Gravitational Waves and Primordial Black Holes from Domain Walls

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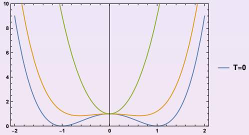
Discrete symmetry breaking

- Simple example: scalar field with Z_2 symmetry
  $V(\phi) = \frac{\lambda}{4}(\phi^2 - v^2)^2$



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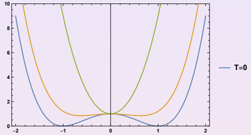

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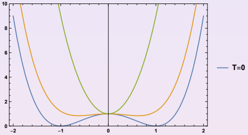

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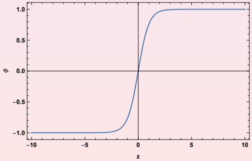
- Domain walls produced at T_{PT}, $\phi(z) = v \tanh(\sqrt{\lambda/2} vz)$



Domain Walls

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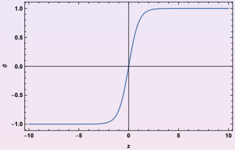

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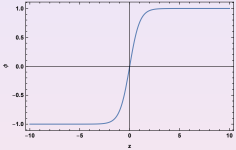


- Thickness $\delta = (\sqrt{\lambda} v)^{-1}$
- Wall with energy per unit area (tension)

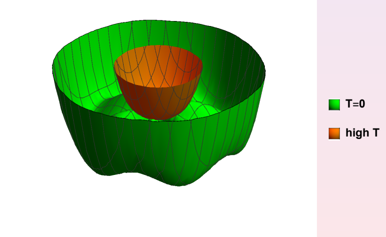
$$\sigma = 2 \int dz V(z) \propto \sqrt{\lambda} v^3$$

Axionic Domain Walls

- Another example: Complex field with $U(1)$ symmetry at high T, broken to Z_N at $T = 0$

$$V(\Phi) = \lambda(|\Phi|^2 - v^2)^2 + V_0 \cos\left(N\frac{a}{v}\right)$$

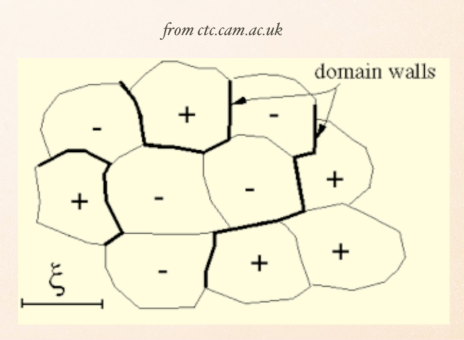
$$\Phi = |\Phi| e^{i\frac{a}{v}}$$



- Discrete minima below some T_{PT}
- Domain walls are produced at T_{PT}

Domain Walls Cosmology

- In expanding Universe with $H = \frac{\dot{a}}{a}$
- At T_{PT} (uncorrelated) values in different patches (separated by $\leq \mathcal{O}(H^{-1})$: causality)



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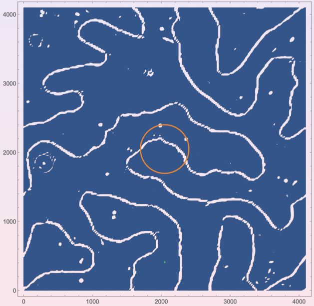

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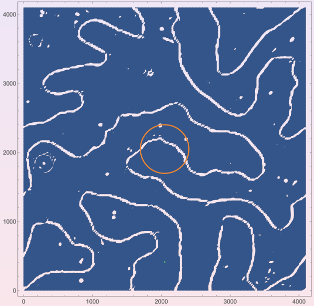

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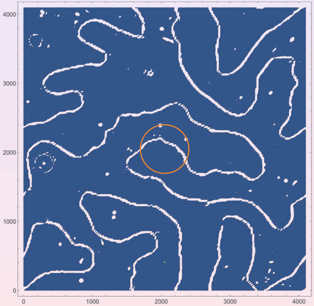
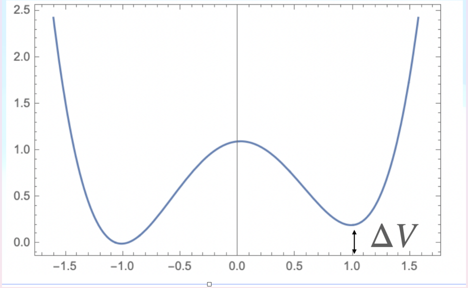


