Gravitational Waves
from the
EW Phase Transition

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The EW Phase Transition

WHY?

➔ Yield Precise Understanding of EWSB in Early Universe

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➔ Yield Precise Understanding of EWSB in Early Universe

➔ **(Possible) Answer to Open Mysteries at Interface of Particle Physics & Cosmology**

Origin of Matter-Antimatter Asymmetry

▶ EW-scale Baryogenesis

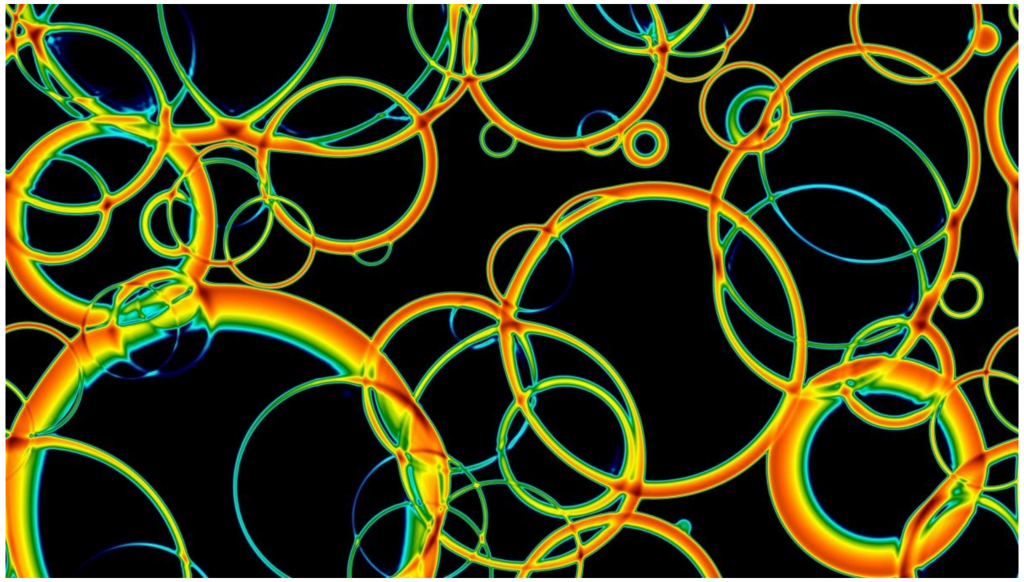
The EW Phase Transition

WHY?

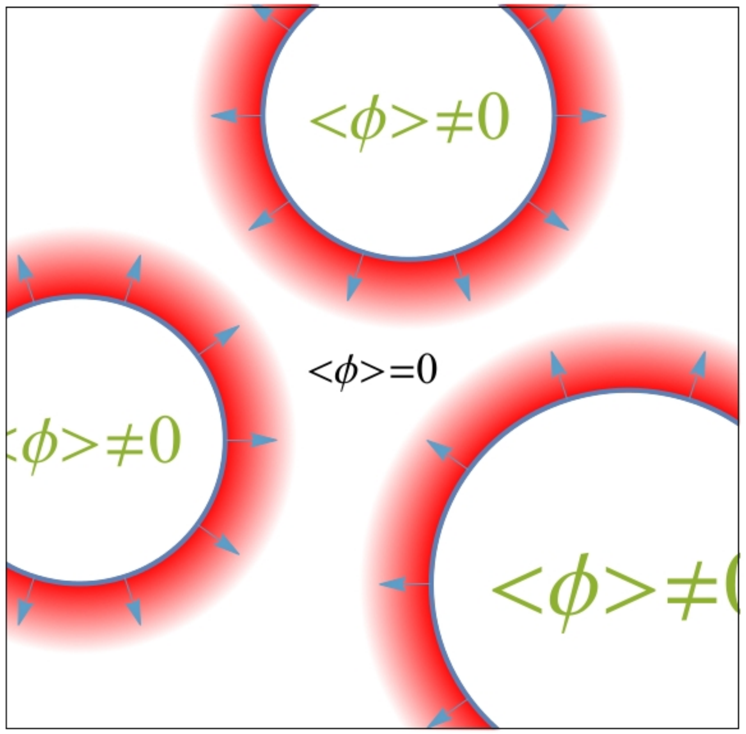
- ➔ Yield Precise Understanding of EWSB in Early Universe
- ➔ (Possible) Answer to Open Mysteries at Interface of Particle Physics & Cosmology
- ➔ **(Possible) Cosmological Relics from the EW Epoch**

Gravitational Wave Signal

Sourced by Collisions of Higgs bubbles from a first order EW phase transition & subsequent plasma motions

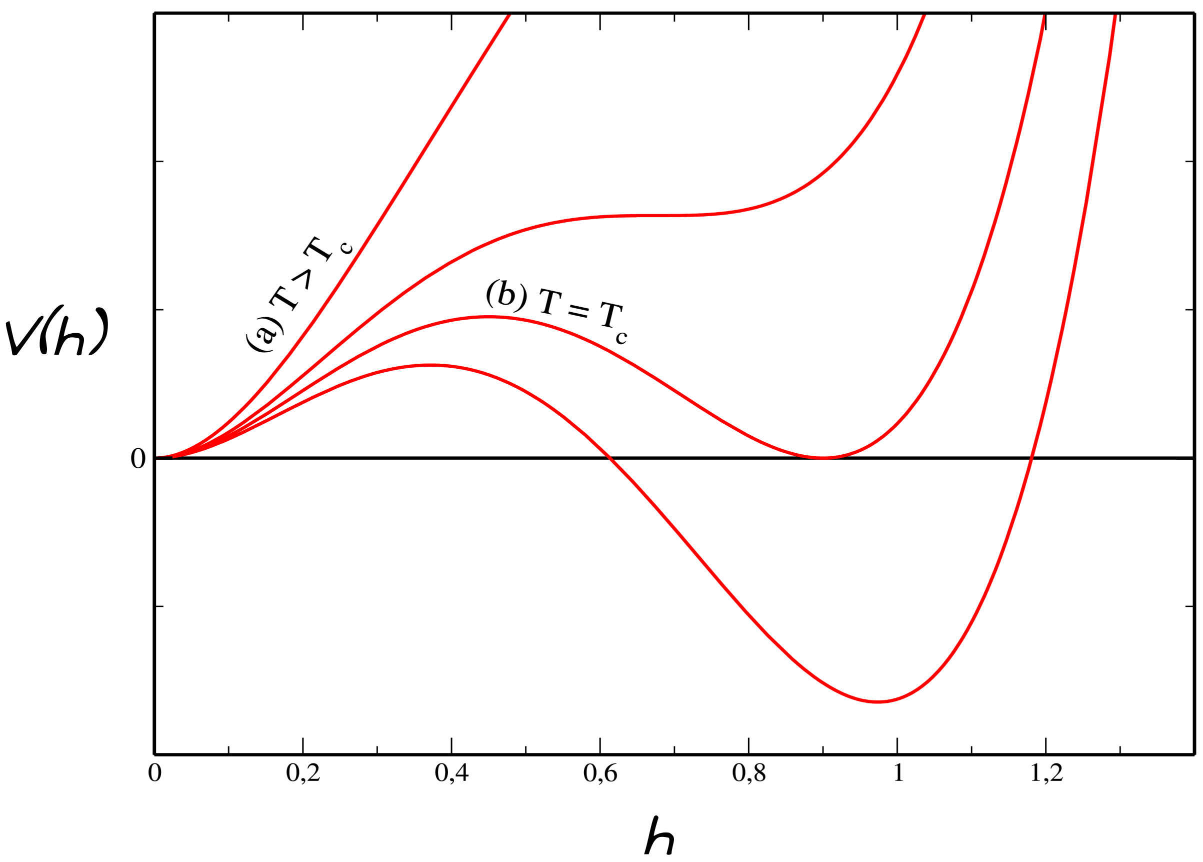


Courtesy of D. Weir (Helsinki)
*Hindmarsh, Huber, Rummukainen, Weir, PRD **92** (2015) 123009*



Assume a 1st Order EW Phase Transition…

Higgs Effective Potential (finite T)



- Phases separated by potential barrier
- Broken phase bubbles nucleate, expand, merge

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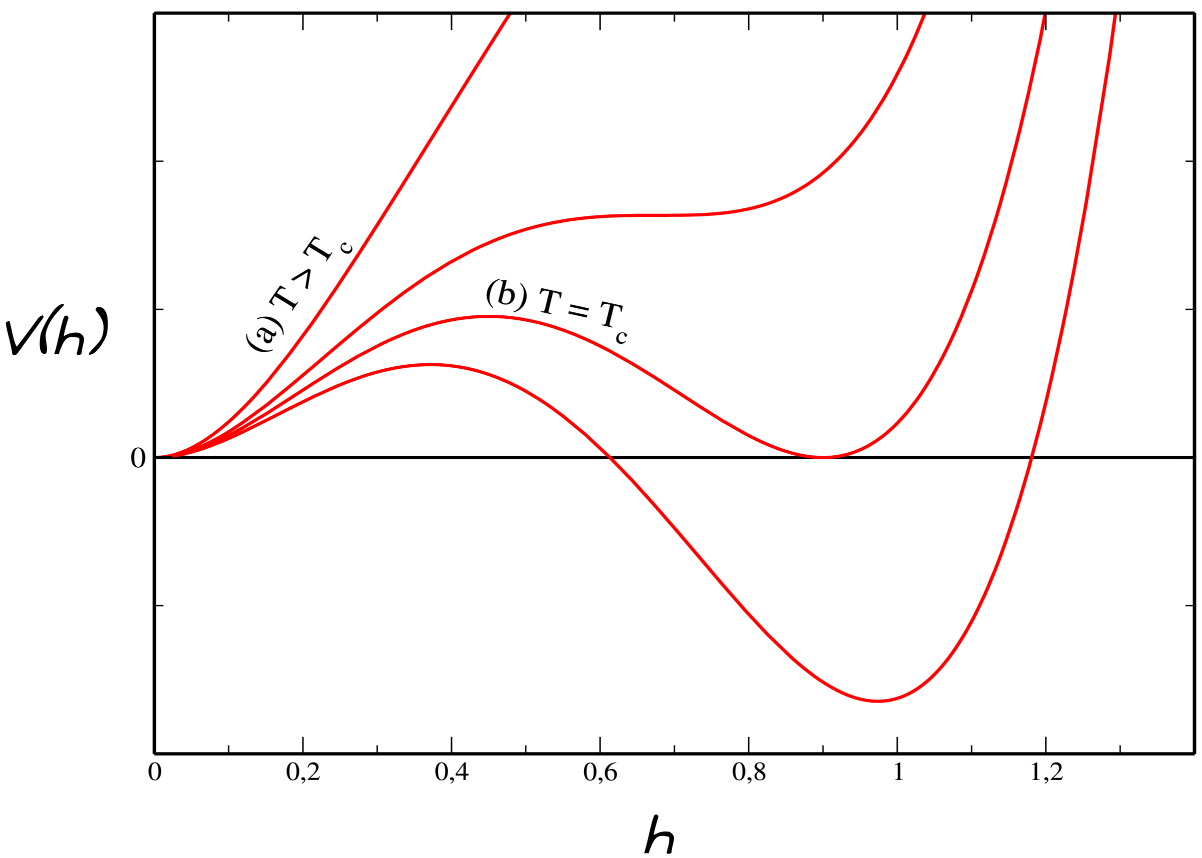

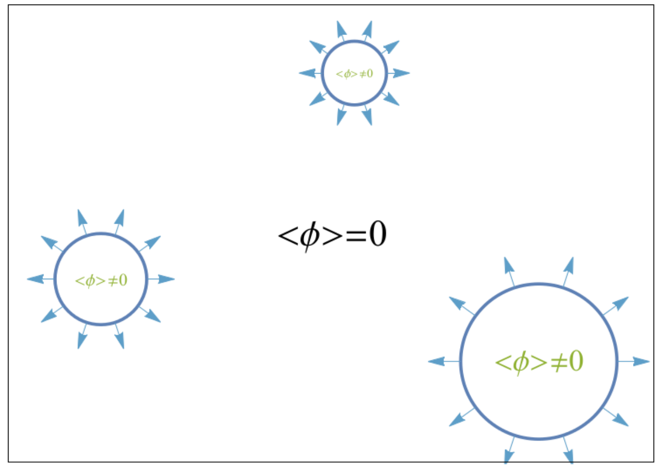

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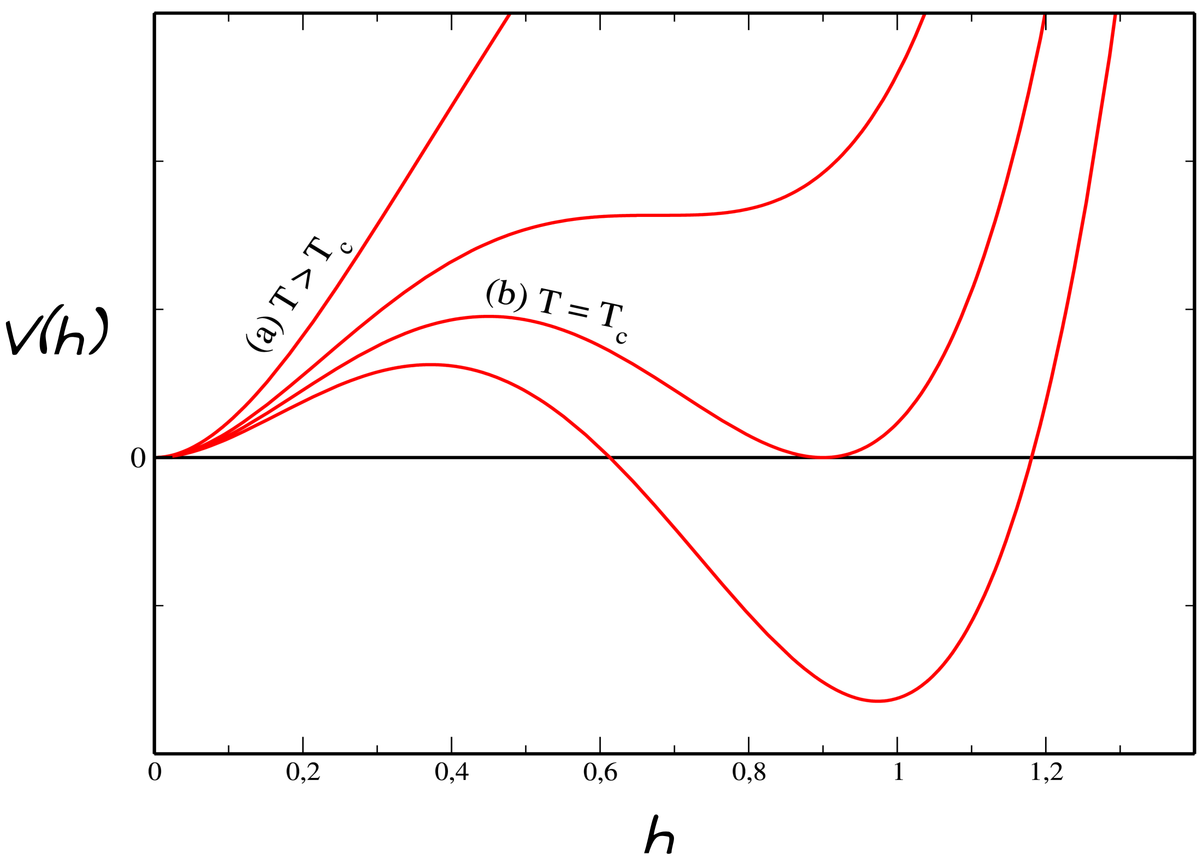

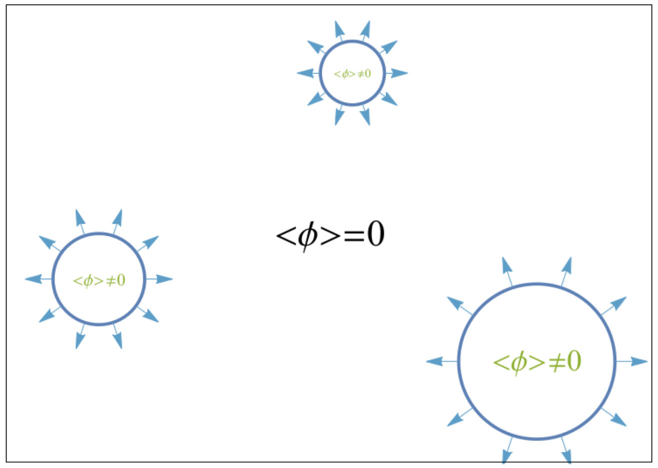

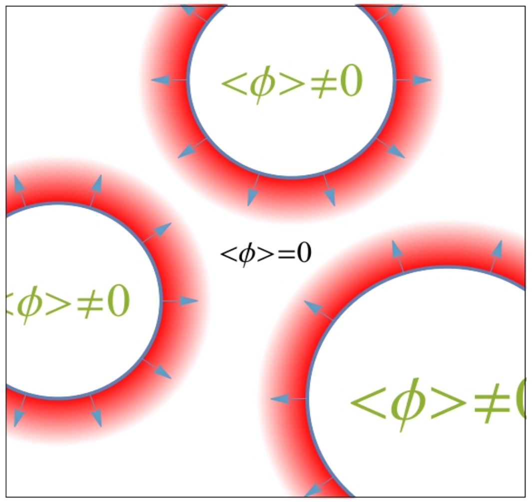

(if in plasma → create fluid waves)

- Phases separated by potential barrier
- Broken phase **bubbles** nucleate, **expand**, merge

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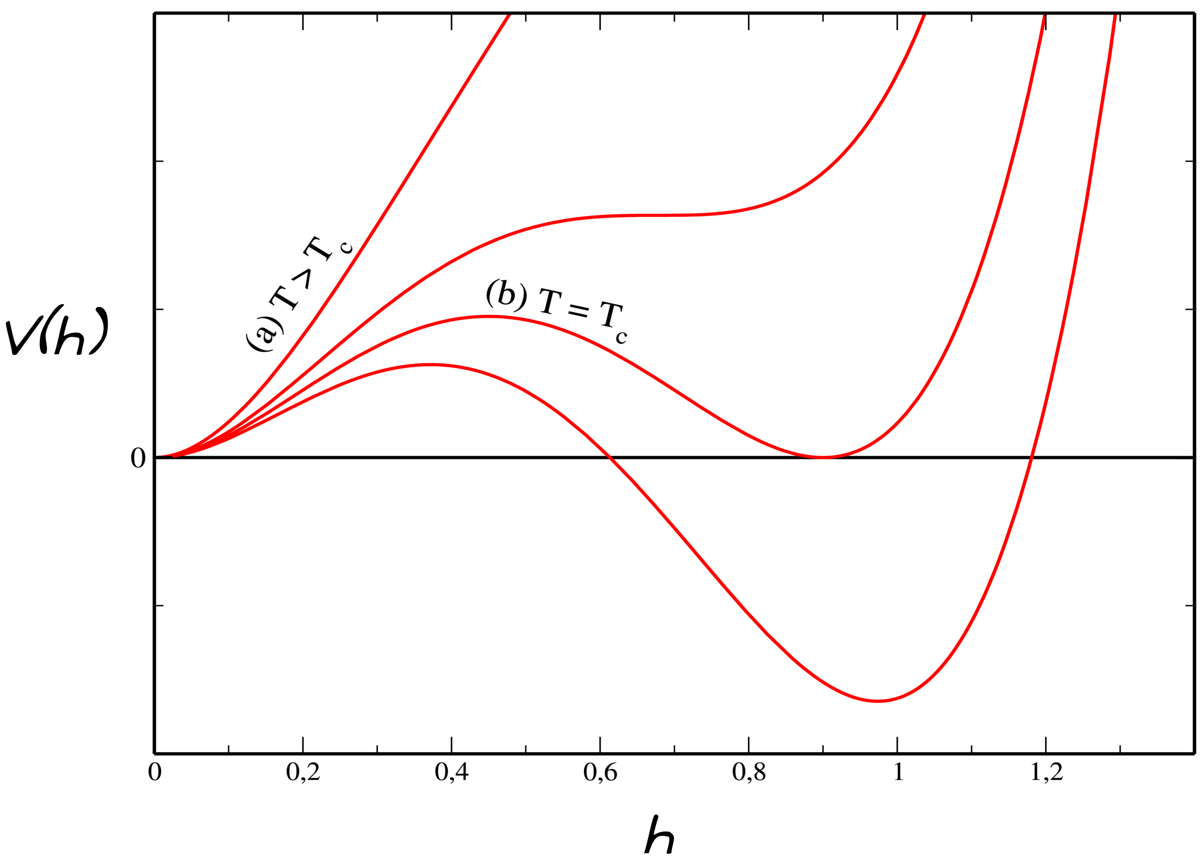

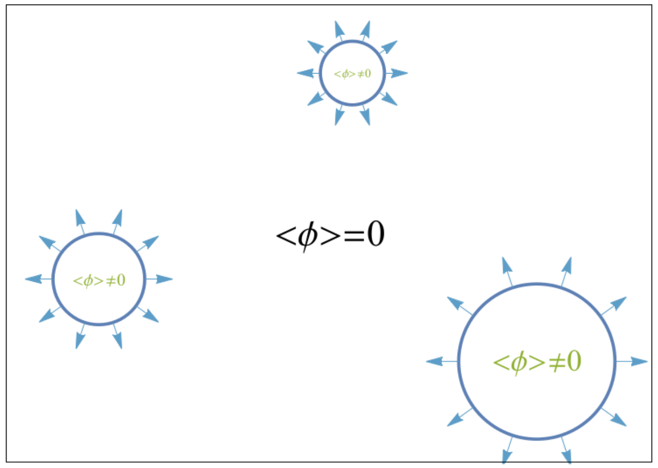

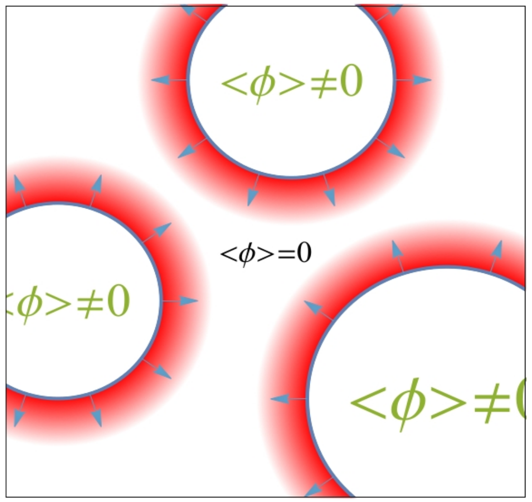

- Phases separated by potential barrier
- Broken phase **bubbles** nucleate, expand, **merge/collide** → Anisotropic Stress

⇩

Sources Gravitational Wave Production

Assume a 1st Order EW Phase Transition...

