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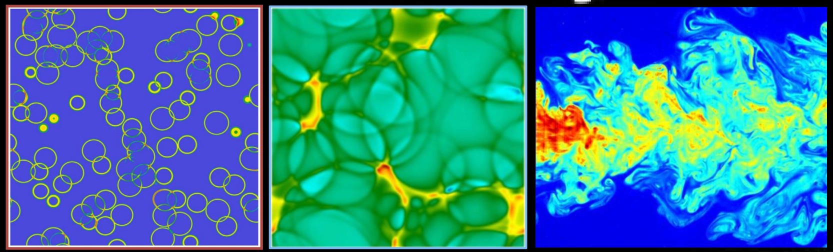
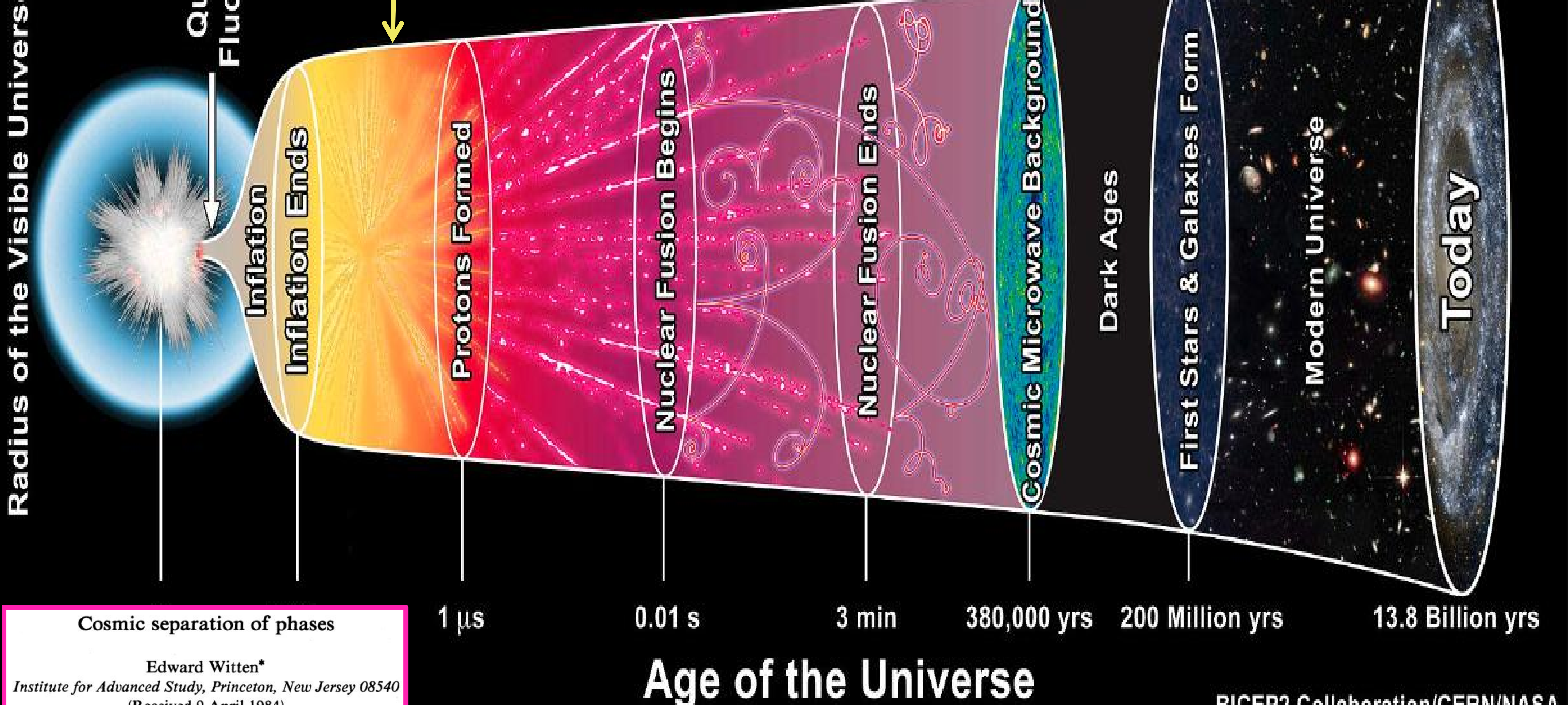
Hearing the Sound from Cosmic Phase Transitions

Huaike Guo

Jan. 1, 2025



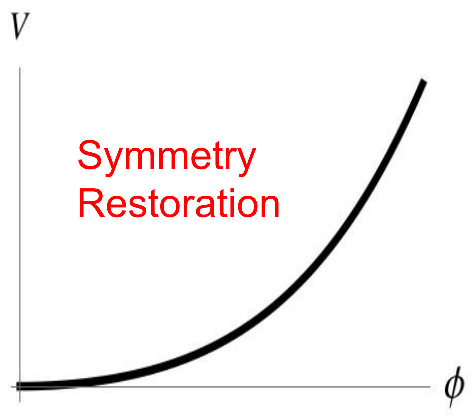


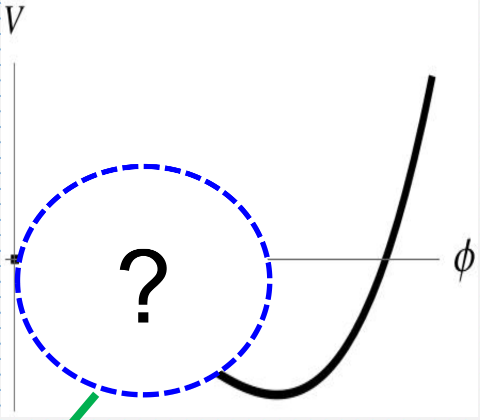
BICEP2 Collaboration/CERN/NASA

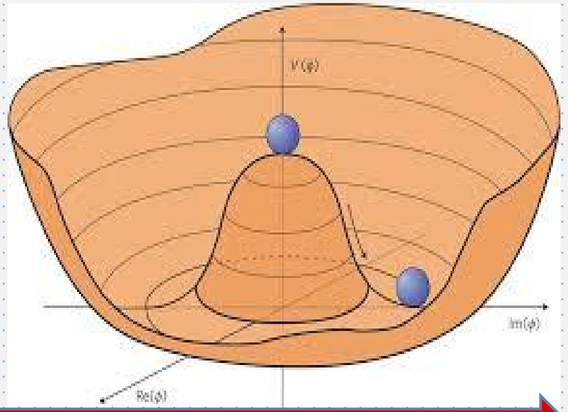
Cosmic separation of phases

Edward Witten*
Institute for Advanced Study, Princeton, New Jersey 08540
(Received 9 April 1984)

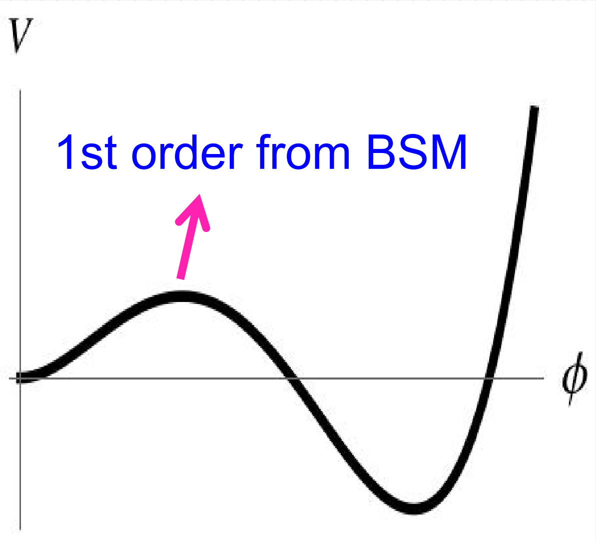
Electroweak Phase Transition

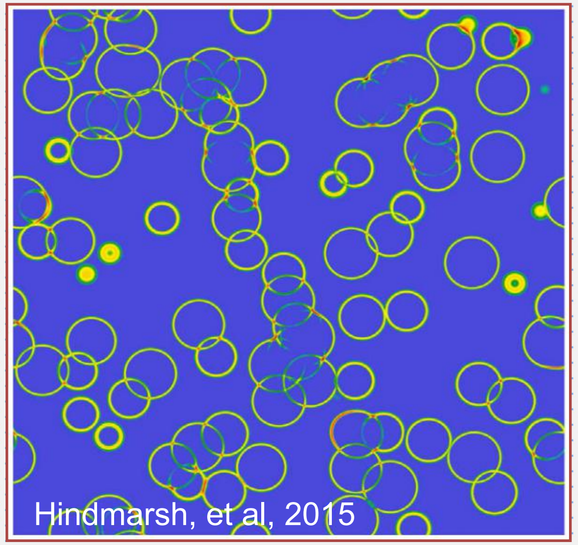






Temperature drops



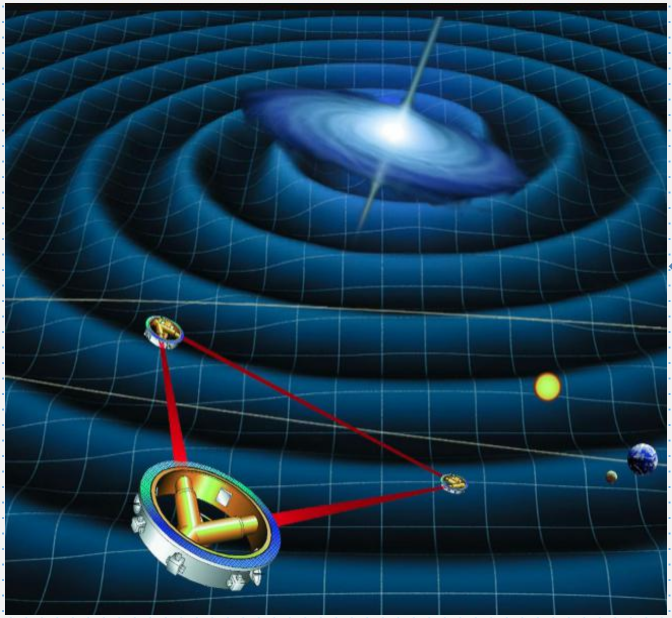


Electroweak Baryogenesis

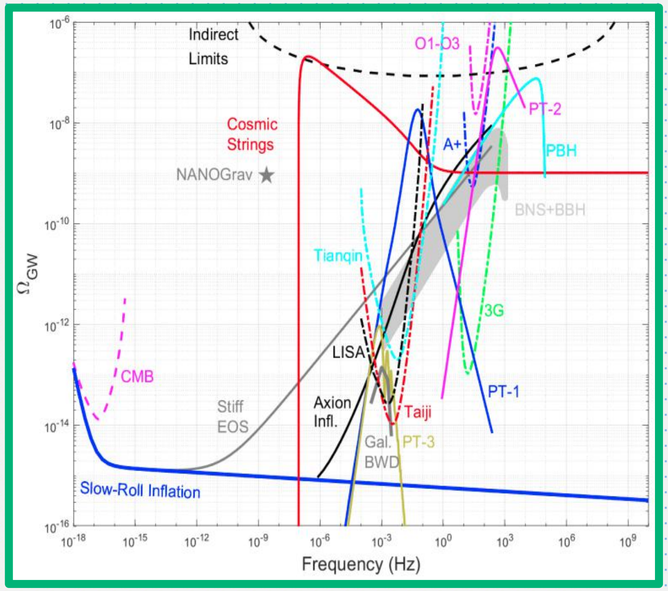
- Modified Higgs potential (Higgs physics, GW)
- Extra CP-violation (EDM, LHC)
- New particles, symmetries (LHC, GW)

