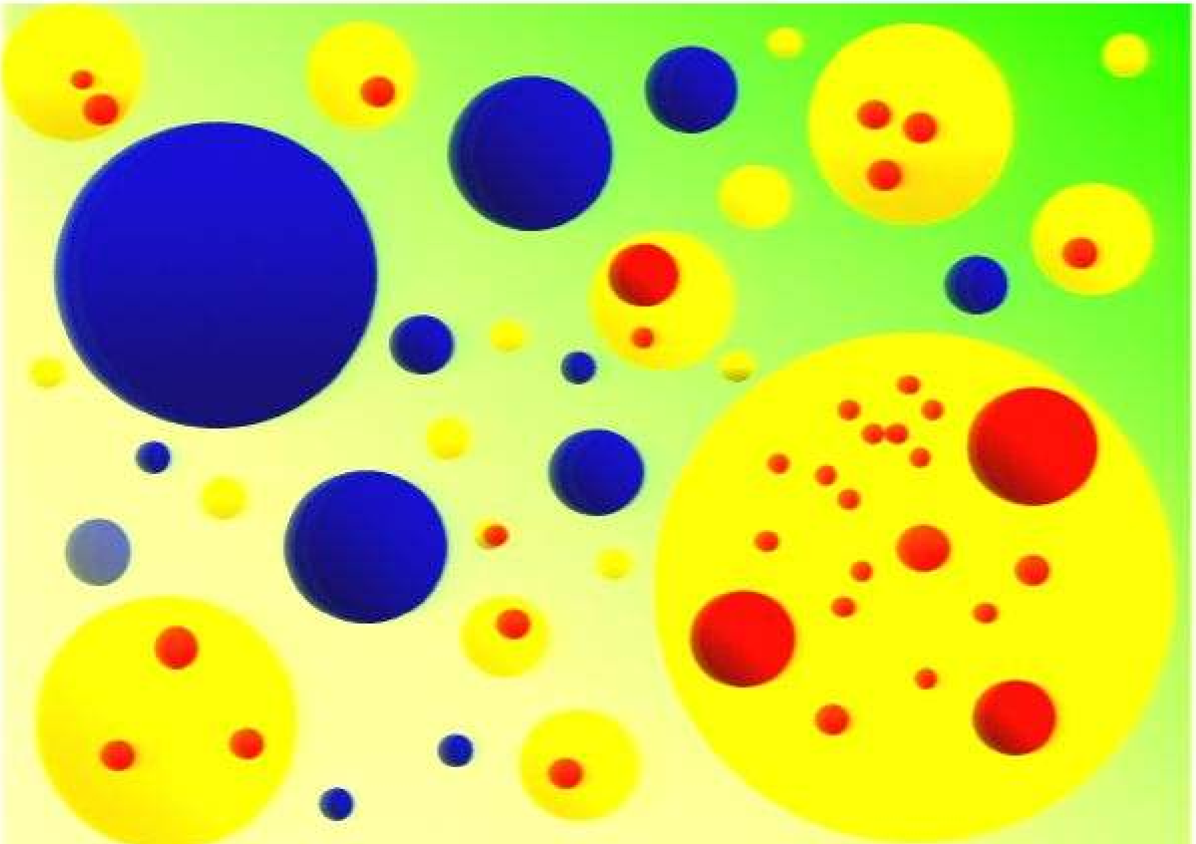
Title: Measures of the multiverse

Date: Jun 05, 2008 09:00 AM

URL: http://pirsa.org/08050059

Abstract: Inflation is generically a never ending process, with new \'pocket universes\' constantly being formed. All possible events will happen an infinite number of times in such an eternally inflating universe. Unless we learn how to compare these infinities, we will not be able to make any predictions at all. I will discuss some proposed approaches to this \'measure problem\'.



Eternally inflating multiverse

The measure problem:

Everything that can happen will happen an infinite number of times. We have to learn how to compare these infinities. (Otherwise we cannot distinguish probable events from highly improbable & cannot make any predictions.)

Empirical approach:

Investigate different measure proposals and discard those which strongly disagree with observations.

Fundamental approach:

Derive measure from fundamental theory.

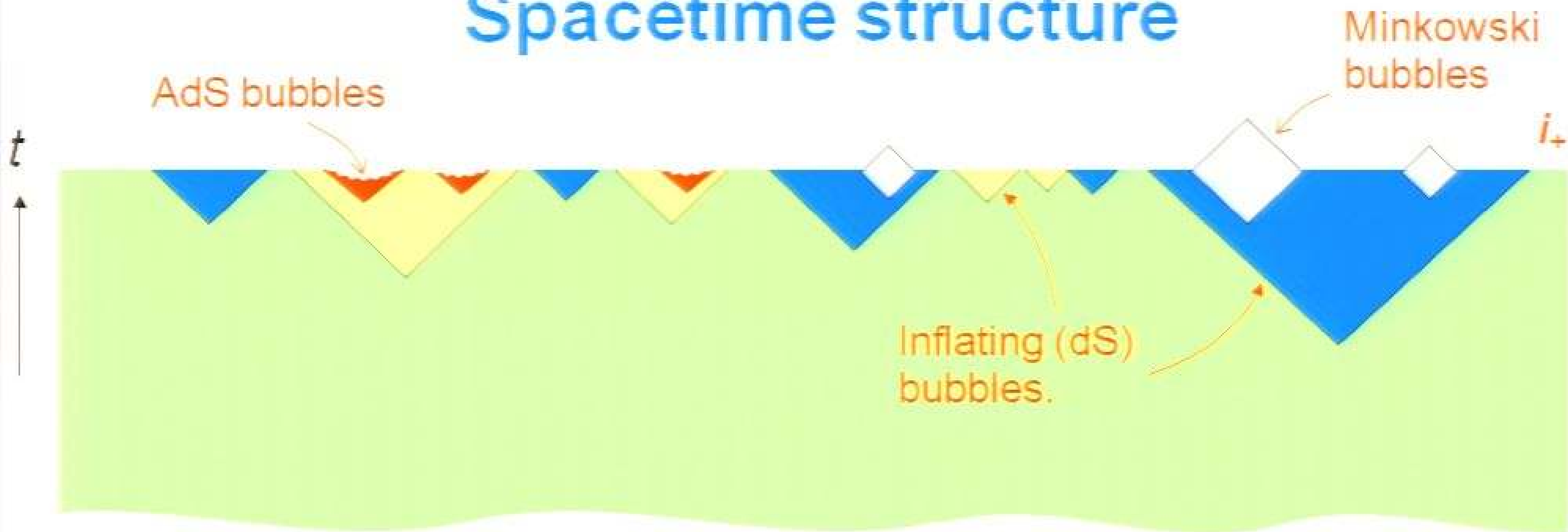
↓

Scale-factor cutoff measure

PLAN

- Spacetime structure.
- Some measure proposals and their problems.
- Measure from fundamental theory?

