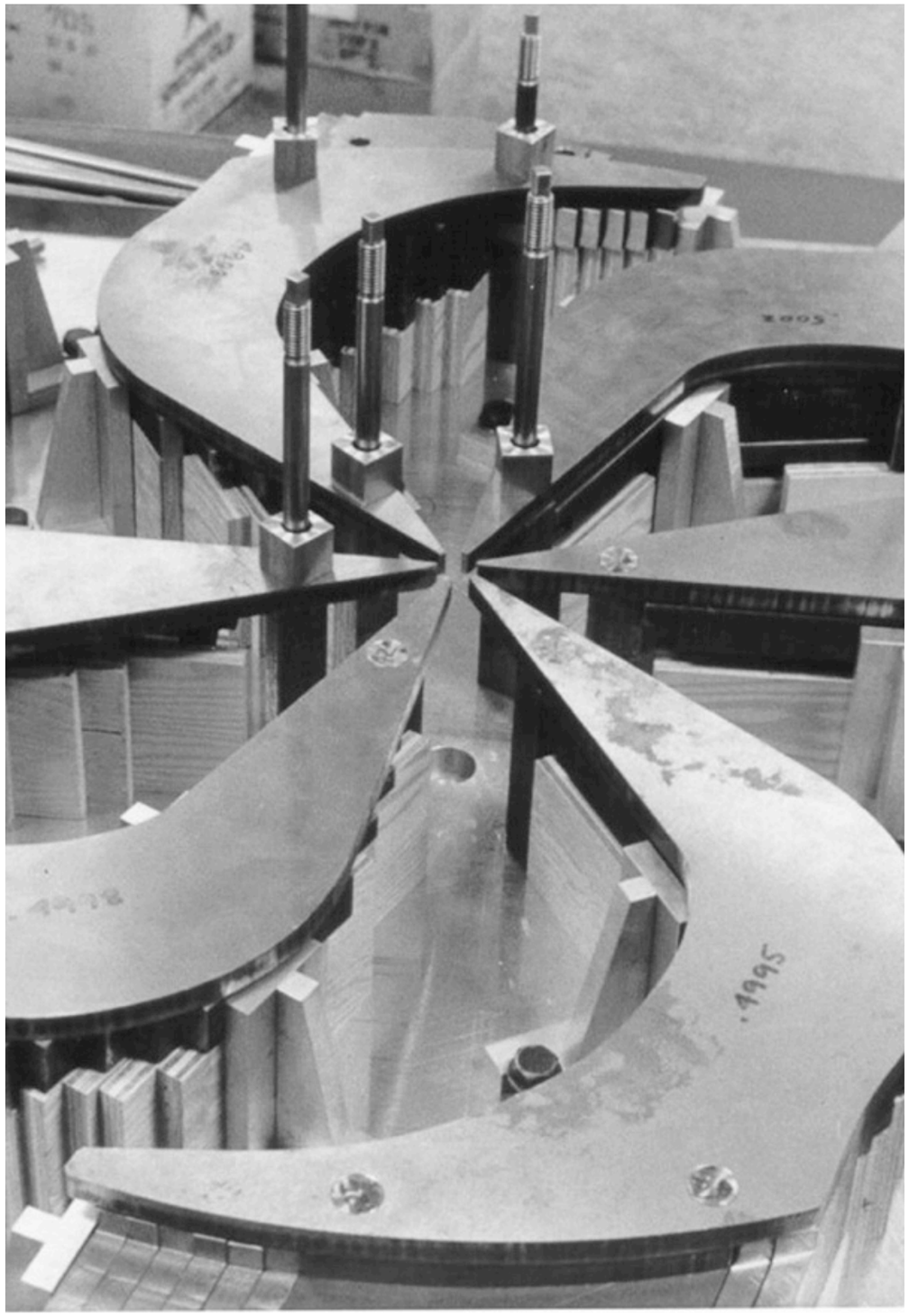
TRIUMF

The see saw mechanism: using cosmology to reach across a desert

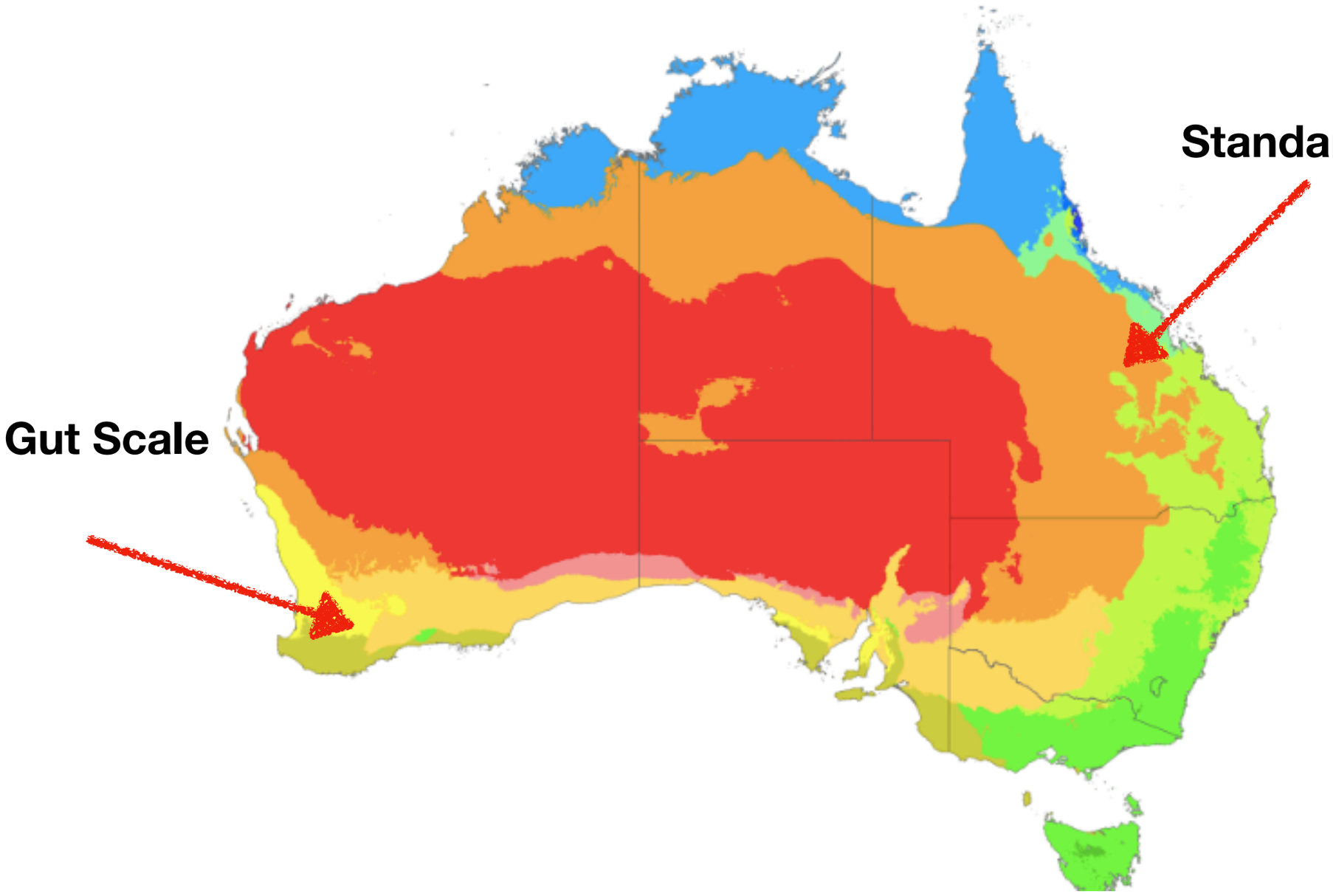
D. Croon, N Fernandez, D. Mckeen and G. White *JHEP 2019*