Morrissey, Ramsey-Musolf [1206.2942]

From Theory to Experiment



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



Gravitational Wave Spectrum

α

β

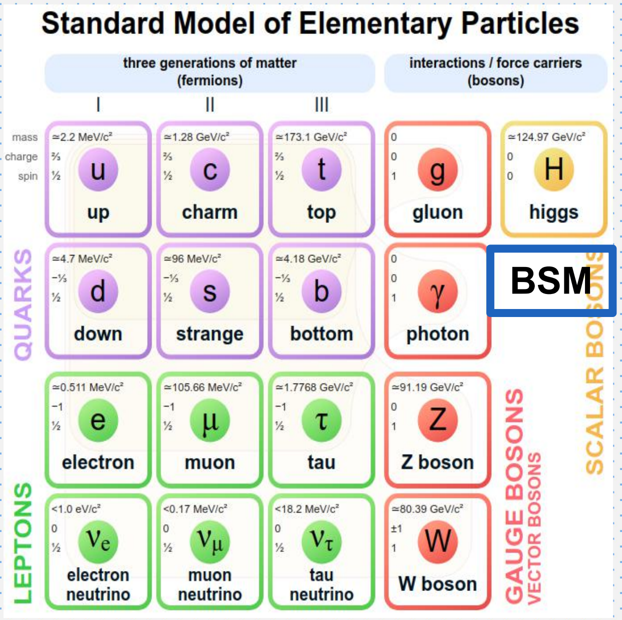
v_w

T_*

g_s

$\ldots$

Phase Transition Parameters



Particle Physics Model

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 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)	✓	✓	✓	✓

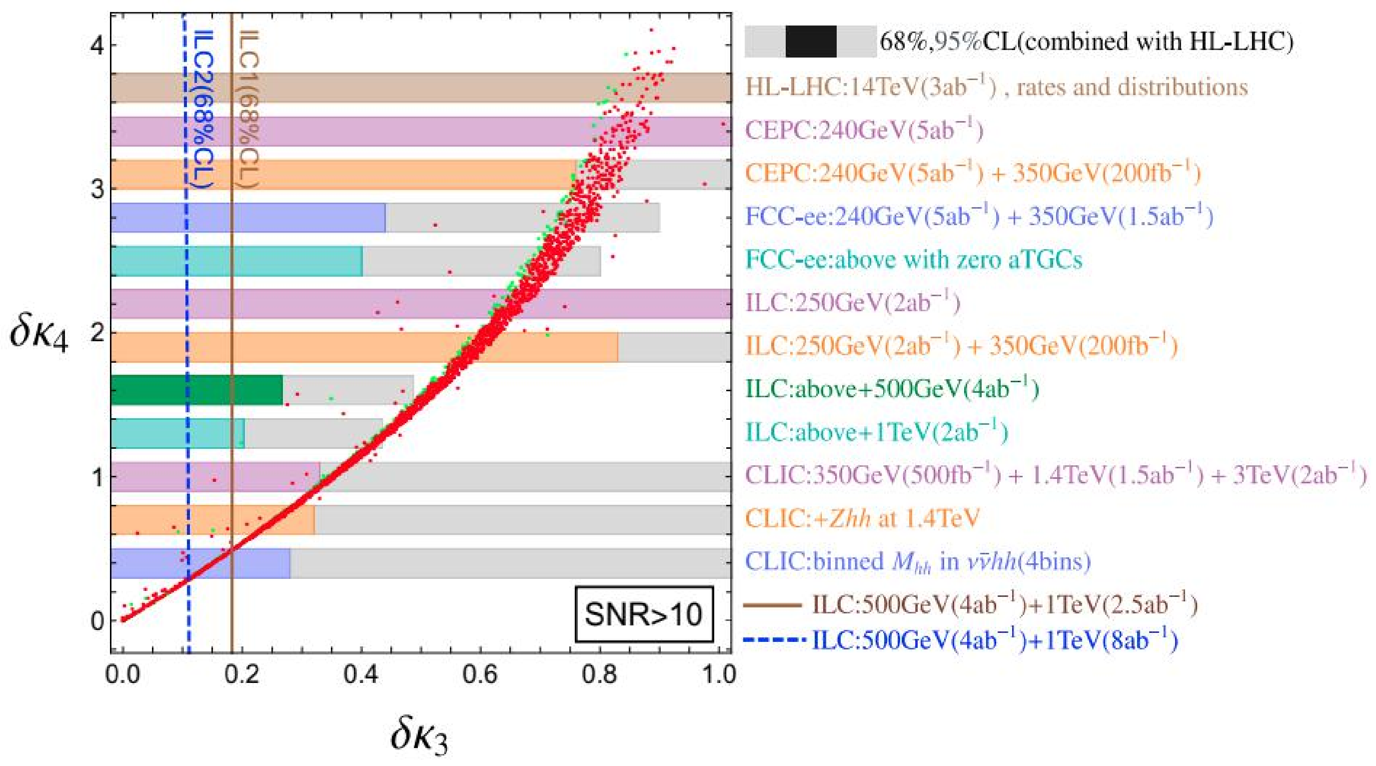
Ghosh, HG, Han, Liu, JHEP [2012.09758]

Collider and GW Complementarity

- 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]

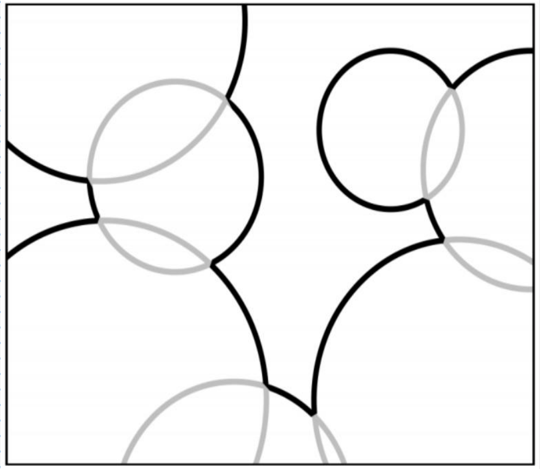
See also
Huang, Long,Wang, PRD [1608.06619],
and many others

Gravitational Wave Sources

The current understanding:

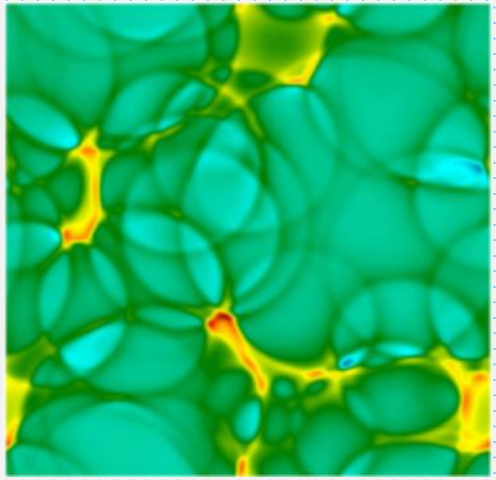
$$\Box \bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu}$$

energy near the wall



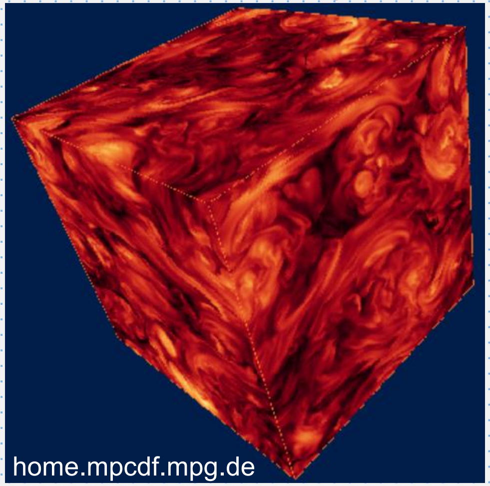
Bubble Collisions

fluid kinetic energy



Sound Waves

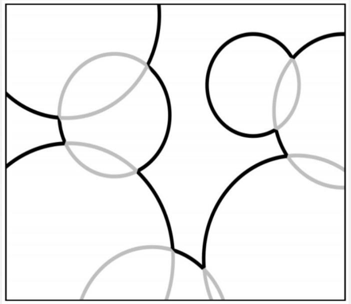
turbulent fluid + magnetic field



Magnetohydrodynamic Turbulence

GW Spectra

bubble collision

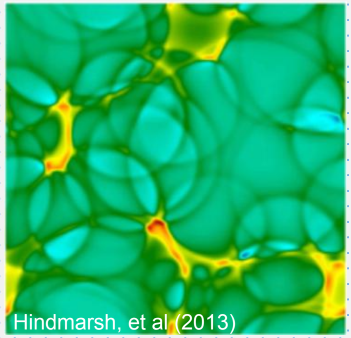


$$\Omega_{\rm coll}(f)h^2 = 1.67\times10^{-5}\Delta\left(\frac{H_{\rm pt}}{\beta}\right)^2\left(\frac{\kappa_\phi\alpha}{1+\alpha}\right)^2 \times\left(\frac{100}{g_*}\right)^{1/3}S_{\rm env}(f),$$

Energy density Spectrum

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

sound waves



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

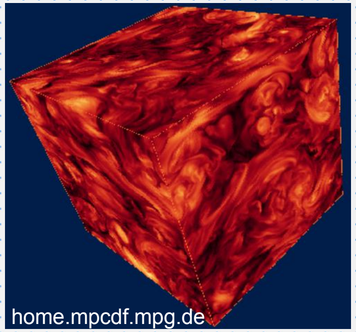
$$\Upsilon = 1-(1+2\tau_{\rm sw}H_{\rm pt})^{-1/2}$$ (RD)

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

$$\Upsilon = \frac{2[1-y^{3(w-1)/2}]}{3(1-w)}$$

HG, Yang Xiao, ... [2410.23666]

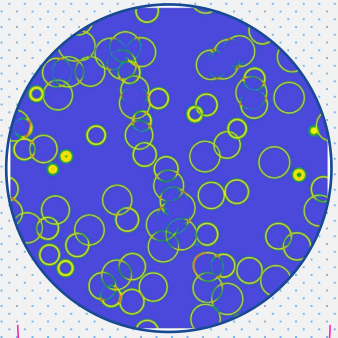
MHD



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

Chiara Caprini et al JCAP [1512.06239]

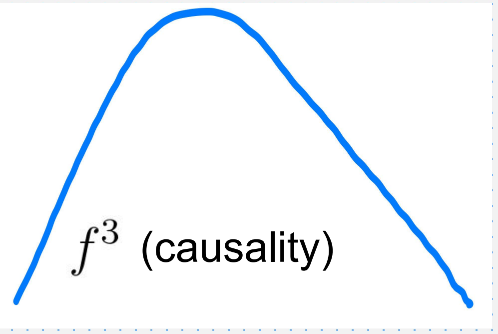
Basic Properties



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



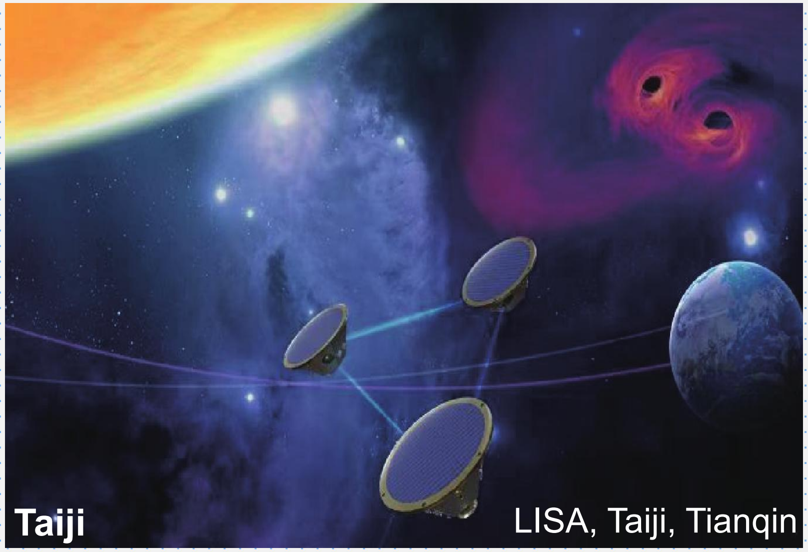
Cai, Pi, Sasak, PRD [1909.13728]