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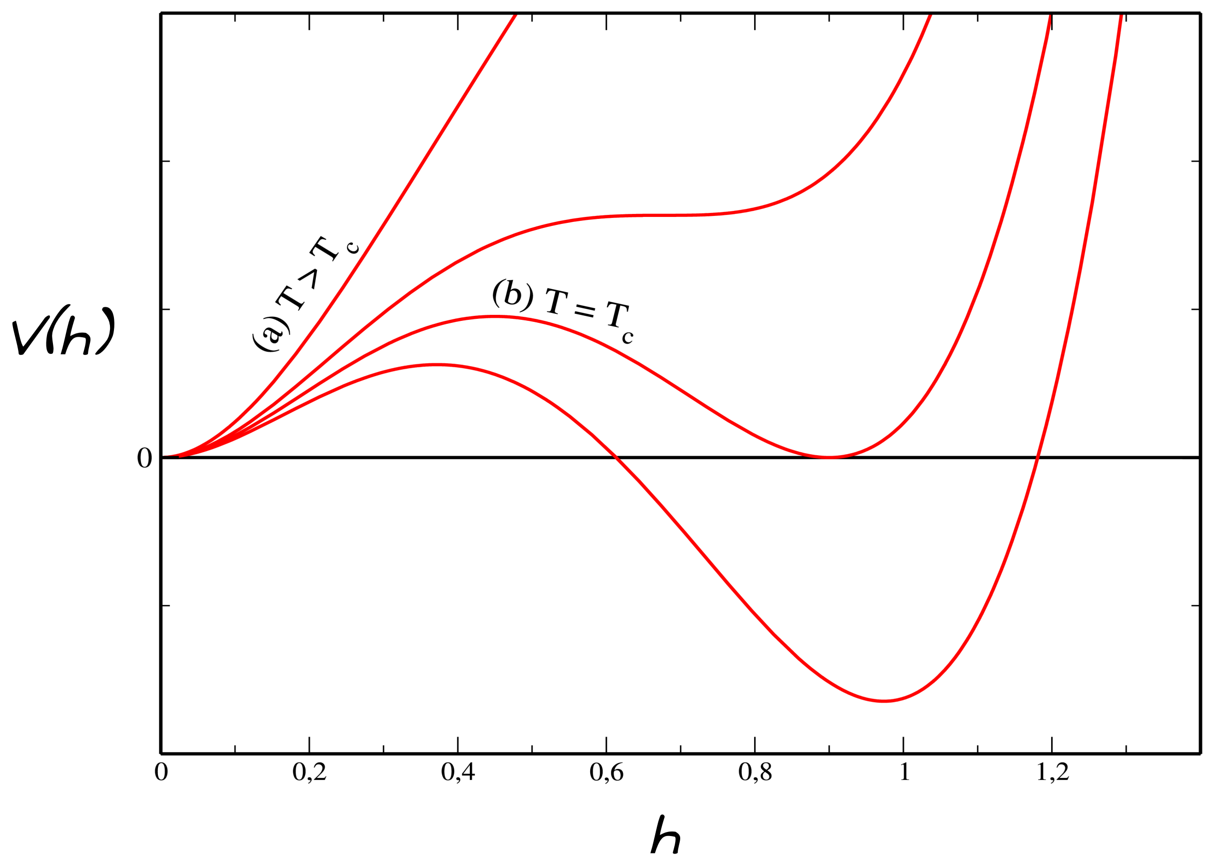
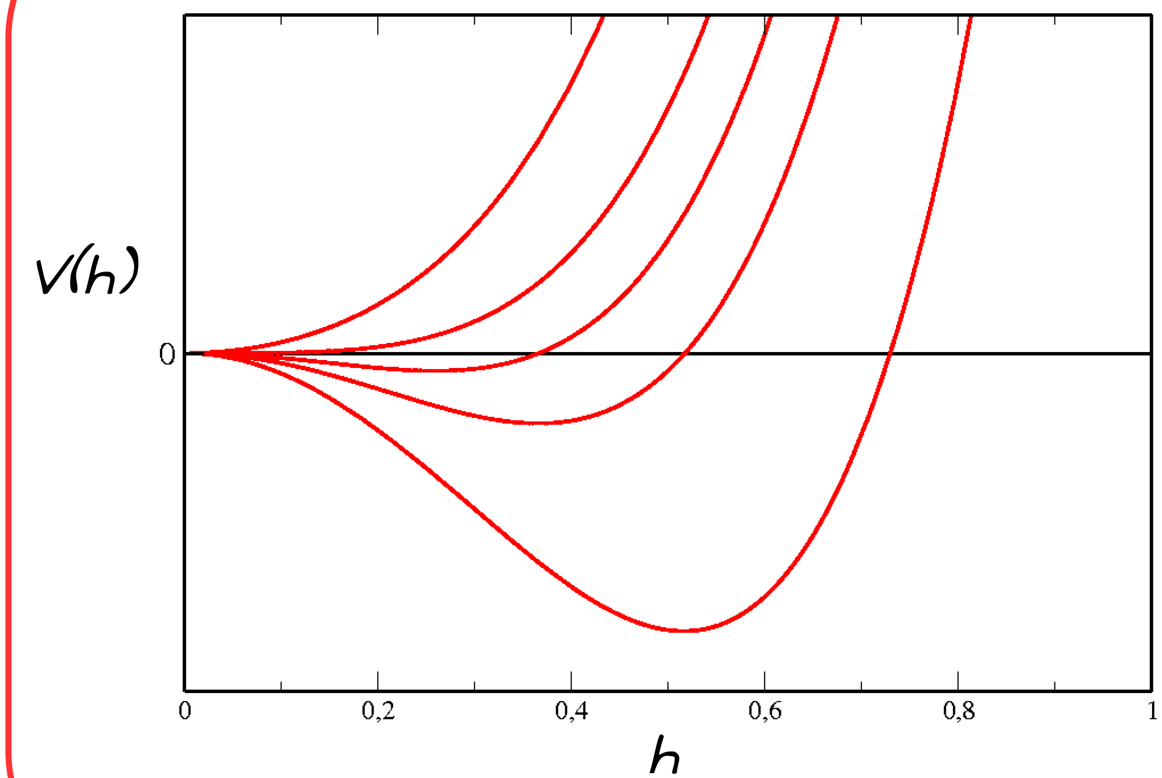


In the Standard Model...



NO 1st Order EW Phase Transition

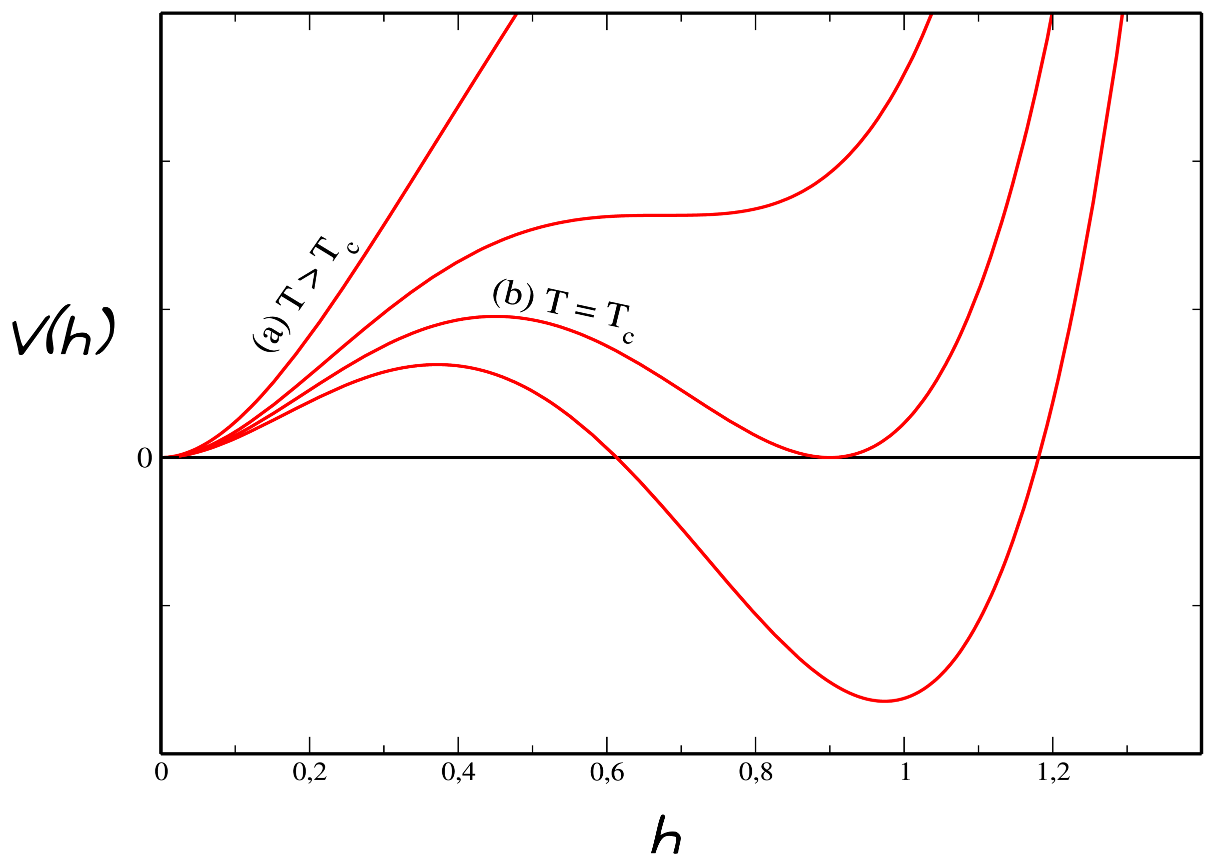
EWPT (non-perturbatively) is smooth cross-over

Kajantie, Laine, Rummukainen, Shaposhnikov, Phys. Rev. Lett. ***77*** *(1996) 2887*

Physics Beyond the SM can induce a 1st Order EW Phase Transition

Assume a 1^{st} Order Phase Transition...

Effective Potential (finite T)



Two "Types" of Cosmological 1^{st} Order PTs

- "Vacuum" Transitions

  Fluid/plasma effects negligible

  (either plasma is very diluted or coupling between transition field and plasma small/non-existent)

  Bubble walls accelerate until collision

  Energy of PT stored in bubble walls

- Thermal Transitions

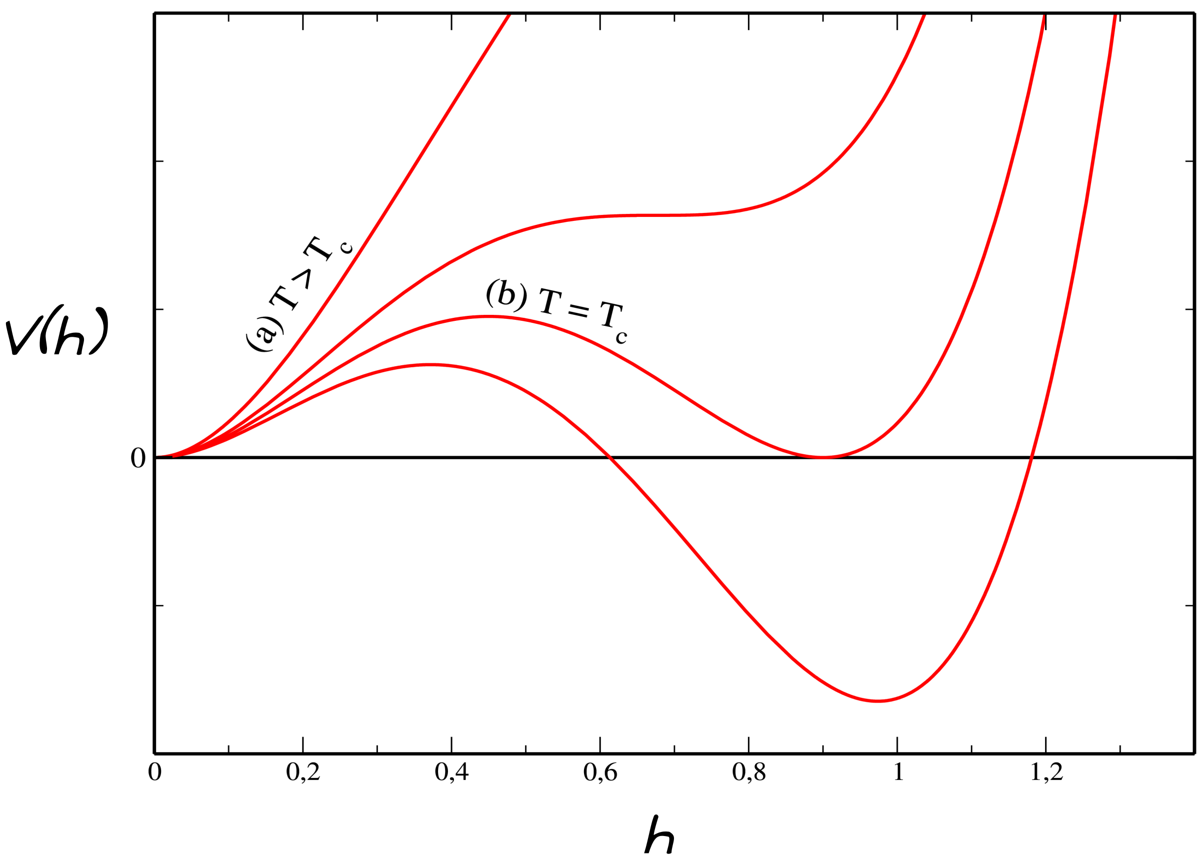
  Energy of PT transferred to plasma

  Plasma exerts friction on bubble wall

  Terminal bubble wall velocity
  (steady state)

Assume a 1st Order Phase Transition...

Effective Potential (finite T)



- Decay rate $\Gamma(T) \approx T^4 \exp\left(-\frac{S_3(T)}{T}\right)$
- O(3) symmetric action

$$S_3(T) = 4\pi \int dr r^2 \left[\frac{1}{2}\left(\frac{d\phi}{dr}\right)^2 + V(\phi, T)\right]$$

- Bubble profile (bounce)

$$\frac{d^2\phi}{dr^2} + \frac{2}{r}\frac{d\phi}{dr} - \frac{\partial V(\phi, T)}{\partial \phi} = 0$$

$$\phi(r \to \infty) = 0 \quad \text{and} \quad \dot{\phi}(r = 0) = 0$$

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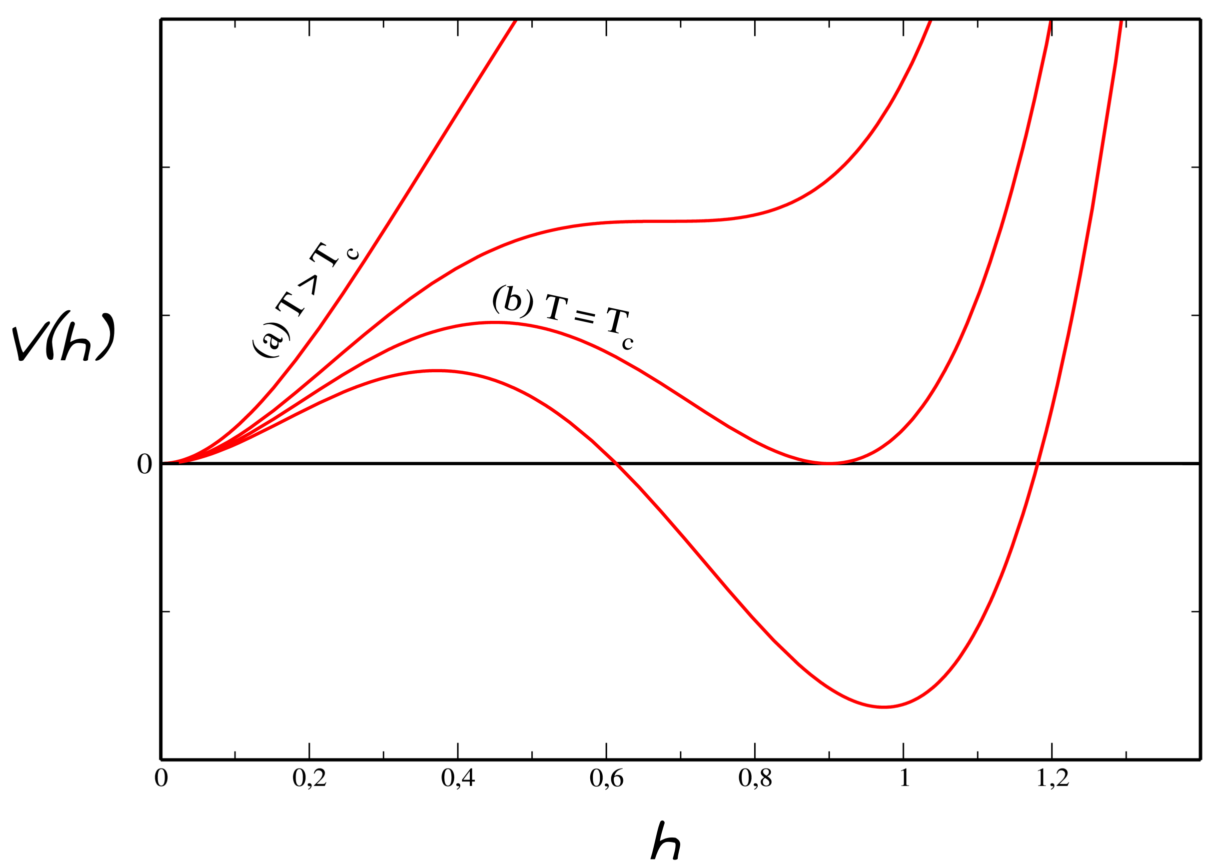

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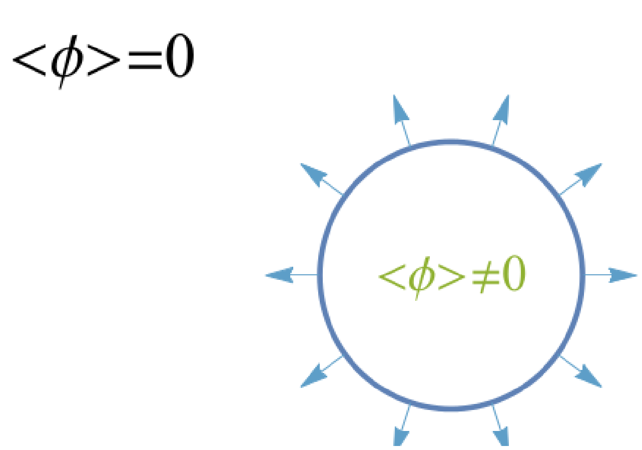

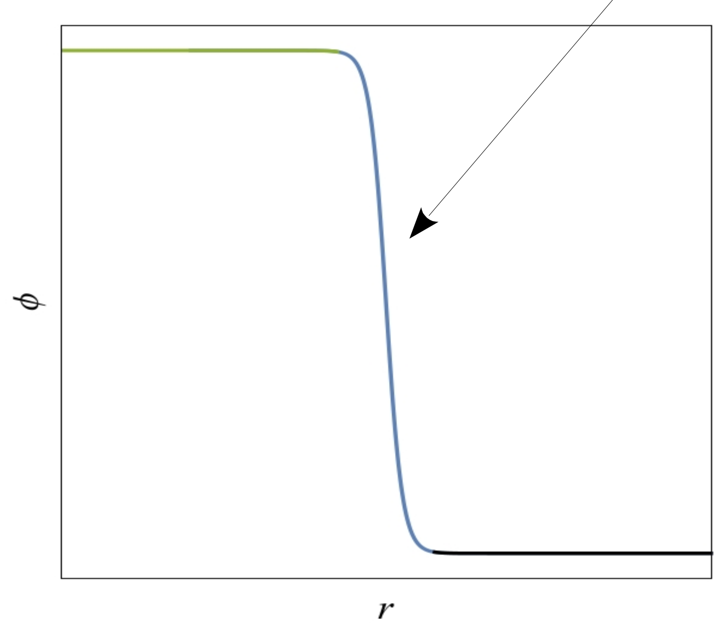

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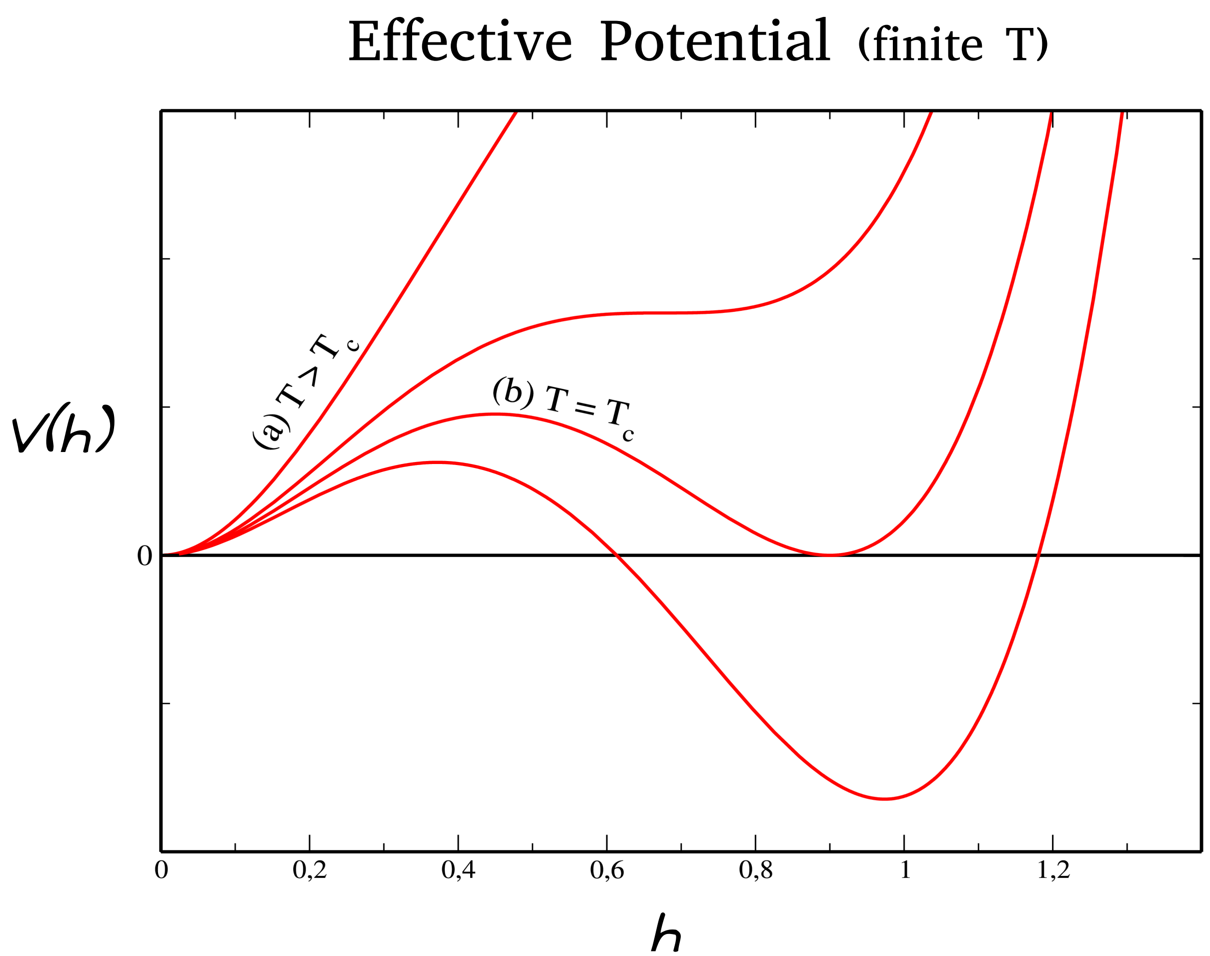

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Nucleation temperature:

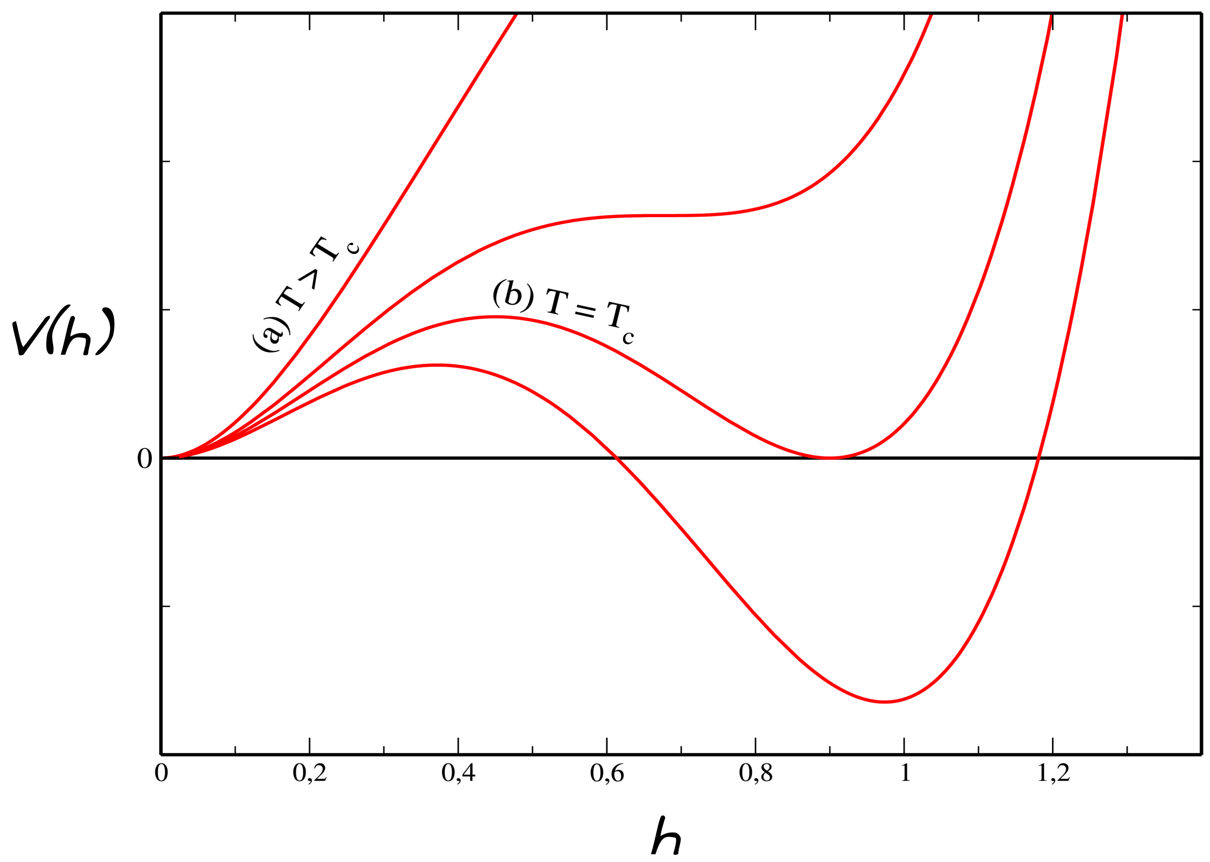
One Higgs bubble per Horizon volume (on average)

$$N(T_n) = \int_{t_c}^{t_n} dt \frac{\Gamma(t)}{H(t)^3} = \int_{T_n}^{T_c} \frac{dT}{T}\frac{\Gamma(T)}{H(T)^4} = 1$$

*Linde, Phys. Lett. B**100** (1981) 37; Nucl. Phys. B**216** (1983) 421*

Assume a 1st Order Phase Transition...

