① saoghal.net/pages/uhwsmo.html

GWs from a strong EWPT

LISA (1702.00786 + SciRD)

2.5 Mkm

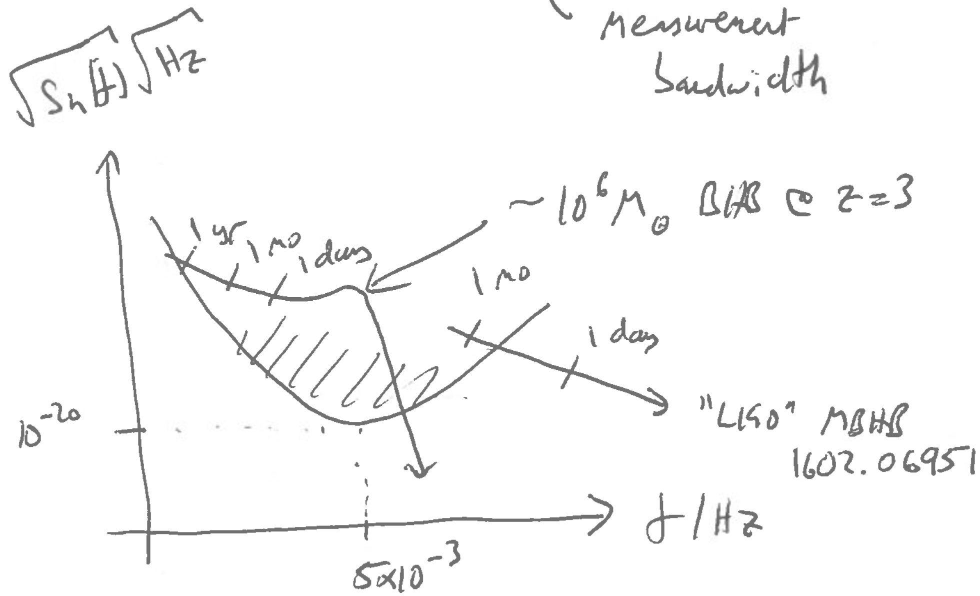
- 3 spacecraft
- launch 2034
- ~4yr mission

Sensitivity quoted as characteristic strain

$$S_h(f) = \frac{|\tilde{h}(f)|^2}{f_{MBW}}$$

← freq. domain strain

f_{MBW} ← measurement bandwidth



② Binaries

- 1000's resolvable
- Millions more stochastic (hopefully resolvable)
- Input from Gaia, LSST, etc.
- "Verification binaries" seen with both GW & EM.

(beneath which ...)

Cosmological stochastic BG

Hubble radius at $T = T_{*} = 100$ GeV

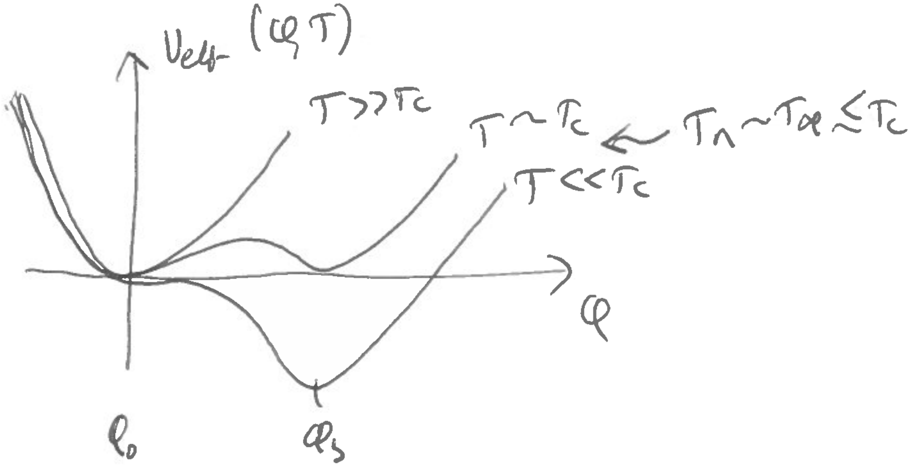
- = (when GWs made)

~ few cm → (today) ~ few × 10^8 km / AU

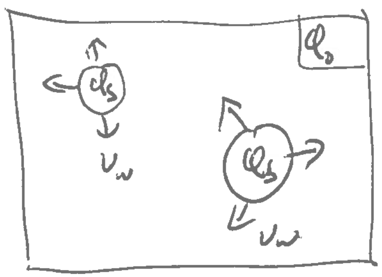
[≈ few × (galactic binary radius)]

⇒ important, but doable, to resolve / deal with binary background.

