Gravity Wave Probe of Cosmology w/ an Electroweak Scale Phase Transition

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[focus: works with Andrew Long, Peng Zhou, Sean Tulin, Liantao Wang]

New Microphysics

- LHC may discover new physics at the electroweak scale: the origin of electroweak symmetry breaking.

- Higgs is a possible scalar involved, but many additional scalars may be involved.

$\longrightarrow$ motivates the existence of electroweak scale PT

- The GW spectrum peaks near the sensitivity range of LISA

Probe of H

BBN + relative isotope measurements probe H(1 MeV)

dark sector constrained (sterile neutrinos, dark energy,…)

This talk: using gravity waves to constrain H(100 GeV)

[1003.2462 w/ Peng Zhou]

assumption: 1st order EW scale PT took place generating gravity waves

Probe of H

inflaton (solves flatness + horizon + relic; generates density perturbations)

(re)heats (couples to SM)

Moduli oscillate

gravitino

Leptogenesis

Probe with GW

LHC

EWPT

Baryon chemical potential freeze in

WIMP freeze out

QCD PT

axion oscillates

BBN

BBN

Neutrinos decouple

matter dominate

CDM clusters

neutral H

Clean, linear

stars reionize

DE dominates

Hot baryons, lensing
More challenging systematic errors (nonlinearities, plasma physics)

Probing the dark sector:

1st order PT → gravity wave (an observable)

$\downarrow$ probe

dark sector: DM, DE

i.e. 1st order PT generates a probe of the dark sector.

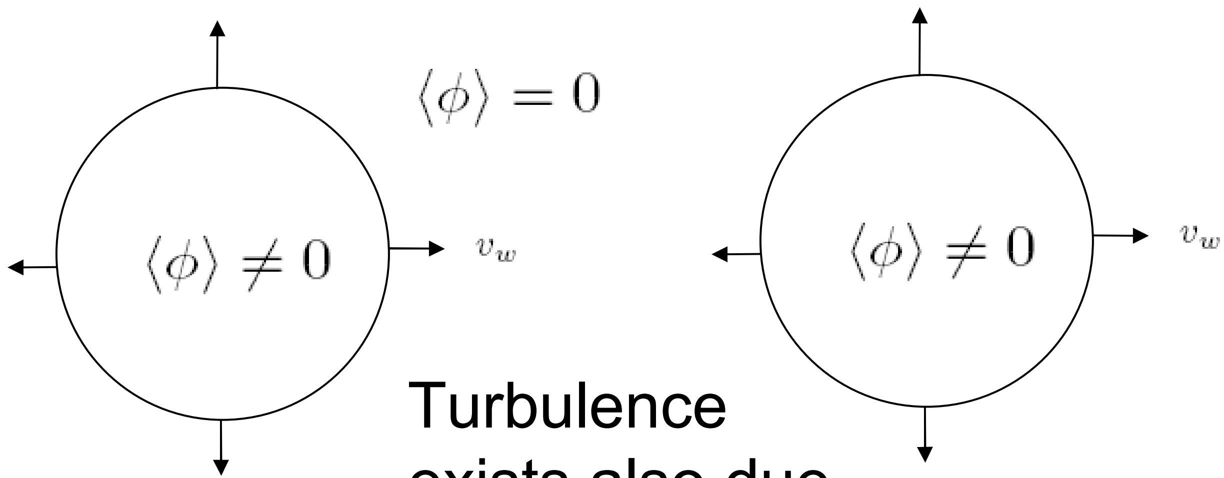
Gravity is all knowing:

$$H = \frac{\sqrt{\rho_{\rm SM} + \rho_{\rm dark}}}{\sqrt{3}M_p}$$

Q: How does the gravity wave spectrum change compared to that of the SM if H shifts (i.e. dark sector contributes)?

