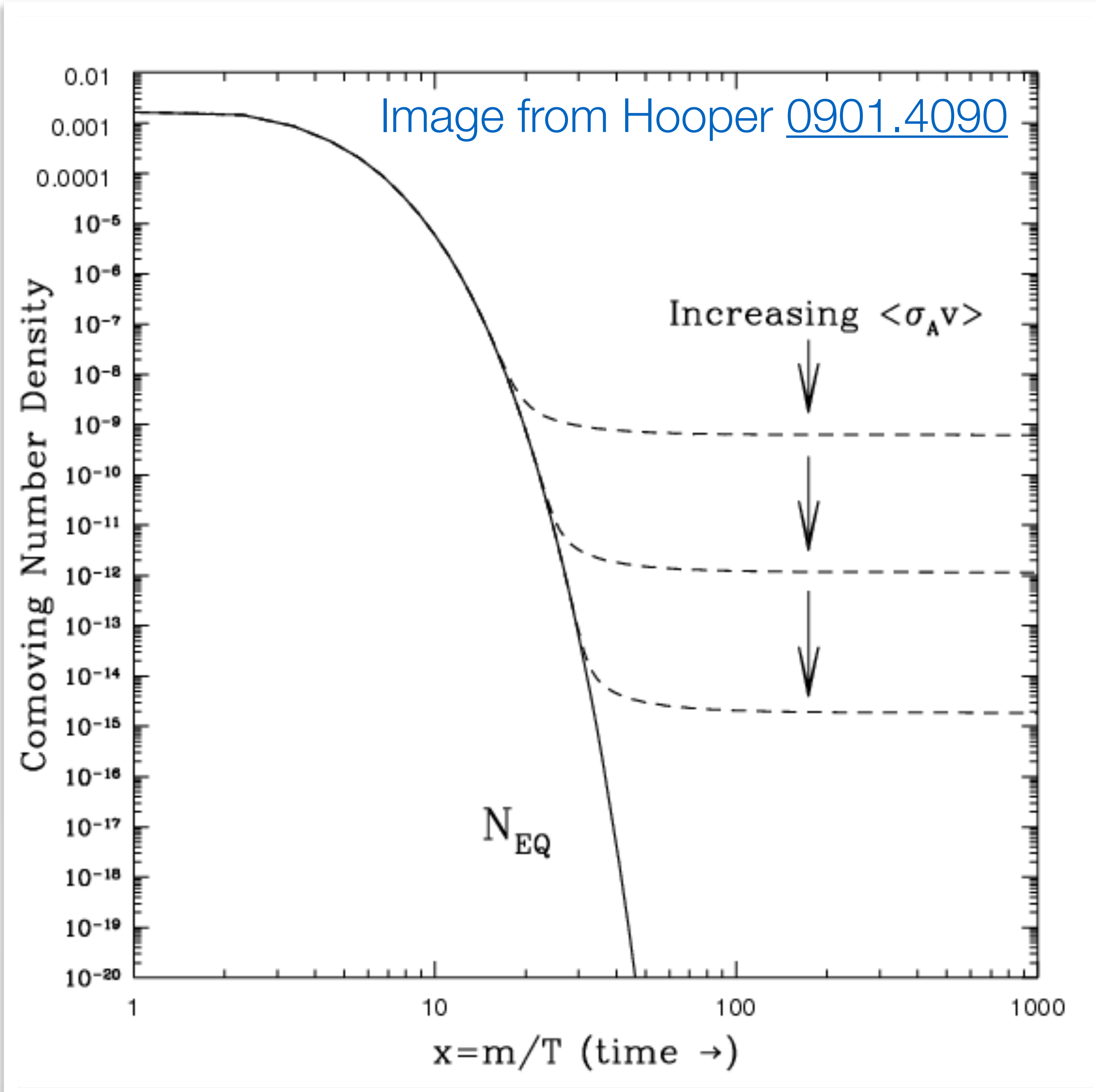
Dark Matter from Cosmological Phase Transitions

Joachim Kopp (CERN & Uni Mainz)
Chung And University BSM Workshop | 08.02.2022

DM in the early Universe: Thermal Freeze-Out



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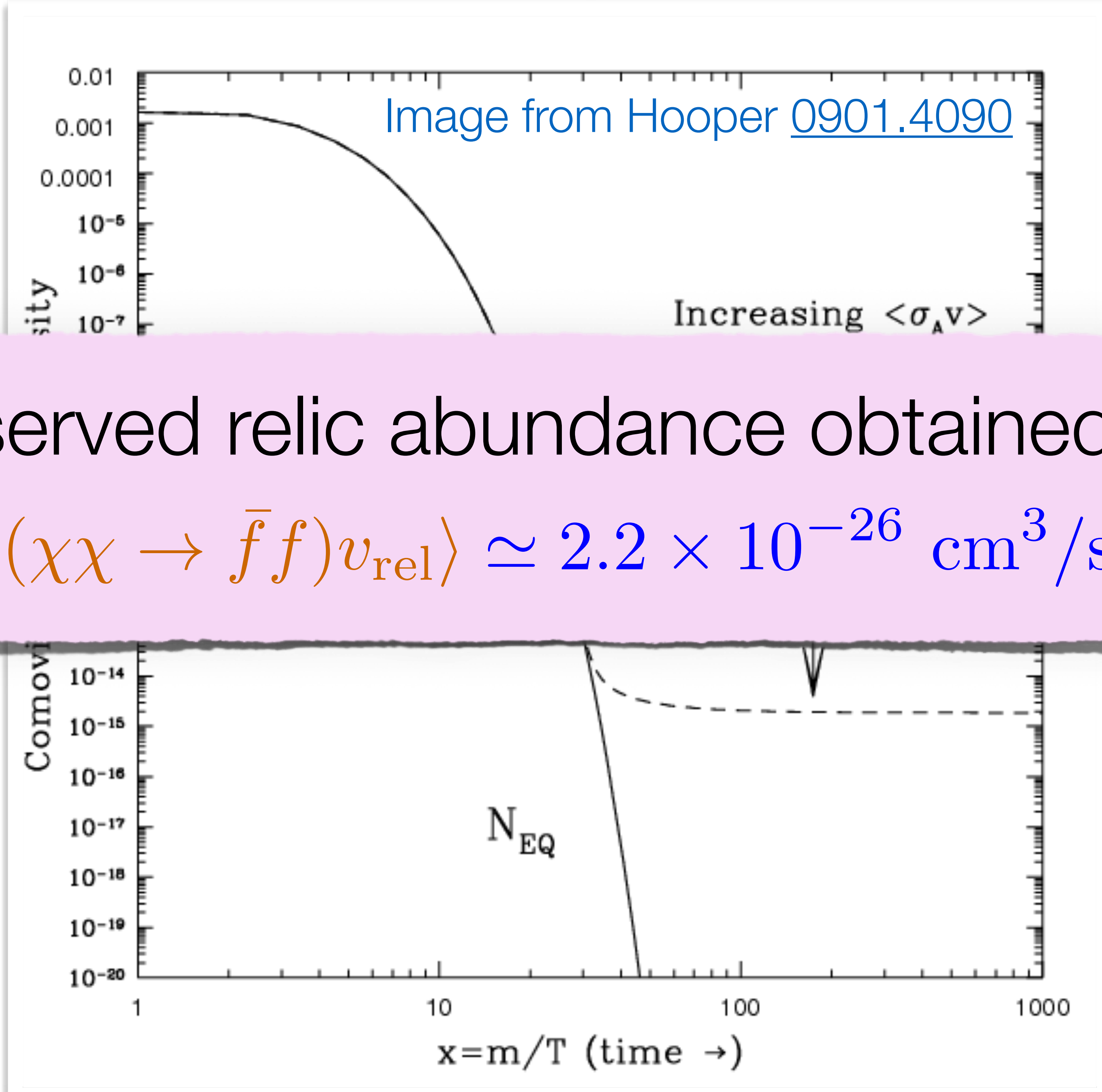

observed relic abundance obtained for

$$\langle \sigma(\chi\chi \to \bar{f} f) v_{\rm rel} \rangle \simeq 2.2 \times 10^{-26}\ {\rm cm}^3/{\rm sec}$$

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Beyond Thermal Freeze-Out

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- One alternative: setting the DM abundance in a cosmological phase transition
- This talk:
  - Filtered Dark Matter
  - Primordial Black Holes from Phase Transitions

Phase Transitions Primer

Phase Transitions in Everyday Life

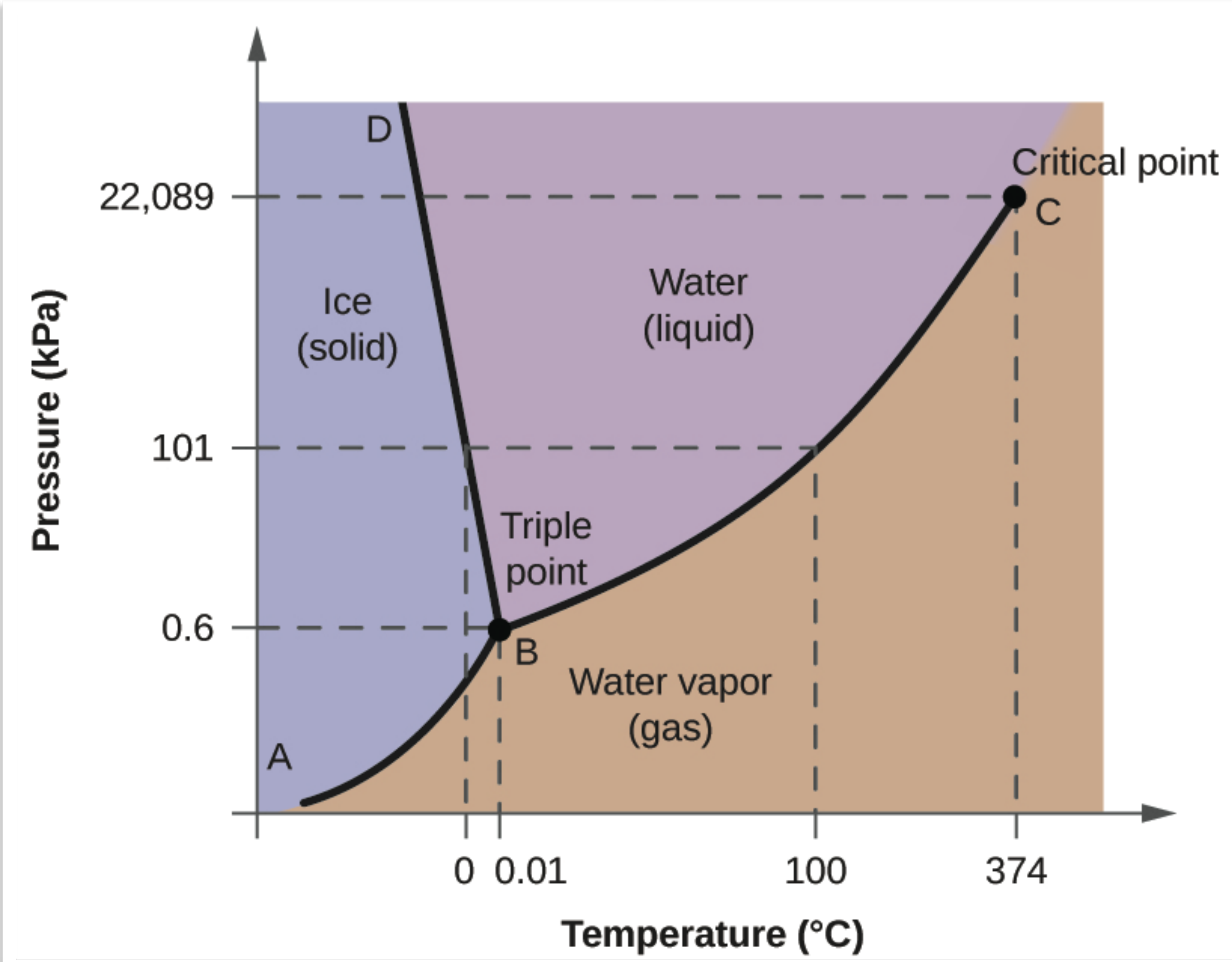
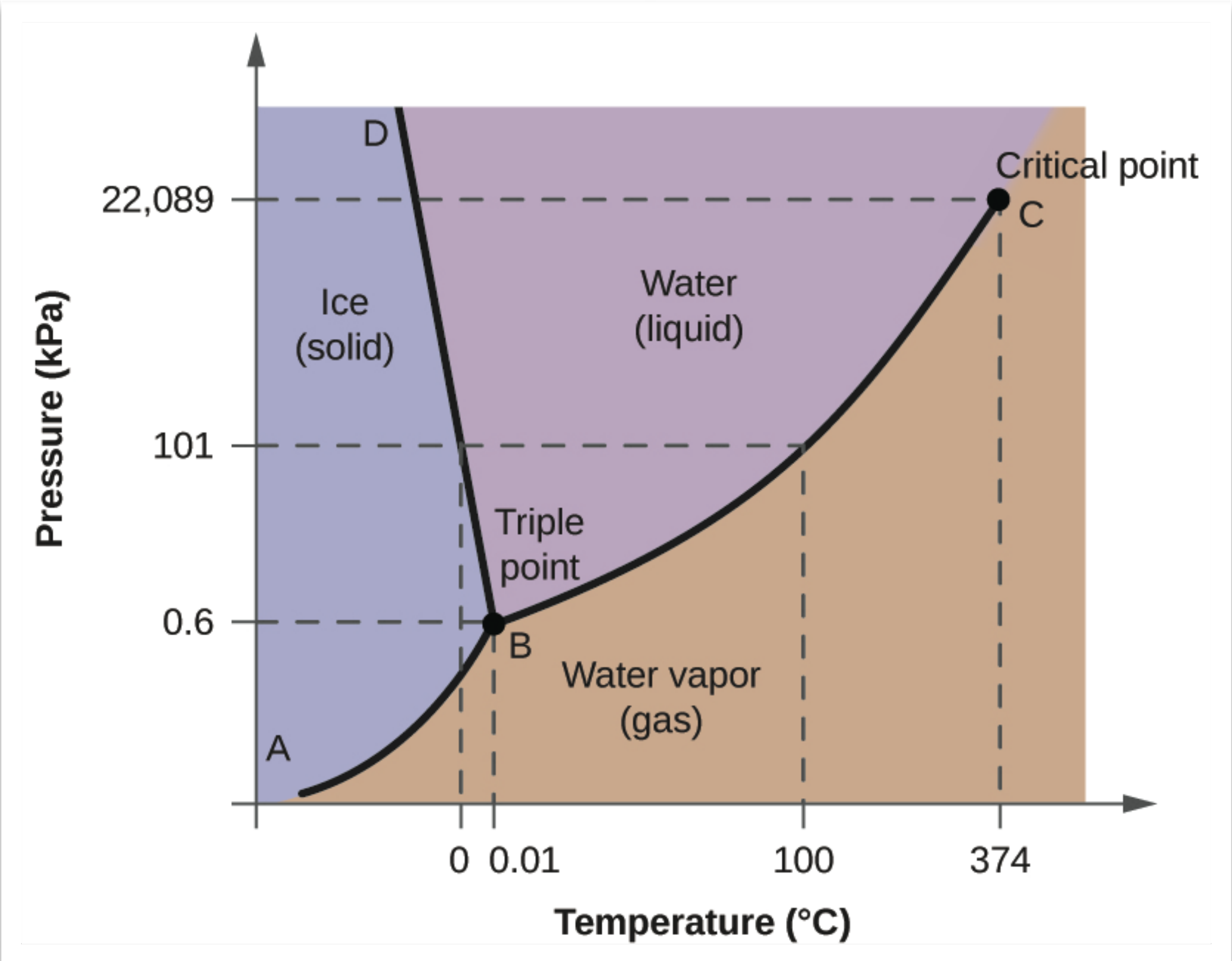


Image Credit: libretexts.org

Phase Transitions in (a Physicist's) Everyday Life



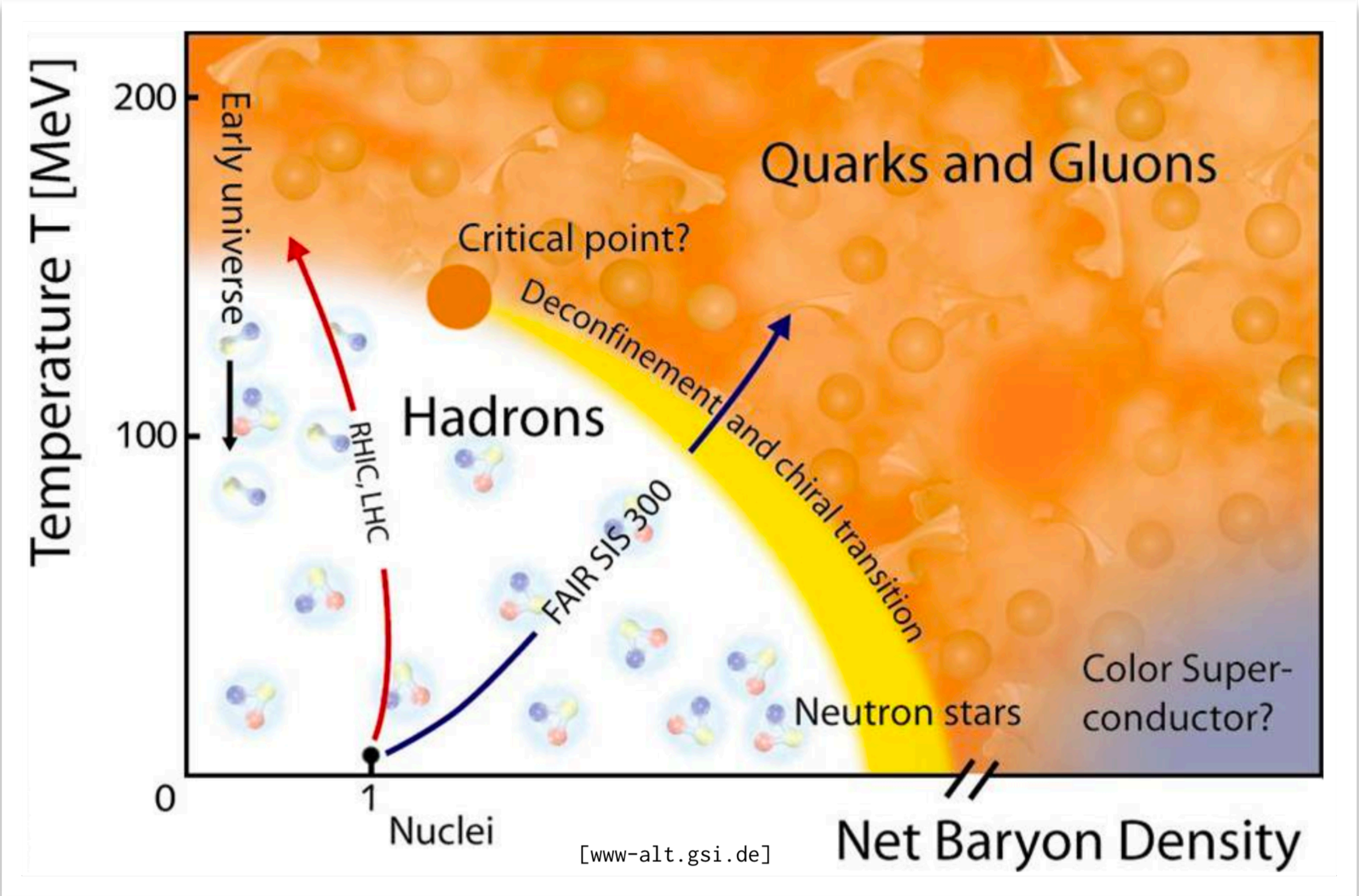


Image Credit: libretexts.org, Ralf-Arno Tripolt

The Order of a Phase Transition

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

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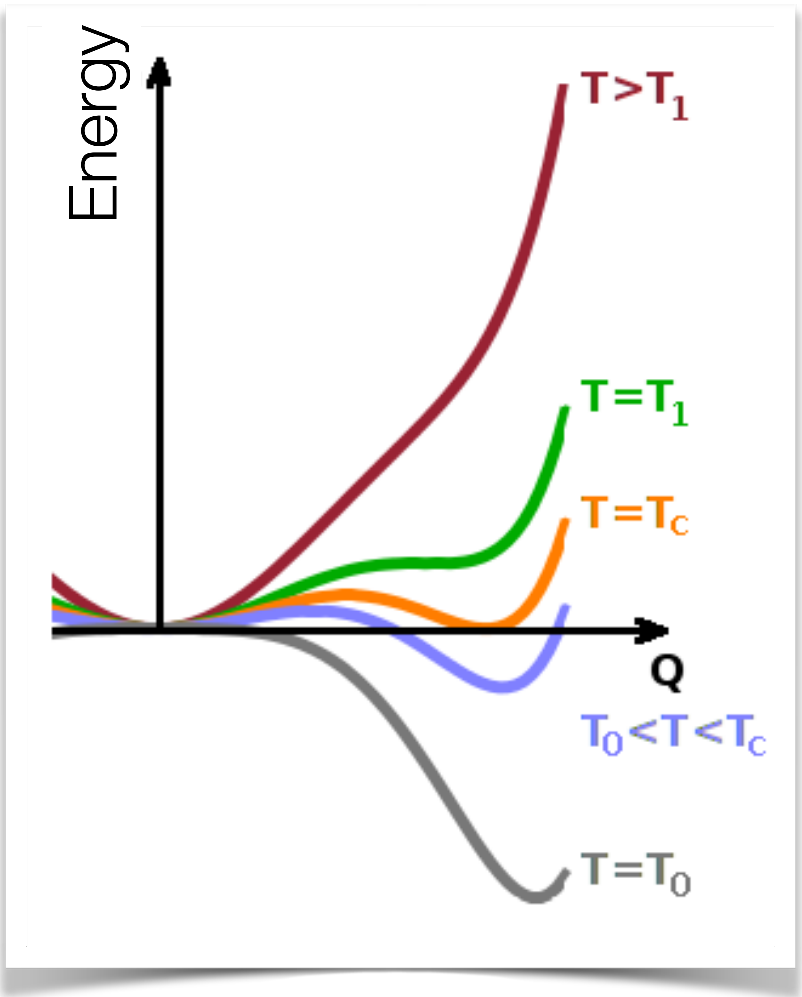

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- ☑ Order Parameter O: a quantity measuring the change in the … nsition
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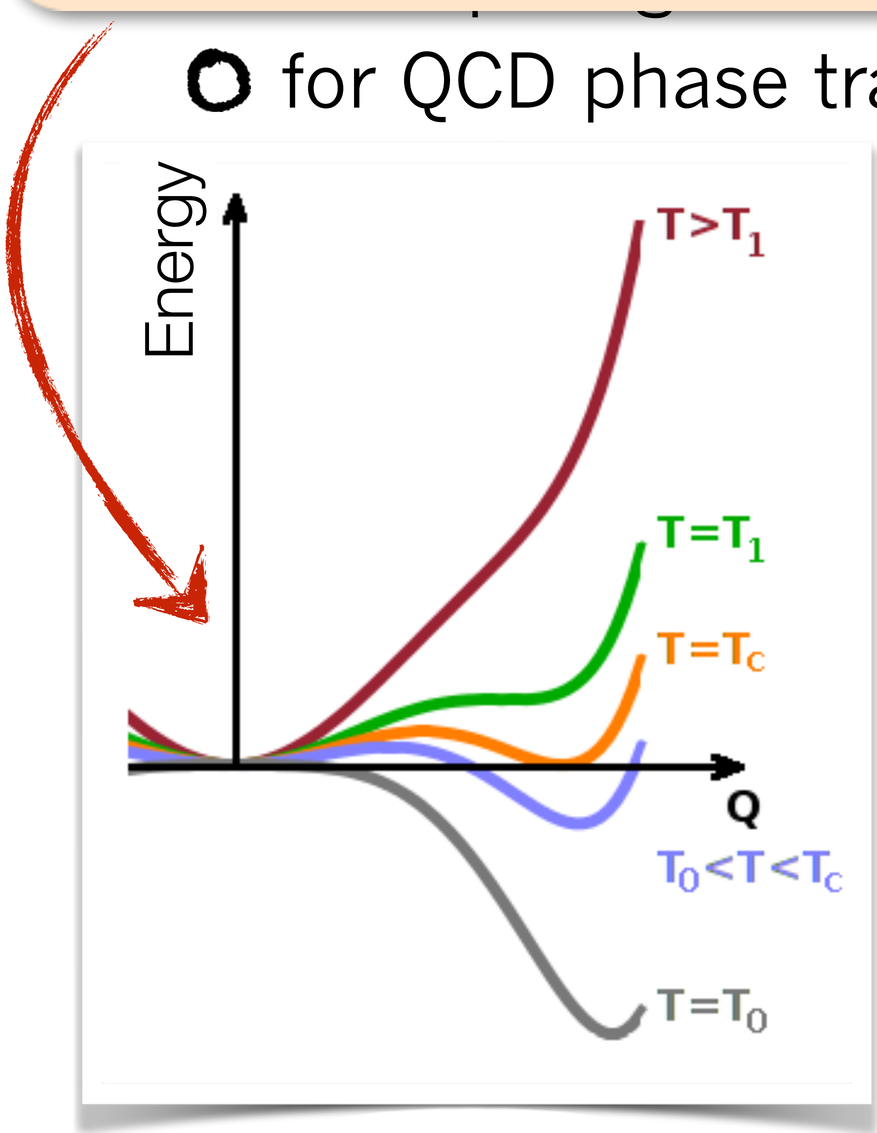
  - for QCD phase transition: quark condensate $\langle \bar{q}_L q_R \rangle$

1st order transition
order parameter changes discontinuously



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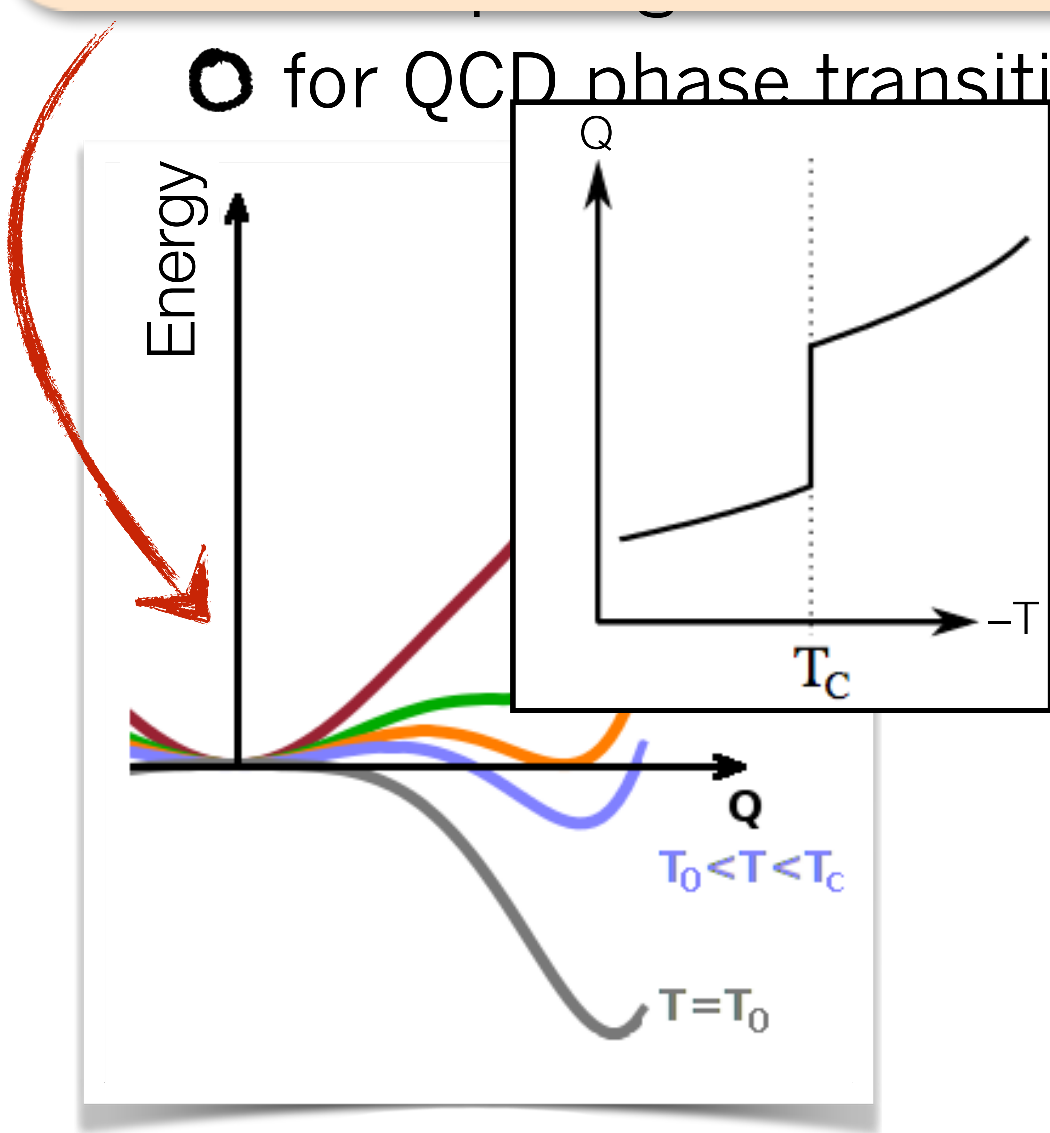

