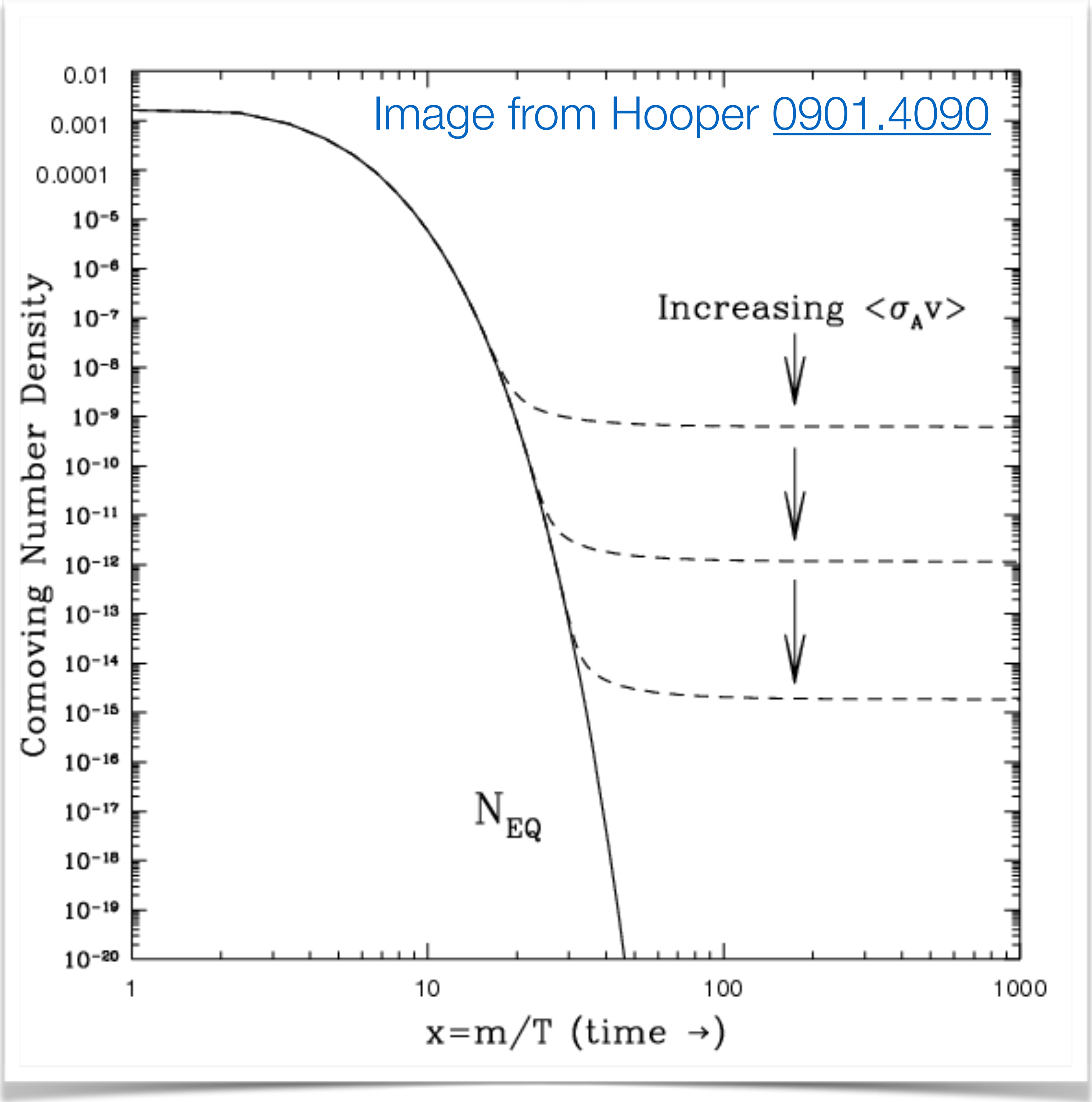
Filtered Dark Matter

Setting the DM Abundance Through a First-Order Phase Transition

Joachim Kopp (CERN & Uni Mainz)
Invisibles / Elusives Webinar | 14.01.2020

DM in the early Universe: Thermal Freeze-Out



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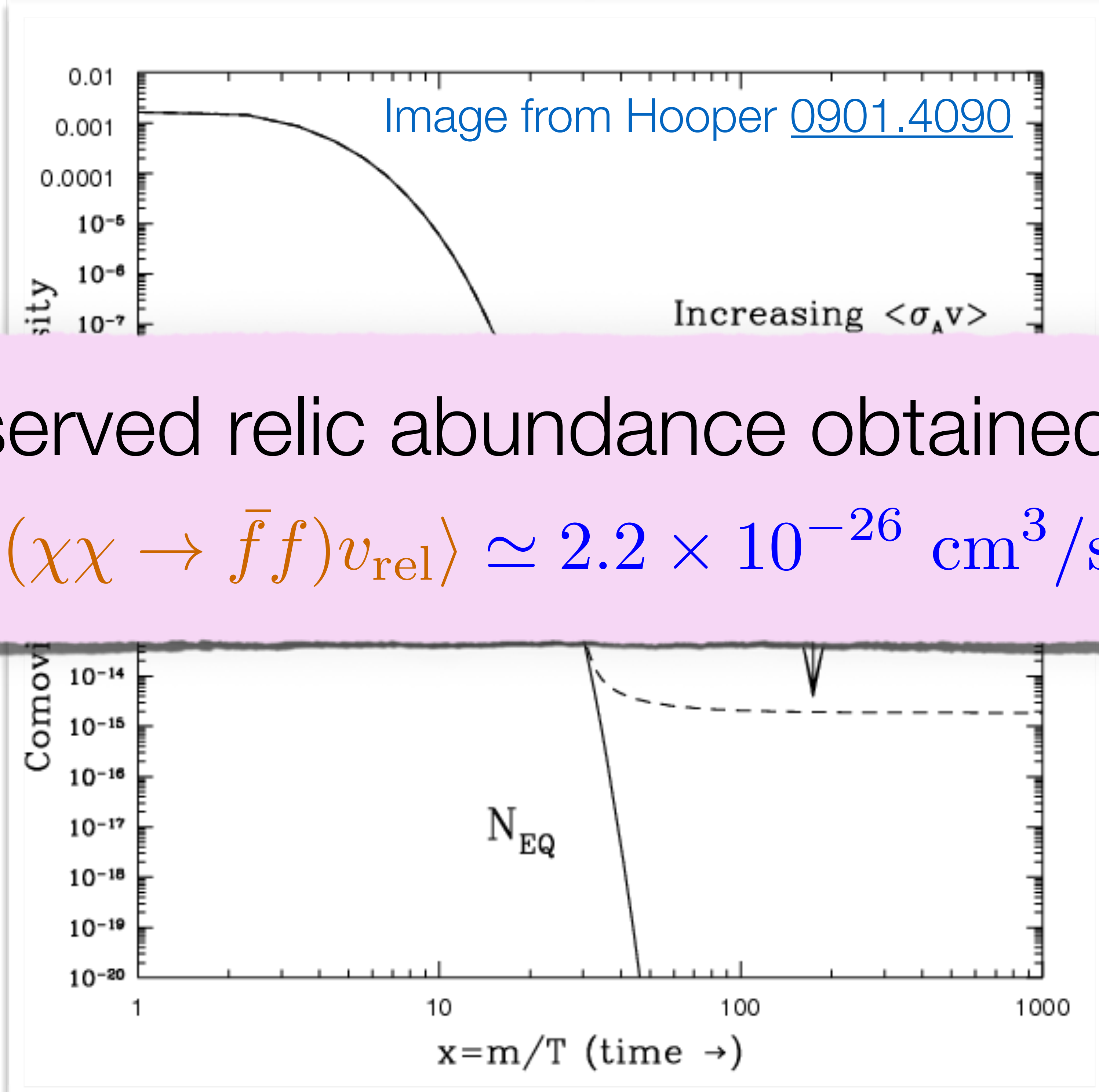

observed relic abundance obtained for

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

Beyond Thermal Freeze-Out

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  - indirect searches (cosmic rays from DM annihilation)
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- No showstoppers yet, but the community is beginning to worry
- One alternative: setting the DM abundance in a cosmological phase transition
  ➠ this talk

Phase Transitions Primer

Phase Transitions in Everyday Life

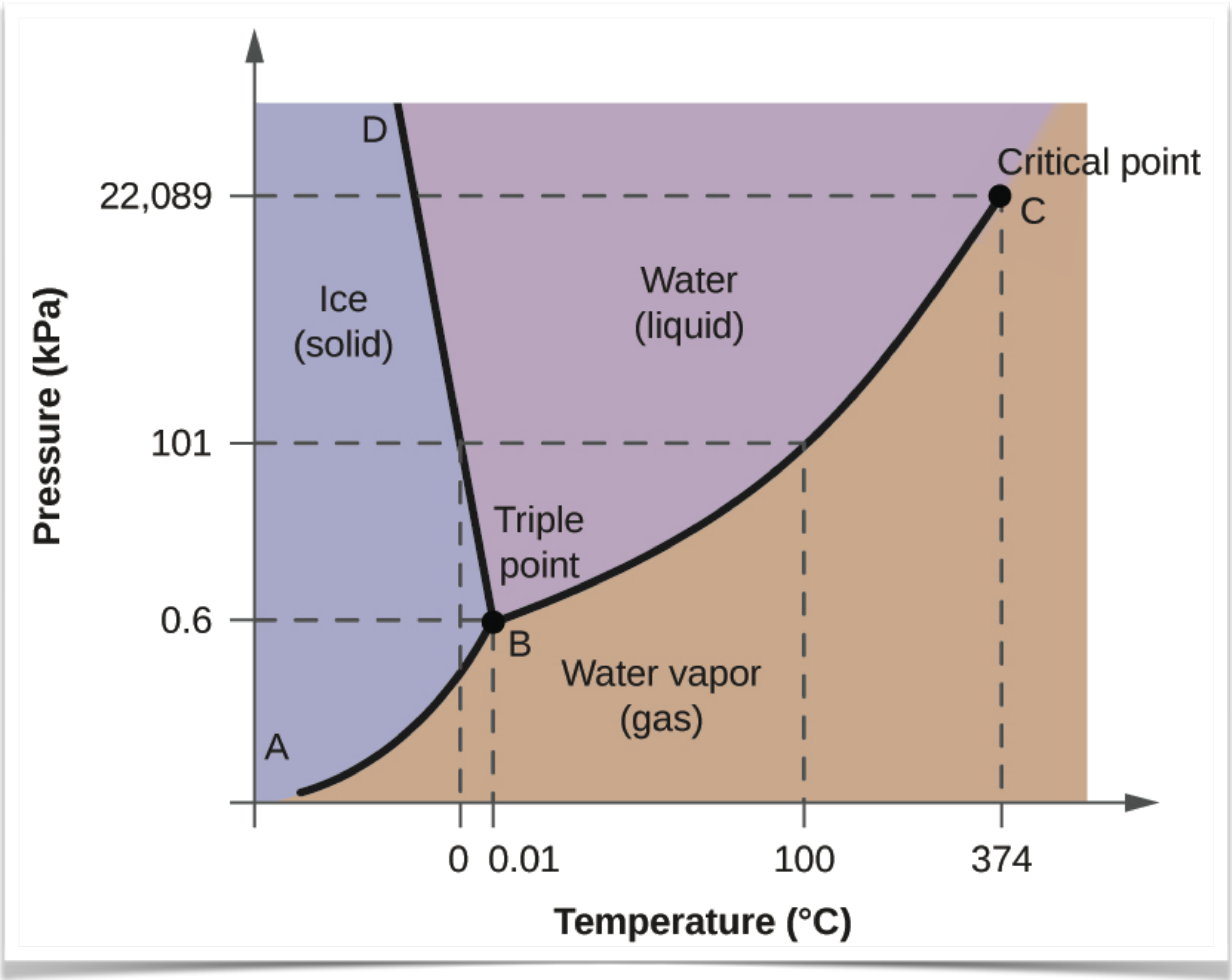

Image Credit: libretexts.org

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

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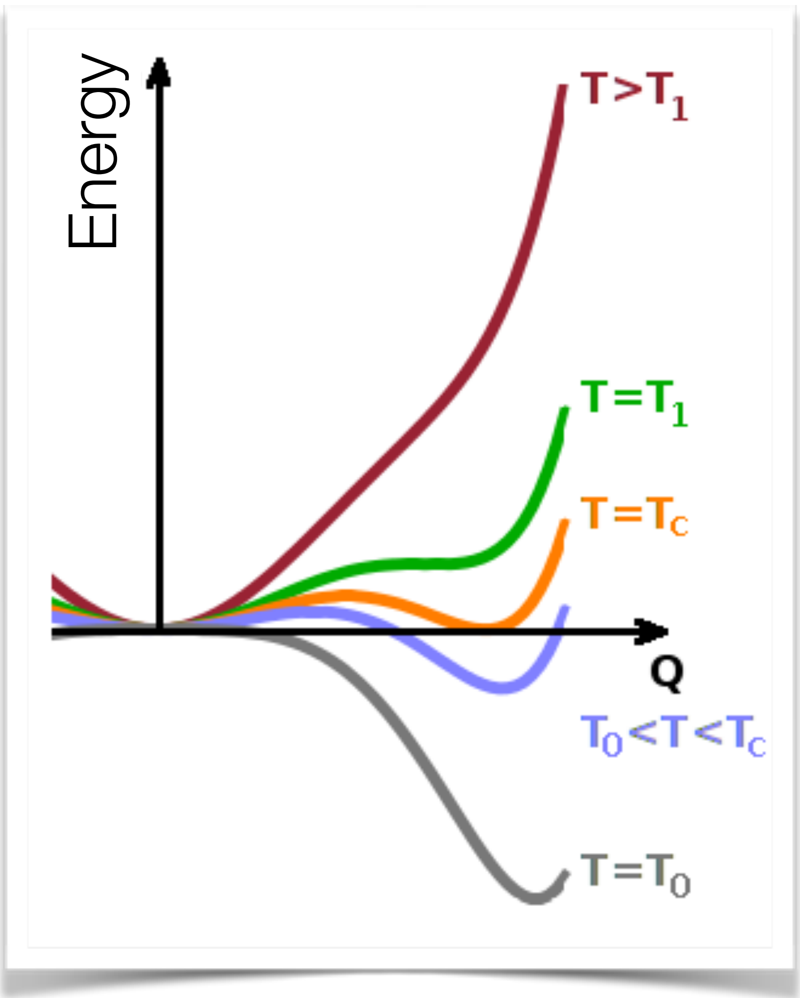

The Order of a Phase Transition

1^{st} order transition

order parameter changes discontinuously

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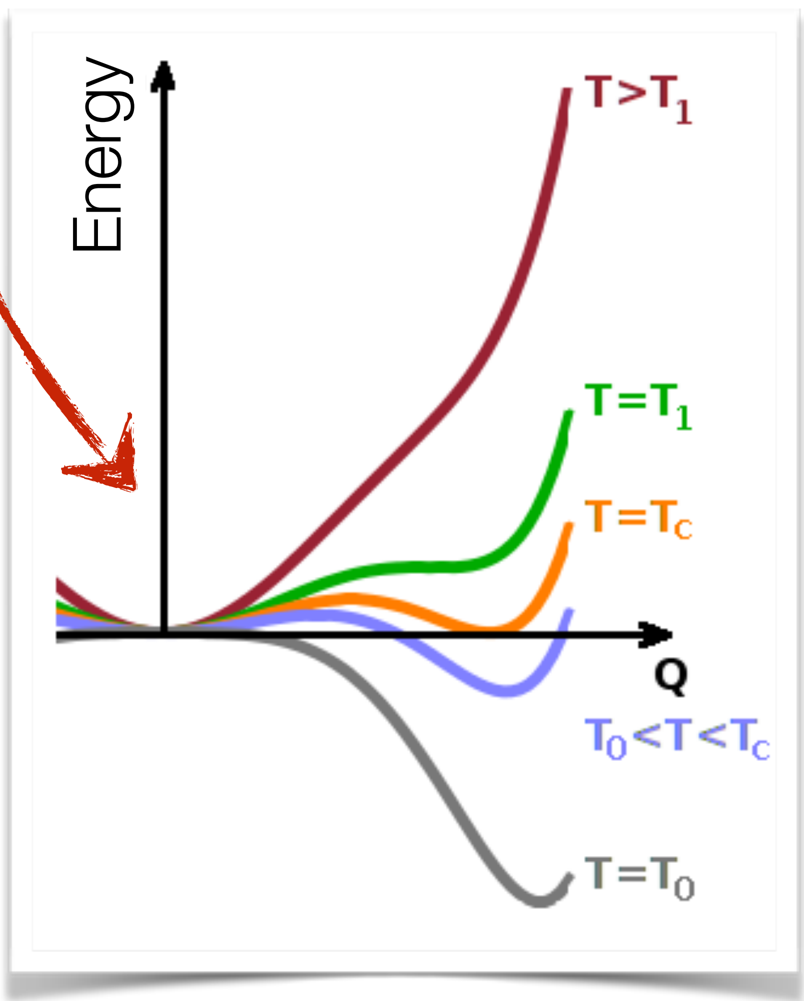

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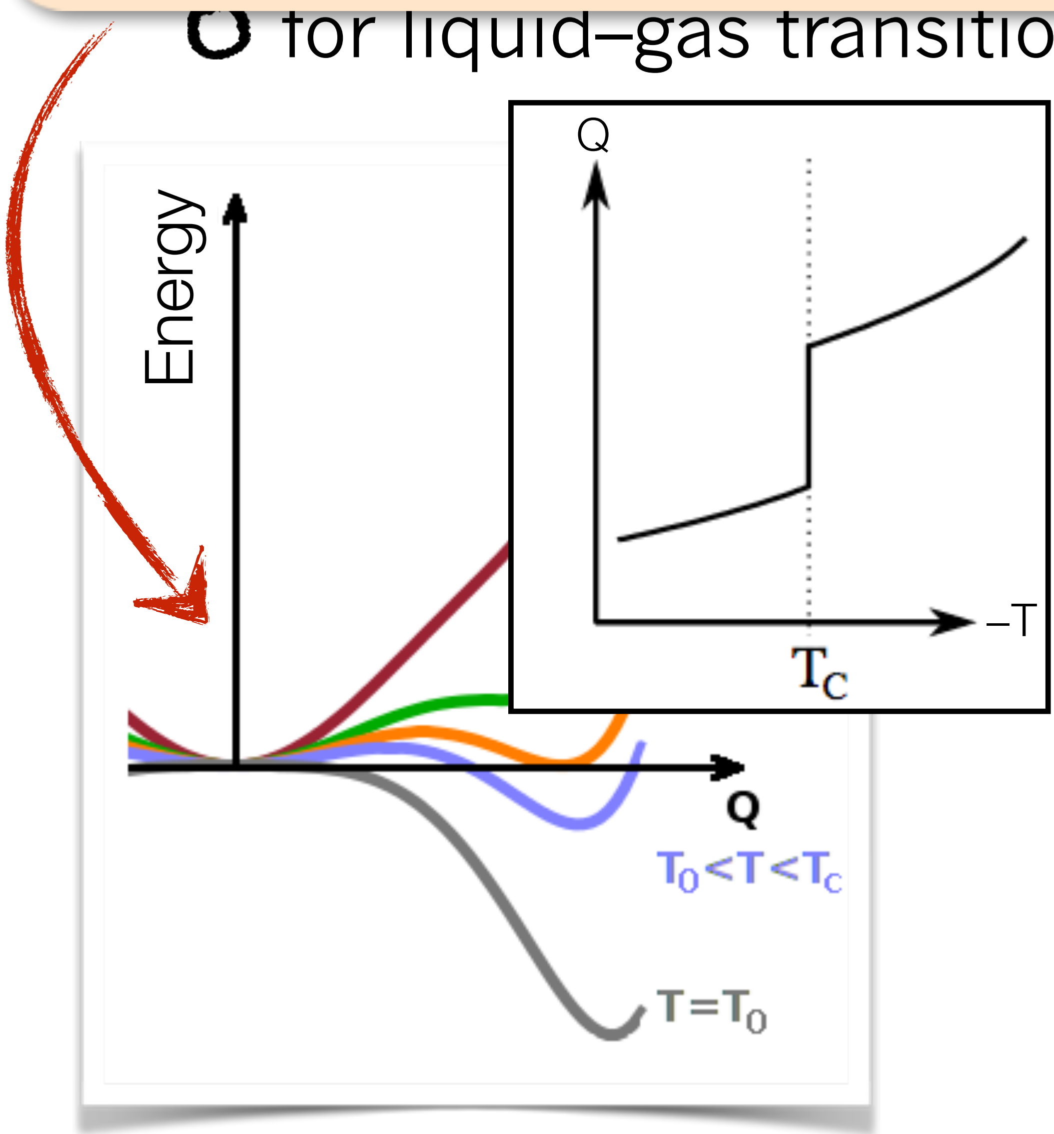

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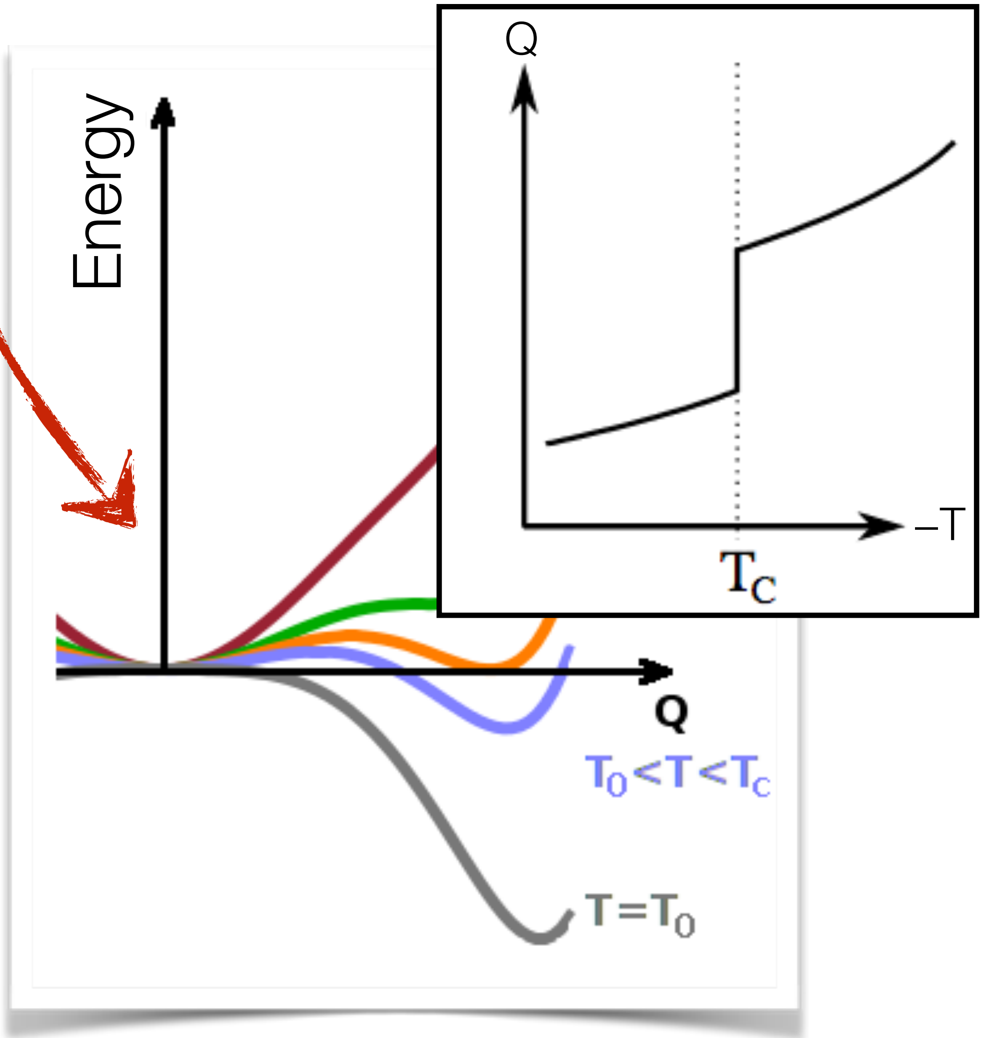

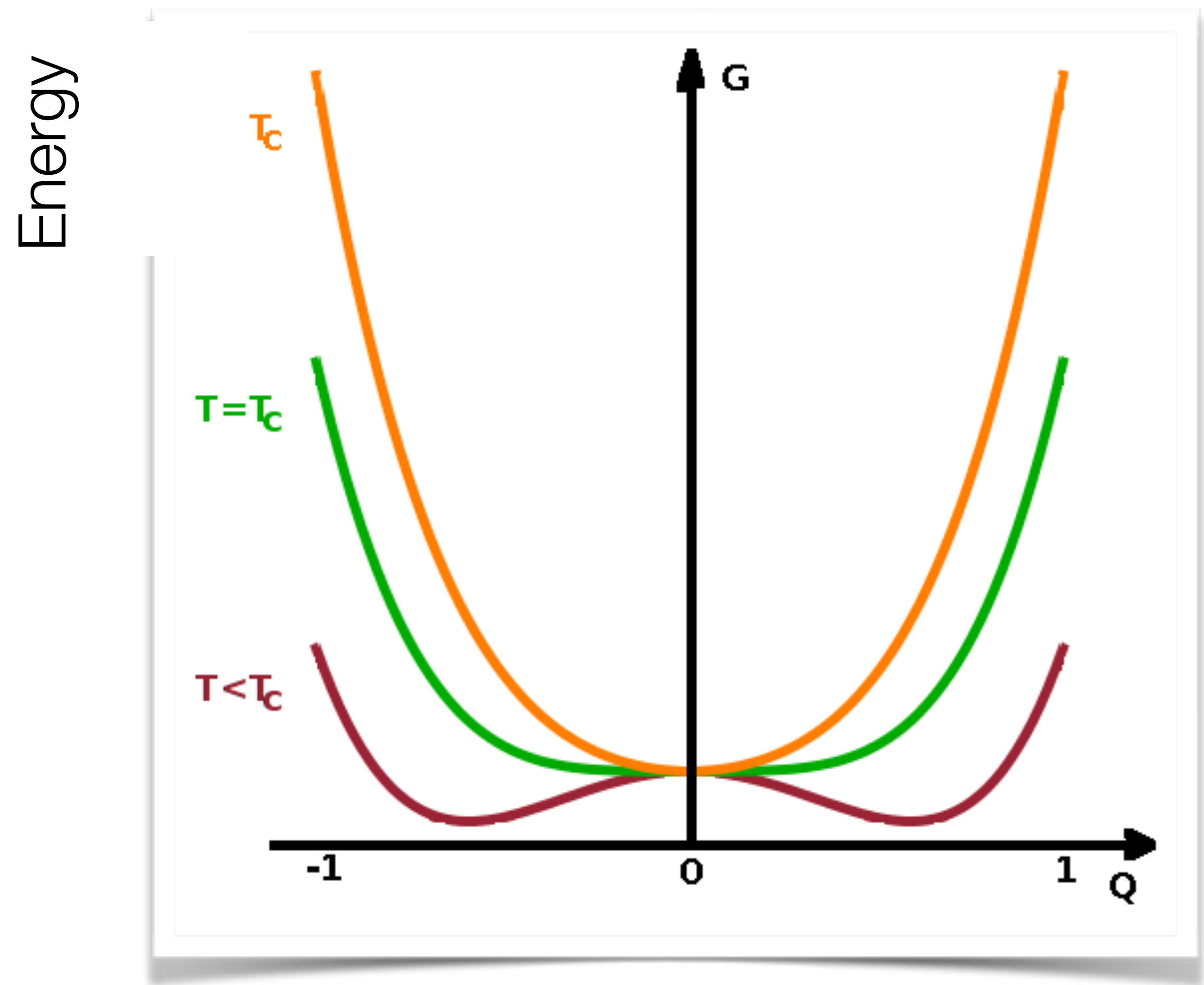

Images: Rudi Winter, Caroline Röhr and Heinz Gericke

The Order of a Phase Transition

1^{st} order transition
order parameter changes discontinuously

2^{nd} order transition / crossover
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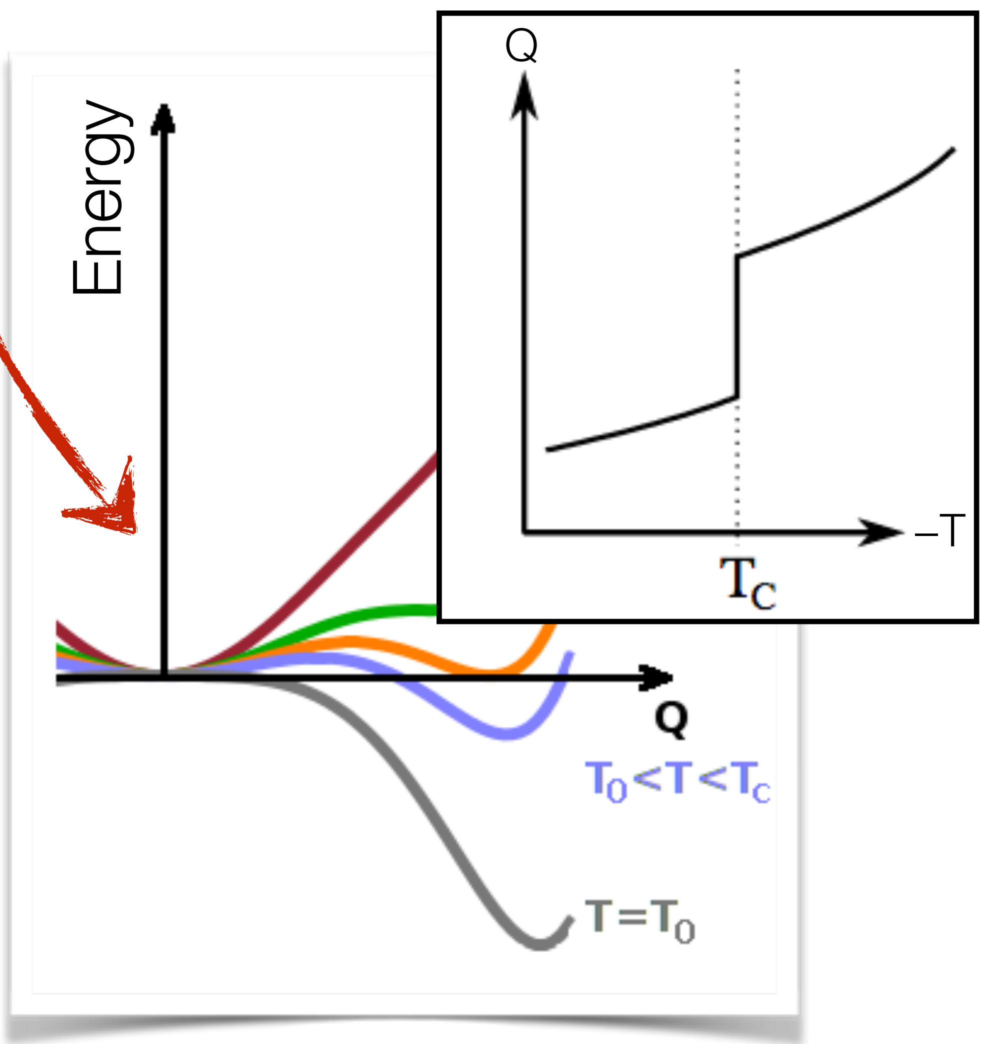

