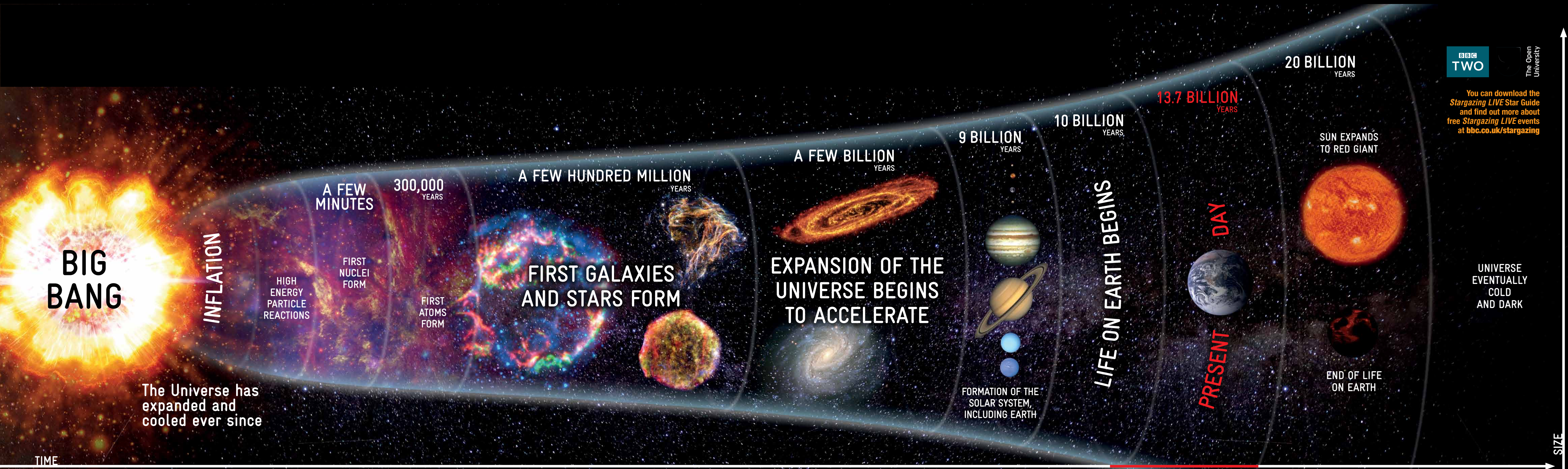


GRAVITATIONAL WAVES FROM PHASE TRANSITIONS

BOGUMIŁA ŚWIEŻEWSKA
UNIVERSITY OF WARSAW

DIVING INTO "UNOBSERVABLE" PAST



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

TIME

SIZE

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 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.
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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 decelerated – but a few billion years after the Big Bang, the expansion began to accelerate. The acceleration is caused by a mysterious force known as 'dark energy', the nature of which is completely unknown.
--	---

TODAY

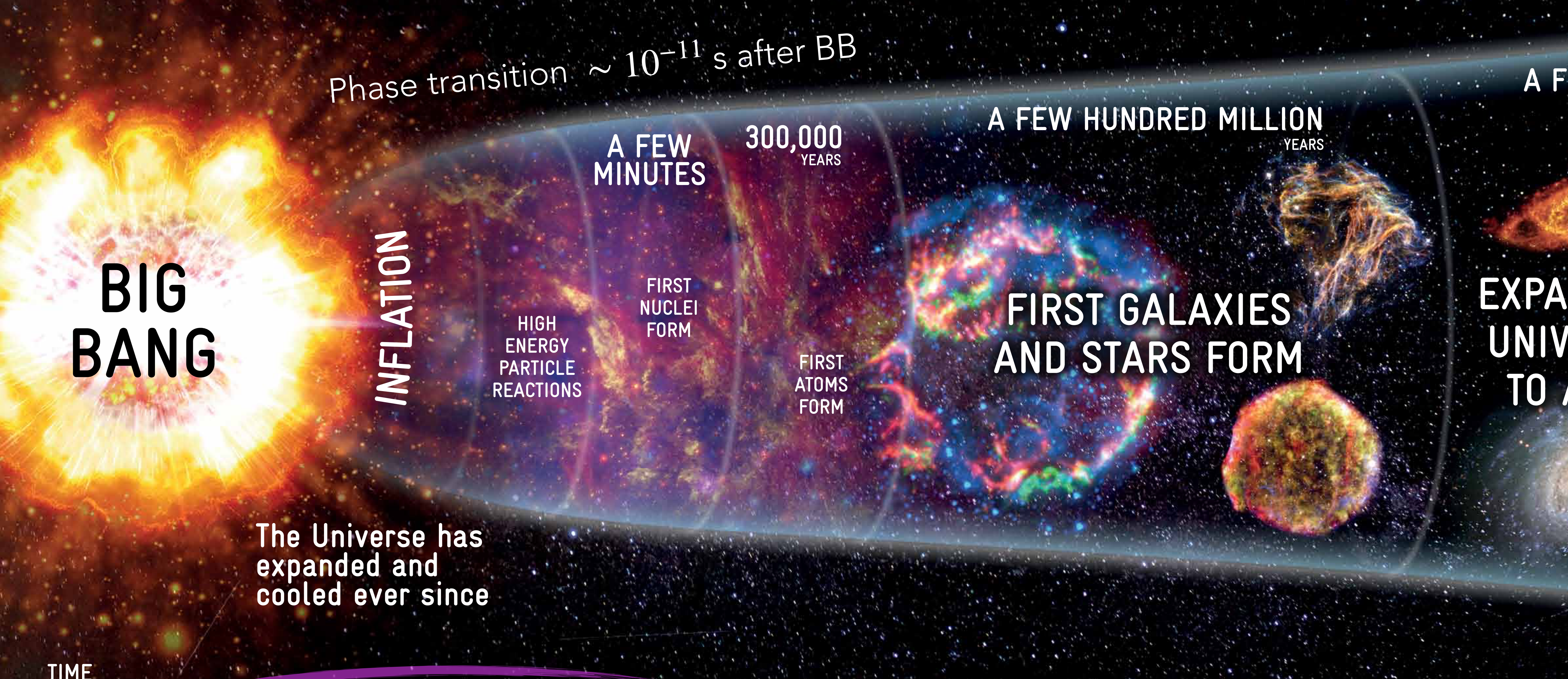
9 BILLION YEARS The Sun, along with its eight planets, and all the asteroids, comets and Kuiper Belt objects, such as Pluto, form from the debris left behind by earlier generations of stars.	10 BILLION YEARS The first life appears on Earth in the form of simple cells. Impacting comets and asteroids might have contributed organic molecules to Earth. Life spreads across the globe.
--	--

FUTURE

13.7 BILLION YEARS This is where we are today. Using our own ingenuity, humanity is probing the depths of the Universe and trying to unravel its mysteries, from our tiny, home planet, Earth. The visible Universe contains billions of galaxies, each comprising billions of stars. Within our own Galaxy, hundreds of exoplanets have been discovered orbiting other stars.	20 BILLION YEARS In a few billion years the Sun's outer layers will expand as it turns into a Red Giant star. Life on Earth will become impossible. Expansion of the Universe will continue to accelerate.	10¹⁰⁰ YEARS Stars no longer form; matter is trapped in black holes or dead stars. Protons decay and black holes evaporate, leaving the Universe to its ultimate fate as cold, dead, empty space, containing only radiation, which itself too will eventually disperse.
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Stargazing LIVE is a BBC and Open University co-production. Credit: Photography sourced from NASA.

[Image source: BBC.CO.UK]



Phase transition $\sim 10^{-11}$ s after BB

BIG BANG

INFLATION

HIGH ENERGY PARTICLE REACTIONS

A FEW MINUTES

FIRST NUCLEI FORM

300,000 YEARS

FIRST ATOMS FORM

A FEW HUNDRED MILLION YEARS

FIRST GALAXIES AND STARS FORM

The Universe has expanded and cooled ever since

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 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)

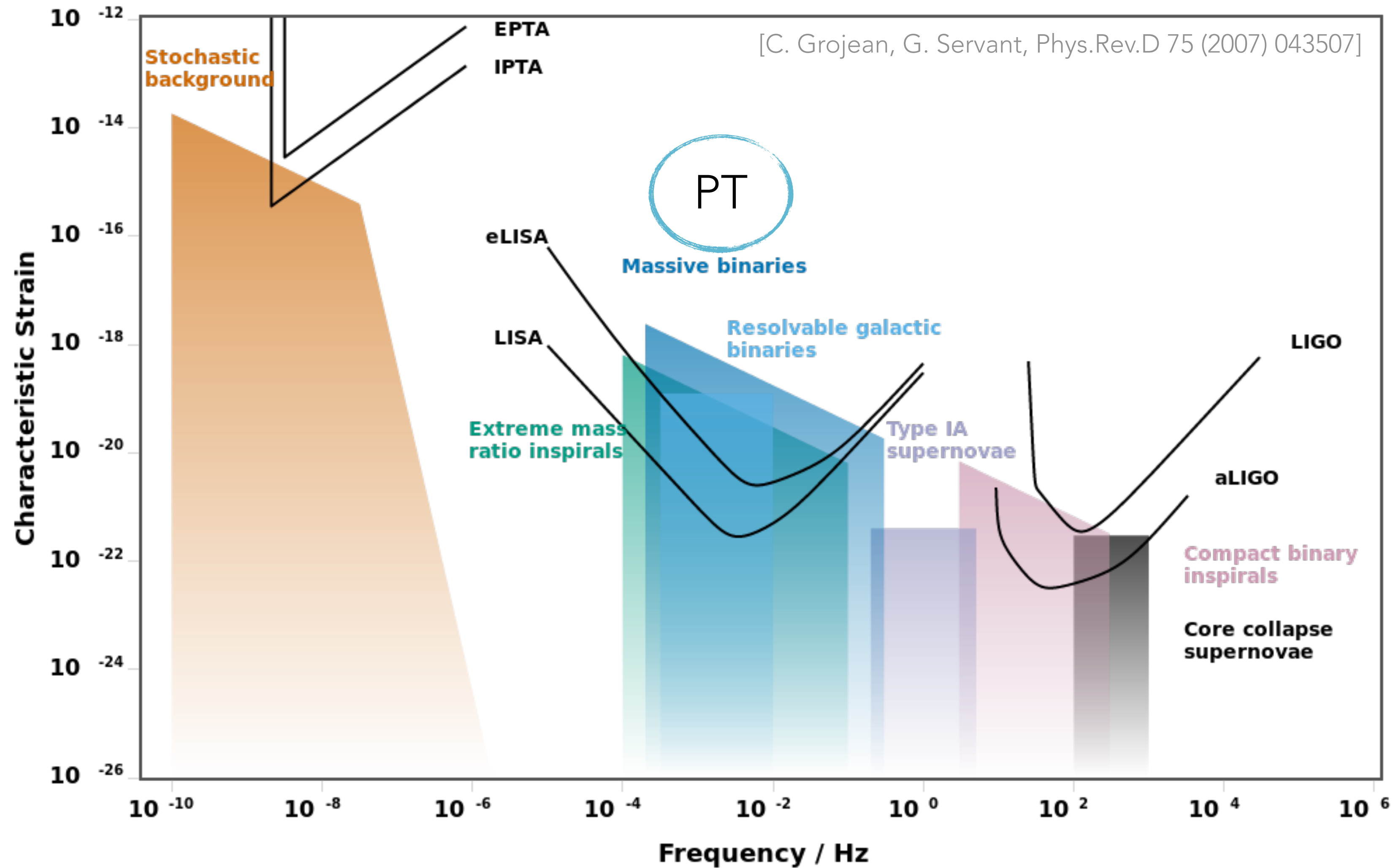
A FEW HUNDRED MILLION YEARS

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

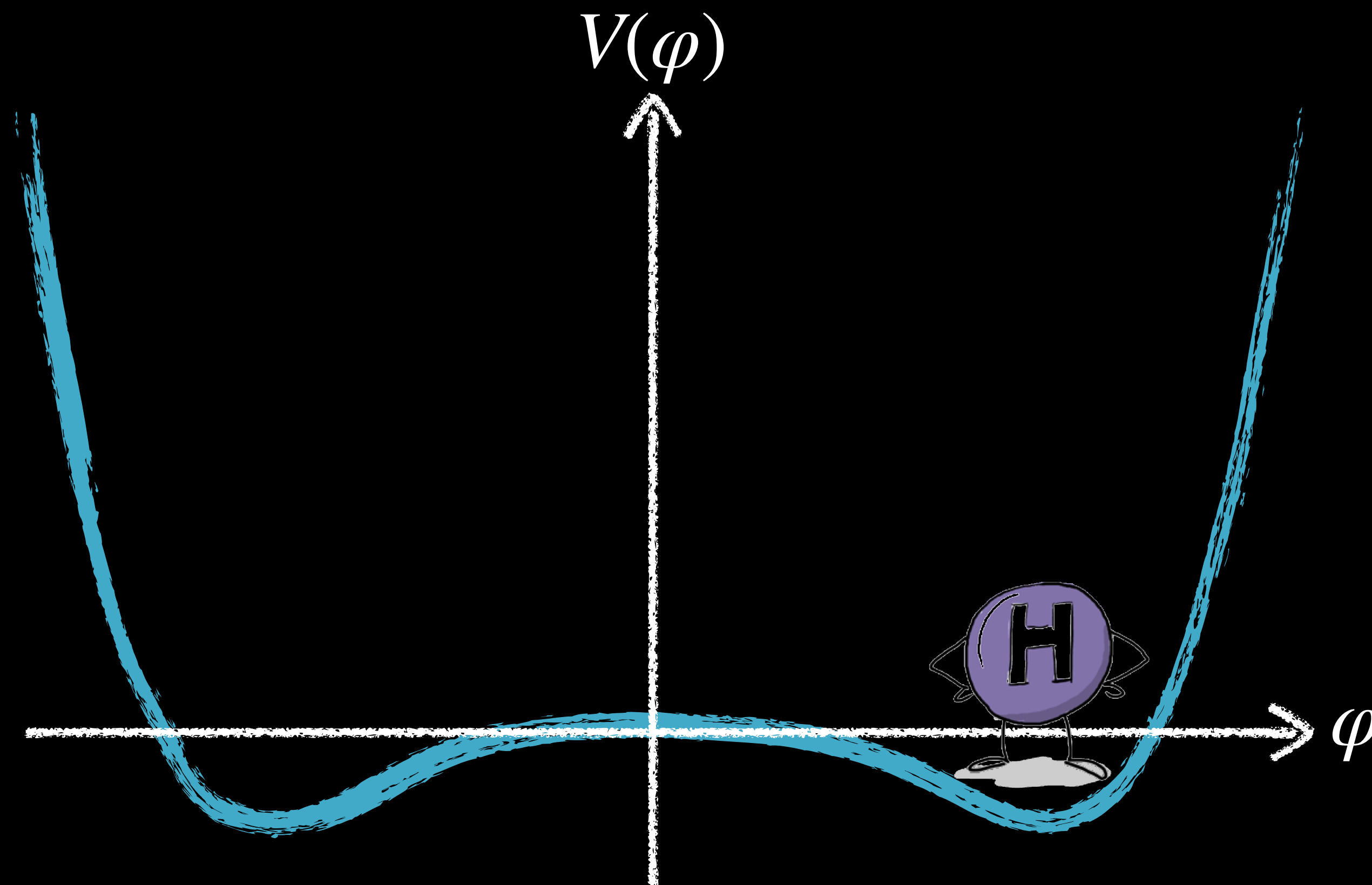
Initially, the expansion of the Universe accelerates. The acceleration is a force known as 'dark energy', completely unknown.

GRAVITATIONAL WAVES FROM A PT

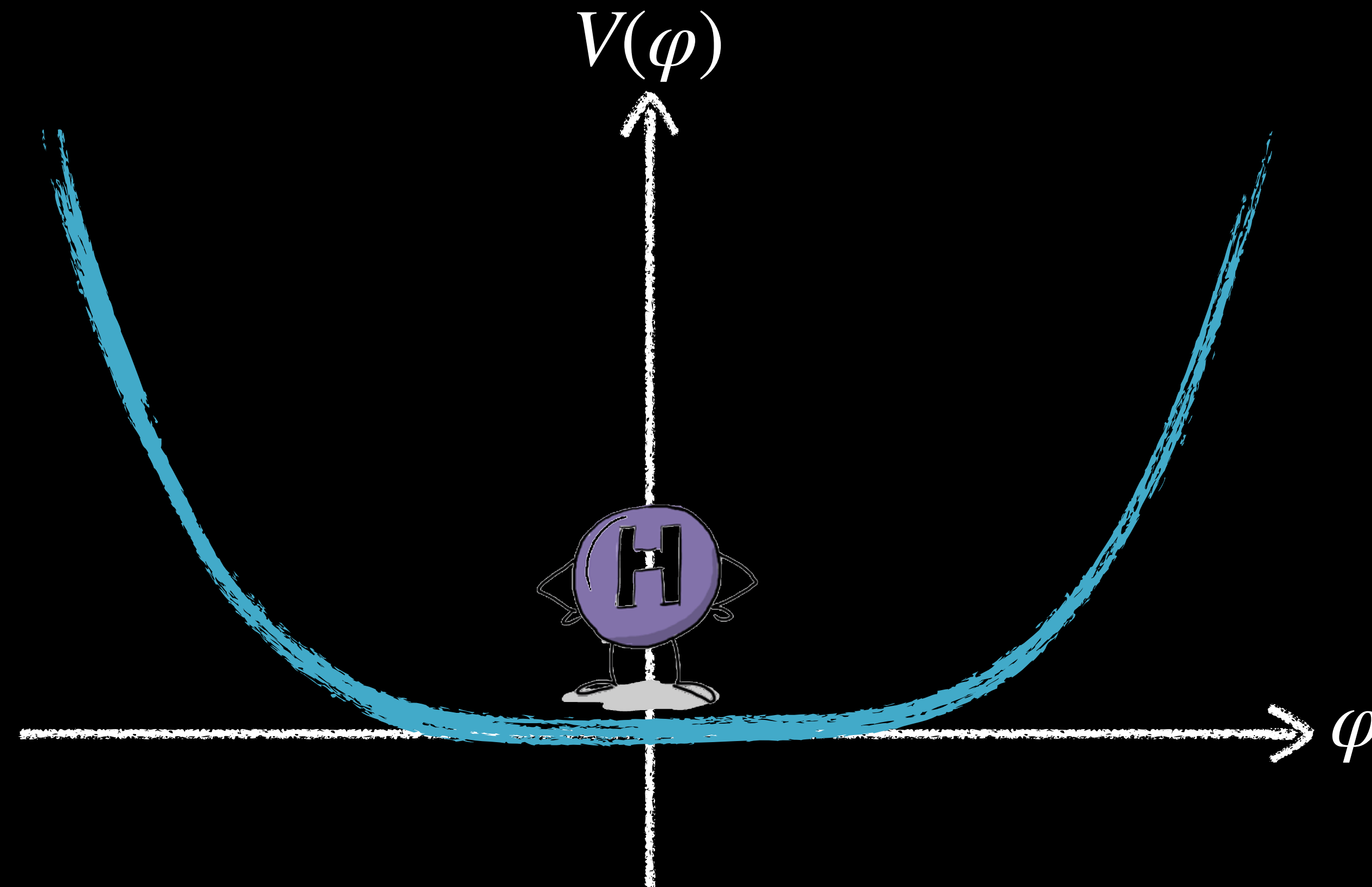


[figure credit: Christopher Moore, Robert Cole and Christopher Berry]

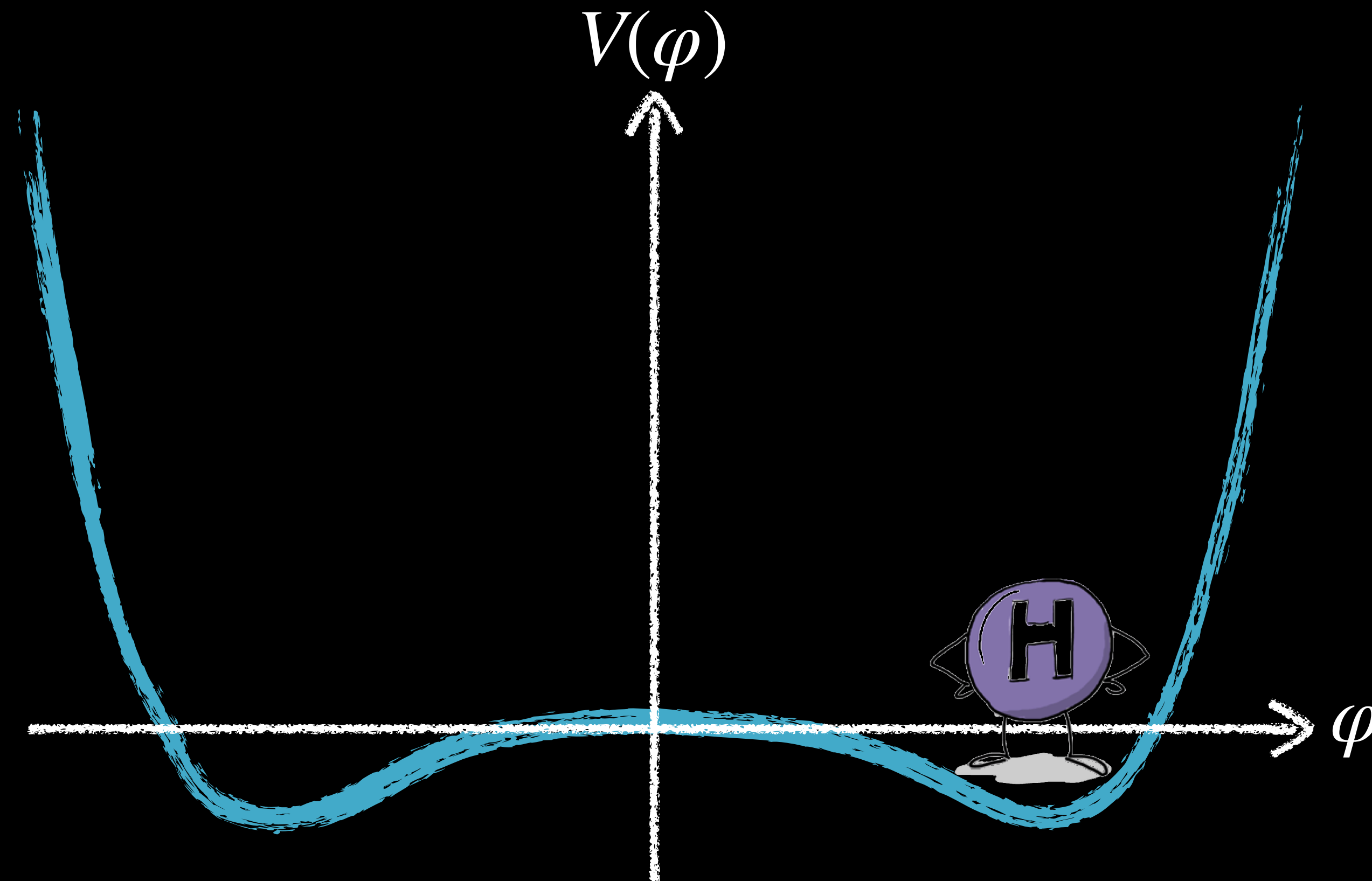
EXPERIMENT: HIGGS EXISTS



THEORY: NO VEV IN THE PAST



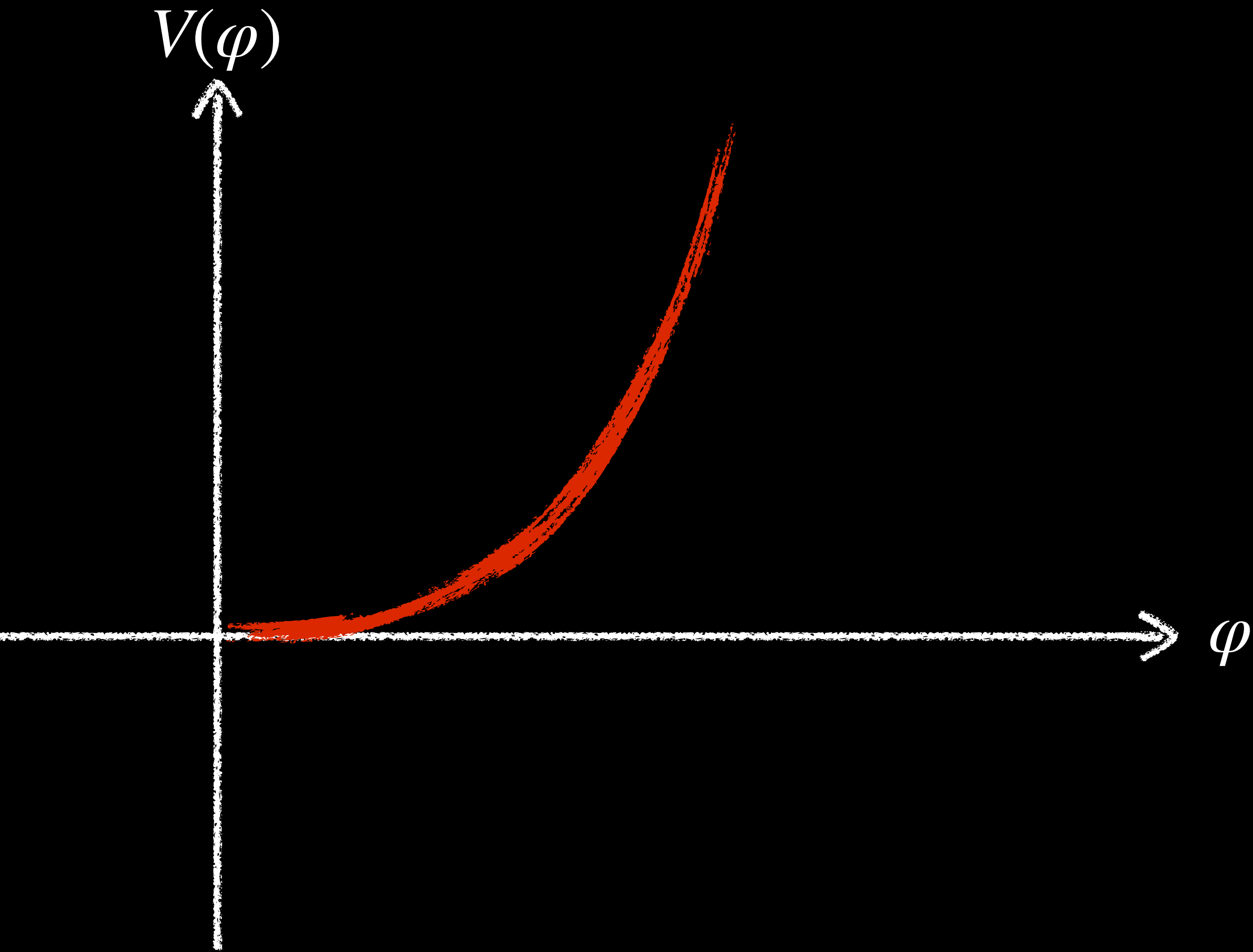
PHASE TRANSITION HAPPENED!



