宇宙相变引力波和新物理

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中国科学院大学
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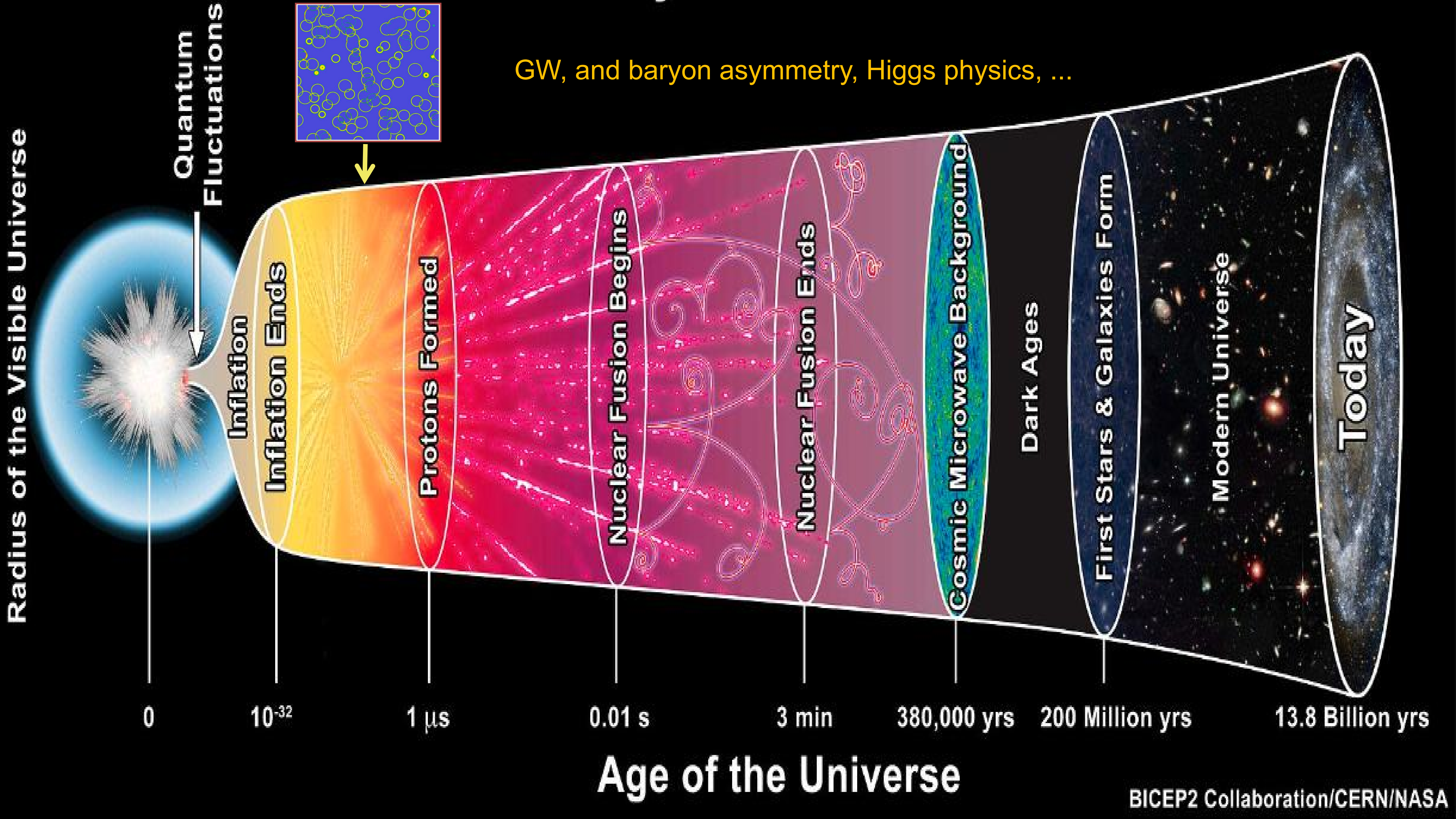
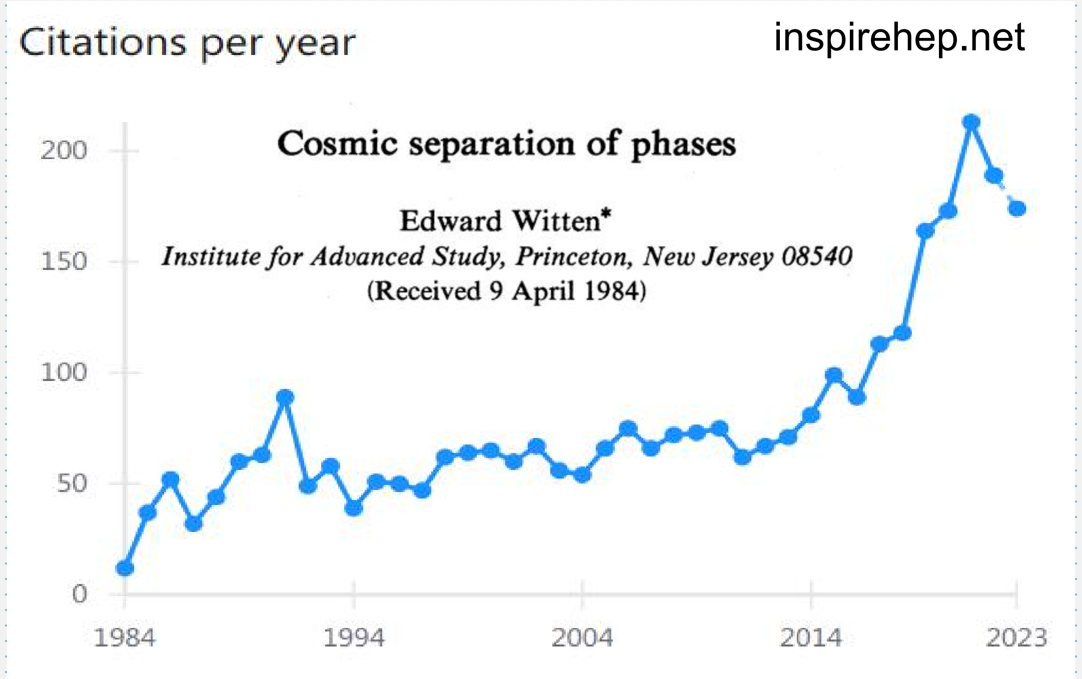
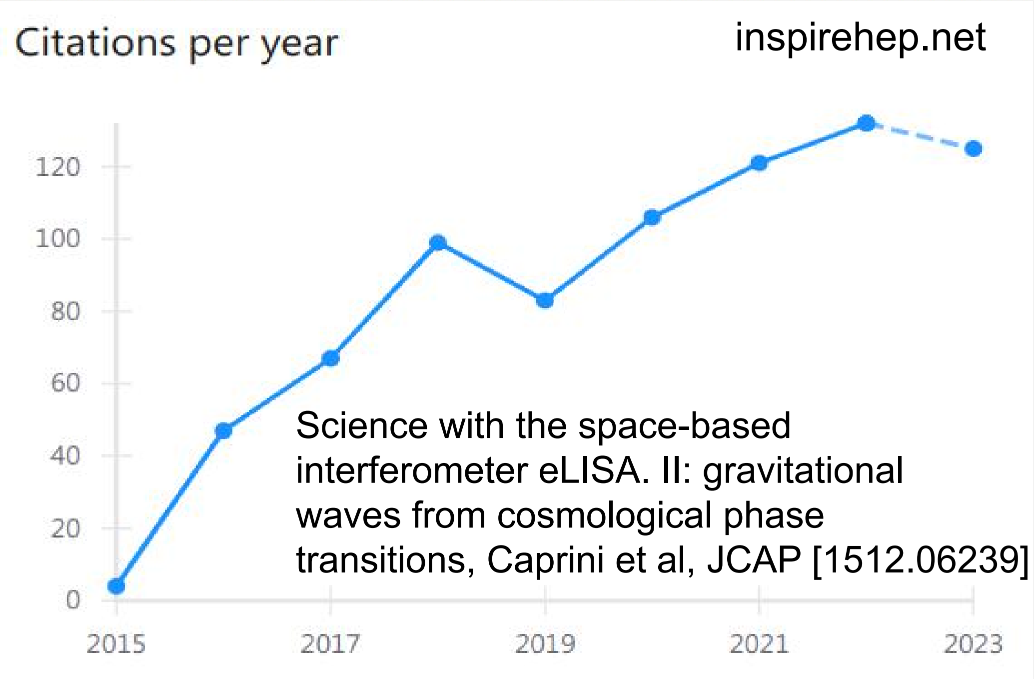
2024-8-28

2024年BESIII新物理研讨会


GW, and baryon asymmetry, Higgs physics, ...
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





