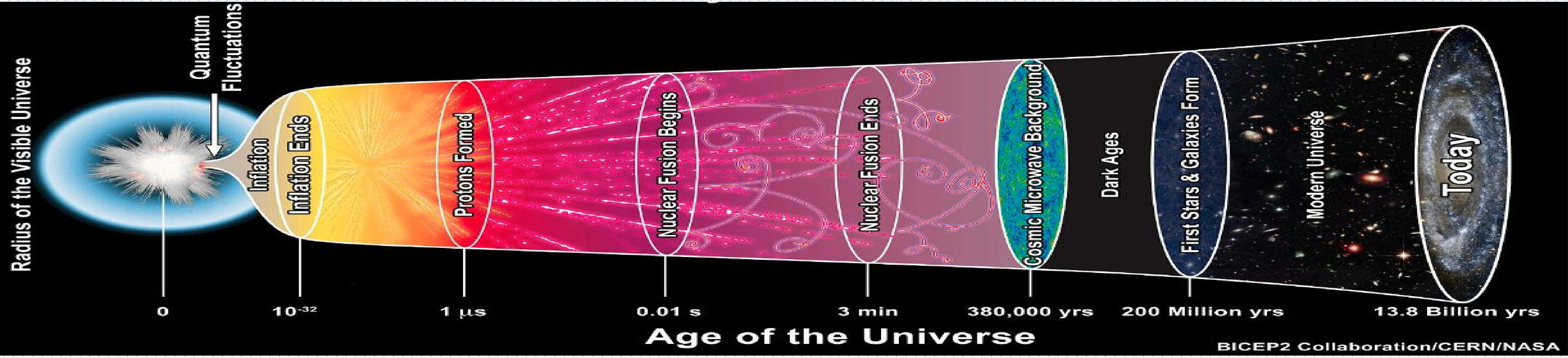
Electroweak Phase Transition



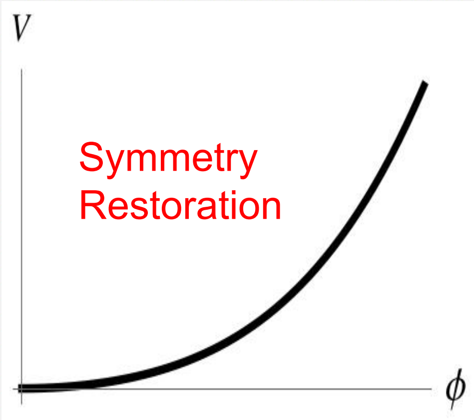


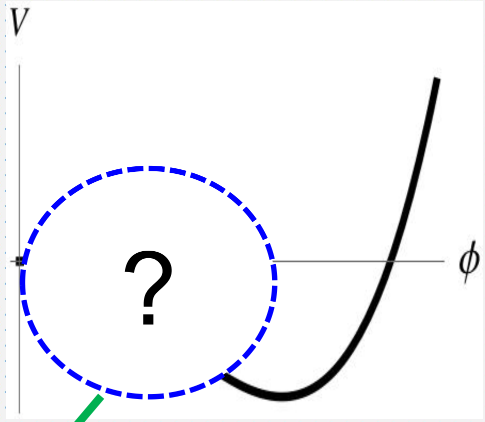


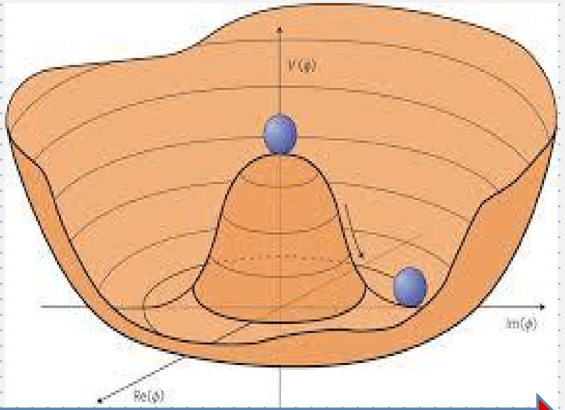
Temperature drops



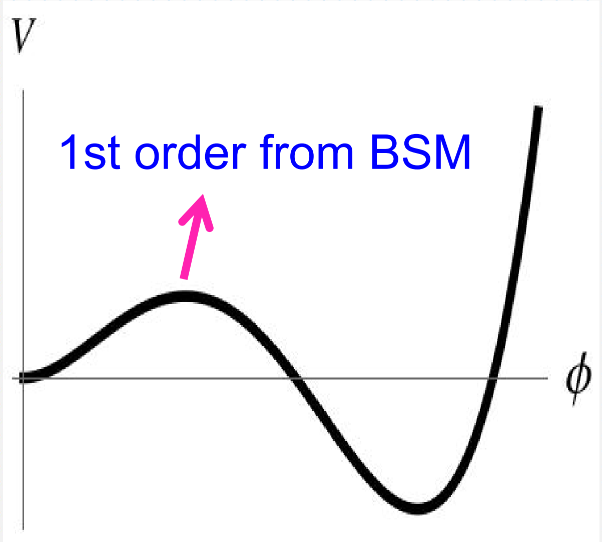
Electroweak Phase Transition

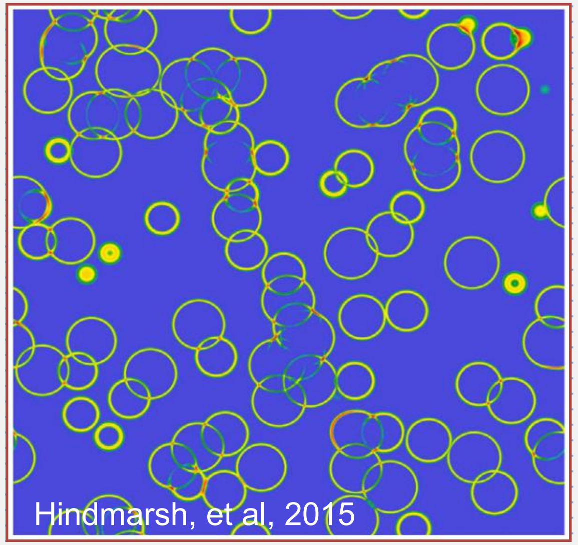






Temperature drops





Electroweak Baryogenesis

- Modified Higgs potential (Higgs physics, GW)
- Extra CP-violation (EDM, LHC)
- New particles, symmetries (LHC, GW)

Trodden, Rev.Mod.Phys [9803479]

Phenomenological Studies

Detection of early-universe gravitational-wave signatures and fundamental physics

Robert Caldwell, Yanou Cui, Huai-Ke Guo ✉, Vuk Mandic, Alberto Mariotti, Jose Miguel No, Michael J. Ramsey-Musolf, Mairi Sakellariadou ✉, Kuver Sinha, Lian-Tao Wang, Graham White, Yue Zhao, Haipeng An, Ligong Bian, Chiara Caprini, Sebastien Clesse, James M. Cline, Giulia Cusin, Bartosz Fornal, Ryusuke Jinno, Benoit Laurent, Noam Levi, Kun-Feng Lyu, Mario Martinez, Andrew L. Miller, Diego Redigolo, Claudia Scarlata, Alexander Sevrin, Barmak Shams Es Haghi, Jing Shu, Xavier Siemens, Danièle A. Steer, Raman Sundrum, Carlos Tamarit, David J. Weir, Ke-Pan Xie, Feng-Wei Yang & Siyi Zhou — Show fewer authors

General Relativity and Gravitation **54**, Article number: 156 (2022) | Cite this article

arXiv > hep-ph > arXiv:2203.08206

High Energy Physics - Phenomenology

[Submitted on 15 Mar 2022]

Probing the Electroweak Phase Transition with Exotic Higgs Decays

Marcela Carena, Jonathan Kozaczuk, Zhen Liu, Tong Ou, Michael J. Ramsey-Musolf, Jessie Shelton, Yikun Wang, Ke-Pan Xie

arXiv > hep-ph > arXiv:2203.10046

High Energy Physics - Phenomenology

[Submitted on 18 Mar 2022]

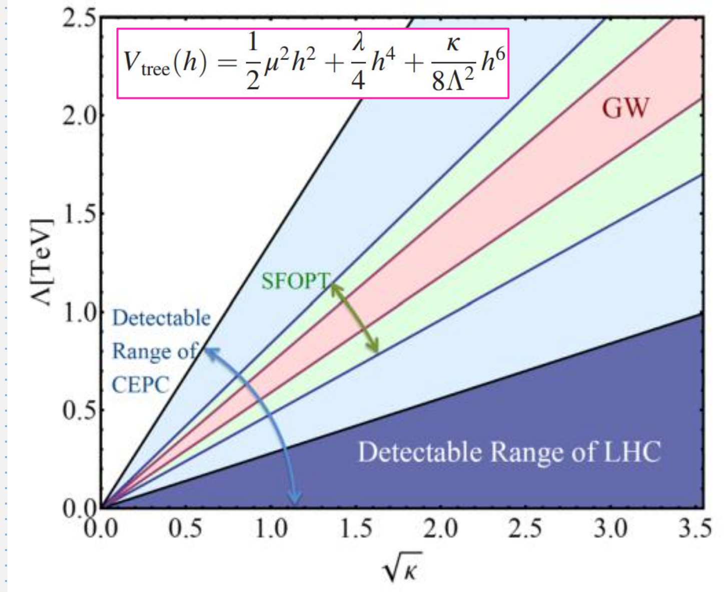
Scalar-mediated dark matter model at colliders and gravitational wave detectors -- A White paper for Snowmass 2021

Jia Liu, Xiao-Ping Wang, Ke-Pan Xie

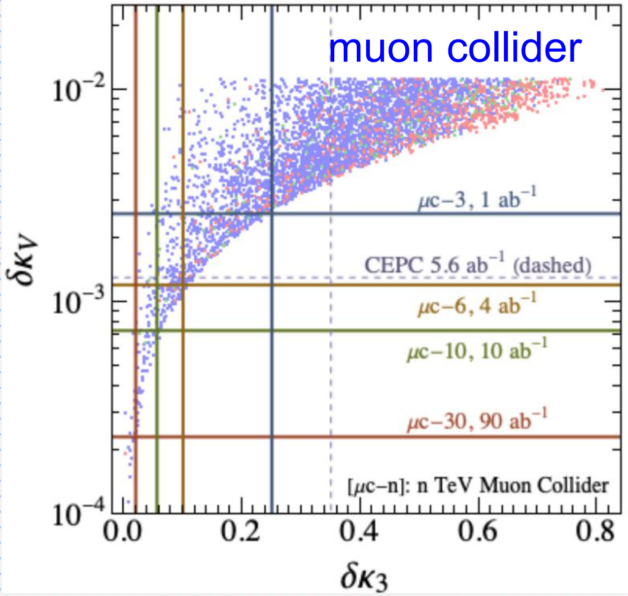
Snowmass 2021 White papers

Models	Strong 1st 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)	✓	✓	✓	✓

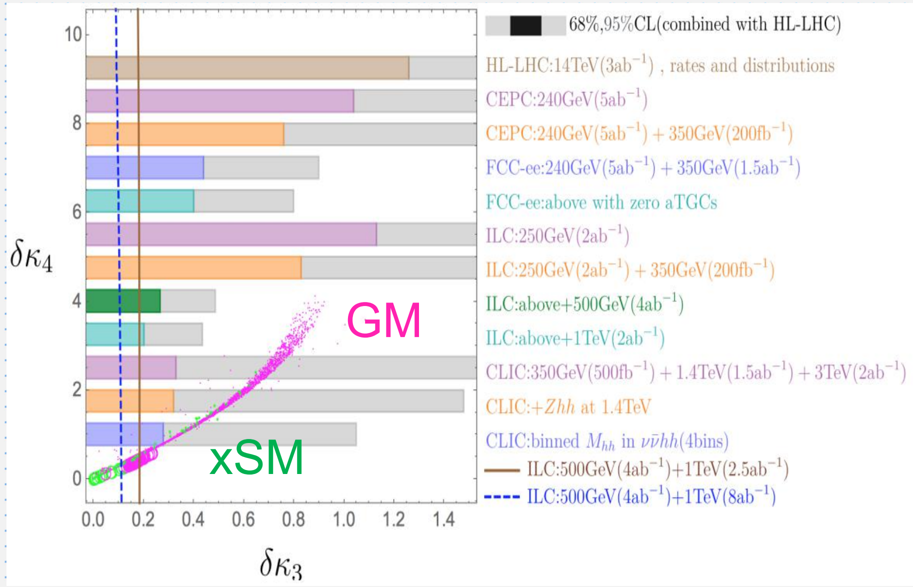
Ghosh,HG,Han,Liu, JHEP [2012.09758]



