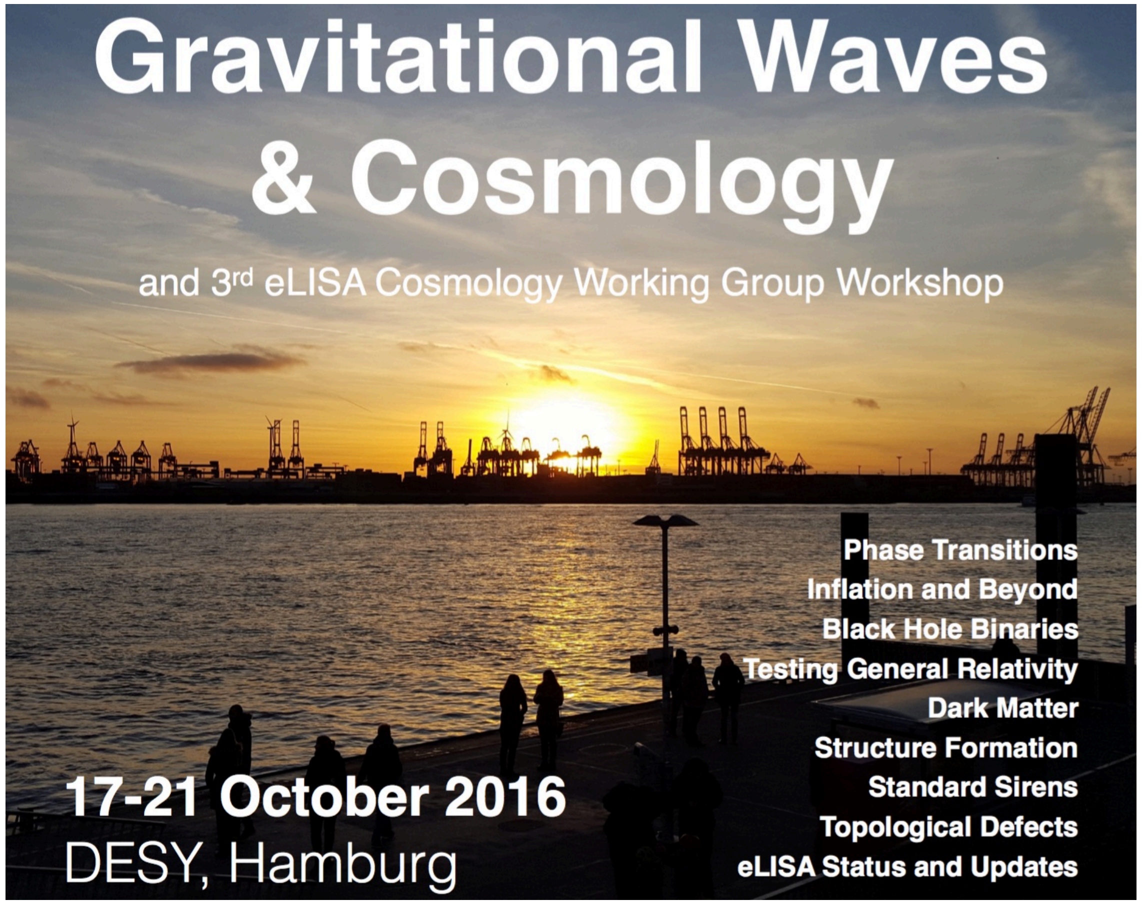
The String Soundscape

John March-Russell
University of Oxford



Isabel Garcia Garcia, Sven Krippendorf, JMR — arXiv:1607.06813 and work in progress

Gravitational Waves

- After LIGO's great discovery clear that many new detectors will be built!

- The astrophysical potential of GW detectors has been extensively studied → Black Holes, Neutron stars, Supernovae

- What can GW experiments tell us about Beyond the Standard Model physics?

GW detectors for BSM

Some examples:

- Inflation
- Strong 1st order EW (& QCD) phase transitions

  perfect for LISA
  (if they were strong!)
- Probing the existence of a QCD axion due to BH super-radiance

GW detectors for BSM

Some examples:

- Inflation
- Strong 1st order EW (& QCD) phase transitions

  perfect for LISA
  (if they were strong!)

- Probing the existence of a QCD axion due to BH super-radiance

here: can gravity wave detectors probe aspects of string theory?

Strings: the Good, the Bad, & the Ugly

Strings: the Good, the Bad, & the Ugly

Strings: the Good, the Bad, & the Ugly

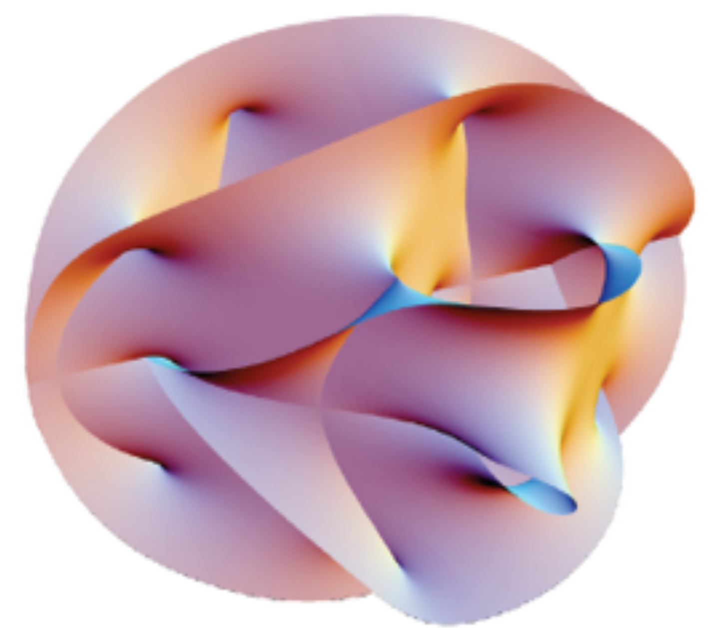
Stringy theory makes no definite
low energy, $E \ll M_{str}$, predictions

Strings: the Good, the Bad, & the Ugly

Stringy theory makes no definite *low energy*, $E \ll M_{str}$, predictions

why?

there appear to be a vast number, $10^{(\text{few} \times 100)}$, of vacuum solutions (different compactifications down to 4d), each with different 4d IR physics



Strings: the Good, the Bad, & the Ugly

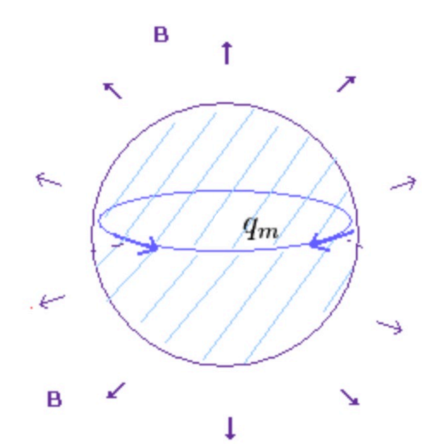
Exponential number of vacua due to multiplicity of discrete "fluxes"

Bousso-Polchinski, GKP, KKLT,...

roughly, for each "n-sphere" in compactification can turn on (pairs of) flux quanta, eg 3-spheres

$$\frac{1}{4\pi^2}\int_{S^3} F_3 = M \in \mathbb{Z}$$

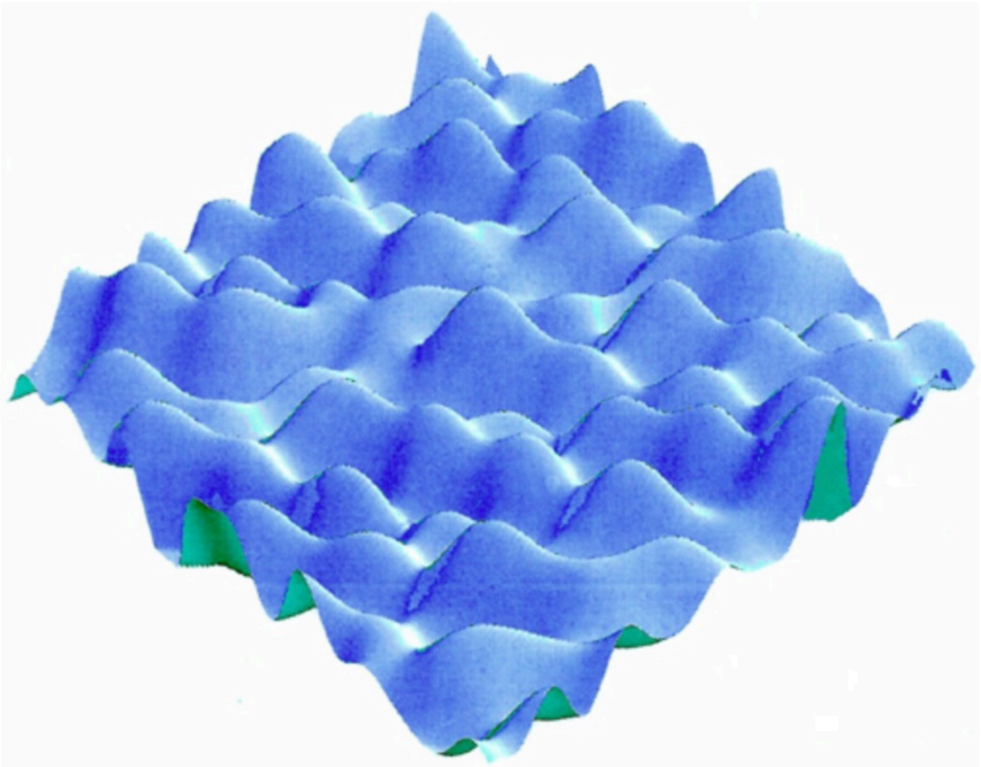
cf, magnetic flux



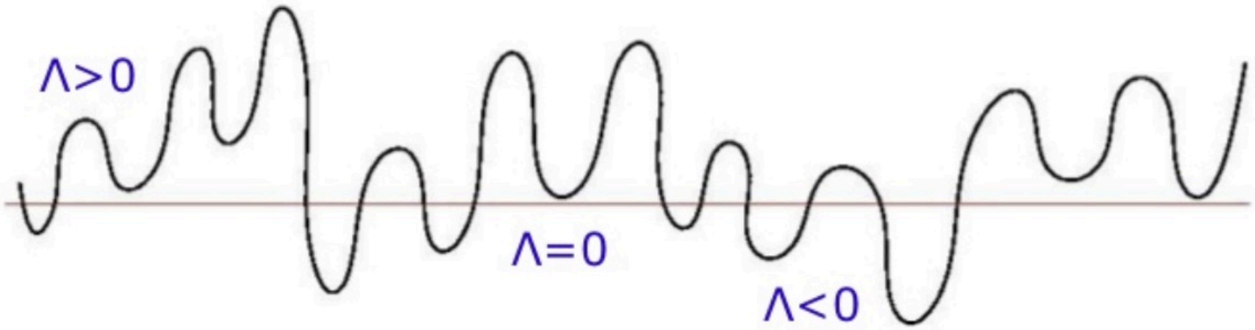
"b_3" such independent 3-spheres

typically, $b_3 \sim$ few x 100, and $|M| < 10$-100

Strings: the Good, the Bad, & the Ugly

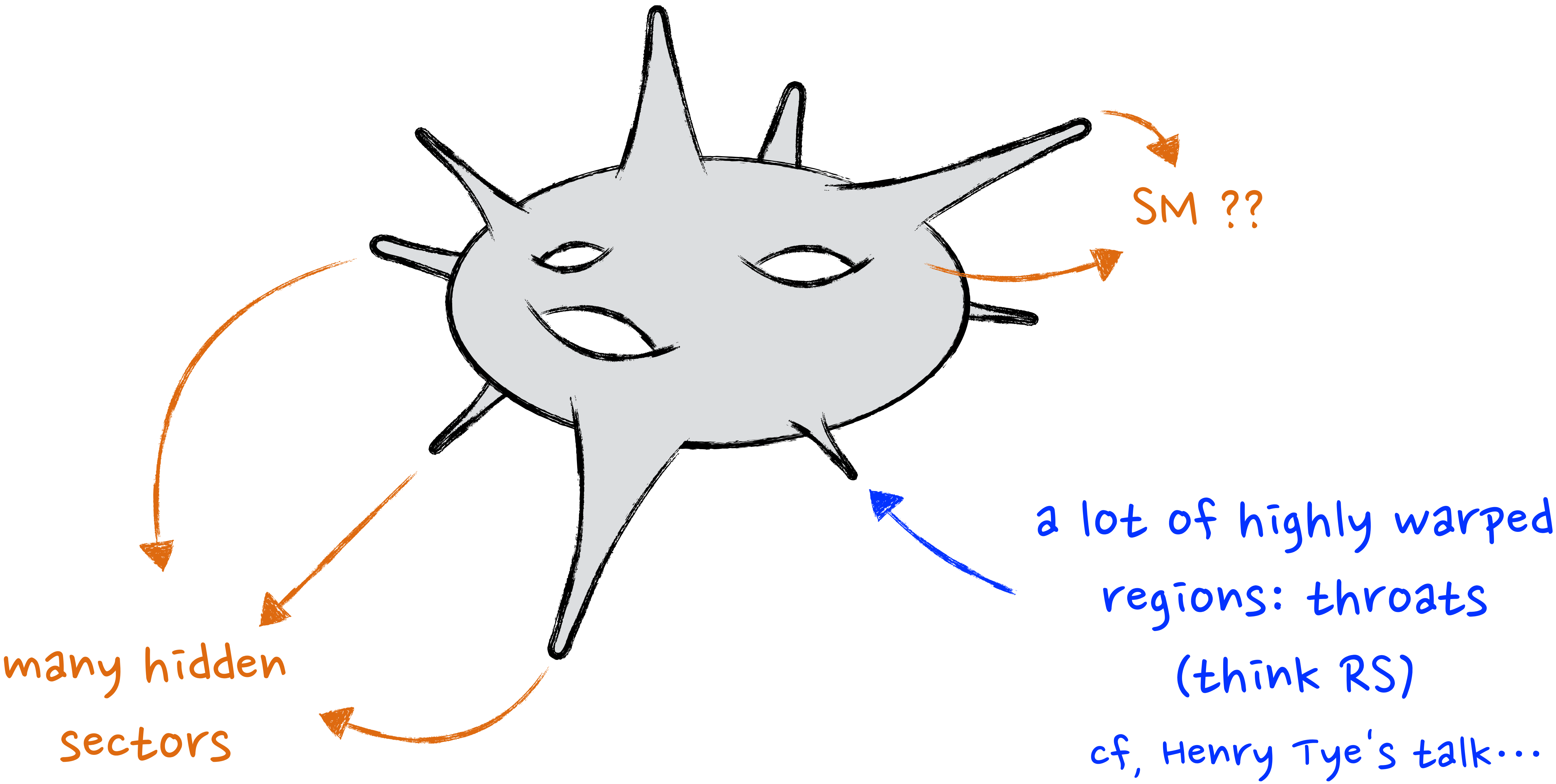


Resulting "landscape" of vacua allows us to scan Cosmo Const
— ugly as involves anthropics + we can't (yet) compute distribution
— but only known game in town for CC, so vitally important to test/investigate!



