# Exploring the Very Early Universe with Gravitational Waves

John March-Russell

OR

# A Gravitational Wave Odyssey

Odyssey - *a long adventure with many strange and unexpected episodes*

# Many Open Questions

Plenty of questions remain unanswered within the current paradigm of particle physics and cosmology — the Standard Model + Hot Big Bang

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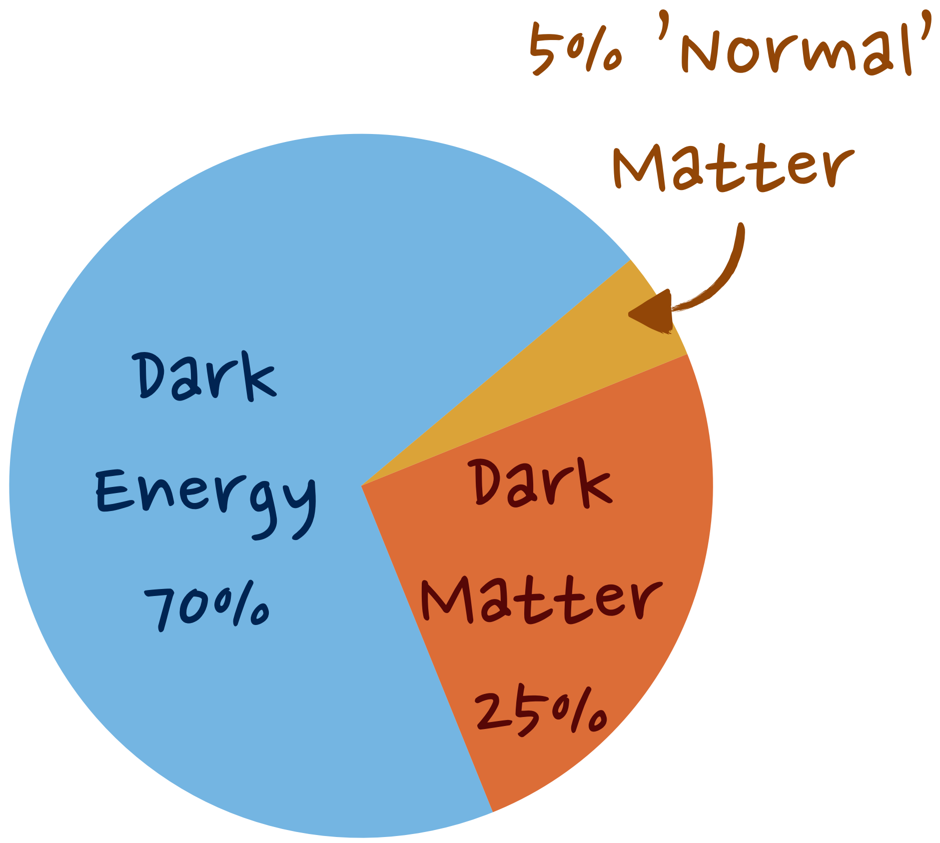

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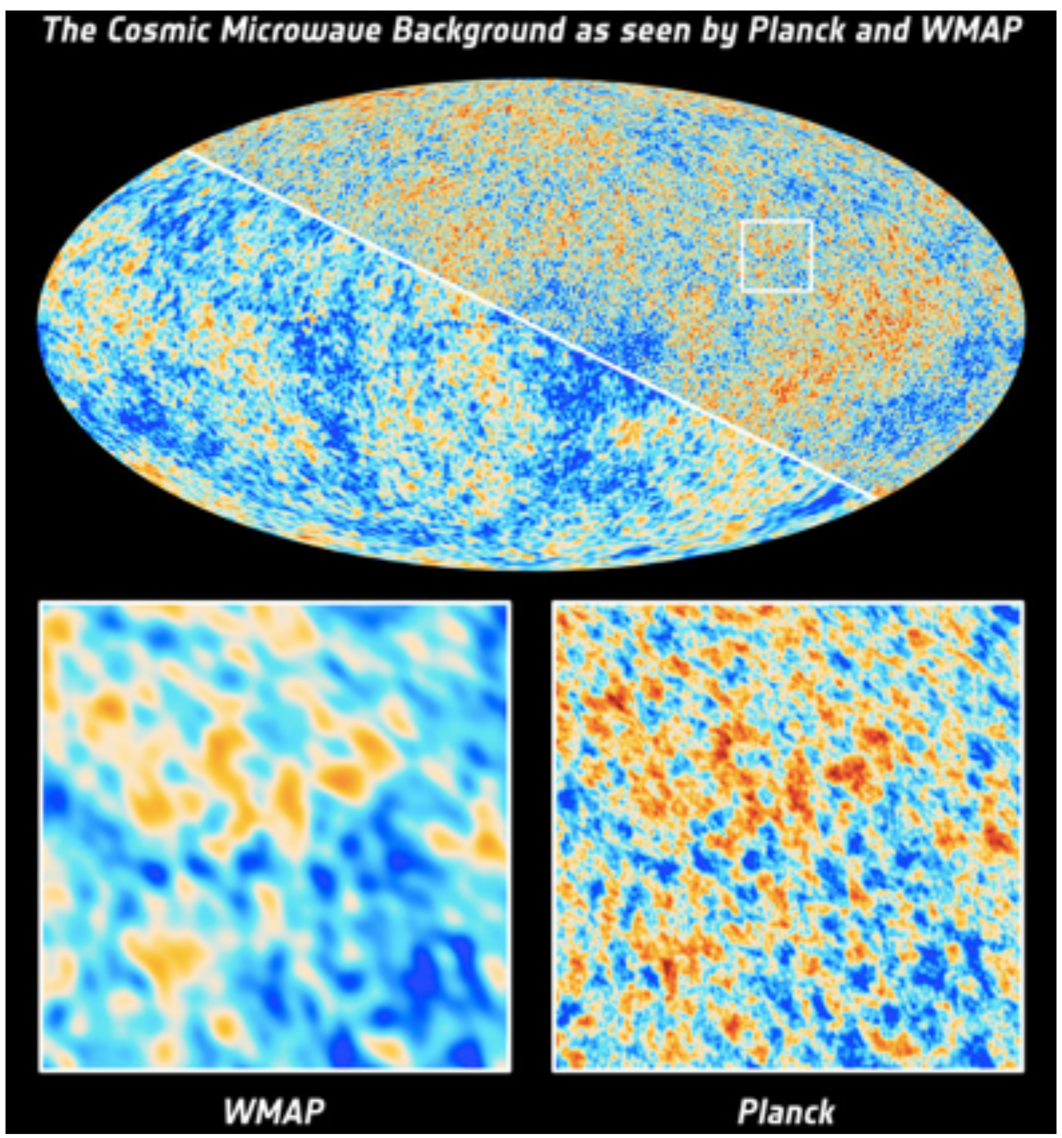
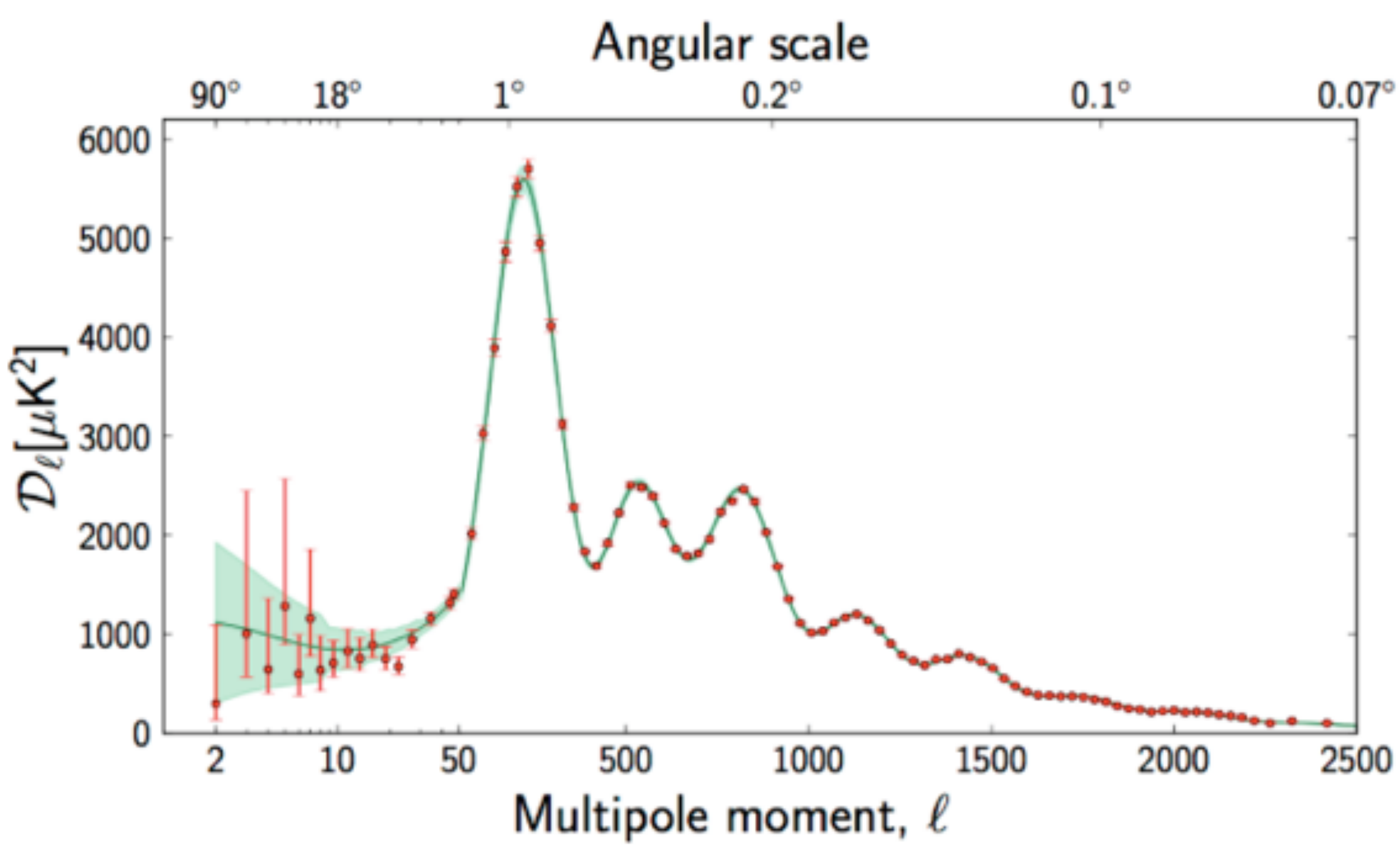
- Physics of *very early* Universe?

  unlikely to be just (boring) thermal equilibrium all the way back...

