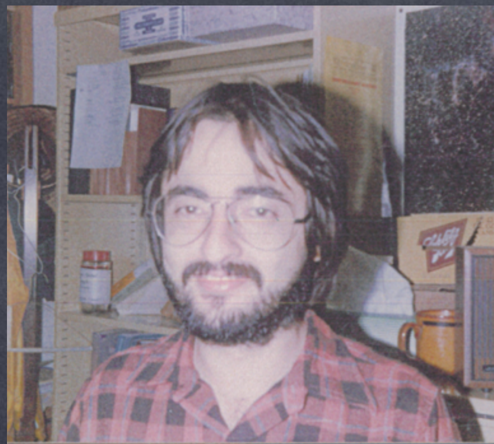

Fernandofest May 2016

The Future is Stochastic (Probably)

EFT for super-Hubble modes
&
Resumming IR inflationary behaviour

CPB, Holman, Tasinato, Williams

1408.5002 & 1512.00169

Fernandofest May 2016

Cambridge Spy Ring

From Wikipedia, the free encyclopedia

The **Cambridge Spy Ring** was a ring of spies recruited in part by Soviet scout Arnold Deutsch in the United Kingdom, who passed information to the Soviet Union during World War II and was active at least into the early 1950s. Four members of the ring were originally identified: Kim Philby (cryptonym: Stanley), Donald Duart Maclean (cryptonym: Homer), Guy Burgess (cryptonym: Hicks) and Anthony Blunt (cryptonyms: Tony, Johnson). Once jointly known as the **Cambridge Four** and later as the **Cambridge Five**, the number increased as more evidence came to light.

The term "Cambridge" refers to the recruitment of the group during their education at the University of Cambridge in the 1930s. Debate surrounds the exact timing of their recruitment by Soviet intelligence; Anthony Blunt claimed that they were not recruited as agents until they had graduated. Blunt, an Honorary Fellow of Trinity College, was several years older than Burgess, Maclean, and Philby; he acted as a talent-spotter and recruiter for most of the group save Burgess.[1]

Several people have been suspected of being additional members of the group; John Cairncross (cryptonym: Liszt) was identified as such by Oleg Gordievsky, although many others have also been accused of membership in the Cambridge ring. Both Blunt and Burgess were members of the Cambridge Apostles, an exclusive and prestigious society based at Trinity and King's Colleges. Cairncross was also an Apostle. Other Apostles accused of having spied for the Soviets include Michael Whitney Straight, Victor Rothschild and Guy Liddell.

Contents [hide]