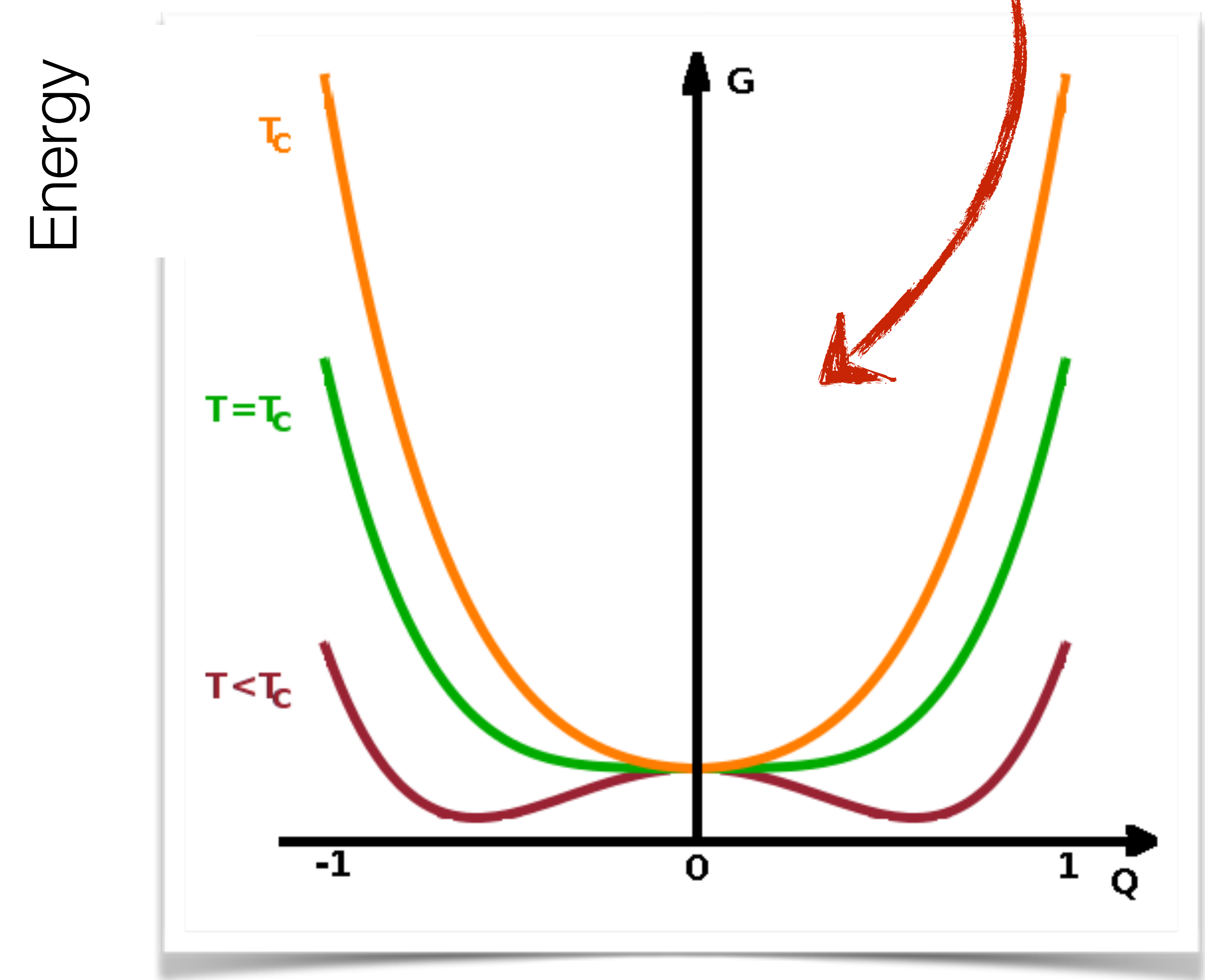

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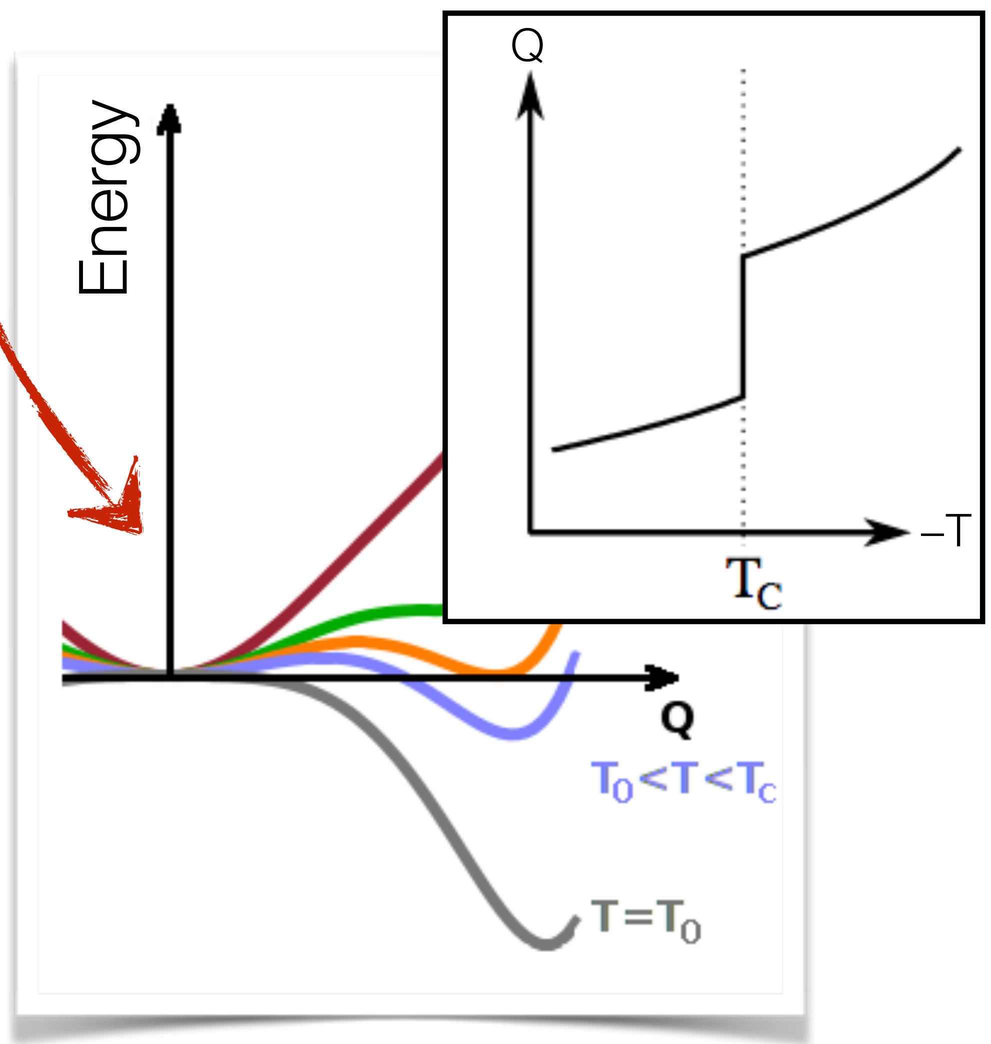

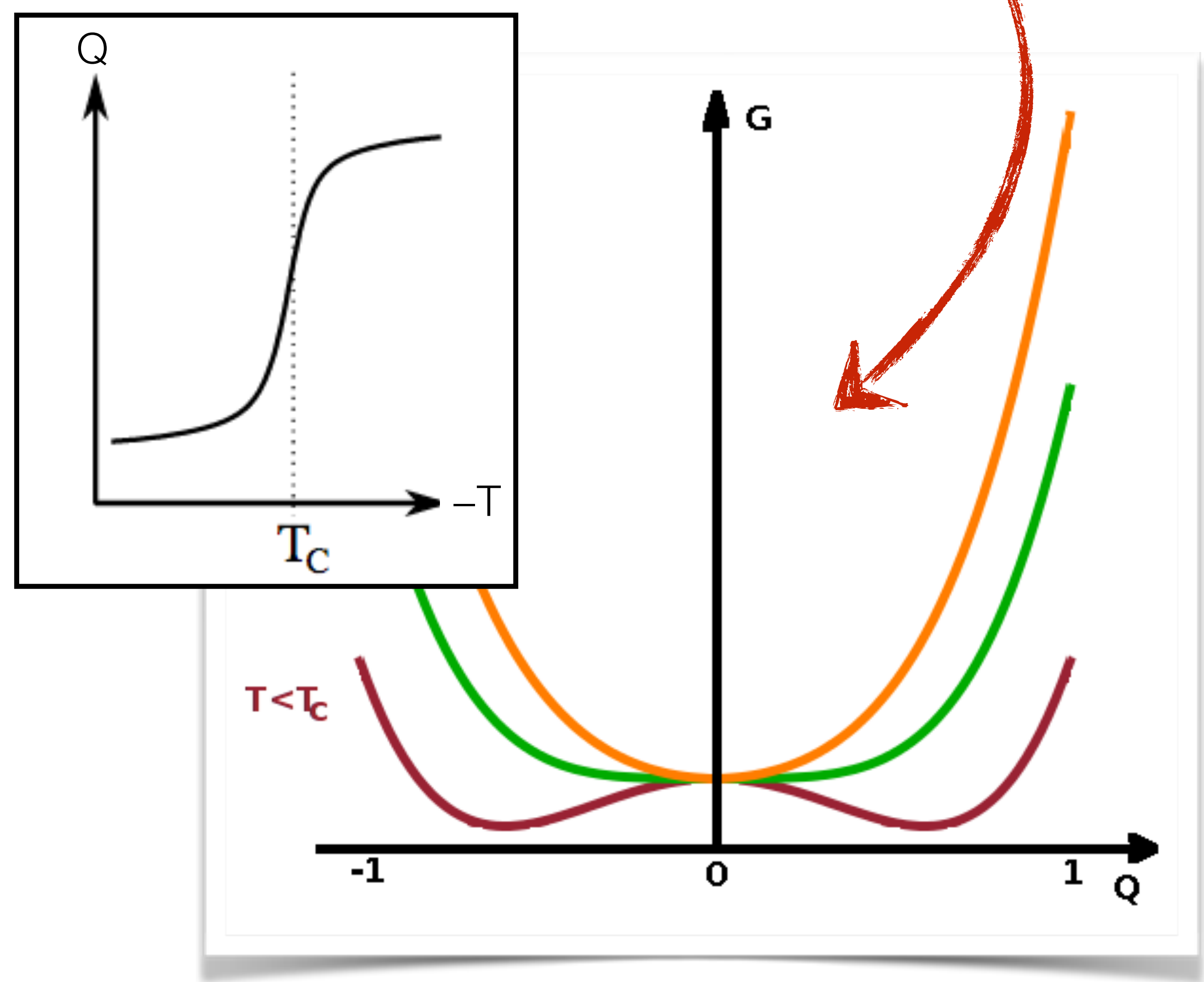

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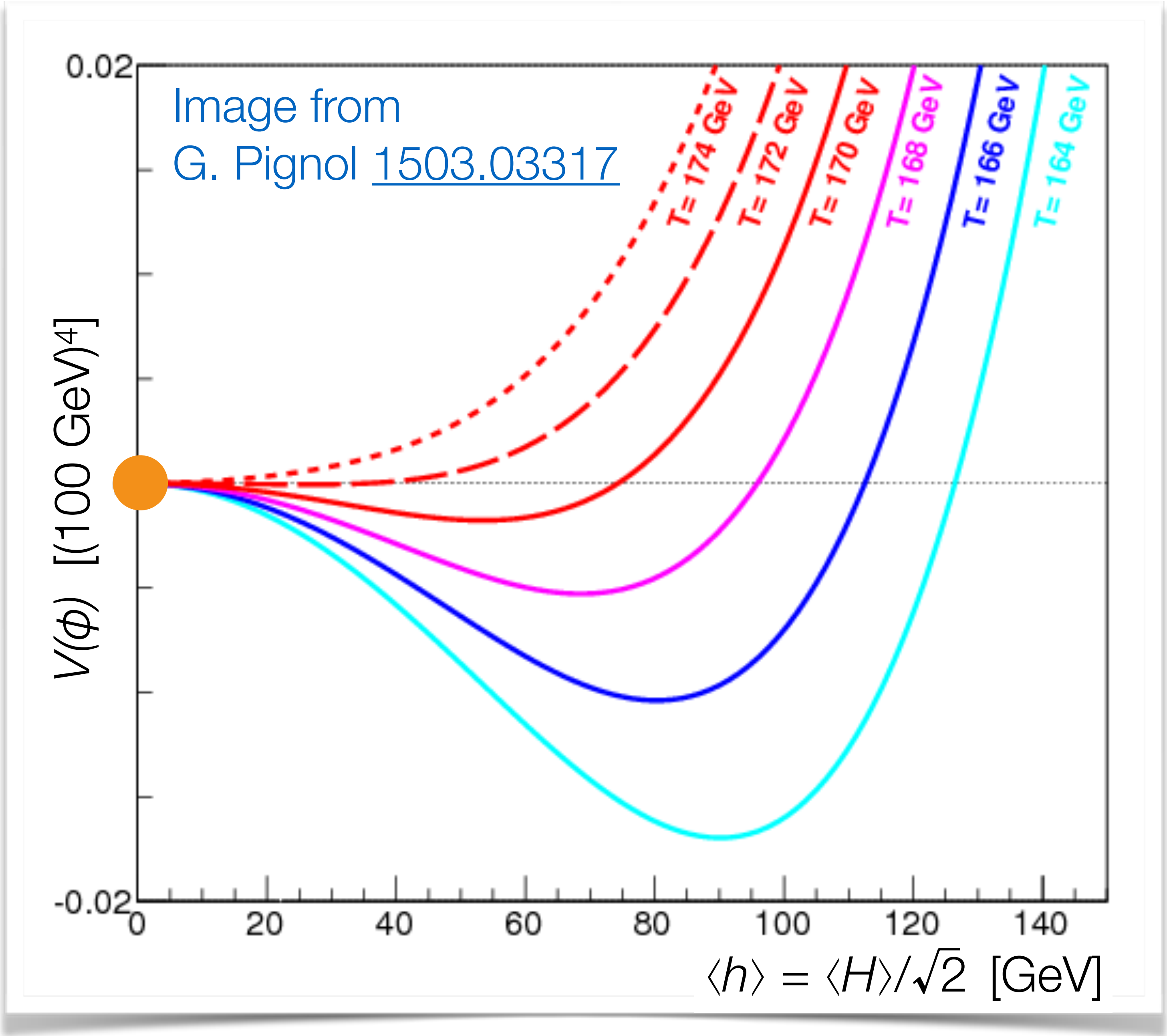
The Electroweak Phase Transition



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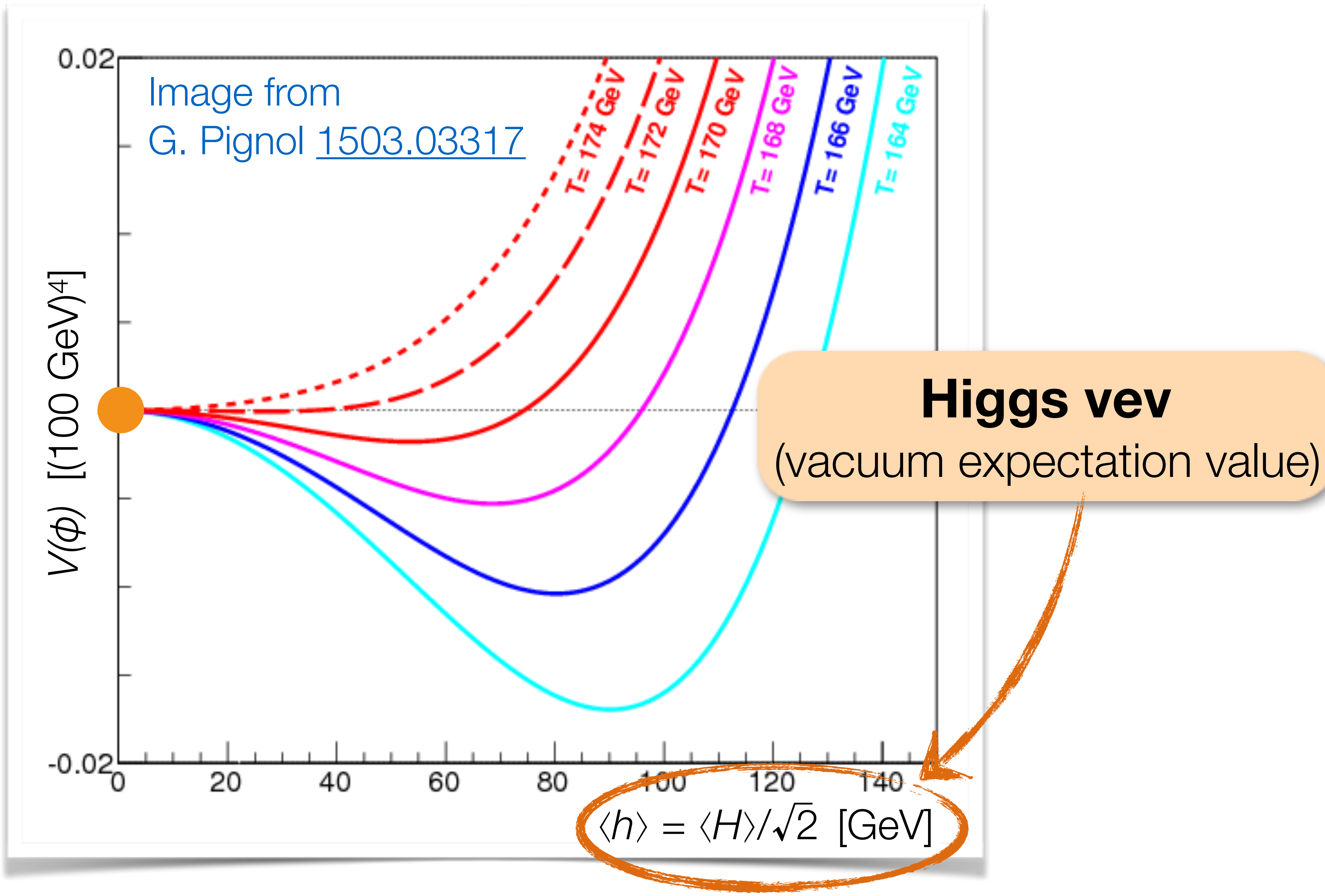

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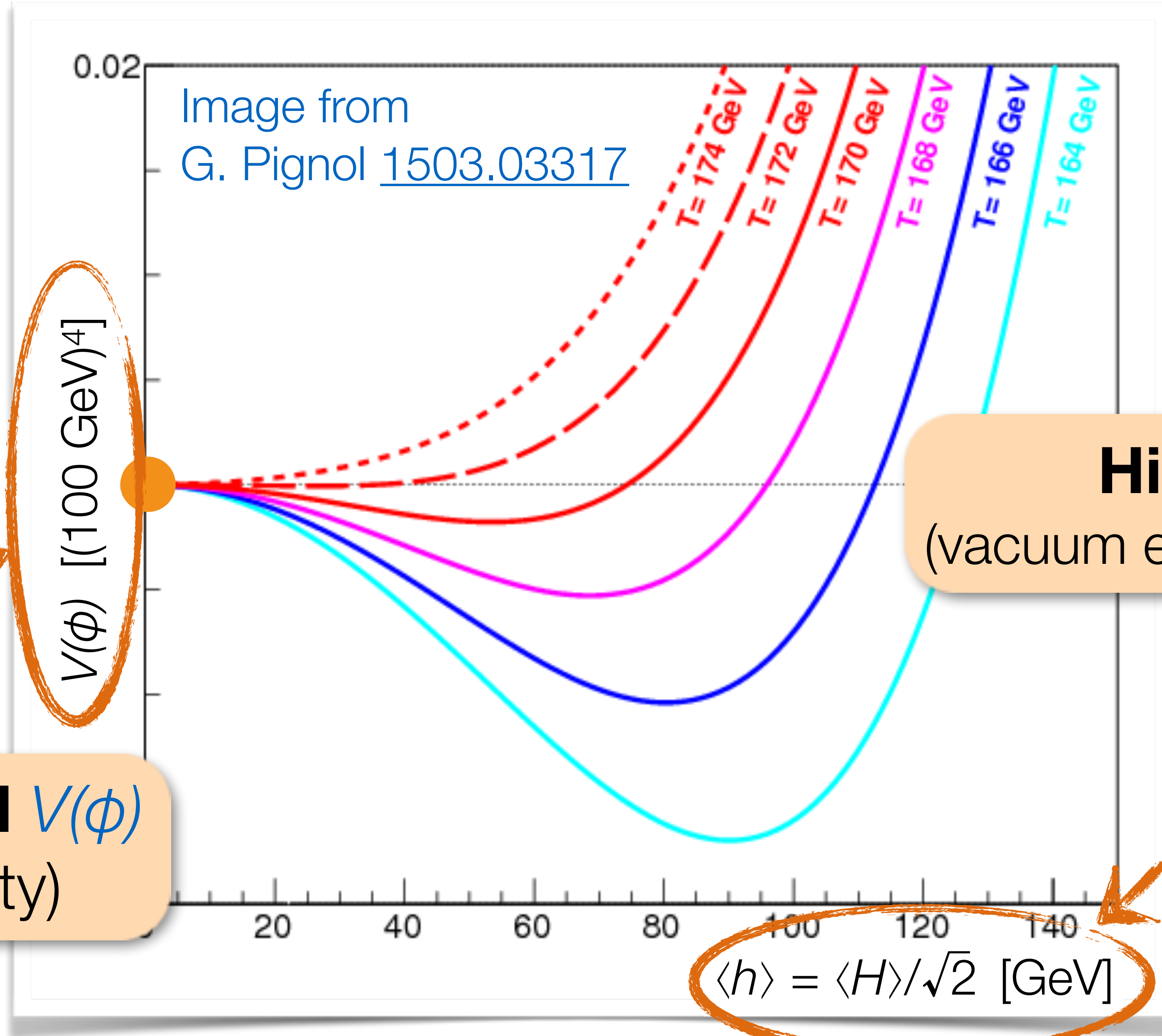

Higgs vev
(vacuum expectation value)

Higgs potential $V(\phi)$
(energy density)

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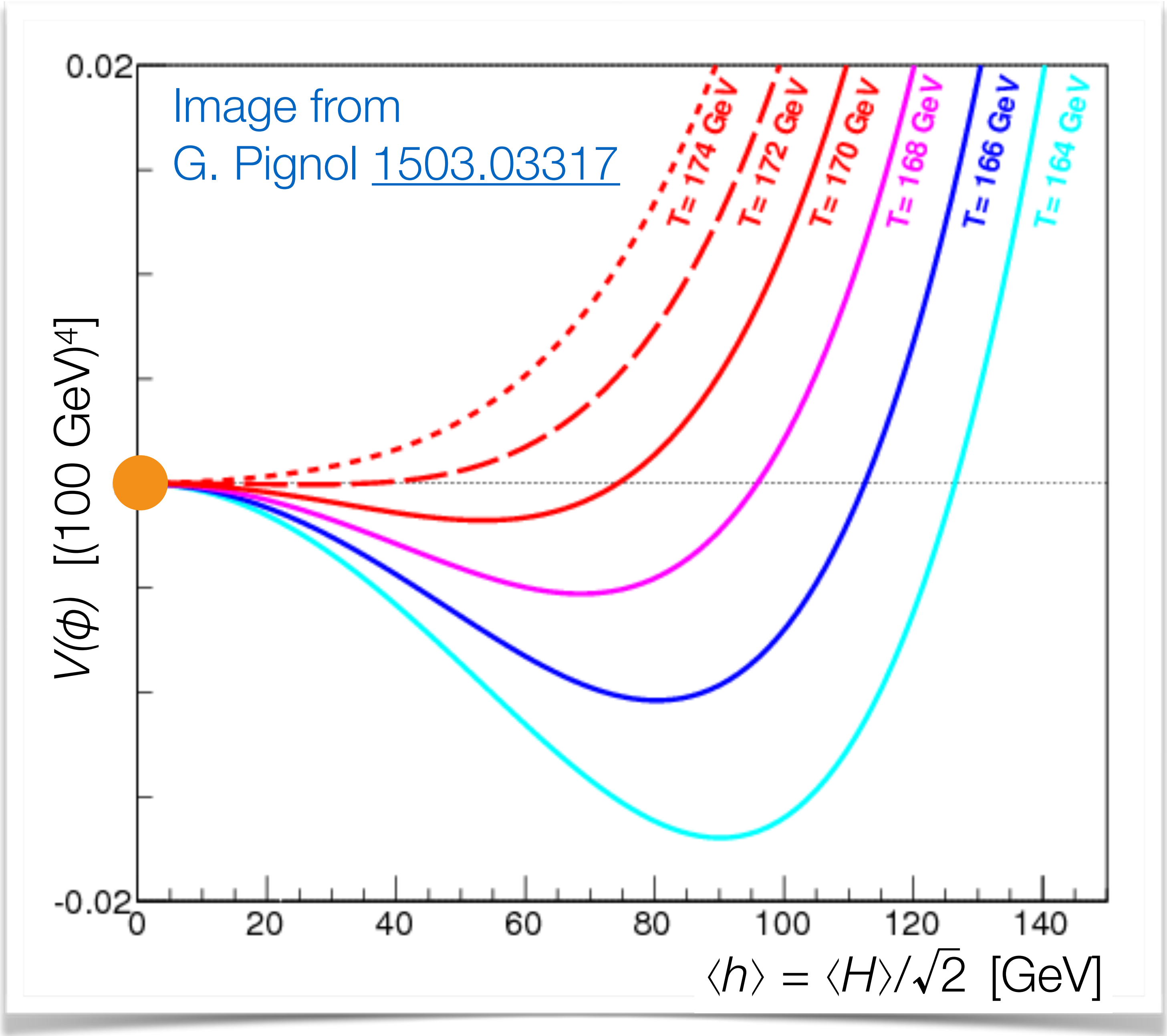

