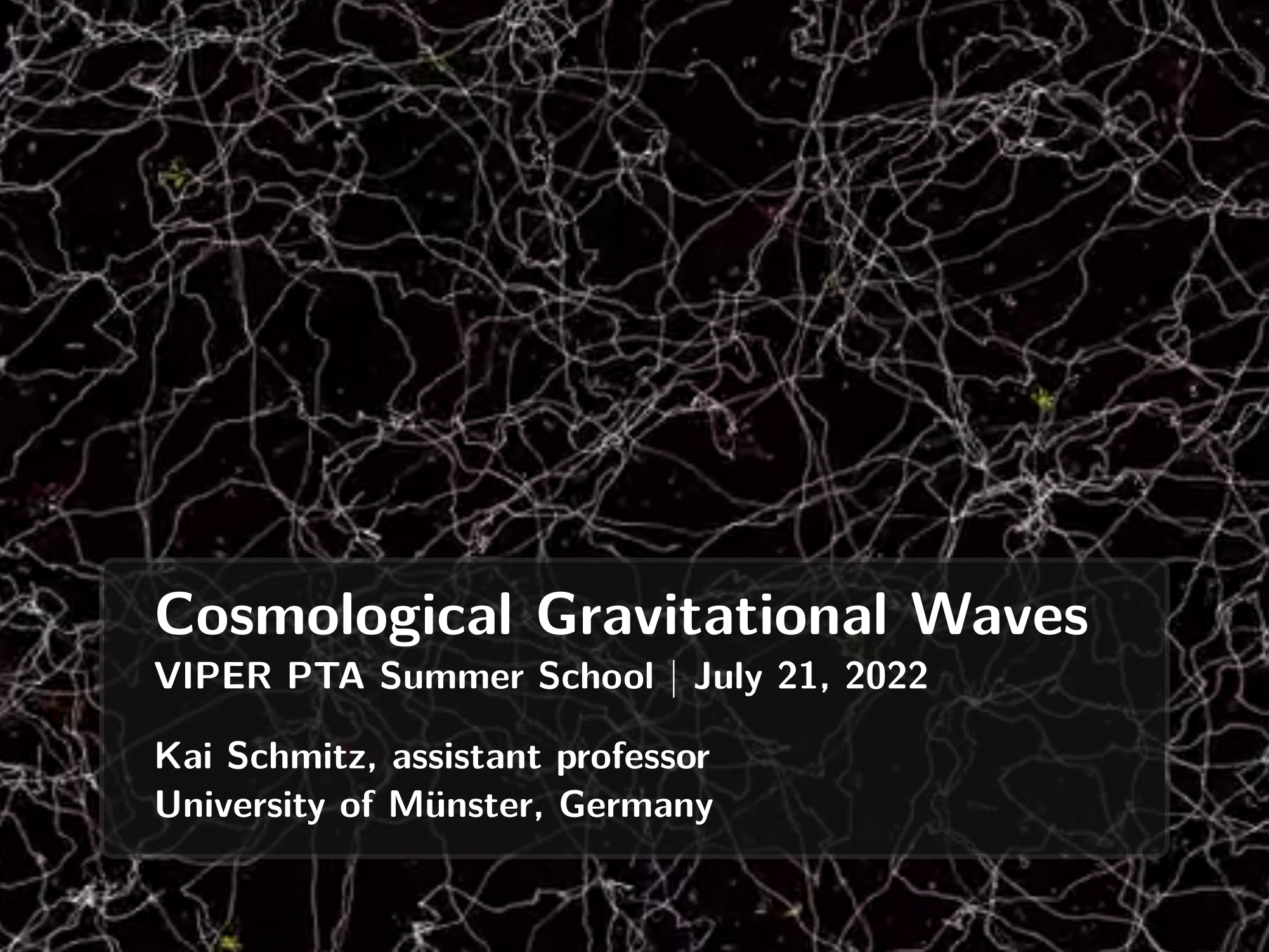

Cosmological Gravitational Waves

VIPER PTA Summer School | July 21, 2022

Kai Schmitz, assistant professor
University of Münster, Germany

First glimpse of a SGWB signal?

Strong evidence for a new stochastic *red process* in latest pulsar timing data

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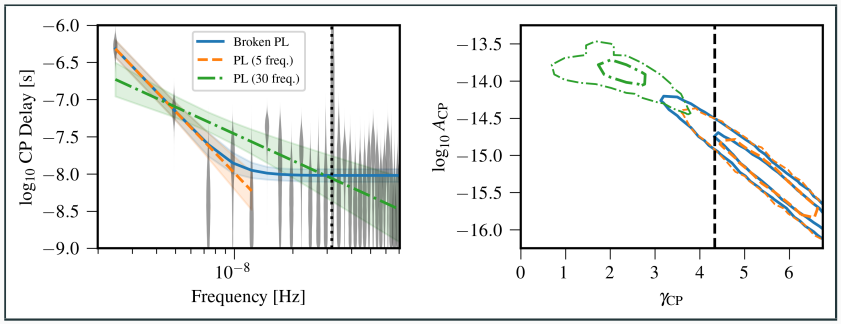

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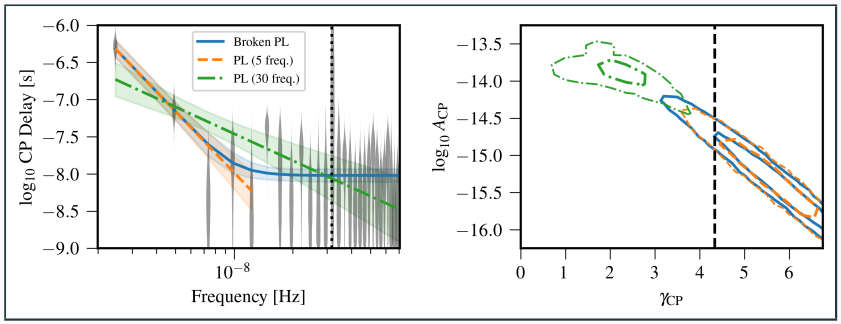
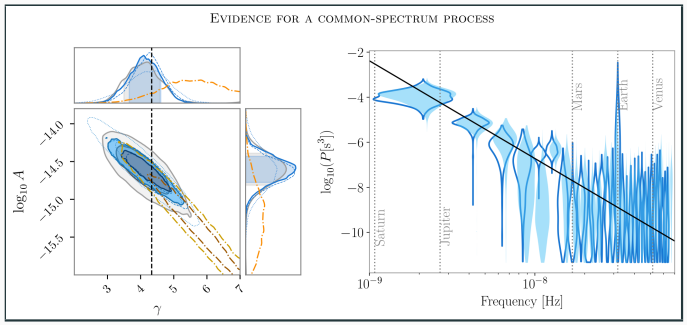


PPTA [2107.12112]



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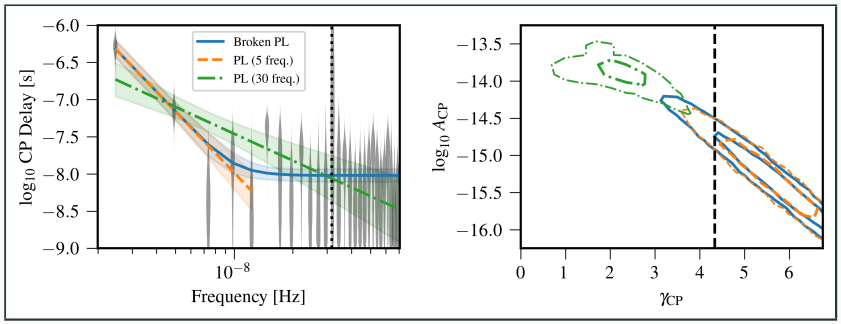

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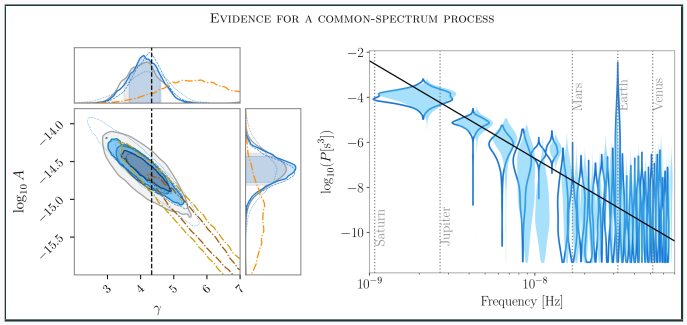
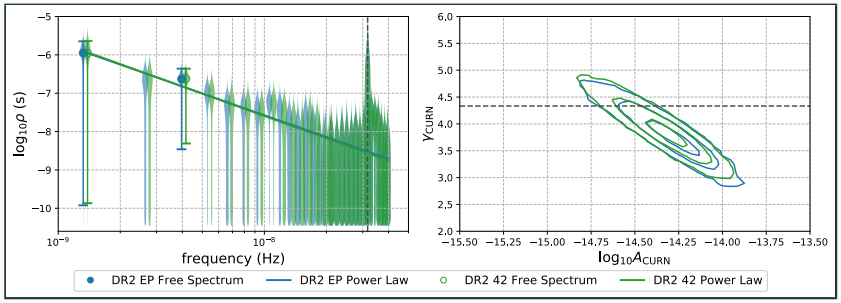


EPTA [2110.13184]



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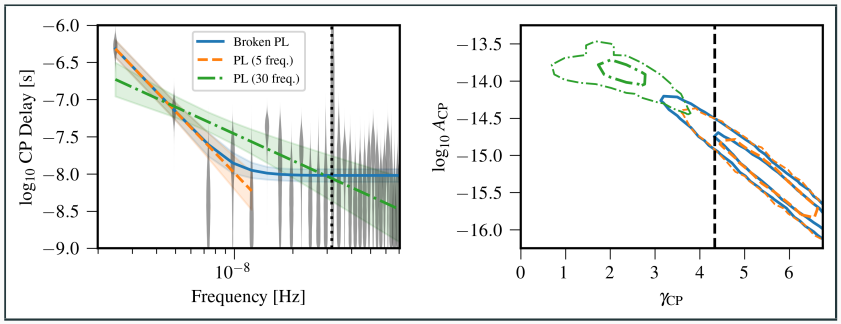

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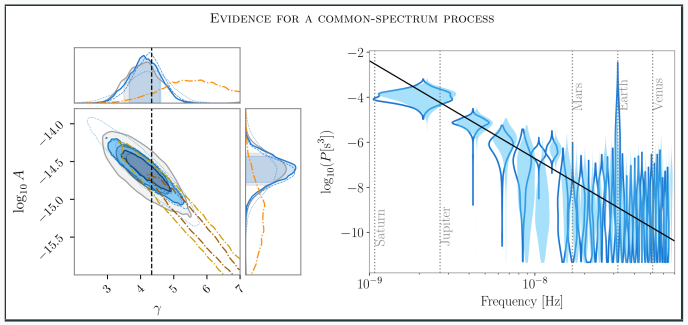

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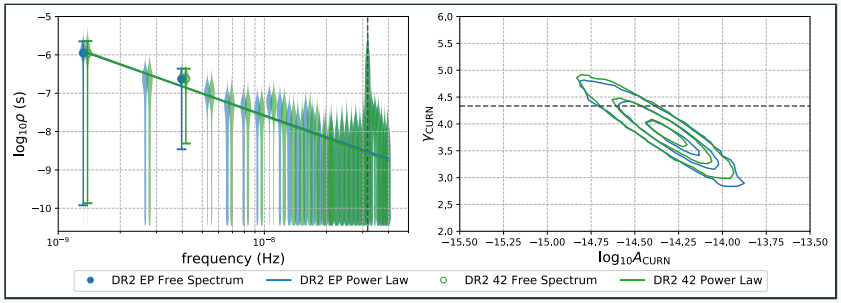
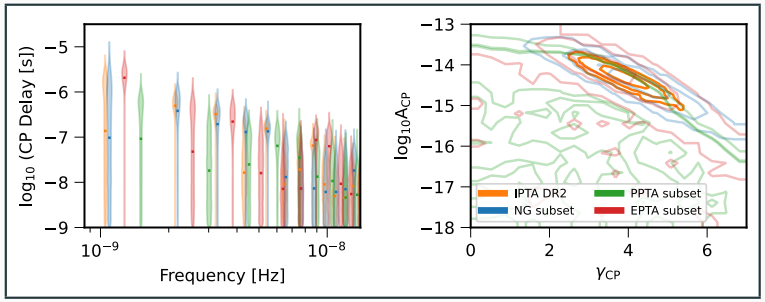


IPTA [2201.03980]



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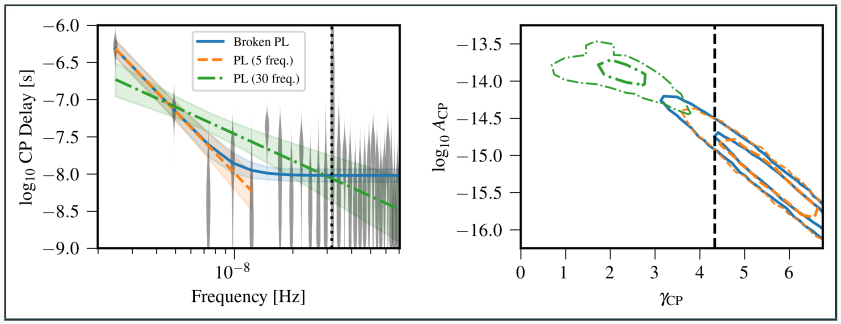

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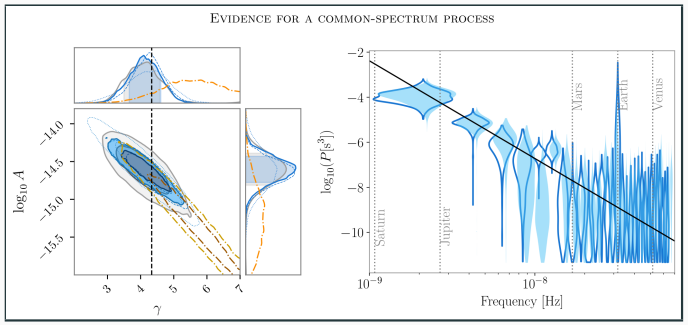

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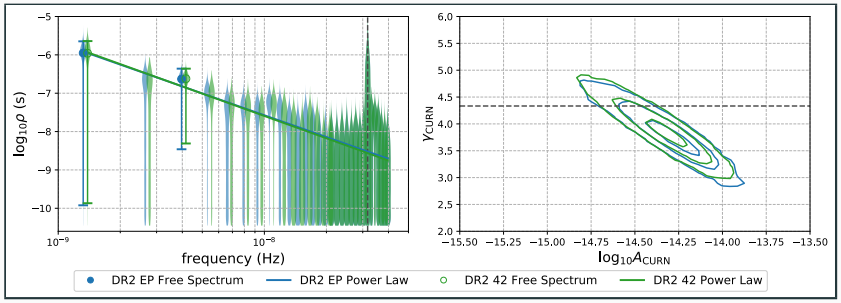

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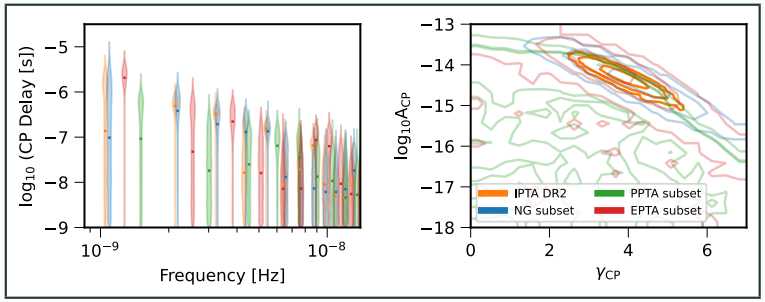
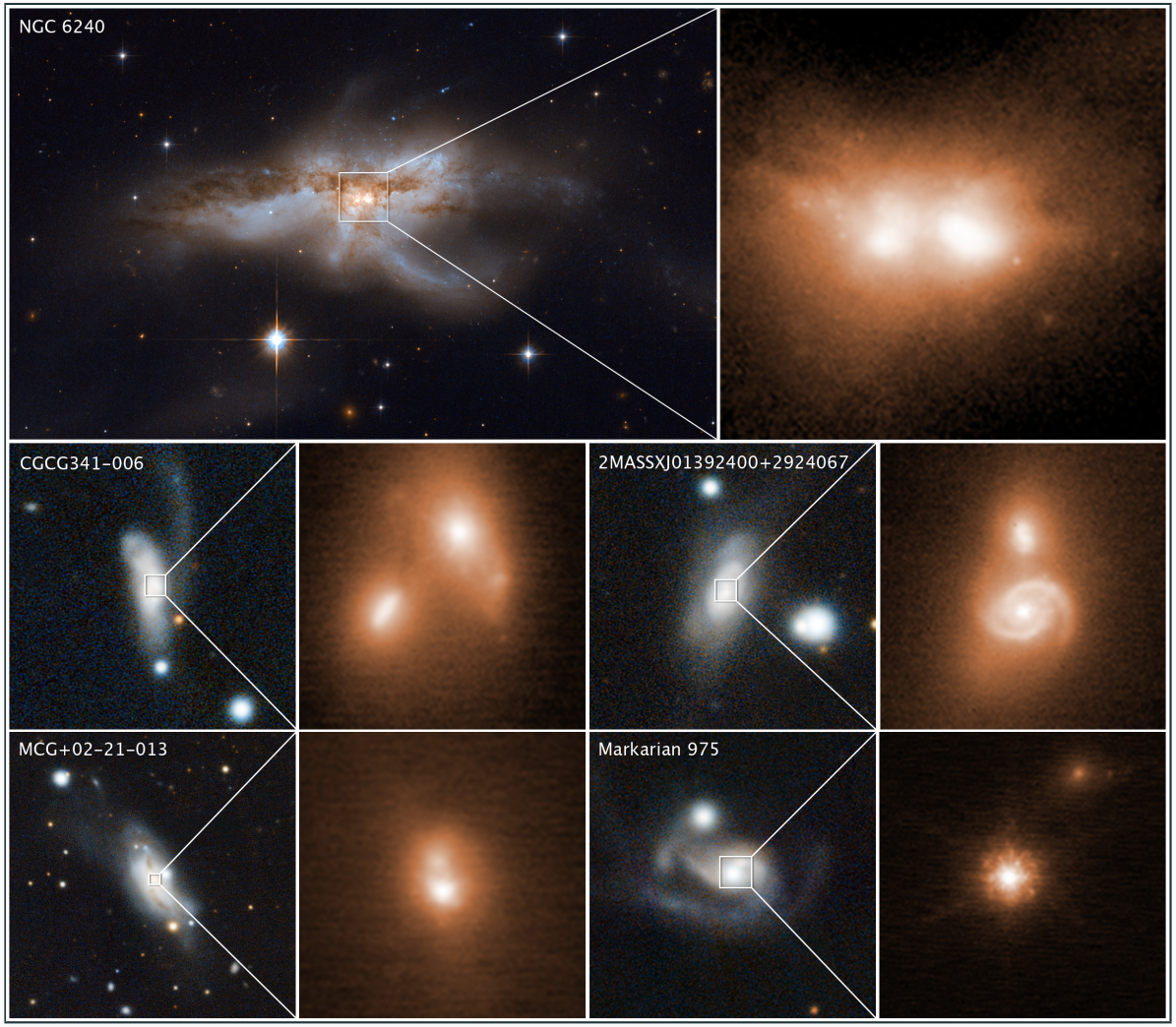


Not yet a detection, but consistent with interpretation in terms of GWs!

Astrophysical interpretation

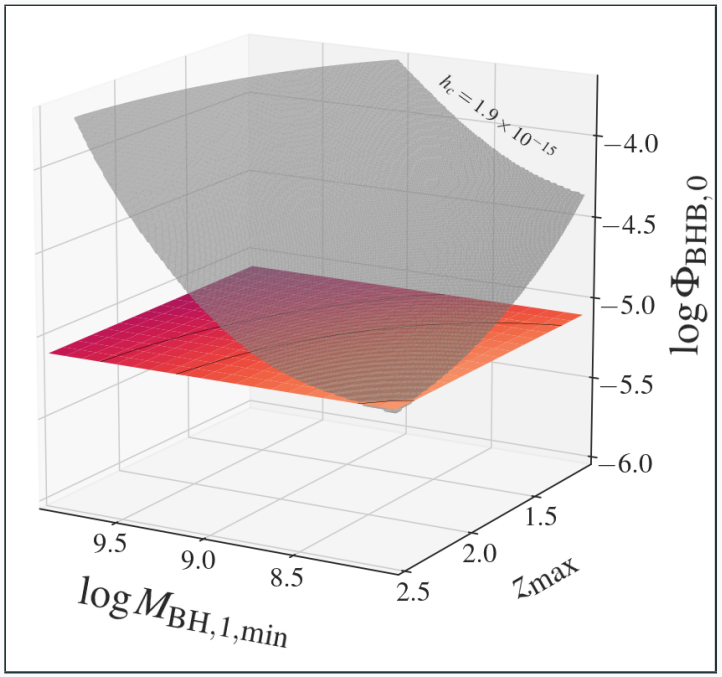
[hubblesite.org]



Mergers of supermassive black-hole binaries (SMBHBs) after galaxy mergers

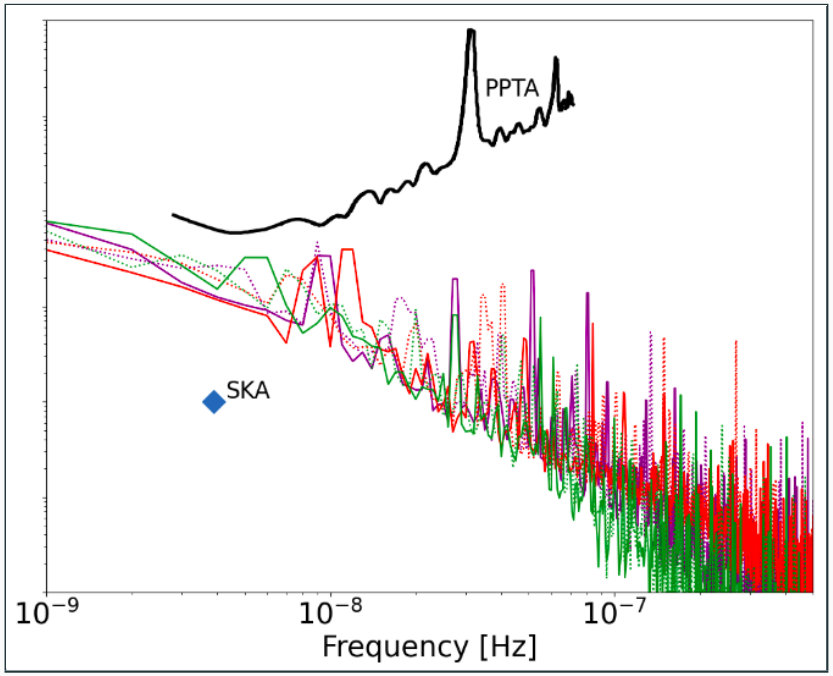
SMBHB models and simulations

SMBHB population model based on empirical quasar population



[Casey-Clyde et al.: 2107.11390]

Simulation based on SHARK galaxy evolution model (delay: 1 Gyr)



[Curyło, Bulik: 2108.11232]

- Left: $\Phi_{\mathrm{BHB},0}$ is $\mathcal{O}(10)$ times larger than previous estimates, e.g., 1708.03491
- Right: Time delays of around 100 Myr to 1 Gyr not enough to explain amplitude

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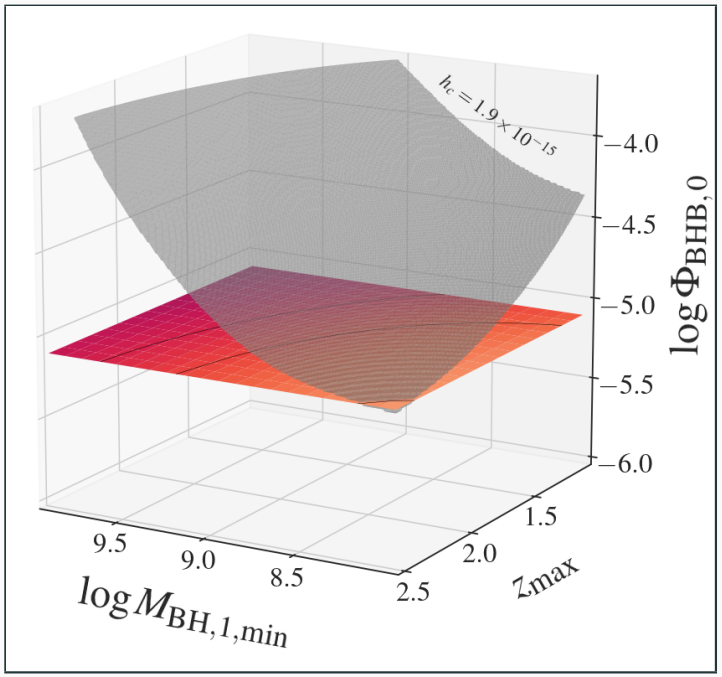

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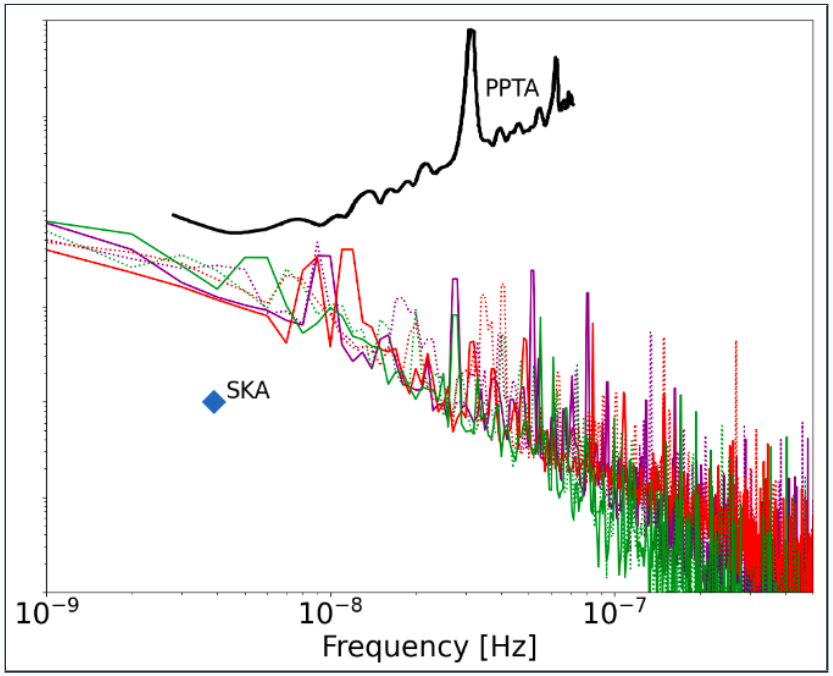

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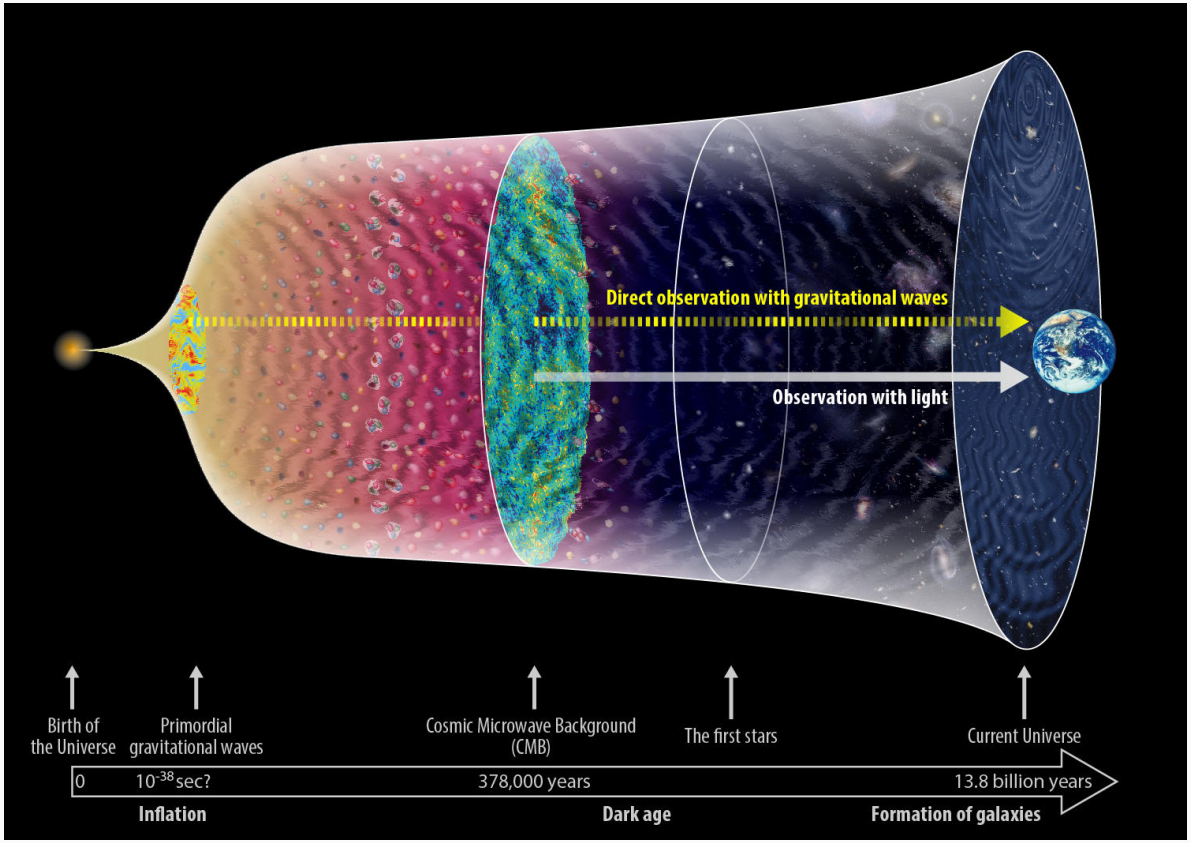
This might tell us something about our models and simulations ... or about the signal

Cosmological gravitational waves

[National Astronomical Observatory of Japan, gwpo.nao.ac.jp]

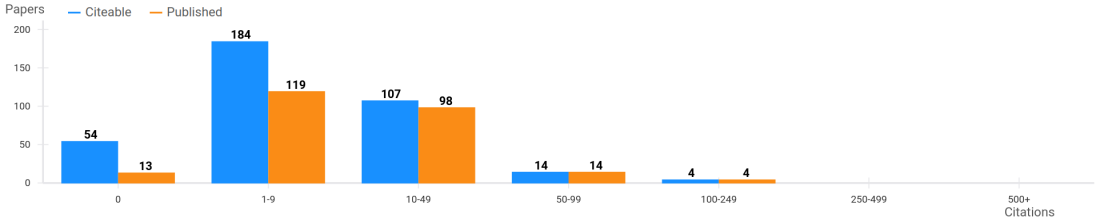


Viable possibility: Signal receives contributions from SMBHBs + X (or X only?)
$\rightarrow$ Probe cosmology of the early Universe and particle physics at high energies

Cosmic strings [2009.06555, 2009.06607, 2009.10649, 2009.13452, 2102.08923] **Primordial black holes** [2009.07832, 2009.08268, 2009.11853, 2010.03976, 2101.11244] **Phase transitions** [2009.09754, 2009.10327, 2009.14174, 2009.14663, 2101.08012] **Audible axions and axion strings** [2009.11875, 2012.06882] **Inflation** [2009.13432, 2010.05071, 2011.03323] **Domain walls** [2009.13893, 2012.14071]

Overwhelming reaction in the particle physics community

Papers	363	248
Citations	4,001	3,702
h-index	30	30
Citations/paper (avg)	11	14.9



NANOGrav Data Hints at Primordial Black Holes as Dark Matter #1

V. De Luca (Geneva U., Dept. Theor. Phys. and Geneva U., CAP), G. Franciolini (Geneva U., Dept. Theor. Phys. and Geneva U., CAP), A. Riotto (Geneva U., Dept. Theor. Phys. and INFN, Rome and Geneva U., CAP) (Sep 17, 2020)

Published in: *Phys.Rev.Lett.* 126 (2021) 4, 041303 • e-Print: 2009.08268 [astro-ph.CO]

pdf links DOI cite 136 citations

Has NANOGrav found first evidence for cosmic strings? #2

Simone Blasi (Heidelberg, Max Planck Inst.), Vedran Brdar (Heidelberg, Max Planck Inst.), Kai Schmitz (CERN) (Sep 14, 2020)

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Solar-Mass Primordial Black Holes Explain NANOGrav Hint of Gravitational Waves #4

Kazunori Kohri (INS, Tokyo and Tsukuba, Graduate U. Adv. Studies and Tokyo U., IPMU), Takahiro Terada (IBS, Daejeon, CTPU) (Oct 2, 2020)

Published in: *Phys.Lett.B* 813 (2021) 136040 • e-Print: 2009.11853 [astro-ph.CO]

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Gravitational Waves and Dark Radiation from Dark Phase Transition: Connecting NANOGrav Pulsar Timing Data and Hubble Tension #5

Yuichiro Nakai (Tsung-Dao Lee Inst., Shanghai and Shanghai Jiaotong U.), Motoo Suzuki (Tsung-Dao Lee Inst., Shanghai and Shanghai Jiaotong U.), Fuminobu Takahashi (Tohoku U. and Tokyo U., IPMU), Masaki Yamada (Tohoku U.) (Sep 27, 2020)

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NANOGrav 2009.04496: 423 citations and dozens of possible interpretations

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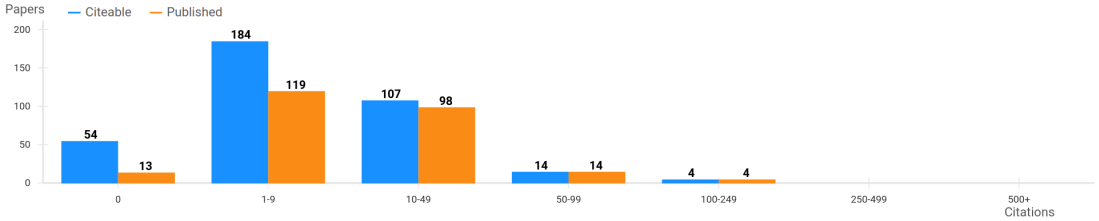

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❶ Primordial black holes ❷ Cosmic strings ❸ Phase transition ❹ Inflation ...

