Constraining the inflaton potential with gravitational waves from oscillons

JAN TRÄNKLE (3rd YEAR PHD @ ITP HANNOVER U.)

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BASED ON: 2512.XXXXX WITH K. LOZANOV & M. SASAKI

Emmy Noether-Programm

DFG Deutsche Forschungsgemeinschaft

Leibniz Universität Hannover

Motivation

- unknown expansion history between end of inflation and radiation domination

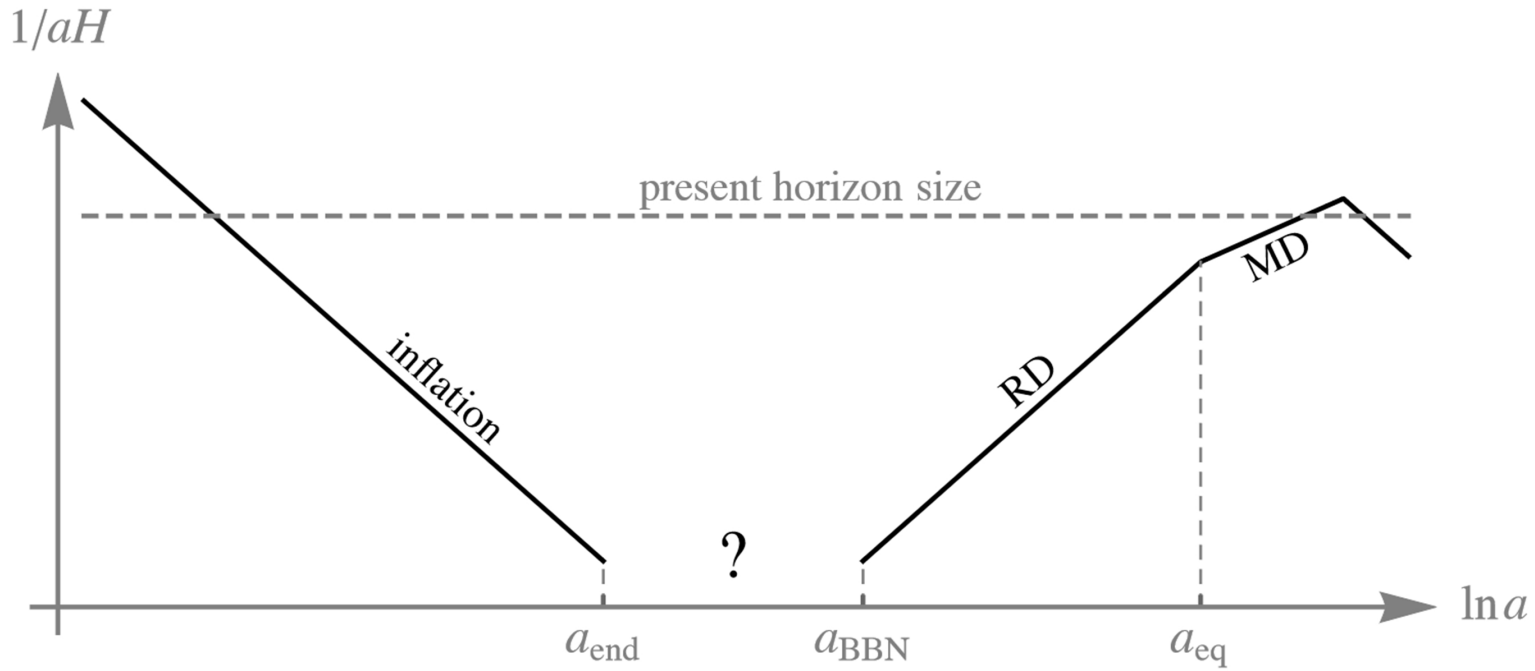
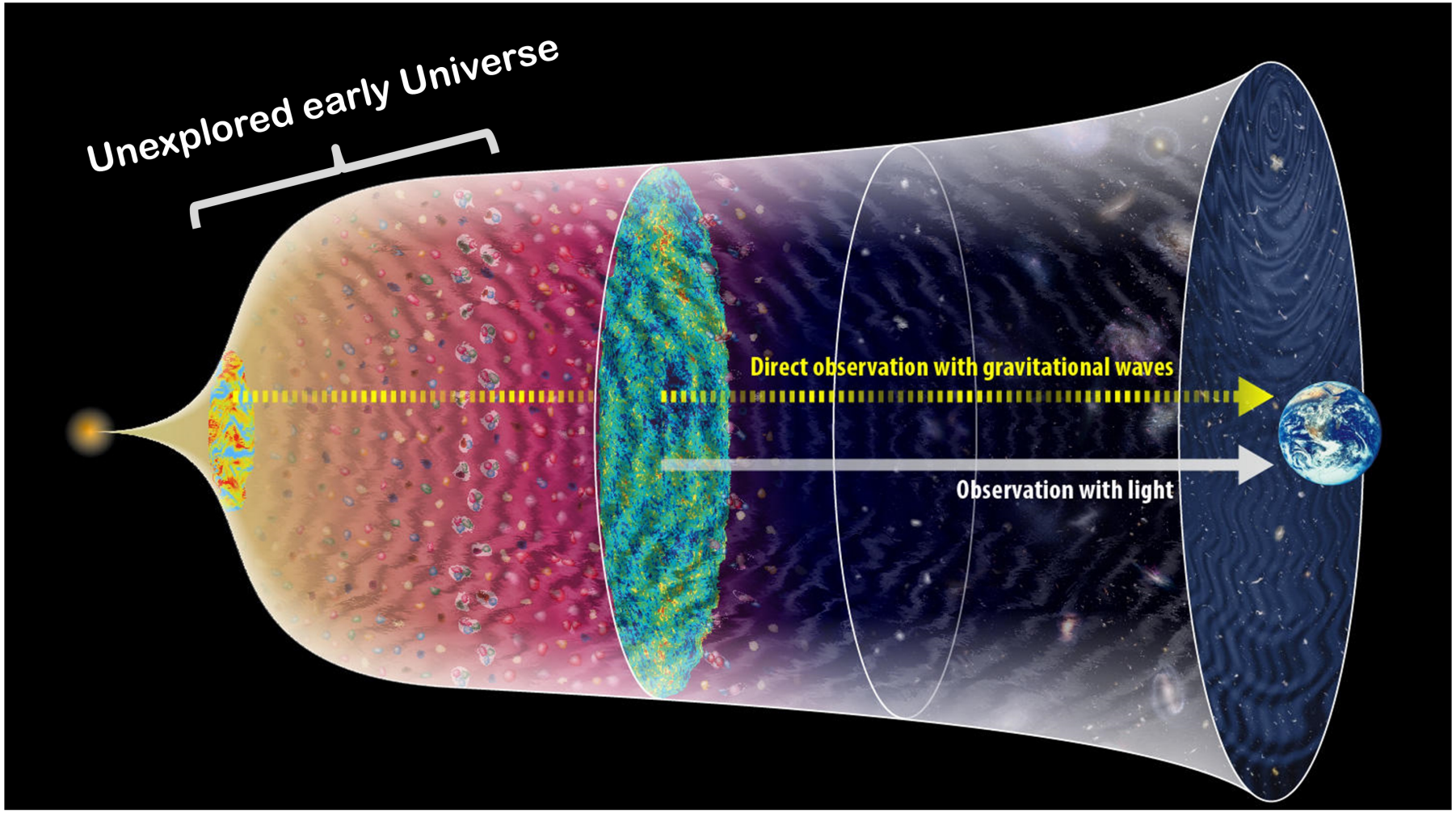


Figure: Allahverdi et al. [2006.16182]


Unexplored early Universe
Direct observation with gravitational waves
Observation with light

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Constraining the inflaton potential with gravitational waves from oscillons