Spacetime structure

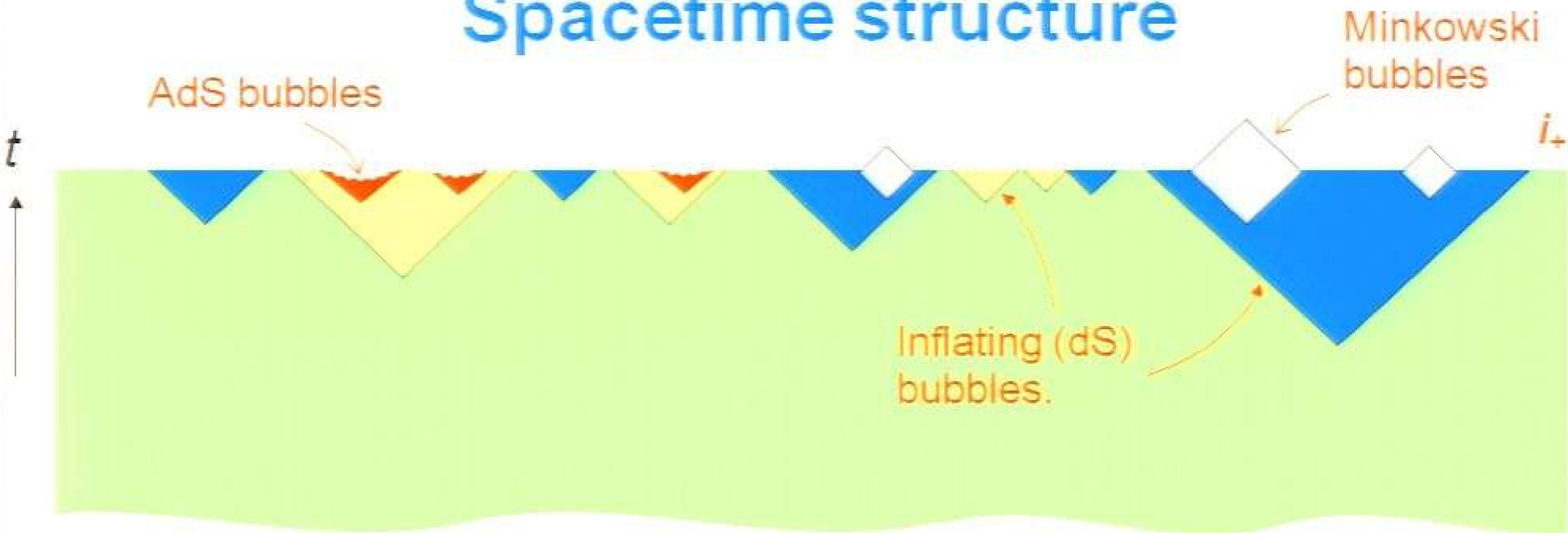


- Bubbles nucleate and expand at nearly the speed of light.
- Terminal & recyclable bubbles
- Eternal fractals
- Inflating spacetimes are past-incomplete – but this should not be relevant for the measure.

Use this as a measure selection criterion.

Some measure proposals and their problems

Spacetime structure

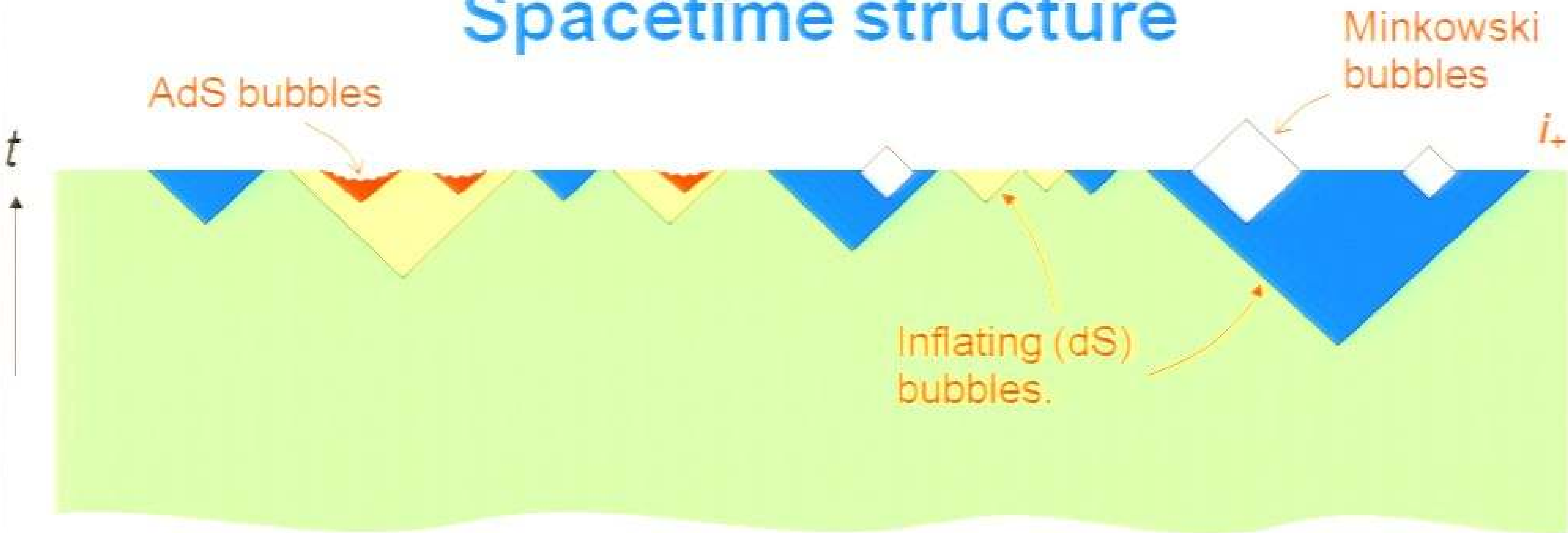


- Bubbles nucleate and expand at nearly the speed of light.
- Terminal & recyclable bubbles
- Eternal fractals
- Inflating spacetimes are past-incomplete – but this should not be relevant for the measure.

Use this as a measure selection criterion.

