# Some applications of Q balls in the early Universe

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*Based on arXiv:2105.11655 with Lauren Pearce, Daniel Vagie and Alex Kusenko*
*and arXiv 2111.xxxx with Lauren Pearce, Volodymyr Takhistov and Alex Kusenko*

Q balls are macroscopic objects that can exist in the early Universe

Conditions

1. A potential that is flatter than quadratic

$$\frac{V(\phi)}{\phi^2} \supset minimum$$

2. A conserved charge

When both are satisfied the energy of a bunch of scalar quanta forming an extended macroscopic object is lower than the same number of quanta being free particles

$$E = UV + A\sigma + \frac{Q^2}{\phi^2 V}$$

**In the thin wall approximation, energy of a Q ball:**

$$E = UV + A\sigma + \frac{Q^2}{\phi^2 V}$$

**Radius of a Q-ball**

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

**Energy of each quanta in a Q ball**

$$\omega = \sqrt{\frac{2U}{\phi^2}}$$

# Part 1: Higgs Balls

**Higgs example:**

1. **Early enough in the Universe, Higgs decays are slow compared to H**
2. **Naively the Higgs potential is much faster than quadratic**

$$V = -\mu^2 |H^\dagger H| + \lambda |H^\dagger H|^2$$

**However, the potential flattens out in the early Universe for two reasons**

1. $\lambda \to \lambda(\mu)$
2. $V \to V + cT^2h^2 - ETh^3$

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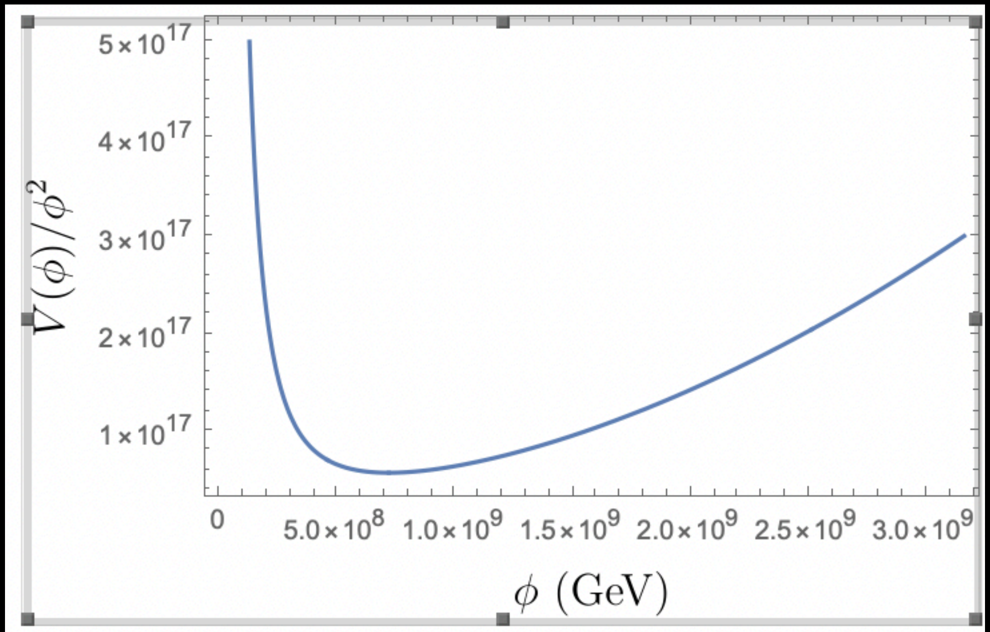

