Insights into Fundamental Physics from Cosmological Gravitational Wave Sources

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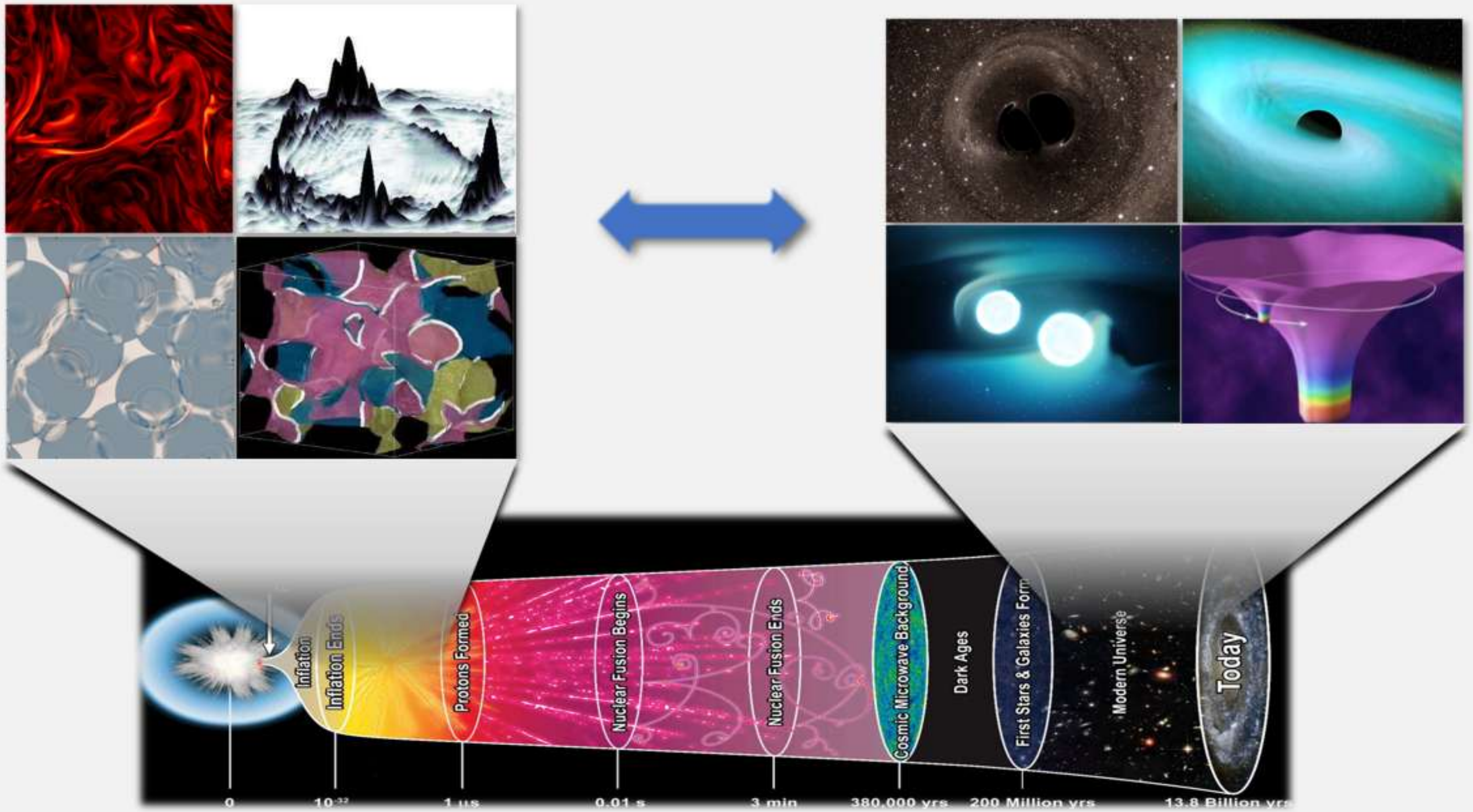
Based on:
- **Jing Liu**, Ligong Bian, Zong-Kuan Guo, Rong-Gen Cai, Shao-Jiang Wang, Phys.Rev.Lett. 126 (2021) 14, 141303
- **Jing Liu**, Phys.Rev.D 108 (2023) 12, 123544
- Chengjie Fu, **Jing Liu**, 2506.14366
- Zhen-Min Zeng, **Jing Liu**, Zong-Kuan Guo, Phys.*Rev.D* 108 (2023) 6, 063005

TAUP2025

August 26th, 2025, Xichang

Contents

Cosmological Sources   Compact Binaries

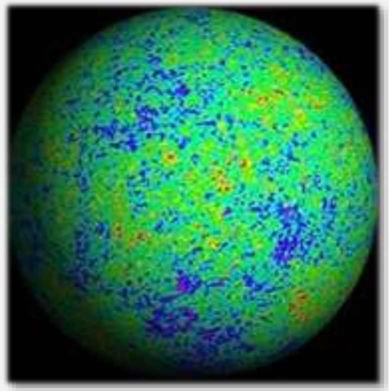


Common features

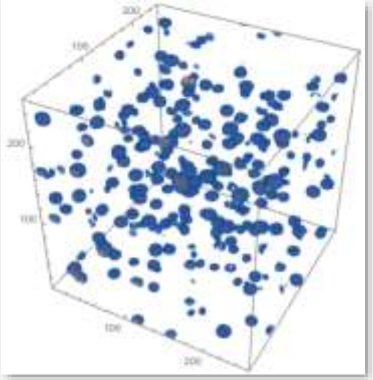
1. Stochastic continuous and approximately isotropic GW background
2. Generally speaking, in the early Universe
3. Motivated by new physics

