The Disastrous Situation…

Experiments over the last year have verified our standard model, and confirmed the earlier indirect indications of no new physics to better than 5 sigma

The Disastrous Situation…

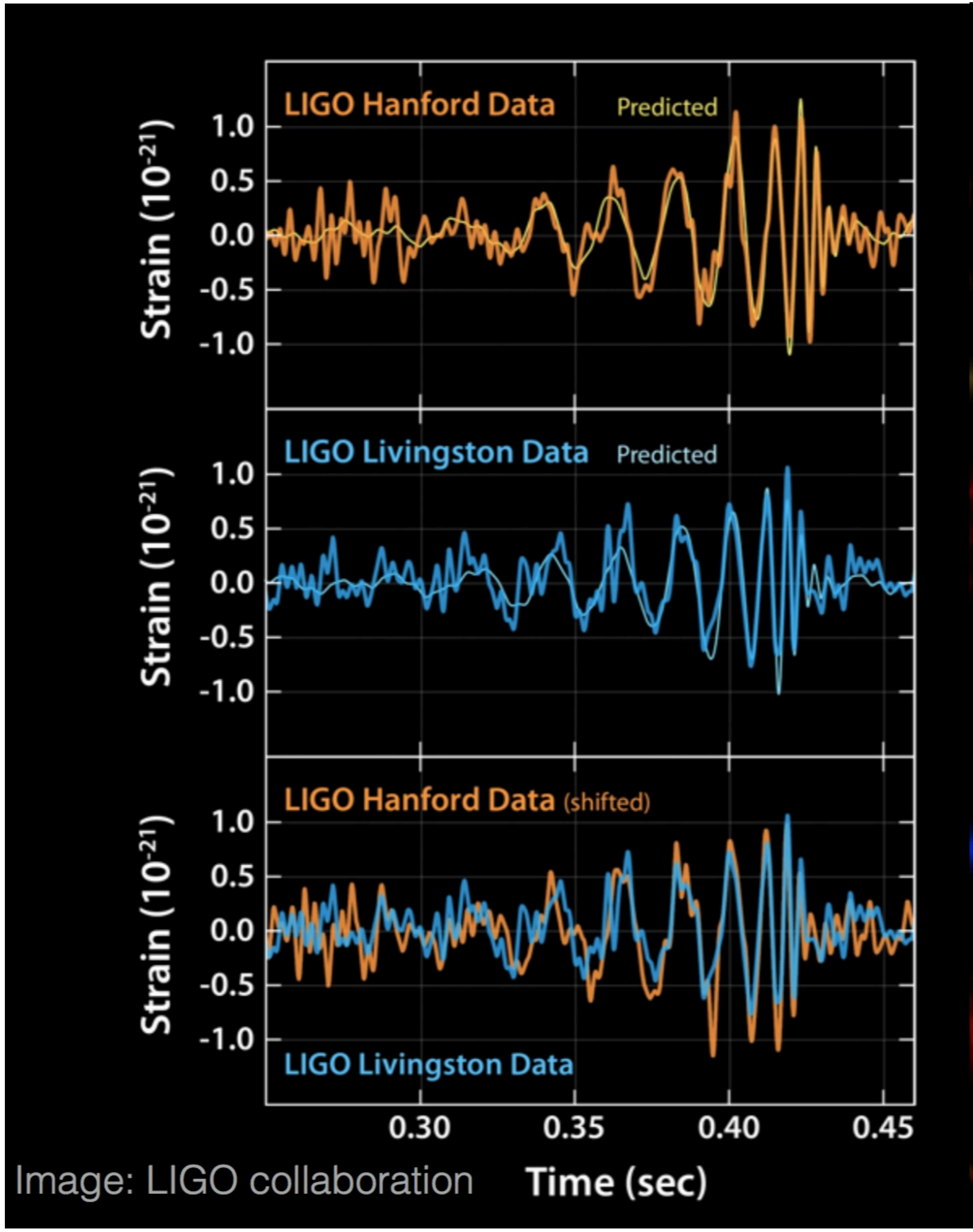
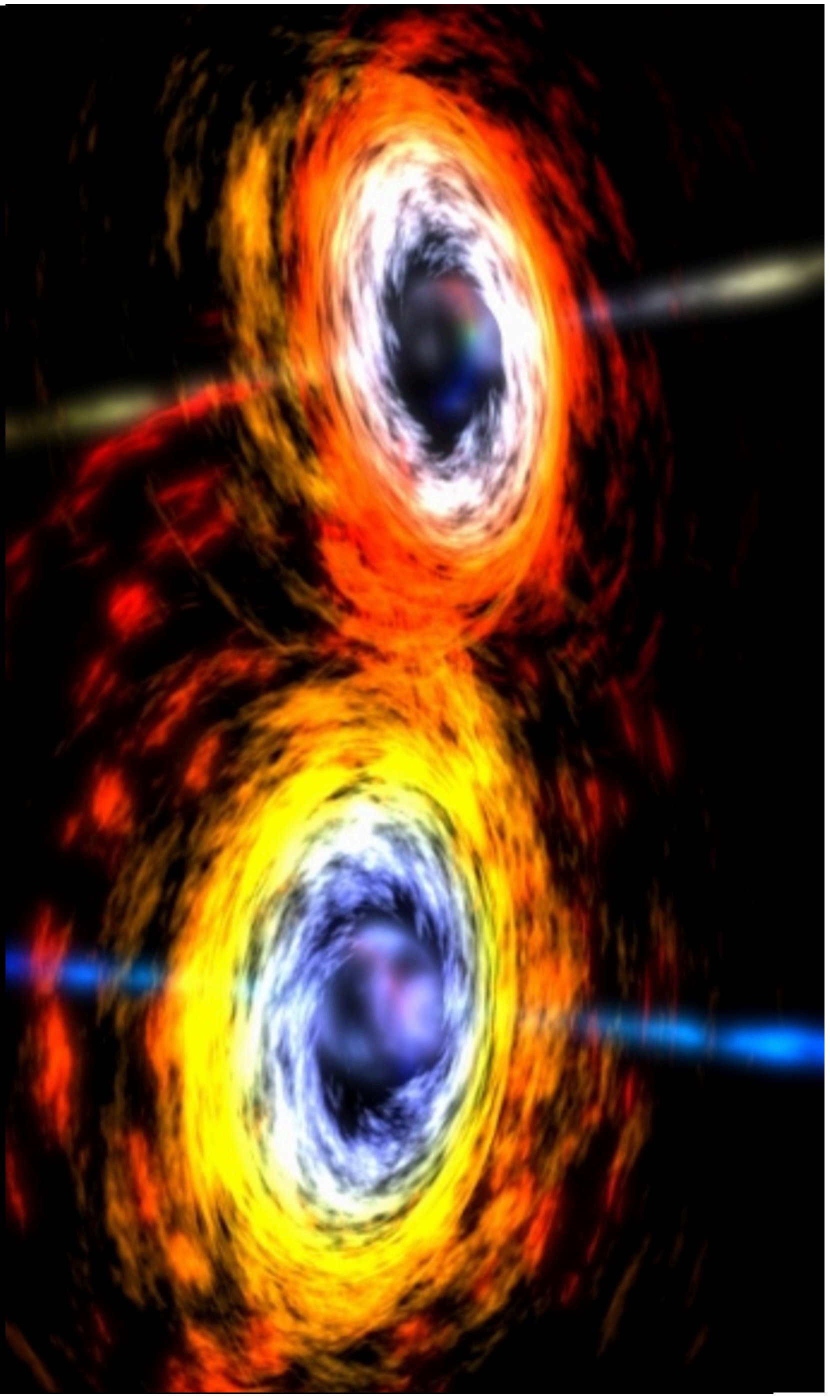


Image: LIGO collaboration



just terrible…!

The String Soundscape

…or, what gravity wave detectors can tell us about BSM physics

John March-Russell
Oxford University

Isabel Garcia Garcia, Sven Krippendorf, JMR — arXiv:1607.06813

Gravitational Waves

- GW have been directly observed by LIGO, and many new detectors will be built
- The astrophysical potential of GW detectors has been extensively studied

  e.g. see Lasky *et al.* arXiv:1511.05994

  Black Holes

  Neutron stars

  pulsars

  supernovae
- Can we use GW experiments to learn about BSM?

GW detectors for BSM

There are *a few* examples:

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

  perfect for eLISA (if they existed!)

  Review: Caprini *et al.* arXiv:1512.06239
- Probing the existence of a QCD axion due to BH super-radiance

  with aLIGO

  Arvanitaki et al. arXiv:
  1411.2263 & 1604.03958

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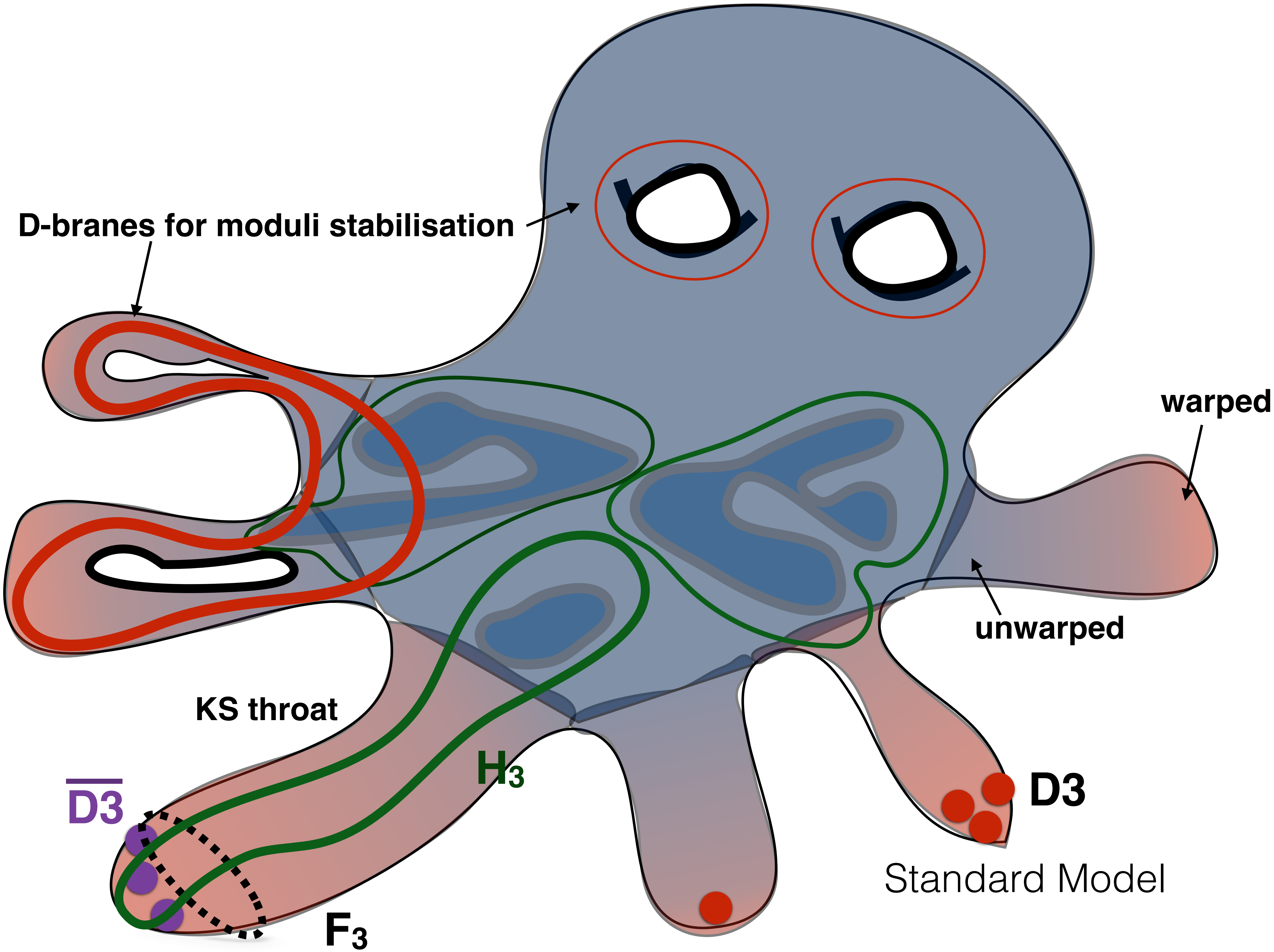
with aLIGO

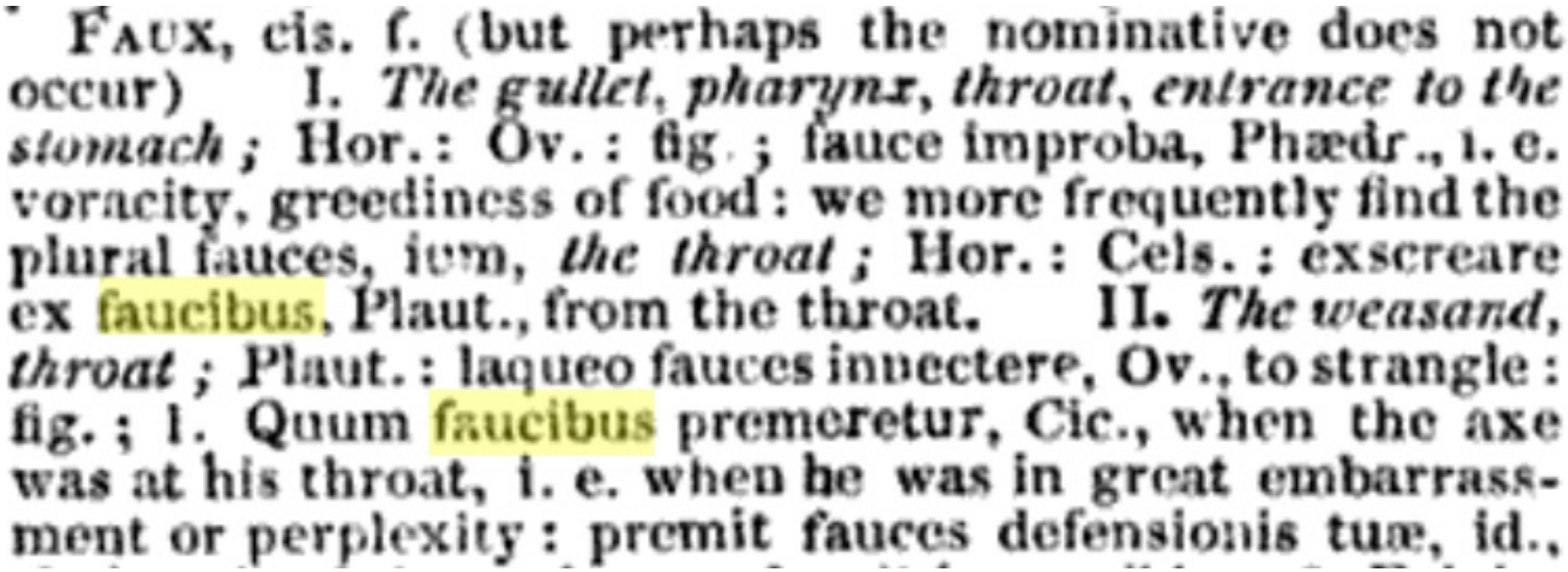
+ GW signals from vacuum decay in String Theory motivated scenarios

