Phase Transitions in the Early Universe

Joachim Kopp (CERN & Uni Mainz)
EP / TH Physics Workshop | Crozet | 21.10.2019

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Outline

- ☑ Phase Transitions Primer
- ☑ The Electroweak Phase Transition
- ☑ Extended Higgs Sectors
- ☑ Implications:
  - Dark Matter
  - Gravitational Waves
  - Baryogenesis
  - Higgs Physics at Colliders
- ☑ Summary

Phase Transitions in Everyday Life

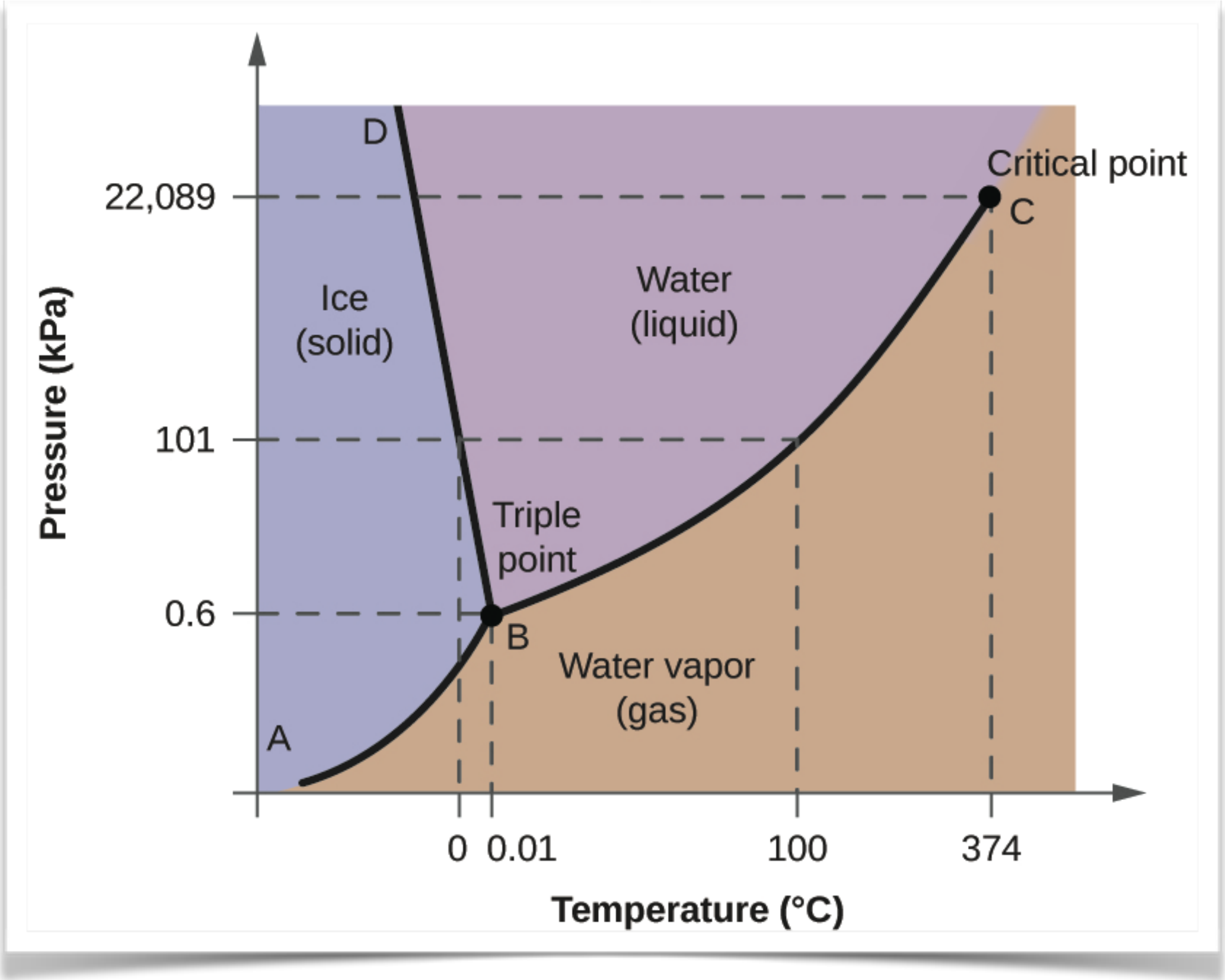
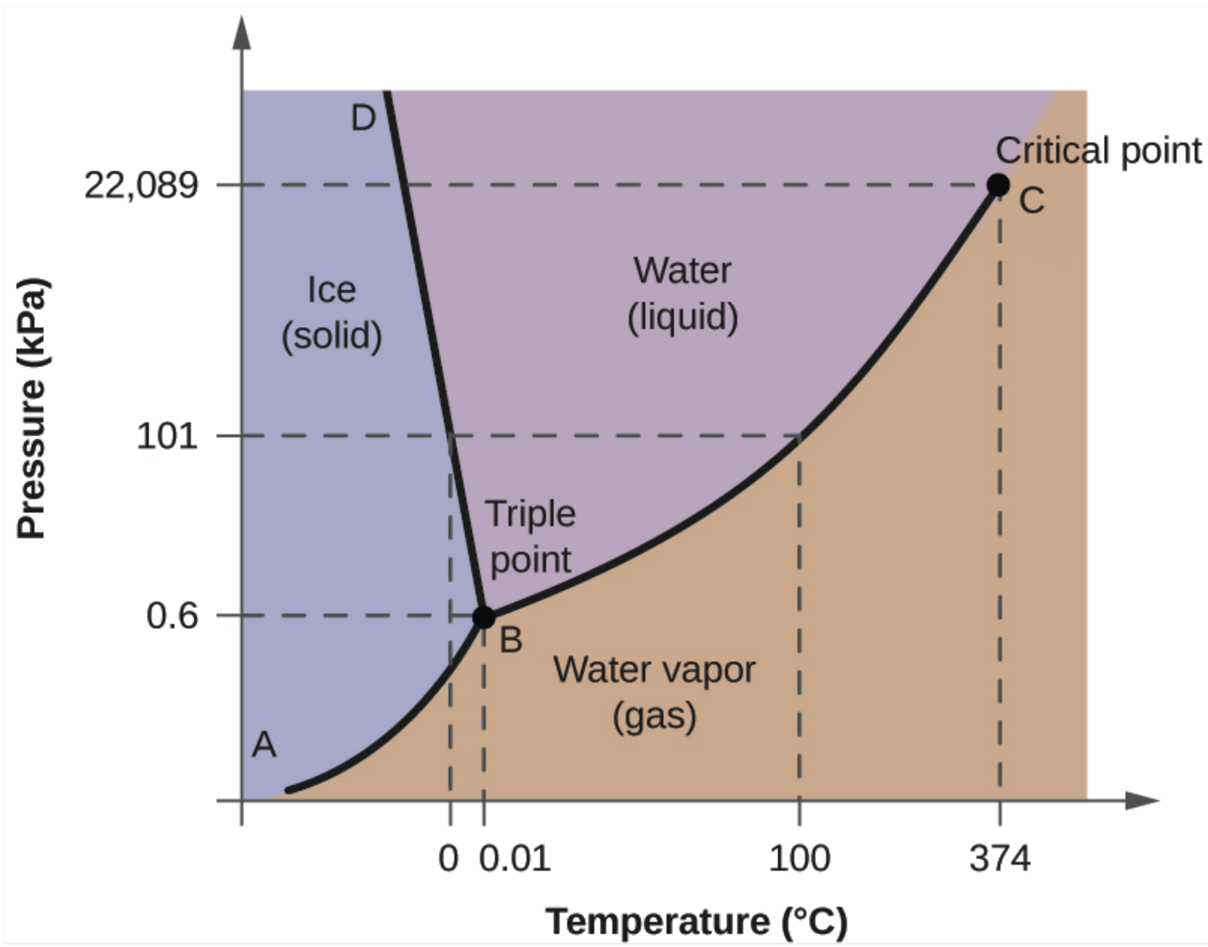


