Baryogenesis, Dark Matter, and PTA signal from a Dark Conformal Phase Transition

Sudhakantha Girmohanta

July 10, 2024

Based on:

1. Fujikura, Girmohanta, Nakai and Suzuki [PLB 846, 138203 (2023)]

2. Fujikura, Girmohanta, Nakai and Zhang [arXiv:2406.12956]

RENCONTRES DU VIETNAM

上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

I. Introduction

Pulsar Timing Arrays, nano-Hz Gravitational waves, and supermassive black hole binaries (SMBHB)

The spectrum of gravitational waves

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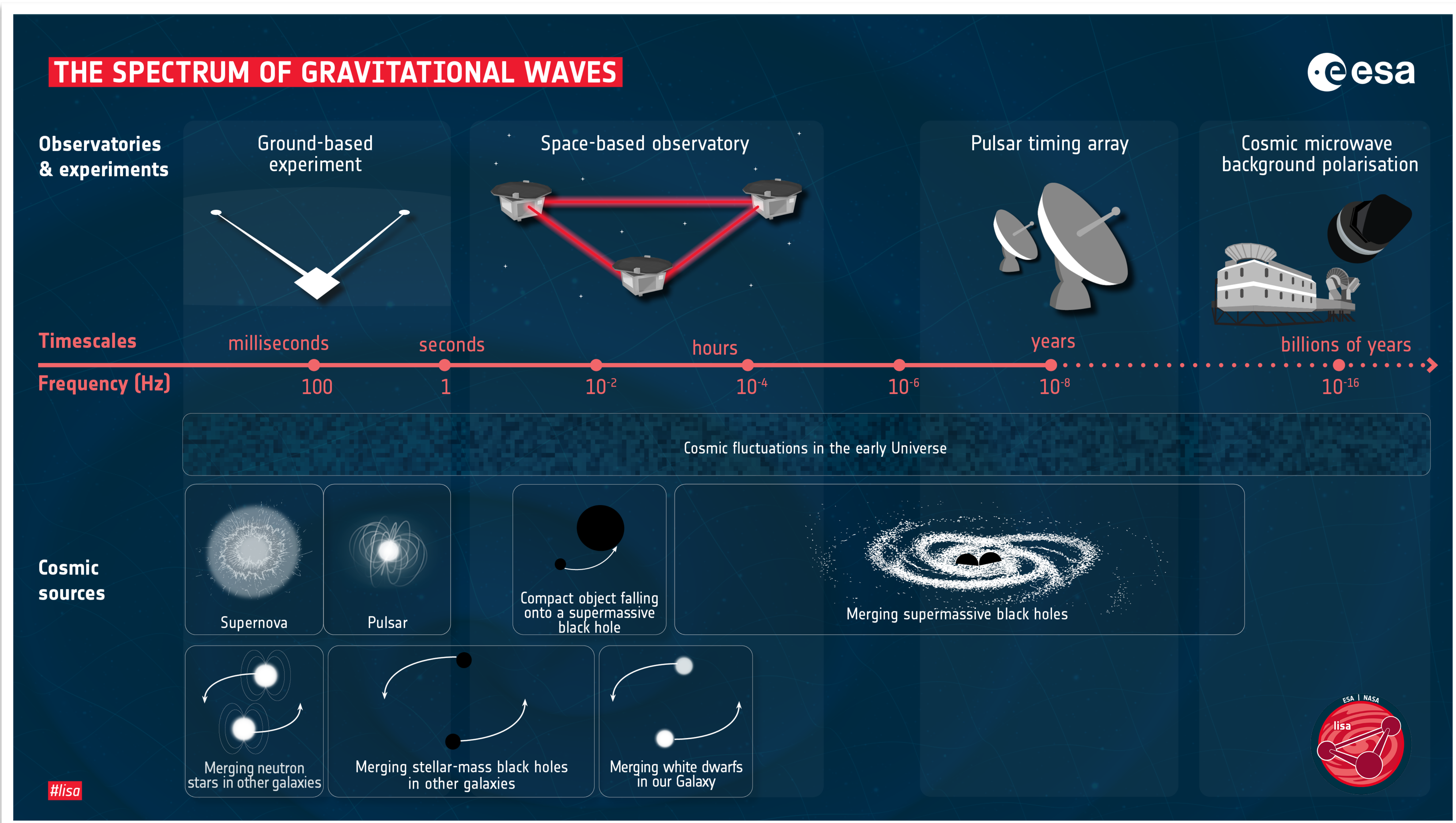

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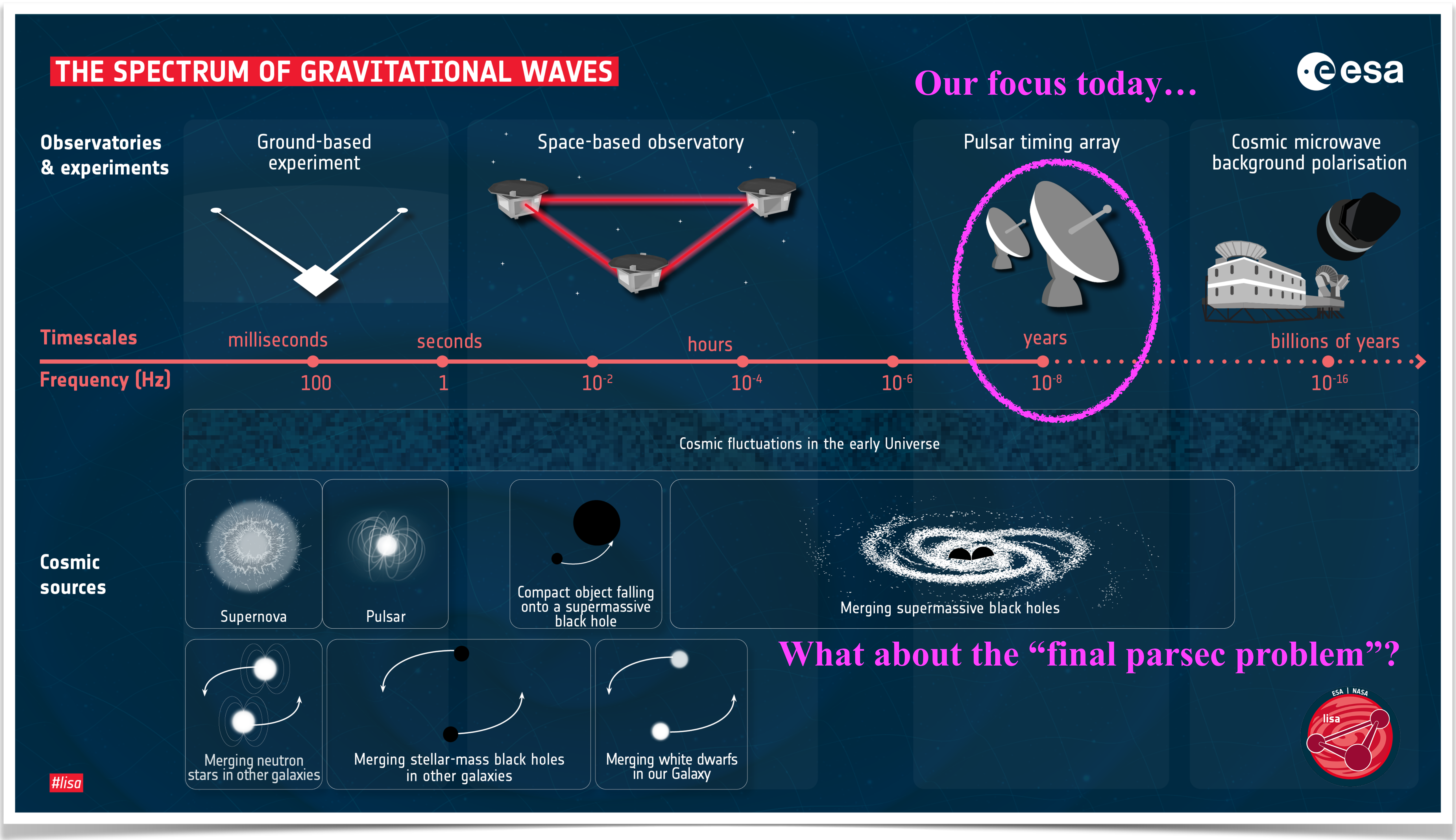

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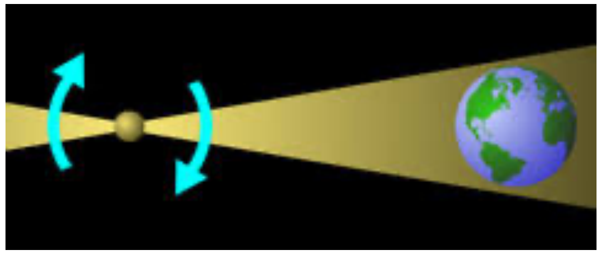

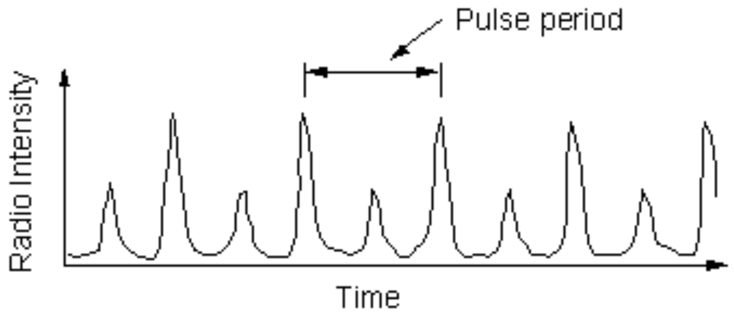

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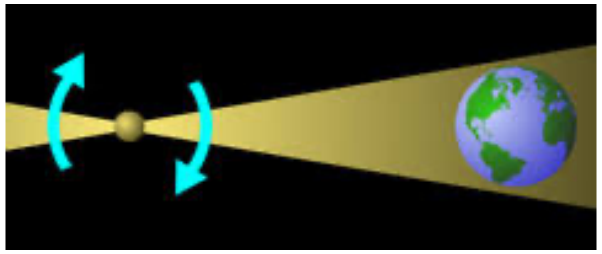
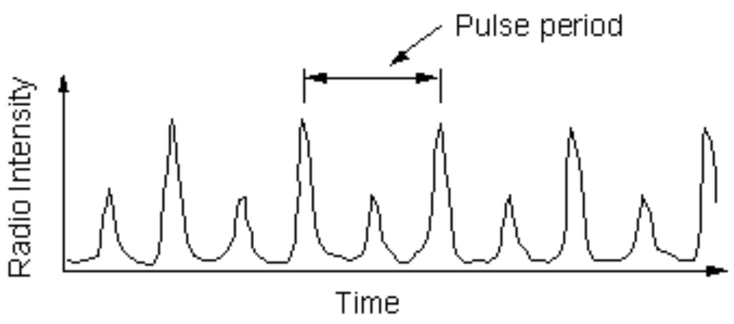
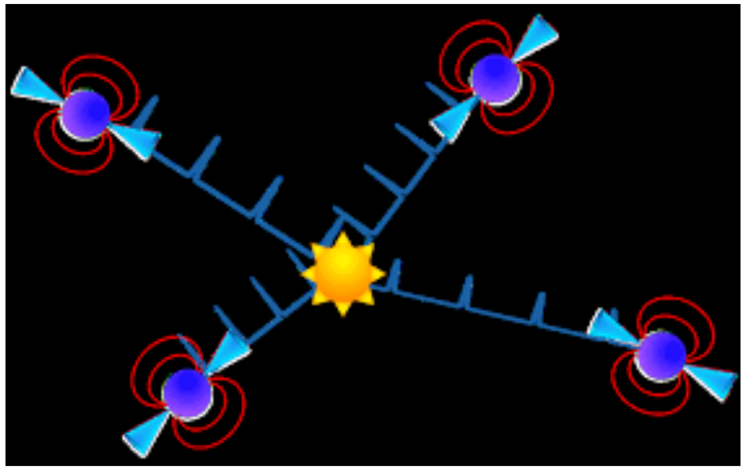




Earth-pulsar system as gravitational wave antenna.

Gravitational waves change the arrival time of pulses.

Estabrook, Wahlquist '75; Sazhin '77; Detweiler '79



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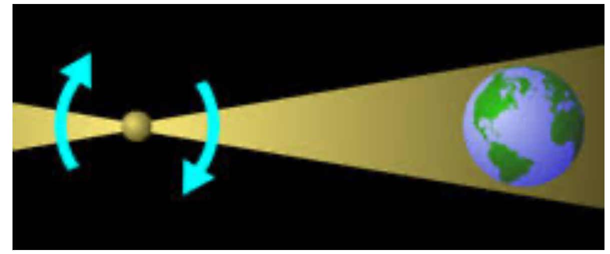

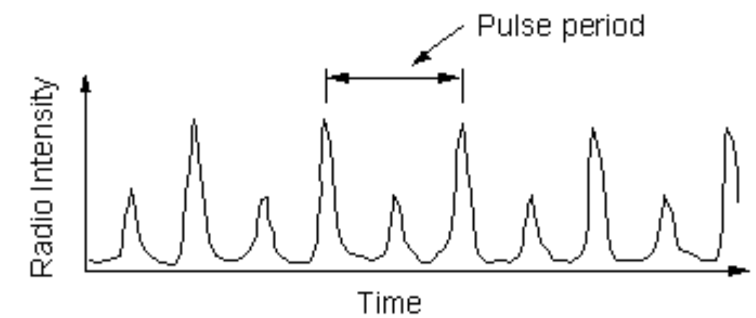

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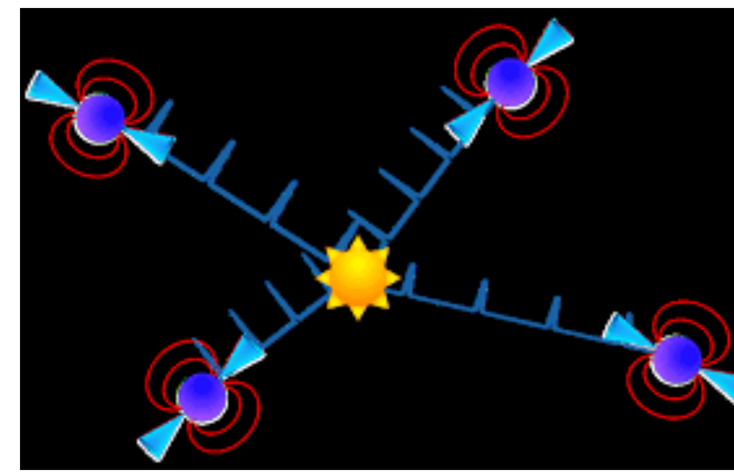

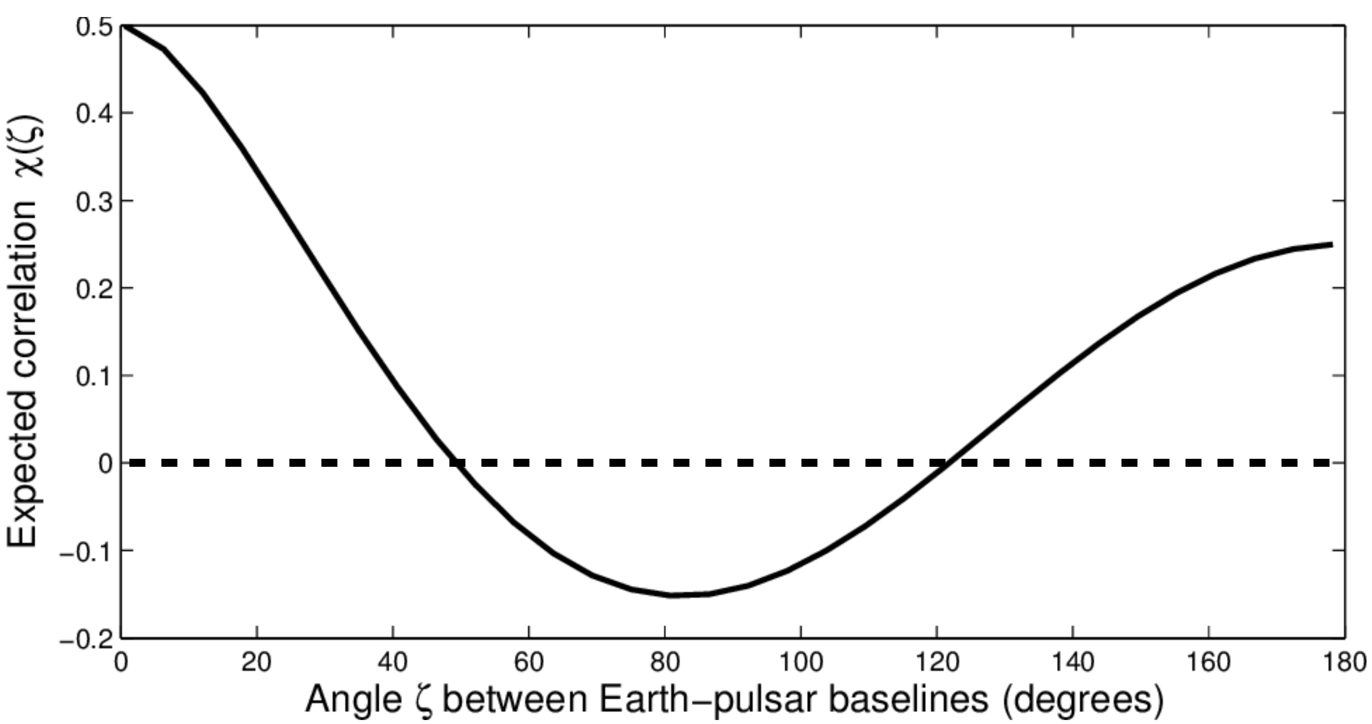

GW: Distinctive quadrupolar inter-pulsar correlation. **Hellings, Downs '82**

$$\frac{\Delta\nu_i(t)}{\nu_i} = \alpha_i h(t) + n_i(t),$$

$$\alpha_{ij} \equiv \frac{1}{4\pi}\int \alpha_i \alpha_j \, d\Omega = \frac{1-\cos\gamma_{ij}}{2}\ln\left(\frac{1-\cos\gamma_{ij}}{2}\right) - \frac{1}{6}\,\frac{1-\cos\gamma_{ij}}{2} + \frac{1}{3}, \qquad (5)$$

where γ_{ij} is the angle between the two pulsars.

