

THEORETICAL PHYSICS SYMPOSIUM 2024

PROBING EARLY UNIVERSE USING GRAVITATIONAL WAVES

BOGUMIŁA ŚWIEŻEWSKA
UNIVERSITY OF WARSAW

Based on work in collaboration with:

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phase
transitions

relativistic fluid
dynamics

data
analysis

cold atoms

thermal
field theory

EFT
fundamental
interactions

gravitational
waves

COSMO UW

NICHOLAS
ORLOFSKY

DANIELE
PERRI

MAXIM
LALETIN

PIOTR
TOCZEK

PAULINA
MICHALAK

MACIEJ
KIERKLA



IGNACY
NAŁĘCZ



MARCIN BADZIAK

MICHAŁ
ŁUKAWSKI

ADAM
GOMUŁKA

KRZYSZTOF
SZAFRĄNSKI

MAREK LEWICKI

ADAM
GONSTAL

BOGUMIŁA ŚWIEŻEWSKA

MATEUSZ
KULEJEWSKI

JUAN
CAMILO
GARNICA
AGUIRRE



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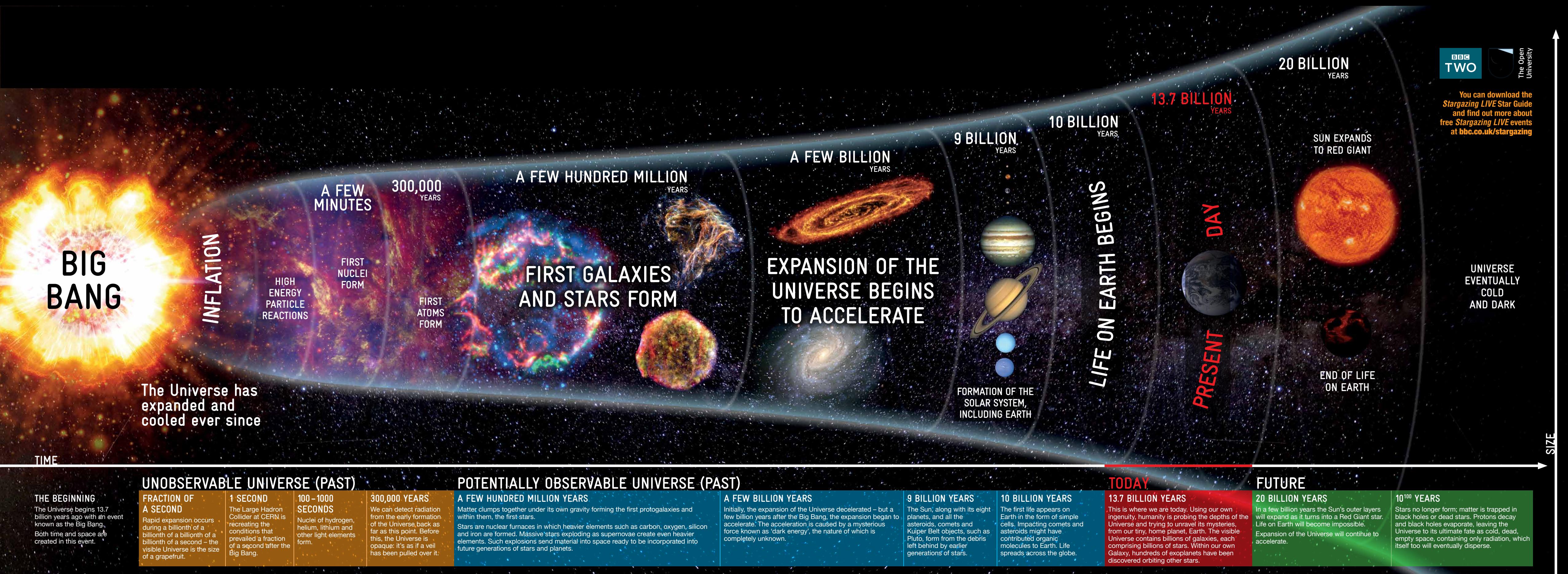
ADAM
GONSTAL

BOGUMIŁA ŚWIEŻEWSKA

MATEUSZ
KULEJEWSKI

JUAN
CAMILO
GARNICA
AGUIRRE

LOOKING BACK IN TIME



[Image source: BBC.CO.UK]



The Open University

You can download the *Stargazing LIVE* Star Guide and find out more about free *Stargazing LIVE* events at bbc.co.uk/stargazing

EM ASTRONOMY

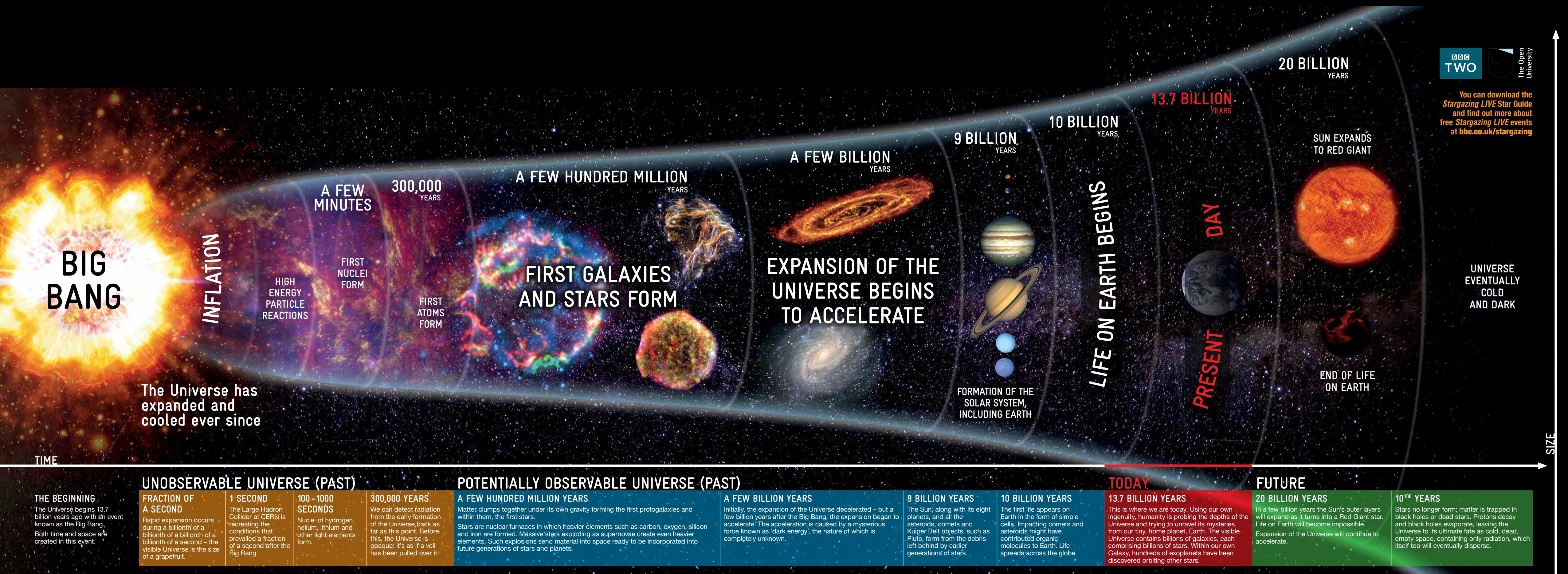


$z \sim 14.32 (+0.08/-0.20)$

born ~ 300 million years after the big bang

distance ~ 13.4 billion lightyears

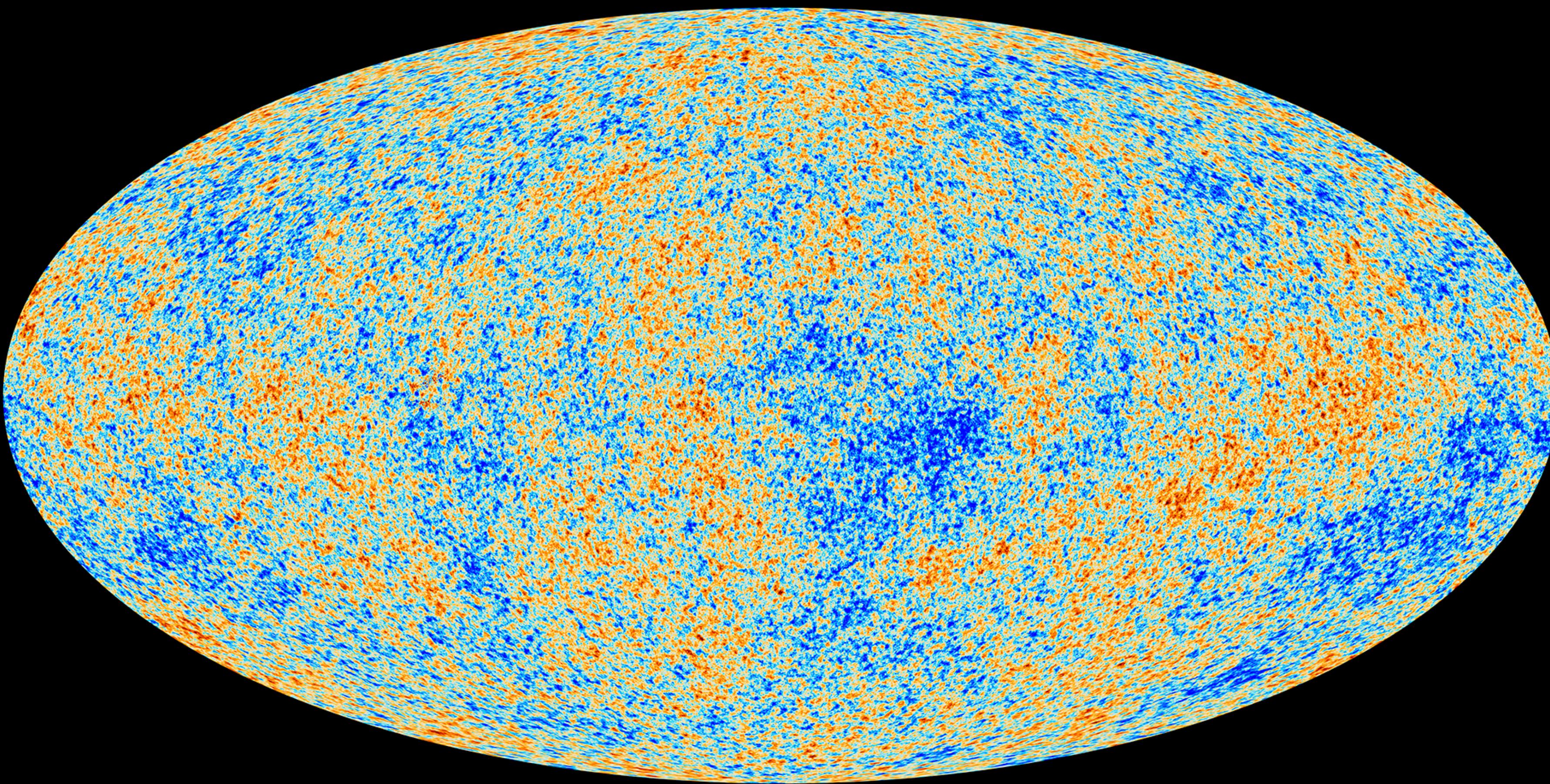
LOOKING BACK IN TIME



Stargazing LIVE is a BBC and Open University co-production. Credit: Photography sourced from NASA.

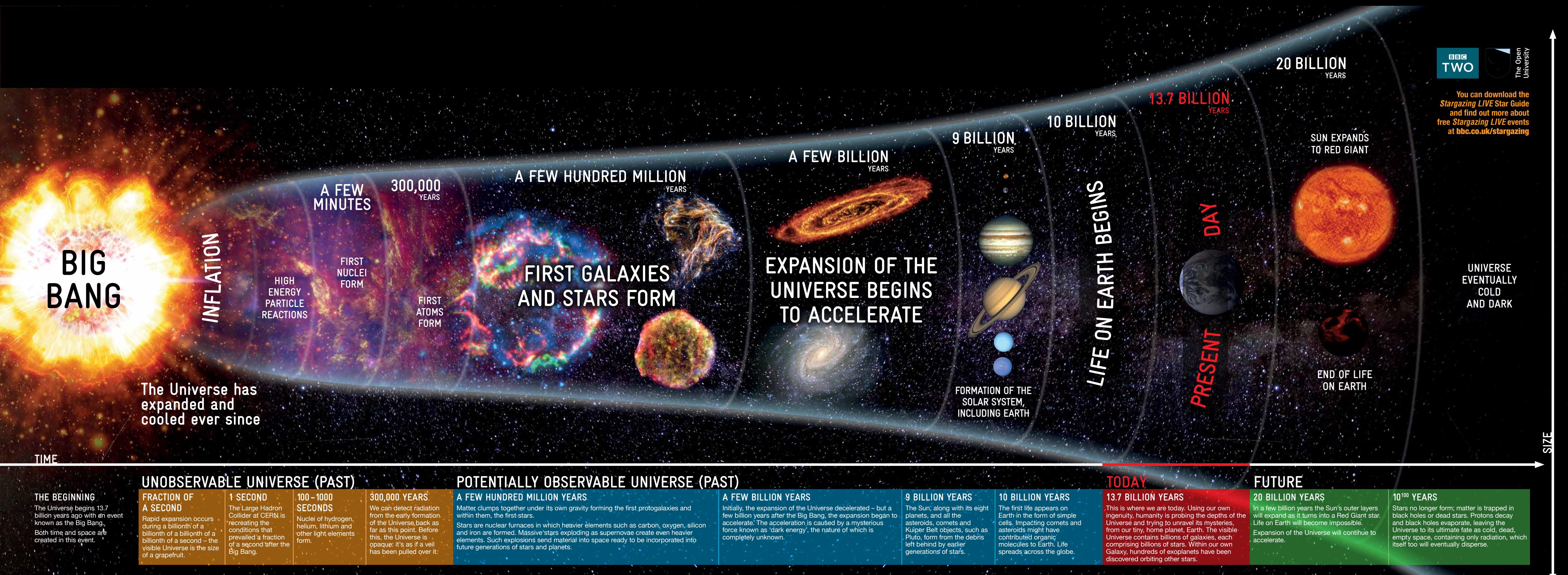
[Image source: BBC.CO.UK]

COSMIC MICROWAVE BACKGROUND



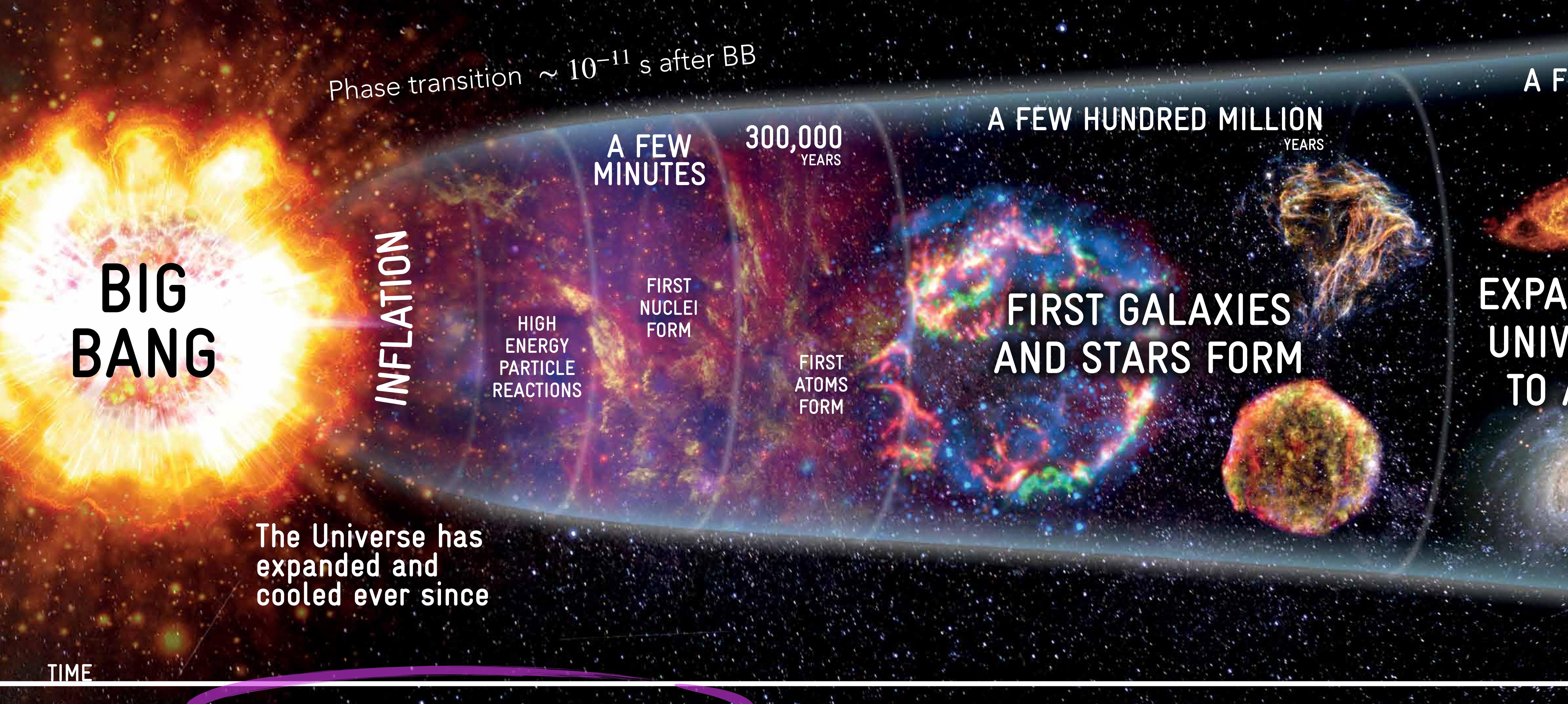
$$T = 2.7255 \pm 0.0003 \text{ K}$$

LOOKING BACK IN TIME



The Open University

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TIME

UNOBSERVABLE UNIVERSE (PAST)

THE BEGINNING

The Universe begins 13.7 billion years ago with an event known as the Big Bang. Both time and space are created in this event.

FRACTION OF A SECOND

Rapid expansion occurs during a billionth of a billionth of a billionth of a billionth of a second – the visible Universe is the size of a grapefruit.

1 SECOND

The Large Hadron Collider at CERN is recreating the conditions that prevailed a fraction of a second after the Big Bang.

100–1000 SECONDS

Nuclei of hydrogen, helium, lithium and other light elements form.

300,000 YEARS

We can detect radiation from the early formation of the Universe back as far as this point. Before this, the Universe is opaque: it's as if a veil has been pulled over it.

POTENTIALLY OBSERVABLE UNIVERSE (PAST)

A FEW HUNDRED MILLION YEARS

Matter clumps together under its own gravity forming the first protogalaxies and within them, the first stars. Stars are nuclear furnaces in which heavier elements such as carbon, oxygen, silicon and iron are formed. Massive stars exploding as supernovae create even heavier elements. Such explosions send material into space ready to be incorporated into future generations of stars and planets.