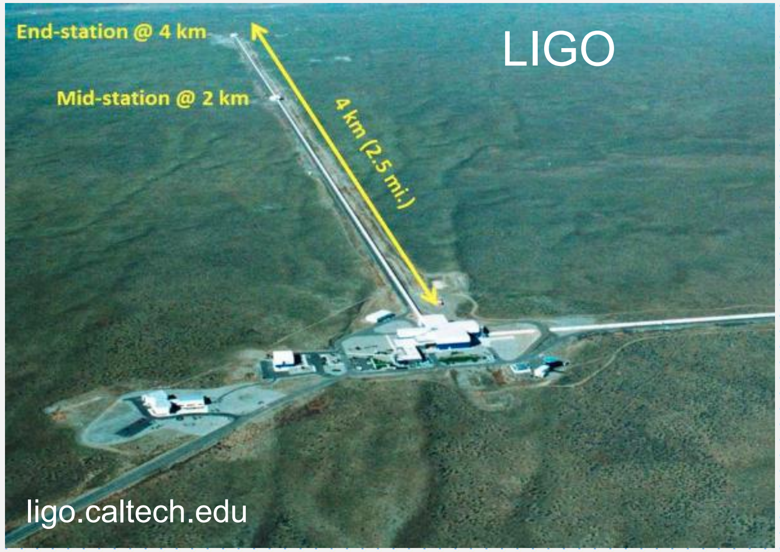
nHz (~100MeV) QCD scale

~mHz : (~100GeV) weak scale

~100Hz (~PeV - EeV) high scale

中国脉冲星测时阵列（CPTA）





Multiband Searches

NANOGrav, ApjL [2306.16219]

EPTA [2306.16227]

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

Bian et al [2307.02376]

Wu, Chen, Huang [2307.03141]

...

Boileau et al, MNRAS [2105.04283]
LISA: Caprini et al [2403.03723]
Network: Wang, Han, PRD [2108.11151] ...
TDI optimization: Wang, Li, Xu, Fan, PRD [2201.10902]
...

Romero,Martinovic,Callister,HG,Martínez,Sakellariadou, Yang,Zhao, PRL [2102.01714]
Badger, ..., HG, ..., PRD [2209.14707]
Jiang, Huang, JCAP [2203.11781]
Yu, Wang, PRD [2211.13111]

nHz (~100MeV) QCD scale

EPTA

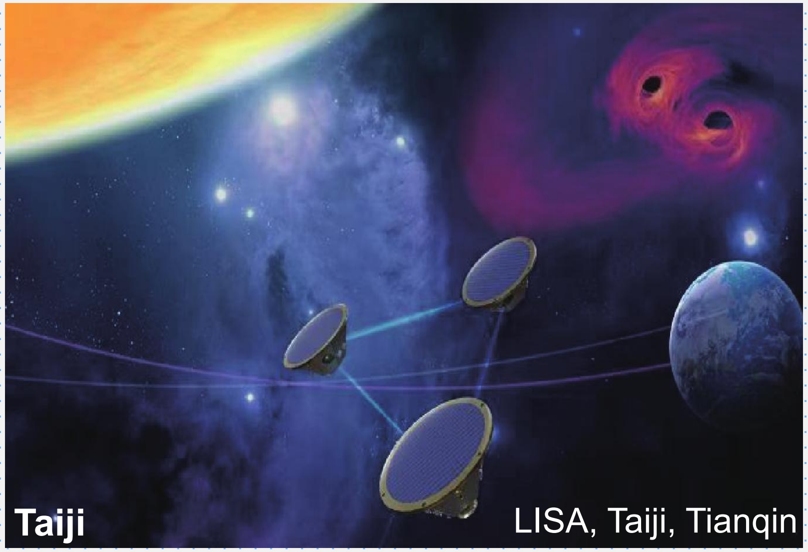
NANOGrav Physics Frontiers Center

PPTA

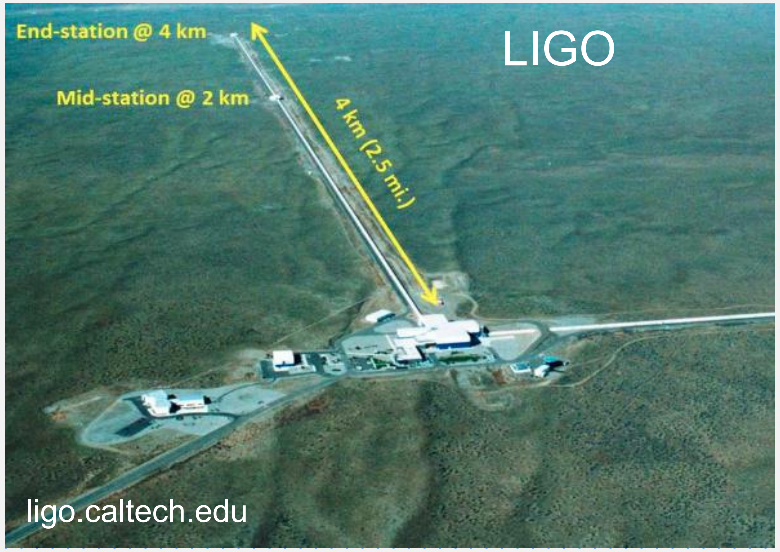
InPTA Indian Pulsar Timing Array

中国脉冲星测时阵列（CPTA）

~mHz : (~100GeV) weak scale



~100Hz (~PeV - EeV) high scale



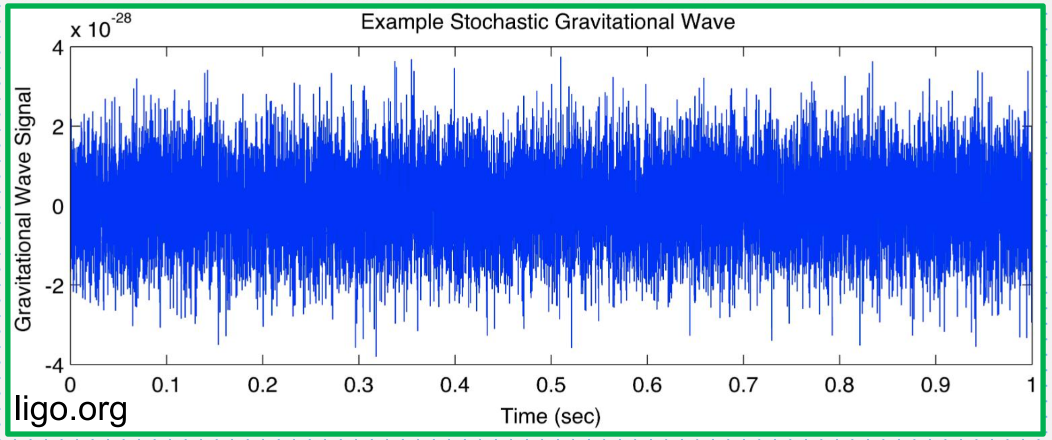
high-scale PT

Detection at LIGO

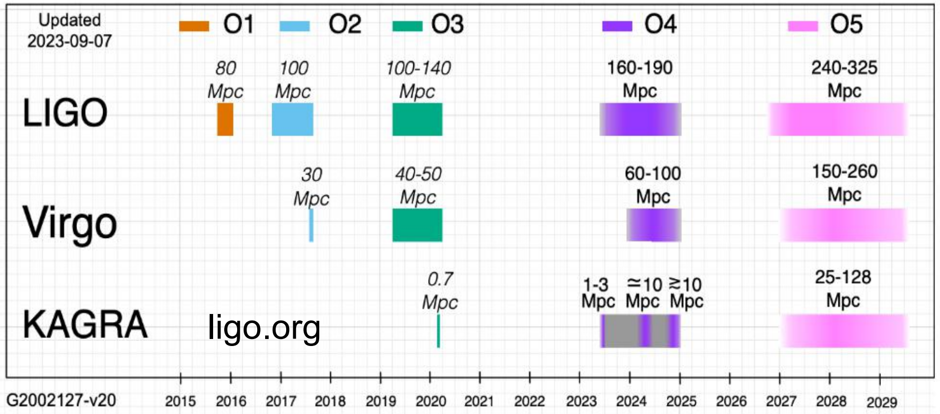
✓ Gaussian, Stationary, Isotropic, Unpolarized

$$\langle h_A^*(f,\Omega)\, h_{A'}(f',\Omega')\rangle = \frac{3H_0^2}{32\pi^3}\delta^2(\Omega,\Omega')\delta_{AA'}\delta(f-f')f^{-3}\Omega_{\rm GW}(f)$$

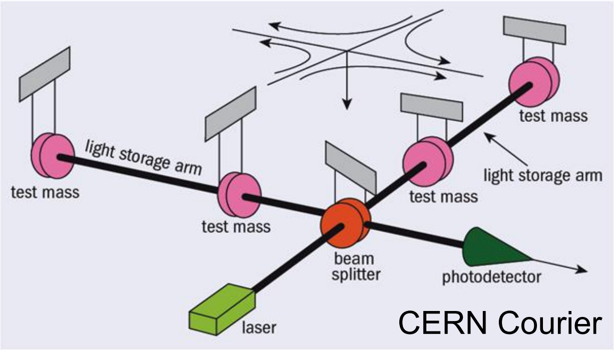
stochastic GWs: noise-like

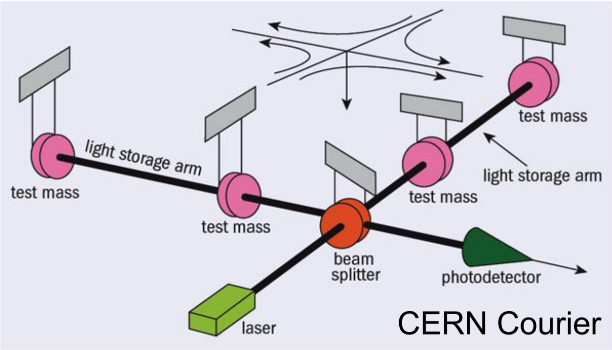


O1+O2+O3@LIGO (H1, L1), Virgo



solution: cross-correlation





high-scale PT

Detection at LIGO

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

Bubble Collision

95% CL UL with fixed Tpt and beta/Hpt

Phenomenological model (bubble collisions)				
$\Omega_{\rm coll}^{95\%}(25\ \text{Hz})$				
$\beta/H_{\rm pt} \backslash T_{\rm pt}$	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

Broken Power Law

95% CL UL (CBC+BPL)