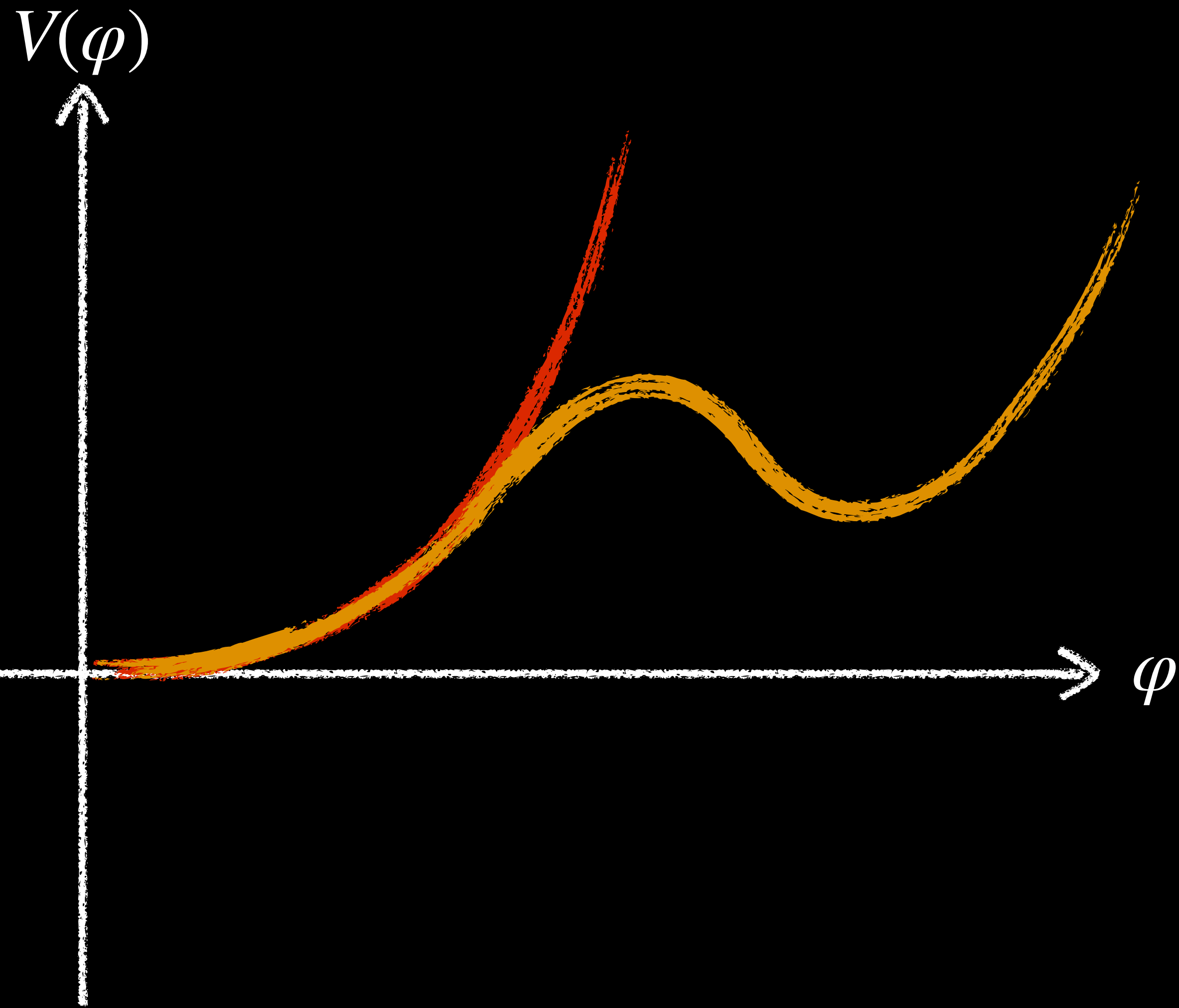
STOCHASTIC
GRAVITATIONAL-
WAVE BACKGROUND
FROM FIRST-ORDER
PHASE TRANSITIONS



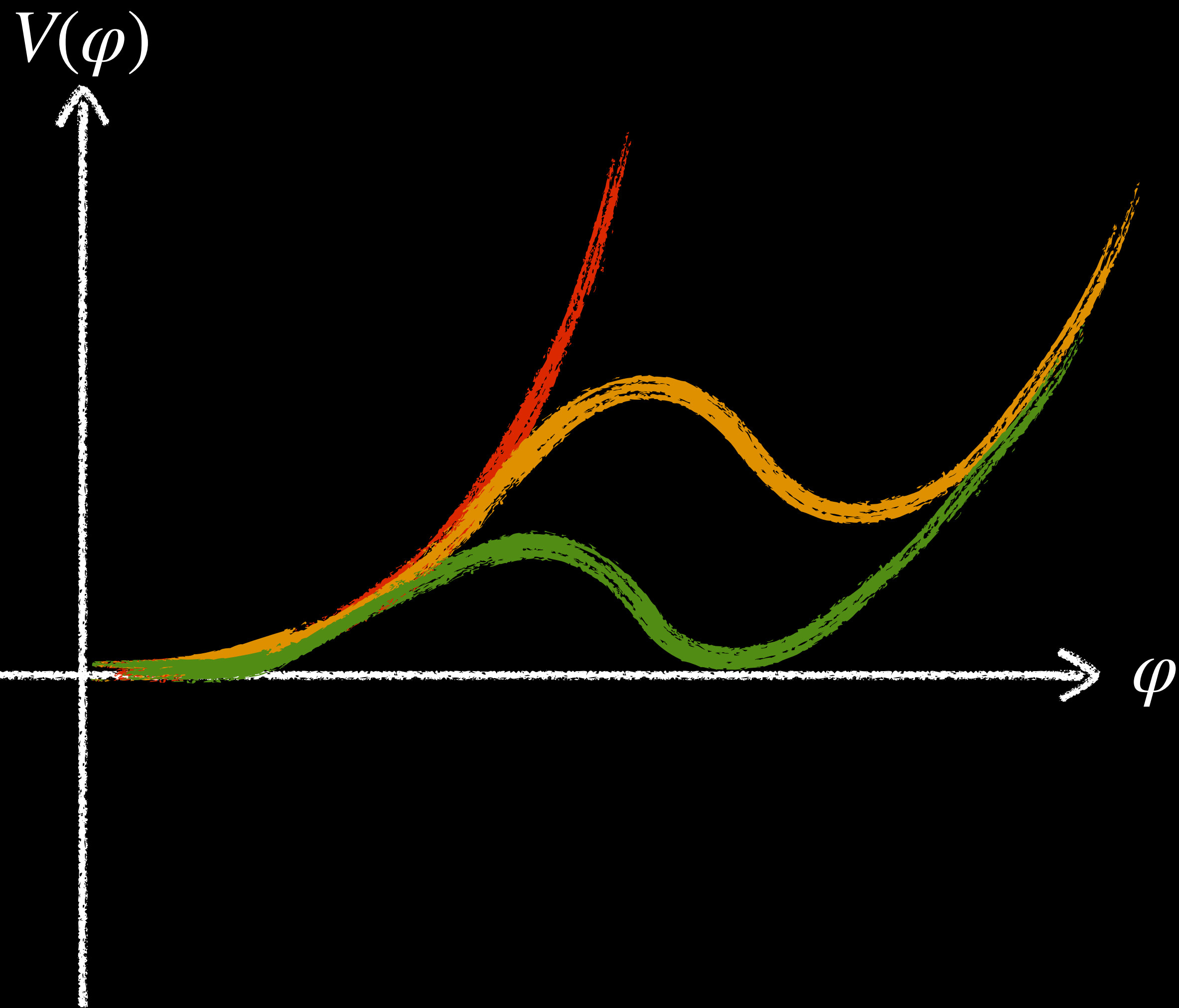
FIRST-ORDER PHASE TRANSITION



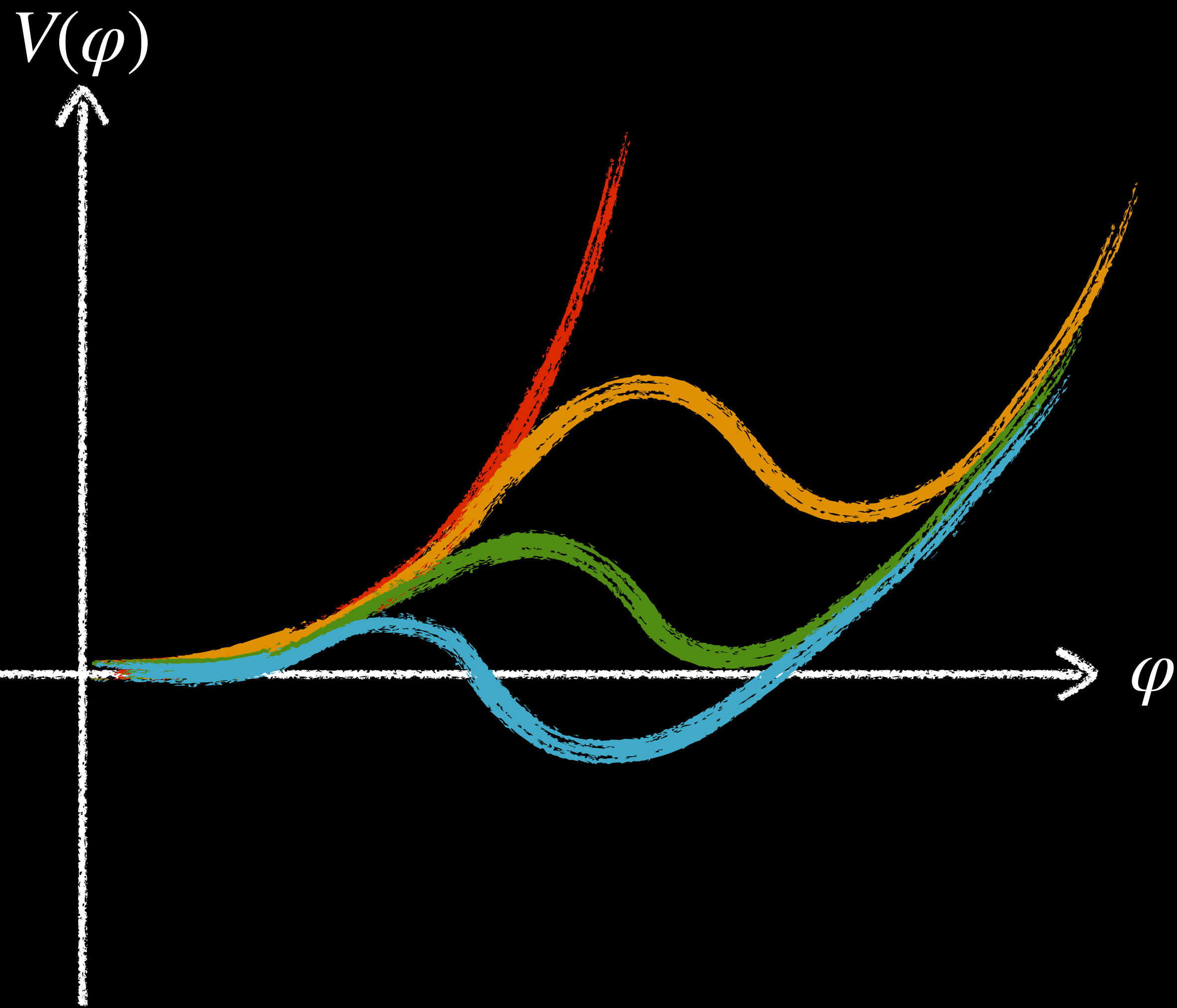
FIRST-ORDER PHASE TRANSITION



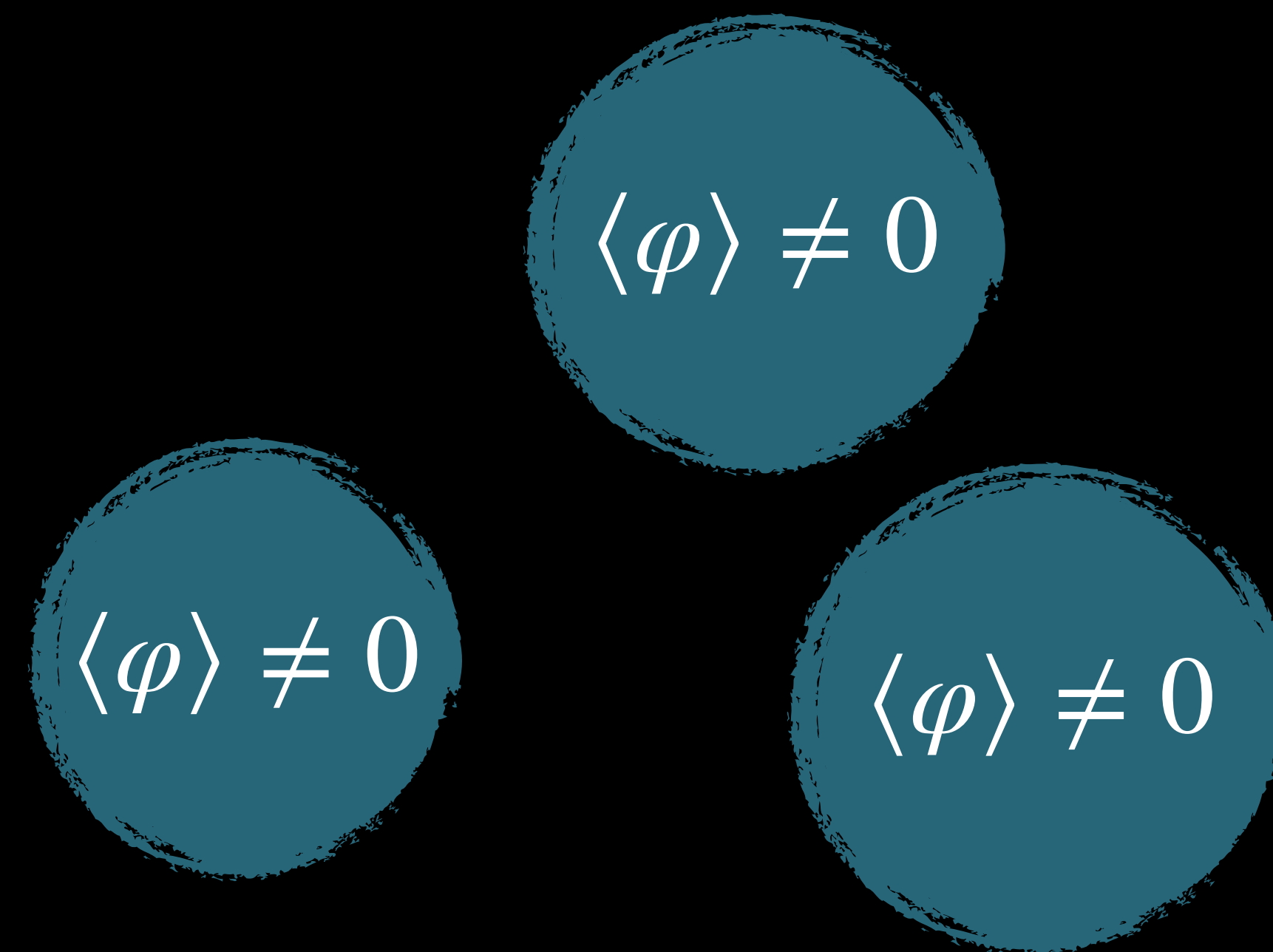
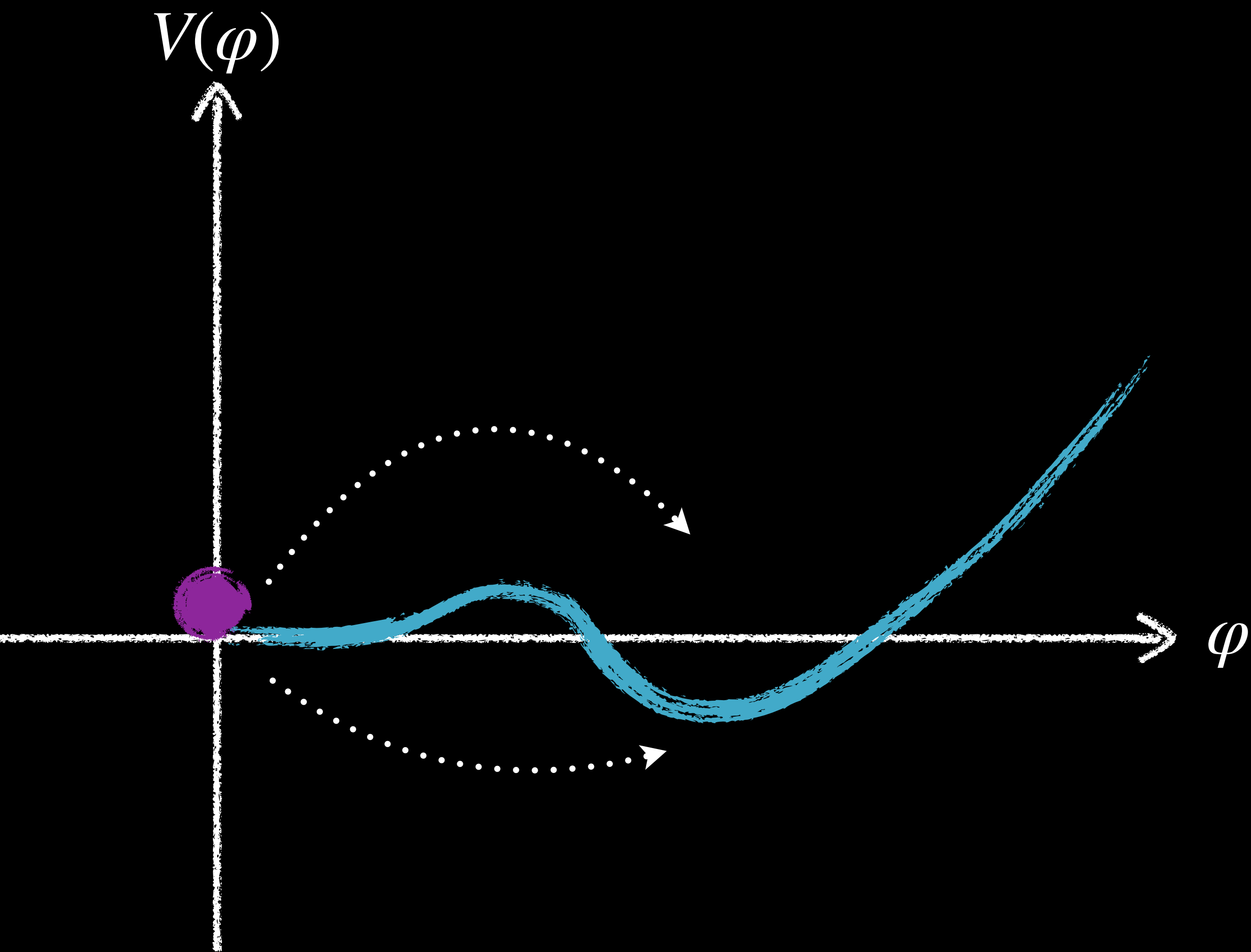
FIRST-ORDER PHASE TRANSITION



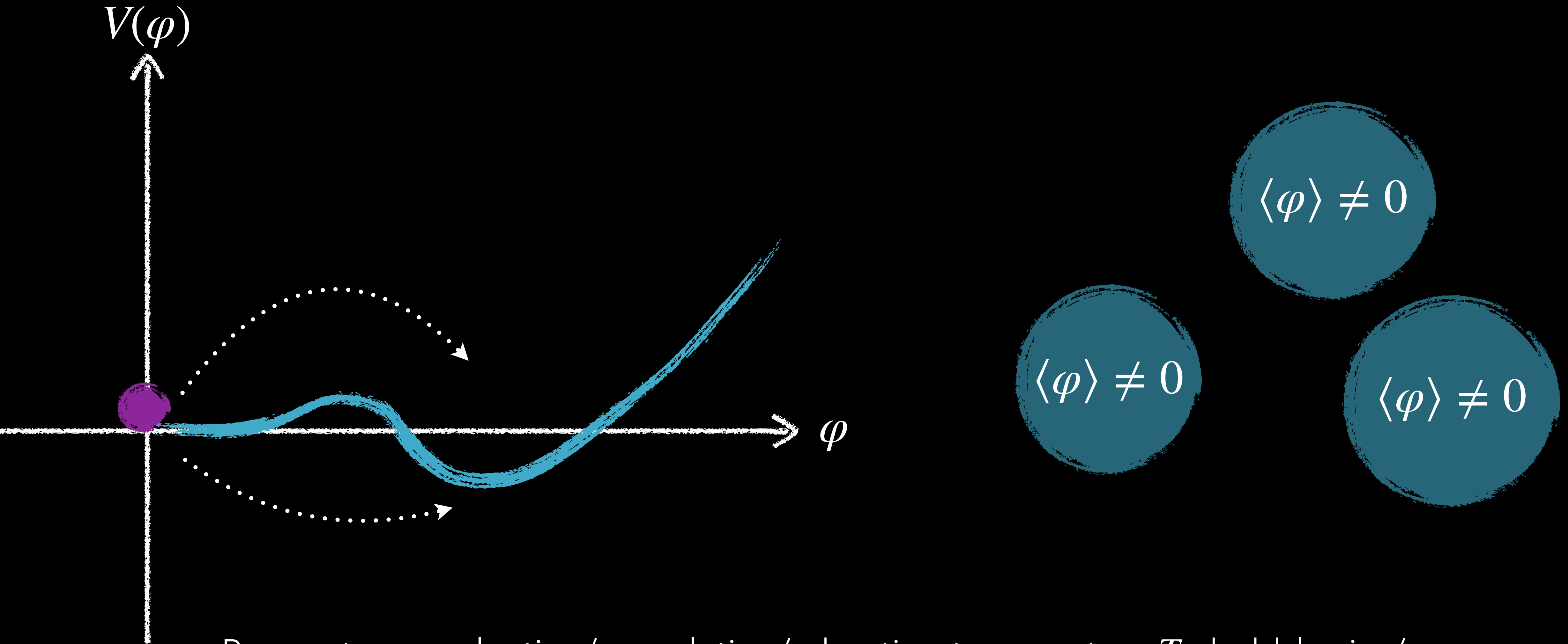
FIRST-ORDER PHASE TRANSITION



FIRST-ORDER PHASE TRANSITION



FIRST-ORDER PHASE TRANSITION



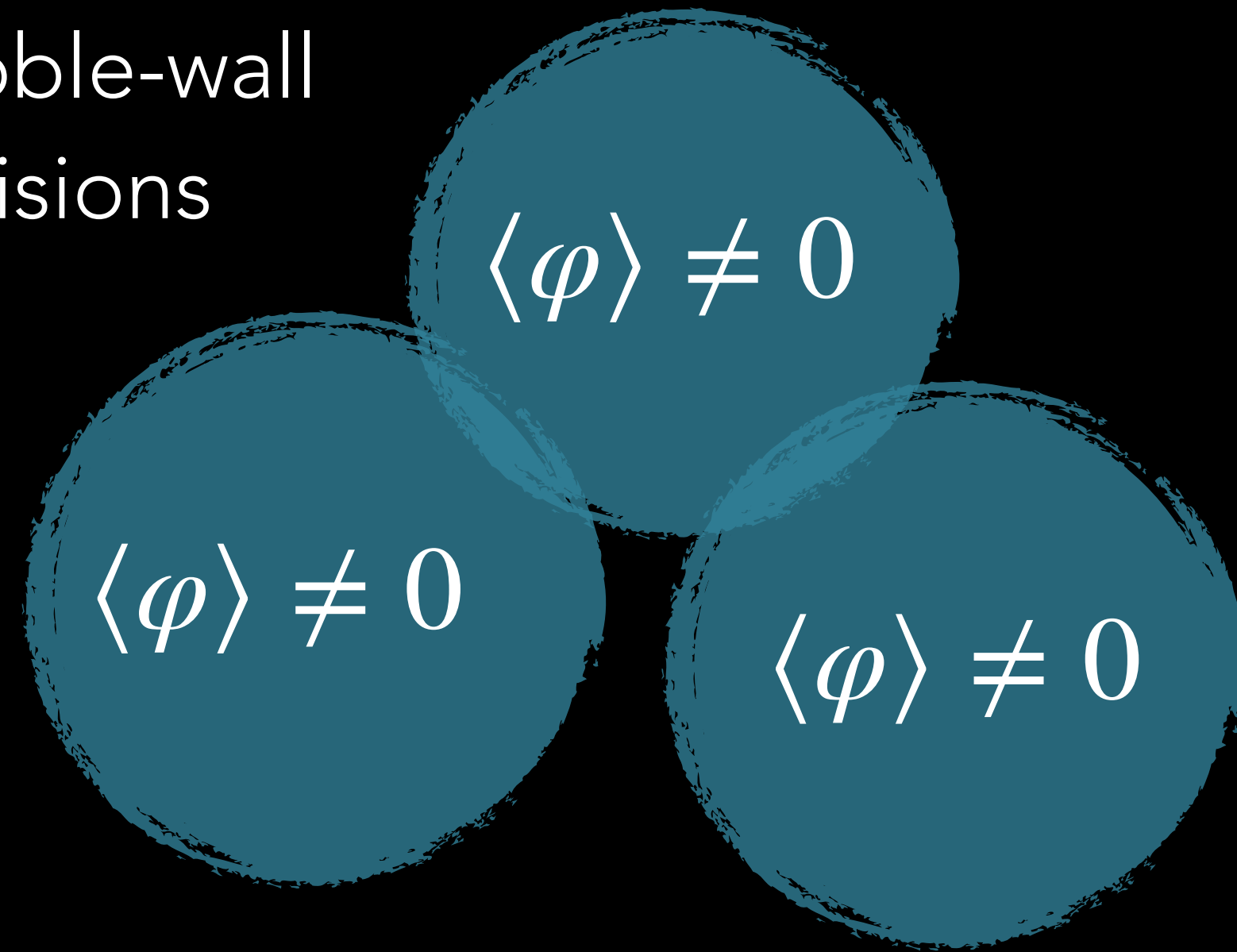
Parameters: nucleation/percolation/reheating temperature T_* , bubble size/
transition rate R_*/β_* , transition strength α , bubble-wall velocity v_w

BUBBLES AND PLASMA SOURCE GRAVITATIONAL WAVES


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

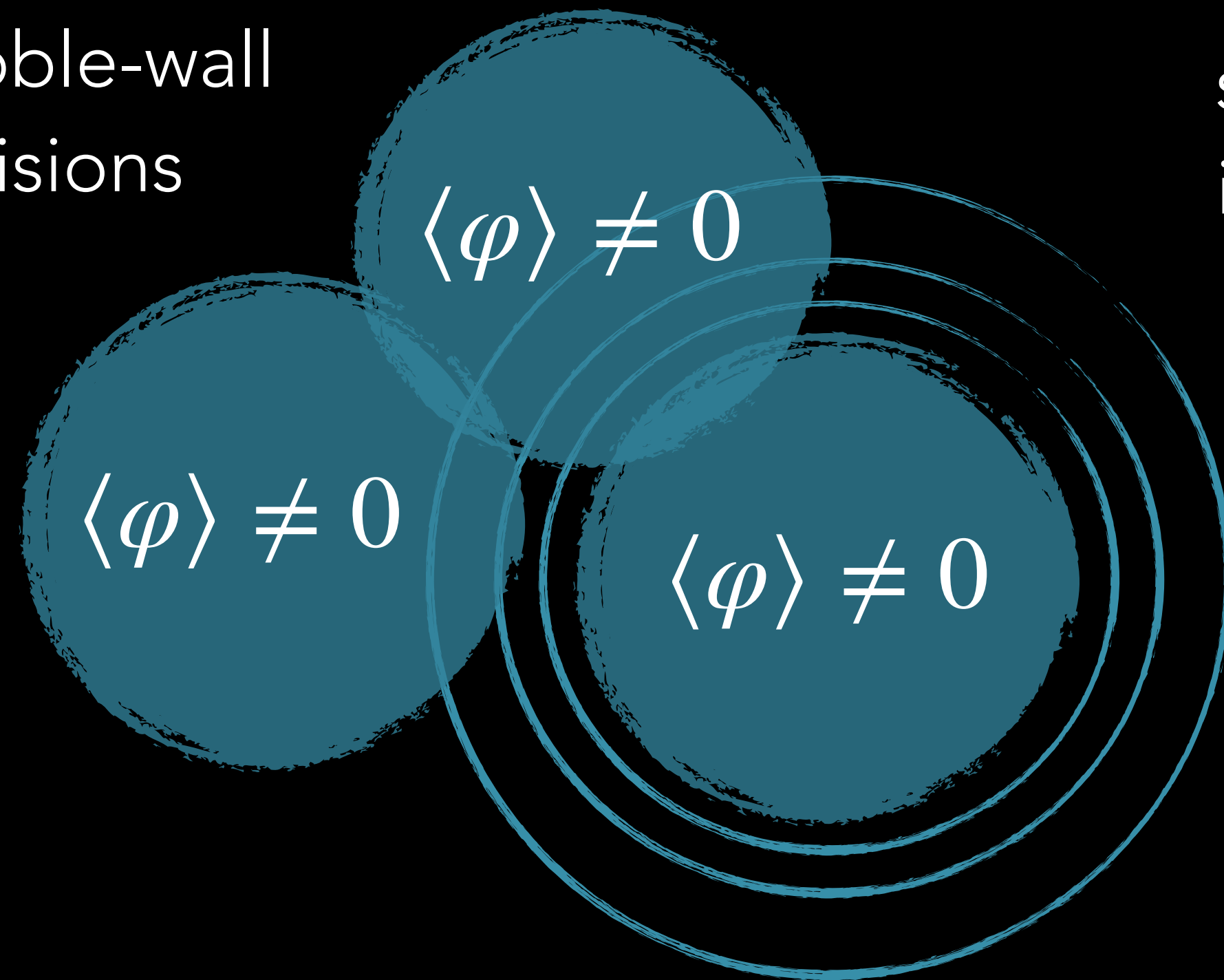
BUBBLES AND PLASMA SOURCE GRAVITATIONAL WAVES