J. Dror, T. Hiramatsu, K. Kohri, H. Murayama and G. White *Physics review letters 2020*



Motivation

- **Nature sometimes produces big deserts**



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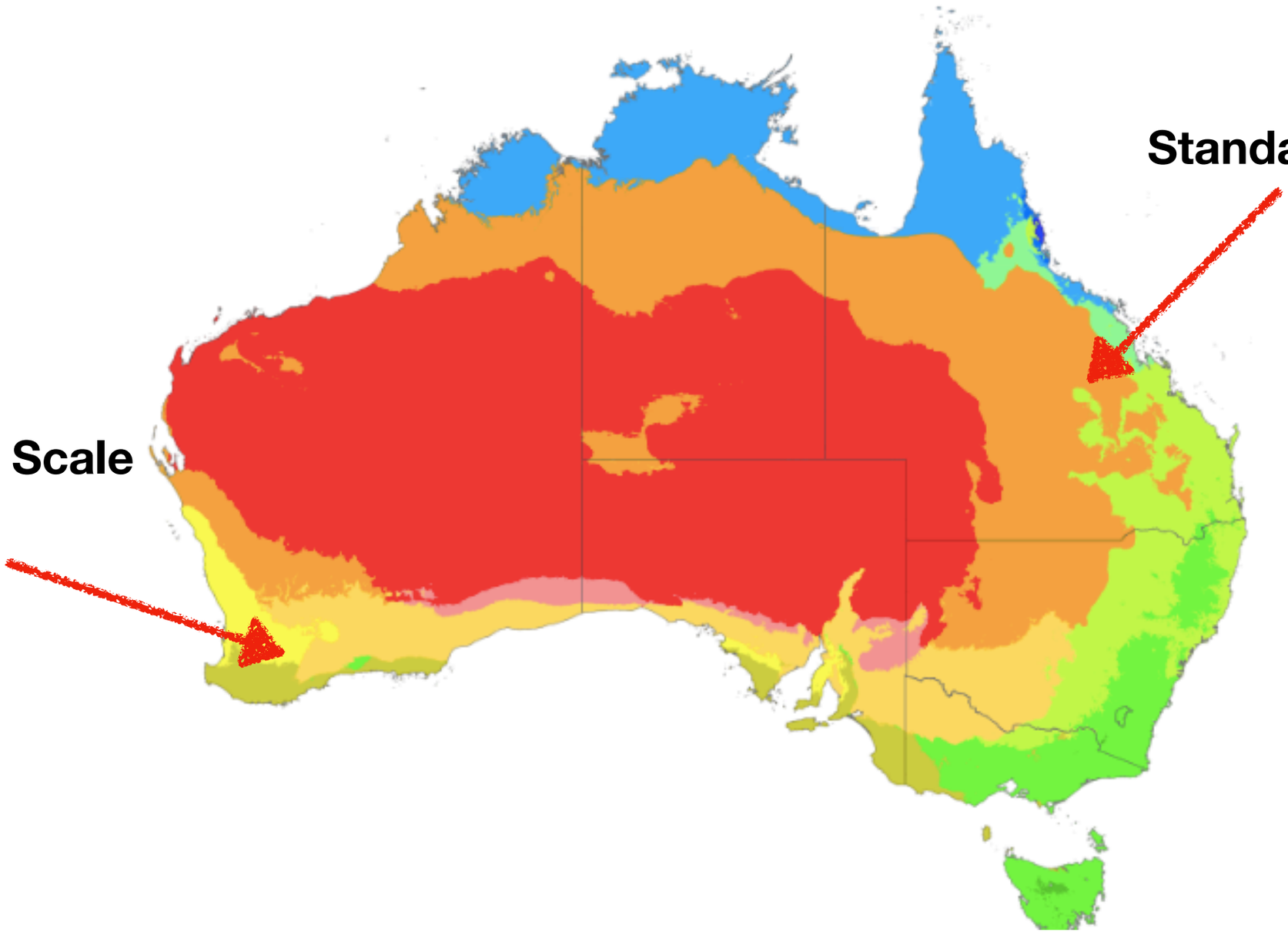

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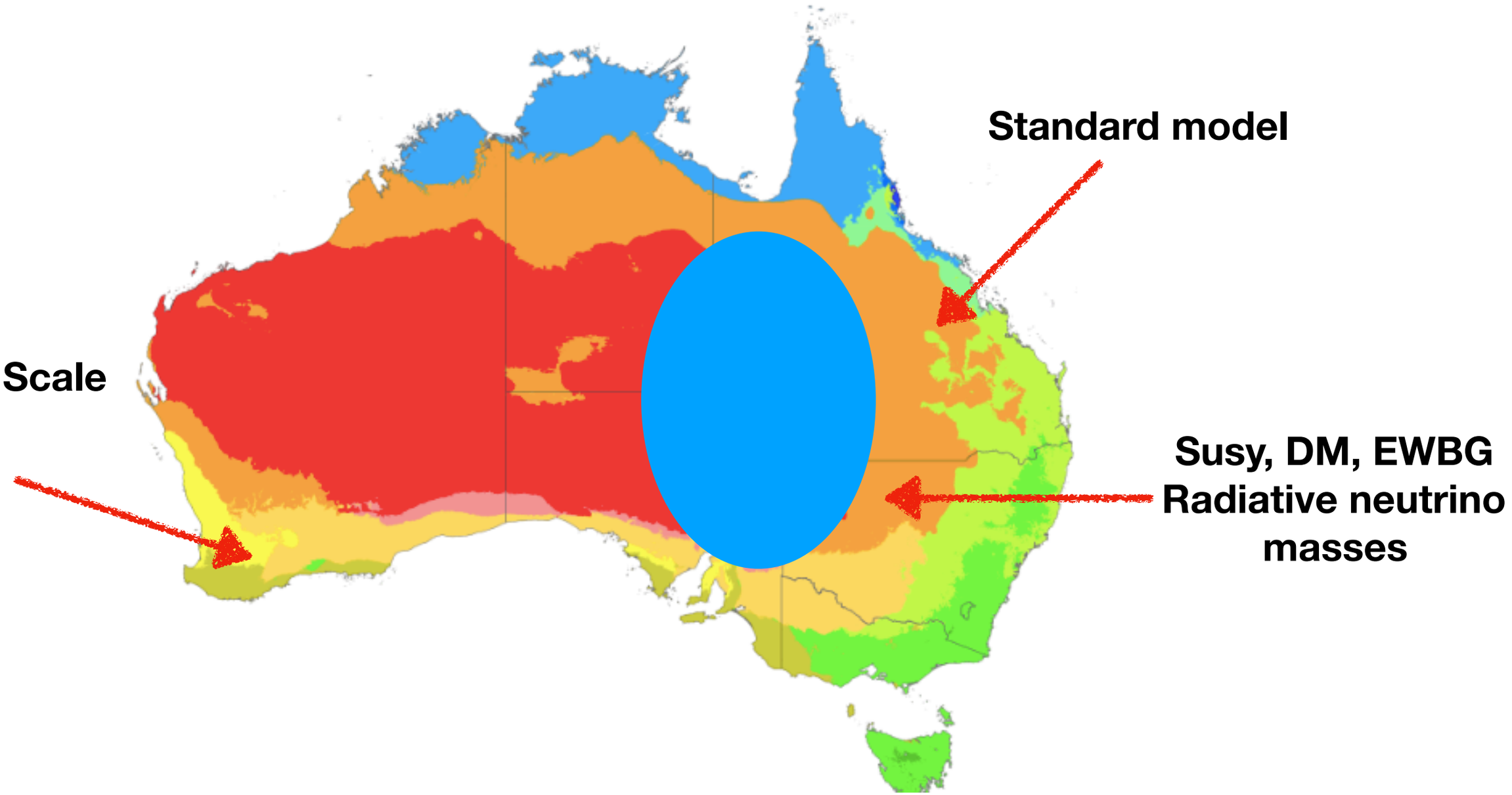

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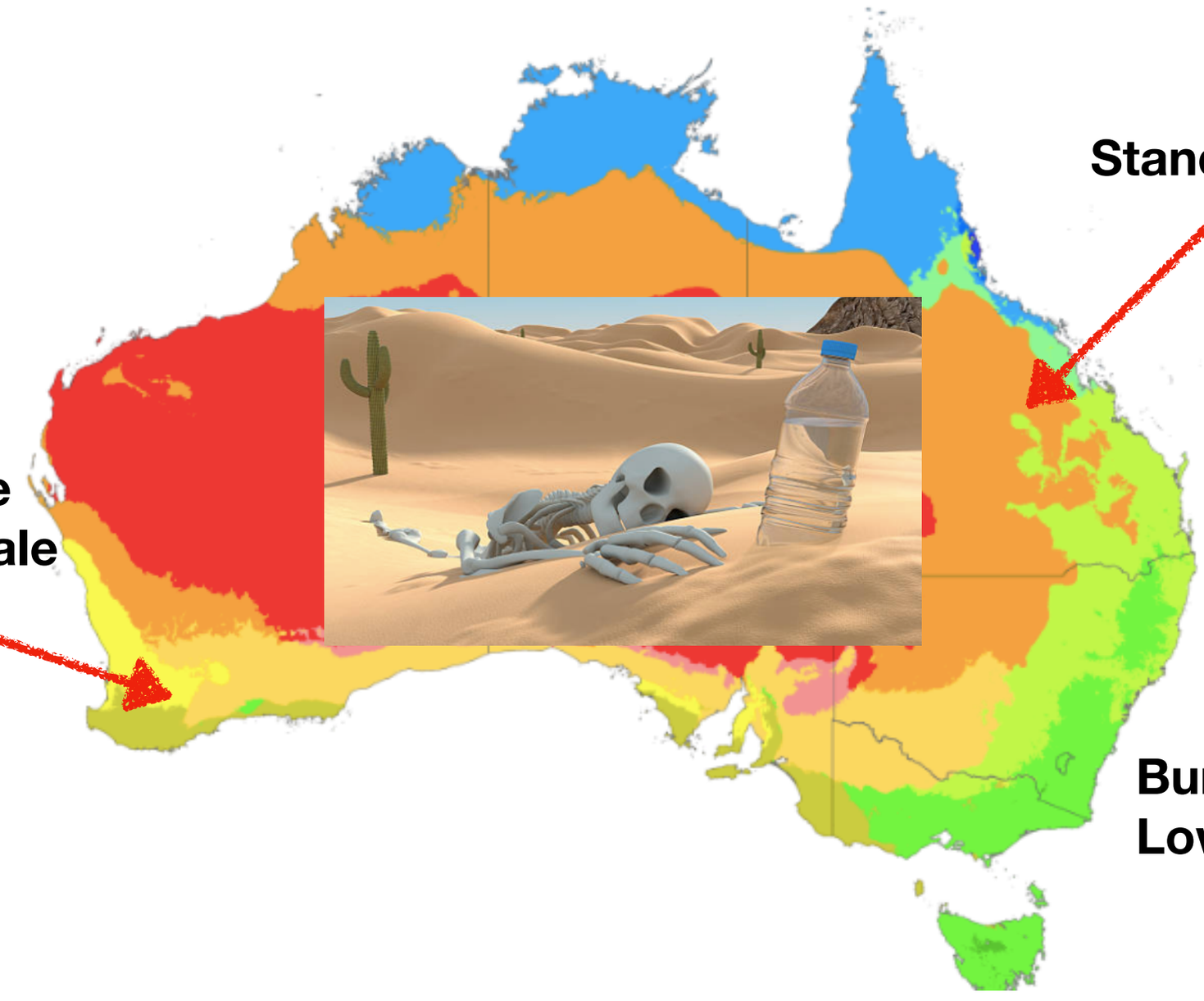