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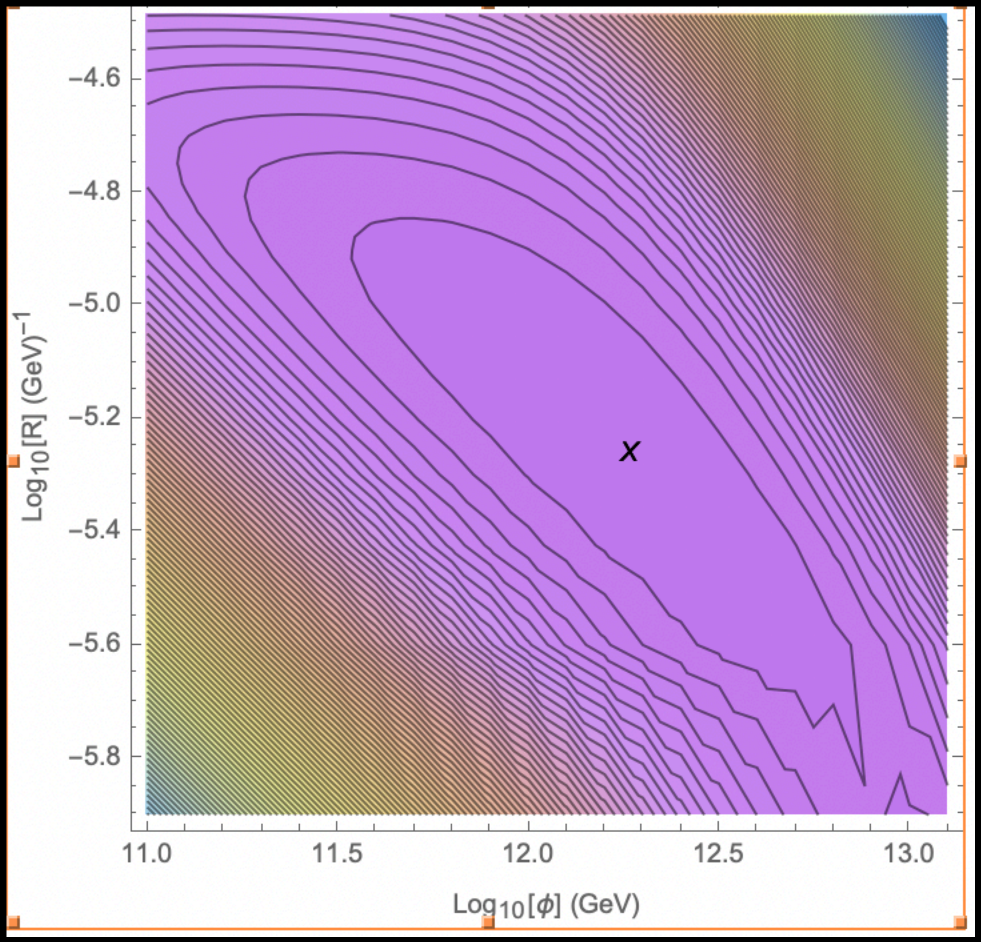
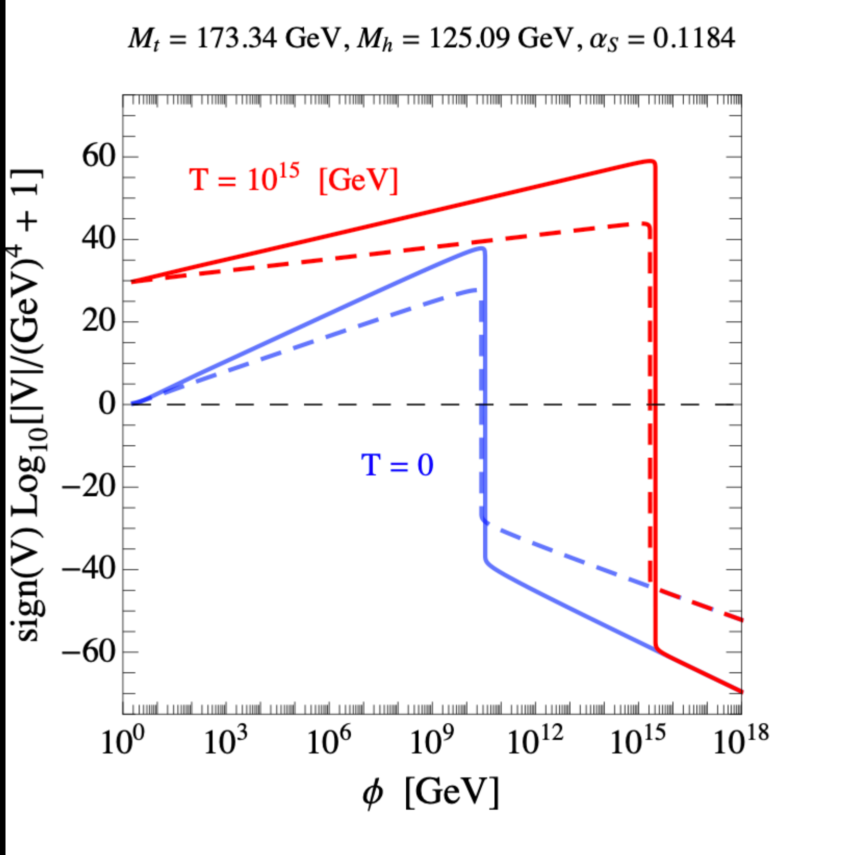


When is Higgs number a good conserved quantum number?

Naively quite high temperatures! $\mathcal{O}(10^{13})$ GeV!