Gravity Waves from EWPT

Collision:



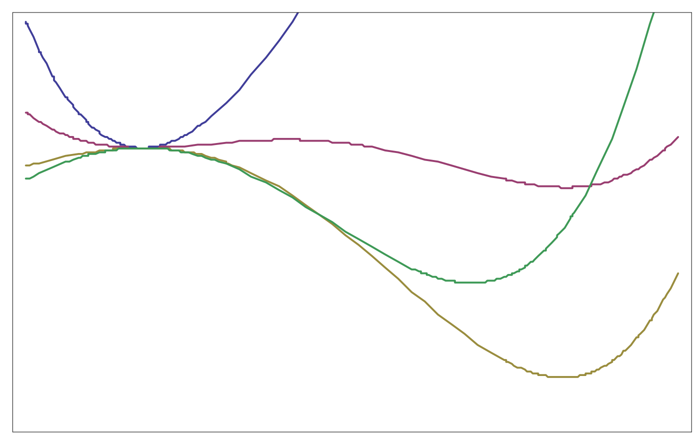
Turbulence exists also due to stirring.

$$\Gamma(t) = A(t) e^{-S(t)}$$

$$\Gamma \sim A \exp\left[-S(t_i) - \boxed{\frac{dS}{dt}|_{t_i}} (t - t_i) \right]$$

$$\frac{dS}{dt} = -H \frac{dS}{d\ln T}$$

$$\Delta t = t_f - t_i \propto \frac{1}{|\frac{dS}{dt}|} = \boxed{\frac{1}{H} \frac{1}{\frac{dS}{d\ln T}}}$$



End game is important.

Gravity Wave at EWPT

Following arguments of 0711.2593 and astro-ph/9310044:

$$\rho_{GW} \sim \frac{1}{M_p^2}\left(\frac{a_{PT}}{a}\right)^4 \langle \frac{d}{dt}\left(\frac{1}{\Box}T_{ij}\right)\frac{d}{dt}\left(\frac{1}{\Box}T_{ij}\right)\rangle|_{PT}$$

$$\left\langle \tilde{T}_{ij}(t_1', \vec{k}_1)\tilde{T}^*_{ij}(t_2', \vec{k}_2)\right\rangle = (2\pi)^3\delta^{(3)}(\vec{k}_1 - \vec{k}_2)P(k_1, t_1', t_2')\left[\rho_f^{\rm rest}\gamma_{v_f}^2 v_f^2\right]^2 a_*^2$$

$$\frac{d\rho_{GW}}{d\ln k} = \frac{1}{(2\pi)^2}\frac{1}{M_p^2}\left(\frac{a_*}{a}\right)^4\left[\rho_f^{\rm rest}\gamma_{v_f}^2 v_f^2\right]^2 a_*^2\int dt_1' dt_2' \cos\left[k(t_1' - t_2')\right]\left[k^3 P(k, t_1', t_2')\right]$$

Stress tensor amplitude

propagation

Spatial dependence of correlator: bubble wall spatial distribution /deformations

Uncertain due to comp difficulty

See e.g. 0901.1661 and Caprini and Durrer 06 for a discussion of uncertainties.

Gravity Wave at EWPT

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dimless

Stress tensor amplitude

propagation

Spatial dependence of correlator: bubble wall spatial distribution /deformations

Uncertain

Dimensionful parameters:

BC scales: $t_*^{-1},\ T$

Short distance scales: $m_h(0)$

Nonequilibrium scales: $(\Delta t)^{-1},\ H$

100 GeV

10^{-12} GeV

10^{-14} GeV

Decoupling and Mass Scale Left

Intuition:

Dimensionful parameters:

coordinate origin

BC scales: t_*^{-1}, T

Short distance scales: $m_h(0)$

Nonequilibrium scales: $(\Delta t)^{-1}$, H

100 GeV

Λ

Integrate out

Effects of H through these ops are suppressed by $(H/\Lambda)^n$

10^{-12} GeV

10^{-14} GeV

$= \text{dimless number} \times H$

Scales of interest for measurement.