Effective Potential (finite T)



Two KEY Phase Transition Quantities:

- (Available) Transition Energy (normalized)

$$\alpha = \frac{\epsilon}{a_+ T^4}$$

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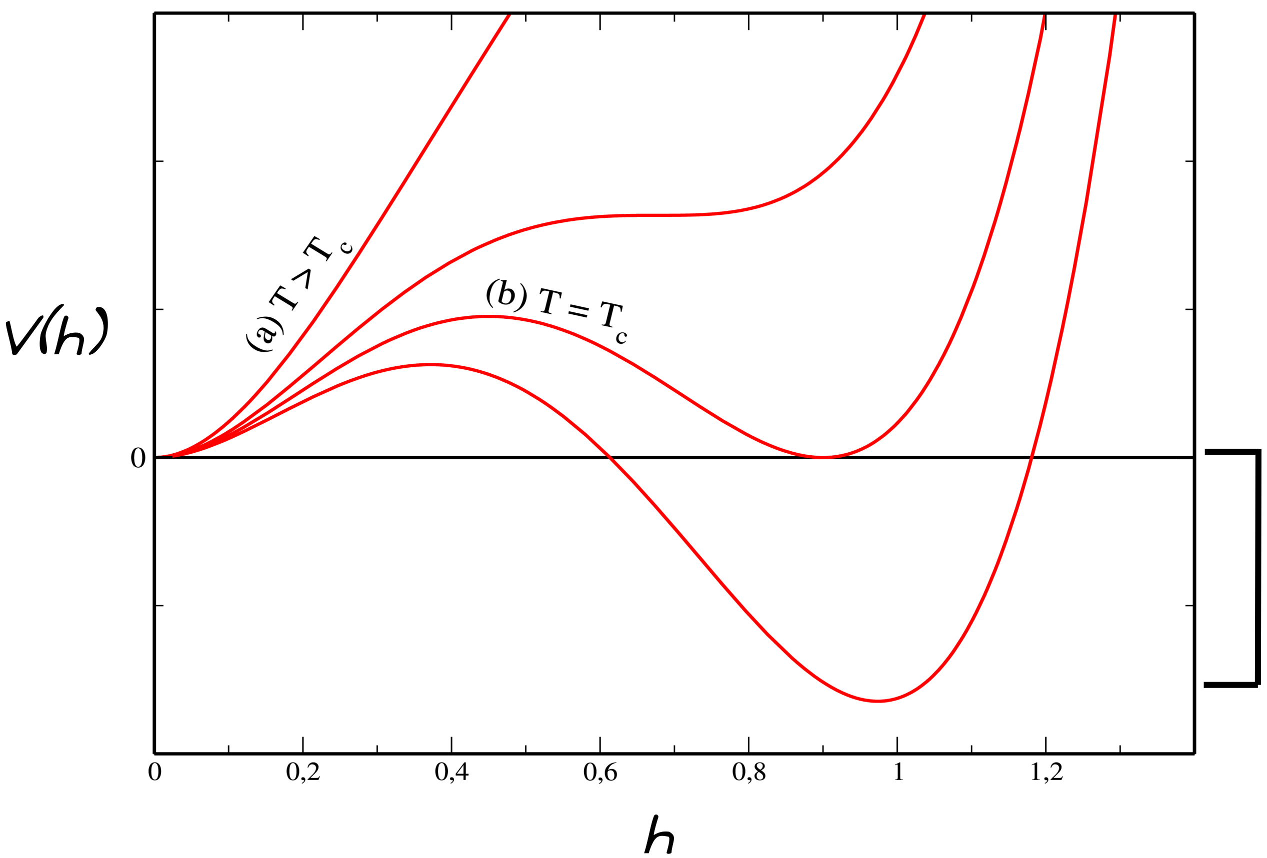

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Radiation Energy Density

Assume a 1st Order Phase Transition...

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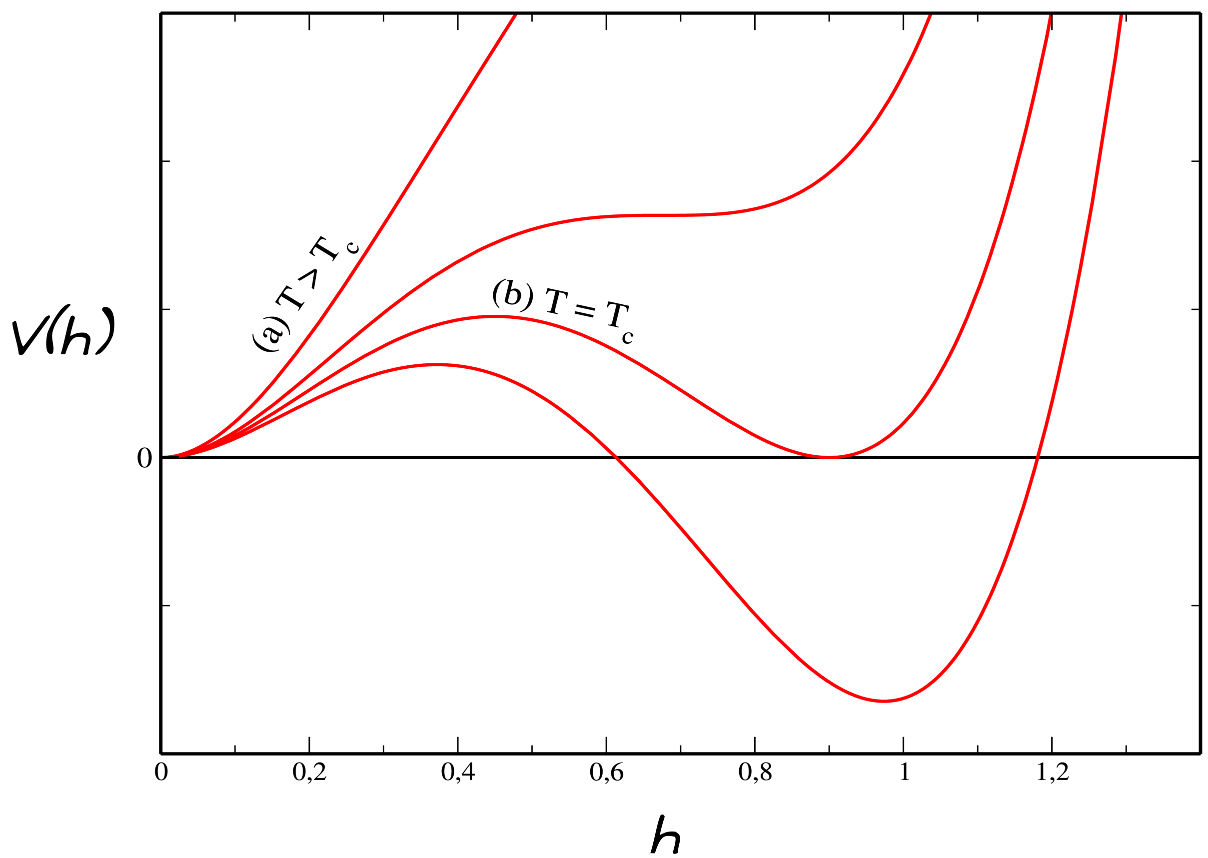

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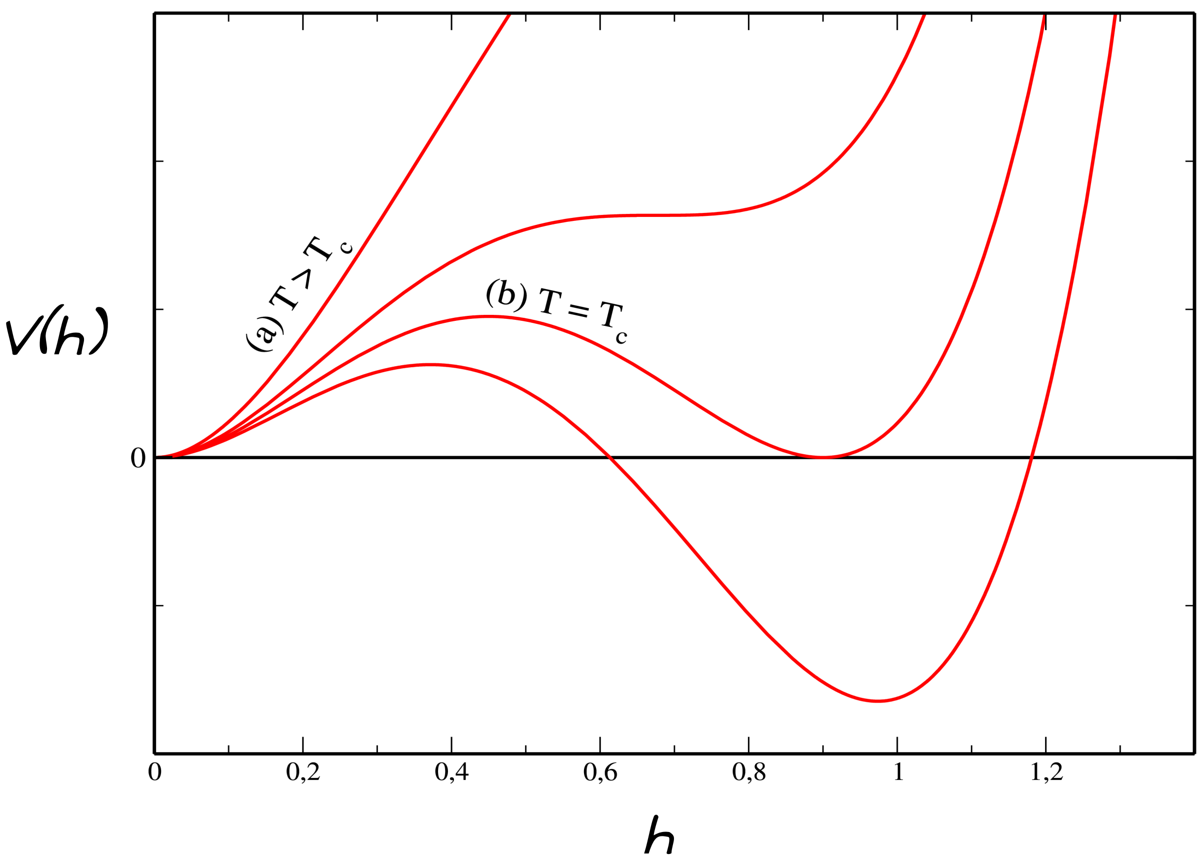

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$$\frac{\beta}{H} \equiv -\frac{dS_3}{dt}\Big|_{t=t_n} \approx T\frac{d(S_3/T)}{dT}\Big|_{T=T_n}$$

(Related to the change of the Decay Rate)

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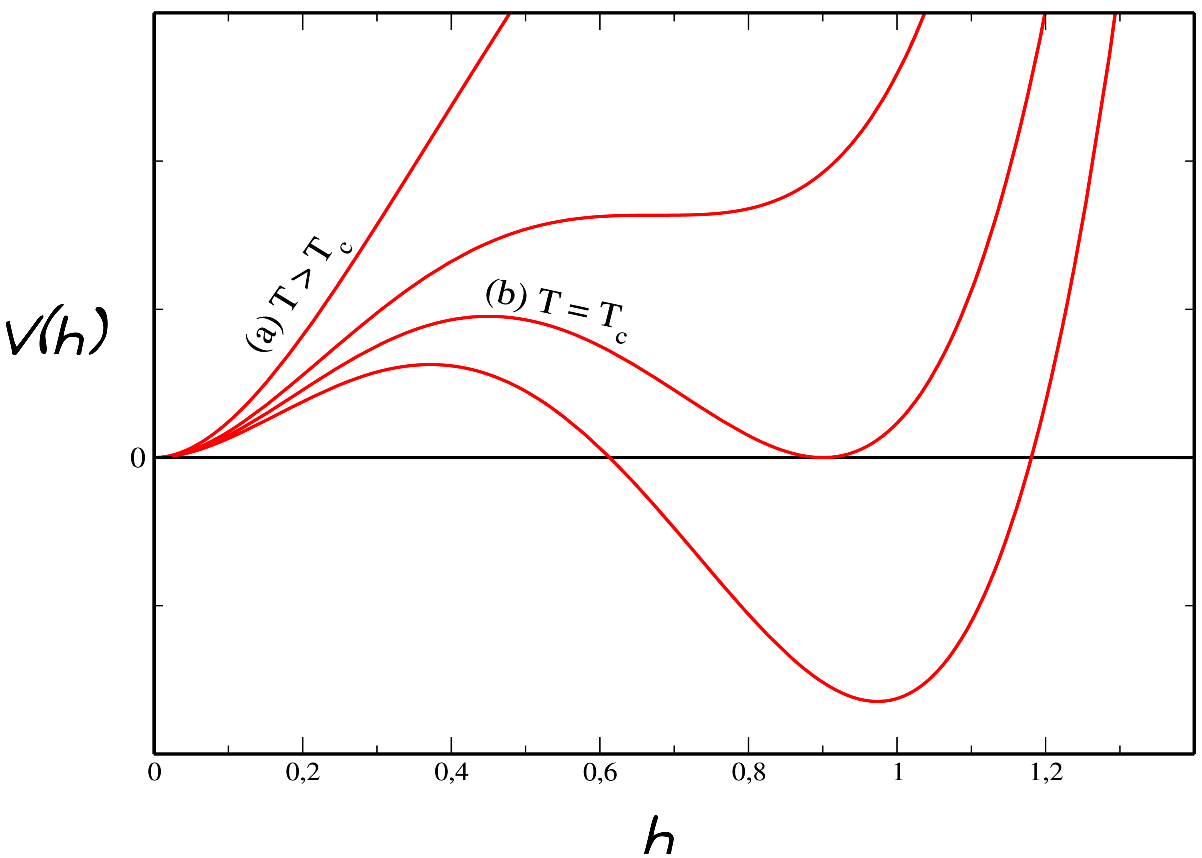

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Average number of bubbles per horizon at the time of bubble coalescence/percolation

(Transition Completes, T_* **)**

H_*

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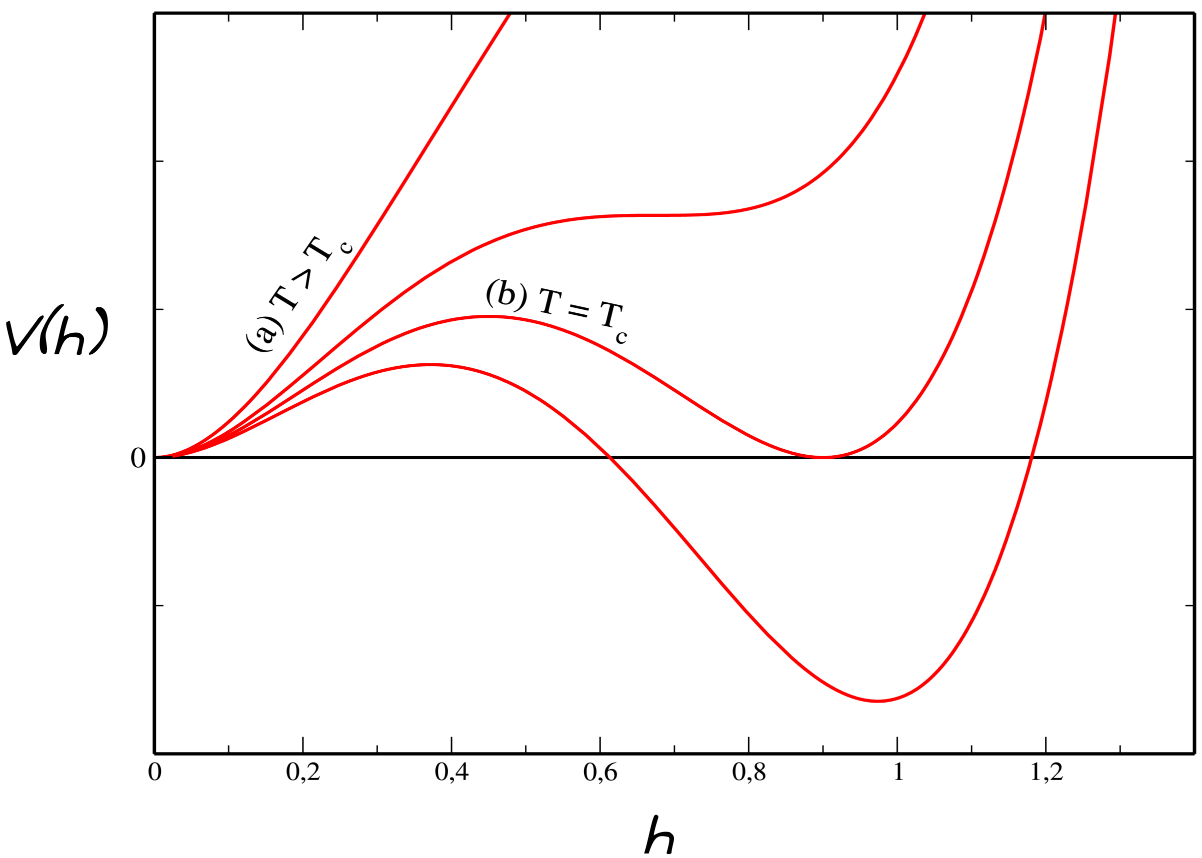

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(Related to the change of the Decay Rate)

Average number of bubbles per horizon at the time of bubble coalescence/percolation

(Transition Completes, T_*)

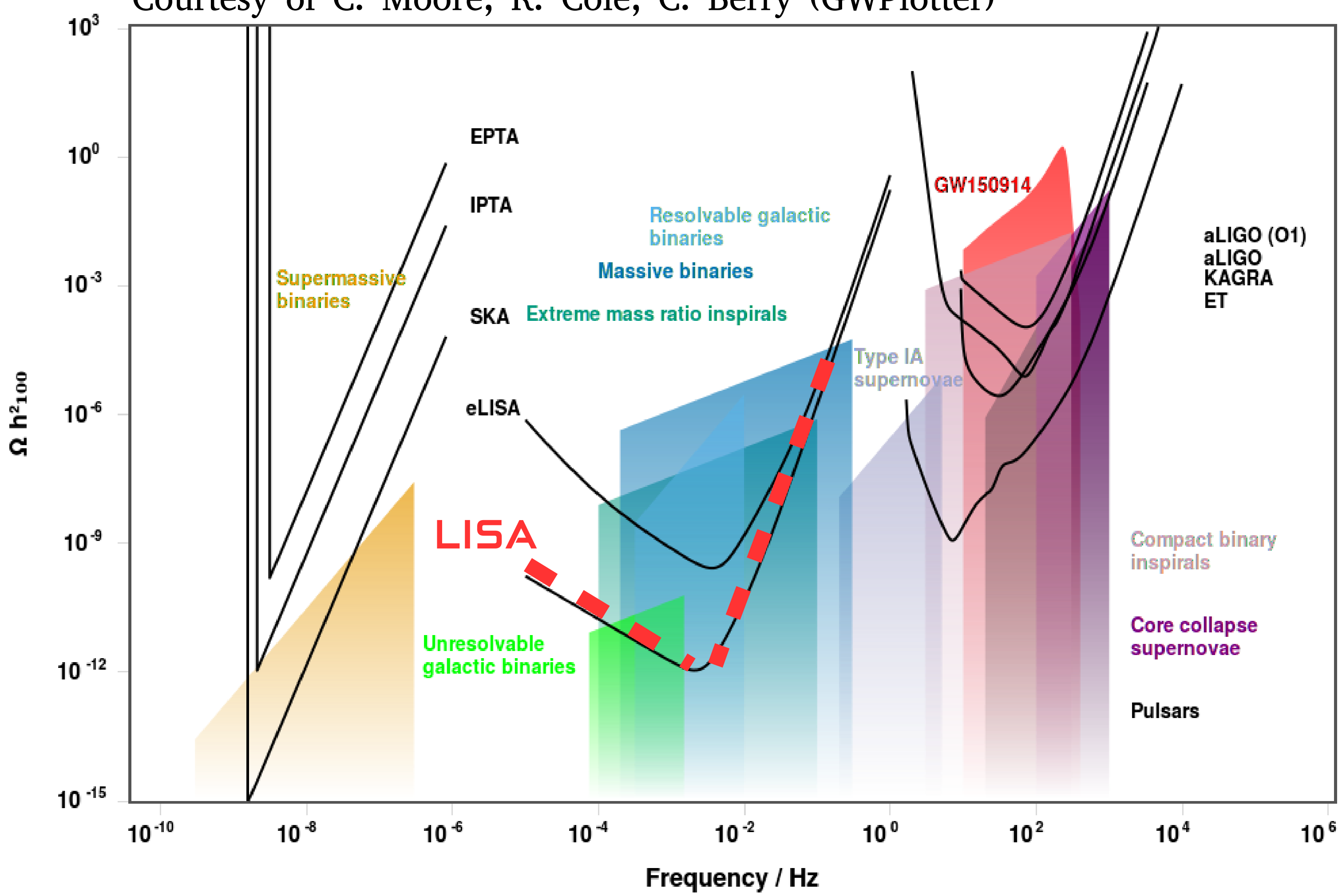
H_*

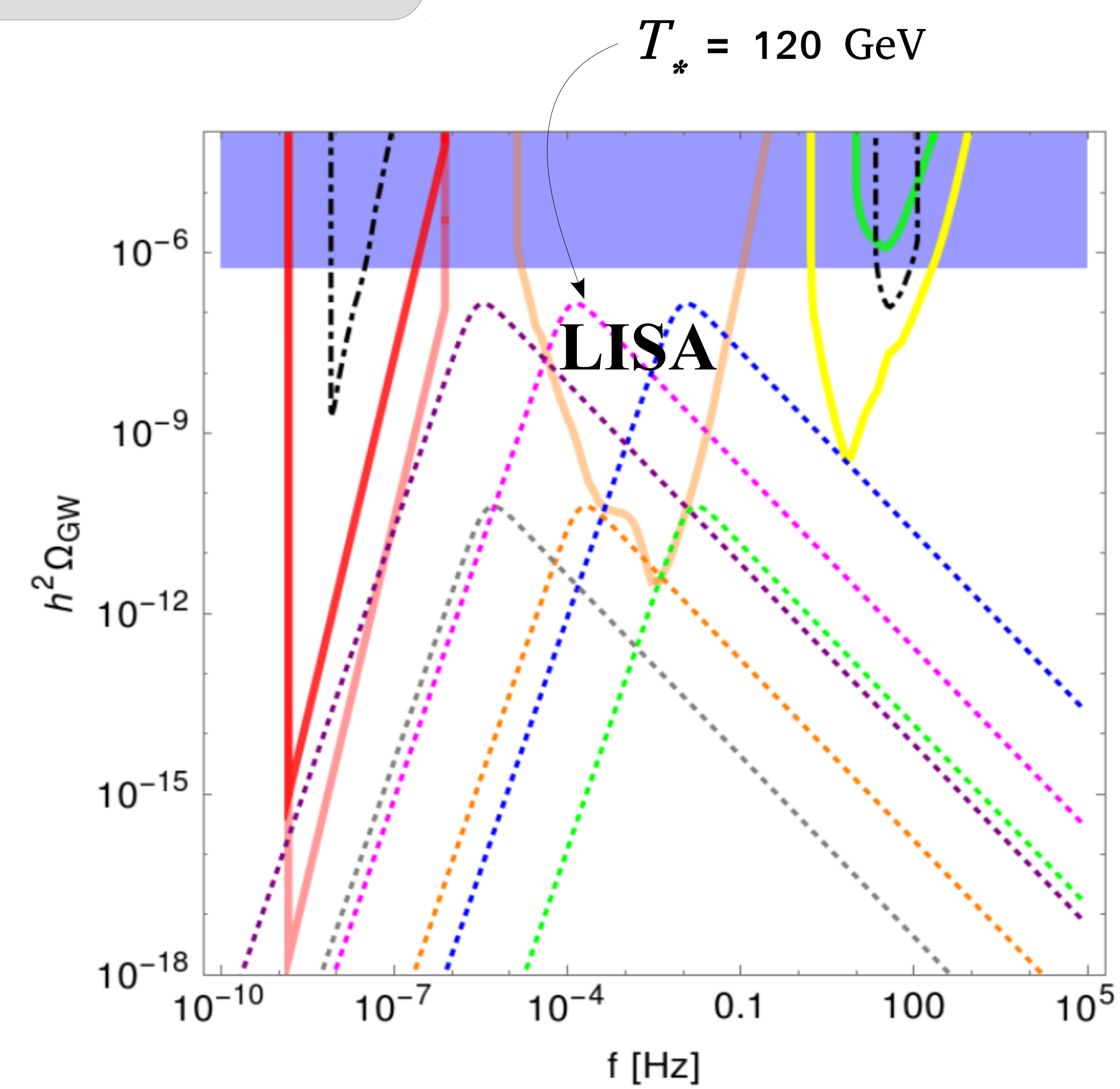
- GW frequency ~ **size of bubbles @ collision**
- For $T_* \sim 100$ GeV and $\frac{\beta}{H_*} \sim 100$, GW frequency (redshifted to today!) ~ **mHz**