Some measure proposals and their problems

Spacetime structure



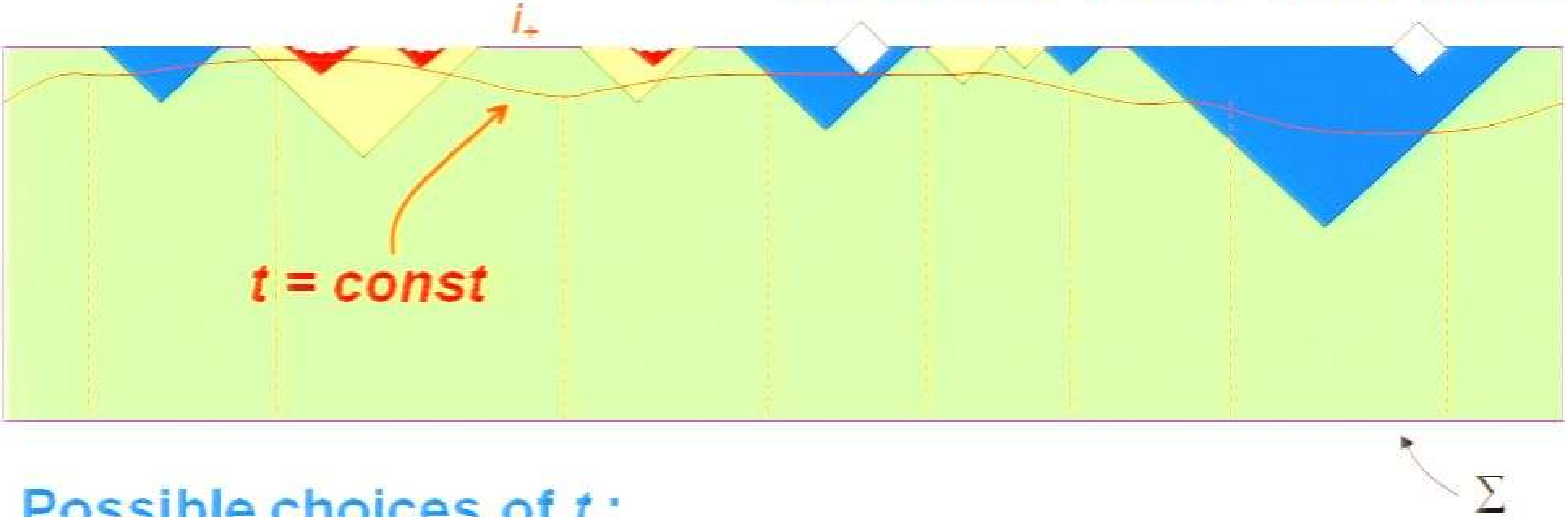
- Bubbles nucleate and expand at nearly the speed of light.
- Terminal & recyclable bubbles
- Eternal fractals
- Inflating spacetimes are past-incomplete – but this should not be relevant for the measure.

Use this as a measure selection criterion.

Some measure proposals and their problems

Global time cutoff:

Count only observations that were made before some time t.



Possible choices of t :

(i) proper time $t = \tau$ along geodesics orthogonal to Σ ;

(ii) scale-factor time. $t = a$

Garcia-Bellido, Linde & Linde (1994)
A.V. (1995); Linde (2007)

$t \to \infty$ ⟹ steady-state evolution.

The distribution does not depend on the initial state (but depends on what we use as t).

Proper time cutoff leads to "youngness paradox"

Linde & Mezhlumian (1996), Guth (2001), Tegmark (2004), Bousso, Freivogel & Yang (2007

Volume in regions of any kind grows as

$$V_j \propto e^{\kappa\tau}, \quad \kappa \sim H_{\max} \sim M_{Pl}.$$

Driven by fastest-expanding vacuum

Observers who take less time to evolve are rewarded by a huge volume factor.

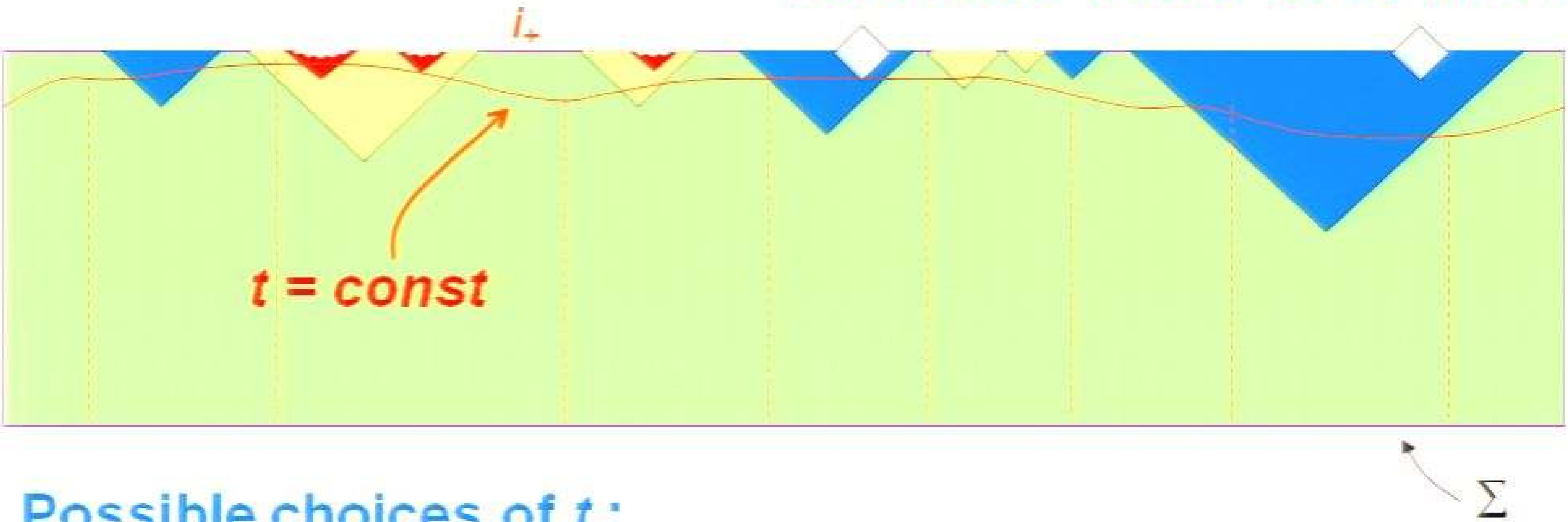
Observers who evolve faster than us by $\Delta\tau = 1\,\mathrm{Gyr}$ and measure $T_{CMB} = 2.9\mathrm{K}$ are more numerous by

$$\exp(\kappa\,\Delta\tau) = \exp(10^{60})$$

Proper-time cutoff is ruled out.

Global time cutoff:

Count only observations that were made before some time t.



Possible choices of t :

(i) proper time $t = \tau$ along geodesics orthogonal to Σ ;
(ii) scale-factor time. $t = a$

Garcia-Bellido, Linde & Linde (1994); A.V. (1995); Linde (2007)

$t \to \infty$ ➡ steady-state evolution.

The distribution does not depend on the initial state (but depends on what we use as t).

Proper time cutoff leads to "youngness paradox"

Linde & Mezhlumian (1996), Guth (2001), Tegmark (2004), Bousso, Freivogel & Yang (2007

Volume in regions of any kind grows as

$$V_j \propto e^{\kappa\tau}, \quad \kappa \sim H_{max} \sim M_{Pl}.$$

Driven by fastest-expanding vacuum

Observers who take less time to evolve are rewarded by a huge volume factor.