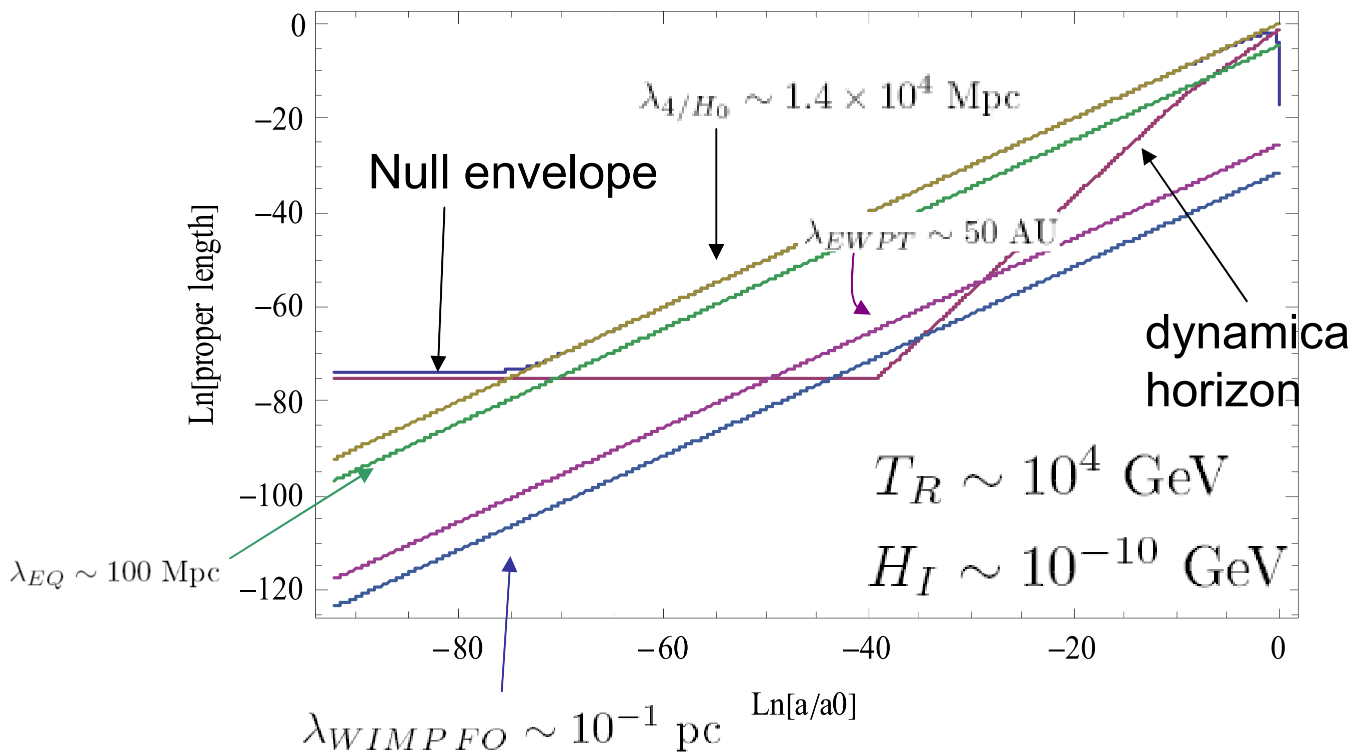
More accurately, it is a classical analog + (reasonable and mild) assumptions:

1) $\frac{k}{a_*} \in [10^{-13}, 10^{-7}] \left(\frac{g_*(t_0)}{3.9}\right)^{-1/3} \left(\frac{g_*(t_*)}{10^2}\right)^{1/3} \left(\frac{T_*}{10^2 \text{ GeV}}\right) \text{GeV}$ estimated LISA & BBO sens.

2) $\langle T_{ij}(t_1', \vec{x}) T_{ij}(t_2', \vec{y})\rangle = \left[\rho_B^{\text{rest}} \gamma_{v_f}^2 v_f^2\right]^2 a_*^2 \int \frac{d^3k_1}{(2\pi)^3} e^{i\vec{k}_1\cdot(\vec{x}-\vec{y})} P(k_1, t_1', t_2')$ approx order of magnitude

3) Dominant support of $\langle T_{ij}(t_1', \vec{x}_1) T_{ij}(t_2', \vec{x}_2)\rangle$ in the interval $t \in [t_*, t_* + \Delta t]$

Observational Scales



Approximate linearity of gravity waves and the decoupling of observable scales compared to short distance scales lead to the expansion rate being the dominant conformal breaking scale of interest.

GW as a Probe of Early Universe H

$= \text{dimless number} \times H^{-1}$

Observe:

$[M]^0 \rightarrow \boxed{F_{k\Delta t}((t'_1 - t_*)/\Delta t, (t'_2 - t_*)/\Delta t) \equiv k^3 P(k, t'_1, t'_2)}$

assumption of leading conformal symmetry breaking scale.

$$\frac{d\rho_{GW}}{d\ln k} = \frac{1}{(2\pi)^2}\frac{1}{M_p^2}\left(\frac{a_*}{a}\right)^4\left[\rho_f^{\text{rest}}\gamma_{v_f}^2 v_f^2\right]^2 a_*^2 \int dt'_1 dt'_2 \cos\left[k(t'_1 - t'_2)\right]\left[k^3 P(k, t'_1, t'_2)\right]$$

