Gravitational Wave Radiation as a probe of Dark Sectors

RICE
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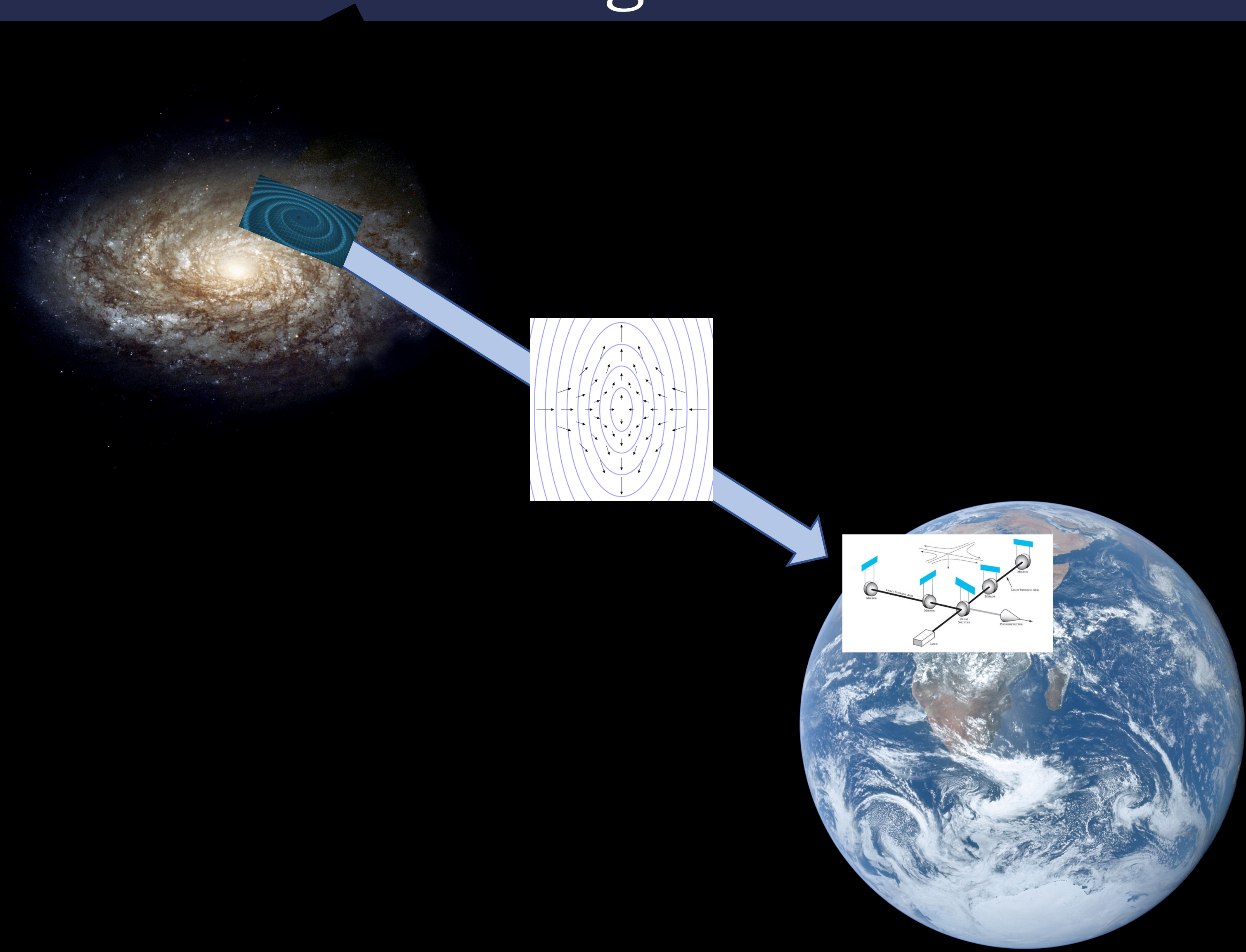
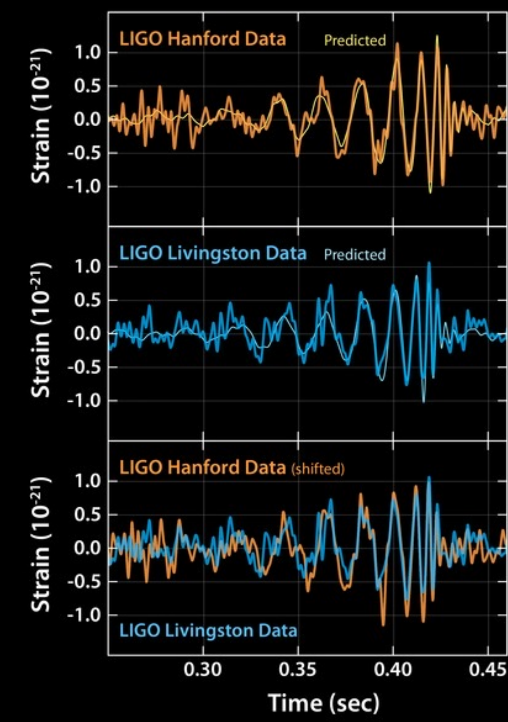
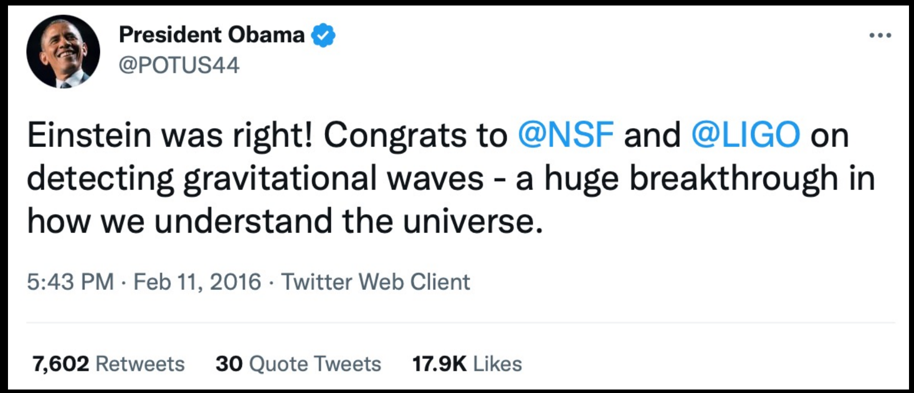
Rice University
@ Dark Interactions
Nov 15, 2022

Introduction

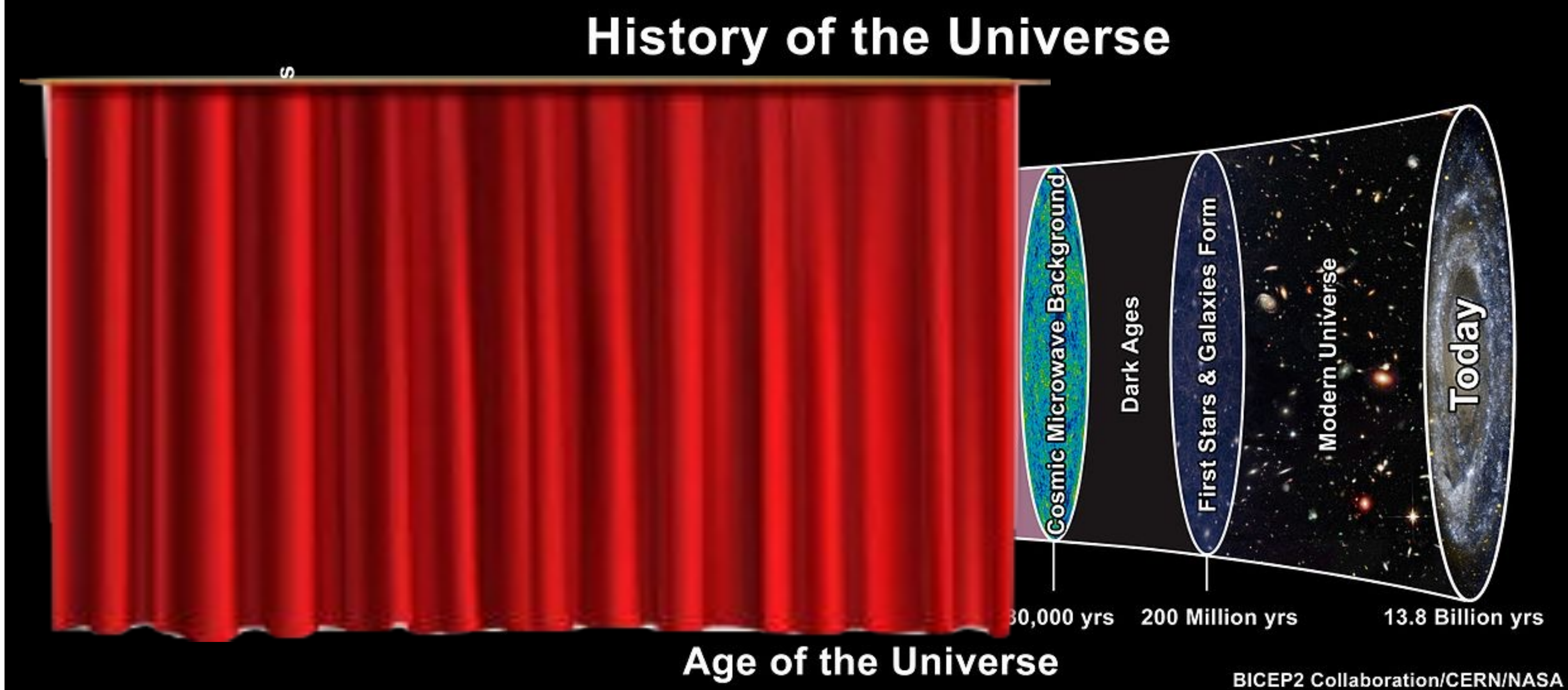
First detection of gravitational wave radiation!