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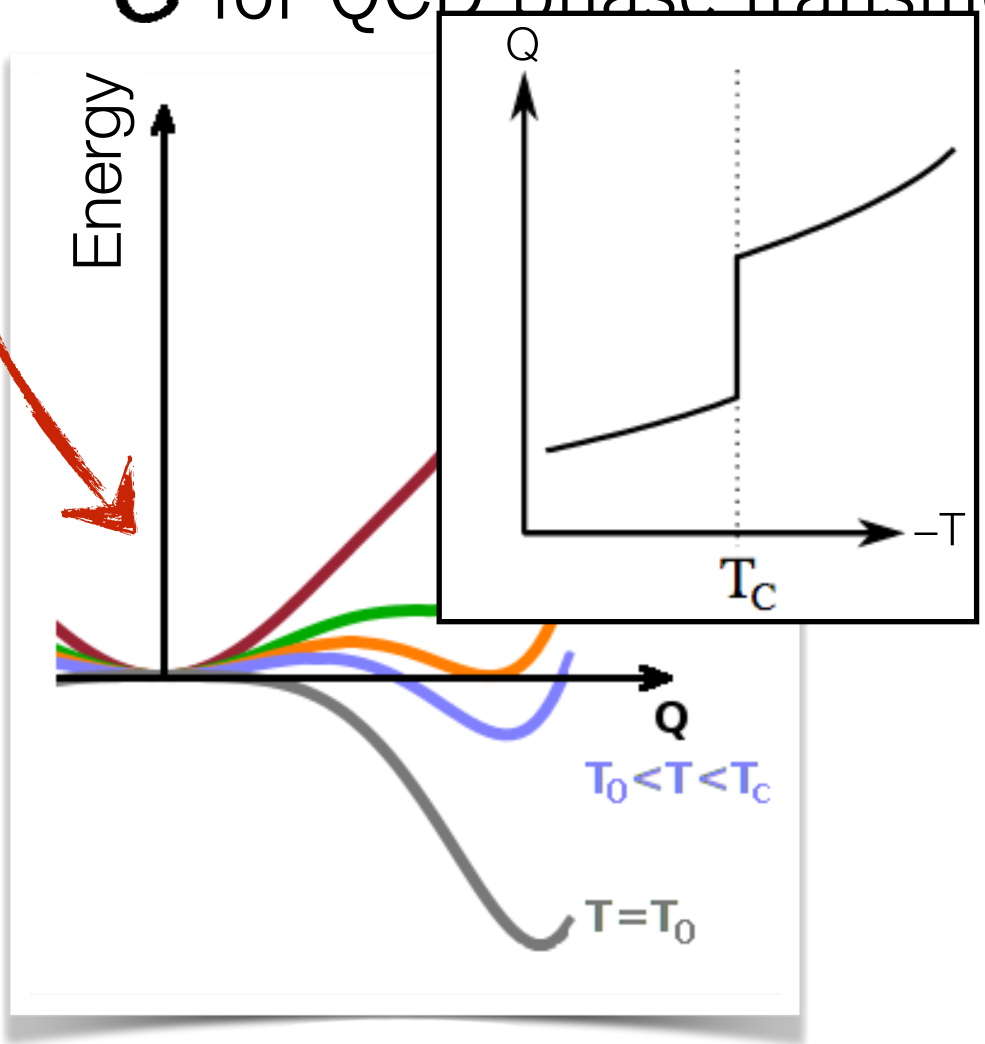

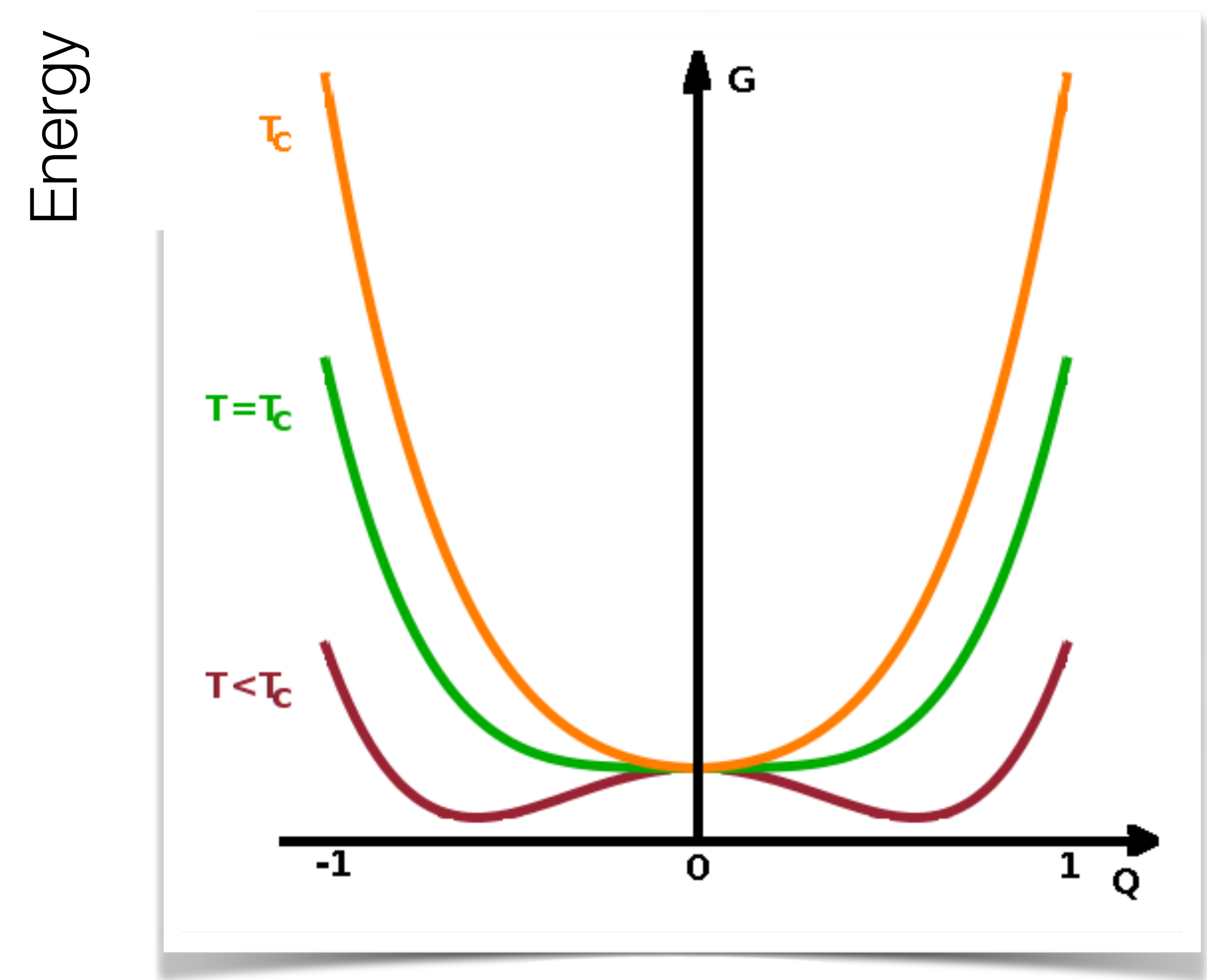

Images: Rudi Winter, Caroline Röhr and Heinz Gericke

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2nd order transition / crossover
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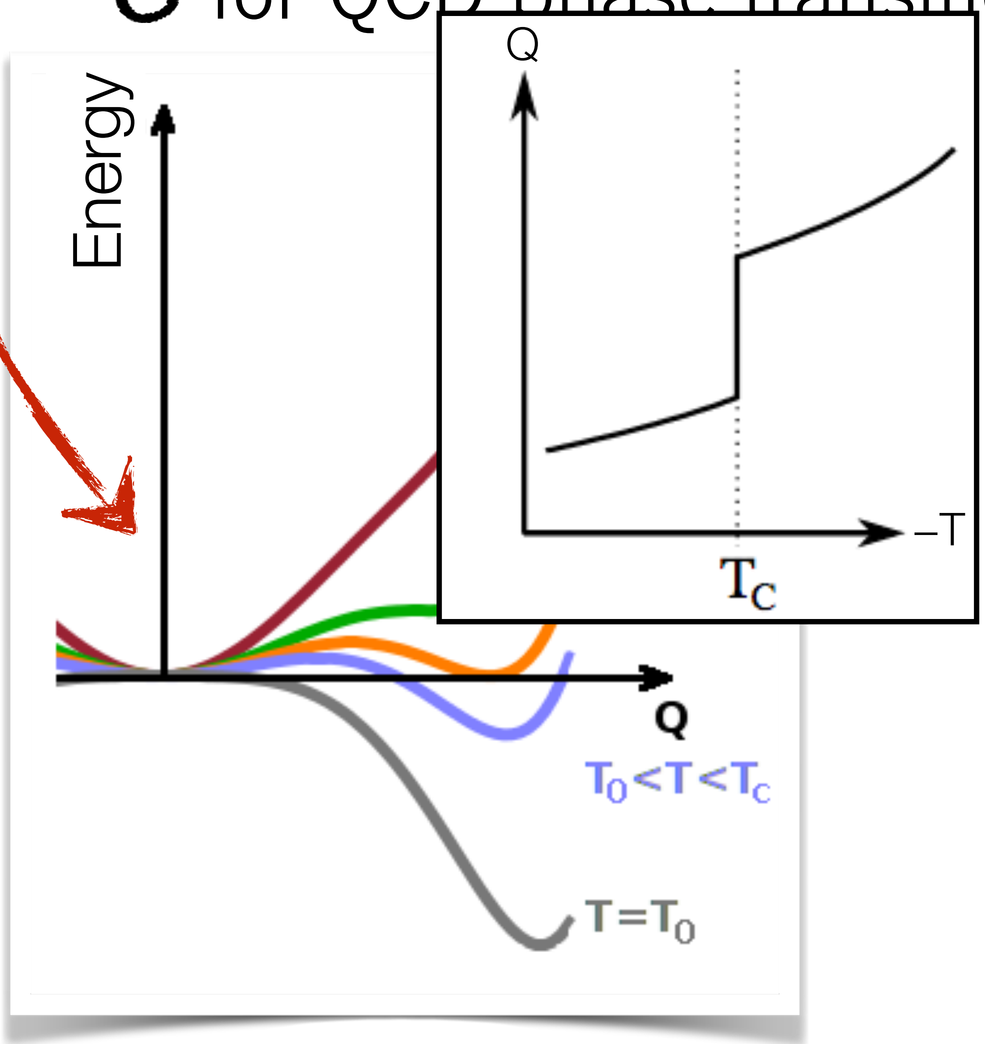

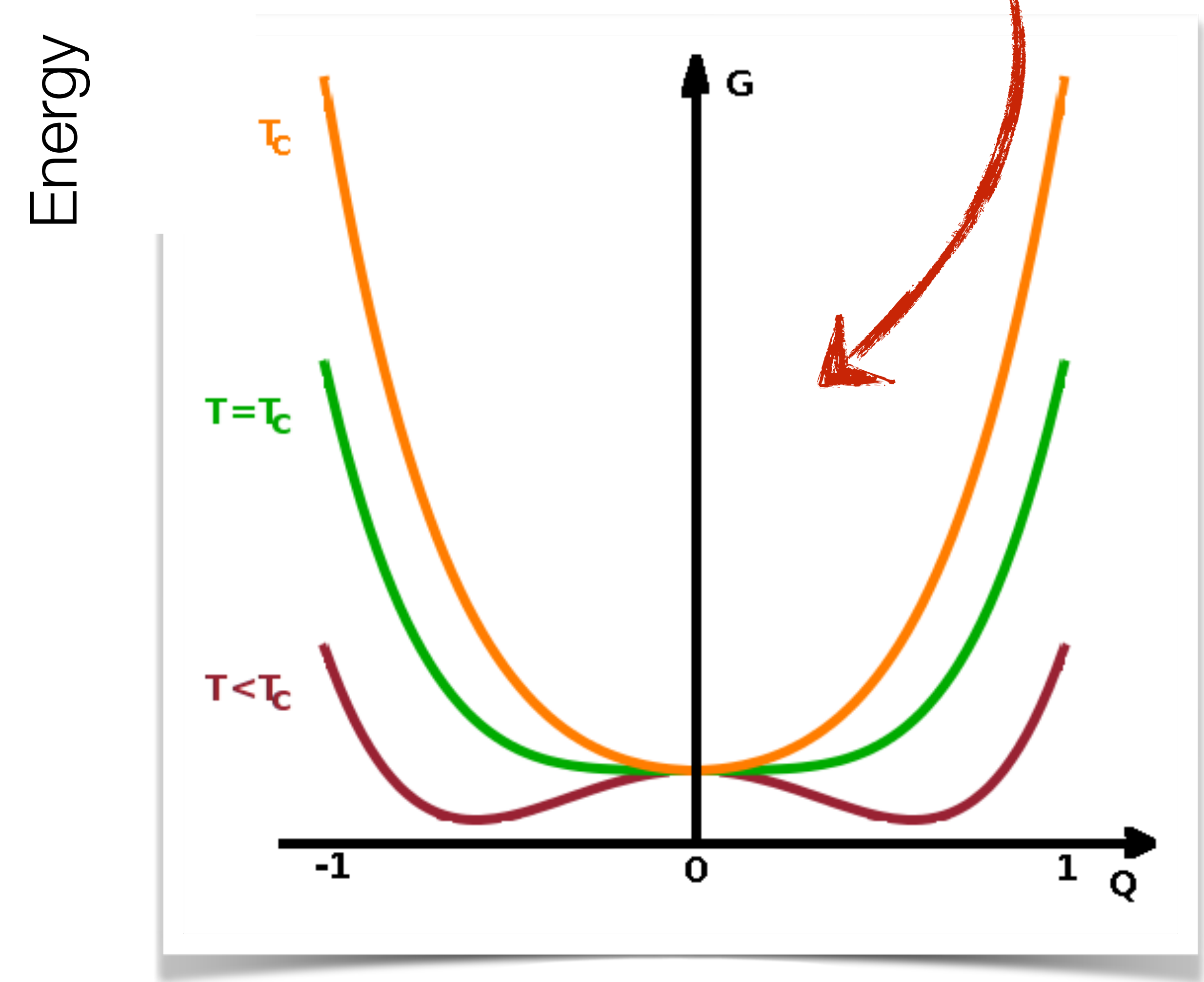

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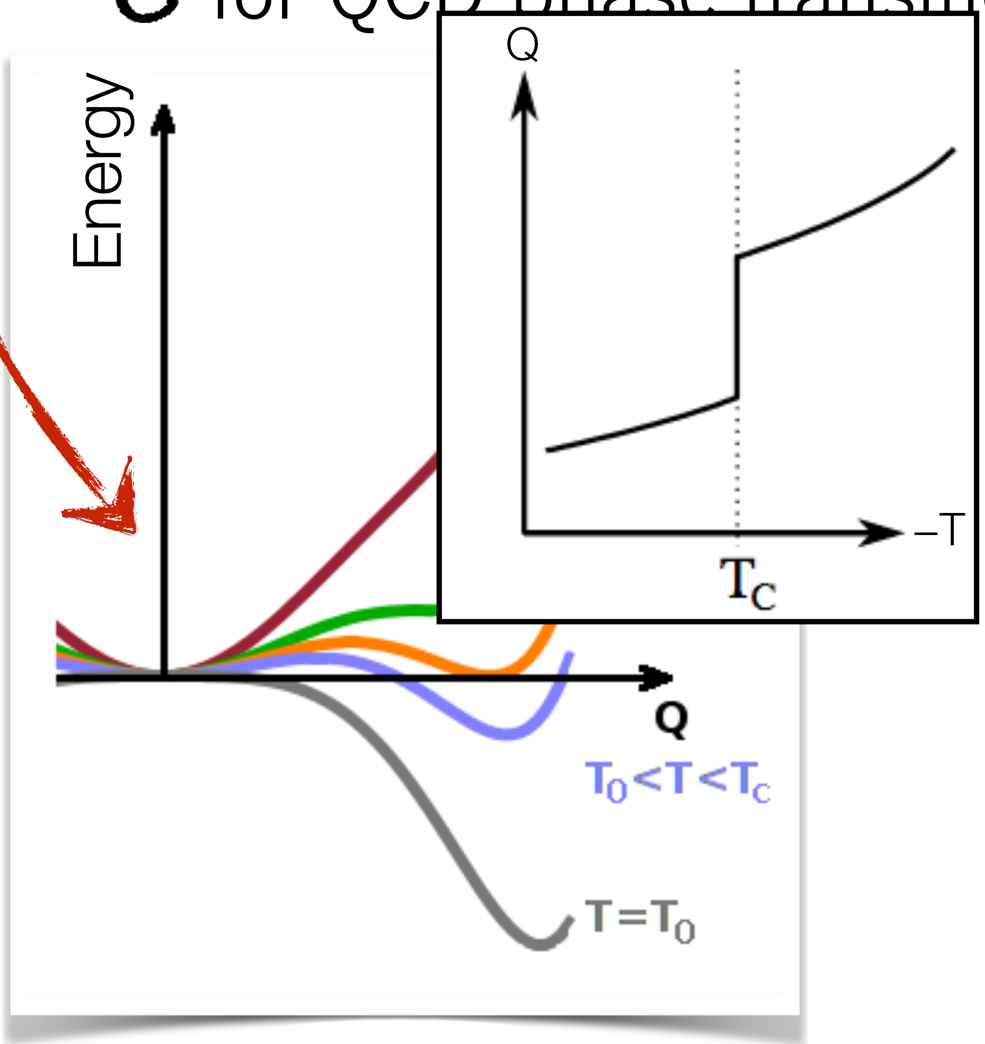

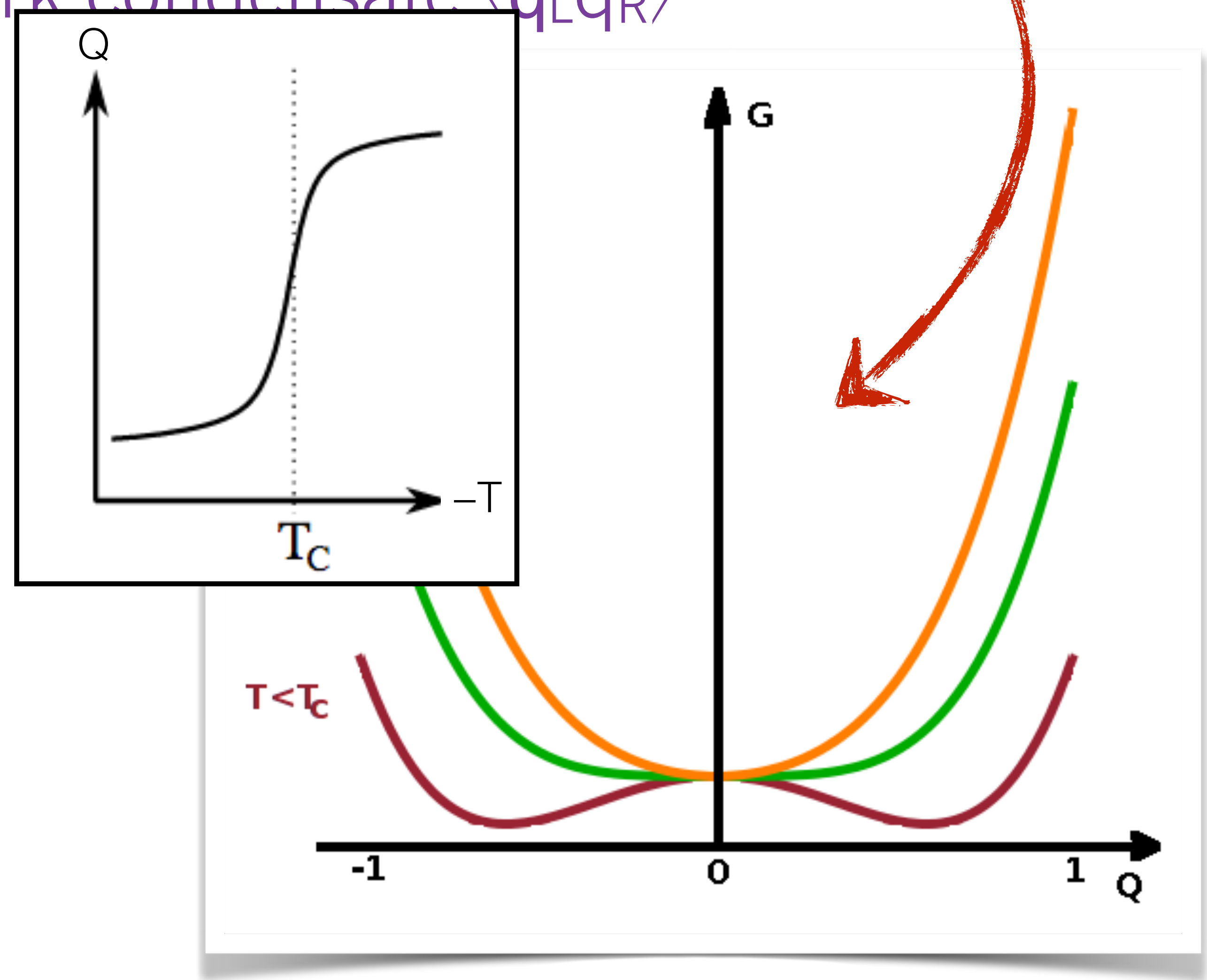

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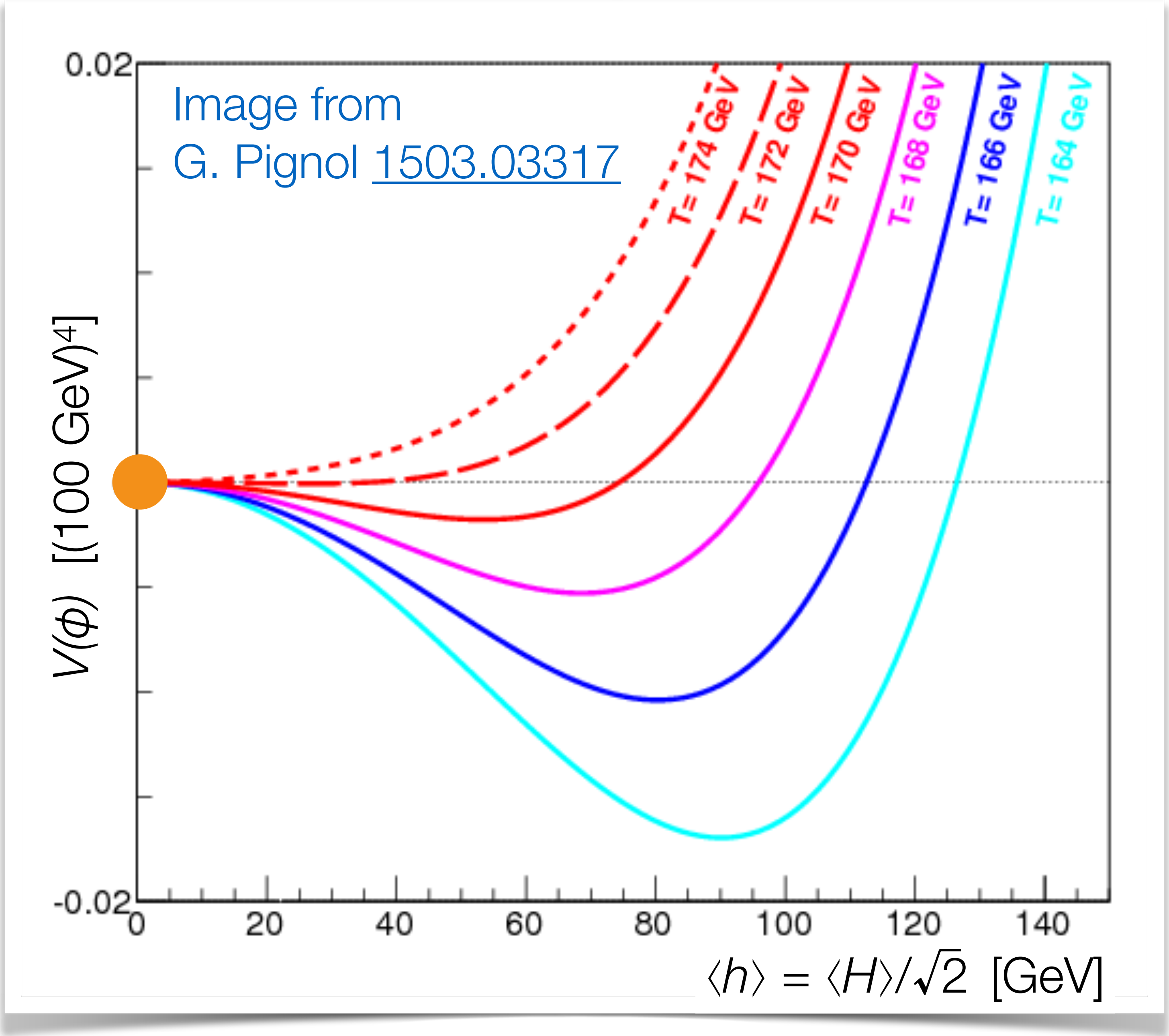
The Electroweak Phase Transition



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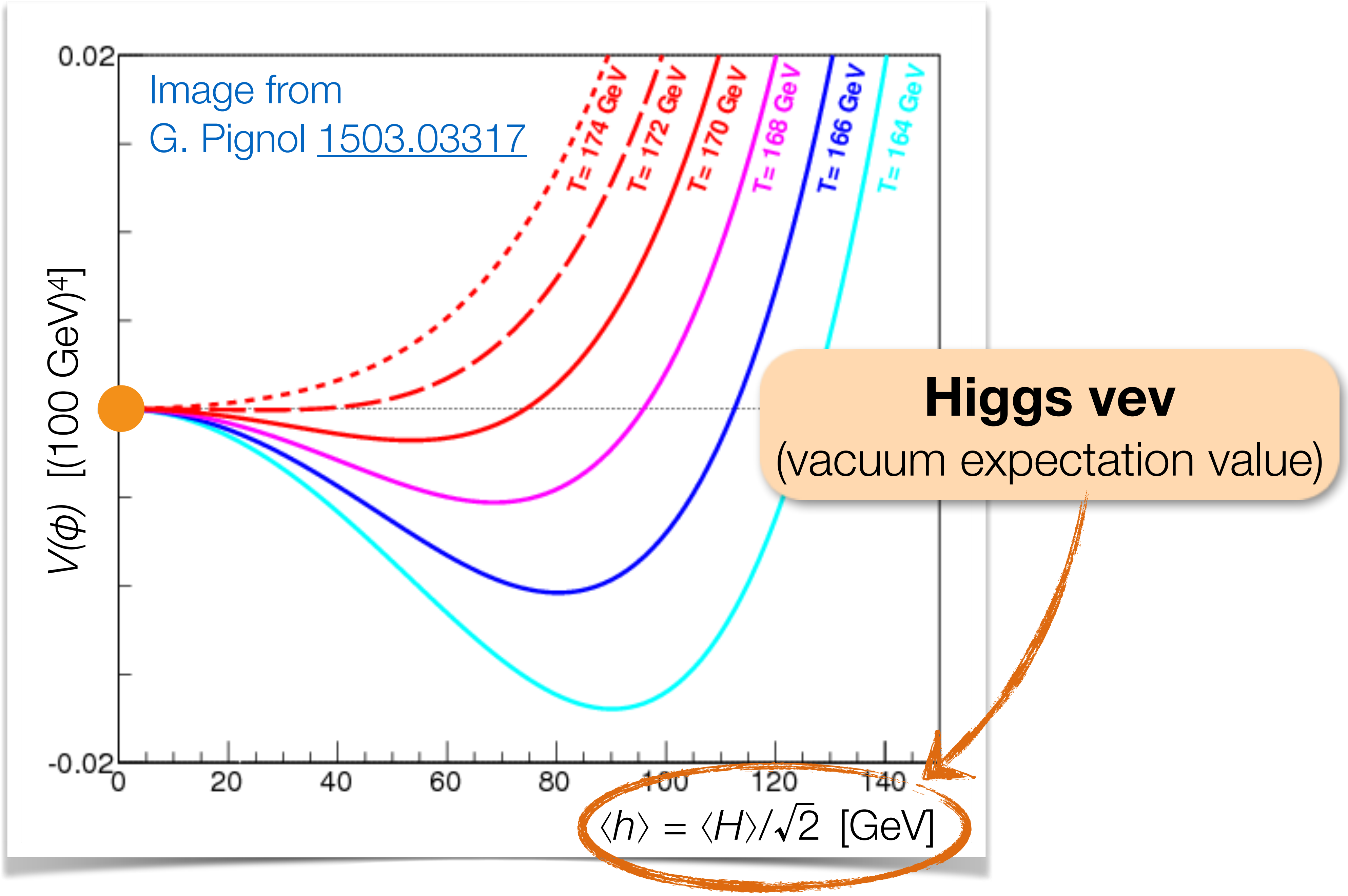

