Gravitational Wave Signals of Affleck-Dine Baryogenesis

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Pennsylvania State University-New Kensington

Based on:
G. White, L. Pearce, D. Vagie, and A. Kusenko
PRL 127 (2021) 18,1 18 (arXiv:2105.11655)

Affleck-Dine Baryogenesis

I. Affleck and M. Dine,
Nucl. Phys. B 249, 361 (1985)

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M. Dine, L. Randall, and S. Thomas
Nucl. Phys. B 458, 291 (1996)

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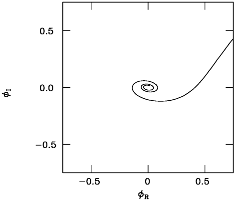

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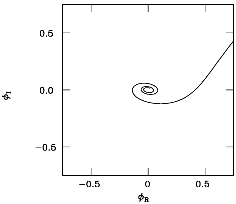
- After inflation, VEV coherently evolves & condensate fragments, producing a baryon and/or lepton asymmetry
- Fragmentation can produce observable gravitational waves, which are *not* the subject of this talk



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- Parameterize with:
  - $\omega = \sqrt{2V(v)/v^2}$: Energy per unit charge
  - v: VEV inside the Q-ball

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- Prospects for detecting...

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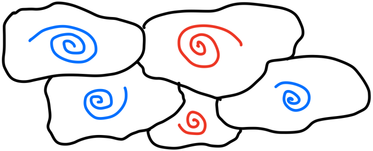

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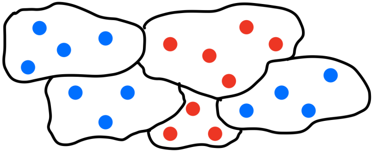

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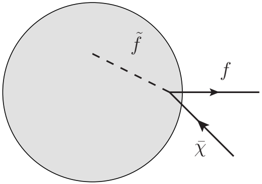

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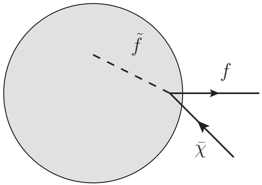
  Parameterize with effective coupling $y_{\rm eff}$



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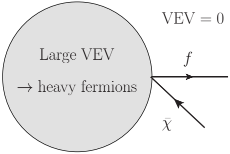

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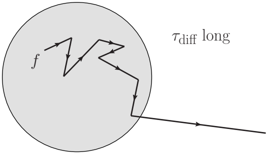
  - If decay isn't forbidden, decay products have to diffuse out
    $\rightarrow$ Fermi sea fills up



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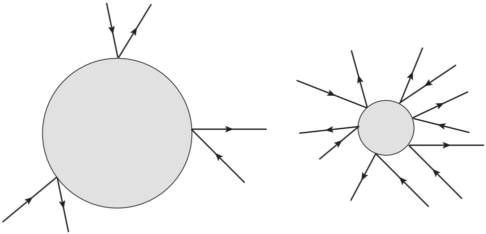

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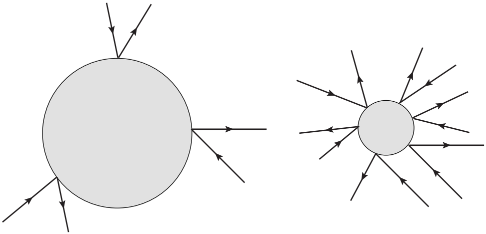
  $\rightarrow$ Decay is effectively instantaneous (like black holes)



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- Importance of large symmetric component: $r \sim Y_{B0}$

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T. Hiramatsu, M. Kawasaki, F. Takahashi
JCAP 1006:008 (2010)

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  - Gravity-mediated: Less clear with highly elliptical orbits, but simulations still seem to show a peak
- Early matter domination epoch ends rapidly when the Q-balls instantaneously decay
- Decay does slightly dilute the baryon asymmetry:

$$Y_B = Y_{B0}\left(1 + \frac{4Y_{B0}}{3r}T_{\rm decay}\right)^{-3/4}$$

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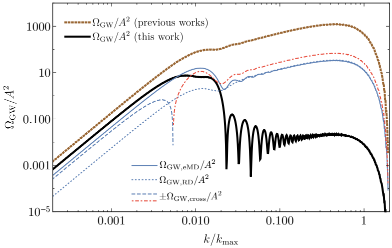