Opening a new window onto the early universe



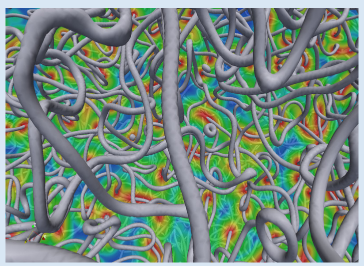
Primordial gravitational waves

[image: A. Stuver/LIGO]
[LIGO + Virgo Collab (1612.02029)]

sources

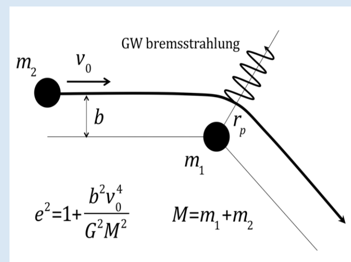
$$\ddot{h}_{\mu\nu}(t,\boldsymbol{x}) - \boldsymbol{\nabla}^2 h_{\mu\nu}(t,\boldsymbol{x}) = M_{\rm pl}^{-2}\, T_{\mu\nu}(t,\boldsymbol{x})$$

Topological Defects

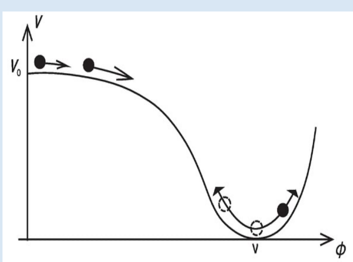


Magnetic Fields

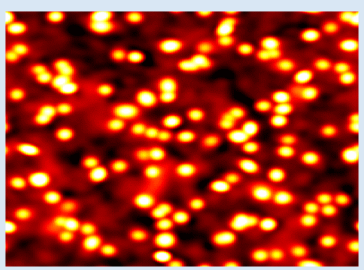
Primordial plasma



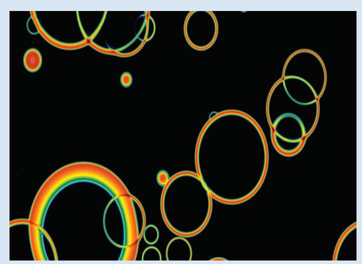
Preheating



Exotic compact objs.

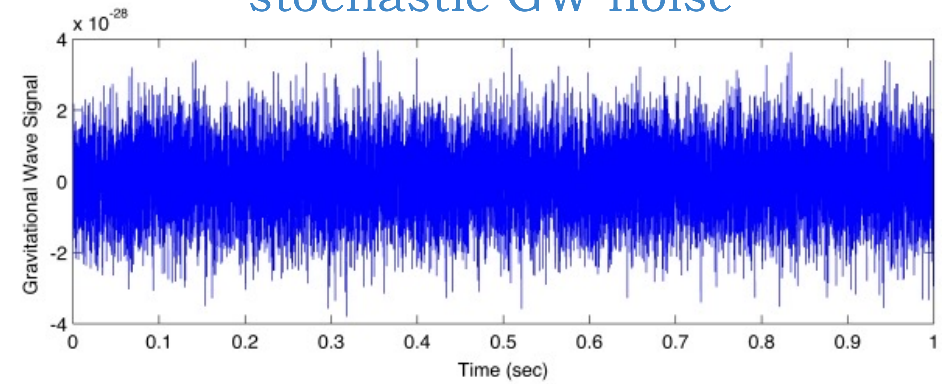


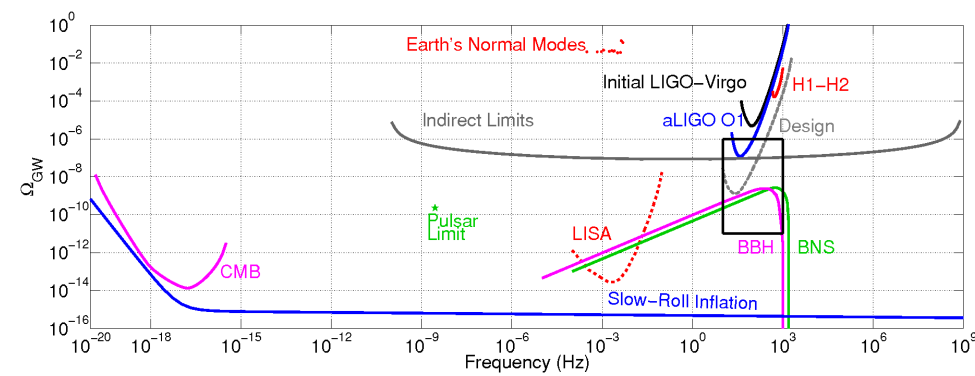
Bubble collisions



signal

stochastic GW noise



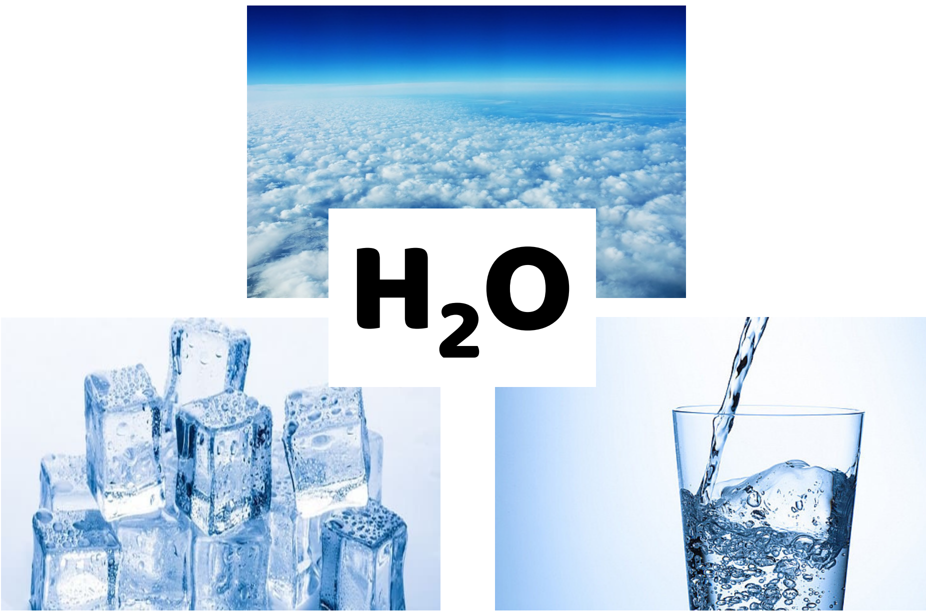


Part 1 of 3

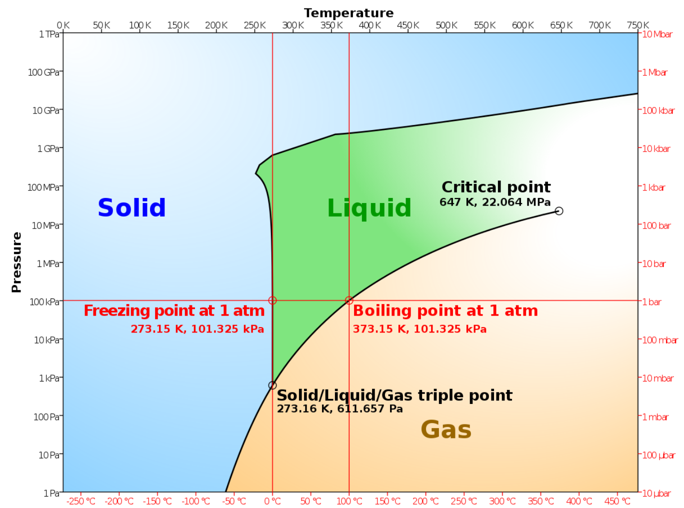
cosmological first-order phase transitions

Cosmological first-order phase transition

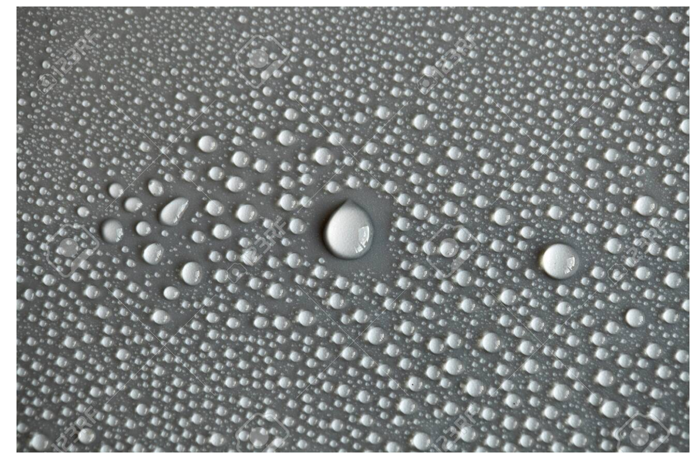
phases



phase diagram



first-order
phase transition
(condensation)

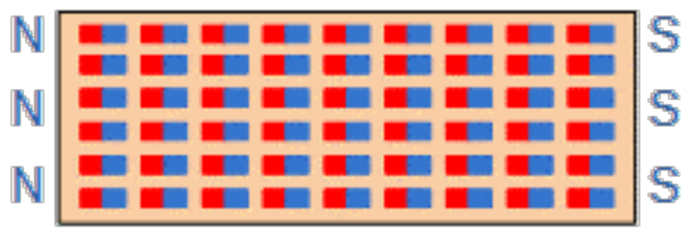


Question: did the cooling primordial plasma experience a phase transition?

