Dark Matter and Cosmological Phase Transitions

Joachim Kopp (CERN & JGU Mainz)

Dark Matter Beyond the Weak Scale • Durham • 26 March 2024

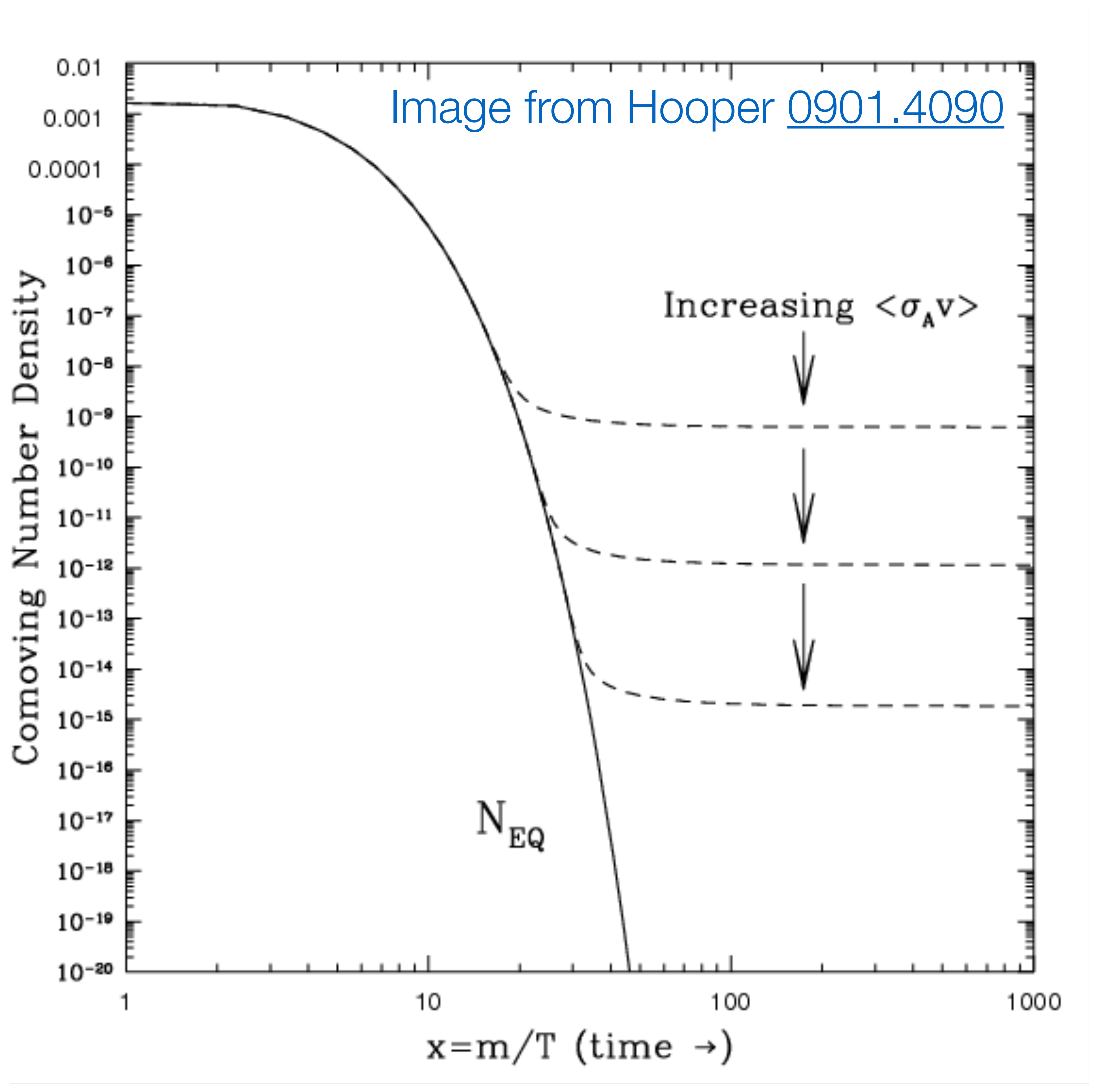
Beyond Thermal Freeze-Out

- Continued absence of signals in
  - direct DM searches (DM–nucleus scattering)
  - indirect DM searches (cosmic rays from DM annihilation)
  - collider searches (production of DM particles)
- No showstoppers yet, but a good moment to look beyond
- One alternative: setting the DM abundance in a cosmological phase transition
- This talk:
  - DM annihilation, decay, and freeze-in around a phase transition
  - “Filtered” Dark Matter
  - Primordial black holes from phase transitions

Dark Matter Decay Between Phase Transitions

DM Decay Between Phase Transitions

- Observed DM abundance requires a mechanism that depletes DM by several orders of magnitude, then stops
- Idea: DM decay.
- Example:
  - Phase transition shifts particle masses, making DM unstable
  - DM partly decays
  - 2nd PT restores stability



The Vev Flip-Flop

- Toy Model: SM + singlet scalar S

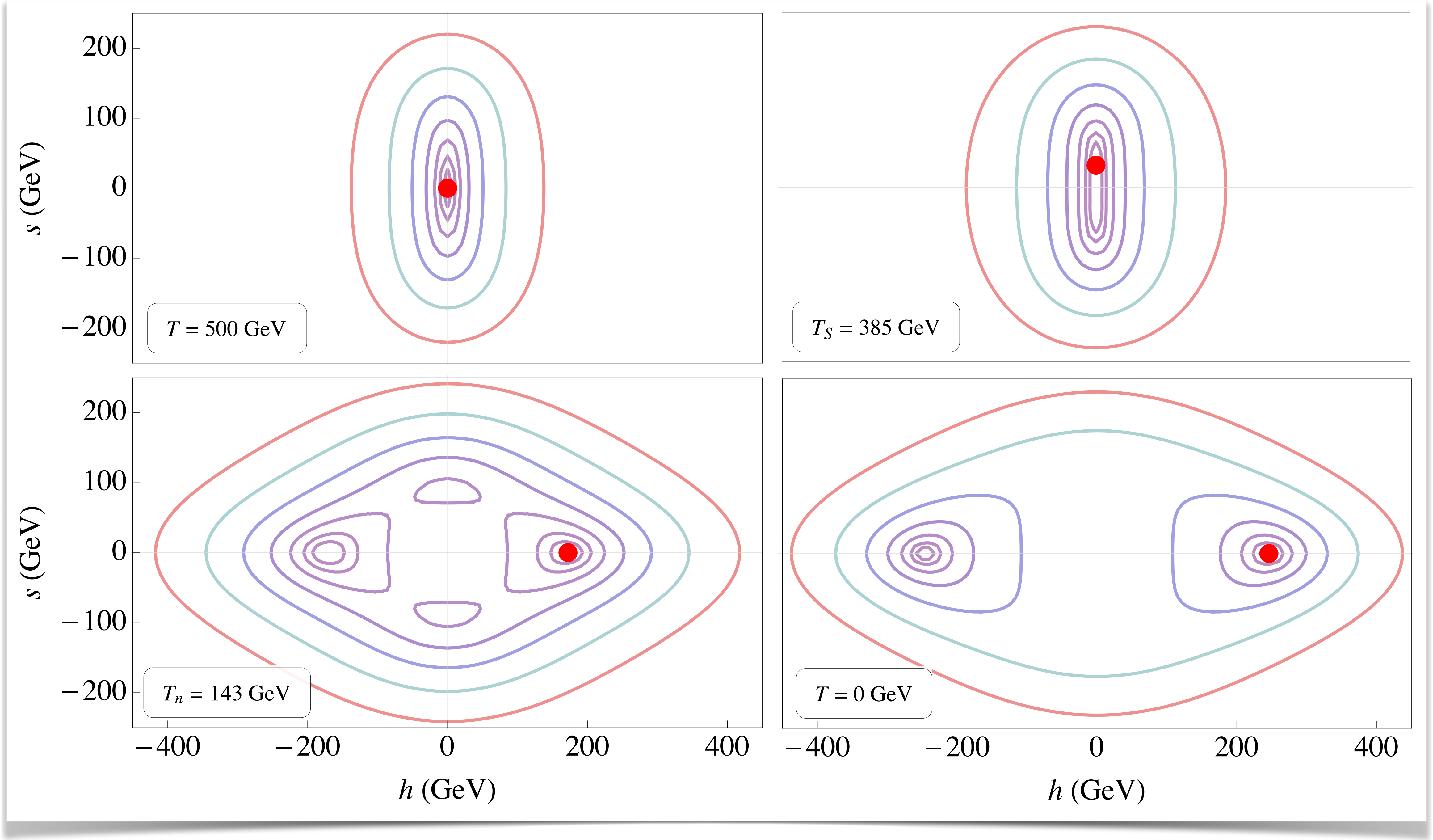
$$V^{\text{tree}} = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 - \mu_S^2 S^\dagger S + \lambda_S (S^\dagger S)^2 + \lambda_p (H^\dagger H)(S^\dagger S)$$

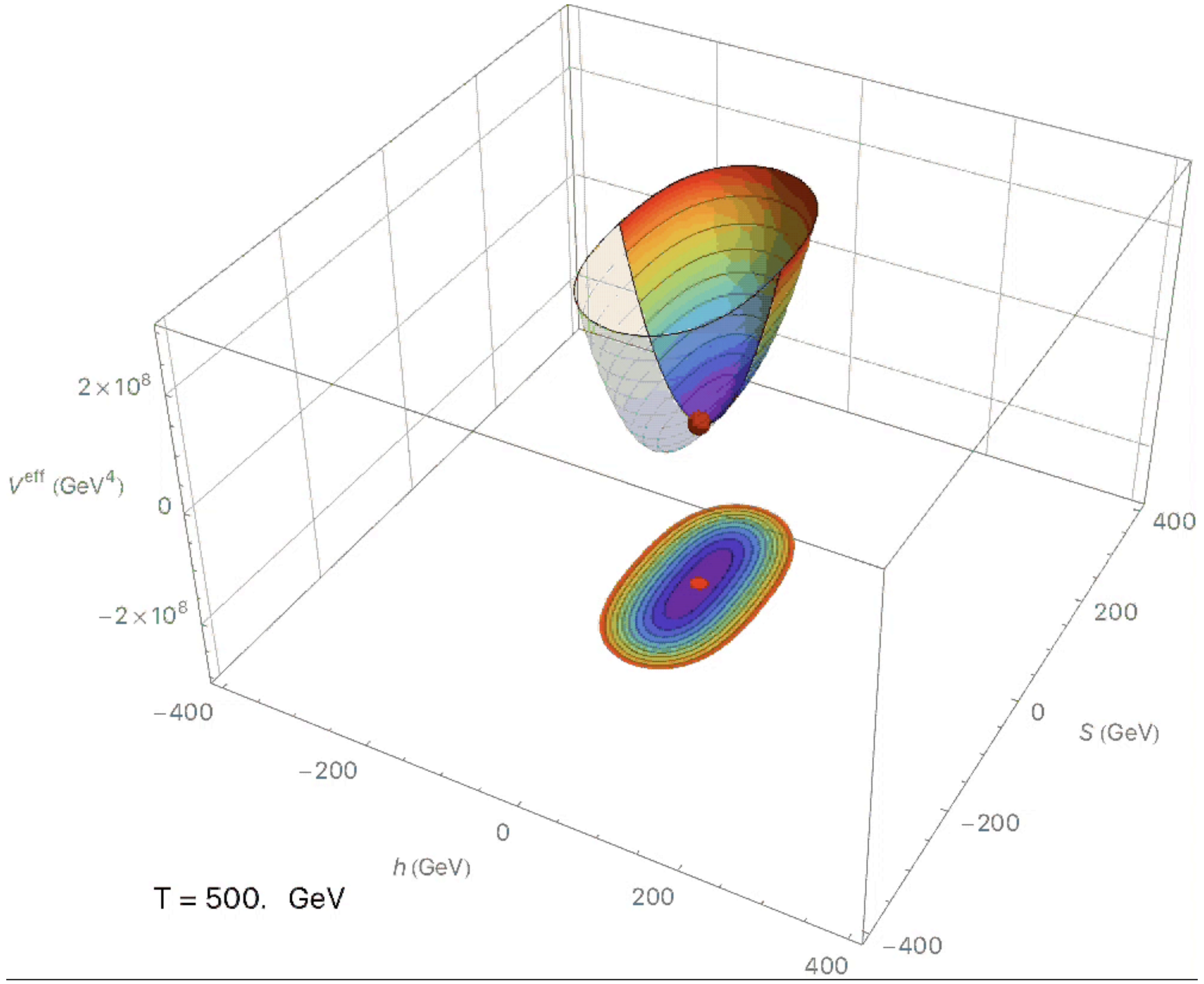
- Typical behavior: 2-step phase transition
  - High T: $\langle S \rangle = 0$, $\langle H \rangle = 0$
  - Intermediate T: $\langle S \rangle \neq 0$, $\langle H \rangle = 0$
  - Low T: $\langle S \rangle = 0$, $\langle H \rangle \neq 0$

Profumo *et al.* 0705.2425
Cline *et al.* 0905.2559
Espinosa Konstandin Riva 1107.5441
Cui Randall Shuve 1106.4834
Cline Kainulainen 1210.4196
Fairbairn Hogan 1305.3452
Curtin Meade Yu 1409.0005
Baker JK 1608.07578
Baker Breitbach JK Mittnacht 1712.03962
Baker Mittnacht 1811.03101

The Vev Flip-Flop

Animation: Mike Baker using `CosmoTransitions`
Wainwright 1109.4189, Kozaczuk Profumo Haskins Wainwright 1407.4134





- ☐ $T > 400$ GeV: $\langle S \rangle = 0$, $\langle H \rangle = 0$ (thermal corrections dominate V_{eff})
- ☐ $T \sim 400$ GeV: S develops vev ➠ DM unstable $\lambda_p (H^\dagger H)(S^\dagger S)$
- ☐ $T \sim 150$ GeV: H develops vev ➠ Feedback through
  ➠ $m_{S,\text{eff}}$ changes sign, $\langle S \rangle \to 0$, DM stable

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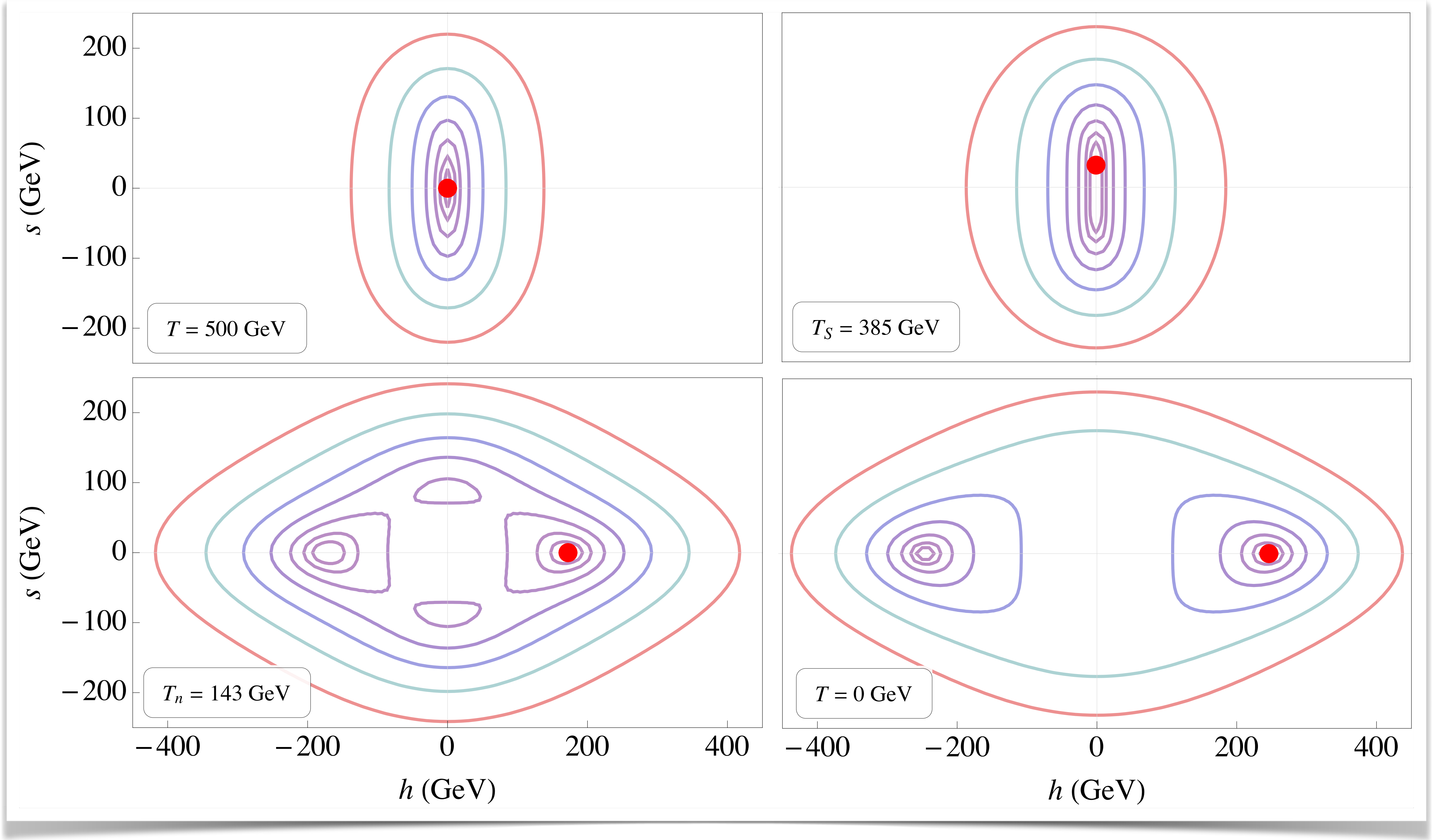

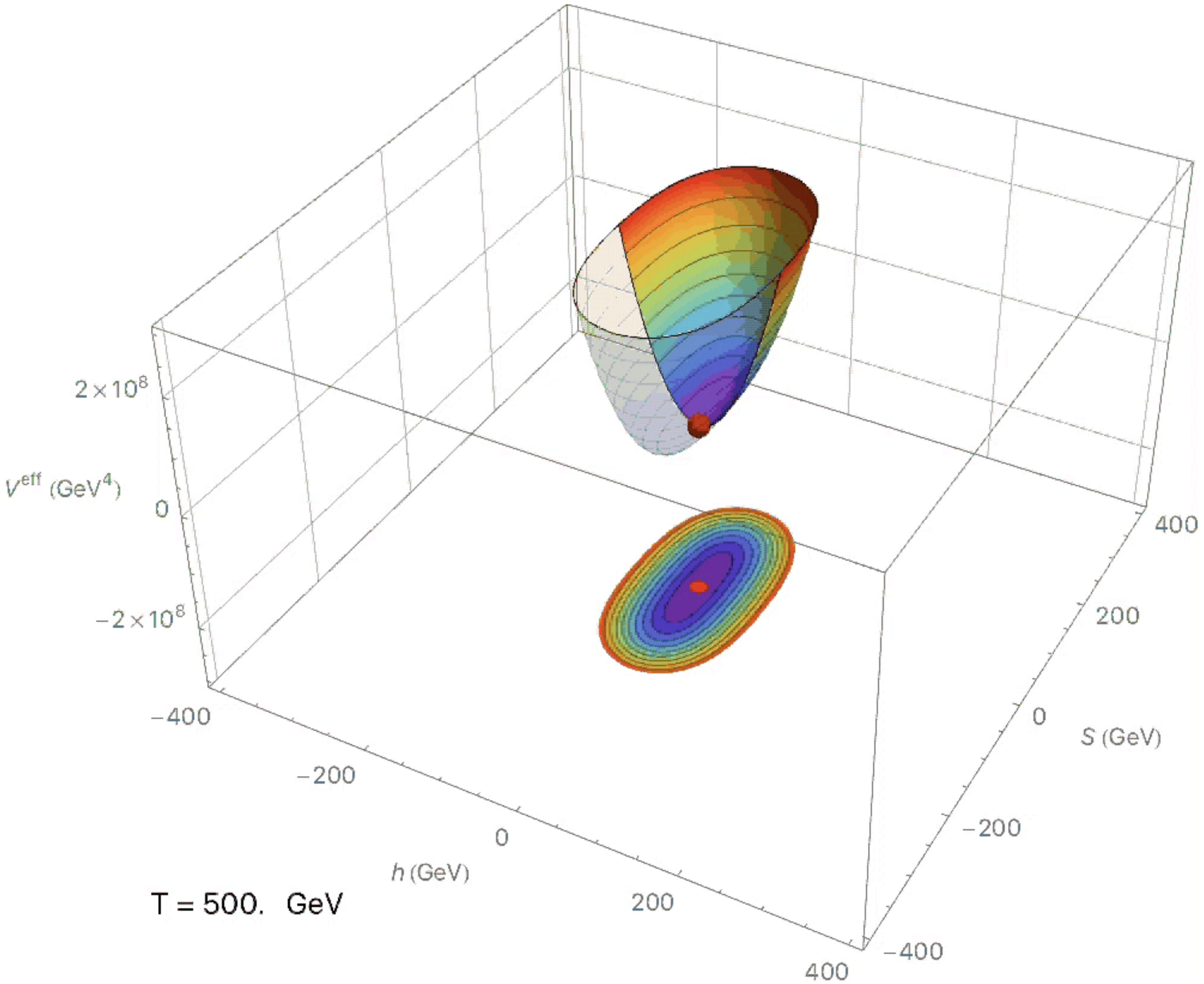

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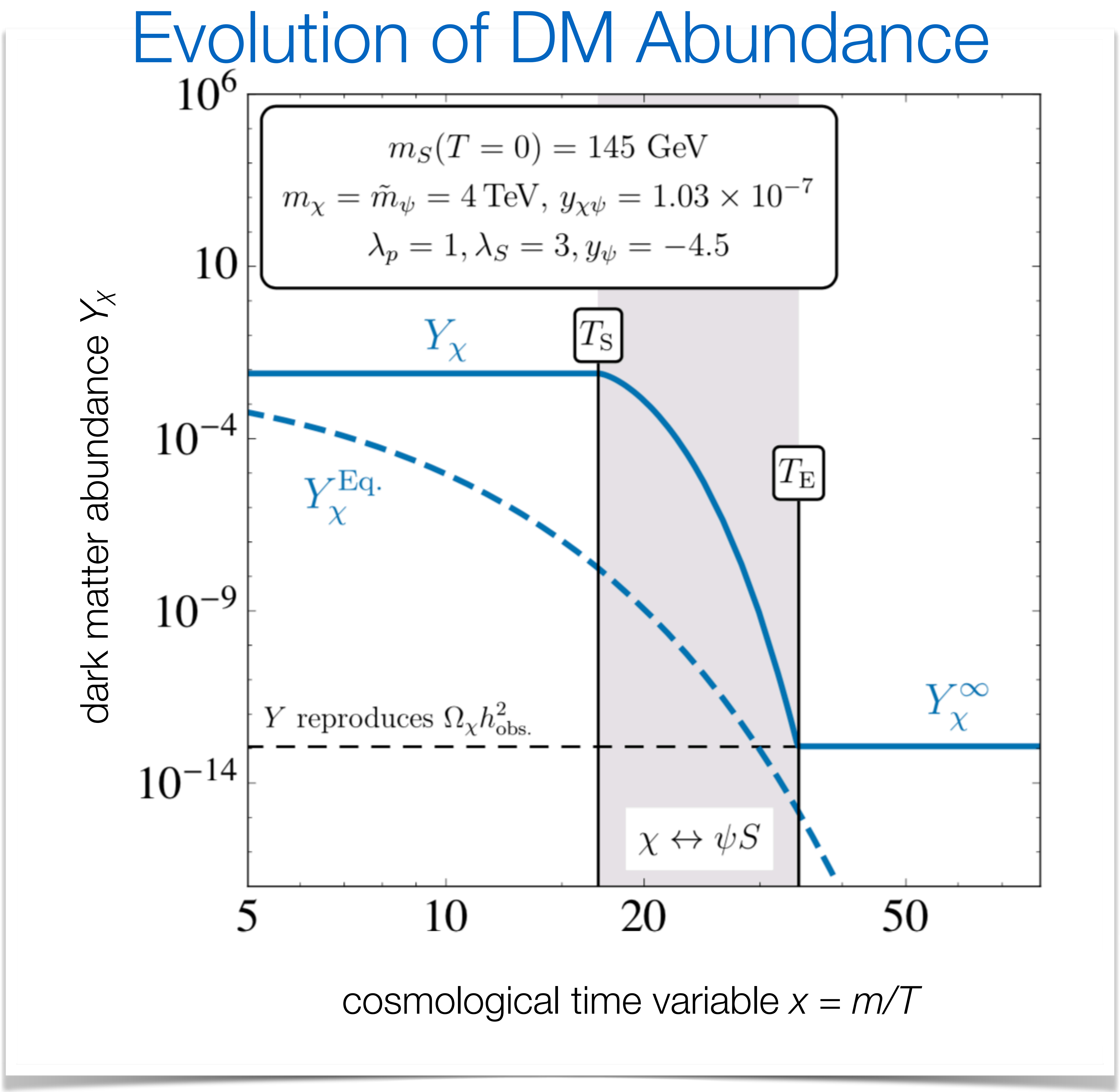
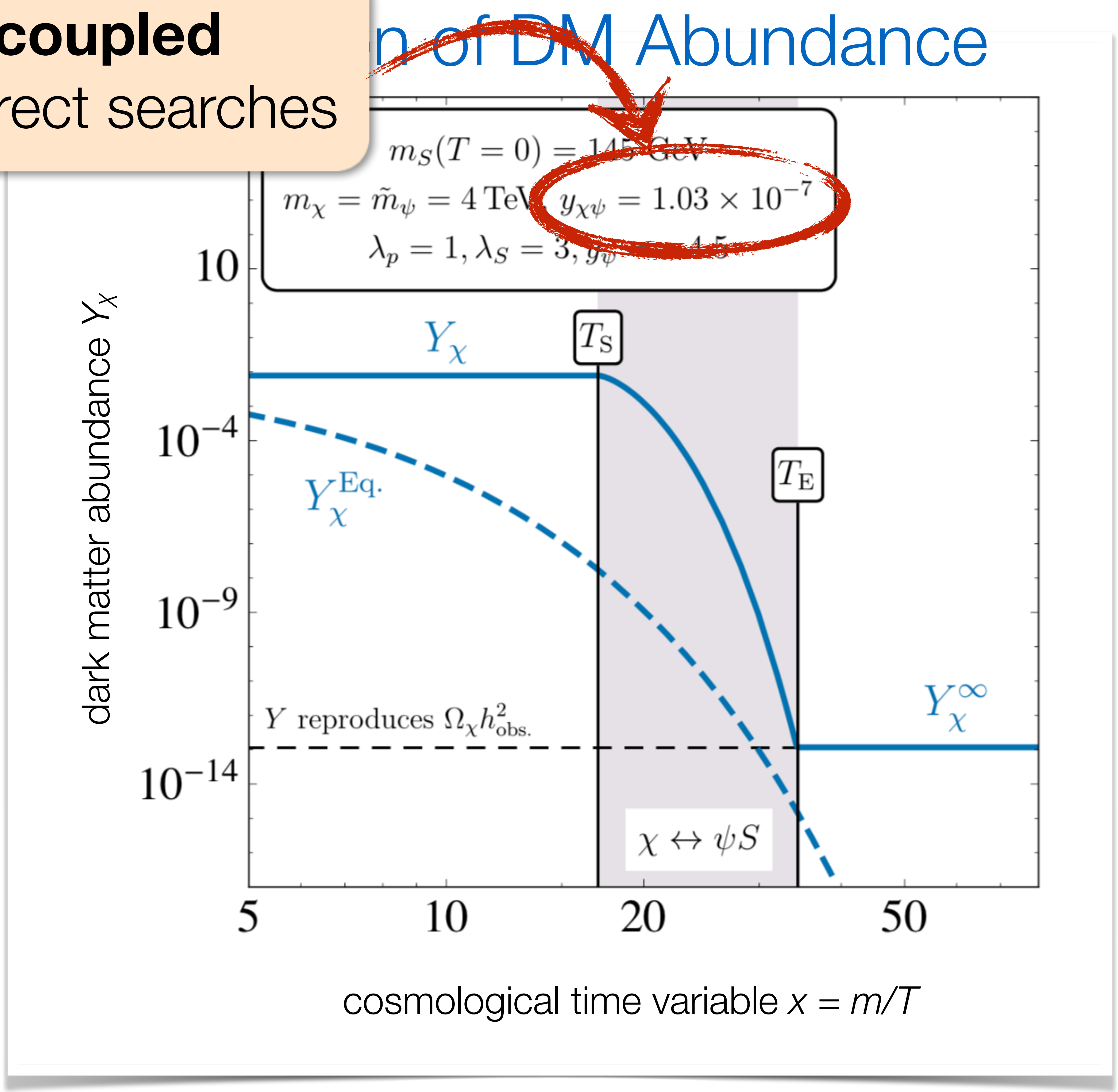
DM Decay Between Phase Transitions



Baker Mittnacht arXiv:1811.03101
see also Baker JK arXiv:1608.07578

DM Decay Between Phase Transitions

DM very weakly coupled
difficult for direct & indirect searches



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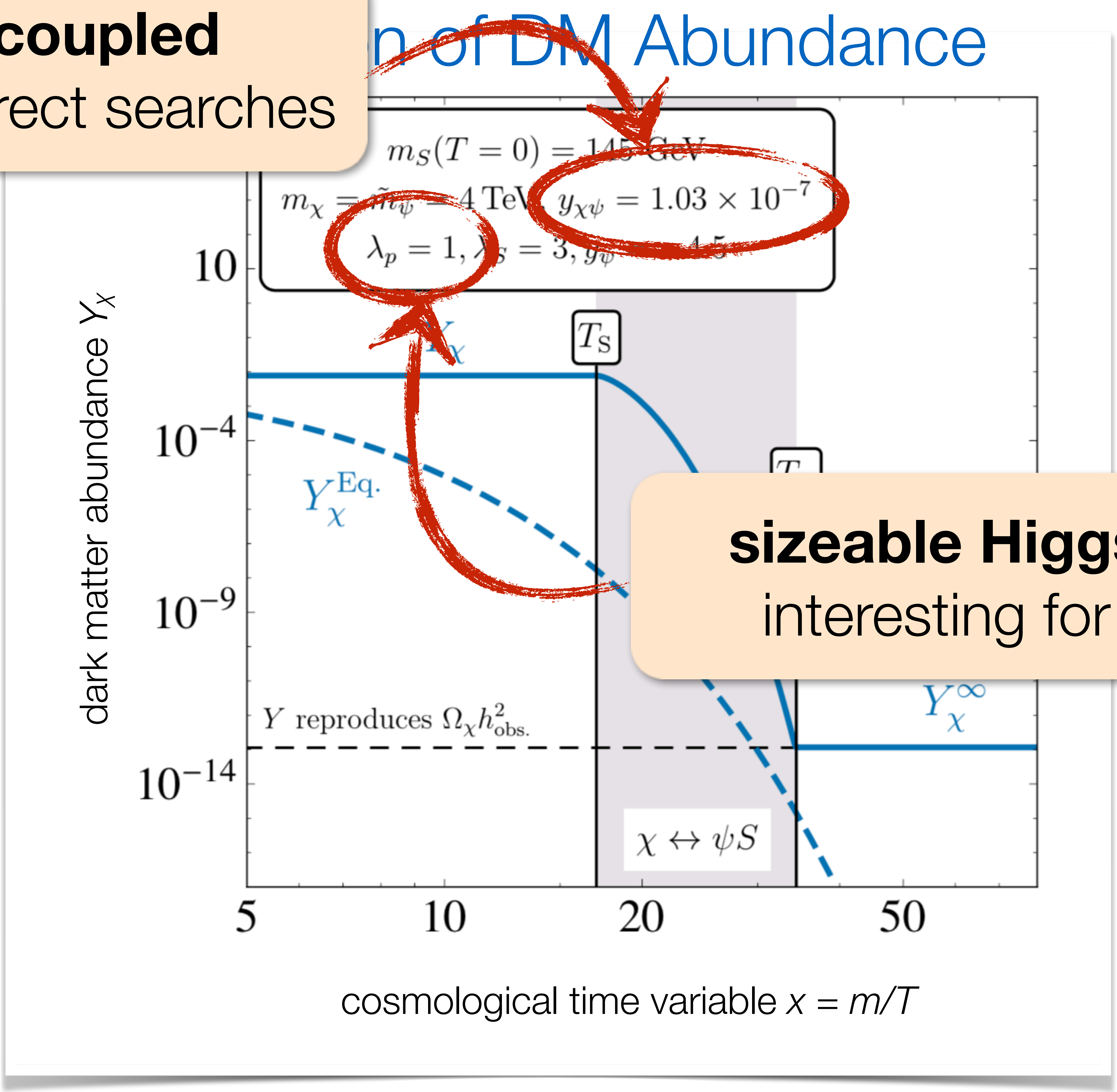

sizeable Higgs portal coupling
interesting for collider searches

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see also Baker JK arXiv:1608.07578

Thermal Effects in Dark Matter Freeze-In

DM Freeze-In in Higgs Portal Models

- Toy Model: SM + singlet scalar S + DM fermion χ + fermion ψ

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu S)(\partial^\mu S) + \bar\psi(i\partial\!\!\!/ - m_\psi)\psi + \bar\chi(i\partial\!\!\!/ - m_\chi)\chi$$
$$+ \left[y_{\psi\chi}\,\bar\psi S \chi + h.c.\right] + y_\chi\,\bar\chi\chi S + y_\psi\,\bar\psi\psi S - V(H,S)$$

- Scalar Potential:

$$V(H,S) = -\mu_H^2 H^\dagger H + \lambda_{H4}\,(H^\dagger H)^2 - \frac{1}{2}\mu_S^2 S^2 + \frac{\lambda_{S4}}{4!} S^4$$
$$+ \frac{\lambda_{S3}}{3!}\,\mu_S S^3 + \lambda_{p3}\mu_S\,S(H^\dagger H) + \frac{\lambda_{p4}}{2}\,S^2(H^\dagger H)\,.$$