Since here in Trieste the seafood is *so* good

I'm sure that you'll vividly be able to picture the
type-IIB string flux compactification landscape

the string *polyfaucibus*

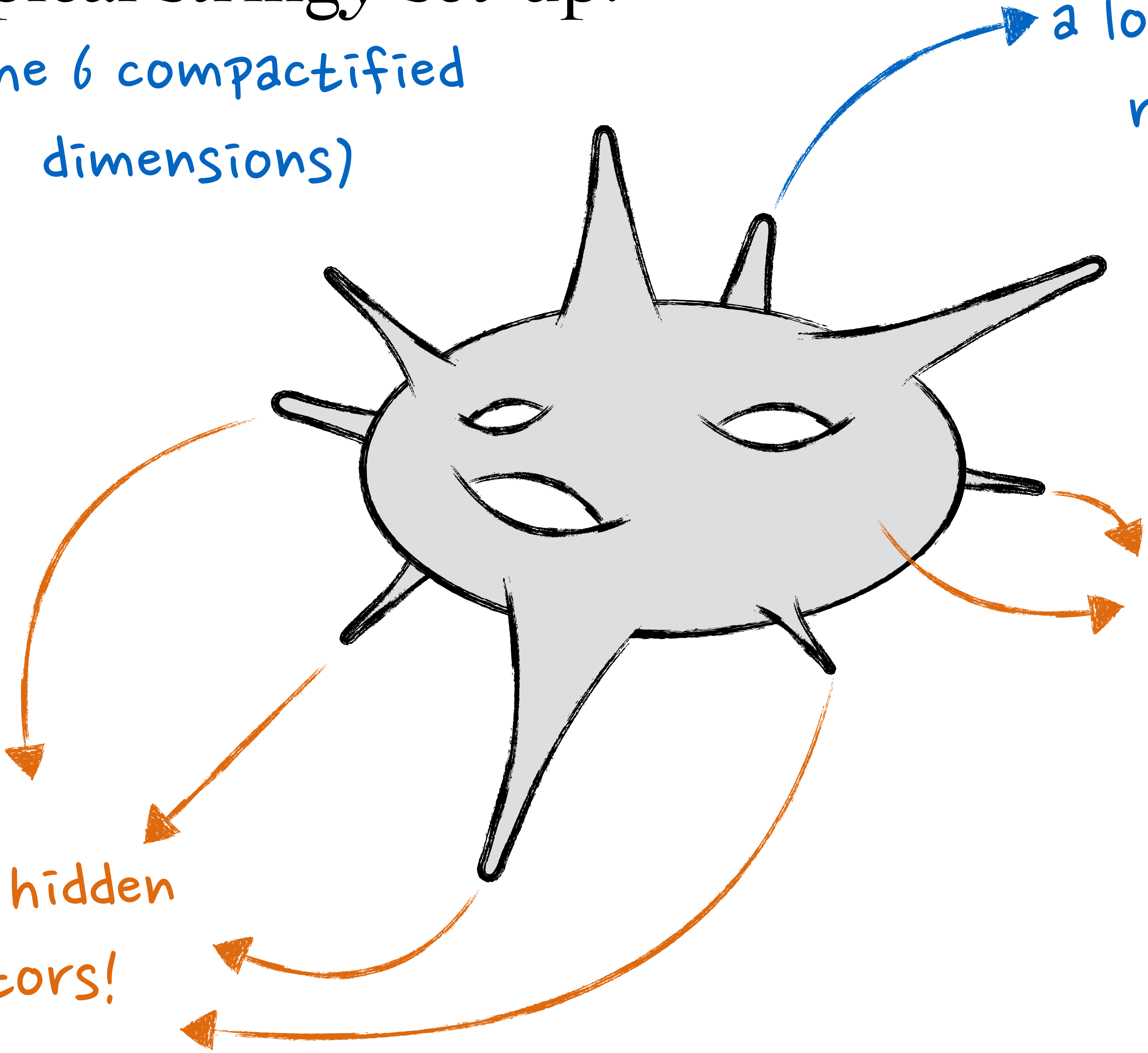




FAUX, cis. f. (but perhaps the nominative does not occur) I. *The gullet, pharynx, throat, entrance to the stomach;* Hor.: Ov.: fig.; fauce improba, Phædr., i. e. voracity, greediness of food: we more frequently find the plural fauces, ium, *the throat;* Hor.: Cels.: exscreare ex faucibus, Plaut., from the throat. II. *The weasand, throat;* Plaut.: laqueo fauces innectere, Ov., to strangle: fig.; 1. Quum faucibus premeretur, Cic., when the axe was at his throat, i. e. when he was in great embarrassment or perplexity: premit fauces defensionis tuæ, id.,

String Flux Compactifications

A typical stringy set-up:



(the 6 compactified dimensions)

a lot of highly warped regions: throats (think RS!)

SM ???

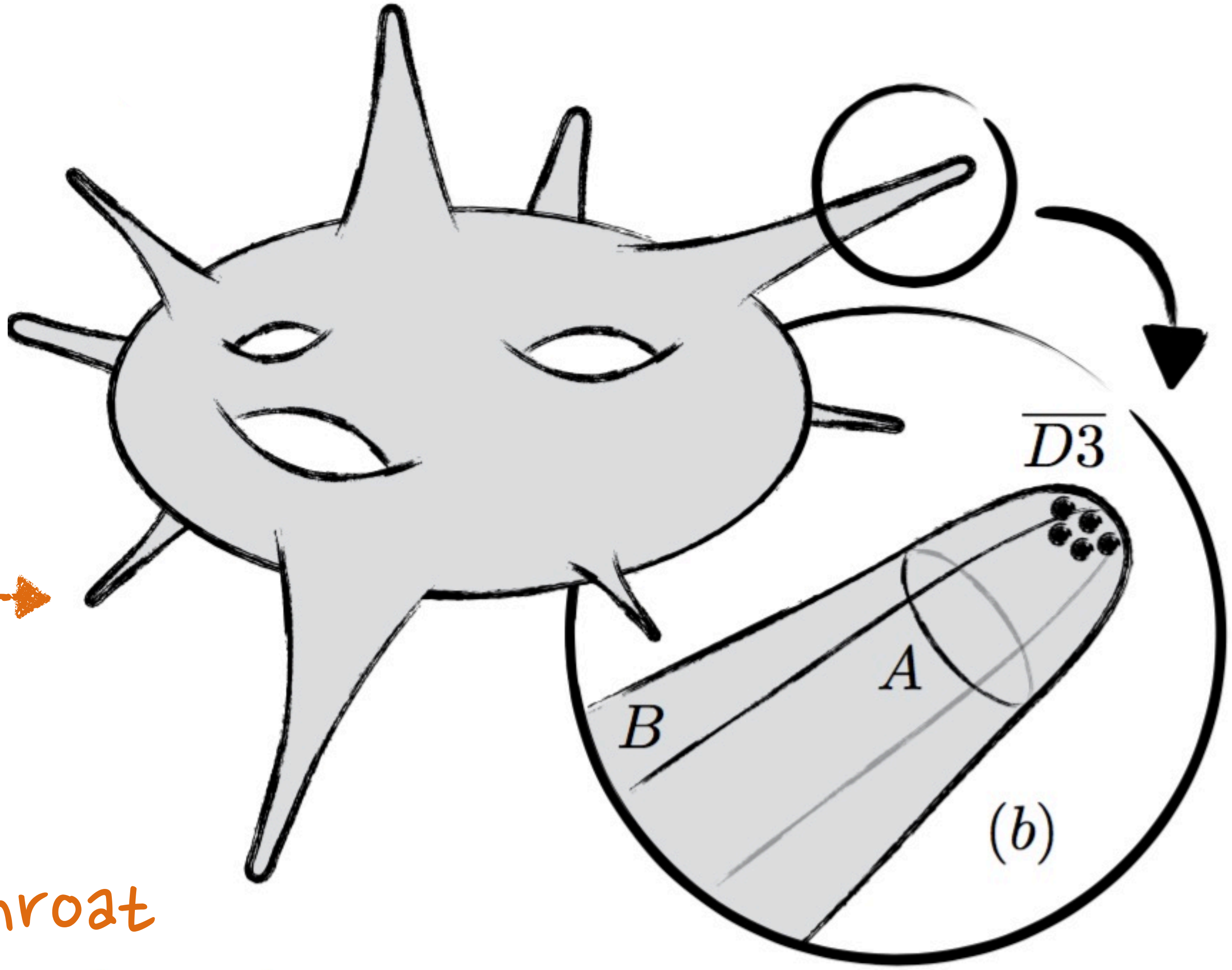
many hidden sectors!

String Flux Compactifications

Throats are due to back-reaction from fluxes (need *many* pairs of integer fluxes K, M for the landscape)

