A wrinkle in (space)-time: how gravitational waves can be used to probe hidden sectors

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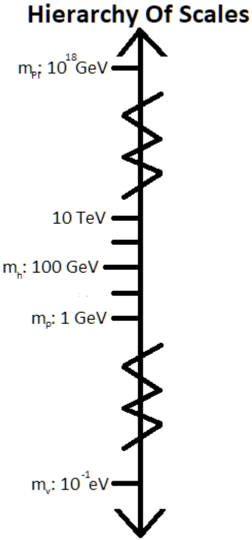
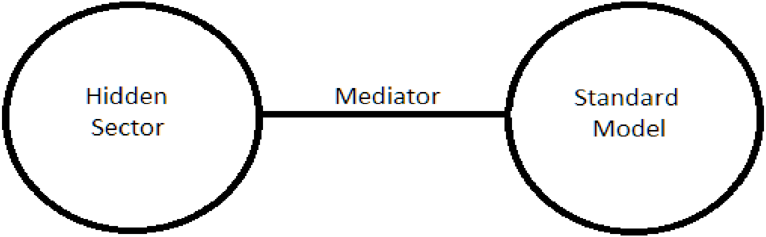
- Why is the mass of the Higgs so much smaller than the Planck mass?
- Quantum corrections to the Higgs mass should make the mass huge — one would expect a mass comparable to the scale where new physics appears.
- Many possible solutions: SUSY, anthropic principle, and more.



Hidden Sectors

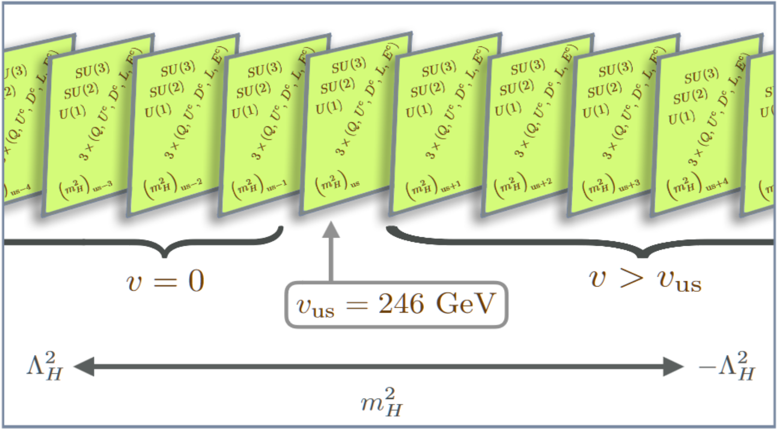


Hidden Sector

A hypothetical collection of new types of particles that interact with the Standard Model very weakly — typically via a new mediator particle.

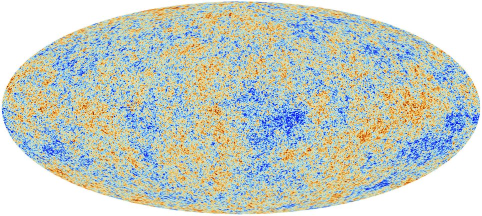
- Hidden sectors are often thermally decoupled from the SM for most of their lifetime and (mostly) evolve independently.

Nnaturalness



(Arkani-Hamed *et al*. Phys. Rev. Lett. 117, 251801 (2016))

Constraints



- Each of the N sectors possess relativistic degrees of freedom.
- Extra relativistic particles can alter the expansion history of the universe or affect light element abundances.
- Current Planck and BAO measurements showing: $N_{eff} = 2.99^{+0.34}_{-0.33}$ (in SM, $N_{eff} = 3.046$).

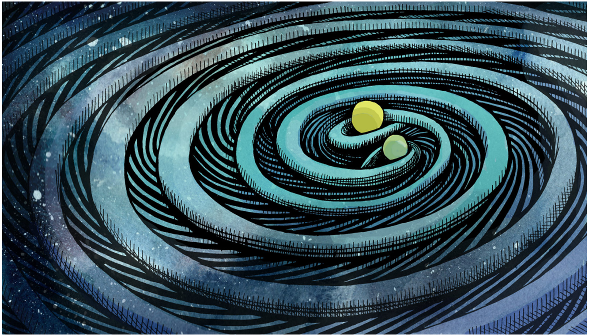
$$\Delta N_{eff} = \frac{4}{7}\left(\frac{11}{4}\right)^{4/3} g_h \xi_h^4.$$

- Here, g_h is the degrees of freedom in the hidden sector and ξ_h is the temperature ratio of the hidden sector and our sector.

How Do We Find Nnaturalness?