Standard model

Gut Scale
Seesaw scale

Burke and Wills
Low energy model builder?

Seesaw and leptogenesis

- **Seesaw and leptogenesis mechanism**

$$\Delta\mathscr{L} \sim -MNN \longleftrightarrow m_\nu \sim \frac{yv^2}{M}$$

Seesaw and leptogenesis

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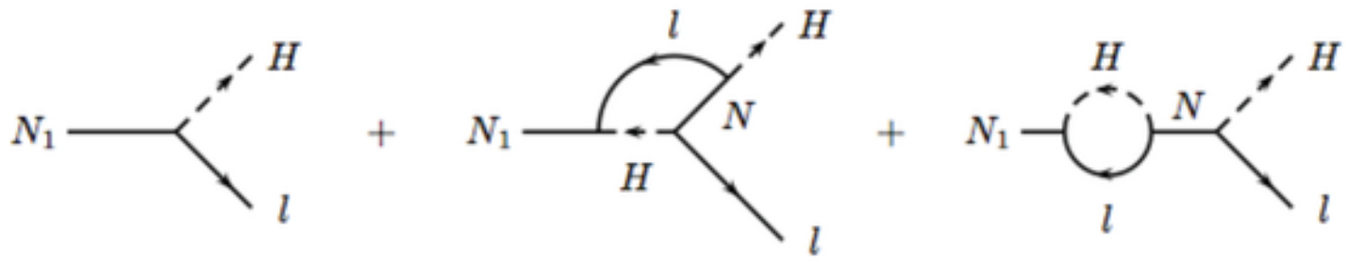
$$\Delta\mathscr{L} \sim -MNN \longleftrightarrow m_\nu \sim \frac{yv^2}{M}$$

Sterile term explicitly breaks L

CPV decays



Sphalerons convert L asymmetry into a baryon asymmetry

Thermal leptogenesis requires $M_1 \gtrsim 10^9$ GeV

Worse…$M_1 \gtrsim 10^{11}$ in the minimal scenario!

Seesaw and leptogenesis

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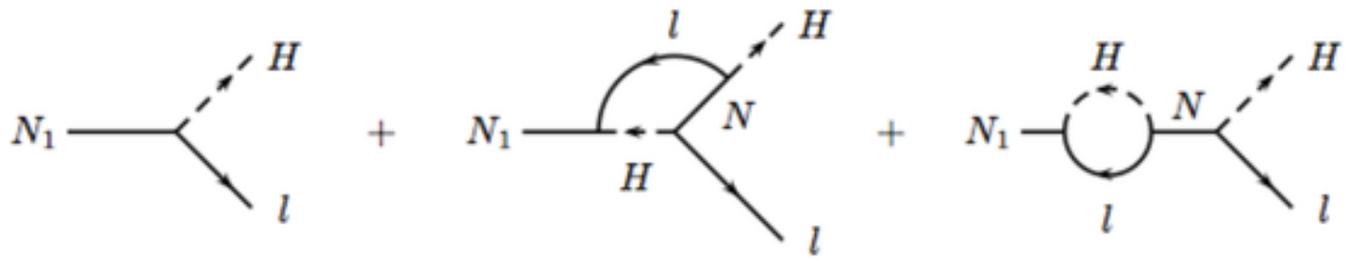

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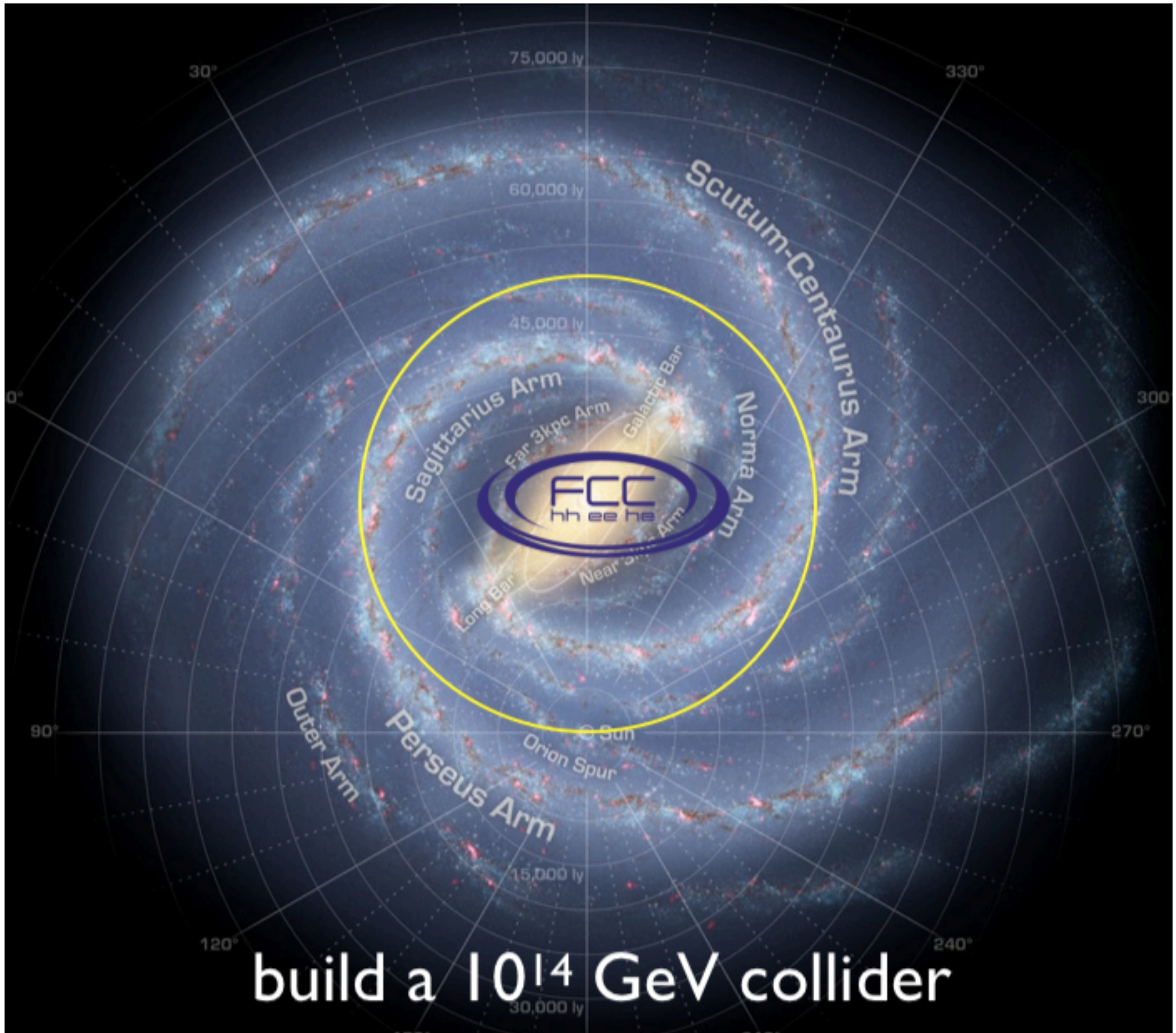
Seesaw and leptogenesis



Seesaw and archaeology

Can we do indirect tests?

$0\nu\beta\beta$ **decay is a known tool**

Can cosmology be an additional tool?

Seesaw and gravitational waves

Two options:

1. **Bare Minimal - Steriles just exist and nothing else exists but the inflaton (ignore DM)**
2. **B-L is spontaneously broken as part of a larger GUT breaking pattern**

Cosmology can indirectly test both cases!

