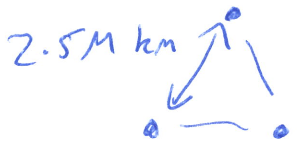
"Gravitational waves & why you should care"

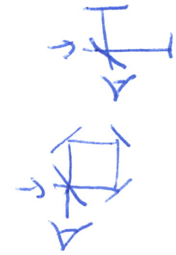
LISA (1702.00786 + Sci RD)

* 3 space craft, launch in 2034, 4 year mission



talk about the spacecraft + design + LISA pathfinder

* 2 independent ~~Michelson~~ "Michelson" interferometers or 1 "Sagnac" interferometer



* joint ESA-NASA mission
* cosmological stochastic BG is part of science case

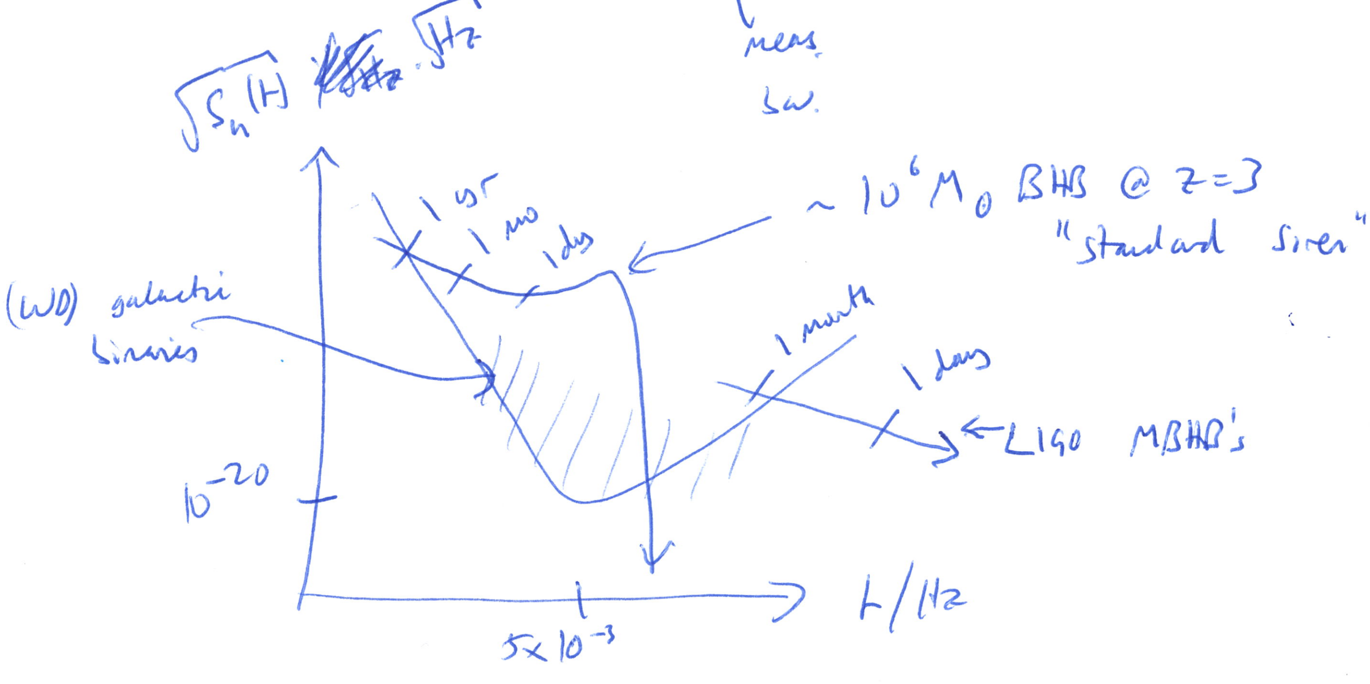
talk about working group membership etc.