A FEW BILLION YEARS

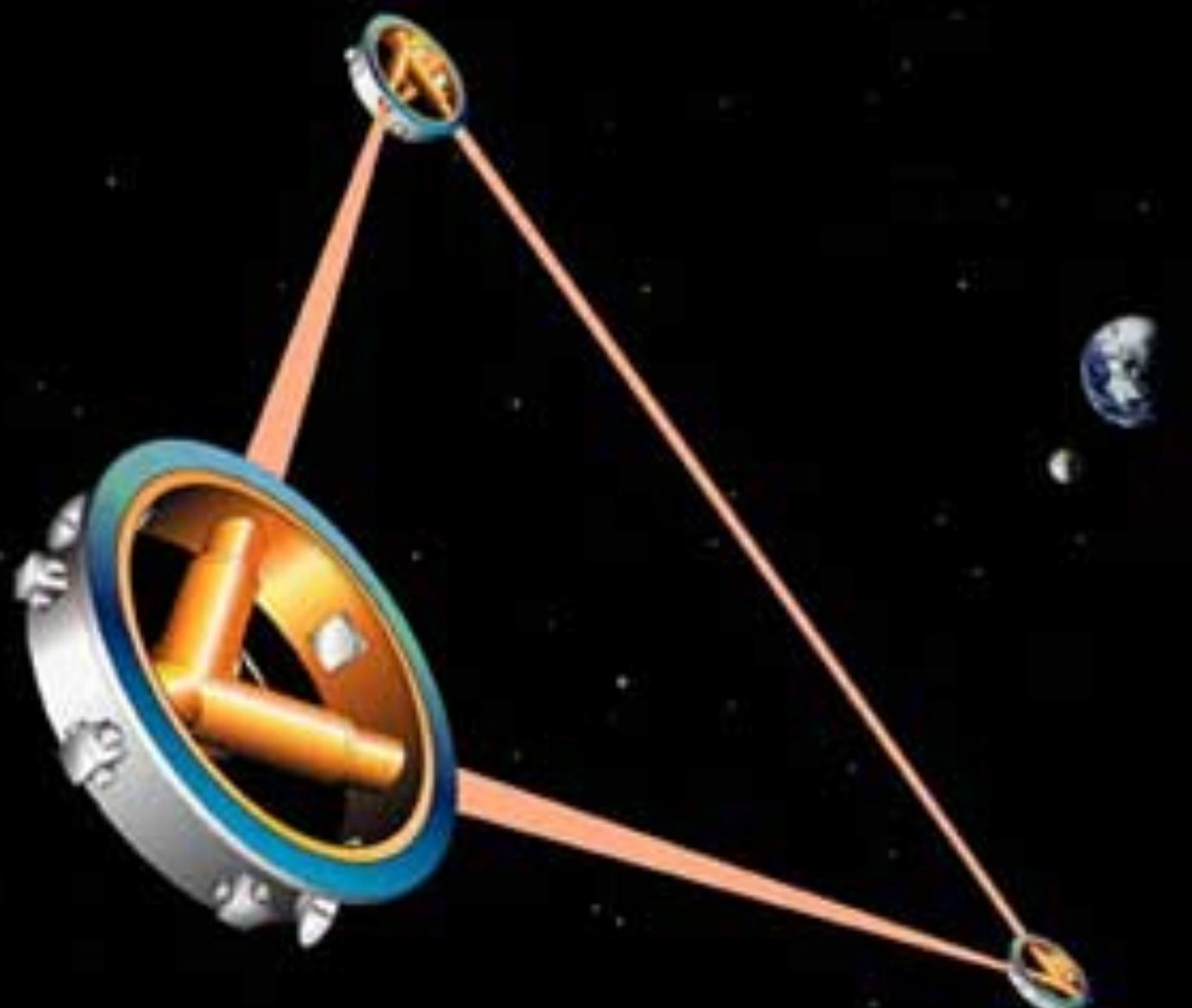
Initially, the expansion of the Universe accelerates. The acceleration is a force known as 'dark energy', completely unknown.

LISA

LASER INTERFEROMETER SPACE ANTENNA

- Arm length: 2.5 mln km
- 50 mln km from the Earth (in Lagrange point)
- Launch ~ 2037?
- Sensitive to lower frequencies than terrestrial detectors

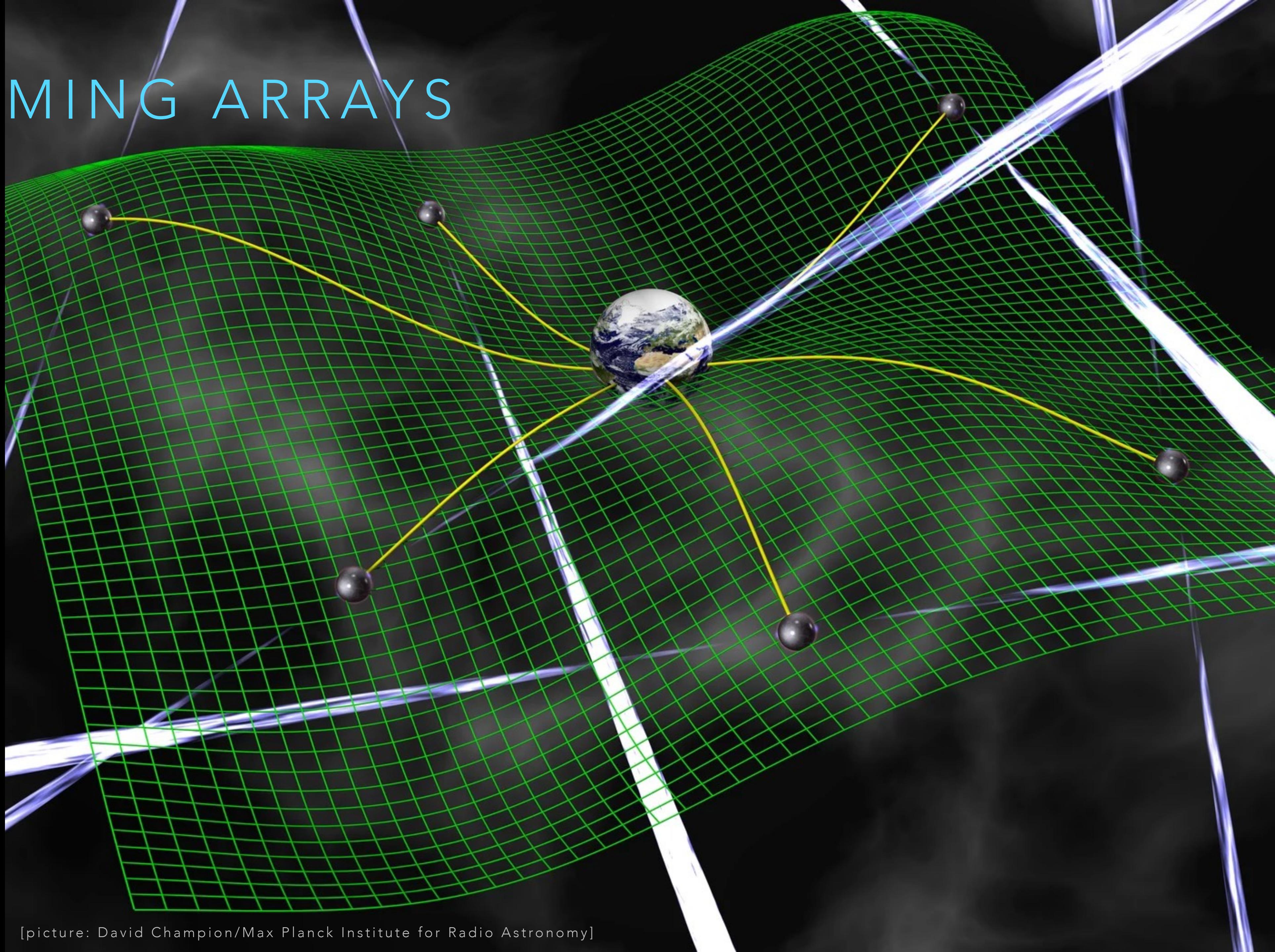
Will probe early-Universe sources!



PULSAR TIMING ARRAYS

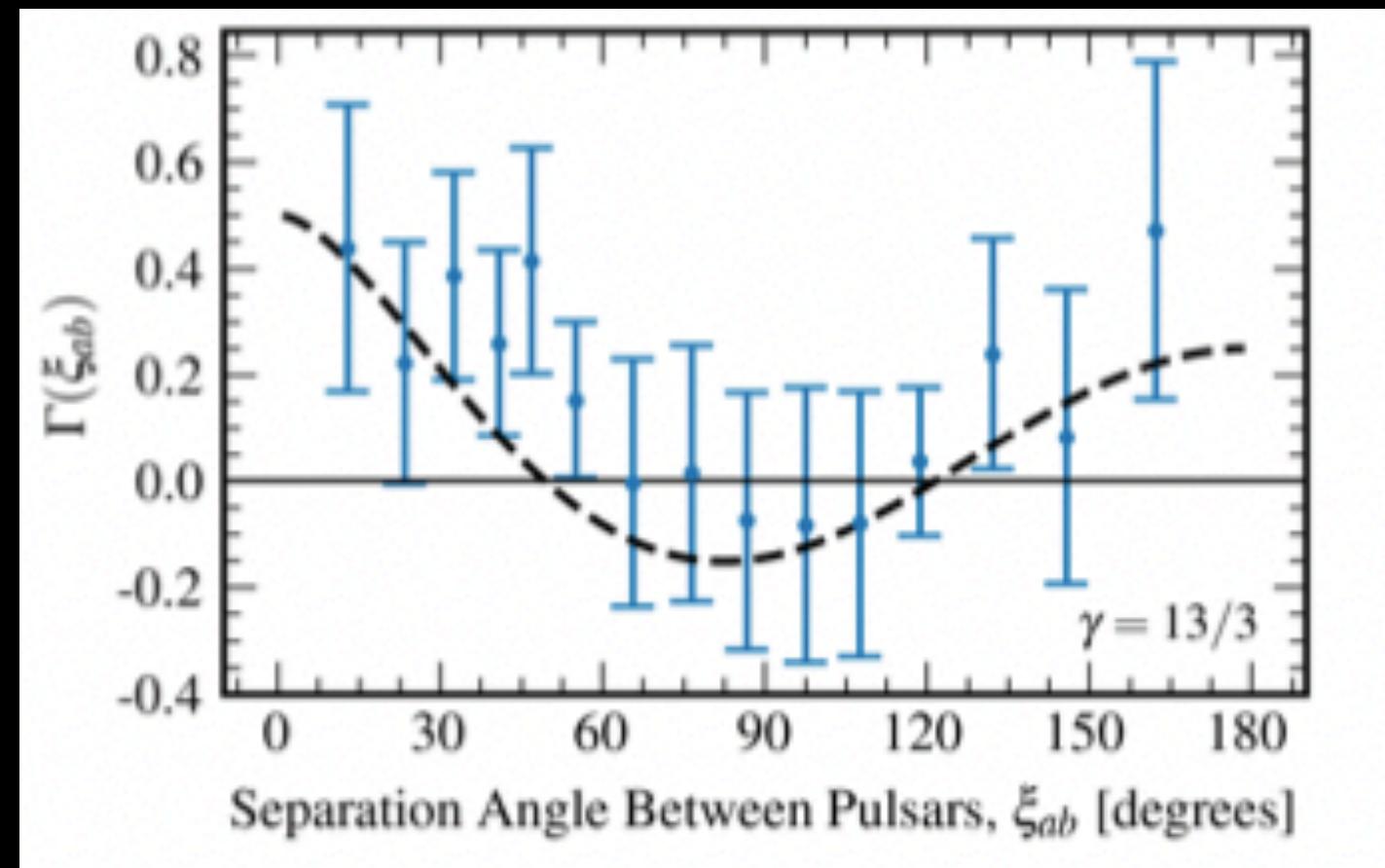
- Parkes Pulsar Timing Array
- European Pulsar Timing Array
- North American Nanohertz Observatory for Gravitational Waves
- Indian Pulsar Timing Array

In the future: SKA.



[picture: David Champion/Max Planck Institute for Radio Astronomy]

STOCHASTIC GW BACKGROUND

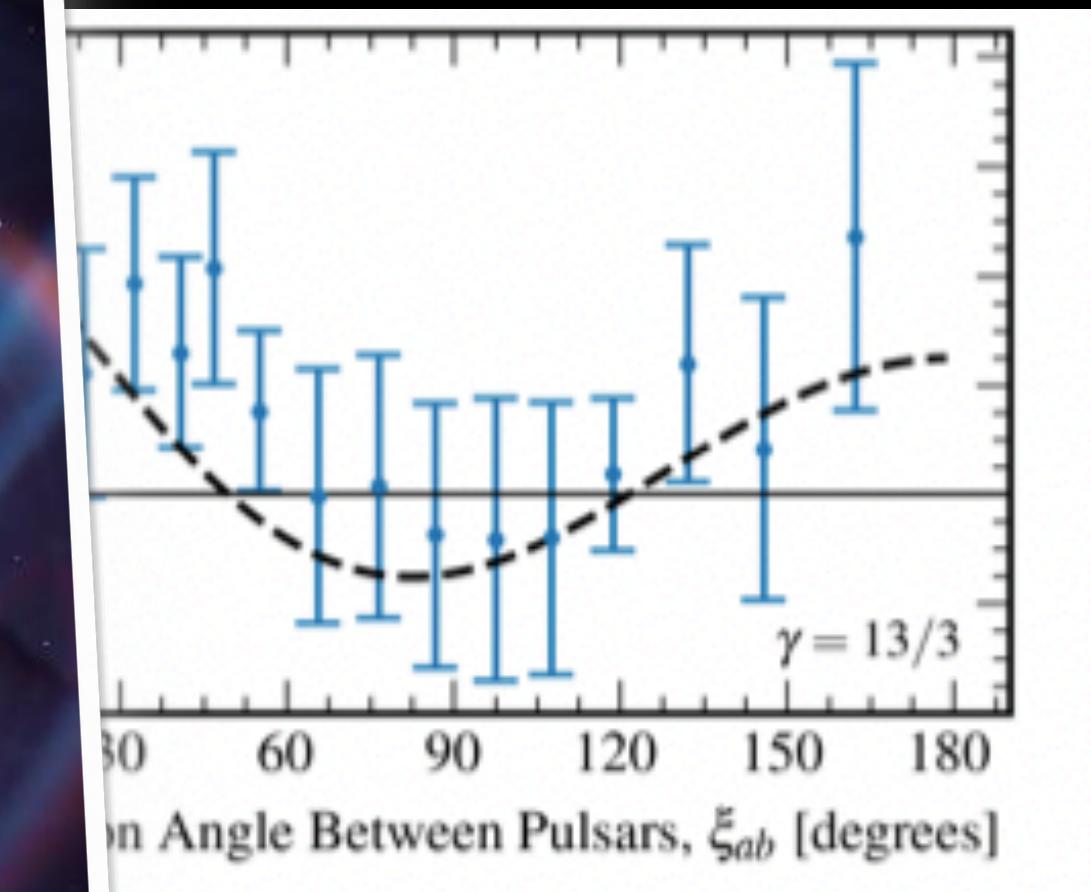


[G. Agazie et al. (NANOGrav Collaboration),
Astrophys. J. Lett. 951, L8 (2023), arXiv:2306.16213]

STOCHASTIC GW BACKGROUND

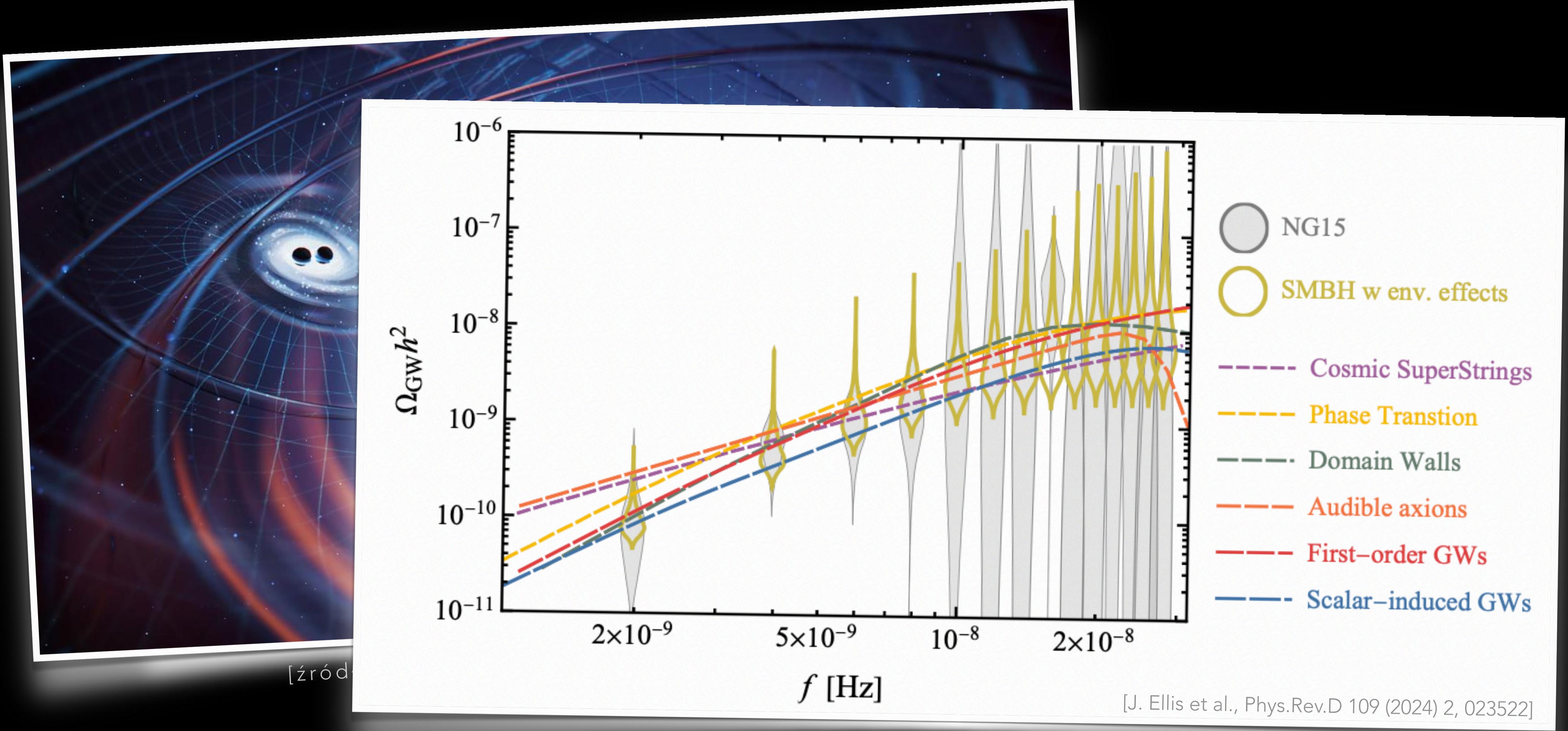


[źródło: nanograv.org, Olena Shmahało]



[et al. (NANOGrav Collaboration),
ApJL 951, L8 (2023), arXiv:2306.16213]

STOCHASTIC GW BACKGROUND



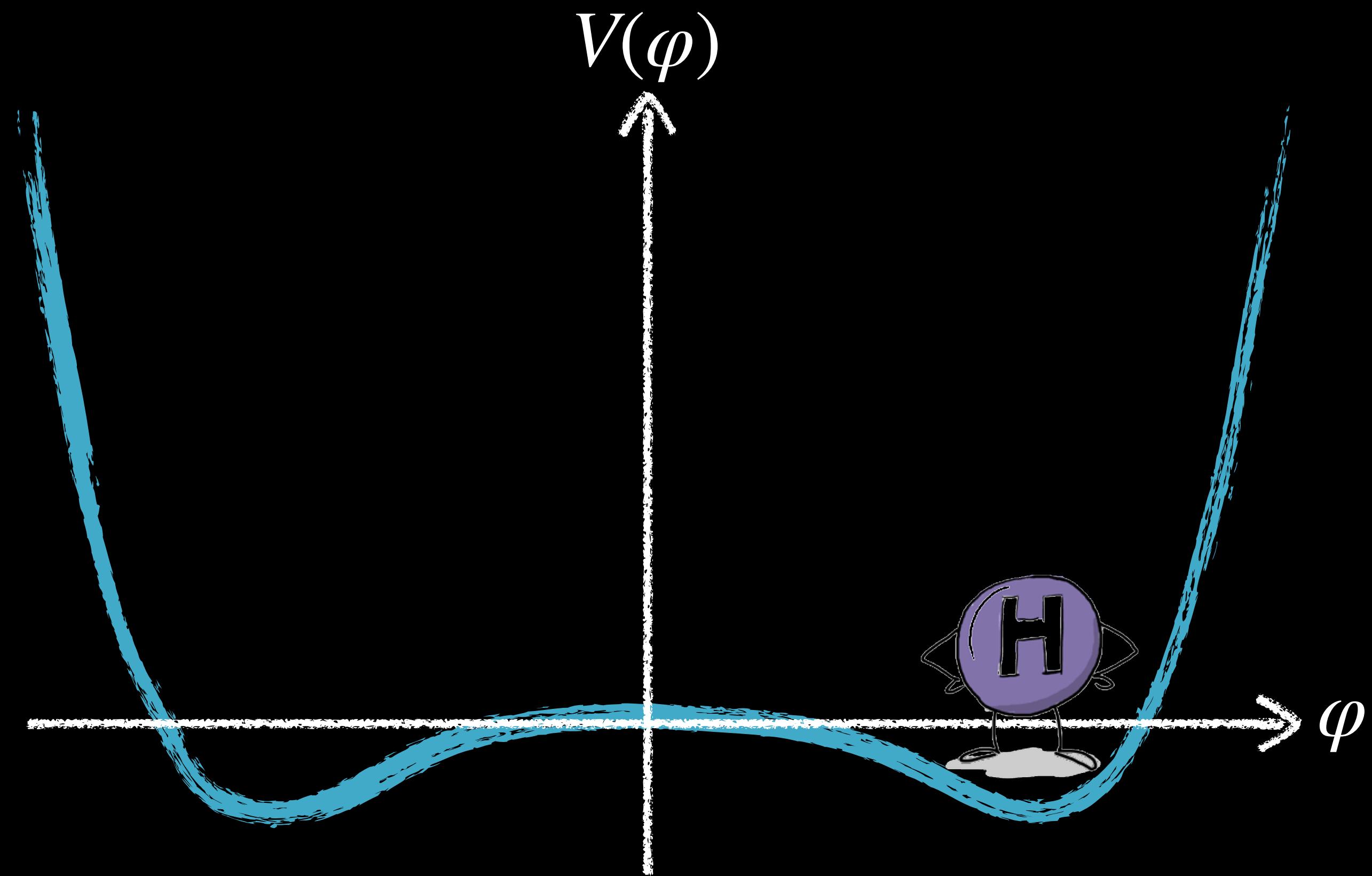
[źródło]