GW sources within GR

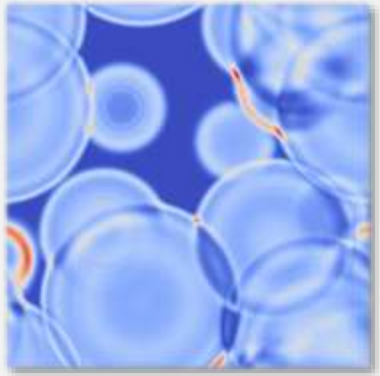
Curvature perturbations



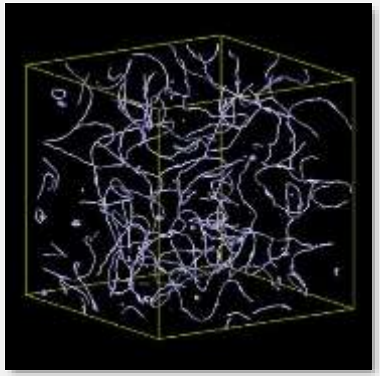
Condensate fragmentation



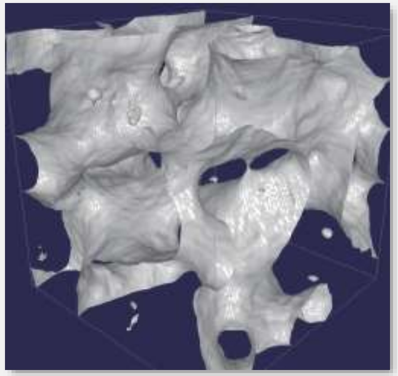
first-order phase transition

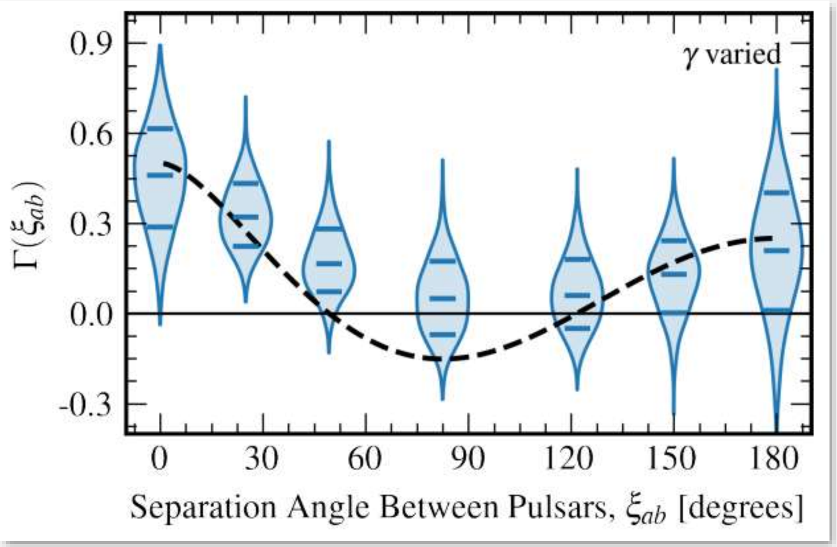


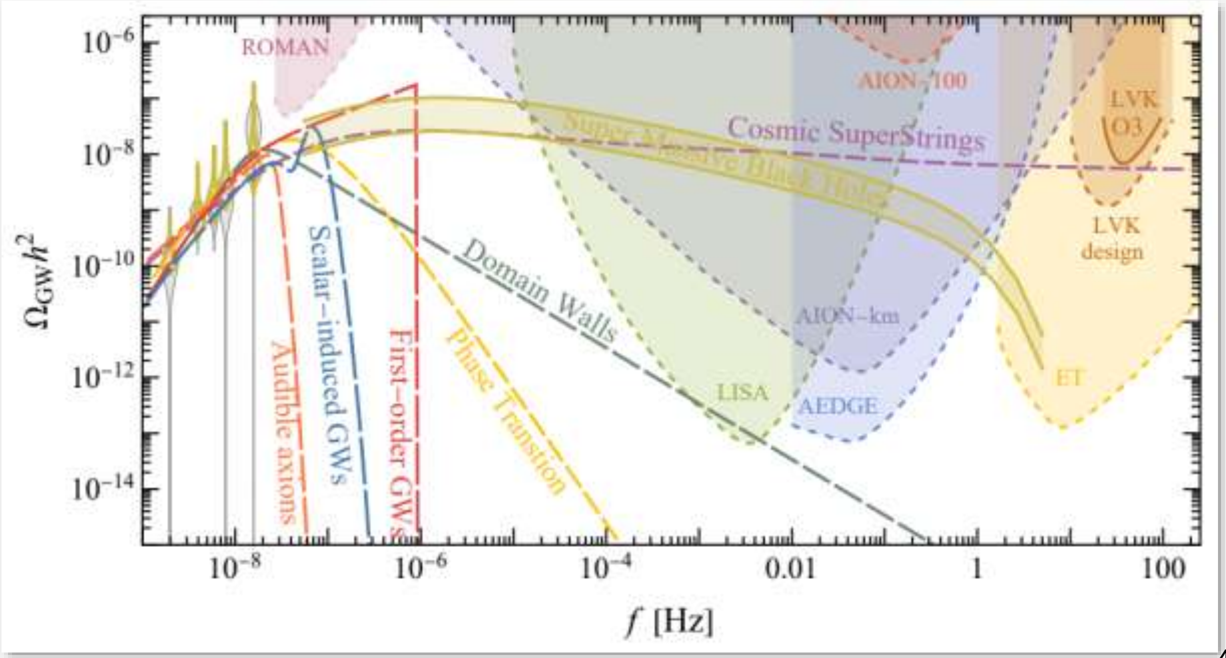
cosmic string

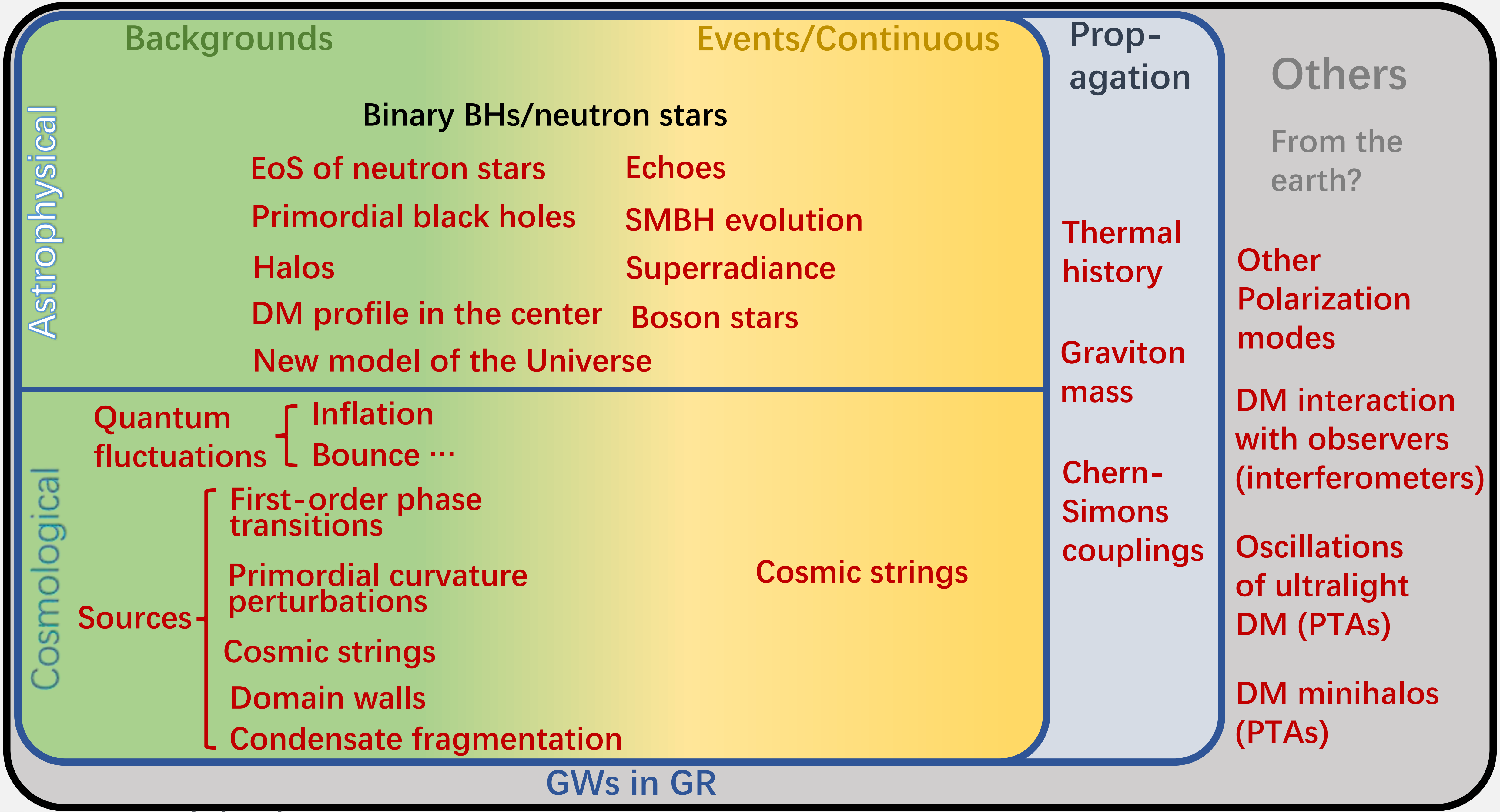


domain wall







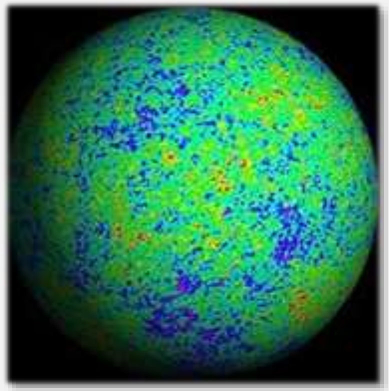


To Be Added

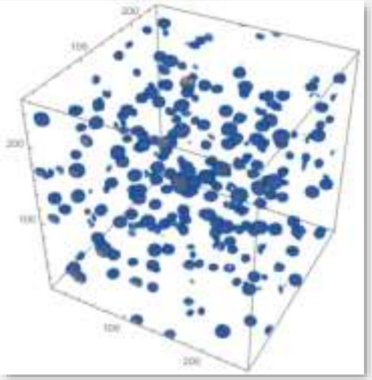
Signal

The origin

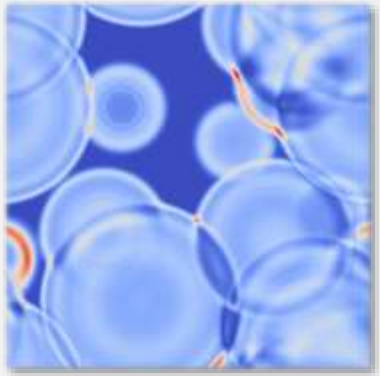
Curvature perturbations



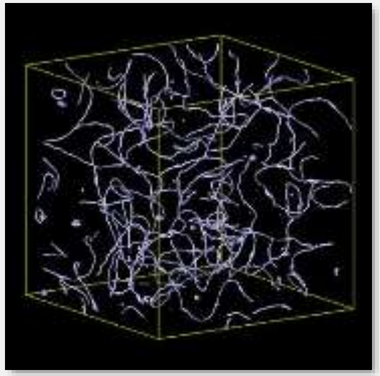
Condensate fragmentation



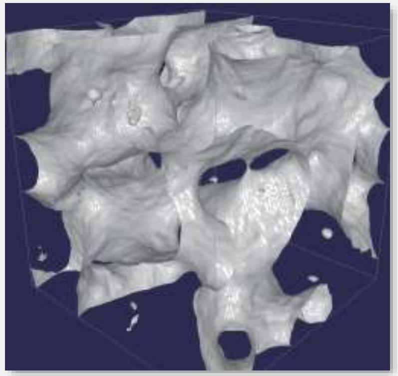
first-order phase transition



cosmic string



domain wall



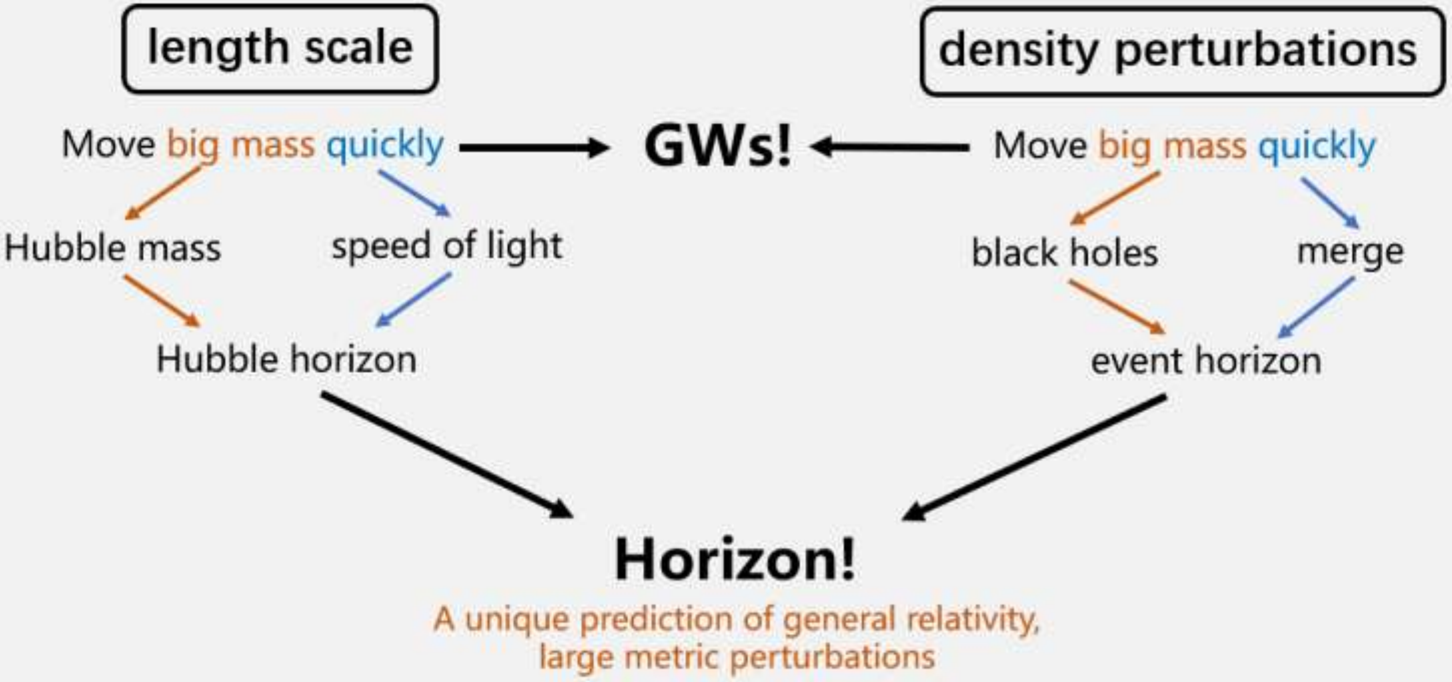
- **Inflation**
  - Induced after inflation
- **End of Inflation**
  - Spectators after inflation
- **After Inflation**
  - During inflation
- **After inflation**
  - Induced by fluctuations during inflation or diluted by inflation

Inflation

