The Scalar Era in the Early Universe

Probing BSM Scalar Fields with Gravitational Waves.

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Based on arXiv:1904.07870 [hep-ph].
In collaboration with **Francesco d'Eramo (Padua)**.

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Outline

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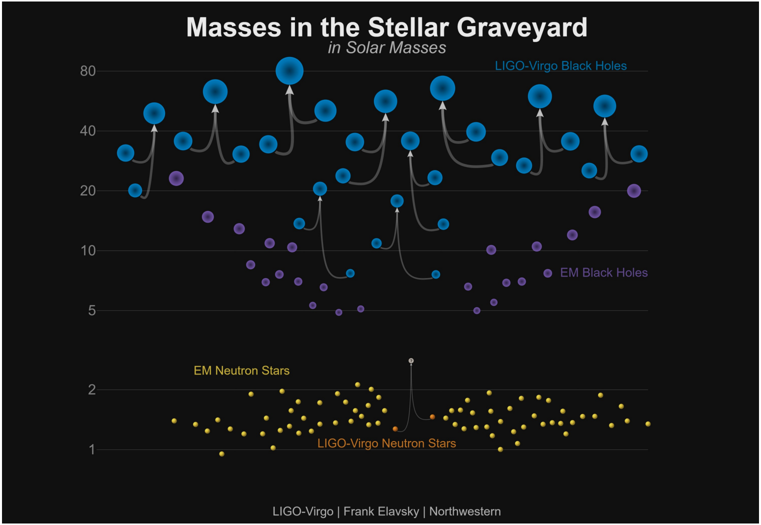
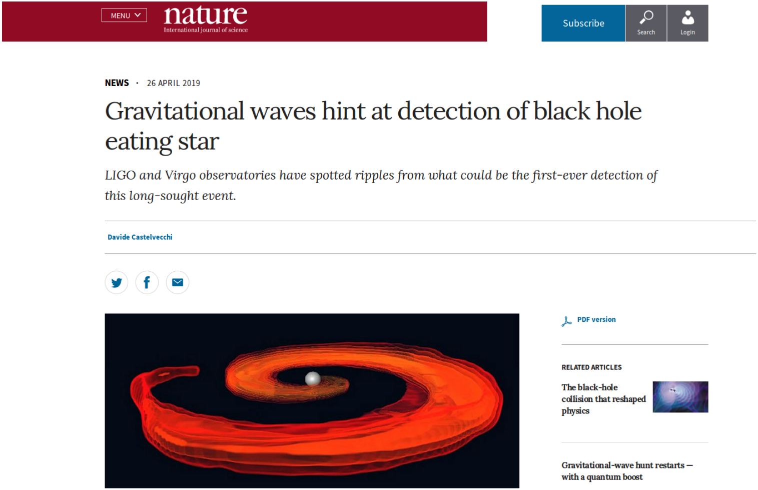
1. Gravitational waves
2. Scalar era
3. BSM applications
4. Conclusions

Gravitational waves



[LIGO/Virgo | Gravitational-Wave Transient Catalog (GWTC) 1 | 1811.12907]

LIGO/Virgo observing run 3



NEWS · 26 APRIL 2019

Gravitational waves hint at detection of black hole eating star

LIGO and Virgo observatories have spotted ripples from what could be the first-ever detection of this long-sought event.

Davide Castelvecchi

RELATED ARTICLES

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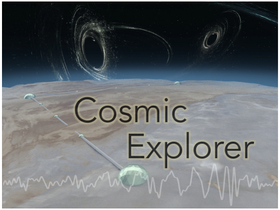
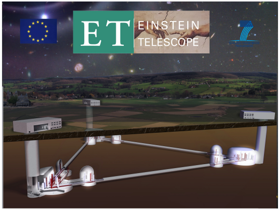
Gravitational-wave hunt restarts — with a quantum boost

[LIGO/Virgo | Nature 569, 15-16 (2019)]