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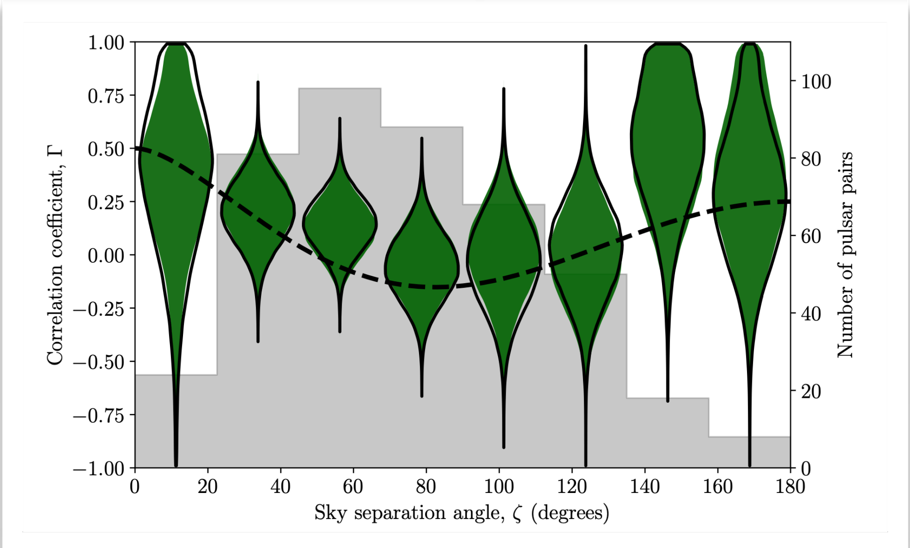

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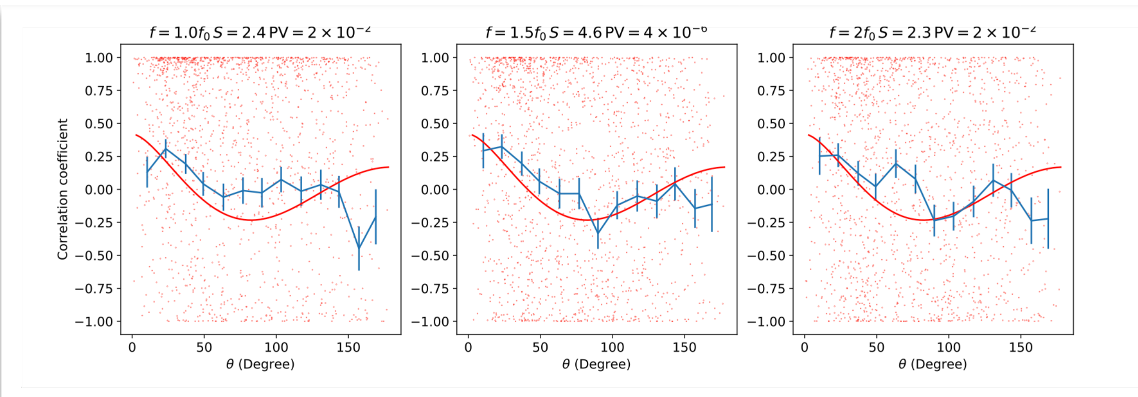
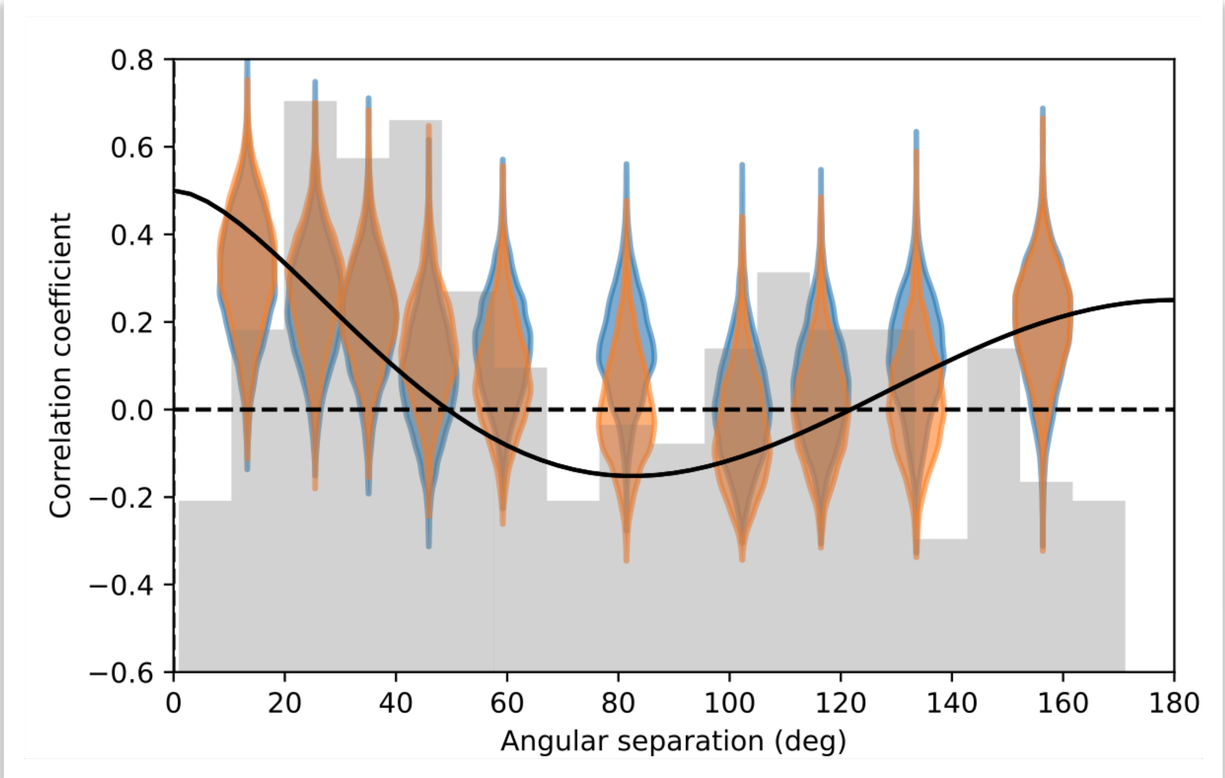
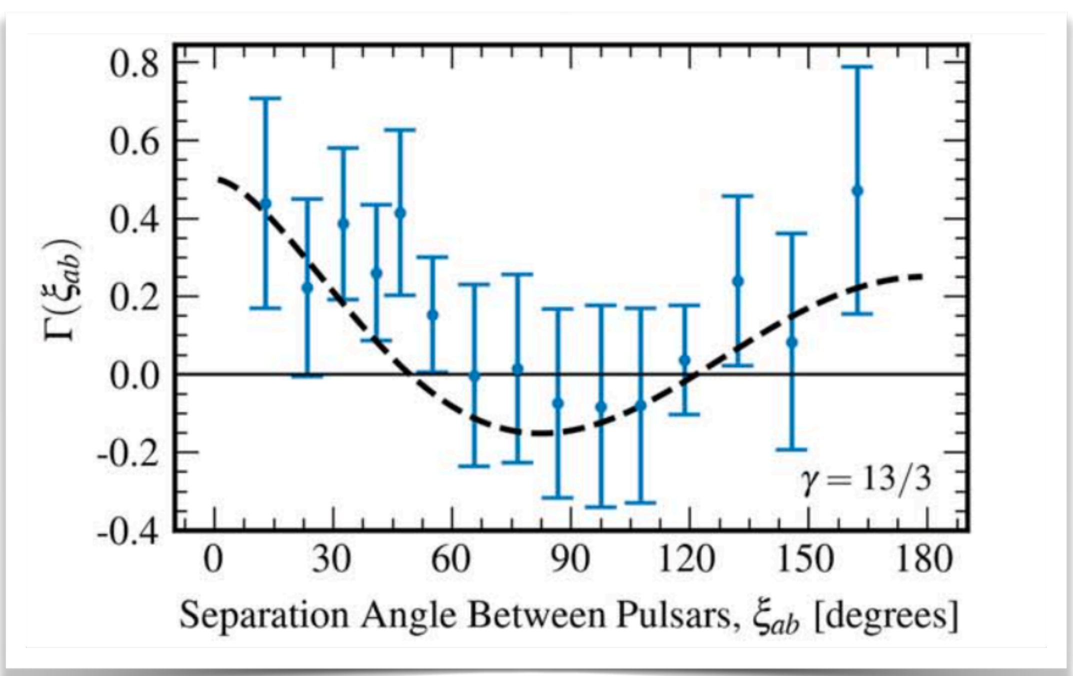


EPTA+InPTA



NANOGrav



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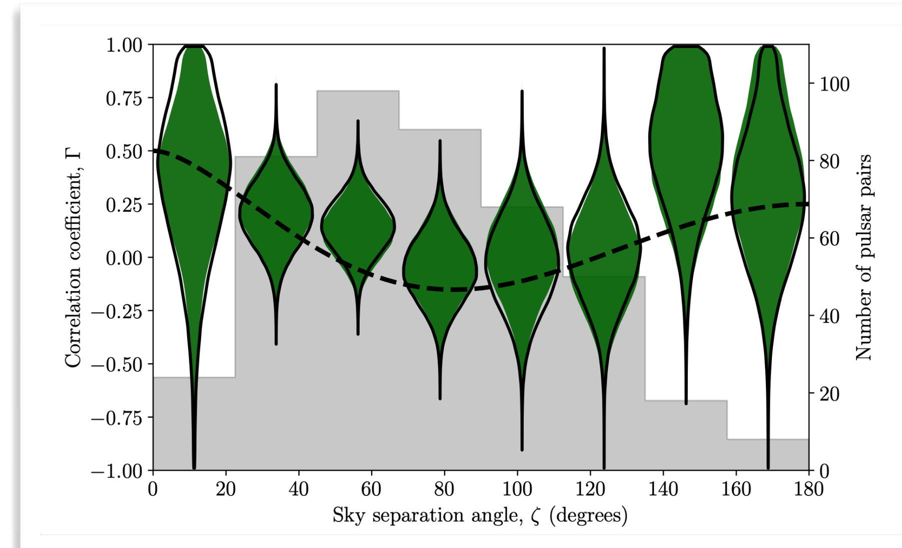

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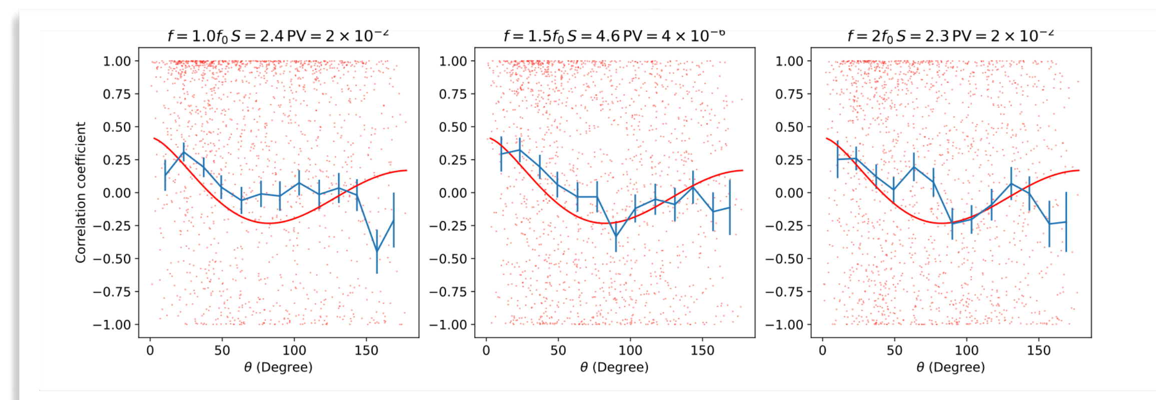

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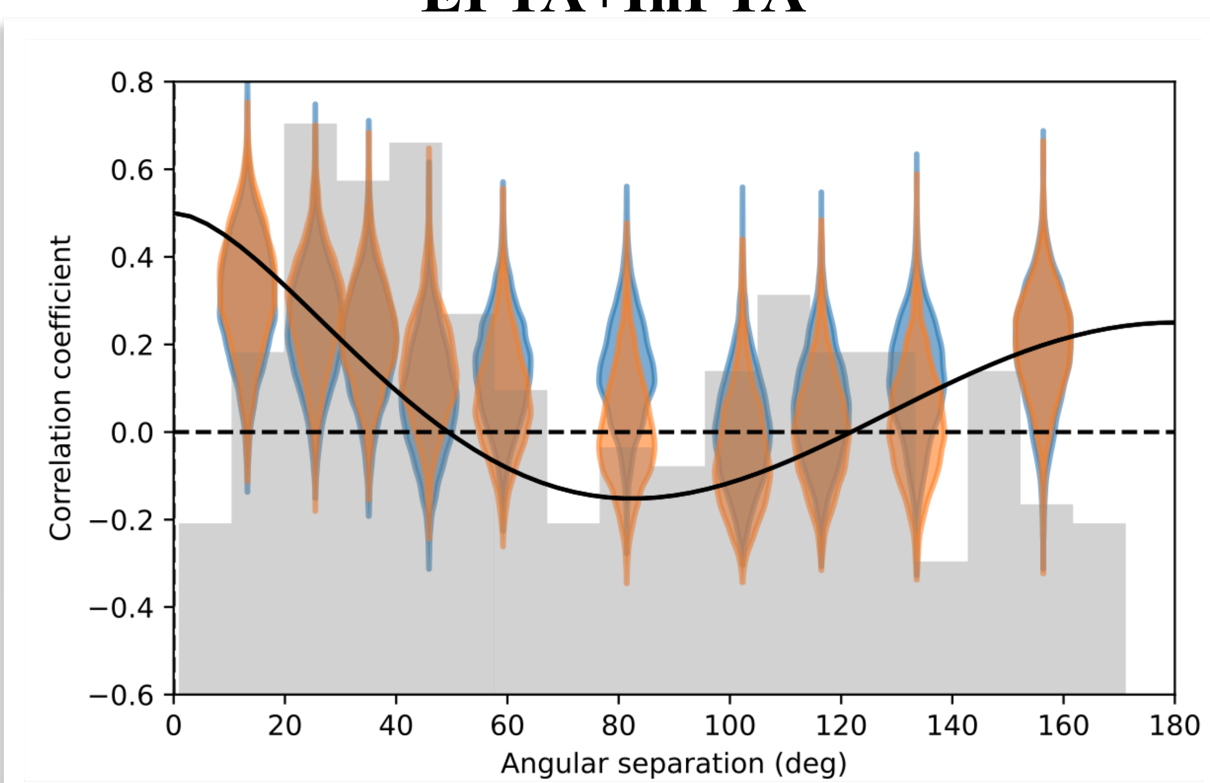

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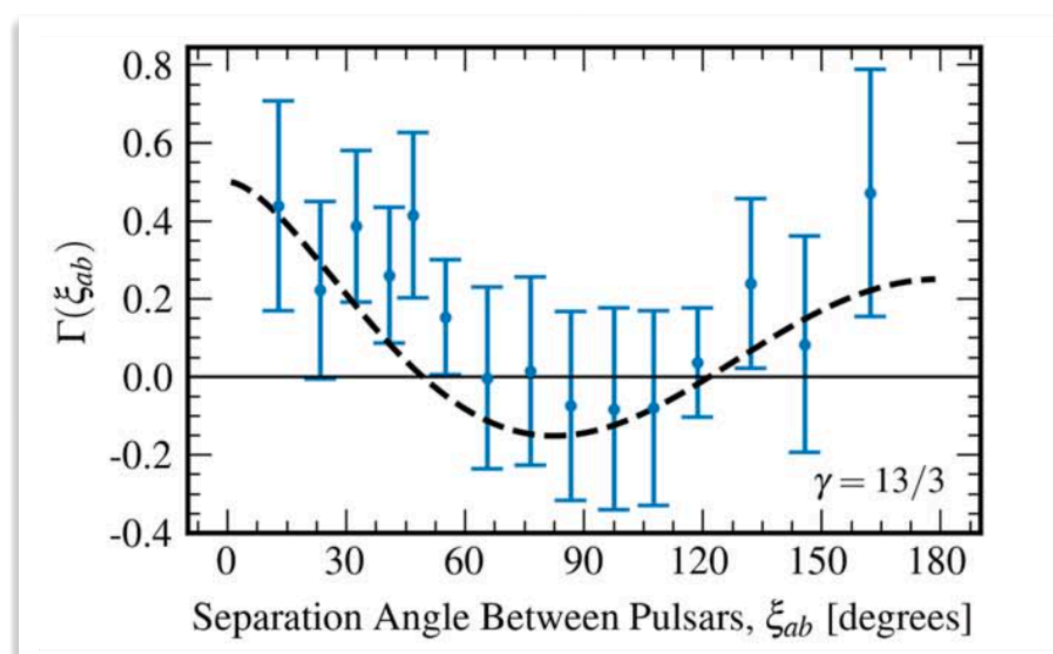

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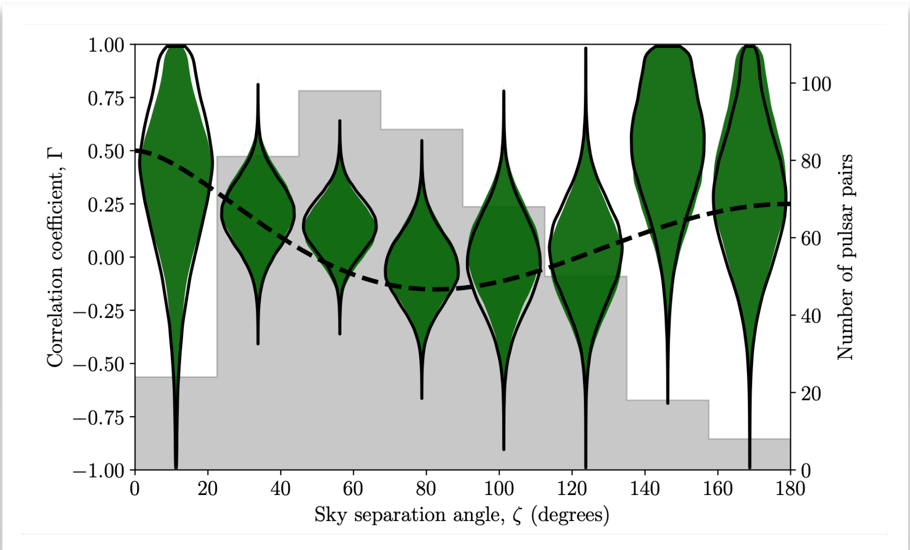