Are there any other ways we could look for Nnaturalness?
What about hidden sectors in general?

Gravitational Waves



- Disturbances in the curvature of spacetime; predicted in 1916 by Einstein as a consequence of General Relativity.
- Directly observed in 2015 by the LIGO and VIRGO collaborations.
- Potentially provide a window into the very early universe.

Gravitational Wave Physics

- Although currently measured gravitational waves signals have all come from binary mergers, there are other sources of gravitational waves.
- Hidden sector models can produce *stochastic gravitational wave backgrounds*.
- These backgrounds are caused by domain wall collisions that occurred all over the sky.
- Domain walls are generated via *phase transitions*.

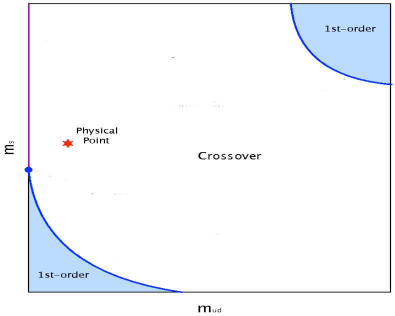
Phase Transitions I

- A phase transition occurs when a substance changes its state.

- A QCD phase transition occurs when the quarks and gluons flying around in early universe plasma condense into baryons.

Phase Transitions II

- Classified as 1st or 2nd order.
- 1st order phase transitions can lead to the production of detectable gravitational waves.
- Our QCD sector features a cross-over phase transition, but “dark QCD" sectors could have undergone 1st order transitions.



(Ogilvie. J.Phys. A45 (2012) 483001)

Standard And Exotic Sector Phase Transitions

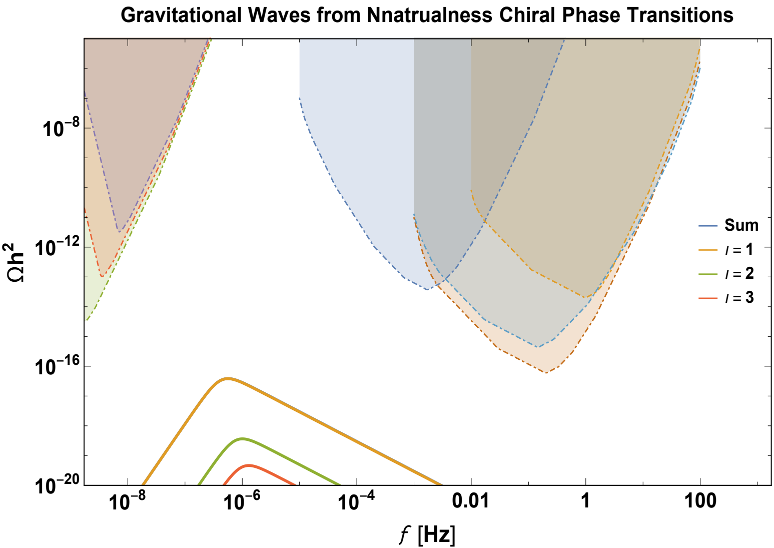
Standard Sectors

Every sector has a different higgs mass parameter that controls the mass of the entire sector (if it goes up, all the masses increase). QCD phase transitions occur in every sector, but the energy they occur at depends on the sector's higgs mass.

Exotic Sectors

All quarks are ultralight. As a result, all phase transitions are strongly first order and at $\Lambda_{QCD} \approx 90\,\mathrm{MeV}$.

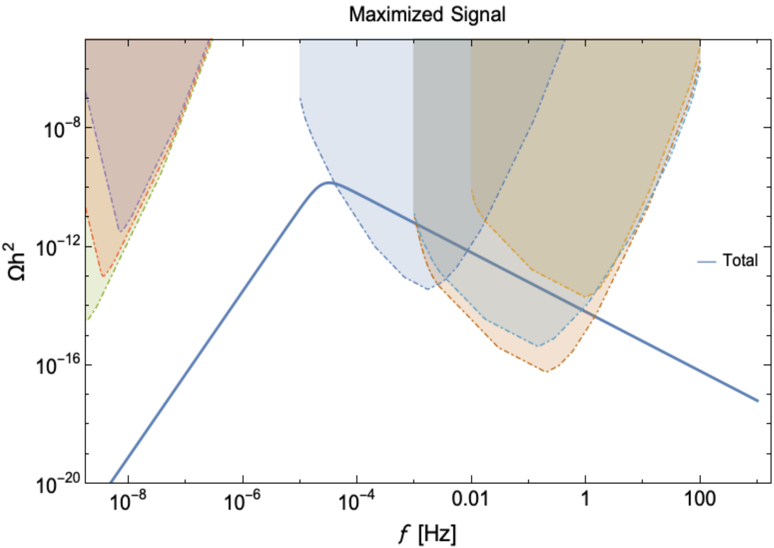
Nnaturalness Gravitational Wave Signatures