$$\frac{1}{4\pi^2}\int_A F_3 = M ,$$

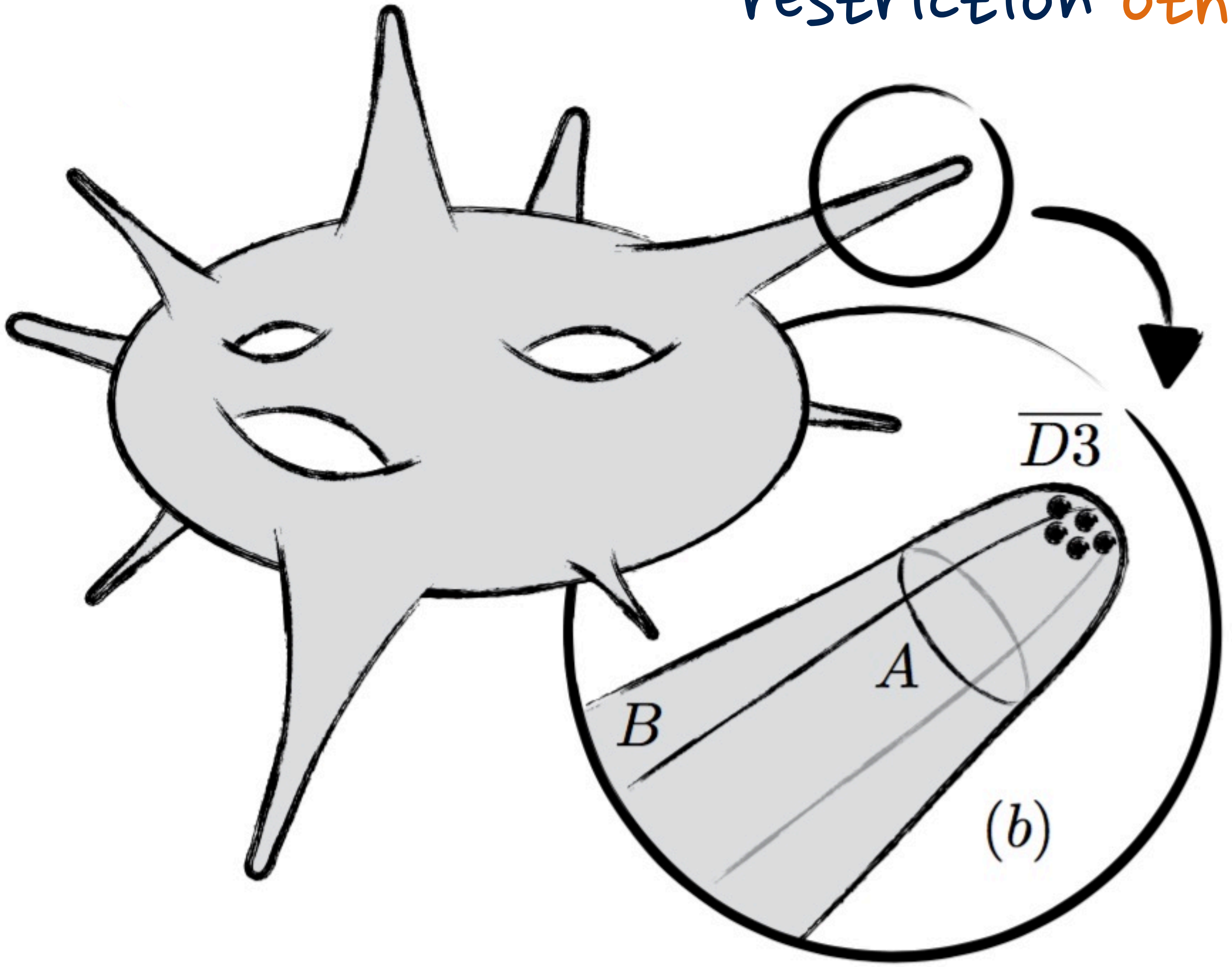
$$\frac{1}{4\pi^2}\int_B H_3 = -K$$



warp factor at throat tip $w_{IR} \sim \exp(-2\pi K/3Mg_s)$

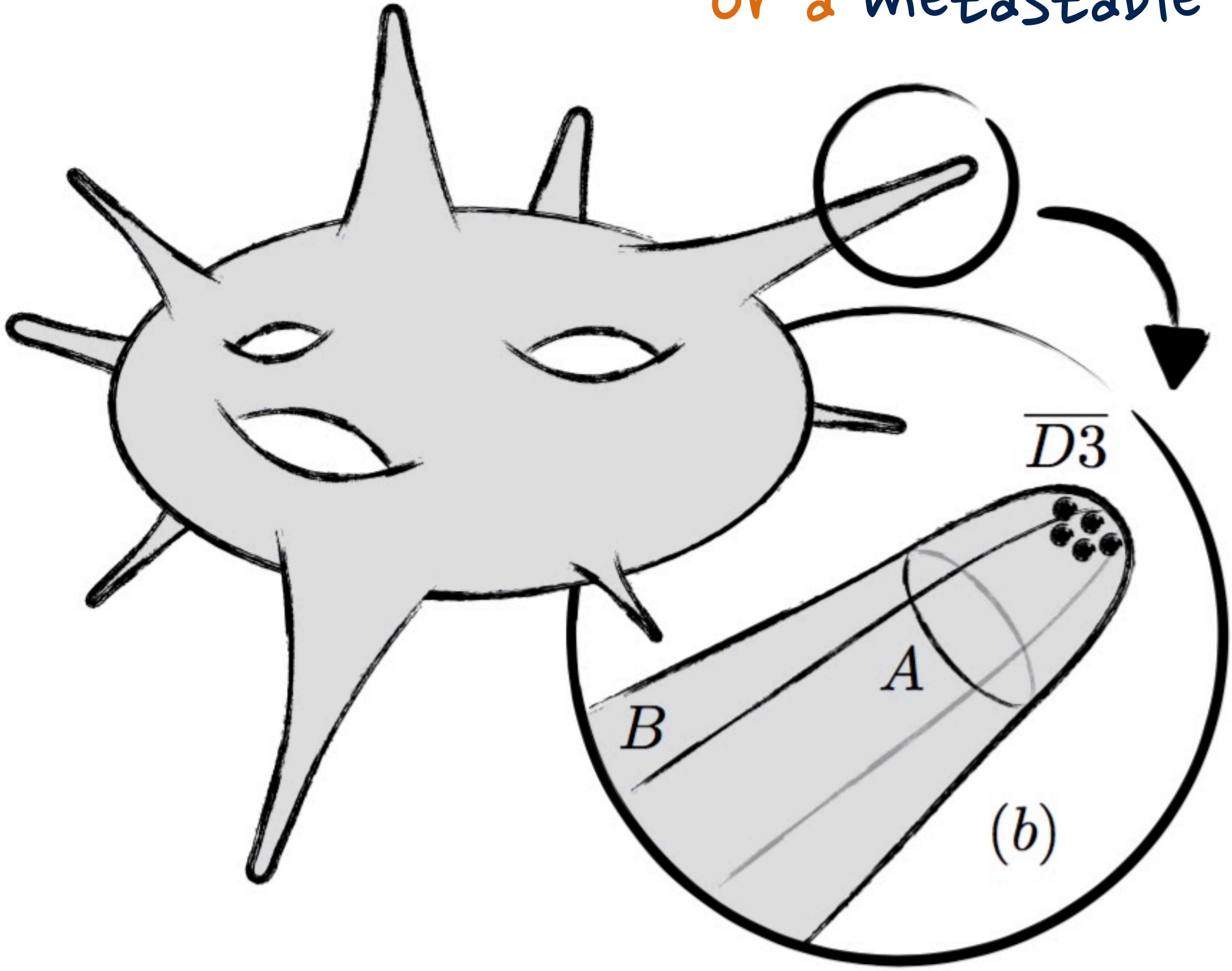
String Flux Compactifications

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

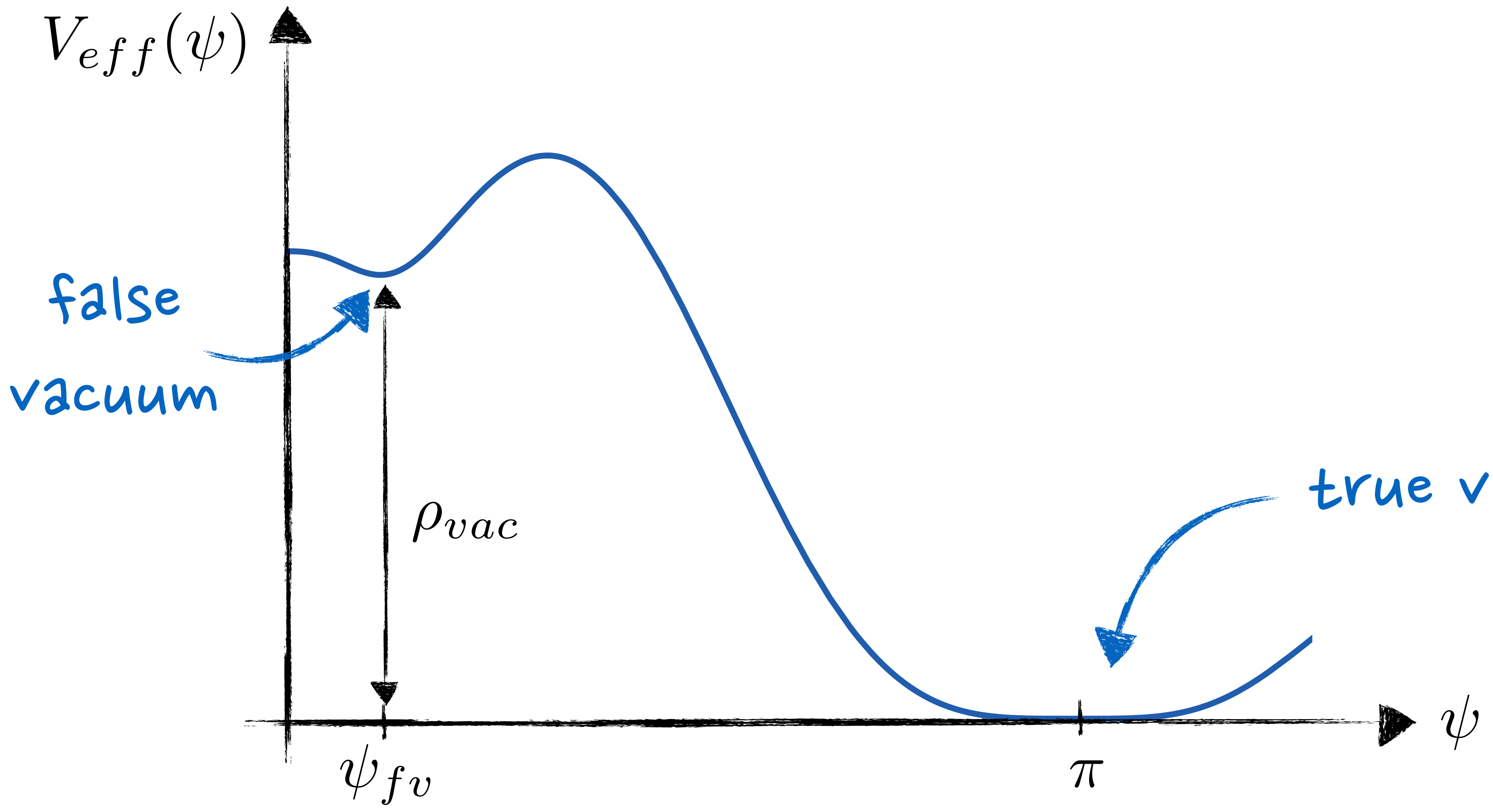


String Flux Compactifications

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

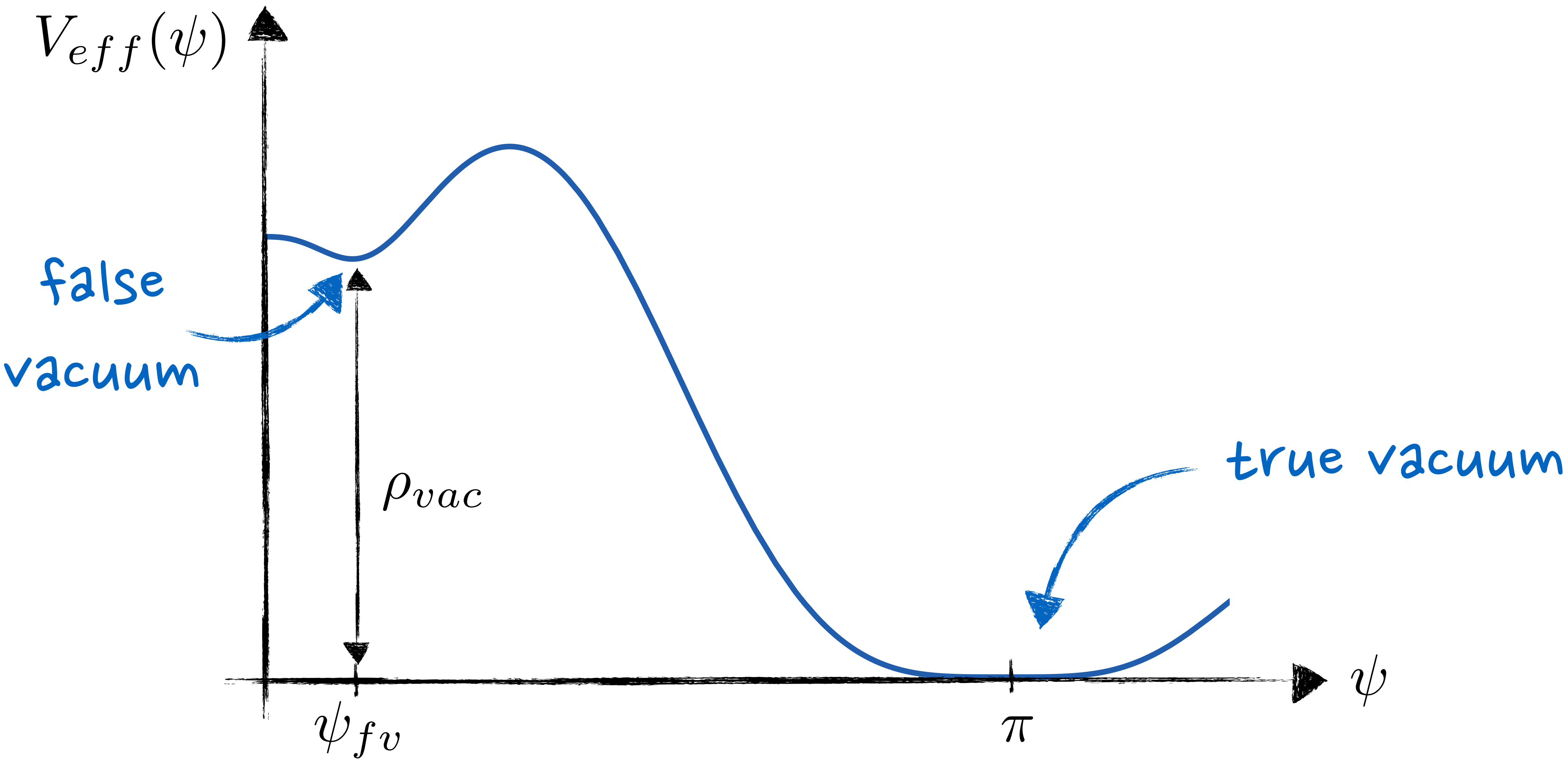


String Flux Compactifications

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 I've set $M_{str}=1$ and am 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

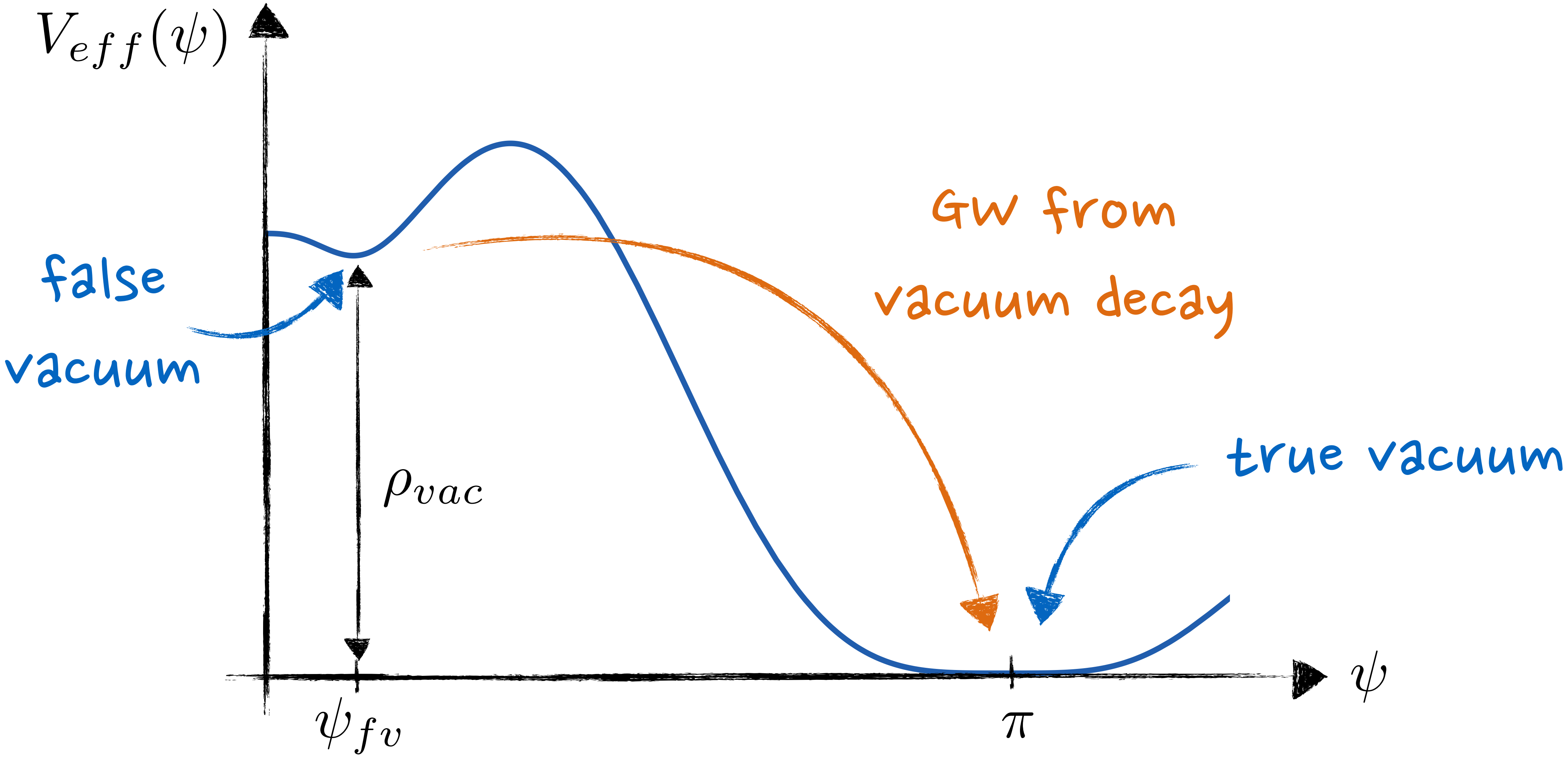
$$r_c = (\pi - 3 + b_0^4)/(4\pi) \approx 0.08$$

barrier disappears, so define

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

String Flux Compactifications

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



String Flux Compactifications

For this talk some simplifying assumptions:

- *After inflation*, throat in its metastable vacuum
- Visible sector reheated at $T_{rh} \gtrsim 4 \text{ MeV}$ but hidden throat sector left at $T_{th} \approx 0$

so decay occurs via quantum tunnelling

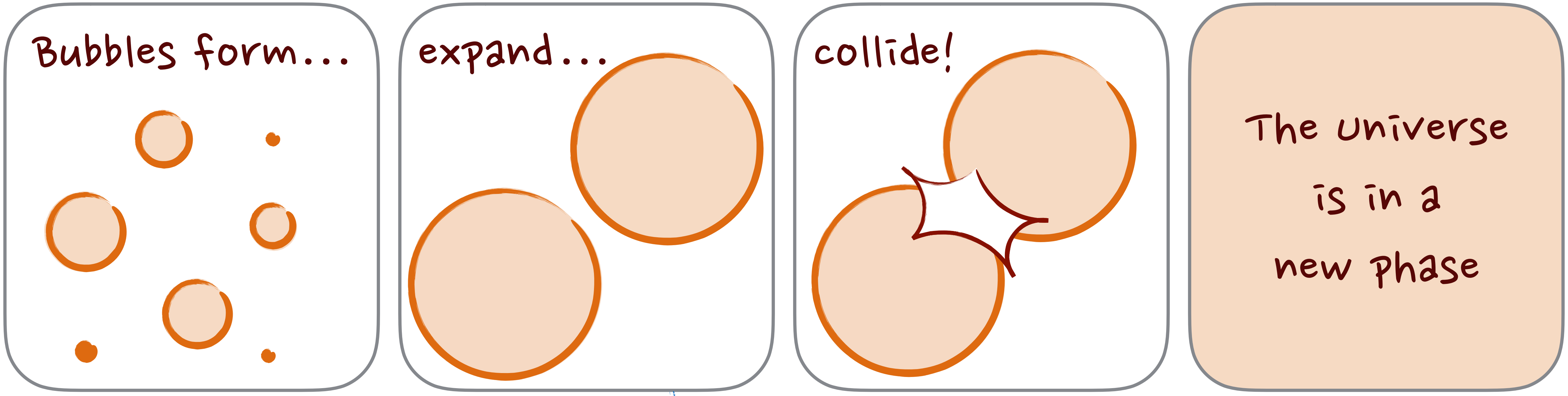
- Universe radiation dominated throughout

(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

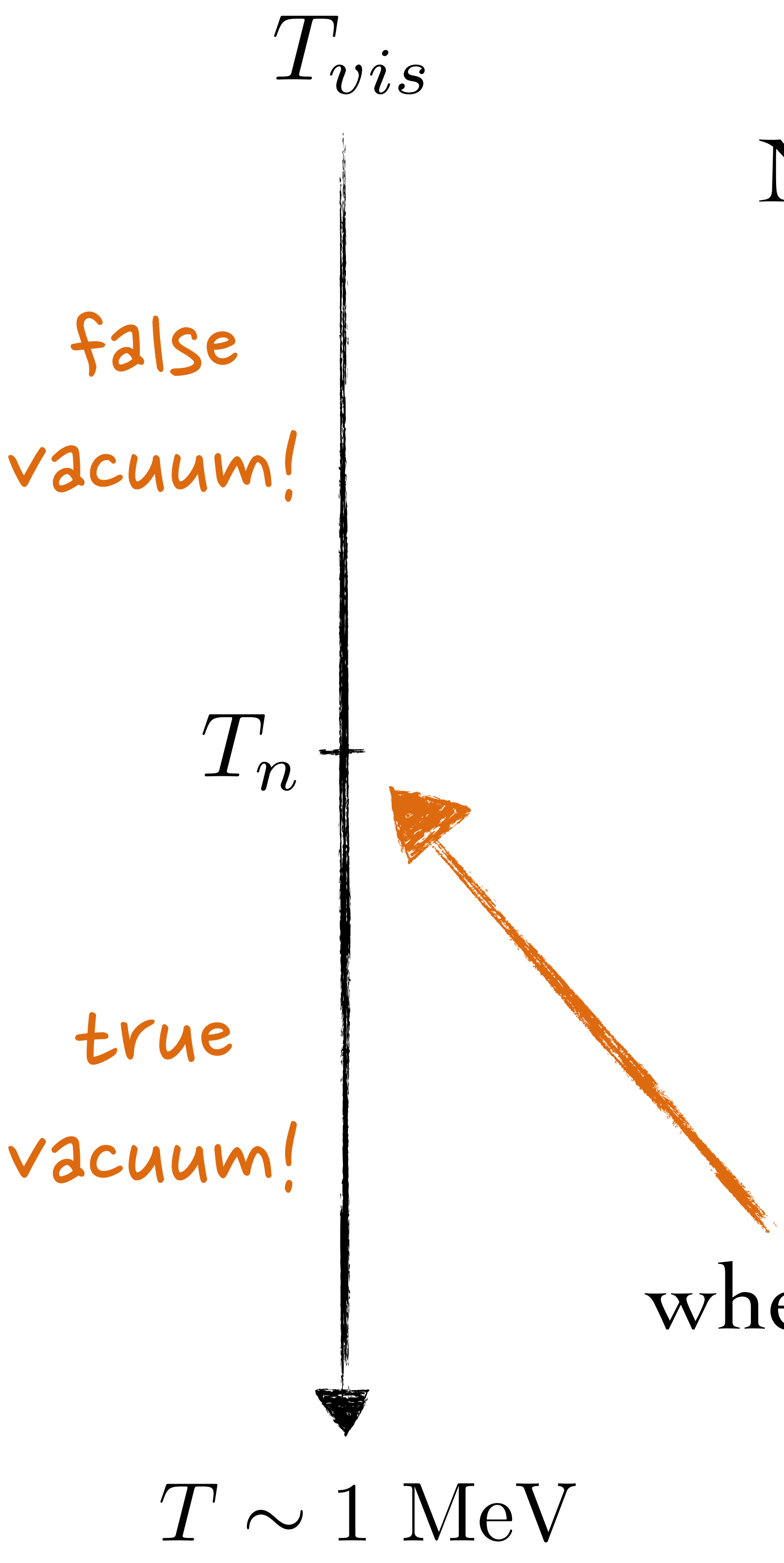
Bubbles of the true vacuum are nucleated in the early universe



They quickly start expanding at the speed of light

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

Vacuum decay



Nucleation probability increases as T_{vis} falls

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

decay rate per unit volume (T independent)

decreases as the temperature drops

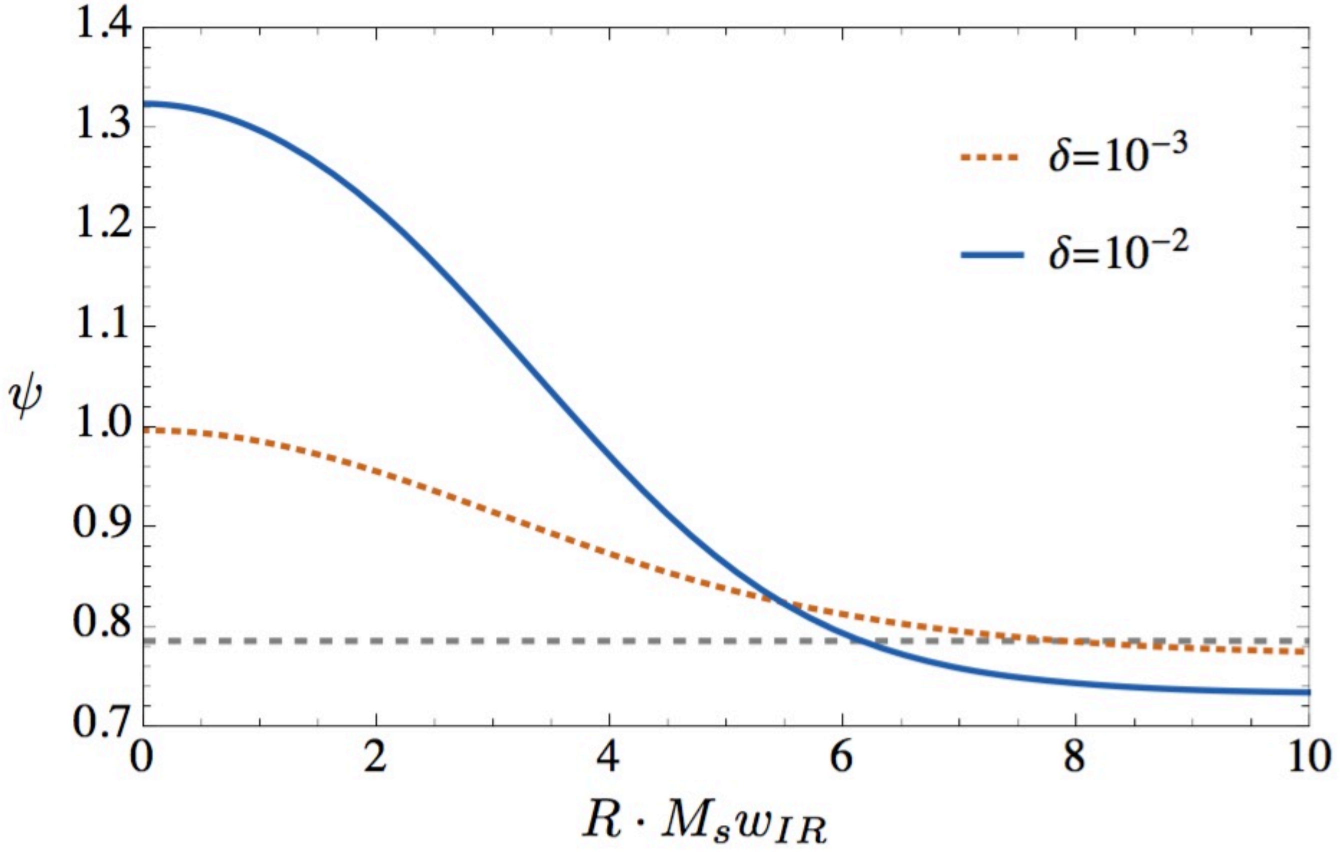
when $\frac{\Gamma}{H(T_n)^4} \approx 1$ the transition starts

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

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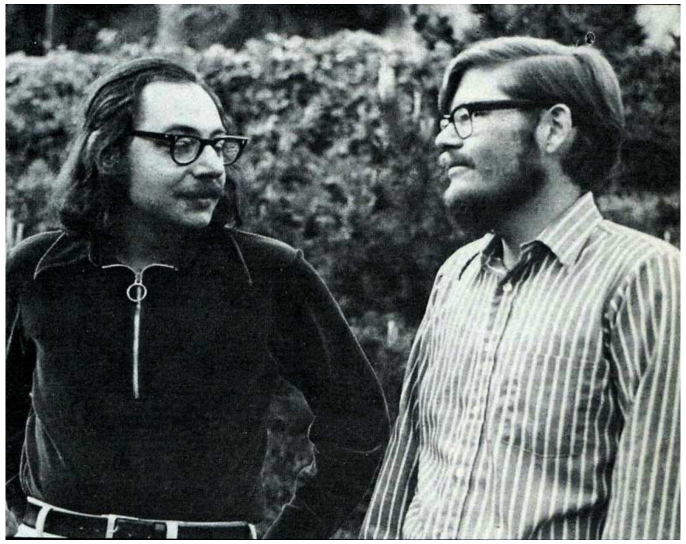

$$\Gamma \sim m^4 e^{-B} \qquad B = S[\psi_B] - S[\psi_{fv}]$$

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

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

visible temperature

at bubble collision

$$T_c \approx 0.62 T_n$$

duration of transition

in Hubble times

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

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visible temperature at bubble collision