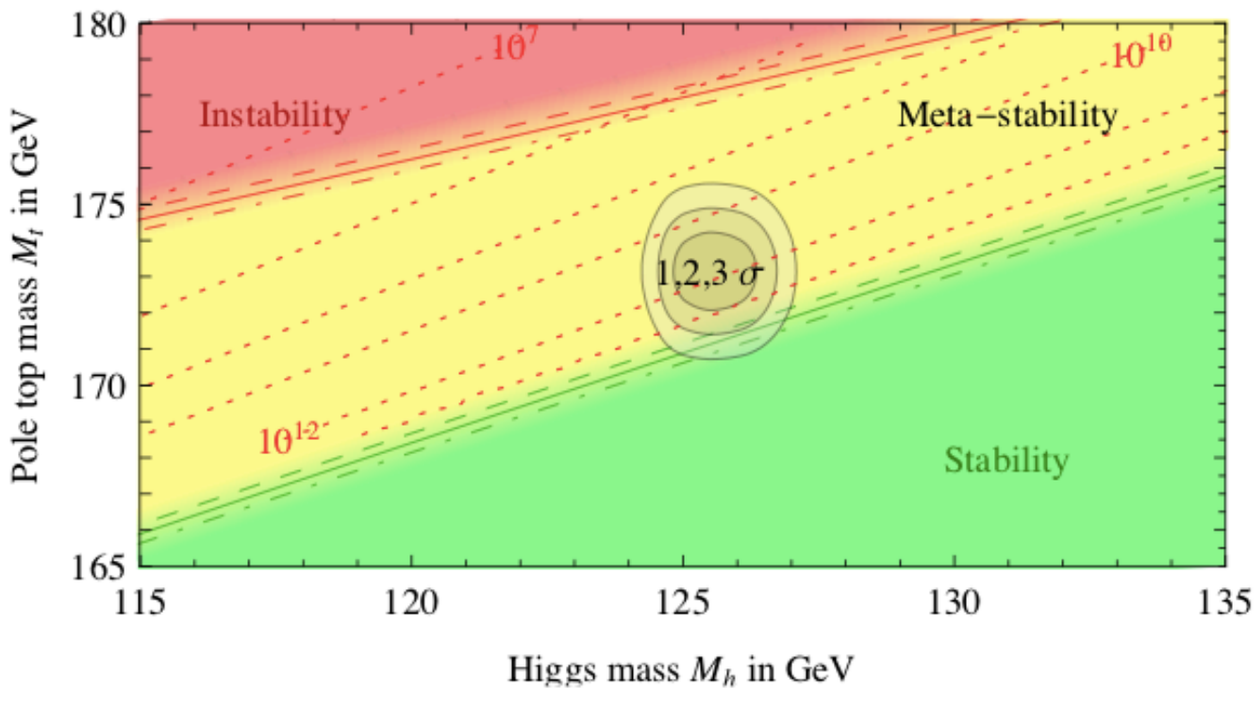
Cosmology and minimal seesaw

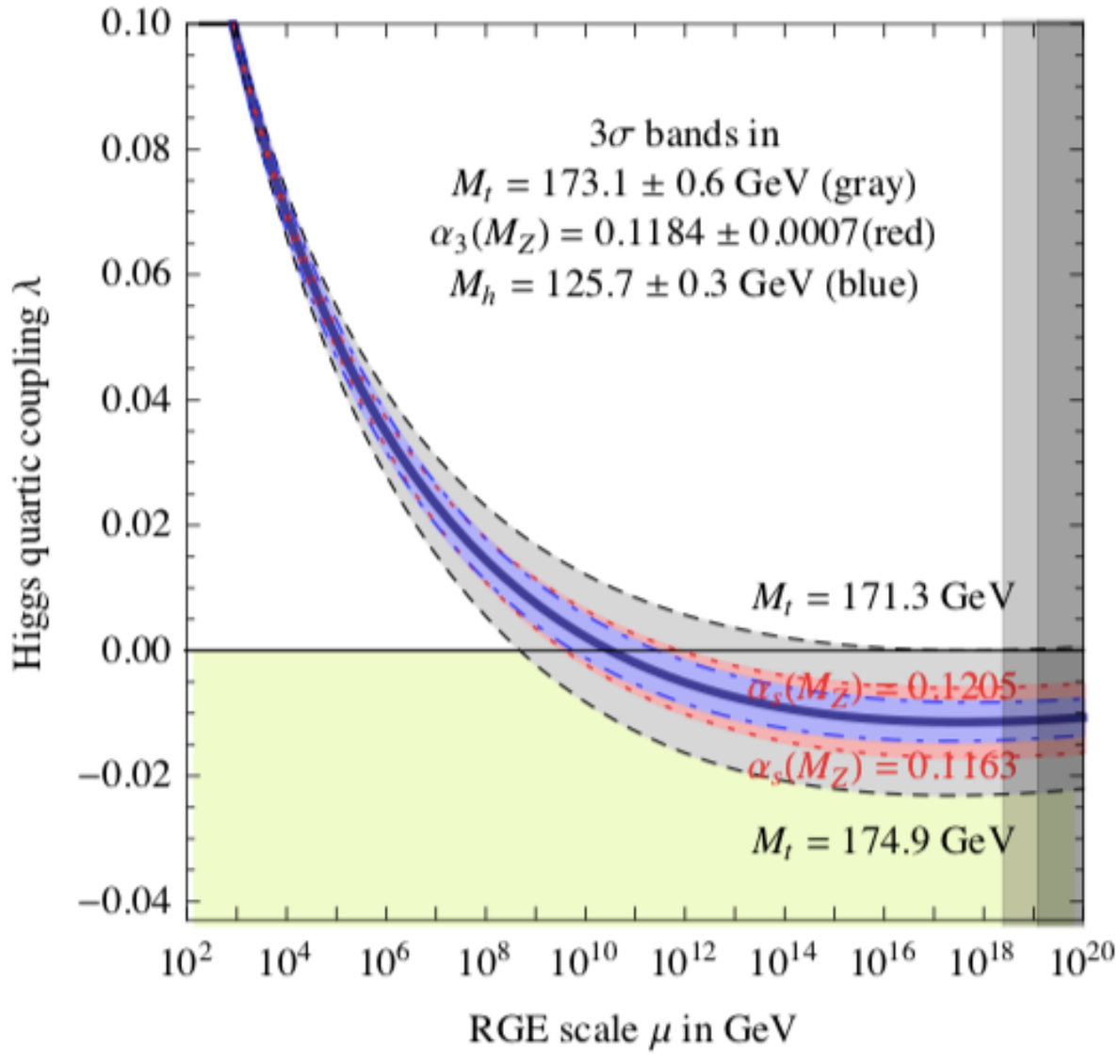
1st case seems the nightmare scenario.

But we still have a handle in vacuum stability and Planck data!

Cosmology and minimal seesaw

$$V = -\frac{\mu^2(h)}{2}h^2 + \frac{\lambda(h)}{4}h^4$$





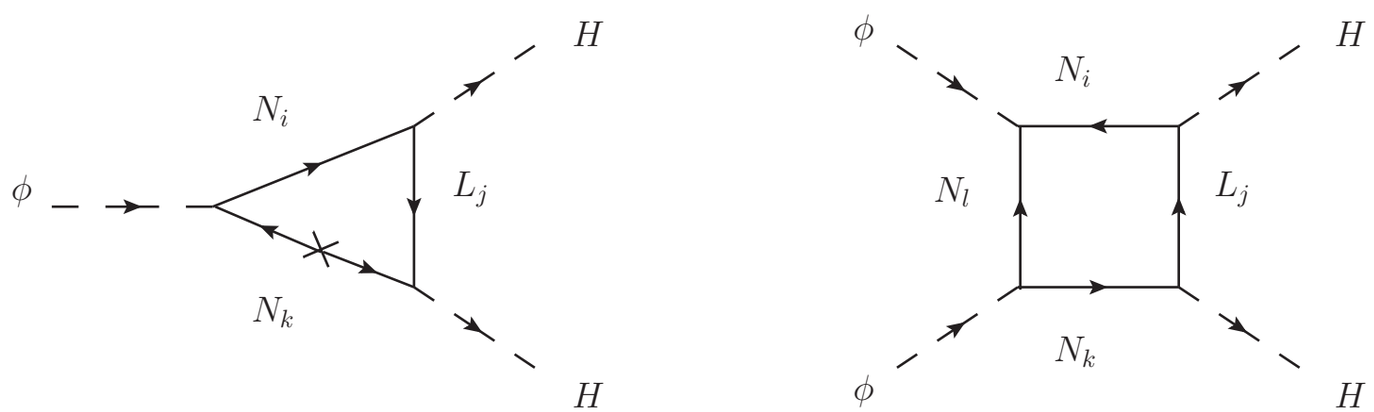
Degrassi et al 2012

Cosmology and minimal seesaw

$$\mathscr{L} = \mathscr{L}_{\rm SM} - \sum (M_{ij} + \lambda_{ij}\phi) N_i^c N_j - m^2\phi^2 - \sigma\phi\,|H|^2 - g\phi^2\,|H|^2$$

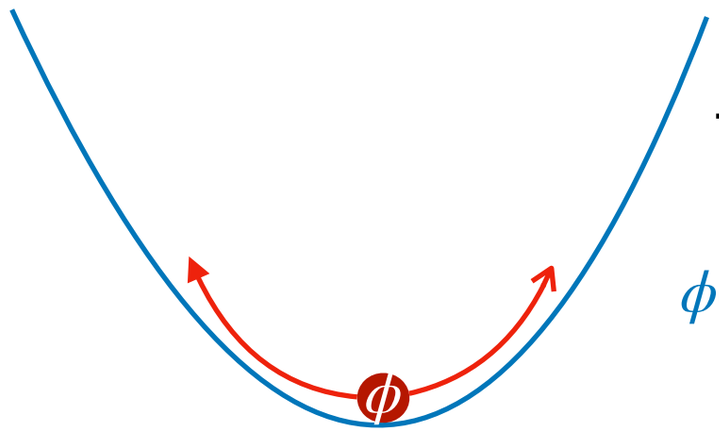
Effective mass at the end of inflation

Radiatively induced



Cosmology and minimal seesaw

Oscillation of ϕ at the end of inflation



Catastrophic production of Higgs!

