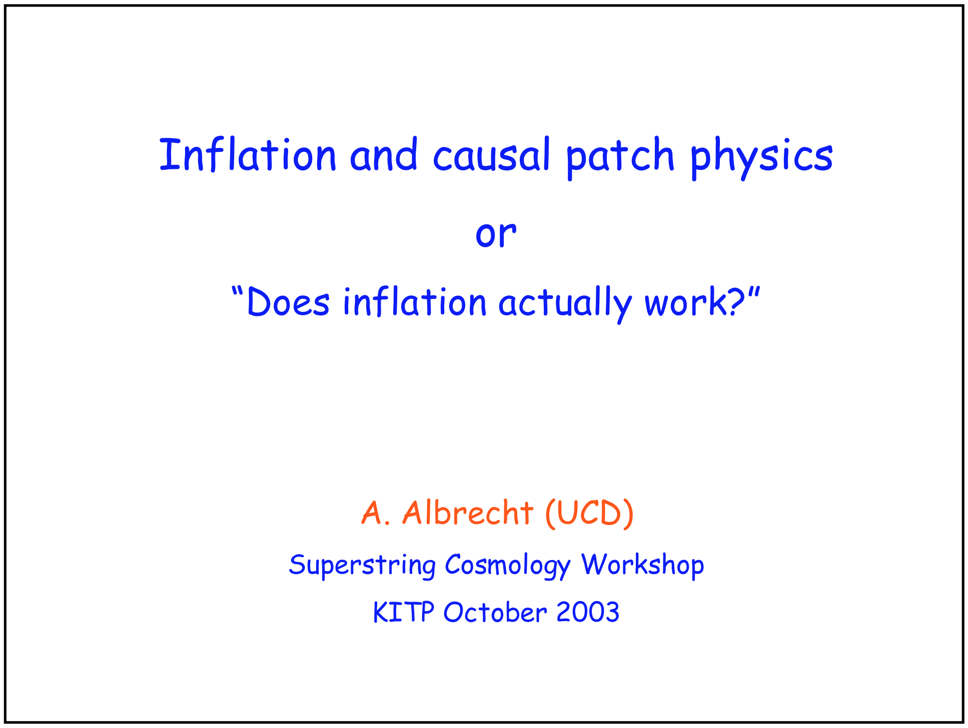


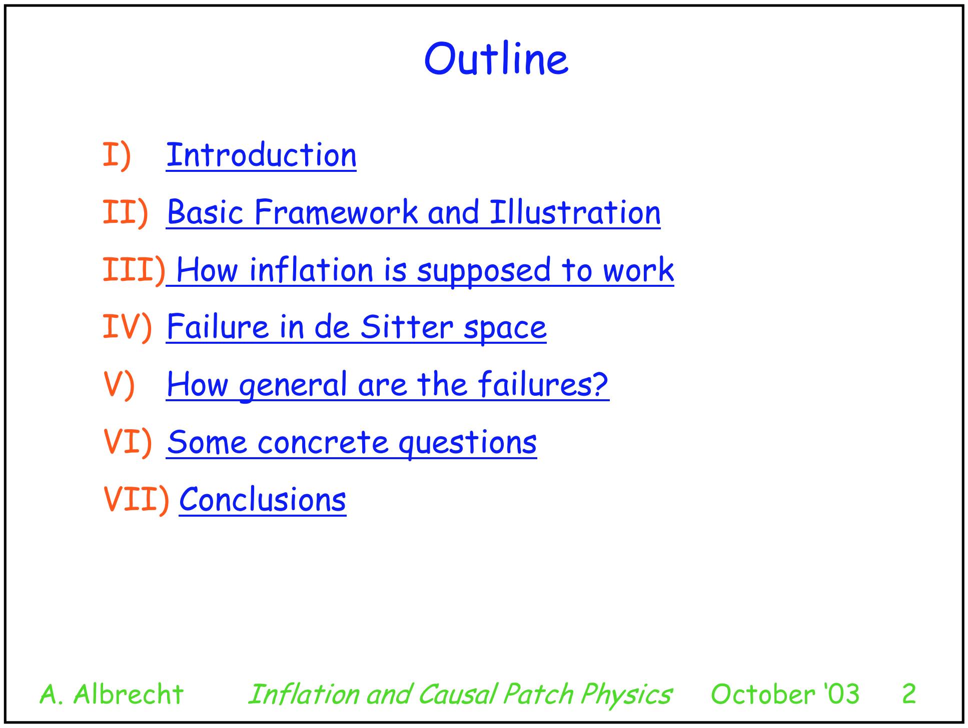
Inflation and causal patch physics

or

“Does inflation actually work?”

A. Albrecht (UCD)

Superstring Cosmology Workshop
KITP October 2003



Outline

I) Introduction
II) Basic Framework and Illustration
III) How inflation is supposed to work
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VI) Some concrete questions
VII) Conclusions

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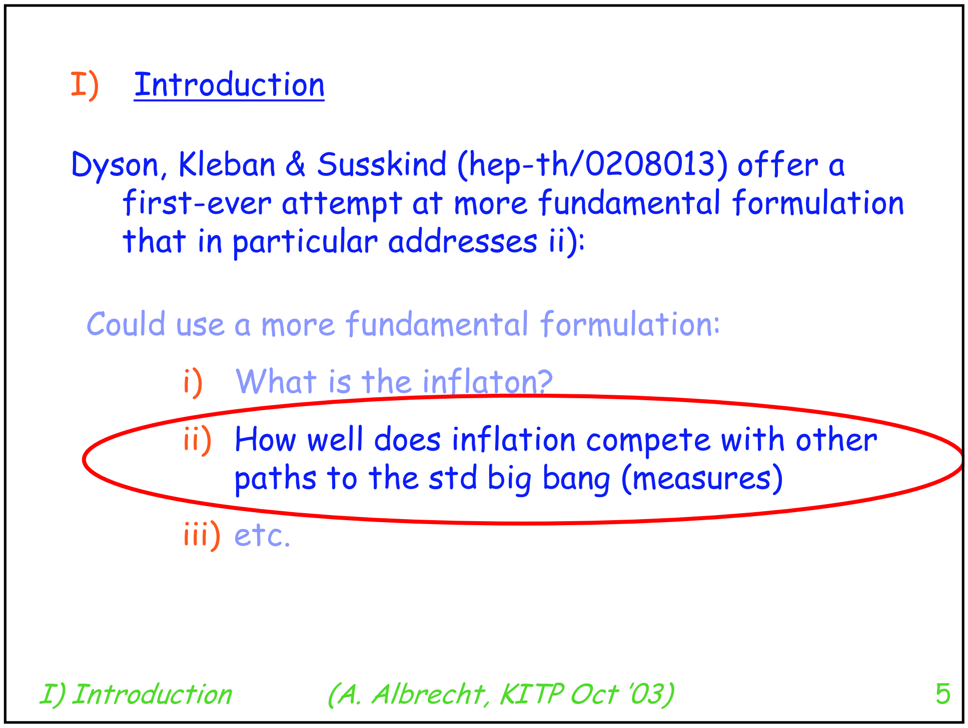
I) Introduction

Things everybody knows about Cosmic Inflation:

- Solves cosmological puzzles
- Makes a host of predictions
- Has faced the possibility of falsification and emerged a brilliant success.
- Could use a more fundamental formulation:
  - i) What is the inflaton?
  - ii) How well does inflation compete with other paths to the std big bang? (measures)
  - iii) etc.



I) Introduction

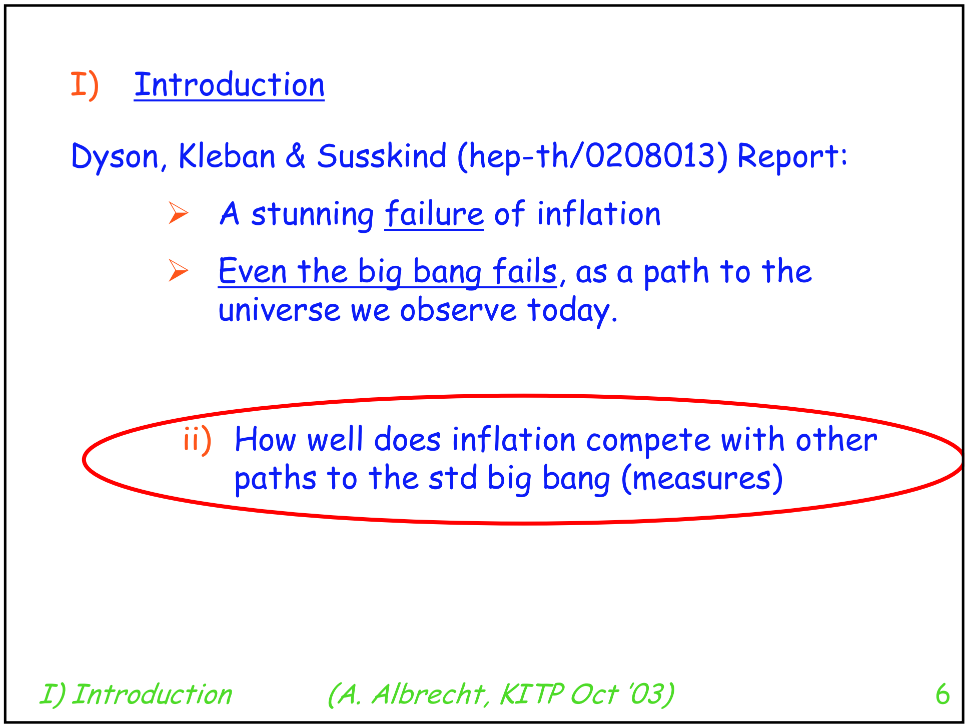
Dyson, Kleban & Susskind (hep-th/0208013) offer a first-ever attempt at more fundamental formulation that in particular addresses ii):

Could use a more fundamental formulation:

i) What is the inflaton?

ii) How well does inflation compete with other paths to the std big bang (measures)

iii) etc.

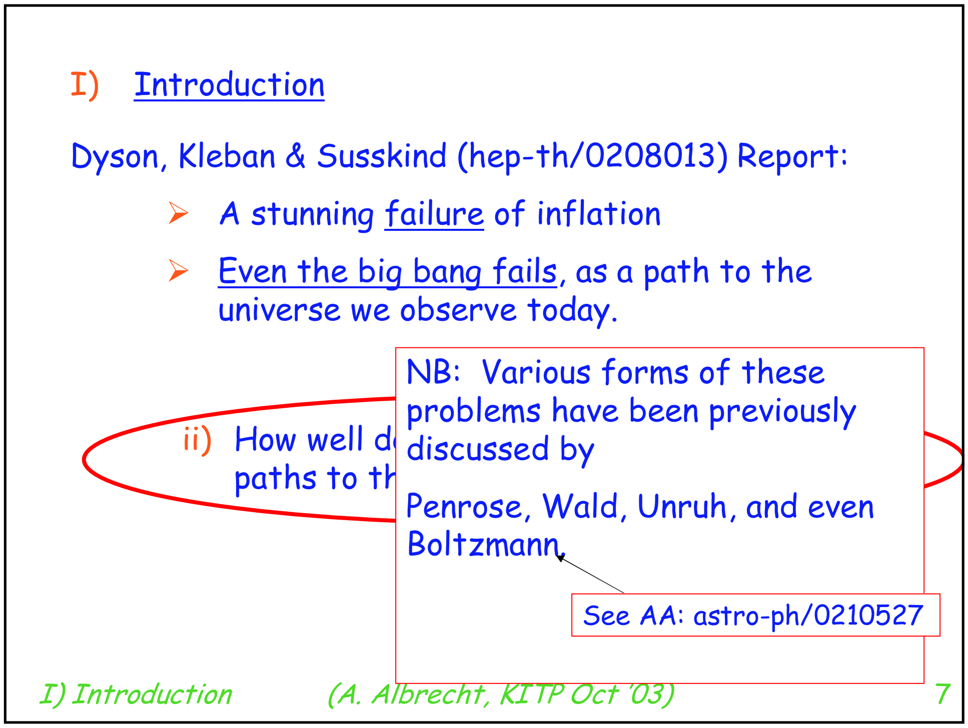


I) Introduction

Dyson, Kleban & Susskind (hep-th/0208013) Report:

- ➢ A stunning failure of inflation
- ➢ Even the big bang fails, as a path to the universe we observe today.

ii) How well does inflation compete with other paths to the std big bang (measures)



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Dyson, Kleban & Susskind (hep-th/0208013) Report:

- A stunning failure of inflation
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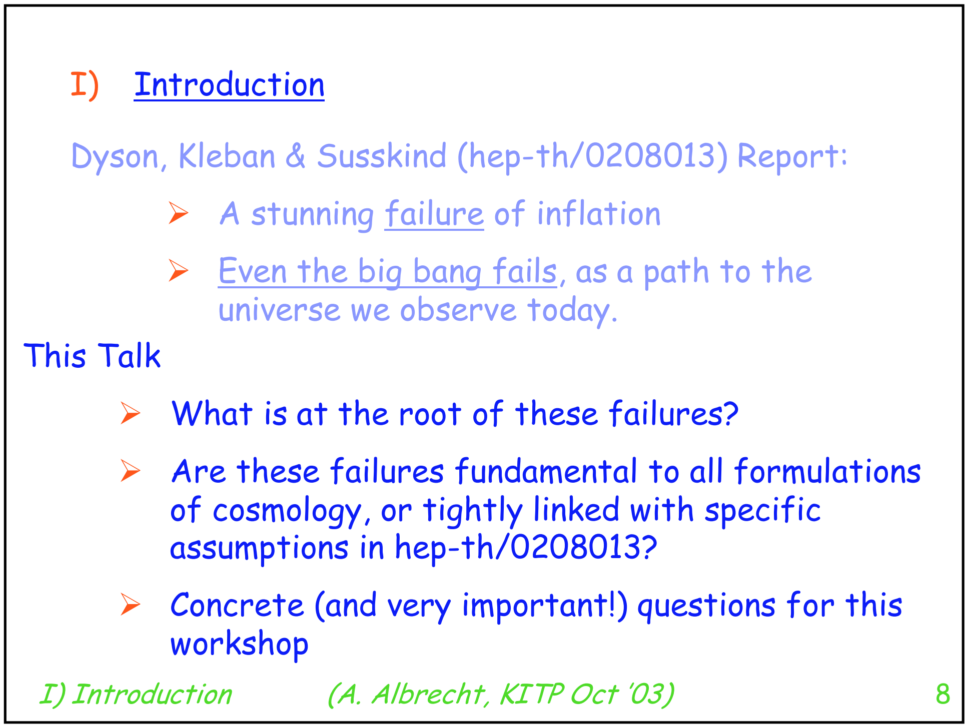
ii) How well d
paths to th

NB: Various forms of these problems have been previously discussed by

Penrose, Wald, Unruh, and even Boltzmann

See AA: astro-ph/0210527

I) Introduction *(A. Albrecht, KITP Oct '03)* 7



I) Introduction

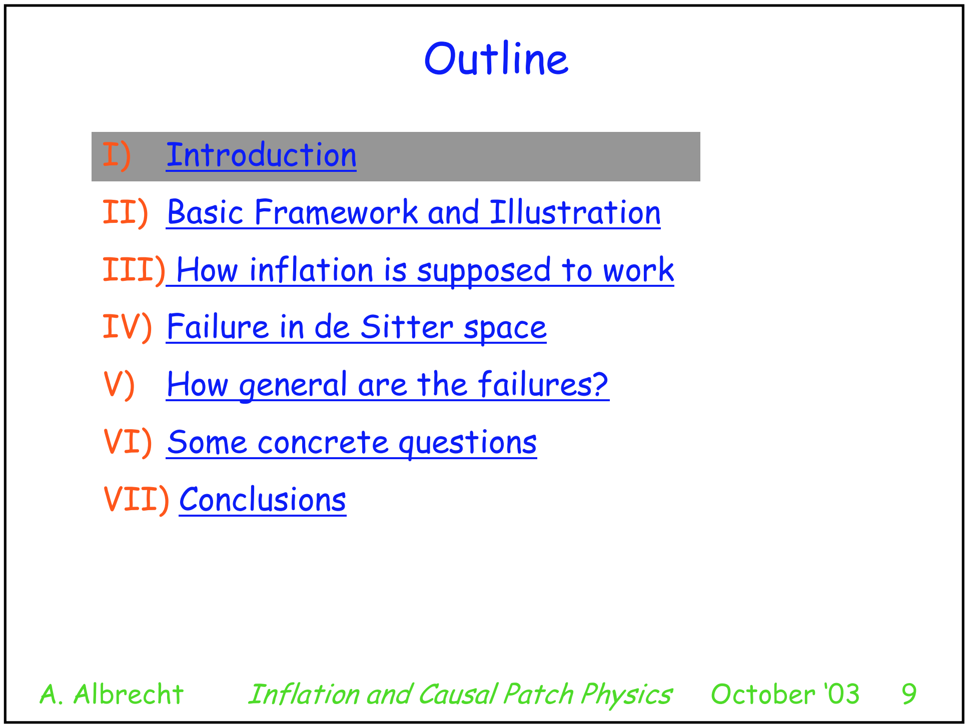
Dyson, Kleban & Susskind (hep-th/0208013) Report:

- A stunning failure of inflation
- Even the big bang fails, as a path to the universe we observe today.

This Talk

- What is at the root of these failures?
- Are these failures fundamental to all formulations of cosmology, or tightly linked with specific assumptions in hep-th/0208013?
- Concrete (and very important!) questions for this workshop

I) Introduction *(A. Albrecht, KITP Oct '03)* 8



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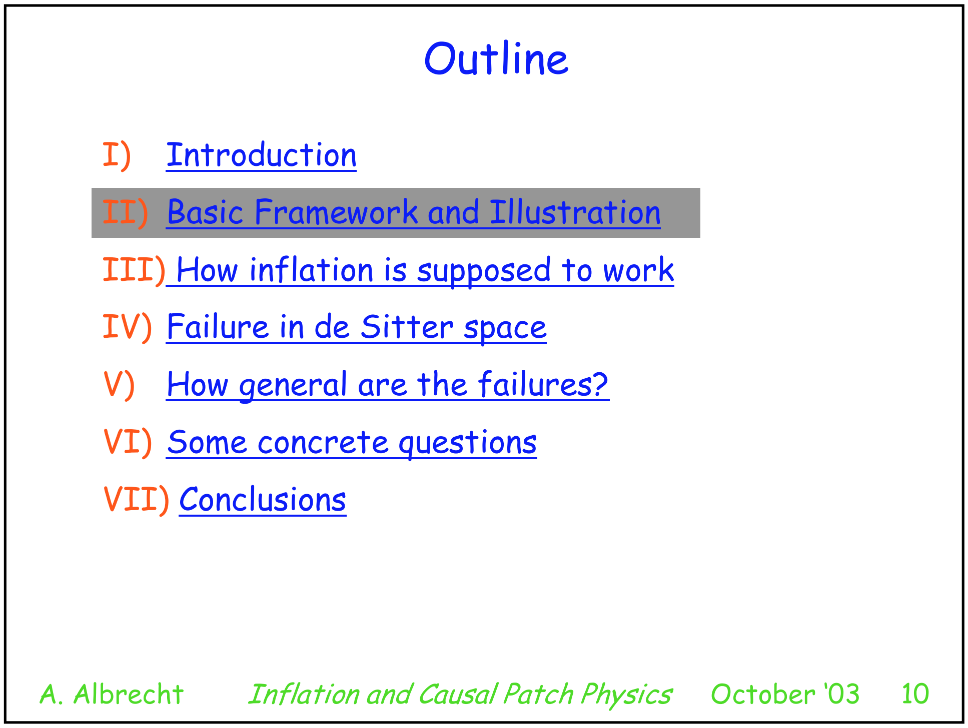

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II) Basic Framework and Illustration

- The universe spends most of its time in “equilibrium”
- The equilibrium state is given by an observer’s causal patch in de Sitter space with a very small Λ.
- Cosmology given by the generation of rare fluctuations away from this eqm. state.
- Recurrence times/probabilities given by:

$$\boxed{t_{fluct} = t_R \frac{N_{fluct}}{N_{tot}} = t_R \frac{e^{S_{fluct}}}{e^{S_\Lambda}}} \qquad \boxed{P_{fluct} = \frac{t_{fluct}}{t_R} = \frac{e^{S_{fluct}}}{e^{S_\Lambda}} = e^{S_{fluct}-S_\Lambda}}$$

II) Basic Framework and Illustration

- Recurrence times/probabilities given by:

$$\boxed{t_{fluct} = t_R \frac{N_{fluct}}{N_{tot}} = t_R \frac{e^{S_{fluct}}}{e^{S_\Lambda}}} \qquad \boxed{P_{fluct} = \frac{t_{fluct}}{t_R} = \frac{e^{S_{fluct}}}{e^{S_\Lambda}} = e^{S_{fluct}-S_\Lambda}}$$

t_{fluct} = Recurrence time for a particular fluctuation

t_R = Recurrence time for whole system

N_{fluct} = Number of microstates consistent with the fluctuation

N_{Tot} = Total microstates of system

$S_\Lambda \approx \Lambda^{-1}$ = Total microstates of system

P_{fluct} = Probability of fluctuation

II) Basic Framework and Illustration

- Recurrence times/probabilities given by:

$$t_{fluct} = t_R \frac{N_{fluct}}{N_{tot}} = t_R \frac{e^{S_{fluct}}}{e^{S_\Lambda}}$$

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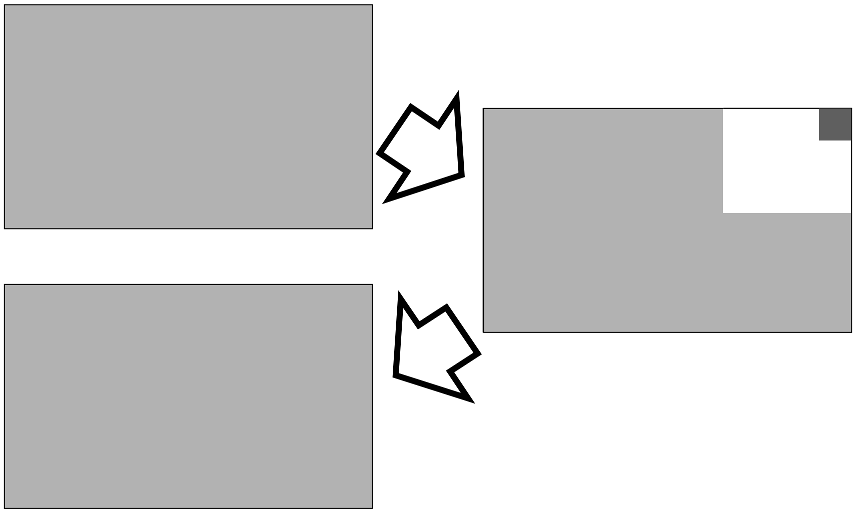
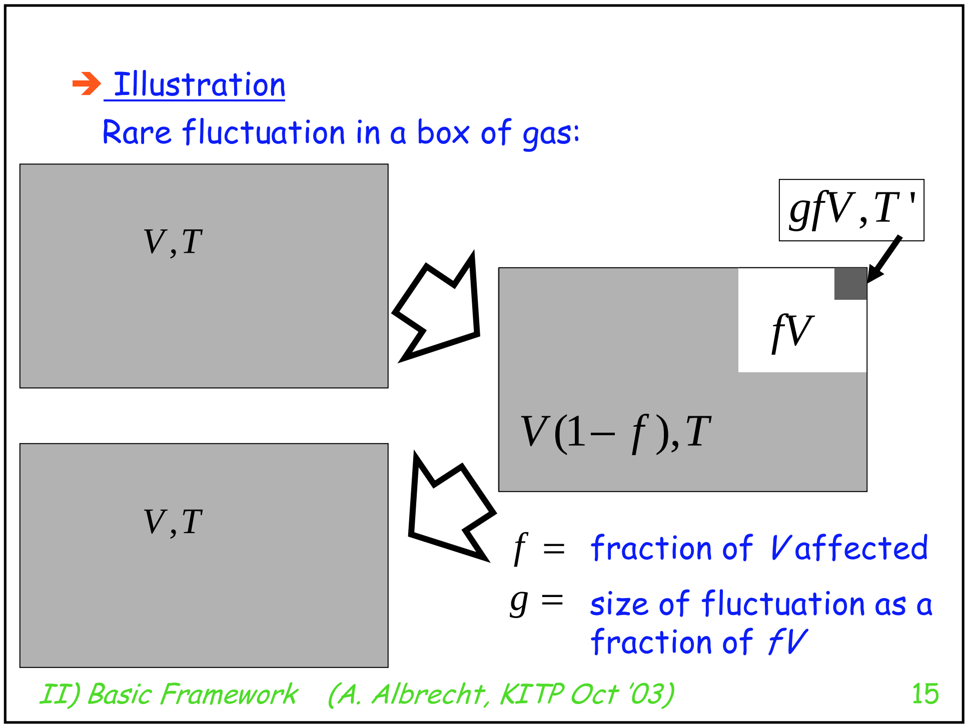
P_{fluct} = Probability of fluctuation