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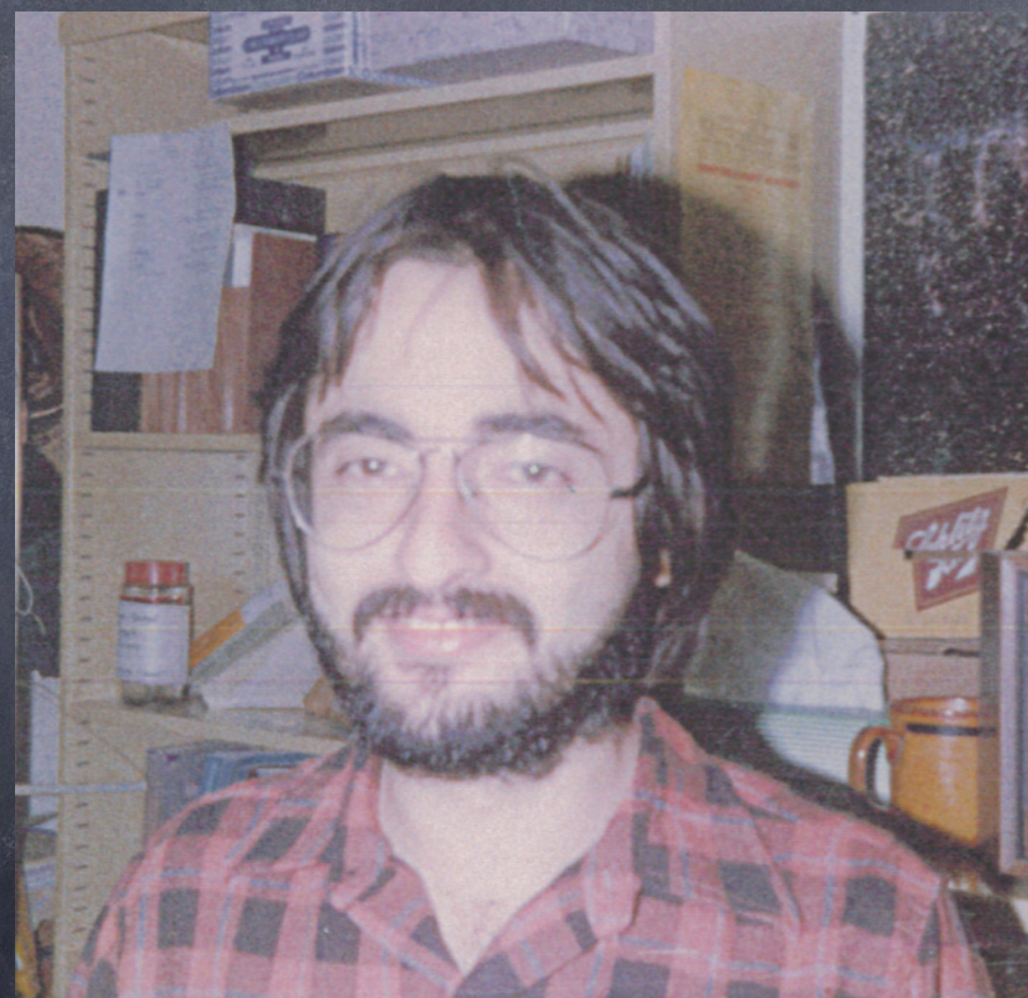
1408.5002 & 1512.00169

The past: great fun (certainly)