Models

- Inflaton potentials favoured by CMB data

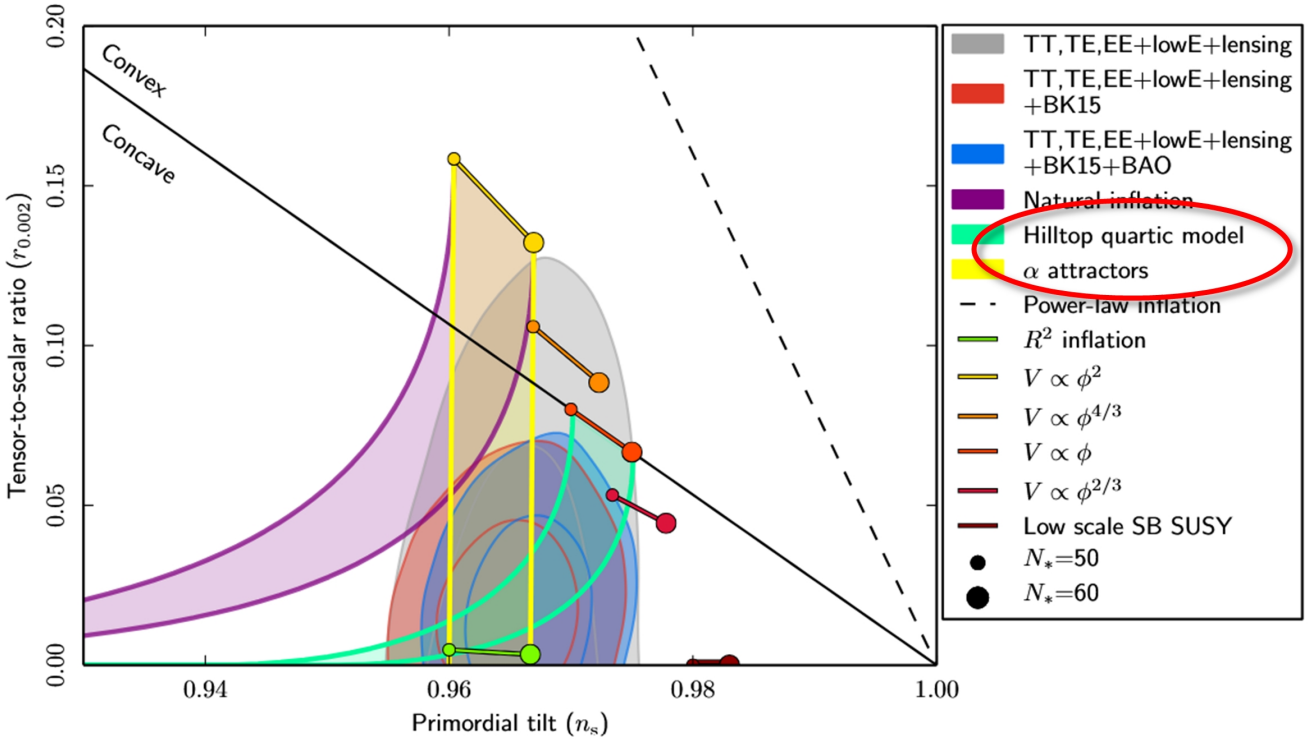

Figure: *Planck* 2018

Models

- α-attractor T-model

$$V(\phi) = \frac{m^2 M^2}{2} \tanh^{2n}\left(\left(\frac{|\phi|}{M}\right)^{1/n}\right)$$

Kallosh, Linde (2013)

- generalized axion monodromy

$$V(\phi) = \frac{m^2 M^2}{q}\left(\left(1 + \left(\frac{\phi}{M}\right)^2\right)^{q/2} - 1\right)$$

Silverstein, Westphal (2008)

- hilltop (squared)

$$V(\phi) = \frac{m^2 M^2}{2p^2}\left(1 - \left(\frac{\phi}{M}\right)^p\right)^2$$

Boubekeur, Lyth (2005)

Models

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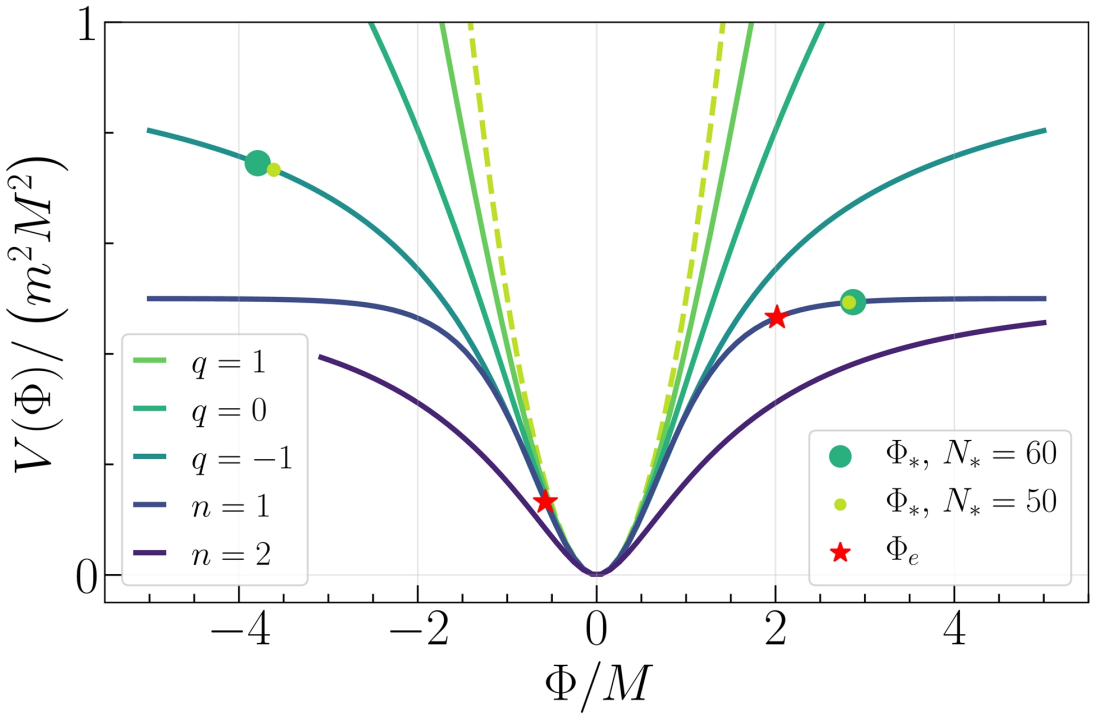
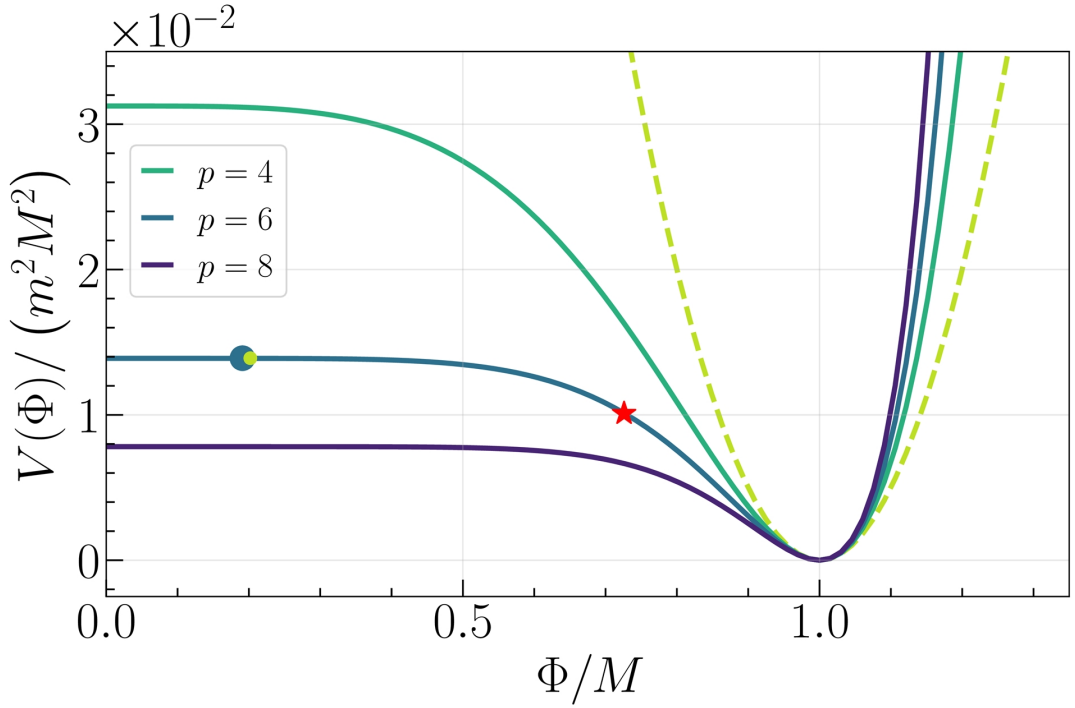
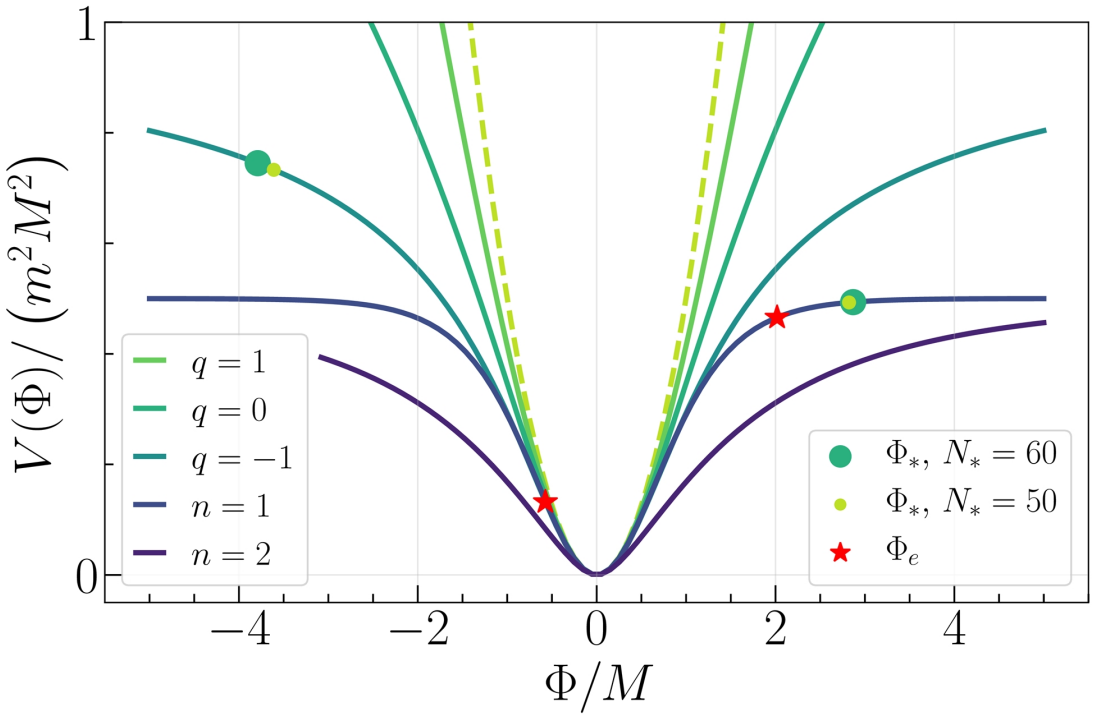
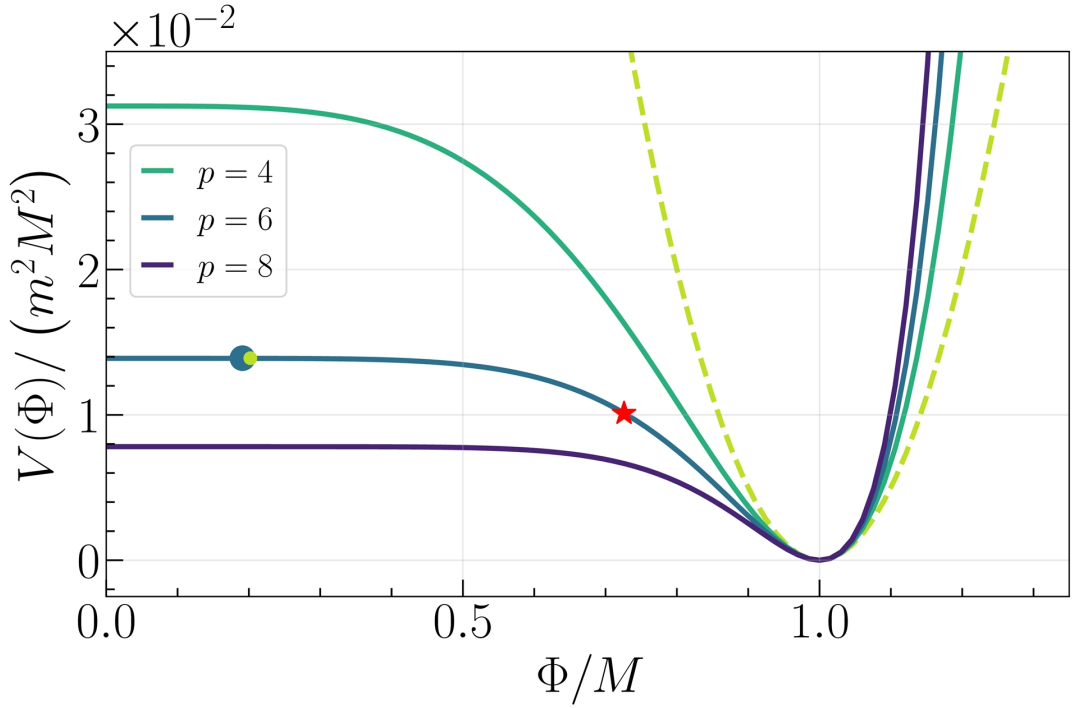