[J. Ellis et al., Phys.Rev.D 109 (2024) 2, 023522]

PHASE TRANSITION IN THE EARLY UNIVERSE

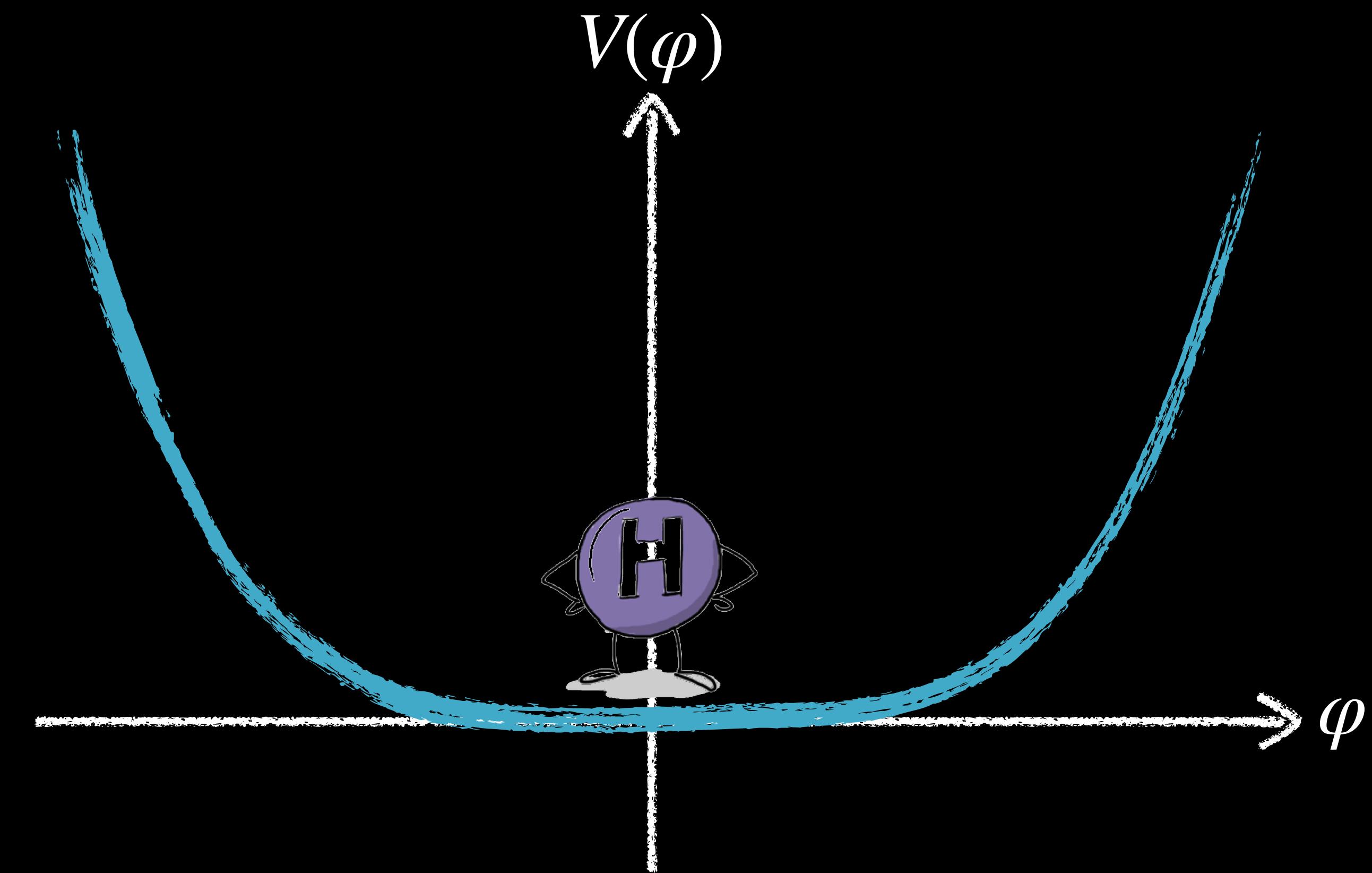


EXPERIMENT: HIGGS EXISTS

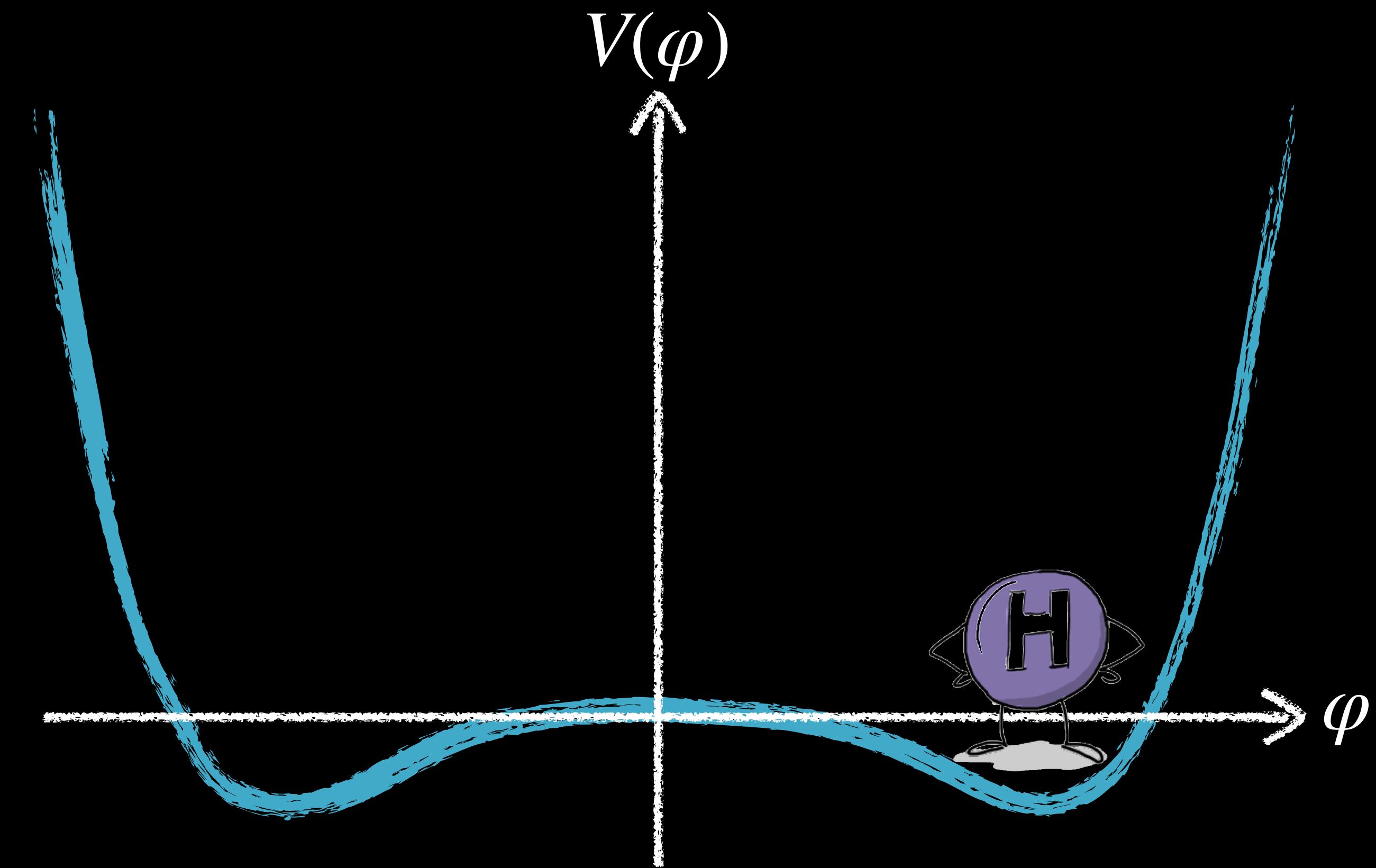


[Image from PhD Comics]

THEORY: SYMMETRY RESTORED AT HIGH T



PHASE TRANSITION HAPPENED!

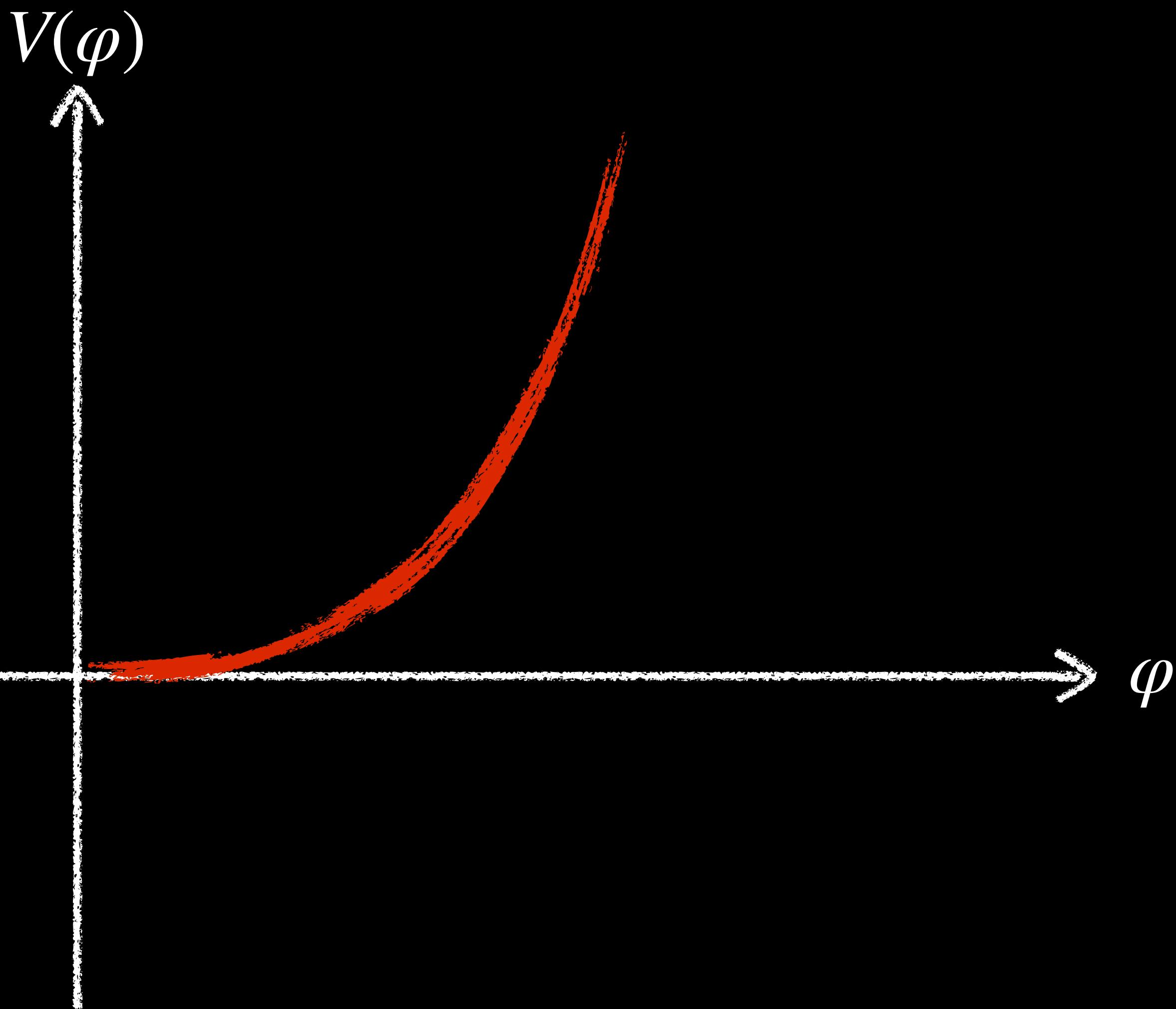


[Image from PhD Comics]

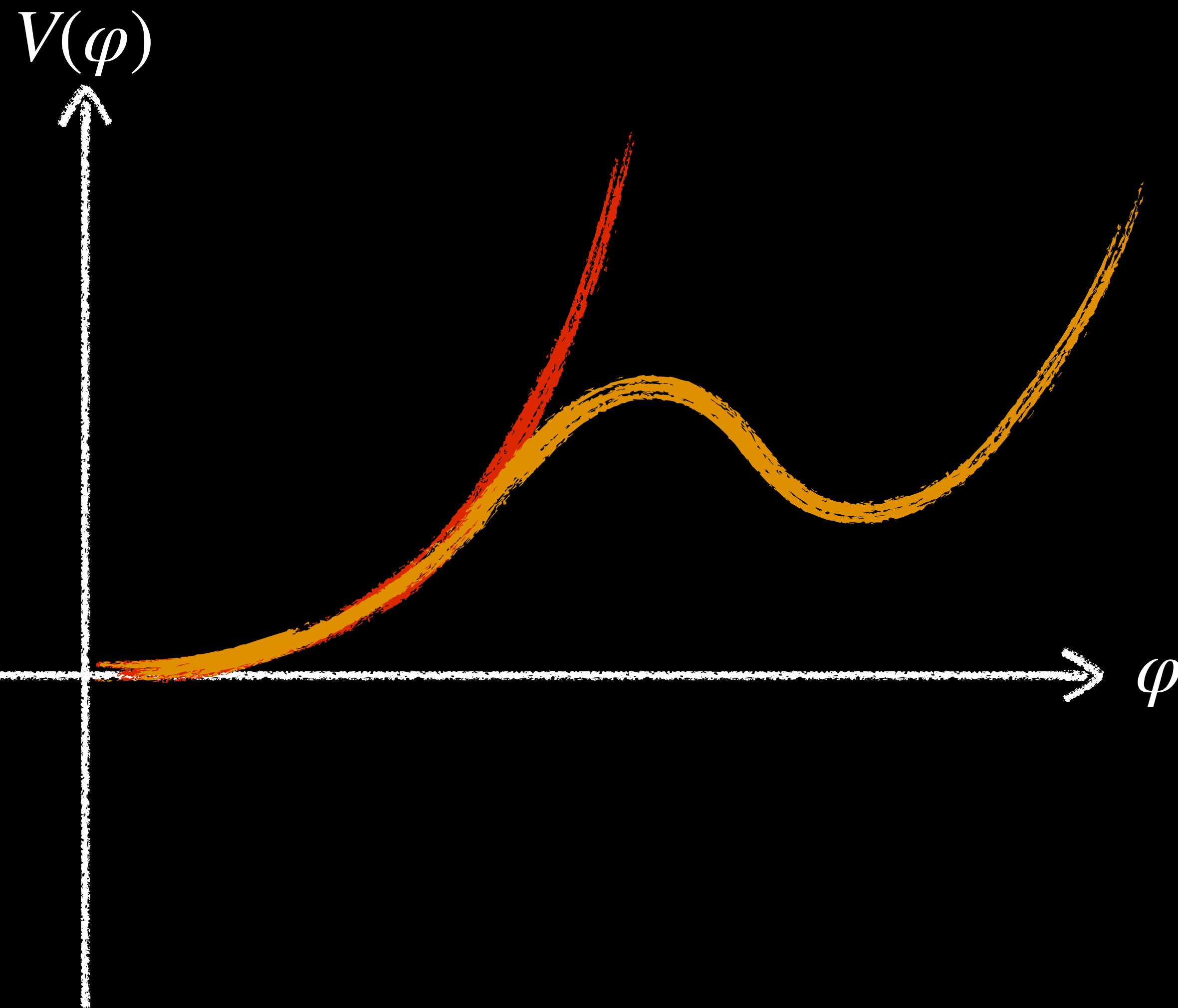
In the SM the PT is a crossover.

The search for a first-order PT is
a search for New Physics!