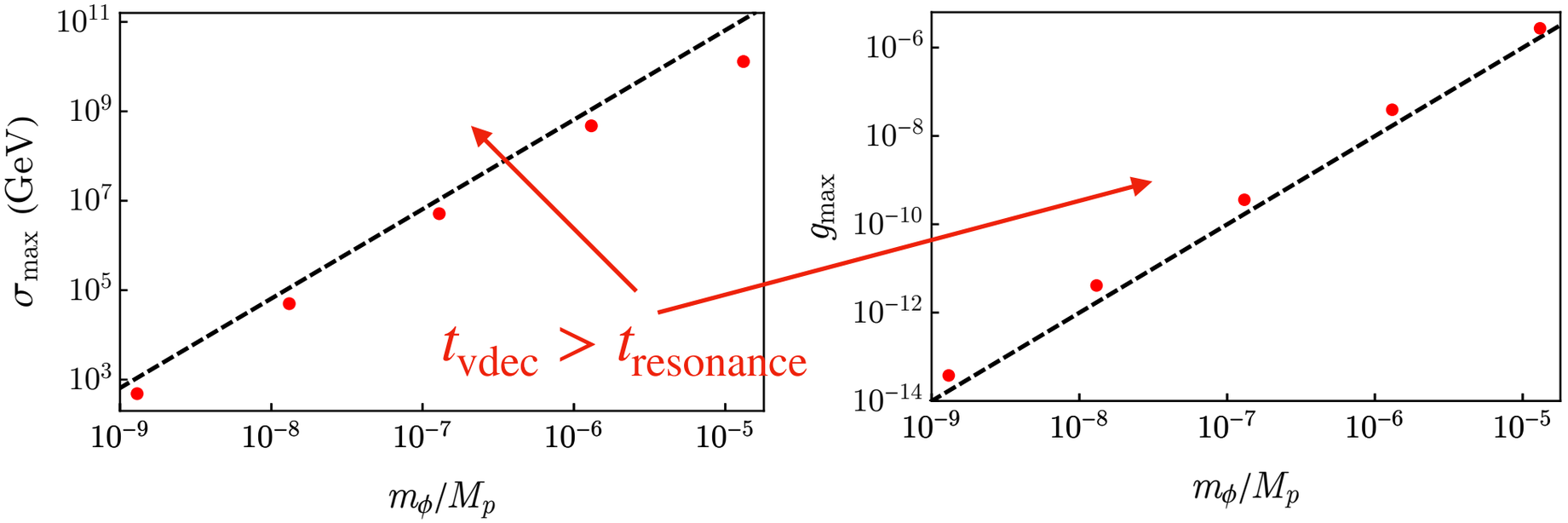
$$\phi(t) \sim \frac{\Phi}{m_\phi t}\cos m_\phi t \qquad \mu = \sqrt{\langle h^2 \rangle}$$

Tachyonic resonance lasts for a time $t_{\rm res} \sim \sqrt{\frac{g}{6\pi}}\frac{M_{\rm pl}}{m_\phi^2}$

Time scale for $\sqrt{\langle h^2 \rangle} > 10^{10}\ {\rm GeV} \rightarrow t_{vdec} \propto \frac{1}{m_\phi}$

See also Enqvist et al 1608.08848

Cosmology and minimal seesaw



Ultra-conservative scenario - ϕ only couples to first generation steriles

$$\left|\delta\sigma\right| \simeq \frac{\lambda}{2\pi^2}(Y^\dagger Y)_{11} M_1 \log\frac{M_{\rm Pl}}{m_\phi} \qquad \left|\delta g\right| \simeq \frac{\lambda^2}{2\pi^2}(Y^\dagger Y)_{11} \log\frac{M_{\rm Pl}}{m_\phi}$$

Cosmology and minimal seesaw

$$\frac{dn_{B-L}}{dt} + 3Hn_{B-L} = \frac{\epsilon_1 \Gamma_{N_1}}{M_i}\left(\rho_{N_1} - \rho_{N_1}^{\rm eq}\right) - W n_{B-L}\,.$$

$$\epsilon_1 = \frac{3\,{\rm Im}\left[(Y^\dagger Y)^2_{21}\right]}{16\pi (Y^\dagger Y)_{11}} f\left(\frac{M_2^2}{M_1^2}\right),$$

$$(Y^\dagger Y)_{ij} = \frac{\sqrt{M_i M_j}}{v}\left(\frac{m_3}{v} R^*_{i3} R_{j3} + \frac{m_2}{v} R^*_{i2} R_{j2}\right)$$

$$\epsilon_1 \simeq \frac{3}{16\pi}\frac{M_1 m_3}{v^2}\sin 2\beta\left[1 + \frac{5M_1^3}{9M_2^3} + \mathcal{O}\left(\frac{M_1^5}{M_2^5}\right)\right] \simeq 10^{-5}\sin 2\beta\left(\frac{M_1}{10^{11}\ {\rm GeV}}\right)$$

$$\eta_B \sim 10^{-2}\epsilon_1 \kappa_f \qquad\qquad \kappa_f \leq (2\pm 1)\times 10^{-2}\left(\frac{0.01\ {\rm eV}}{0.0086\ {\rm eV}}\right)^{1.1}$$

$$M_1 \gtrsim (10^{10} - 10^{11})$$

Cosmology and minimal seesaw

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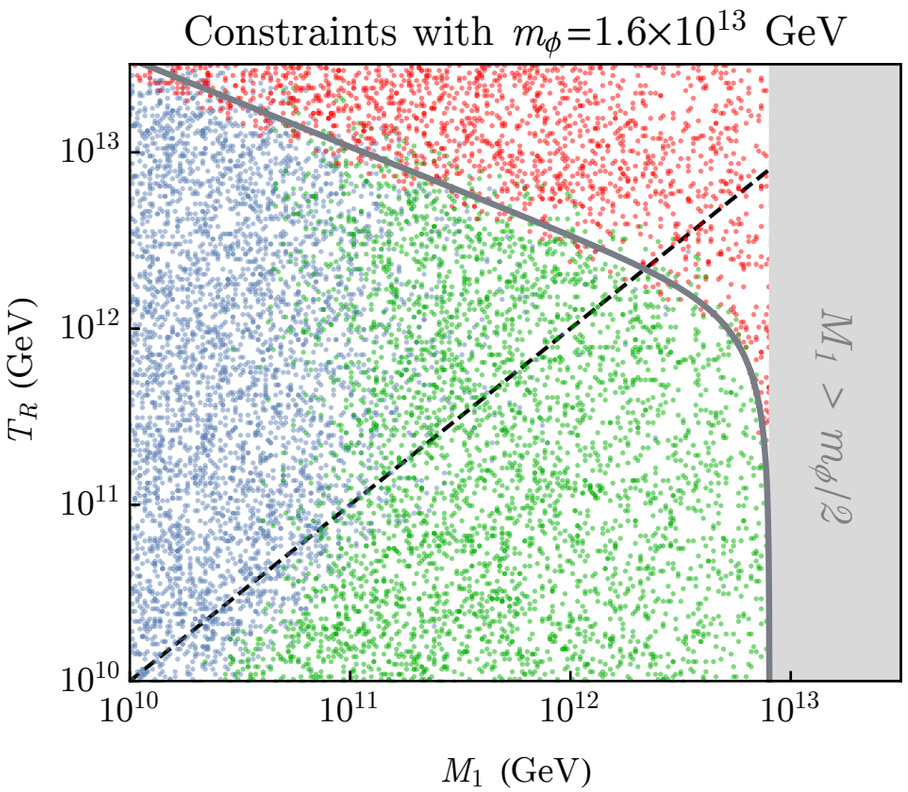
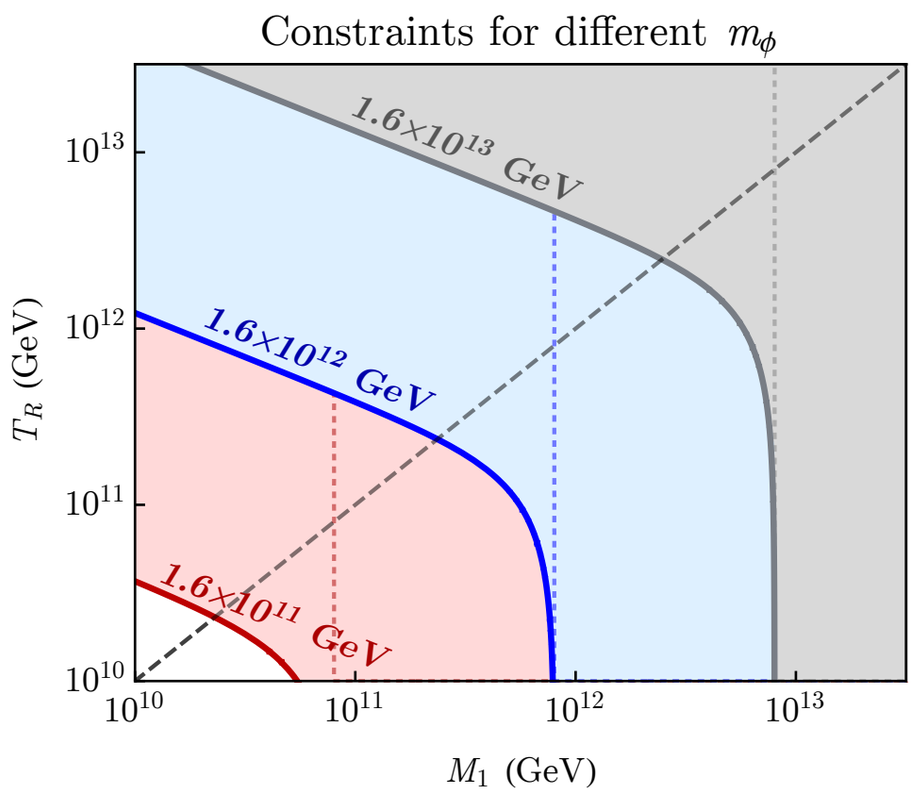