1. Quantum fluctuations during inflation
2. The dynamics of inflaton or spectators during inflation

Phase transitions

1. Direct production of GWs during first-order phase transitions
2. GWs from topological defects as the consequence of phase transitions



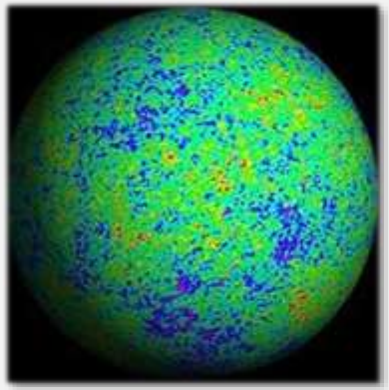
Cosmological

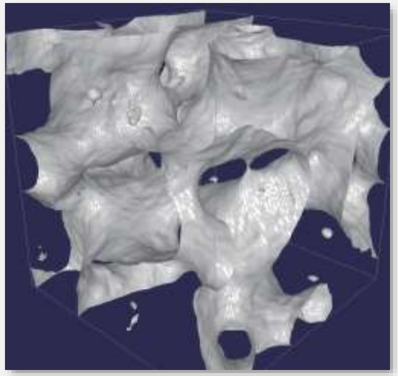
Astrophysical

$\sim$ Hubble scale

$$\text{Energy scale} < 10^7\,\text{GeV} \times f/\text{Hz}$$

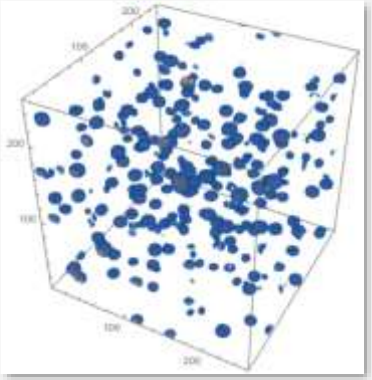
Naturally horizon scale



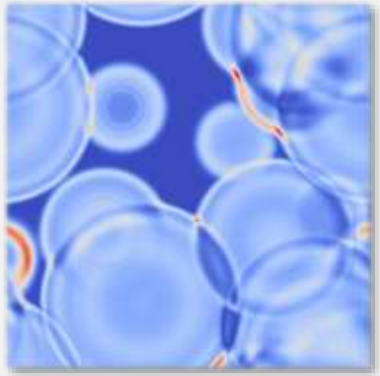


Parameter dependent:

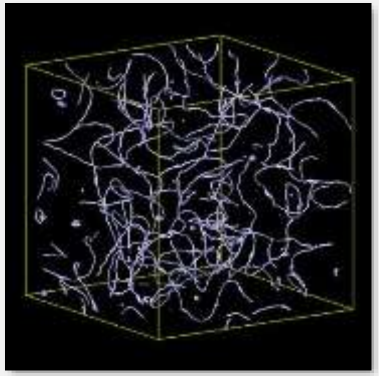
1.resonance band



2.PT speed



3.string interval

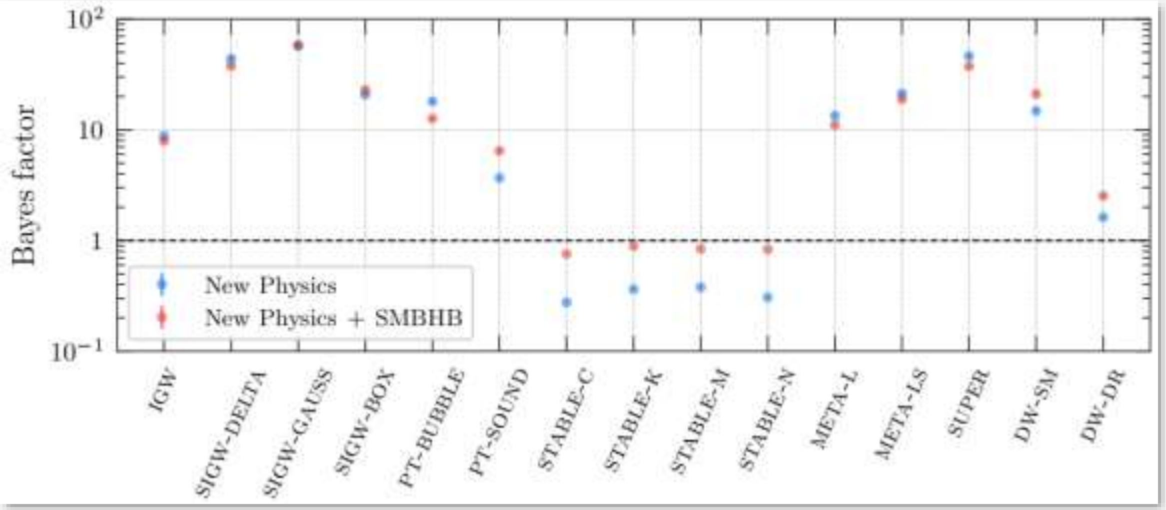


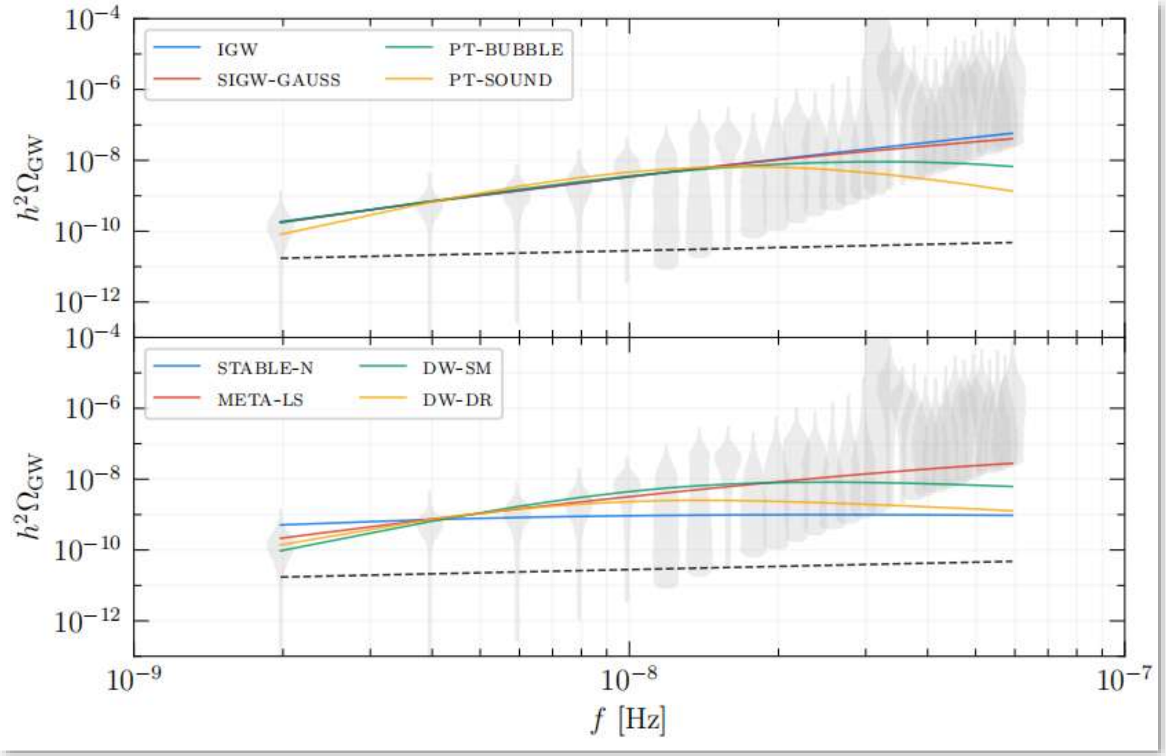
Observations

Direct LIGO and PTA at present, LVK for constraints and PTA for interpretations

CE/ET, LISA/Taiji/Tianqin, DECIGO/BBO, SKA, μ-era, high-frequency detectors…

Indirect binaries, astrometry, magnetic fields, primordial black holes, BBN, Neff





