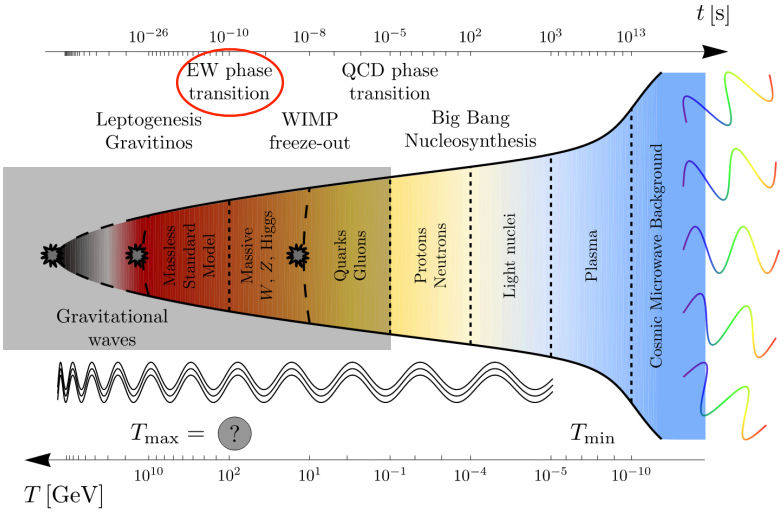
Reliable dynamics in a hot Universe

Andreas Ekstedt

Uppsala University

First Nordic Cosmology Meeting

The Cosmological History



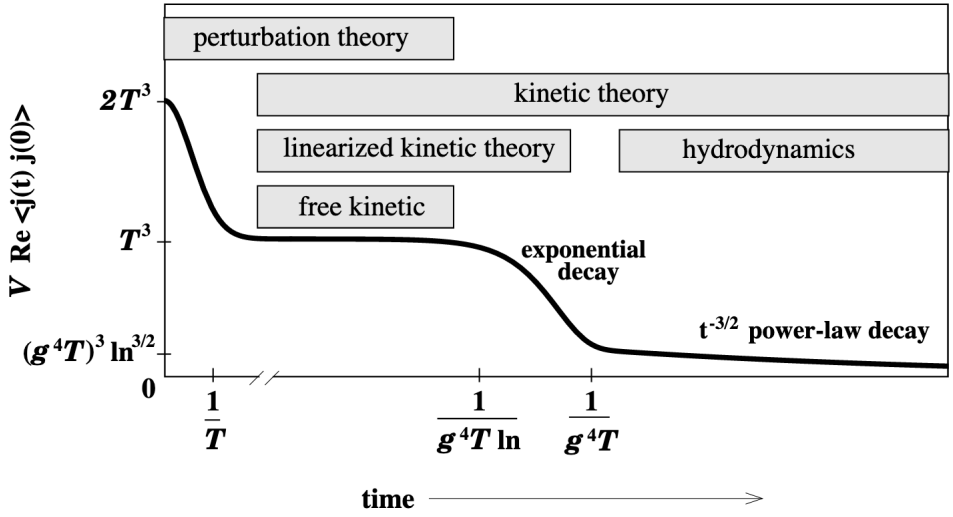
Adapted from 1307.3887

This talk

Effective dynamical equations at high temperatures

Perturbative corrections to nucleation rates

Dynamical processes in a nutshell



Arnold, Yaffe 98

How do fields evolve?

Classical equations of motion

$$-\ddot{\phi} + \nabla^2\phi - V'_{\text{eff}}(\phi) + F_{\text{dis}}(\phi, T) + \underbrace{\zeta(x)}_{\text{Thermal noise}} = 0,$$