Image Credit: libretexts.org

Phase Transitions Primer

Phase Transitions in (a Physicist's) Everyday Life



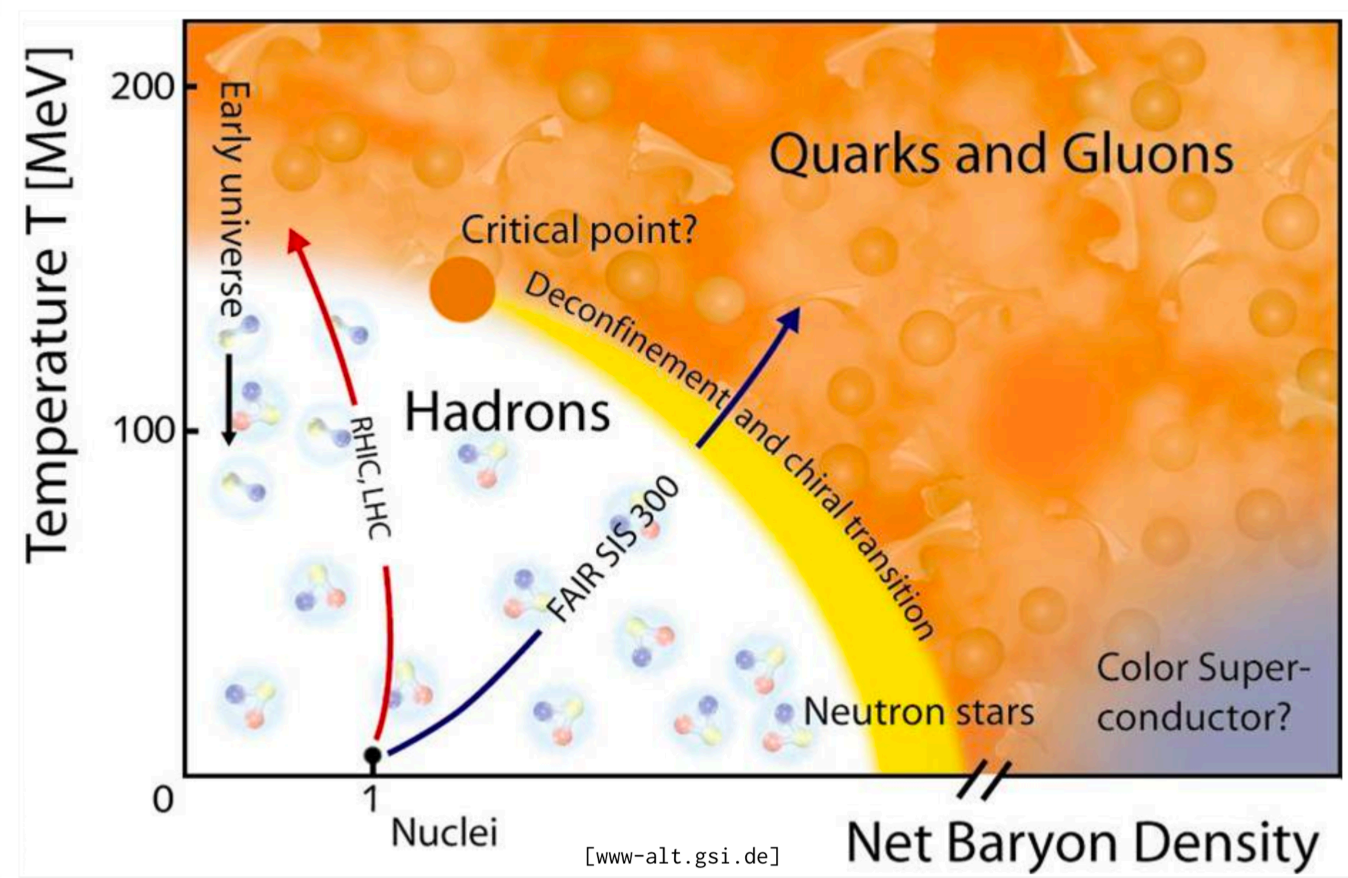


Image Credit: libretexts.org, Ralf-Arno Tripolt

The Order of a Phase Transition

- Order Parameter: 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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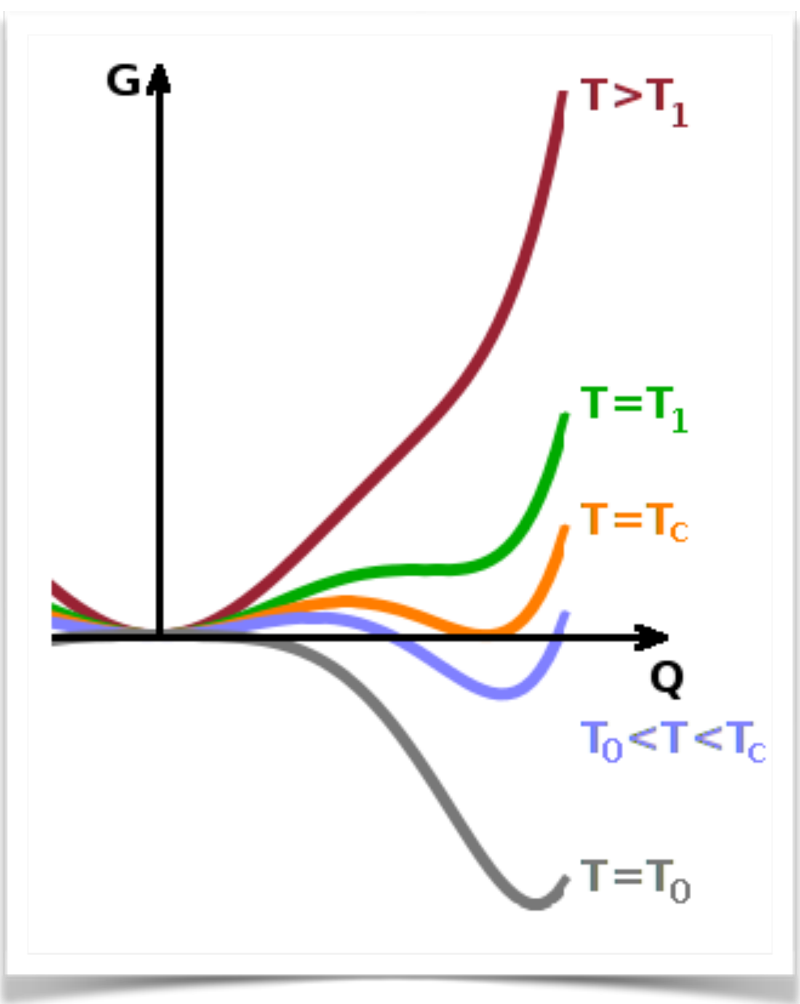

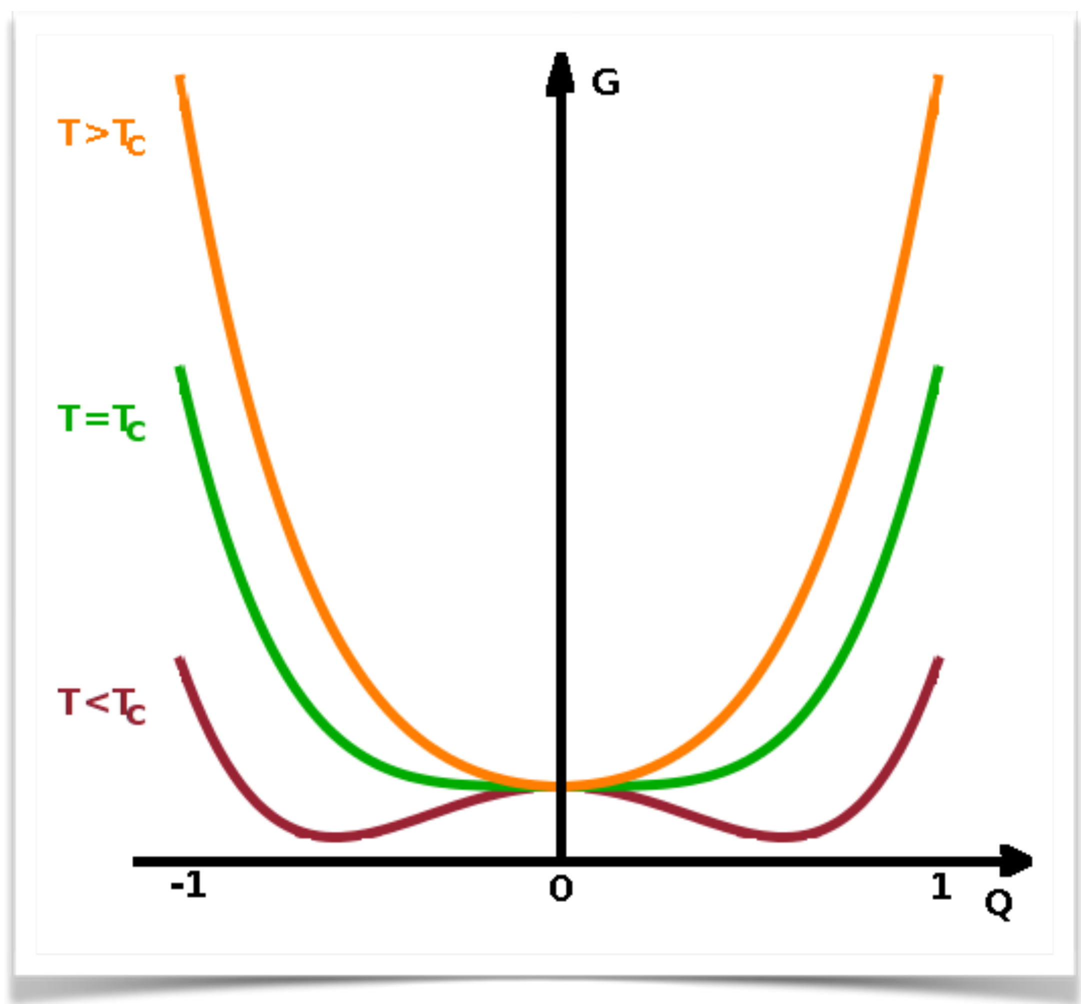

Images: Rudi Winter

The Order of a Phase Transition

1st order phase transition
order parameter changes discontinuous

...y measuring the change in the ...ansition

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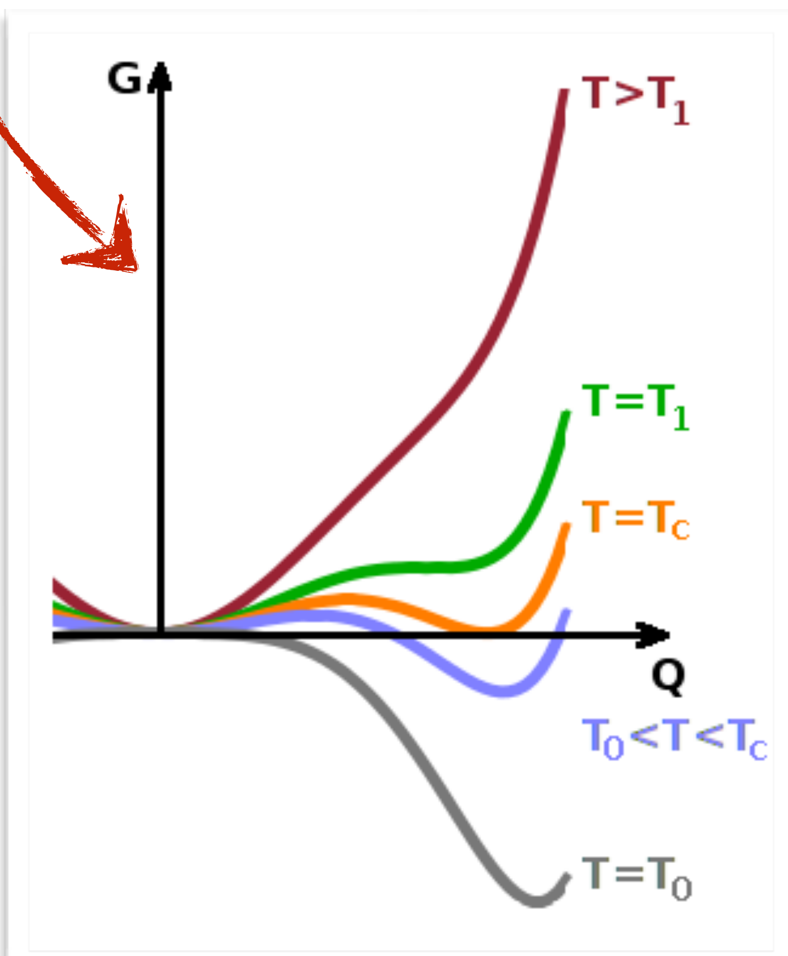
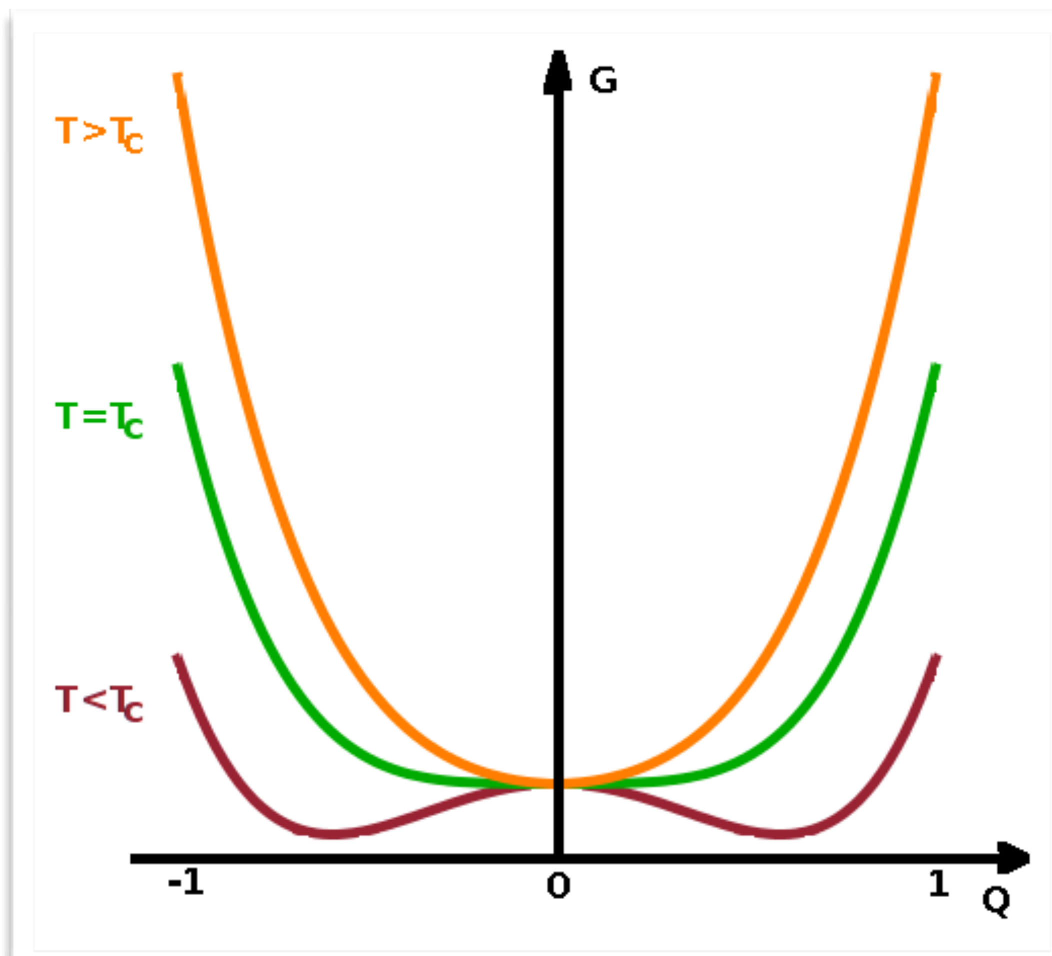