NB: Assumes "ergodic" behavior

➔ Illustration

Rare fluctuation in a box of gas:



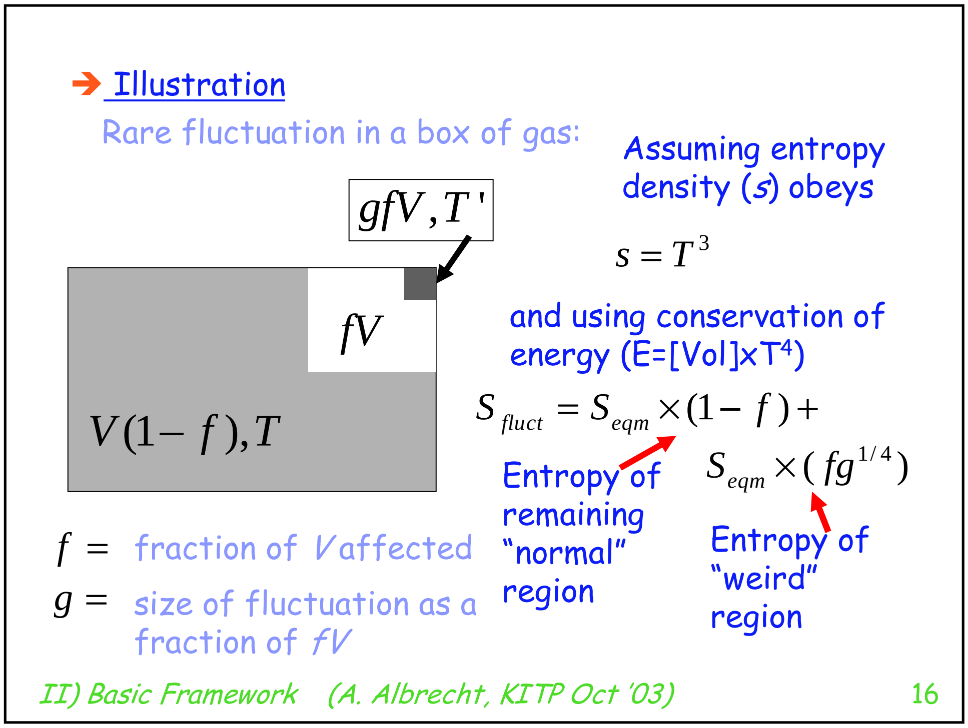


➔ Illustration

Rare fluctuation in a box of gas:

f = fraction of V affected

g = size of fluctuation as a fraction of fV



➔ Illustration

Rare fluctuation in a box of gas:

Assuming entropy density (s) obeys

$$s = T^3$$

and using conservation of energy (E=[Vol]xT^4)

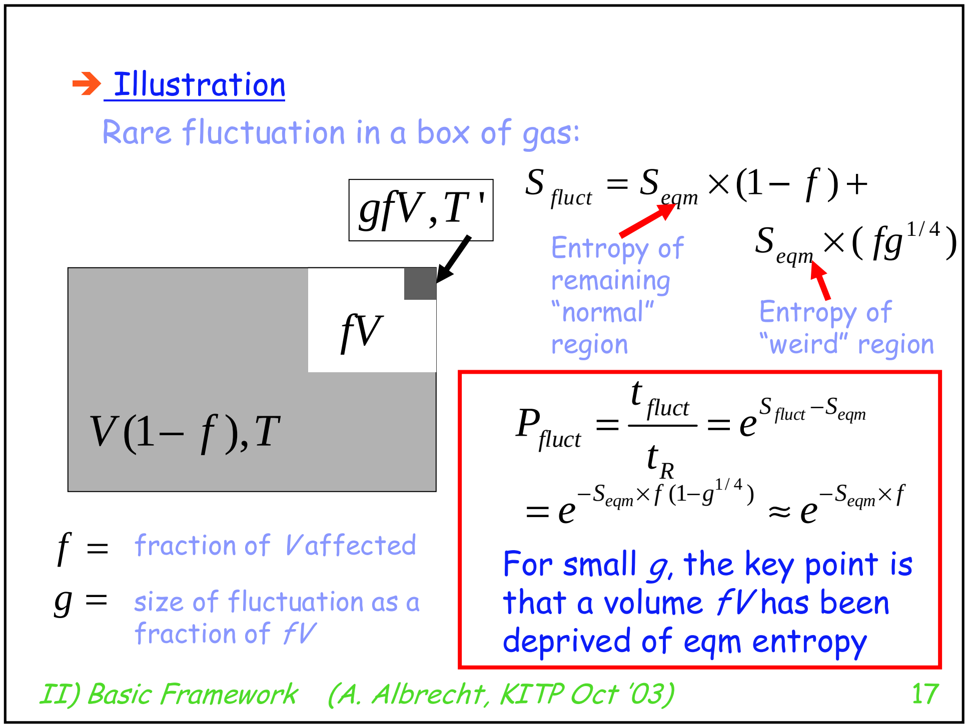
$$S_{fluct} = S_{eqm} \times (1-f) + S_{eqm} \times (fg^{1/4})$$

Entropy of remaining "normal" region

Entropy of "weird" region

f = fraction of V affected

g = size of fluctuation as a fraction of fV



→ Illustration

Rare fluctuation in a box of gas:

$$S_{fluct} = S_{eqm}\times(1-f) + S_{eqm}\times(fg^{1/4})$$

Entropy of remaining "normal" region

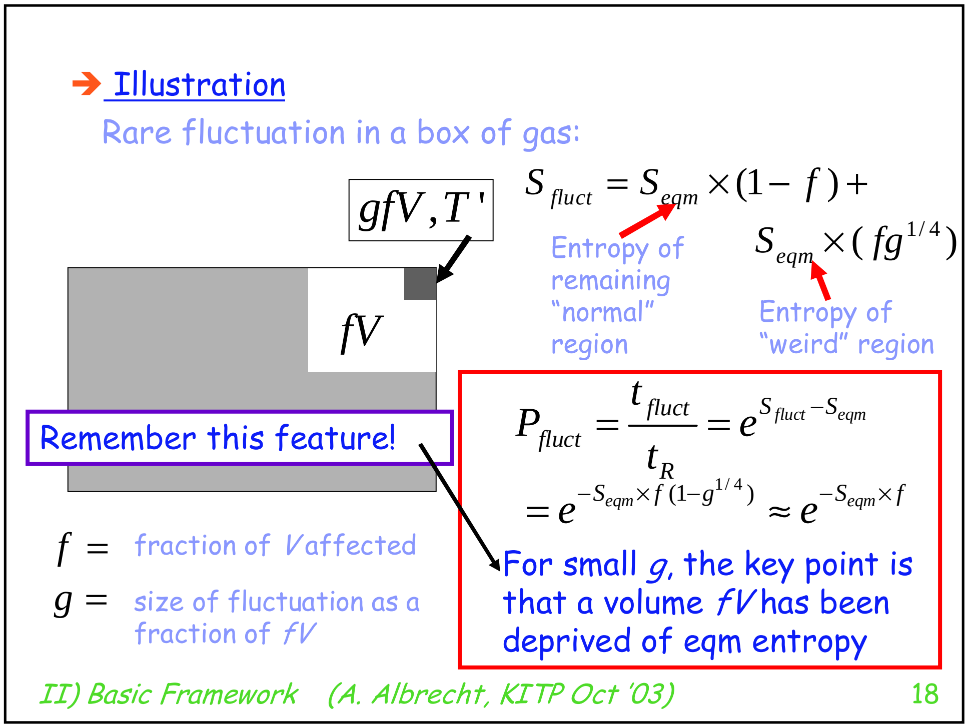
Entropy of "weird" region

$$P_{fluct} = \frac{t_{fluct}}{t_R} = e^{S_{fluct}-S_{eqm}}$$
$$= e^{-S_{eqm}\times f(1-g^{1/4})} \approx e^{-S_{eqm}\times f}$$

For small *g*, the key point is that a volume *fV* has been deprived of eqm entropy

f = fraction of *V* affected

g = size of fluctuation as a fraction of *fV*



→ Illustration

Rare fluctuation in a box of gas:

$$S_{fluct} = S_{eqm}\times(1-f) + S_{eqm}\times(fg^{1/4})$$

Entropy of remaining "normal" region

Entropy of "weird" region

Remember this feature!

$$P_{fluct} = \frac{t_{fluct}}{t_R} = e^{S_{fluct}-S_{eqm}}$$
$$= e^{-S_{eqm}\times f(1-g^{1/4})} \approx e^{-S_{eqm}\times f}$$

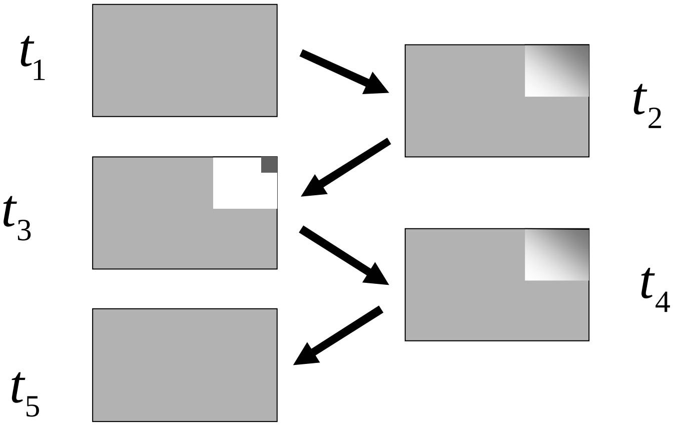
For small *g*, the key point is that a volume *fV* has been deprived of eqm entropy

f = fraction of *V* affected

g = size of fluctuation as a fraction of *fV*

➔ Illustration

NB: You must choose the *minimum* entropy point to get the right answer ($S(t_3)$, not $S(t_2)$ or $S(t_4)$)



II) Basic Framework and Illustration

General Comments:

- ➢ Assumed ergodicity + specific physical system➔ concrete framework for calculating recurrence times and probabilities.
- ➢ Dyson et al use this scheme to quantify the competition between different paths to the observed universe..
- ➢ Fischler & Banks (2002): QM fails on $t \ll t_R$. AA: "don't worry".
- ➢ This is stat mech, *not* thermodynamics!