Not impossible for preheating for two reasons

1. Preheating temperature can be about 2 orders of magnitude higher
2. The instability scale grows with temperature



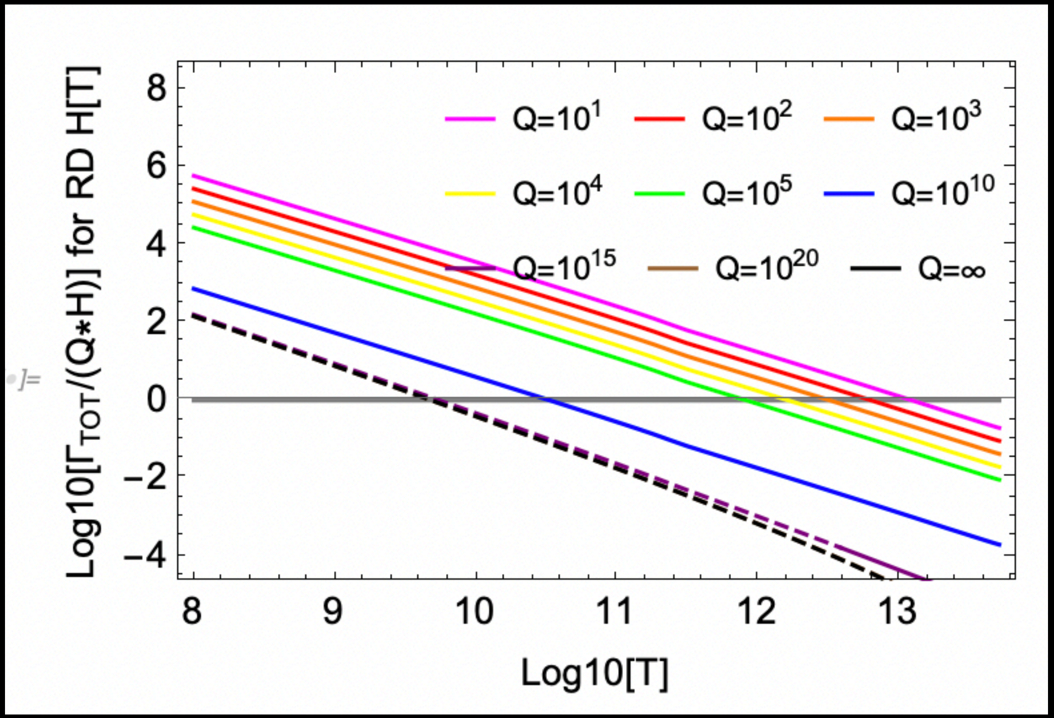

3. In any case, within experimental error, the Instability scale can be higher than this

## When is Higgs number a good conserved quantum number?

**Naively quite high temperatures!** $\mathcal{O}(10^{13})$ GeV!

**For Higgs balls though, stability looks even rosier**

1. **Fermions can only decay at the surface due to Pauli Blocking inside**
2. **Decay rate to gluons would be dominant but Higgs quanta is below the transverse gluon Debye mass**



**Note on hypercharge:**

**Higgs balls with a large H number require a local hypercharge asymmetry to cancel the hypercharge, otherwise there is a maximum size Higgs ball**

**To minimize the energy, the system produces fermions at the same time the phase starts spinning**

*We have a new macroscopic object in the Standard Model!*

**Now what to do with it?**

**Weinberg operator** $\frac{v_H^2}{\Lambda^2} LL$ **unsuppressed for huge vev**

**Can have CP violating interactions between neutrinos and the Higgs wall**

**Results in an (up to) O(1) asymmetry in the Higgs ball which is suppressed by the volume fraction within the balls**

$$R \sim \left( \frac{Q}{\omega v^2} \right)^{1/3} \sim Q^{1/3}/T << R_H$$

**Stay tuned for details in upcoming paper**

**Summary part 2:**

**New macroscopic object in the standard model**

**Higgs charge is a conserved quantity in the early Universe**

**The Standard Model Higgs potential at finite temperature allows a Higgs ball solution**

**Can be used to facilitate Baryogenesis**

**No doubt many other applications (e.g. very heavy freeze out dark matter)**

# Part 2: Q balls formed by Affleck Dine Baryogenesis

## Baryon asymmetry of the Universe:

## A triumph and a mystery

$$Y_B = \frac{n_B - \bar{n}_B}{s} \approx \frac{n_B}{s} = \begin{cases} (7.3 \pm 2.5) \times 10^{-11}, \mathrm{BBN} \\ (9.2 \pm 1.1) \times 10^{-11}, \mathrm{WMAP} \\ (8.59 \pm 0.11) \times 10^{-11}, \mathrm{Planck}\,. \end{cases}$$