Cosmology and minimal seesaw

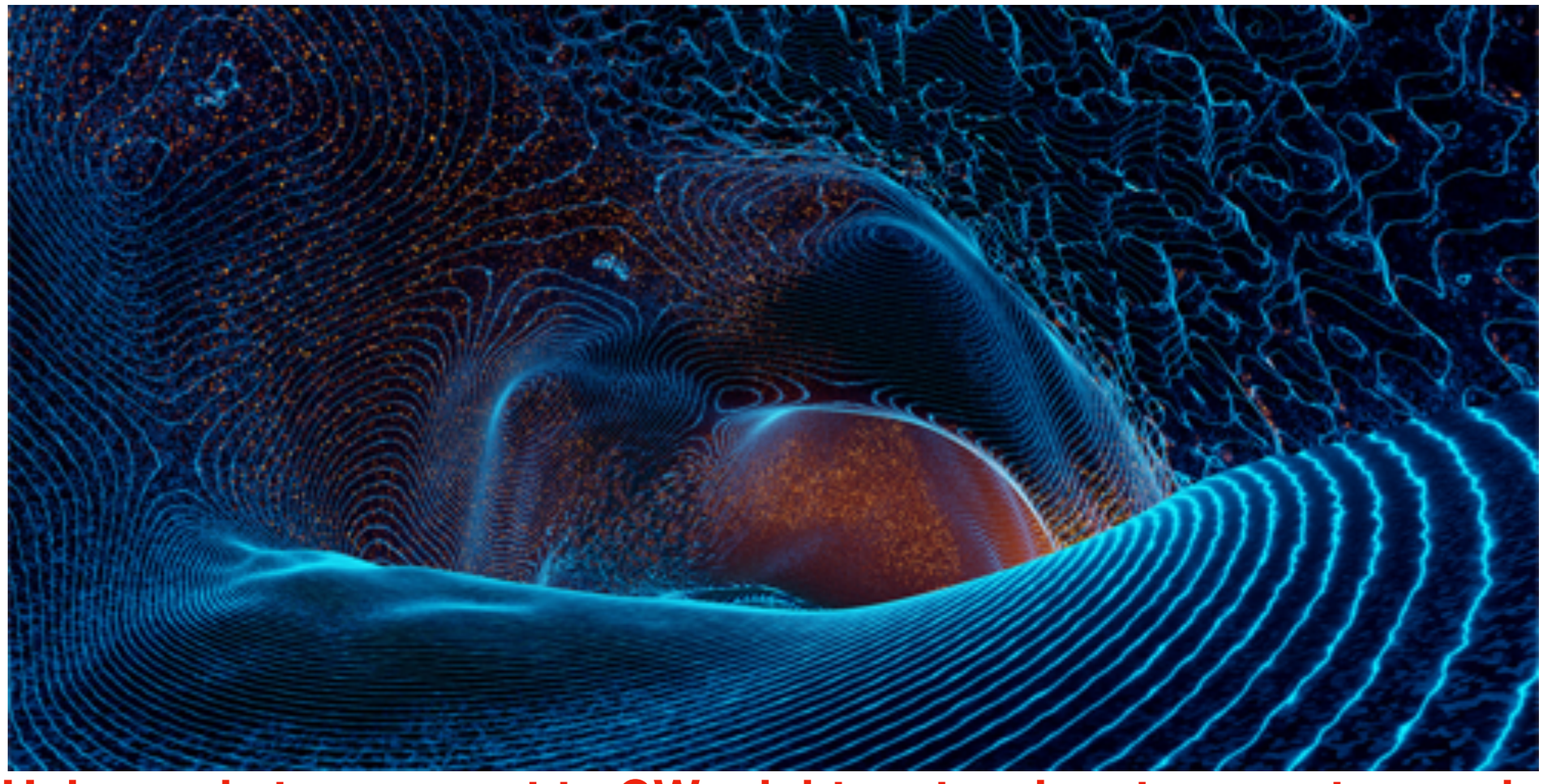
Can test minimal see-saw through

1. **Precise measurements of m_t and m_h**
2. **Precise measurements/bounds of n_s and r**

Seesaw and gravitational waves

What about the 2nd scenario where $B-L$ is spontaneously broken?

Can Gravitational waves be a tool?



Universe is transparent to GWs right up to when temperatures where seesaw scale!

Seesaw and gravitational waves

What about the 2nd scenario where $B-L$ is spontaneously broken?

Can Gravitational waves be a tool?

1. **Bubble collision, turbulence and acoustic contributions during a 1st order PT**
2. **Textures during a 2nd order phase transition**
3. **Cosmic strings**

All can be in principle generated during a B-L breaking transition
That generates MNN

Seesaw and gravitational waves

- **Phase transitions only visible with large amount of supercooling** ✗
- **Local textures are high frequency spectra** ✗
- **Strings give a scale invariant spectra** ✓

Seesaw and gravitational waves

Can categorize symmetry breaking patterns by the homotopy group of the vacuum manifold:

1. $\pi_0(\mathscr{M}) \neq 1 \rightarrow$ Domain Wall
2. $\pi_1(\mathscr{M}) \neq 1 \rightarrow$ String
3. $\pi_2(\mathscr{M}) \neq 1 \rightarrow$ Monopole
4. $\pi_3(\mathscr{M}) \neq 1 \rightarrow$ Texture

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$\mathscr{M}$ **disconnected**

$\mathscr{M}$ **not simply connected**

$\mathscr{M}$ **topologically equivalent to a circle**

$\mathscr{M}$ **topologically equivalent to a 3 sphere**

Seesaw and gravitational waves

- **Minimalist approach: gauge groups at most rank 5, non-anomalous with only N and SM fermions**
- **Insist inflation happens in any path after monopoles**

$G_{\rm disc} = G_{\rm sm} \times \mathbb{Z}_N$

$G_{B-L} = G_{\rm sm} \times U(1)_{B-L}$

$G_{LR} = SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$G_{421} = SU(4)_{PS} \times SU(2)_L \times U(1)_Y$

