The Scalar Era

Listening for New Scalar Fields with Gravitational Waves.

Kai Schmitz

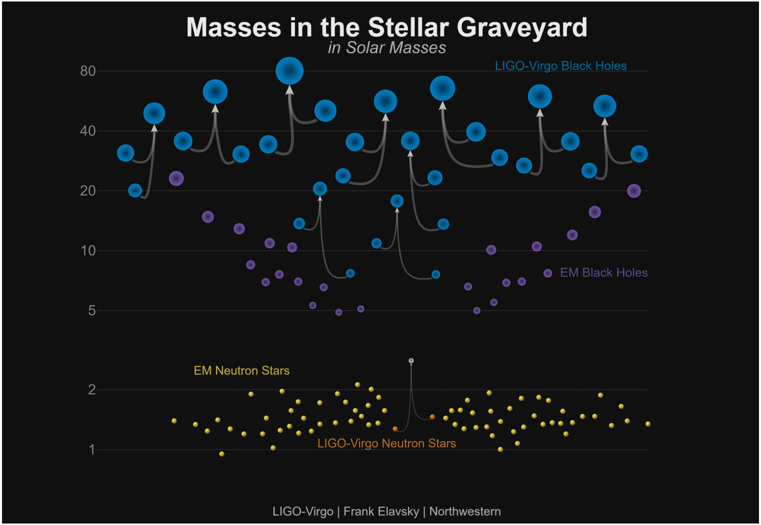
Postdoc at the *Dipartimento di Fisica e Astronomia "Galileo Galilei"*

at the *Università degli Studi di Padova*, Padua, Italy

Based on ARXIV:1904.07870 [HEP-PH].
In collaboration with **Francesco d'Eramo (Padua)**.

Portorož Workshop 2019: Precision Era in High Energy Physics
Astroparticle and Cosmology 2 Session | Portorož, Slovenia | 18/04/2019

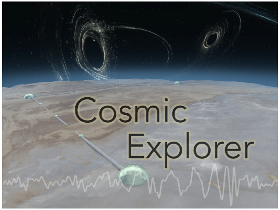
Gravitational waves

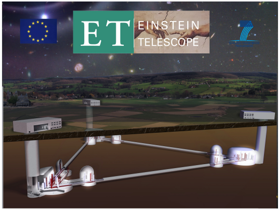


[LIGO/Virgo | Gravitational-Wave Transient Catalog (GWTC) 1 | 1811.12907]

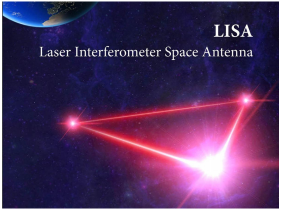
Era of gravitational-wave astronomy

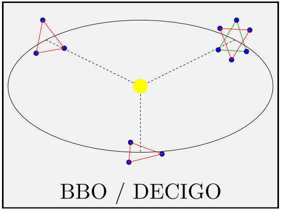
Ground



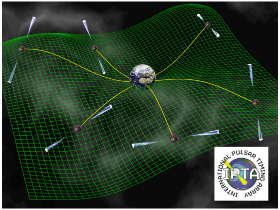


Space



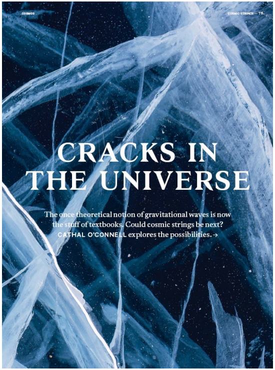


Sky



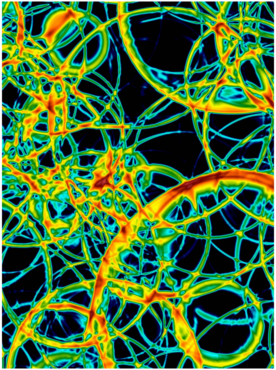
Cosmological gravitational-wave signals

Topological defects



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

First-order phase transitions



[David Weir | 1705.01783]

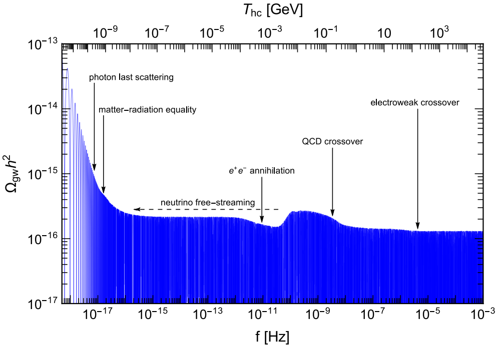
→ See talks by Vedran Brdar and Stephan Huber

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

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

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

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

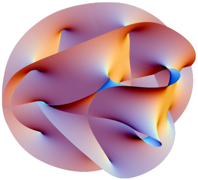
Sub-horizon modes are redshifted according to $a(u)$ $\rightarrow$ Logbook of the expansion history!