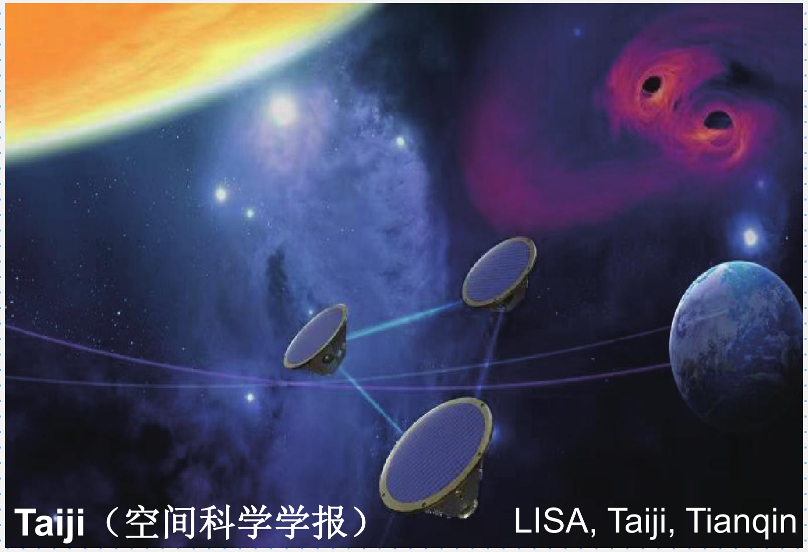
EPTA

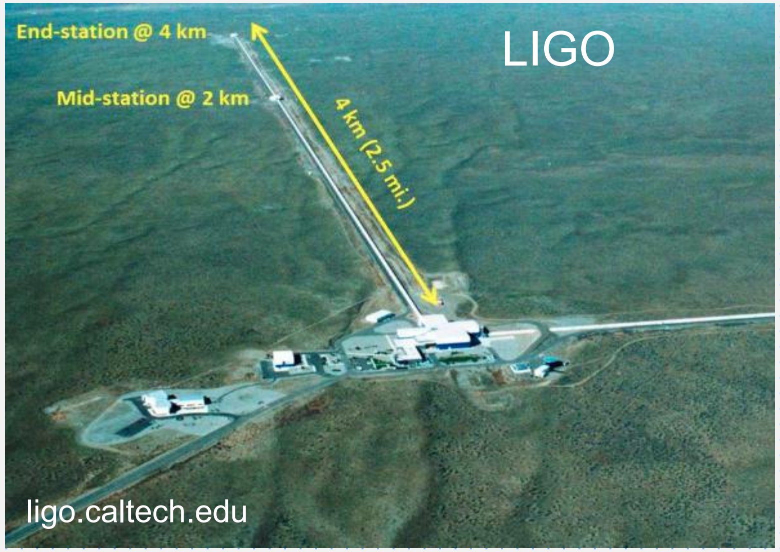
NANOGrav Physics Frontiers Center

PPTA

InPTA Indian Pulsar Timing Array

中国脉冲星测时阵列（CPTA）

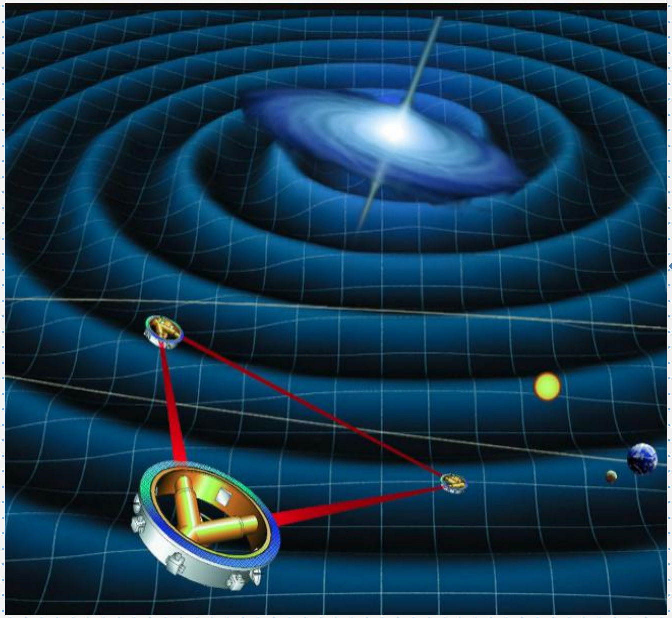




From Theory to Experiment

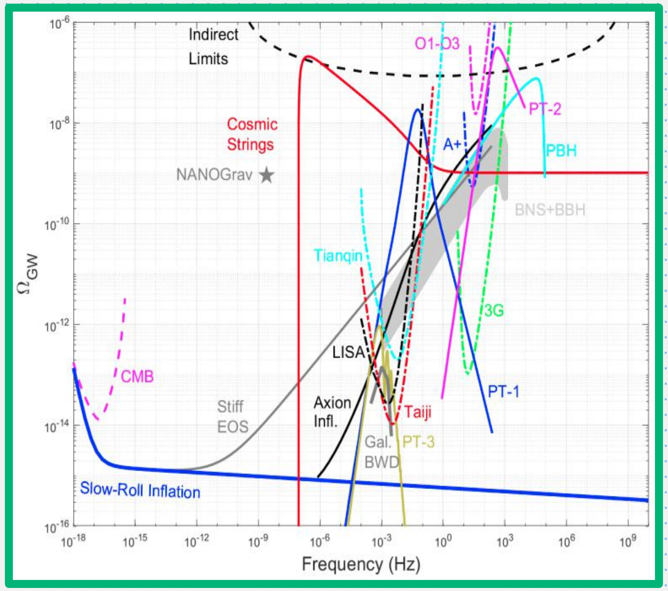
theorist

3



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

2



Gravitational Wave Spectrum

1

α

β

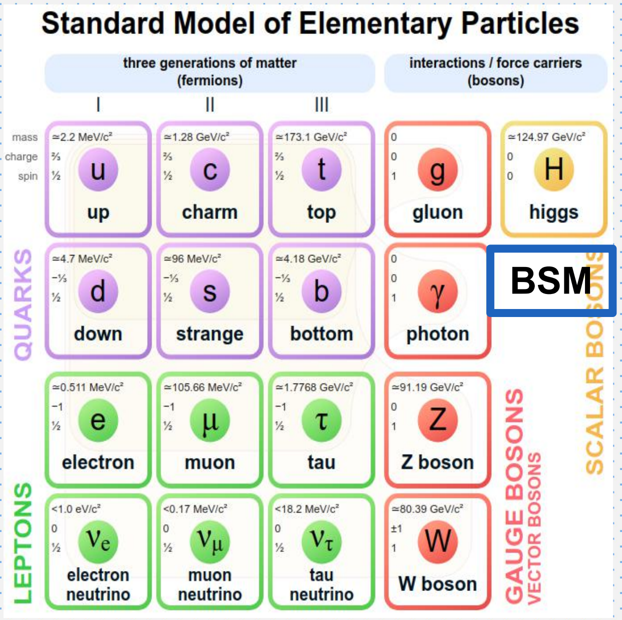
v_w

T_*

g_s

...

Phase Transition Parameters



Particle Physics Model

experimentalist

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

Search... Help |

High Energy Physics - Phenomenology

[Submitted on 18 Mar 2022]

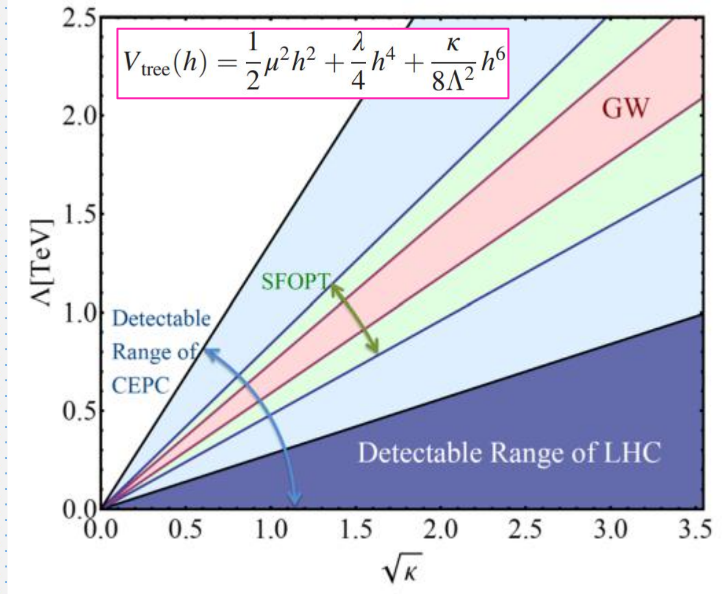
Scalar-mediated dark matter model at colliders and gravitational wave detectors -- A White paper for Snowmass 2021

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

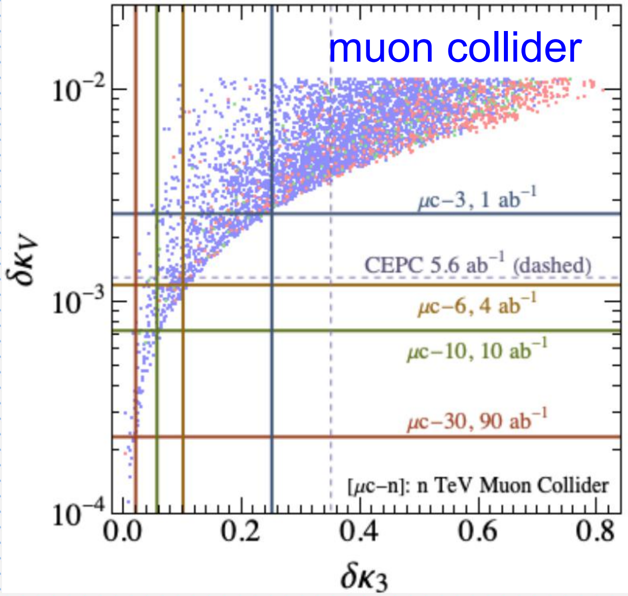
Snowmass 2021 White papers

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)	✓	✓	✓	✓

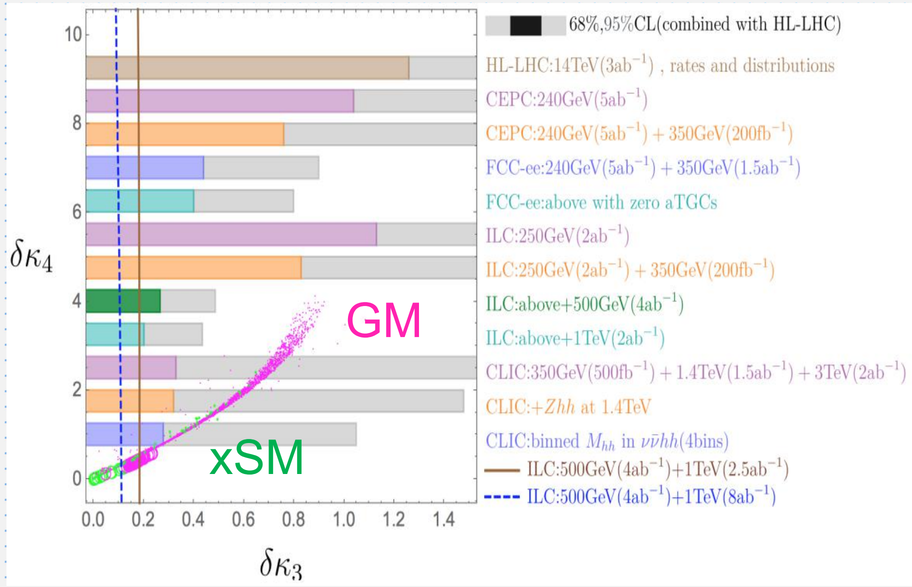
Ghosh,HG,Han,Liu, JHEP [2012.09758]



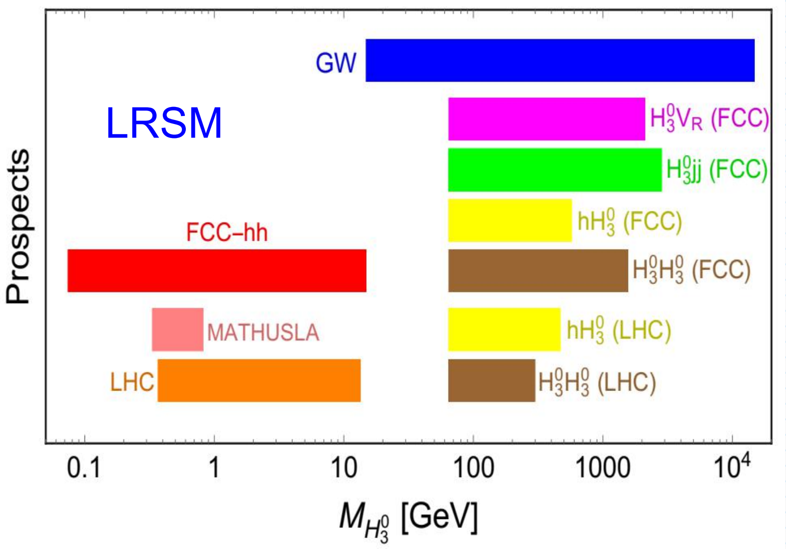
Fapeng Huang, Yi-Fu Cai, Xinmin Zhang, et al, PRD [1601.01640]



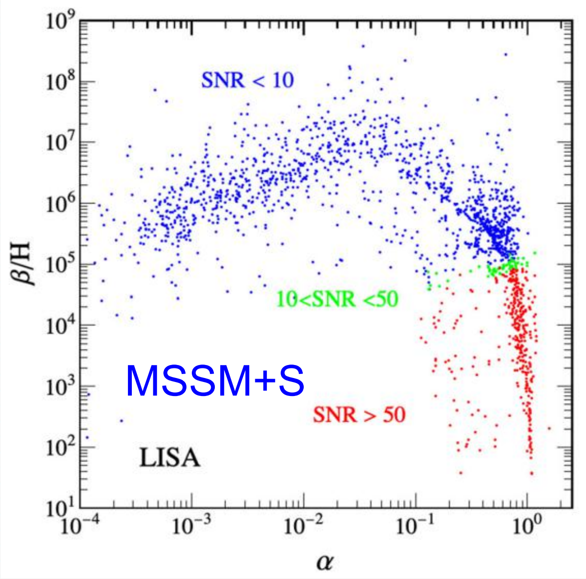
Wei Liu, Ke-Pan Xie, JHEP [2101.10469]



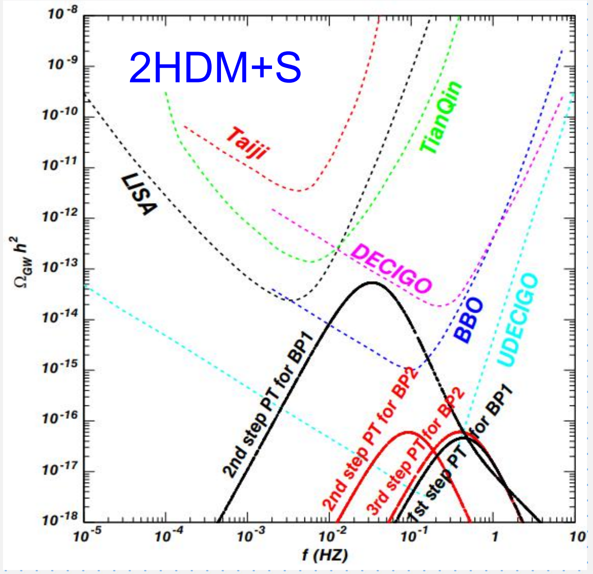
Ligong Bian, HG, Yongcheng Wu, Ruiyu Zhou, PRD [1906.11664]



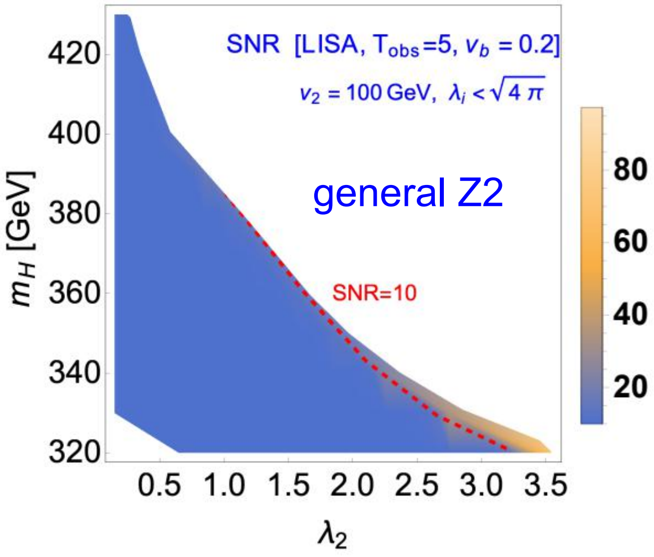
Mingqiu Li, Qi-Shu Yan, Yongchao Zhang, Zhijie Zhao, JHEP [2012.13686]