# Looking for New Physics

- *EM-radiation observations:* Observations *over many wavelengths,* especially Cosmic Microwave Background (CMB) observations, have given us detailed information about the Universe back to ~400,000 yrs after "birth"




WMAP & PLANCK collaborations

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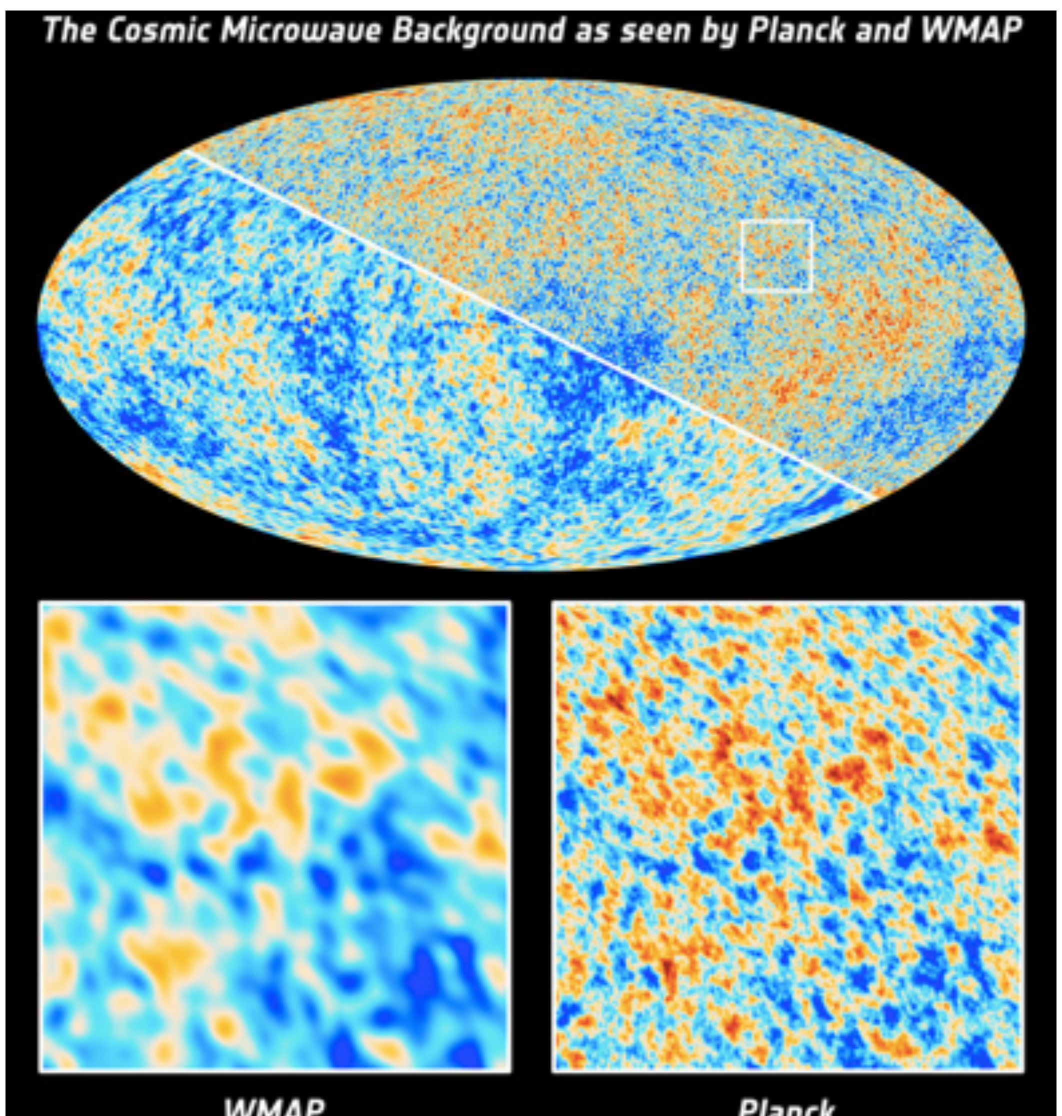
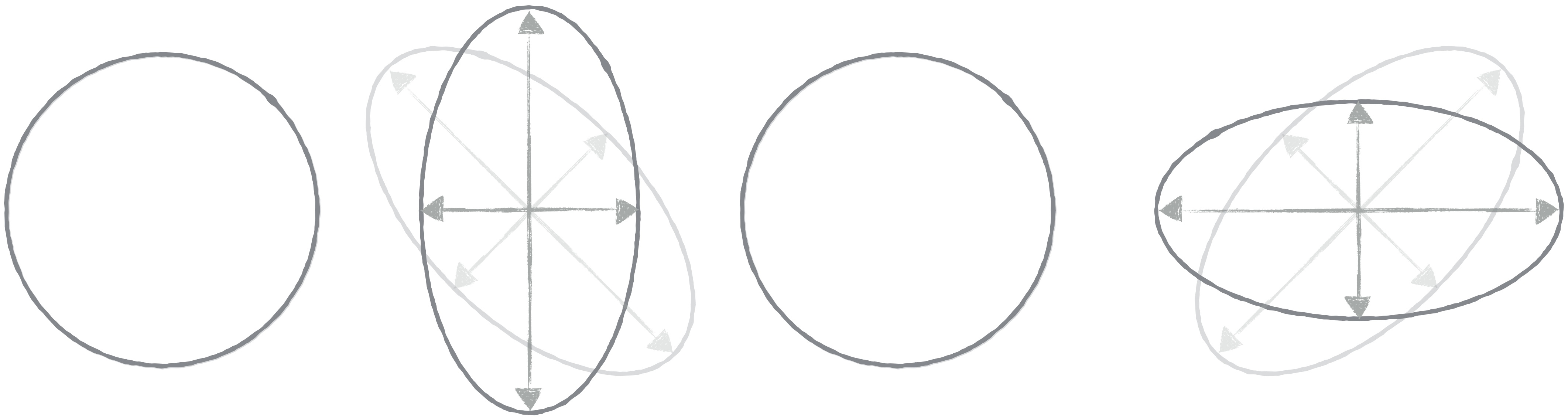



can we similarly use Gravity waves to learn about even earlier physics?

# Gravitational Waves

- GWs are a prediction of GR



- The amount of relative stretching and squeezing is the strain of the GW, $\tilde{h}$, which is generated by (changing) energy-momentum

$$h_{\mu\nu}(t, \vec{x}) = \frac{4G}{c^4} \int \frac{T_{\mu\nu}(\vec{x}', t - |\vec{x} - \vec{x}'|/c)}{|\vec{x} - \vec{x}'|} d^3x'$$

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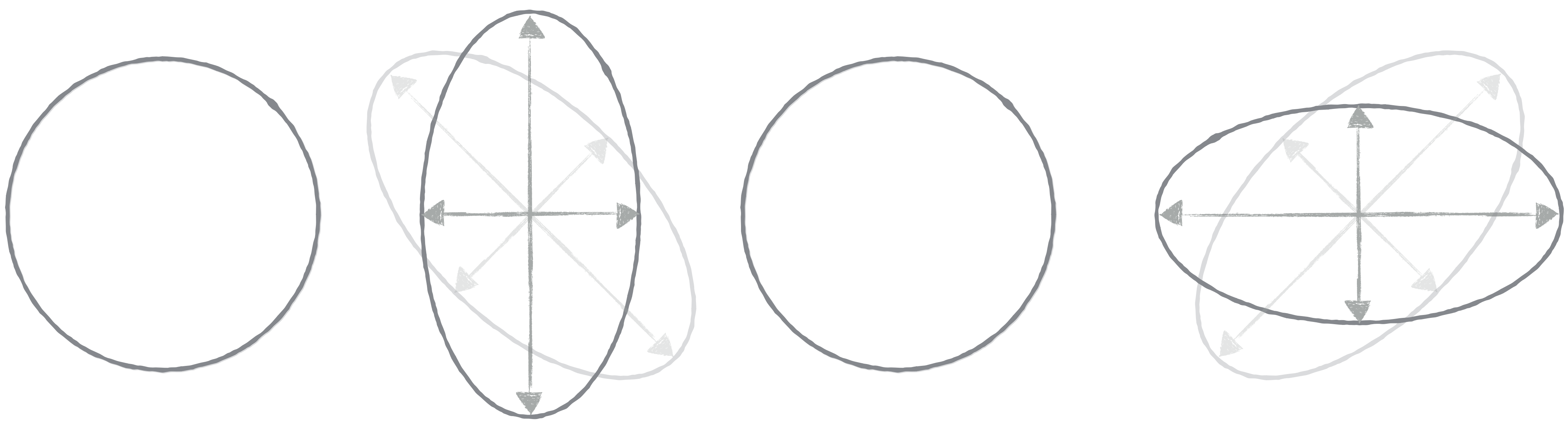