③ **First-order phase transitions**



→ Thermal transition: bubbles expand in SM plasma, and experience friction $(v_w \lesssim c)$



Rate/unit volume/unit time

$$\Gamma(T) = A(T)\, e^{-S_3(T)/T}$$

$A(T) \sim T^4$

Non-perturbative: hep-ph/0009132

④ Then timescale (inverse) over which bubbles are made depends on how fast $\Gamma(T)$ varies:

$$\frac{\beta}{H_p} = T_p \left.\frac{dS}{dT}\right|_{T_p}$$

Characteristic radius $R_p = (8\pi)^{1/3} \dfrac{v_w}{\beta}$

Another important parameter is

$$\alpha \equiv \alpha^{\theta}_{T_p} = \frac{\Delta\theta(T)}{\varepsilon_r(T)}$$

where

$$\Delta\theta(T) = -\frac{T}{4}\frac{d}{dT}\Delta V + \Delta V$$

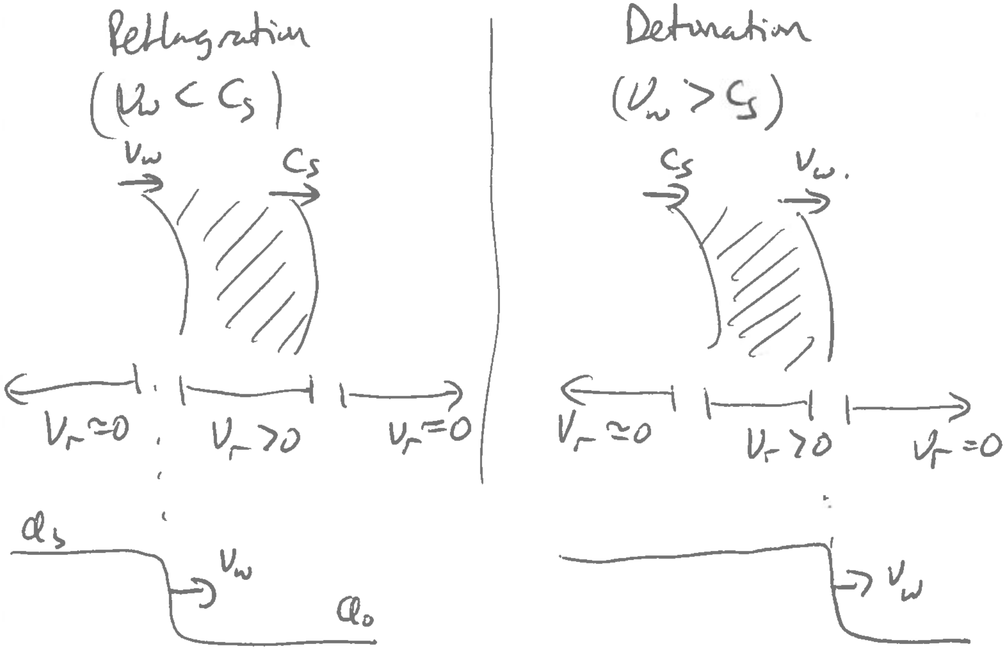
$$\Delta V(T) = V_{eff}(\varphi_0, T) - V_{eff}(\varphi_s, T)$$

⇓

$$\left\{\alpha, \frac{\beta}{H_p}, v_w, T_p, [g_p]\right\}$$ parameters that control non-eq^n dynamics

Energy budget (1004.4187)

(5) What do the reaction fronts look like?