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

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

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

Sound Waves

95% CL UL

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

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

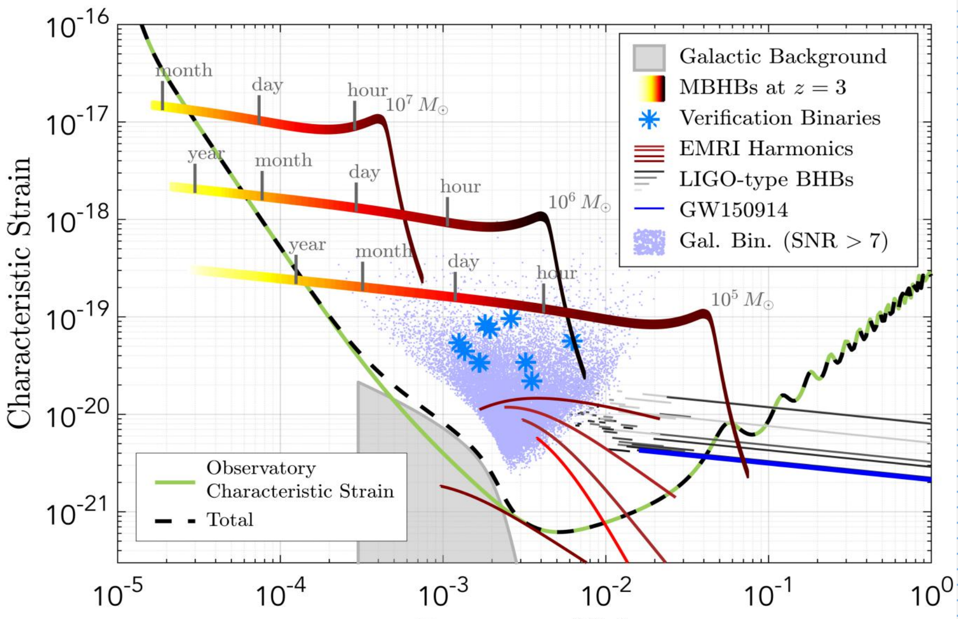
See also Jiang, Huang, JCAP[2203.11781], Yu, Wang, PRD[2211.13111]

Electroweak-scale PT

Detection in Space

Detection with a single detector

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



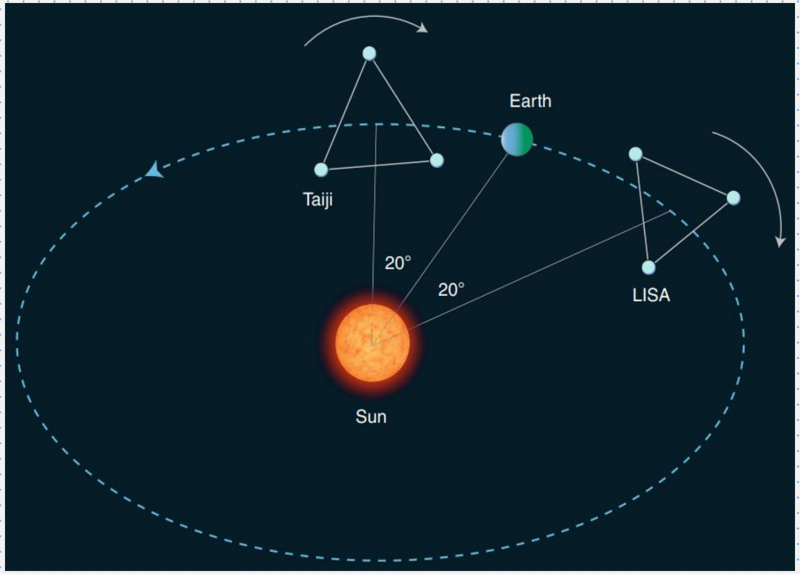
LISA [1702.00786]

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]

Gowling et al, JCAP [2209.13551, 2106.05984]
Caprini, Jinno, Lewicki, ..., JCAP [2403.03723]
Hindmarsh, Hooper, Minkkinen, Weir [2406.04894]

Electroweak-scale PT

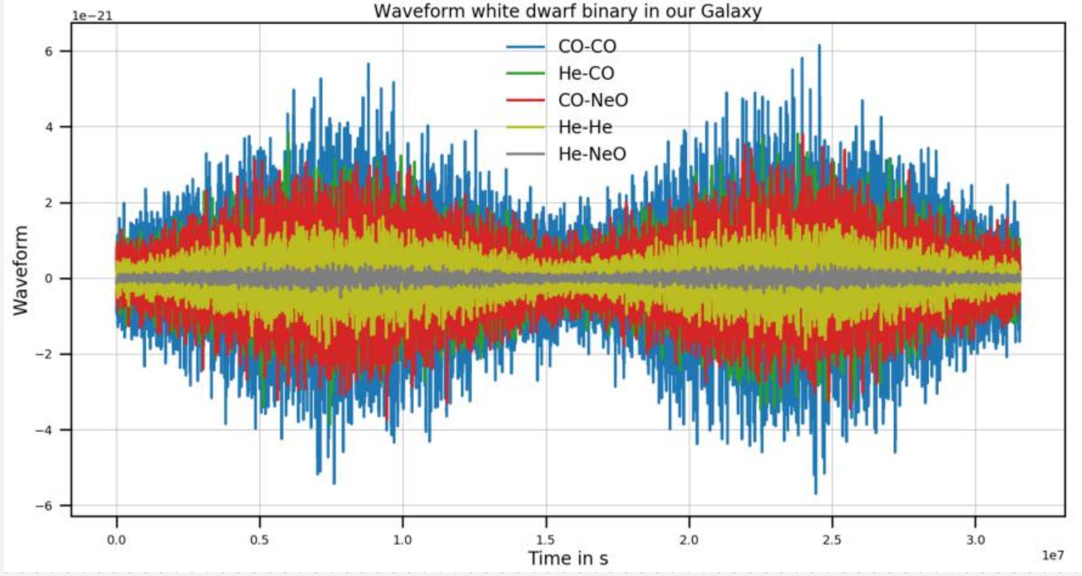
Detection in Space

Cosmological

- Inflation
- Phase transitions (EW, GUT, etc)
- Cosmic strings, Domain walls
- SIGW
- PBH

Astrophysical

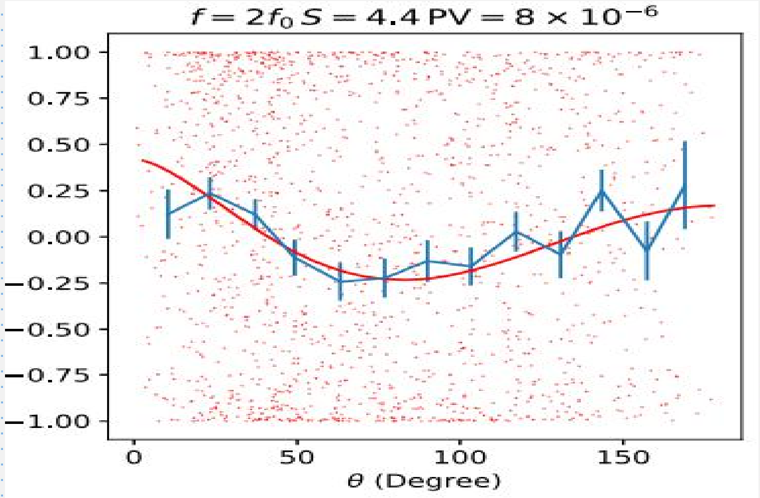
- Galactic DWD
- BBH, BNS, etc
- EMRI
- SMBH binary



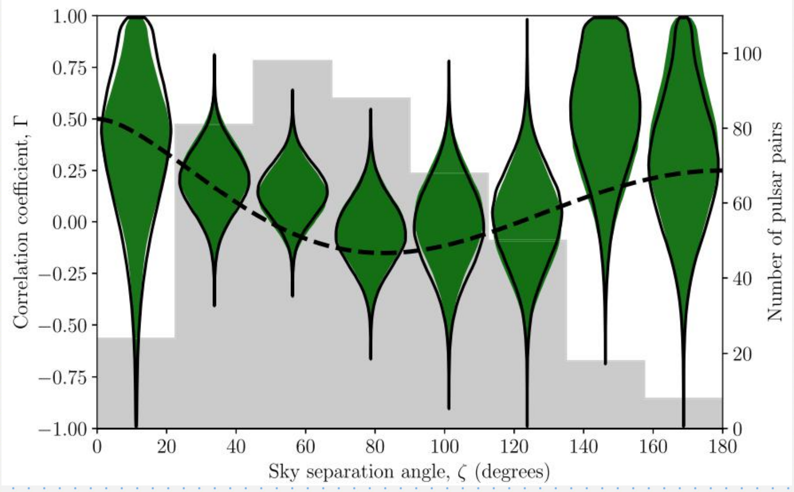
Boileau et al, MNRAS [2105.04283]

QCD-scale PT

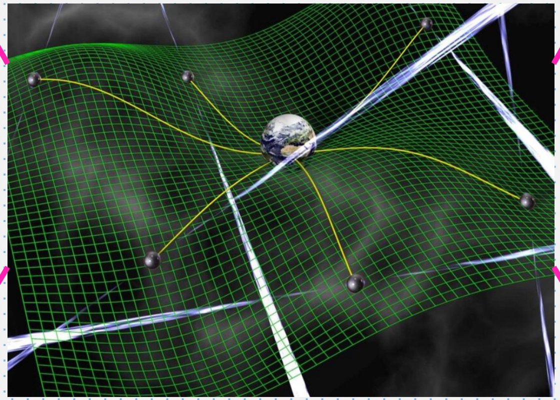
Detection with PTA

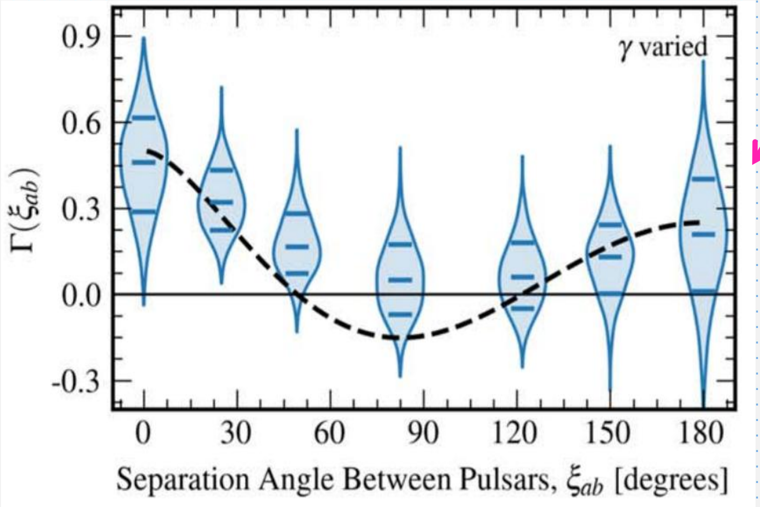


CPTA, RAA, [2306.16216]

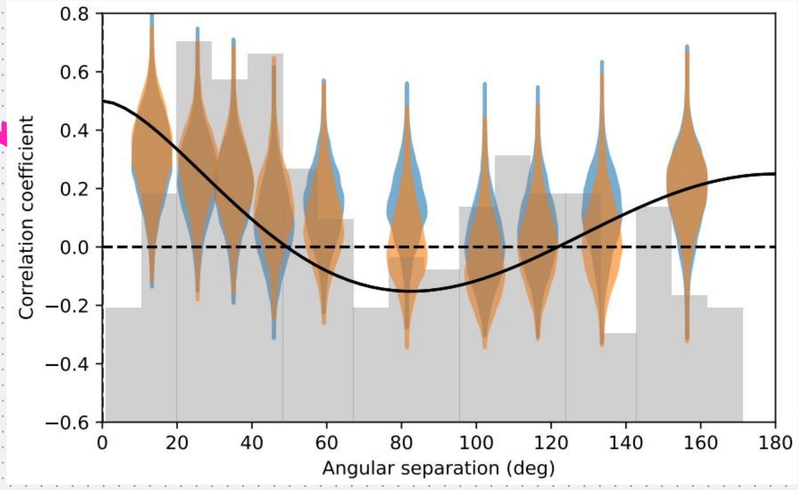


PPTA, ApjL [2306.16215]