Baker Breitbach JK Mittnacht 1712.03962

CERN Neutrino PLATFORM JG|U

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- ☐ Scalar Potential:

assumed small

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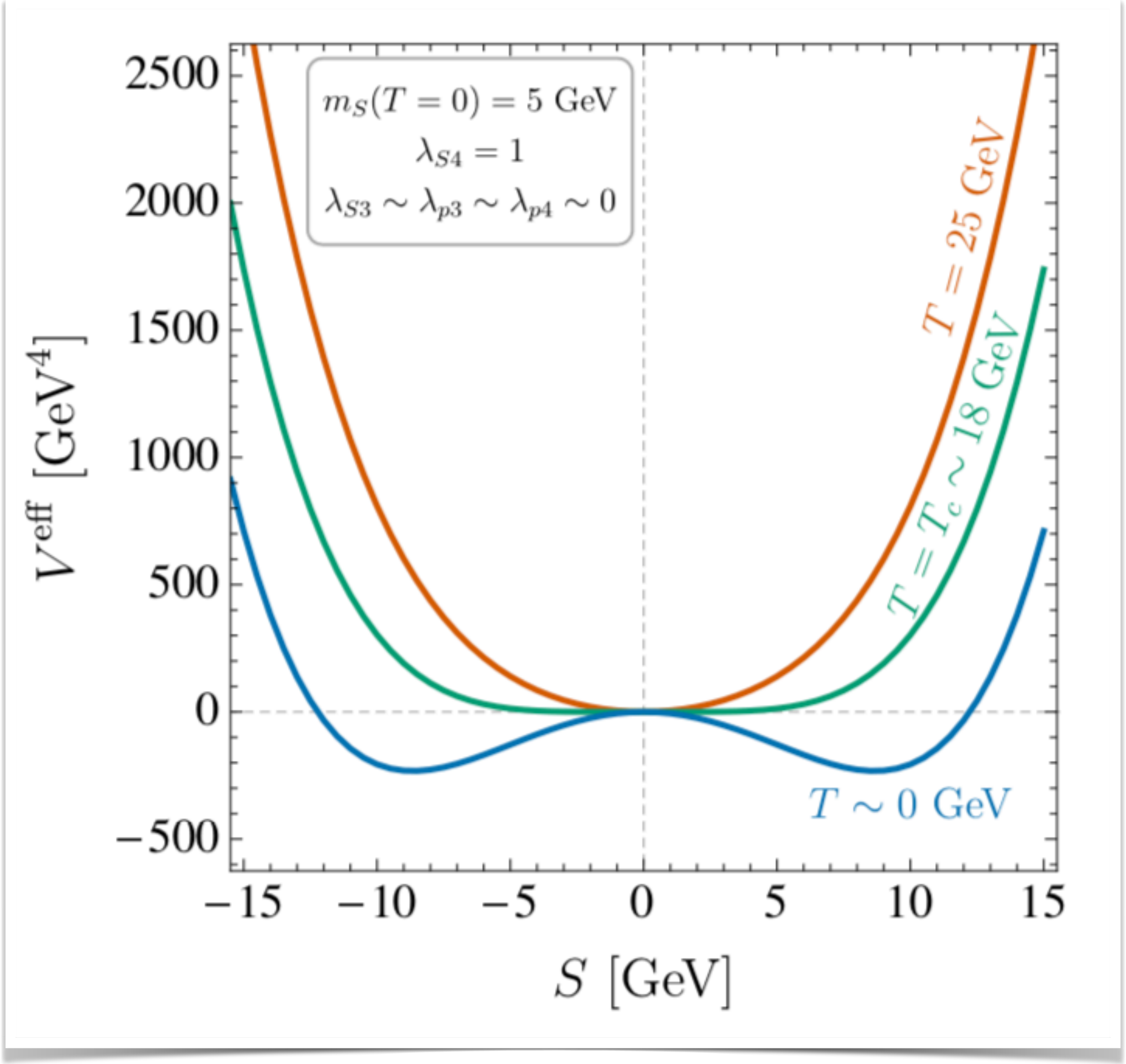
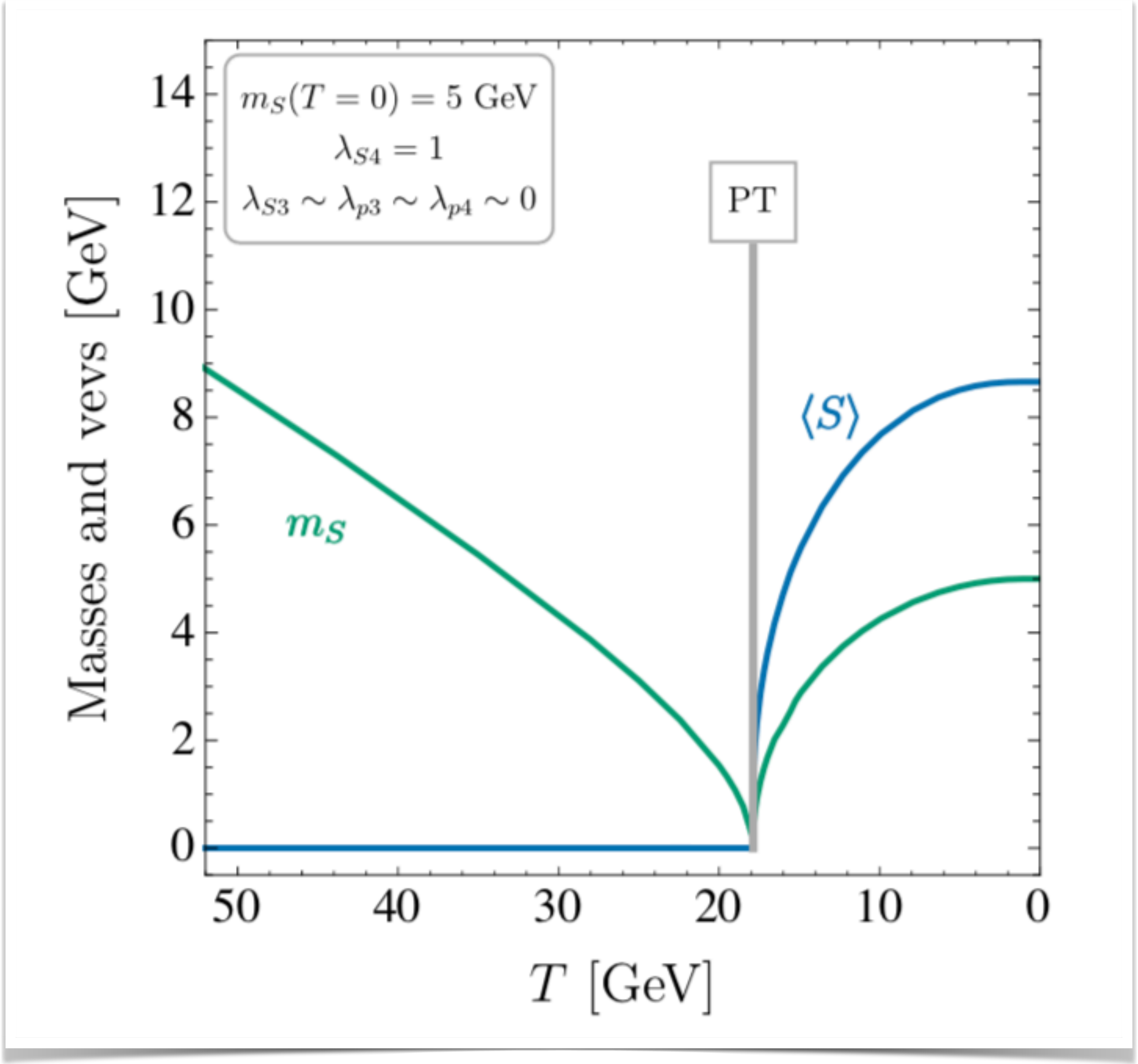
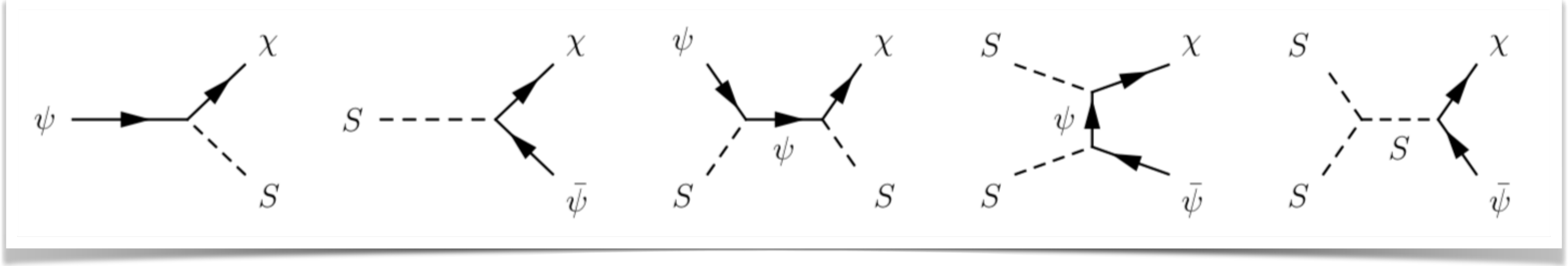
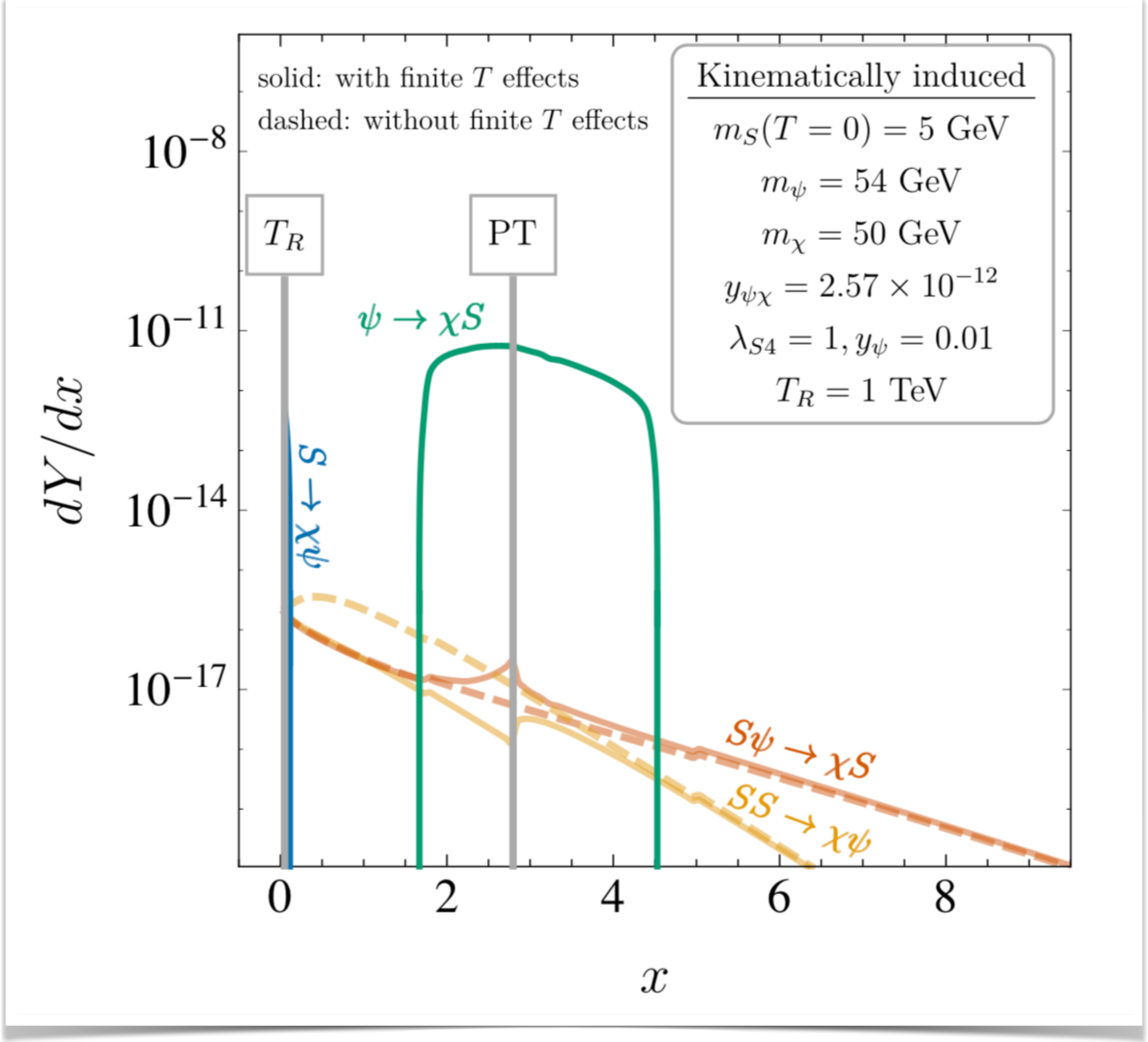
Effective Potential and Thermal Masses

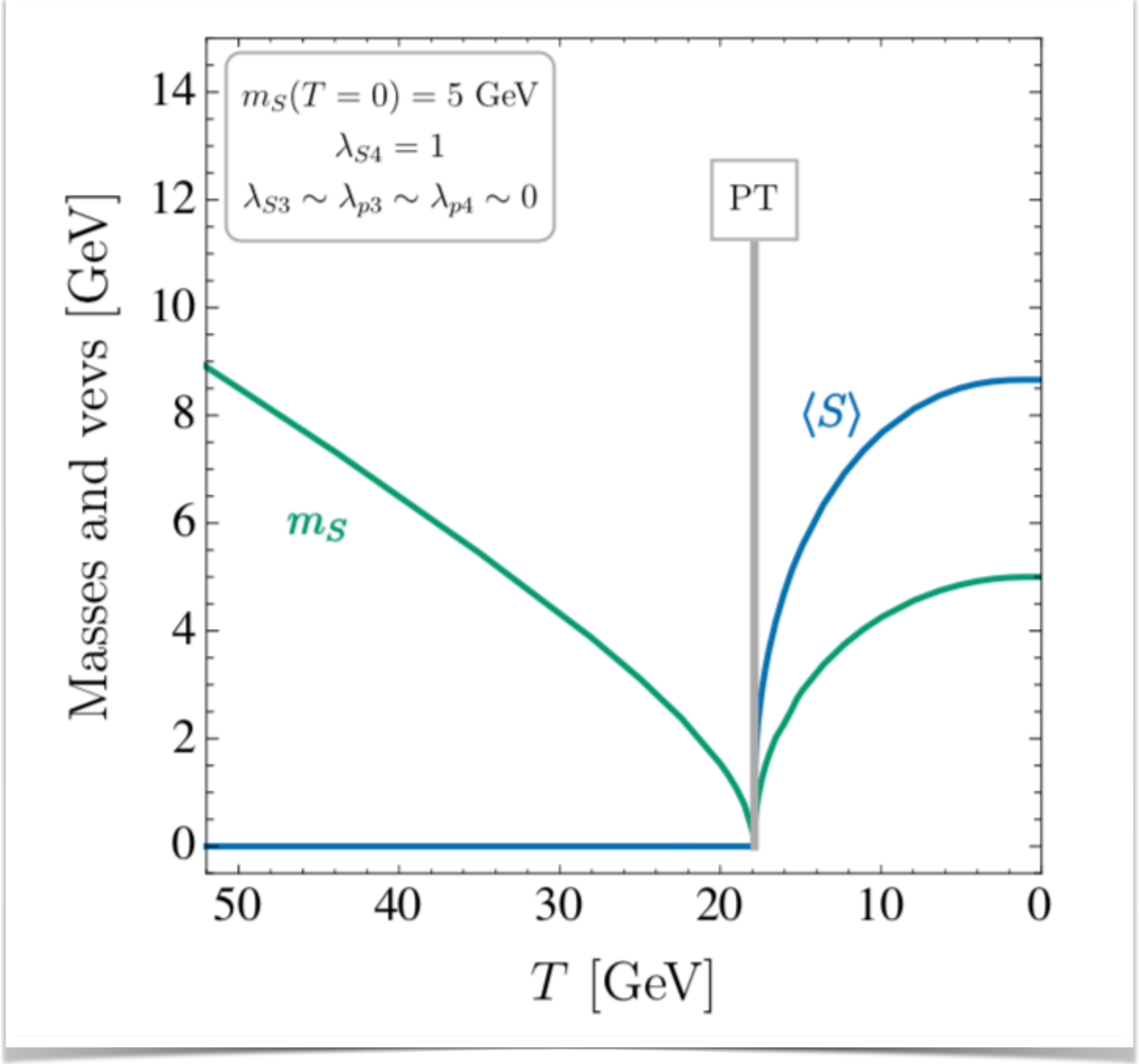




Dark Matter Freeze-In







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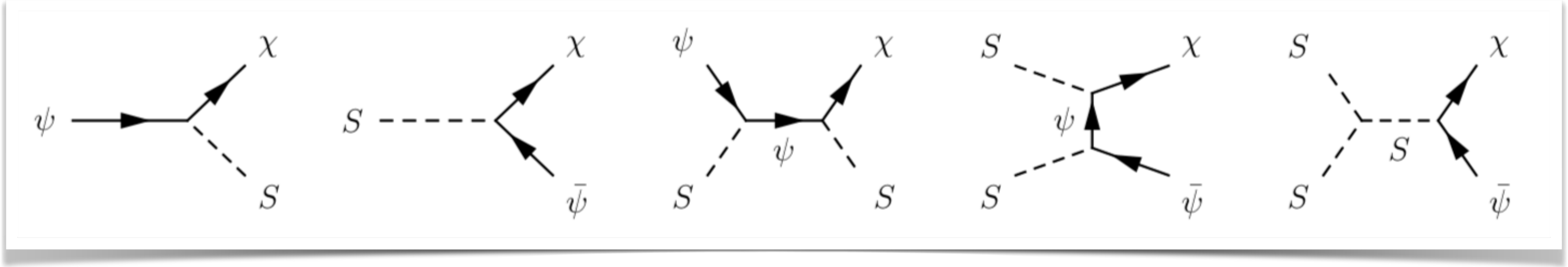
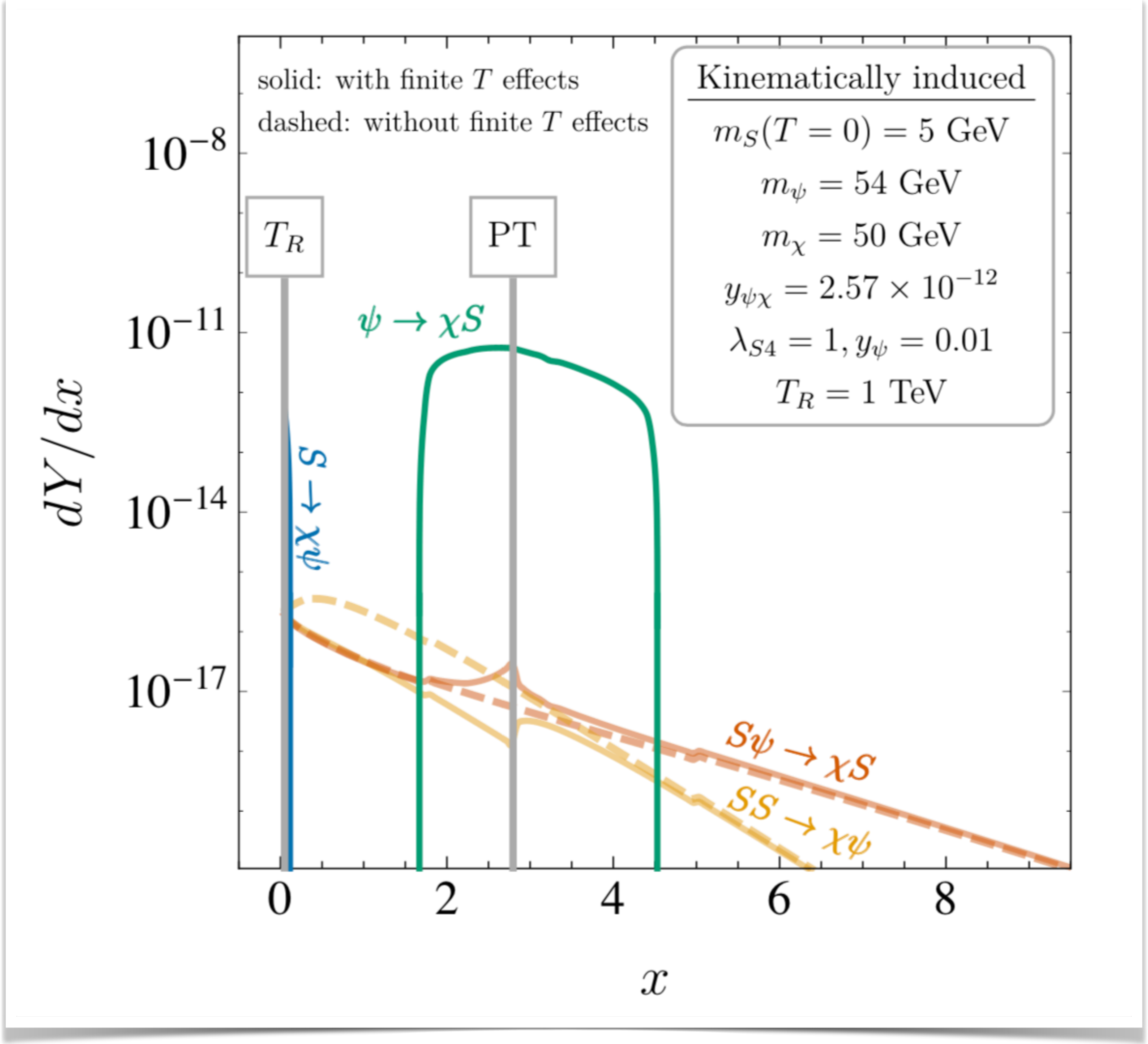
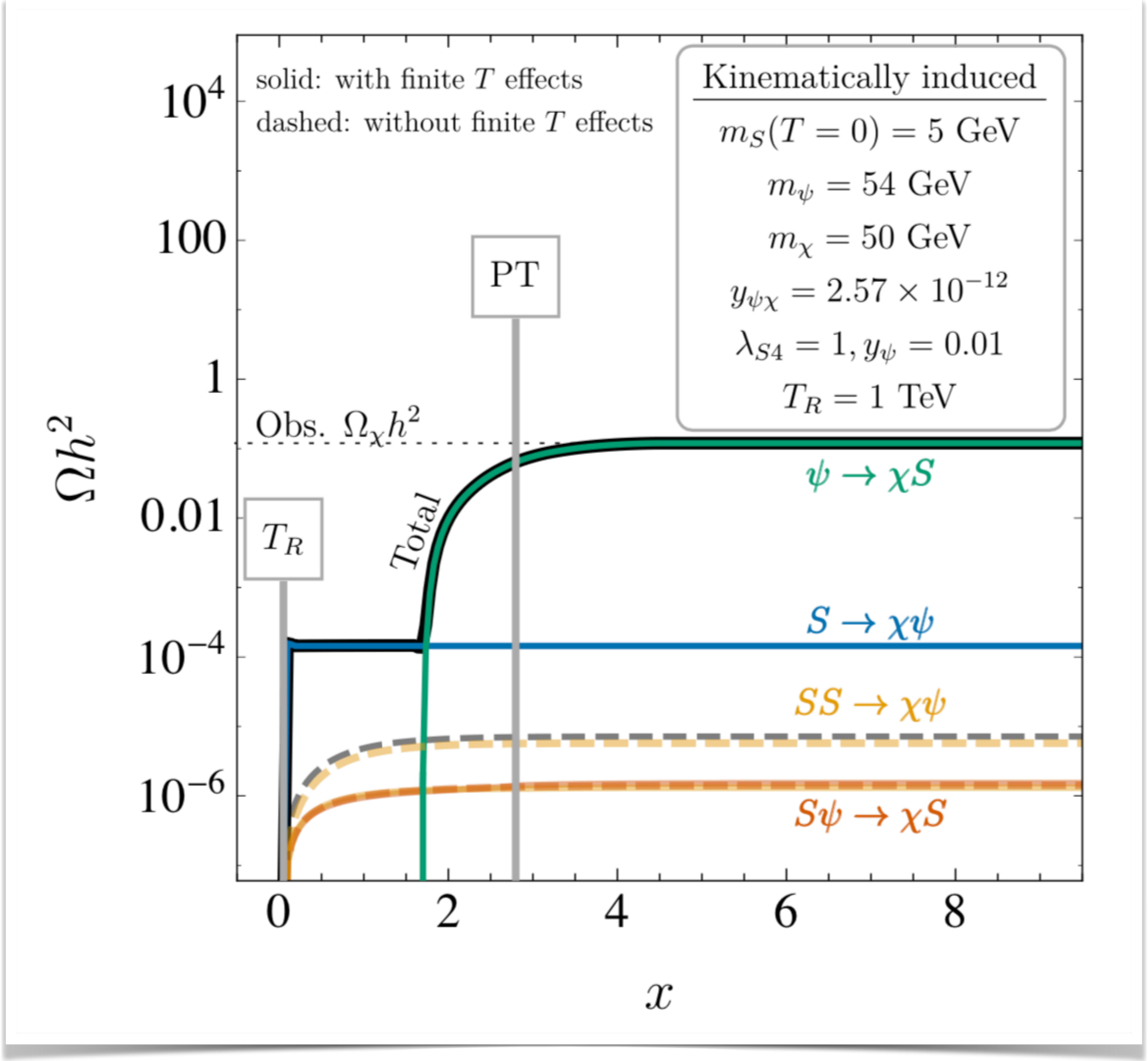


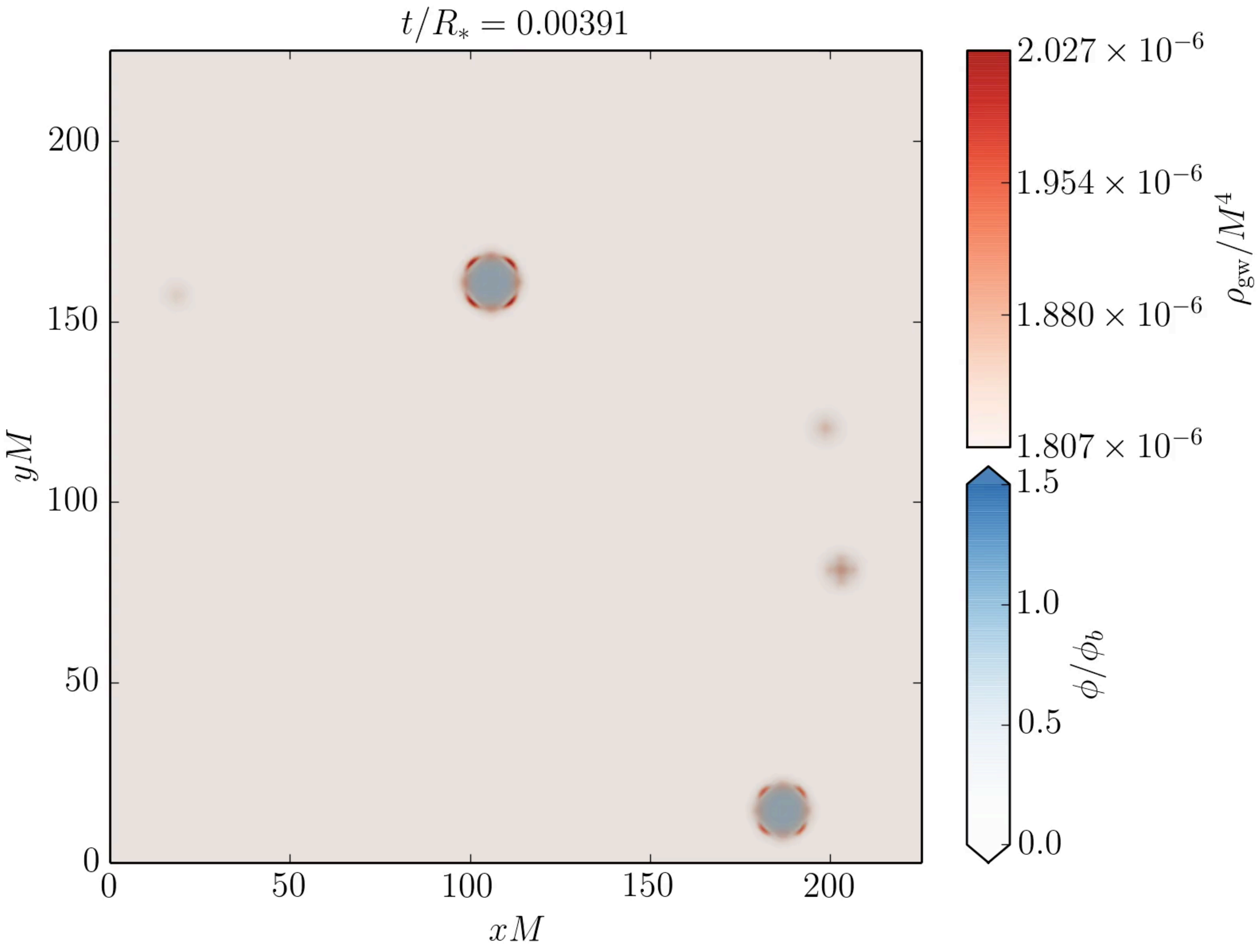




CERN Neutrino PLATFORM JG|U

Filtered Dark Matter

DM Filtering at Bubble Walls



Witten 1984, Cutting Hindmarsh Weir 2018

DM Filtering at Bubble Walls

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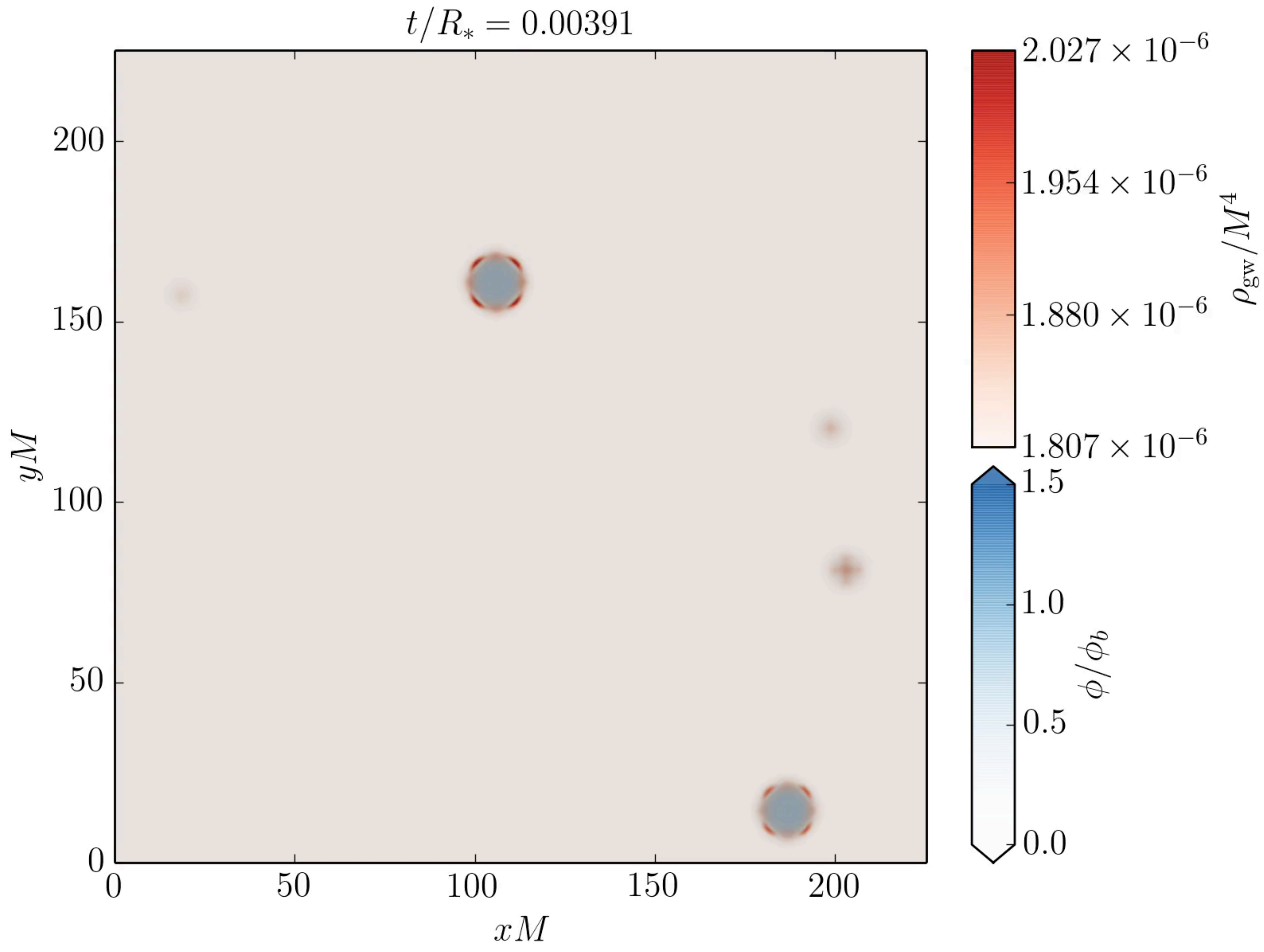

DM Decay Between Phase Transitions

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- Assume DM (χ) acquires mass during a phase transition

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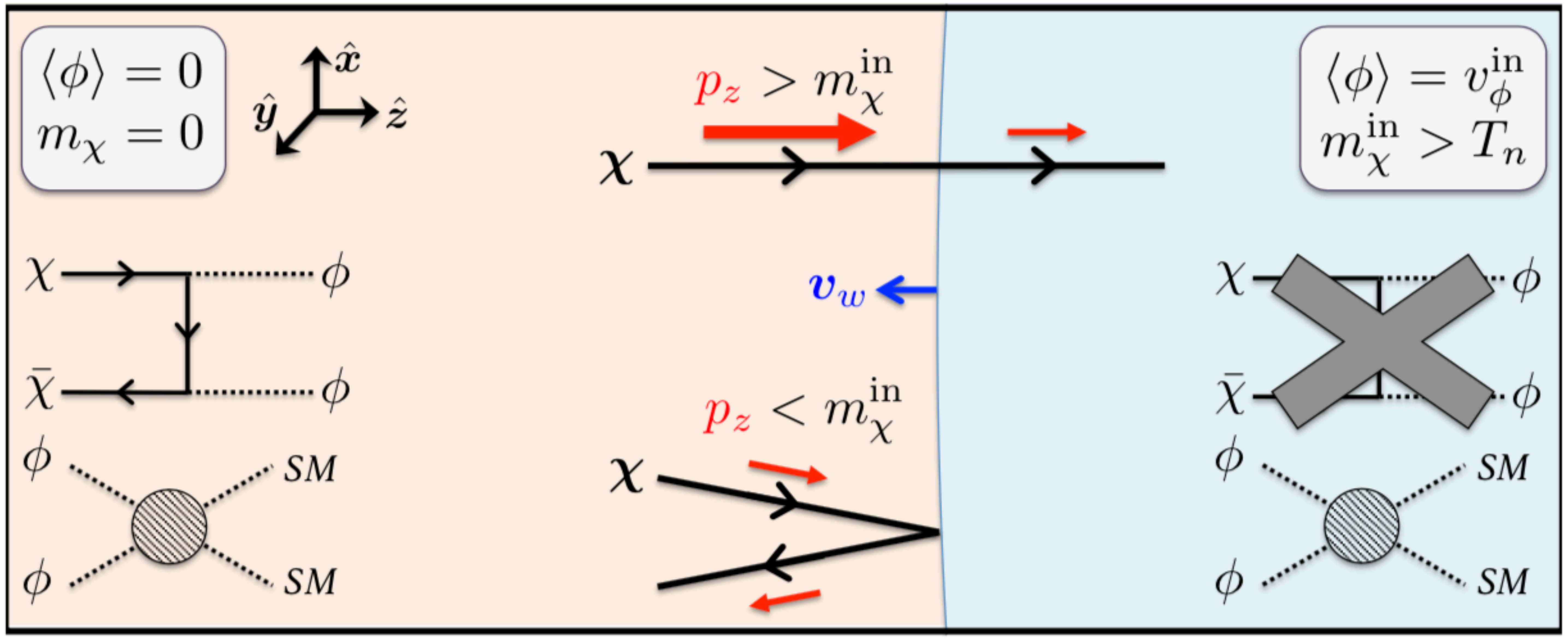