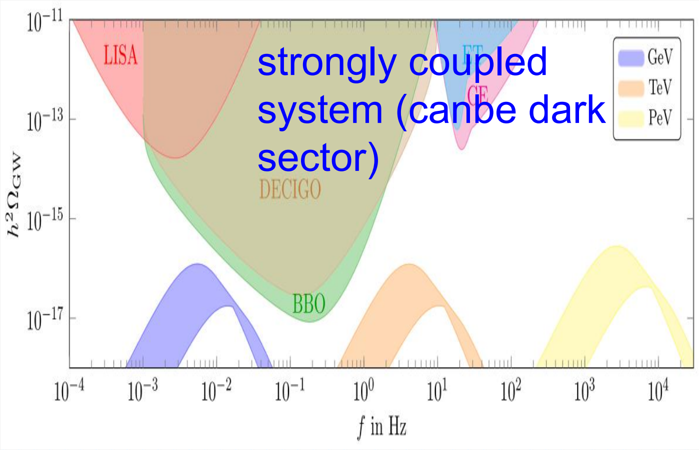
Wenyu Wang, Ke-Pan Xie, Wu-Long Xu, Jin Min Yang, EPJC [2204.01928]



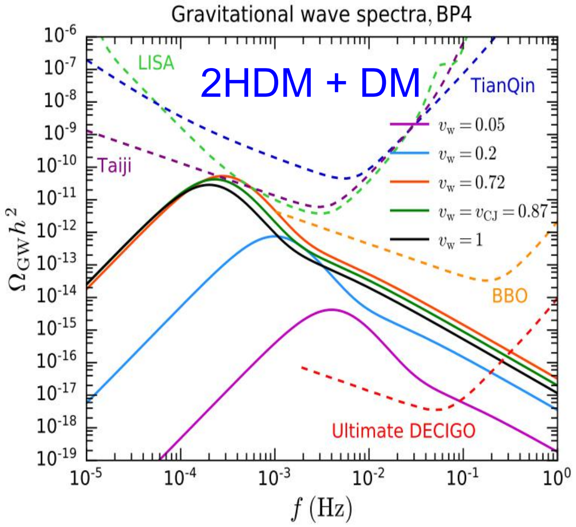
Songtao Liu, Lei Wang, PRD [2302.04639]



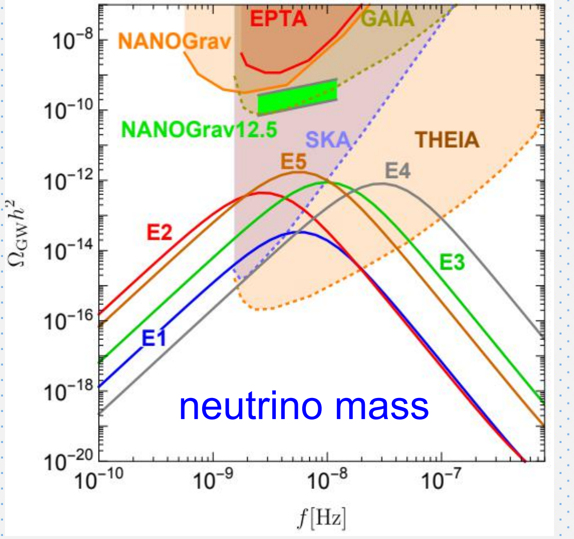
Qing-Hong Cao, Katsuya Hashino, Xu-Xiang Li, Jiang-Hao Yu [2212.07756]



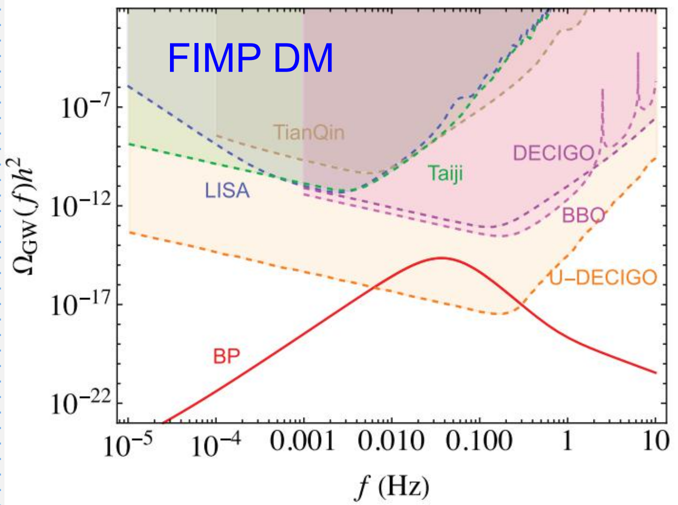
Zhi-Wei Wang, et al, PRD [2012.11614]



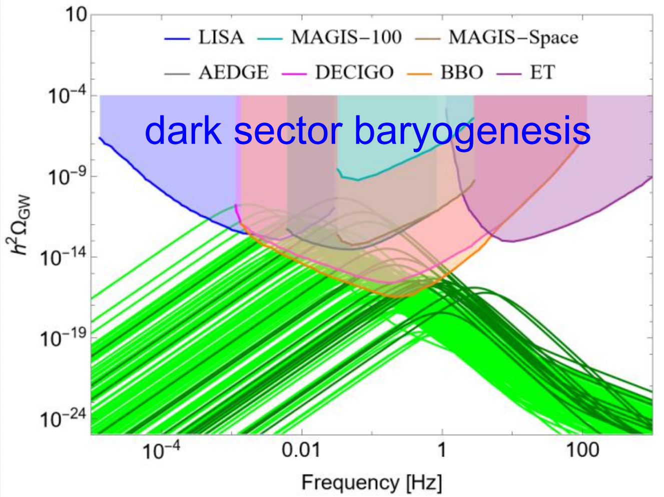
Zhao Zhang, Chengfeng Cai, Xue-Min Jiang, Yi-Lei Tang, Zhao-Huan Yu, and Hong-Hao Zhang, JHEP [2102.01588]



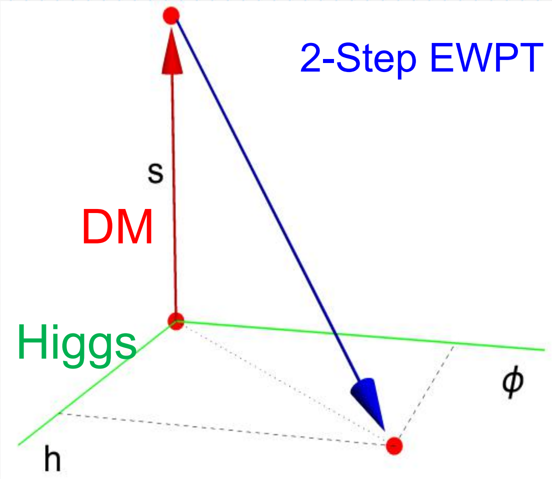
Pasquale Di Bari, Danny Marfatia, Ye-Ling Zhou, JHEP [2106.00025]



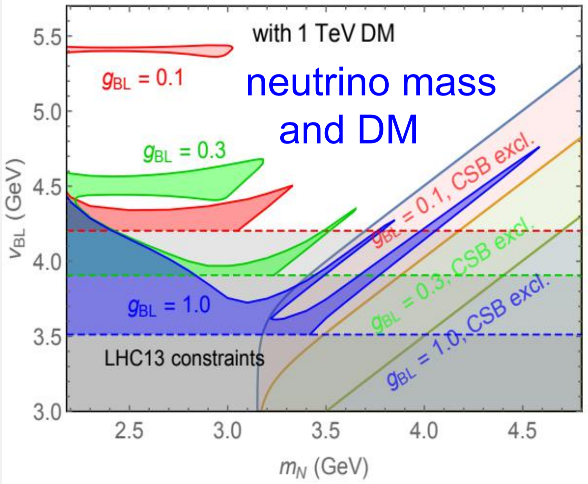
Xuewen Liu, Shu-Yuan Guo, Bin Zhu, Ying Li, Sci.Bull. [2022.06.011]



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

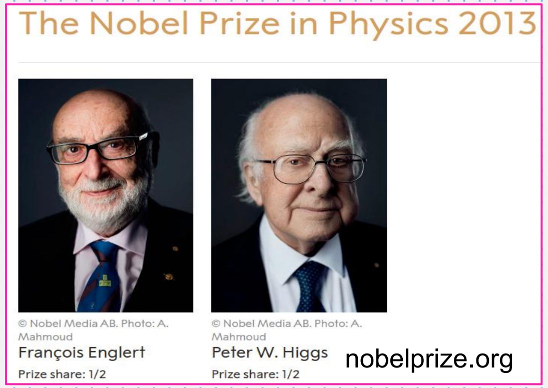


Wei Chao, HG, Jing Shu, JCAP [1702.02698]

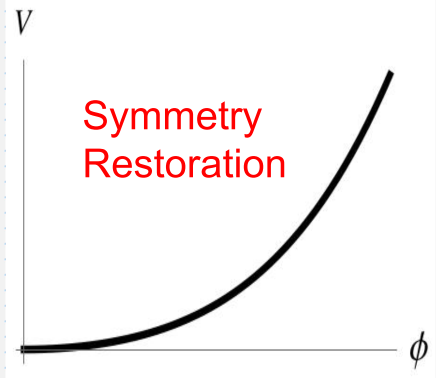


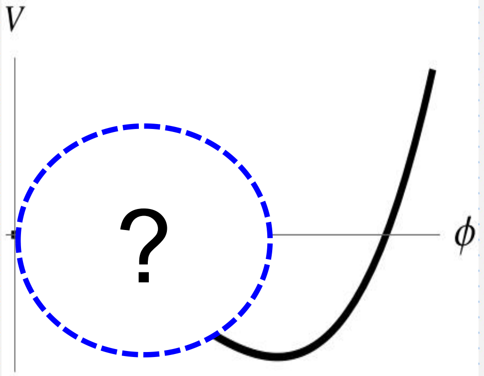
Ligong Bian, Wei Cheng, HG, Yongchao Zhang, CPC [1907.13589]

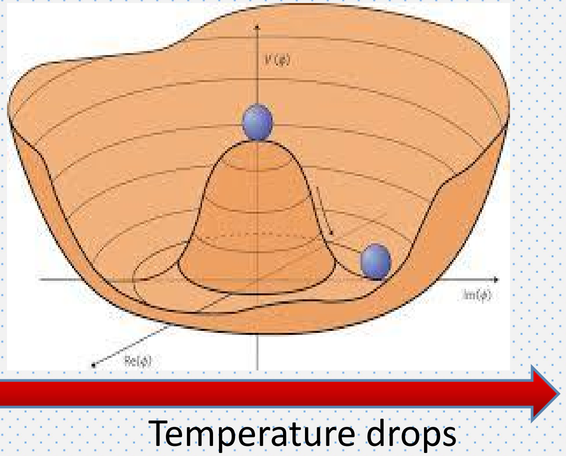
Electroweak Phase Transition

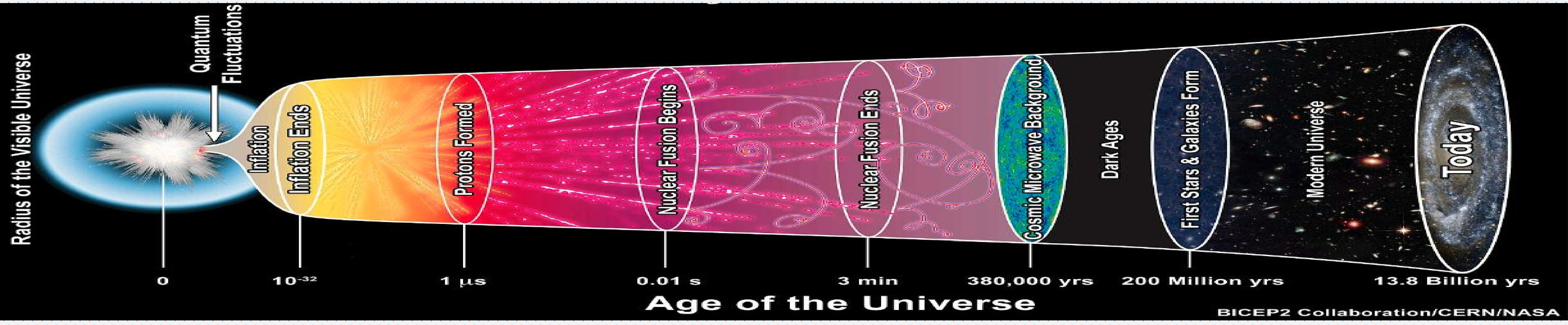


$$SU(3)_C \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_C \times U(1)_{EM}$$