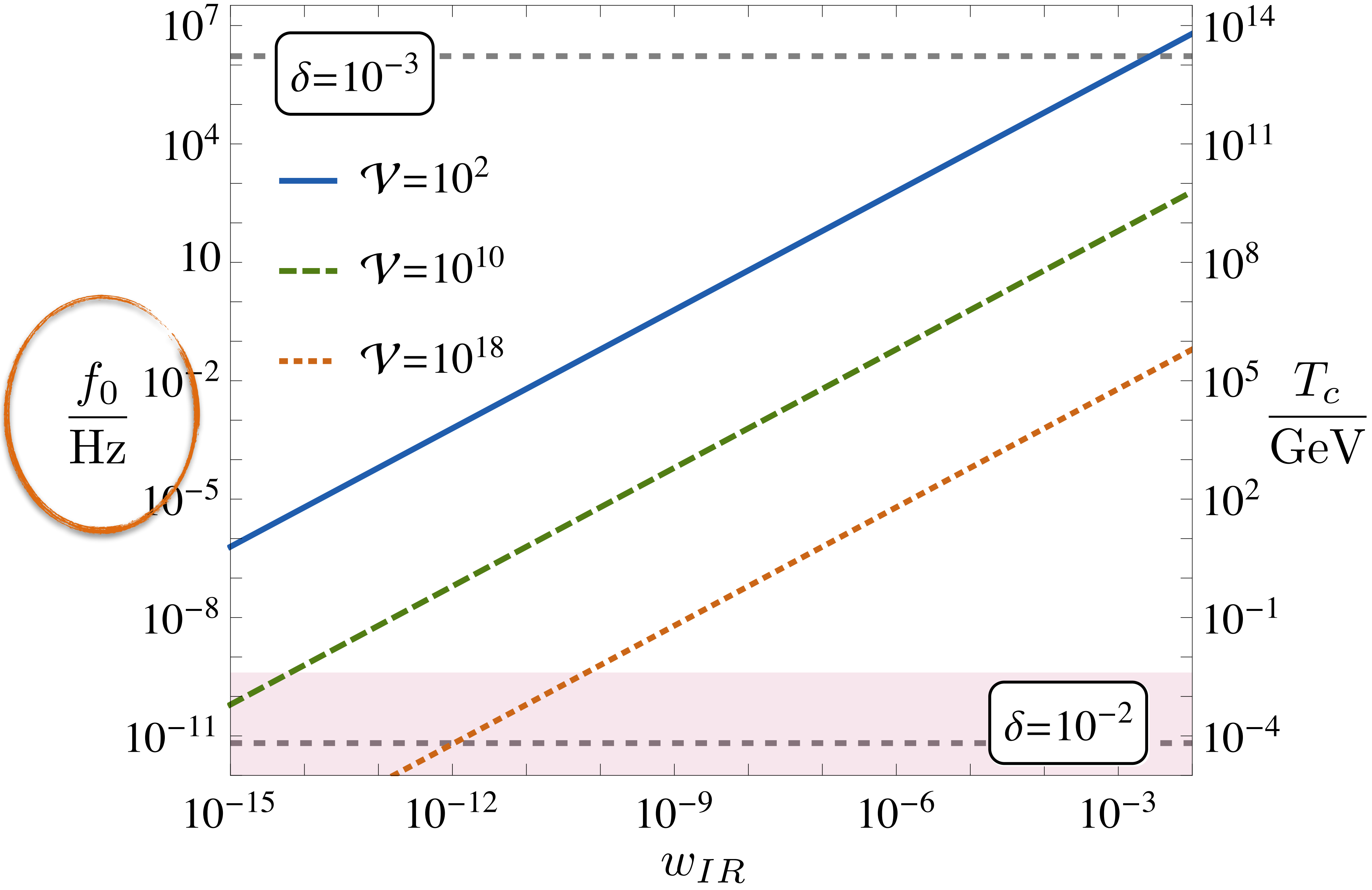
$$T_c \approx 0.62 T_n$$

duration of transition in Hubble times

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

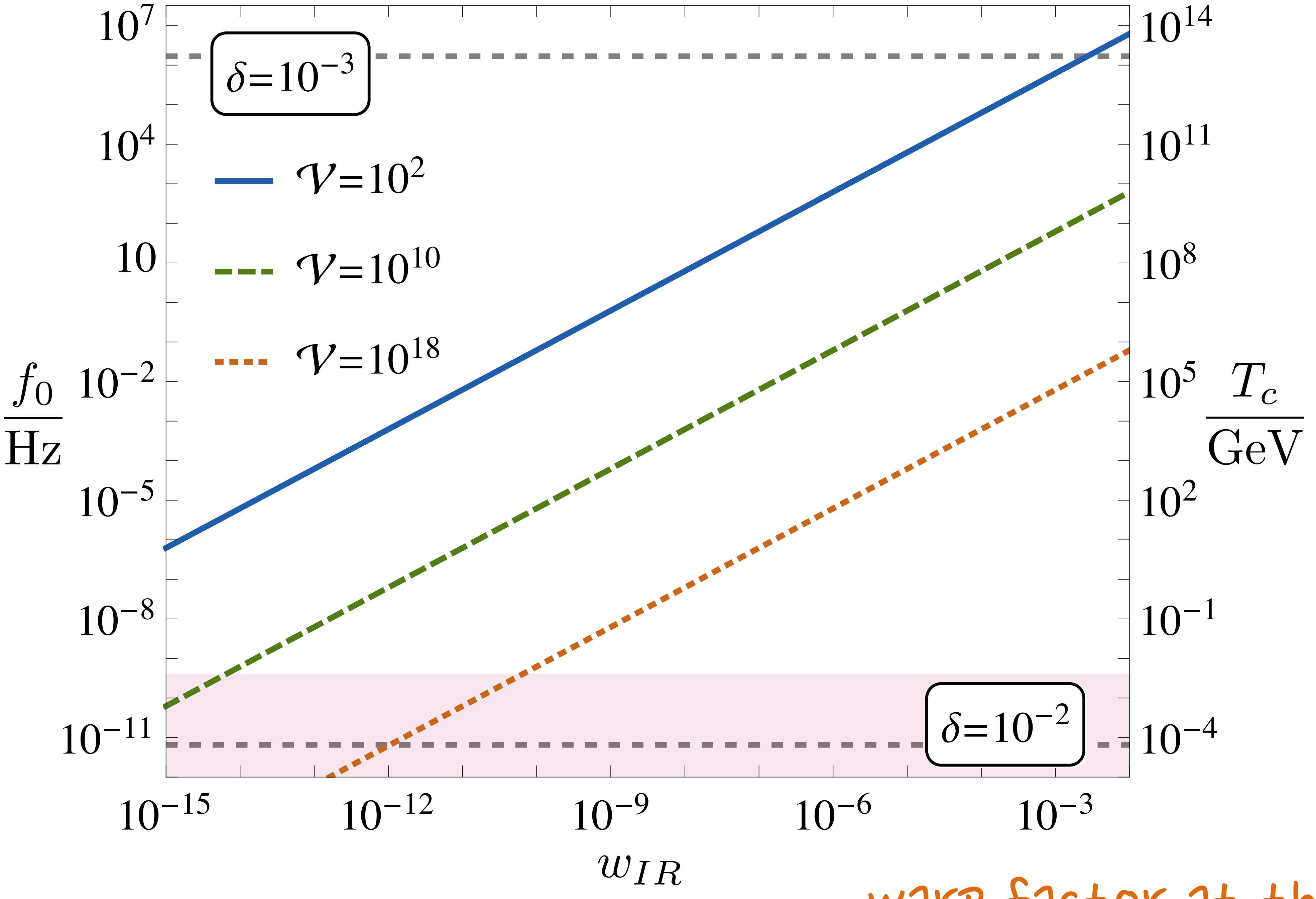
nucleation temperature T_n is exponentially sensitive to underlying throat parameters so f_0 scans

GW peak frequency



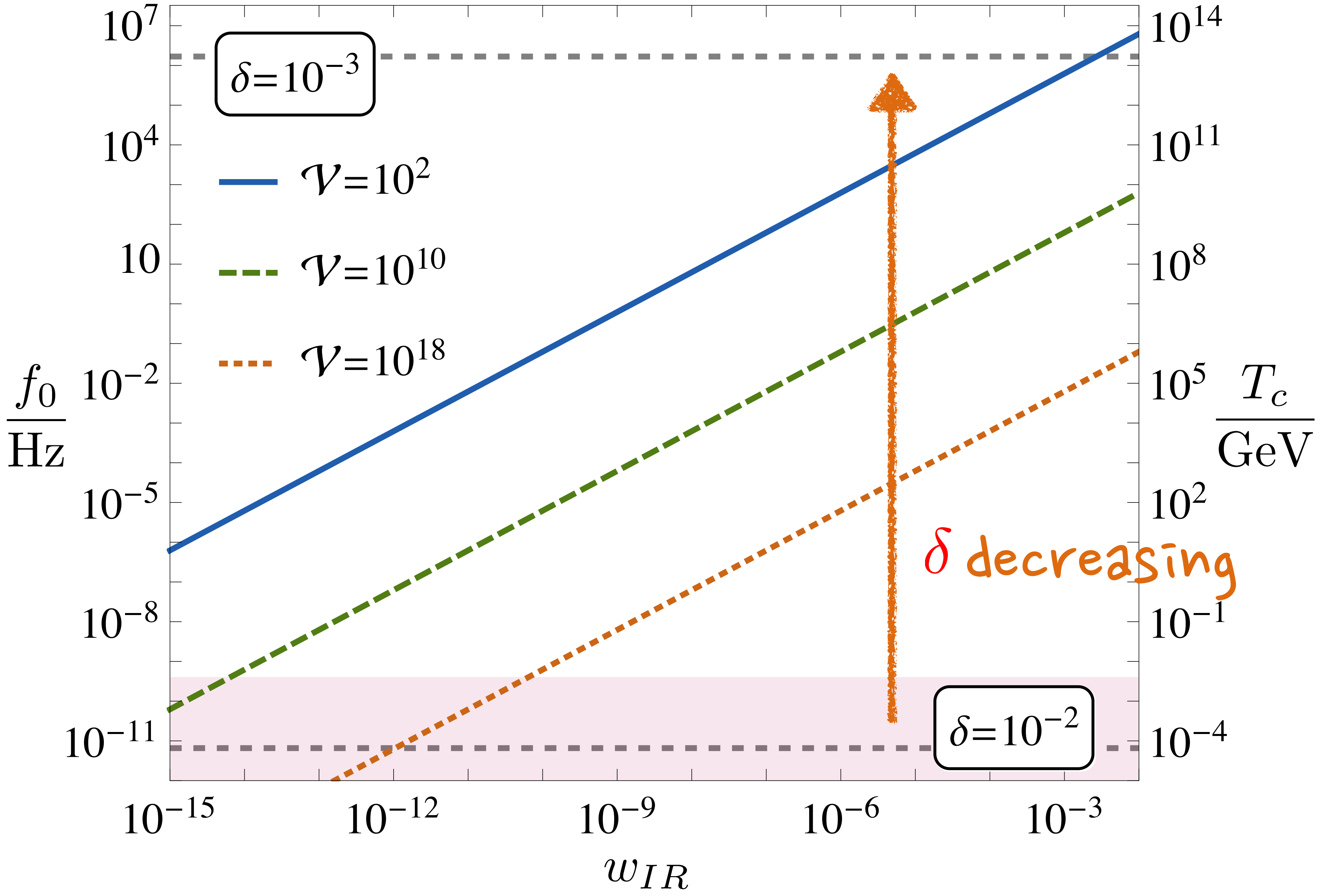
(here have fixed $M=10^2$ and $g_s=0.03$)