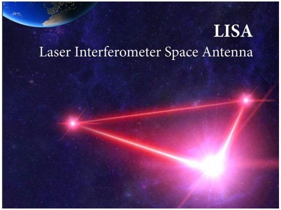
Era of gravitational-wave astronomy

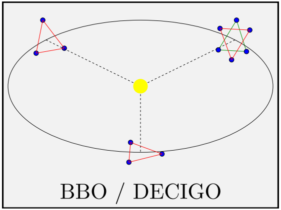
Ground



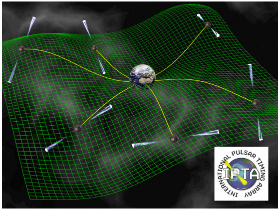


Space



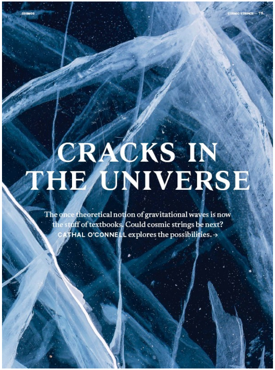


Sky



Cosmological gravitational-wave signals

Topological defects

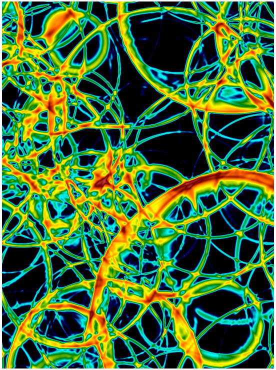


CRACKS IN THE UNIVERSE

The once theoretical notion of gravitational waves is now the stuff of textbooks. Could cosmic strings be next? CATHAL O'CONNELL explores the possibilities. →

[Cathal O'Connell | COSMOS Magazine 04/2018]

First-order phase transitions



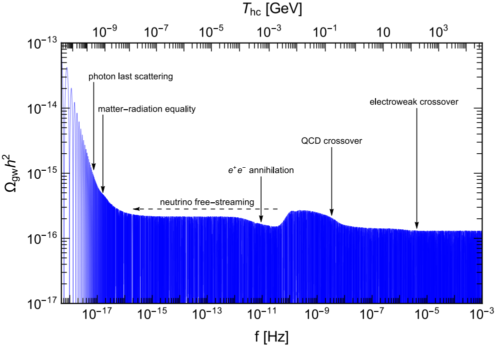
[David Weir | 1705.01783]

Inflation

[NASA / WMAP Science Team]

→ This talk: Use the stochastic background of inflationary GWs to probe new particle physics

Primordial gravitational waves from inflation



[Ken'ichi, Saikawa, Satoshi Shirai | 1803.01038]

- Tensor perturbations of the metric

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

- Stretched to super-horizon size during inflation, frozen till re-entry
- EOM for Fourier modes ($u = k\tau$)

$$\boxed{\left(\frac{d^2}{du^2} + \frac{2}{a}\frac{da}{du}\frac{d}{du} + 1\right) h_k^{+,\times} = 0}$$

Sub-horizon modes are redshifted according to $a(u)$ → Logbook of the expansion history!

- Measure reheating temperature after inflation. [0802.2452, 0804.1827, 1110.4169, 1305.3392, ...]
- Determine equation of state during the QCD phase transition. [1010.4857, 1904.01046]
- Our work: **Probe the presence of new scalar fields in the early Universe.**

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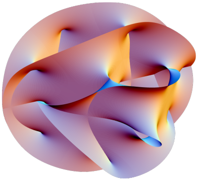
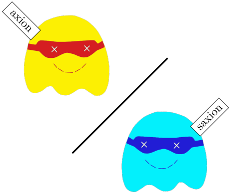
Scalar fields in the early Universe

Toy model of a scalar field ϕ with mass m_ϕ, decay rate Γ_ϕ, and initial field value $\phi_{\rm ini}$

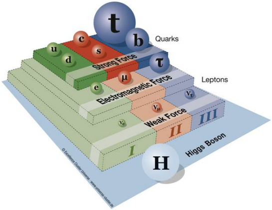
Modulus field in string theory



Saxion in SUSY axion model



Flavon field in a flavor model



Modified expansion history:

1. Scalar field fixed at $\phi_{\rm ini}$ until $H \sim m_\phi$ $\rightarrow$ Radiation domination after inflation
2. Oscillations around potential minimum $\rightarrow$ Scalar-field domination / *The Scalar Era*
3. Scalar field decays at $t \sim 1/\Gamma_\phi$ into radiation $\rightarrow$ Standard radiation domination

The scalar era

Klein-Gordan equation

$$\boxed{\left[\frac{d^2}{dt^2} + \left(3\,H + \Gamma_\phi\right)\frac{d}{dt} + m_\phi^2\right]\phi = 0}$$