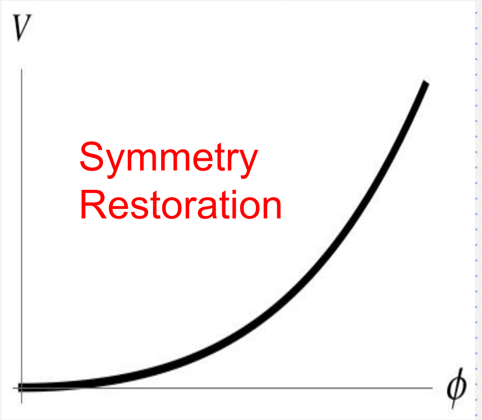


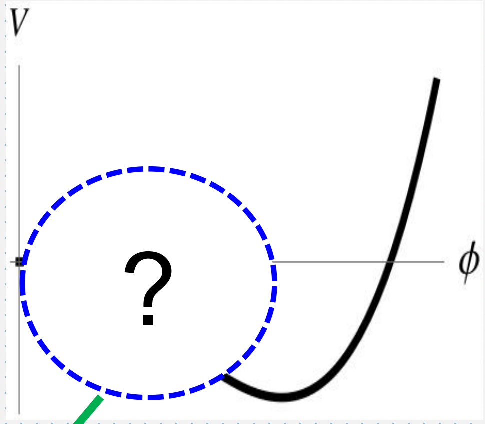


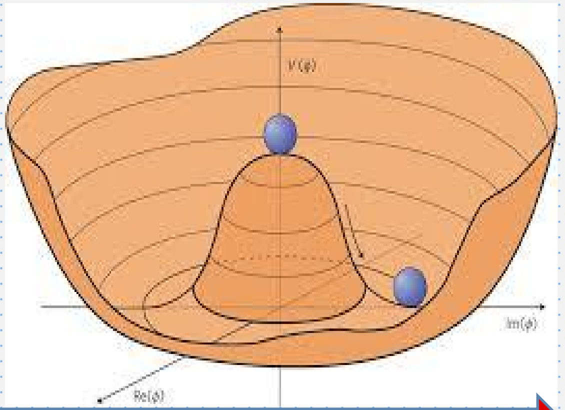




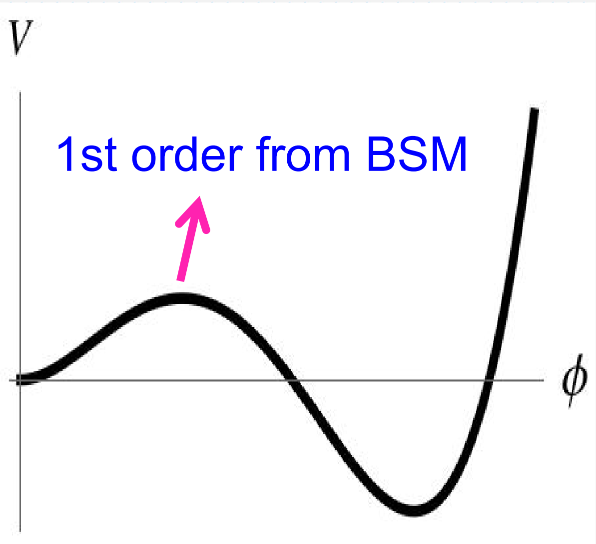
Electroweak Phase Transition

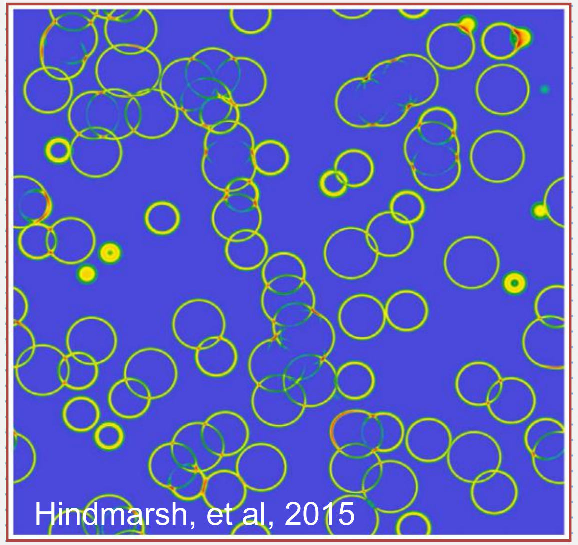






Temperature drops





→ Electroweak Baryogenesis

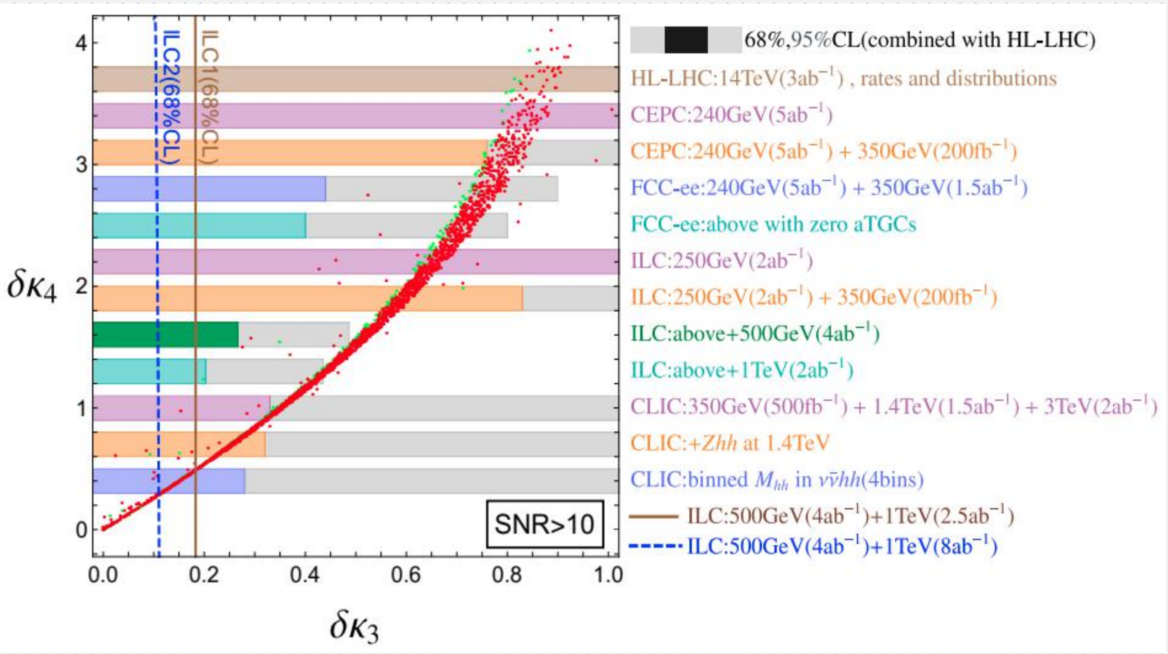
- Modified Higgs potential (Higgs physics, GW)
- Extra CP-violation (EDM, LHC, BESIII)
- New particles, symmetries (LHC, GW)

Trodden, Rev.Mod.Phys [9803479]

Collider and GW Complementarity

Contents

Snowmass 2021 Whitepaper, GRG [2203.07972]



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

Simplest model: xSM (SM + S)

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

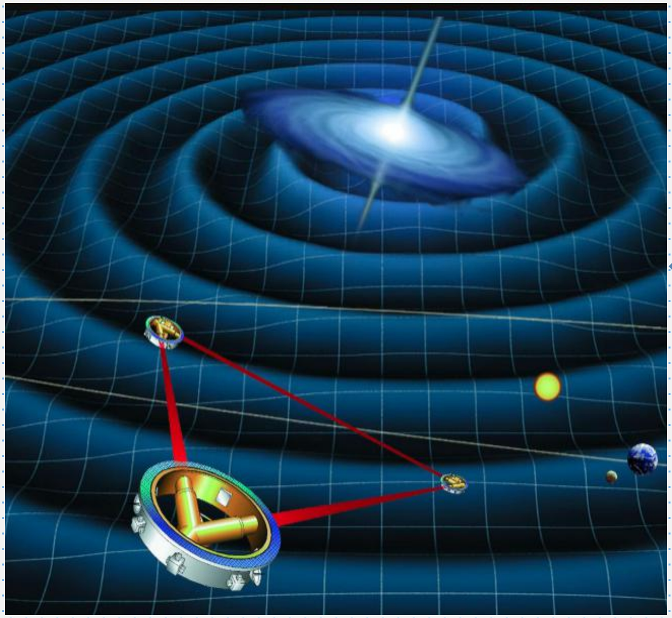
Collider and Gravitational Wave Complementarity in Exploring the Singlet Extension of the Standard Model

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]

Recent Developments

theorist



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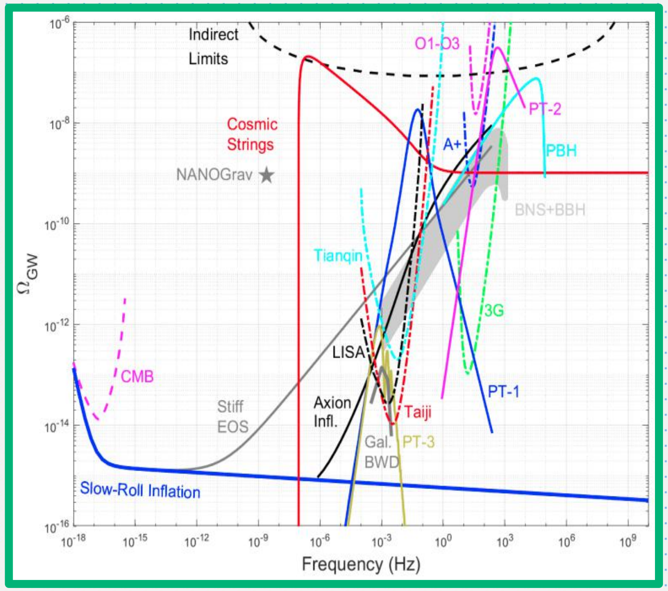


2

α

β

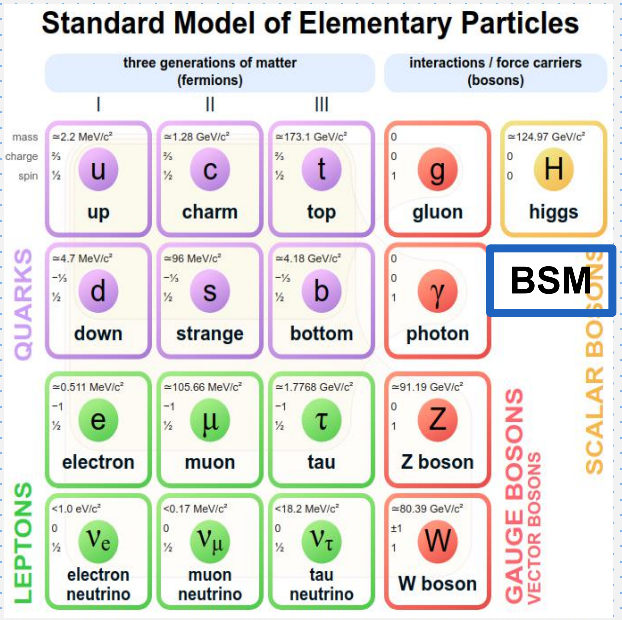
v_w

T_*

g_s

...

1



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

Gravitational Wave Spectrum

Phase Transition Parameters

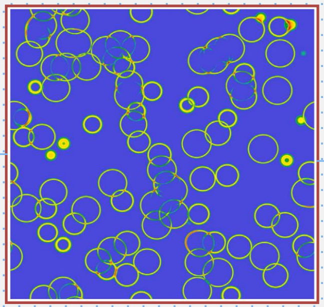
Particle Physics Model

experimentalist

Bubble Nucleation Rate

1

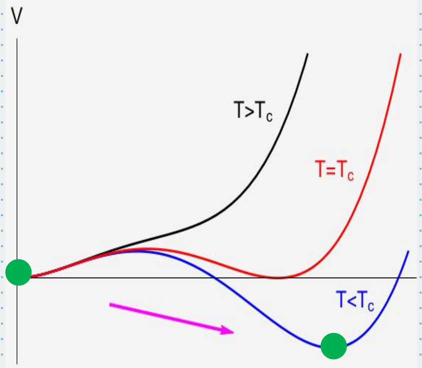
How fast the bubbles are generated?