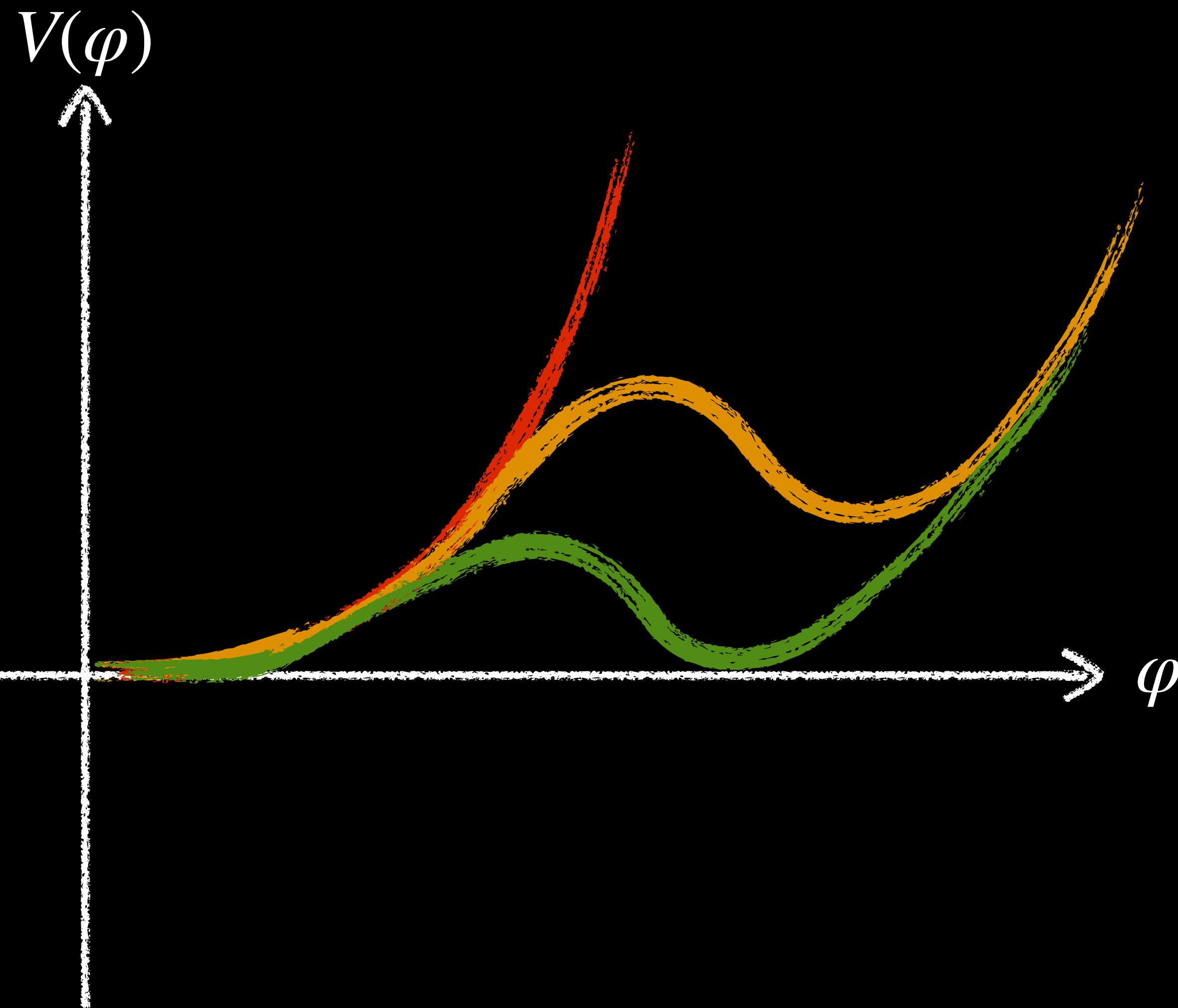
FIRST-ORDER PHASE TRANSITION



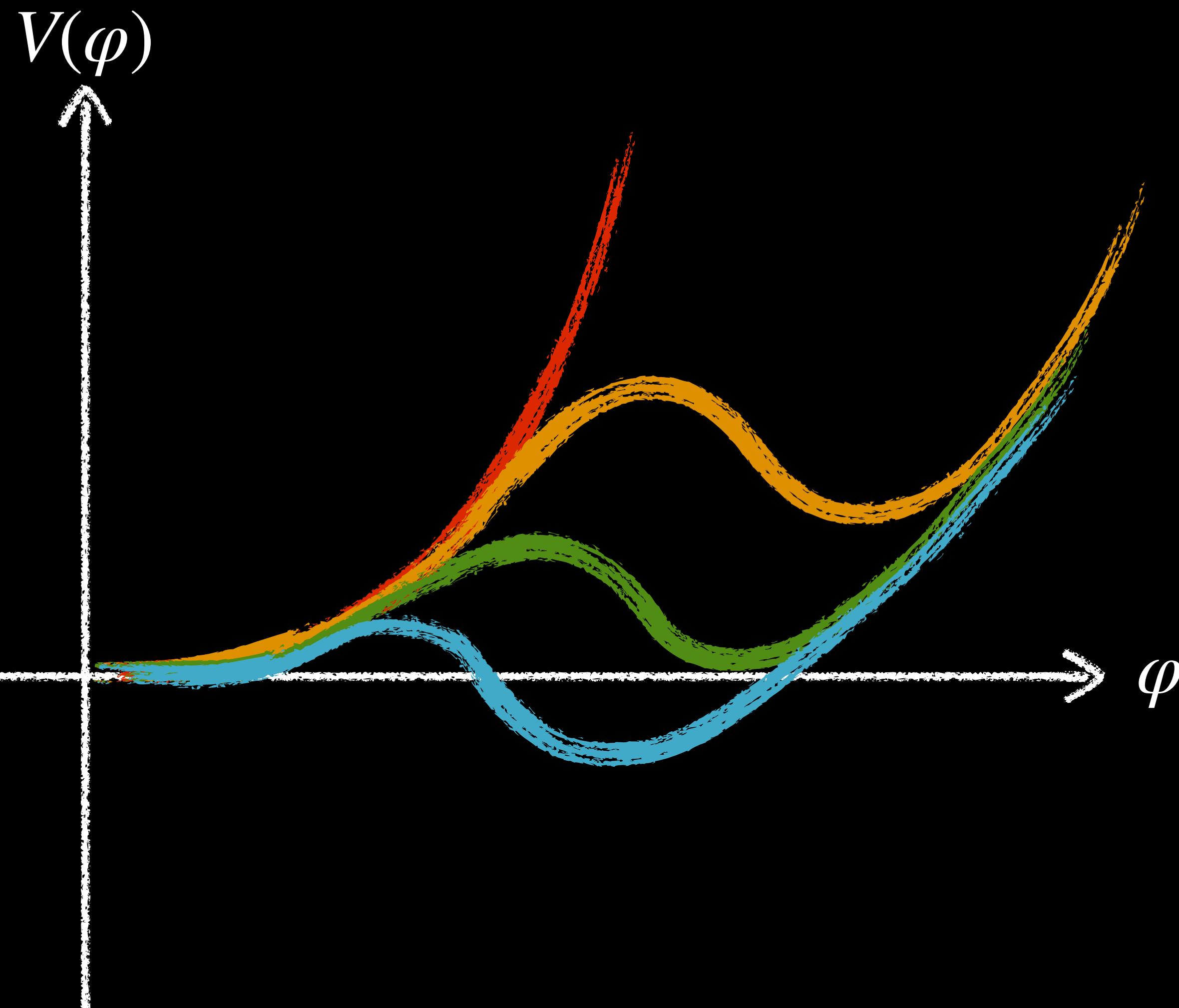
FIRST-ORDER PHASE TRANSITION



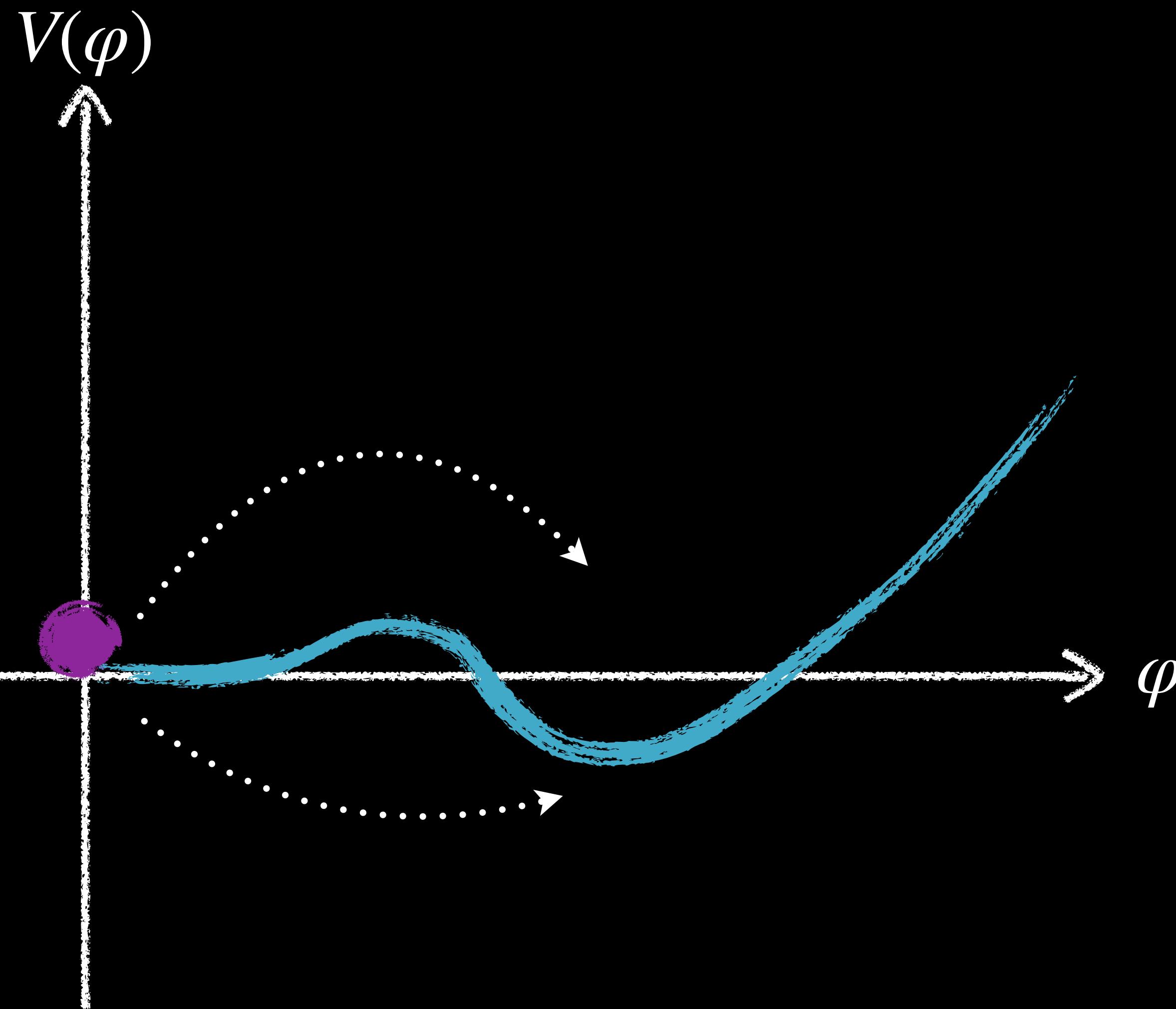
FIRST-ORDER PHASE TRANSITION



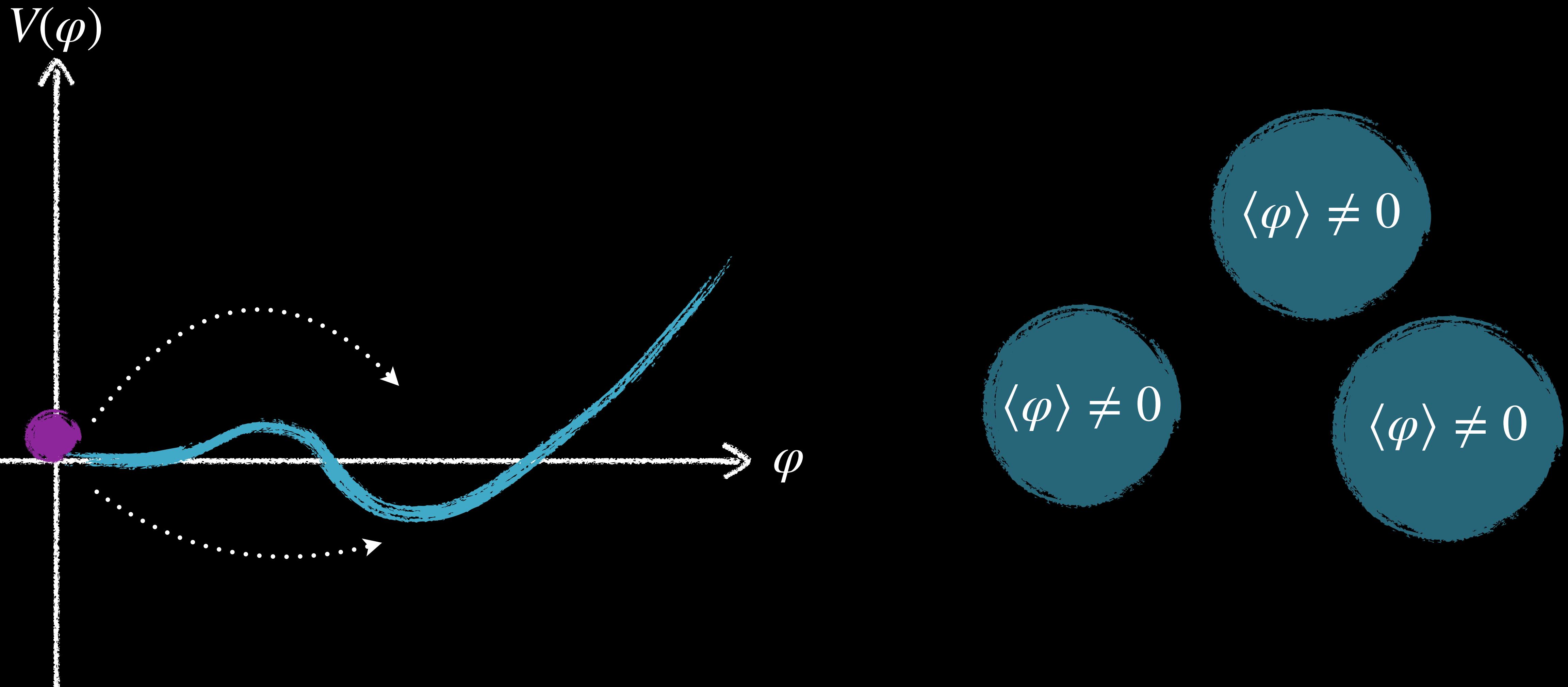
FIRST-ORDER PHASE TRANSITION



FIRST-ORDER PHASE TRANSITION



FIRST-ORDER PHASE TRANSITION



STOCHASTIC GRAVITATIONAL- WAVE BACKGROUND FROM FIRST-ORDER PHASE TRANSITIONS

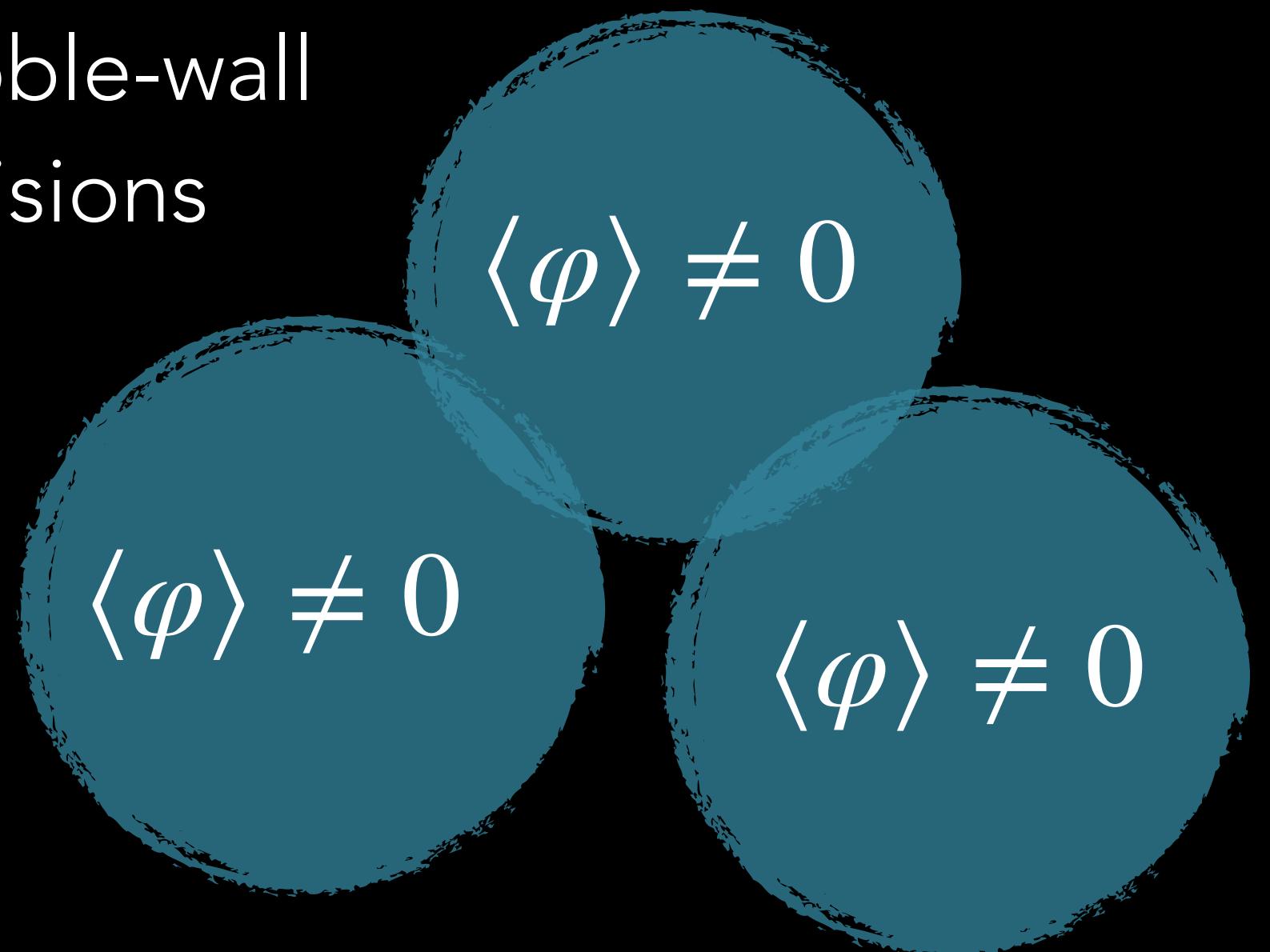


SOURCES OF GRAVITATIONAL WAVES

$$\langle \varphi \rangle \neq 0$$

SOURCES OF GRAVITATIONAL WAVES

bubble-wall
collisions



SOURCES OF GRAVITATIONAL WAVES

bubble-wall
collisions

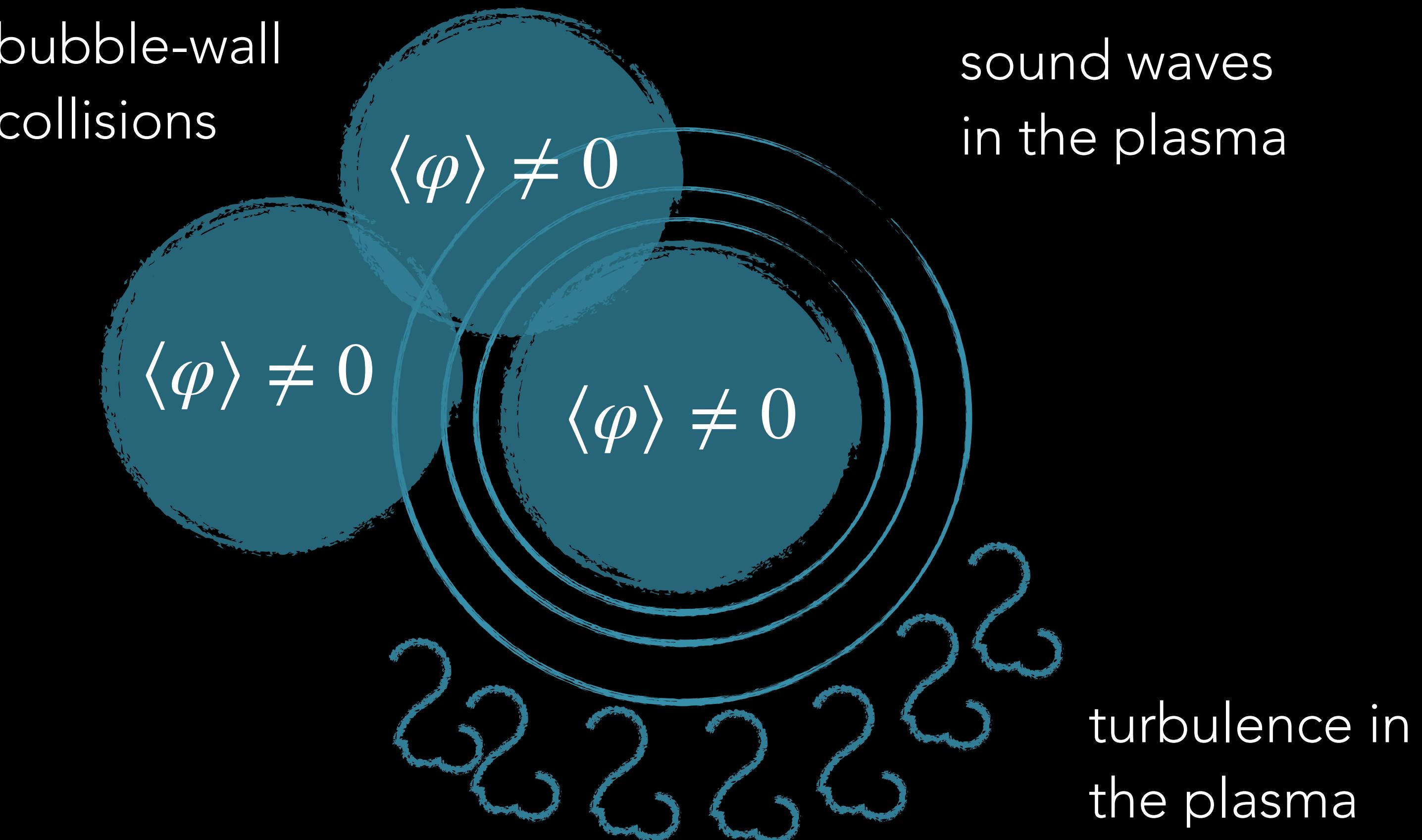
$$\langle \varphi \rangle \neq 0$$