- By dimensional analysis $\rho_{DW}|_{\text{scaling}} \approx \sigma H$
- For σ large enough DWs quickly dominate over radiation background, $\rho_{RAD} = 3H^2 M_{Pl}^2$
- $\Longrightarrow$ Domain wall problem! (unless $\sigma^{1/3} \lesssim 100$ MeV)

Way out: Domain Walls Annihilation

- Possible way out:
- Make them unstable, assuming a small "bias" ΔV



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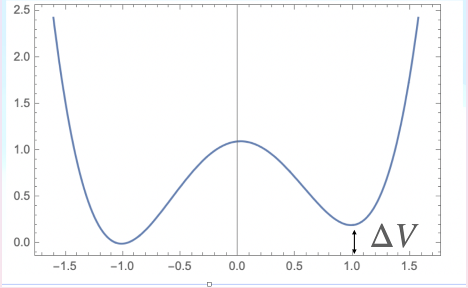

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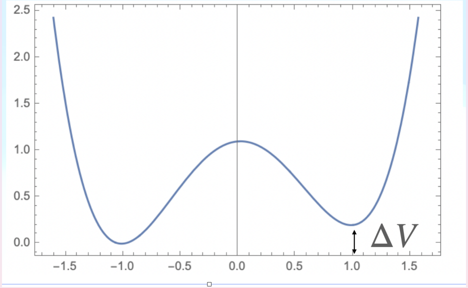

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- Alternatives:
  - Initial "population bias"
  - ... maybe symmetry restoration at low-T? "Inverse Phase Transition" (Babichev et al. Phys.Rev.D 2023)

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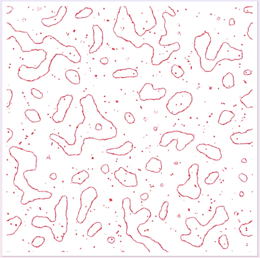

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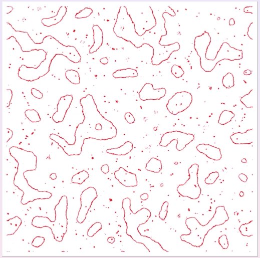

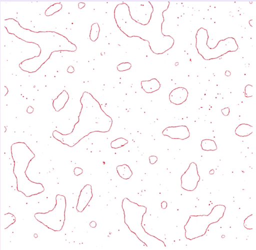

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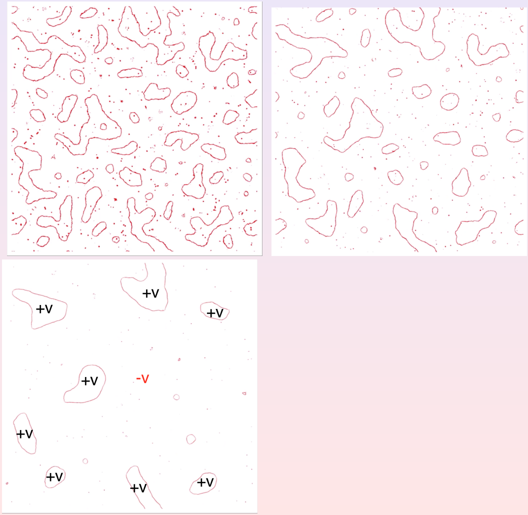

Domain Walls Annihilation

Domain Walls
Gravitational Waves from DWs
Pulsar Timing Arrays (PTA)
Network Collapse
PBH

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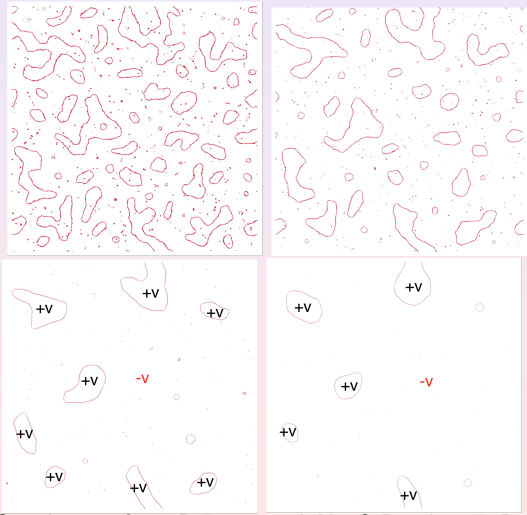

