GRAVITATIONAL WAVES FROM PHASE TRANSITIONS

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UNIVERSITY OF WARSAW

DIVING INTO "UNOBSERVABLE" PAST

[Image source: BBC.CO.UK]

UNOBSERVABLE UNIVERSE (PAST)

POTENTIALLY OBSERVABLE 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.

A FEW HUNDRED MILLION YEARS

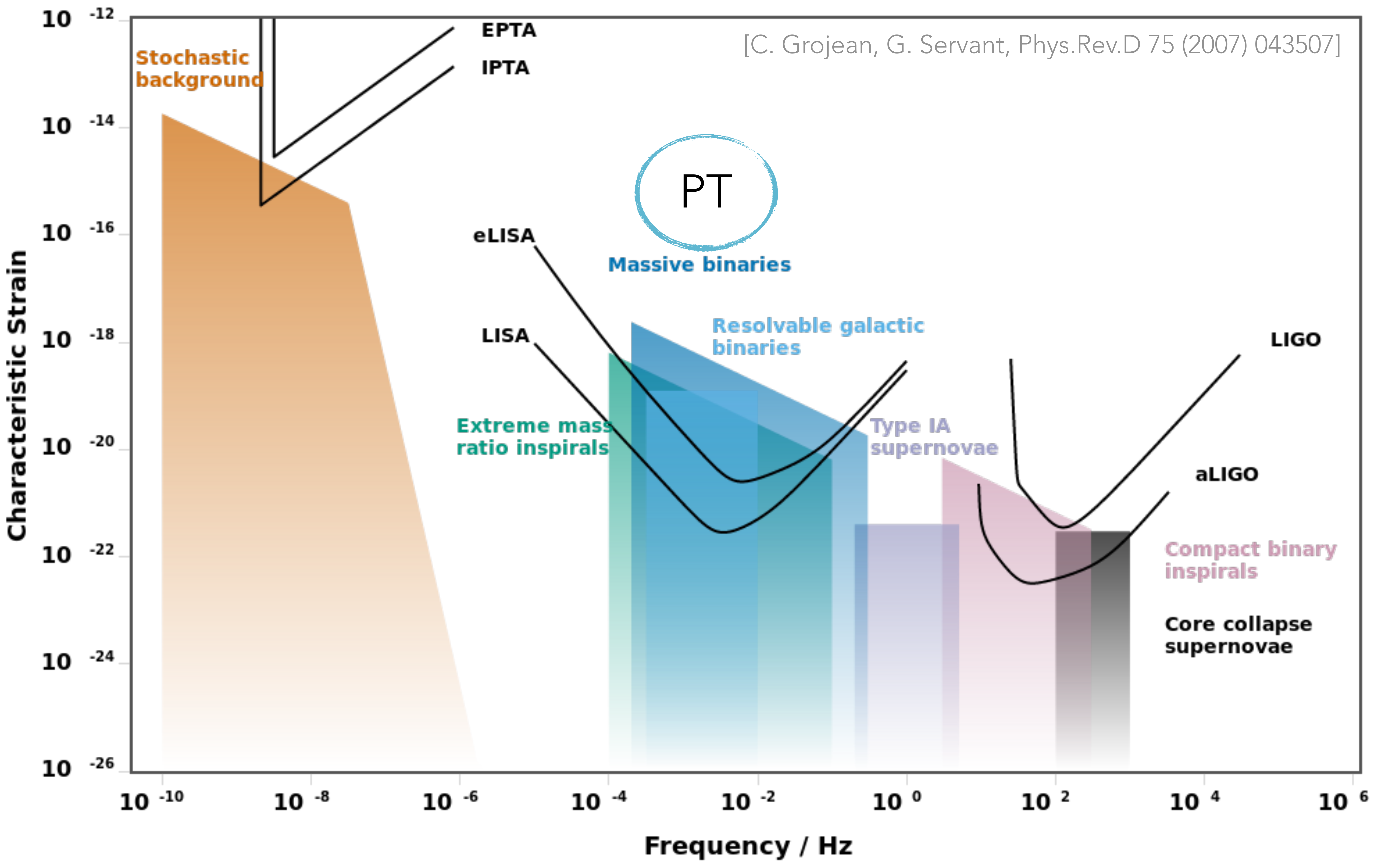
Matter clumps together under its own gravity forming the first protogalaxies and within them, the first stars.

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

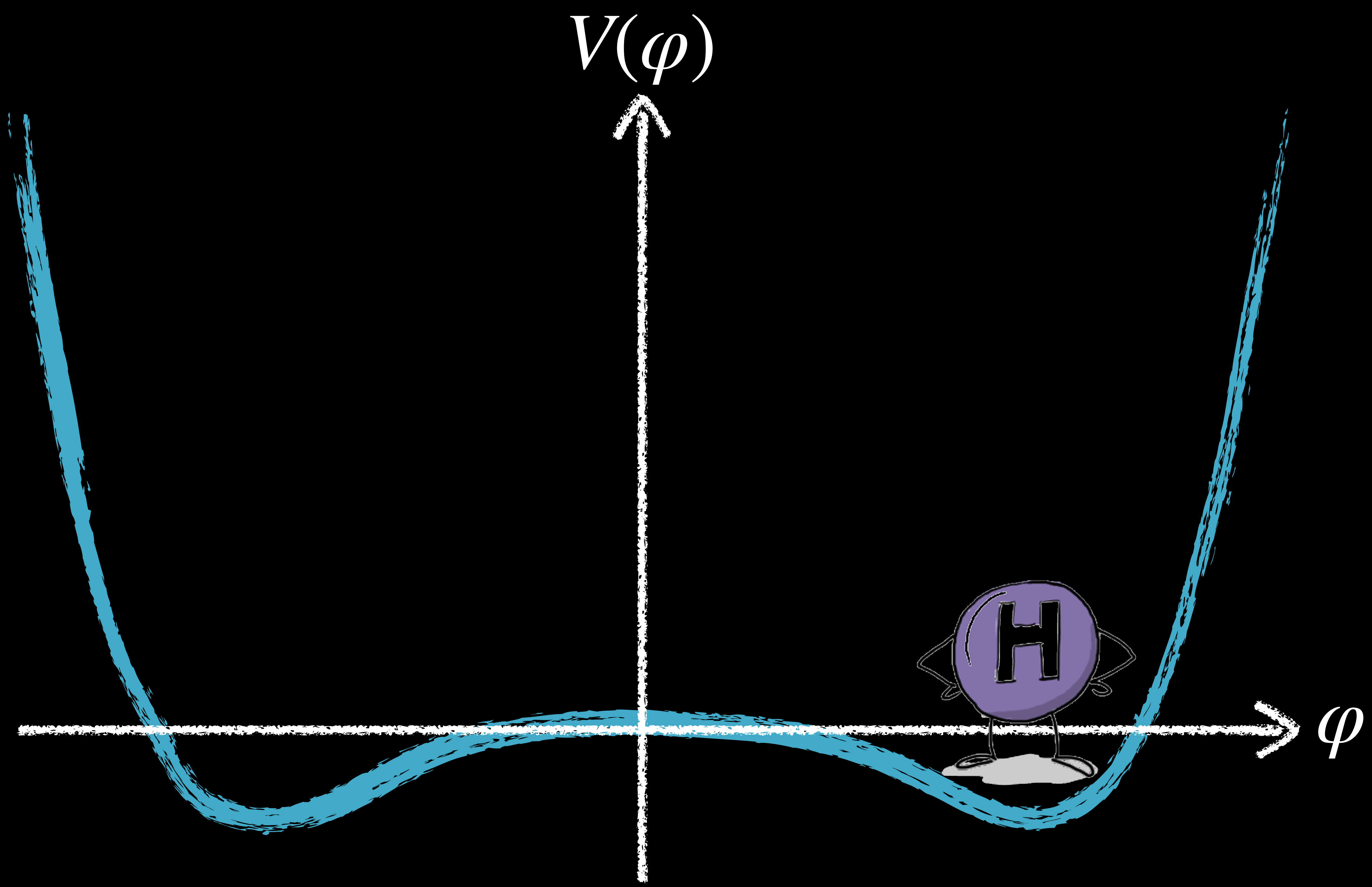
Initially, the expansion of the U
few billion years after the Big B
accelerate. The acceleration is
force known as 'dark energy',
completely unknown.

GRAVITATIONAL WAVES FROM A PT



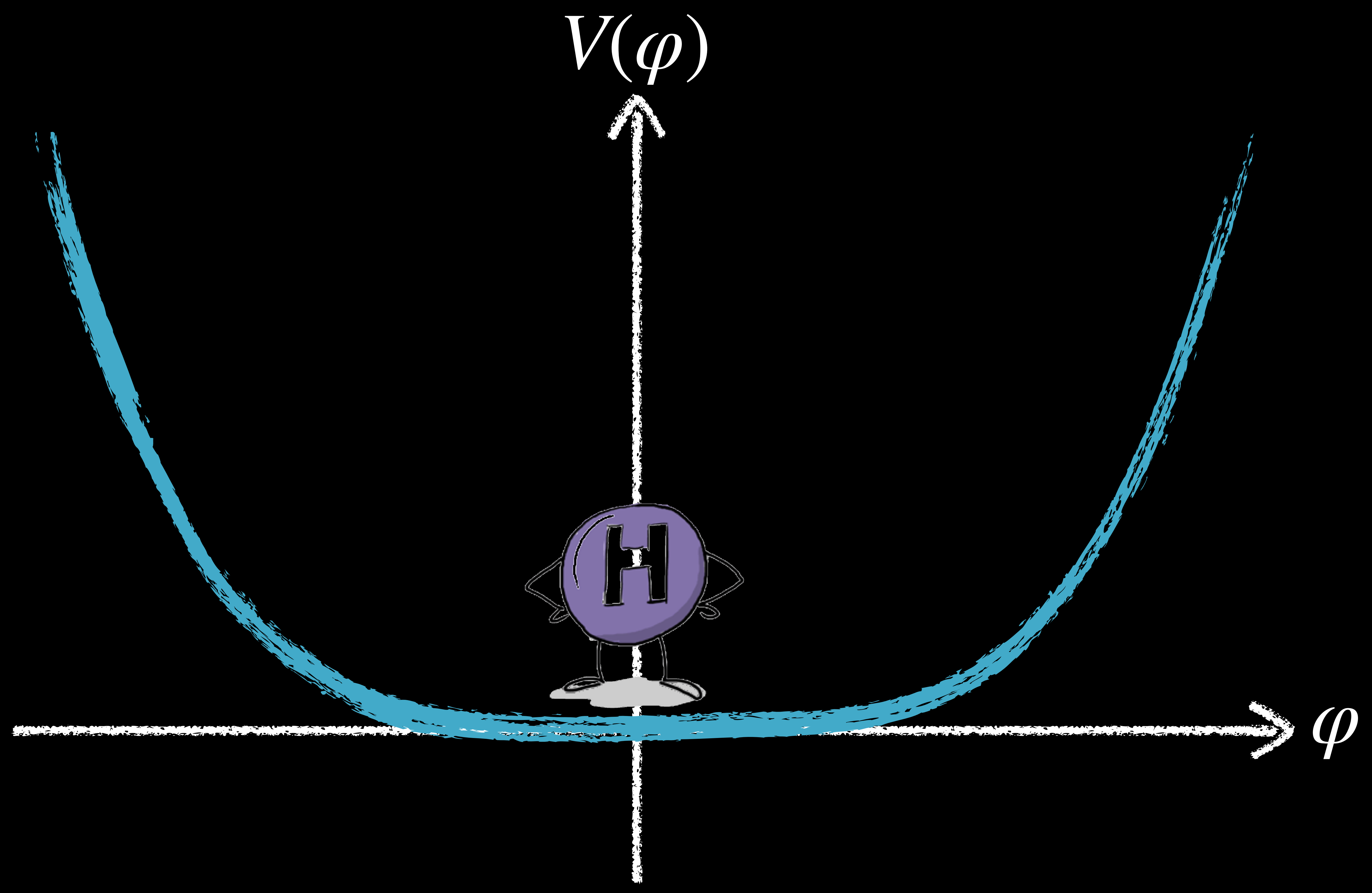
[figure credit: Christopher Moore, Robert Cole and Christopher Berry]

EXPERIMENT: HIGGS EXISTS

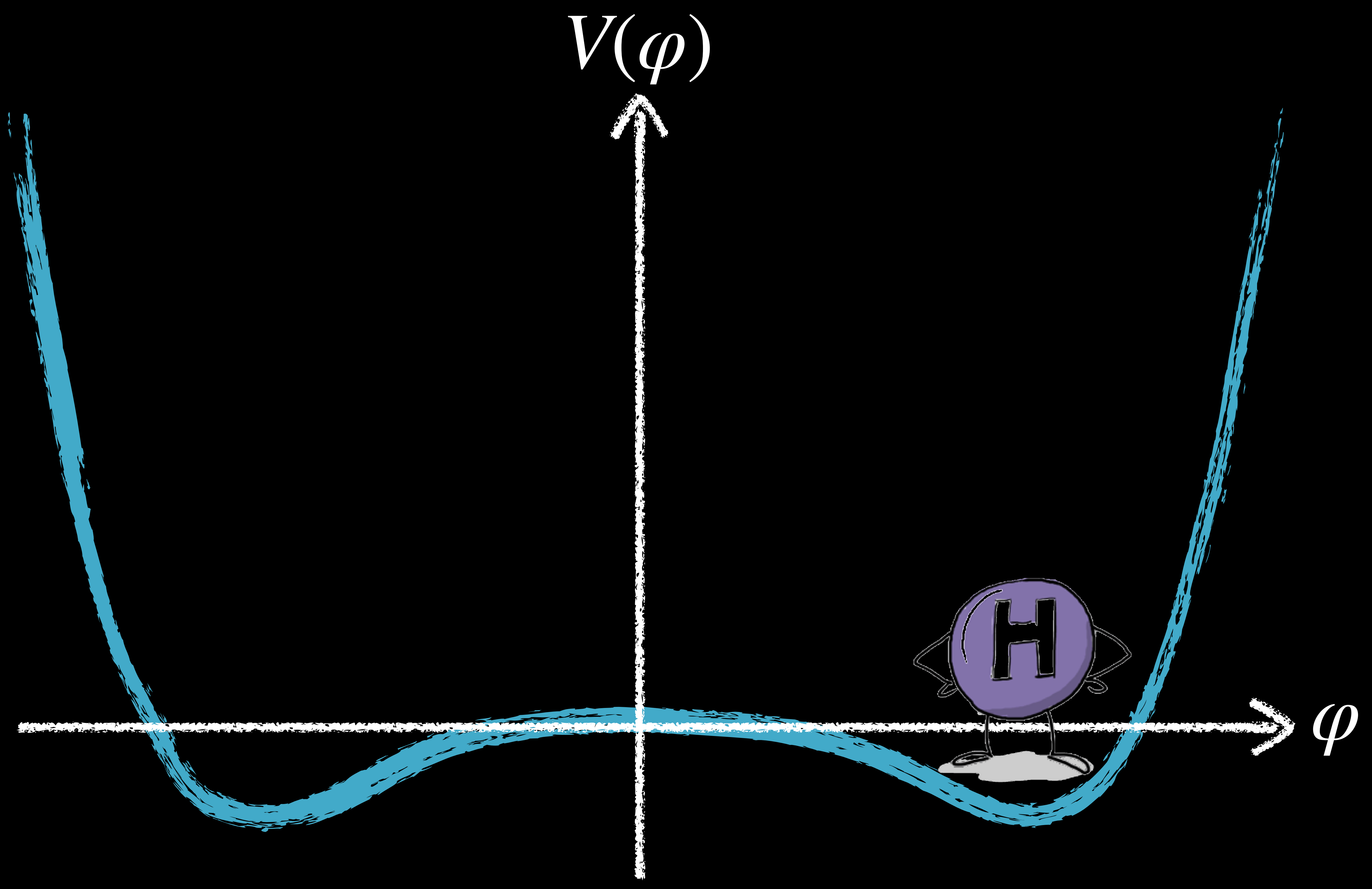


[Image from PhD Comics]

THEORY: NO VEV IN THE PAST



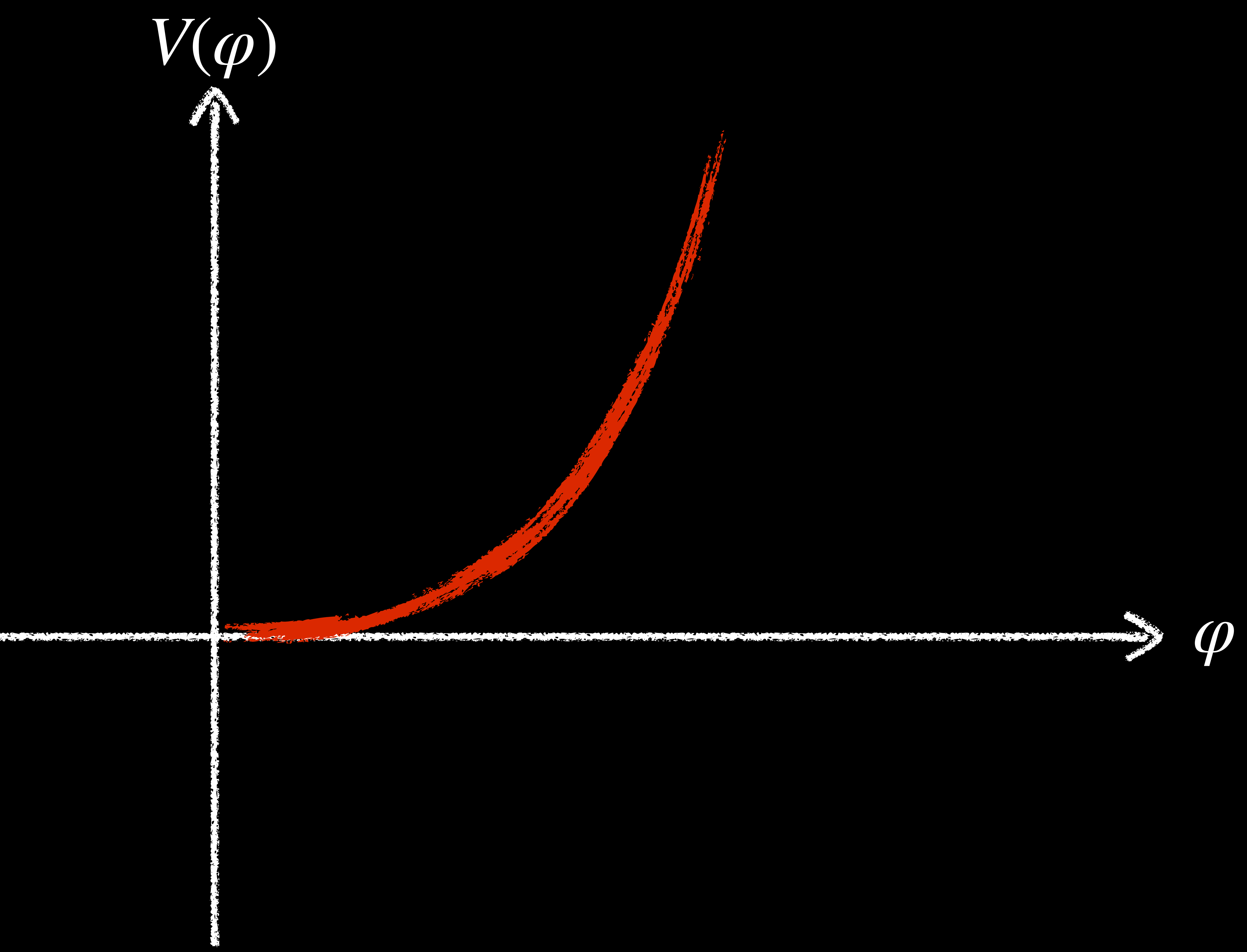
PHASE TRANSITION HAPPENED!



[Image from PhD Comics]

STOCHASTIC GRAVITATIONAL-WAVE BACKGROUND FROM FIRST-ORDER PHASE TRANSITIONS

FIRST-ORDER PHASE TRANSITION



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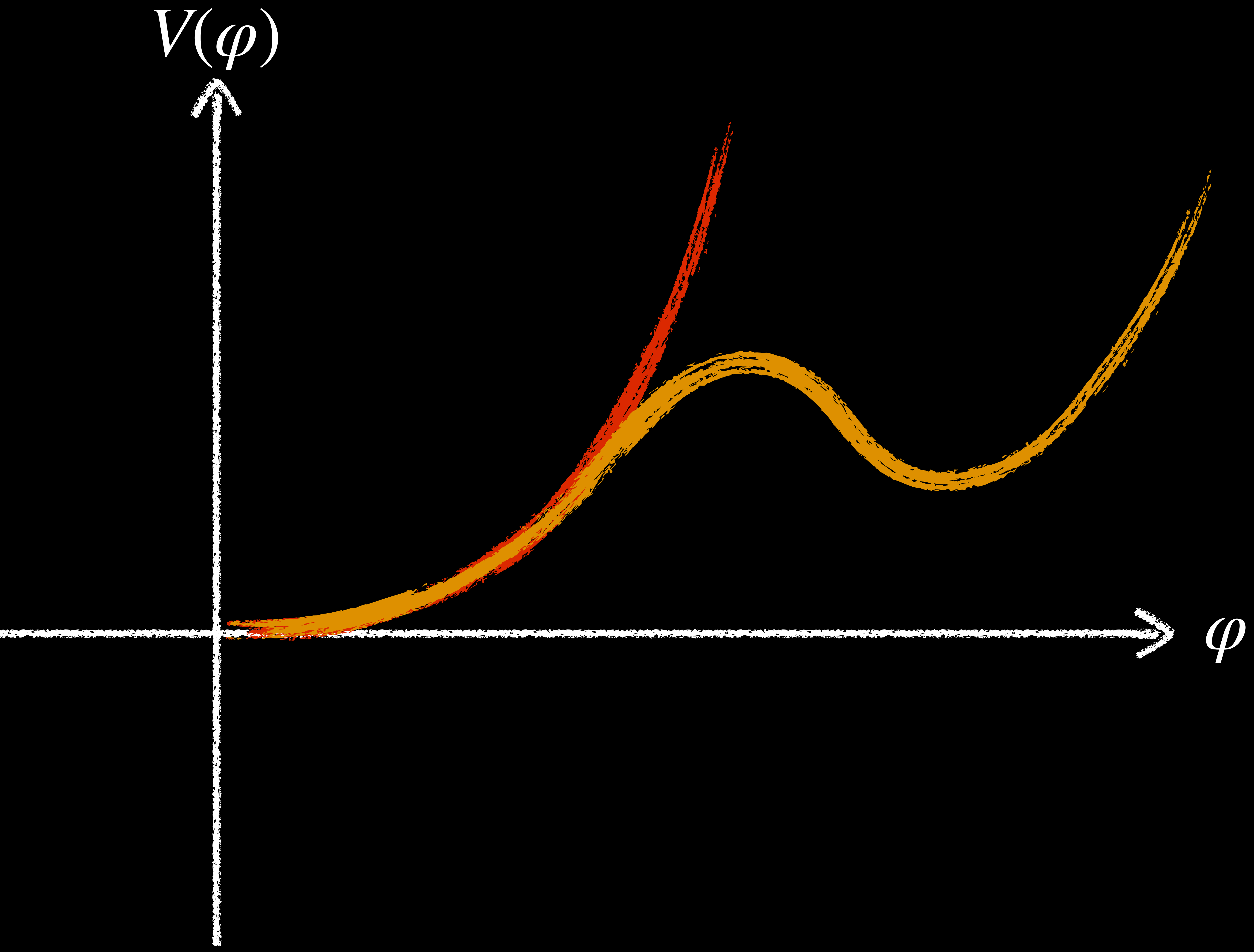

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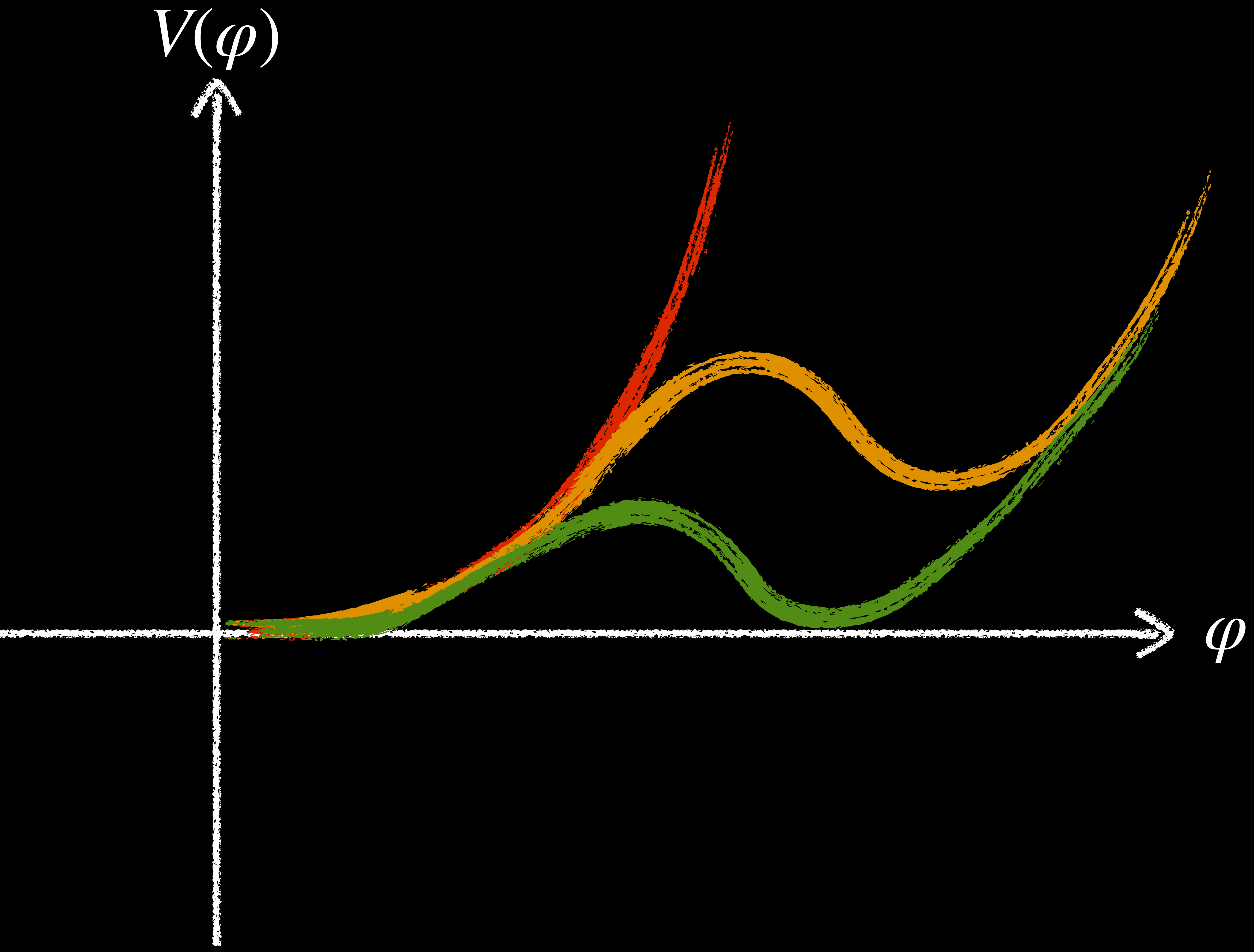