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K. Inomata, et. al.,
Phys. Rev. D 100, 043532 (2019)

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- Modes that enter horizon during matter domination grow...
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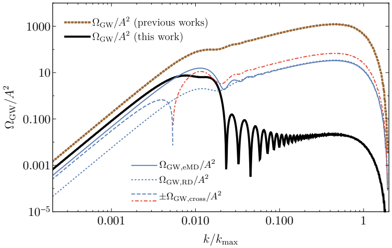
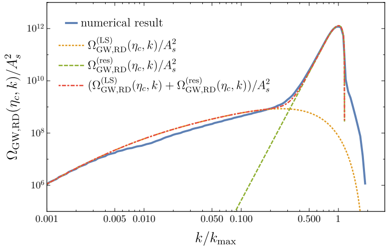
- But behavior at peak depends on end of matter domination:
  - Gradual end: Suppression
  - Fast end: Resonance-like enhancement





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- Act as a source to resonantly enhance induced gravitational waves comoving with the sound wave

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Downside: Ability to distinguish between scenarios...

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- Reheat temperature T_0: Determines initial radiation energy density $\rightarrow T_{\rm eq}$
- Effective Yukawa $y_{\rm eff}$: Determines decay temperature $T_{\rm decay}$

Parameters

Calculated:

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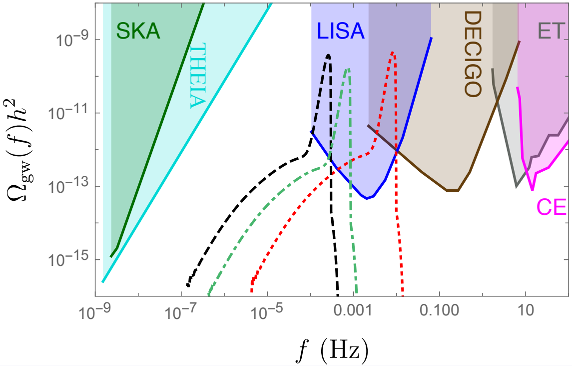
Calculated:

- $T_{\rm eq}$ and $T_{\rm decay}$
- Initial charge Q_0:

$$Q_0 = \frac{3 Y_{B0} M_{\rm Pl}^3}{800\sqrt{5}\pi^{5/2} g_*^{1/2} r T_0^3}$$

for $N_Q = 1000$ (gravity-mediated)

Results: Benchmark Scenarios



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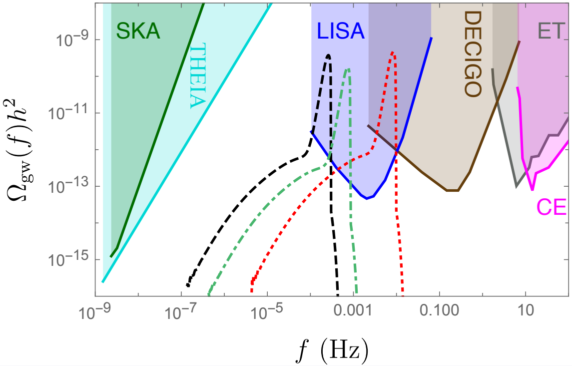

Signal depends on:

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- Length of early matter domination period: Sets amplitude

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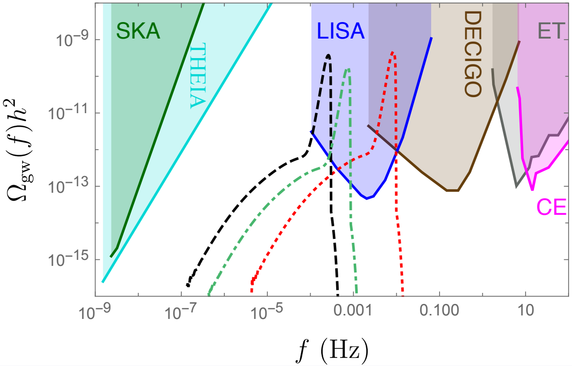