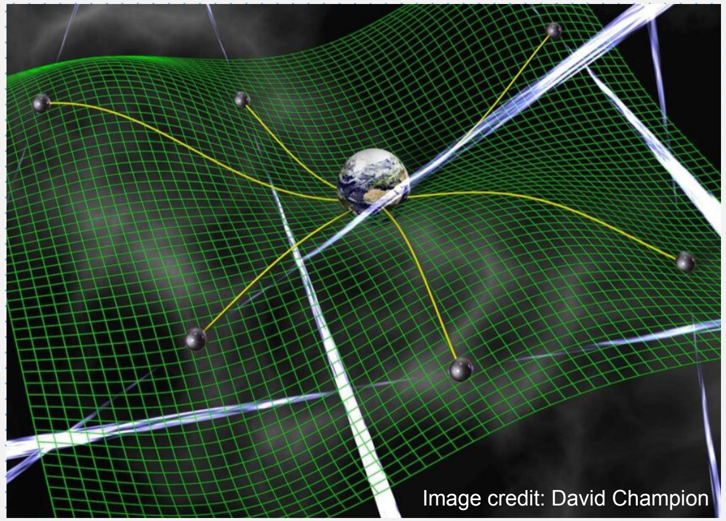
NANOGrav, ApjL [2306.16213]



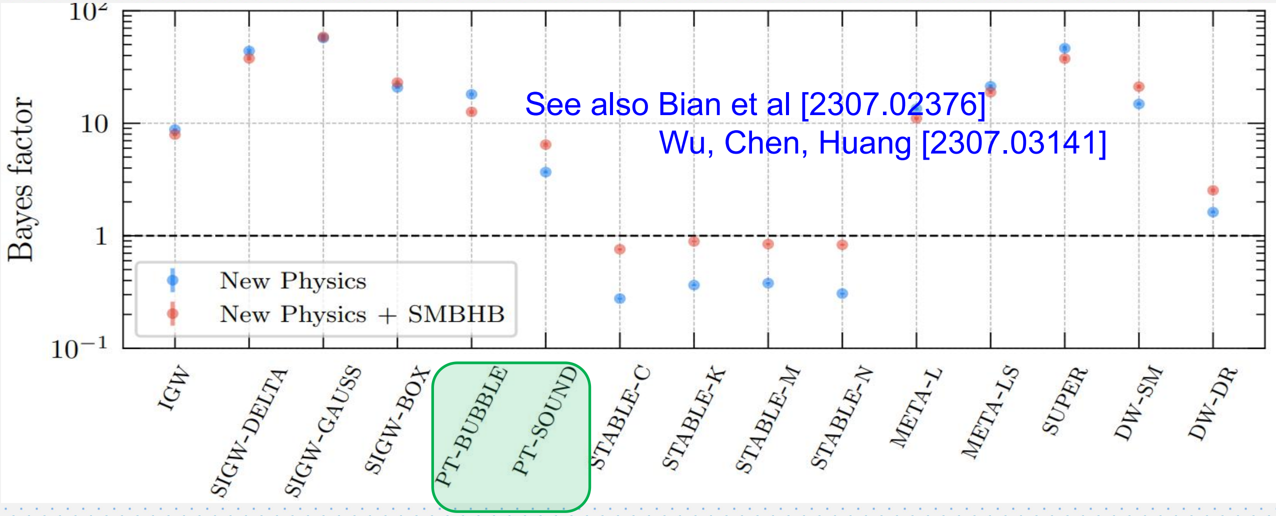
EPTA, A&A [2306.16214]

QCD-scale PT

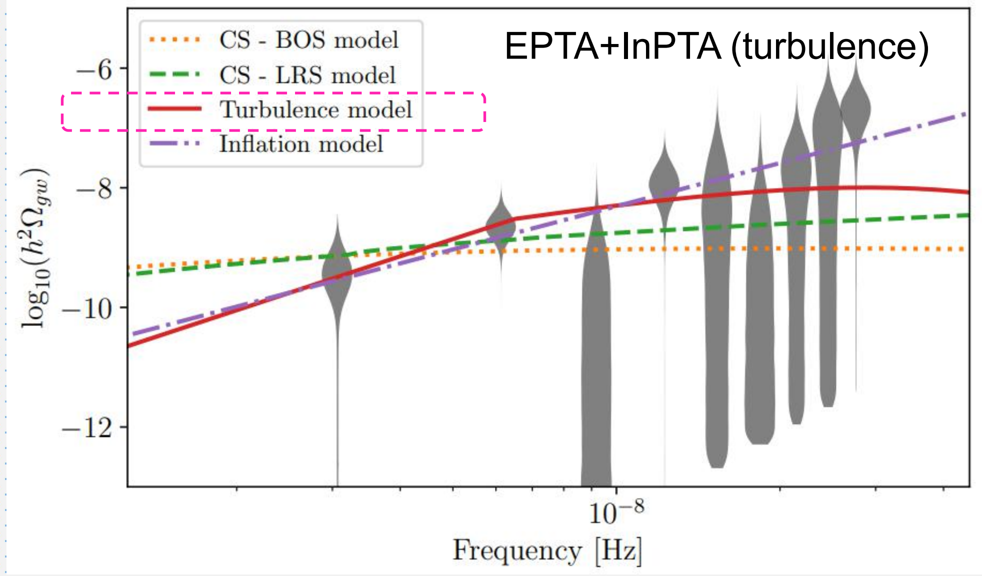
Detection with PTA

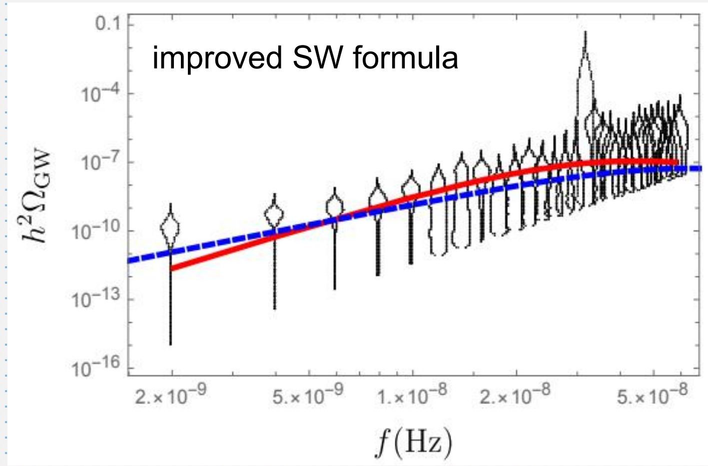


NANOGrav, ApjL [2306.16219]



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





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

Problem: 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]

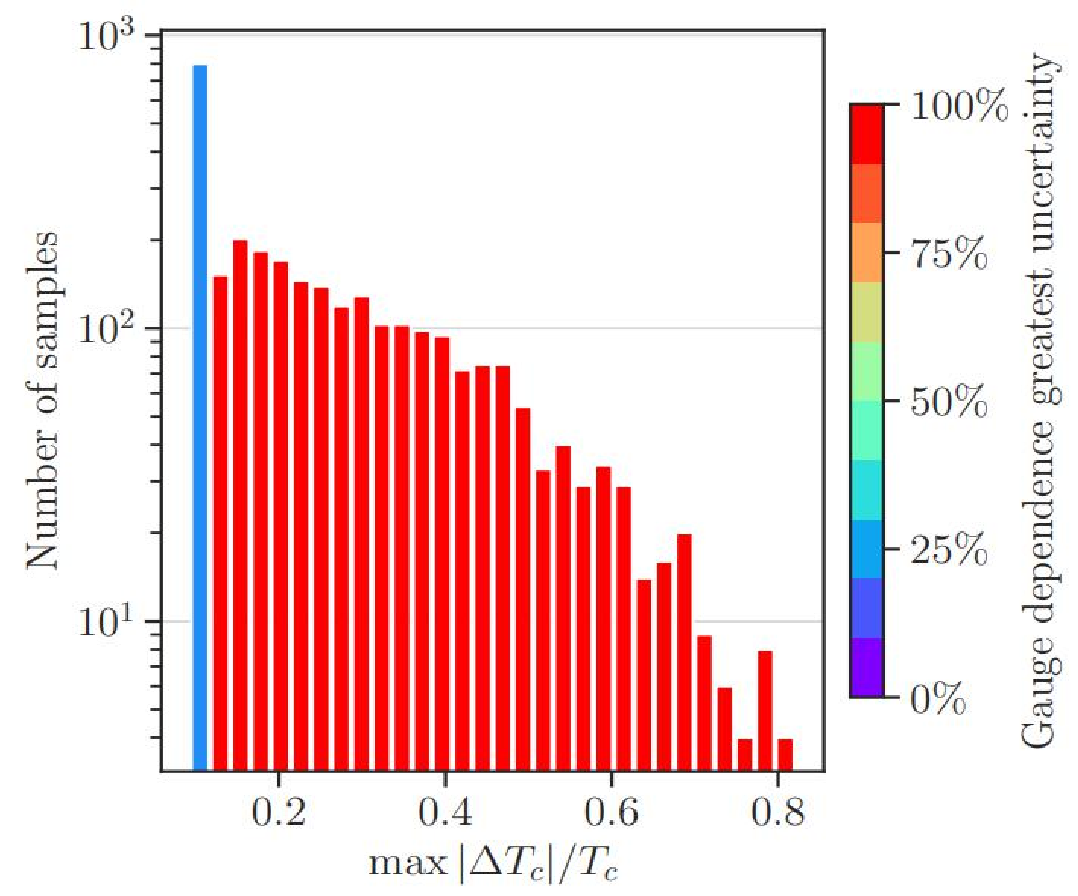
Uncertainty	pre-factor1	pre-factor2	pre-factor3
T_p	0.003%	0.003%	0.002%
βR^*	8.1%	7.9%	5.9%
N_{tot}	11.4%	11.0%	9.8%
$f^{peak}_{\beta R^*}$	11.8%	12.0%	14.1%
$\Omega_{GW} h^2_{\beta R^*}$	37.6%	36.5%	28.9%
f^{peak}_{sim}	36.4%	36.4%	35.1%
$\Omega_{GW} h^2_{sim}$	334.0%	330.8%	336.7%

HG, Xiao, Yang, Zhang, PRD [2310.04654]