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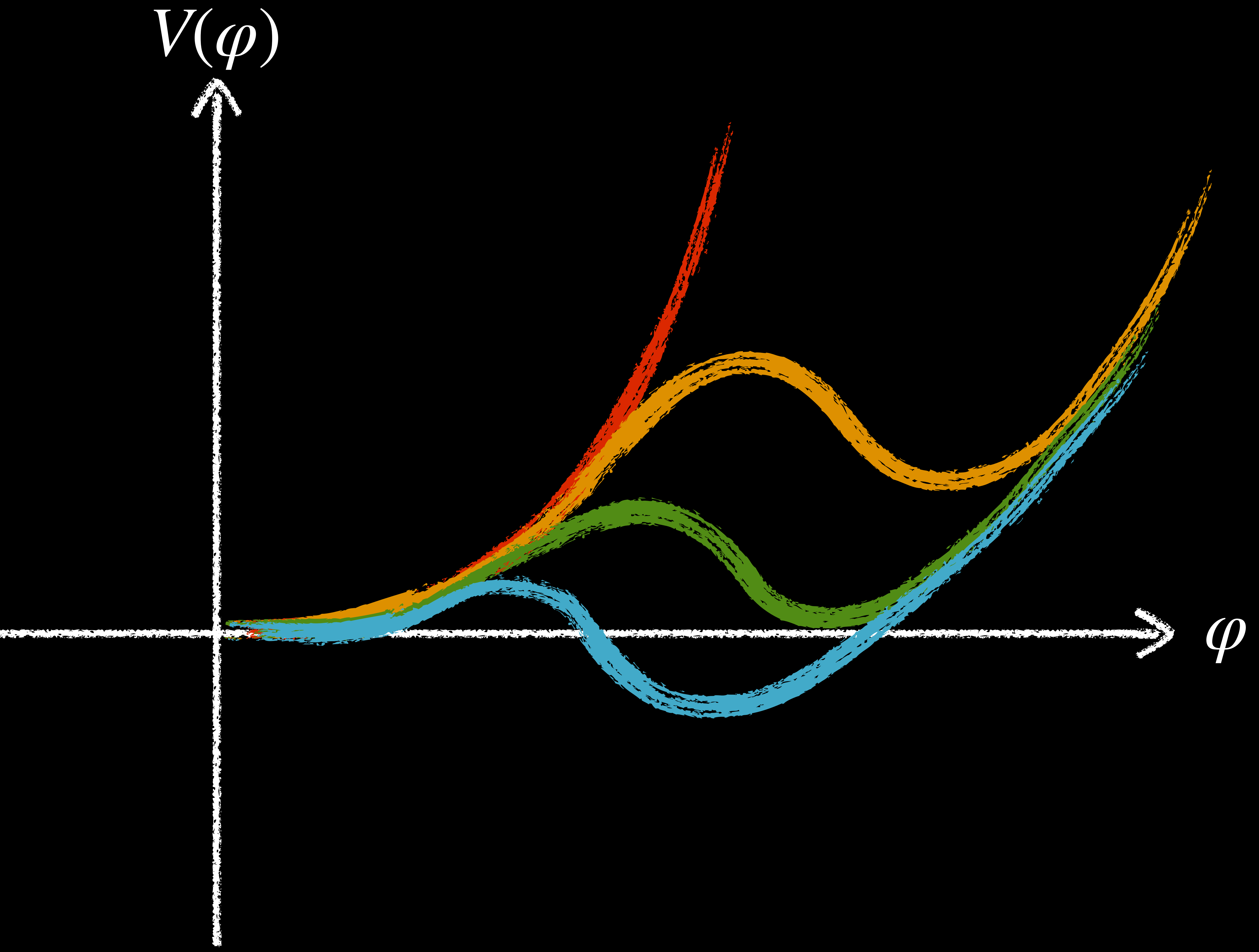

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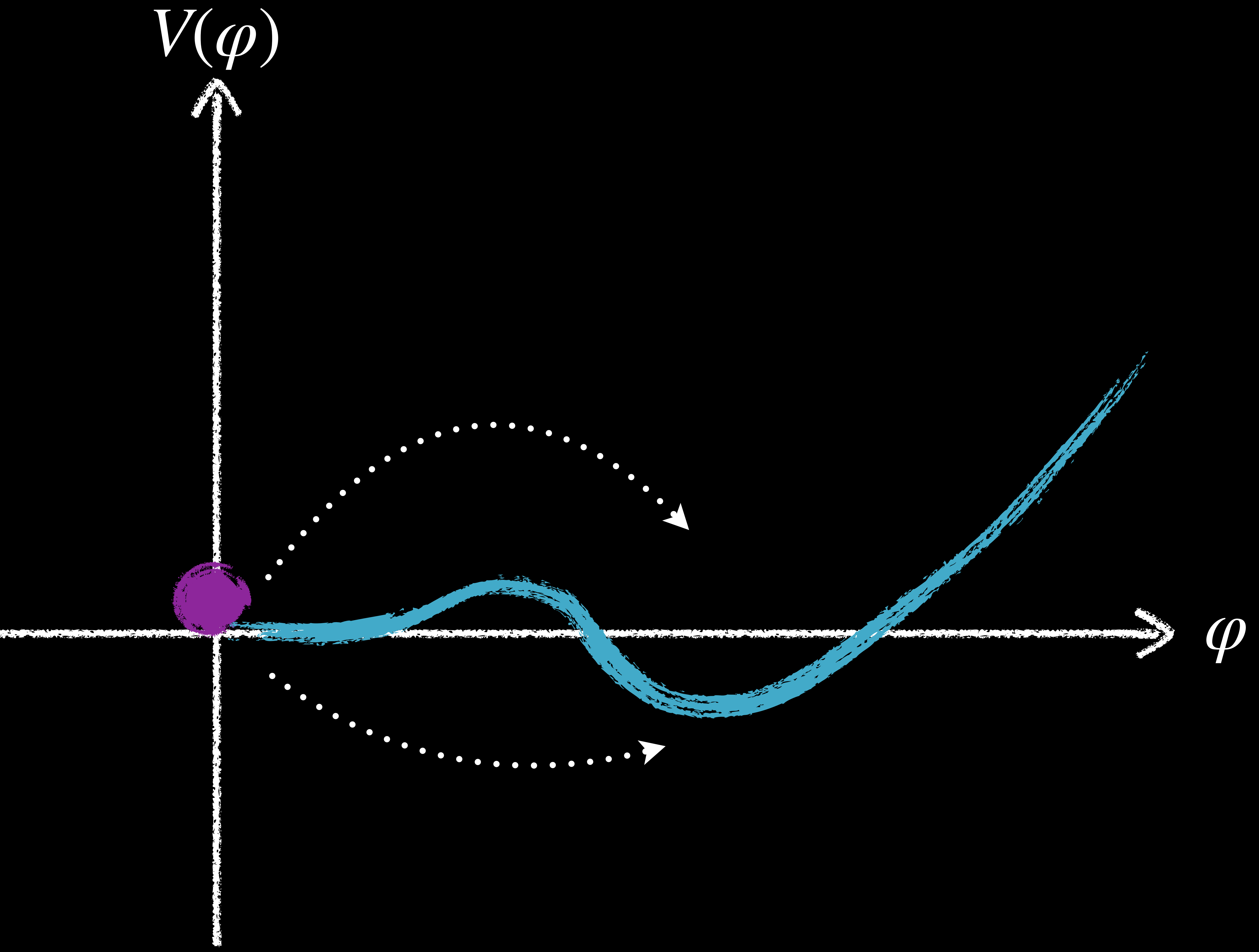

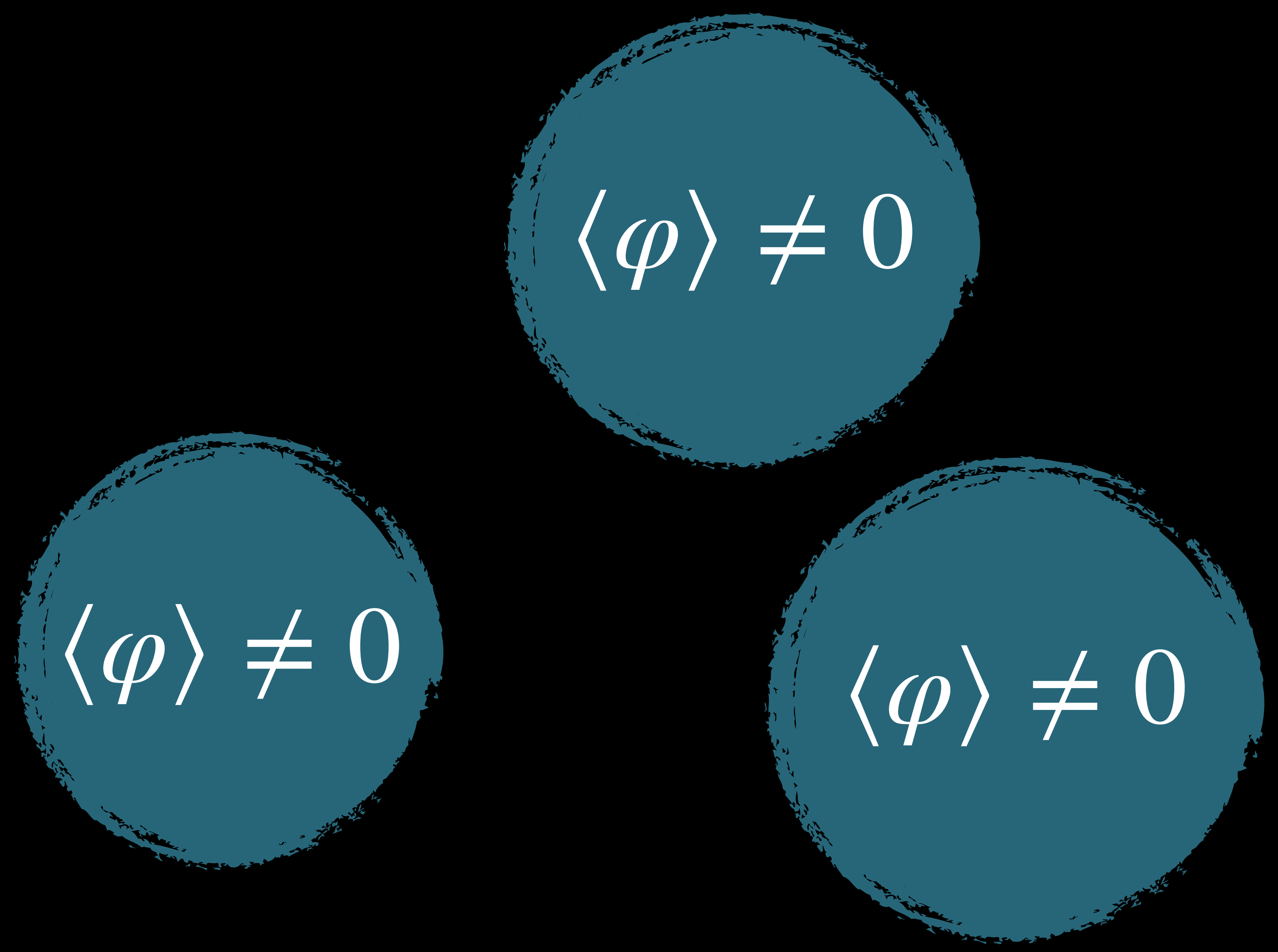

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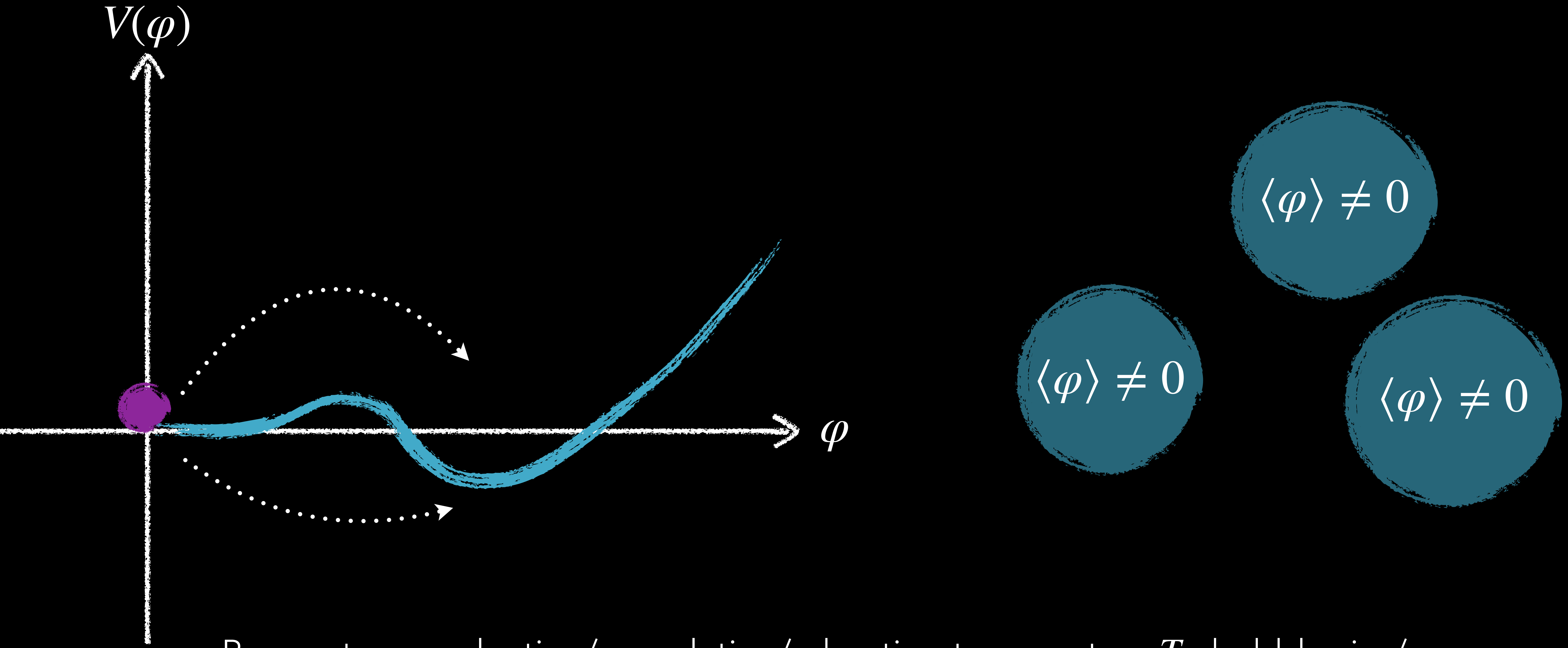
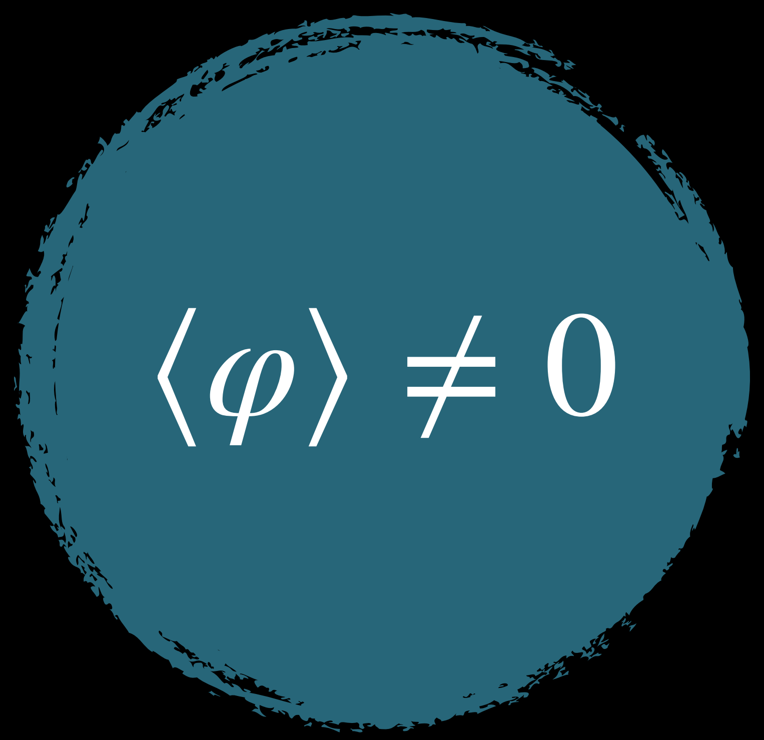


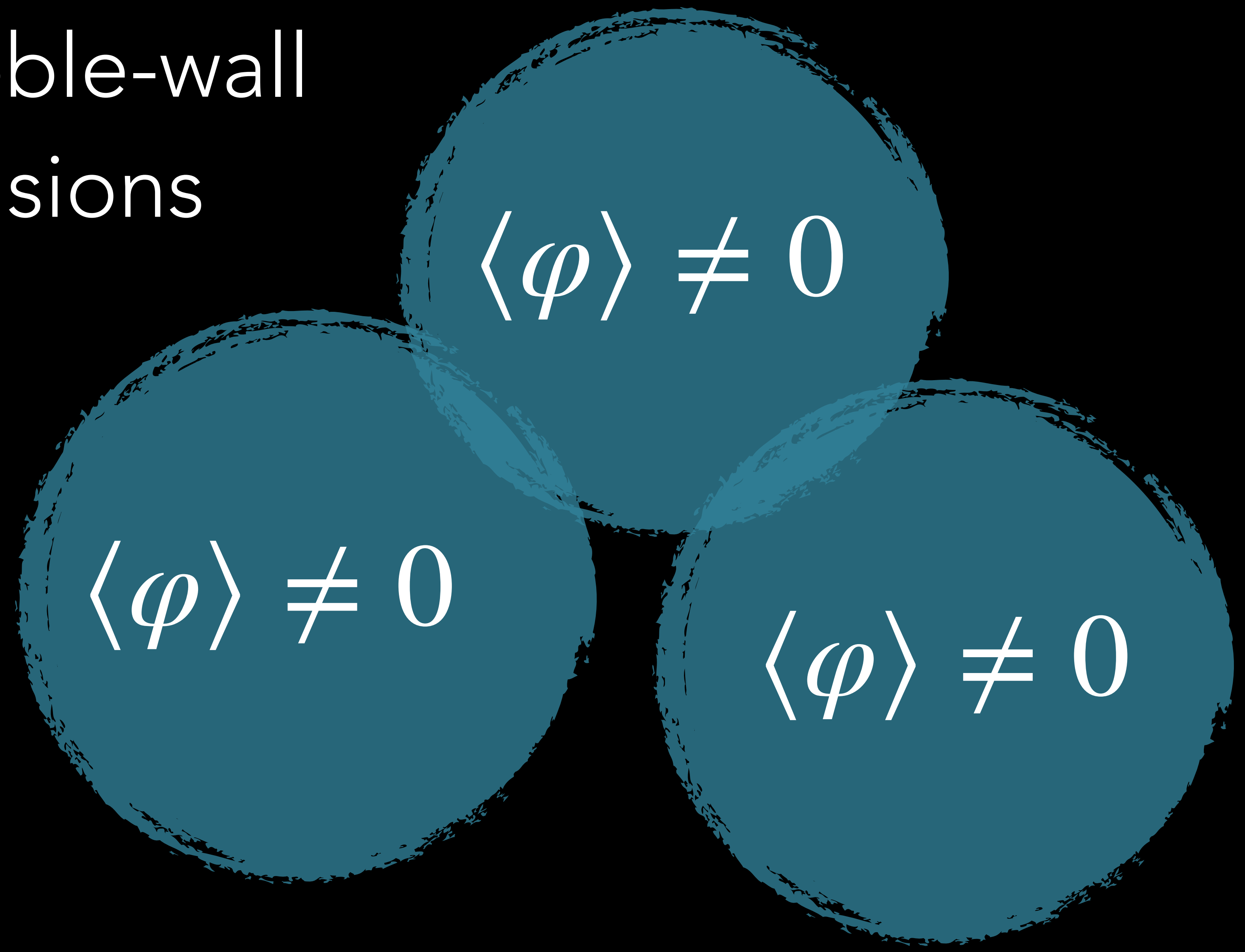
Parameters: nucleation/percolation/reheating temperature T_*, bubble size/transition rate R_*/β_*, transition strength α, bubble-wall velocity v_w

BUBBLES AND PLASMA SOURCE GRAVITATIONAL WAVES



BUBBLES AND PLASMA SOURCE GRAVITATIONAL WAVES

bubble-wall collisions



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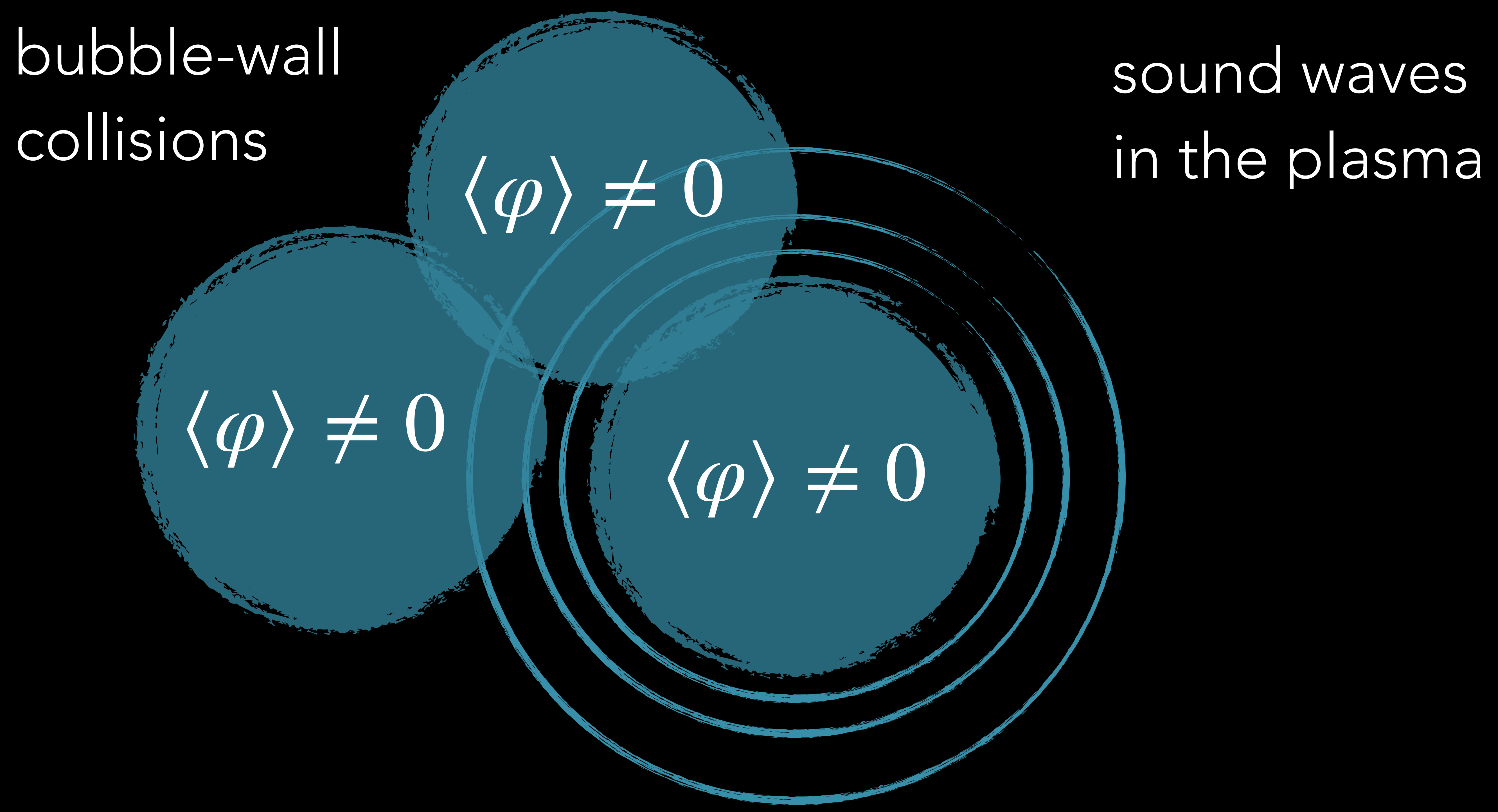

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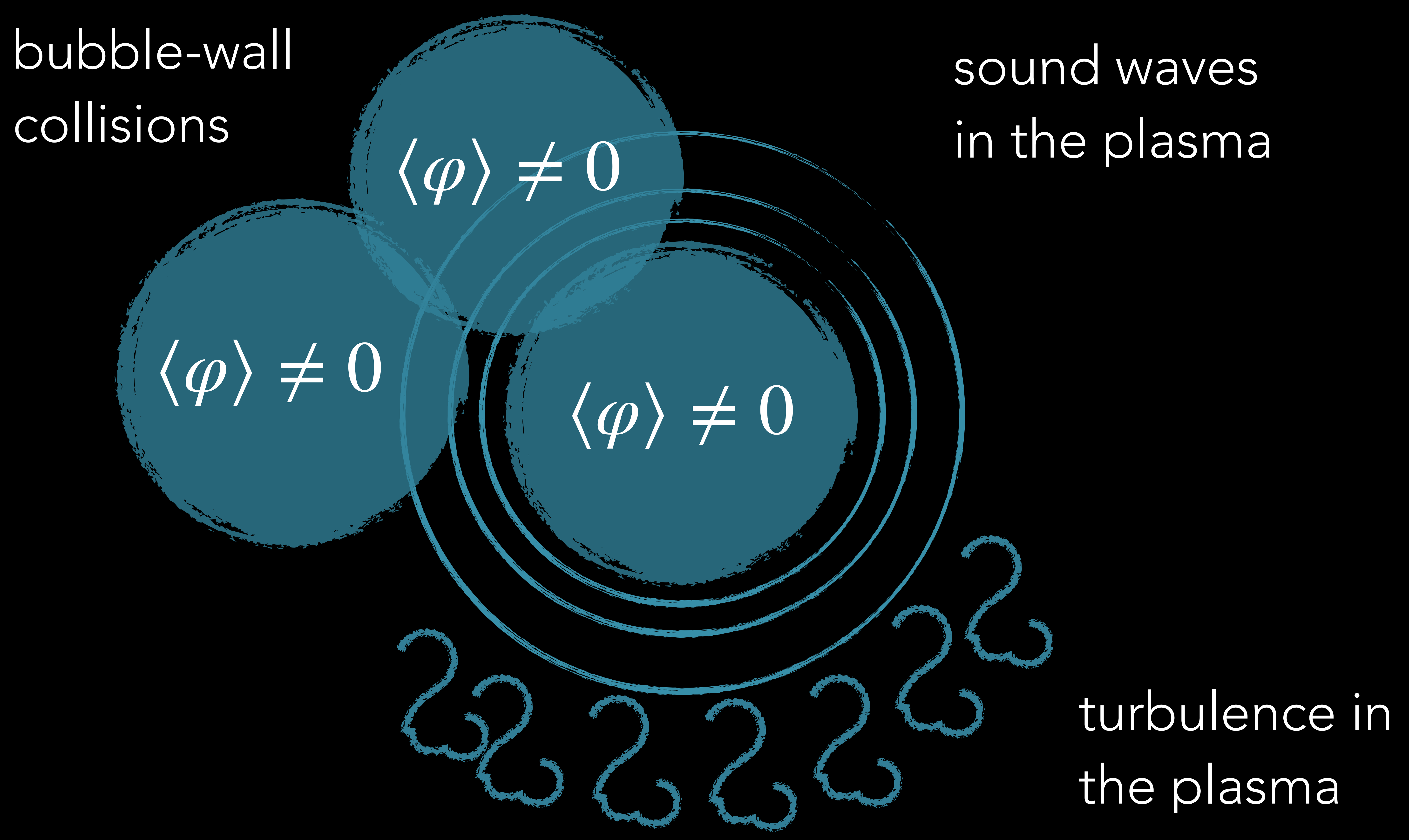
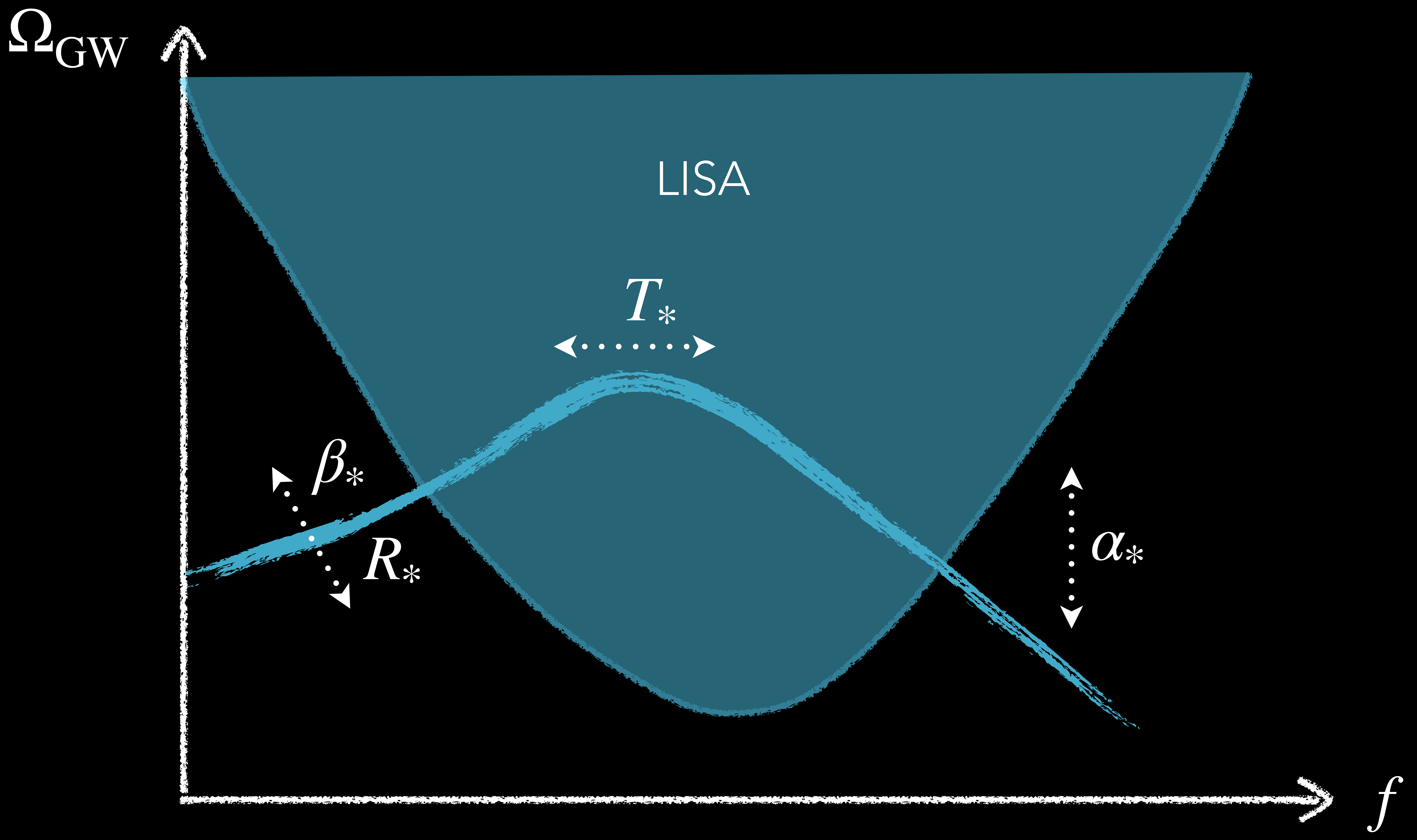