Sensitivity measured as characteristic strain

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

$h(f)$ = strain signal

$\tilde{h}(f)$ = freq. domain



Binaries

* 1000's resolvable
* Millions "stochastic" (but hopefully subtractable)
* complementarity with ~~Gai~~ Gaia, LSST, etc.
* A few "verification binaries" which can be jointly seen in GW & EM.

Standard sirens

* Independent measurement of H from (eg) MBHB's out to $z \lesssim 6$ (with EM)

Cosmological stochastic BG

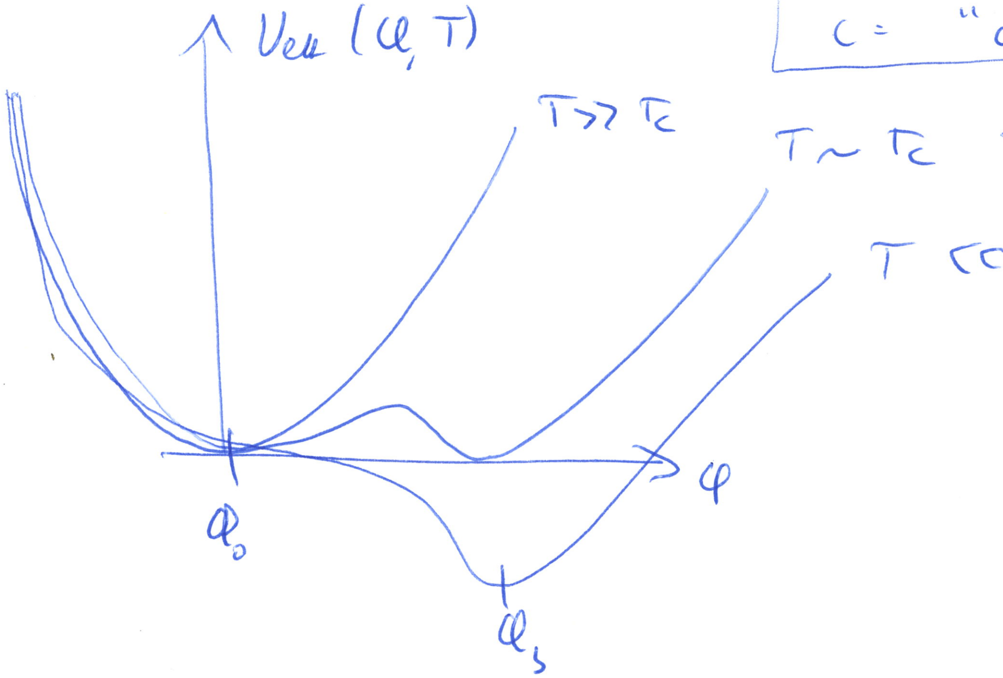
Hubble radius at $T = T_{\phi} \simeq 100$ GeV
~few Cm redshifted to today $\Rightarrow$ ~few $\times 10^{8}$ km
(same as typical galactic binaries!)

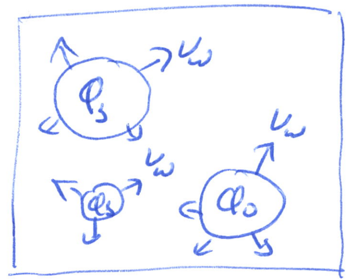
[NB
$$h^2 \Omega_{gw} = \frac{2\pi^2}{3H_0^2} f^3 S^2(f)$$
]

$\Rightarrow$ important, but doable, to resolve / deal with binary foreground

First-order phase transitions

$*$ = when GWs produced
n = " "nucleation"
c = " "critical"





(Assuming thermal transition)

$$\Gamma(T) = \underset{\uparrow \atop \sim T^4}{A(T)}\, e^{-\overbrace{S_3(T)/T}}$$

rate / unit volume → [hep-ph/0009132]

The timescale over which bubbles nucleate depends on how fast the ~~rate at which~~ nucleation rate is changing

$$\frac{\beta}{H_*} = \left[T \frac{d}{dT} \left(\frac{S_3(T)}{T} \right) \right]_{T = T_*}$$

(If $\frac{\beta}{H_*}$ too small, phase transition never completes)

characteristic radius is $R_* = (8\pi)^{1/3} \frac{v_w}{\beta}$

Once we have nucleated the bubbles, need to know how much energy will be dumped into them.