References

Literature

- Book: M. Maggiore, *Gravitational Waves. Vol. 1: Theory and Experiments* Oxford University Press (2007), ISBN-13: 978-0198570745.
- Book: M. Maggiore, *Gravitational Waves. Vol. 2: Astrophysics and Cosmology* Oxford University Press (2018), ISBN-13: 978-0198570899.
- Review: C. Caprini and D. G. Figueroa, *Cosmological Backgrounds of Gravitational Waves*, Class. Quant. Grav. **35** (2018) 163001, [arXiv:1801.04268].

Lecture notes (slides)

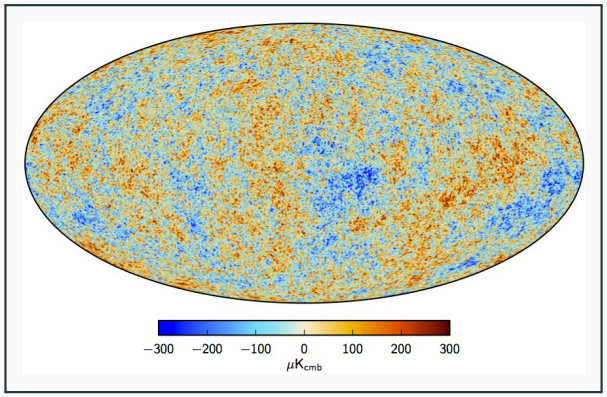
- K. Schmitz, Lectures at Heidelberg Graduate Days 2021 `http://doi.org/10.5281/zenodo.4678780` (881-page PDF file)

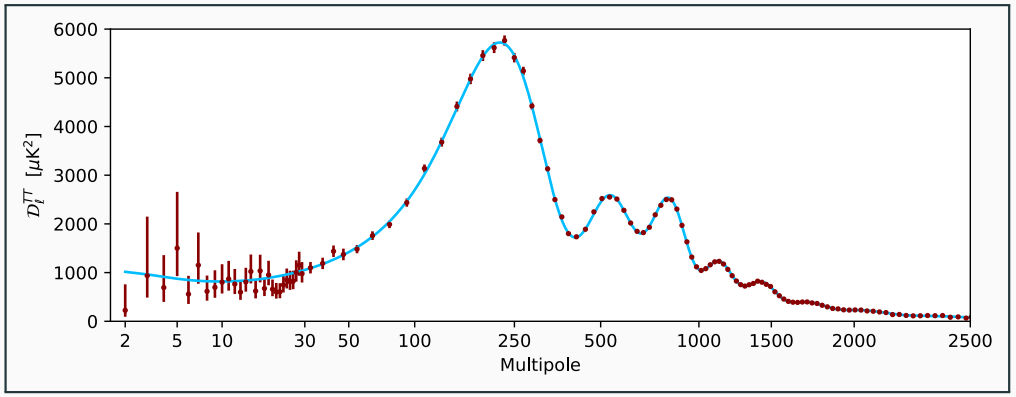
YouTube videos

- K. Schmitz, Lectures at Chung-Ang University, `https://youtu.be/0-tMnRArrZA`, `https://youtu.be/nJ9of9dt_1c`, `https://youtu.be/xFI8PBsAoqY` (10 hours)

Primordial GWs from cosmic inflation

Cosmic inflation





[PLANCK Collaboration 2018]

Inflation: Stage of accelerated expansion in the early universe

- Explains size, homogeneity, and isotropy of our Universe on cosmological scales
- Quantum fluctuations during inflation seed structure formation on galactic scales

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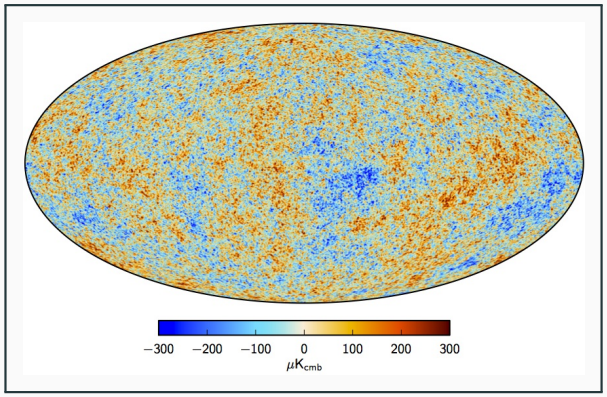

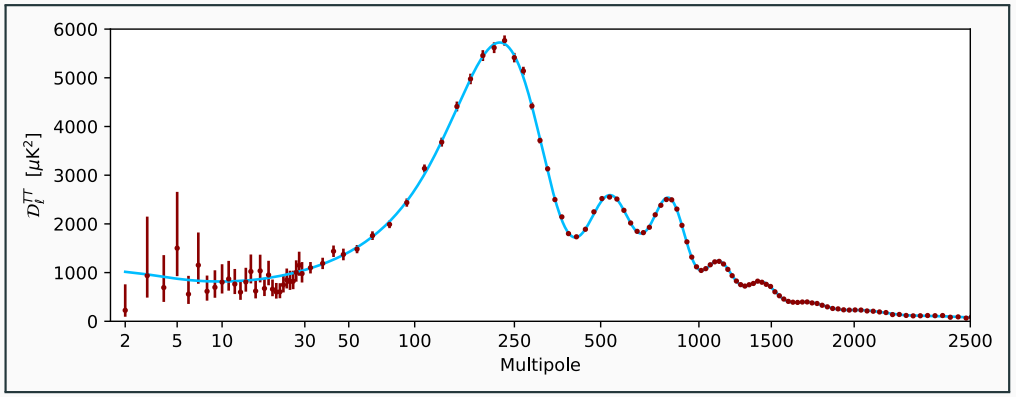

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Microscopic dynamics

- Scalar "inflaton" field ϕ slowly rolls down scalar potential ("slow-roll inflation")
- $V(\phi) \approx \text{const} \approx$ slowly decaying cosmological constant $\rightarrow$ exponential expansion
- Vacuum continuously sources perturbations in the inflaton field and in the metric

[Guth 1981] [Linde 1982] [Albrecht & Steinhardt 1982]

Primordial tensor perturbations

Action for transverse–traceless tensor perturbations from Einstein–Hilbert action

$$S = \frac{m_{\mathrm{Pl}}^2}{2} \int d^4x \sqrt{-g}\, R \qquad \supset \qquad S_h^{(2)} = -\frac{m_{\mathrm{Pl}}^2}{8} \int d\eta\, d^3\boldsymbol{x}\, a^2(\eta)\, \eta^{\mu\nu}\, \partial_\mu h_{ij}\, \partial_\nu h_{ij}$$

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Go to Fourier space; introduce new field variables $v_p(\eta, \boldsymbol{k}) = m_{\mathrm{Pl}}/\sqrt{2}\, a(\eta)\, h_p(\eta, \boldsymbol{k})$:

$$S_h^{(2)} = \frac{1}{2} \sum_{p=+,\times} \int d\eta\, \frac{d^3\boldsymbol{k}}{(2\pi)^3} \left[|v_p'(\eta, \boldsymbol{k})|^2 - \left(k^2 - \frac{a''}{a} \right) |v_p(\eta, \boldsymbol{k})|^2 \right]$$

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$$v_k'' + \left(k^2 - \frac{a''}{a} \right) v_k = 0$$

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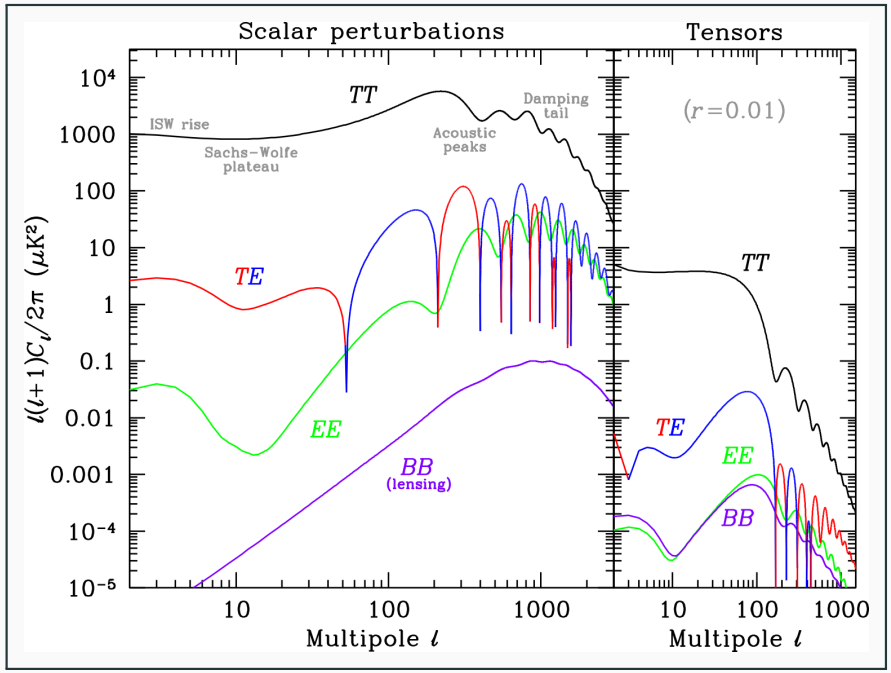
Primordial tensor spectrum

$$\langle 0|\, h_{ij}(\eta, \boldsymbol{k})\, h_{ij}^*(\eta, \ell)\, |0\rangle = \frac{2\pi^2}{k^3}\, \delta^{(3)}(\boldsymbol{k} - \ell)\, \mathcal{P}_h(k)\,, \qquad \boxed{\mathcal{P}_h(k) \approx 2 \left(\frac{H_k}{\pi\, m_{\rm Pl}} \right)^2}$$

CMB observables

[Review of Particle Physics (2020), pdg.lbl.gov]



Primordial scalar + tensor perturbations source temperature + polarization anisotropies

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s-1} \approx \frac{1}{8\,\epsilon}\left(\frac{H_k}{\pi\, m_{\rm Pl}}\right)^2, \qquad \mathcal{P}_h(k) = r\, A_s \left(\frac{k}{k_*}\right)^{n_t} \approx 2\left(\frac{H_k}{\pi\, m_{\rm Pl}}\right)^2$$

with the slow-roll parameter $\epsilon = -\dot{H}/H^2$ measuring the deviation from dS expansion

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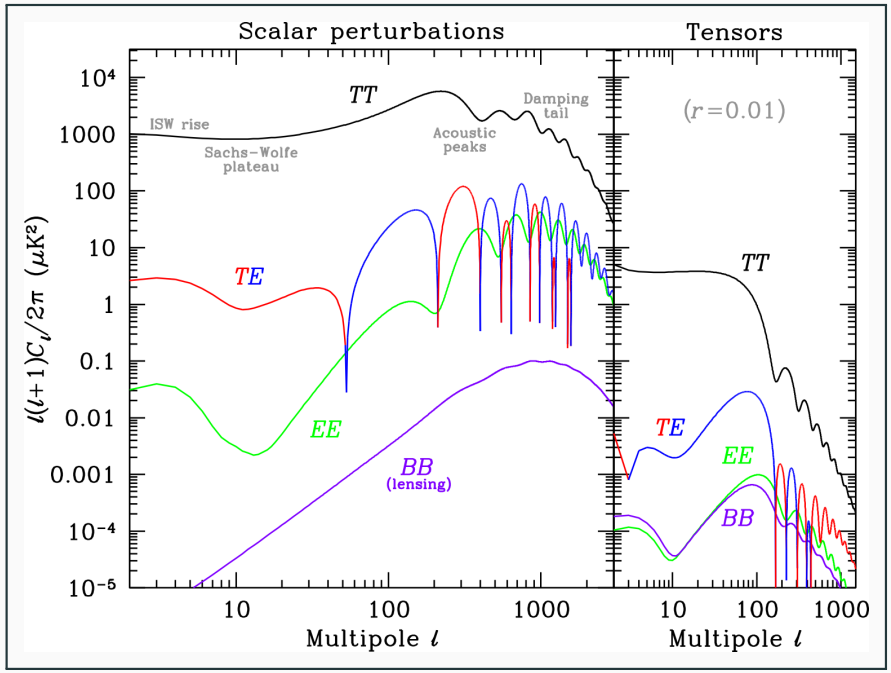

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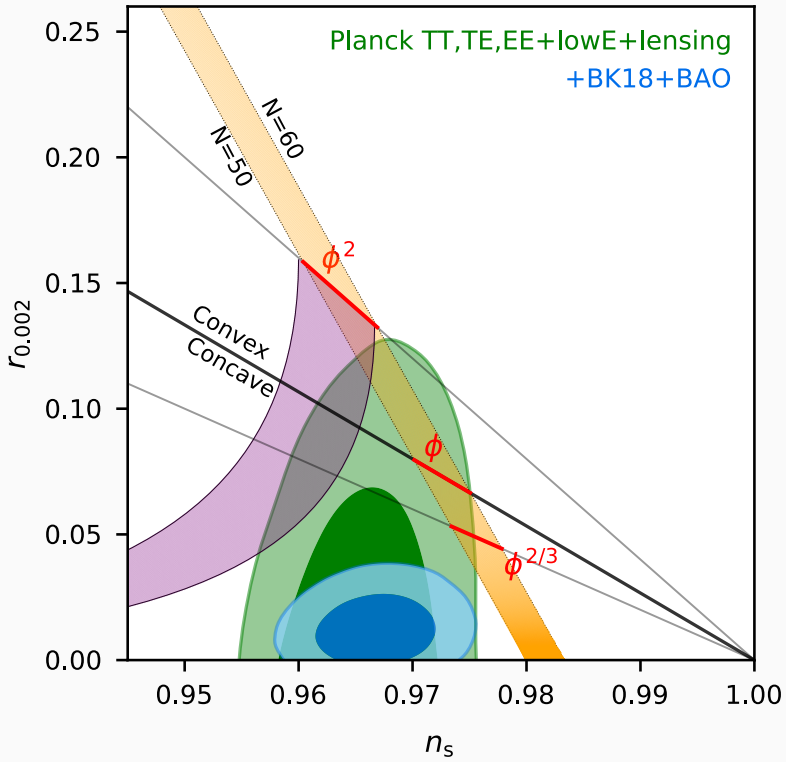
with the slow-roll parameter $\epsilon = -\dot{H}/H^2$ measuring the deviation from dS expansion

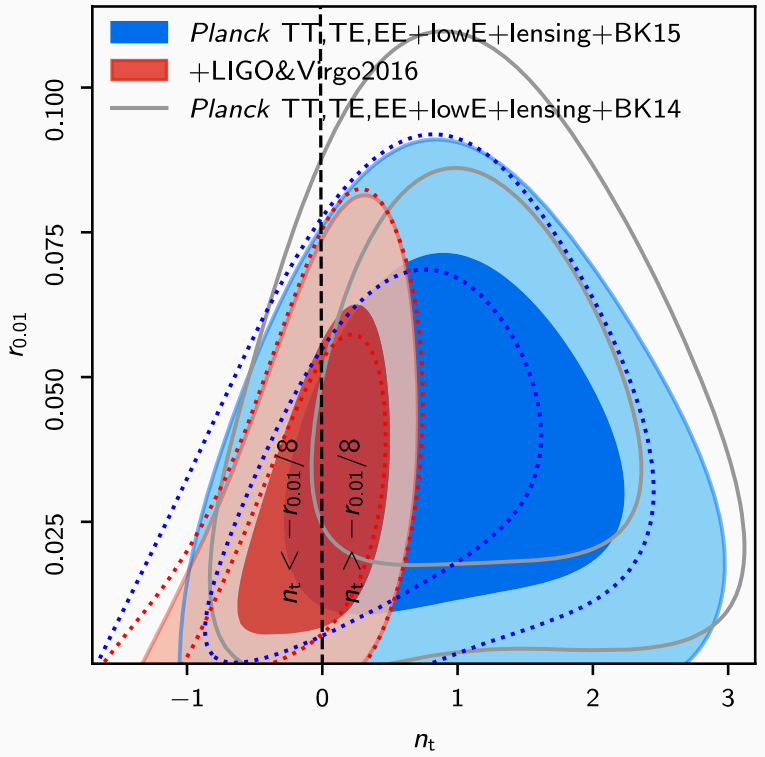
Consistency relation in single-field slow-roll inflation: $\boxed{n_t = \dfrac{d\ln \mathcal{P}_h}{d\ln k} \approx -2\,\epsilon = -\dfrac{r}{8}}$

Observational constraints

Scalar spectral index versus $r_{0.002}$



Tensor spectral index versus $r_{0.01}$



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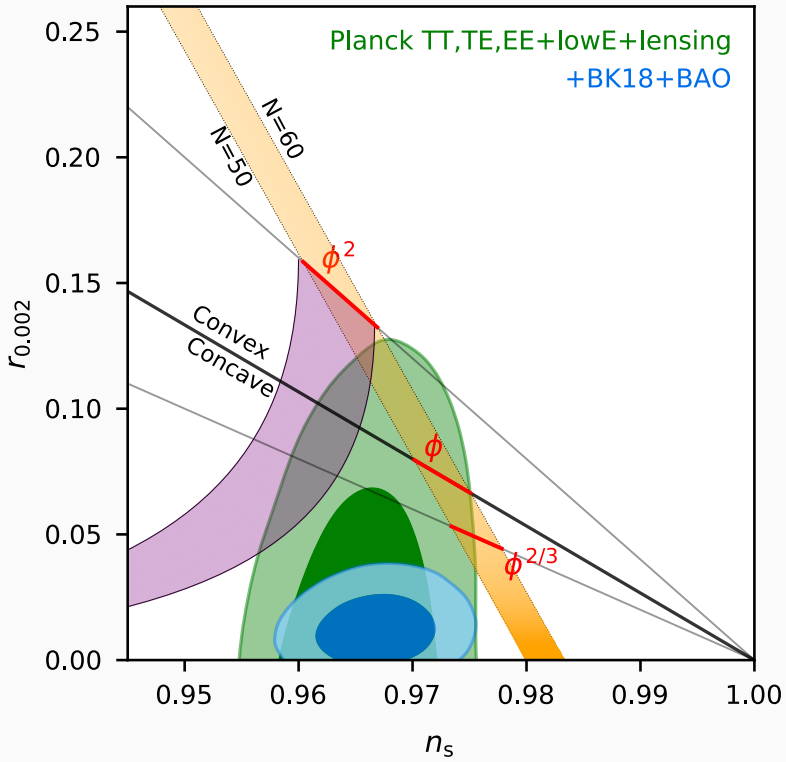

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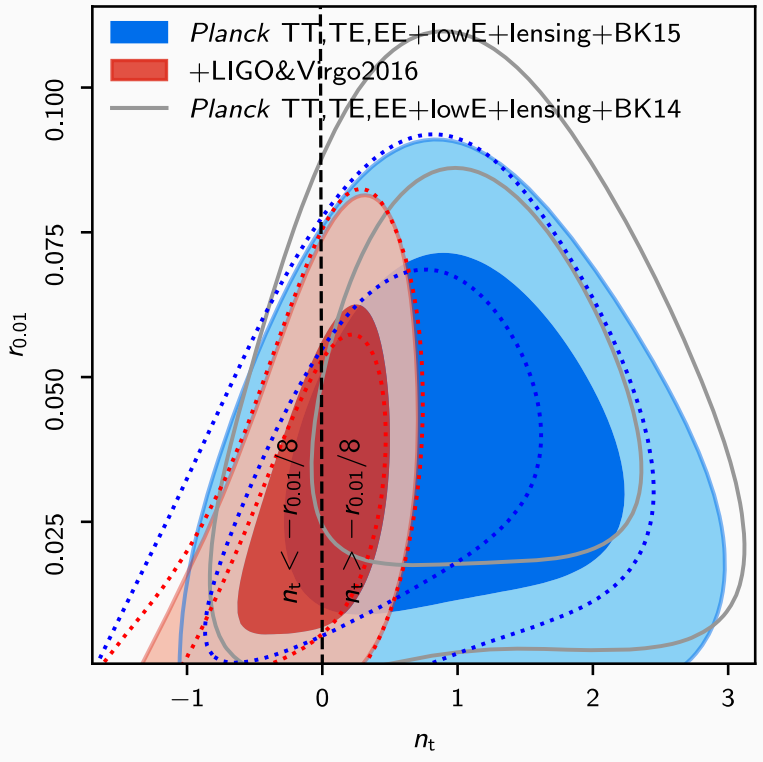

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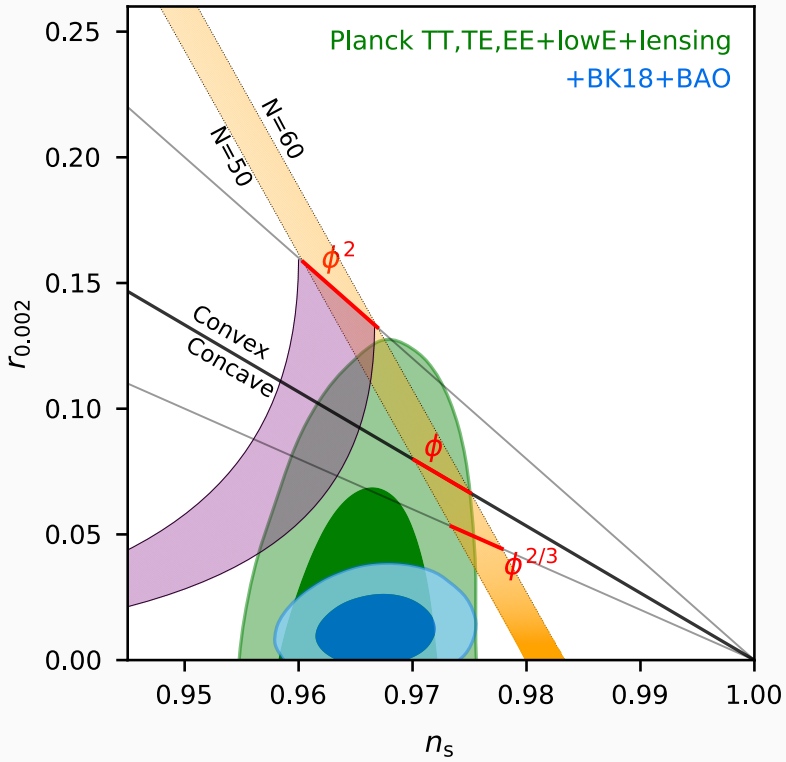

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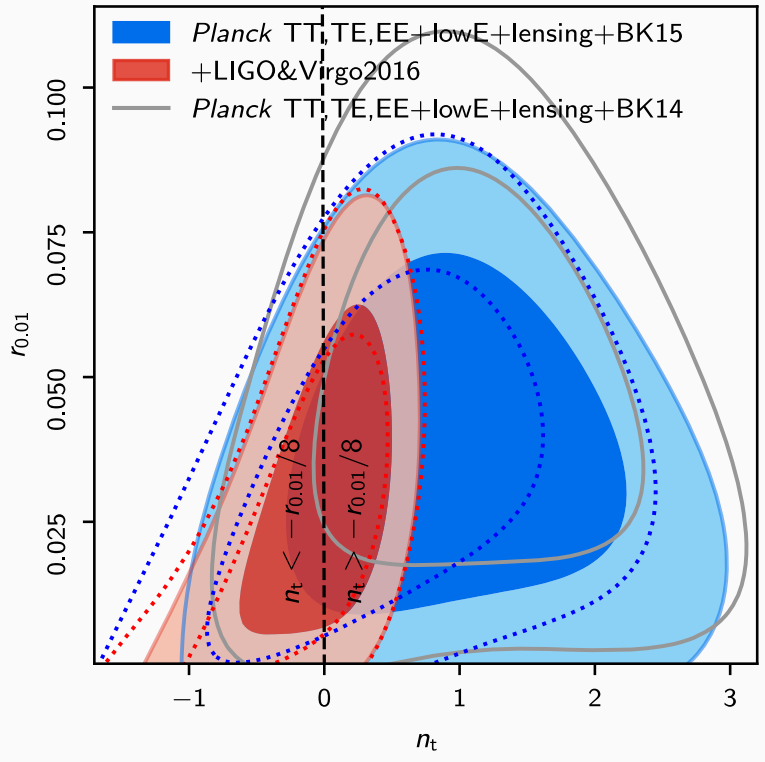

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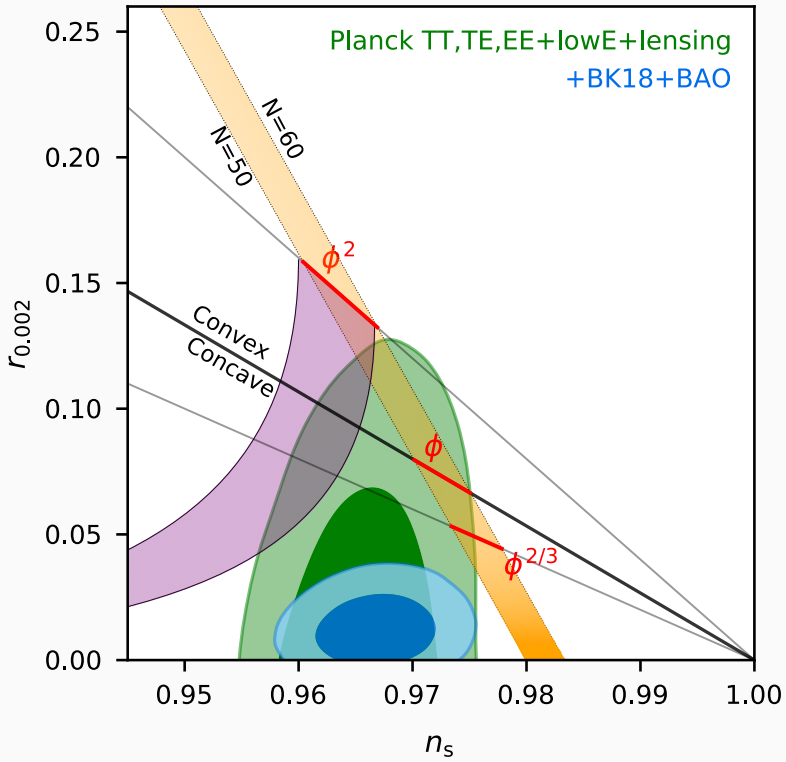