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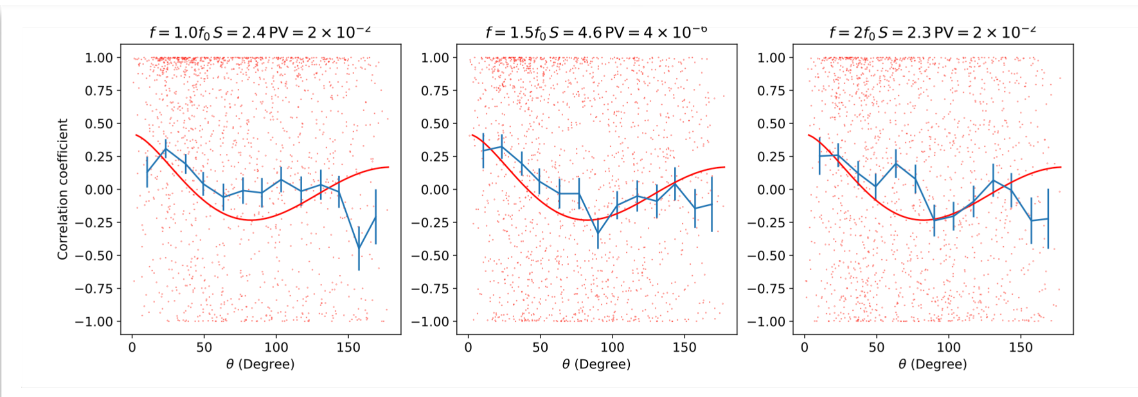

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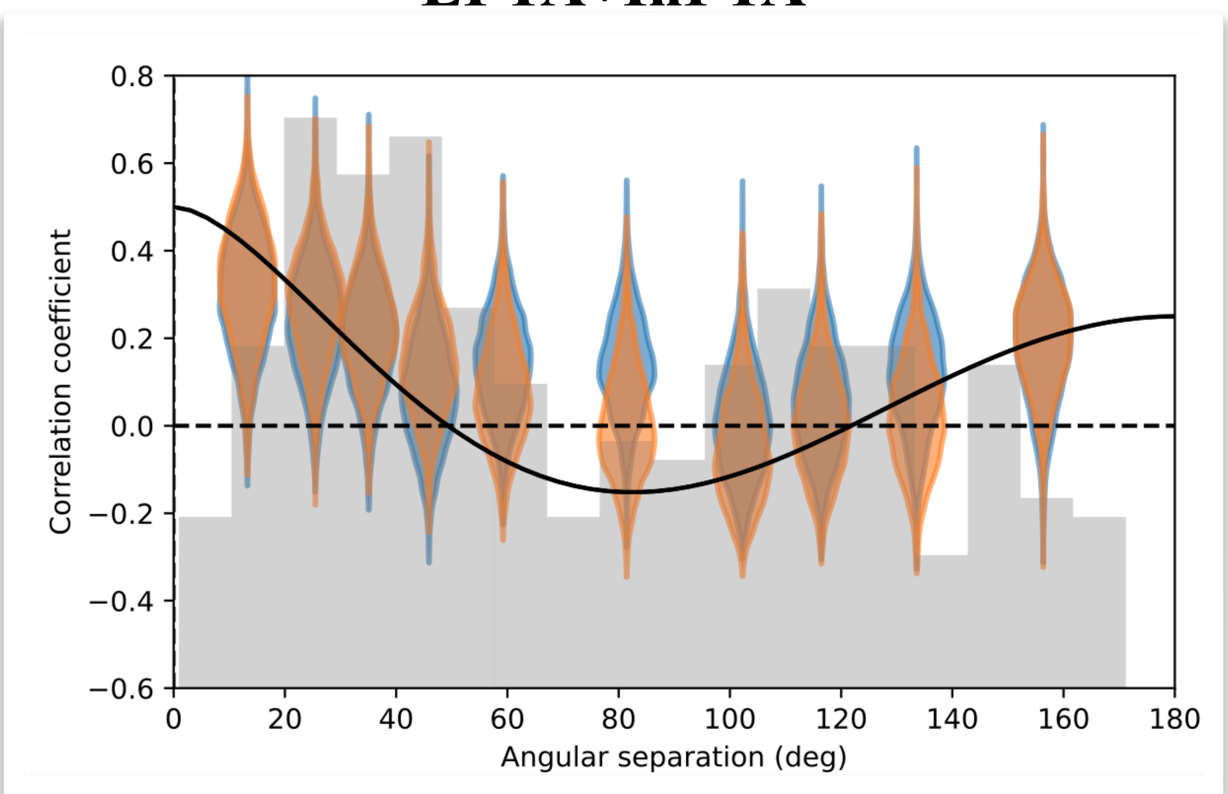

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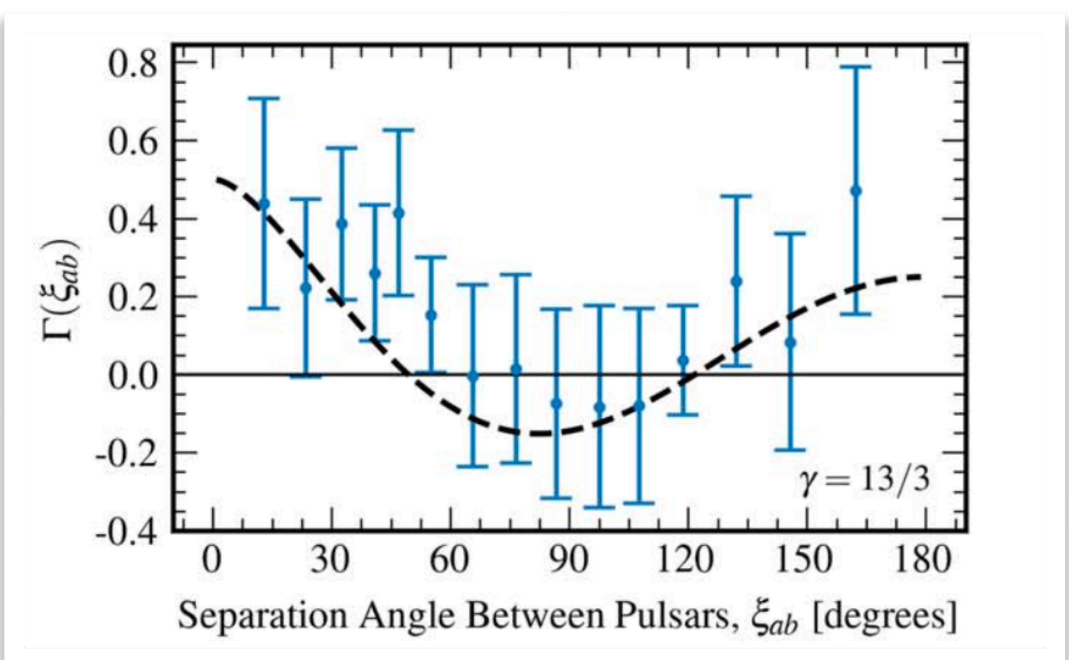

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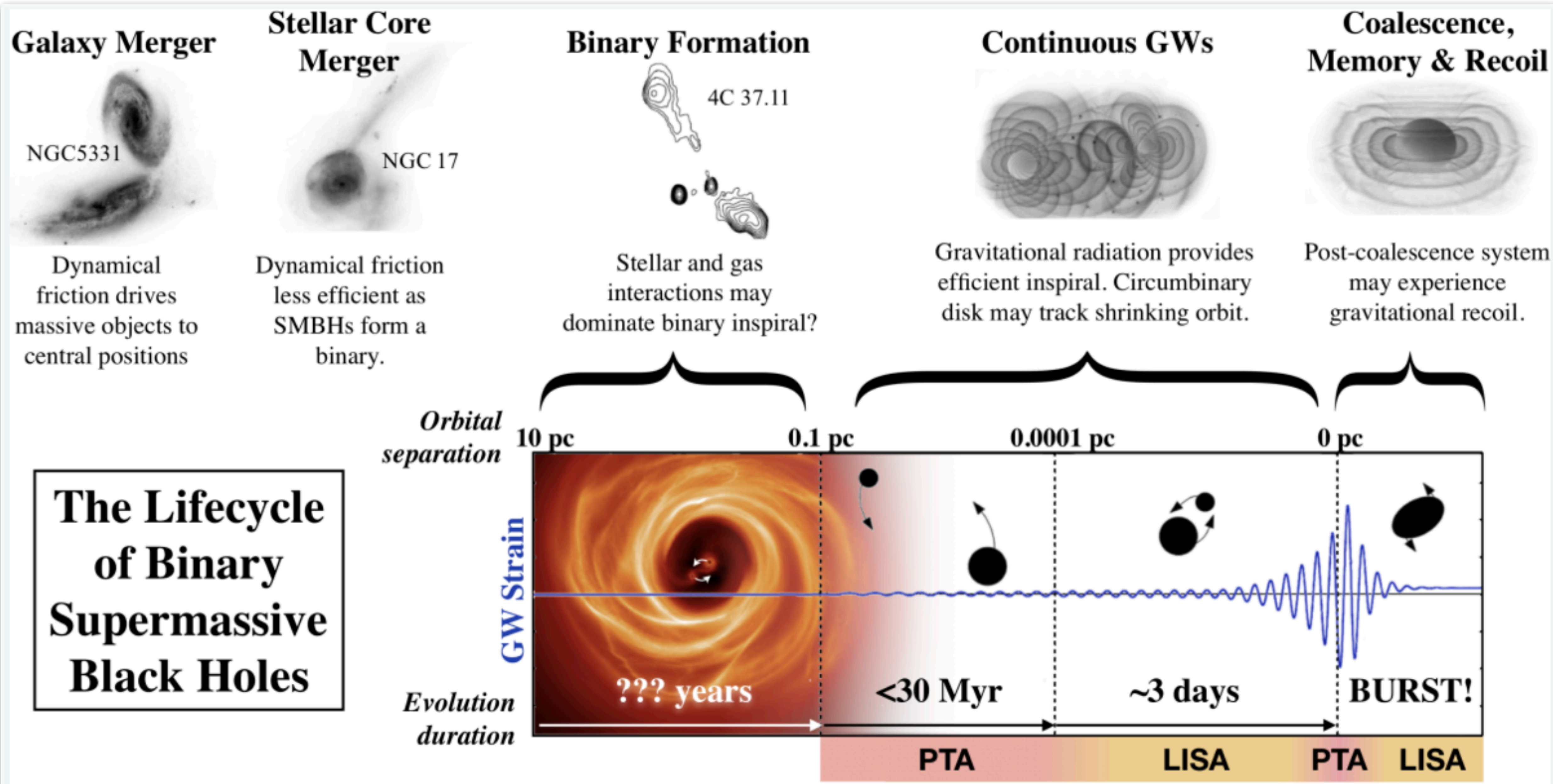

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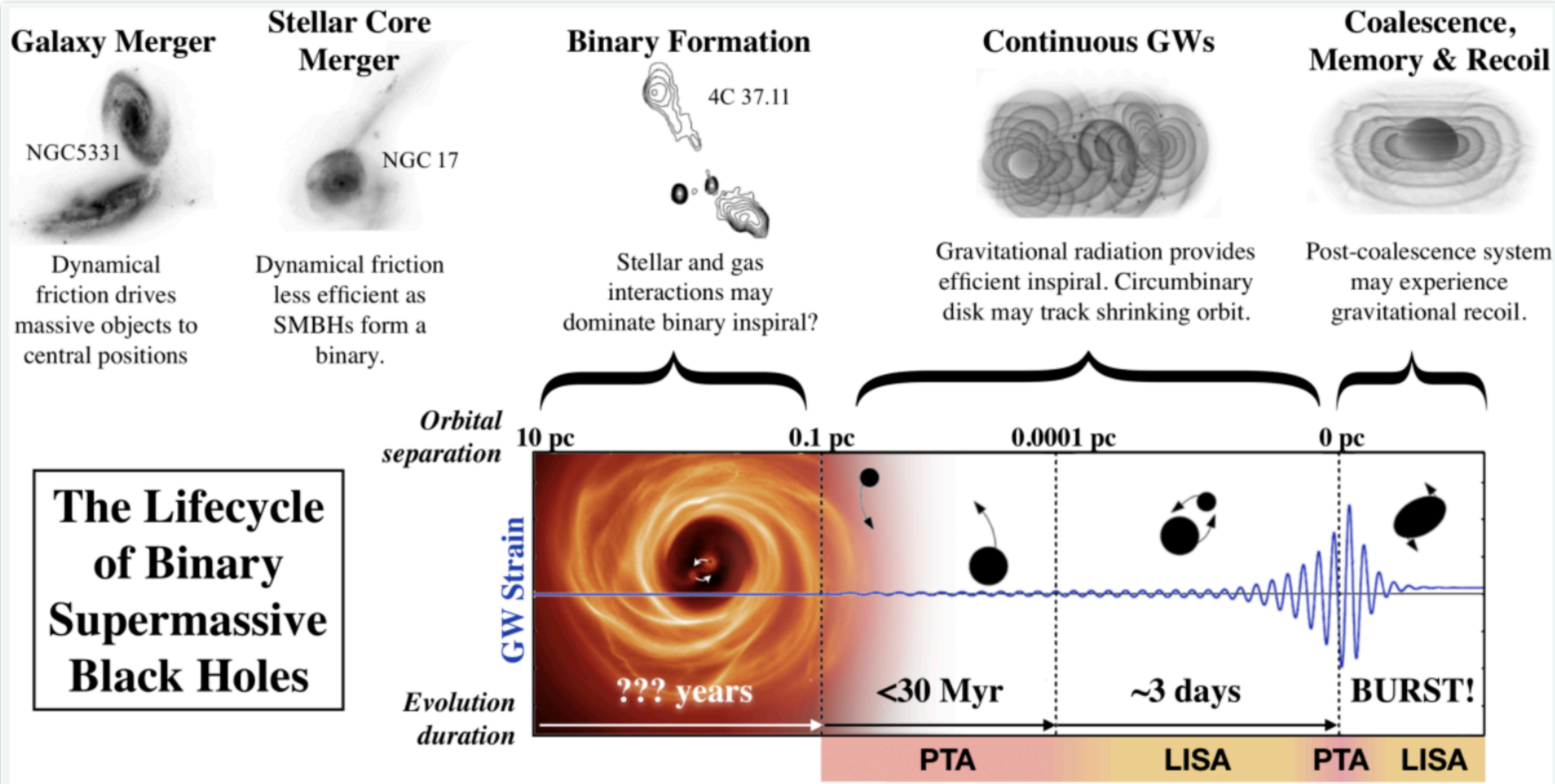

But…one has to first get to a orbital separation of ~ 0.01 pc.

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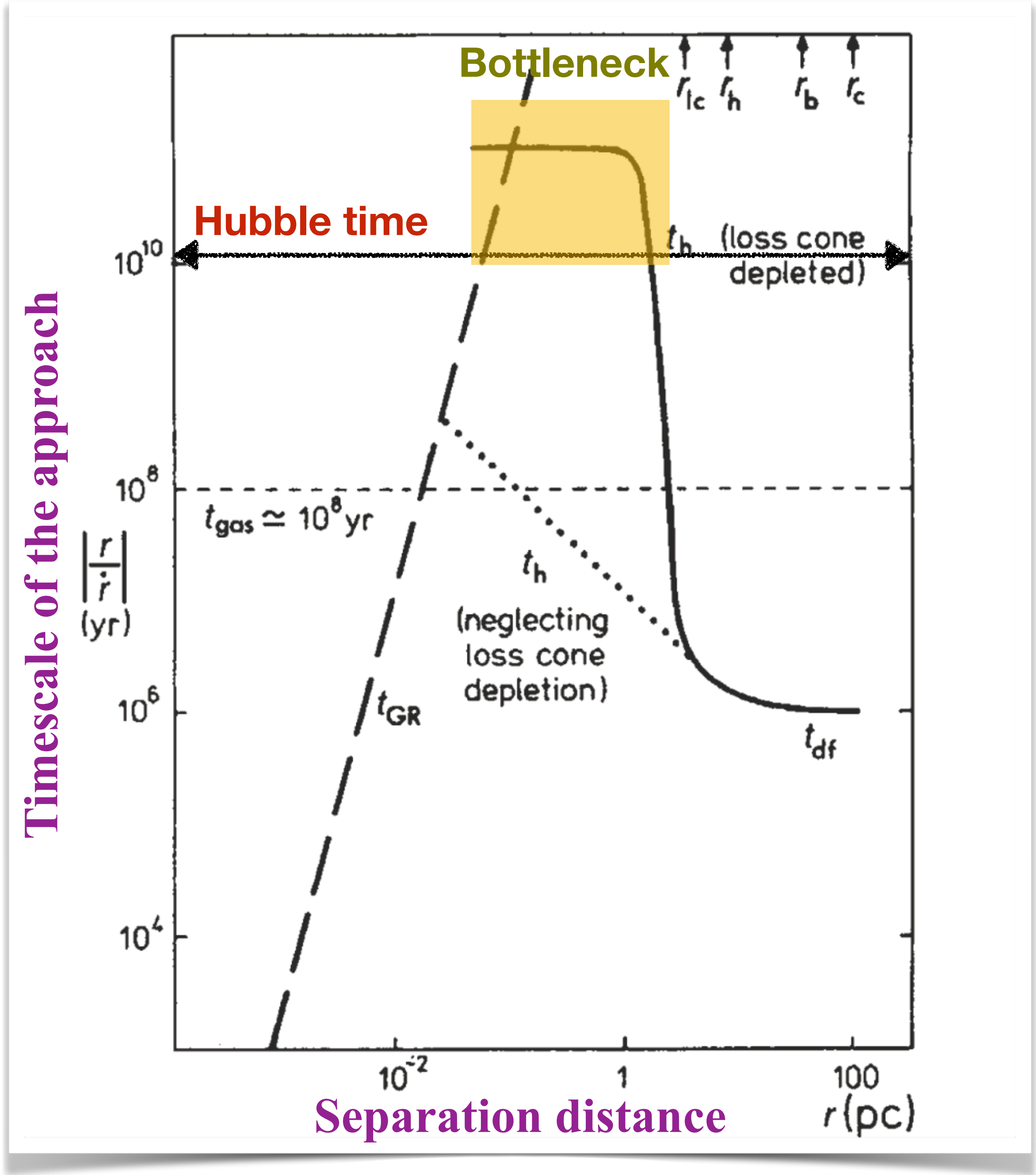
SMBHB come closer together due to dynamical friction.