Strings: the Good, the Bad, & the Ugly

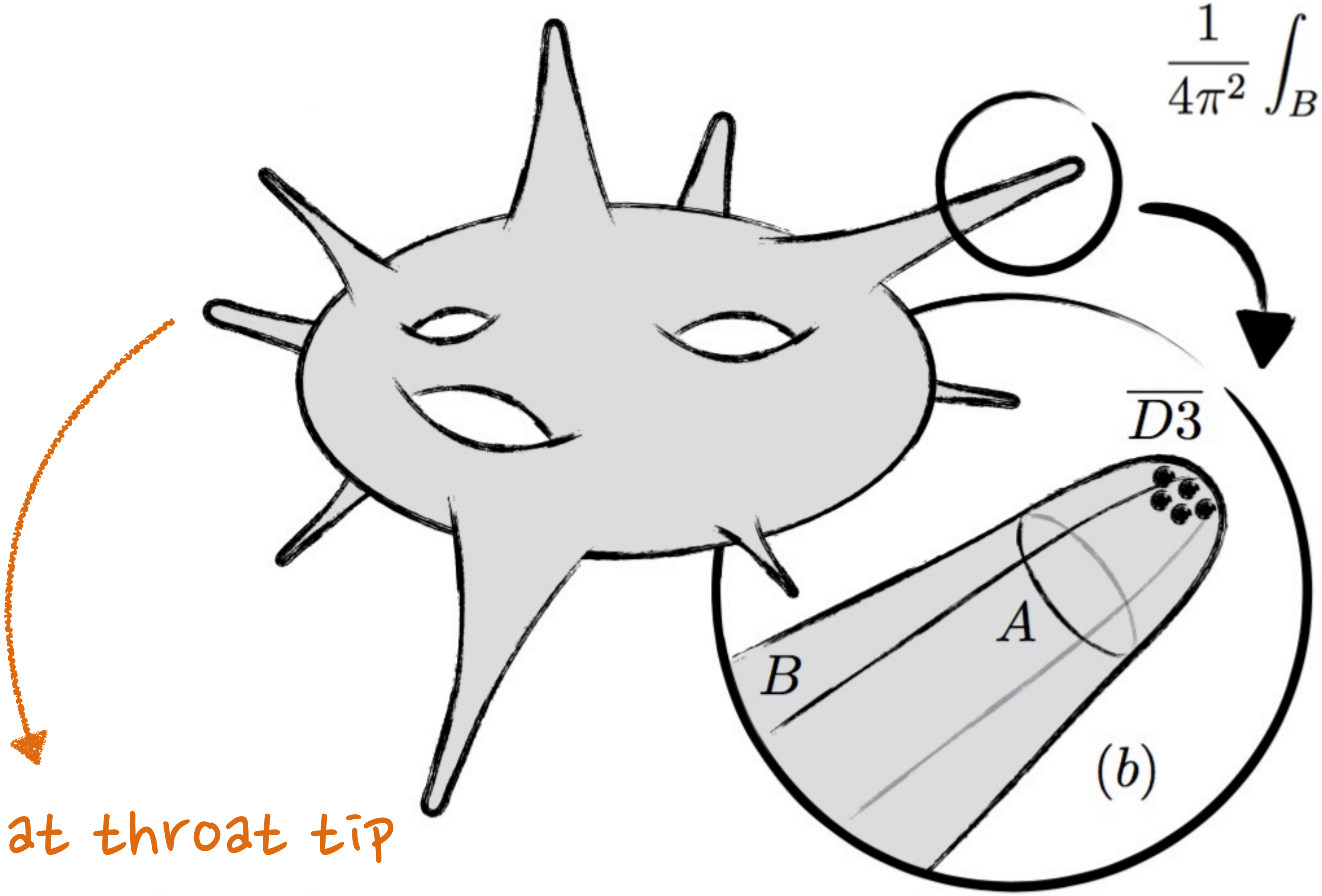
string landscape generically implies many hidden sectors which we can search for!



String Flux Compactifications

Throats are due to back-reaction from fluxes

$$\frac{1}{4\pi^2}\int_A F_3 = M\ ,$$
$$\frac{1}{4\pi^2}\int_B H_3 = -K$$

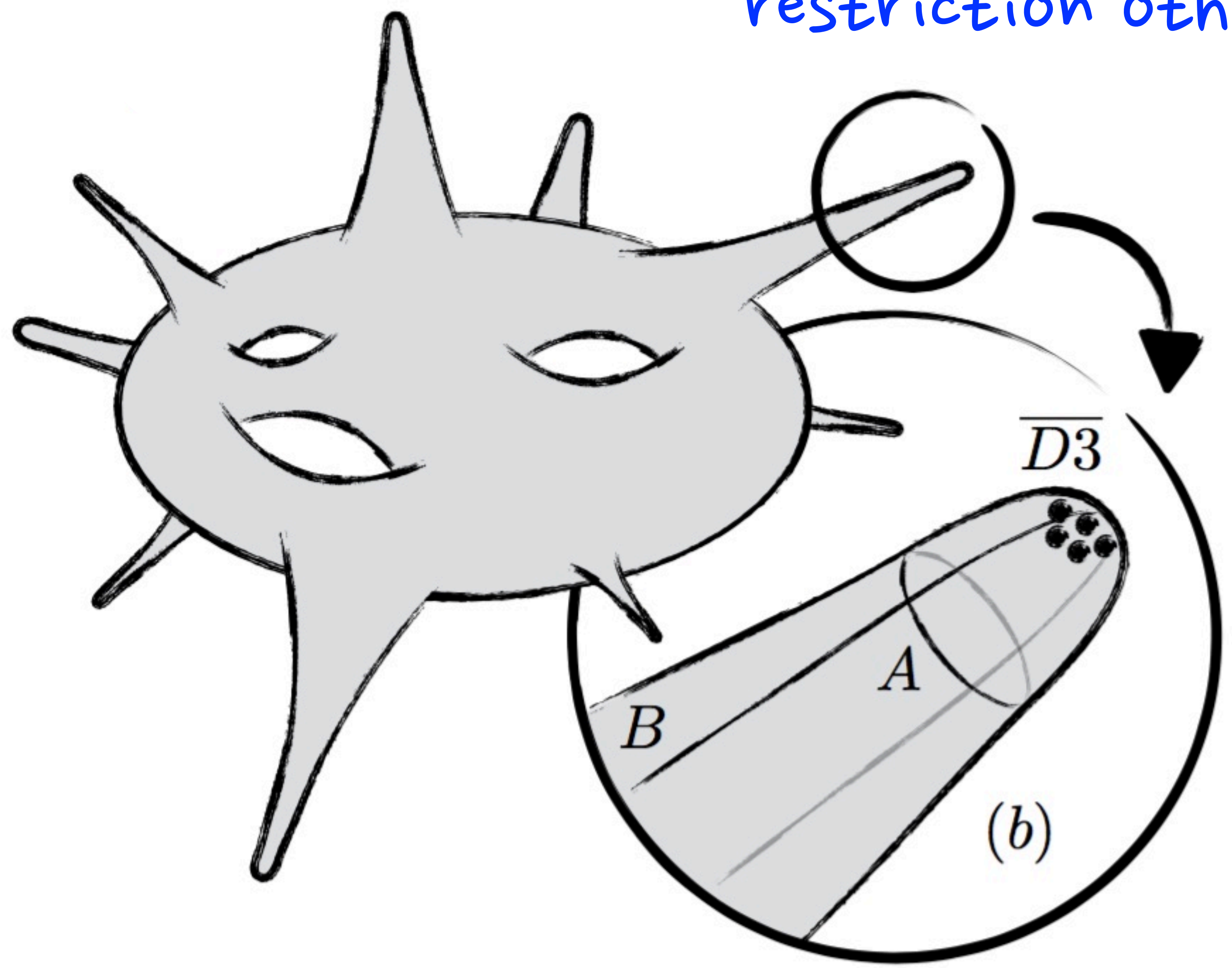


warp factor at throat tip

$w_{IR} \sim \exp(-2\pi K/3Mg_s)$ also scans

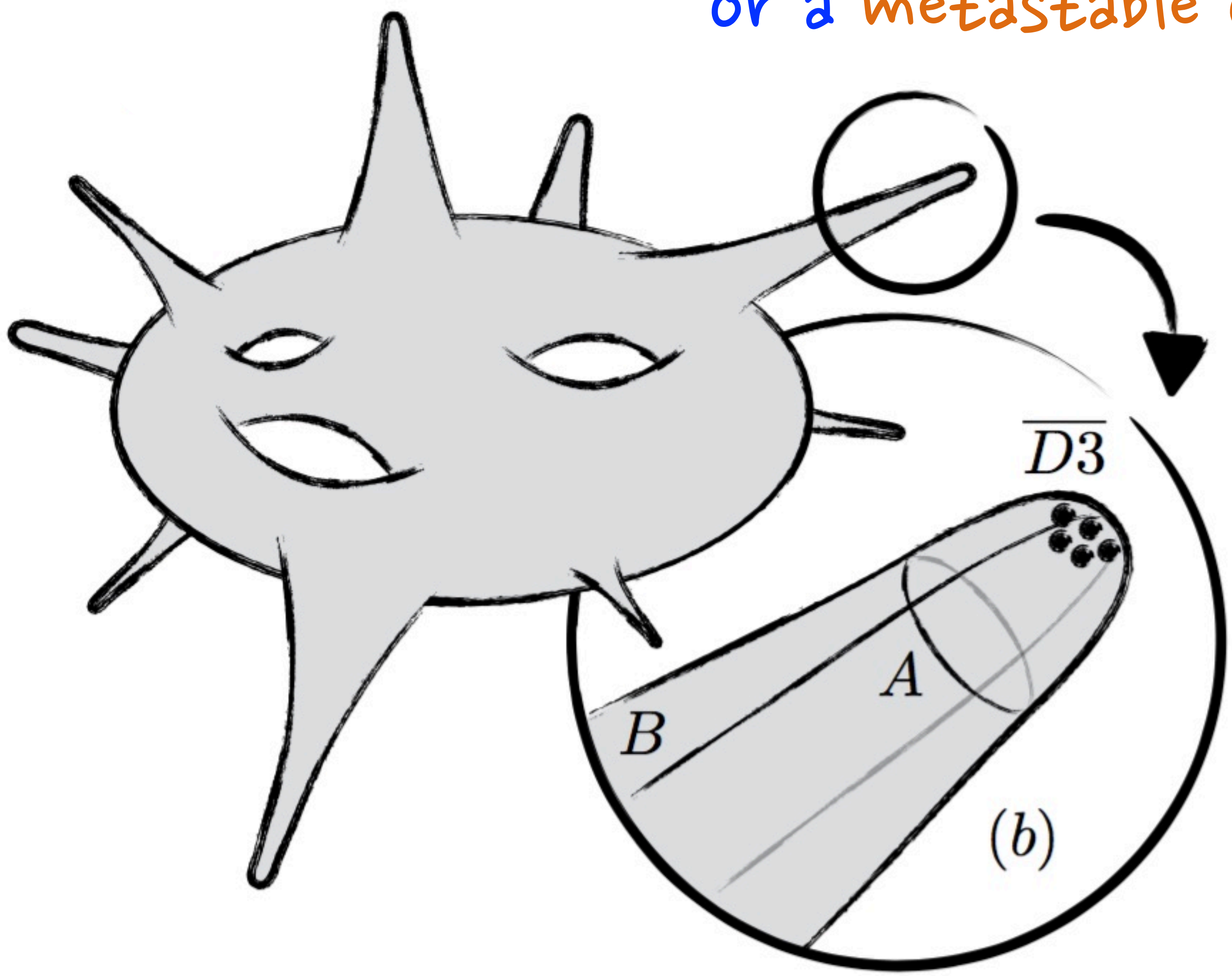
String Flux Compactifications

a lot of these throats have anti-D3 branes (it is a severe restriction otherwise)



String Flux Compactifications

these p anti-D3's lead to either a classically unstable configuration or a metastable one

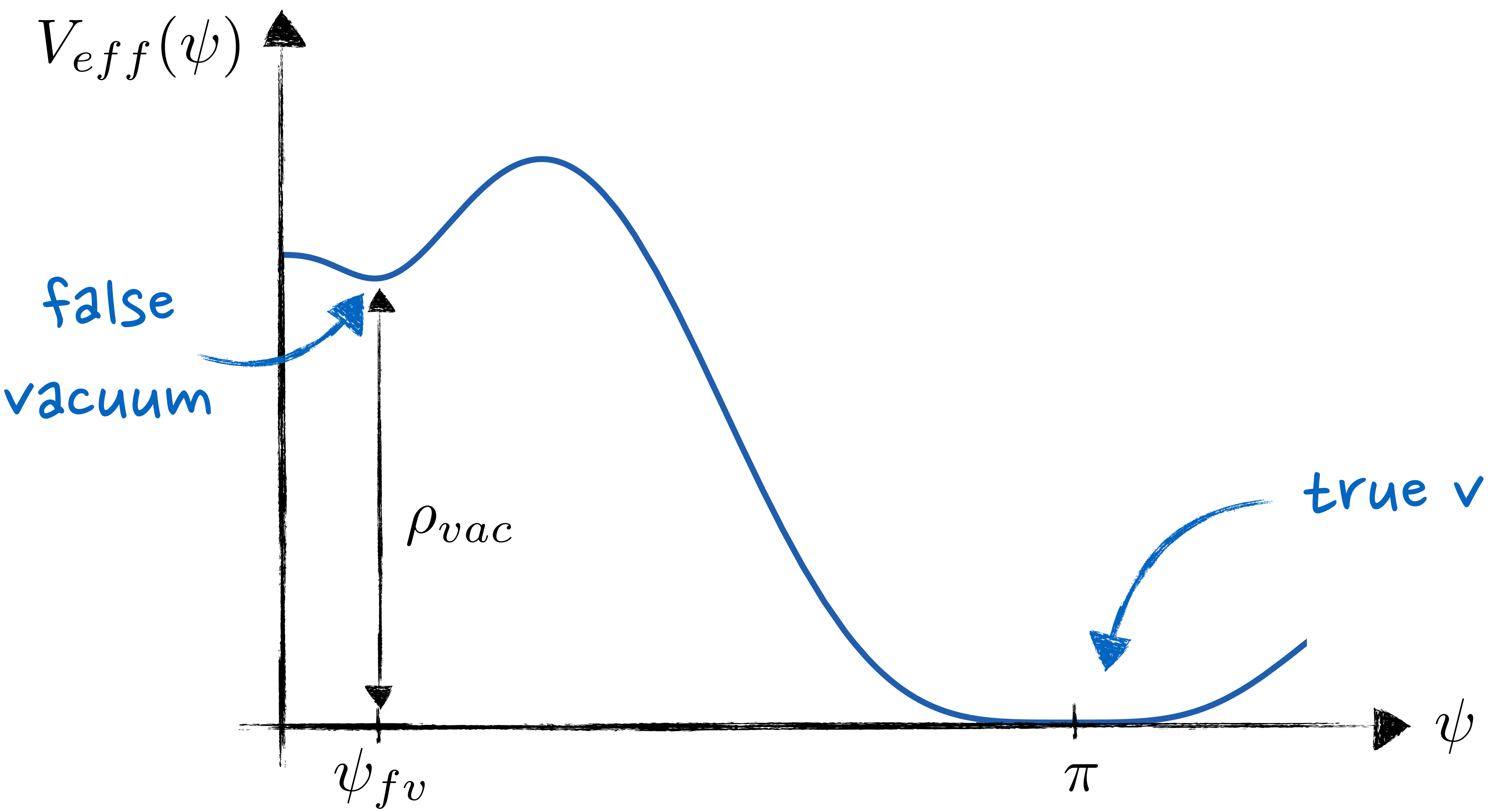


String Flux Compactifications

A typical throat features a metastable, SUSY-breaking, false vacuum, as well as a true (locally) SUSY-preserving one