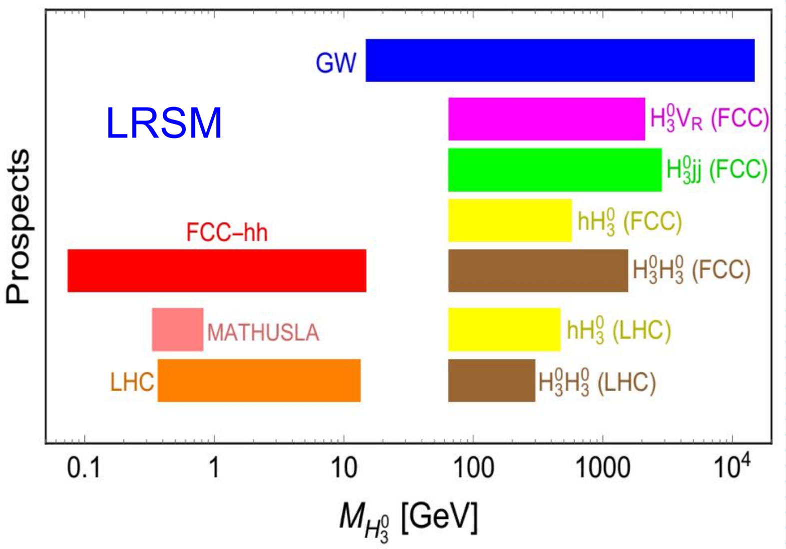
Fapeng Huang, Yi-Fu Cai, Xinmin Zhang, et al, PRD [1601.01640]



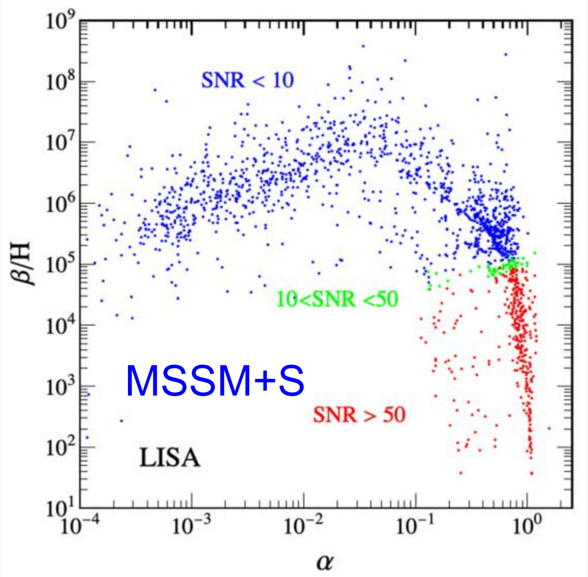
Wei Liu, Ke-Pan Xie, JHEP [2101.10469]



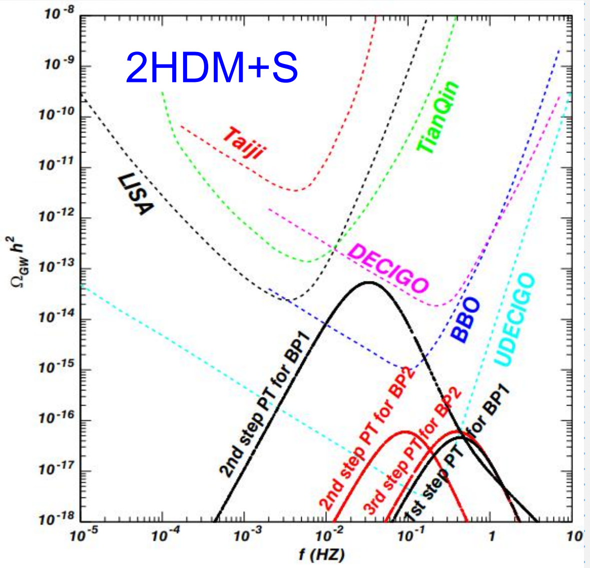
Ligong Bian, HG, Yongcheng Wu, Ruiyu Zhou, PRD [1906.11664]



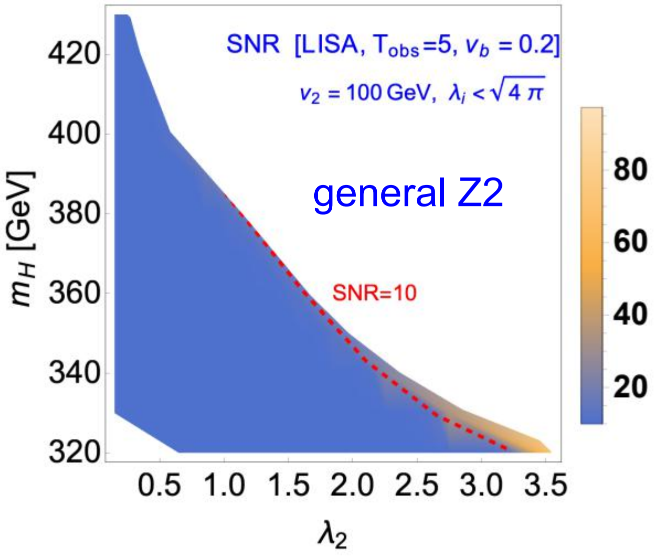
Mingqiu Li, Qi-Shu Yan, Yongchao Zhang, Zhijie Zhao, JHEP [2012.13686]



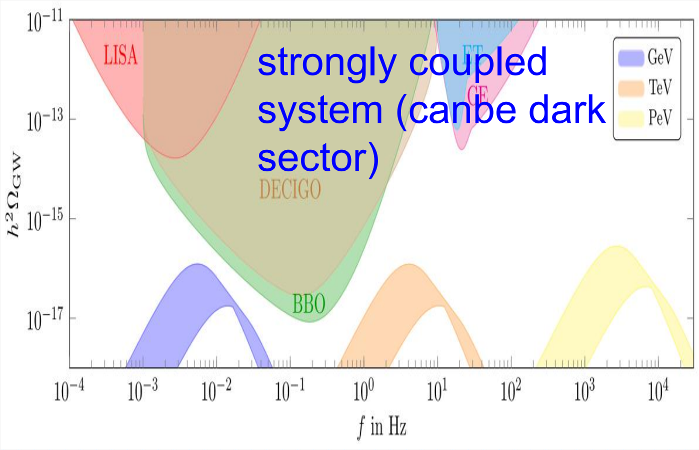
Wenyu Wang, Ke-Pan Xie, Wu-Long Xu, Jin Min Yang, EPJC [2204.01928]



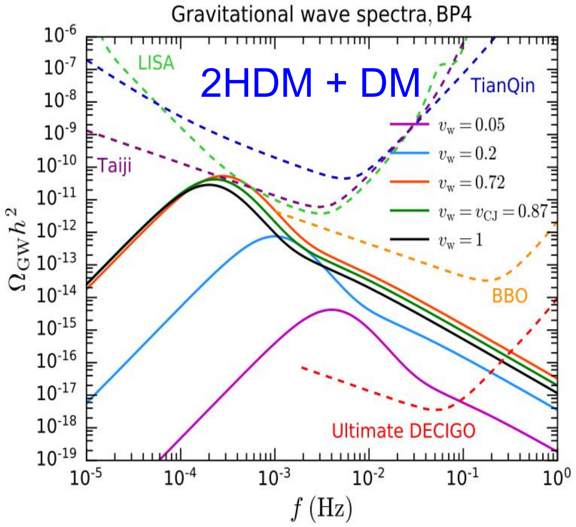
Songtao Liu, Lei Wang, PRD [2302.04639]



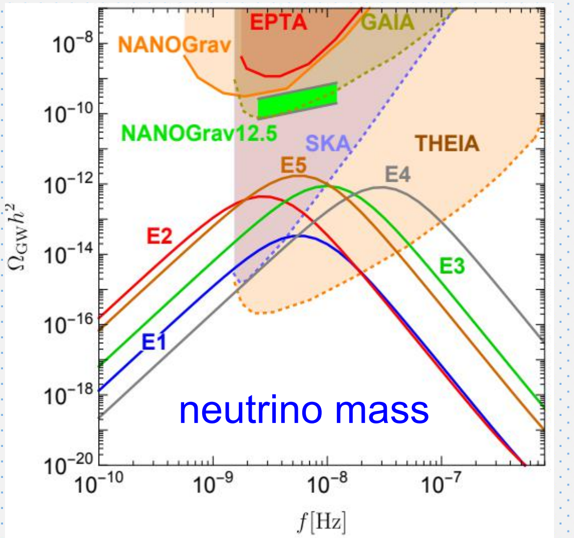
Qing-Hong Cao, Katsuya Hashino, Xu-Xiang Li, Jiang-Hao Yu [2212.07756]



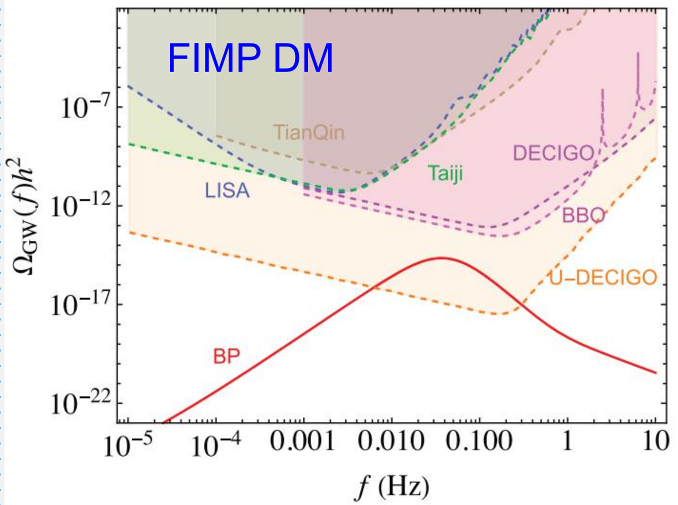
Zhi-Wei Wang, et al, PRD [2012.11614]



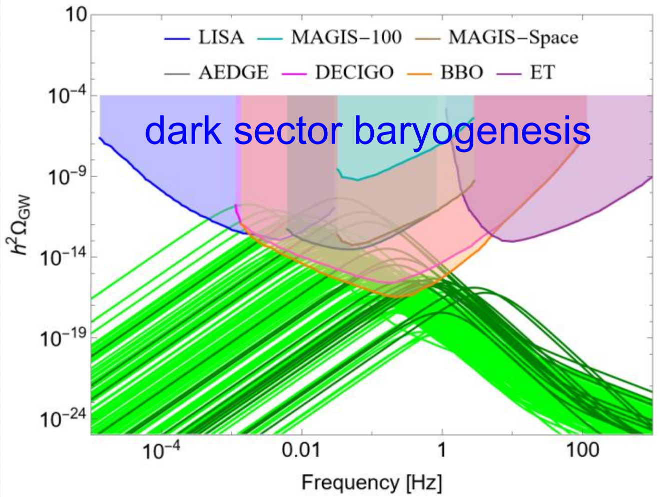
Zhao Zhang, Chengfeng Cai, Xue-Min Jiang, Yi-Lei Tang, Zhao-Huan Yu, and Hong-Hao Zhang, JHEP [2102.01588]



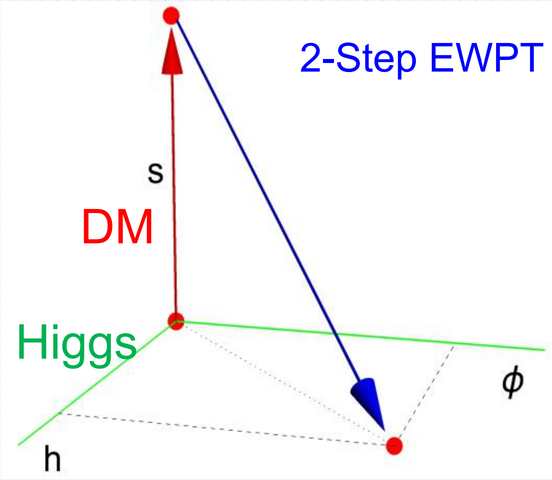
Pasquale Di Bari, Danny Marfatia, Ye-Ling Zhou, JHEP [2106.00025]



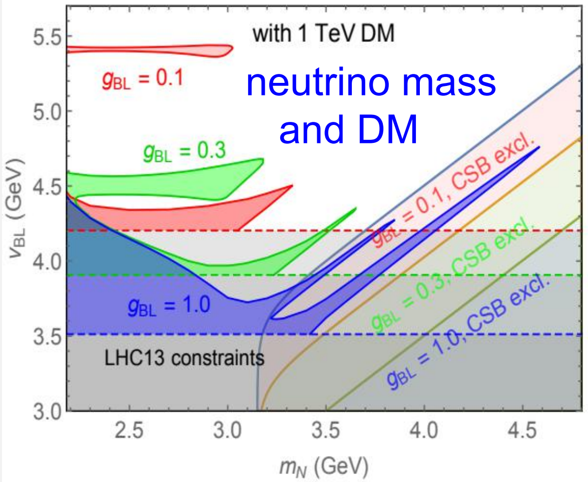
Xuewen Liu, Shu-Yuan Guo, Bin Zhu, Ying Li, Sci.Bull. [2022.06.011]



Marcela Carena, Ying-Ying Li, Tong Ou, Yikun Wang, JHEP [2210.14352]



Wei Chao, HG, Jing Shu, JCAP [1702.02698]



Ligong Bian, Wei Cheng, HG, Yongchao Zhang, CPC [1907.13589]