Baker JK Long, arXiv:1912.02830

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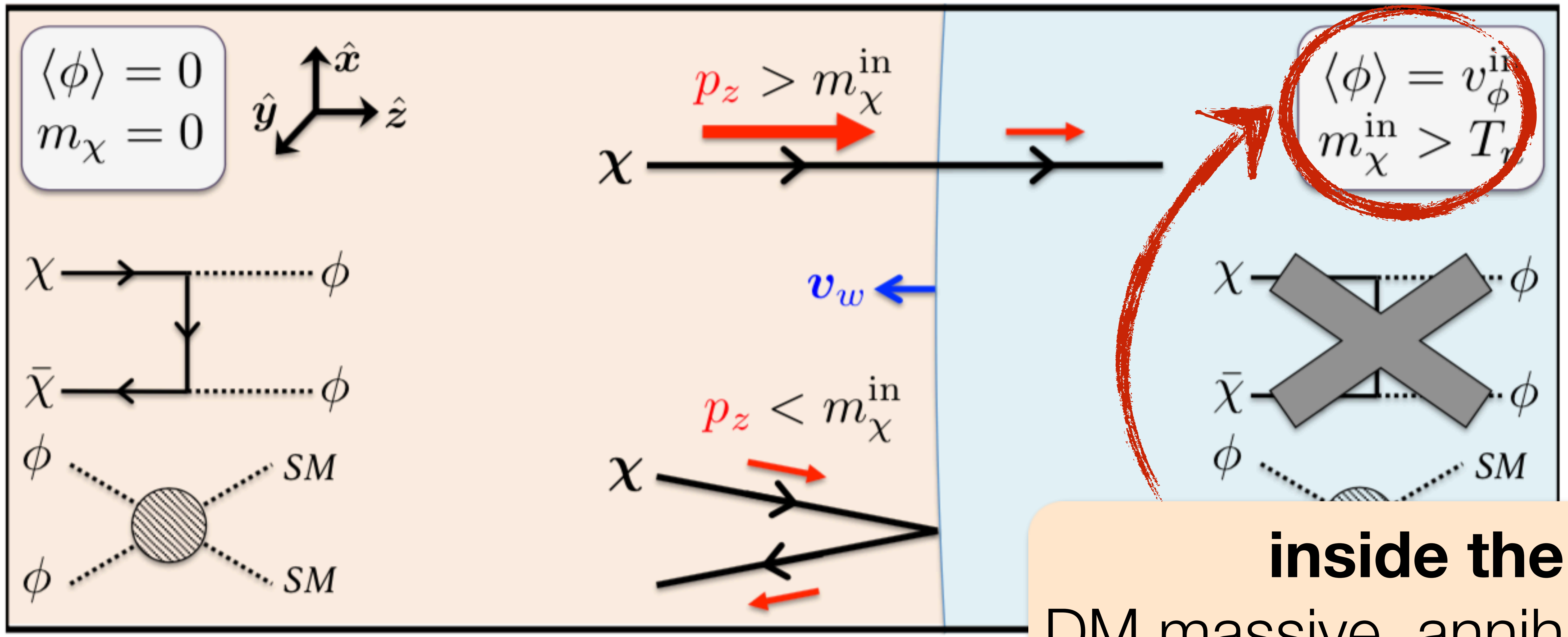

inside the bubble
DM massive, annihilation frozen out

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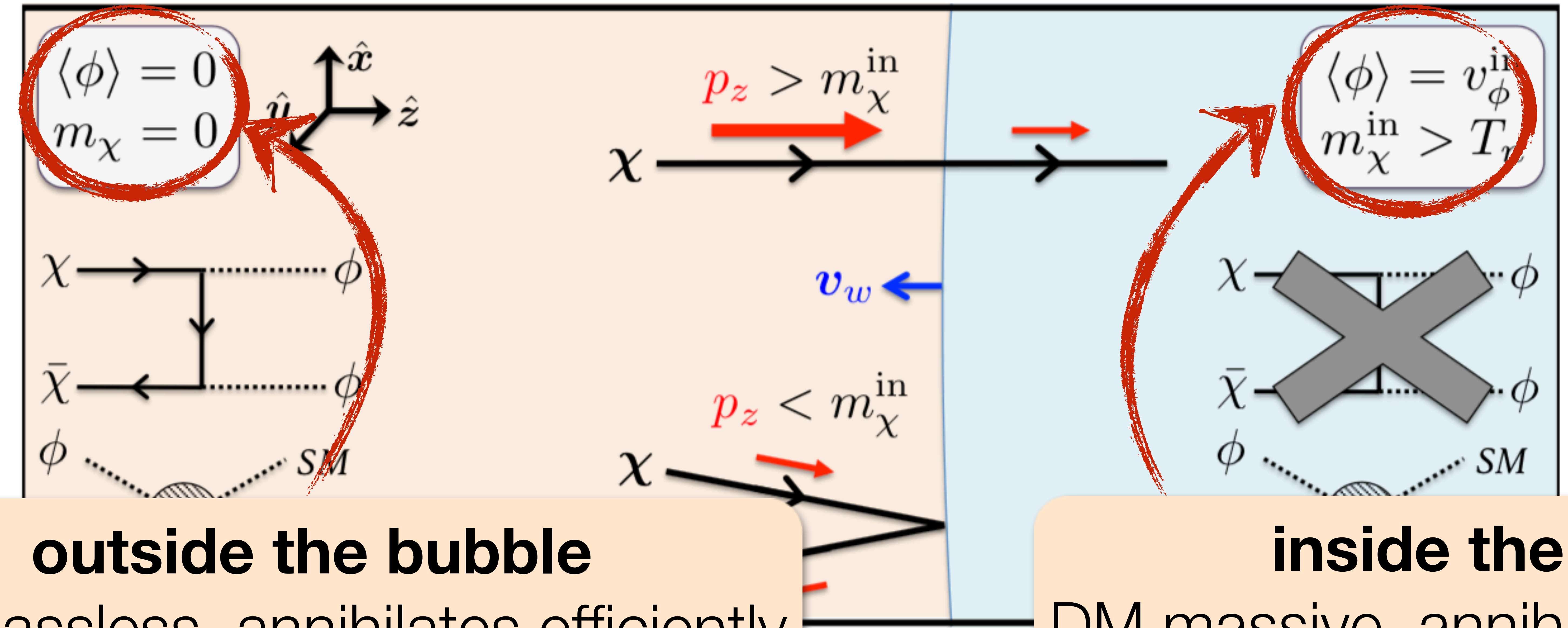

outside the bubble
DM massless, annihilates efficiently

inside the bubble
DM massive, annihilation frozen out

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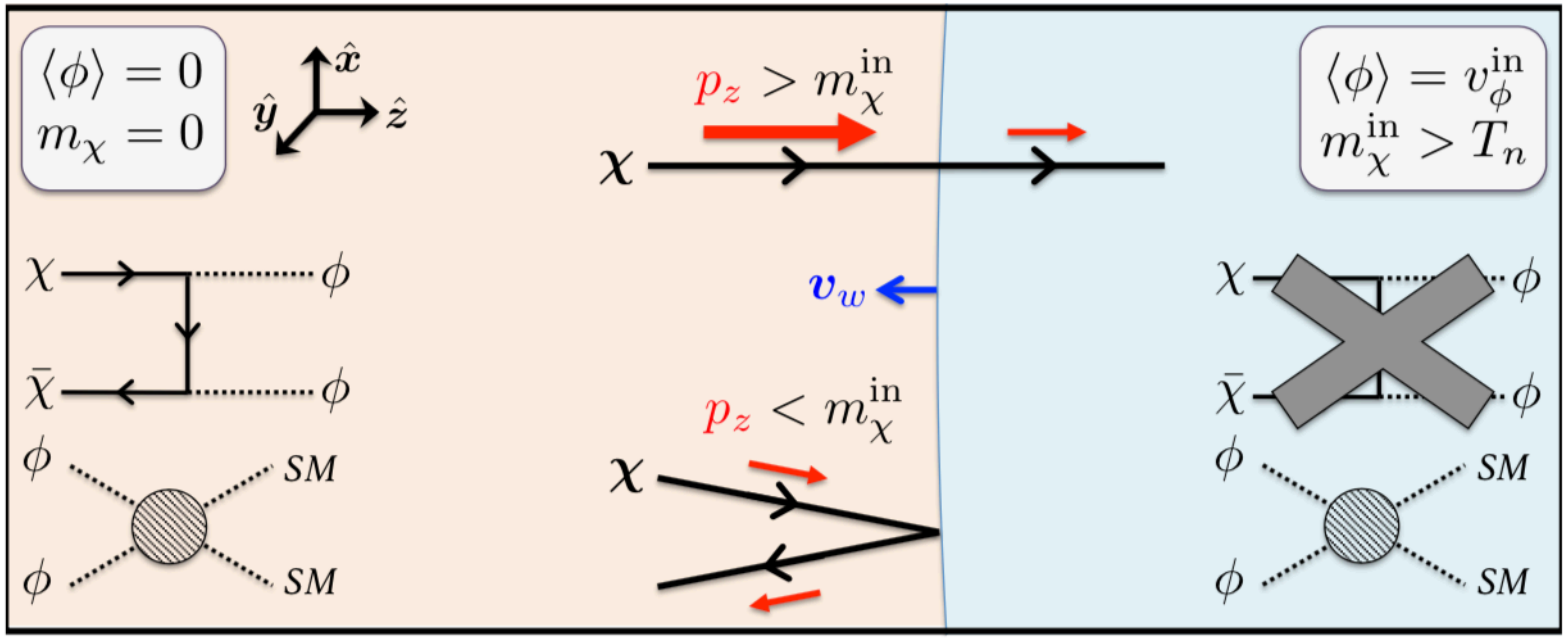

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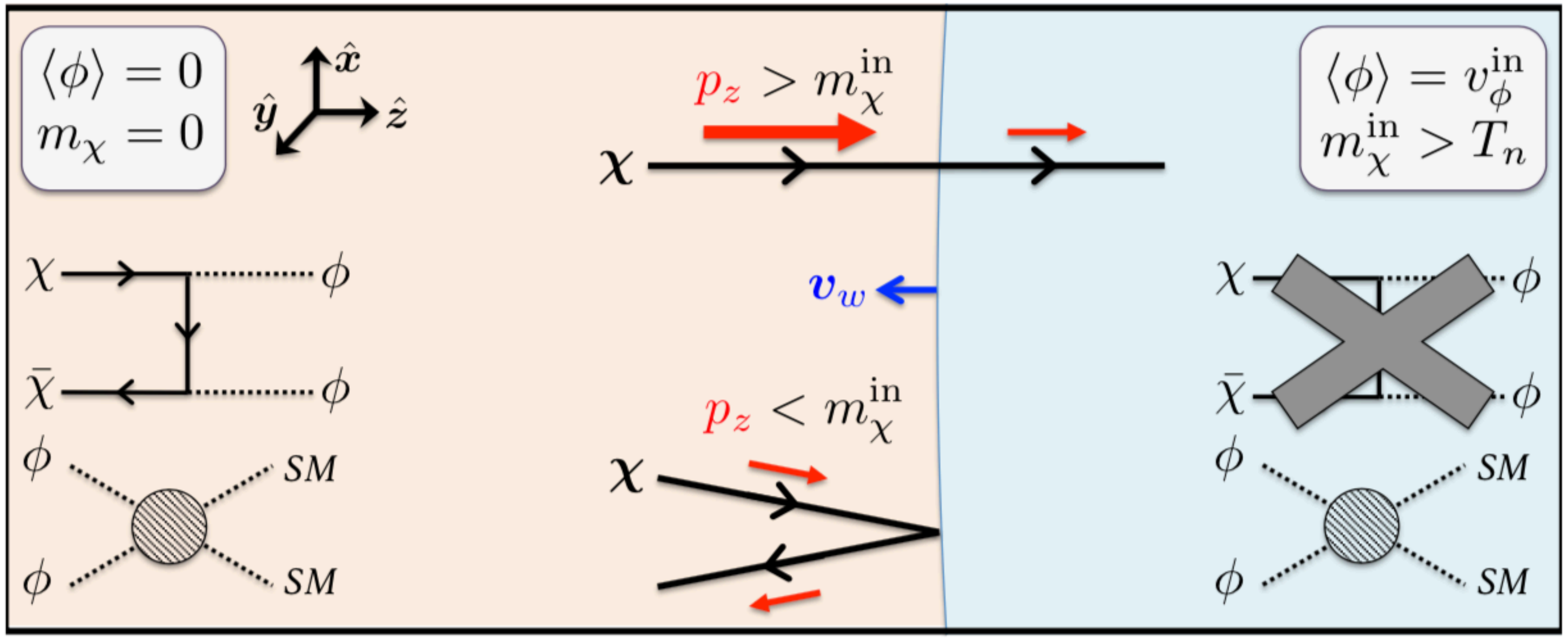

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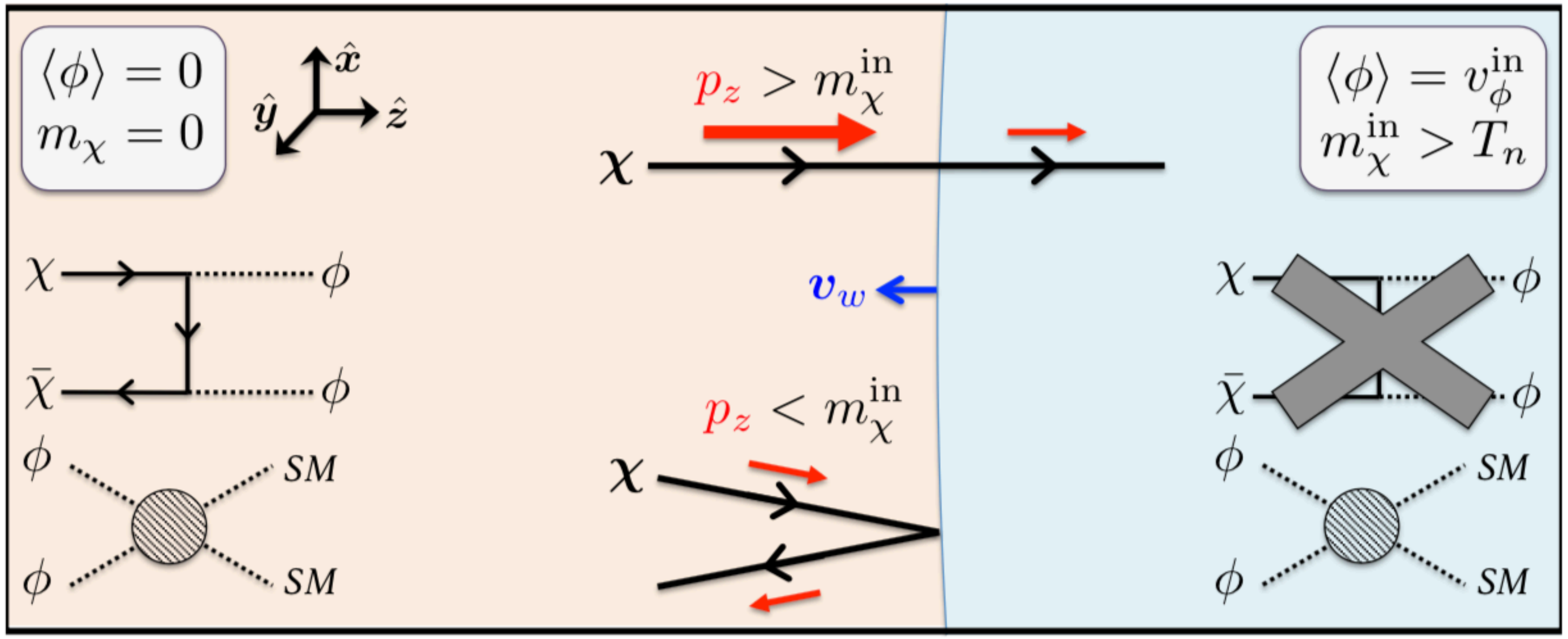

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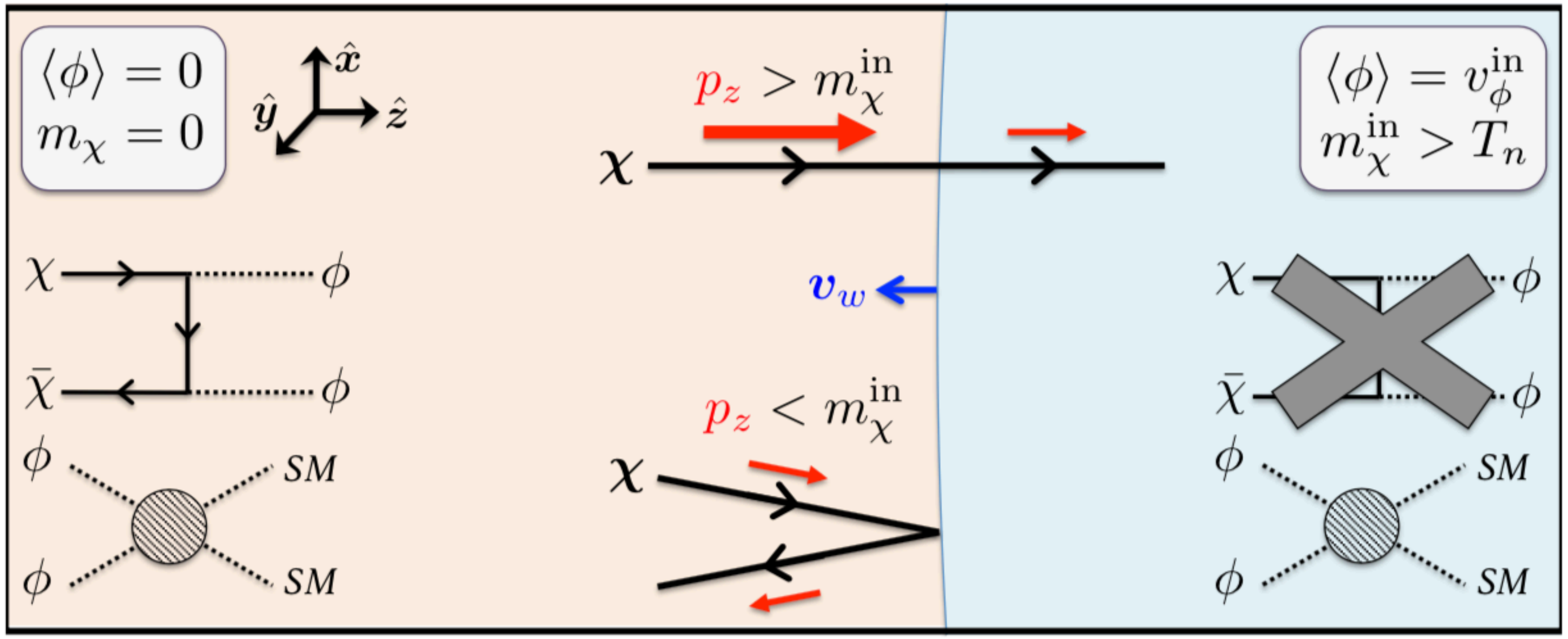
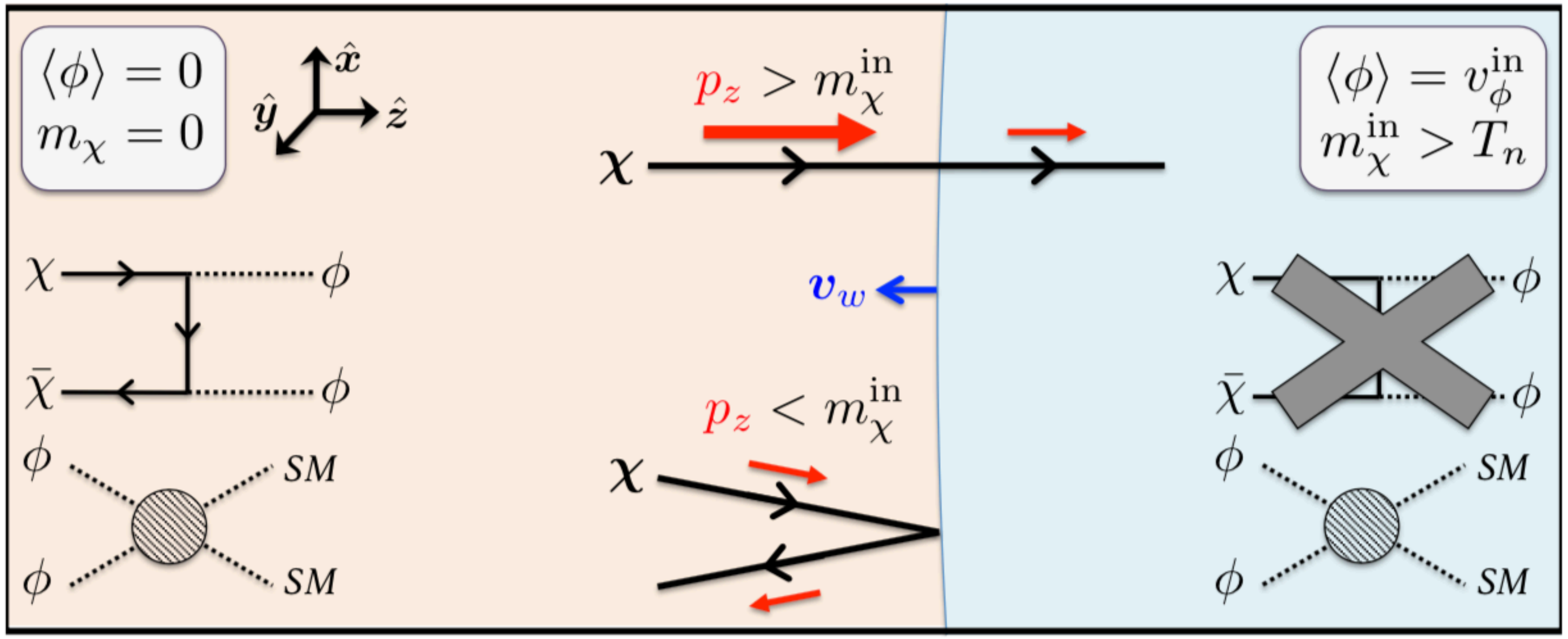


Baker JK Long, arXiv:1912.02830

- ☐ small DM abundance inside the bubble persists
- ☐ most DM particles remain outside, annihilate efficiently

DM Decay Between Phase Transitions



Baker JK Long, arXiv:1912.02830

- small DM abundance inside the bubble persists
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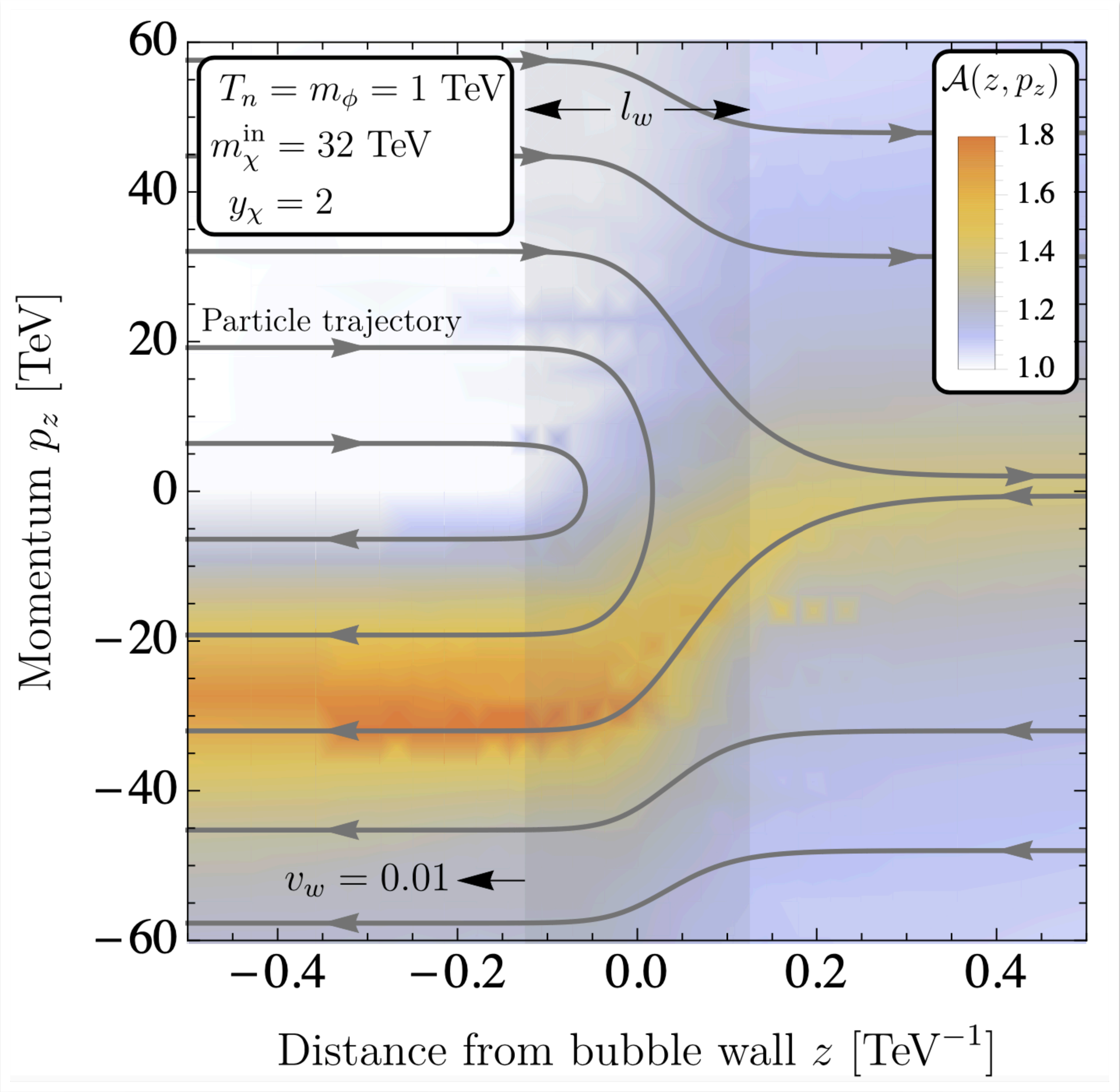
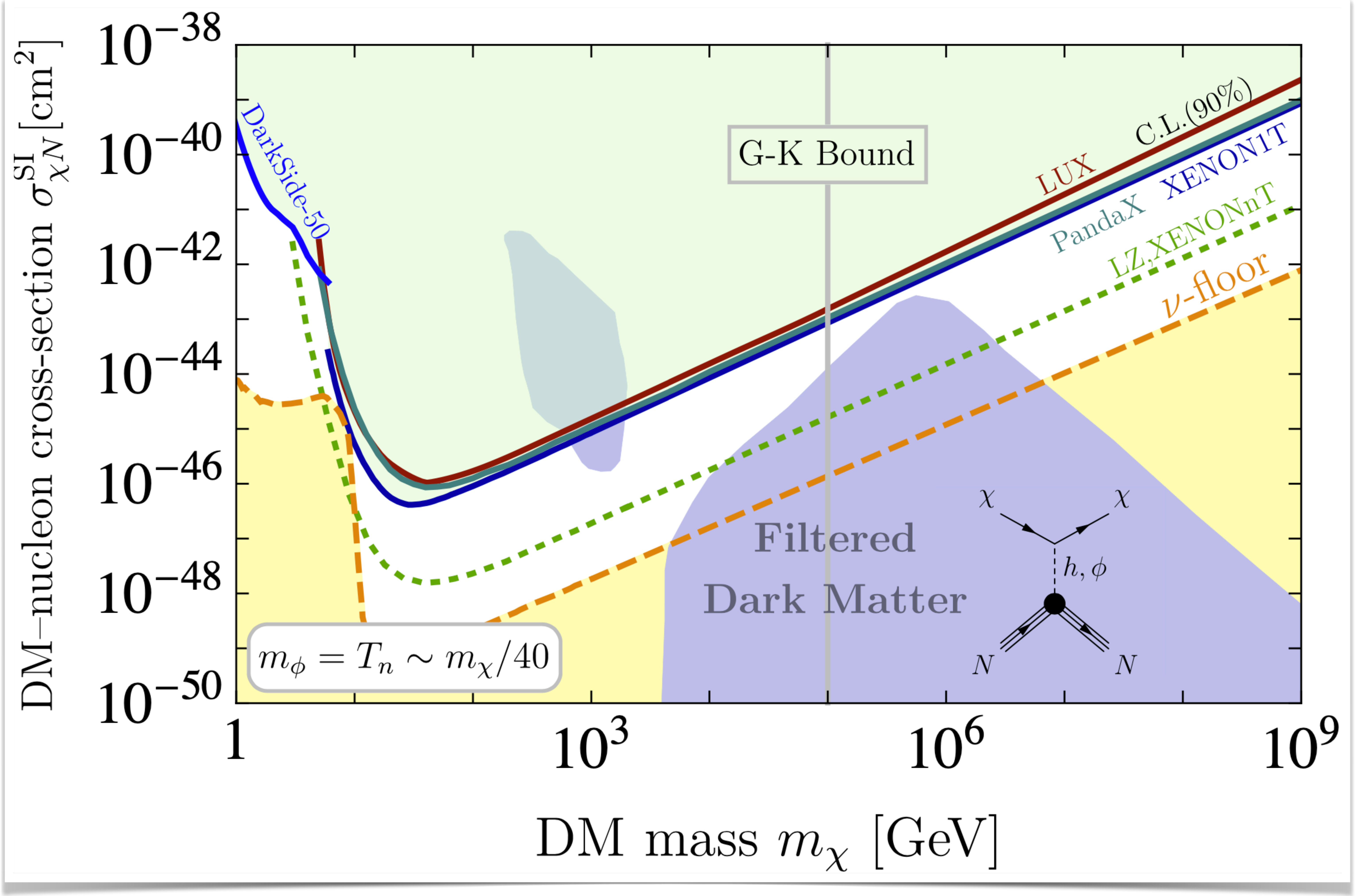
- quantitative description: Boltzmann transport equations

Dark Matter at Bubble Walls



DM Filtering at Bubble Walls



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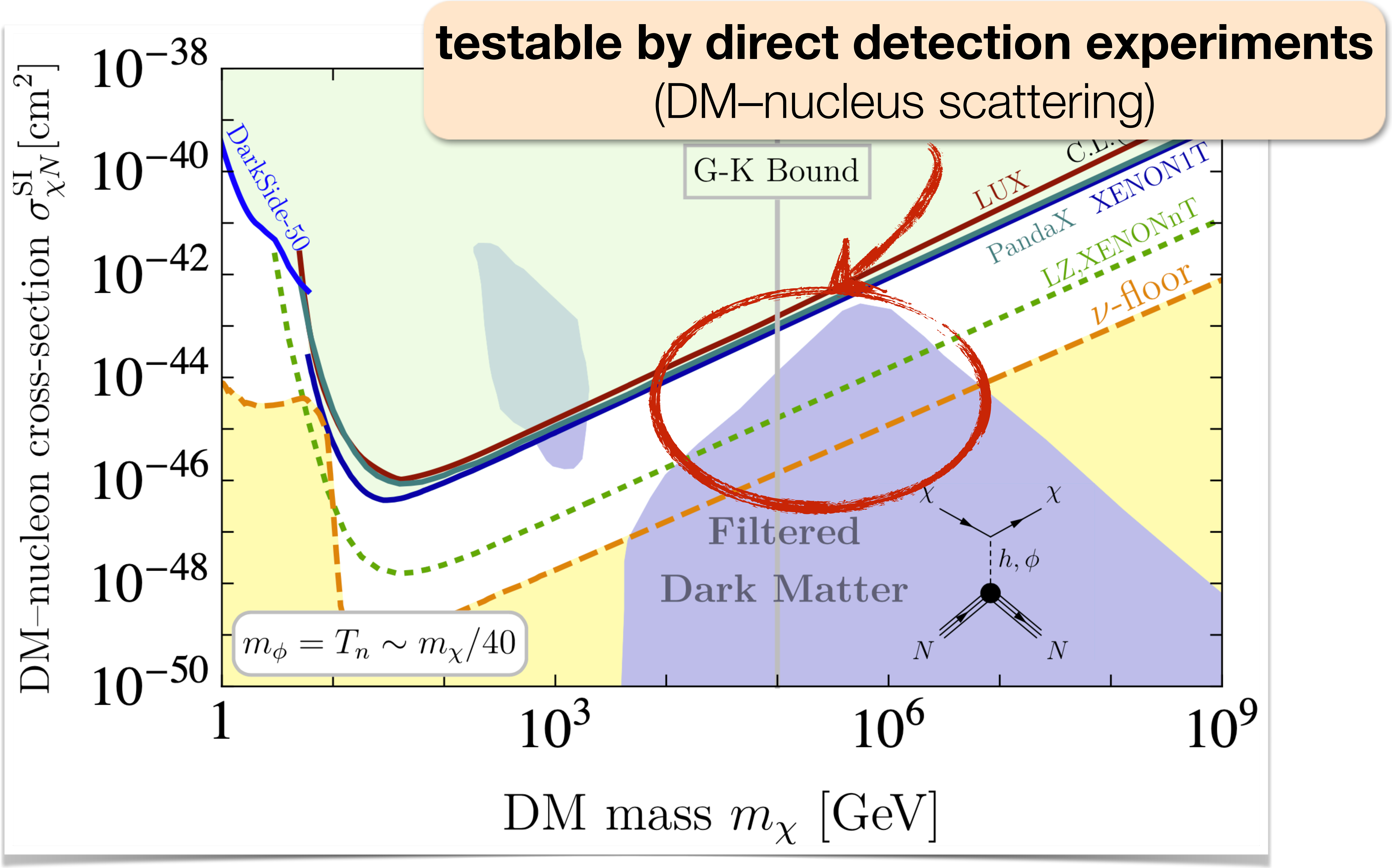