THERMODYNAMICAL PARAMETERS VS GW



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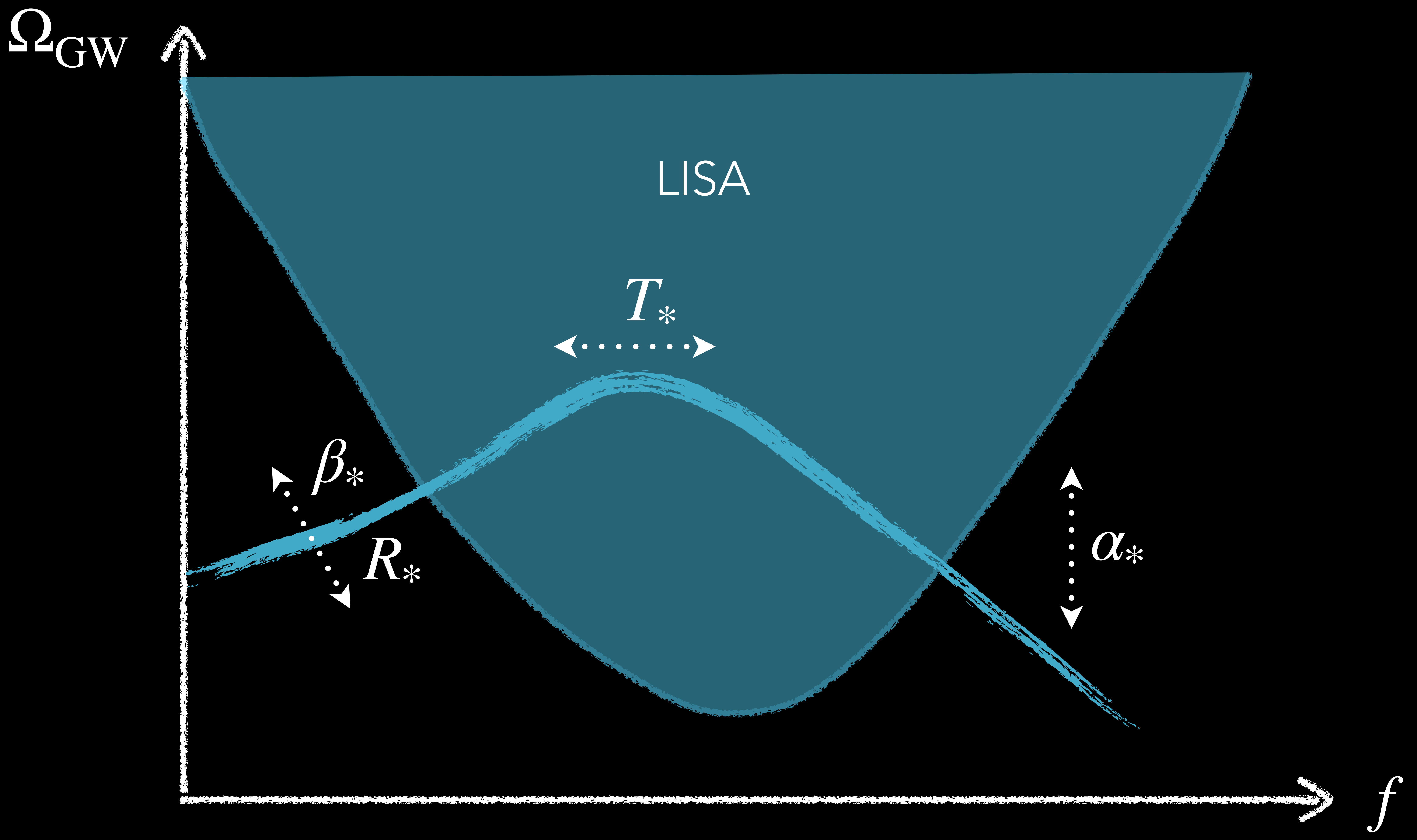
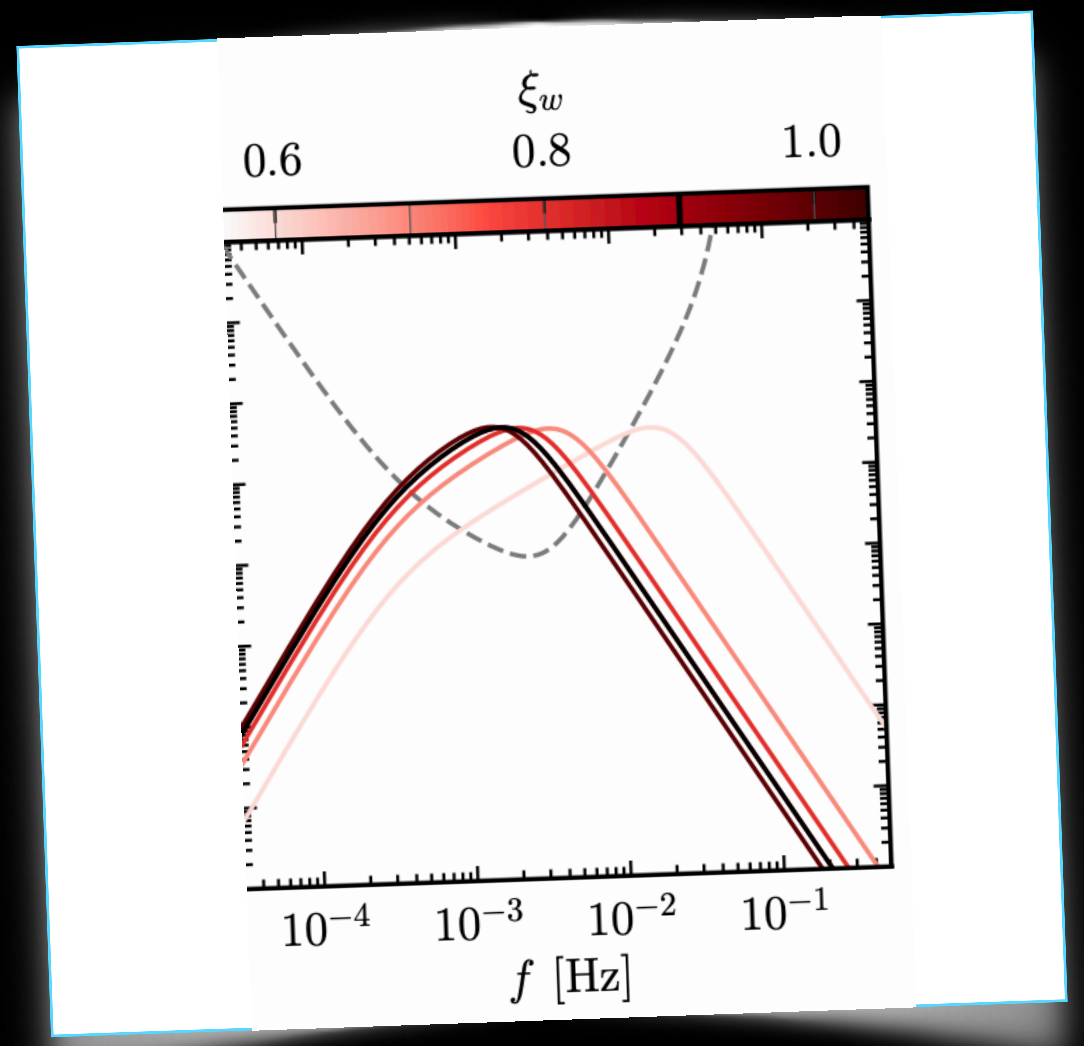


+ wall velocity v_w



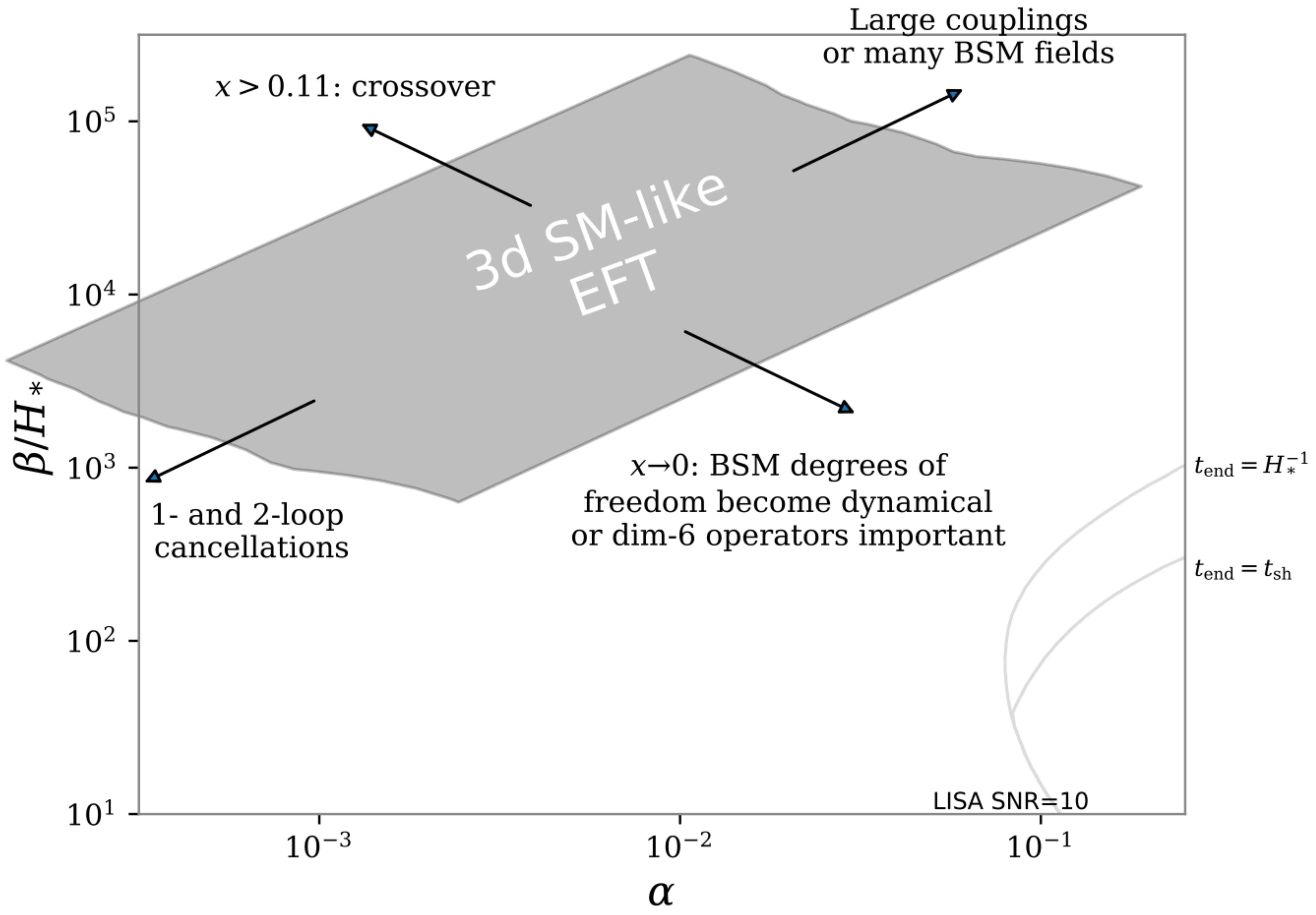
[C. Caprini at al., LISA CosWG, 2403.03723]

In SM the PT is crossover.

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

[K. Kajantie, M. Laine, K. Rummukainen and M. E. Shaposhnikov, Phys. Rev. Lett. 77, 2887 (1996); K. Rummukainen, M. Tsypin, K. Kajantie, M. Laine and M. E. Shaposhnikov, Nucl. Phys. B 532, 283 (1998); F. Csikor, Z. Fodor and J. Heitger, Phys. Rev. Lett. 82, 21 (1999)]

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]

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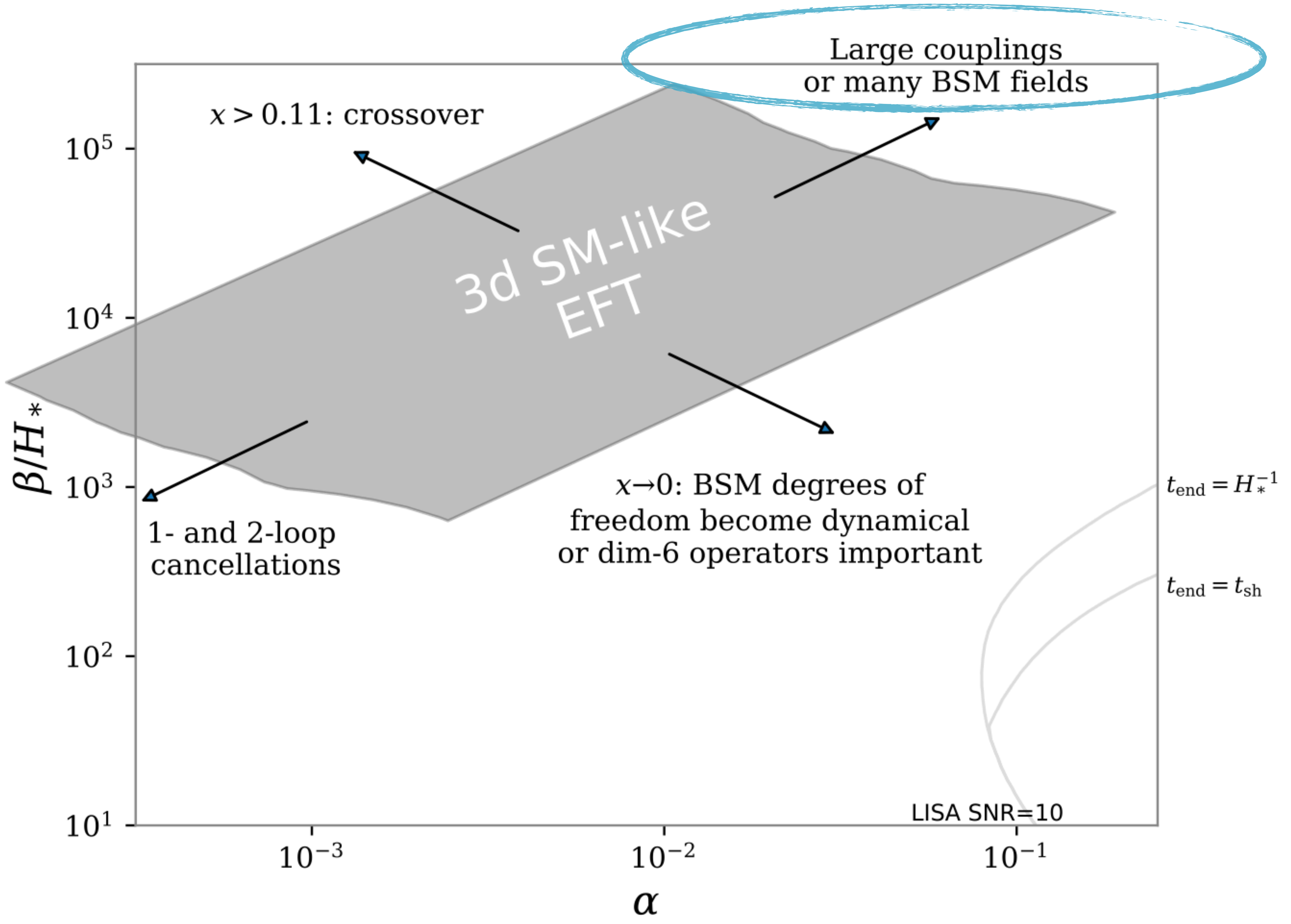

Scalar extensions of the SM (large coupling)

[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]

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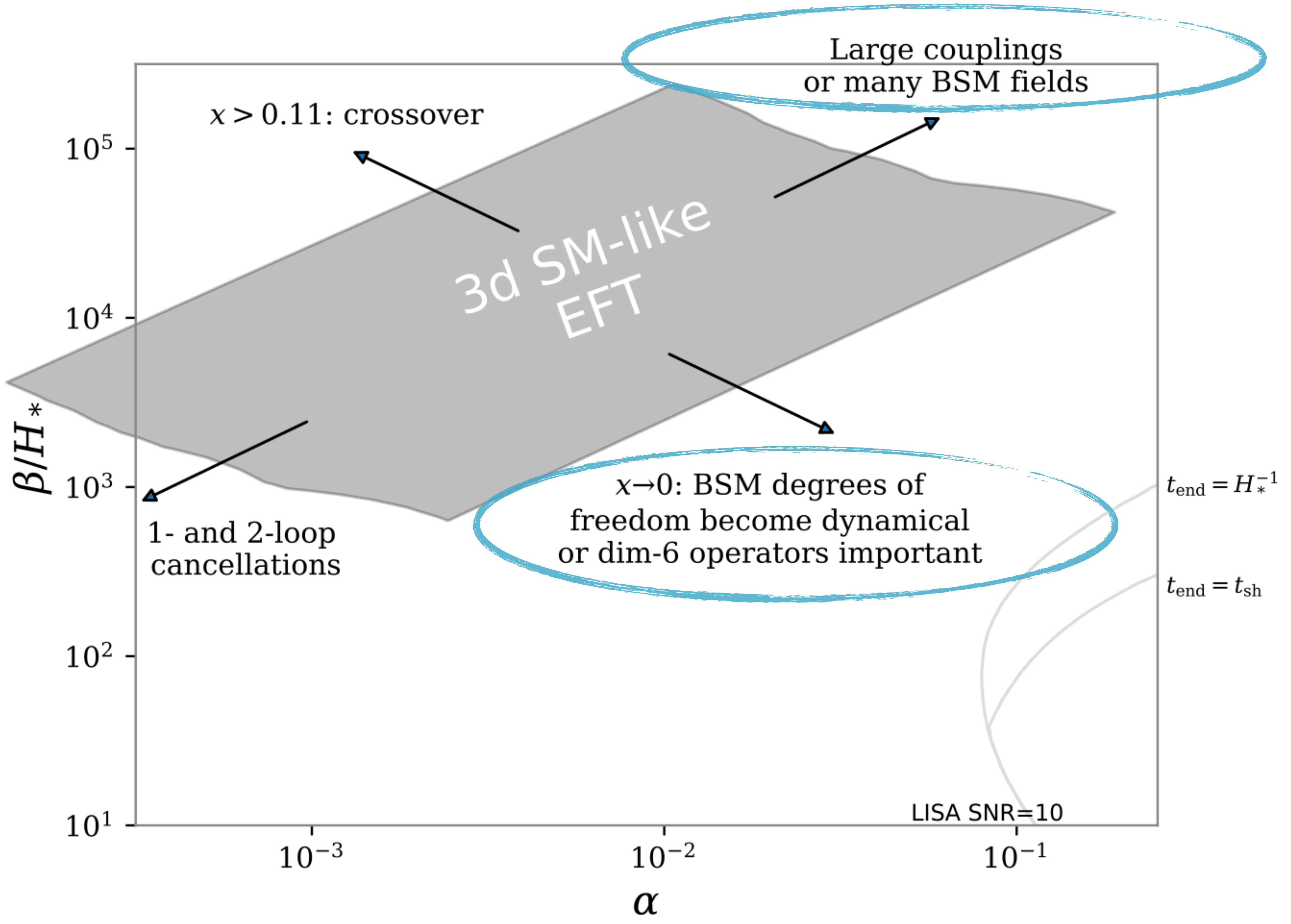
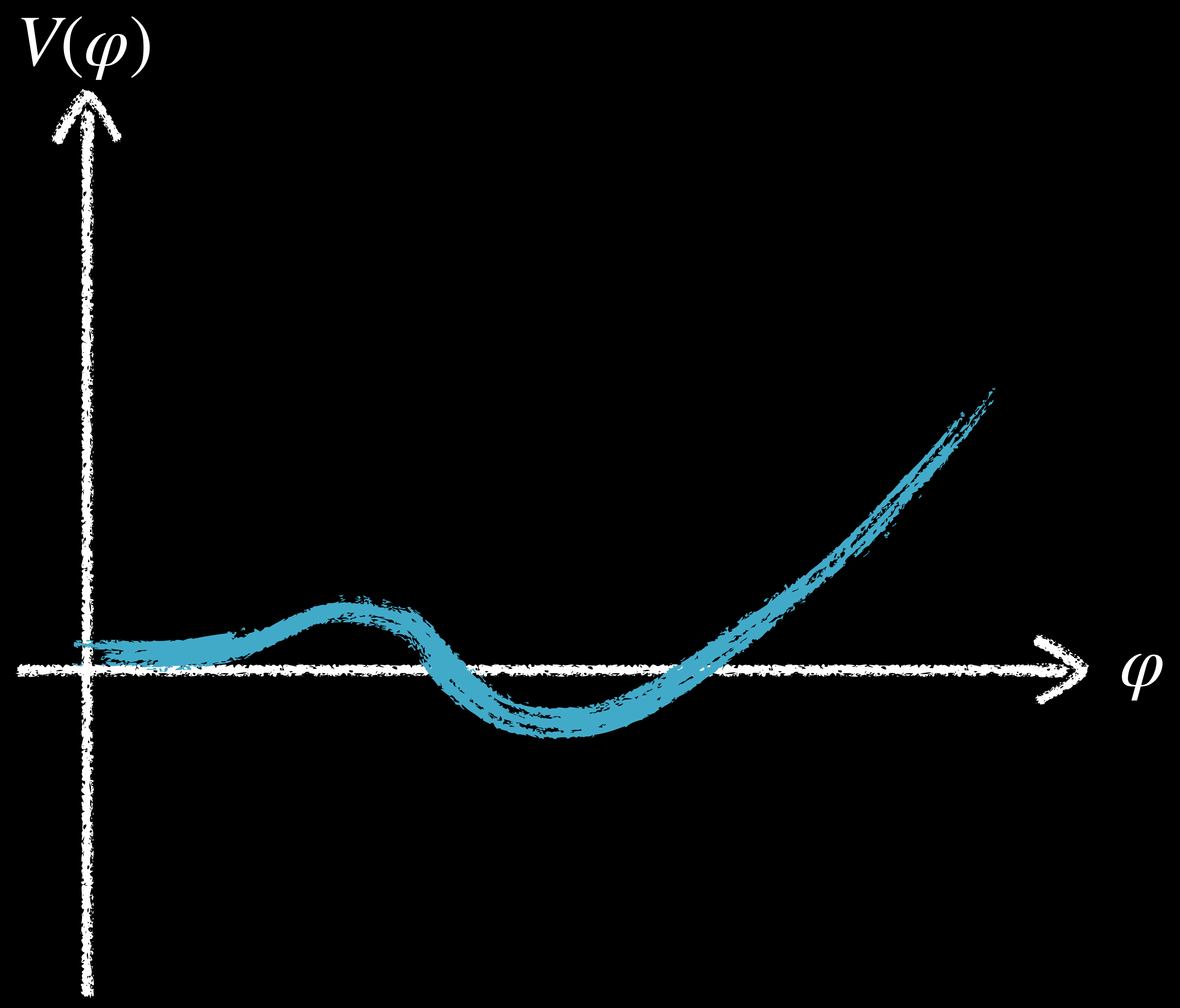