1st Order (EW) Phase Transition

mHz GW Signal in the sensitivity band of future space-based GW detector **LISA**

Courtesy of C. Moore, R. Cole, C. Berry (GWPlotter)





Figueroa et al., PoS GRASS2018 (2018) 036

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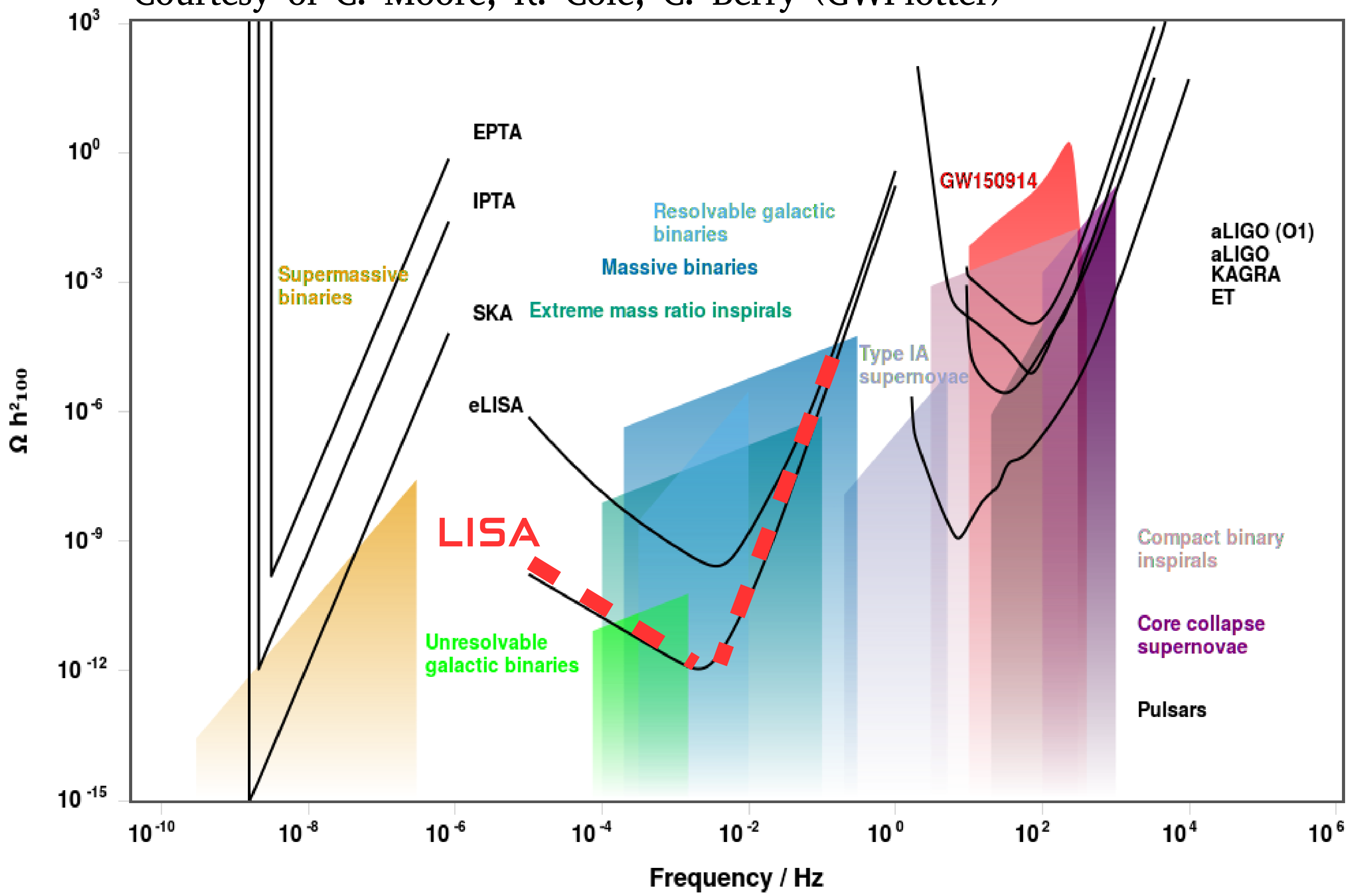
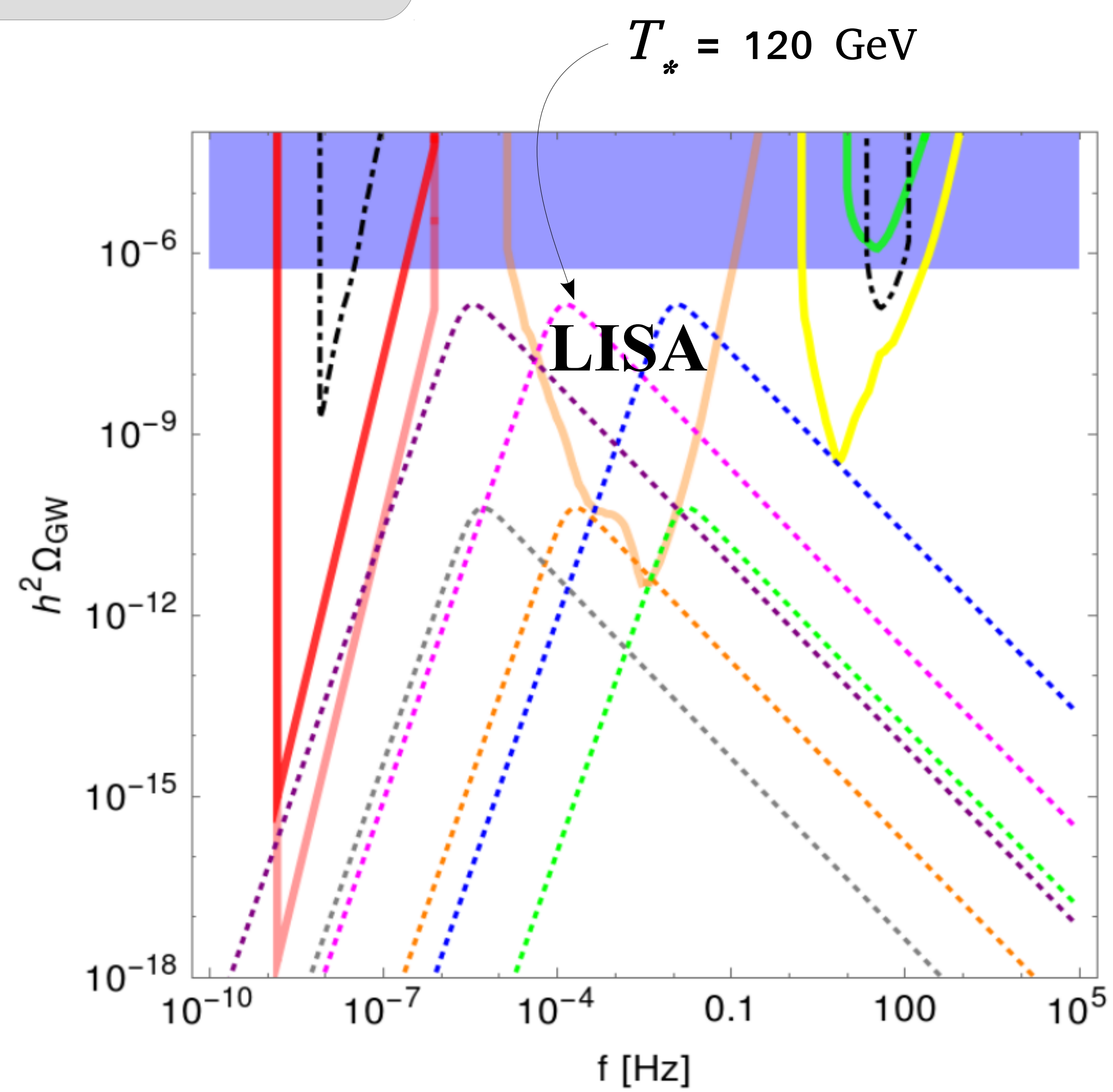




Figueroa et al., PoS GRASS2018 (2018) 036

LISA can probe the **EW epoch** of the early Universe

(

https://www.elisascience.org/

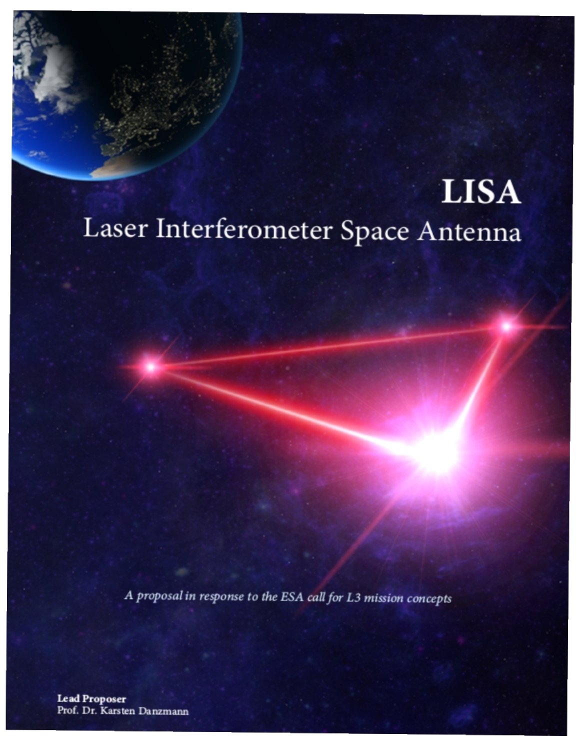
The LISA Mission

(Laser Interferometer Space Antenna)

A brief status report

Thanks to G. Nardini

2017: LISA proposal to ESA

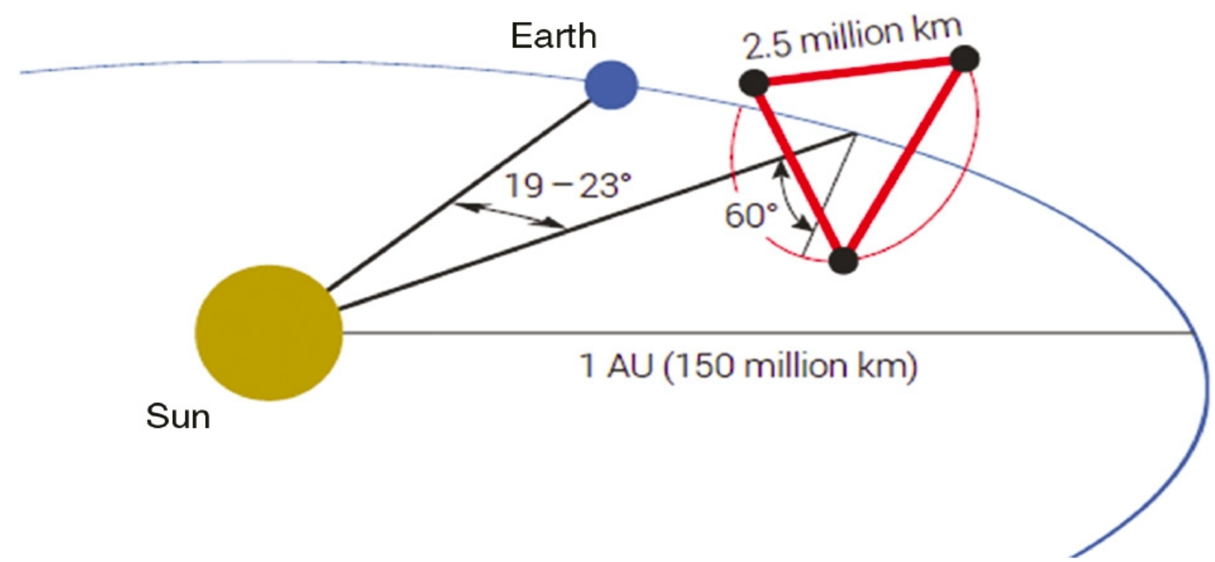


LISA Collaboration, 1702.00786

Launch date **2030-2034**

LISA Mission selected by ESA (Summer **2017**)

+ (On Jan 22 2018, LISA passed ESA's Mission Definition Review)



4 years of lifetime (w. consumables up to 10 years)

2.5 MKm (arm length)

From the proposal:

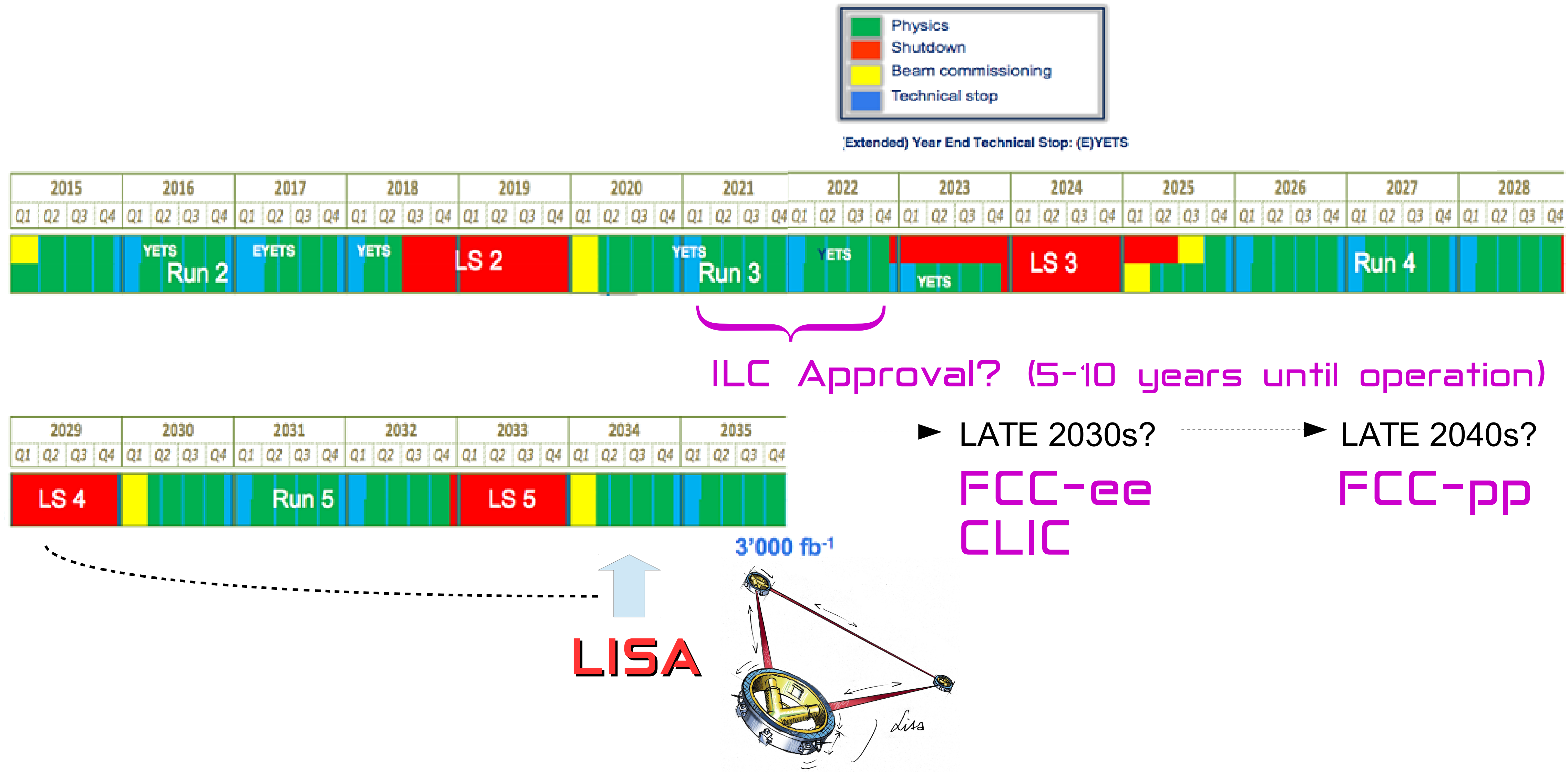
Audley et al, arXiv:1702.00786

SI7.2 : Measure, or set upper limits on, the spectral shape of the cosmological stochastic GW background

OR7.2: Probe a broken power-law stochastic background from the early Universe as predicted, for example, by first order phase transitions [21] (other spectral shapes are expected, for example, for cosmic strings [22] and inflation [23]). Therefore, we need the ability to measure $\Omega = 1.3 \times 10^{-11} \left(f/10^{-4}\,\mathrm{Hz}\right)^{-1}$ in the frequency ranges $0.1\,\mathrm{mHz} < f < 2\,\mathrm{mHz}$ and $2\,\mathrm{mHz} < f < 20\,\mathrm{mHz}$, and $\Omega = 4.5 \times 10^{-12} \left(f/10^{-2}\,\mathrm{Hz}\right)^{3}$ in the frequency ranges $2\,\mathrm{mHz} < f < 20\,\mathrm{mHz}$ and $0.02 < f < 0.2\,\mathrm{Hz}$.

GW – Collider complementarity

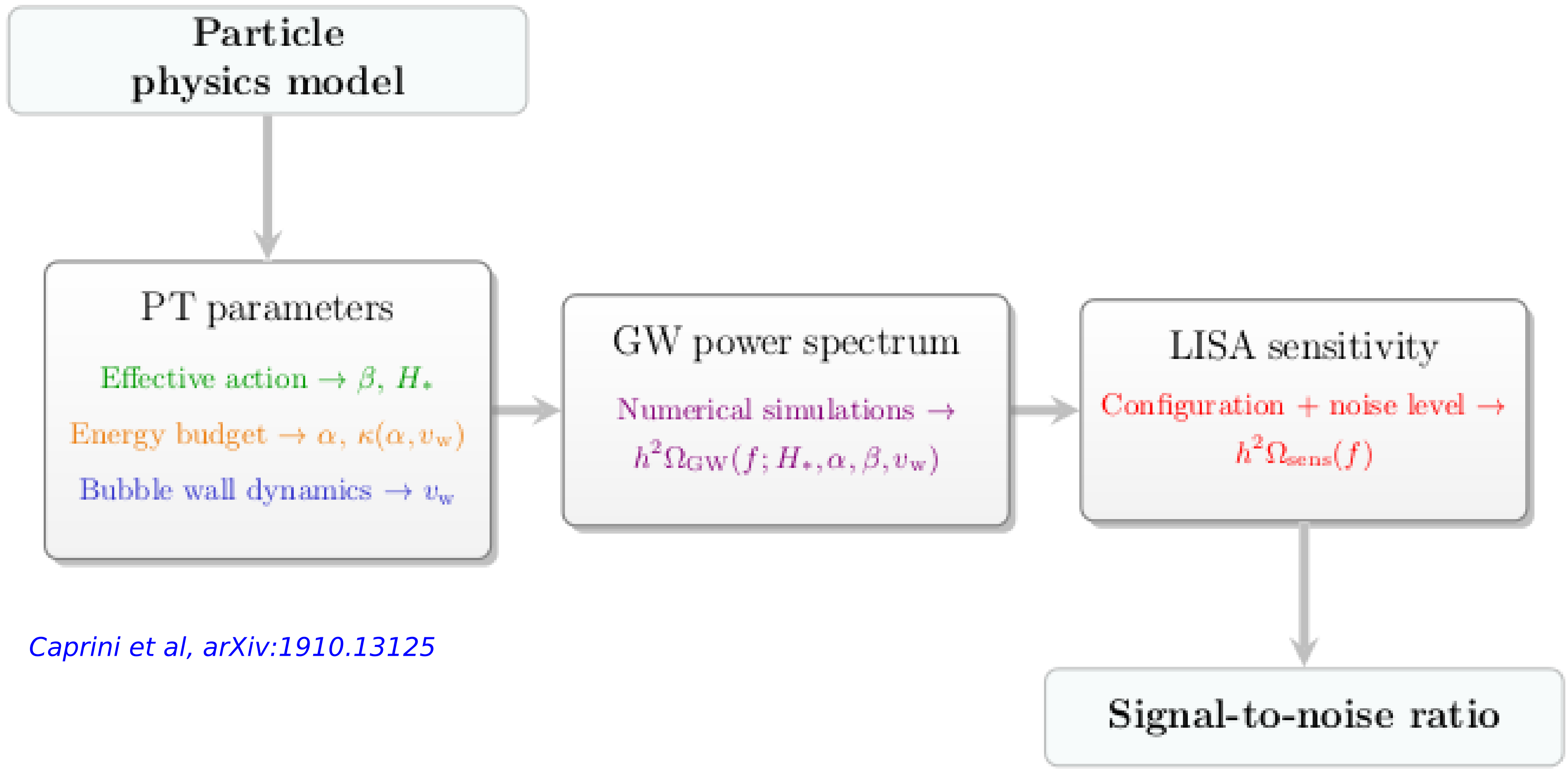
Timeline: LISA GW Observatory in the Context of High-Energy Colliders