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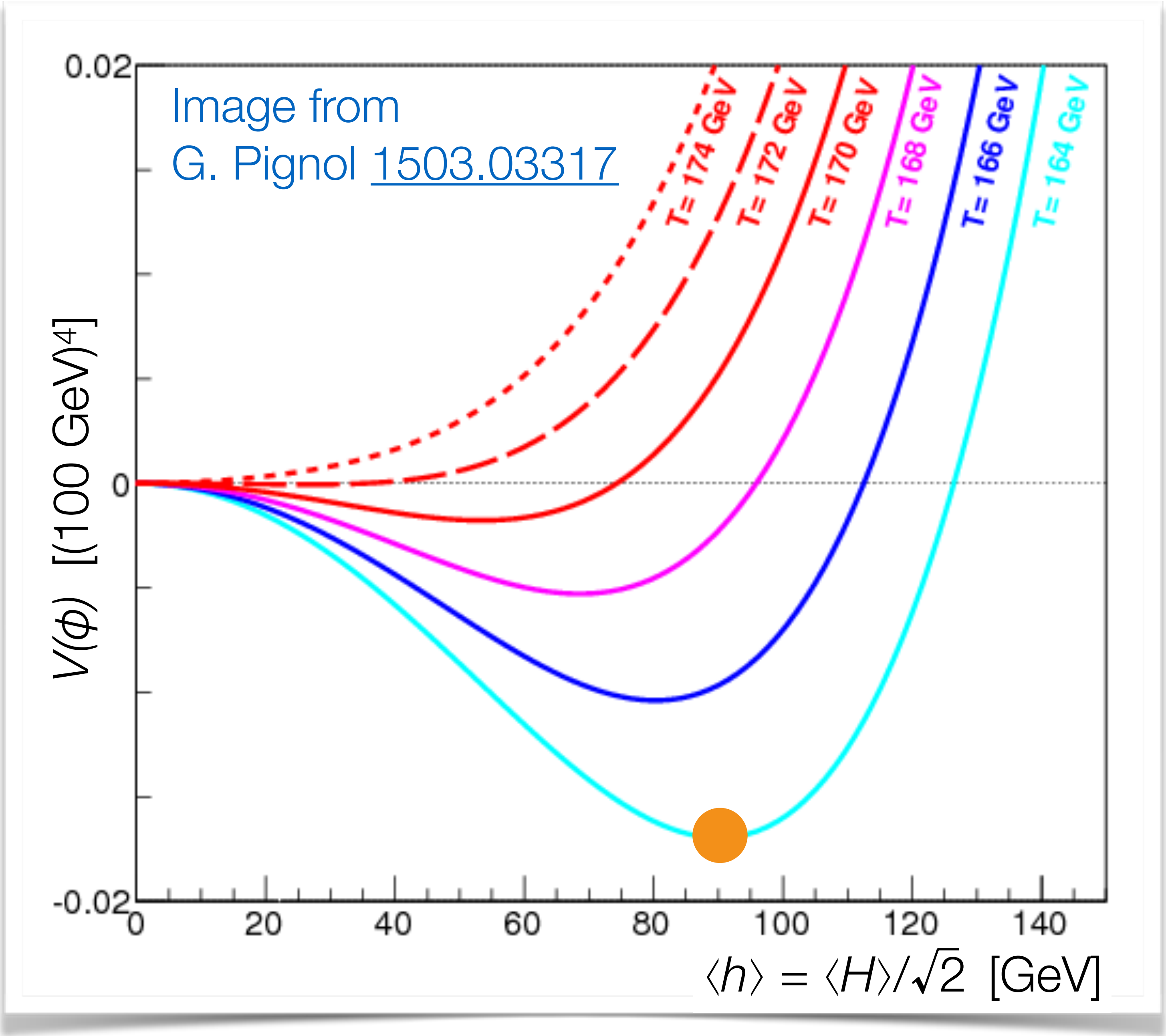

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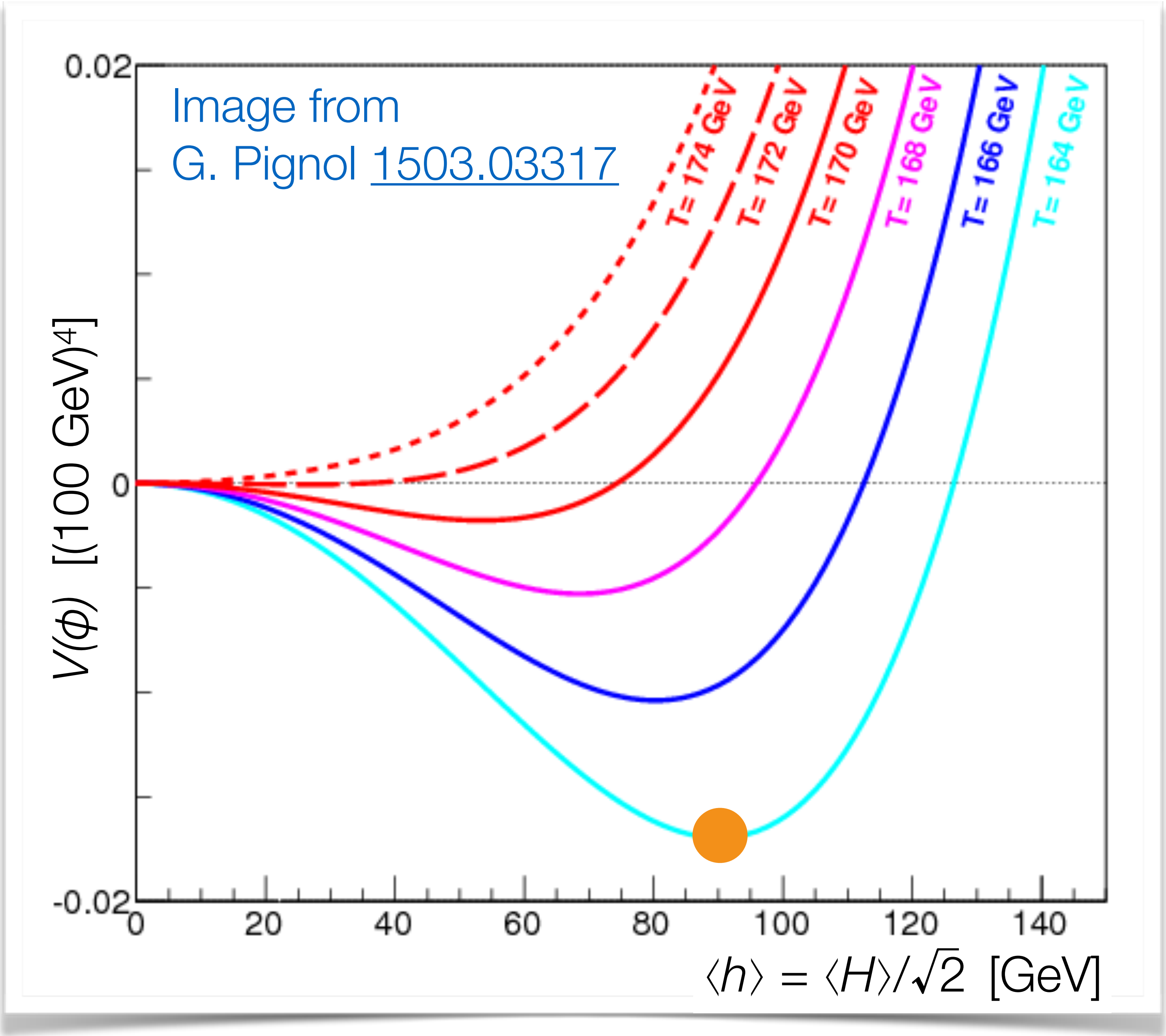

computational details ➠ backup slides

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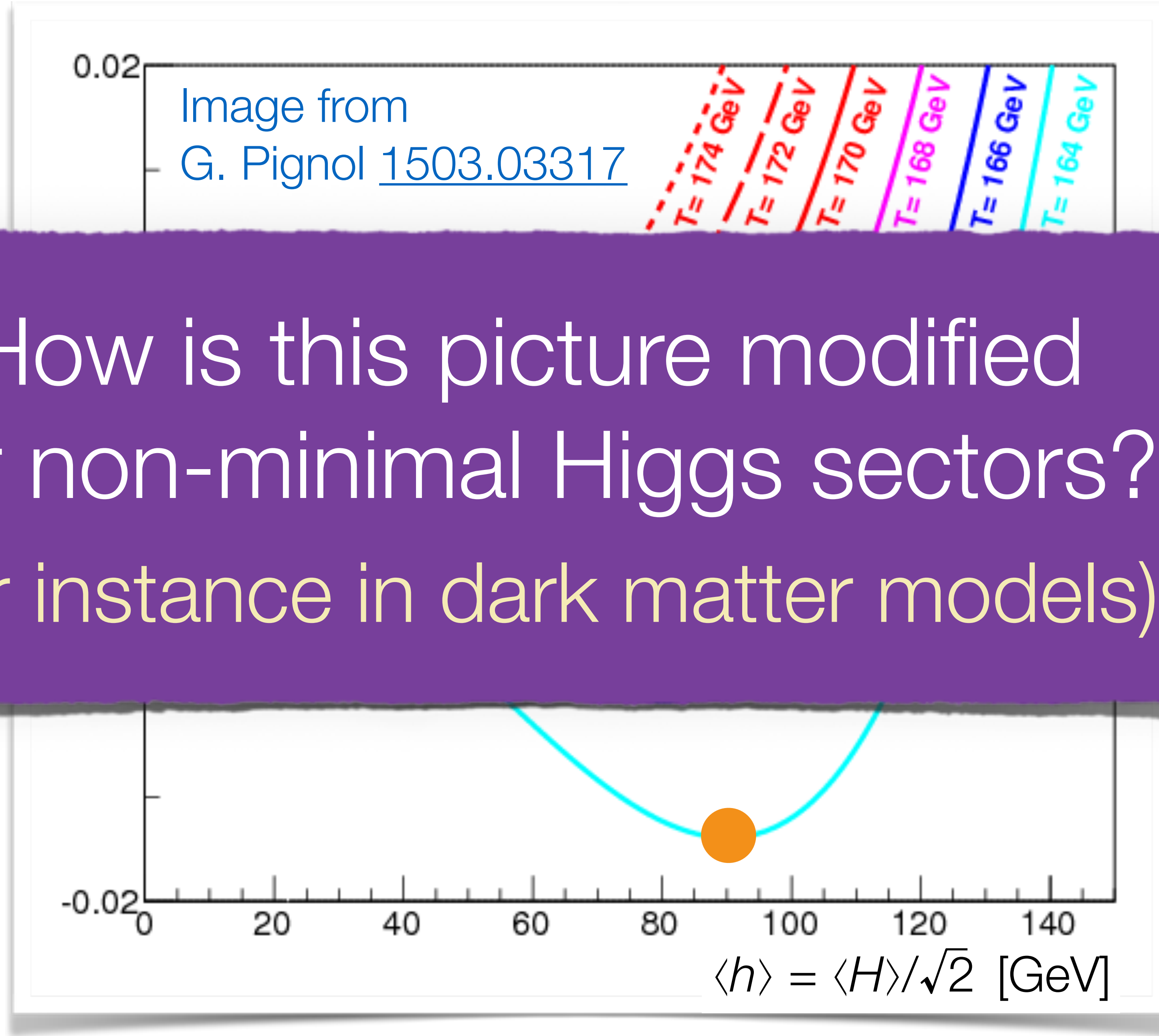

How is this picture modified for non-minimal Higgs sectors?

(for instance in dark matter models)

computational details ➠ backup slides

“Filtered” Dark Matter

Example 2: DM Filtering at Bubble Walls

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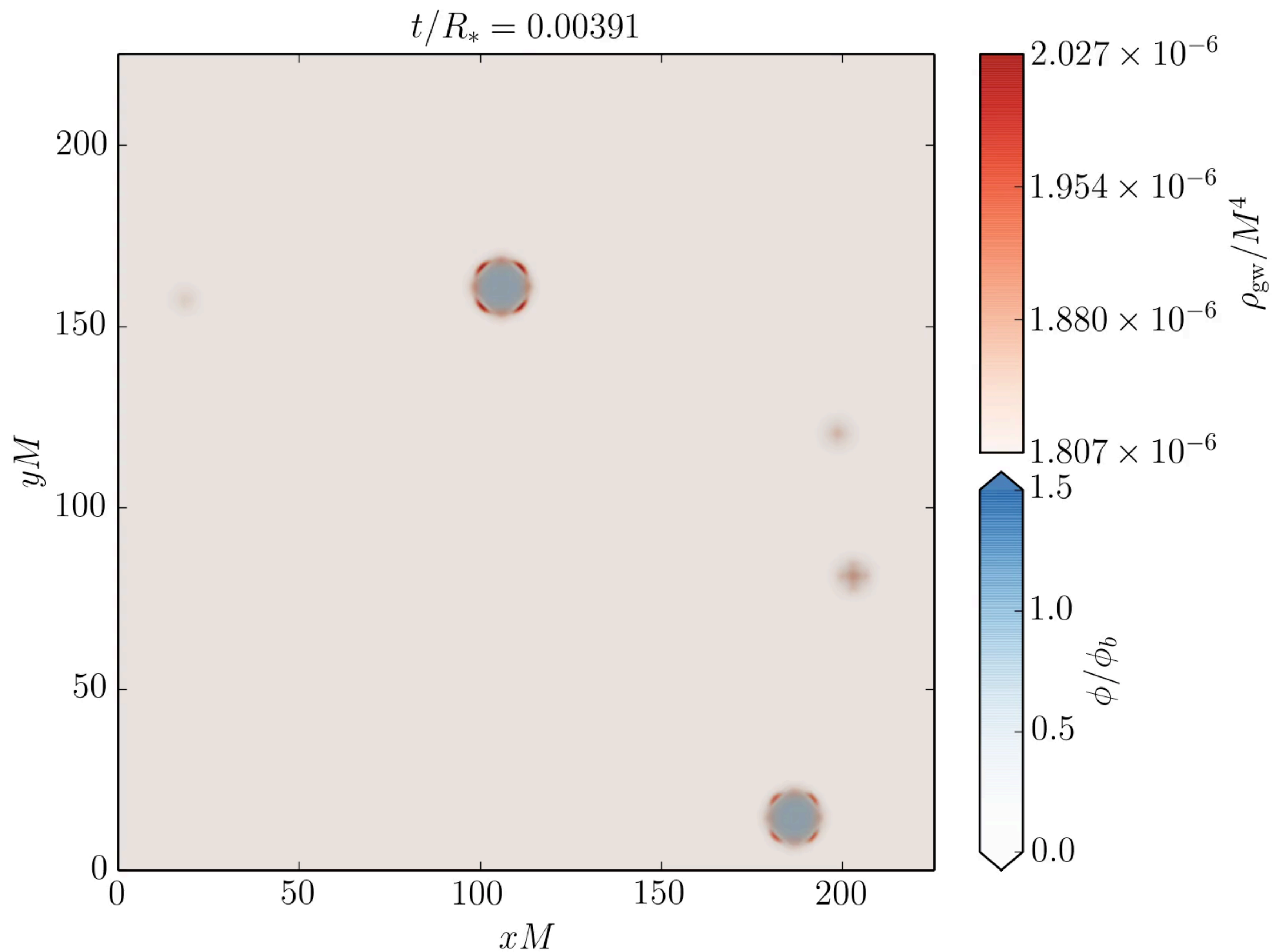
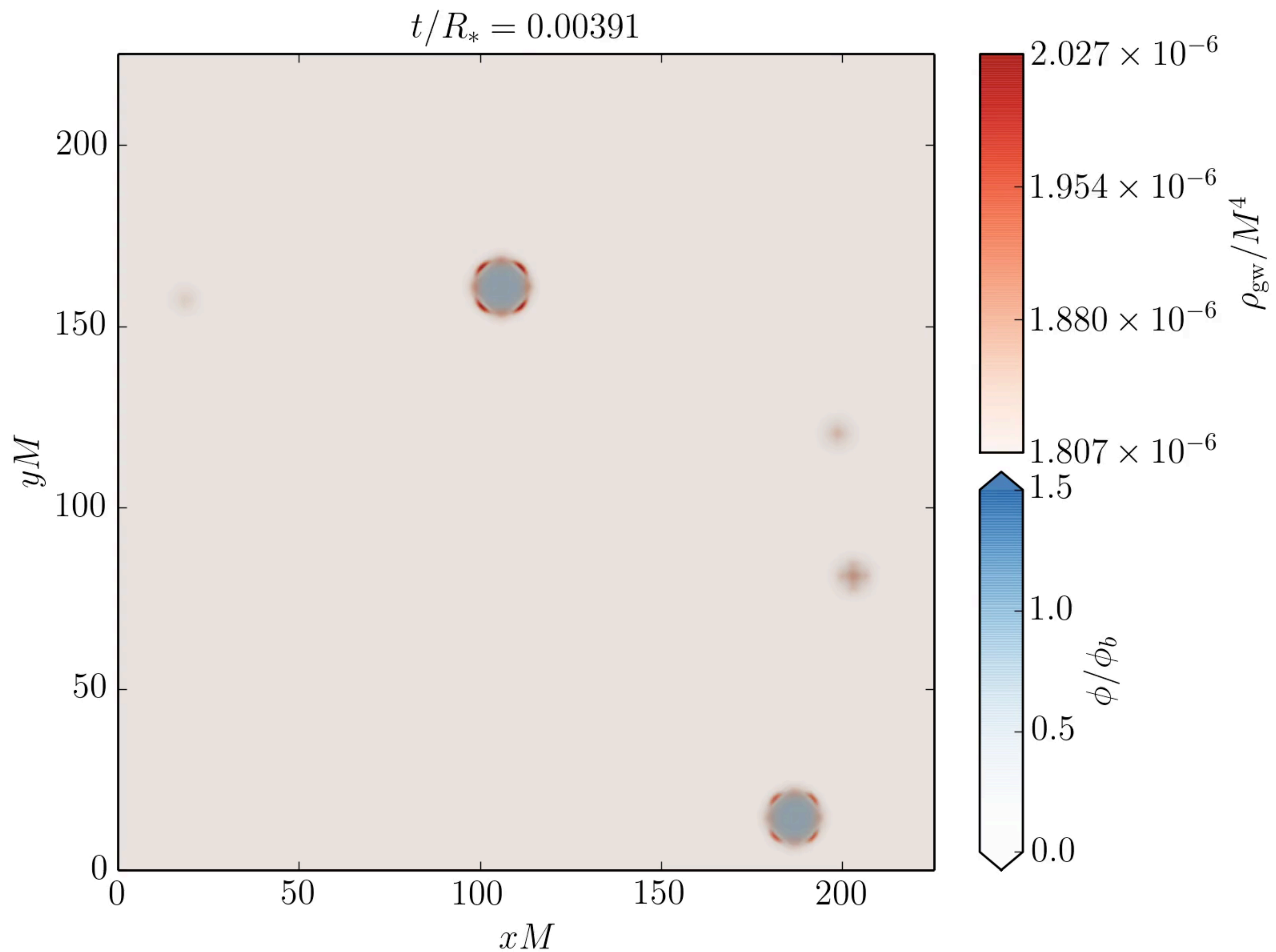


Witten 1984, Cutting Hindmarsh Weir 2018

Example 2: DM Filtering at Bubble Walls



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

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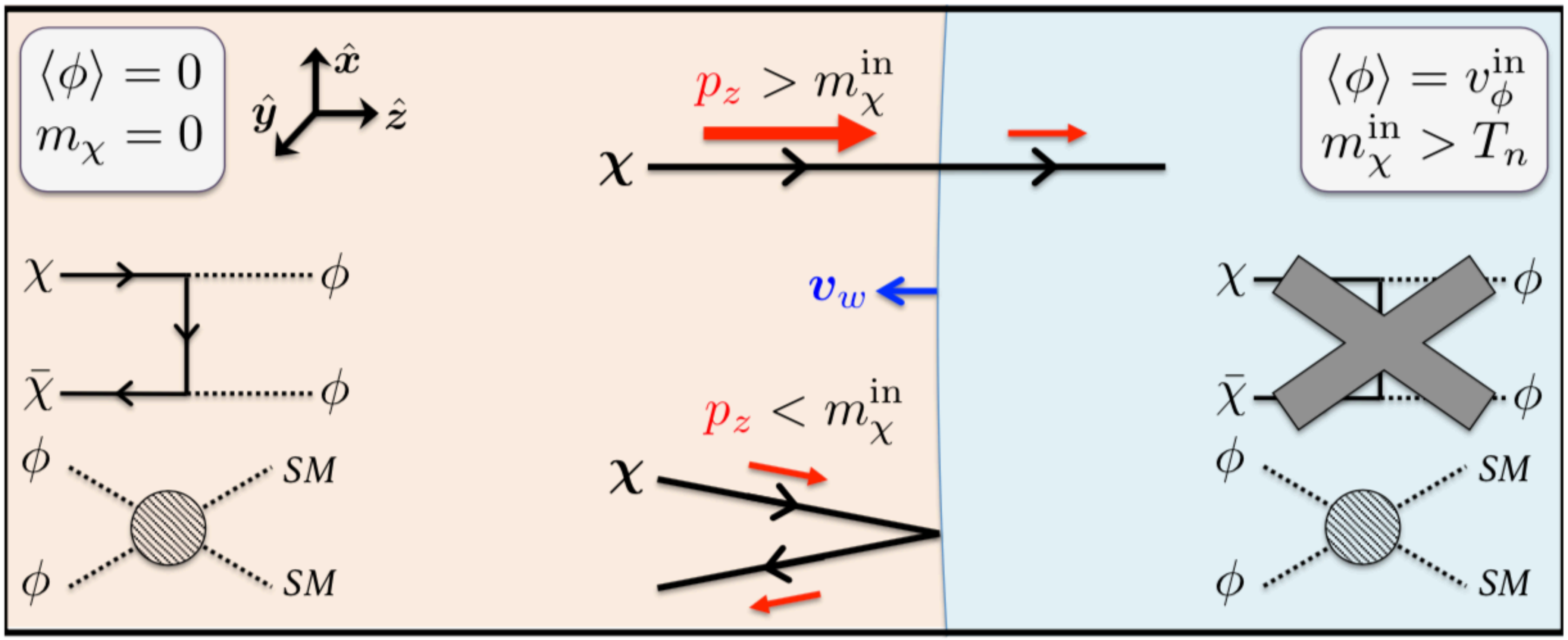

Baker JK Long, arXiv:1912.02830

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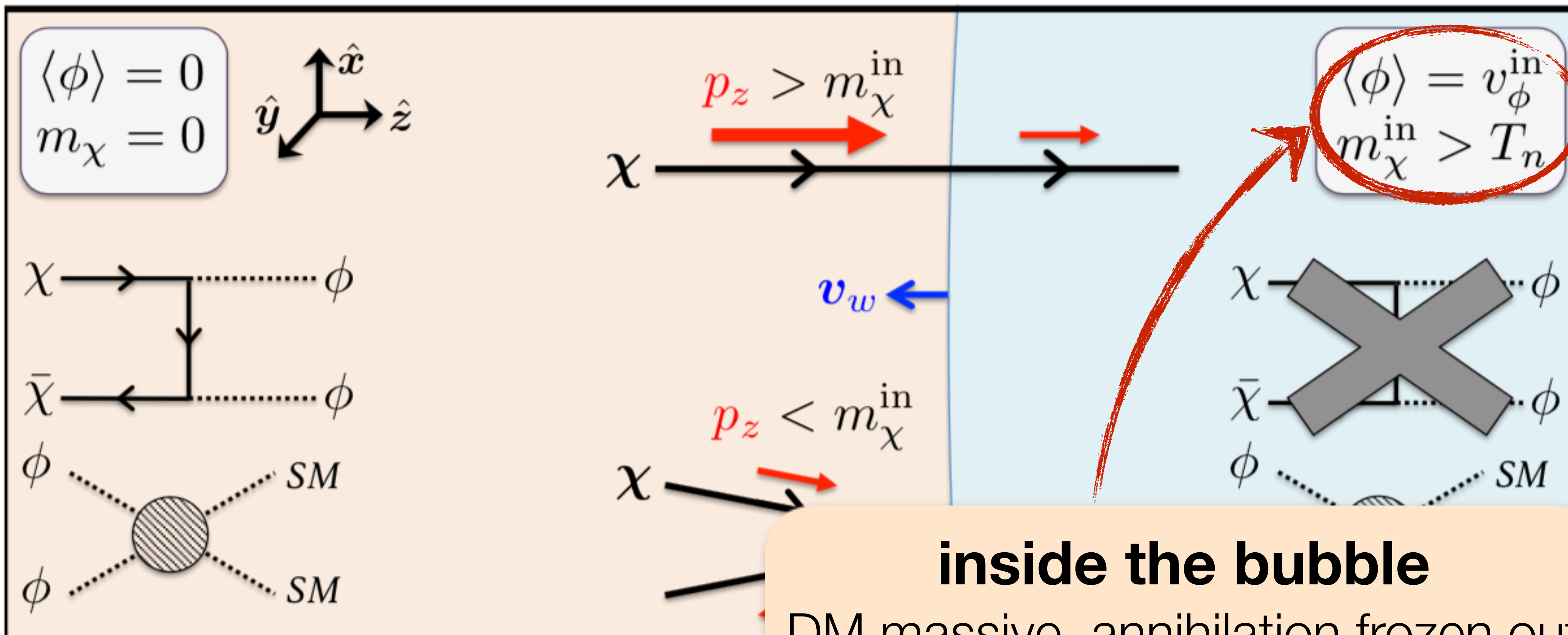

inside the bubble
DM massive, annihilation frozen out

Baker JK Long, arXiv:1912.02830

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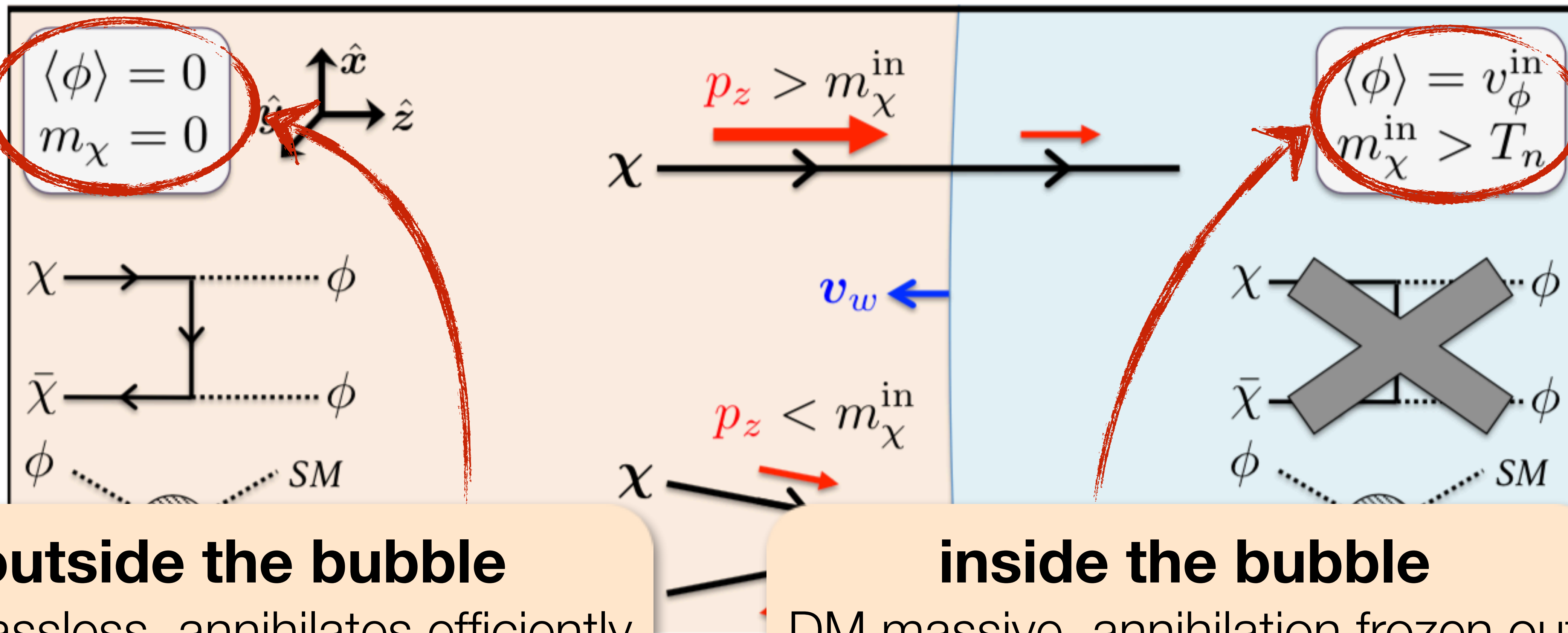

outside the bubble
DM massless, annihilates efficiently

inside the bubble
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Baker JK Long, arXiv:1912.02830