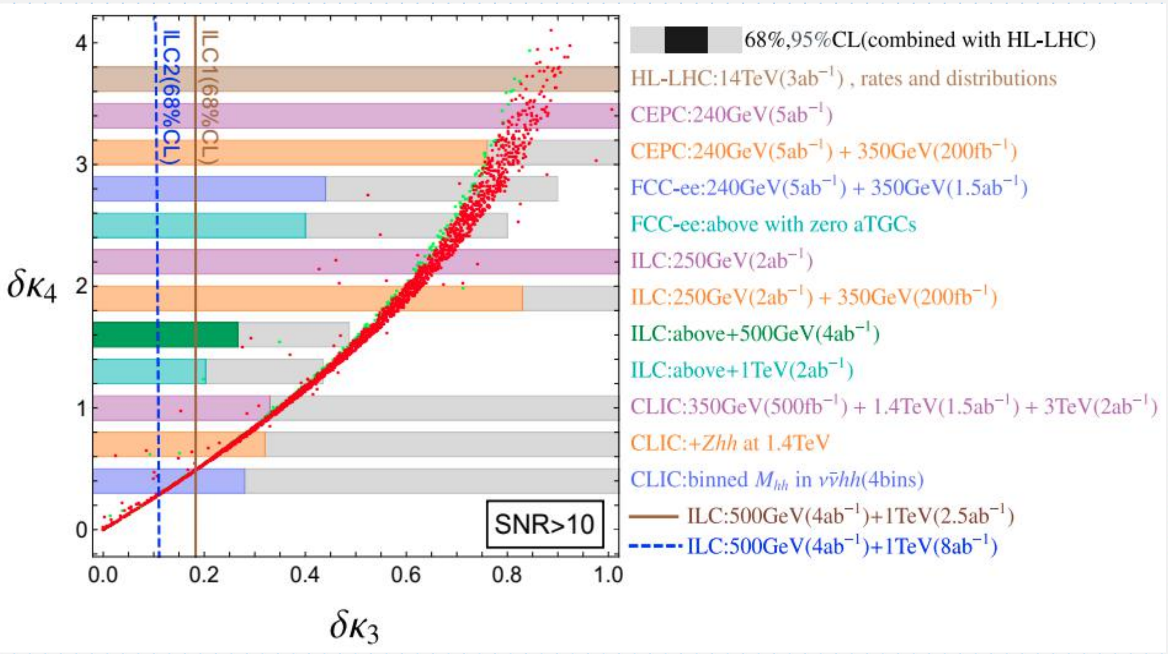
Collider and GW Complementarity

Contents

Snowmass 2021 Whitepaper, GRG [2203.07972]

Session leads: Huaike Guo, Graham White

Session leads: Michael Ramsey-Musolf and Lian-Tao Wang



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

Simplest model: xSM (SM + S)

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

#27

Collider and Gravitational Wave Complementarity in Exploring the Singlet Extension of the Standard Model

Alexandre Alves (Diadema, Sao Paulo Fed. U.), Tathagata Ghosh (Hawaii U.), Huai-Ke Guo (Oklahoma U.), Kuver Sinha (Oklahoma U.), Daniel Vagie (Oklahoma U.) (Dec 21, 2018)

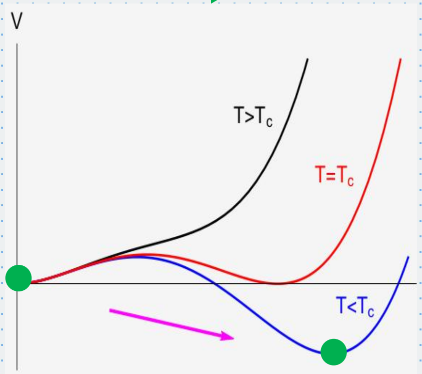
Published in: *JHEP* 04 (2019) 052 • e-Print: 1812.09333 [hep-ph]

Nucleation Rate: Perturbative Method

The Usual Method
(Tree + Coleman-Weinberg + Daisy Resummation)

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

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



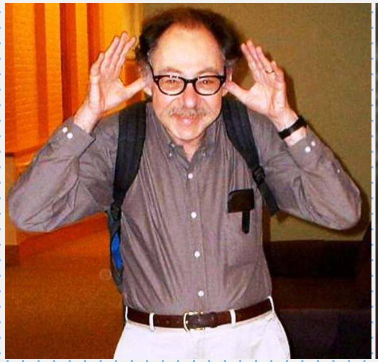
- Infrared problem (Linde, 1980)
- Gauge invariance (ok for high-T expansion)
  (Patel,Ramsey-Musolf, JHEP [1101.4665])

Nucleation rate

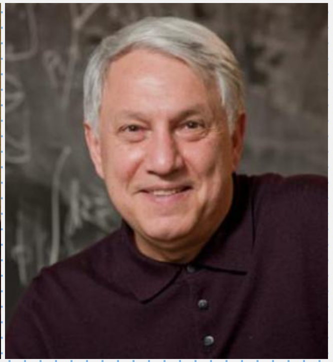
$$p = p_0 \exp\left[-\frac{S_{3,b}(T)}{T}\right]$$

fluctuations

critical bubble



Sidney Coleman



Andrei Linde

Gauge-invariant method proposed

Löfgren, Ramsey-Musolf, et al, PRL [2112.05472], JHEP [2112.08912]

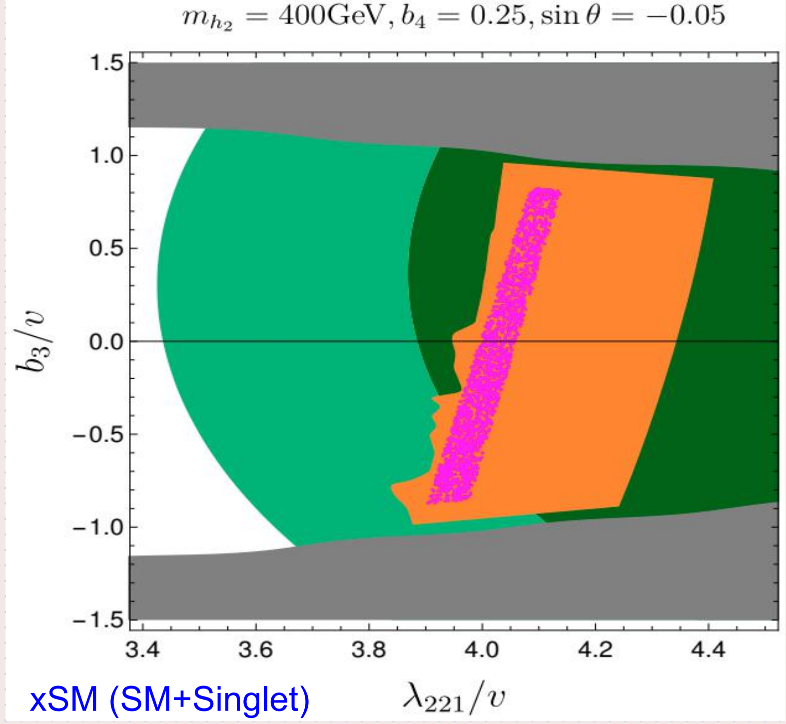
$$S_3 = a_0 g^{-3/2} + a_1 g^{-1/2} + \Delta$$

$$-\frac{1}{T}S_3[\phi_b] = -\frac{1}{T}\int d^3x\left[V_{\rm LO}^{\rm eff}(\phi_b) + V_{\rm NLO}^{\rm eff}(\phi_b) + \frac{1}{2}[1 + Z_{\rm NLO}(\phi_b,T)](\partial_i\phi_b)^2 + \cdots\right]$$

Nucleation Rate: Non-Perturbative Method

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

perturbative vs non-perturbative

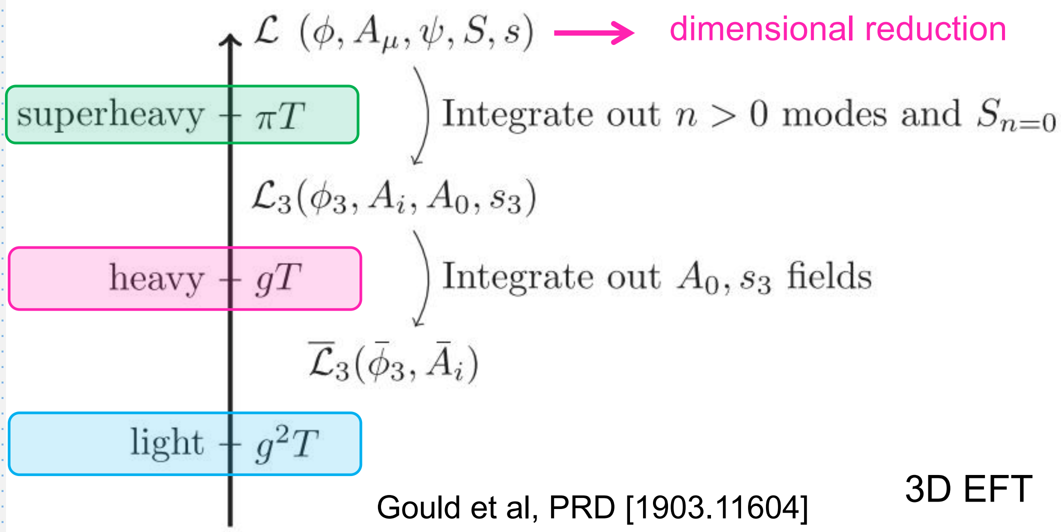


Alves,Goncalves,Ghosh,HG,Sinha, JHEP [1909.05268]

perturbative (high-T, gauge independent)

non-perturbative (high-dim operator needed)

perturbative (full one-loop)

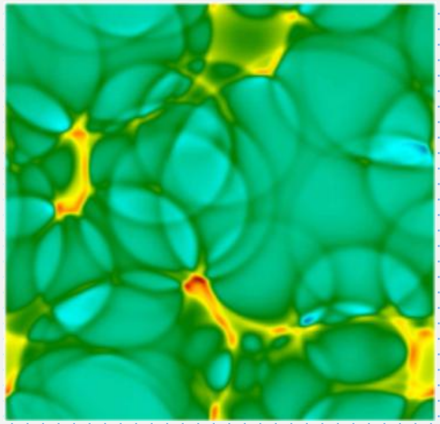


Gould et al, PRD [1903.11604]

3D EFT

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]

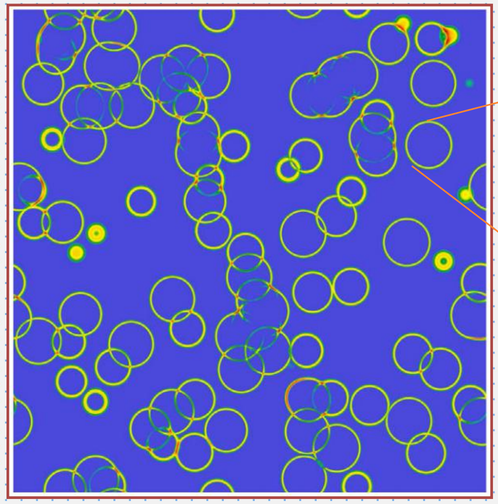
The Picture



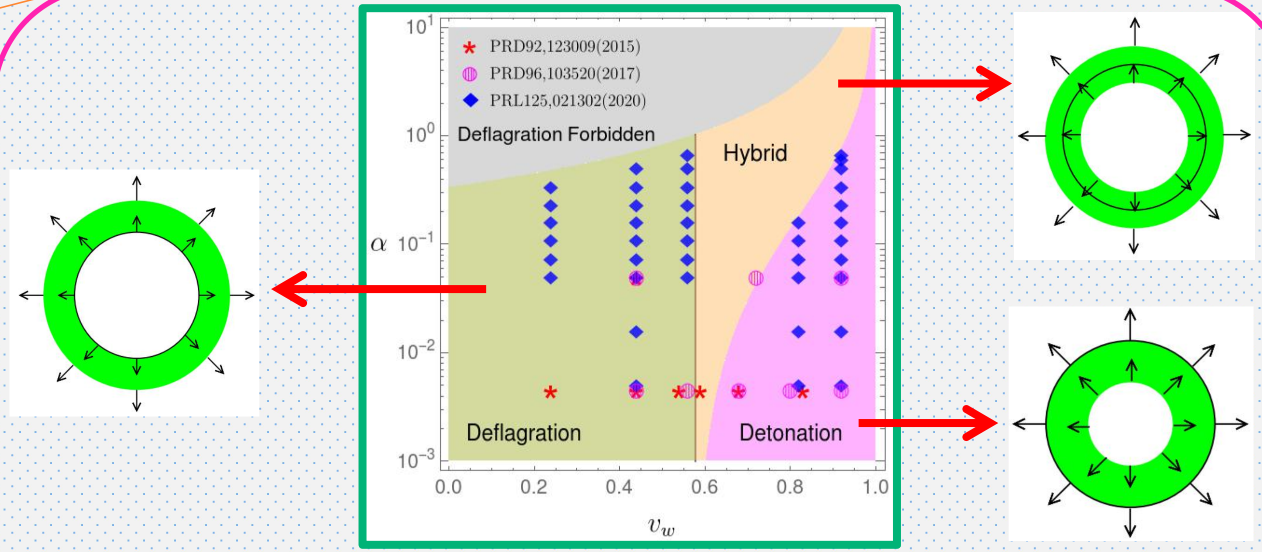
Precise calculation of PT parameters:

Minkowski spacetime: Hindmarsh,Hijazi, JCAP [1909.10040]
Expanding universe: HG,Sinha,Vagie,White, JCAP [2007.08537], JHEP [2103.06933]

- False Vacuum Fraction
- Unbroken Wall Area
- Bubble Lifetime Distribution
- Bubble Number Density



Hindmarsh et al, 2015



Espinosa,Konstandin,No,Servant JCAP [1004.4187]

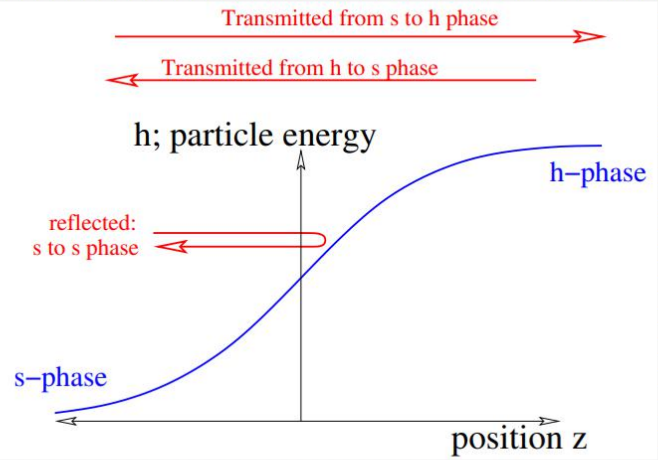
Wall Velocity: vw

Usually chosen as fixed value in baryon asymmetry and GW studies

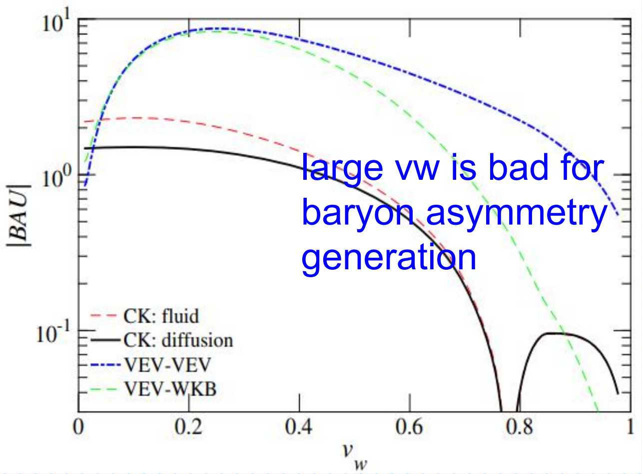
But, significant advances in recent years (driven by GW studies)

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

- 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)
- Hydrodynamic (Cai, Wang, JCAP [2011.11451], Wang, Yuwen, PRD [2205.02492], 2310.07691)



Bodeker,Moore, JCAP [1703.08215]



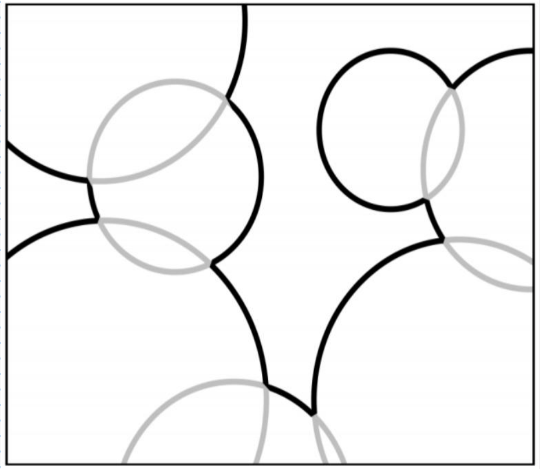
Cline,Kainulainen, PRD [2001.00568]

Gravitational Wave Sources

The current understanding:

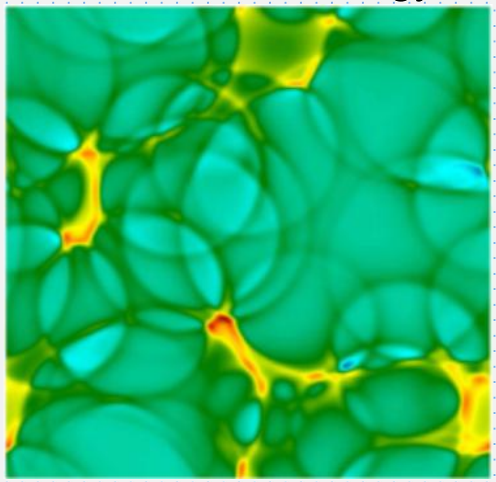
$$\Box \bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu}$$

energy near the wall



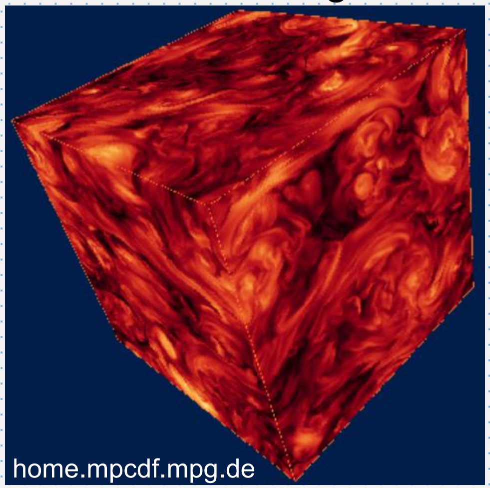
Bubble Collisions

fluid kinetic energy



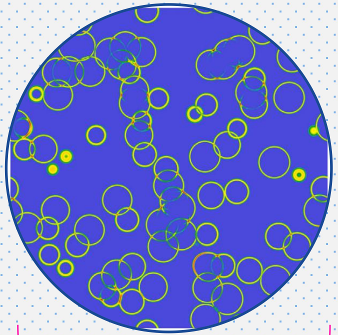
Sound Waves

turbulent fluid + magnetic field



Magnetohydrodynamic Turbulence

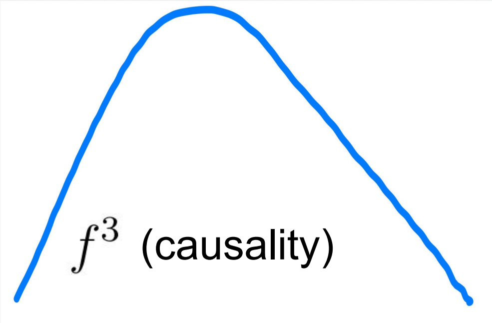
Basic Properties



Hubble size: 1/H*

$$f_{\rm now} = 1.65 \times 10^{-5} \left(\frac{f_{\rm PT}}{\beta}\right)\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{100{\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6} {\rm Hz}$$

~100-1000



Cai, Pi, Sasak, PRD [1909.13728]

nHz (~100MeV) QCD scale

~mHz : (~100GeV) weak scale

~100Hz (~PeV - EeV) high scale

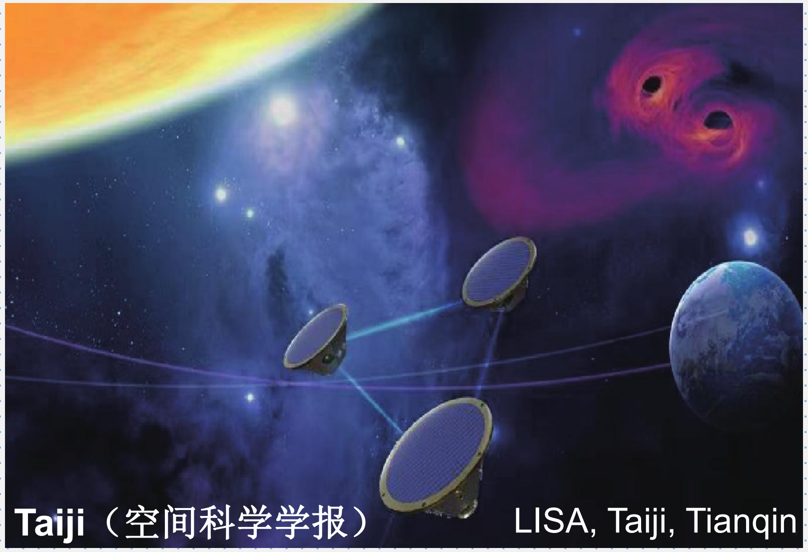
EPTA

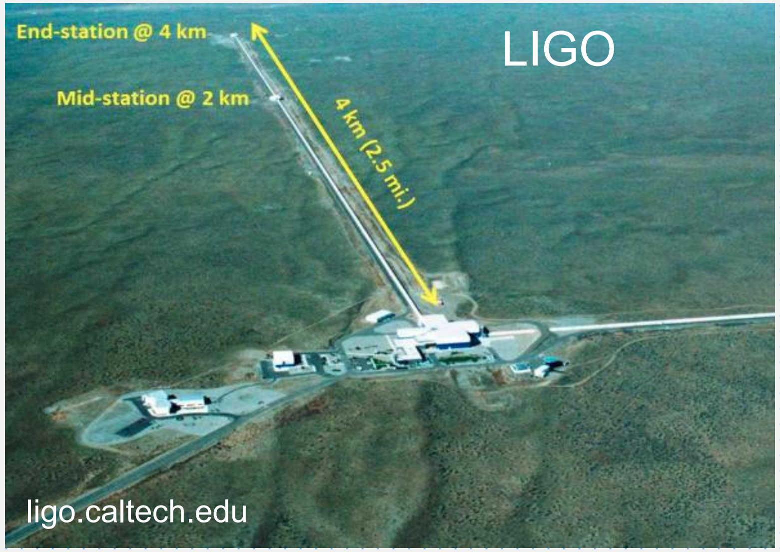
NANOGrav Physics Frontiers Center

PPTA

InPTA Indian Pulsar Timing Array

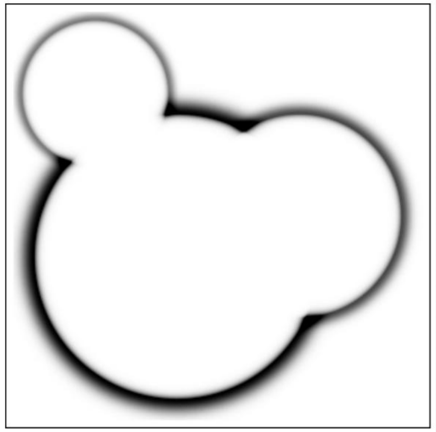
中国脉冲星测时阵列（CPTA）





Bubble Collisions

Envelope approximation:
Kosowsky, Turner, Watkins, Kamionkowski,
PRL69,2026(1992), PRD45,4514(1992), PRD47,4372(1993), PRD [9310044]



thin shell of uncollided walls

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

simulation

$$\Delta = \frac{0.11 v_w^3}{0.42 + v_w^2},$$

$$\frac{f_*}{\beta} = \frac{0.62}{1.8 - 0.1 v_w + v_w^2},$$

$$S_{\rm env} = \left[\frac{3.8 (f/f_{\rm env})^{2.8}}{1 + 2.8 (f/f_{\rm env})^{3.8}}\right]$$

Huber, Konstandin, JCAP [0806.1828]

Chiara Caprini et al JCAP [1512.06239]

analytical

$$\Delta = \frac{0.48 v_w^3}{1 + 5.3 v_w^2 + 5 v_w^4},$$

$$\frac{f_*}{\beta} = \frac{0.35}{1 + 0.069 v_w + 0.69 v_w^4},$$

$$S_{\rm env} = \left[c_l \left(\frac{f}{f_{\rm env}}\right)^{-3} + (1 - c_l - c_h) \left(\frac{f}{f_{\rm env}}\right)^{-1} + c_h \left(\frac{f}{f_{\rm env}}\right)\right]^{-1}$$

$$(c_l = 0.064, \quad c_h = 0.48)$$

Jinno, Takimoto, PRD [1605.01403]

$$\Omega_{\rm BC}(f \gtrsim f_{\rm peak}) \propto f^{-1}$$

$$\Omega_{\rm BC}(f \lesssim f_{\rm peak}) \propto f^{3}$$

Bubble Collisions: Recent Development

- Wall thickness (probe effective potential)

  Cutting et al, PRD [2005.13537], Gould et al, PRD [2107.05657], Mégevand,Membiela, JCAP [2302.13349]

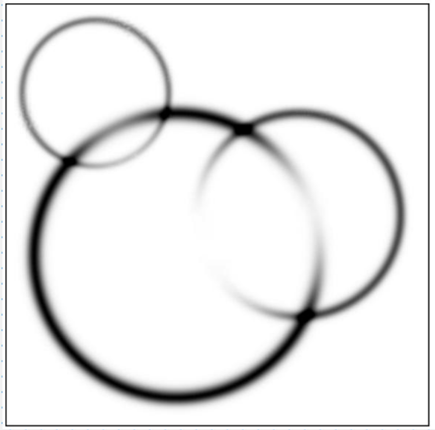
- Duration and Expanding Universe

  Zhong, Gong, Qiu, JHEP [2107.01845]