Thermal effective potential

free energy: $F = E - TS$

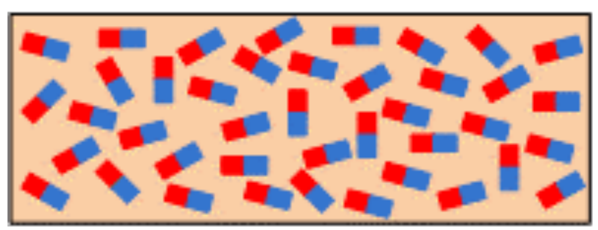
@ low T: min(F) = min(E)



example:

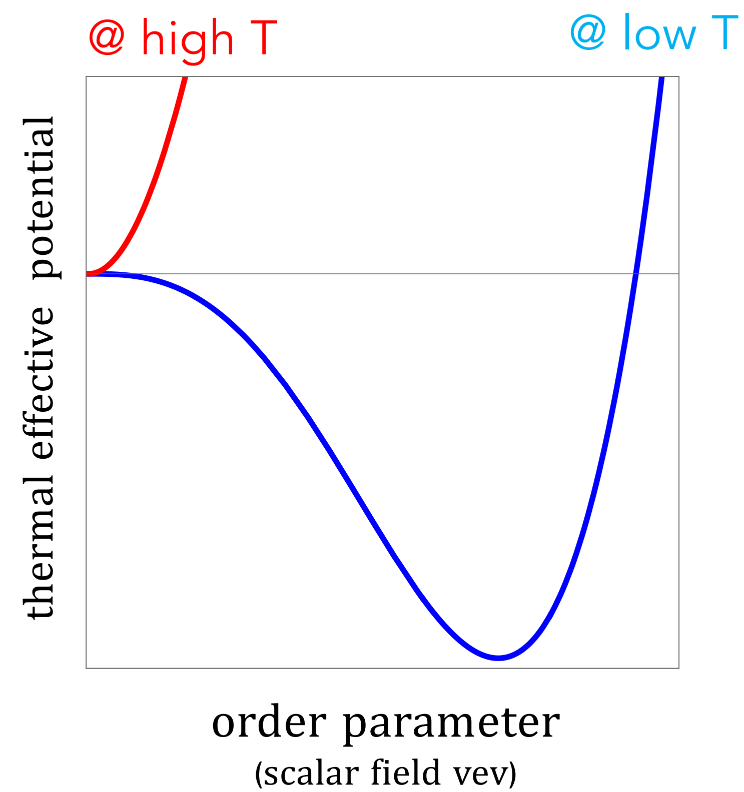
$H_{\text{int}} = -\boldsymbol{\mu} \cdot \boldsymbol{B}$

@ high T: min(F) = max(S)



thermal effective potential:

$$V_{\text{eff}}(\phi, T) = F/V$$

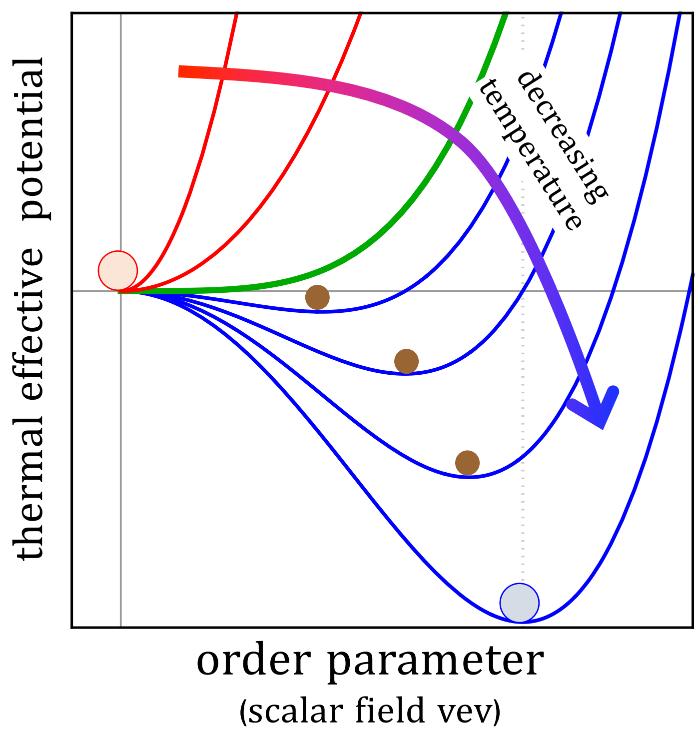


Types of phase transitions

Continuous Crossover

V_{eff} has no barrier

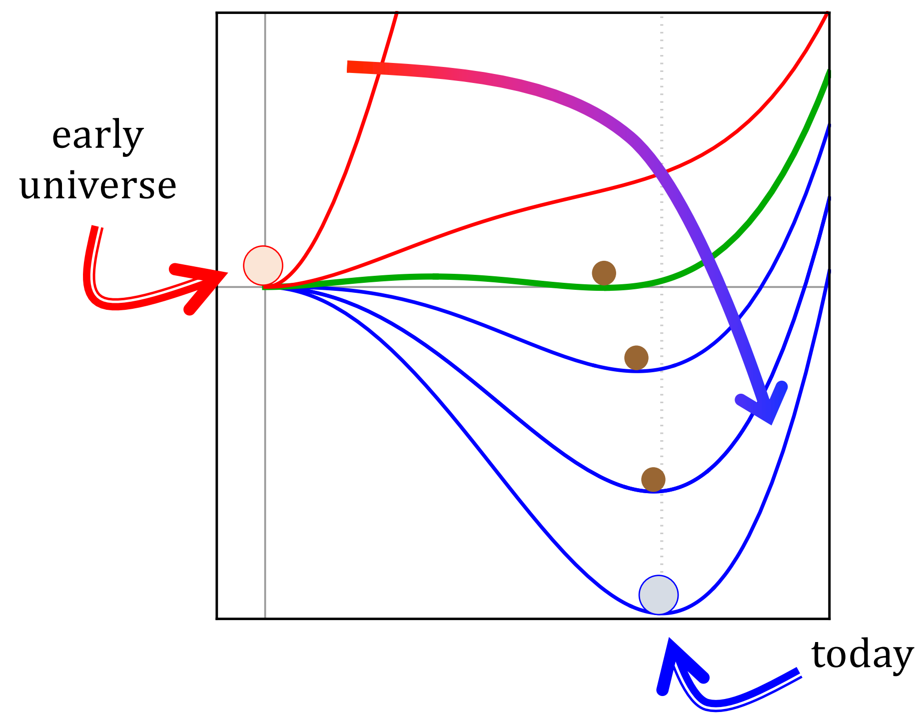
v(T) is continuous



First Order Phase Transition

barrier in V_{eff}

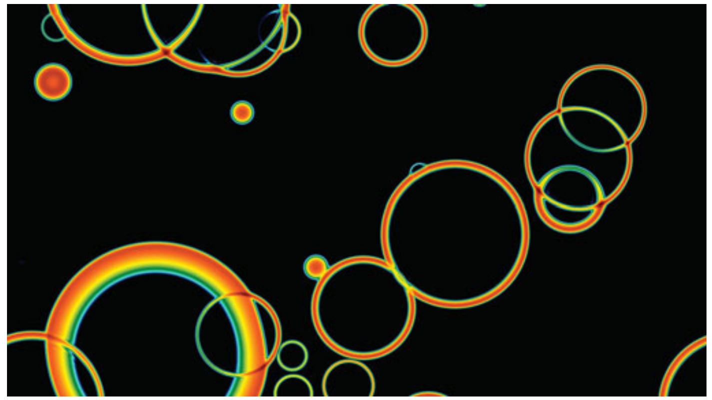
v(T) is discontinuous

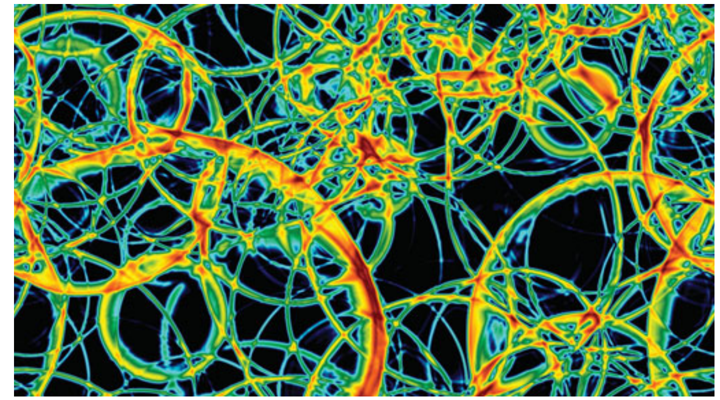


Gravitational wave sources

[Weir (2022)]
[Caprini et. al. (2015)]
[Caprini et. al. (2019)]

bubble dynamics
induce sound waves





3 components
to the GW signal:

bubbles
+ sound
+ turbulence

$$h^2\Omega_{\rm env}(f) = 1.67 \times 10^{-5} \left(\frac{H_*}{\beta}\right)^2 \left(\frac{\kappa\alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_*}\right)^{\frac{1}{3}} \left(\frac{0.11\, v_w^3}{0.42 + v_w^2}\right) S_{\rm env}(f)$$