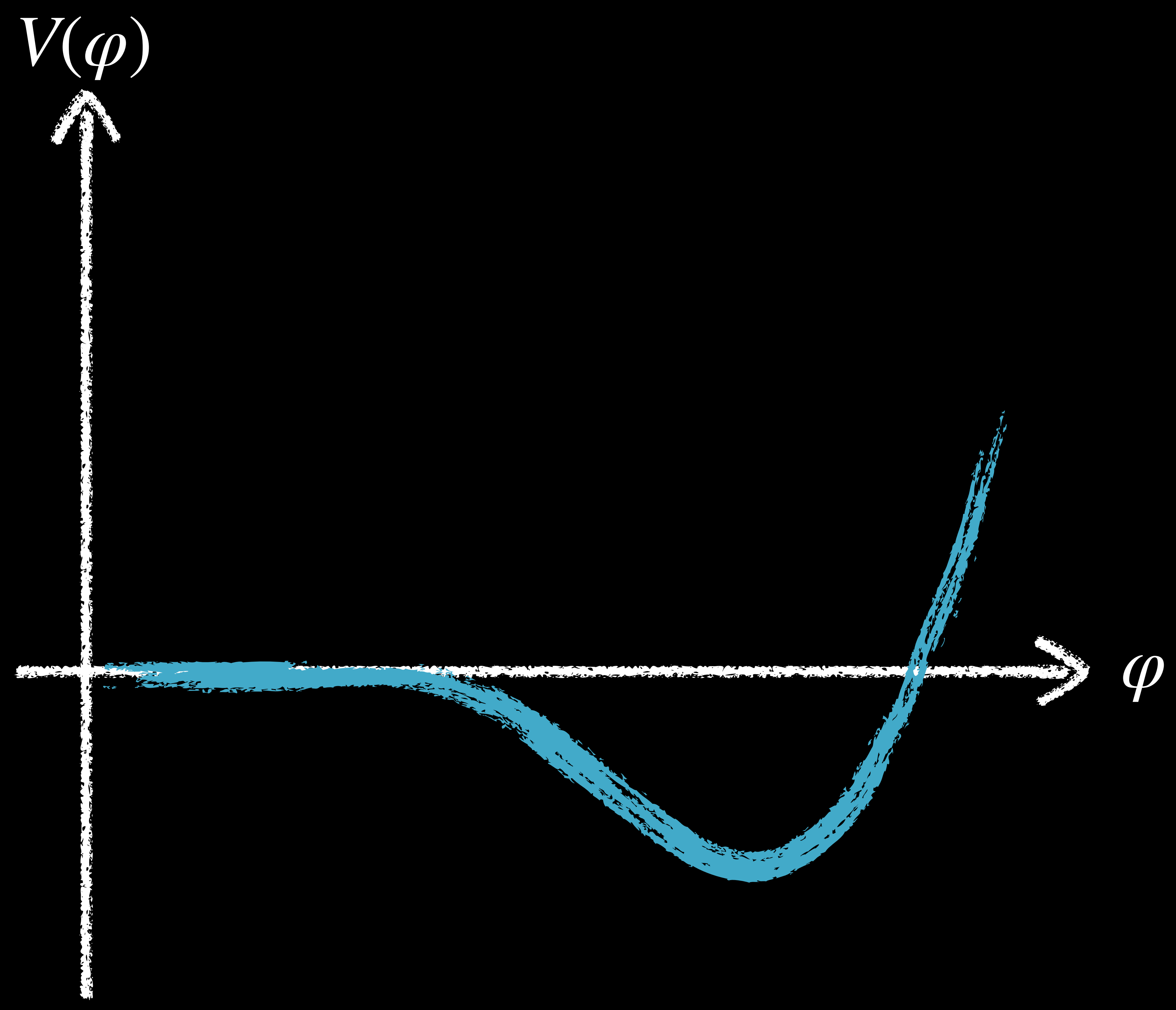
Scalar extensions of the SM (large coupling)

PT for a new field

[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]

PHASE TRANSITION: ORDINARY VS SUPERCOOLED





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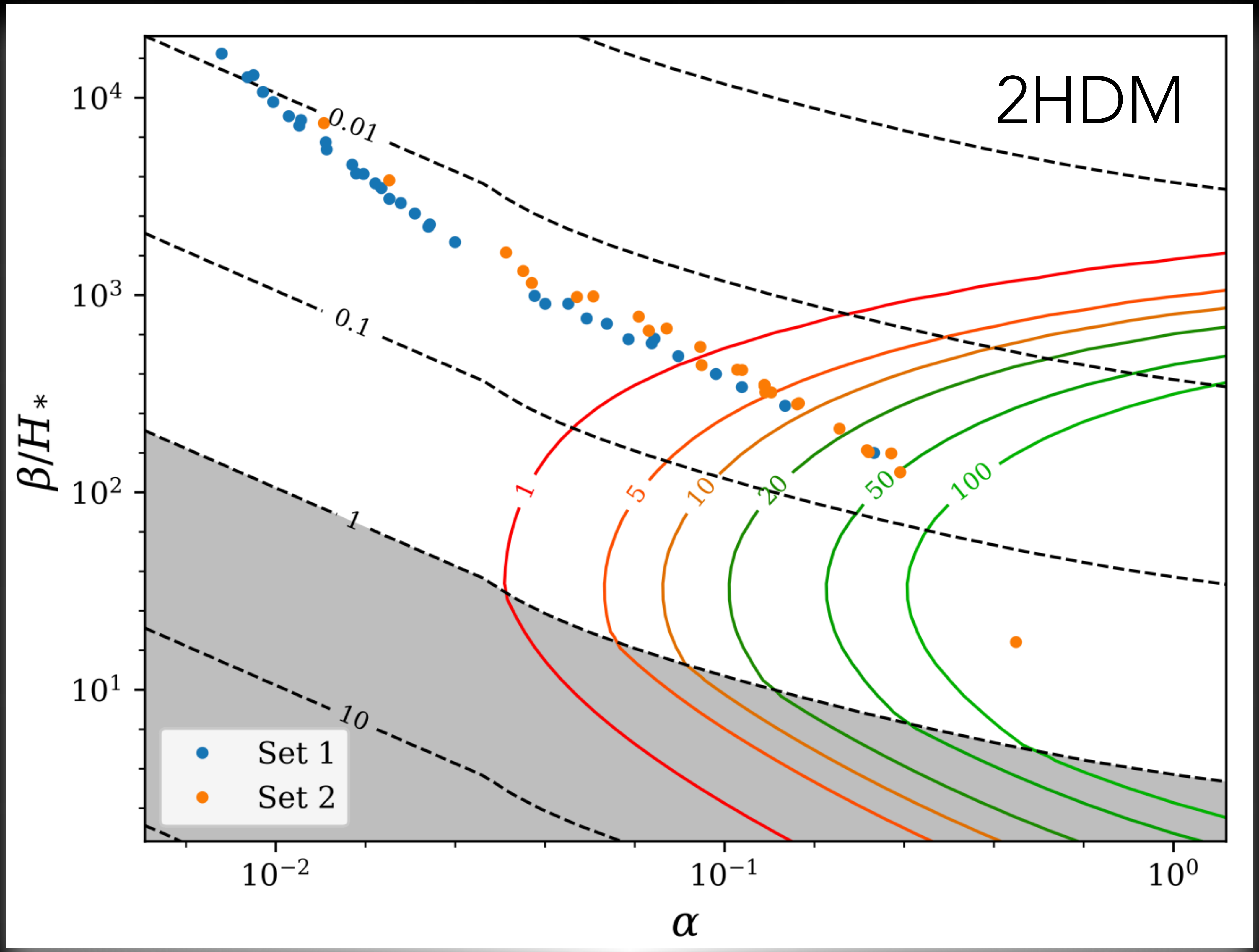
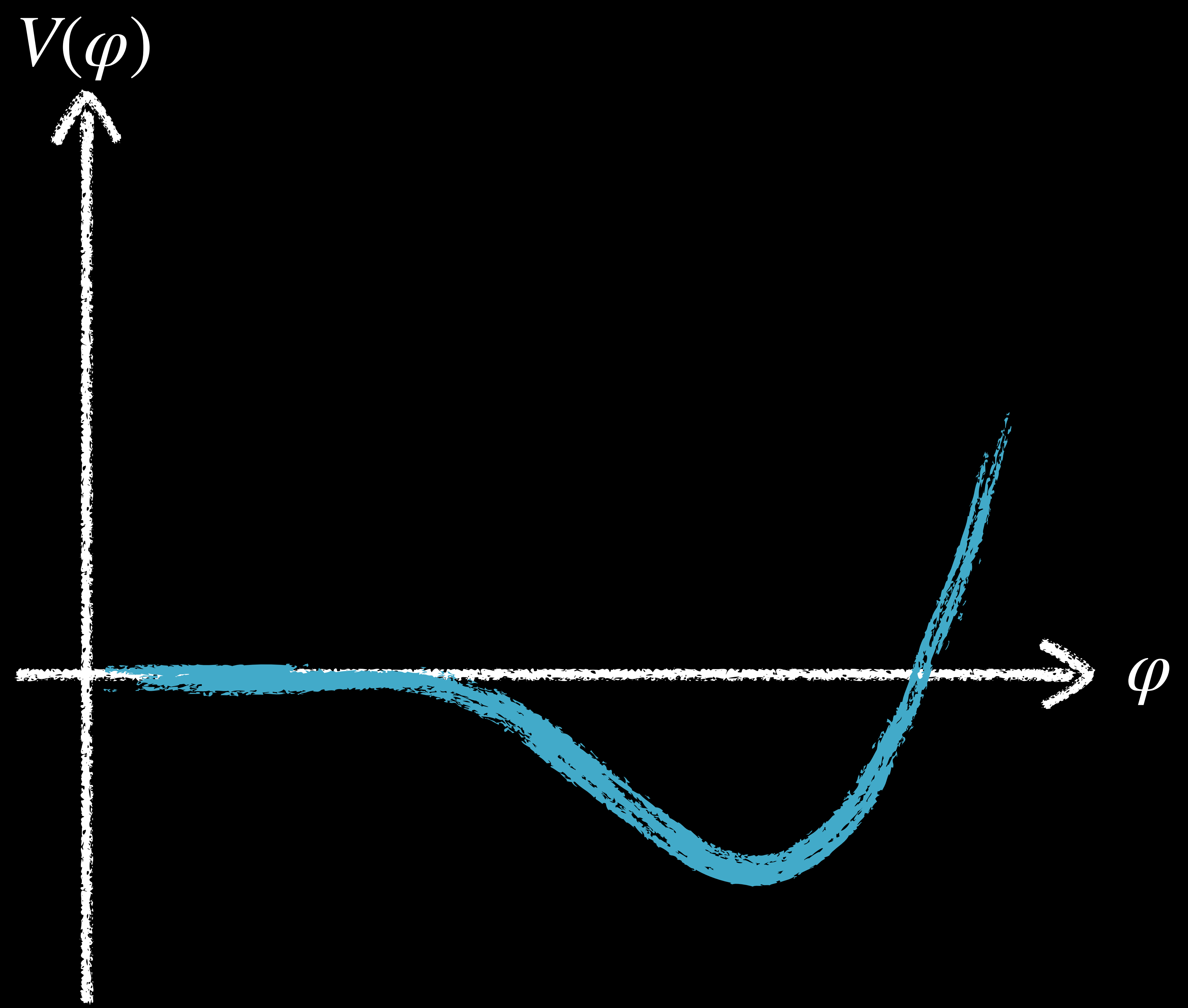


[C. Caprini et al., LISA CosWG, JCAP 03 (2020) 024]



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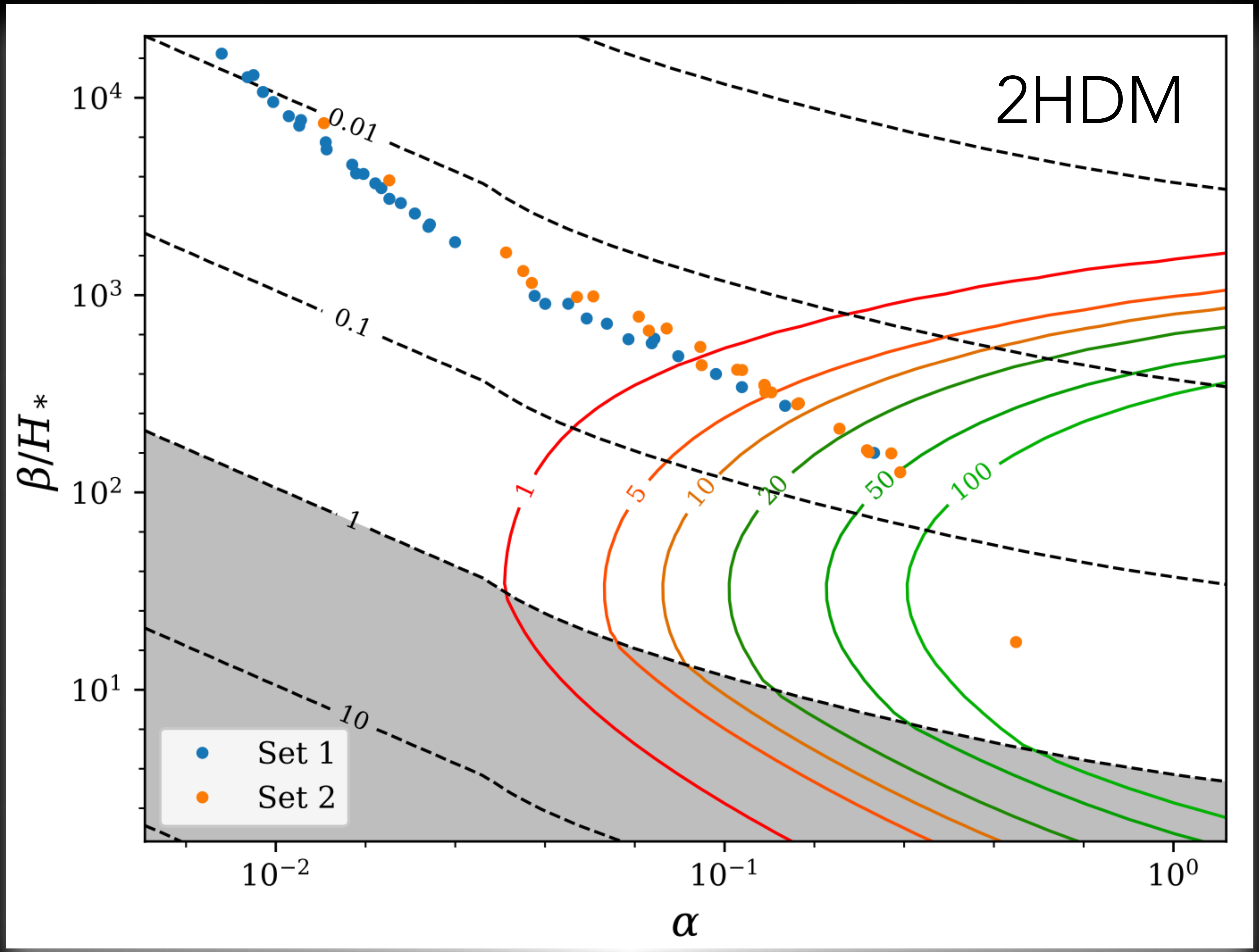

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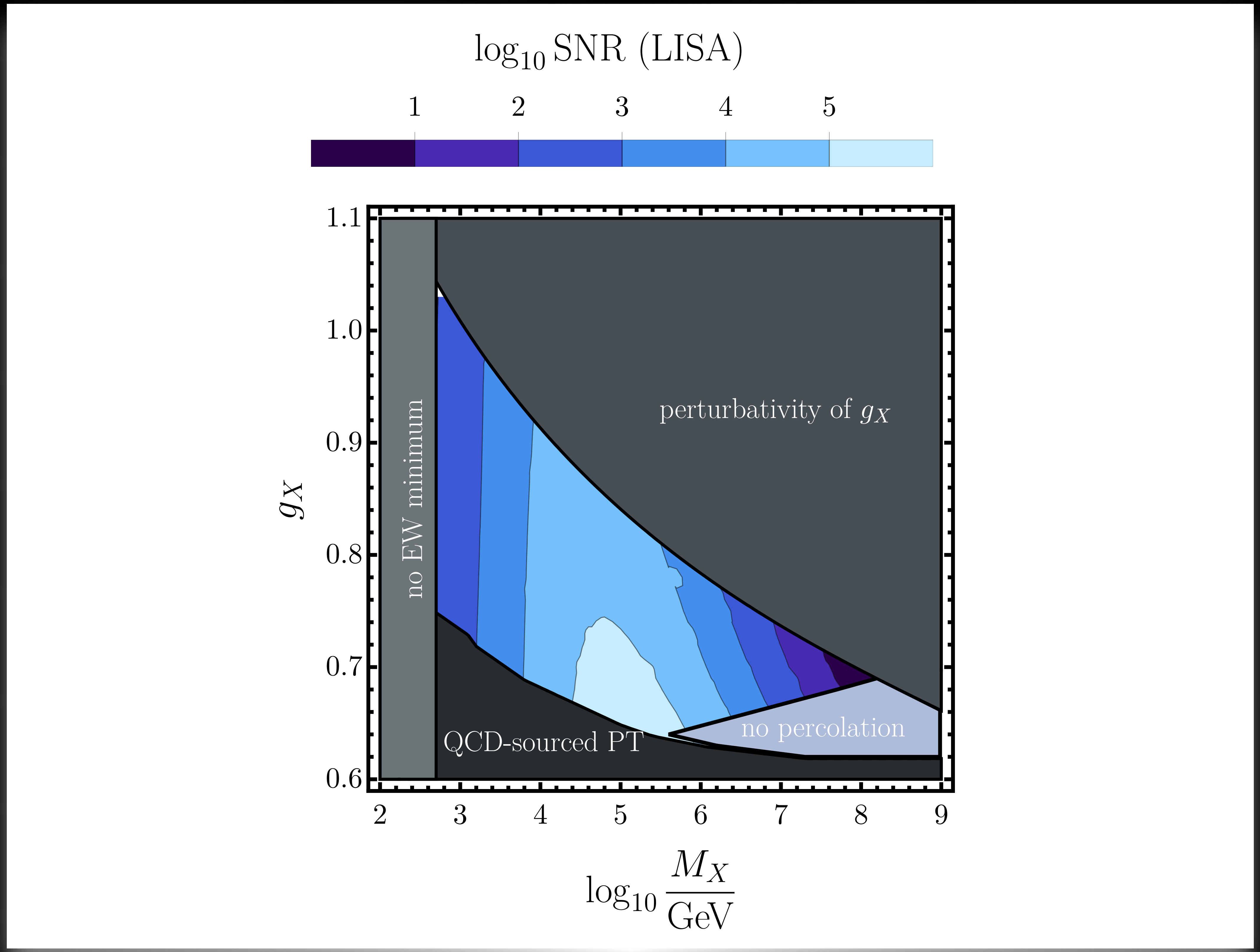

[M. Kierkla, BŚ, T.V.I. Tenkanen, J. van de Vis, *JHEP* 02 (2024) 234]

COSMOLOGICAL FIRST-ORDER PHASE TRANSITION

NUCLEATION

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

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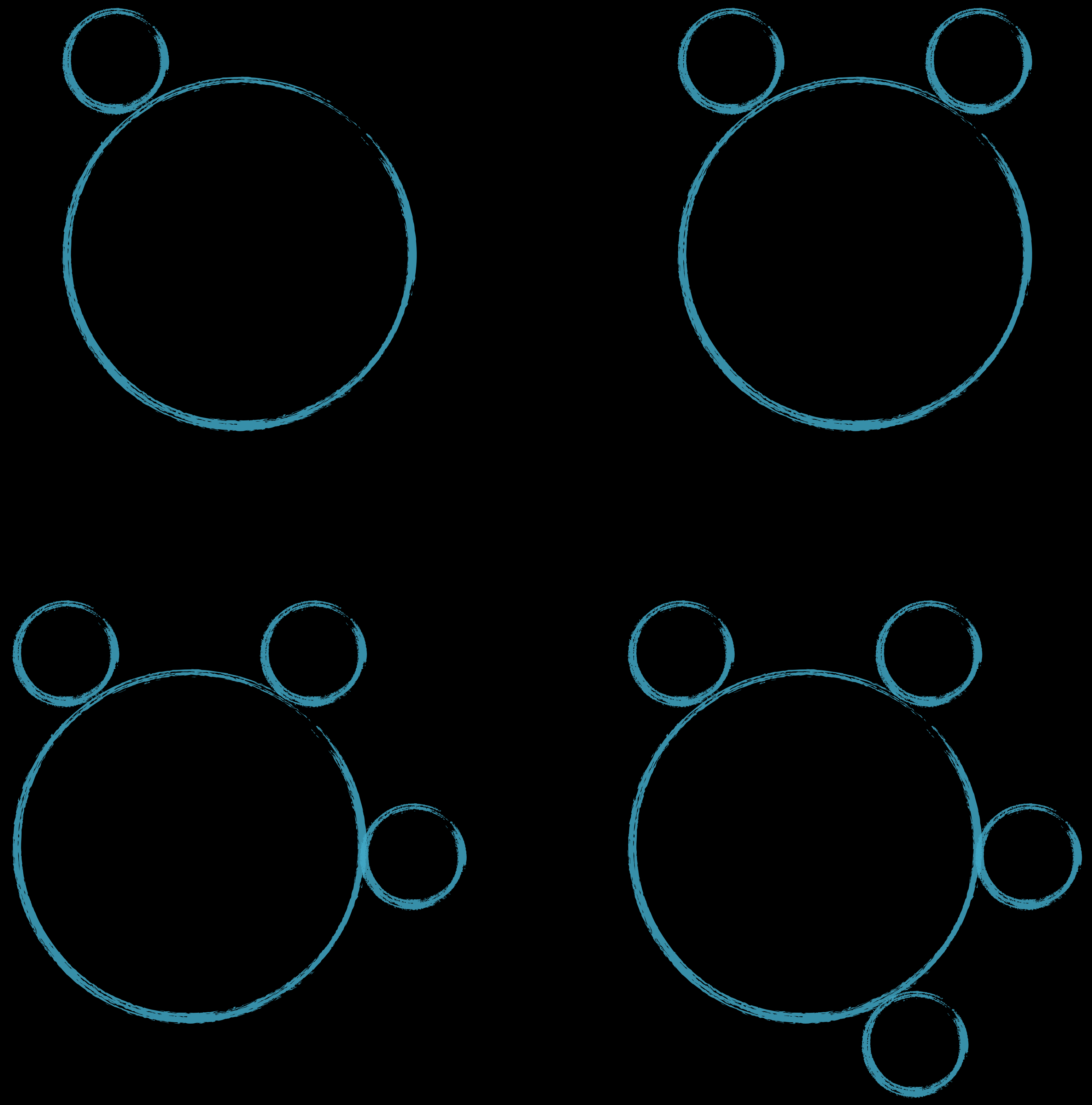
HOW FAR WILL YOU DARE TO GO?

Daisy resummation



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

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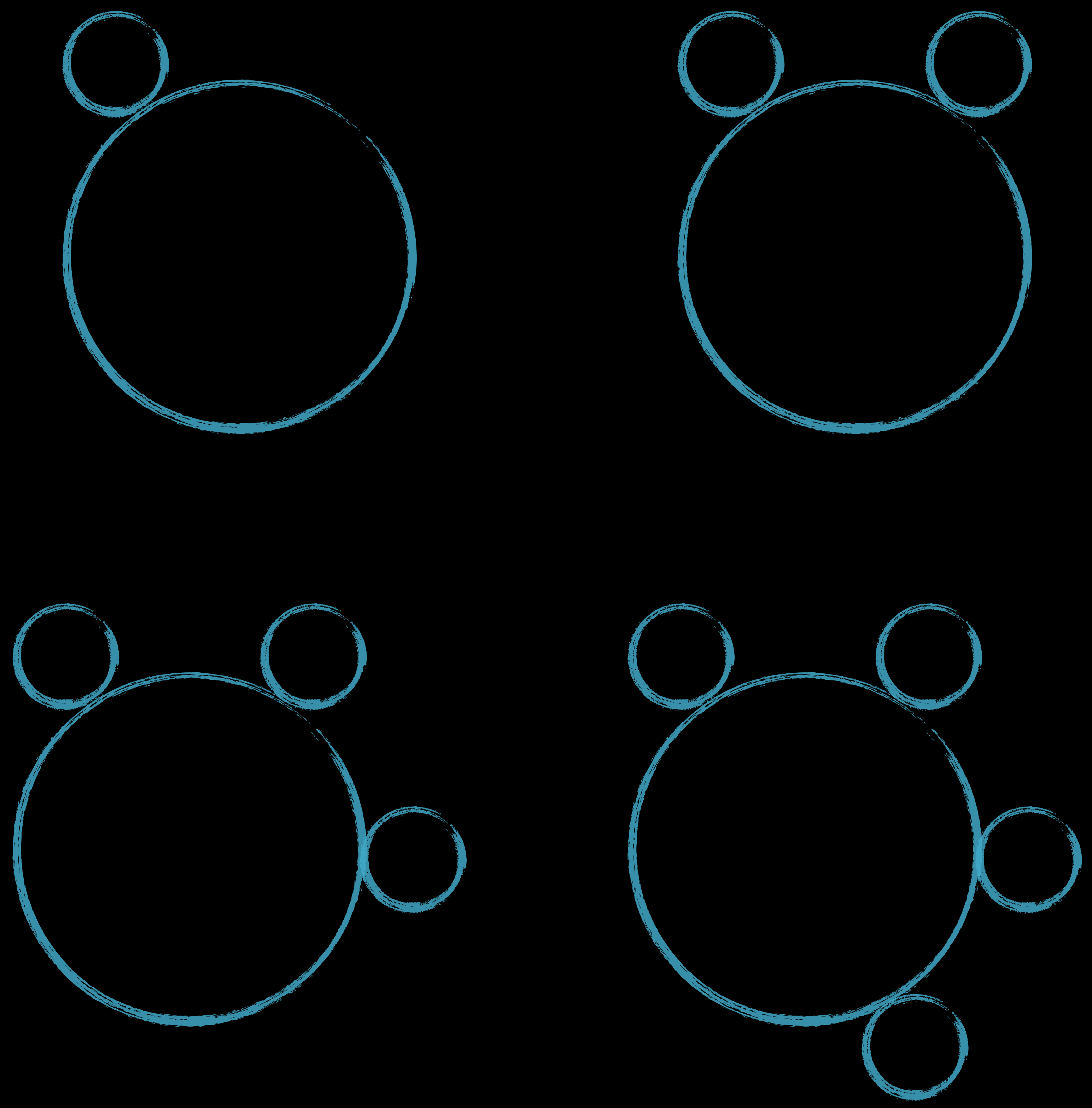
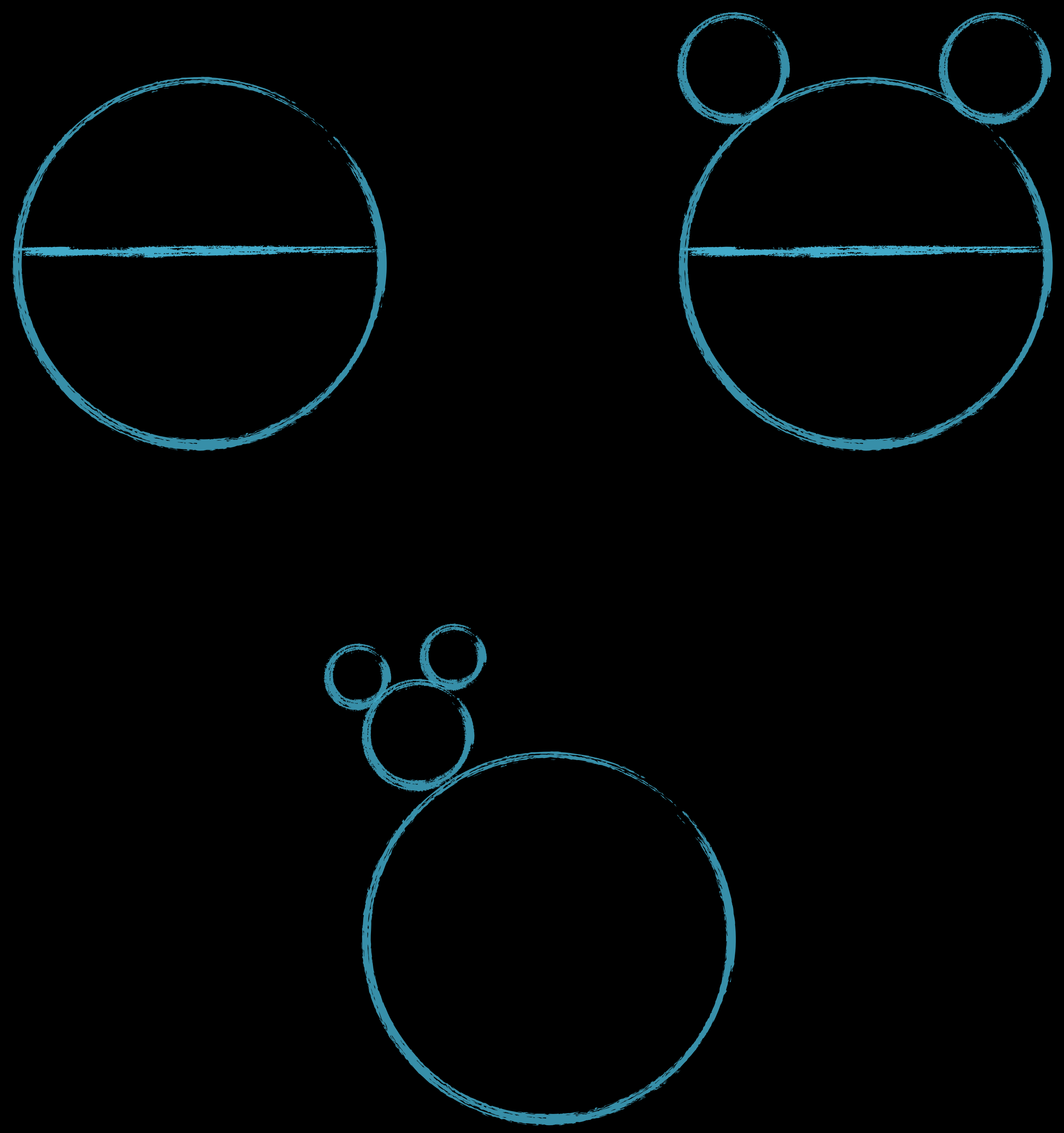