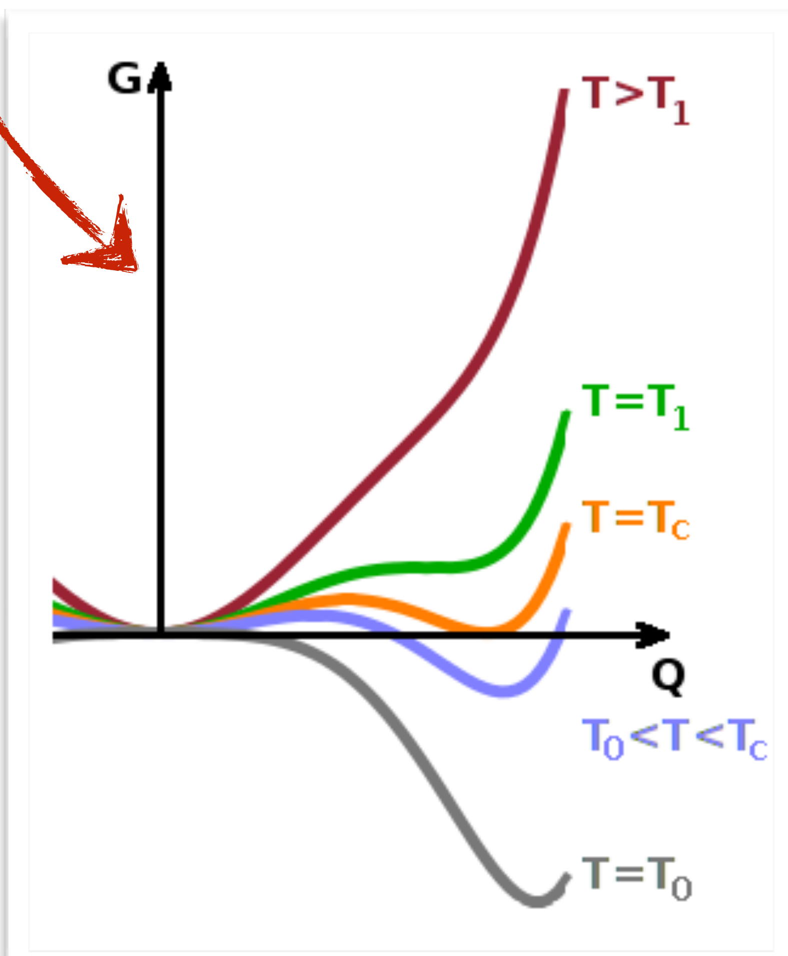
Images: Rudi Winter

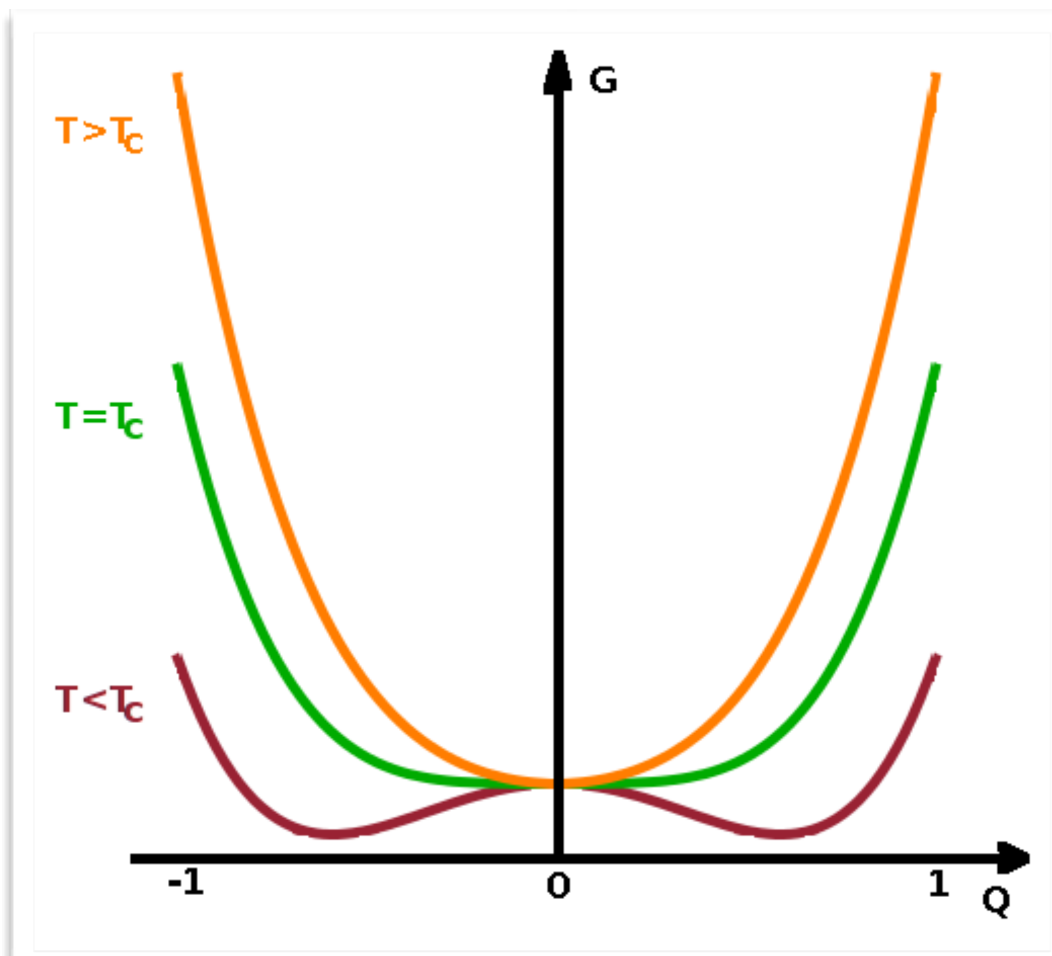
The Order of a Phase Transition

1st order phase transition
order parameter changes discontinuous

2nd order phase transition
order parameter changes continuously
(but its first derivative is discontinuous)

- for liquid–gas transition:
- for QCD phase transition: quark condensate $\langle \bar{q}_L q_R \rangle$





Images: Rudi Winter

Phase Transitions in the Early Universe

- Properties of the primordial plasma change dramatically during phase transitions
- QCD phase transition (T ~ 200 MeV)
  - chiral symmetry broken $SU(3)_L \times SU(3)_R \to SU(3)_V$
  - order parameter: $\langle \bar{q}_L q_R \rangle$
- Electroweak phase transition (T ~ 160 GeV)
  - Electroweak symmetry broken $SU(2)_L \times U(1)_Y \to U(1)_{\rm em}$
  - Higgs acquires vev, fermions and gauge bosons become massive
  - cross-over in the SM, but can be 1^{st} or 2^{nd} order in BSM theories
  - order parameter: Higgs vev v_H

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The Electroweak Phase Transition

Effective Higgs Potential

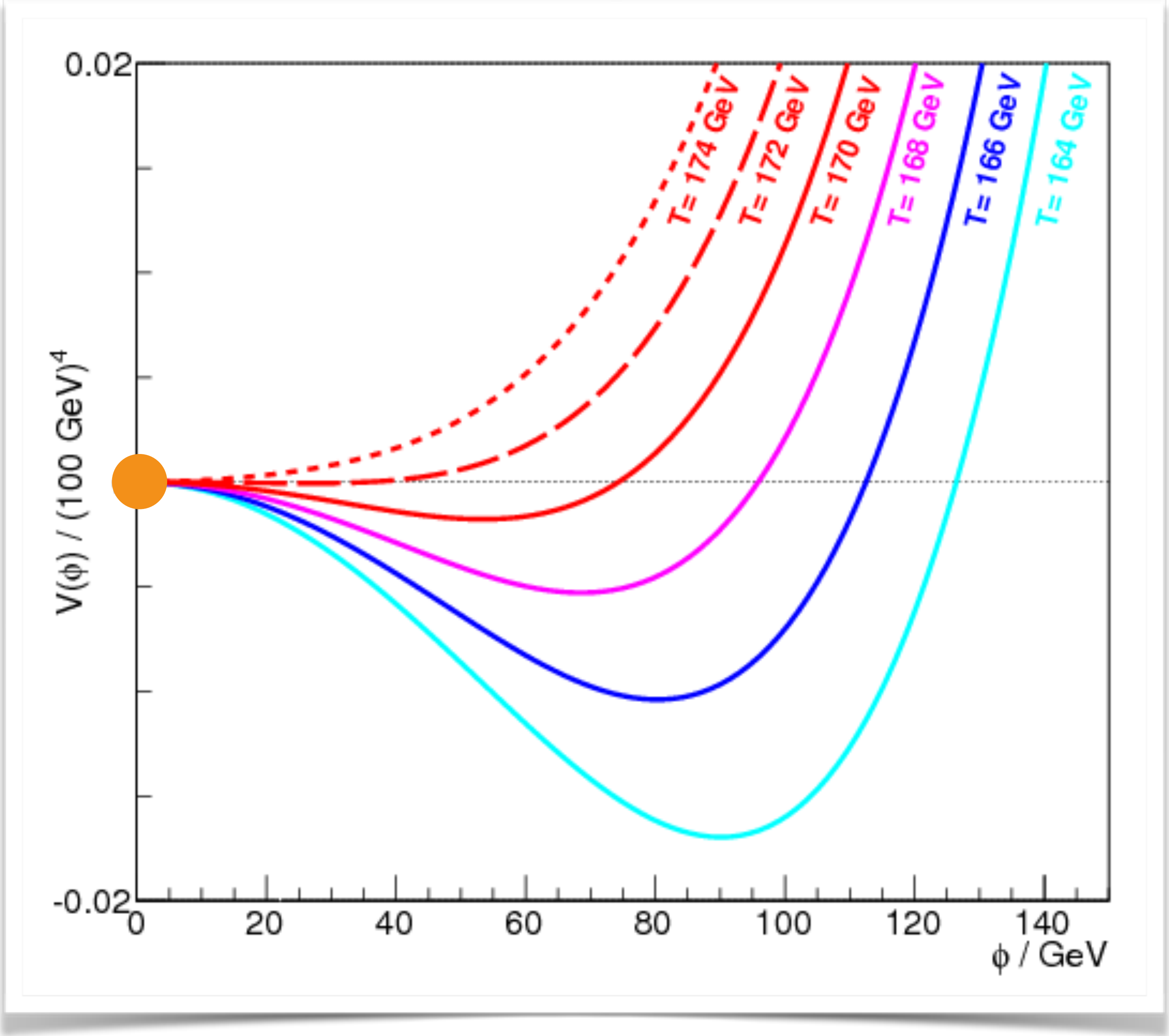
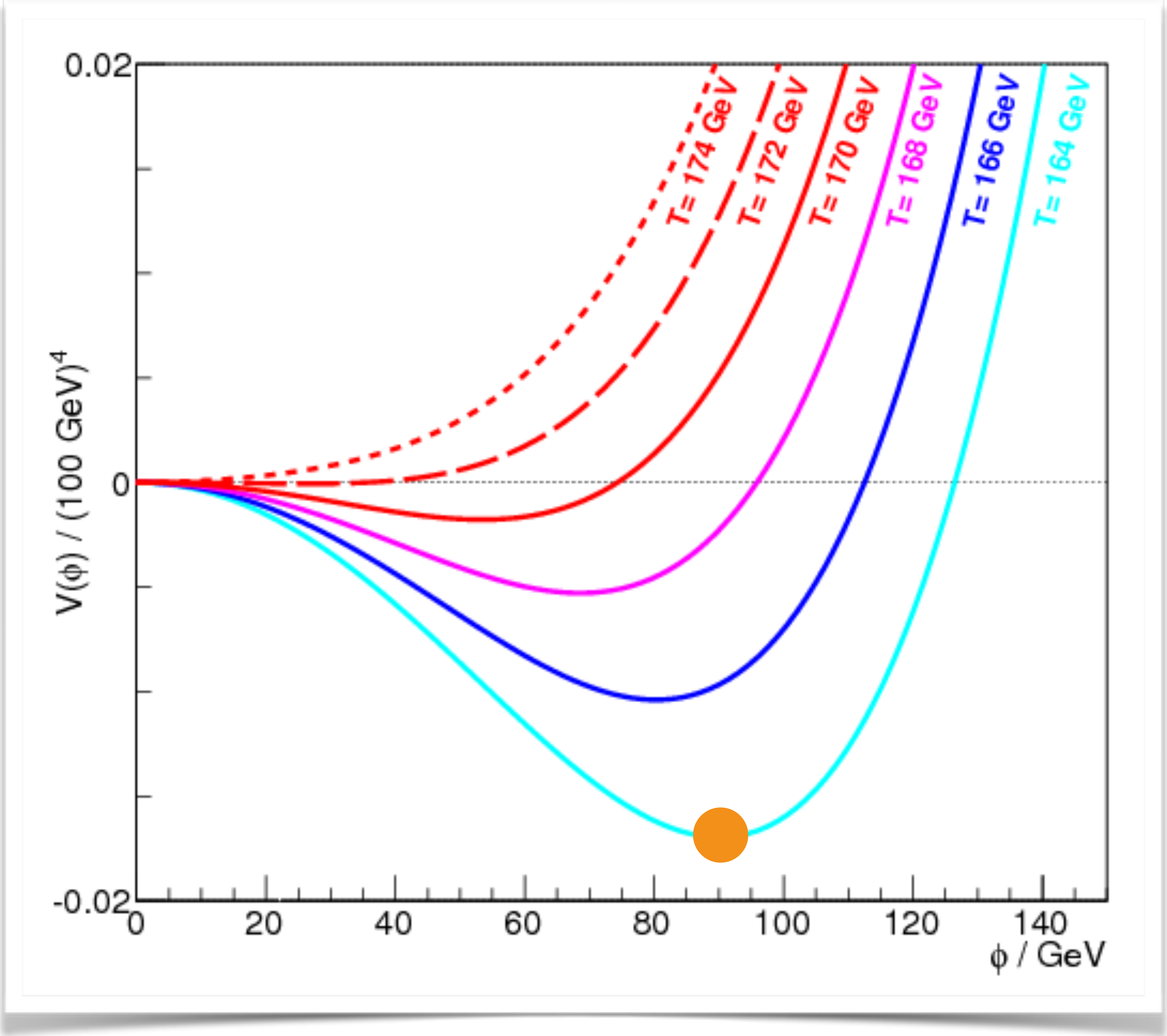


