
First-Order Cosmological Phase Transitions

Michael J. Baker

University of Massachusetts, Amherst

PASCOS 2025
25 July



- Cosmological Phase Transitions
- Filtered Dark Matter
- Primordial Black Hole Production



Cosmological Phase Transitions

Cosmological phase transition

🌐 1 language ▾

Article [Talk](#)

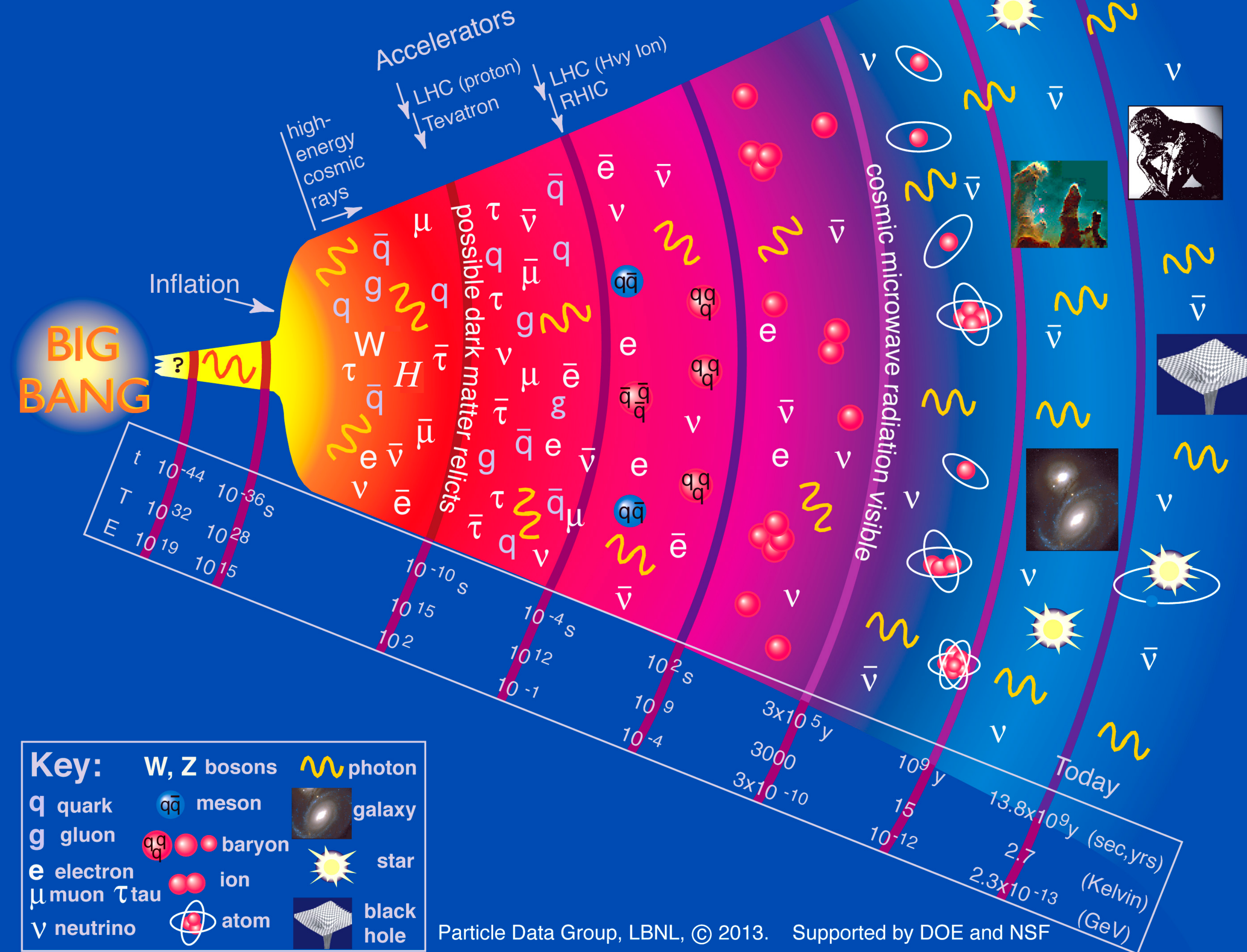
Read [Edit](#) [View history](#) [Tools](#) ▾

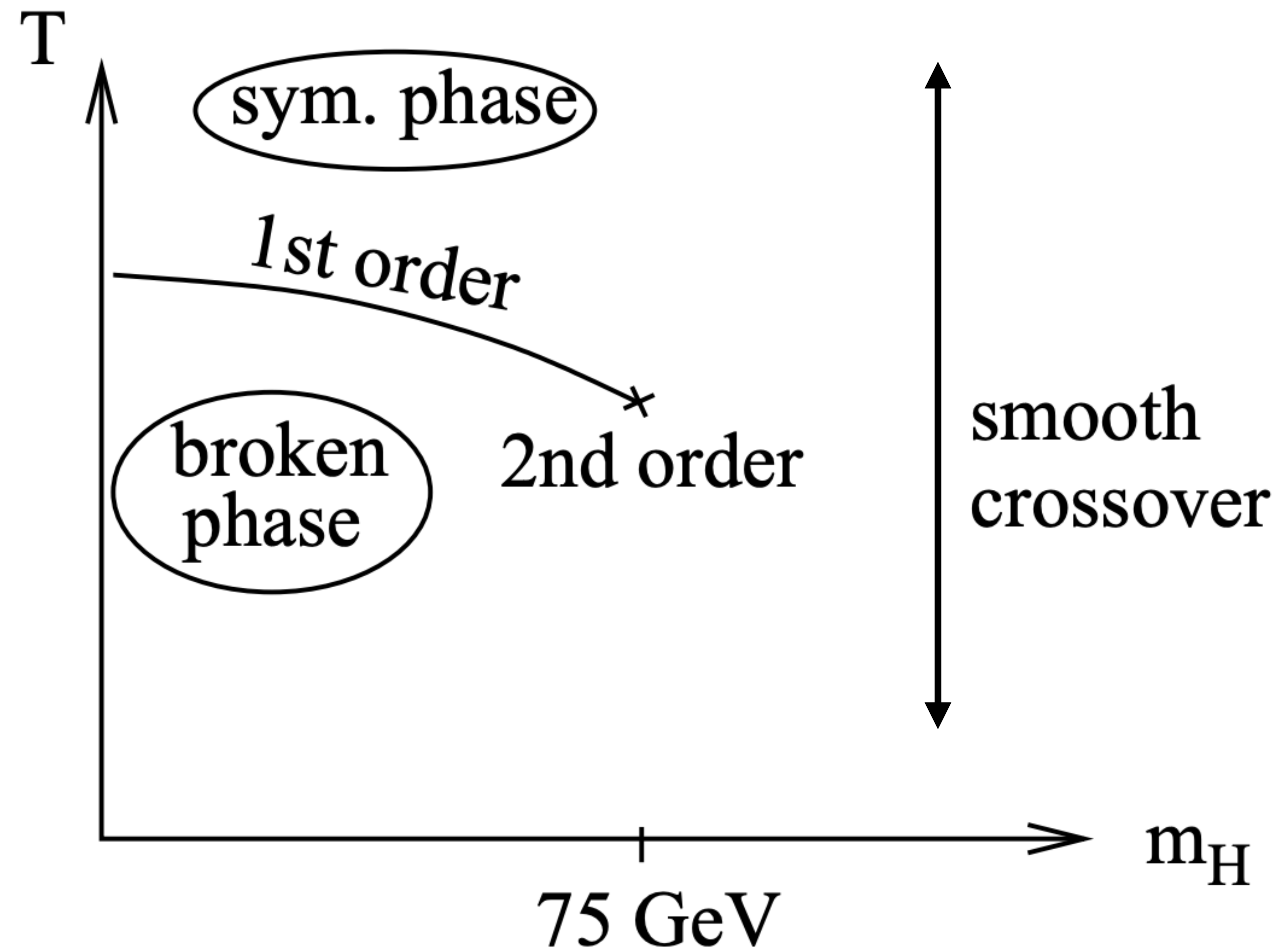
From Wikipedia, the free encyclopedia

A **cosmological phase transition** is an overall change in the [state of matter](#) across the whole universe. The success of the [Big Bang](#) model led researchers to conjecture possible cosmological phase transitions taking place in the very early universe, at a time when it was much hotter and denser than today.^{[1][2]}