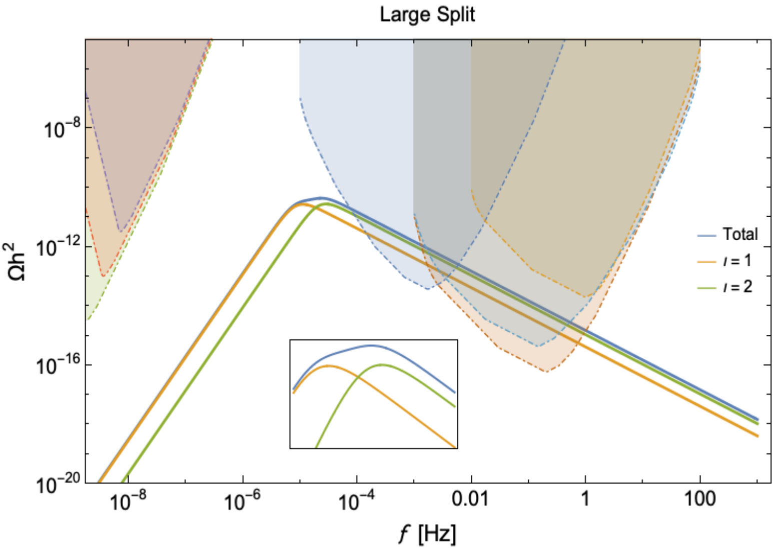
Generalized Multiple Hidden Sector Models

- Nnaturalness can be nicely generalized to an (almost) completely generic multi-hidden sector model if we relax the requirement that sectors with small higgs mass parameters are preferentially reheated.
- This generalization allows us to look at GW signatures of sectors that undergo phase transitions at different temperatures and thus have different peak frequencies.
- Crucially, this allows us to get GW spectra that overlap and create unique signatures.
- In all scenarios, we made certain to respect N_{eff} constraints.

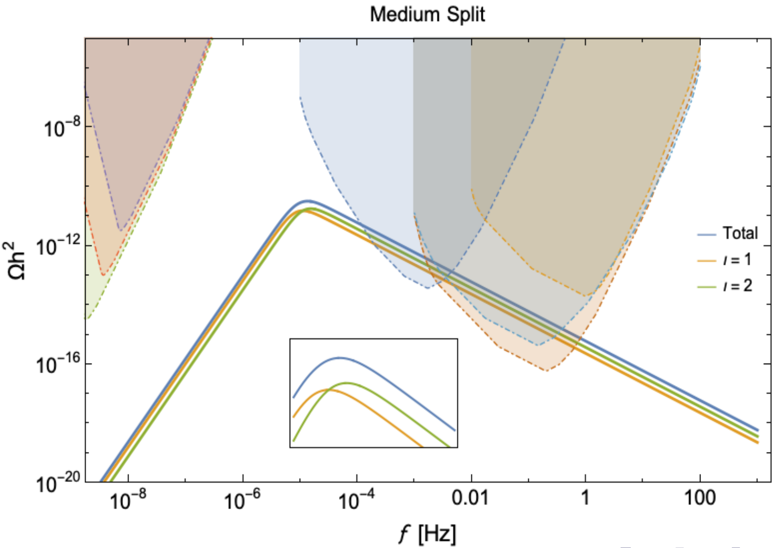
Gravitational Wave Signatures For Maximally Reheated Hidden Sector



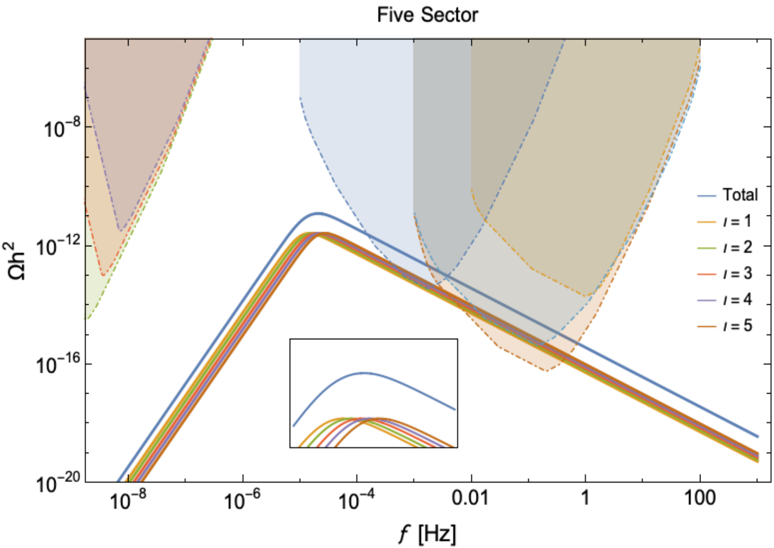
Gravitational Wave Signatures For 2 Hidden Sectors (Large Split)



