Emergent particles of de Sitter:

Thermal interpretation of the stochastic formalism and beyond

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Outline

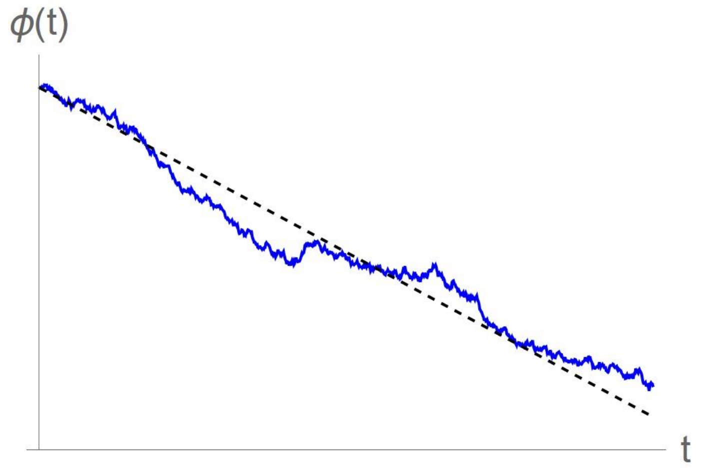
- Introduction
  - Stochastic formalism of slow-rolling scalar field during inflation
- Giving thermal interpretation
  - The formalism & heat bath model
- And beyond
  - 1^{st} slow-roll condition & Hubble expansion
- Discussion and Conclusion

Introduction

Starobinsky (1986)
Starobinsky, Yokoyama (1994)

- The stochastic formalism
  - IR EFT for a slow-rolling scalar field in inflation; "superhorizon coarse-grained" 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, …
- "Looks similar" to dS thermodynamics
  - Appearance of $T_{dS} = H/2\pi$ gives intuitive understanding

Introduction

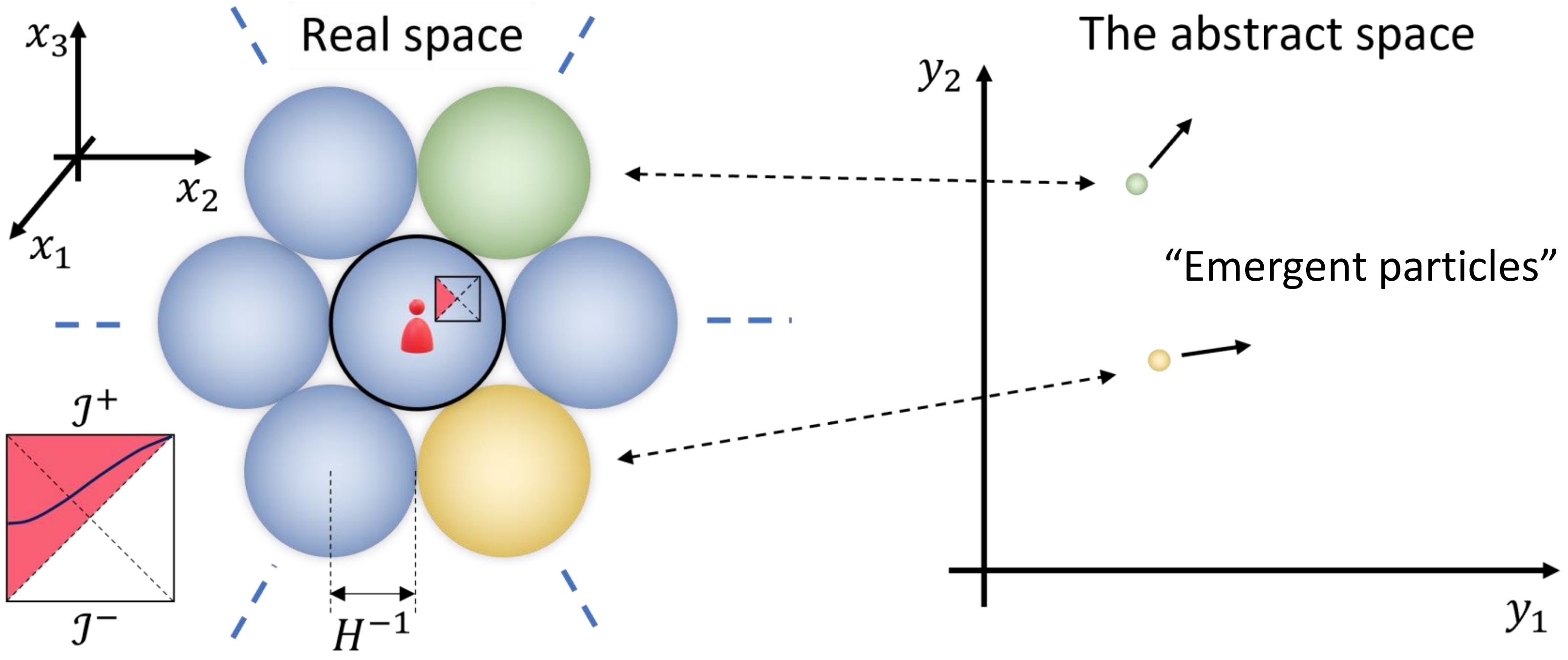
Finelli, Marozzi, Starobinsky, Vacca, Venturi (2009)
Rigopoulos (2013) & (2016)

