What can we learn from the stochastic gravitational wave background produced by oscillons?

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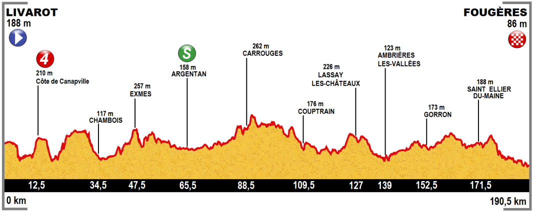
Swiss Cosmology Days 2018
February 5, 2018

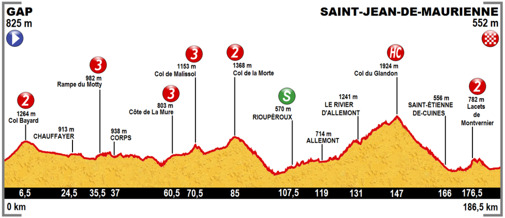
Based on
S. Antusch, F. Cefala and S. Orani, arXiv:1712.03231 [astro-ph.CO]
and references therein.

Gravitational waves as a cosmological fingerprint?

GW background predicted by some theory



GW background predicted by some other theory



What should we aim for?

Theories

Think out of the box → new phenomena?!

Observation

Larger bandwidth + higher sensitivity

Better understanding of known phenomena

Specific phenomena ↔ specific features in the GW background

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Think out of the box $\rightarrow$ new phenomena?!

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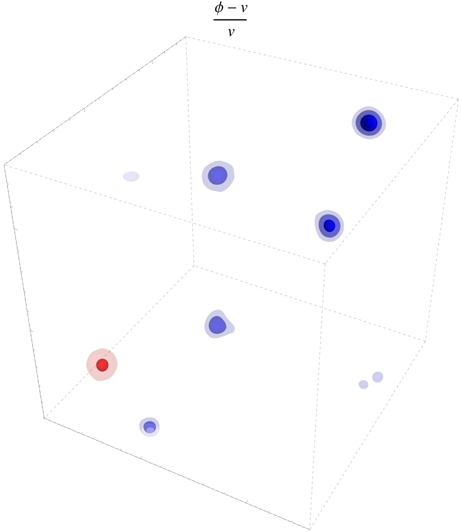
Example: Oscillons (this talk)

Example: GWs from Oscillons

spatially localized, oscillatory scalar field configurations with large amplitude



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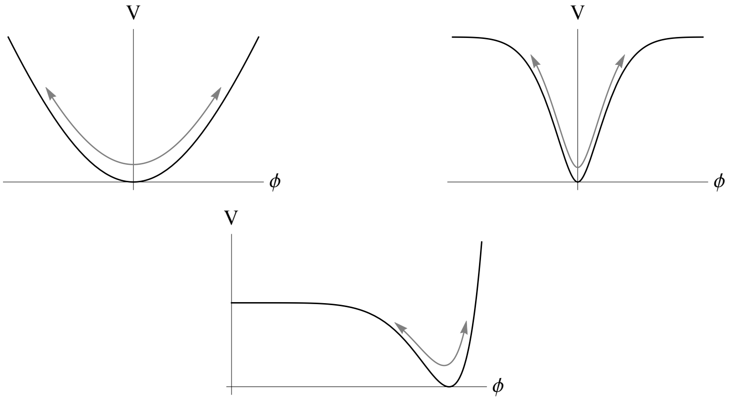
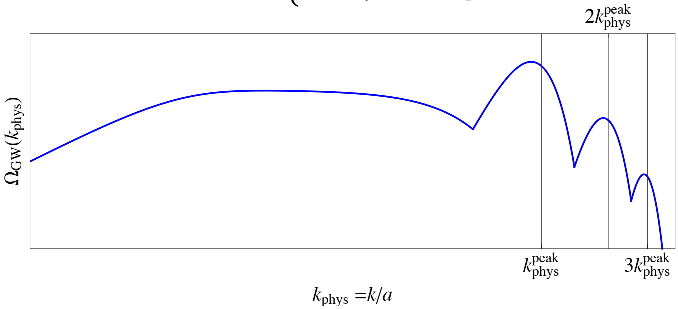
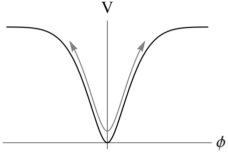


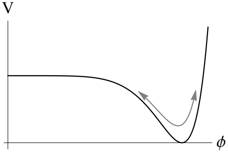
Example: GWs from Oscillons

spatially localized, oscillatory scalar field configurations with large amplitude

$$\text{typically:} \quad k_{\text{phys}}^{\text{peak}} \lesssim \begin{cases} 2\,m & \text{symmetric potentials} \\ m & \text{asymmetric potentials} \end{cases}$$