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In non-rel limit

$$h_{jk}^{TT} = \frac{2G}{c^4}\frac{1}{r}\ddot{\mathcal{I}}_{jk}^{TT}(t - r/c)$$

with

$$\mathcal{I}^{jk} = I^{jk} - \frac{1}{3}\delta^{jk}\delta_{lm}I^{lm}$$

$$I^{jk} = \int d^3x\ \rho(t, \vec{x})x^j x^k$$

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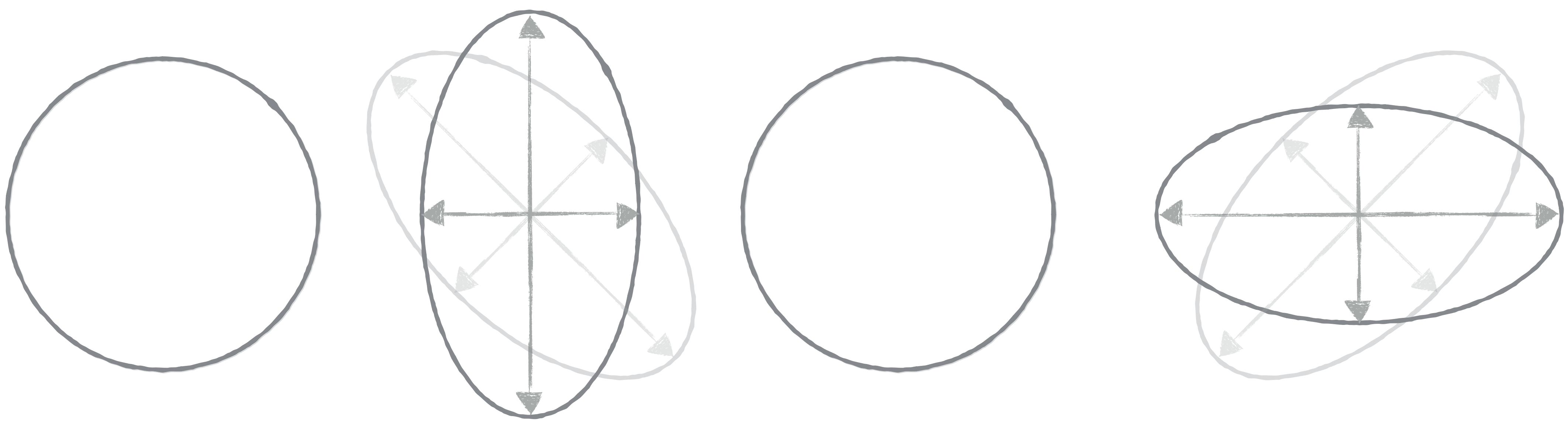

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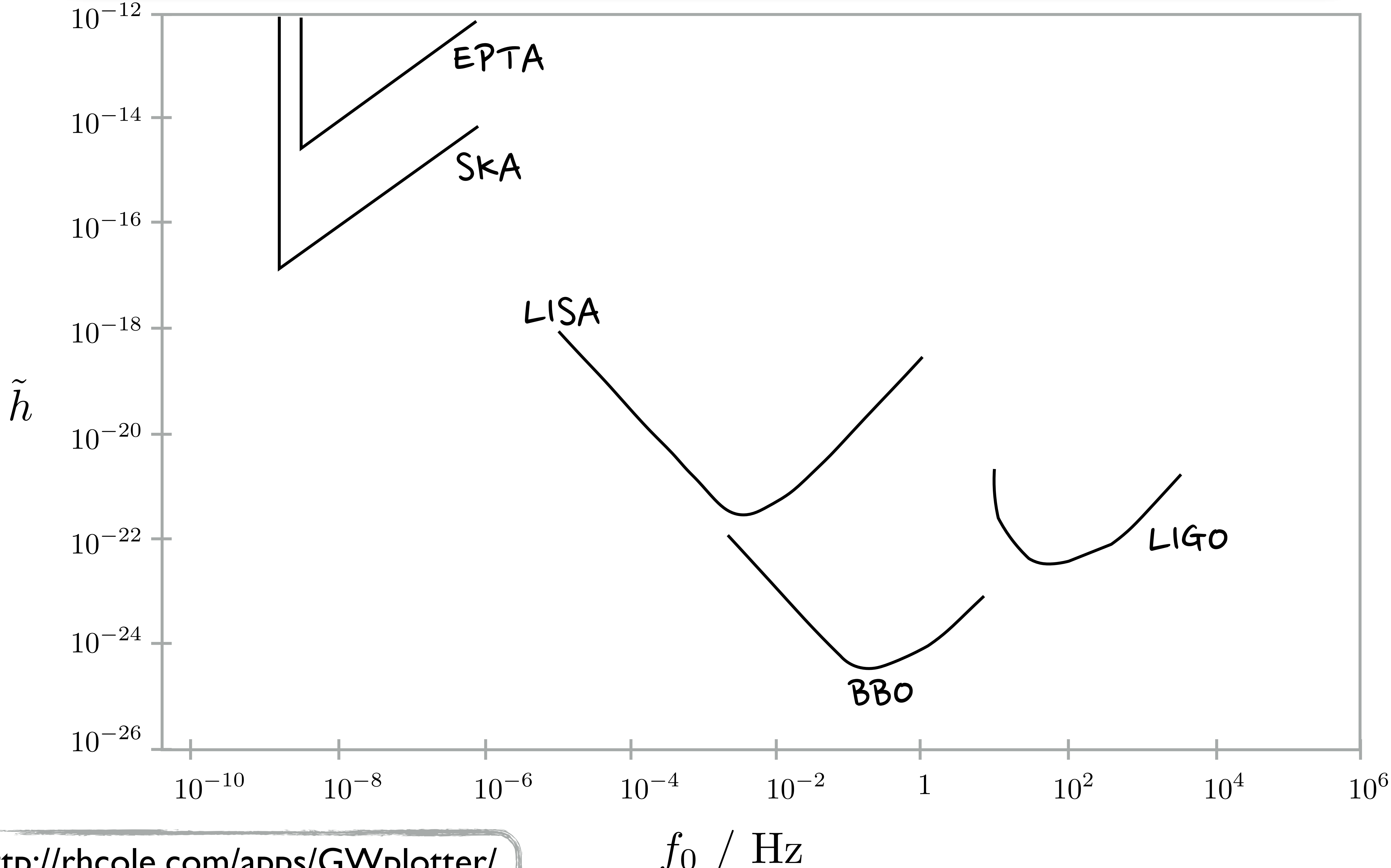
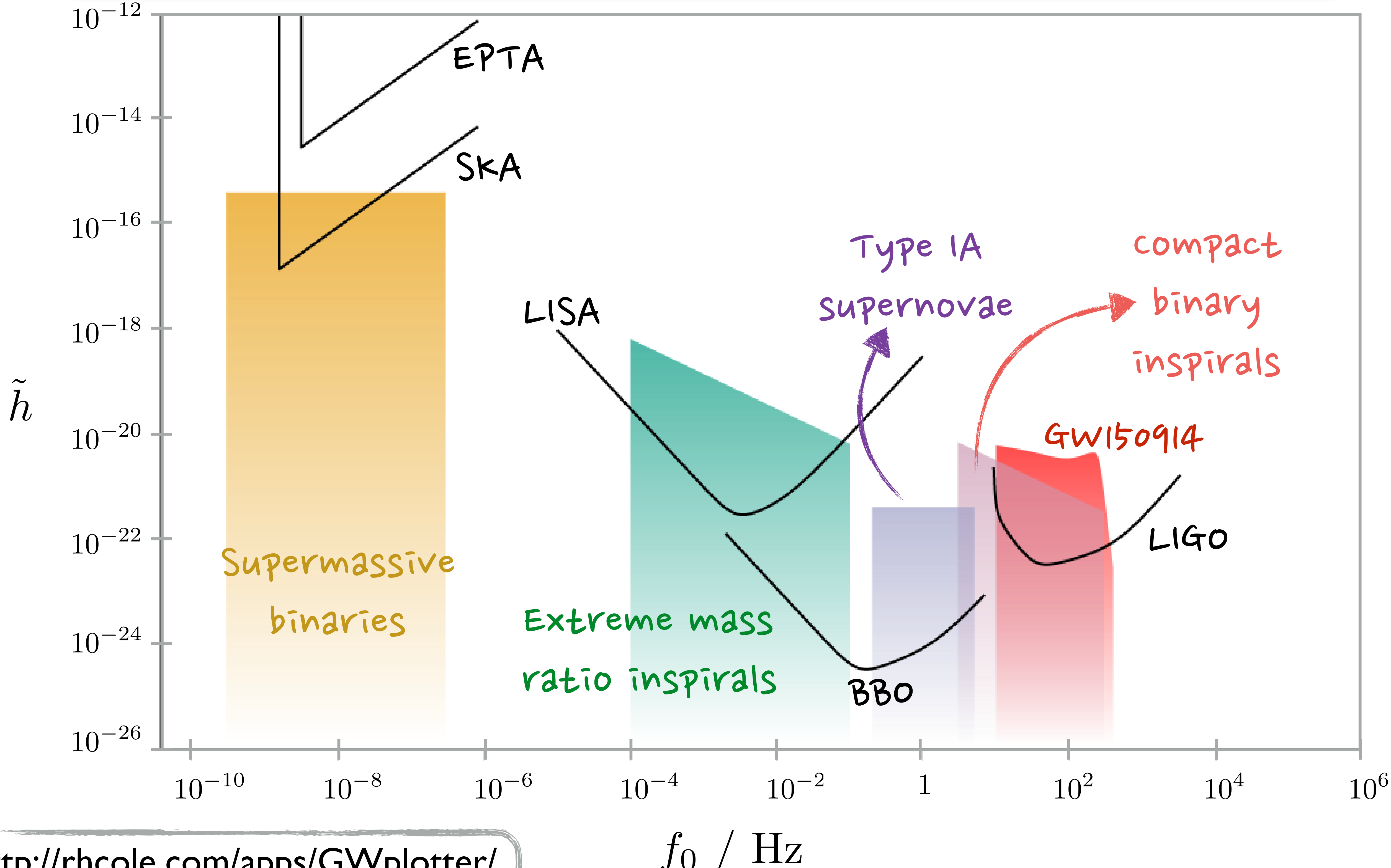
GW detectors are designed to detect
the (tiny) strain of an incoming GW