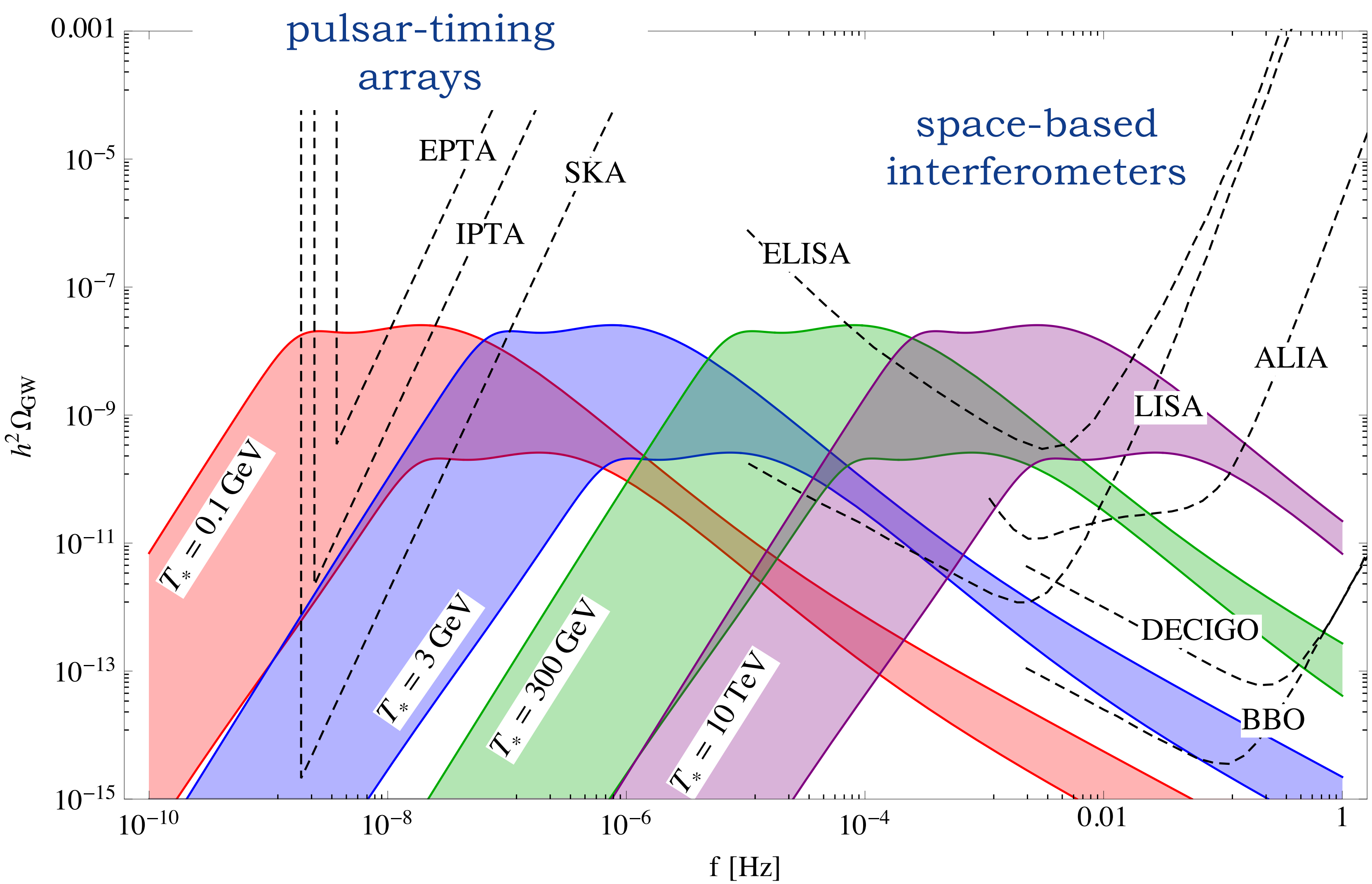
$$h^2\Omega_{\rm sw}(f) = 2.65 \times 10^{-6} \left(\frac{H_*}{\beta}\right) \left(\frac{\kappa_v\alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_*}\right)^{\frac{1}{3}} v_w\, S_{\rm sw}(f)$$

$$h^2\Omega_{\rm turb}(f) = 3.35 \times 10^{-4} \left(\frac{H_*}{\beta}\right) \left(\frac{\kappa_{\rm turb}\,\alpha}{1+\alpha}\right)^{\frac{3}{2}} \left(\frac{100}{g_*}\right)^{1/3} v_w\, S_{\rm turb}(f)$$

β^{-1} = duration of PT; $\alpha \sim \Delta V/T^4$ = energy liberated; v_w = wall speed

GW signal & sensitivity

[Schwaller (2015)]



higher T_*
- ➔ earlier phase trans.
- ➔ smaller Hubble scale
- ➔ shorter wavelength
- ➔ higher frequency

shaded band
= model uncertainty in phase transition strength

upshot: gravitational waves from dark sector phase transitions may be within reach of near-future observations

Open questions

Ongoing work seeks to address

- How quickly and efficiently does hydrodynamic turbulence develop?
- How do we calculate Ω_{gw} for strongly-coupled phase transitions?
- How do bubbles interact with the ambient plasma?
- How do these interactions affect the bubble wall dynamics (v_w)?
- Can these interactions be responsible for generating other relics?
  - baryon asymmetry of the universe
  - dark matter
  - dark radiation
- …

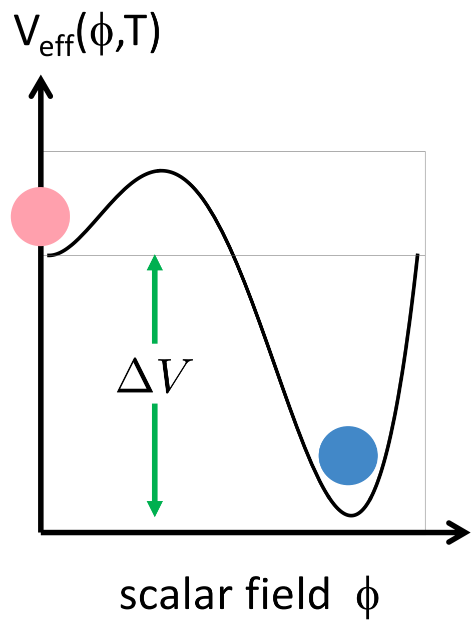
Part 2 of 3

bubble wall dynamics at cosmological first-order phase transitions

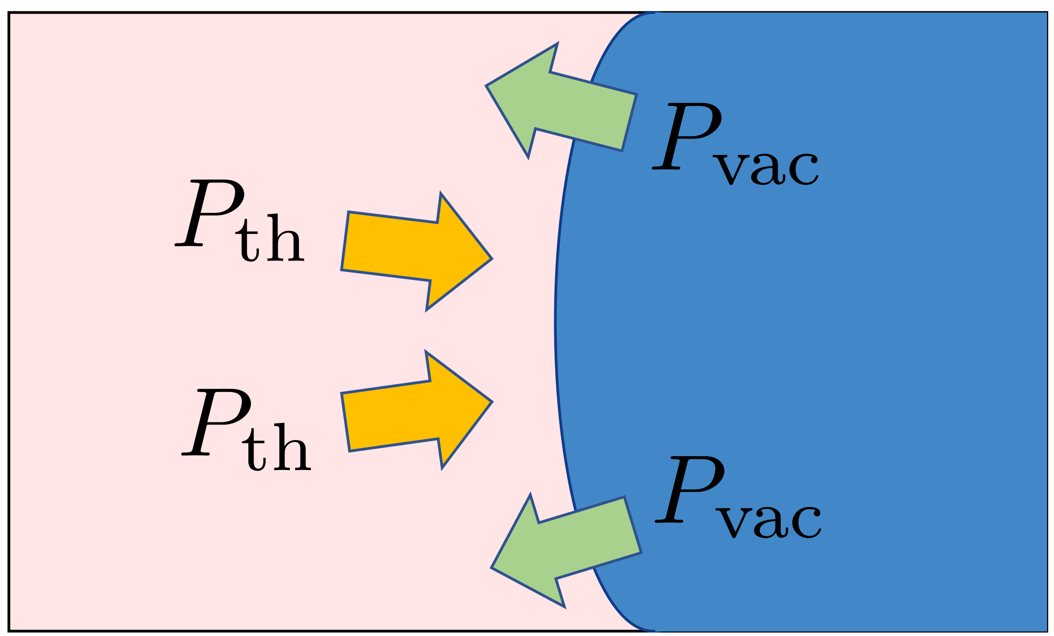
[Hoche, Kozaczuk, AL, Turner, & Wang (2007.10343)]
[Hoche, AL, Turner, & Wang (ongoing)]