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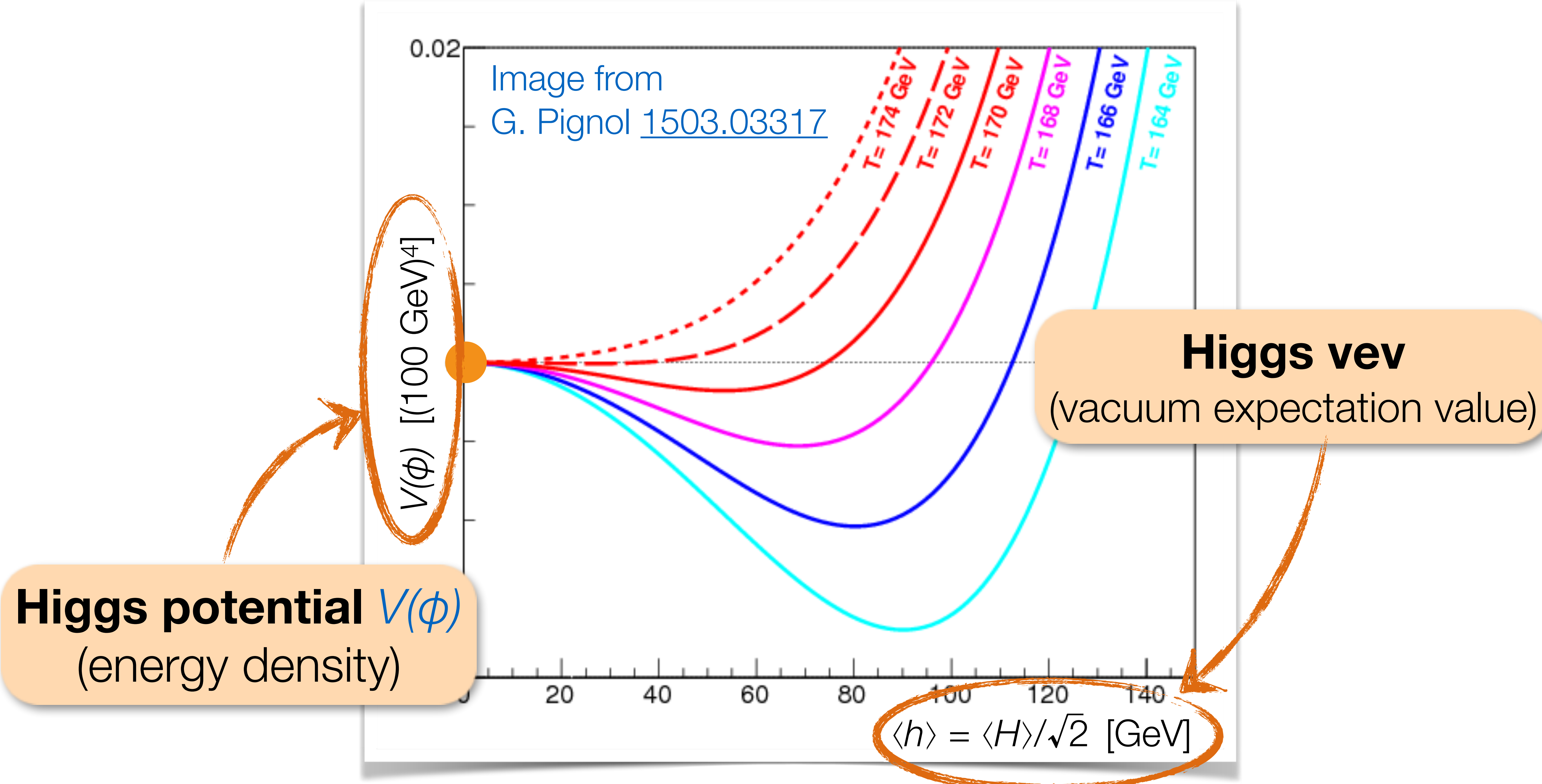

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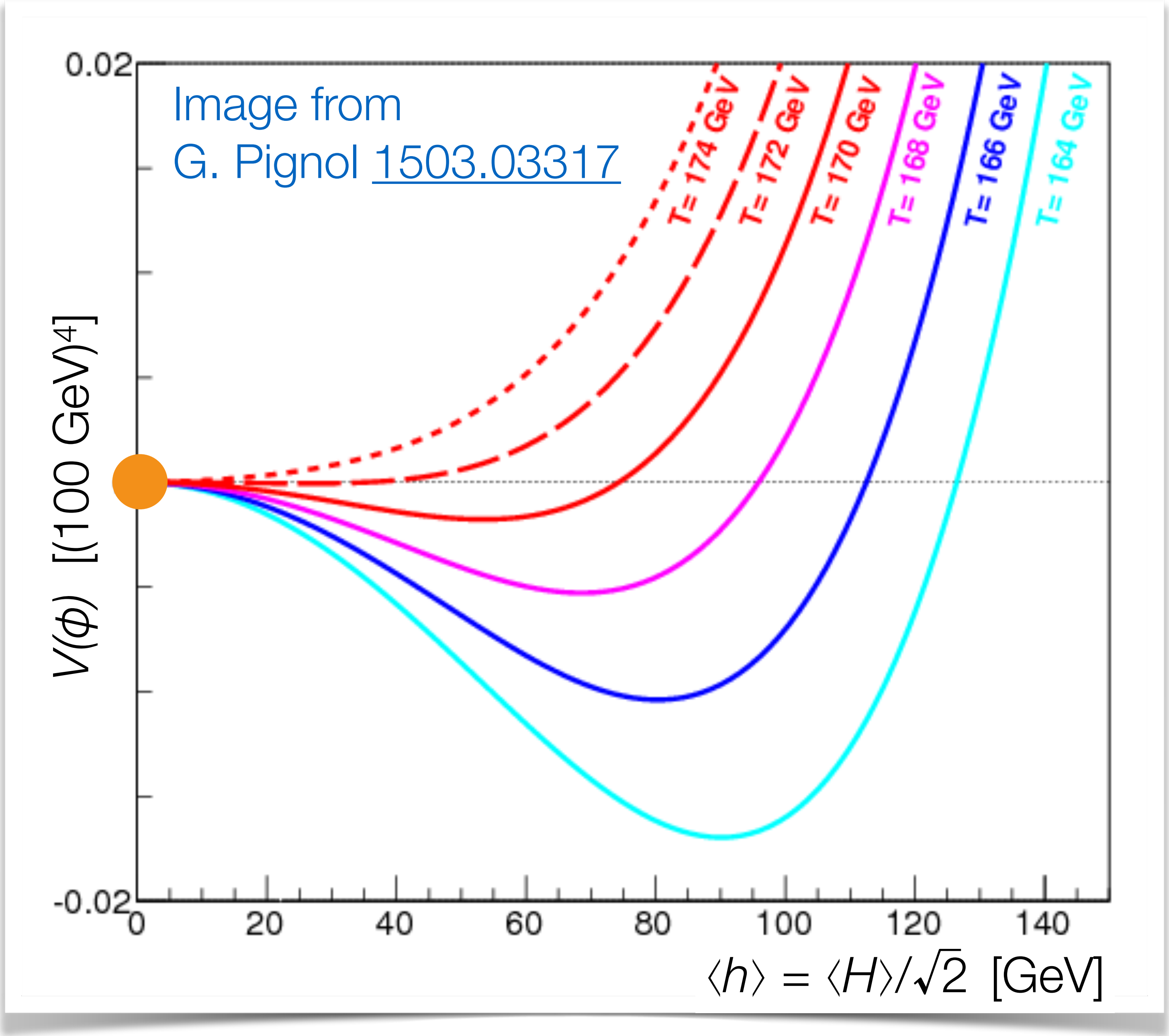

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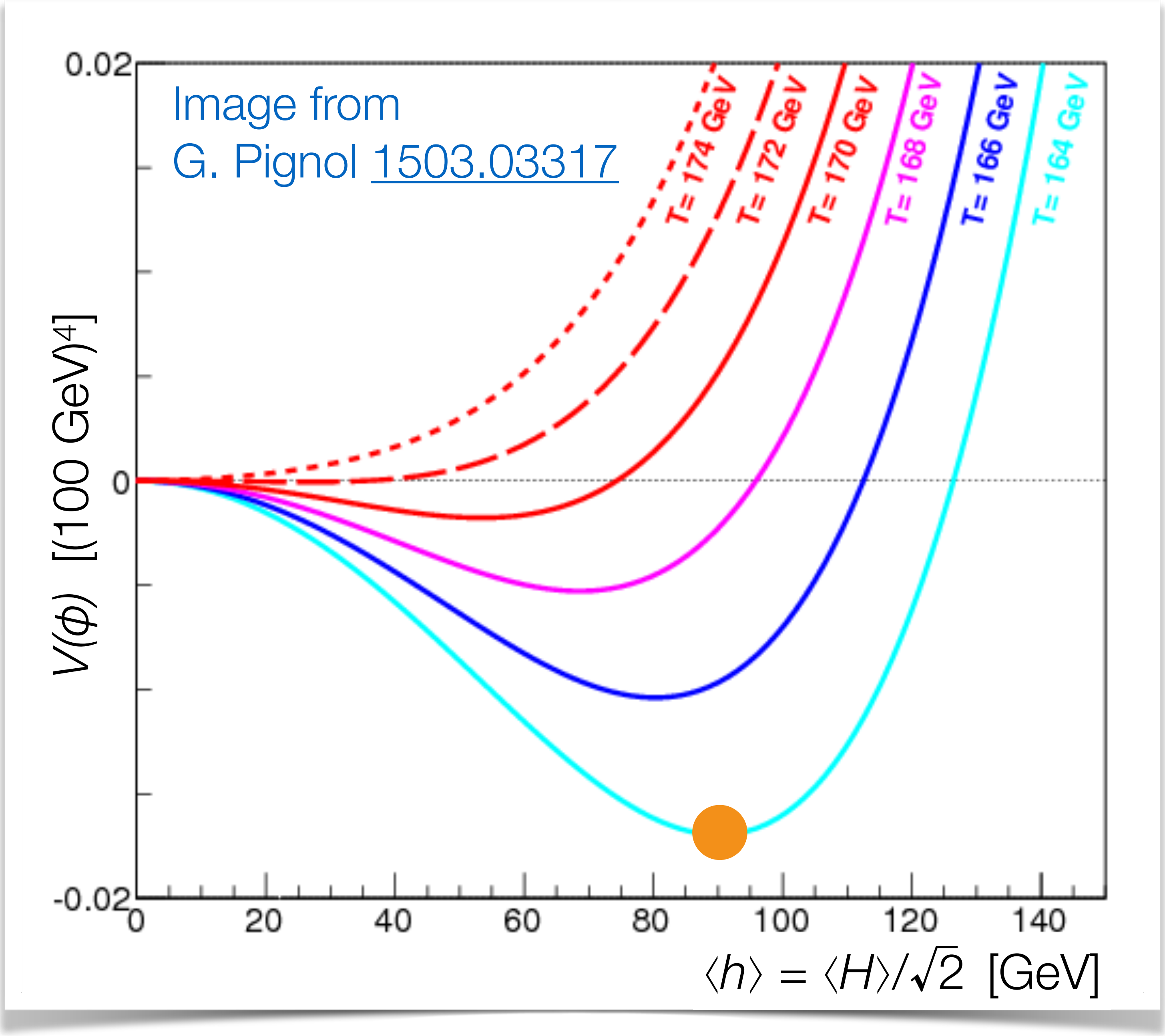

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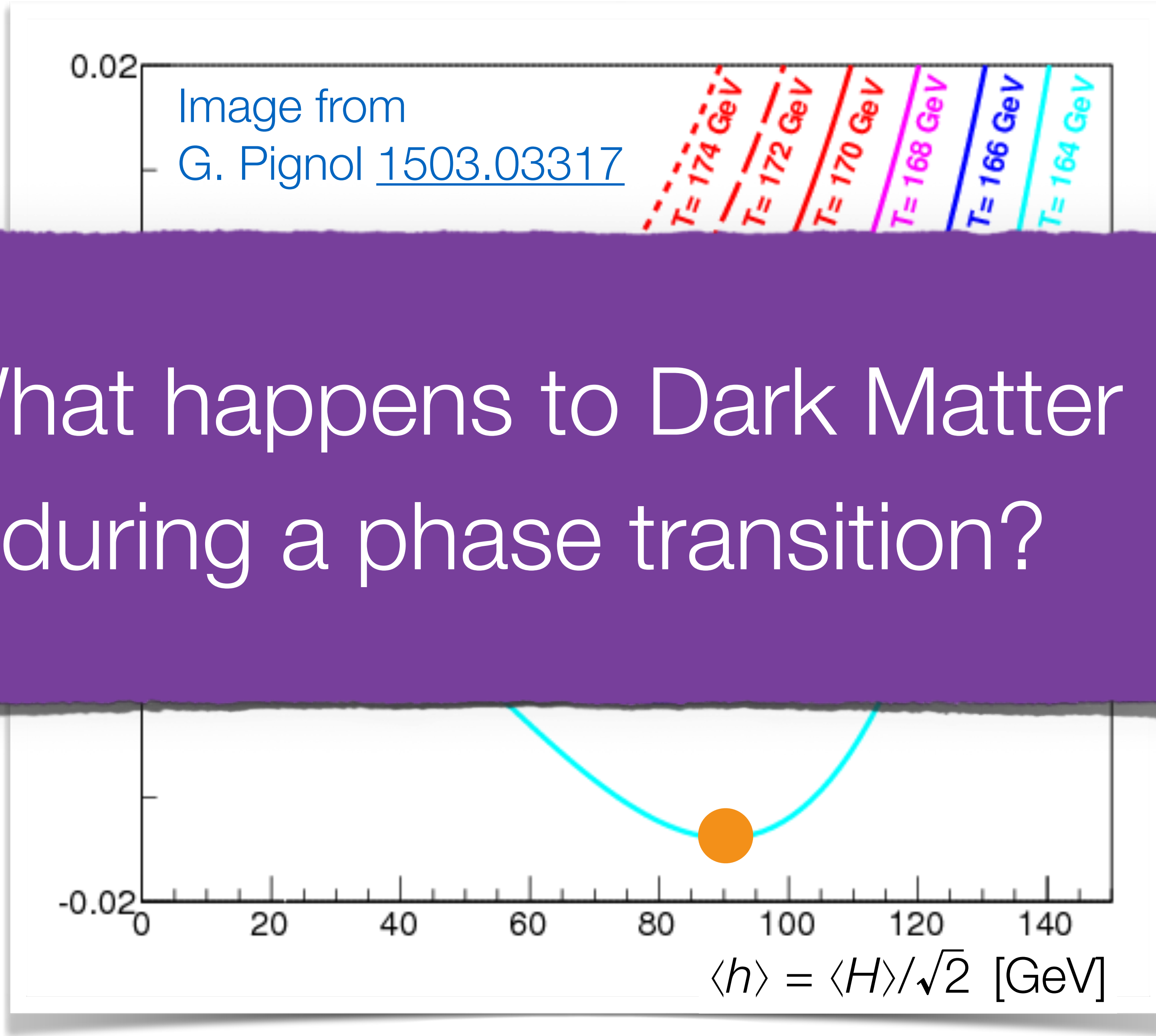
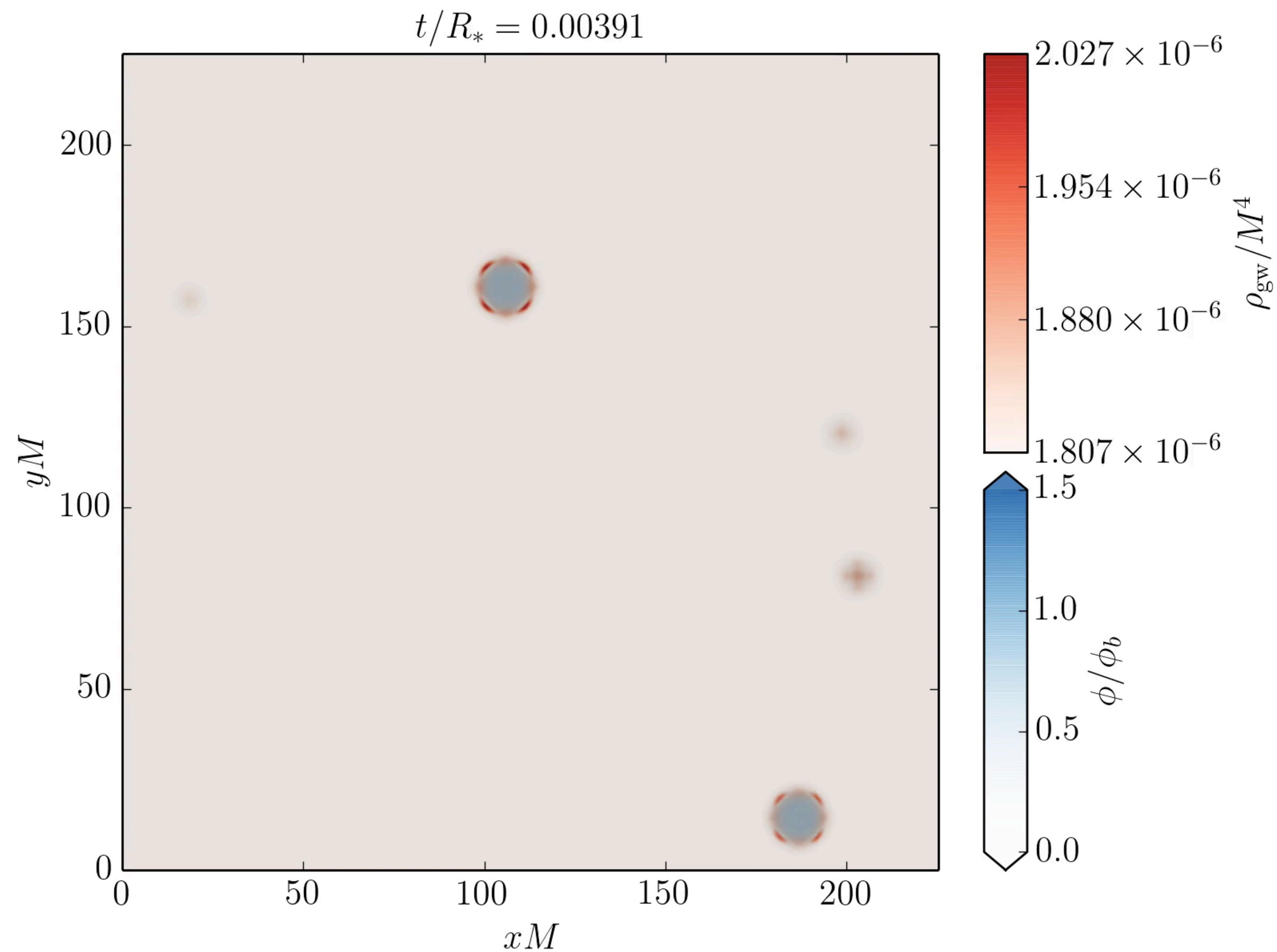


What happens to Dark Matter during a phase transition?

“Filtered” Dark Matter

DM Filtering at Bubble Walls



Witten 1984, Cutting Hindmarsh Weir 2018

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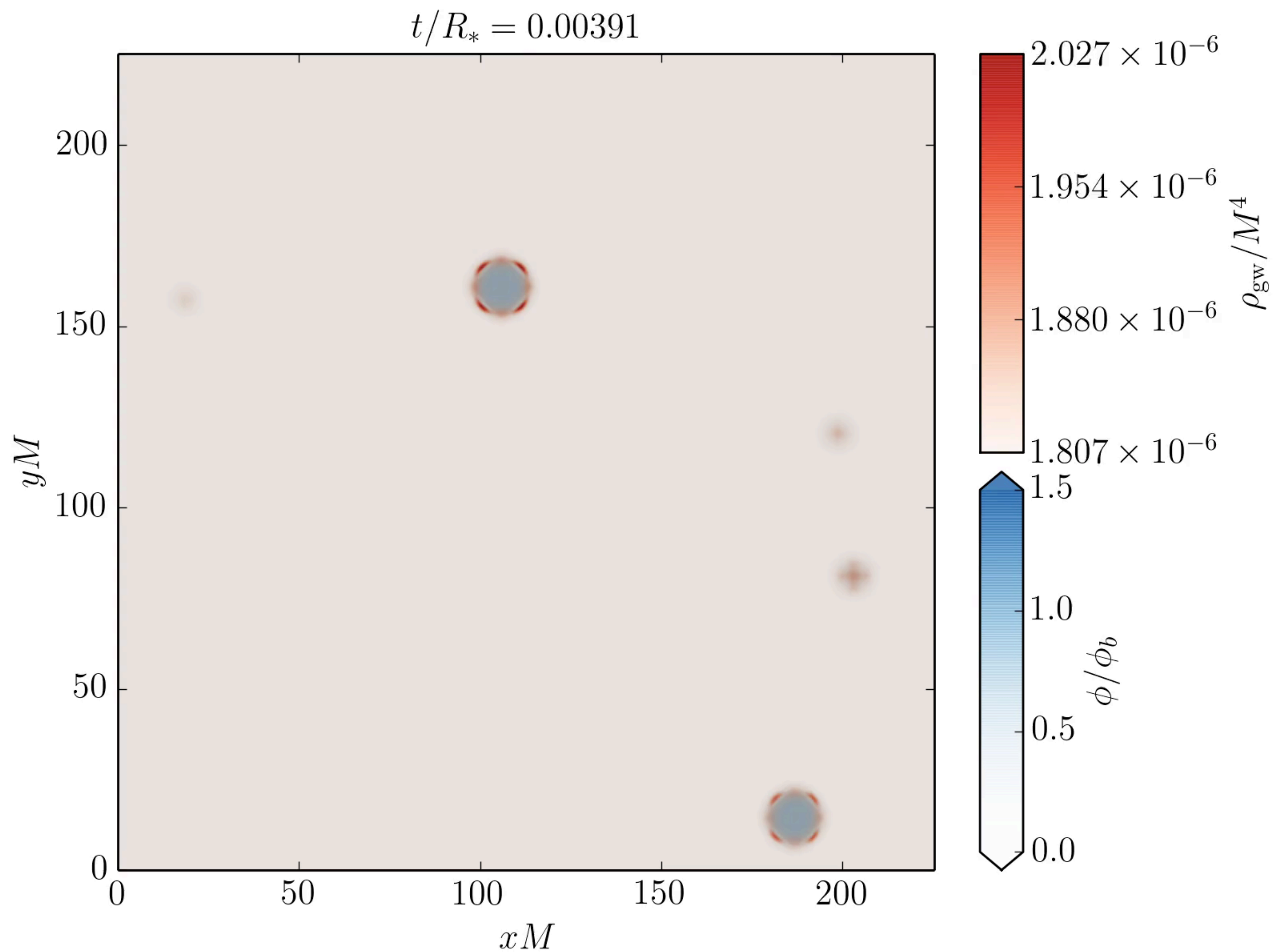

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$$\mathcal{L} \supset -y_{\rm DM}\, \phi \bar{\chi} \chi$$

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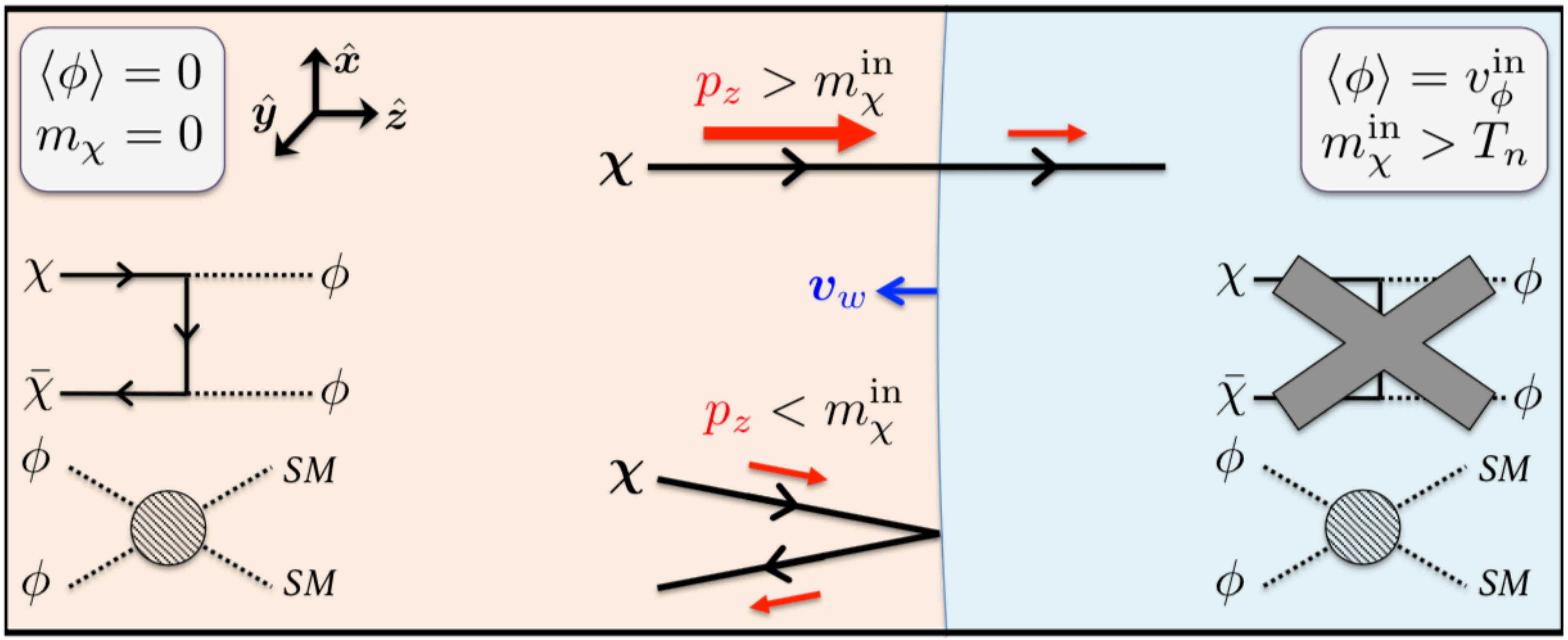

Baker JK Long, arXiv:1912.02830

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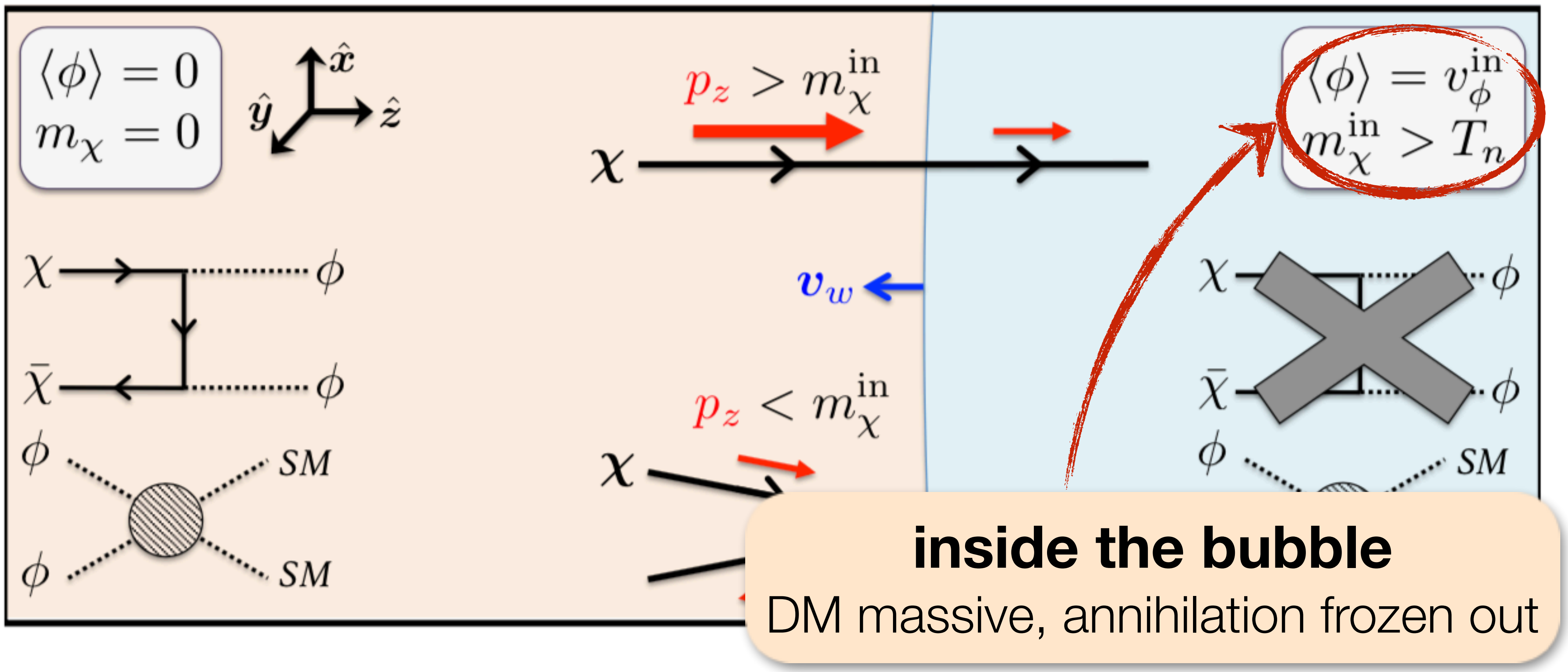