[P. Arnold, O. Espinosa, Phys.Rev.D 47 (1993) 3546, R.R. Parwani, *Phys.Rev.D* 45 (1992) 4695]

Dimensional reduction



[P. H. Ginsparg, Nucl. Phys. B170 (1980) 388, T. Appelquist, R. D. Pisarski, Phys. Rev. D23 (1981) 2305, K. Kajantie, M. Laine, K. Rummukainen, M. E. Shaposhnikov, Nucl. Phys. B 458 (1996) 90]

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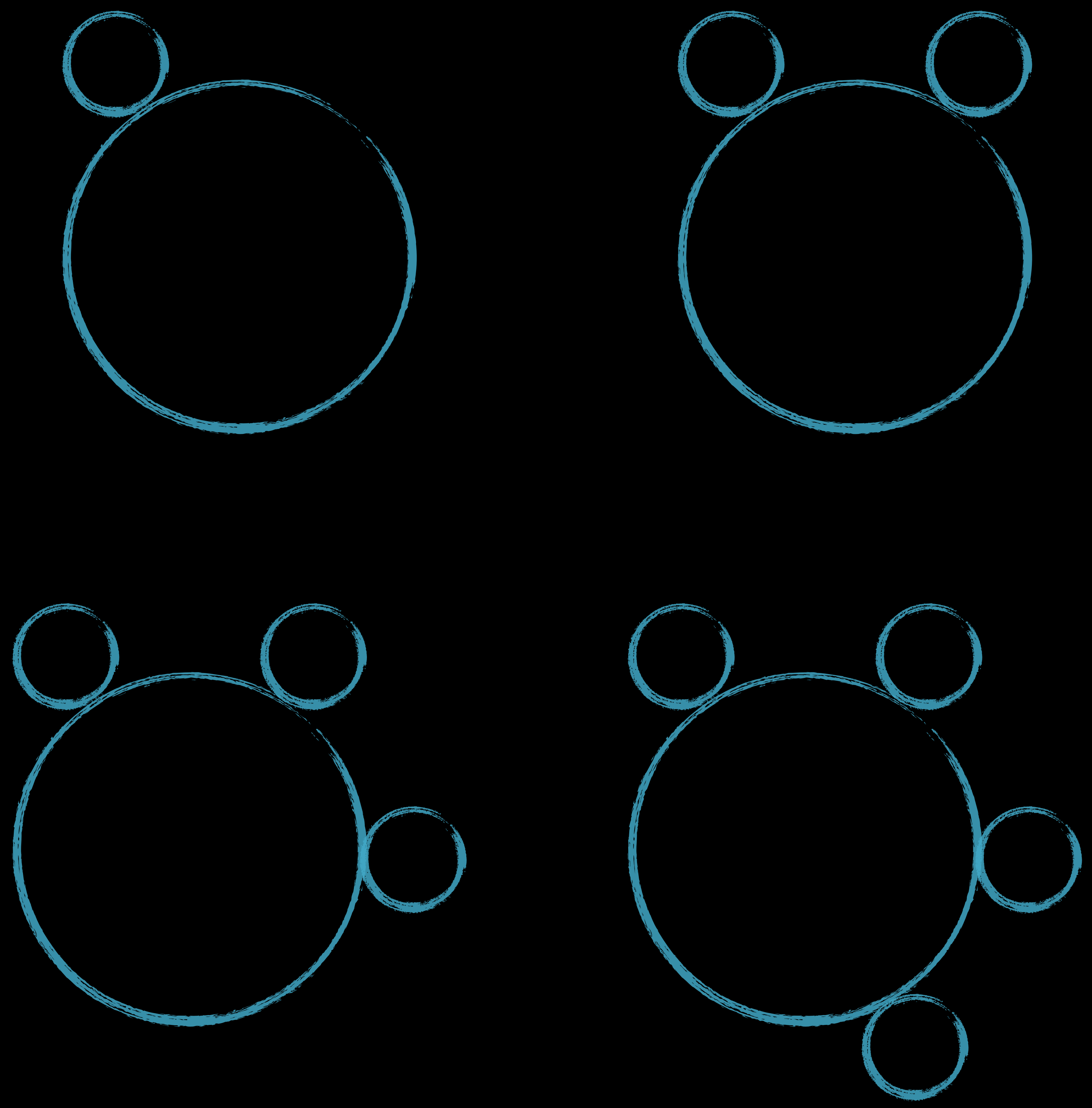


[P. Arnold, O. Espinosa, Phys.Rev.D 47 (1993) 3546, R.R. Parwani, *Phys.Rev.D* 45 (1992) 4695]

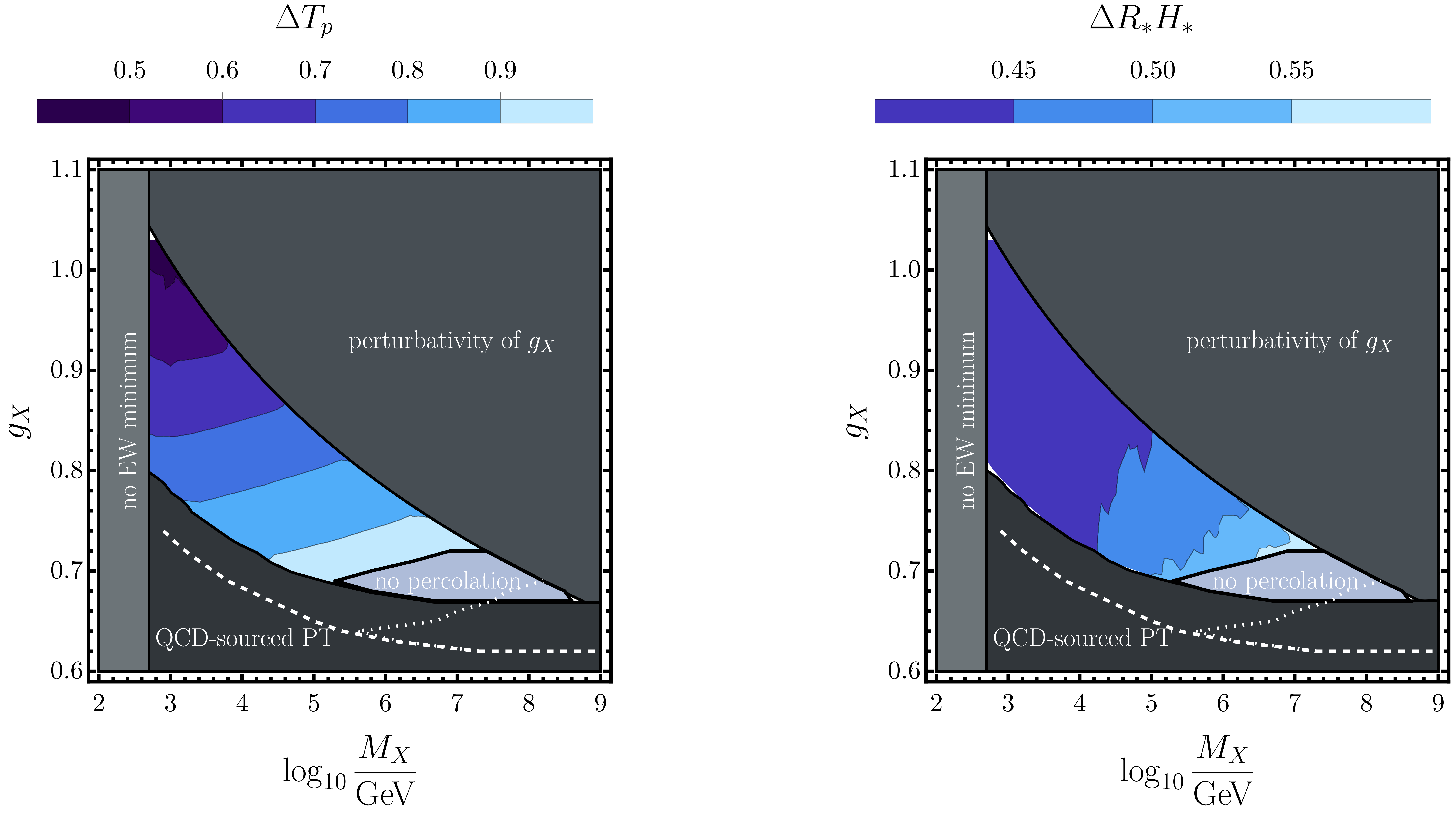
Dimensional reduction

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. B170 (1980) 388, T. Appelquist, R. D. Pisarski, Phys. Rev. D23 (1981) 2305, K. Kajantie, M. Laine, K. Rummukainen, M. E. Shaposhnikov, Nucl. Phys. B 458 (1996) 90]

DR FOR SUPERCOOLED PT



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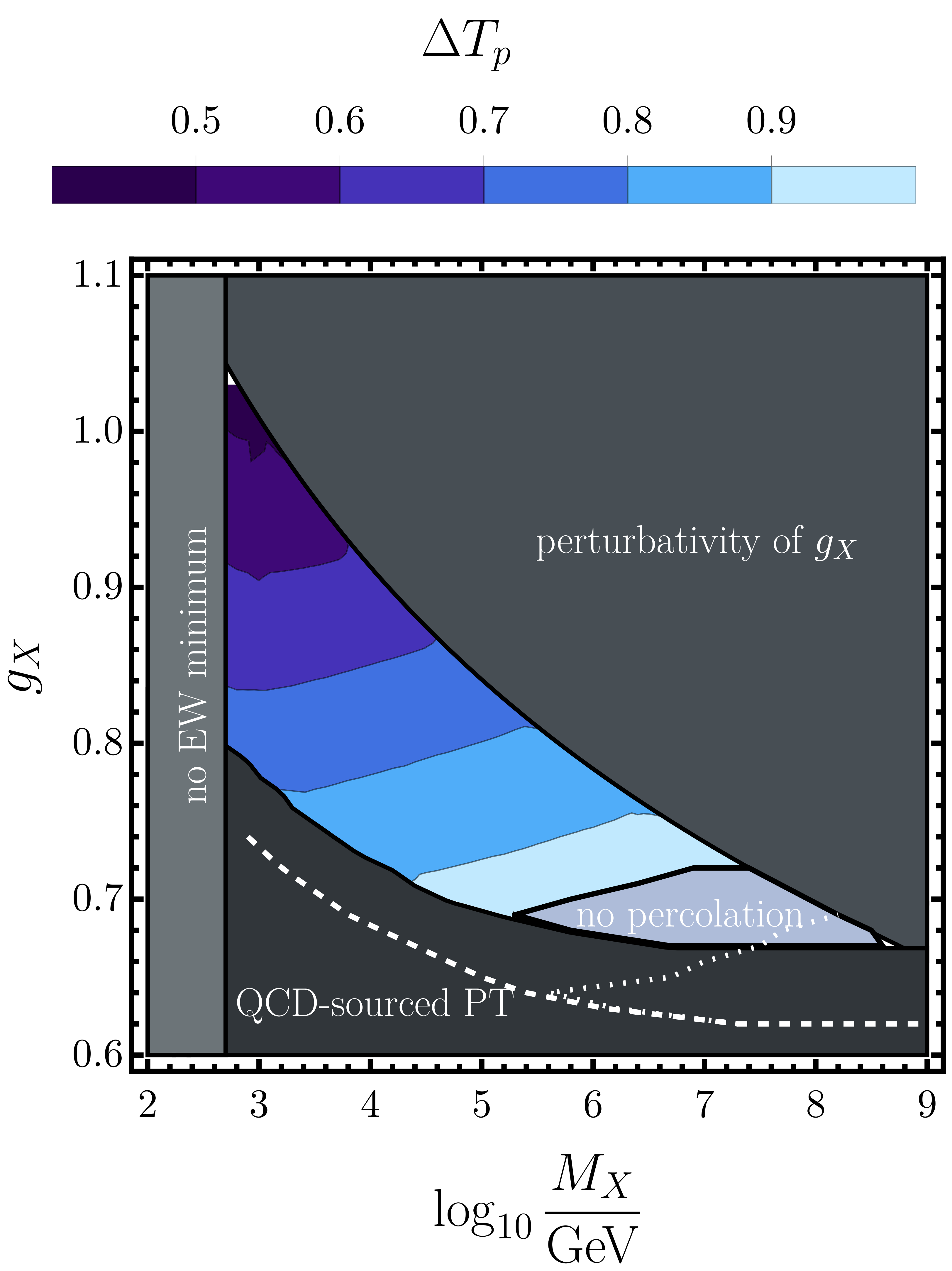

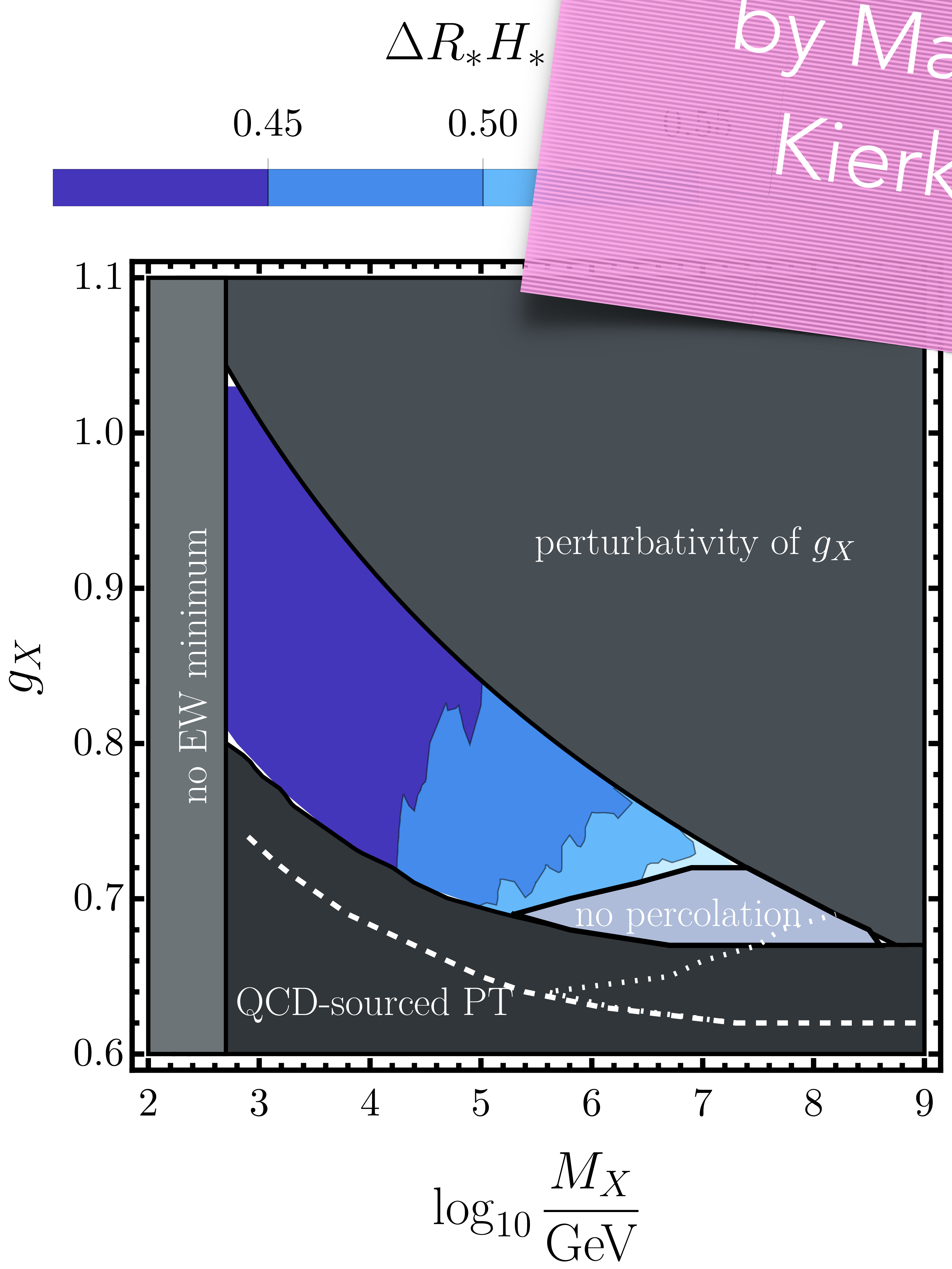

see the poster by Maciej Kierkla

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

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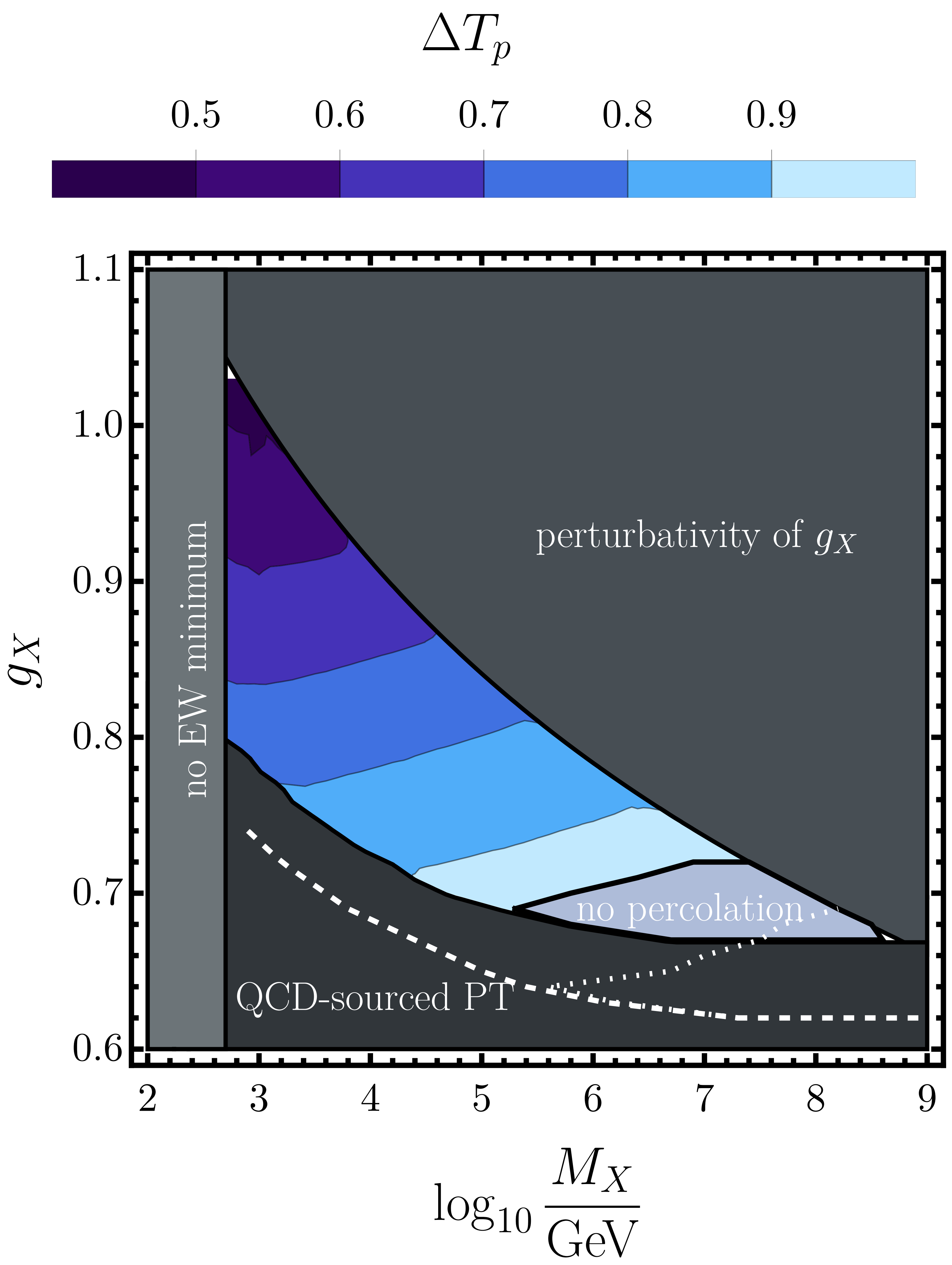

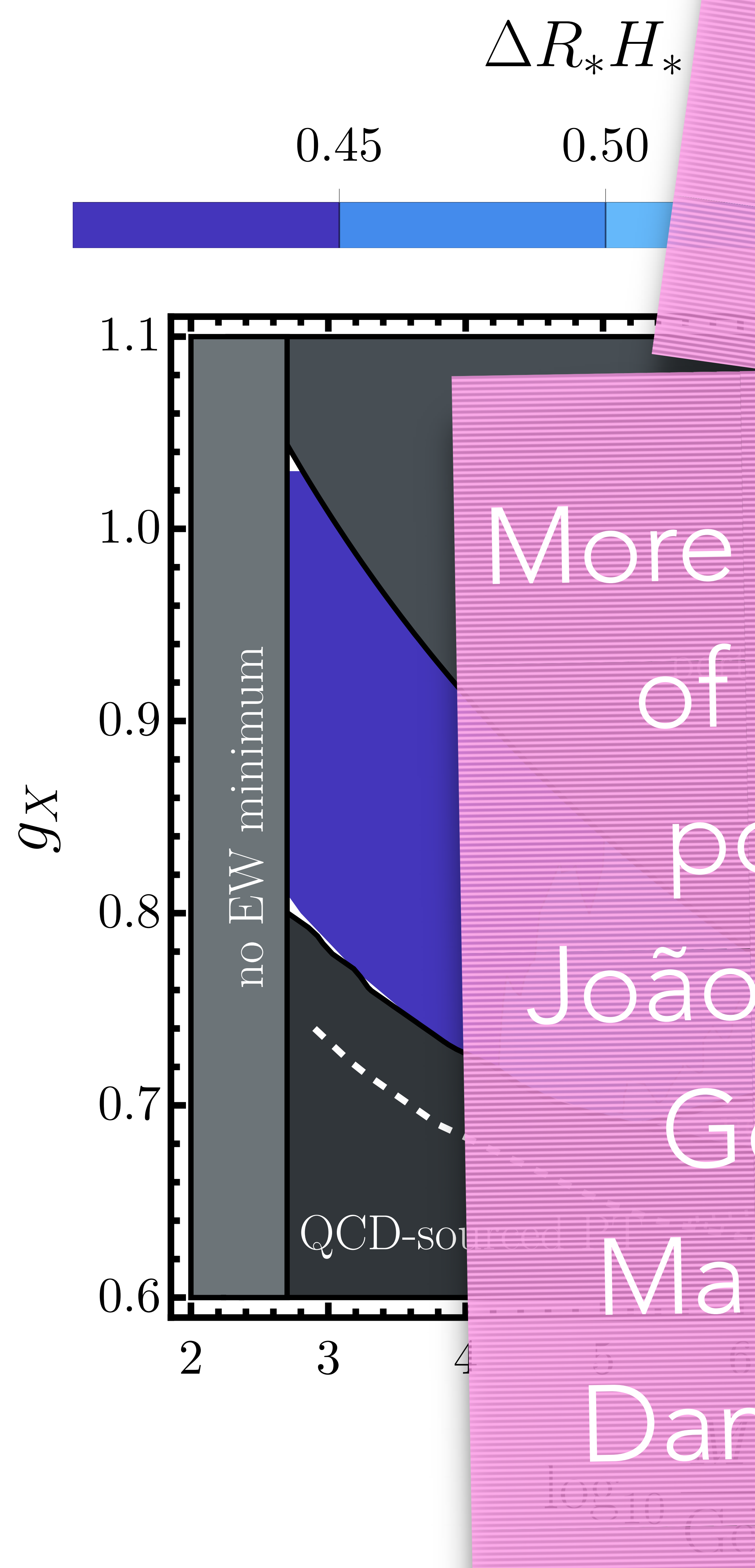

see the poster by Maciej Kierkla

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

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

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A_{det} necessary to increase precision

→BubbleDet

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

NUCLEATION

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see the poster by Anna Kormu

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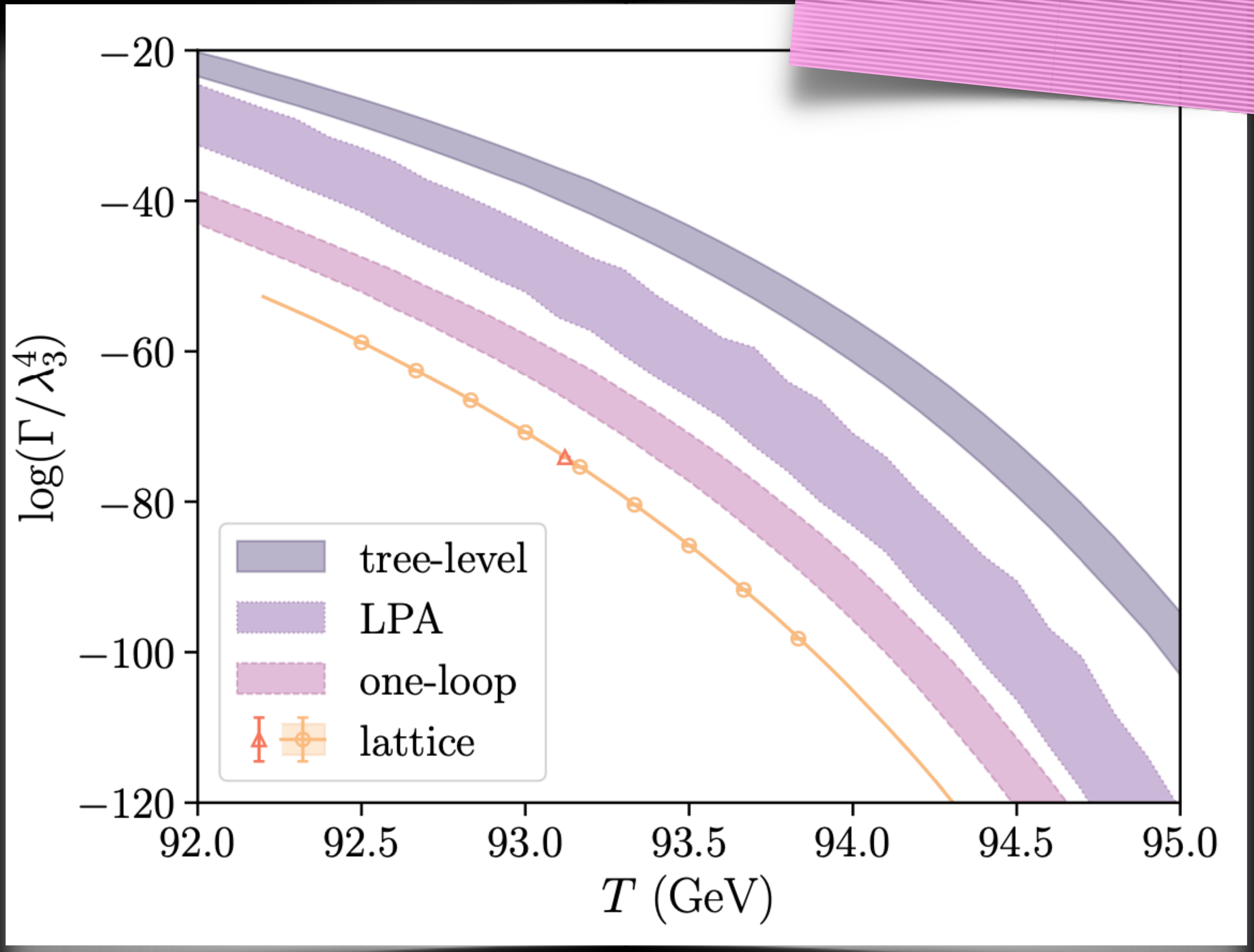
[A. Ekstedt, O. Gould, J. Hirvonen, JHEP 12 (2023) 056]