After LHC, LISA is next step in exploration of EW scale physics

)

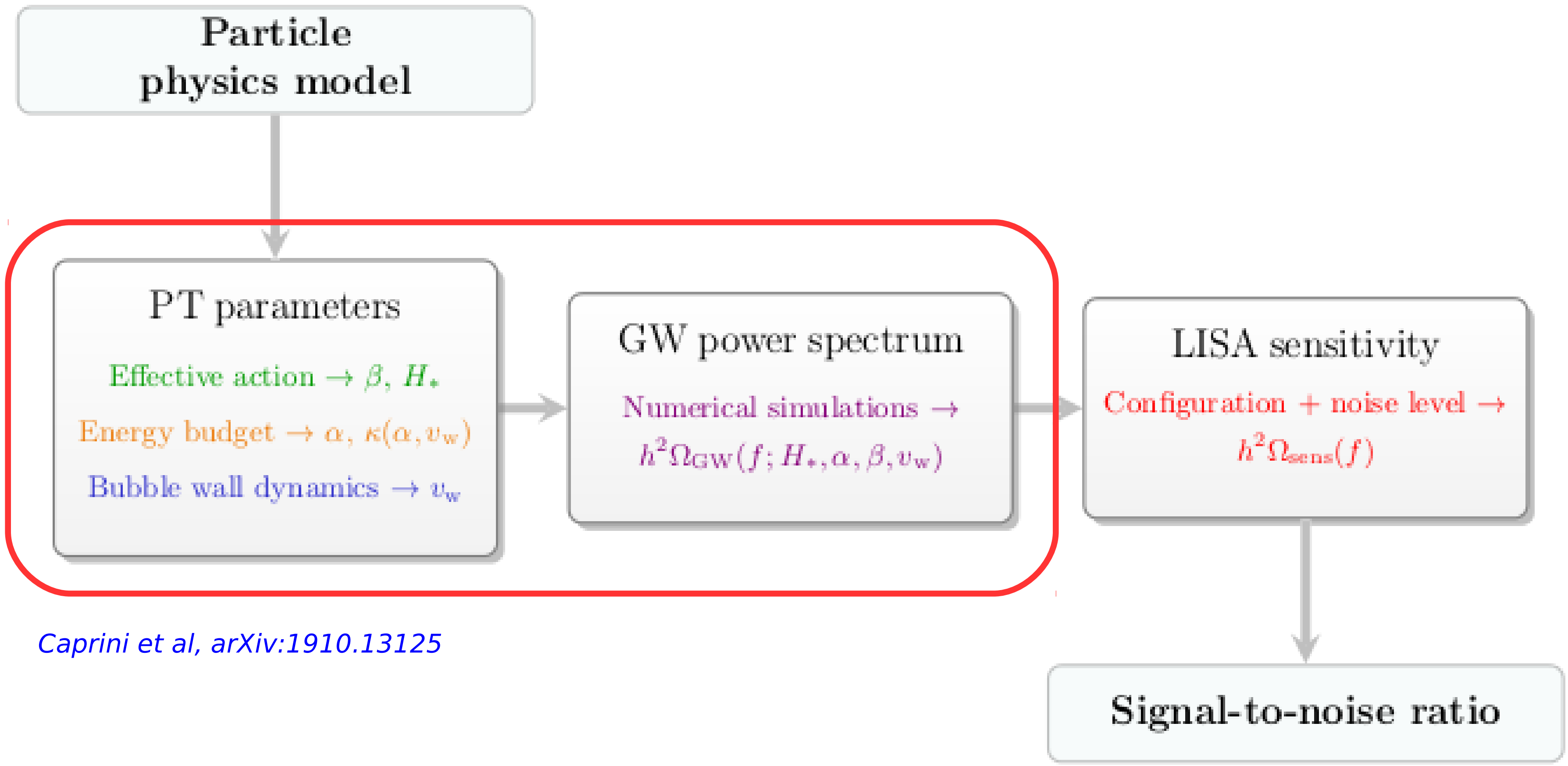
GW from the EW Phase Transition with **LISA**



Caprini et al, arXiv:1910.13125

Assess the capability of LISA to probe GW signal from EW epoch ⇨ **BSM physics**

GW from the EW Phase Transition with LISA



Caprini et al, arXiv:1910.13125

Assess the capability of LISA to probe GW signal from EW epoch ⇨ **BSM physics**

Need to predict GW signal as robustly as possible

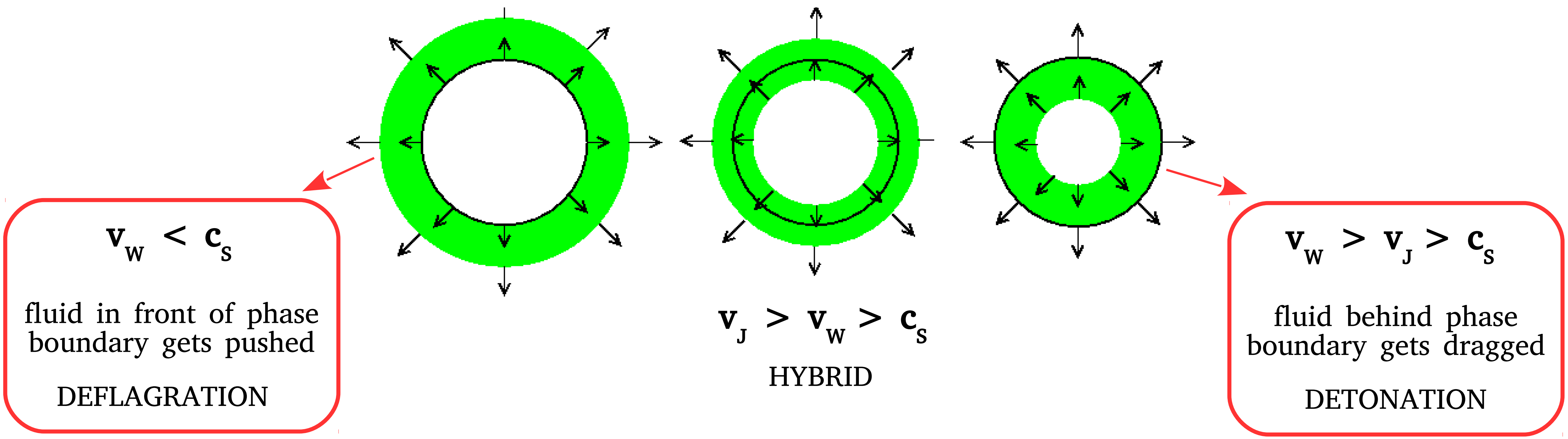
Thermal EW Phase Transition

Energy liberated from phase change **transferred** (mostly) **to plasma**

- ❑ Kinetic energy ⇨ Thermal plasma bulk motion
- ❑ Thermal energy ⇨ Thermal plasma gets heated up

Depending on Higgs bubble wall velocity, energy transfer to plasma creates different types of **expanding fluid shells**

*Laine, Phys. Rev. D**49** (1994) 3847*
*Espinosa, Konstandin, No, Servant, JCAP **1006** (2010) 028*



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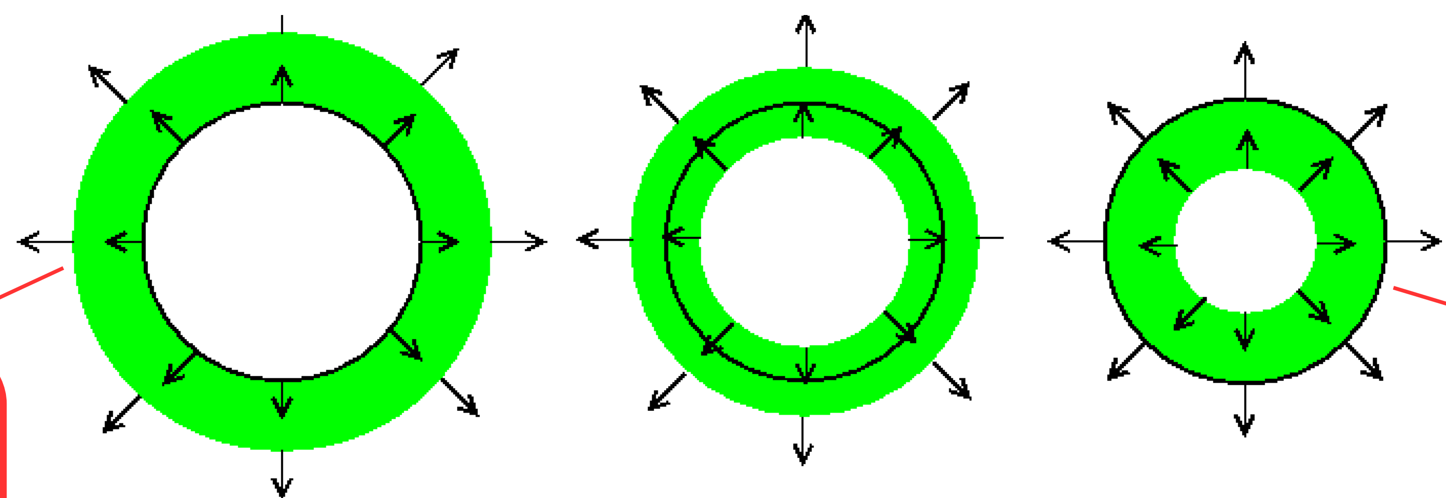


$v_w < c_s$

fluid in front of phase boundary gets pushed

DEFLAGRATION

$v_J > v_w > c_s$

HYBRID

$v_w > v_J > c_s$

fluid behind phase boundary gets dragged

DETONATION

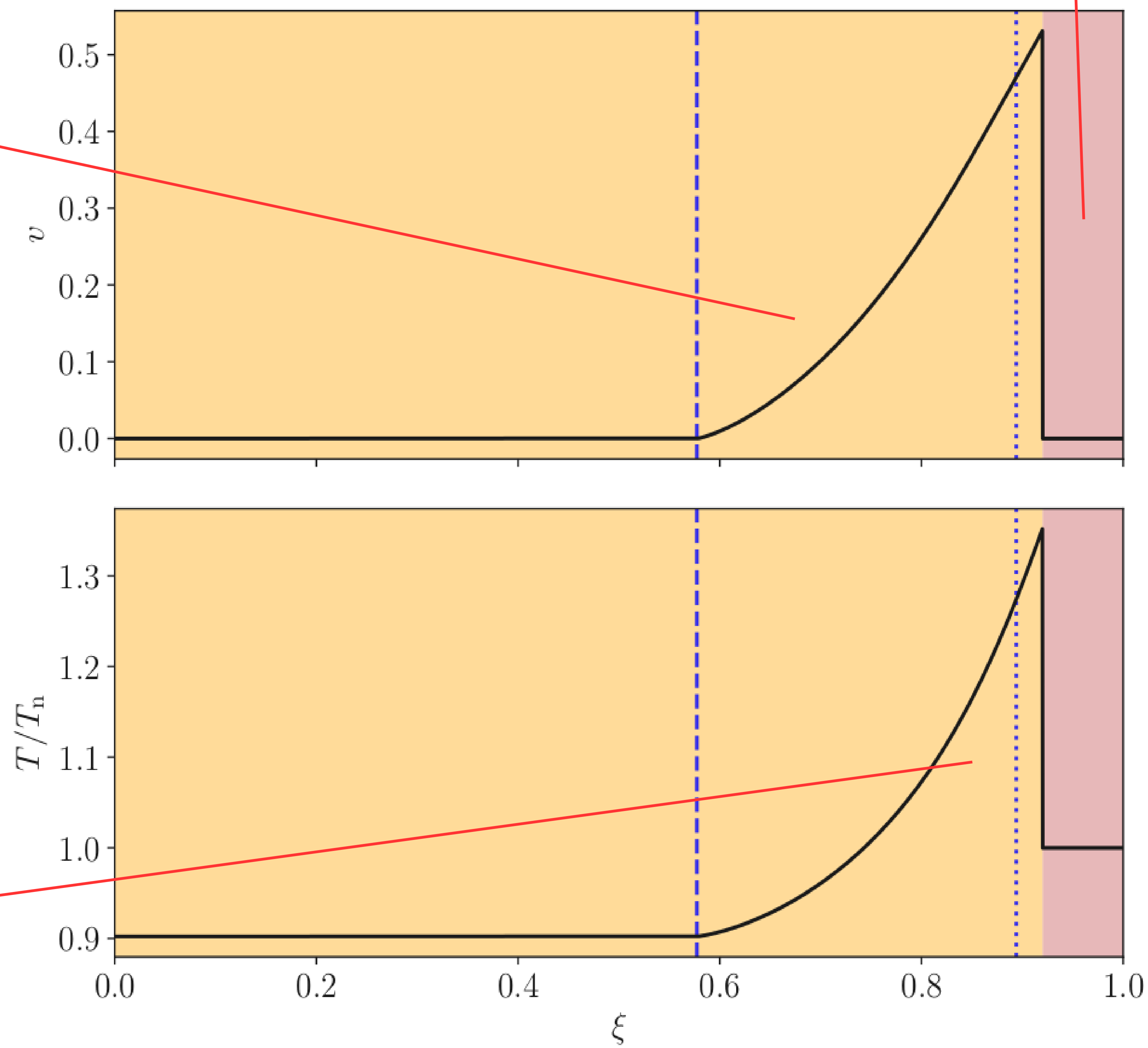
"Self-similar"

Fluid velocity and temperature depend on $\xi = r/t$

Detonations ($v_w > v_J > c_s$)

fluid at rest in front of bubble

fluid behind phase boundary gets dragged, until it becomes at rest again



fluid heated inside bubble

Courtesy of D. Cutting (Sussex)

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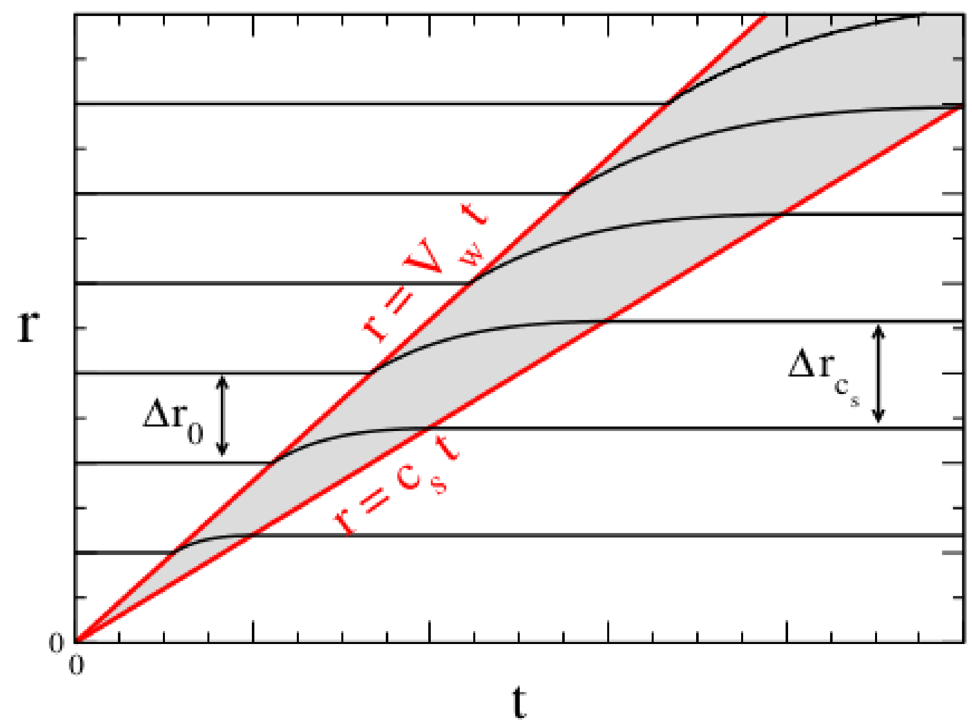
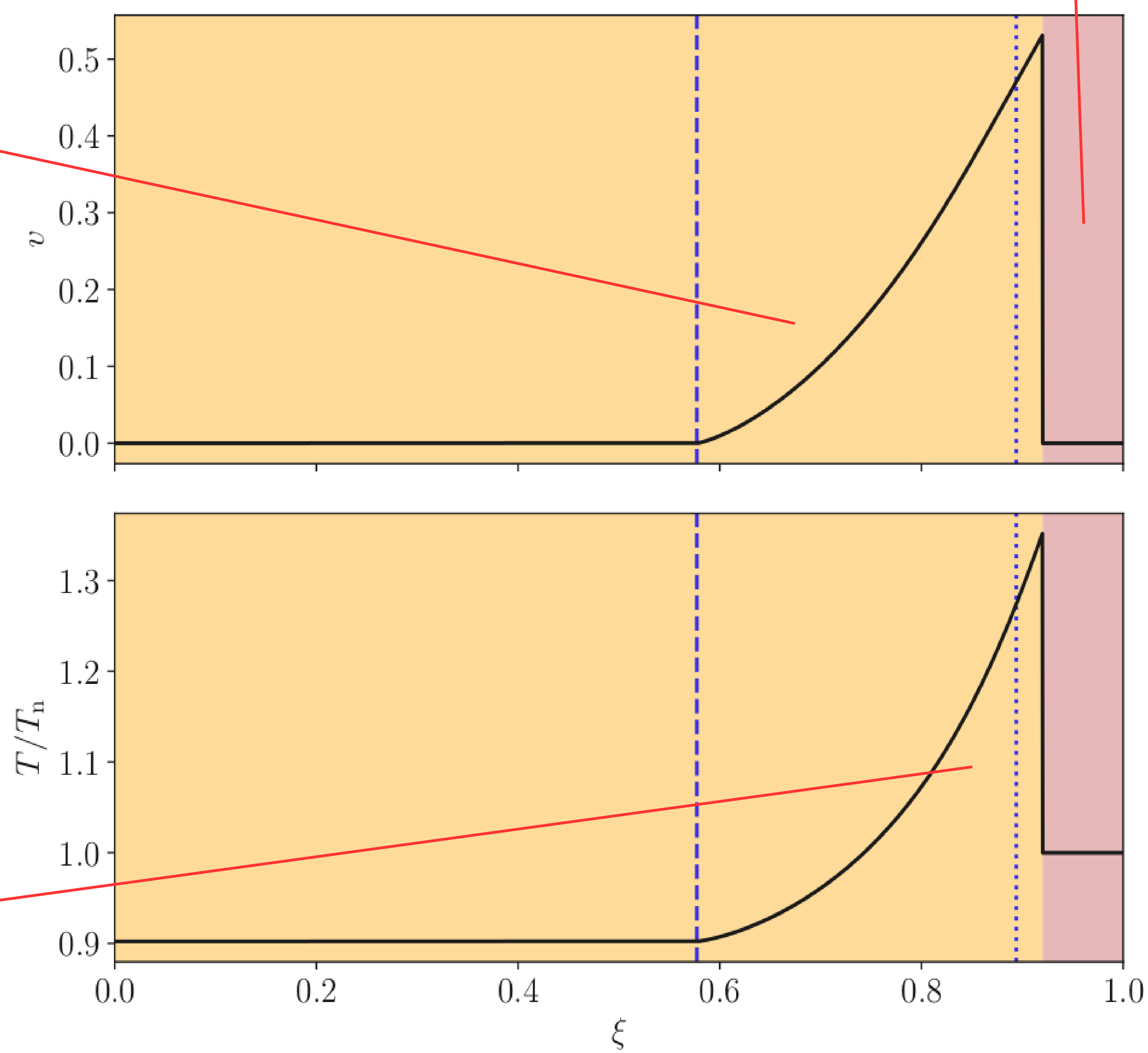


Caprini, No, JCAP **1201** (2012) 031



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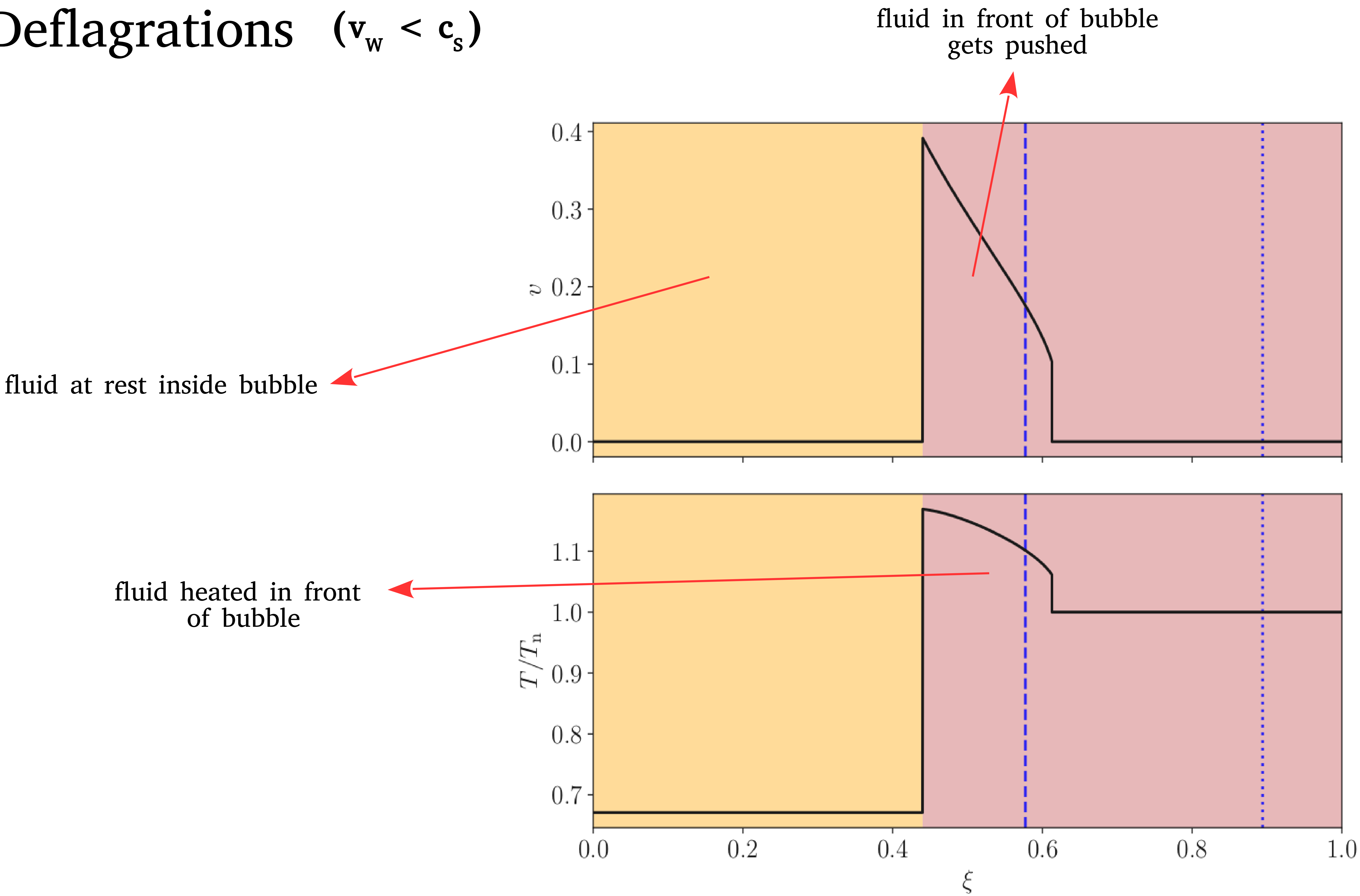
Deflagrations $(v_w < c_s)$



Courtesy of D. Cutting (Sussex)

Fluid shell Profiles

$$\partial^\mu T_{\mu\nu}^{\text{plasma}} = 0$$

(with appropriate boundary conditions on bubble wall)