Observers who evolve faster than us by $\Delta\tau = 1\,\mathrm{Gyr}$ and measure $T_{CMB} = 2.9\mathrm{K}$ are more numerous by

$$\exp(\kappa\,\Delta\tau) = \exp(10^{60})$$

Proper-time cutoff is ruled out.

Scale-factor cutoff – a mild youngness bias

Growth of volume: $V_j \propto a^{\gamma}, \quad \gamma \approx 3.$

$(3-\gamma) \propto \lambda_{\min}$ – decay rate of the slowest-decaying vacuum

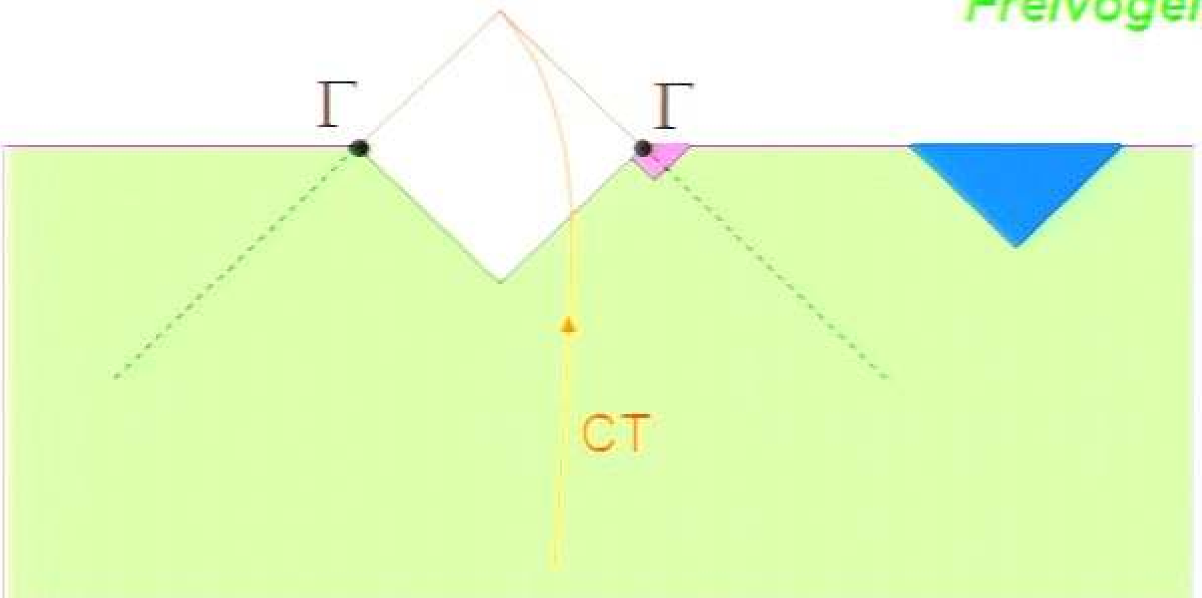
The probability of living at T = 2.9K is enhanced only by $(T/T_0)^3 \approx 1.2$.

Not ruled out and may have interesting observational consequences.

Causal patch (census-taker) measure

Freivogel, Sekino, Susskind & Yeh (2006
Susskind (2008

Related idea: **Bousso (2007)**



Include only spacetime region accessible to a single observer (CT).

CT will sees an infinite number of other bubbles (that collide with his bubble), but their abundances depend on the nucleation rates in the parent vacuum.

⟹ *The measure depends on the initial state.*

Holography: The 4D theory in the region accessible to CT is equivalent (*dual*) to a Euclidean 2D field theory on Γ.

Scale-factor cutoff – a mild youngness bias

Growth of volume: $V_j \propto a^{\gamma}, \quad \gamma \approx 3.$

$(3-\gamma) \propto \lambda_{\min}$ – decay rate of the slowest-decaying vacuum

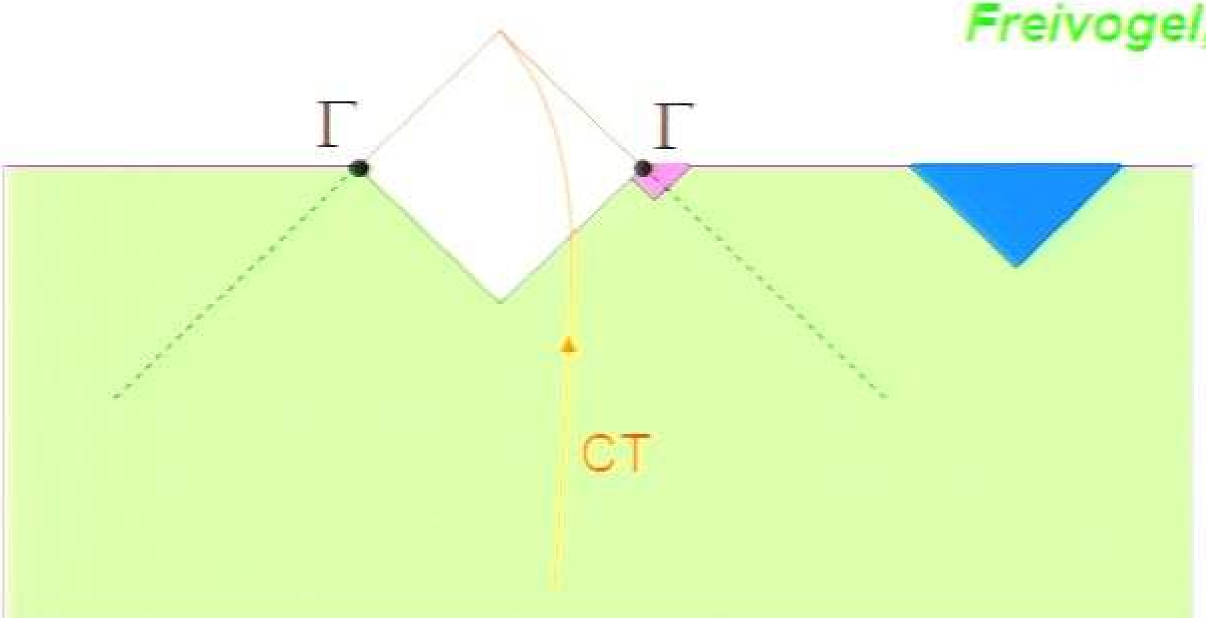
The probability of living at T = 2.9K is enhanced only by $(T/T_0)^3 \approx 1.2$.

Not ruled out and may have interesting observational consequences.

Causal patch (census-taker) measure

Freivogel, Sekino, Susskind & Yeh (2006
Susskind (2008

Related idea: **Bousso (2007)**



Include only spacetime region accessible to a single observer (CT).

CT will sees an infinite number of other bubbles (that collide with his bubble), but their abundances depend on the nucleation rates in the parent vacuum.

➡ *The measure depends on the initial state.*

Holography: The 4D theory in the region accessible to CT is equivalent (*dual*) to a Euclidean 2D field theory on Γ.