GWs from oscillons

$$ds^2 = -dt^2 + a^2(t)(\delta_{ij} + h_{ij})dx^i dx^j$$

Scalar field evolution +

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{1}{a^2}\nabla^2 h_{ij} = \frac{2}{m_{\mathrm{Pl}}^2}\Pi_{ij}^{\mathrm{TT}} \tag{1}$$

with

$$\Pi_{ij}^{\mathrm{TT}} = \frac{1}{a^2}T_{ij}^{\mathrm{TT}} = \frac{1}{a^2}\left[\partial_i\phi\partial_j\phi\right]^{\mathrm{TT}} \text{ Contains scalar field evolution}$$

Given some oscillon system: How can we solve (1)?

1. **Lattice simulations:** Given some model $V(\phi) \rightarrow$ perform lattice simulations
2. **Semi-analytical treatment:** Find a way to model an "oscillon system" (i.e scalar field evolution, cosmological background, ...) $\rightarrow$ calculate Π_{ij}^{TT} and solve (1) in Fourier space $\rightarrow$ **computationally less expensive + easier to study effects of oscillon characteristics on GW background**

GWs from oscillons

What we want:

Solving the equation for h_{ij} yields:

J. F. Dufaux et al. Phys. Rev. D **76** (2007) 123517 [arXiv:0707.0875 [astro-ph]]

$$\Omega_{\rm GW}(k,\tau) = \frac{k^3}{2\,a^4\,\rho_{\rm c}\,m_{\rm Pl}^2}\frac{1}{\mathcal{V}}\int\frac{d\Omega}{(2\,\pi)^3}\sum_{i,j}\left[\left|\int_{\tau_i}^{\tau_f} d\tau'\cos(k\tau')\,a(\tau')\,T_{ij}^{\rm TT}(\mathbf{k},\tau')\right|^2 + \left|\int_{\tau_i}^{\tau_f} d\tau'\sin(k\tau')\,a(\tau')\,T_{ij}^{\rm TT}(\mathbf{k},\tau')\right|^2\right] \quad \text{where} \quad T_{ij}^{\rm TT} = [\partial_i\phi\partial_j\phi]^{\rm TT}$$

What we need:

- Some background cosmology, i.e. $a(\tau)$
- An analytic expression for $T_{ij}^{\rm TT}$ $\rightarrow$ “artificial” oscillons

Modelling the oscillon dynamics

Assumptions

- **Oscillons: profile and evolution**

$$\phi_{\text{multi}}(\mathbf{x},t) = \sum_{q=1}^{N} \Phi_q(t)\, \mathcal{F}_q(\mathbf{x},t)$$

$$\mathcal{F}_q(\mathbf{x},t) = e^{\frac{-a^2(t)}{2}\frac{(x-x^q)^2}{R_x^2}+\frac{(y-y^q)^2}{R_y^2}+\frac{(z-z^q)^2}{R_z^2}} \qquad \Phi_q(t) = A\,\cos(\omega_{\text{osc}}t+\varphi_q)$$

- **Oscillon asymmetry ($\equiv \Delta$)**

$$R_x = R_z \equiv R, \quad \text{and} \quad R_y = R\,(1+\Delta)$$

$$\mathcal{O}(0.1) \lesssim \Delta = \text{cst.} \lesssim \mathcal{O}(1)$$

- **Oscillons positions and phases**

$\mathbf{x}^q$ and φ_q random with minimum distance between oscillons $\geq 4\,R$

Modelling the oscillon dynamics

Modelling the oscillon dynamics

Based on our assumptions:

$$
\begin{aligned}
T_{ij}^{\mathrm{TT}}(\mathbf{k},t) &\simeq \Lambda_{ij,lm}(\hat{\mathbf{k}})\sum_q \Phi_q^2(t)\int d^3\mathbf{x}\, e^{-i\mathbf{k}\mathbf{x}}\partial_l\mathcal{F}_q(\mathbf{x},t)\partial_m\mathcal{F}_q(\mathbf{x},t) \\
&= \Lambda_{ij,lm}(\hat{\mathbf{k}})\,\mathcal{T}_{lm}(\mathbf{k},t)\sum_q A^2\,\cos^2(\omega_{\mathrm{osc}}t+\varphi_q)\,e^{-i\,\mathbf{k}\,\mathbf{x}^q}
\end{aligned}
$$

with

$$
\begin{aligned}
\mathcal{T}_{ij}^{TT}(\mathbf{k},t) &= \Lambda_{ij,lm}(\hat{\mathbf{k}})\mathcal{T}_{lm}(\mathbf{k},t) \\
&= e^{-\frac{R^2\left(k_x^2+k_z^2+k_y^2(1+\Delta)^2\right)}{4\,a^2(t)}}\;\frac{\pi^{3/2}\Delta(\Delta+2)R}{4a(t)(\Delta+1)}\,f_{ij}(\mathbf{k})
\end{aligned}
$$