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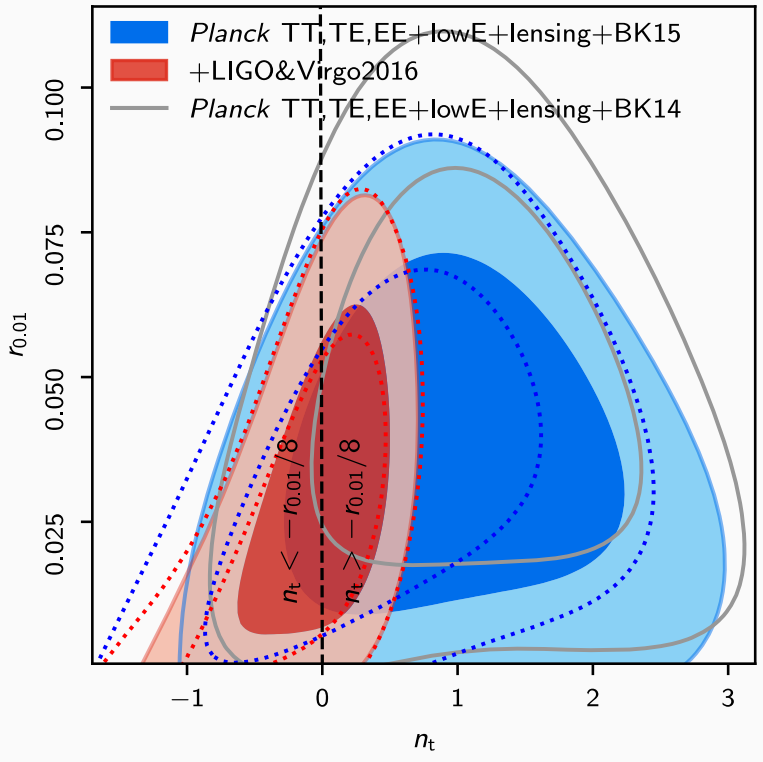

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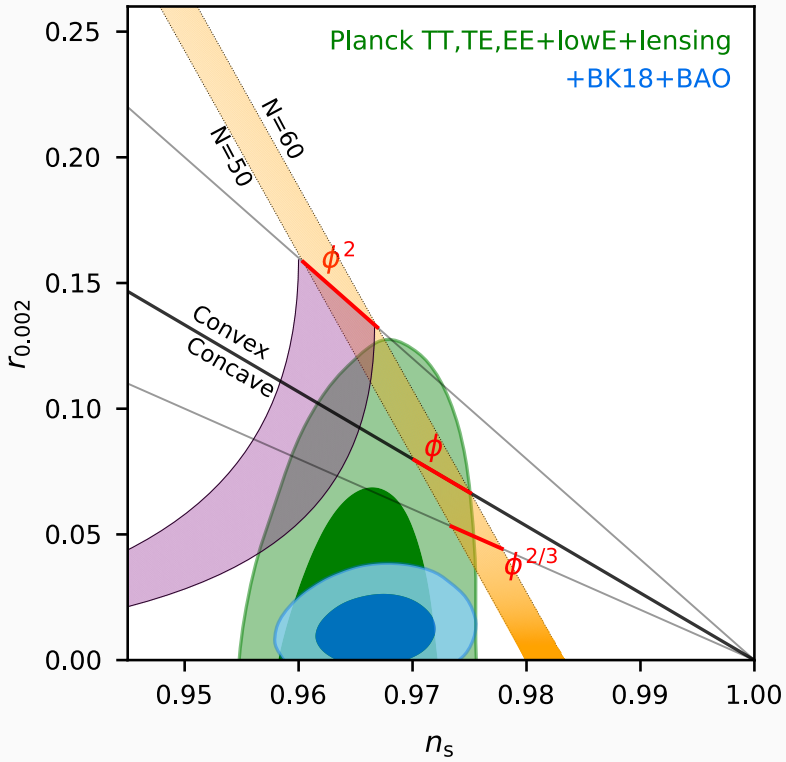

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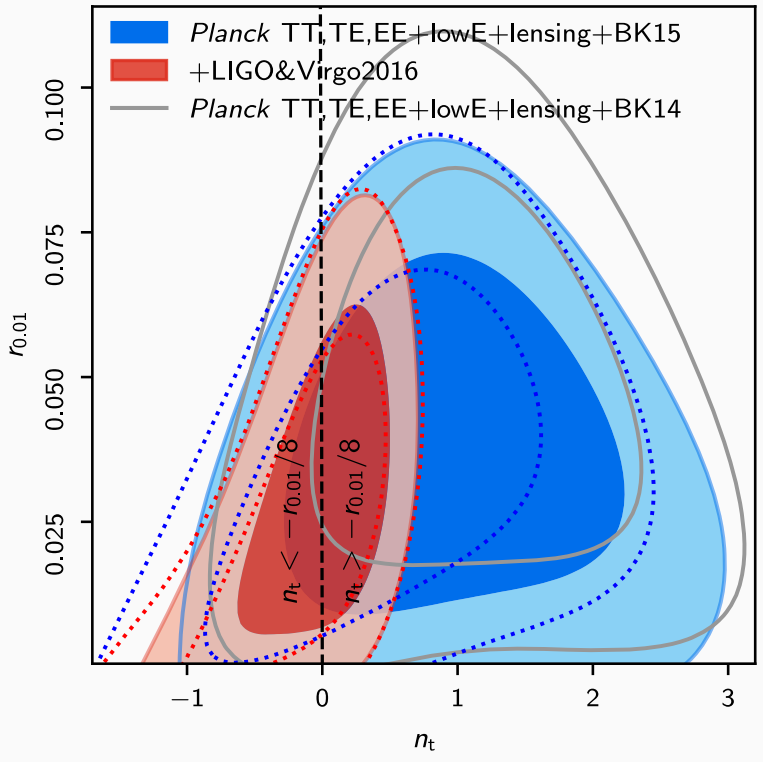

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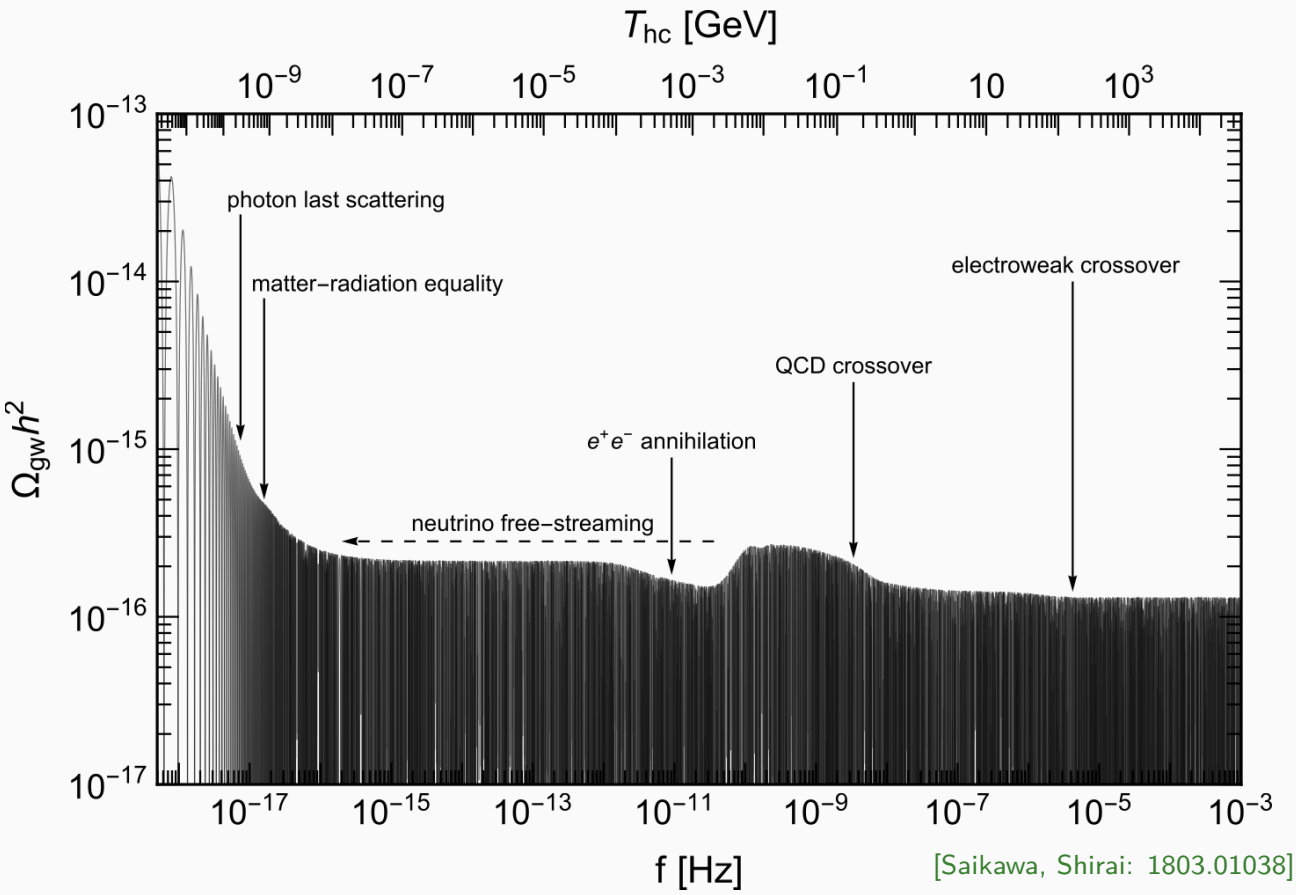
- Tighter constraints if power law naively extrapolated to higher frequencies

Logbook of the expansion history



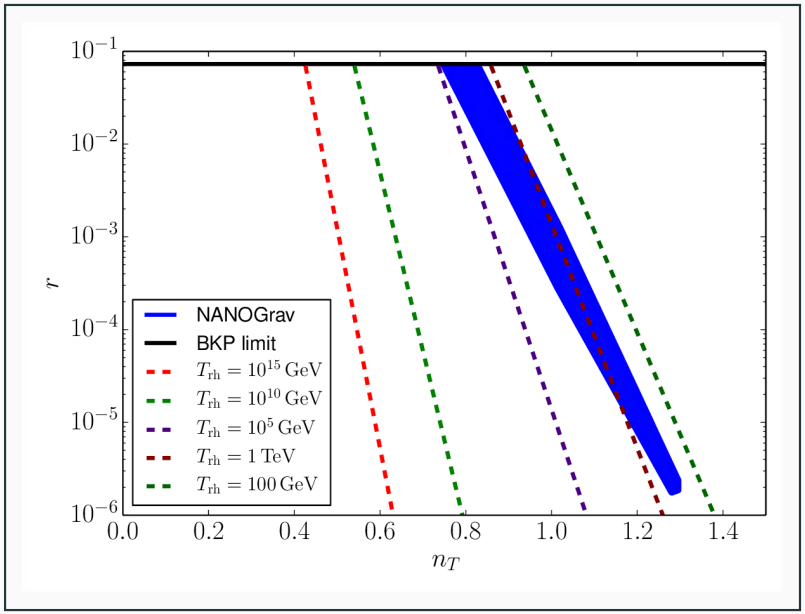
[Saikawa, Shirai: 1803.01038]

Scale-invariant GW spectrum from inflation, redshifted to the present epoch

- Cosmic logbook encoding the entire expansion history of the early Universe
- Major events in the early Universe leave their imprint in the SGWB signal
- Approximately flat plateau at $\Omega_{\rm gw} \sim \Omega_{\rm r}/24\, r A_s \sim 2 \times 10^{-16}\,(r/0.044)$

Inflationary GWs in the PTA band

Index and amplitude at low f (CMB)



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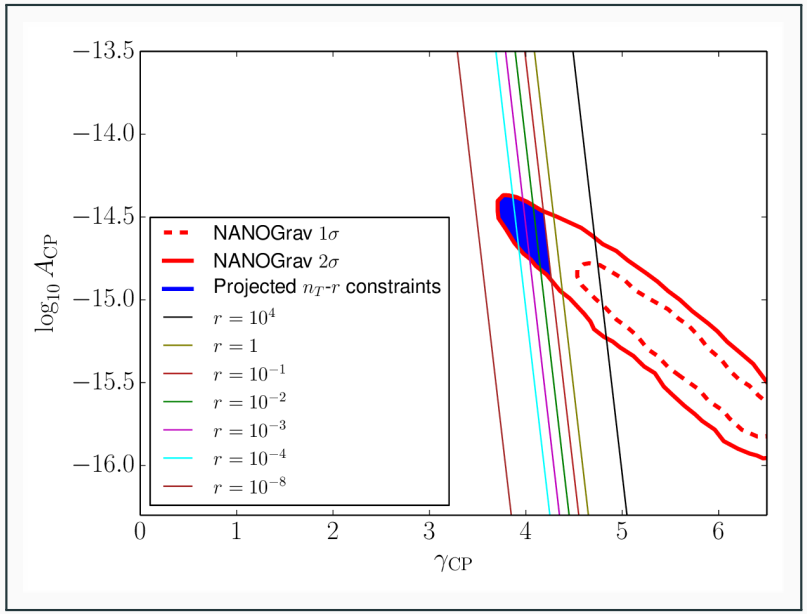

[Vagnozzi: 2009.13432]

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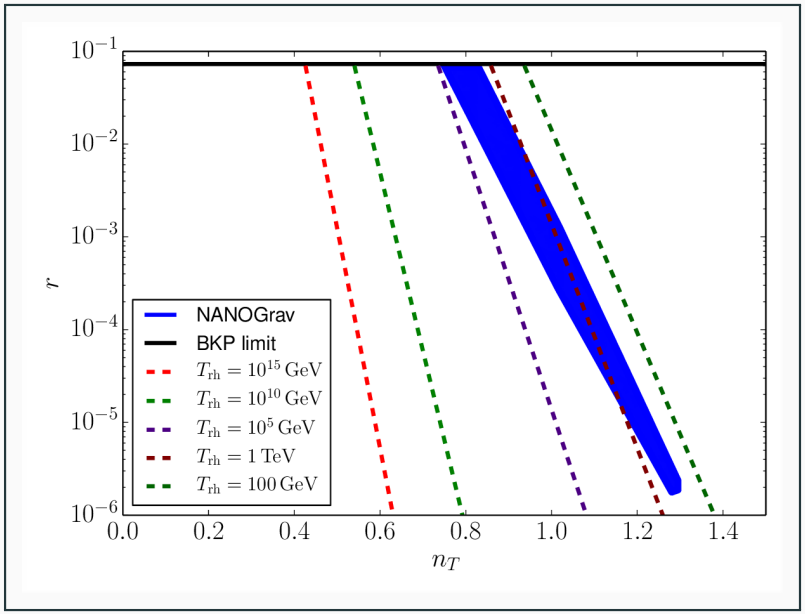

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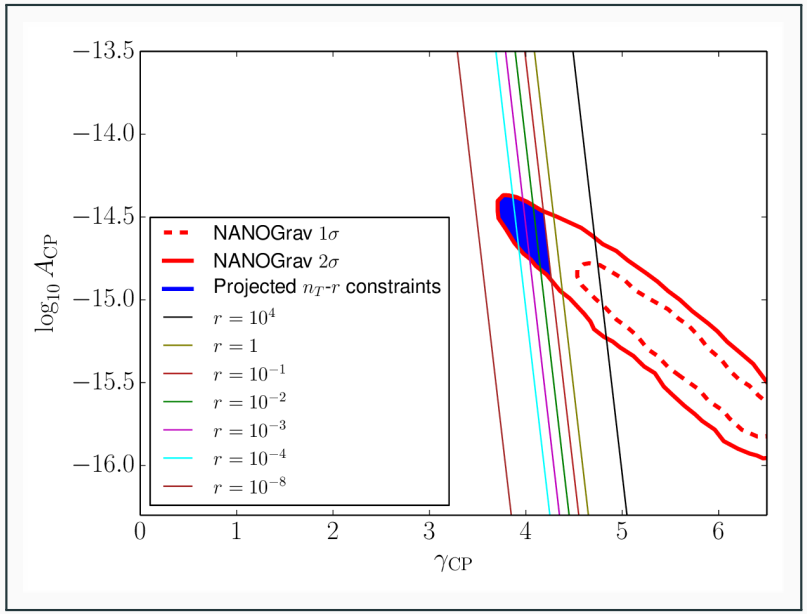

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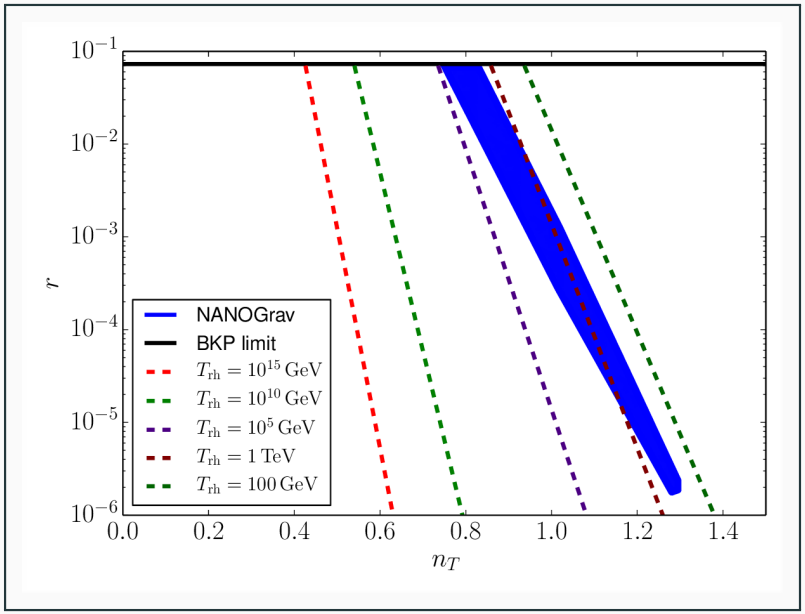

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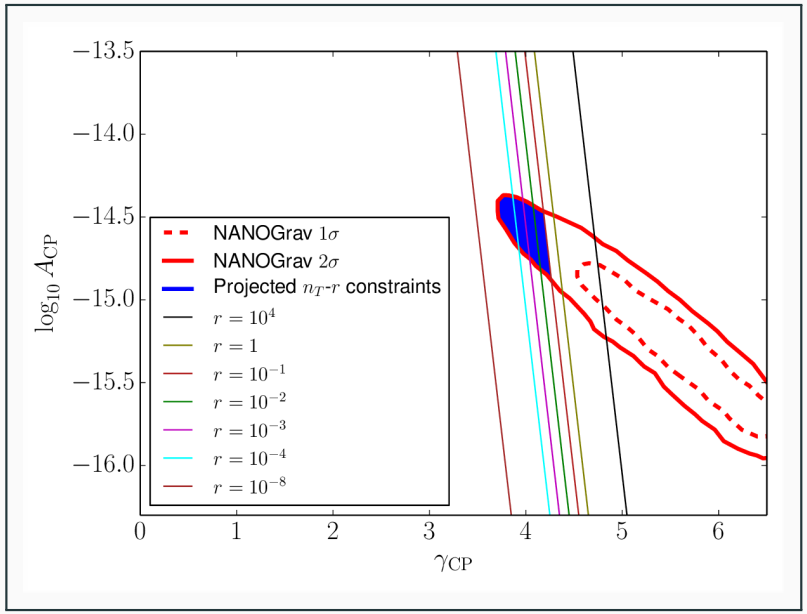

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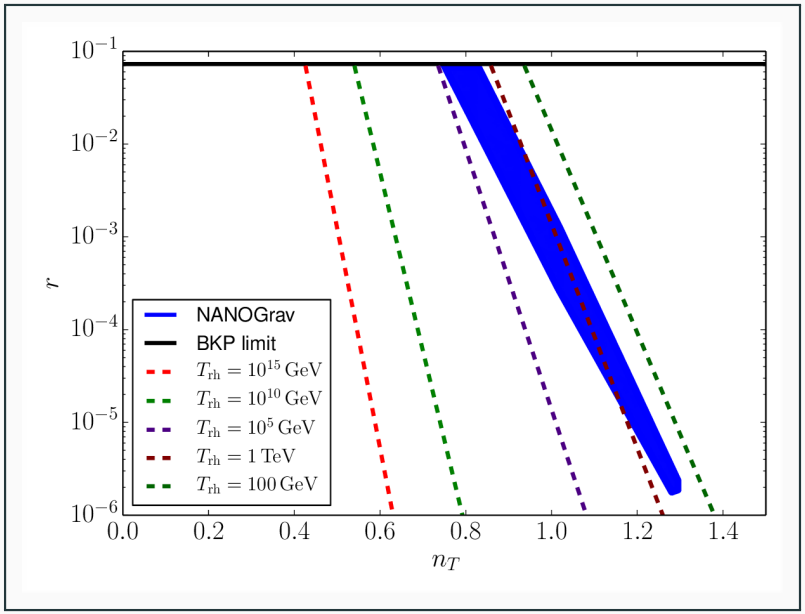

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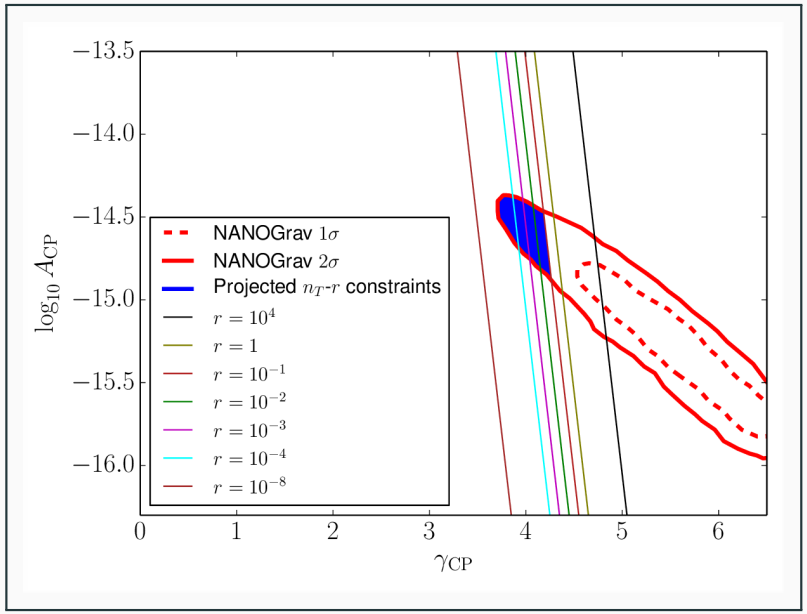

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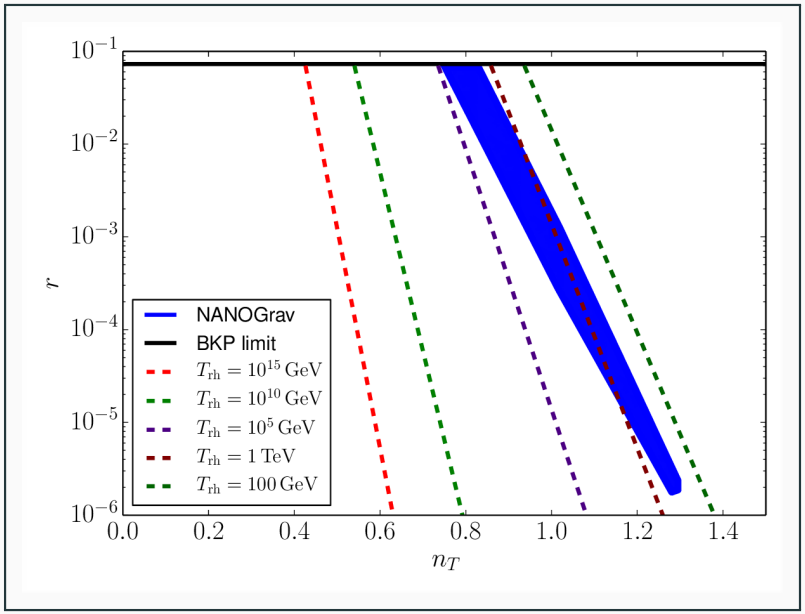

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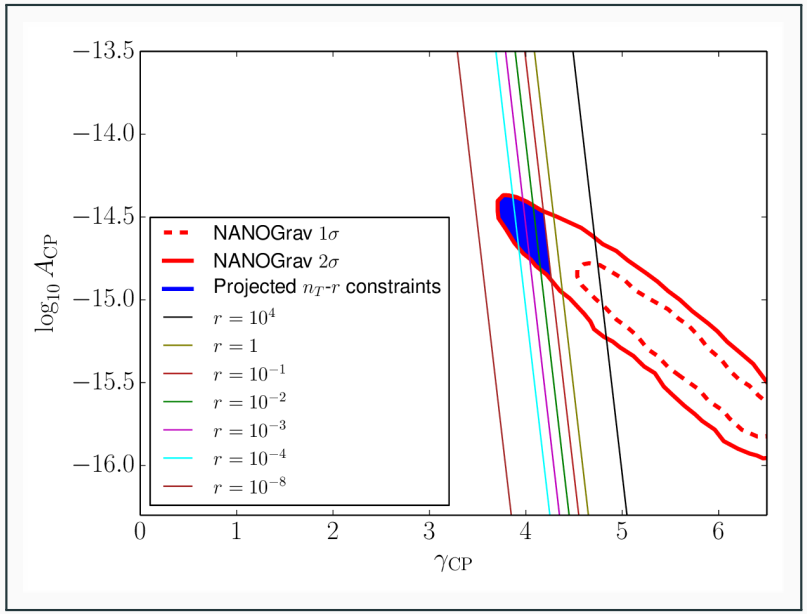

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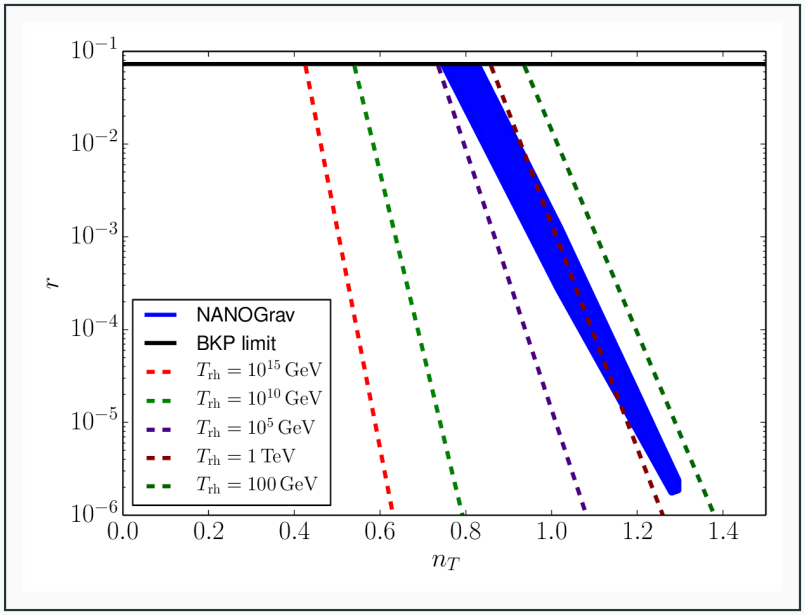

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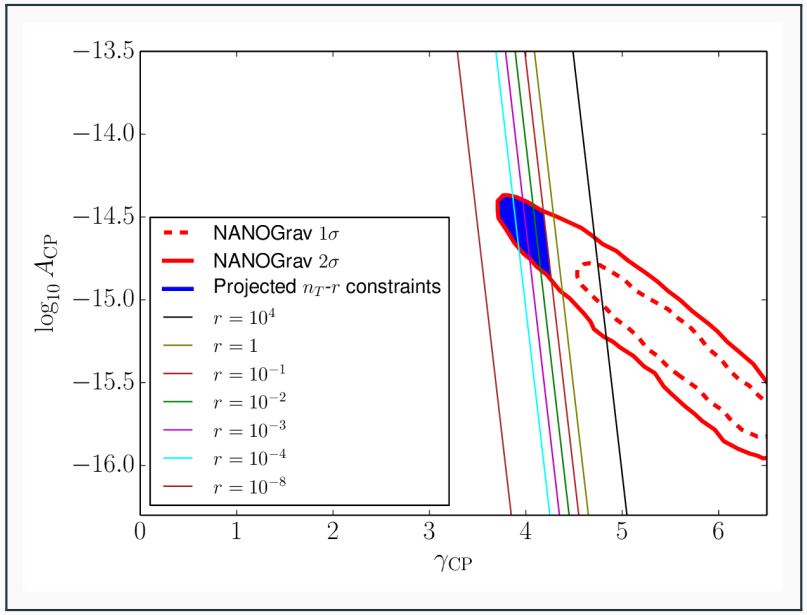

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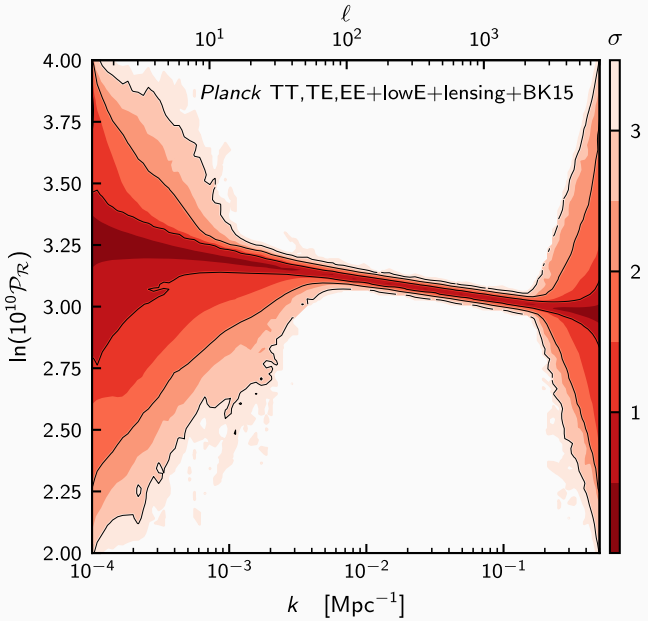
- Project idea ❷: Consider specific nonminimal inflation model, e.g., axion inflation

