Title: Physics Beyond the Standard Theory of Inflation and Dark Energy

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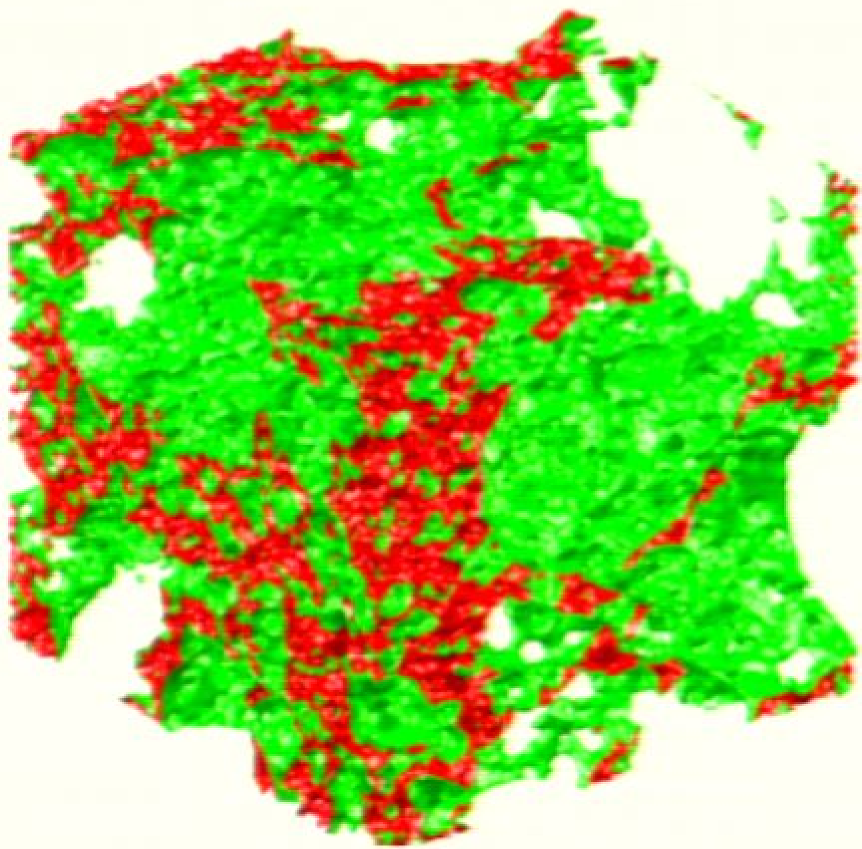
Abstract: Inflationary cosmology not only provided a simple solution to various cosmological problems, but also made predictions later confirmed by observations. Despite of its success, a straightforward extrapolation of the theory to higher energy scales led to new problems and seems to require new physics. In this talk I review the new problems, discuss their possible resolutions and speculate on possible predictions of the new physics.

Physics beyond the standard theory of inflation and dark energy



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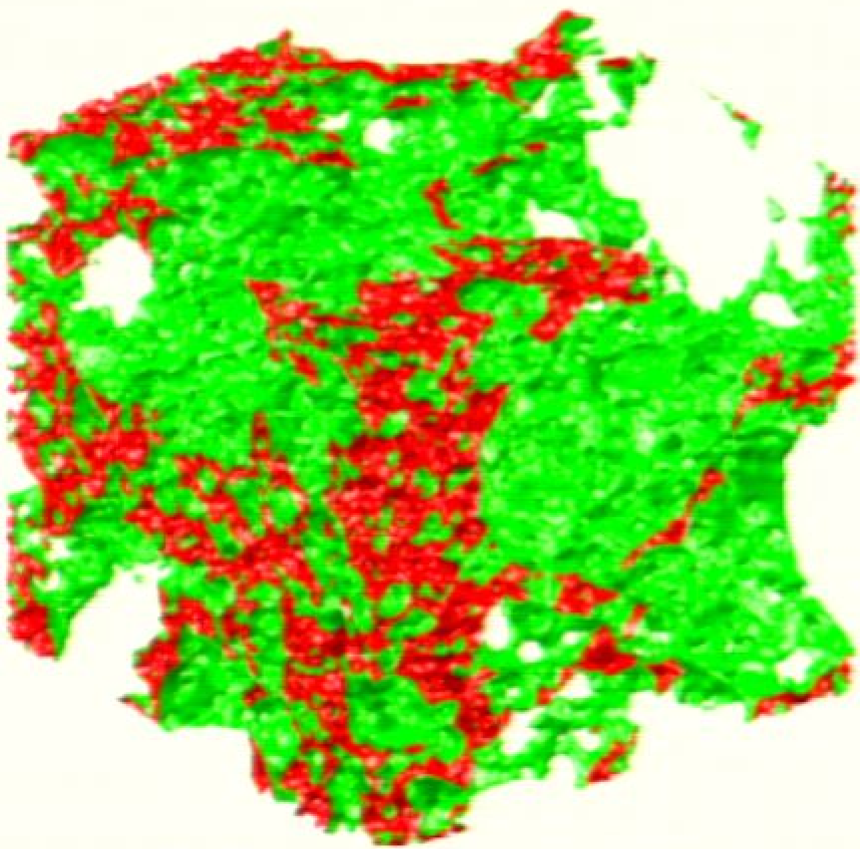