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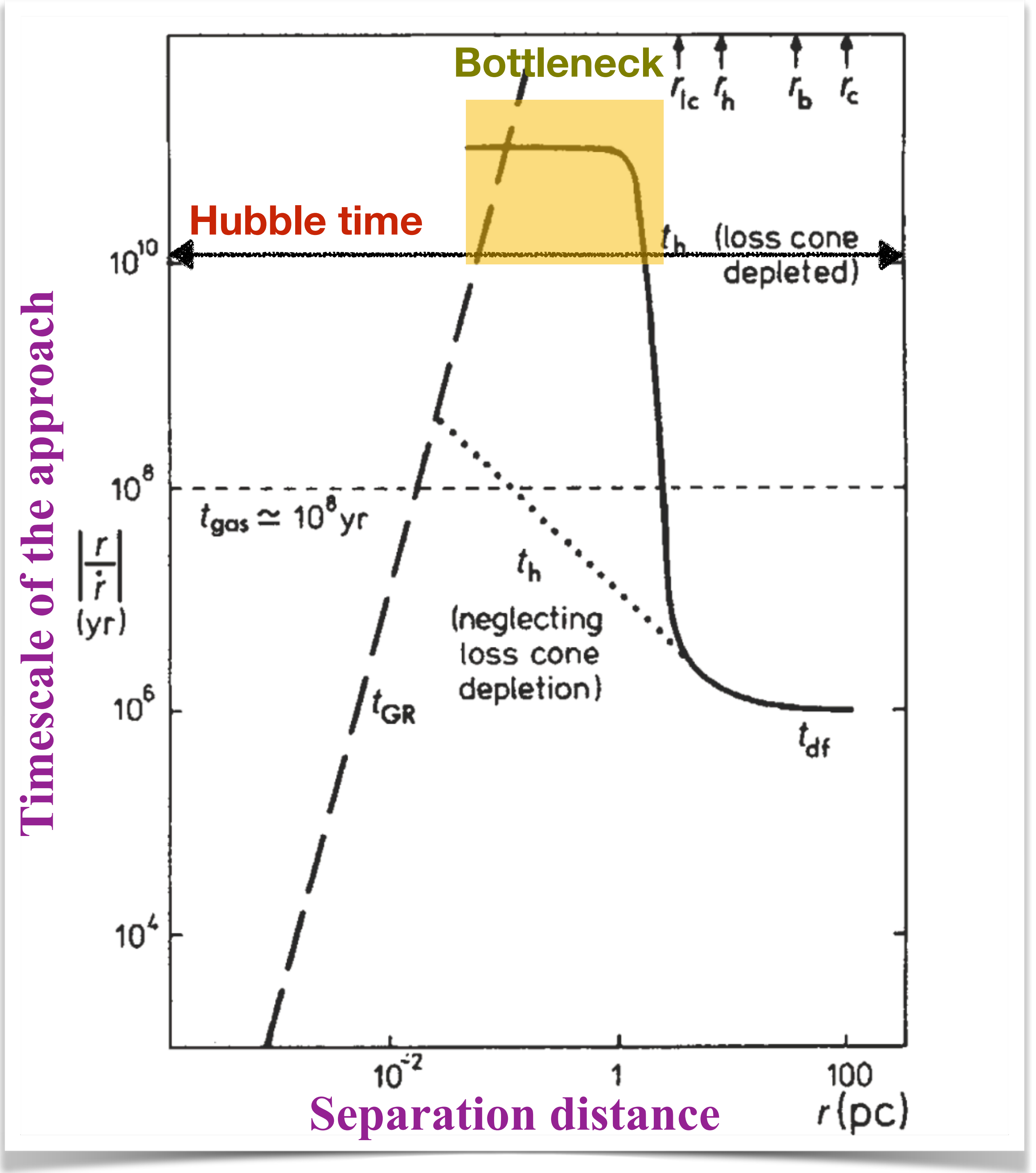

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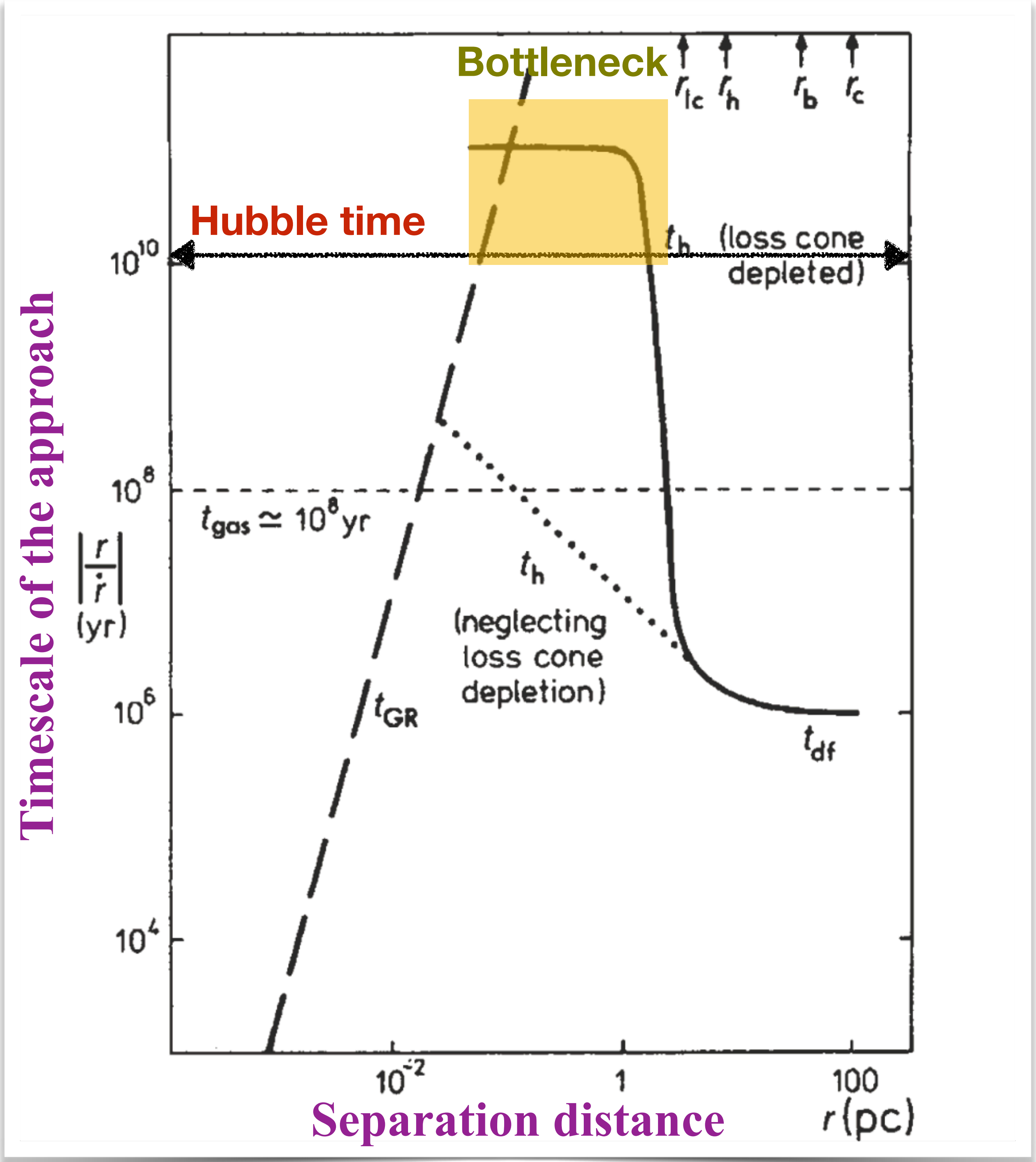

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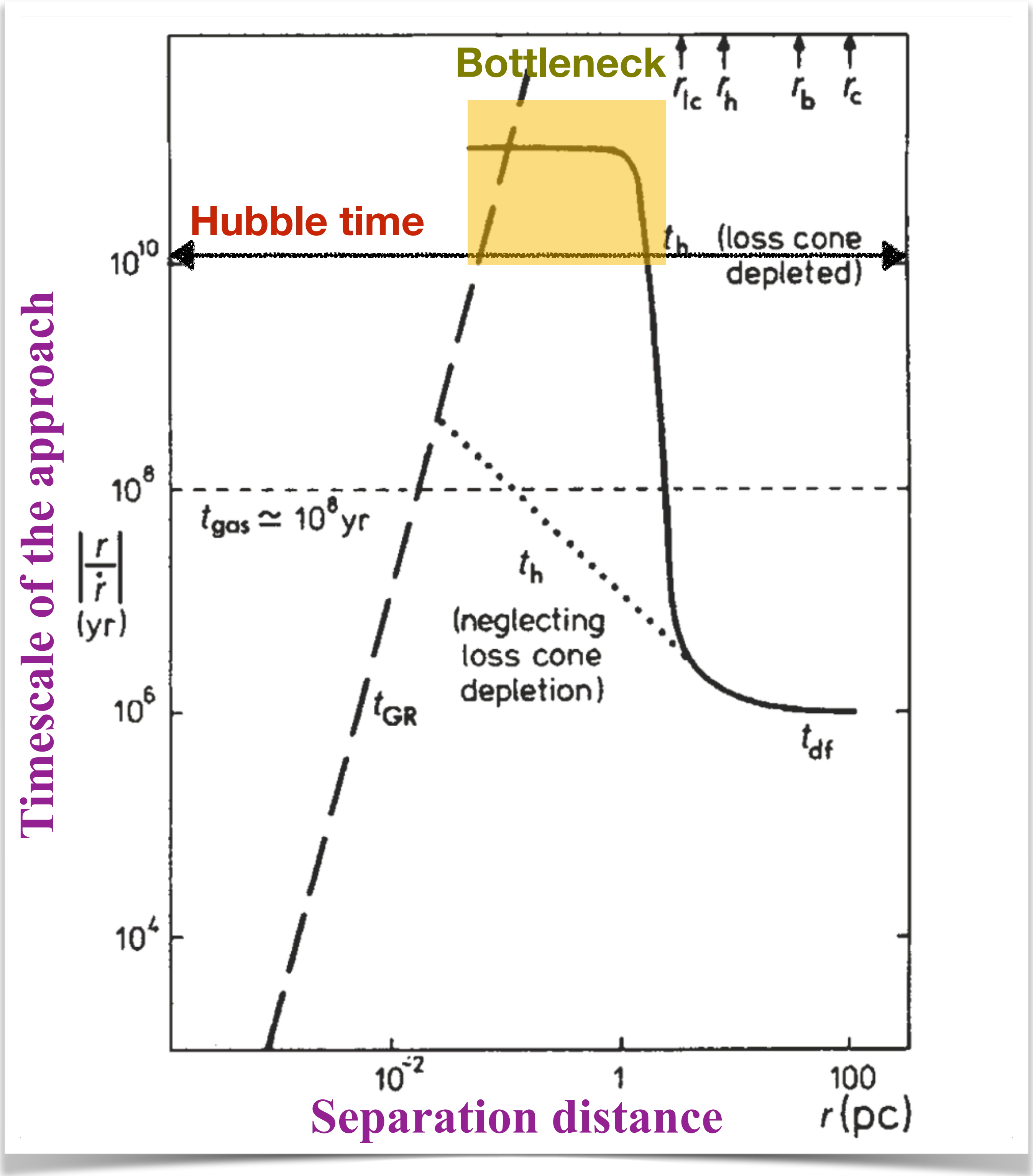

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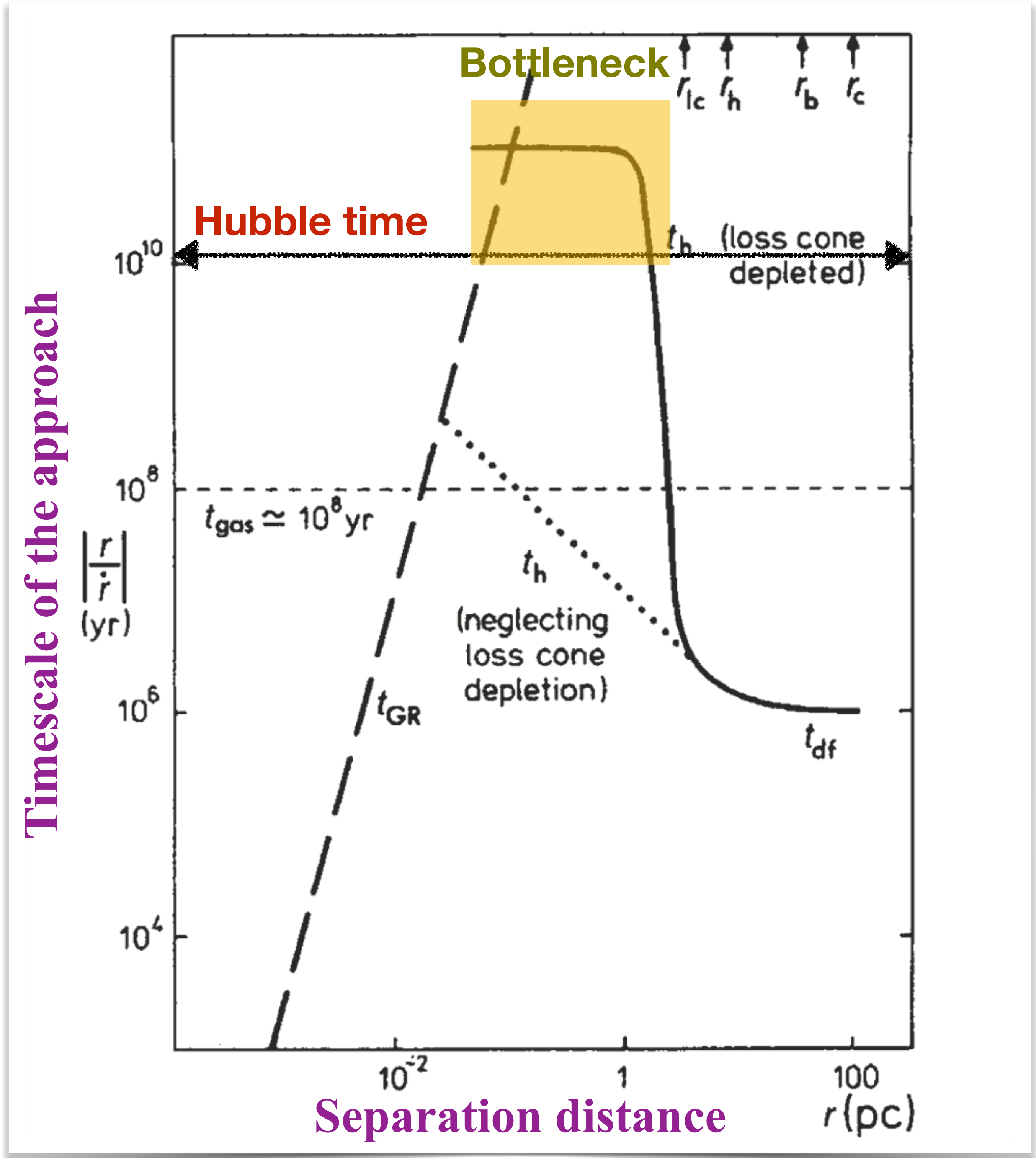

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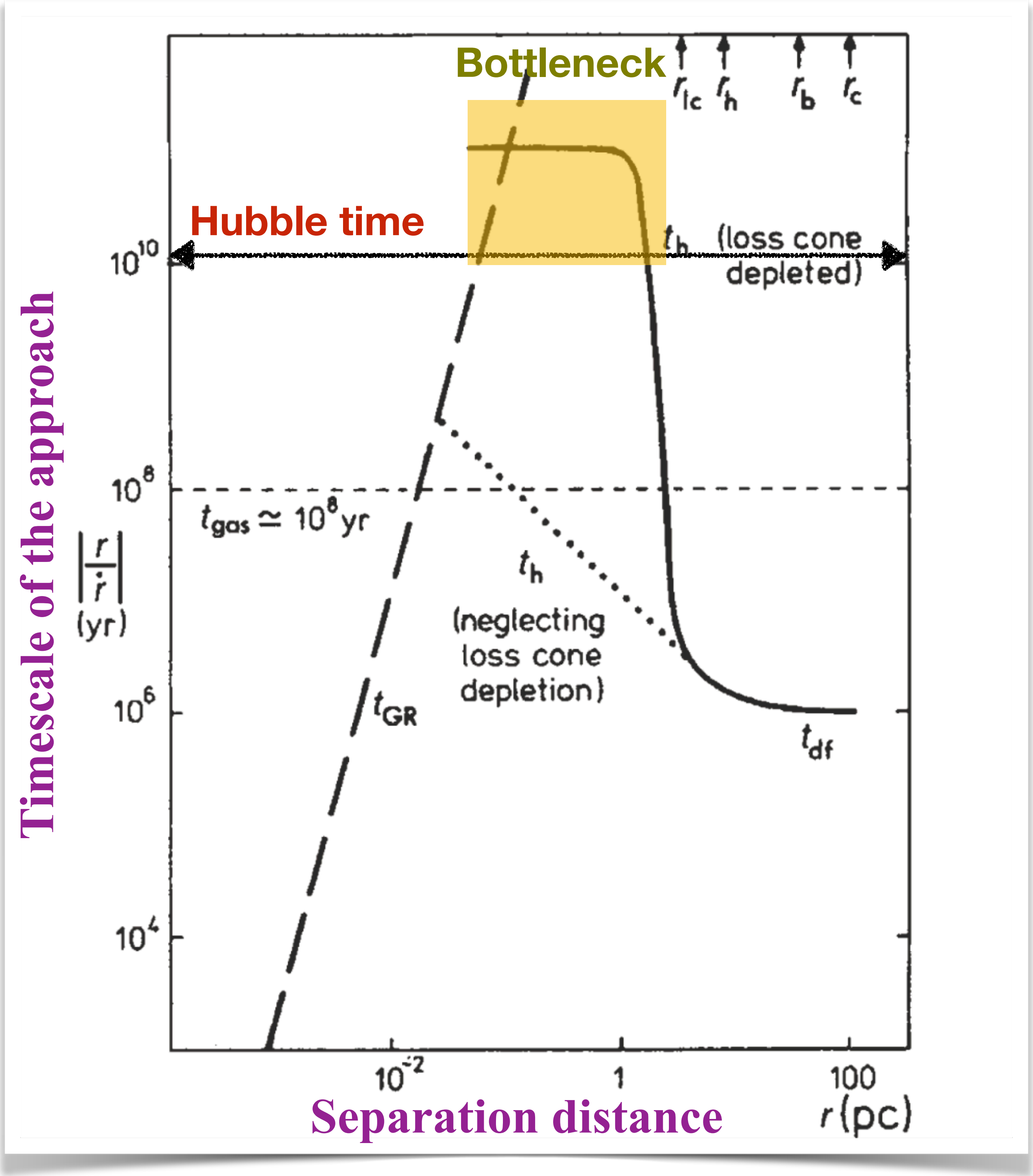
Do SMBHBs merge in the lifetime of the Universe?