Figure: Simulations from R.Ferreira, A.N., O.Pujolas, F. Rompineve,

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Relic GW from Domain walls

- More precisely, simulations in scaling give

$$\boxed{\Omega_{\rm GW} h^2 \simeq 0.05 \; (\Omega_\gamma^0 h^2) \; \tilde{\epsilon} \left(\frac{\rho_{\rm DW}}{\rho_{\rm rad}} \right)^2_{T=T_*}},$$

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- Two free parameters σ (or α_*) and T_*

GW spectra: simulations

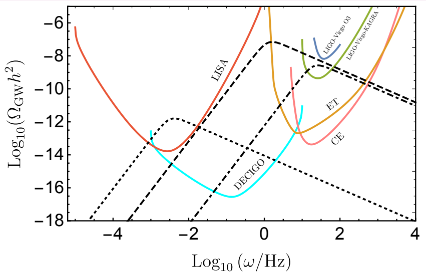
- GW spectrum $\rho_{\rm GW} \equiv \int \frac{d\rho_{\rm GW}}{d\log k}\frac{dk}{k}$:

$$\frac{d\rho_{GW}}{d\log k} = \begin{cases} f^3 \text{ for } f < f^0_{\rm peak}, \text{ (causality)} \\ f^{-1} \text{ for } f > f^0_{\rm peak}\,, \left(\text{until cutoff given by DW width}\right). \end{cases}$$

Hiramatsu, Kawasaki, Saikawa, 2014 (grid size $= 1024^3$)

R.Ferreira, A.N., O.Pujolas, F. Rompineve, JCAP 06 (2024) 020 (grid size $= 2040^3$)

Kitajima, Lee, Murai, Takahashi, Yin, 2306.17146, (grid size $= 4096^3$)



GW Search from Domain Walls in PTA

- Search for GW from Domain Walls :

$$\Omega_{\rm GW,DW}(f)h^2 \simeq 10^{-10}\,\tilde{\epsilon}\left(\frac{10.75}{g_*(T_\star)}\right)^{\frac{1}{3}}\left(\frac{\alpha_\star}{0.01}\right)^2 S\left(\frac{f}{f_p^0}\right),$$

  where $\tilde{\epsilon} \simeq 0.1 - 1$ (efficiency parameter)

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R. Z. Ferreira, A.N., O. Pujolas, F. Rompineve, e-Print: 2204.04228

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- $S(x)$ models the shape:

$$S(x) = \frac{(\gamma+\beta)^\delta}{(\beta x^{-\frac{\gamma}{\delta}} + \gamma x^{\frac{\beta}{\delta}})^\delta},$$

$$\begin{cases} \text{At low frequency } S \propto f^3 \\ \text{At high } f\text{, simulations suggest } \delta \approx \beta \approx 1 \implies S \propto f^{-1} \end{cases}$$

R. Z. Ferreira, A.N., O. Pujolas, F. Rompineve, e-Print: 2204.04228

Decay of the network

- Assume DW decay into ϕ quanta and subsequently:
- Two scenarios

$$\begin{cases} \phi \text{ Decay to Dark Radiation problem if too much} \\ \phi \ \mathrm{Decay \ to \ Standard \ Model \ Before \ BBN} \ \ T_* \gtrsim 3MeV \end{cases}$$

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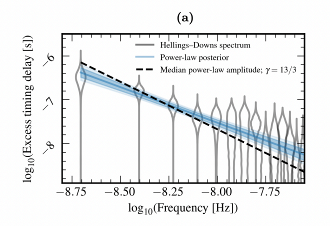
$$\Delta N_{\rm eff} = \frac{\rho_{\rm DR}}{\rho_\nu} \approx \frac{\rho_{\rm DW}}{\rho_\nu} = 13.6 g_*|_{T_*}^{-1/3} \alpha_*$$

,

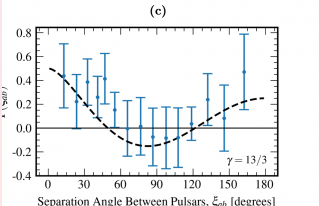
- Current limits $\Delta N_{\rm eff} \lesssim 0.3 - 0.37$
  (*Planck 2018 + DESI BAO+ Pantheon+BBN, I. Allali, A.N., F. Rompineve, 2404.15220*)

NANOGRAV 15 year

- *North American Nanohertz Observatory for Gravitational Waves* (Agazie et al. Ap.J. Lett. (2023))
- Strong evidence for common-spectrum stochastic process