$$\langle \varphi \rangle \neq 0$$

$$\langle \varphi \rangle \neq 0$$

sound waves
in the plasma

SOURCES OF GRAVITATIONAL WAVES



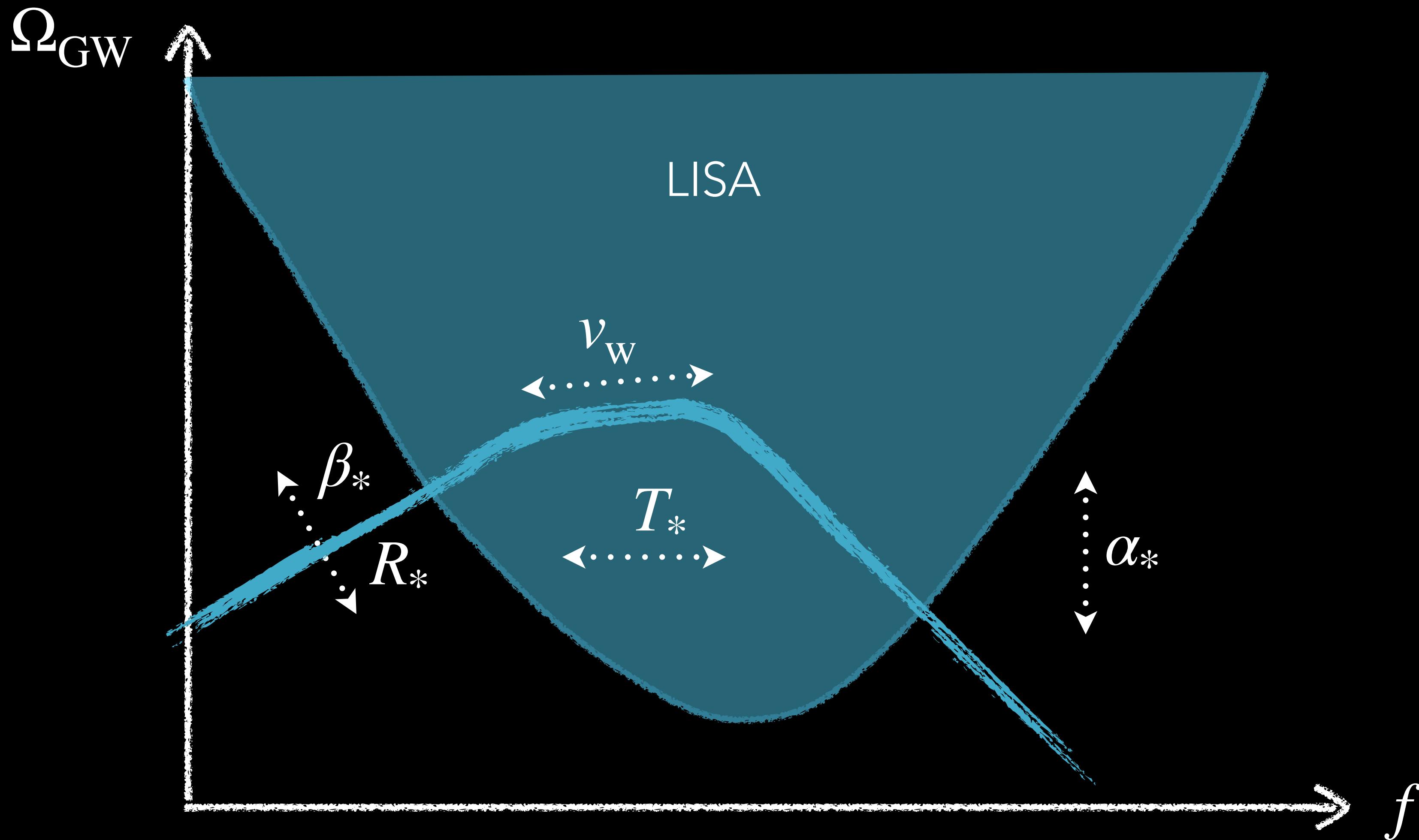
STOCHASTIC GW SPECTRUM

spectrum of the GW
energy density per
logarithmic frequency

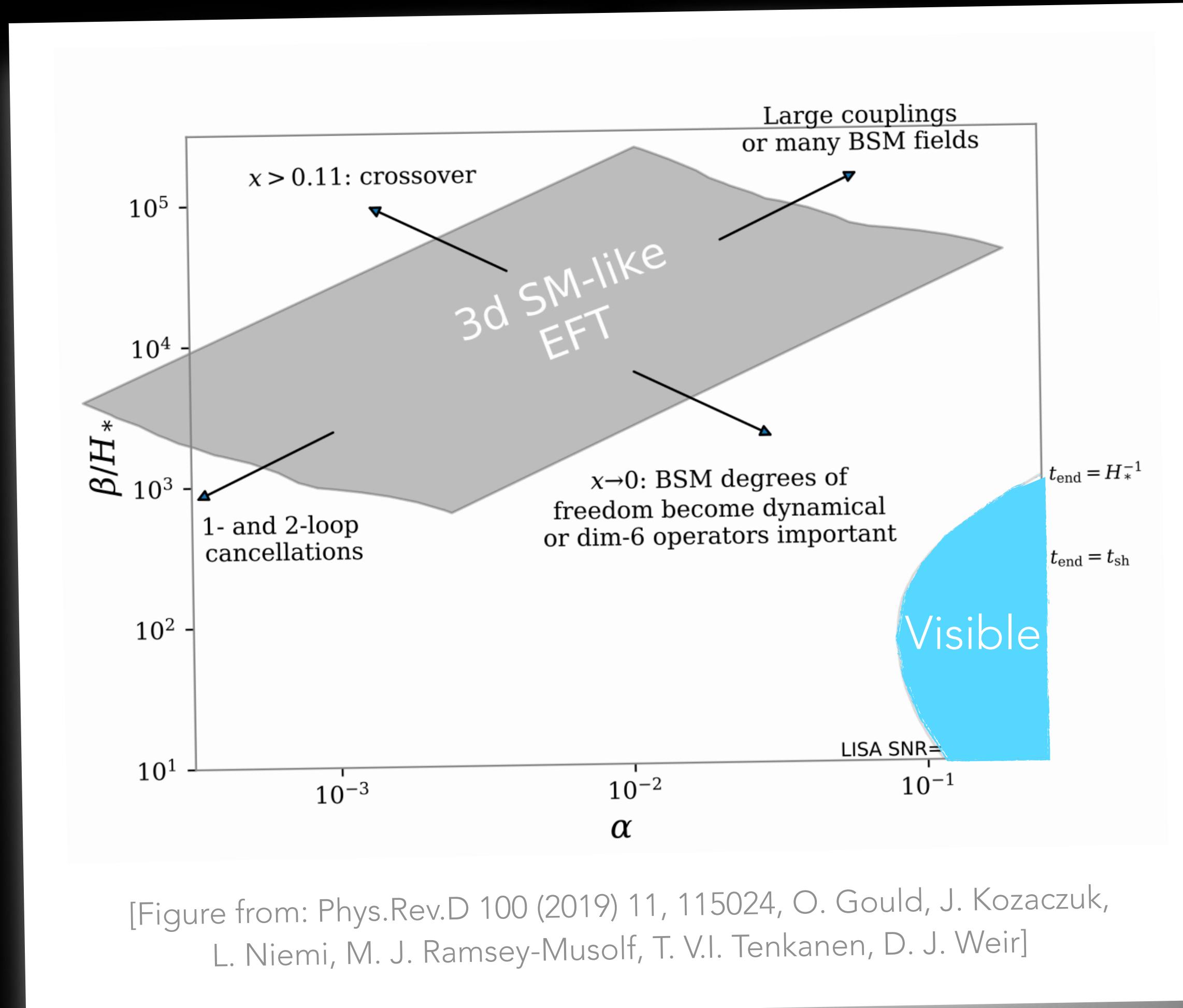
$$\Omega_{\text{GW}}(f) = \frac{1}{\rho_c} \frac{d\rho_{\text{GW}}}{d \log f}$$

normalised to
the critical density

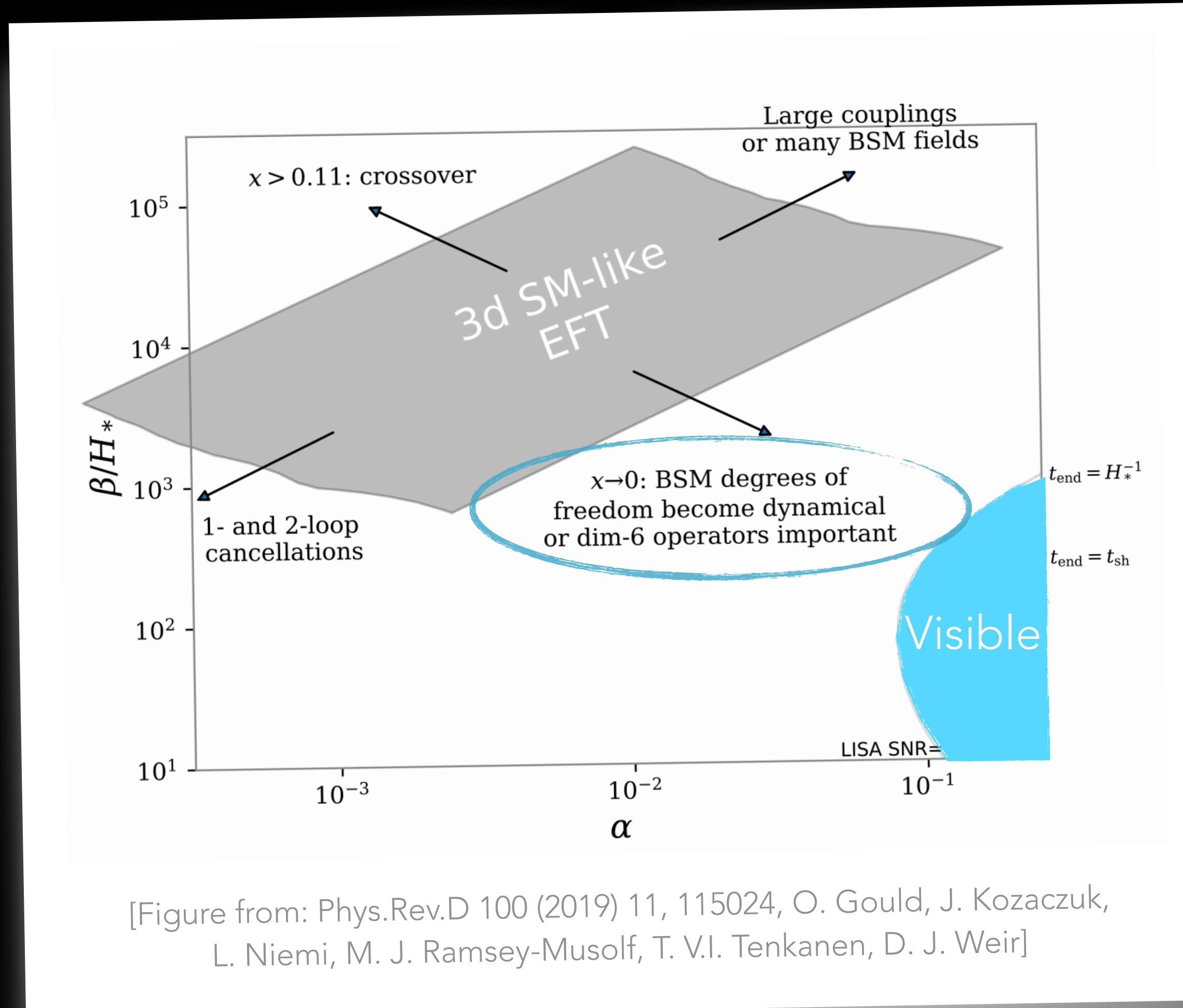
THERMODYNAMICAL PARAMETERS VS GW



OBSERVABLE PT CANNOT BE TOO SM-LIKE



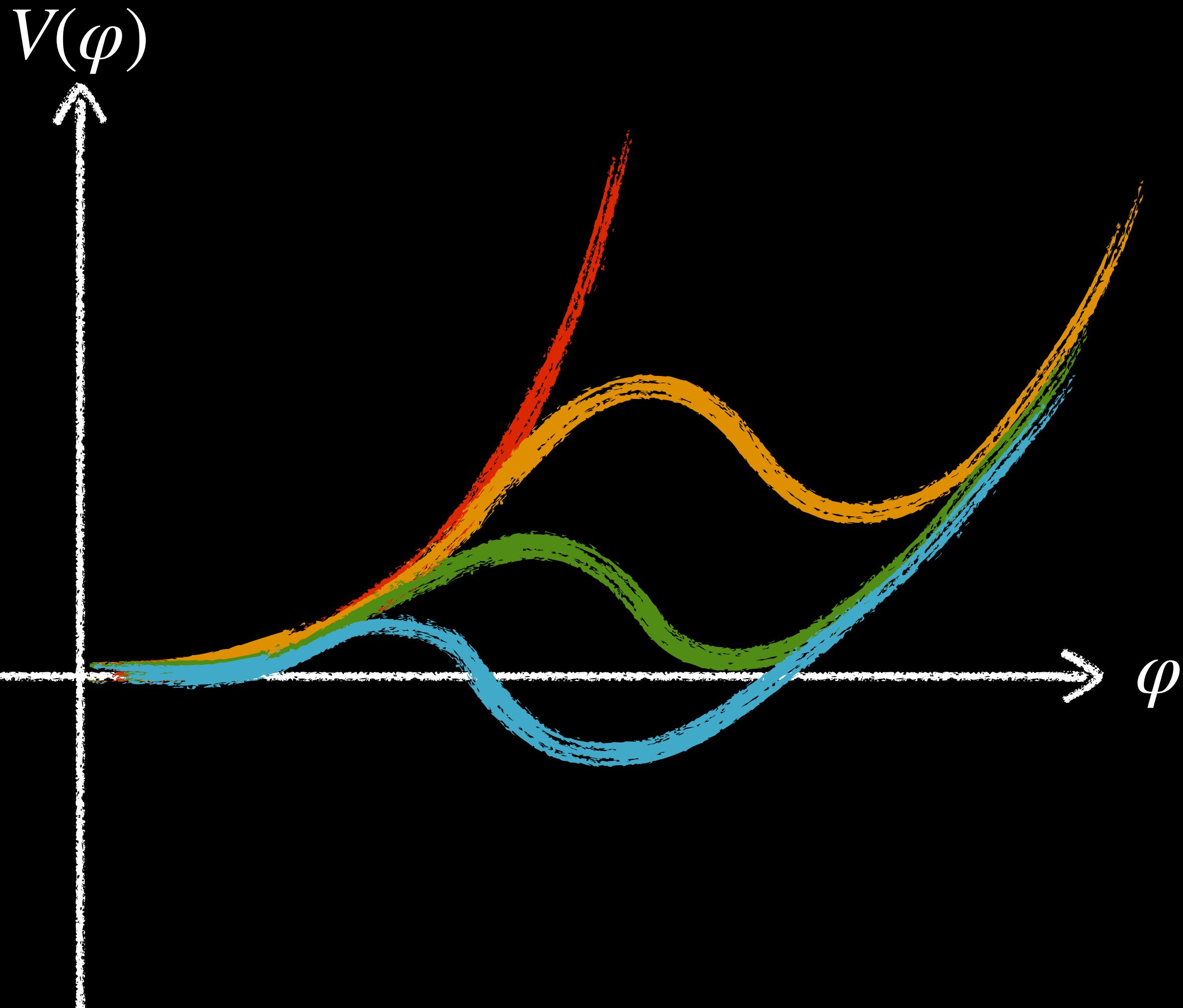
OBSERVABLE PT CANNOT BE TOO SM-LIKE



SUPERCOOLING



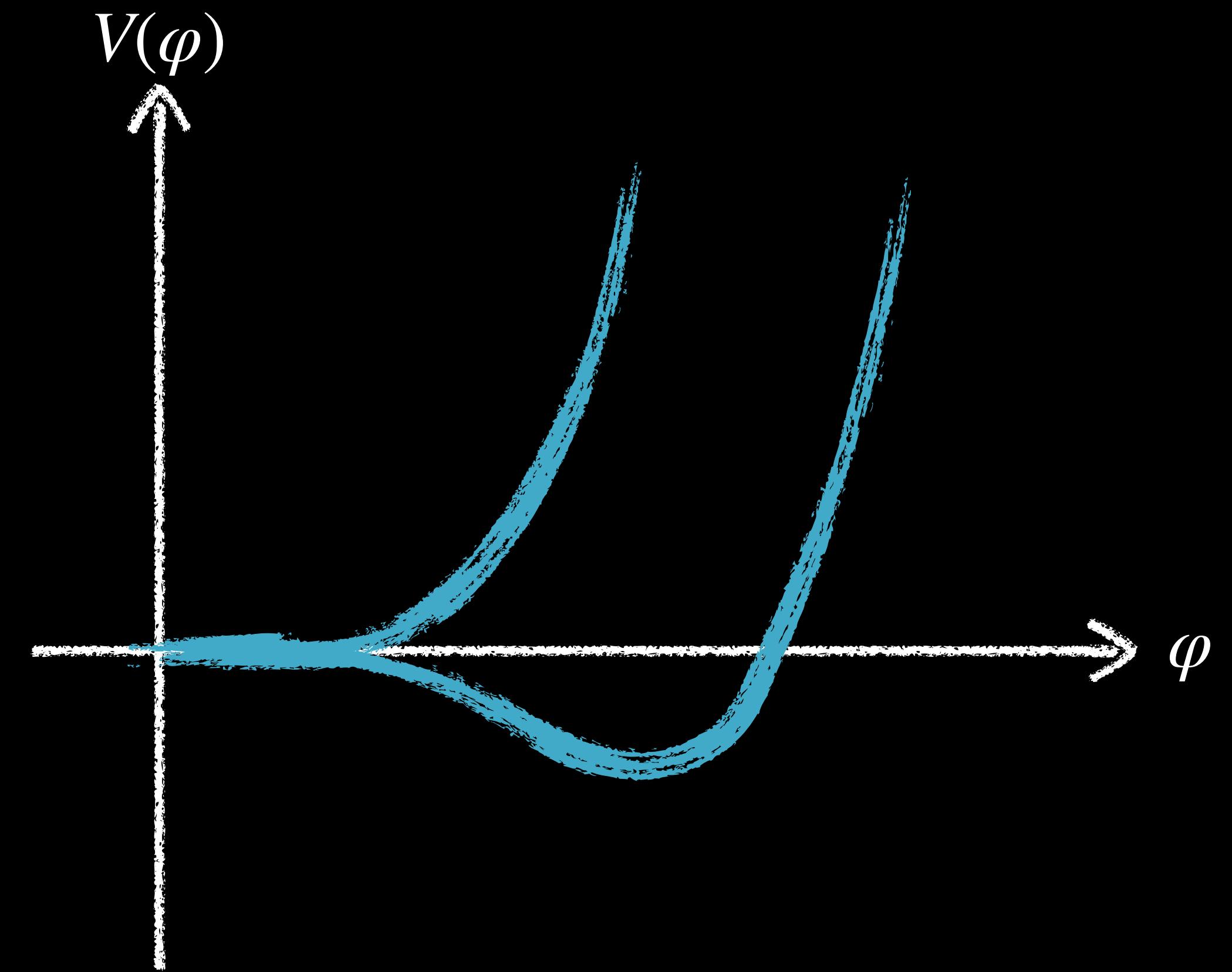
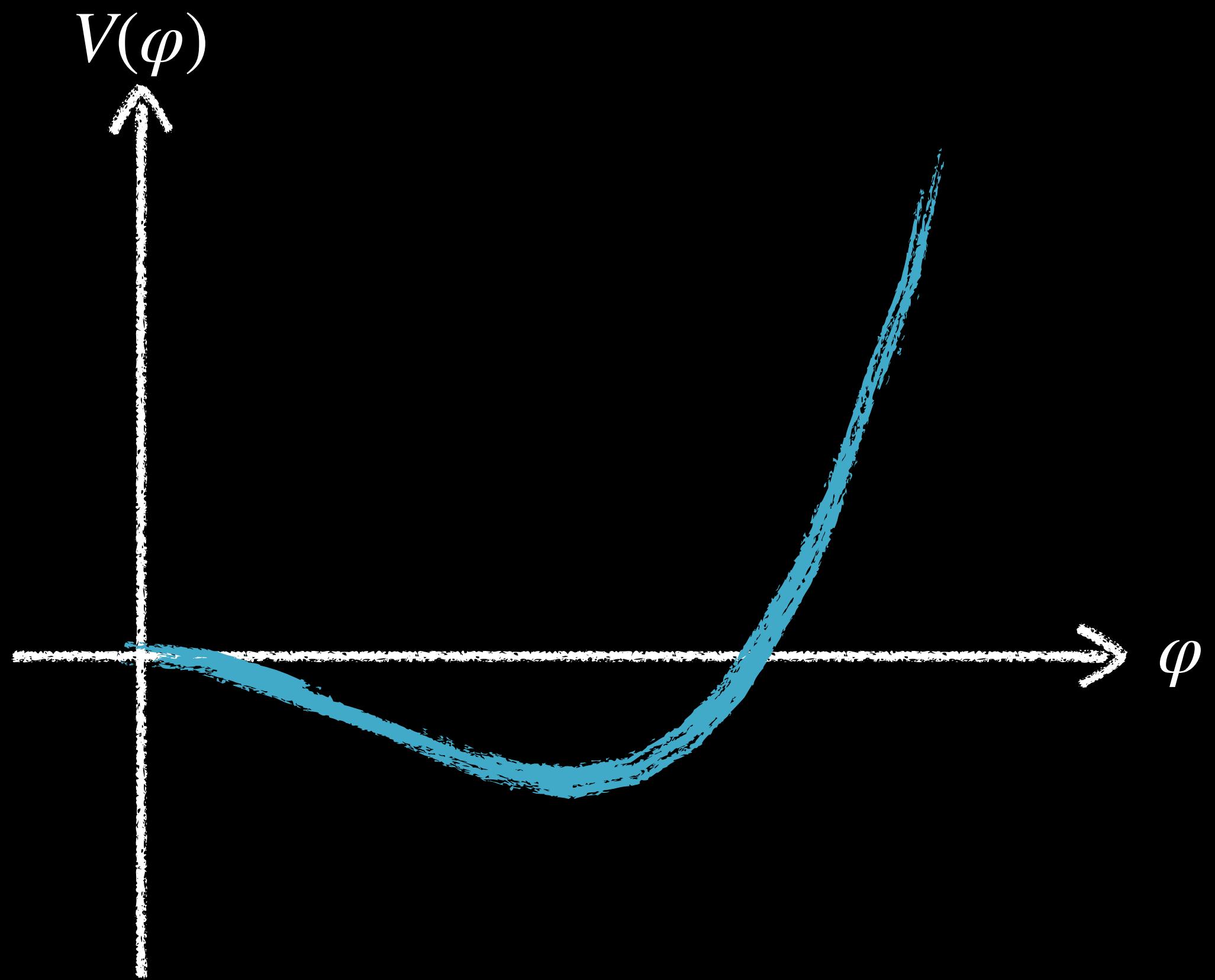
SUPERCOOLED PT