Since $\Delta t \propto \frac{1}{H(T_*)}$, $H(T_*)$ sensitivity can be read off.

$$\left(H^{(U)}\right)^2 = \frac{\rho_R}{3M_p^2} \qquad H^2 = \frac{\rho_R + \rho_{\text{hidden}}}{3M_p^2} \qquad \xi \equiv \frac{H(T_*)}{H^{(U)}(T_*)}$$

$$\boxed{\frac{d\rho_{GW}(k)}{d\ln k} \rightarrow \frac{1}{\xi^2}\frac{d\rho_{GW}(k/\xi)}{d\ln k}}$$

[1003.2462 w/ Peng Zhou]

Observational Predictions are More Complicated

What is measured:

$$\frac{\rho_G}{\rho_R}$$

Can still suffer from non-standard cosmological dependence.
e.g. late time entropy dilution (more later).

Good and bad.

Don't be Fooled

[Kamionkowski, Kosowsky, Turner 94]

Numerical simulation:

$$\Omega_{GW} h^2 \approx 1.1 \times 10^{-6} \kappa^2 \left(\frac{H_*}{\beta}\right)^2 \left(\frac{\alpha}{1+\alpha}\right)^2 \left(\frac{v_w^3}{0.24 + v_w^3}\right) \left(\frac{100}{g_*}\right)^{1/3}$$

$$f_{max} \approx 5.2 \times 10^{-8} \mathrm{Hz} \left(\frac{\beta}{H_*}\right) \left(\frac{T_*}{1 \text{ GeV}}\right) \left(\frac{g_*}{100}\right)^{1/6}$$

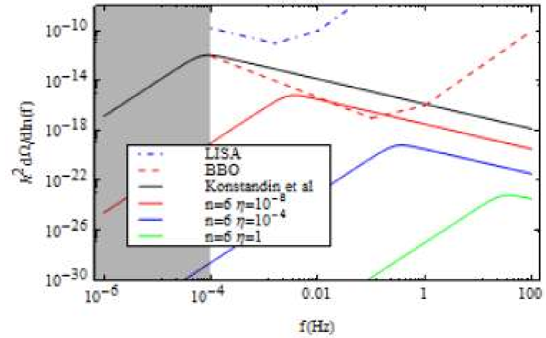
$$\xi \equiv \frac{H(T_*)}{H^{(U)}(T_*)}$$

$$\frac{d\rho_{GW}(k)}{d\ln k} \longrightarrow \frac{1}{\xi^2} \frac{d\rho_{GW}(k/\xi)}{d\ln k}$$

[1003.2462 w/ Peng Zhou]

Naïvely contradiction. However consistent since H_* has origins here to denote temperature and **not** the expansion rate.

Why Is the Amplitude Small?



Can't we just make this large?

$$\frac{d\rho_{GW}}{d\ln k} = \frac{1}{(2\pi)^2}\frac{1}{M_p^2}\left(\frac{a_*}{a}\right)^4\left[\rho_f^{\text{rest}}\gamma_{v_f}^2 v_f^2\right]^2 a_*^2\int dt_1' dt_2' \cos\left[k(t_1'-t_2')\right]\left[k^3 P(k,t_1',t_2')\right]$$

$$\begin{aligned}
\frac{\rho_{\rm GW}}{\rho_R} &\sim \left(\frac{\rho_f^2\times(\Delta t)^2}{M_p^2}\right)/\rho_R \\
&\sim \left(\frac{\rho_R\rho_f\times(\Delta t)^2}{M_p^2}\right)/\rho_R \\
&\sim \frac{\rho_f\times(\Delta t)^2}{M_p^2} \\
&\sim (H_{\rm rad}\Delta t)^2
\end{aligned}$$

$$P(t) = P(t_i)\exp\left(-C_1\int_{t_i}^{t} dt' \exp\left[\left(-S_*^{(3)} + \frac{(t'-t_*)H_*}{1+\frac{1}{3}\frac{d\ln g_{*S}}{d\ln T}}\frac{dS^{(3)}}{d\ln T}\Big|_{t_*}\right)/T(t')\right]T^4(t')V_3(t_i,t')a^3(t')\right)$$