Models

- Inflaton potentials favoured by CMB data ⟶ supporting oscillons





Inflaton self-interaction

- expansion around quadratic minimum

$$V(\phi) = \tfrac{1}{2} m^2 \phi^2 + V_{\rm nl}(\phi)$$

$$V_{\rm nl}(\phi \ll M) \approx g\phi^3 - \lambda\phi^4 + \ldots$$

$$\lambda = c_\lambda \frac{m^2}{M^2}$$

$$g = c_g \frac{m^2}{M}$$

Amin et al. [1106.3335]
Amin [1006.3075]

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- attractive self-interaction $V_{\rm nl}(\phi) < 0 \Longleftrightarrow \lambda > 0$

- fragmentation for $M \lesssim 5 \times 10^{-2} M_{\rm Pl}$

Amin et al. [1106.3335]
Amin [1006.3075]

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Oscillon formation

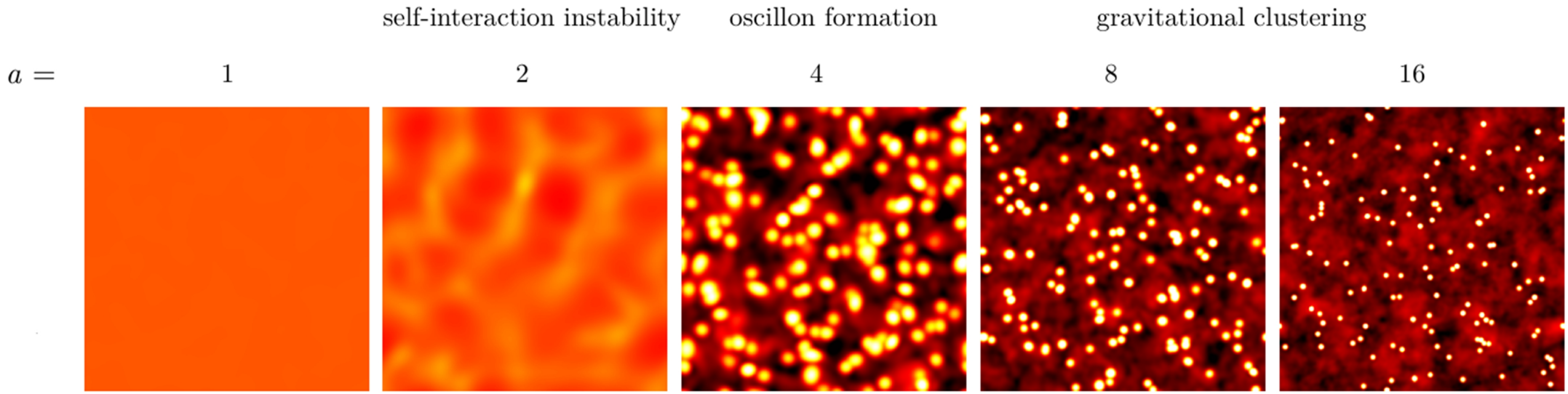
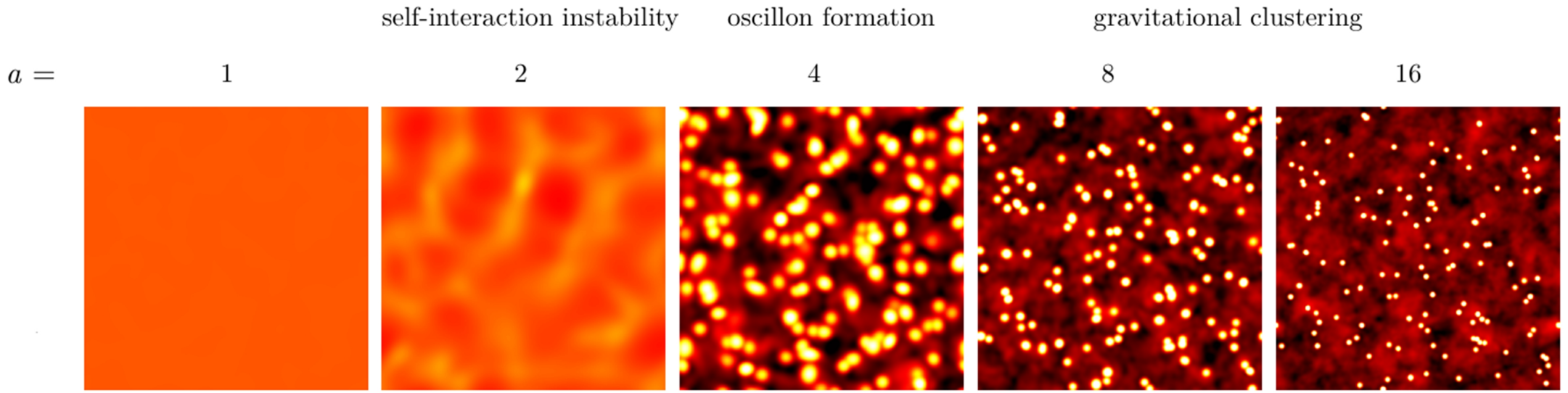


Figure: Amin, Mocz [1902.07261], Allahverdi et al. [2006.16182]

[Talk by Josu Aurrekoetxea]