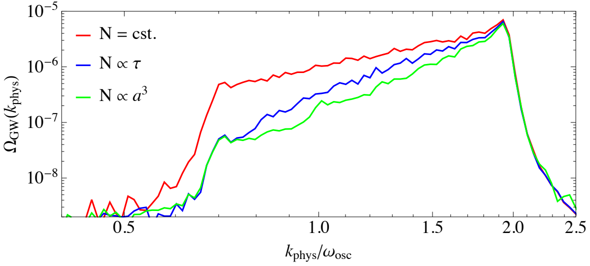
Two quick observations:

Remember $\Omega_{\mathrm{GW}}(k,\tau)\sim\left|\int_{\tau_i}^{\tau_f}d\tau'...T_{ij}^{\mathrm{TT}}(\mathbf{k},\tau')\right|^2$:

$$\Omega_{\mathrm{GW}}(k,\tau)\propto A^4$$

for small Δ $\quad \Omega_{\mathrm{GW}}(k,\tau)\propto\Delta^2+\mathcal{O}(\Delta^4) \quad\Rightarrow\quad$ spherical oscillons $\rightarrow$ no GWs

Varying number of oscillons $N(t)$



- Amplitude of the spectrum independent of how N changes!
- Scaling with the number of oscillons:

$$\Omega_{GW}^{N} \sim \Omega_{GW}^{\text{single}} (N \pm \delta) \quad \text{with} \quad \delta \lesssim \mathcal{O}(1)$$

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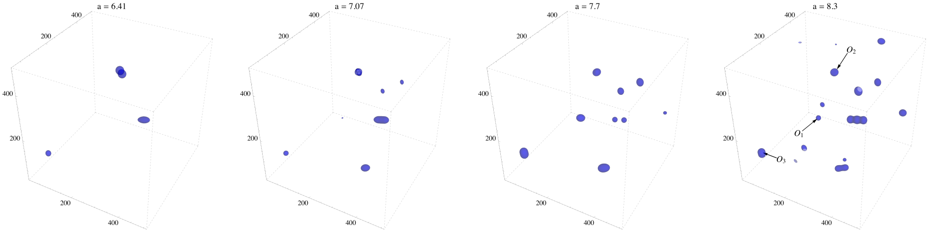

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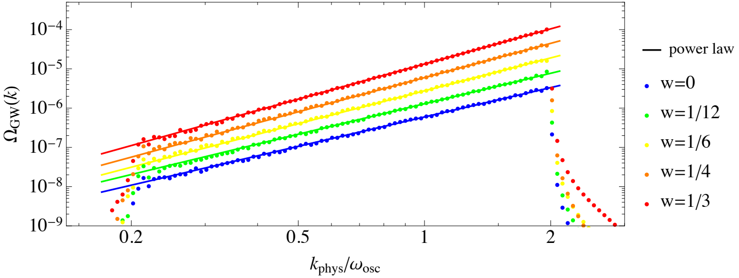
Different background cosmologies

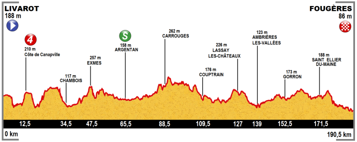


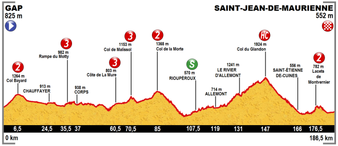
$$\boxed{\Omega_{\rm GW}(k_{\rm phys}) = A_{\rm GW}\left(\frac{k_{\rm phys}}{\omega_{\rm osc}}\right)^{n_{\rm GW}}}$$

$$\boxed{A_{\rm GW}(w) \propto e^{\kappa\, w} \quad \text{and} \quad n_{\rm GW}(w) \propto w}$$

($A_{\rm GW} \equiv$ amplitude of the peak $k_{\rm phys} = \omega_{\rm osc}$, $n_{\rm GW} \equiv \frac{d \log \Omega_{GW}}{d \log k_{\rm phys}}$)

Thank you!