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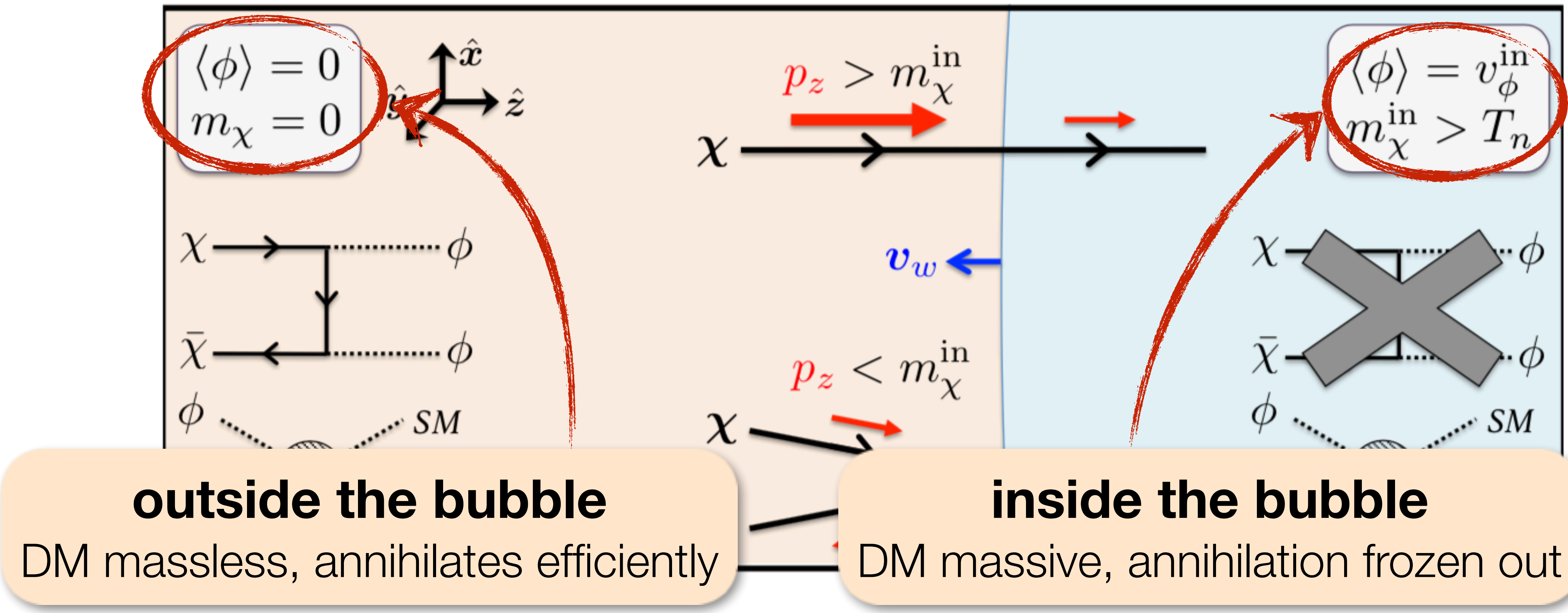

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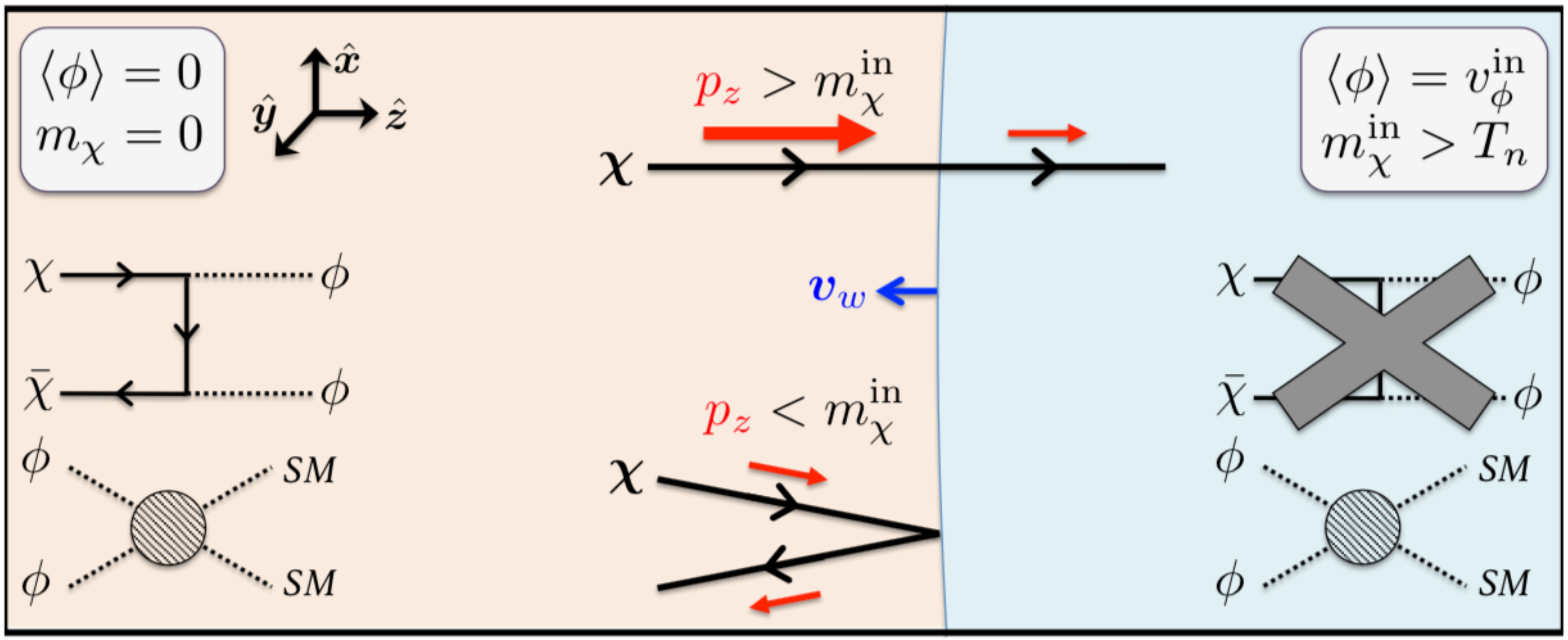

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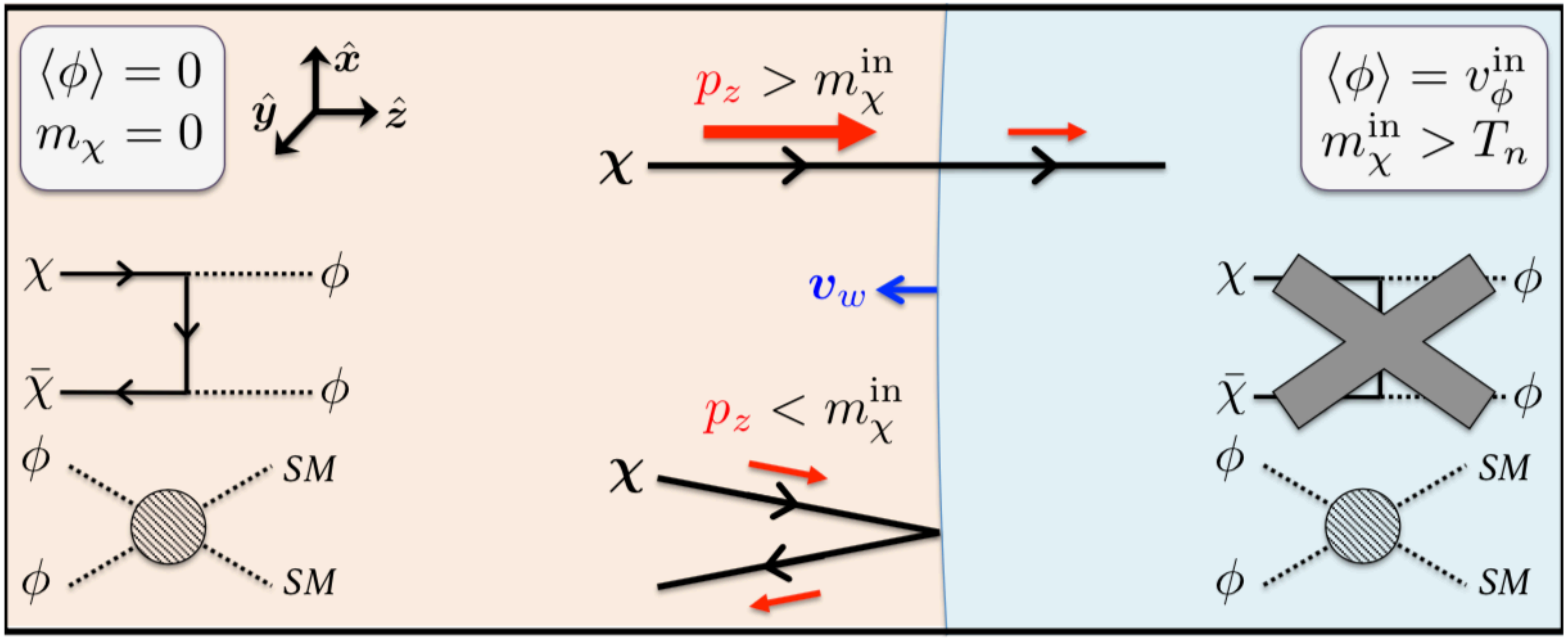

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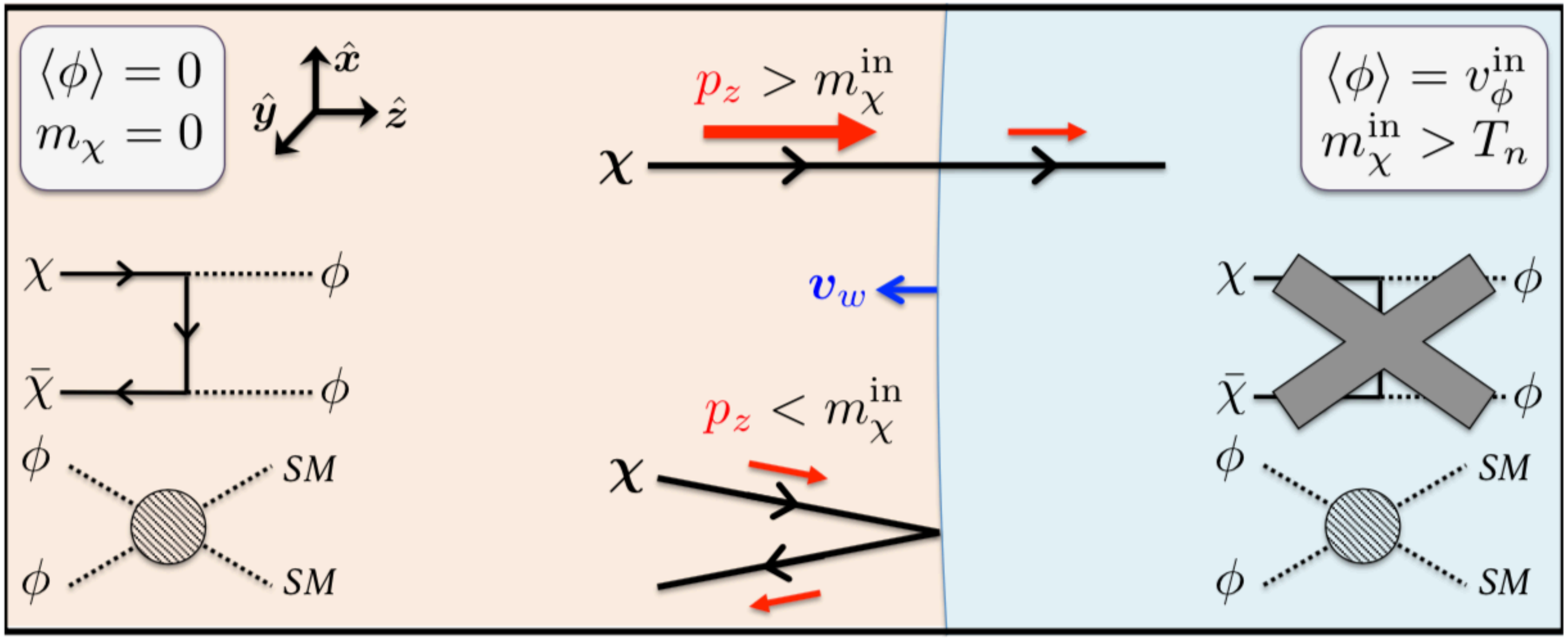

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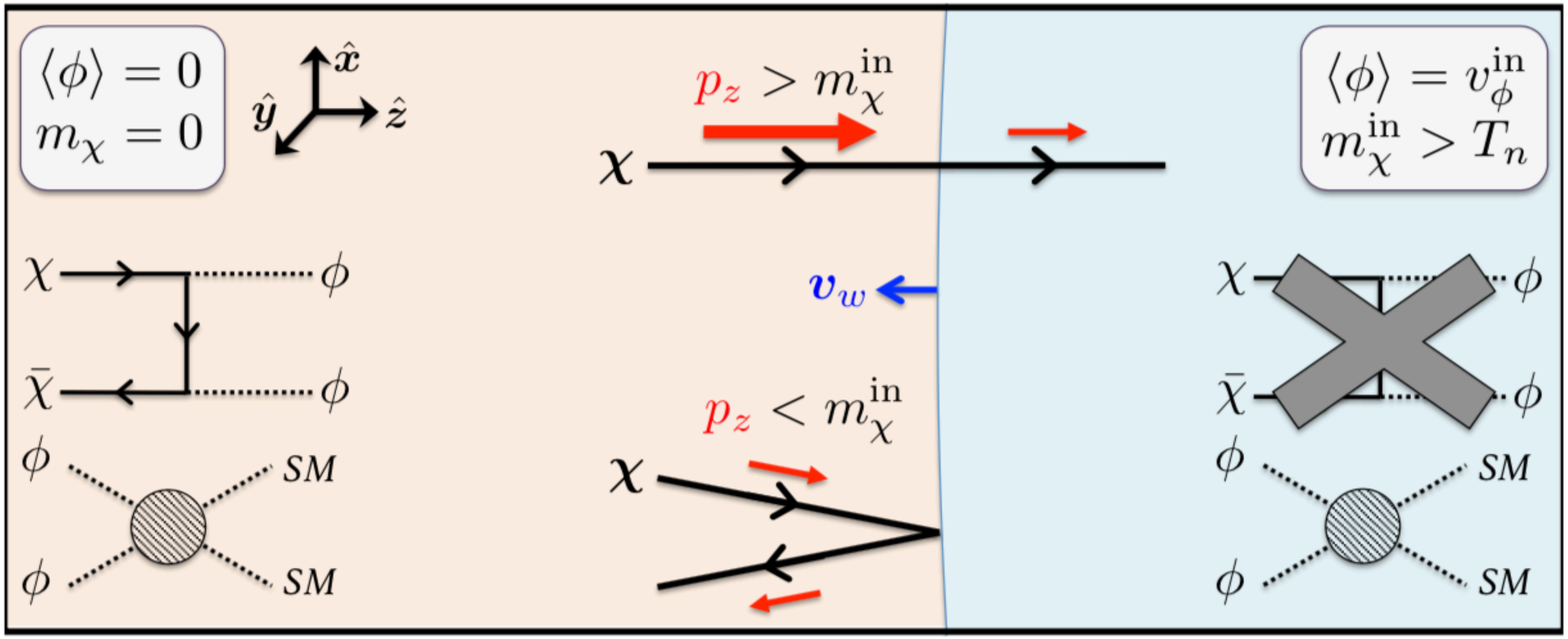
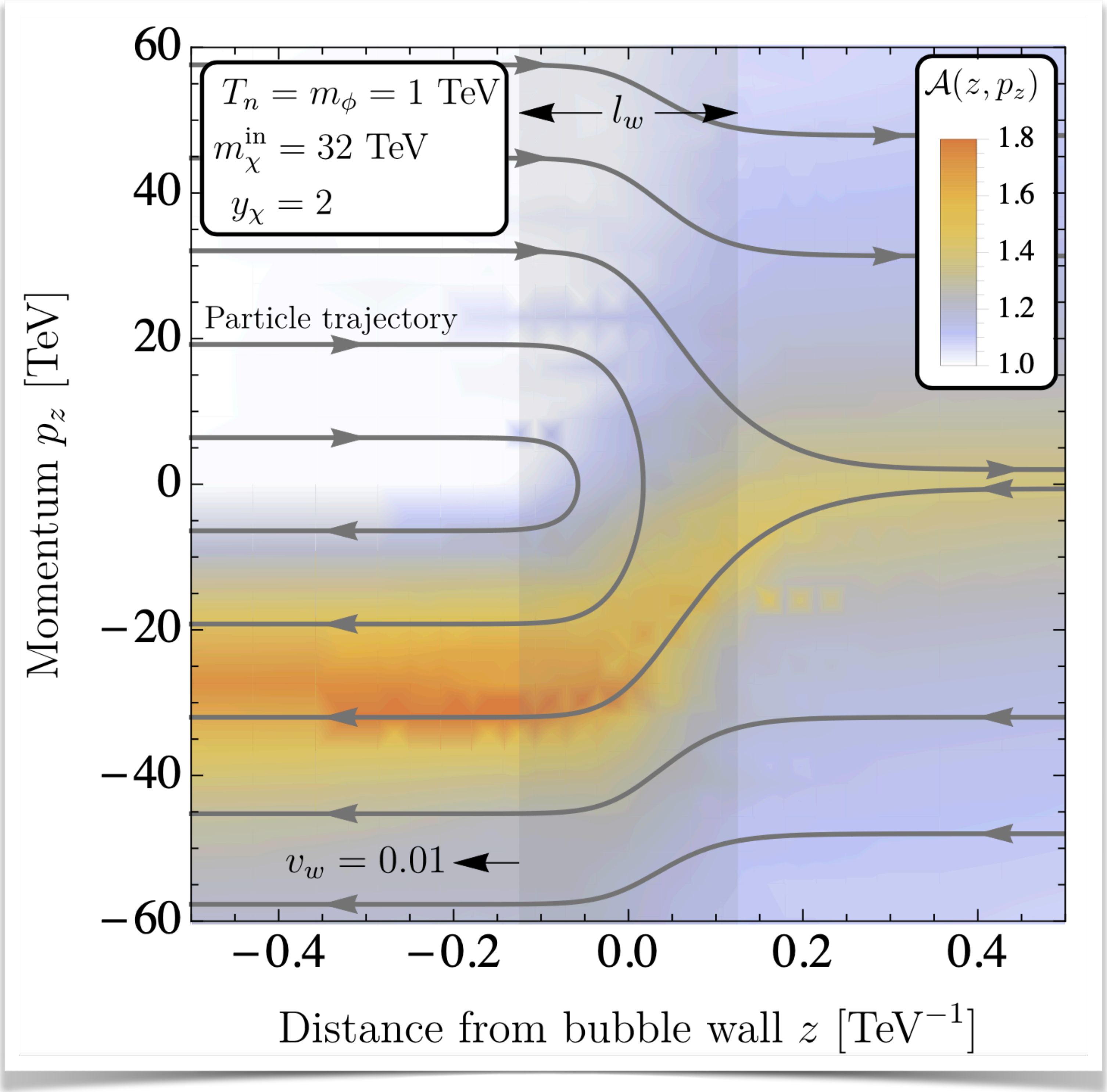


- small DM abundance inside the bubble persists
- most DM particles remain outside, annihilate efficiently

Baker JK Long, arXiv:1912.02830

Dark Matter at Bubble Walls



Solving the Boltzmann Equations

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collision term
change in phase space distribution
due to collision and annihilation

Solving the Boltzmann Equations

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☑ Liouville operator

$$\mathbf{L}[f_\chi] = \frac{df_\chi}{dt^w} = \frac{\partial f_\chi}{\partial t^w} + \frac{\partial \mathbf{x}^w}{\partial t^w}\frac{\partial f_\chi}{\partial \mathbf{x}^w} + \frac{\partial \mathbf{p}^w}{\partial t^w}\frac{\partial f_\chi}{\partial \mathbf{p}^w}$$

The Liouville Operator

$$\mathbf{L}[f_\chi] = \frac{df_\chi}{dt^w} = \frac{\partial f_\chi}{\partial t^w} + \frac{\partial \mathbf{x}^w}{\partial t^w}\frac{\partial f_\chi}{\partial \mathbf{x}^w} + \frac{\partial \mathbf{p}^w}{\partial t^w}\frac{\partial f_\chi}{\partial \mathbf{p}^w}$$

Simplifications:

- stationarity ($\partial f_\chi / \partial t^w = 0$)
- translation invariance in *x* and y
- integrate over *x* and y (to reduce number of variables)
- make ansatz $f_\chi = \mathcal{A}(z^w, p_z^w) \exp\left(-\frac{E^p}{T}\right)$

(superscript “w”: wall rest frame, “p”: plasma rest frame)

full details in Baker JK Long, arXiv:1912.02830

The Collision Term

$$g_\chi \int \frac{dp_x dp_y}{(2\pi)^2} \mathbf{C}[f_\chi] = \sum_{\text{spins}} \int \frac{dp_x dp_y}{(2\pi)^2} \, d\Pi_{q^p} \, d\Pi_{k^p} \, d\Pi_{l^p} \, \frac{(2\pi)^4}{2E_p^p} \delta^{(4)}(p^p + q^p - k^p - l^p) |\mathcal{M}|^2$$

$$\cdot \left[f_{\chi_p} f_{\bar{\chi}_q} (1 \pm f_{\phi_k})(1 \pm f_{\phi_l}) - f_{\phi_k} f_{\phi_l} (1 \pm f_{\chi_p})(1 \pm f_{\bar{\chi}_q}) \right],$$

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integrate out *x* and *y*

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phase space integrals

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The Collision Term

matrix element

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distribution functions,
Pauli blocking / Bose enhancement

full details in Baker JK Long, arXiv:1912.02830

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- Simplifications:
  - same as for the Liouville operator, but also
  - neglect Pauli blocking / Bose enhancement

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Solving the Boltzmann Equation

- After simplifications, Boltzmann equation takes the form

$$\left[\left(\frac{p_z}{m_\chi}\frac{\partial}{\partial z}-\left(\frac{\partial m_\chi}{\partial z}\right)\frac{\partial}{\partial p_z}-\left(\frac{\partial m_\chi}{\partial z}\right)\frac{v_w}{T_n}\right)\mathcal{A}(z,p_z)\right]\frac{g_\chi m_\chi T_n}{2\pi}\exp\left[\frac{v_w p_z-\sqrt{m_\chi^2+(p_z)^2}}{T_n}\right]=g_\chi\int\frac{\mathrm{d}p_x\,\mathrm{d}p_y}{(2\pi)^2}\,\mathbf{C}[f_\chi]$$

- A PDE of the form

$$a(z^w,p_z^w)\frac{\partial\mathcal{A}}{\partial z^w}+b(z^w,p_z^w)\frac{\partial\mathcal{A}}{\partial p_z^w}=c(\mathcal{A},z^w,p_z^w)$$

can be solved by the method of characteristics

- Define parametric curve via

$$\frac{dz^w(\lambda)}{d\lambda}=a(z^w,p_z^w)\,,\qquad\frac{dp_z^w(\lambda)}{d\lambda}=b(z^w,p_z^w)$$

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- Solution along the curve is given by

$$\frac{d\mathcal{A}\big(z^w(\lambda), p_z^w(\lambda)\big)}{d\lambda} = c\big(\mathcal{A}(\lambda), z^w(\lambda), p_z^w(\lambda)\big)$$

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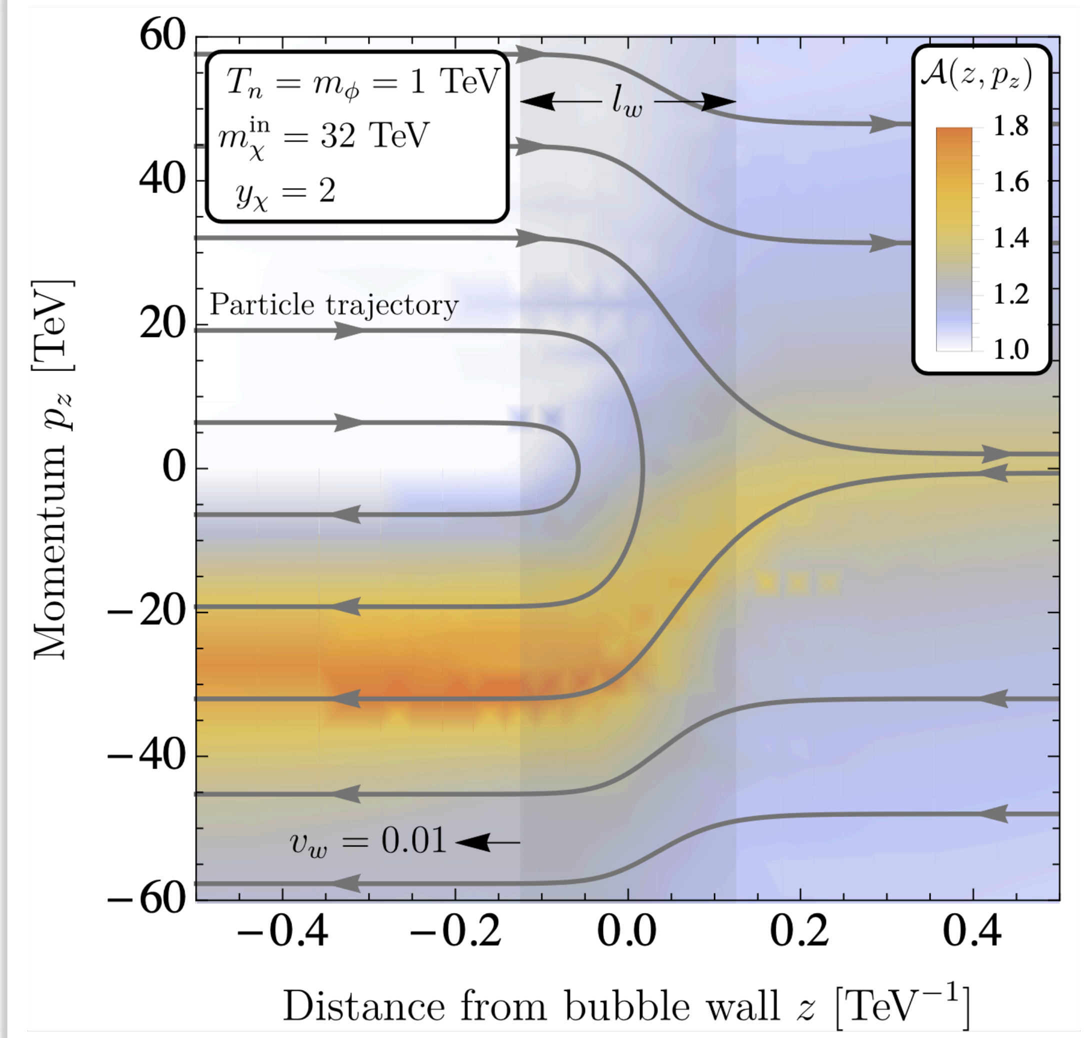
- Physical interpretation:
  - curves = particle trajectories