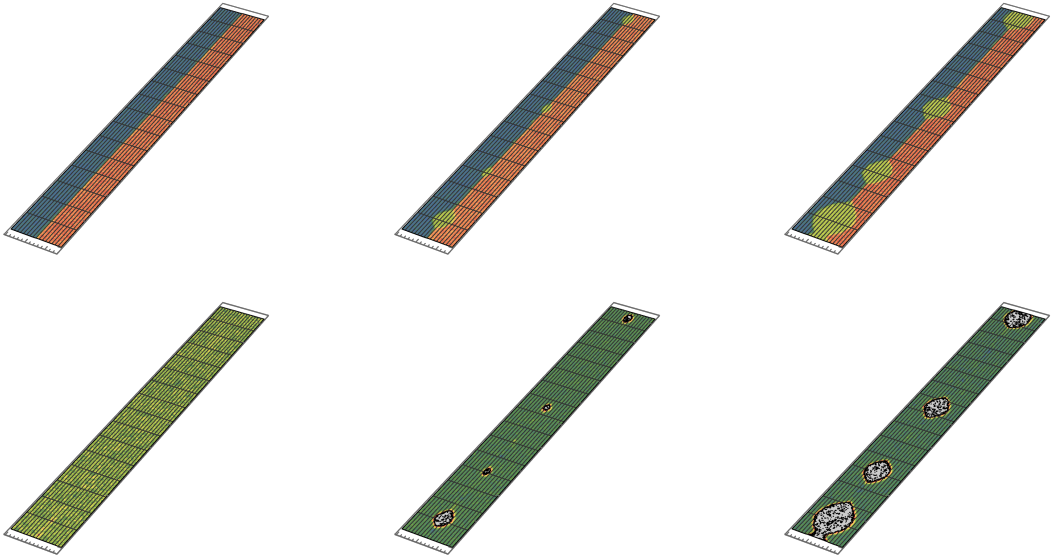
$$F_{\text{dis}}(\phi) \sim \eta_\phi(\phi)\dot{\phi} + \xi_\phi(\phi)\vec{\nabla}\cdot\vec{u}$$

$$L = \begin{cases} \lambda_c \sim T^{-1} & \text{The Compton wave-length of plasma particles} \\ \lambda_d \sim (gT)^{-1} & \text{The screening, or Debye, length} \\ \lambda_m \sim (g^4 T)^{-1} & \text{The mean-free path between collisions} \end{cases}$$

A different theory for each length scale

Screening $\rightarrow$ Collisions & Thermal masses $\rightarrow$ Friction, Viscosity & Noise

Example: Bubbles seeded by domain walls (work with Blasi)

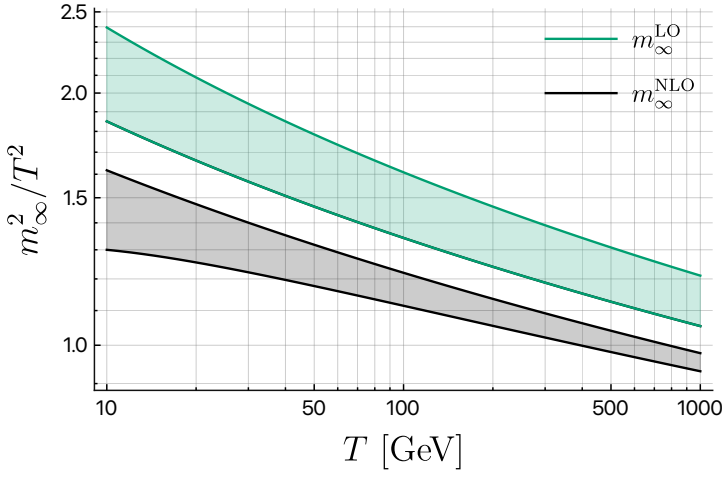


Some recent theory results

Two-loop QED hard thermal loops	Carignano et.al 19
Dense N^3LO pressure	Kneur, Fernandez; Seppänen,Säppi et.al 23
"Almost" NLO transport coefficients	Ghiglieri et.al 18
Two-loop QCD hard thermal loops	Ekstedt 23; Gorda et.al 23
Effective theories for bubble nucleation	Gould, Hirvonen 21
$\rightarrow$ Gauge invariance	Tenkanen, Löfgren et.al 21
Consistent expansions for scalar potentials	Gould, Tenkanen 23

And much more!

Gluon masses at two loops



$\sim$ 30% correction for QCD

What about hydrodynamics?