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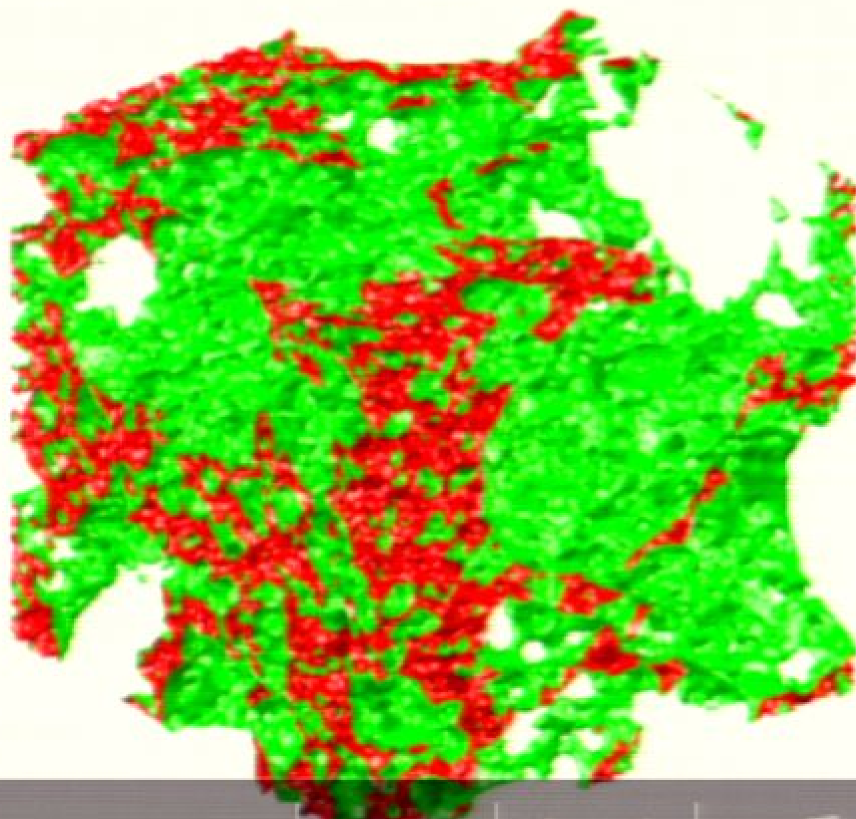

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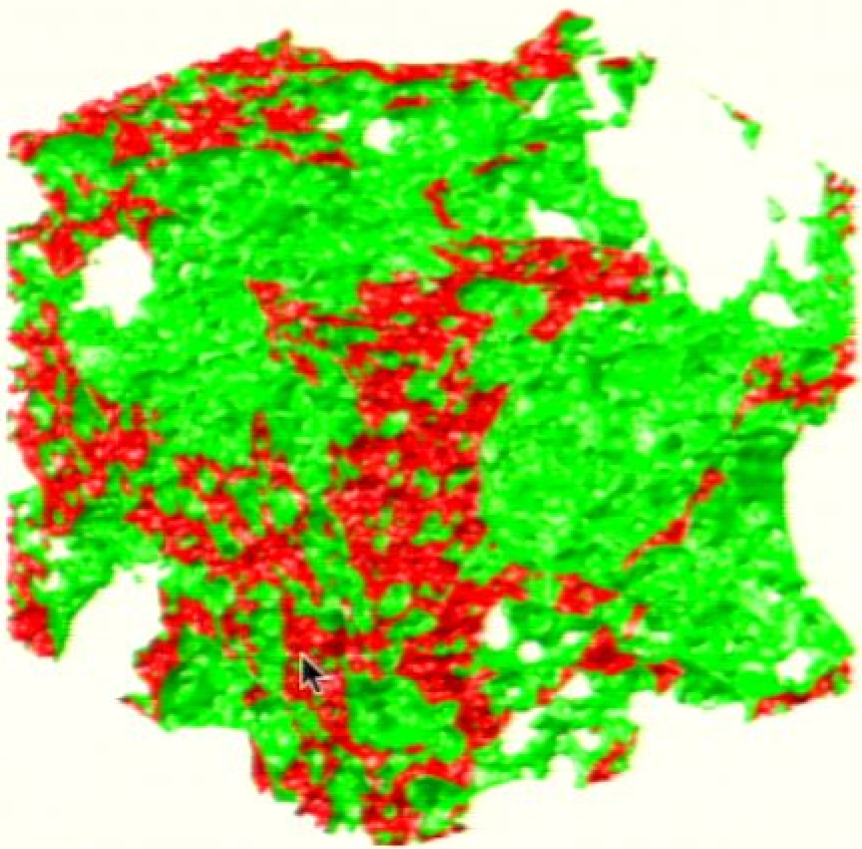