- First evidence for HD angular correlation from GW



NANOGRAV 15 year

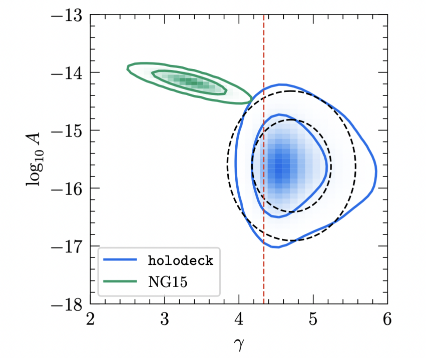
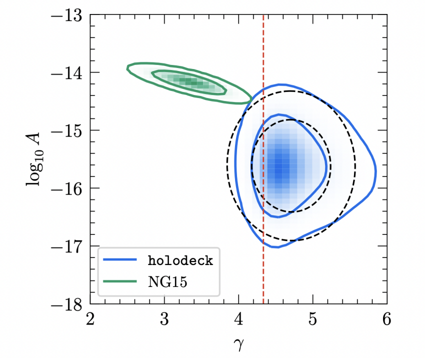


Figure: Afzal et al. Ap.J. Lett. (2023)

- Most "conservative" interpretation: GW from SuperMassive Black Hole Binaries (SMBHB)

$$h(f) = A\left(\frac{f}{f_{yr}}\right)^{\frac{3-\gamma}{2}},$$

NANOGRAV 15 year



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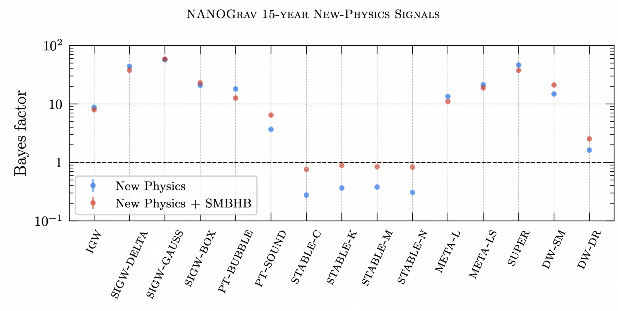
- NANOGrav analysis for several new physics models:



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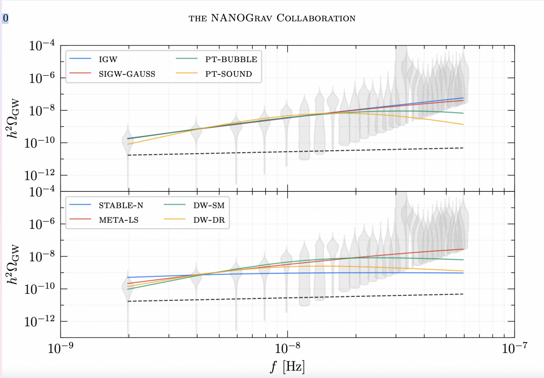
$B_{10} < 1$ means that H1 is disfavored, while B_{10} values in: $[10^{0.0}, 10^{0.5}], [10^{0.5}, 10^{1.0}], [10^{1.0}, 10^{1.5}], [10^{1.5}, 10^{2.0}], [10^{2.0}, \infty)$ interpreted as: negligibly small, substantial, strong, very strong, and decisive evidence in favor of H1.

NANOGRAV 15 year

- NANOGrav analysis for several new physics models:



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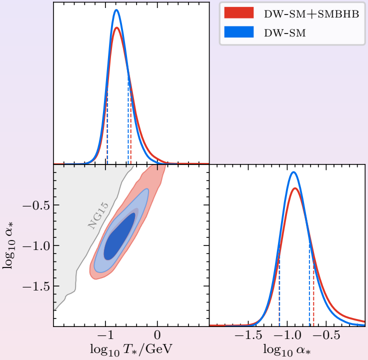
Results (CASE I): Decay into Standard Model



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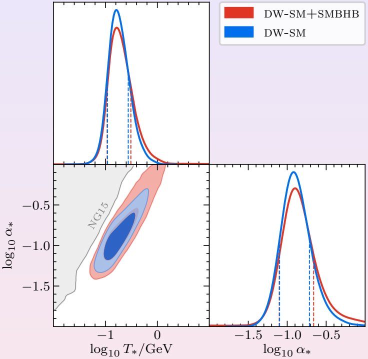

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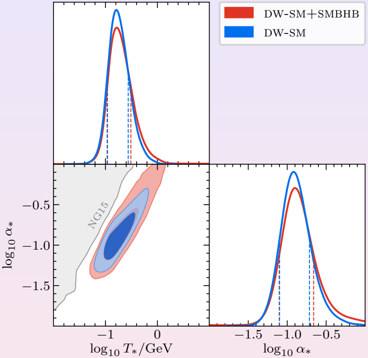