Image from arXiv:1503.03317

Effective Higgs Potential



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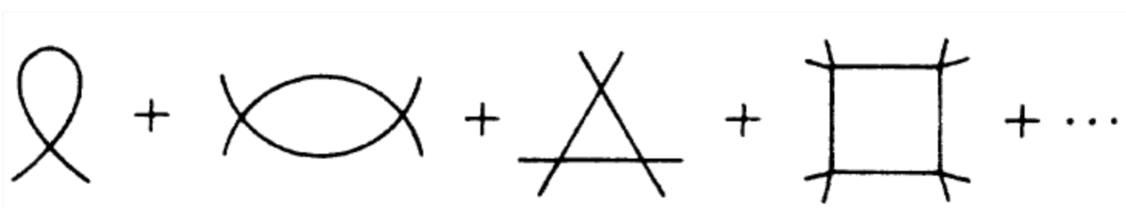
Scalar Potentials at Finite Temperature

☑ 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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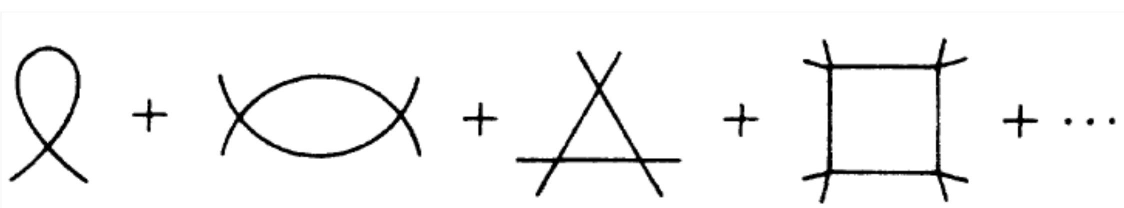

$$V^{\text{CW}}[\phi] = \sum_{n=1}^{\infty} \int \frac{d^4k}{(2\pi)^4} \frac{1}{2n} \left(\frac{2\lambda\phi}{k^2 - m^2} \right)^n$$

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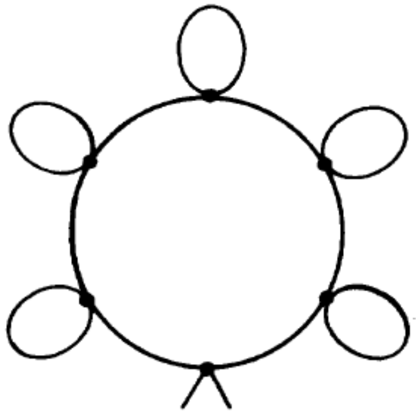
☑ Resummed "Daisy" Corrections   Dolan Jackiw 1974, Carrington 1992



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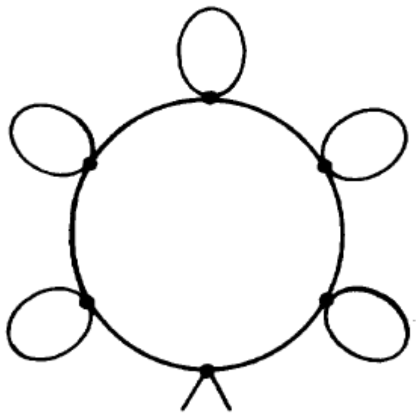
- *n* one-vertex bubbles, one *n*-vertex bubble:

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



- One-vertex bubbles yield thermal mass $\Pi(T)$

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

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Extended Higgs Sectors

The Vev Flip-Flop

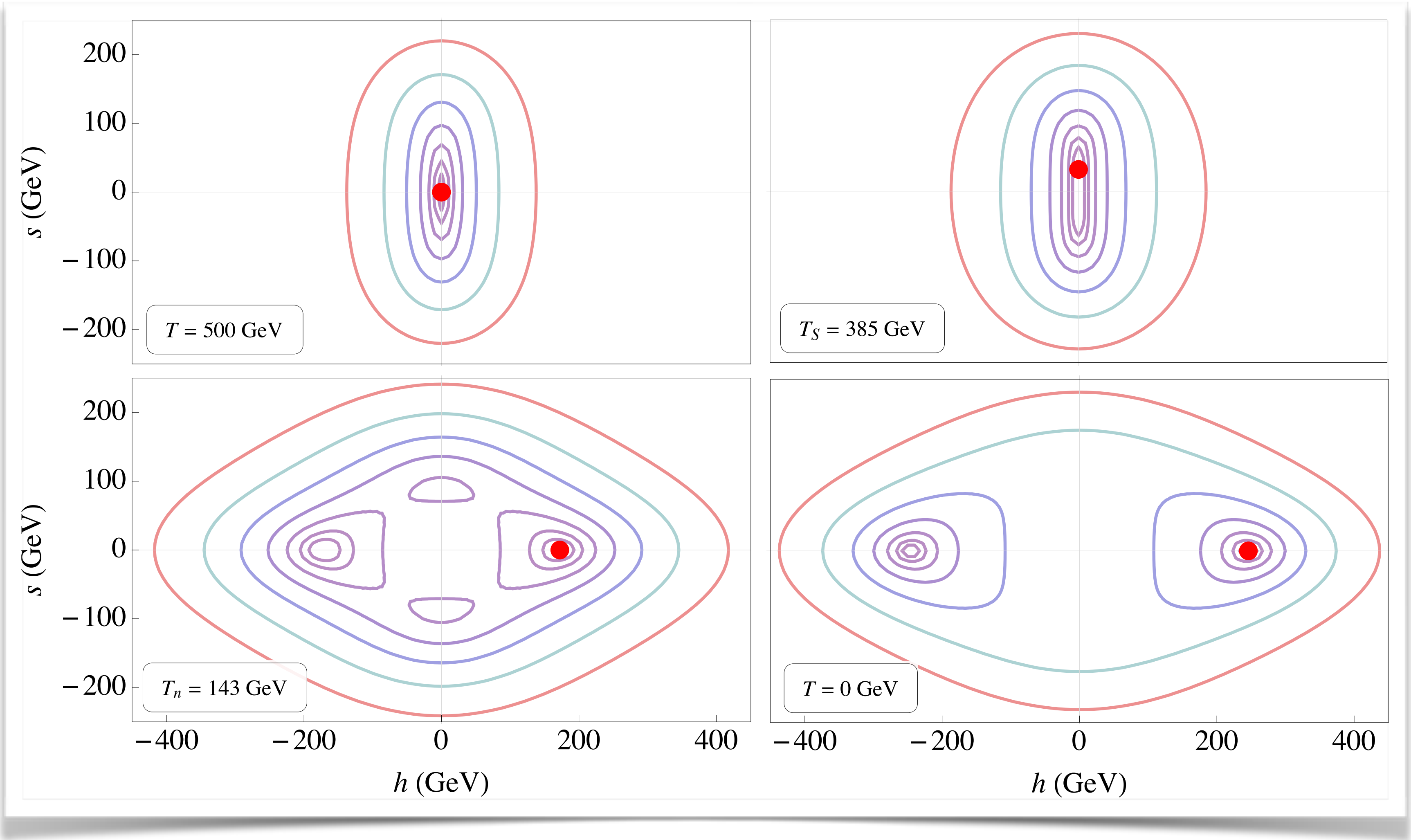
- Toy Model: SM + singlet scalar S

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

- 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 Laporte Yamashita Kraml 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