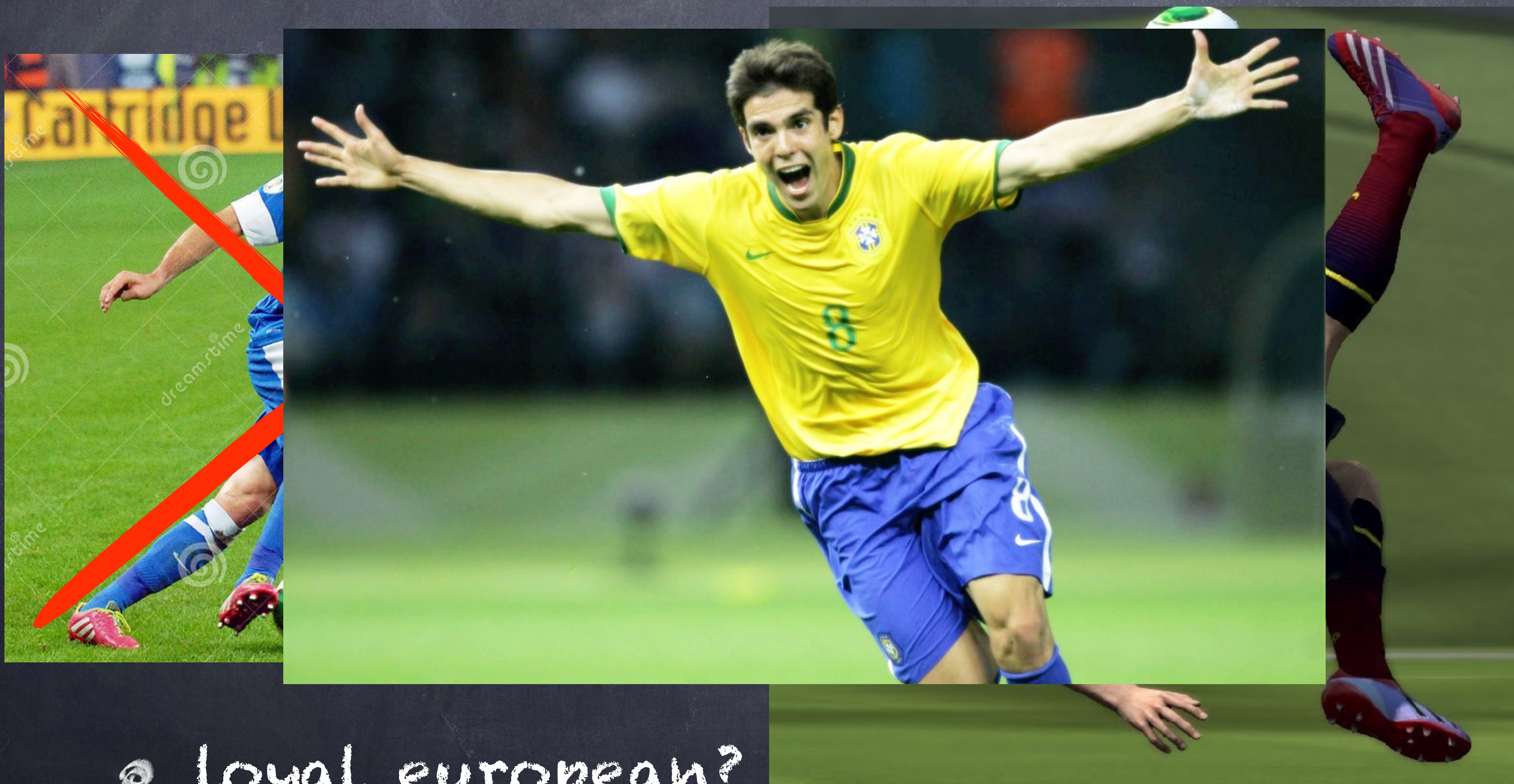
- "Quien es mas macho" beard growing competition

A man with a passion

A man with a passion

- also, physics.

A man with a passion



- loyal european?

Administrative genius

- Observed during moves on many visits over the years

Shared many projects

- "Import-export" business...(1985)

Ideal collaborator

- 54 'classic' papers together, starting from "Burgess, Font & Me" in 1985 (including non-renormalisation theorem) to this year (2016)
  - Heterotic EFT, Bosonization/duality, Int-Scale strings, String inflation, 6D and the CC Problem, Branonium...
  - Pioneers in social media: 1986 IAS-CERN e-gossip pipeline
- My role: bad advice. The ideas I told him wouldnt work include (but are not limited to):
  - S duality, LVS, research w move to ICTP, etc etc etc