Gravitational waves

$$\Box h_{ij} = (16\pi G)(\tau_{ij}^{f})^{TT}$$ ← transverse-traceless part

↑ fluid stress-energy

$$\tau_{ij}^{f} = w\, u_i u_j$$

define $$\bar{U}_f^2 = \frac{1}{wV}\int_V d^3x\, \tau_{ii}^{f}$$

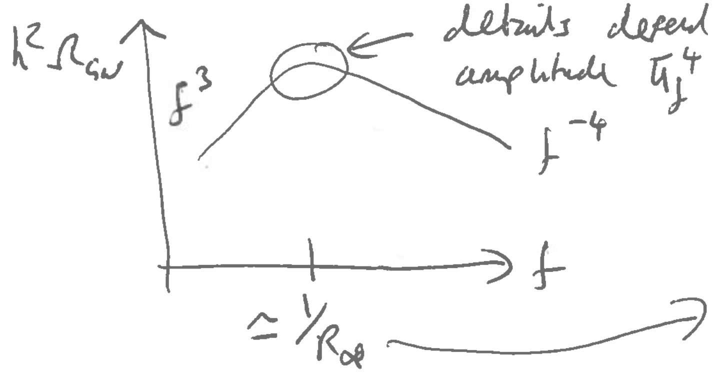
"enthalpy-weighted average velocity"

(6) What sources GWs?

When $t \lesssim \mathrm{Min}\{H_*^{-1}, R_*/\bar{U}_f\}$: Sound (?) ⇐ Shocks, turbulence, ...

(Hubble damping → H_*^{-1})

Sound : conservative option



details depend on α, v_w, ...
amplitude $\bar{U}_f^4$

$$\Delta R_* \simeq R_* \frac{|v_w - c_s|}{c_s}$$

BUT This is based on simulations with ~~[illegible]~~ $\alpha \sim 10^{-3}$ (!)

[Optional: simulation details] → (7)

$$(\partial_\mu \partial^\mu \phi)\partial^\nu \phi - \frac{\partial V_{eff}}{\partial \phi}(\phi, T)\,\partial^\nu \phi$$

$$= \eta(\phi, v_w, T)\, u^\mu \partial_\mu \phi\, \partial^\nu \phi$$

$$\partial_\mu(w\, u^\mu u^\nu) - \partial^\nu p + \frac{\partial V_{eff}}{\partial \phi}(\phi, T)\,\partial^\nu \phi$$

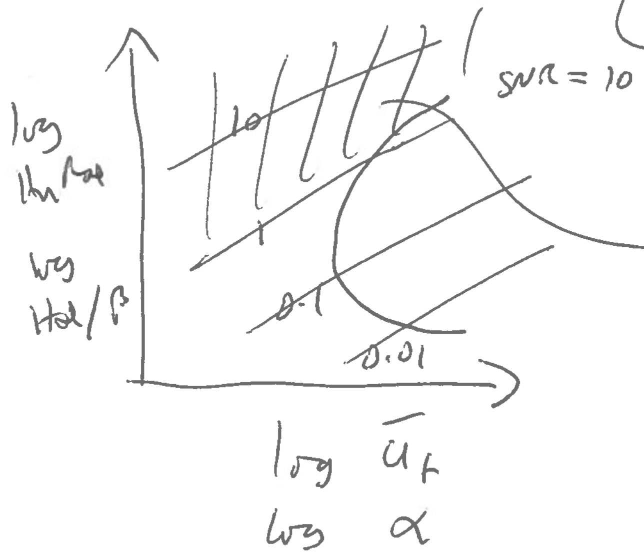
$$= -\eta(\phi, v_w, T)\, u^\mu \partial_\mu \phi\, \partial^\nu \phi$$

(7) <u>What happens to the sound source when $\alpha \sim 10^{-1}$?</u>

(ptplot.org)

→ Simulations of ideal fluid u^μ (≃ SM plasma) coupled to scalar field φ with friction term.

→ "Bag model" EoS, (not real eff pot).



→ $\frac{R_*}{\bar{U}_f} H_* \gtrsim 1$

⇒ Hubble damping wins.

(8) · <u>Do nonlinearities / weird stuff appear?</u>

1/ Detonations : ~~...~~ ($v_w > c_s$) : no

(at least not in the ~~...~~ immediate aftermath of the transition)

2/ Deflagrations : ($v_w < c_s$) : yes!

→ ~~...~~ Plasma reheats

→ Walls slow down

→ Kinematic ~~...~~ efficiency → 0 (as $\alpha \to \alpha_{max}$)

→ Less GWs than expected

→ Vorticity