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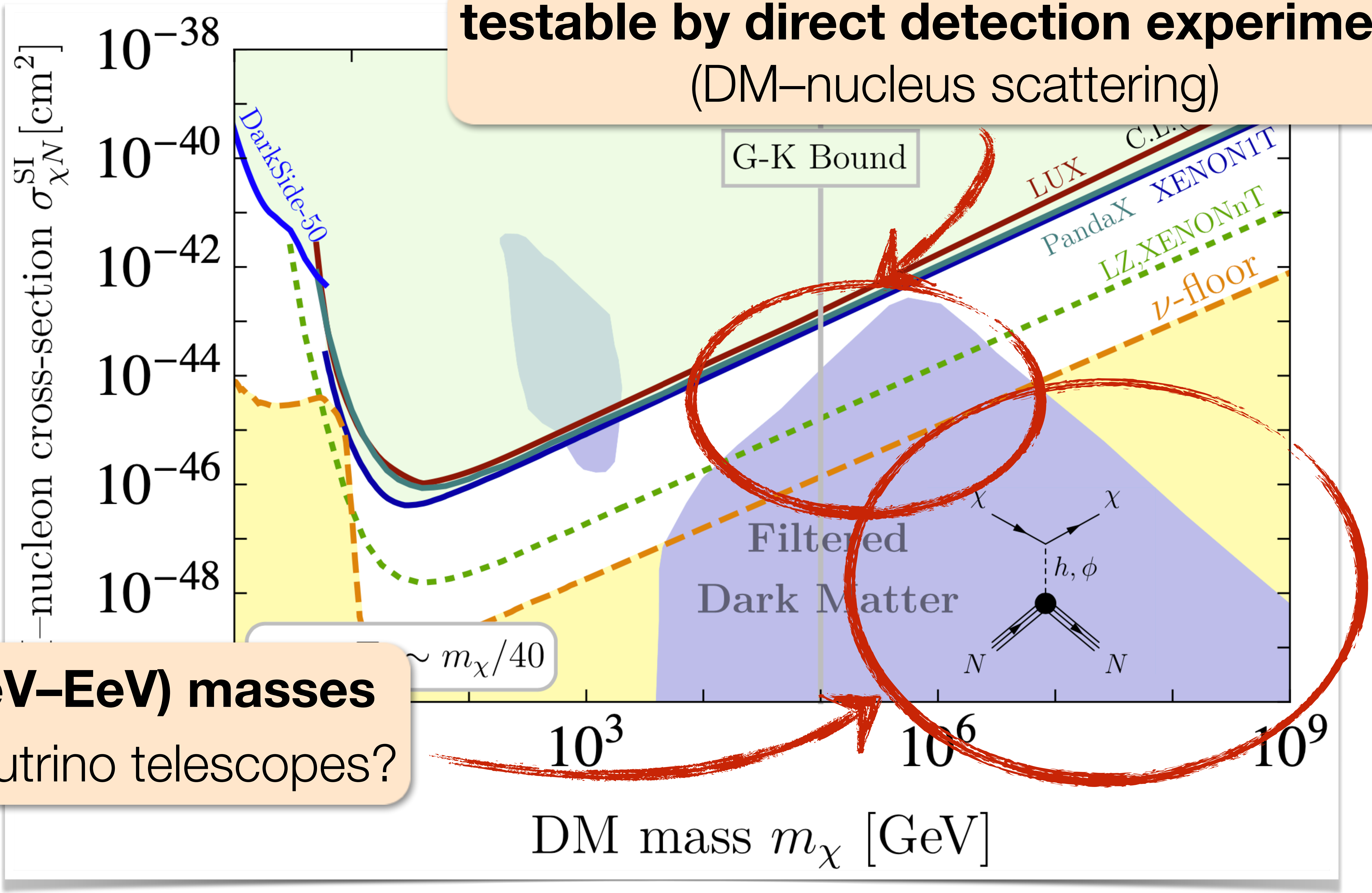


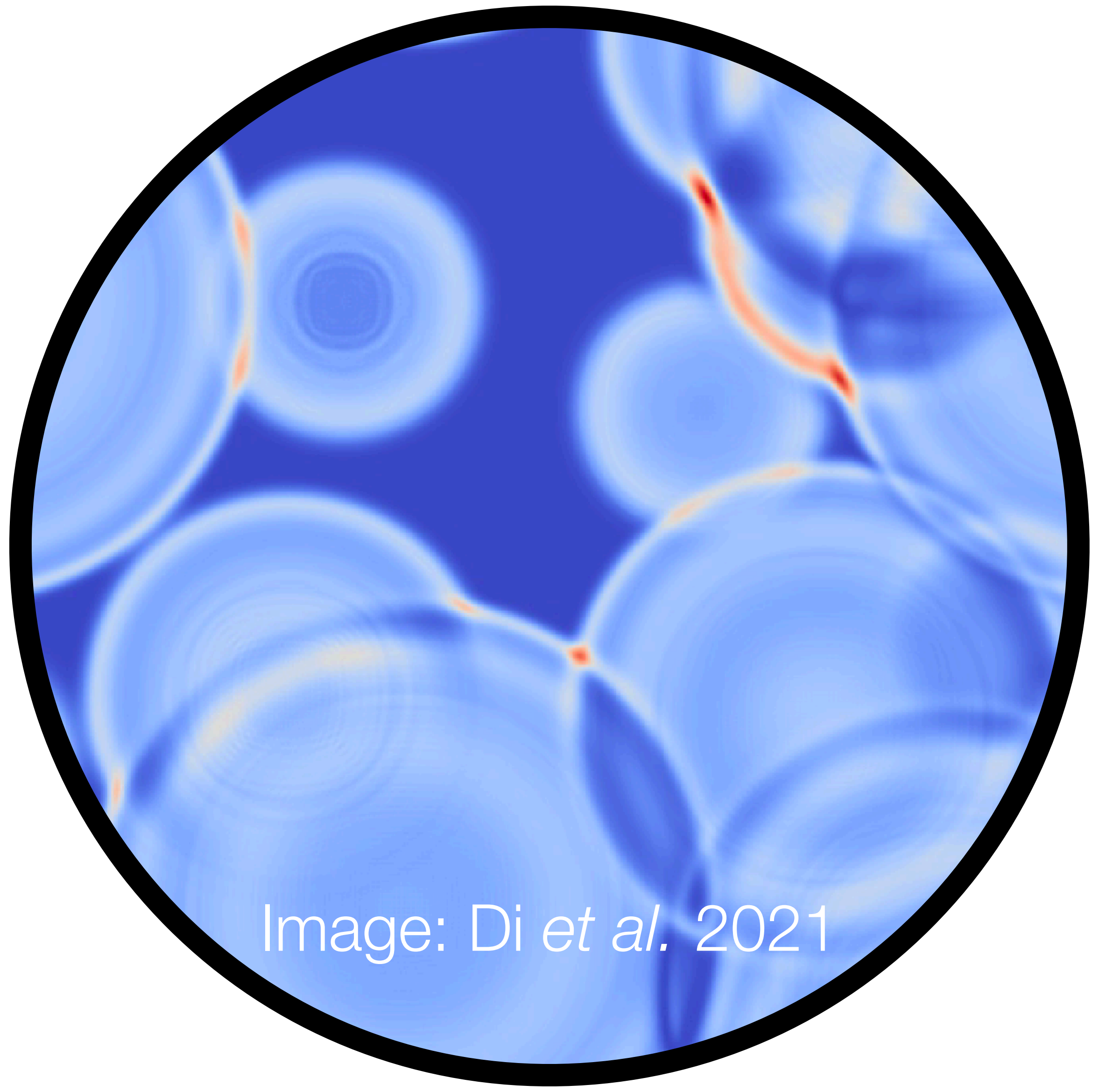
testable by direct detection experiments
(DM–nucleus scattering)

works for $\mathcal{O}$(PeV–EeV) masses
➠ searches in neutrino telescopes?

Baker JK Long, arXiv:1912.02830

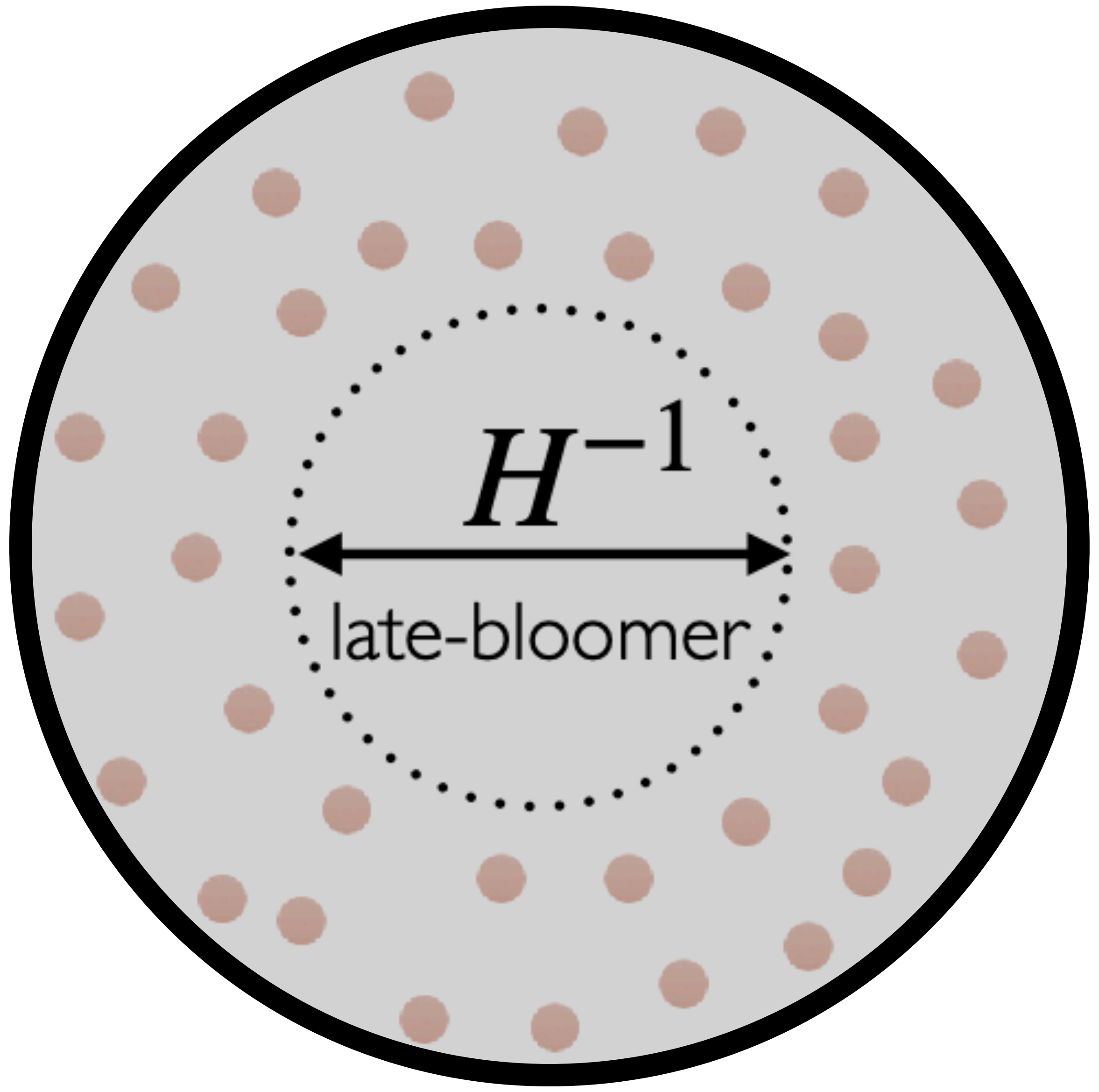
Primordial Black Holes from Phase Transitions

Primordial Black Holes From Phase Transitions



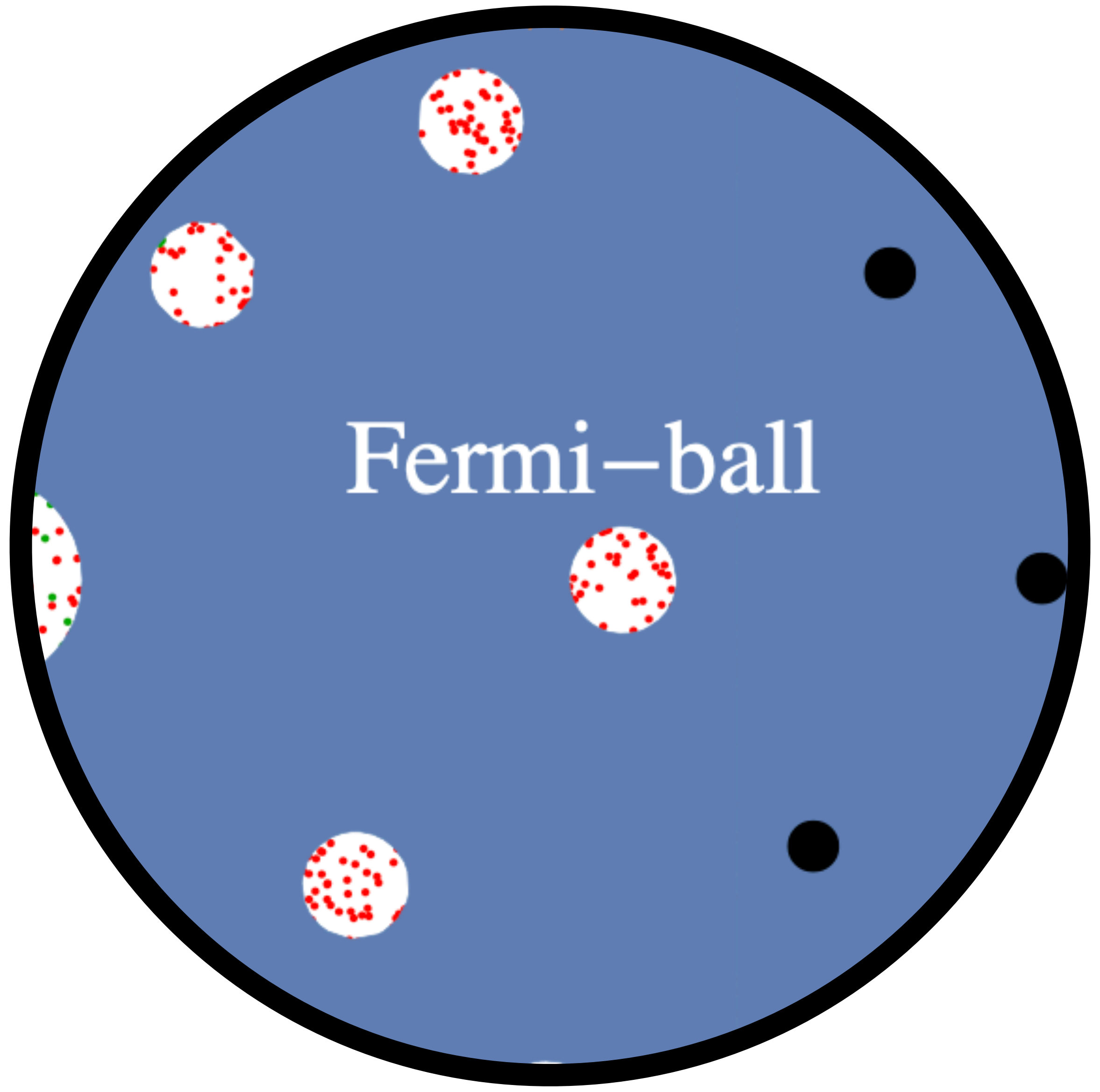
bubble wall collisions

Hawking Moss Stuart 1982
Moss 1994



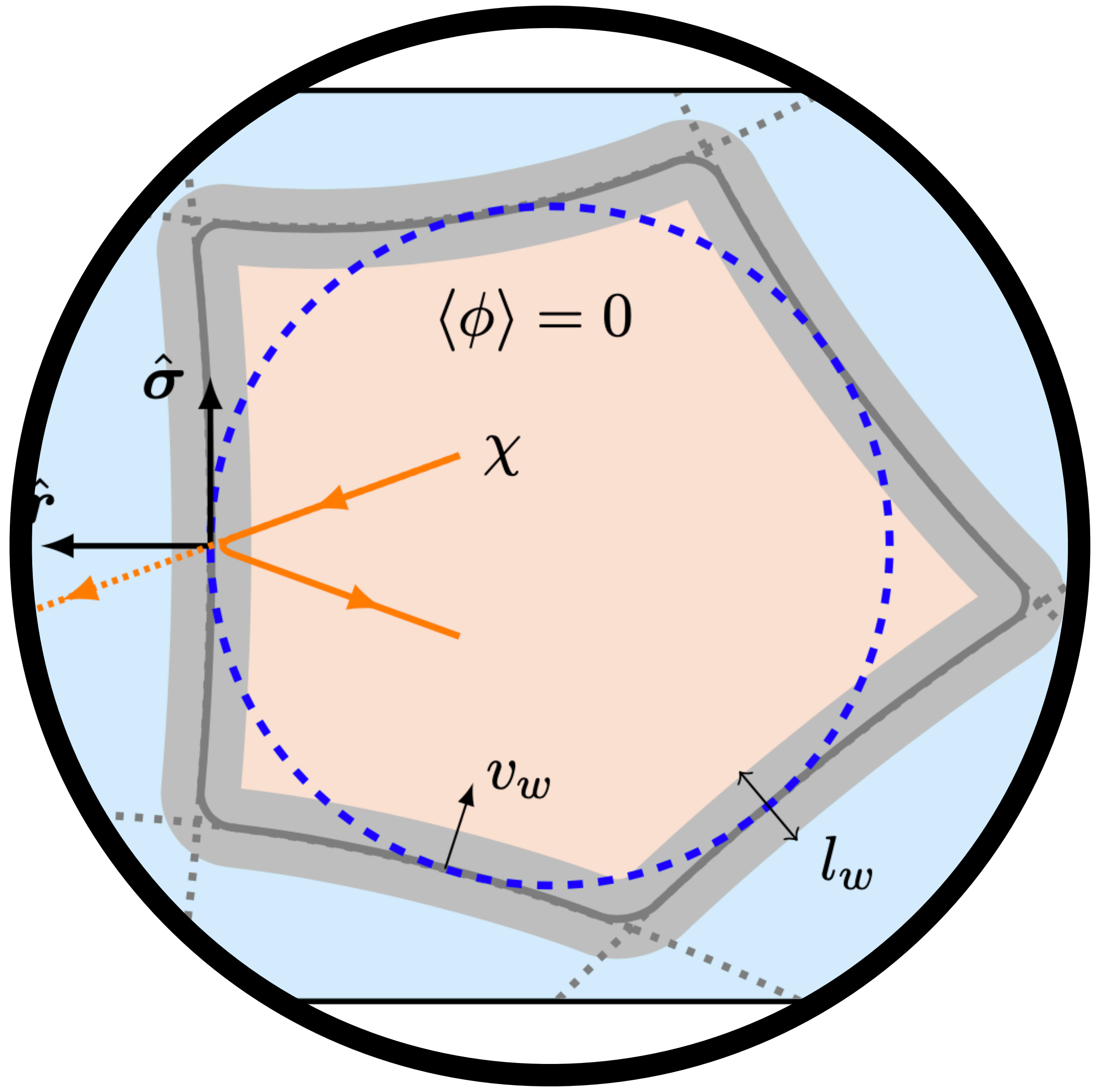
collapse of inflating false-vacuum pockets

Sato Sasaki Kodama Maeda 1981
Gouttenoire Volansky 2305.04942



collapse of Fermi balls

Gross *et al.* 2105.02840
Kawana XIe 2106.00111
Huang Xie 2201.07243

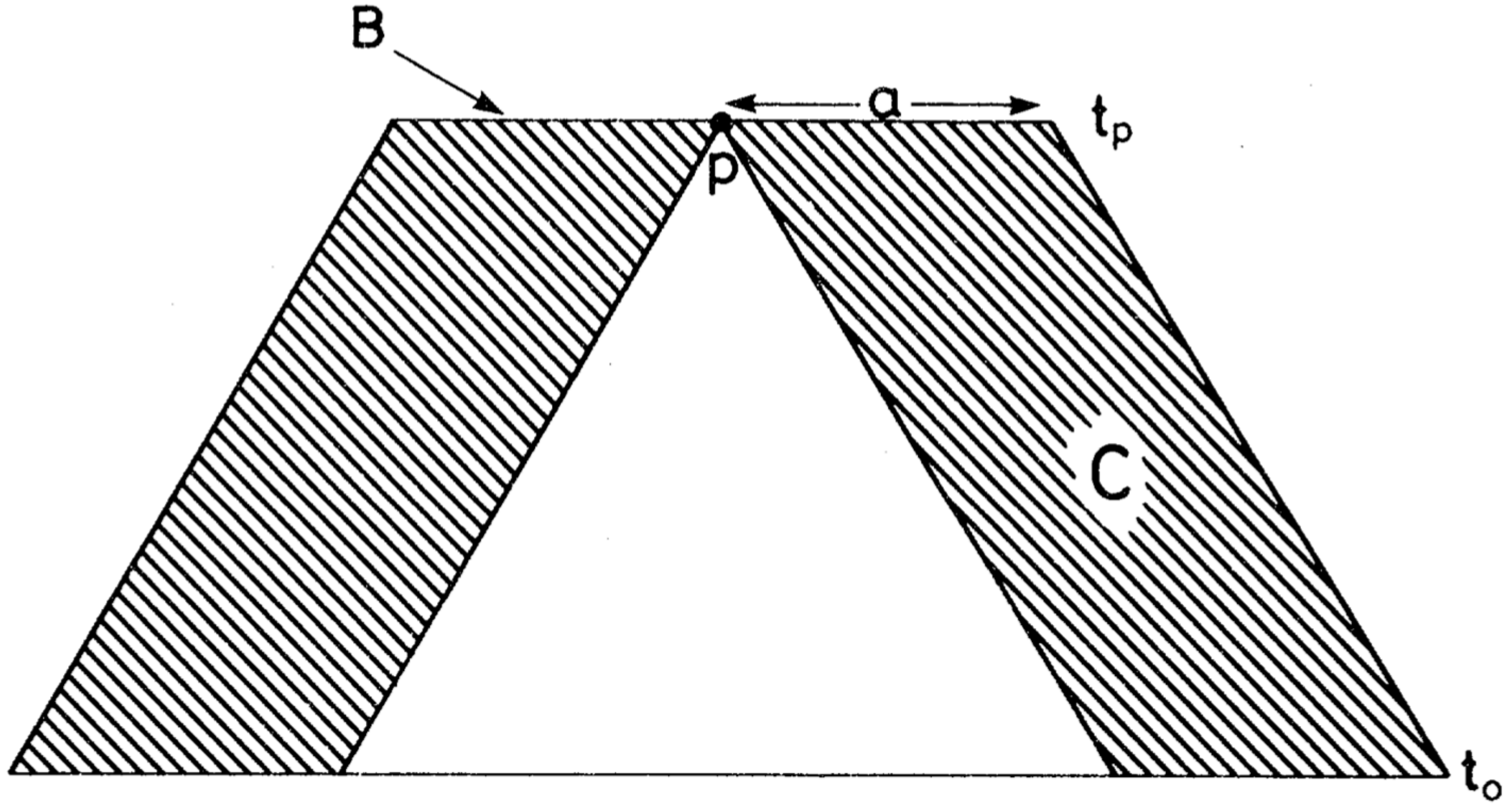


compression followed by direct collapse

Breitbach *et al.*
2105.07481, 2110.00005

#1: Bubble Wall Collisions

B = spherical region of radius *a*



Hawking Moss Stuart 1982
Moss 1994

- ☐ assume Universe initially inflating
- ☐ probability for no nucleation in past light cone of *p:*

$$e^{-4\pi N H^{-3}(t_p - t_0)/3}$$

- ☐ surface energy density of bubble wall arriving at *p*

$$\gamma\sigma = \tfrac{1}{3}\epsilon^4 H^{-1} = \frac{m_P{}^2}{8\pi} H$$

- ☐ for *n* bubbles, energy density within B is

$$\tfrac{1}{8} n a^2 H m_P{}^2$$

- ☐ require this to be $> a M_P^2/2$

#1: Bubble Wall Collisions

nucleation rate per unit volume

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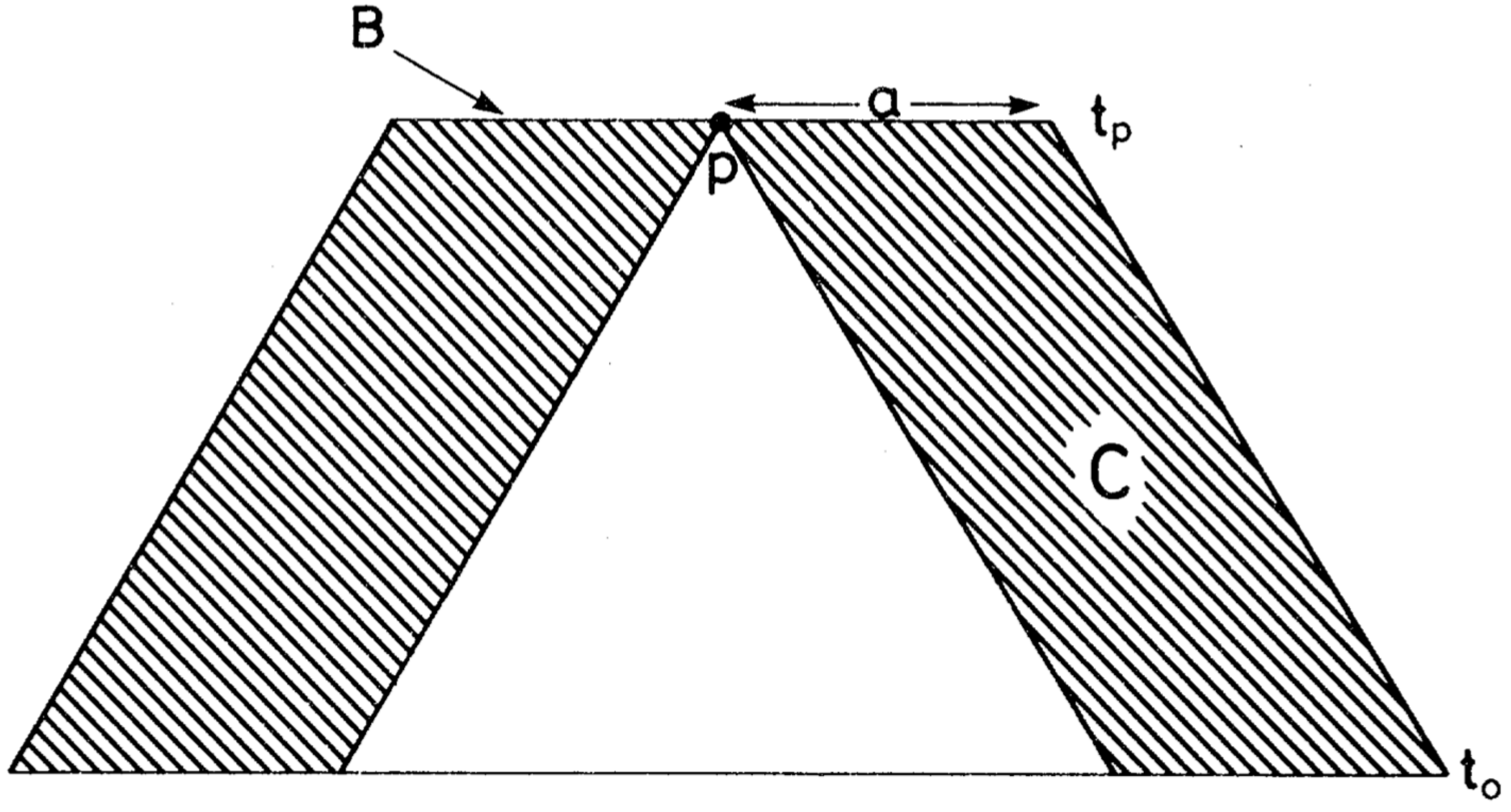

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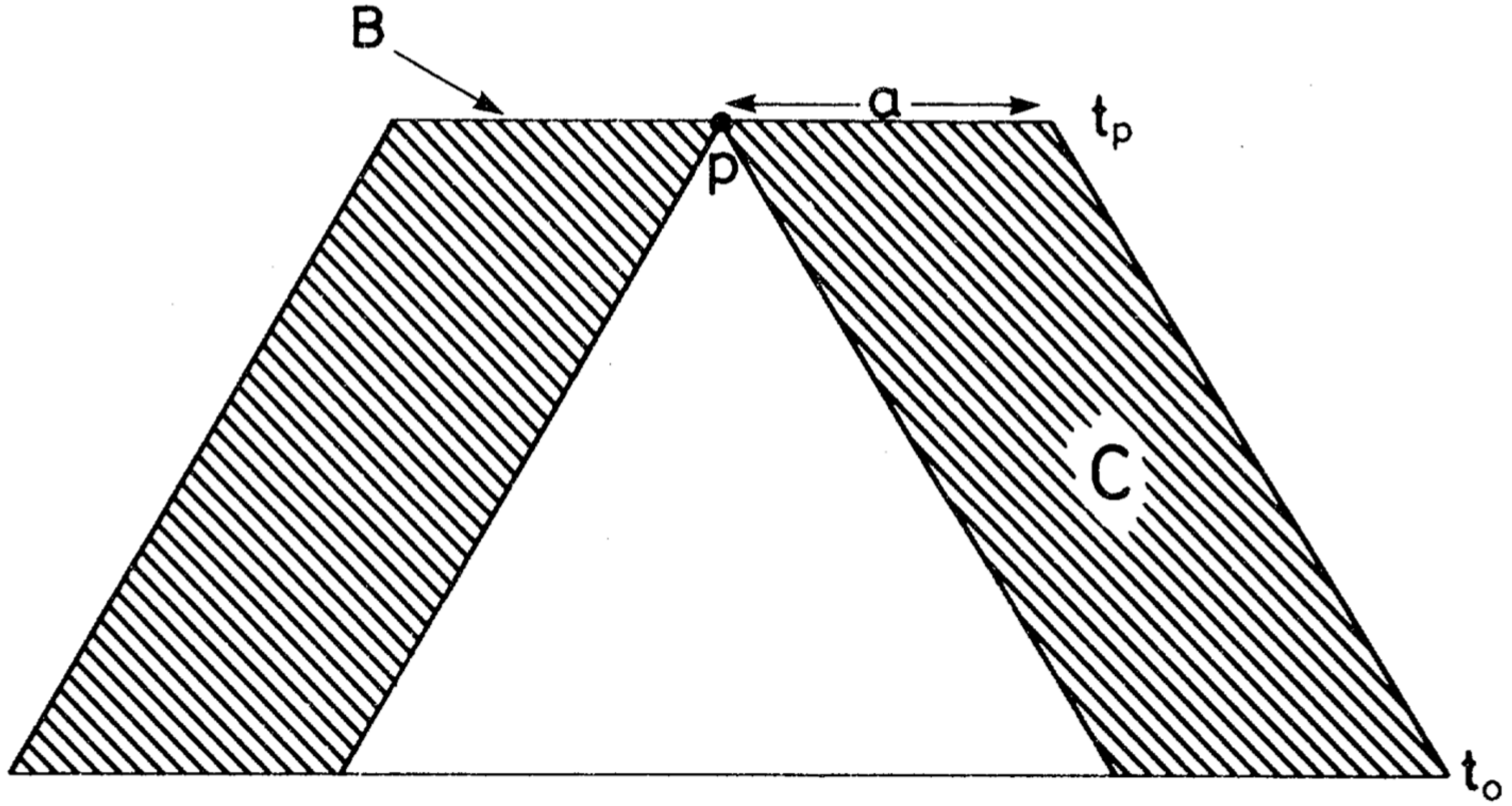

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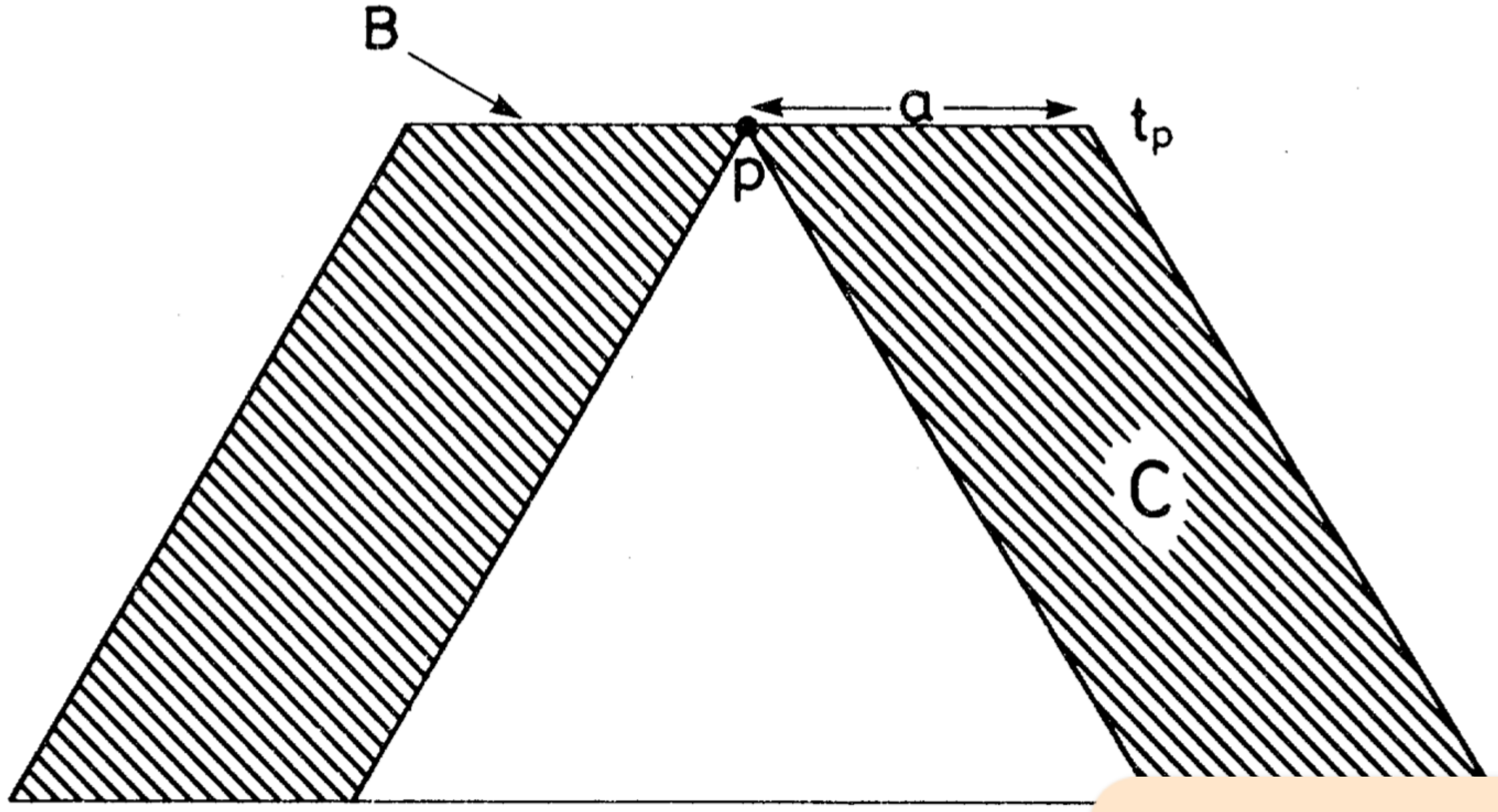

latent heat release

Hawking Moss Stuart 1982
Moss 1994

- assume Universe initially inflating
- probability for no nucleation in past light cone of *p*:

$$e^{-4\pi N H^{-3}(t_p - t_0)/3}$$

- surface energy density of bubble wall arriving at *p*

$$\gamma\sigma = \tfrac{1}{4}\epsilon^4 H^{-1} = \frac{m_P{}^2}{8\pi} H$$

- for *n* bubbles, energy density within B is

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- require this to be $> a M_P^2/2$