Local Thermal Equilibrium

$$T_{\mu\nu}^{plasma} = w\, u_\mu u_\nu - g_{\mu\nu}\, p$$

$$w = e + p$$

$$u_\mu = \frac{(1, \mathbf{v})}{\sqrt{1-\mathbf{v}^2}} = (\gamma, \gamma \mathbf{v})$$

Self-similarity

$$v(r,t) = v(\xi = r/t)$$

Estimate of Energy available for GW production

(fluid bulk motion for one bubble)

$$\overline{U}_{\rm f}^2 = \frac{3}{e\, v_{\rm w}^3} \int w(\xi)\, v^2 \gamma^2 \xi^2 d\xi \;= \frac{\kappa\alpha}{1+\alpha}$$

(enthalpy weighted) plasma
RMS four velocity

Hindmarsh, Huber, Rummukainen, Weir, PRD ***96*** *(2017) 103520*

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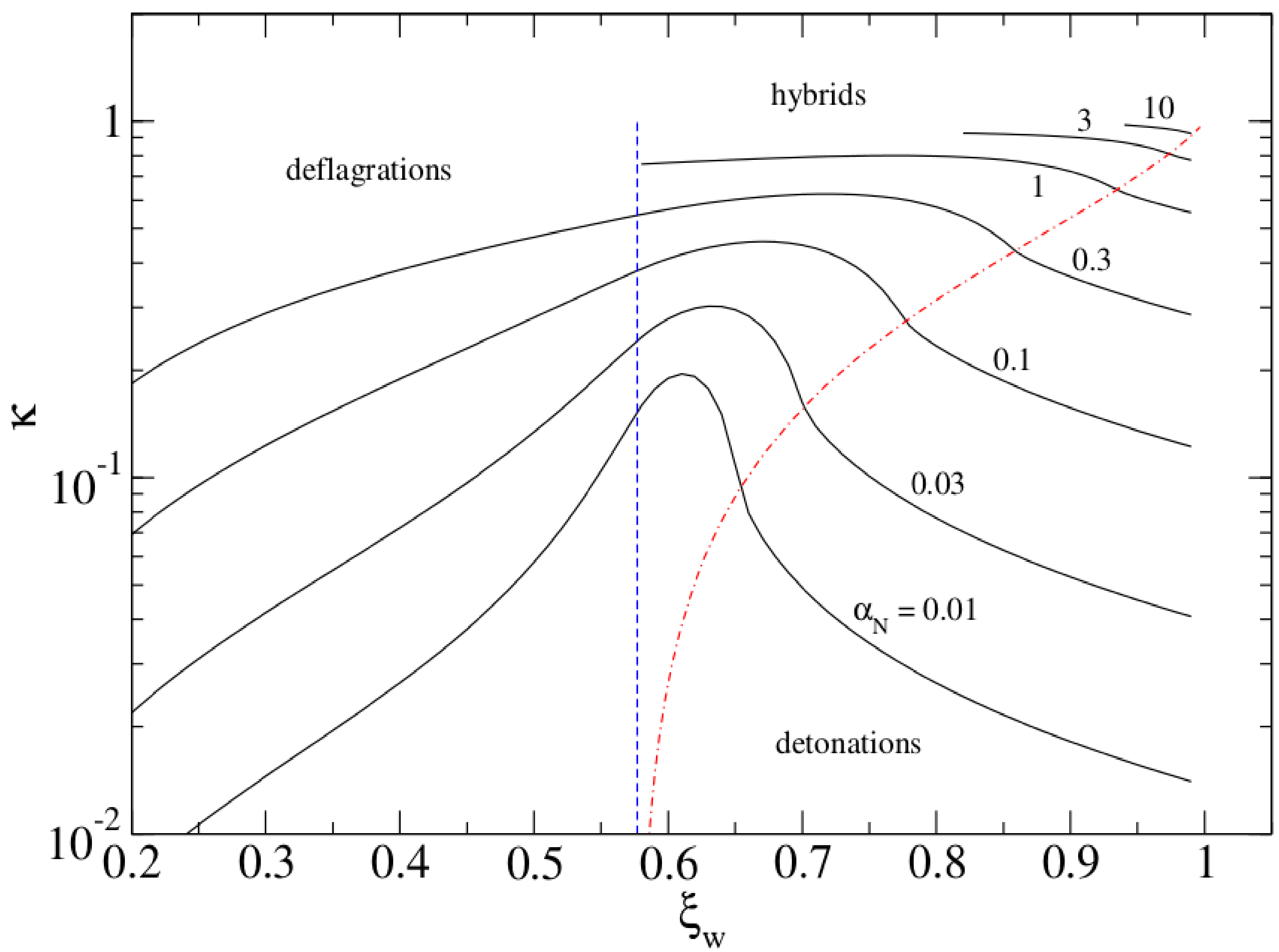
(enthalpy weighted) plasma RMS four velocity

*Hindmarsh, Huber, Rummukainen, Weir, PRD **96** (2017) 103520*



Efficiency coefficient
(PT Energy Budget)

*Kamionkowski, Kosowsky, Turner, PRD **49** (1994) 2837*

*Espinosa, Konstandin, No, Servant, JCAP **1006** (2010) 028*

Gravitational Waves from Phase Transitions

- Gravitational waves (GWs) produced by several sources in a PT:

$$h^2\Omega_{\rm gw} = h^2\Omega_\phi + h^2\Omega_{\rm sw} + h^2\Omega_{\rm turb}$$

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LISA Cosmology Working Group effort to provide state-of-art:

2015 CosWG Review

*Caprini et al, JCAP **1604** (2016) 001*

Science with the space-based interferometer eLISA. II: Gravitational waves from cosmological phase transitions

Chiara Caprini[a], Mark Hindmarsh[b,c], Stephan Huber[b], Thomas Konstandin[d], Jonathan Kozaczuk[e], Germano Nardini[f], Jose Miguel No[b], Antoine Petiteau[g], Pedro Schwaller[d], Géraldine Servant[d,h], David J. Weir[i]

+ very recent update

Caprini et al, arXiv:1910.13125

LISA CosWG-19-04

Detecting gravitational waves from cosmological phase transitions with LISA: an update

Chiara Caprini[a], Mikael Chala[b,c,†], Glauber C. Dorsch[d], Mark Hindmarsh[e,f], Stephan J. Huber[f], Thomas Konstandin[g,‡], Jonathan Kozaczuk[h,i,j,§], Germano Nardini[k], Jose Miguel No[l,m], Kari Rummukainen[e], Pedro Schwaller[n], Geraldine Servant[g,o], Anders Tranberg[k], David J. Weir[e,p,¶]
For the LISA Cosmology Working Group

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*Kosowsky, Turner, Watkins, PRL **69** (1992) 2026; PRD **45** (1992) 4514*
*Huber, Konstandin, JCAP **0809** (2008) 022*
*Weir, PRD **93** (2016) 124037*
*Cutting, Hindmarsh, Weir, PRD **97** (2018) 123513*

In general, negligible expect for very strong supercooling $\Rightarrow$ $\alpha >> 1$

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In general, negligible expect for very strong supercooling ⇒ $\alpha >> 1$

Such amount of supercooling incompatible with PT completion...
Ellis, Lewicki, No, JCAP ***1904*** *(2019) 003*

...except for conformal scalar potentials

Gravitational Waves from Phase Transitions

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*Hindmarsh, Huber, Rummukainen, Weir, PRL **112** (2014) 041301; PRD **92** (2015) 123009; PRD **96** (2017) 103520*
*Hindmarsh, PRL **120** (2018) 071301*
*Konstandin, JCAP **1803** (2018) 047*
Hindmarsh, Hijazi, arXiv:1909.10040

Typically dominant signal

GW power spectrum (numerical simulations)

$$\frac{d\Omega_{\rm gw,0}}{d\ln(f)} = 0.687 F_{\rm gw,0} K^2 (H_* R_*/c_s)\tilde{\Omega}_{\rm gw} C\left(\frac{f}{f_{\rm p,0}}\right)$$

Peak amplitude
(at maximum)

Peak frequency
(at maximum)

Spectral Shape
(Broken Power Law)

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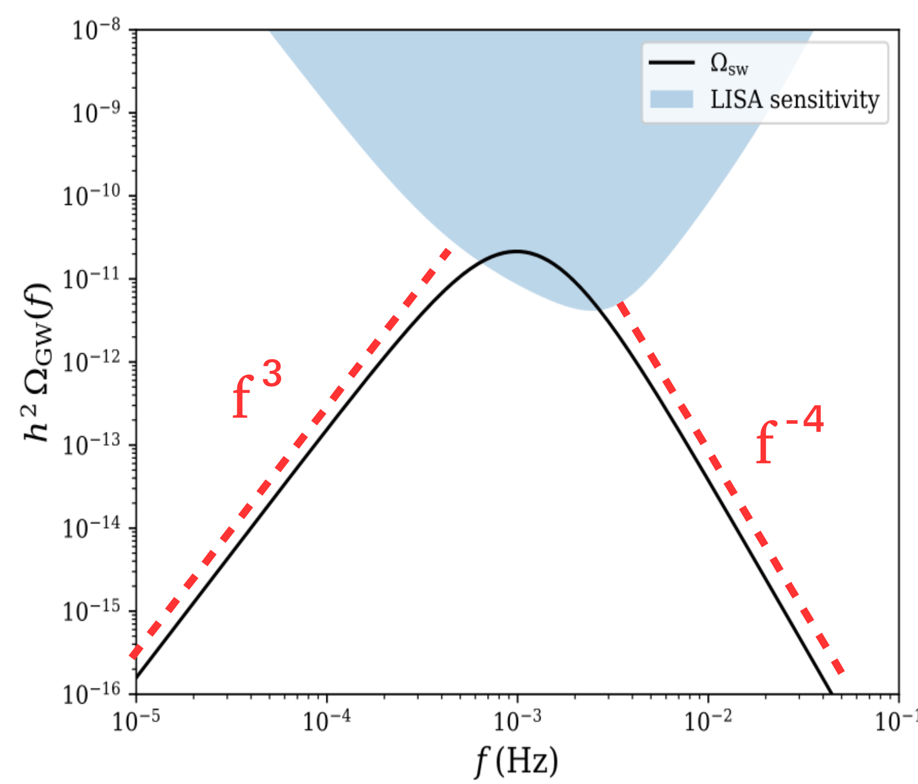
$$C(s) = s^3\left(\frac{7}{4+3s^2}\right)^{\frac{7}{2}}$$



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$$F_{\rm gw,0} = (3.57 \pm 0.05) \times 10^{-5}\left(\frac{100}{g_*}\right)^{\frac{1}{3}}$$

$$\tilde{\Omega}_{\rm gw} \sim 10^{-2}$$

(from simulation)

$$K = \frac{\langle w\gamma^2 v^2\rangle}{\bar{e}} = \Gamma \bar{U}_{\rm f}^2$$

Kinetic Energy Fraction

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After $\tau_{\rm sh} \sim L_{\rm f}/\overline{U}_{\rm f}$, fluid becomes nonlinear (shock formation)

⇩

Sound wave GW source shuts-off

characteristic fluid length scale

$$\frac{d\Omega_{\rm gw,0}}{d\ln(f)} = 0.687 F_{\rm gw,0} K^2 (H_* R_*/c_s) \tilde{\Omega}_{\rm gw} C\left(\frac{f}{f_{\rm p,0}}\right) \times H_*\tau_{\rm sh}$$

$$H_*\tau_{\rm sh} = H_* R_*/K^{1/2} < 1$$

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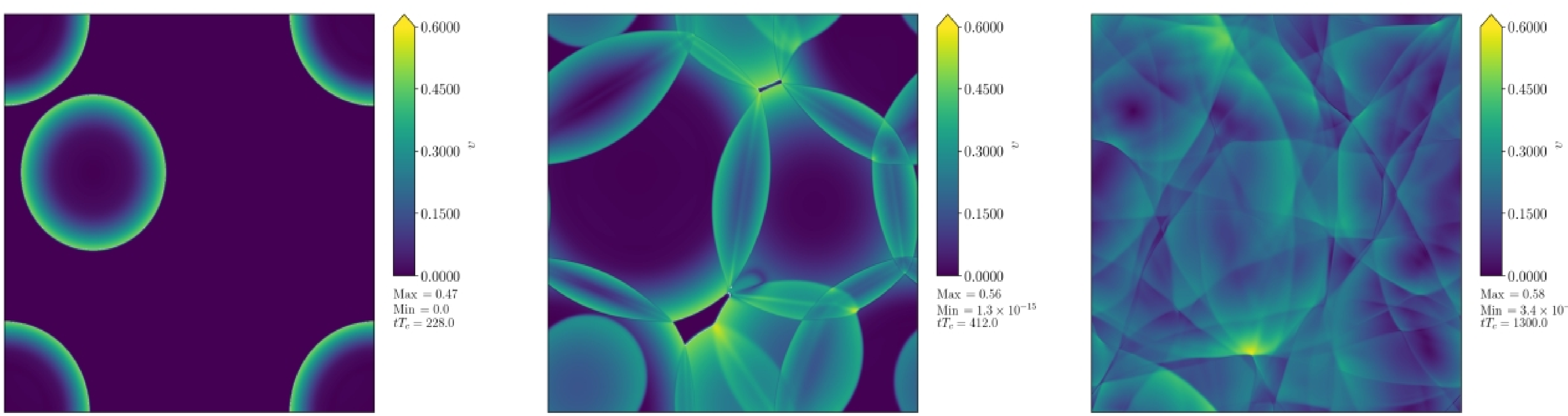

Cutting, Hindmarsh, Weir, arXiv:1906.00480

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- $h^2\Omega_{\rm turb}$ sourced by plasma turbulence (vortical modes)

*Gogoberidze, Kahniashvili, Kosowsky, PRD **76** (2007) 083002*
*Caprini, Durrer, Servant, JCAP **0912** (2009) 024*
Roper Pol, Mandal, Brandenburg, Kahniashvili, Kosowsky, arXiv:1903.08585

→ Turbulent flow expected to develop when sound waves shut-off

→ **Vorticity can also coexist with sound waves for deflagrations and α > 0.1**

Cutting, Hindmarsh, Weir, arXiv:1906.00480

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Numerical simulations still ongoing

Gravitational Waves from Phase Transitions

Duration of sound wave GW source

Initially assumed linear fluid regime lasts approx. a Hubble time

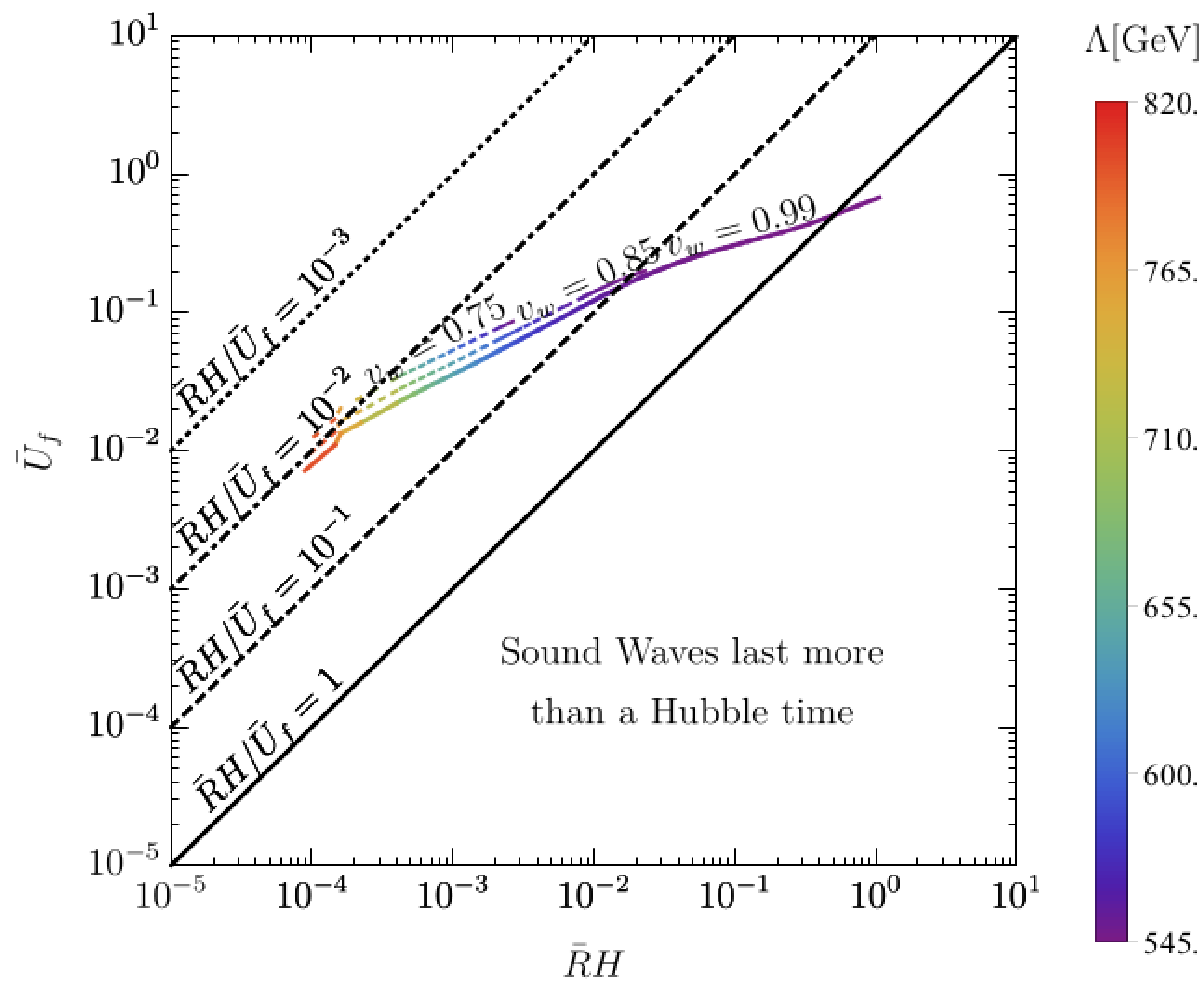
$$\tau_{\rm sh} \gtrsim H_*^{-1}$$

But non-linearities generally "cut short" the sound wave GW source:

Ellis, Lewicki, No, JCAP **1904** (2019) 003

Concrete BSM example:

$$V(H) = -m^2|H|^2 + \lambda|H|^4 + \frac{1}{\Lambda^2}|H|^6$$



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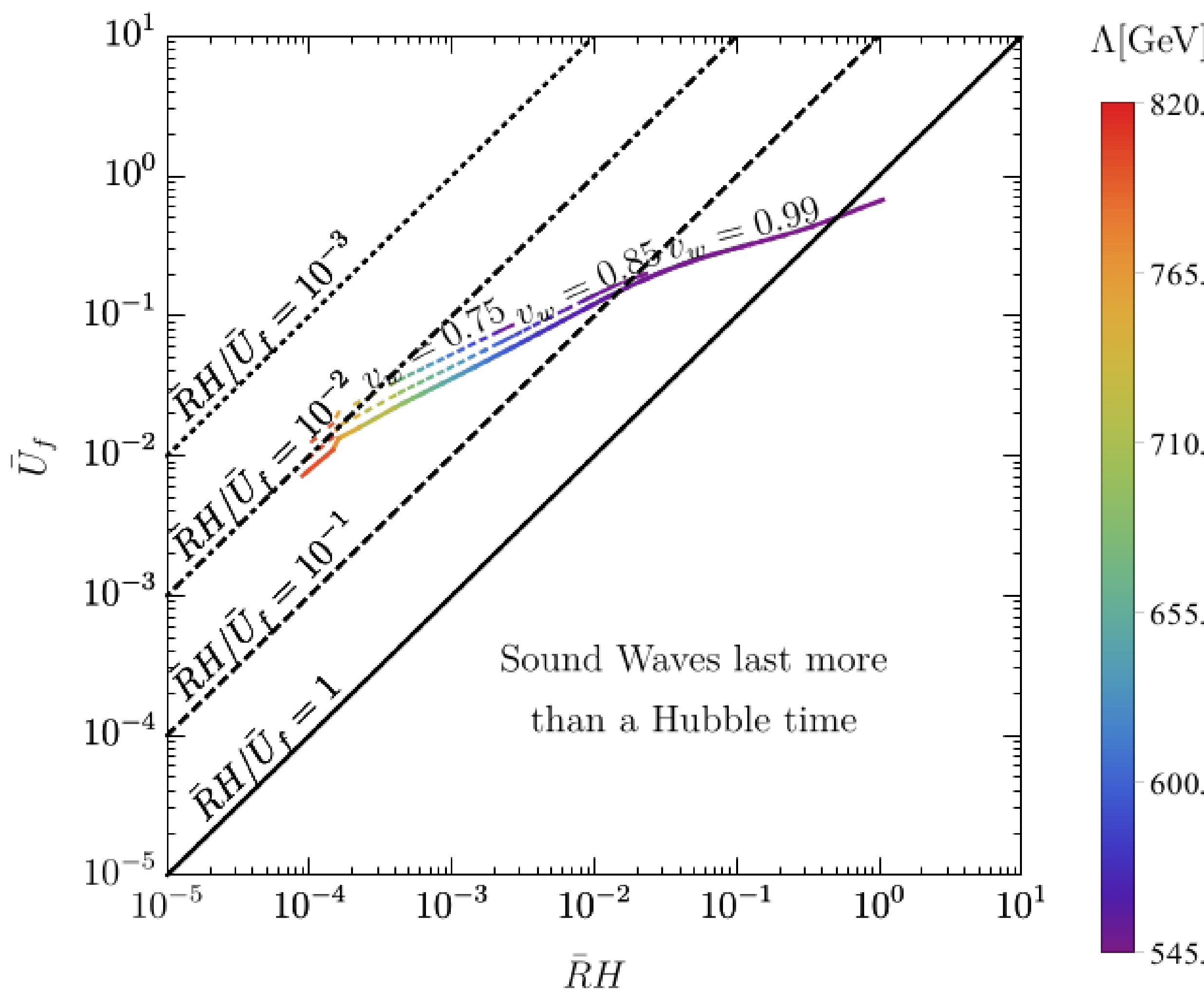

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+ Ongoing work (stay tunned!)