Benchmarks: $k_{\rm max} = 470/\eta_{\rm end}$ (Any longer and modes would become non-linear)

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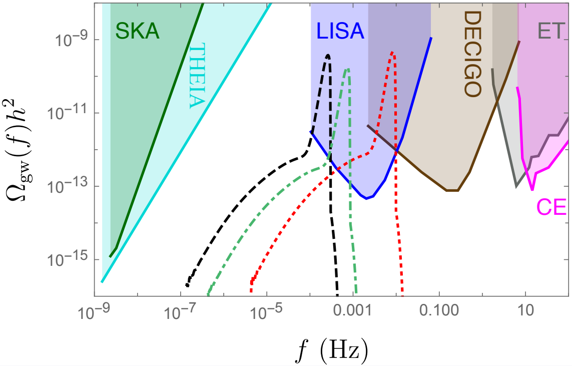

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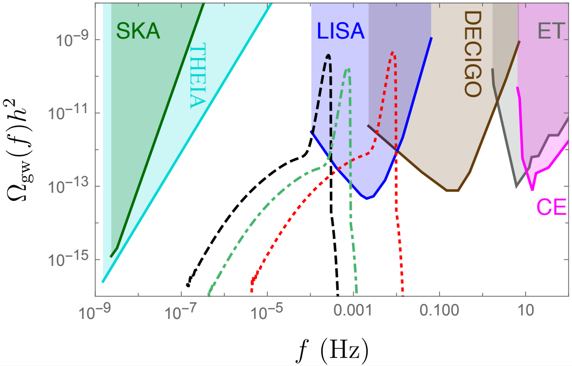

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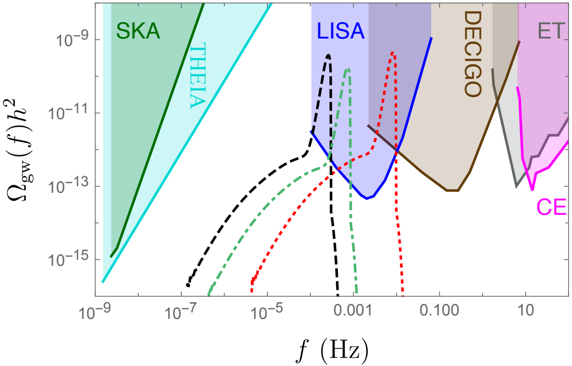

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- Lower temperatures preferred due to gravitino problem

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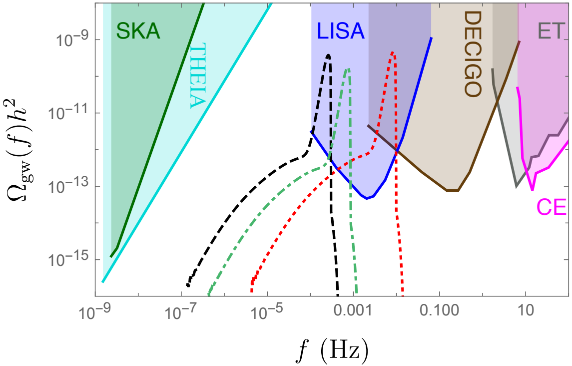

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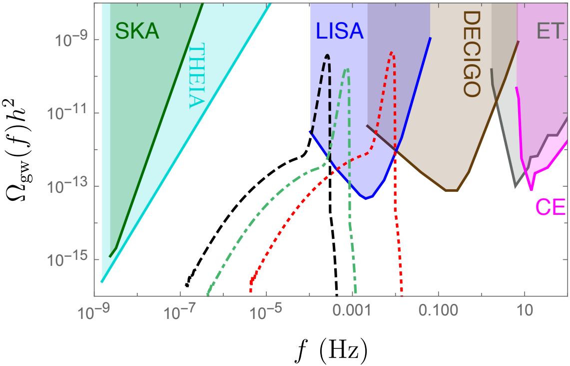
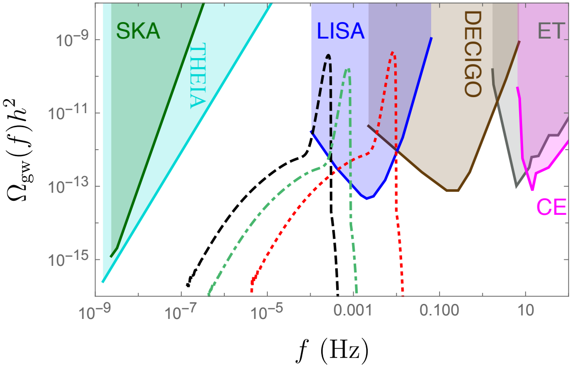