bubble-wall
collisions



BUBBLES AND PLASMA SOURCE GRAVITATIONAL WAVES

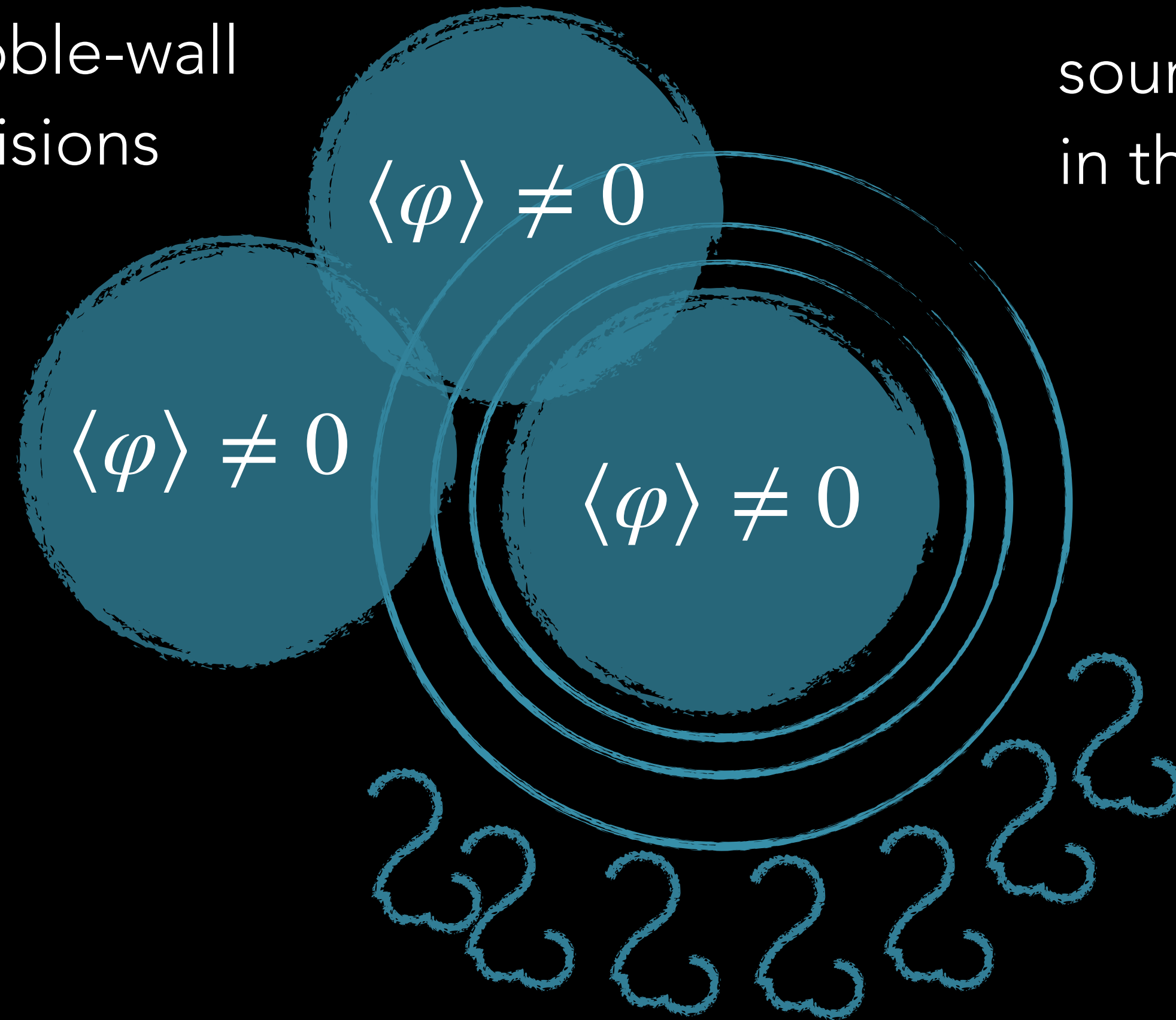
bubble-wall
collisions



sound waves
in the plasma

BUBBLES AND PLASMA SOURCE GRAVITATIONAL WAVES

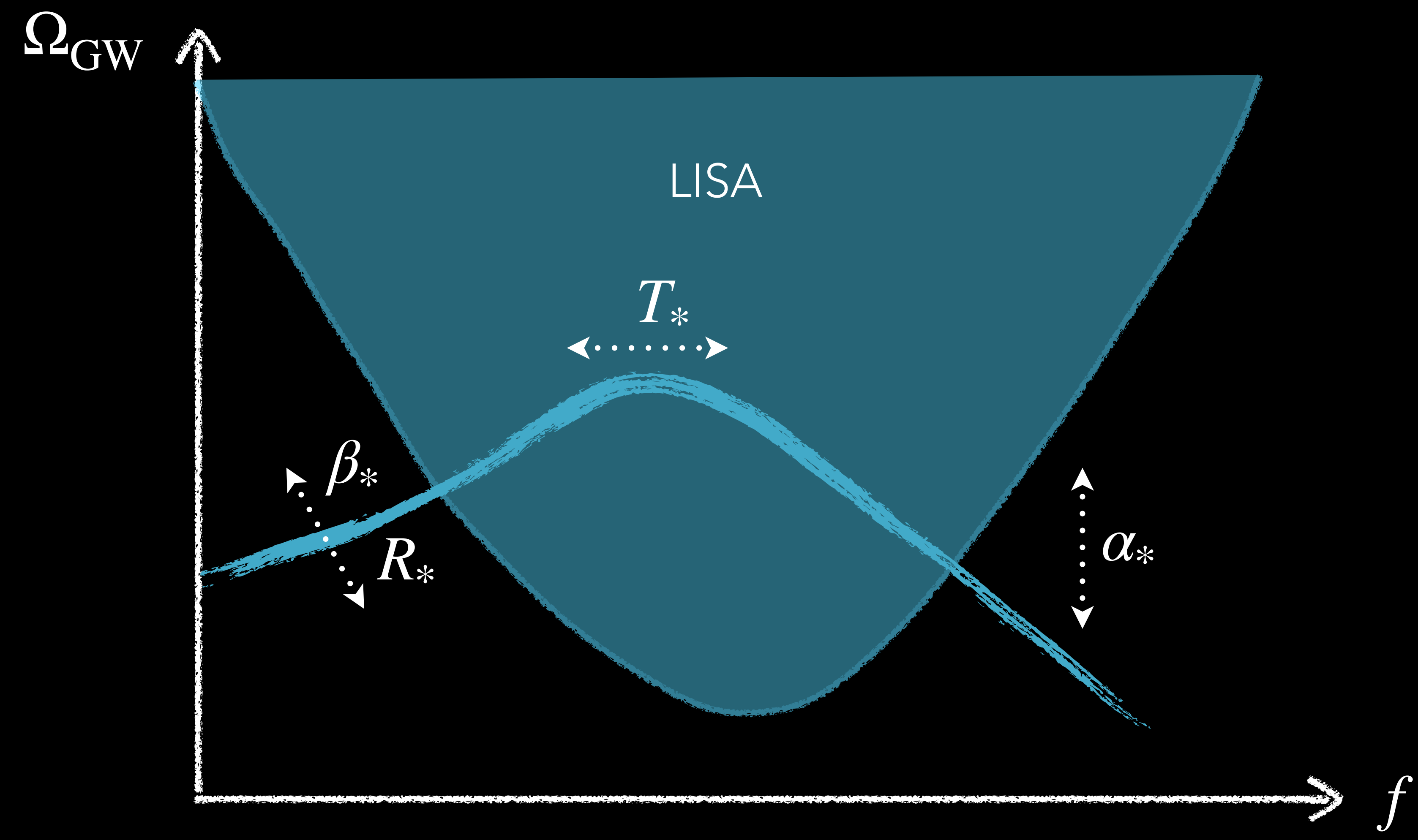
bubble-wall
collisions



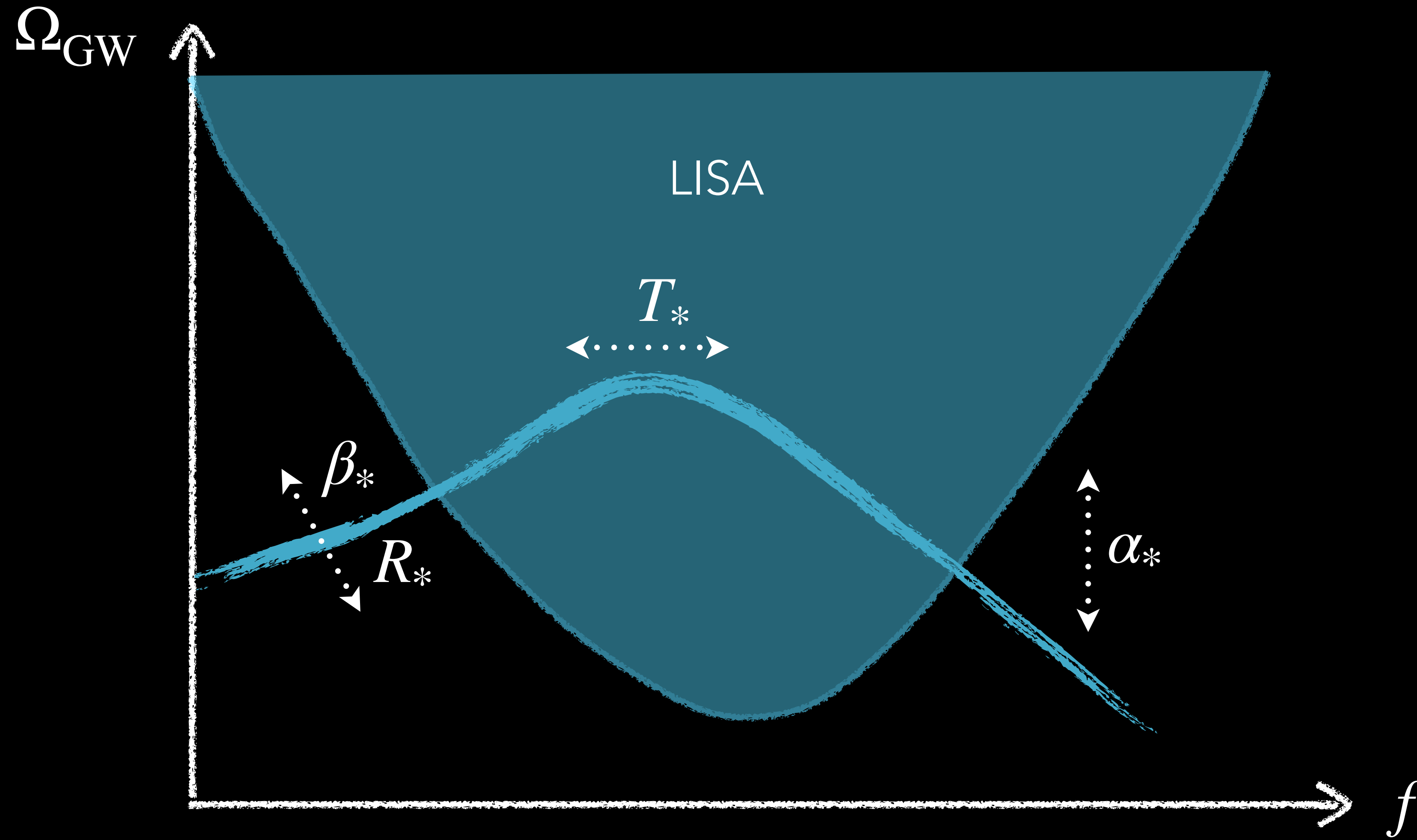
sound waves
in the plasma

turbulence in
the plasma

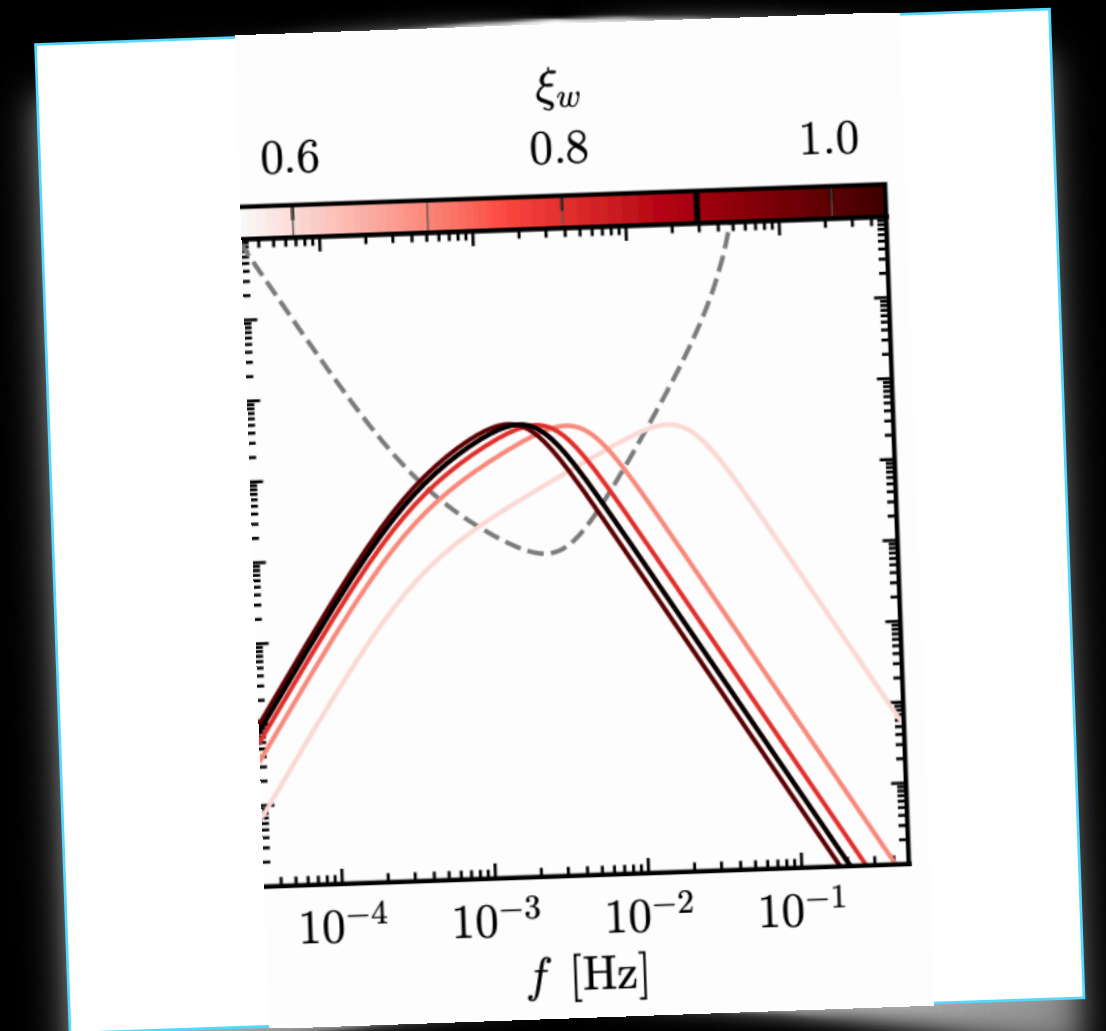
THERMODYNAMICAL PARAMETERS VS GW



THERMODYNAMICAL PARAMETERS VS GW



+ wall velocity v_w

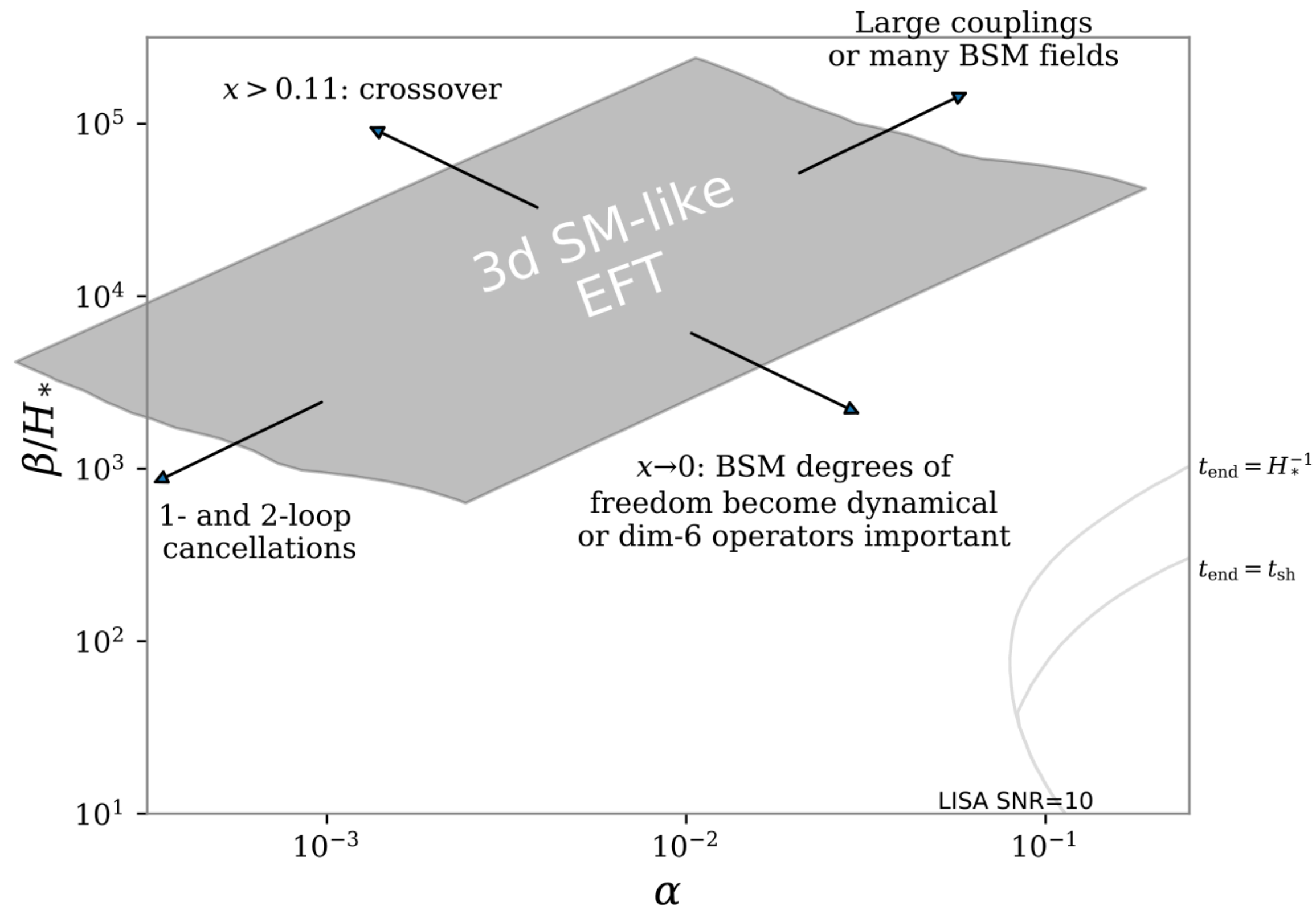


[C. Caprini et al., LISA CosWG, 2403.03723]

In SM the PT is crossover.

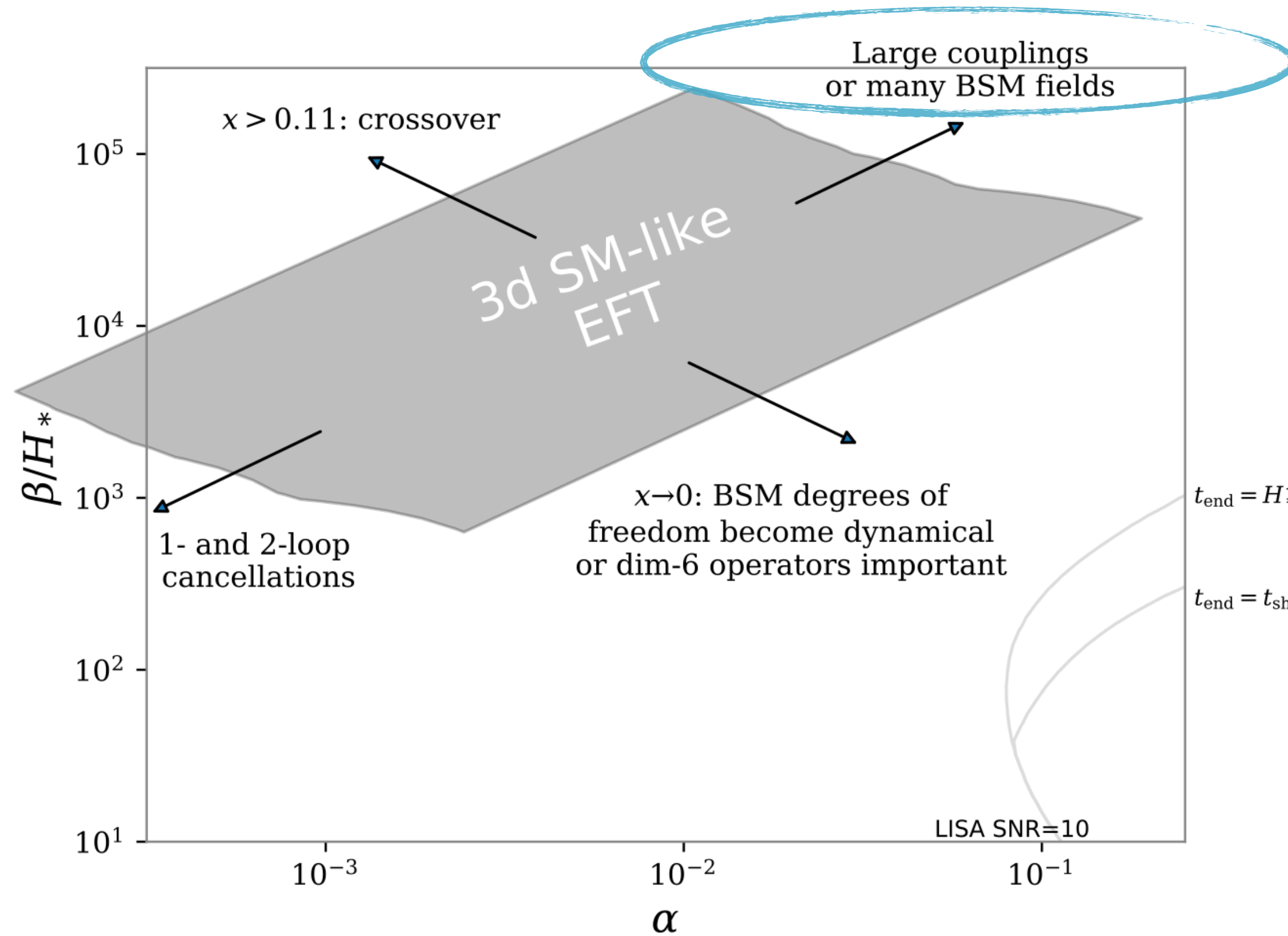
The search for a first-order PT is
a search for New Physics!

FIRST-ORDER PT CANNOT BE SM-LIKE



[Figure from: Phys.Rev.D 100 (2019) 11, 115024, O. Gould, J. Kozaczuk, L. Niemi, M. J. Ramsey-Musolf, T. V.I. Tenkanen, D. J. Weir]

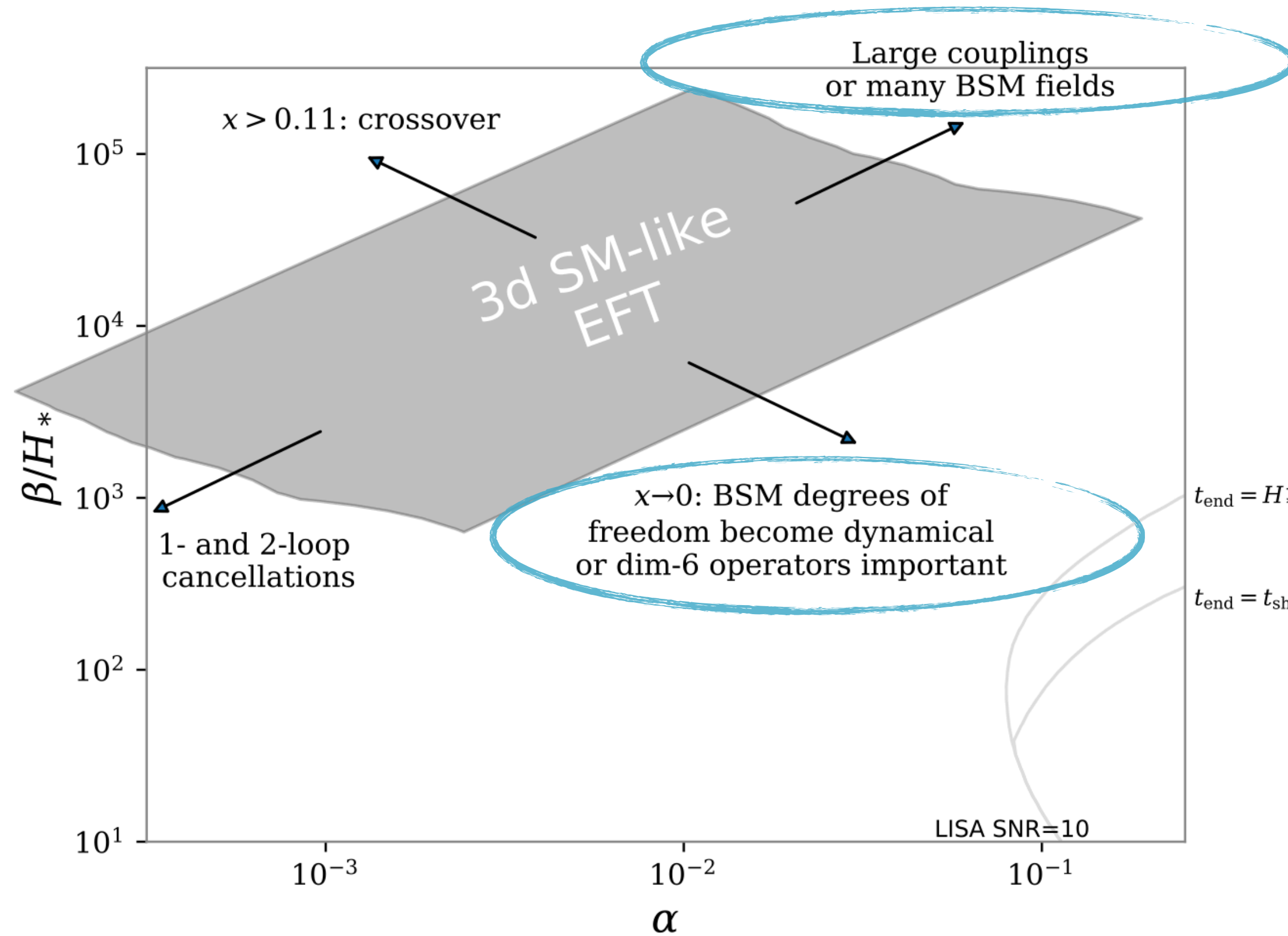
FIRST-ORDER PT CANNOT BE SM-LIKE



Scalar extensions of the SM
(large coupling)

[Figure from: Phys.Rev.D 100 (2019) 11, 115024, O. Gould, J. Kozaczuk, L. Niemi, M. J. Ramsey-Musolf, T. V.I. Tenkanen, D. J. Weir]

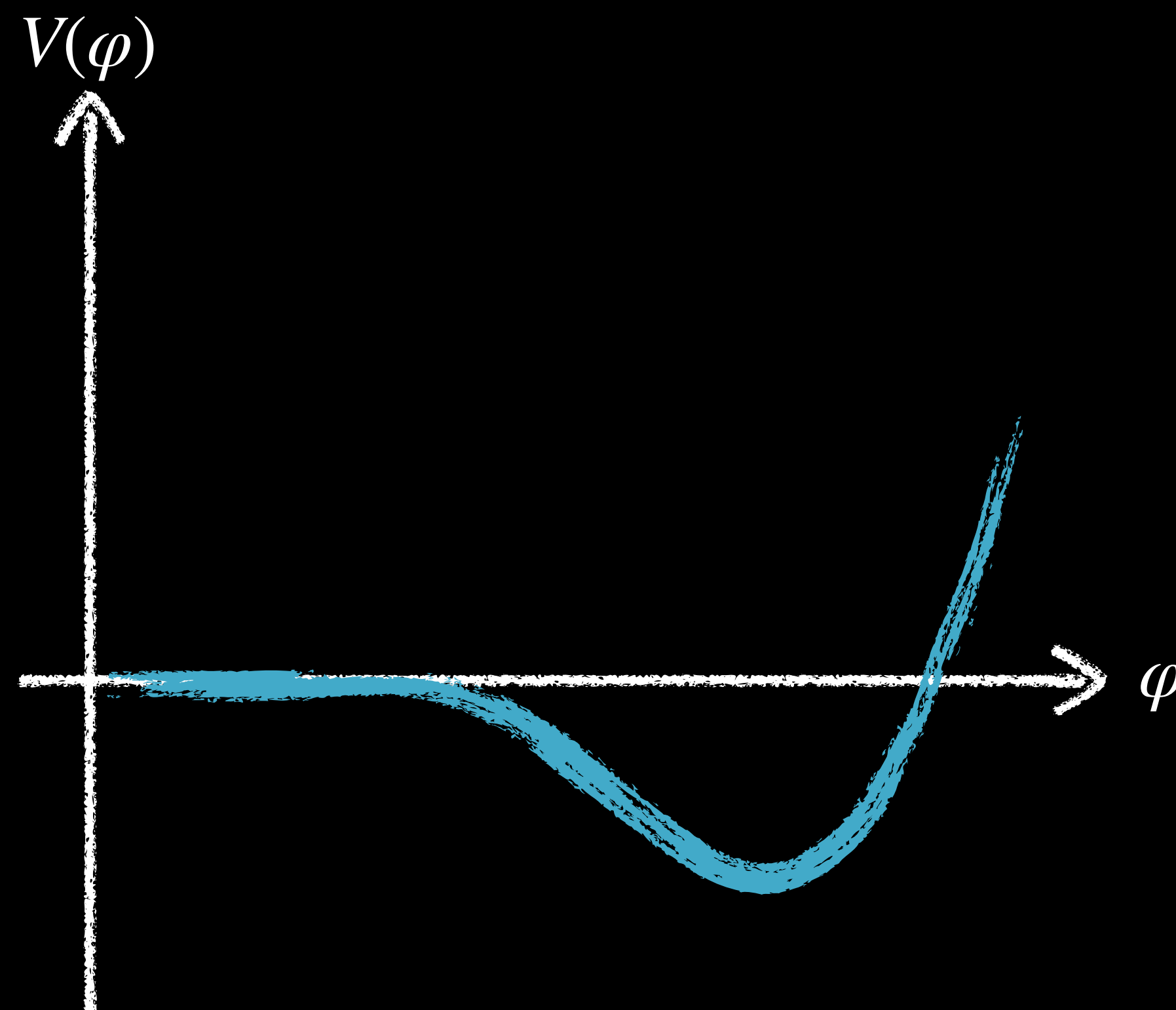
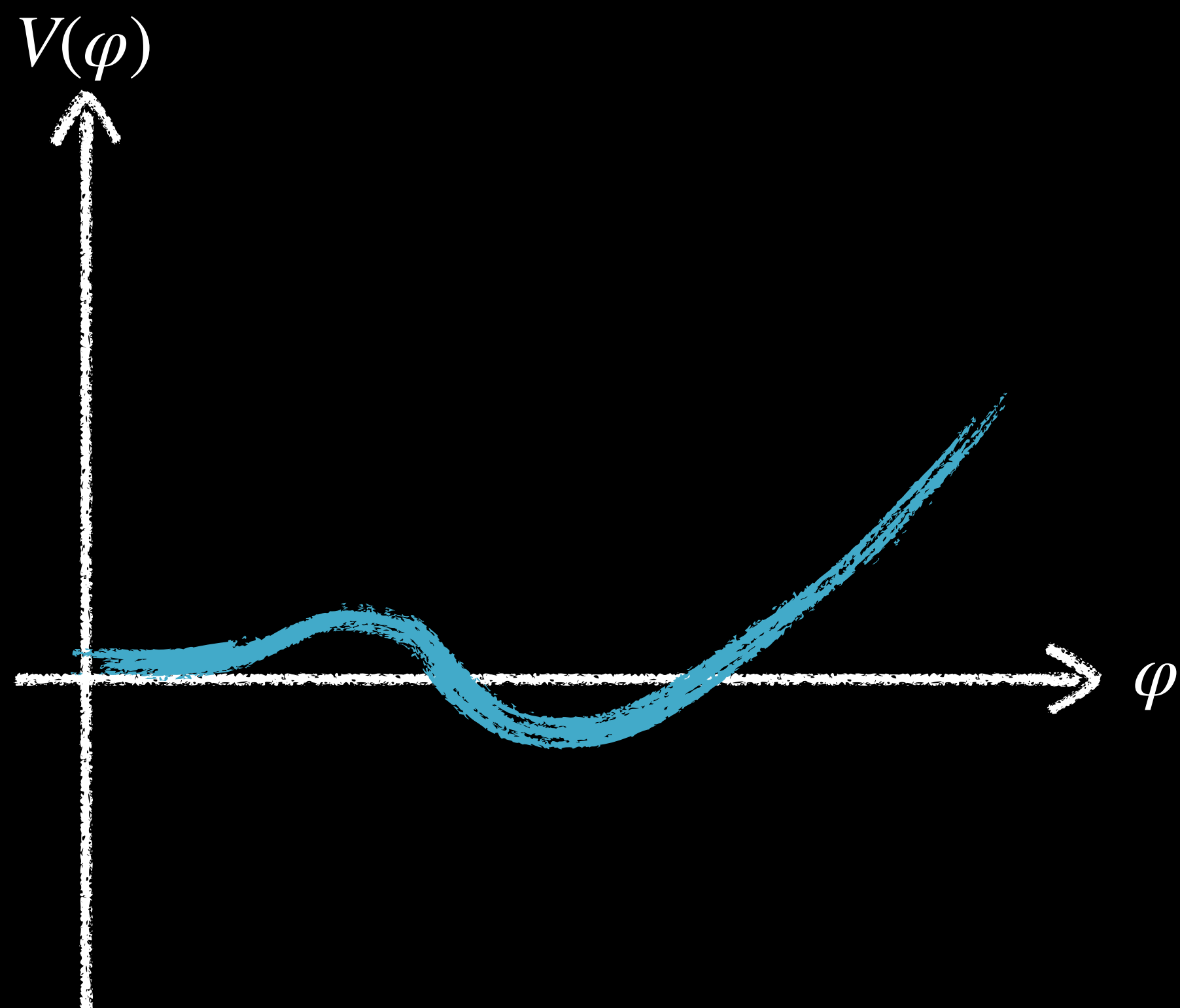
FIRST-ORDER PT CANNOT BE SM-LIKE