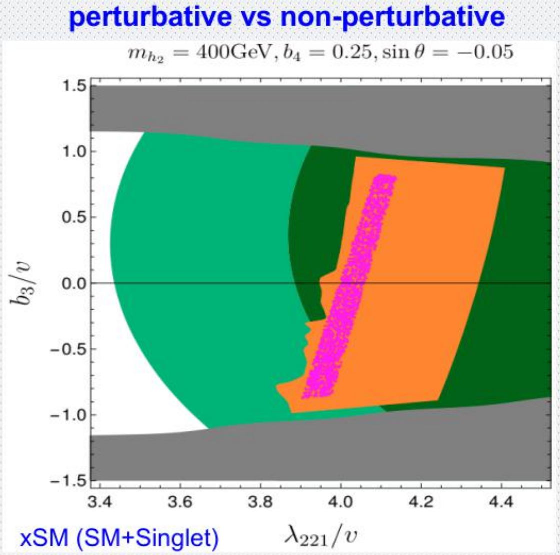
Perturbative Method

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

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

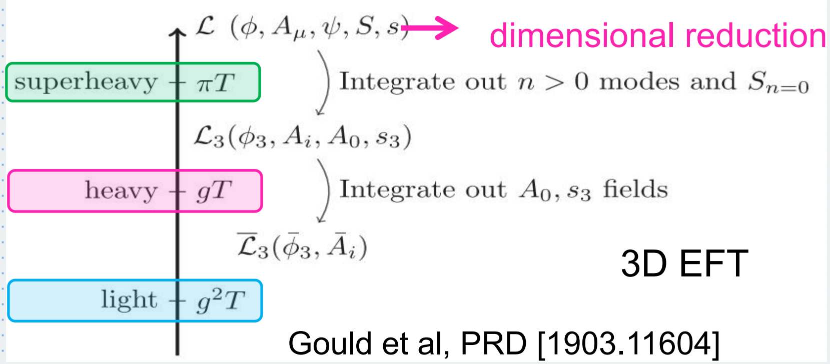


- Infrared problem (Linde, 1980)
- Gauge invariance (ok for high-T expansion)
  possible solution: Löfgren, Ramsey-Musolf, et al, PRL [2112.05472], JHEP [2112.08912]



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

Nonperturbative Method



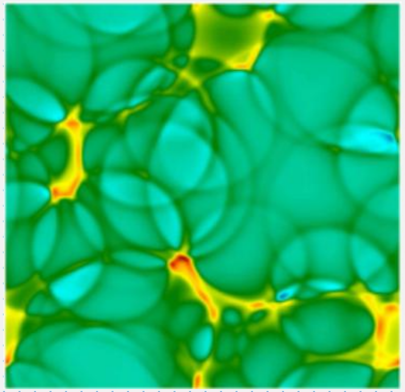
Gould et al, PRD [1903.11604]

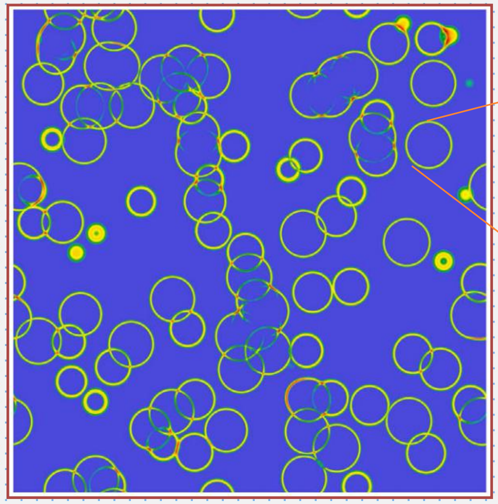
Dimensional Reduction (Status)		
SM	√	Farakos,Kajantie,Rummukainen,Shaposhnikov (1994)
MSSM	√	Cline,Kainulainen(1996), Losada(1996), Laine (1996)
xSM (SM + Singlet)	√	Brauner,Tenkanen,Tranberg,Vuorinen,Weir, JHEP [1609.06230]
ΣSM (SM + Triplet)	√	Niemi,Patel,Ramsey-Musolf,Tenkanen,Weir, PRD [1802.10500]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

2

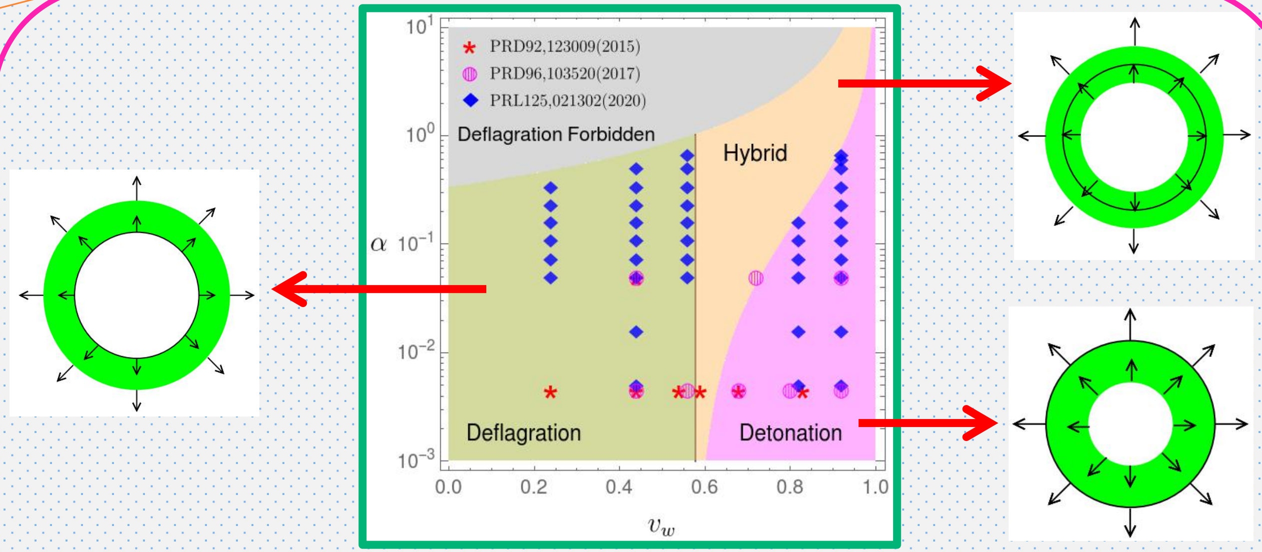
Better Understand the Picture

- How fast the wall expands?
- How the energy is distributed?
- Are there new phenomena?
- ...





Hindmarsh et al, 2015



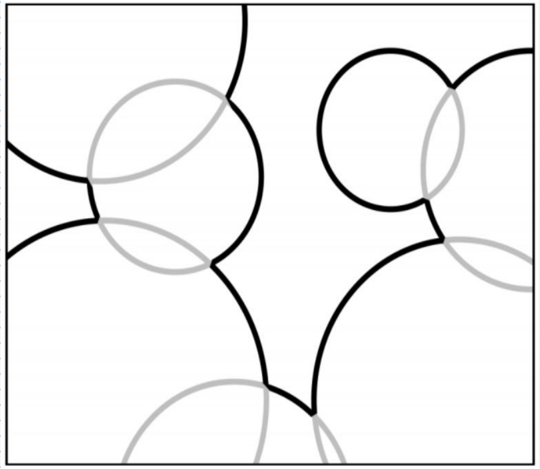
Espinosa,Konstandin,No,Servant JCAP [1004.4187]

Gravitational Wave Production

The current understanding:

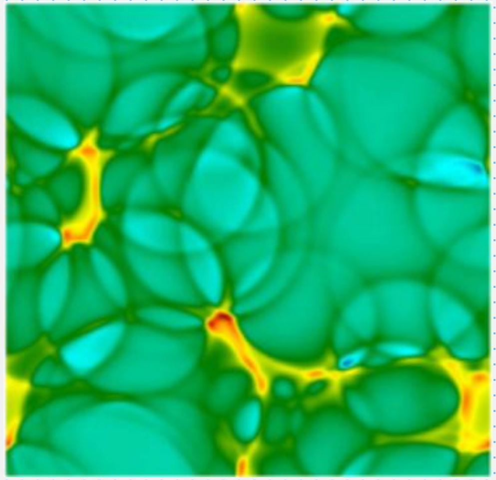
$$\Box \bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu}$$

energy near the wall



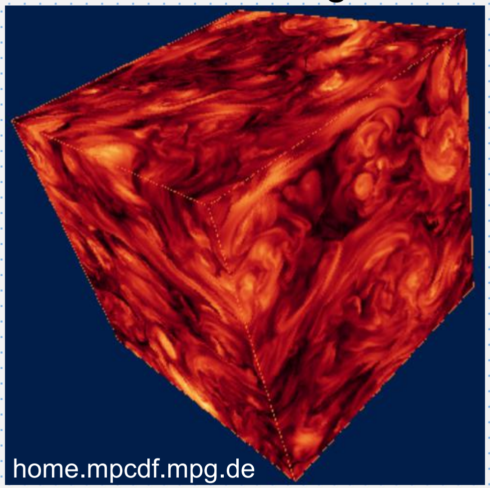
Bubble Collisions

fluid kinetic energy



Sound Waves

turbulent fluid + magnetic field

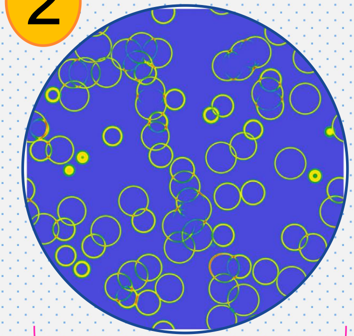


Magnetohydrodynamic Turbulence

Observable: $$\Omega_{\rm GW}(f) = \frac{d\rho_{\rm GW}}{\rho_c d\log f}$$

Basic Properties

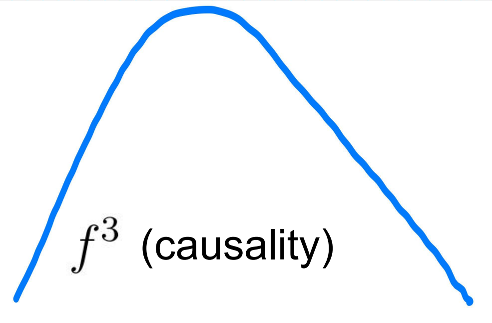
2



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

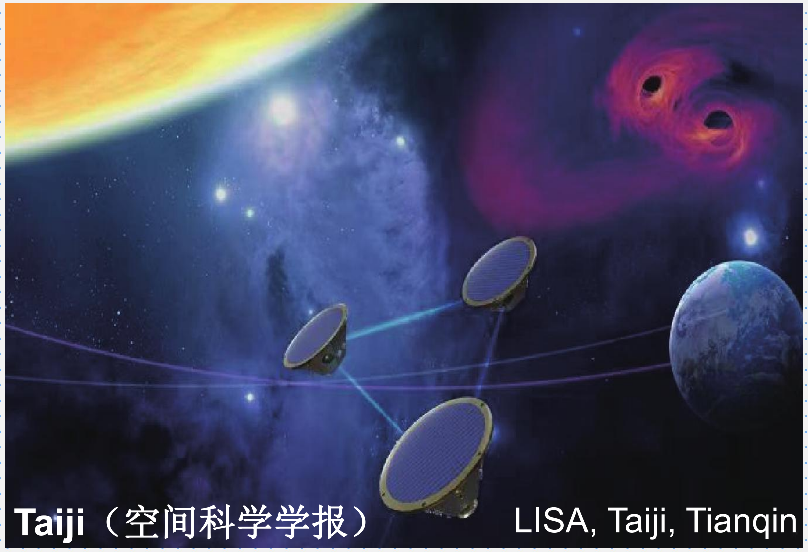
EPTA

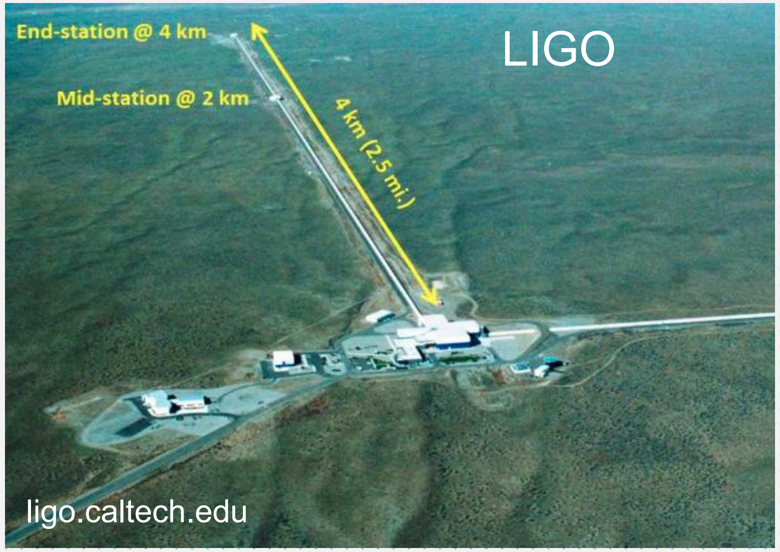
NANOGrav Physics Frontiers Center

PPTA

InPTA Indian Pulsar Timing Array

中国脉冲星测时阵列（CPTA）

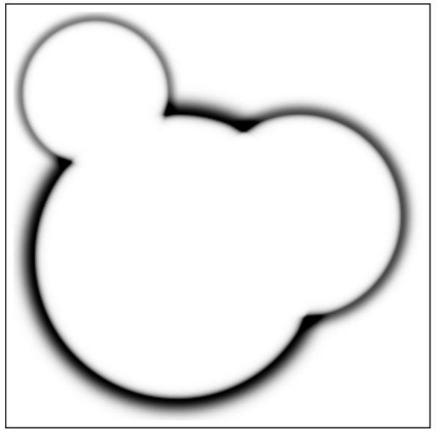




2

Bubble Collisions

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



thin shell of uncollided walls

$$h^2\Omega_{\rm BC}(f) = 1.67\times10^{-5}\left(\frac{100}{g_*}\right)^{1/3}\Delta(v_w)\left(\frac{H_n}{\beta}\right)^2\left(\frac{\kappa_\phi\alpha}{1+\alpha}\right)^2 S_{\rm env}(f)$$

simulation

$$\Delta = \frac{0.11v_w^3}{0.42+v_w^2},$$
$$\frac{f_*}{\beta} = \frac{0.62}{1.8-0.1v_w+v_w^2},$$
$$S_{\rm env} = \left[\frac{3.8(f/f_{\rm env})^{2.8}}{1+2.8(f/f_{\rm env})^{3.8}}\right]$$