Associated observables

- Anisotropies
- Primordial black holes,
- Particle dark matter models,
- Curvature perturbations,
- Primordial magnetic fields,
- Background evolution,
- Baryon asymmetry, and so on…

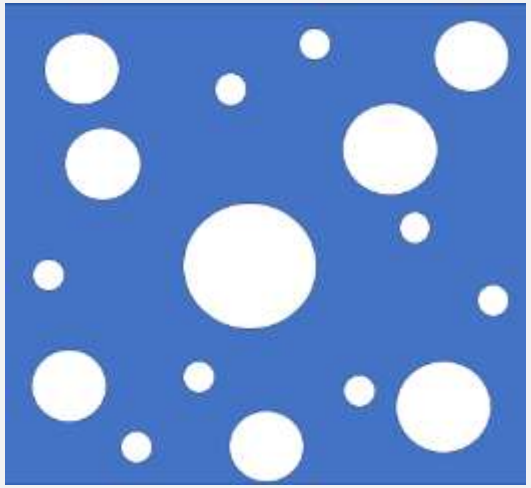
- Dark matter
- Hubble tension
- Baryon asymmetry
- Intergalactic magnetic fields
- The seed of supermassive black holes

Ockham's razor

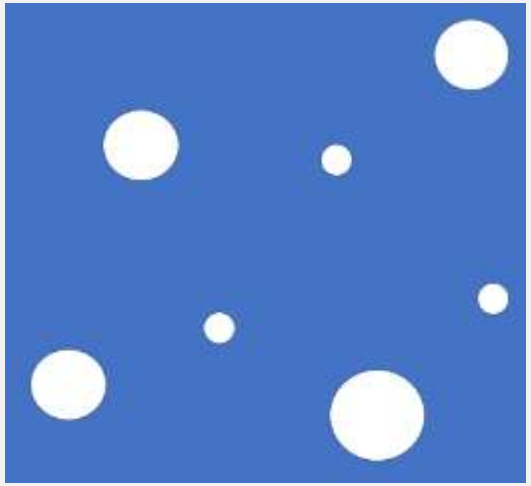
Mutual verification/constraints

In the FLRW Universe

Vacuum energy ~ constant
Radiation ~ a^{-4}
Cold matter ~ a^{-3}



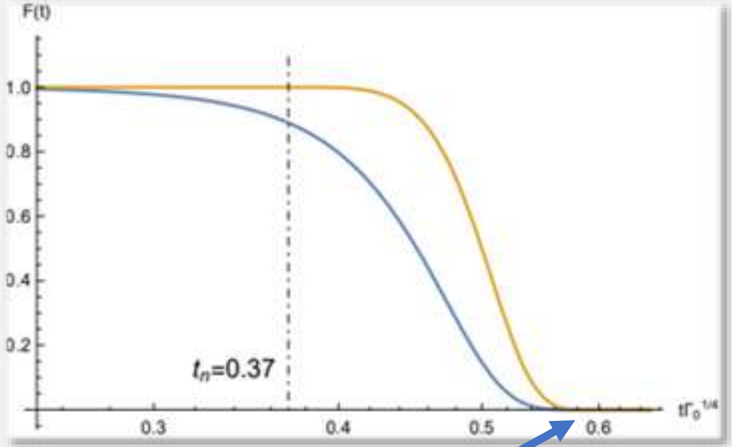
Region 1



Region 2

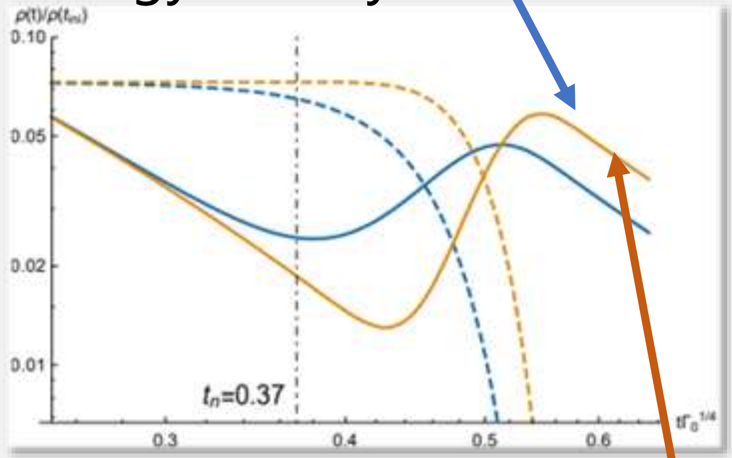
Region 1		Region 2
Faster	The speed of vacuum decay	Slower
Lower	Energy density after the FOPT	Higher

False vacuum fraction



δρ/ρ reaches the maximum when false vacuum completely decay inside

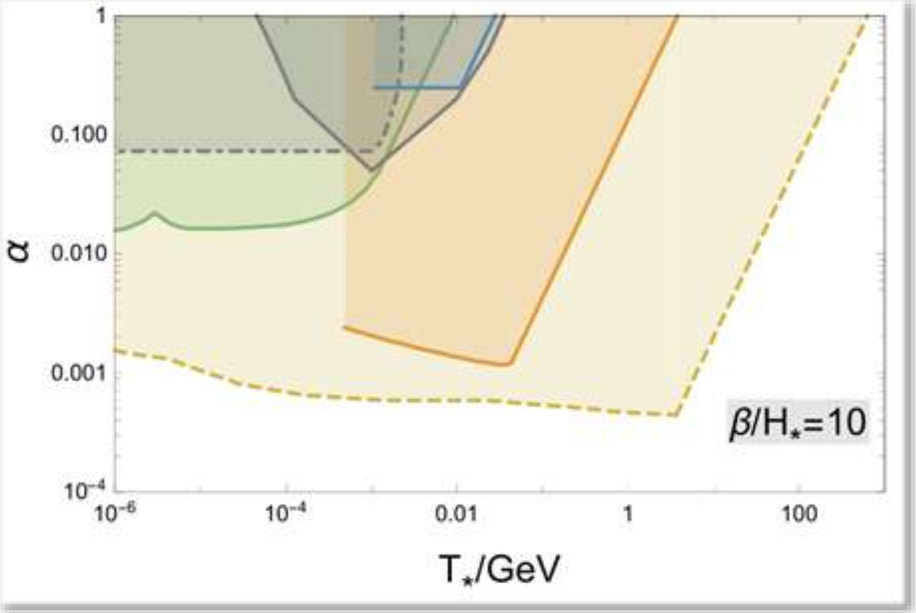
Energy density

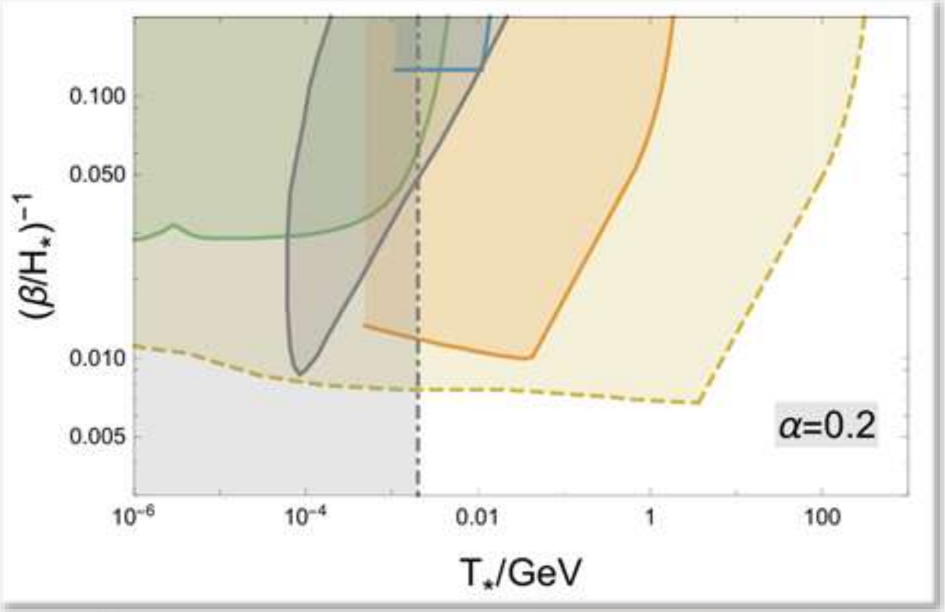


Vacuum energy decays into radiation and relativistic bubble walls

Constraints on PT parameters

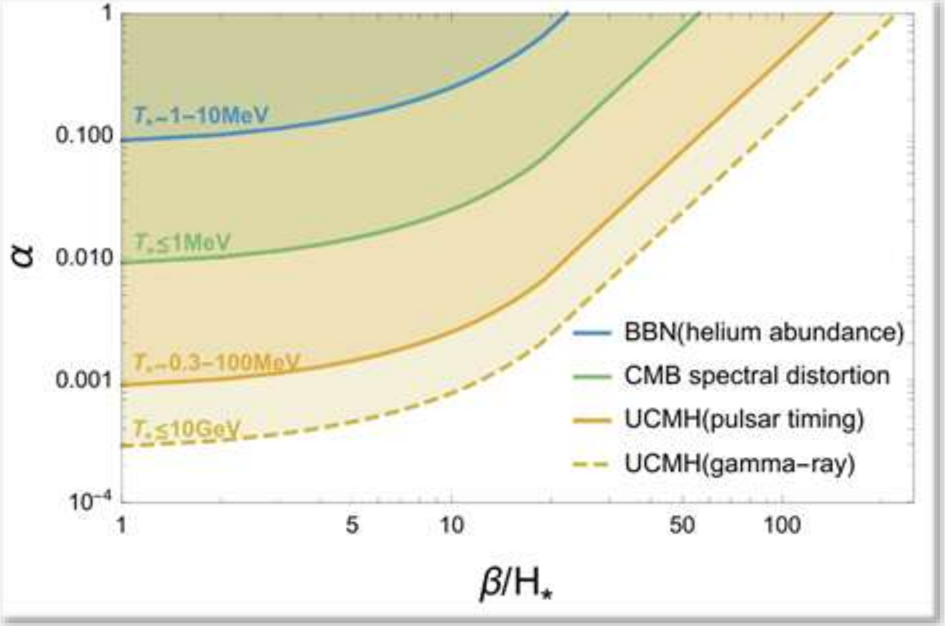
Jing Liu, Ligong Bian, Zong-Kuan Guo, Rong-Gen Cai, Shao-Jiang Wang, Phys.Rev.Lett. 126 (2021) 14, 141303