# GW Sensitivity Curves




http://rhcole.com/apps/GWplotter/

# Astrophysical GW Sources

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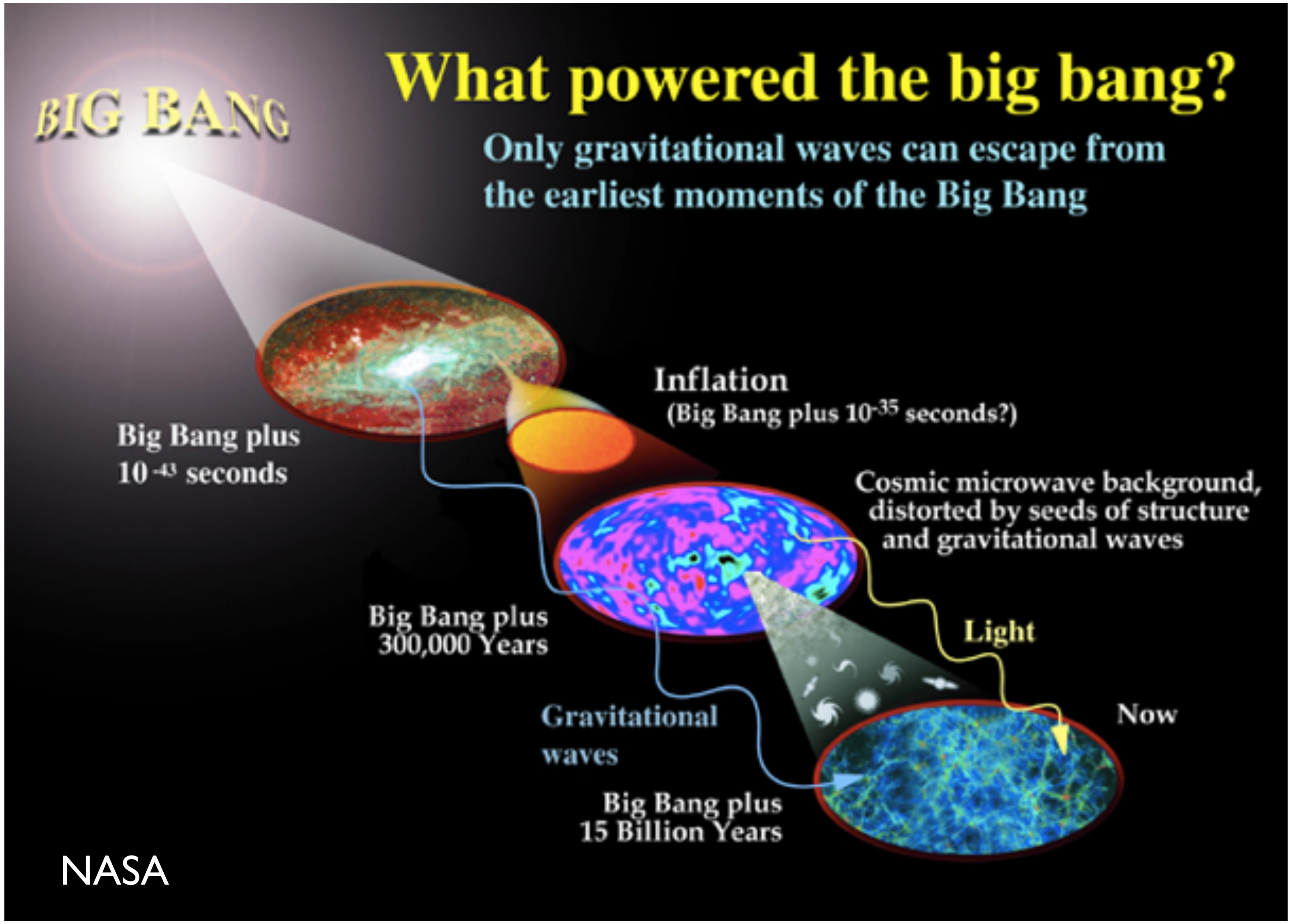
# Early Universe GW Sources?

We instead interested in GW sources in the very early Universe, just after birth, $10^{-43}\ \mathrm{s} \lesssim t \lesssim 1\ \mathrm{s}$, *the epoch that is currently completely unexplored*

# GWs as Probes of Early Universe

GWs have properties that make them excellent probes of the Early Universe

- GWs freely travel from the earliest times

  unlike for light, the universe is transparent to GWs before 300000yrs!

- Gravity couples *to all sources of energy-momentum*

  nothing can hide from gravity! (unlike situation for all other forces)

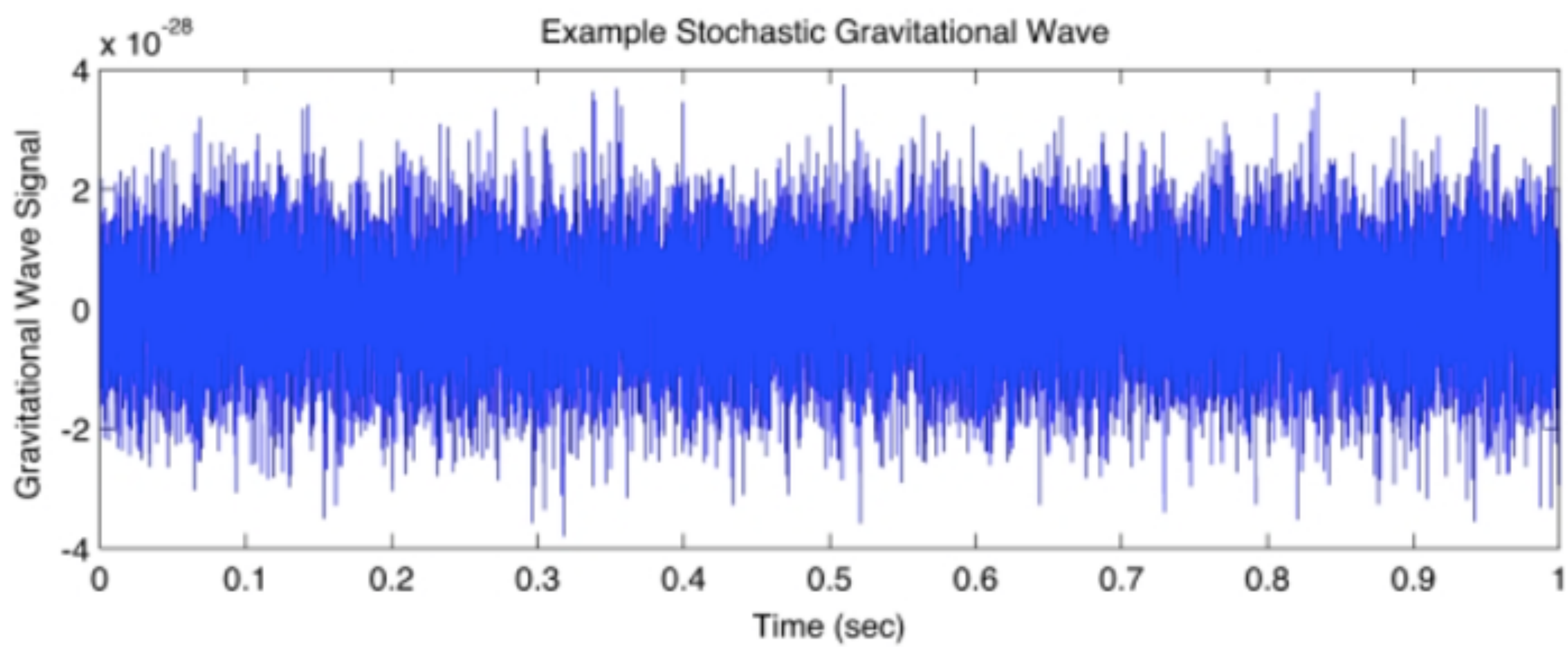
- Gravity couples *universally*

  there is no ambiguity in the strength of the gravitational interaction! (again unlike other forces)

# Listening to Early Universe GWs

Relic gravitational waves from the early evolution of the universe:

Similarly to the CMB, these GWs arise from a large number of independent, random events combining to create a *random* (*stochastic*) *cosmic gravitational wave background* that effectively GW detectors "*listen*" to



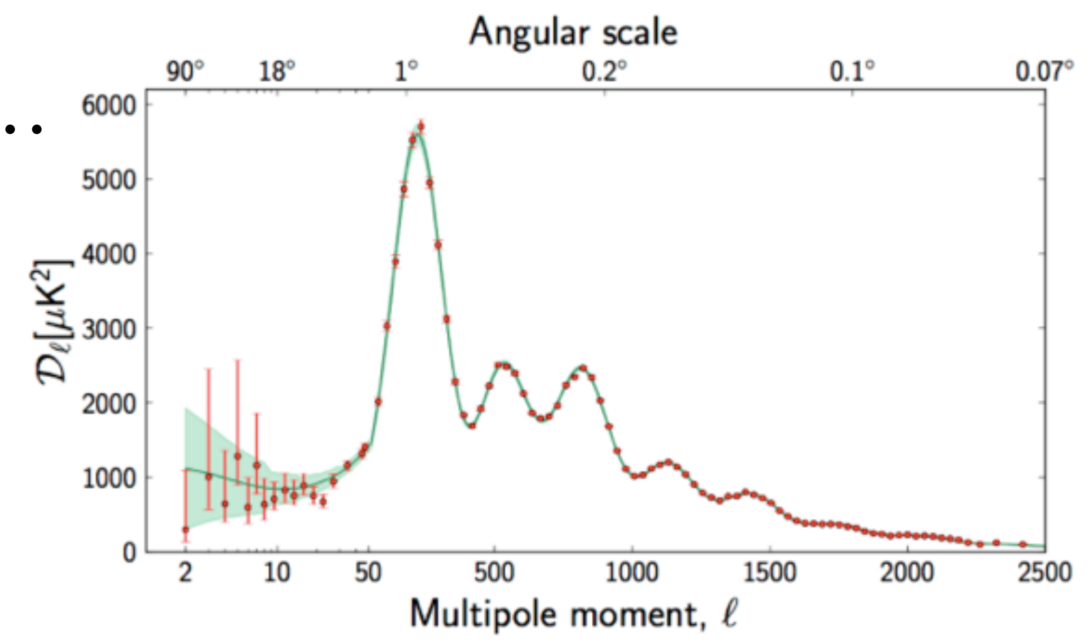

**An example signal from an stochastic gravitational wave source. [Image:A. Stuver/LIGO]**

The sound these gravitational waves would produce is a continuous static-like "noise" and will (likely) be statistically same from every part of the sky, like CMB