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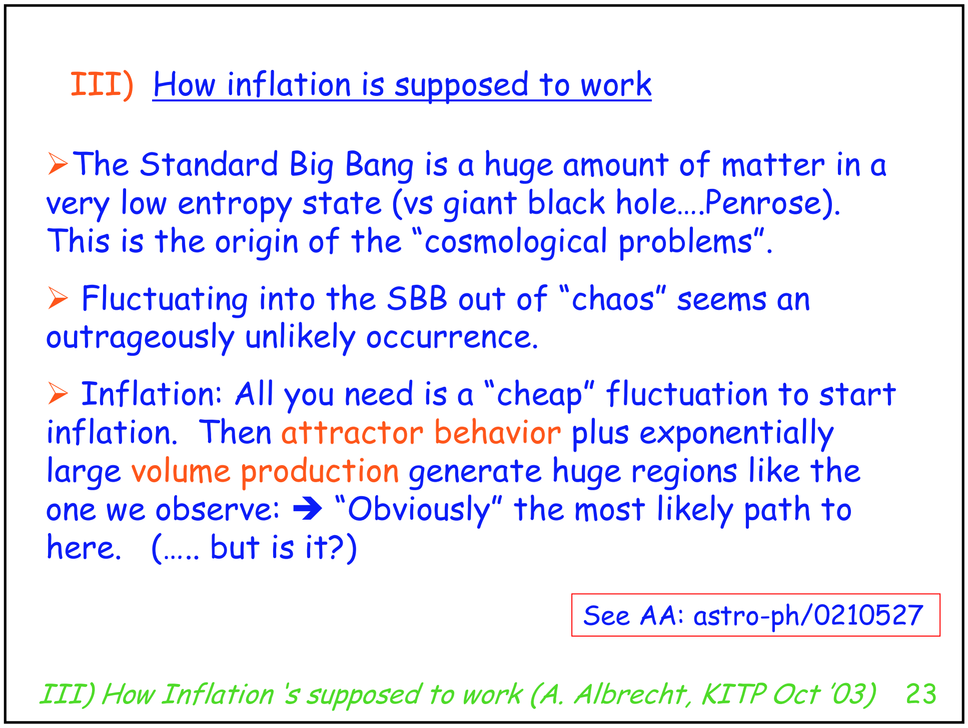
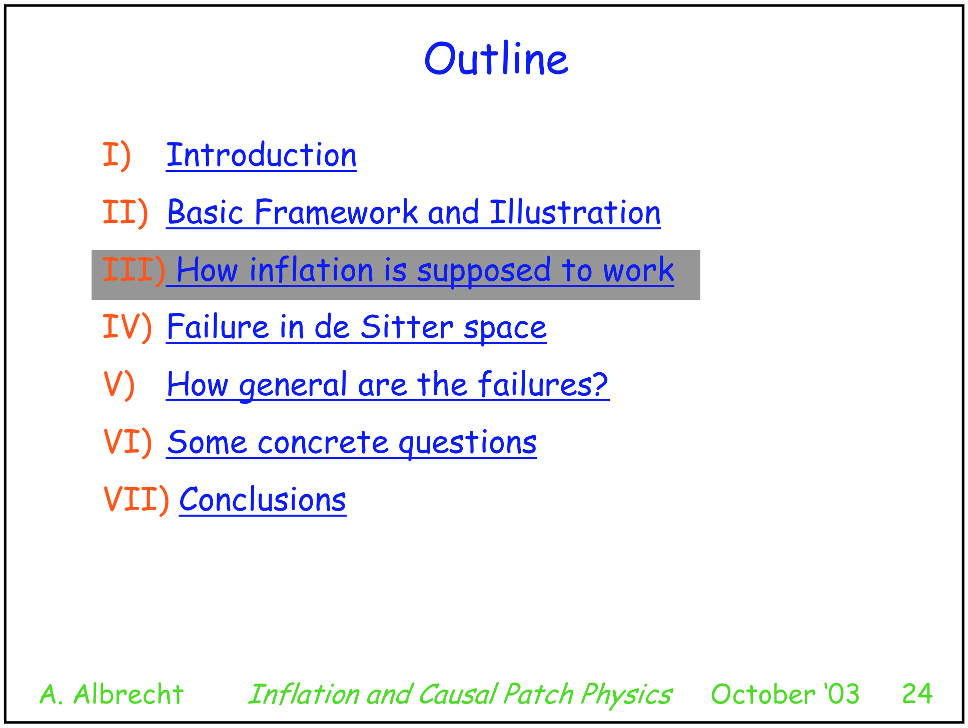


III) How inflation is supposed to work

- The Standard Big Bang is a huge amount of matter in a very low entropy state (vs giant black hole….Penrose). This is the origin of the "cosmological problems".
- Fluctuating into the SBB out of "chaos" seems an outrageously unlikely occurrence.
- Inflation: All you need is a "cheap" fluctuation to start inflation. Then attractor behavior plus exponentially large volume production generate huge regions like the one we observe: ➔ "Obviously" the most likely path to here. (….. but is it?)

See AA: astro-ph/0210527



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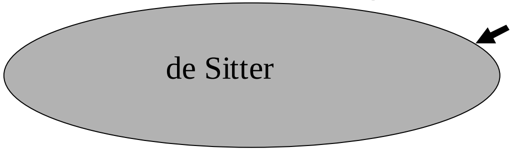
IV) Failure in de Sitter space

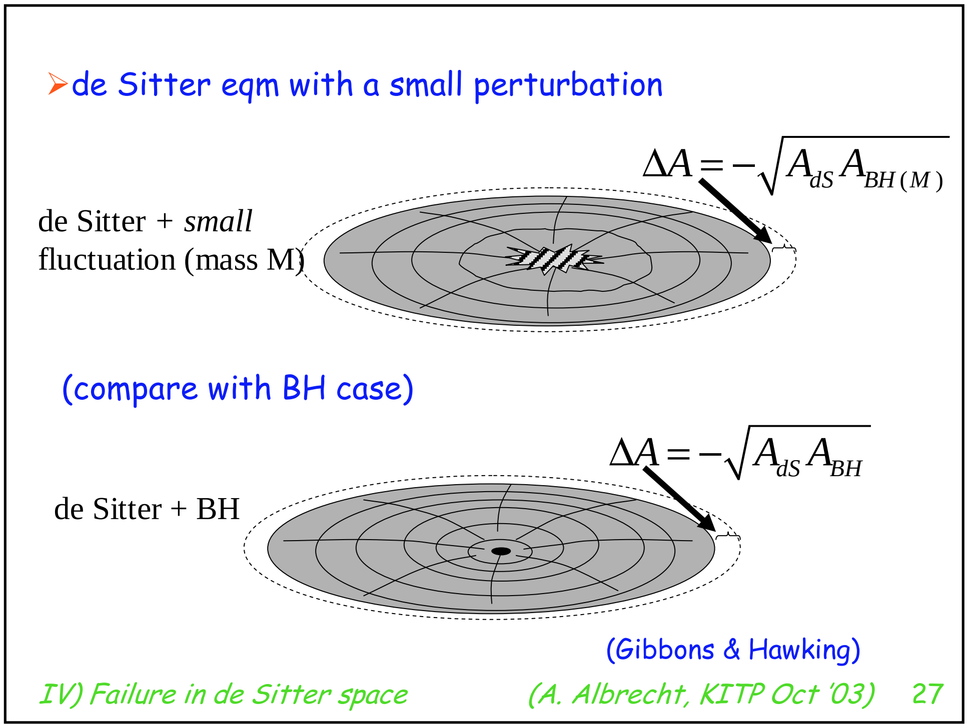
Dyson, Kleban & Susskind (hep-th/0208013)

- ➢Starting point: de Sitter eqm

$$S \propto A = H^{-2} = \Lambda^{-1}$$



NB: Λ must be small enough to give current acceleration…. could be much smaller.



- de Sitter eqm with a small perturbation

$$\Delta A = -\sqrt{A_{dS} A_{BH(M)}}$$

de Sitter + *small*
fluctuation (mass M)

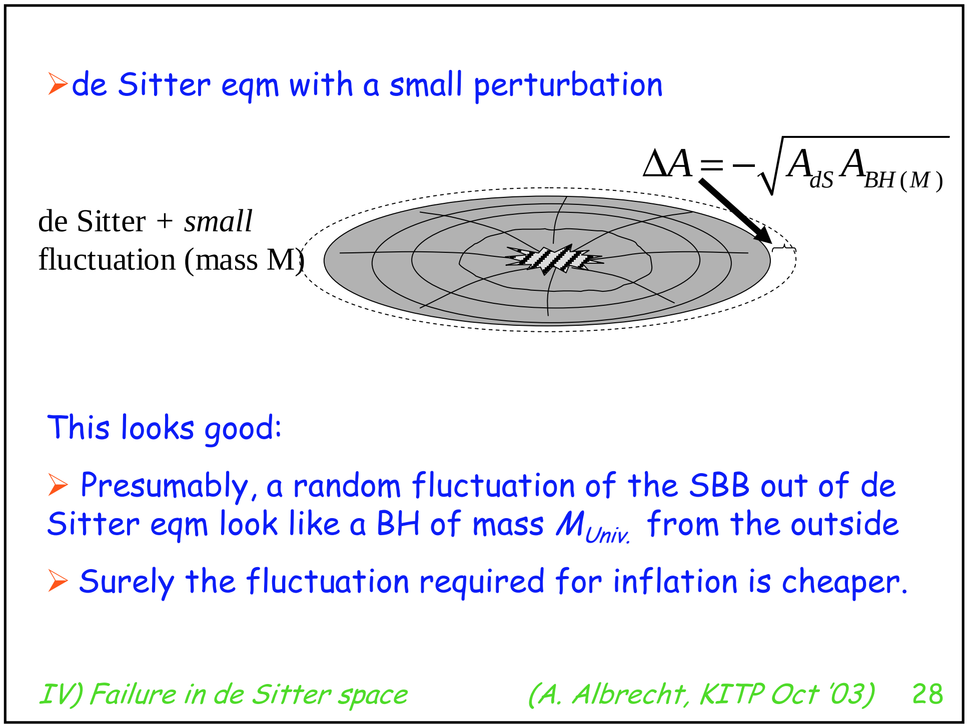
(compare with BH case)

$$\Delta A = -\sqrt{A_{dS} A_{BH}}$$

de Sitter + BH

(Gibbons & Hawking)

IV) Failure in de Sitter space *(A. Albrecht, KITP Oct '03)* 27



- de Sitter eqm with a small perturbation

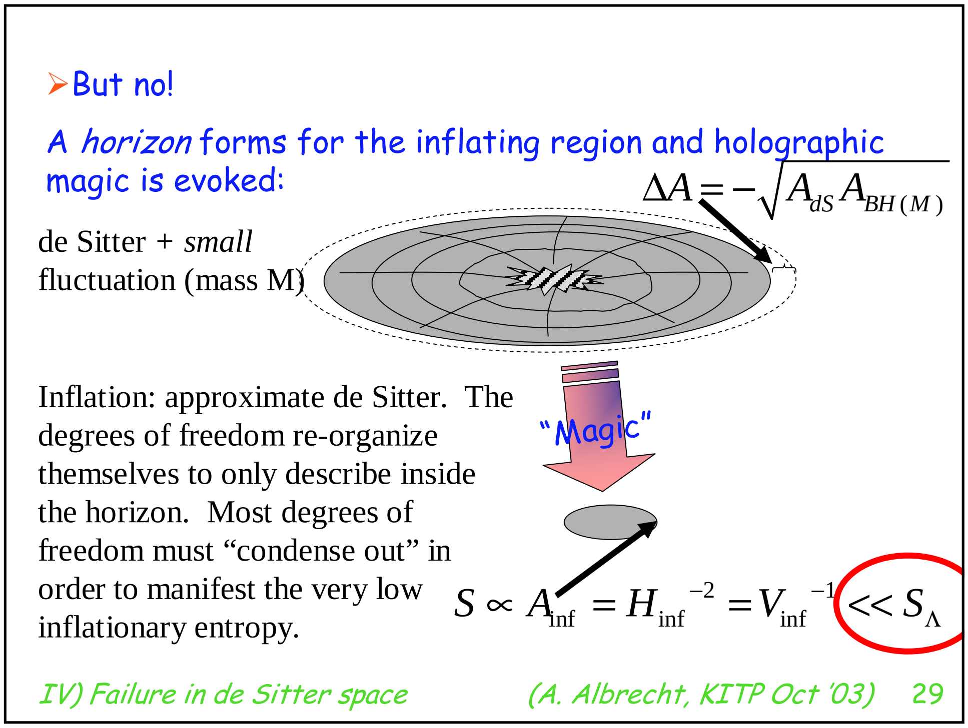
$$\Delta A = -\sqrt{A_{dS} A_{BH(M)}}$$

de Sitter + *small*
fluctuation (mass M)

This looks good:

- Presumably, a random fluctuation of the SBB out of de Sitter eqm look like a BH of mass $M_{Univ.}$ from the outside
- Surely the fluctuation required for inflation is cheaper.

IV) Failure in de Sitter space *(A. Albrecht, KITP Oct '03)* 28



- But no!