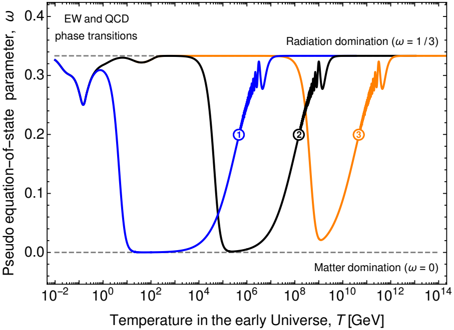
Covariant energy conservation

$$\boxed{\left[\frac{d}{dt} + 4\,\frac{g_{*,s}\left(\rho_R\right)}{g_{*,\rho}\left(\rho_R\right)}\,H\right]\rho_R = \Gamma_\phi\,\dot\phi^2}$$

Friedmann equation for $H = \dot a / a$

$$\boxed{H^2 = \frac{1}{3\,M_{\rm Pl}^2}\left(\frac{1}{2}\,\dot\phi^2 + \frac{1}{2}\,m_\phi^2\,\phi^2 + \rho_R\right)}$$

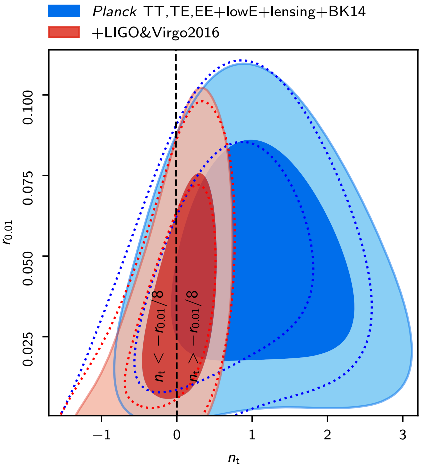
Pseudo EOS parameter ω, such that $a \propto t^{2/3/(1+\omega)}$



- Solve coupled system of equations in order to determine modified expansion history.
- Transfer function χ_k for the stochastic background of primordial GWs from inflation:

$$\boxed{\Omega_{\rm GW}^0\left(f\right) \simeq \frac{1}{12}\,\frac{k^2}{a_0^2 H_0^2}\left|\chi_k\right|^2 \mathcal{P}_{\rm tensor}^{\rm inflation}\left(k\right)\,, \quad f = \frac{k}{2\pi\,a_0}}$$

Primordial gravitational-wave background



[PLANCK | 1807.06211]

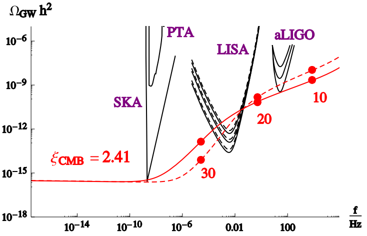
$$\boxed{\mathcal{P}_{\text{tensor}}^{\text{inflation}} = r\, A_{\text{scalar}}^{\text{COBE}} \left(\frac{k}{k_{\text{CMB}}}\right)^{n_t}}$$

Optimistic but viable and realistic ansatz; explore *maximal* reach of future GW experiments

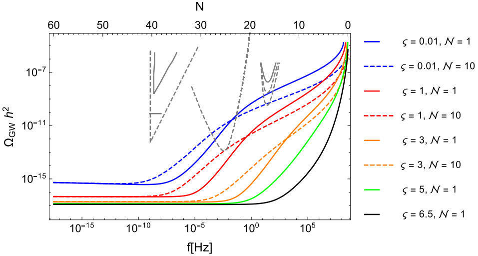
- Maximal amplitude
  → Tensor-to-scalar ratio $r = 0.07$
- Blue spectrum
  → Tensor spectral index $n_t = 0.4$
- Consistent with all current bounds from CMB, LIGO/Virgo, BBN, etc.
- Must go beyond the consistency relation $n_t = -r/8$ of single-field slow-roll inflation.

Example: Axion inflation coupled to gauge fields

[1109.0022, 1110.3327, 1203.5849,1603.01287, 1707.07943, 1904.01488, ...]