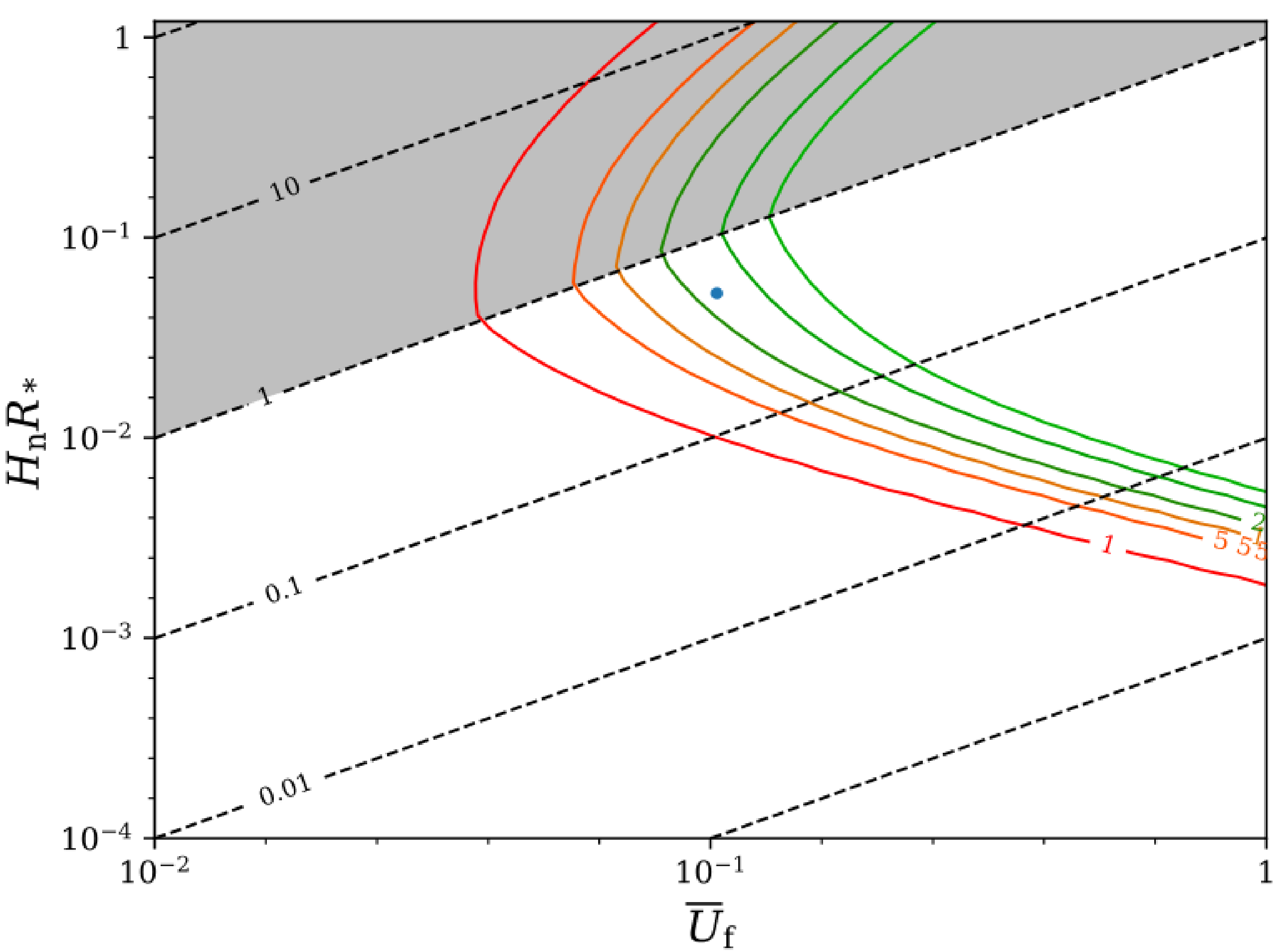
Ellis, Lewicki, No, To appear

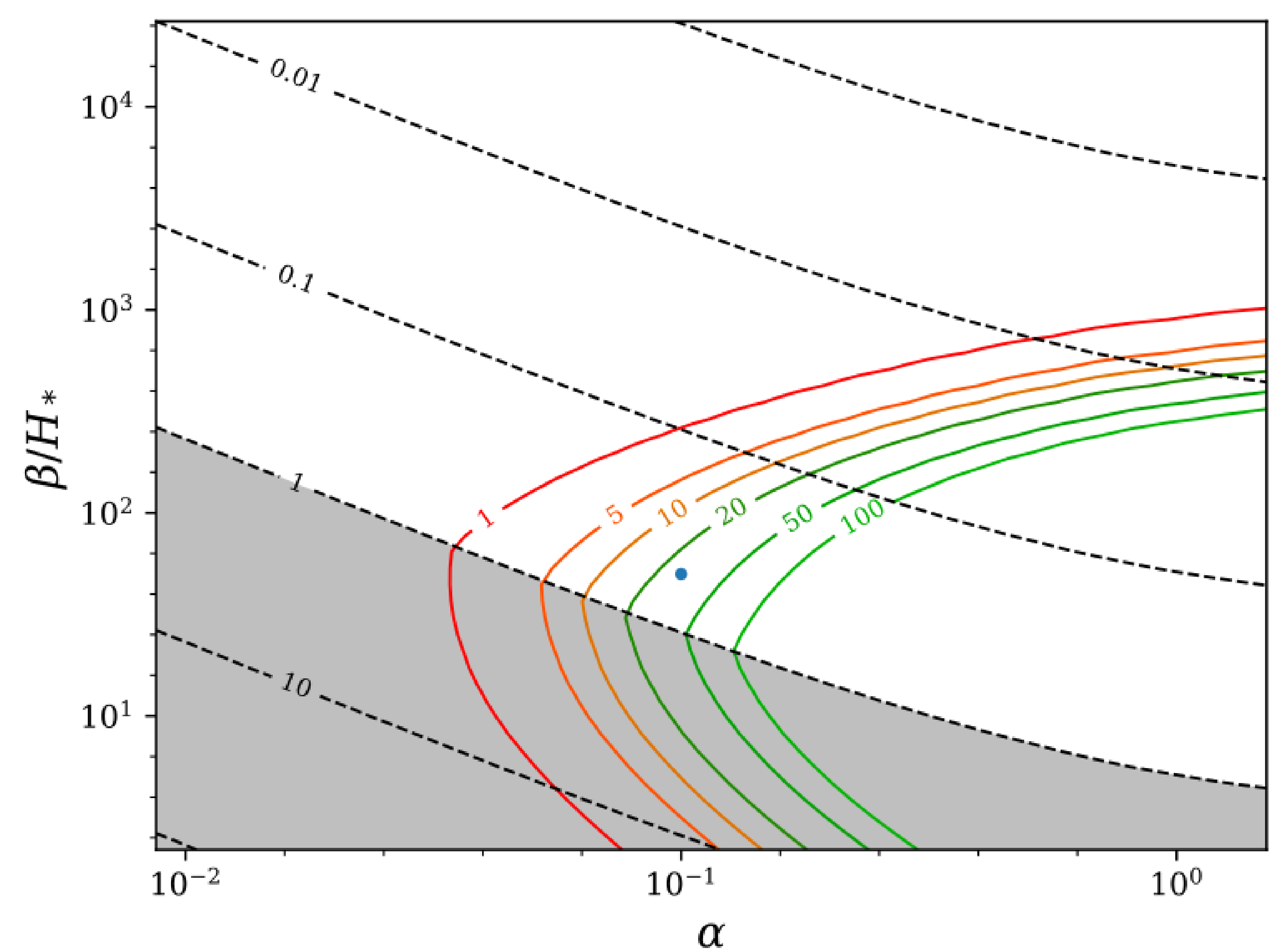
Gravitational Waves from Phase Transitions

LISA signal to noise

$$\mathrm{SNR} = \sqrt{\mathcal{T}\int_{f_{\min}}^{f_{\max}} \mathrm{d}f \left[\frac{h^2\Omega_{\mathrm{GW}}(f)}{h^2\Omega_{\mathrm{Sens}}(f)}\right]^2}$$

$$h^2\Omega_{\mathrm{Sens}}(f) = \frac{2\pi^2}{3H_0^2} f^3 S_h(f)$$





PTPlot Tool - D. Weir

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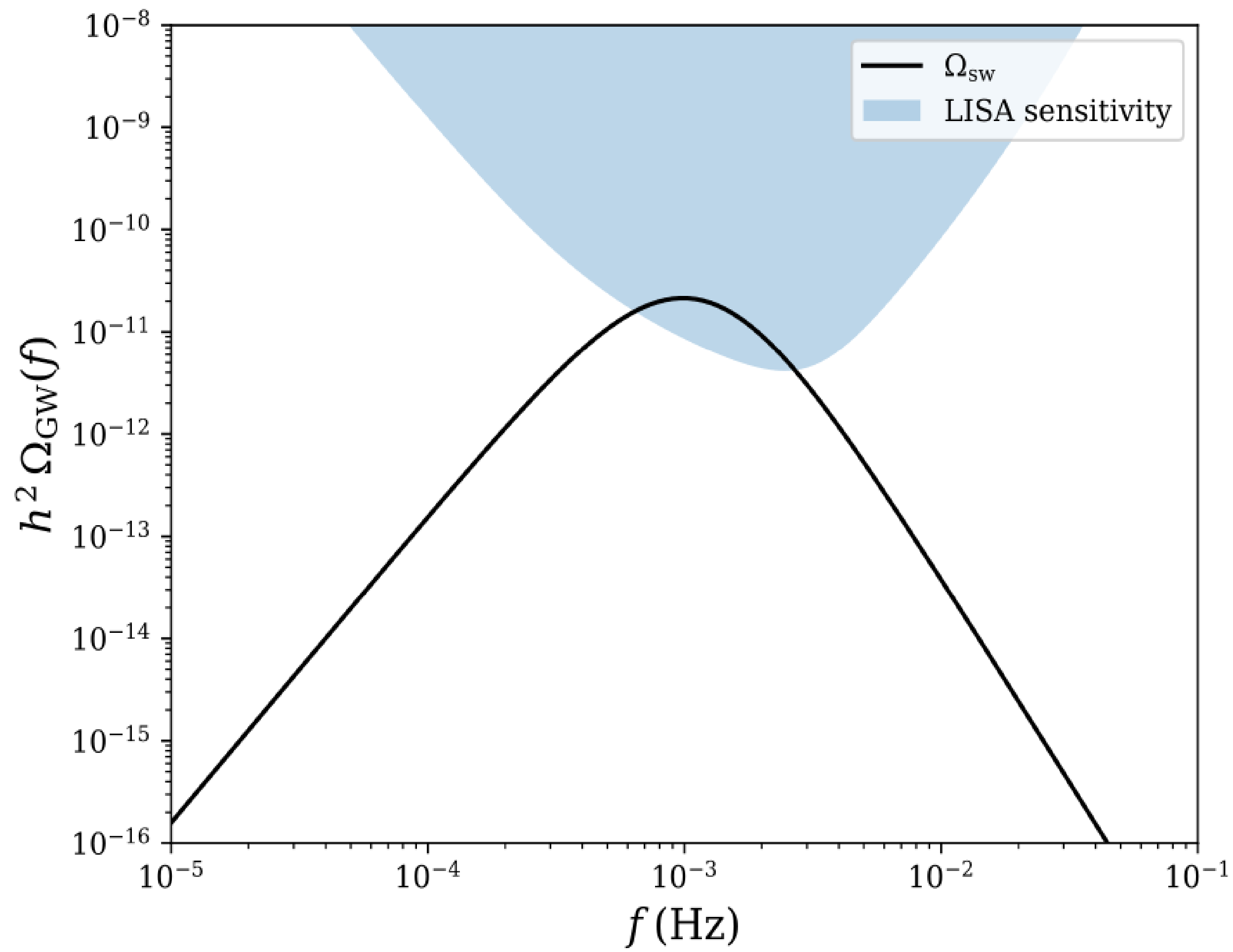
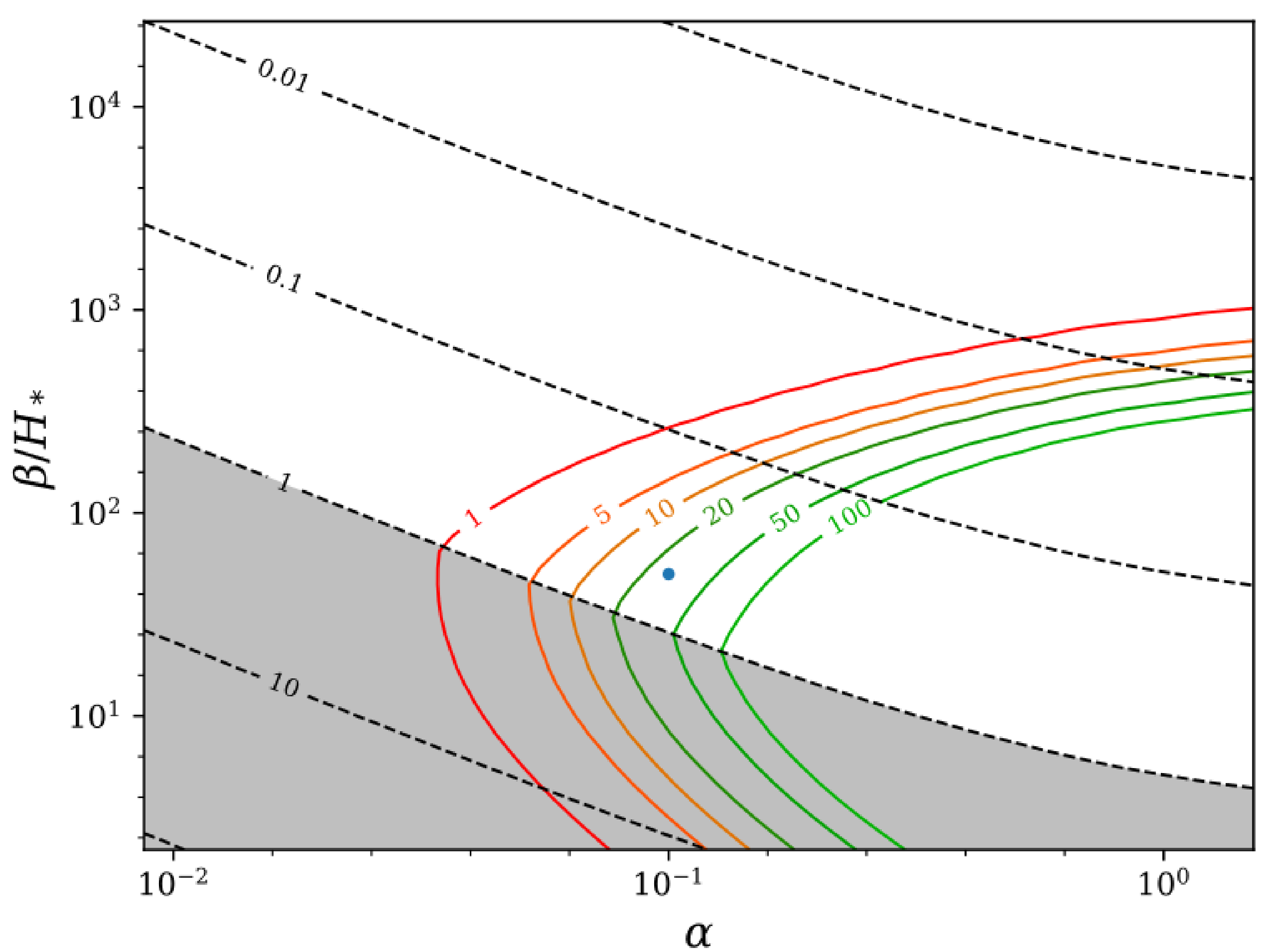




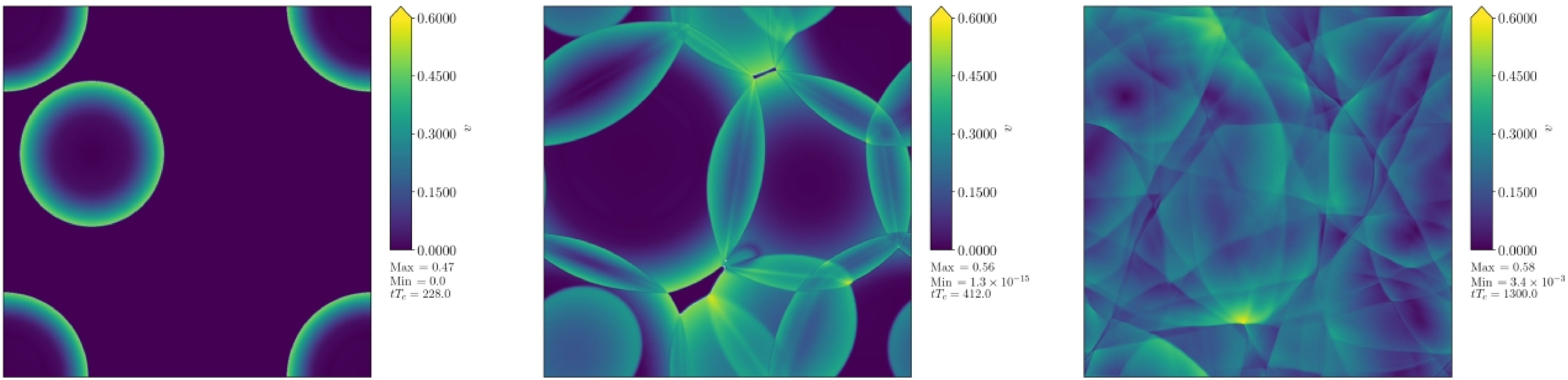
PTPlot Tool - D. Weir

Gravitational Waves from Phase Transitions

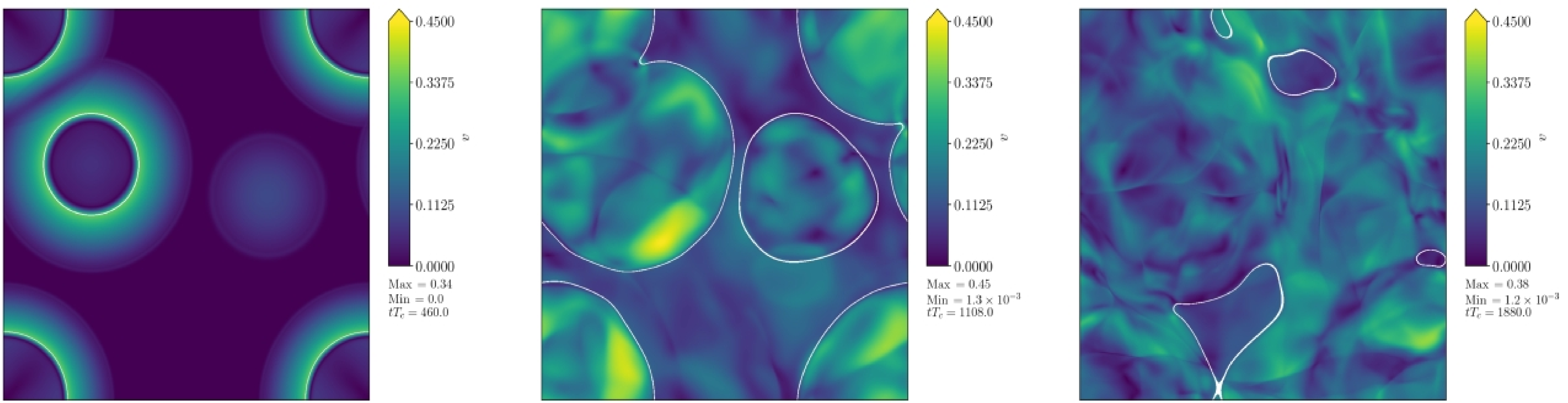
Understanding of vorticity generation is ongoing...

Cutting, Hindmarsh, Weir, arXiv:1906.00480

Detonations (α > 0.1)



Deflagrations (α > 0.1)



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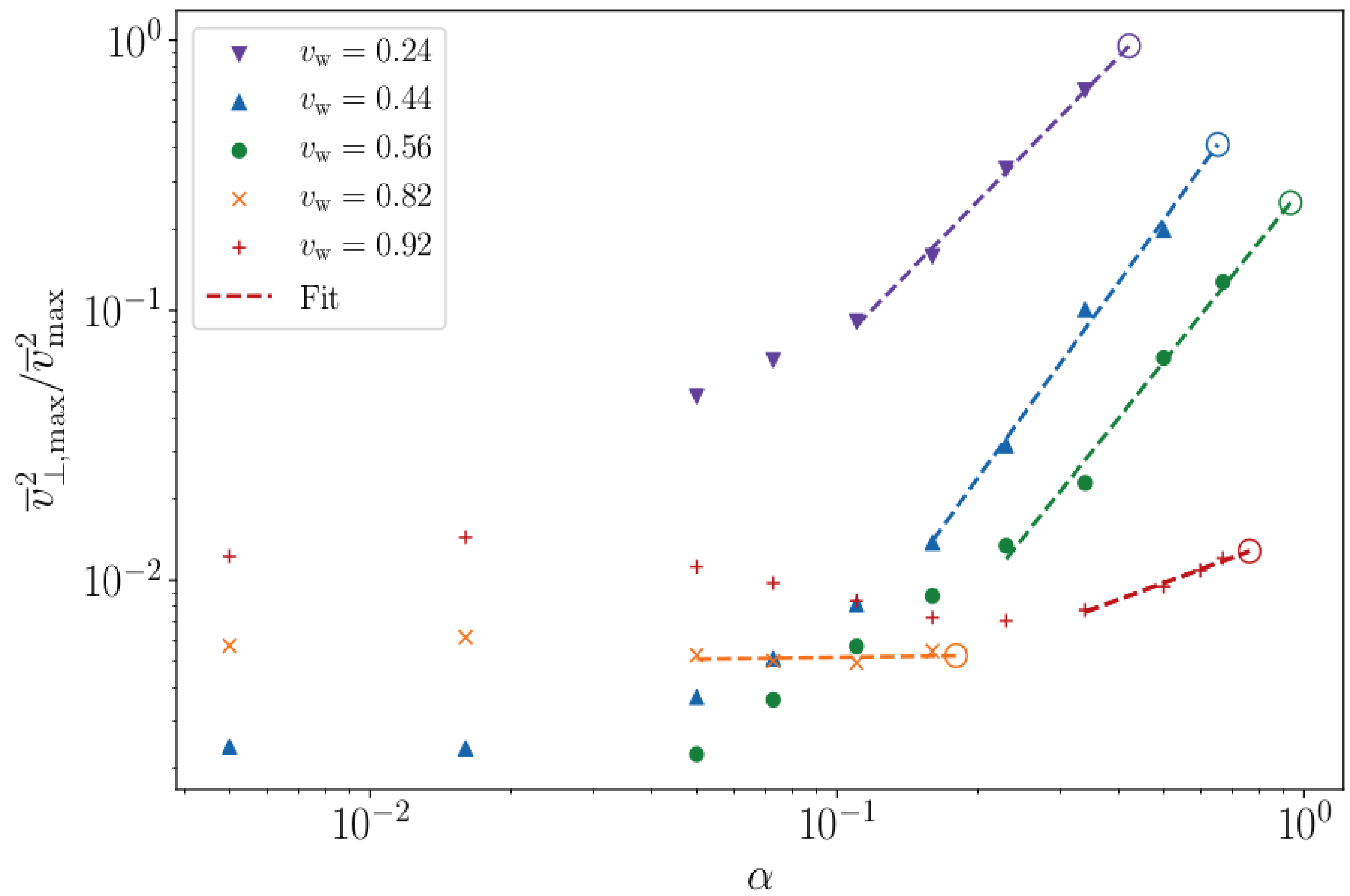

Deflagrations with large α (> 0.1) generate significant vorticity coexisting with sound waves!

In the last couple of min...

GW generation *vs* EW Baryogenesis in 1^{st} Order EW Phase Transition

In the last couple of min...

GW generation *vs* EW Baryogenesis in 1st Order EW Phase Transition

GWs: Sizable plasma bulk motion ⇨ **Sizable v_w**

EWBG: Velocities ~ 0.05 - 0.1 preferred
(efficient transport)

Incompatible?