- But not actually a thermal effect
  - Spin dependence, resultant spectrum, …
  - “Superhorizon modes”. Not an effect of cosmological horizon of a local observer
- Can we still pursue thermal interpretation?
  - Classical field evolution ↔ classical thermal system
  - Minimal setup: dS background + 1 spectator field ϕ

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

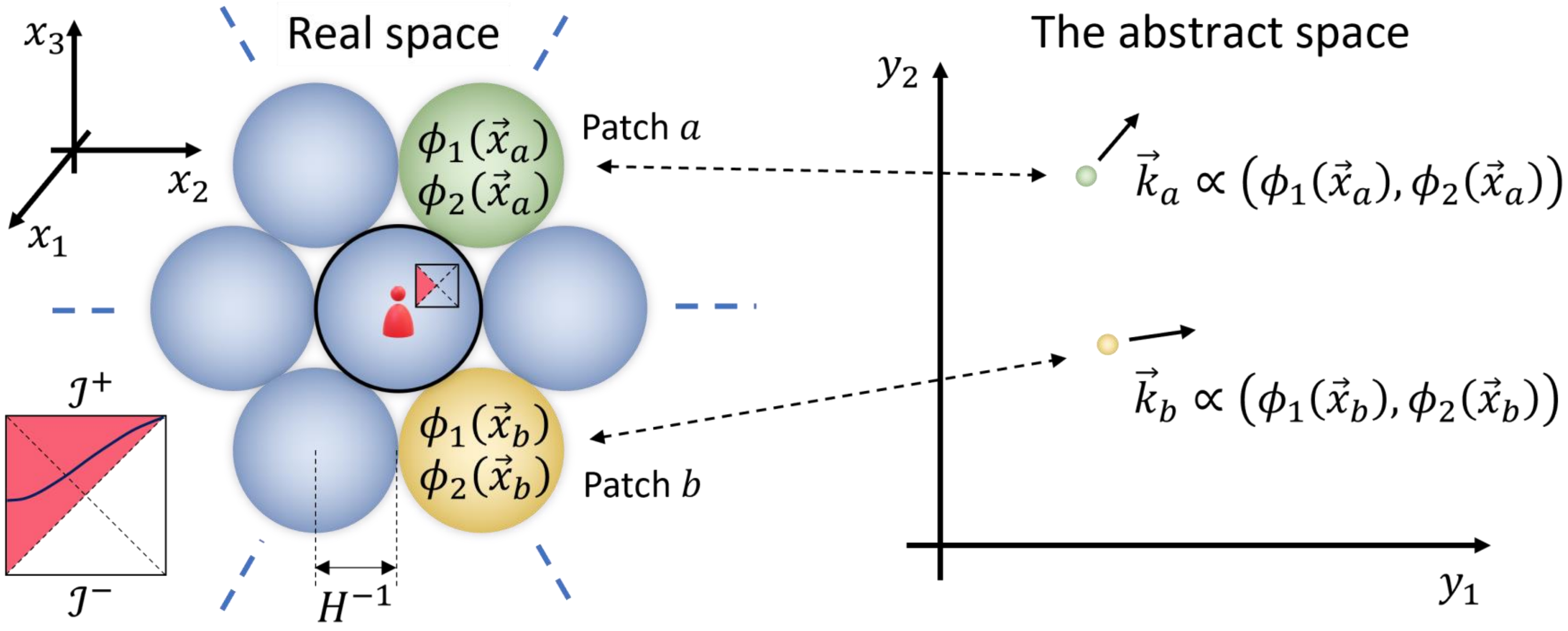
The formalism

- 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

- Substitute 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

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

  - ~ 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 ("photon gas")
  - $c = 3H/m_\phi$: "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 particles are absorbed by emergent particles upon collision

Bath particle

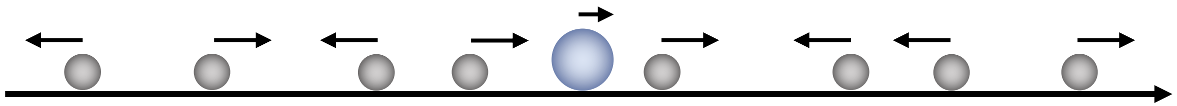
$f(p) \propto e^{-\beta c|p|}$