[Juan Garcia-Bellido, Marco Peloso, Caner Unal | 1610.03763]



[Valerie Domcke, Francesco Muia, Mauro Pieroni, Lukas Witkowski | 1704.03464]

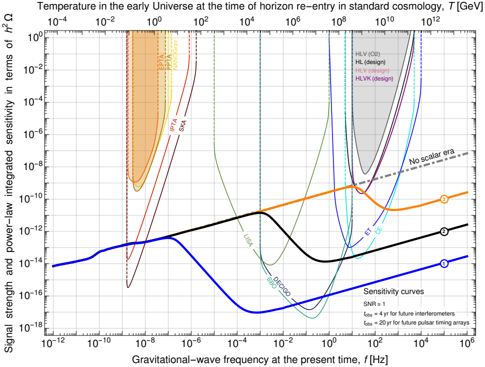
Consider cosmic inflation described by

$$\boxed{-\mathscr{L} \supset 1/2\,(\partial a)^2 + V(a) + 1/4\,FF + \theta/4\,F\tilde{F}\,, \quad \theta = a/f}$$

- PNGB of a spontaneously broken global symmetry. Flat potential protected by shift symmetry.
- Coupling of the *CP*-odd axion field to gauge fields via the *CP*-odd Chern–Simons density.
- Scalar and tensor perturbations receive (1) inflaton, (2) gauge-field, and (3) metric contributions.

Our strategy in the following: Assume a pure power-law background across all relevant frequencies.

Final gravitational-wave spectrum



Benchmark values ($\phi_{\rm ini} = 10^{18}\,\mathrm{GeV}$)

③ $m_\phi = 10^{6}\ \mathrm{GeV},\ \Gamma_\phi = 10^{0}\ \mathrm{GeV}$

② $m_\phi = 10^{1}\ \mathrm{GeV},\ \Gamma_\phi = 10^{-8}\ \mathrm{GeV}$

① $m_\phi = 10^{-4}\,\mathrm{GeV},\ \Gamma_\phi = 10^{-16}\,\mathrm{GeV}$

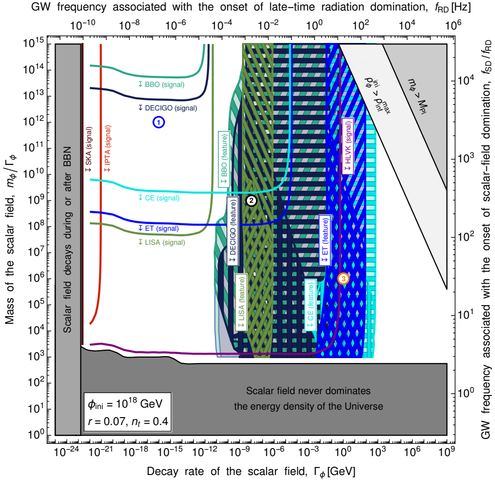
Experimental sensitivities

- Power-law-integrated sensitivity curves → visual representation
- SNRs computed based on strain noise power spectral densities

$$\boxed{\mathrm{SNR}^2 = N\,t_{\rm obs} \int_{f_{\rm min}}^{f_{\rm max}} df \left[\frac{\Omega_{\rm signal}(f)}{\Omega_{\rm noise}(f)}\right]^2}$$

The scalar era imprints a characteristic step-like feature on the primordial GW background.

Experimental prospects



Signal-to-noise ratios (SNRs)

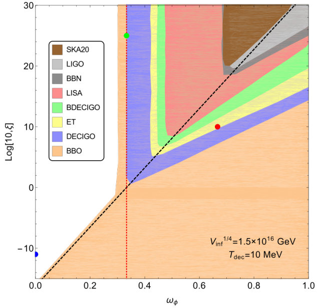
1. Total SNR based on full spectrum
→ *Will an experiment be able to see **at least some signal**?*
2. Reduced SNR after subtracting a power-law fit of the spectrum
→ *Will an experiment be able to see **a feature in the spectrum**?*

Each parameter points translates into an experimental fingerprint. Point ②:

- LISA, DECIGO, BBO will observe a departure from a power law.
- CE, IPTA, and SKA will detect a stochastic GW background.
- ET and HLVK will not observe any primordial GW signal.

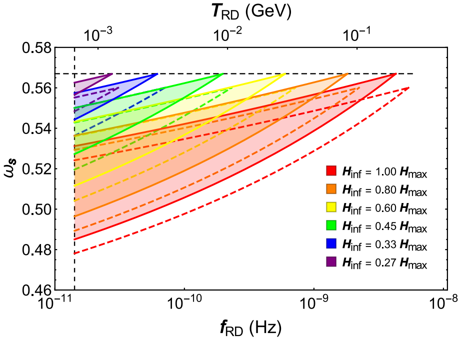
Very recent work related to our analysis

Yesterday on the arXiv



[Nicolás Bernal, Fazlollah Hajkarim | 1905.10410]

Today on the arXiv



[Daniel G. Figueroa, Erwin H. Tanin | 1905.11960]

Some differences to our work

- Exotic fluid with *constant* EOS → No field oscillations around the potential minimum.
- Generalization to stiff EOS, $1/3 < \omega < 1$. Must go beyond scalar field in harmonic potential.
- No SNR analysis → Simplified parameter study based on sensitivity curves.
- Subset of GW experiments. No distinction, no correlation between “signals” and “features”.