Bubble wall dynamics

So we've nucleated a bubble … now how quickly does it grow (v_w)?



force/area = pressure



(1) runaway scenario

thermal pressure is negligible

$$P \approx P_{\text{vac}} = \Delta V$$

$$\text{runaway:} \quad \begin{cases} v_w \to c \\ \gamma_w \to \infty \end{cases}$$

(2) terminal scenario

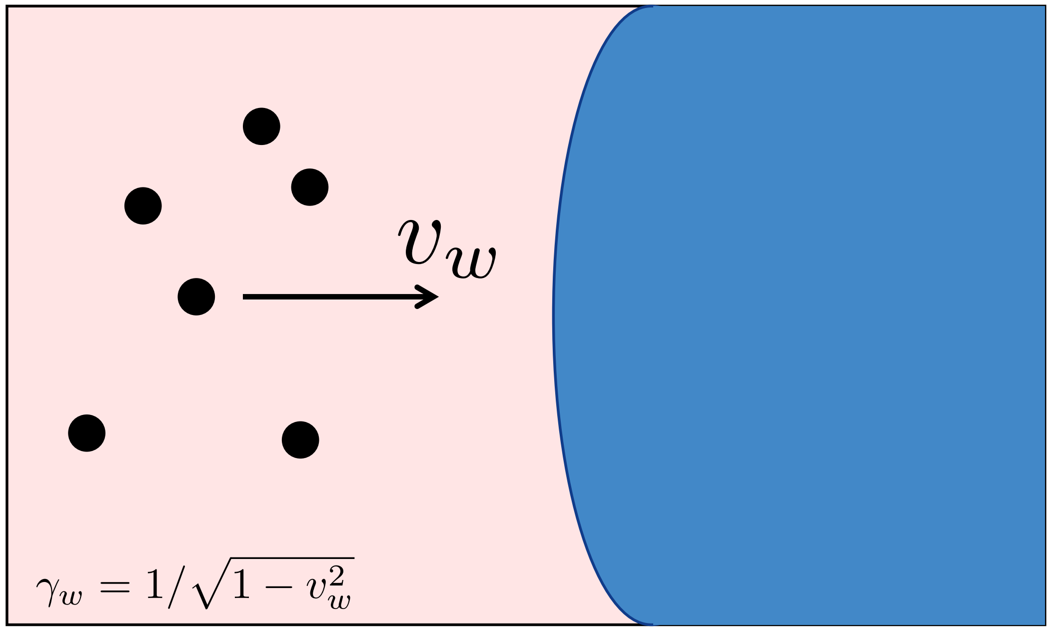
thermal pressure grows with v_w

$$P \approx P_{\text{vac}} - P_{\text{th}}$$

$$\text{terminal:} \quad v_w \to v_{\text{term}}$$

Calculating thermal pressure

work in wall's rest frame & assume the wall is super-sonic ($v_w > c_s$)



$$P_{\mathrm{therm}} = \int \mathrm{d}\mathcal{F} \, \langle \Delta p_z \rangle$$

Incident flux

$$\mathrm{d}\mathcal{F} = \frac{\mathrm{d}^3\boldsymbol{p}}{(2\pi)^3} \, f(\boldsymbol{p}) \, \frac{p_z}{E_p}$$

note that: $dF \sim dp_z \sim \gamma_w T$ ➔ increasing with γ_w

the big question: how does $\langle \Delta p_z \rangle$ scale with increasing γ_w?

Calculating <Δp_z>

[Bodeker & Moore (2009)]

suppose: a particle's mass is lifted from m_1 to m_2 at the wall

consider: a particle enters the bubble while remaining on-shell

$$\left.\begin{aligned} \Delta E &= 0 \\ \Delta \boldsymbol{p}_\perp &= 0 \\ E &= \sqrt{|\boldsymbol{p}|^2 + m^2} \end{aligned}\right\} \Rightarrow \Delta p_z = \frac{m_2^2 - m_1^2}{2E_p}$$

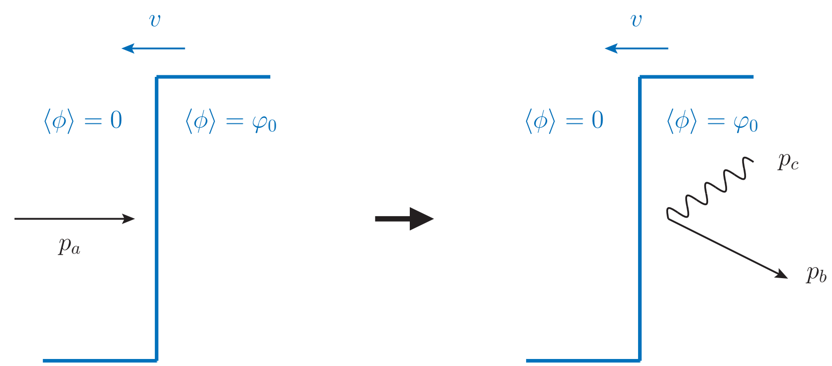
note that: $\Delta p_z \sim (E_p)^{-1} \sim (\gamma_w)^{-1}$

- ➔ implying $P_{therm} \sim (\gamma_w)^0$
- ➔ and recall $P_{vac} \sim (\gamma_w)^0$
- ➔ so runaway is possible if

$P_{vac} > P_{therm}$

[Bodeker & Moore (2017)]
[Prokopec, Rezacek, & Swiezewska (2018)]
[Azatov & Vanvlasselaer (2020)]
[Azatov, Vanvlasselaer, & Yin (2021)]
[Gouttenoire, Jinno, Sala (2022)]
[De Curtis et. al. (2022)]
[Laurent & Cline (2022)]
[Azatov et. al. (2022)]

open question: what is the impact of transition radiation?



$$\langle \Delta p_z \rangle = \int \mathrm{d}\mathbb{P}_{a\to b_1\cdots b_n}\, \Delta p_z$$

$$\mathrm{d}\mathbb{P}_{a\to b_1\cdots b_n} = \frac{1}{2E_a} \prod_{i=1}^{n} \mathrm{d}\Pi_{b_i} \times (2\pi)^3\, \delta^{(1)}(\Delta E)\, \delta^{(2)}(\Delta \boldsymbol{p}_\perp)\, |\mathcal{M}_{a\to b_1\cdots b_n}|^2$$

Towards an all-order calculation

[Hoche, Kozaczuk, AL, Turner, Wang (2007.10343)]

our approach

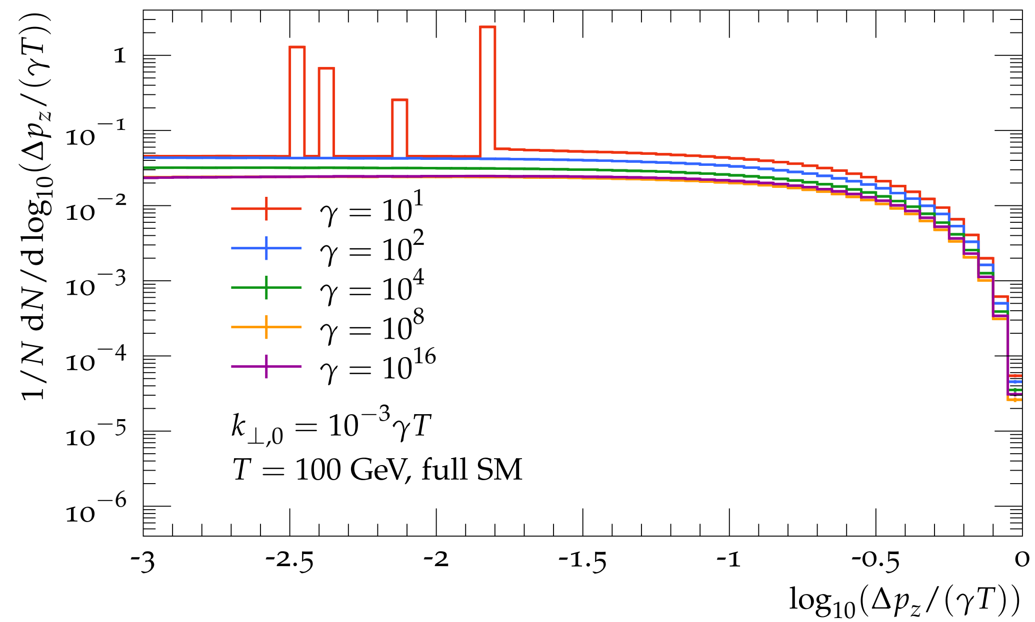
We consider an electroweak phase transition at T = 100 GeV with the full Standard Model particle content in the plasma.