A *horizon* forms for the inflating region and holographic magic is evoked:

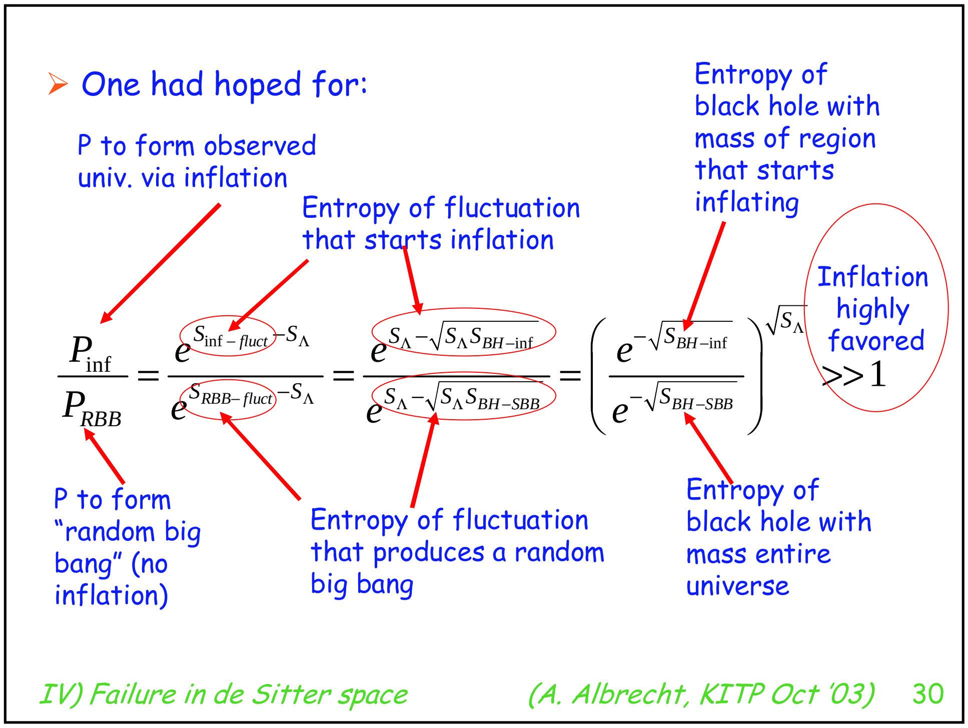
$$\Delta A = -\sqrt{A_{dS} A_{BH(M)}}$$

de Sitter + *small* fluctuation (mass M)

Inflation: approximate de Sitter. The degrees of freedom re-organize themselves to only describe inside the horizon. Most degrees of freedom must "condense out" in order to manifest the very low inflationary entropy.

$$S \propto A_{\inf} = H_{\inf}^{-2} = V_{\inf}^{-1} << S_{\Lambda}$$

IV) Failure in de Sitter space *(A. Albrecht, KITP Oct '03)* 29



- One had hoped for:

P to form observed univ. via inflation

Entropy of fluctuation that starts inflation

Entropy of black hole with mass of region that starts inflating

$$\frac{P_{\inf}}{P_{RBB}} = \frac{e^{S_{\inf-fluct}-S_{\Lambda}}}{e^{S_{RBB-fluct}-S_{\Lambda}}} = \frac{e^{S_{\Lambda}-\sqrt{S_{\Lambda}S_{BH-\inf}}}}{e^{S_{\Lambda}-\sqrt{S_{\Lambda}S_{BH-SBB}}}} = \left(\frac{e^{-\sqrt{S_{BH-\inf}}}}{e^{-\sqrt{S_{BH-SBB}}}}\right)^{\sqrt{S_{\Lambda}}} >> 1$$

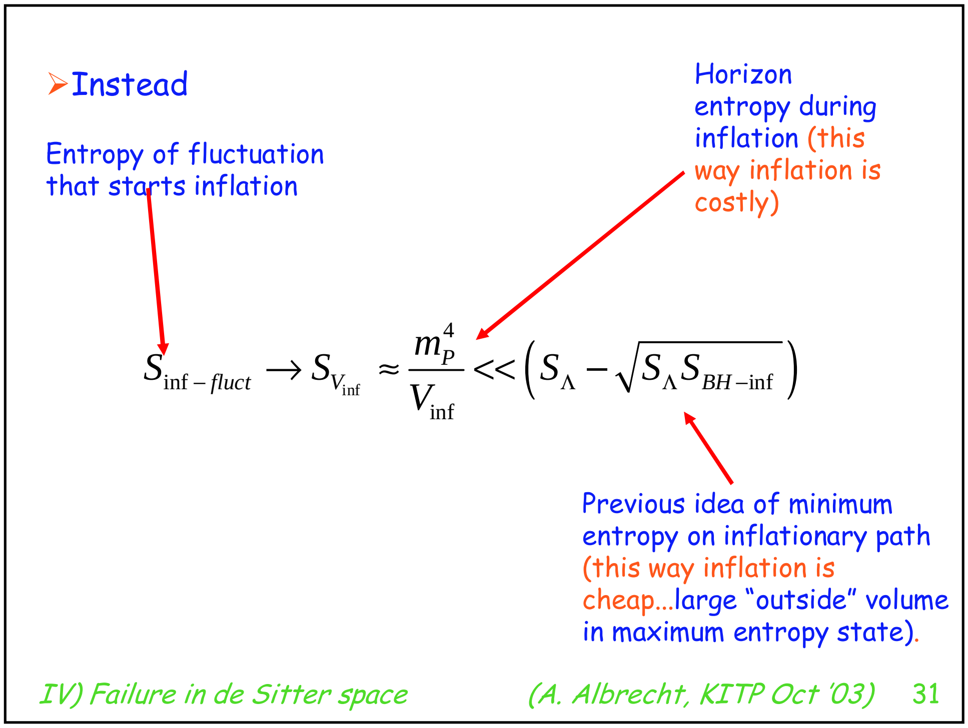
Inflation highly favored

P to form "random big bang" (no inflation)

Entropy of fluctuation that produces a random big bang

Entropy of black hole with mass entire universe

IV) Failure in de Sitter space *(A. Albrecht, KITP Oct '03)* 30



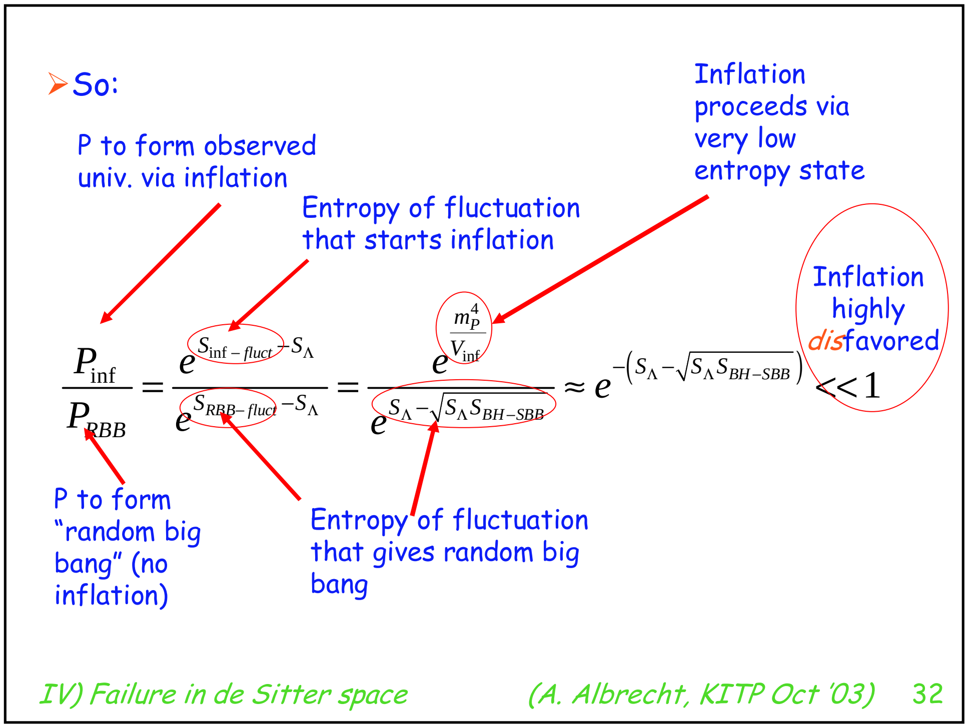
- **Instead**

Entropy of fluctuation that starts inflation

Horizon entropy during inflation (this way inflation is costly)

$$S_{\inf - fluct} \to S_{V_{\inf}} \approx \frac{m_P^4}{V_{\inf}} << \left(S_\Lambda - \sqrt{S_\Lambda S_{BH - \inf}} \right)$$

Previous idea of minimum entropy on inflationary path (this way inflation is cheap…large “outside” volume in maximum entropy state).



- **So:**

P to form observed univ. via inflation

Inflation proceeds via very low entropy state

Entropy of fluctuation that starts inflation

$$\frac{P_{\inf}}{P_{RBB}} = \frac{e^{S_{\inf - fluct} - S_\Lambda}}{e^{S_{RBB - fluct} - S_\Lambda}} = \frac{e^{\frac{m_P^4}{V_{\inf}}}}{e^{S_\Lambda - \sqrt{S_\Lambda S_{BH - SBB}}}} \approx e^{-\left(S_\Lambda - \sqrt{S_\Lambda S_{BH - SBB}} \right)} << 1$$

Inflation highly disfavored

P to form “random big bang” (no inflation)

Entropy of fluctuation that gives random big bang

➢Volume factors:

Q: According to Dyson *et al* the "cheap fluctuation" is an illusion. Can it be made up for by exponentially large volume produced by inflation?

A Consider a "volume enhancement" of

$$P_{\inf} \to P_{\inf} N_{H_0}$$

where N_{H_0} is the number of different reheated volumes that are the size of the observed universe

➢Volume factors (cont.)

A Consider a "volume enhancement" of $P_{\inf} \to P_{\inf} N_{H_0}$

But $N_{H_0}^{\max} = \left(\frac{\Lambda_0}{\Lambda}\right)^{3/2}$ (or $N_{H_0}^{\max} = A\left(\frac{\Lambda_0}{\Lambda}\right)^{5/2}$)

$$N_{H_0} \geq e^{\left(S_\Lambda - \sqrt{S_\Lambda S_{BH-SBB}}\right)}$$

and $S_\Lambda = S_{\Lambda_0} \frac{\Lambda_0}{\Lambda} = S_{\Lambda_0} \left(N_{H_0}^{\max}\right)^{-2/3}$

So $\boxed{N_{H_0} \geq e^{S_{\Lambda_0} \left(N_{H_0}^{\max}\right)^{1/\alpha}}}$

PROBLEM: increasing $N_{H_0}^{\max}$ by decreasing Λ makes the issue worse (larger heat bath means condensing it all out is a worse deal).

- Standard big bang also fails to beat out higher entropy competition.
- AA: Not surprising, a new version of "Boltzmann's Brain". (cheapest/most likely fluctuation is your brain fluctuating briefly out of chaos)
- The standard big bang never had a hope of resolving "Boltzmann's Brain", but inflation did.