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II. Phase Transition Interpretation

First-order phase transition in a nearly conformal dark sector
and the production of gravitational waves

Fujikura, Girmohanta, Nakai and Suzuki [PLB 846, 138203 (2023)]

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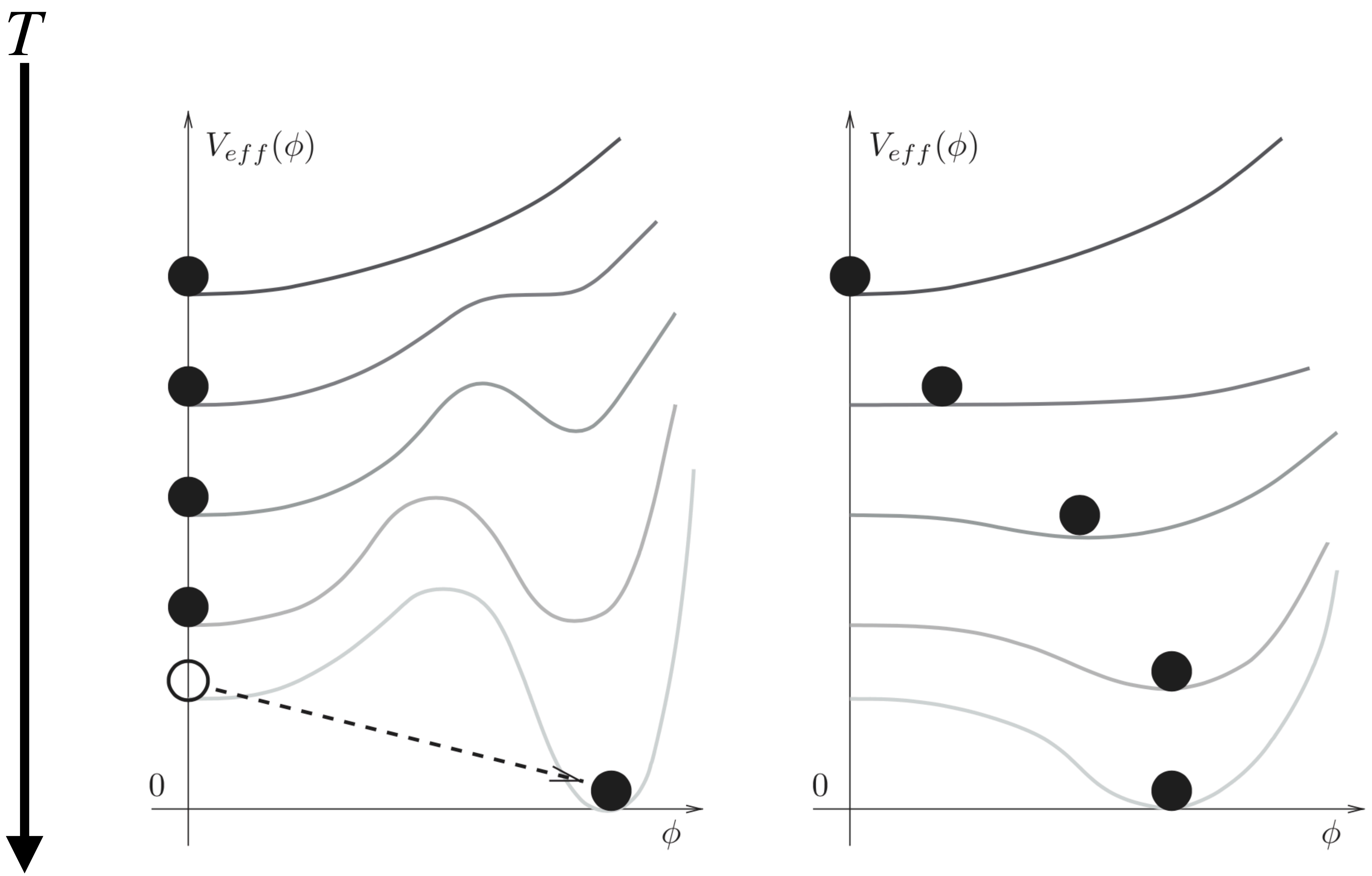

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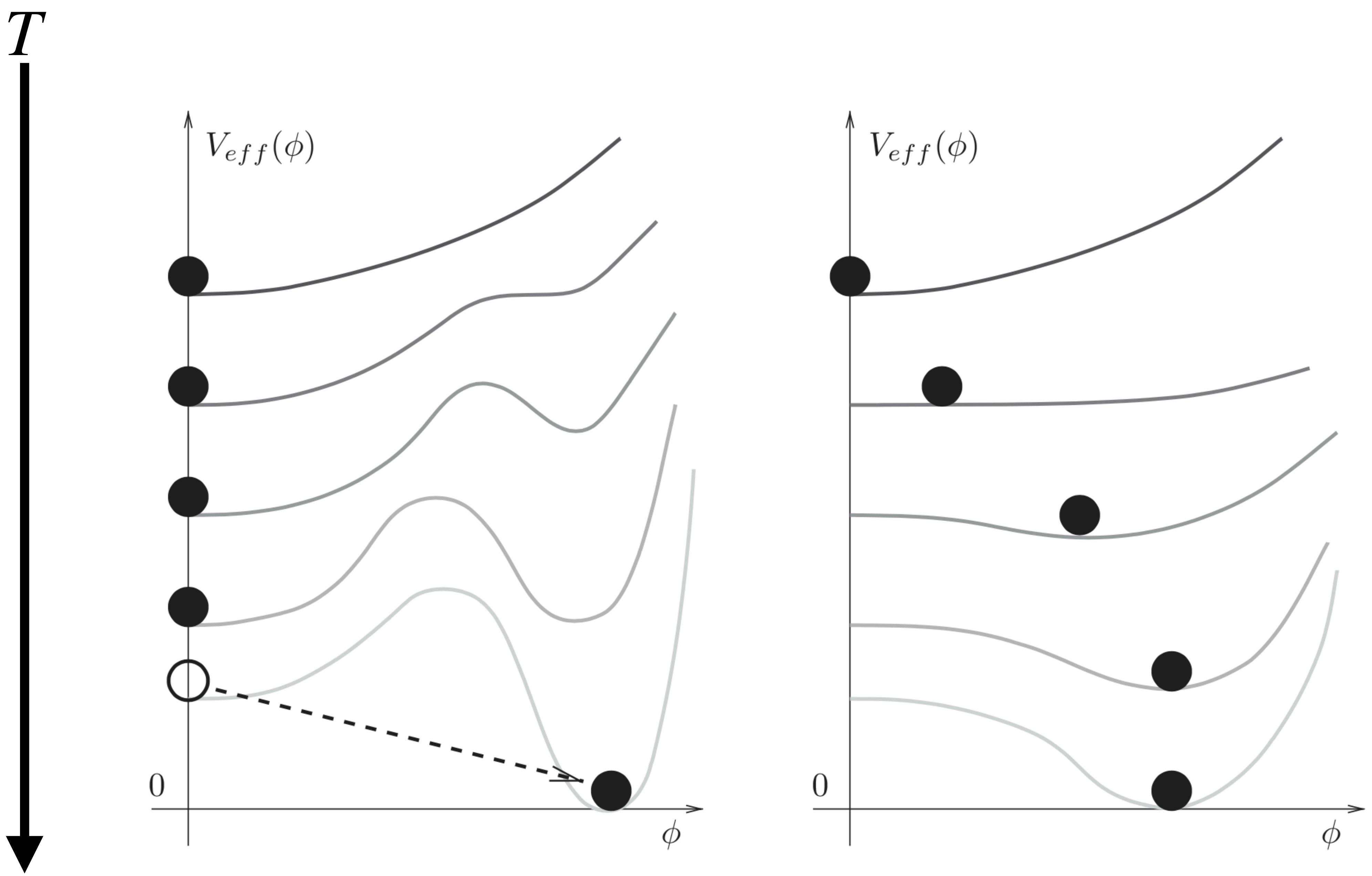

1st order **2nd order**

1st order phase transition proceeds via nucleation, expansion and merger of bubbles of the true ground state.

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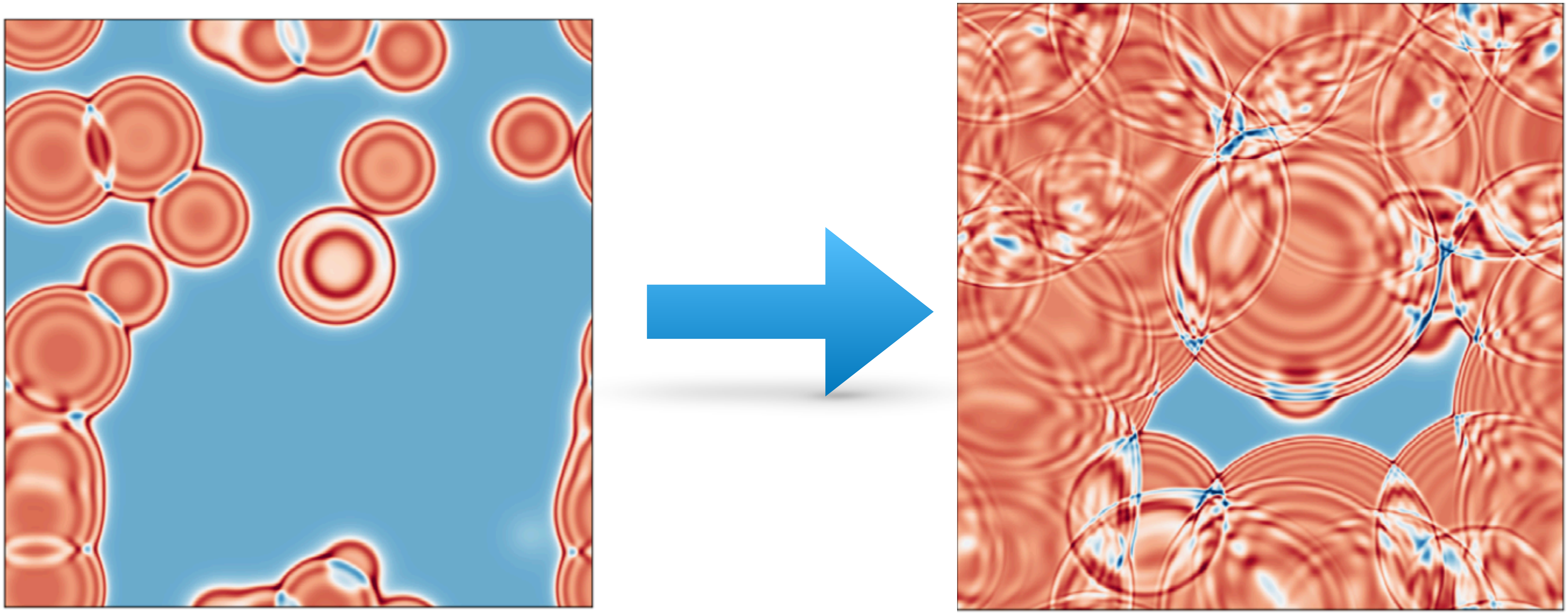

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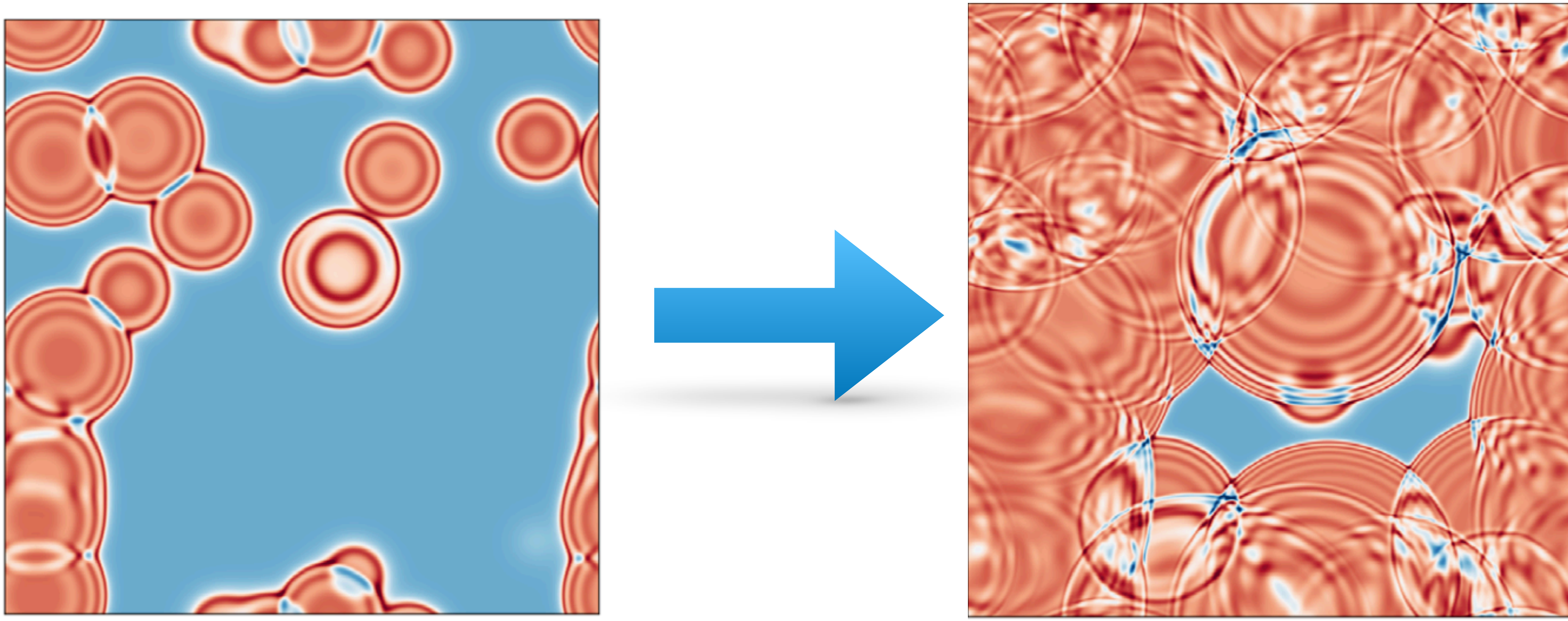


$$f_0 = f_* \frac{a(\tau_*)}{a(\tau_0)}$$

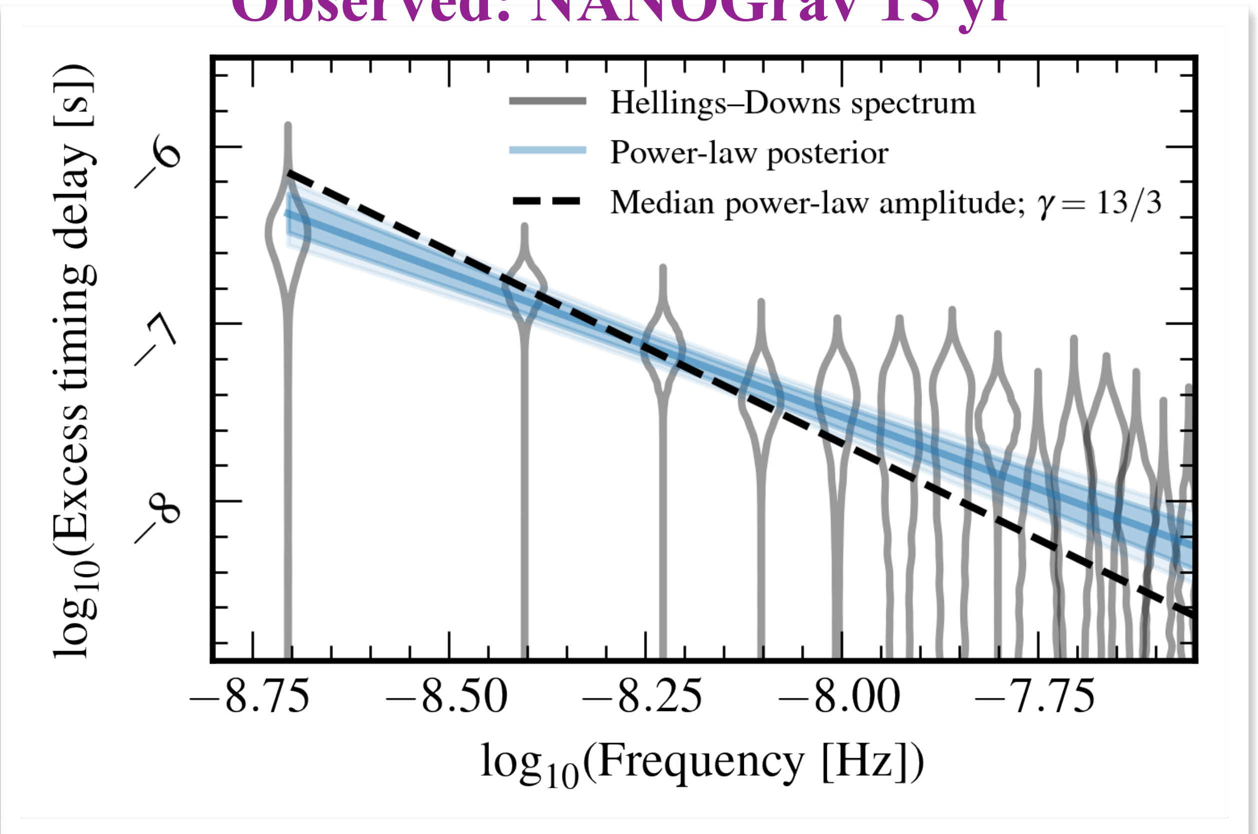
$$f_0 \simeq 10^{-8}\ \text{Hz} \left(\frac{T_*}{1\ \text{GeV}} \right)$$

Observed frequency f_0 is redshifted and is associated with the epoch when GW was produced.

Motivation

Phase transition provides a better fit to the data than SMBHB only expectation.