- 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.**

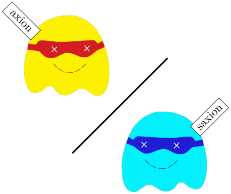
Scalar fields in the early Universe

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

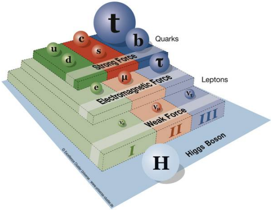
Modulus field in string theory



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

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

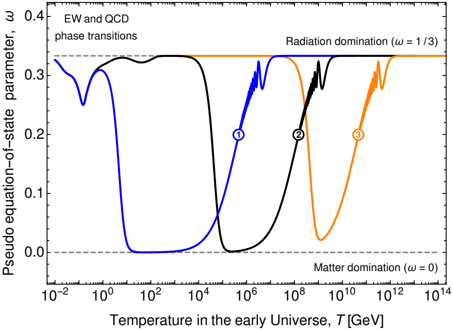
Covariant energy conservation

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

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

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

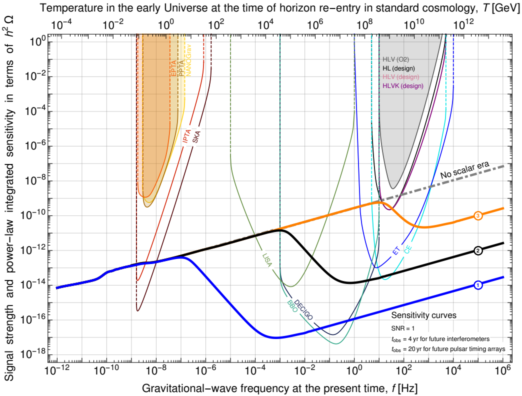
Pseudo EOS parameter ω, such that $a \propto t^{2/3/(1+\omega)}$



- 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:

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

Final gravitational-wave spectrum



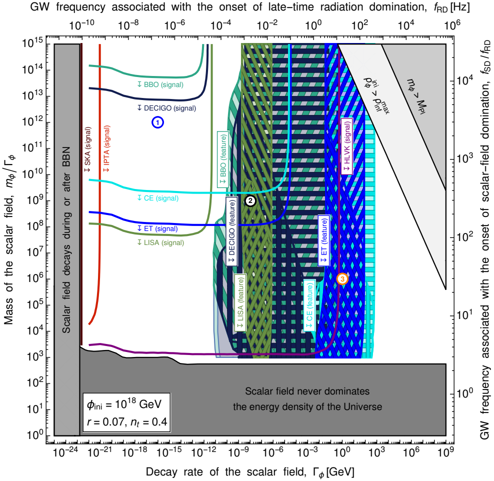
$$\mathcal{P}_{\text{tensor}}^{\text{inflation}} = r\, A_{\text{scalar}}^{\text{COBE}} \left(\frac{k}{k_{\text{CMB}}}\right)^{n_t}$$

Optimistic ansatz, explore *maximal* reach of future GW experiments

- Maximal amplitude → tensor/scalar ratio $r = 0.07$
- Blue spectrum → tensor index $n_t = 0.4$
- See, *e.g.*, natural inflation coupled to gauge fields.
  [1109.0022, 1110.3327, 1203.5849, 1603.01287, 1707.07943, 1904.01488, ...]

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

Experimental prospects



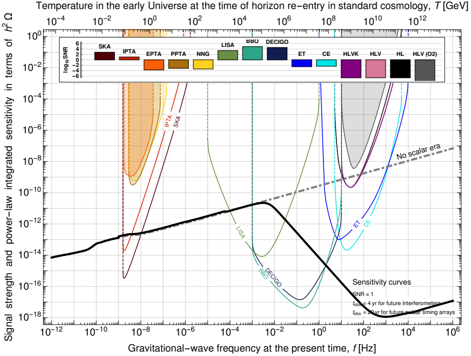
Signal-to-noise ratios (SNRs)

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.

Application: 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

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

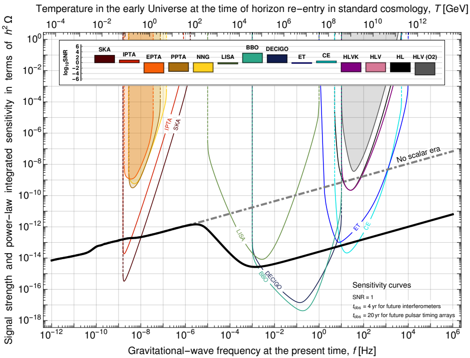
Examples from the recent literature

- 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]

Application: Scalar era driven by a flavon field

Baryogenesis from flavon decays

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



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

Probe entropy production in GW experiments.

1. Froggatt-Nielsen flavor model

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

2. Primordial flavon asymmetry translates into LR asymmetry

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

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.

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.

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.

Thank you for your attention!