See AA: astro-ph/0210527

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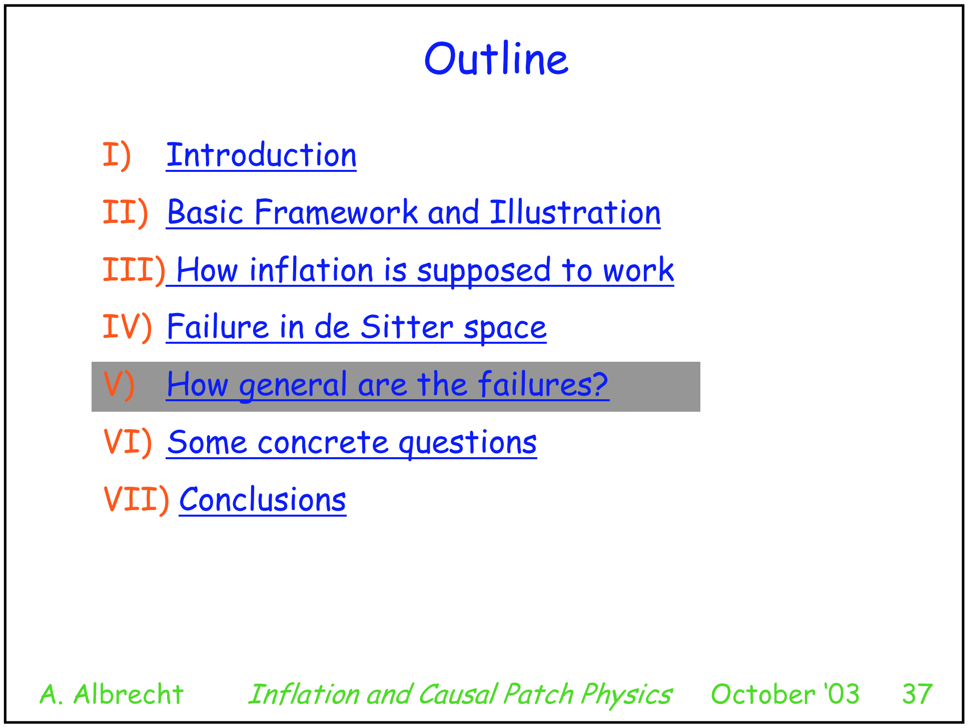

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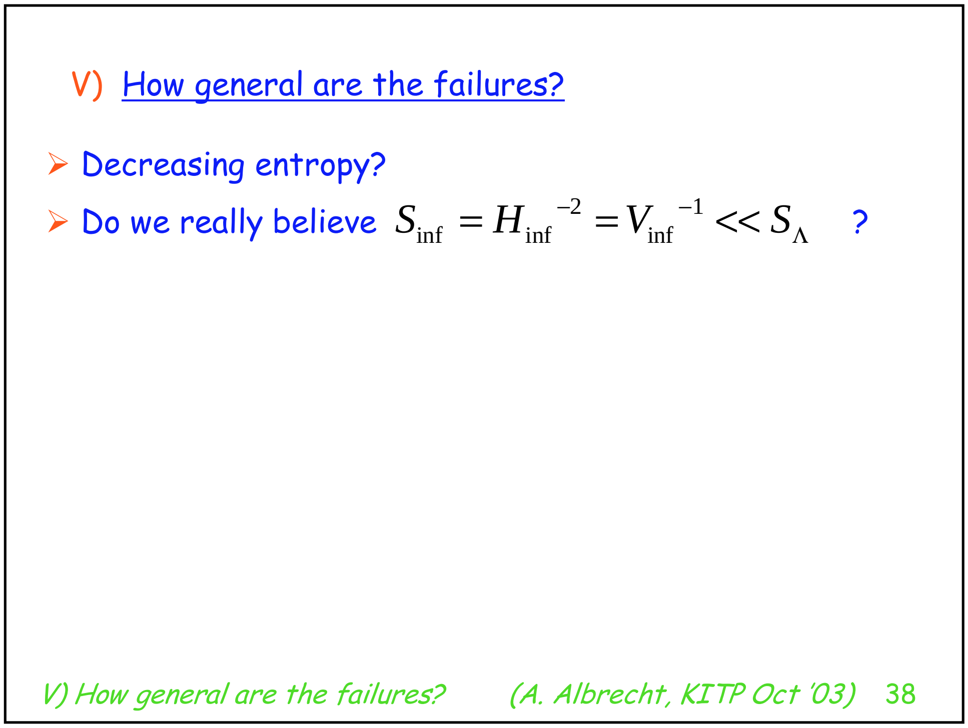
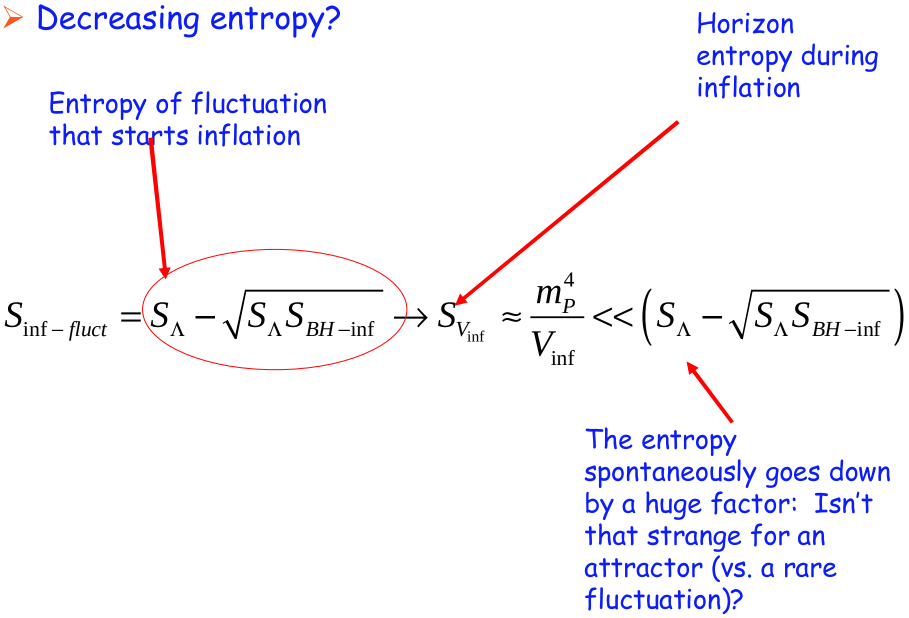


V) How general are the failures?

- Decreasing entropy?
- Do we really believe $S_{\inf} = H_{\inf}^{-2} = V_{\inf}^{-1} << S_{\Lambda}$?

➢ Decreasing entropy?



Horizon entropy during inflation

Entropy of fluctuation that starts inflation

$$S_{\inf-fluct} = S_\Lambda - \sqrt{S_\Lambda S_{BH-\inf}} \to S_{V_{\inf}} \approx \frac{m_P^4}{V_{\inf}} << \left(S_\Lambda - \sqrt{S_\Lambda S_{BH-\inf}}\right)$$

The entropy spontaneously goes down by a huge factor: Isn't that strange for an attractor (vs. a rare fluctuation)?

V) How general are the failures? *(A. Albrecht, KITP Oct '03)* 39

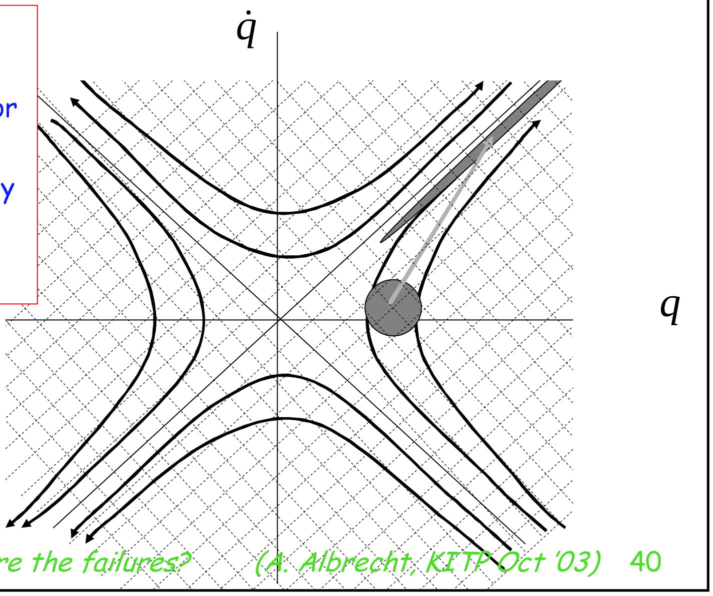
➢ Decreasing entropy?

Careful! "Entropy decrease" can come naturally with attractors:

The upside down SHO has

-Attractor behavior (squeezing)

-Increasing entropy according to the coarse-graining given by the grid



V) How general are the failures? *(A. Albrecht, KITP Oct '03)* 40

- Decreasing entropy?

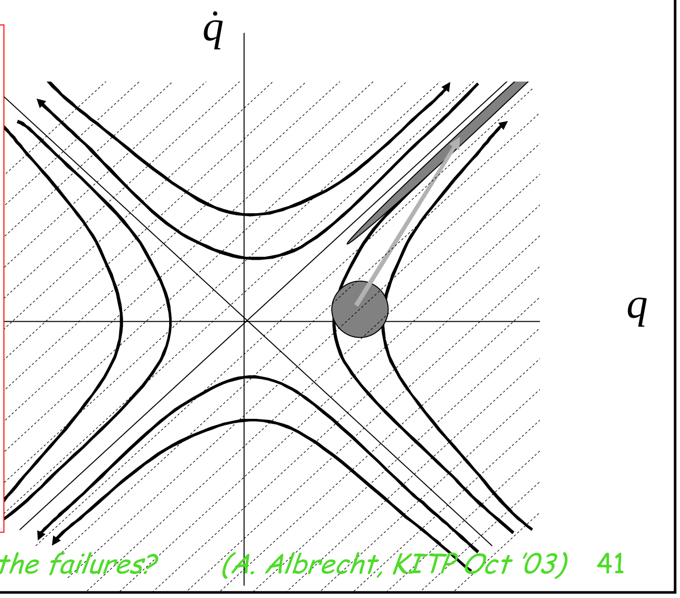
Careful! "Entropy decrease" can come naturally with attractors:

The upside down SHO has

-Attractor behavior (squeezing)

-DEcreasing entropy according to this (different) coarse-graining given by the new grid

n.b. this coarse-graining is especially nice for discussing the attractor. (But NOT ergodic)



- Decreasing entropy?

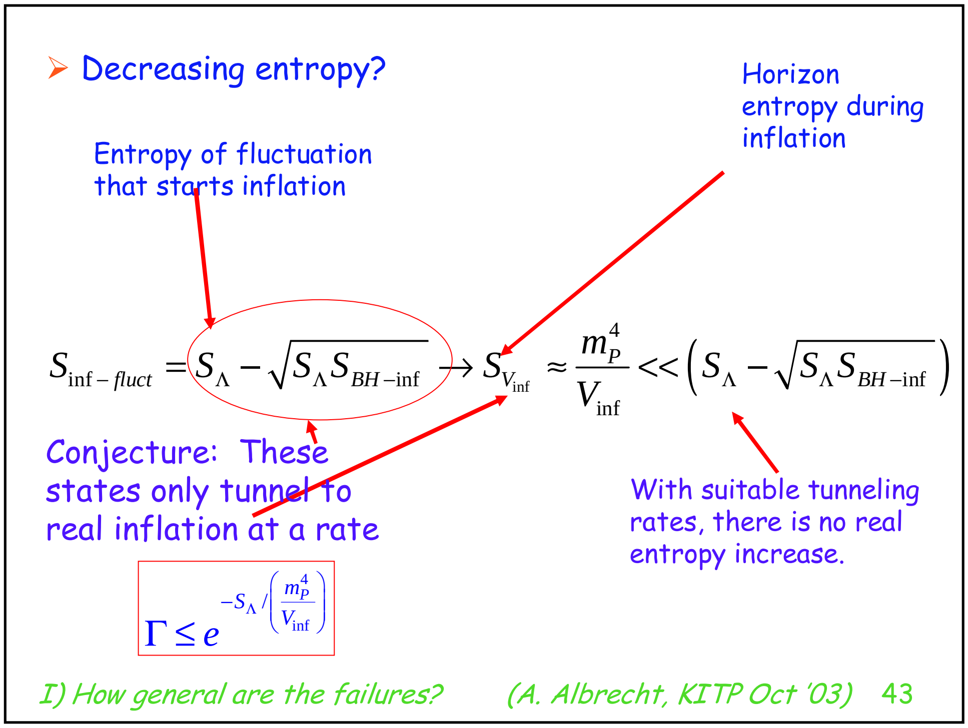
- Perhaps nothing more than an artifact of a particular coarse graining scheme

- But: there is the tunneling from pre-inflation to proper inflation.

~1990: Farhi Guth & Guven; Fischler Morgan & Polchinski

See also: Trodden & Vachaspati

-It has been conjectured that the tunneling rate "magically" introduces the right suppression factor, so that the entropy "does not really go down"



- Decreasing entropy?