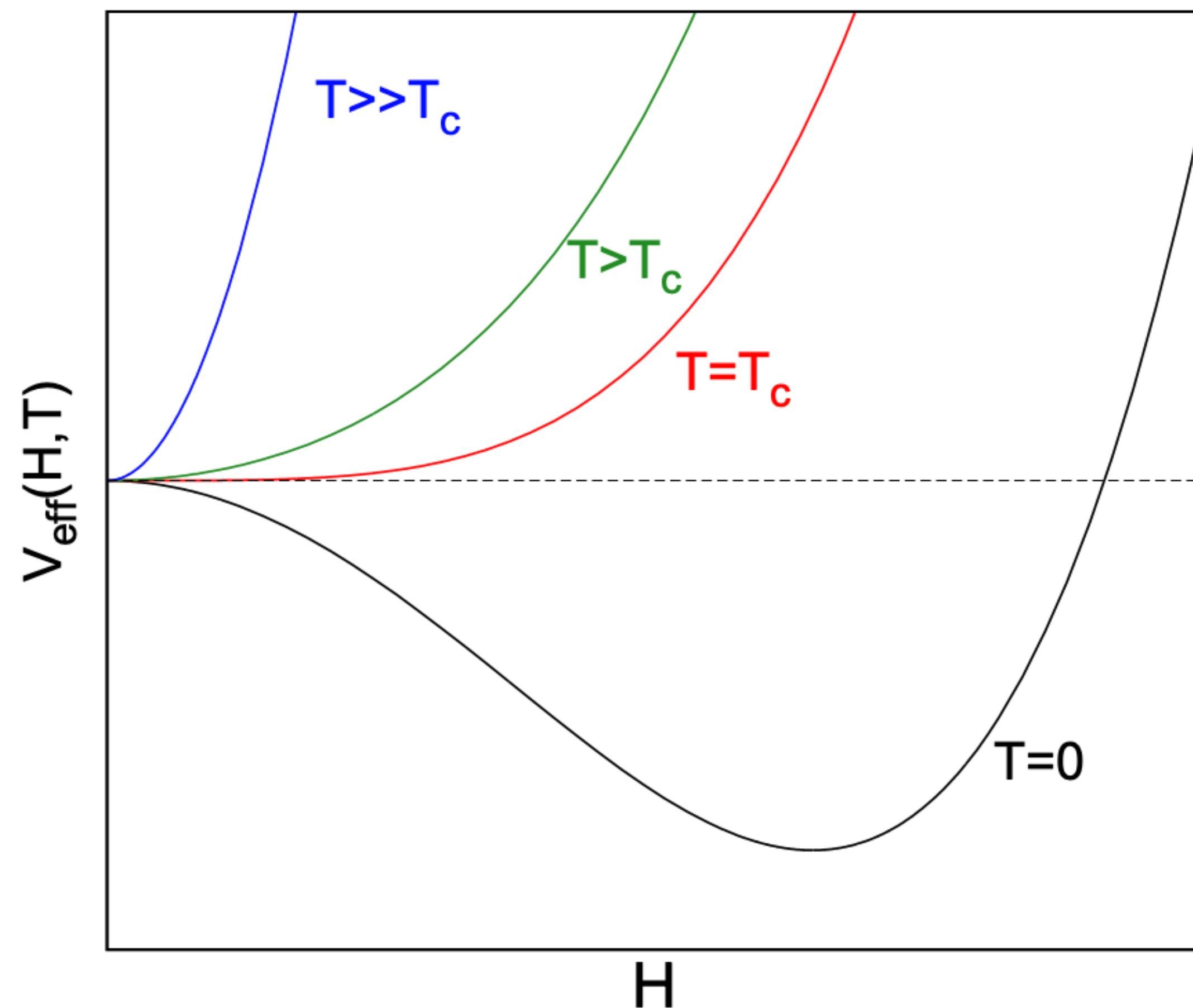
Any cosmological phase transition may have left signals which are observable today, even if it took place in the first moments after the Big Bang, when the universe was [opaque to light](#).^[3]