Kachru, Pearson, Verlinde: hep-th/0112197

Physics described by effective angular scalar field ψ

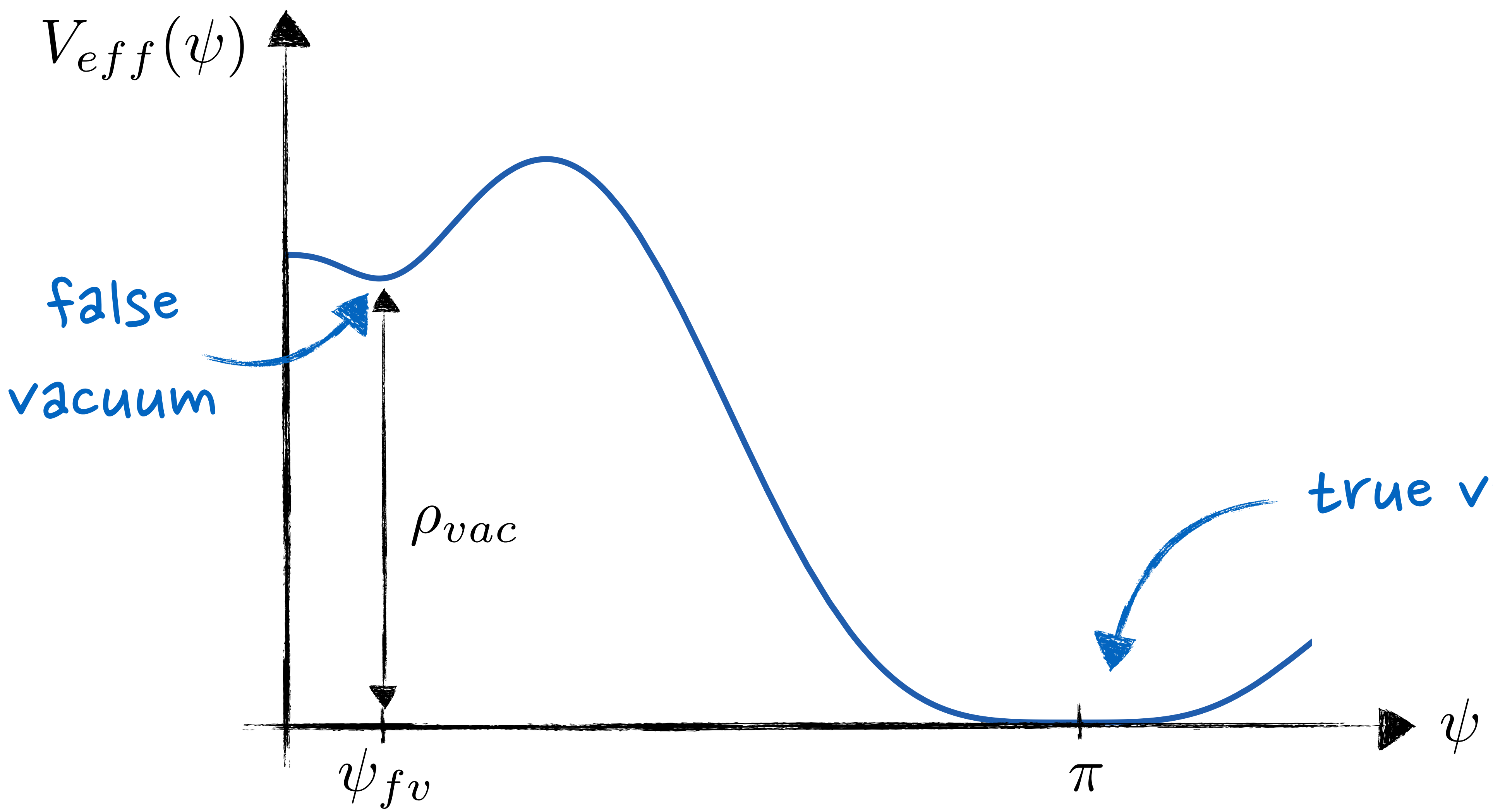


String Flux Compactifications

leading effective Lagrangian

$$\mathcal{L} \approx \frac{\mu_3 M}{g_s}\left(-V_2(\psi)\sqrt{1-\partial_\mu\psi\partial^\mu\psi}+\frac{1}{2\pi}(2\psi-\sin 2\psi)\right),$$

$$V_2(\psi)=\frac{1}{\pi}\sqrt{b_0^4\sin^4\psi+(\pi\frac{p}{M}-\psi+\frac{1}{2}\sin 2\psi)^2}$$



String Flux Compactifications

$$\mathcal{L} \approx \frac{\mu_3 M}{g_s}\left(-V_2(\psi)\sqrt{1-\partial_\mu\psi\partial^\mu\psi} + \frac{1}{2\pi}(2\psi - \sin 2\psi)\right),$$

$$V_2(\psi) = \frac{1}{\pi}\sqrt{b_0^4 \sin^4\psi + (\pi\frac{p}{M} - \psi + \frac{1}{2}\sin 2\psi)^2}$$

non-standard DBI-like kinetic terms (makes a difference to critical bubble profile, and later evolution)

(here set $M_{str}=1$ and working in red-shifted units so tip warp factor w_{IR} is hidden)

String Flux Compactifications

$$\mathcal{L} \approx \frac{\mu_3 M}{g_s} \left(-V_2(\psi)\sqrt{1 - \partial_\mu \psi \partial^\mu \psi} + \frac{1}{2\pi}(2\psi - \sin 2\psi) \right),$$

$$V_2(\psi) = \frac{1}{\pi}\sqrt{b_0^4 \sin^4 \psi + (\pi \frac{p}{M} - \psi + \frac{1}{2}\sin 2\psi)^2}$$

as ratio p/M=r reaches a critical value

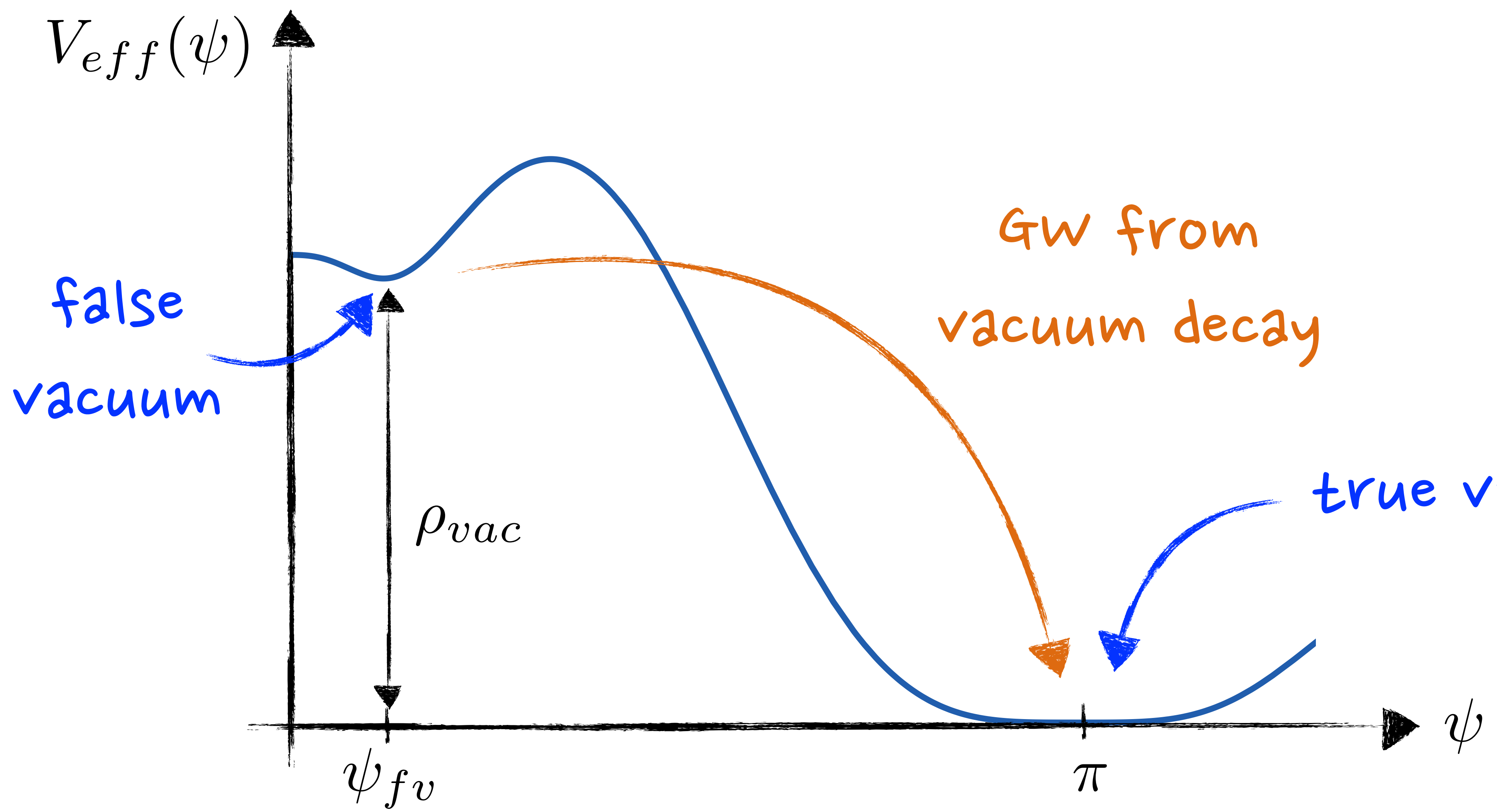
$$r_c = (\pi - 3 + b_0^4)/(4\pi) \approx 0.08$$

barrier disappears, so define

$$\frac{p}{M} \equiv r_c(1 - \delta) \qquad 0 < \delta \ll 1$$

String Flux Compactifications

as $\delta \to 0$ false vacuum decay becomes fast



General Hidden-Sector Set-up

- Interested in *post inflation* transitions

General Hidden-Sector Set-up

- Interested in *post inflation* transitions
- One or more throats left in its metastable vacuum

General Hidden-Sector Set-up

- Interested in *post inflation* transitions
- One or more throats left in its metastable vacuum
- In general post-inflation reheating *does not* heat all (visible + hidden) sectors equally

General Hidden-Sector Set-up

- Interested in *post inflation* transitions
- One or more throats left in its metastable vacuum
- In general post-inflation reheating *does not* heat all (visible + hidden) sectors equally
- Simplifying assumption for this talk: Visible sector reheated but hidden throat sector left at $T_{th} \approx 0$ (this also motivated by ΔN_{eff} constraint)

$\Rightarrow$ decay occurs via quantum tunnelling in absence of external thermal plasma to which it couples

(may be relaxed to include thermally-assisted transitions)

General Hidden-Sector Set-up

- Interested in *post inflation* transitions
- One or more throats left in its metastable vacuum
- In general post-inflation reheating *does not* heat all (visible + hidden) sectors equally
- Simplifying assumption for this talk: Visible sector reheated but hidden throat sector left at $T_{th} \approx 0$ (this also motivated by ΔN_{eff} constraint)

$\Rightarrow$ decay occurs via quantum tunnelling in absence of external thermal plasma to which it couples

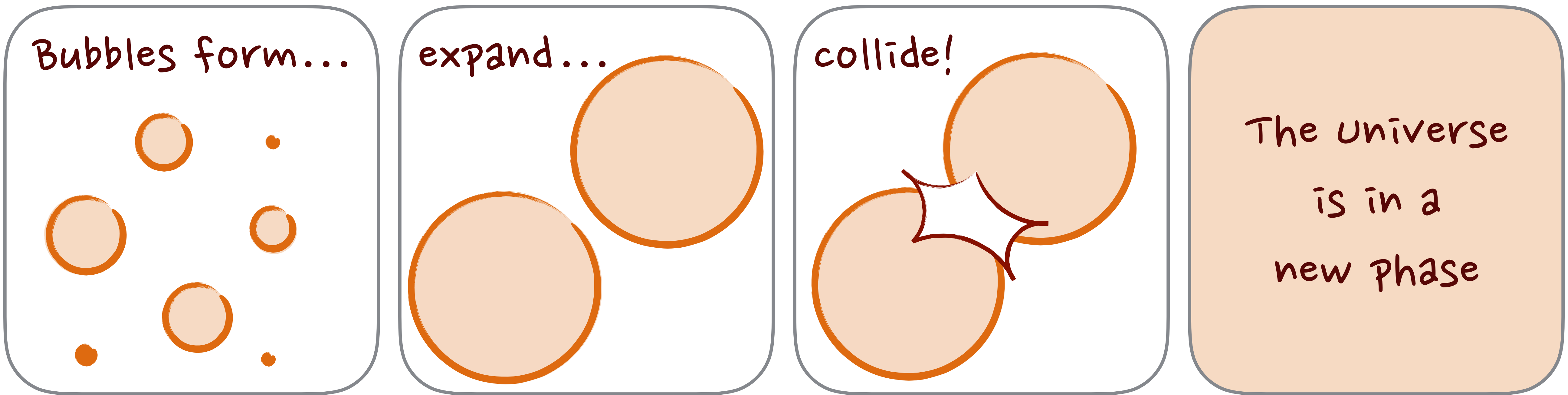
(may be relaxed to include thermally-assisted transitions)

- Also assume for simplicity: Universe radiation dominated throughout

(may be relaxed to include a phase of matter domination)

$$\rho_{total}(T) = \rho_{rad}(T) + \rho_{vac} \quad \text{with} \quad \alpha(T) \equiv \frac{\rho_{vac}}{\rho_{rad}(T)} \leq 1$$

Vacuum decay



They quickly start expanding at the speed of light

Bubbles collide, emitting gravity waves (and maybe forming some PBHs too...)