Horizon entropy during inflation

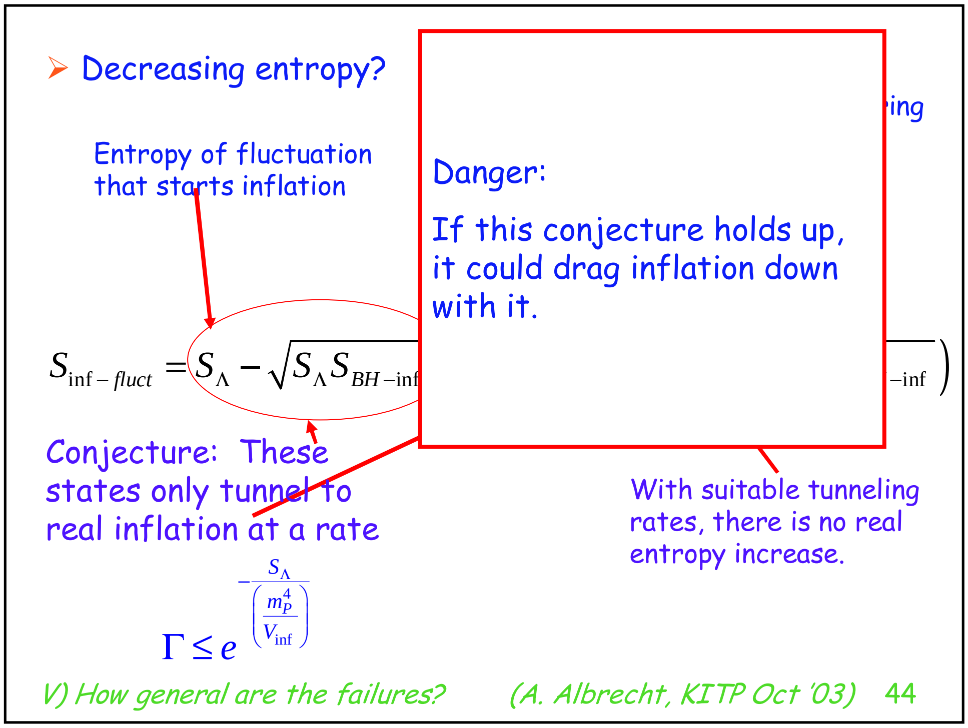
Entropy of fluctuation that starts inflation

$$S_{\inf-fluct} = S_\Lambda - \sqrt{S_\Lambda S_{BH-\inf}} \to S_{V_{\inf}} \approx \frac{m_P^4}{V_{\inf}} << \left(S_\Lambda - \sqrt{S_\Lambda S_{BH-\inf}}\right)$$

Conjecture: These states only tunnel to real inflation at a rate

$$\boxed{\Gamma \le e^{-S_\Lambda/\left(\frac{m_P^4}{V_{\inf}}\right)}}$$

With suitable tunneling rates, there is no real entropy increase.



- Decreasing entropy?

ing

Entropy of fluctuation that starts inflation

$$S_{\inf-fluct} = S_\Lambda - \sqrt{S_\Lambda S_{BH-\inf}}$$

$-\inf\Big)$

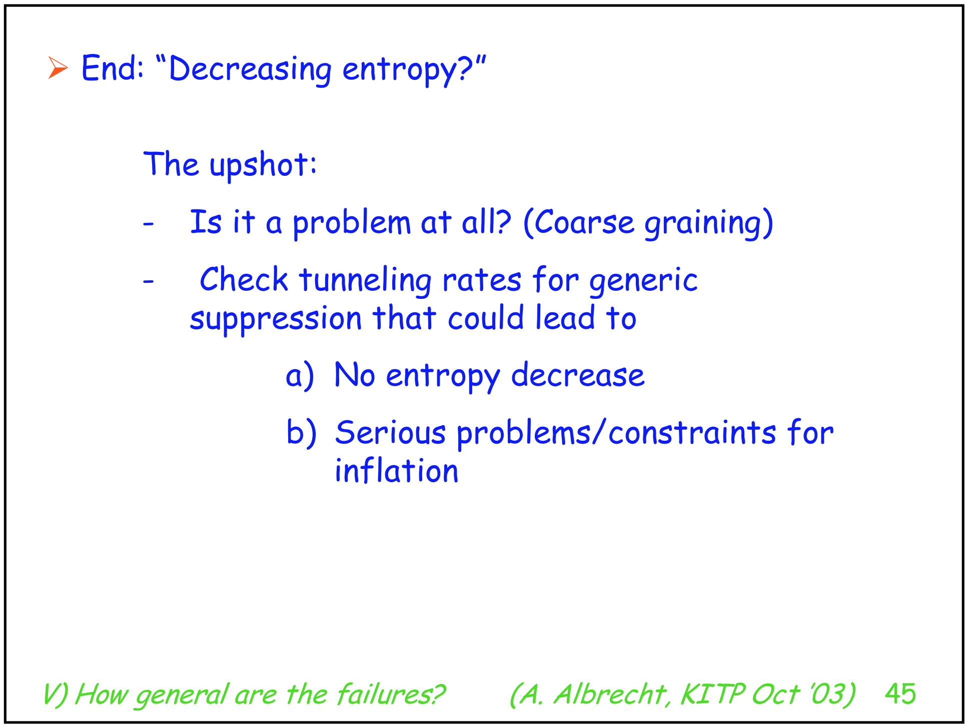
Danger:

If this conjecture holds up, it could drag inflation down with it.

Conjecture: These states only tunnel to real inflation at a rate

$$\Gamma \le e^{-\frac{S_\Lambda}{\left(\frac{m_P^4}{V_{\inf}}\right)}}$$

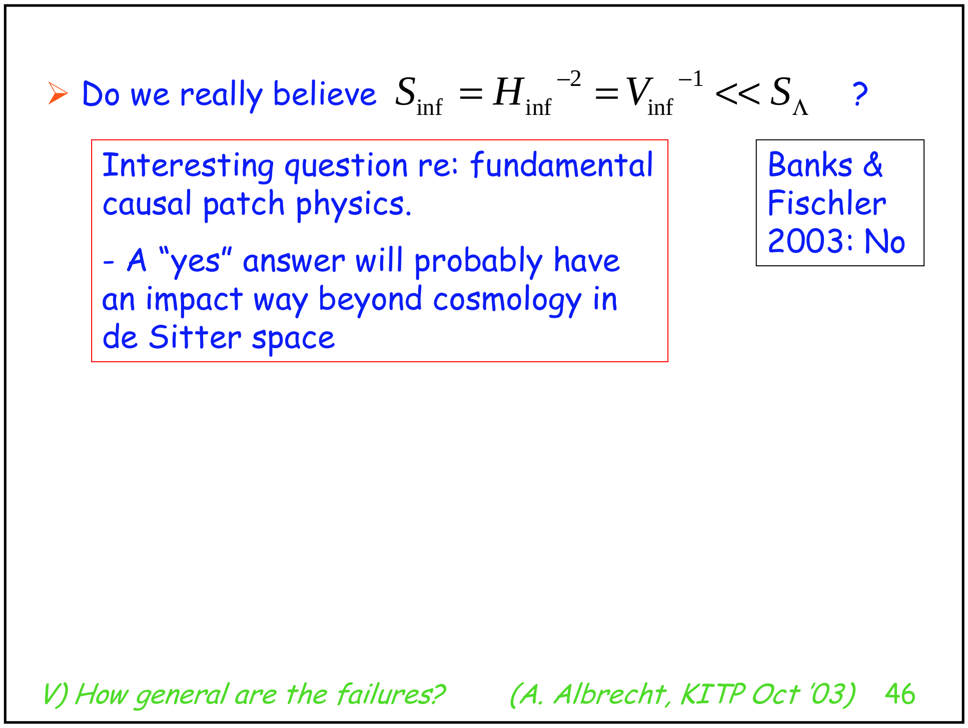
With suitable tunneling rates, there is no real entropy increase.



- End: “Decreasing entropy?”

The upshot:

- Is it a problem at all? (Coarse graining)
- Check tunneling rates for generic suppression that could lead to
  - a) No entropy decrease
  - b) Serious problems/constraints for inflation



- Do we really believe $S_{\text{inf}} = H_{\text{inf}}^{-2} = V_{\text{inf}}^{-1} << S_{\Lambda}$?

Interesting question re: fundamental causal patch physics.

- A “yes” answer will probably have an impact way beyond cosmology in de Sitter space

Banks & Fischler 2003: No

- Do we really believe $S_{\mathrm{inf}} = H_{\mathrm{inf}}^{-2} = V_{\mathrm{inf}}^{-1} << S_{\Lambda}$?

Interesting question re: fundamental causal patch physics.

- A "yes" answer will probably have an impact way beyond cosmology in de Sitter space

Banks & Fischler 2003: No

AA, Kaloper & Song 2003: Perhaps?

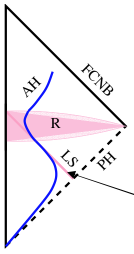
AH: Apparent horizon

R: Reheating

LS: Light Sheet

PH: Past Horizon

FCNB: Future Null Causal Boundary



$S_{leak} \le \frac{\varepsilon}{3} M_P^2 H^{-2}$

IV) How general are the failures?

- Decreasing entropy?
- Do we really believe $S_{\mathrm{inf}} = H_{\mathrm{inf}}^{-2} = V_{\mathrm{inf}}^{-1} << S_{\Lambda}$?

➔ General comment: Many of the issues in play appear to generalize beyond the "fluctuation out of de Sitter eqm" case

➔Specifically: There is a competitive advantage of producing the universe starting with a "cheap" initial fluctuation. Can inflation achieve it?.

➔ NB: Theory of competing fluctuations essential. (Not provided so far in "landscape" discussion.)

Outline

- I) Introduction
- II) Basic Framework and Illustration
- III) How inflation is supposed to work
- IV) Failure in de Sitter space
- V) How general are the failures?
- VI) Some concrete questions
- VII) Conclusions

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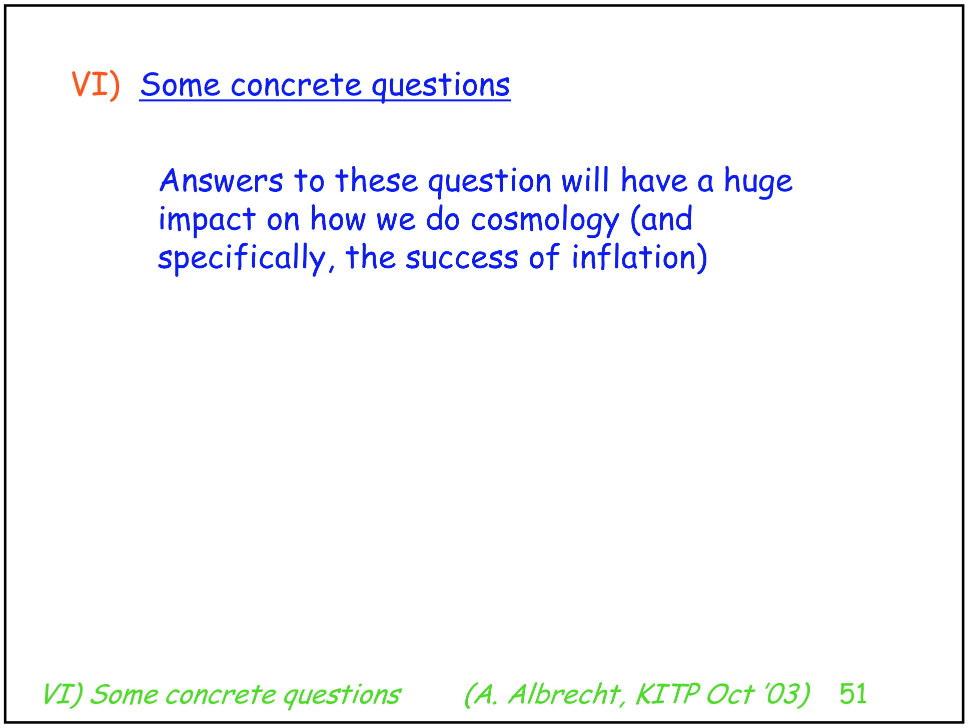
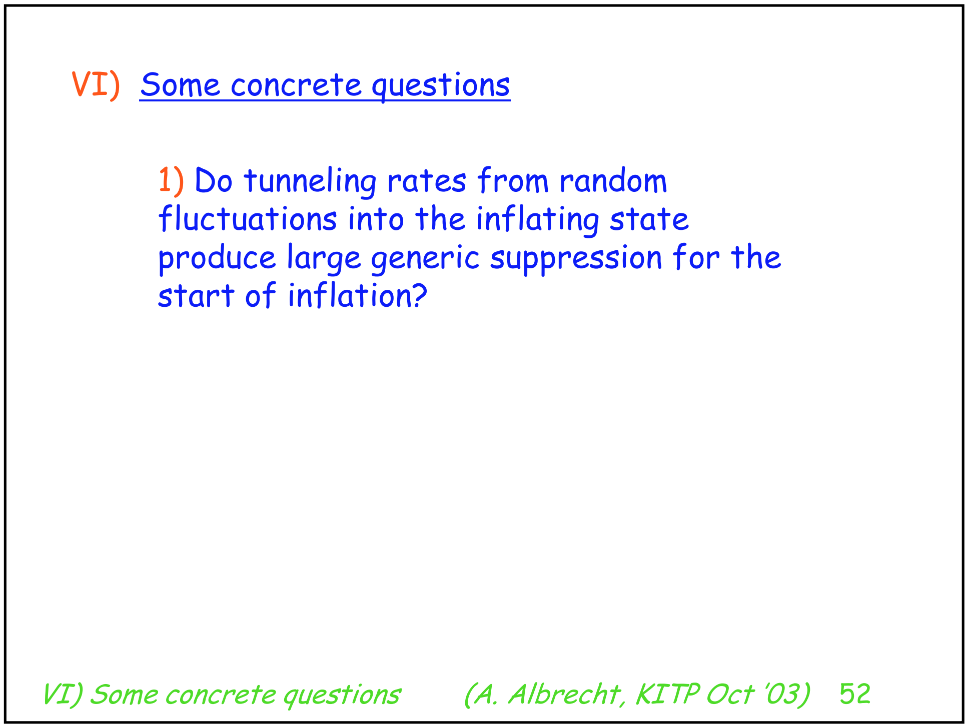