Pocket-based measure

Garriga, Schwartz-Perlov, A.V. & Winitzki (2005)
Easther, Lim & Martin (2005)

$$P_j \propto p_j w_j$$

p_j – bubble abundance.

Select $\mathcal{N}$ geodesics at random out of the congruence. Count only bubbles crossed by at least one geodesic. Take limit $\mathcal{N} \to \infty$

w_j – weight factor.

Sample equal comoving volumes in all bubbles.
(All bubble spacetimes are identical at early times

Large inflation inside bubbles is rewarded: $P_j \propto Z_j^3$ ← expansion factor during inflation

This leads to some problems…

"Q catastrophe"

Feldstein, Hall & Watari (2005)
Garriga & A.V. (2006)
Graesser & Salem (2007)

The expansion factor Z_j depend exponentially on the shape of inflaton potential $V(\varphi)$.

$P_j \propto Z_j^3$ ⟹ Parameters sensitive to $V(\varphi)$ have exponential probability distributions.

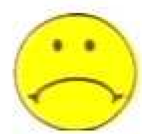
In particular the amplitude of density perturbations Q.

Same Z-dependence in "stationary" measure. *Linde (2007)*

Scale-factor cutoff:

$$P_j \propto Z_j^{-\delta}, \qquad \delta <<< 1.$$

Mild Z-dependence ⟹ no catastrophe.

	Youngness paradox	Q catastrophe	Dependence on initial state
Proper time cutoff			
Scale factor cutoff			
Pocket-based measure			
Stationary measure			
Causal patch measure			

"Q catastrophe"

Feldstein, Hall & Watari (2005)
Garriga & A.V. (2006)
Graesser & Salem (2007)

The expansion factor Z_j depend exponentially on the shape of inflaton potential $V(\varphi)$.

$P_j \propto Z_j^3$ ⟹ Parameters sensitive to $V(\varphi)$ have exponential probability distributions.

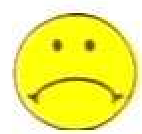
In particular the amplitude of density perturbations Q.

Same Z-dependence in "stationary" measure. Linde (2007)

Scale-factor cutoff:

$$P_j \propto Z_j^{-\delta}, \qquad \delta <<< 1.$$

Mild Z-dependence ⟹ no catastrophe.

	Youngness paradox	Q catastrophe	Dependence on initial state
Proper time cutoff			
★ **Scale factor cutoff**			
Pocket-based measure			
Stationary measure			
Causal patch measure			

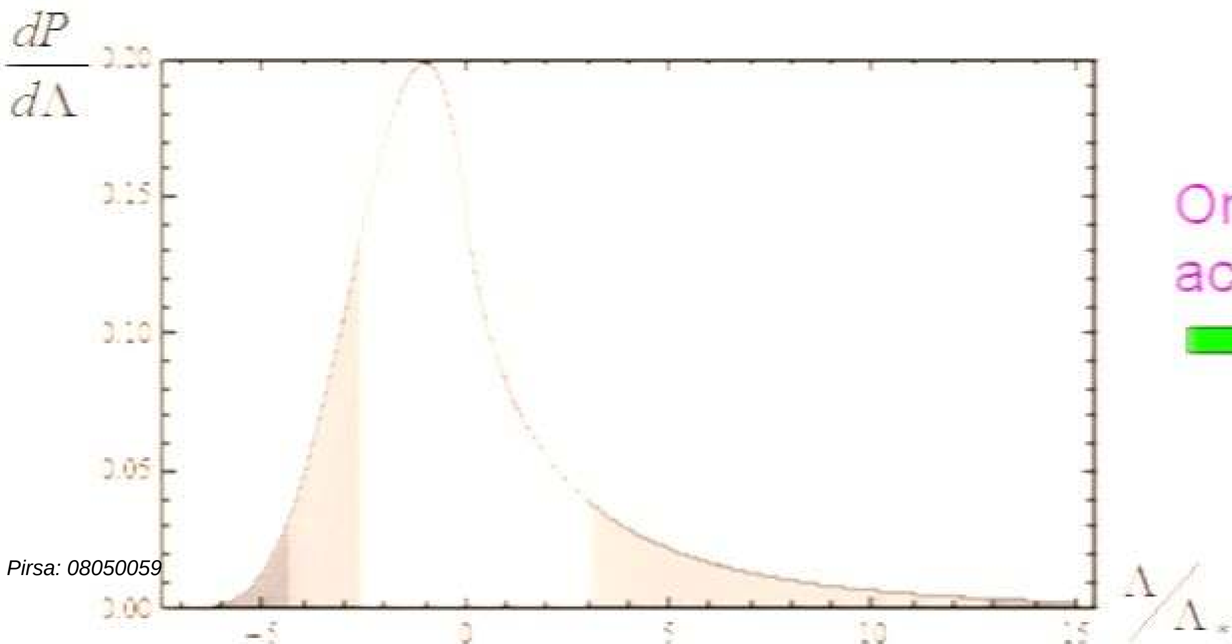
Predictions for Λ and Ω in scale-factor cutoff measure

Probability distribution for Λ

De Simone, Guth, Salem & A.V. (2008)

Assumptions:

- Number of observers is proportional to the fraction of matter clustered in large galaxies ($M \geq 10^{12} M_{\odot}$).
- Observers do their measurements at a fixed time = 5 Gyr after galactic halo collapse.
- Contracting regions with $\Lambda < 0$ are hazardous for life.



Once Λ dominates, expansion accelerates, triggering the cutoff

→ Large Λ are suppressed

Predictions for Ω:

Depend on the slow-roll expansion factor Z in the bubbles.

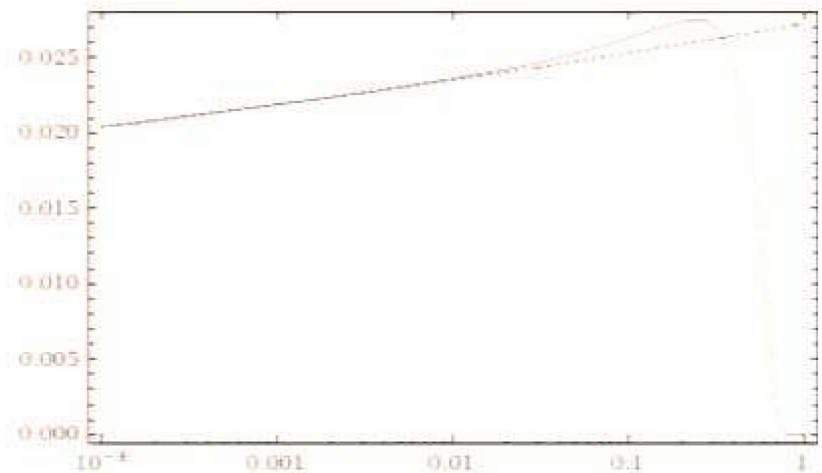
For measures that favor large inflation:

$$P_j \propto Z_j^3 \quad \Longrightarrow \quad \Omega = 1.$$

Scale-factor cutoff:

$$P_j \propto Z_j^{3-\gamma}, \qquad 3 - \gamma << 1.$$

Detectable negative curvature is possible, but not likely (P < 5%) – unless large Z are exponentially suppressed in the landscape.