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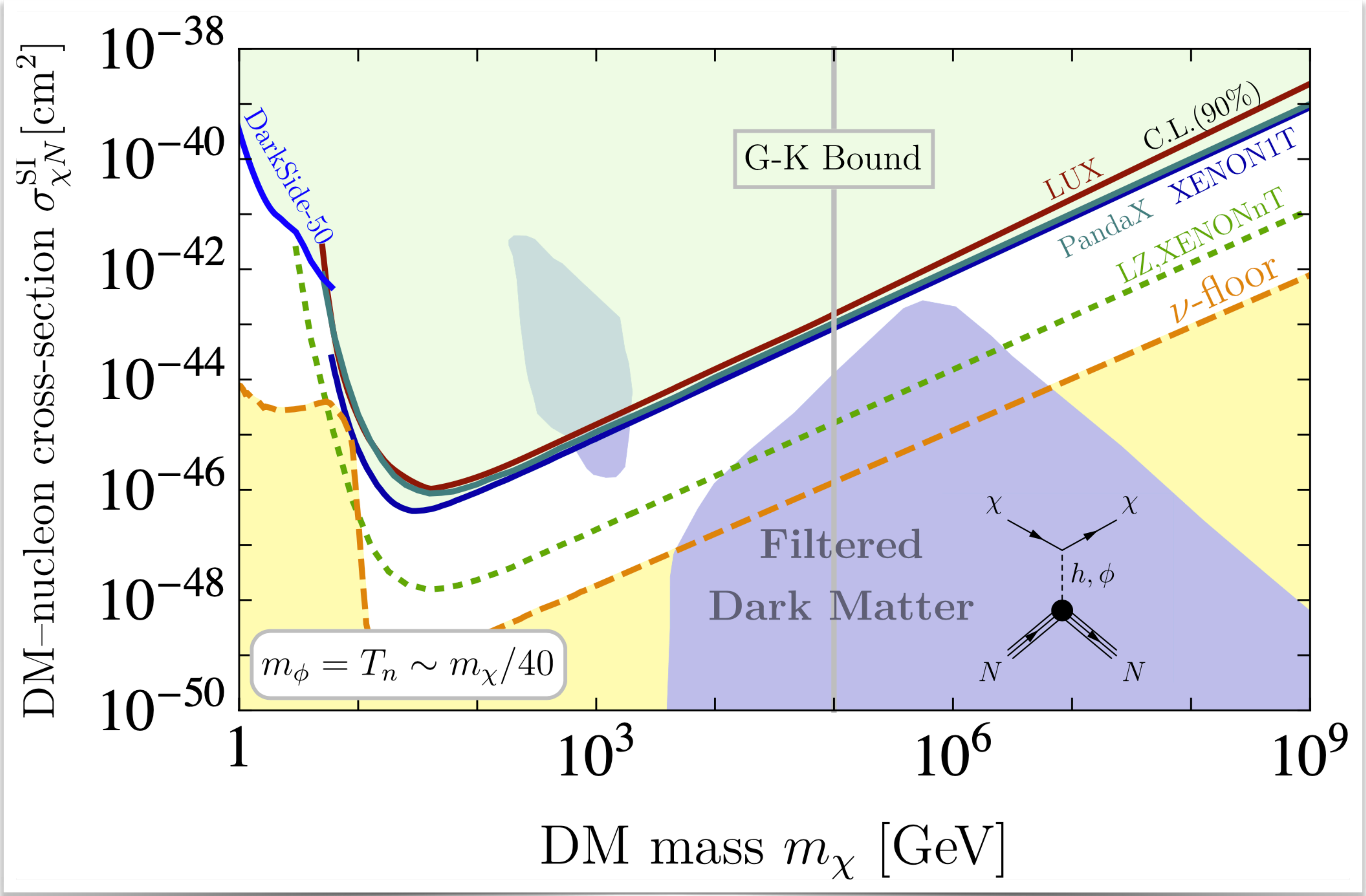

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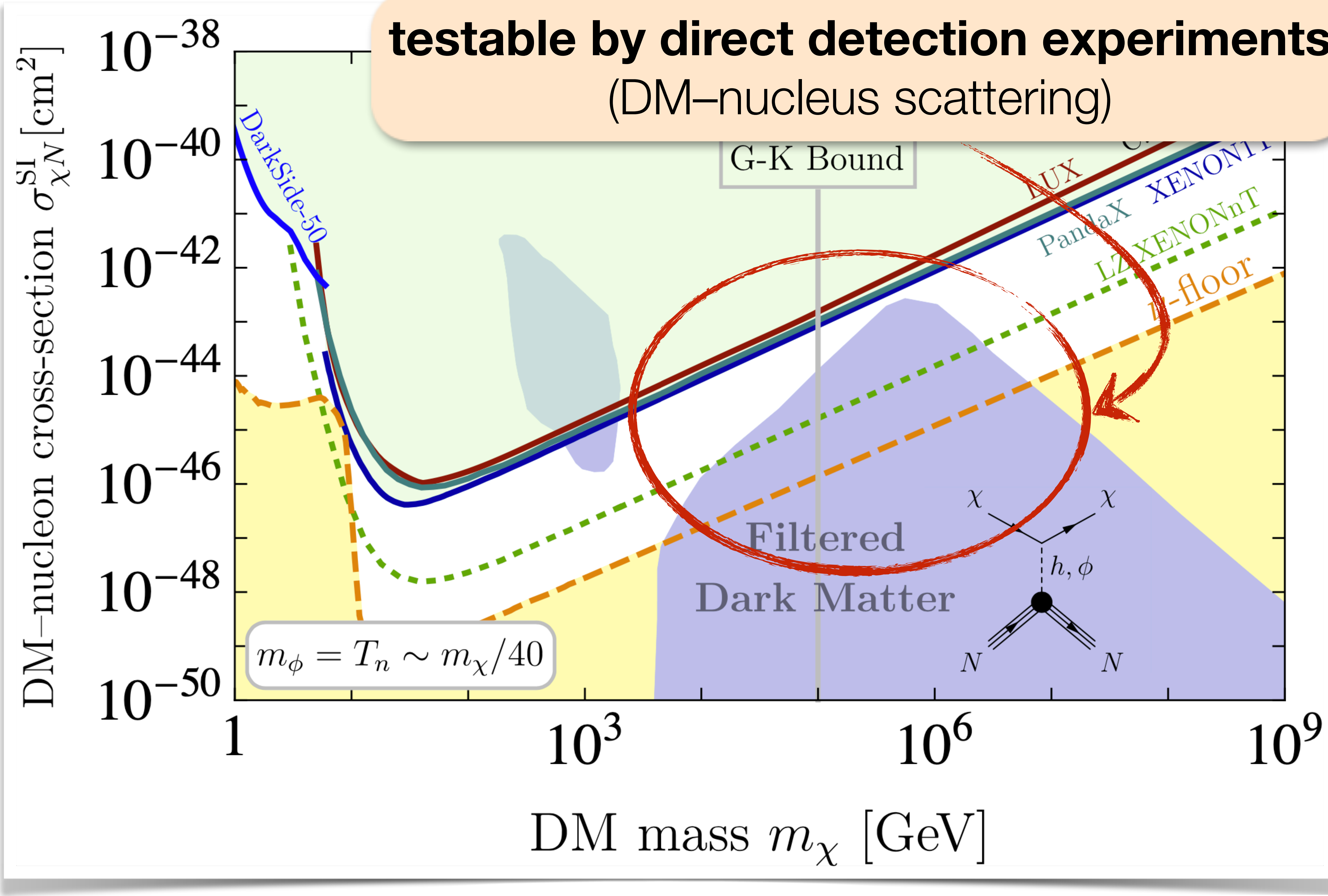
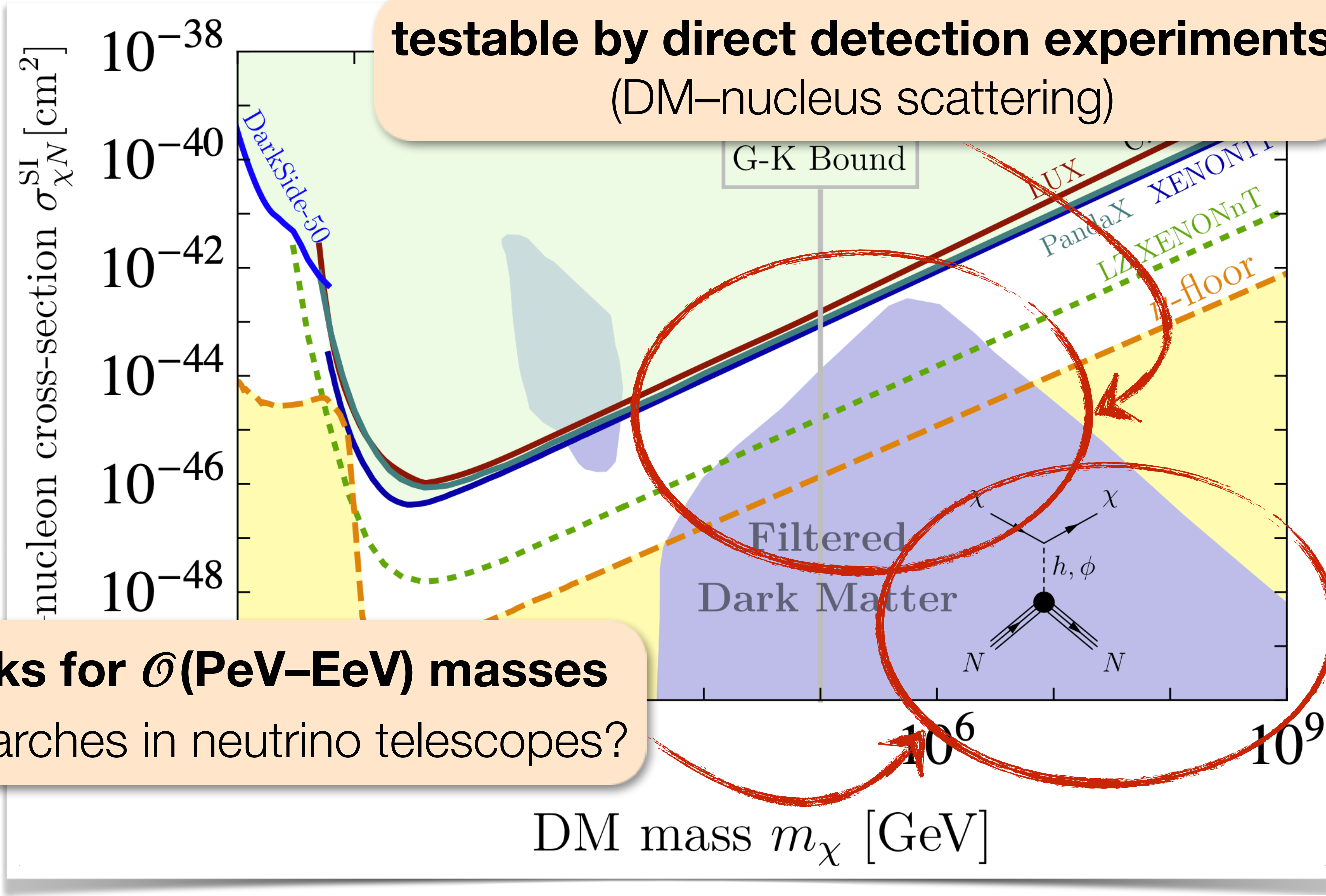
DM Filtering at Bubble Walls

testable by direct detection experiments
(DM–nucleus scattering)



Baker JK Long, arXiv:1912.02830

DM Filtering at Bubble Walls



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

Filtered Baryogenesis

☑ can be combined with a baryogenesis mechanism:

- CP-violating χ–ϕ interaction leads to chiral asymmetry in χ (analogous to electroweak baryogenesis)
- portal operator converts chiral asymmetry to lepton asymmetry
- SM sphalerons produce a baryon asymmetry

Baker Breitbach JK Mittnacht Soreq arXiv:2112.08987

Filtered Baryogenesis

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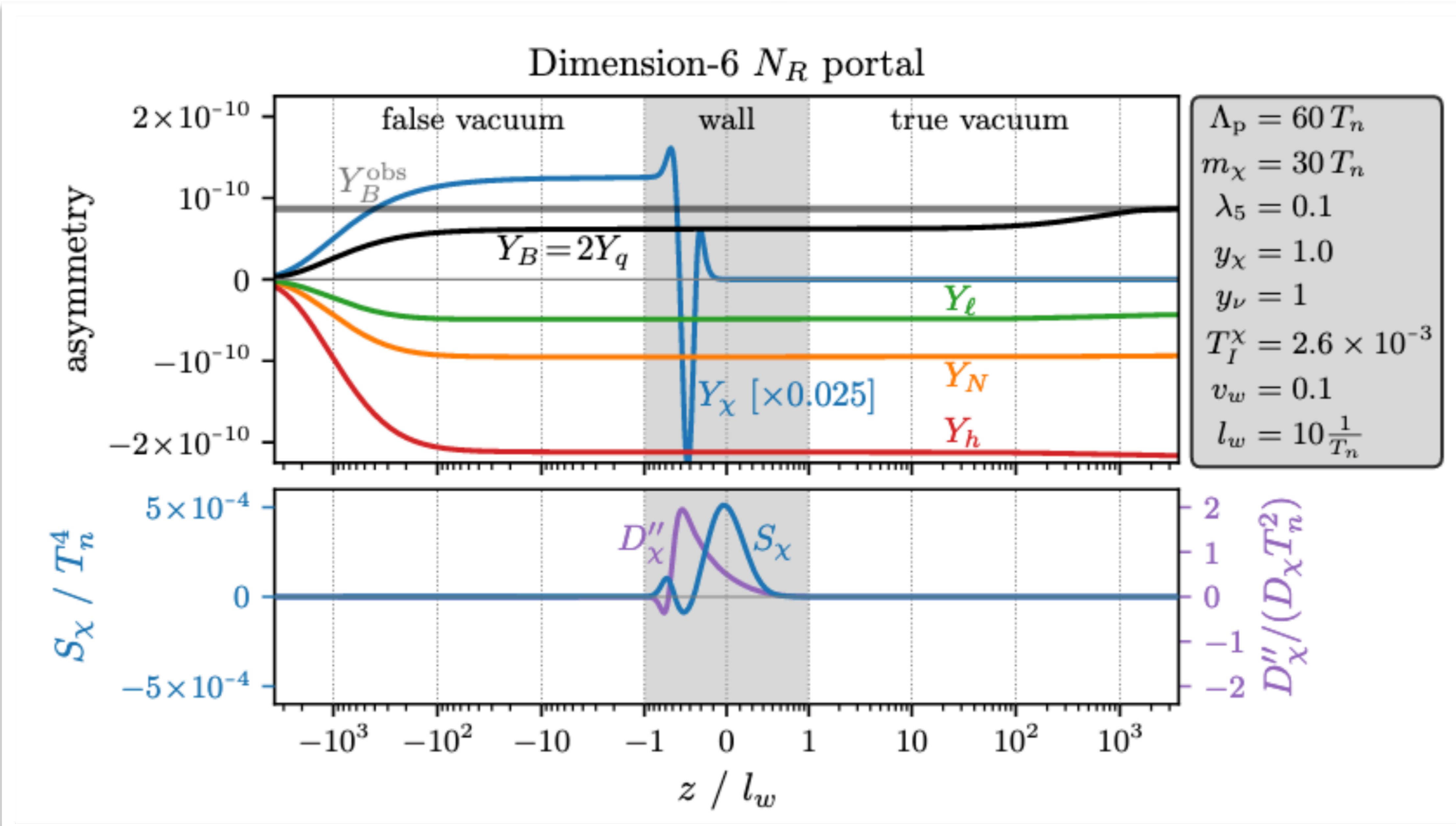

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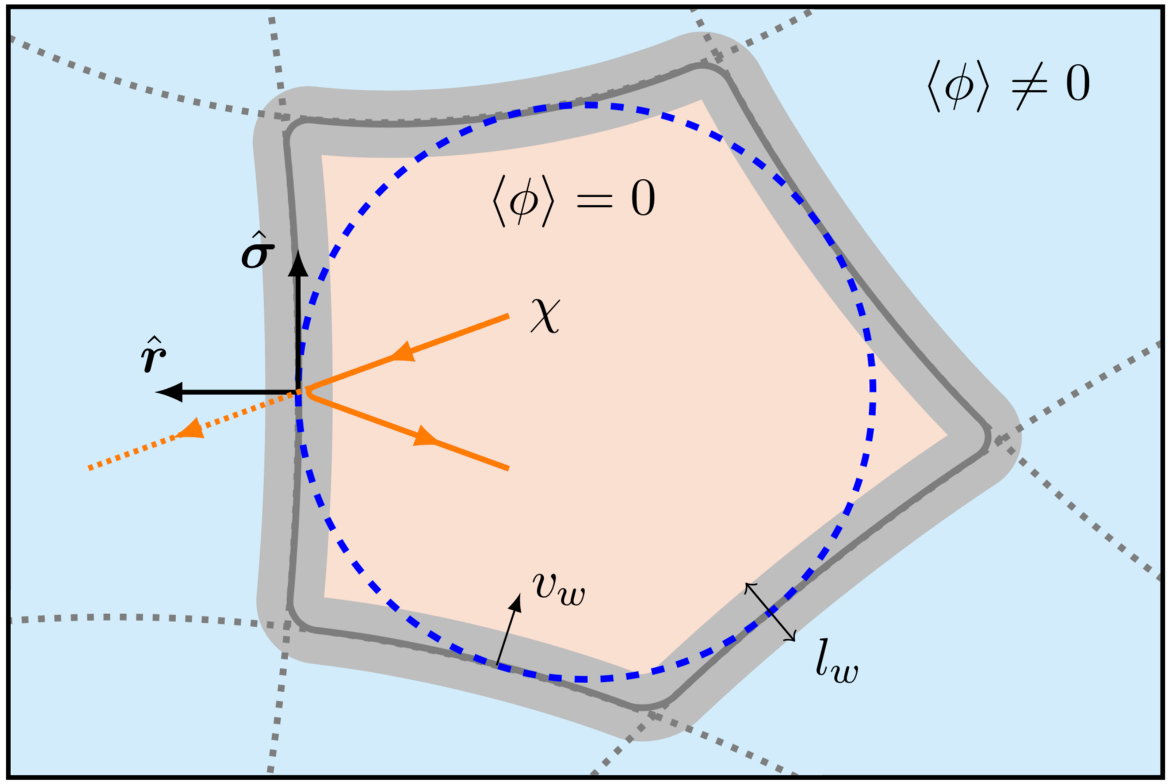
Primordial Black Holes from Phase Transitions

A Modified Scenario with Less Annihilation

- ☑ 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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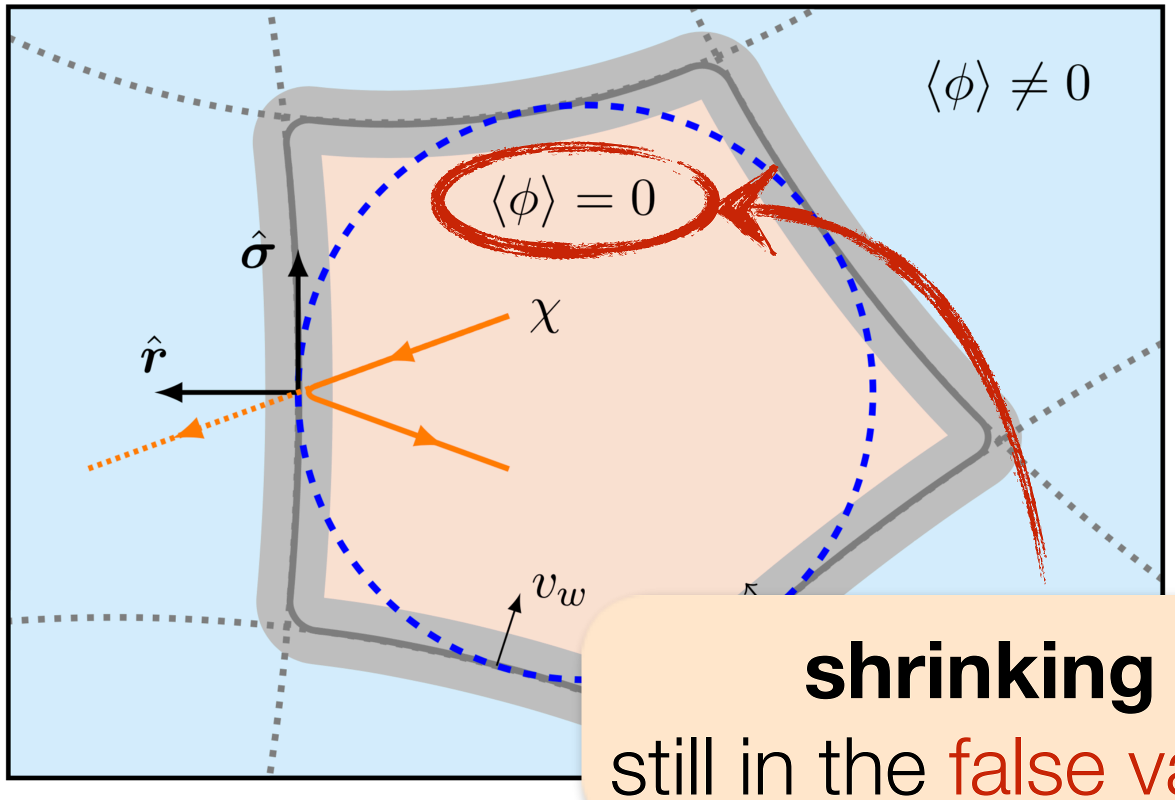

shrinking bubble
still in the false vacuum phase

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

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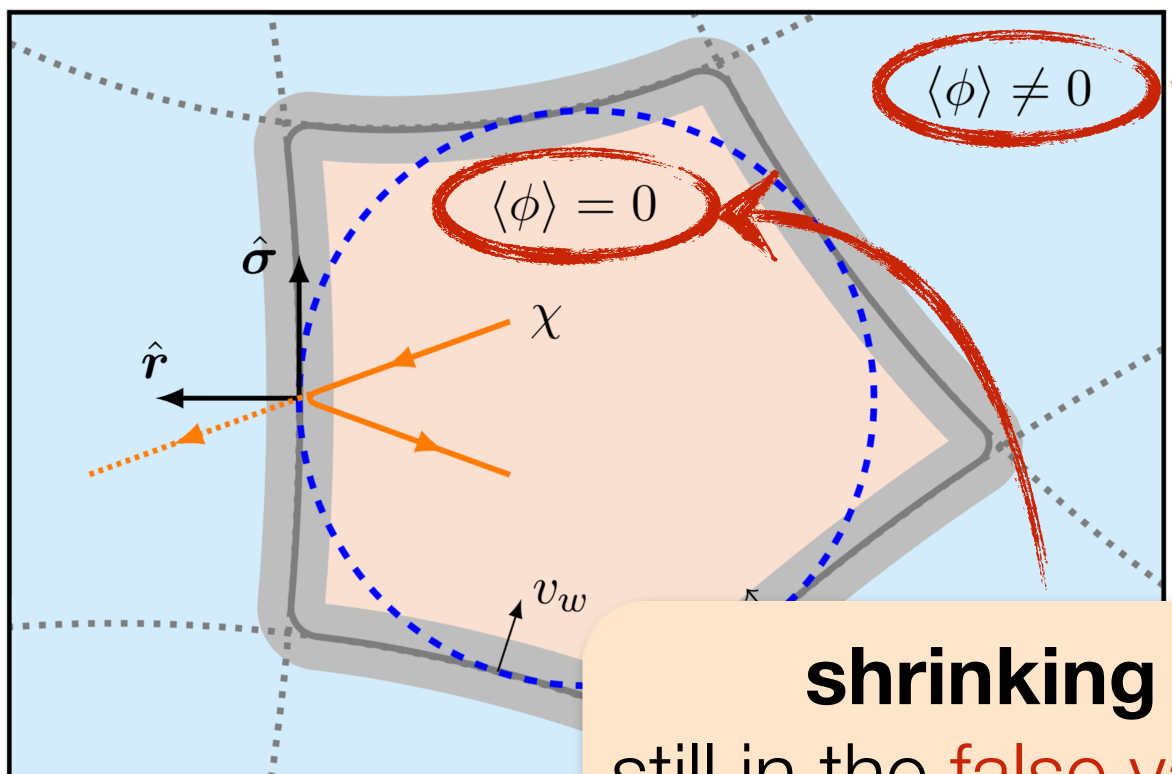
most of the Universe already in the true vacuum phase



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

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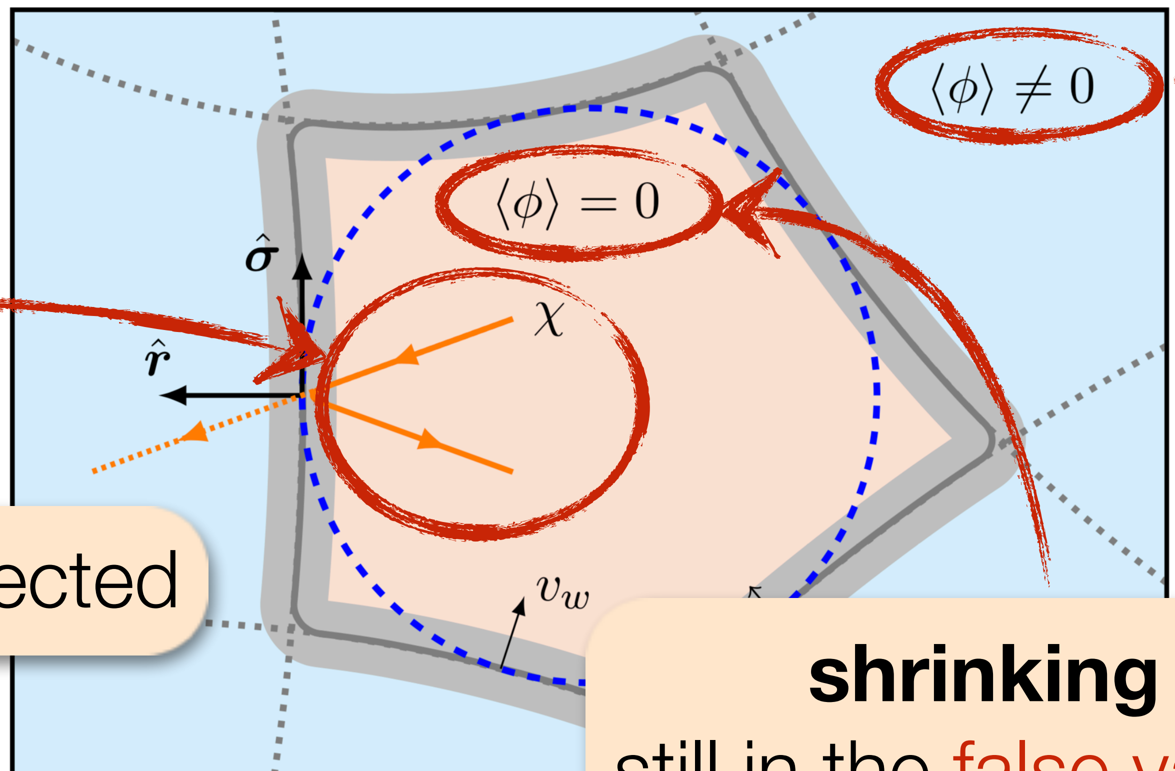
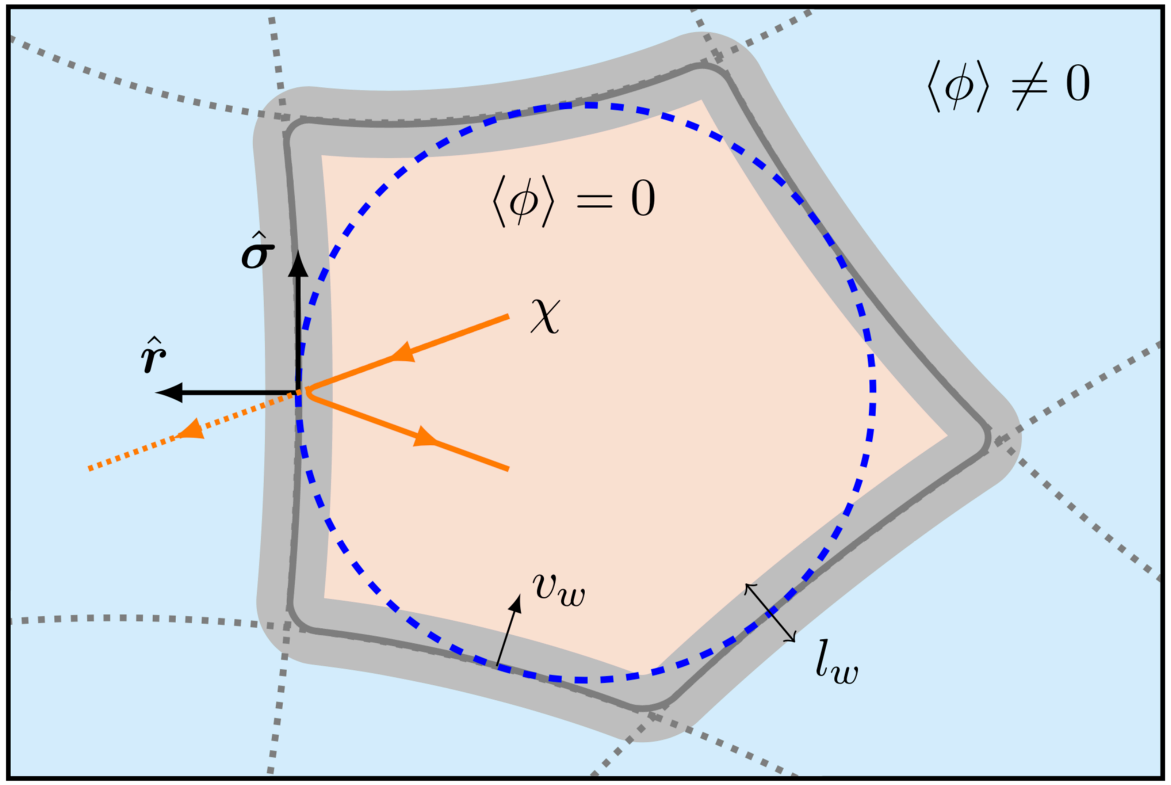


most χ particles reflected

shrinking bubble
still in the false vacuum phase

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

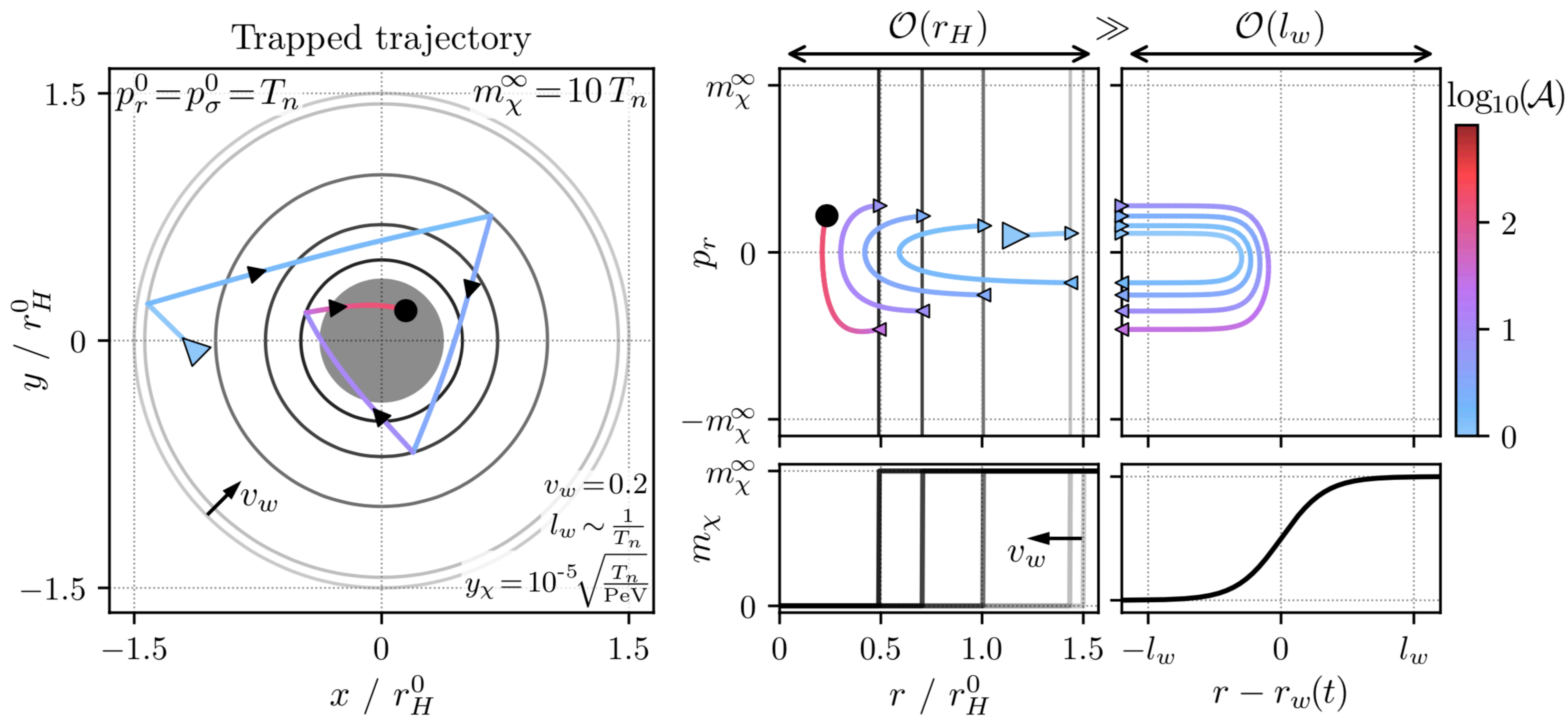
A Modified Scenario with Less Annihilation