History of the Universe

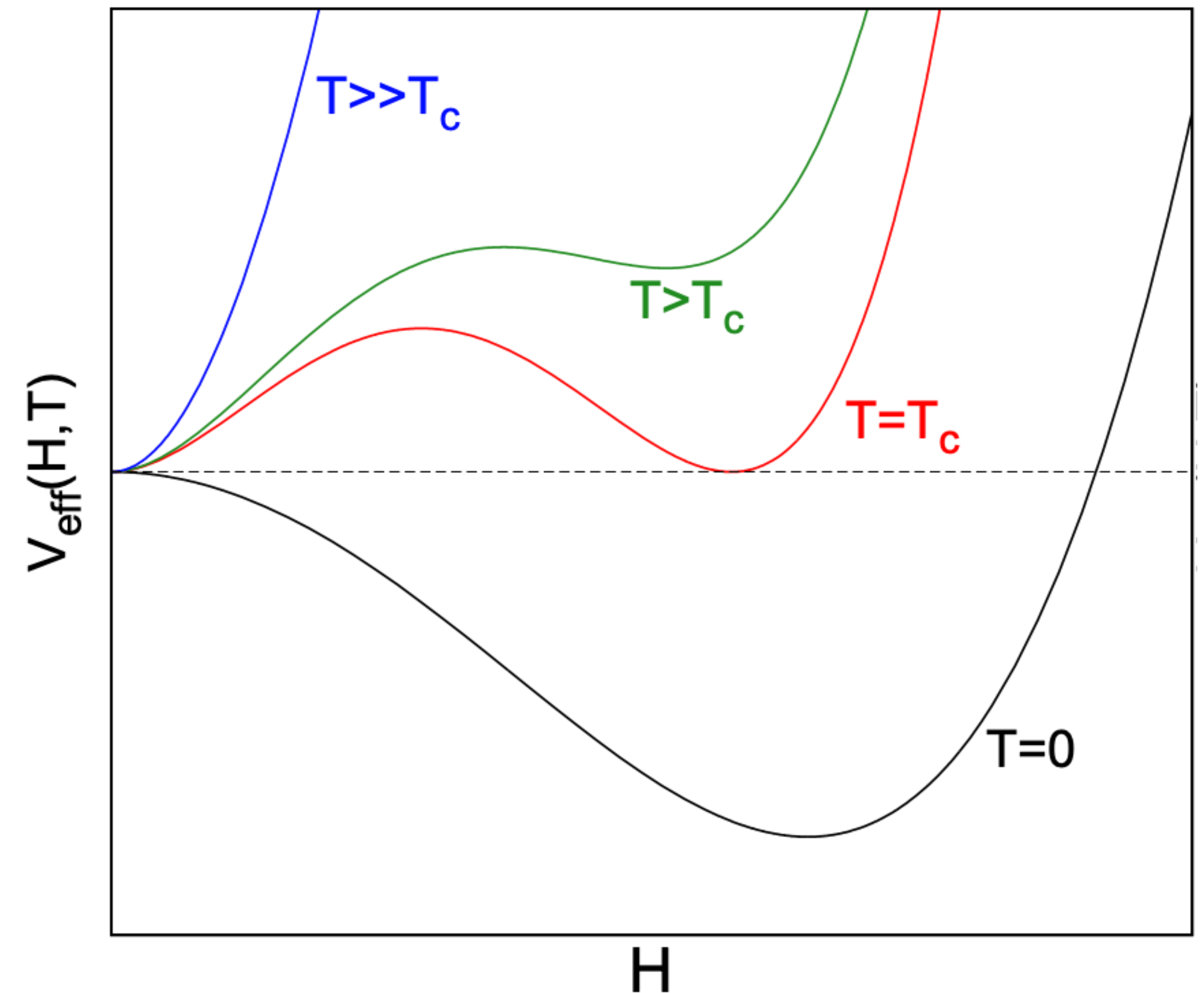




Second-Order Phase Transition and Crossover

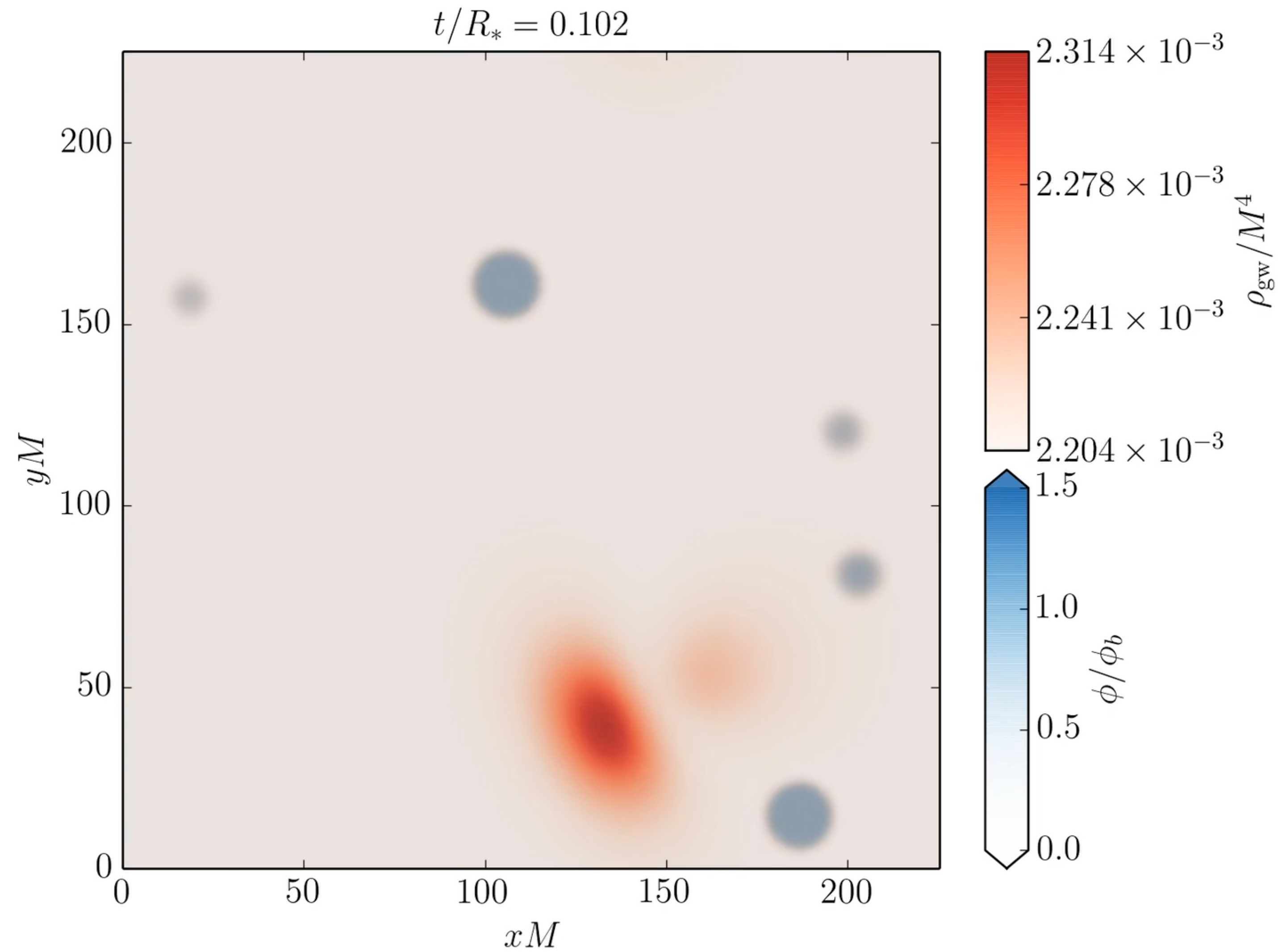


First-Order Phase Transition

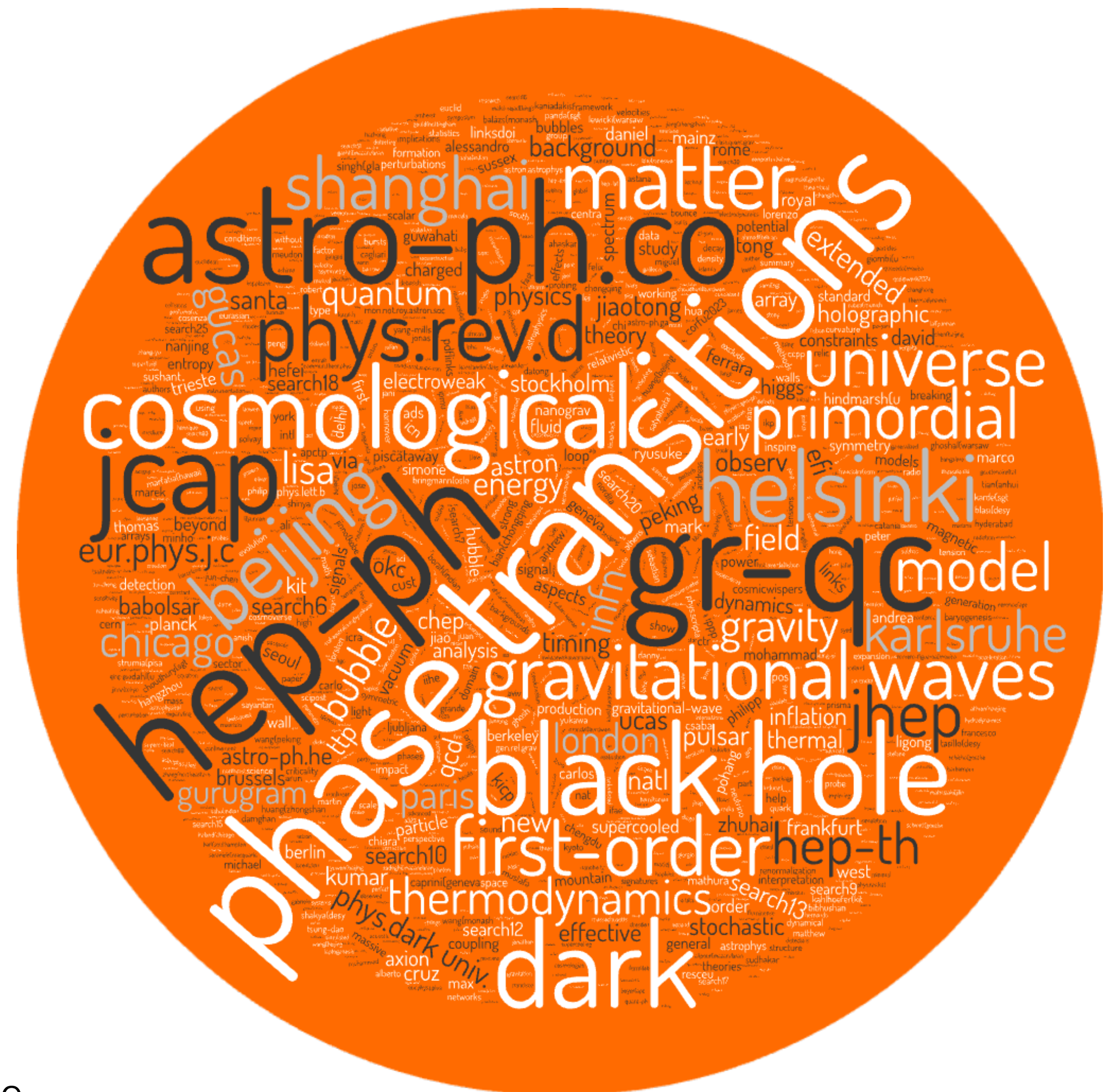
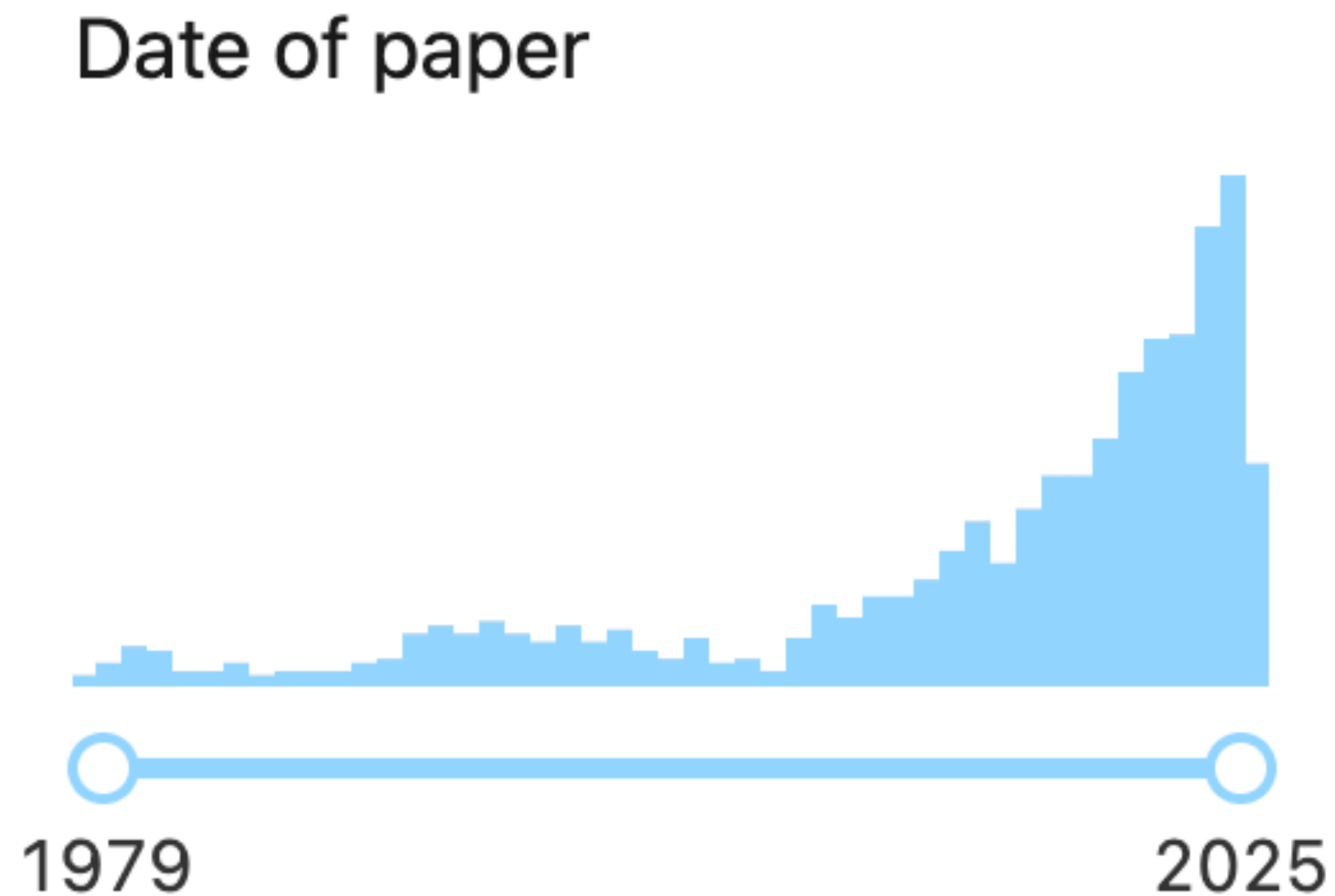




Cosmological Phase Transitions



<https://vimeo.com/255031420> - Cosmic Defects - Gravitational waves from a cosmological vacuum phase transition - scalar field value



Cause

- Scalar vev
 - EWPT
 - MSSM
 - THDM
 - New light scalars
 - Dark sectors, ...
- Confinement
 - QCD
 - Composite Higgs
 - Dark sectors, ...

Calculation

- Temperature
- Latent heat release
- Bubble nucleation rate
- Bubble wall speed
- Finite T approximations
- Lattice computations
- Wall speed
- Gauge invariance, ...

Effect

- EW baryogenesis
- Gravitational waves
- Dark matter production
- PBH production
- Primordial magnetic fields
- Topological defects, ...