$$\delta_H \equiv \sqrt{(\delta\rho(H_*^{-1})/\rho)^2} \propto \alpha(\beta/H_*)^{-5/2}$$

More strict for low-scale and slow FOPTs



What if dark matter are produced from an FOPT?

Numerical simulations from Prof. Ligong Bian

Zou, Jintao and Zhu, Zhiqing and Zhao, Zizhuo and Bian, Ligong, 2502.20166

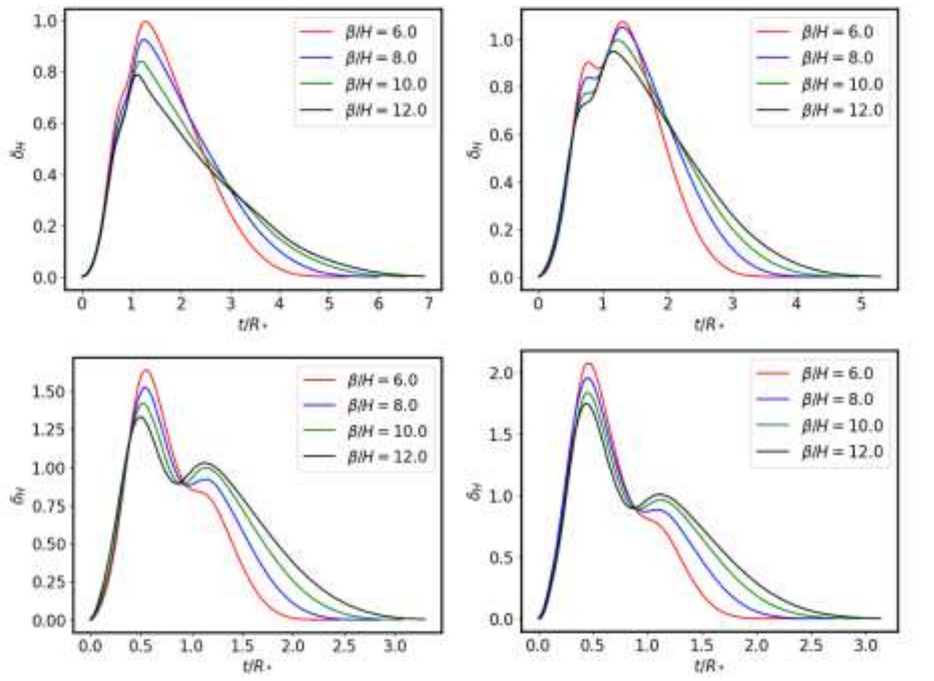


FIG. 2: Evolution diagram of $\delta_H(t) = \int \frac{dk}{k}\mathcal{P}_\delta(t)$ during FOPT process. The panels are arranged in a 2×2 grid: $\alpha = 0.5$ (top-left), $\alpha = 1$ (top-right), $\alpha = 5$ (bottom-left), and $\alpha = 10$ (bottom-right). The contribution from smaller scales ($kR^* > 1.3$) has been droped.

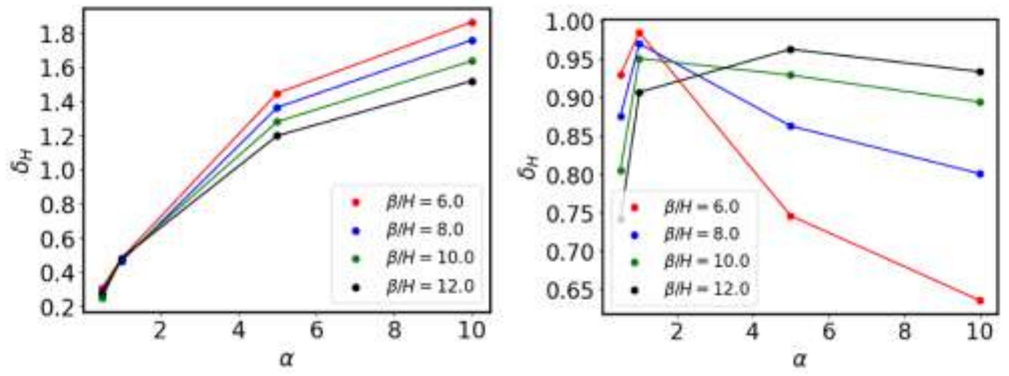


FIG. 3: For $\beta/H = 6, 8, 10, 12$, the left panel shows δ_H at the first peak $t/R^* = 0.5$, while the right panel presents δ_H at the second peak $t/R^* = 1.2$.

The second peak comes from the energy flow.

An FOPT that only affect the coupling…

$$V_{\text{int}} \sim \chi\phi\psi\overline{\psi}$$

FOPT field

Massive, cold matter

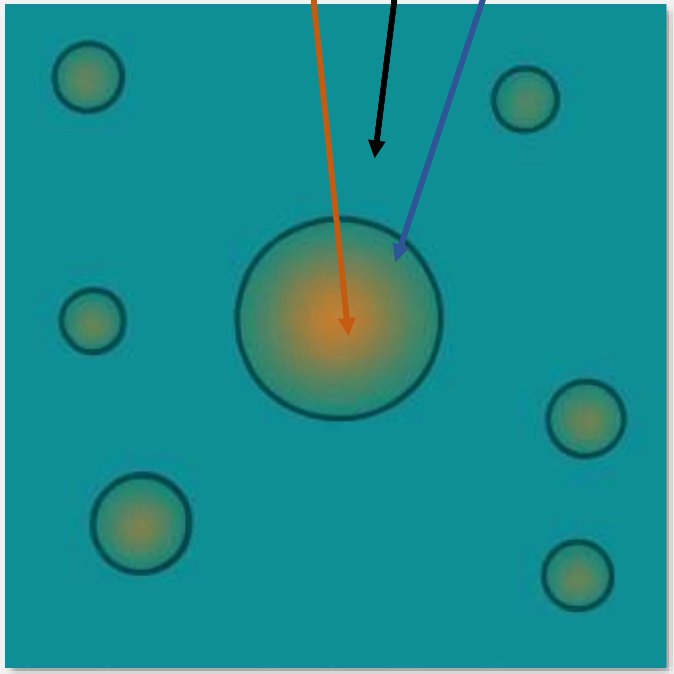
Radiation

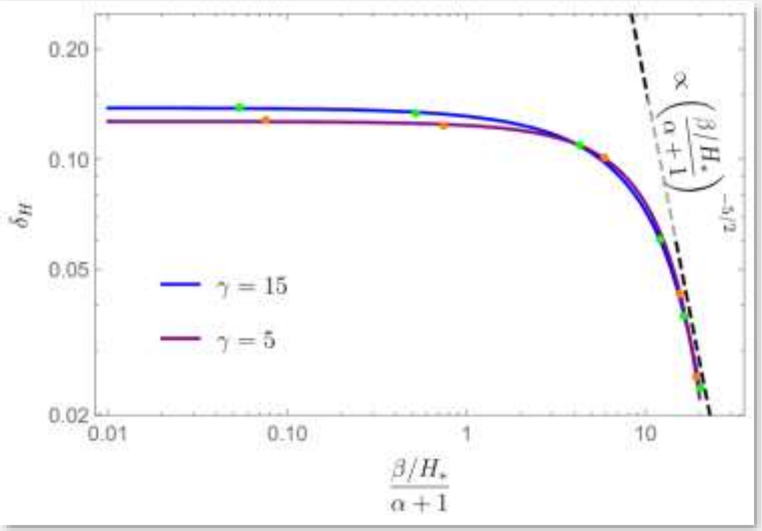
Xiao-Bin Sui, **Jing Liu**, Rong-Gen Cai, 2509.xxxxx

