Emergent particles of a dS universe:

Thermal interpretation of the stochastic formalism and beyond

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arXiv: 2310.15216 [gr-qc]

Outline

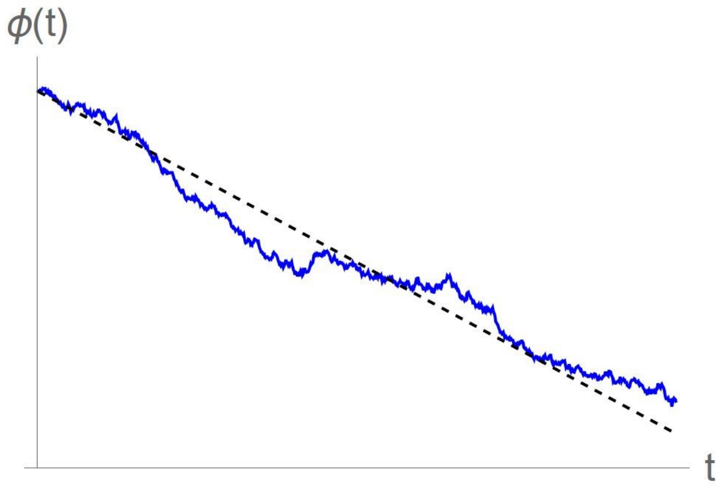
- Introduction
  - Stochastic formalism of slow-rolling scalar field during inflation
- Giving thermal interpretation
  - The formalism & heat bath model
- And beyond
  - 1^{st} slow-roll condition & Hubble expansion
- Discussion and Conclusion

Introduction

Starobinsky (1986)
Starobinsky, Yokoyama (1994)

- The stochastic formalism
    - IR EFT for a slow-rolling scalar field in inflation; "coarse-grained" ($k \ll aH$) field
    - Classical random evolution: Langevin equation