Observed: NANOGrav 15 yr



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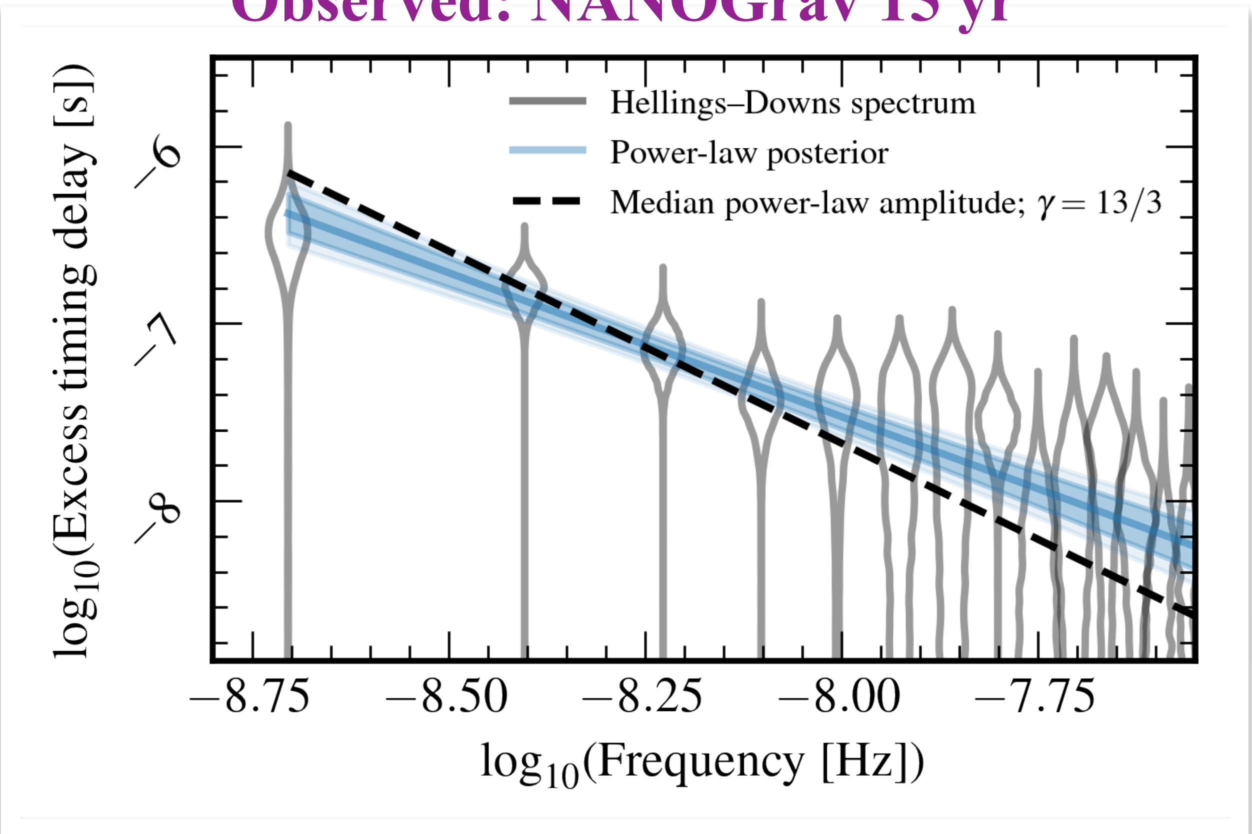

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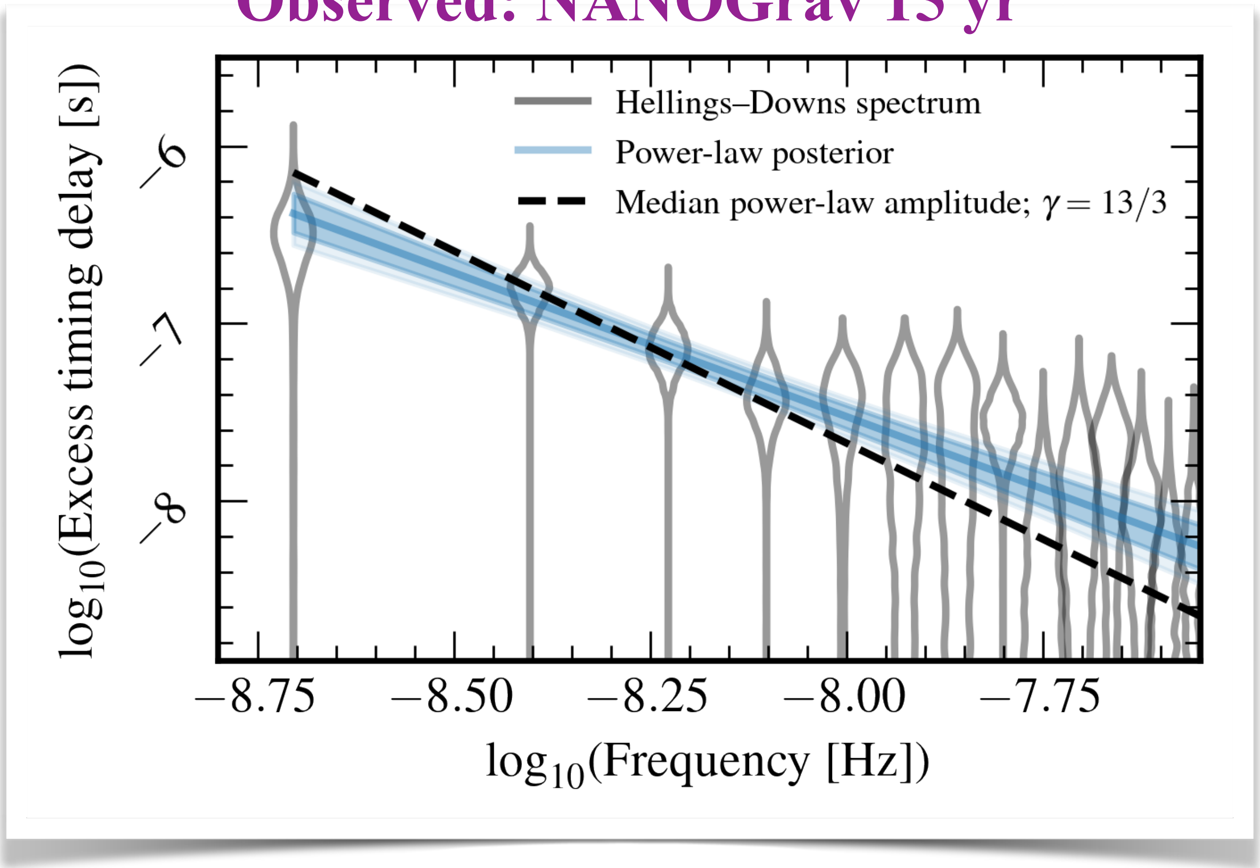

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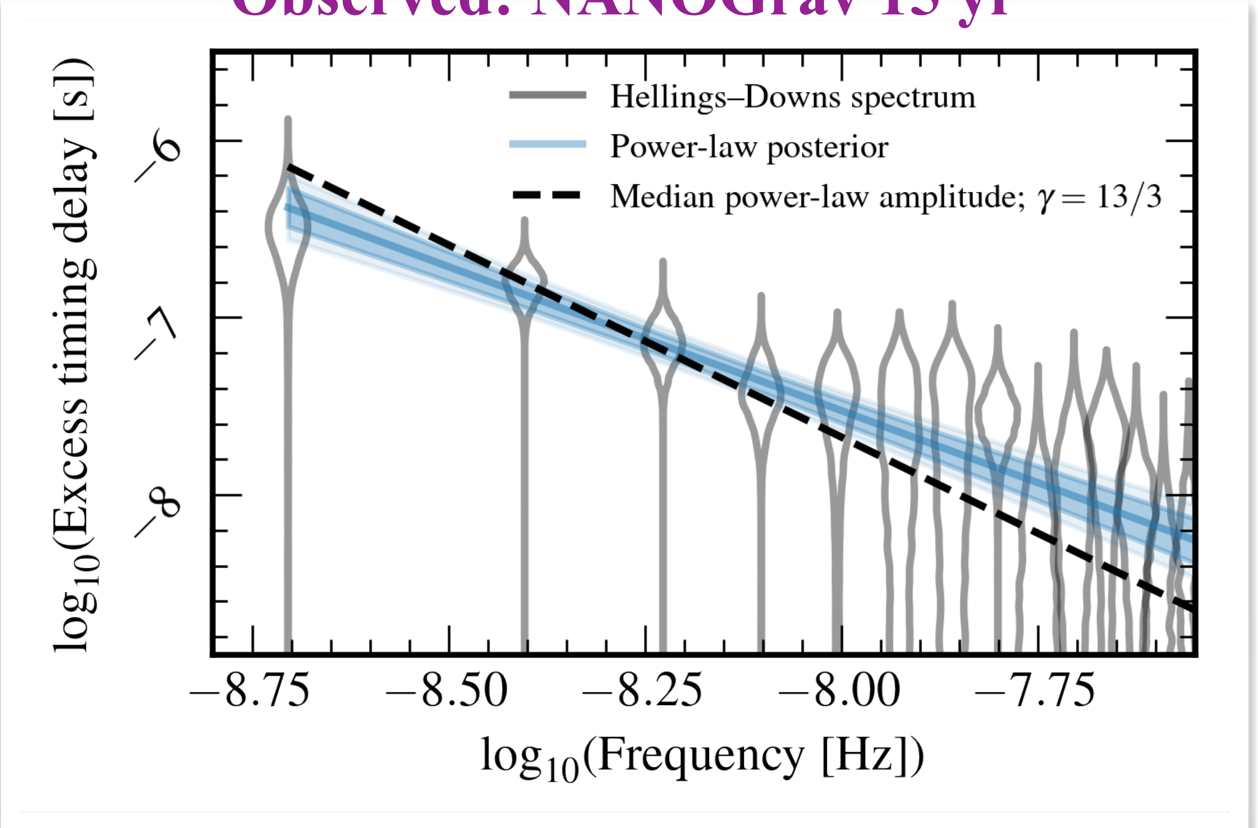

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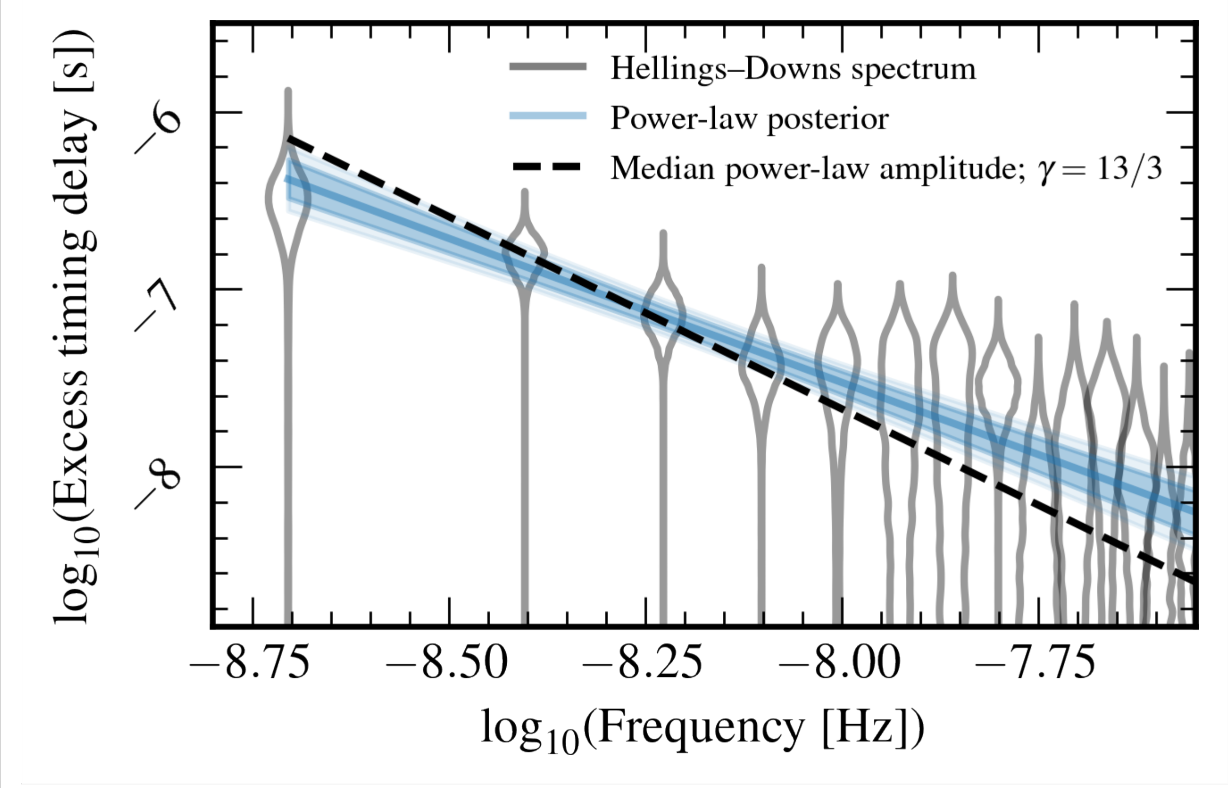

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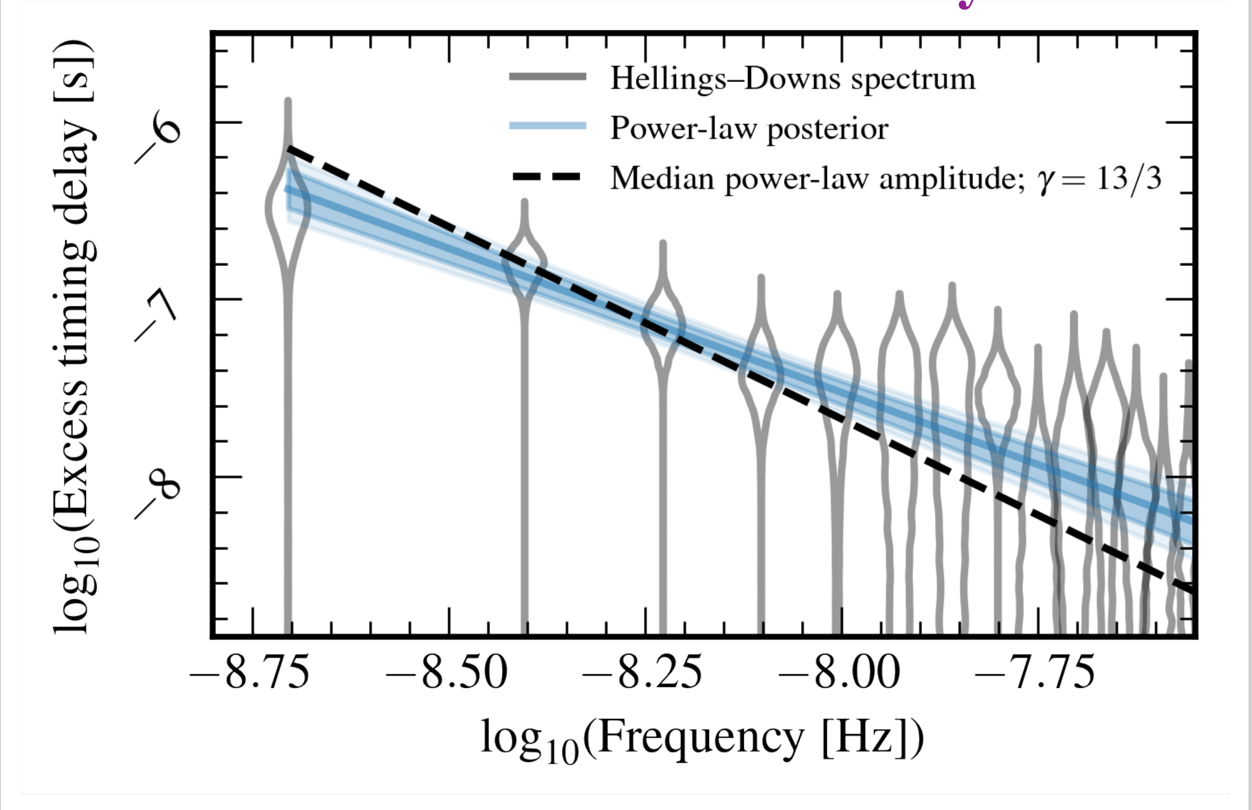

From the underlying field theory to GW spectra

Calculate the bubble nucleation rate from the bounce action S_B
$\Gamma \sim T^4 e^{-S_B}$

Calculable Effective parameters
α: Latent heat released
β: Bubble nucleation rate
v_w: Bubble wall speed

Extensive numerical simulations have given approximate analytical fit for the resulting GW spectrum

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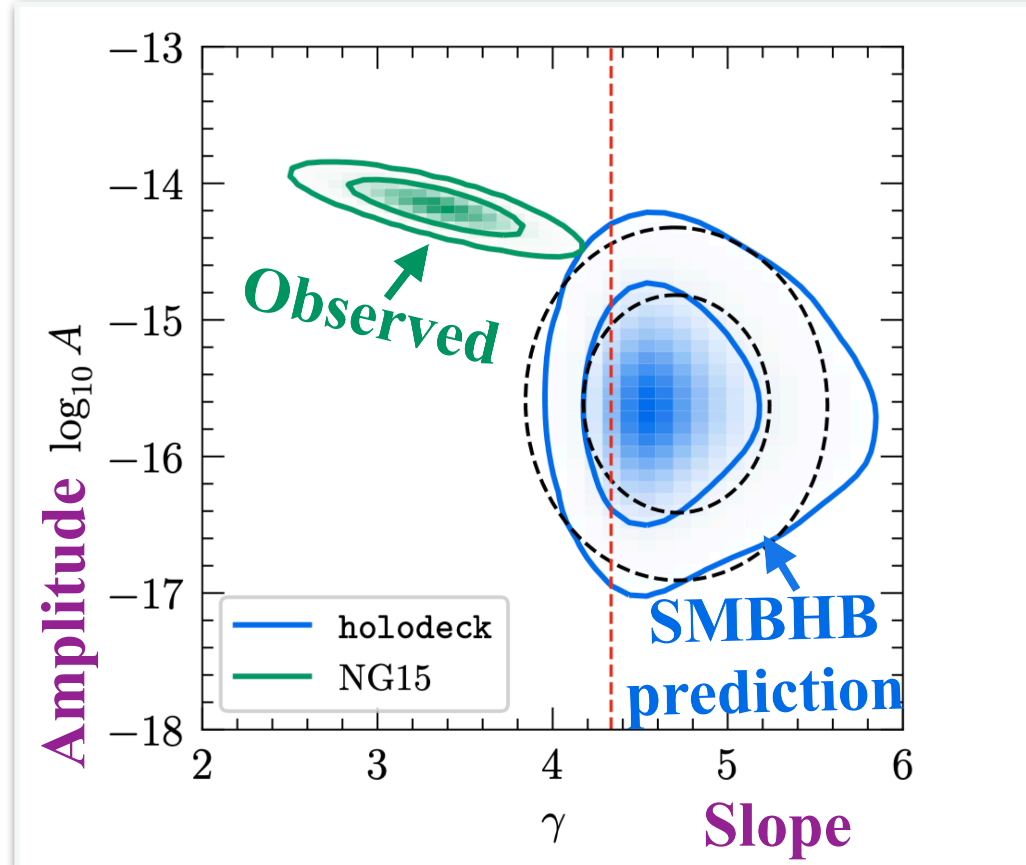