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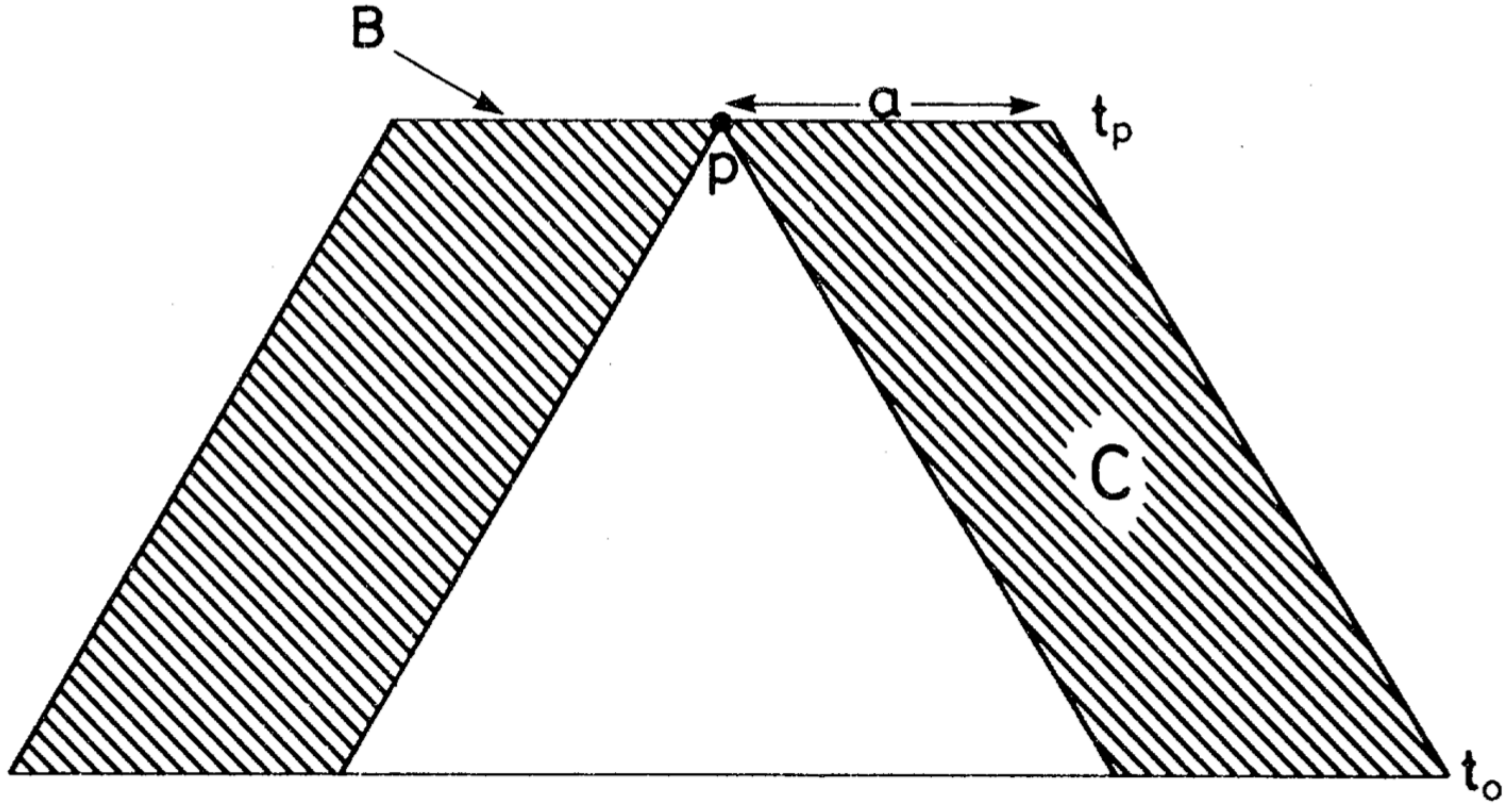

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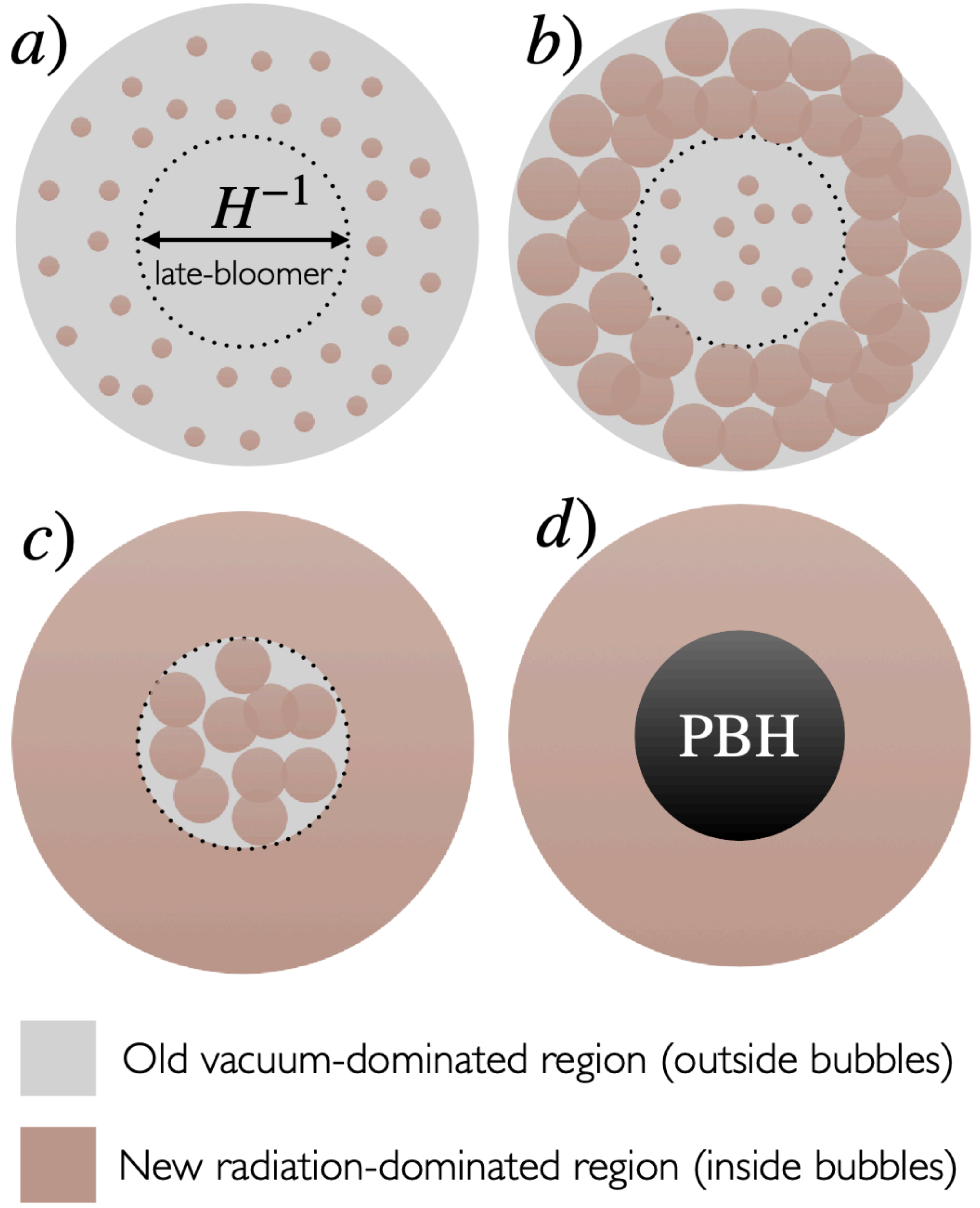
#2: Collapse of Inflating False-Vacuum Pockets



- ☐ Supercooled PT
  ➠ Universe inflates initially
- ☐ Bubble nucleation is stochastic
  - some regions transition later
  - generate energy longer
- ☐ Resulting overdensity may collapse to PBH

Sato Sasaki Kodama Maeda 1981
Gouttenoire Volansky 2305.04942

#3: Collapse of Fermi Balls

Gross *et al.* 2105.02840
Kawana XIe 2106.00111
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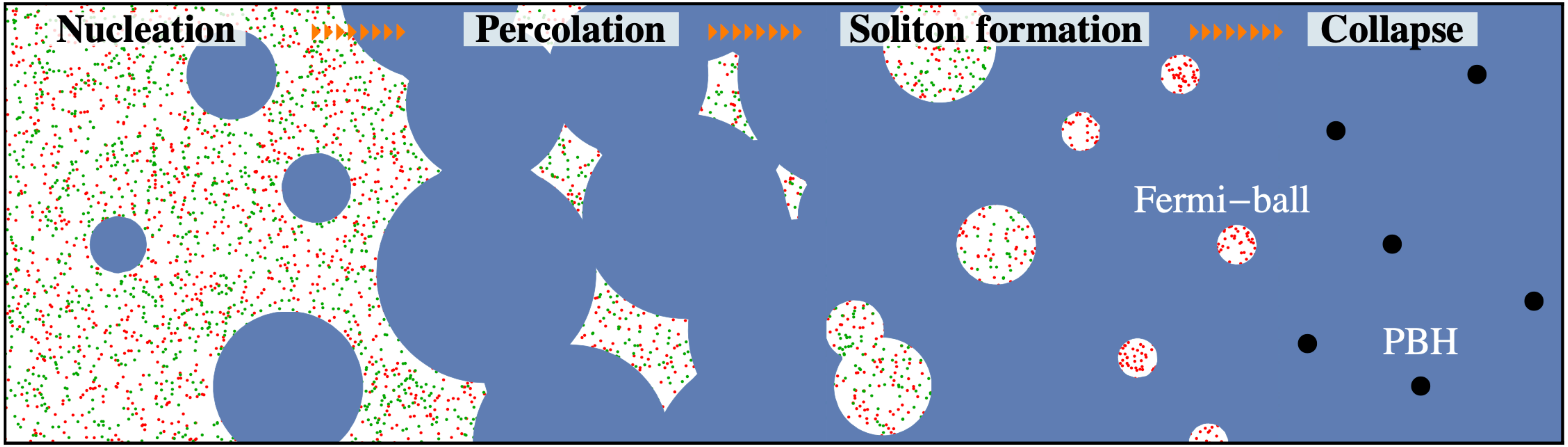
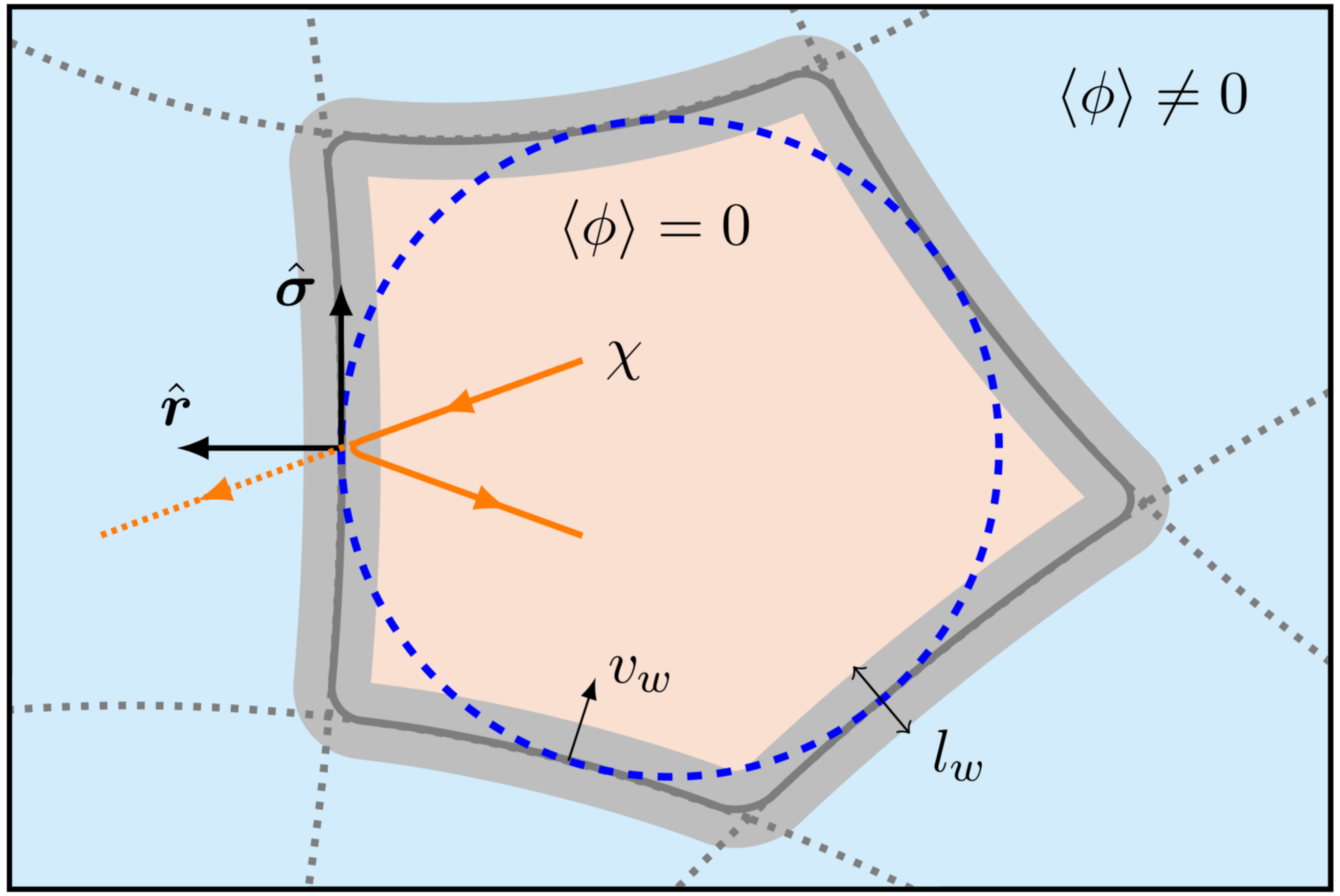


- fermions χ acquire mass during PT ➠ too heavy to enter bubbles (cf. Filtered DM)
- false-vacuum pockets containing the χ never transition ➠ "Fermi Balls"
- pockets collapse under gravity or due to Yukawa force

#4: Compression and Direct Collapse

- ☐ Assume fermion χ acquires mass during phase transition
- ☐ but cannot annihilate efficiently
- ☐ χ overdensity builds up in front of the bubble wall



Baker Breitbach JK Mittnacht, arXiv:2105.07481 and arXiv:2110.00005

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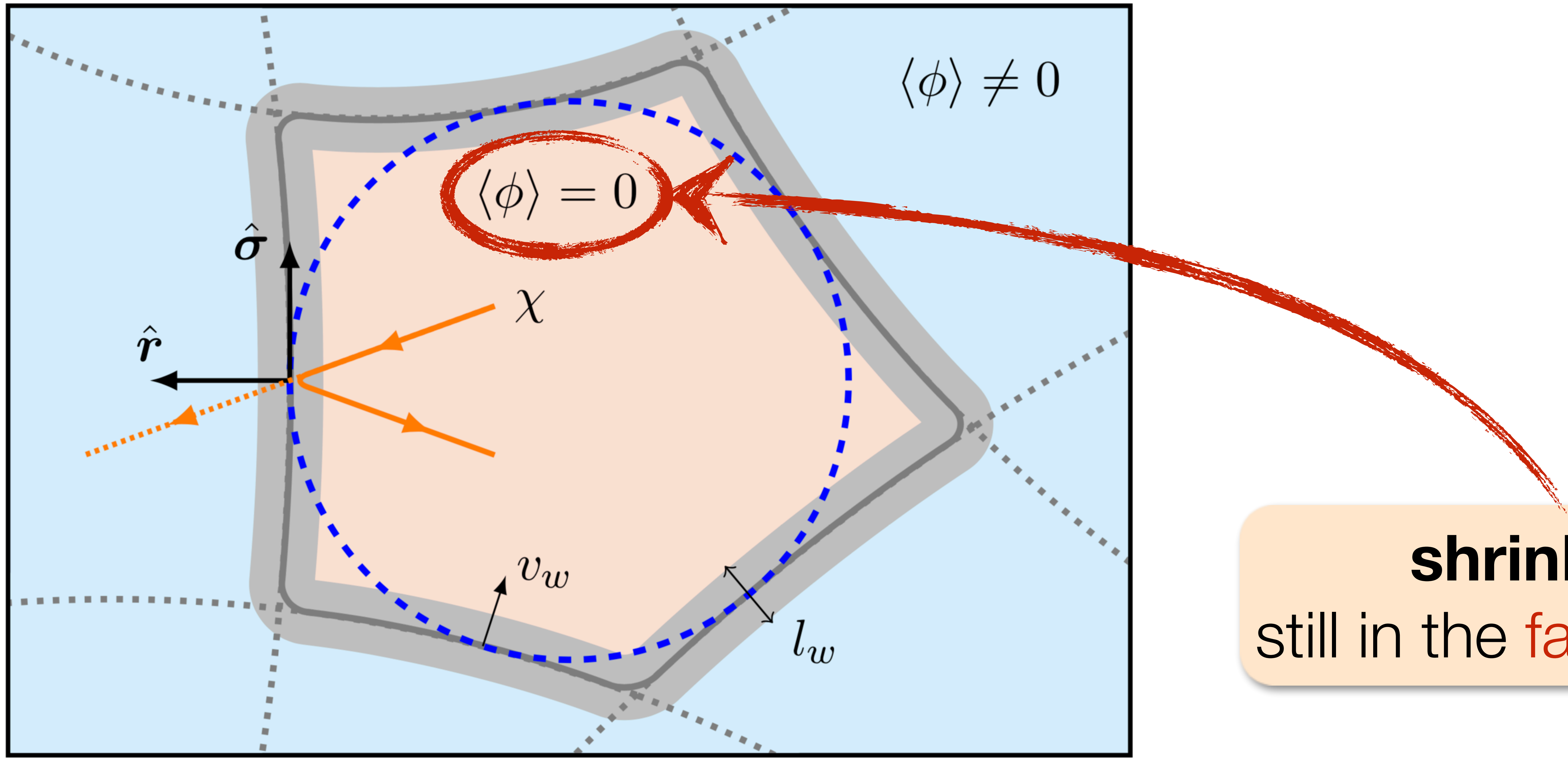

shrinking bubble
still in the false vacuum phase

Baker Breitbach JK Mittnacht, arXiv:2105.07481 and arXiv:2110.00005

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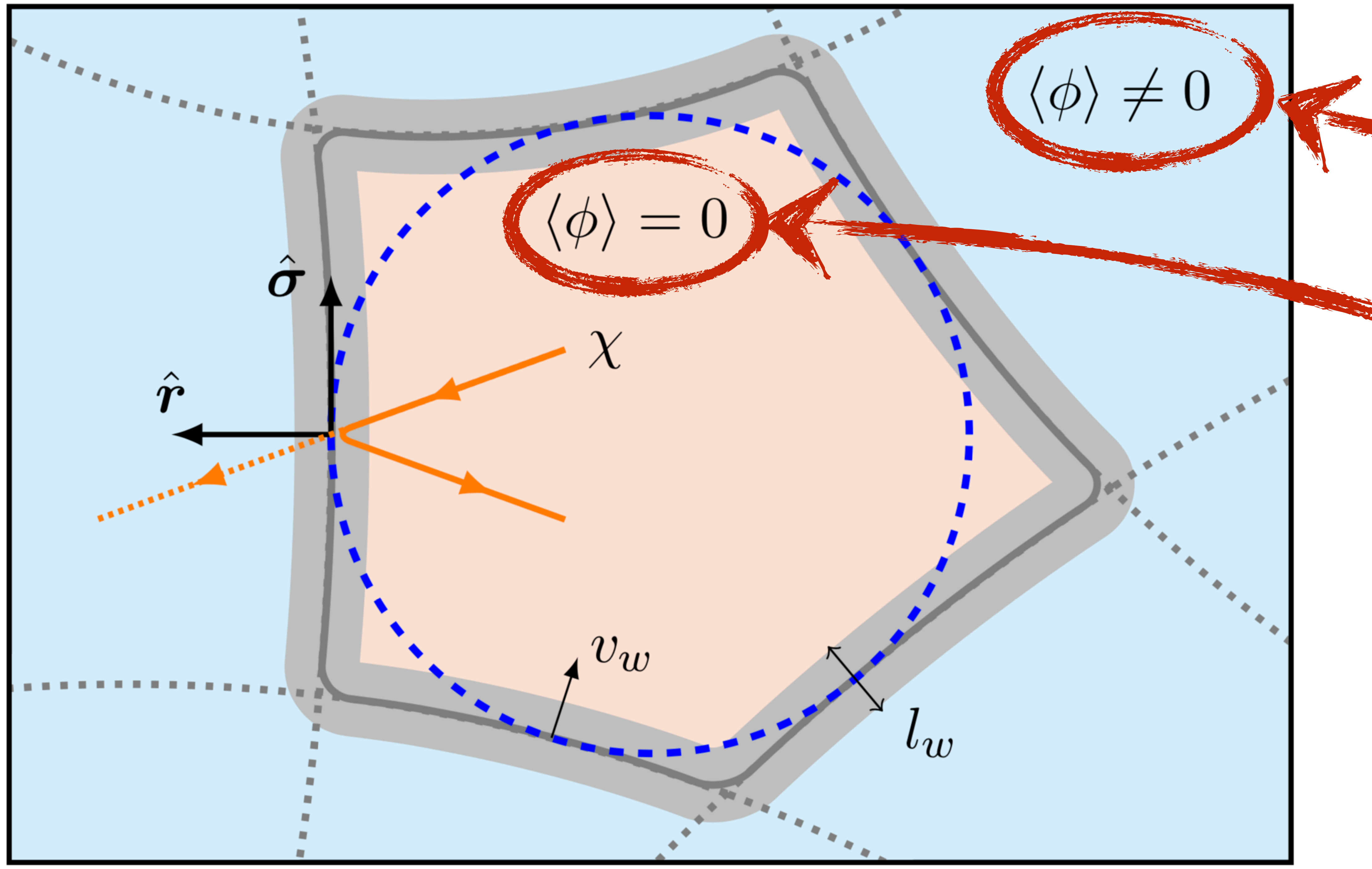

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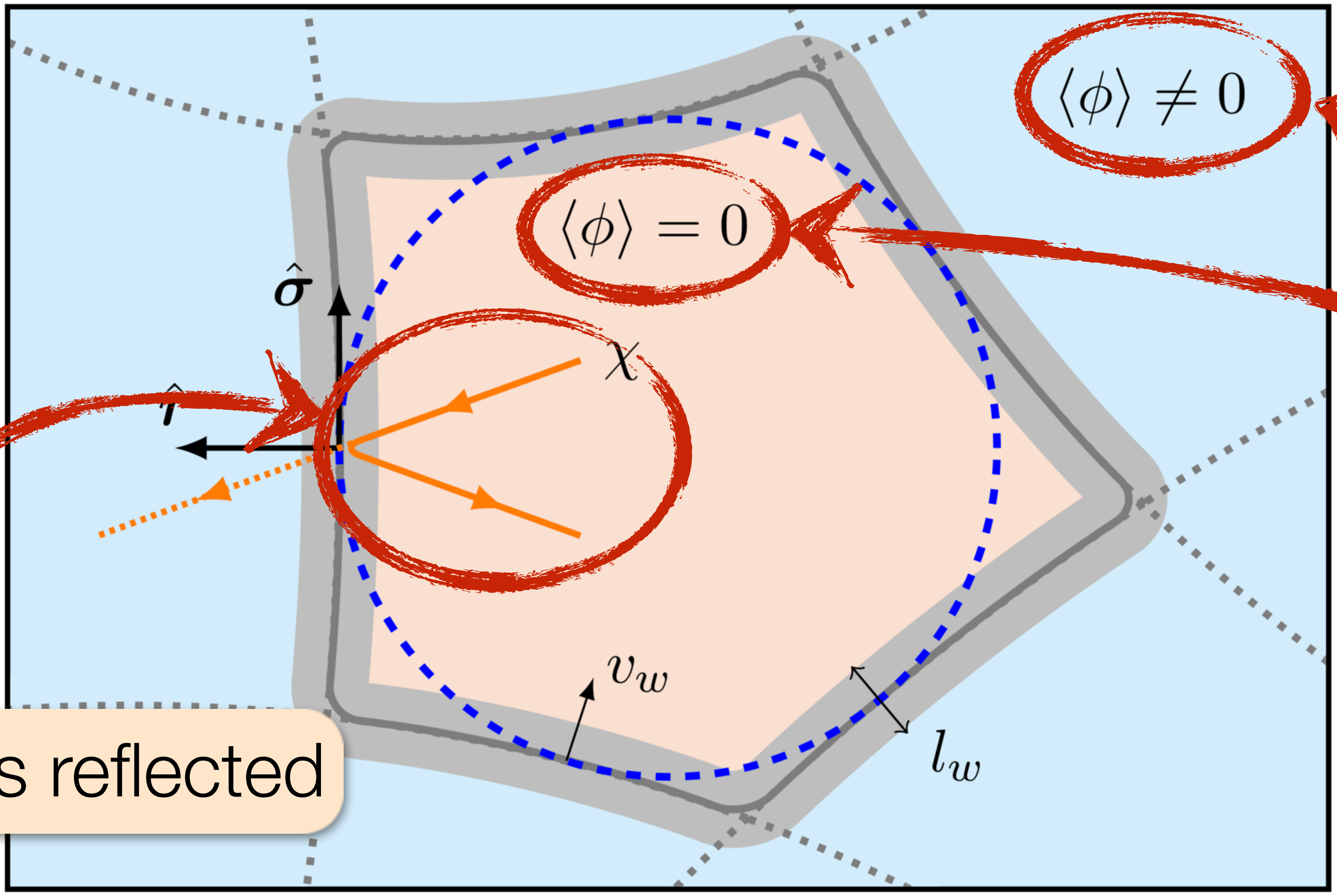
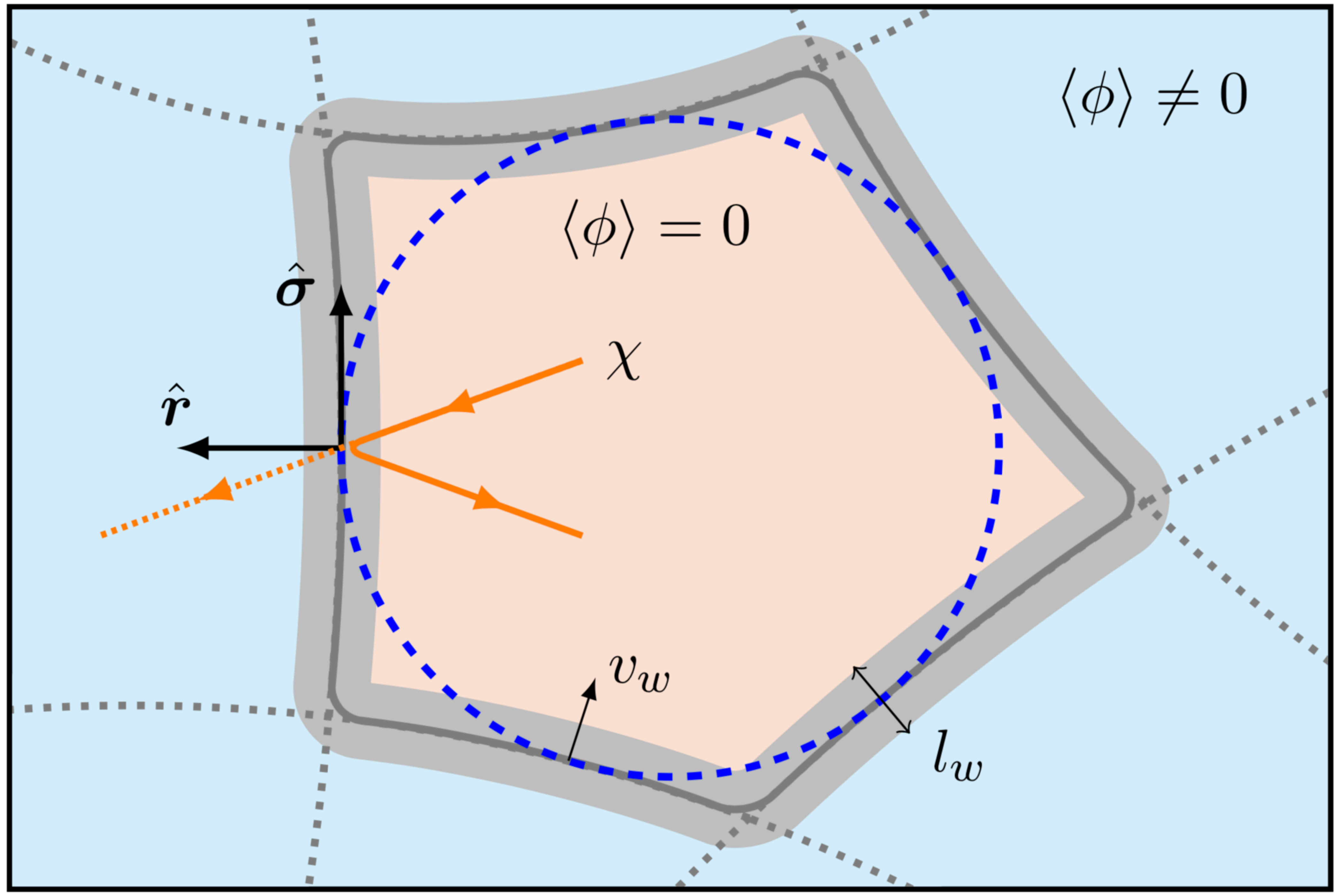


most χ particles reflected

shrinking bubble
still in the false vacuum phase

Baker Breitbach JK Mittnacht, arXiv:2105.07481 and arXiv:2110.00005

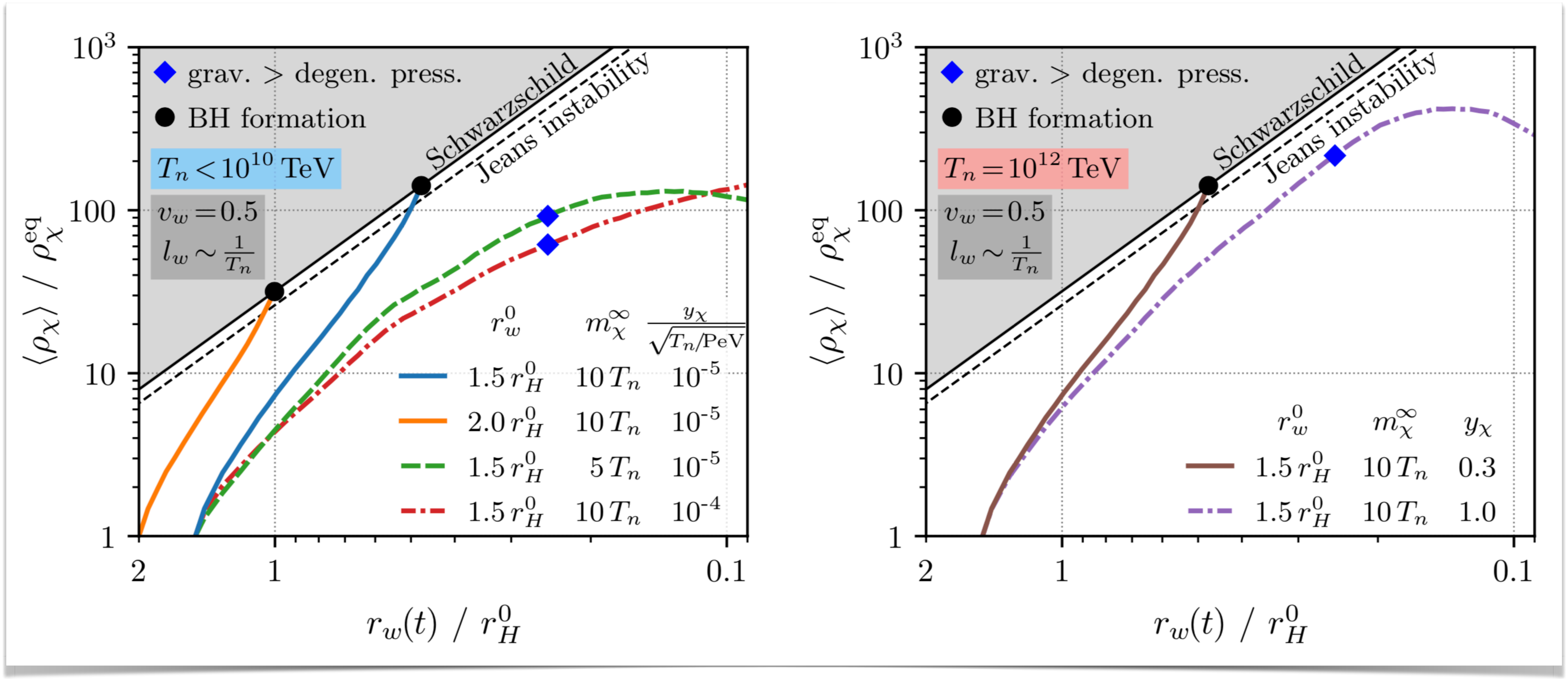
#4: Compression and Direct Collapse



- if population of χ particles shrinks below its Schwarzschild radius, a **black hole** forms

Baker Breitbach JK Mittnacht, arXiv:2105.07481 and arXiv:2110.00005

Bubble Trajectories



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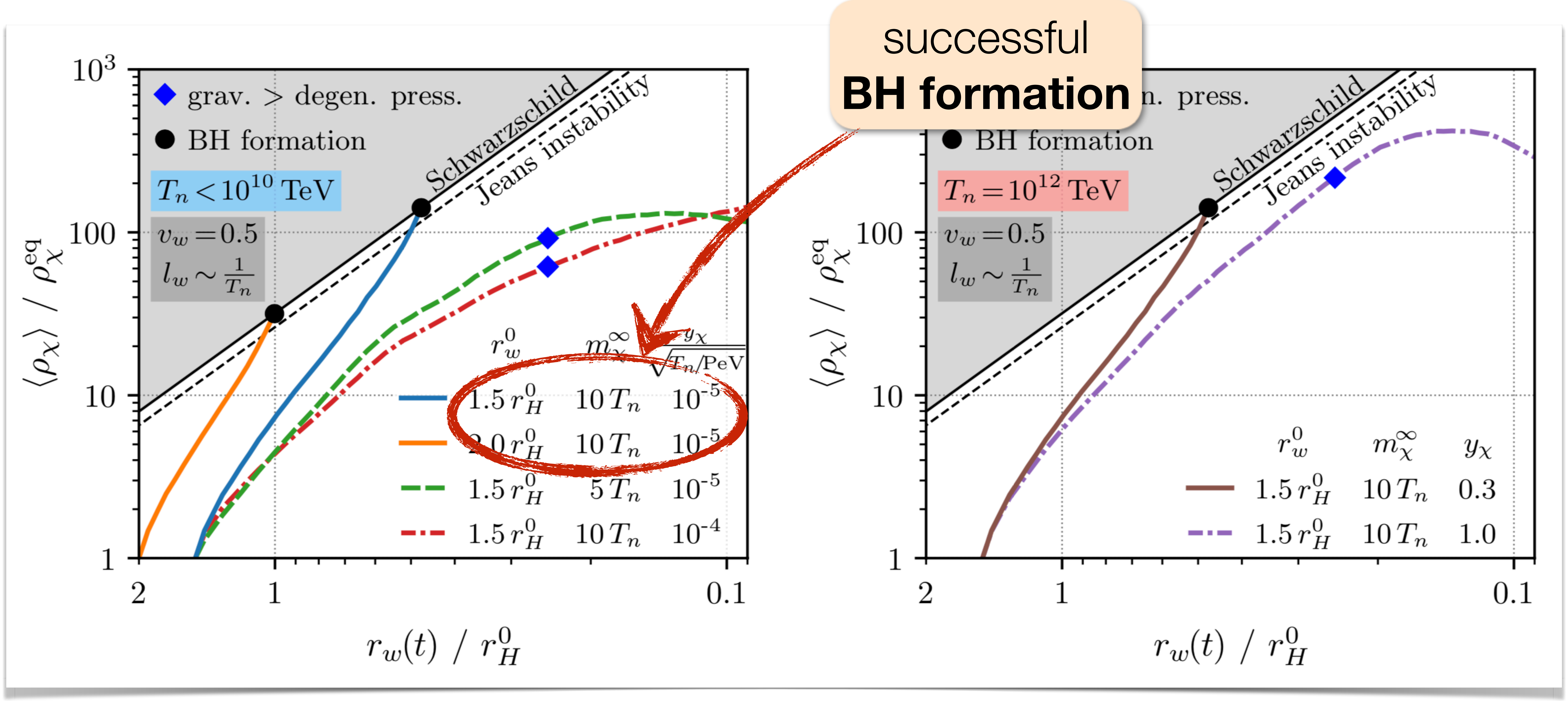