Gravitational Wave Signatures For 2 Hidden Sectors (Medium Split)



Gravitational Wave Signatures For 5 Hidden Sectors



Summary

- Nnaturalness in its original form will not provide gravitational wave signatures that are probeable by next generation experiments.
- However, more general multiple hidden sectors can create unique detectable signatures.
- Provides theoretical impetus to design experiments that can measure in the gap between space based interferometers and pulsar timing arrays.
- Demonstrated that stochastic gravitational wave backgrounds can feature spectra that are not power laws.
- This gives us a unique signature of multiple hidden sector models that can be looked for in upcoming experiments.
- Finally, this forces us to rethink our assumptions made in experiment sensitivity: how does sensitivity change when gravitational wave backgrounds diverge from a power law?

Thank you!

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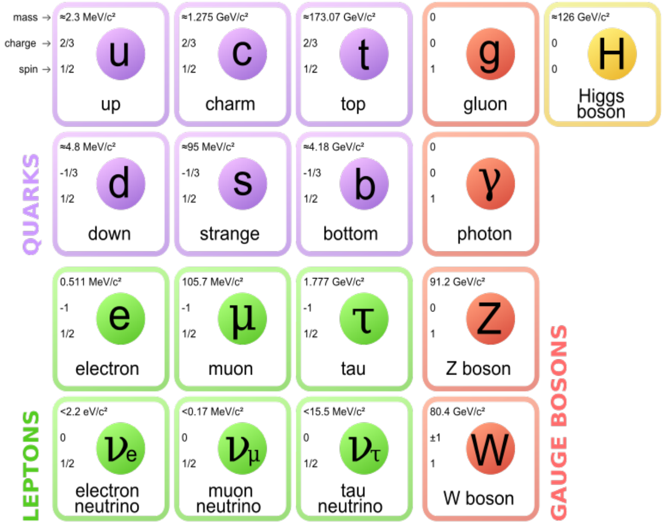
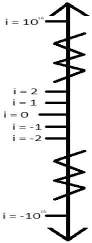
What We Know: The Standard Model



Model Setup

- Provides a solution to the hierarchy problem by stipulating that there are N sectors with Higgs mass parameters that range between some cutoff:
- The particle content and couplings of each of these additional sectors are identical to the SM, with the exception of the Higgs mass parameter.



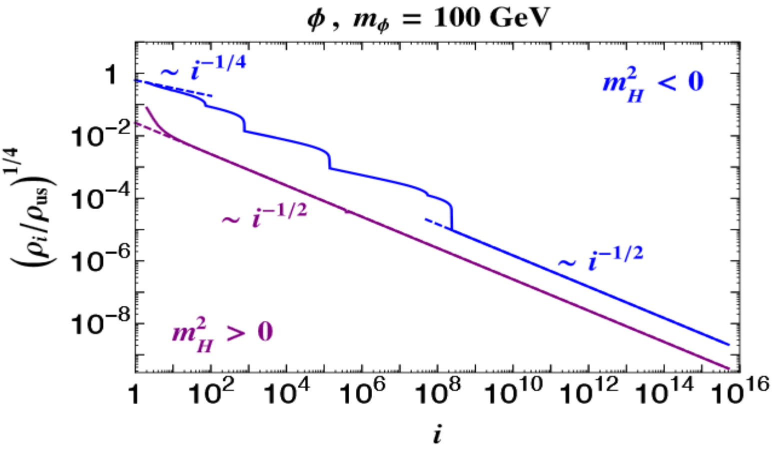
Standard Sectors

Sectors with $m_H^2 < 0$. We assume that the standard sector with the smallest absolute value of m_H^2 is the Standard Model. As $|m_H^2|$ gets larger, the sector's particles get heavier.

Exotic Sectors

Sectors with $m_H^2 > 0$. In this case, electroweak symmetry is preserved below the mass of the Higgs and all other particles are very light.

Sector Energy Density



(Arkani-Hamed *et al*. Phys. Rev. Lett. 117, 251801 (2016))