$v = \pm c$

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

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

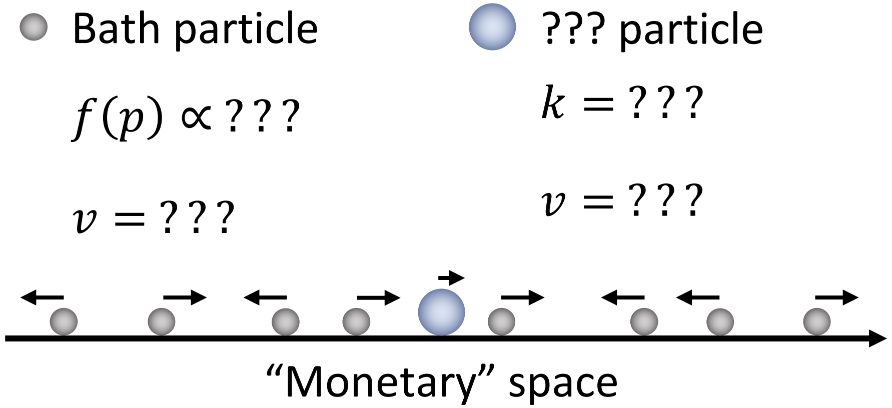
Quantum field evolution (real space)

Giving thermal interpretation

- "Heat bath engineering" is possible for any random-walking variable

???

No physics



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

And beyond

- What about energy conservation?
  - Bath particles are absorbed = Perfectly inelastic collisions → Kinetic energy loss
- Hubble expansion = (Massive) Particle creation in the abstract space
  - "A horizon-sized region → $e^3 \simeq 20$ horizon-sized regions in $\Delta t = 1/H$"
  - "An emergent particle → $e^3 \simeq 20$ emergent particles in $\Delta t = 1/H$"
- Postulation: The two together satisfy energy conservation
  - Required to fix the three model parameters (giving the 3rd equation)