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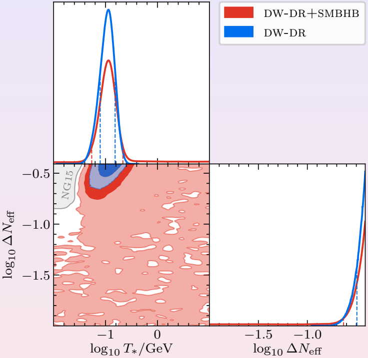
- In a $\mathbb{Z}_2$ model with $V(\phi) = \lambda(\phi^2 - v^2)^2$, $\implies$ $v \approx (100\,TeV)/\lambda^{1/3}$

Results (CASE II): Decay into Dark Radiation



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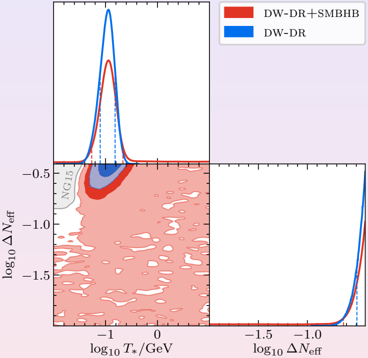

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- Future Forecast: $\Delta N_{\rm eff} \gtrsim 0.16$ visible by forthcoming experiments (Simons Observatory, DESI, Euclid)

Overlap with LISA?

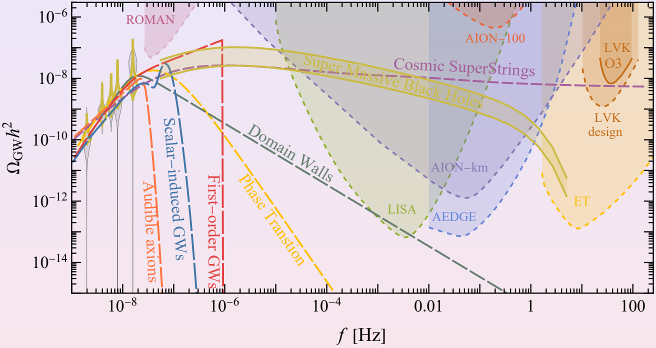

Figure: J.Ellis et al., PhysRevD.109.023522

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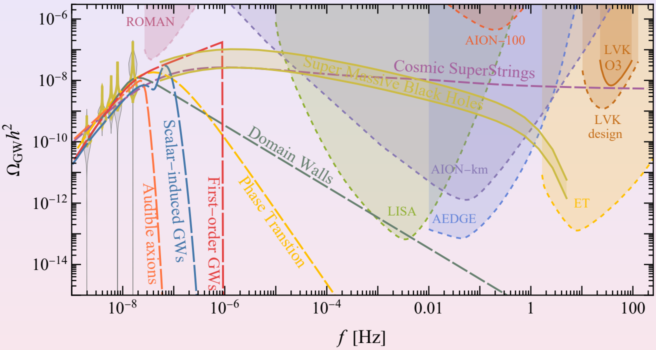

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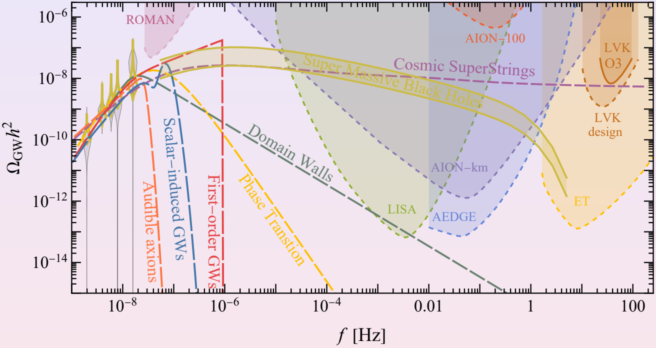

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- Depends on high k behavior: $1/k$?
- Work in progress...

Primordial Black Holes?