We assume that the the momentum transfer at the wall may be as large as the scale of the incident particle's momentum γT.

We account for running of the couplings between IR & UV scales.

We numerically and analytically study the resultant showering. This can be especially important if there are massless particles in the plasma since the splitting is IR-enhanced.

result: distribution over possible longitudinal momentum transfers



$$\langle \Delta p_z \rangle \approx 1\% \times \gamma_w T$$

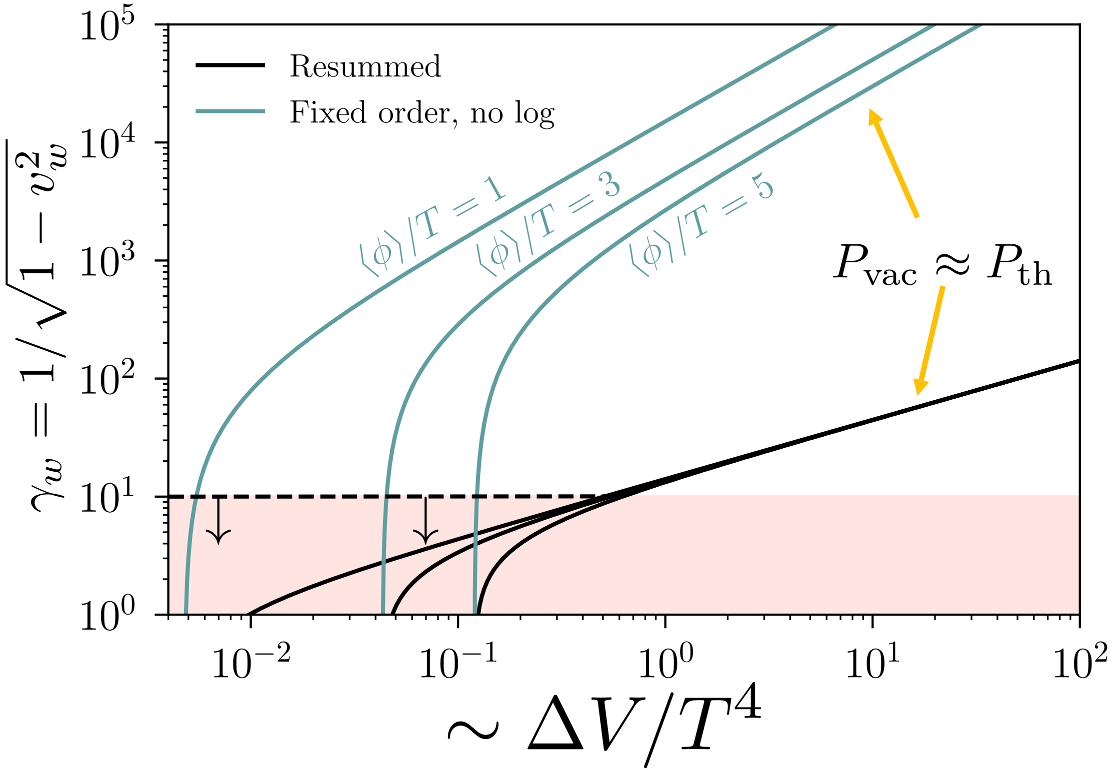
$$P_{\mathrm{th}} \sim \gamma_w^2 T^4$$

Parametrically larger pressure than previous studies

Implications & ongoing work

[Hoche, Kozaczuk, AL, Turner, Wang (2007.10343)]

impact on bubble wall dynamics



Thermal pressure is enhanced due to transition radiation.
Bubble wall terminal velocity is decreased (black curves).

ongoing activities

Whereas our study focused on the physics of the shower, it didn't account for a possible UV momentum cutoff associated with the finite wall thickness.

We're continuing to study what impact this `form factor` suppression is expected to have on $\langle \Delta p_z \rangle$.

We're also exploring how alternative formalisms (e.g., semi-classical current) lead to consistent results for $\langle \Delta p_z \rangle$.

Part 3 of 3

dark relics from cosmological phase transitions

[Bai & AL (2018)]
[Bai, AL, & Lu (2018)]
[Bai, AL, & Lu (2020)]

Dark matter from first-order phase transitions

motivation

A 1st order PT can be abrupt, making it a natural environment in which to investigate the origin of cosmological relics, such as dark matter, through out-of-equilibrium processes

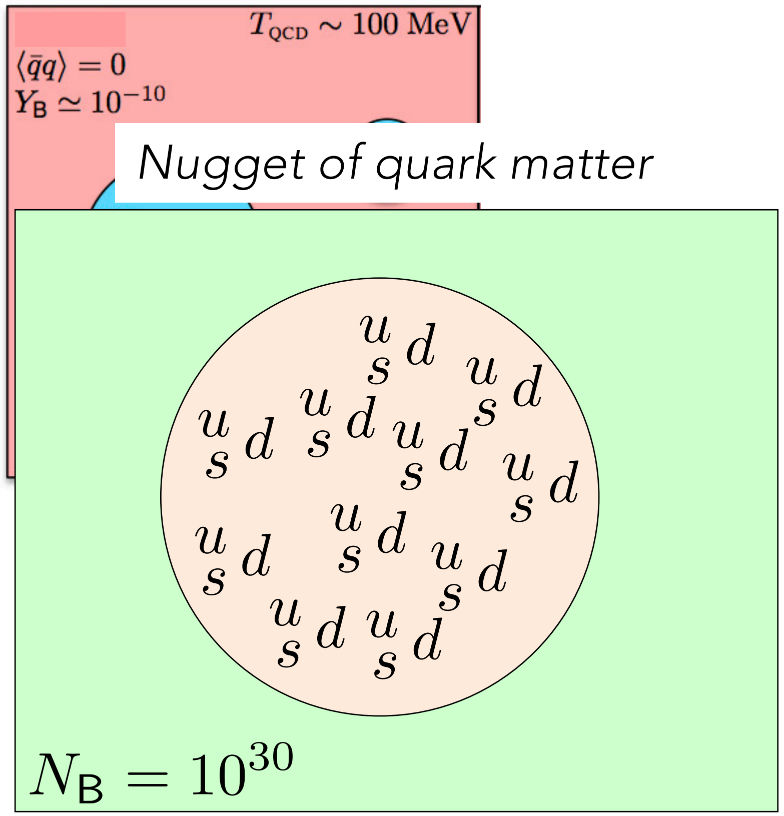
some examples

quark nuggets	Witten (1984)
PT after freeze out	Cohen, Morrissey, & Pierce (2008)
PT-induced freeze out	Chung, AL, & Wang (2011)
TeV WIMPs from EWPT	Falkowski & No (2012)
dynamic freeze-in	Baker, Breitbach, Kopp, & Mittnacht (2017)
VEV flip-flop	Baker & Mittnacht (2018)
super-cool dark matter	Hambye, Strumia, & Teresi (2018)
dark quark nuggets	Bai, AL, & Lu (2018)
asymmetric DM	Hall, Konstandin, McGhee, & Murayama (2019)
filtered dark matter	Baker, Kopp, & AL (2020)
relativistic bubbles	Azatov, Vanvlasselaer, & Yin (2021)

Witten's nuggets of quark matter

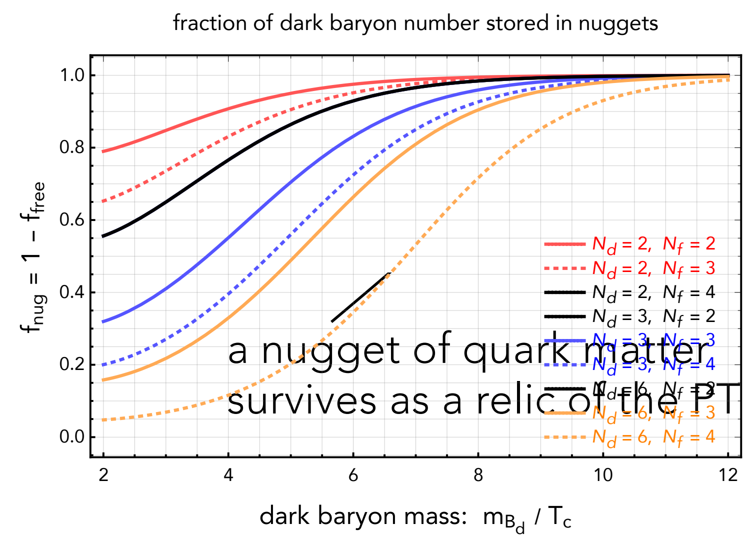
[Witten (1984)]

(1) Bubbles of hadronic phase nucleate in the background quark-gluon plasma.