Fernando Network

- Seven of the "Racetrack" Eight

The Future is Stochastic

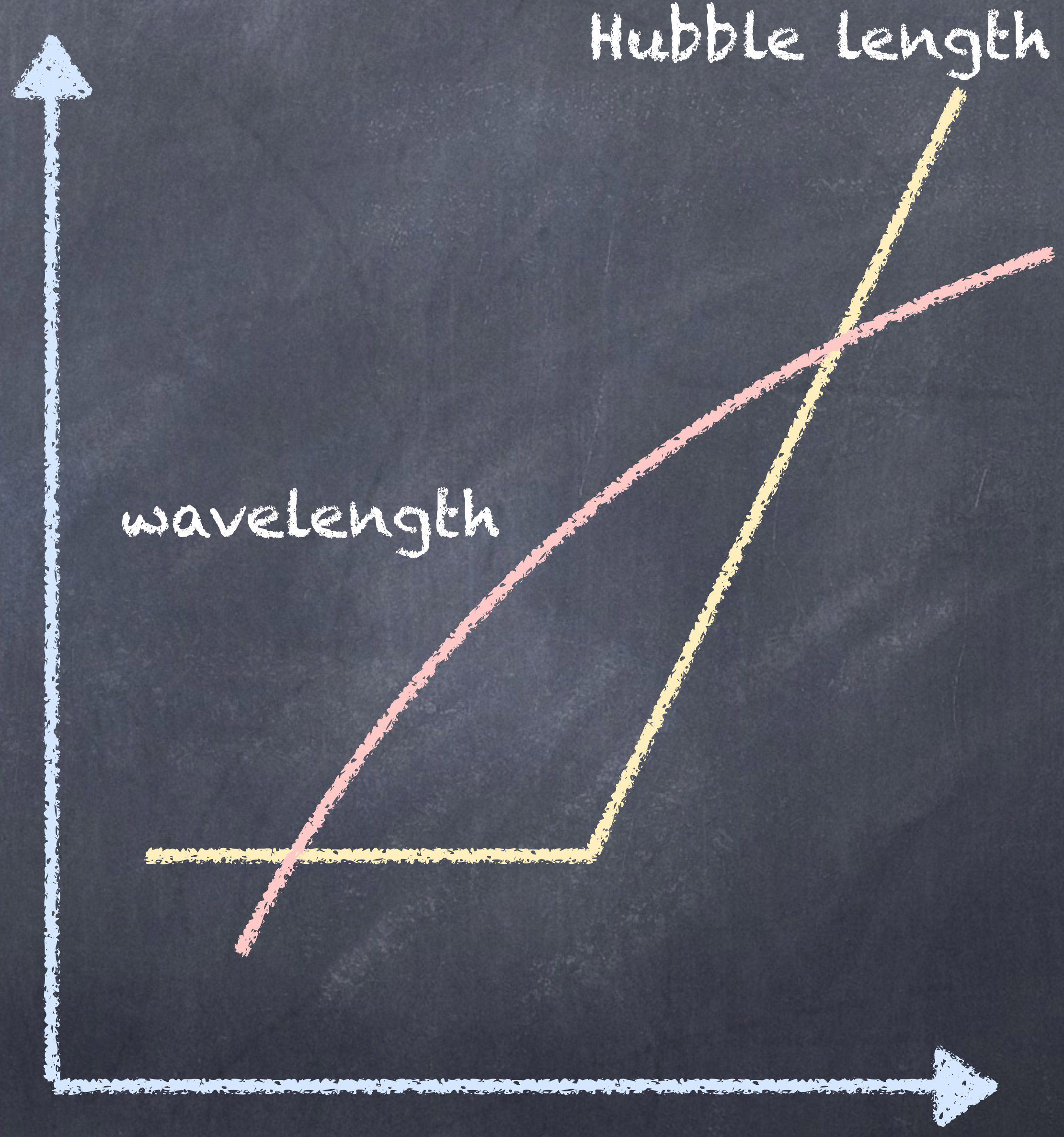
- IR problems for inflationary calcs
- EFT for super-Hubble modes
- Quantum optics
- Stochastic inflation
- Schrodinger's cosmologist
- Information loss in BHs?

Outline

- Motivation
- Open EFTs
  - Secular evolution
  - Stochastic inflation
- Decoherence

Motivation

- Extra-Hubble modes are key to success of inflationary predictions
    - What is their EFT?
- What quantifies theoretical error?