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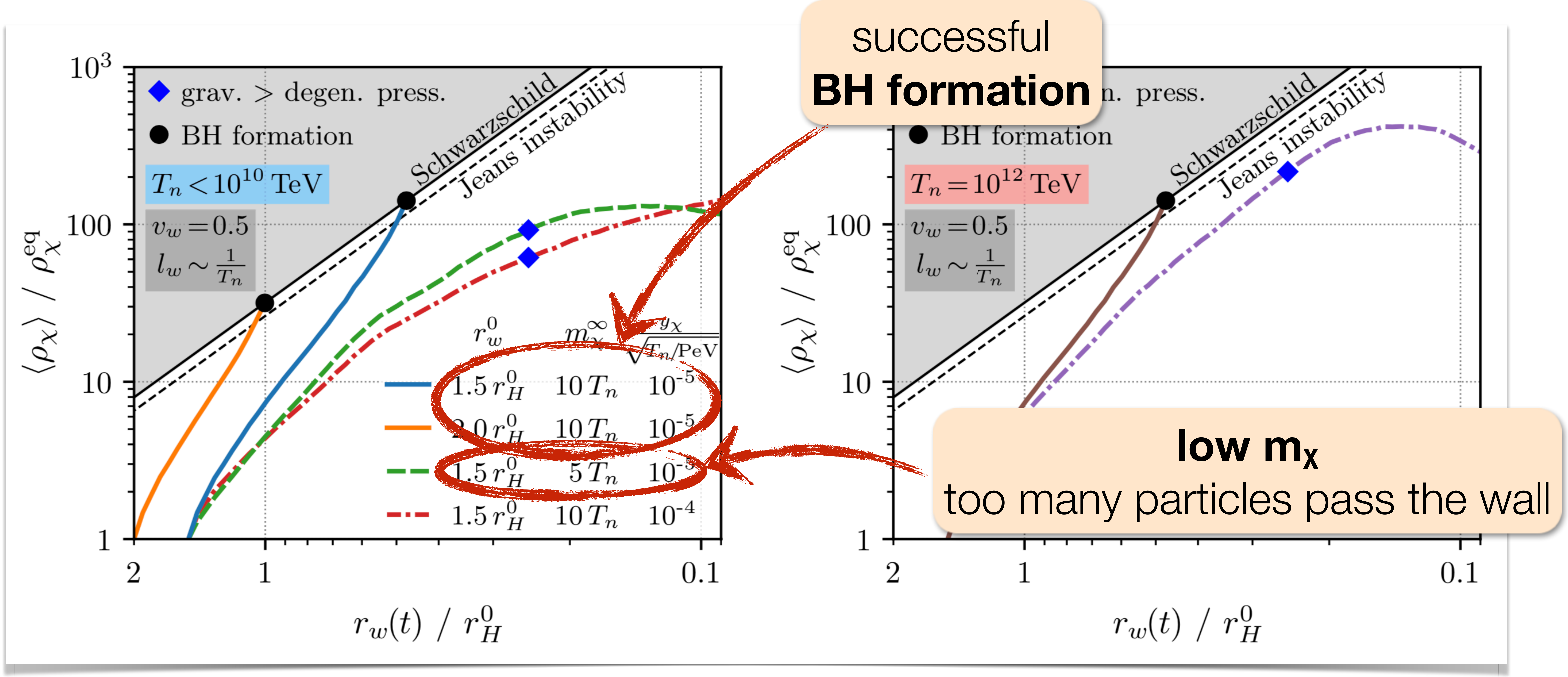

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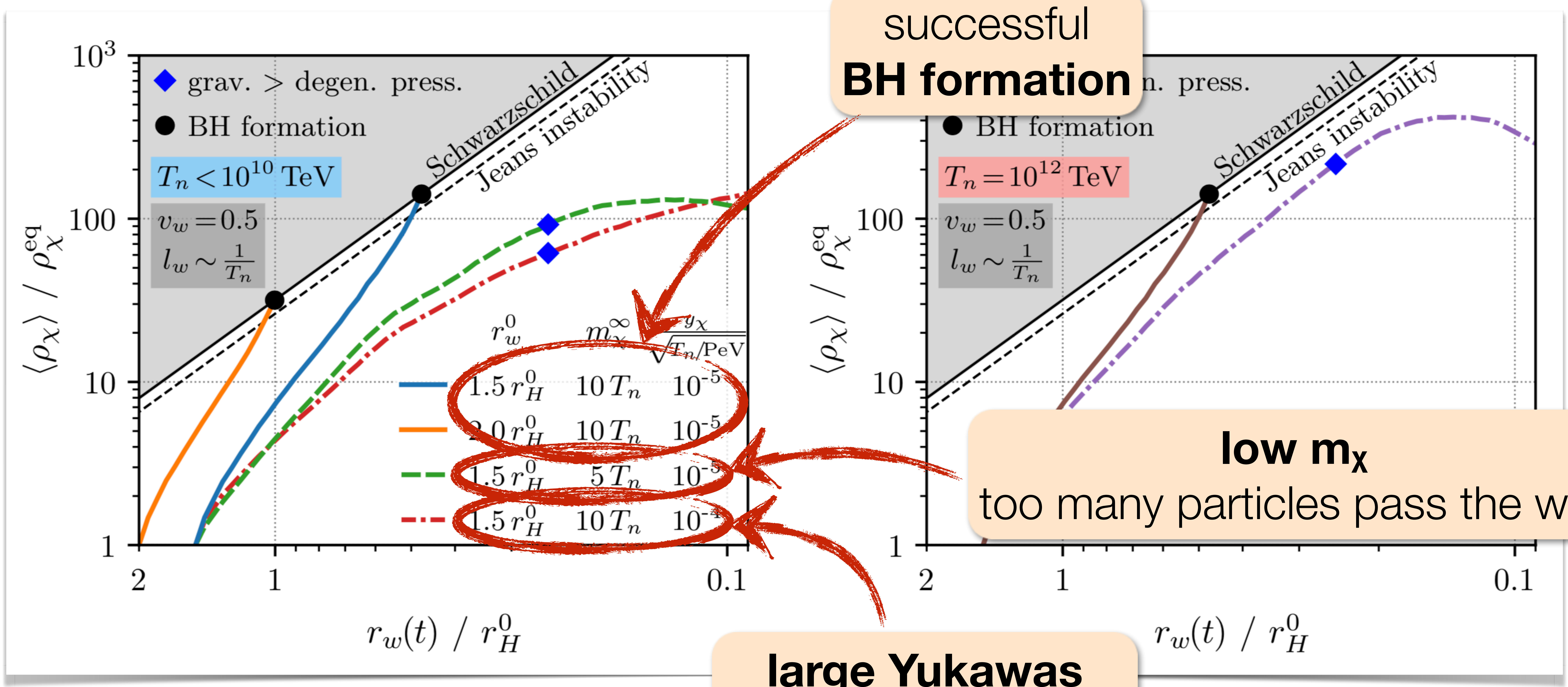


successful
BH formation

low m_χ
too many particles pass the wall

large Yukawas
annihilation too large

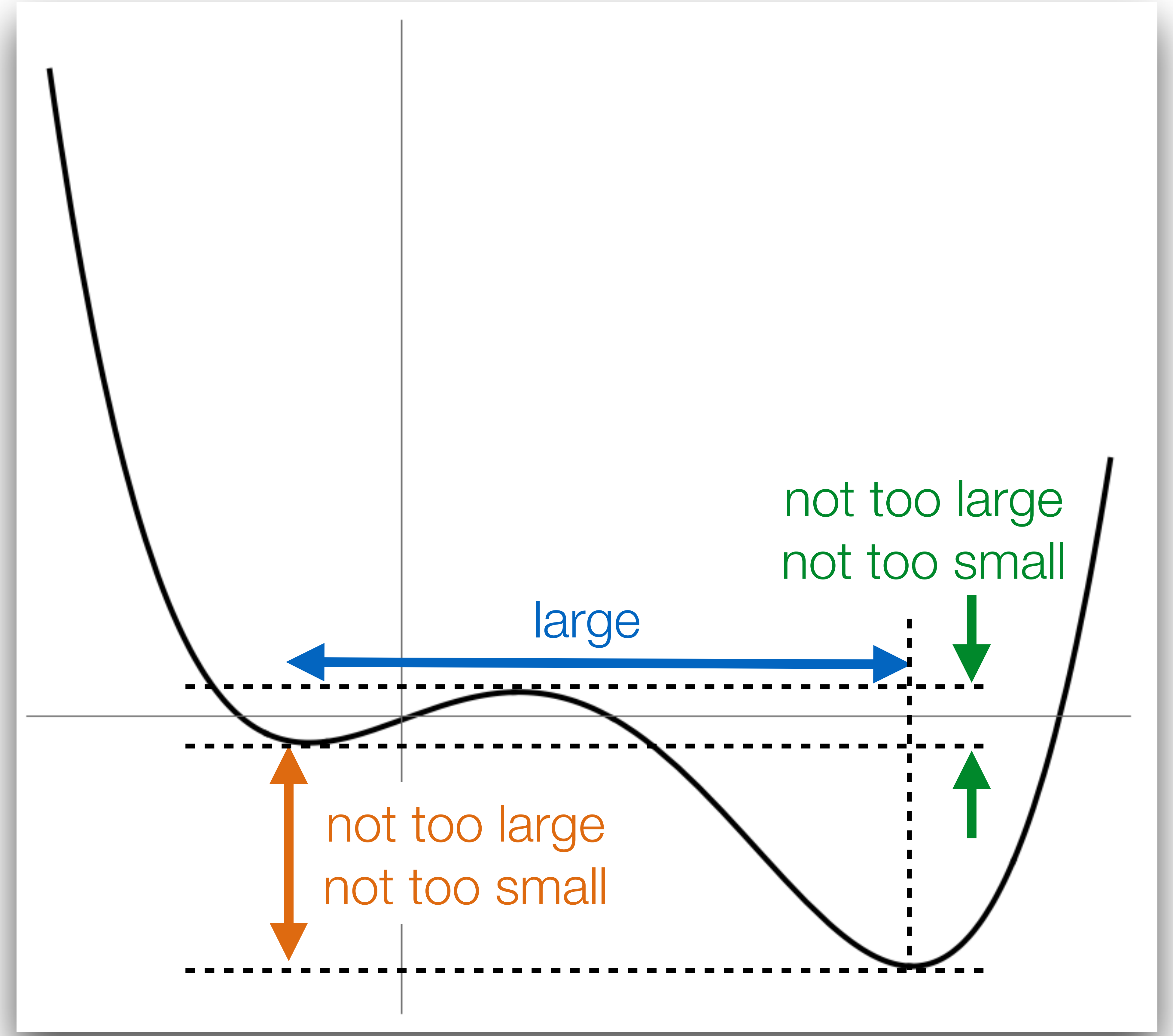
Baker Breit[...] .07481 and arXiv:2110.00005

Requirements

- ☐ large bubble radii ($\gtrsim r_H$):
  - larger Schwarzschild radius
    ➟ BH formation easier
  - requires slow PT
    ($\lesssim$ one bubble per Hubble volume)
  - supercooled PT?

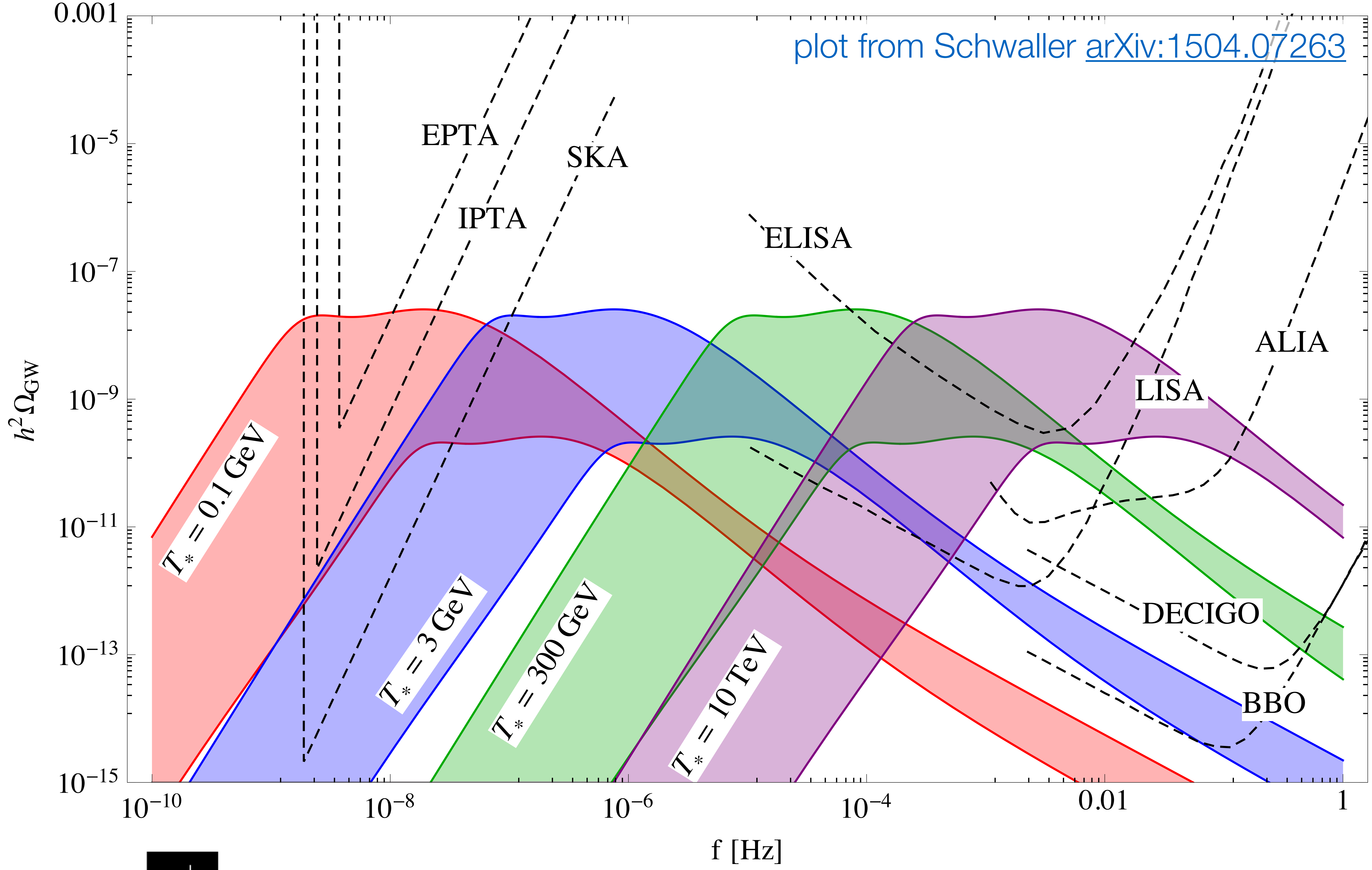
Hambye Struma Teresi, arXiv:1805.01473
delle Rose Panico Redi Tesi, arXiv:1912.06139

- ☐ constraints on the strength of the PT
  - large enough
    to overcome pressure from χ overdensity
  - small enough
    to avoid intermittent vacuum domination
- ☐ large fermion masses



Complementary Signals and Opportunities

Gravitational Waves from Phase Transitions



Electroweak Baryogenesis

- Consider 1st order electroweak PT
  e.g. SM + real singlet scalar
- Penetrating bubble walls is difficult for top quarks
  (massless outside, massive inside)
- Permeability can be larger for t_L than t_R
  requires new CP-violating interaction
- Deficit of t_L outside the bubbles

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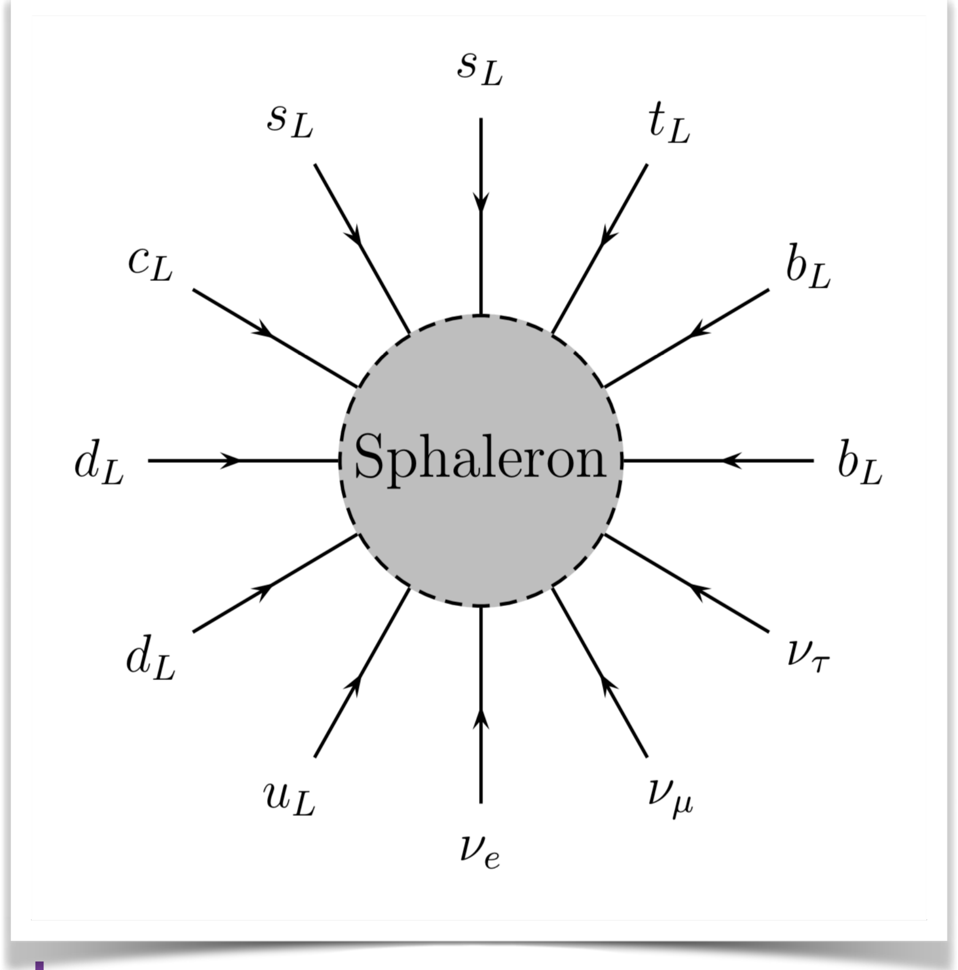

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  requires new CP-violating interaction
- ☐ Deficit of t_L outside the bubbles

- ☐ $B+L$ violated by sphalerons
  - weak interaction
    ➠ affects t_L, but not t_R
  - active only outside the bubbles (ewk symmetry broken inside)
  - $B–L$ remains conserved
- ☐ entropy maximisation implies that leptons are converted to baryons
- ☐ ➠ net gain in baryon number
- ☐ excess baryons are eventually swept up by the advancing bubble

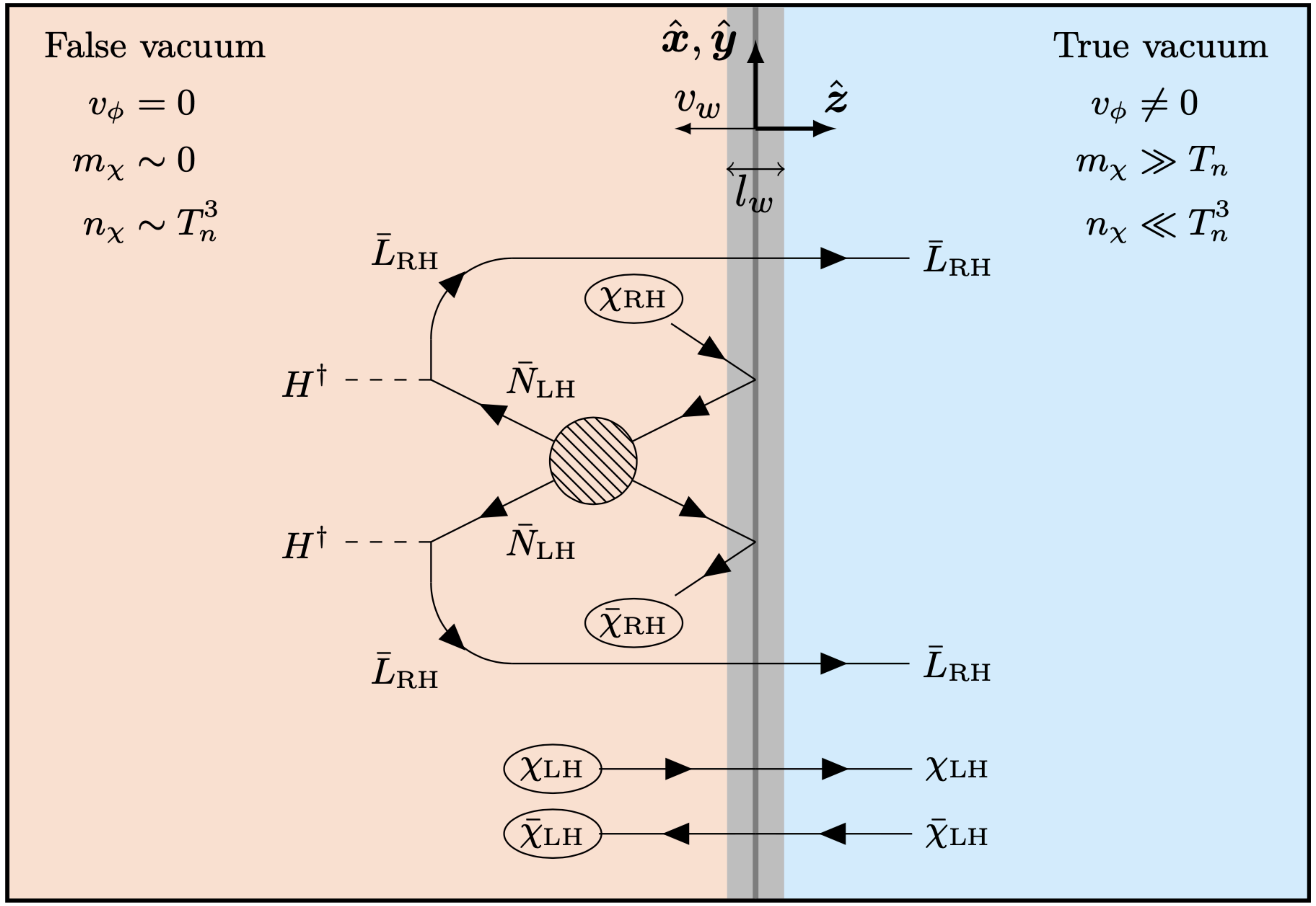
Image: Wilfried Buchmüller, hep-ph/9812447

Filtered Baryogenesis

- combines Filtered DM with ewk-style baryogengesis
- χ_{LH}, $\bar{\chi}_{LH}$ enters bubbles more easily than χ_{RH}, $\bar{\chi}_{RH}$
- Portal interaction, e.g.

$$\mathcal{L}_\mathrm{p} = \frac{1}{\Lambda_\mathrm{p}^2} \sum_{j=1,2,3} (\overline{N_R^j} N_R^{jc}) (\overline{\chi_R} \chi_L)$$

  produces excess of LH leptons
- Resulting lepton asymmetry is converted to baryon asymmetry by sphalerons



Baker Breitbach JK Mittnacht Soreq arXiv:2112.08987

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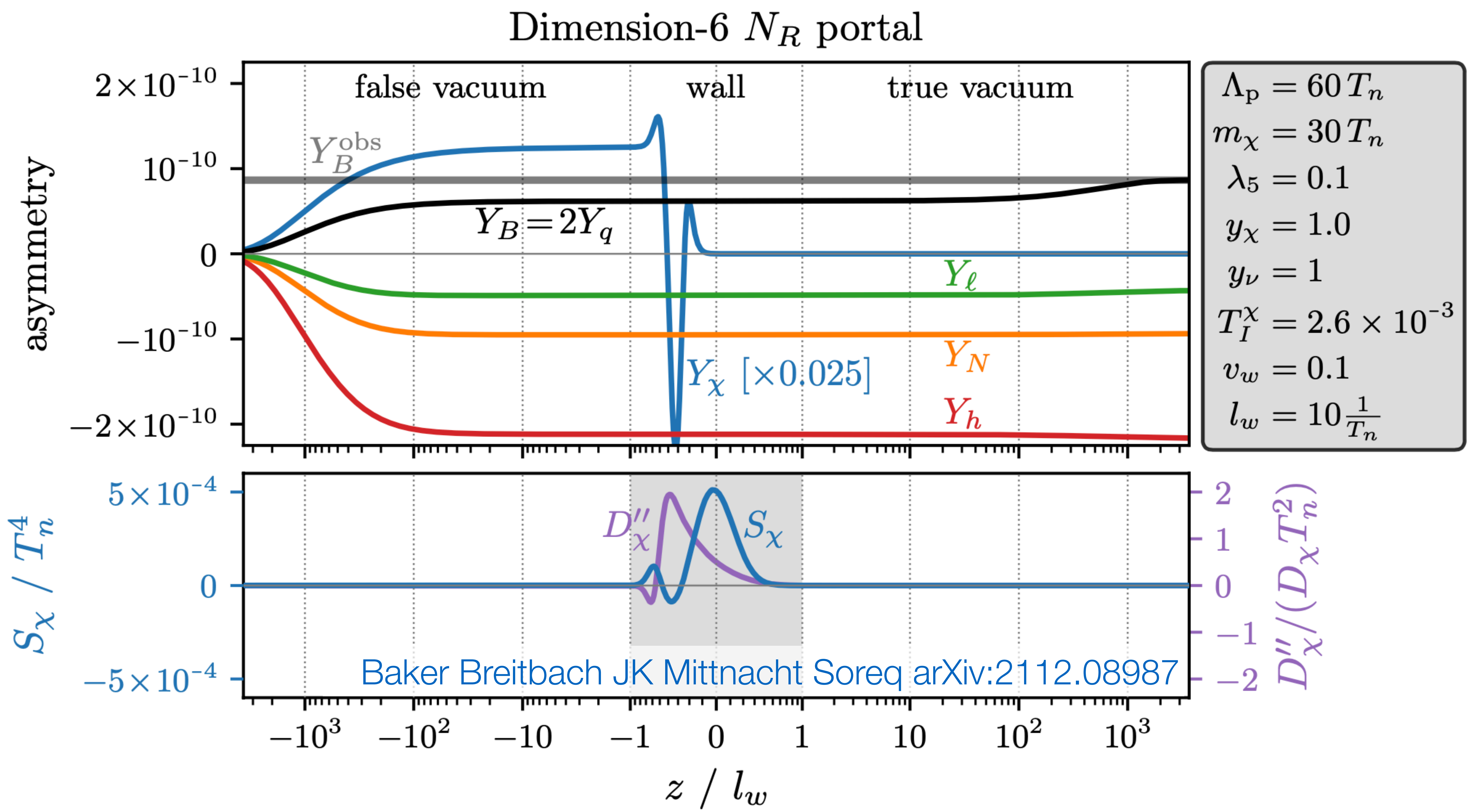

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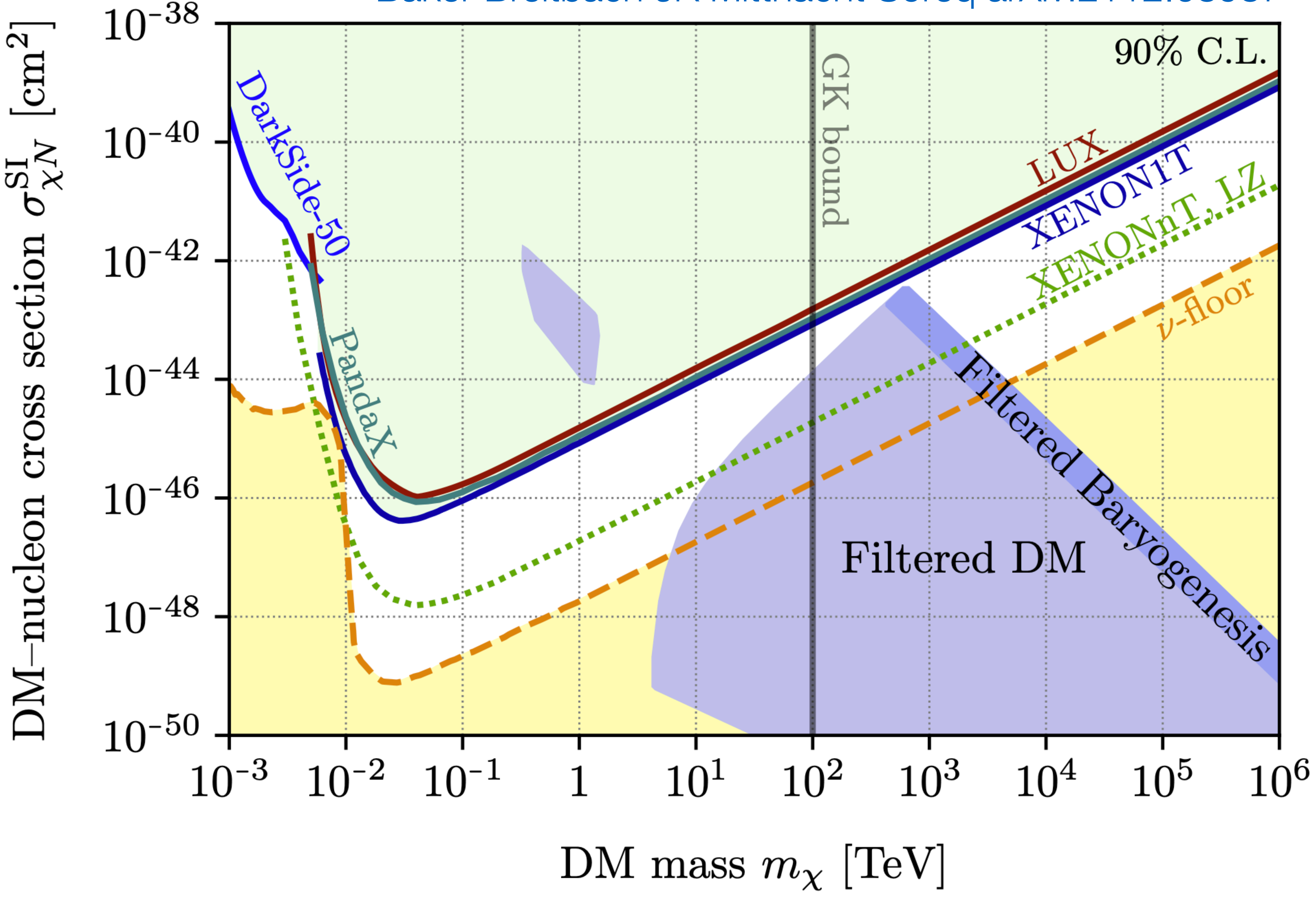

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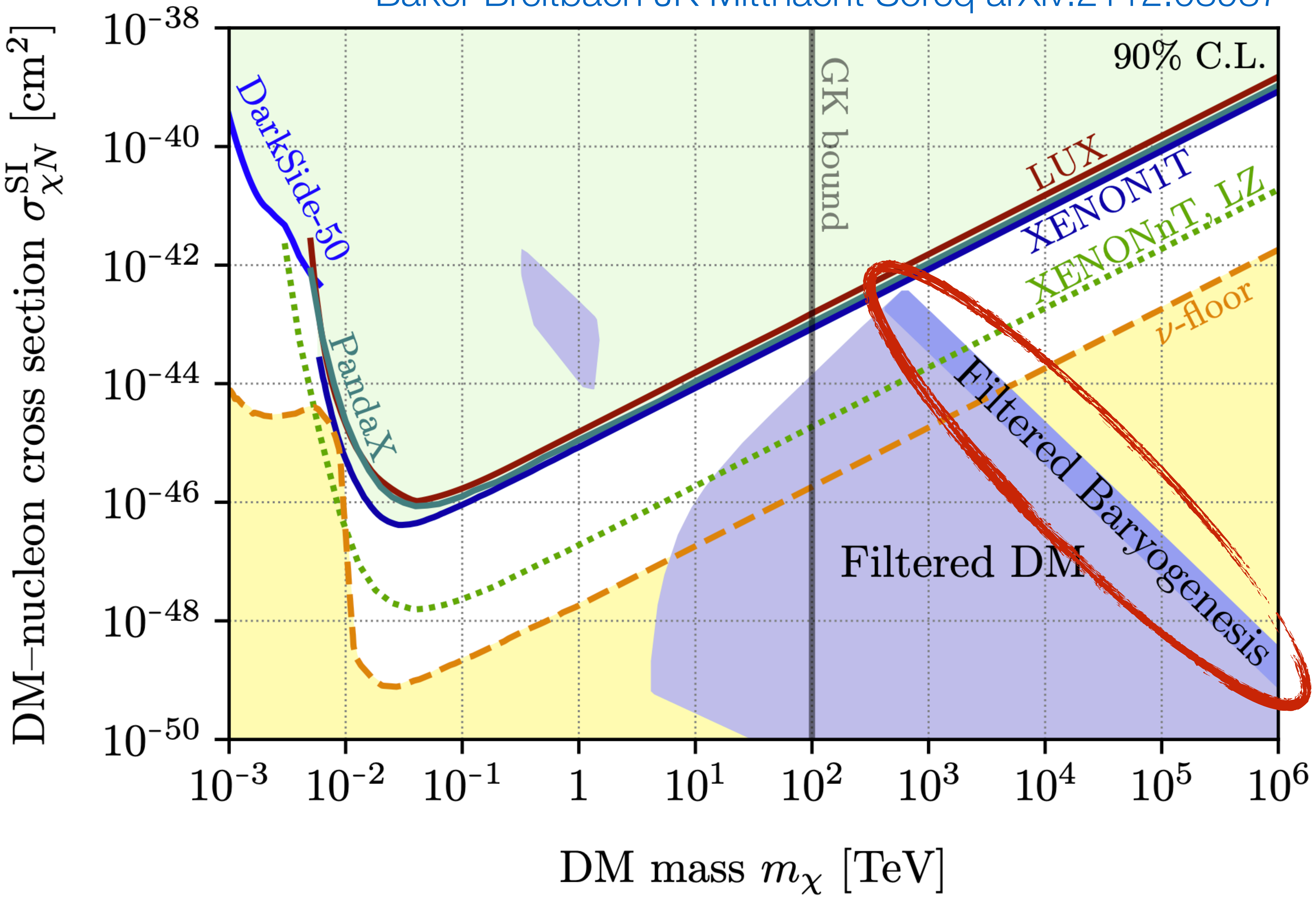

Collider Signals

- Early Universe phase transitions often controlled by scalar fields S
- Connection to the SM: Higgs portal $(S^\dagger S)(H^\dagger H)$
- Testable at colliders:
  - Invisible Higgs decays
  - If $\langle S \rangle \neq 0$: mixing between S and H
    ➜ electroweak precision observables (S, T, U parameters)
    ➜ modified H branching ratios
    ➜ direct observation of S
    (similar production/decay channels as H, but suppressed by mixing)
  - Precision measurements of Higgs self-coupling
    (e.g. in di-Higgs production)

Barger *et al.*, https://arxiv.org/abs/0706.4311
Robens & Stefaniak, arXiv:1601.07880

Summary

Summary

Phase Transition in the early Universe

- ☐ can set the dark matter abundance by "filtering" — Baker JK Long 1912.02830
- ☐ can produce primordial black holes — Baker Breitbach JK Mittnacht 2105.07481, 2110.00005
- ☐ can dramatically alter dark matter freeze-in — Baker Breitbach JK Mittnacht 1712.03962
- ☐ can switch dark matter decay on and off — Baker JK 1608.07578, Baker Mittnacht 1811.03101
- ☐ can produce dark matter nuggets — Bai Long Lu 1810.04360, Hong Jung Xie 2008.04430, Gross Landini Strumia Teresi 2105.02840
- ☐ can facilitate new baryogengesis mechanisms — Baker *et al.* 2112.08987
- ☐ ...