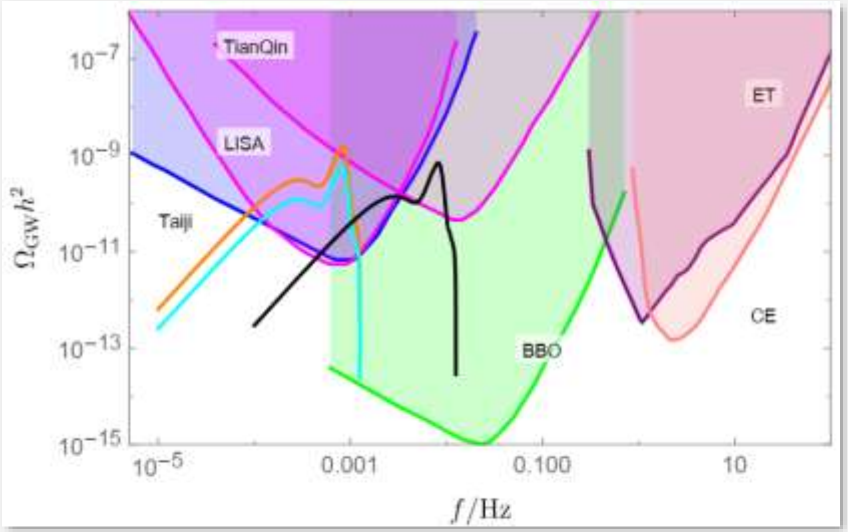
$$H^2 = \frac{1}{3}(\rho_r + \rho_{m1} + \rho_{m2}) \,,$$

$$\frac{d\left(\rho_{m2} a^3\right)}{dt} = -\frac{d\left(\rho_{m1} a^3\right)}{dt} - \Gamma \rho_{m2} a^3$$

$$\frac{d\left(\rho_r a^4\right)}{dt} = \Gamma \rho_{m2} a^4$$



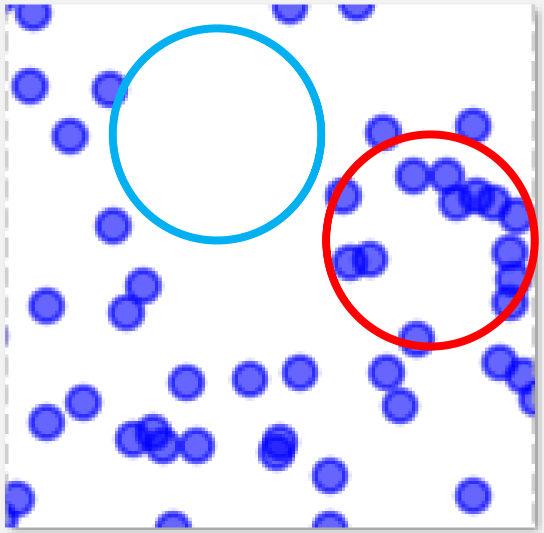




Generate strong density perturbations and scalar-induced GWs with very weak FOPT

Curvature perturbations induced by Poisson distributions

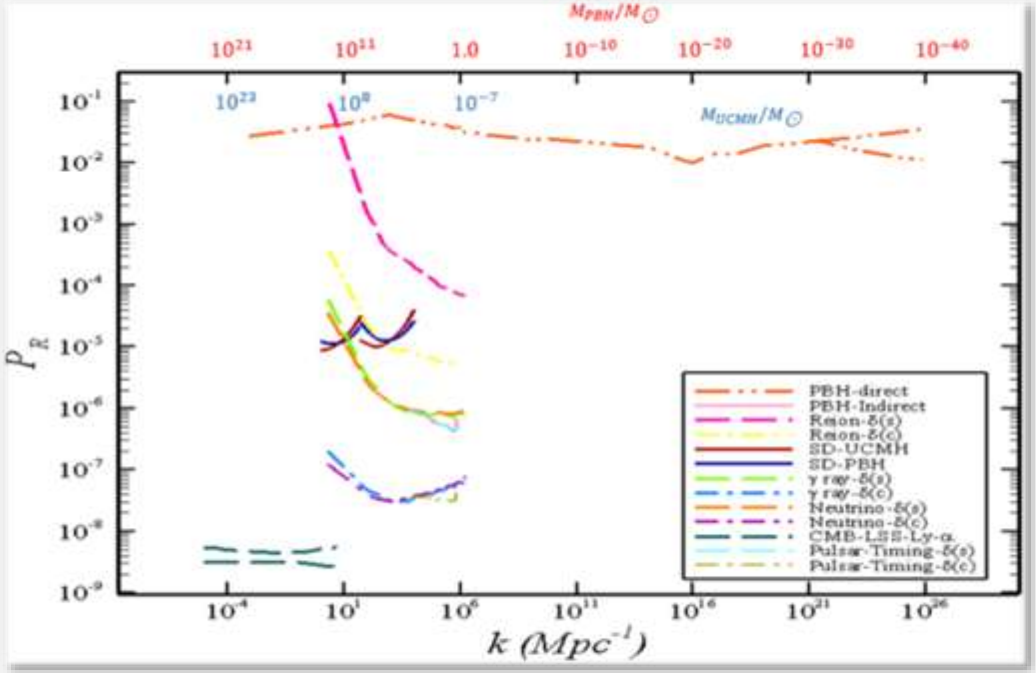
Zhen-Min Zeng, Jing Liu, Zong-Kuan Guo, Phys.*Rev.D* 108 (2023) 6, 063005



The formation processes are independent of each other

primordial black holes,
Q-balls,
oscillons,
spherical domain walls and cosmic strings···

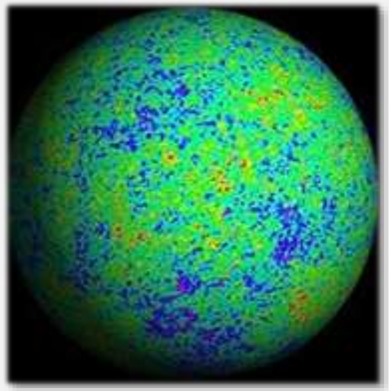
$$\mathcal{P}_{\mathcal{R}}(k) \propto k^3$$



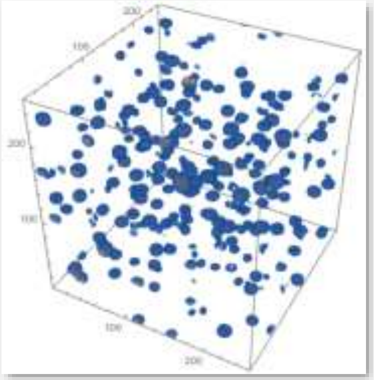
Razieh Emami, George Smoot, JCAP 01 (2018) 007

CMB anisotropies
CMB spectral distortions
Big-Bang nucleosynthesis
Primordial black holes
Ultracompact minihalos

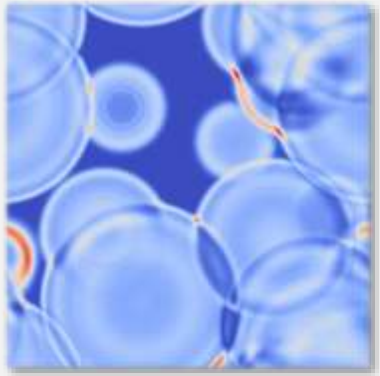
Power of PTA experiments to constrain nanohertz GW sources



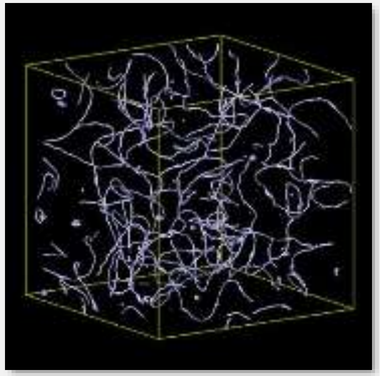
$\delta_H \sim \sqrt{P_R(k)}$



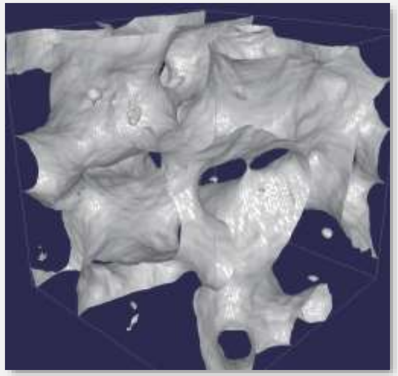
$\delta_H \sim \alpha(\frac{k_{\rm res}}{a_* H_*})^{-\frac{3}{2}}$



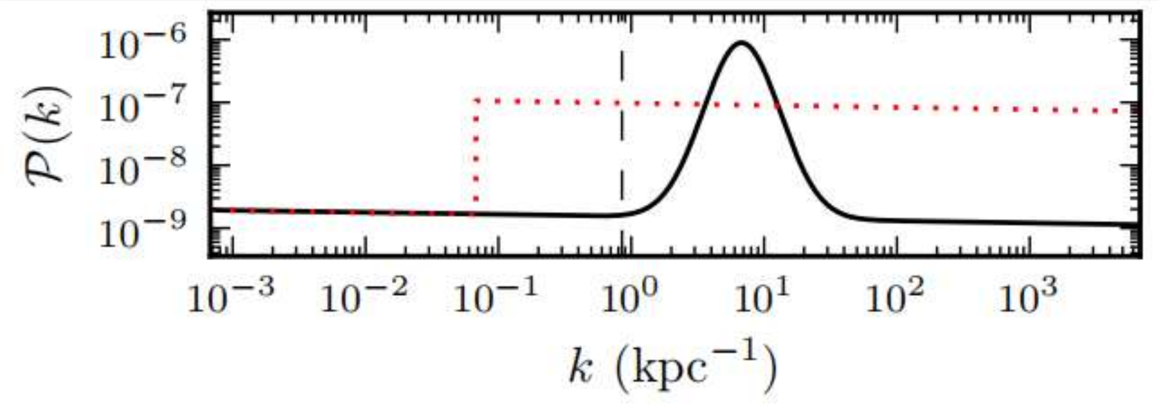
$\delta_H \sim \alpha(\frac{\beta}{H_*})^{-\frac{5}{2}}$