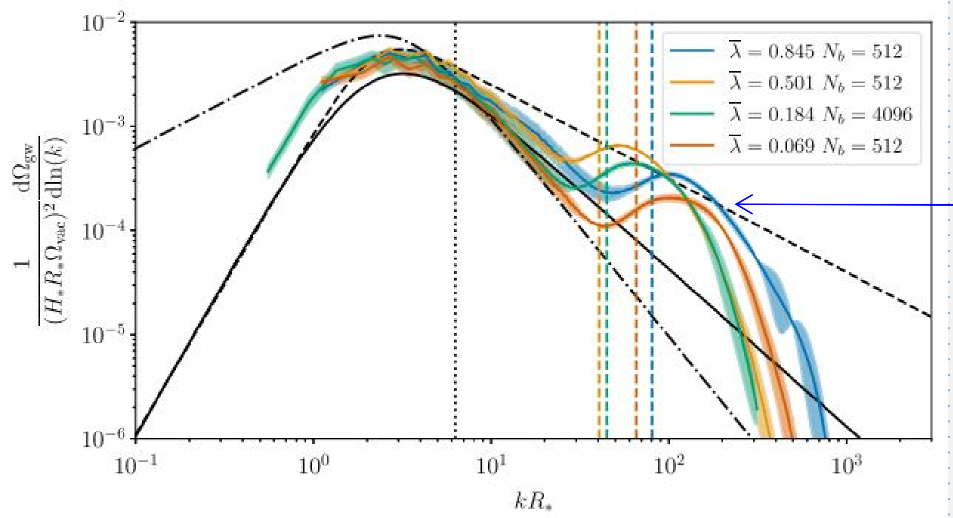
- Scalar + Gauge

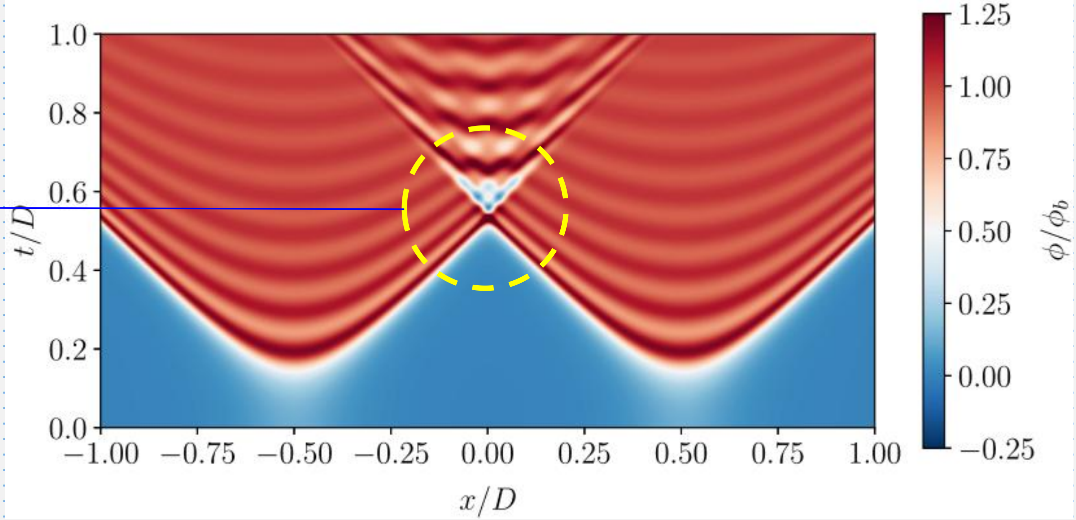
  Di, Wang, Zhou, Bian, Cai, Liu, PRL [2012.15625], Yang, Bian, PRD [2102.01398], Lewicki, Vaskonen, EPJC [2007.04967]

Bulk flow model



Jinno,Takimoto, JCAP [1707.03111], Konstandin, JCAP [1712.06869]



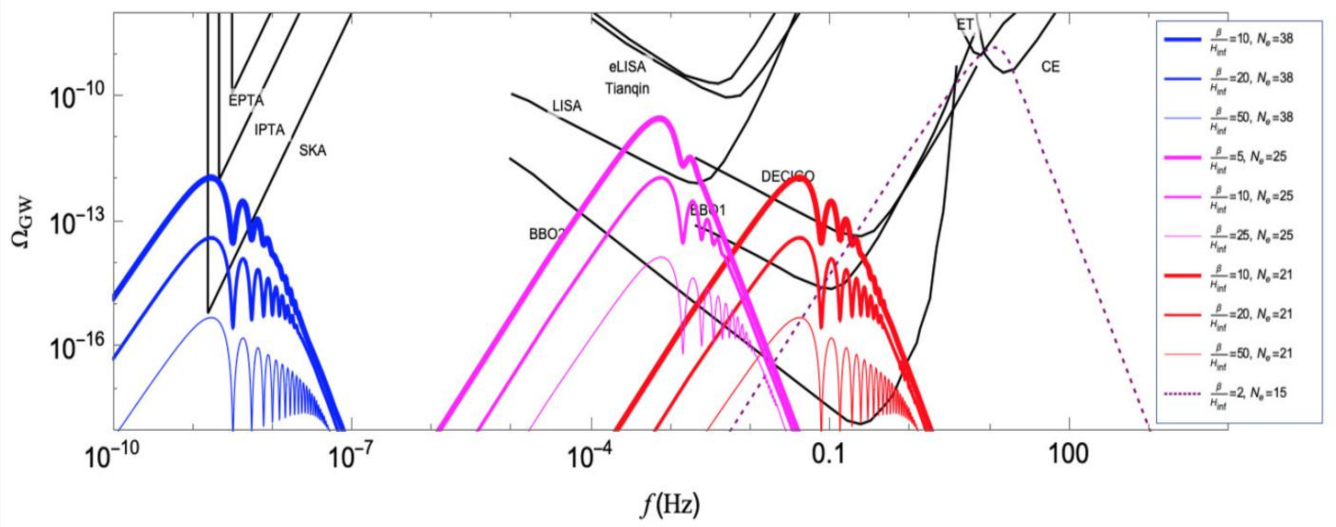


Bubble Collisions during Inflation

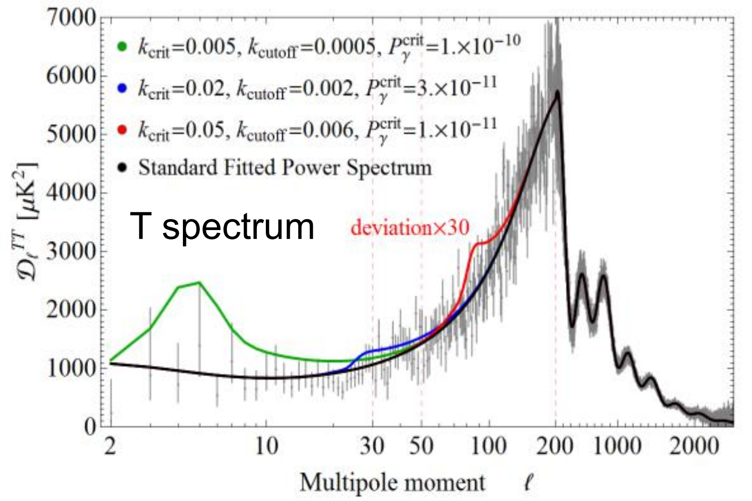
PT in the spectator field (sigma), with negligible energy density

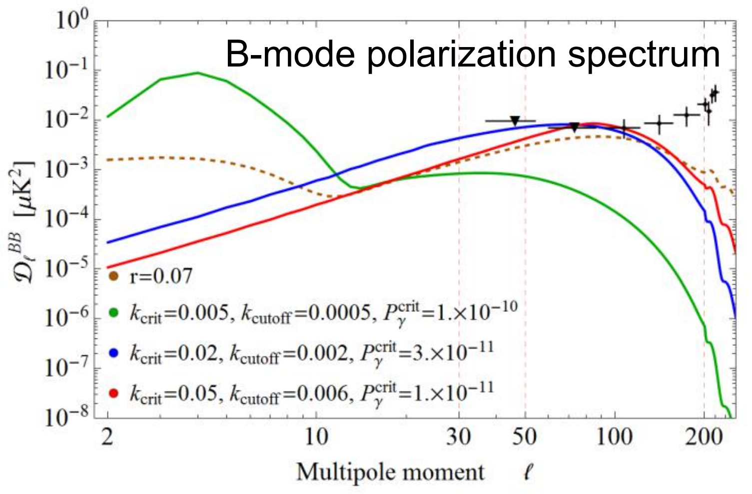
$$\mathcal{L} = -\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \frac{1}{2}g^{\mu\nu}\partial_\mu\sigma\partial_\nu\sigma - V(\phi,\sigma)$$

An, Lyu, Wang, Zhou, CPC [2009.12381], JHEP [2201.05171]
An, Tong, Zhou, [2208.14857]
An, Yang, [2304.02361]

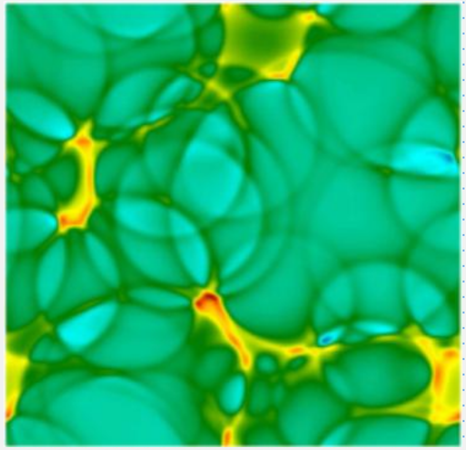


Jiang,Liu,Sun,Wang, PLB [1512.07538]





Sound Waves



Hindmarsh,Huber,Rummukainen,Weir, PRL [1304.2433]

$$T^{ij} \propto (p+e) v^i v^j$$

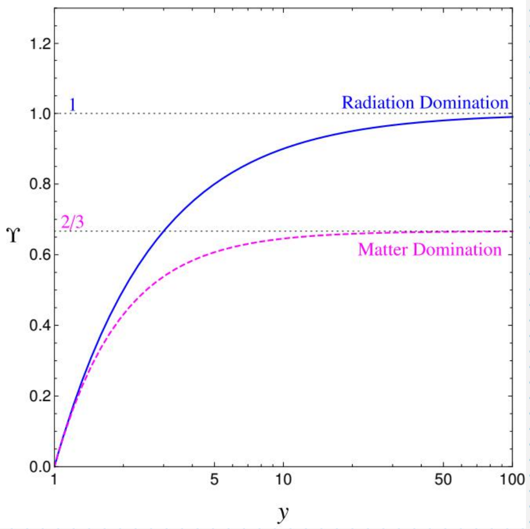
$$h^2\Omega_{\rm sw}(f) = 2.65 \times 10^{-6} \left(\frac{100}{g_*}\right)^{\frac{1}{3}} \left(\frac{H_*}{\beta}\right) \left(\frac{\kappa_{\rm sw}\alpha}{1+\alpha}\right)^2 v_w S_{\rm sw}(f) \Upsilon(\tau_{\rm sw})$$

$$S_{\rm sw}(f) = \left(\frac{f}{f_{\rm sw}}\right)^3 \left[\frac{7}{4+3(f/f_{\rm sw})^2}\right]^{7/2} \qquad f_* = \frac{2\beta}{\sqrt{3}v_w} \approx \frac{3.4}{R_*}$$

Hindmarsh,Huber,Rummukainen,Weir, PRD [1504.03291]

$$\Omega_{\rm SW}(f \gtrsim f_{\rm peak}) \propto f^{-4}$$

$$\Omega_{\rm SW}(f \lesssim f_{\rm peak}) \propto f^{3}$$



Slight different fit obtained by the same group, PRD [1704.05871]

$$\Upsilon = 1 - (1 + 2\tau_{\rm sw} H_{\rm pt})^{-1/2}$$ (radiation domination)

HG, Sinha, Vagie, White, JCAP [2007.08537]

Sound Waves: Recent Development

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

HG, Sinha, Vagie, White, JCAP [2007.08537]

#1

Phase Transitions in an Expanding Universe: Stochastic Gravitational Waves in Standard and Non-Standard Histories

Huai-Ke Guo (Oklahoma U.), Kuver Sinha (Oklahoma U.), Daniel Vagie (Oklahoma U.), Graham White (TRIUMF) (Jul 16, 2020)

Published in: *JCAP* 01 (2021) 001 • e-Print: 2007.08537 [hep-ph]

pdf | DOI | cite | claim | reference search | 166 citations

PHYSICAL REVIEW LETTERS **127,** 251302 (2021)

Editors' Suggestion | Featured in Physics

Searching for Gravitational Waves from Cosmological Phase Transitions with the NANOGrav 12.5-Year Dataset

Zaven Arzoumanian,[1] Paul T. Baker,[2] Harsha Blumer,[3,4] Bence Bécsy,[5] Adam Brazier,[6,7] Paul R. Brook,[3,4] Sarah Burke-Spolaor,[3,4,8] Maria Charisi,[9] Shami Chatterjee,[6] Siyuan Chen,[10,11,12] James M. Cordes,[6] Neil J. Cornish,[5] Fronefield Crawford,[13] H. Thankful Cromartie,[6] Megan E. DeCesar,[14,15*] Paul B. Demorest,[16] Timothy Dolch,[17,18] Justin A. Ellis,[19] Elizabeth C. Ferrara,[20,21,22] William Fiore,[3,4] Emmanuel Fonseca,[23] Nathan Garver-Daniels,[3,4] Peter A. Gentile,[3,4] Deborah C. Good,[24] Jeffrey S. Hazboun,[25] A. Miguel Holgado,[26,27] Kristina Islo,[28] Ross J. Jennings,[6] ...