- During collapse DW contain False Vacuum "pockets"

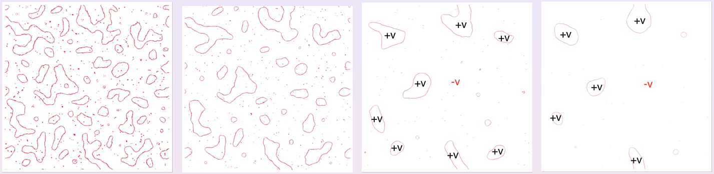

Figure: R.Ferreira, A.N., O.Pujolas, F. Rompineve, JCAP 06 (2024)

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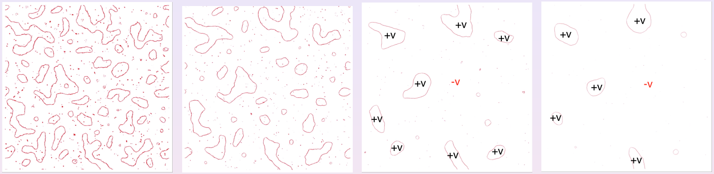

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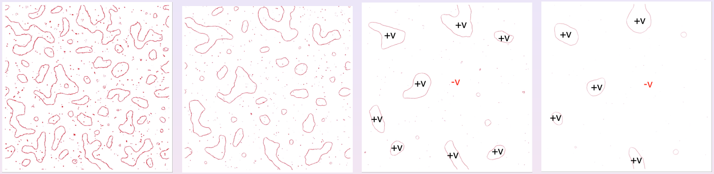

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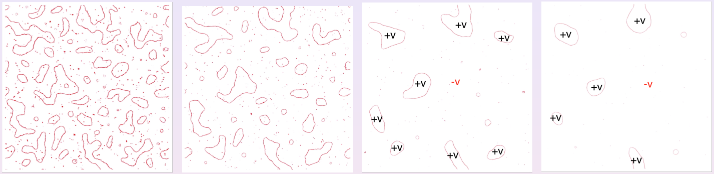

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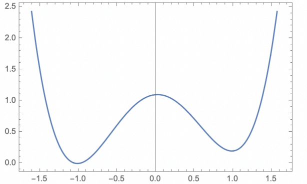
  - Danger of overproduction when fitting NANOGrav? (Gouttenoire, Vitagliano, 2306.17841, Phys.Rev.D 2024)
  - Generic PBH production mechanism (dark matter)

Closer look to: collapse of the network

- Biased potential $V_{\rm bias} = \Delta V\left(\frac{\phi}{v}\right)$, or $V_{\rm bias} = \Delta V\left(\frac{\phi}{v}\right)^3$



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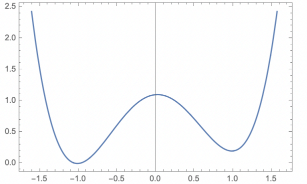

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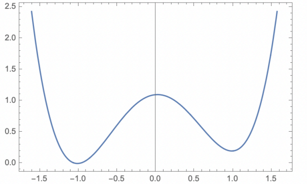

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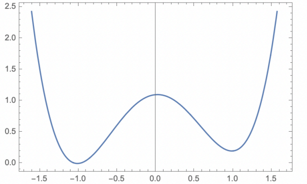

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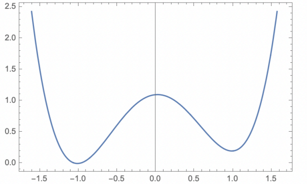

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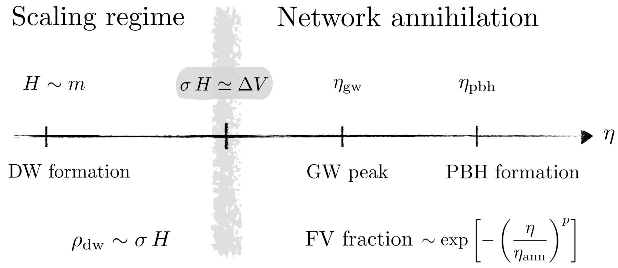

- We find GW peak delay in simulations: one Hubble time later

Delay of GW peak

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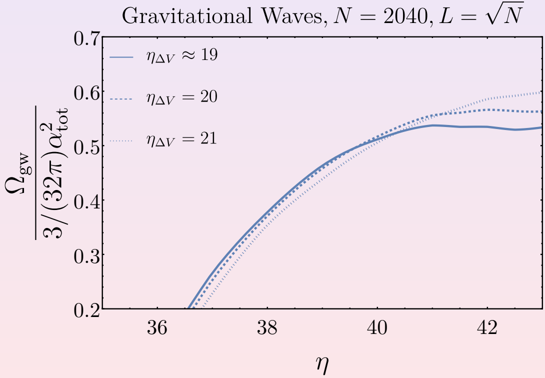