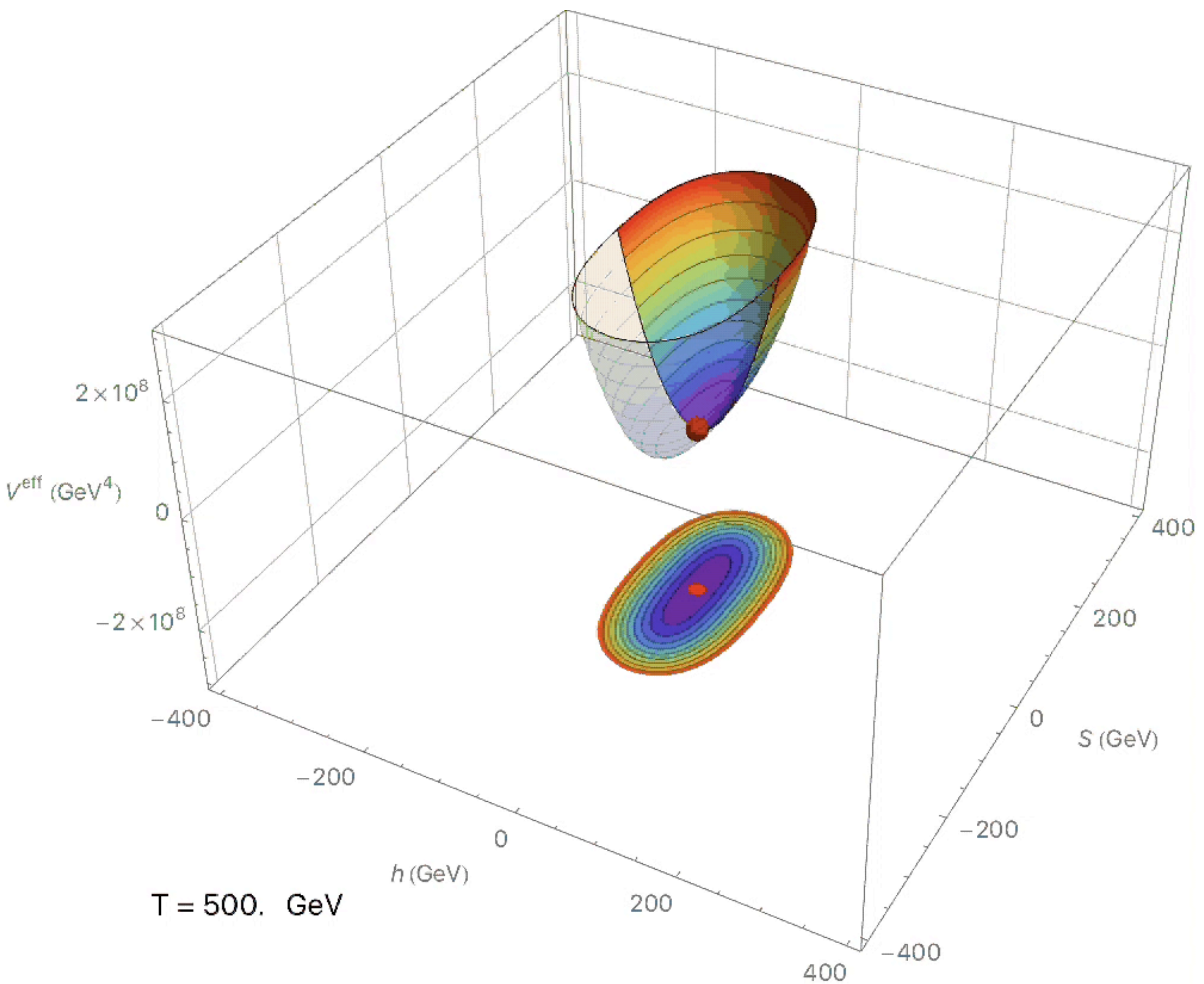
The Vev Flip-Flop



- ☑ $T > 400$ 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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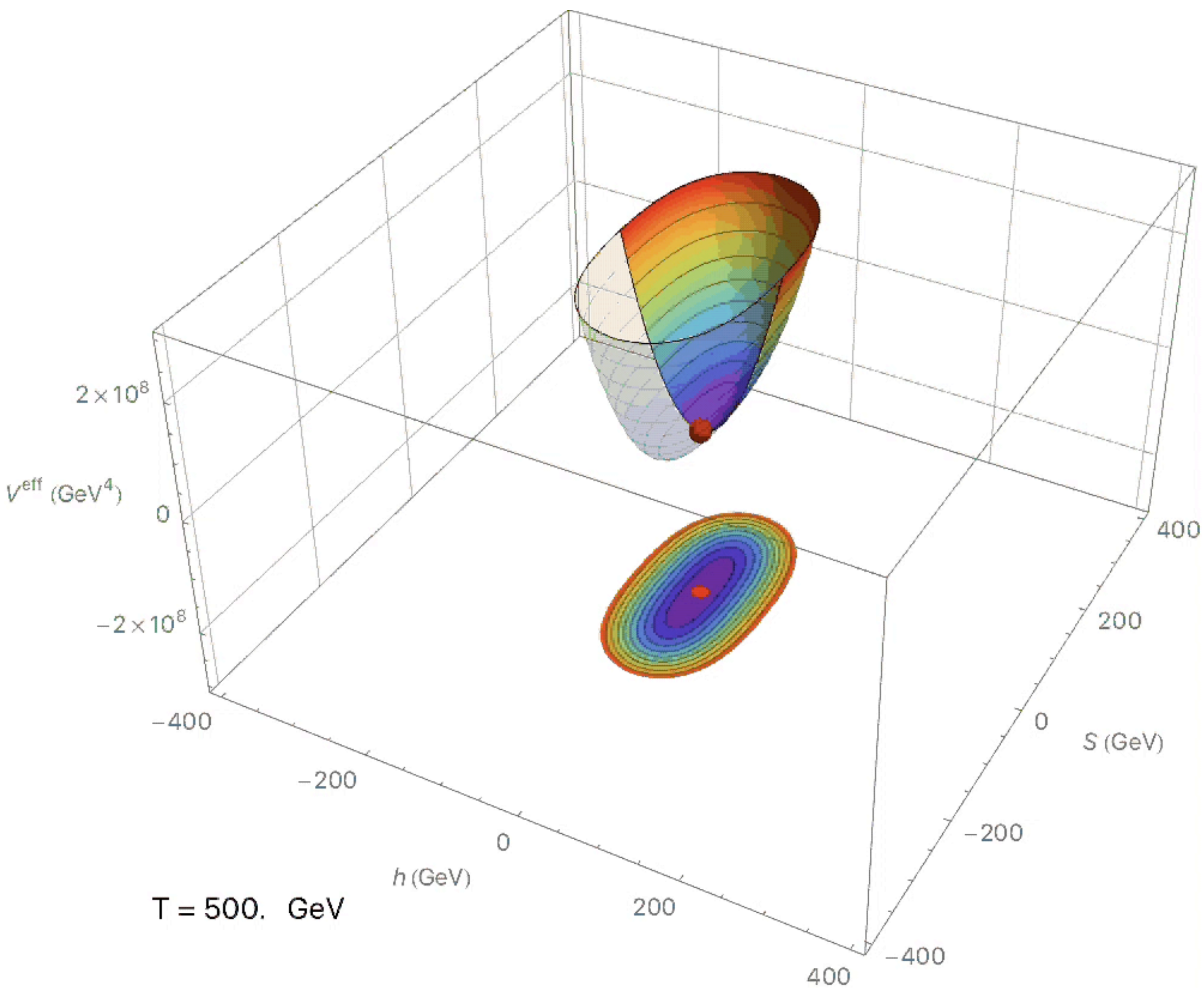

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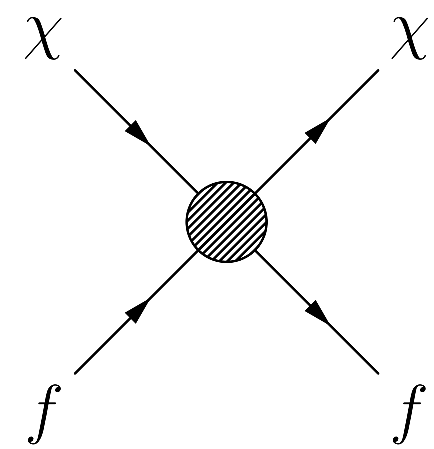
Implications 1

Dark Matter

Standard Lore: Thermal Freeze-Out

- Early on: DM in thermal equilibrium with SM

  e.g. via $\bar{\chi}\chi \longleftrightarrow \bar{f}f$



- Number density: $n_{\chi,\mathrm{eq}} = \int \frac{d^3p}{(2\pi)^3} \exp\left[-E_\chi(\vec{p})/T\right]$

- T drops, interactions freeze out

- Described by Boltzmann equation

$$\frac{dn_\chi}{dt} + 3n_\chi\frac{\dot{a}}{a} = -\Big(n_\chi^2\langle\sigma(\chi\chi\to\bar{f}f)v_{\mathrm{rel}}\rangle - n_f^2\langle\sigma(\bar{f}f\to\chi\chi)v_{\mathrm{rel}}\rangle\Big)$$

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- ☑ Detailed balance: $n_f^2\langle\sigma(\bar{f}f\to\chi\chi)v_{\rm rel}\rangle = n_{\chi,\rm eq}^2\langle\sigma(\chi\chi\to\bar{f}f)v_{\rm rel}\rangle$
- ☑ Final Boltzmann equation

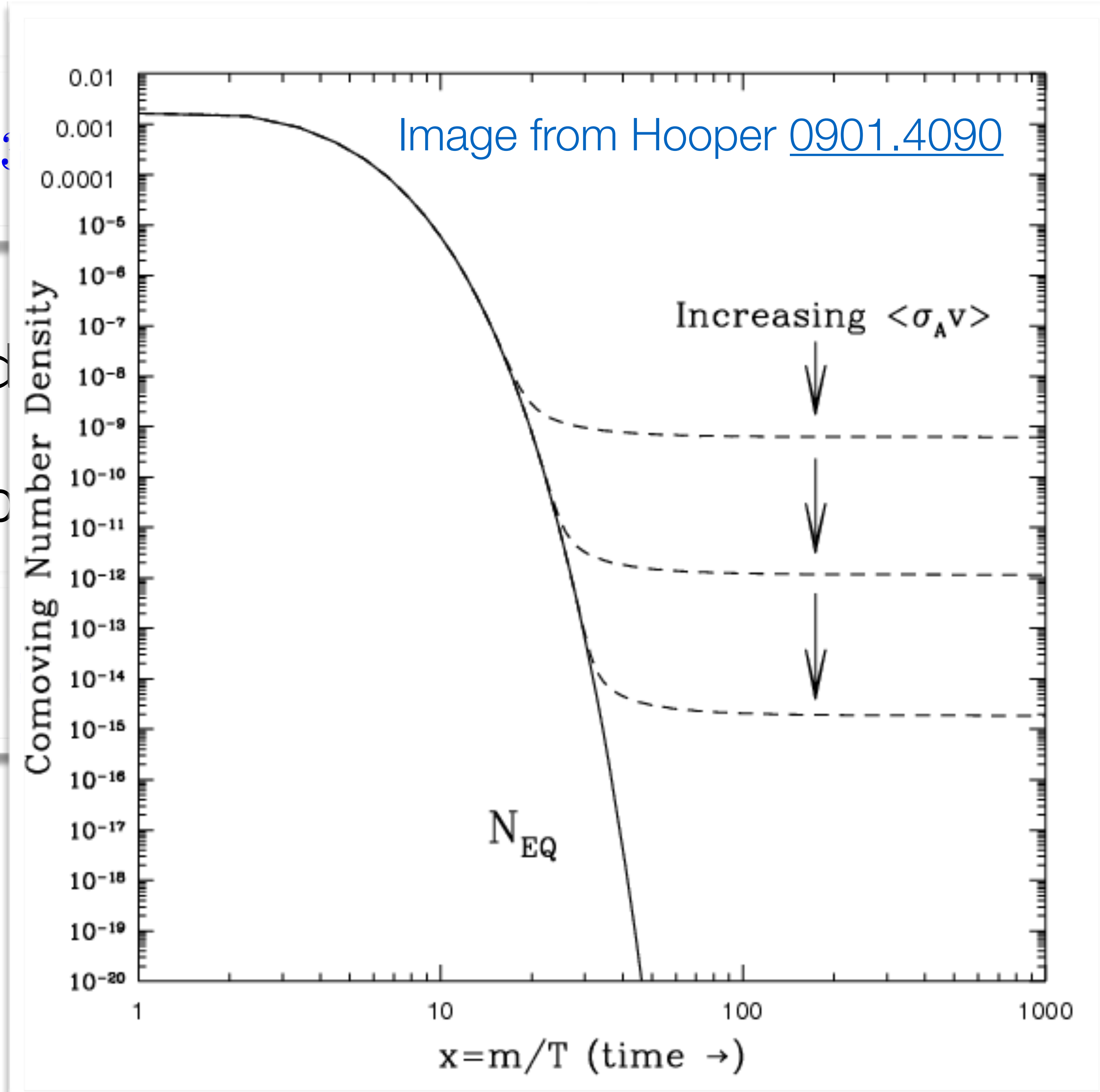
$$\frac{dn_\chi}{dt} + 3n_\chi\frac{\dot{a}}{a} = -\langle\sigma(\chi\chi\to\bar{f}f)v_{\rm rel}\rangle\big(n_\chi^2 - n_{\chi,\rm eq}^2\big)$$

Standard Lore: Thermal Freeze-Out

$\frac{dn_\chi}{dt} + 3$ … $\to \chi\chi) v_{\rm rel} \rangle \big)$

- ☑ Detailed … $\chi\chi \to \bar{f} f) v_{\rm rel} \rangle$
- ☑ Final Bo…

$\frac{dn_\chi}{dt} +$ …



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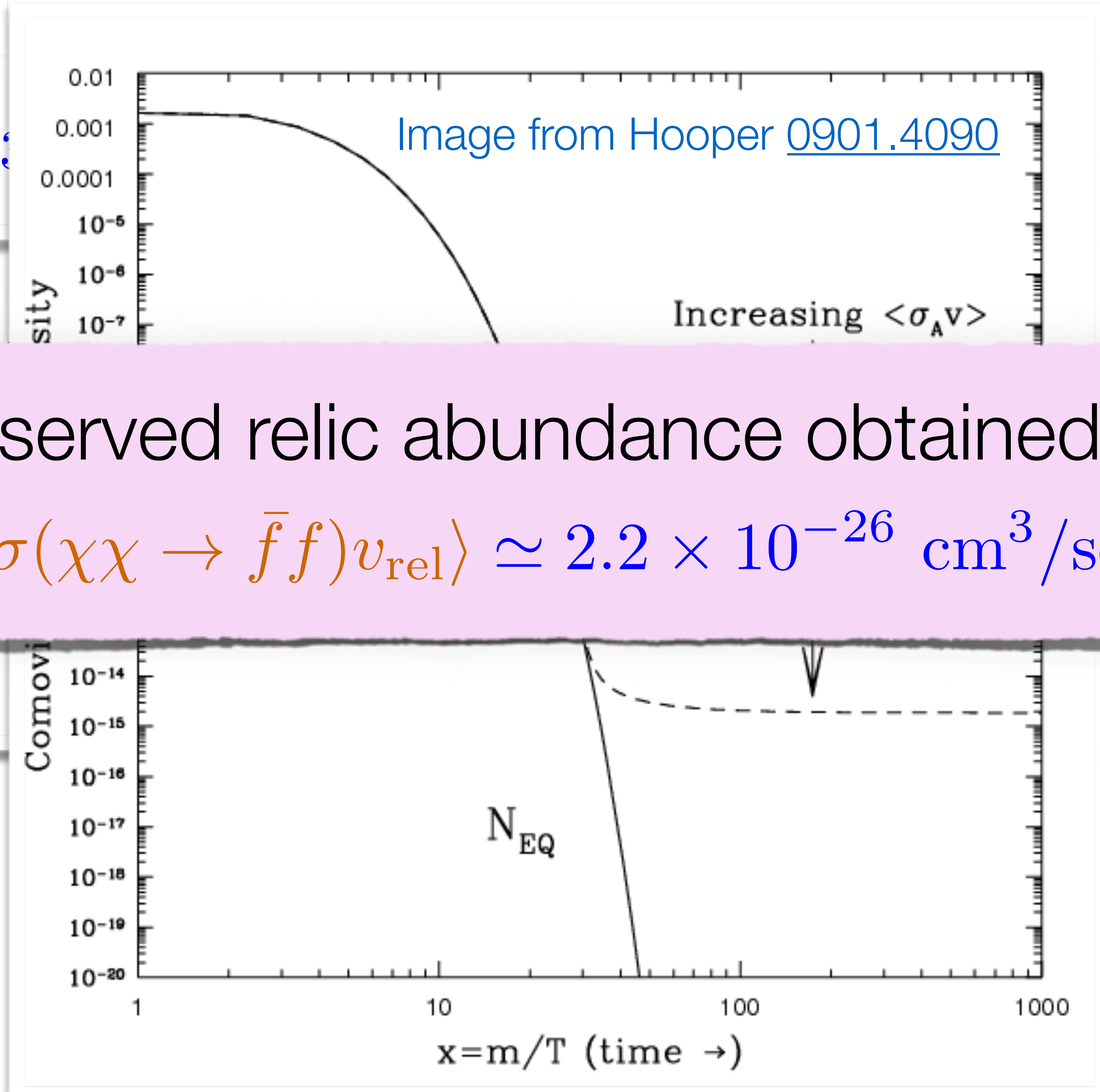

observed relic abundance obtained for

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

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- ☑ Expect new particles at ~ 100 GeV
- ☑ SM-like couplings ~ α_{em} ~ 0.01
- ☑ Expect $\langle \sigma(\chi\chi \to \bar{f}f) v_{\rm rel} \rangle \simeq \mathrm{few} \times 10^{-26}\ \mathrm{cm}^3/\mathrm{sec}$