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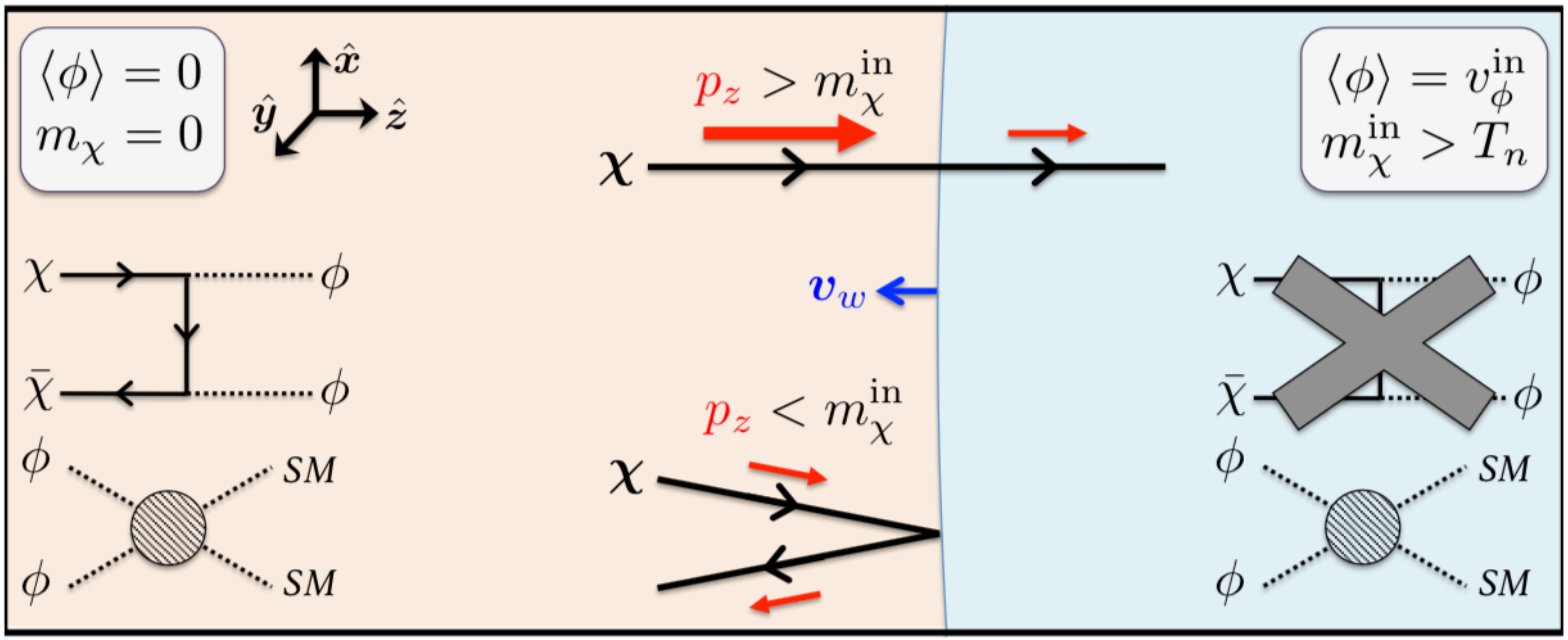

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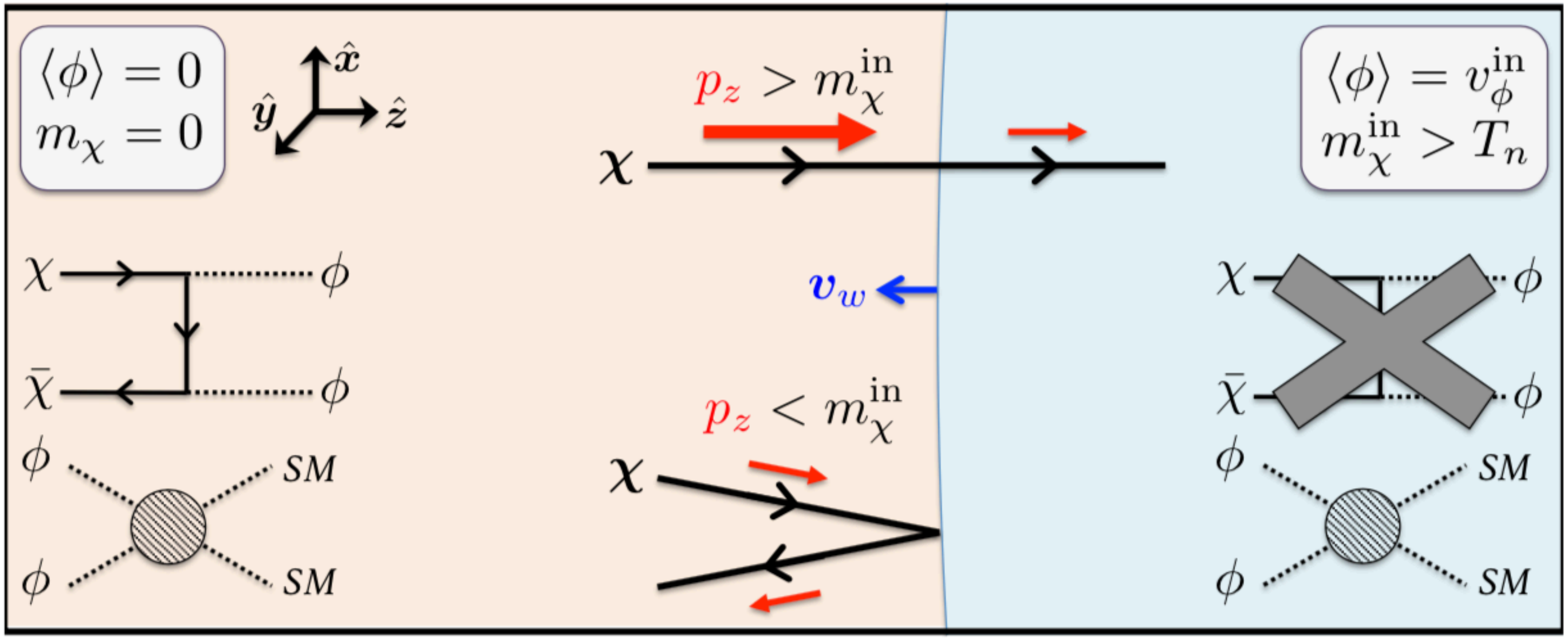

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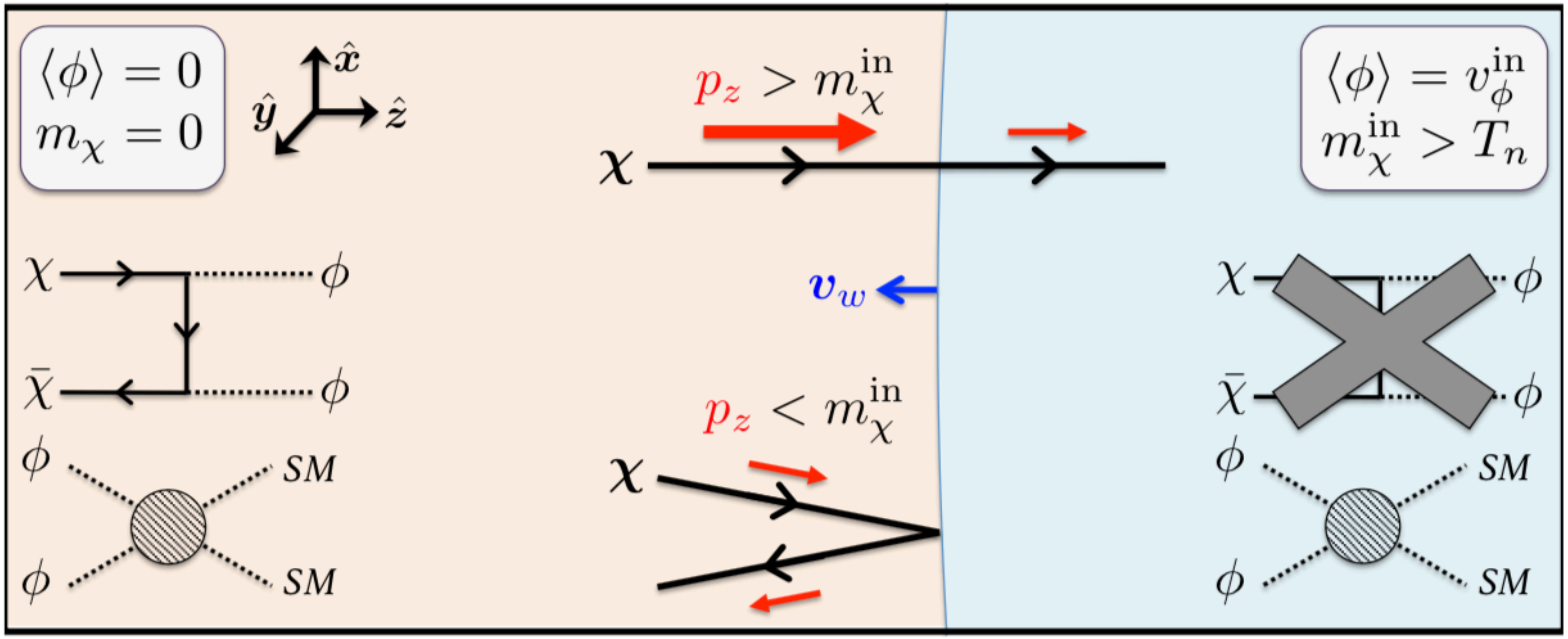

☑ small DM abundance inside the bubble persists

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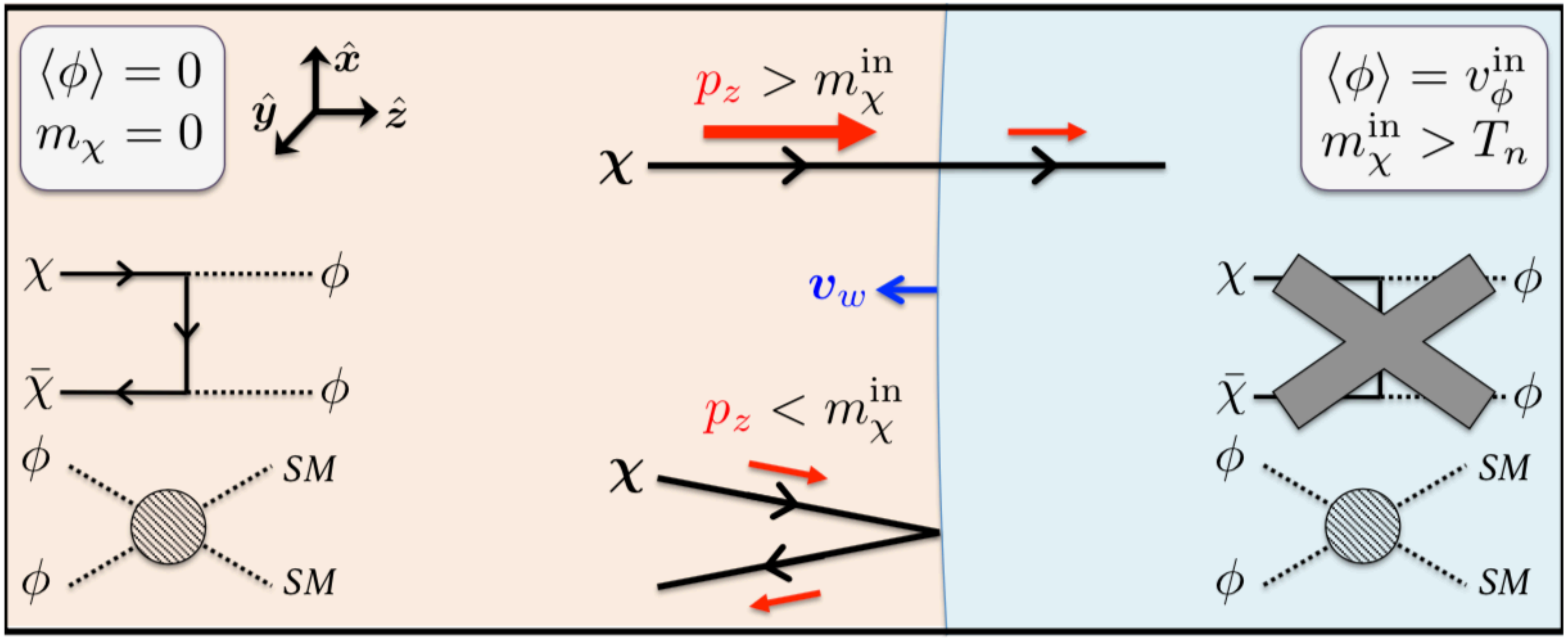
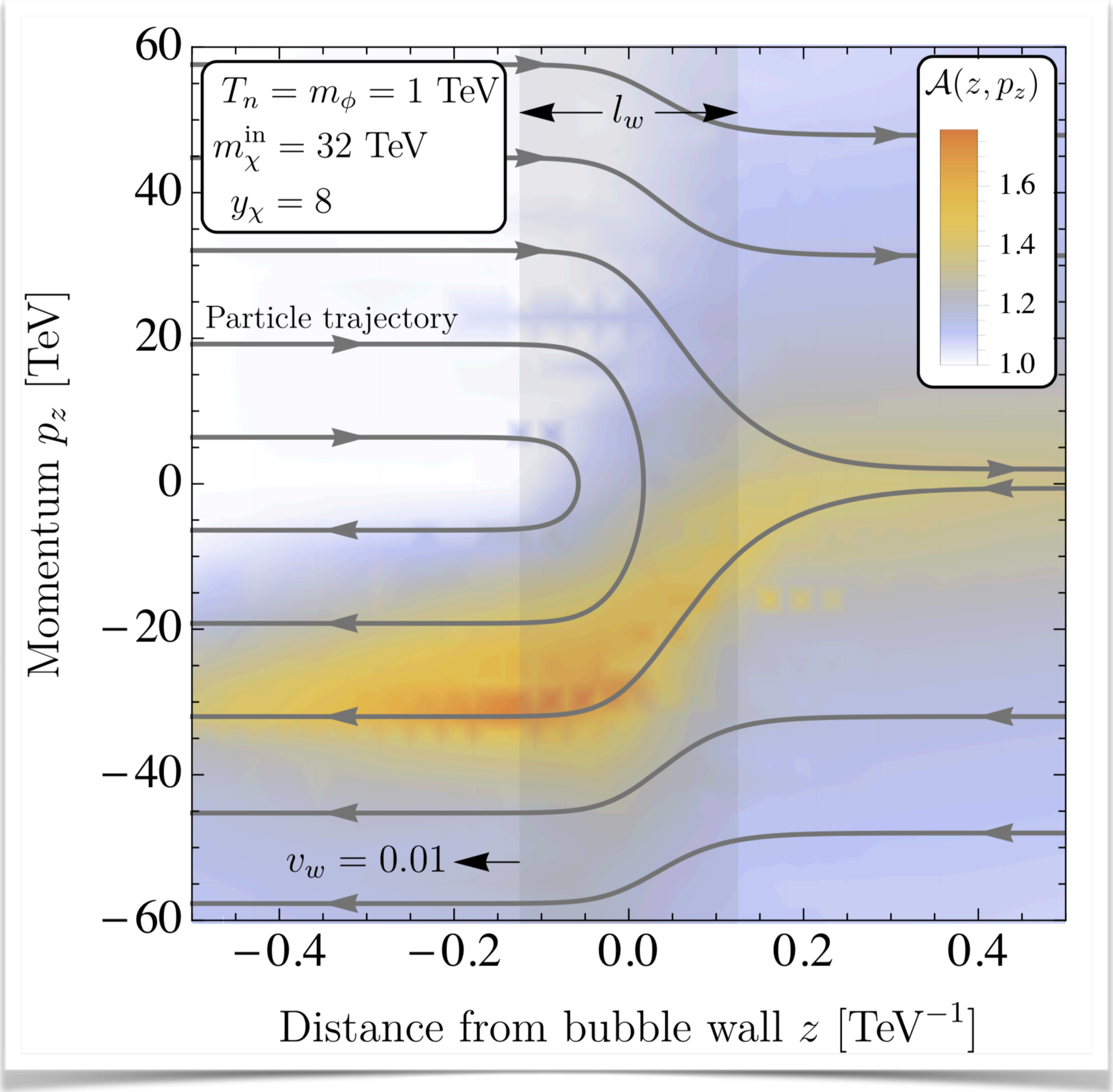


- ☑ small DM abundance inside the bubble persists
- ☑ most DM particles remain outside, annihilate efficiently

Baker JK Long, arXiv:1912.02830

Dark Matter at Bubble Walls



Solving the Boltzmann Equations

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Liouville operator
total time derivative of phase space distribution

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

Solving the Boltzmann Equations

- General Boltzmann Equation

$$\mathbf{L}[f_\chi] = \mathbf{C}[f_\chi]$$

- 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

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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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phase space integrals

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

full details in Baker JK Long, arXiv:1912.02830

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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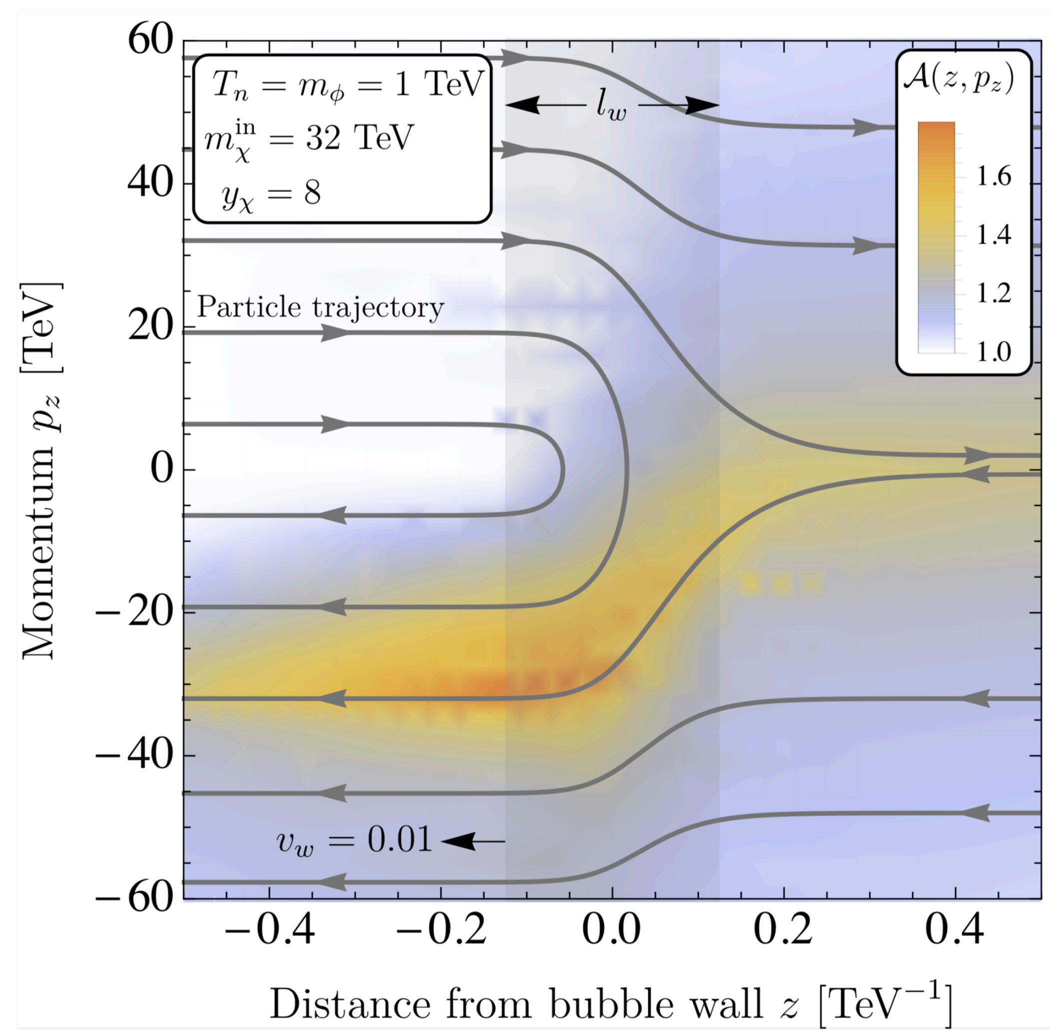
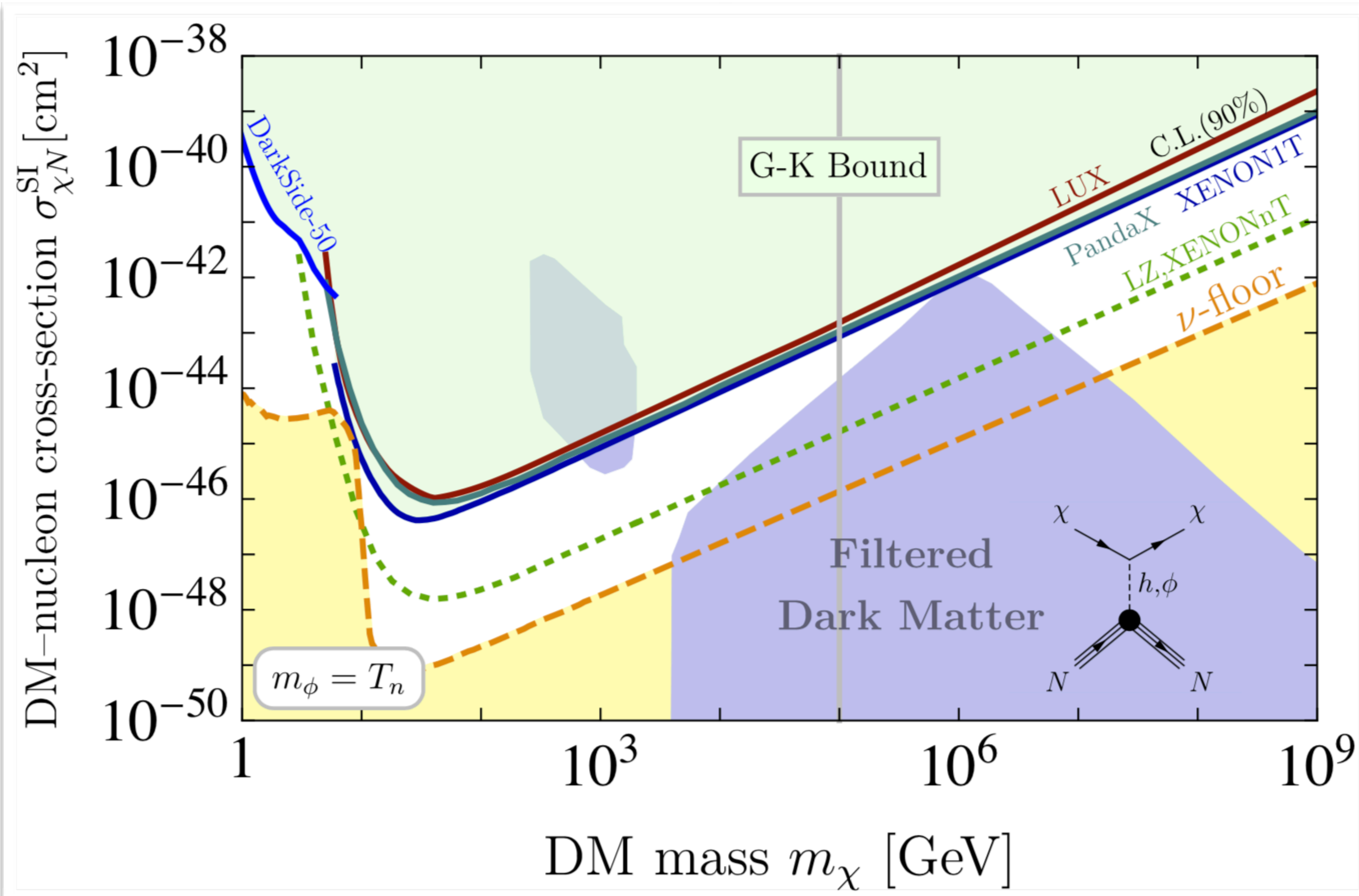
- Physical interpretation:
  - curves = particle trajectories



Parameter Space



Baker JK Long, arXiv:1912.02830 *(today)*

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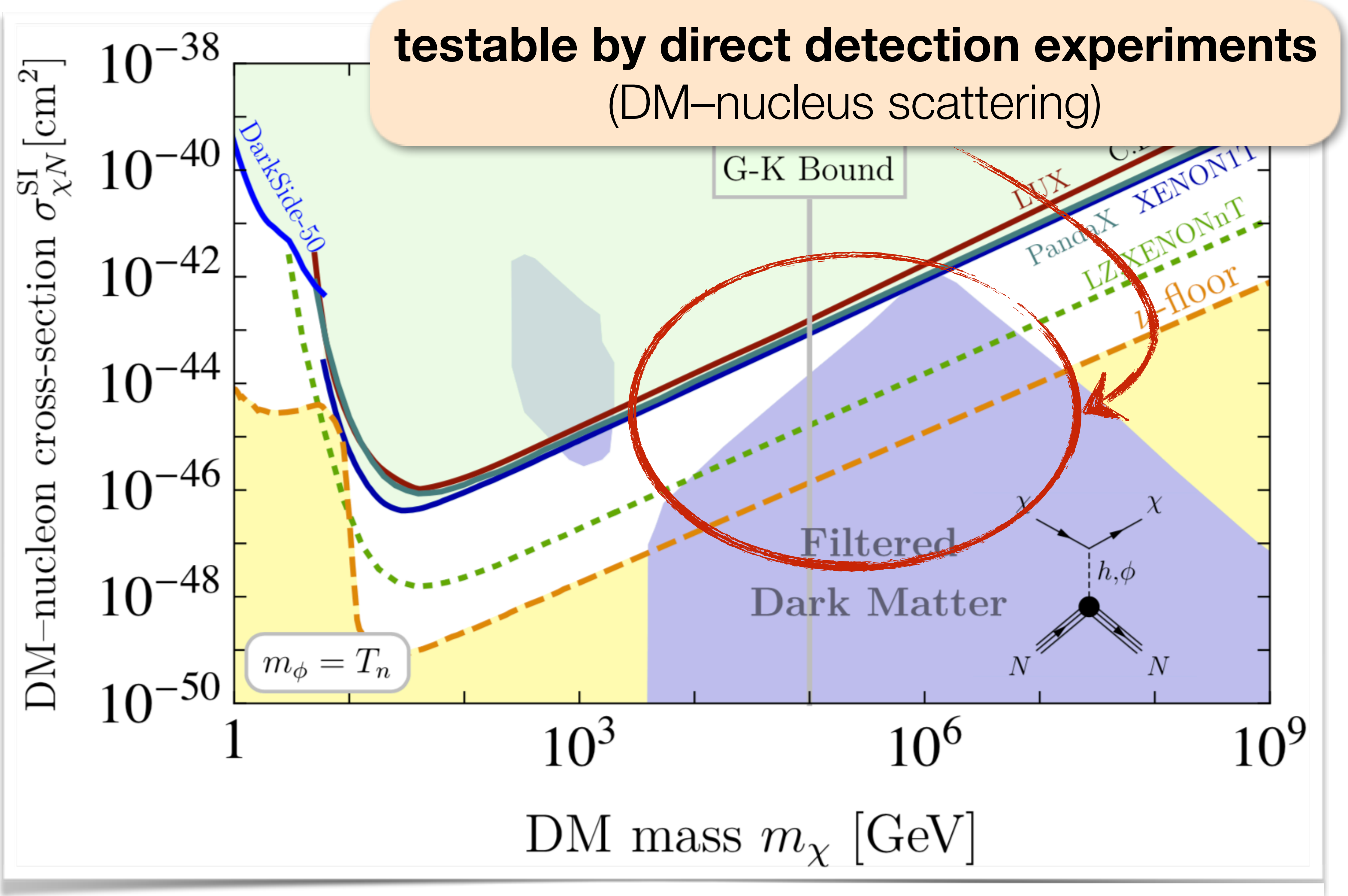

