Implications of a new SU(2) flavour group in early-universe phase transitions

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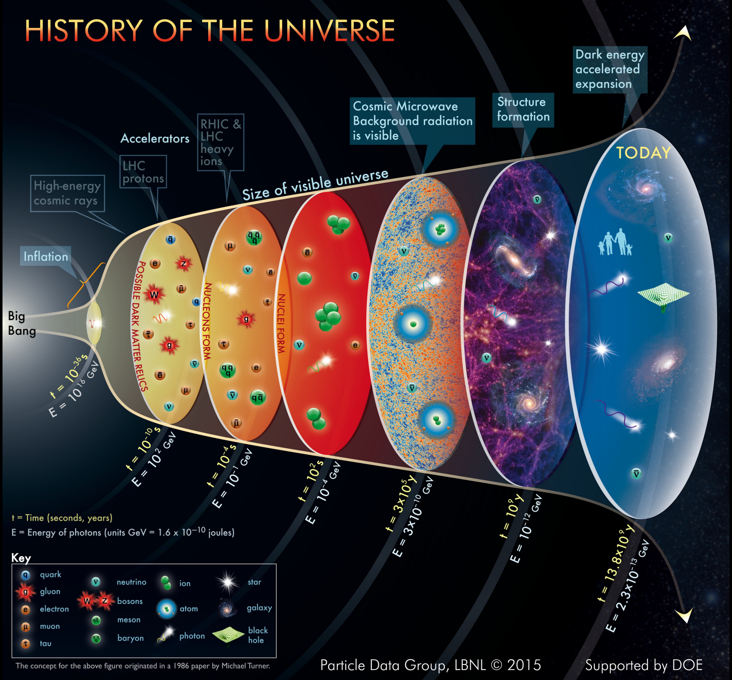
Overview

1. Gravitational waves: a backstage pass to the (early) universe
2. What influences a (first order) phase transition?
3. A flavour-transfer model
4. Future prospects


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
$t = 10^{-4}$ s
$E = 10^{-1}$ GeV
$t = 10^{2}$ s
$E = 10^{-4}$ GeV
$t = 3\times10^{5}$ y
$E = 3\times10^{-10}$ GeV
$t = 10^{9}$ y
$E = 10^{-12}$ GeV
$t = 13.8\times10^{9}$ y
$E = 2.3\times10^{-13}$ GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6×10^{-10} joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
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The allure of gravitational waves

To explore beyond the CMB and CνB...

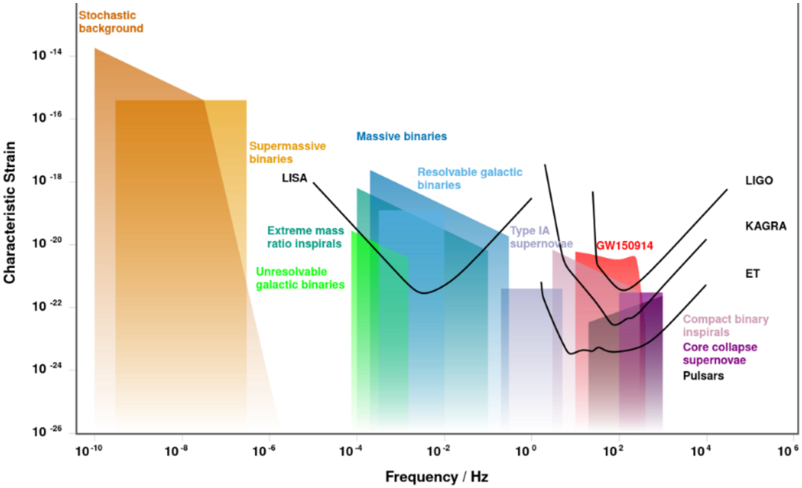
- Phase transitions: QCD ($\sim$ 100 MeV), EW ($\sim$100 GeV)

  $\hookrightarrow$ Baryogenesis + baryon asymmetry, EWSB **FOPT $\leftrightarrow$ BSM**