Motivation

- Late-time and IR effects make finding an EFT even more important

$$\mathcal{L} = -\sqrt{-g}\left[\frac{1}{2}(\partial\phi)^2 + \frac{\lambda}{4!}\,\phi^4\right]$$

$$\langle\phi^{2n}\rangle = (2n-1)!!\left(\frac{H^2}{4\pi^2}\,\ln a\right)^n\left[1 - \frac{n(n+1)}{2}\left(\frac{\lambda}{36\pi^2}\right)\ln^2 a + \cdots\right]$$

Tsamis & Woodard

Motivation

- Secular effects have their root in a general issue

$$\langle \phi^{2n} \rangle = (2n-1)!! \left(\frac{H^2}{4\pi^2} \ln a \right)^n \left[1 - \frac{n(n+1)}{2} \left(\frac{\lambda}{36\pi^2} \right) \ln^2 a + \cdots \right]$$

- Perturbative methods generically fail at late times

$$U(t) = \exp\left[-i(H_0 + H_{\rm int})t \right]$$

Motivation

- Normally IR divergences cancel for physical quantities (a la Bloch-Nordsieck)
- This appears to be true as well for single-field inflationary models with IR effects gauge artefacts
- General statement (multiple scalars, other massless fields, tensor modes, etc) not known

Senatore, Zaldarriagga

Motivation

- Normally IR divergences cancel for physical quantities (a la Bloch-Nordsieck)
- Often large logarithms survive IR cancellation, with IR scale that is system-dependent (not universal)

$$A \ln\left(\frac{\mu}{\omega}\right) + A \ln\left(\frac{m}{\mu}\right) = A \ln\left(\frac{m}{\omega}\right)$$

Motivation

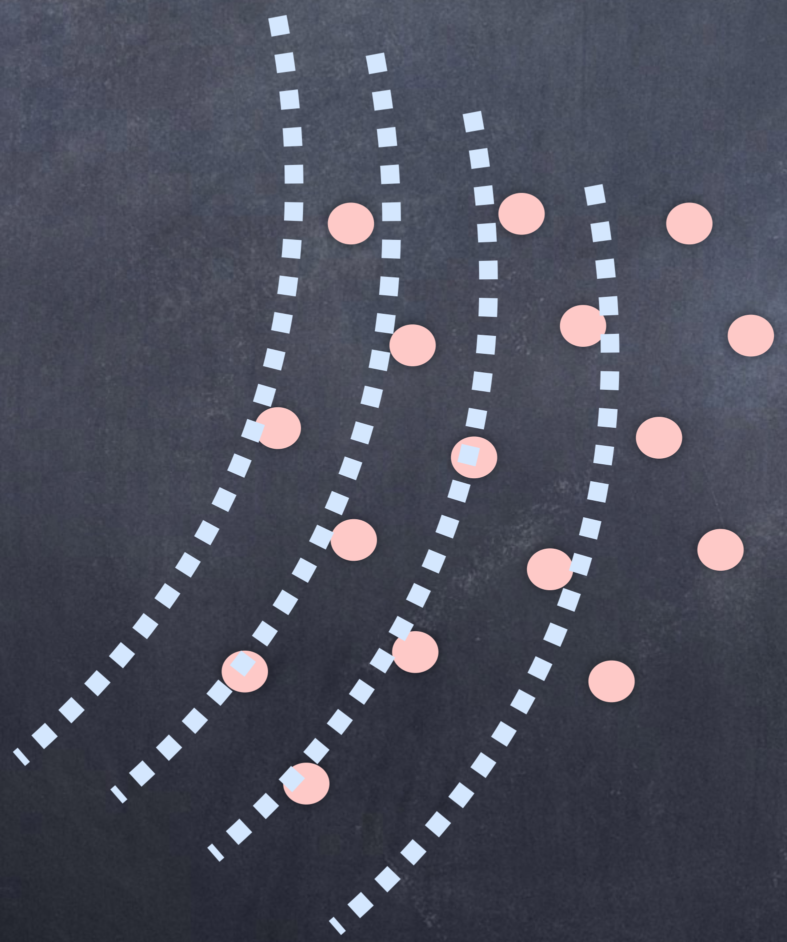
- Usually define EFT in terms of effective action (or hamiltonian), but *none* has emerged for inflation