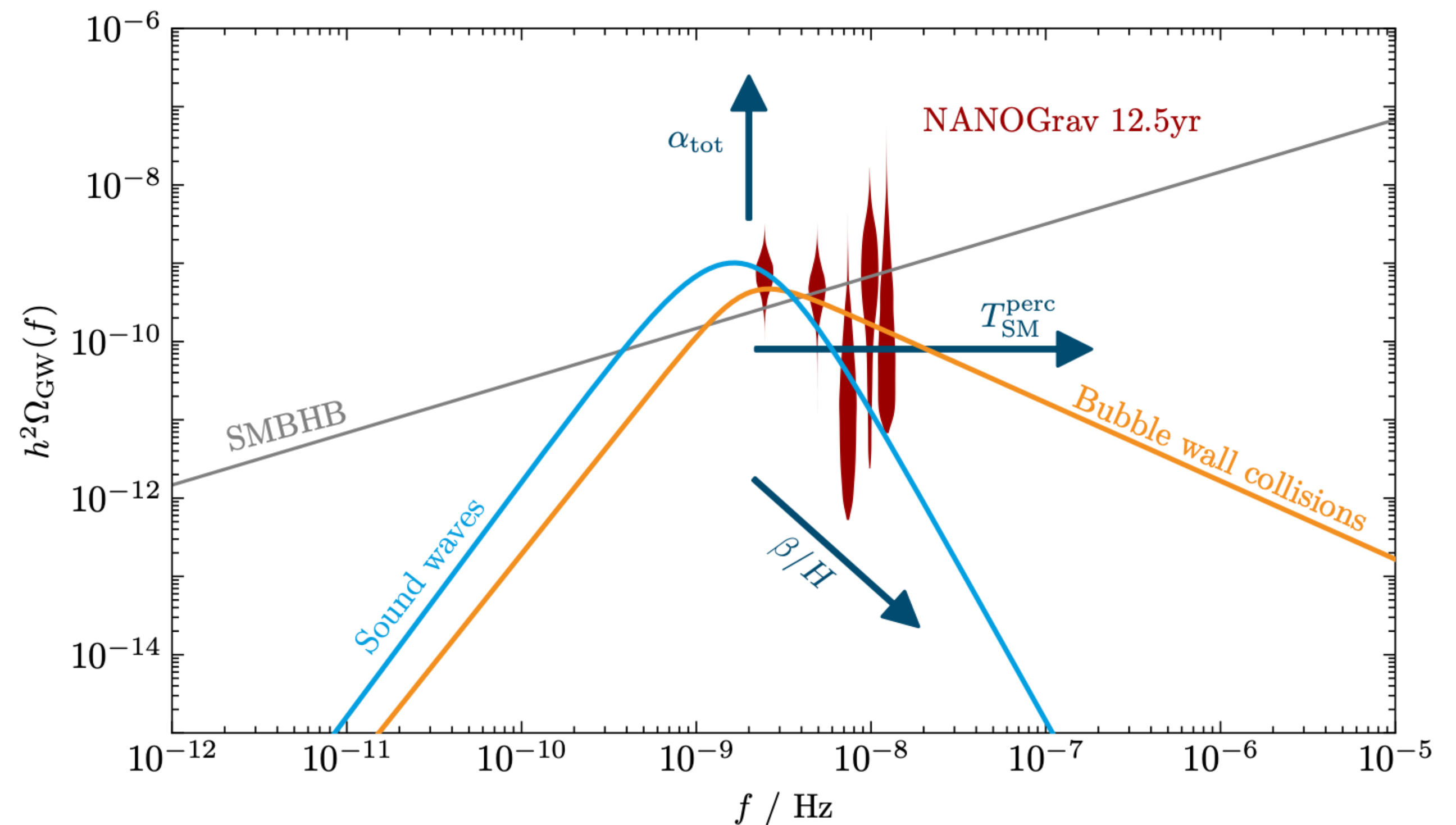
Evidence:

We have no direct evidence for the electroweak, QCD or any BSM phase transitions

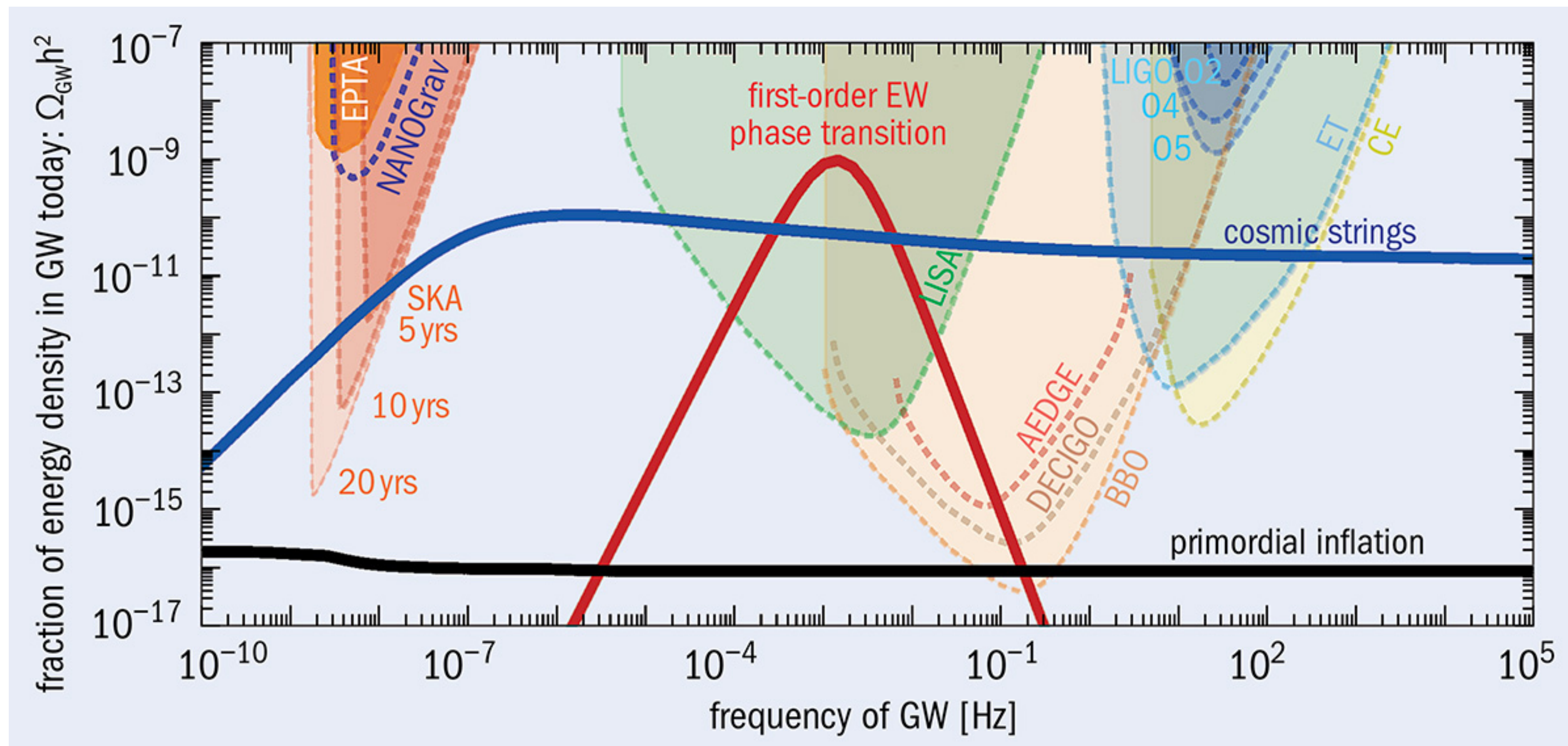
Theoretical expectation that the electroweak and QCD phase transitions occurred

NANOGrav has
detected a stochastic
gravitational wave
background,

which could come from
many possible sources



But different origins have different signals, and upcoming and proposed experiments will probe a wide variety of possibilities