Oscillon formation



Abundant formation $\beta \lesssim \mathcal{O}(1)$

early matter-domination $N_{\rm osc} \sim \mathcal{O}(10)$

Figure: Amin, Mocz [1902.07261], Allahverdi et al. [2006.16182]

Oscillon properties

- oscillon profile: oscillating core + small radiation tail

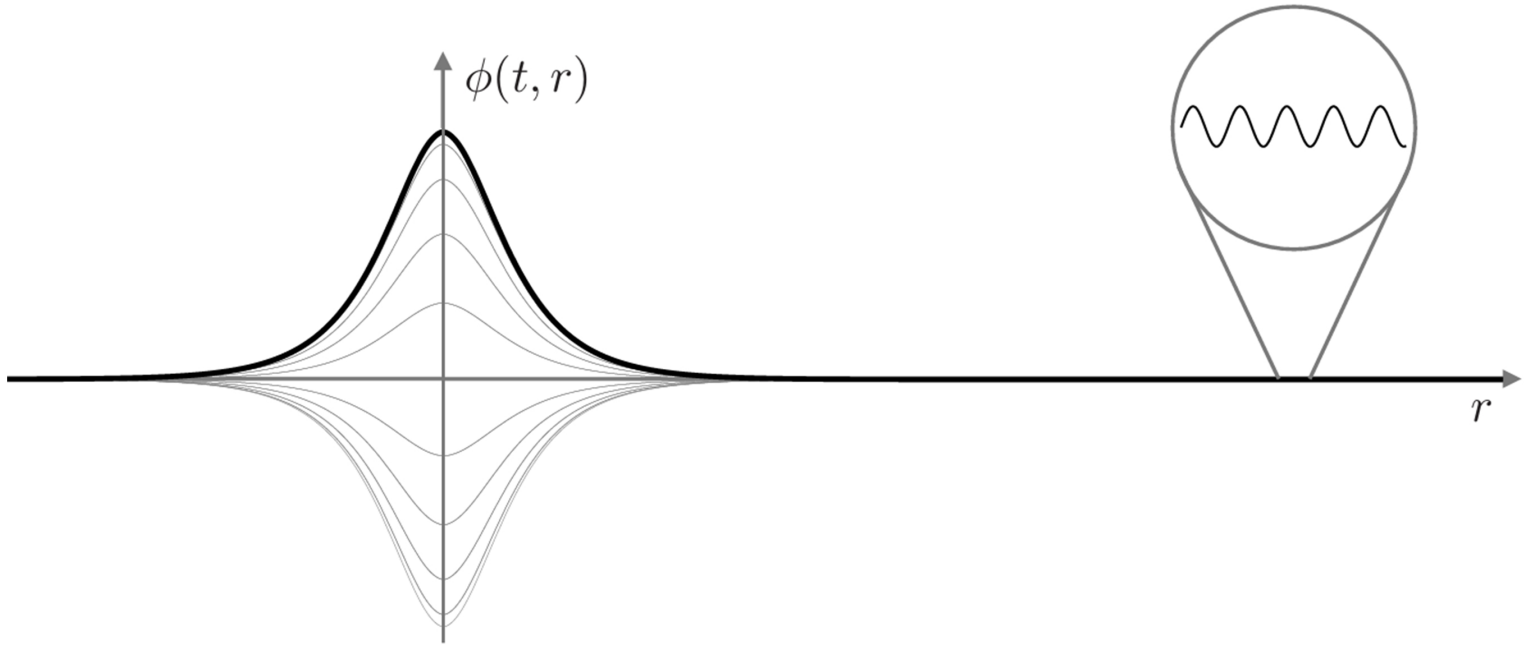
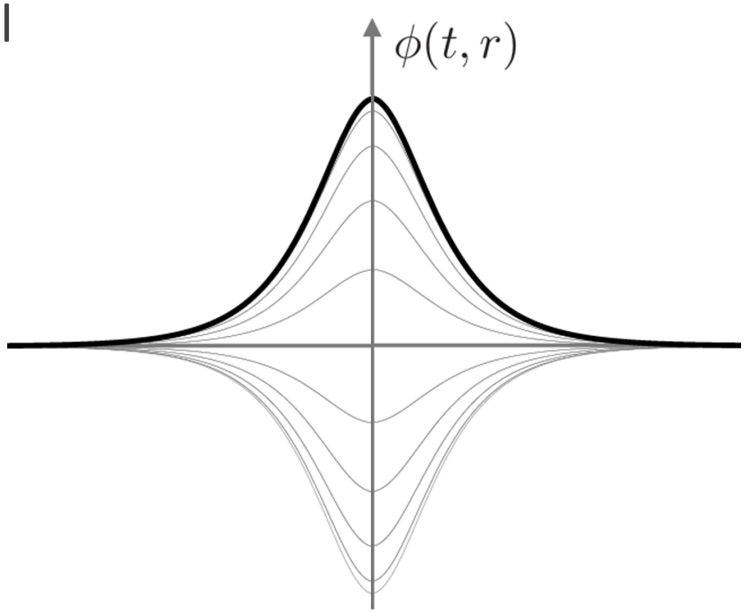


Figure: Zhang et al. [2004.01202]

Oscillon properties

- oscillon profile: oscillating core + small radiation tail
- remarkable lifetimes $\sim(10^6 - 10^8)m^{-1}$
- single oscillon mass $m_{\rm osc} = \mathcal{O}[10^2]\frac{M^2}{m} \gg m$



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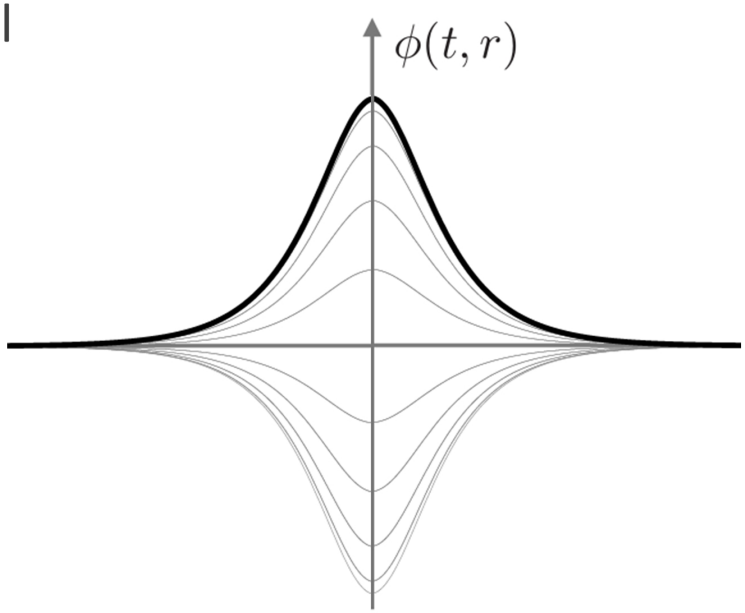
- remarkable lifetimes $\sim(10^6 - 10^8)m^{-1}$
- single oscillon mass $m_{\rm osc} = \mathcal{O}[10^2]\frac{M^2}{m} \gg m$
- rapid final decay to (scalar) radiation



⚠ $\longrightarrow$ enhanced production of induced GWs !

Inomata et al. [1904.12879]

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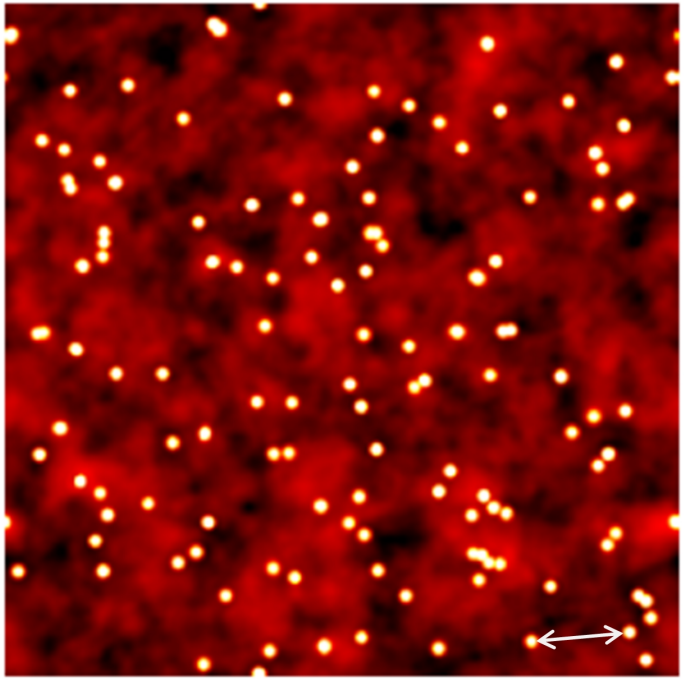
Oscillon induced GWs