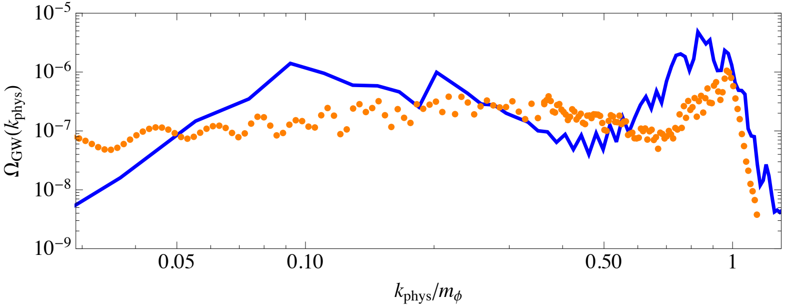
src: https://commons.wikimedia.org/wiki/File:Profile_stage_7_Tour_de_France_2015.png (left), https://commons.wikimedia.org/wiki/File:Profile_stage_5_Tour_de_France_2015.png (right)

Conclusions

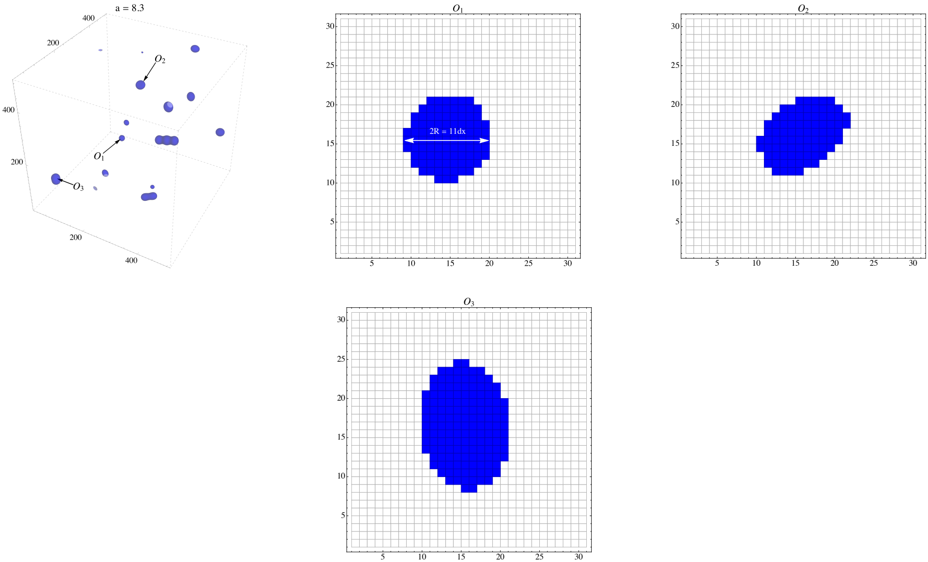
- GWs can potentially teach us a lot about the physics of the (early) universe $\rightarrow$ probes at many different scales?!
- As long as oscillons are asymmetric, they are active sources of GW production
- The characteristics of oscillon cosmologies manifest themselves in the stochastic background of GW $\rightarrow$ part of a cosmological fingerprint?!

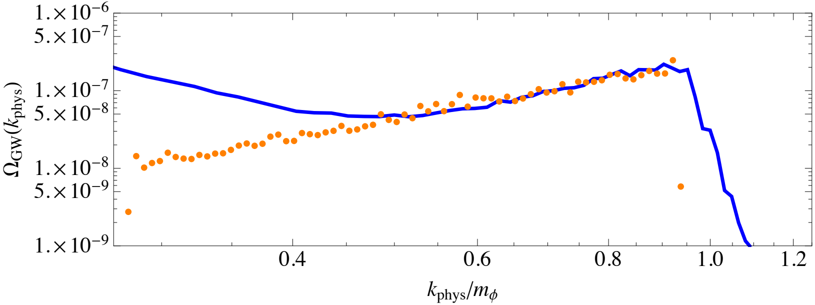
More movies?

- Stringy oscillons: https://particlesandcosmology.unibas.ch/downloads/oscillons-from-string-moduli-movies.html
- Oscillons in hilltop inflation: https://particlesandcosmology.unibas.ch/fileadmin/user_upload/particlesandcosmology-unibas-ch/files/hilltop_preheating.html


10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$\Omega_{\rm GW}(k_{\rm phys})$
0.05
0.10
0.50
1
$k_{\rm phys}/m_\phi$

Semi-analytics vs. attice simulations: KKLT scenario




$1.\times10^{-6}$
$5.\times10^{-7}$
$1.\times10^{-7}$
$5.\times10^{-8}$
$1.\times10^{-8}$
$5.\times10^{-9}$
$1.\times10^{-9}$
$\Omega_{\rm GW}(k_{\rm phys})$
0.4
0.6
0.8
1.0
1.2
$k_{\rm phys}/m_\phi$

Semi-analytics vs. attice simulations: KKLT scenario