- $y_{\rm eff} \sim$ SM $y_{\rm bottom}$ (red, dotted), $y_{\rm up}$ (olive, dot-dashed), and $y_{\rm e}$ (black, dashed)
- Smaller couplings decay later $\rightarrow$ lower frequency peak

Results: Benchmark Scenarios



DECIGO: 3 units, observation time of 1 year, LISA: observation time of 4 years, THEIA: observation time of 20 years, Einstein Telescope: observation time of 1 year

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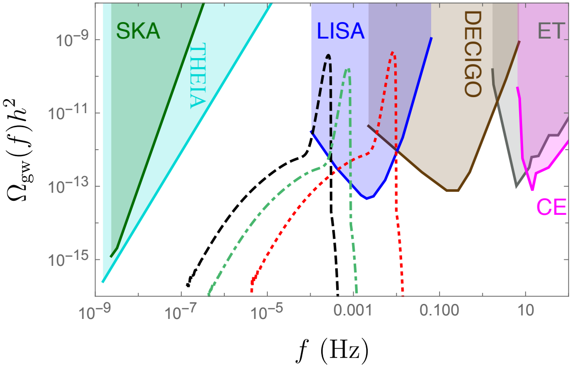

ω (GeV)	v (GeV)	Y_{B0}	r	T_0 (GeV)	N_Q	$y_{\rm eff}$
6.66×10^5	3.80×10^{10}	1.11×10^{-8}	1.56×10^{-8}	4.59×10^6	1000	0.024
8.45×10^5	1.92×10^9	1.36×10^{-8}	2.76×10^{-7}	8.04×10^6	1000	1.4×10^{-5}
9.95×10^5	7.21×10^9	2.10×10^{-8}	1.38×10^{-6}	3.56×10^6	1000	2.9×10^{-6}

Asymmetry parameter $r \sim Y_{B0}$ expected

N_Q from gravity-mediated SUSY-breaking simulations

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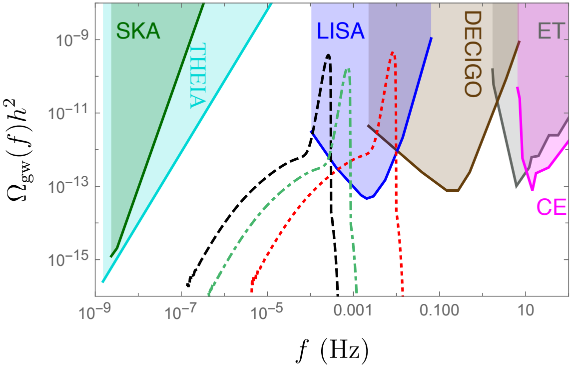

Calculated parameters:

Q_0	T_{eq} (GeV)	T_{decay} (GeV)
1.14×10^{31}	6.34×10^{5}	1368
1.47×10^{29}	55520	138
5.18×10^{29}	20050	458

Q_0 in range suggested by simulations

$Y_B \gtrsim 10^{-10}$

Gravity-Mediated

- Sample potential (gravity-mediated):

$$V(\Phi) = m^2|\Phi|^2 \left(1 + K \log\left(\frac{|\Phi|^2}{m^2}\right)\right) + \frac{1}{\Lambda^2}|\Phi|^6$$

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m (GeV)	Λ (GeV)
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- Confirmed in thin wall regime ($|\Phi|^6$ term relevant)

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- Thick wall Q-balls have $\Gamma_{\mathrm{Q-ball}}/Q \sim Q^{-3/4}$
- So we expect instantaneous decay (& sharply peaked mass spectrum)
- Expect to also have a gravitational wave signal from poltergeist mechanism, but need further work to find frequency & magnitude

Conclusions & Future Work

- Affleck-Dine baryogenesis is a well-motivated scenario the produces an observable gravitational wave signal via the poltergeist mechanism:

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Thank you! Questions?