Huber, Konstandin, JCAP [0806.1828]

Chiara Caprini et al JCAP [1512.06239]

analytical

$$\Delta = \frac{0.48v_w^3}{1+5.3v_w^2+5v_w^4},$$
$$\frac{f_*}{\beta} = \frac{0.35}{1+0.069v_w+0.69v_w^4},$$
$$S_{\rm env} = \left[c_l\left(\frac{f}{f_{\rm env}}\right)^{-3} + (1-c_l-c_h)\left(\frac{f}{f_{\rm env}}\right)^{-1} + c_h\left(\frac{f}{f_{\rm env}}\right)\right]^{-1}$$
$$(c_l = 0.064, \quad c_h = 0.48)$$

Jinno, Takimoto, PRD [1605.01403]

2

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]

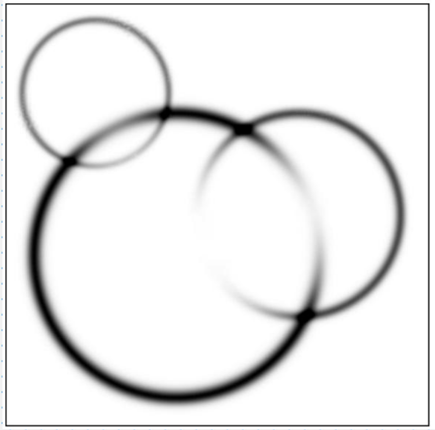
- Duration and Expanding Universe

  Zhong, Gong, Qiu, JHEP [2107.01845]

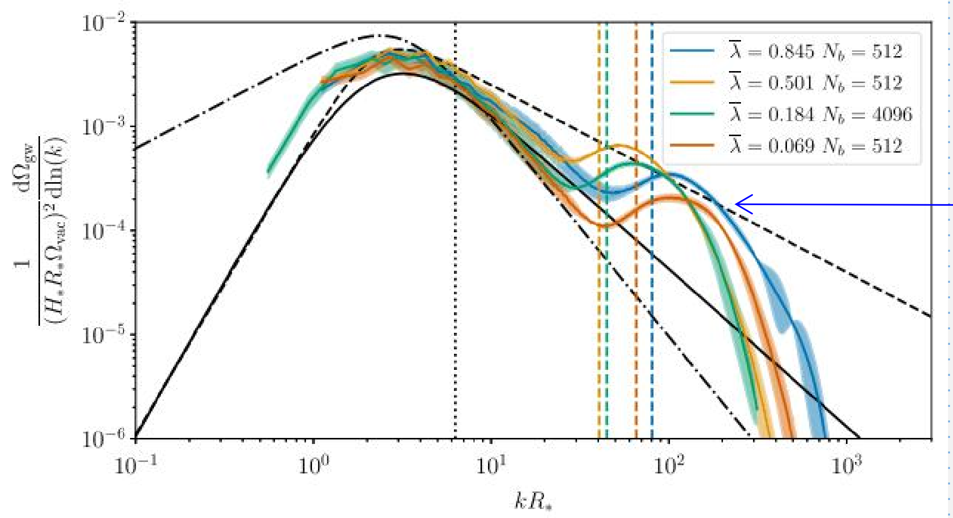
- Scalar + Gauge

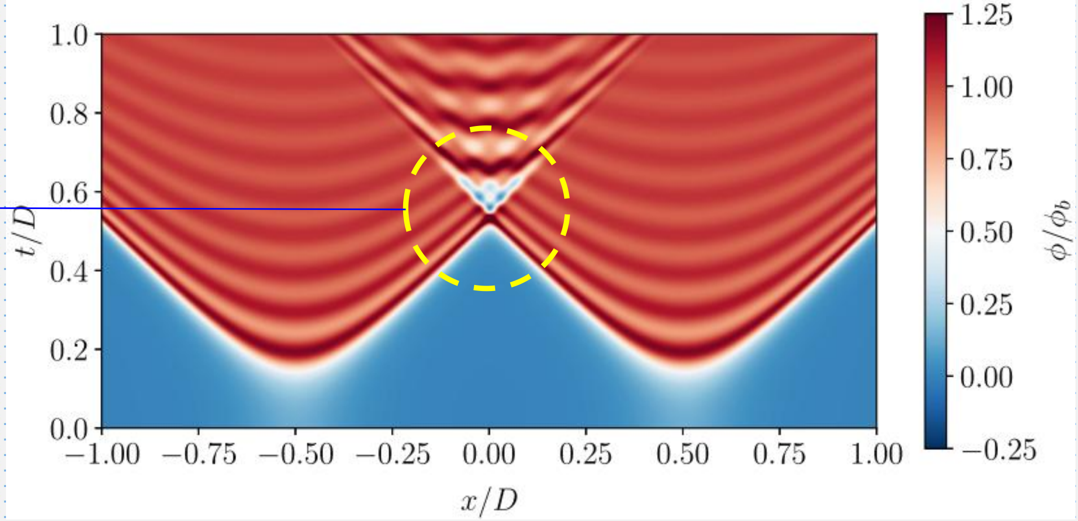
  Di, Wang, Zhou, Bian, Cai, Liu, PRL [2012.15625], Yang, Bian, PRD [2102.01398],
  Lewicki, Vaskonen, EPJC [2007.04967]

Bulk flow model



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





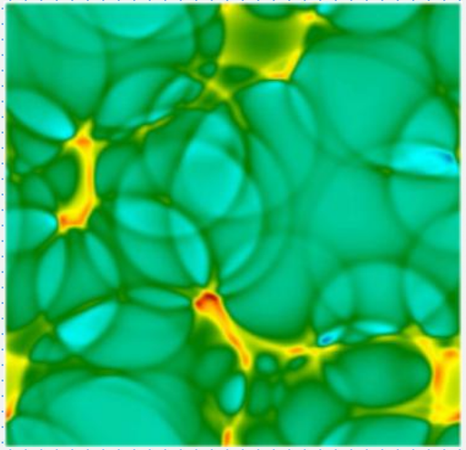
2

Sound Waves

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

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

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



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

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

Widely adopted, including LIGO, NANOGrav, ...

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 189 citations

2

Sound Waves: Recent Development

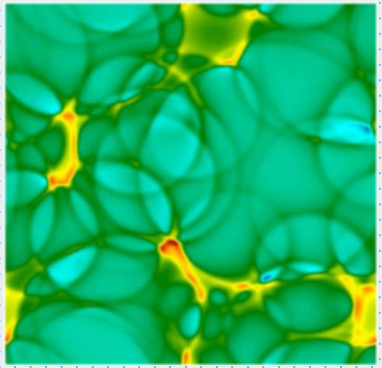
Analytical Modelling

- 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]

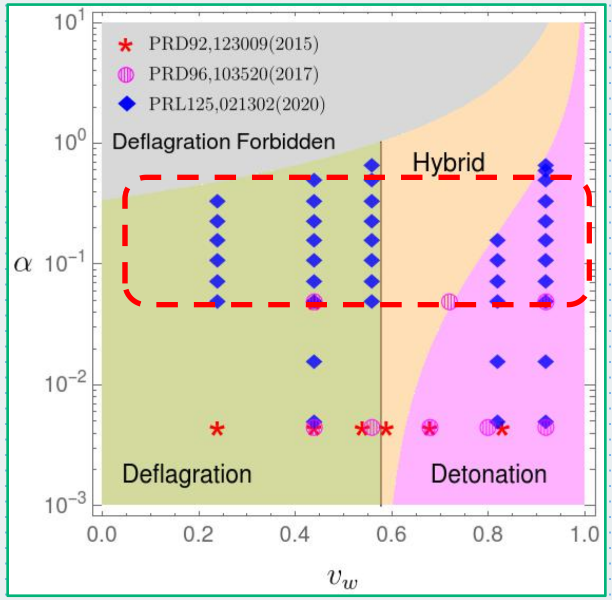
$$v^i_{\mathbf{q}} = \sum_{n=1}^{N_b} v^{i(n)}_{\mathbf{q}}$$

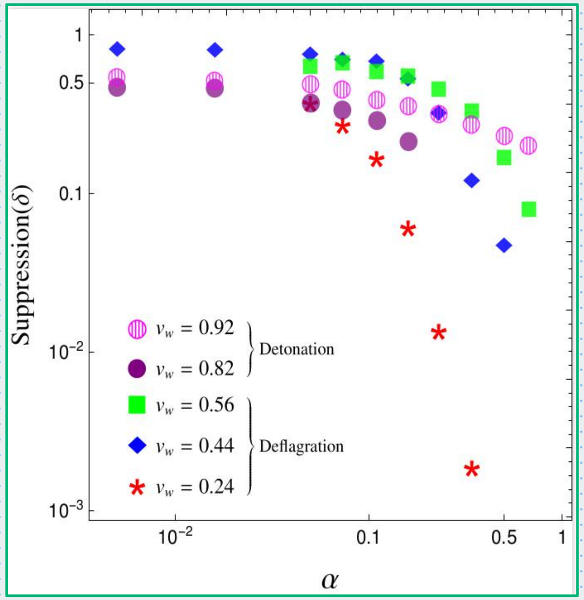


Numerical Simulation

- 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]

2

Magnetohydrodynamic Turbulence

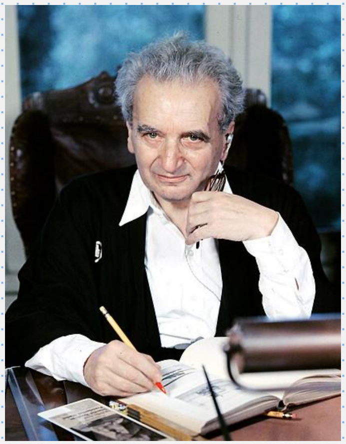
Earlier studies based on Kolmogorov spectrum:
Kamionkowski,Kosowsky,Turner, PRD [9310044]
Kosowsky,Mack,Kahniashvili, PRD [0111483]
Gogoberidze,Kahniashvili,Kosowsky, PRD [0705.1733]

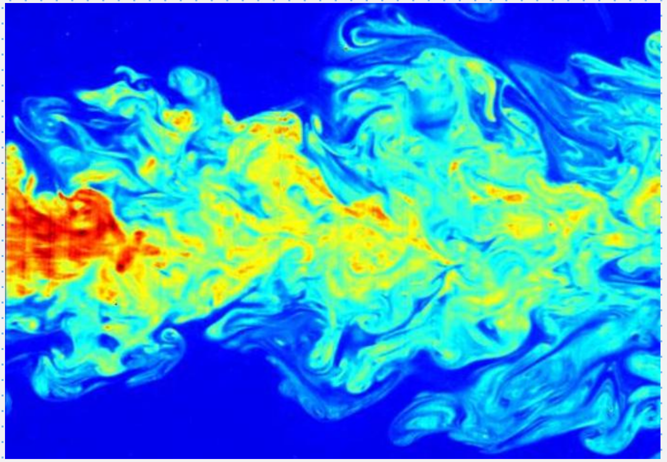
$$T^{ij} \sim (p+e)v^i v^j - B_i B_j$$

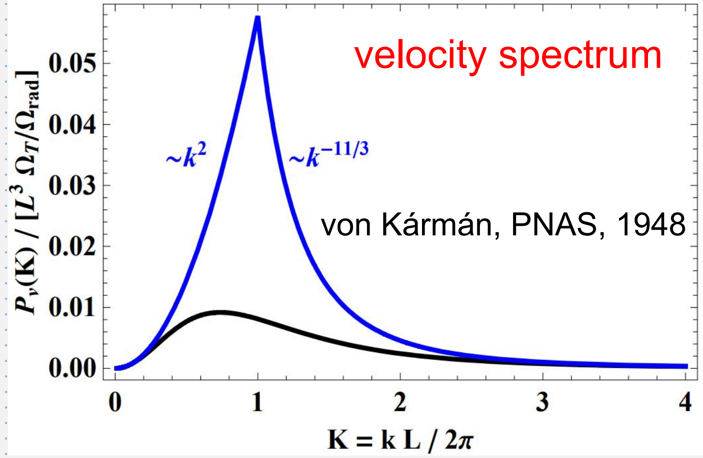
$$h^2\Omega_{\rm turb}(f) = 3.35\times 10^{-4}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_{\rm turb}\,\alpha}{1+\alpha}\right)^{\frac{3}{2}}\left(\frac{100}{g_*}\right)^{1/3} v_w\, S_{\rm turb}(f)$$