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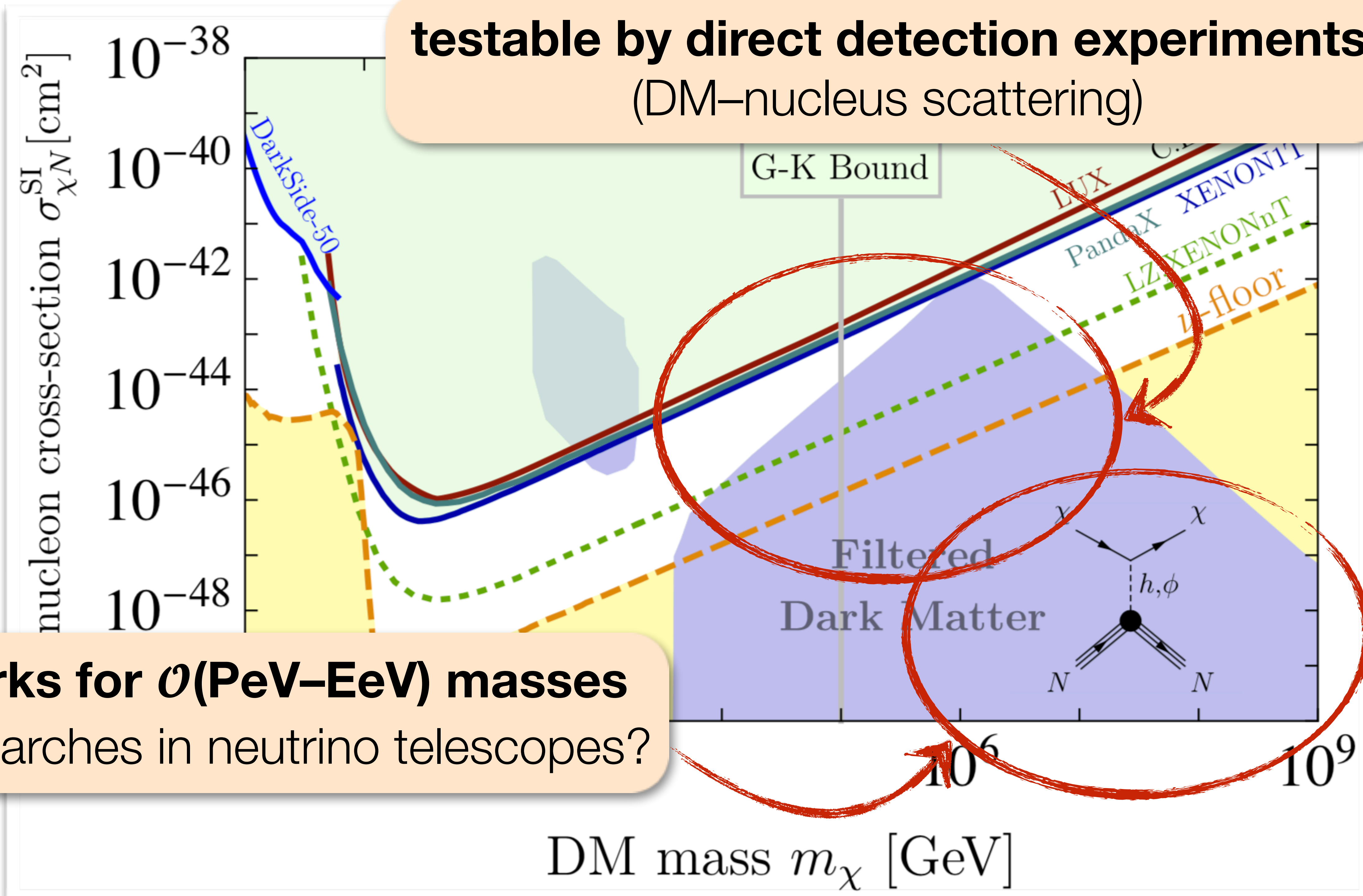
Parameter Space

testable by direct detection experiments
(DM–nucleus scattering)



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

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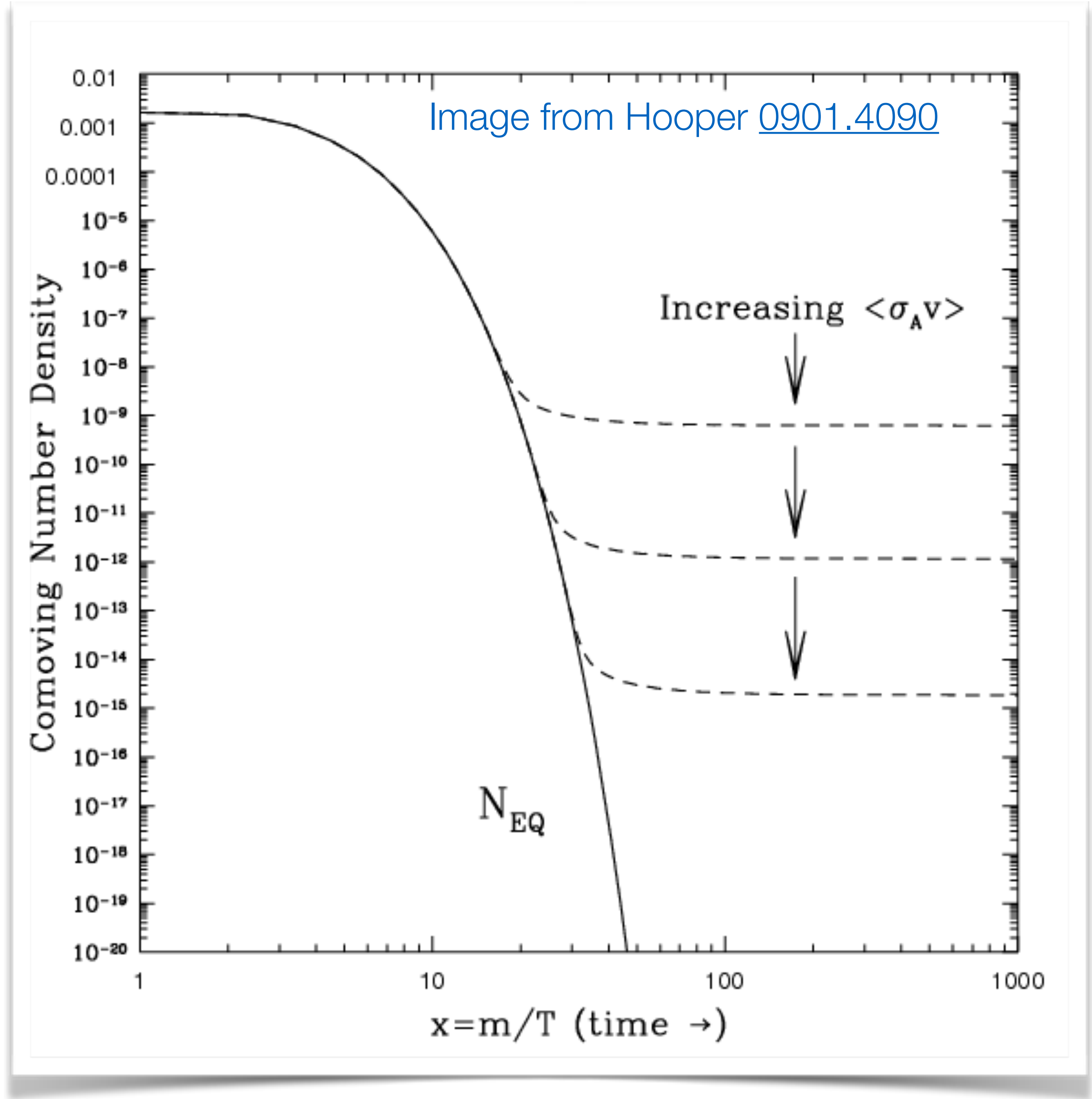
Dark Matter Decay
Between Phase Transitions

DM Decay Between Phase Transitions



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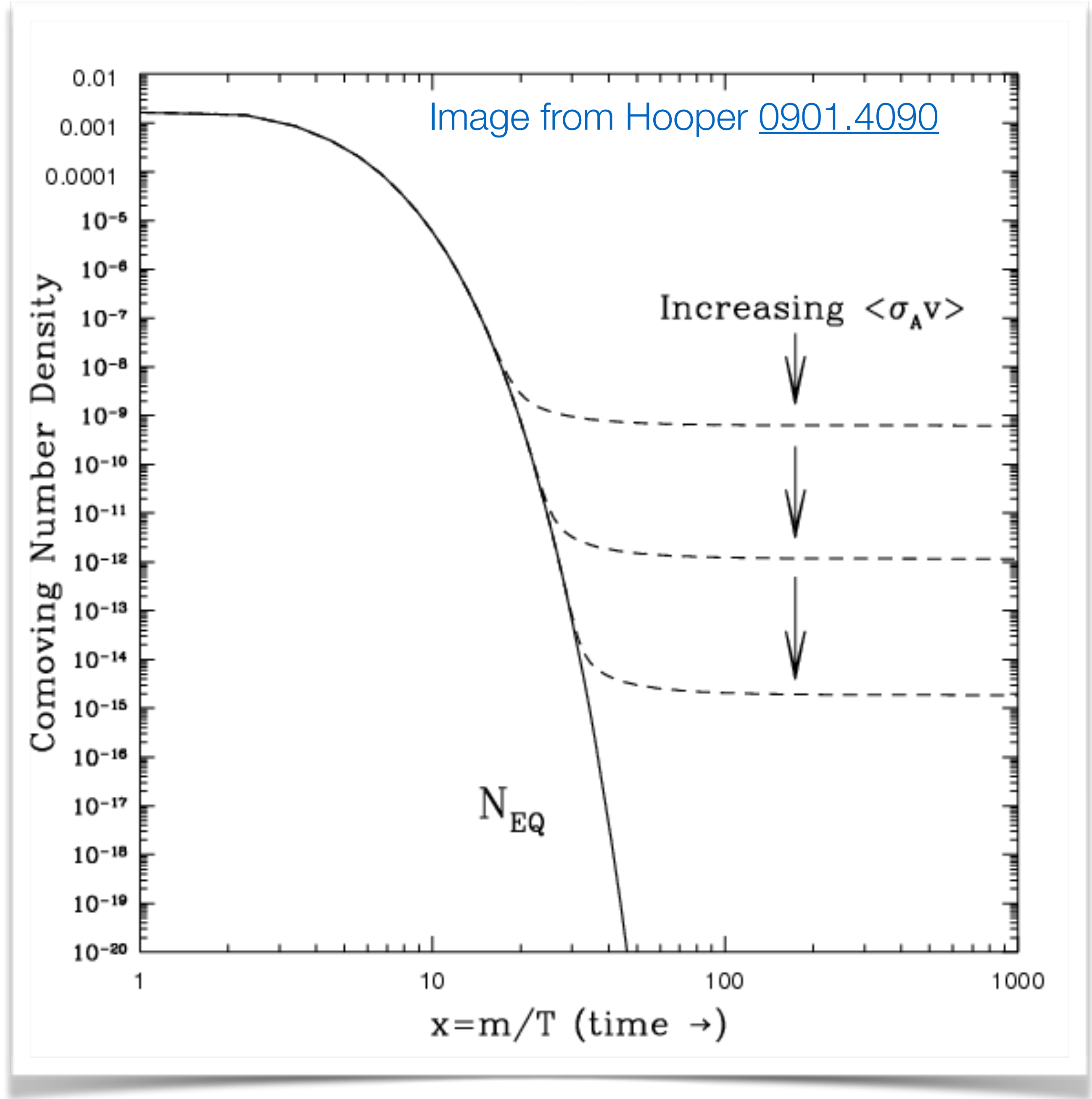
- Observed DM abundance requires a mechanism that depletes DM by several orders of magnitude, then stops



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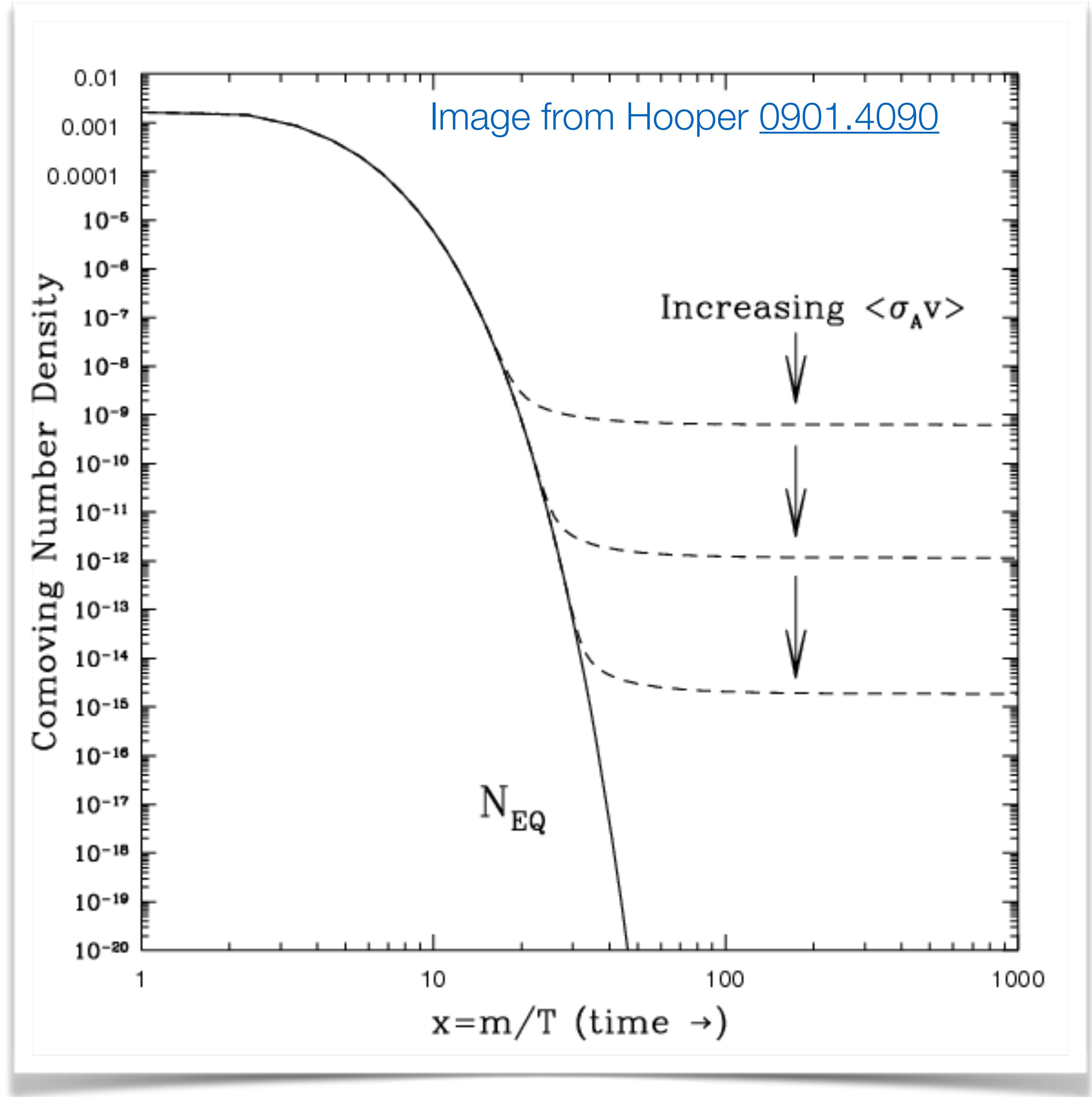
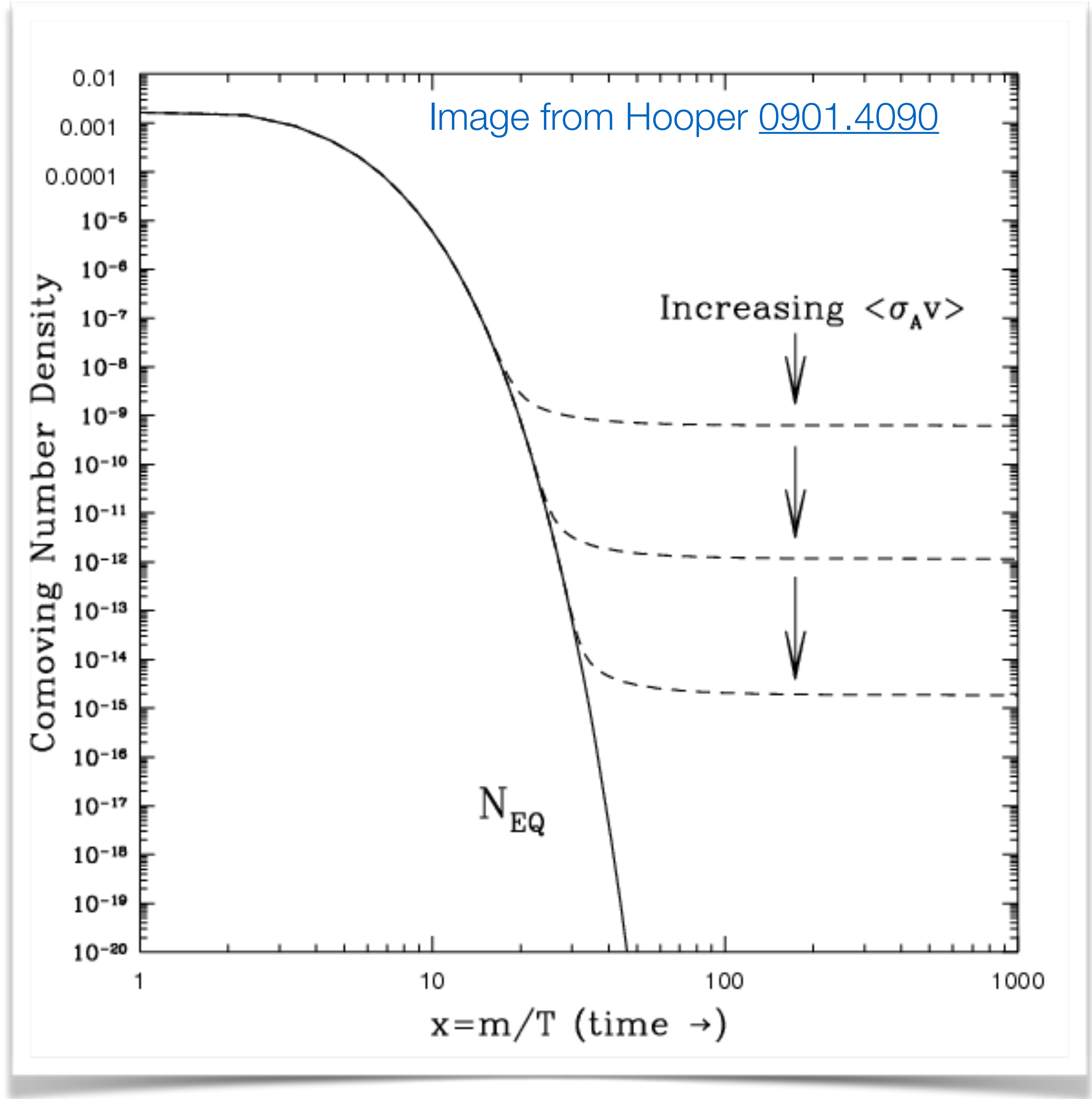
- ☑ Idea: DM decay!



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 phase transition 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

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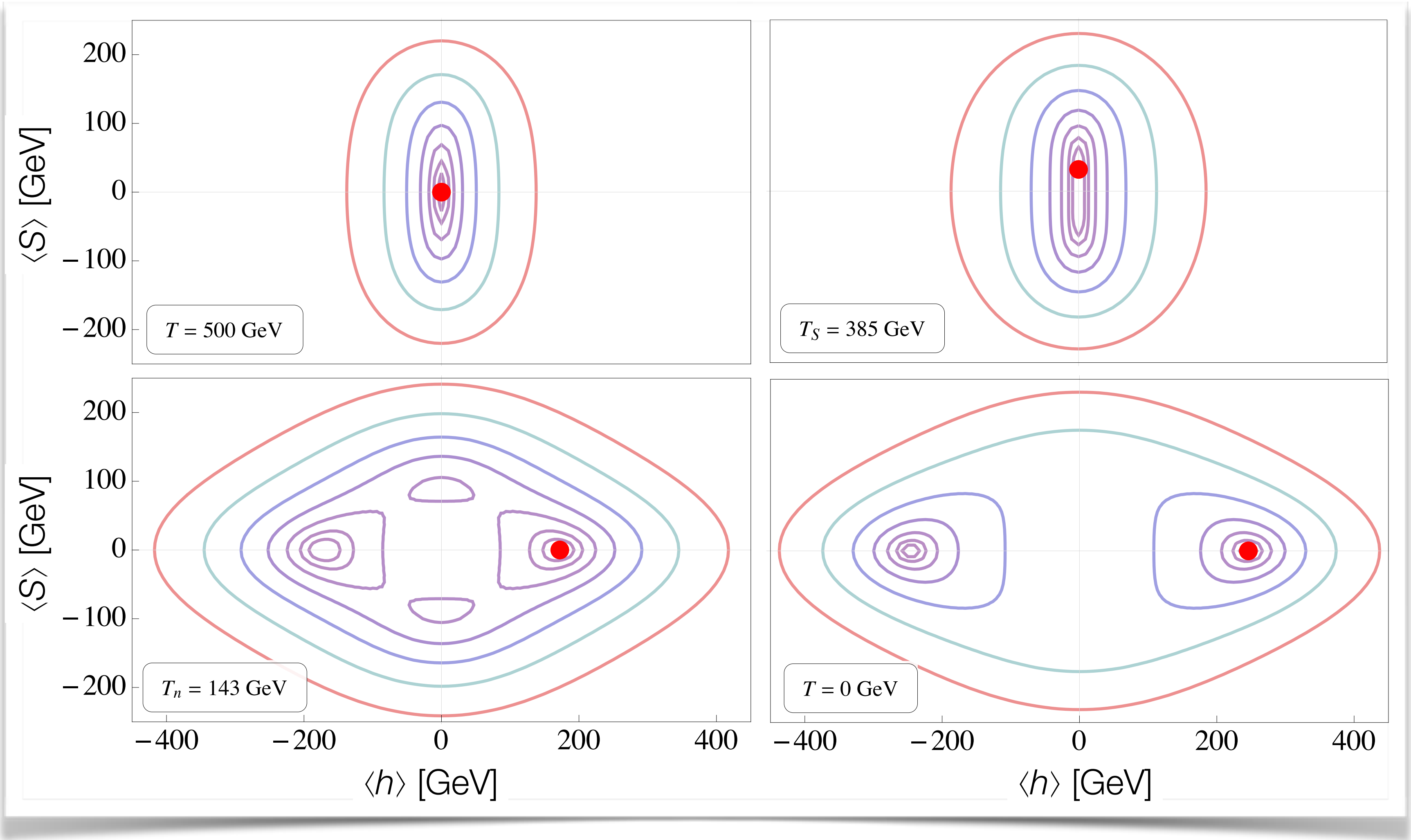
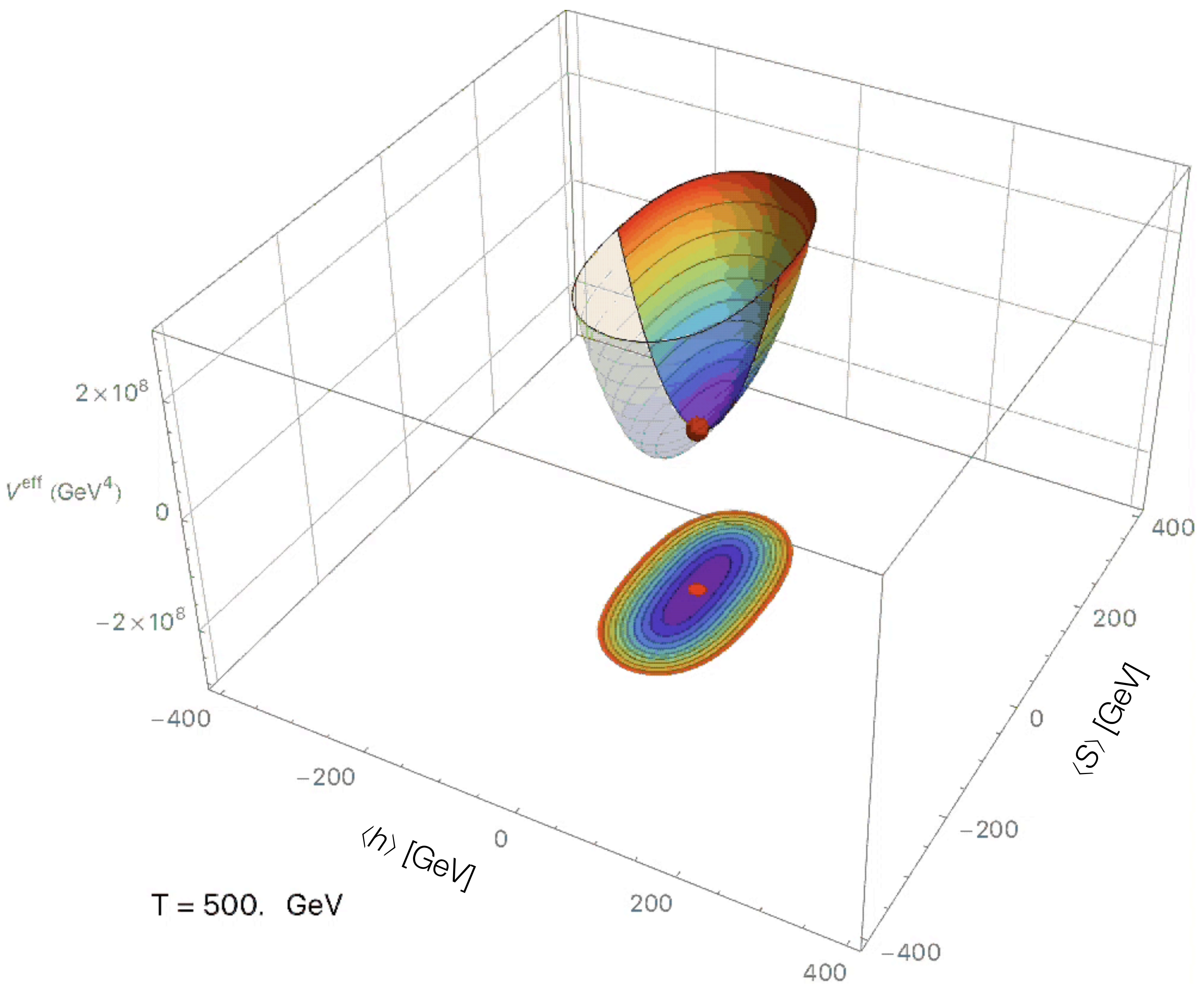
The Vev Flip-Flop



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

➠ $m_{S,\text{eff}}$ changes sign, $\langle S \rangle \to 0$, DM stable

The Vev Flip-Flop



Computed by Mike Baker using `CosmoTransitions`

Wainwright 1109.4189, Kozaczuk Profumo Haskins Wainwright 1407.4134

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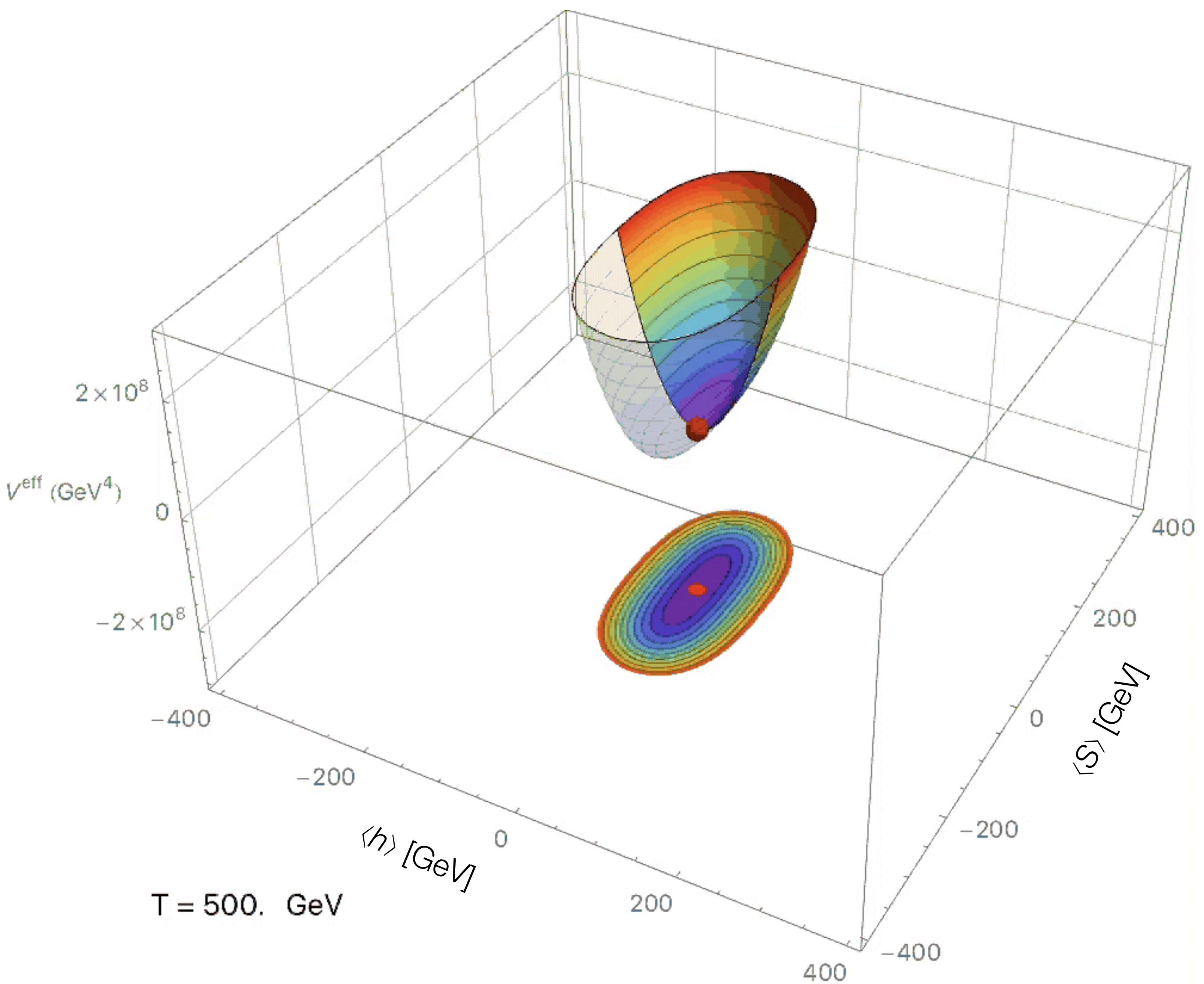