## Affleck Dine Mechanism

- SUSY has many flat directions
- Some violate B or L

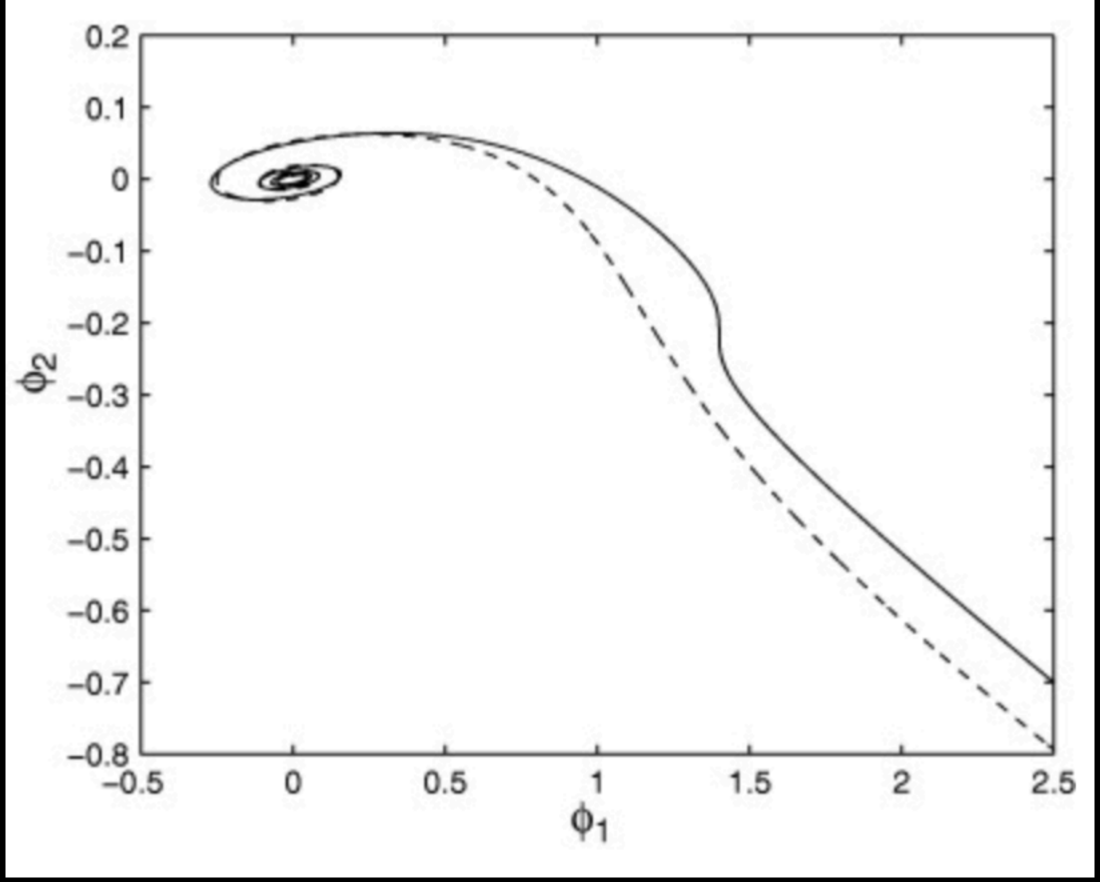