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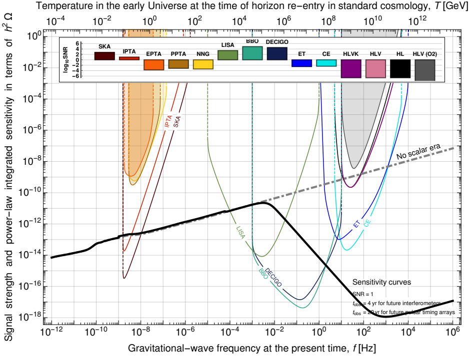
Heavy modulus in 4D string compactification



$$m_\phi = 10^{10}\,\mathrm{GeV}\,,\ \Gamma_\phi = 10^{-7}\,\mathrm{GeV}\,,\ \phi_{\mathrm{ini}} = 10^{18}\,\mathrm{GeV}$$

Probe end of scalar era in GW experiments.

Generic properties

$$\Gamma_\phi \sim \frac{m_\phi^3}{M_{\mathrm{Pl}}^2}\,, \quad \phi_{\mathrm{ini}} \sim M_{\mathrm{Pl}}$$

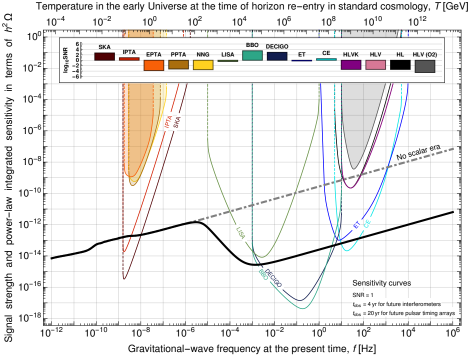
Examples from the recent literature

- DM production during a scalar era driven by several moduli.
  [Rouzbeh Allahverdi, Jacek Osiński | 1812.10522]
- Baryon cooling by milli-charged DM during a modulus-driven scalar era in order to explain the EDGES 21-cm signal.
  [Mansi Dhuria | 1812.11915]

Scalar era driven by a flavon field

Baryogenesis from flavon decays

[Mu-Chun Chen, Seyda Ipek, Michael Ratz | 1903.06211]



$$\boxed{m_\phi = 3\,\mathrm{TeV}\,,\ \Gamma_\phi = 10^{-13}\,\mathrm{GeV}\,,\ \phi_{\rm ini} = 10^{16}\,\mathrm{GeV}}$$

Probe entropy production in GW experiments.

1. Froggatt-Nielsen flavor model

$$\boxed{\mathscr{L} \sim \left(\frac{v+\phi}{\Lambda}\right)^{n_{ij}} \bar{e}_R^i \ell_L^j \tilde{H}}$$

2. Primordial flavon asymmetry translates into LR asymmetry

$$\boxed{\phi \rightarrow e_R \bar{\ell}_L H\,, \quad \phi^* \rightarrow \bar{e}_R \ell_L \tilde{H}}$$

3. $e_R/\bar{e}_R$ do not equilibrate during flavon-driven scalar era.

4. Electroweak sphalerons convert $\ell_L/\bar{\ell}_L$ asymmetry into a nonzero baryon asymmetry.

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Conclusions

A broad class of BSM models may be tested in upcoming GW experiments.

- String moduli, flavon fields, supersymmetric axion partners, ...
- Important implications for other relics such as dark matter and the baryon asymmetry.

The scalar era represents an important experimental benchmark scenario.

- Highlights the complementarity of future GW experiments across the entire spectrum.
- Evidence for SD would change our understanding of particle physics and cosmology.

Future directions

- Relax assumptions w.r.t. primordial spectrum, initial field value, scalar potential, ...
- Self-consisted embedding in an inflation model that generates a blue-tilted spectrum.

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Thank you for your attention!

Supplementary Material

Strain noise power spectral densities