Primordial black holes (PBHs)

Enhanced curvature perturbations



[PLANCK Collaboration: 1807.06211]

Primordial scalar power spectrum only well known at CMB scales

$$\mathcal{P}_{\mathcal{R}} = \frac{1}{24\pi^2}\frac{1}{\epsilon}\frac{V}{m_{\rm Pl}^4} \simeq (2.10 \pm 0.06) \times 10^{-9} \qquad \text{at} \qquad k_{\rm CMB} = 0.05\,\text{Mpc}^{-1}$$

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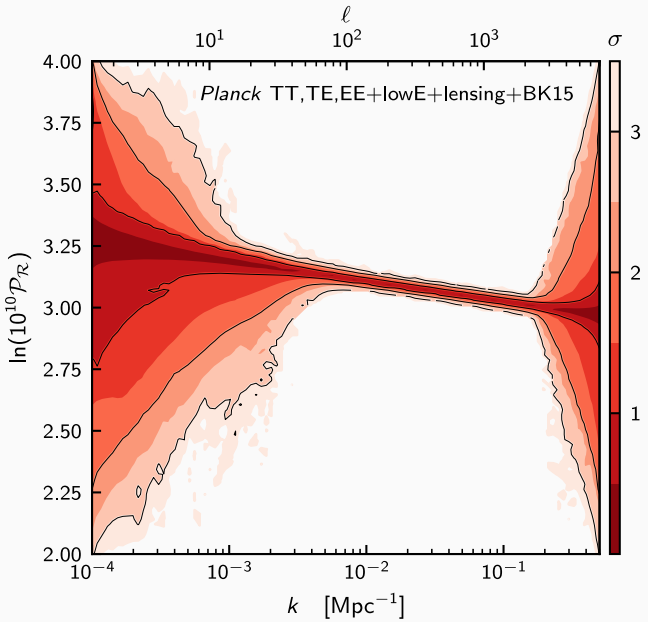

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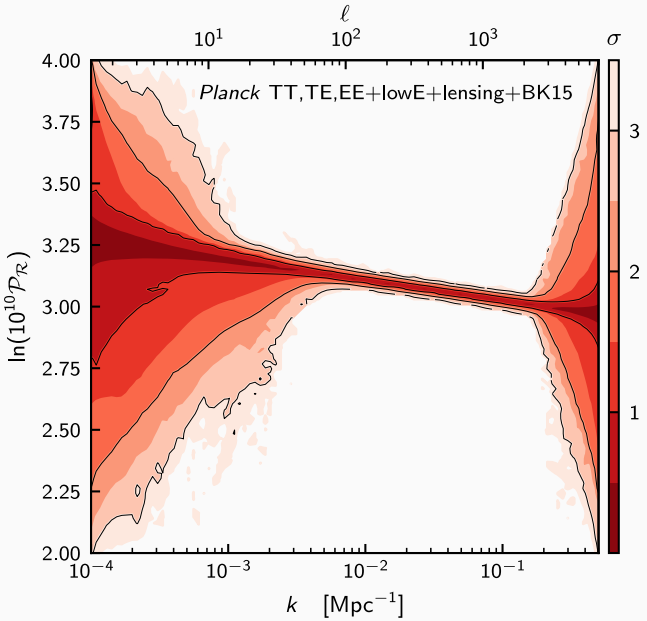

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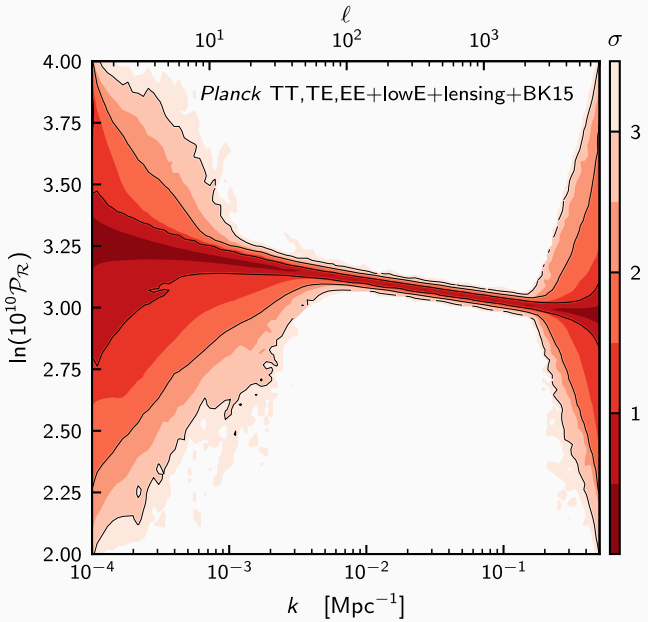

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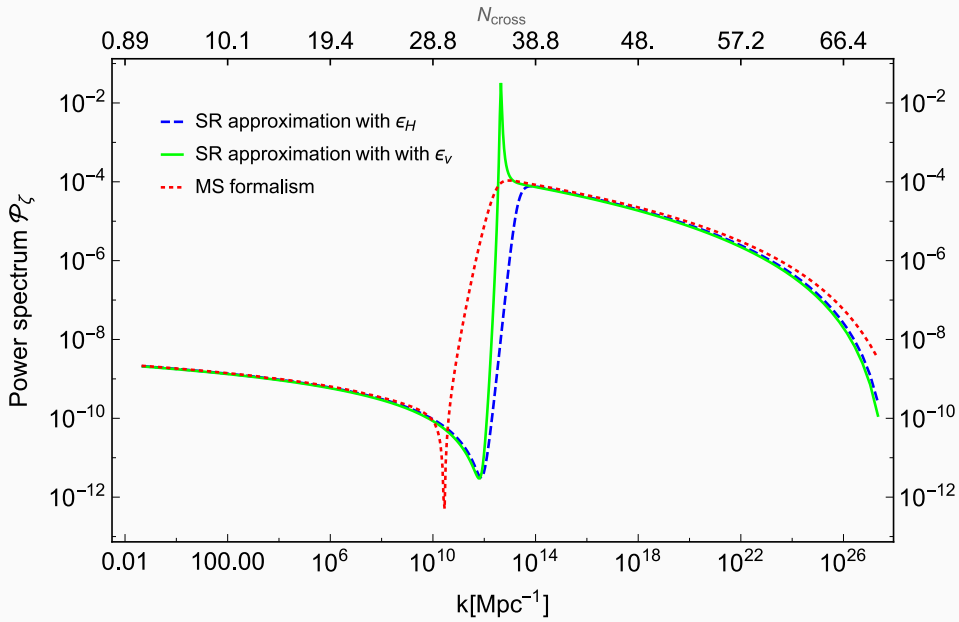

[Drees, Xu: 1905.13581]

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- E.g.: Critical Higgs inflation, saddle point in scalar potential at low field values

Scalar-induced GWs (SIGWs) at second order in perturbation theory

Cosmological perturbation theory

- Scalar and tensor modes couple to each other at second order, $h_{ij} \leftrightarrow \partial_i \Phi \partial_j \Phi$

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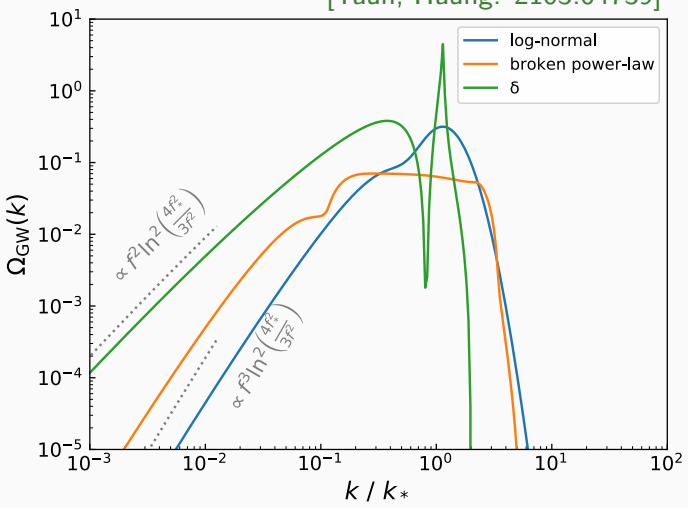
[Yuan, Huang: 2103.04739]



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with some complicated transfer function f

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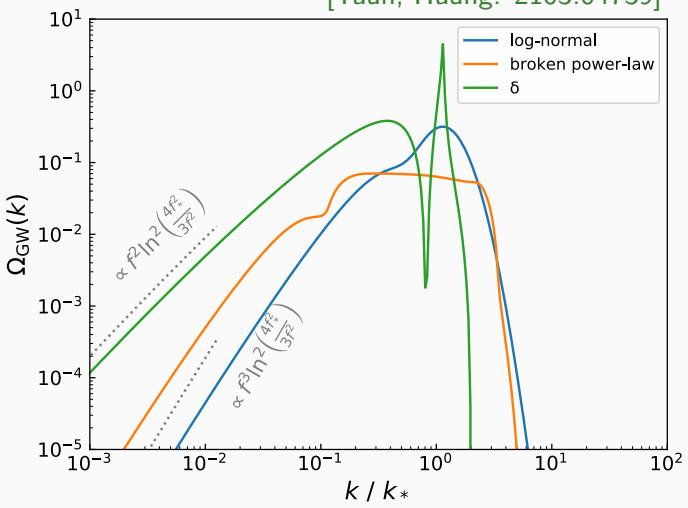

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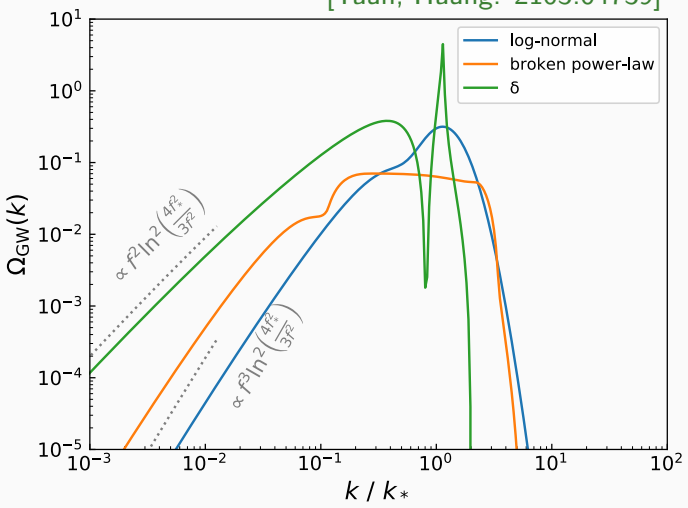

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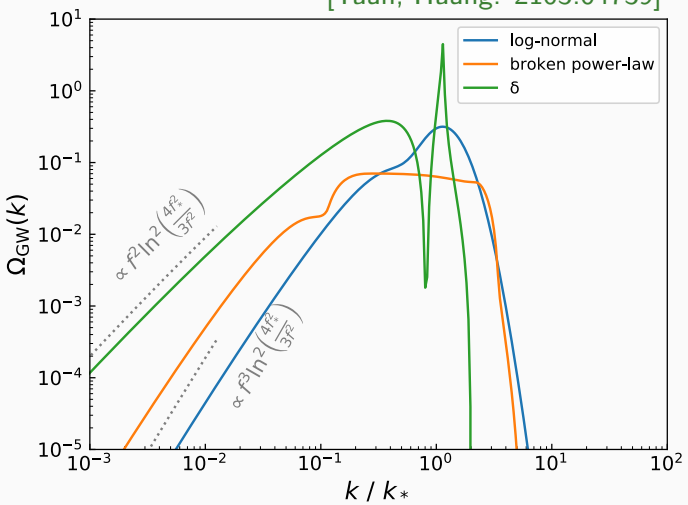

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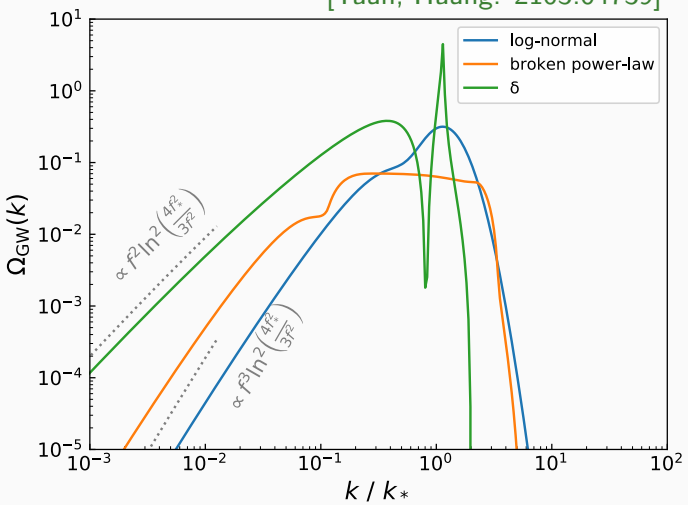

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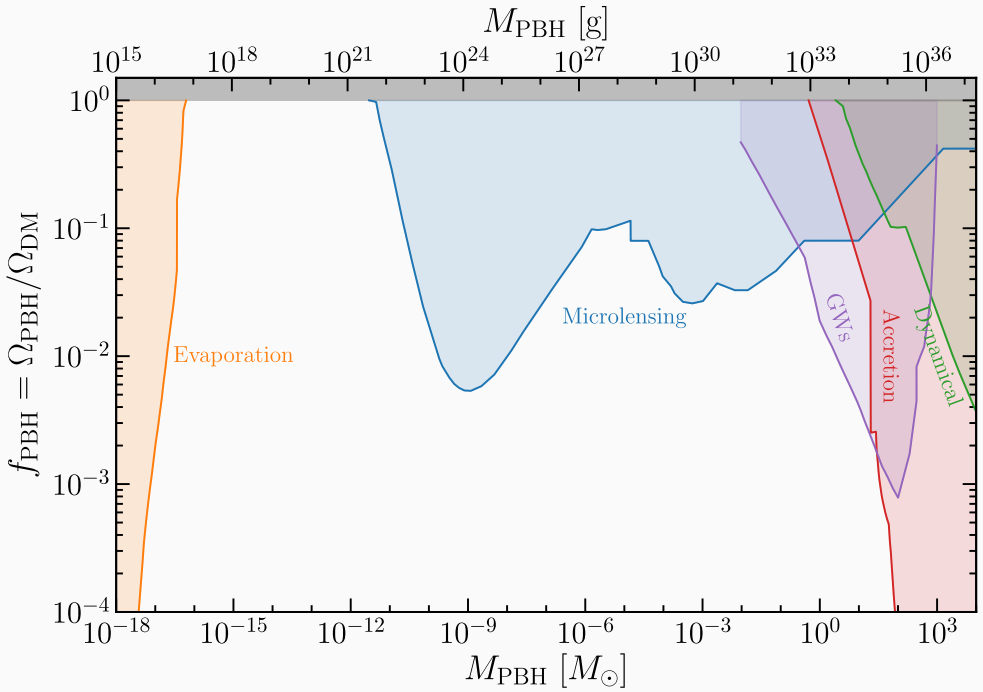
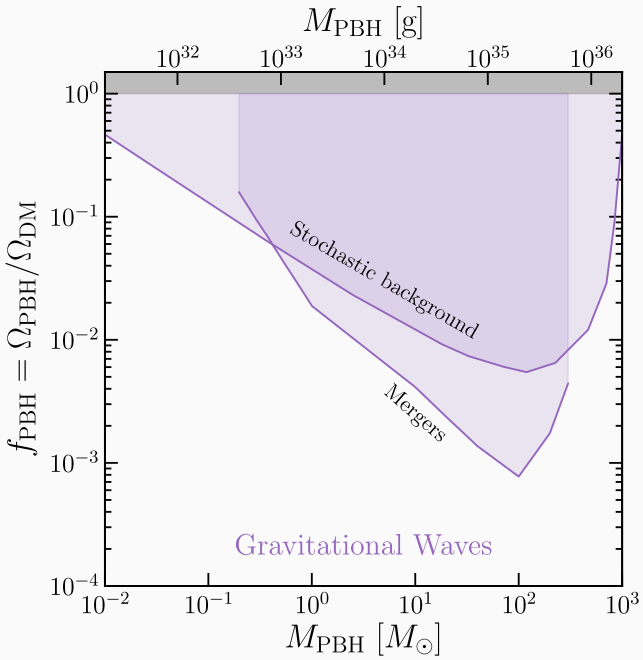
Depending on $\mathcal{P}_\zeta$, second-order scalar-induced GWs can dominate the SGWB signal!

Associated PBH formation





[Green, Kavanagh: 2007.10722]

Collapse of horizon mass when overdense regions re-enter the causal horizon

- Statistics of primordial density perturbations translate into PBH mass fraction

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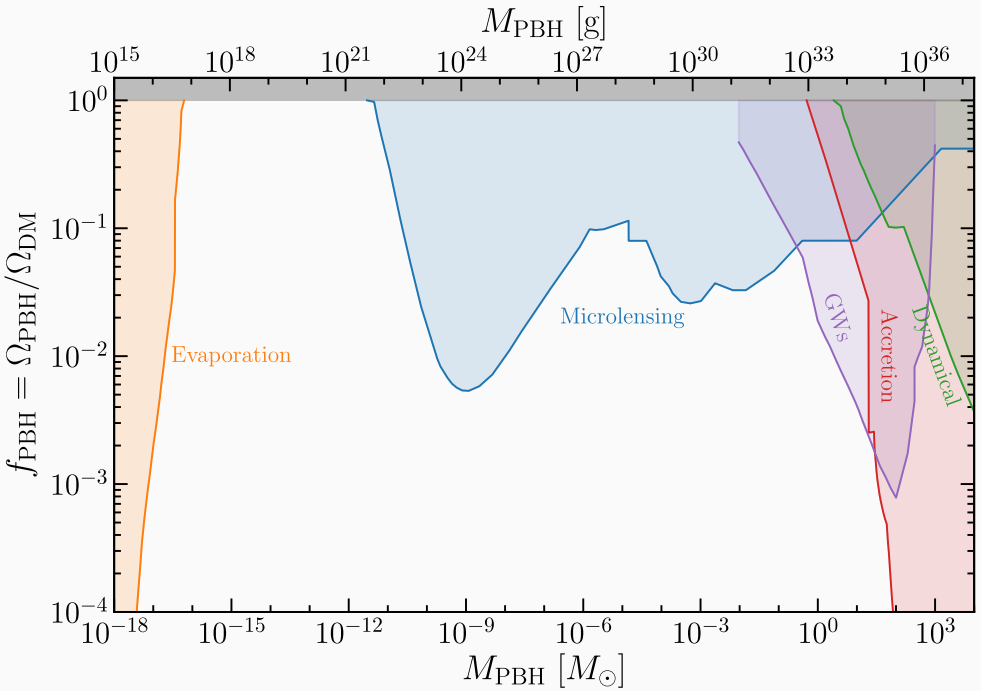

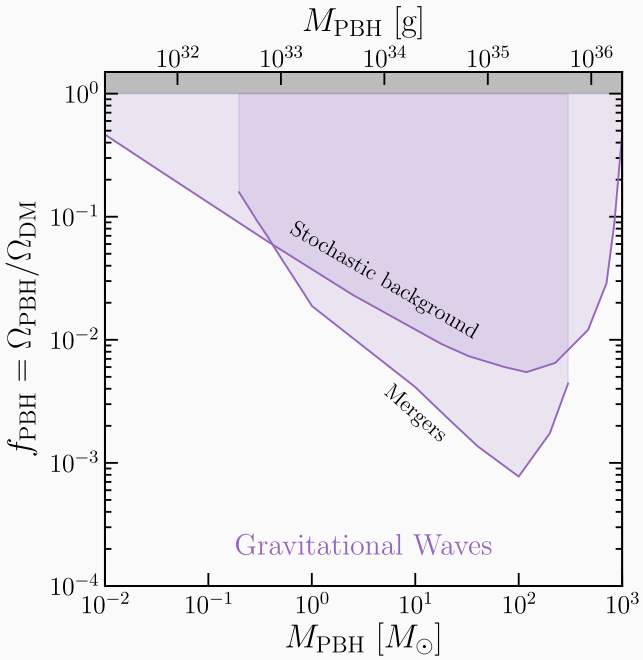

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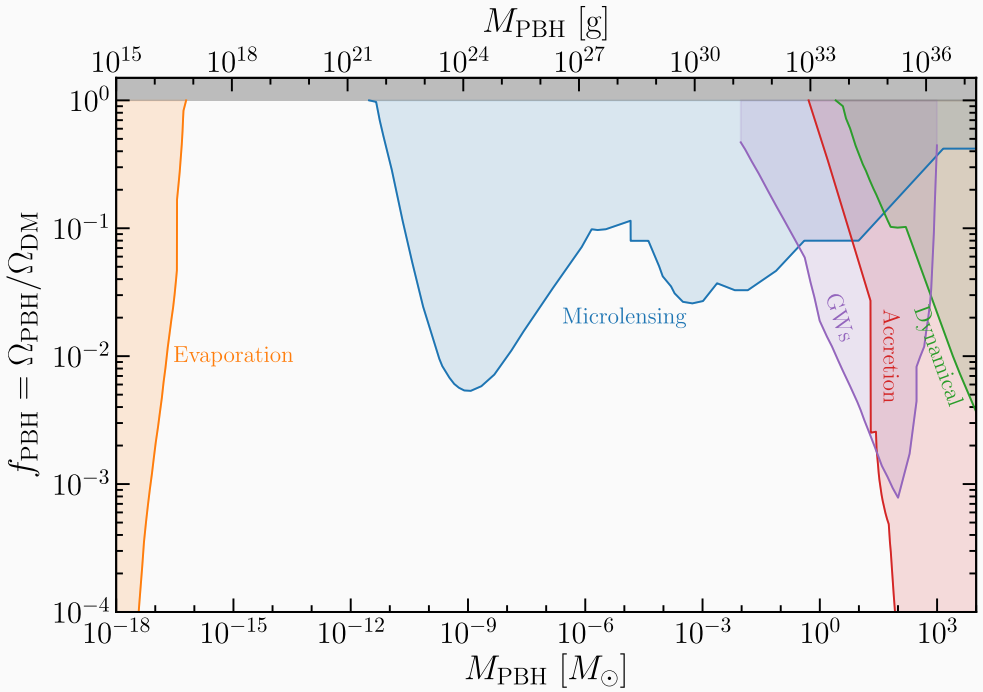

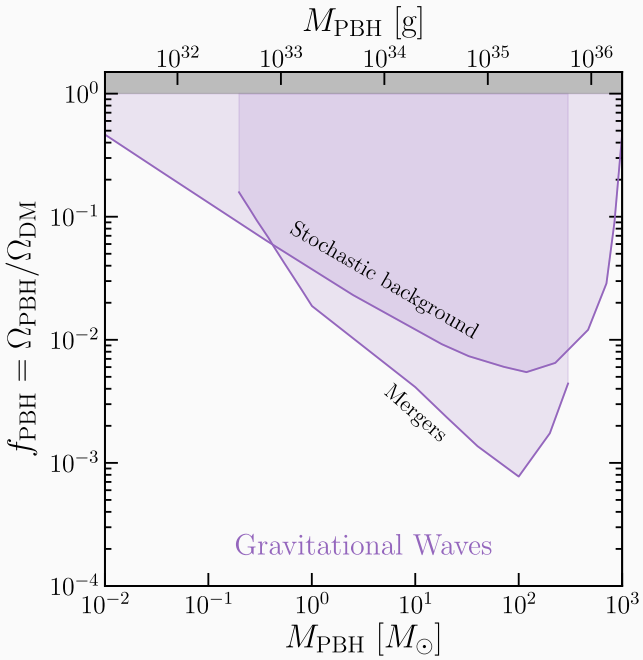

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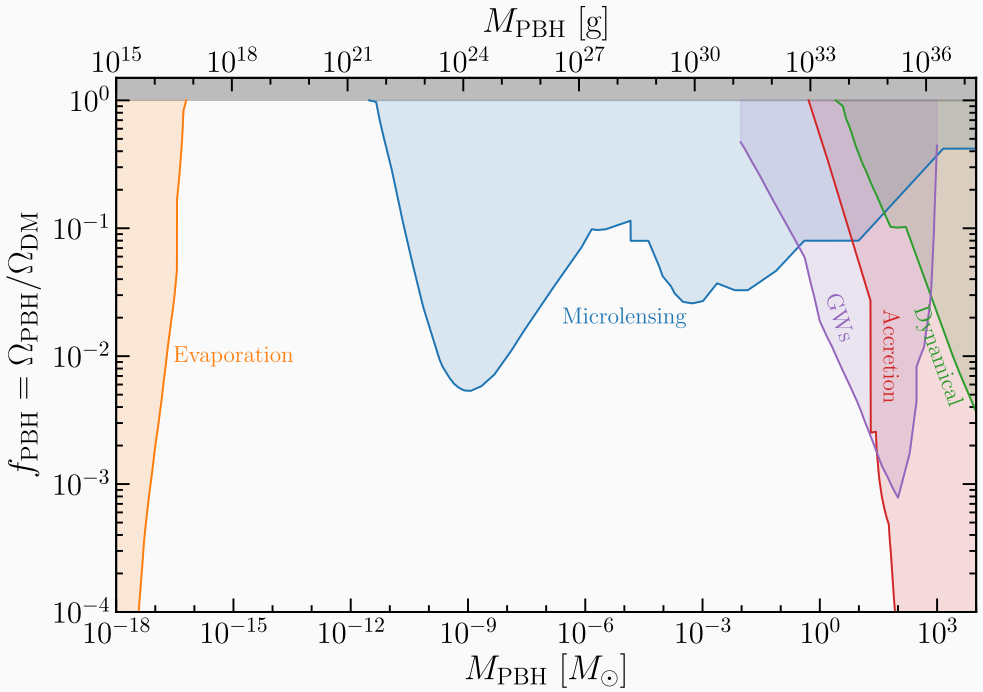

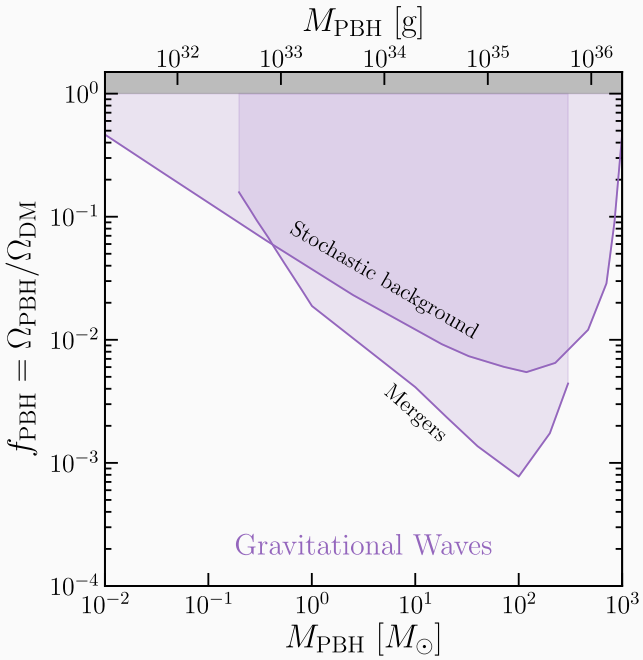

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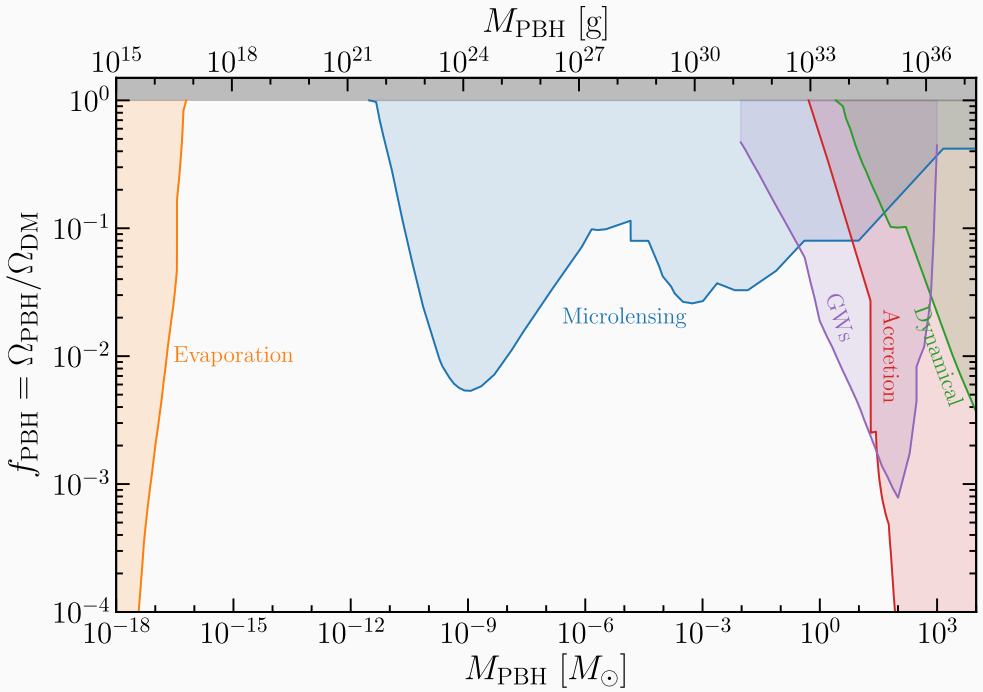