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OUTLINE

STANDARD INFLATION AND DARK ENERGY

- Standard inflation
  - explained (flatness, horizon, etc.)
  - predicted (spectrum of perturbations, gravity waves, etc.)
- Weinberg's principle
  - explained (smallness of cosmological constant)
  - predicted (cosmological constant of order 10^{-120})
- Hawking's solution of CC problem (i.e. $p(\Lambda) \sim e^{\frac{24\pi^2}{\Lambda}}$), explains smallness, but does not predict its value.
- Problems of extrapolating
  - Problem #1: Infinite spacetime
  - Problem #2: Exponential expansion
  - Problem #3: Defining observers or observables ...
- Semiclassical description does not seem to be enough.

Hope: Theory of Quantum Gravity will fix all of the problems.

Paradoxes with Cutoff Measures

- Proton decay experiment [Linde, V.V., Winitzki (2009)]
  - refinement of stationary measure proposal
- Guth-Vanchurin paradox [Guth, V.V. (2011+ε)]
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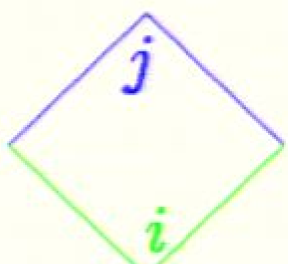