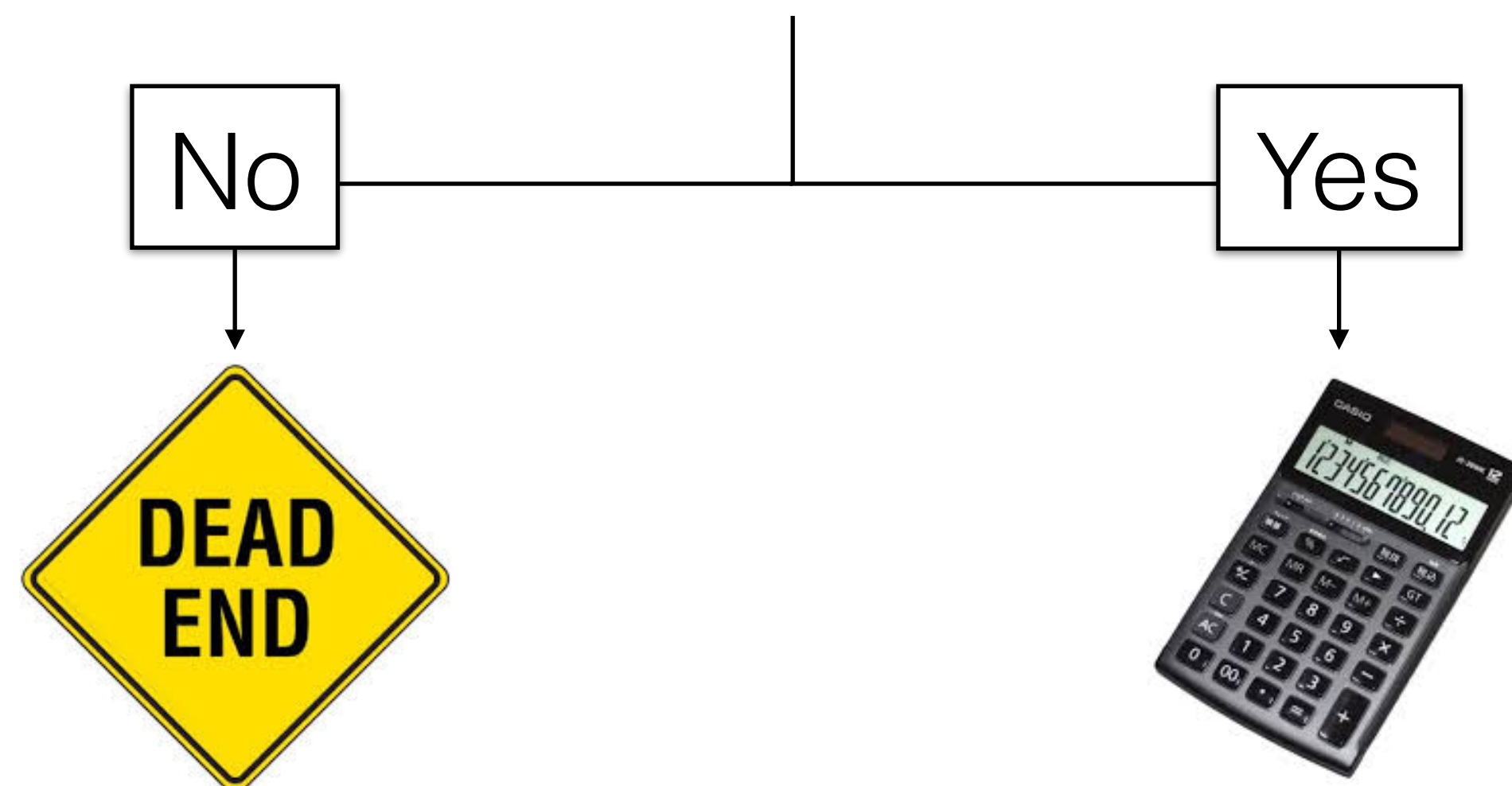


Filtered Dark Matter

Dark Matter is

- Stable
- Cold
- Dark
- Not part of the Standard Model
- Abundance known to 2% accuracy
 - DM density $\sim 5 \times$ baryonic density

Non-gravitational DM-SM interaction?



- Favoured production mechanism (thermal freeze-out) has not been seen, despite massive effort with DD, ID and colliders
- Griest-Kamionkowski bound

$$\Omega_{\text{DM}} h^2 \stackrel{\text{f.o.}}{\sim} \frac{1}{\langle \sigma v \rangle} \stackrel{\text{p.w.}}{\gtrsim} \frac{1}{\left(\frac{4\pi}{m_{\text{DM}}^2 v_{\text{rel}}} \right)} \implies m_{\text{DM}} \lesssim 300 \text{ TeV}$$

- We present a new mechanism which has a large viable parameter space and goes beyond the GK bound

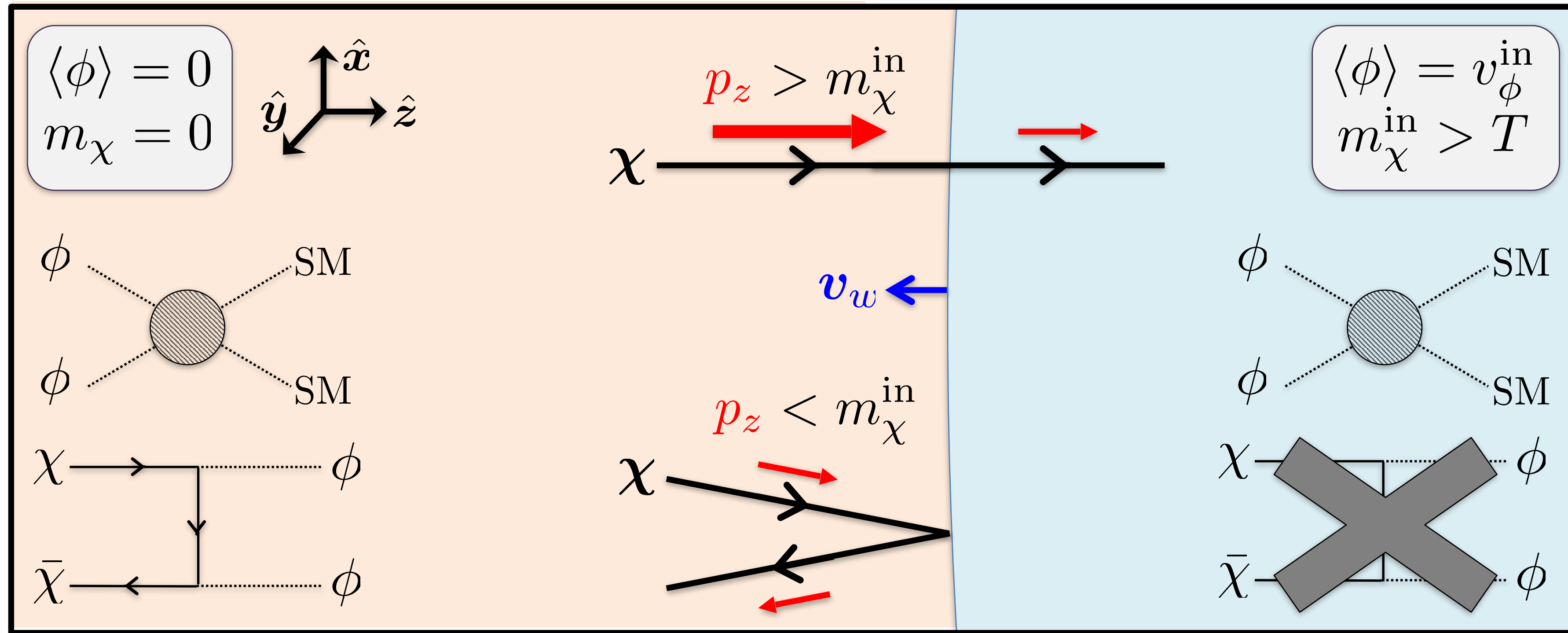
1912.02830 (PRL) - MJB, J. Kopp, A. Long

2112.08987 (JHEP) - MJB, M. Breitbach, J. Kopp, L. Mitnacht, Y. Soreq

$$\mathcal{L} \supset -y_\chi \phi \bar{\chi} \chi - \beta \phi^2 H^\dagger H - V(\phi)$$

Assume potential gives first-order phase transition
with large order parameter $\langle \phi \rangle \gtrsim T$

$$-y_\chi \phi \bar{\chi} \chi \xrightarrow{\text{PT}} -y_\chi \langle \phi \rangle \bar{\chi} \chi = -m_\chi \bar{\chi} \chi$$