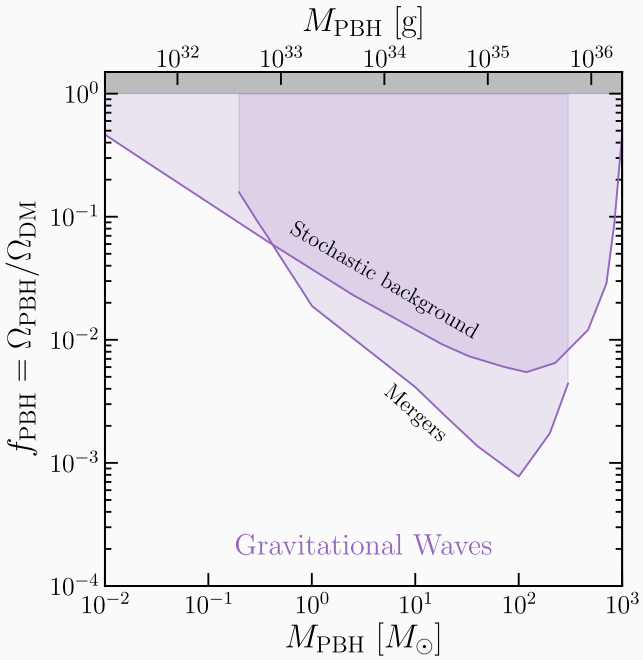

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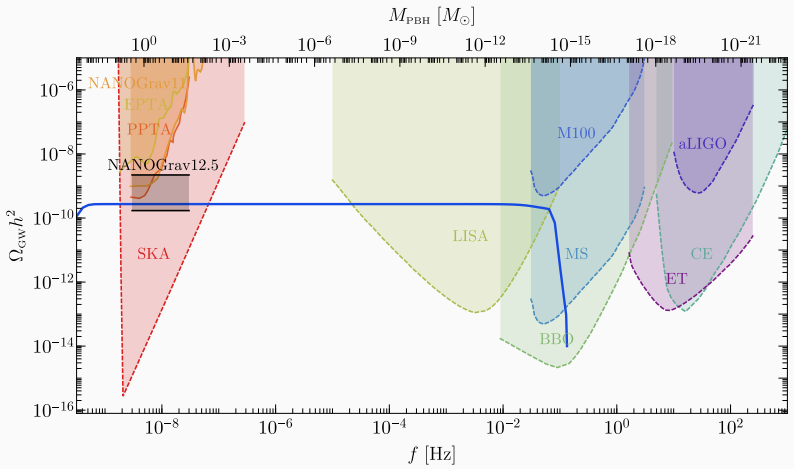
- ... as well as for the GW signals / stochastic background from PBH mergers

PBH interpretation of the PTA signal

[De Luca, Franciolini, Riotto: 2009.08268]

$10^{-12}\ M_\odot$ PBHs + PBH dark matter



[Kohri, Terada: 2009.11853]

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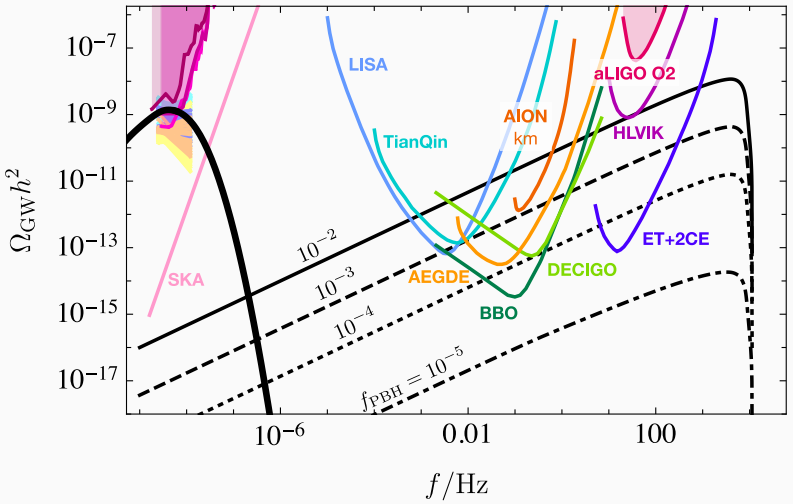

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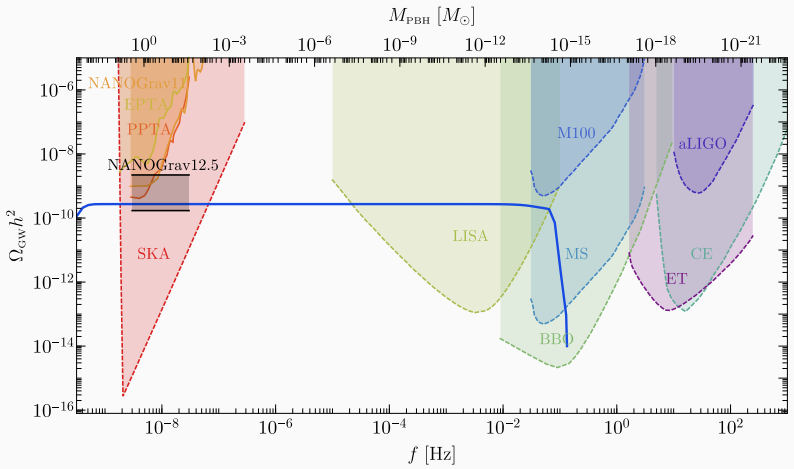

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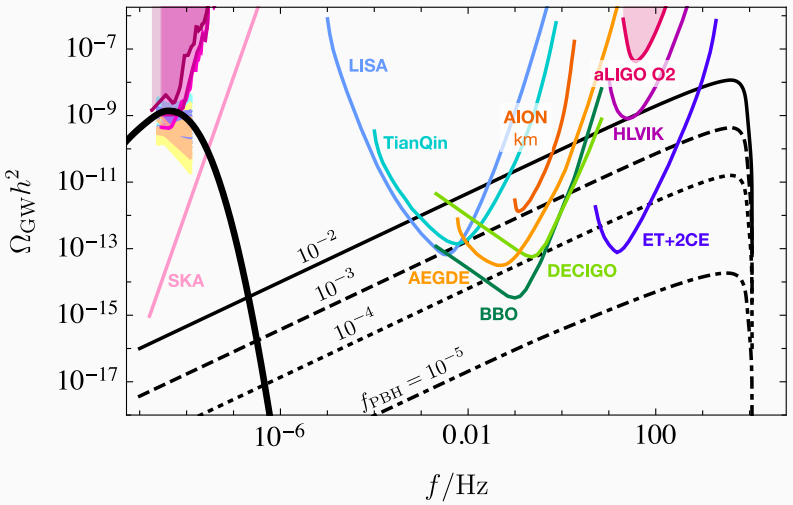

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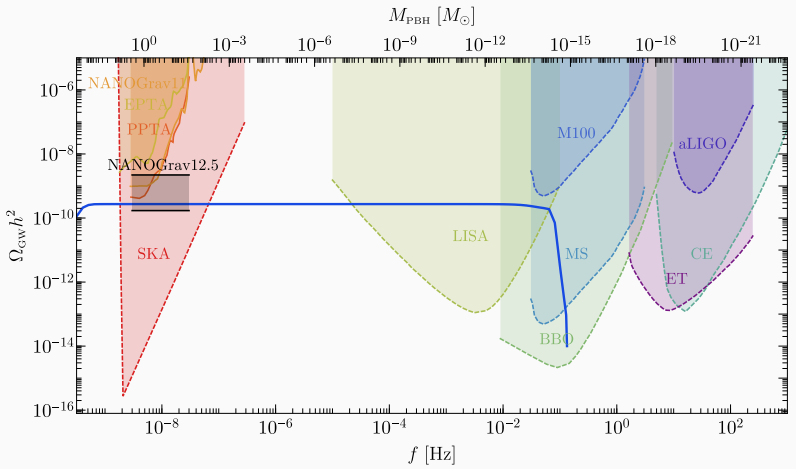

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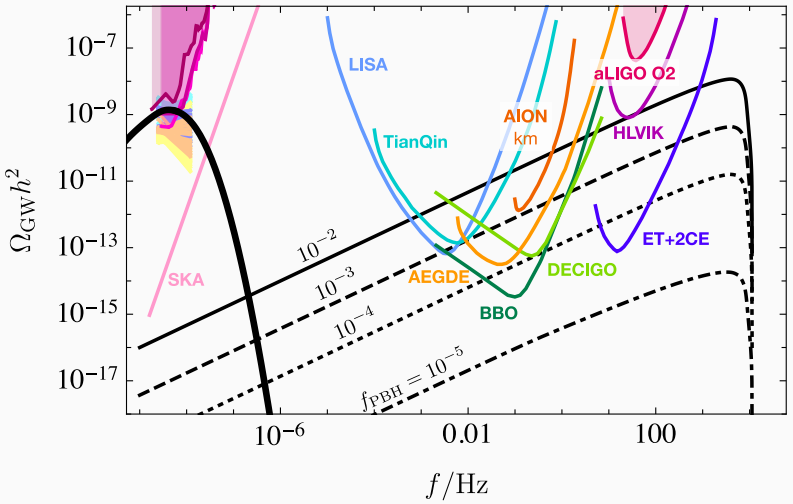

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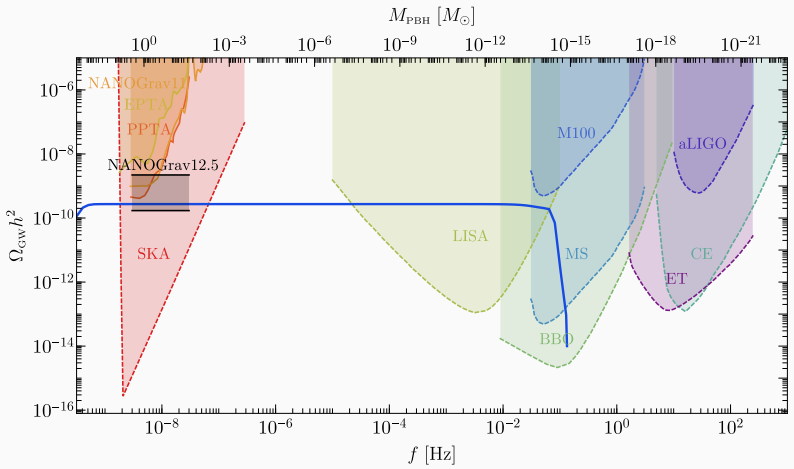

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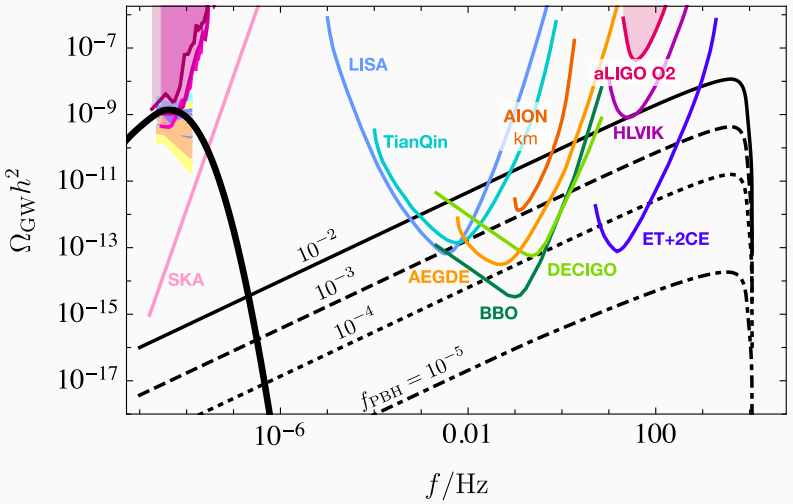

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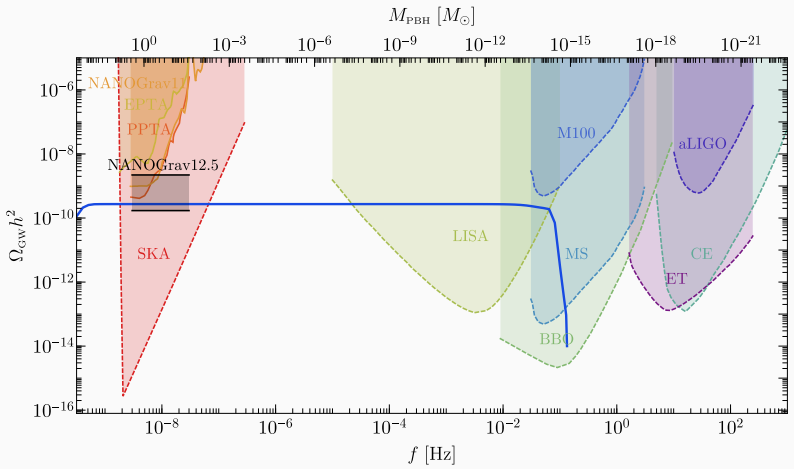

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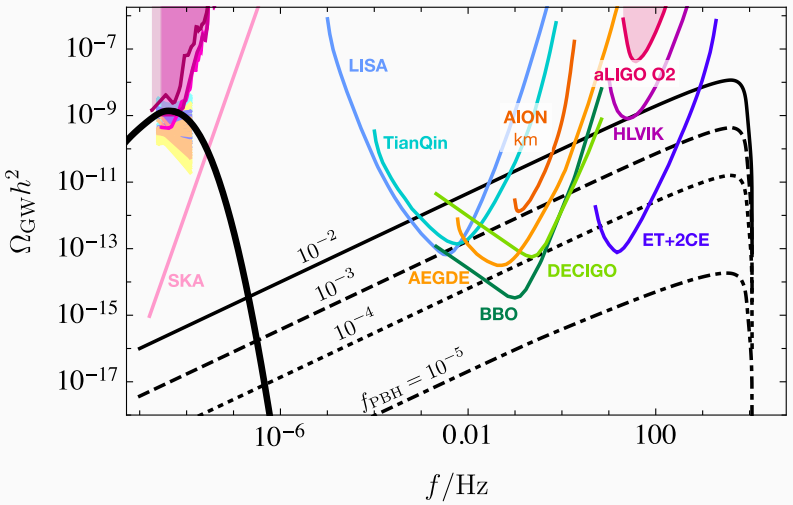

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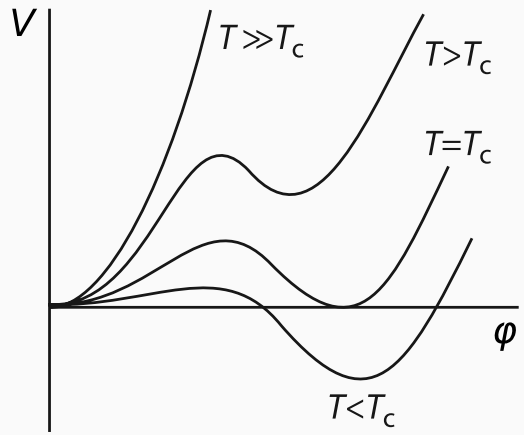
Cosmological phase transitions

First-order phase transitions

First-order phase transition



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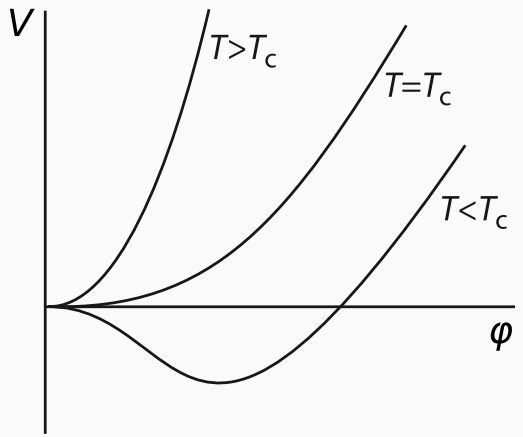

[Kinnunen, Baarsma, Martikainen, Törmä: 1706.07076]

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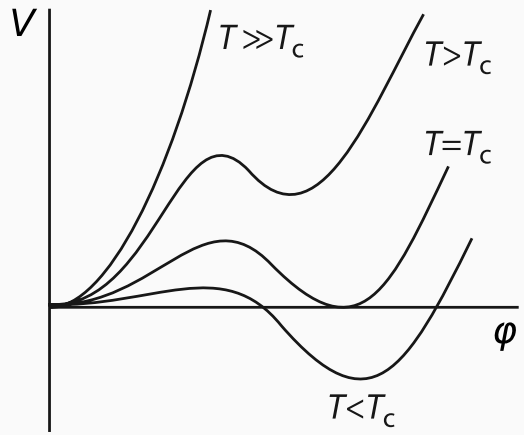

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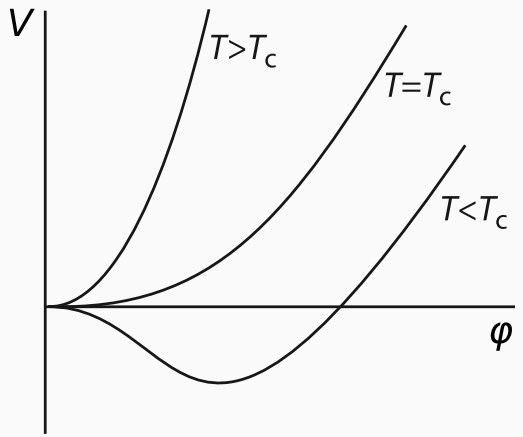

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GWs from strong first-order phase transitions (SFOPTs)

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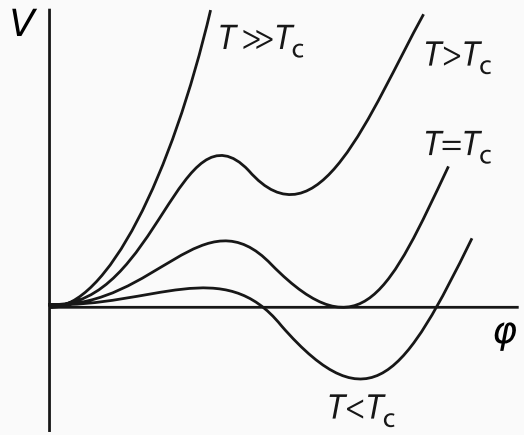

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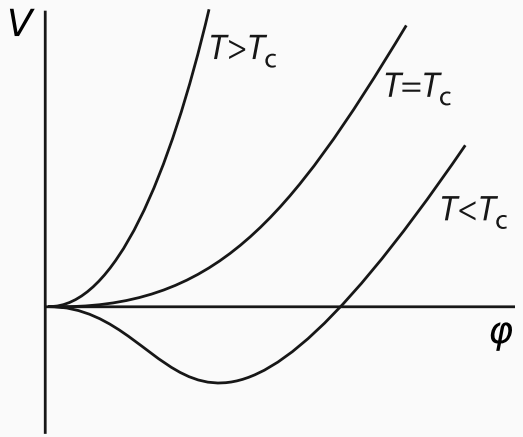

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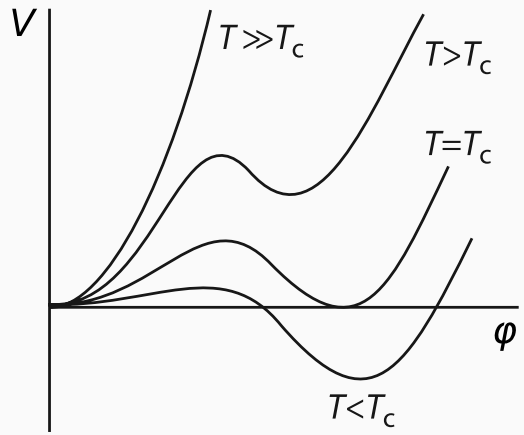

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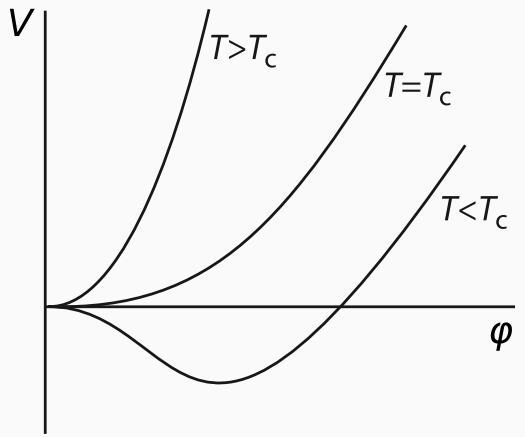

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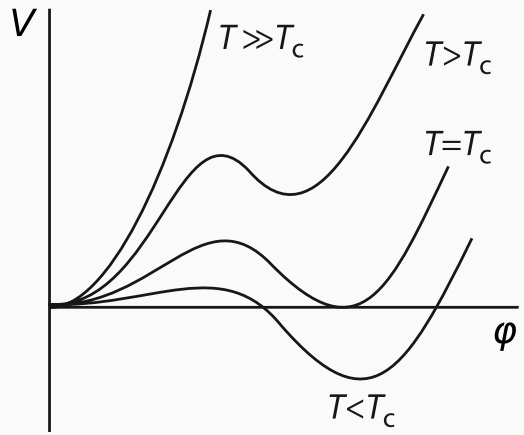

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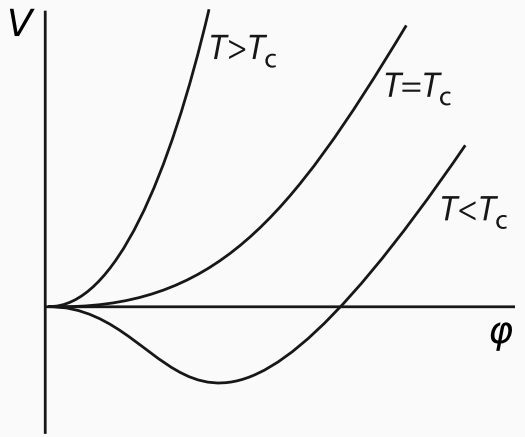

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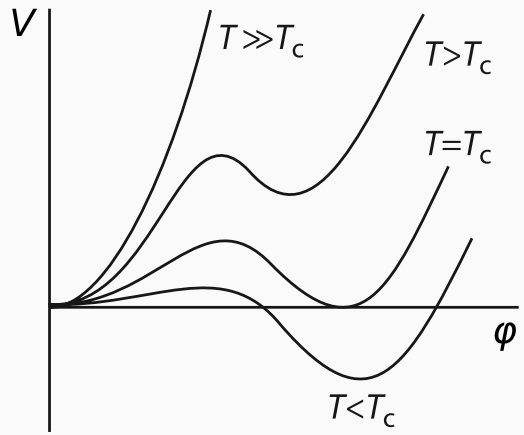

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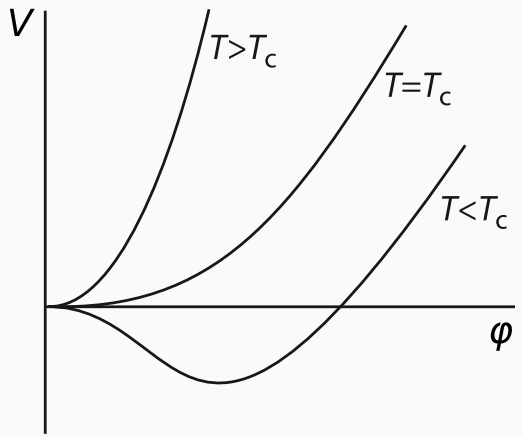

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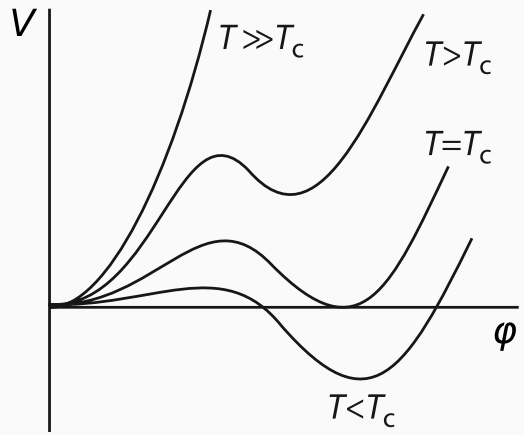

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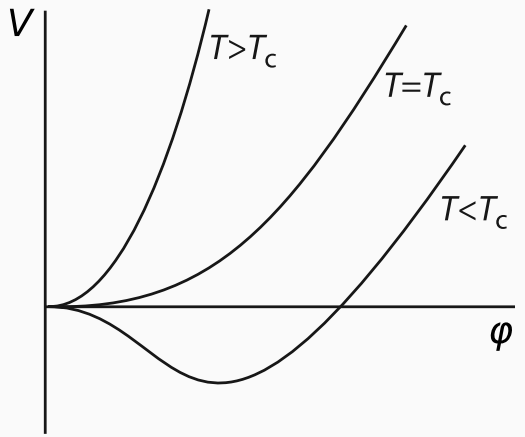

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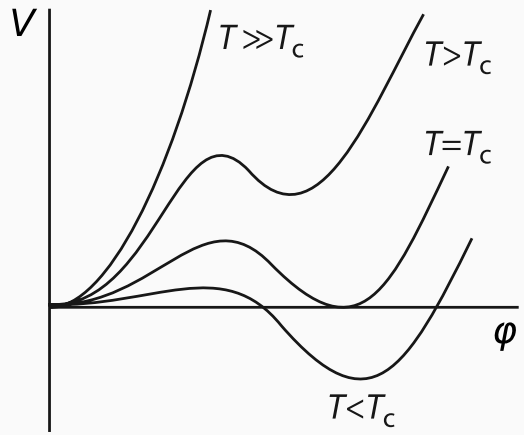

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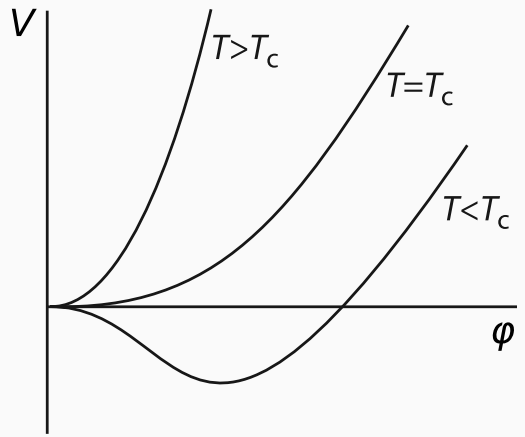

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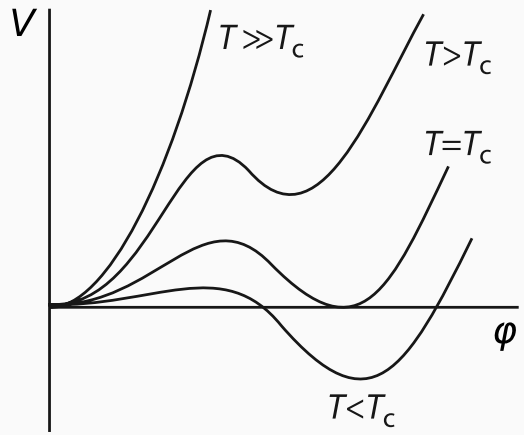

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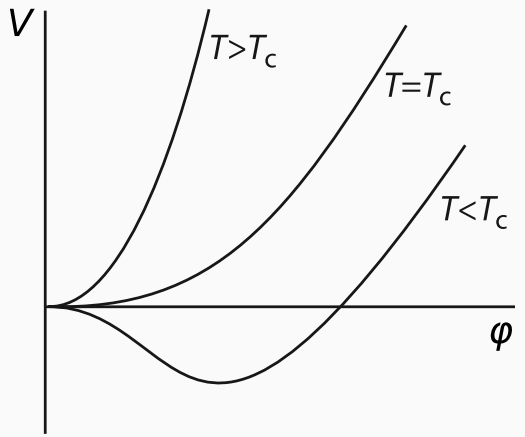

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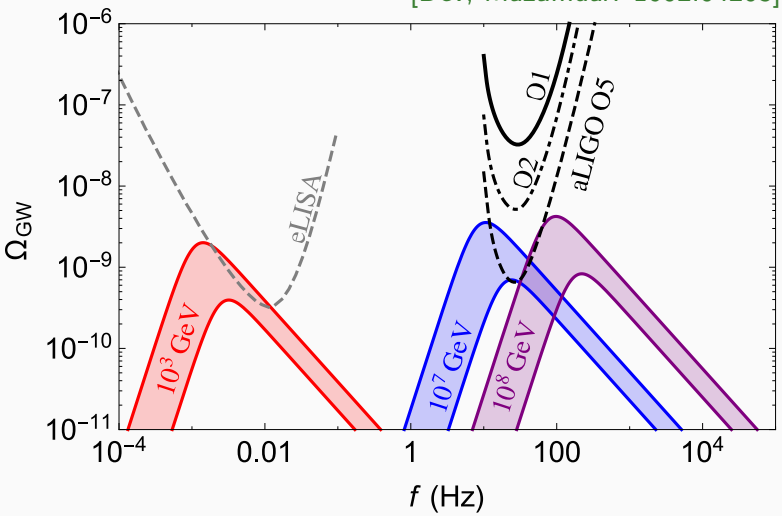
- Ω_{t}: Magnetohydrodynamic turbulence, vortical motion in the bulk plasma

Example: GWs from sound waves

[Dev, Mazumdar: 1602.04203]



Relevant parameters

- Strength parameter $\alpha = \Delta\theta/\rho_{\rm rad}$
- Inverse duration $\beta = -d/dt\, S_E$
- Temperature scale T_*
- Bubble wall velocity v_w

Frequency: $$f_{\rm sw}^{\rm peak} \sim 1\,{\rm mHz} \left(\frac{1}{v_w}\right) \left(\frac{\beta/H_*}{100}\right) \left(\frac{g_*}{100}\right)^{1/6} \left(\frac{T_*}{100\,{\rm GeV}}\right)$$