$1-\Omega$

Freivogel, Kleban, Martinez & Susskind (2006), Salem (2008)

A measure from fundamental theory?

Based on work with Jaume Garriga

Predictions for Ω:

Depend on the slow-roll expansion factor Z in the bubbles.

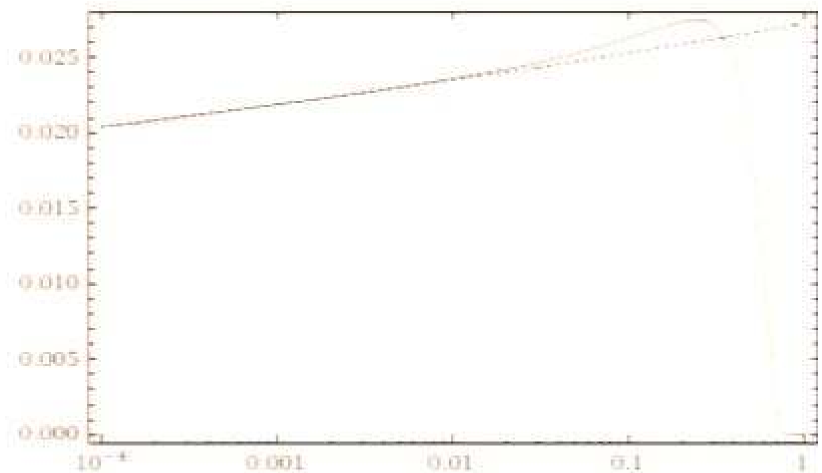
For measures that favor large inflation:

$$P_j \propto Z_j^3 \quad \Longrightarrow \quad \Omega = 1.$$

Scale-factor cutoff:

$$P_j \propto Z_j^{3-\gamma}, \qquad 3 - \gamma << 1.$$

Detectable negative curvature is possible, but not likely ($P < 5\%$) – unless large Z are exponentially suppressed in the landscape.



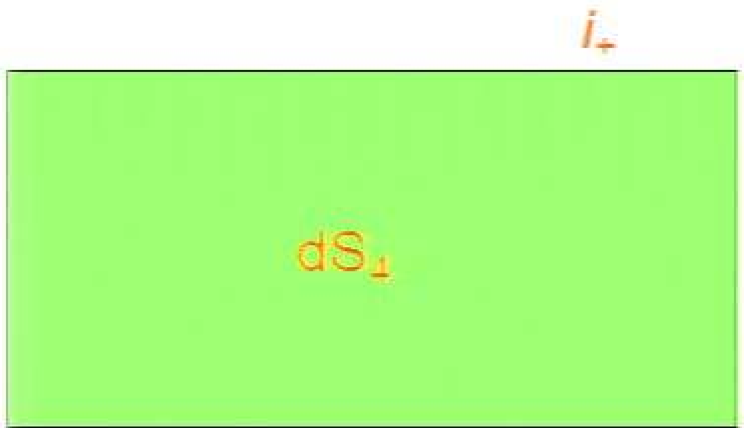
Freivogel, Kleban, Martinez & Susskind (2006), Salem (2008)

A measure from fundamental theory?

Based on work with Jaume Garriga

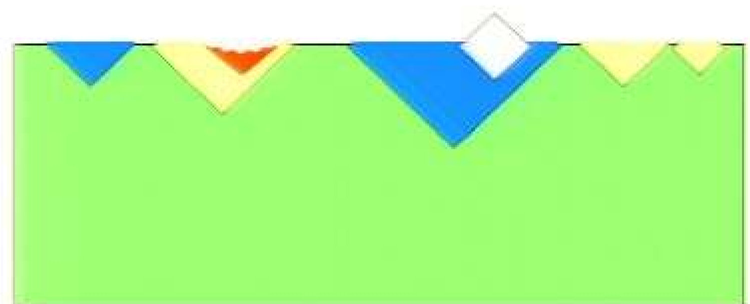
Strominger (2001):

The 4D theory describing an asymptotically de Sitter space is equivalent to a 3D Euclidean theory at the future infinity i_+.



But dS space is metastable, so there is no such thing as asymptotically dS space.

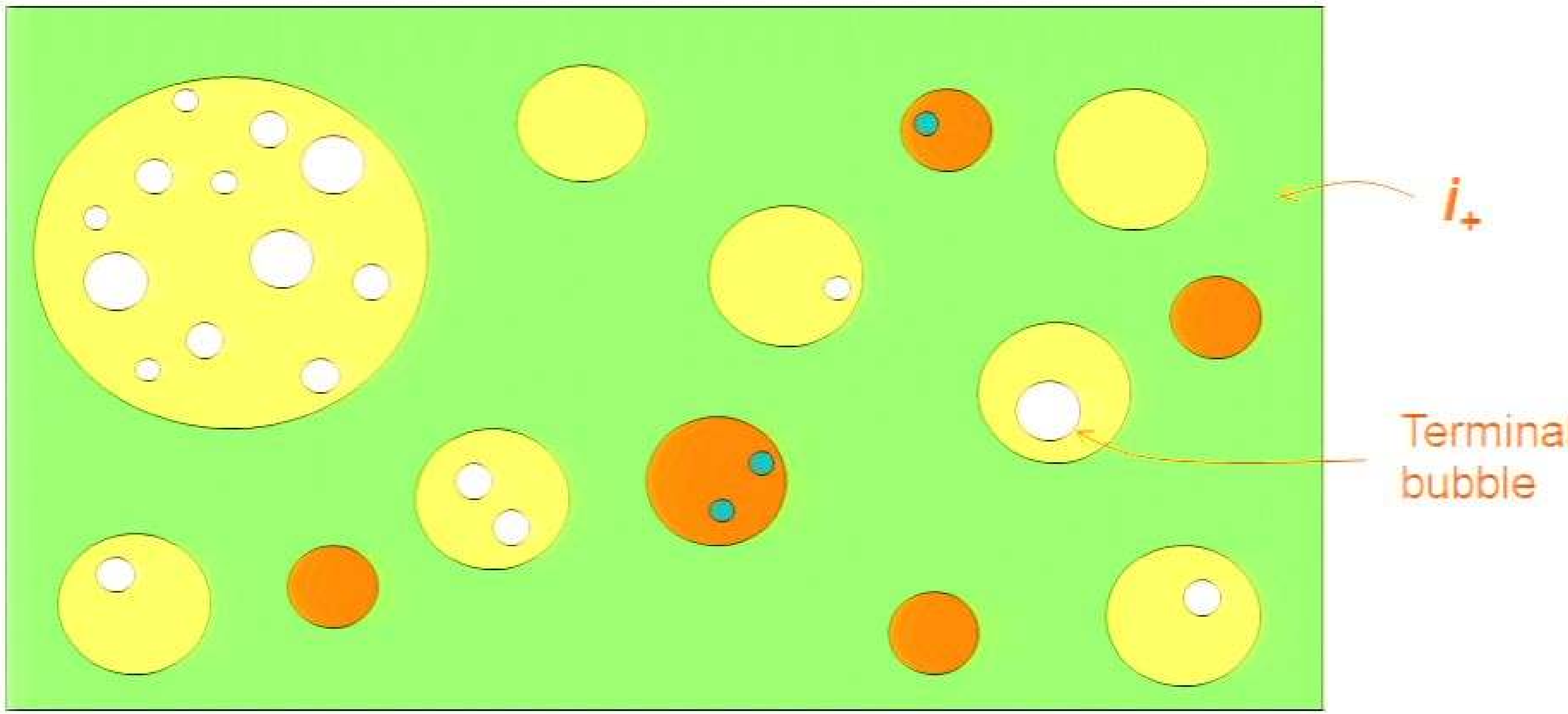
The actual future infinity looks like this:



Our conjecture:

The 4D theory describing the evolution of the multiverse is equivalent to a 3D Euclidean theory at the future infinity (suitably defined).

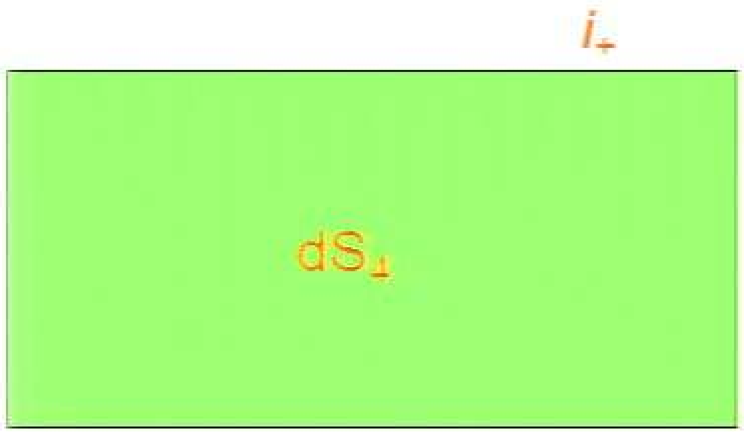
Structure of future infinity



- There are bubbles inside bubbles inside bubbles… Each bubble becomes a fractal "sponge" in the limit.
- Terminal Minkowski *(and AdS?)* bubbles correspond to holes (with 2D CFTs on their boundaries). ***Freivogel, Sekino, Susskind & Yeh (2006***
- dS bubbles correspond to instantons of the 3D theory on i_+.

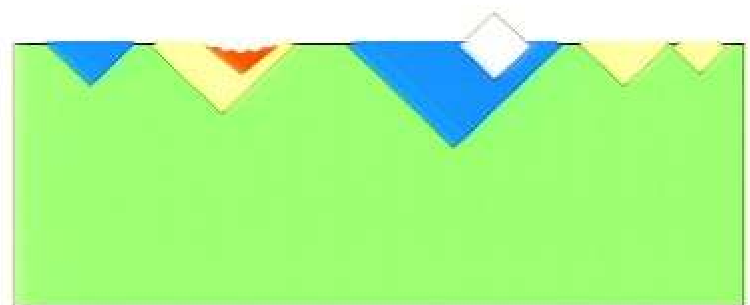
Strominger (2001):

The 4D theory describing an asymptotically de Sitter space is equivalent to a 3D Euclidean theory at the future infinity i_+.



But dS space is metastable, so there is no such thing as asymptotically dS space.

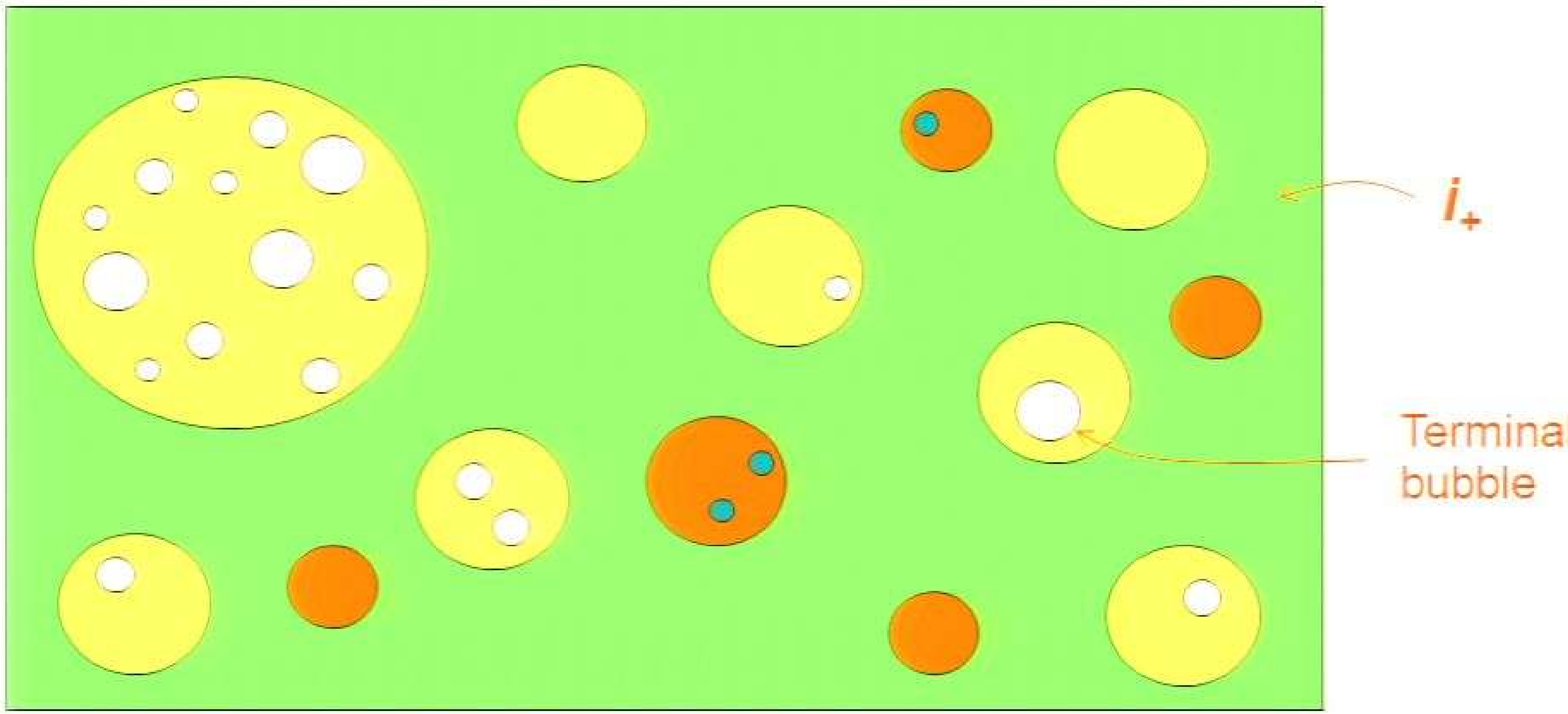
The actual future infinity looks like this:



Our conjecture:

The 4D theory describing the evolution of the multiverse is equivalent to a 3D Euclidean theory at the future infinity (suitably defined).