Suppresses $H\Delta t$

Intuition for Difficulty

$$
\begin{tikzcd}[column sep=huge, row sep=huge]
H\Delta t \uparrow \arrow[r, "\text{larger supercooling}"] \arrow[d, "\text{O(1)}"'] & \dfrac{S^{(3)}}{T} \uparrow \arrow[d, "\text{without tuning}"] \\
\dfrac{dS^{(3)}}{dT} \downarrow \arrow[r, phantom, "\Rightarrow\ \Leftarrow"] & \dfrac{dS^{(3)}}{dT} \uparrow
\end{tikzcd}
$$

Intuition using Equations

$$V = \frac{1}{2}\left[m^2 + cT^2\right]\phi^2 - E\phi^3 + \frac{\lambda}{4}\phi^4$$

e.g. $$c_{SM} = \frac{1}{24v^2}\left(6m_t^2 + 6m_b^2 + 6m_w^2 + 3m_z^2 + \frac{3}{2}m_h^2\right) \approx 0.18$$

Numerical:

hep-ph/9203203 $$\frac{S^{(3)}}{T} \approx \frac{5\left[m^2 + cT^2\right]^{3/2}}{TE^2}\left(1 + \frac{\alpha}{4}\left[1 + \frac{2.4}{1-\alpha} + \frac{0.26}{(1-\alpha)^2}\right]\right)$$

$$\alpha = \frac{\lambda}{2}\frac{\left[m^2 + cT^2\right]}{E^2}$$

Divergent:

$$\frac{S^{(3)}}{T_c} \approx \frac{10}{\lambda}\sqrt{\frac{c}{1-\alpha(0)}}\left(1 + \frac{\alpha(T_c)}{4}\left[1 + \frac{2.4}{1-\alpha(T_c)} + \frac{0.26}{(1-\alpha(T_c))^2}\right]\right)$$

1

as $T \to T_c - \varepsilon$ $$\frac{dS^{(3)}}{dT} \approx \frac{2}{c\lambda^{5/2}\left[1 - \frac{\lambda m^2}{2E^2}\right]}\left(\frac{E}{\varepsilon}\right)^3$$

essentially thin wall.

Applications

Kination Phase of Quintessence

Quintessence's main difference from CC = kinetic energy

$$\ll \rho_Q$$

$$\rho_Q = \frac{1}{2}\dot{Q}^2 + V(Q)$$

$$\left(\frac{a_*}{a}\right)^6$$

Energy disappears relative to rad by BBN.

$$\xi = \sqrt{1 + \left(\frac{a_{\rm bbn}}{a}\right)^2 \eta} \qquad \eta \equiv \left(\frac{\rho_Q}{\rho_R}\right)_{\rm BBN}$$

1-parameter model

$$\frac{d\rho_{GW}(k)}{d\ln k} \longrightarrow \frac{1}{\xi^2}\frac{d\rho_{GW}(k/\xi)}{d\ln k}$$