Vacuum decay

T_{vis}

Nucleation probability increases as T_{vis} falls

false vacuum!

$$\sim \frac{\Gamma}{H(T)^4}$$

decay rate per unit volume (T independent)

decreases as the temperature drops

T_n

true vacuum!

when $\frac{\Gamma}{H(T_n)^4} \approx 1$ the transition starts

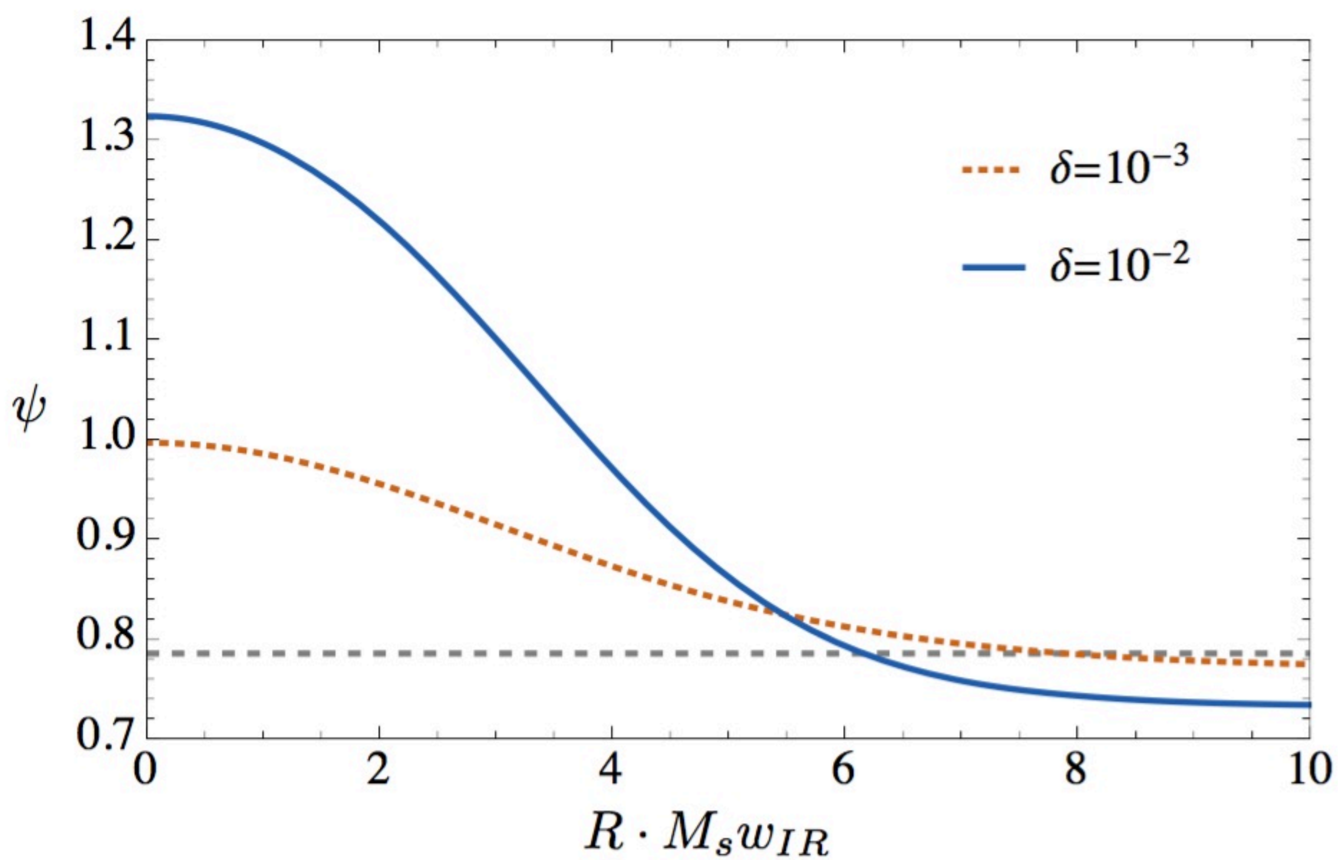
$T \sim 1$ MeV

Vacuum decay

Nucleation probability given by Coleman's bounce solution

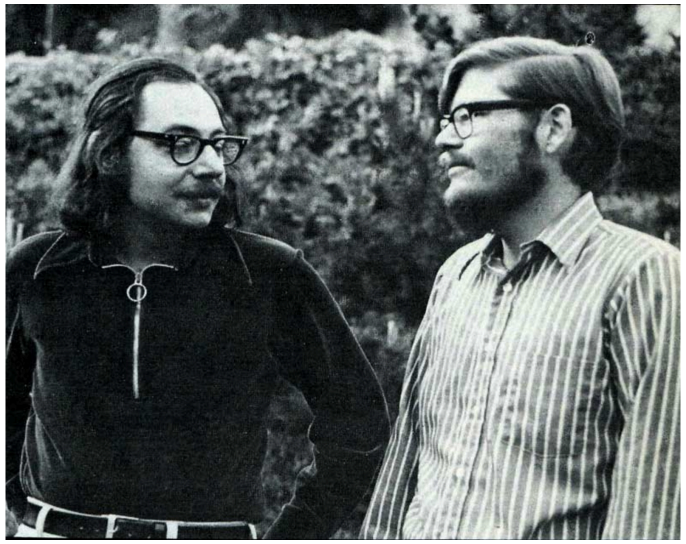
$$\Gamma \sim m^4 e^{-B} \qquad B = S[\psi_B] - S[\psi_{fv}]$$

We find for our system always a *thick-walled* bounce



Vacuum decay

Nucleation probability given by Coleman's bounce solution



$$\Gamma \sim m^4 e^{-B} \qquad B = S[\psi_B] - S[\psi_{fv}]$$

We find for our system always a *thick-walled* bounce

$$B = 2\pi^2 \mu_3 b_0^4 g_s M^3 f(\delta) \approx 36 \; \frac{g_s}{0.03} \left(\frac{M}{10^2} \right)^3 \frac{f(\delta)}{f(10^{-3})}$$

$$f(\delta) \approx 0.38 \; \delta^{1/2} + 6.0 \; \delta$$

Gravity Wave Spectrum

Putting everything together we find a stochastic gravity wave spectrum with approximate peak frequency

$$f_0 \sim 10^{-5}\ \text{Hz} \left(\frac{g_*(T_c)}{100}\right)^{1/6} \left(\frac{T_c}{100\ \text{GeV}}\right) \frac{1}{t_* H(T_c)}$$

visible temperature at bubble collision

$$T_c \approx 0.62 T_n$$

duration of transition in Hubble times

$$t_* H(T_c) = \mathcal{O}(1)$$

Gravity Wave Spectrum

Putting everything together $\Rightarrow$ a stochastic gravity wave spectrum with approximate peak frequency

$$f_0 \sim 10^{-5}\ \text{Hz} \left(\frac{g_*(T_c)}{100}\right)^{1/6} \left(\frac{T_c}{100\ \text{GeV}}\right) \frac{1}{t_* H(T_c)}$$

visible temperature at bubble collision

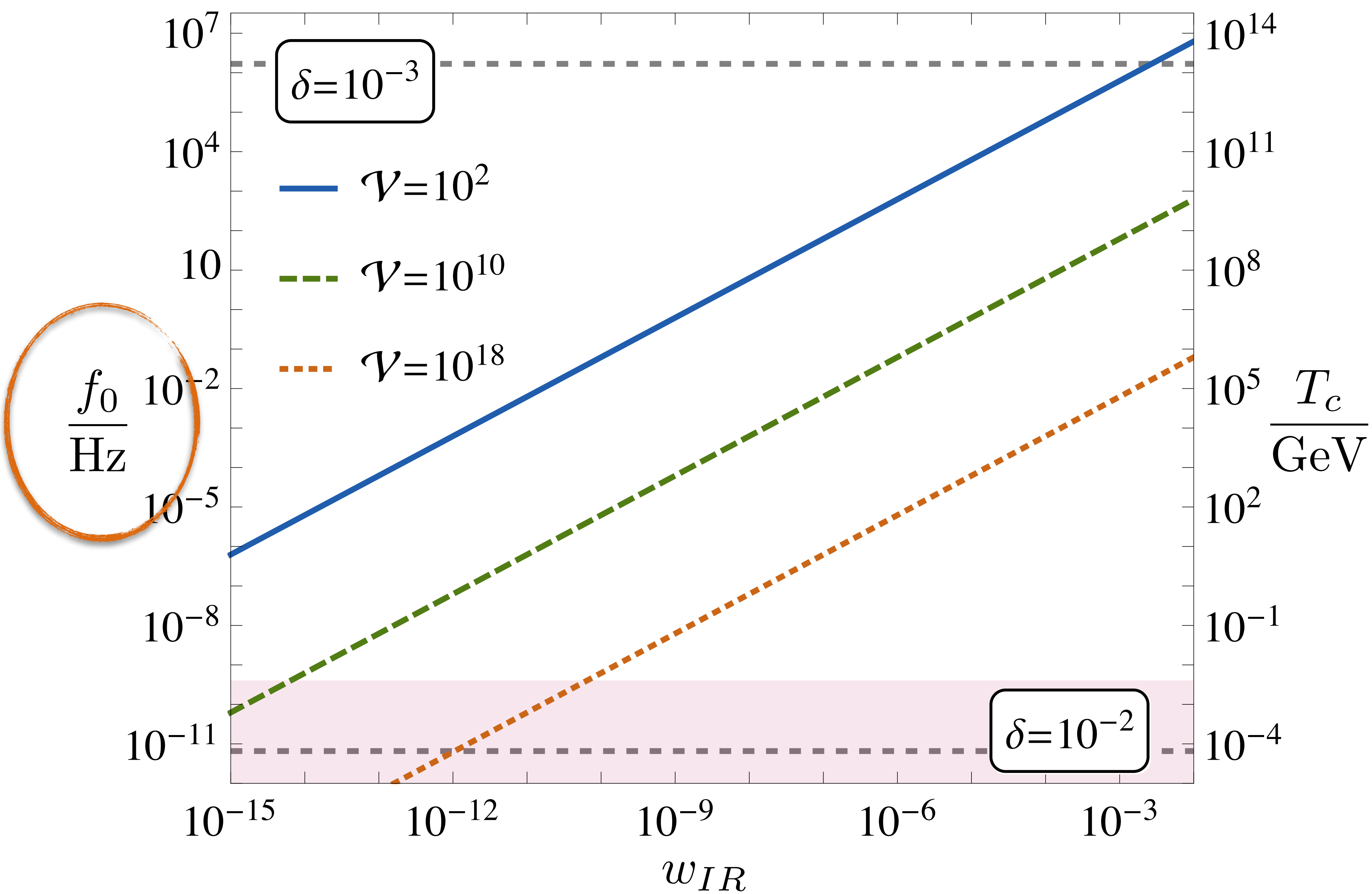
$$T_c \approx 0.62 T_n$$

duration of transition in Hubble times

$$t_* H(T_c) = \mathcal{O}(1)$$

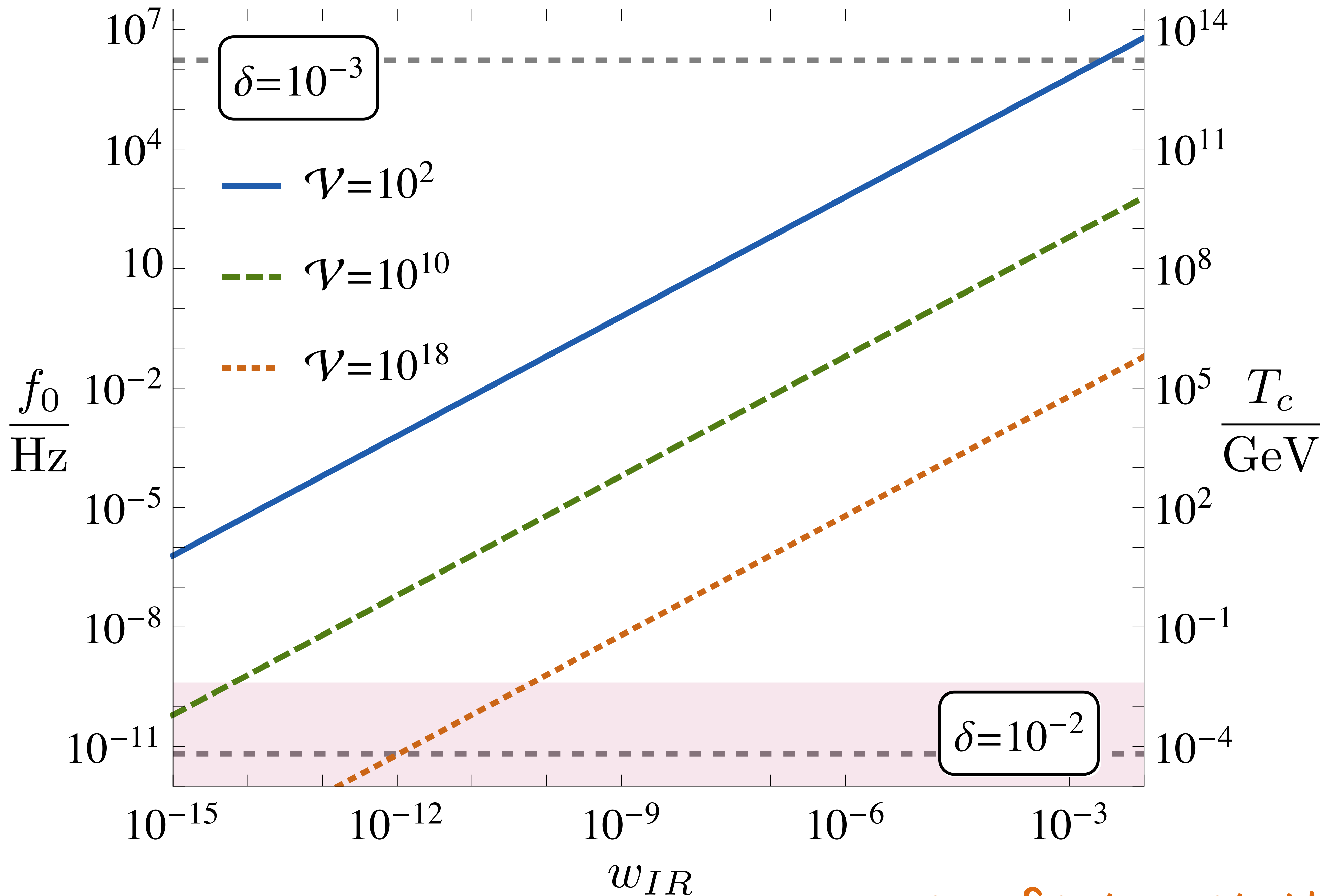
because of scanning of throat parameters, T_n and f_0 scan