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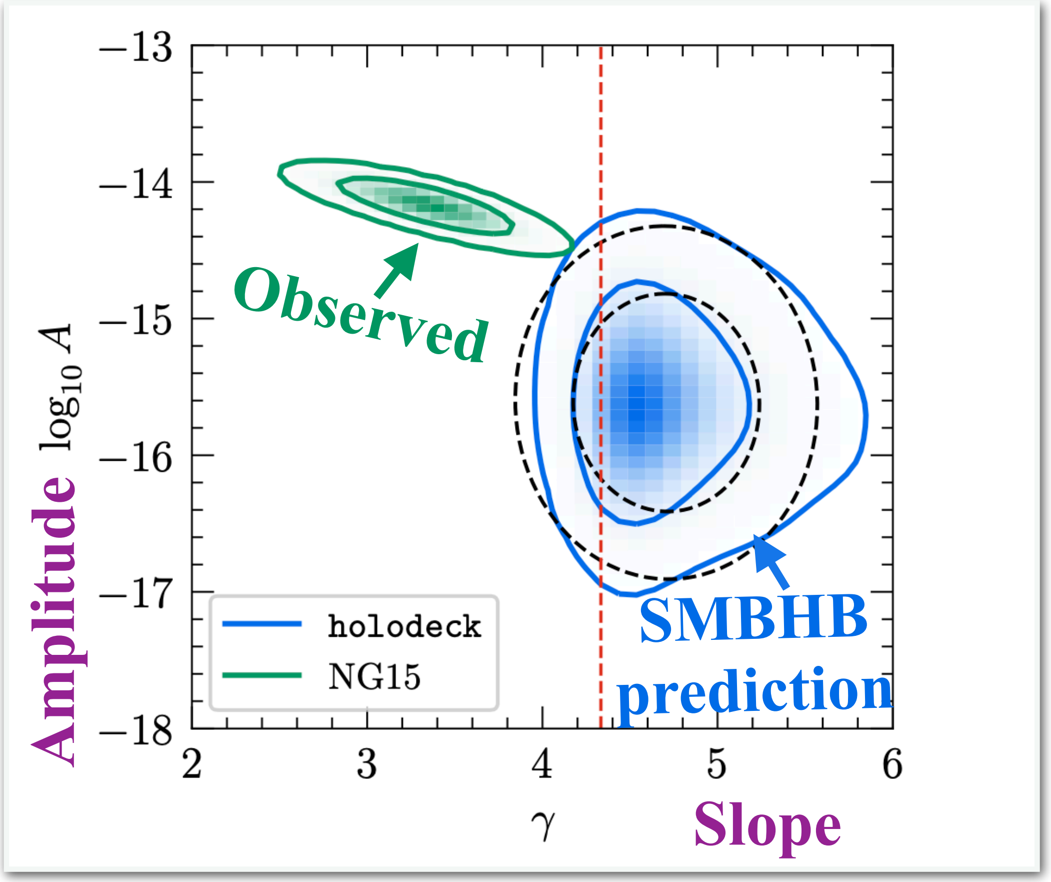

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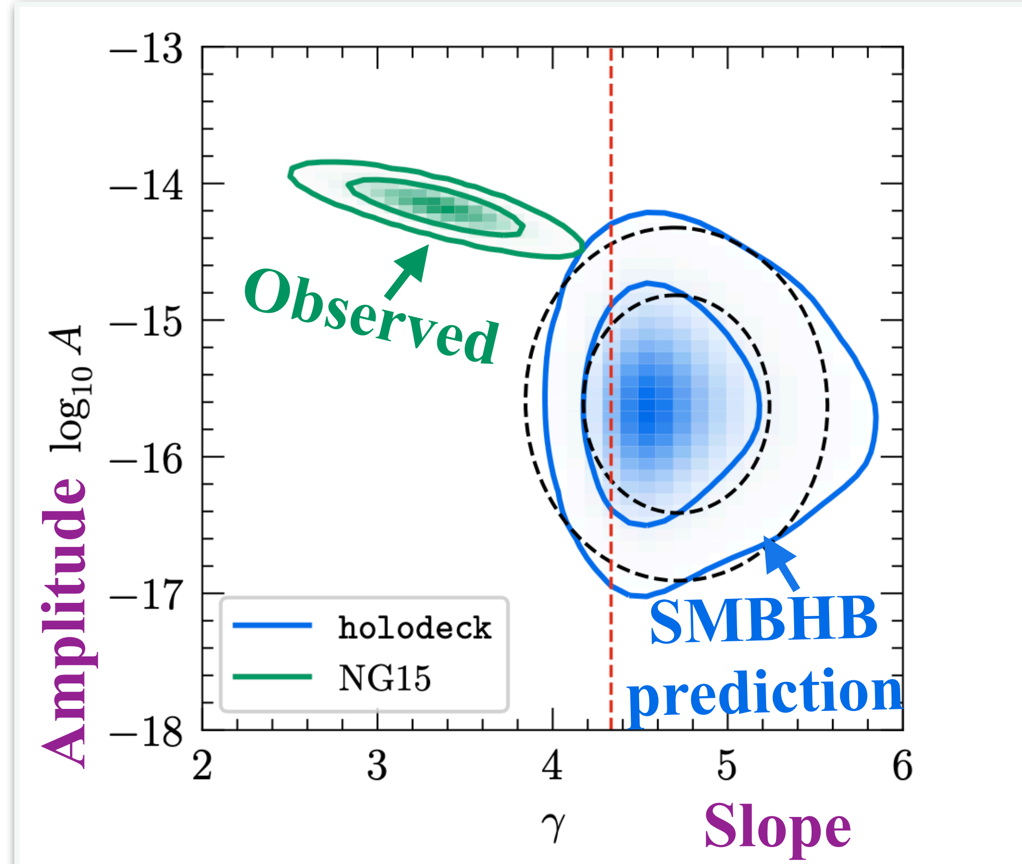

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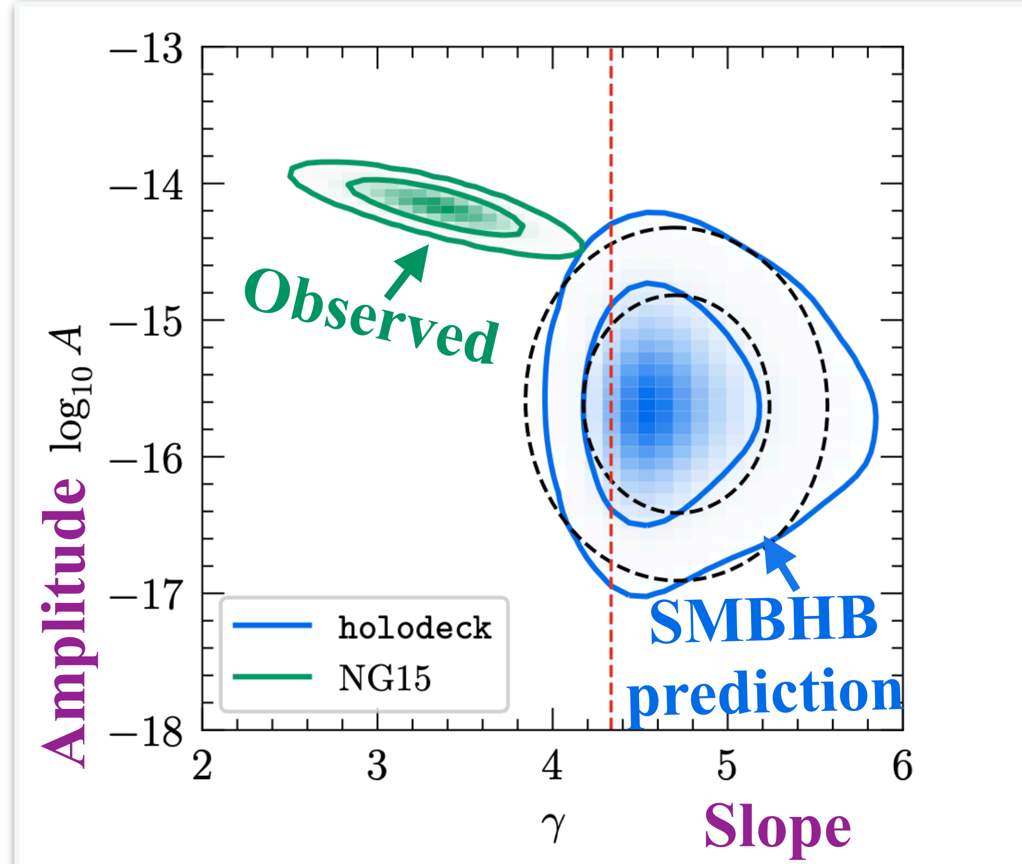

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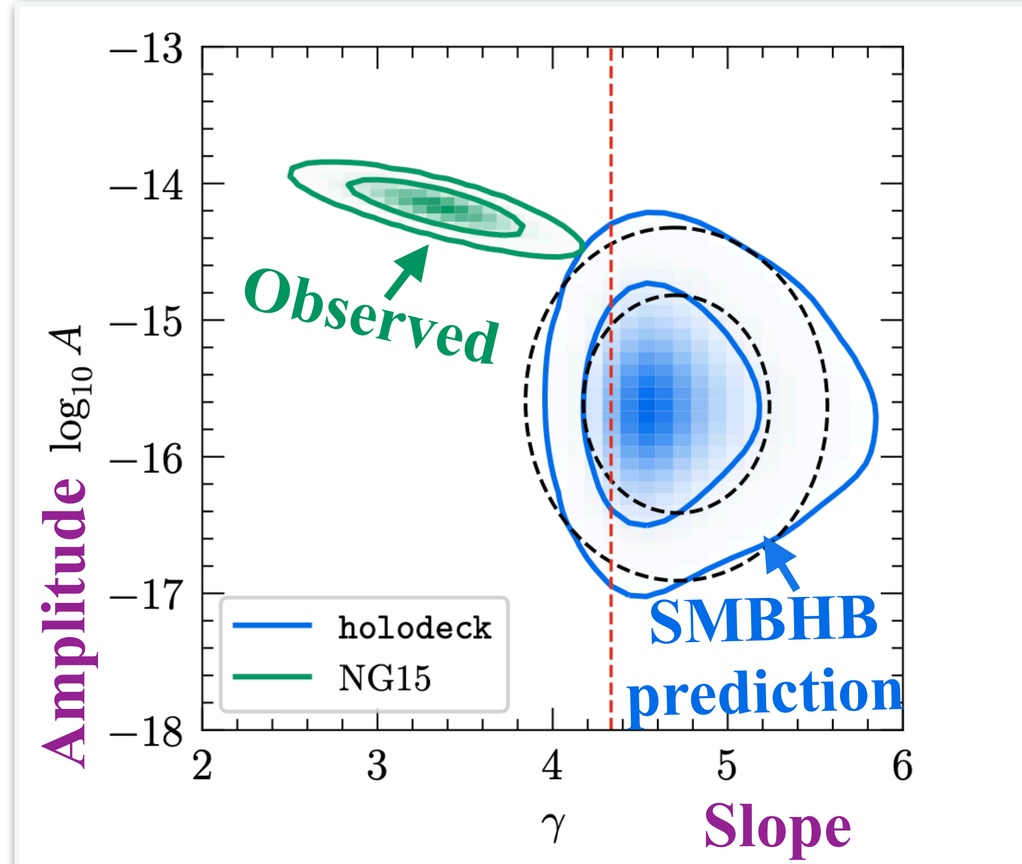

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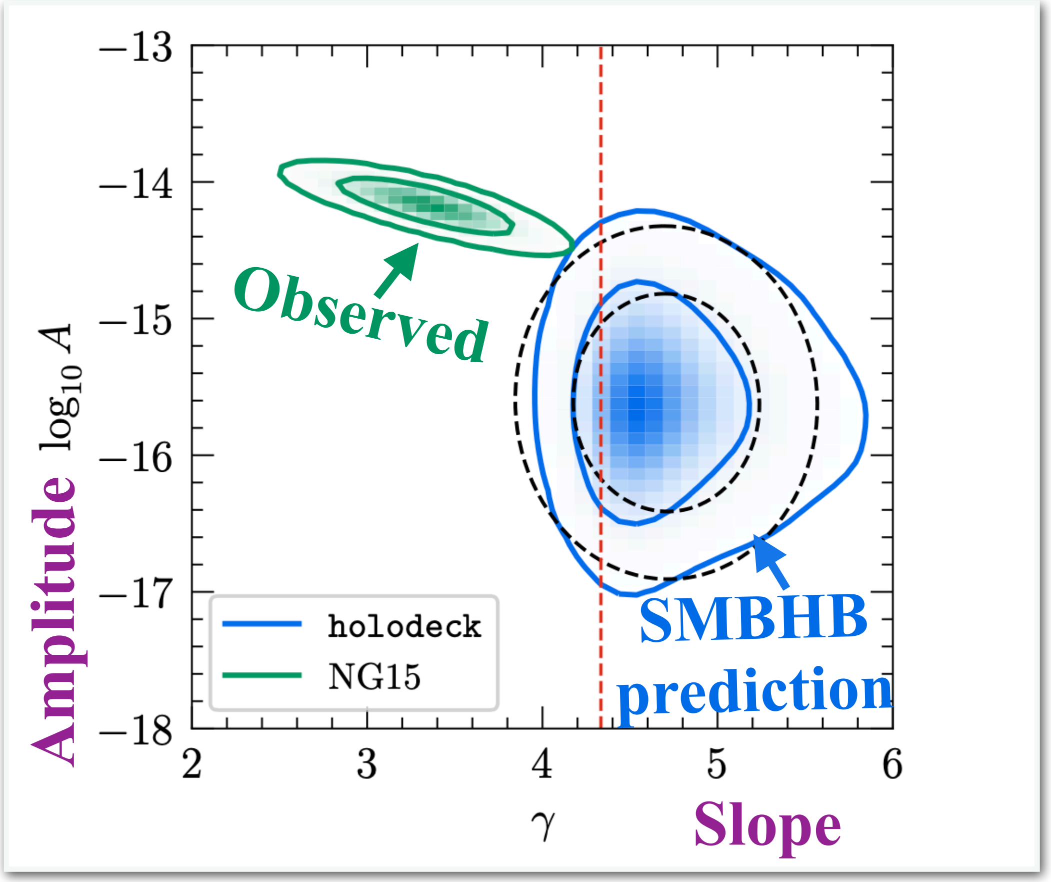

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Utilize weakly coupled description of deconfining phase transition via AdS/CFT.

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$T^{(D)} \gg T_c^{(\mathrm{D})}$

4D conformal dark sector with large N
+
dark pure $SU(N_H)$ Yang-Mills

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4D conformal dark sector with large N
+
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$SU(N_H)$ confines $\Longrightarrow$ drives spontaneous breaking of conformal invariance $\Longrightarrow$ generates dilaton (φ) effective potential

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Confinement-deconfinement phase transition and generation of gravitational waves

Rattazzi+ 2002 ; Servant+ 2017

Dual 5D description

IR brane replaced by an event horizon + $SU(N_H)$ in the bulk

Dark $SU(N_H)$ confinement generates radion potential

Below $T_c^{(D)}$: IR brane configuration has lower free-energy

IR brane bubbles appear and a strong first-order phase transition proceeds.

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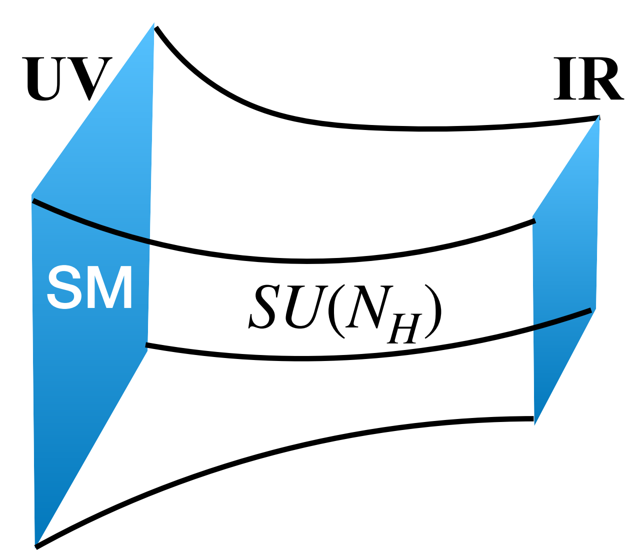

$SU(N_H)$ **confinement generates** $V_{\rm eff}(\varphi)$

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$$\frac{1}{g_{\rm H}^2(Q,\varphi)} = -\frac{b_{\rm CFT}}{8\pi^2}\ln\left(\frac{k}{\varphi}\right) - \frac{b_{\rm H}}{8\pi^2}\ln\left(\frac{k}{Q}\right)$$

Running of $SU(N_{\rm H})$ coupling $g_{\rm H}$ from UV scale k to $Q \lesssim \varphi$. $b_{\rm CFT} = -\xi N$, $b_{\rm H} = 11N_{\rm H}/3$.

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Condensate provides dilaton potential $V_{\rm eff}(\varphi)$.