GW peak frequency

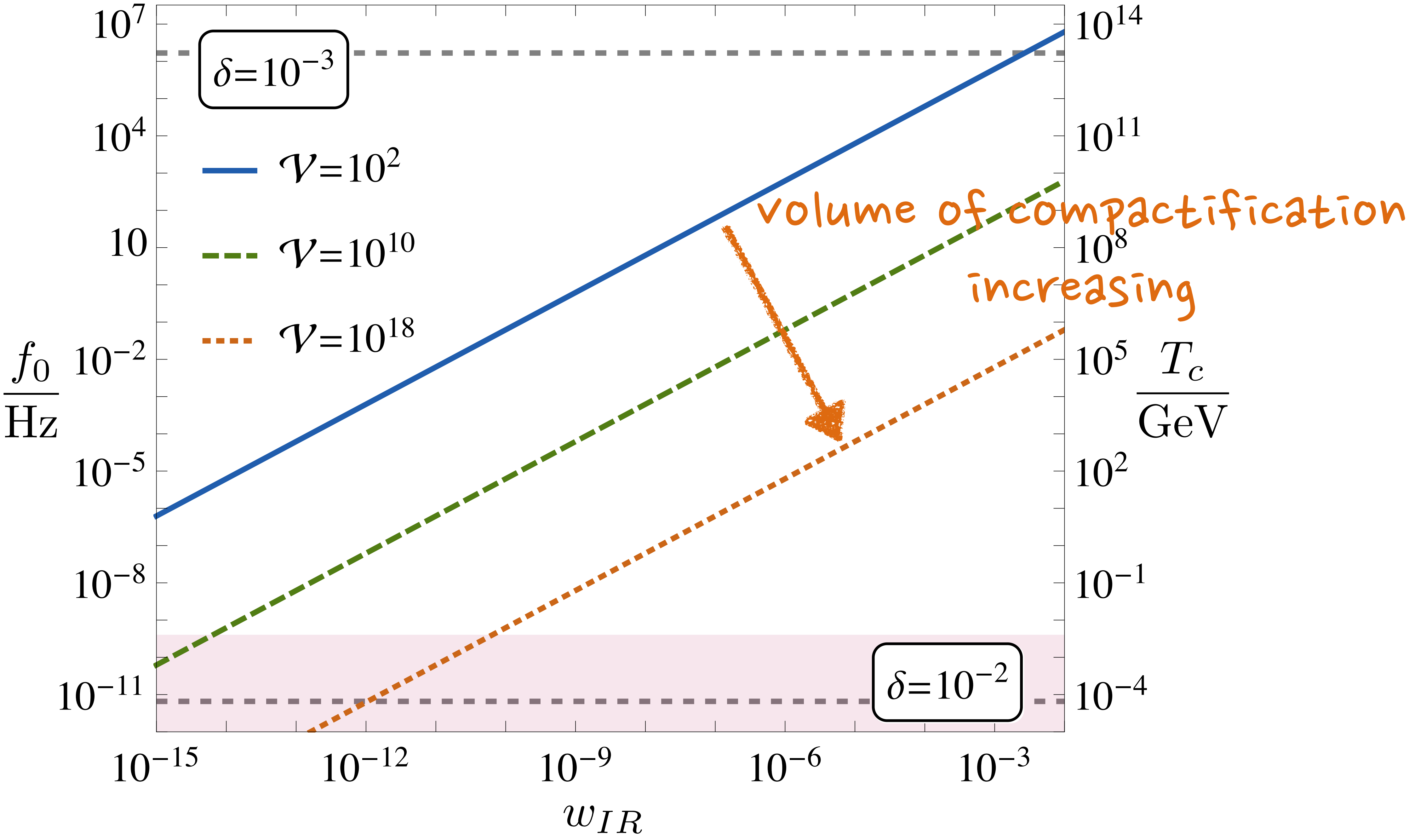


warp factor at the tip of the throat

GW peak frequency

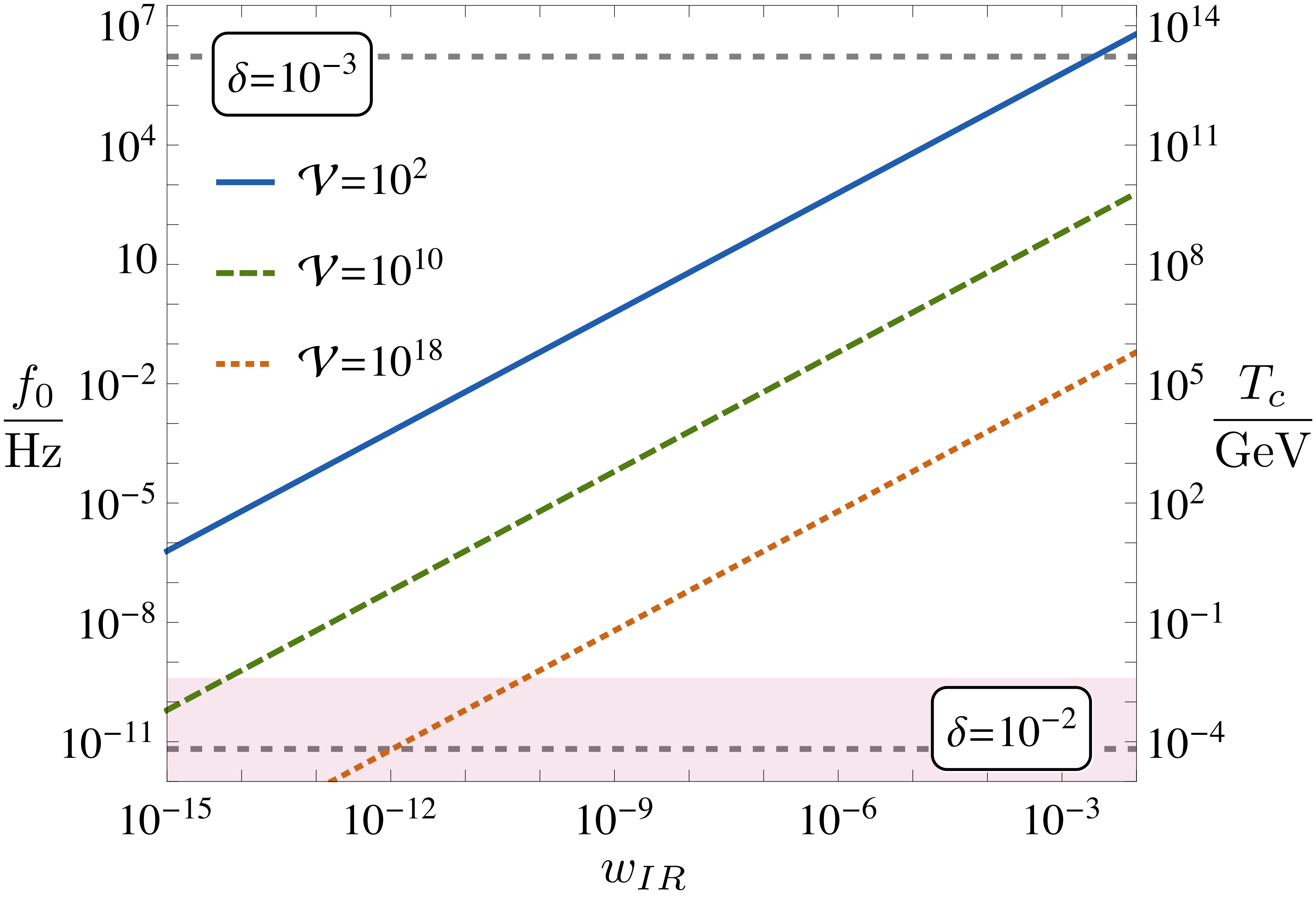


GW peak frequency



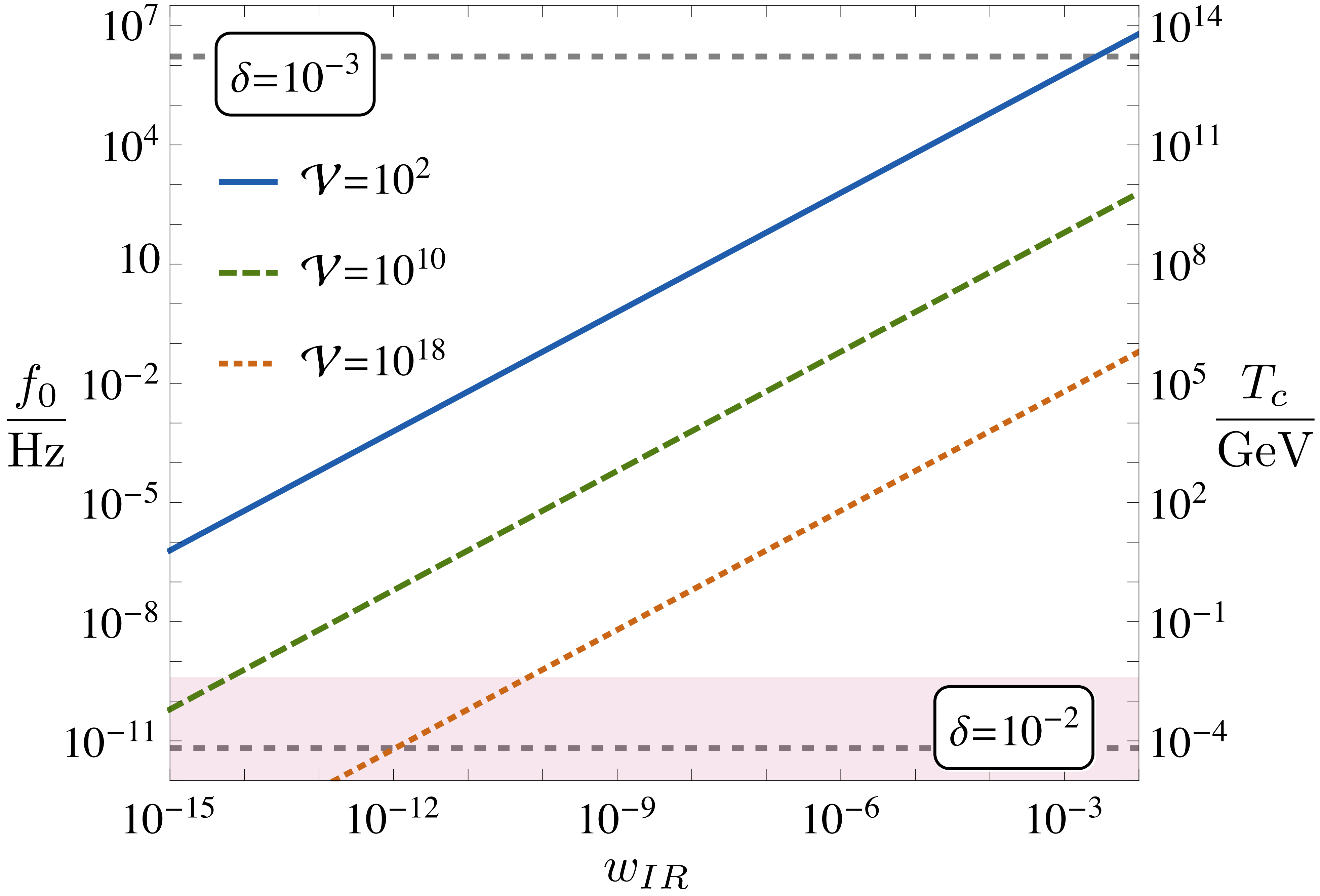
volume of compactification increasing

GW peak frequency



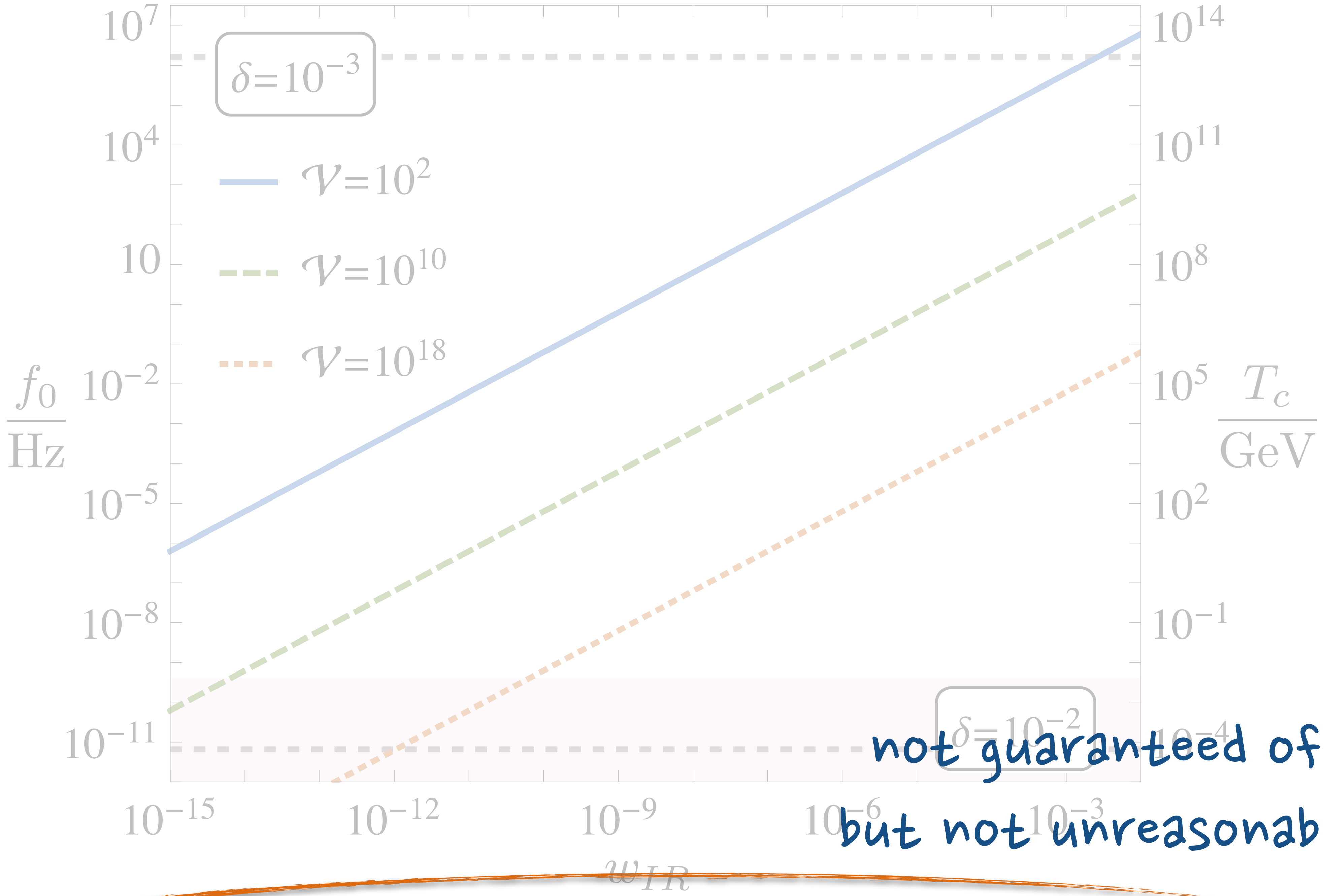
The frequency can span the entire range being/to-be probed by gravity-wave detectors

GW peak frequency



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

GW peak frequency



not guaranteed of course
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

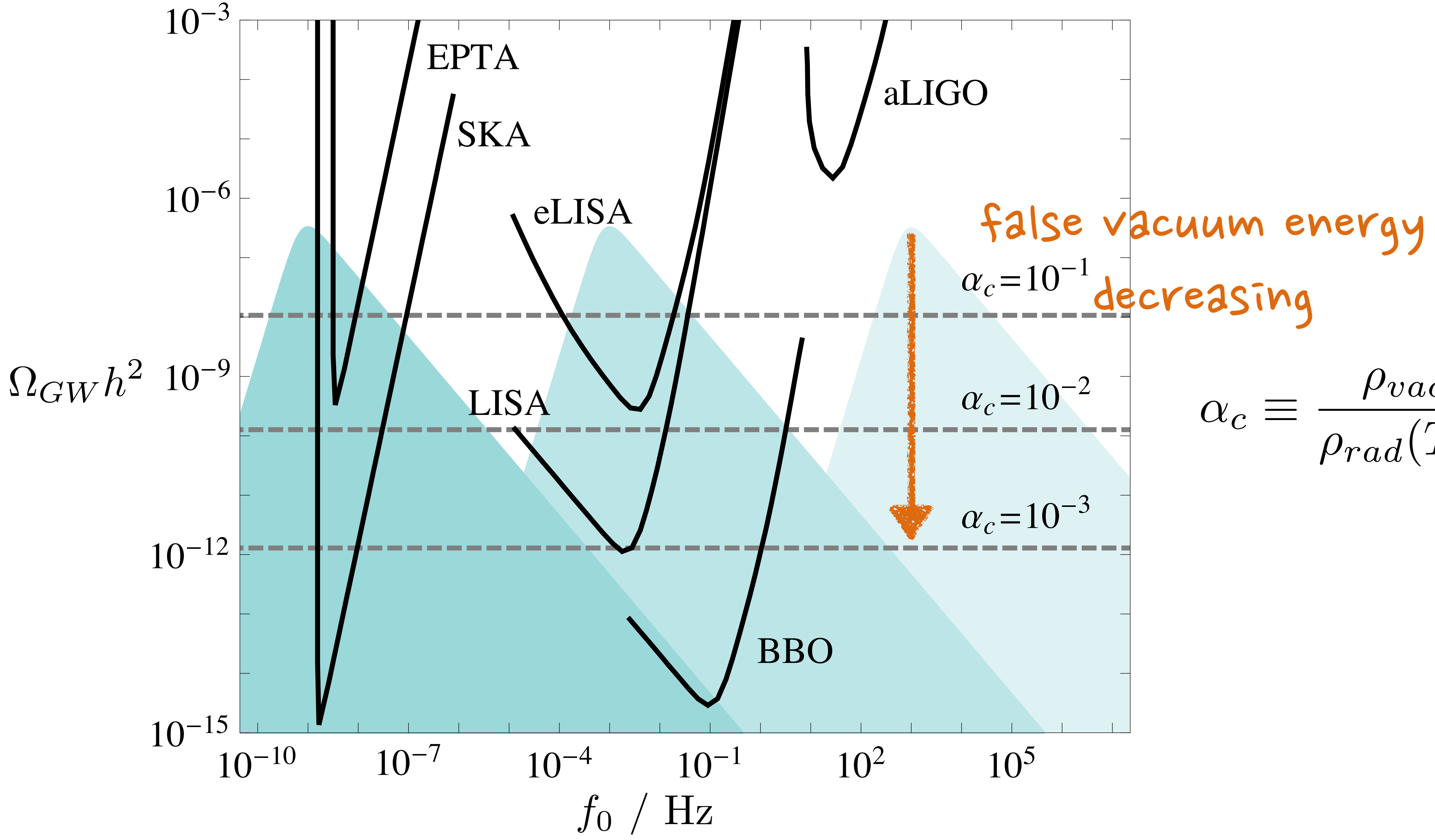
$$\Omega_{GW}h^2(f_0) \sim 10^{-6}\left(\frac{\alpha_c}{1+\alpha_c}\right)^2\left(\frac{100}{g_*}\right)^{1/3}(t_* H(T_c))^2$$

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)