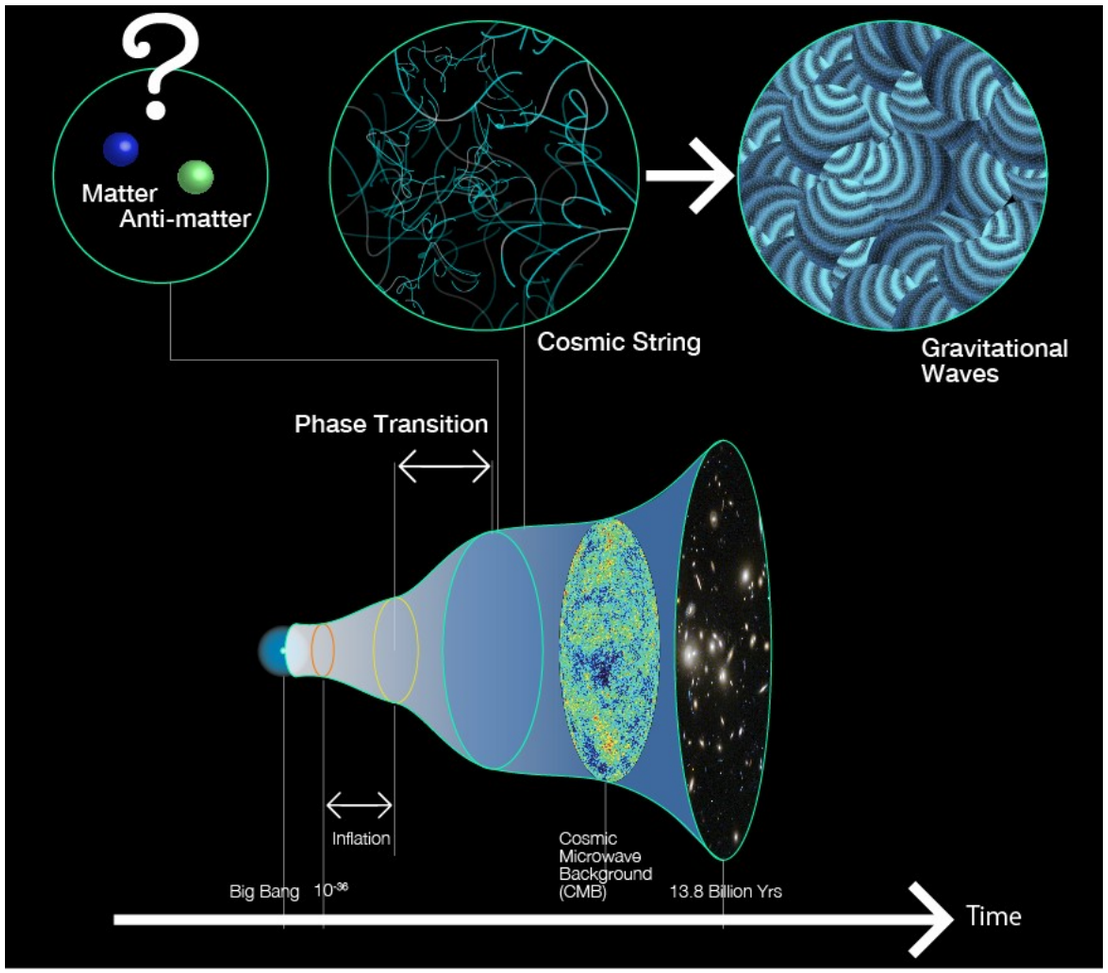
$G_{\rm flip} = SU(5) \times U(1)$

	$\langle\phi\phi\rangle v_R v_R/M_{Pl}$		$\langle\phi\rangle v_R v_R$	
	$H = G_{\rm SM}$		$H = G_{\rm SM} \times \mathbb{Z}_2$	
G	**defects**	**Higgs**	**defects**	**Higgs**
$G_{\rm disc}$	domain wall*	$B-L=1$	domain wall*	$B-L=2$
G_{B-L}	abelian string*	$B-L=1$	$\mathbb{Z}_2$ string†	$B-L=2$
G_{LR}	texture*	$(\mathbf{1},\mathbf{1},\mathbf{2},\frac{1}{2})$	$\mathbb{Z}_2$ string	$(\mathbf{1},\mathbf{1},\mathbf{3},1)$
G_{421}	none	$(\mathbf{10},\mathbf{1},2)$	$\mathbb{Z}_2$ string	$(\mathbf{15},\mathbf{1},2)$
$G_{\rm flip}$	none	$(\mathbf{10},1)$	$\mathbb{Z}_2$ string	$(\mathbf{50},2)$

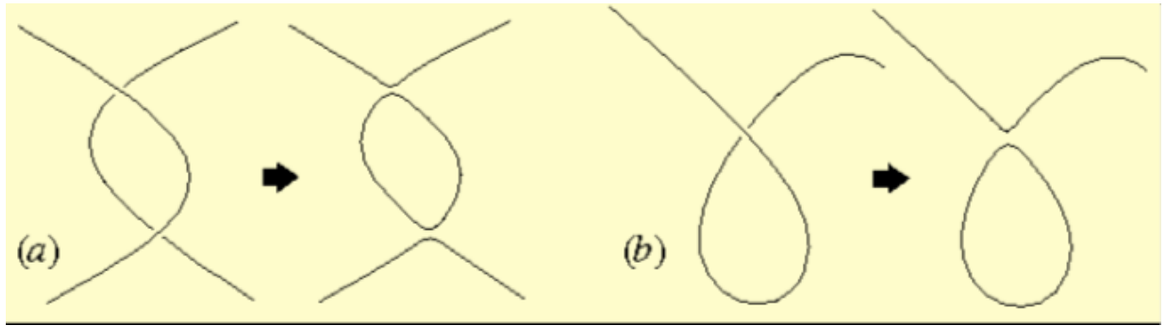
Z_2 matter parity: flips signs of all fermions

- **Cosmic string network production is generic!**

Seesaw and gravitational waves



Cosmic network tries to simplify producing GWs



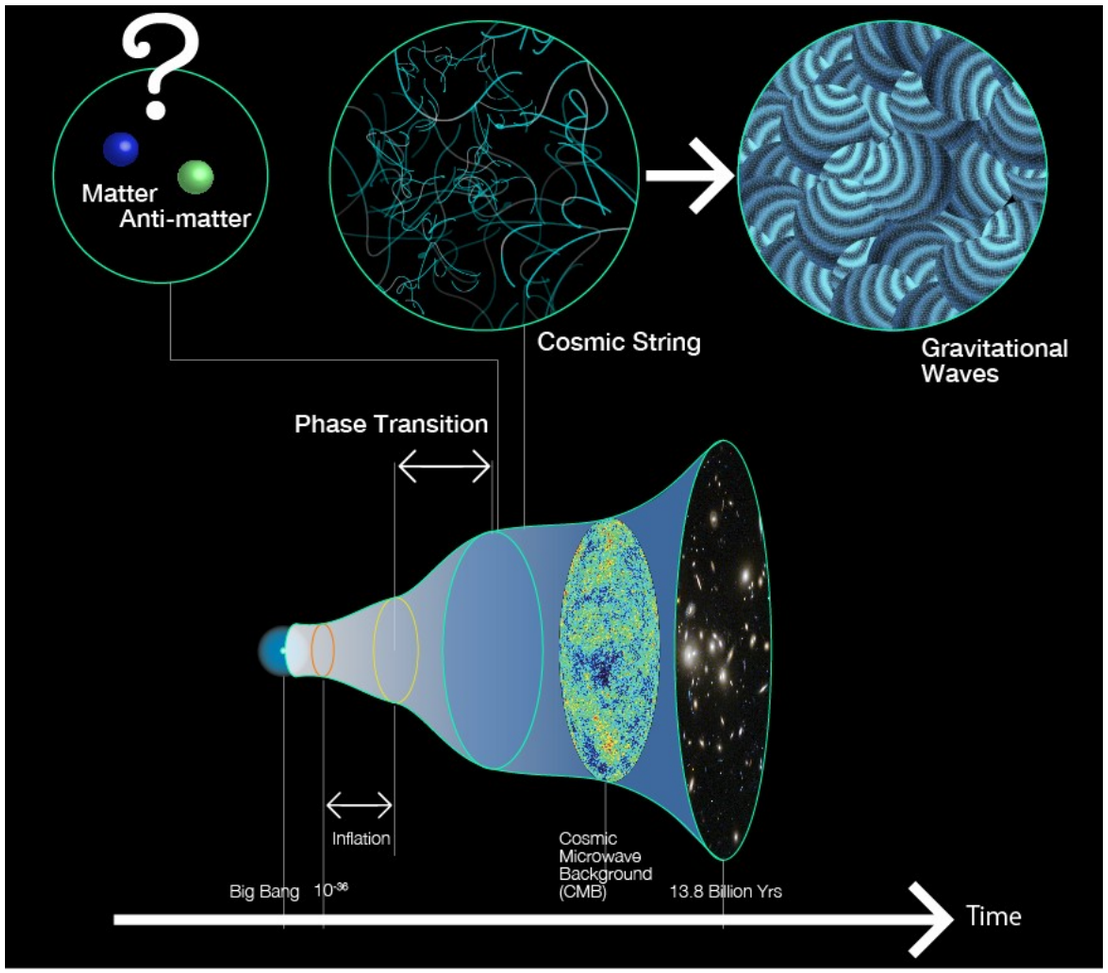
Loop formed at time $l_i = \alpha t_i$

Assume large loops that peak at a given α

Strings enter a scaling regime at some time τ_f

String tension is given by symmetry breaking scale $\mu \sim v^2$

Seesaw and gravitational waves



$$\Omega_{\rm GW} = \sum_{k=1}^{\infty} \Omega_{\rm GW}^{(k)}(f)$$

$$\Omega_{\rm GW}^{(k)} = \Omega_0^{(k)}(f) \int_1^{\tau_0} d\tau \frac{C_{\rm eff}(\tau_i)}{\tau_i^4} \frac{a^2(\tau) a^3(\tau_i)}{a_0^5} \Theta(\tau_i - \tau_F)$$

$$\Omega_0^{(k)}(f) = \frac{1}{\rho_c} \frac{2k}{2f} \frac{\mathcal{F}_\alpha \Gamma^{(k)} G\mu^2}{\alpha^2 t_F^3}$$