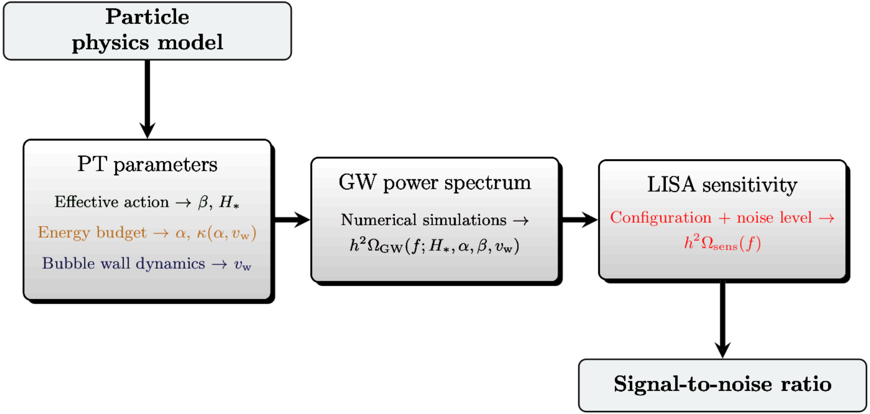
- Inflation ($\sim 10^{16}$ GeV)

- Exotic: cosmic strings, primordial black holes, Planck scale

- GR violation: $>$ 2 polarisation states, modified dispersion relation, sub- or super-luminal propagation, etc.

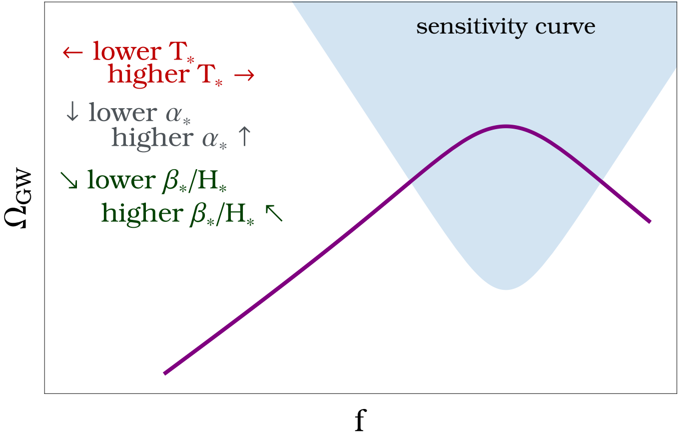


C. Moore, R. Cole, & C. Berry's GWplotter

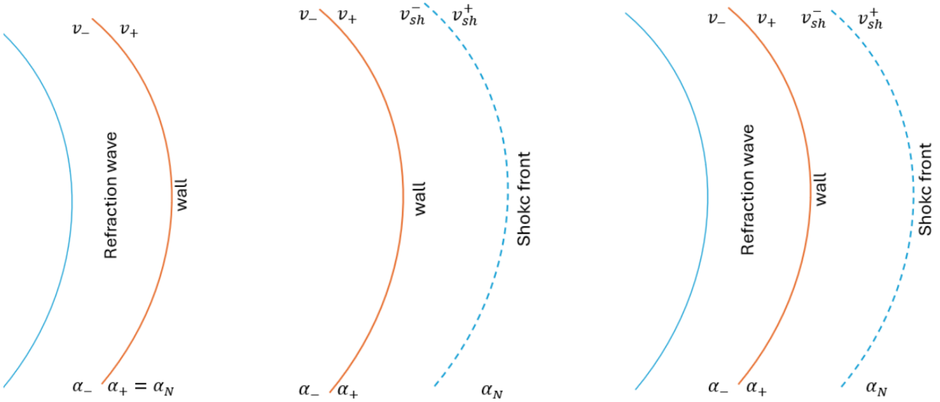


C. Caprini *et al.* JCAP 03 (2020).

Piecewise function: broken power law joined at f_{peak}



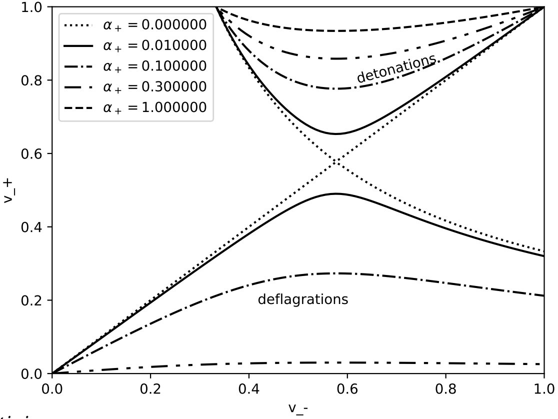
Influence of wall speed v_w?