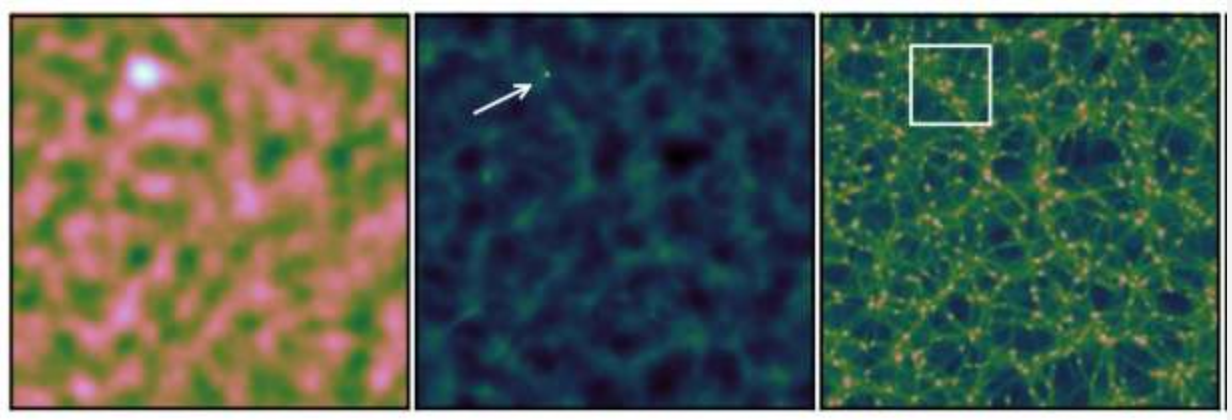


$\delta_H \sim \mu$



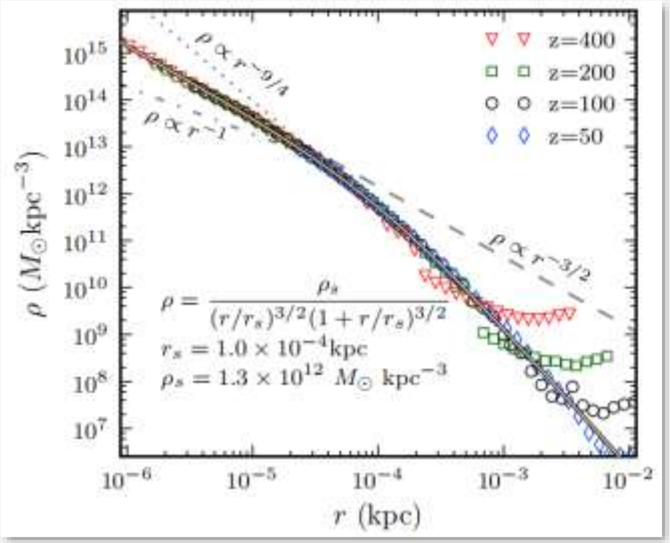
$\delta_H \approx \mathcal{A}\sigma/t_*$



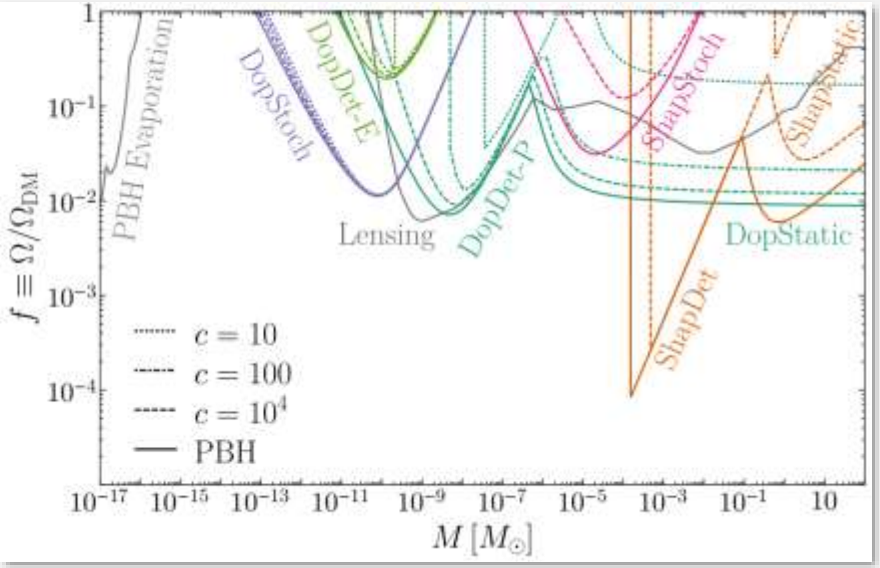


The formation of compact dark matter halos

Power of PTA experiments to constrain nanohertz GW sources



Delos, M. Sten and Erickcek, Adrienne L. and Bailey, Avery P. and Alvarez, Marcelo A.,1712.05421



Harikrishnan Ramani et al JCAP12(2020)033

Mass function

$$P_0 = \min\left(\frac{M_0}{M_i}\frac{1}{\sqrt{2\pi}\delta_H}\int_{\delta_{min}}^{+\infty} d\delta \exp\left(\frac{-\delta^2}{2\delta_H^2}\right), 1\right)$$

$$M_i = \frac{4}{3}\pi(a_* H_*)^{-3}\rho_{DM,0} \qquad \delta_{min} \sim 0.001$$

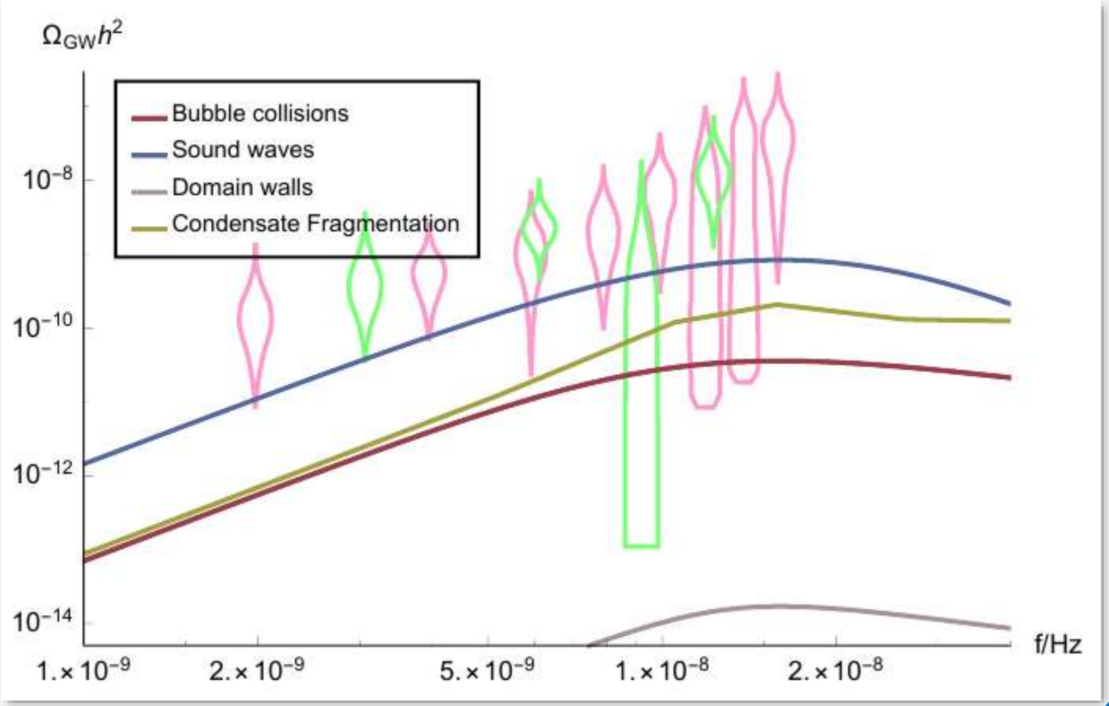
This result is valid for all of the cold DM models and does not rely on the decay products of DM.