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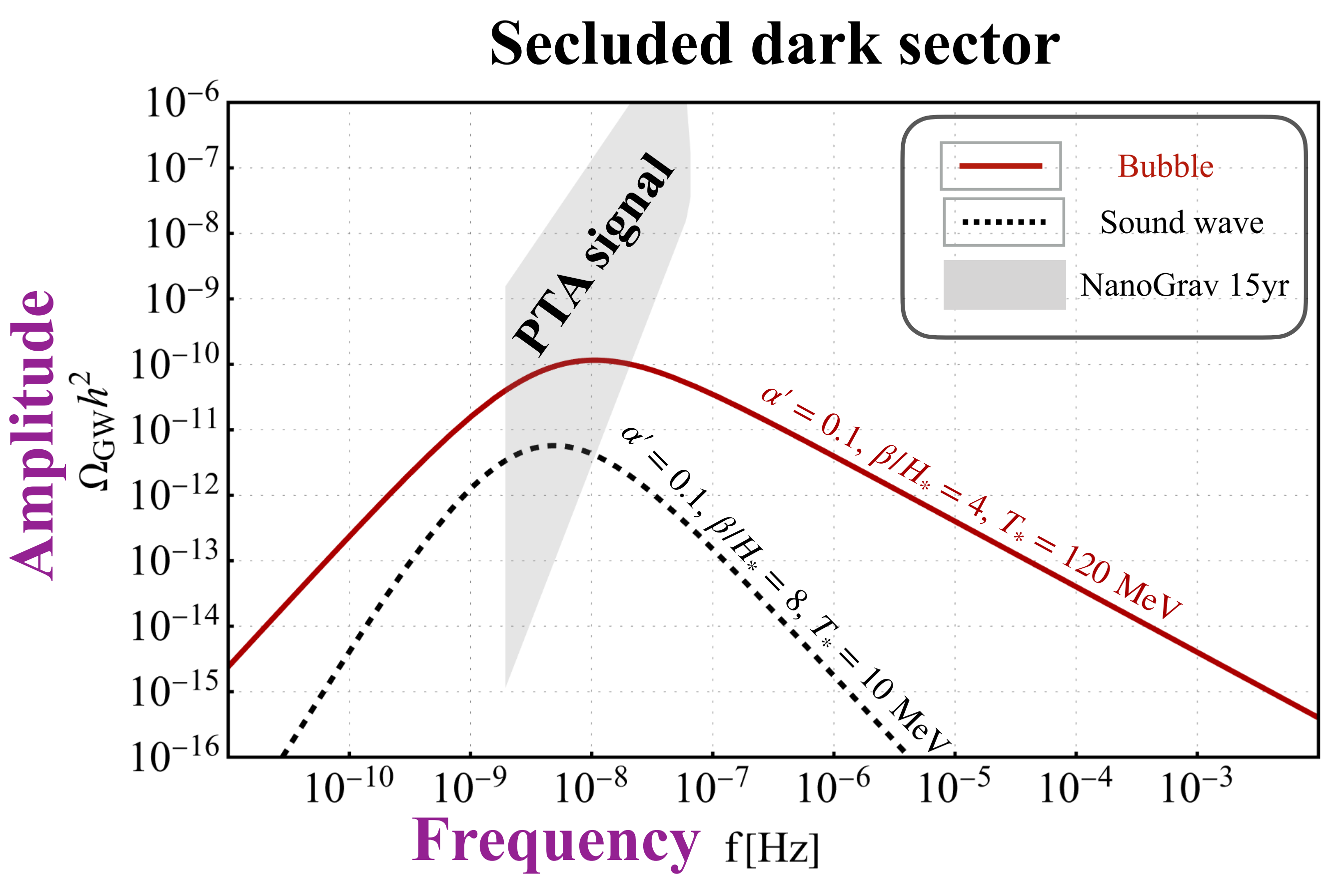

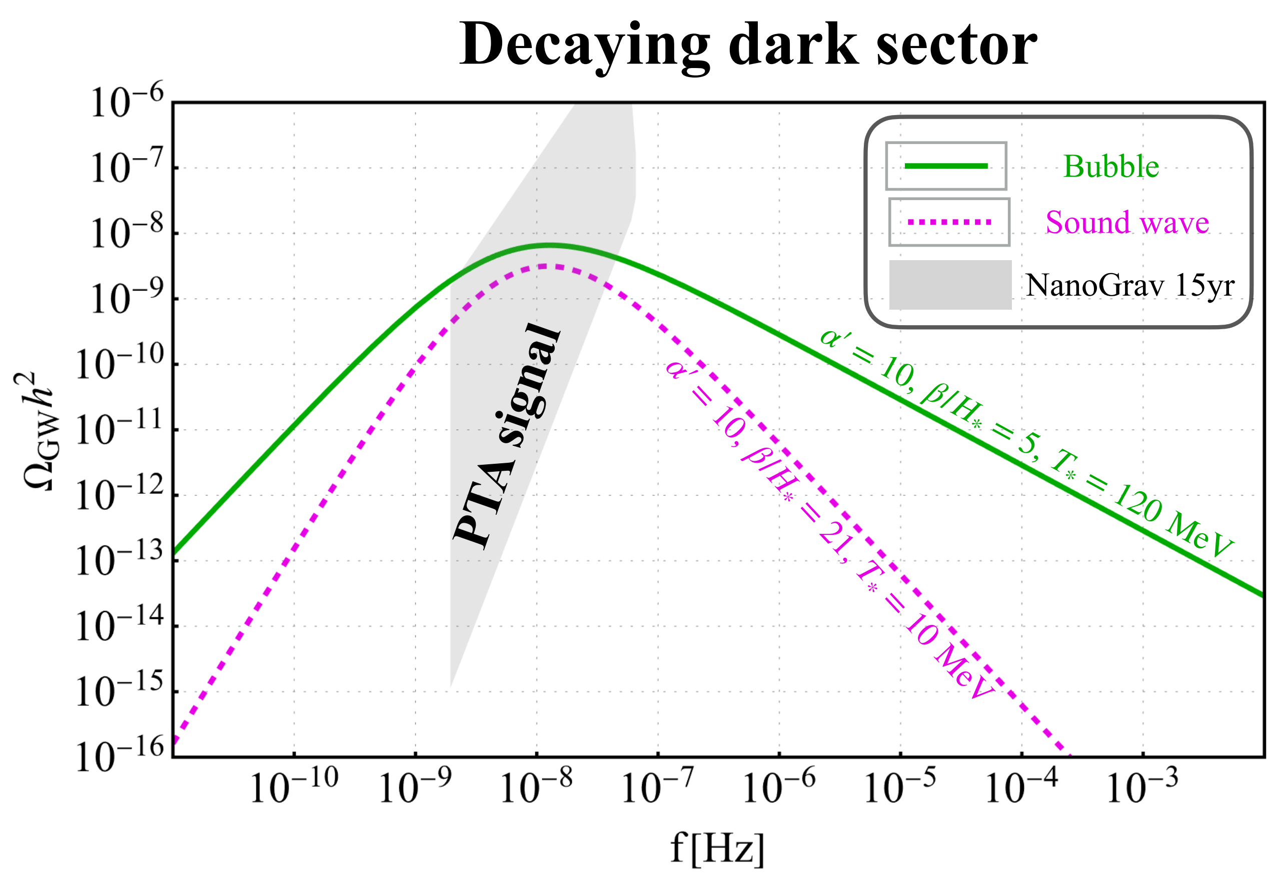

III. Cold Darkogenesis

Theoretical challenges to the phase transition interpretation and possible resolution: *Dark Matter and Baryon Asymmetry*

Fujikura, Girmohanta, Nakai and Zhang, arXiv:2406.12956

The Problem: Supercooling and Mini-inflation

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Schwaller et. al. JHEP 10 171 (2023)

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The model

Dilaton stabilization → $SU(N_H)$; **Cold darkogenesis** → $SU(2)_D$; **Dark baryon number** → $U(1)_D$

	Fields	$SU(N_H)$	$SU(2)_D$	$U(1)_D$	
Spin 0	H_D	$\mathbf{1}$	$\mathbf{2}$	0	→ Spontaneous breaking of $SU(2)_D$
Spin 1/2	$L_{\chi,i} \equiv \begin{pmatrix} \psi_{1,i} \\ \psi_{2,i} \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	1	→ $U(1)_D$ anomalous under $SU(2)_D$
Spin 1/2	$\chi_{1,i}\,,\,\chi_{2,i}$	$\mathbf{1}$	$\mathbf{1}$	-1	→ Neutron portal interaction for asymmetry sharing with SM
Spin 1/2	f_j	$\mathbf{N}_H$	$\mathbf{1}$	$1/N_H$	→ Baryon dark matter
Spin 1/2	$\bar{f}_j$	$\overline{\mathbf{N}}_H$	$\mathbf{1}$	$-1/N_H$	

$i = 1,\cdots,N_{D_L}\ ;\ j = 1,\cdots,N_{D_B}$

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$$V(\varphi, H_\mathrm{D}) = V_\mathrm{eff}(\varphi) + \frac{\lambda}{4}\left[H_\mathrm{D}^\dagger H_\mathrm{D} - \frac{v_\mathrm{D}^2}{2}\left(\frac{\varphi}{\varphi_\mathrm{min}}\right)^2\right]^2 .$$

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- The later induces **dark lepton number violation via anomaly.**

$$\partial_\mu j^\mu_{\mathrm{D_L}} = N_{\mathrm{D_L}} \frac{g_\mathrm{D}^2}{32\pi^2} \mathrm{Tr}\left(W_\mathrm{D}^{\mu\nu} \widetilde{W}_{\mathrm{D},\mu\nu}\right) \;;\quad \mathcal{O}_\mathrm{CPV} = \delta_\mathrm{CP} \frac{H_\mathrm{D}^\dagger H_\mathrm{D}}{\Lambda_\mathrm{CP}^2} \frac{g_\mathrm{D}^2}{32\pi^2} \mathrm{Tr}\left(W_\mathrm{D}^{\mu\nu} \widetilde{W}_{\mathrm{D},\mu\nu}\right)$$

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- With C & CP violation, $\delta N \equiv N_{\rm CS} - N_{\rm H} > 0$ and $\delta N < 0$ winding configurations evolve differently, generating a net dark lepton number $\mathscr{D}_{\rm L,in}$.

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$$\mathscr{D}_{\mathrm{L,in}} \simeq 10^{-10}\left(\frac{N_{D_{\mathrm{L}}}}{2}\right)\left(\frac{\delta_{\mathrm{CP}}}{10^{-4}}\frac{\varphi_{\min}^2}{\Lambda_{\mathrm{CP}}^2}\right)\left(\frac{\alpha_{\mathrm{D}}}{1.5\times10^{-2}}\right)^4\left(\frac{\lambda}{10^{-4}}\right)^{-3/2}\left(\frac{5v_{\mathrm{D}}}{\varphi_{\min}}\right)^{1/2}\left(\frac{\varphi_{\min}}{2T_{\mathrm{RH}}}\right)^3$$

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✦ The DM is **self-interacting** via the mediation of dark pions $\pi_{\rm D}$ with cross-section:

$$\frac{\sigma_{p_{\rm D}p_{\rm D}}}{m_{p_{\rm D}}} \sim 1\ {\rm cm^2/g}\left(\frac{\Lambda_{\rm H,0}}{m_{p_{\rm D}}}\right)\left(\frac{\Lambda_{\rm H,0}}{a_{\rm D}^{-1}}\right)^2\left(\frac{150\ {\rm MeV}}{\Lambda_{\rm H,0}}\right)^3 \quad ; \quad a_{\rm D}\ \textbf{: scattering length .}$$

Tulin Yu (2017) ; Kribs (2016)

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$\lambda_h \lesssim 0.1$ **from Higgs invisible decay.**

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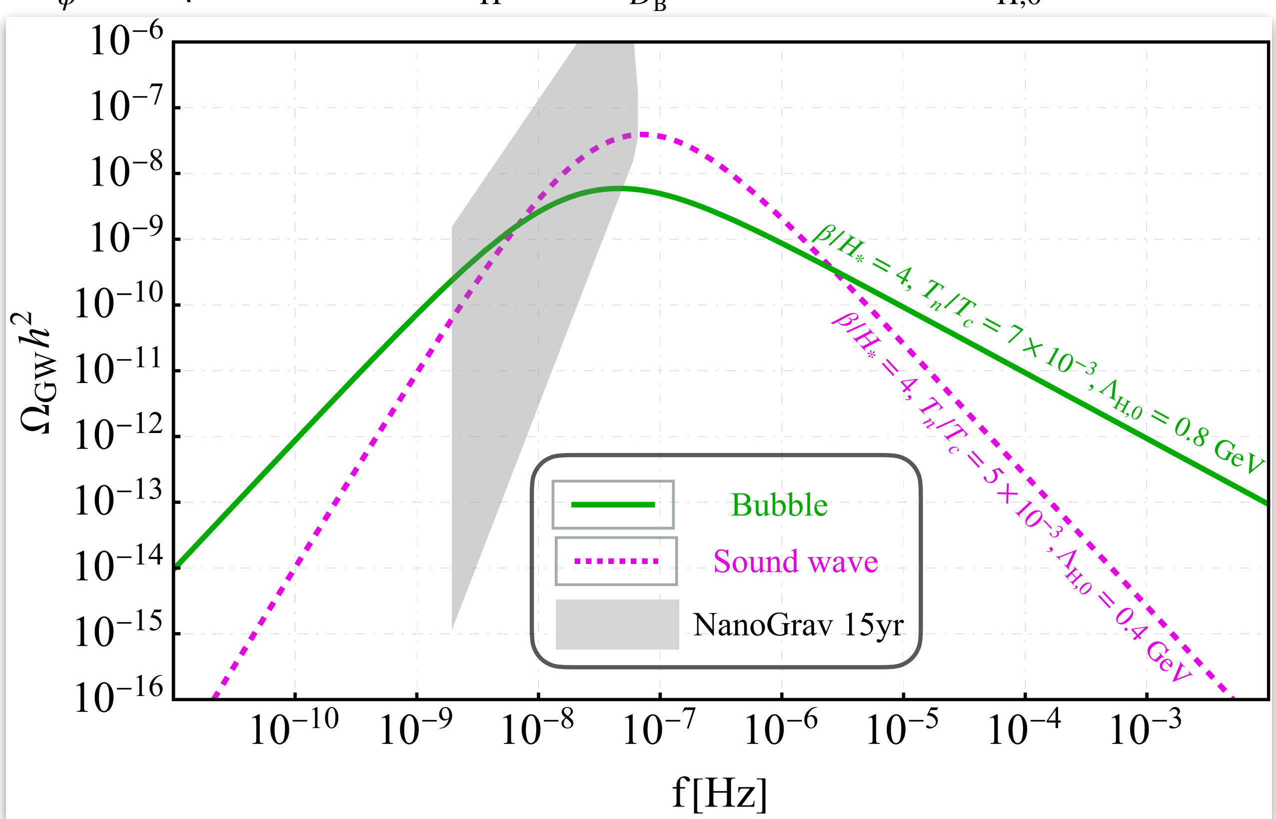
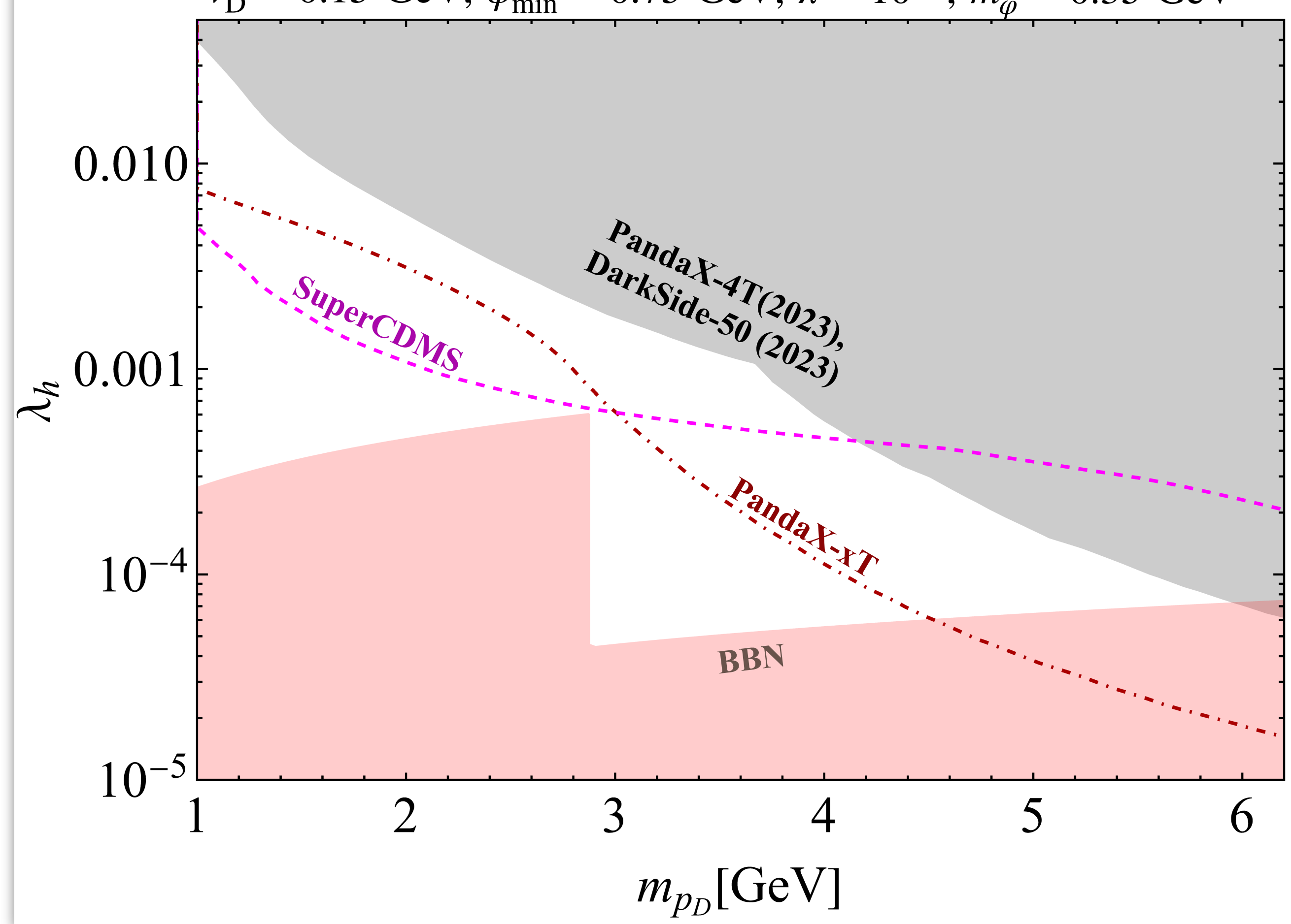
PTA signal explanation together with DM and baryon asymmetry

$\lambda_\varphi = 1,\ \eta = 8,\ N = 10,\ N_H = 5,\ N_{D_B} = 10,\ n = 0.15,\ \Lambda_{H,0} = 0.8$GeV



$v_D = 0.15$ GeV, $\varphi_{min} = 0.75$ GeV, $\lambda = 10^{-4}$, $m_\varphi = 0.35$ GeV



Conclusions

- ✓ Dark first-order phase transition is a promising interpretation of the observed PTA signal.
- ✓ **Confining nearly conformal phase transition** can realize a supercooled phase transition to explain the data. We analyzed it using the dilaton effective potential.
- ✓ Both secluded dark sector (together with SMBHB) and decaying dark sector can explain the observed signal.
- ✓ The strong supercooling exponentially dilutes away pre-existing baryon asymmetry and DM, posing a challenge to this scenario.
- ✓ We provide a concrete scenario of **cold darkogenesis** where the baryon asymmetry and DM are produced utilizing the phase transition.
- ✓ Future direct detection searches for DM and mono-jet searches at colliders will probe this model further.

Thank you for your time! Questions?