mean separation $\sim k_{\rm osc}^{-1}$

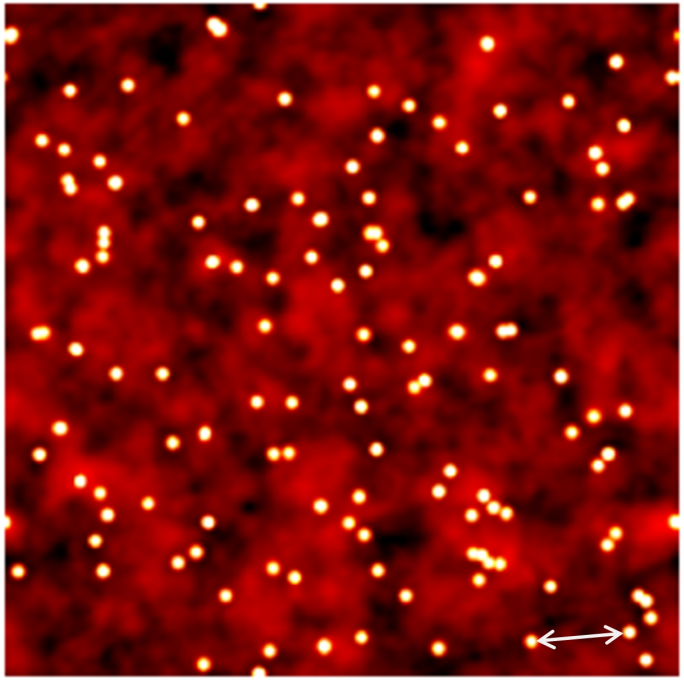
Poissonian number density fluctuations $\delta_{\rm osc}$

$$\mathcal{P}_{\delta_{\rm osc,f}} \propto (k/k_{\rm osc})^3$$

Figure: Amin, Mocz [1902.07261]

G. Domènech [2109.01398]

Oscillon induced GWs



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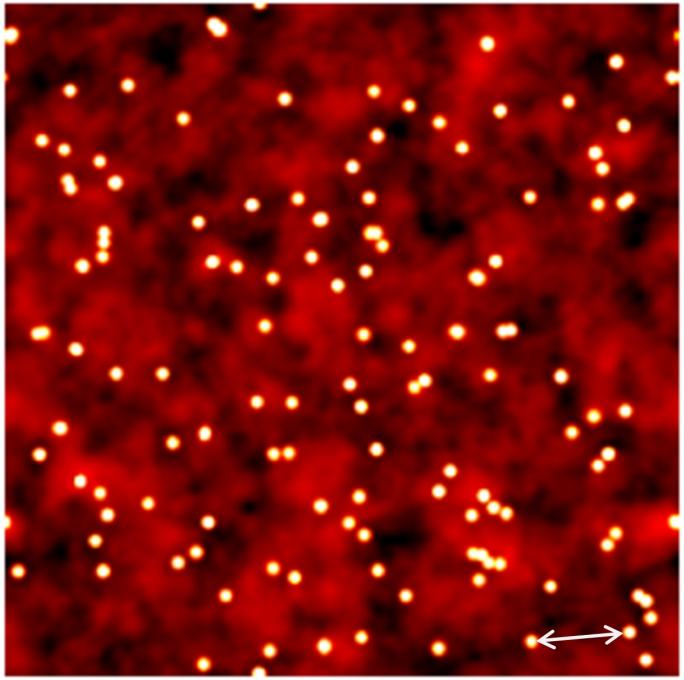

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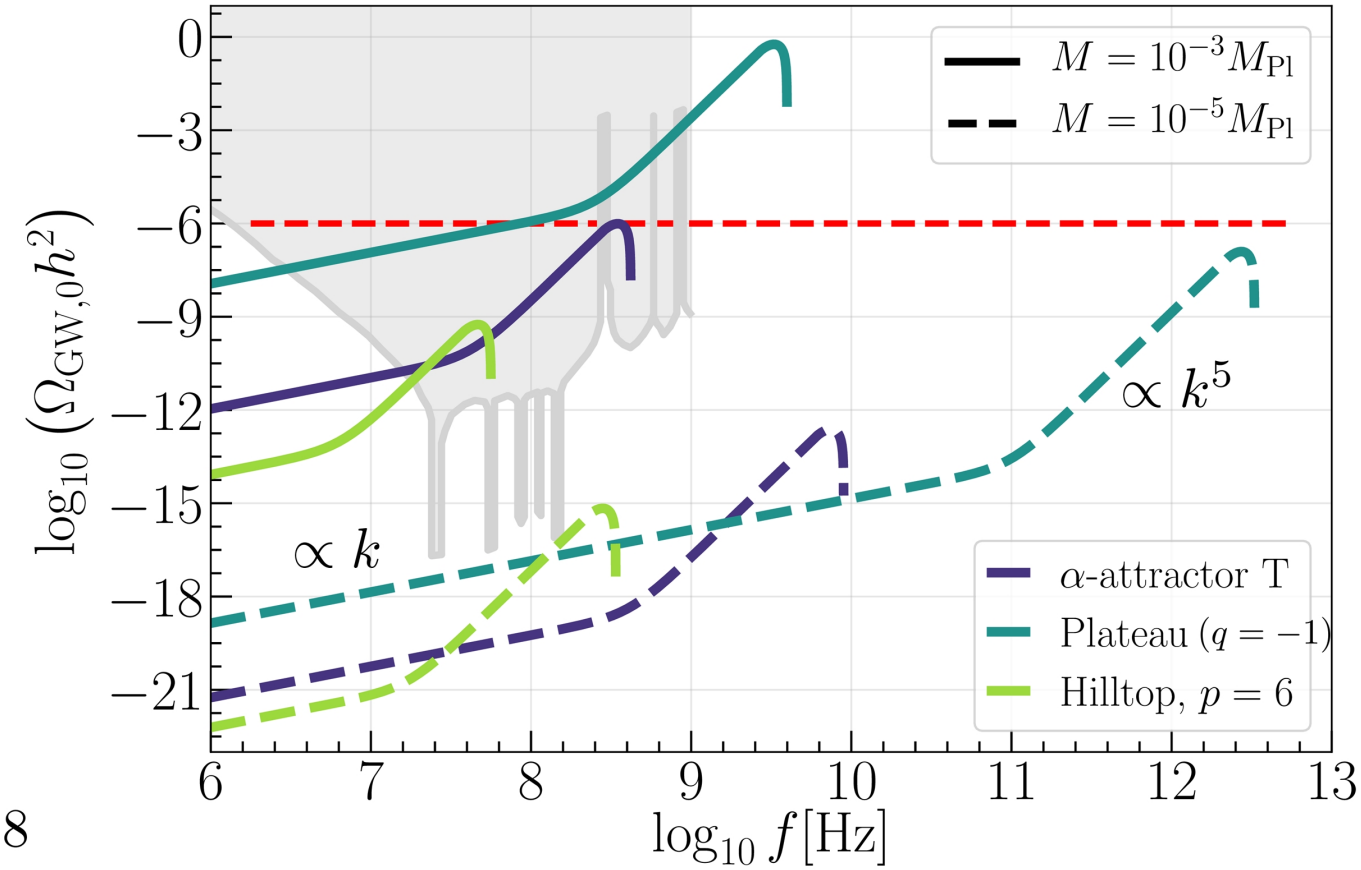
$G^{(2)}_{\mu\nu} = T^{(2)}_{\mu\nu}$ $\Longrightarrow$ scalar induced GWs h_{ij}

Figure: Amin, Mocz [1902.07261]

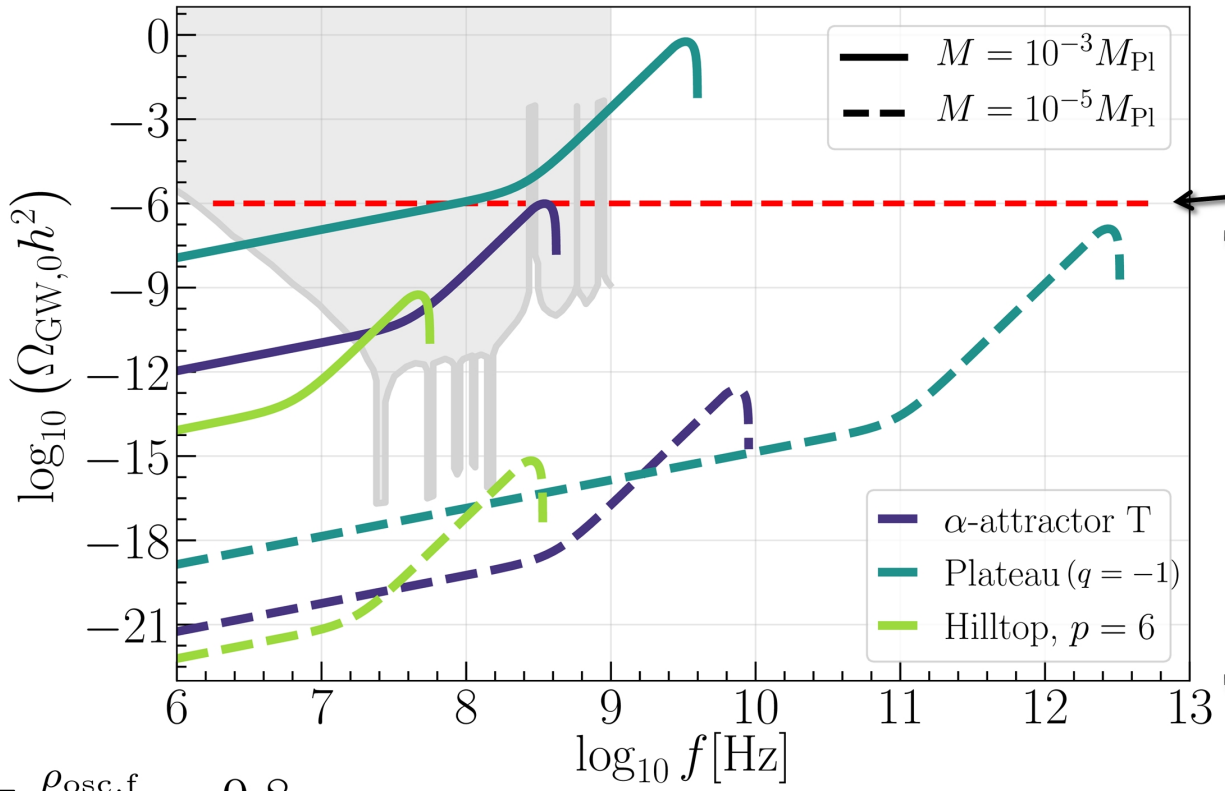
G. Domènech [2109.01398]