In massless phase, DM in thermal equilibrium, orders of magnitude too much DM

Only high momentum DM pass through bubble wall and survive, reduces abundance

Numerically solve Boltzmann equation

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

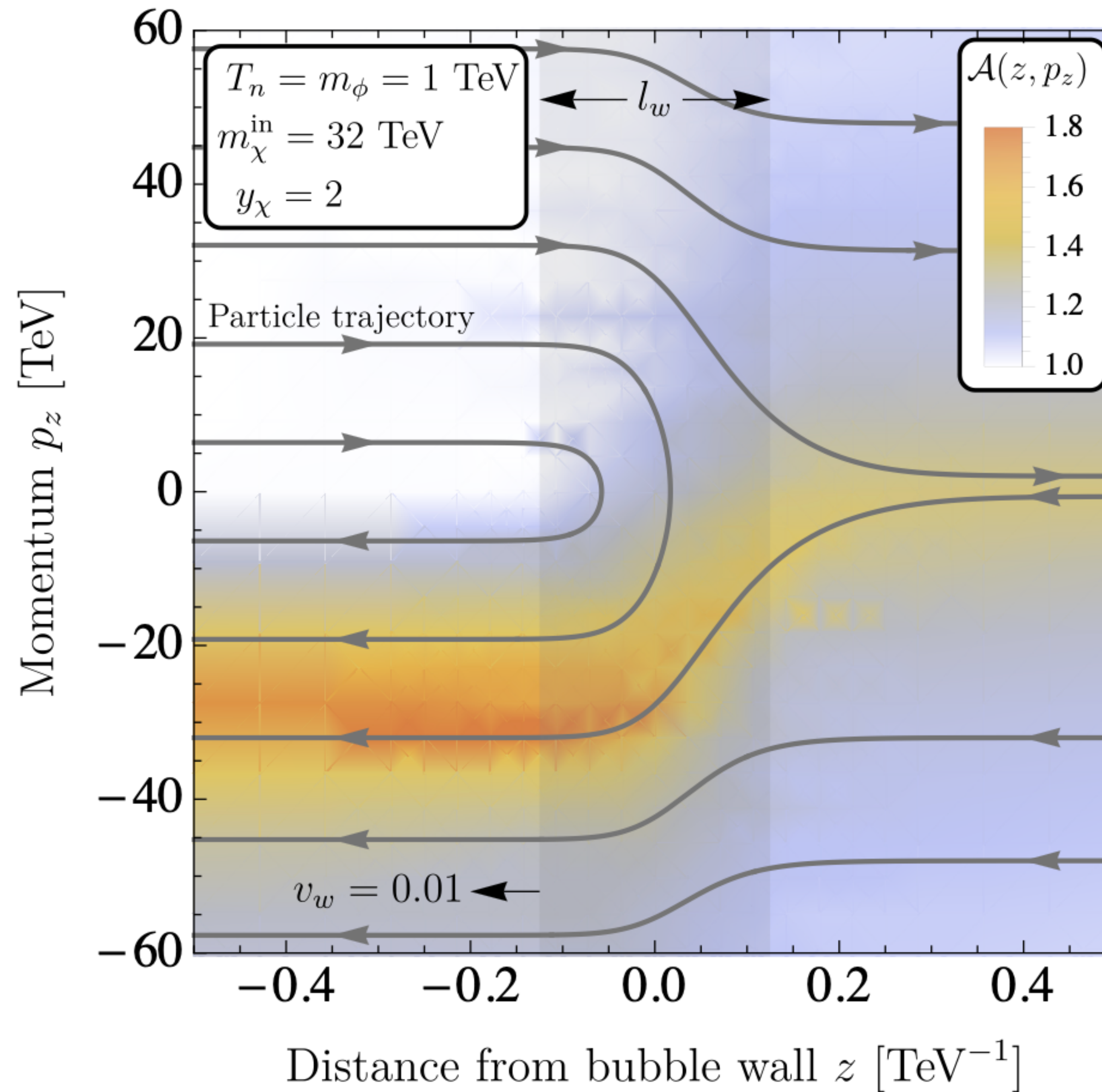
Introduce ansatz

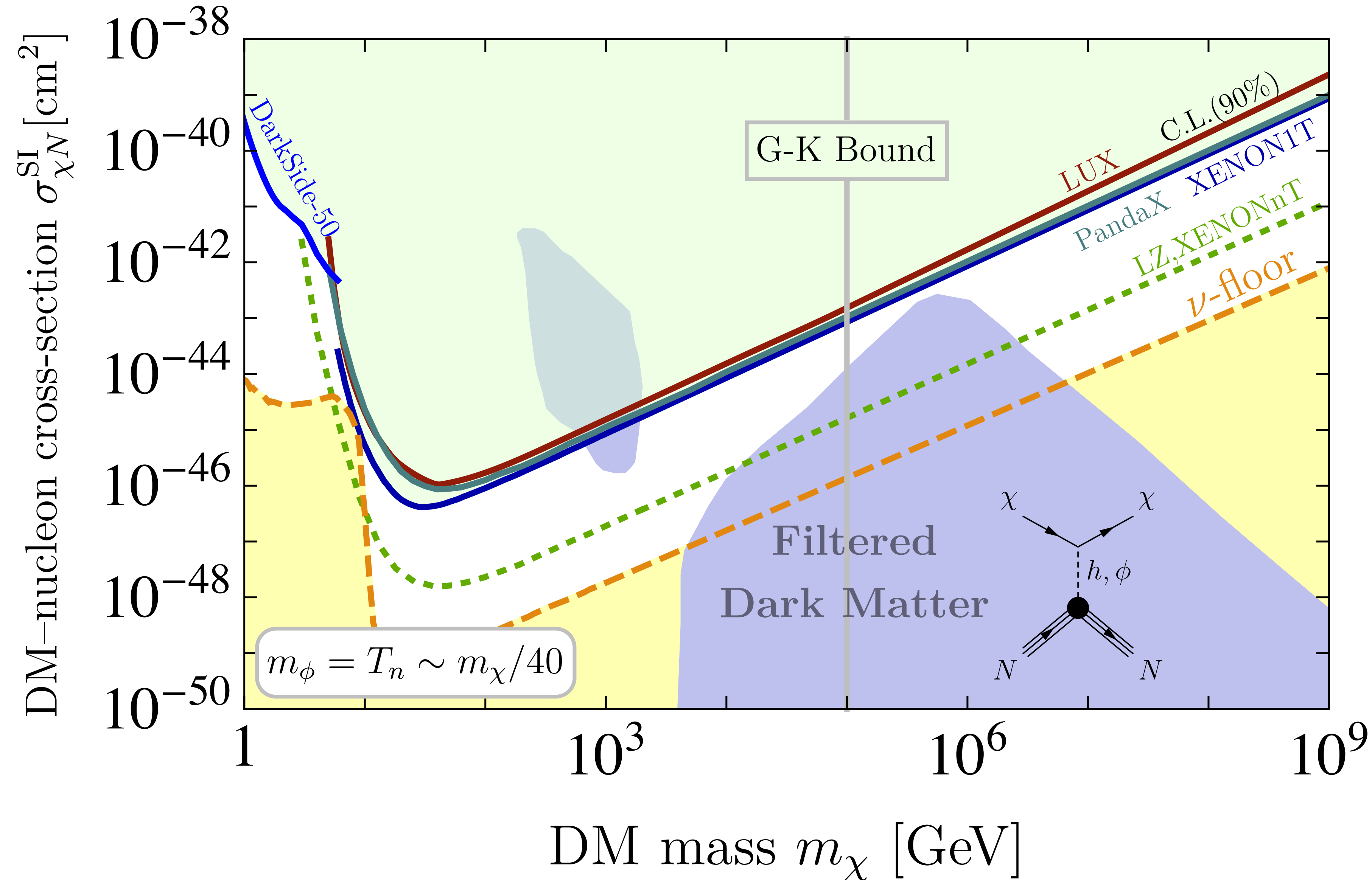
$$f_\chi = \mathcal{A}(z, p_z) \times f_\chi^{\text{eq}}(\vec{x}, \vec{p})$$

Integrate over unimportant variables and assume steady state

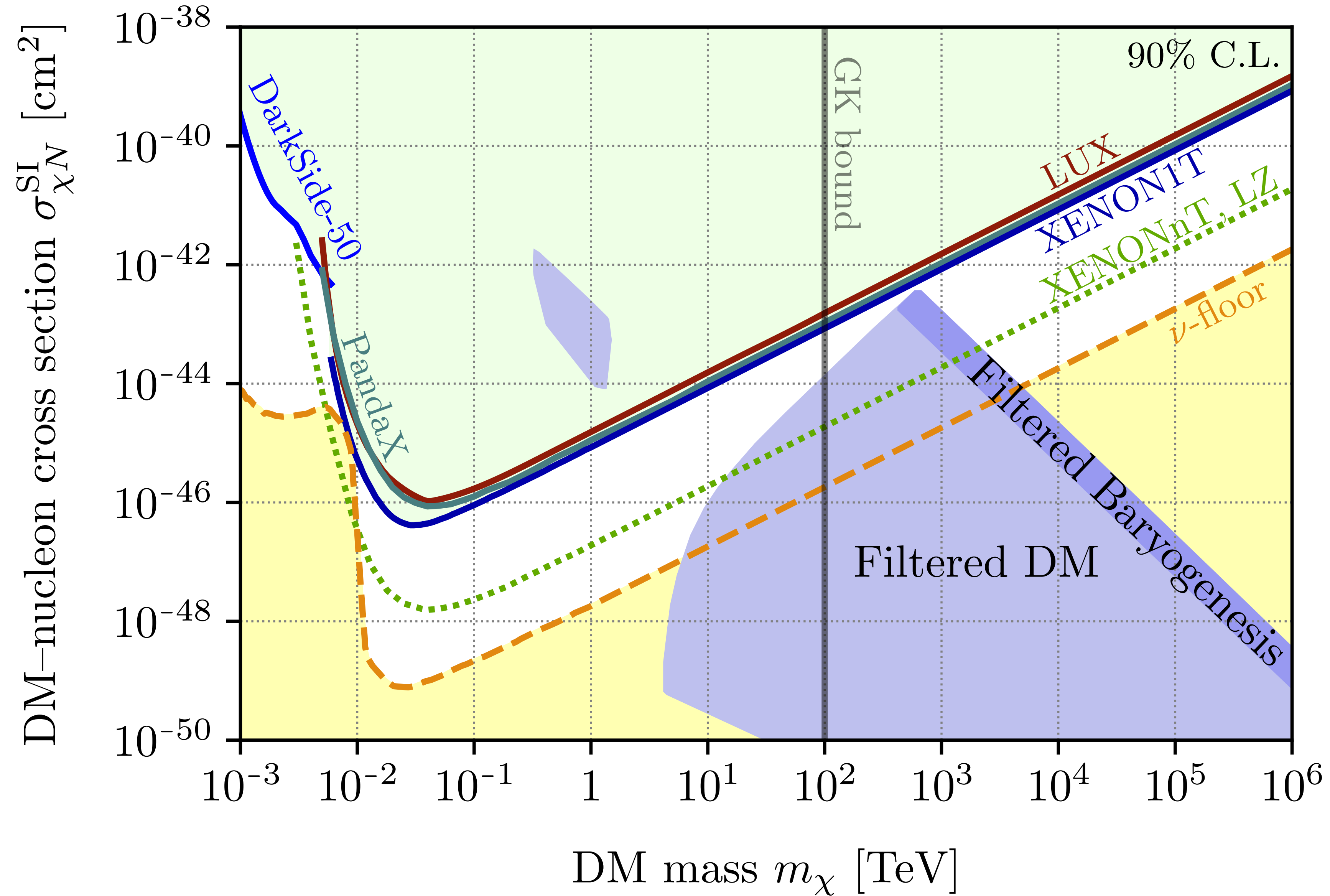
$$g_\chi \int \frac{dp_x dp_y}{(2\pi)^2} \mathbf{L}[f_\chi] = g_\chi \int \frac{dp_x dp_y}{(2\pi)^2} \mathbf{C}[f_\chi]$$