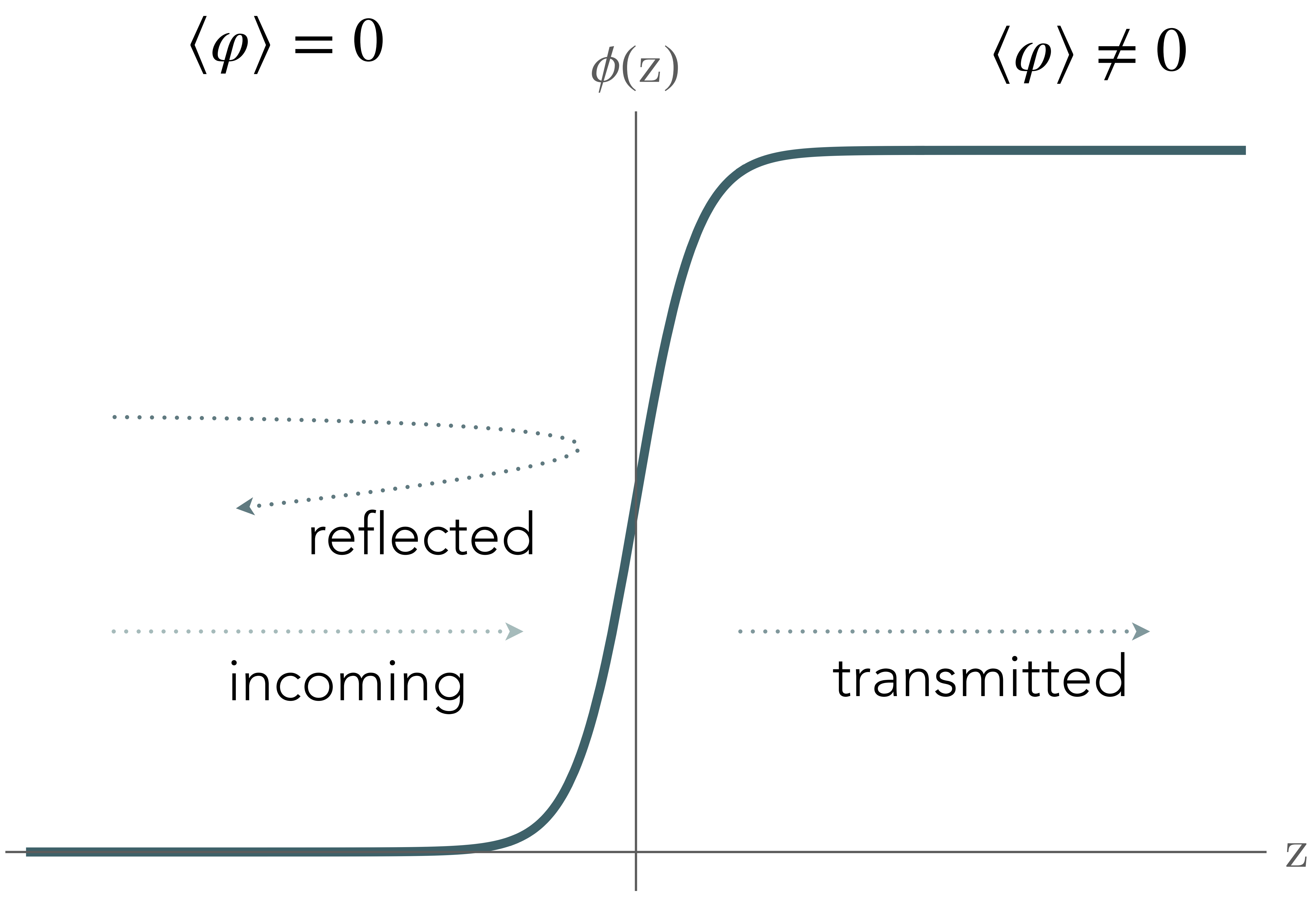


[O.Gould, A.Kormu, D. J. Weir, 2404.01876]

BUBBLE-WALL VELOCITY

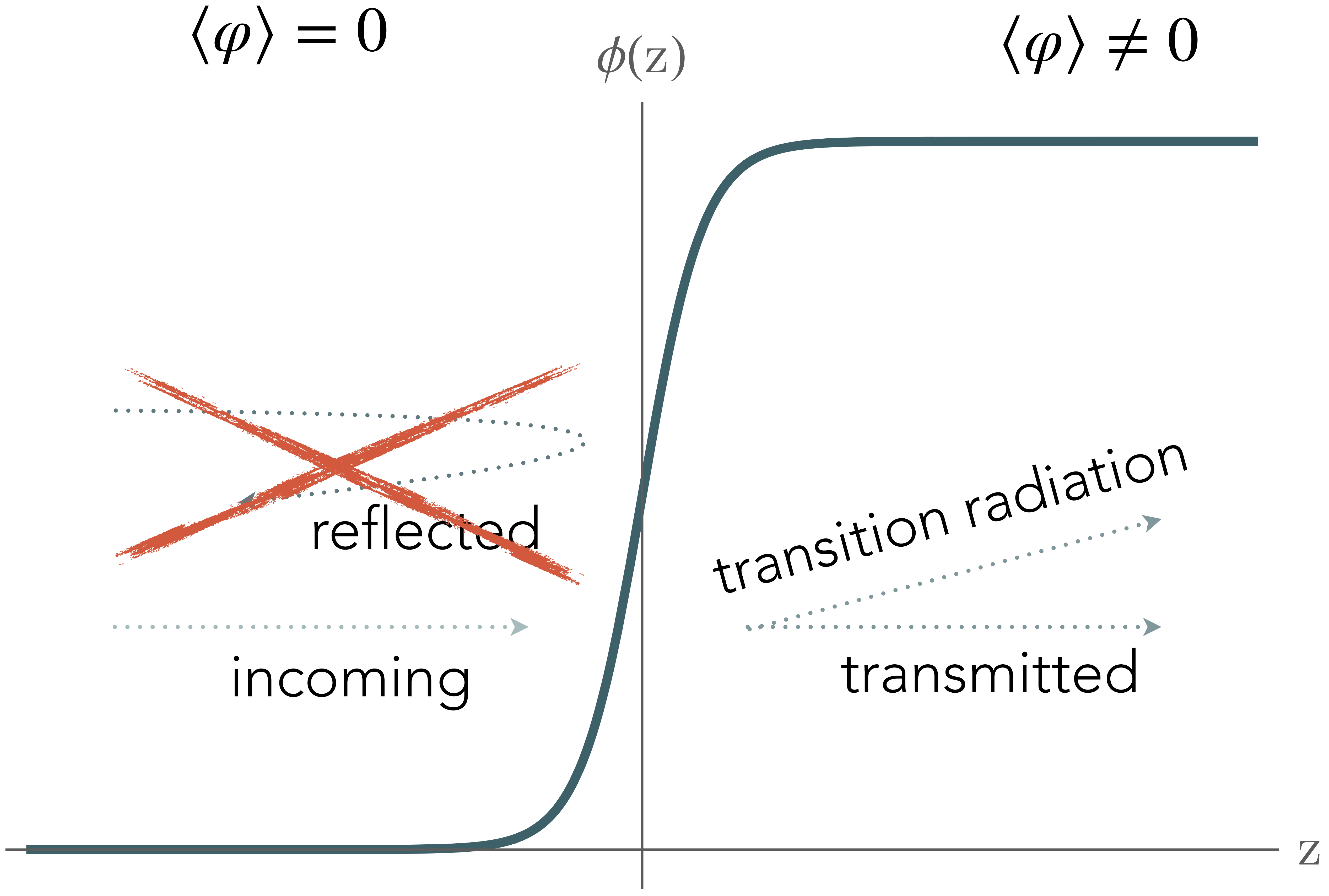
FOR GW AND BARYOGENESIS

WALL VELOCITY



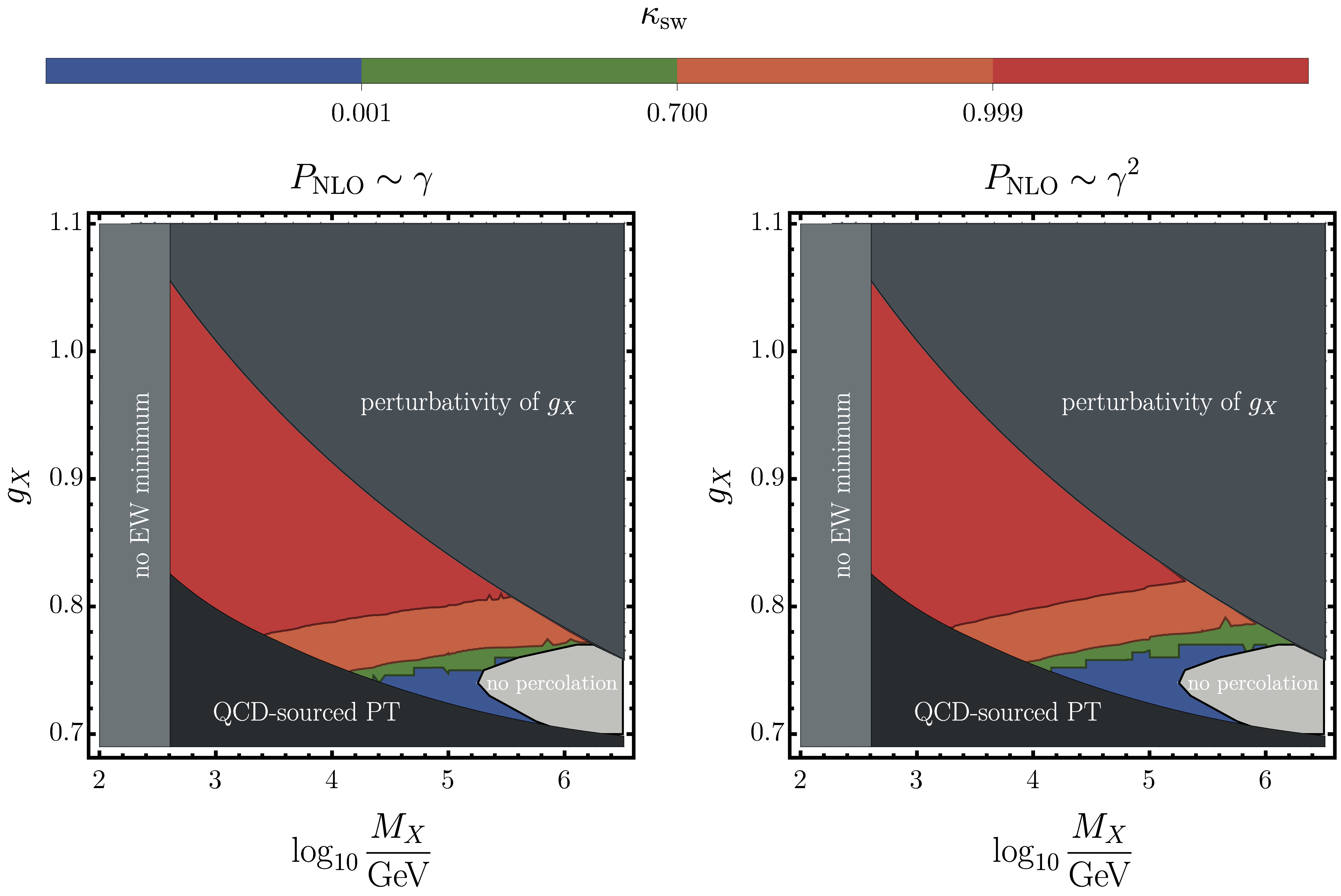
[G. D. Moore and T. Prokopec, Phys. Rev. D 52 (1995) 7182–7204,
Phys. Rev. Lett. 75 (1995) 777–780 ,
B. Laurent and J. M. Cline, Phys. Rev. D 102 no. 6, (2020) 063516,
Phys. Rev. D 106 no. 2, (2022) 023501,
G. C. Dorsch, S. J. Huber, and T. Konstandin, JCAP 12 (2018) 034]

RUNAWAY BUBBLES?



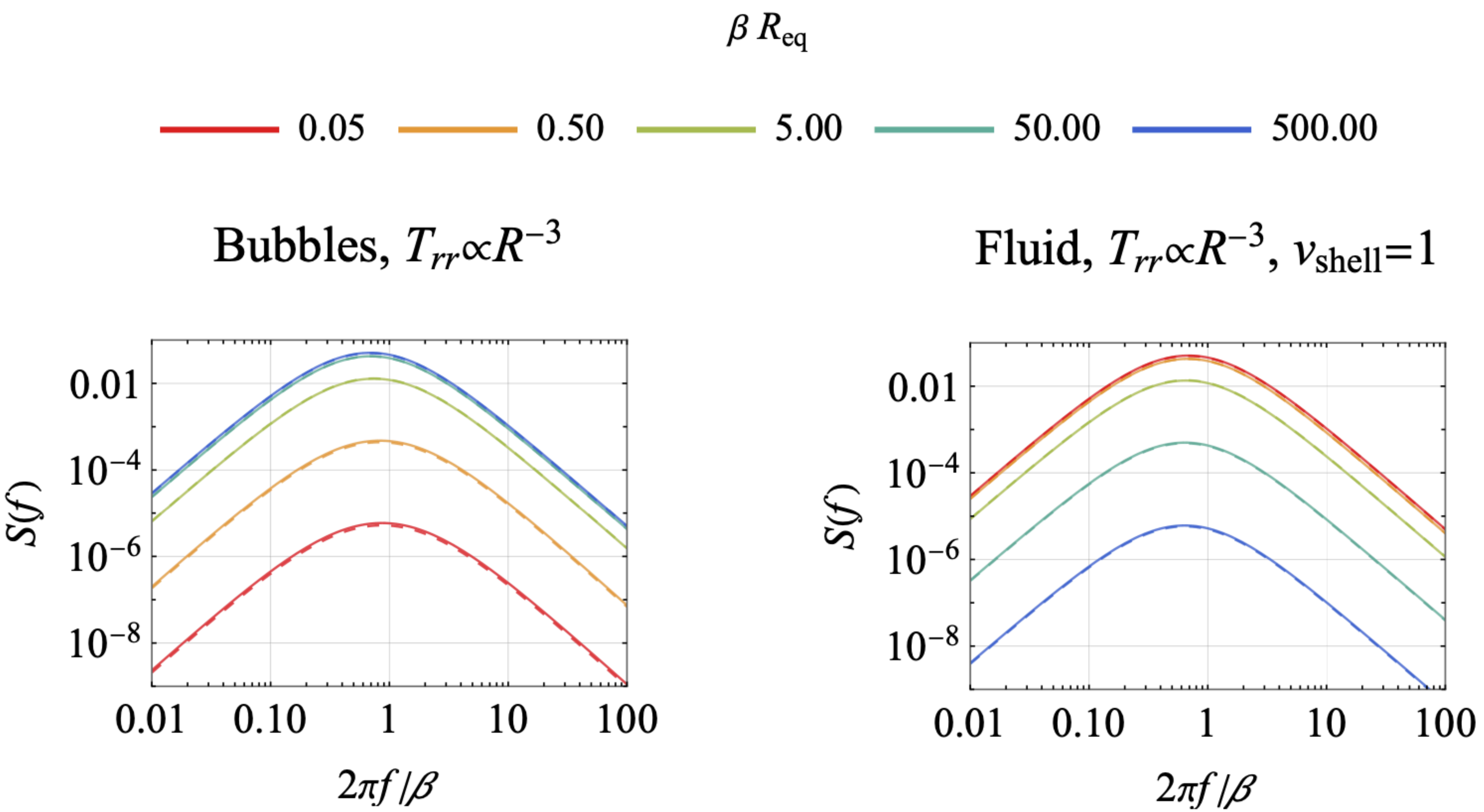
[D. Bodeker and G. D. Moore, JCAP 05 (2009) 009, JCAP 05 (2017) 025,
S. Höche, J. Kozaczuk, A. J. Long, J. Turner, and Y. Wang, JCAP 03 (2021) 009 ,
Y. Gouttenoire, R. Jinno, and F. Sala, JHEP 05 (2022) 004]

RUNAWAY BUBBLES?



[M. Kierkla, A. Karam, BŚ, JHEP 03 (2023) 007]

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]

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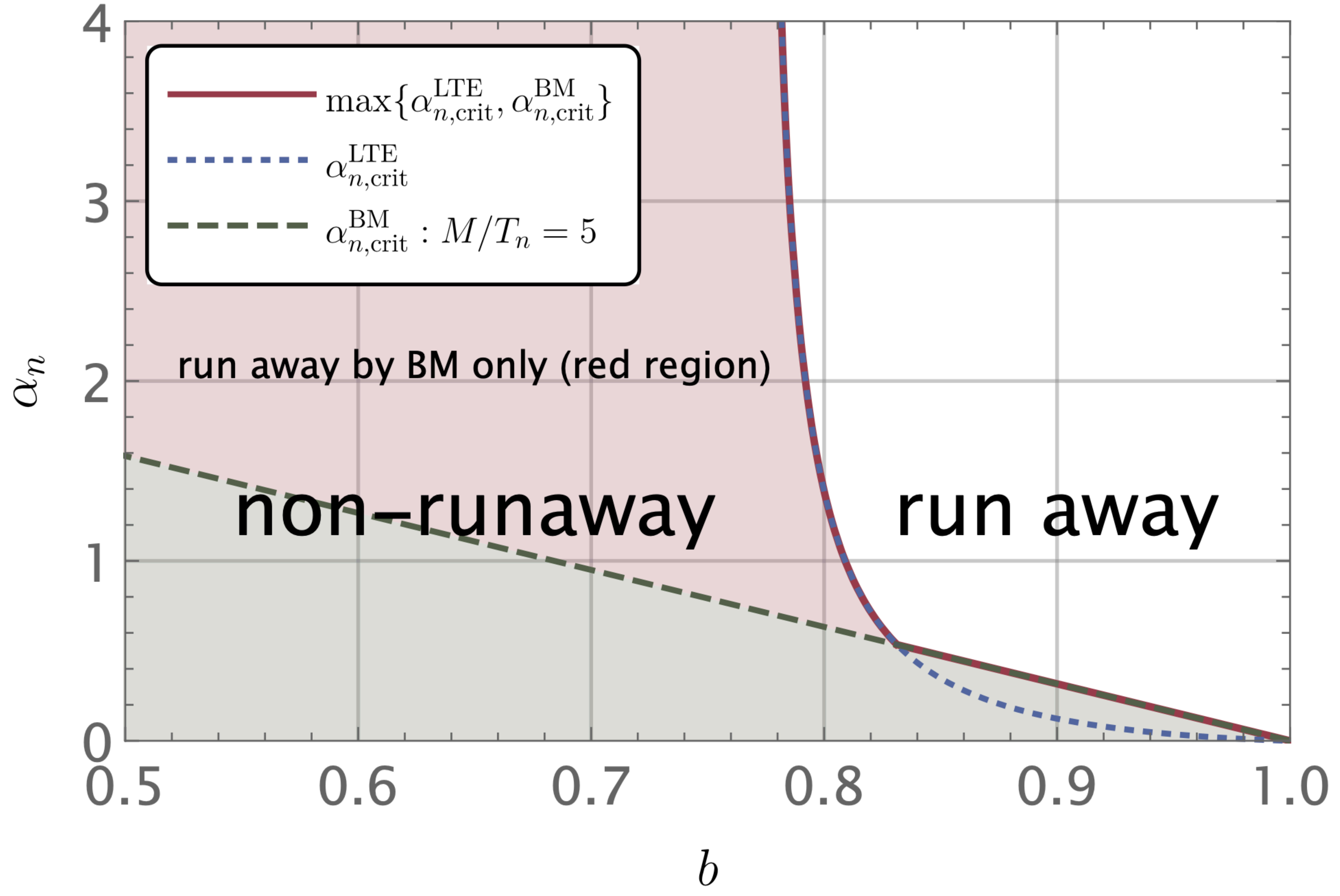

[W.-Y. Ai, X. Nagels, M. Vanvlasselaer, *JCAP* 03 (2024) 037]

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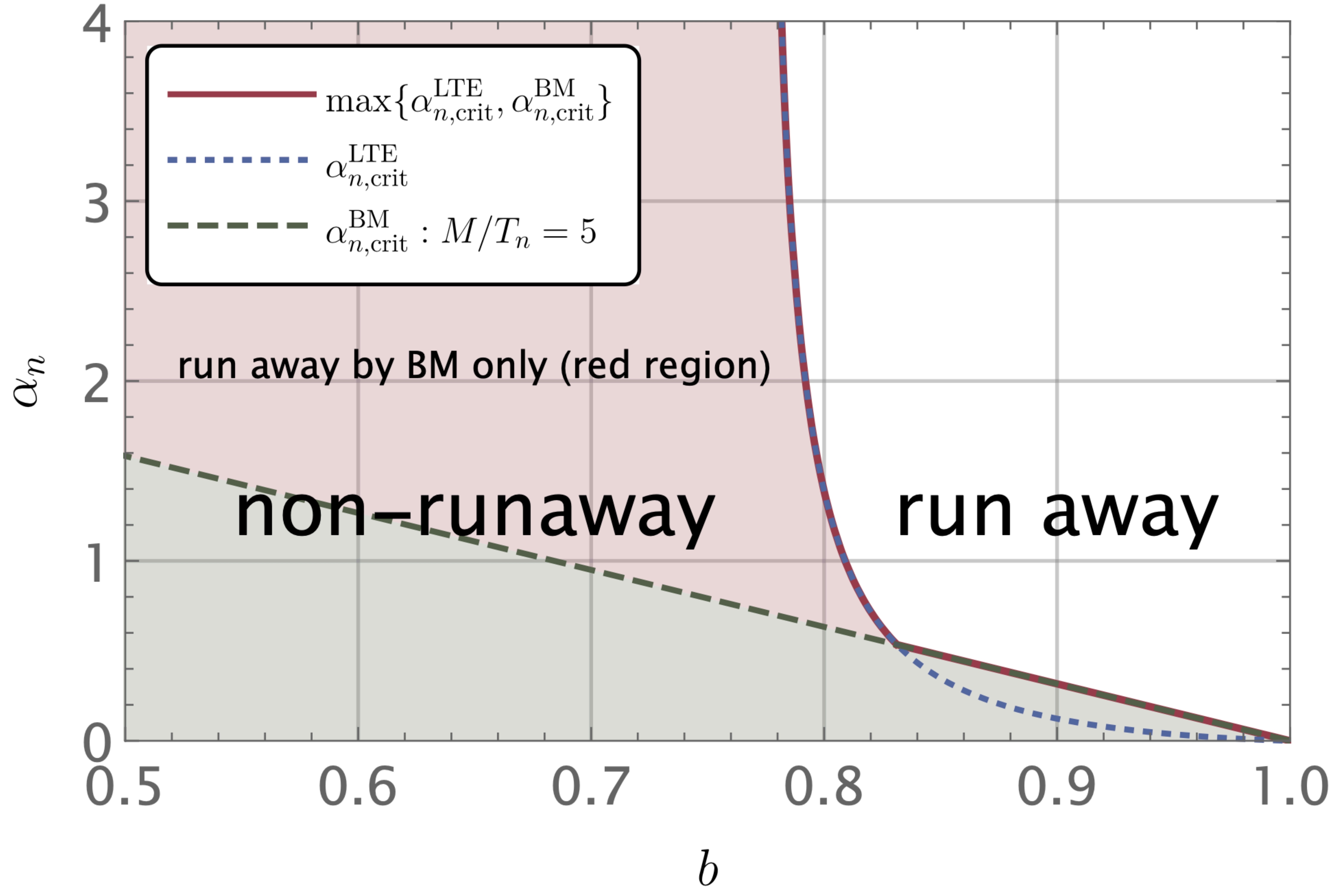