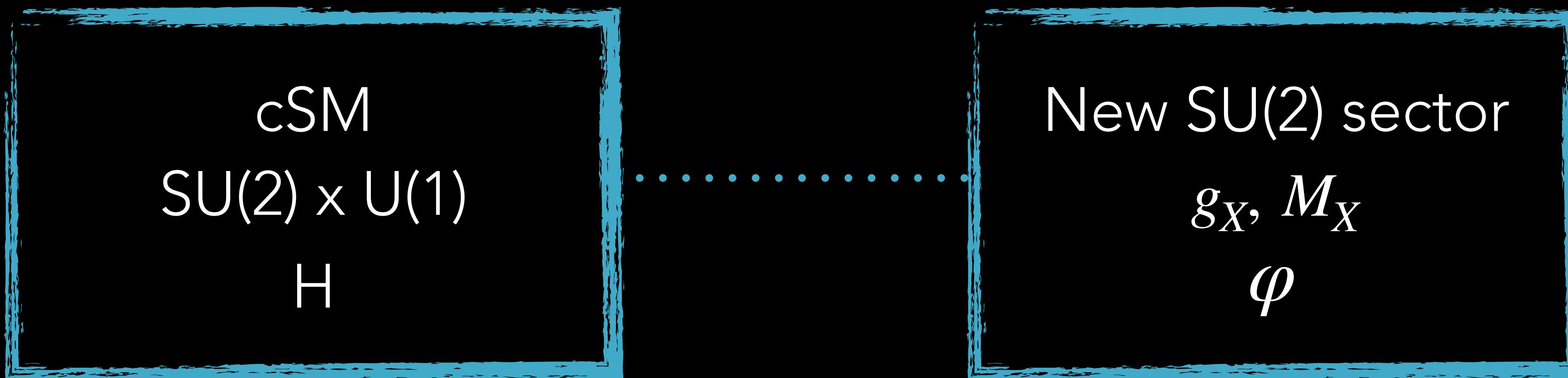
$$T_* \ll T_{\text{critical}}$$

$$\alpha \approx \frac{\Delta V}{\rho_{\text{rad}}} \gg 1$$

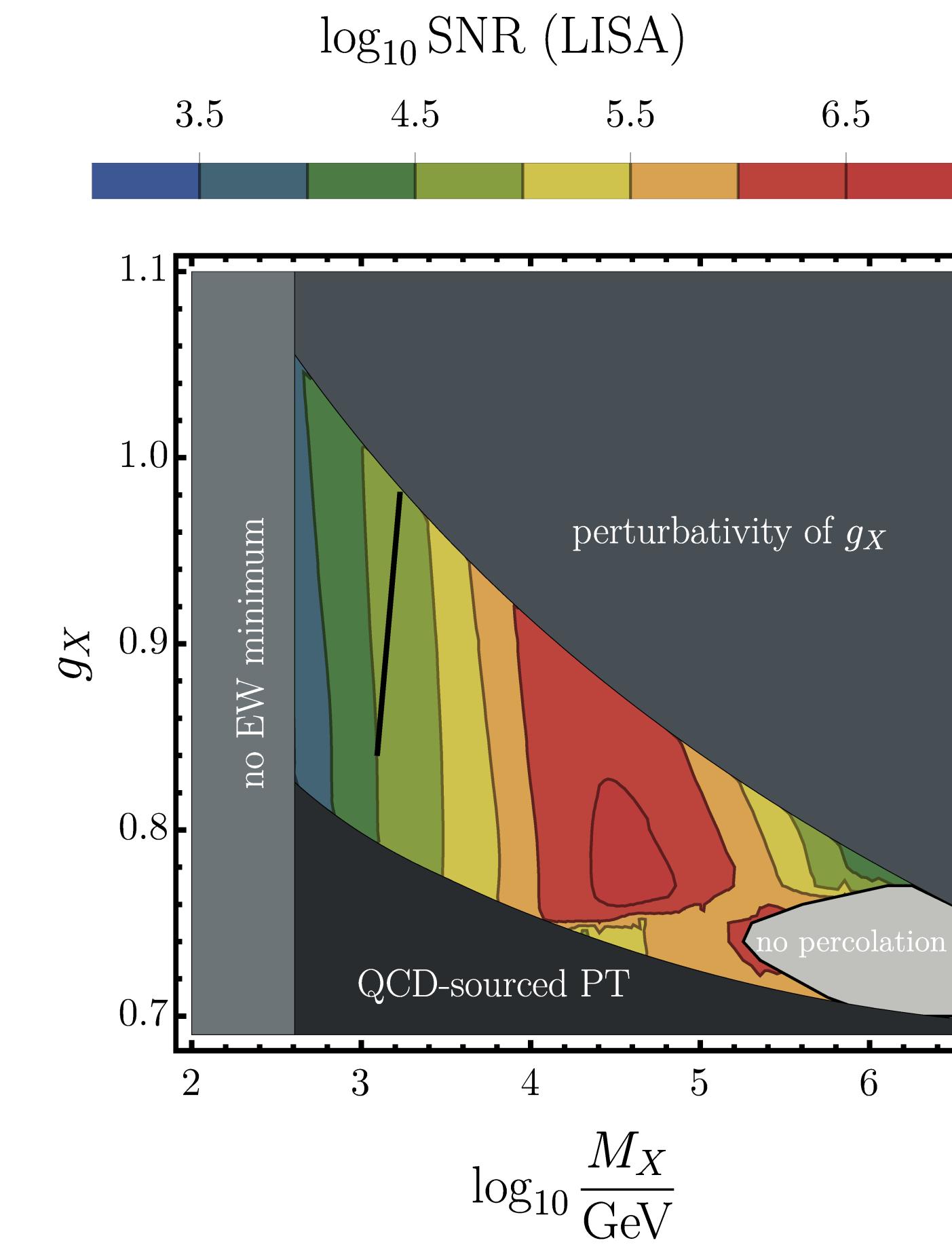
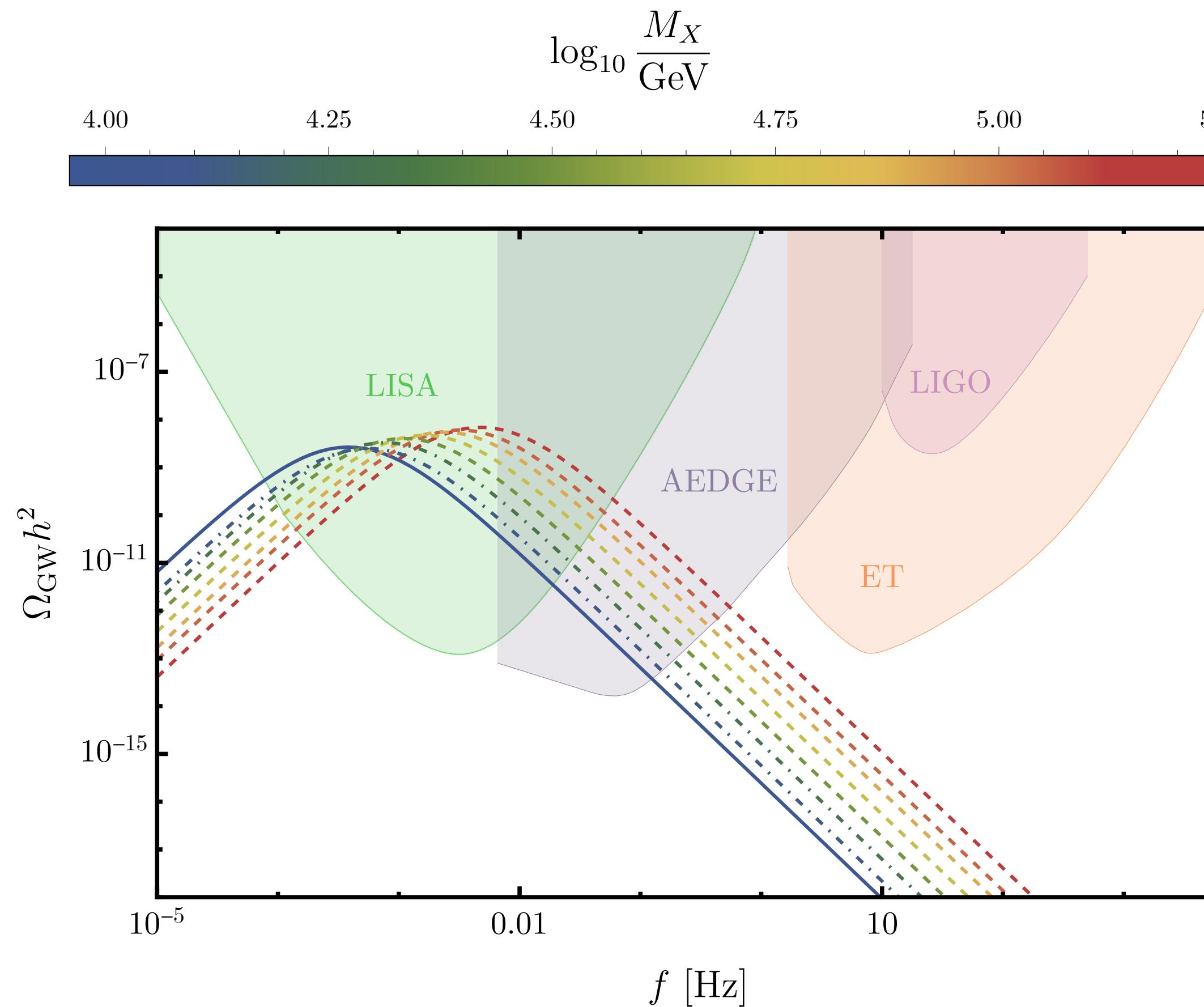
ARCHETYPE: CLASSICAL SCALE INVARIANCE



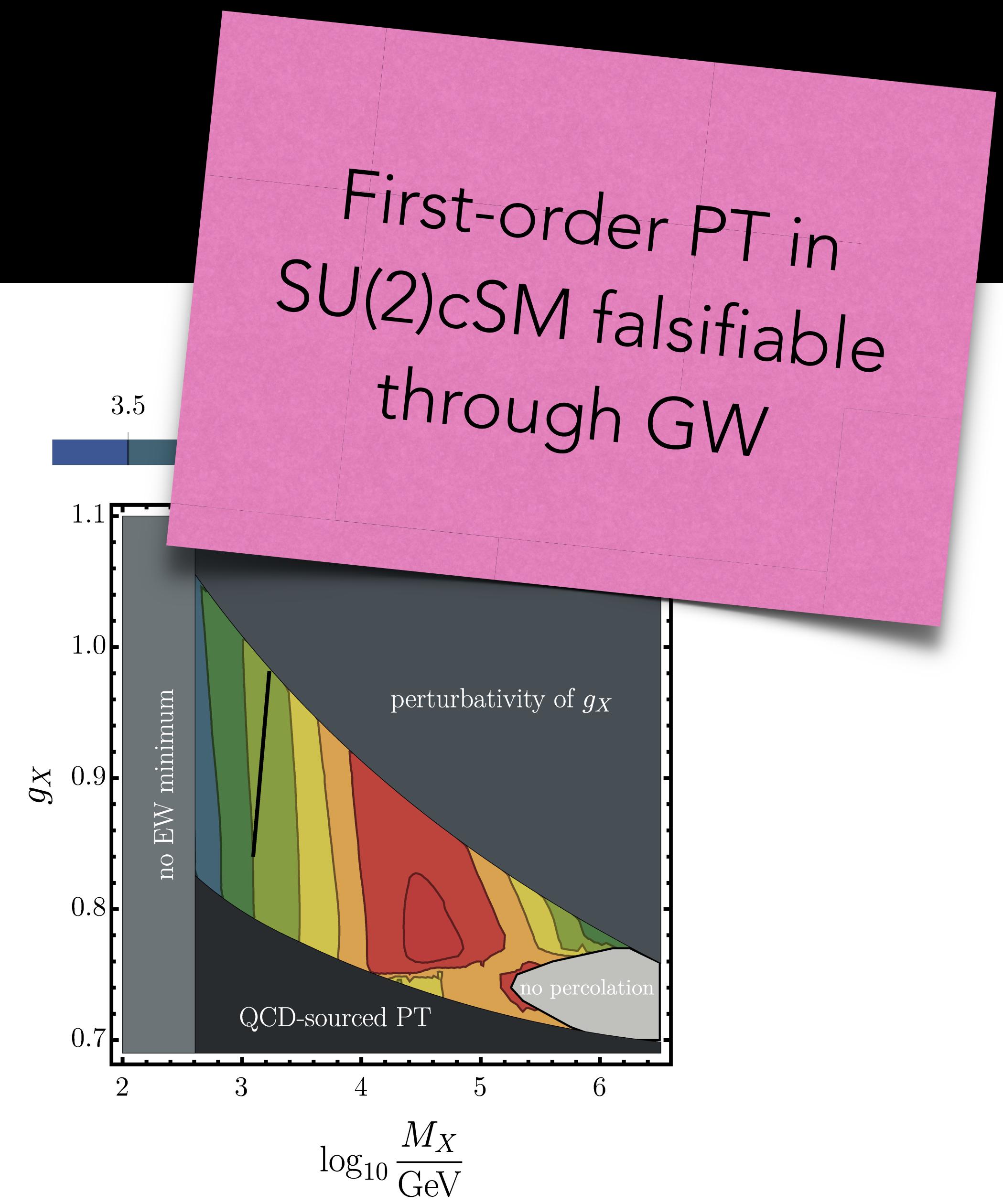
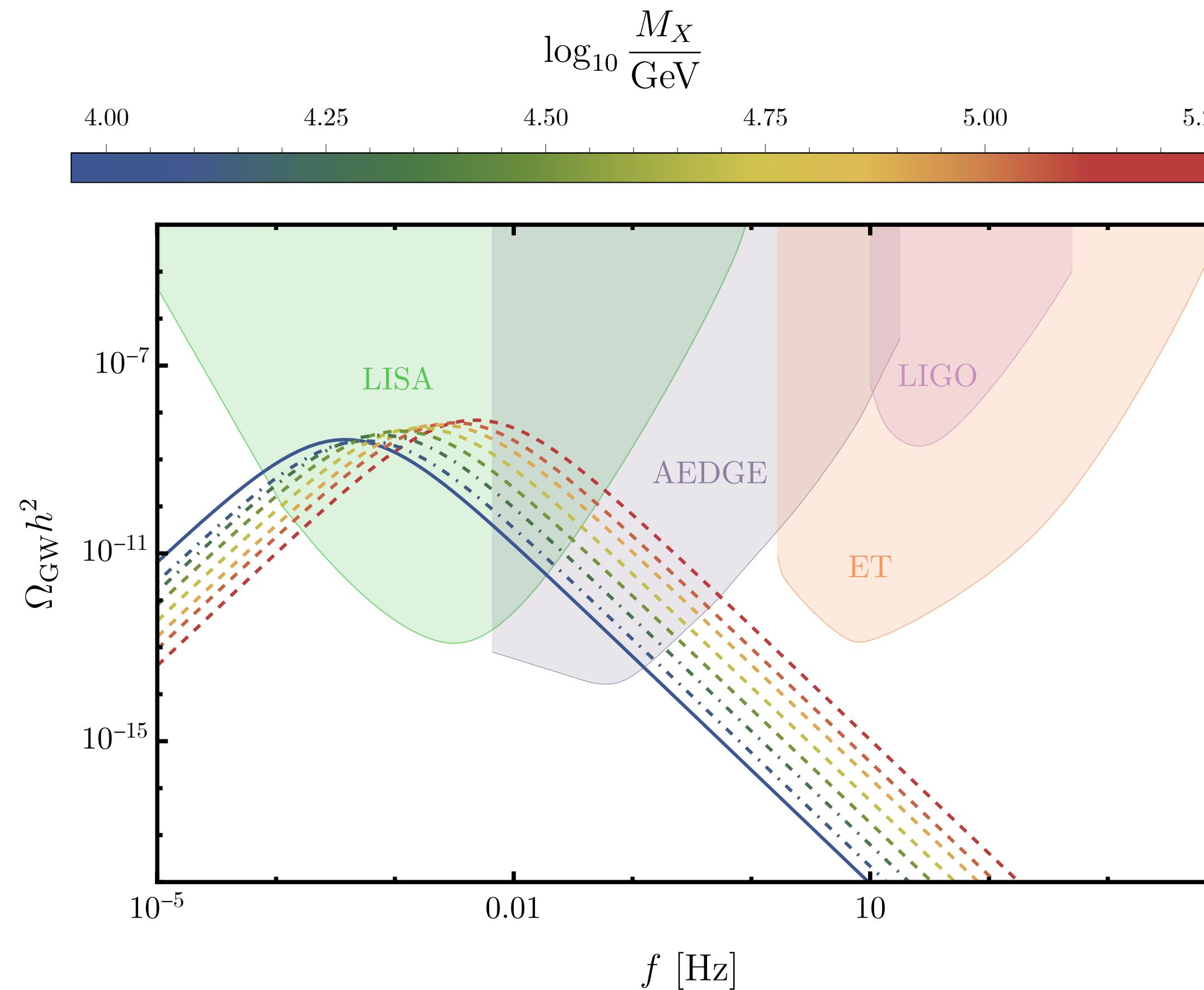
THE MODEL