(NANOGrav Collaboration)

> considered in this work. Because of the finite lifetime [54,55] of the sound waves, to derive Ω_{SW} Eq. (4) needs to be multiplied by a suppression factor $\Upsilon(\tau_{SW})$ given by [54]
>
> $$\Upsilon(\tau_{SW}) = 1 - (1 + 2\tau_{SW} H_*)^{-1/2} \qquad (6)$$

THE ASTROPHYSICAL JOURNAL LETTERS, 951:L11 (56pp), 2023 July 1 https://doi.org/10.3847/2041-8213/acdc91

© 2023. The Author(s). Published by the American Astronomical Society.

OPEN ACCESS

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

Adeela Afzal[1,2], Gabriella Agazie[3], Akash Anumarlapudi[3], Anne M. Archibald[4], Zaven Arzoumanian[5], Paul T. Baker[6], Bence Bécsy[7], Jose Juan Blanco-Pillado[8,9,10], Laura Blecha[11], Kimberly K. Boddy[12], Adam Brazier[13,14], Paul R. Brook[15], Sarah Burke-Spolaor[16,17], Rand Burnette[7], Robin Case[7], Maria Charisi[18], Shami Chatterjee[13], Katerina Chatziioannou[19], Belinda D. Cheeseboro[16,17], Siyuan Chen[20], Tyler Cohen[21], James M. Cordes[13], Neil J. Cornish[22], Fronefield Crawford[23], H. Thankful Cromartie[13,77], Kathryn Crowter[24], Curt J. Cutler[19,25], Megan E. DeCesar[26], Dallas DeGan[7], Paul B. Demorest[27], Heling Deng[7], Timothy Dolch[28,29], Brendan Drachler[30,31], Richard von Eckardstein[1], Elizabeth C. Ferrara[32,33,34], William Fiore[16,17], Emmanuel Fonseca[16,17], Gabriel E. Freedman[3], Nate Garver-Daniels[16,17], Peter A. Gentile[16,17], Kyle A. Gersbach[18], Joseph Glaser[16,17], Deborah C. Good[35,36], Lydia Guertin[37], Kayhan Gültekin[38], Jeffrey S. Hazboun[7], Sophie Hourihane[19], Kristina Islo[3], Ross J. Jennings[16,17,78], Aaron D. Johnson[3,19], Megan L. Jones[3], Andrew R. Kaiser[16,17], David L. Kaplan[3], Luke Zoltan Kelley[39], Matthew Kerr[40], Joey S. Key[41], Nima Laal[7], Michael T. Lam[30,31], William G. Lamb[18], T. Joseph W. Lazio[25], Vincent S. H. Lee[19], Natalia Lewandowska[42], Rafael R. Lino dos Santos[1,43], Tyson B. Littenberg[44], ...

The NANOGrav Collaboration

> time of matter–radiation equality. The production of GWs from sound waves stops after a period τ_{sw}, when the plasma motion turns turbulent (Ellis et al. 2019a, 2019b, 2020; Guo et al. 2021). In Equation (34), this effect is taken into account by the suppression factor
>
> $$\Upsilon(\tau_{sw}) = 1 - (1 + 2\tau_{sw} H_*)^{-1/2}, \qquad (36)$$

Sound Waves: Recent Development

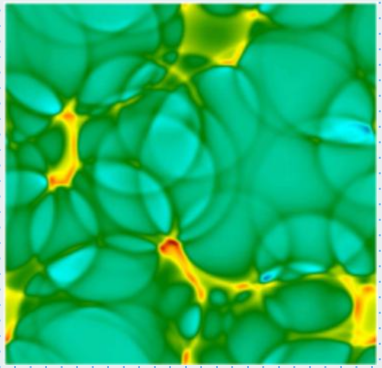
Analytical Modelling

- Refine the sound shell model
- Synergy with simulations

Sound Shell Model

Hindmarsh, PRL [1608.04735]
Hindmarsh, Hijazi, JCAP [1909.10040]
HG, Sinha, Vagie, White, JCAP [2007.08537]
Cai, Wang, Yuwen, PRD Letter [2305.00074]
Pol, Procacci, Caprini [2308.12943]

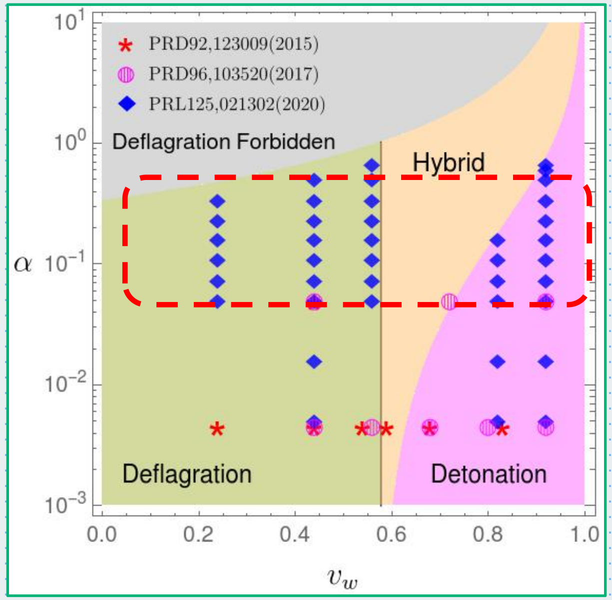
$$v^i_{\mathbf{q}} = \sum_{n=1}^{N_b} v^{i(n)}_{\mathbf{q}}$$

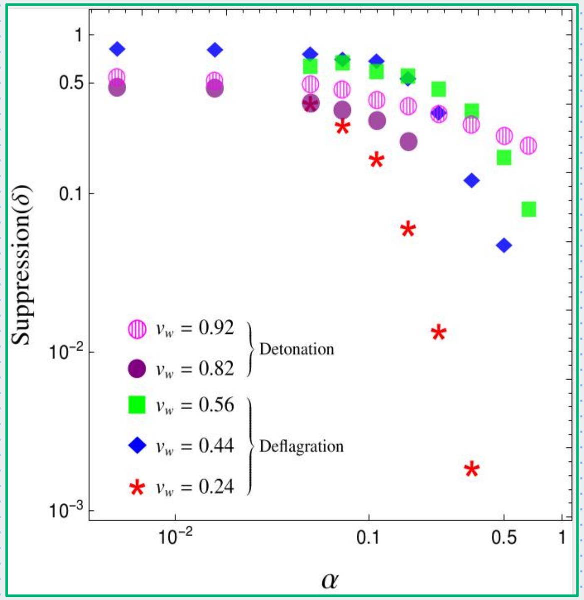


Numerical Simulation

- Suppression found for strong transitions with small vw
- Need to cover more parameter space (very strong PT)

$$h^2\Omega_{\rm sw}(f) = 2.65\times 10^{-6}\left(\frac{100}{g_*}\right)^{\frac{1}{3}}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_{\rm sw}\alpha}{1+\alpha}\right)^2 v_w S_{\rm sw}(f)\Upsilon(\tau_{\rm sw})$$





Cutting, Hindmarsh, Weir, PRL [1906.00480]

Magnetohydrodynamic Turbulence

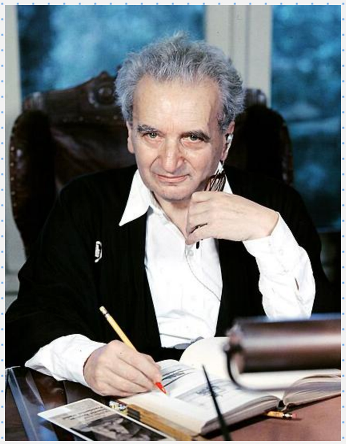
Earlier studies based on Kolmogorov spectrum:
Kamionkowski,Kosowsky,Turner, PRD [9310044]
Kosowsky,Mack,Kahniashvili, PRD [0111483]
Gogoberidze,Kahniashvili,Kosowsky, PRD [0705.1733]

$$T^{ij} \sim (p+e)v^i v^j - B_i B_j$$

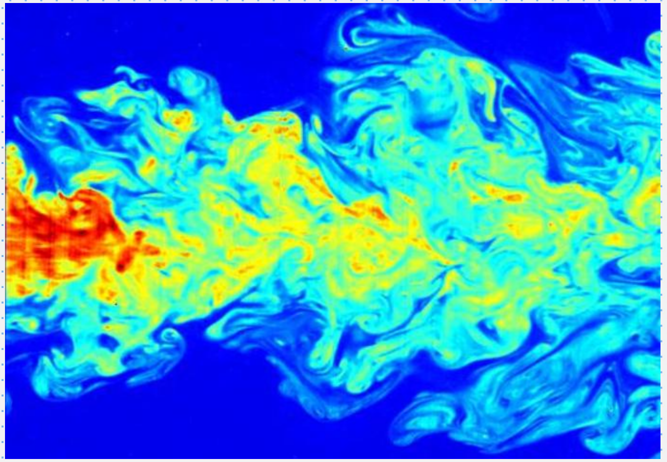
$$h^2\Omega_{\rm turb}(f) = 3.35\times10^{-4}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_{\rm turb}\,\alpha}{1+\alpha}\right)^{\frac{3}{2}}\left(\frac{100}{g_*}\right)^{1/3} v_w\, S_{\rm turb}(f)$$

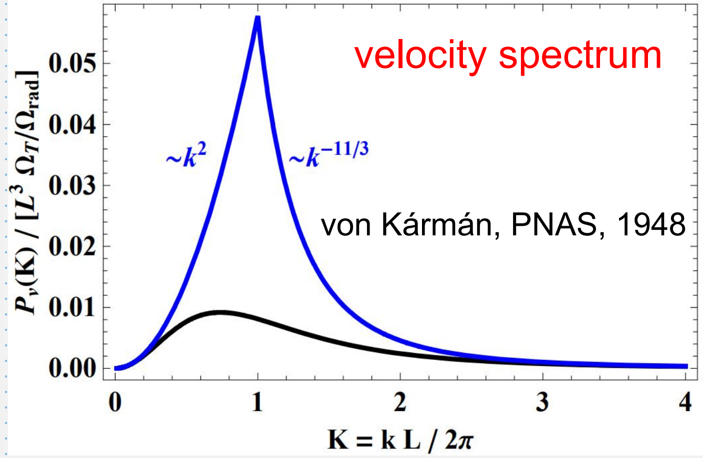
Caprini,Durrer,Servant, JCAP [0909.0622] (used von Kármán's spectrum)

Andrey Nikolaevich Kolmogorov



Theodore von Kármán

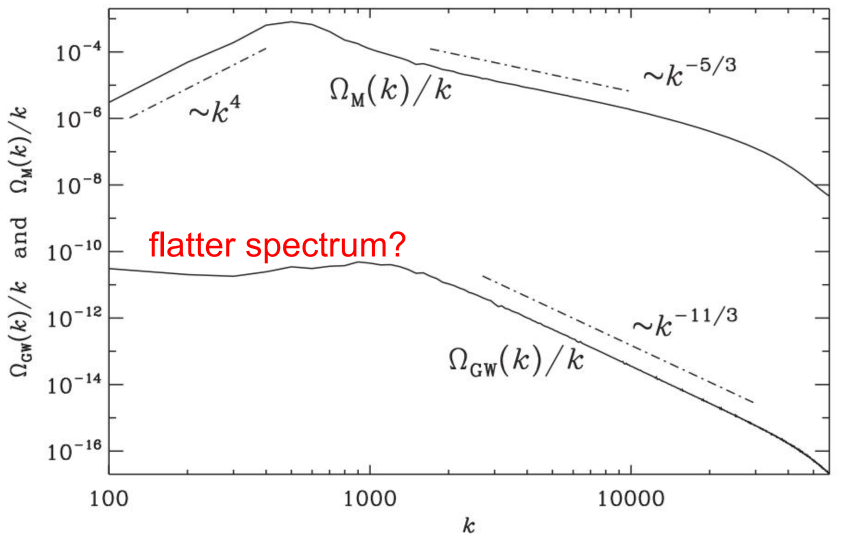




Magnetohydrodynamic Turbulence: Recent Development

Progress on numerical simulations, and analytical modellings

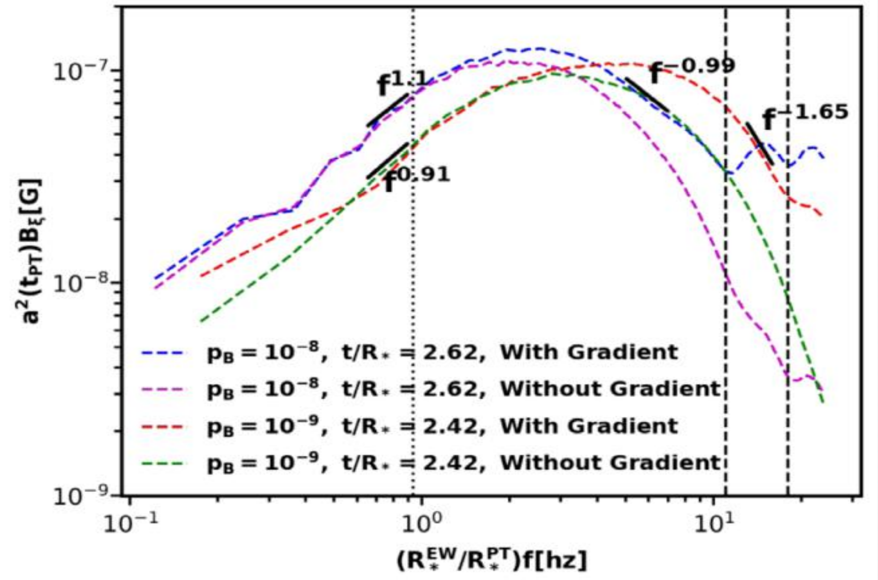
- Strong dependence on initial conditions
- Flatter spectrum at low frequency (violate causality?)