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Example 1: Decay Between Phase Transitions

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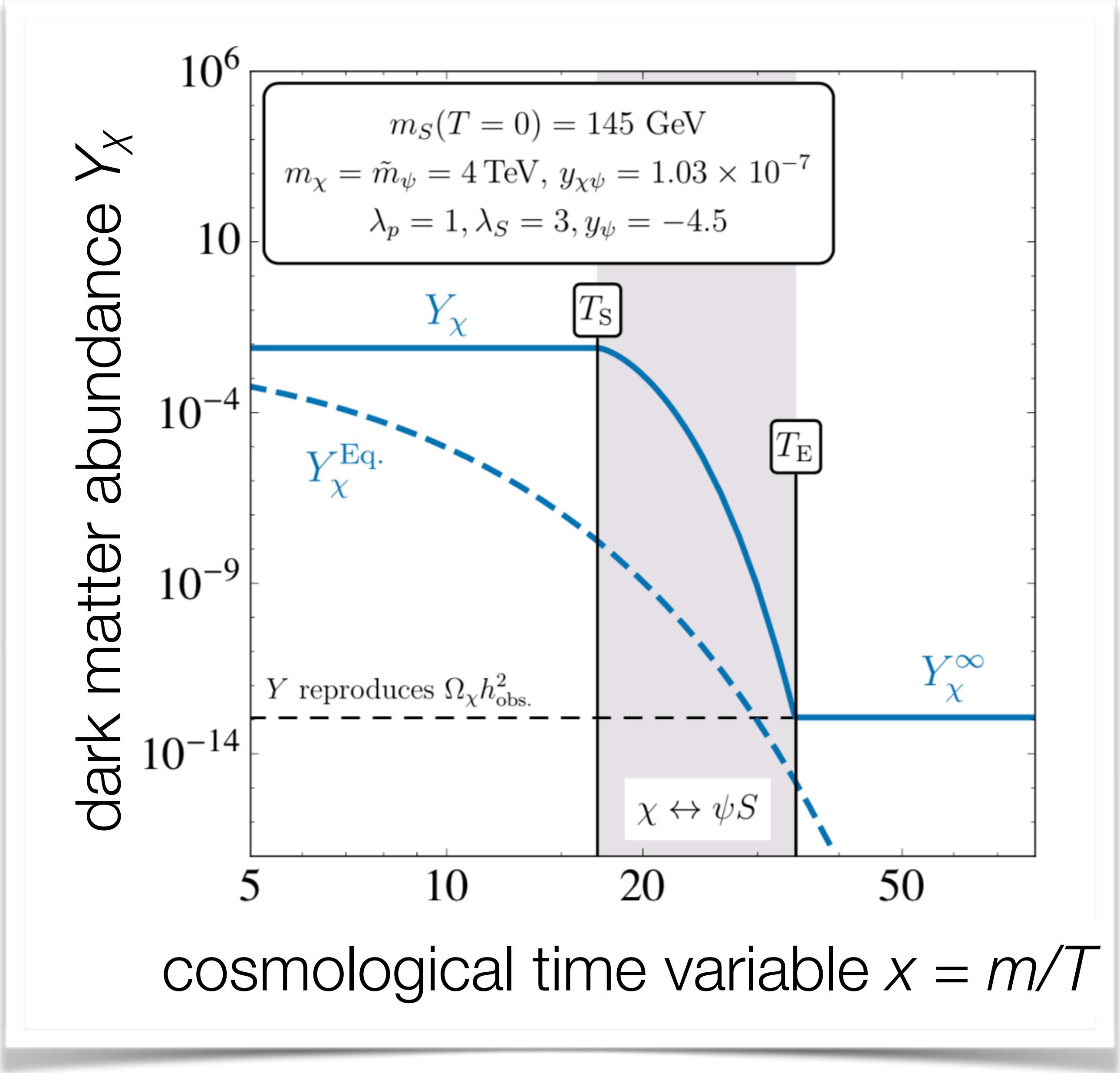
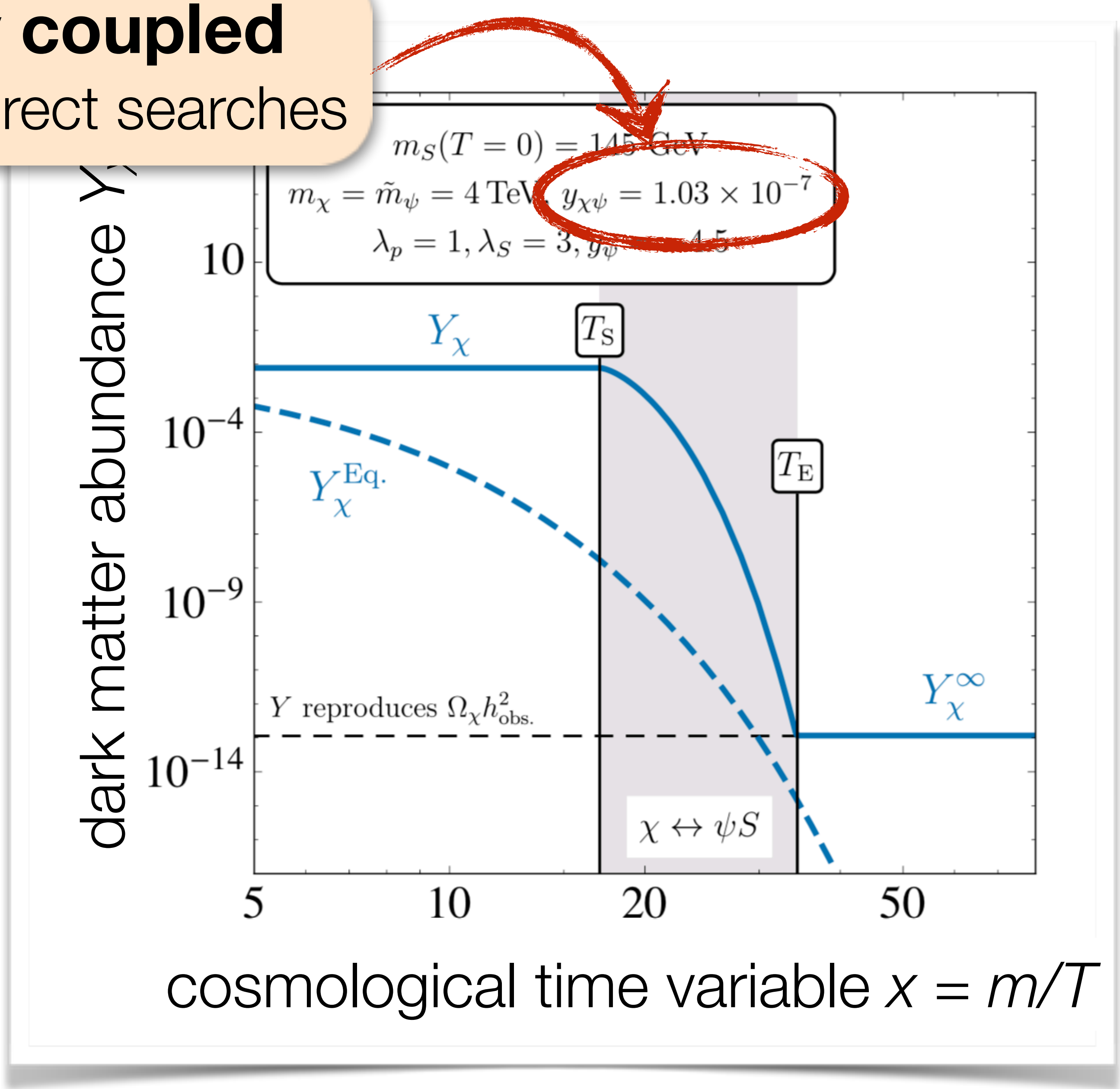


Baker Mittnacht arXiv:1811.03101
see also Baker JK arXiv:1608.07578

Example 1: Decay Between Phase Transitions

Evolution of DM Abundance

DM very weakly coupled
difficult for direct & indirect searches



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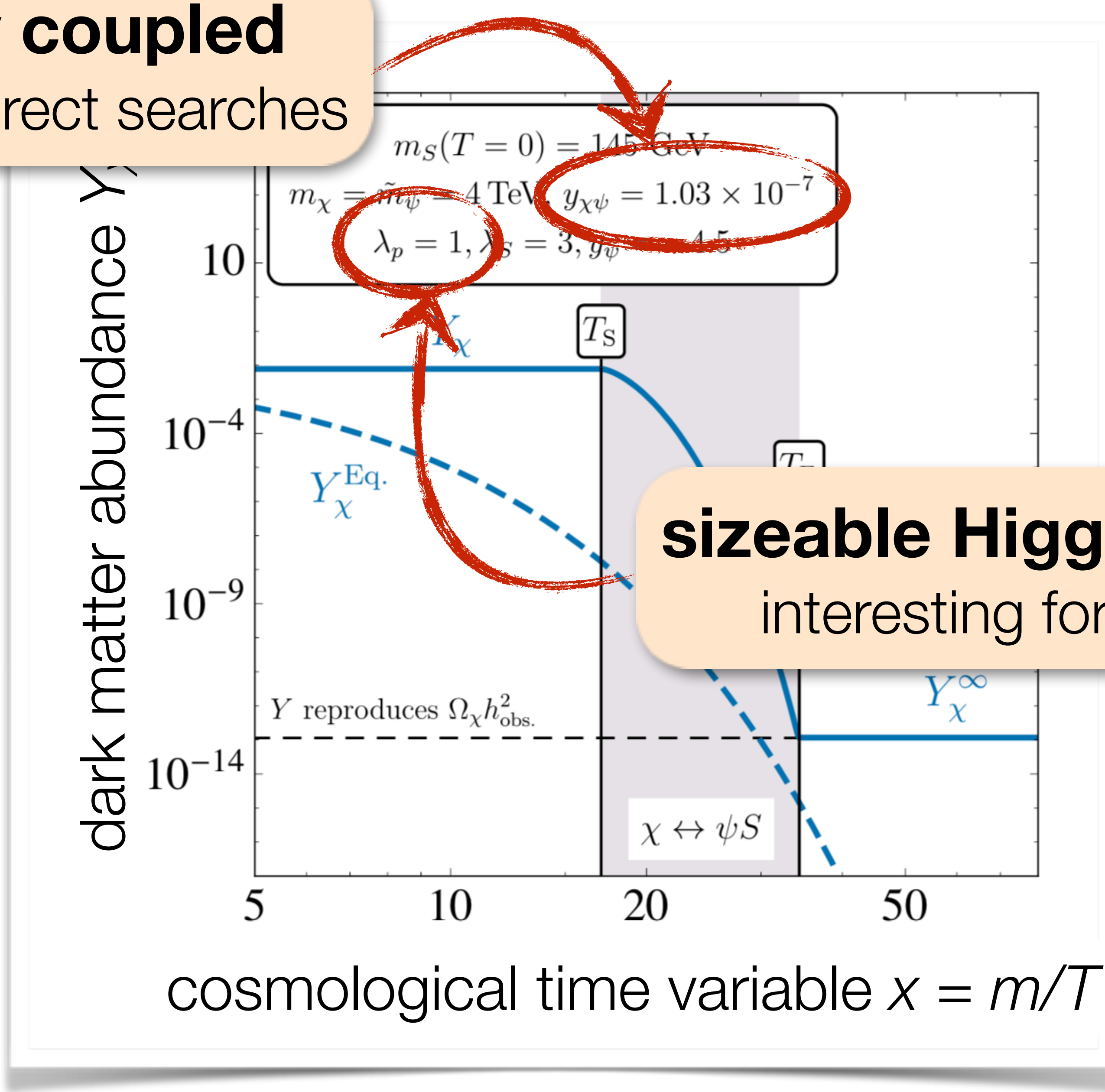

sizeable Higgs portal coupling
interesting for collider searches

Baker Mittnacht arXiv:1811.03101
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Implications for the LHC

Connections to Higgs Physics at Colliders

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    - → electroweak precision observables (S, T, U parameters)
    - → modified H branching ratios
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  - 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

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Summary

Summary

Phase Transition in the early Universe

- ☑ imply abrupt change in the primordial plasma
- ☑ often depend on the dynamics of scalar particles
- ☑ can determine the dark matter abundance in multiple ways
- ☑ have consequences for
  - Higgs precision measurements
  - gravitational wave observations ➠ backup slides
  - baryogenesis ➠ backup slides

Thank you!

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Bonus Slides

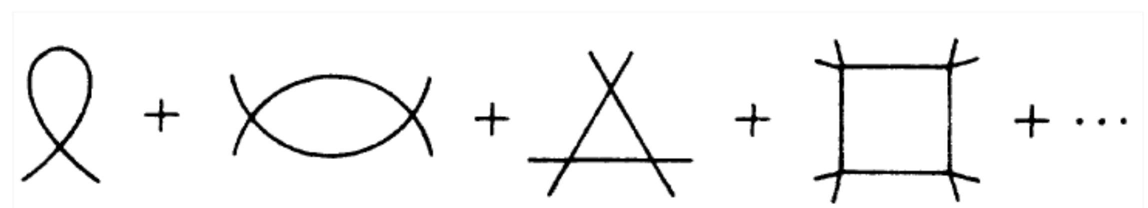
Scalar Potentials at Finite Temperature

☑ Tree level potential

$$V^{\mathrm{tree}} = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

☑ Coleman—Weinberg

Coleman Weinberg 1973, Dolan Jackiw 1974



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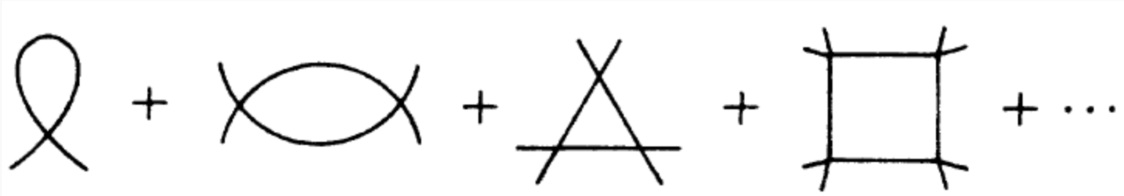

$$V^{\text{CW}}[\phi] = \sum_{n=1}^{\infty} \int \frac{d^4k}{(2\pi)^4} \frac{1}{2n} \left(\frac{2\lambda\phi}{k^2 - m^2} \right)^n$$

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

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

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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.

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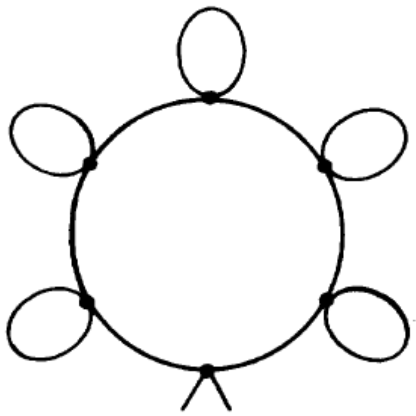
- Resummed "Daisy" Corrections [Dolan Jackiw 1974, Carrington 1992]



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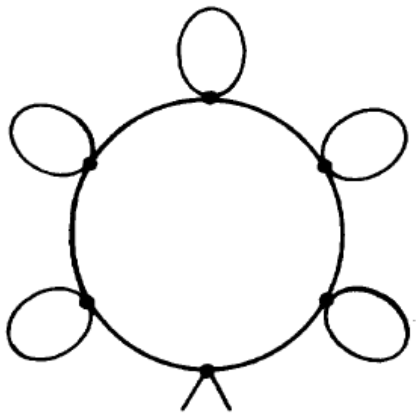
☑ Resummed "Daisy" Corrections   Dolan Jackiw 1974, Carrington 1992

- 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 $\Pi(T)$

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

A Toy Model

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

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

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

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

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DM decay products

Baker Mittnacht arXiv:1811.03101

Baker JK

small

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

temporarily allows decay

$\chi \to \psi\, S$

large enough

to keep ψ in equilibrium

$\langle S \rangle$ **affects ψ mass**

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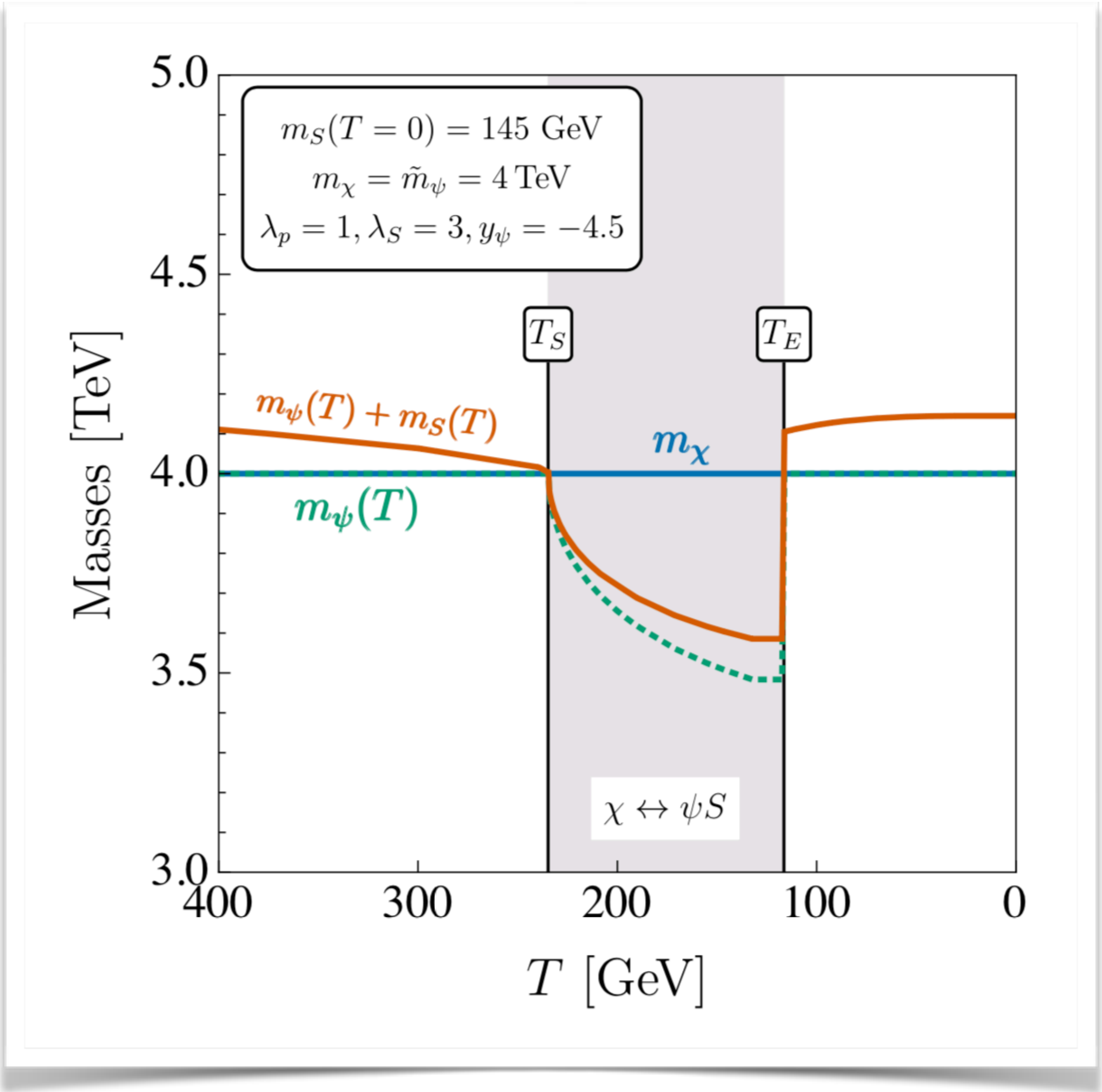
Cosmological Evolution

Evolution of Particle Masses



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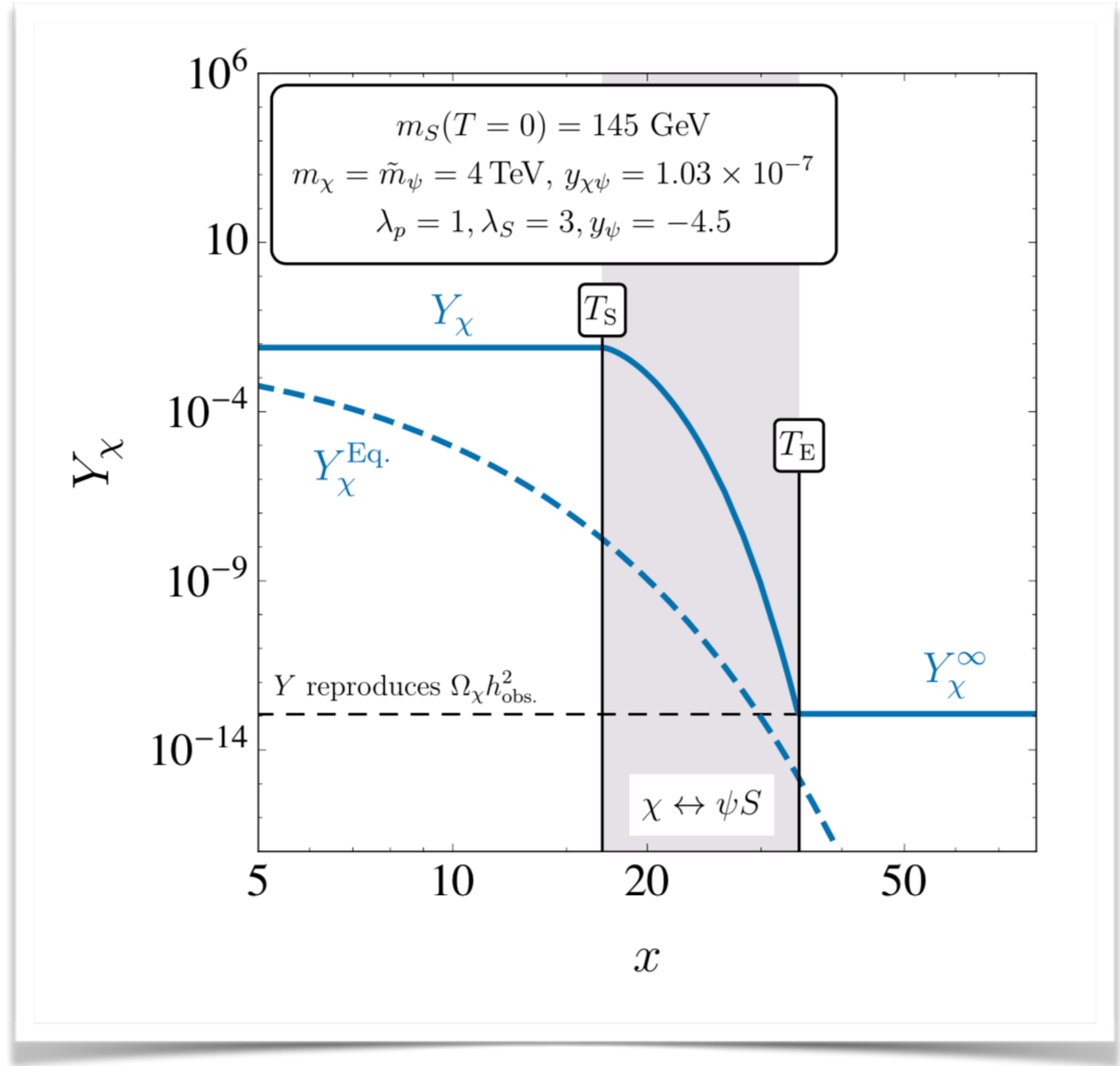

Baker Mittnacht [arXiv:1811.03101]
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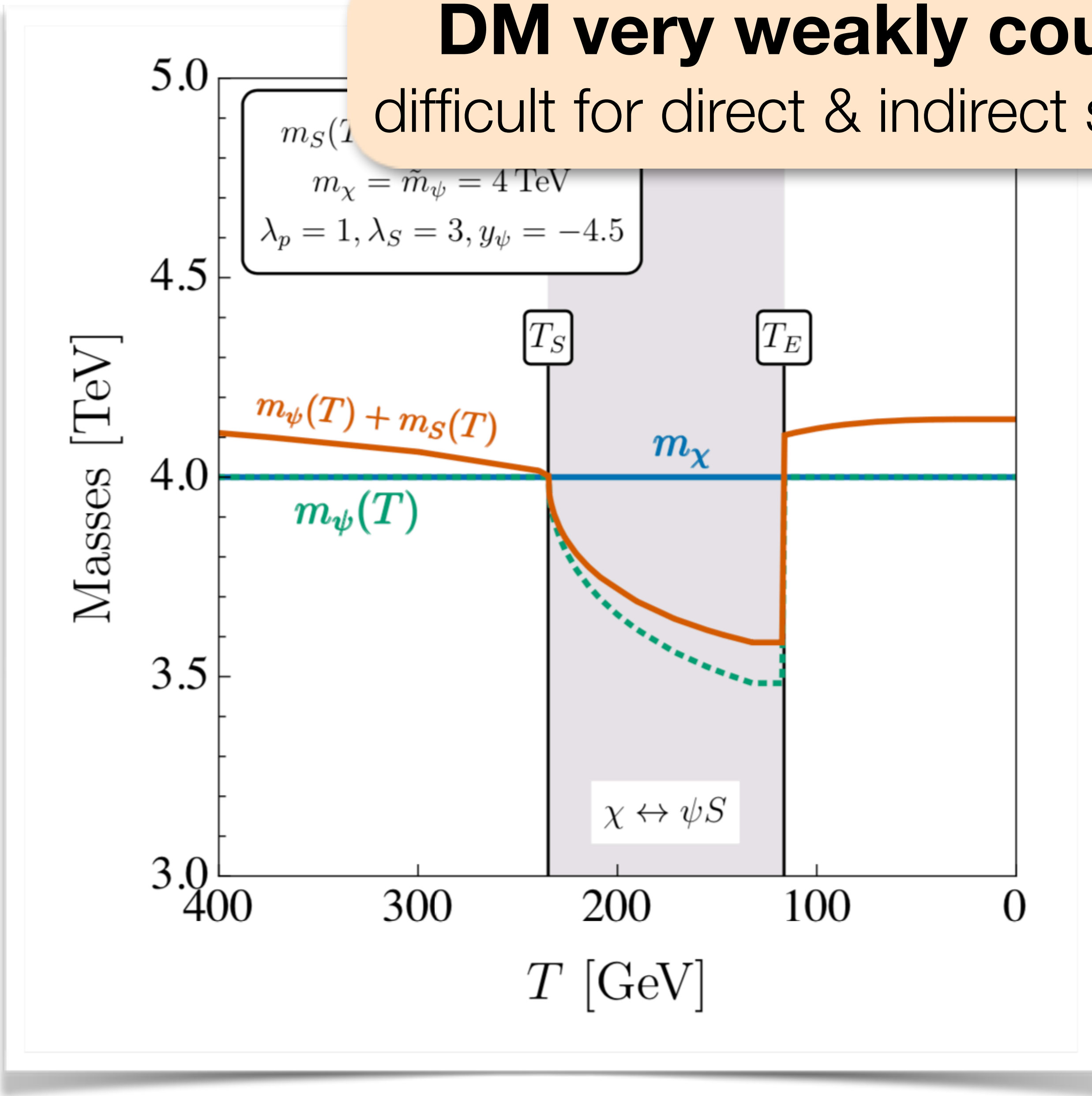