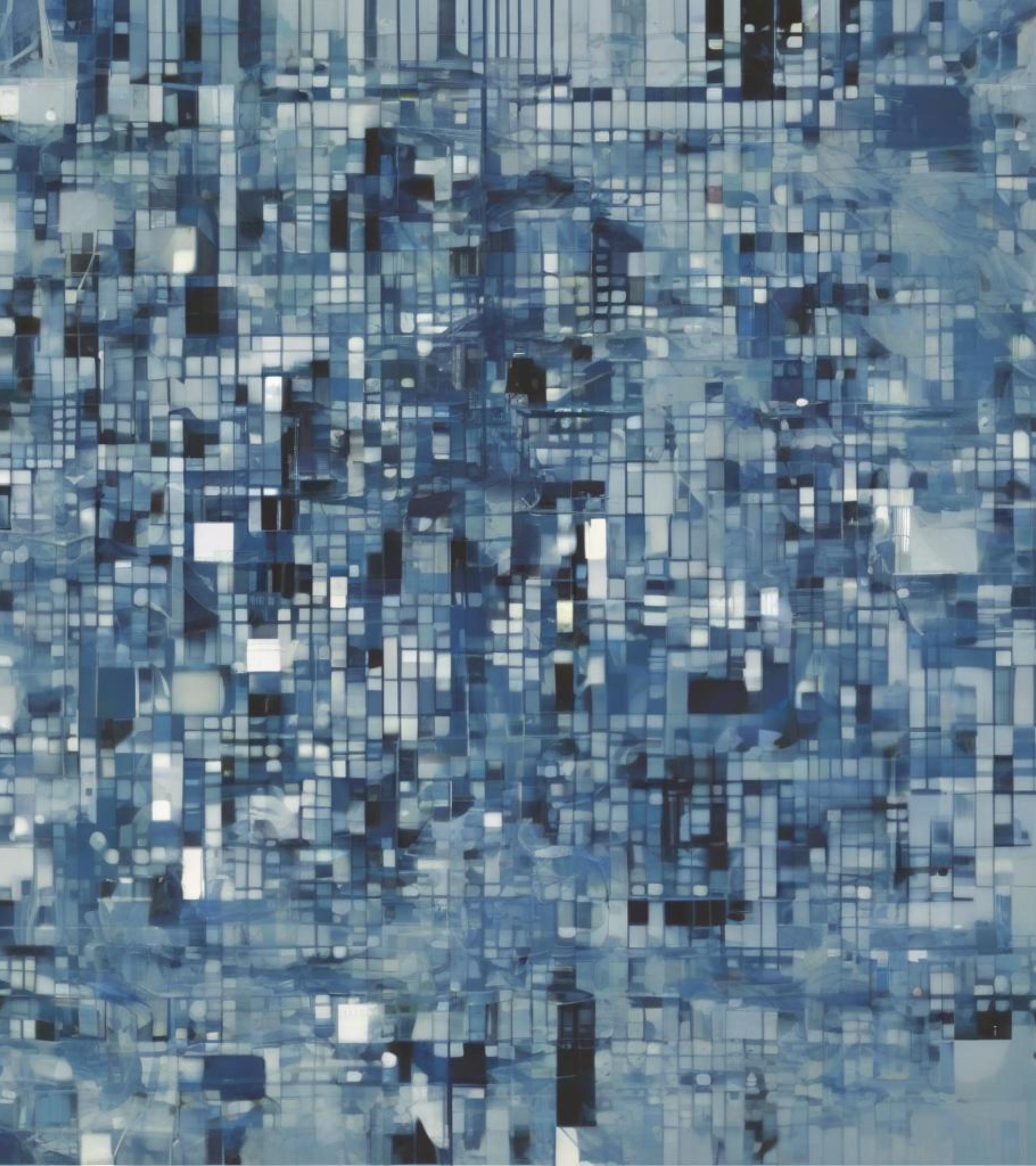
VERY STRONG GW SIGNAL



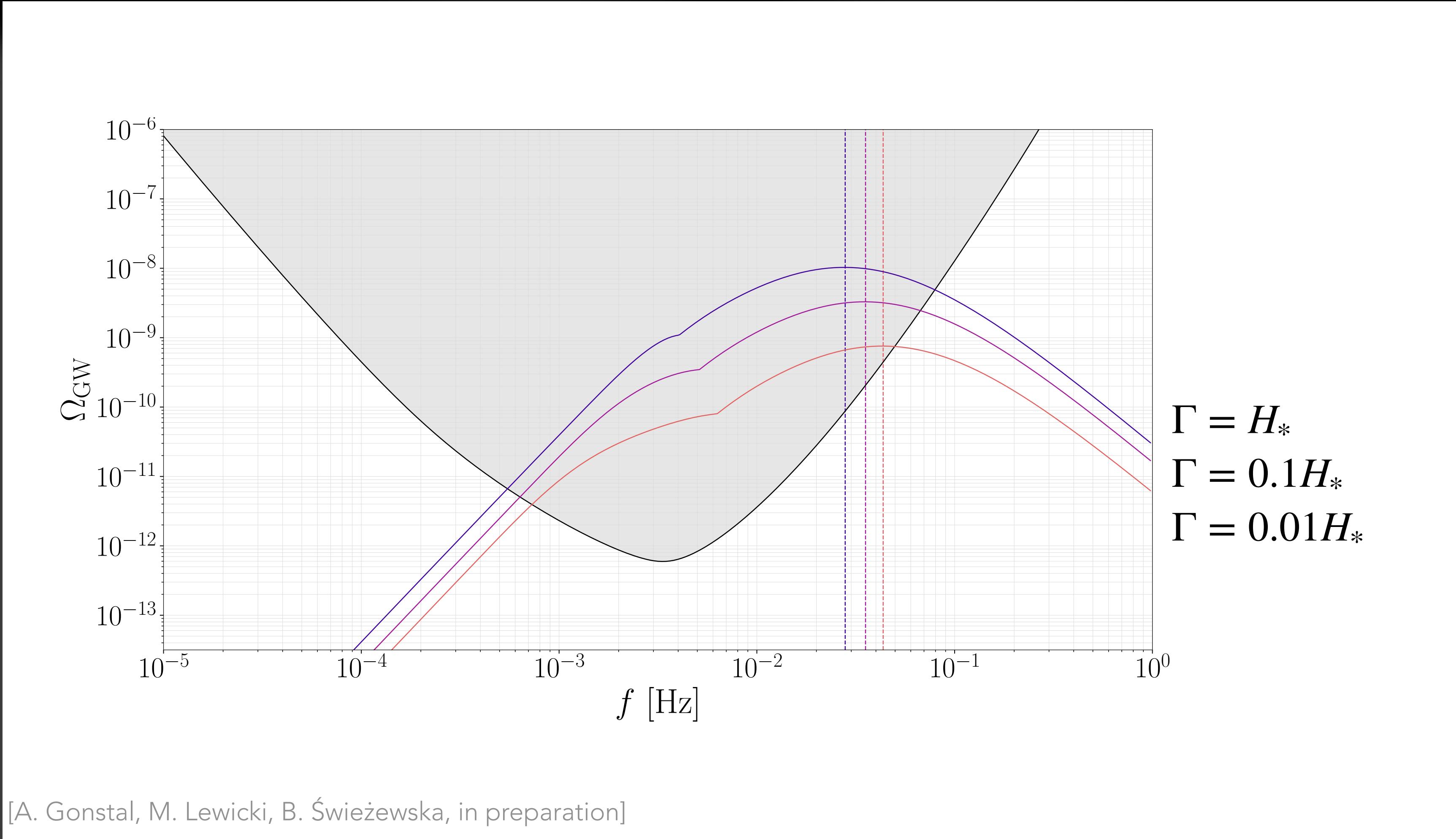
VERY STRONG GW SIGNAL



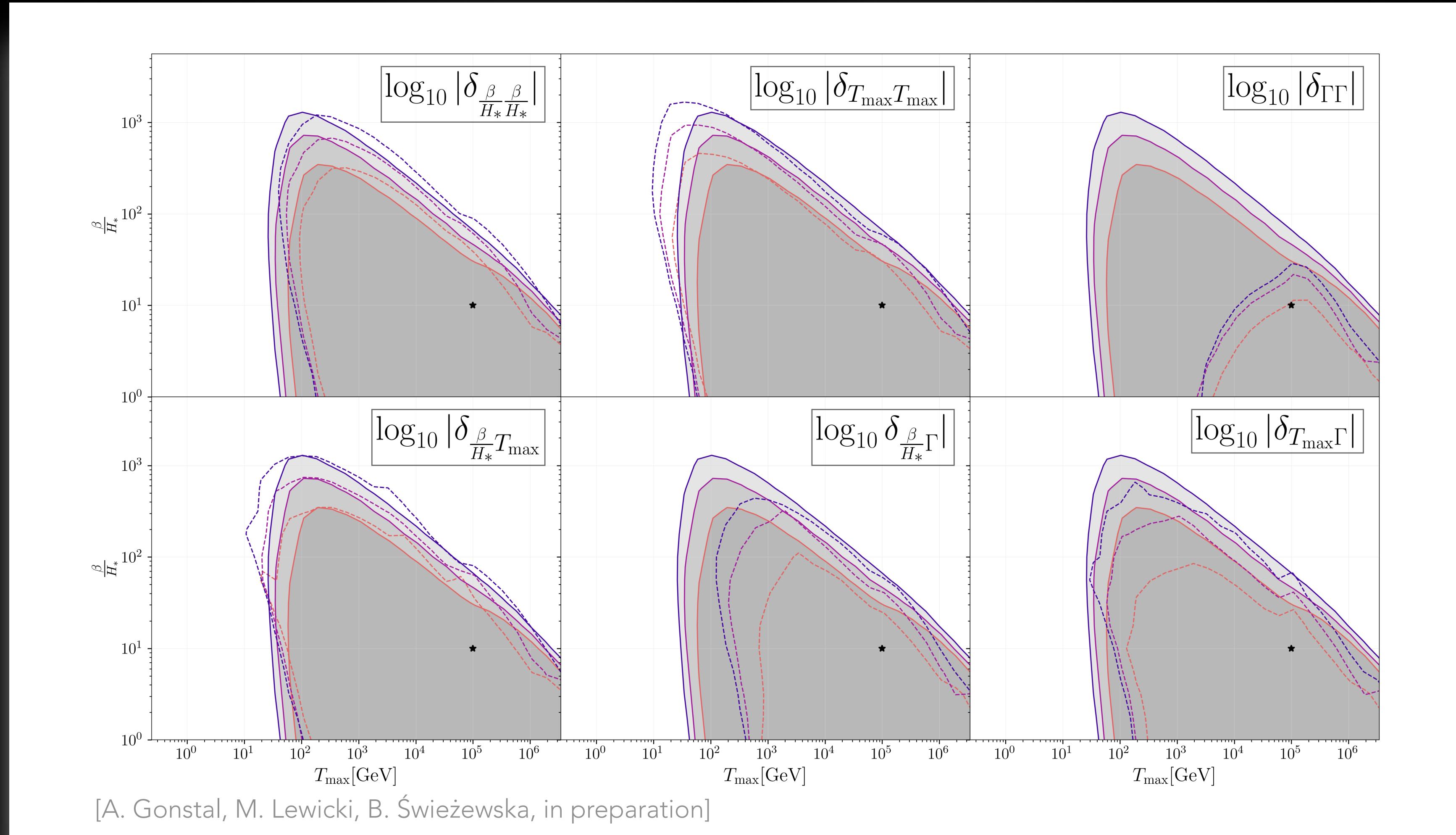
FISHER-MATRIX
ANALYSIS OF THE
SIGNAL



WHAT CAN WE LEARN FROM THE SIGNAL?



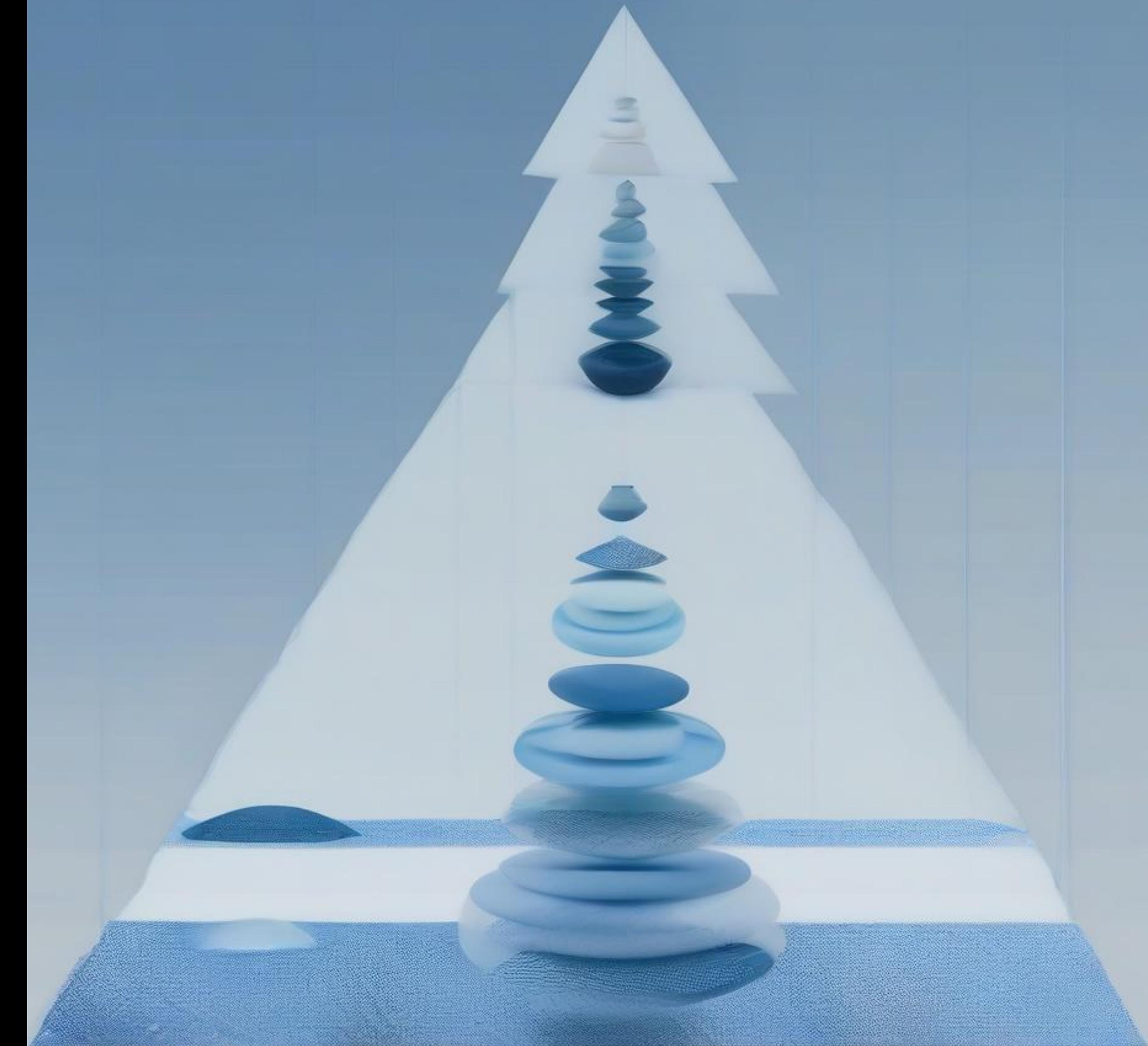
WHAT CAN WE LEARN FROM THE SIGNAL?



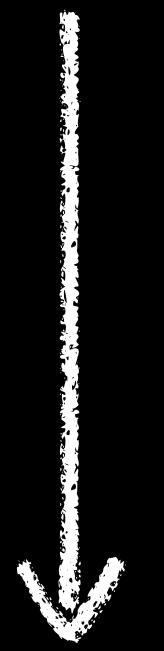
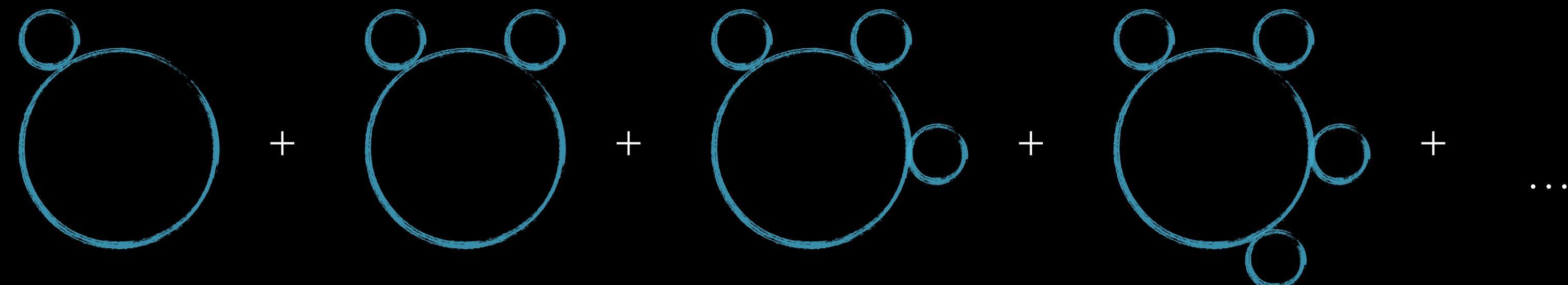
WITH GREAT POWER, COMES GREAT RESPONSIBILITY



HIGH-T 3D EFT FOR
PRECISION



HIGH-TEMPERATURE EFFECTIVE FIELD THEORY



Systematic way of
organizing resummations

Dimensional reduction:
effective field theory in the presence of
temperature-related energy scales

SUPERCOOLING AT HIGH TEMPERATURE??



High-temperature
effective field
theory

???

.....
Supercooled
phase transition



SUPERCOOLING AT HIGH TEMPERATURE??