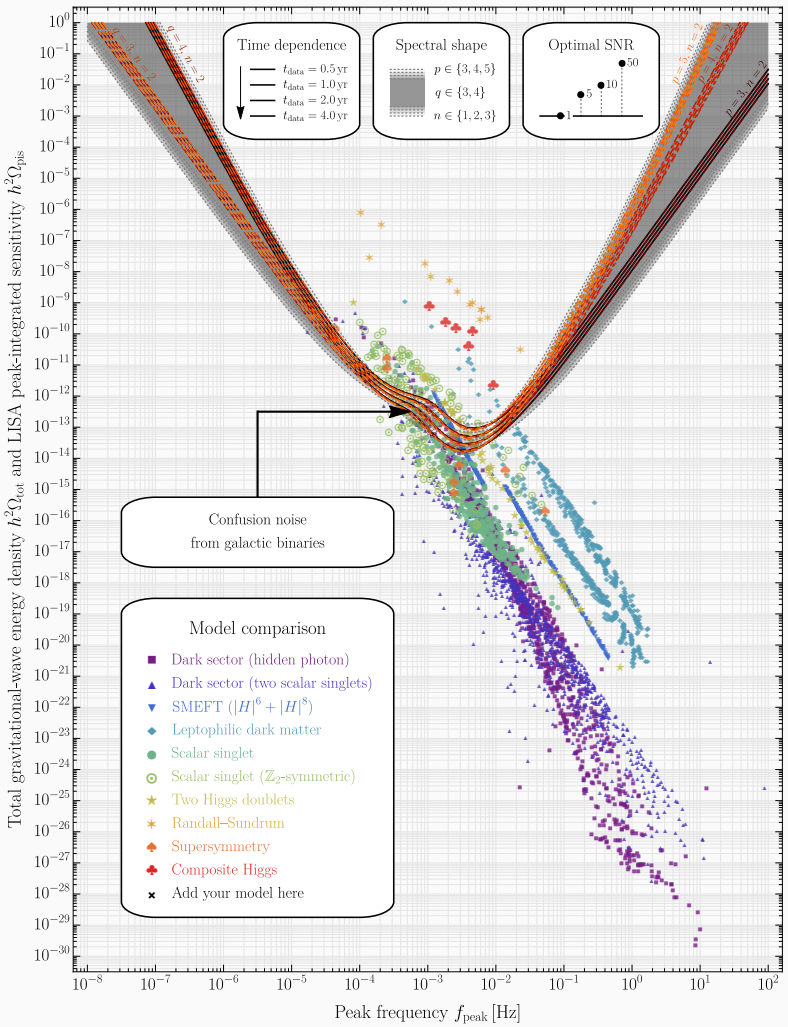
Amplitude: $$\Omega_{\rm sw}^{\rm peak} \sim 10^{-8} \min\{1, H\tau_{\rm sh}\} \left(\frac{v_w}{1}\right) \left(\frac{100}{\beta/H_*}\right) \left(\frac{100}{g_*}\right)^{1/3} \left(\frac{\kappa\,\alpha}{1+\alpha}\right)^2$$

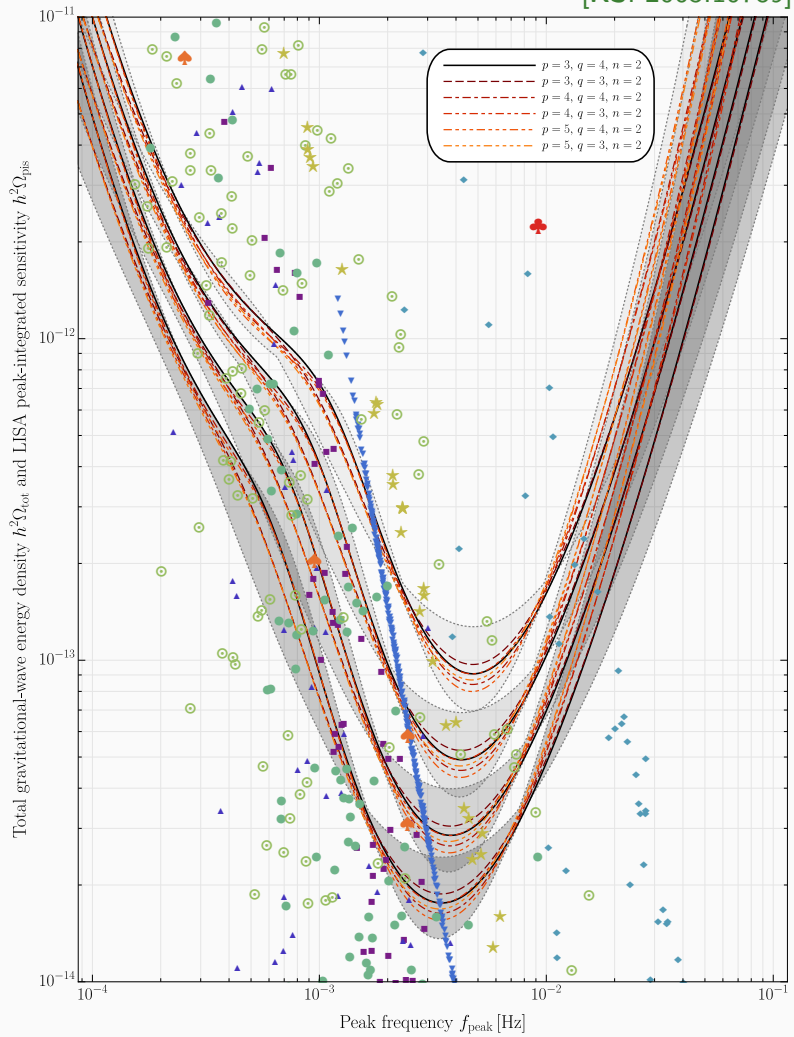
Shape: $$S_{\rm sw}(f) = \frac{(f/f_{\rm peak})^p}{\left[q/(p+q) + p/(p+q)\left(f/f_{\rm peak}\right)^n\right]^{(p+q)/n}}, \quad \{p,q,n\} = \{3,4,2\}$$

[Hindmarsh: 1608.04735] [Hindmarsh, Huber, Rummukainen, Weir: 1704.05871] [Ellis, Lewicki, No: 1809.08242, 2003.07360] [Ellis, Lewicki, No, Vaskonen: 1903.09642] [Hindmarsh, Hijazi: 1909.10040] [Giese, Konstandin, van de Vis: 2004.06995]

LISA sensitivity to GWs from sound waves

[KS: 2005.10789]

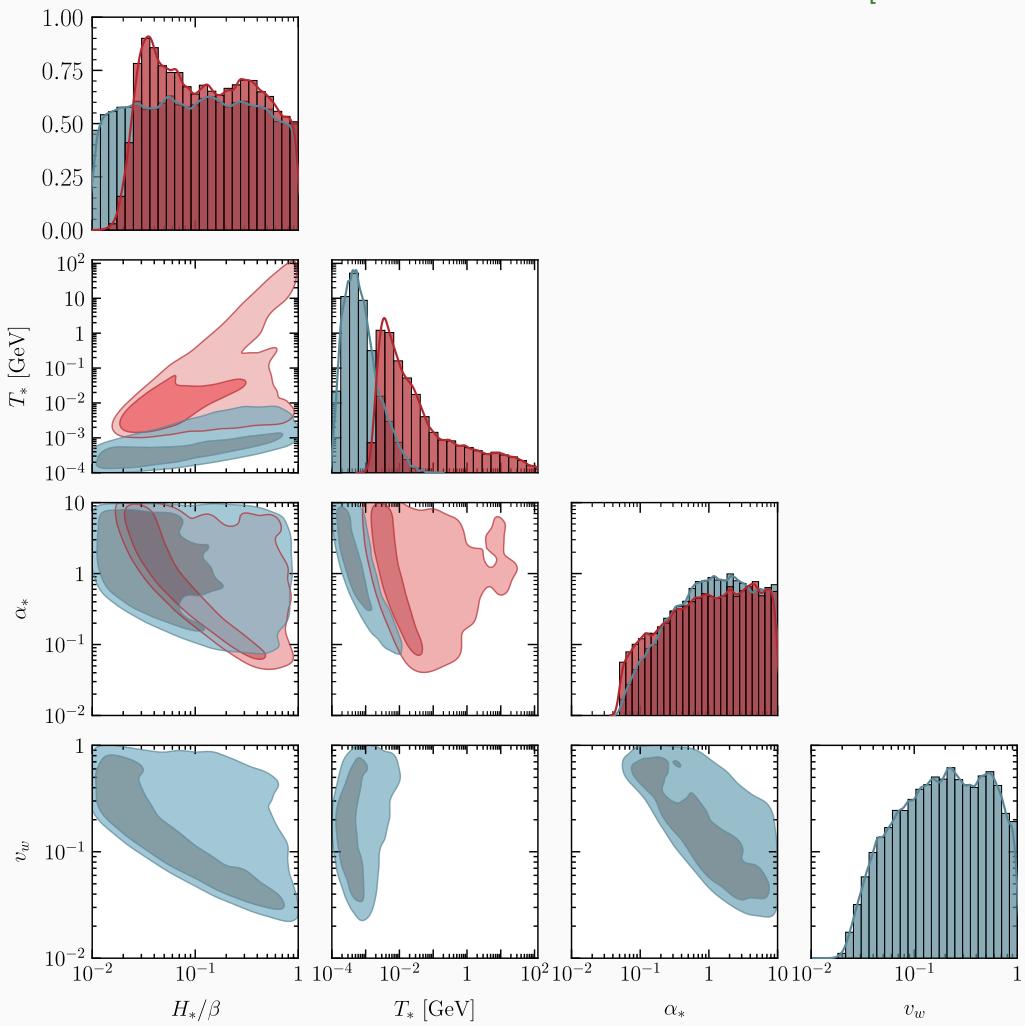




- Peak-integrated sensitivity: LISA sensitivity projected onto $f_{\rm peak} - h^2\Omega_{\rm tot}$ plane
- Project idea ❹: Repeat analysis for PTAs, compile "atlas" of relevant models

Search for GWs from a SFOPT with the NANOGrav 12.5-year data

[NANOGrav collaboration: 2104.13930]

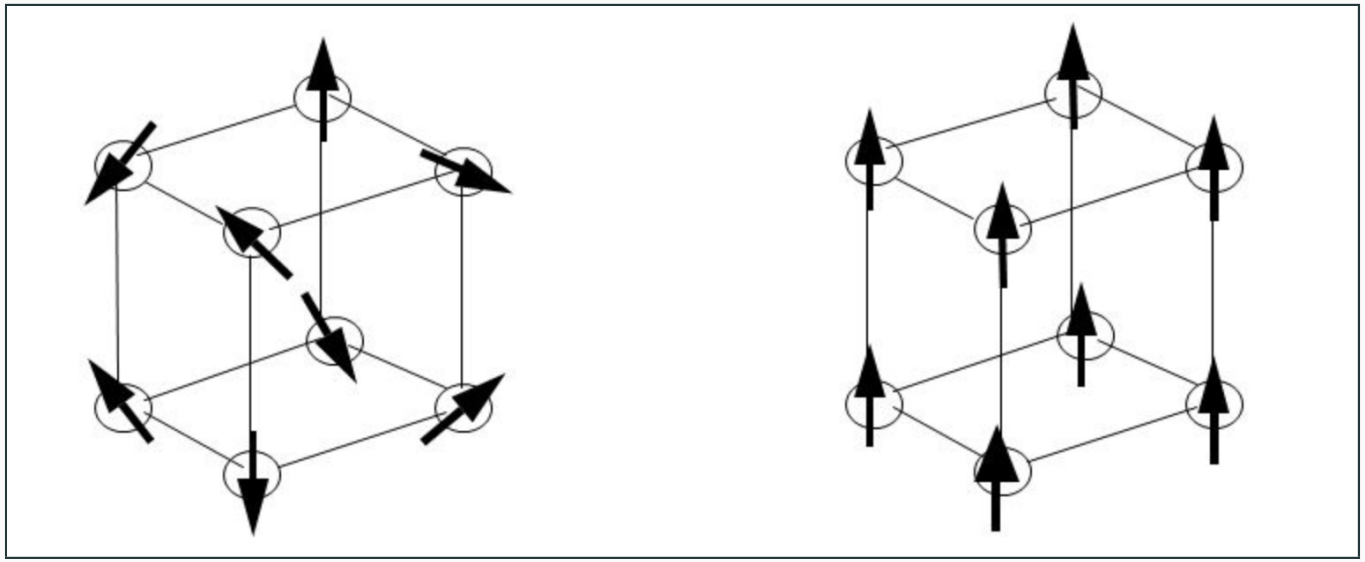


- Blue: GWs from sound waves only; red: GWs from bubble collisions only
- Preference for low temperature scale T_*; phase transition in a hidden sector

Cosmic defects

Magnetic domains in a ferromagnet

[wikimedia.org]



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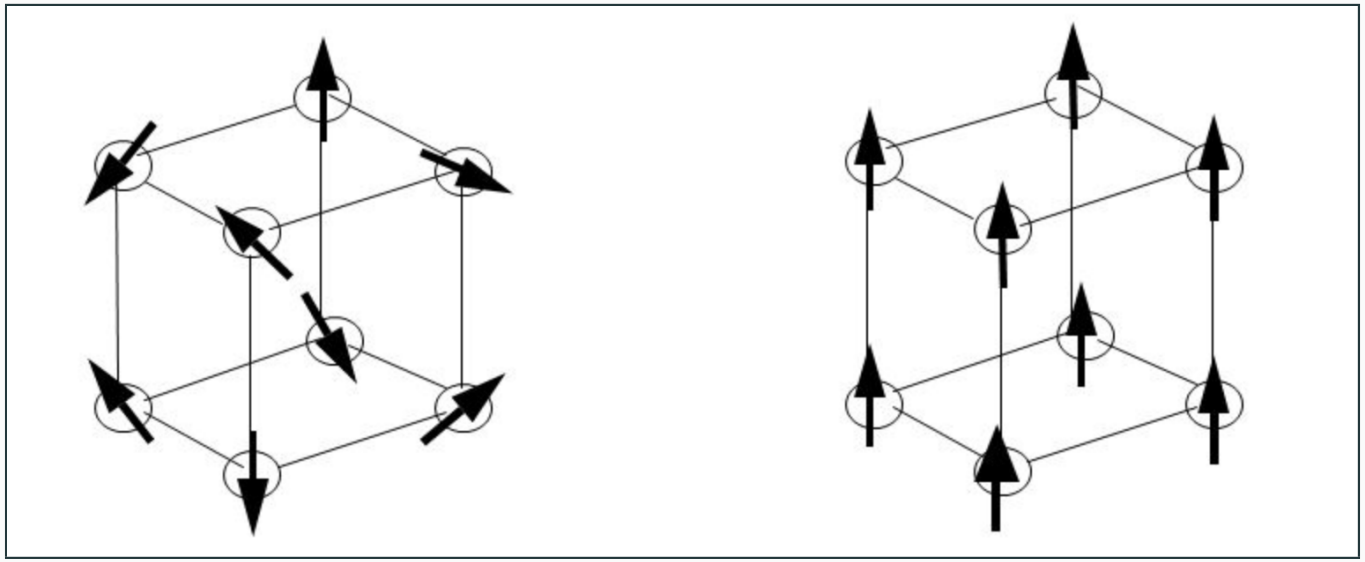
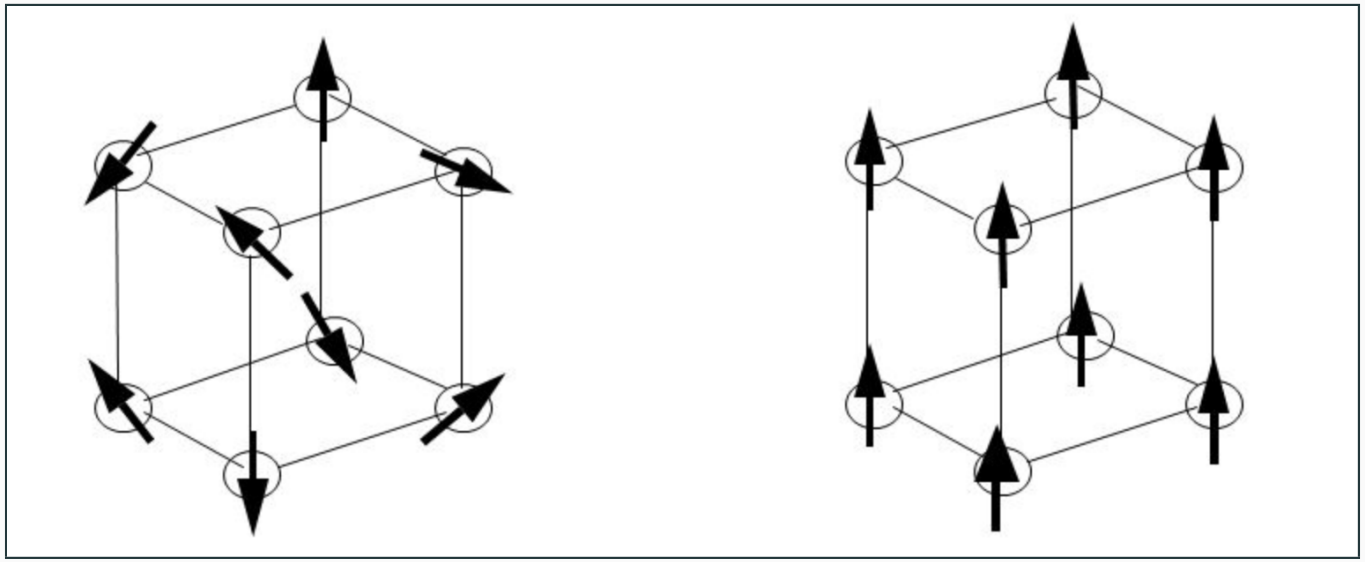


Magnetization in a ferromagnet

- Phase transition at the Curie temperature: paramagnet $\rightarrow$ ferromagnet

Magnetic domains in a ferromagnet

[wikimedia.org]



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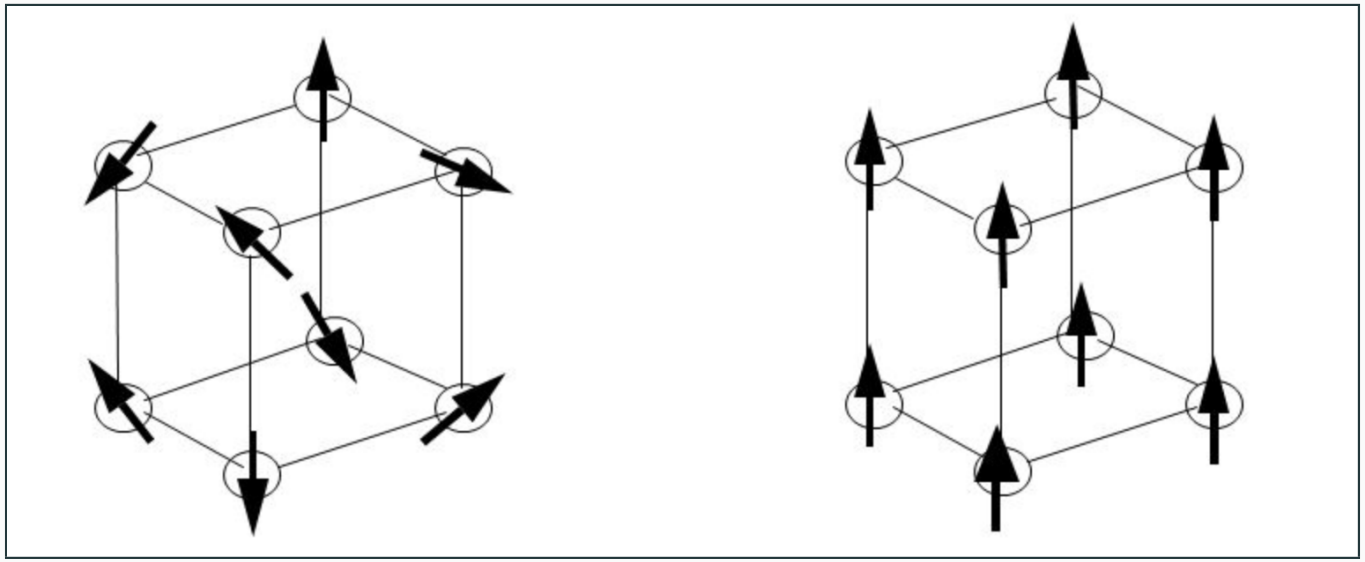

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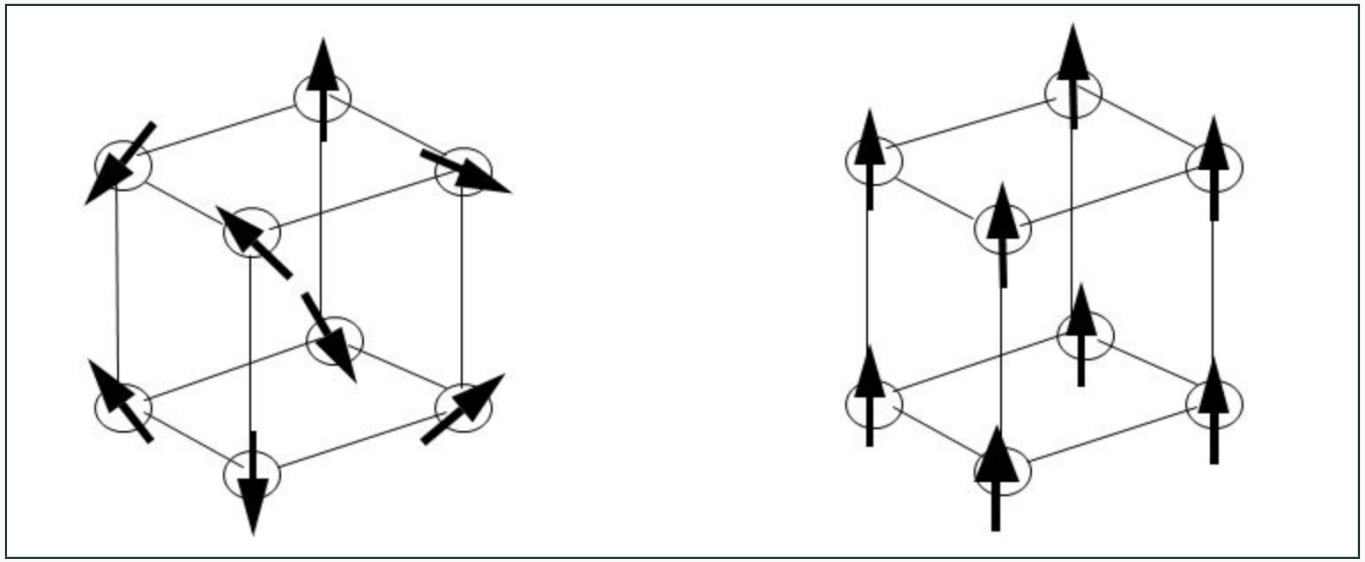

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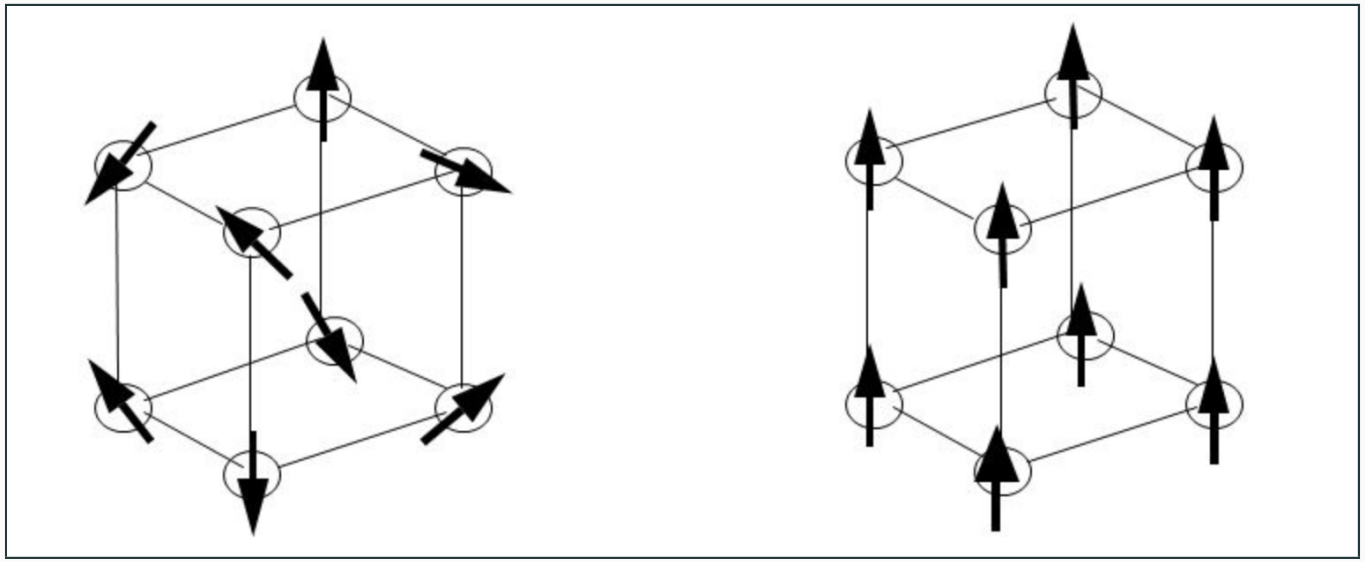

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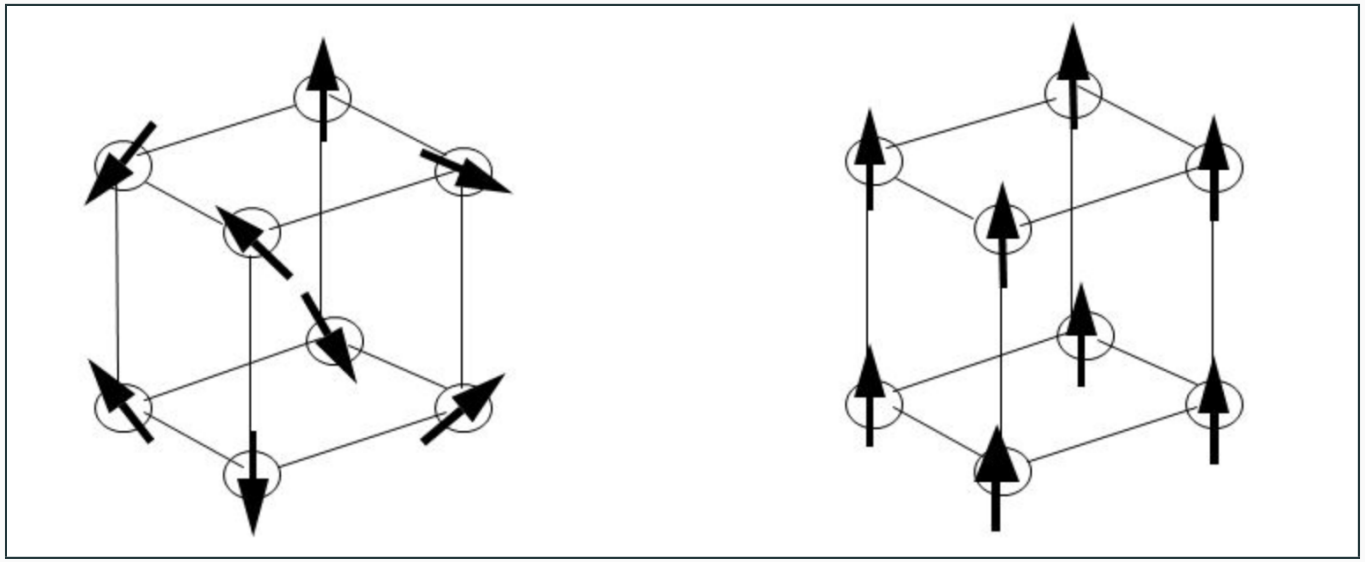

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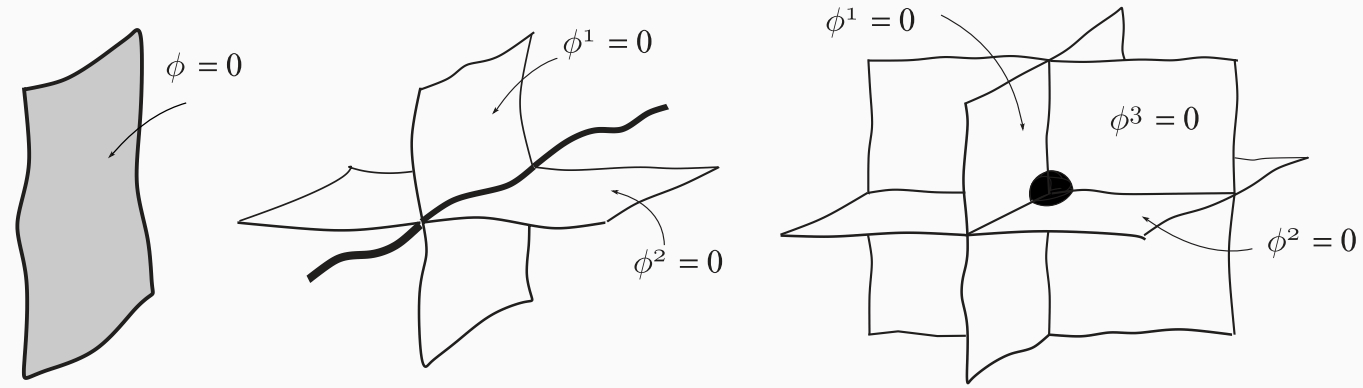
Similar phenomenology after phase transitions in the early Universe!