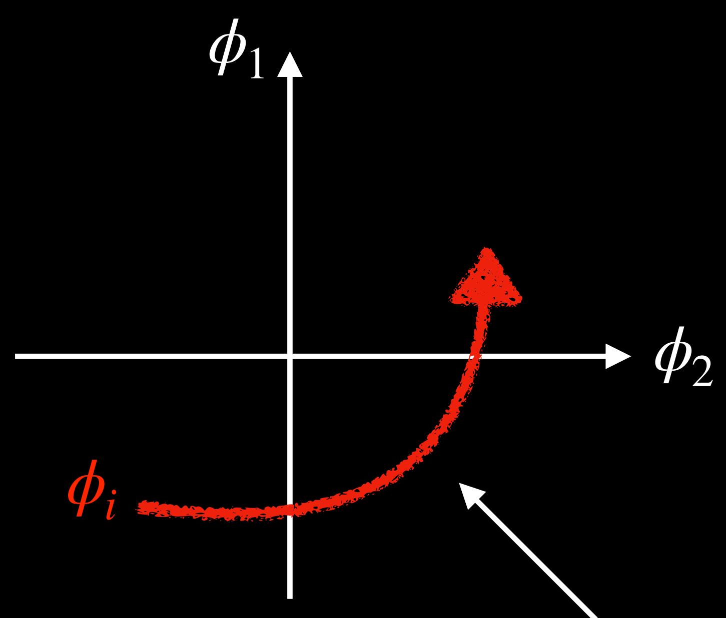
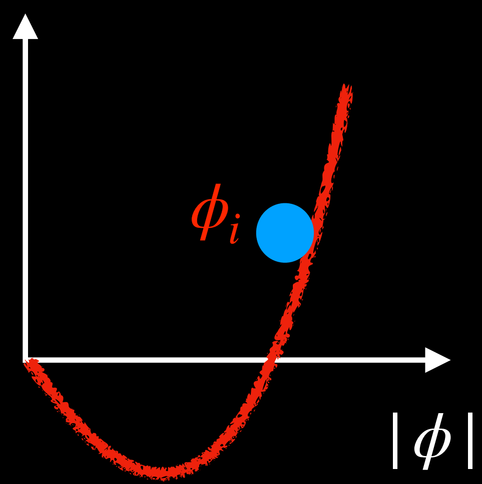
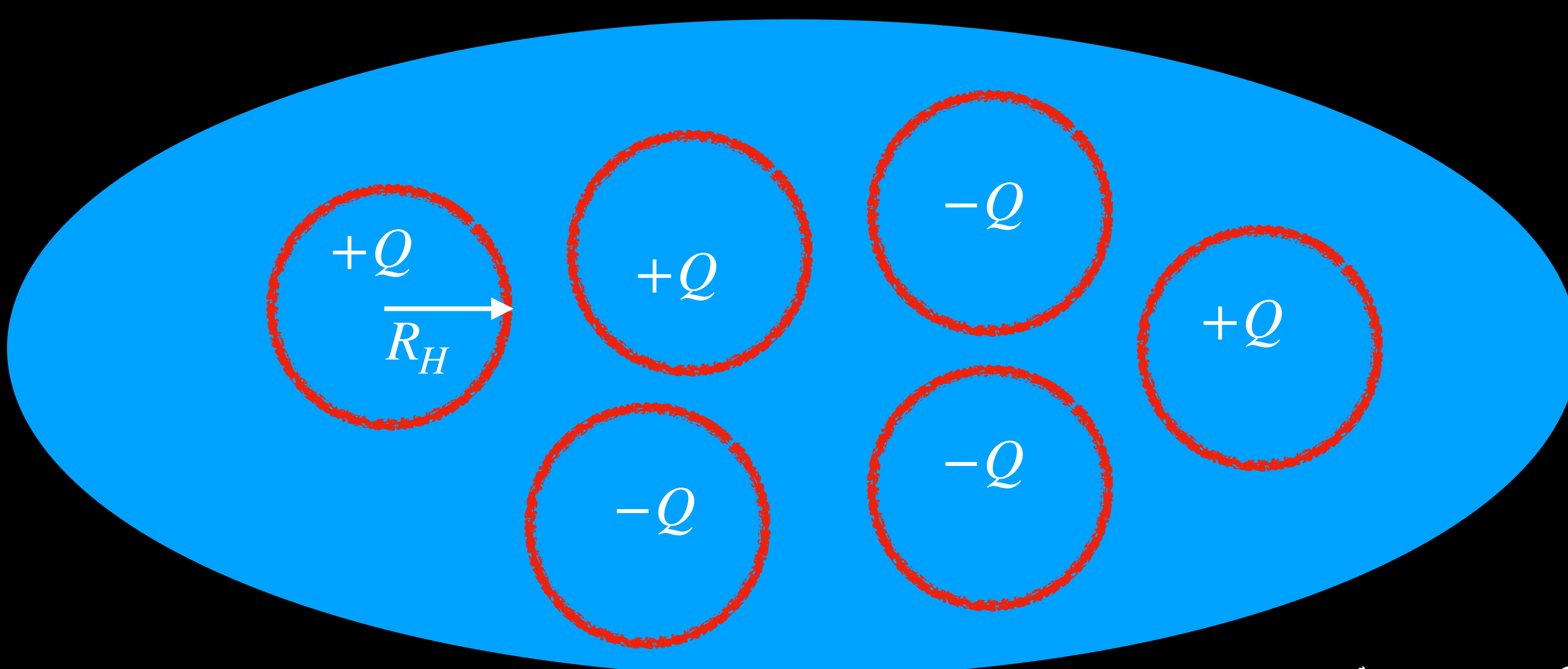