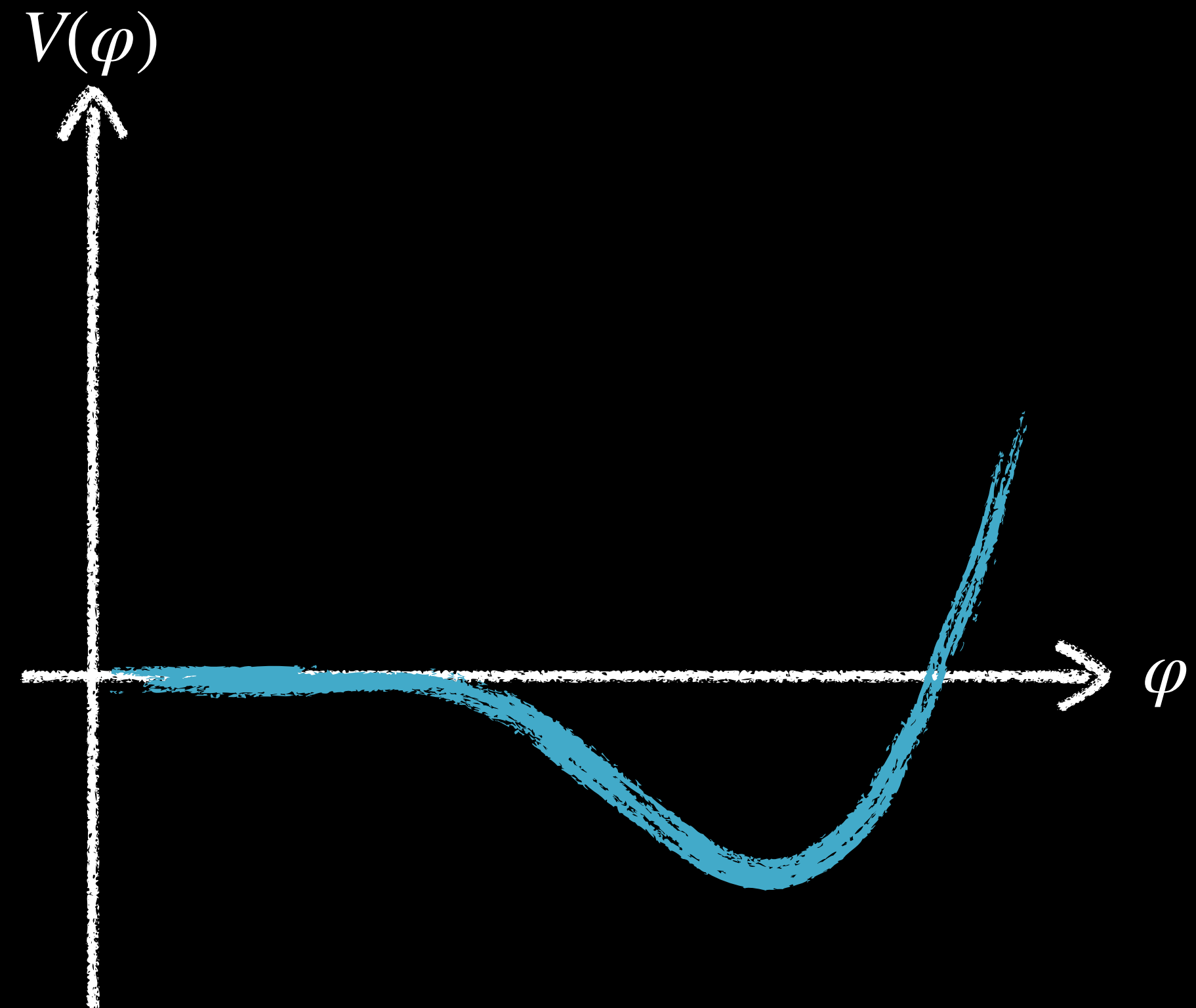
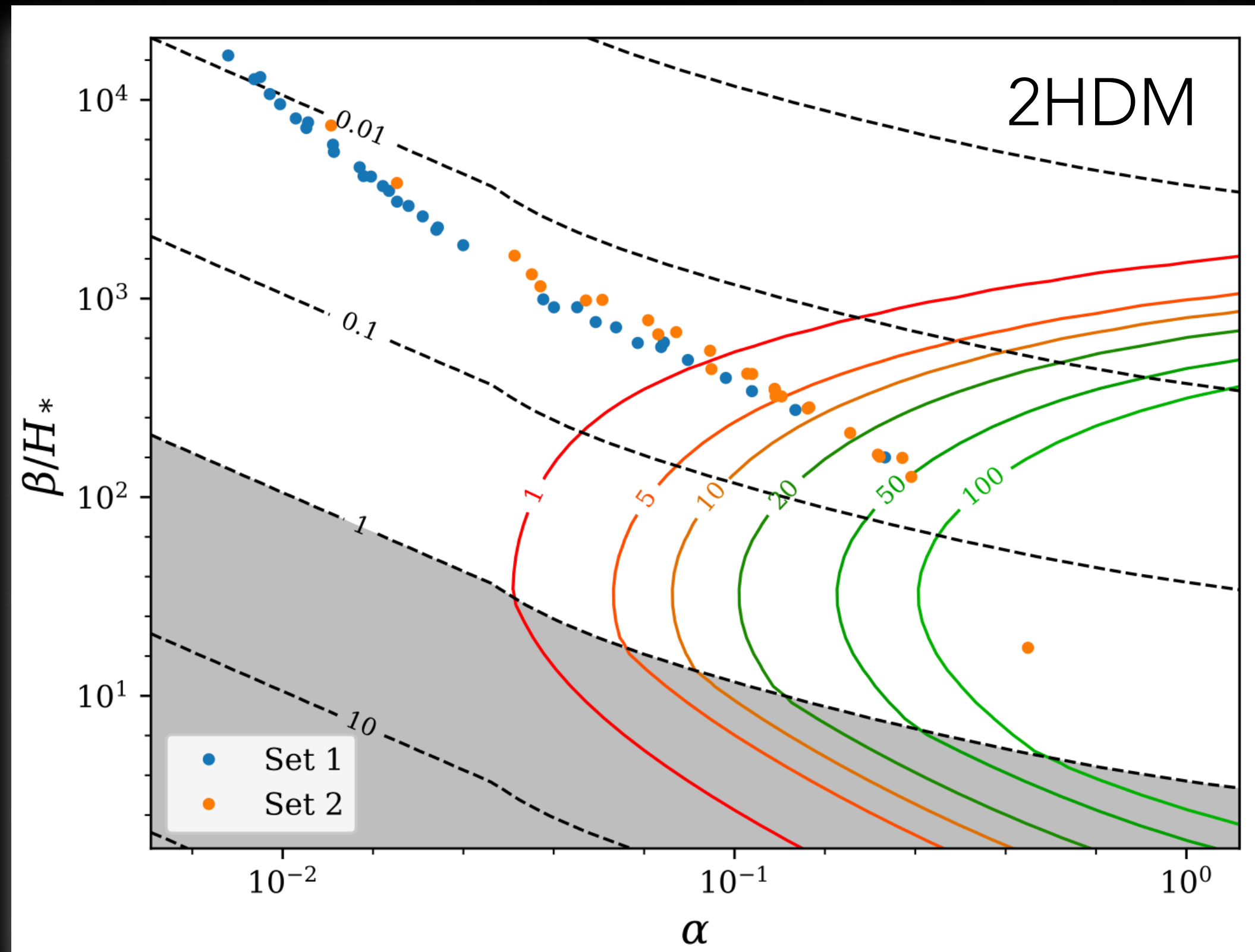
Scalar extensions of the SM
(large coupling)

PT for a new field

PHASE TRANSITION: ORDINARY VS SUPERCOOLED

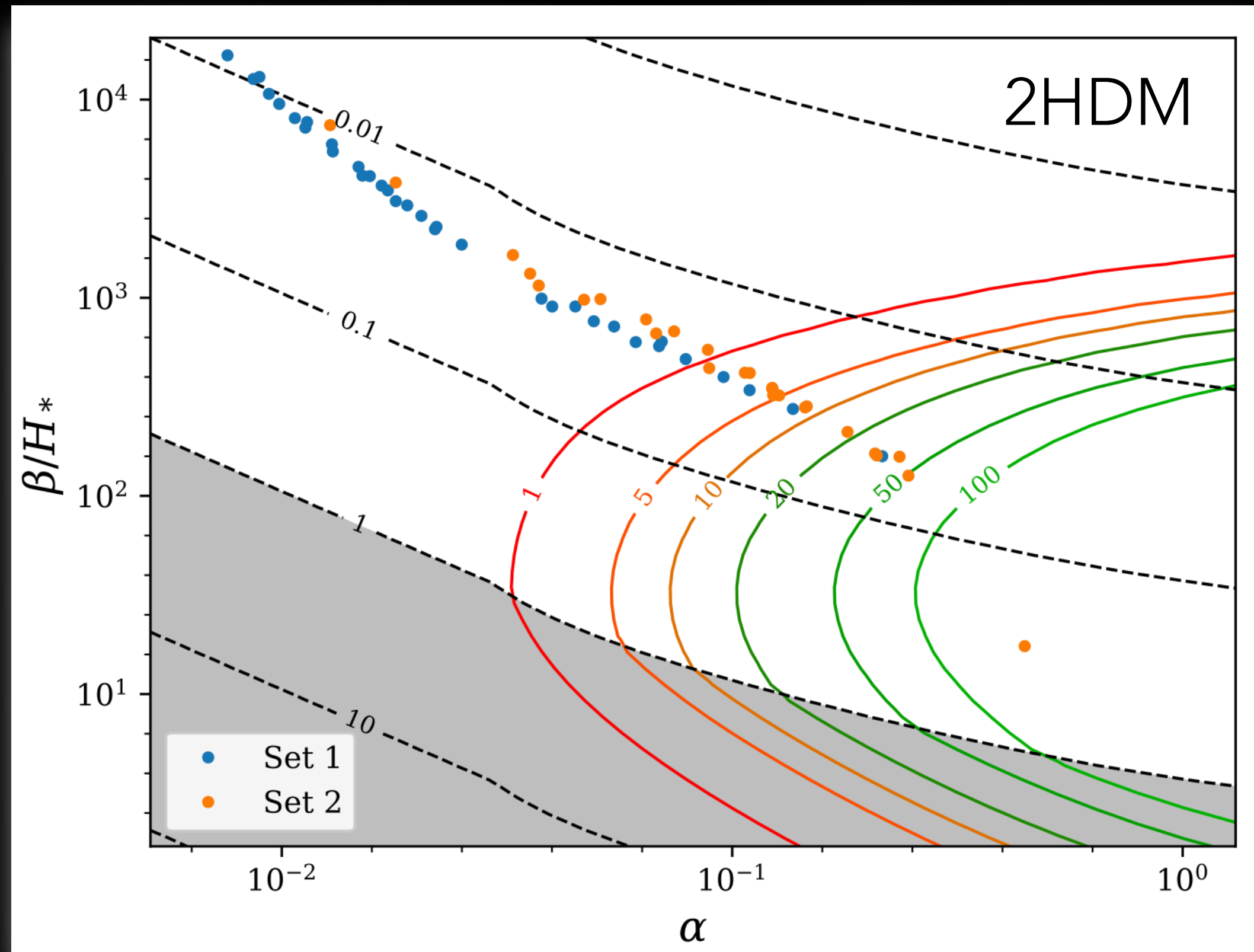


PHASE TRANSITION: ORDINARY VS SUPERCOOLED

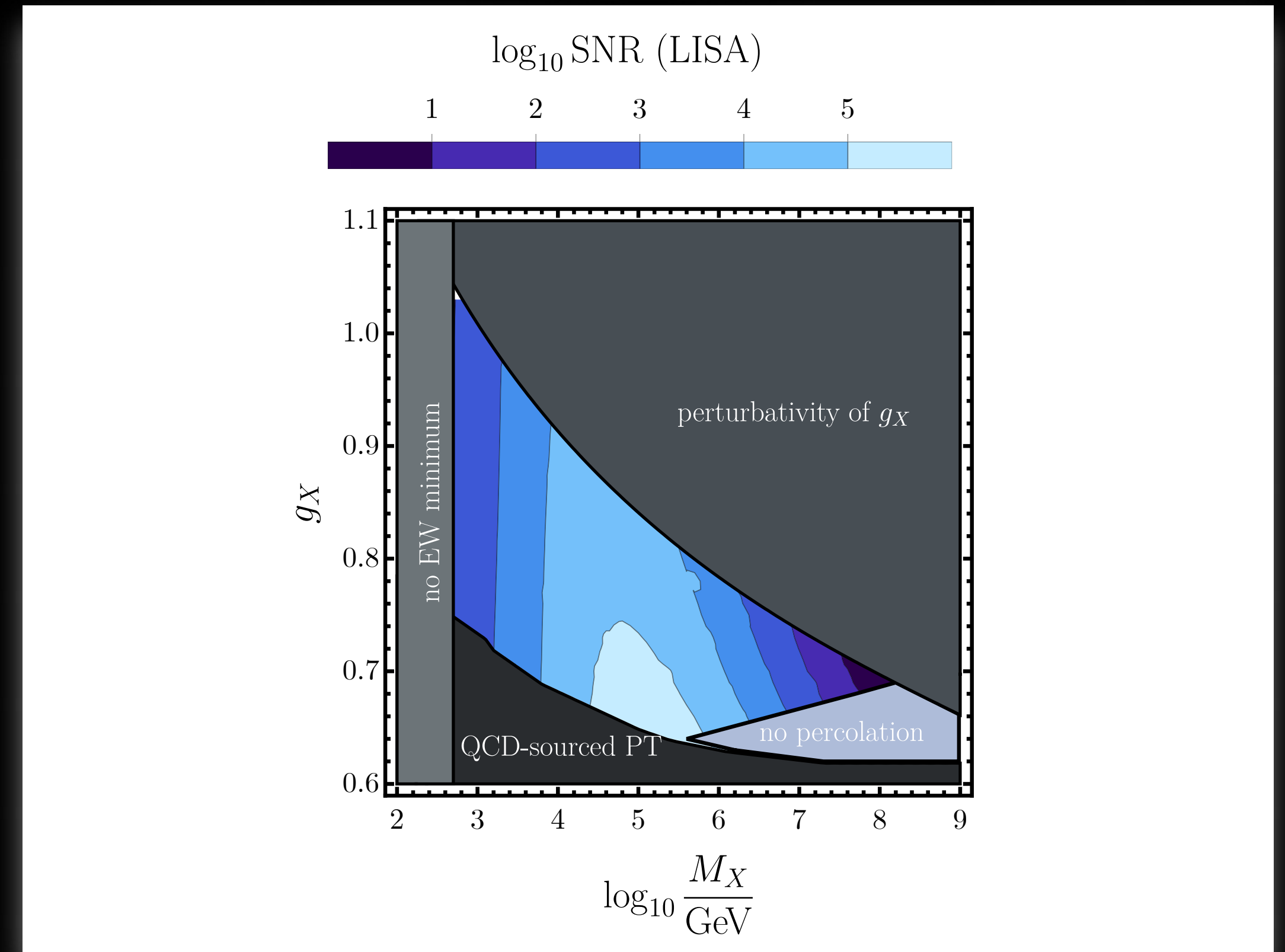


[C. Caprini et al., LISA CosWG, JCAP 03 (2020) 024]

PHASE TRANSITION: ORDINARY VS SUPERCOOLED



[C. Caprini et al., LISA CosWG, JCAP 03 (2020) 024]



[M. Kierkla, BŠ, T.V.I. Tenkanen, J. van de Vis, JHEP 02 (2024) 234]

COSMOLOGICAL
FIRST-ORDER PHASE
TRANSITION



NUCLEATION

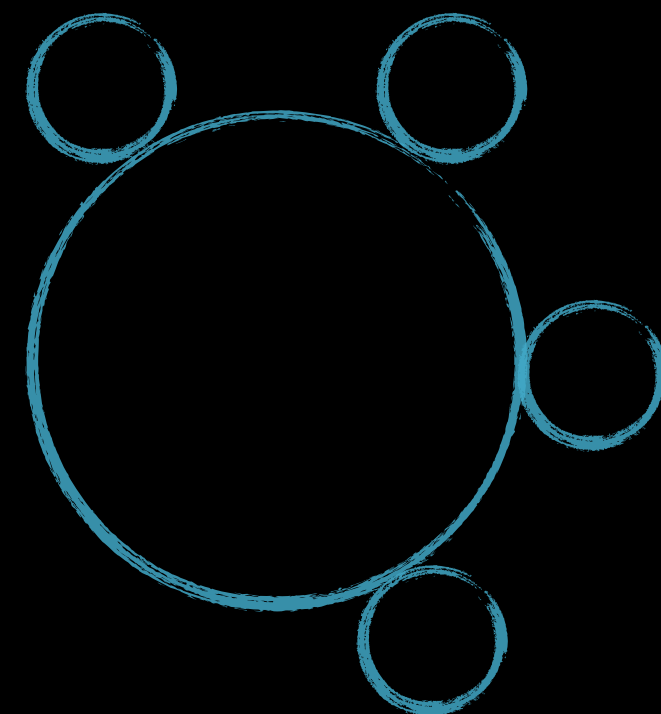
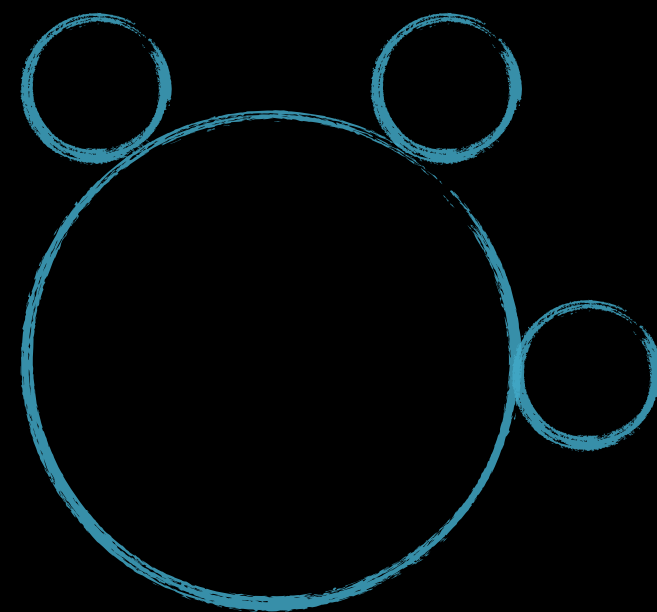
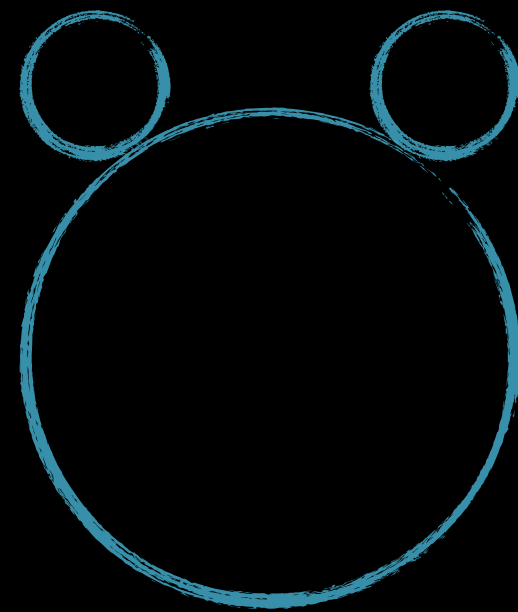
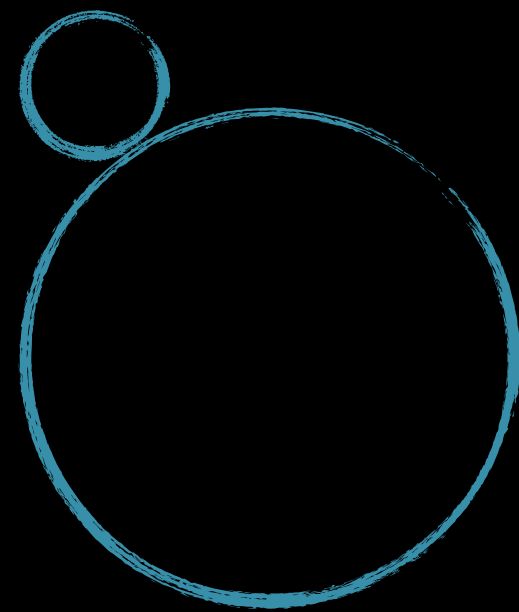
$$\Gamma = A_{\text{dyn}} \cdot A_{\text{stat}} = A_{\text{dyn}} \cdot A_{\text{det}} \cdot \exp(-S)$$

NUCLEATION

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

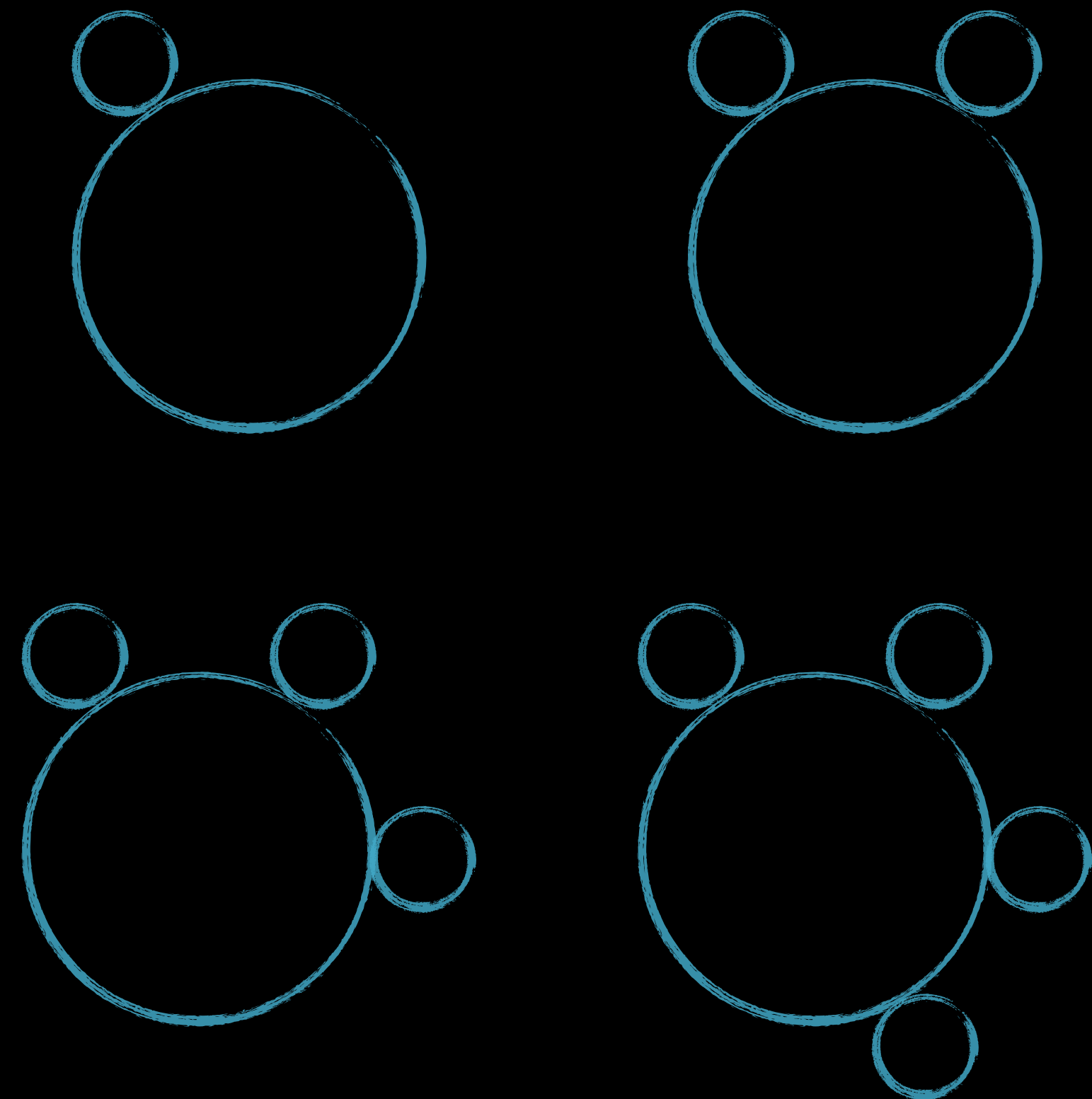
HOW FAR WILL YOU DARE TO GO?

Daisy resummation



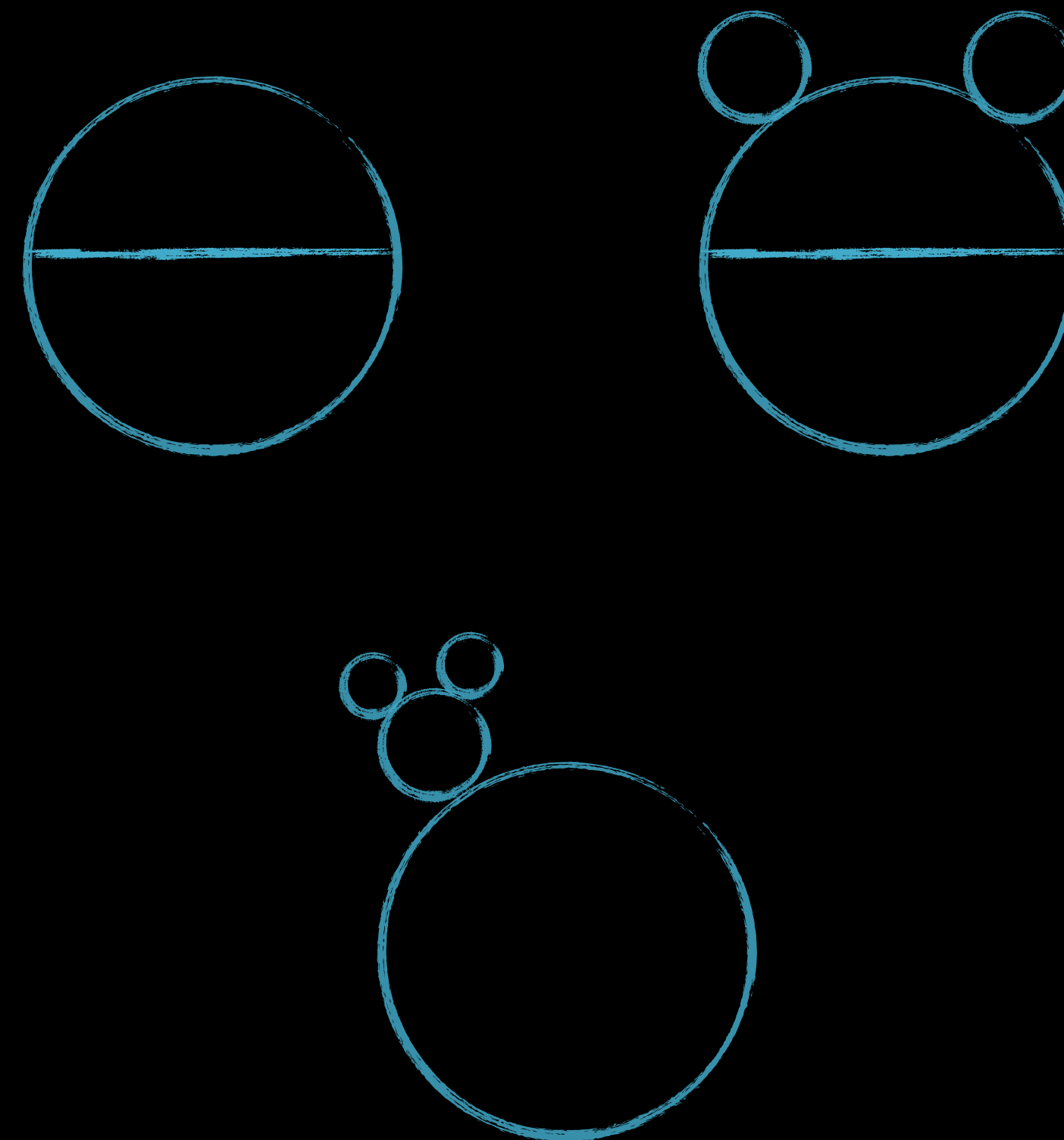
HOW FAR WILL YOU DARE TO GO?