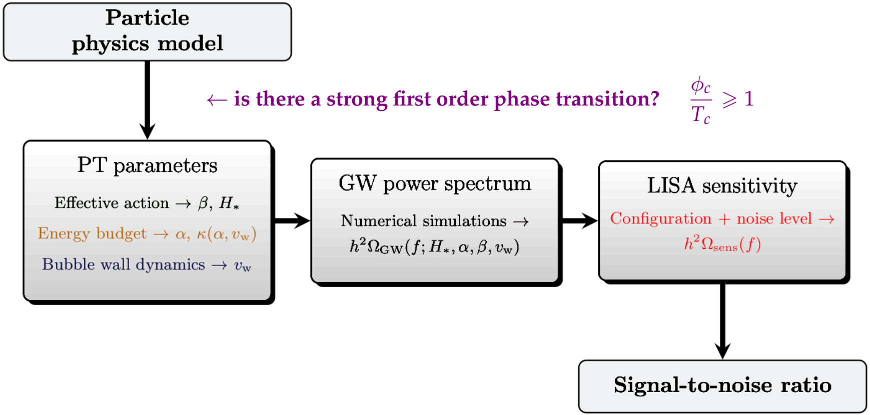
detonation: $v_{sym} > c_s$ deflagration: $v_{sym} < c_s$ hybrid: $v_{sym} < c_s$

Influence of phase transition parameters

velocity in the symmetrical phase (v_+) plotted as a function of velocity in the broken phase (v_-)

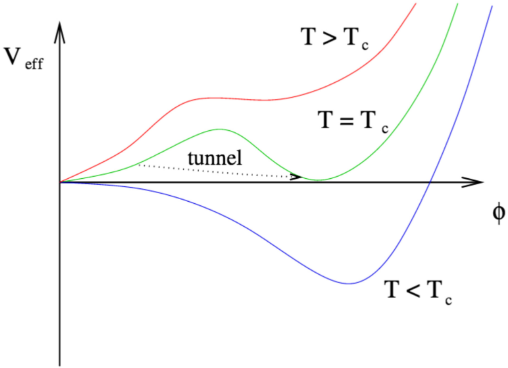


Ongoing work by T. Demartini


Particle physics model
← is there a strong first order phase transition? $\frac{\phi_c}{T_c} \geqslant 1$
PT parameters
Effective action → β, H_*
Energy budget → α, $\kappa(\alpha, v_w)$
Bubble wall dynamics → v_w
GW power spectrum
Numerical simulations →
$h^2\Omega_{GW}(f; H_*, \alpha, \beta, v_w)$
LISA sensitivity
Configuration + noise level →
$h^2\Omega_{sens}(f)$
Signal-to-noise ratio

To determine the first order phase transition

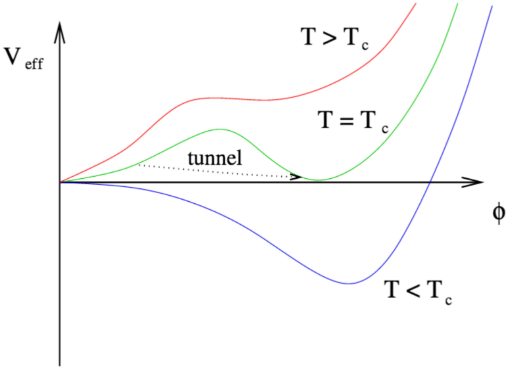
$$V_{eff} = V_{tree} + V_{CW} + V_{Temp} - V_{daisy}$$