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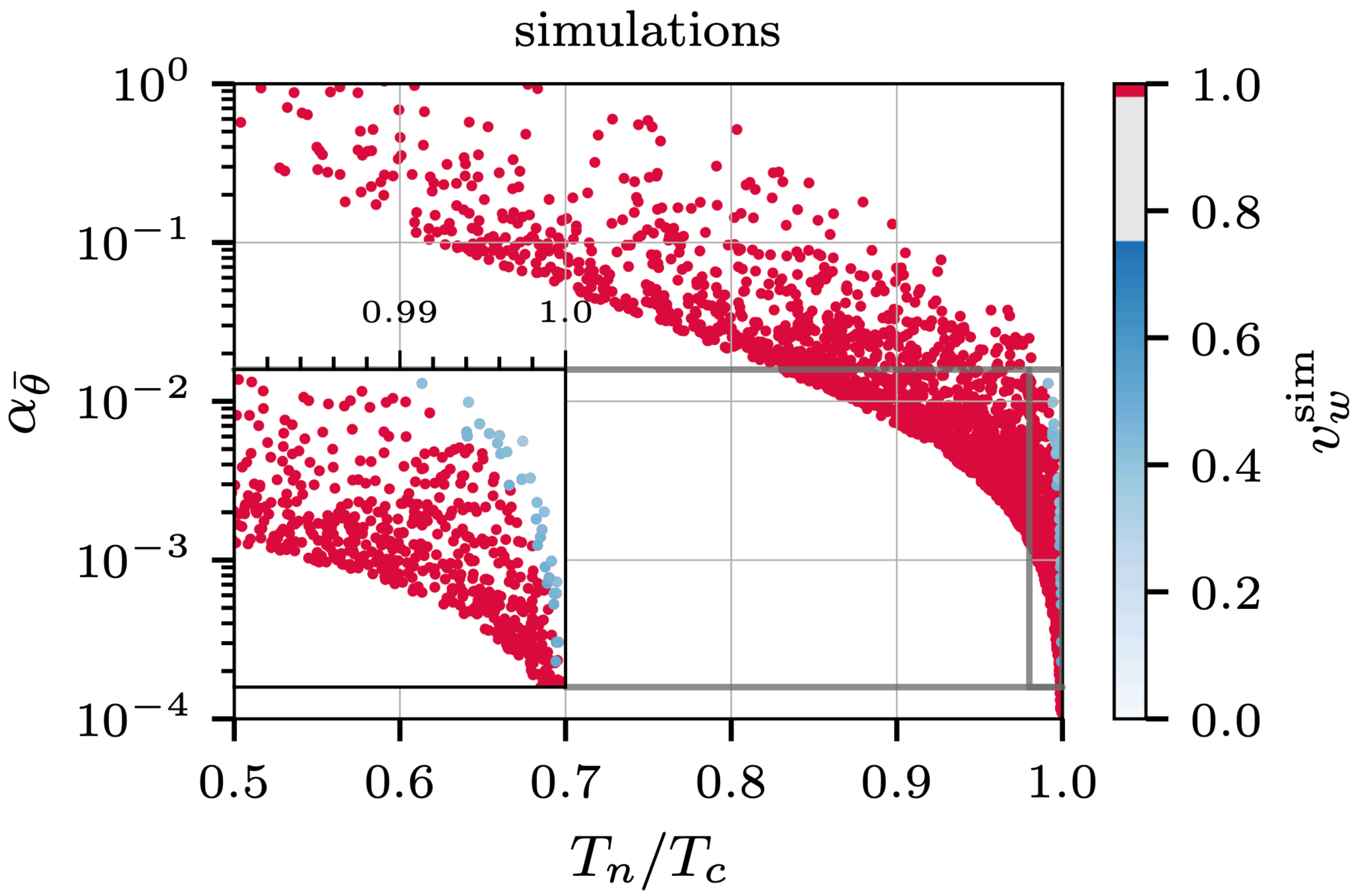
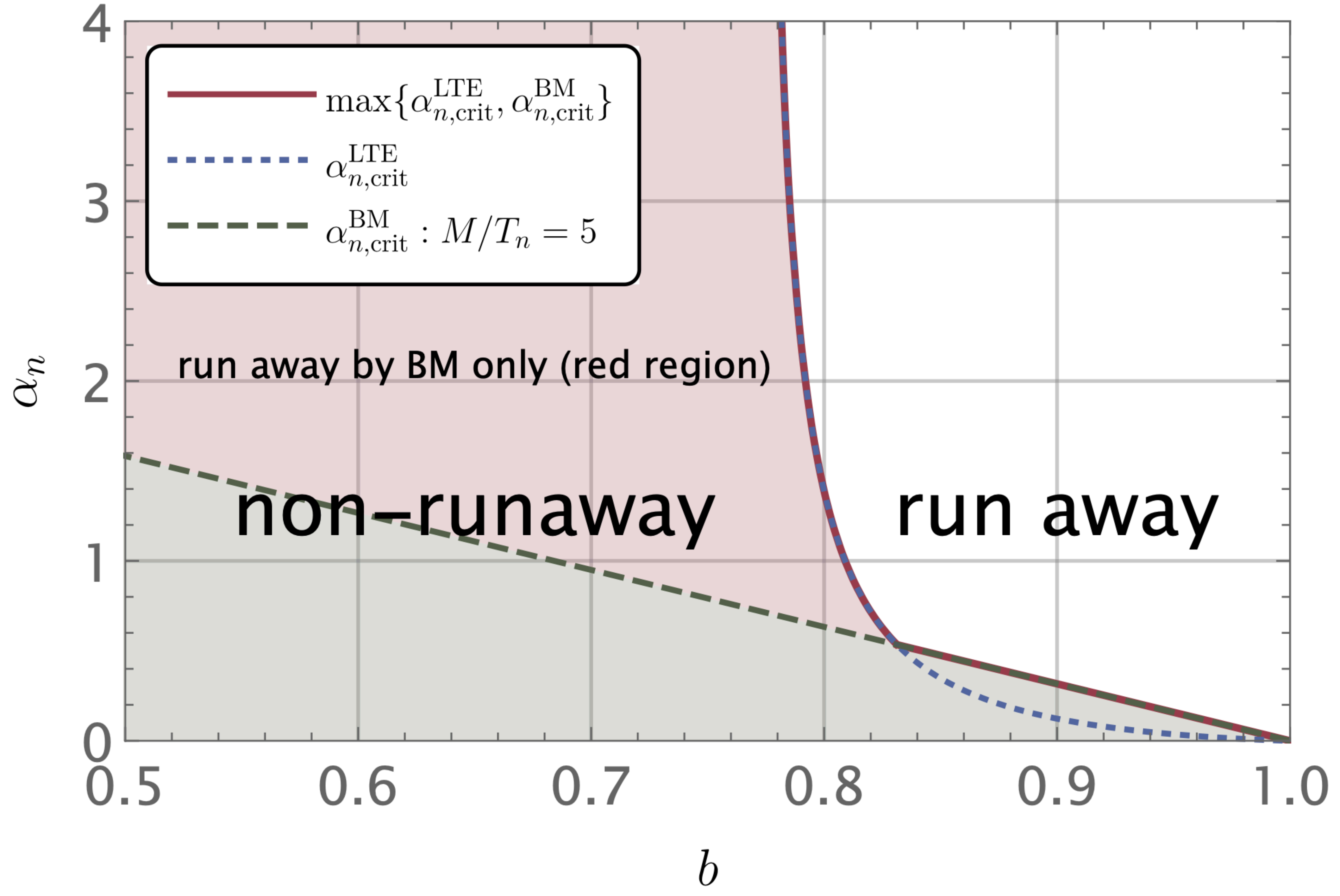


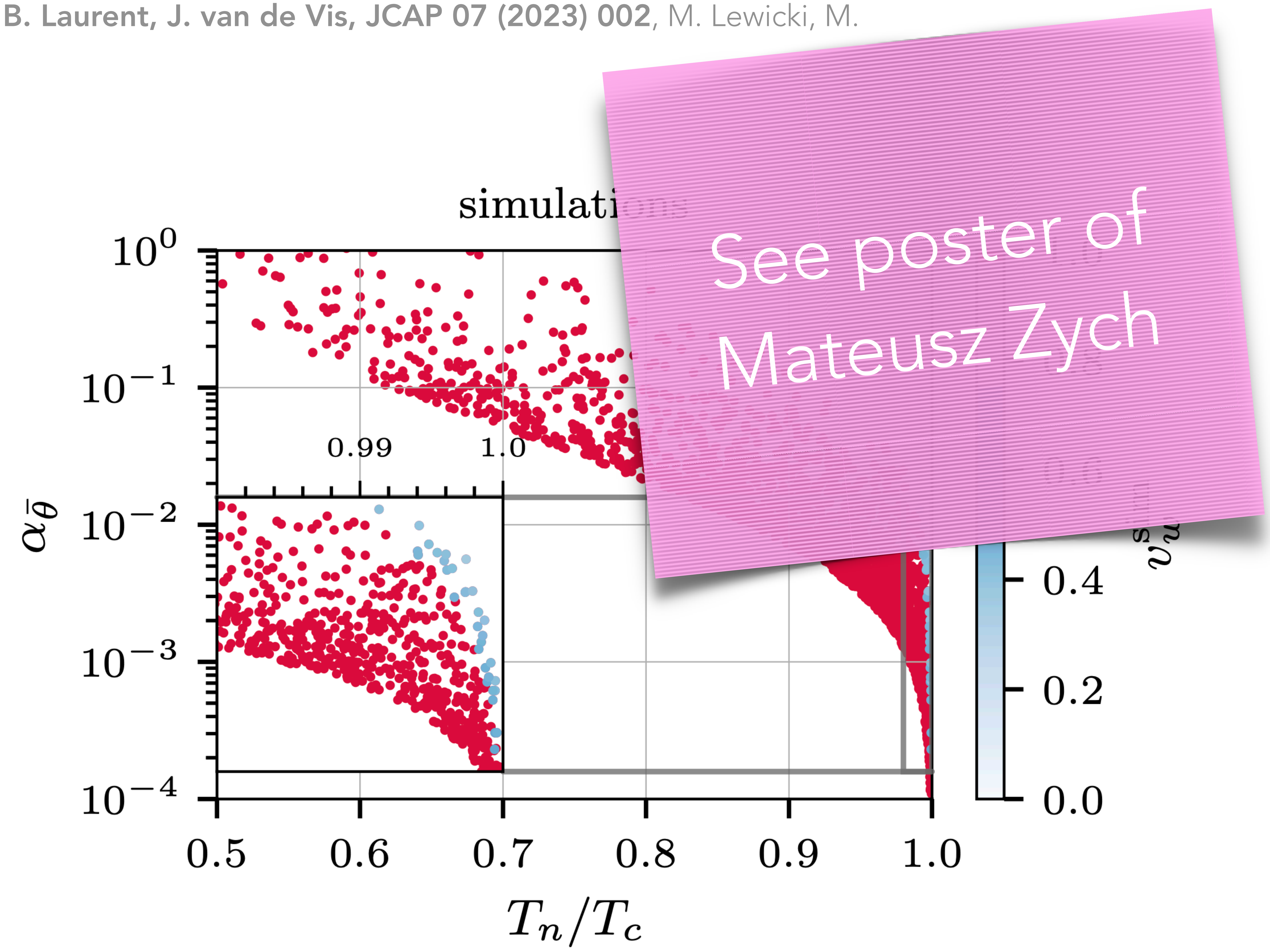
[T. Krajewski, M. Lewicki, M. Zych, JHEP 05 (2024) 011]

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]

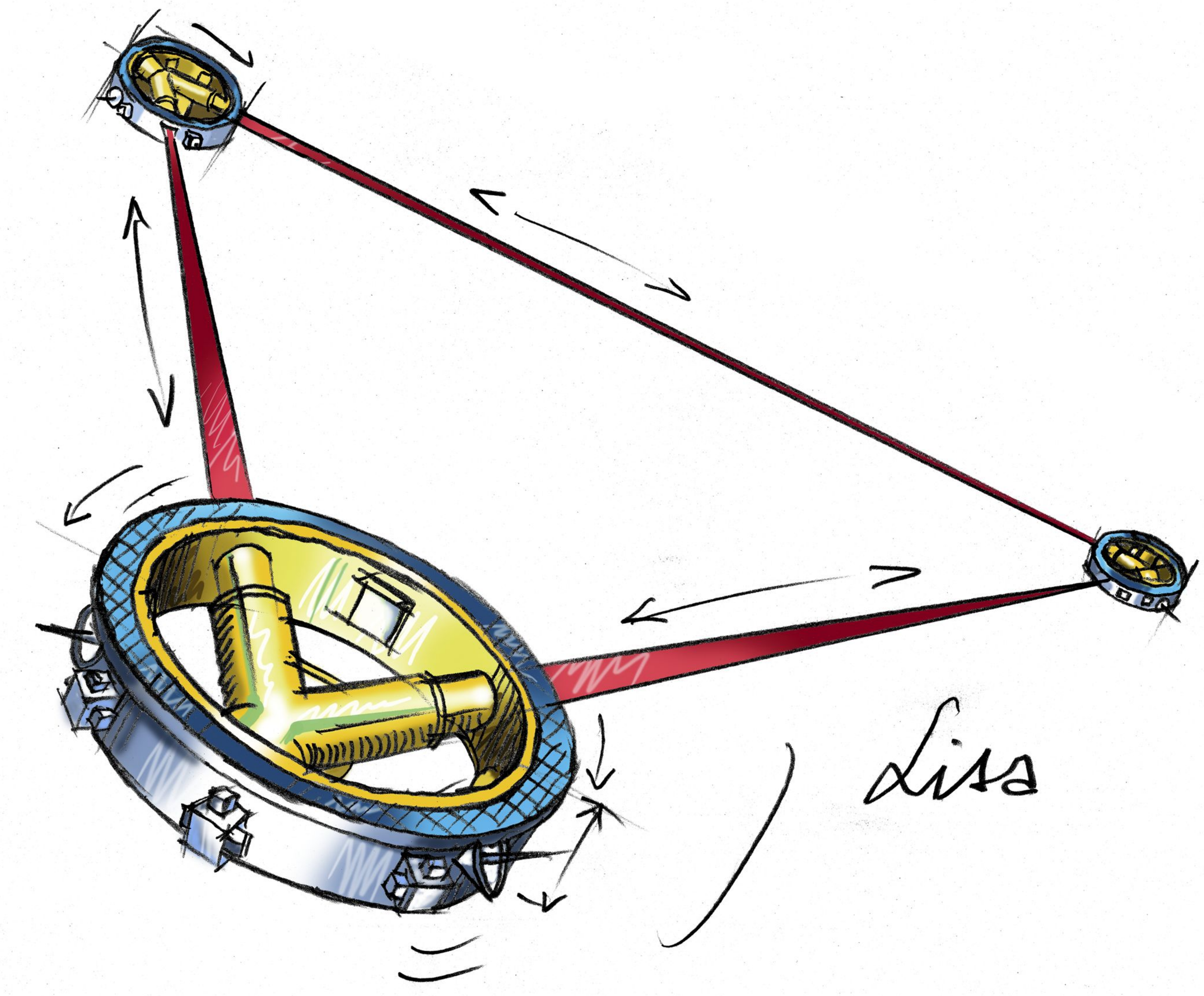


[W.-Y. Ai, X. Nagels, M. Vanvlasselaer, *JCAP* 03 (2024) 037]

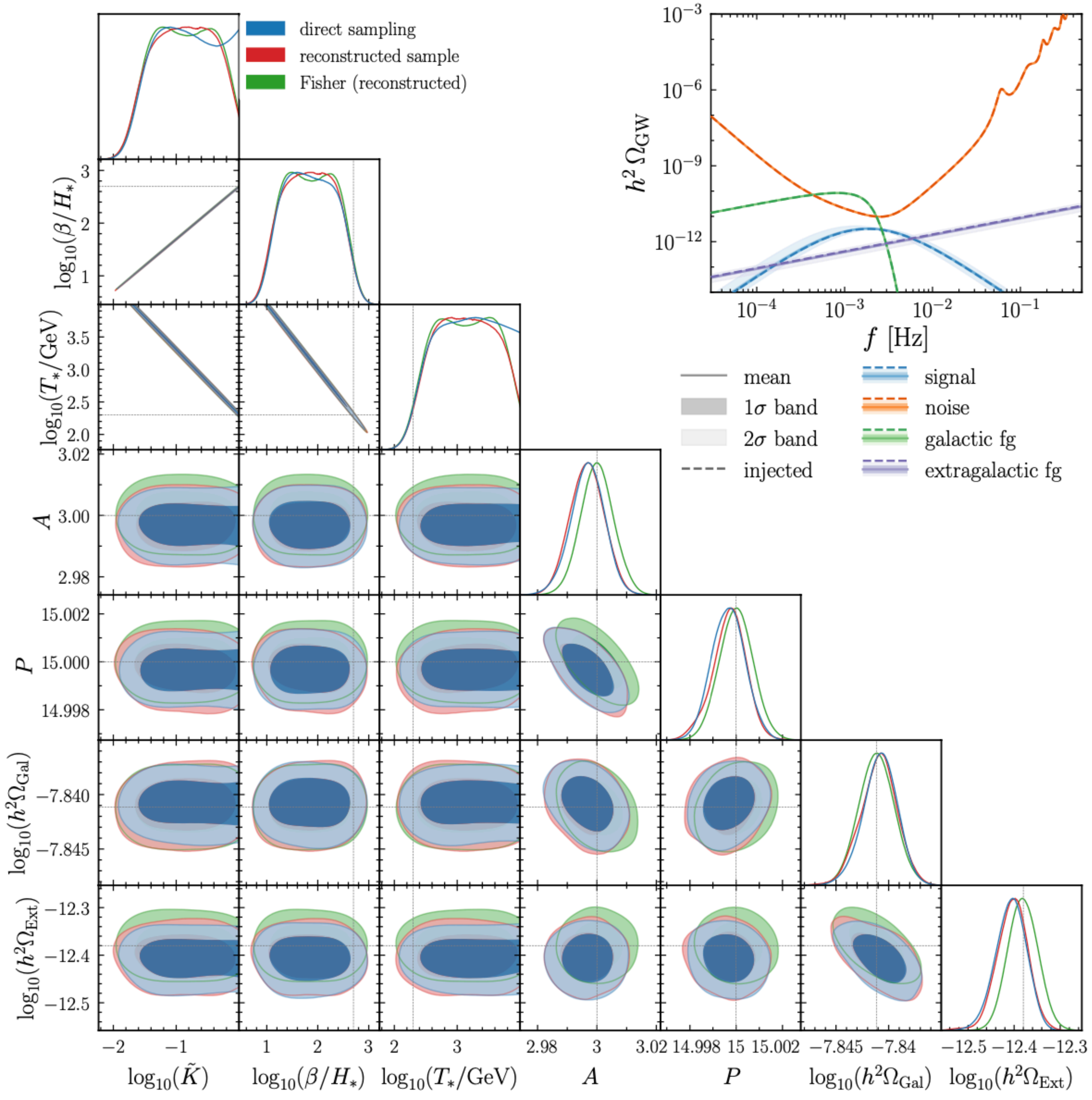


[T. Krajewski, M. Lewicki, M. Zych, JHEP 05 (2024) 011]

WHAT WILL WE LEARN FROM OBSERVATIONS?

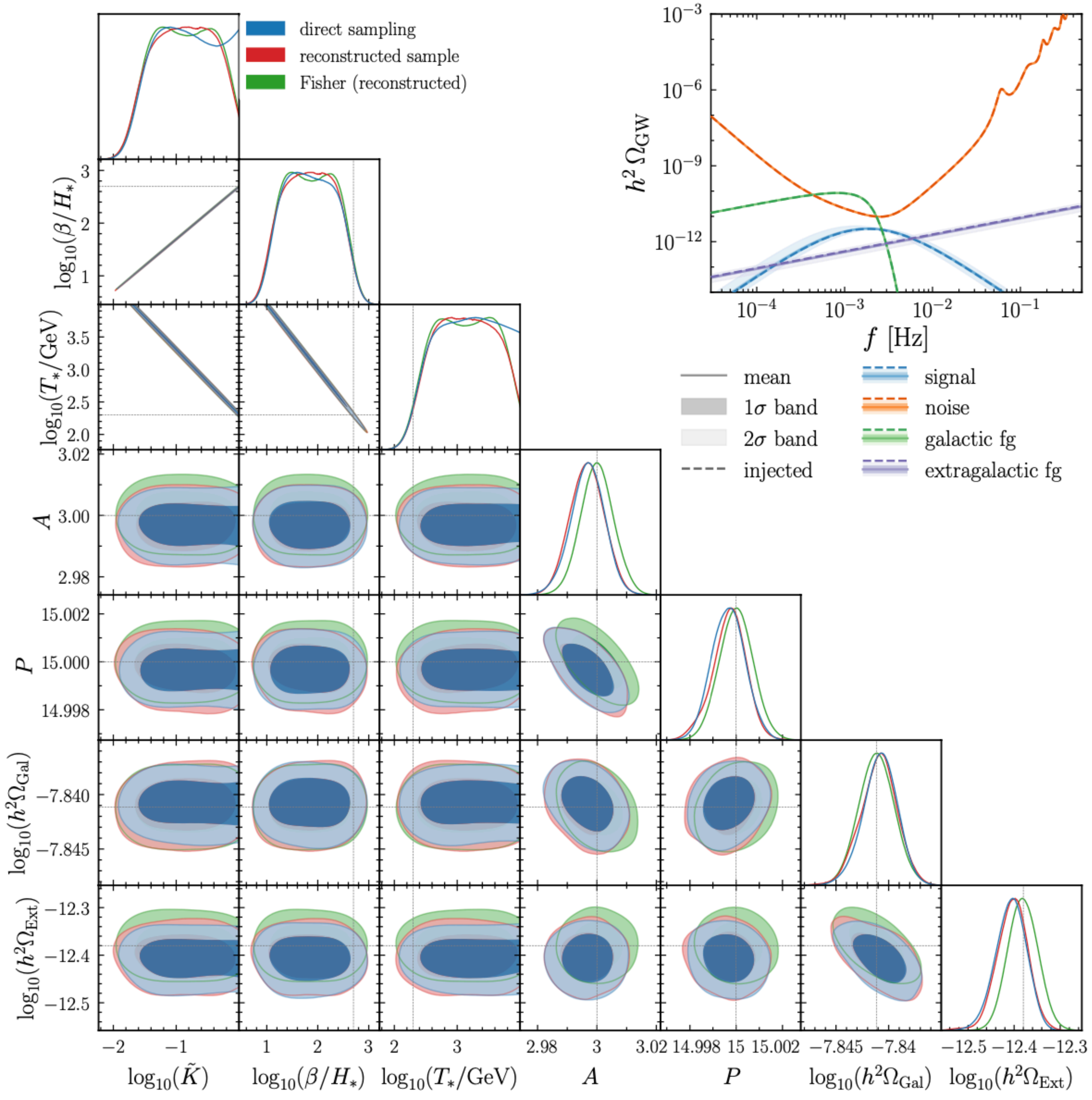


PARAMETER RECONSTRUCTION WITH LISA

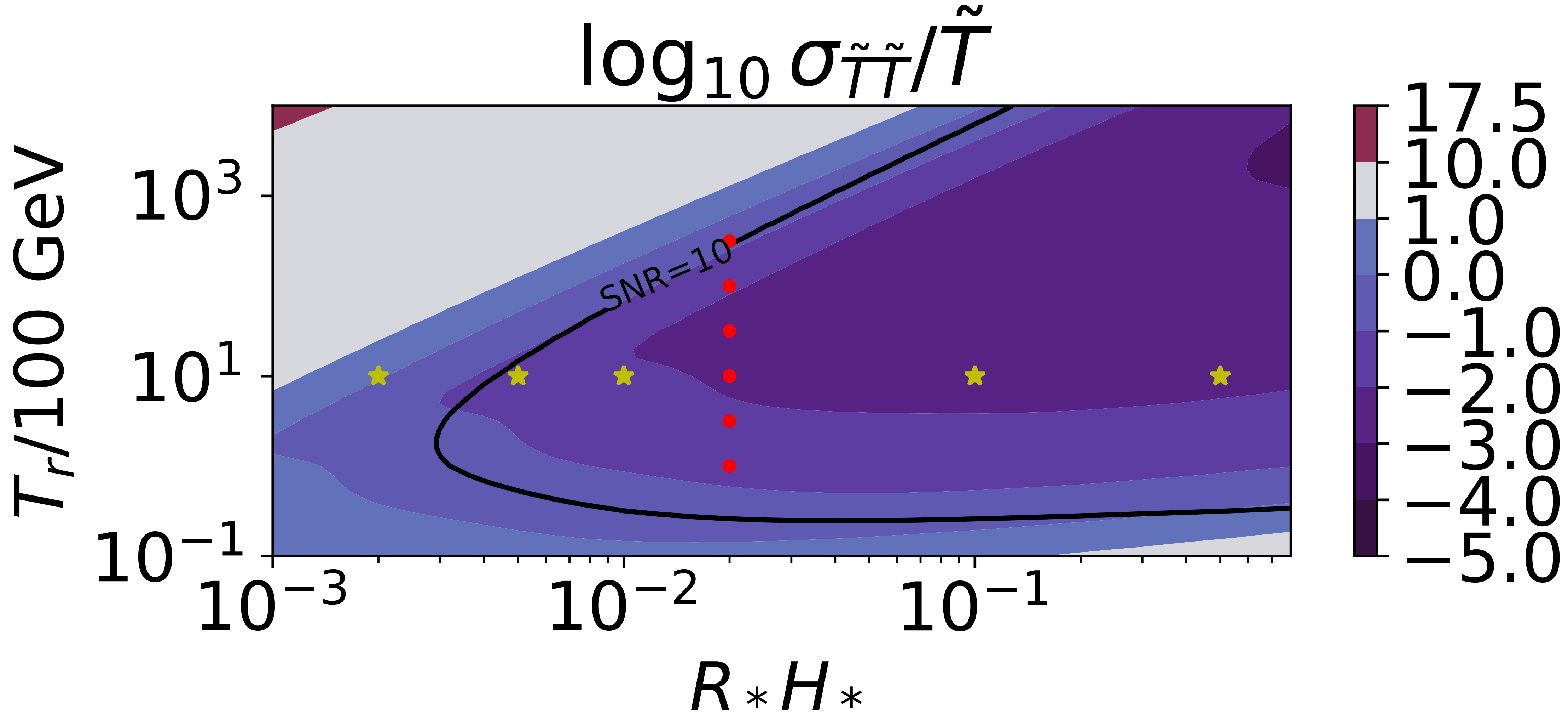


[C. Caprini at al., LISA CosWG, 2403.03723]

PARAMETER RECONSTRUCTION WITH LISA

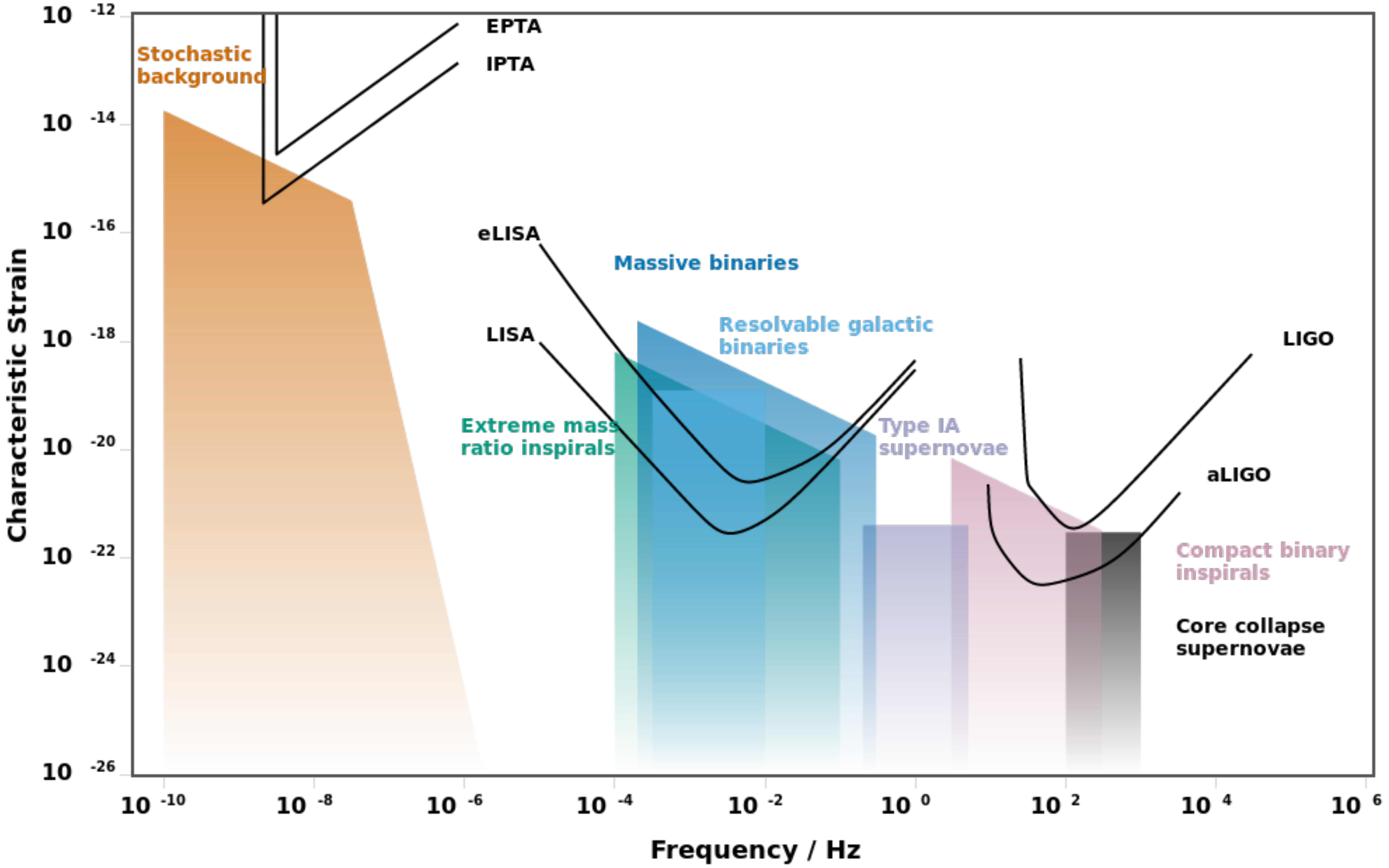


[C. Caprini at al., LISA CosWG, 2403.03723]



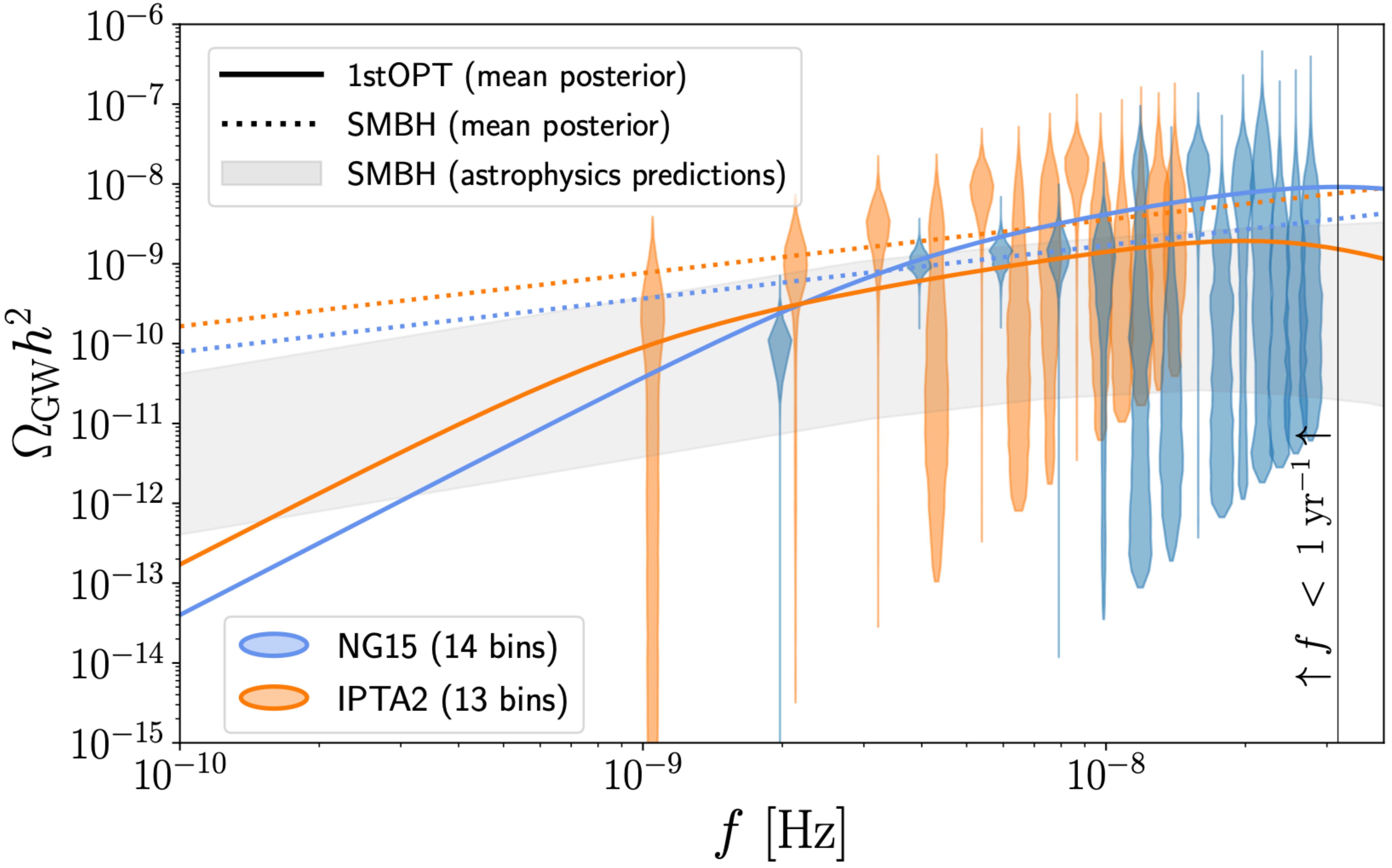
[A. Gonstal, Msc Thesis, 2023, Warsaw]

GRAVITATIONAL WAVE DETECTORS



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

HAVE WE ALREADY SEEN A SIGNAL IN PTA?