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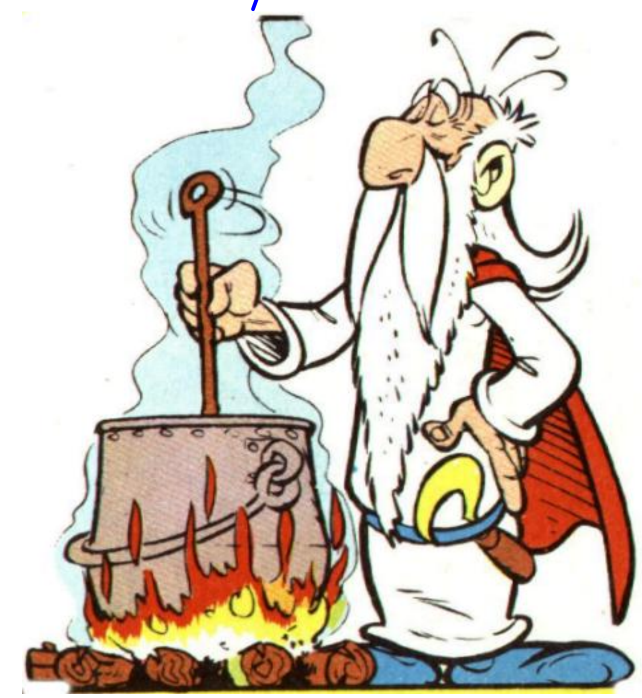
WIMP Miracle



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Problems with the Standard Scenario

- Continued absence of signals in
  - direct DM searches (DM–nucleus scattering)
  - indirect searches (cosmic rays from DM annihilation)
  - collider searches (missing energy signatures)
- No showstoppers yet, but the community is beginning to worry

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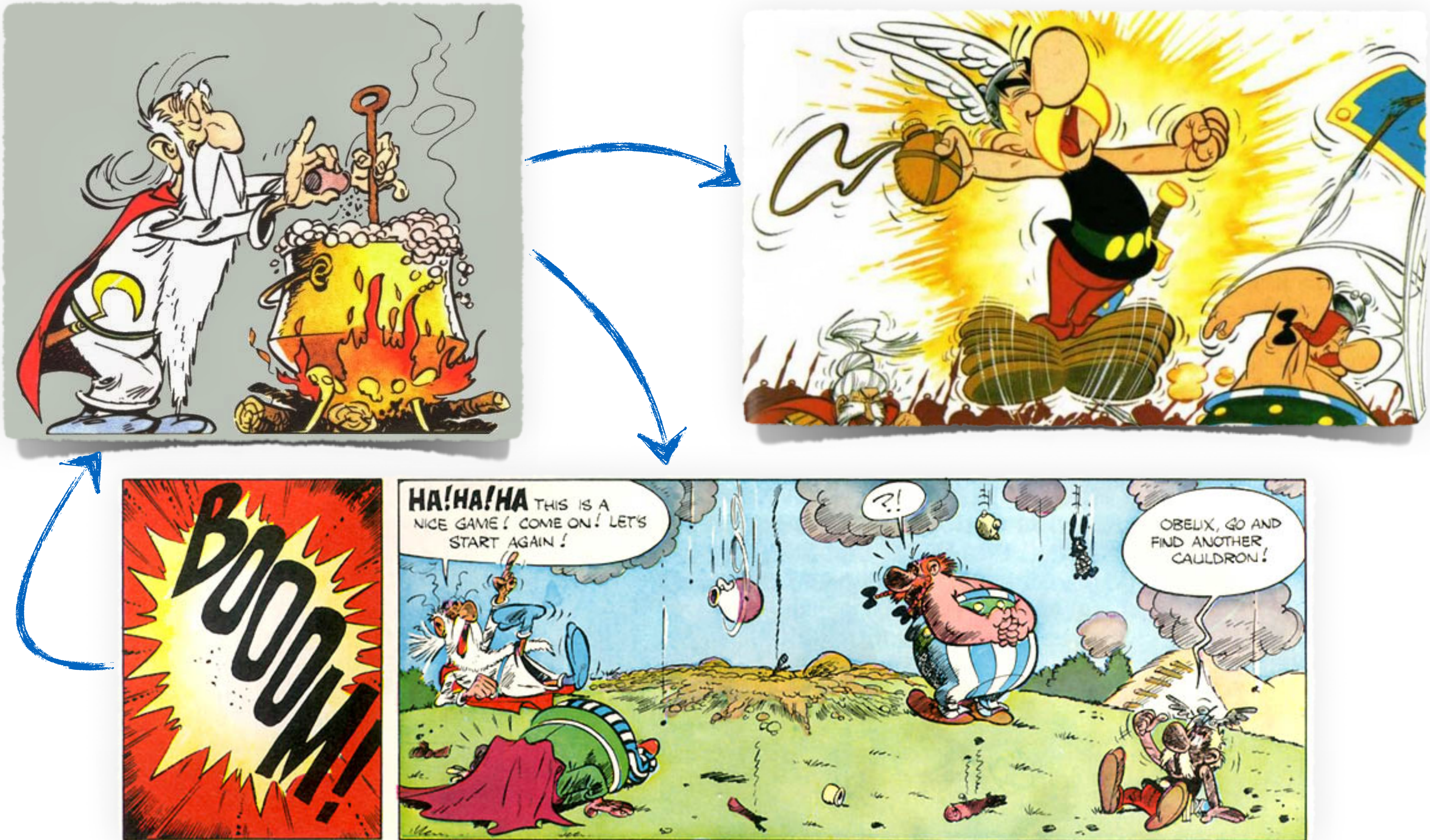
Dark Matter Model Building Flowchart



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
  - 2^{nd} phase transition restores symmetry

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

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

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new scalar

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small

➟ χ out of equilibrium

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large enough

to keep ψ in equilibrium

$\langle S\rangle$ affects ψ mass

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stabilizes DM

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r Mittnacht arXiv:1811.03101

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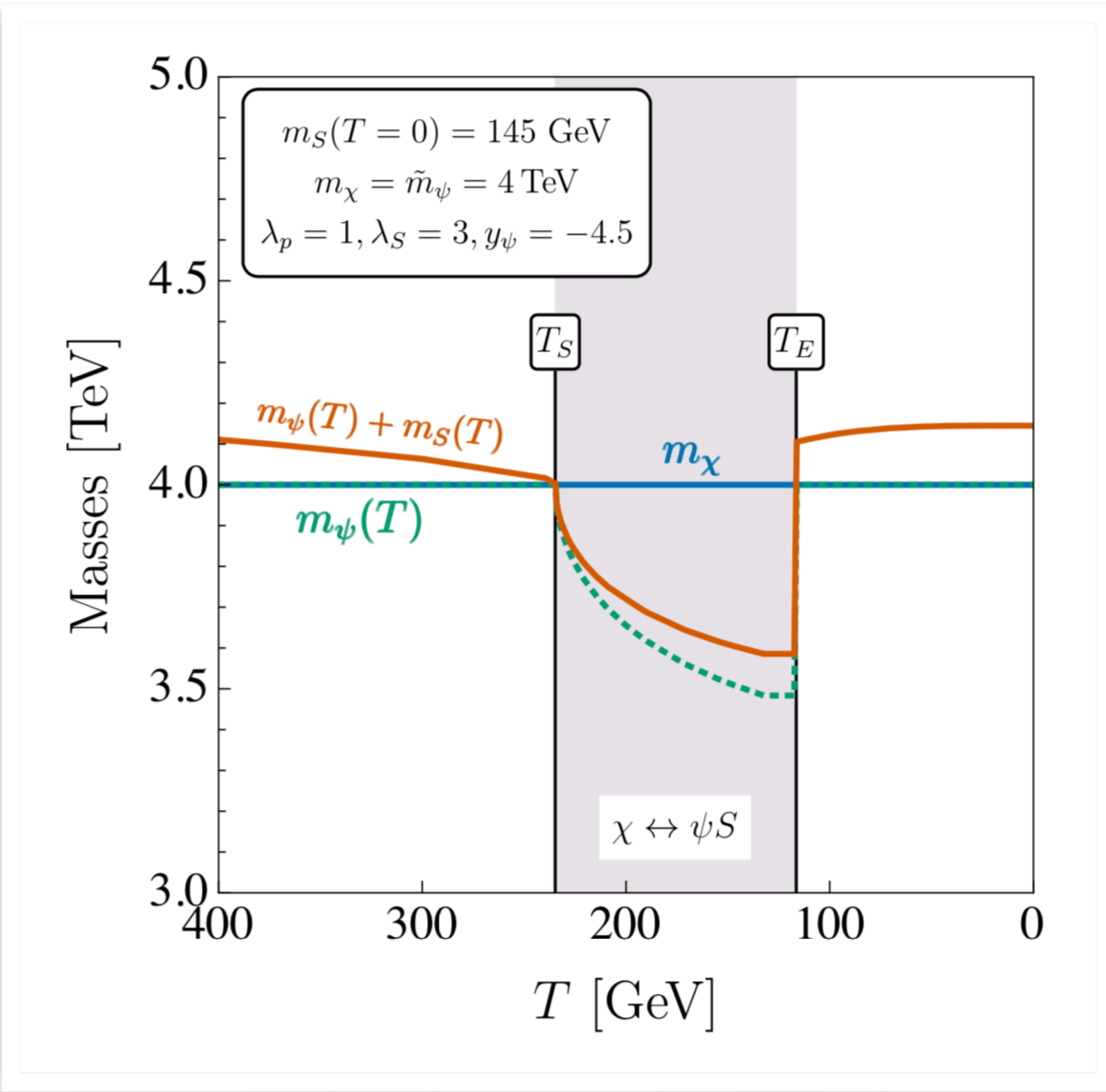
$$\mathcal{L} \supset -\left[y_{\chi\psi}\bar{\psi}S\chi + h.c.\right] - y_\chi\bar{\chi}S\chi - y_\psi\bar{\psi}S\psi$$