$$d\phi = -\frac{V'(\phi)}{3H}dt + \sqrt{\frac{H^3}{4\pi}}\,dW$$

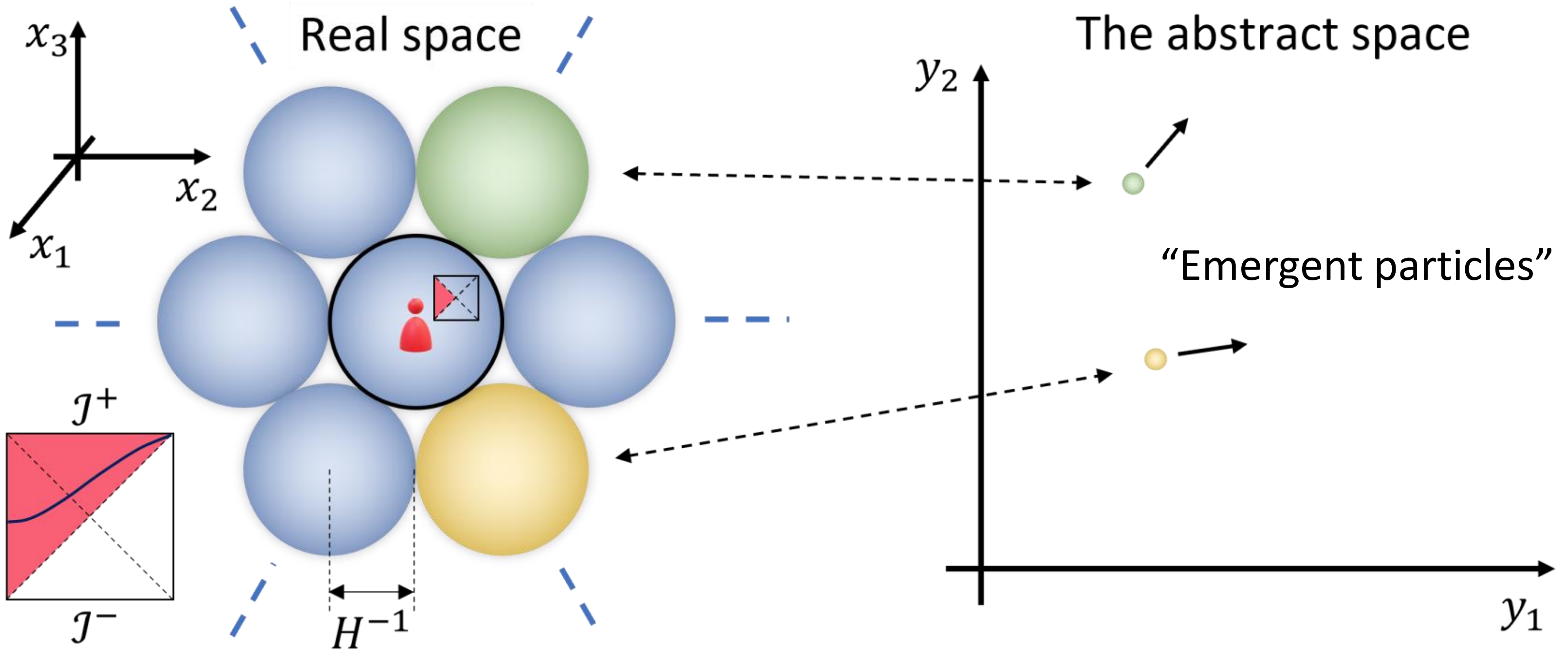


-
    - Used for non-perturbative calculations of $P(k)$, PBH, …
- Can we pursue thermal interpretation?
    - Classical field evolution ↔ classical thermal system
    - Minimal setup: dS background + 1 spectator field ϕ

The formalism

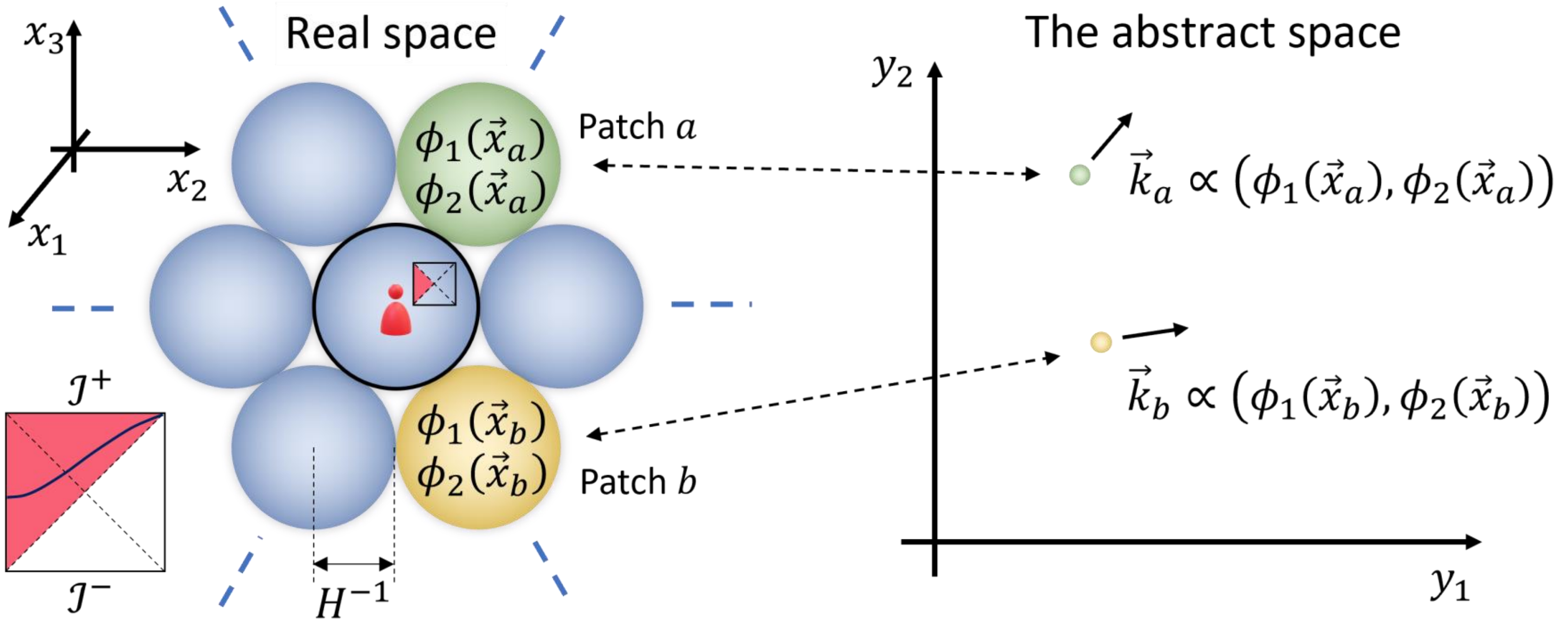
Effective Lagrangian approach:
Rigopoulos (2013) & (2016)

- Horizon-sized patches in real 3D space as particles in a virtual space
  - This is a formalism. I'm NOT claiming a new theory of spacetime.