Daisy resummation



[P. Arnold, O. Espinosa, *Phys.Rev.D* 47 (1993) 3546, R.R. Parwani, *Phys.Rev.D* 45 (1992) 4695]

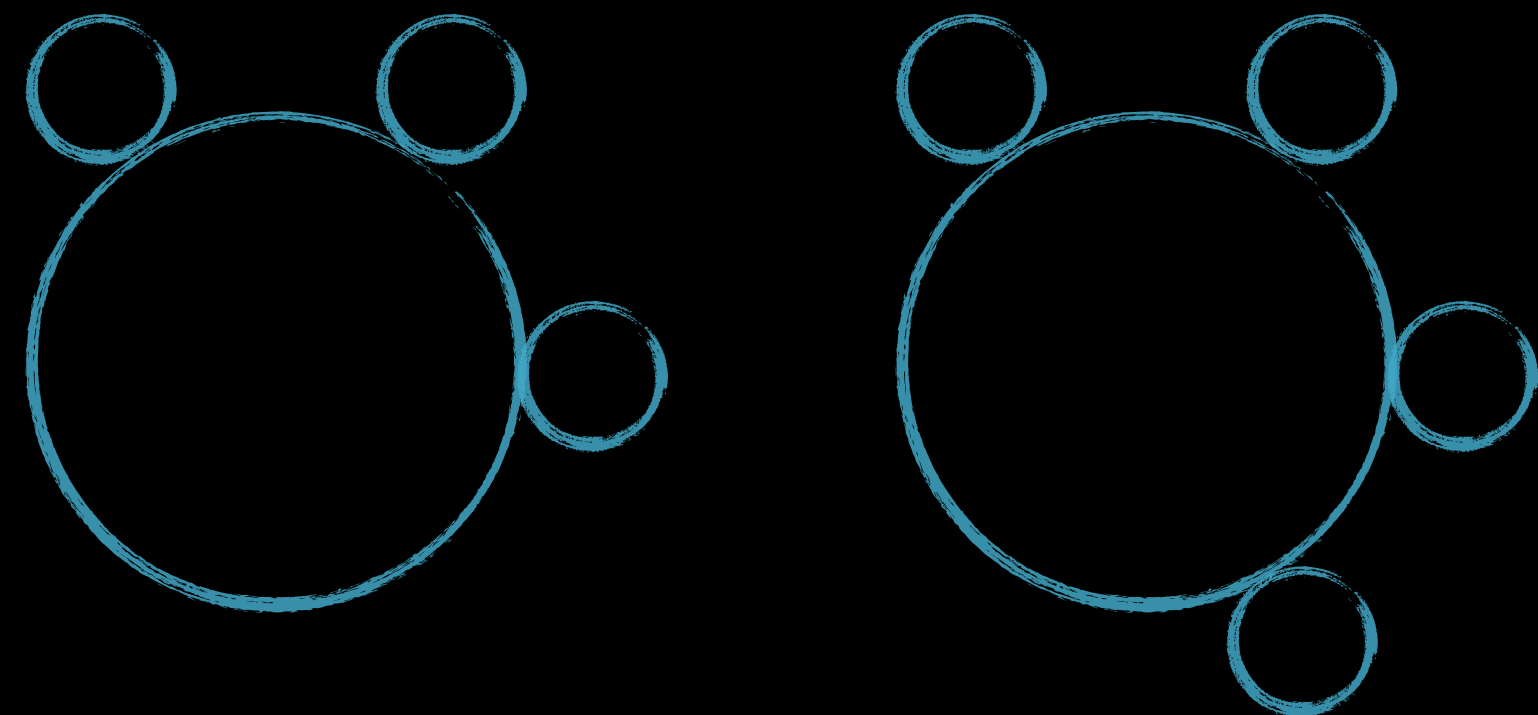
Dimensional reduction



[P. H. Ginsparg, *Nucl. Phys. B*170 (1980) 388, T. Appelquist, R. D. Pisarski, *Phys. Rev. D*23 (1981) 2305, K. Kajantie, M. Laine, K. Rummukainen, M. E. Shaposhnikov, *Nucl. Phys. B* 458 (1996) 90]

HOW FAR WILL YOU DARE TO GO?

Daisy resummation



[P. Arnold, O. Espinosa, *Phys.Rev.D* 47 (1993) 3546, R.R. Parwani, *Phys.Rev.D* 45 (1992) 4695]

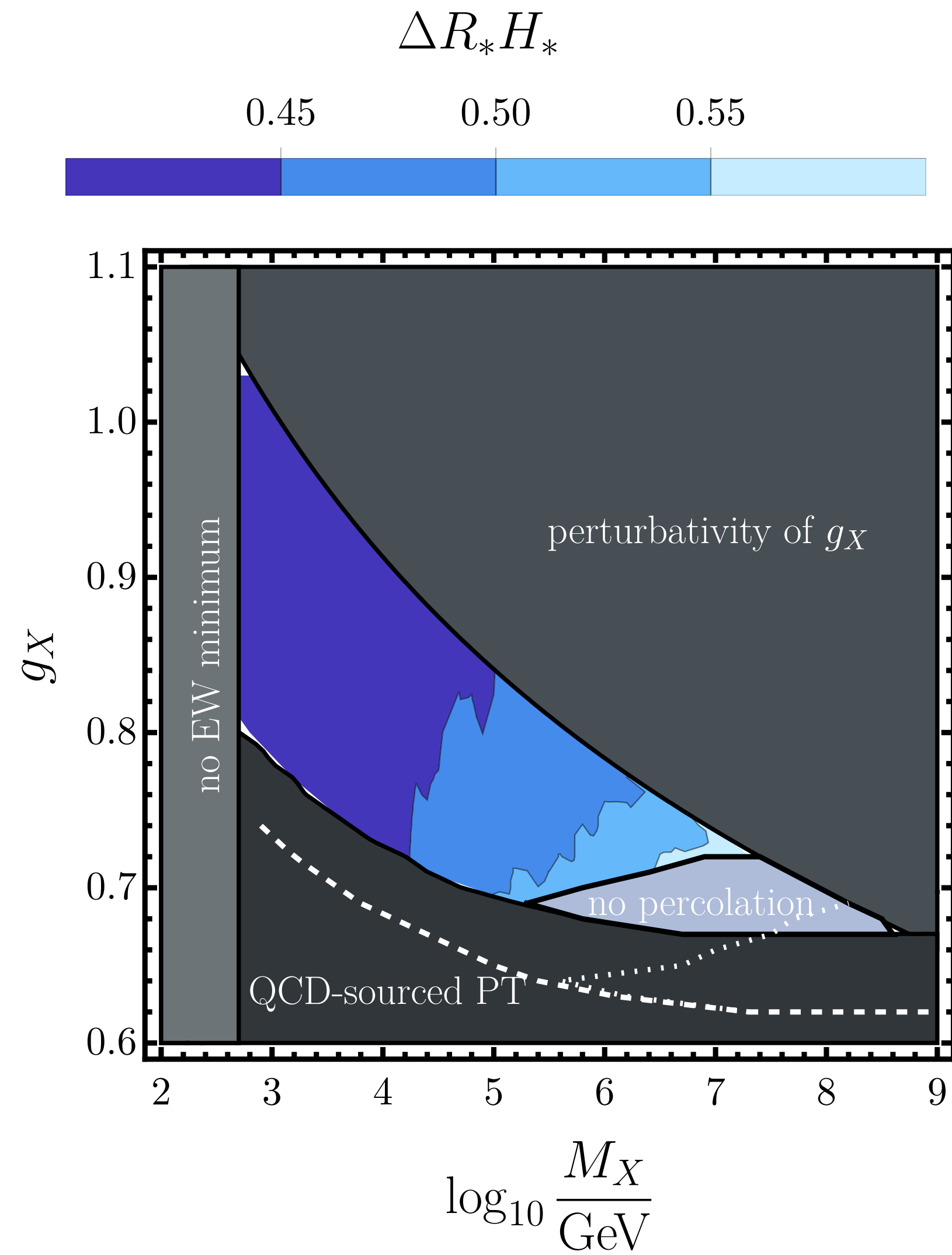
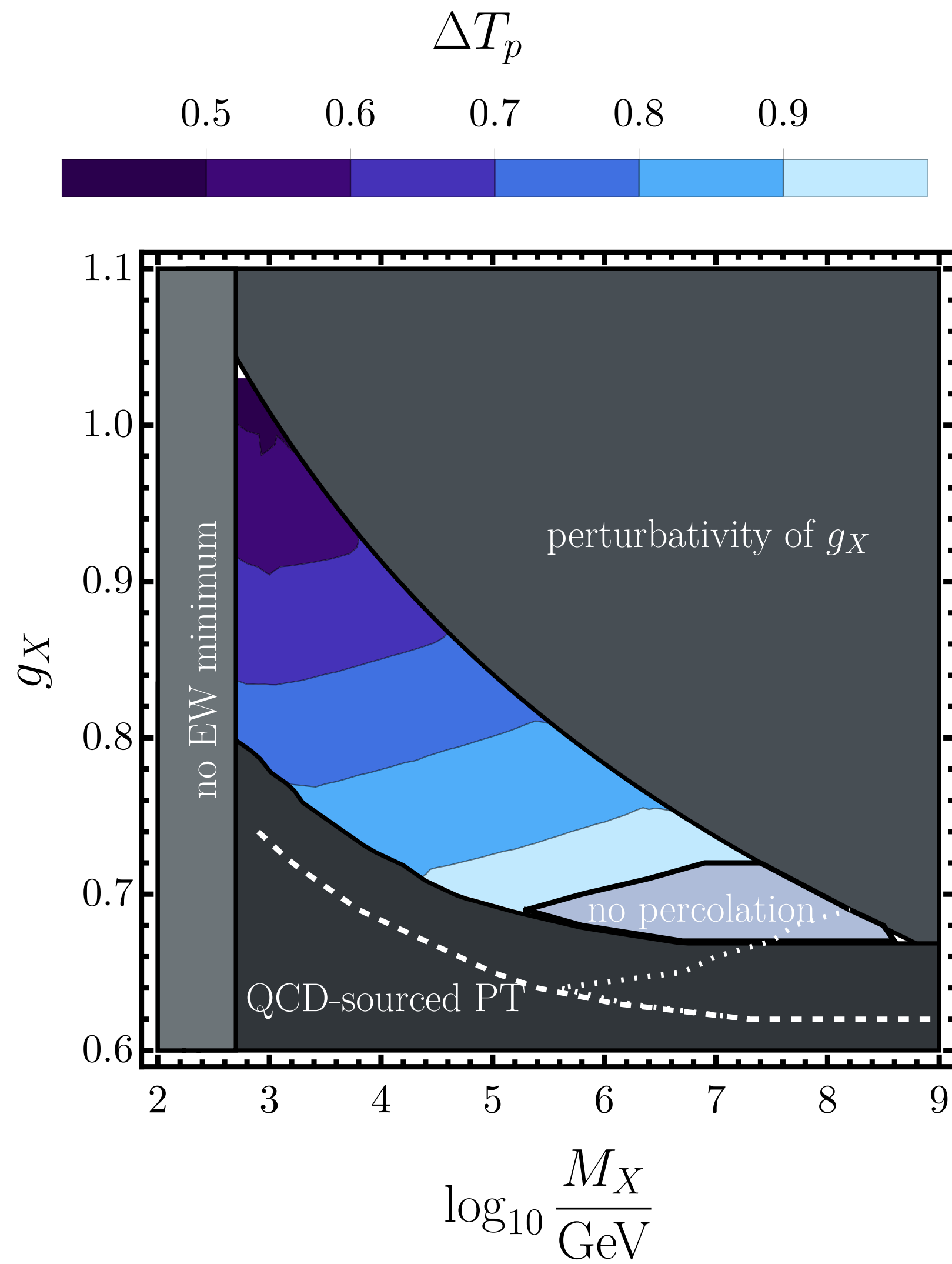
Dimensional reduction

Now available in a
public code DRalgo

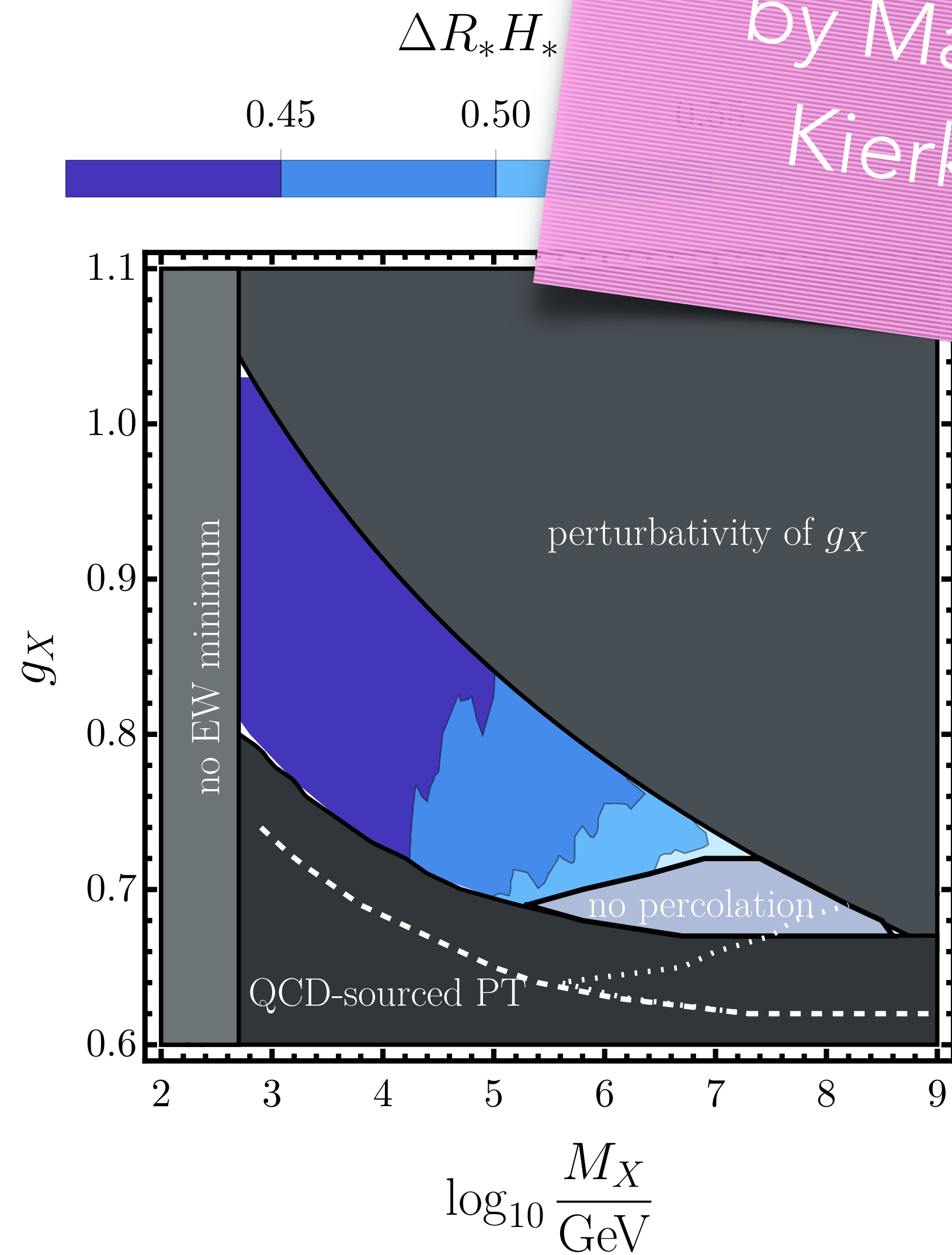
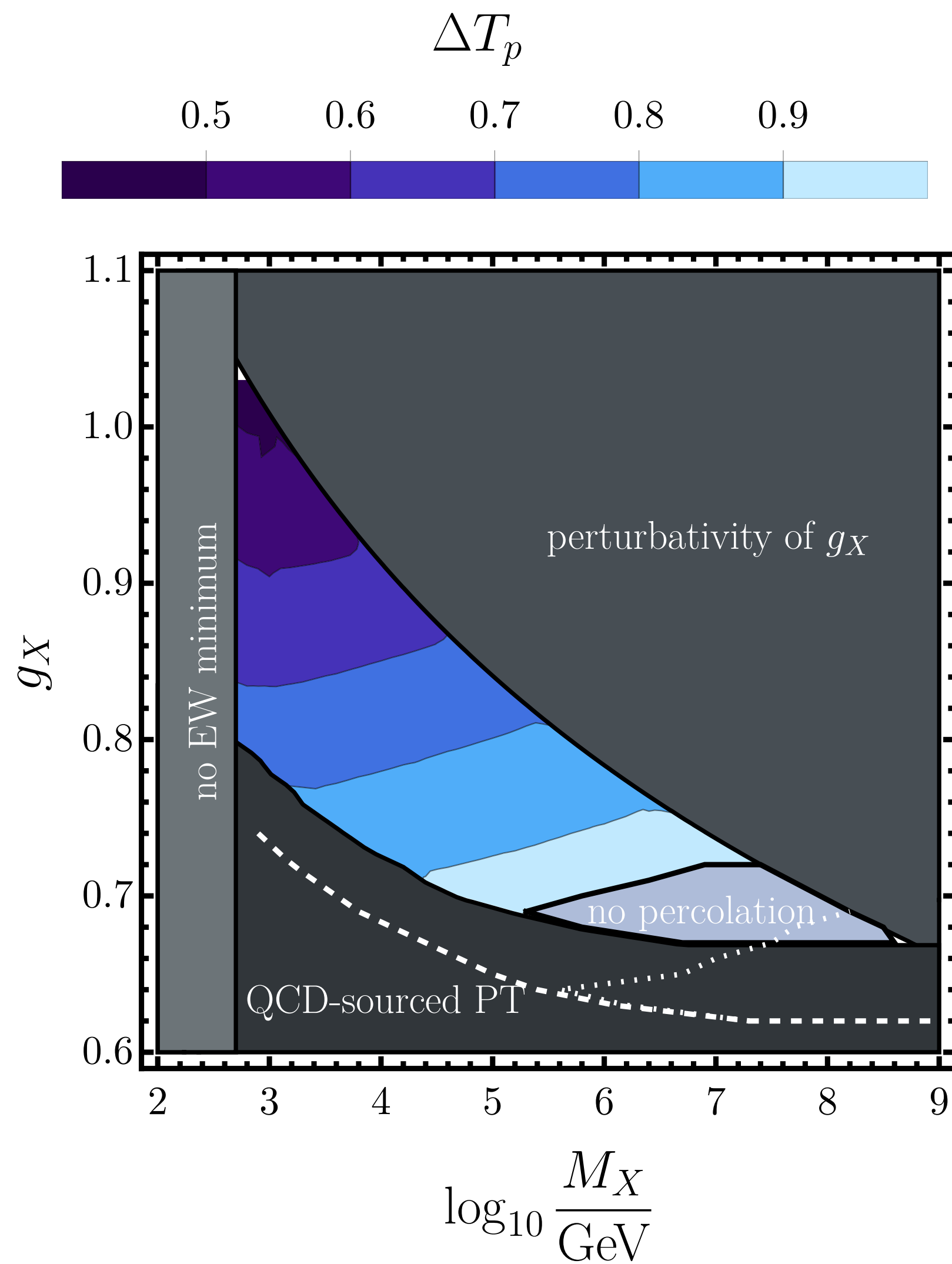
[A. Ekstedt, T.V.I. Tenkanen, P. Schicho,
Comput.Phys.Commun. 288 (2023) 108725]

[P. H. Ginsparg, *Nucl. Phys. B*170 (1980) 388, T. Appelquist, R. D. Pisarski, *Phys. Rev. D*23 (1981) 2305, K. Kajantie, M. Laine, K. Rummukainen, M. E. Shaposhnikov, *Nucl. Phys. B* 458 (1996) 90]

DR FOR SUPERCOOLED PT

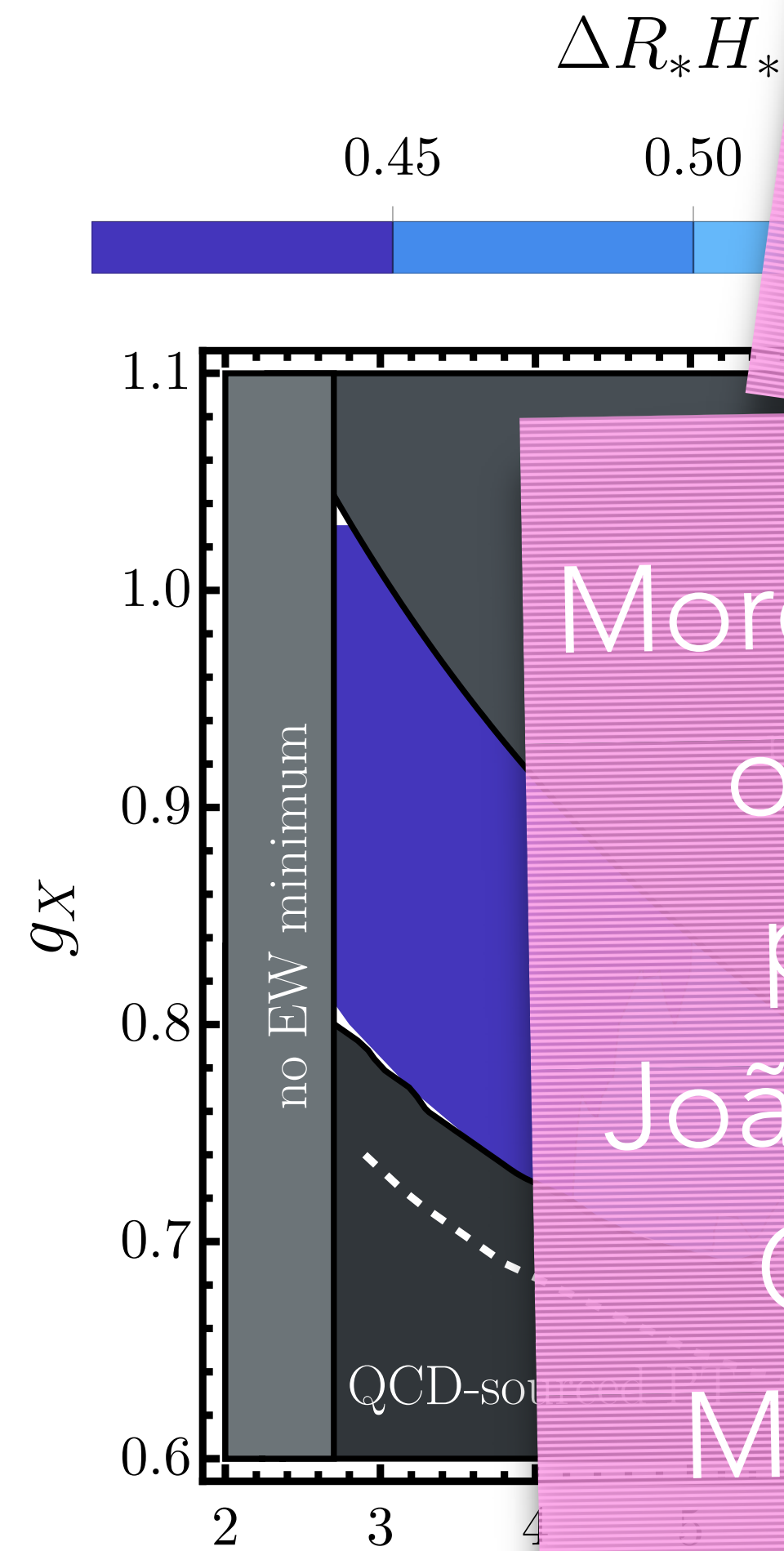
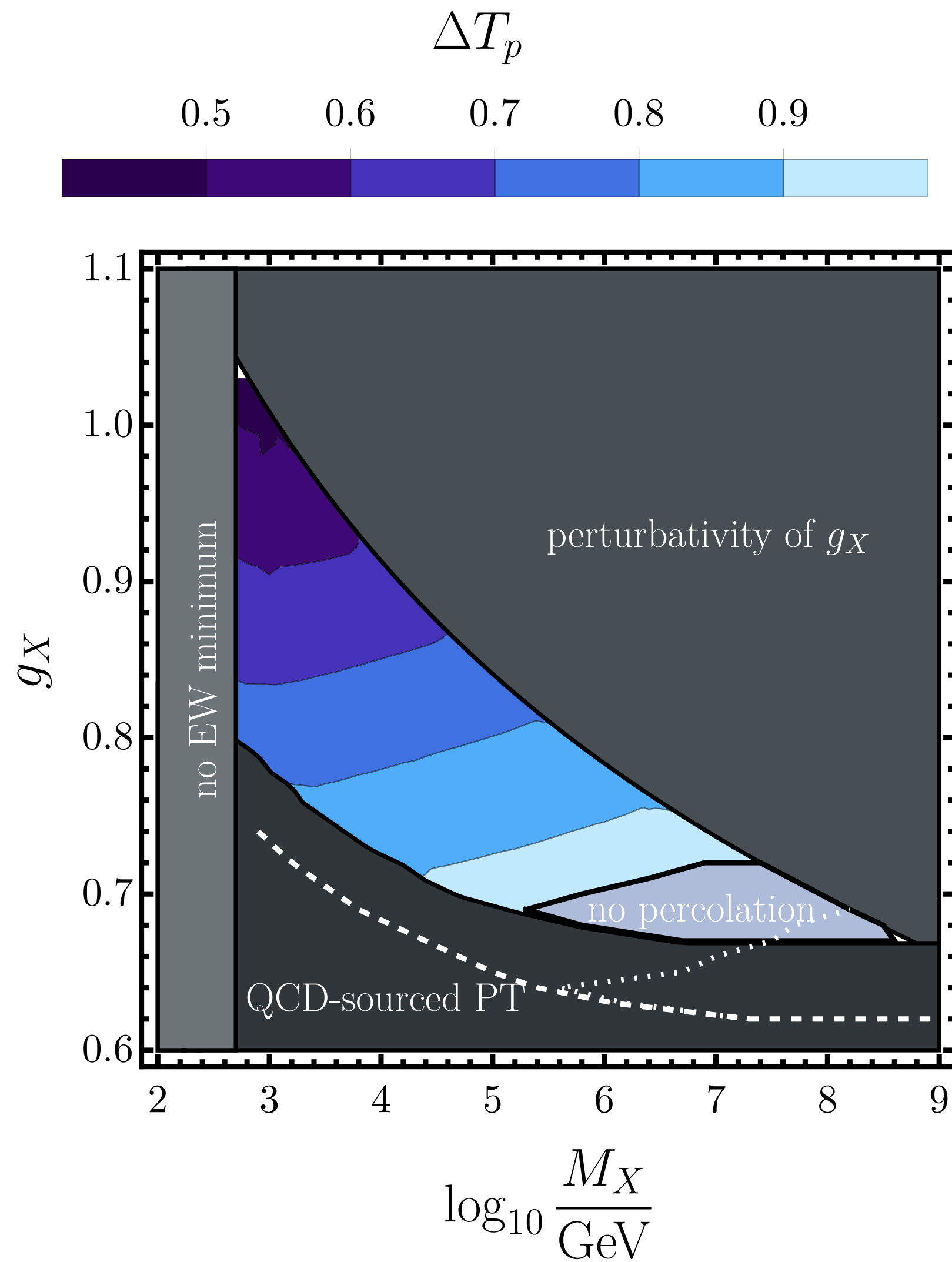


DR FOR SUPERCOOLED PT



see the poster
by Maciej
Kierkla

DR FOR SUPERCOOLED PT



see the poster
by Maciej
Kierkla

More applications
of DR in the
posters of:
João Pedro Pino
Gonçalves,
Marco Finetti,
Daniel Schmitt

NUCLEATION

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

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A_{det} necessary to increase
precision