GW peak frequency



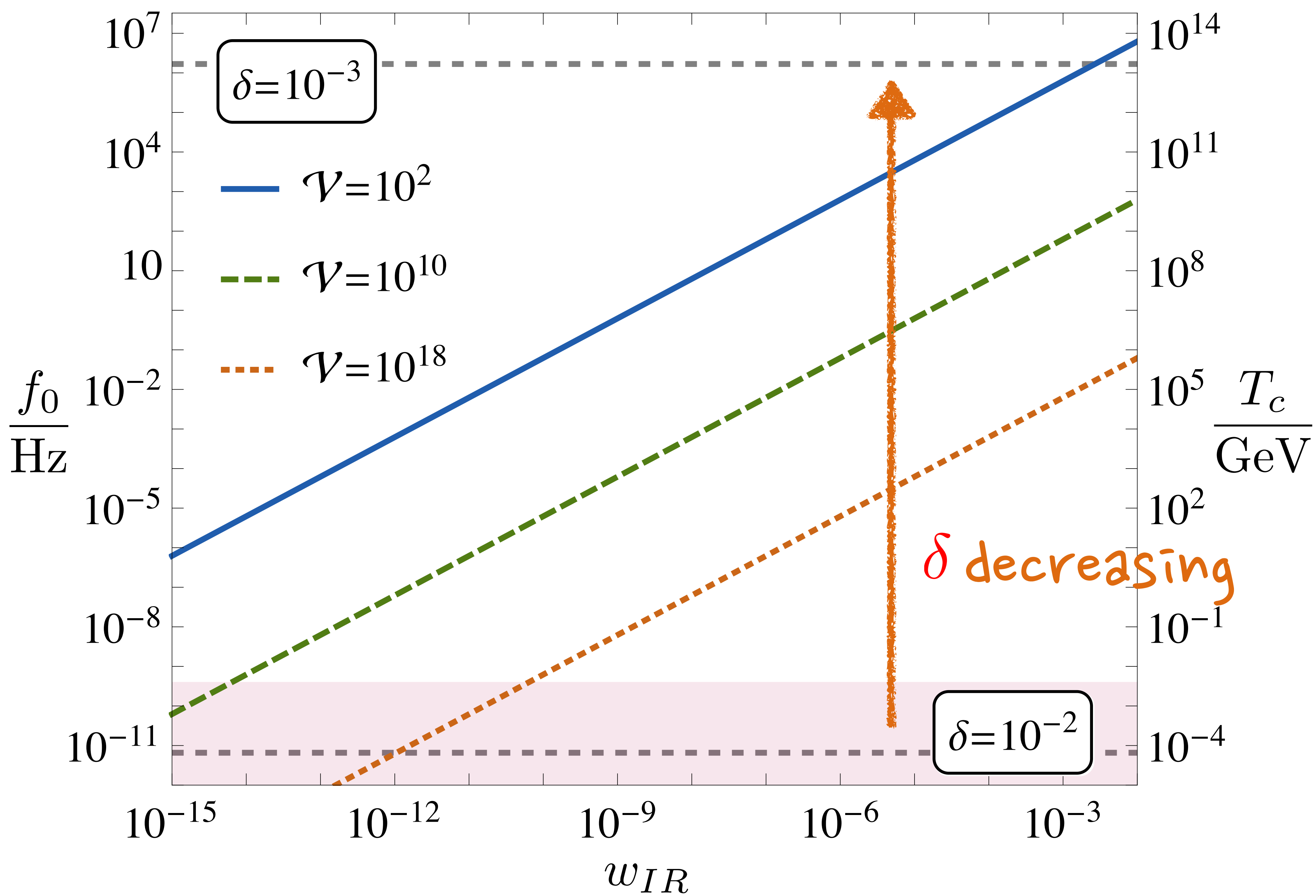
(here have fixed $M=10^2$ and $g_s=0.03$)

GW peak frequency

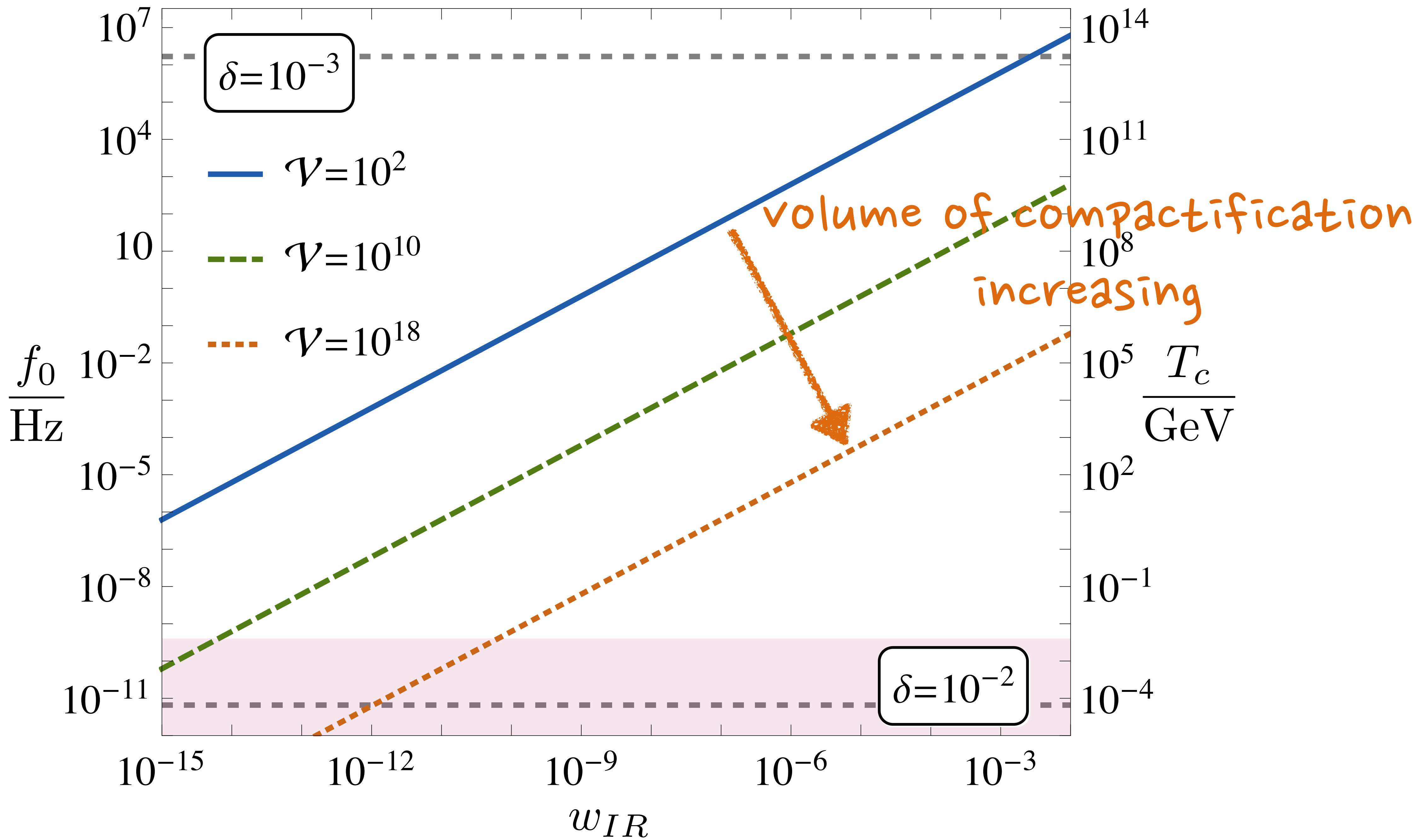


warp factor at the tip of the throat

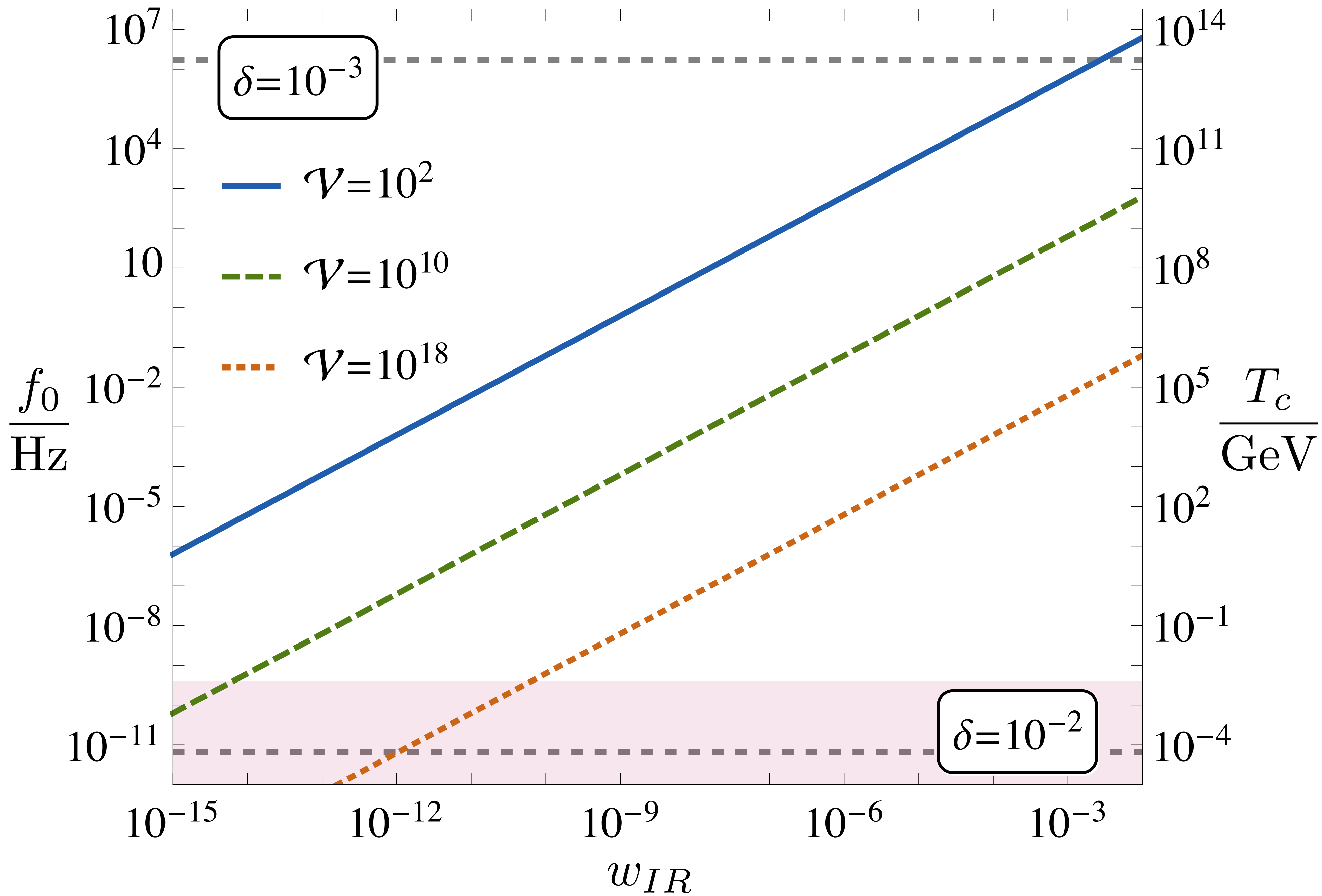
GW peak frequency



GW peak frequency

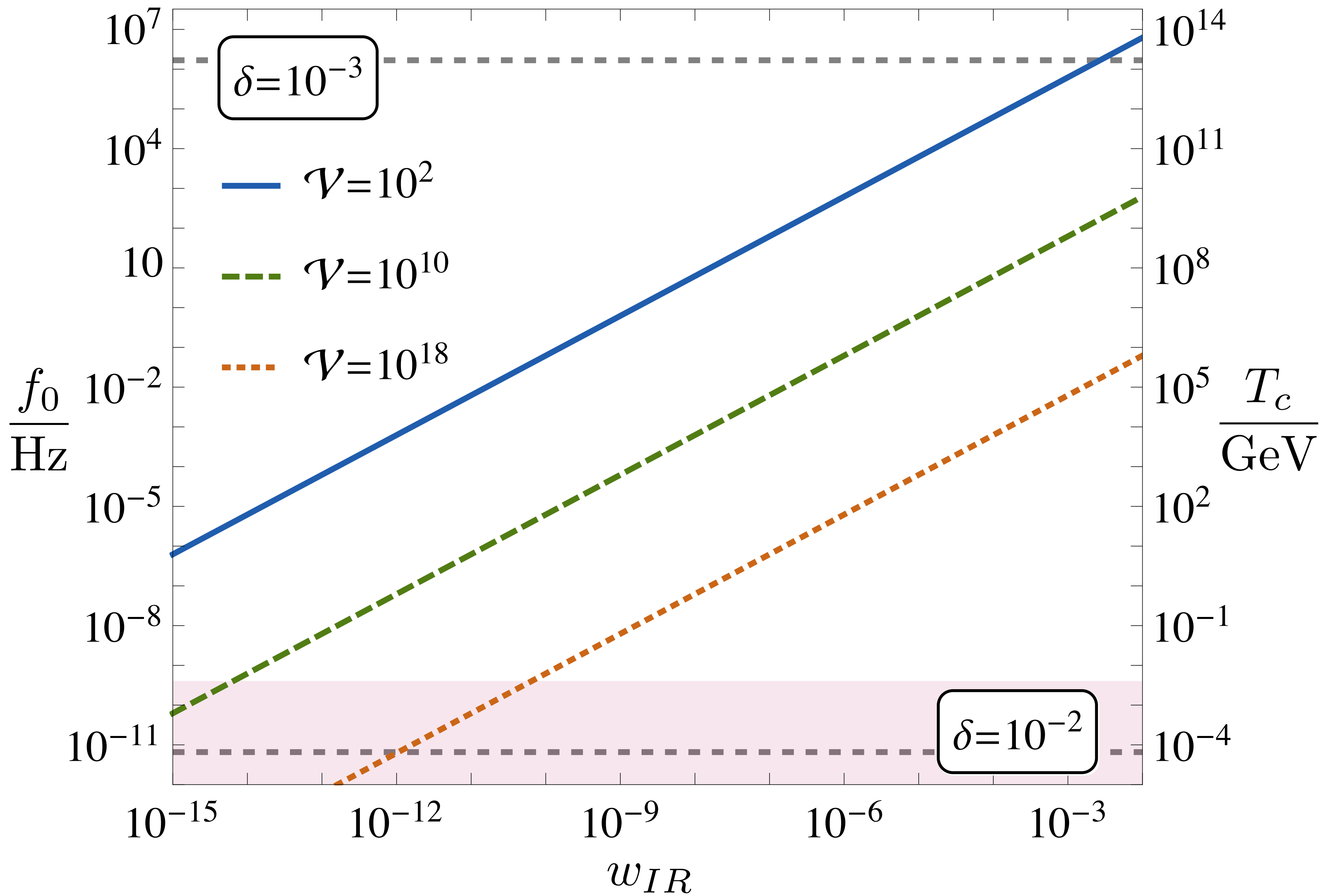


GW peak frequency



The frequency can span the entire range being/to-be probed by gravity-wave detectors