G. White, *A Pedagogical Intro to Baryogenesis*

$$V_{eff} = V_{tree} + V_{CW} + V_{Temp} - V_{daisy}$$

resummation of dominant thermal corrections $\hookleftarrow$



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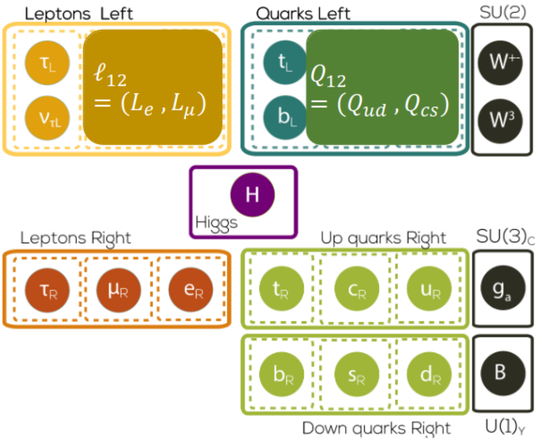
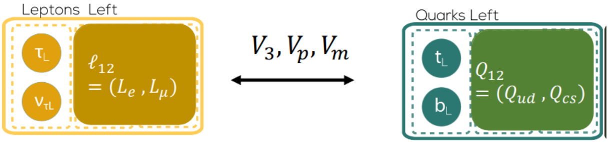


$+$ **SU(2)$_f$**

3 new "W-like" gauge bosons
carry a "flavour-charge"

L. Darme, A. Deandrea, F. Mahmoudi's *Gauge SU(2)$_f$ flavour transfers* *new flavour gauge bosons transfer flavour from one fermionic sector to another*



gauge bosons are all of mass $M_V = g_f/4$ *with gauge coupling* g_f *as a free parameter*

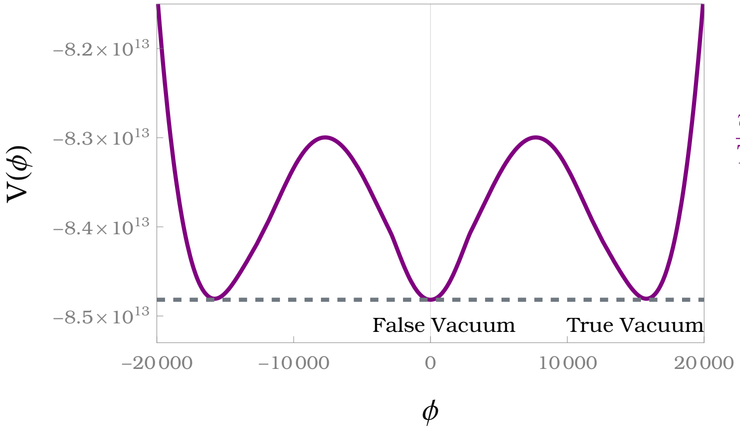
$$\mathcal{L}_{\text{eff}} \supset -\sum_{a,f,f'} \frac{g_f^2}{8M_V^2} \left(2\delta^{i\ell}\delta^{jk} - \delta^{ij}\delta^{k\ell}\right) \left(\bar{f}_i \gamma^\mu f_j\right) \left(\bar{f}'_k \gamma_\mu f'_\ell\right)$$

The model: contributing degrees of freedom

hierarchical rotation matrices realised in A. Greljo & A. E. Thomsen's Rising through the ranks: $m_S \ll m_{R_u}, m_{R_d}$