Fraction of dark baryon number stored in nuggets:

$$f_{\rm nug} = 1 - f_{\rm free} \approx 1 - \frac{N_{\rm bary} N_d}{N_f} \frac{\sqrt{2\pi}}{3\zeta(3)} \left(\frac{m_{B_d}}{T_c} \right)^{3/2} e^{-m_{B_d}/T_c}$$



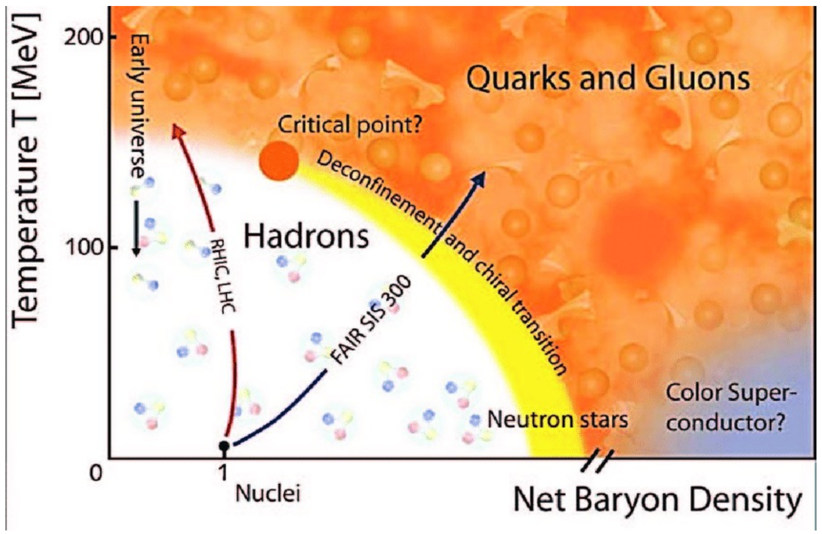
Suppose that the cosmological QCD phase transition was 1st order.

Nuggets of dark quark matter?

not to be confused with asymmetric dark matter nuggets [Wise & Zhang (2014)], [Gresham, Lou, & Zurek (2017)]

[Pisarski & Wilczek (1984)]
[Frieman & Giudice (1990)]

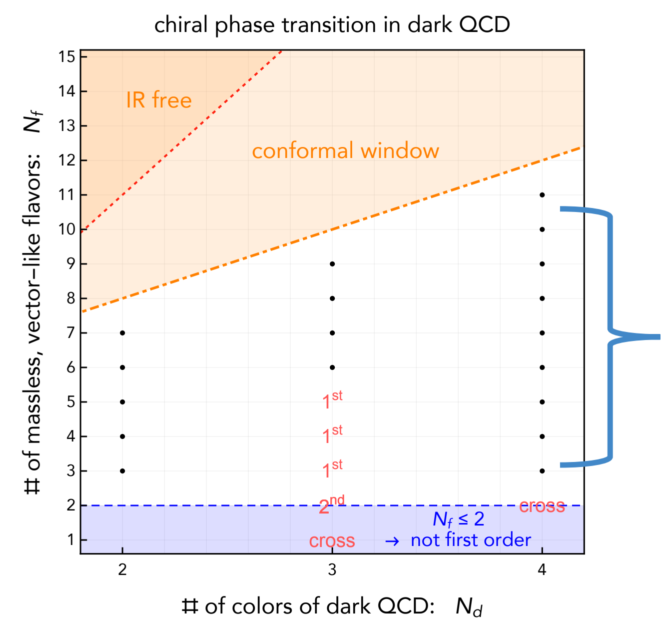
the SM fails to create nuggets



lattice studies
& heavy-ion experiment
tell us: QCD is a crossover

going BSM for confinement

- technicolor
- composite Higgs
- twin Higgs
- SUSY-breaking sectors
- dark QCD



confinement via 1^{st} order PT

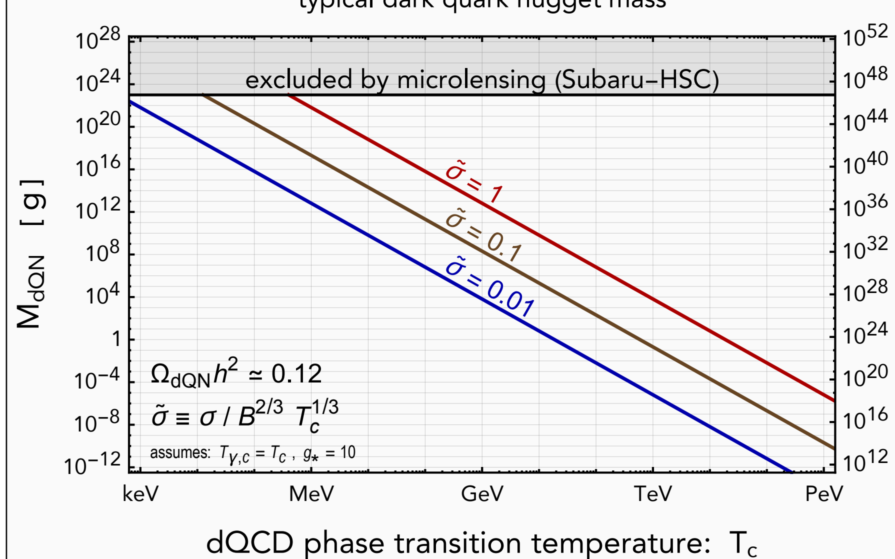
Properties of dark quark nuggets

[Bai, AL, & Lu (1810.04360)]

(bubble wall surface tension, σ, relates to the bubble nucleation rate)

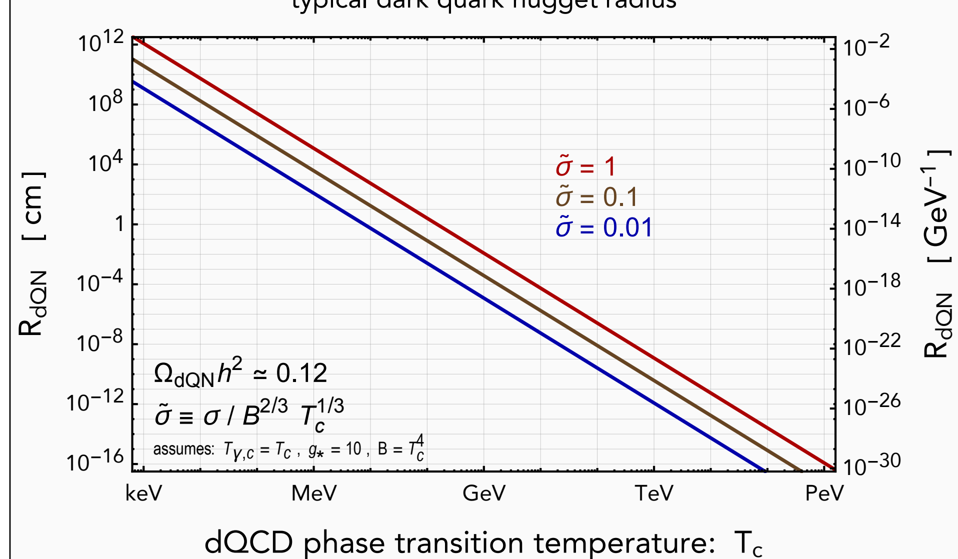
Mass

$$M_{\rm dQN} \simeq (2.06\times 10^{11}\ {\rm g}) \left(\frac{T_{\gamma,c}}{0.1\ {\rm GeV}}\right)^{-3} \left(\frac{\tilde{\sigma}}{0.1}\right)^{9/2}$$