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


Andrey Nikolaevich Kolmogorov


Theodore von Kármán



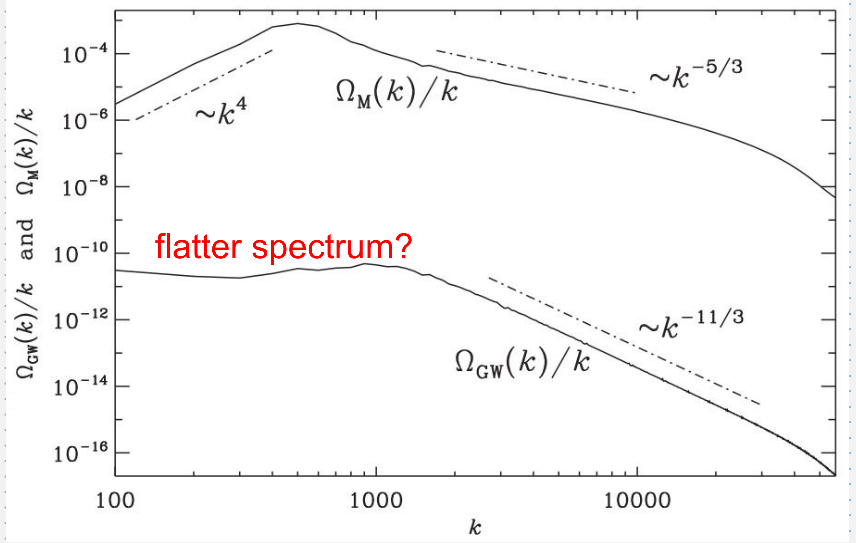


② Magnetohydrodynamic Turbulence: Recent Development

Progress on numerical simulations, and analytical modellings

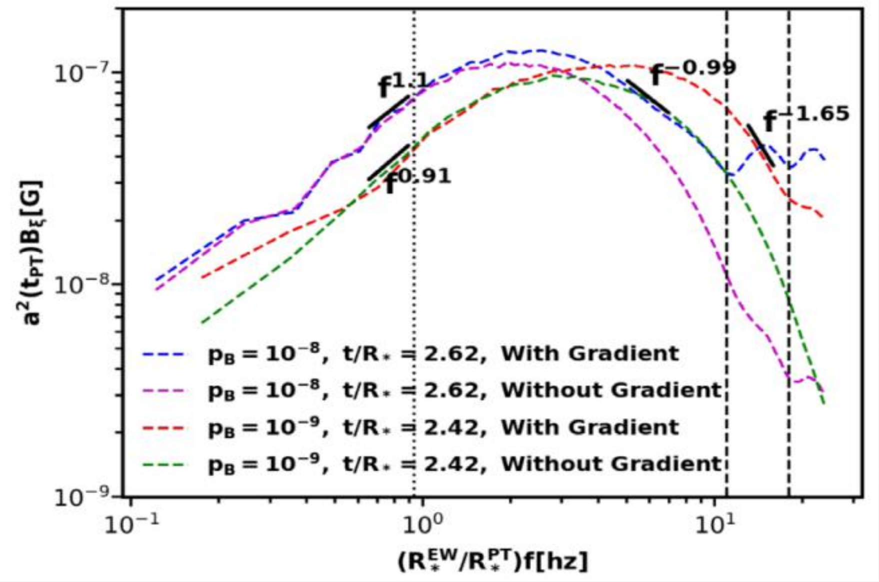
- Strong dependence on initial conditions
- Flatter spectrum at low frequency (violate causality?)

Magnetic Field Generation (simulation)



Pol et al, PRD [1903.08585]

as initial conditions?



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]

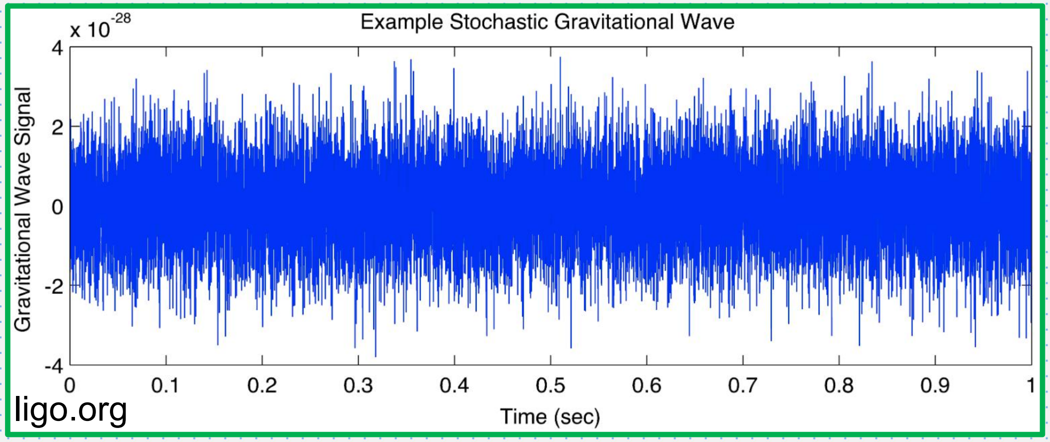
Detection at LIGO

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

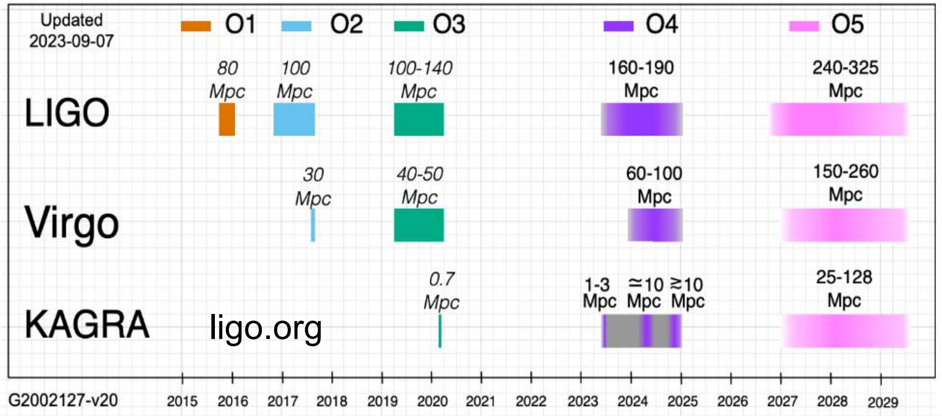
- No Evidence for Broken Power Law Signal
- No Evidence for Bubble Collision Domination Signal
- No Evidence for Sound Waves Domination Signal

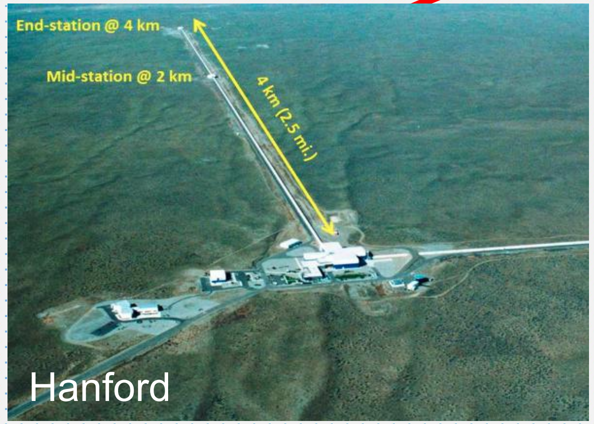
See also: Jiang, Huang, JCAP [2203.11781], Yu, Wang, PRD [2211.13111]

stochastic GWs: noise-like



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





solution: cross-correlation

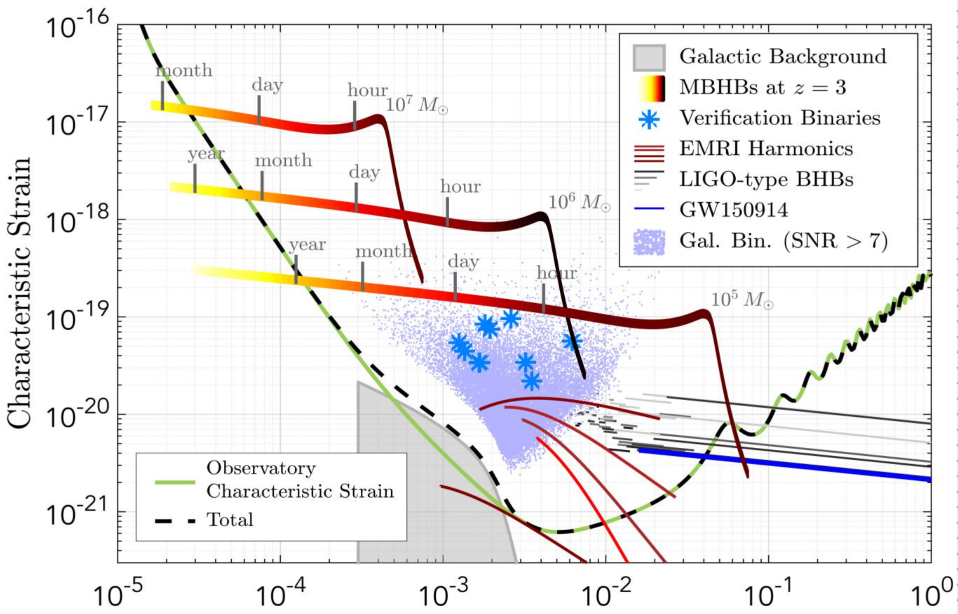
3

Detection at LISA/Taiji/Tianqin

Electroweak-scale PT

Detection with a single detector

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



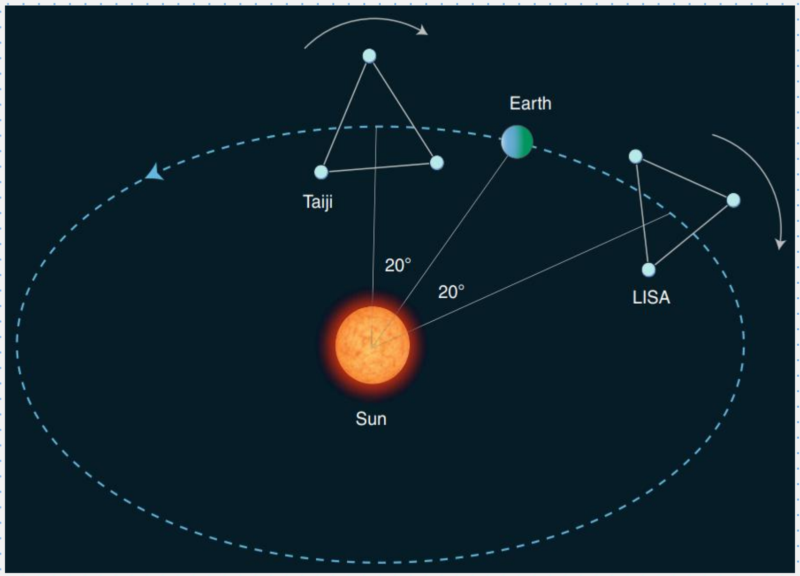
LISA [1702.00786]

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]