*Figure from review by Rouzbeh Allahverdi and Anupam Mazumdar*




**CPV operator gives (counter) clockwise bias**




Elegant but difficult to test!!

# Can GWs help?

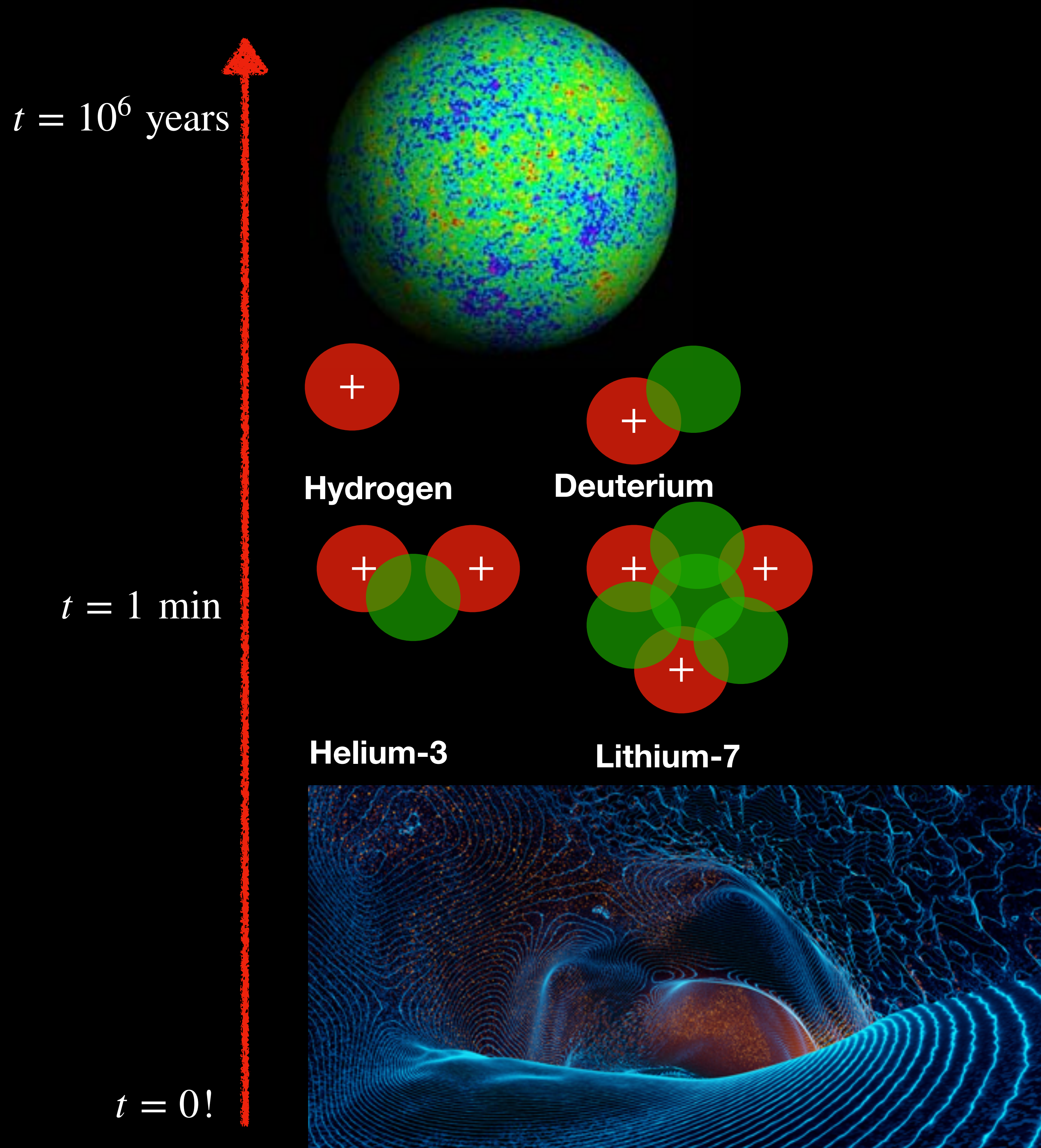
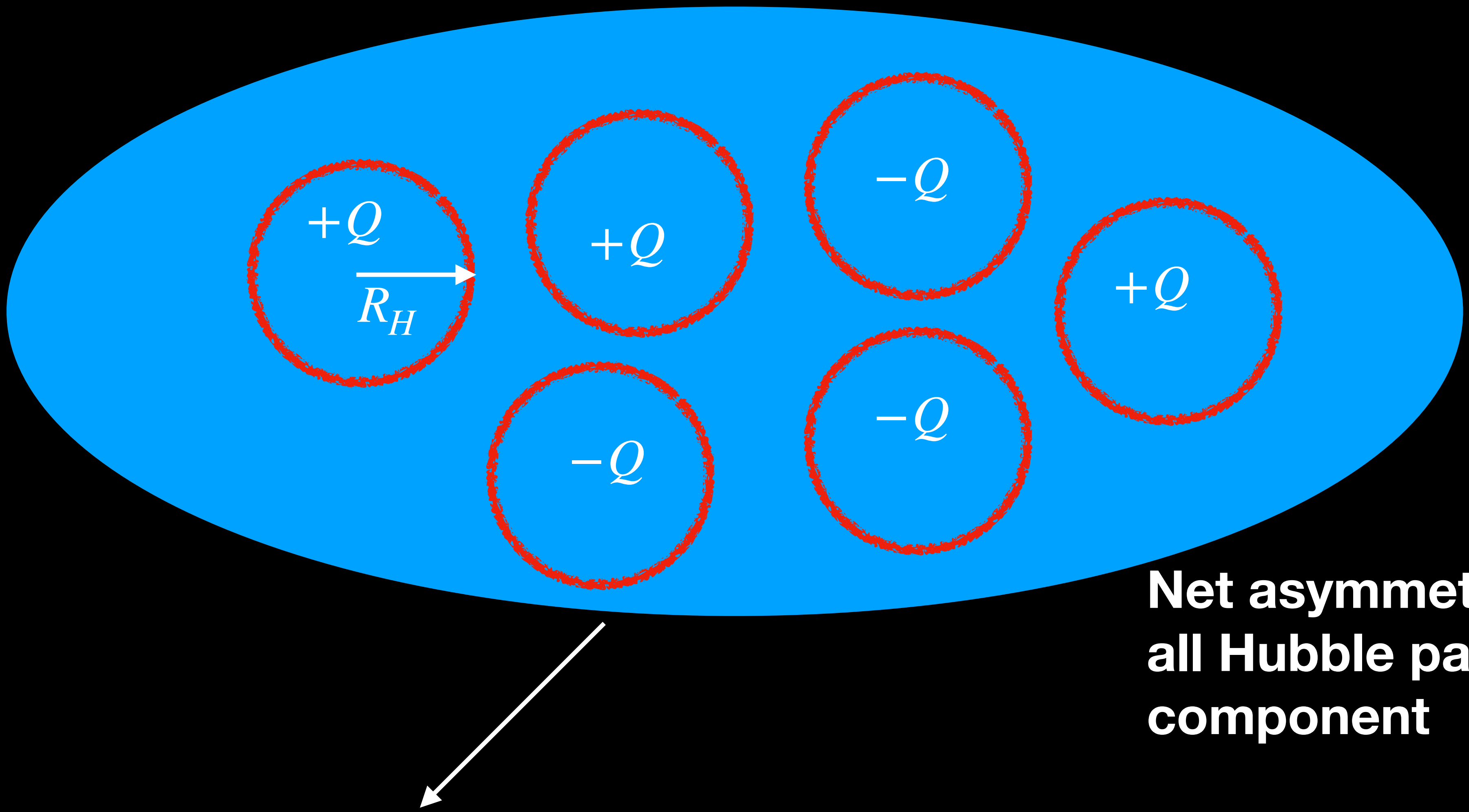