Pol et al, PRD [1903.08585]

as initial conditions?

Magnetic Field Generation (simulation)



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

Modelling: Sharma, Brandenburg, PRD [2206.00055]
Time decorrelation: Auclair et al, JCAP [2205.02588]
Decay, viscosity: Dahl et al, PRD [2112.12013]
Polarization: Pol et al, JCAP [2107.05356]

high-scale PT

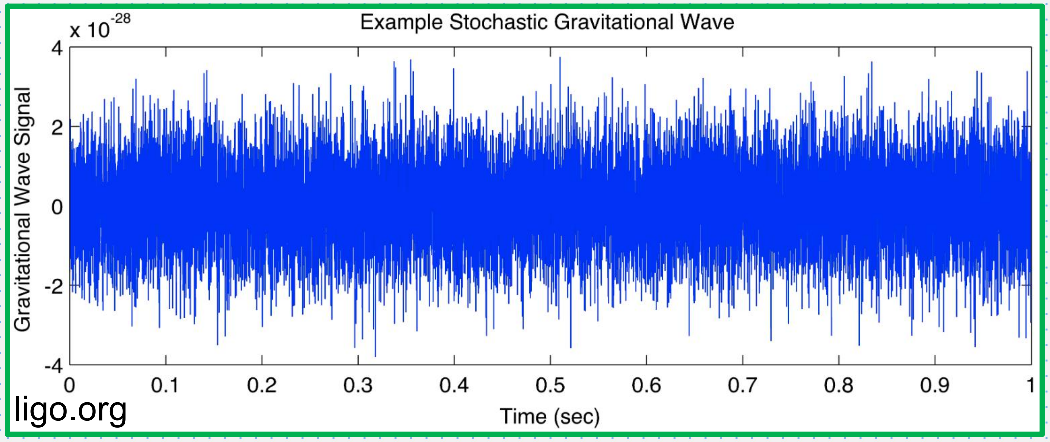
Detection at LIGO

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

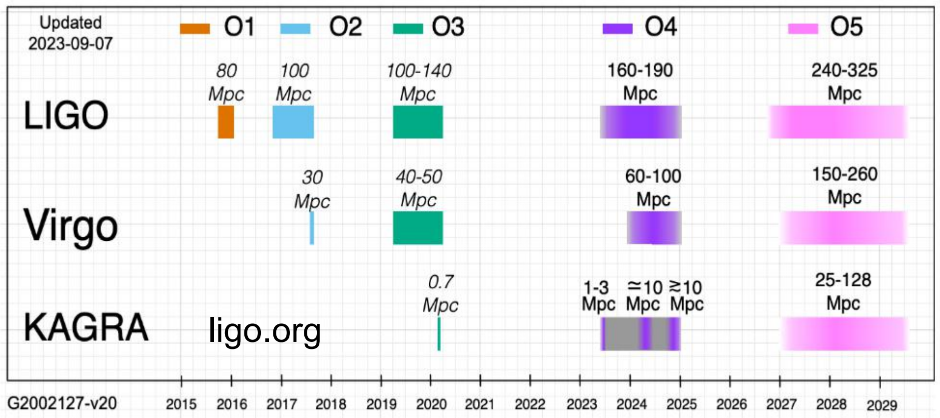
- No Evidence for Broken Power Law Signal
- No Evidence for Bubble Collision Domination Signal
- No Evidence for Sound Waves Domination Signal

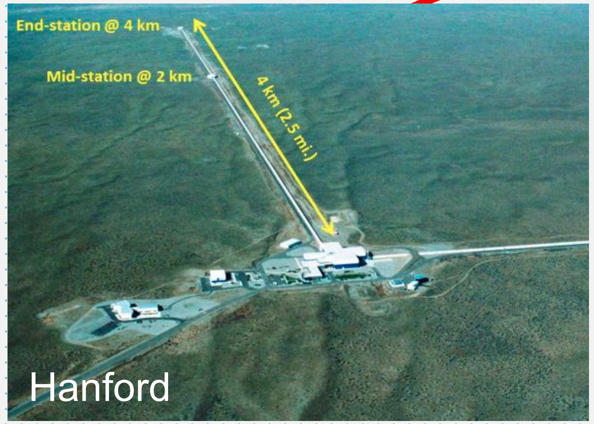
See also: Jiang, Huang, JCAP [2203.11781], Yu, Wang, PRD [2211.13111]

stochastic GWs: noise-like



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



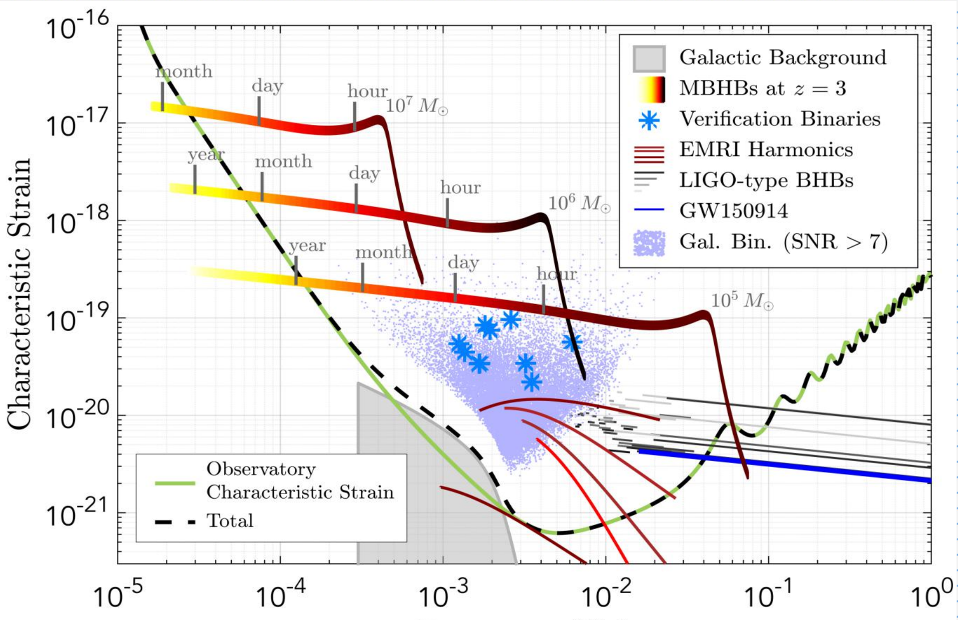


solution:
cross-correlation

Detection at LISA/Taiji/Tianqin

Detection with a single detector

- Complicated, and correlated noise
- Complications from time-delay interferometry
- Solution: null channel method, or with a network



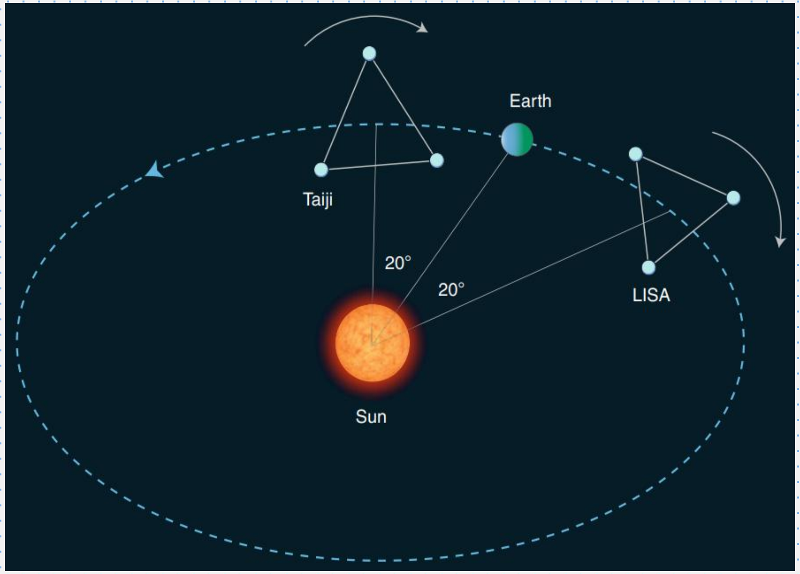
LISA [1702.00786]

galactic foreground + astro background + cosmic background

SGWB detectable down to $\Omega_{GW} \sim O(10^{-13})$

Boileau et al, MNRAS [2105.04283]

The LISA–Taiji network

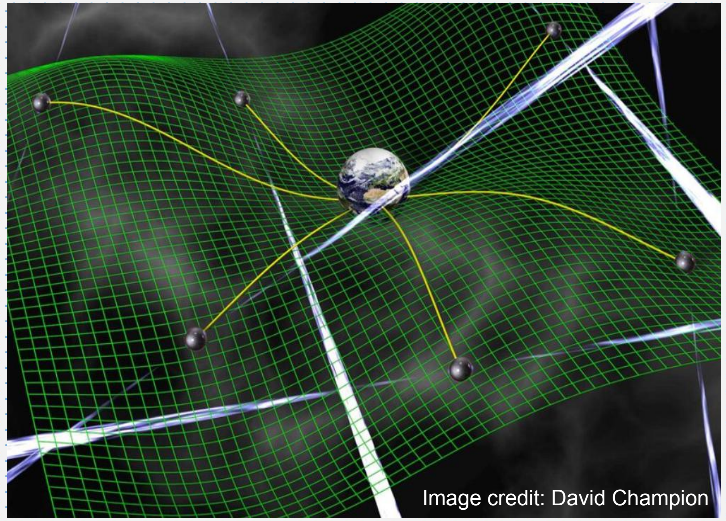


Ruan, Liu, Guo, Wu, Cai, Nature Astron [2002.03603]
Cai et al [2305.04551]

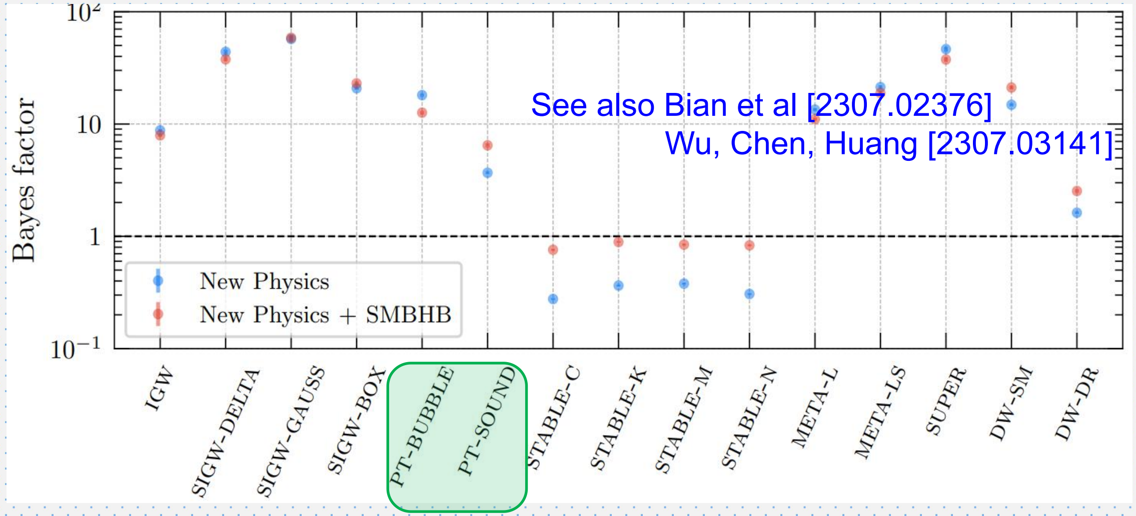
PT Parameter Estimation: Gowling et al, JCAP [2209.13551, 2106.05984]