$$\langle \mathcal{O}_1(\ell) \cdots \mathcal{O}_n(\ell) \rangle = \int \mathcal{D}\ell \, \mathcal{D}h \; e^{iS(\ell,h)} \, \mathcal{O}_1(\ell) \cdots \mathcal{O}_n(\ell)$$
$$= \int \mathcal{D}\ell \; e^{iS_{\text{eff}}(\ell)} \, \mathcal{O}_1(\ell) \cdots \mathcal{O}_n(\ell)$$

$$e^{iS_{\text{eff}}(\ell)} = \int \mathcal{D}h \; e^{iS(\ell,h)}$$

Open EFTs

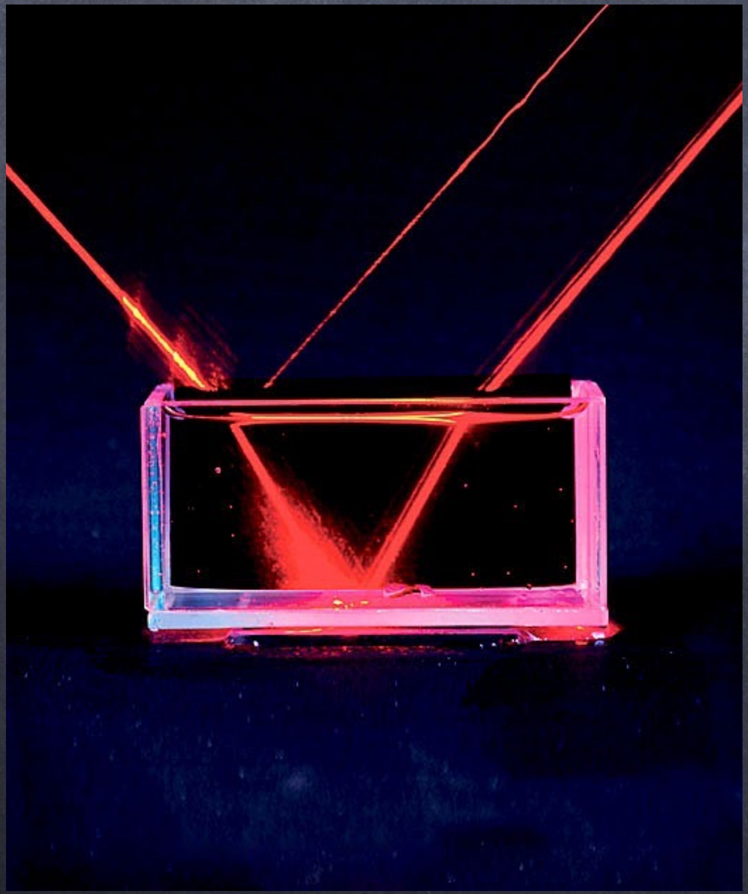
- Better analogy for inflation is effective description of a particle moving through a medium



Information can be exchanged so Hamiltonian description need not exist

Open EFTs

- Better analogy for inflation is effective description of a particle moving through a medium



Information can be exchanged so Hamiltonian description need not exist

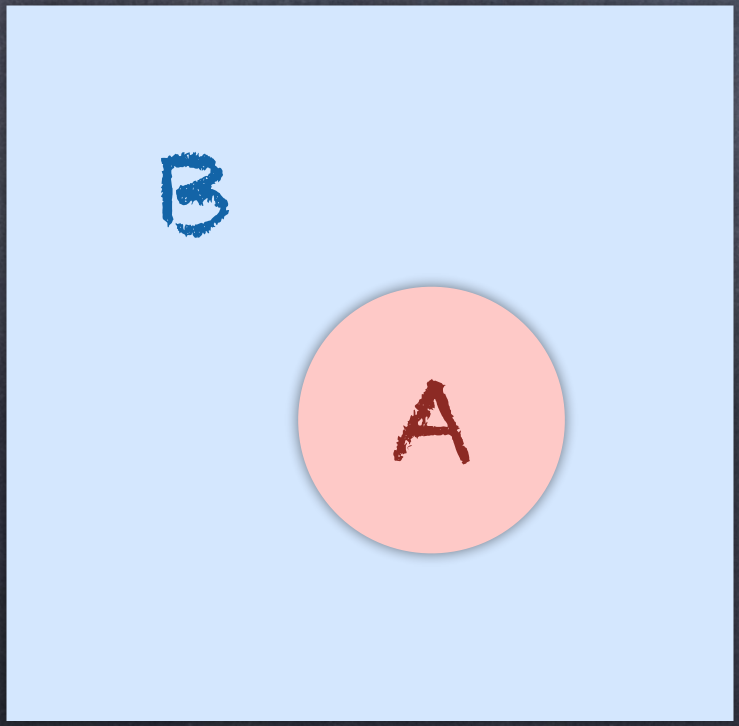
Naive perturbation theory fails at late times