GW peak frequency



requires that at least one of the many throats in a typical flux compactification has δ in suitable range

GW signal strength

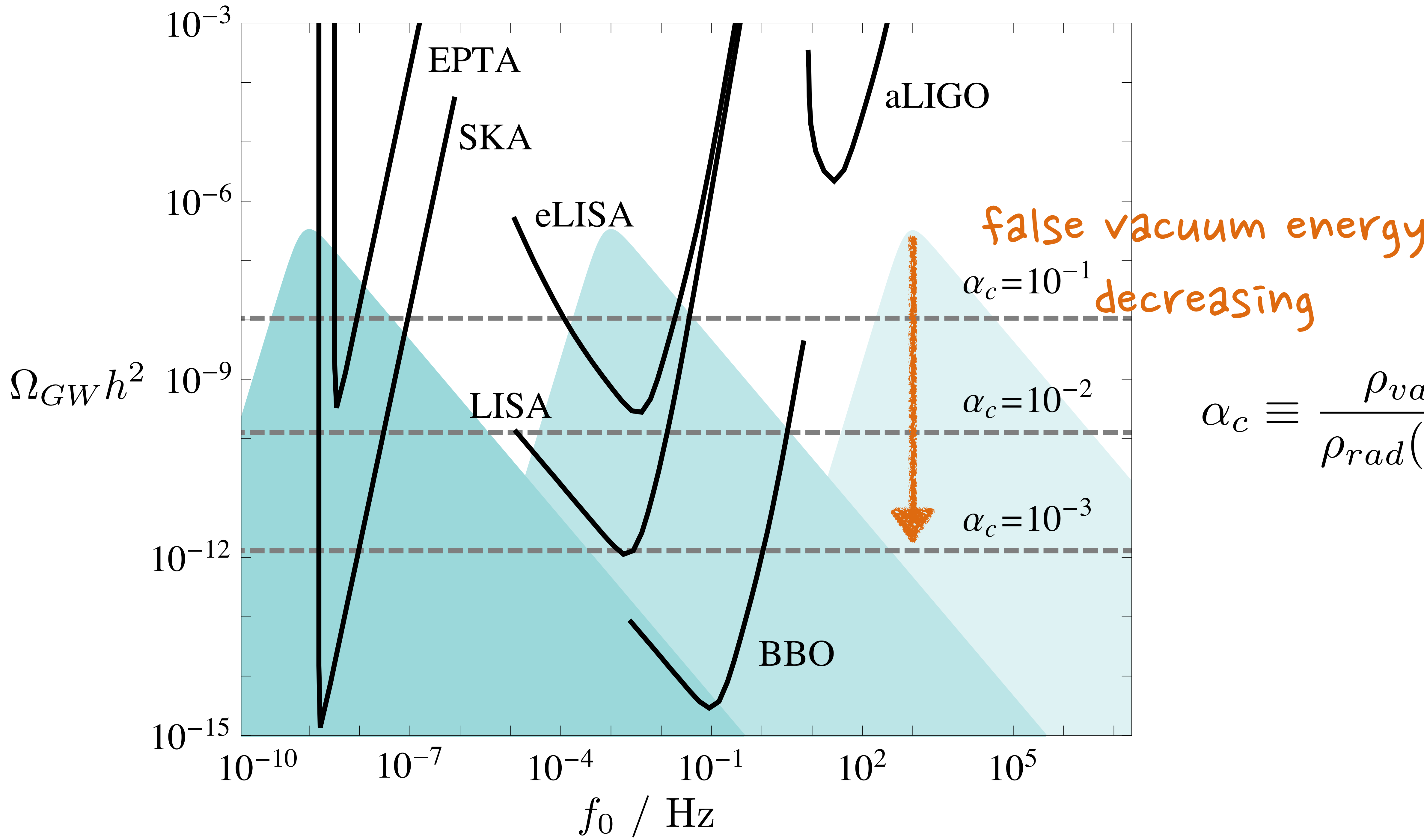
$$\Omega_{GW} h^2(f_0) \sim 10^{-6} \left(\frac{\alpha_c}{1+\alpha_c} \right)^2 \left(\frac{100}{g_*} \right)^{1/3} (t_* H(T_c))^2$$

LARGE potential Signal strength is large due to:

- long duration of transition (nucleation rate does not increase with falling T unlike thermal case)

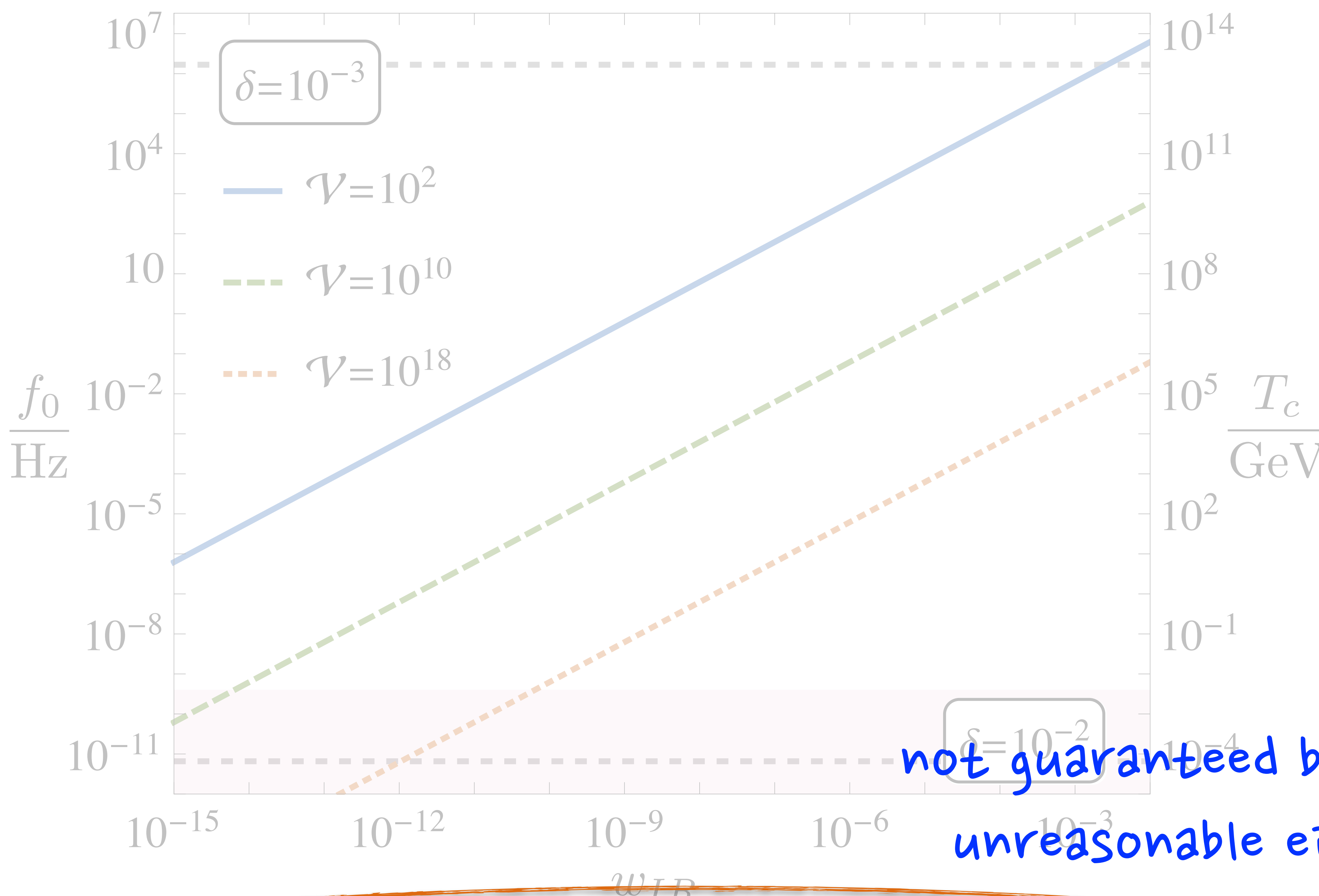
- ultra-relativistic expansion of bubbles (no thermal plasma to impede expansion)