**Image credits: WMAP,**
**Phys. Rev. Lett. 124, 041804**




Net asymmetry averaged over all Hubble patches. Asymmetric component

$$r = \frac{n_{\bar{Q}} - n_Q}{n_{\bar{Q}} + n_Q}$$

Form Q balls if decays are sufficiently slow, and the potential allows

$$\mathrm{Min}\left[\frac{V(\phi)}{\phi^2}\right] \neq 0$$

Simulations show Q balls have a large symmetric component. So initial energy density in Q balls is large

**Simulations show Q balls have a large symmetric component. So initial energy density in Q balls is large**

$$\rho_Q = Q_0 \omega n_0$$

**Where**

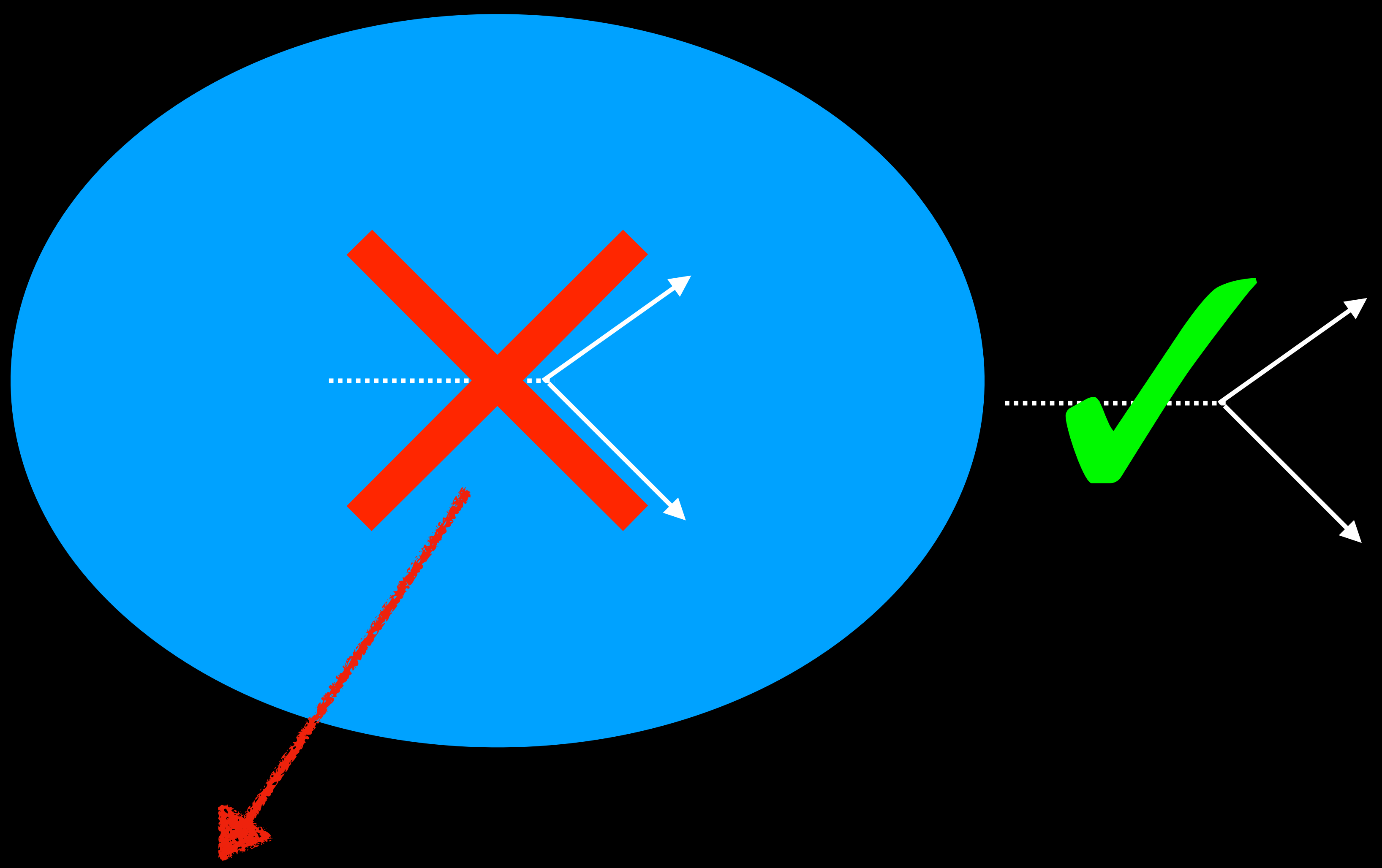
$$n_0 \sim N_Q H_0^3$$

**Simulations show** $N_Q \sim 10^3$ **gravity mediation and** $N_Q \sim \mathcal{O}(1)$ **for gauge mediation.** $Q_0$ **can be written in terms of the initial baryon asymmetry**

$$Q_0 = \frac{3 Y_{B_0} M_{\text{Pl}}^3}{800\sqrt{5}\pi^{5/2} g_* r T_0^3}$$

B(L) balls are usually long lived

- Gauge singlet (so no decay into gauge bosons)



Forbidden either kinematically or due to Pauli blocking

Decay rate has surface to volume ratio suppression

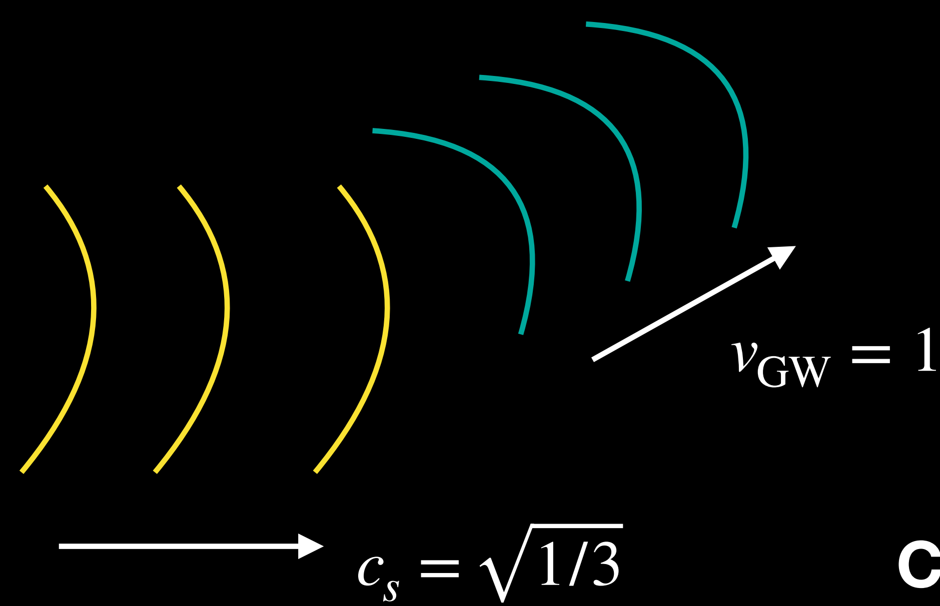
*Early period of matter domination followed by a sudden transition to radiation*