☑ 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

Typical Particle Tajectories (1)



- ☑ particle reflected multiple times
- ☑ eventually ends up in black hole

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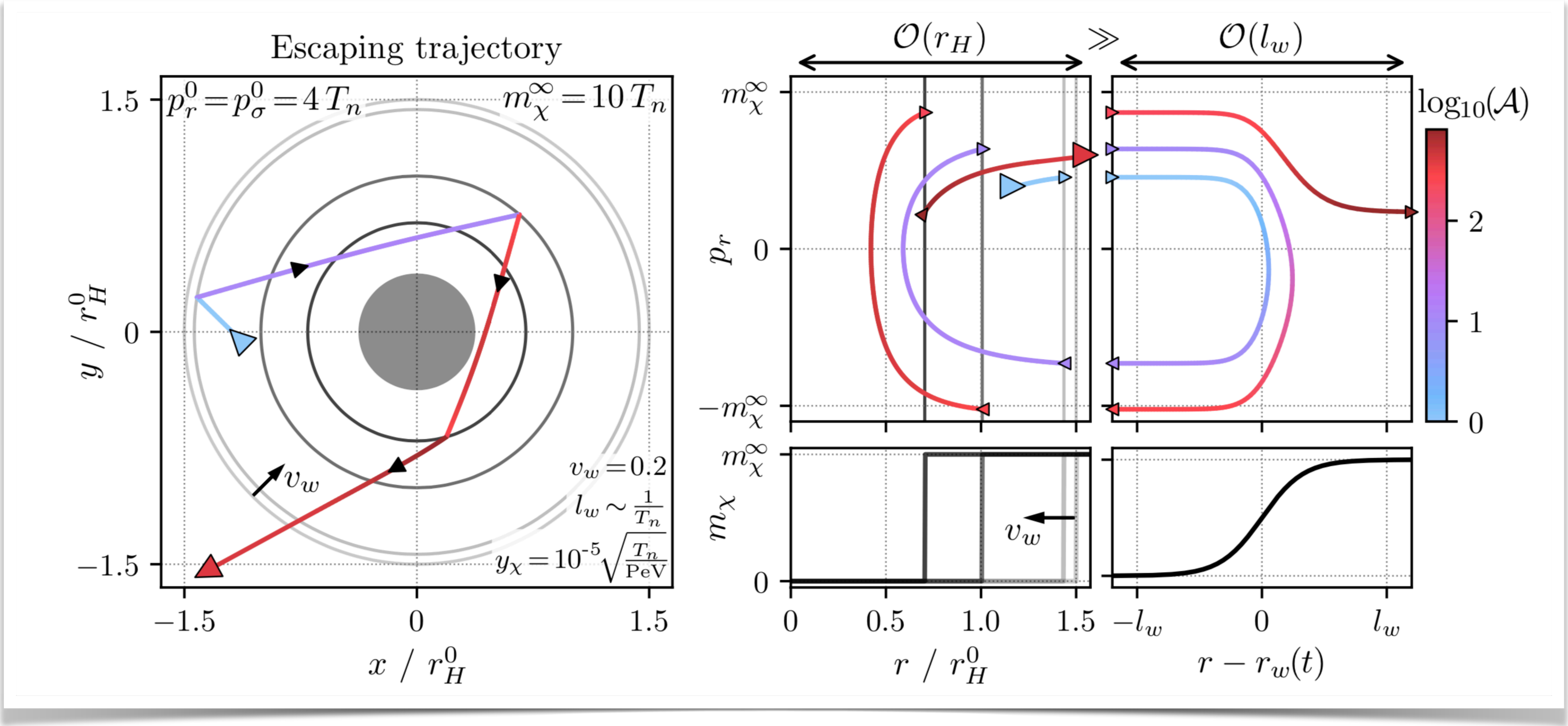
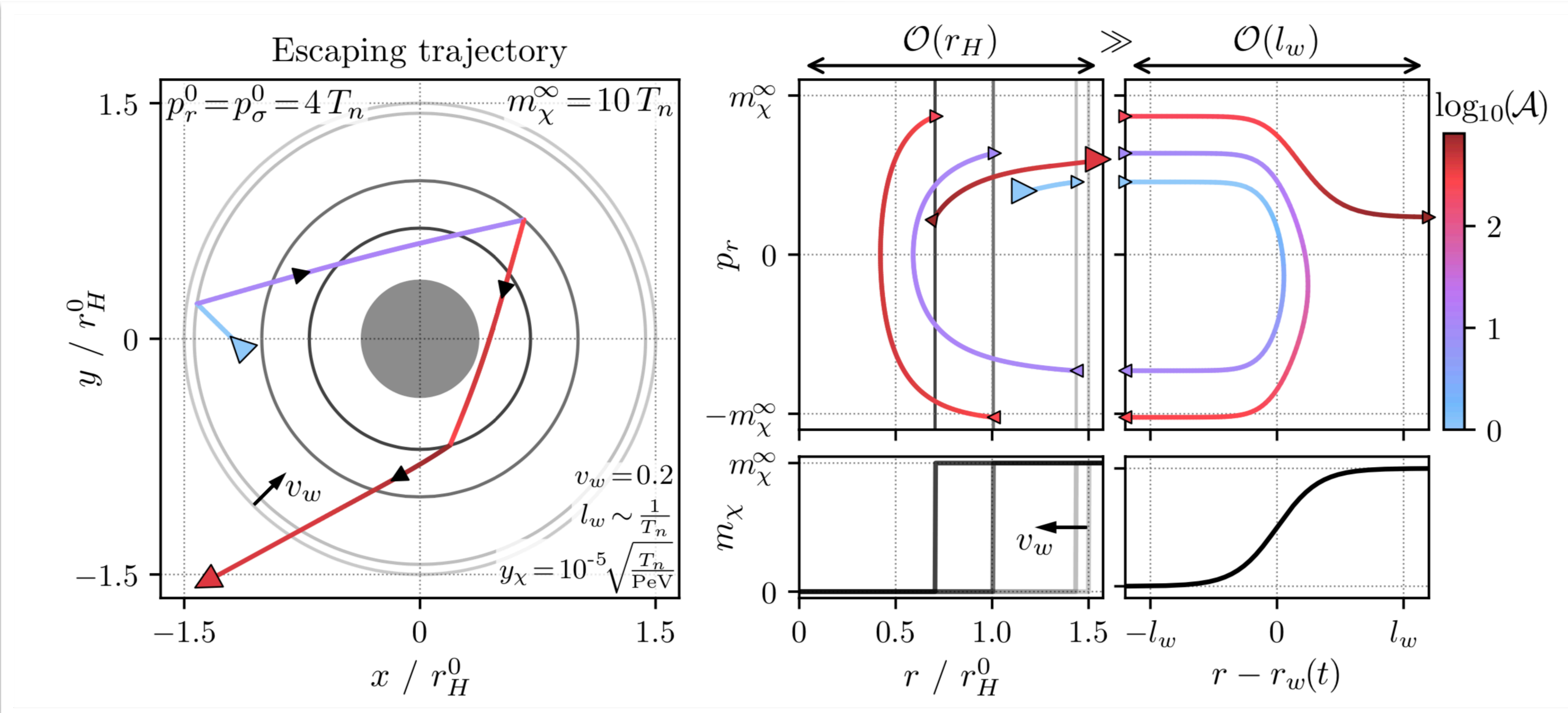
Typical Particle Tajectories (2)



Typical Particle Tajectories (2)



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

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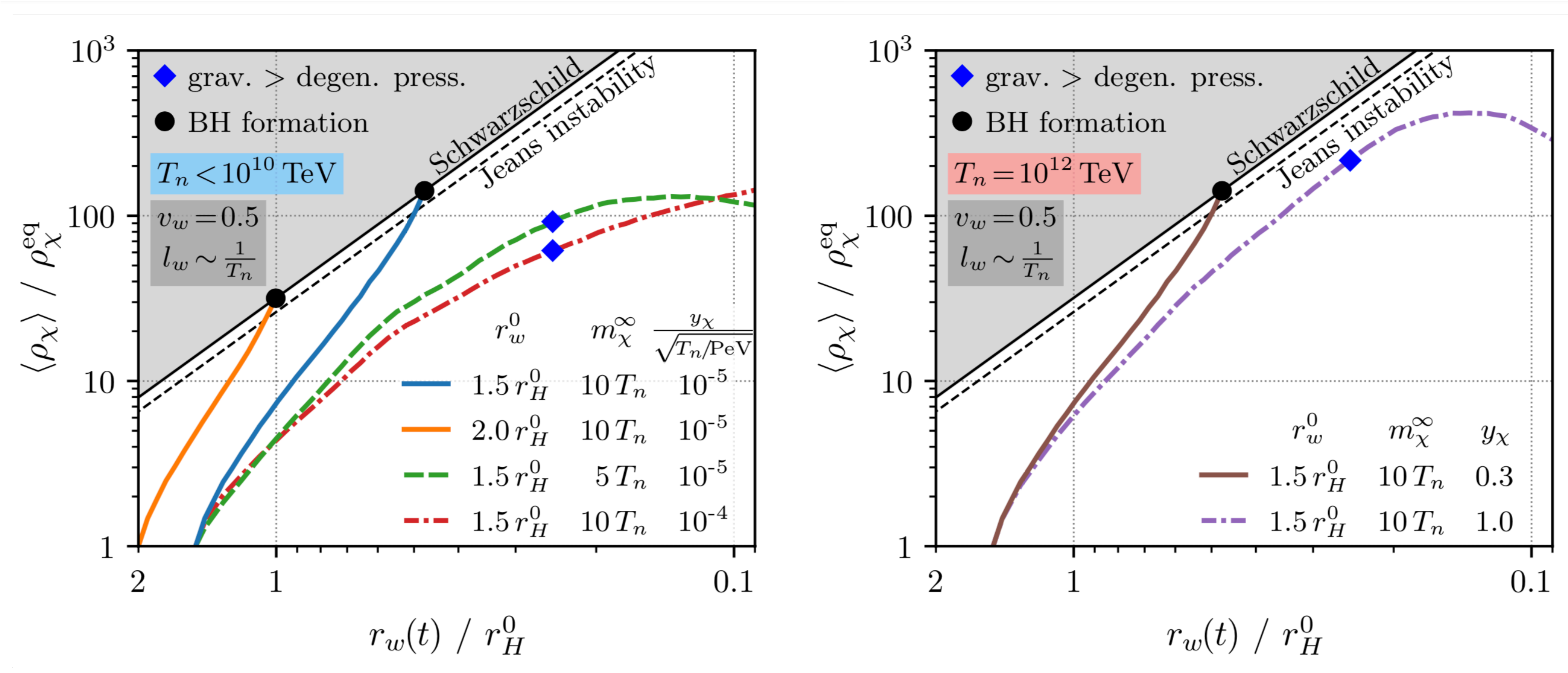
Bubble Trajectories



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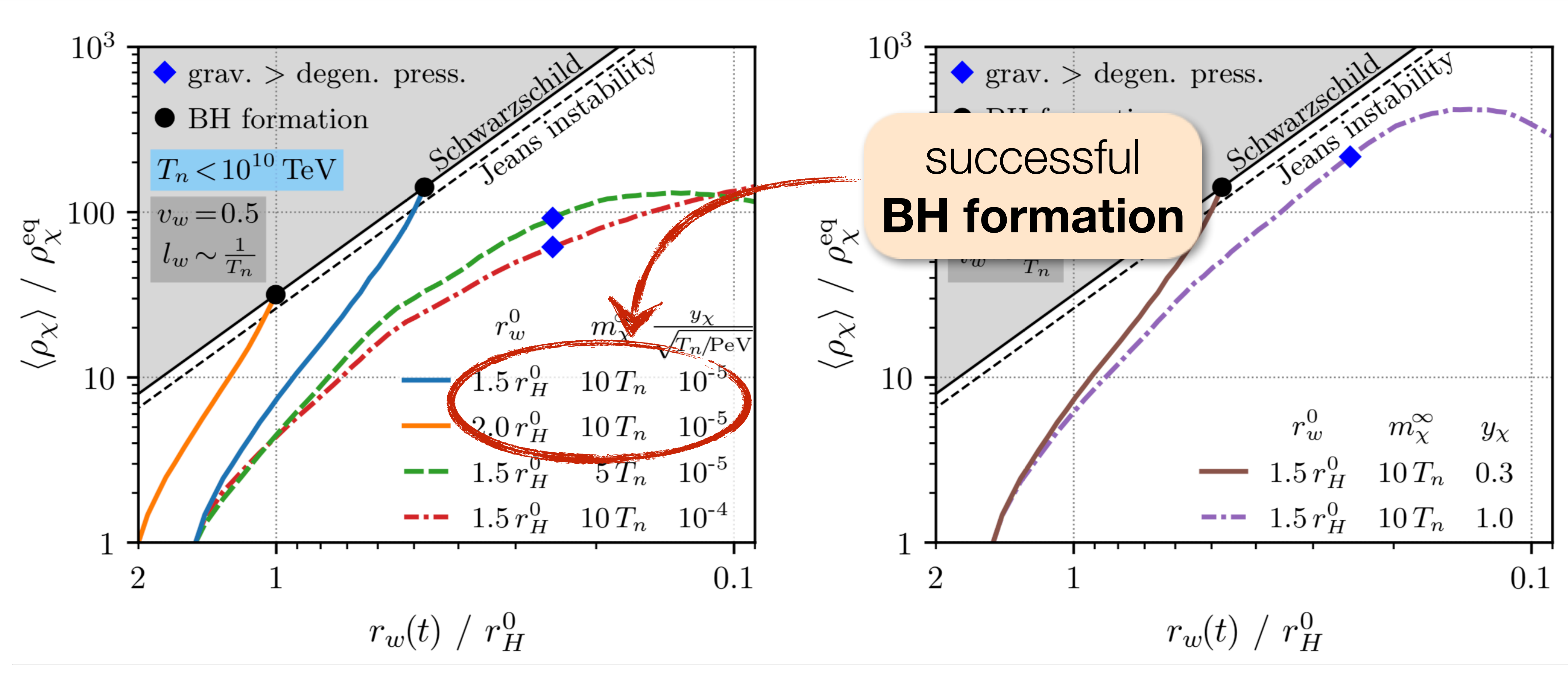

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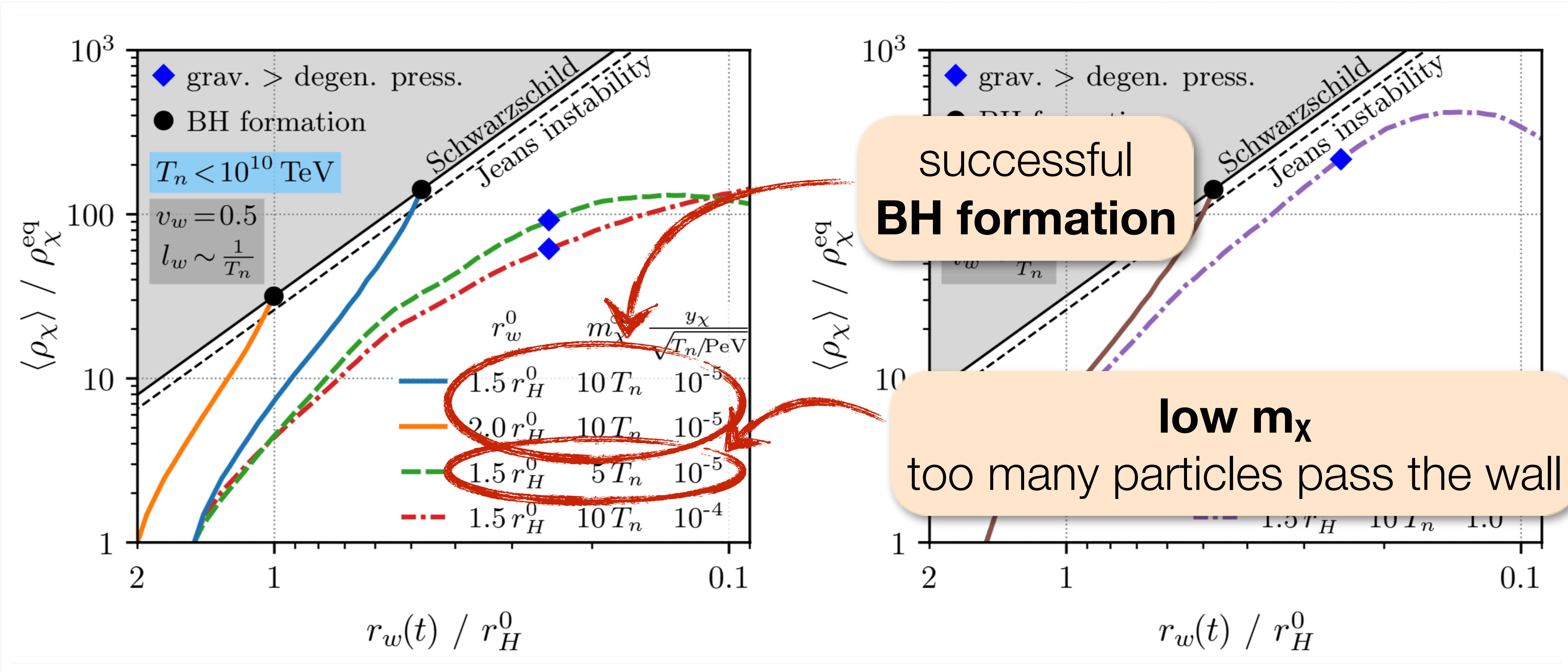

Baker Breitbach JK Mittnacht, arXiv:2105.07481 and arXiv:2110.00005

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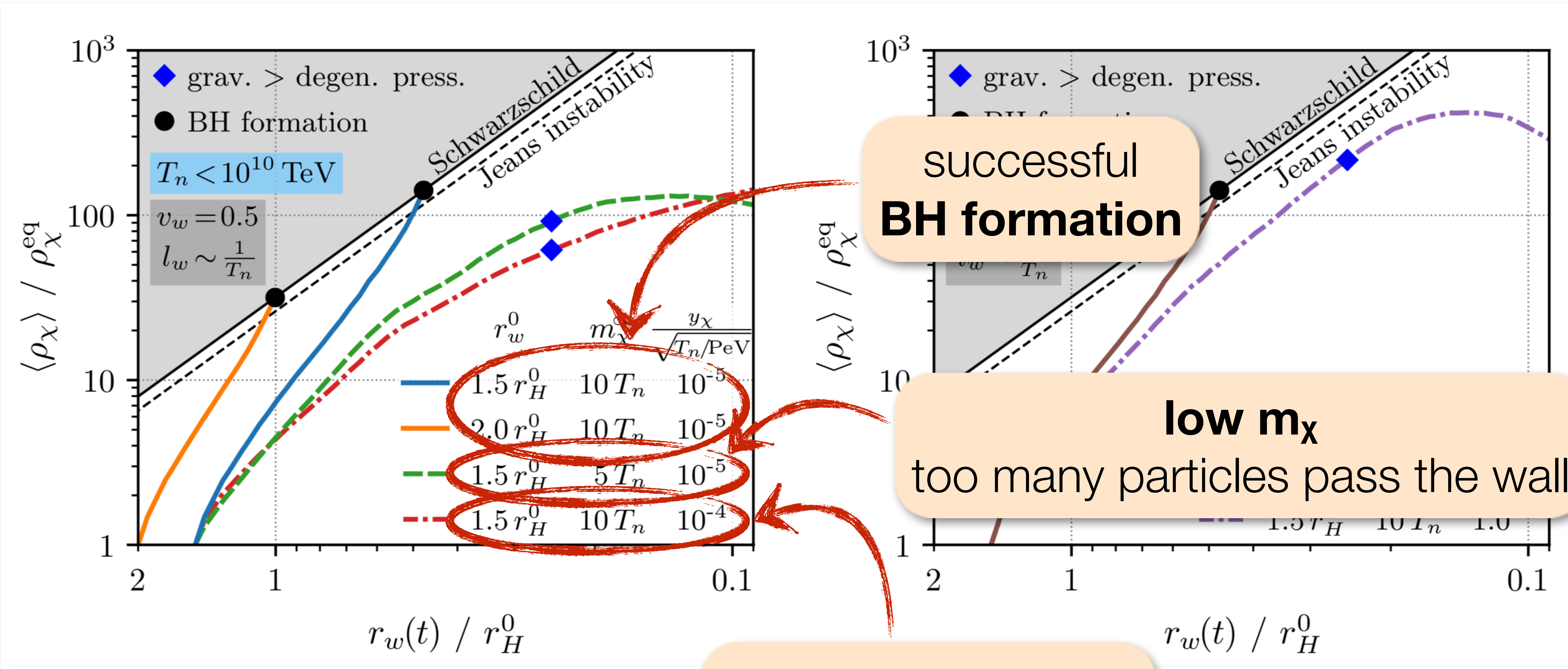


successful
BH formation

low m_χ
too many particles pass the wall

large Yukawas
annihilation too large

Baker Breitbach J... 481 and arXiv:2110.00005

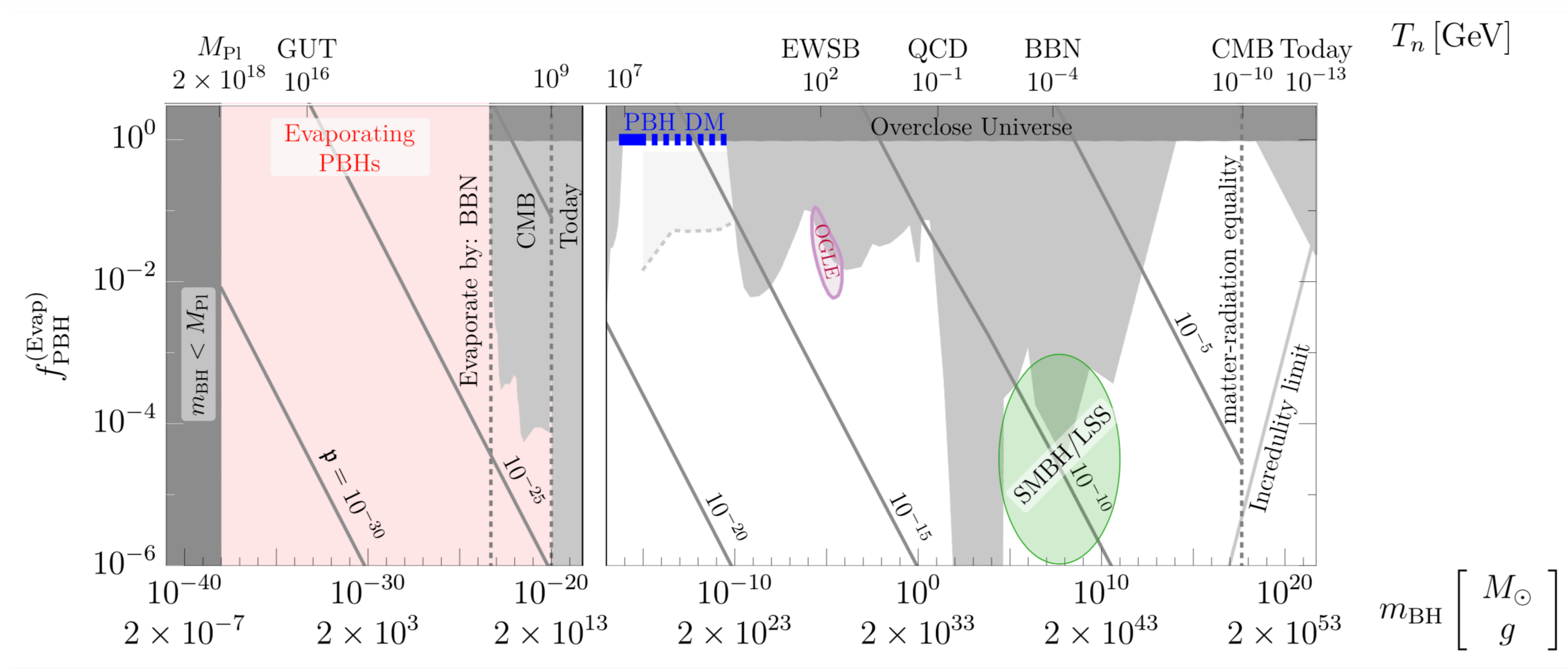
Requirements

- ☑ large bubble radii ($\gtrsim r_H$):
  - larger Schwarzschild radius ➟ BH formation easier
  - requires slow PTs ($\lesssim$ one bubble per Hubble volume)
  - realised for instance in supercooled PTs