Figure: R.Ferreira, A.N., O.Pujolas, F. Rompineve, JCAP 2024

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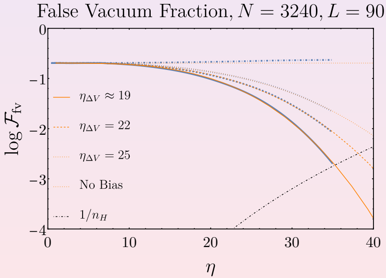

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with $L = \eta_{\Delta V}$ (correlation length = Hubble size at $\eta_{\Delta V}$)

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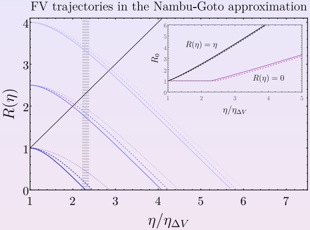

Figure: R.Ferreira, A.N., O.Pujolas, F. Rompineve, JCAP 06 (2024) 020

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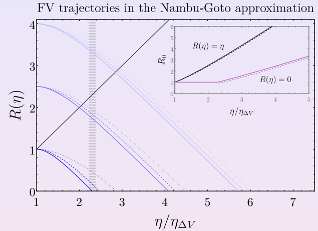

Figure: R.Ferreira, A.N., O.Pujolas, F. Rompineve, JCAP 06 (2024) 020

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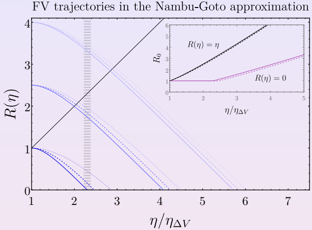

Figure: R.Ferreira, A.N., O.Pujolas, F. Rompineve, JCAP 06 (2024) 020

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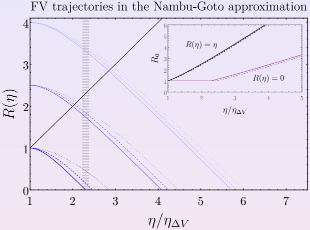

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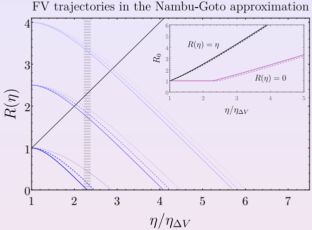

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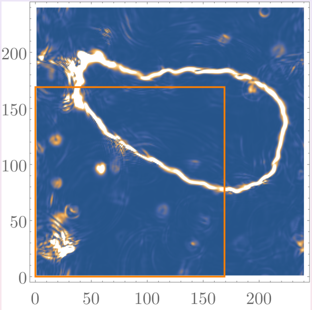
Late birds entering the Hubble radius



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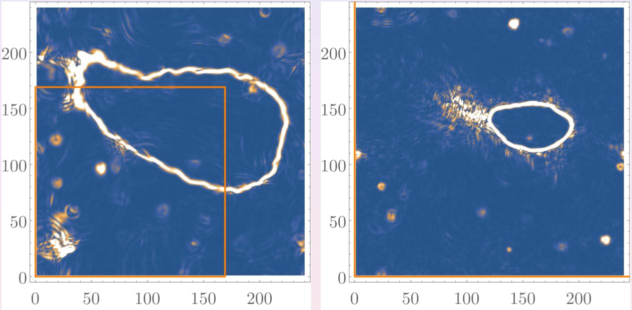

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"Late birds" collapse

- Late birds could collapse to PBH
- Compare Schwartzschild radius $r_s(t) = 2GM(t)$ with size $r_{\rm POCKET}$ at horizon entry:

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- Late birds with $\frac{r_s}{r_{\rm POCKET}} = \alpha_{POCKET}\Big|_{\rm hor.entry} \lesssim 1$

  $\implies$ could collapse slightly later inside horizon?

- Degree of sphericity is crucial

- Uncertainty on threshold $\implies$ large uncertainty on abundance

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- PBH mass: horizon mass at collapse epoch ($T_{\rm PBH} \approx 10 \sim 100$ MeV)
- After collapse scales like matter, cannot exceed present abundance

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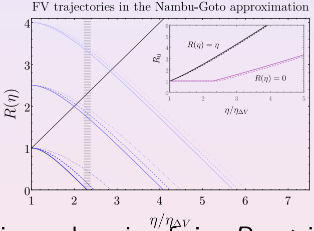

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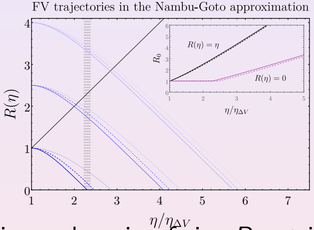