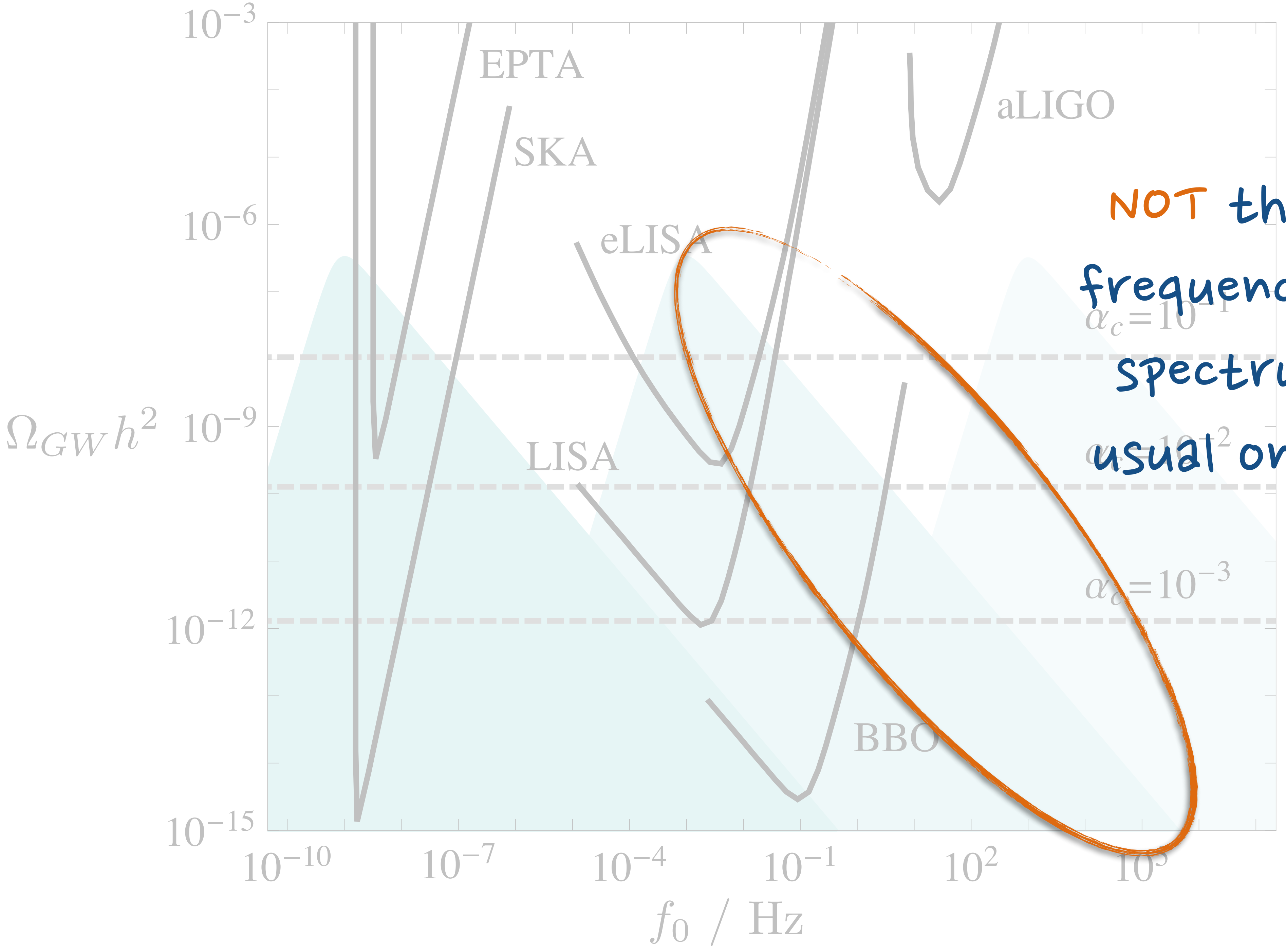
GW signal strength



false vacuum energy decreasing

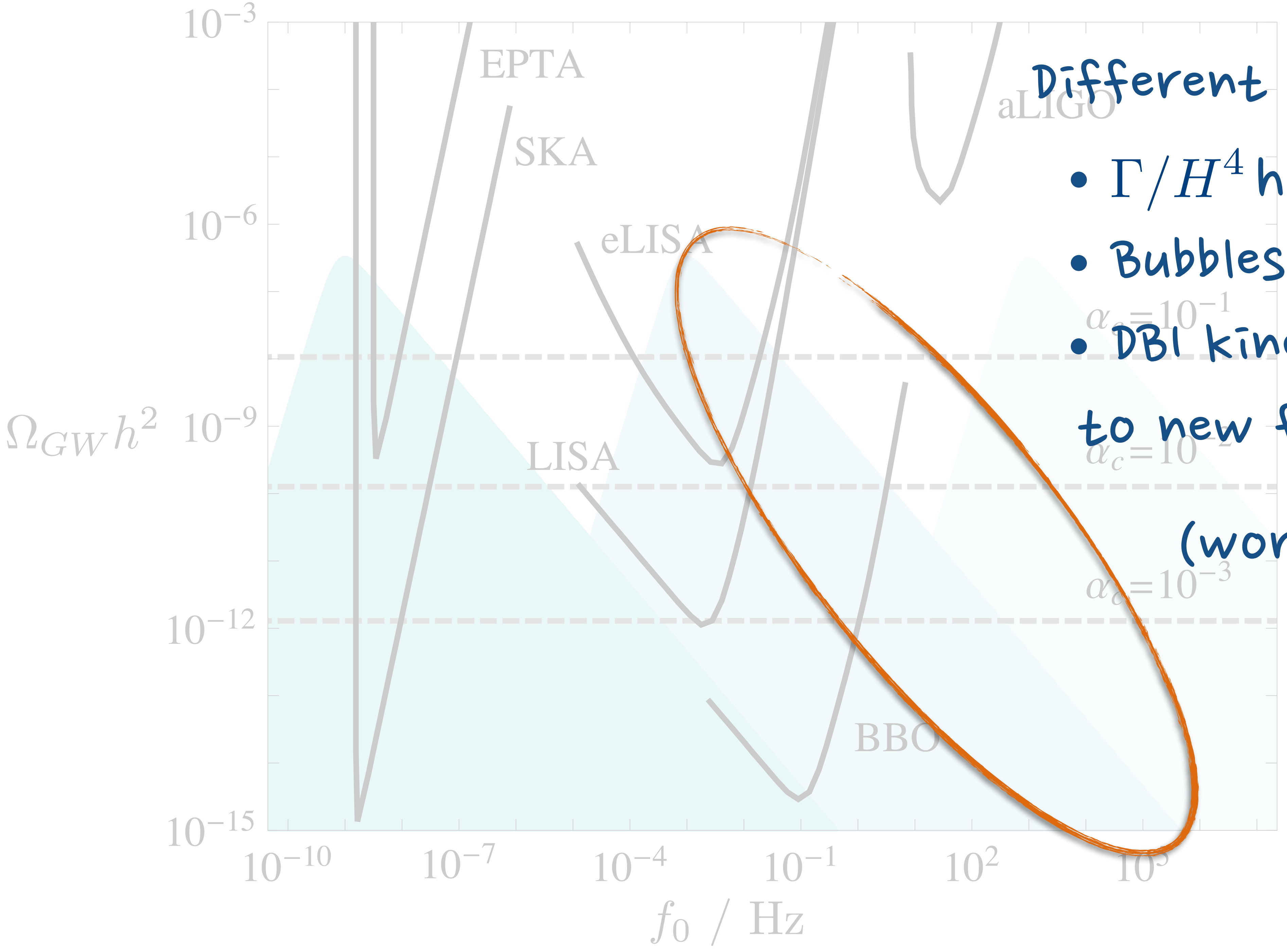
$$\alpha_c \equiv \frac{\rho_{vac}}{\rho_{rad}(T_c)}$$

GW signal strength



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

GW signal strength

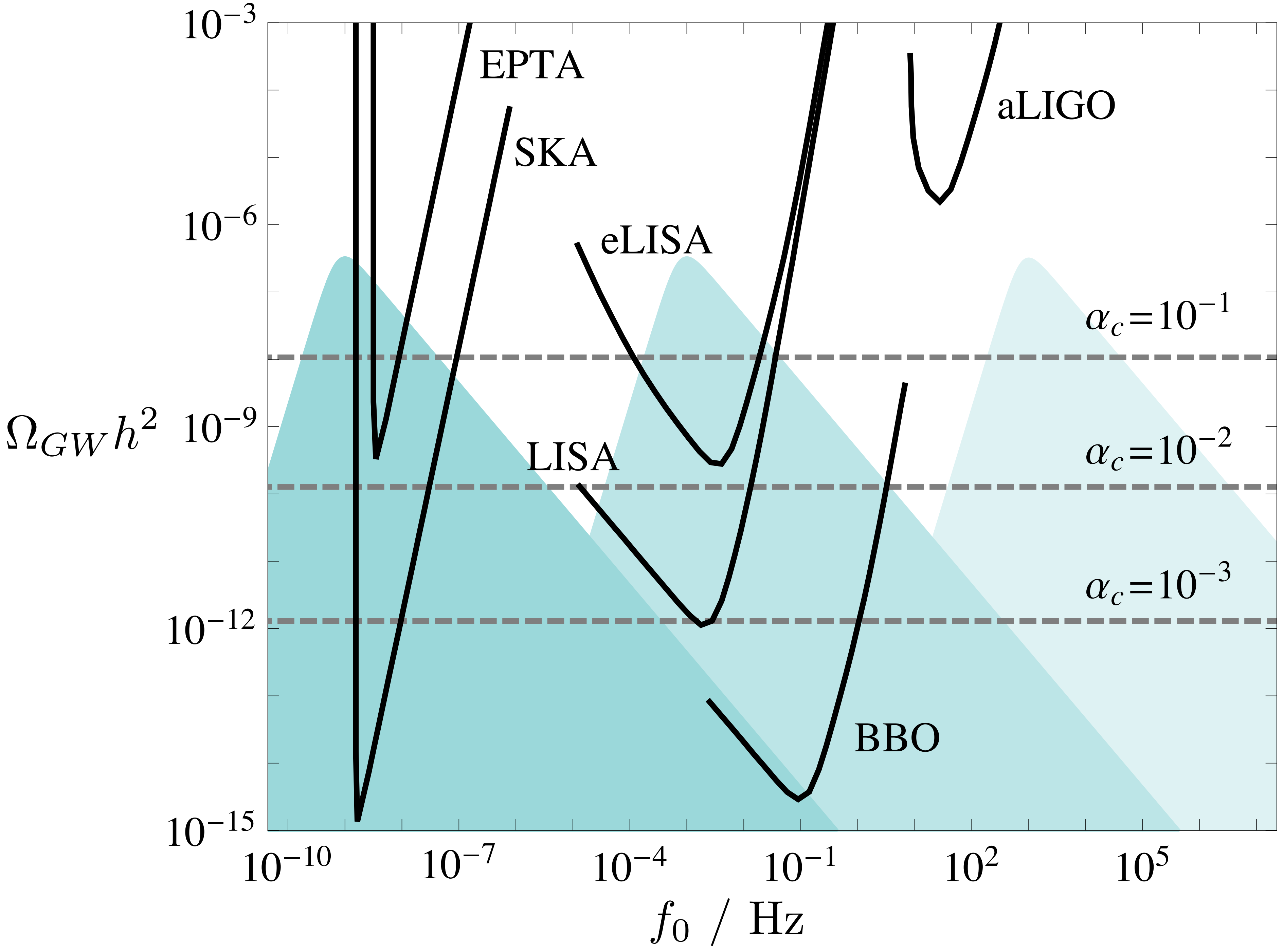


Different because

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

(work in progress)

GW signal strength

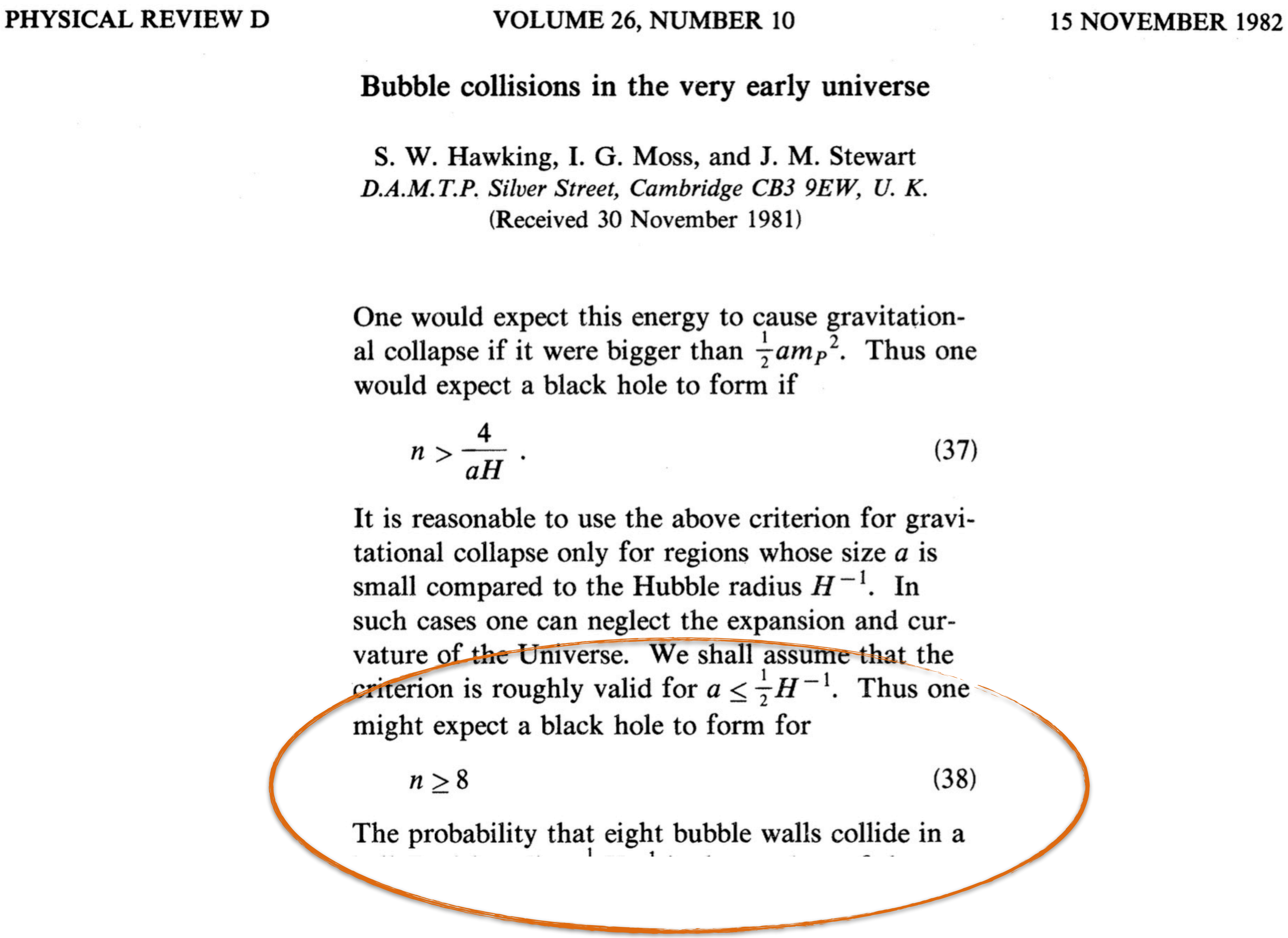


high-frequency
part of spectrum
sensitive to
underlying
(string) model!