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

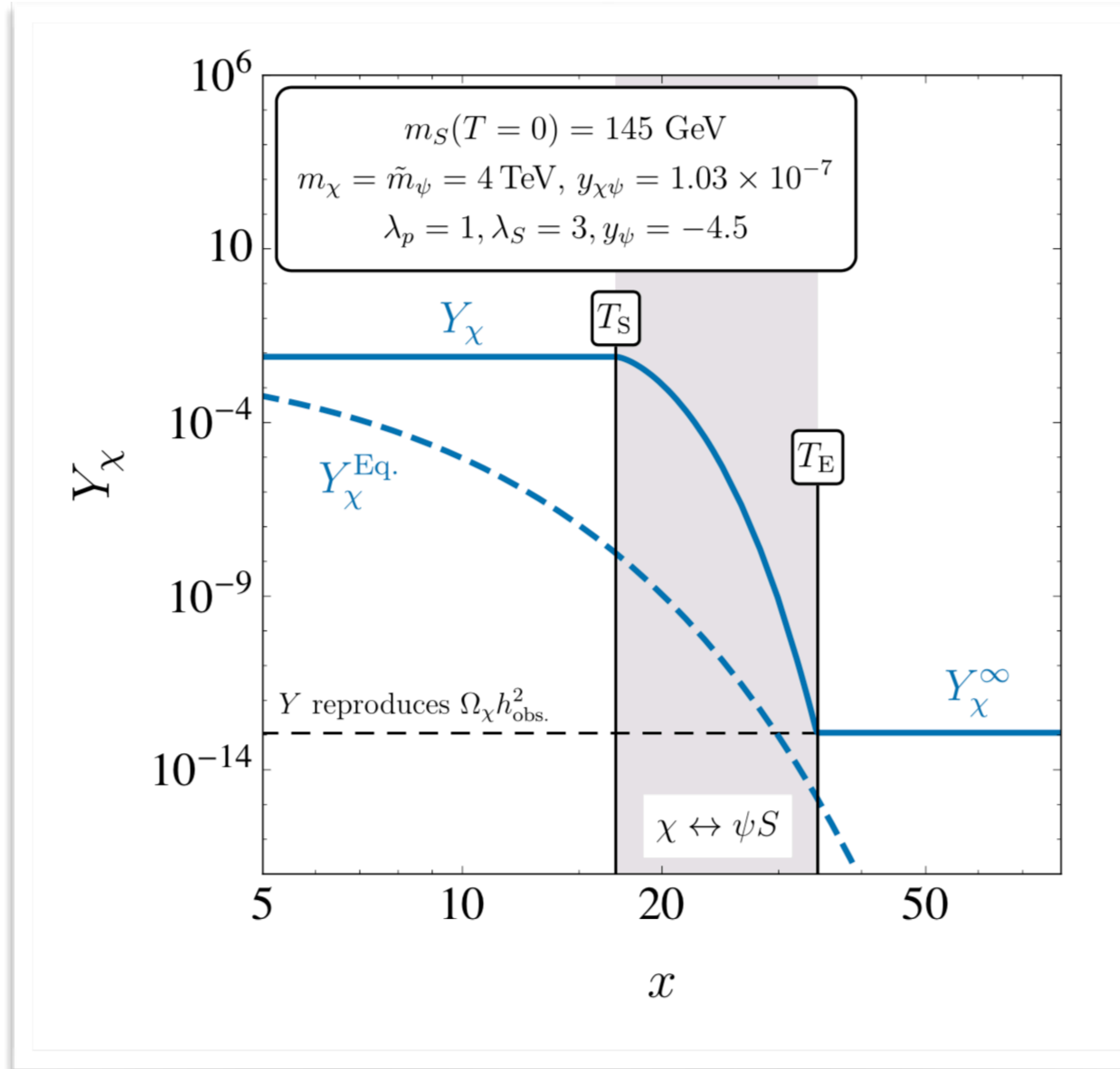
large enough
to keep ψ in equilibrium
$\langle S \rangle$ **affects ψ mass**

Cosmological Evolution

Evolution of Particle Masses



Evolution of DM Abundance



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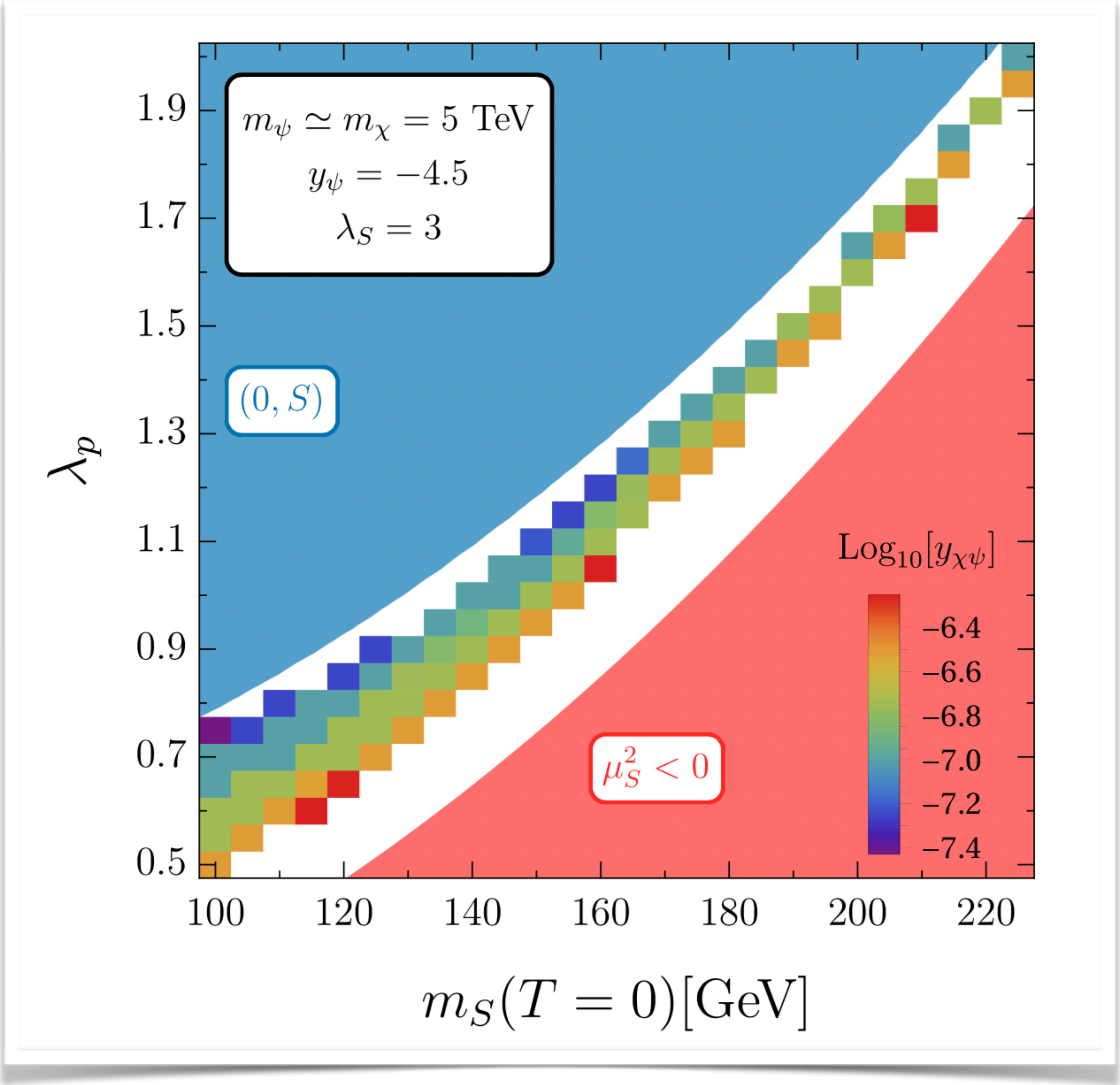
Parameter Space



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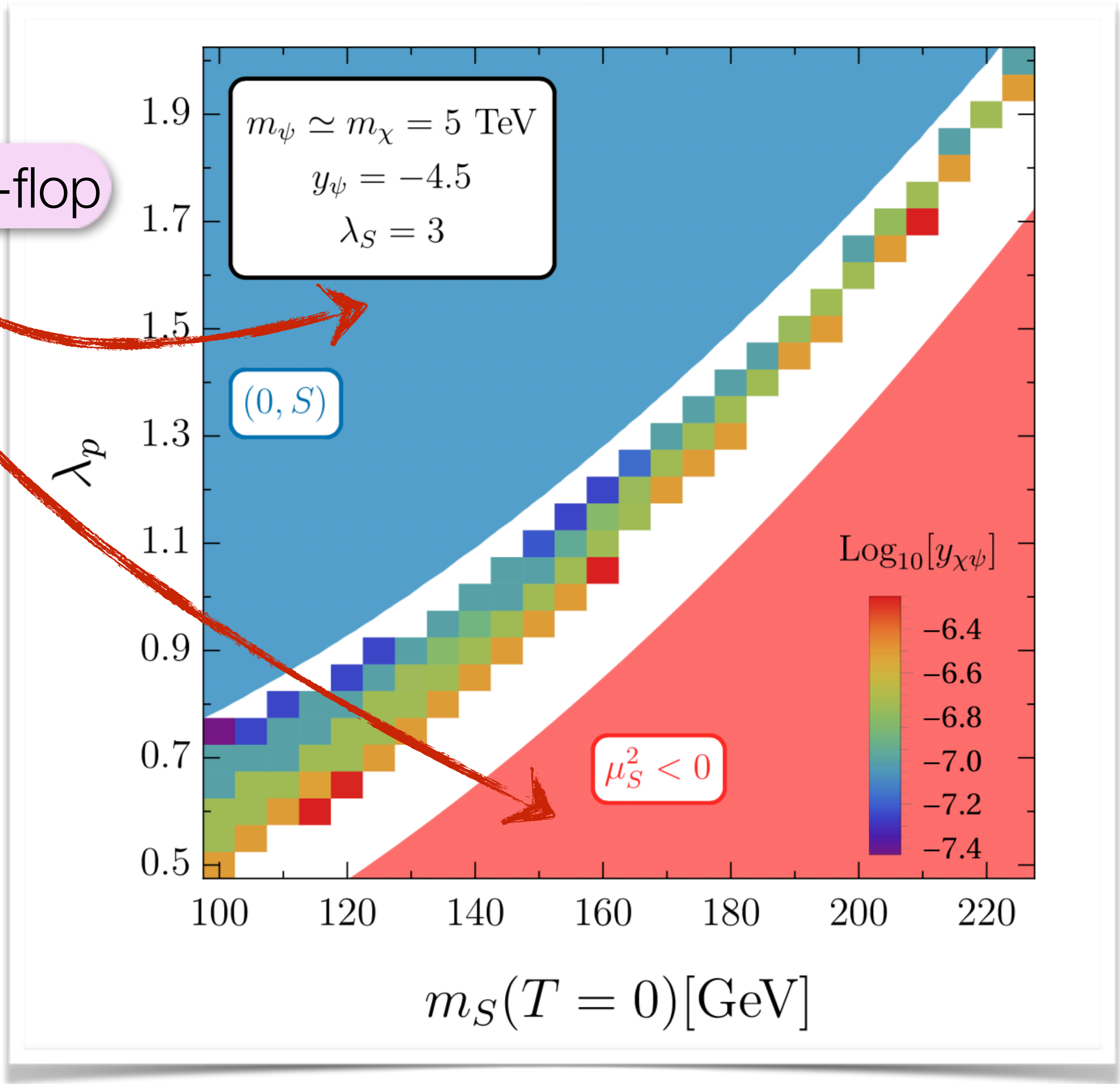
Parameter Space