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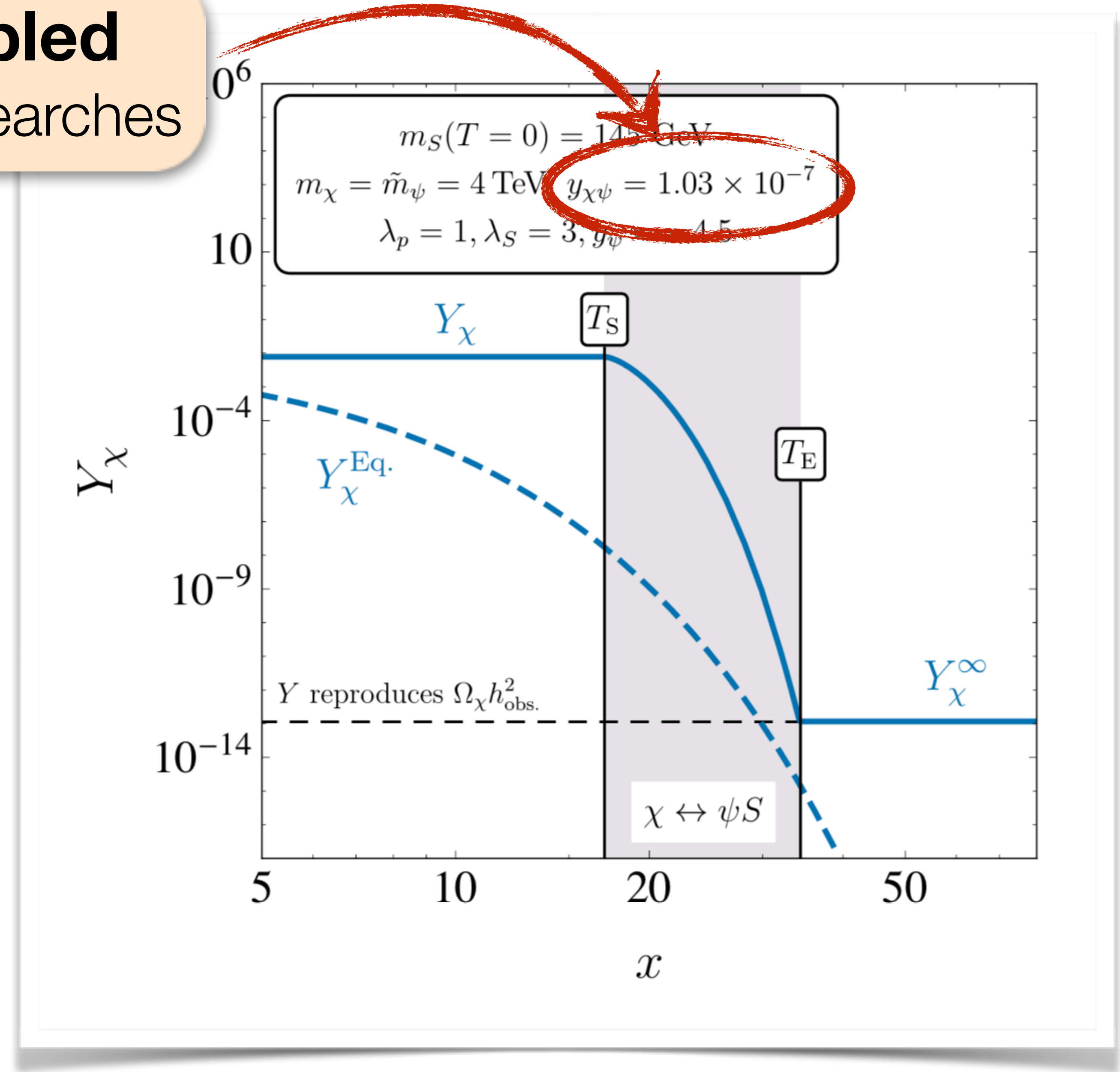

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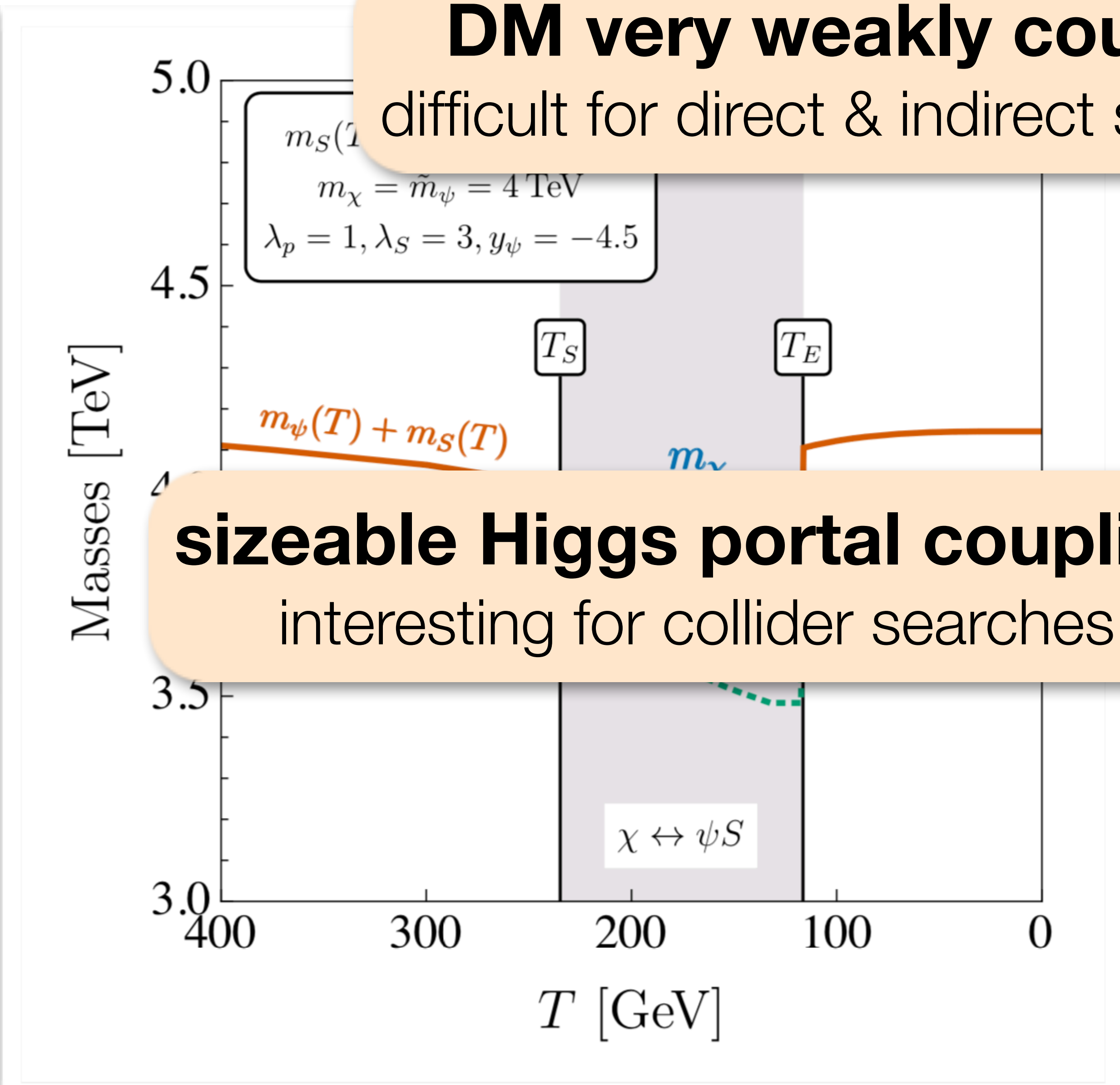

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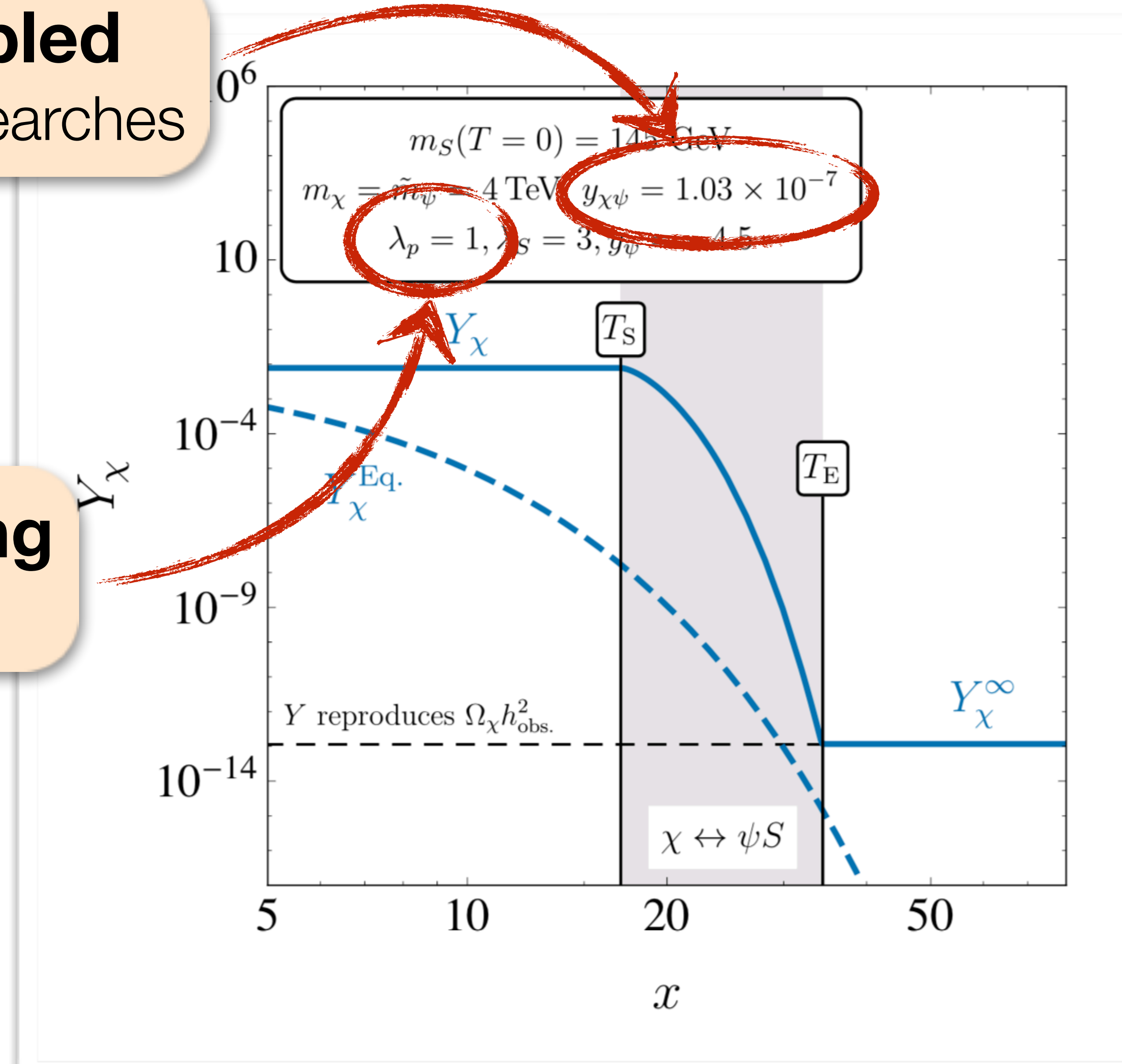

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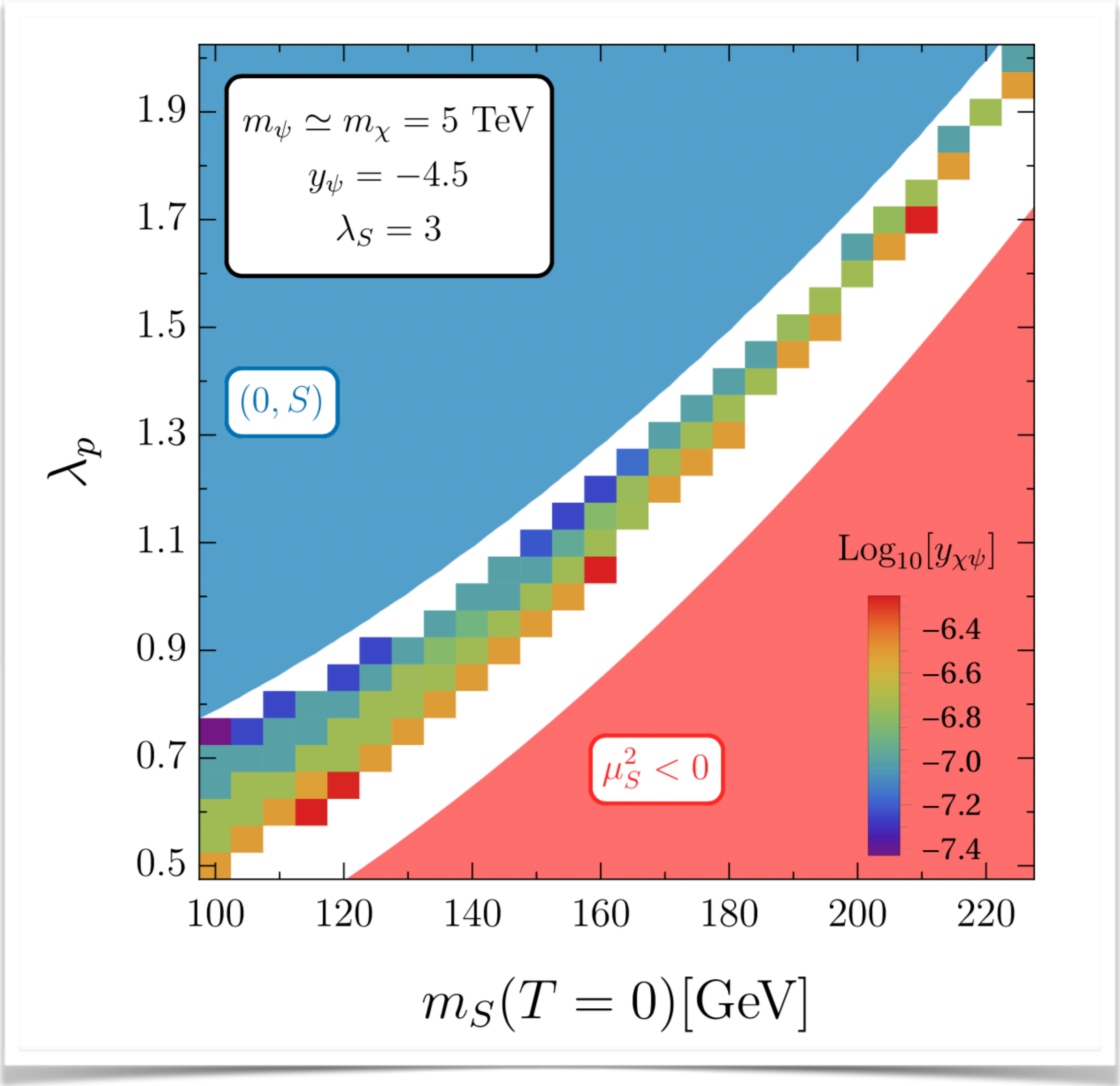
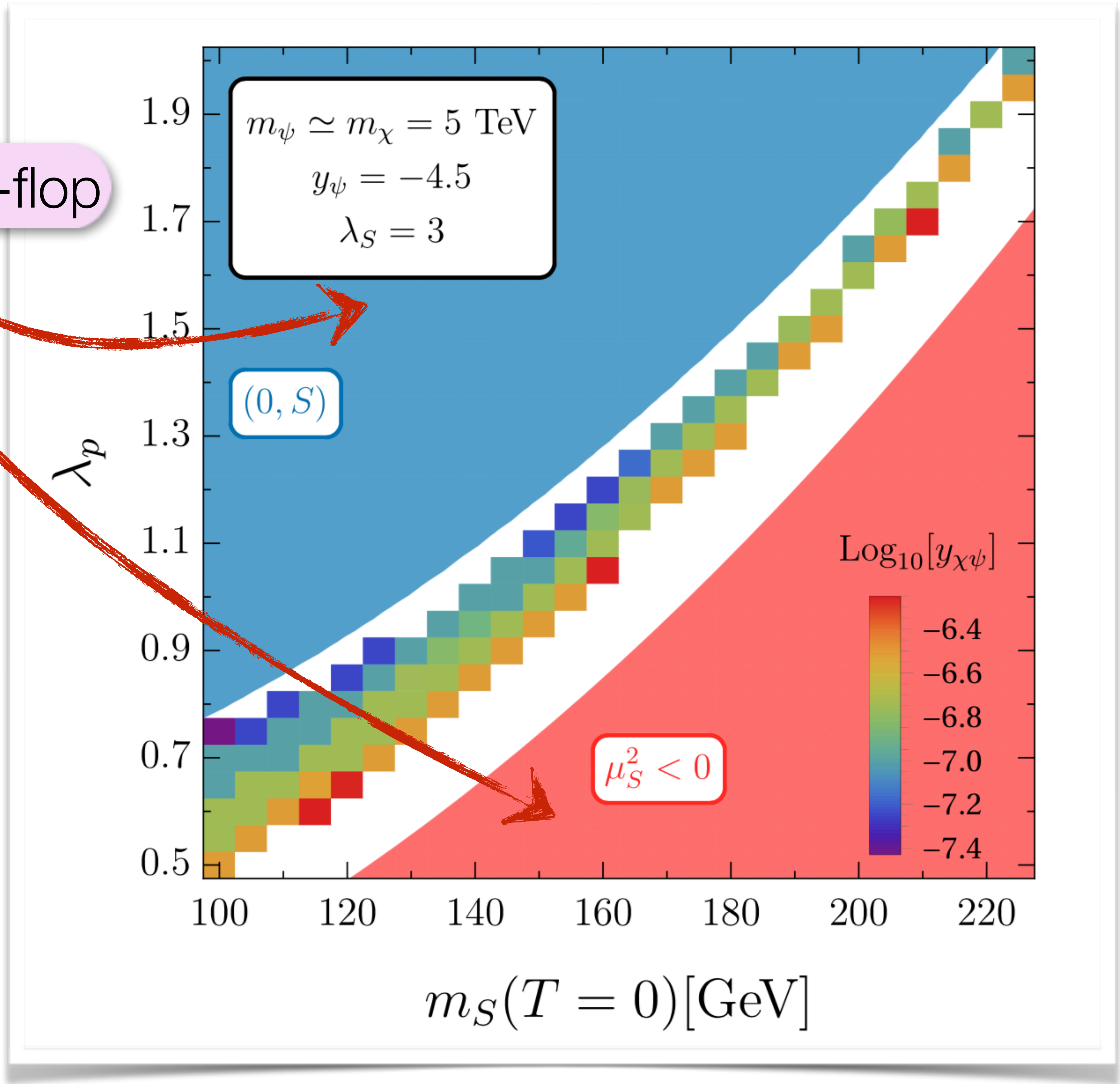
Parameter Space



Parameter Space

no vev flip-flop



Further Implications

☑ Gravitational waves

- 1^{st} 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

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Implications B1

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

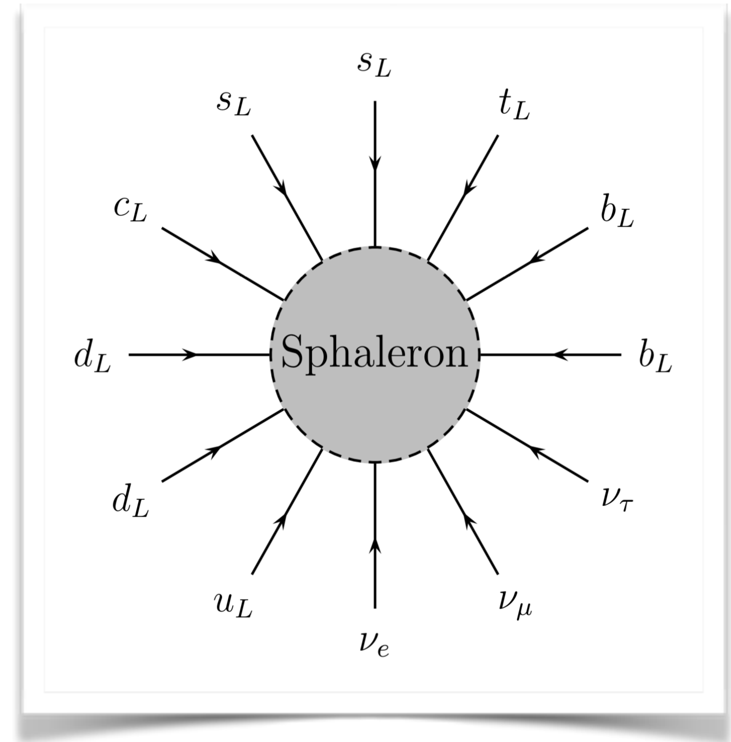


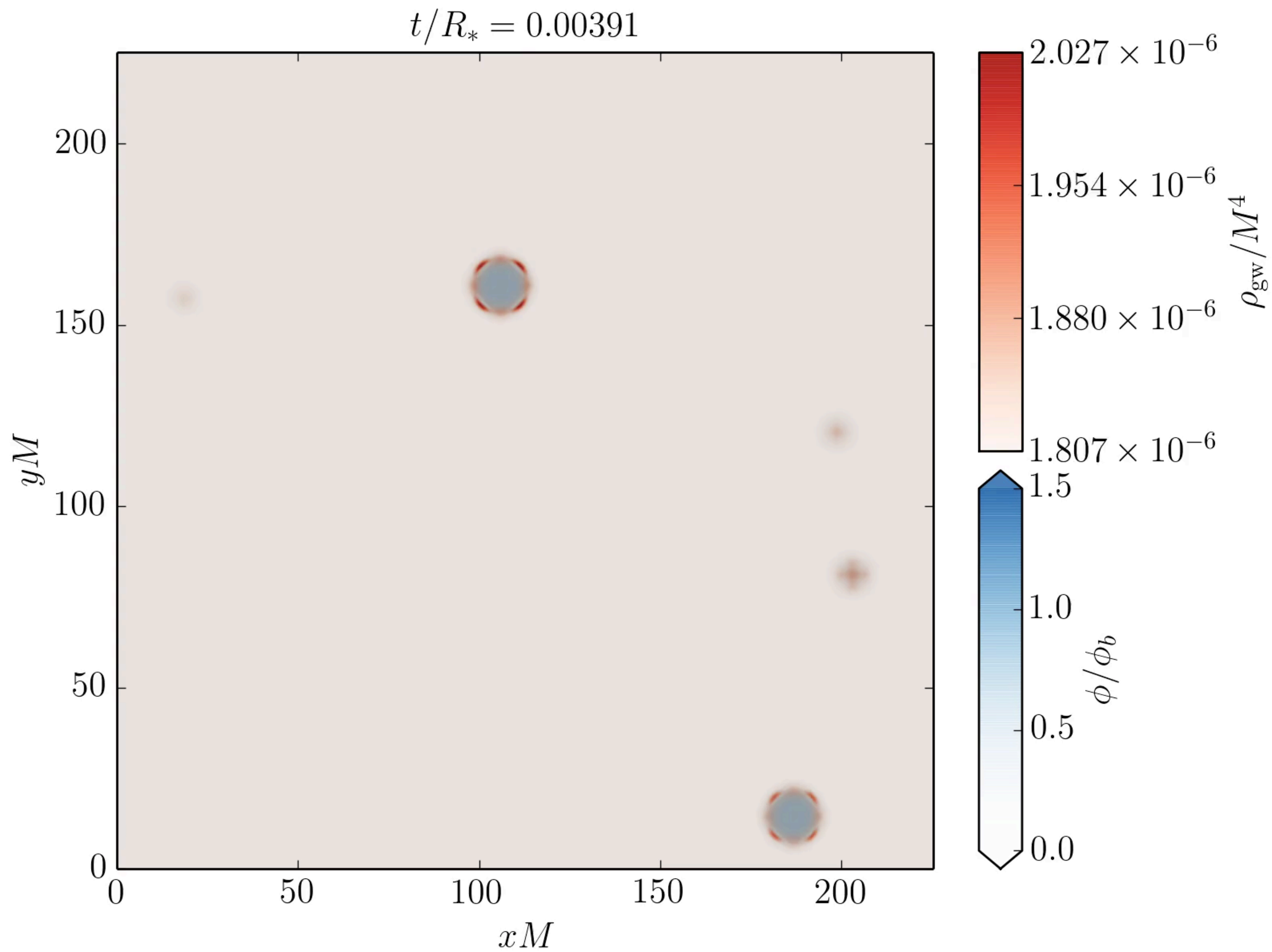
Image: Wilfried Buchmüller, hep-ph/9812447

Implications B2
Gravitational Waves

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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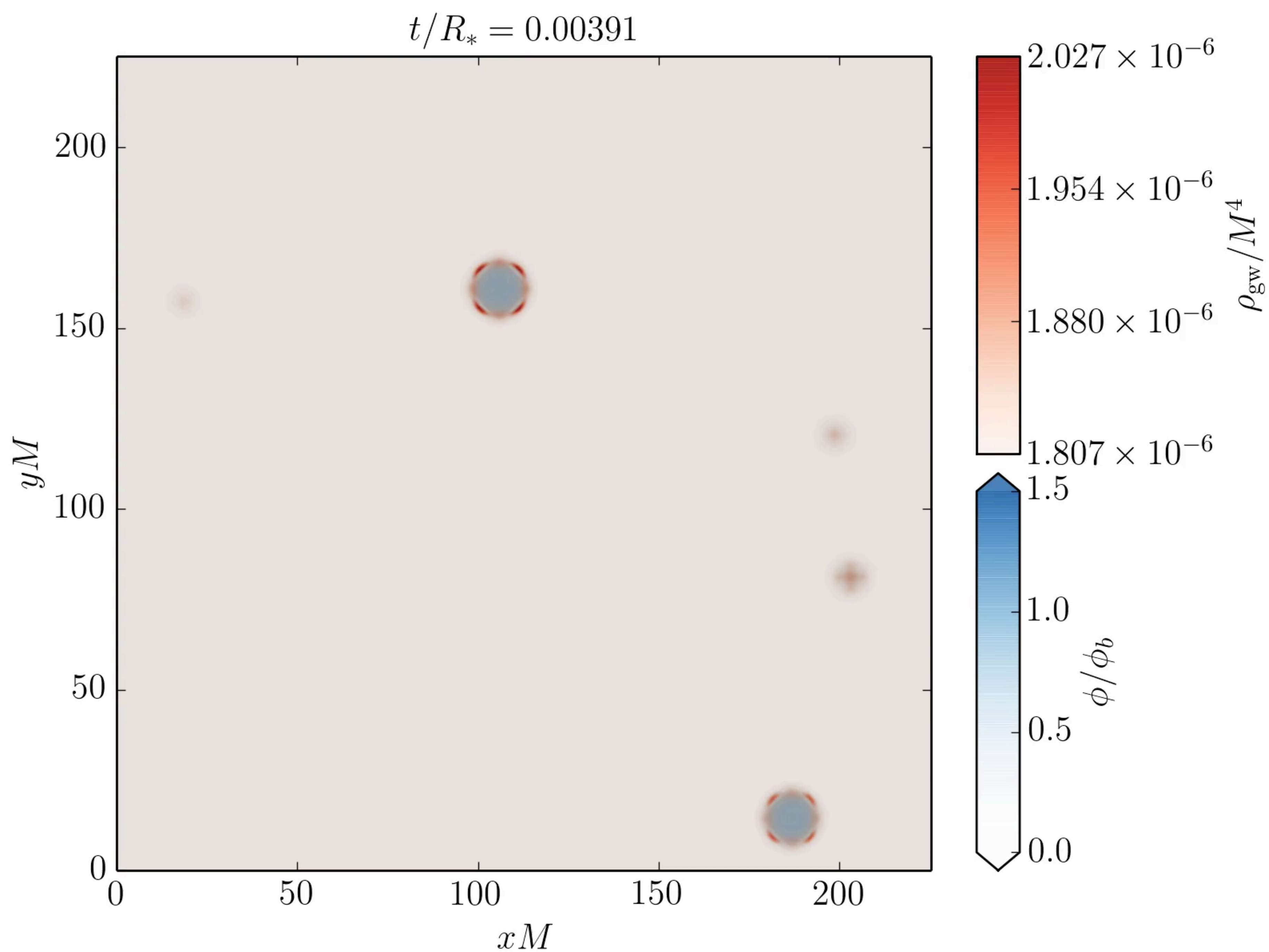


Gravitational Waves from Phase Transitions

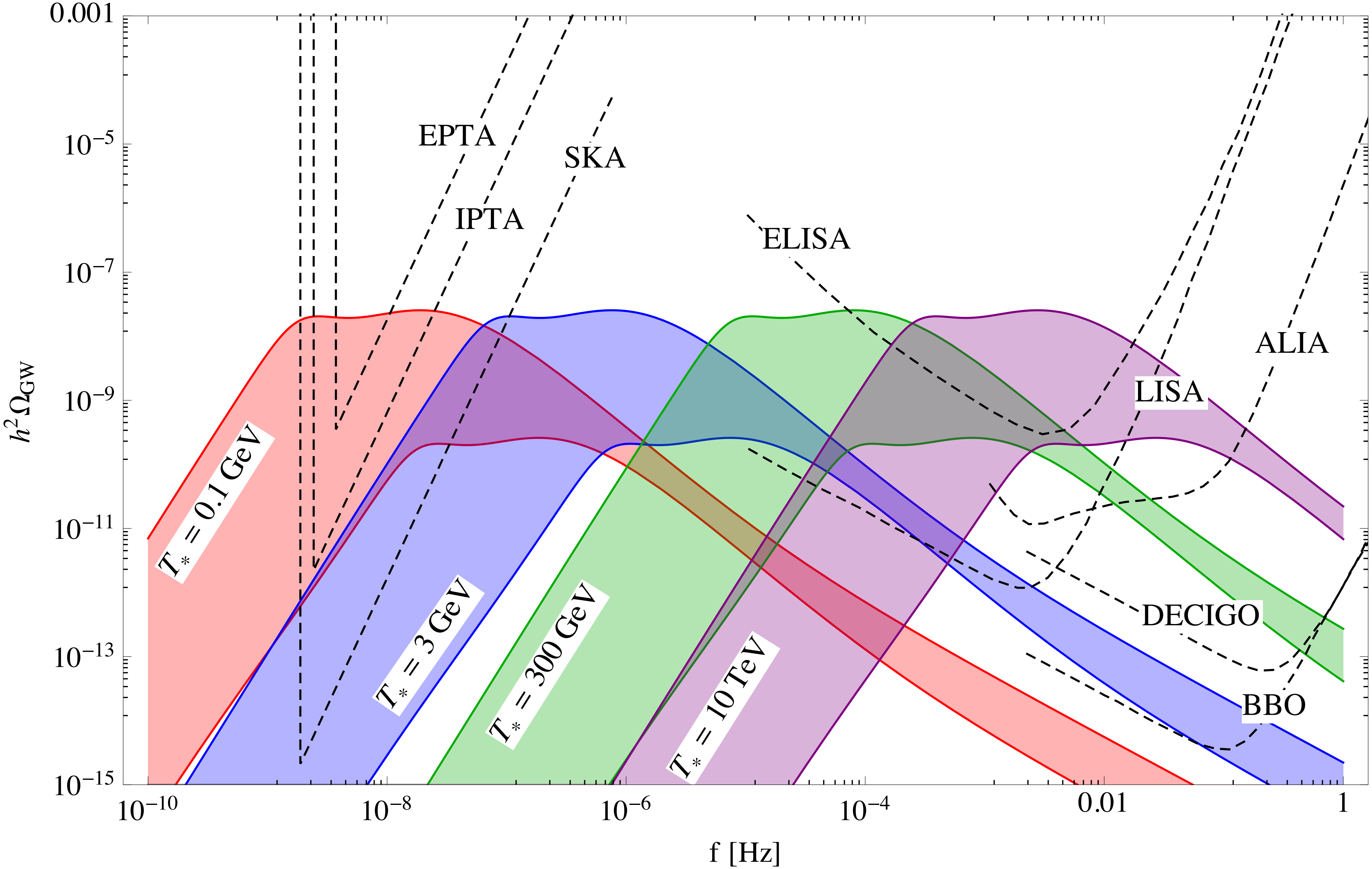
- Three contributions
  - Bubble collisions
  - Collisions of sound waves generated during bubble expansion
  - Turbulence in the plasma