Topological defects in the early Universe

[Viatcheslav Mukhanov: Physical Foundations of Cosmology, Cambridge University Press (2005)]



domain wall string monopole

Consider spontaneous symmetry breaking in an N-dimensional scalar field space:

$$V(\Phi) = \frac{\lambda}{4}\left(\Phi^2 - v^2\right)^2, \qquad \Phi = \frac{1}{\sqrt{N}}\left(\phi_1, \phi_2, \cdots, \phi_N\right)^T$$

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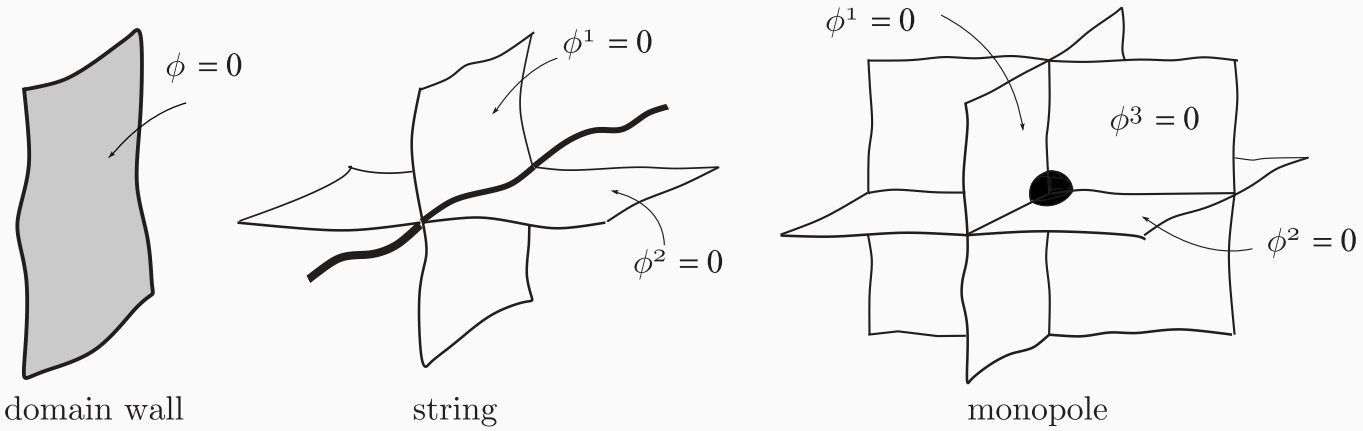

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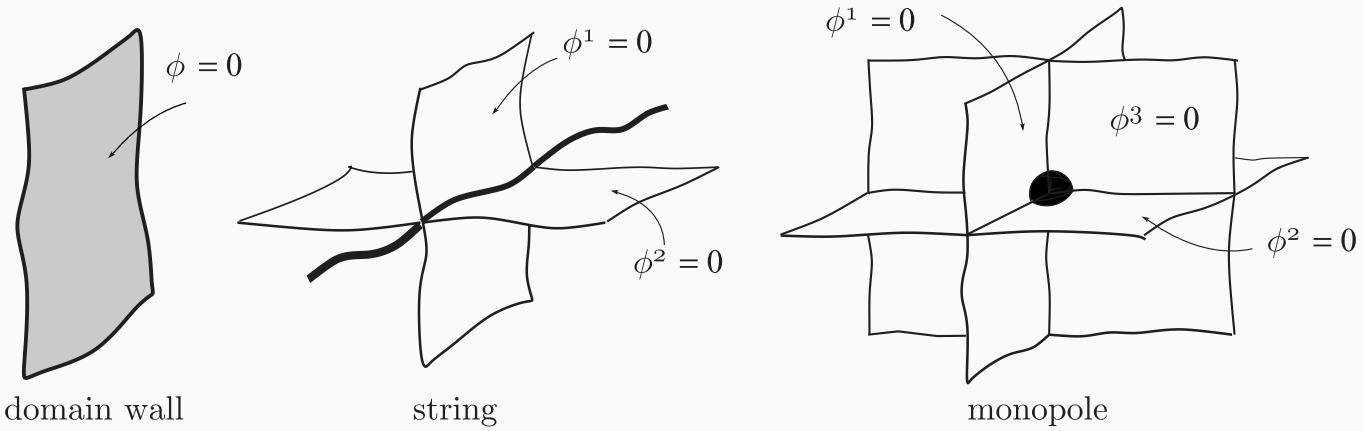

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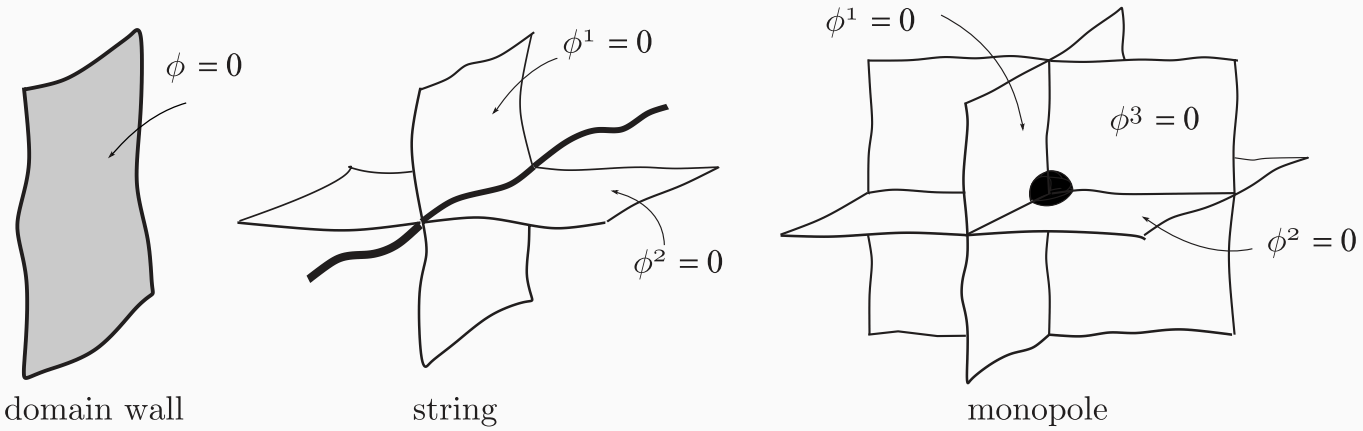

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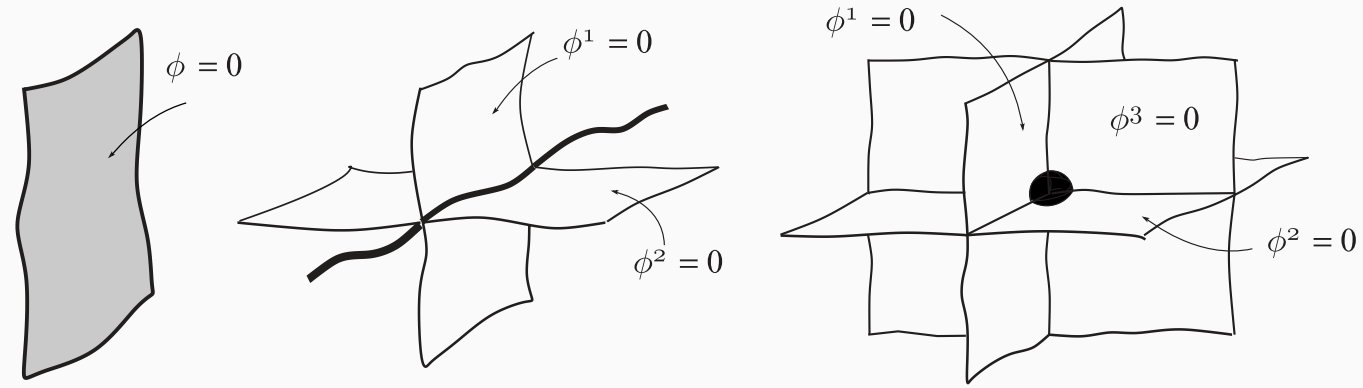

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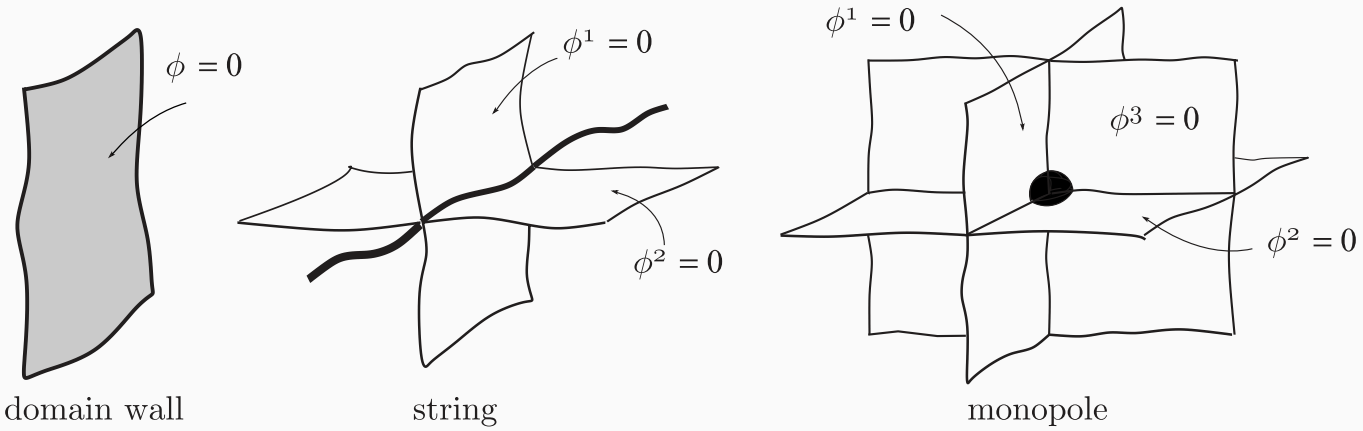

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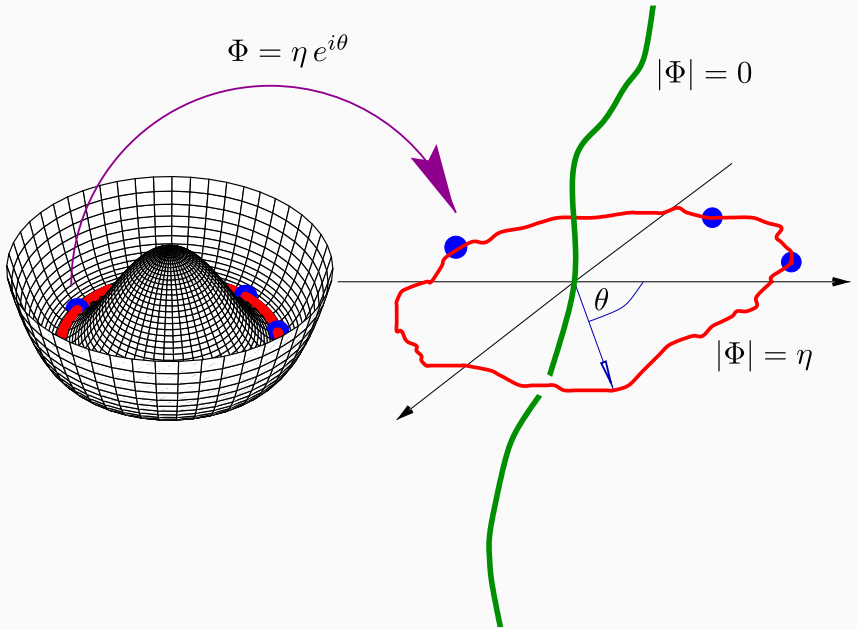
- In addition, whole zoo of composite defects, non-topological defects, etc.

Cosmic strings

[Ringeval: 1005.4842]



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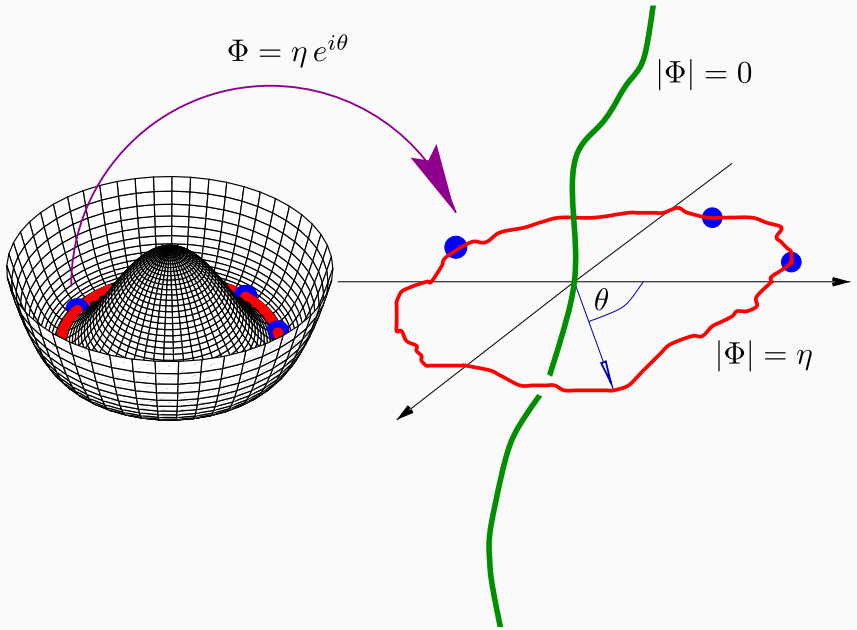

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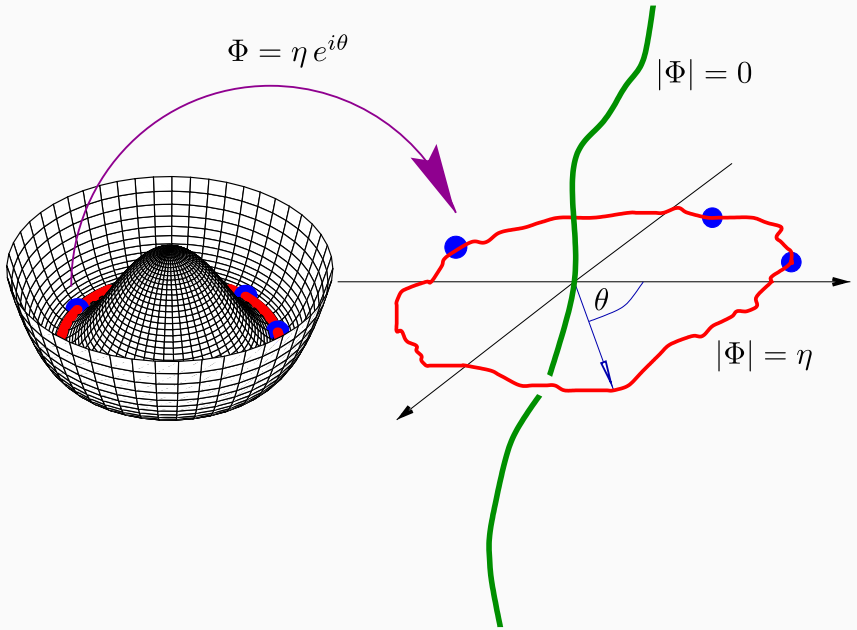

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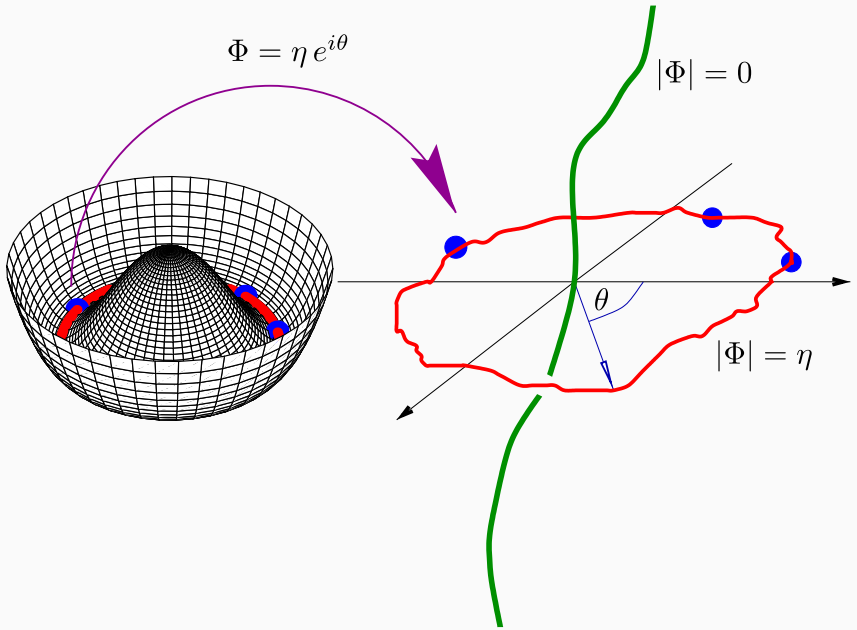

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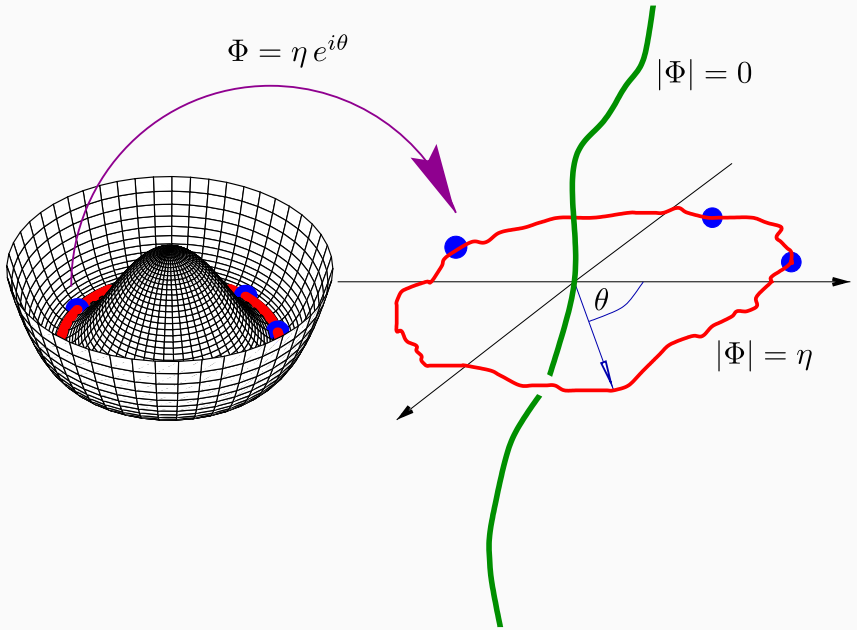

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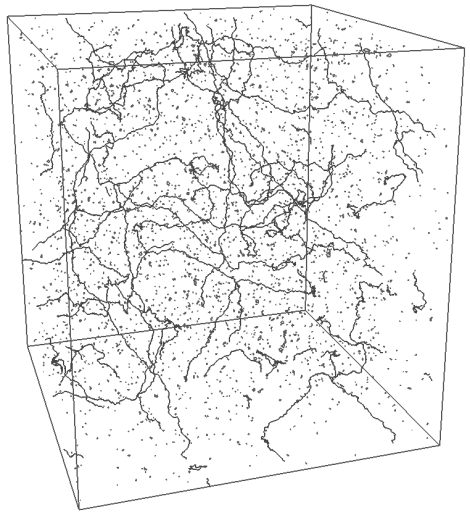
- α: Size of string loops at the time of formation, in units of H^{-1}

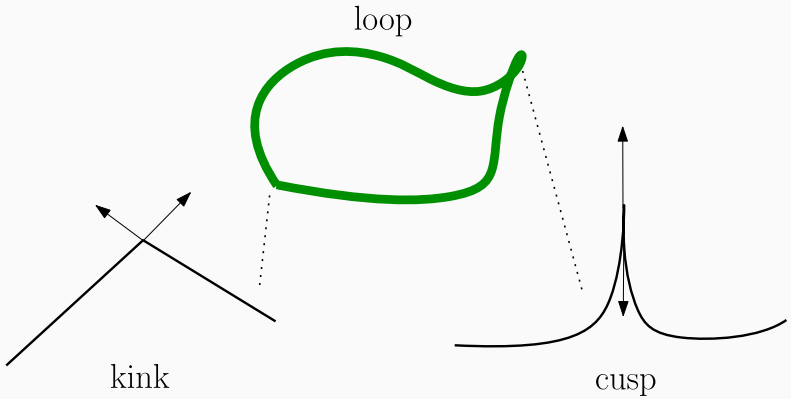
Gravitational waves from cosmic strings

[Allen, Martins, Shellard: ctc.cam.ac.uk/outreach]



Infinite strings and string loops;
scaling regime: $\rho_{\rm cs} \propto \rho_{\rm crit} \propto H^2$

[Gouttenoire, Servant, Simakachorn: 1912.02569]



Gravitational waves from

- Cusps
- Kinks
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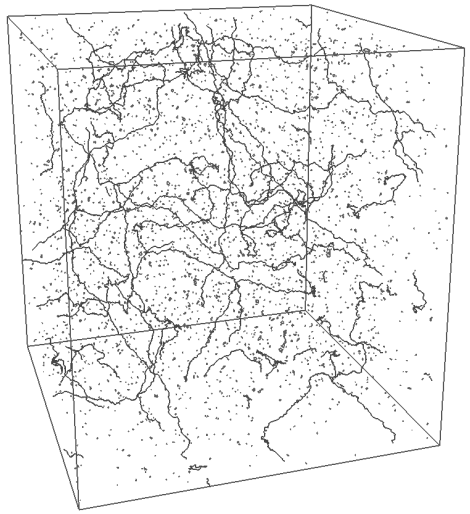

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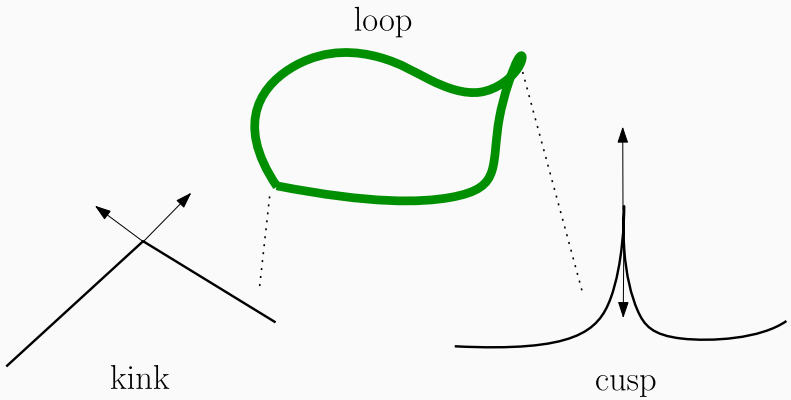

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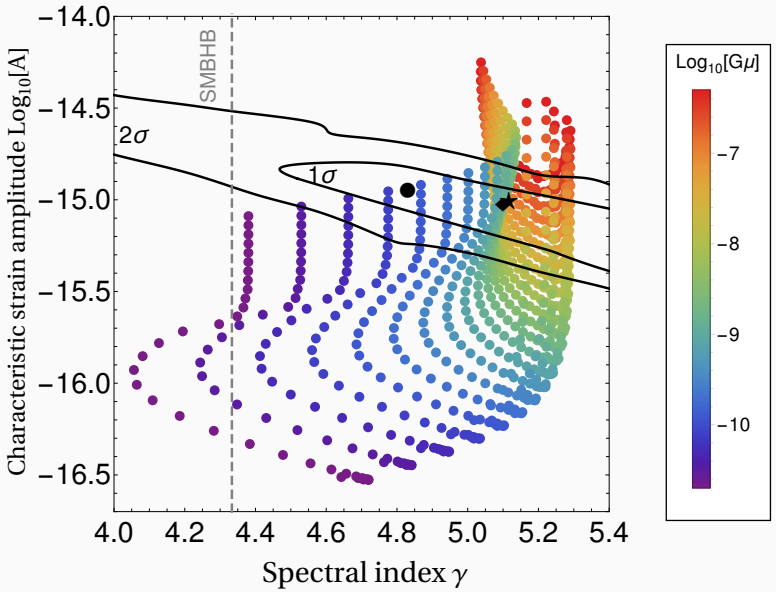
- Nambu–Goto action: infinitely thin strings, no particle emission
- Abelian-Higgs model: short-lived loops, decay into massive particles
- Nonminimal models: Metastable strings, current-carrying cosmic strings, ...

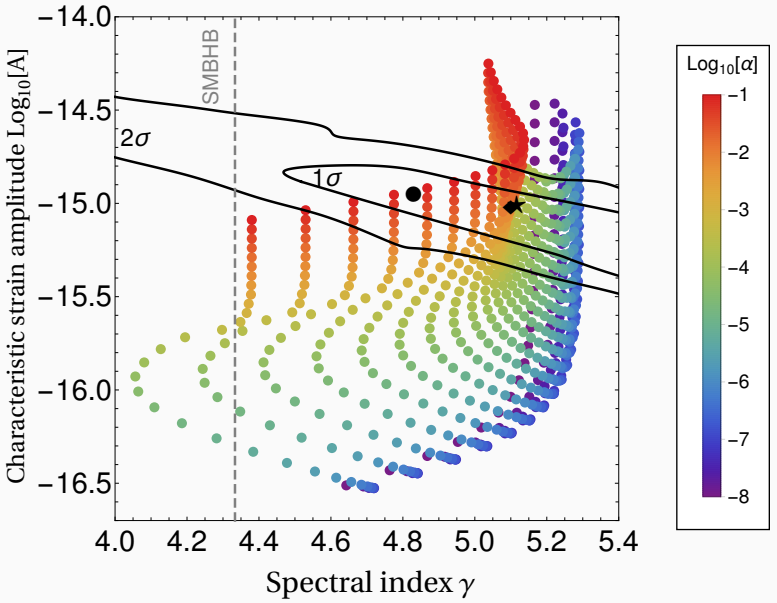
[Vachaspati, Vilenkin: PRD 31 (1985) 3052] [LISA Cosmology Working Group, Auclair et al.: 1909.00819]

Cosmic-string interpretation of the PTA signal

[Blasi, Brdar, **KS**: 2009.06607]
[See also Ellis, Lewicki: 2009.06555]



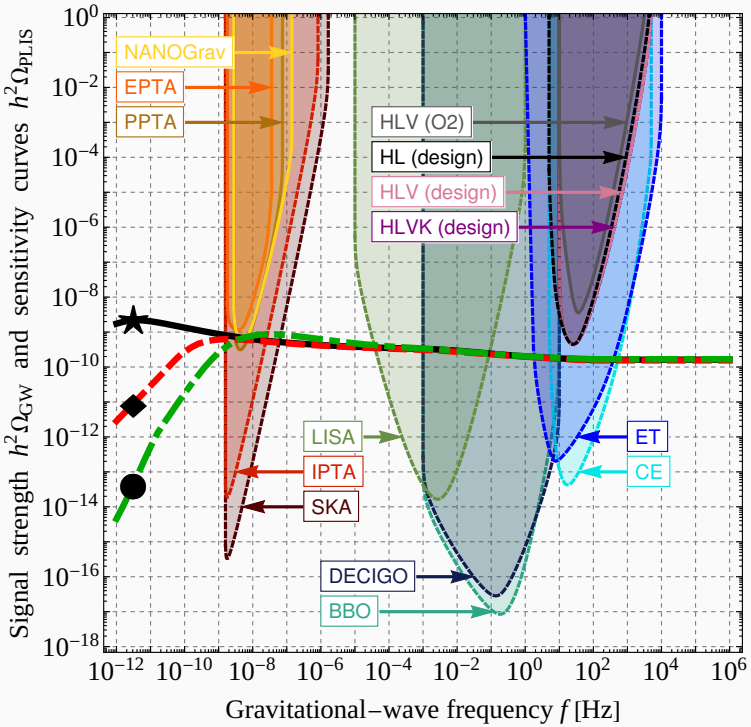
Color code: String tension $G\mu$



Color code: Loop size α

- Fit GW spectrum in the NANOGrav frequency range by a power law
- Straightforward to populate NANOGrav $1\,\sigma$ and $2\,\sigma$ posteriors on A and γ
- IPTA DR2 seems to prefer smaller γ and larger $A \rightarrow$ metastable strings?