→ BubbleDet

NUCLEATION

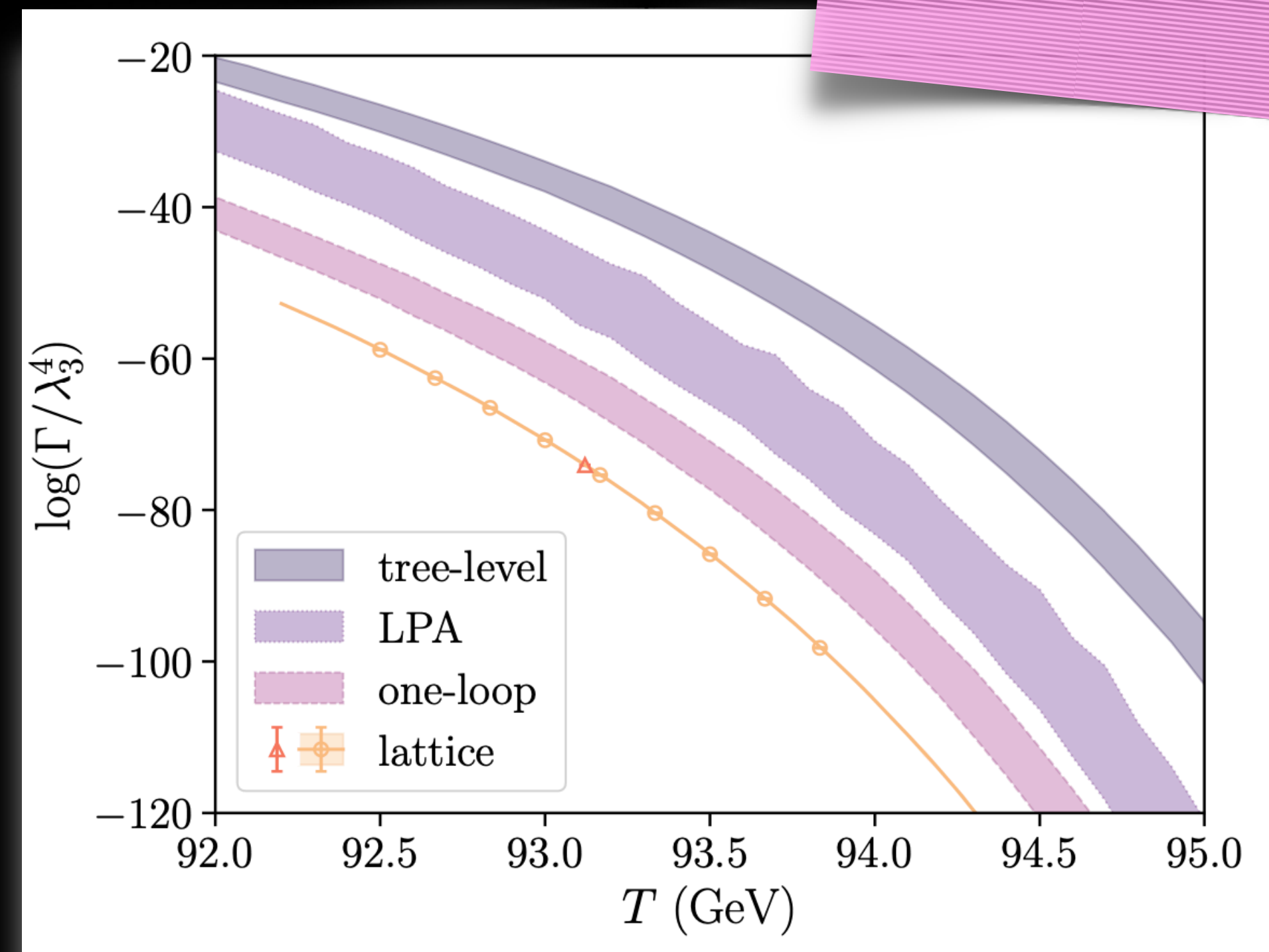
$$\Gamma = A_{\text{dyn}} \cdot A_{\text{stat}} = A_{\text{dyn}} \cdot A_{\text{det}} \cdot \exp(-S)$$

see the poster
by Anna Kormu

A_{det} necessary to increase
precision

→ BubbleDet

[A. Ekstedt, O. Gould, J. Hirvonen, JHEP 12 (2023) 056]



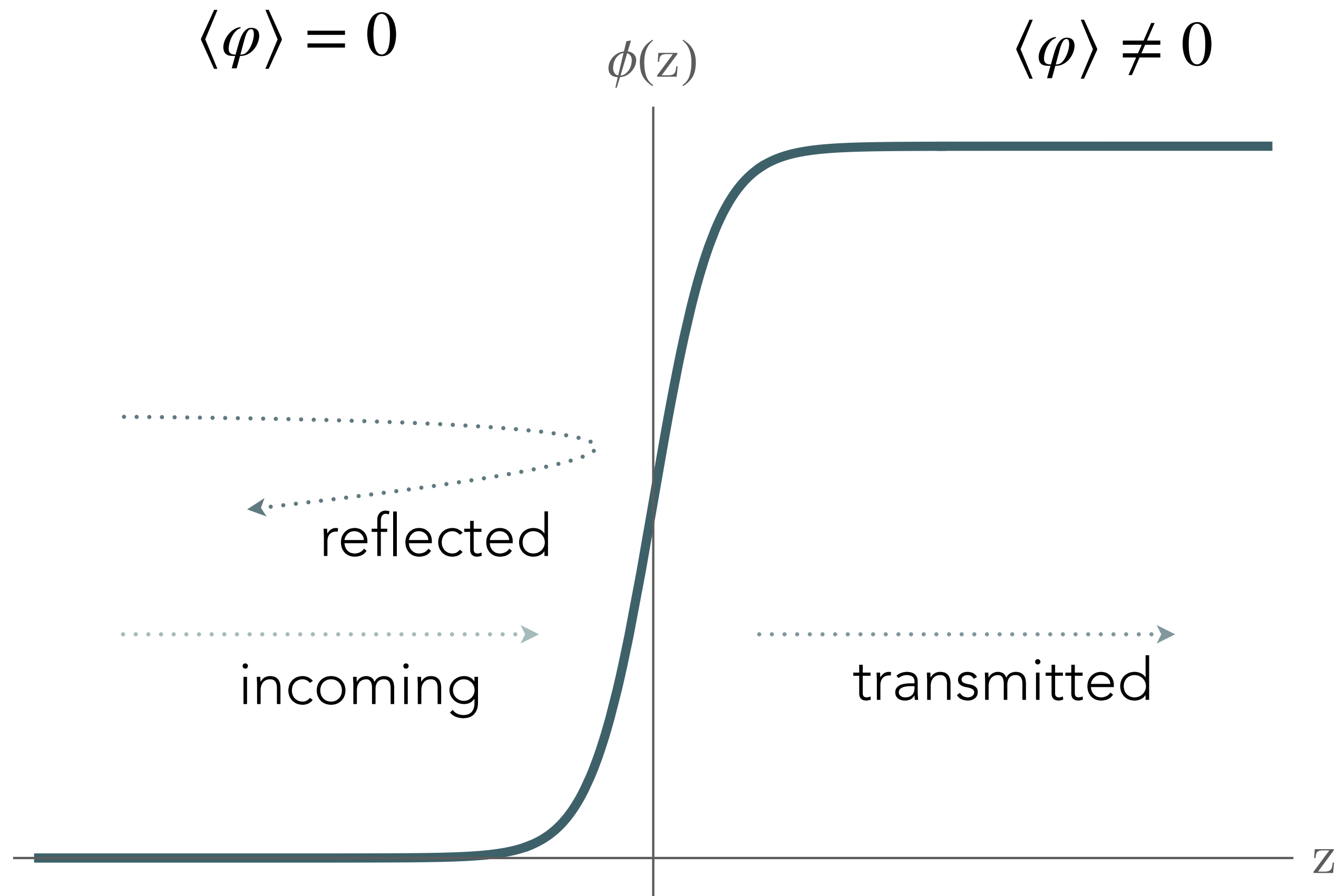
[O.Gould, A.Kormu, D. J. Weir, 2404.01876]

BUBBLE-WALL VELOCITY

FOR GW AND BARYOGENESIS

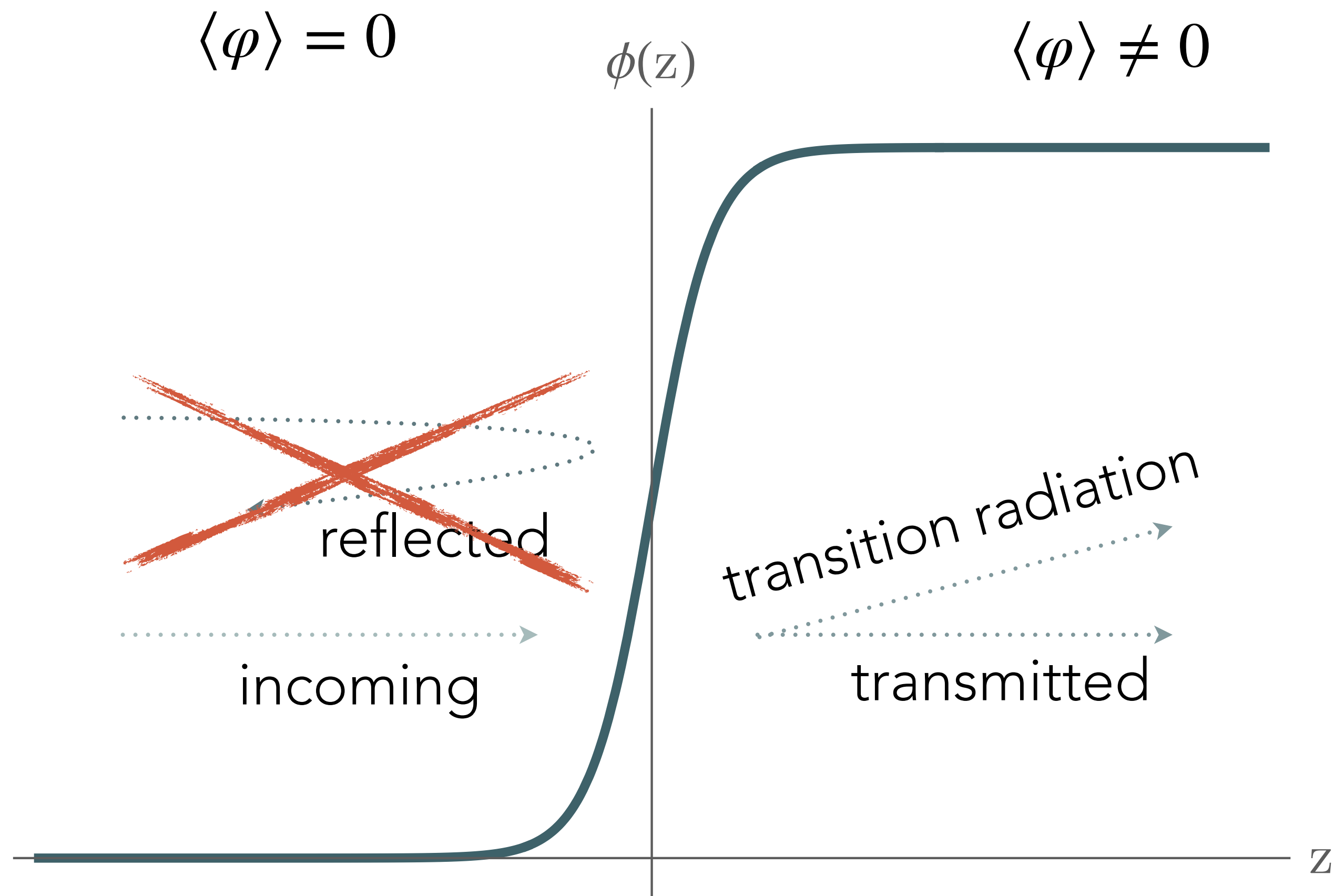


WALL VELOCITY



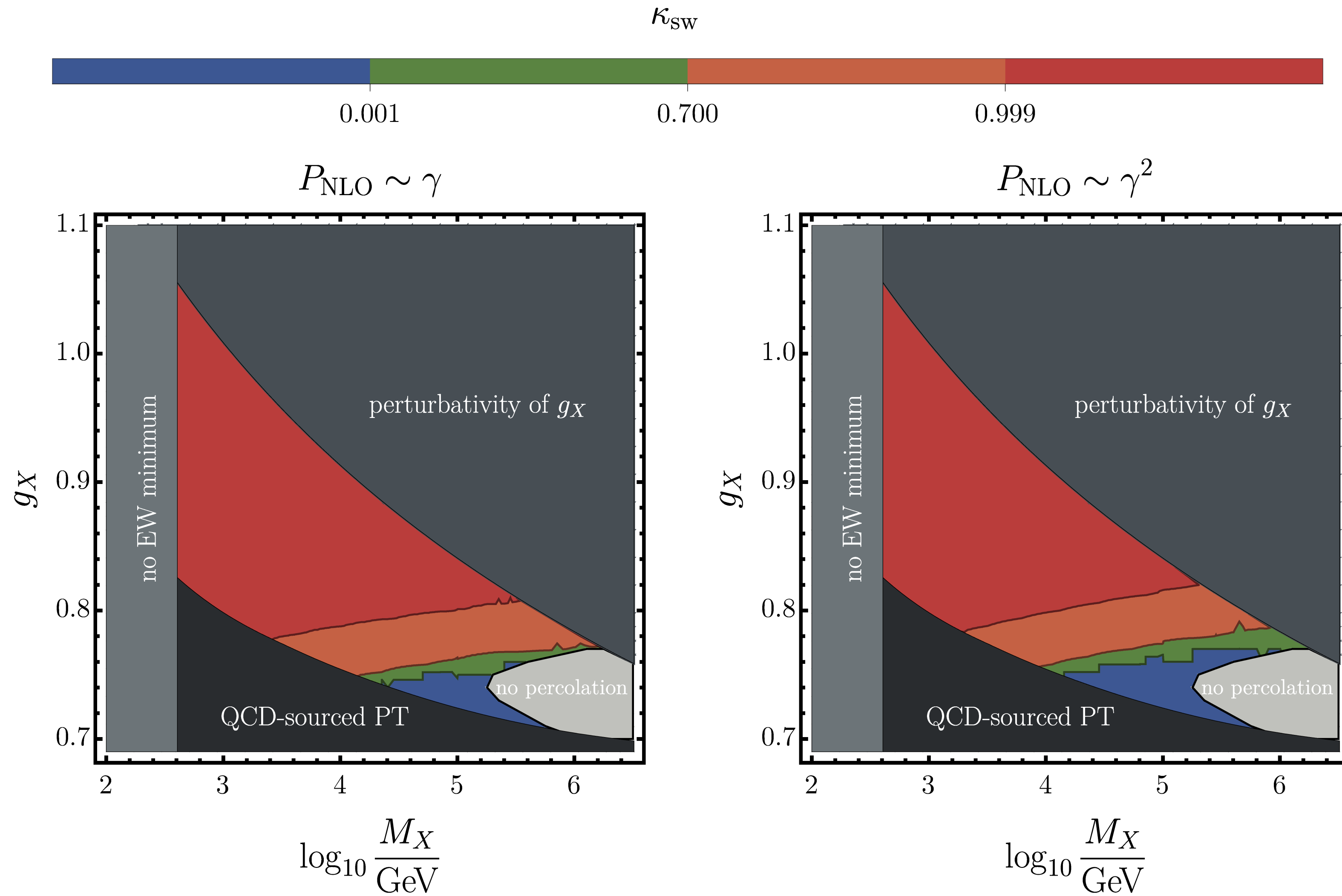
[G. D. Moore and T. Prokopec, Phys. Rev. D 52 (1995) 7182–7204,
Phys. Rev. Lett. 75 (1995) 777–780 ,
B. Laurent and J. M. Cline, Phys. Rev. D 102 no. 6, (2020) 063516,
Phys. Rev. D 106 no. 2, (2022) 023501,
G. C. Dorsch, S. J. Huber, and T. Konstandin, JCAP 12 (2018) 034]

RUNAWAY BUBBLES?

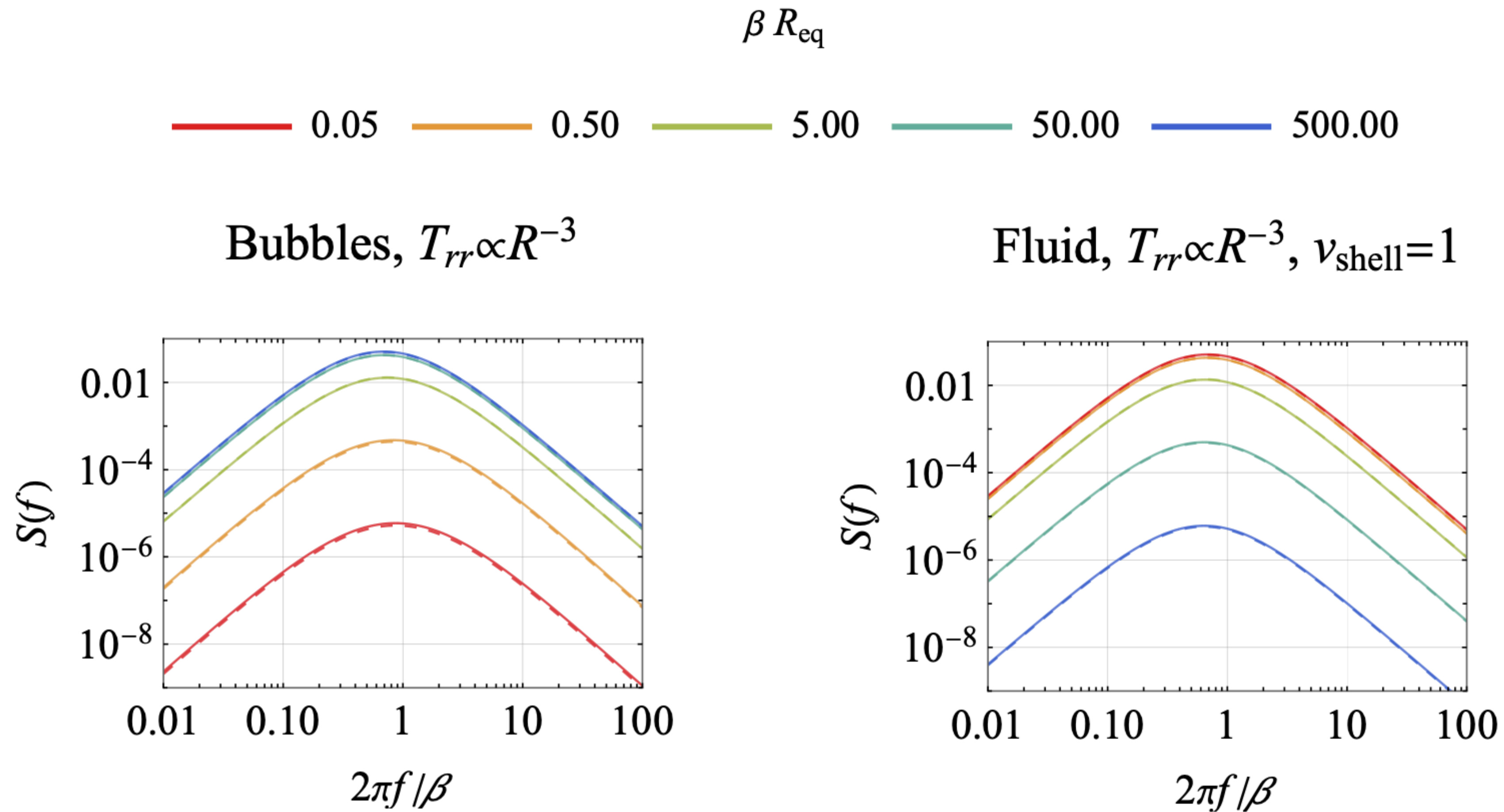


[D. Bodeker and G. D. Moore, JCAP 05 (2009) 009, JCAP 05 (2017) 025,
S. Höche, J. Kozaczuk, A. J. Long, J. Turner, and Y. Wang, JCAP 03 (2021) 009 ,
Y. Gouttenoire, R. Jinno, and F. Sala, JHEP 05 (2022) 004]

RUNAWAY BUBBLES?



RUNAWAY BUBBLES?



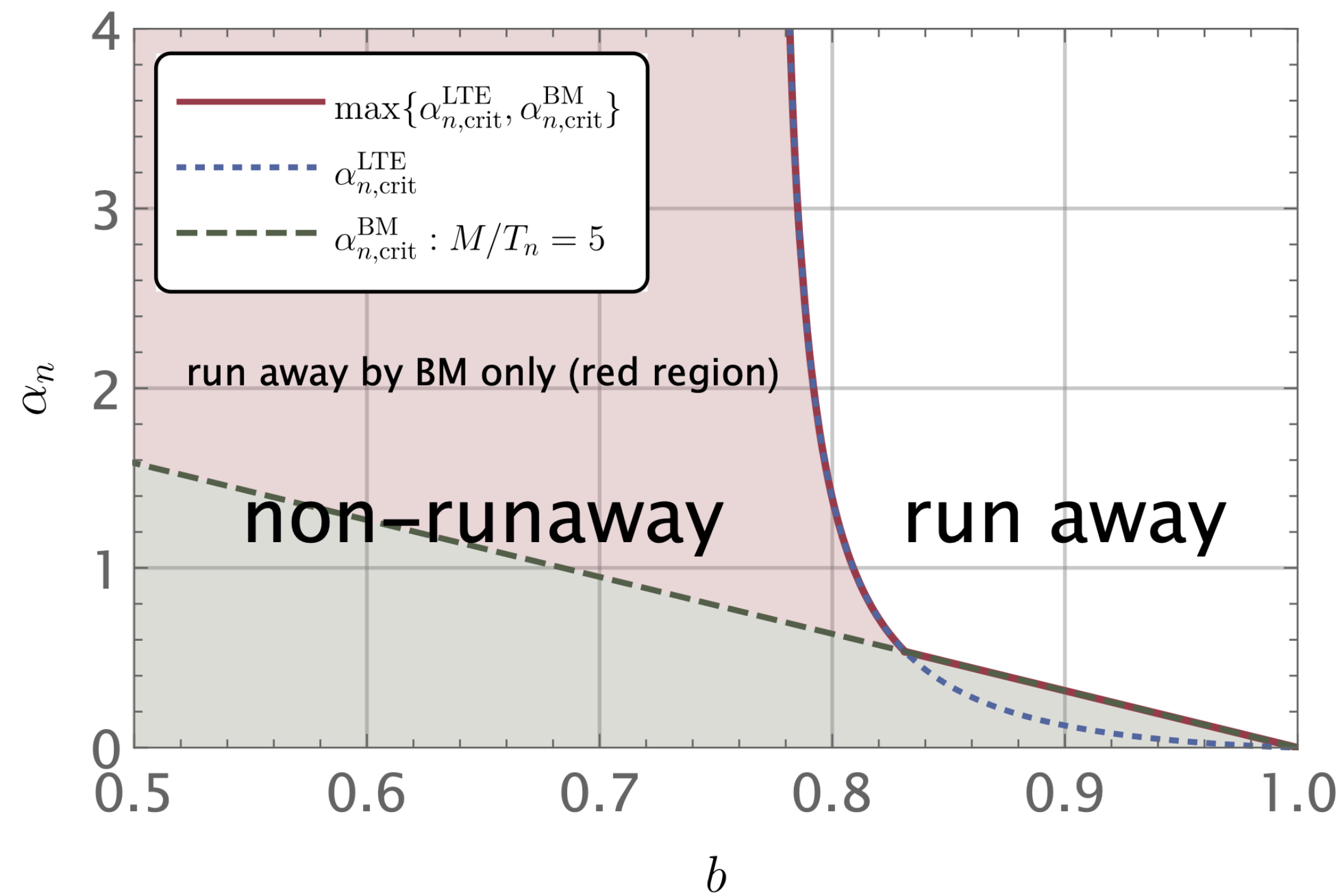
[results and plots from: M. Lewicki and V. Vaskonen, Eur.Phys.J.C 83 (2023) 2, 109]

IS LOCAL THERMAL EQUILIBRIUM USEFUL?

[T. Konstandin, J. M. No, JCAP 02 (2011) 008, M. Barroso Mancha, T. Prokopec, and BS, JHEP 01 (2021) 070 , S. Balaji, M. Spannowsky, and C. Tamarit, JCAP 03 (2021) 051, W.-Y. Ai, B. Garbrecht, and C. Tamarit, JCAP 03, (2022) 015 , **W.-Y. Ai, B. Laurent, J. van de Vis, JCAP 07 (2023) 002**, M. Lewicki, M. Merchand, and M. Zych, JHEP 02 (2022) 017]

IS LOCAL THERMAL EQUILIBRIUM USEFUL?

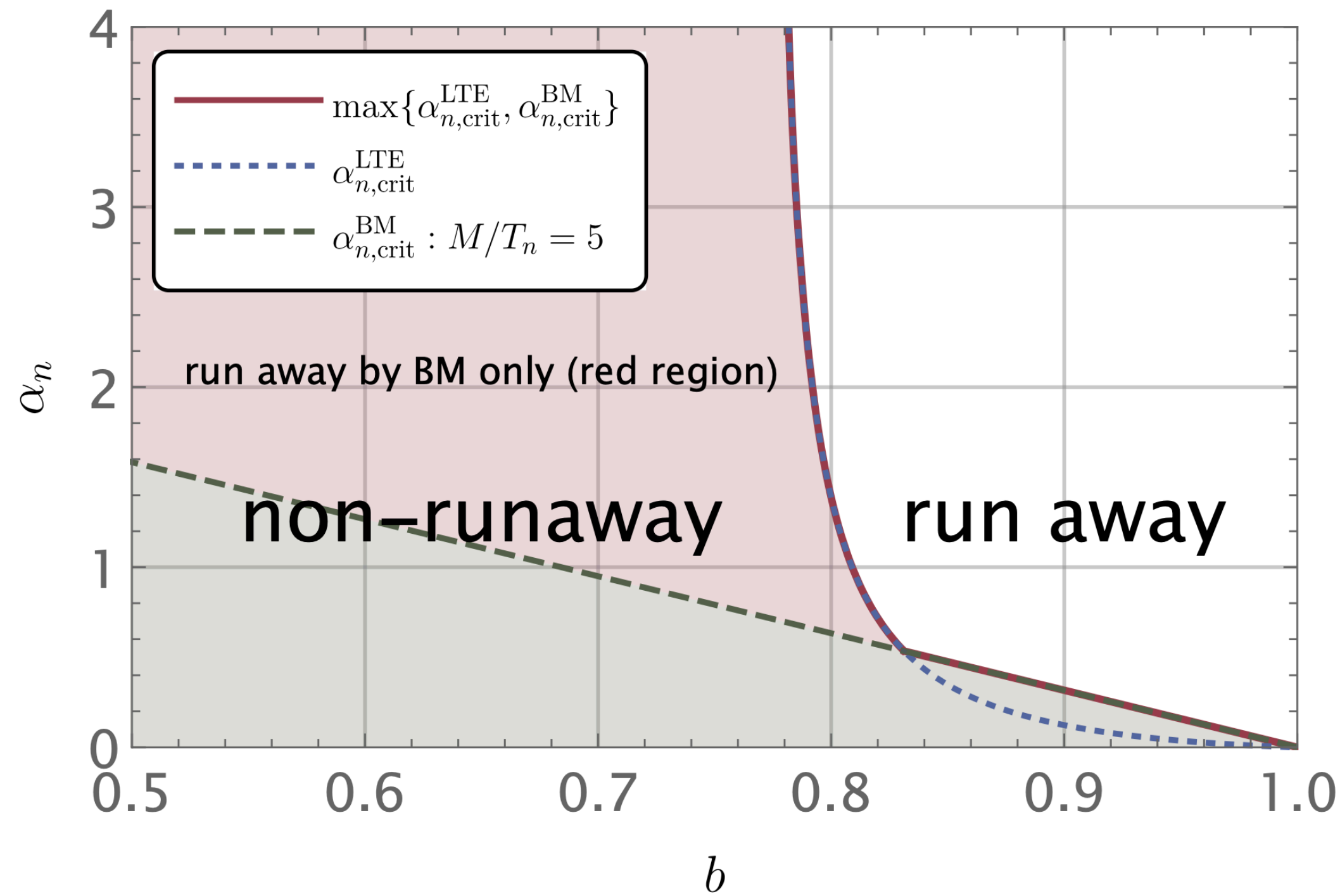
[T. Konstandin, J. M. No, JCAP 02 (2011) 008, M. Barroso Mancha, T. Prokopec, and BS, JHEP 01 (2021) 070 , S. Balaji, M. Spannowsky, and C. Tamarit, JCAP 03 (2021) 051, W.-Y. Ai, B. Garbrecht, and C. Tamarit, JCAP 03, (2022) 015 , **W.-Y. Ai, B. Laurent, J. van de Vis, JCAP 07 (2023) 002**, M. Lewicki, M. Merchand, and M. Zych, JHEP 02 (2022) 017]



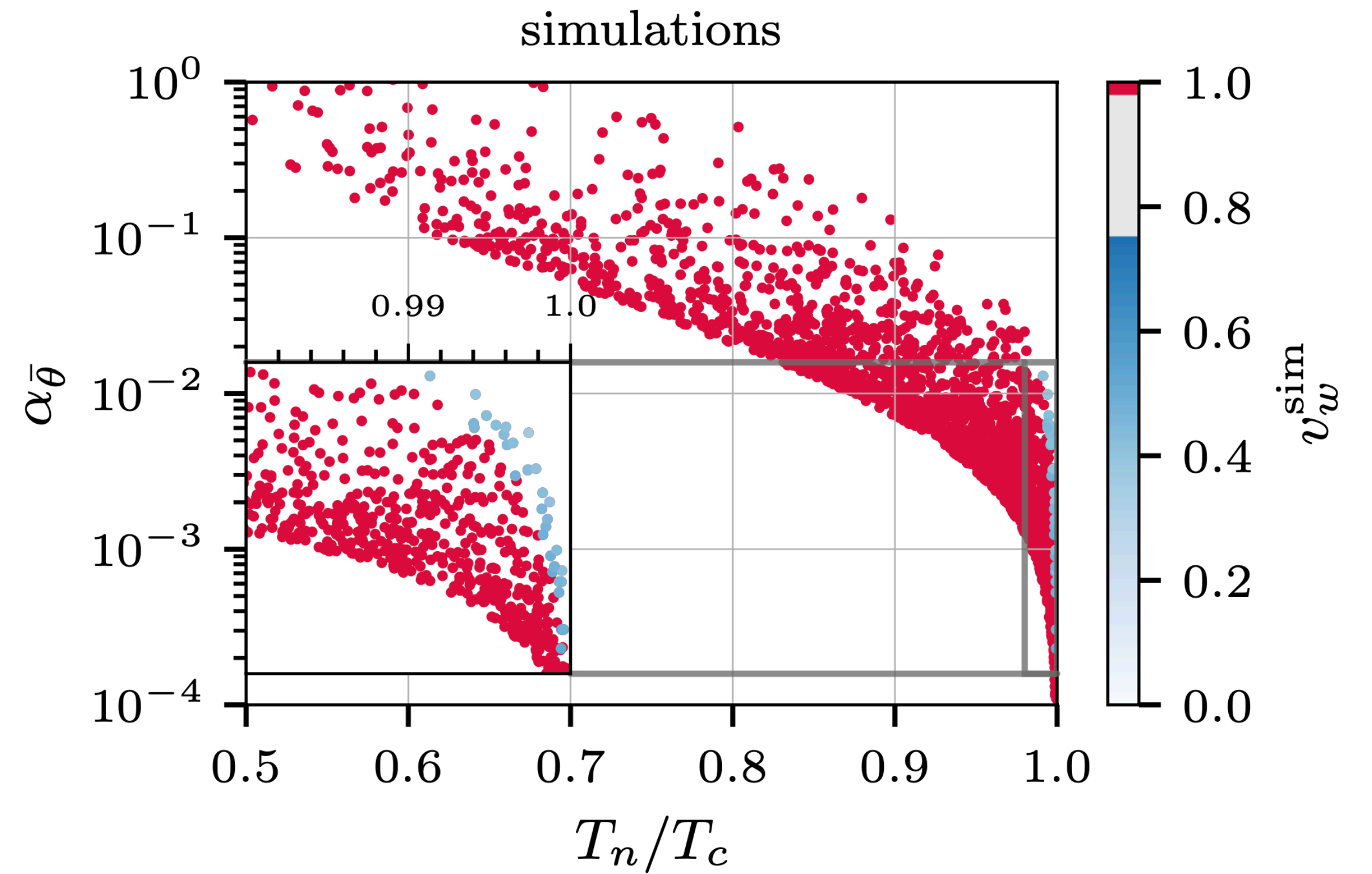
[W.-Y. Ai, X. Nagels, M. Vanvlasselaer, JCAP 03 (2024) 037]

IS LOCAL THERMAL EQUILIBRIUM USEFUL?