GW signal strength



$$\alpha_c \equiv \frac{\rho_{vac}}{\rho_{rad}(T_c)}$$

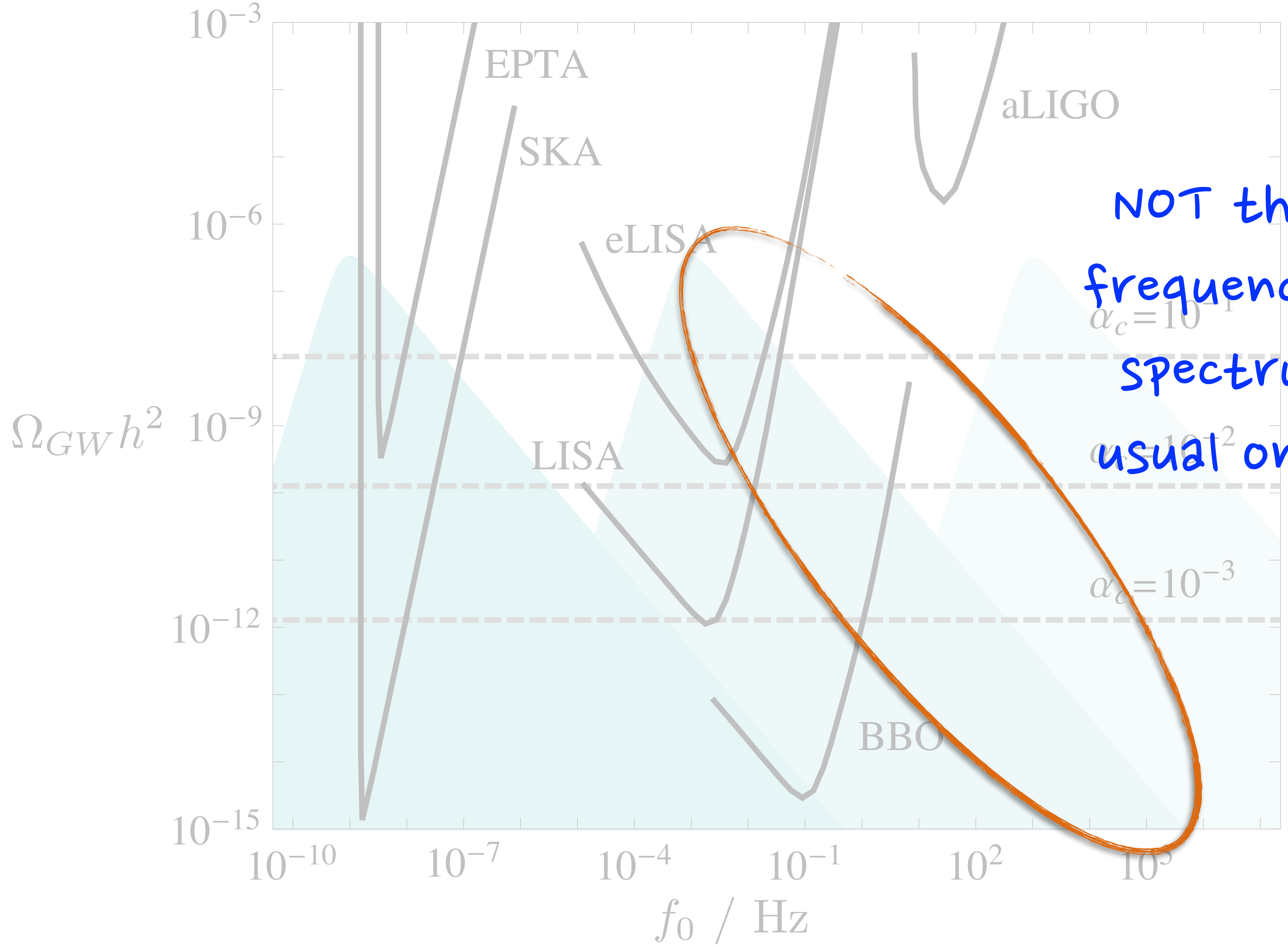
GW peak frequency



not guaranteed but not unreasonable either

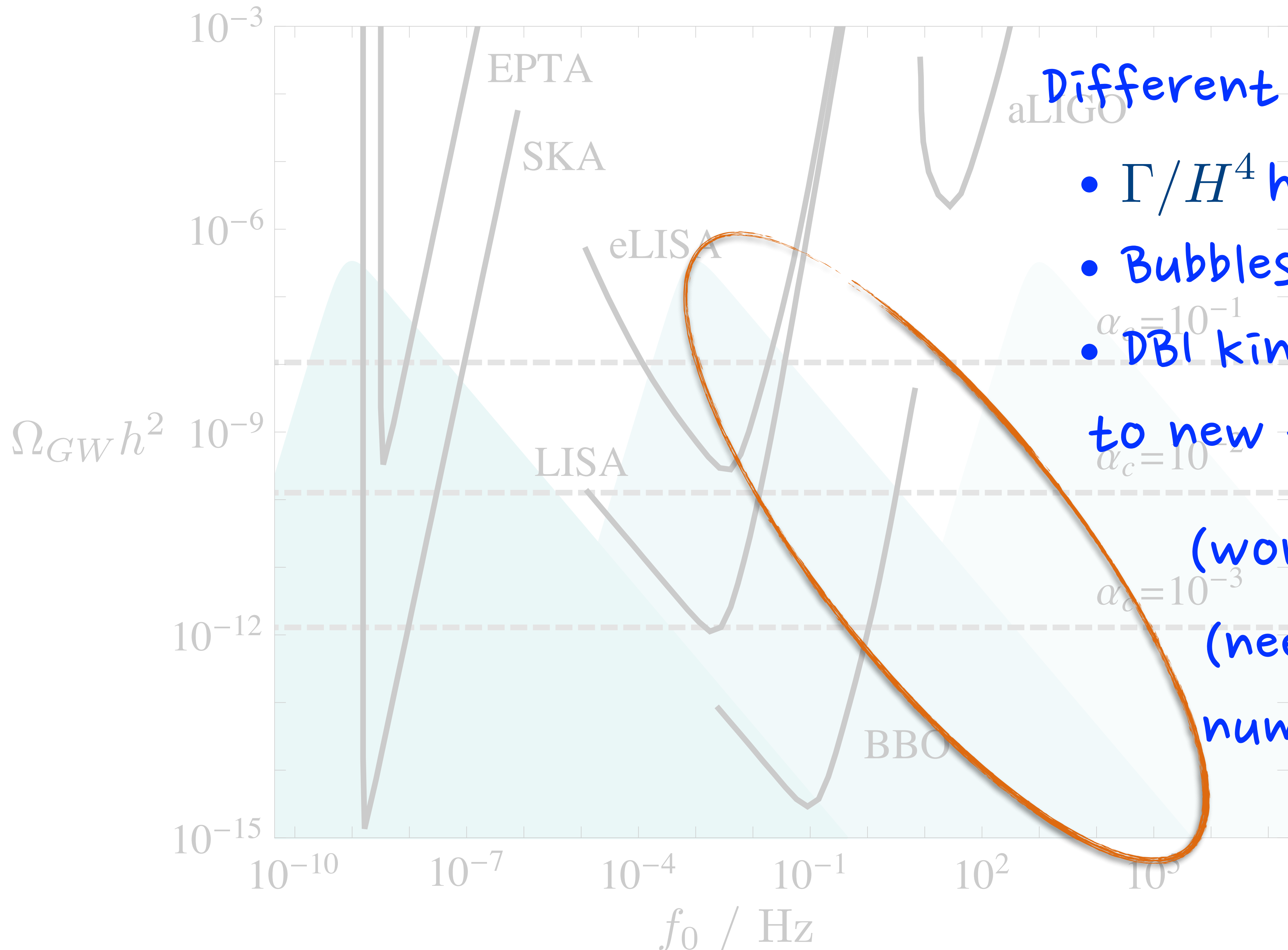
requires that at least one of the many throats in a typical flux compactification has δ in suitable range

GW signal strength



NOT the actual high-frequency behaviour of spectrum – just the usual one for guidance

GW signal strength



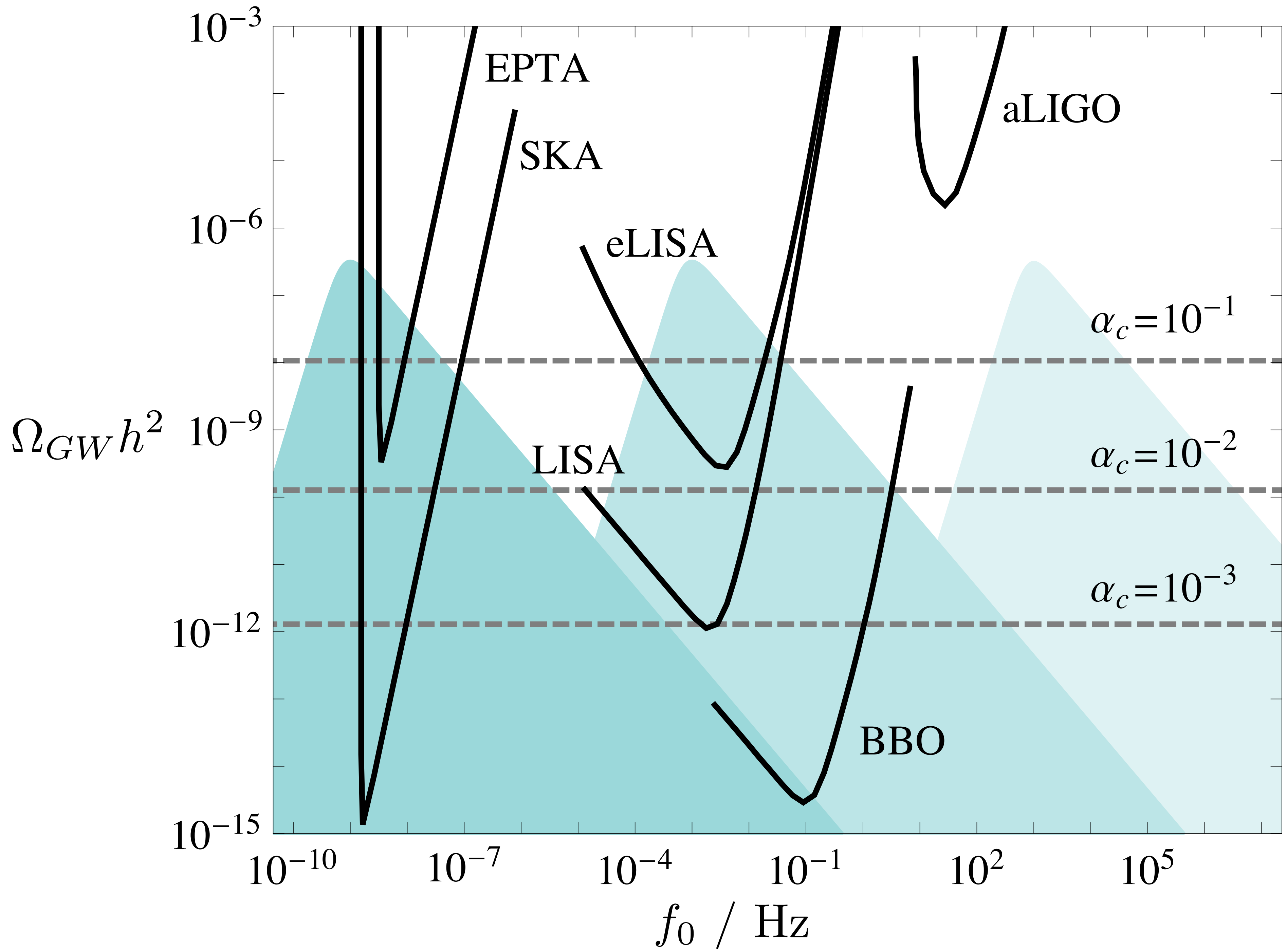
Different because

- Γ/H^4 has unusual T-dep
- Bubbles are thick-wall
- DBI kinetic-term leads to new features

(work in progress)

(needs dedicated numerics!)

GW signal strength



high-frequency part of spectrum sensitive to underlying (string) model!

cf. usual finite-T phase transitions

Recall, usually

$$\Gamma(t) \sim \exp\left(-S(t)\right)$$

and define duration of transition

$$\beta = -dS/dt|_{t_{nucl}}$$

In our case beta=0 and transition lasts a long time (and distribution of bubble sizes quite different)

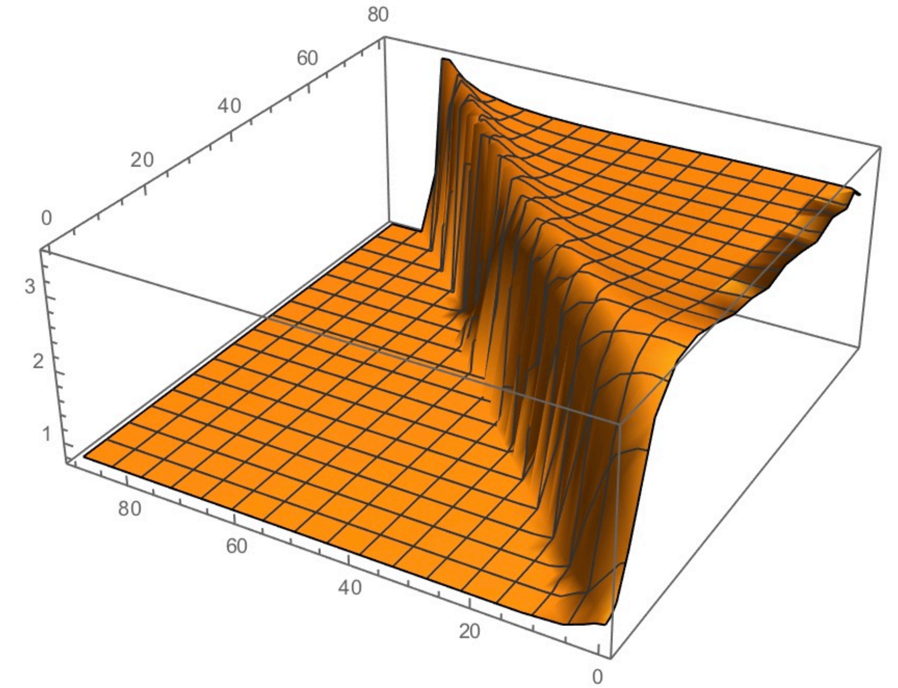
cf. usual finite-T phase transitions

Moreover, α parameter can be large — limited by fate of hidden-sector energy — dark radiation? DM? cosmic strings? …

cf. usual finite-T phase transitions

Moreover, α parameter can be large — limited by fate of hidden-sector energy — dark radiation? DM? cosmic strings? …

Also, because of the lack of a thermal plasma with which the bubble walls interact, the walls expand ultra-relativistically, and there is no substantial contribution from sound waves & MHD turbulence (UV spectrum different)



Big Question

Could we ever extract this primordial stochastic background from astrophysical stochastic foreground??

possibly helped by potential large size and high-freq of signal (above ~10kHz not much foreground?!)

Black hole production?

The most interesting "high-frequency" issue is the possible formation of primordial black holes

An old story, but in fact, very incomplete...

PHYSICAL REVIEW D VOLUME 26, NUMBER 10 15 NOVEMBER 1982

Bubble collisions in the very early universe

S. W. Hawking, I. G. Moss, and J. M. Stewart
D.A.M.T.P. Silver Street, Cambridge CB3 9EW, U. K.
(Received 30 November 1981)

One would expect this energy to cause gravitational collapse if it were bigger than $\frac{1}{2}am_P{}^2$. Thus one would expect a black hole to form if

$$n > \frac{4}{aH} \; . \tag{37}$$

It is reasonable to use the above criterion for gravitational collapse only for regions whose size a is small compared to the Hubble radius H^{-1}. In such cases one can neglect the expansion and curvature of the Universe. We shall assume that the criterion is roughly valid for $a \le \frac{1}{2}H^{-1}$. Thus one might expect a black hole to form for

$$n \ge 8 \tag{38}$$

The probability that eight bubble walls collide in a

PHYSICAL REVIEW D VOLUME 50, NUMBER 2 15 JULY 1994

Singularity formation from colliding bubbles

Ian G. Moss
Department of Physics, University of Newcastle upon Tyne, NE1 7RU, United Kingdom

(Received 7 October 1993)

Some indication of conditions that are necessary for the formation of black holes from the collision of bubbles during a supercooled phase transition in the early Universe is explored. Two colliding bubbles can never form a black hole. Three colliding bubbles can refocus the energy in their walls to the extent that it becomes infinite.

PACS number(s): 98.80.Cq, 04.60.Ds, 97.60.Lf

PHYSICAL REVIEW D VOLUME 28, NUMBER 8 15 OCTOBER 1983

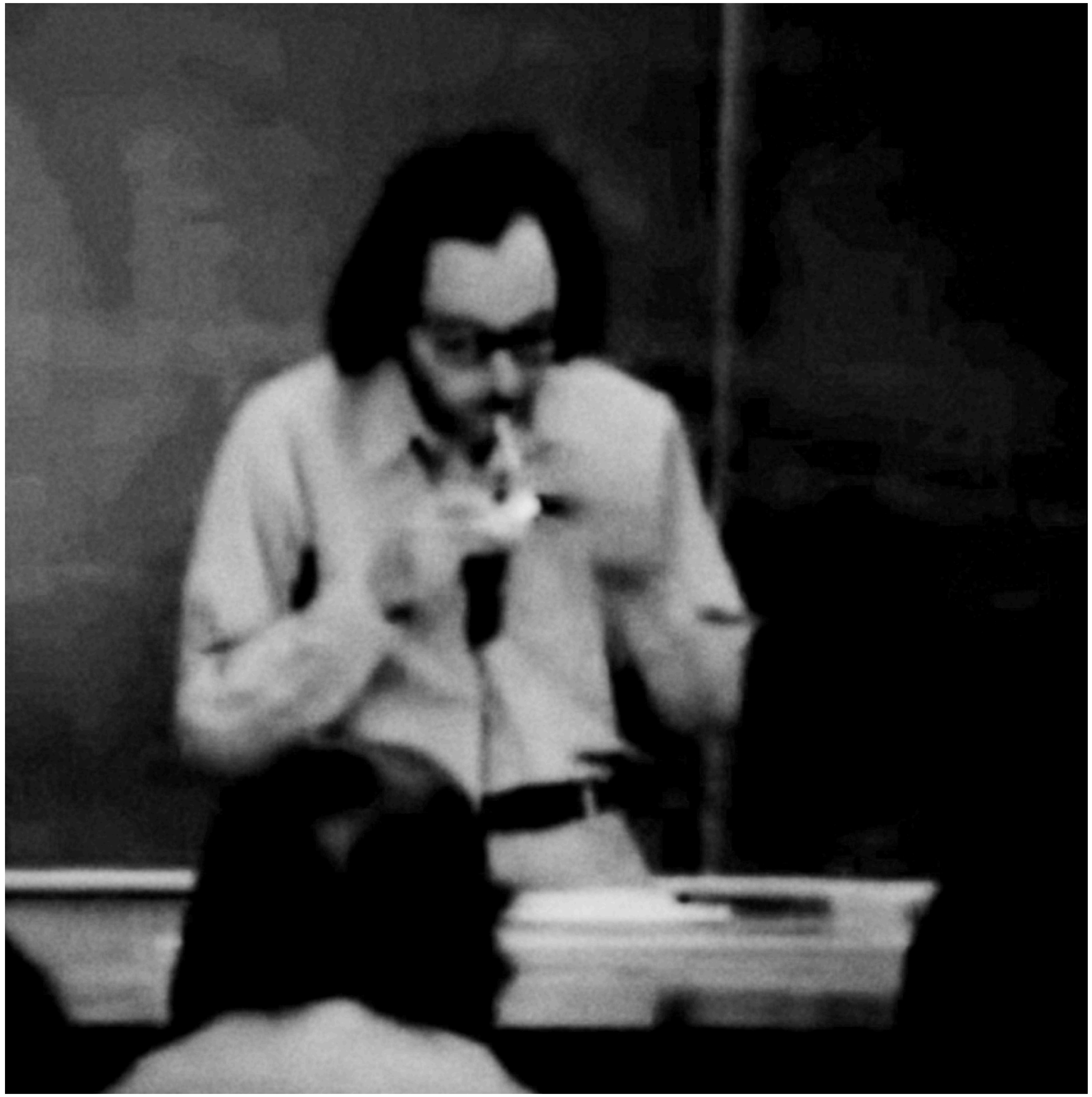
Gravitational effects in bubble collisions