Observational prospects



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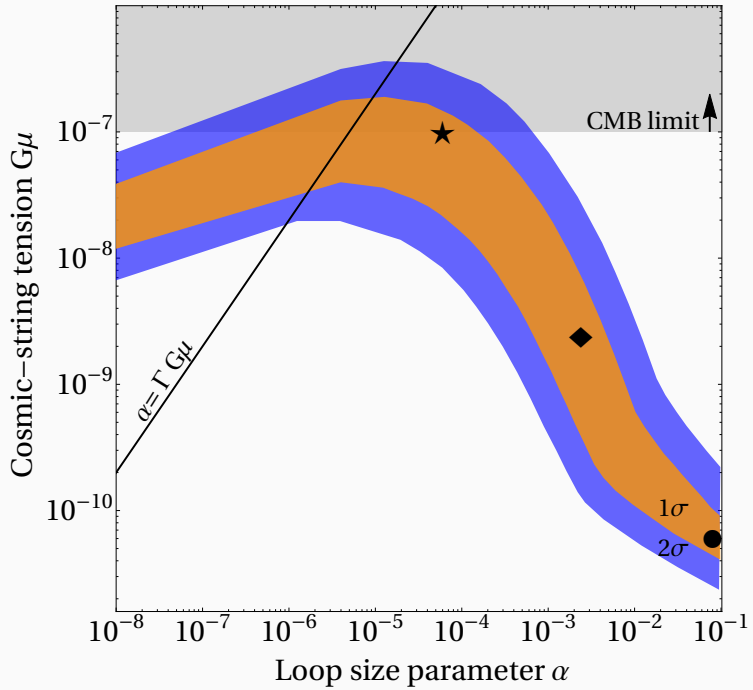


Complementarity

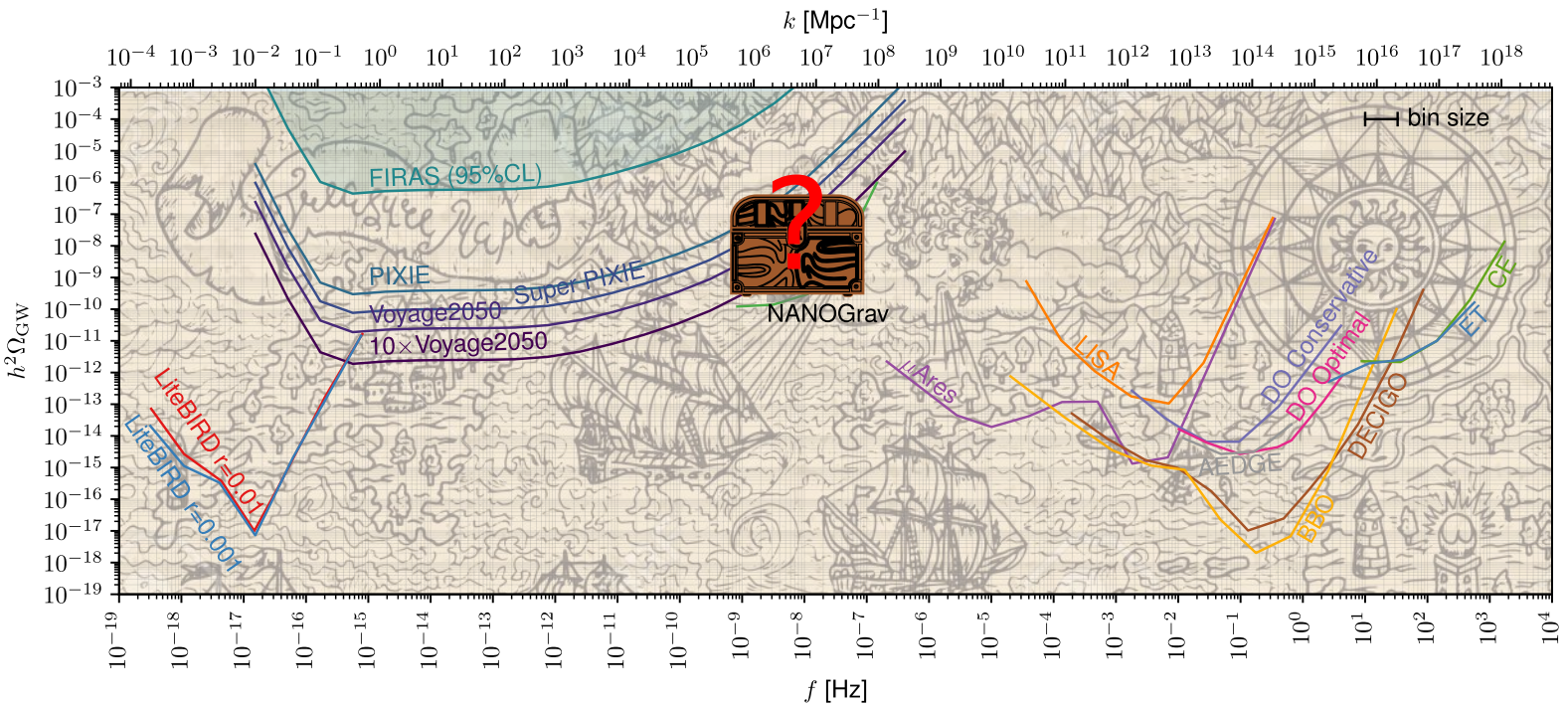
- Entire viable parameter space will be probed in future GW experiments

Relation to grand unification

- $G\mu \sim 10^{-(10\cdots7)}$ points to $U(1)$ breaking scale $v \sim 10^{14\cdots16}\,\mathrm{GeV}$

Conclusions

Summary



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- Insights into cosmic inflation, phase transitions, grand unification, etc.
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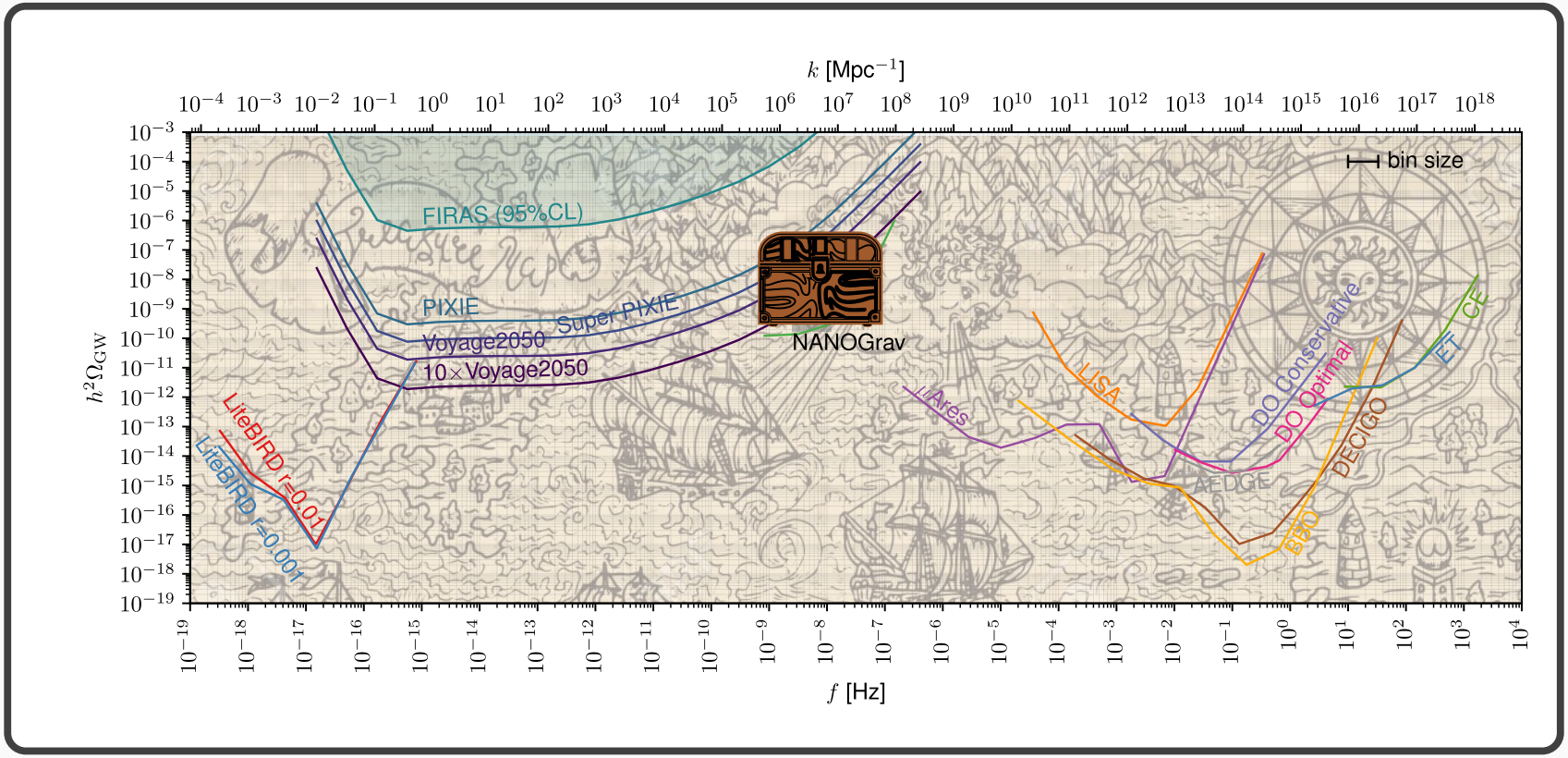

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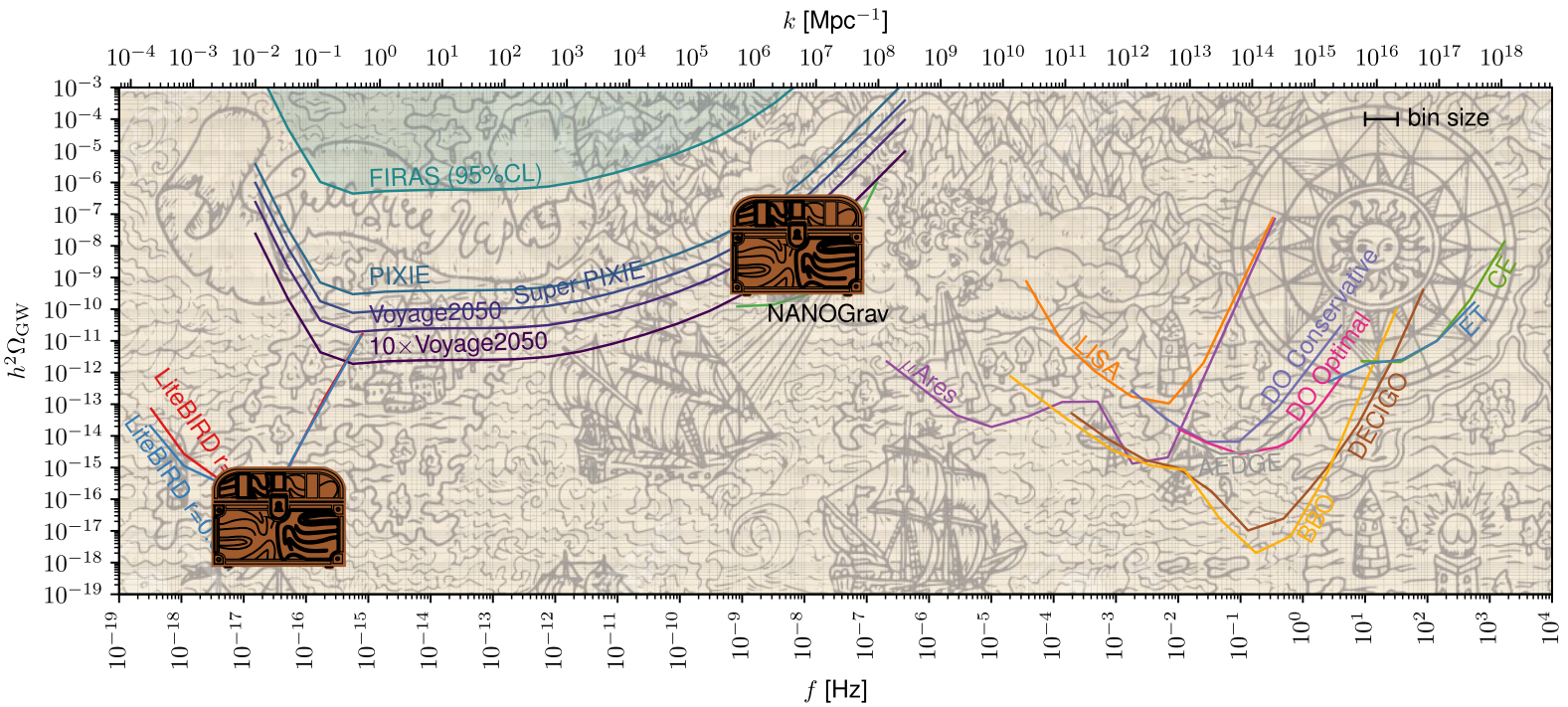

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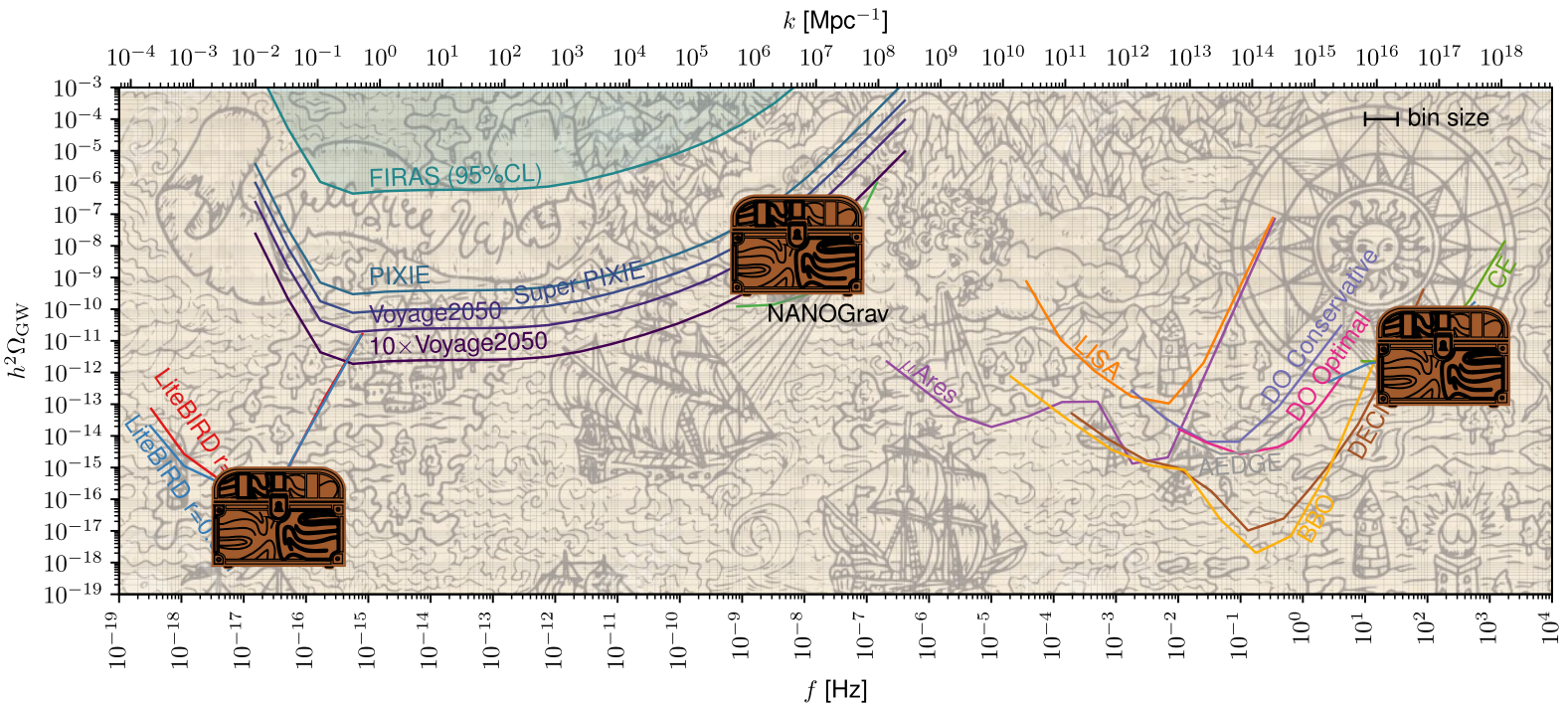

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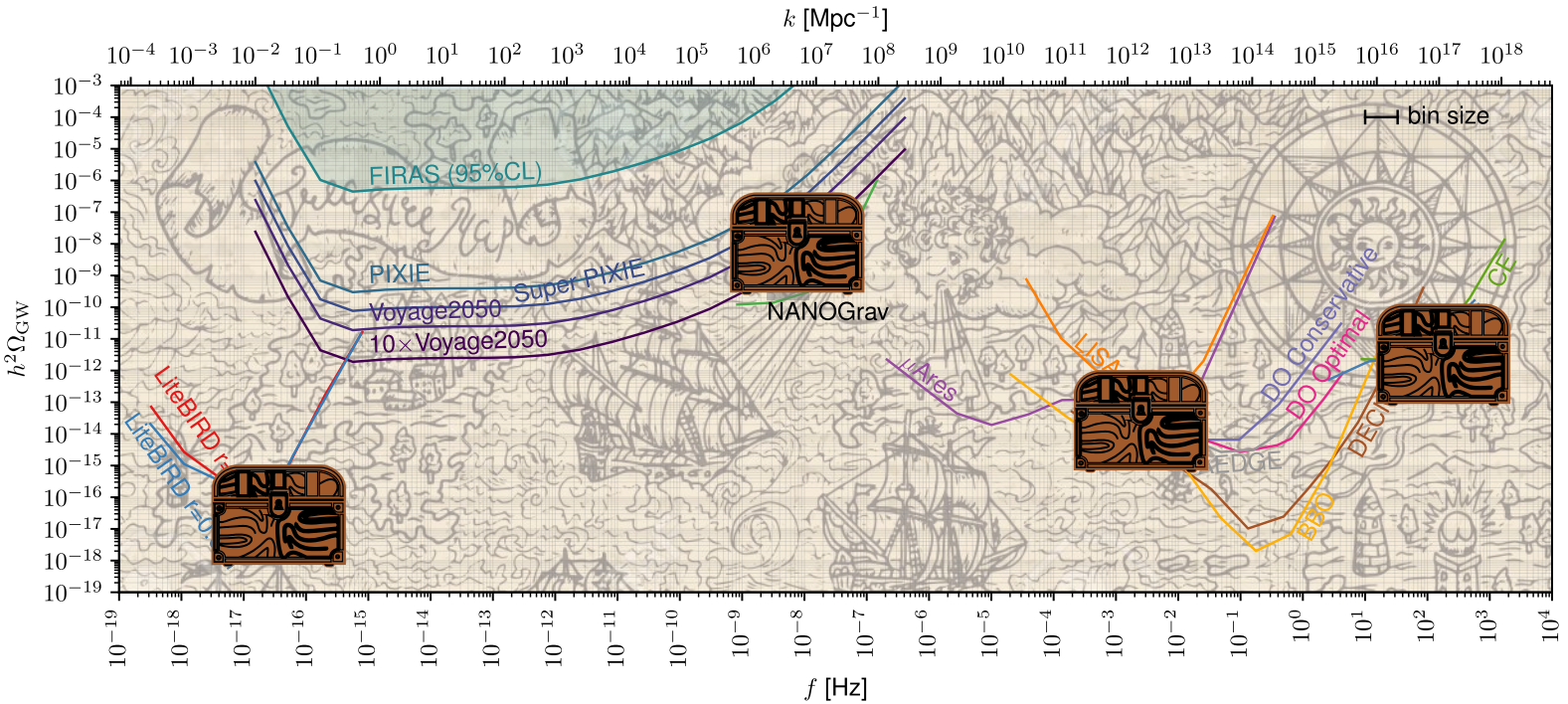

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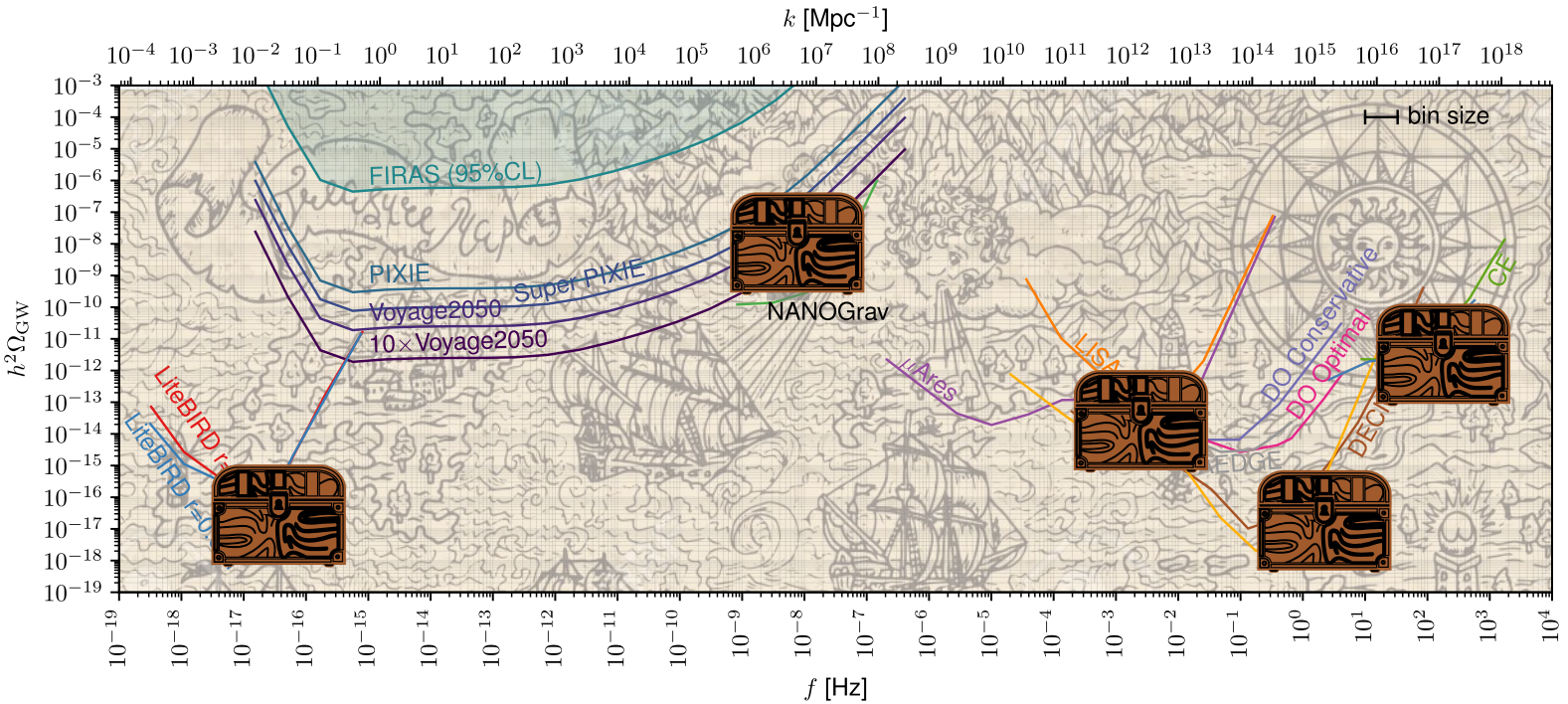

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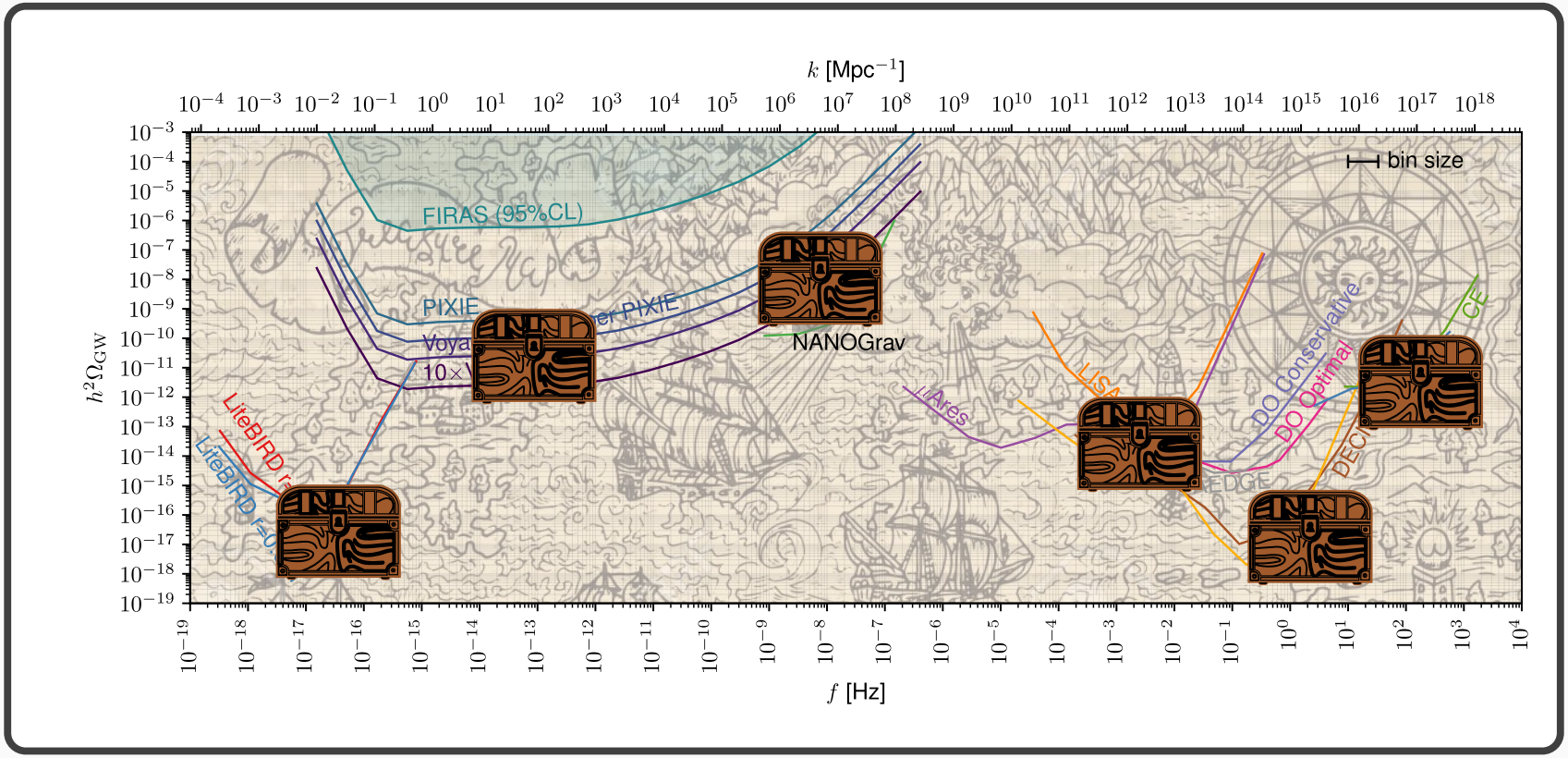

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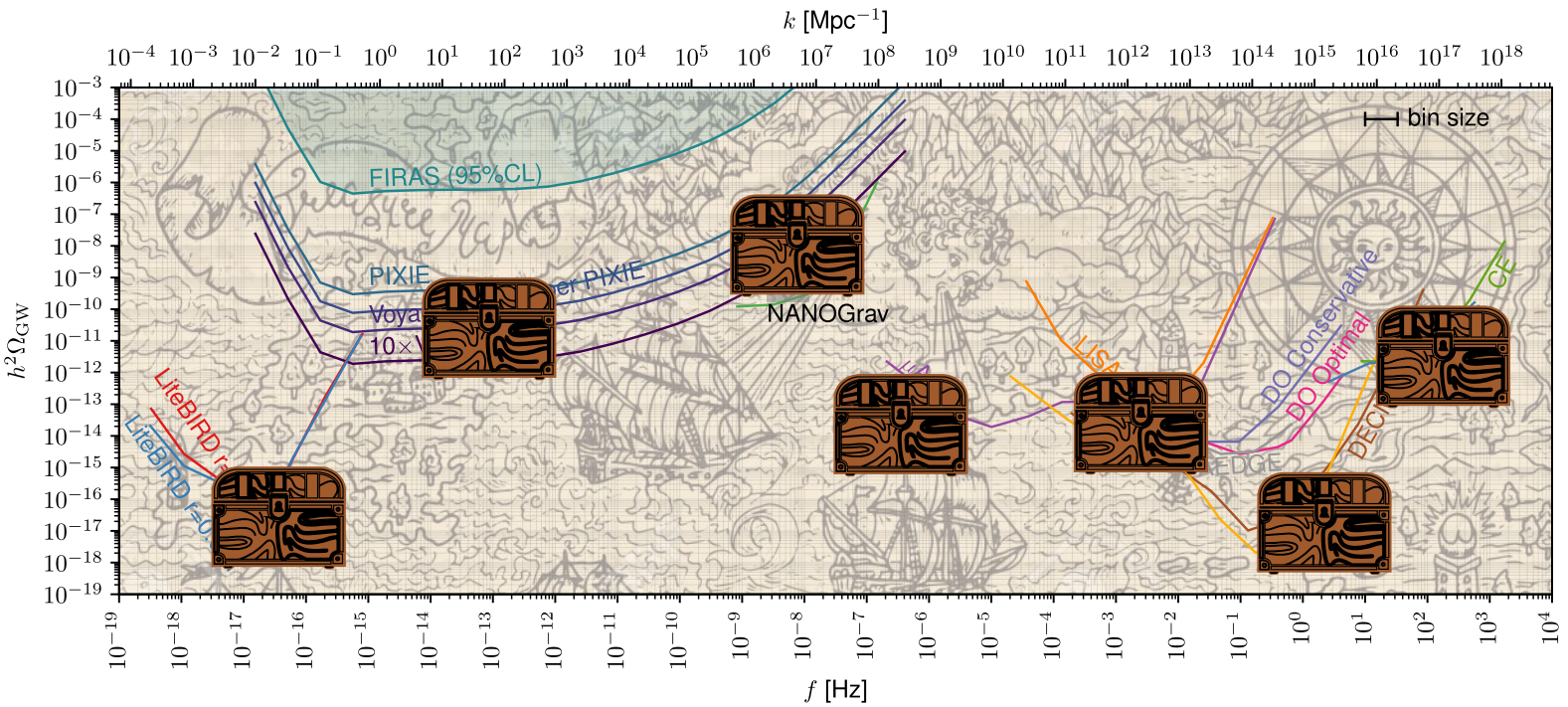

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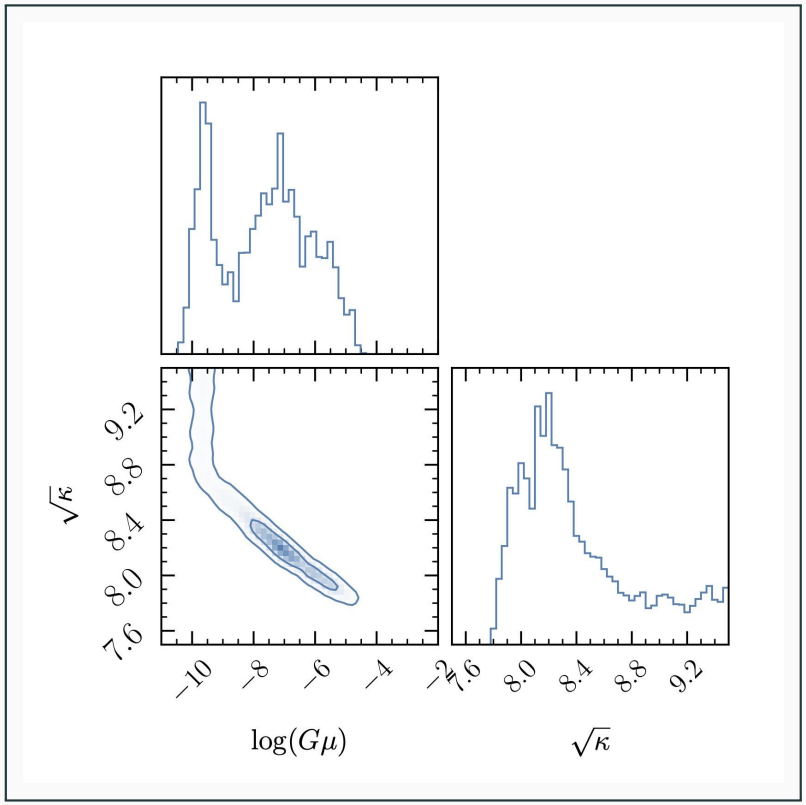
Outlook

Preliminary results!!! IPTA DR2 search for metastable strings



On-going analyses

- IPTA DR2: Search for GWs from cosmic strings (stable, metastable, ...)
- IPTA DR2: Search for GWs from a cosmological phase transition
- NANOGrav 15-year data: Search for a whole range of exotic GW sources

Stay tuned!

And thanks a lot for your attention