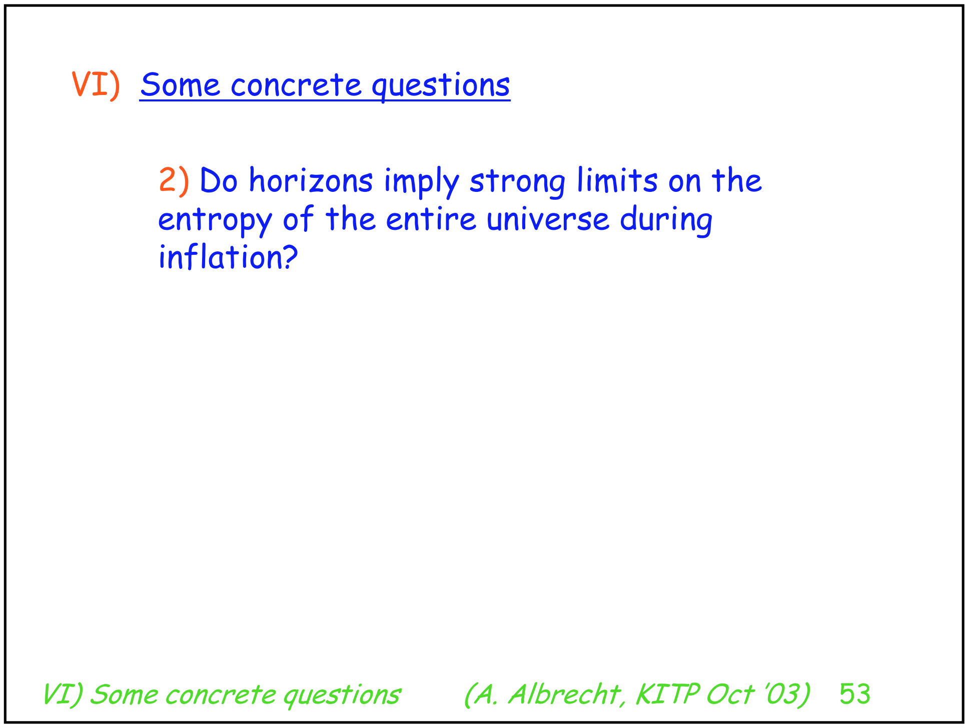
VI) Some concrete questions

Answers to these question will have a huge impact on how we do cosmology (and specifically, the success of inflation)



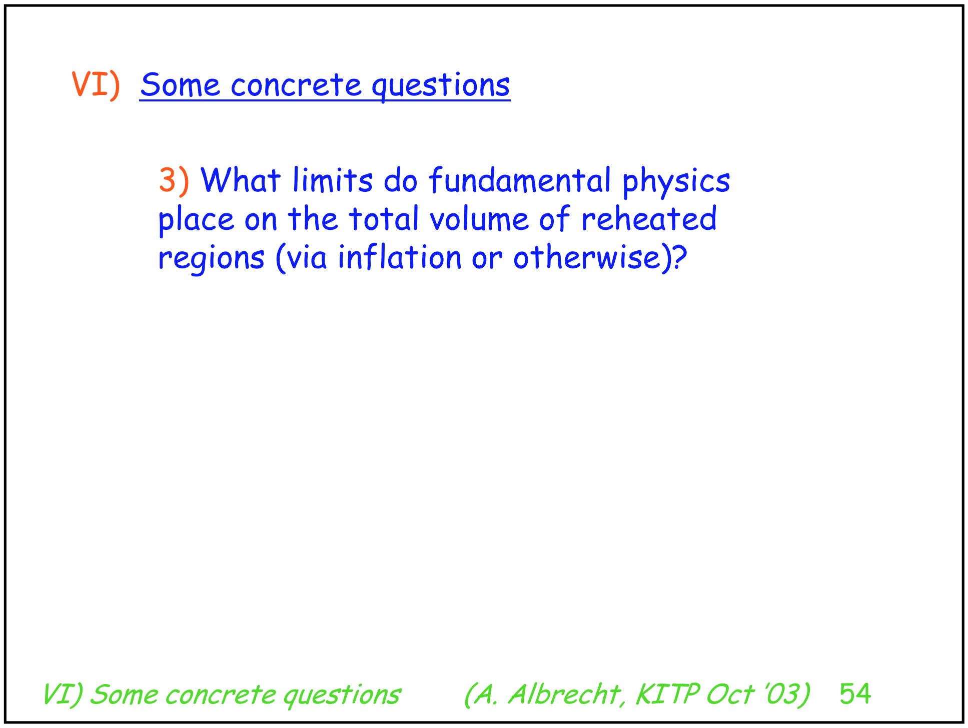
VI) Some concrete questions

1) Do tunneling rates from random fluctuations into the inflating state produce large generic suppression for the start of inflation?



VI) Some concrete questions

2) Do horizons imply strong limits on the entropy of the entire universe during inflation?



VI) Some concrete questions

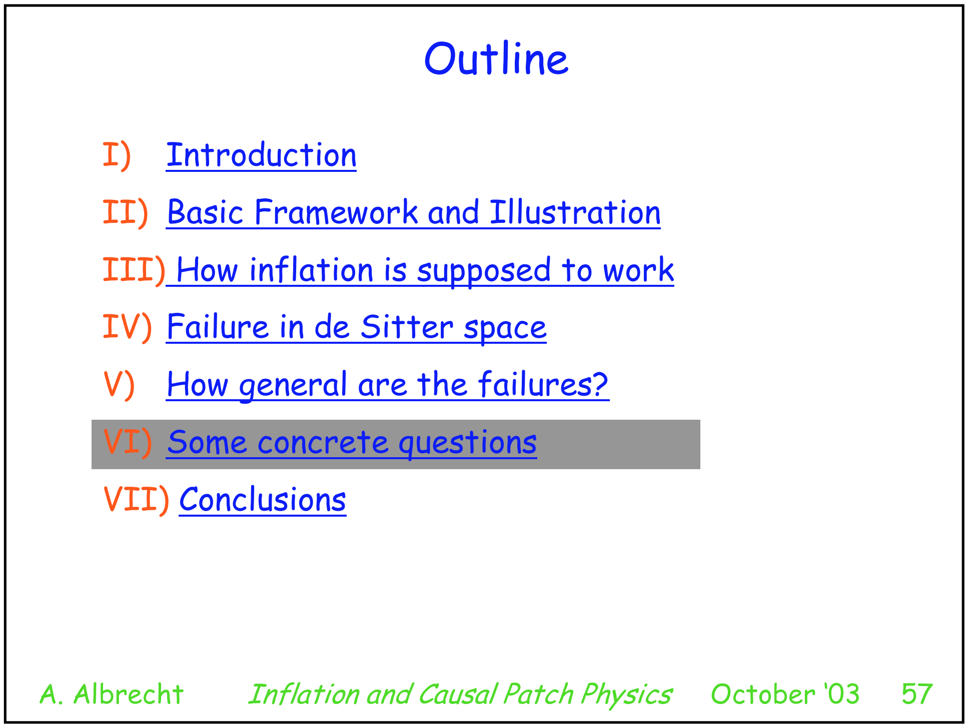
3) What limits do fundamental physics place on the total volume of reheated regions (via inflation or otherwise)?

VI) Some concrete questions

4) Are there other specific frameworks where cosmology can be seen as competing fluctuations (vs de Sitter eqm). (No boundary proposal?)

VI) Some concrete questions

5) Do you believe the assumptions of Dyson et al to rule out a fundamental cosmological constant?



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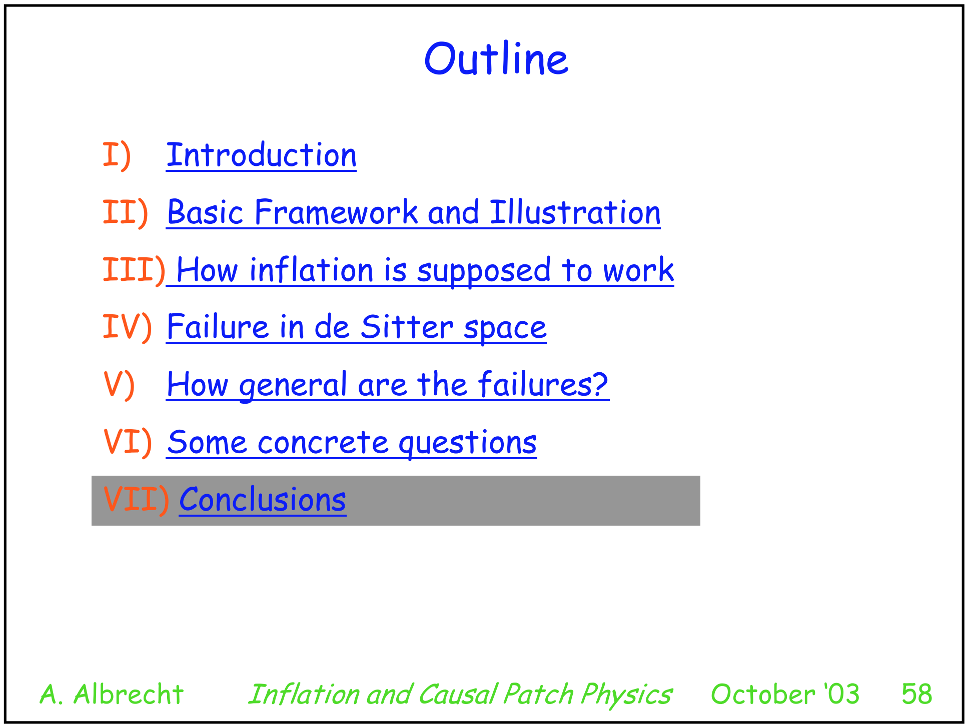

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VII) Conclusions

➔A quantitative analysis of competing paths to the big bang may be coming within reach.

➔ There are specific questions, some of which seem tractable, which could have a radical impact on how we do cosmology (for example, the success or failure of inflation).

- Check w/ NK
- Check volume calc