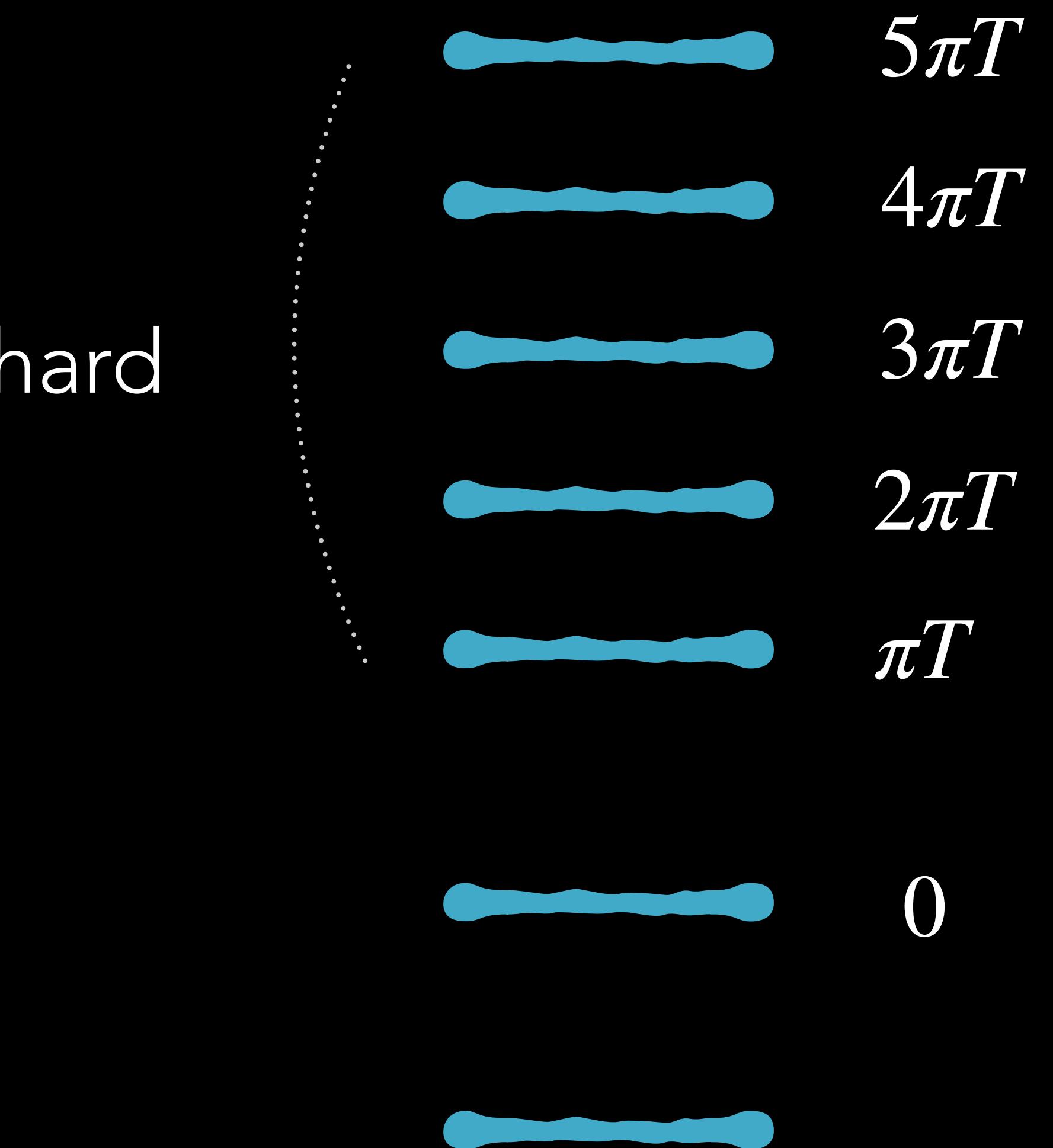
High-temperature
effective field
theory



Supercooled
phase transition



HT EFT CONSTRUCTION

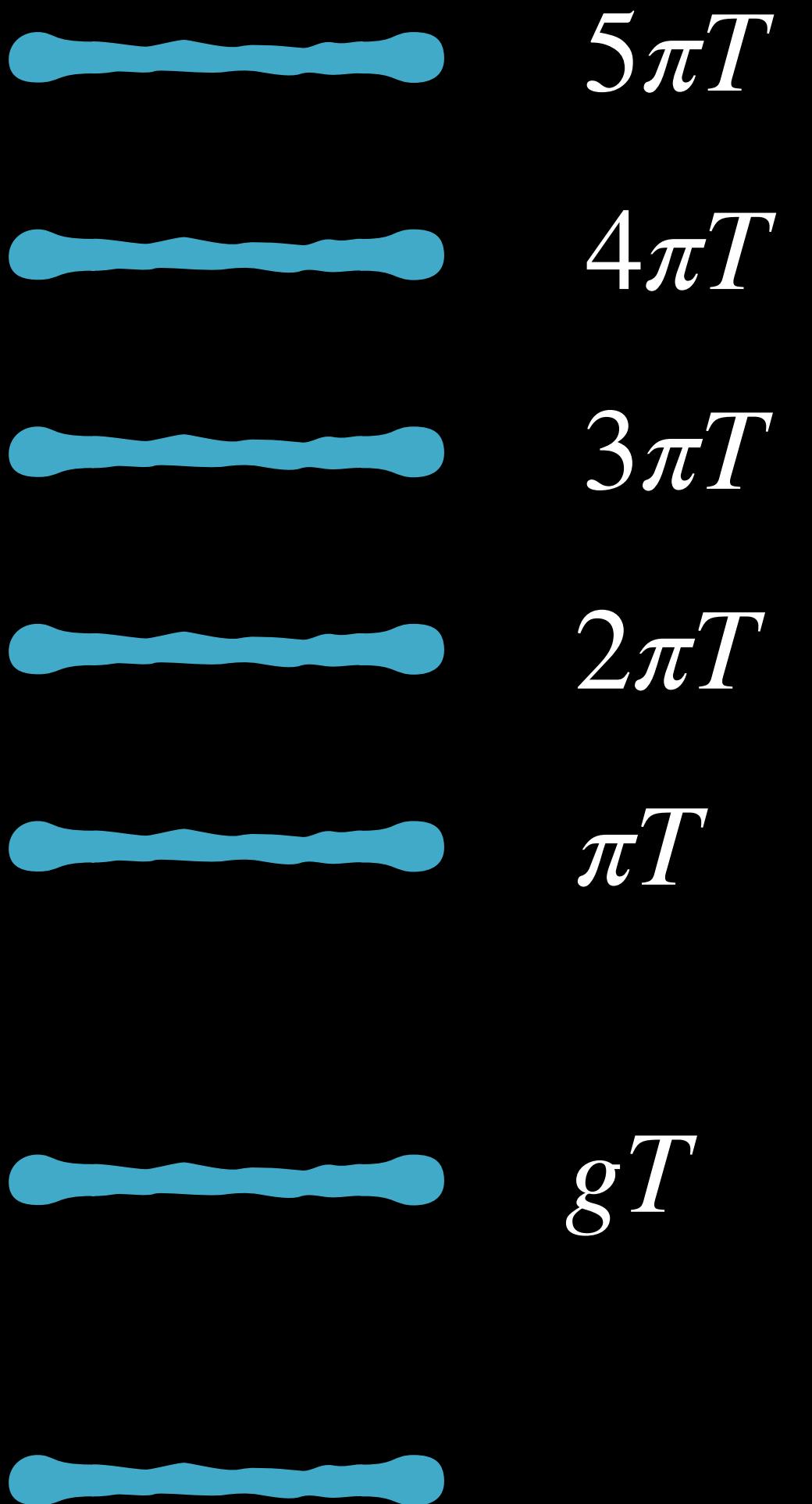


HT EFT CONSTRUCTION

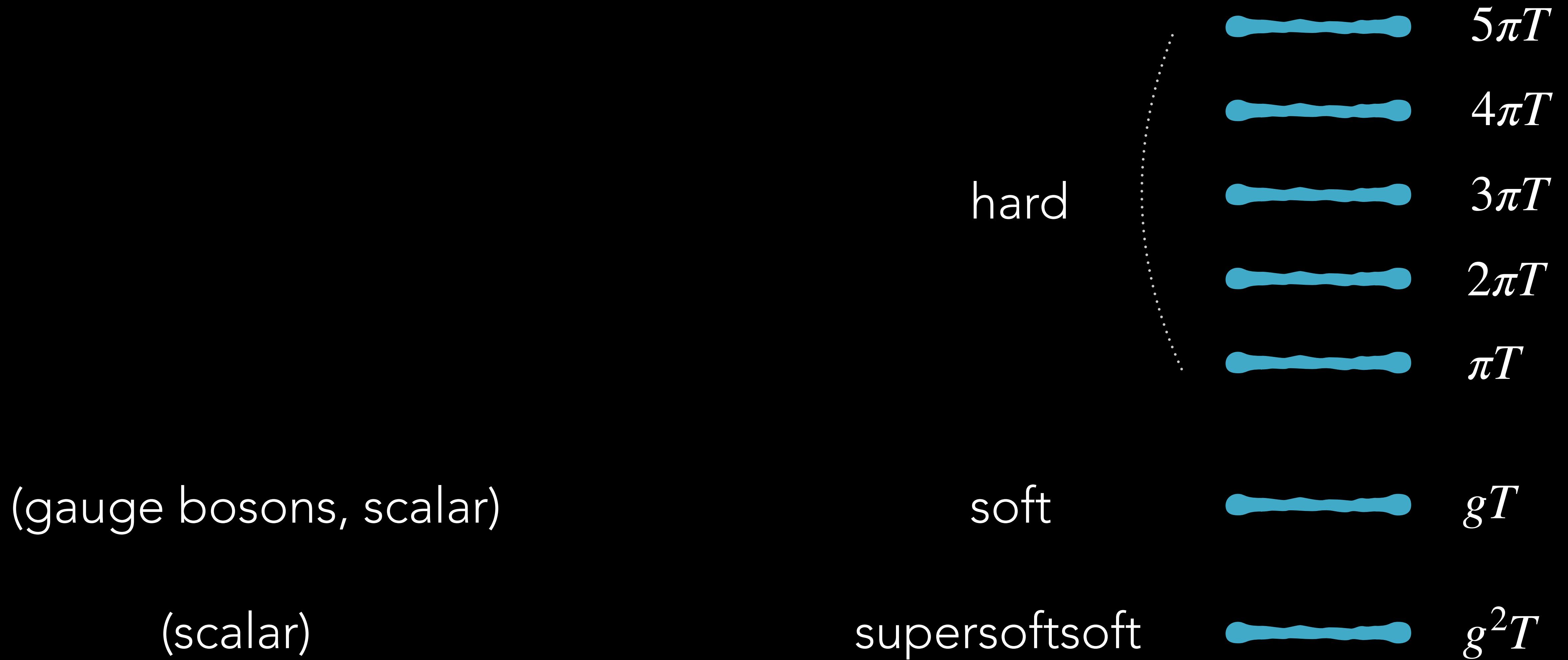
(gauge bosons, scalar)

hard

soft



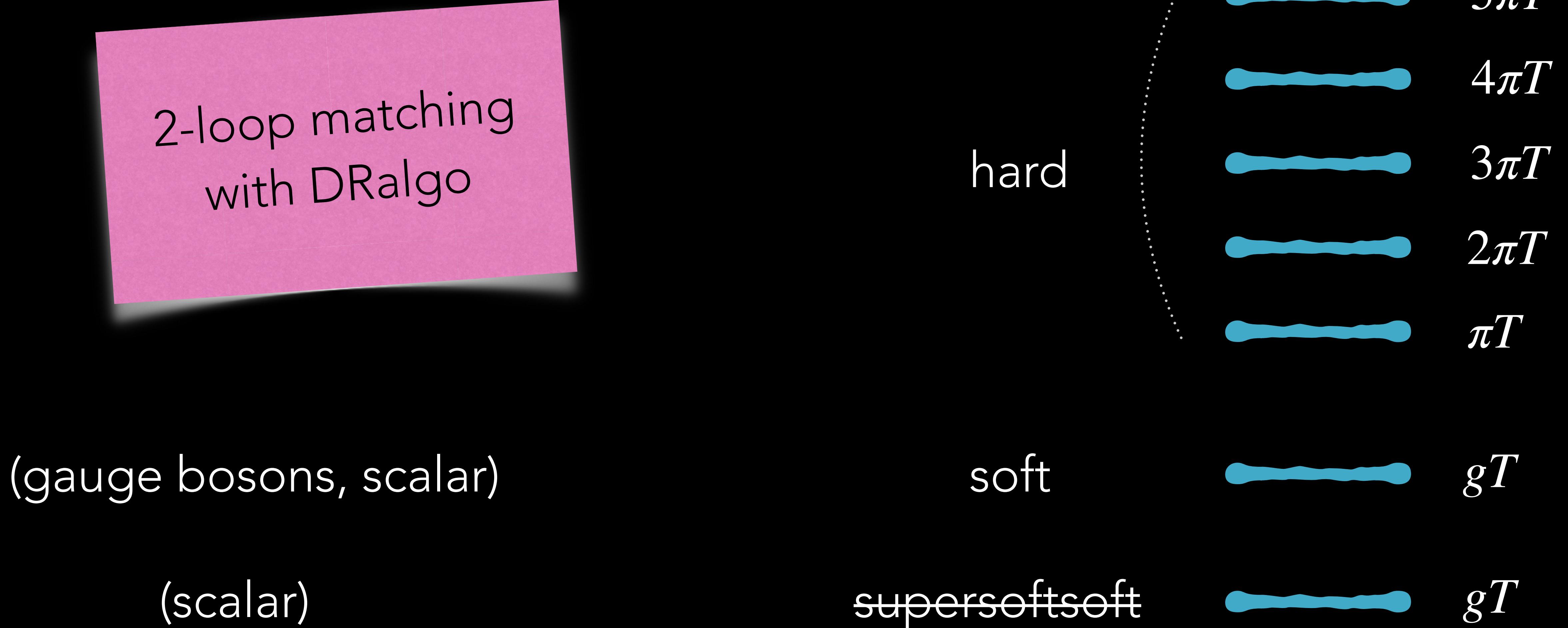
HT EFT CONSTRUCTION



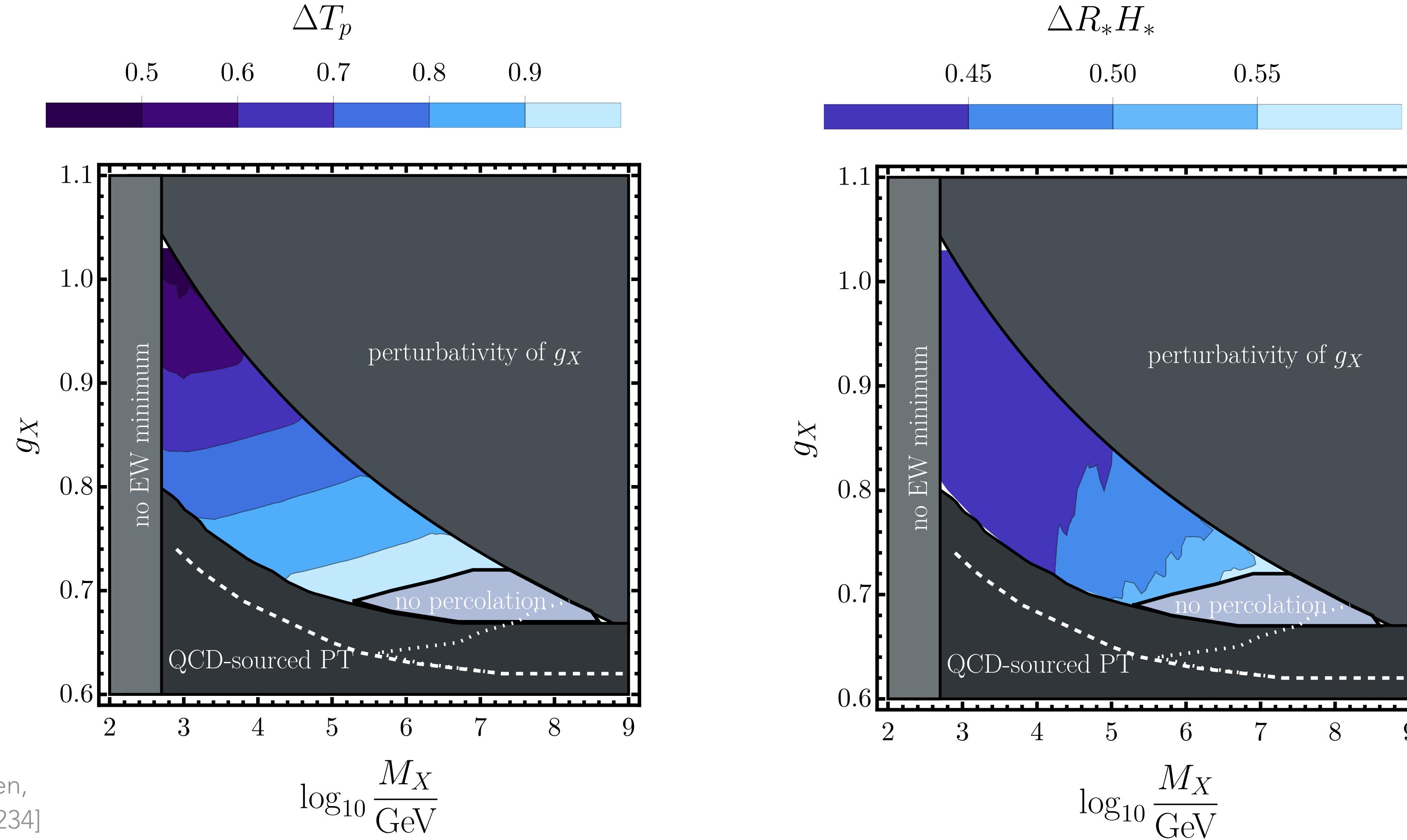
HT EFT CONSTRUCTION



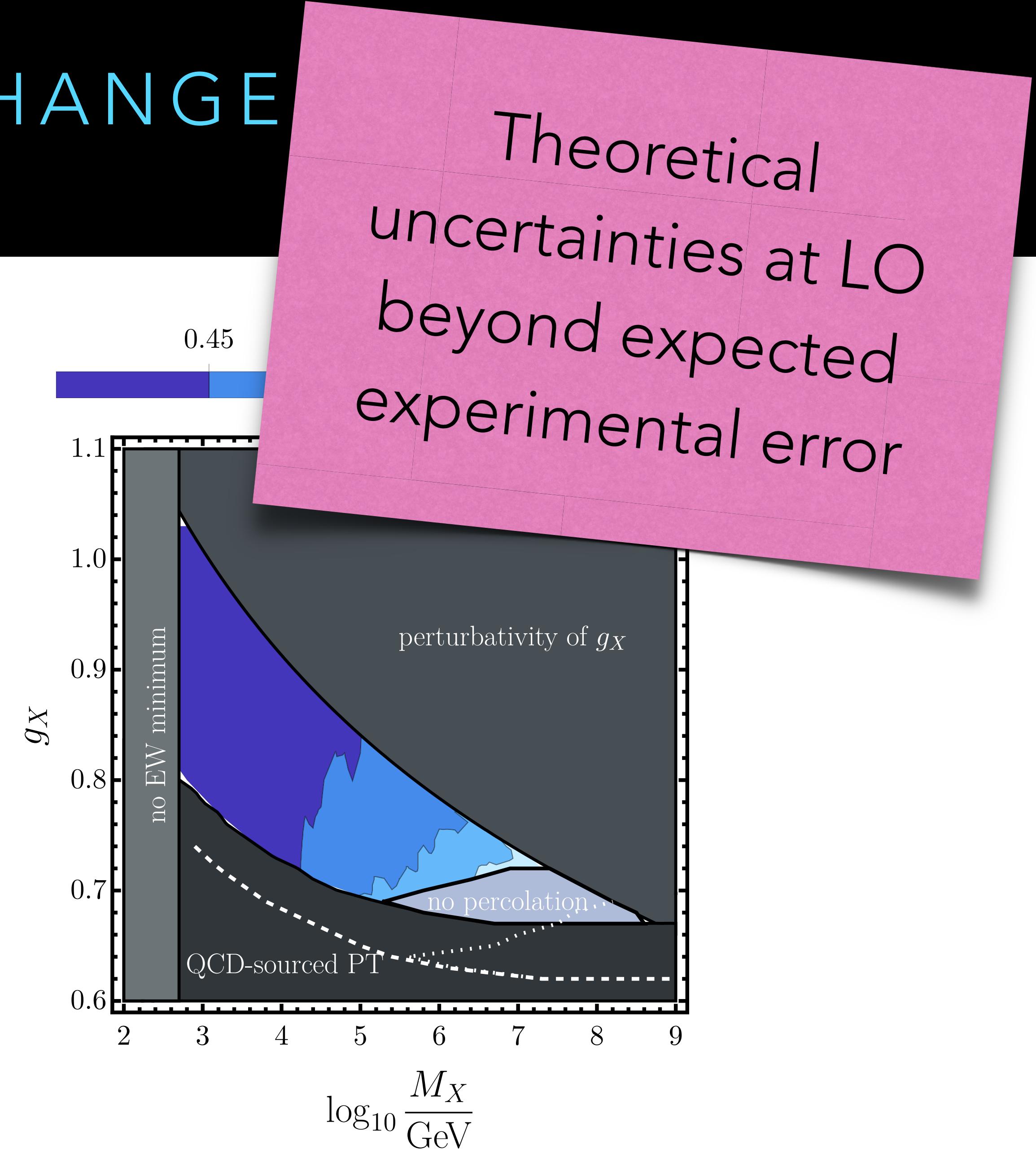
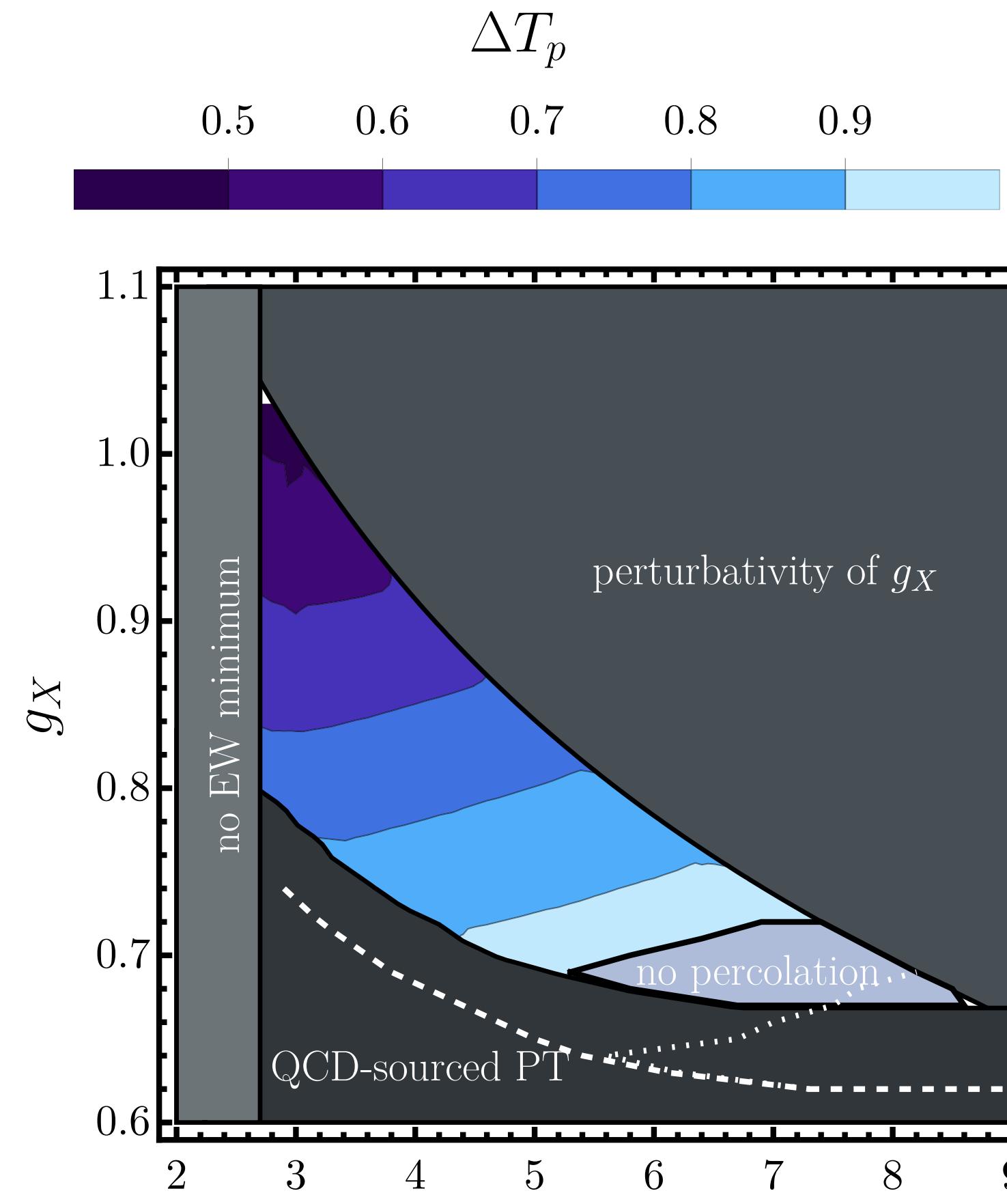
HT EFT CONSTRUCTION



IMPROVED PRECISION CHANGES PREDICTIONS



IMPROVED PRECISION CHANGE



FURTHER QUESTIONS

$$\Gamma = A_{\text{dyn}} \cdot A_{\text{stat}} = A_{\text{dyn}} \cdot A_{\text{det}} \cdot \exp(-S_{\text{eff}})$$

Current:

Range of applicability of the EFT and
the gradient expansion for consistent
and precise nucleation rate

[M. Kierkla, P. Schicho, BŚ, T.V.I. Tenkanen, J. van de Vis,
in preparation]

Future:

- Out-of-equilibrium effects during nucleation
[with Juan Camilo Garnica-Aguirre]
- Energy transfer during the phase transition (reheating)
[with Mateusz Kulejewski]

SUMMARY



TAKE-HOME MESSAGE

TAKE-HOME MESSAGE

Early Universe
will be probed
with the use of
gravitational
waves

TAKE-HOME MESSAGE

Early Universe
will be probed
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We can learn
about
fundamental
interactions from
a (strong enough)
GW signal

TAKE-HOME MESSAGE

Early Universe
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We can learn
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interactions from
a (strong enough)
GW signal

Lots of
interesting
Physics involved
in a PT in the
early Universe

THANK YOU