Define phase transition strength α: (small supercooling, no reheating)

$$\alpha^h_{T_*} = \frac{h(T_*)}{\mathcal{E}_r(T_*)} \quad \begin{array}{l} \leftarrow \text{latent heat} \\ \leftarrow \frac{g\pi^2 T^4}{30} \end{array}$$

or

$$\alpha^\theta_{T_*} = \frac{\Delta\theta(T)}{\mathcal{E}_r(T)}$$

where $\Delta\theta(T) = -\frac{T}{4}\frac{d}{dT}\Delta V + \Delta V$ (diff in trace anomaly $\div 4$.)

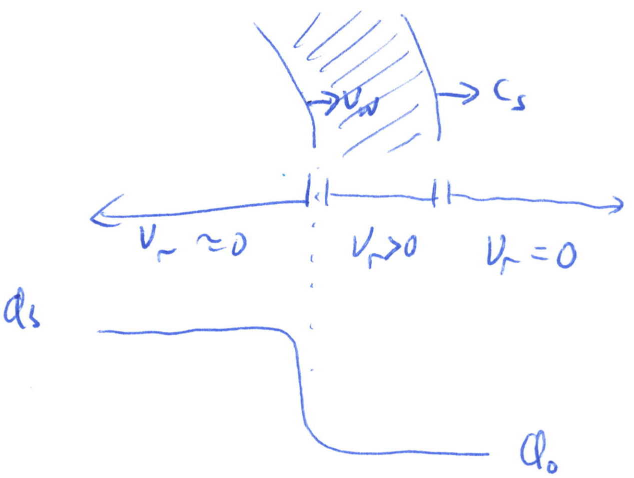
and $\Delta V(T) = V_{eff}(\varphi_0, T) - V_{eff}(\varphi_s, T)$

These can numerically differ by 50%.

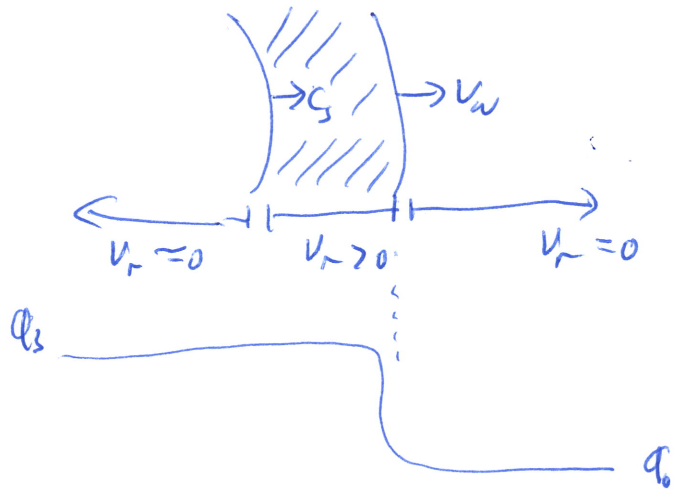
Where does the energy go? Mostly into the SM plasma and moving the walls.

Depending on v_w: (show movies of |H| here)

Deflagration $(v_w < c_s)$



Detonation $(v_w > c_s)$



5

Away from the bubble walls: "ideal" hydro (for now)
so get scaling solution parametrised by $\boxed{\xi = r/t}$

<u>parameters</u> α_{T_φ}, $\underbrace{v_w, \frac{\beta}{H_\varphi}}_{(R_\varphi)}$, T_φ (g_φ)

Simulations

I do simulations of an ideal fluid u^μ coupled to a relativistic scalar field φ.

$$(\partial_\mu \partial^\mu \varphi)\partial^\nu\varphi - \frac{\partial V_{eff}(\varphi, T)}{\partial \varphi}\partial^\nu\varphi = \eta(\varphi, v_w) u^\mu \partial_\mu \varphi \partial^\nu \varphi$$