Induced GW spectrum



$$\beta \equiv \frac{\rho_{\rm osc,f}}{\rho_{\rm f}} = 0.8$$

Induced GW spectrum



$\Delta N_{\rm eff} < 0.30$

$\Omega_{\rm GW}^{\rm peak}(\beta, t_{\rm osc}, m_{\rm osc}, H_{\rm f})$

$f_{\rm peak} \gtrsim \mathcal{O}[10^7]\rm Hz$

$\beta \equiv \frac{\rho_{\rm osc,f}}{\rho_{\rm f}} = 0.8$

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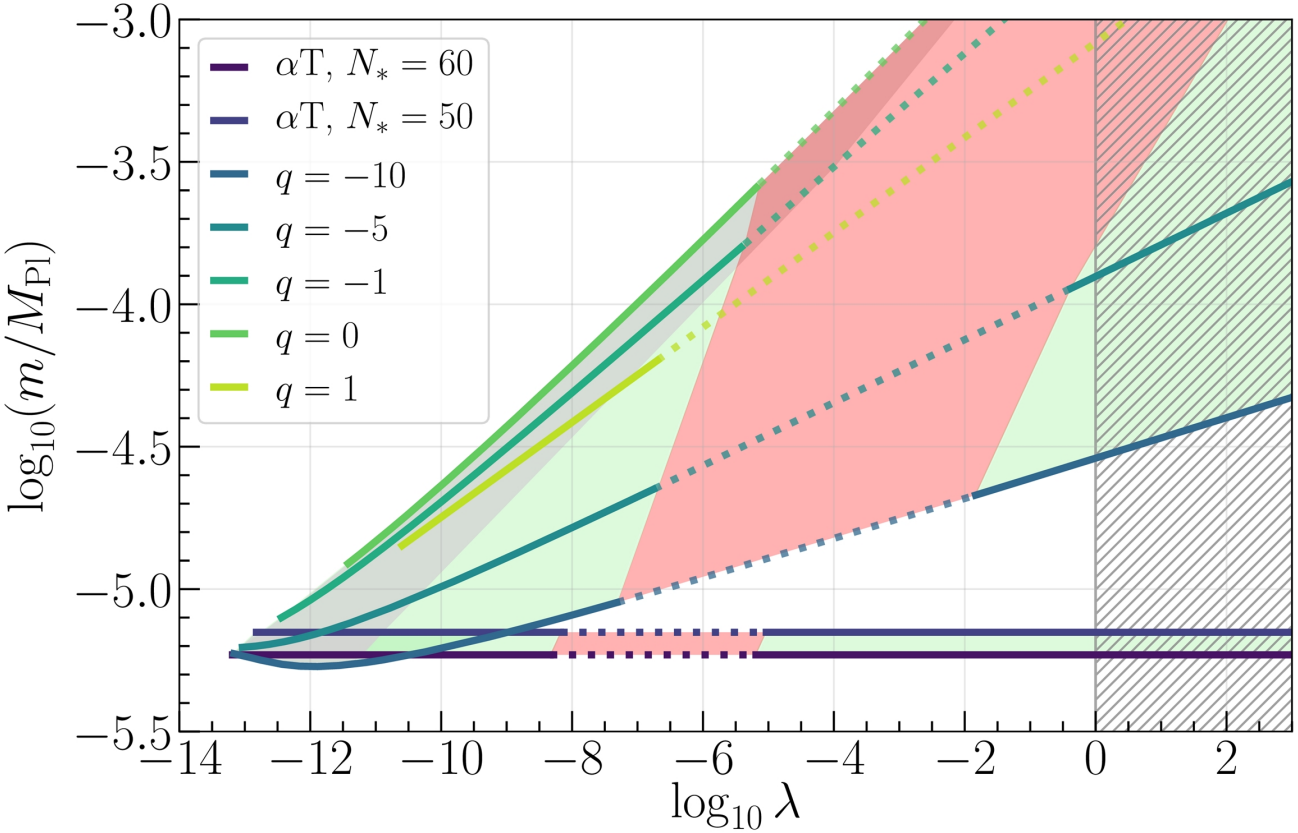
Parameter space