~energy emitted per mode

String tension is given by symmetry breaking scale $\mu \sim v^2$

Caveats

Caveat 1: String cutting

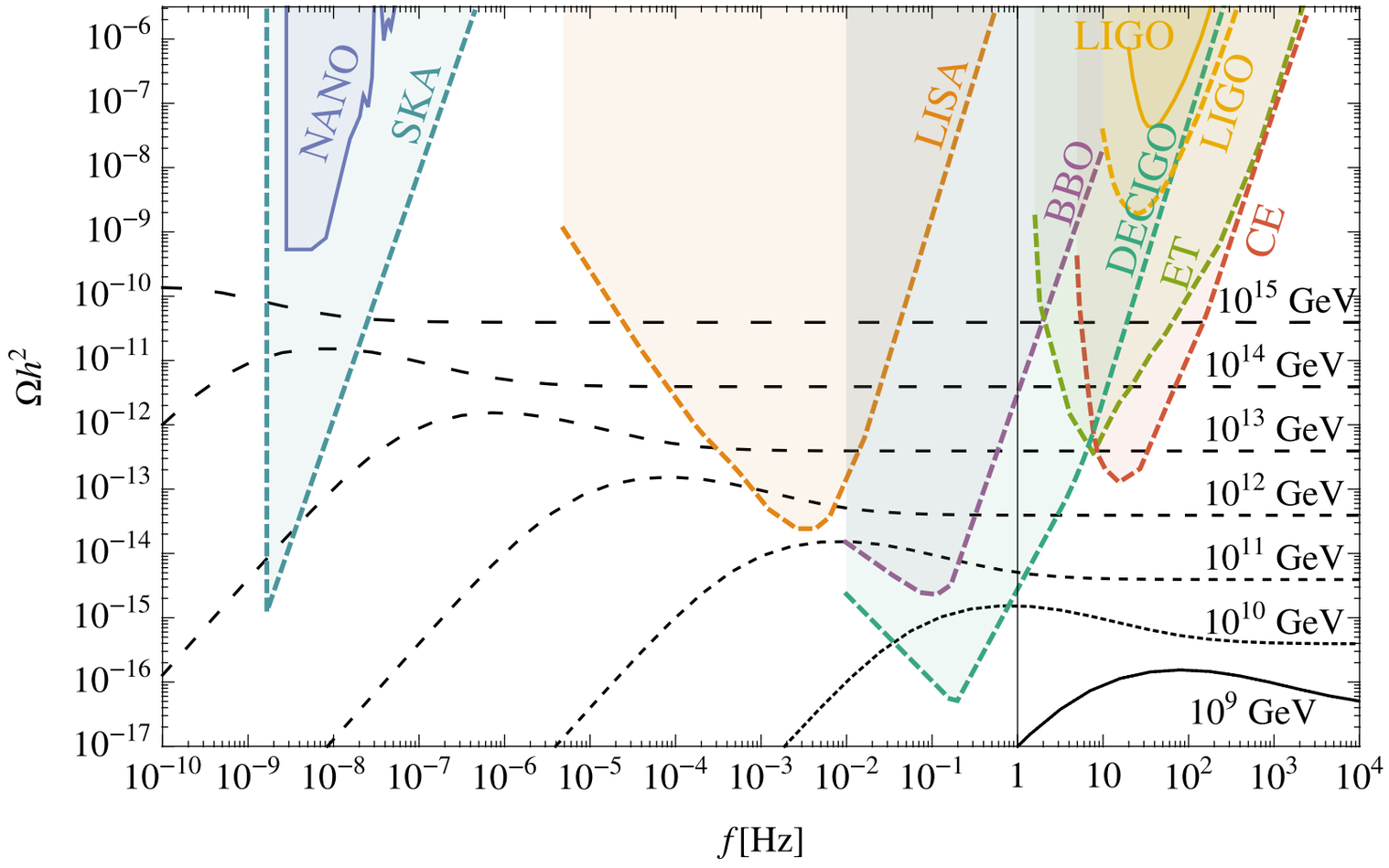
Tunnelling process

Caveat 2: Field theoretic simulations contradict other simulations

Needs to be understood!

Results

Results: Full parameter space for thermal leptogenesis can be explored!

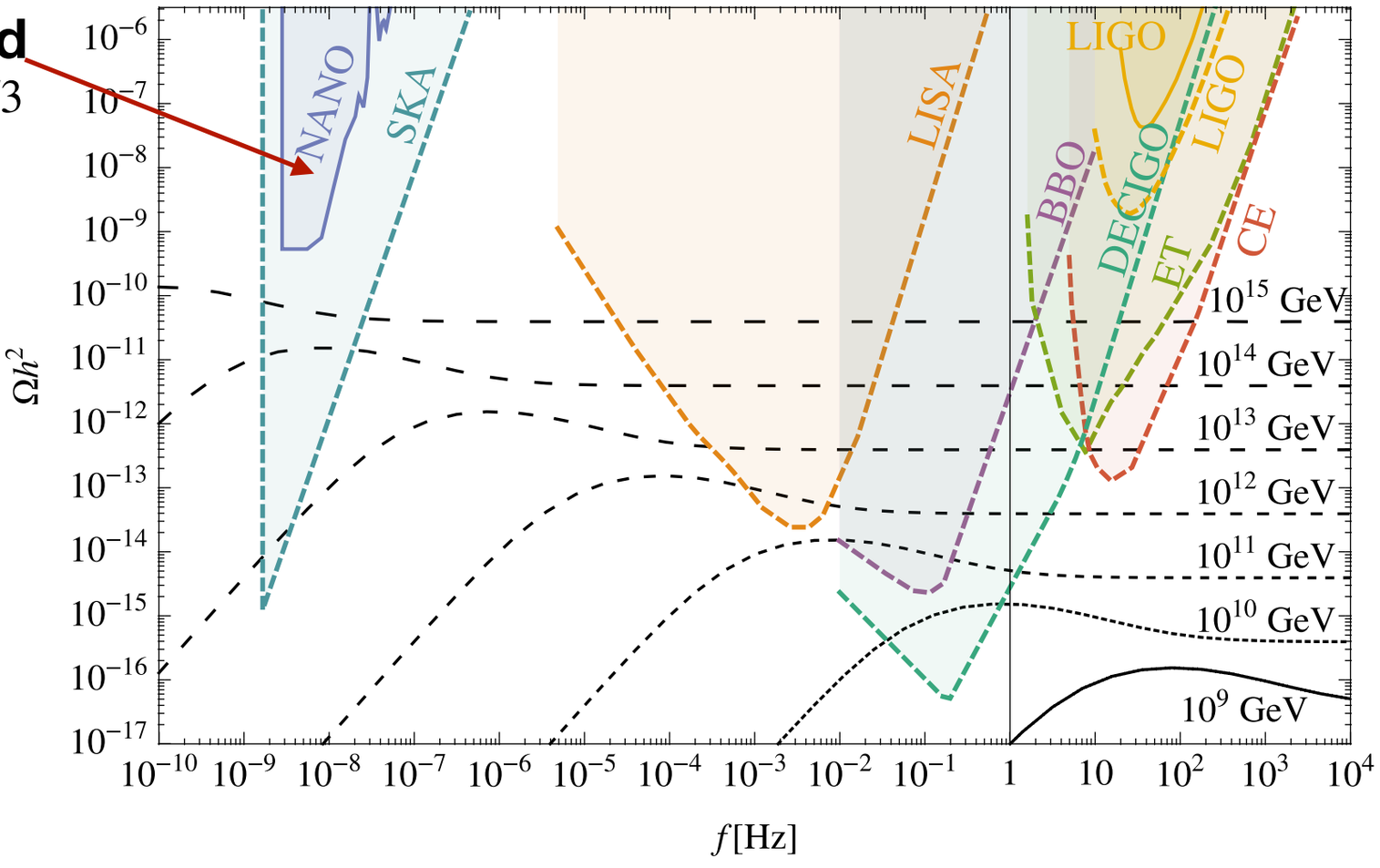


Using correlations between neighbouring bins Nano-Grav already constrains high scale leptogenesis!

Results

Results: Full parameter space for thermal leptogenesis can be explored!

SMBH background goes as $f^{2/3}$



Conclusions

Stochastic GW a way of testing seesaw

For Rank ≤ 5 gauge groups more than half of the symmetry breaking paths produce observable GWs

Future detectors probe nearly the entire parameter space relevant for seesaw!

Conclusions

Seesaw is the most convincing explanation for light neutrino masses and the baryon asymmetry

Cosmology allows us to see the unseeable

Indirect measurements from GW detection, to top/higgs mass measurements to Planck constraints on CMB observables could be a way of testing this paradigm ***(see also Ipek et al arXiv:1806.00460)***