Example

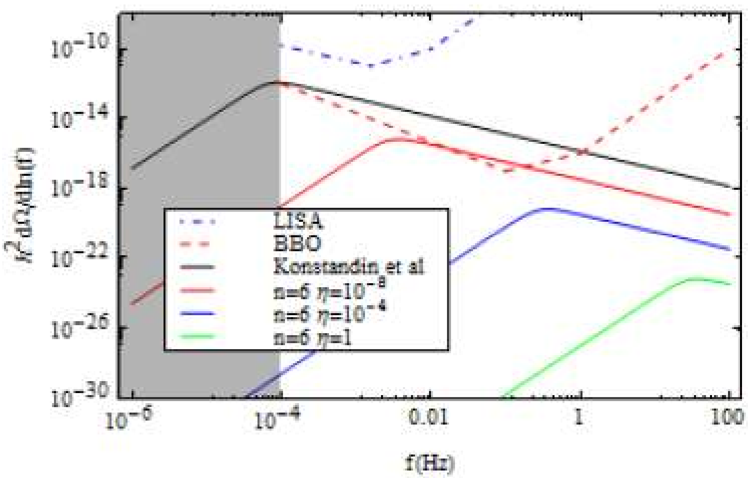
Optimistic example in nMSSM,

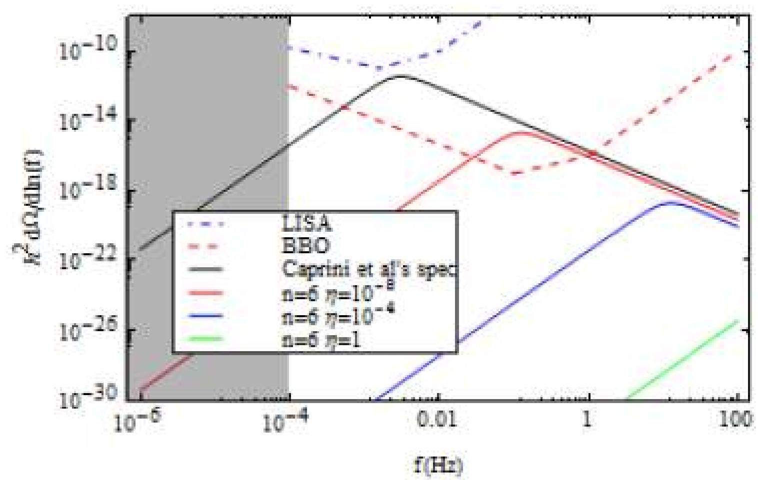
$$W_{nMSSM} = \lambda \hat{S}\hat{H}_1 \cdot \hat{H}_2 - \frac{m_{12}^2}{\lambda}\hat{S} + W_{MSSM}$$ [0709.2091]

$$\frac{V(\vec{\phi}_i) - V(\vec{\phi}_f)}{\rho_{\rm rad}} = 0.2 \qquad v_b = 0.82 \qquad T_* = 70 \text{ GeV}$$