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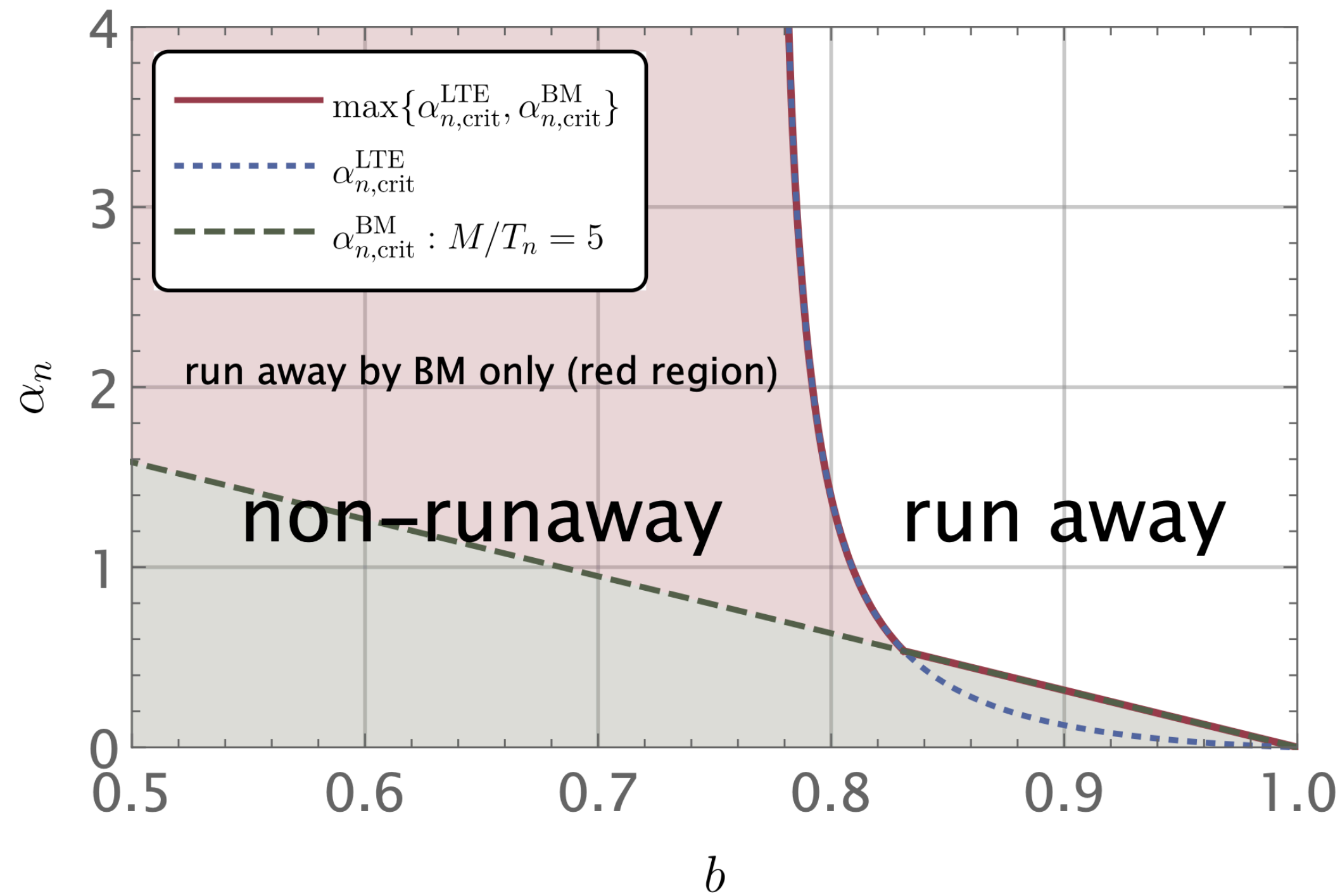
[W.-Y. Ai, X. Nagels, M. Vanvlasselaer, JCAP 03 (2024) 037]



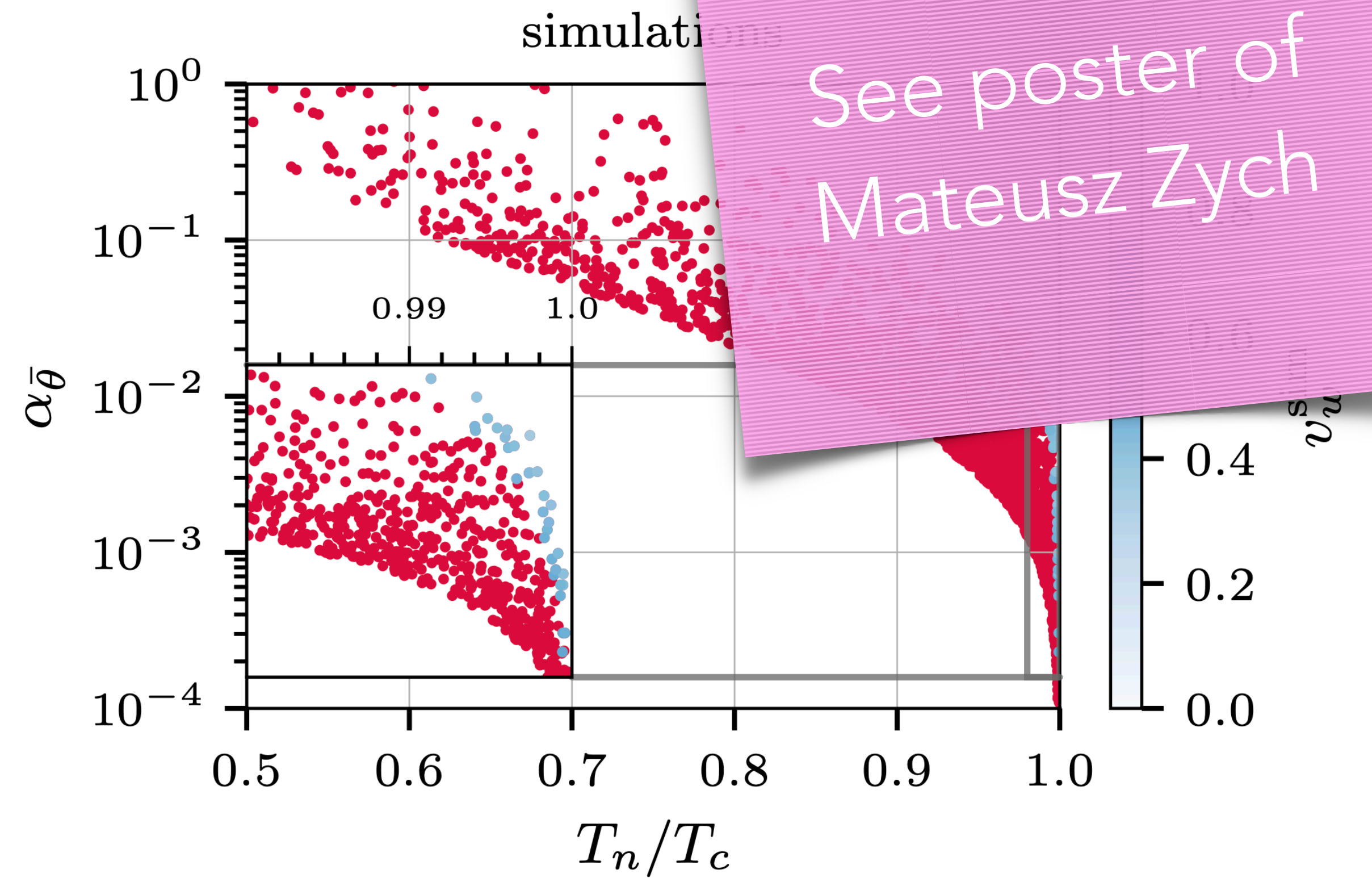
[T. Krajewski, M. Lewicki, M. Zych, JHEP 05 (2024) 011]

IS LOCAL THERMAL EQUILIBRIUM USEFUL?

[T. Konstandin, J. M. No, JCAP 02 (2011) 008, M. Barroso Mancha, T. Prokopec, and BS, JHEP 01 (2021) 070, S. Balaji, M. Spannowsky, and C. Tamarit, JCAP 03 (2021) 051, W.-Y. Ai, B. Garbrecht, and C. Tamarit, JCAP 03, (2022) 015, W.-Y. Ai, B. Laurent, J. van de Vis, JCAP 07 (2023) 002, M. Lewicki, M. Merchand, and M. Zych, JHEP 02 (2022) 017]

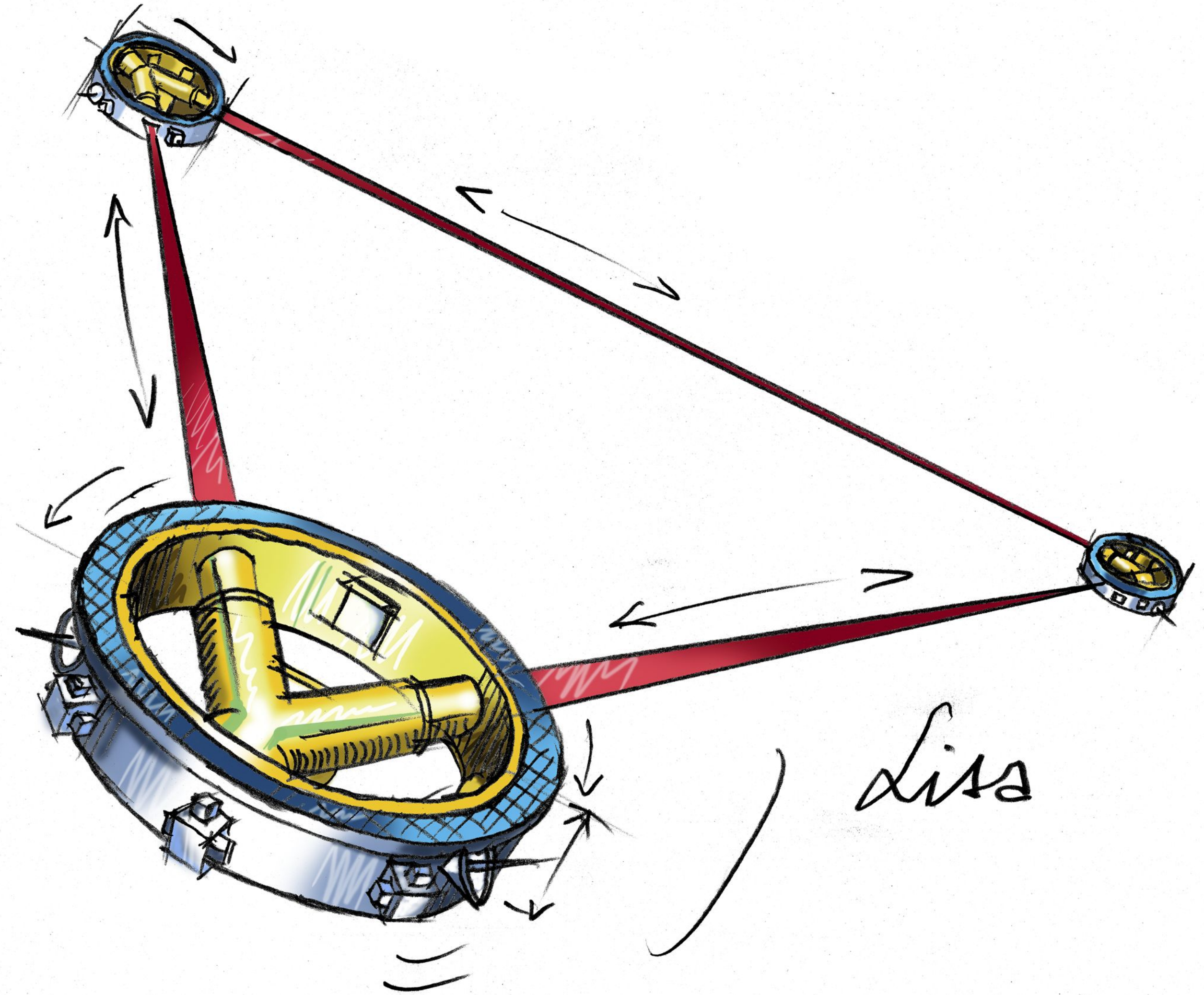


[W.-Y. Ai, X. Nagels, M. Vanvlasselaer, JCAP 03 (2024) 037]

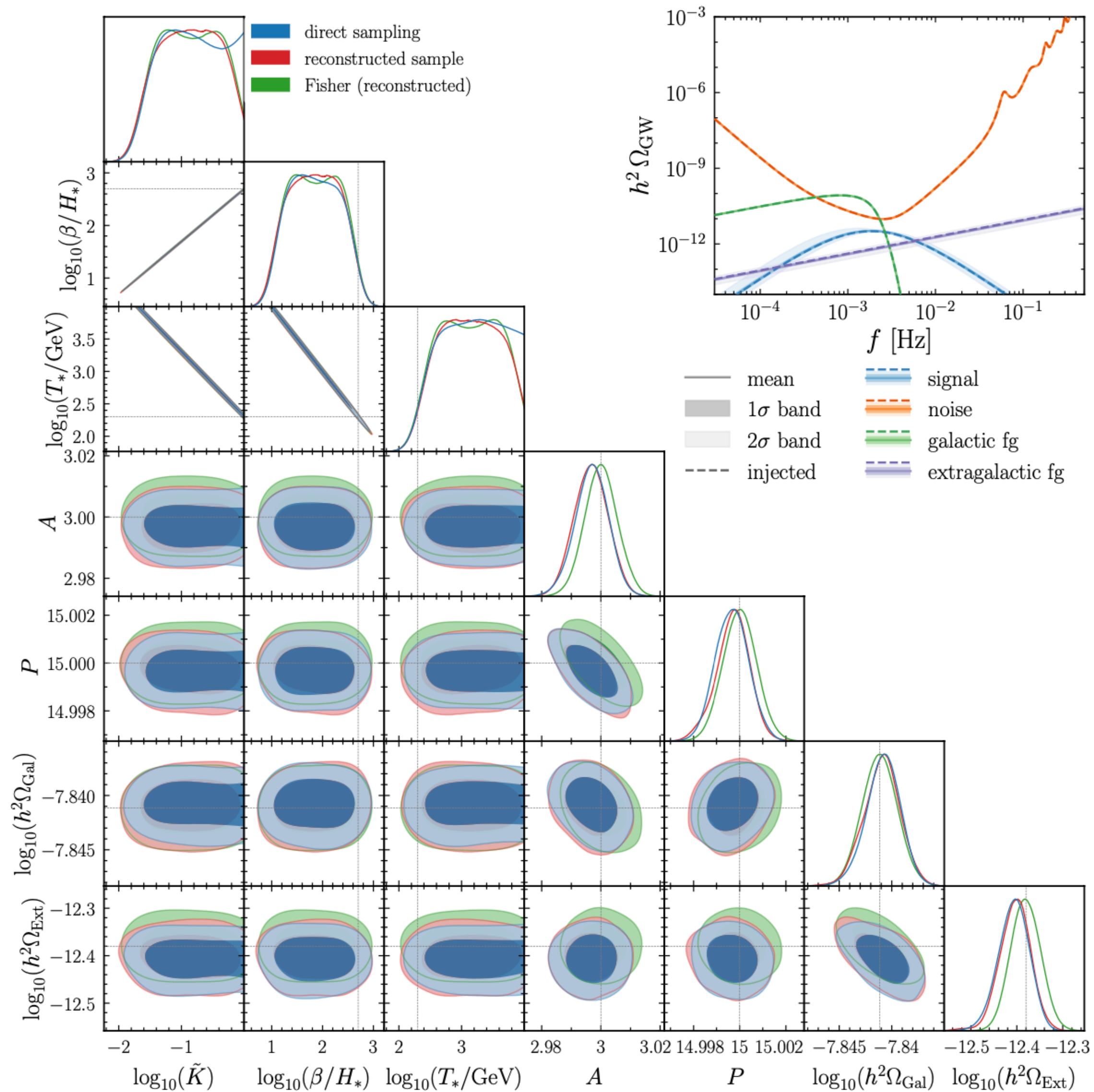


[T. Krajewski, M. Lewicki, M. Zych, JHEP 05 (2024) 011]

WHAT WILL WE
LEARN FROM
OBSERVATIONS?

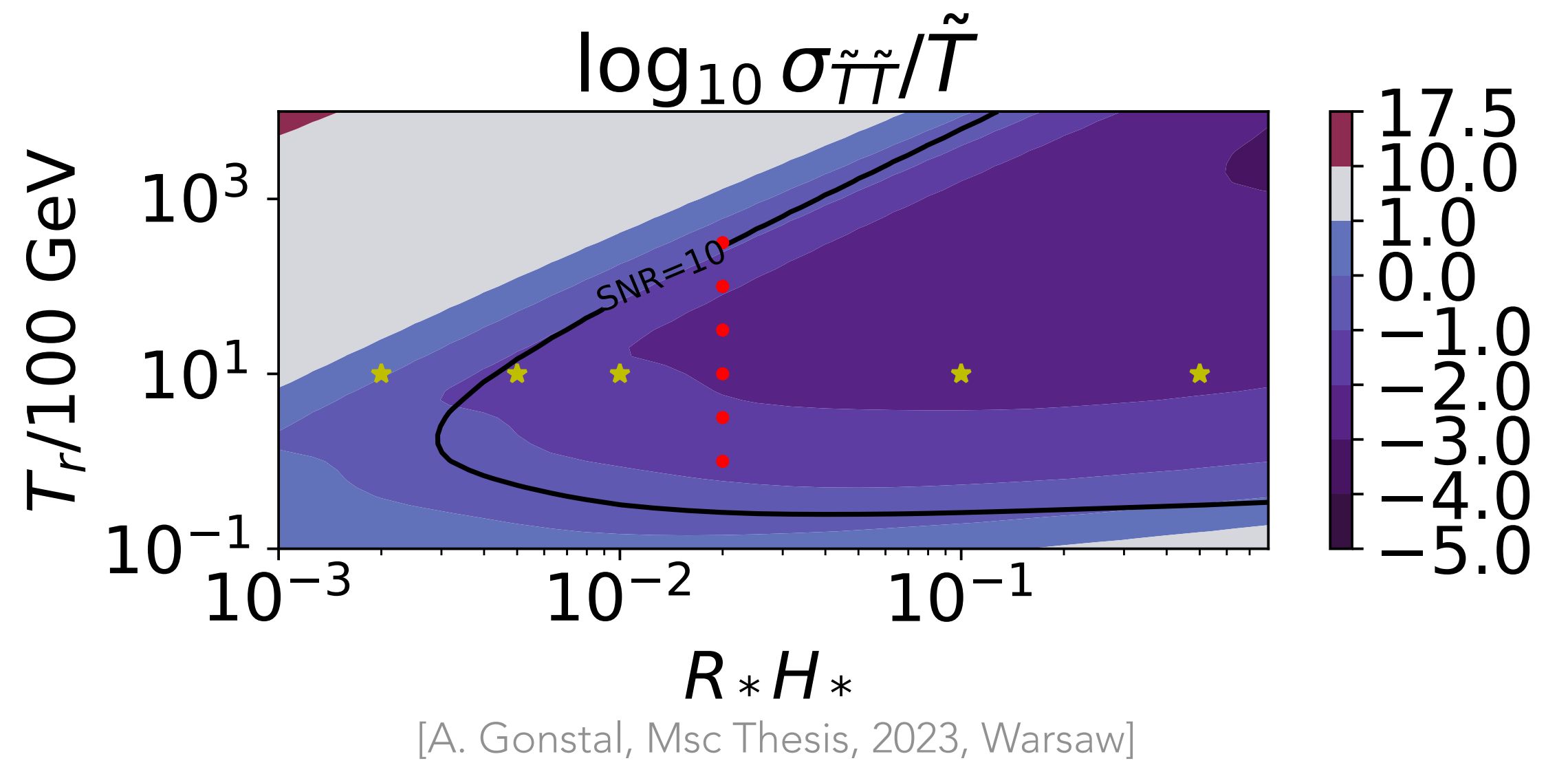
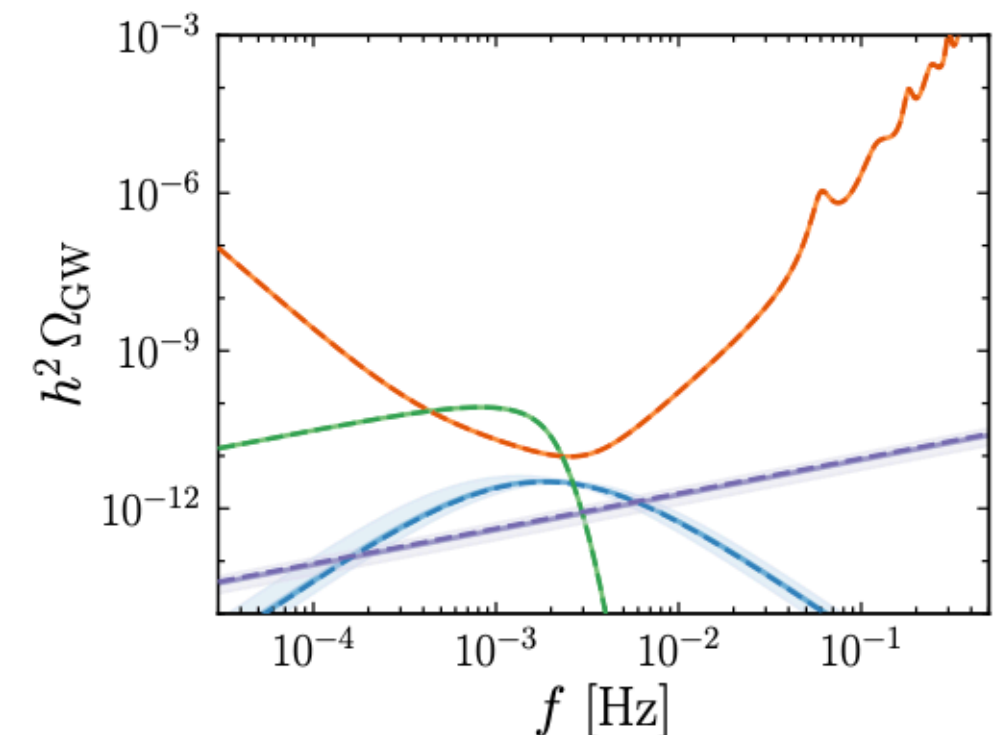
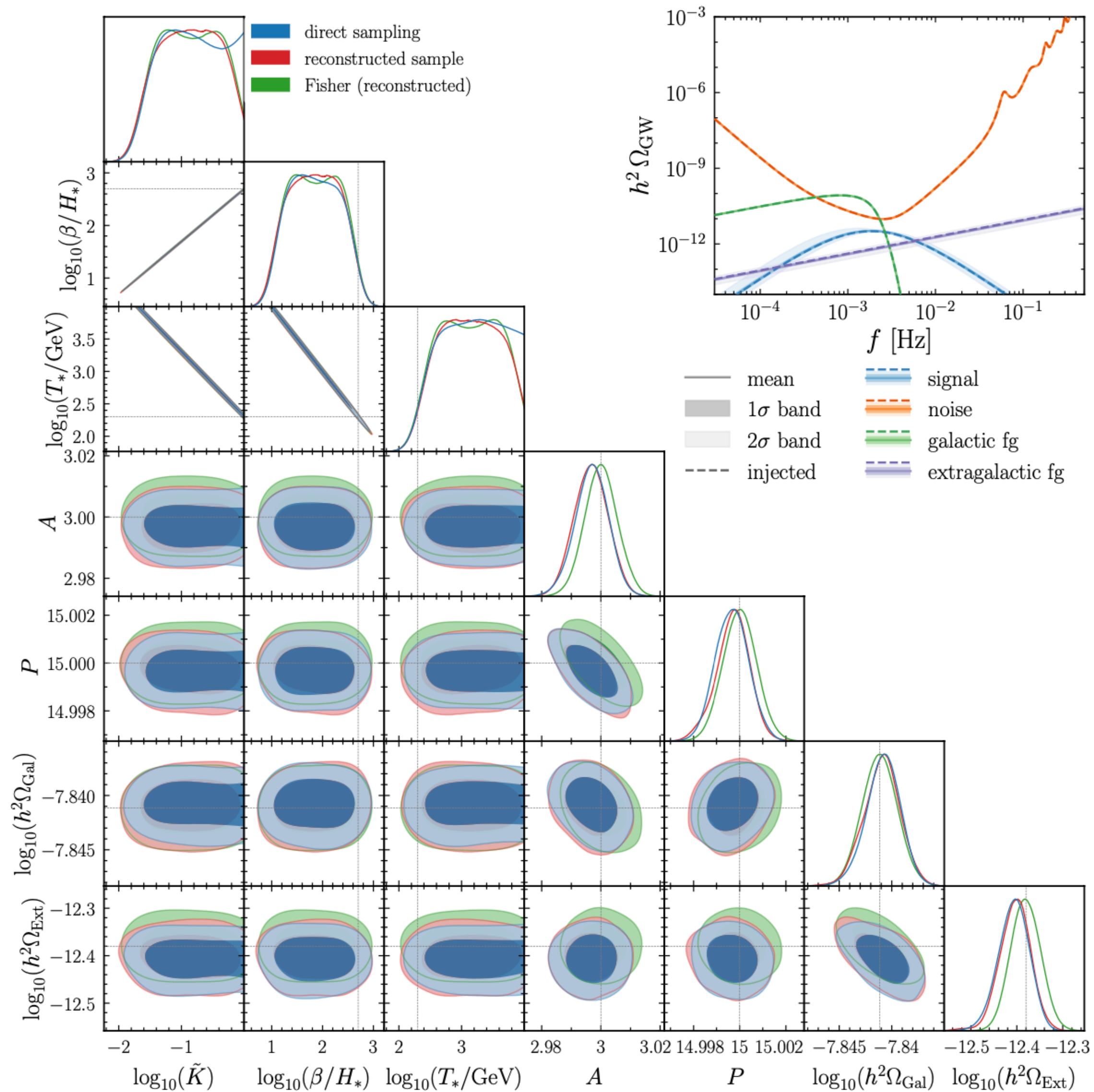


PARAMETER RECONSTRUCTION WITH LISA



[C. Caprini et al., LISA CosWG, 2403.03723]

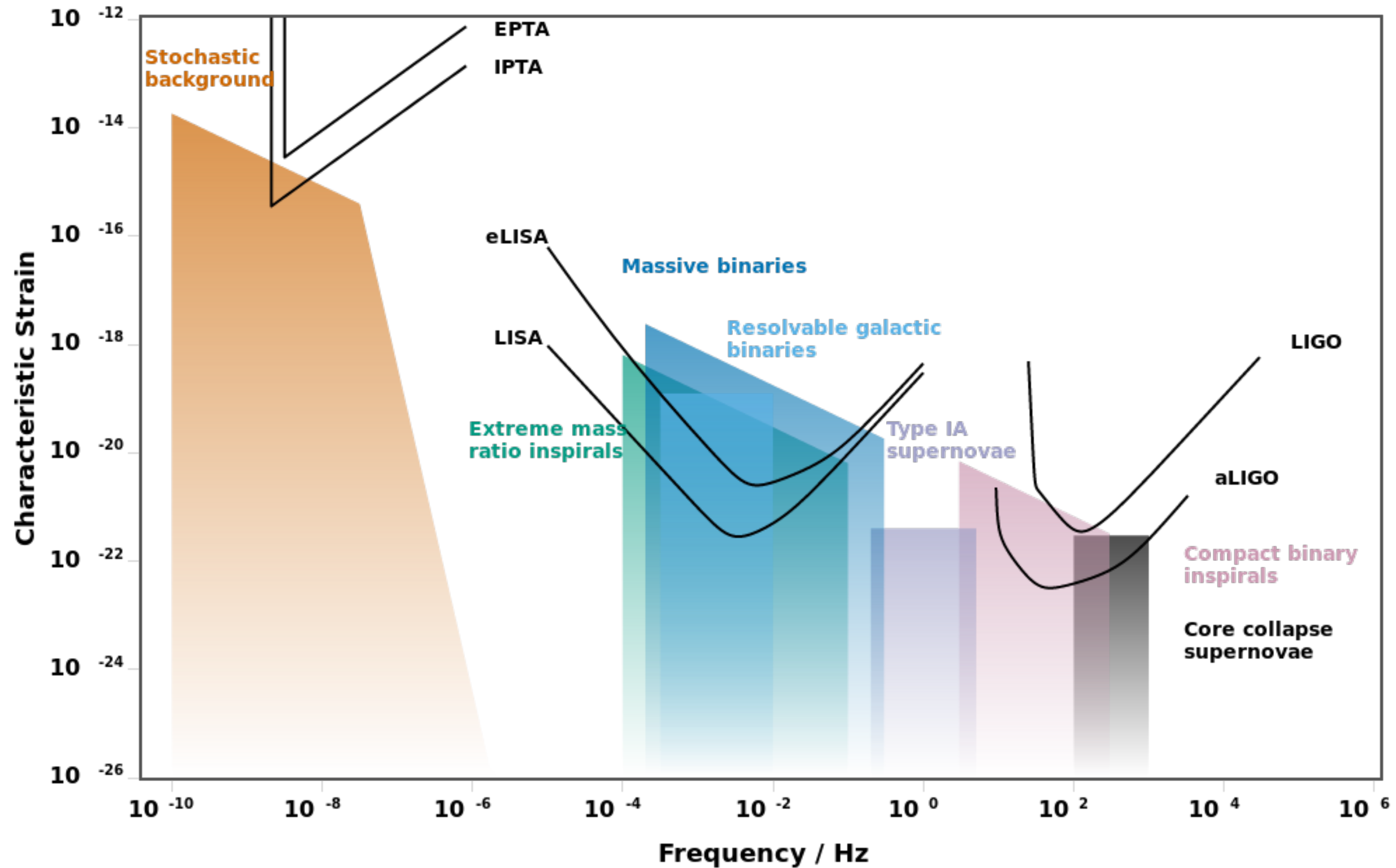
PARAMETER RECONSTRUCTION WITH LISA



[A. Gonstal, Msc Thesis, 2023, Warsaw]