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

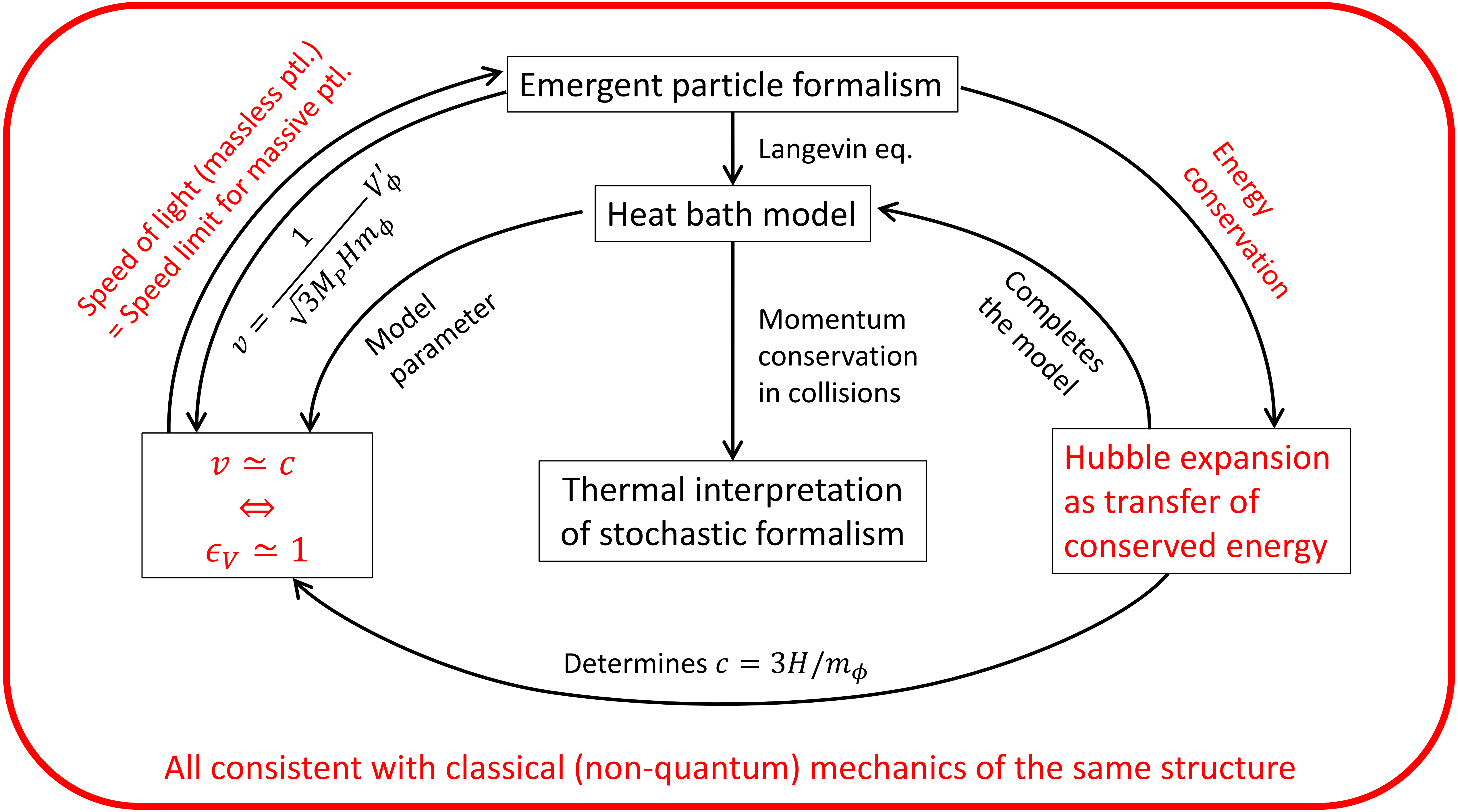
$v \propto V'_\phi$ from the formalism

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

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

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

Quantum field evolution (real space)