# Listening to Early Universe GWs

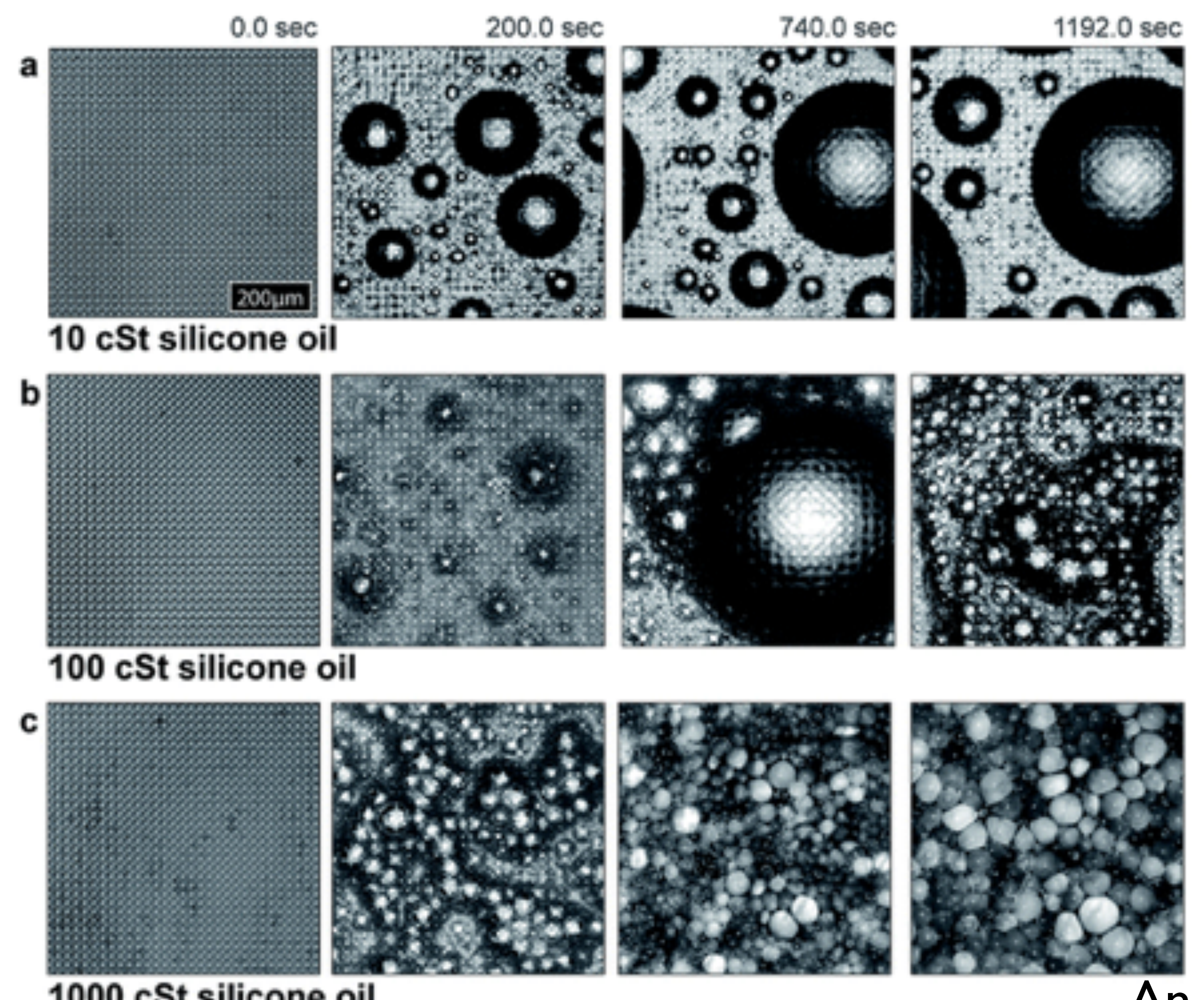
The detailed frequency spectrum of the "noise" carries all the information about the processes going on in the Early universe!

cf CMB case…



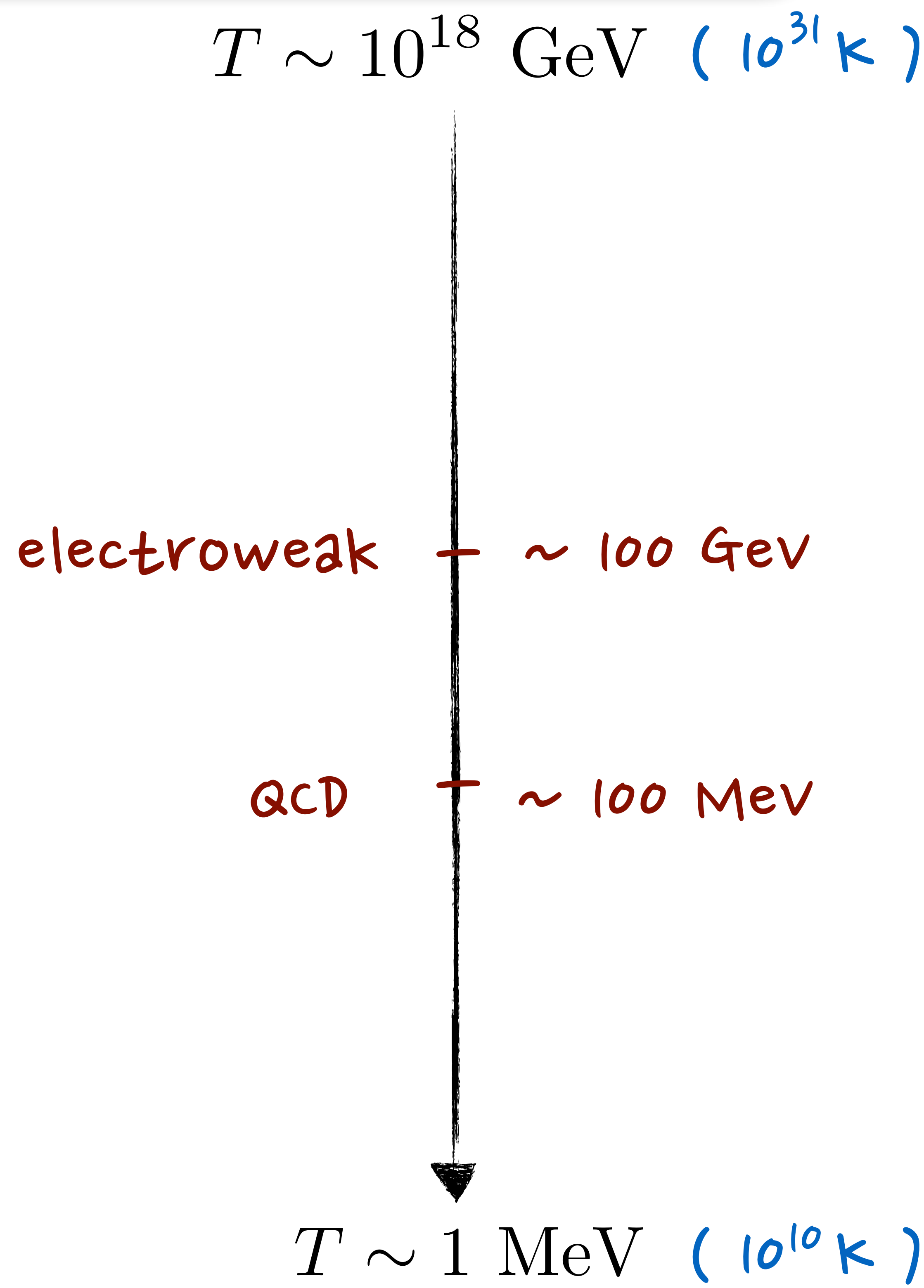
# Early Universe GW Sources

- To efficiently source GWs need *large mass densities moving relativistically* (and in non-spherically symmetric way)
- A very interesting possibility is the relativistic collision of the "walls" separating regions of two different phases (think water boiling, or better supercooled vapour condensing)



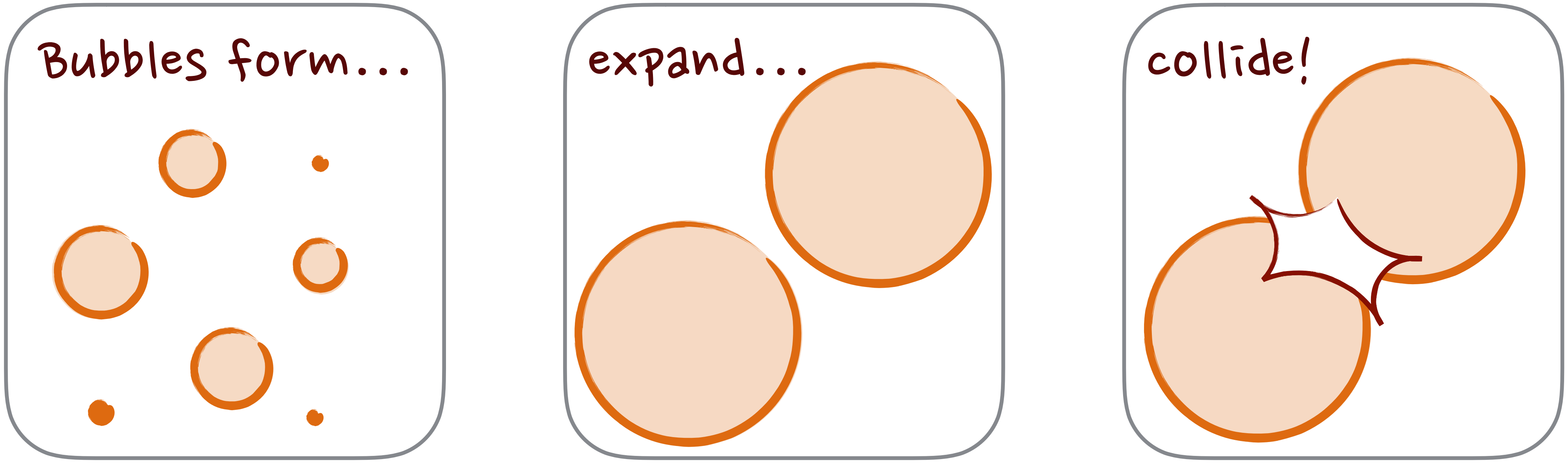

Anand etal

# Early Universe Phase Transitions




- In the Early Universe the visible sector was at very high temperatures
- As the temperature dropped, phase transitions took place
- *If some of these phase transitions were first order, bubble collisions would produce a stochastic GW background*