$\varepsilon + p$

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

~~Hydro & Scalar fo~~ have used $\eta = \tilde{\eta}\frac{\varphi^2}{T}$ mostly in sims

- point of $V_{eff}(\varphi, T)$ and η is to set up α and v_w for the simulation (more than a realistic sim)

$\boxed{\text{(3d \& movie)}}$

sources are

$\tau_{ij}^\varphi = \partial_i \varphi \partial_j \varphi$ $\qquad$ $\tau_{ij}^f = w u_i u_j$

$\bar{U}_\varphi^2 = \frac{1}{wV}\int d^3x\, \tau_{ii}^\varphi$ $\qquad$ $\bar{U}_f^2 = \frac{1}{wV}\int d^3x\, \tau_{ii}^f$

"Three sources of GW's"

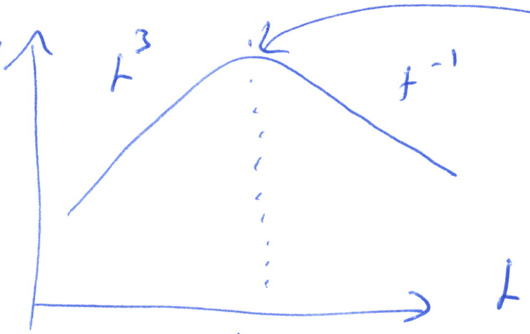
? $h^2 \Omega_{GW} = \underset{①}{h^2 \Omega_{env}} + \underset{②}{h^2 \Omega_{sw}} + \underset{③}{h^2 \Omega_{turb}}$

1/ $h^2 \Omega_{env}$ "envelope approximation"

- collision of ~~[illegible]~~ shells, assumed to be infinitesimally thin ($\varphi(r) \to \delta(r)$)
- shells disappear after collision

results (0806.1828)

$h^2 \Omega_{env}$



$1/R_*$
(redshifted to today)

amplitude $\propto$ energy lost as walls collide (slow walls, thermal transition $\Rightarrow$ small)

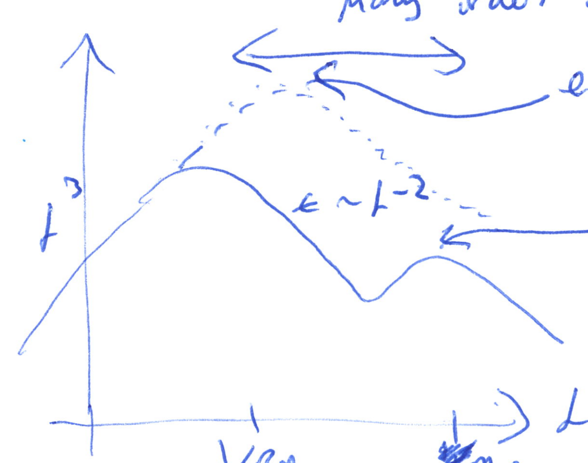
☹ NOT IMPORTANT for thermal transitions

☹ NOT VALID for vacuum transitions

[aside: vacuum transitions (1802.05712) (show David's movie)

many orders of magnitude

envelope approx over-estimates



dynamics at wall scale

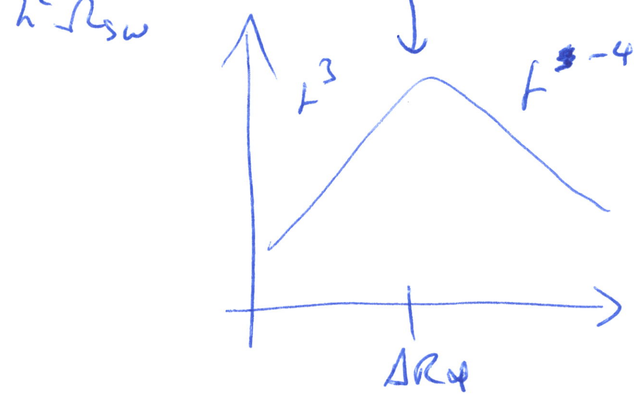
$1/R_*$ m_φ]