QCD-scale PT

PTA

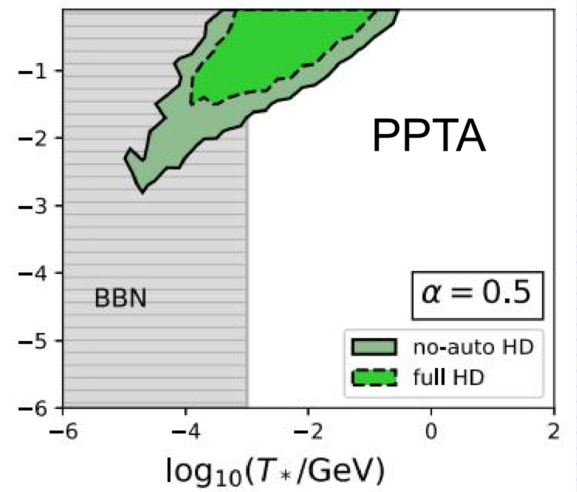


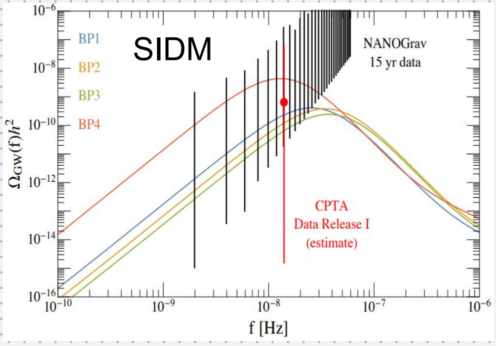
NANOGrav, ApjL [2306.16219]



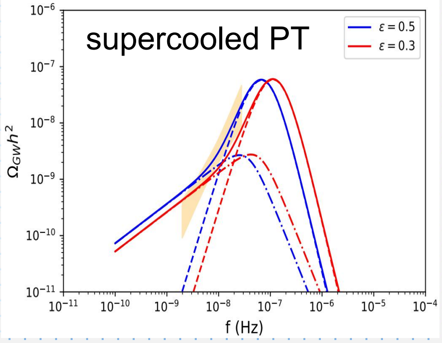
See also Bian et al [2307.02376]
Wu, Chen, Huang [2307.03141]

Xue,Bian,Shu,Yuan,Zhu, et al, PRL [2110.03096]

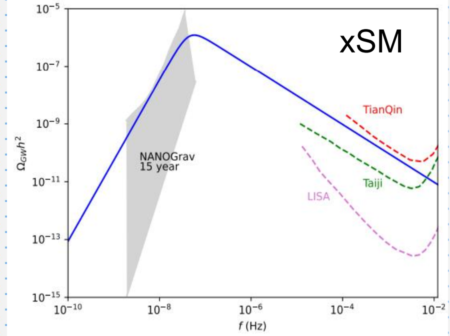




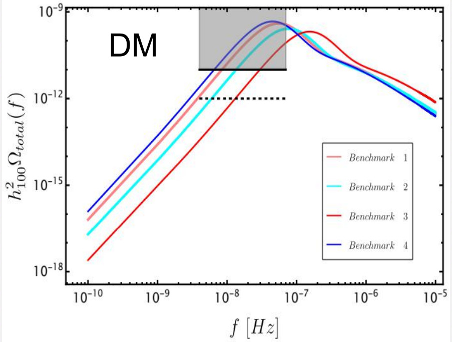
Han,Xie,Yang,Zhang [2306.16966]



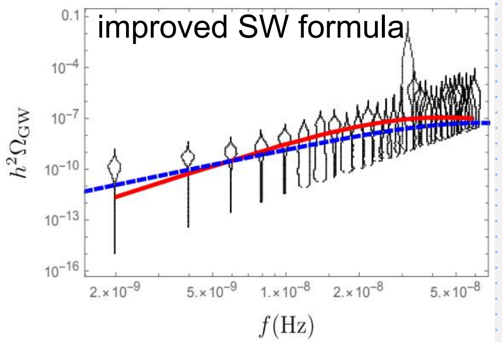
Zu,Zhang,Li,Gu,Tsai,Fan [2306.17239]



Xiao,Yang,Zhang [2307.01072]



Yang,Ma,Jiang,Huang [2306.17827]



Ghosh, Ghoshal, HG, ...[2307.02259]

and many more...

Uncertainties

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

$\Delta\Omega_{GW}/\Omega_{GW}$	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]

Uncertainty	pre-factor1	pre-factor2	pre-factor3
T_p	0.003%	0.003%	0.002%
βR^*	8.1%	7.9%	5.9%
N_{tot}	11.4%	11.0%	9.8%
$f_{\beta R^*}^{peak}$	11.8%	12.0%	14.1%
$\Omega_{GW} h^2_{\beta R^*}$	37.6%	36.5%	28.9%
f_{sim}^{peak}	36.4%	36.4%	35.1%
$\Omega_{GW} h^2_{sim}$	334.0%	330.8%	336.7%

HG, Xiao, Yang, Zhang [2310.04654]

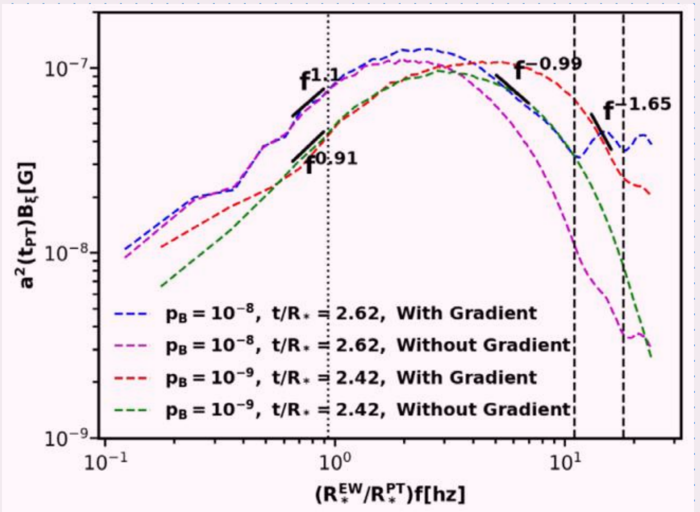
Effect(fixed wall velocity)	Range of error (medium)	Range of error (low)	Type of error
Transition temperature	$\mathcal{O}(10^{-4}$–$10^1)$	$\mathcal{O}(10^{-1}$–$10^0)$	Random
Mean bubble separation	$\mathcal{O}(0$–$10^{-1})$	$\mathcal{O}(10^{-1}$–$10^0)$	Suppression
Fluid velocity	$\mathcal{O}(10^{-2}$–$10^0)$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

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

Sound speed: Wang,Huang,Li, PRD [2112.14650], etc
See also: Athron, Balazs, Fowlie, Morris, White, Yang Zhang, JHEP [2208.01319]

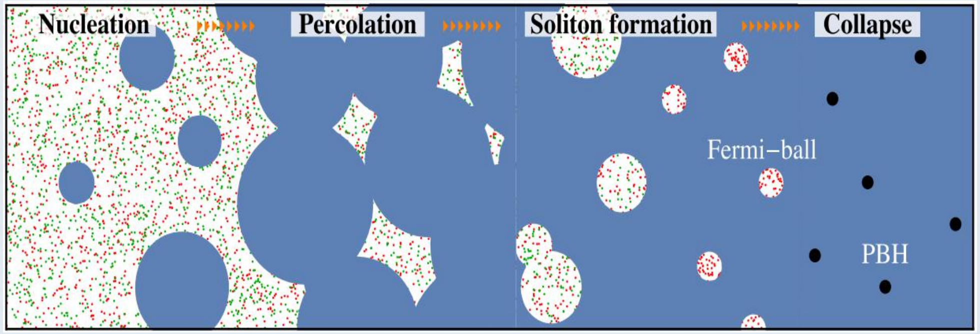
New Observables

Primordial magnetic field



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

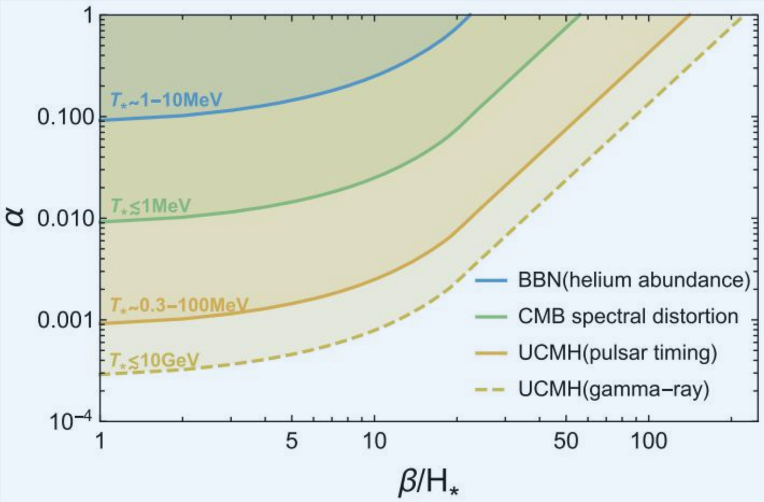
Primordial black holes and Solitons



Hong, Jung, Xie, PRD [2008.04430]
Kawana,Xie,PLB [2106.00111]
Lu,Kawana,Xie, PRD [2202.03439]
Liu,Bian,Cai,Guo,Wang, PRD [2106.05637]

and more...

Curvature perturbations



Liu,Bian,Cai,Guo,Wang,PRL[2208.14086]
Jiang,Liu,Sun,Wang, PLB [1512.07538]

GW Anisotropy: Geller, Hook, Sundrum, Yuhsin Tsai, PRL [1803.10780]
Li, Huang, Wang, Zhang, PRD [2112.01409]
Li, Yan, Huang, PRD [2211.03368]

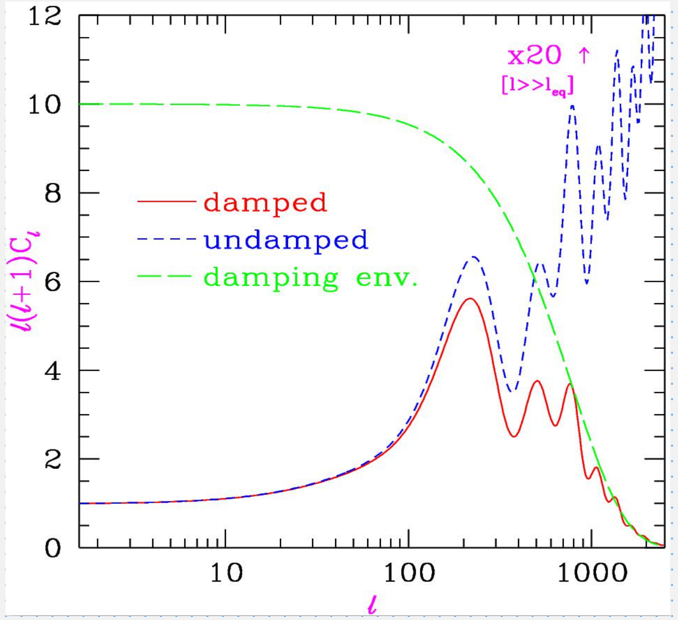
Dissipative Effects as New Observables

- Going beyond the perfect fluid approximation (viscosity, heat conduction)
- Particle physics origin of dissipations (very weak interactions)
- Can be searched for at LIGO, PTA, LISA/Taiji/Tianqin ...

Weinberg, ApJ, 1971

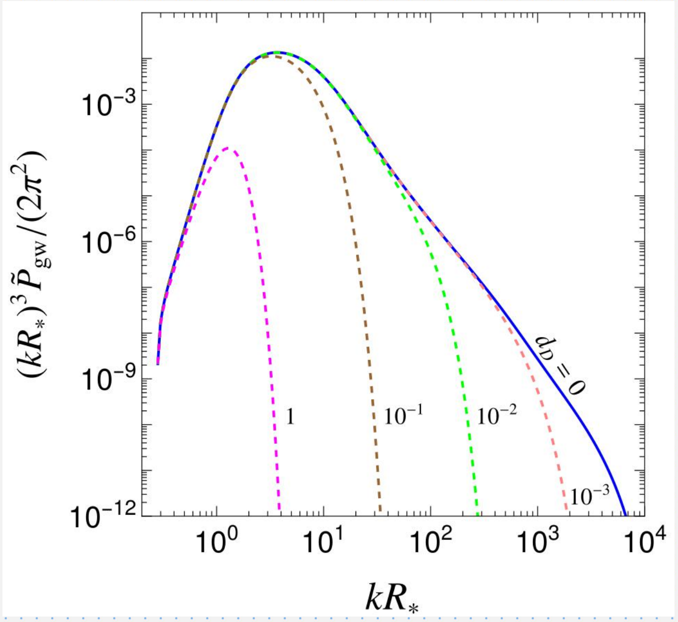
$$\Delta T^{ij} = -\eta\left(\frac{\partial U_i}{\partial x^j} + \frac{\partial U_j}{\partial x^i} - \frac{2}{3}\delta_{ij}\nabla\cdot\mathbf{U}\right) - \zeta\,\delta_{ij}\nabla\cdot\mathbf{U},$$
$$\Delta T^{i0} = -\chi\left(\frac{\partial T}{\partial x^i} + T\dot{U}_i\right). \quad (1)$$

Silk damping of CMB Anisotropy



Hu,White, ApJ [9609079]

damping of GW



HG [2310.10927]

Summary

- Significant advances in phenomenological studies
- Significant advances in PT and GW calculations
- Significant advances in experimental detections (LIGO, PTA, etc)
- More work to be done to probe better particle physics

Thanks!