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

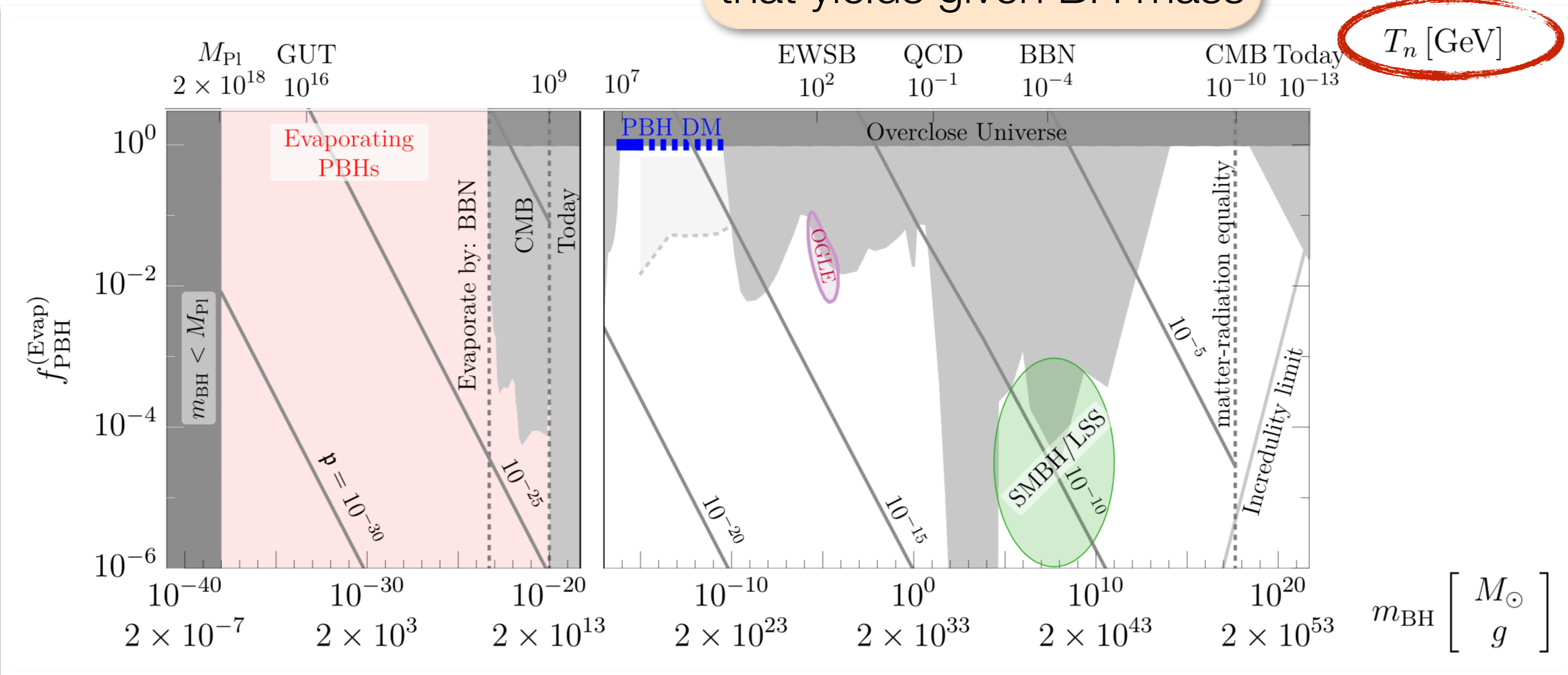
PBH Parameter Space



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

PBH Parameter Space

phase transition
temperature
that yields given BH mass



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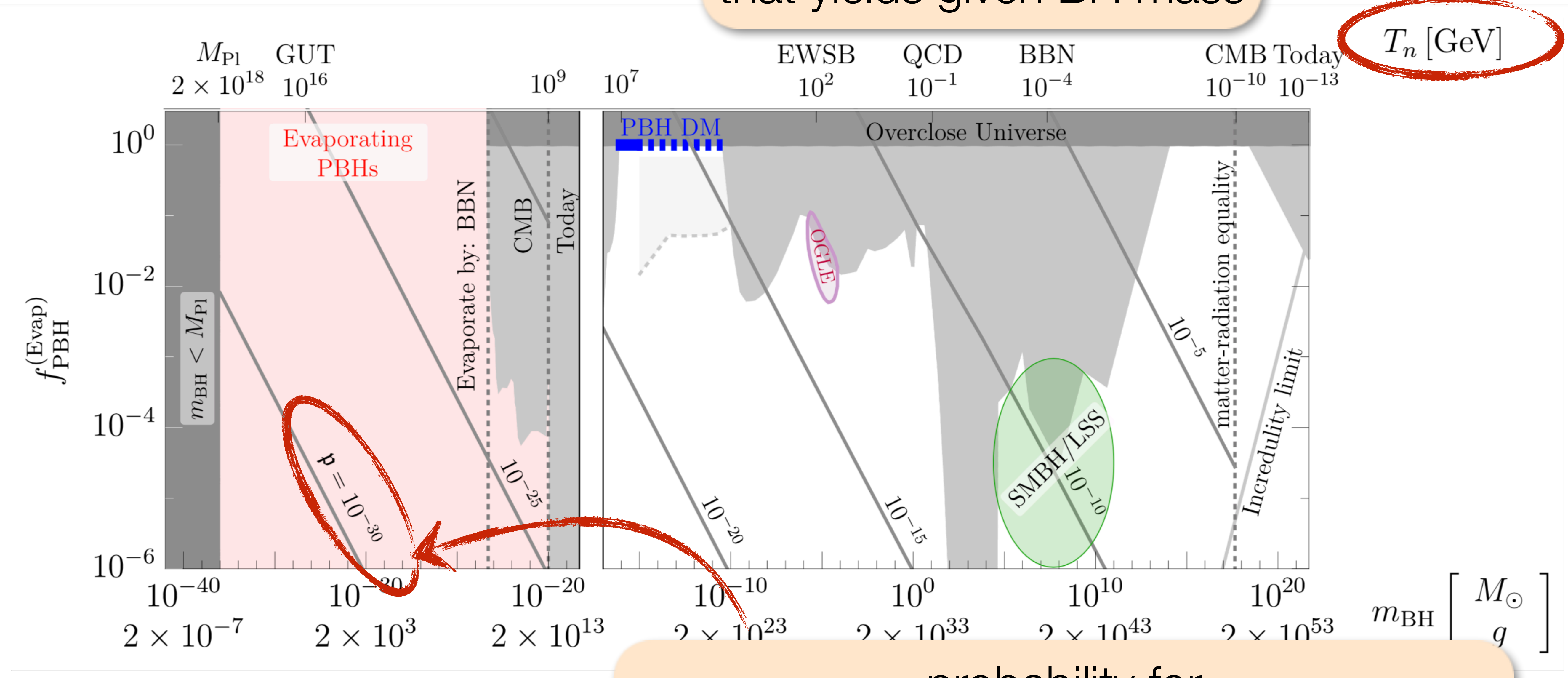

probability for
nucleating a **new true vacuum bubble**
in the shrinking false vacuum one

Baker Breitb … 005

Summary

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Summary

Phase Transition in the early Universe

- ☑ can determine the dark matter abundance by “filtering”
- ☑ can produce primordial black holes

Thank you!

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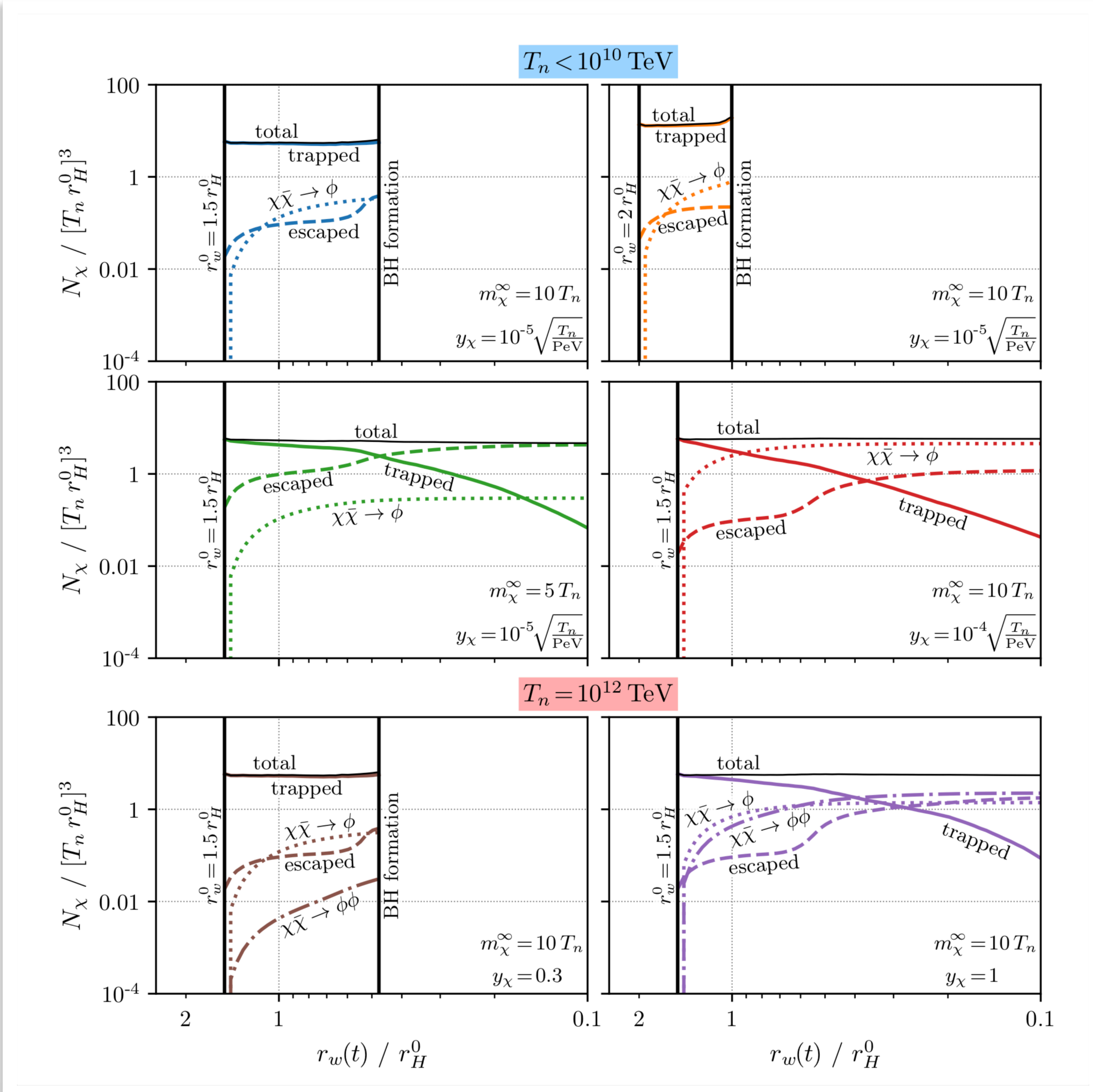
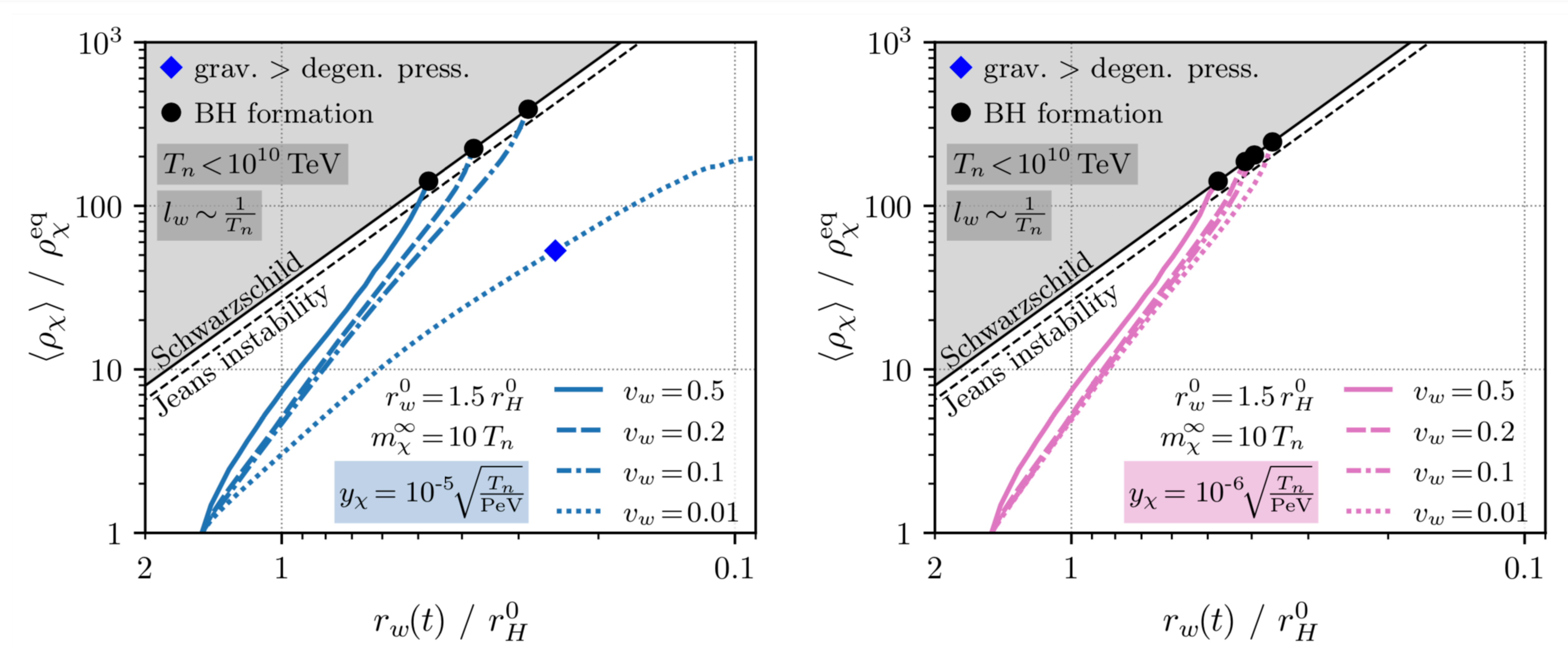
Bonus Slides

PBHs from Phase Transitions

Interplay of Different Processes



Varying the Wall Velocity



Implications B1
Gravitational Waves

Gravitational Wave and Baryogenesis

☑ Gravitational waves

- 1st order phase transitions contribute to stochastic GW background
- relevant processes: bubble collisions, sound waves, turbulence
- potentially detectable by LISA (TeV scale) or by pulsar timing arrays (GeV scale)

e.g. Breitbach JK Madge Opferkuch Schwaller arXiv:1811.11175

☑ Electroweak Baryogenesis

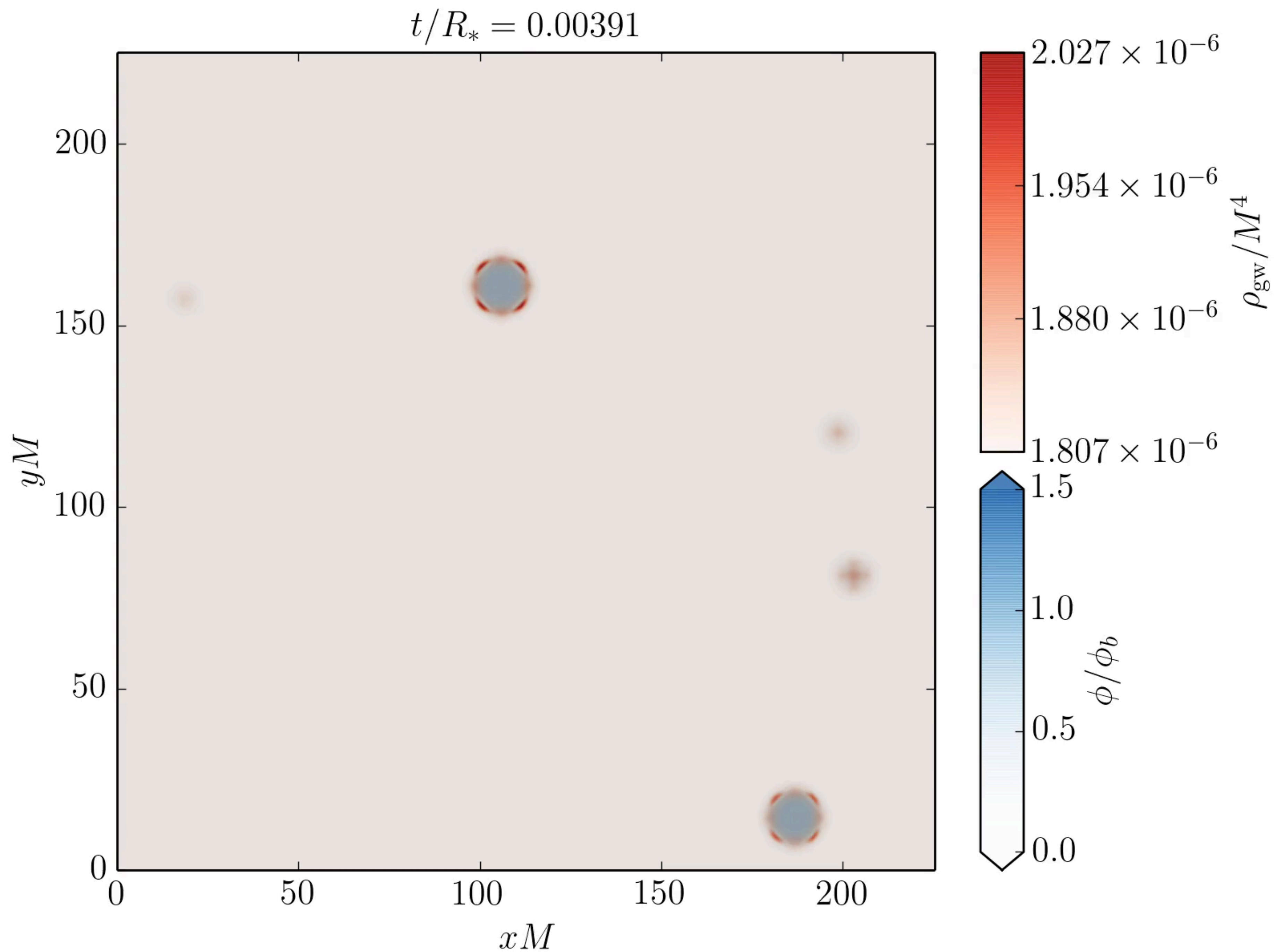
- relate particle–antiparticle asymmetry of the Universe to different permeability of bubble walls for fermions and anti-fermions

Baker Breitbach JK Mittnacht Soreq, *work in progress*

Gravitational Waves from Phase Transitions

- Phase transitions in extended scalar sectors often 1st order
  - ➠ gravitational wave signals?

Witten 1984
Cutting Hindmarsh Weir 2018



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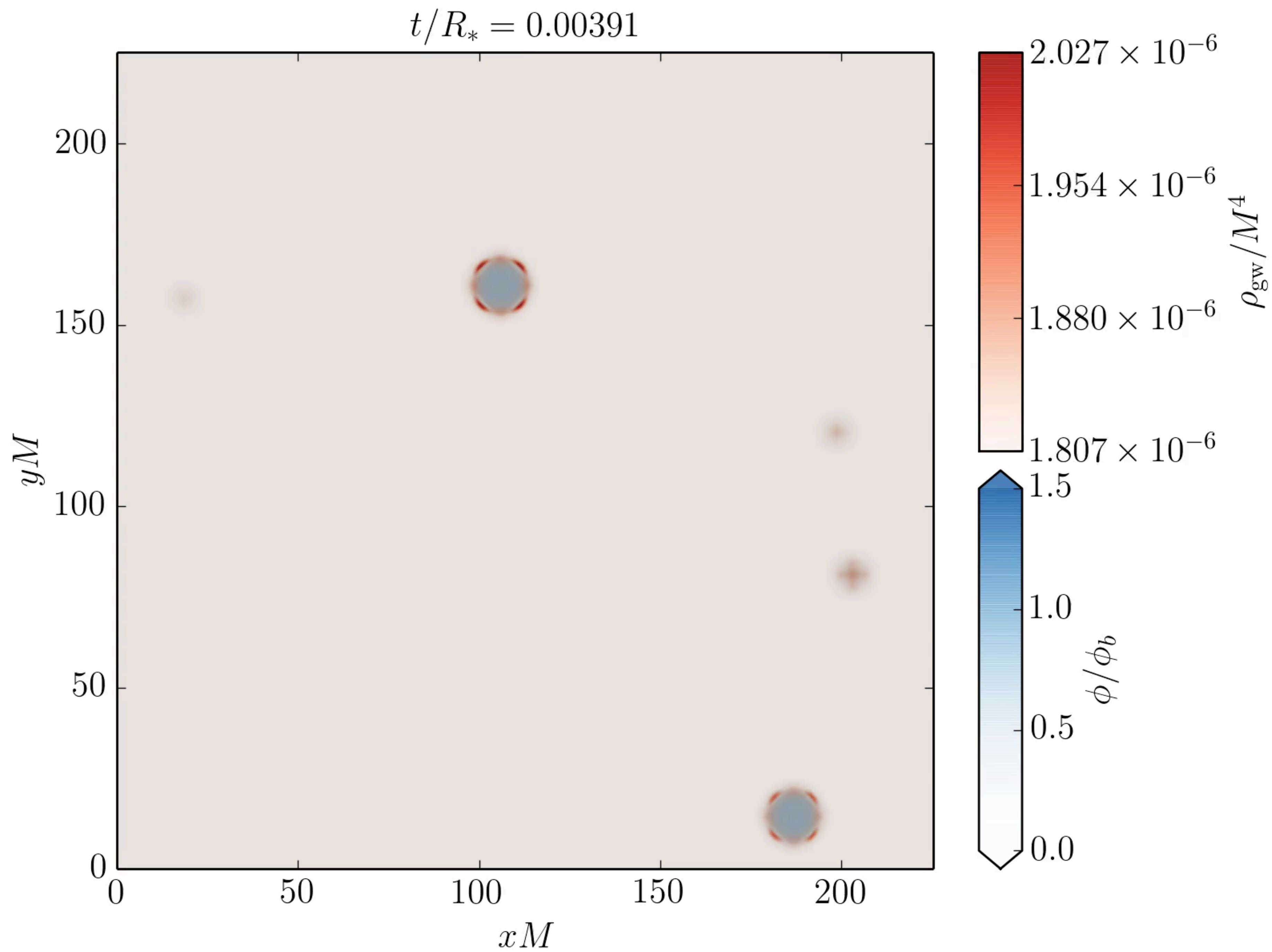

Gravitational Waves from Phase Transitions

- Three contributions
  - Bubble collisions
  - Collisions of sound waves generated during bubble expansion
  - Turbulence in the plasma
- How to compute the GW signal from these contributions:
  - requires numerical simulations (large uncertainties!)
  - Parameterize results, e.g. as

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

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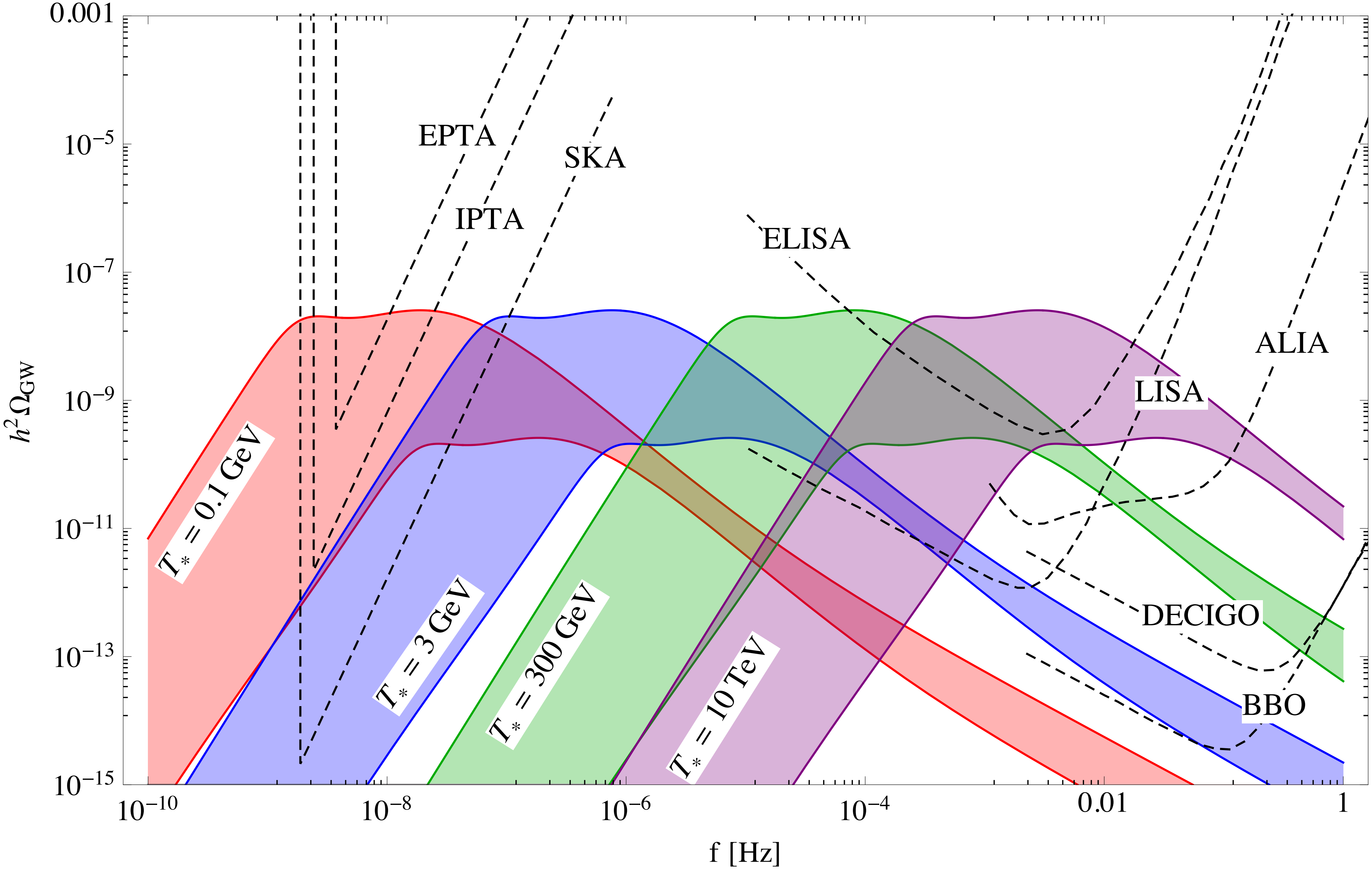
Gravitational Wave Spectra

plot from Schwaller arXiv:1504.07263

see also Breitbach JK Madge Opferkuch Schwaller arXiv:1811.11175



Phase Transition Parameter for GWs

Four relevant parameters

- Bubble nucleation temperature T^{nuc}
- Strength of the phase transition

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

- Inverse duration of phase transition

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

- Bubble wall velocity v_w

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total radiation density

- Inverse duration of phase transition

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

Euclidean action corresponding to the transition path in field space

- Bubble wall velocity v_w

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Phase Transition Parameter for GWs