Can finally solve using the Method of Characteristics



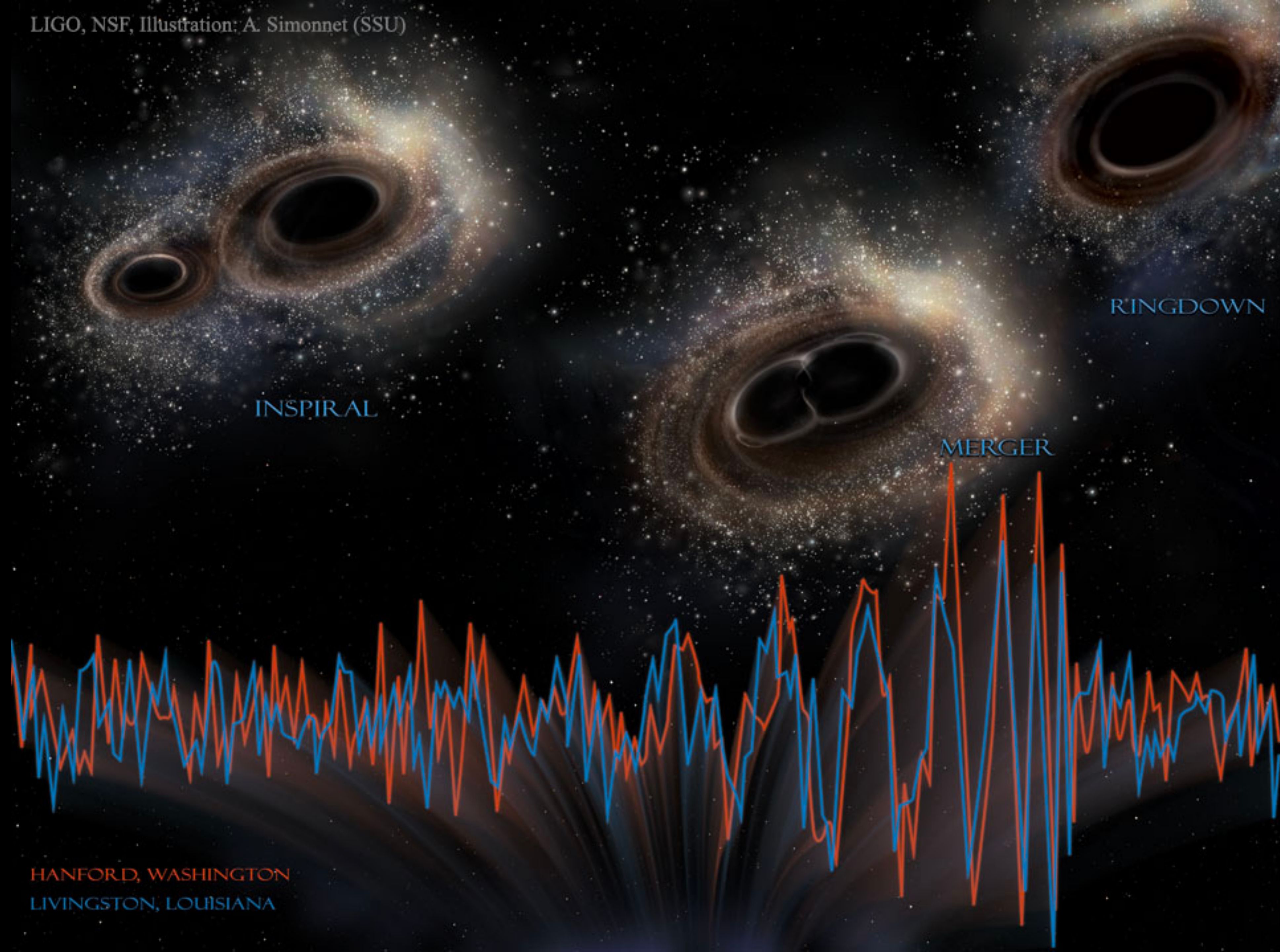








Primordial Black Hole Production

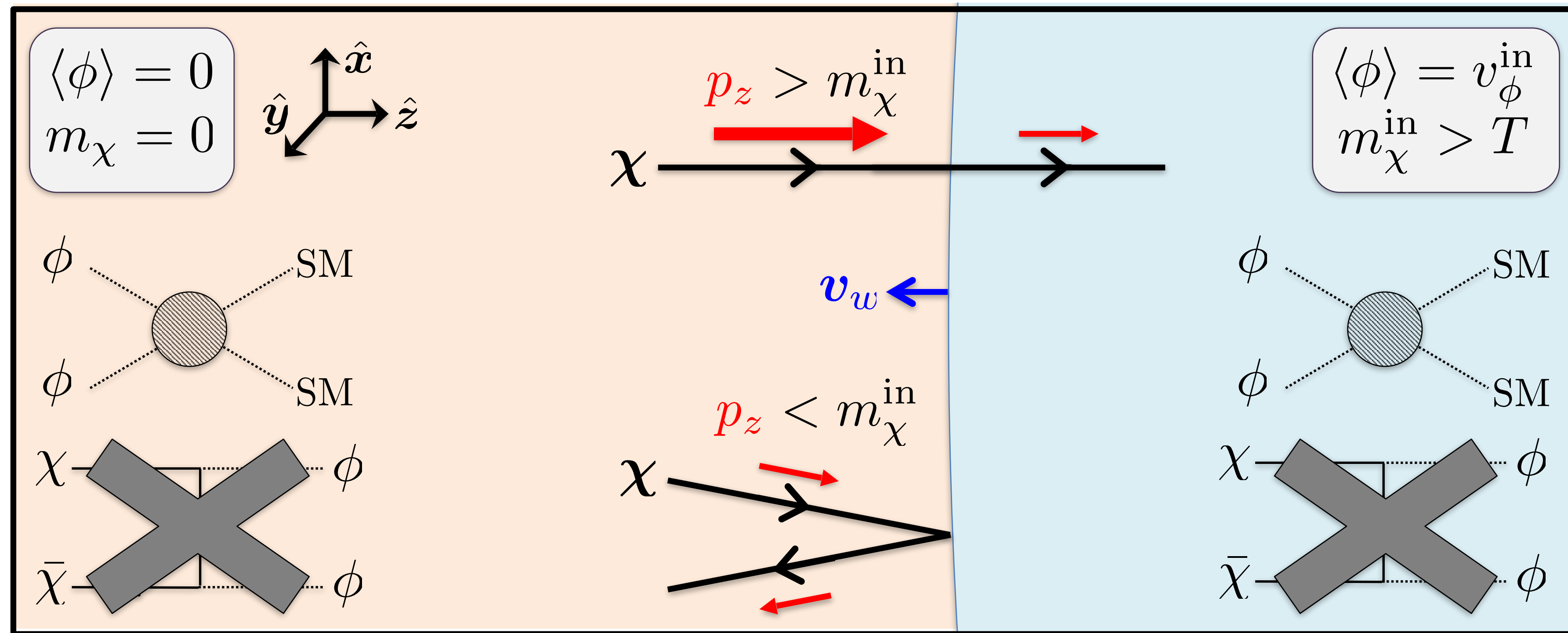


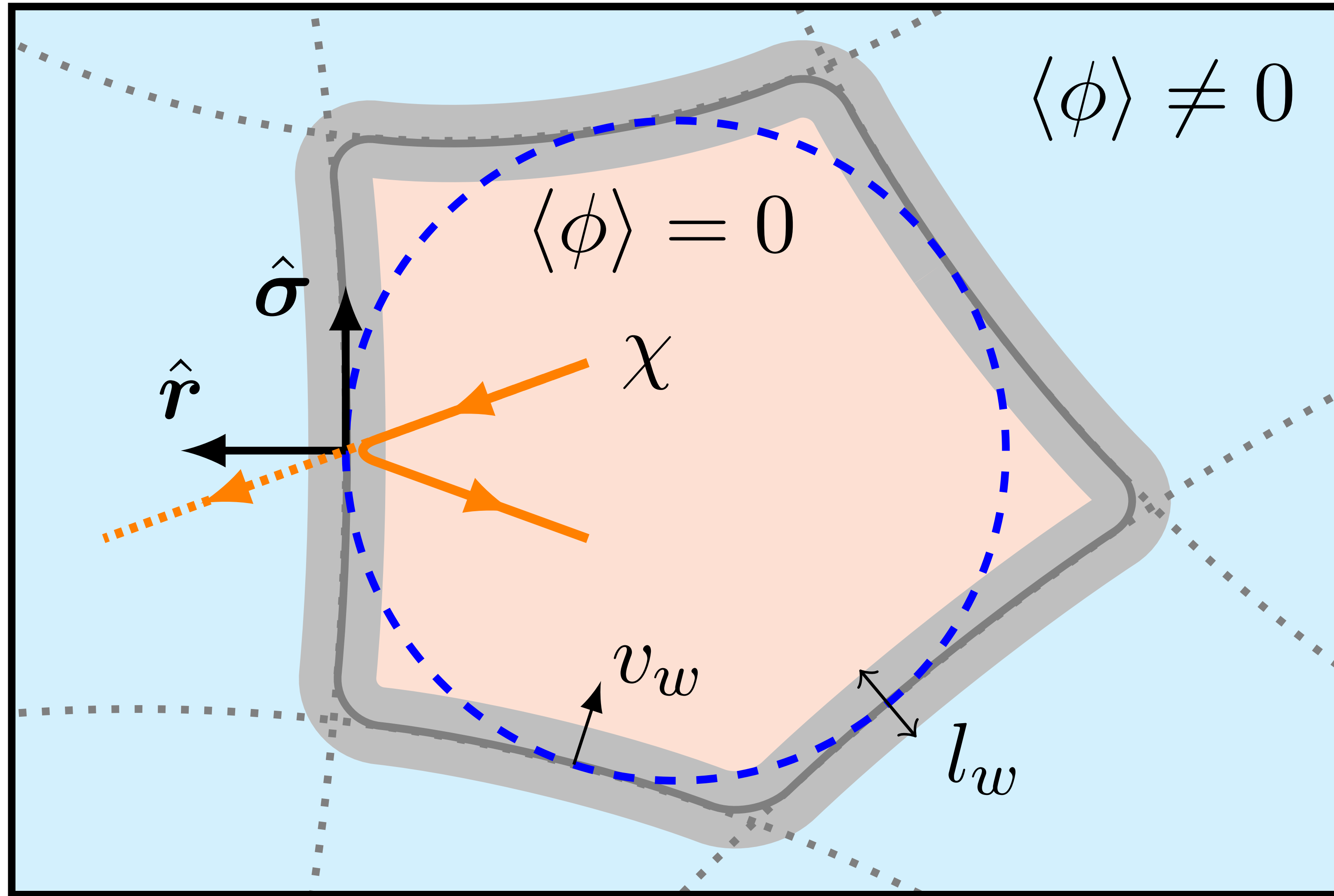


- Motivations
 - Many, some at end of this section
- Several possible production mechanisms
 - Collapse of density perturbations generated during inflation
 - Collapse of topological defects
 - Dynamics of scalar condensates
 - Collision of bubble walls during a first-order PT
- Previous work on first-order PT has only considered energy stored in bubble walls. We focus on a population of particles that interact with the bubble wall