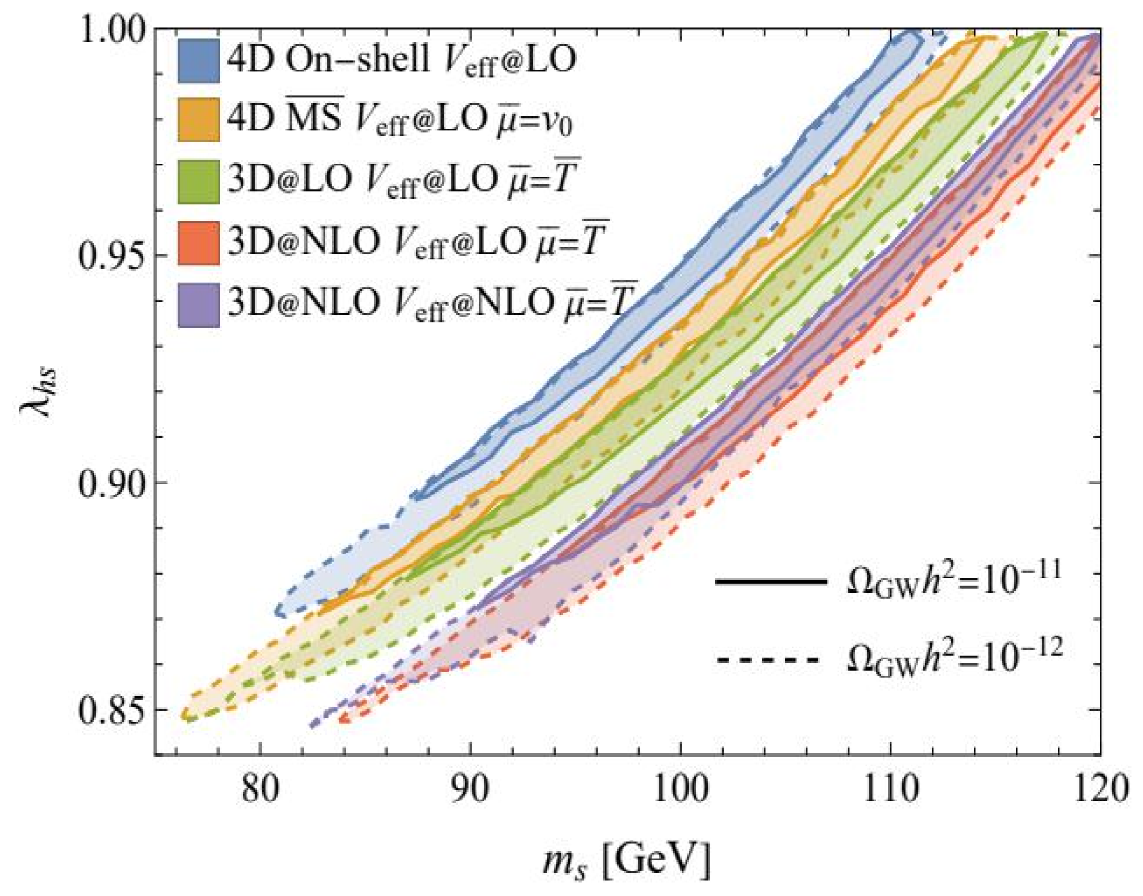
Effect(fixed wall velocity)	Range of error (medium)	Range of error (low)	Type of error
Transition temperature	$\mathcal{O}(10^{-4}$–$10^1)$	$\mathcal{O}(10^{-1}$–$10^0)$	Random
Mean bubble separation	$\mathcal{O}(0$–$10^{-1})$	$\mathcal{O}(10^{-1}$–$10^0)$	Suppression
Fluid velocity	$\mathcal{O}(10^{-2}$–$10^0)$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

Problem: uncertainties

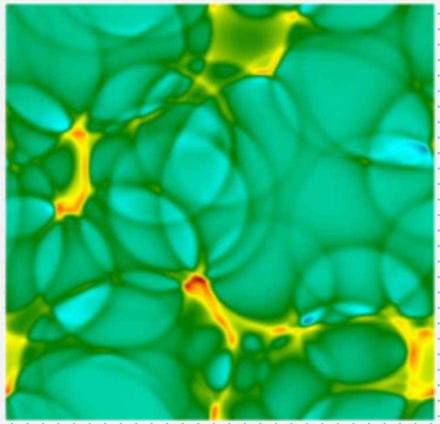


Athron, Balazs, Fowlie, Morris, White, JHEP [2403.03769]



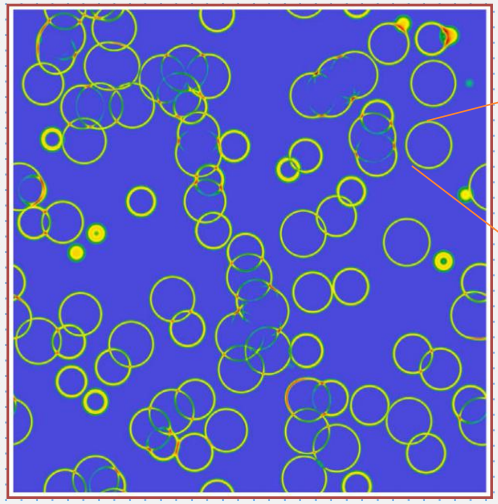
Lewicki, Merchand, Sagunski, Schicho, Schmitt, PRD [2403.03769]

The Picture

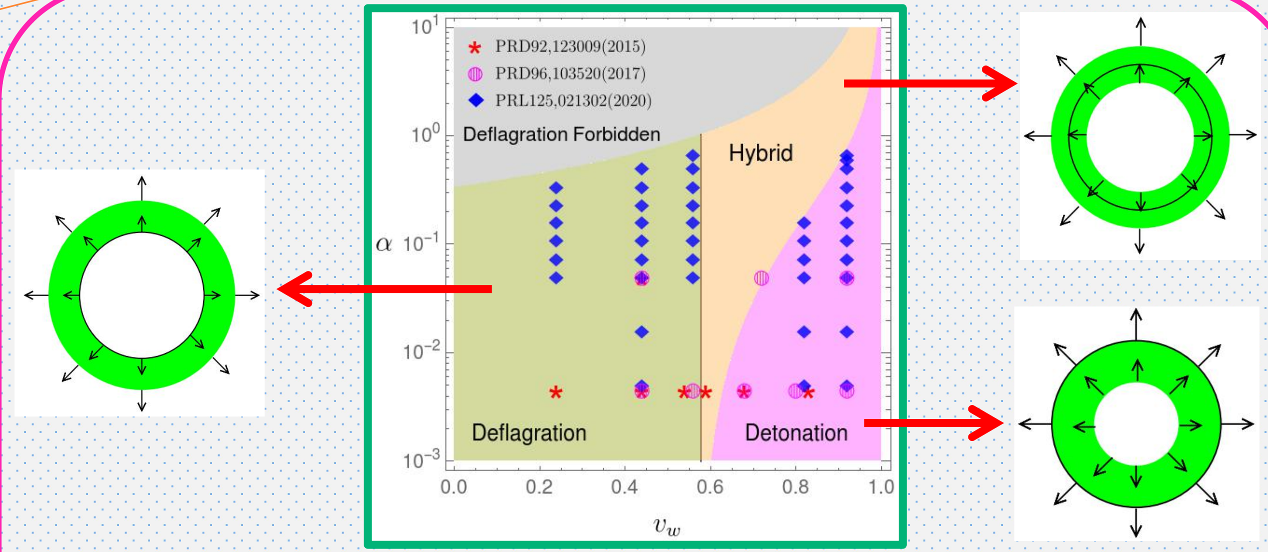


Precise calculation of PT parameters:

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



Hindmarsh et al, 2015



Espinosa,Konstandin,No,Servant JCAP [1004.4187]

New phenomena?

Sound Waves

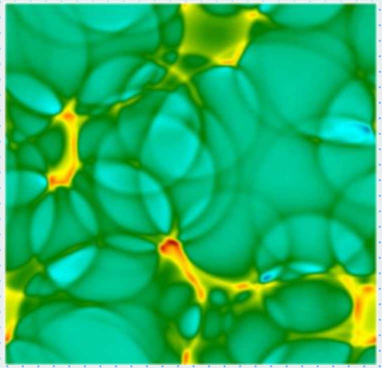
Analytical Modelling

- 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, PRD [2308.12943]
Sharma, Dahl, Brandenburg, Hindmarsh [2308.12916]

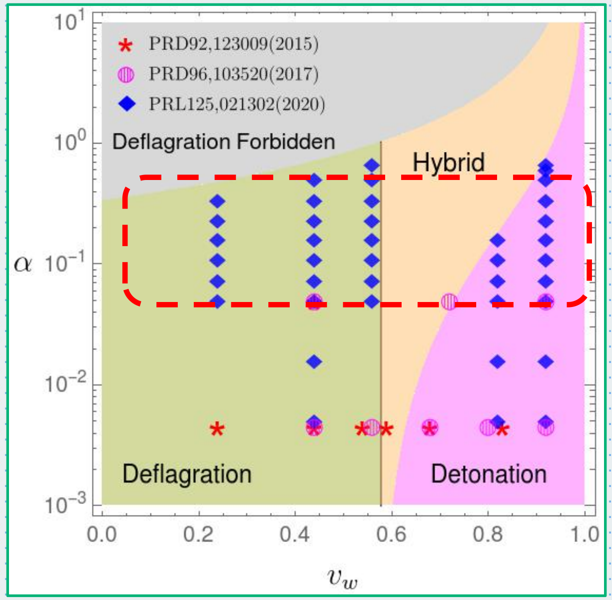
$$v^i_{\mathbf{q}} = \sum_{n=1}^{N_b} v^{i(n)}_{\mathbf{q}}$$

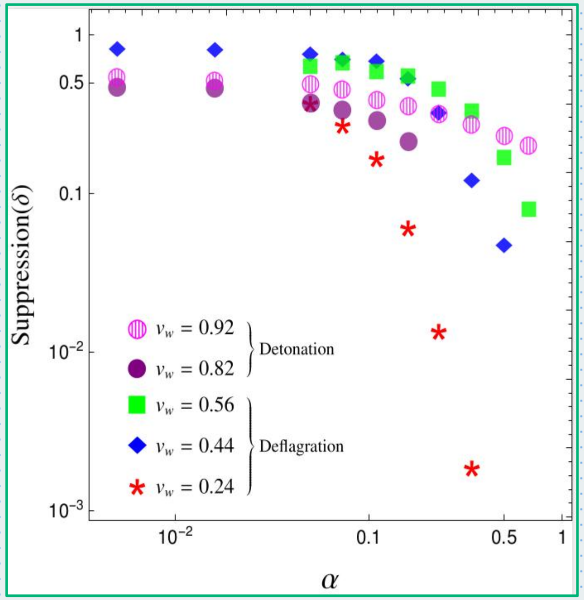


Numerical Simulation

- 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]

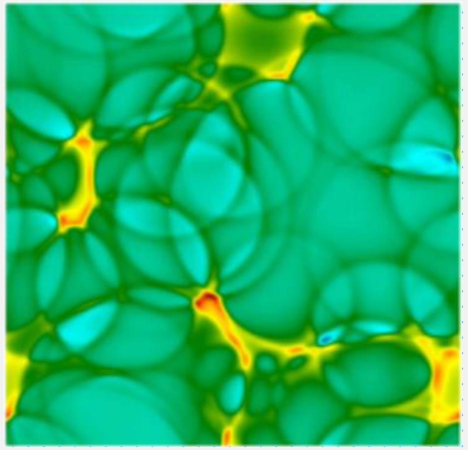
Hybrid approach: Jinno, Konstandin, Rubira, JCAP [2010.00971]

Sound Waves

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

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

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



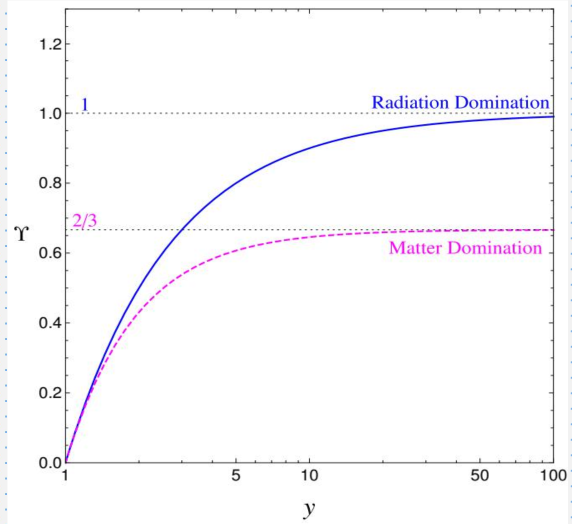
$$S_{\rm sw}(f) = \left(\frac{f}{f_{\rm sw}}\right)^3\left[\frac{7}{4+3(f/f_{\rm sw})^2}\right]^{7/2} \qquad f_* = \frac{2\beta}{\sqrt{3}v_w} \approx \frac{3.4}{R_*}$$

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

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: the Upsilon factor

Why an overall factor (largely f-independent)?