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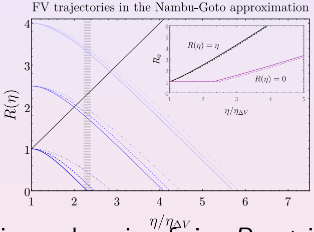

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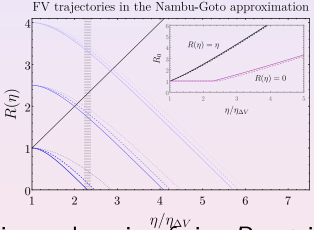

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Phenomenology

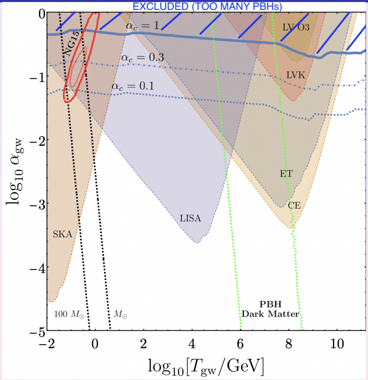

Figure: R.Ferreira, A.N., O.Pujolas, F. Rompineve, JCAP 2024

Bounds on PBH from: Green, Kavanagh, 2021; Carr, Kuhnel, 2022

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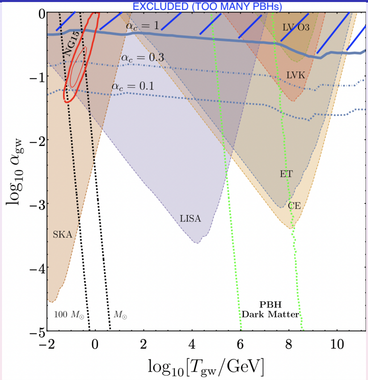

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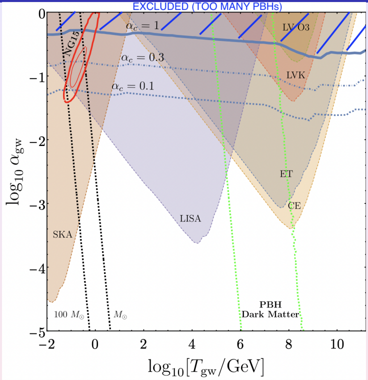

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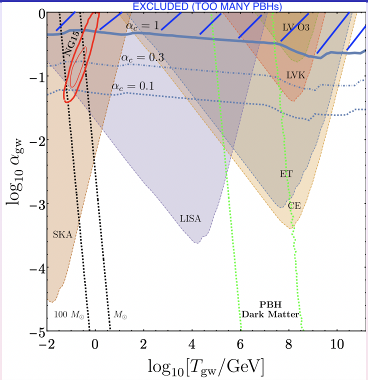

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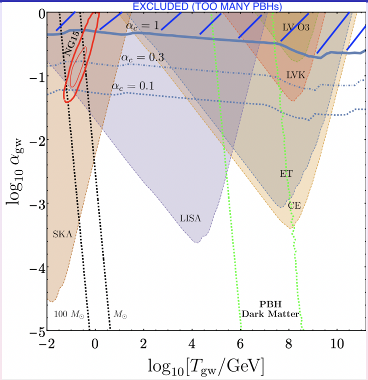

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- More work needed to understand subhorizon collapse of DWs

EXTRA SLIDES

Nambu-Goto equation

$$R'' + \left(\frac{n}{R} - 3R'\frac{a'}{a}\right)\gamma^{-2} + a\,\frac{\Delta V}{\sigma}\gamma^{-3} = 0\,, \qquad (1)$$

$n = 2, 1$ for spherical or cylindrical DW of comoving radius R. Case $n = 0$ corresponds to planar wall placed at $z = R(\eta)$. Primes denote derivatives w.r.t. conformal time ($\gamma \equiv 1/\sqrt{R'^2 - 1}$.)

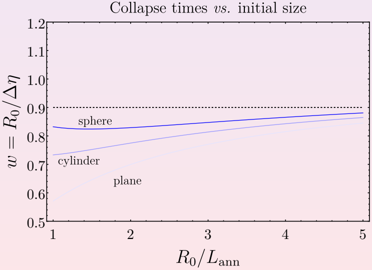

Figure: Ratio of the initial radius R_0 and the (conformal) time to reach $R(\eta) = 0$, $\Delta\eta$, of super-Hubble FV pockets.