- How to compute the GW signal from these contributions:
  - requires numerical simulations (large uncertainties!)
  - Parameterize results, e.g. as

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

Gravitational 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

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

- Inverse duration of phase transition

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

- Bubble wall velocity v_w

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- Strength of the phase transition

latent heat release

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

total radiation density

- Inverse duration of pha

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

- Bubble wall velocity v_w

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Phase Transition Parameter for GWs

Four relevant parameters

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

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

Euclidean action
corresponding to the
transition path in field space

- Bubble wall velocity v_w

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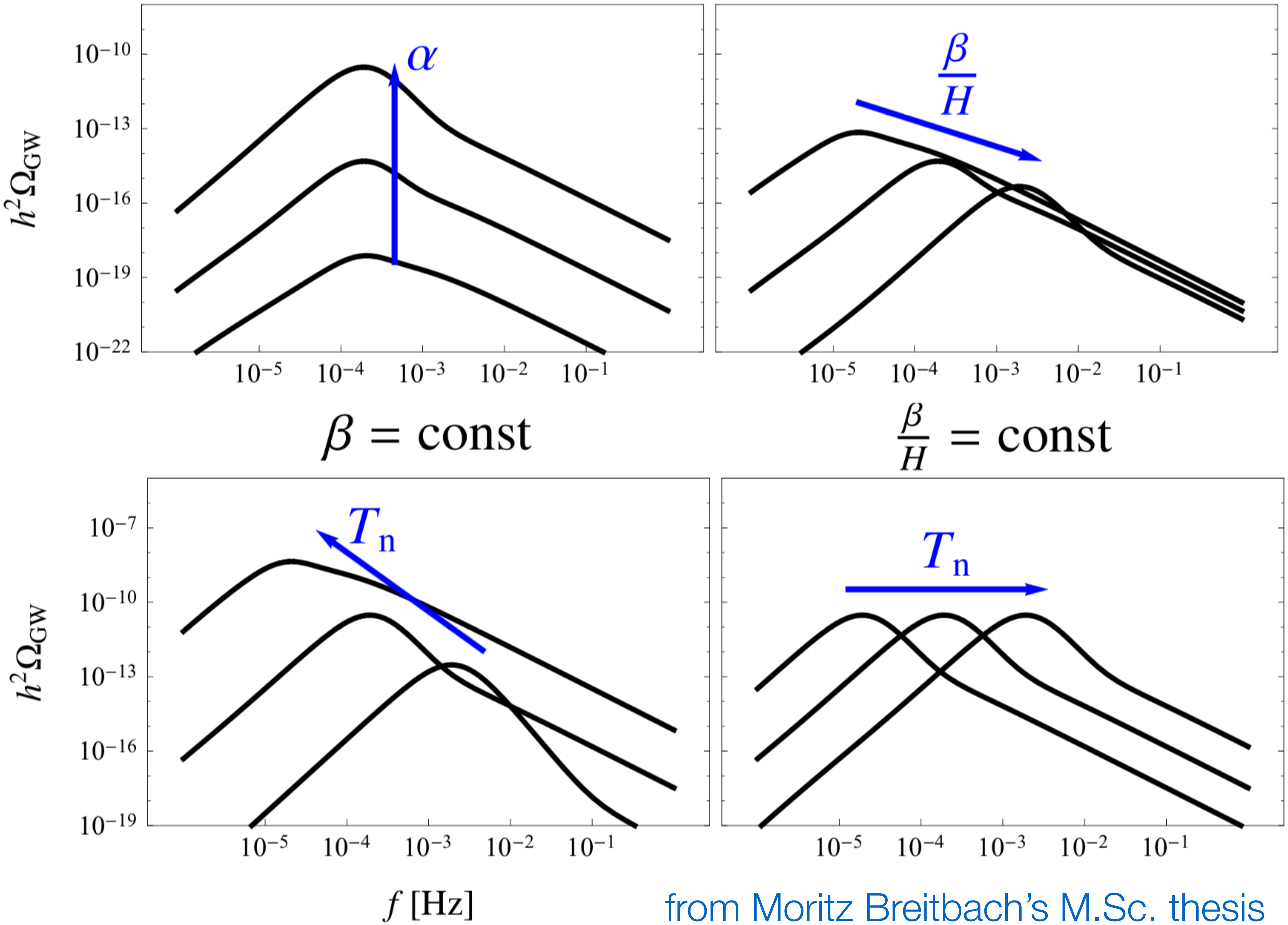
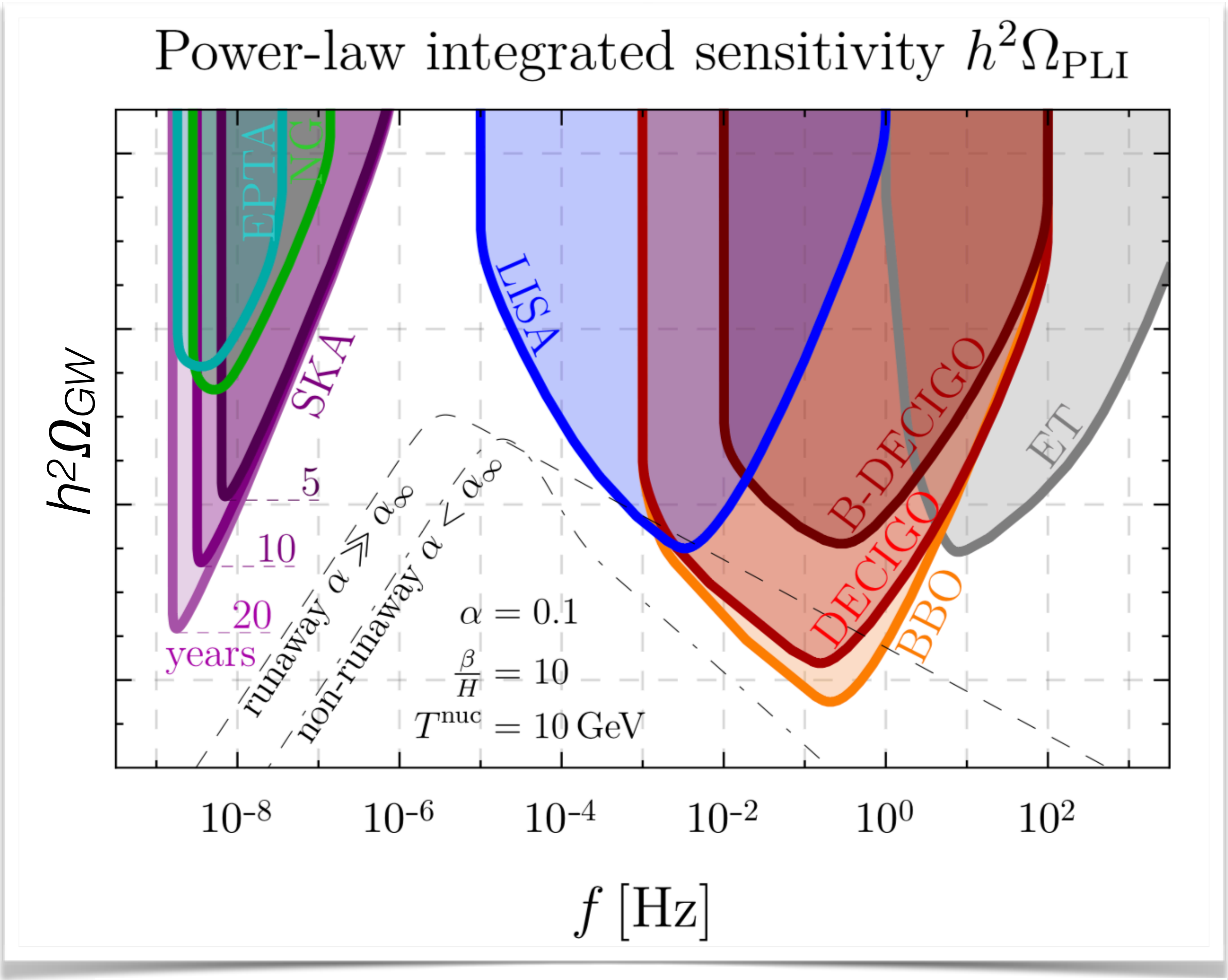
Parameter Dependence of GW Spectra



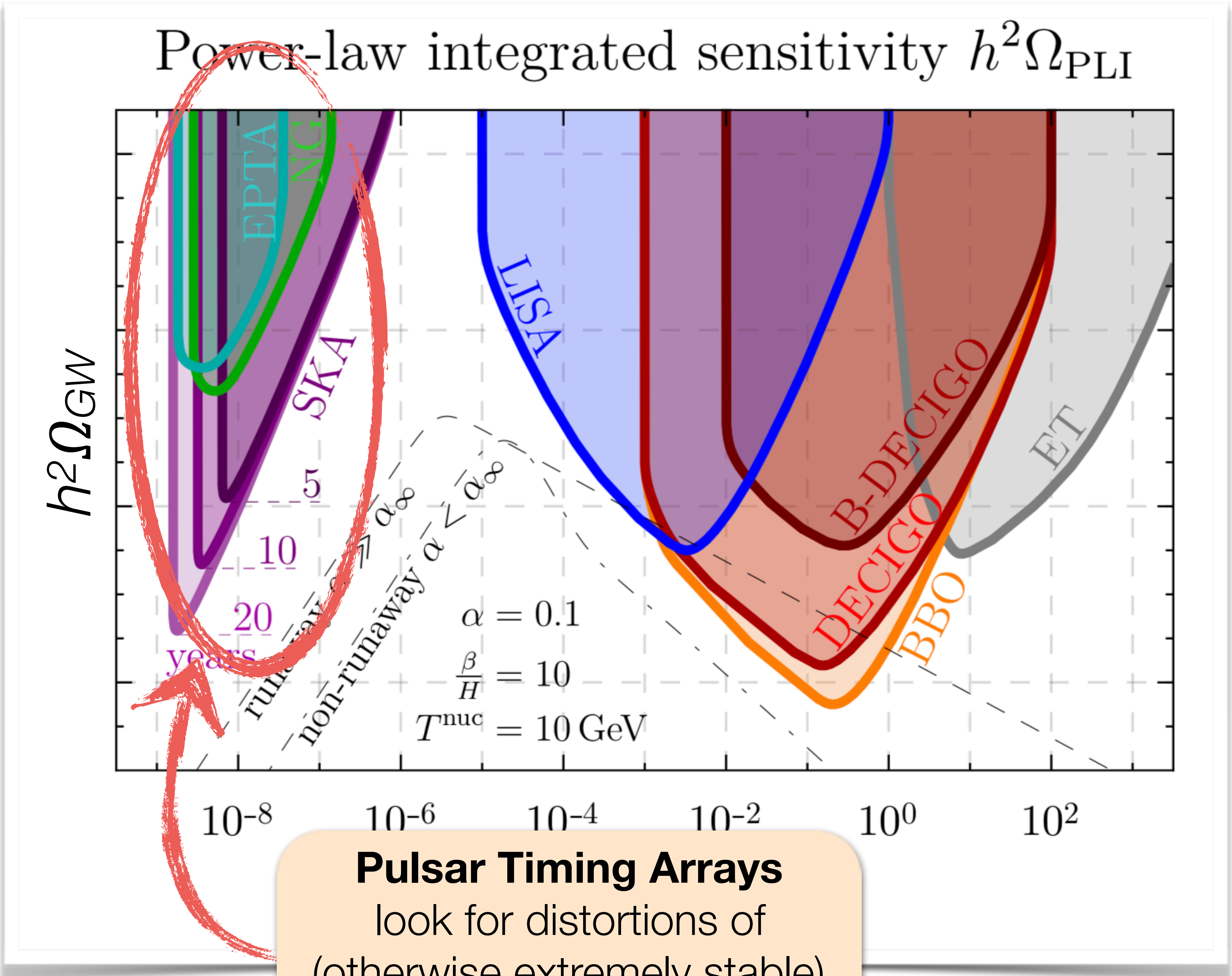
from Moritz Breitbach's M.Sc. thesis

Gravitational Wave Observatories



Breitbach JK Madge Opferkuch Schwaller arXiv:1811.11175

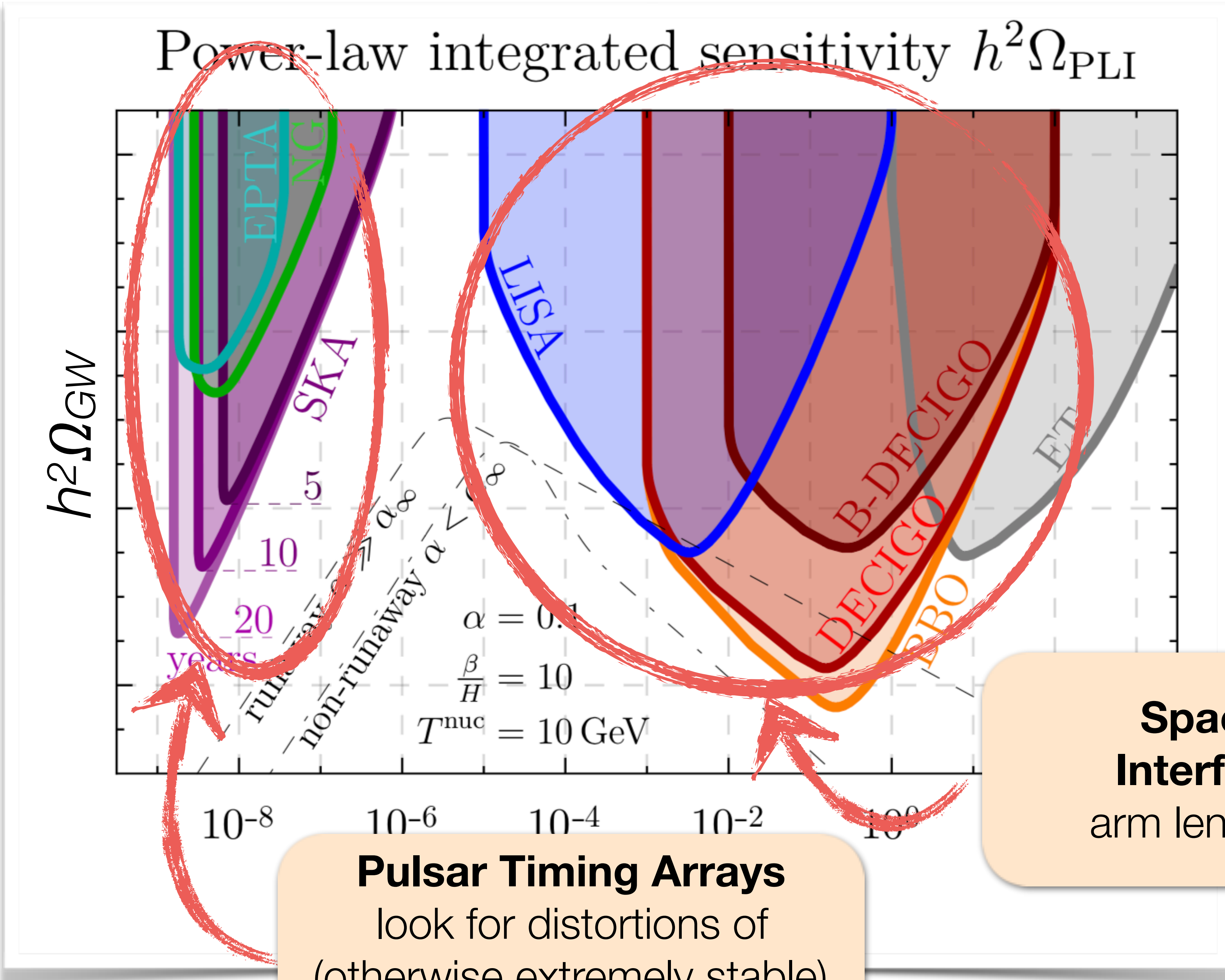
Gravitational Wave Observatories



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

Breitbach … r arXiv:1811.11175

Gravitational Wave Observatories

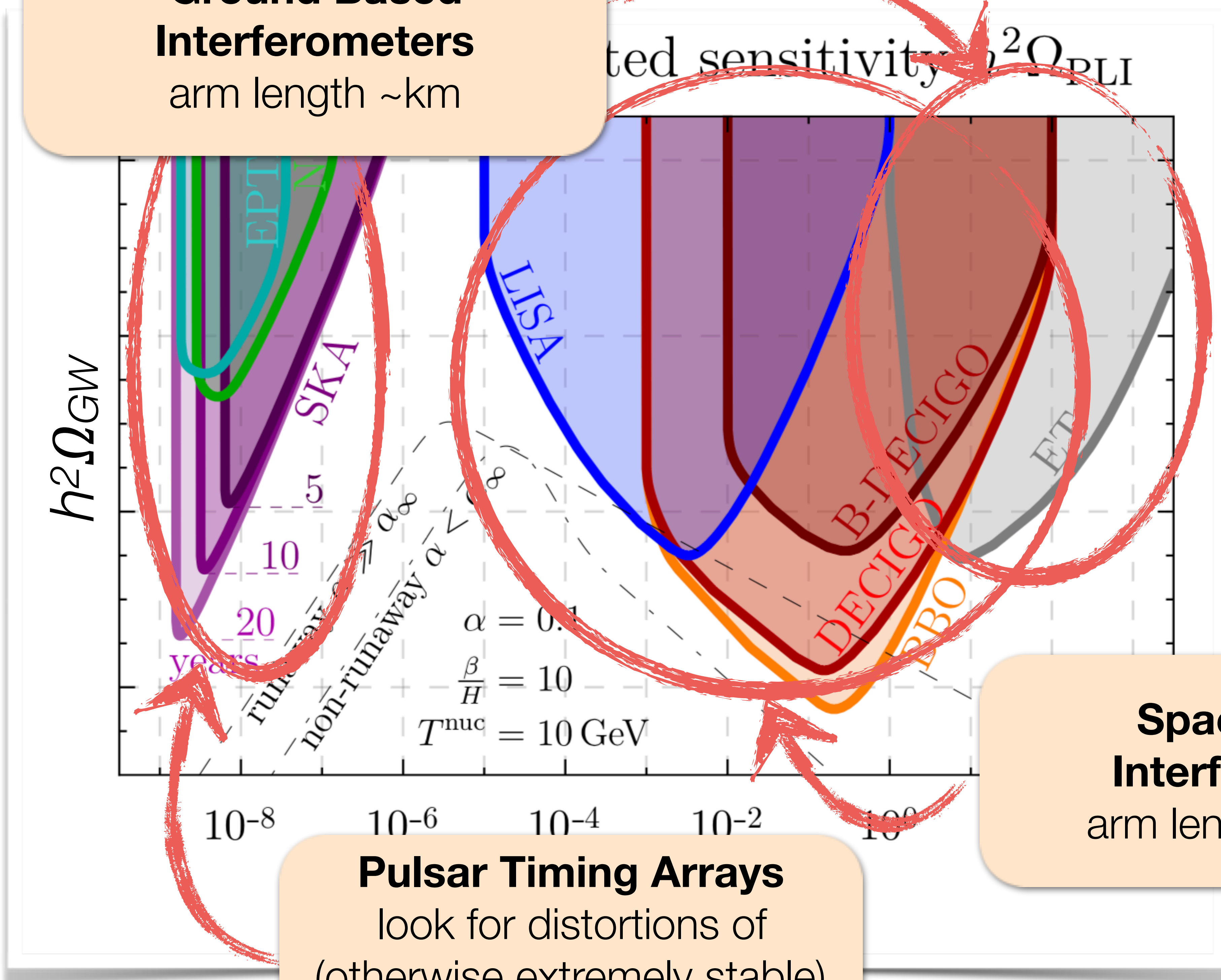


Space Based Interferometers
arm length ~10^6 km

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

Breitbach … er arXiv:1811.11175

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

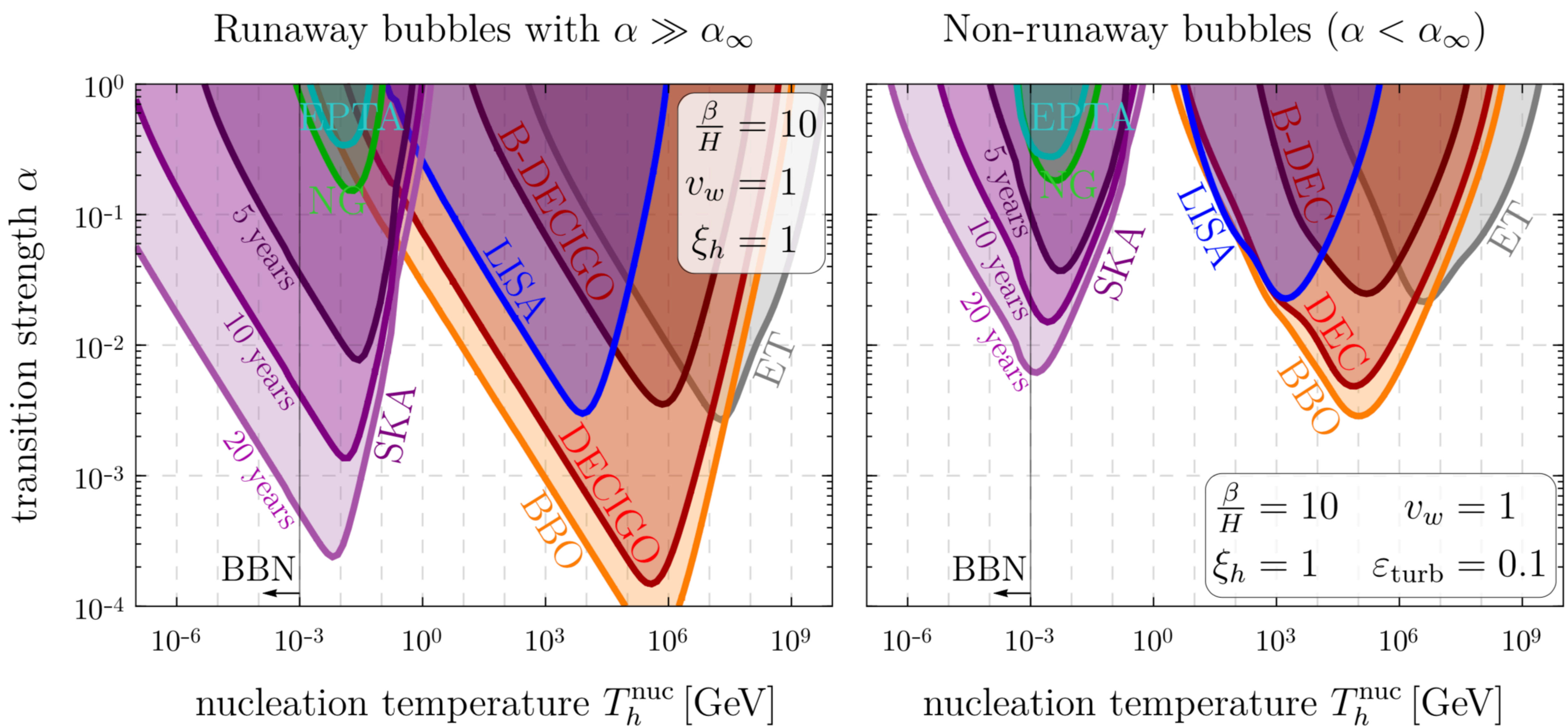
Breitbach ... er arXiv:1811.11175

GWs from Hidden Sector Phase Transitions

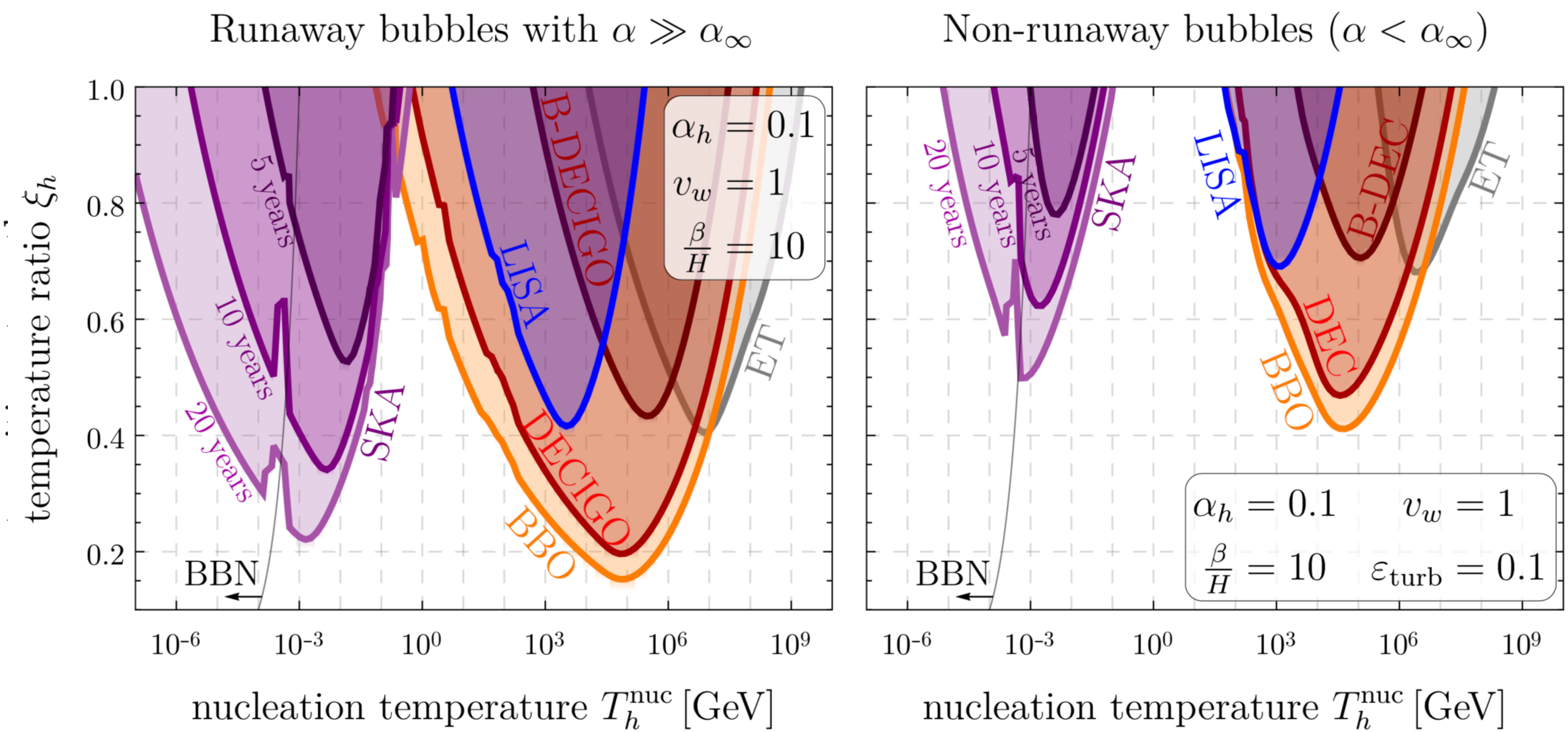
Important Plot Twist

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

Dependence on Hidden Sector Temperature



Dependence on Hidden Sector Temperature



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