- Gaussian
- Stationary
- Autocorrelation time much smaller than Hubble time (|y-| << y+)

$$h_{ij}(\tilde{y}, \mathbf{q}) = \int_{\tilde{y}_s}^{\tilde{y}} d\tilde{y}' G(\tilde{y}, \tilde{y}') \frac{16\pi G a(\tilde{y}')^2 \pi_{ij}^T(\tilde{y}', \mathbf{q})}{q^2}$$

correlator

$$\mathcal{P}_{\rm GW}(y, kR_{*c}) = \frac{[16\pi G\,(\bar{\bar{\epsilon}} + \bar{\bar{p}})\,\bar{U}_f^2]^2}{24\pi^2 H^2 H_s^2} \frac{1}{y^4} (kR_{*c})^3 \times \int dy_- \tilde{\Pi}^2\left(kR_{*c}, \beta_c |\eta_1 - \eta_2|\right) \left[\int dy_+ \frac{\mathcal{G}_2(\tilde{y}, \tilde{y}_1, \tilde{y}_2)}{\tilde{\tilde{k}}^2} \left\{ \begin{matrix} y_1^{-2} y_2^{-2} \\ y_1^{-3/2} y_2^{-3/2} \end{matrix} \right\}\right]$$

factorization

$$\left[\int dy_+ \cdots\right] = \frac{1}{2} \Upsilon(y) \cos\left(\tilde{\tilde{k}} y_-\right)$$

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

y: a/a* (a: scale factor)

radiation domination:
y- = y1-y2
y+=(y1+y2)/2

Sound Waves: the Upsilon factor

A generic formula to describe a wide class of scenarios:

- ❑ Expansion dominated by radiation

$$\Upsilon_{\rm RD} = 1 - \frac{1}{y}$$

- ❑ Expansion dominated by matter

$$\Upsilon_{\rm MD} = \frac{2}{3}\left(1 - \frac{1}{y^{3/2}}\right)$$

- ❑ Generic equation of state

$$\rho \propto a^{-3(1+w)}$$

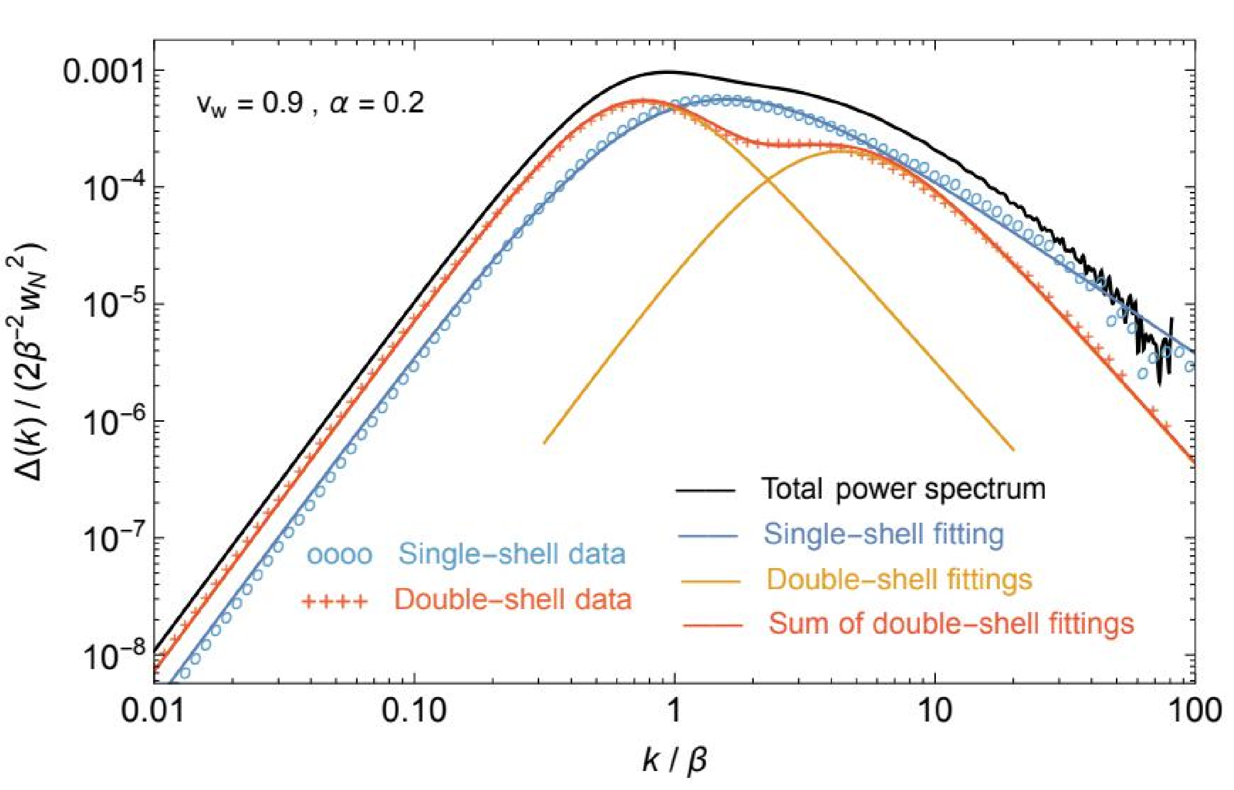
$$\Upsilon = \frac{2[1-y^{3(w-1)/2}]}{3(1-w)}$$

HG, Jiahang Hu, Yang Xiao, Jin Min Yang,Yang Zhang [2410.23666]

A universal factor in all similar stochastic sources.

Sound Waves: Forced Collisions

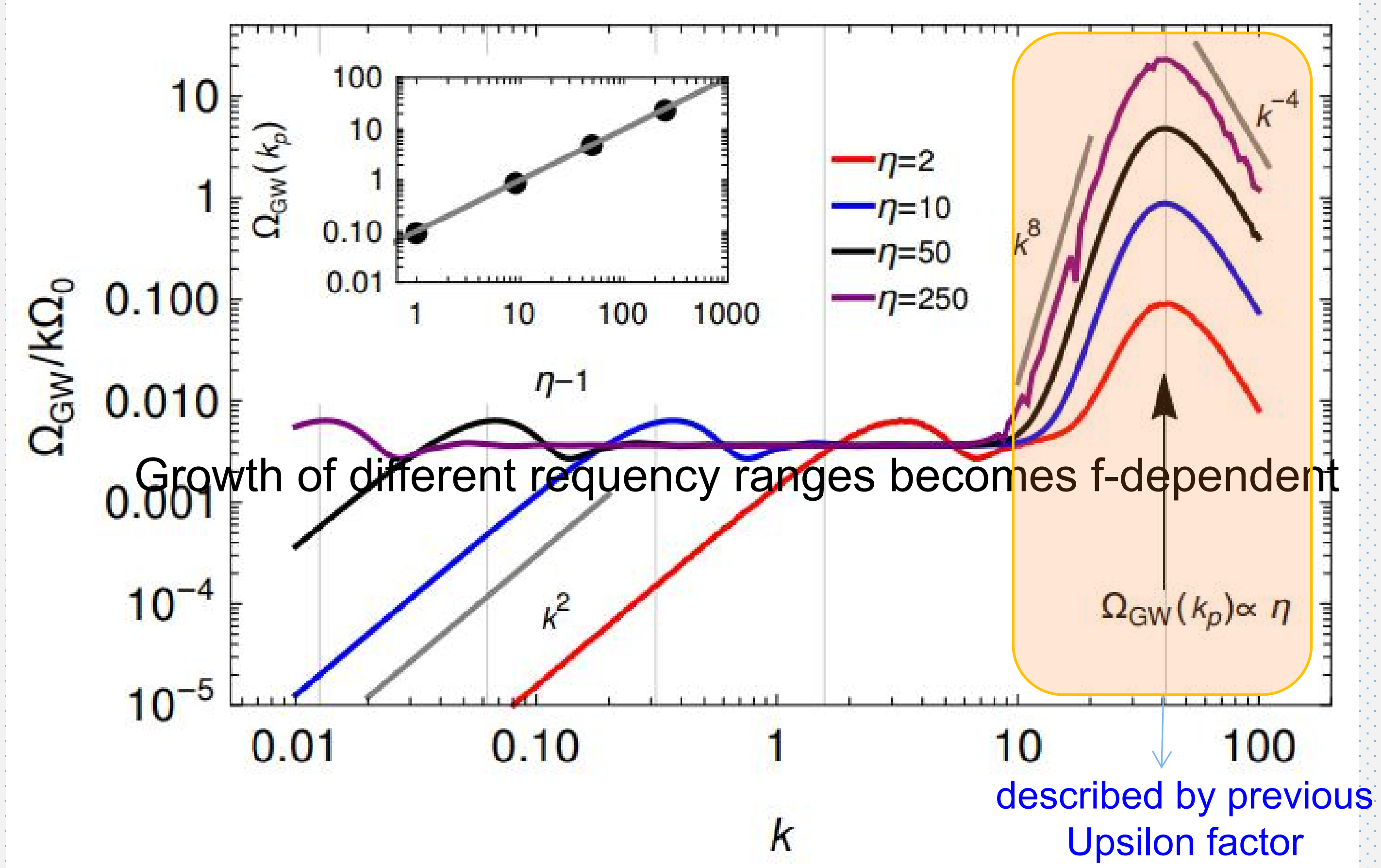
Cai, Wang, Yuwen, PRD Letter [2305.00074]



$$\left.\frac{\mathrm{d}\Omega_{\mathrm{GW}}}{\mathrm{d}\ln k}\right|_{\mathrm{sw}} = \left.\frac{\mathrm{d}\Omega_{\mathrm{GW}}}{\mathrm{d}\ln k}\right|_{\mathrm{sw}}^{\mathrm{forced}} + \left.\frac{\mathrm{d}\Omega_{\mathrm{GW}}}{\mathrm{d}\ln k}\right|_{\mathrm{sw}}^{\mathrm{free}}.$$

Sound Waves: Generalized Upsilon Factor?

- New slopes found for low frequency ranges (k^3 -> k -> k^9)
- Growth rate becomes f-dependent



Pol, Procacci, Caprini, PRD [2308.12943]
Sharma, Dahl, Brandenburg, Hindmarsh [2308.12916]

Dissipative Effects

GW depends on (large) bulk velocity of the system

$$h \sim 10^{-22} \frac{M/M_{\odot}}{r/100\text{Mpc}} \left(\frac{v}{c}\right)^2$$

Dissipative effects dissipate away the bulk kinetic energy (leaves imprint)

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v}\right) = -\nabla p + \mu\nabla^2\mathbf{v} + (\zeta + \frac{1}{3}\mu)\nabla(\nabla\cdot\mathbf{v})$$

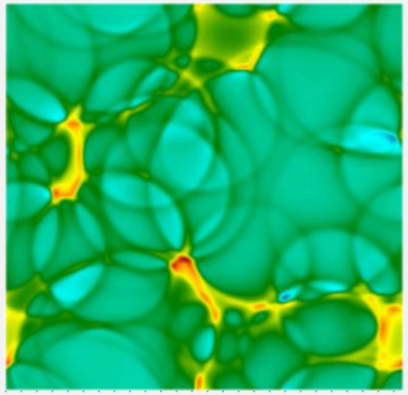
Navier–Stokes equations

So far, it has largely been neglected, especially in connection with new physics.