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 and poorly understood



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)

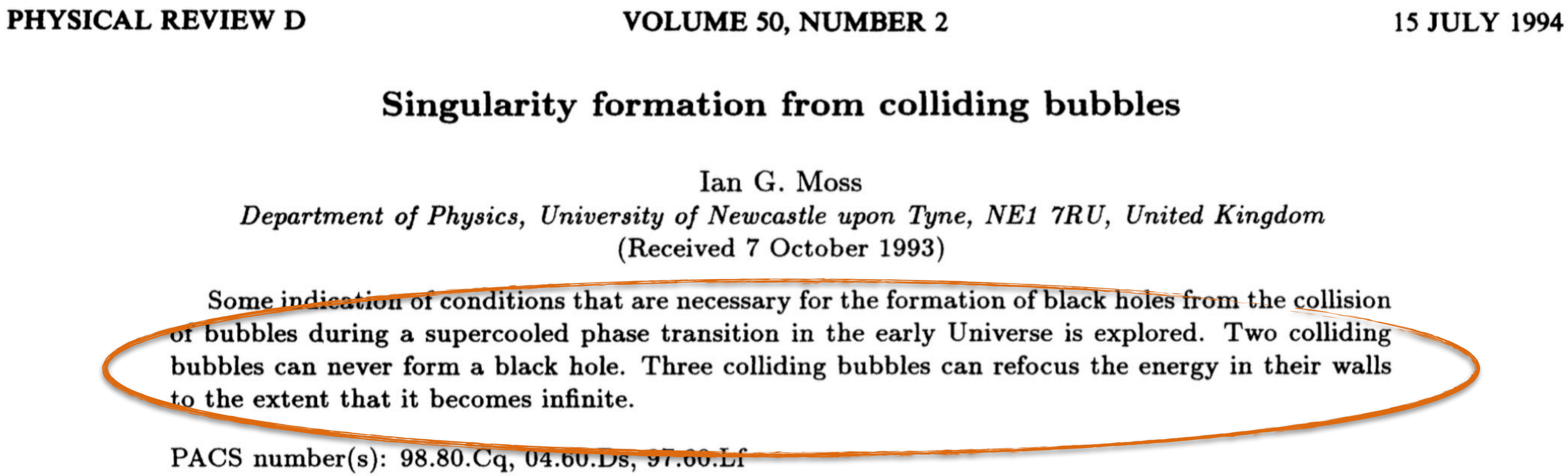
One would expect this energy to cause gravitational collapse if it were bigger than $\frac{1}{2}am_P{}^2$. Thus one would expect a black hole to form if

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

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 $a \leq \frac{1}{2}H^{-1}$. Thus one might expect a black hole to form for

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

The probability that eight bubble walls collide in a



PHYSICAL REVIEW D VOLUME 50, NUMBER 2 15 JULY 1994

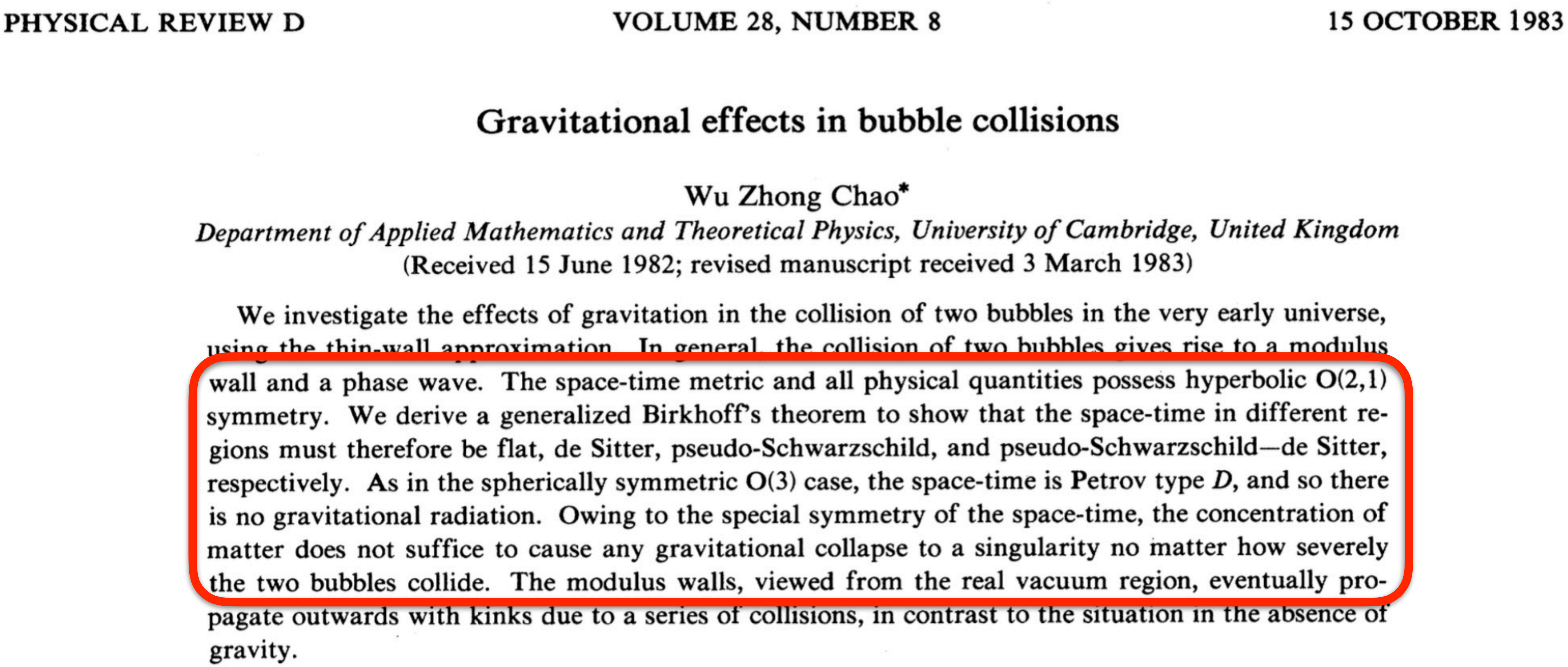
Singularity formation from colliding bubbles

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

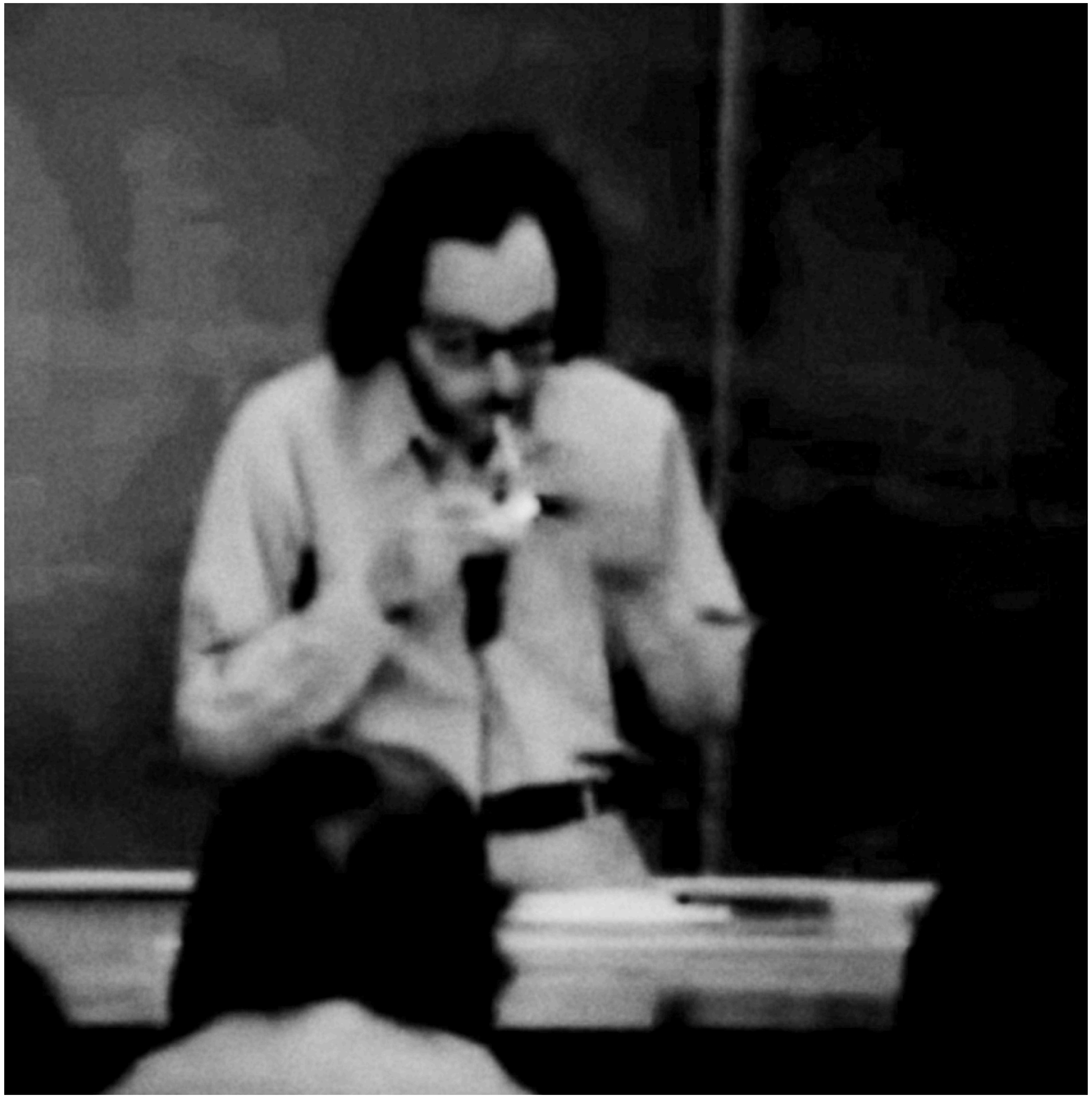
(Received 15 June 1982; revised manuscript received 3 March 1983)

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



…ah the days when one could have a cigarette after (or during) a stimulating seminar

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

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

Return of the bounce

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

Really to get a non-zero decay rate of form

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

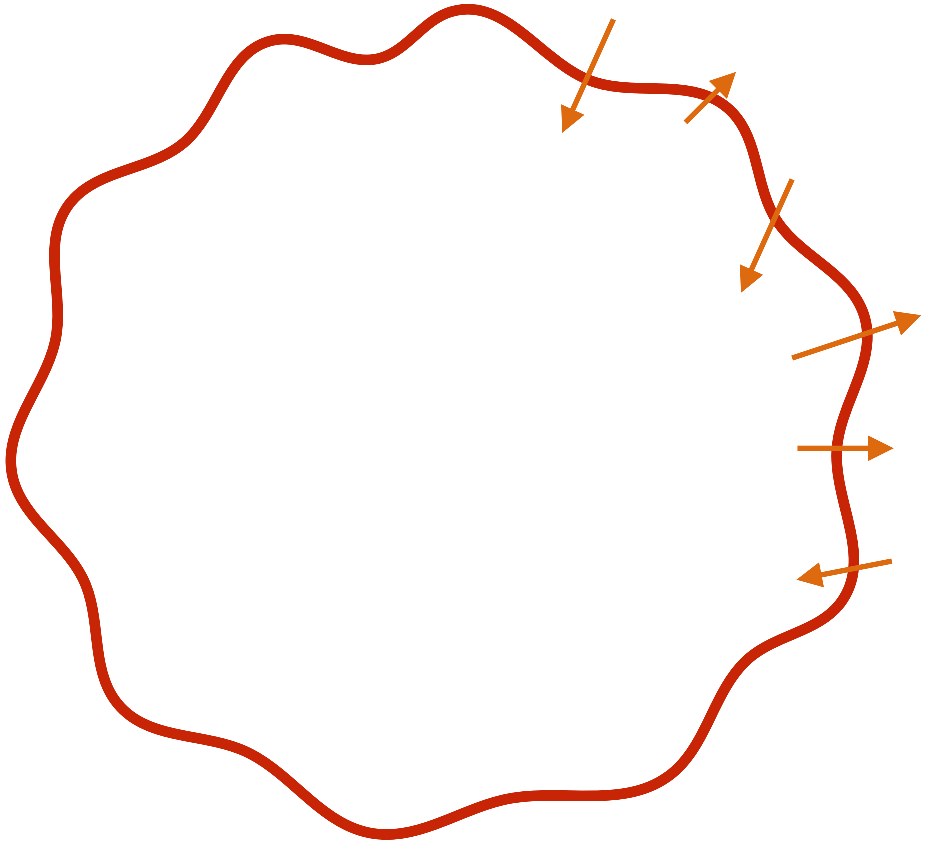
one needs to consider a bundle of nearby configurations

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

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



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

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

Return of the bounce

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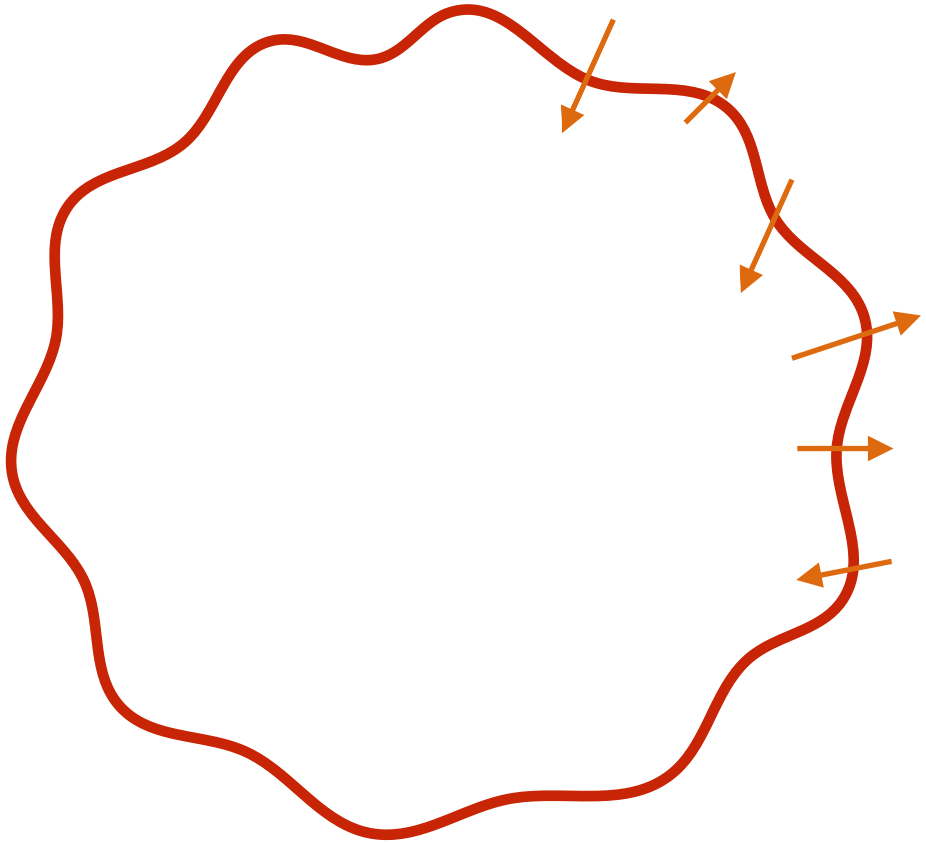

typical relative velocities of parts of wall ~ $1/\sqrt{B}$

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

this symmetry breaking can survive bubble expansion and possibly dominantly determines PBH formation rate and form of mass distribution!

(work in progress - really needs dedicated strong-field-gravity numerics!)

Conclusions

- GW detectors will help shape the future of physics in the coming century

- They can complement the information we get from particle colliders/DM detection experiments/ultra-sensitive small scale experiments

- String theory transitions in post-inflation early universe can be present and lead to (distinctive) GW signatures, and maybe even an interesting population of pBHs!

more to come….

I now think I need that cigarette…