2105.07481 (PLB) - MJB, M. Breitbach, J. Kopp, L. Mitnacht

2110.00005 (PRD) - MJB, M. Breitbach, J. Kopp, L. Mitnacht

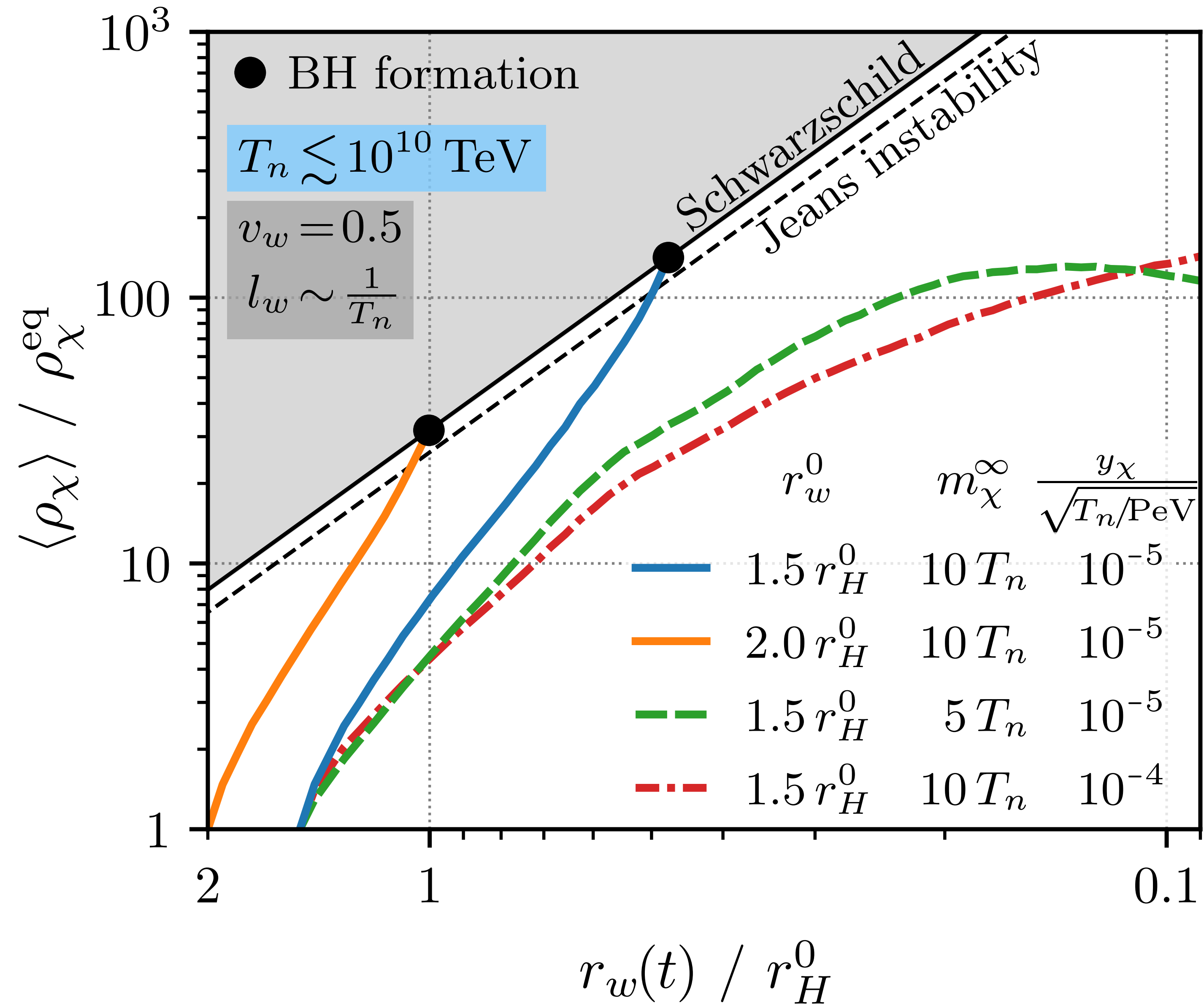




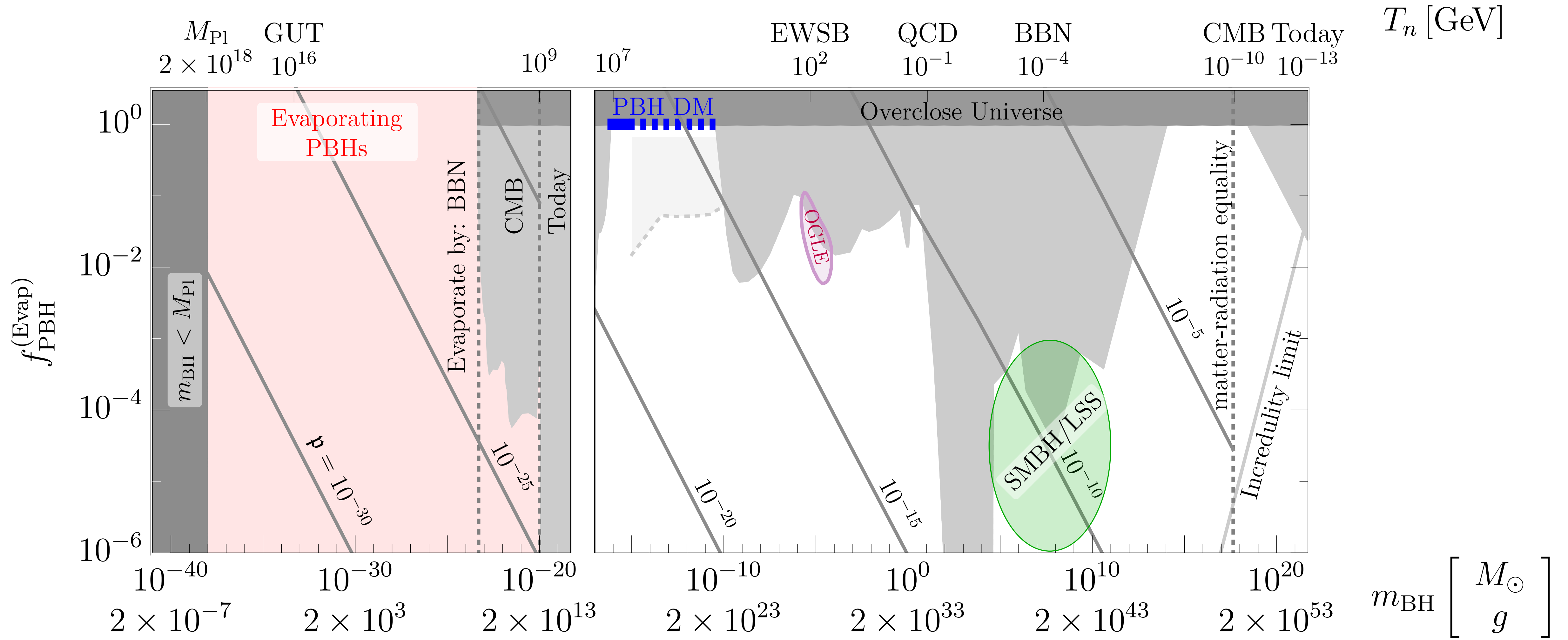
Again numerically solve Boltzmann equation $\mathbf{L}[f_\chi] = \mathbf{C}[f_\chi]$

Now considerably more complicated:

- Retain two momentum directions
- Time dependence
- Need to solve in whole volume, not just near wall



PBH Production: PBH mass and density



- First-order cosmological phase transitions are more-or-less calculable and can lead to a wide range of interesting phenomena
- Presented a novel DM production mechanism
- Presented a novel PBH production mechanism

Thank you!