Wu Zhong Chao*
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, United Kingdom
(Received 15 June 1982; revised manuscript received 3 March 1983)

We investigate the effects of gravitation in the collision of two bubbles in the very early universe, using the thin-wall approximation. In general, the collision of two bubbles gives rise to a modulus wall and a phase wave. The space-time metric and all physical quantities possess hyperbolic O(2,1) symmetry. We derive a generalized Birkhoff's theorem to show that the space-time in different regions must therefore be flat, de Sitter, pseudo-Schwarzschild, and pseudo-Schwarzschild—de Sitter, respectively. As in the spherically symmetric O(3) case, the space-time is Petrov type *D*, and so there is no gravitational radiation. Owing to the special symmetry of the space-time, the concentration of matter does not suffice to cause any gravitational collapse to a singularity no matter how severely the two bubbles collide. The modulus walls, viewed from the real vacuum region, eventually propagate outwards with kinks due to a series of collisions, in contrast to the situation in the absence of gravity.

basically correct, but not exactly…

crucial issue is the SO(3,1) symmetry of a single bubble, and the associated O(2,1) symmetry of two colliding bubbles but some knew otherwise



Return of the bounce

usually stated that the Euclidian bounce solution with O(4) symmetry implies the initial configuration of the nucleated critical bubble is highly symmetric

Return of the bounce

usually stated that the Euclidian bounce solution with O(4) symmetry implies the initial configuration of the nucleated critical bubble is highly symmetric

But Sidney taught me that a single field configuration contributes measure zero to the euclidian functional integral

Return of the bounce

Usually stated that the Euclidian bounce solution with O(4) symmetry implies the initial configuration of the nucleated critical bubble is highly symmetric

Really to get a non-zero decay rate of form

$$\Gamma \sim m^4 e^{-B}$$

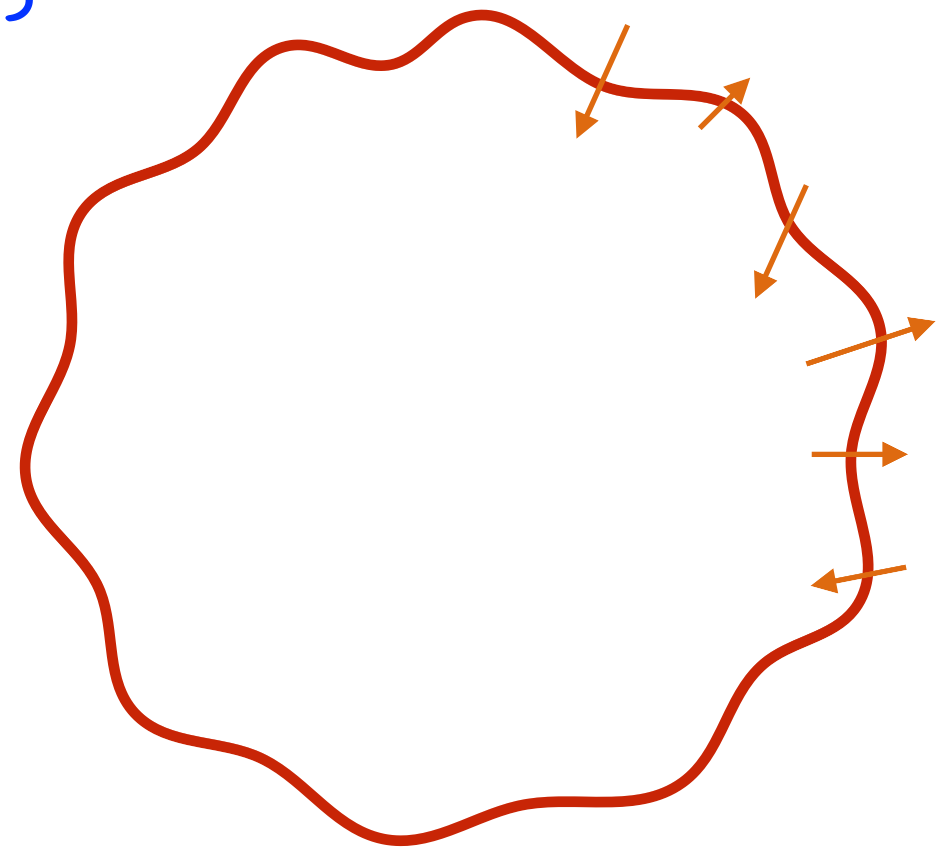
one needs to consider a bundle of nearby configurations

$$I_1 = \frac{i}{2} \Omega T \left| \frac{\det' S_E''(\phi_{\text{bounce}})]}{\det S_E''(\phi_{\text{fv}})} \right|^{-1/2} J \, e^{-[S_E(\phi_{\text{bounce}}) - S_E(\phi_{\text{fv}})]} \, I_0$$

Return of the bounce

~~Usually stated that the Euclidian bounce solution with O(4) symmetry implies the initial configuration of the nucleated critical bubble is highly symmetric~~

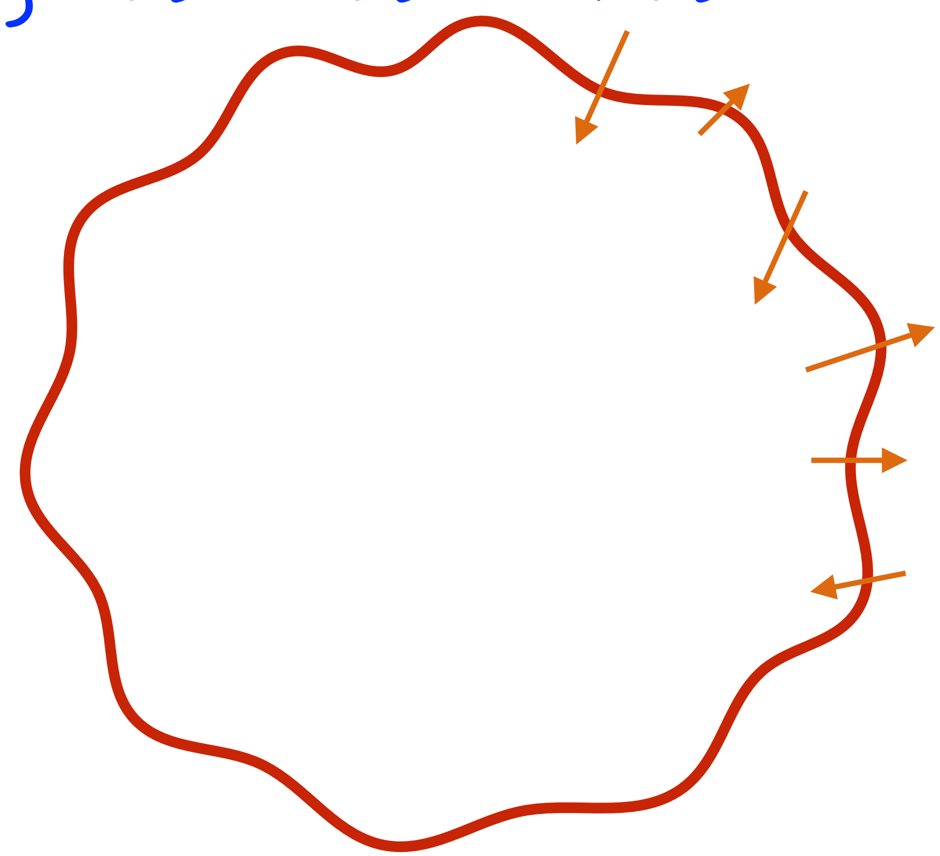
In fact typical configuration at nucleation



Return of the bounce

~~Usually stated that the Euclidian bounce solution with O(4) symmetry implies the initial configuration of the nucleated critical bubble is highly symmetric~~

In fact typical configuration at nucleation

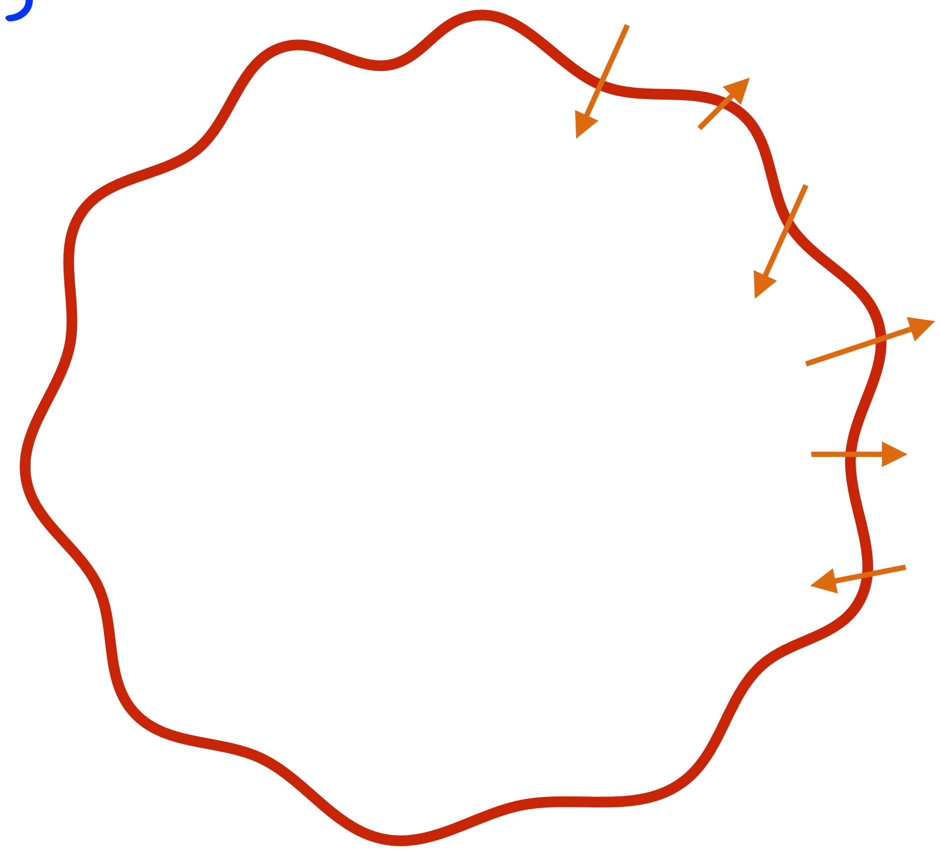


typical relative velocities of parts of wall $\sim 1/\sqrt{B}$

Return of the bounce

~~usually stated that the Euclidian bounce solution with O(4) symmetry implies the initial configuration of the nucleated critical bubble is highly symmetric~~

In fact typical configuration at nucleation



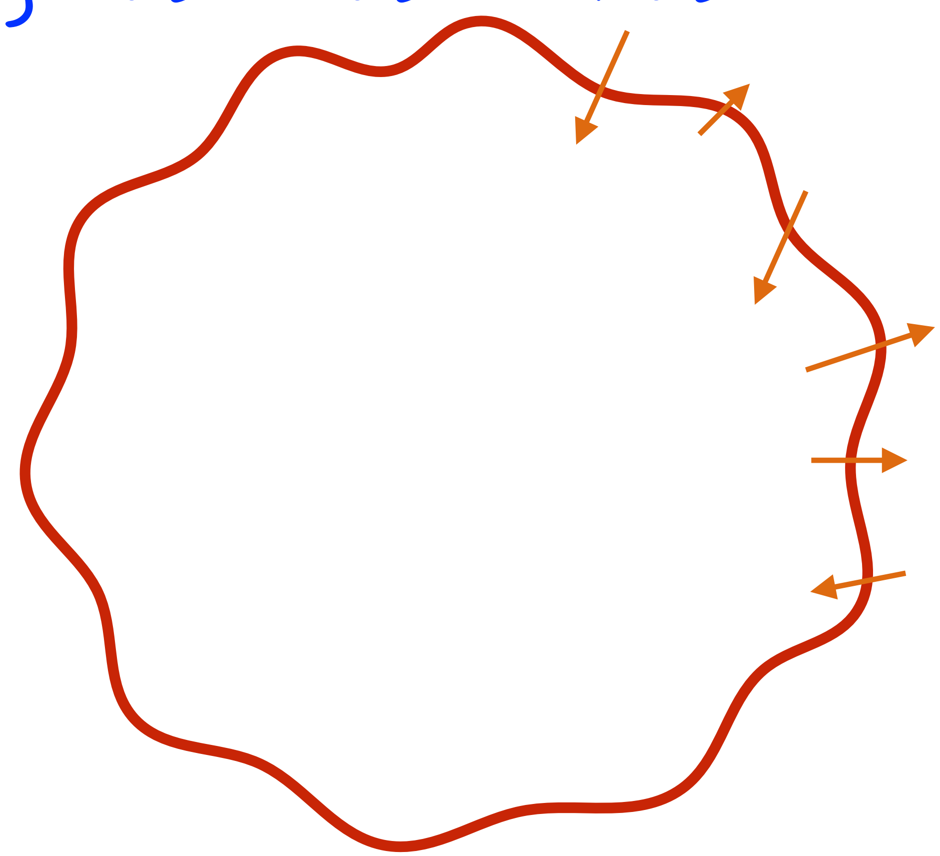
typical relative velocities of parts of wall ~ $1/\sqrt{B}$

typical non-sphericity ~ $1/\sqrt{B}$

Return of the bounce

~~usually stated that the Euclidian bounce solution with O(4) symmetry implies the initial configuration of the nucleated critical bubble is highly symmetric~~

In fact typical configuration at nucleation



typical relative velocities of parts of wall $\sim 1/\sqrt{B}$

typical non-sphericity $\sim 1/\sqrt{B}$

this symmetry breaking can survive bubble expansion and possibly dominantly determines PBH formation rate and form of mass distribution! (really needs dedicated strong-field-gravity numerics)

Conclusions

- GW detectors will help shape the future of physics in the coming century!
- String theory transitions in post-inflation early universe can be present and lead to (possibly distinctive) GW signatures, and maybe even an interesting population of pBHs!
- GW detectors may give us insight on the string landscape!

more to come....