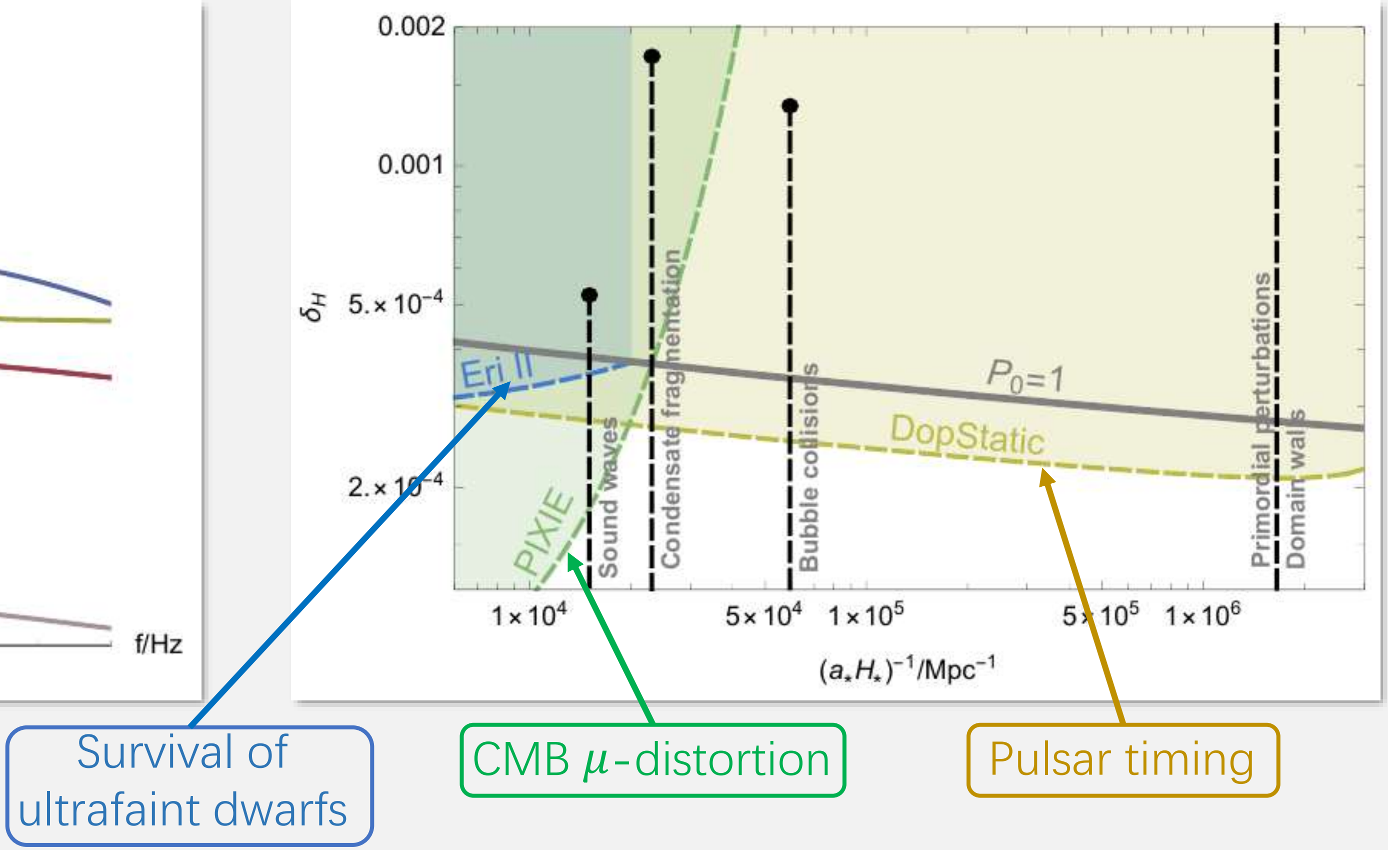
Note that some of the fuzzy/warm dark matter models do NOT apply to this result.

The GW observations in turn give constraints to DM models?

Distinguishing nanohertz gravitational wave sources through the observations of ultracompact minihalos

Jing Liu, Phys.Rev.D 108 (2023) 12, 123544

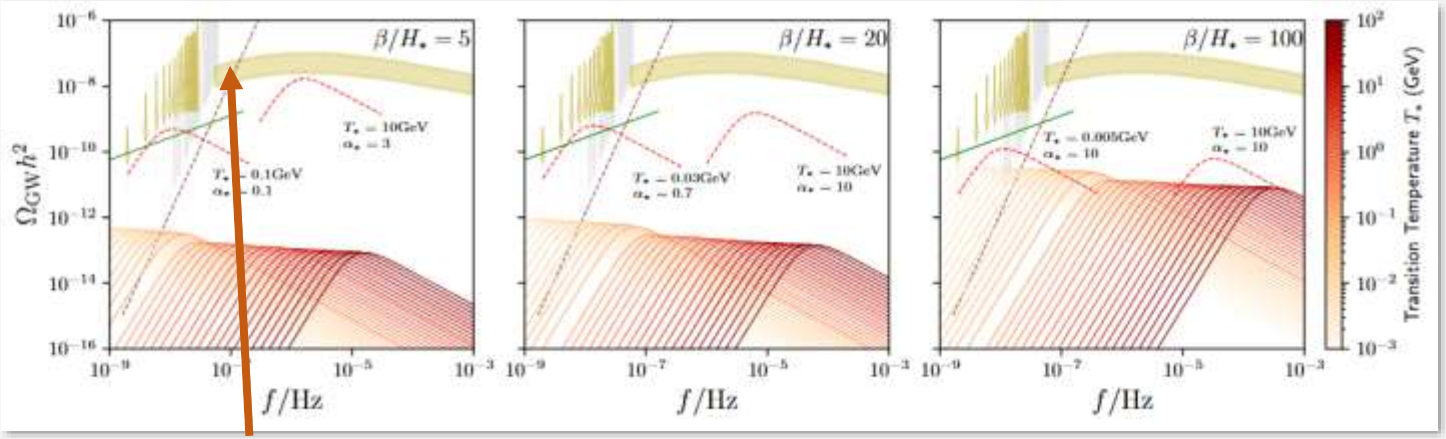




Observations of ultracompact minihalos can help to distinguish the GW sources.

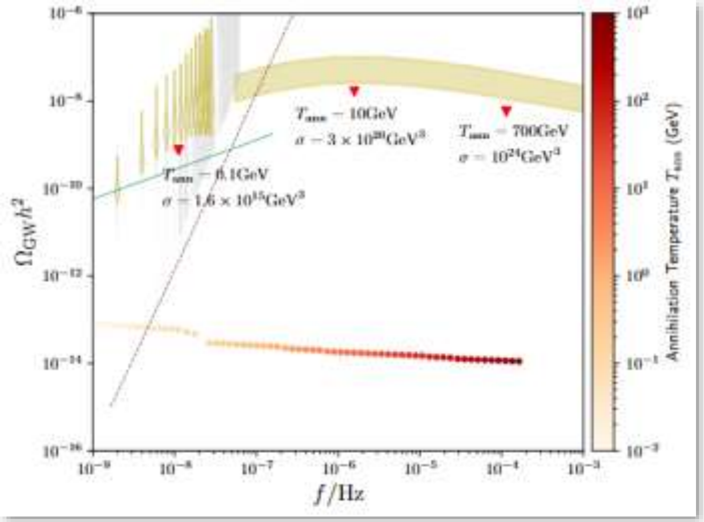
Constraining SGWBs below the astrophysical foregrounds

Chengjie Fu, Jing Liu, 2505.14366

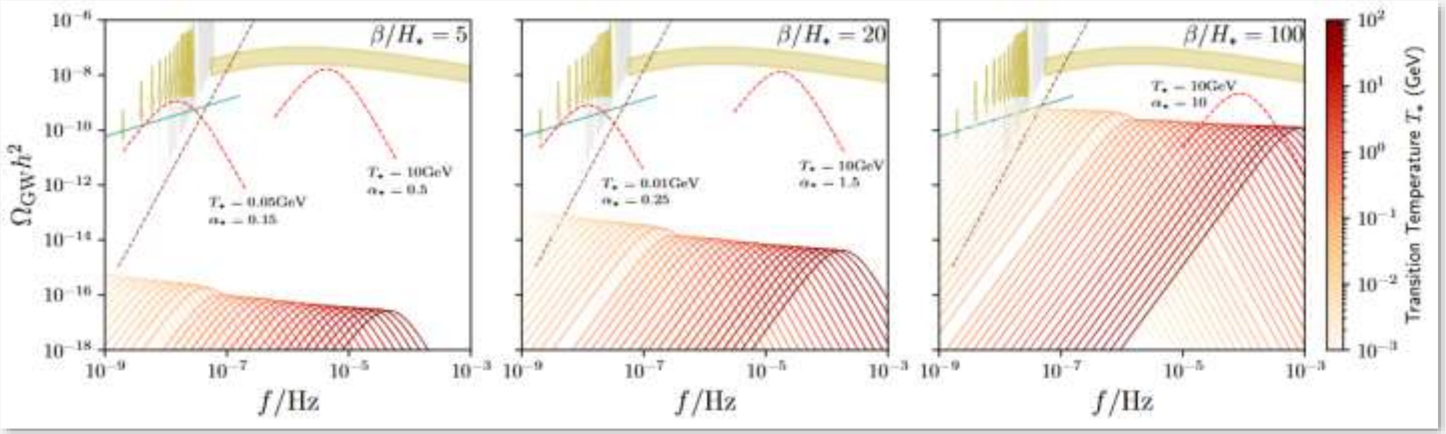


Irreducible astrophysical foreground

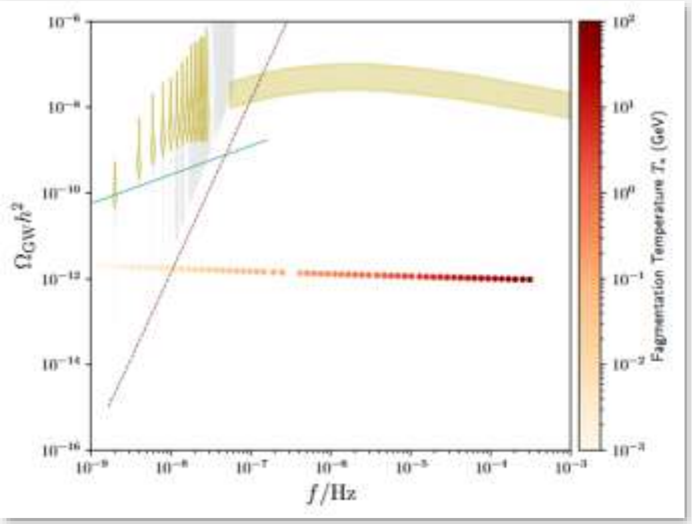
Bubble collisions



Domain walls



Sound waves



Condensate fragmentation

Summary

1. The origin

During/after inflation, or thermal history

2. Mechanisms for producing observable GWs

Large amplitude and large scales

4. Associated observables

Anisotropies, Primordial black holes, curvature perturbations
primordial magnetic fields, baryon asymmetry, and so on…

5. Corresponding techniques

Numerical simulation and (semi)analytic methods

Thanks!