# 1st order Phase Transition



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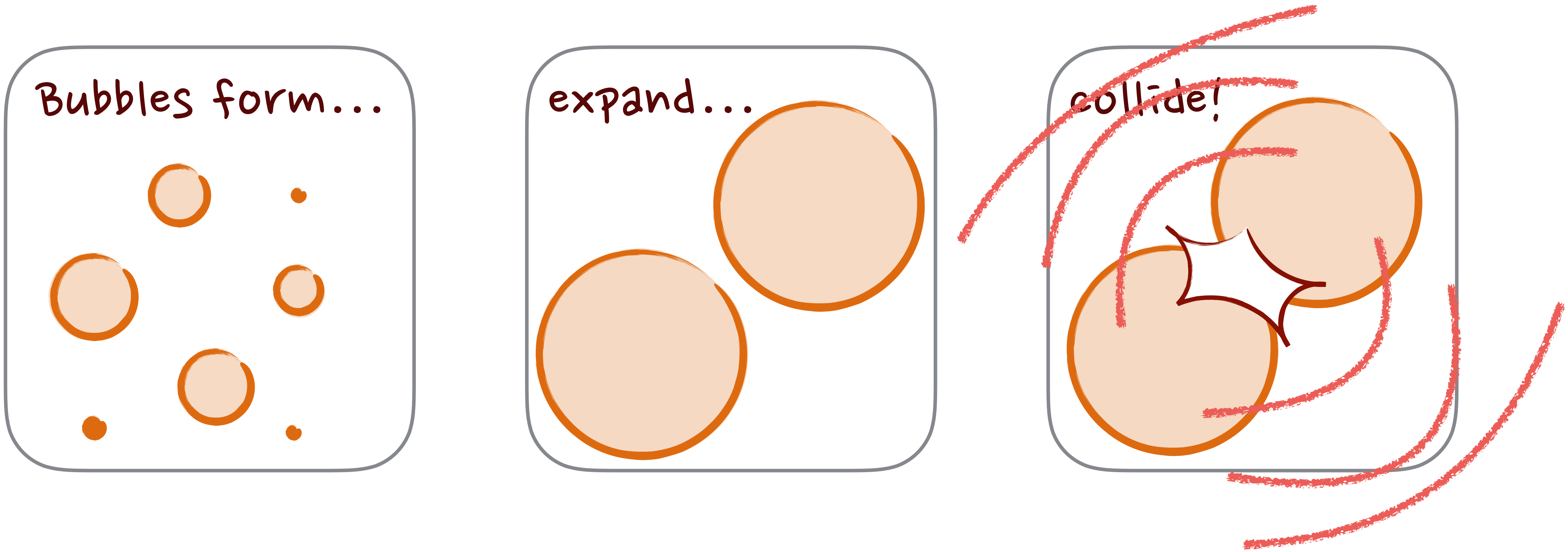
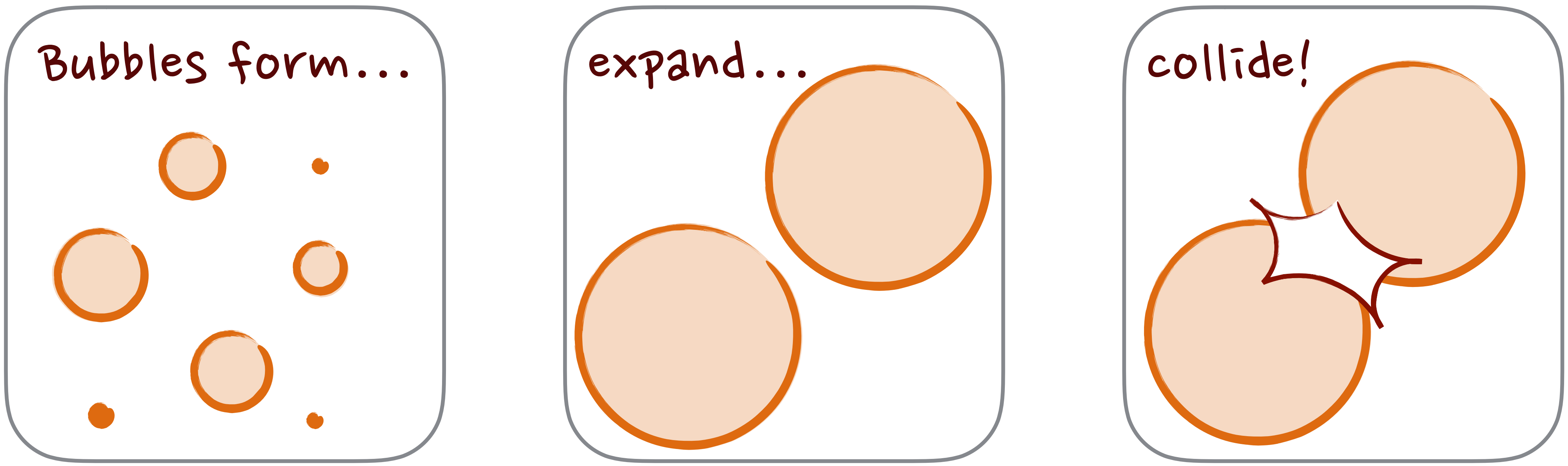



and radiate GWs that we could observe today

# 1st order Phase Transition



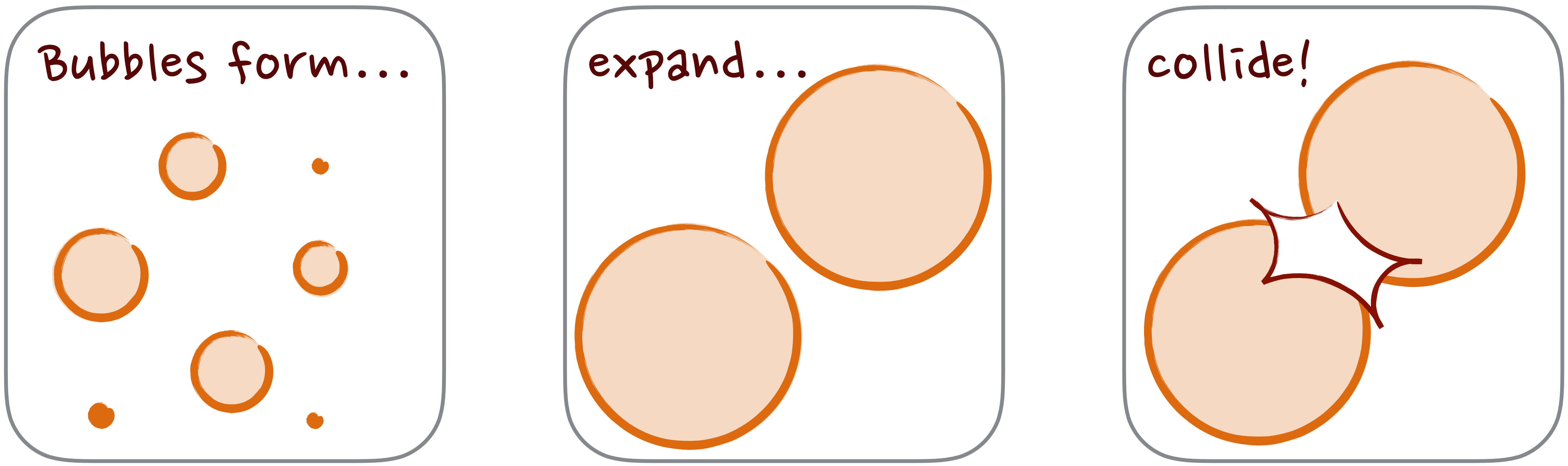

- 1st order electroweak phase transition *could* provide the necessary out of equilibrium dynamics required for Baryogenesis

  very well motivated, but NOT true if SM is all there is...

- Stochastic GW background with peak frequency ~ 1 mHz

  perfect for LISA to detect

# 1st order Phase Transition

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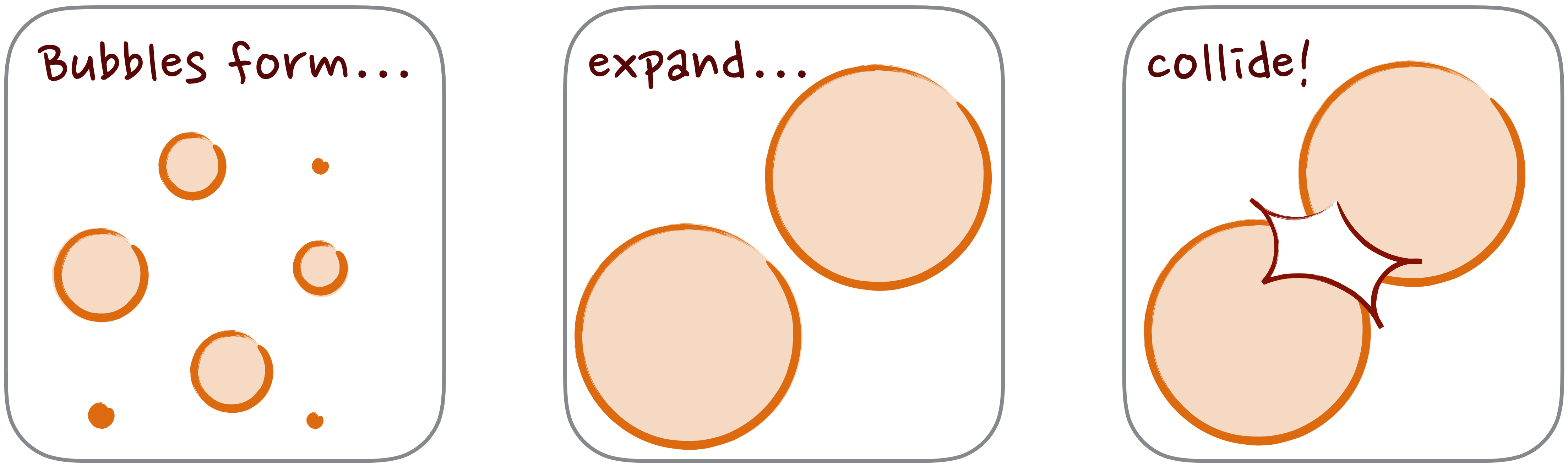


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so must look elsewhere....