no vev flip-flop

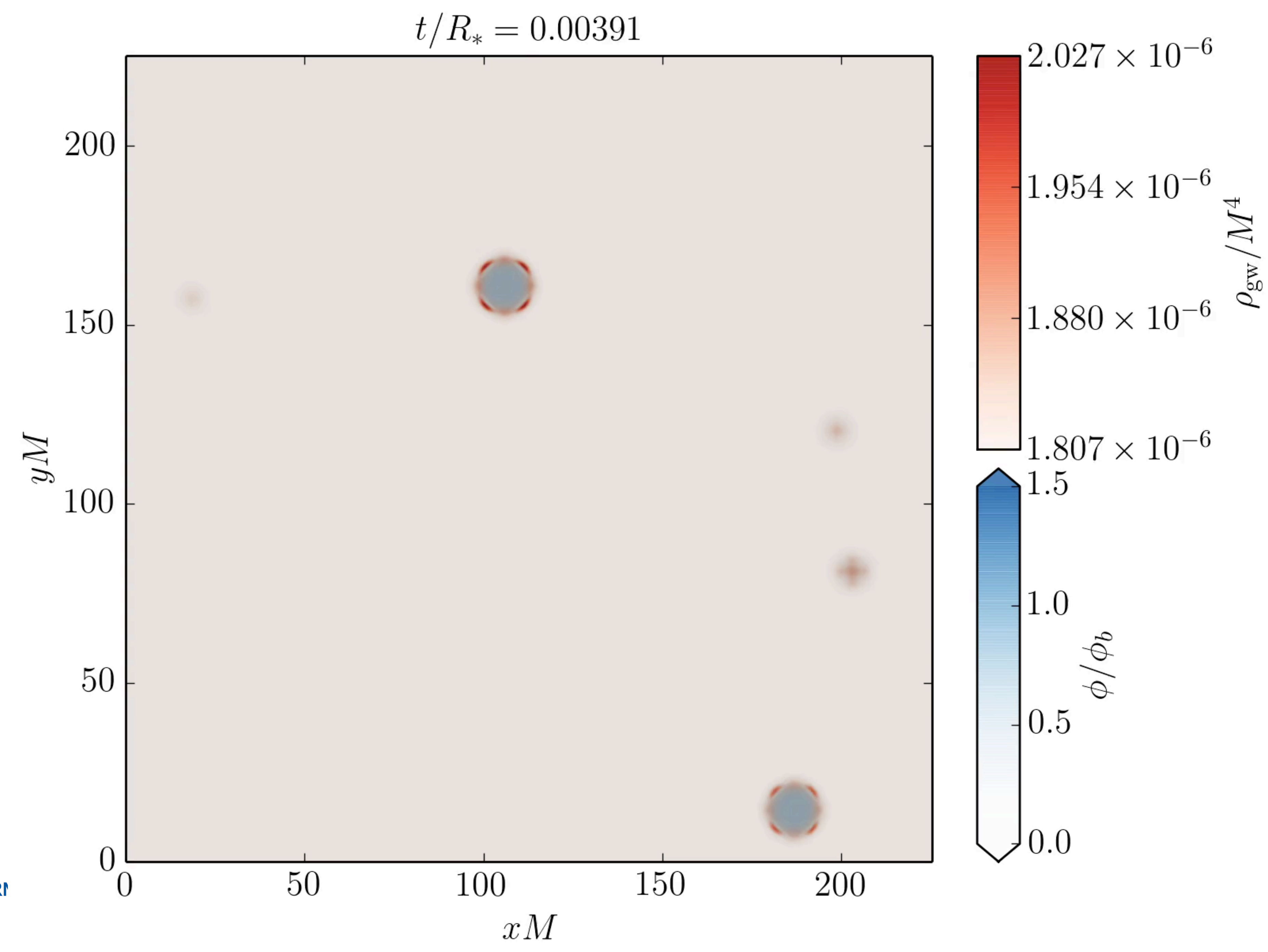


Implications 2
Gravitational Waves

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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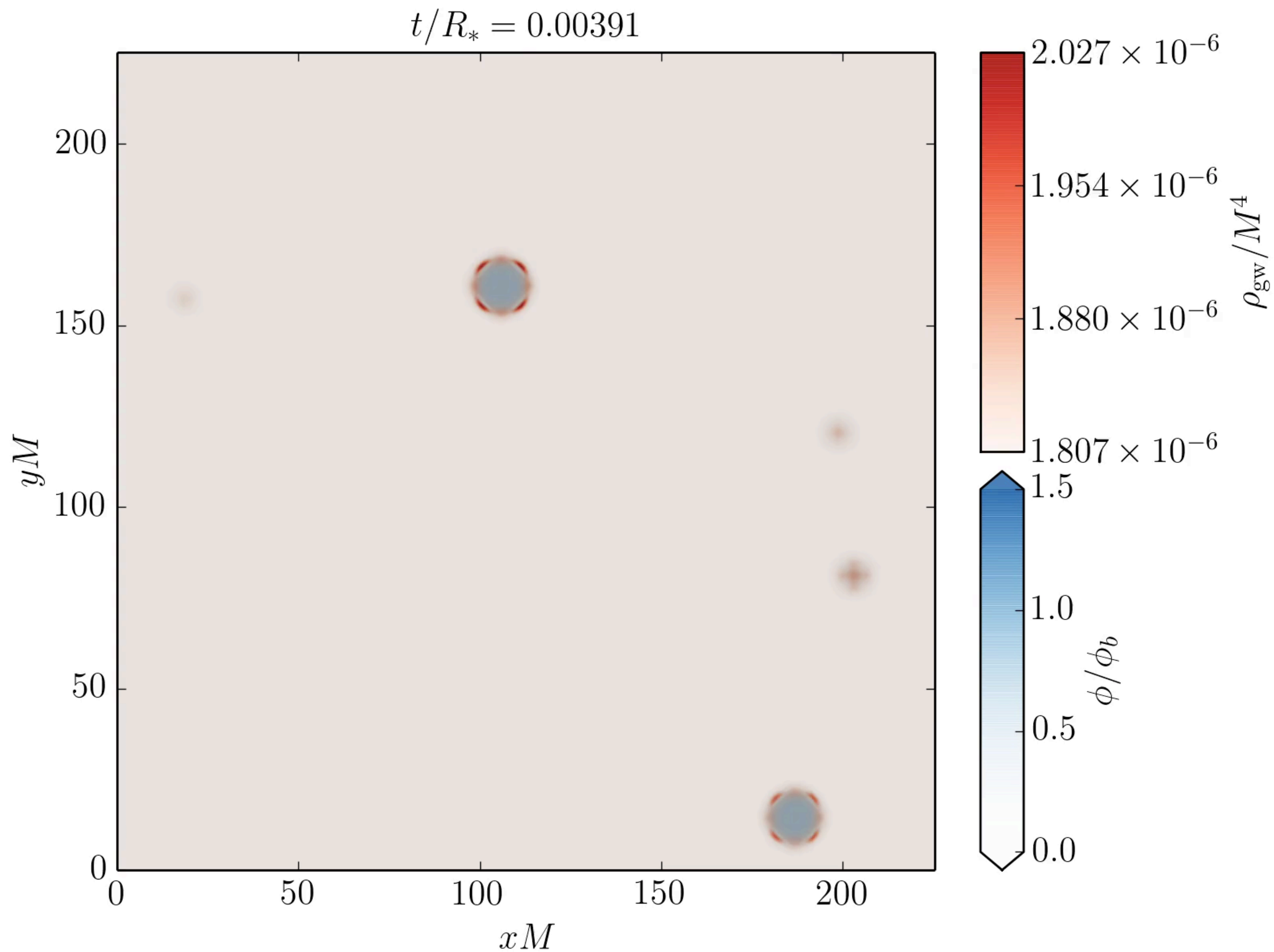
Witten 1984
Cutting Hindmarsh Weir 2018



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

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

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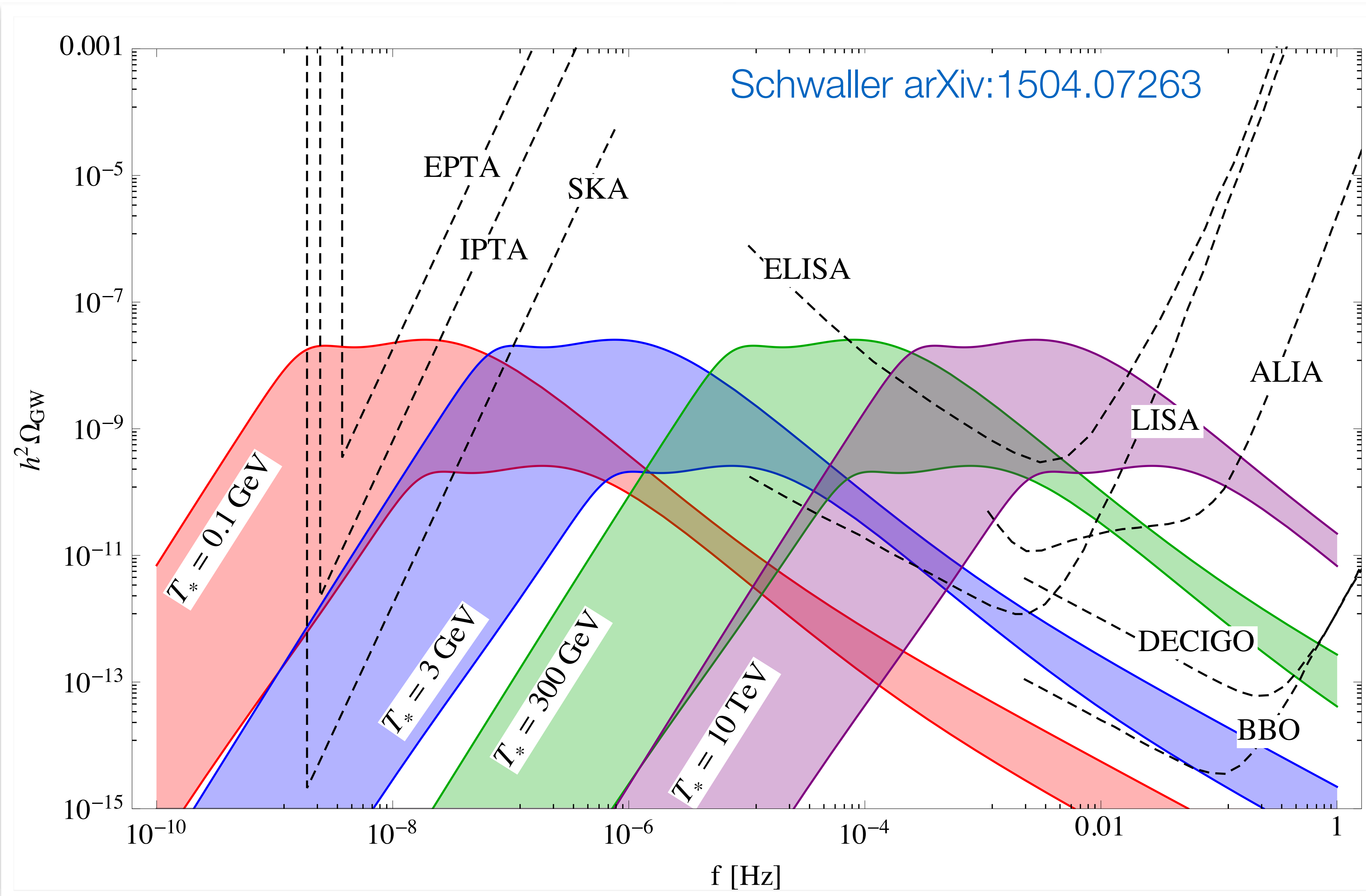
Gravitational Wave Spectra



Implications 3
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

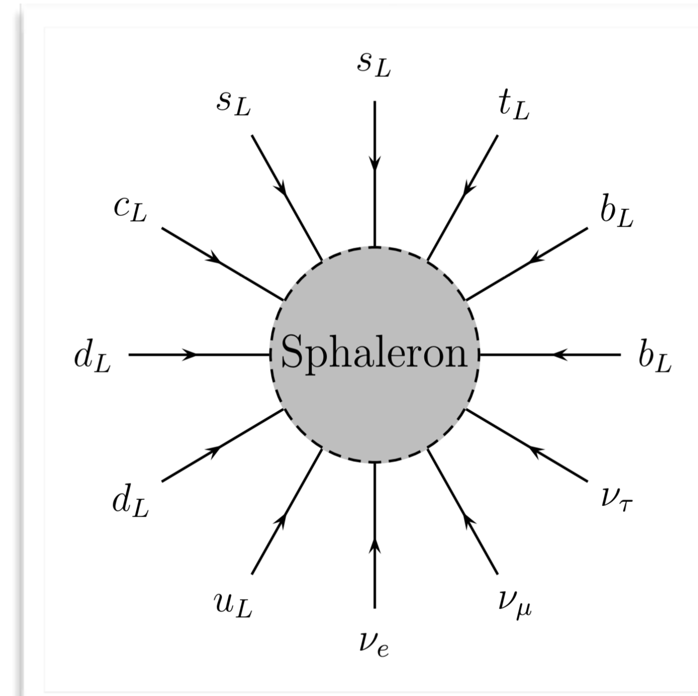


Image: Wilfried Buchmüller, hep-ph/9812447

Implications 4

Higgs Physics at Colliders

Connections to Higgs Physics at Colliders

- ☑ Early Universe phase transitions often controlled by scalar fields
- ☑ 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)
  - Higgs total width
  - 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 affect dark matter abundance
- ☑ may be observable using gravitational waves
- ☑ may be responsible for the particle–antiparticle asymmetry of the Universe
- ☑ can be searched for indirectly by looking for an extended scalar sector

Thank you!

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