Radius

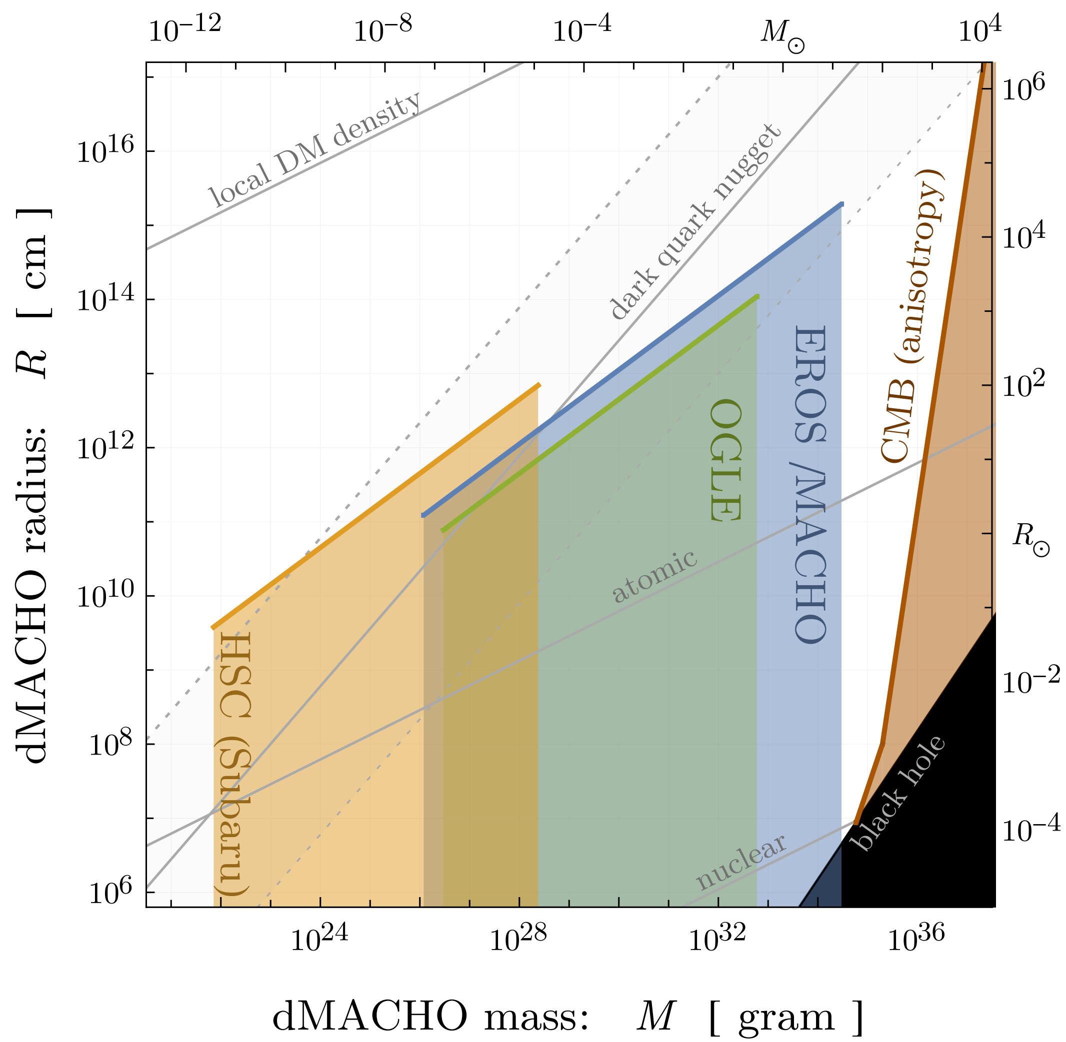
$$R_{\rm dQN} \simeq (0.08\ {\rm cm}) \left[\frac{B}{(0.1\ {\rm GeV})^4}\right]^{-1/3} \left(\frac{T_{\gamma,c}}{0.1\ {\rm GeV}}\right)^{-1} \left(\frac{\tilde{\sigma}}{0.1}\right)^{3/2}$$

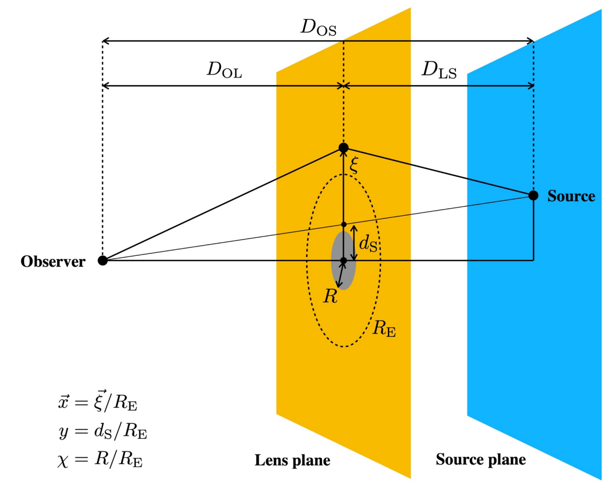


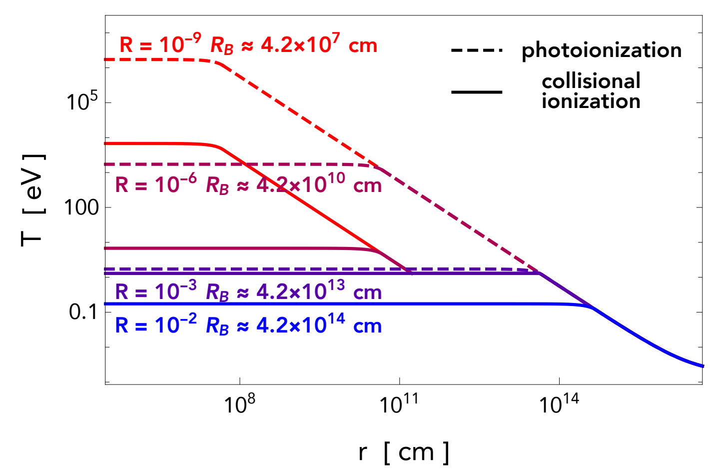
$1\ {\rm g} \simeq 6\times 10^{23}\ {\rm GeV}/c^2$ $\quad$ $1 M_\odot \simeq 1\times 10^{57}\ {\rm GeV}/c^2$

Astrophysical signatures

[Bai, AL, & Lu (2003.13182)]



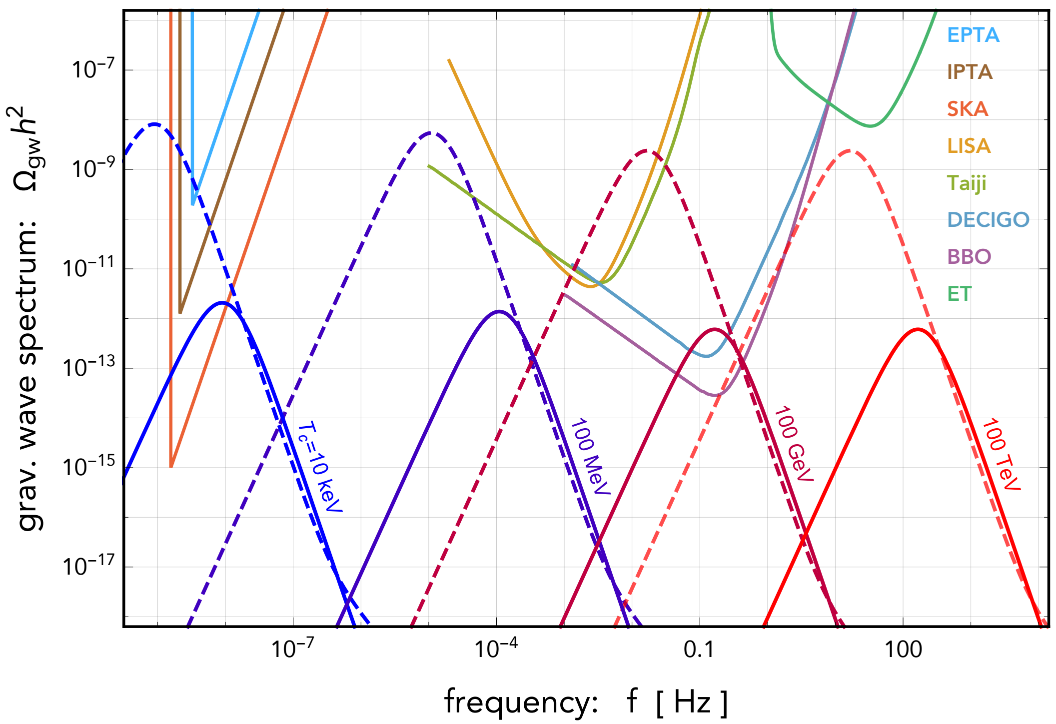




Gravitational wave signatures

[Bai, AL, & Lu (1810.04360)]

expected signal & sensitivities



- Peak freq. is controlled by Hubble scale at time of production.
- Depending on the symmetry breaking scale, the signal could show up at pulsar timing arrays or space-based interferometers.

analytical estimates

$$\Omega_{\rm sw}h^2 = (8.5\times10^{-6})\left(\frac{g_*}{100}\right)^{-1/3}\Gamma^2\,\overline{U}_{\rm f}^4\left(\frac{\beta}{H}\right)^{-1} v_{\rm w}\left(\frac{f}{f_{\rm sw}}\right)^3\left(\frac{7}{4+3(f/f_{\rm sw})^2}\right)^{7/2}$$

$$f_{\rm sw} = (8.9\,\mu{\rm Hz})\,\frac{1}{v_w}\left(\frac{\beta}{H}\right)\left(\frac{z_{\rm p}}{10}\right)\left(\frac{T_{\gamma,c}}{100\ {\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6}$$

discussion

The degrees of freedom are strongly coupled at the confining phase transition, making robust estimates challenging.

More work is needed to accurately estimate parameters of the phase transition -- e.g., duration, latent heat – to derive robust predictions for GW signal.

Summary
&
Conclusion

Summary

Observations of GW radiation will allow us to open a new window onto the early universe

- Space-based interferometers like LISA have a huge potential for discovery

Cosmological first-order phase transitions are an outstanding GW source candidate

- Gravitational wave spectrum (peak freq.) bears the imprint dark sector scale of new physics

Ongoing work to understand the interactions of ultra-relativistic bubble walls with the ambient plasma is needed to establish robust predictions for GWs and assoc. relics

- Specifically, taking into account beyond-leading-order effects (multiple soft radiations)

First-order phase transitions are a natural environment in which to form cosmological relics

- For instance, giving rise to macroscopic, composite dark matter such as dark quark nuggets