$$\lambda = c_\lambda \frac{m^2}{M^2}$$

fixed A_s, n_s
from *Planck*



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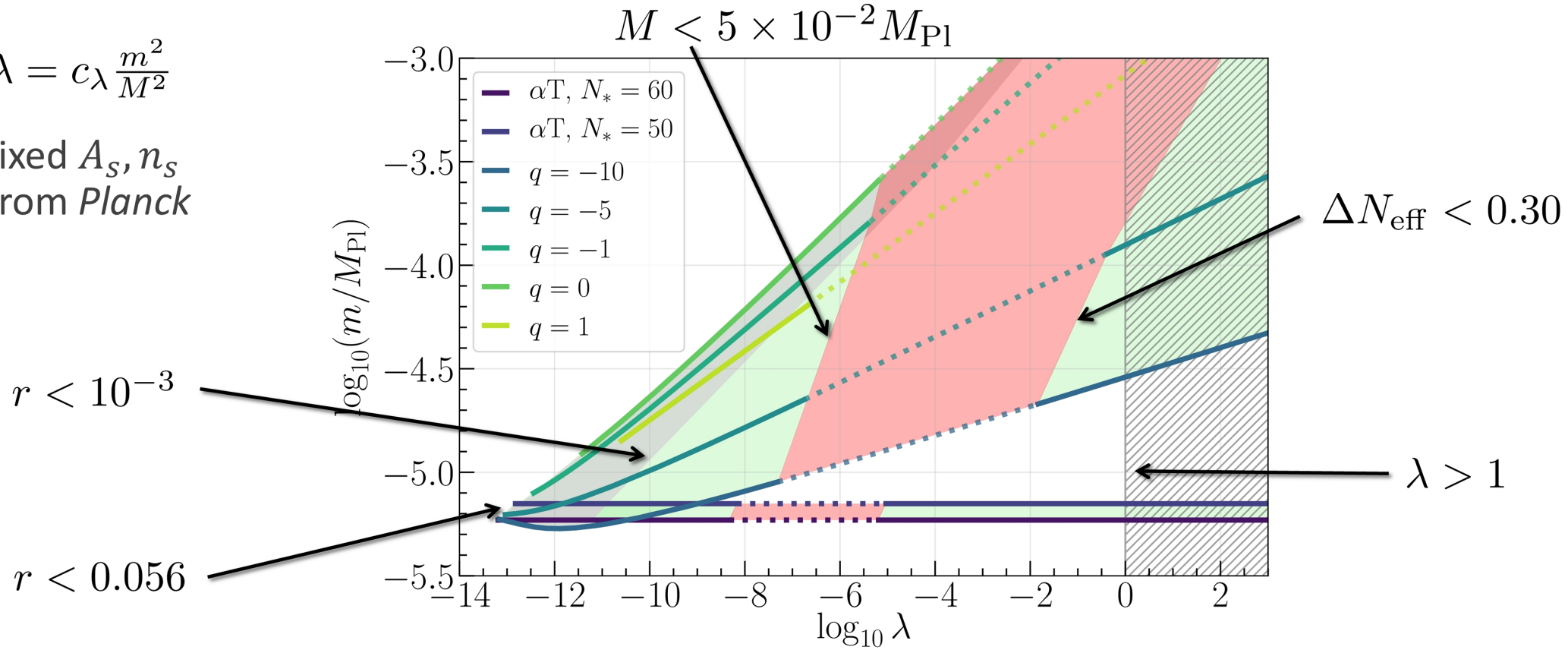
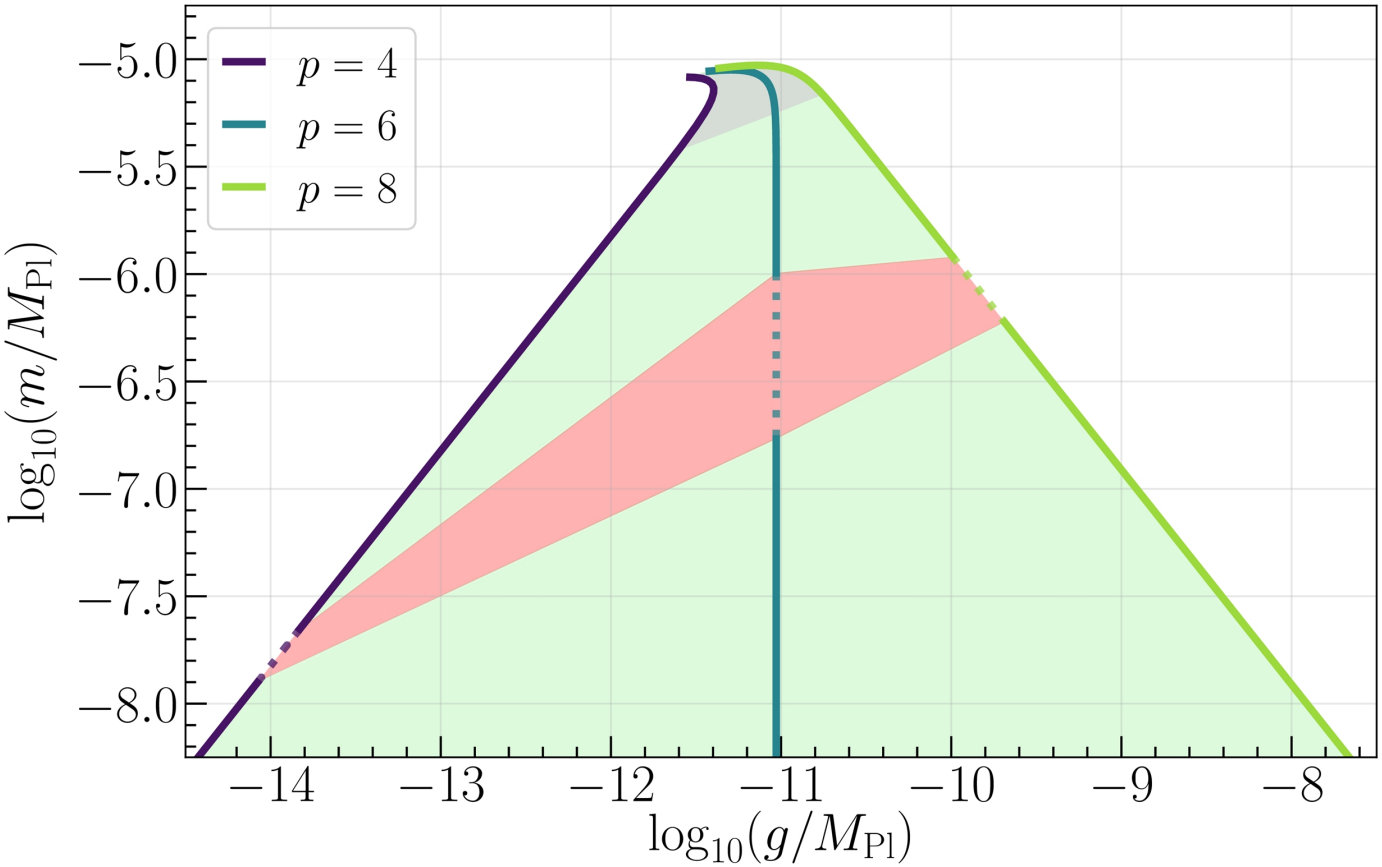


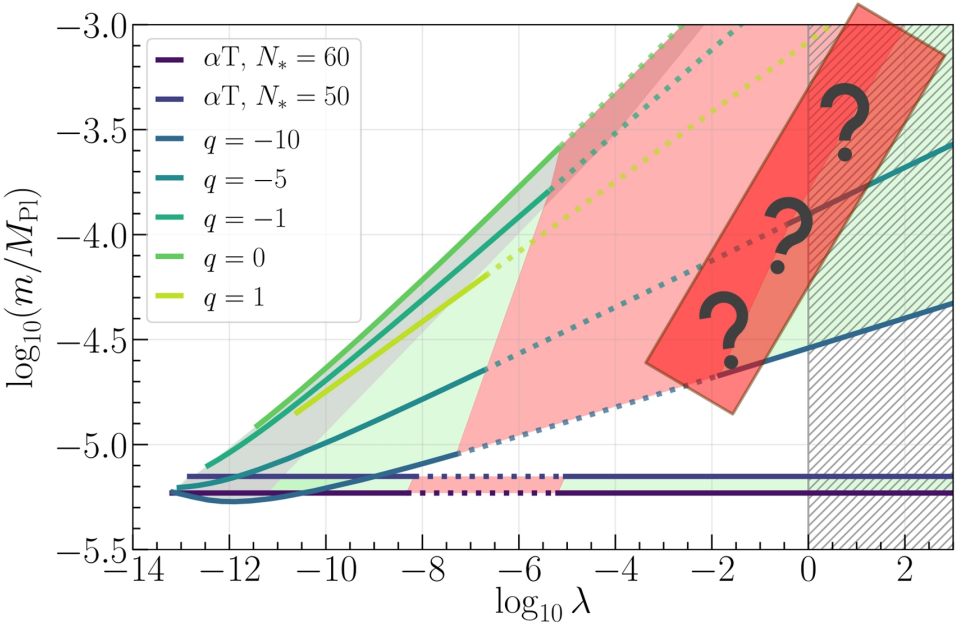
Parameter space

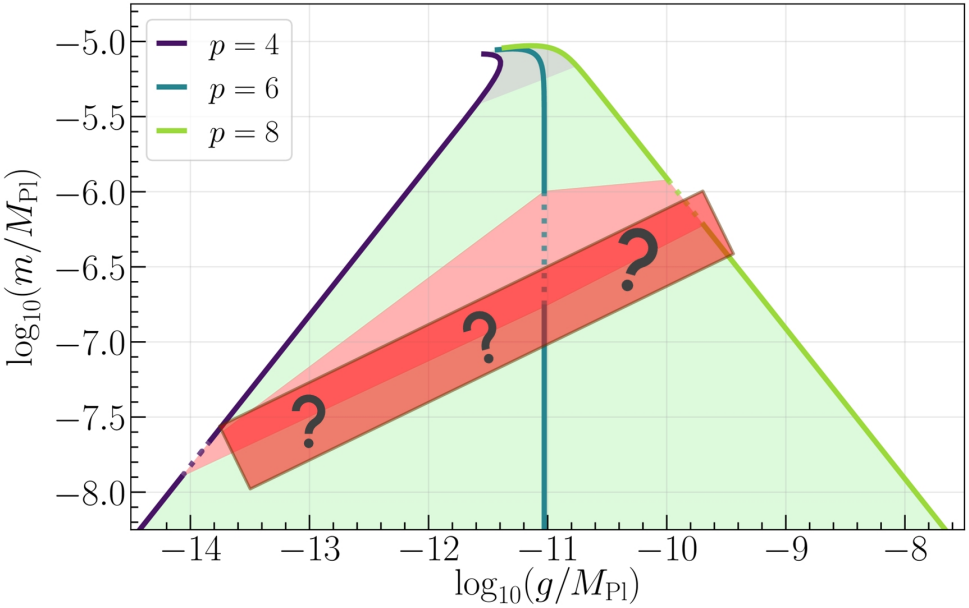
$$g = c_g \frac{m^2}{M}$$



Parameter space

- *caveats*: errorbars from simulations (lifetimes, mass, …), additional GW sources, …





Conclusion

- oscillon formation & domination generically expected in many models
- rapid final decay of oscillons leads to loud induced GW signal
- GW overproduction provides new constraints on parameter space

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Thank you for your attention!

… Questions ?