# Hidden sectors

- *Hidden sectors*: degrees of freedom beyond those of the SM that interact very weakly with the visible sector

  → Dark Matter

  → general feature of String Theory

- They may have never been in thermal equilibrium with us, and could be at a completely different temperature (and in our case *cold*)
- They could have rich structure and dynamics, and could undergo phase transitions/vacuum decay processes
- They may only interact with us gravitationally, so GW detectors may be our only chance to discover them!

# GWs from String Theory

- The existence of multiple vacua is a general prediction of String Theory — a "String Landscape"
- Some of this vacua are metastable — a decay to the true vacuum could take place in the Early Universe
- A stochastic GW background from a process of vacuum decay in the context of String Theory could be within observable reach

Isabel Garcia Garcia, Sven Krippendorf, JM-R; arXiv:1607.06813

"The String Soundscape"

# Metastable String Vacua

Giddings, Kachru, Polchinski: hep-th/0105097
Kachru, Pearson, Verlinde: hep-th/0112197

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

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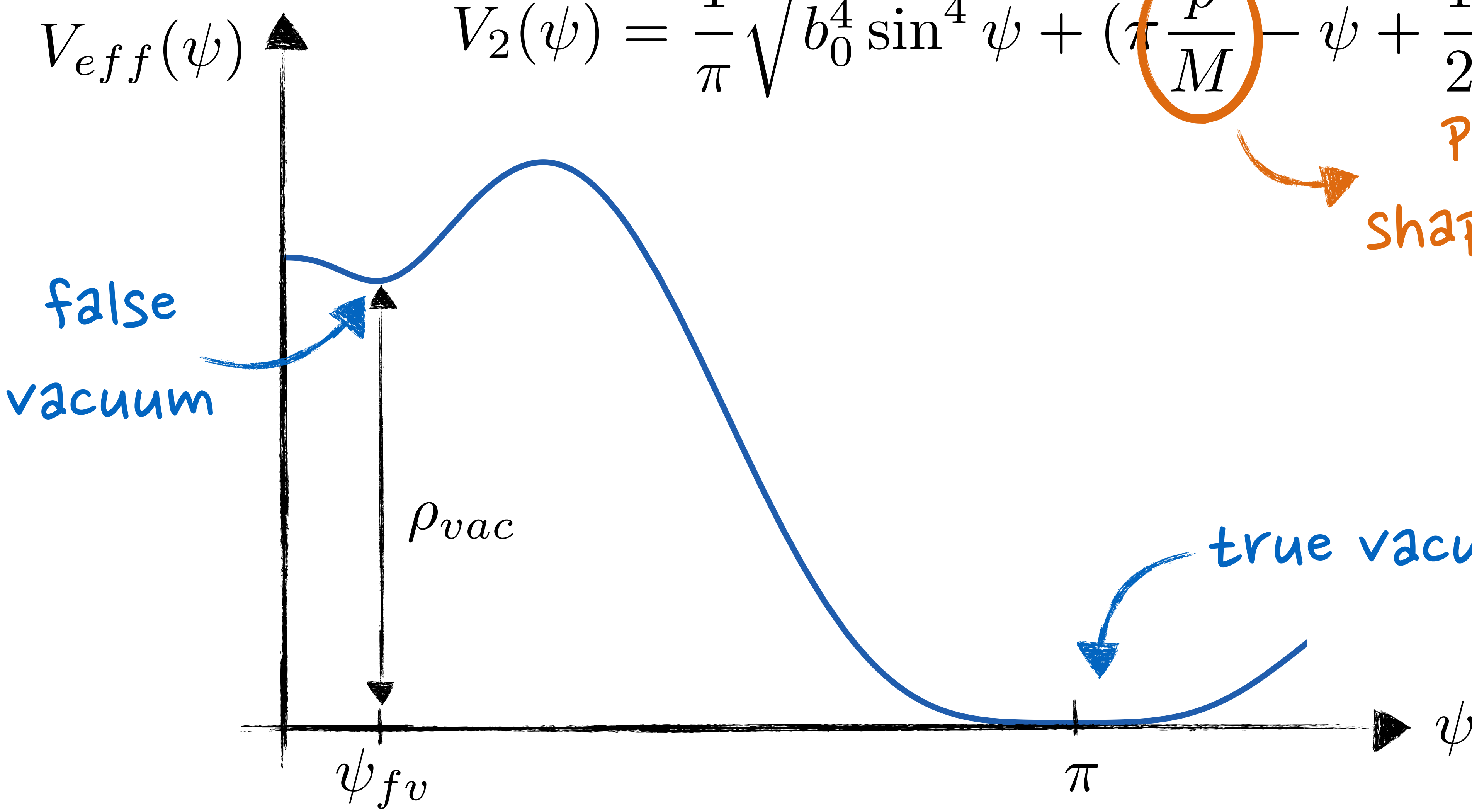

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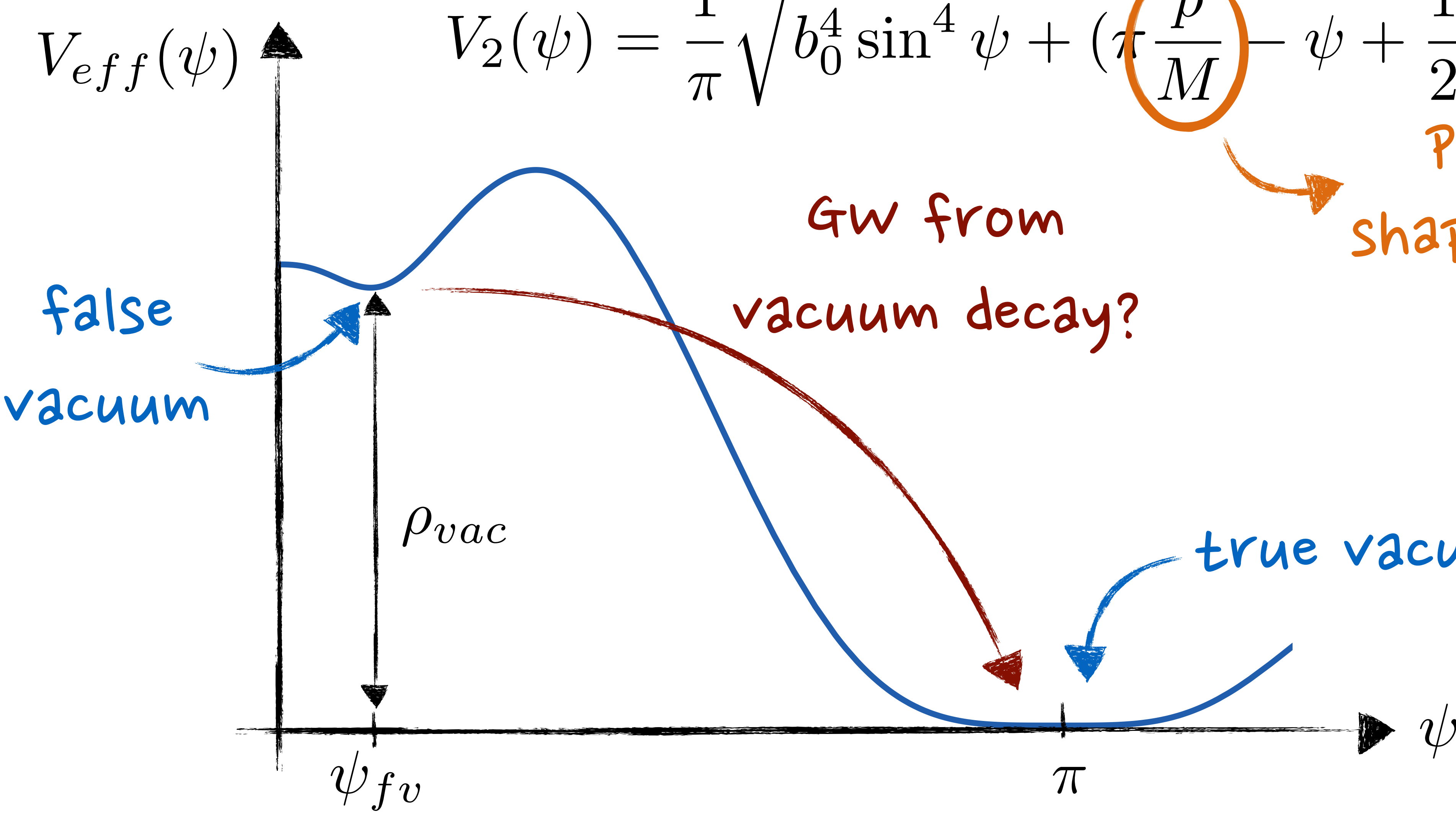
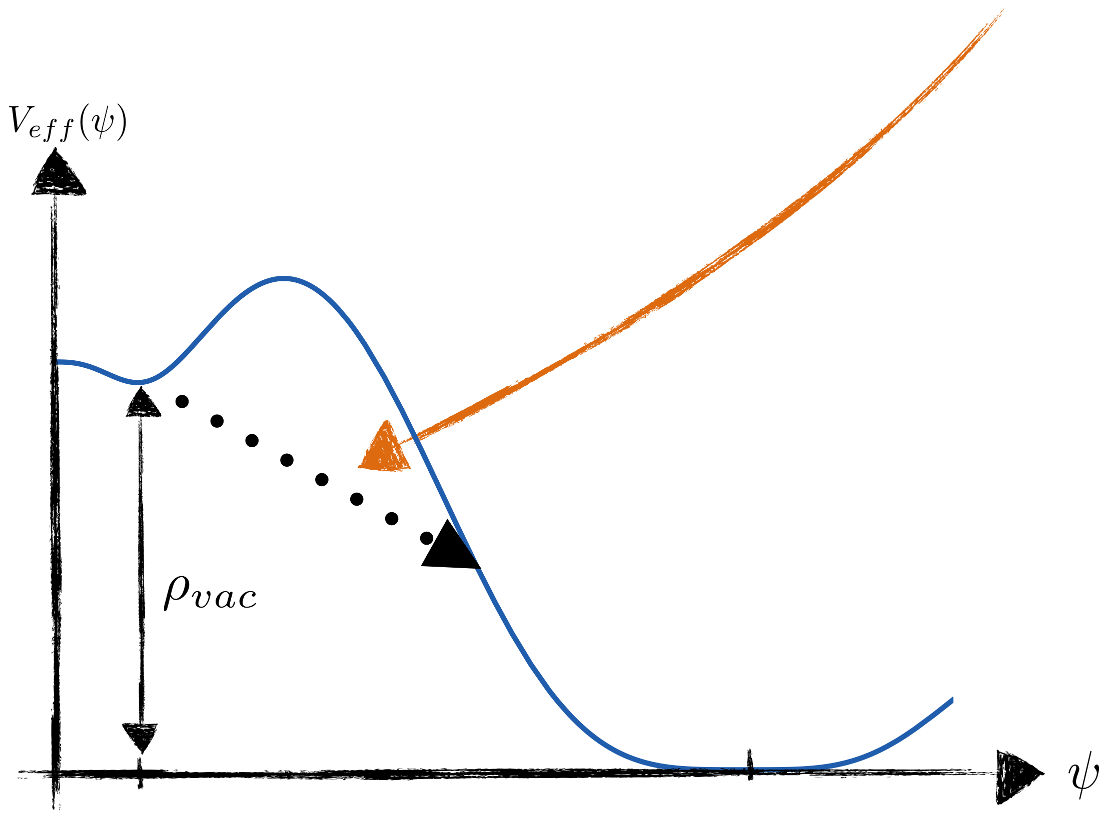
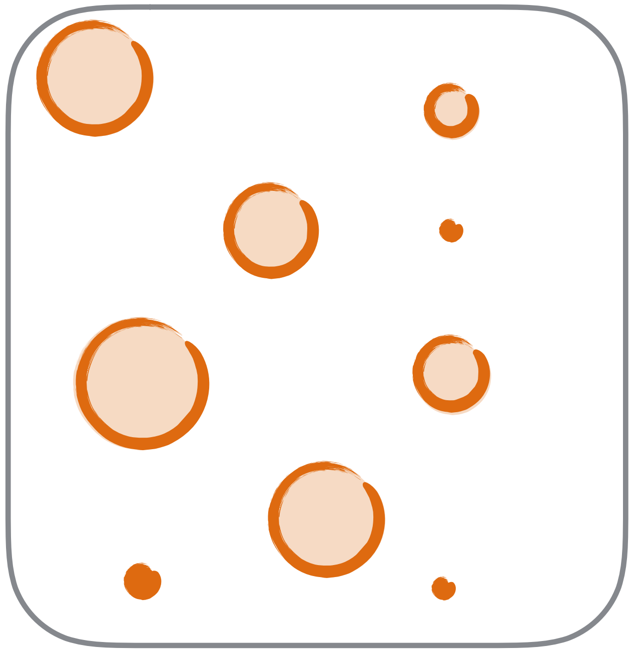