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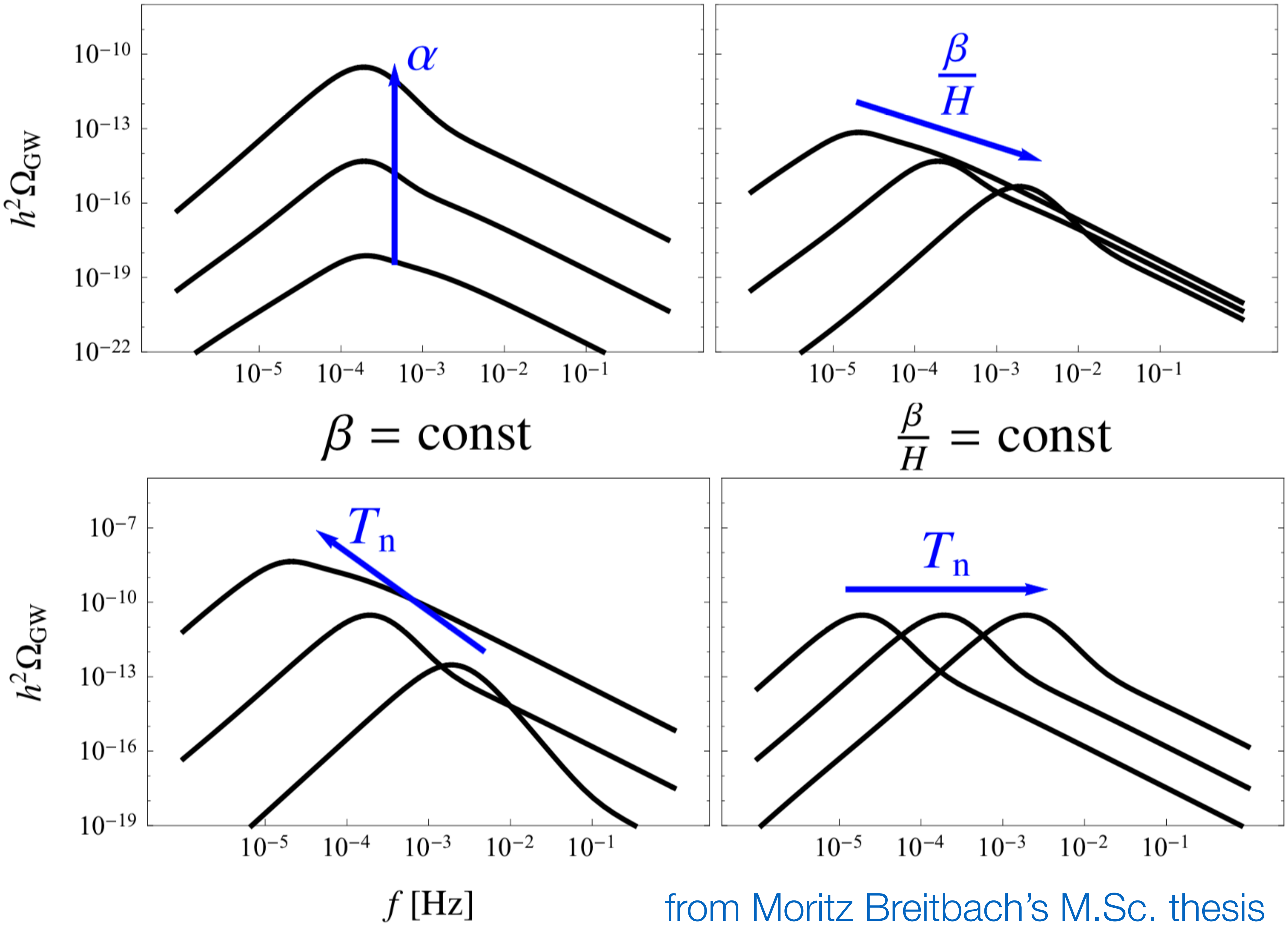
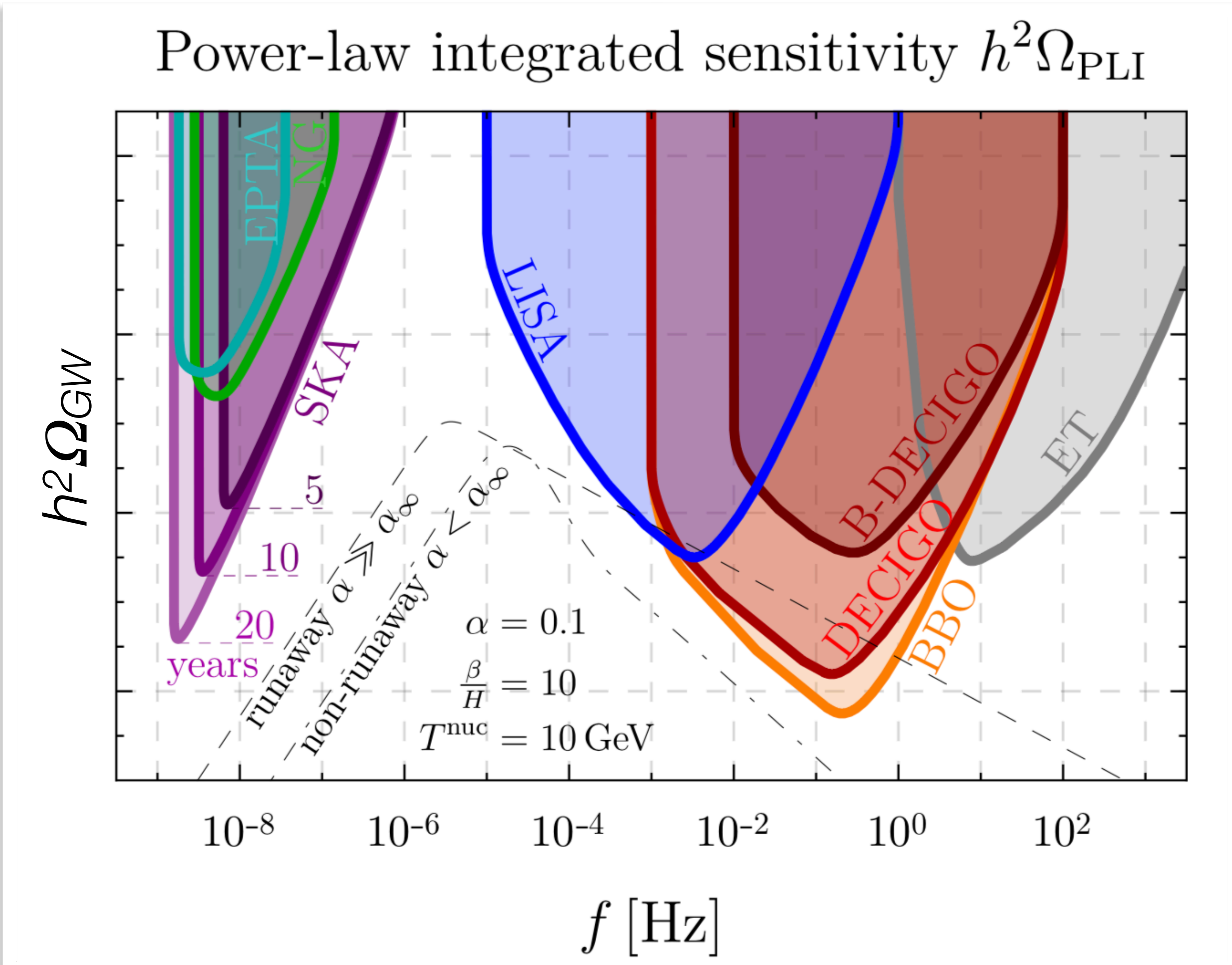
Parameter Dependence of GW Spectra



from Moritz Breitbach's M.Sc. thesis

Gravitational Wave Observatories



Breitbach JK Madge Opferkuch Schwaller arXiv:1811.11175

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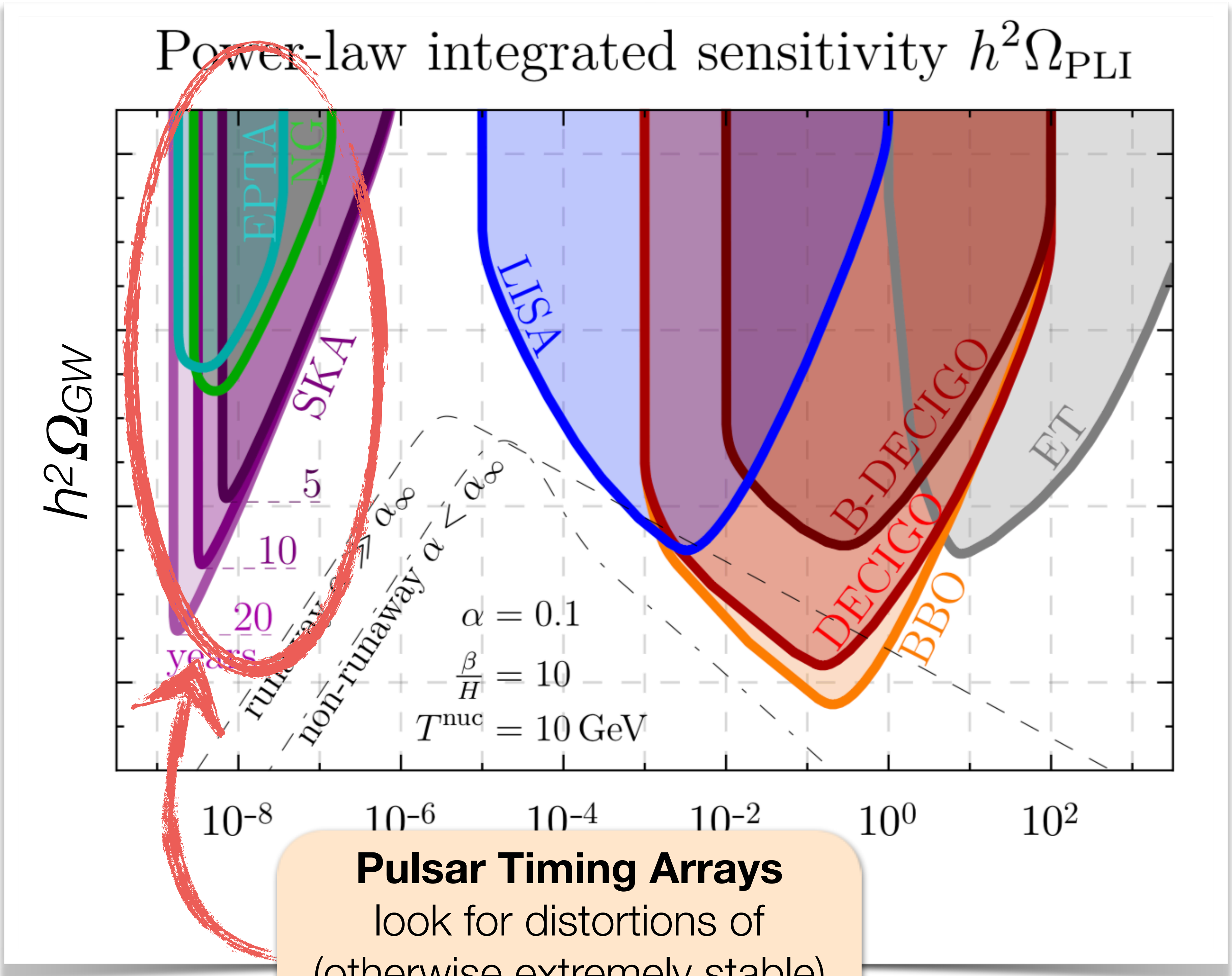

Pulsar Timing Arrays
look for distortions of
(otherwise extremely stable)
pulsar signals

Breitbach … er arXiv:1811.11175

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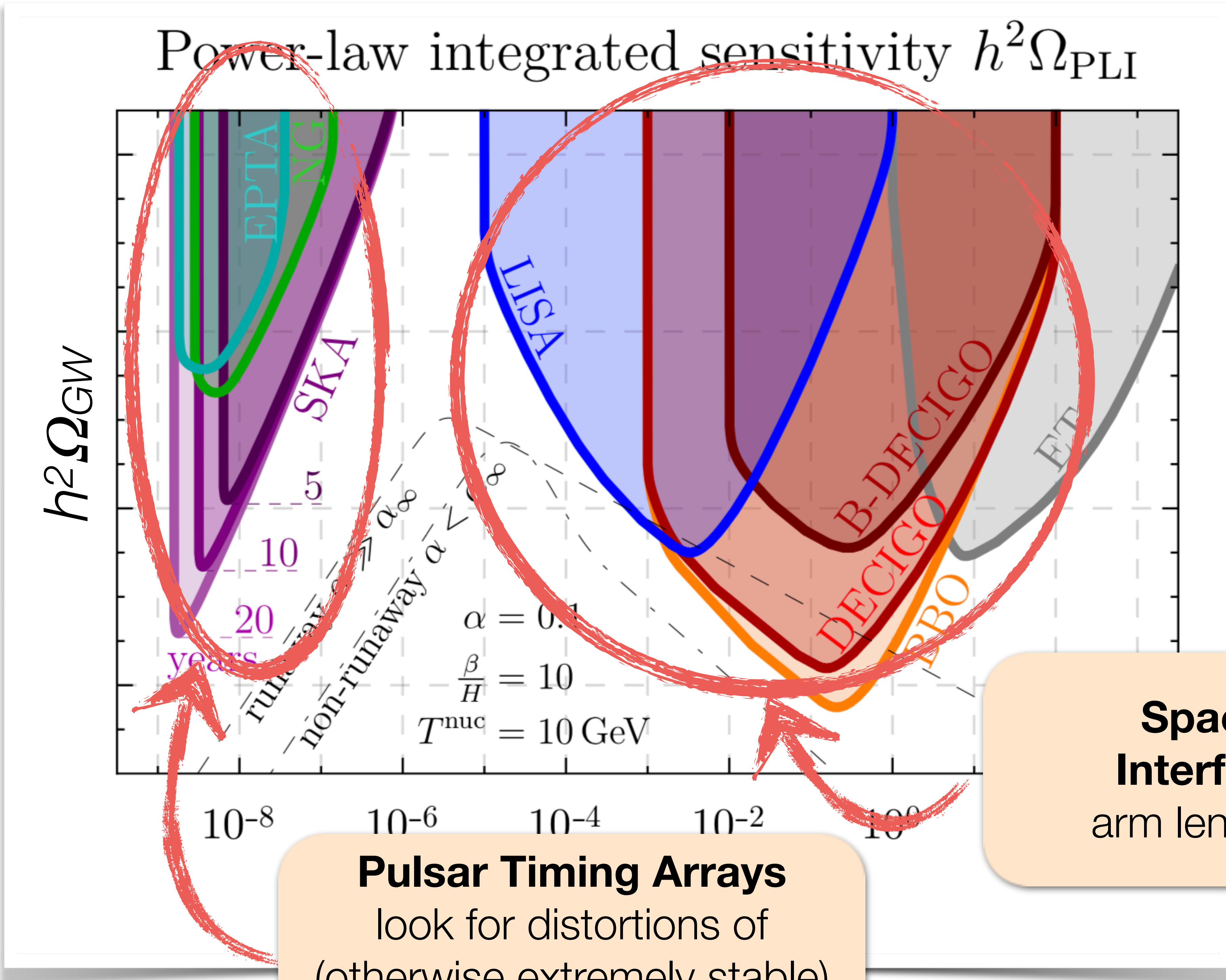

Space Based Interferometers
arm length ~10^6 km

Pulsar Timing Arrays
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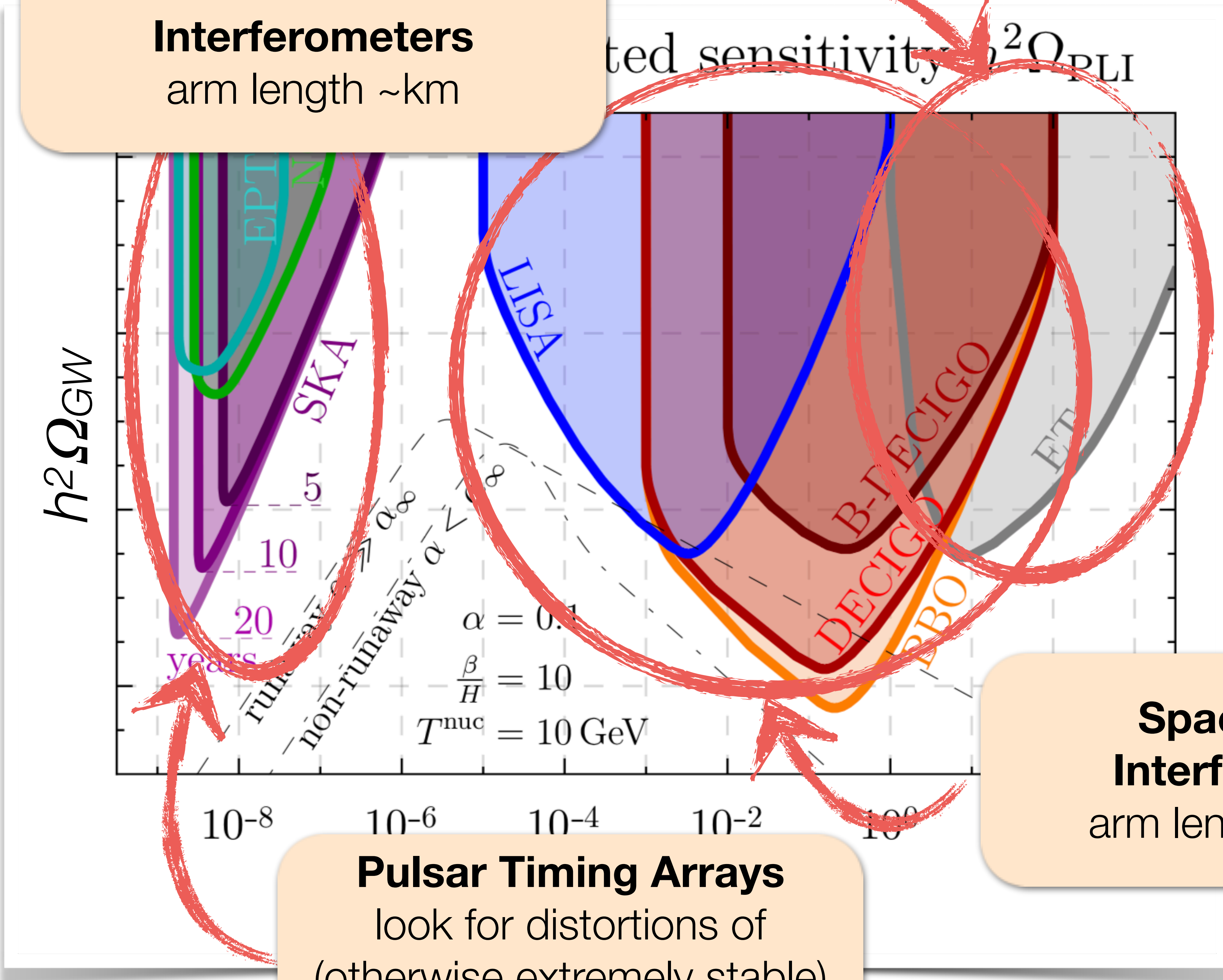
Gravitational Wave Observatories



Ground Based Interferometers
arm length ~km

Space Based Interferometers
arm length ~10^6 km

Pulsar Timing Arrays
look for distortions of (otherwise extremely stable) pulsar signals

Breitbach … er arXiv:1811.11175

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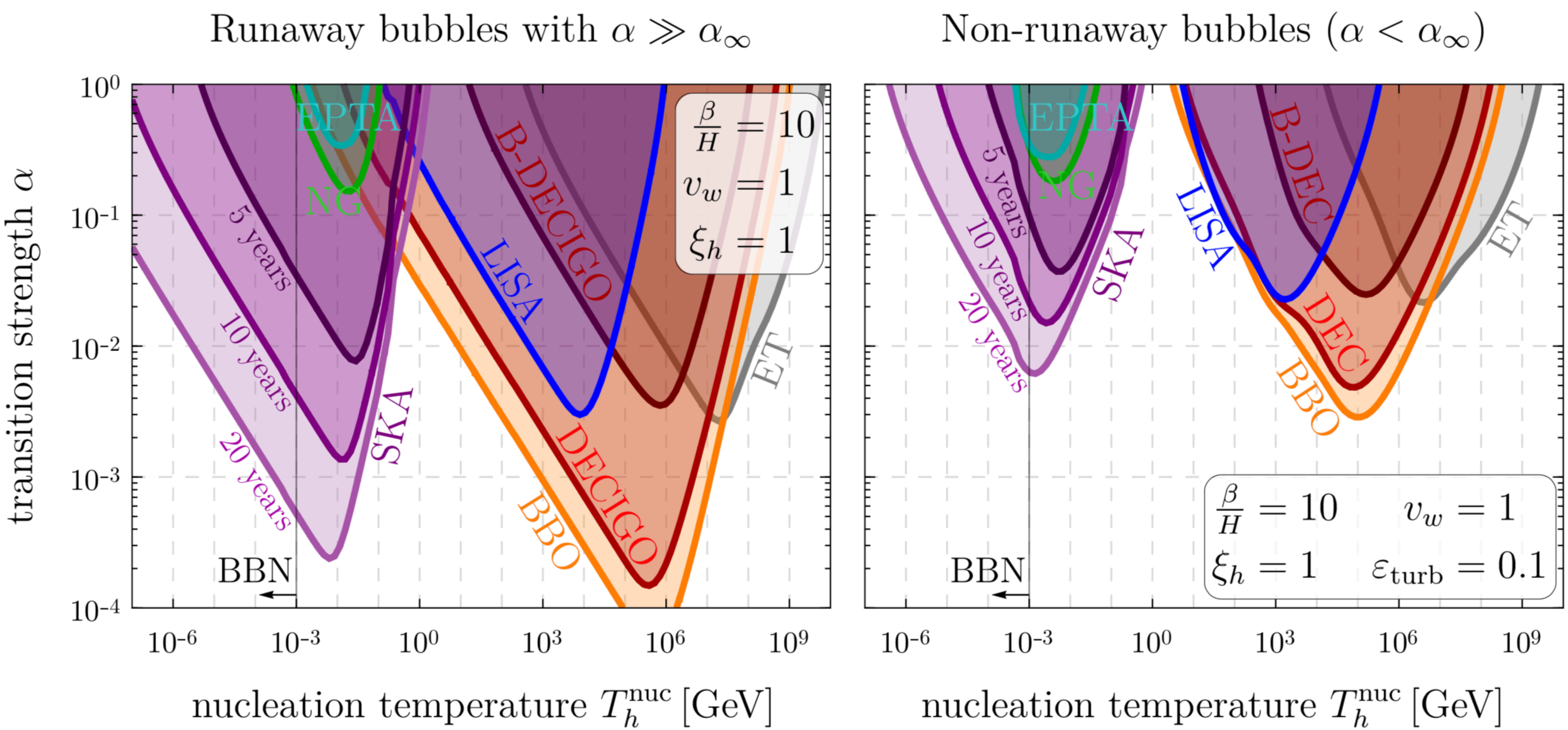
GWs from Hidden Sector Phase Transitions

Important Plot Twist

- hidden sector may have different temperature than visible sector
- parameterized by temperature ratio ξ_h

Dependence on Hidden Sector Temperature



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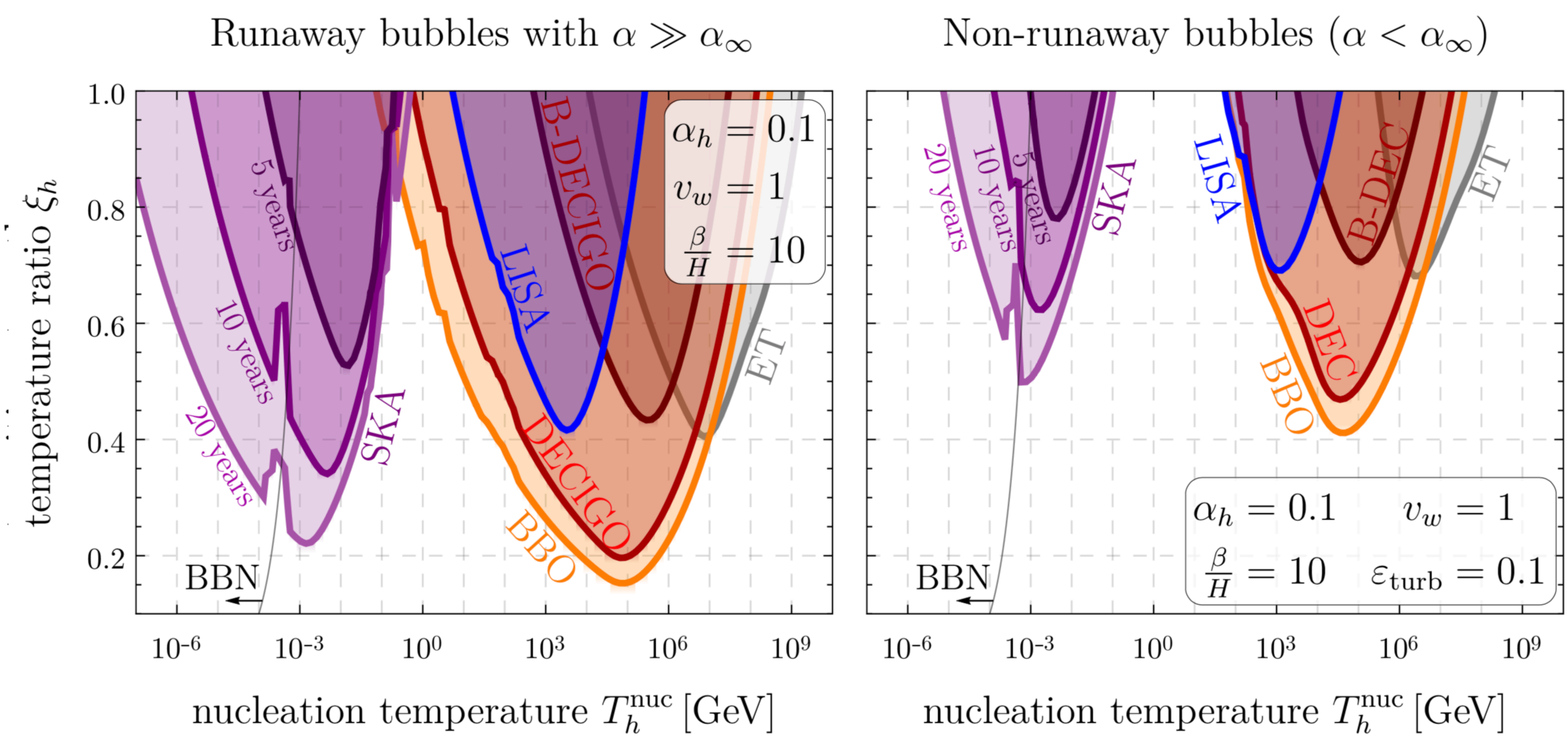

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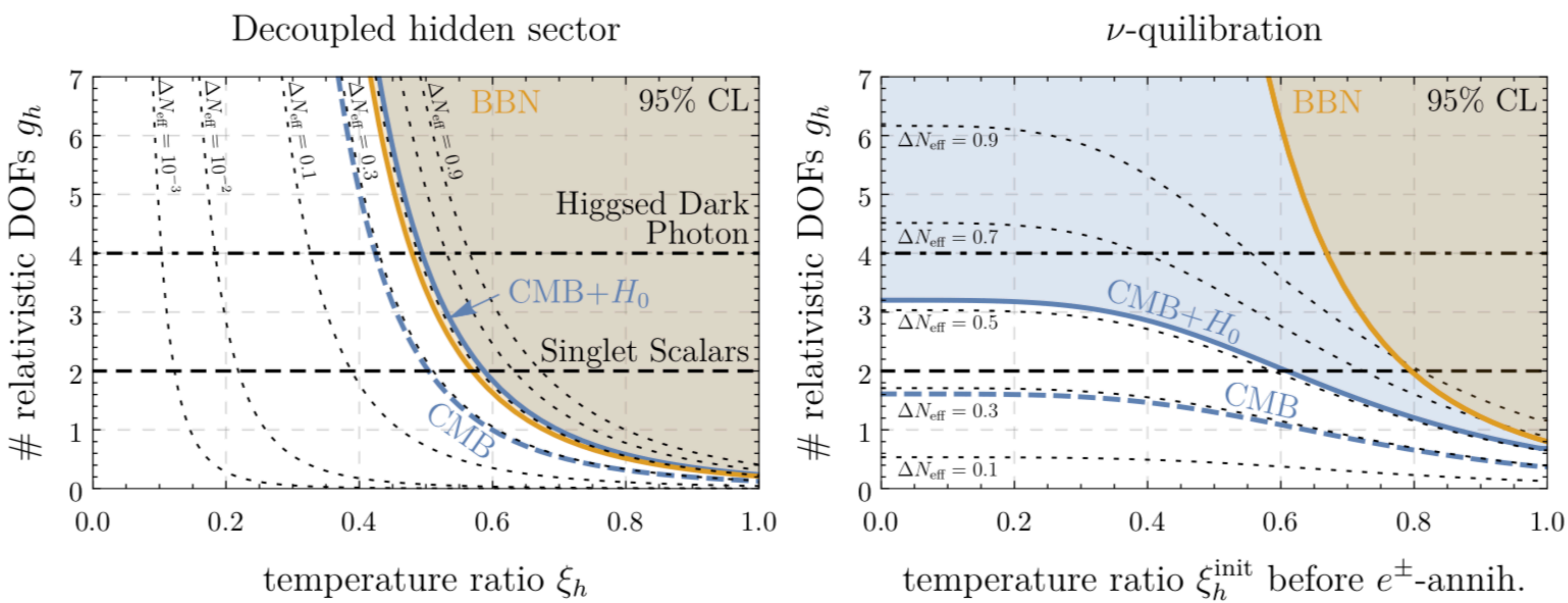
What is Needed for a Strong Phase Transition?

☑ In practice

- difficult to realize sufficiently strong 1st order phase transitions (participating particles must be large fraction of total radiation density)
- easier at lower energies (pulsar timing arrays!)
- but strong constraints from BBN



Implications B2
Baryogenesis

Electroweak Baryogenesis

- ☑ Consider 1st order electroweak phase transition
  e.g. SM + real singlet scalar
- ☑ Penetratring bubble walls is difficult for top quarks
  massless on the outside, massive on the inside ➟ potential wall
- ☑ Permeability can be larger for t_L and t_R
  requires new CP-violating interaction
- ☑ Deficit of t_L outside the bubbles

Electroweak Baryogenesis

- *B*+*L* (baryon number + lepton number) violated by sphaleron transitions
  - effect of the weak interaction ➟ affect only LH particles
  - active only outside the bubble (electroweak symmetry broken inside)
  - *B*–*L* remains conserved
- Entropy maximization implies that baryons are regenerated from leptons
- Net gain in baryon number
- Excess baryons are eventually swept up by advancing bubble walls

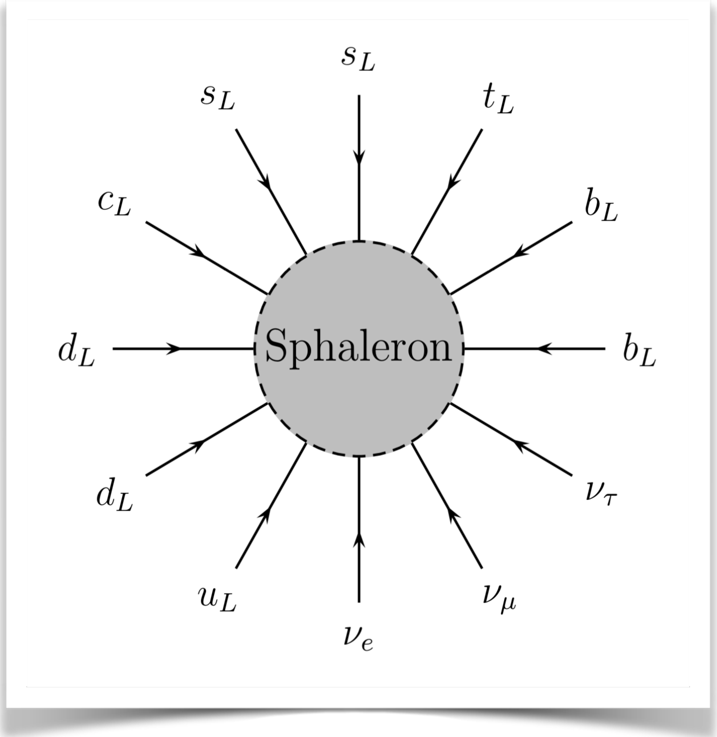


Image: Wilfried Buchmüller, hep-ph/9812447

Implications B3

Collider Observables

Connections to Higgs Physics at Colliders

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- ☑ Connection to the SM: Higgs portal $(S^\dagger S)(H^\dagger H)$

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  - 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)

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    - → 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