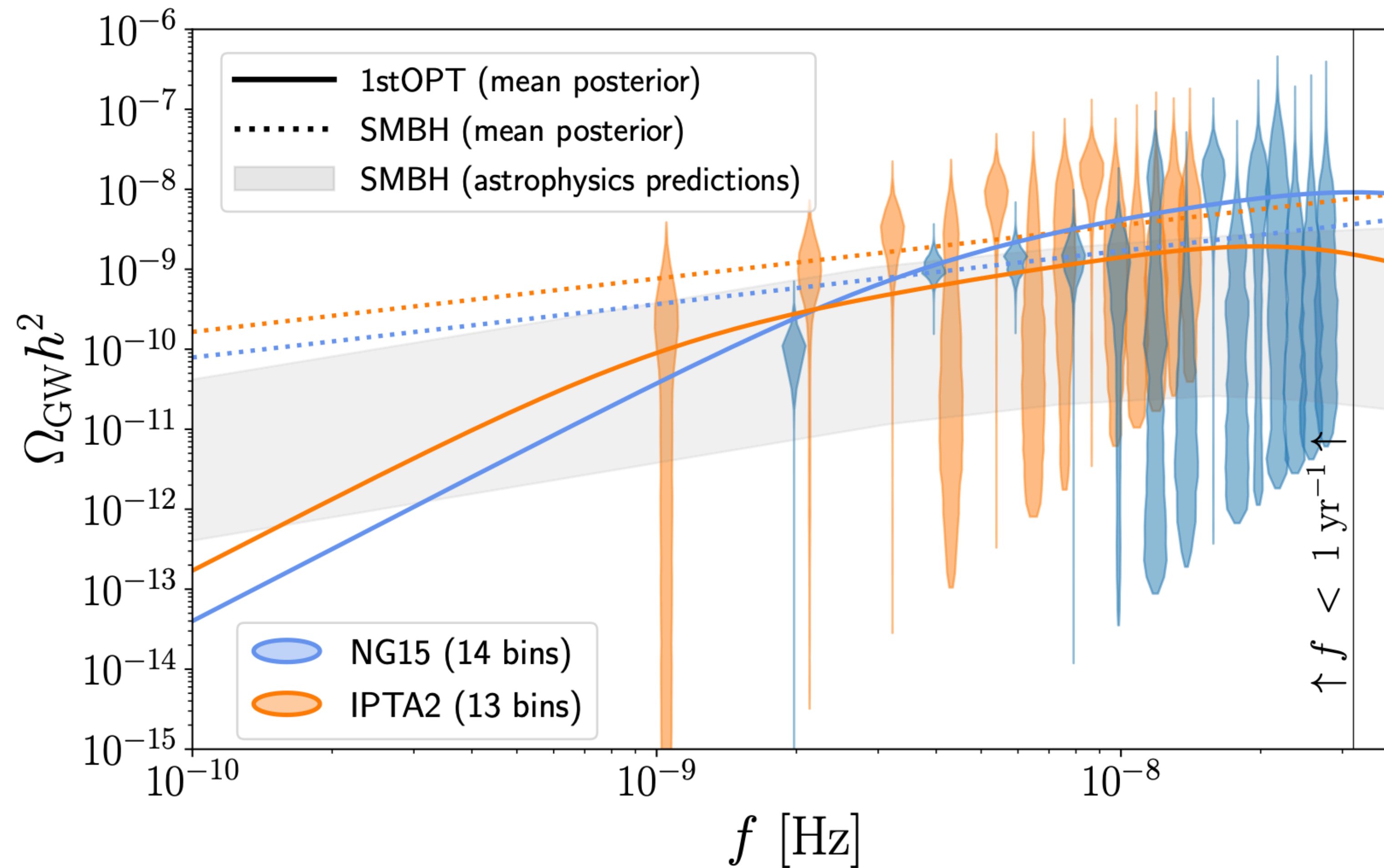
[C. Caprini et al., LISA CosWG, 2403.03723]

GRAVITATIONAL WAVE DETECTORS



[figure credit: Christopher Moore, Robert Cole and Christopher Berry]

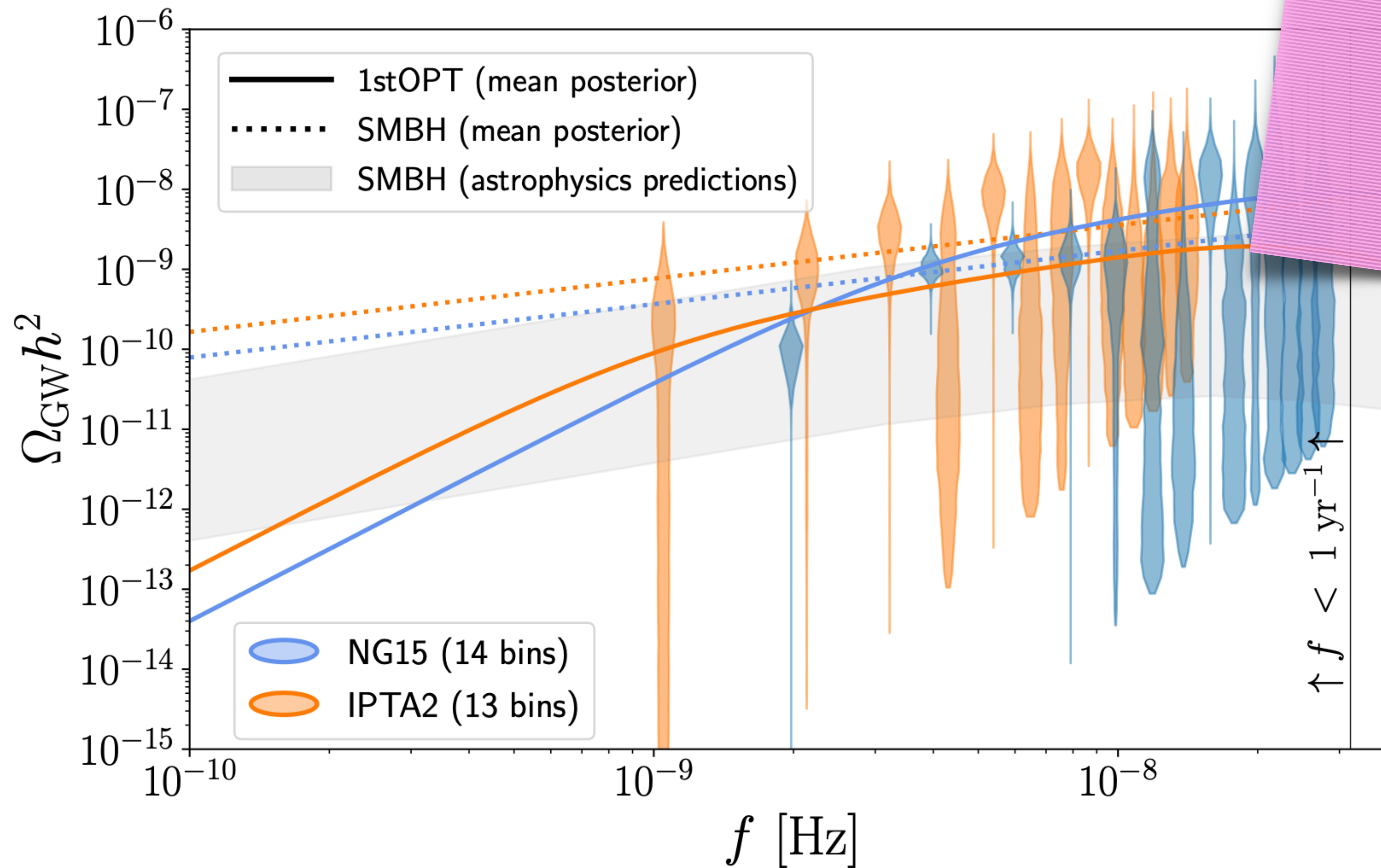
HAVE WE ALREADY SEEN A SIGNAL IN PTA?



[Y. Gouttenoire, Phys.Rev.Lett. 131 (2023) 17]

[J. Ellis, M. Fairbairn, G. Franciolini, G. Hütsi, A. Iovino Jr., M. Lewicki, M. Raidal, J. Urrutia, V. Vaskonen, H. Veermäe, Phys.Rev.D 109 (2024) 2, 023522, T. Bringmann, P. F. Depta, T. Konstandin, K. Schmidt-Hoberg, C. Tasillo, and others]

HAVE WE ALREADY SEEN A SIGNAL



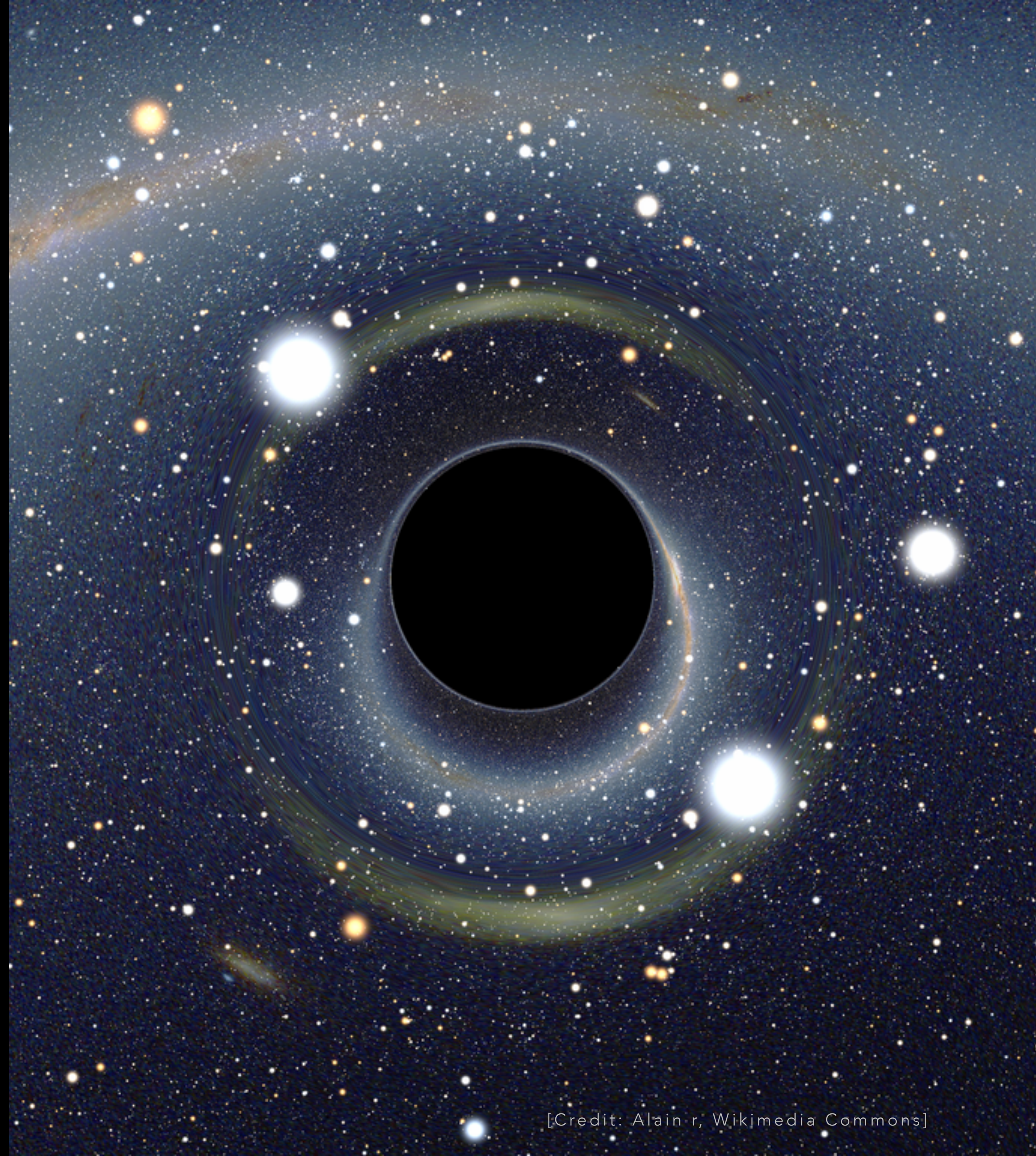
see also talk
by Antonio
Iovino

[Y. Gouttenoire, Phys.Rev.Lett. 131 (2023) 17]

[J. Ellis, M. Fairbairn, G. Franciolini, G. Hütsi, A. Iovino Jr., M. Lewicki, M. Raidal, J. Urrutia, V. Vaskonen, H. Veermäe, Phys.Rev.D 109 (2024) 2, 023522, T. Bringmann, P. F. Depta, T. Konstandin, K. Schmidt-Hoberg, C. Tasillo, and others]

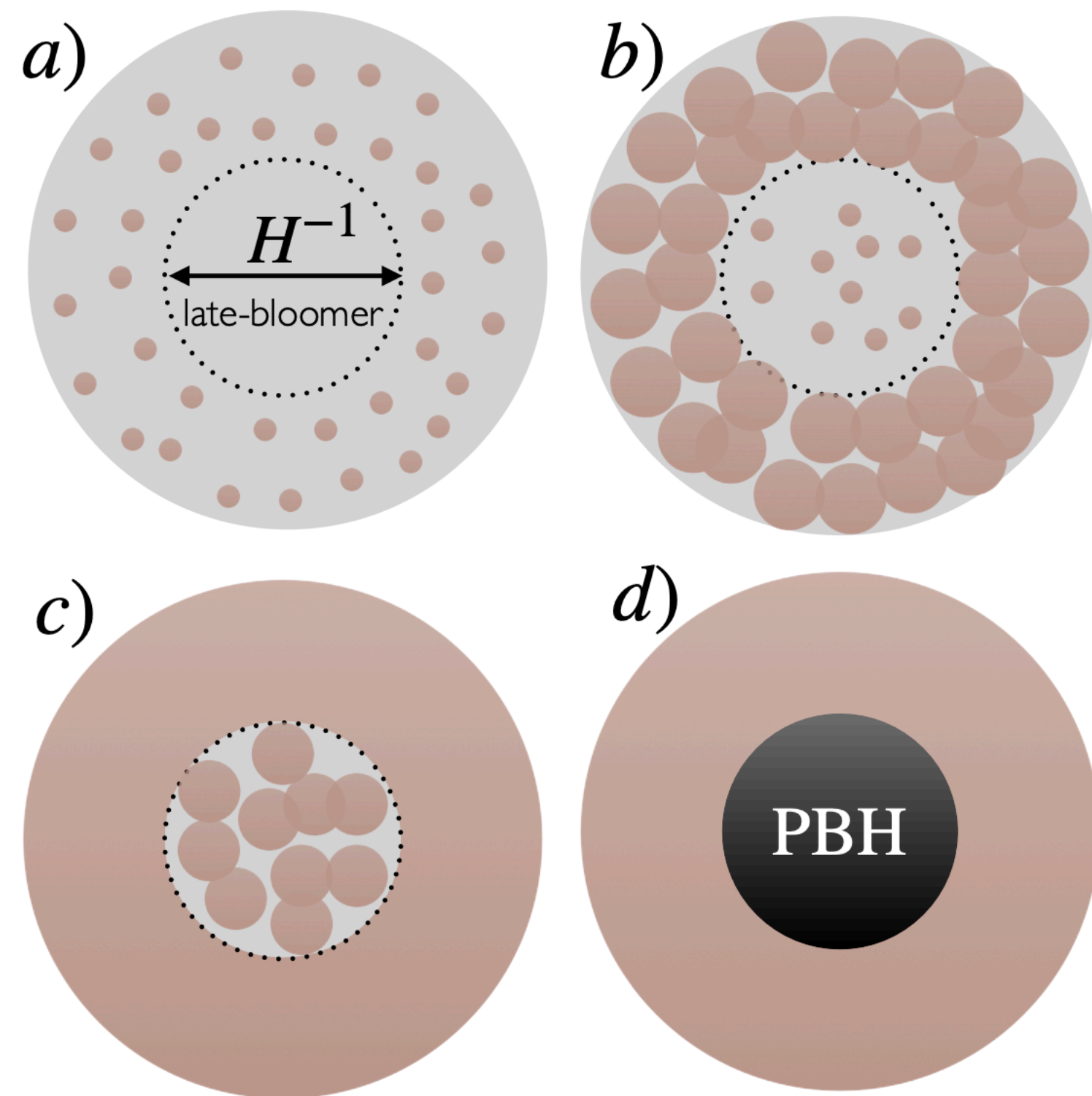
OTHER EFFECTS OF PT

PRIMORDIAL BLACK HOLES AND SECONDARY GW



[Credit: Alain r, Wikimedia Commons]

PRIMORDIAL BLACK HOLES



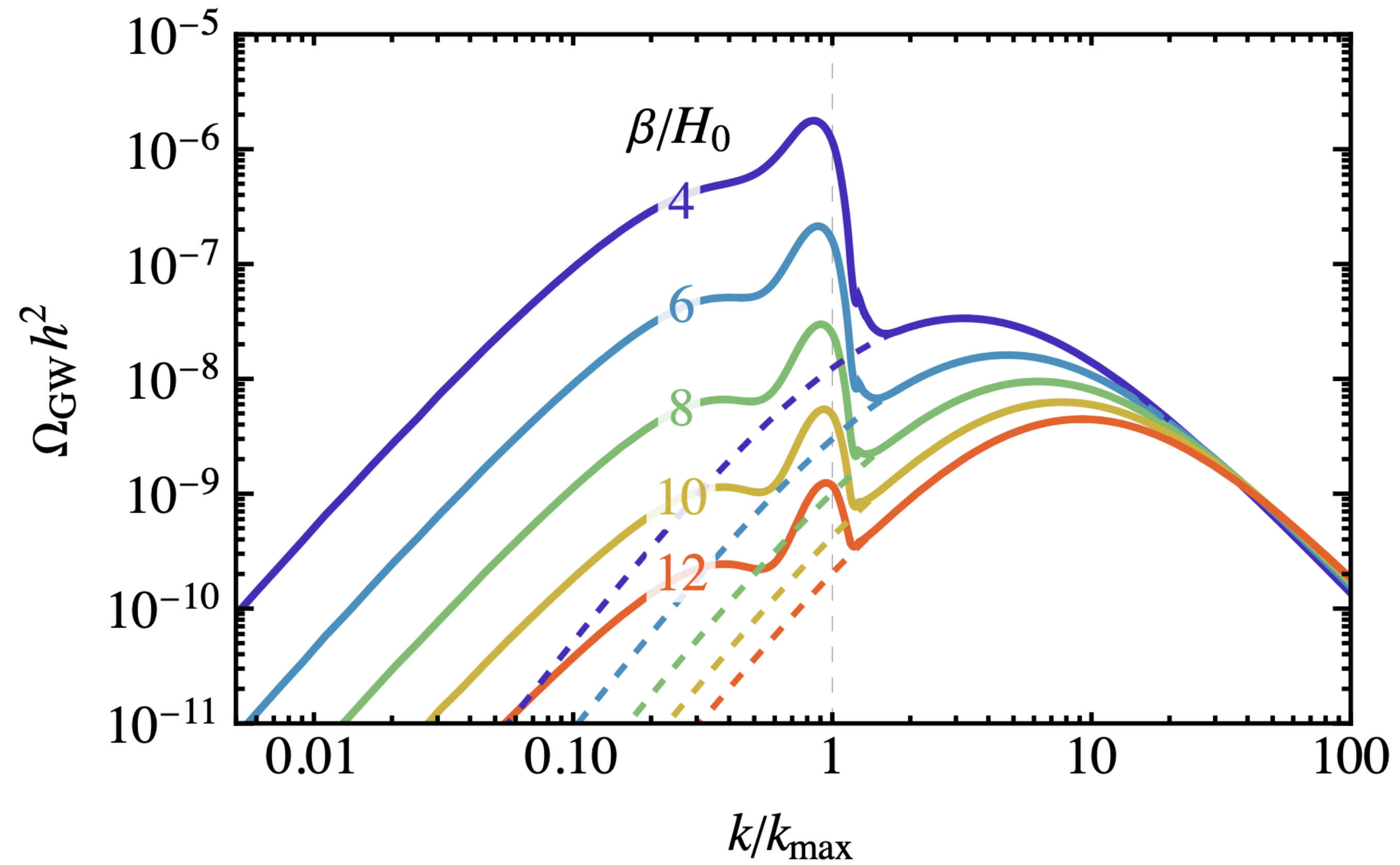
Old vacuum-dominated region (outside bubbles)
New radiation-dominated region (inside bubbles)

[Y. Gouttenoire, T. Volansky, 2305.04942 [hep-ph]]

Too slow PTs excluded due to overabundance of PBH.

[H. Kodama, M. Sasaki, and K. Sato, Prog. Theor. Phys. 68, 1979 (1982),
J. Liu, L. Bian, R.-G. Cai, Z.-K. Guo, and S.-J. Wang, Phys. Rev. D 105, L021303 (2022),
M. Lewicki, P. Toczec, V. Vaskonen, JHEP 09 (2023) 092, 2402.04158]

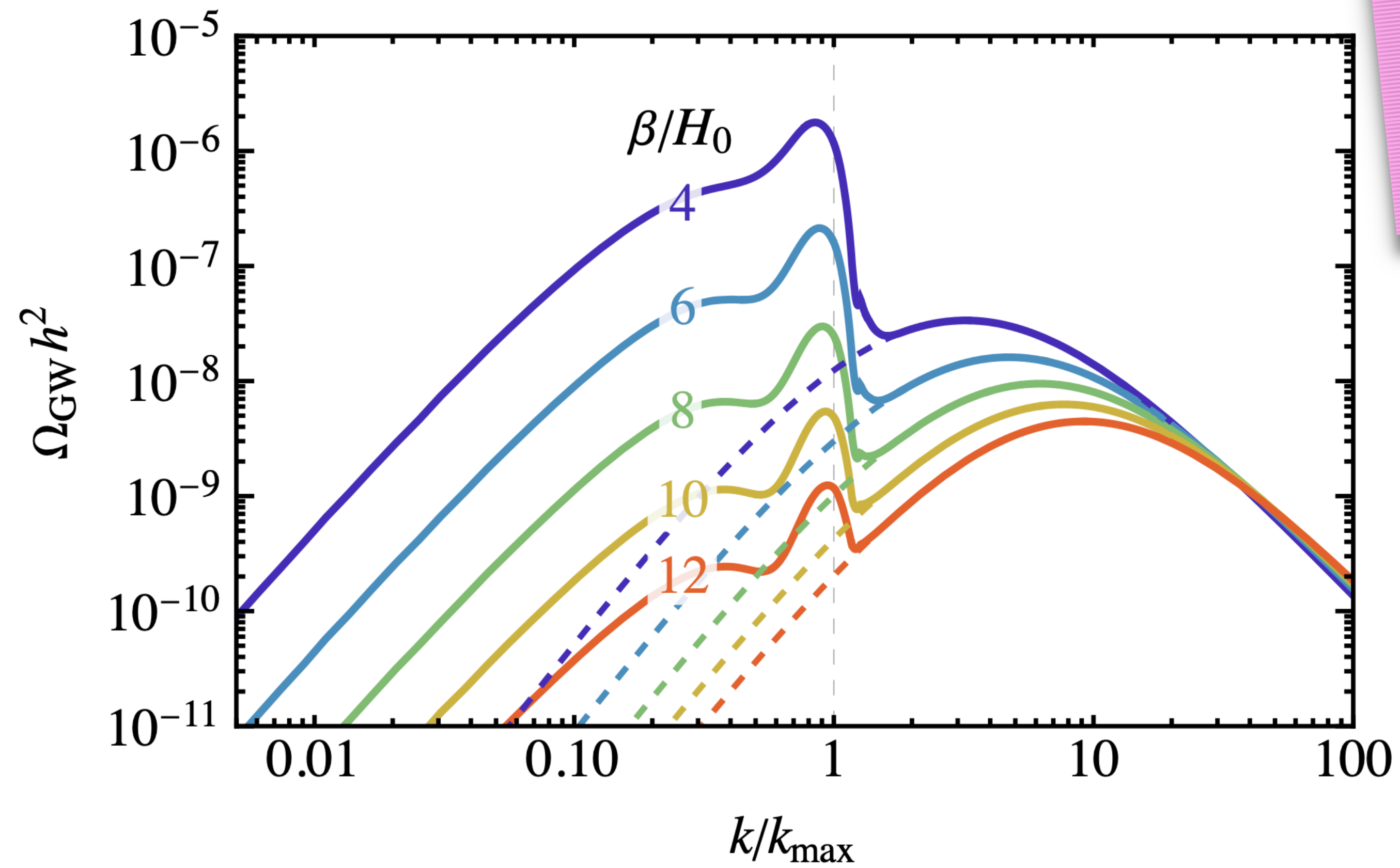
SECONDARY GRAVITATIONAL WAVES



[M. Lewicki, P. Toczek, V. Vaskonen, 2402.04158]

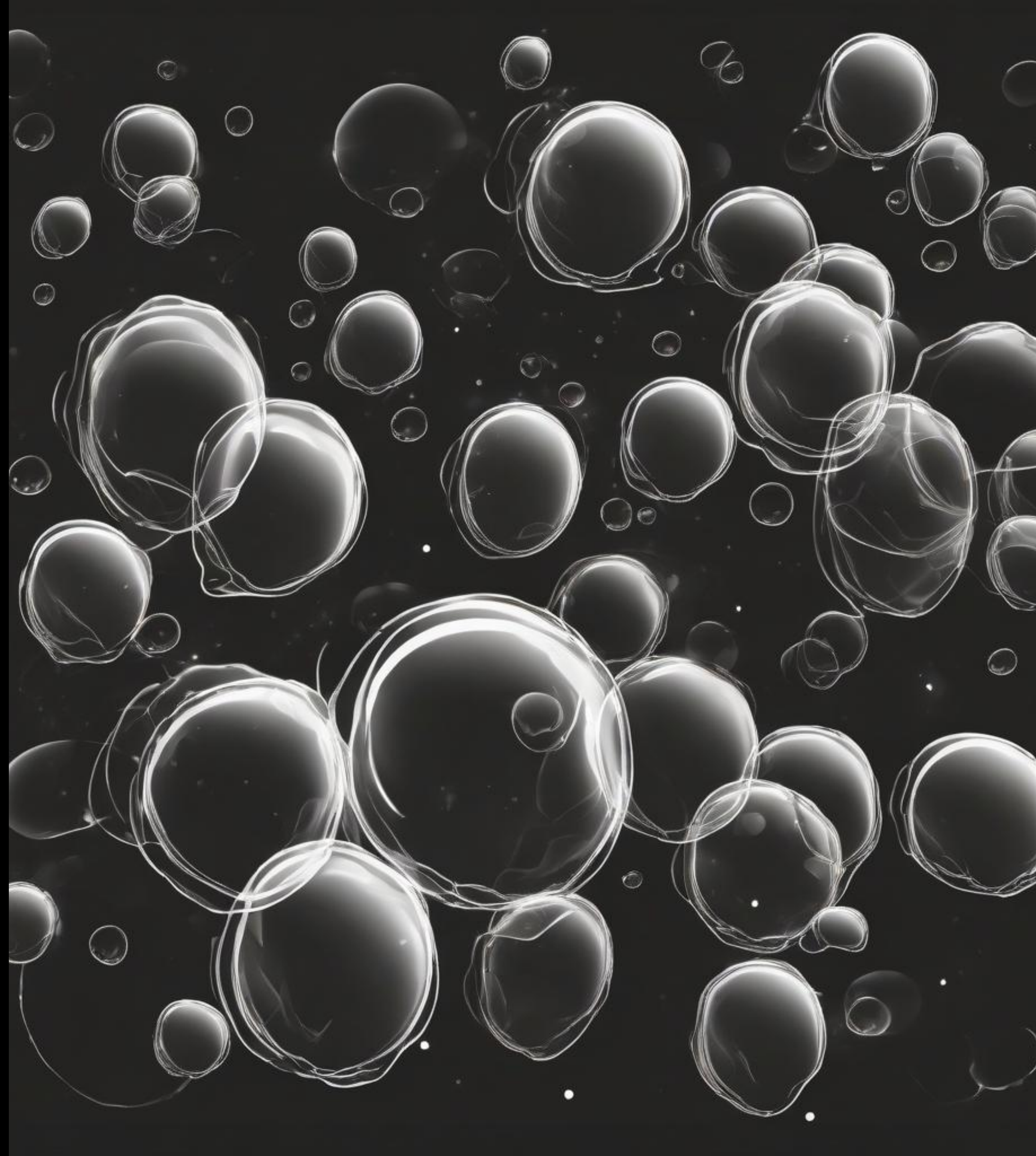
SECONDARY GRAVITATIONAL WAVES

See poster/talk
of Piotr Toczek



[M. Lewicki, P. Toczek, V. Vaskonen, 2402.04158]

SUMMARY



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Progress in
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More needed!

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Other interesting
phenomena
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the PT
(baryogenesis,
DM, PBH).