Thank You!

Bonus Slides

The Order of a Phase Transition

- Order Parameter Q: measures change in the system across the PT
  - for liquid–gas transition: density ρ
  - for QCD phase transition: quark condensate $\langle \bar{q}_L q_R \rangle$

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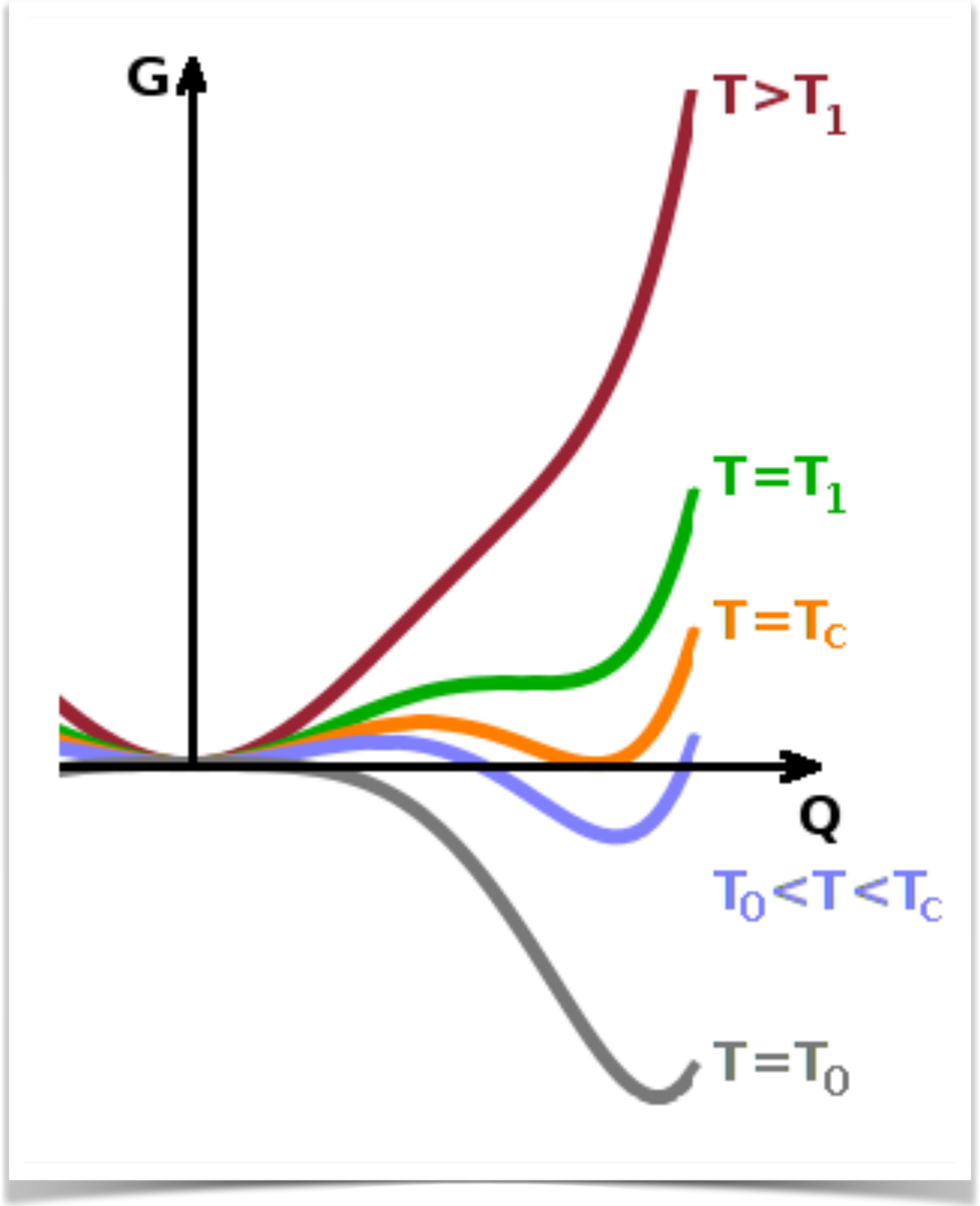

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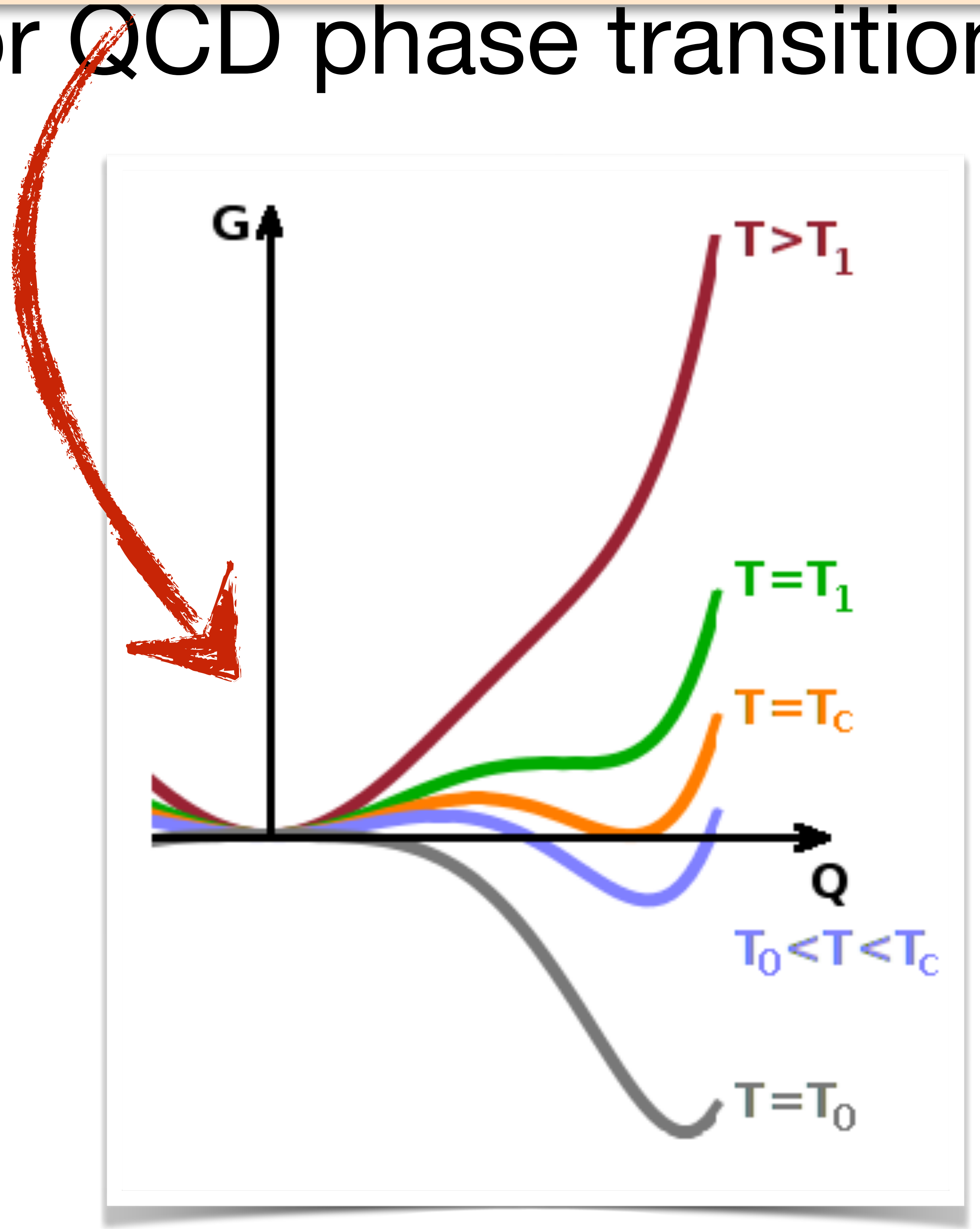
  - o … ρ
  - o for QCD phase transition: quark condensate $\langle \bar{q}_L q_R \rangle$

1st order transition

order parameter changes discontinuously



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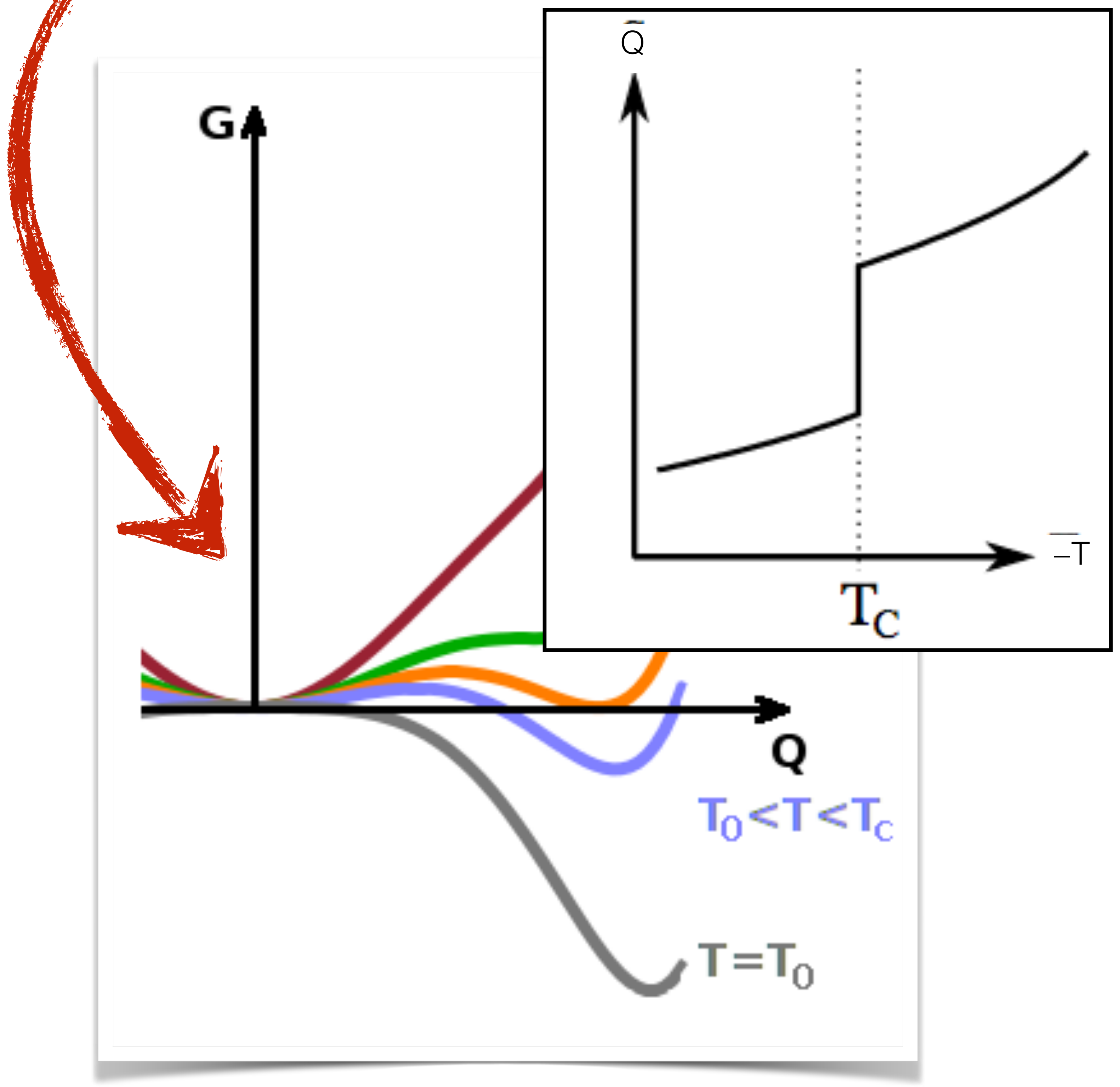

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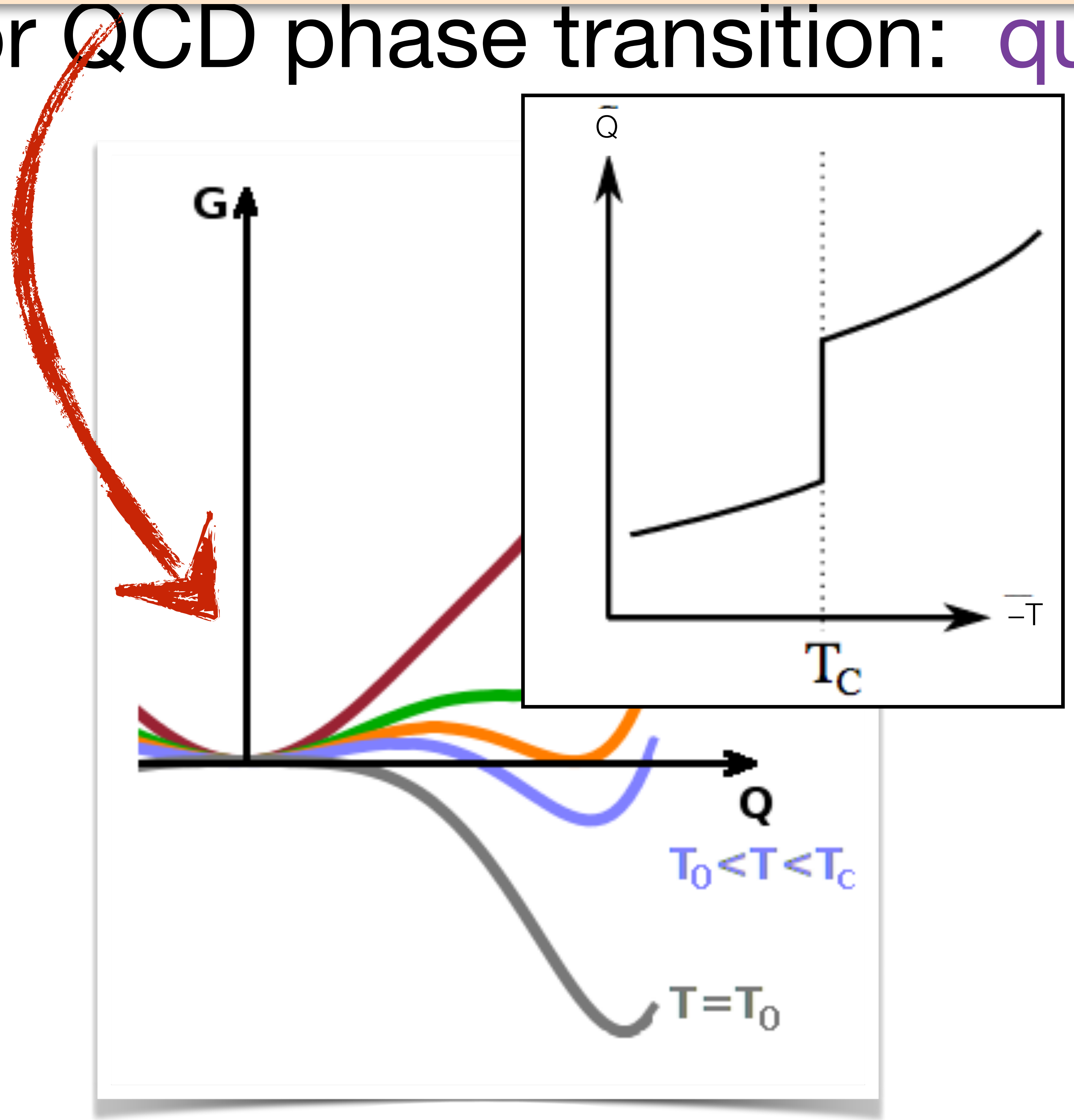

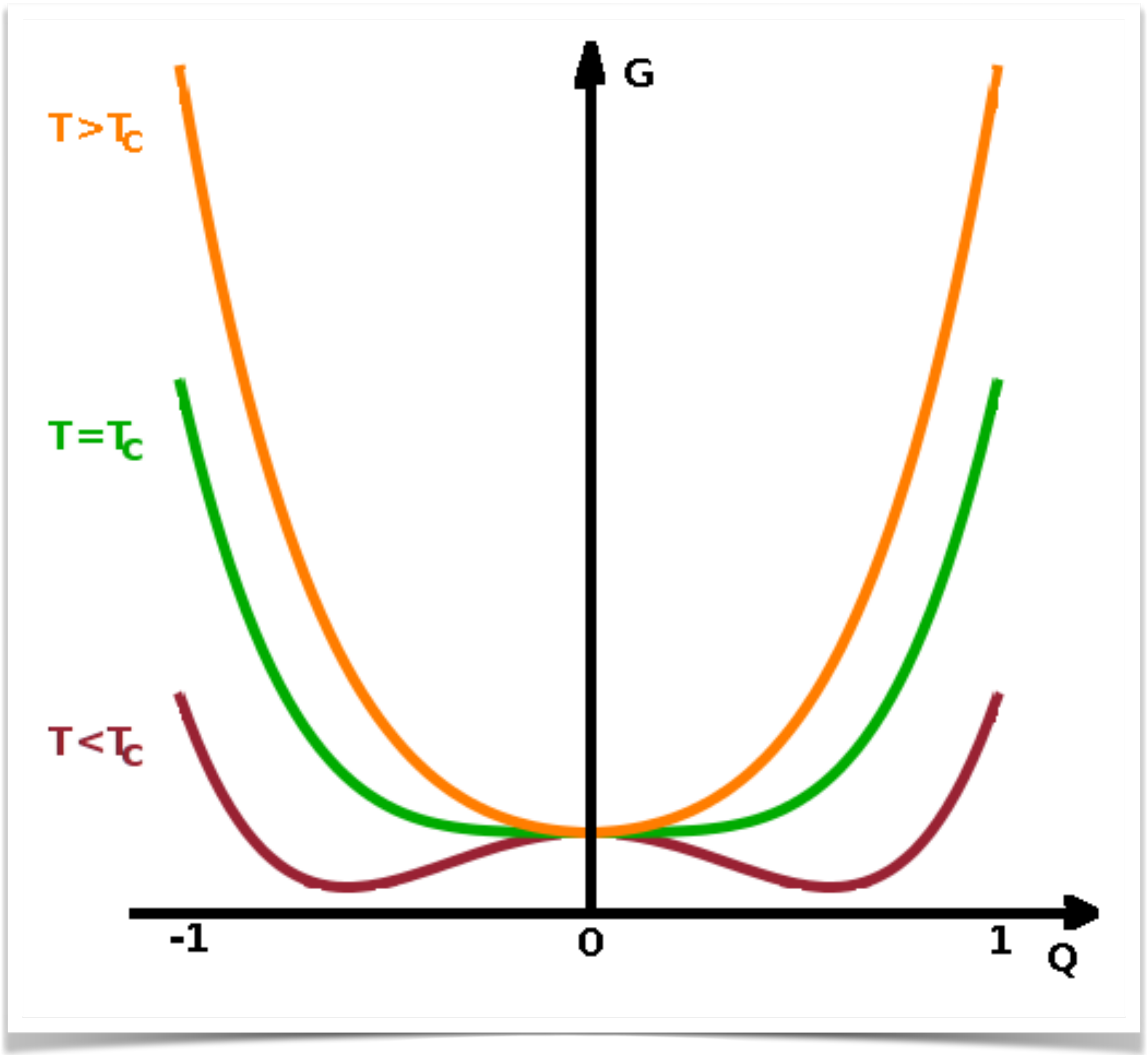

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1st order transition
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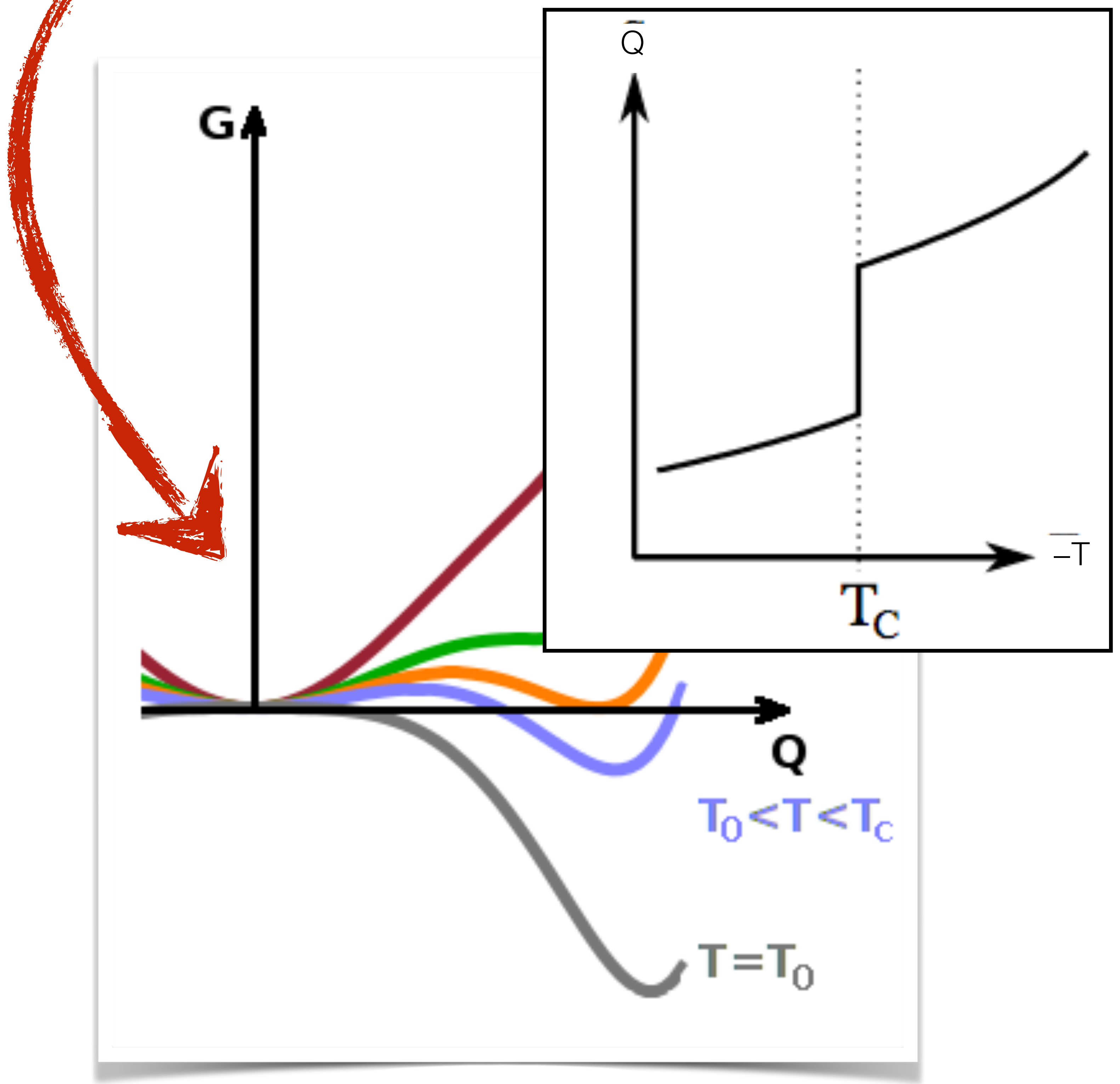
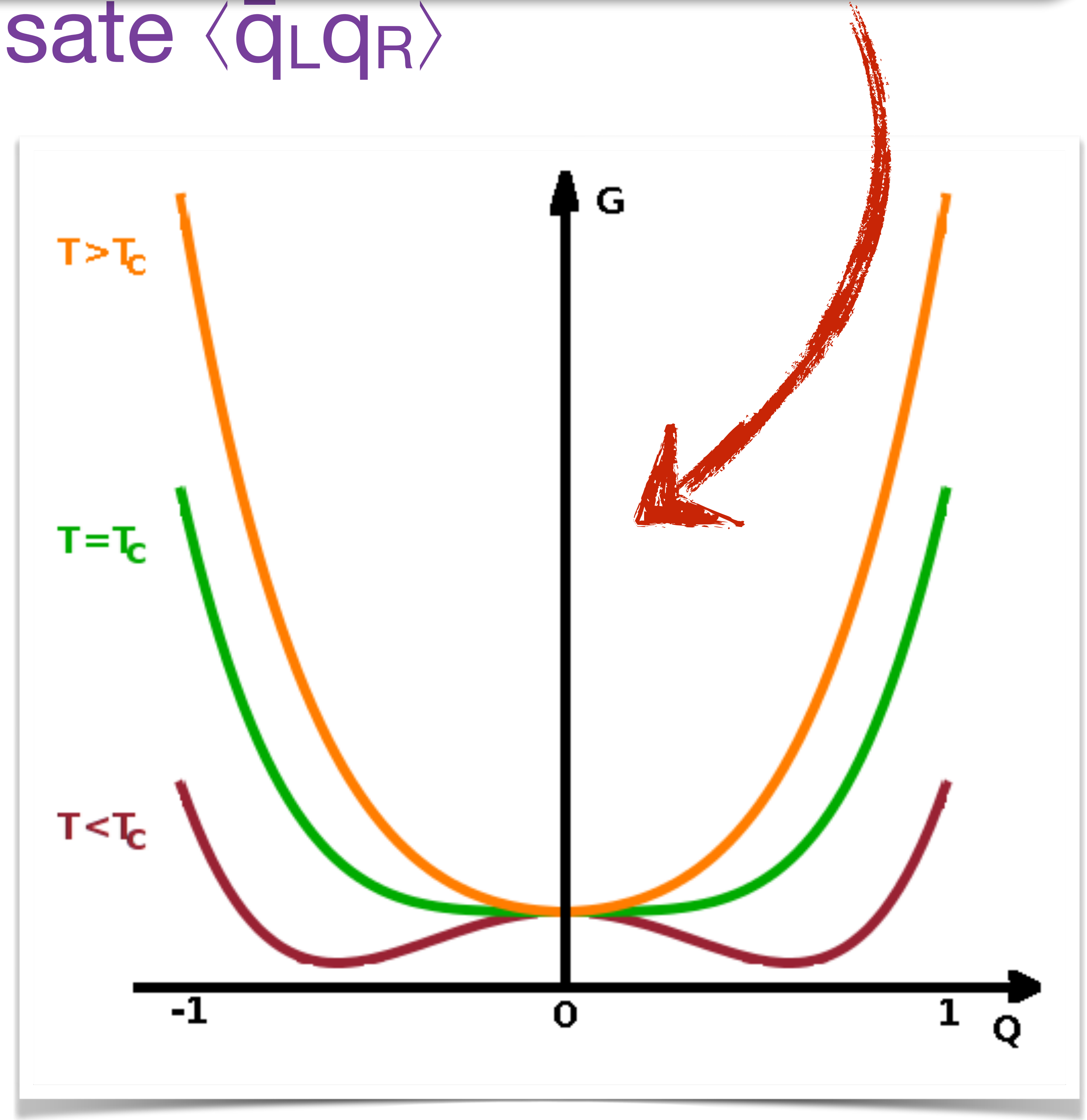
2nd order transition / crossover
order parameter changes continuously





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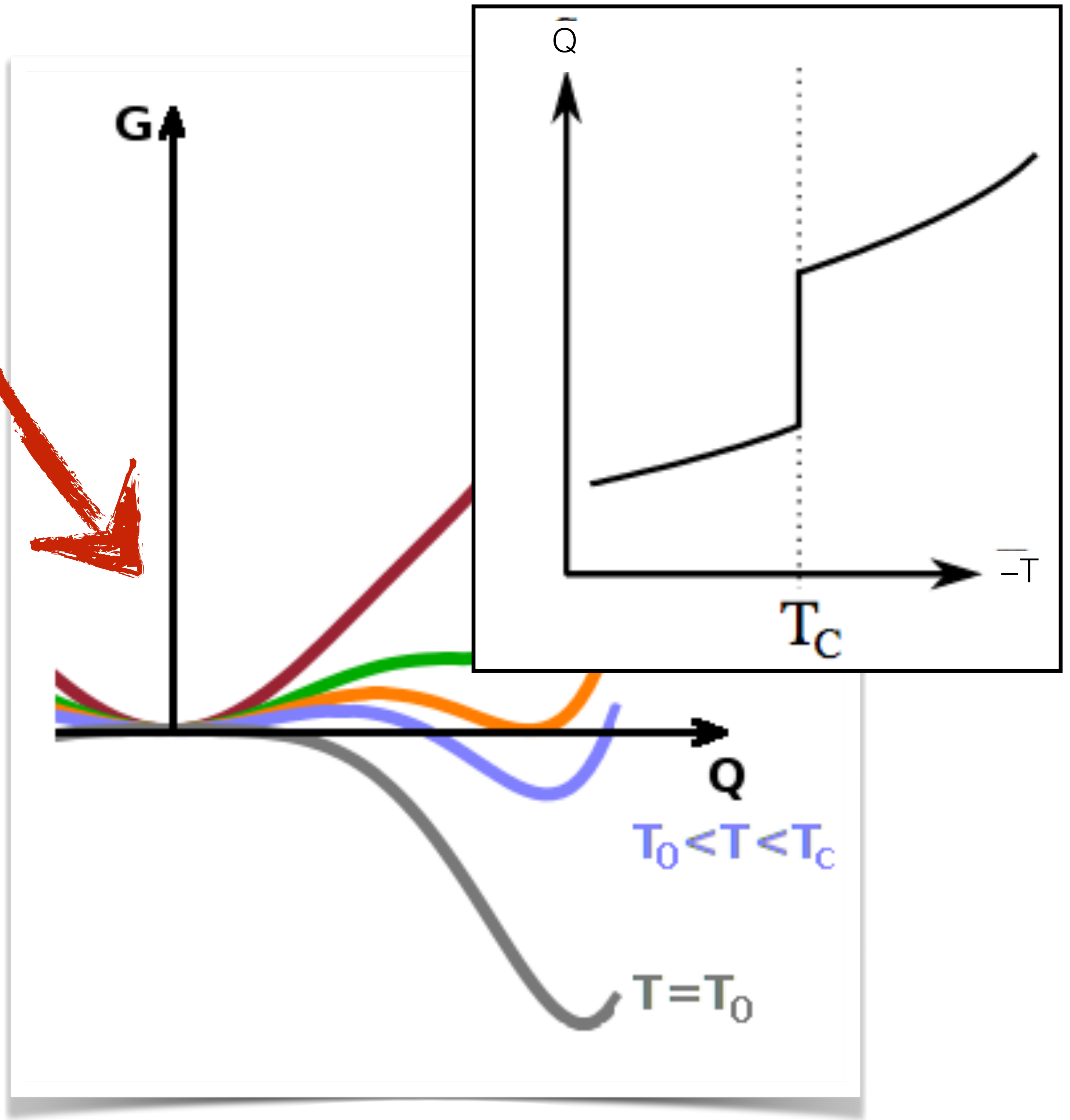
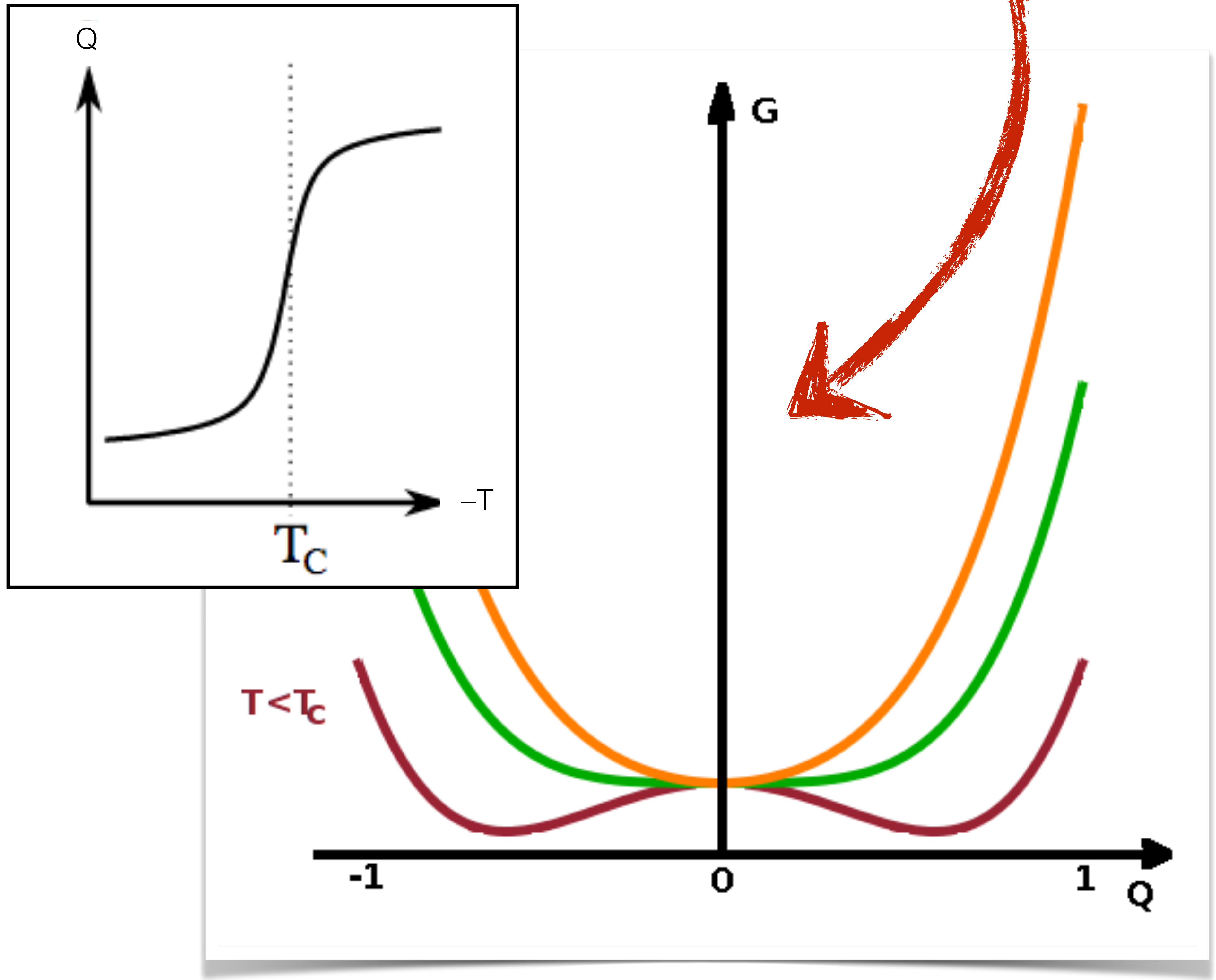
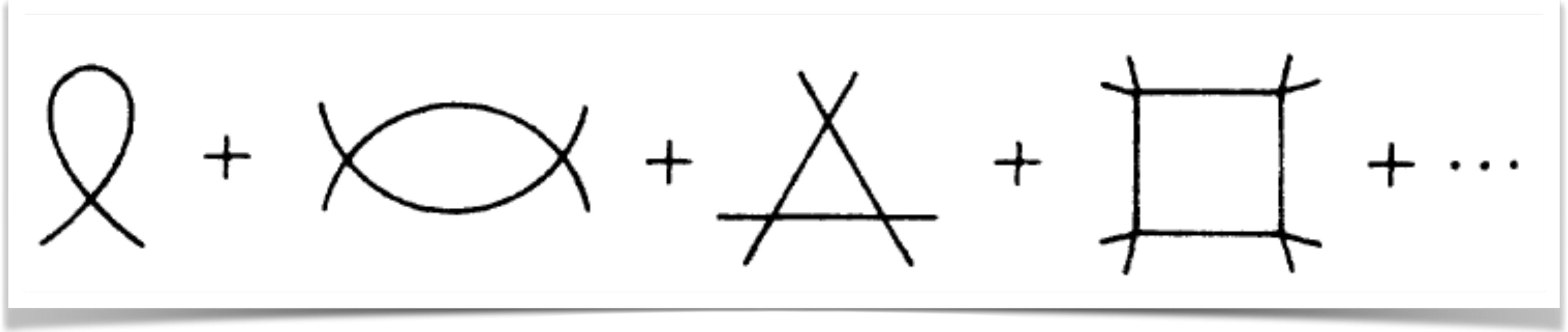