Evaporation Rate

Charge depletion per unit time per unit area of a Q ball is:

$$\frac{dQ}{dt\, dA} = \frac{y_{\rm eff}\, v \omega^2}{64\pi}$$

In the thin wall limit:

$$R = \left(\frac{3Q}{4\pi\omega v^2} \right)^{1/3}$$

which gives

$$\frac{\Gamma_{\rm Q-ball}}{Q} = \frac{y_{\rm eff}\, v \omega^2 Q^{-1/3}}{16} \left(\frac{3}{4\pi\omega v^2} \right)^{2/3}$$

Gravitational Wave Signal: Assumptions

- Sudden end to matter domination:

$$\frac{a(\eta)}{a(\eta_R)} = \begin{cases} \left(\frac{\eta}{\eta_R}\right)^2 \\ 2\frac{\eta}{\eta_R} - 1 \end{cases}, \quad H(\eta) = \begin{cases} \frac{2}{\eta} & (\eta \leq \eta_R) \\ \frac{1}{\eta - \eta_R/2} & (\eta > \eta_R) \end{cases}$$

(η is conformal time, η_R is the end of matter domination)

- Primordial scalar power spectrum:

$$\mathcal{P}_\zeta(k) = \Theta(k_{\rm inf} - k) A_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

for some cutoff scale $k_{\rm inf}$, $A_s = 2.1 \times 10^{-9}$, $n_s = 0.97$, $k_* = 0.05\ \mathrm{Mpc}^{-1}$

- Conformal Newtonian gauge
- Assume Gaussian curvature perturbations

Gravitational Wave Signal

- Scalar perturbations source gravitational waves:

$$\overline{\mathcal{P}_h(\eta, k)} = 4\int_0^\infty dv \int_{|1-v|}^{1+v} du \left(\frac{4v^2 - (1+v^2-u^2)^2}{4vu}\right)^2 \times \overline{I^2(u, v, k, \eta, \eta_R} \mathcal{P}_\zeta(uk)\mathcal{P}_\zeta(vk)$$

- Overall power spectrum is given by:

$$\Omega_{\rm GW}(\eta, k) = \frac{1}{24}\left(\frac{k}{a(\eta)H(\eta)}\right)^2 \overline{\mathcal{P}_h(\eta, k)}$$

Gravitational Wave Signal

- I describes time evolution:
$$I(u,v,k,\eta,\eta_R) = \int_0^{k\eta} d(\overline{k\eta}) \frac{a(\bar{\eta})}{a(\eta)} k G_k(\eta,\bar{\eta}) f(u,v,\overline{k\eta},k\eta_R)$$
- Greens function satisfies:
$$\frac{\partial^2 G(\eta,\bar{\eta})}{\partial\eta^2} + \left(k^2 - \frac{1}{a}\frac{\partial^2 a}{\partial\eta^2}\right) G(\eta,\bar{\eta}) = \delta(\eta-\bar{\eta})$$
- Source:
$$f(u,v,\overline{k\eta},k\eta_R) = \frac{3}{25(1+w)}\Big(2(5+3w)\Phi(u\overline{k\eta})\Phi(v\overline{k\eta})$$
$$+4H^{-1}\frac{\partial}{\partial\eta}\left(\Phi(u\overline{k\eta})\Phi(v\overline{k\eta})\right) + 4H^{-2}\frac{\partial}{\partial\eta}\Phi(u\overline{k\eta})\frac{\partial}{\partial\eta}\Phi(v\overline{k\eta})\Big)$$
- Φ: Gravitational potential

Analytic approximations: K. Inomata, et. al., Phys. Rev. D 100, 043532 (2019)