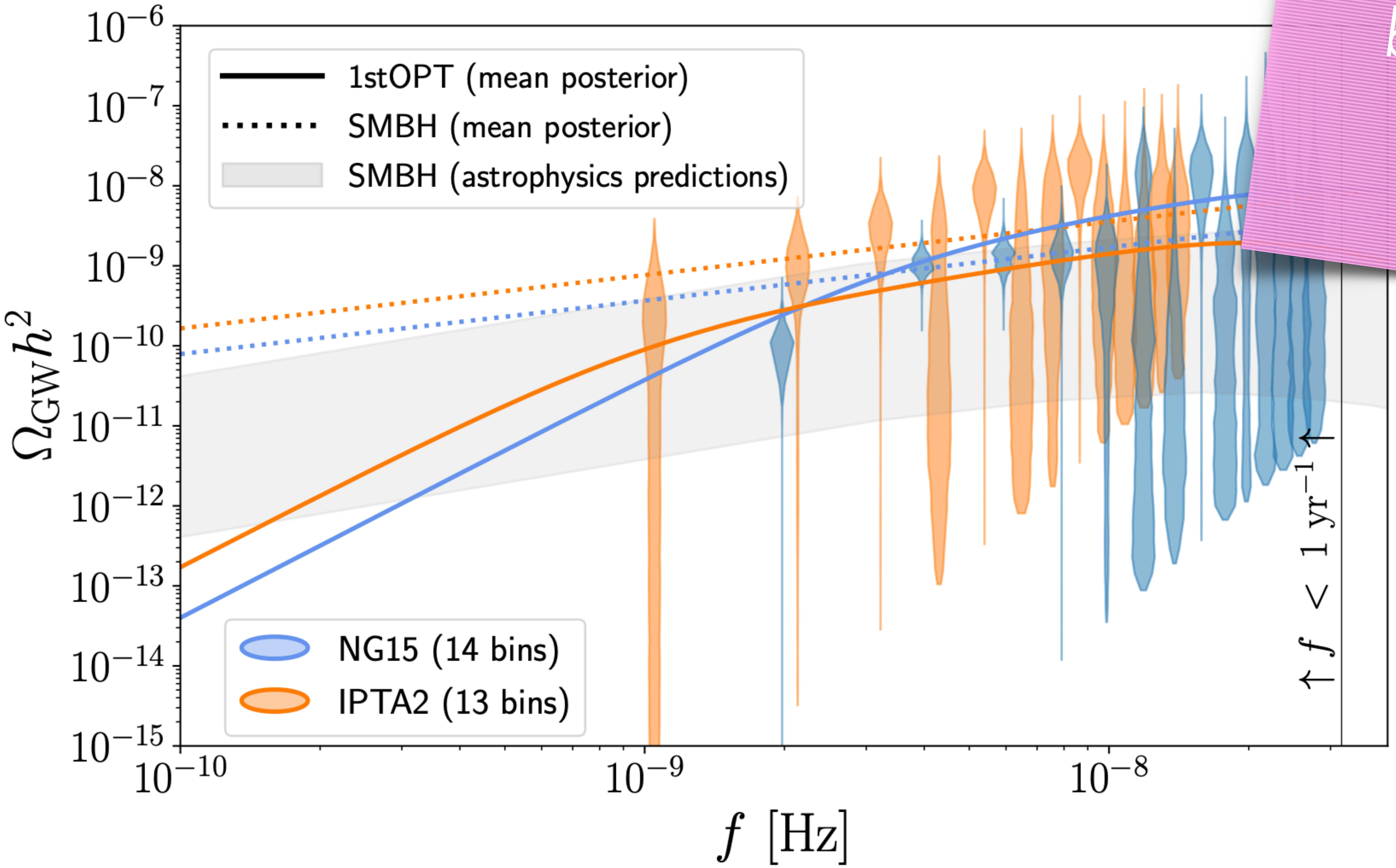


[Y. Gouttenoire, Phys.Rev.Lett. 131 (2023) 17]

[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

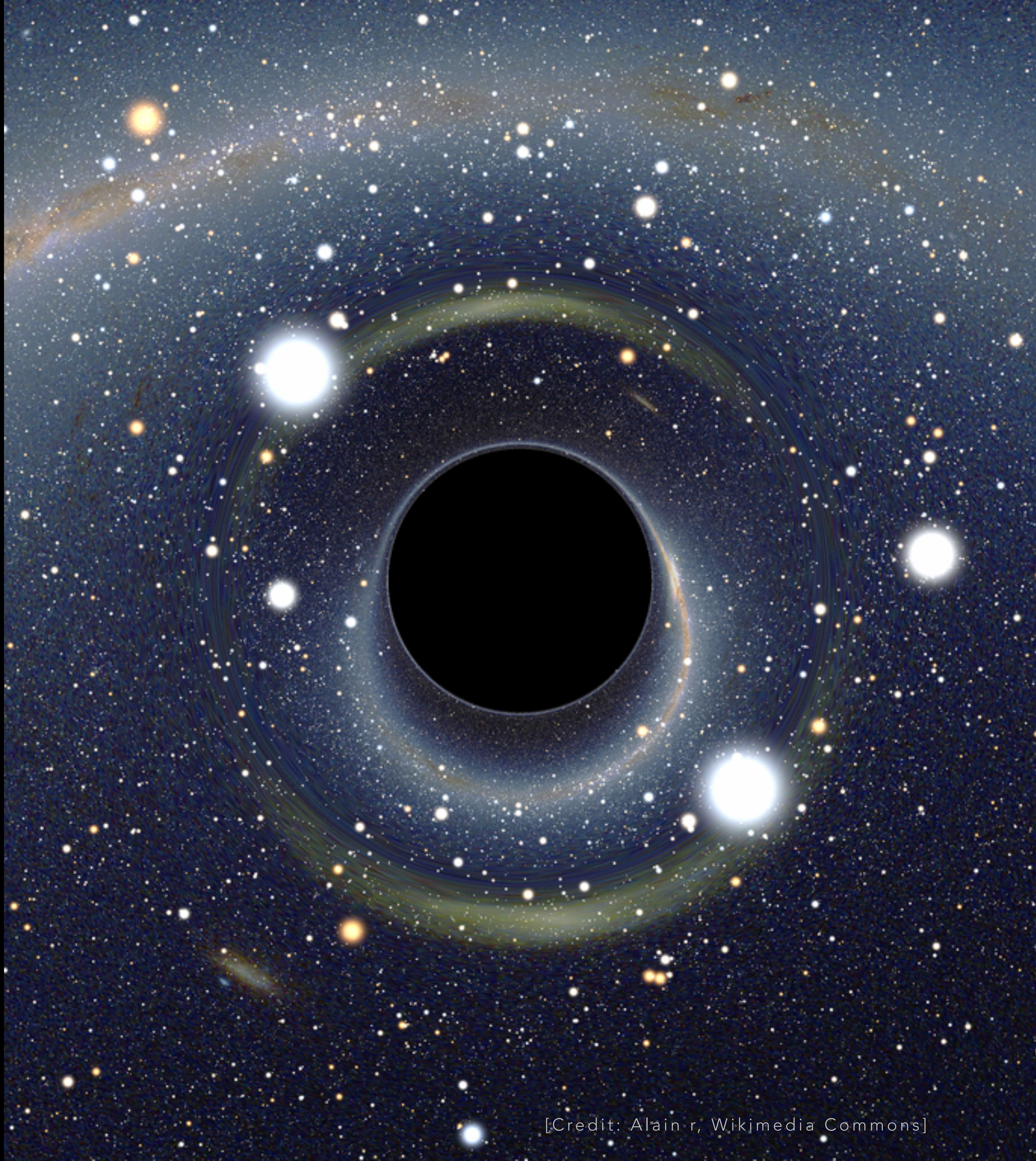


[Y. Gouttenoire, Phys.Rev.Lett. 131 (2023) 17]

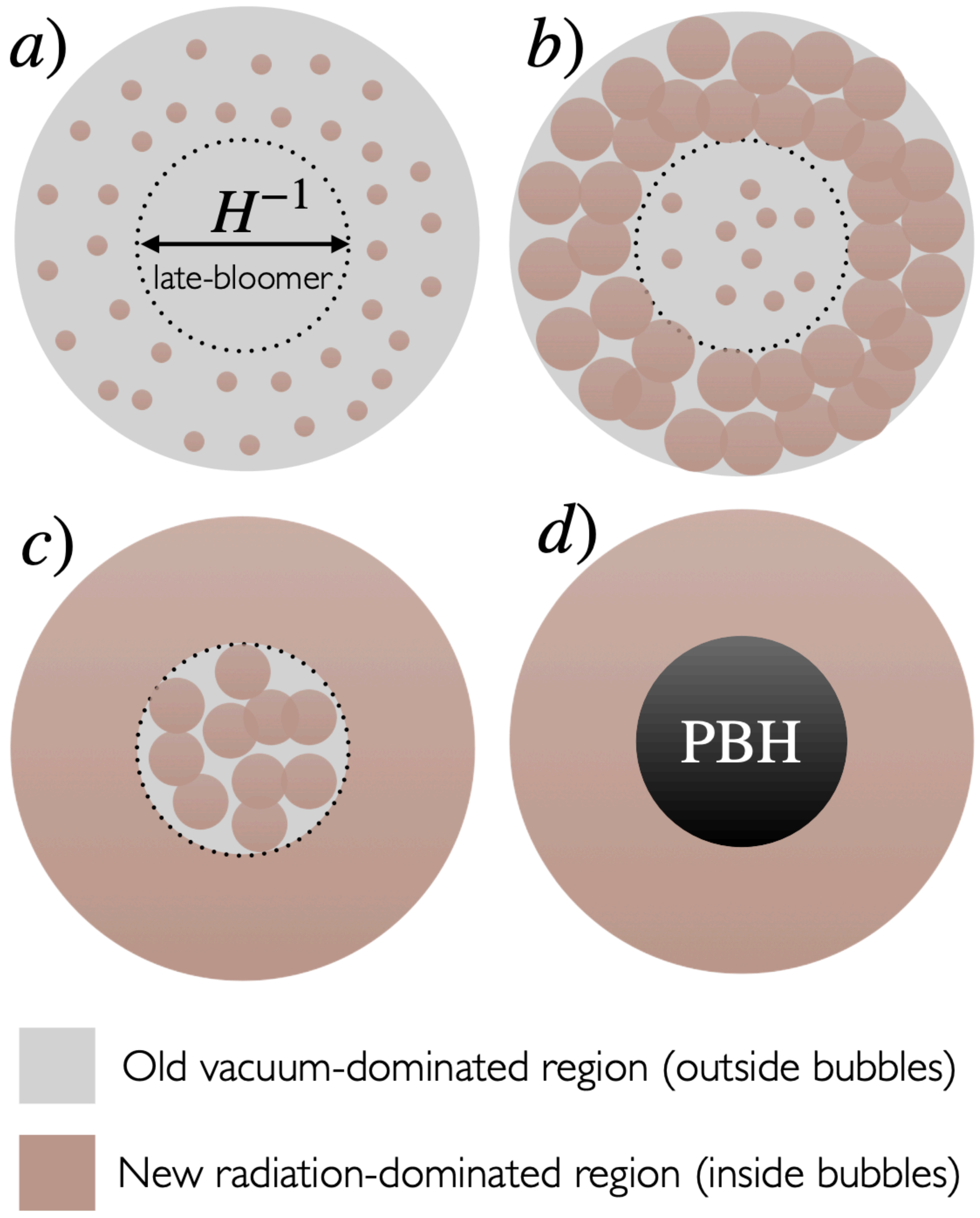
[J. Ellis, M. Fairbairn, G. Franciolini, G. Hütsi, A. Iovino Jr., M. Lewicki, M. Raidal, J. Urrutia, V. Vaskonen, H. Veermäe, Phys.Rev.D 109 (2024) 2, 023522, T. Bringmann, P. F. Depta, T. Konstandin, K. Schmidt-Hoberg, C. Tasillo, and others]

OTHER EFFECTS OF PT

PRIMORDIAL BLACK HOLES AND SECONDARY GW



PRIMORDIAL BLACK HOLES

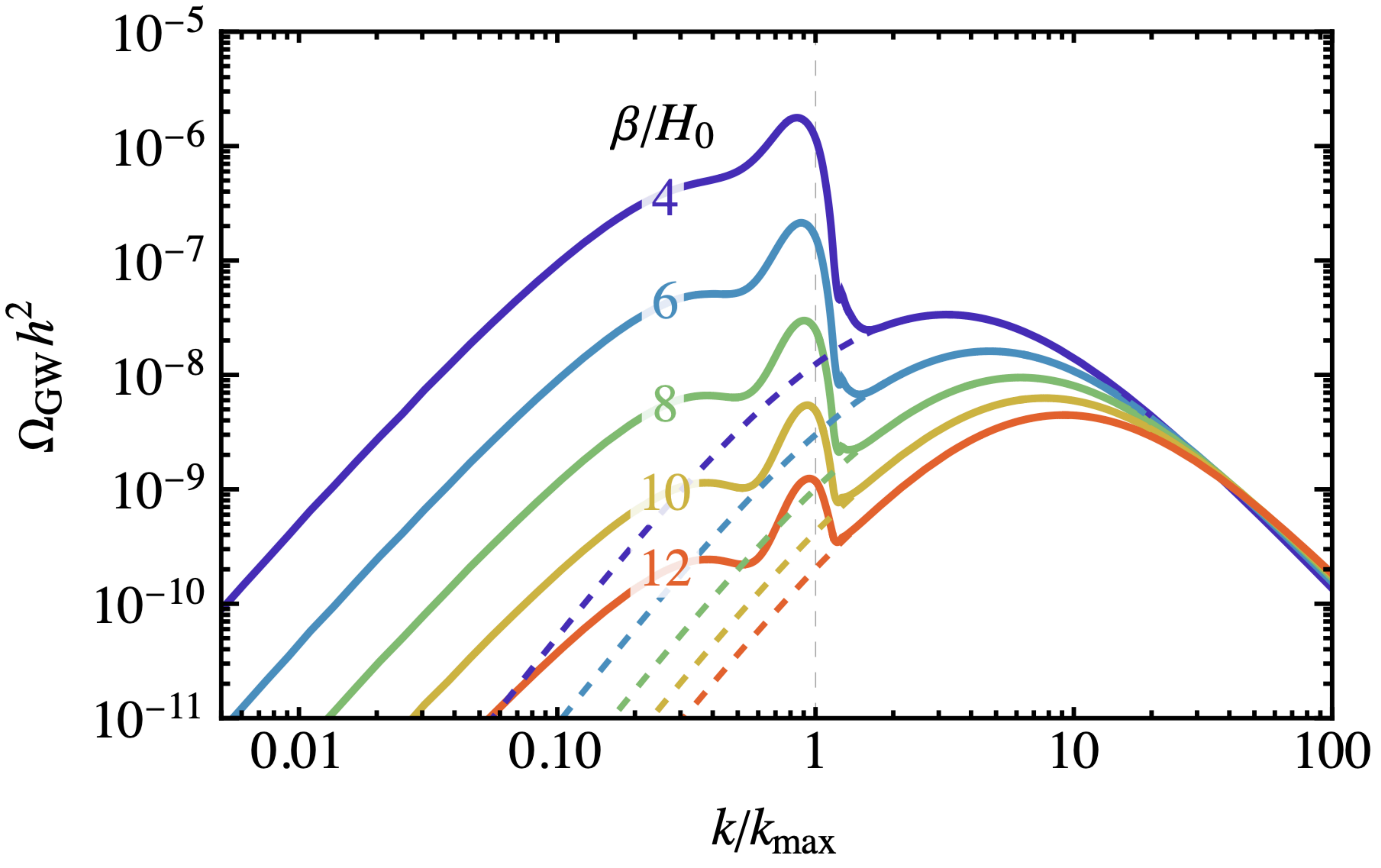


[Y. Gouttenoire, T. Volansky, 2305.04942 [hep-ph]]

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. Toczek, V. Vaskonen, JHEP 09 (2023) 092, 2402.04158]

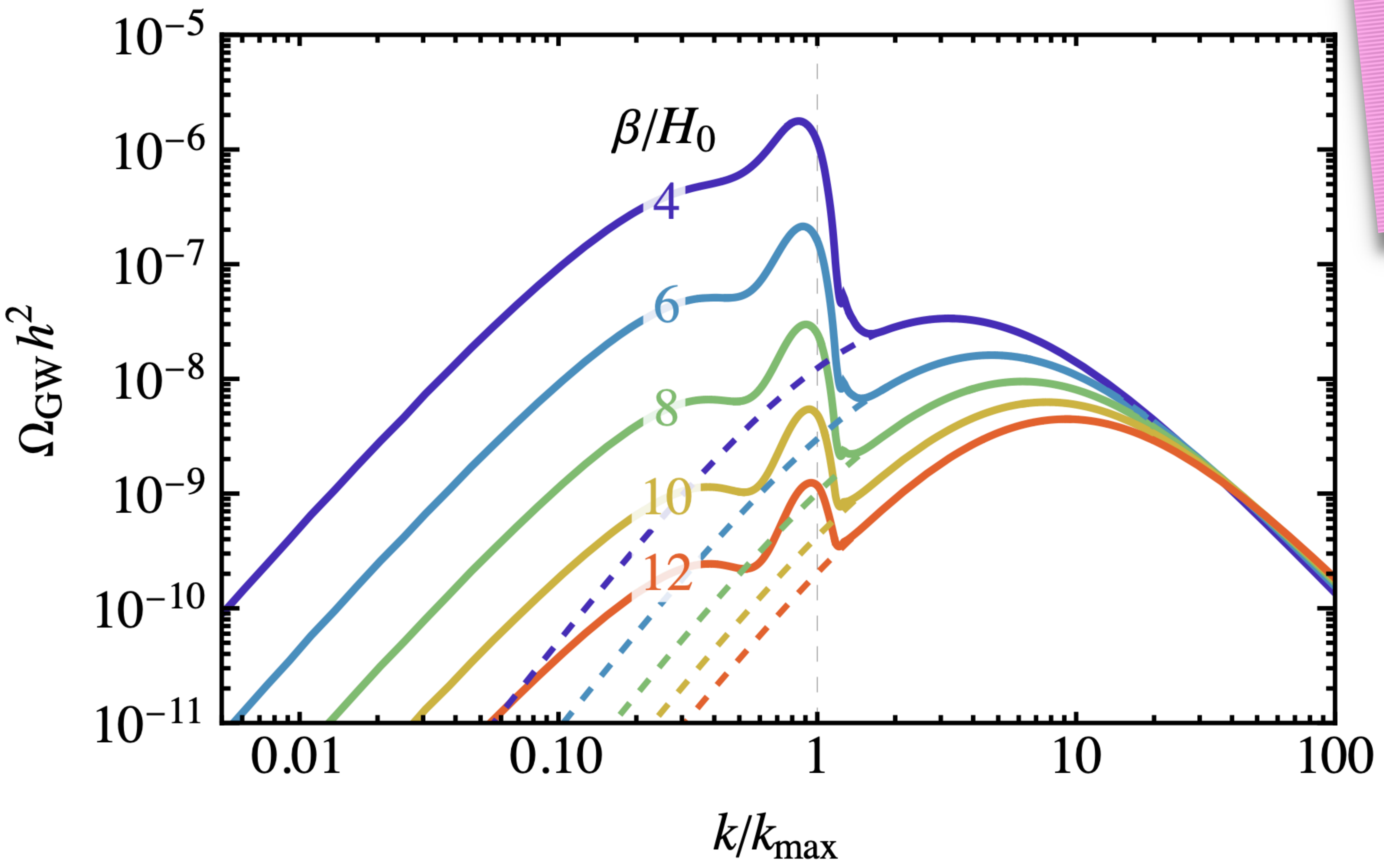
SECONDARY GRAVITATIONAL WAVES



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

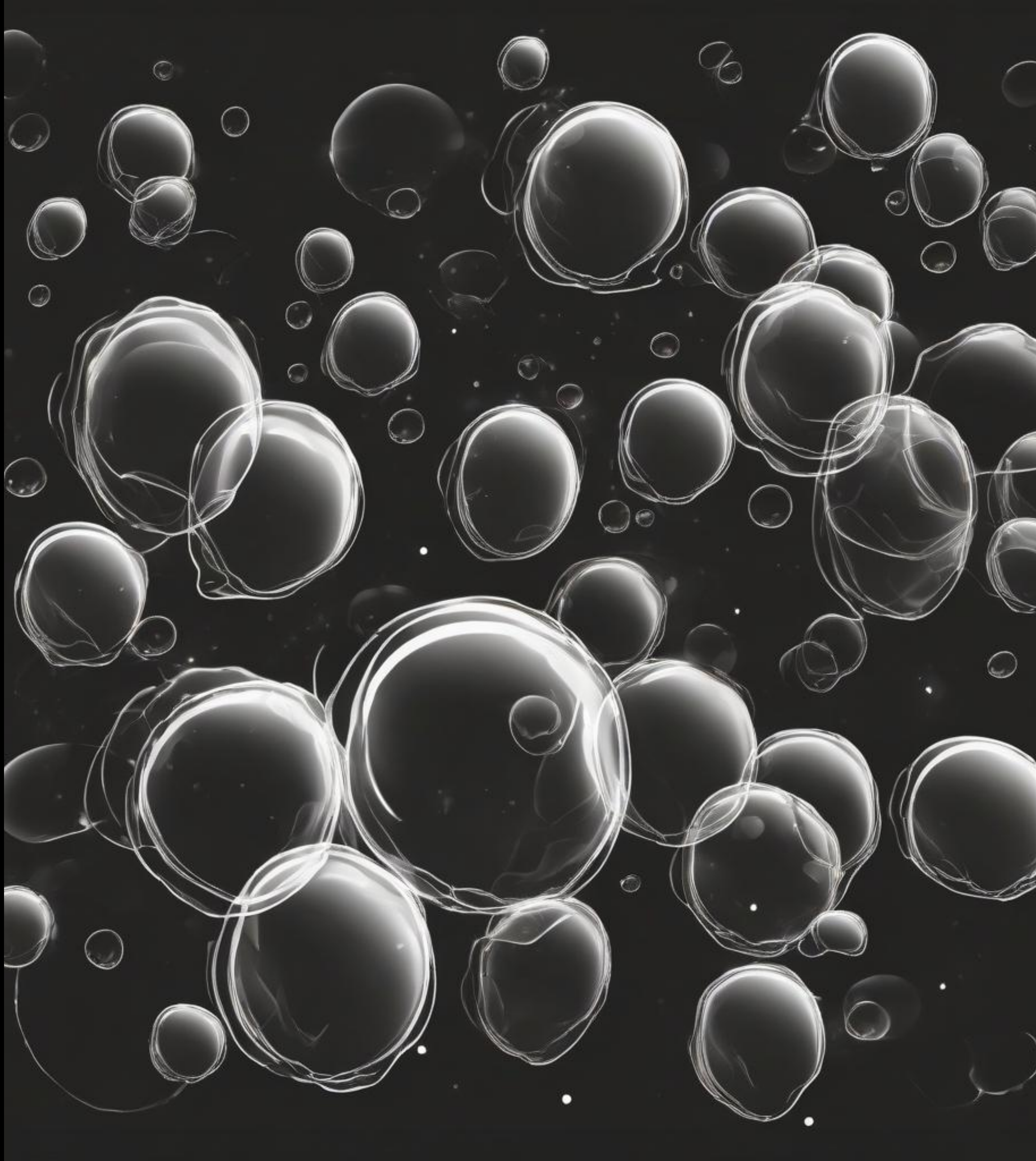
SECONDARY GRAVITATIONAL WAVES

See poster/talk of Piotr Toczek



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

SUMMARY



SUMMARY

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We can learn about New Physics using GWs from PTs.

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Progress in (non)perturbative treatment of PTs. More needed!

We can learn about New Physics using GWs from PTs.

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