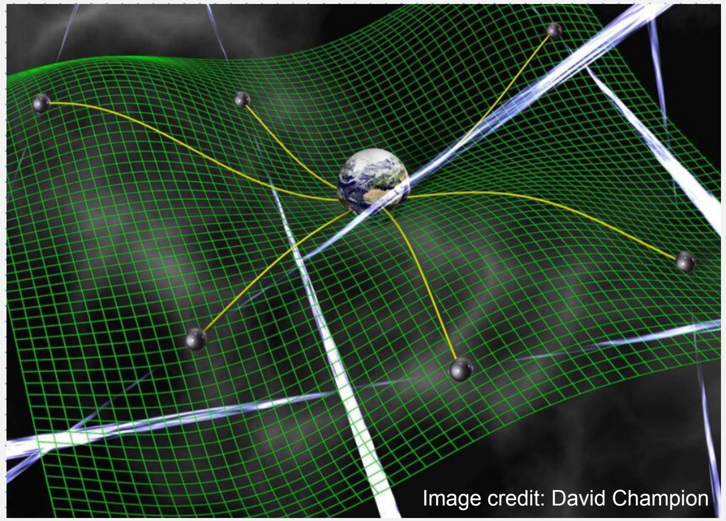
3

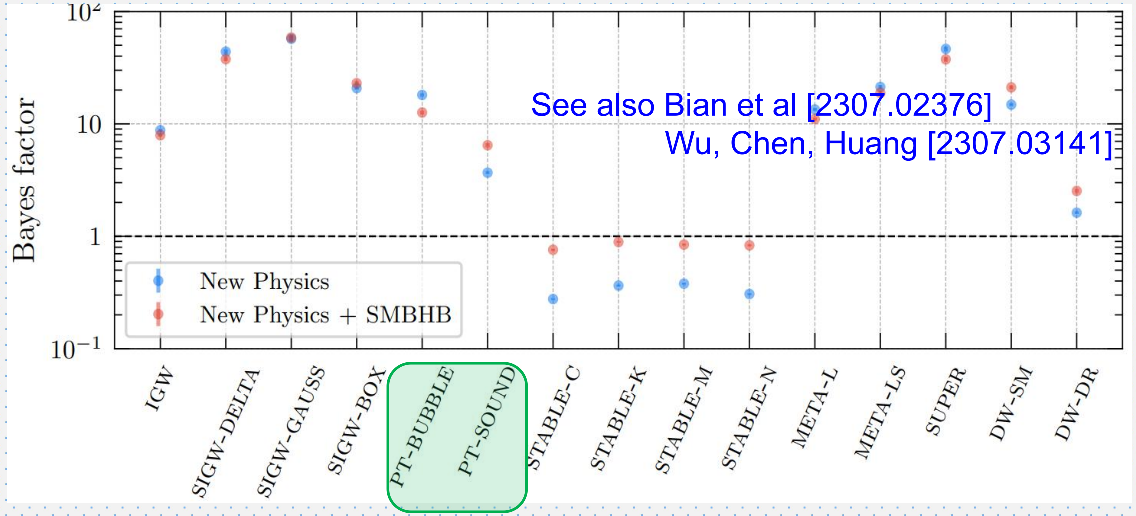
QCD-scale PT

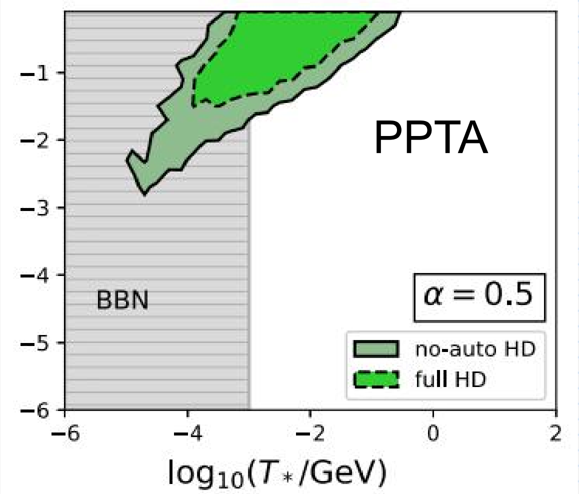
PTA

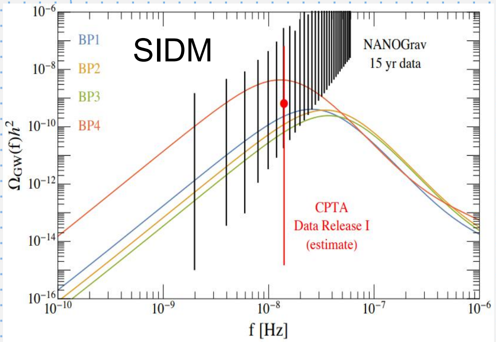
NANOGrav, ApjL [2306.16219]

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

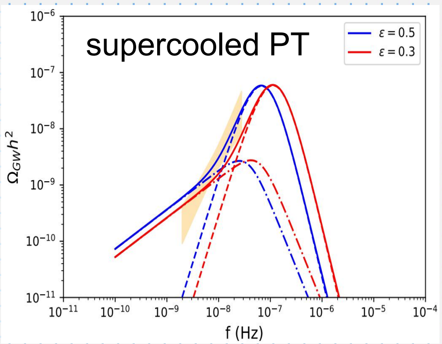




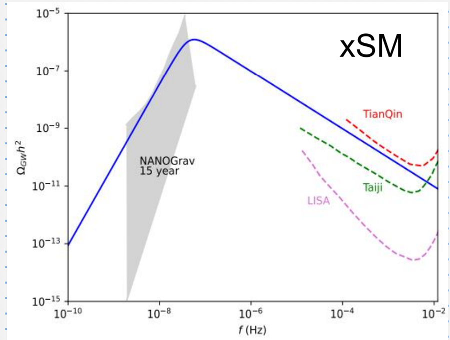




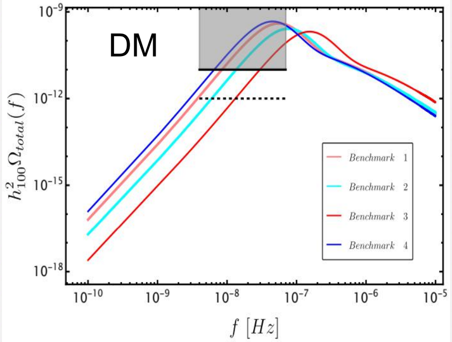
Han,Xie,Yang,Zhang [2306.16966]



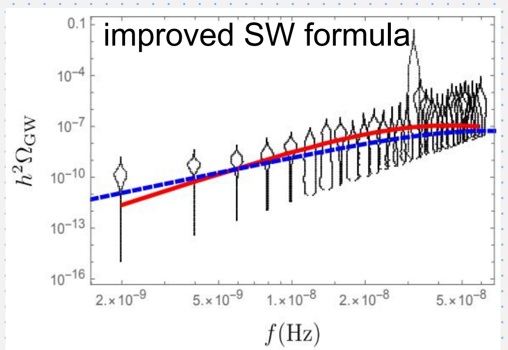
Zu,Zhang,Li,Gu,Tsai,Fan [2306.17239]



Xiao,Yang,Zhang [2307.01072]



Yang,Ma,Jiang,Huang [2306.17827]

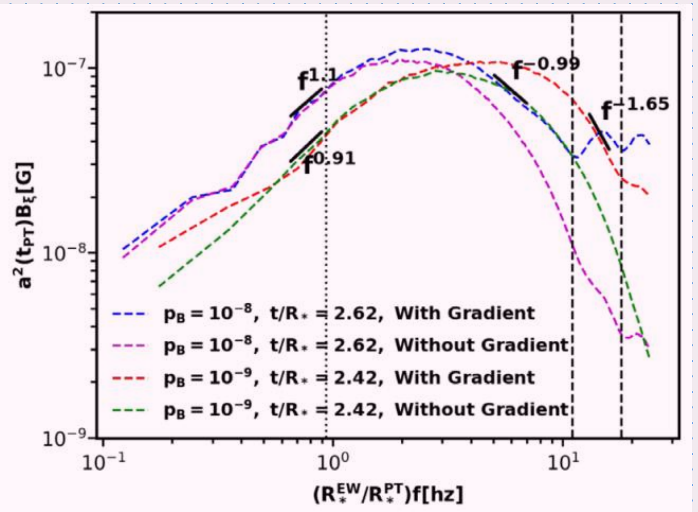


Ghosh, Ghoshal, HG, ...[2307.02259]

and many more...

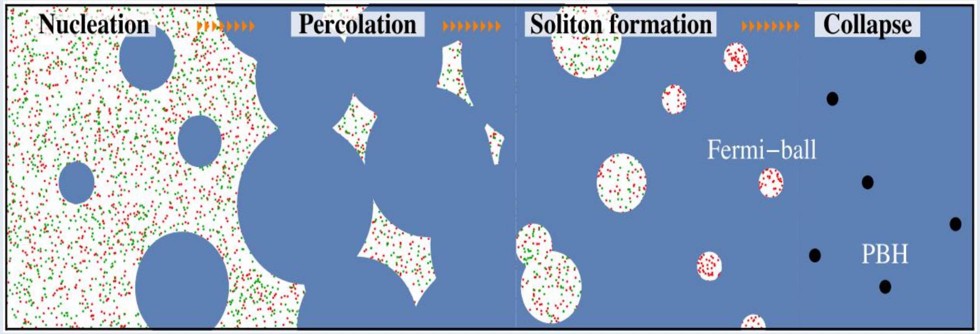
New Observables

Primordial magnetic field



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

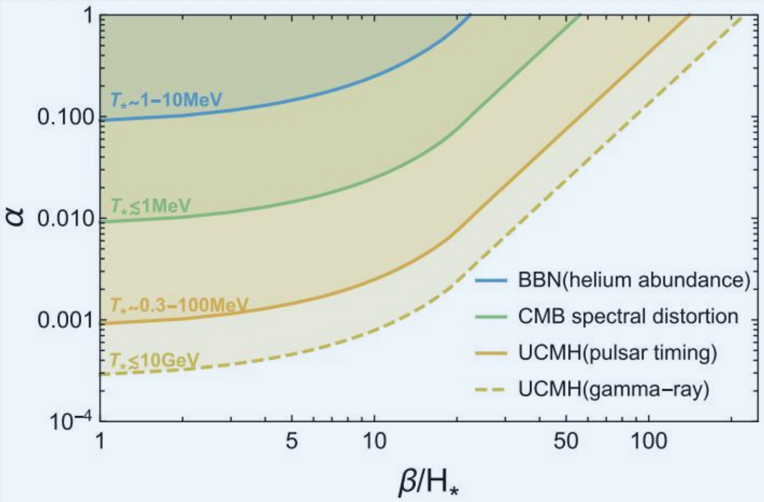
Primordial black holes and Solitons



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]

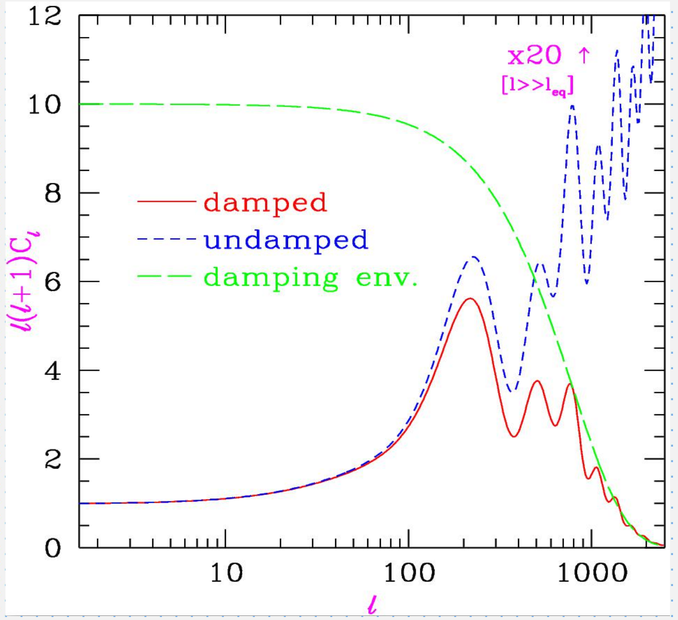
Dissipative Effects as New Observables

- 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

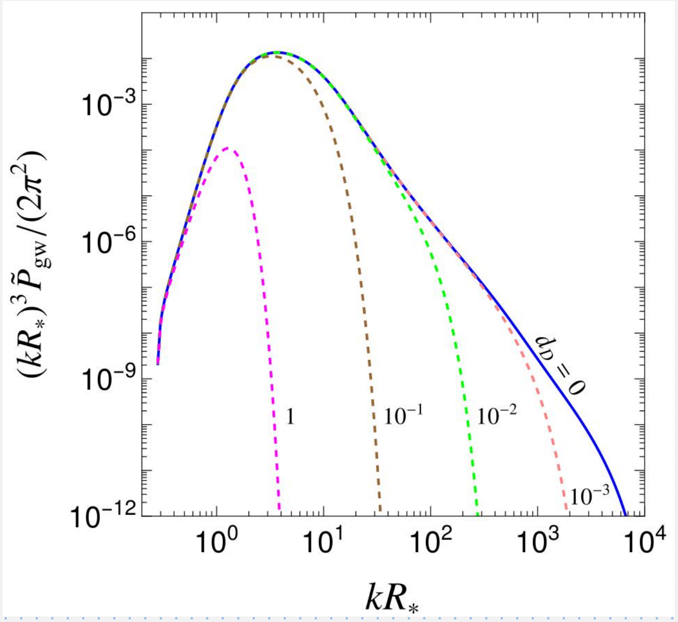
$$\Delta T^{ij} = -\eta \left(\frac{\partial U_i}{\partial x^j} + \frac{\partial U_j}{\partial x^i} - \frac{2}{3}\delta_{ij} \nabla \cdot \mathbf{U} \right) - \zeta \, \delta_{ij} \nabla \cdot \mathbf{U},$$
$$\Delta T^{i0} = -\chi \left(\frac{\partial T}{\partial x^i} + T \dot{U}_i \right). \qquad (1)$$

Silk damping of CMB Anisotropy



Hu,White, ApJ [9609079]

damping of GW



HG [2310.10927]

Summary

- Comprehensive phenomenological studies
- Significant advances in PT and GW calculations
- Significant advances in experimental detections (LIGO, PTA, etc)
- Future: more precise predictions, and measurements

Thanks!