The formalism

1. Field value ∝ momentum; "dual" w.r.t. usual field space
2. "Classical" (non-quantum) mechanics of the same structure



The formalism

- Volume factor for conversion: Hubble volume = $4\pi/3H^3$
- Work-energy theorem: $E_k = W = \int F\,dx = \int v(k)dk$

- By the two assumptions:

Hubble patch in real space	Emergent particle in the Abs. space	Equation
Field value ϕ	Momentum k	$k = \frac{4\pi M_P m_\phi}{\sqrt{3}H^2}\phi$
Potential V_ϕ	Kinetic energy E_k	$E_k = \frac{4\pi}{3H^3}V_\phi$
$V_0 = 3M_P^2H^2$	Mass M	$M = \frac{4\pi M_P^2}{H}$
Potential slope V'_ϕ	Velocity v	$v = \frac{1}{\sqrt{3}M_P H m_\phi}V'_\phi$

The formalism

- Substitution into the Langevin equation for ϕ

Real space

$$d\phi = -\frac{V'(\phi)}{3H}dt + \sqrt{\frac{H^3}{4\pi}}\, dW$$

→

The abstract space

$$dk = -\frac{4\pi M_P^2 m_\phi^2}{3H^2}\, v\, dt + \sqrt{\frac{4M_P^2 m_\phi^2}{3H}}\, dW$$

- ~ classical Brownian motion in a medium at a finite temperature
  - What kind of heat bath would realize the Brownian motion correctly?

Heat bath model

Unsuccessful trials:
Massive bath particles, elastic collisions, …

- Successful model: heat bath of massless particles
  - $c = 3H/m_\phi$: Speed of light (massless particles) in the abstract space
  - $T = H/2\pi = T_{dS}$: Bath temperature
  - $\lambda = 8\pi^2 M_P^2 m_\phi / H^2$: Number density

Bath particle

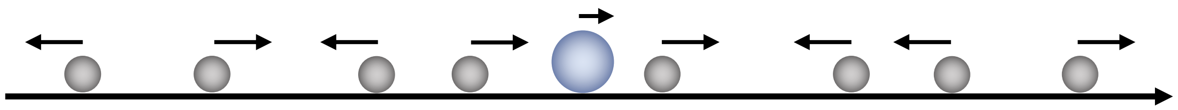
$$f(p) \propto e^{-\beta c|p|}$$

$$v = \pm c$$

Emergent particle

$$k = \frac{4\pi M_P m_\phi}{\sqrt{3}H^2}\phi$$

$$v = \frac{1}{\sqrt{3}M_P H m_\phi} V'_\phi$$



The abstract space (1D)

Giving thermal interpretation

Thermal interpretation. But…

Classical thermal motion (abs. space)

Heat bath of massless particles

- $c = 3H/m_\phi$
- $T = H/2\pi = T_{dS}$
- $\lambda = 8\pi^2 M_P^2 m_\phi / H^2$

Classical mechanics → Momentum conservation (Kinetic theory)

$$dk = -\frac{4\pi M_P^2 m_\phi^2}{3H^2} v\, dt + \sqrt{\frac{4M_P^2 m_\phi^2}{3H}}\, dW$$

↑↓ Emergent particle formalism ↑↓

EFT for coarse-grained field

Mode freezing → Classicality

$$d\phi = -\frac{V'(\phi)}{3H} dt + \sqrt{\frac{H^3}{4\pi}}\, dW$$

Quantum field evolution (real space)

Giving thermal interpretation

- “Heat bath engineering” is possible for any random-walking variable

??? ⟷ No physics

Bath particle

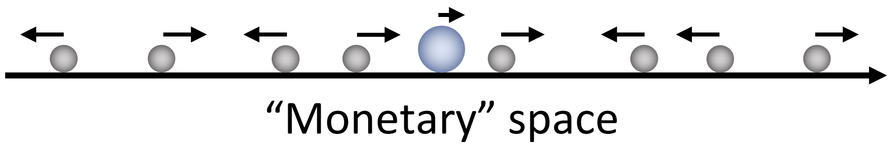
$f(p) \propto ???$

$v = ???$

??? particle

$k = ???$

$v = ???$



- The physical significance comes from the reappearance of other seemingly unrelated quantities and phenomena in consistent ways

And beyond

Unexpected but consistent agreement

Classical thermal motion (abs. space)