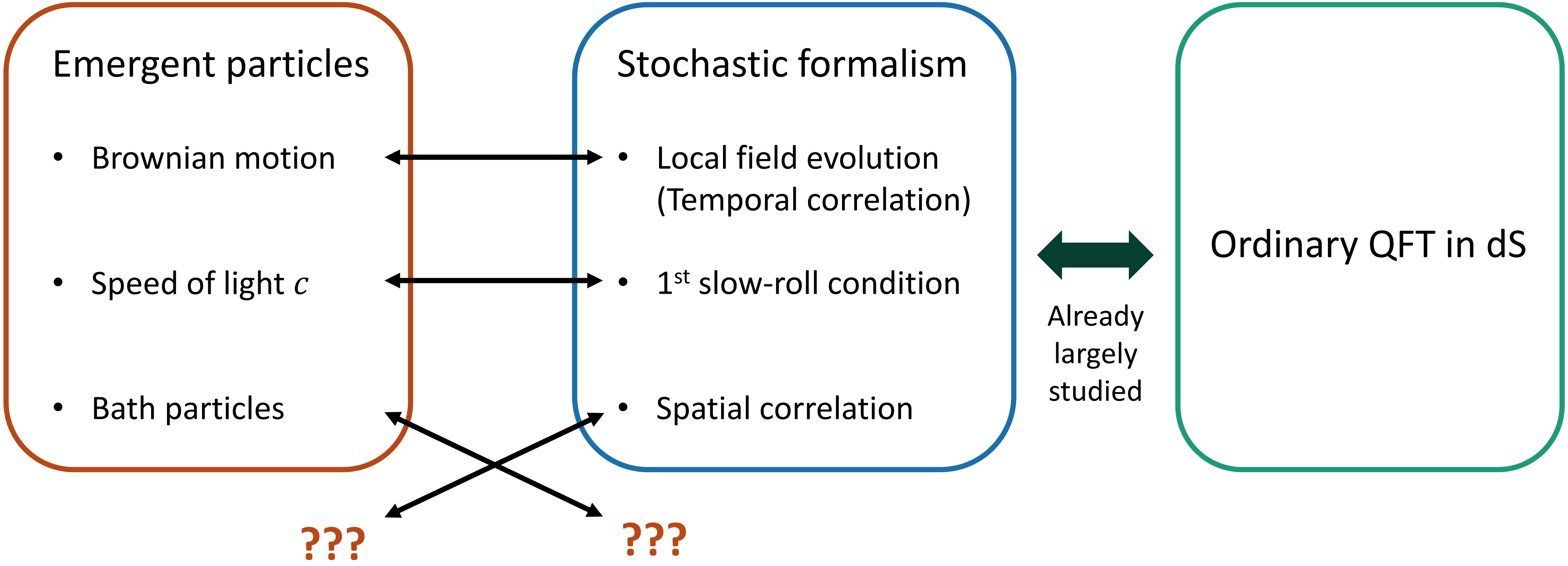
Emergent particle formalism
Langevin eq.
Heat bath model
Momentum conservation in collisions
Thermal interpretation of stochastic formalism
Speed of light (massless ptl.)
= Speed limit for massive ptl.
$v = \frac{1}{\sqrt{3}M_P H m_\phi} V'_\phi$
Model parameter
Energy conservation
Completes the model
$v \simeq c$
$\Leftrightarrow$
$\epsilon_V \simeq 1$
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
- The abstract space (plus ordinary time) is flat spacetime
- A hopeful story: Primitive form of

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

Discussion


Emergent particles
• Brownian motion
• Speed of light c
• Bath particles
Stochastic formalism
• Local field evolution (Temporal correlation)
• 1st slow-roll condition
• Spatial correlation
Already largely studied
Ordinary QFT in dS
???
???

Discussion

Thermal system in Flat spacetime

IR EFT in dS

QFT in dS

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.
- Hope: This is a primitive form of a more complete correspondence between scalar in dS and thermal system in flat spacetime

Thank you for the attention!

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