## Resonantly enhanced gravitational waves

**Initial power spectrum**

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

- **During matter domination perturbations grow**
- **The Q-balls decay faster than exponential**
- **Perturbations cannot melt away in this case but produce sound waves**




**Constructive interference**

## Specific scenario

**Choose gauge mediated scenario**

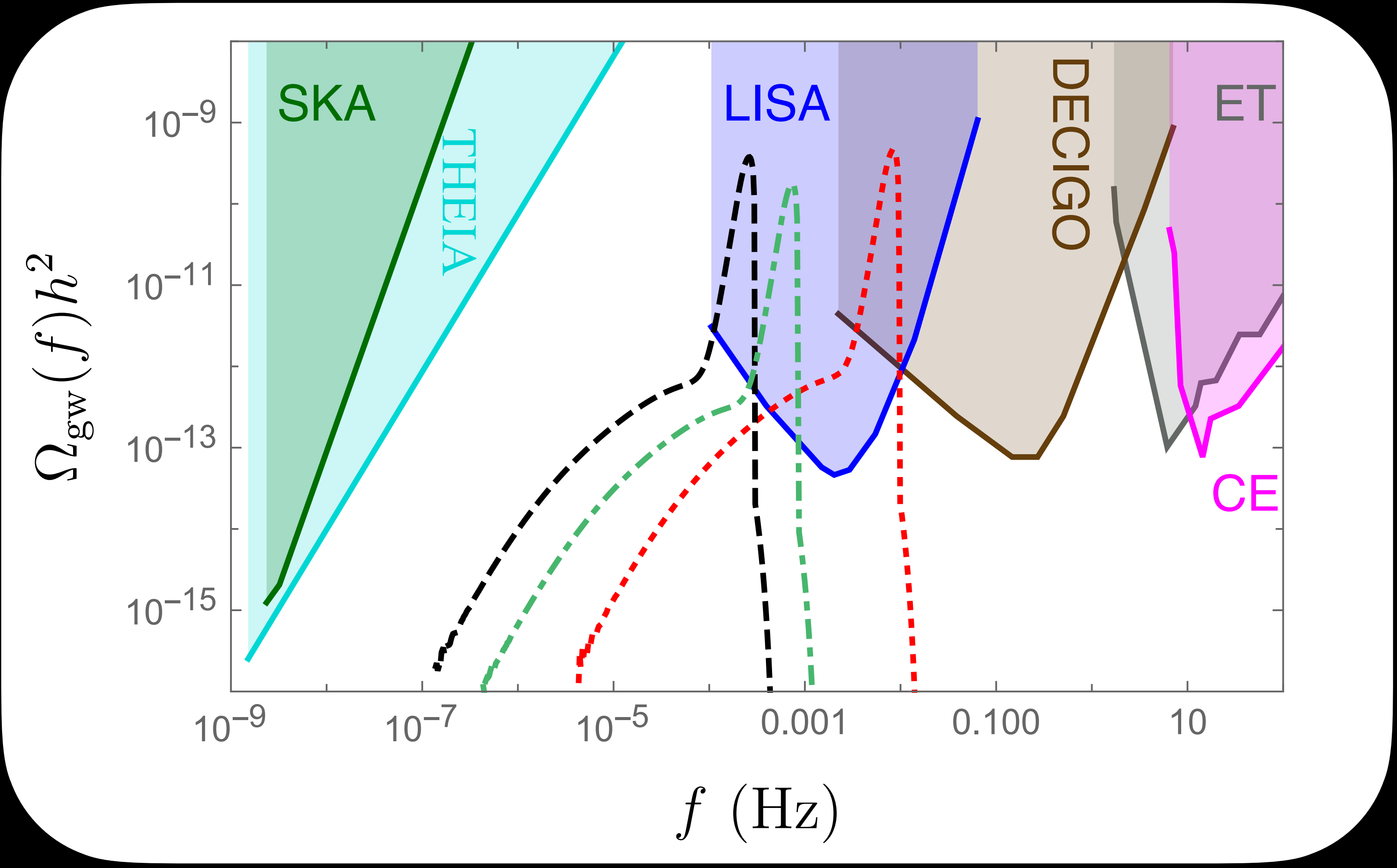
$$V(\Phi) = m^4 \log\left(1 + \frac{|\Phi|^2}{m^2}\right) + \frac{1}{\Lambda^2}|\Phi|^6$$

**With $\Lambda$ in between the inflaton and GUT scale and** $N_Q = 1000$

**Low reheating temperature motivated by gravitino problem(s)**

$$T_R \lesssim 10^7 \text{ GeV}$$

## Benchmarks $y = (y_e, y_\mu, y_b)$



**Comments about scan:**

1. **It is very common for Q-balls to be long lived enough to produce a period of matter domination**
2. **Frequently the matter domination lasts so long that we enter the non-linear regime**

**Distinguishing from other cosmological scenarios**

- Many causes of matter domination do not work as the transition to radiation domination is too slow to resonantly enhance the GWs

- Pbhs also have surface to volume ratio suppression in decay rate

- A possible method to distinguish is GWs is sensitive to the mass spectrum which could be quite different for PBHs and Q-balls

- Need detailed simulations and scans.

Summary part 2:

Affleck Dine Baryogenesis is an elegant paradigm explaining the matter-antimatter asymmetry

Very difficult to test

We argue it generically produces long lived Q-balls that leave a gravitational wave signature

There are limited cosmological scenarios that do this, and there might be methods to distinguish signals

Might be complimentary to other probes of Affleck Dine