Can nevertheless simplify when there is a hierarchy of scales

Open EFTs

- Open EFTs: consider the evolution of a subset A of a larger system B

    eg: light in glass or neutrinos in Sun



$$\rho_A = \mathrm{Tr}_B\, \rho$$

$$\frac{\partial \rho}{\partial t} = -i\left[\rho, H_{\rm int}\right]$$

Open EFTs

- **Open EFTs:** direct perturbative evolution shows state generically depends on entire entanglement history

$$\rho(t) = \rho_0 - i\int_0^t \mathrm{d}\tau\Big[H_{\rm int}(\tau),\rho_0\Big] + (-i)^2\int_0^t \mathrm{d}\tau\int_0^\tau \mathrm{d}\tilde\tau\Big[H_{\rm int}(\tilde\tau),\Big[H_{\rm int}(\tau),\rho_0\Big]\Big] + \cdots$$

but can simplify if correlations die out over time

$$\langle H_{\rm int}(t) H_{\rm int}(t+\tau)\rangle_B \to 0 \qquad \text{for} \quad \tau \gg t_c$$

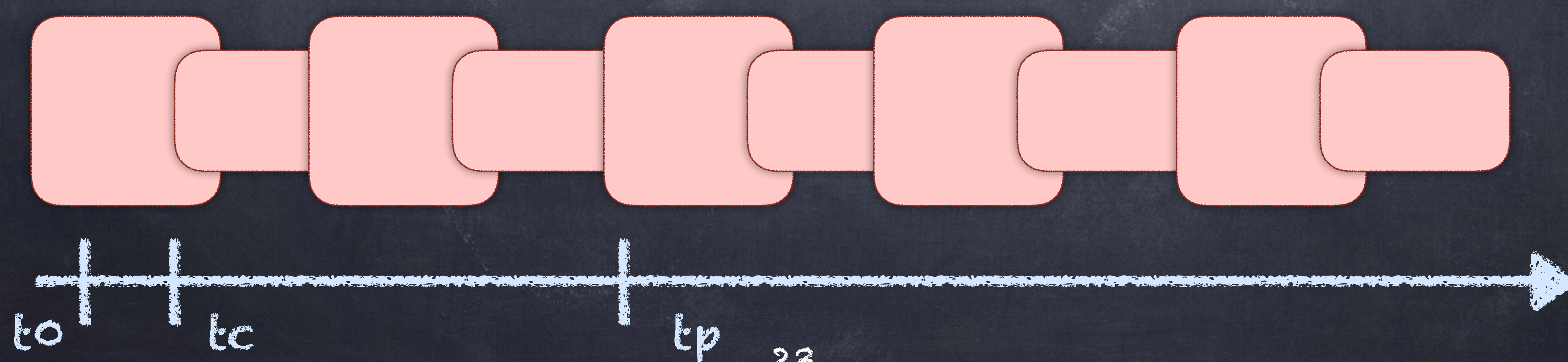
provided tc << tp not so large that perturbation theory fails