# GWs from String Theory

In our case the transition is *dominantly a quantum tunnelling event*



Bubbles quantum nucleate and then expand ultra-relativistically and collide

# GWs from String Theory

Three important parameters describing transition are

$T_c$ - the visible sector (SM) temperature when transition occurs

$\alpha_c \equiv \frac{\rho_{vac}}{\rho_{rad}(T_c)}$ - ratio of liberated vacuum energy to SM thermal energy

$t_*$ - the duration of the transition

In terms of these the characteristic properties of transition can be computed…

GW energy

$$\Omega_{GW,\text{peak}} \sim 10^{-6} \left( \frac{\alpha_c}{1+\alpha_c} \right)^2 (t_* H(T_c))^2$$

Peak frequency

$$f_{GW,\text{peak}} \sim 10^{-5}\text{Hz} \left( \frac{T_c}{100\text{GeV}} \right) \frac{1}{t_* H(T_c)}$$

# Quantum vs Thermal

## Quantum tunnelling

- Bubble walls reach ultra-relativistic limit:

$$v \approx 1 \qquad (\gamma \gg 1)$$

- Duration of transition is *long*

$$t_* \sim H(T_c)^{-1}$$

- Main source of GW is bubble wall collisions

## Thermal transition

- Thermal plasma (usually) prevents relativistic limit:

$$v \sim 0.01 - 0.1$$

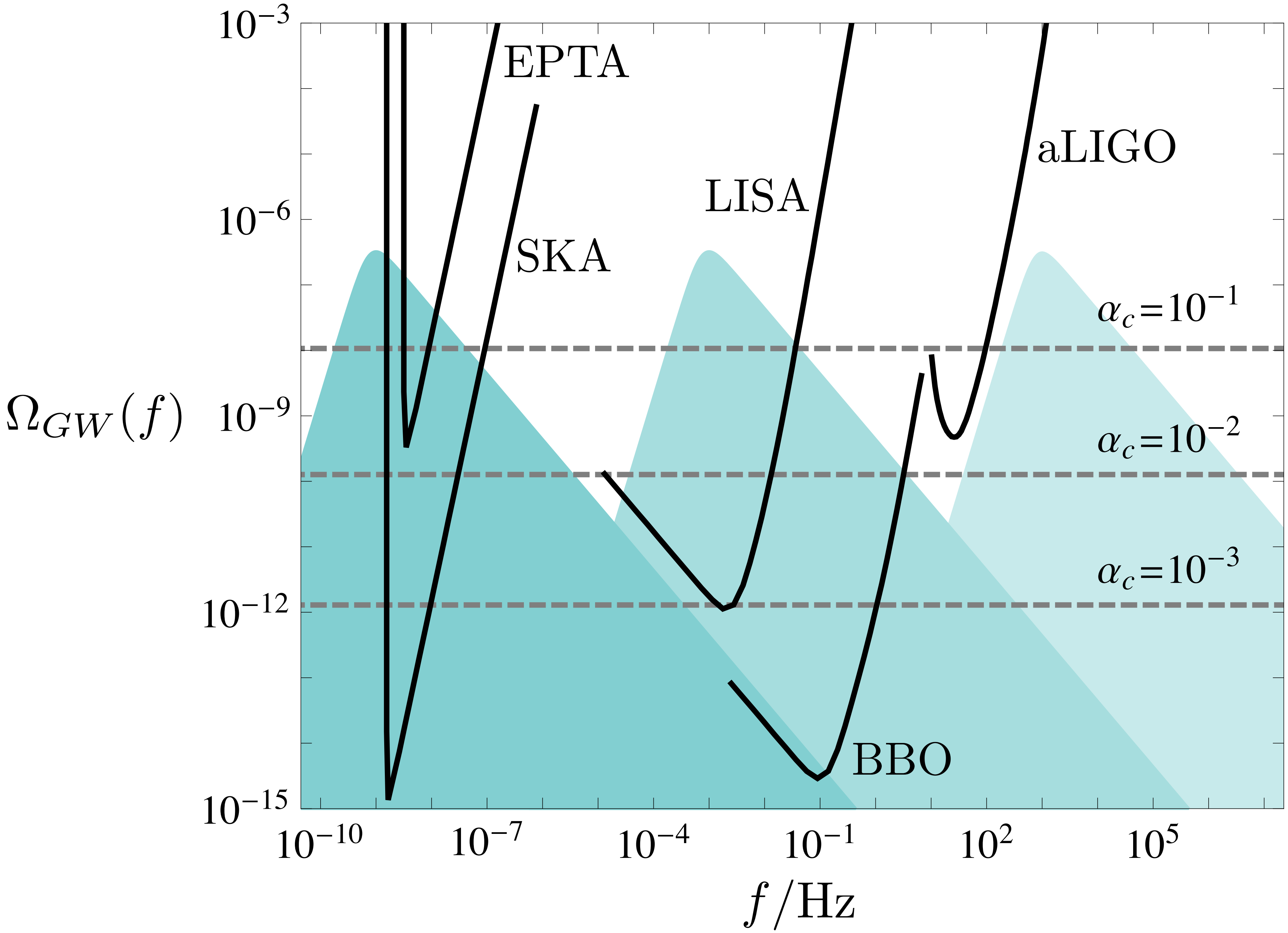
- Duration of transition is *short*

$$t_* \ll H(T_c)^{-1}$$

- Other sources of GW: e.g. turbulence in plasma

see e.g. Caprini *et al.* arXiv:1512.06239

# GW Signal-Strength




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

( from Isabel Garcia Garcia, Sven Krippendorf, JM-R; arXiv:1607.06813)

# Future Work

- Thermal vs quantum transitions lead to qualitatively different GW signals — new features not yet well understood in detail

- High-frequency part of GW signal from String Theory likely different from other "non-stringy" scenarios — again new features not yet well understood

- Fluctuations from sphericity on nucleated bubbles may be sizeable, in particular in non-thermal cases

GWs could be emitted as bubbles expand too!

Primordial Black Holes could be formed in wall collisions!

# Conclusions

Gravitational waves provide a unique and exceptionally exciting probe of the very Early universe (and of very high energy physics)!

The many upcoming GW observatories (operating over a $10^{12}$ frequency range) will make great discoveries!