DM Decay Between Phase Transitions

Scalar Potentials at Finite Temperature

- ☐ Tree level potential $V^{\text{tree}} = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$
- ☐ Coleman—Weinberg Coleman Weinberg 1973, Dolan Jackiw 1974



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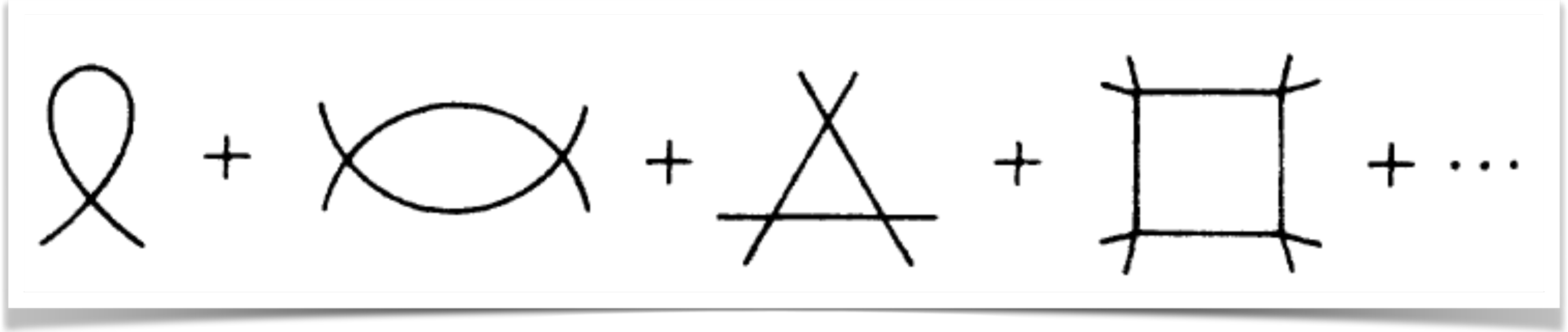

$$V^{\text{CW}}[\phi] = \sum_{n=1}^{\infty} \int \frac{d^4k}{(2\pi)^4} \frac{1}{2n} \left(\frac{2\lambda\phi}{k^2 - m^2} \right)^n$$

  - Sum over *n*
  - Regularize, evaluate integral
  - Renormalize by adding counterterms

$$V^{\text{CW}} = \sum_i \frac{n_i}{64\pi^2} m_i^4(h,S) \left[\log \frac{m_i^2(h,S)}{\Lambda^2} - \frac{3}{2} \right]$$

Scalar Potentials at Finite Temperature

- 1-loop, finite temperature corrections   Dolan Jackiw 1974
  - Evalute 1-loop diagrams
  - Replace vacuum propagators by thermal propagators

    propagator = correlation function $\langle \Phi(x)\, \Phi(y) \rangle$

    in vacuum, points x and y become correlated if a particle propagates from x to y.

    in a thermal bath, long-distance correlations are washed out by interactions with the bath.

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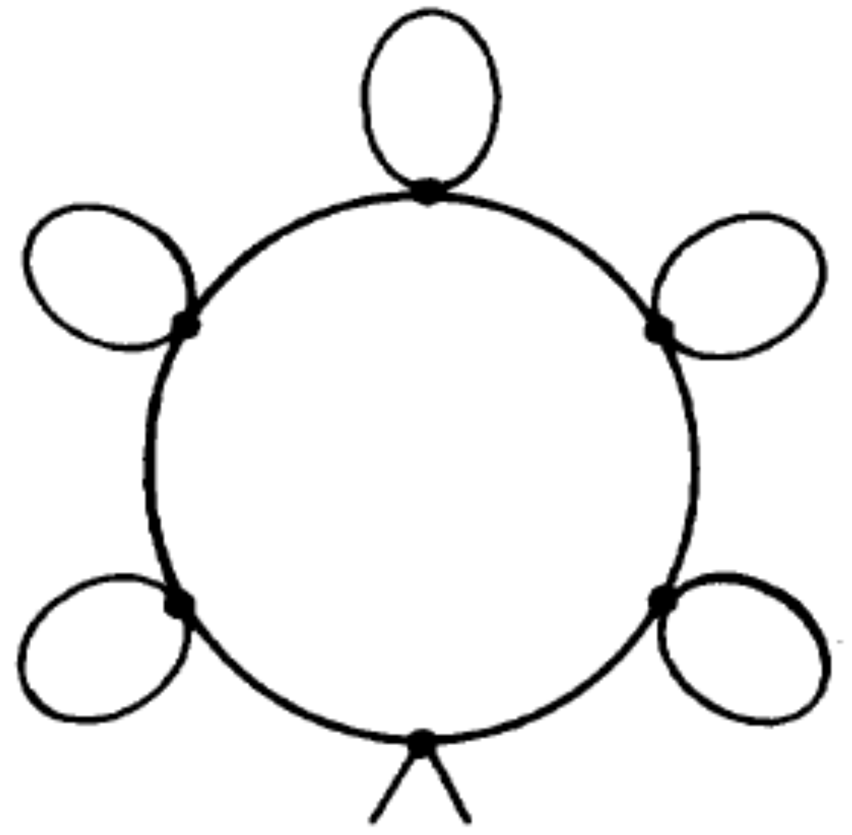

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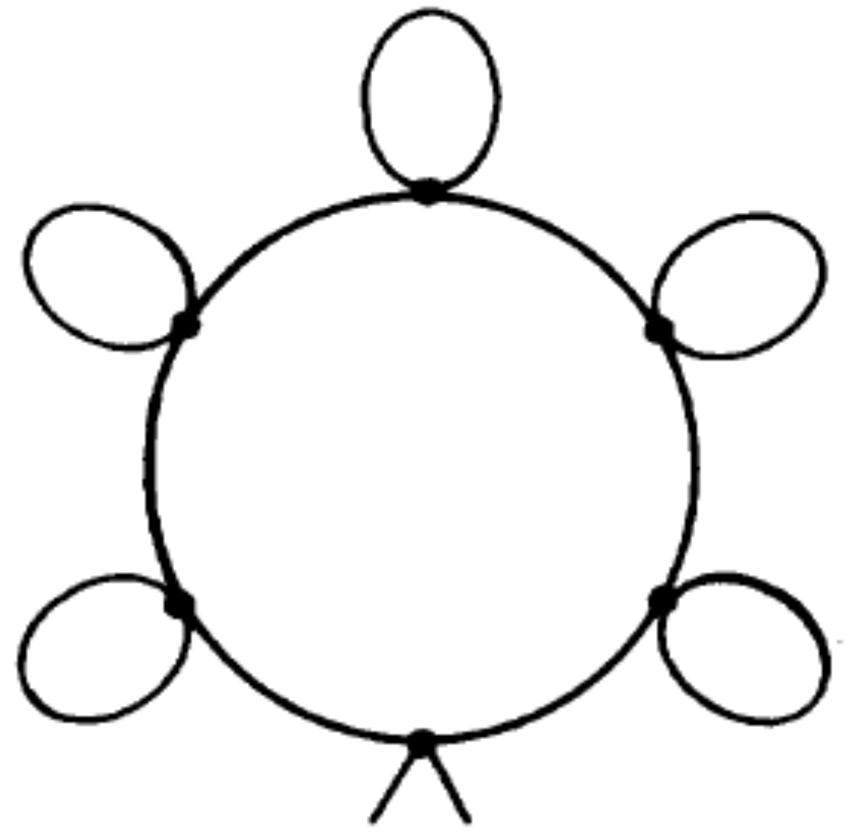
- Resummed "Daisy" Corrections Dolan Jackiw 1974, Carrington 1992
  - *n* one-vertex bubbles, one *n*-vertex bubble:

$$\sum_n \left(\int \frac{d^4k}{(2\pi)^4} \tilde{D}(k) \right)^n \cdot \int \frac{d^4k}{(2\pi)^4} \left(\tilde{D}(k) \right)^n$$



  - One-vertex bubbles yield thermal mass Π(*T*)

$$V^{\text{daisy}} = -\frac{T}{12\pi} \sum_i n_i \Big(\big[m_i^2(h,S) + \Pi_i(T) \big]^{\frac{3}{2}} - \big[m_i^2(h,S) \big]^{\frac{3}{2}} \Big)$$

A Toy Model

Field	Spin	$\mathbb{Z}_2$	mass Scale
S	0	+1	0.1 — 100
χ	½	–1	5 GeV — 5
ψ	½	–1	5 GeV — 5

Baker Mittnacht arXiv:1811.03101
see also Baker JK arXiv:1608.07578

$$\mathcal{L} \supset -\left[y_{\chi\psi}\bar{\psi}S\chi + h.c.\right] - y_\chi \bar{\chi}S\chi - y_\psi \bar{\psi}S\psi$$

A Toy Model

new scalar

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...aker JK...

DM candidate

DM decay products

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➟ χ out of equilibrium

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large enough
to keep ψ in equilibrium
$\langle S\rangle$ affects ψ mass

A Toy Model

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Baker Mittnacht arXiv:1811.03101
aker JK

DM candidate

DM decay products

small
➟ χ out of equilibrium

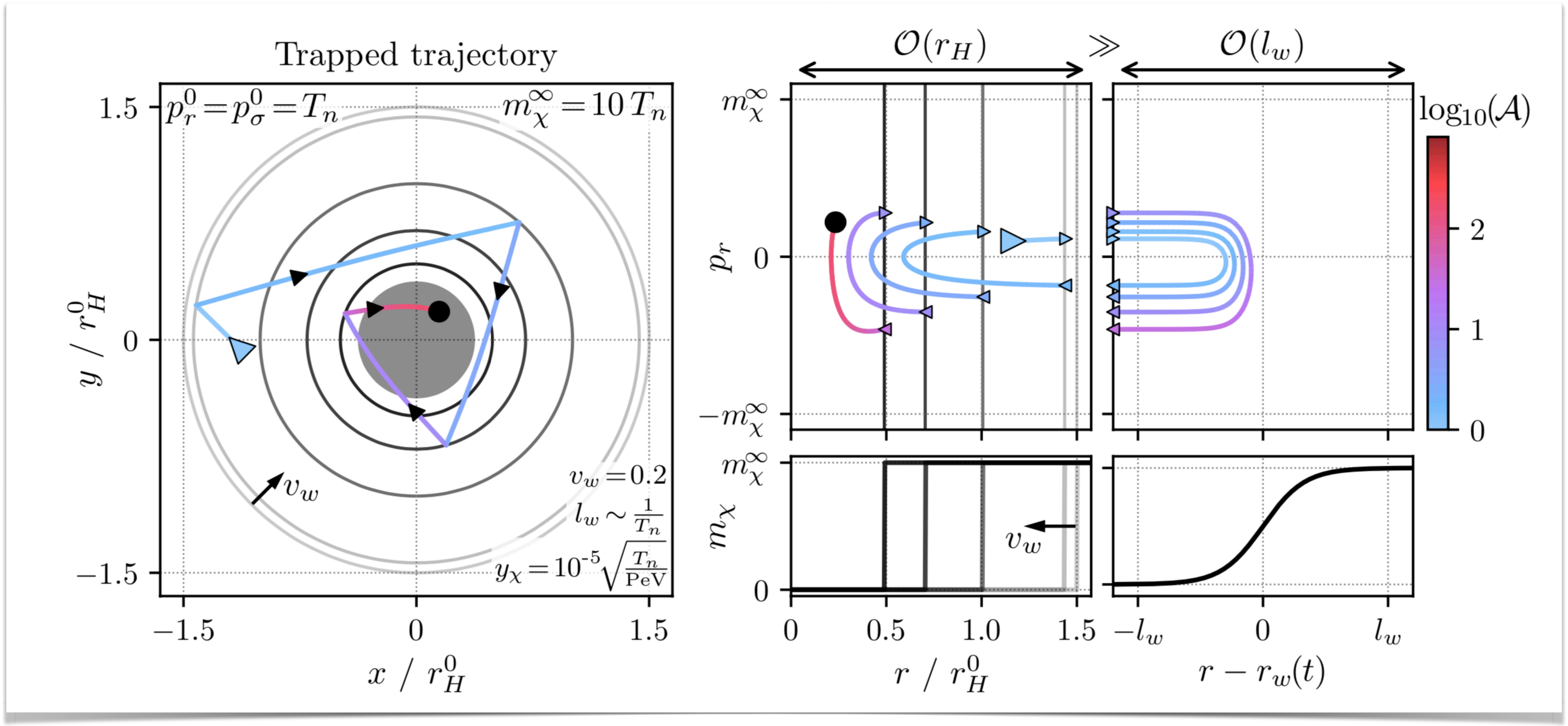
$$\mathcal{L} \supset -\left[y_{\chi\psi}\bar{\psi}S\chi + h.c.\right] - y_\chi \bar{\chi}S\chi - y_\psi \bar{\psi}S\psi$$

temporarily allows decay
$\chi \to \psi\, S$

large enough
to keep ψ in equilibrium
$\langle S \rangle$ **affects** ψ **mass**

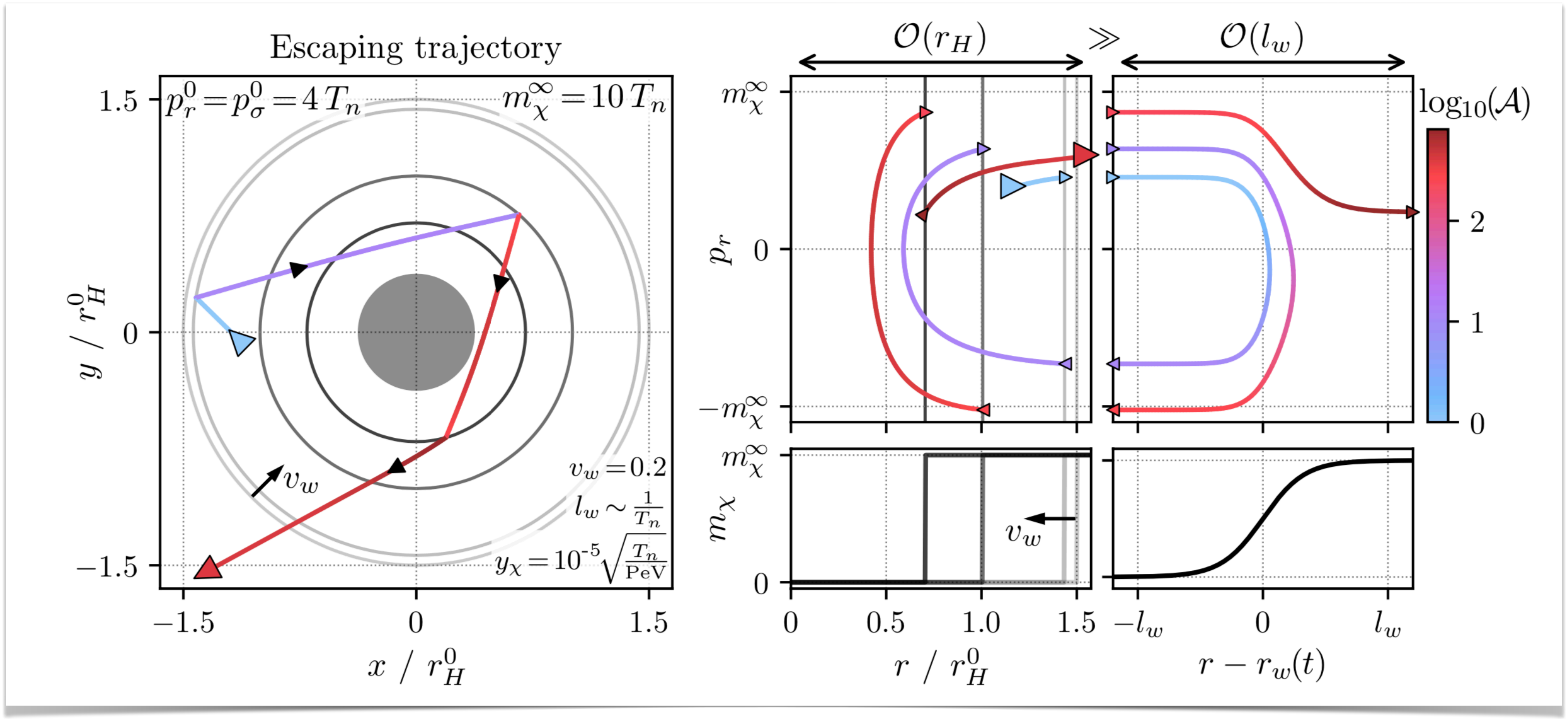
Primordial Black Holes from Phase Transitions

Typical Particle Trajectories (1)



particle reflected multiple times, eventually ends up in black hole

Typical Particle Trajectories (2)



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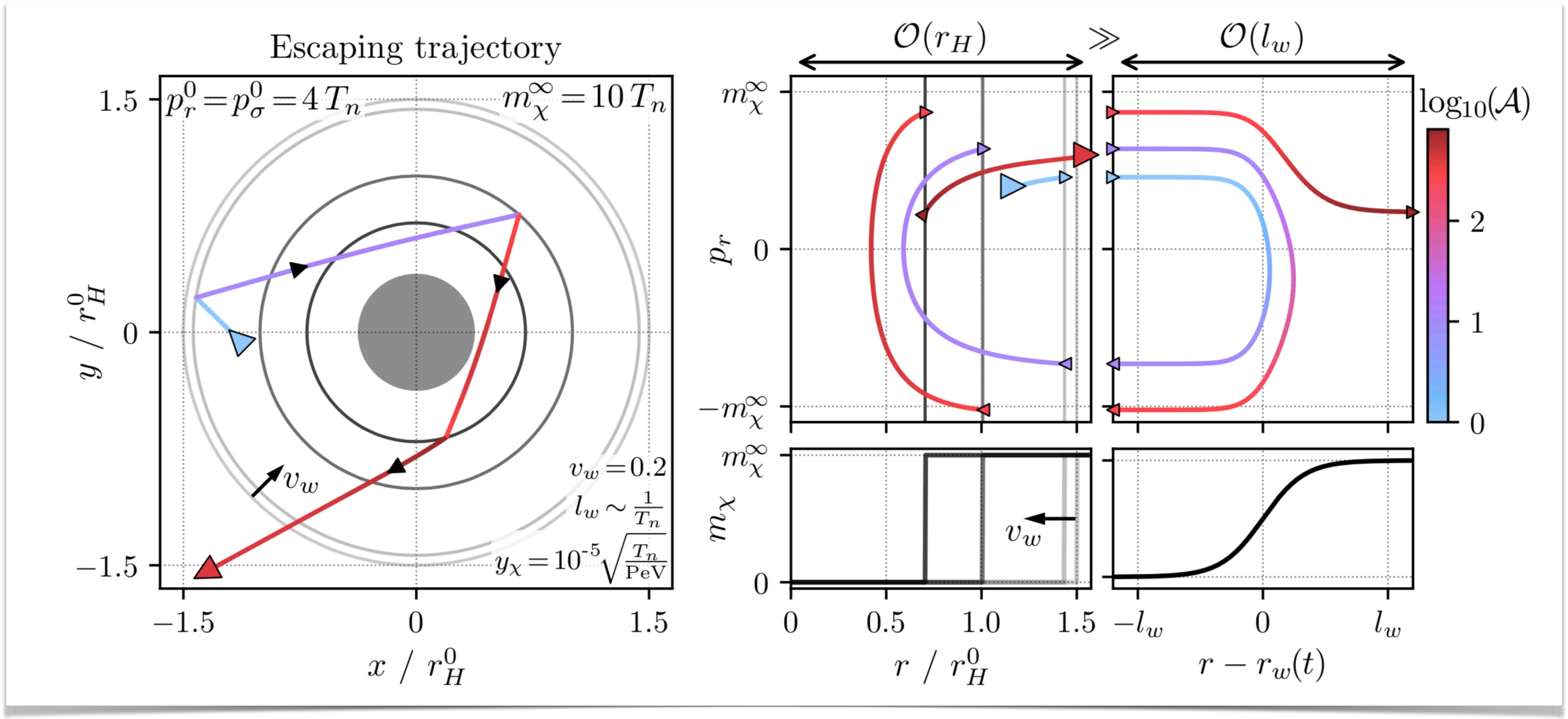
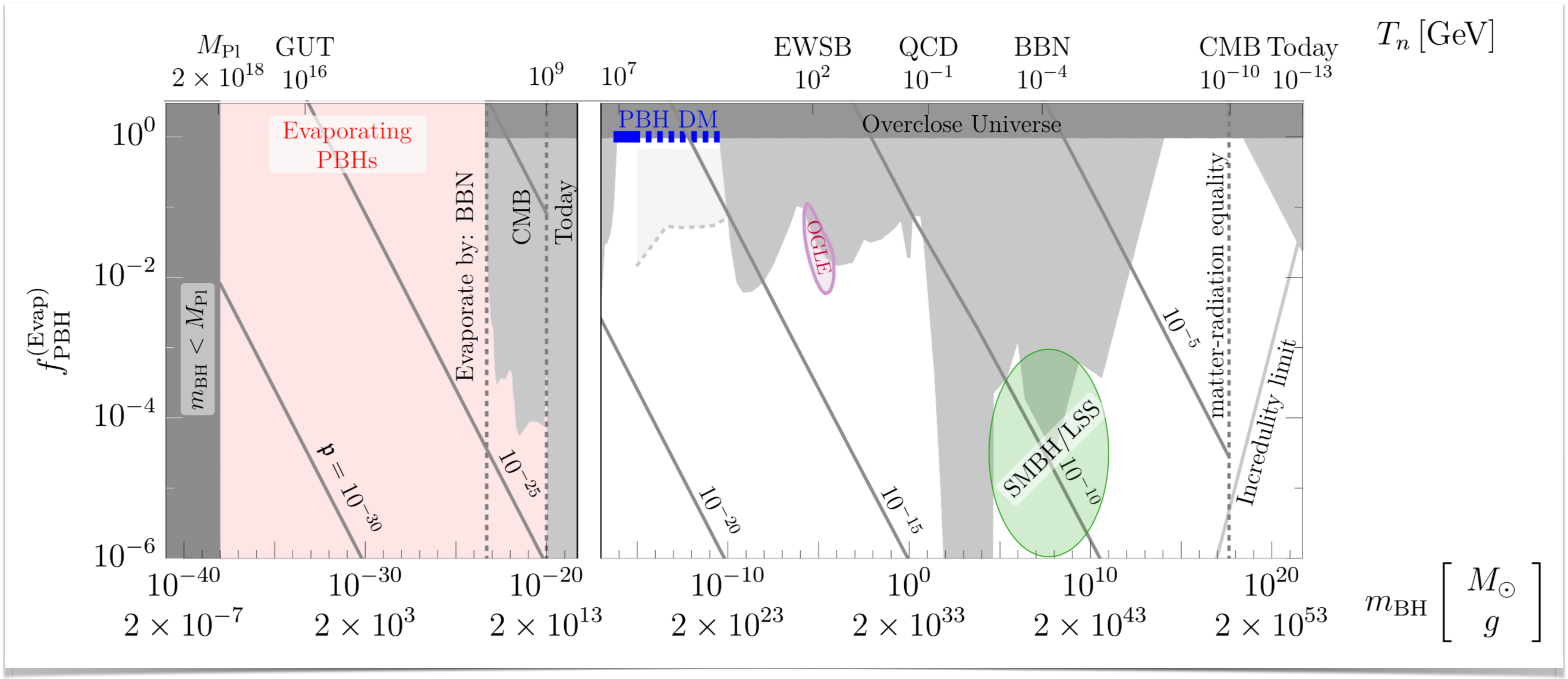


particle reflected multiple times, gains energy each time;
eventually has sufficient energy too pass through the wall

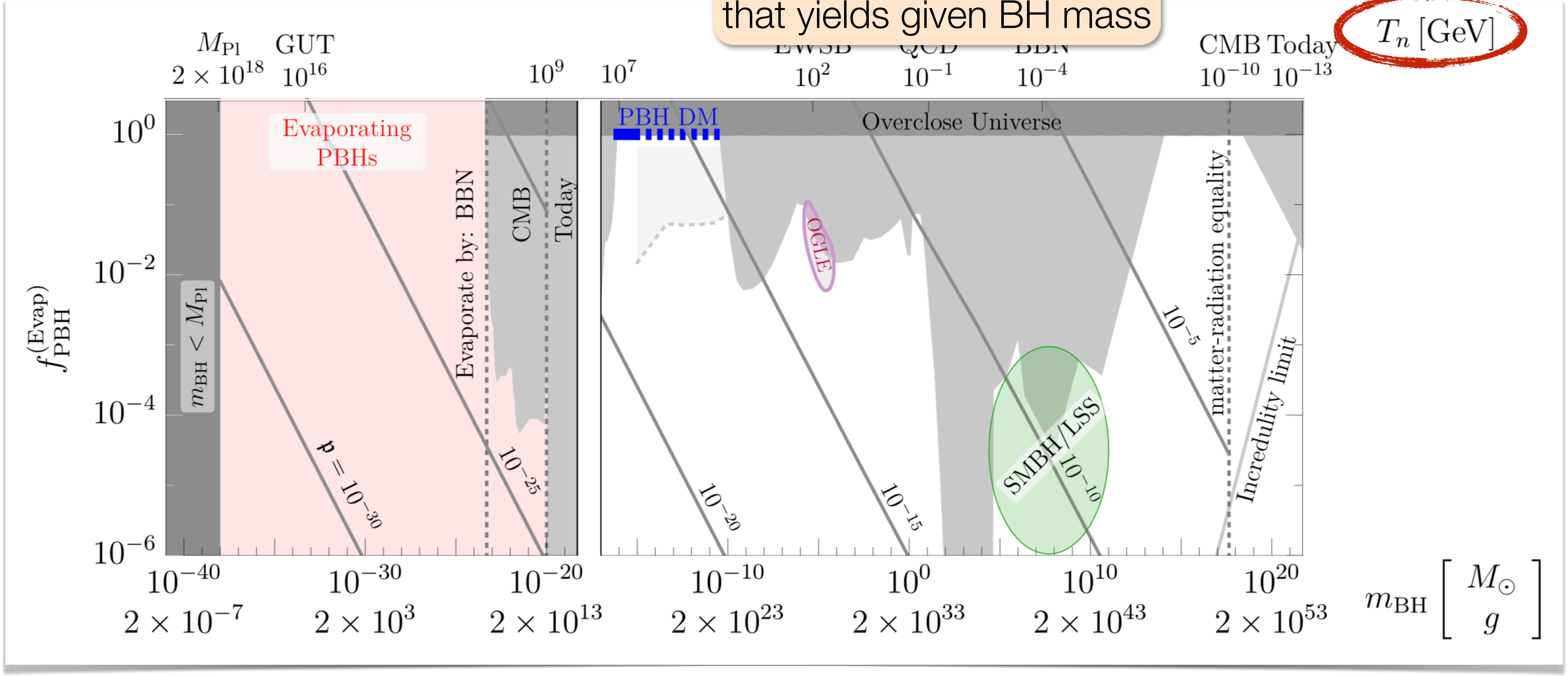
Requirements



Baker Breitbach JK Mittnacht, arXiv:2105.07481 and arXiv:2110.00005

Requirements

phase transition **temperature** that yields given BH mass



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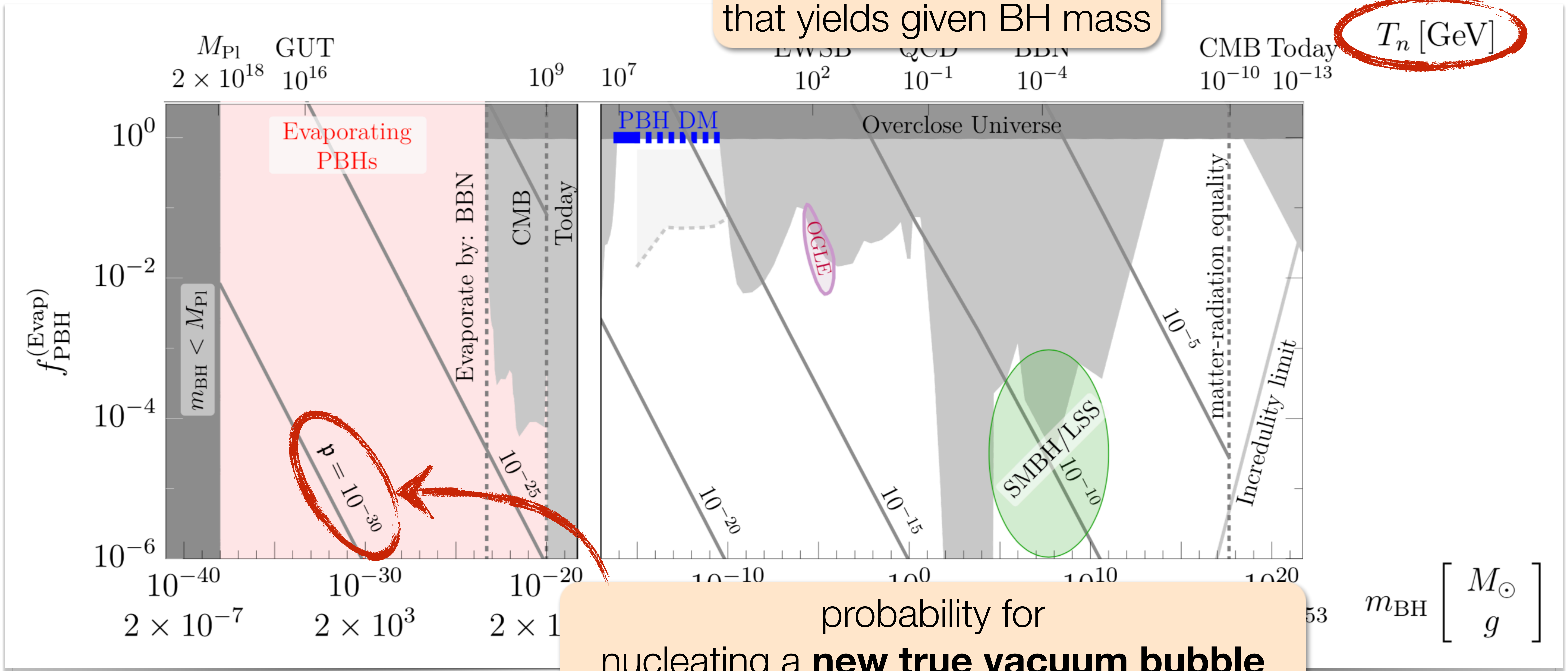
Requirements

phase transition **temperature** that yields given BH mass



probability for nucleating a **new true vacuum bubble** in the shrinking false vacuum one

…and arXiv:2110.00005

Complementary Signals and Opportunities

Gravitational Waves from Phase Transitions

- Three contributions
  - bubble collisions
  - collisions of sound waves (generated during bubble collisions)
  - turbulence
- How to compute GW signals from these contributions
  - requires numerical simulations (large uncertainties)
  - Results parameterised e.g. as

$$\Omega_{\rm GW}(f) \equiv \frac{1}{\rho_c}\frac{\mathrm{d}\rho_{\rm GW}(f)}{\mathrm{d}\log f} \simeq \mathcal{N}\,\Delta\left(\frac{\kappa\,\alpha}{1+\alpha}\right)^p\left(\frac{H}{\beta}\right)^q s(f)$$

Gravitational Waves from Phase Transitions

- Four relevant parameters
  - bubble nucleation temperature T^{nuc}
  - strength of the phase transition

$$\alpha \equiv \frac{\epsilon}{\rho_R} = \frac{1}{\rho_R}\left(-\Delta V + T^{\rm nuc} \frac{\partial \Delta V}{\partial T}\bigg|_{T^{\rm nuc}} \right)$$

  - inverse duration of the phase transition

$$\frac{\beta}{H} = T_h^{\rm nuc} \frac{{\rm d}S_E(T)}{{\rm d}T}\bigg|_{T_h^{\rm nuc}}$$

  - bubble wall velocity v_w

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  - strength of the p[hase transition] latent heat release

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total radiation density

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Euclidean action corresponding to the transition path in field space

  - bubble wall velocity v_w

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