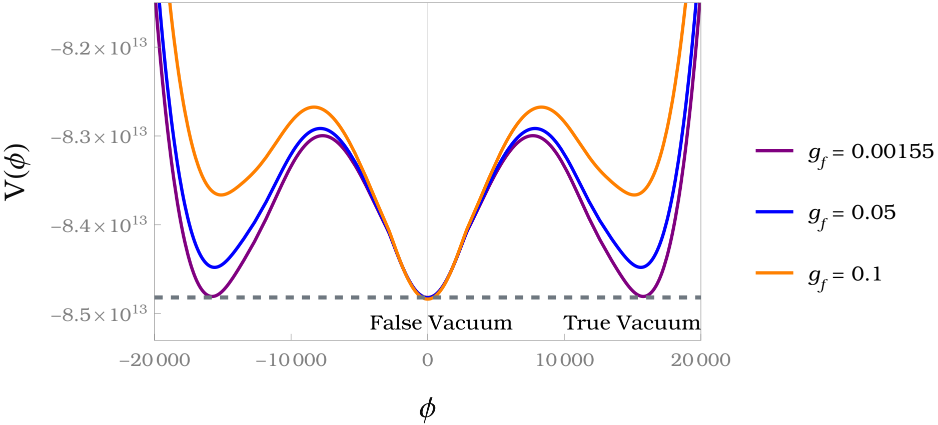
Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$SU(2)_f$	*DoF*	coupling
H	1	2	1/2	1	1	$\lambda_H = -0.291$
G	1	2	1/2	1	3	$\lambda_\phi = 0.291$
Φ	1	1	0	2	1	$\lambda_\phi = 0.291$
S	3	1	2/3	2	$3 \times 2 = 6$	$g_S = 0.0109$
V	1	1	0	3	$3 \times 3 = 9$	$g_f = 0.00155$

preliminary !

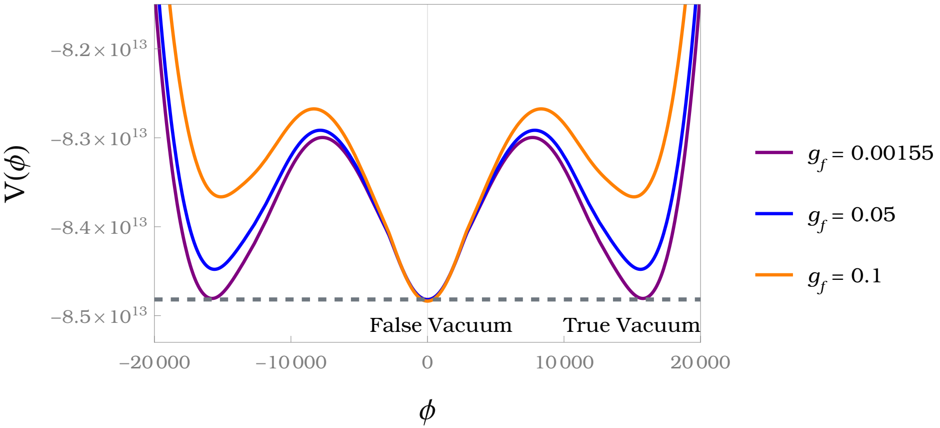


$$\frac{v_c}{T_c} \sim \frac{15778}{2550} \approx 7.01 > 1$$

Do we see a phase transition?



Do we see a phase transition?



$\Rightarrow$ heavier M_V corresponds to lower T_C

Future prospects (next immediate steps)

- ⋆ Implement into DRalgo for higher-order loop corrections
- ⋆ "Gravitational wave detectors complementary to particle colliders"

  ↪ how much of the parameter space is reduced by known collider constraints?

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- ⋆ simulation chain for signal exclusion using Bayesian inference & publically-available LIGO-Virgo-KAGRA data [Demartini *et al.*]

Thank you

Backup slides

Parameters influencing FOPT

Bubble wall velocity v_w after nucleation $(0 < v_w \leq 1)$.

Phase transition strength α, ratio of the trace of the energy momentum tensor and the energy density in the symmetric phase (free; usually $\alpha_{\sim}10^{-2} - 10^{0}$).

Inverse phase transition duration $\beta*$, expressed relative to the Hubble rate H_* (dimensionless). Assume duration to be short enough s.t. expansion of the universe can be neglected, $\beta/H_* \gtrsim 1$ $(H_\mathrm{n} \simeq H_*)$.

Transition temperature T_* is the temperature of the universe right after the phase transition (set freely based on the chosen model; $T_\mathrm{n} \simeq T_*$)

Towards nucleation temperature

$\xrightarrow{\text{decreasing s.t. } T < T_c}$