Structure of future infinity



- There are bubbles inside bubbles inside bubbles… Each bubble becomes a fractal "sponge" in the limit.
- Terminal Minkowski *(and AdS?)* bubbles correspond to holes (with 2D CFTs on their boundaries). ***Freivogel, Sekino, Susskind & Yeh (2006***
- dS bubbles correspond to instantons of the 3D theory on i_+.

Measure problem:

IR (long-time) cutoff in 4D ⟺ *UV* (short-distance) cutoff in 3D.

Renormalization of 3D theory: integrate out (comoving) short-wavelength modes. The remaining modes have $\lambda_c > 1/M$

The corresponding 4D modes have wavelengths $\lambda > \frac{1}{M} a(x,t) \equiv \lambda_{\min}(x,t)$

Require $\lambda_{\min} < \delta$ -- the 4D cutoff scale

This can either be regarded as a coarse-graining scale or as a 4D renormalization scale

⟹ $a_{\max} = M\delta$ -- scale factor cutoff

$M \to \infty, \qquad a_{\max} \to \infty.$

Different choices of geodesic congruence ⟹ different $a(x,t)$ – related by conformal transformations at i_+.

The measure is independent of this choice in the limit $a_{\max} \to \infty$

⟹ The 3D theory is conformally invariant in the limit $M \to \infty$

CONCLUSIONS

- Scale-factor cutoff is a promising measure proposal.
- Prediction for Λ is a good fit to the data.
- No *Q* catastrophe.
- Independent of the initial state.
- Is suggested by fundamental theory (?)

Measure problem:

IR (long-time) cutoff in 4D ⟺ *UV* (short-distance) cutoff in 3D.

Renormalization of 3D theory: integrate out (comoving) short-wavelength modes. The remaining modes have $\lambda_c > 1/M$

The corresponding 4D modes have wavelengths $\lambda > \frac{1}{M} a(x,t) \equiv \lambda_{\min}(x,t)$

Require $\lambda_{\min} < \delta$ -- the 4D cutoff scale

This can either be regarded as a coarse-graining scale or as a 4D renormalization scale

⟹ $a_{\max} = M\delta$ -- scale factor cutoff

$$M \to \infty, \qquad a_{\max} \to \infty.$$

Different choices of geodesic congruence ⟹ different $a(x,t)$
– related by conformal transformations at i_+.

The measure is independent of this choice in the limit $a_{\max} \to \infty$

⟹ The 3D theory is conformally invariant in the limit $M \to \infty$

CONCLUSIONS

- Scale-factor cutoff is a promising measure proposal.
- Prediction for Λ is a good fit to the data.
- No Q catastrophe.
- Independent of the initial state.
- Is suggested by fundamental theory (?)

"Q catastrophe"

Feldstein, Hall & Watari (2005)
Garriga & A.V. (2006)
Graesser & Salem (2007)

The expansion factor Z_j depend exponentially on the shape of inflaton potential $V(\varphi)$.

$P_j \propto Z_j^3$ ⟹ Parameters sensitive to $V(\varphi)$ have exponential probability distributions.

In particular the amplitude of density perturbations Q.

Same Z-dependence in "stationary" measure. Linde (2007)

Scale-factor cutoff:

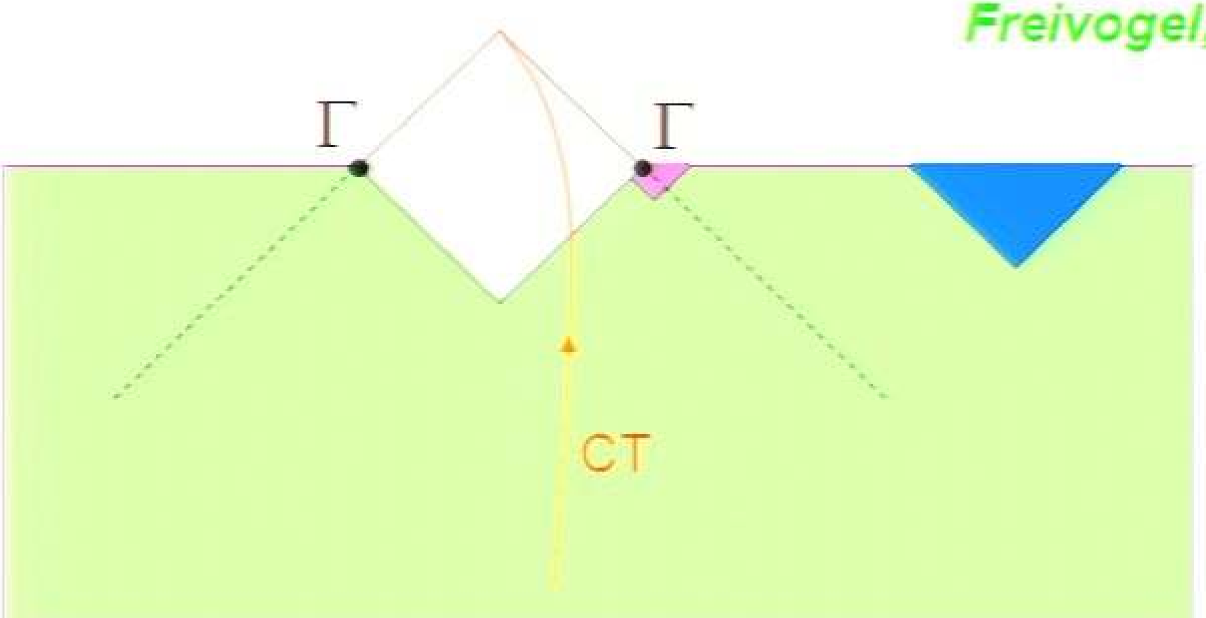
$$P_j \propto Z_j^{-\delta}, \qquad \delta <<< 1.$$

Mild Z-dependence ⟹ no catastrophe.

Causal patch (census-taker) measure

Freivogel, Sekino, Susskind & Yeh (2006
Susskind (2008

Related idea: ***Bousso (2007)***



Include only spacetime region accessible to a single observer (CT).

CT will sees an infinite number of other bubbles (that collide with his bubble), but their abundances depend on the nucleation rates in the parent vacuum.

⟹ *The measure depends on the initial state.*

Holography: The 4D theory in the region accessible to CT is equivalent (*dual*) to a Euclidean 2D field theory on Γ.