Effects of Dissipation

- Disturbed fluid comes into rest eventually

$$v^i(\eta, \mathbf{x}) = \int \frac{d^3q}{(2\pi)^3} \left[v^i_{\mathbf{q}} e^{-i\omega\eta + i\mathbf{q}\cdot\mathbf{x}} + c.c. \right]$$



$$v^i_{\mathbf{q}}(\eta) \propto \exp\left[-\int \Gamma(\mu, \zeta, \xi) d\eta \right]$$

$$\Gamma \propto q^2$$

shear viscosity

bulk viscosity

$$\Delta T^{ij} = -\mu\left(\frac{\partial U_i}{\partial x^j} + \frac{\partial U_j}{\partial x^i} - \frac{2}{3}\delta_{ij}\nabla\cdot\mathbf{U}\right) - \zeta\delta_{ij}\nabla\cdot\mathbf{U},$$

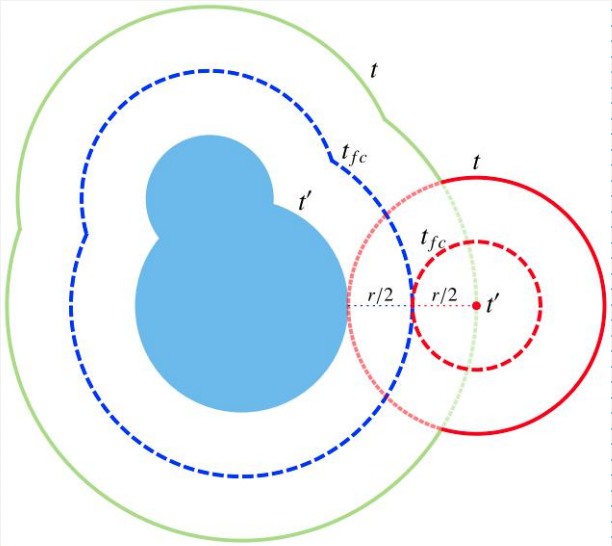
$$\Delta T^{i0} = -\chi\left(\frac{\partial T}{\partial x^i} + T\dot{U}_i\right). \quad (1)$$

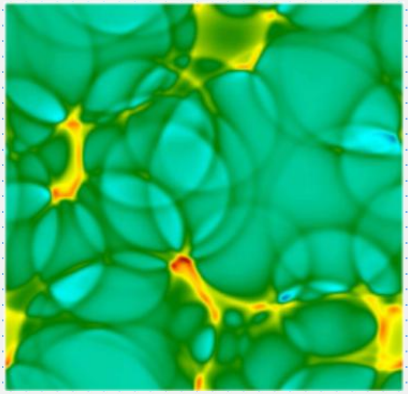
thermal conduction

Weinberg, ApJ, 1971

Euler equation -> Navier–Stokes equations

Effects of Dissipation with the Sound Shell Model





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

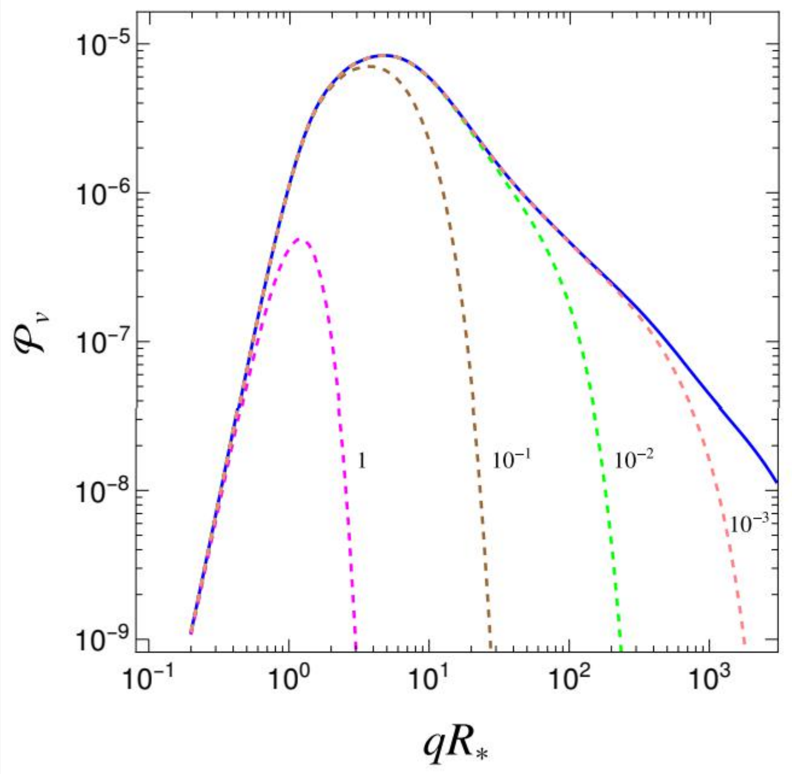
$$v^i_{\mathbf{q}}(\eta) = \sum_{n=1}^{N_b} v^{i(n)}_{\mathbf{q}} \exp\left[-\int_{\eta_d^{(n)}}^{\eta} \Gamma d\bar{\eta}\right] \theta(\eta - \eta_d^{(n)})$$

bubble destruction time

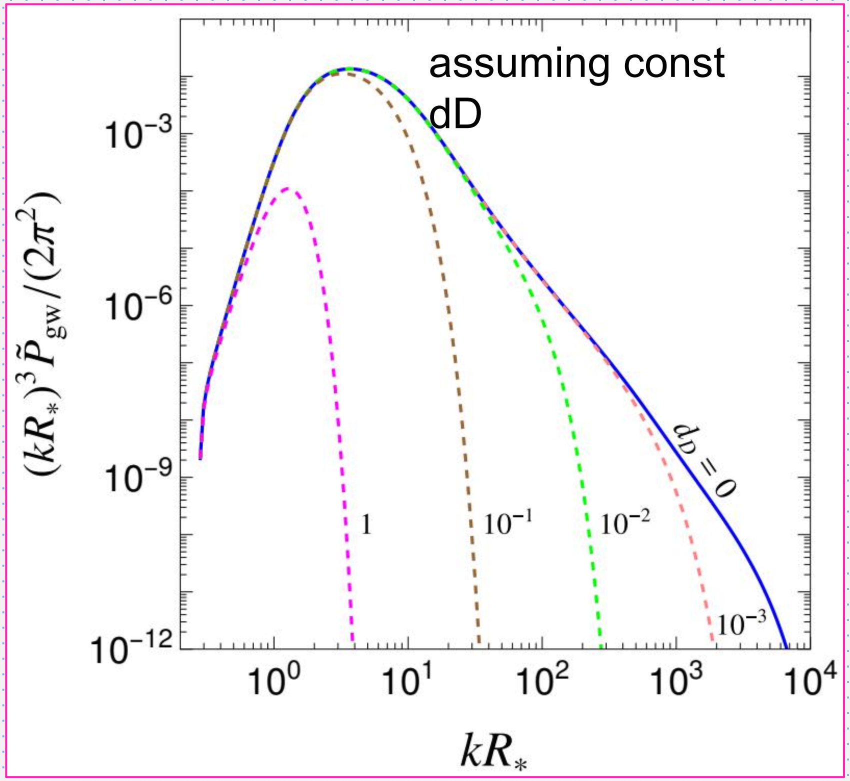
Effects of Dissipation: Damping of GW Spectrum

- Peak frequency in strongly dissipative systems
- Upsilon factor might not appear

damped velocity power spectrum



damped GW spectrum

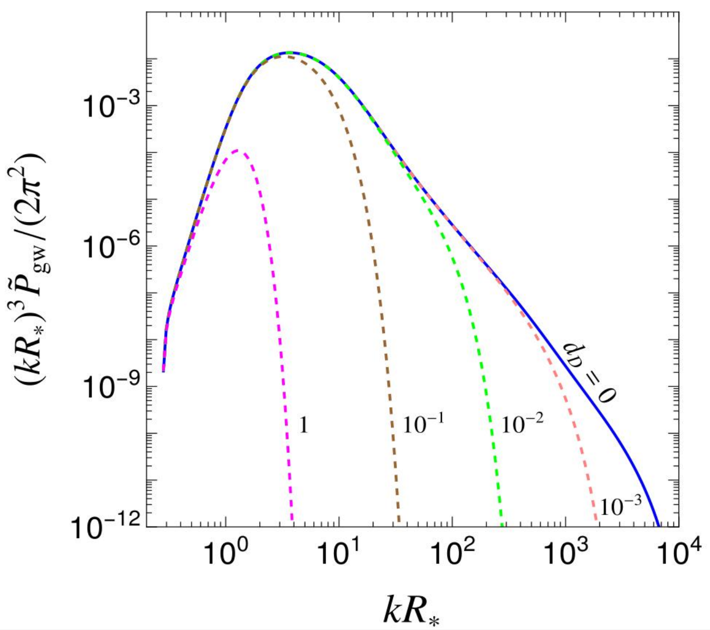


HG [2310.10927]

Dissipative Effects as New Observables

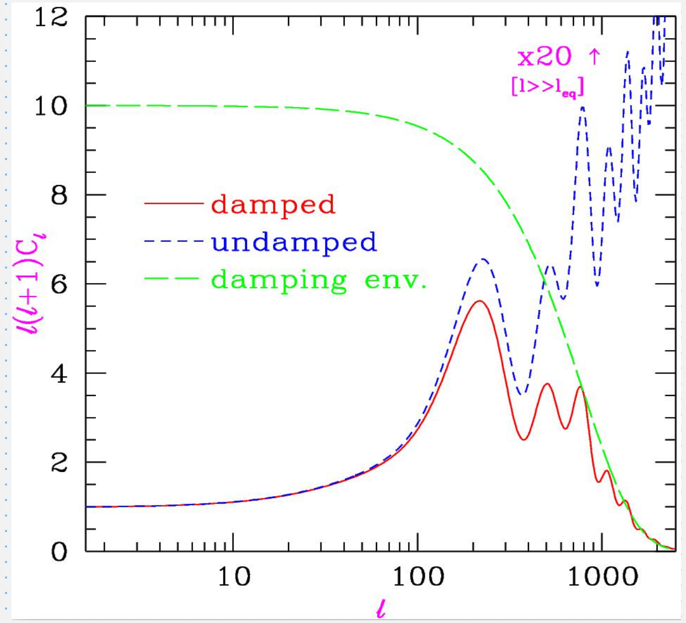
- Probe very weak interactions (analog: Silk damping)
- Break parameter degeneracy
- Can be searched for at LIGO, PTA, LISA/Taiji/Tianqin ...

damping of GW



HG [2310.10927]

Silk damping of CMB Anisotropy



Hu,White, ApJ [9609079]

Dissipative Effects: Lifetime of Sound Waves

- Expansion of the universe provides an effective lifetime
- Dissipation effects, when strong, provide a shorter effective lifetime
- Onset of MHD turbulence serves as a cut-off (dissipation causes changes)

Realistic cases: intertwining of these effects (makes GW spectrum model dependent)

Model dependent spectrum carries information about each model (break parameter degeneracy)

Summary

- Phase transition is an important target for all GW experiments
- Precision studies now become high priority
- Progress in GW spectrum from sound waves (slope, growth rate)
- Dissipative effects can serve as new observables

Thanks!