Energy conservation

- Hubble expansion & bath particle collision

→ Speed of light

$c = 3H/m_\phi$

Classical mechanics →

$v = c$ *is expected to be*

- Speed limit for massive particle
- $v \ll c$ physics breaks down

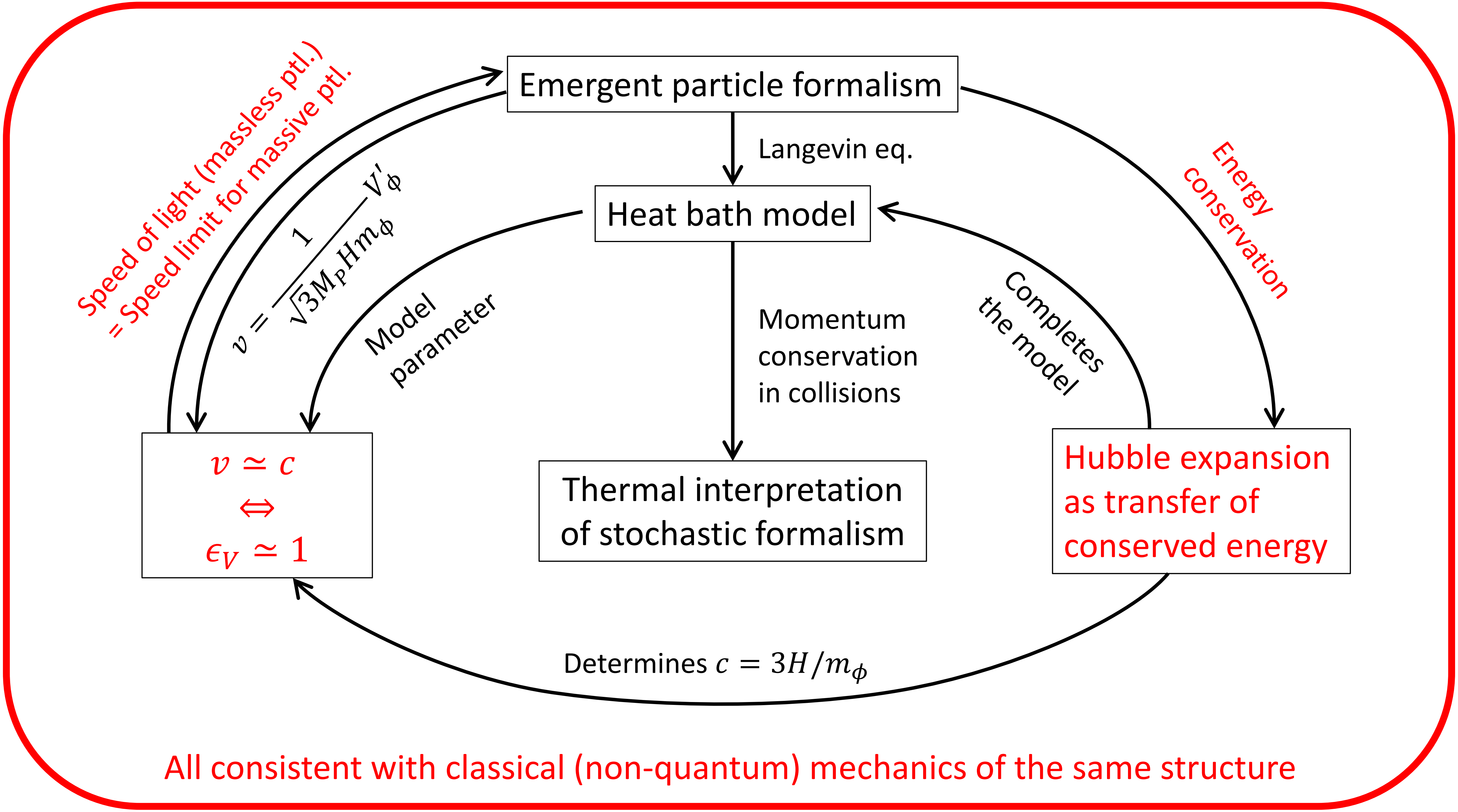
$v \propto V'_\phi$ from the formalism

$\epsilon_V = 1$ (or $V'_\phi = 3\sqrt{2}M_P H^2$) *is*

- Potential slope limit for slow-roll
- (Quasi-) dS expansion breaks down

Slow-rolling field $\xrightarrow{\epsilon_V}$

Quantum field evolution (real space)


Emergent particle formalism
Langevin eq.
Heat bath model
Momentum conservation in collisions
Thermal interpretation of stochastic formalism
Speed of light (massless ptl.)
= Speed limit for massive ptl.
$v = \frac{1}{\sqrt{3}M_P H m_\phi} V'_\phi$
Model parameter
$v \simeq c$
$\Leftrightarrow$
$\epsilon_V \simeq 1$
Energy conservation
Completes the model
Hubble expansion as transfer of conserved energy
Determines $c = 3H/m_\phi$
All consistent with classical (non-quantum) mechanics of the same structure

Discussion

- Properties of the abstract space
  - Time & spatial translation symmetry (energy & momentum conservation)
  - But no Lorentz symmetry (generalized relativistic effect; $k \propto \phi,\ E_k \propto V_\phi,\ v \propto V'_\phi$)
    - The usual relativistic mechanics is recovered for a specific form of potential
- Primitive form of …?

$$[\text{ scalar in dS at IR }] \cap [\text{ flat spacetime Q (thermal) FT }] \neq \emptyset$$

  - After having the quantum version…

Summary

- A thermal interpretation of stochastic formalism is obtained by proposing a correspondence between causal patches in dS and particles in an abstract space.
- Consistent reinterpretation of the 1st slow-roll condition and the Hubble expansion are also achieved, giving further physical significance.

Thank you for the attention!

THK; 2310.15216 [gr-qc]