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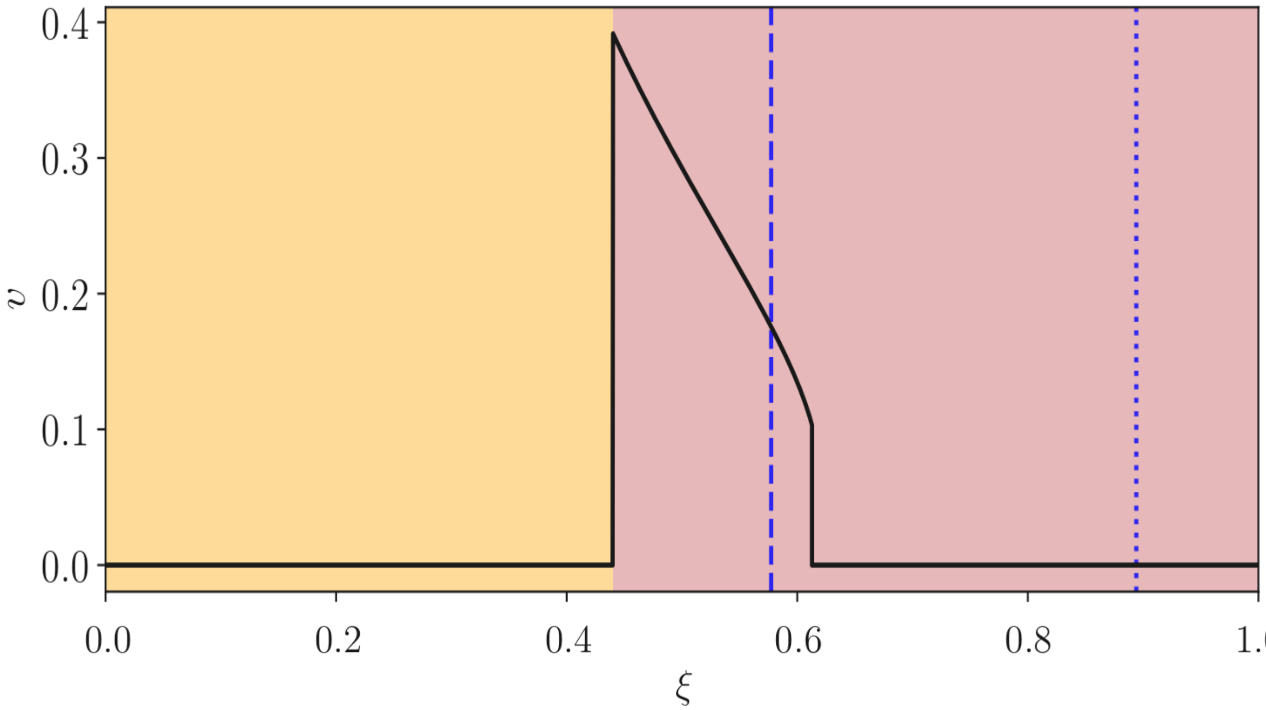


Relevant velocities are not the same...
(for deflagrations)

*No, PRD **84** (2011) 124025*

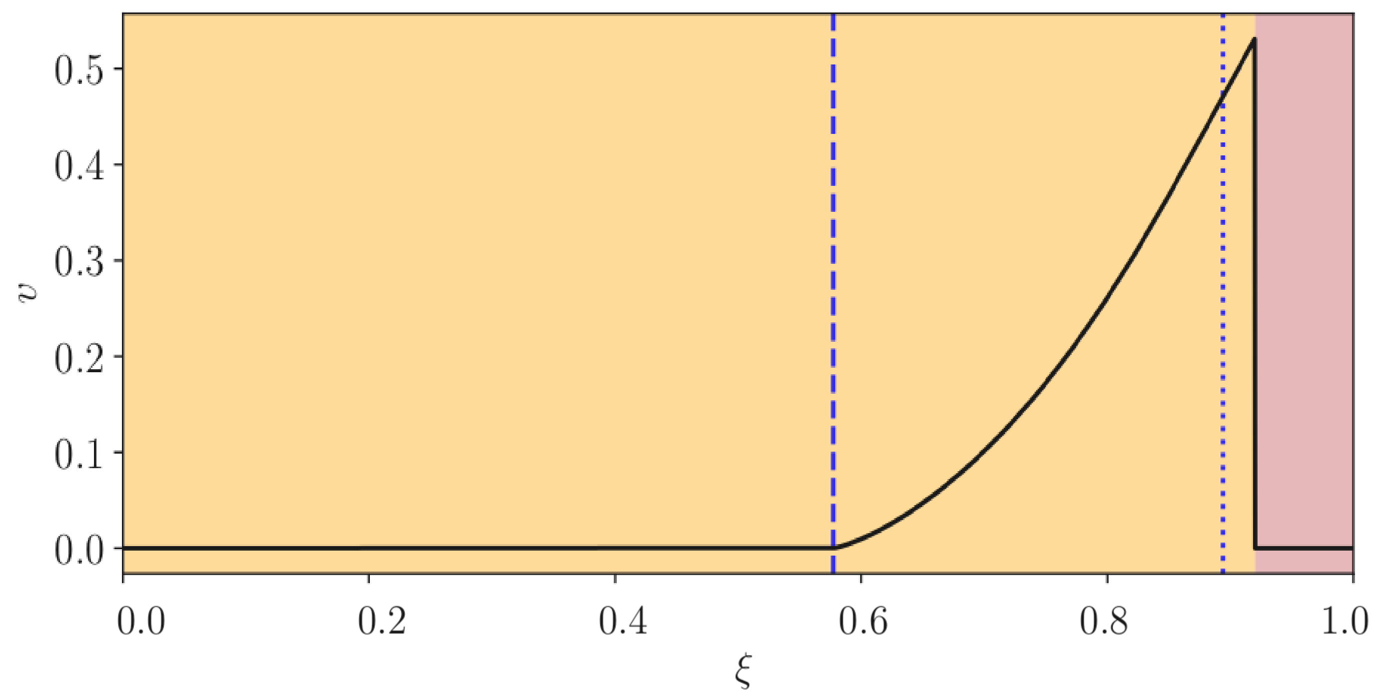
GWs: Fluid velocity (bubble rest frame)

EWBG: Fluid velocity (bubble wall rest frame)
(relative velocity between bubble wall and plasma in front)

In the last couple of min...

GW generation *vs* EW Baryogenesis in 1st Order EW Phase Transition

For detonations: EWBG would not work
(inefficient transport)



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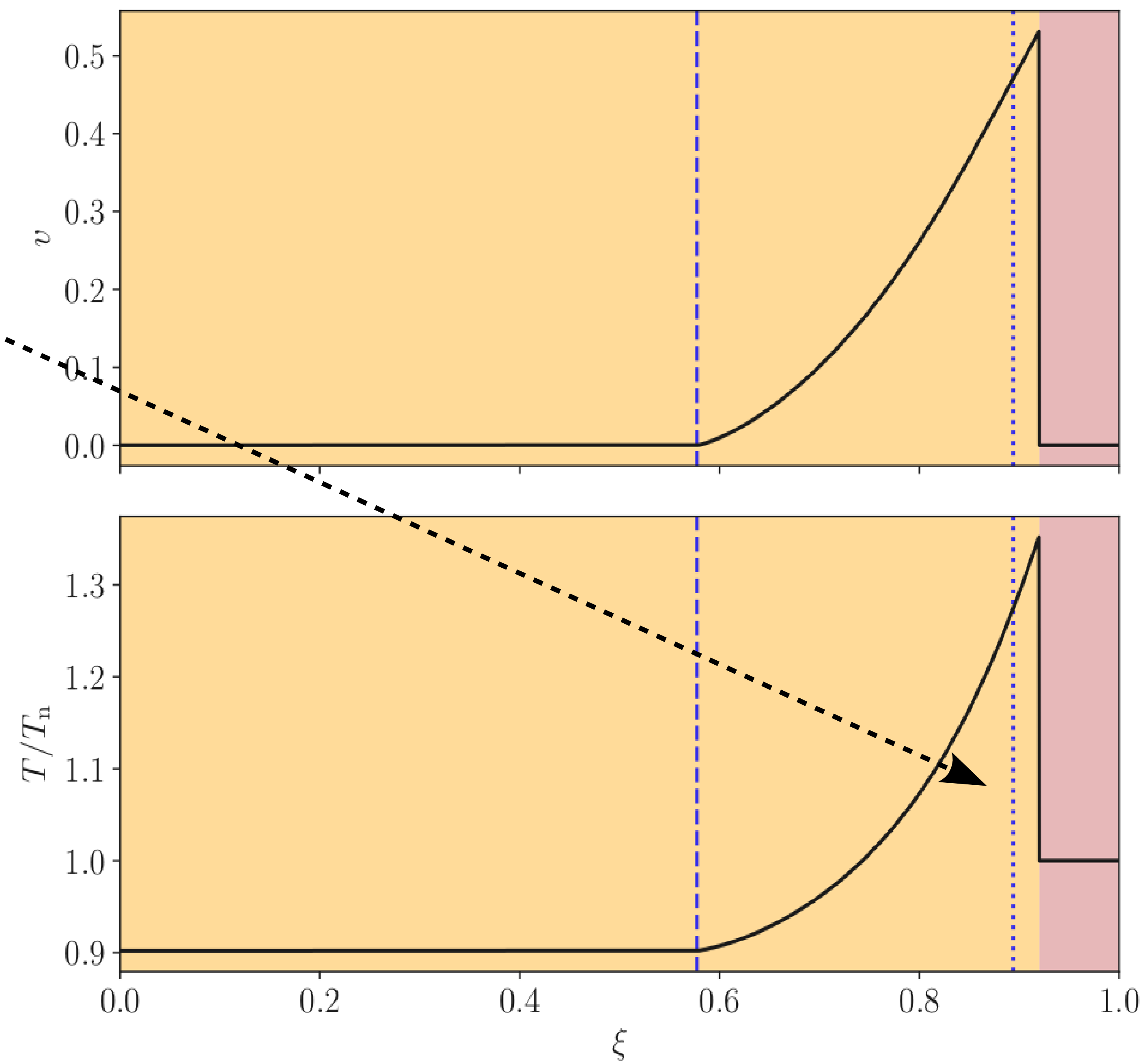
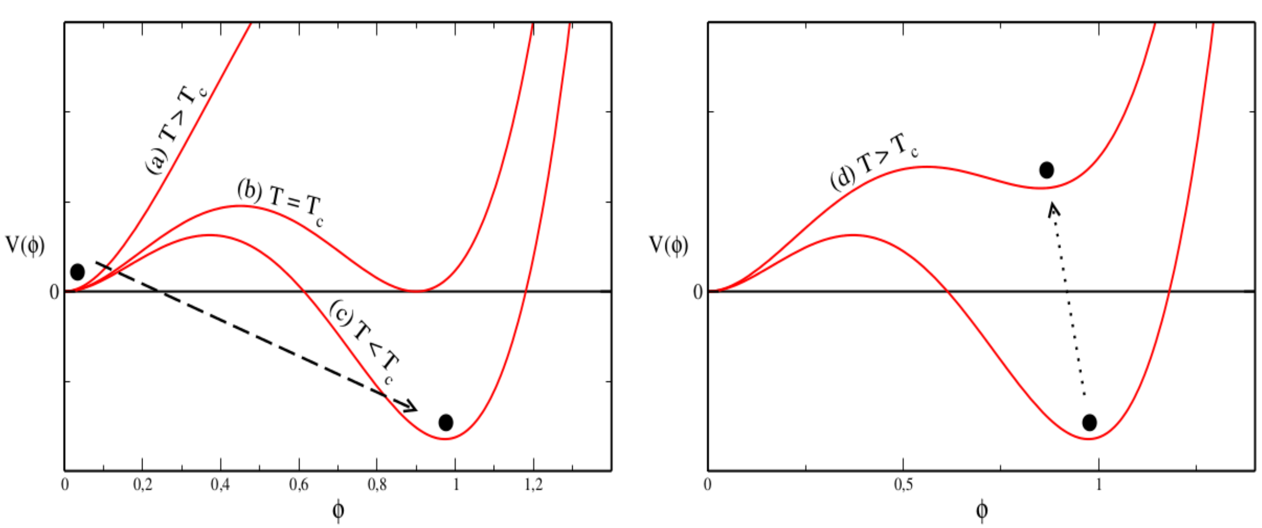
However... for detonations plasma is reheated behind bubble wall



Possible to do EWBG from local back-tunneling (if T > T_c) in broken phase due to reheating!

Caprini, No, JCAP ***1201*** *(2011) 031*



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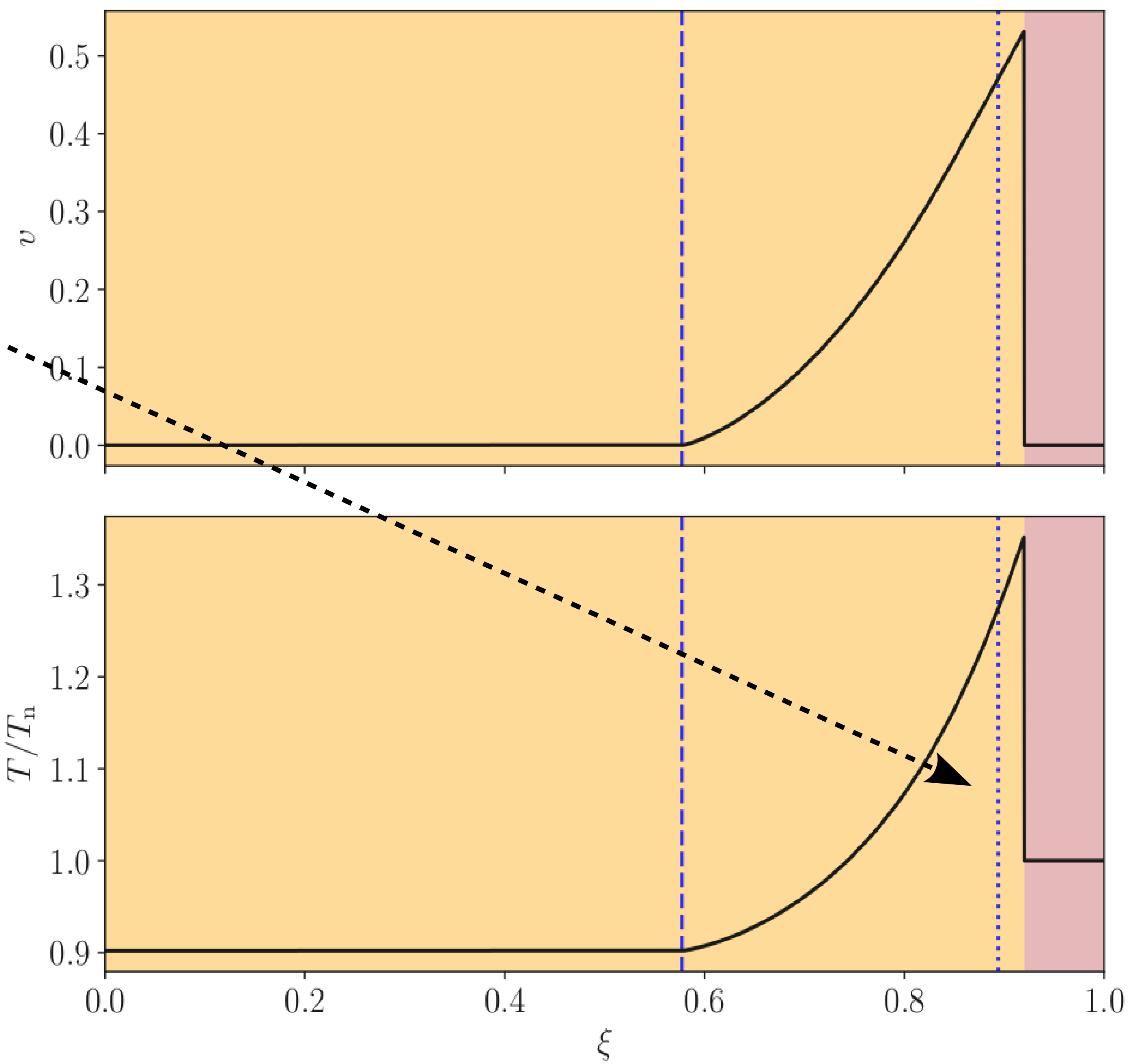

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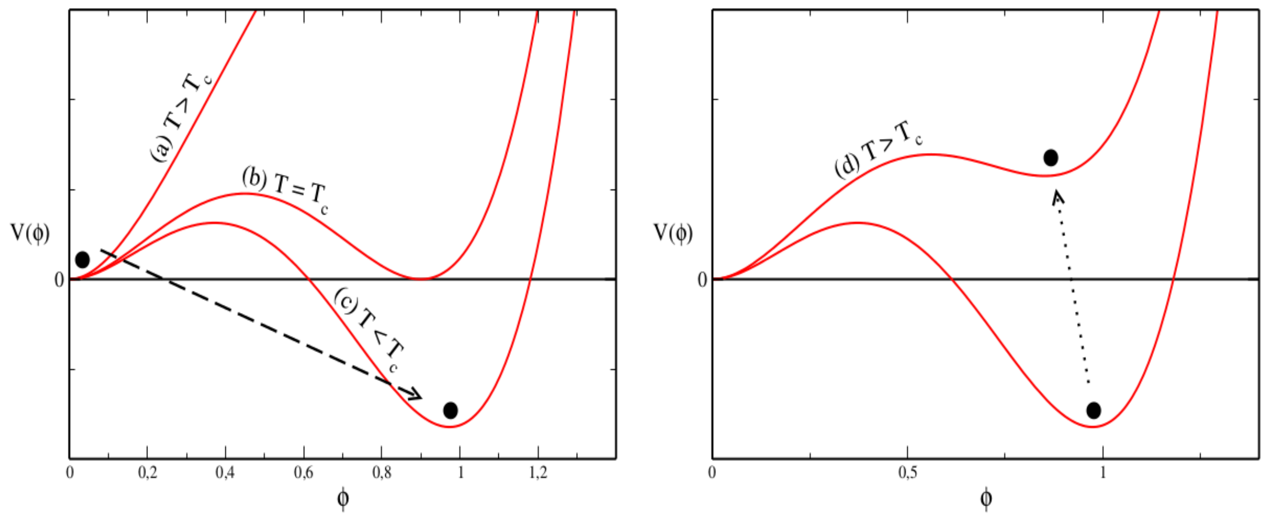


"Supersonic EWBG"

Thank you!


KEEP
CALM
AND
BACKUP
YOUR
WORK

Higgs Evolution in Early Universe → FINITE-TEMPERATURE EFFECTIVE POTENTIAL

$$V_{\rm eff}(h,T) = V_0(h) + V_0^{\rm loop}(h) + V_T(h,T)$$

Tree-level potential | Loop corrections | Thermal corrections

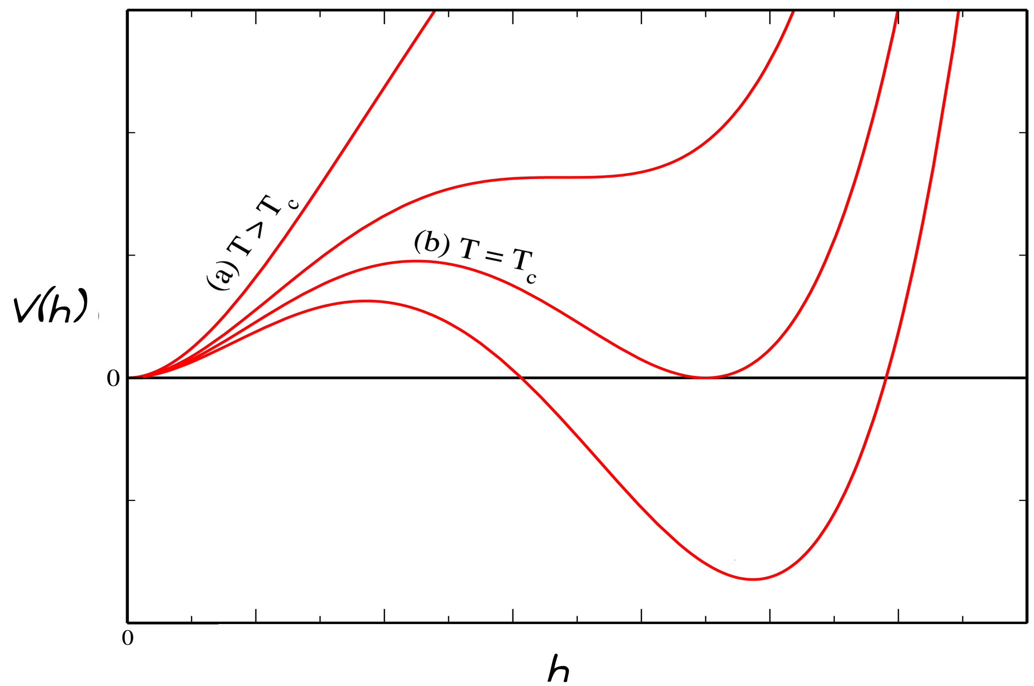
Non-analytic term $(m^2)^{3/2}$ in $V(h,T)$ from Matsubara Zero-modes

(only present for bosons)

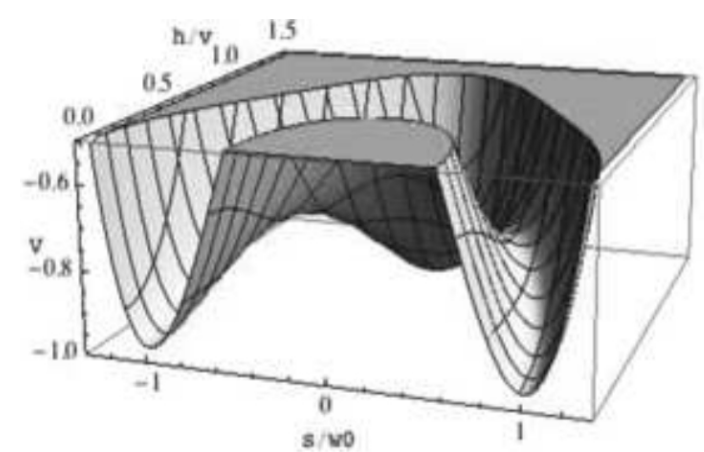
(Perturbative) Nature of EWPT

1st Order:

$\langle h \rangle = 0 \to \langle h \rangle = h(T)$ Discontinuous



Multiple fields involved in the EWPT may allow for tree-level potential barrier

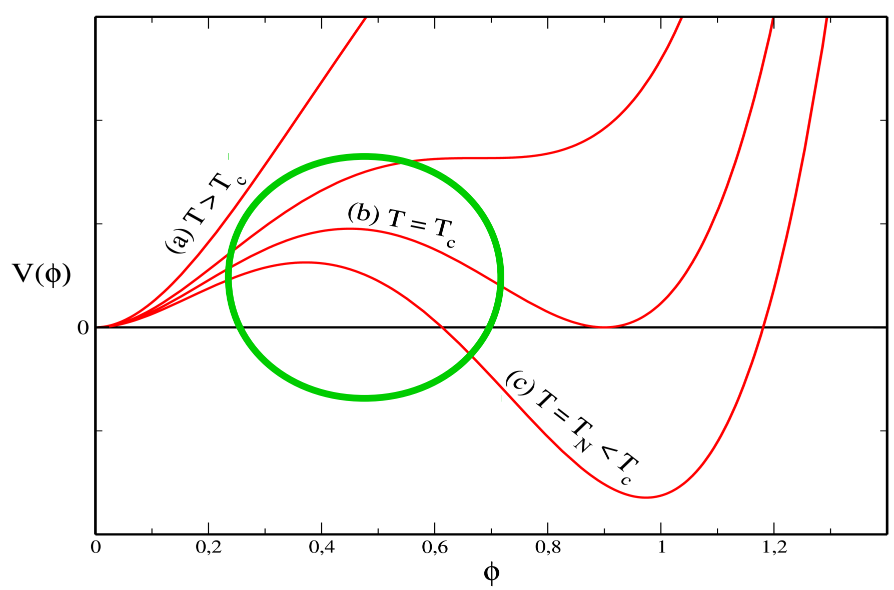


BSM: New Physics sizeably coupled to Higgs can drastically change the EWPT nature

- ▶ New Physics should induce deviations in Higgs couplings
- ▶ New Physics needed close to EW scale

Some further aspects of the EW Phase Transition

Effective Potential (finite T)



$$V_{\rm eff}(h,T) = V_0(h) + V_0^{\rm loop}(h) + V_T(h,T)$$

1-loop

$$V_1^T(h,T) = \frac{T^4}{2\pi^2}\left[\sum_i \pm n_i J_\pm\left(\frac{m_i^2(h)}{T^2}\right)\right]$$

$$J_\pm(x) = \int_0^\infty dy\, y^2 \log\left[1 \mp \exp\left(-\sqrt{x^2+y^2}\right)\right]$$

High-T expansion:

$$T^4 J_+\left(\frac{m^2}{T^2}\right) = -\frac{\pi^4 T^4}{45} + \frac{\pi^2 m^2 T^2}{12} - \frac{T\pi(m^2)^{3/2}}{6} - \frac{(m^4)}{32}\log\frac{m^2}{a_b T^2}$$

$$T^4 J_-\left(\frac{m^2}{T^2}\right) = \frac{7\pi^4 T^4}{360} - \frac{\pi^2 m^2 T^2}{24} - \frac{(m^4)}{32}\log\frac{m^2}{a_f T^2},$$

$$V_{\rm eff}(h,T) \approx (a\,T^2 - \mu^2)\,h^2 - E(T)\,h^3 + \lambda_{\rm eff}(T)\,h^4$$