2/ $h^2\Omega_{sw}$ "sound waves"

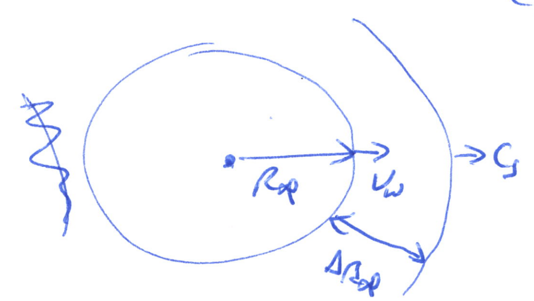
(1704.05871 or 1608.04735 for a semi-analytic version that mostly matches results)

$\propto \bar{U}_f^4$

(amplitude depends on α, v_w)



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



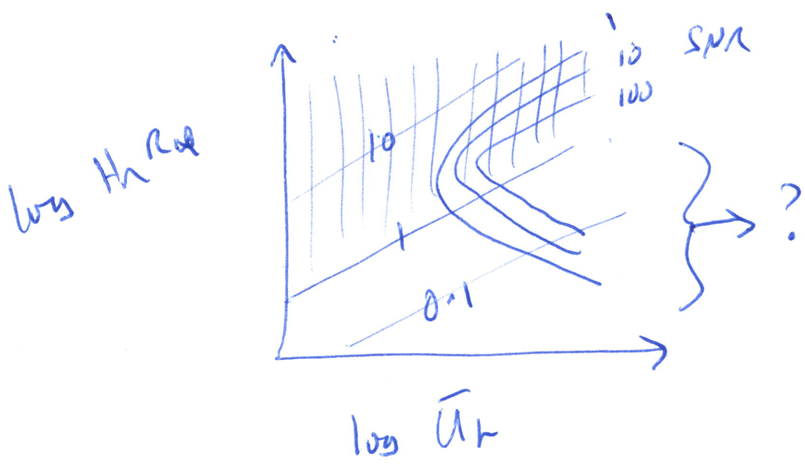
The source is on for time $\sim \frac{1}{H_*}$ and is constant until shocks start to form

$$\tau_{sh} = \frac{R_*}{\bar{U}_f}$$

R_* ← stirring scale

$\bar{U}_f$ ← "average fluid velocity"

Fully developed turbulence forms on the same timescale. We can therefore ignore turbulence if $\frac{R_*}{\bar{U}_f} \times H_* \gtrsim 1$



3/ Turbulence?

If $\frac{R_{*}}{\bar{U}_f} \times H_{*} < 1$ need to consider turbulence.

$$\boxed{h^2 \Omega_{gw}(f) \propto f^{-5/3}}$$

Generally expected to follow Kolmogorov 1S.

Work in this direction: 0909.0622

Energy is transferred ~~to~~ from R_{*} to a dissipative scale $L_d \ll R_{*}$ over a time also given by ~~$\frac{R_{*}}{\bar{U}_f} \times H_{*}$~~ $\frac{R_{*}}{\bar{U}_f}$ ~~H~~

→ fully developed turbulence.

→ if $\frac{R_{*}}{\bar{U}_f} < \frac{1}{\beta}$, turbulence develops <u>during</u> phase transition → stationary turbulence.

generally assume this but not guaranteed.

$h^2 \Omega_{gw}(f) \propto f^{-9/2}$ (Kamionkowski et al.) astro-ph/9310044

$h^2 \Omega_{gw}(f) \propto f^{-7/2}$ (Kosowsky et al.) astro-ph/0111483

$h^2 \Omega_{gw}(f) \propto f^{-8/3}$ (Caprini & Durrer) astro-ph/0603476

$h^2 \Omega_{gw}(f) \propto f^{-9/2}$ (Gogoberidze et al.) 0705.1733

$h^2 \Omega_{gw}(f) \propto f^{-5/3}$ (Caprini et al.) 0909.0622

amplitude hard to model

→ Conservative choice not to rely on turbulence.