Open EFTs

- **The point:** if you can integrate the coarse-grained evolution equation

$$\frac{\partial \rho_A}{\partial t} = F(\rho_A, \rho_B, H_{\rm int})$$

can trust the solution even for $t \gg t_p$ provided there are overlapping regions each of which satisfies $t_c \ll \Delta t \ll t_p$



Stochastic Inflation

CPB, Holman, Tasinato & Williams

- For super-Hubble modes in cosmology: sector A consists of modes with $k/a \ll H$ and it is crossing of modes through Hubble scale that makes Open EFT the more useful framework
- Stochastic inflation corresponds to dropping all interactions at horizon exit except those with the background spacetime
  - Useful to compute $\langle \phi \,|\, \rho_A \,|\, \phi' \rangle$ for ϕ position-space field coarse grained over Hubble scale

Stochastic Inflation

Starobinsky

- In stochastic formulation diagonal elements ($P = \langle \phi | \rho A | \phi' \rangle$) is governed by

$$\frac{\partial P}{\partial t} = \frac{\partial}{\partial \phi}\left[N\frac{\partial P}{\partial \phi} + \frac{\partial}{\partial \phi}\Big(FP\Big)\right]$$

with coefficients N and F given by

$$N = \frac{H^3}{8\pi^2} + \cdots \qquad \text{and} \qquad F = \frac{V'(\phi)}{3H} + \cdots$$

Stochastic Inflation

- For $V = \lambda\,\phi^4$ this FP equation is known to capture the IR singular part of the field theory

Tsamis & Woodard

$$\frac{\partial P}{\partial t} = \frac{H^3}{8\pi^2}\frac{\partial^2 P}{\partial \phi^2} + \frac{\lambda}{18H}\frac{\partial}{\partial \phi}\left(\phi^3 P\right)$$

late-time is described by static solution, dP/dt = 0:

Starobinsky

$$P \propto \exp\left[-\frac{8\pi^2 V}{3H^4}\right]$$

Stochastic Inflation

- Derivation as leading part of Master equation shows why FP equation should resum the late-time behaviour in more general systems
- Must also include corrections (eg in m/H and ε): these needed to give results that are IR safe:
    - Expect late-time P(ϕ) to be finite because this appears in the expression for any observable

Stochastic Inflation

CPB, Holman & Tasinato

- For example if we compute N and F as functions of m/H and ε = -(dH/dt)/H^2

$$F = CH\phi \approx \frac{m^2\phi}{(3-\epsilon)H} + \cdots$$

$$N = \frac{H^3}{8\pi^2}\mathcal{F}(\nu) \approx \frac{H^3}{8\pi^2}\left[1 + k(3-2\nu) + \cdots\right]$$

$$C = \frac{3-\epsilon}{2}\left[1 - \sqrt{1 - \frac{4m^2}{(3-\epsilon)H^2}}\right] \qquad \nu = \frac{3-\epsilon}{2(1-\epsilon)}\sqrt{1 - \frac{4m^2}{(3-\epsilon)^2H^2}}$$

Stochastic Inflation

CPB, Holman & Tasinato

- Variance of field is IR singular

$$\frac{1}{2}\partial_t\langle(\phi-\langle\phi\rangle)^2\rangle = \langle N\rangle + (\langle\phi F\rangle - \langle\phi\rangle\langle F\rangle)$$

- Although variance is IR singular, corrections ensure N and $F(\phi)$ are not; guaranteeing IR finite $P(\phi)$ at late times

Conclusions

- IR and secular issues in cosmology are a special case of the general problem of perturbative failure at late times
  - Similar statement for BH information loss?
- Solution and late-time resummation is provided by same methods as are useful elsewhere
  - Master-equation methods for reduced density matrix
- For inflation find Stochastic inflation as leading description, and this explains evidence for stochastic inflation resumming IR divergences in simple examples
  - Spin-off: shows why primordial quantum fluctuations decohere

Happy 60th B-day

- may there be many more!