Additional Material

Relating parameters & observables

- potential slow-roll parameters

$$\epsilon_V(\phi_e) = \frac{M_{\rm Pl}^2}{2}\left(\frac{V_\phi(\phi)}{V(\phi)}\right)^2\Big|_{\phi_e} \simeq 1 \longrightarrow \phi_e(M)$$

$$n_s = 1 - 6\epsilon_V(\phi_*) + 2\eta_V(\phi_*) \longrightarrow \phi_*(M)$$

$$\Big\}\ N_*(M)$$

$$\eta_V = M_{\rm Pl}^2 \frac{V_{\phi\phi}(\phi)}{V(\phi)}$$

$$A_s = \frac{1}{8\pi^2\epsilon_V(\phi_*)}\frac{H_*^2}{M_{\rm Pl}^2} \longrightarrow m(M)$$

$$r = 16\epsilon_V(\phi_*) = \frac{2}{A_s\pi^2}\frac{H_*^2}{M_{\rm Pl}^2} \longrightarrow M < M_{\rm max}$$

$$A_s \simeq 2.1 \times 10^{-9}$$

$$n_s \simeq 0.965$$

$$r < 0.056$$

[1] *Planck* 2018

(Classical) Decay rate

- decay rate (α-attractor T-model):

3ω radiation suppressed in dip

$\longrightarrow$ quasi-stable attractor solution with unique oscillon mass m_{osc}

$\longrightarrow$ extremely long lifetime

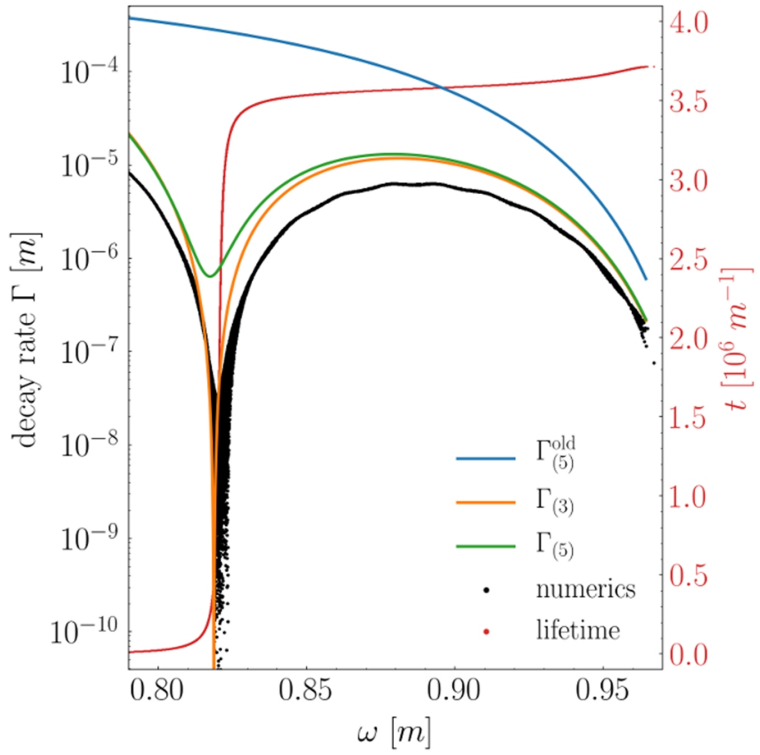


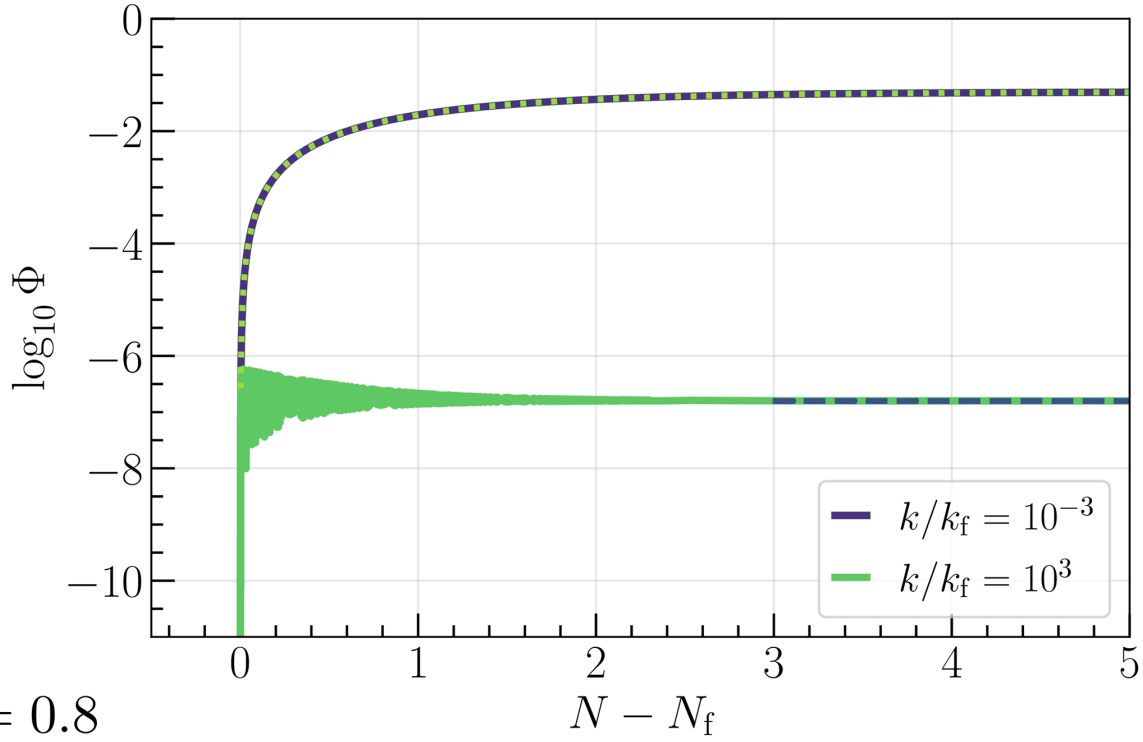
Figure: Zhang et al. [2004.01202]

Model	c_g	c_λ	$r < 0.056$	$r < 10^{-3}$	$\tau_{\rm osc} = t_{\rm osc} m$	$N_{\rm osc}$	N_*	$\bar{H}_{\rm f}$
α-attractor T ($n = 1$)	0	1/3	$M < 12 M_{\rm Pl}$	$M < 1.3 M_{\rm Pl}$	$\gtrsim 3 \times 10^6$	7	57	$1/\sqrt{6}$
Axion monodromy ($q = 1$)	0	1/8	$M \lesssim M_{\rm Pl}$[a]	(ruled out)	$\sim 3 \times 10^8$	11	71[a]	$\sqrt{\frac{M_{\rm Pl}}{3\sqrt{2}M}}$
Logarithmic ($q = 0$)	0	1/4	$M < 3.2 M_{\rm Pl}$	$M \ll M_{\rm Pl}$	$\sim \mathcal{O}(1) \times 10^8$	9	$29 - 44$	0.415
Plateau ($q = -1$)	0	3/8	$M < 8.3 M_{\rm Pl}$	$M < 0.018 M_{\rm Pl}$	$\gtrsim 6 \times 10^8$	10	$38 - 50$	$1/\sqrt{3}$
Hilltop ($p = 4$)	3/2	$-17/8$	$M < 36 M_{\rm Pl}$	$M < 8.5 M_{\rm Pl}$	$\sim \mathcal{O}(1) \times 10^5$	4	$54 - 86$	$1/(4\sqrt{2})$
Hilltop ($p = 6$)	5/2	$-155/24$	$M < 51 M_{\rm Pl}$	$M < 8.5 M_{\rm Pl}$	$\sim \mathcal{O}(1) \times 10^6$	5	$53 - 71$	$1/(6\sqrt{2})$
Hilltop ($p = 8$)	7/2	$-105/8$	$M < 67 M_{\rm Pl}$	$M < 9.3 M_{\rm Pl}$	$\sim 2 \times 10^6$	5	$52 - 67$	$1/(8\sqrt{2})$

Simulations: Zhang et al. [2004.01202], Lozanov, Amin [1710.06851], Olle et al. [1906.06352], Antusch et al. [1907.00611]

Curvature perturbation

- isocurvature initial conditions $\Phi(0) = 0$



$\propto \mathcal{C}_1(\beta)\delta_{\mathrm{osc,f}}$

$\propto \mathcal{C}_2(\beta)\delta_{\mathrm{osc,f}}\kappa^{-2}$ $\qquad \kappa = \left(\frac{k}{k_{\mathrm{f}}}\right)$

Poisson eq.

$k^2\Phi \propto \delta_{\mathrm{osc}}$

$\beta \equiv \frac{\rho_{\mathrm{osc,f}}}{\rho_{\mathrm{f}}} = 0.8$

Induced Gravitational Waves

- Perturbed FLRW metric

$$ds^2 = a^2(\tau)\left[-(1-2\Phi)\mathrm{d}\tau^2 + (\delta_{ij} + 2\Phi\delta_{ij} + h_{ij})\,\mathrm{d}x^i\mathrm{d}x^j\right]$$

$$\downarrow$$

$$G_{\mu\nu} = T_{\mu\nu}$$

$$\downarrow$$

- Tensor perturbations at 2nd order

$$h_k''(\tau) + 2\mathcal{H}h_k'(\tau) + k^2 h_k(\tau) = \mathcal{S}_k(\tau) \propto (\Phi + \Phi'/\mathcal{H})^2$$

G. Domènech [2109.01398]

Induced Gravitational Waves

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- Spectral GW energy density

$$\Omega_{\rm GW}(k) \sim \langle h_{ij}h_{ij}\rangle \sim \int dv \int du\, \overline{I^2}(k\tau, u, v)\, \langle\Phi\Phi\rangle(uk)\langle\Phi\Phi\rangle(vk)$$

- largest contribution to GWs from rapid transition $w = 0 \longrightarrow 1/3$ right after oscillon decay (Poltergeist mechanism)

G. Domènech [2109.01398]
Inomata et al. [1904.12879]