$$\beta/H_* = 30$$

Apply to 2 analytic estimates:
Huber, Konstandin 08;
Caprini, Durrer, Servant 07



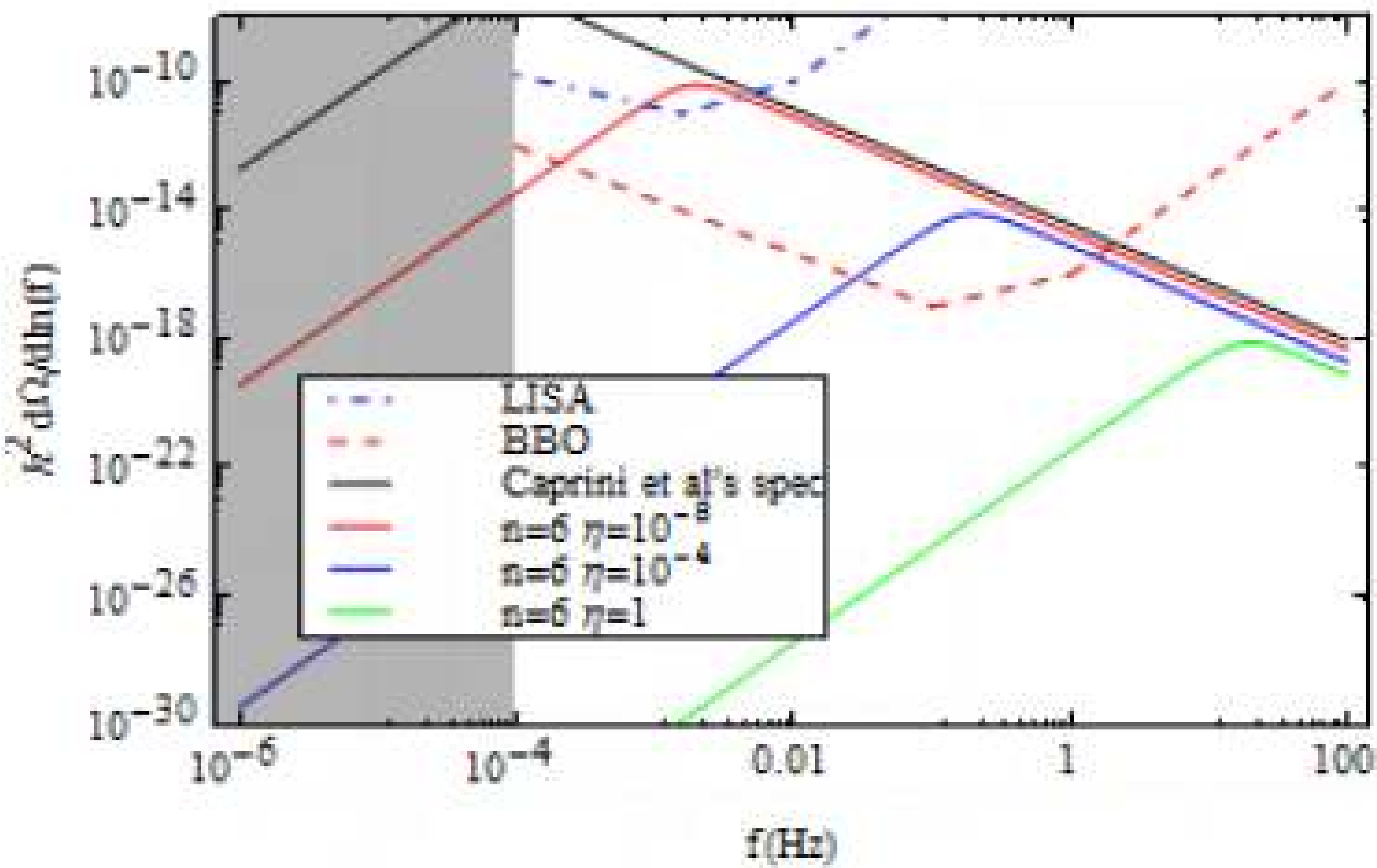


[1003.2462 w/ Peng Zhou]

Good: can rule out kination
Bad: may be negative signal

More Favorable …

$\beta/H_U = 1$ $\qquad \dfrac{V(\vec{\phi}_i) - V(\vec{\phi}_f)}{\rho_{\rm rad}} = 1$



Web of Constraints

Kination conjecture (1 parameter model)

DE
$w'(a) \neq 0$
[astro-ph/0207396, hep-ph/0309220, 0704.3285]

DM
fix discrepency
[astro-ph/0207396, hep-ph/0309220, 0706.2375]

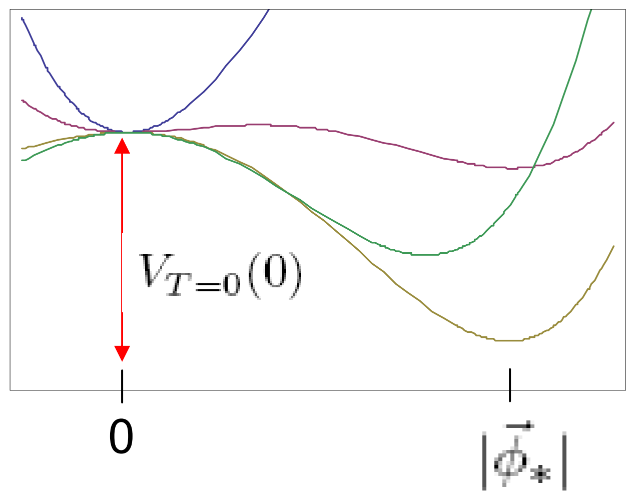
Inflation
no B-mode
[0704.3285, 0904.0675]

GW
peak shift
[0704.3285]
details of spectrum
[1003.2462 w/ Peng Zhou]

Pamela/ HEAT excess
i) boost factor
[0704.3285]
ii) model dep.