Effective energy-momentum tensor

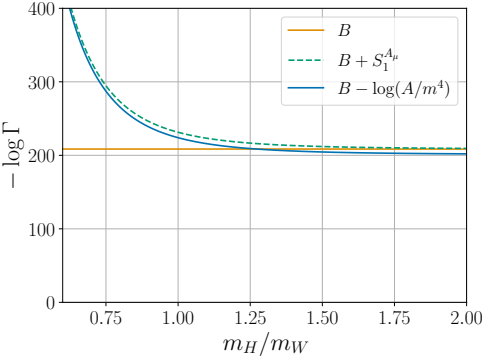
$$T^{\mu\nu}_{\text{eff}} \sim T^{\mu\nu}(\phi) + \underbrace{\overbrace{\sum_a \int p^\mu p^\nu f^a}^{\text{Leading-order result}} + \overbrace{\sum_{ab} \lambda^{ab} \int f^a f^b}^{\text{Two-loop correction}} + \ldots}_{\text{Effective hydrodynamics}}$$

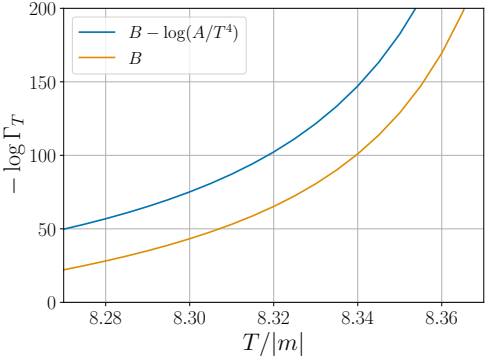
$\rightarrow$ Dimensionally reduced result + dynamical terms

Dissipation : $g_{\mu\nu} T^{\mu\nu}_{\text{dis}} \sim \zeta \nabla \cdot u + \eta_\phi \phi^3 u \nabla \phi + \ldots \rightarrow$ Soon automatized to two-loops

BubbleDet Gould, Hirvonen, Ekstedt 23

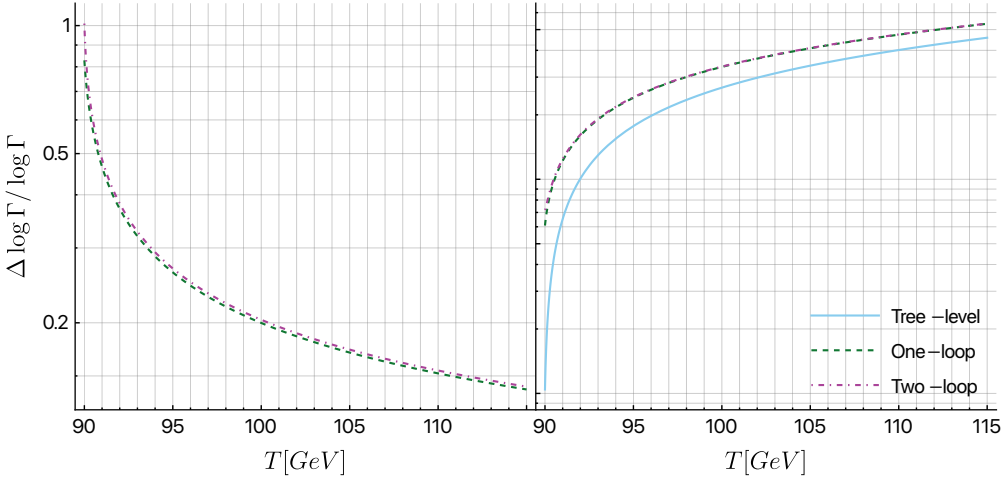
Automatized one-loop nucleation rates: $\Gamma \sim A\exp(-E/T)$





Takeaway: $A \sim T^4$ is a **horrible** approximation

Perturbation expansion works



Exciting times ahead

Three-loop effective potentials & nucleation rates

Scalar friction to full leading order

Effective energy-momentum tensors to two loops

Dynamical field equations to two loops

Impact of thermal noise & viscosity effects