EW Bgenesis
out of equilib
[0704.3285]
details needs work

CC Energy Contribution



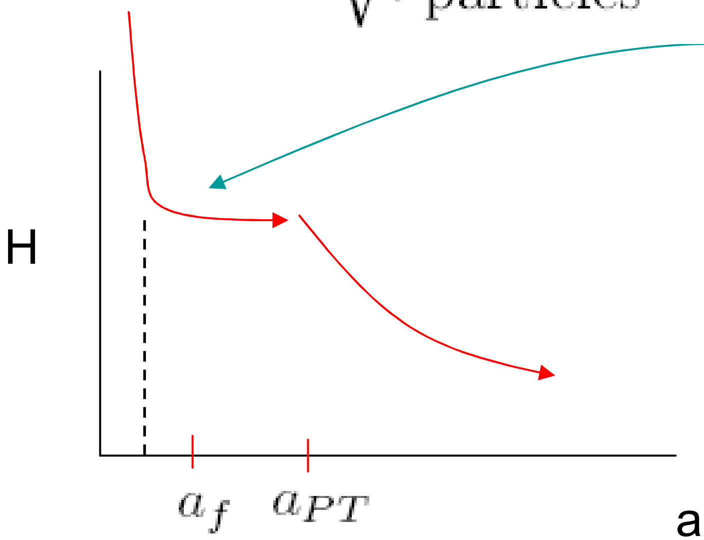
Assumptions

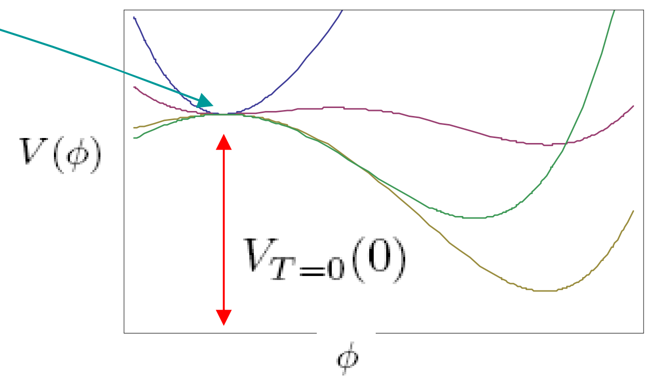
A crucial assumption made in these drawings: V at T=0 has been tuned to zero by a cosmological constant. This is consistent with a large class of landscape ideas.

$$\{\partial_i V_{T=0}(\vec{\phi}_*) = 0\}$$

$$V_{T=0}(\vec{\phi}_*) = V_{\mathrm{classiical}}(\vec{\phi}_*) + V_{\mathrm{quantum}}(\vec{\phi}_*) + V_{\Lambda} = 0$$

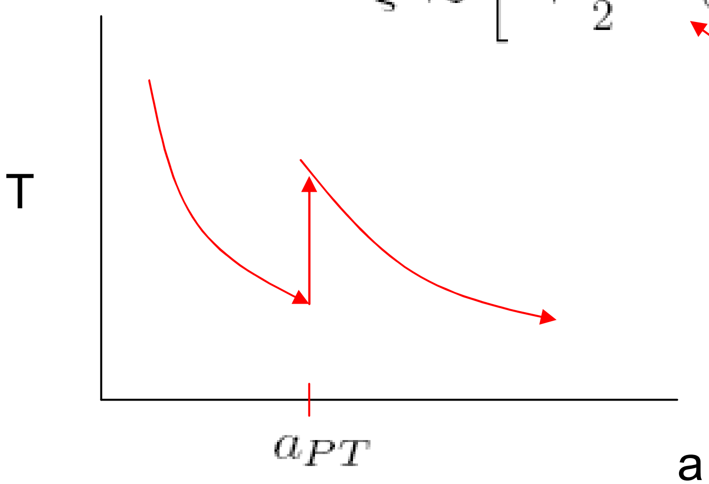
$$H \propto \sqrt{\rho_{\text{particles}} + V_{T=0}(\langle \phi(T) \rangle)}$$





$$\xi \equiv \frac{H(T_*)}{H^{(U)}(T_*)}$$

$$\xi \approx \left[1 + \frac{\epsilon_1}{2} x^4 \kappa(x) + \overbrace{\frac{2}{3}\epsilon_2 \Theta(x - (1+\delta)) + \frac{\epsilon_{31}\Theta(x-(1+\delta)) + \epsilon_{32} f(x)}{6}}^{\text{Dominant background}}\right]$$



Piece we want $\sim \dfrac{V_{T=0}(\langle \phi(T) \rangle)}{\rho_{\text{particles}}}$

$$\sim \frac{1}{g_*(T_c)} < 10^{-2}$$

Since entropy maximized

[Related work complete with Long, Tulin and Wang.]

Better for QCD PT, but different talk.

CC shift near 100 GeV?

Tuned CC conjecture

Connection to collider

negligible

DM

fix discrepency

Requires heavy dark matter since

$$m_X \approx 1\mathrm{TeV}\left(\frac{T_F}{50\ \mathrm{GeV}}\right)$$

GW

EW Bgenesis

Summary

1) New microphysics of electroweak scale PTs may be discovered.

2) Gravity wave astronomy may play a similar role as BBN relative isotope measurements for T= electroweak scale.

$$\frac{d\rho_{GW}(k)}{d\ln k} \rightarrow \frac{1}{\xi^2}\frac{d\rho_{GW}(k/\xi)}{d\ln k} \qquad \xi \equiv \frac{H(T_*)}{H^{(U)}(T_*)}$$

(1003.2462)

3) In principle (although unlikely), GW may even probe the fine tuning conjecture of the cosmological constant!