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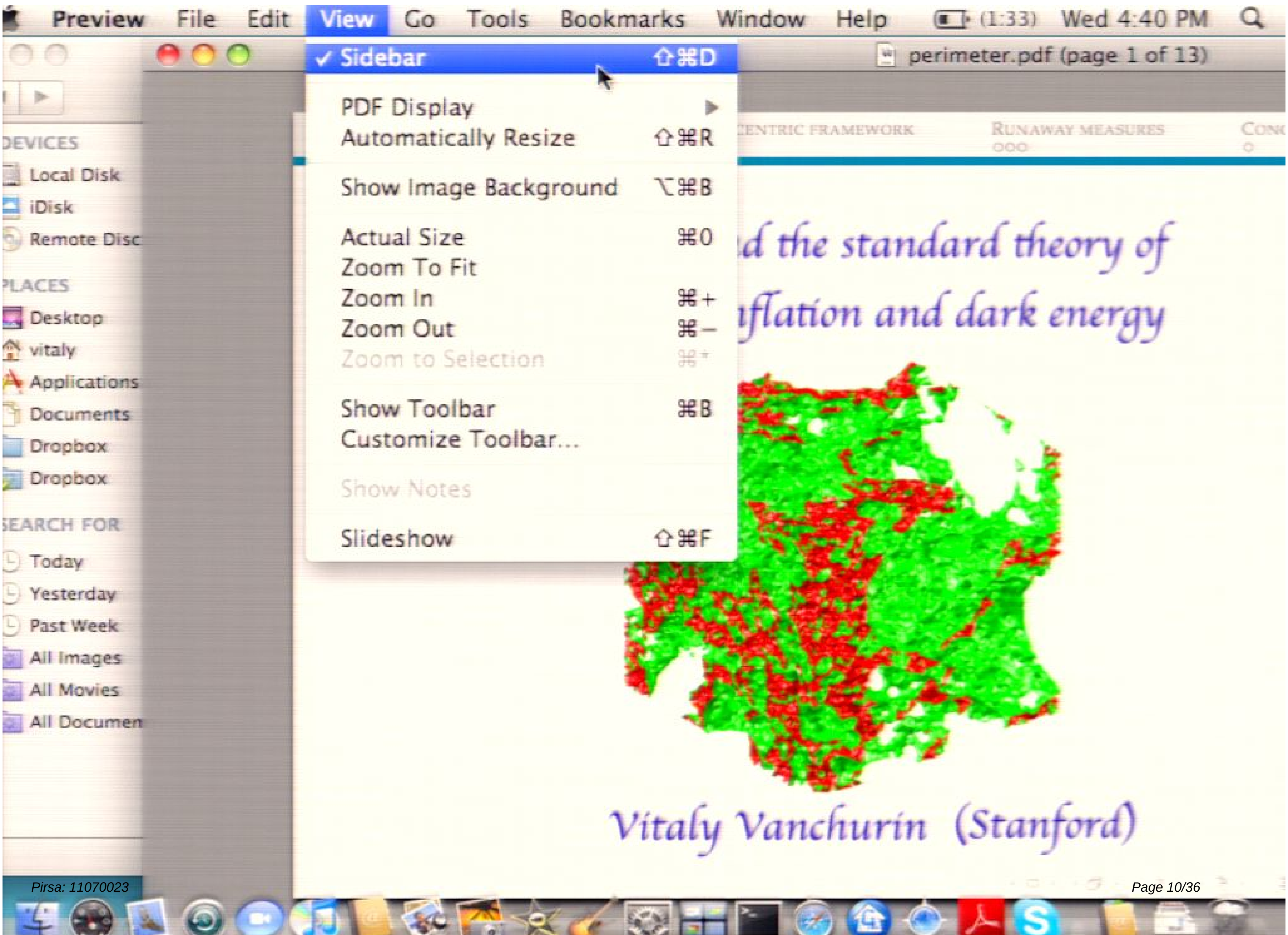
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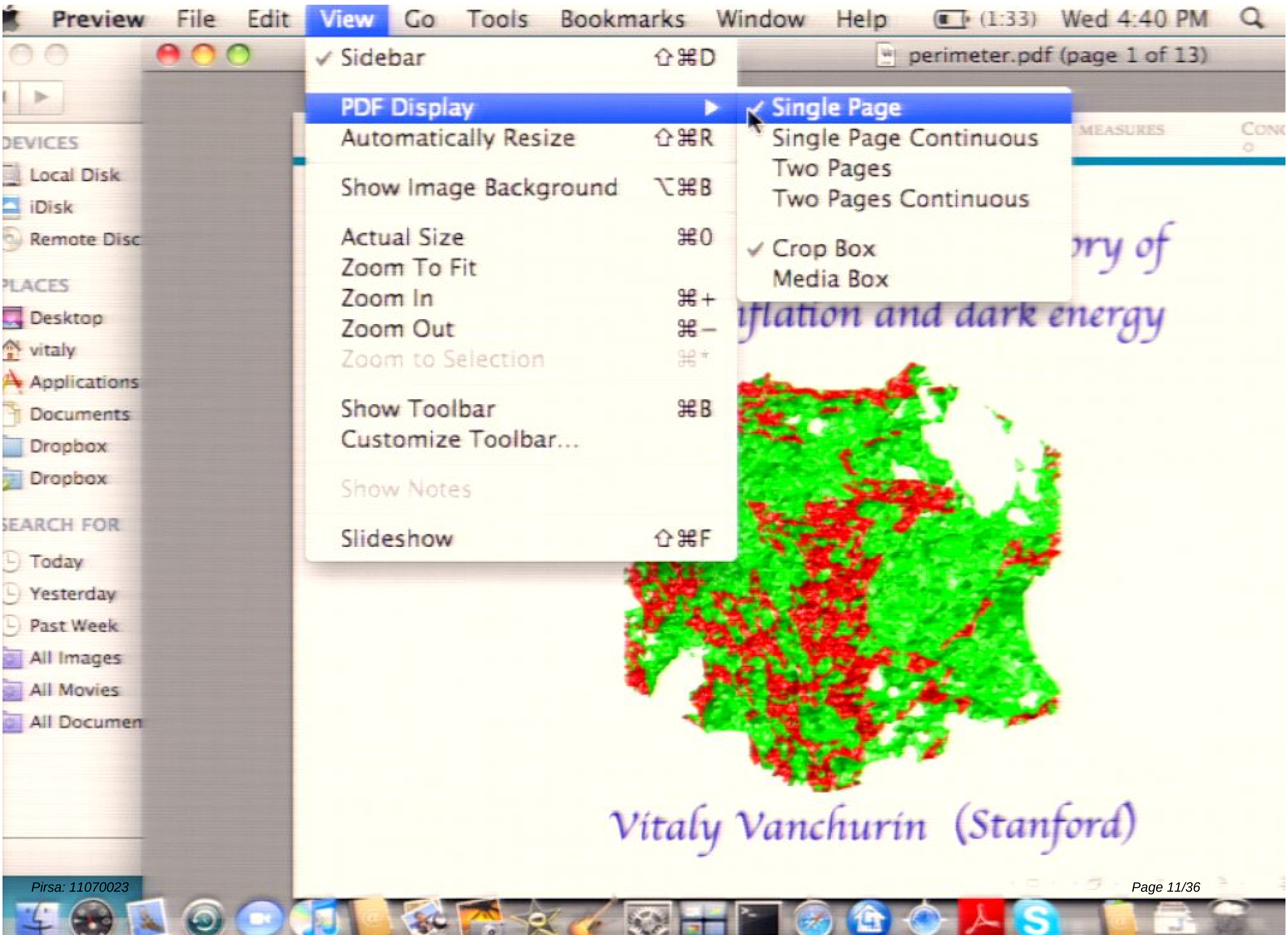
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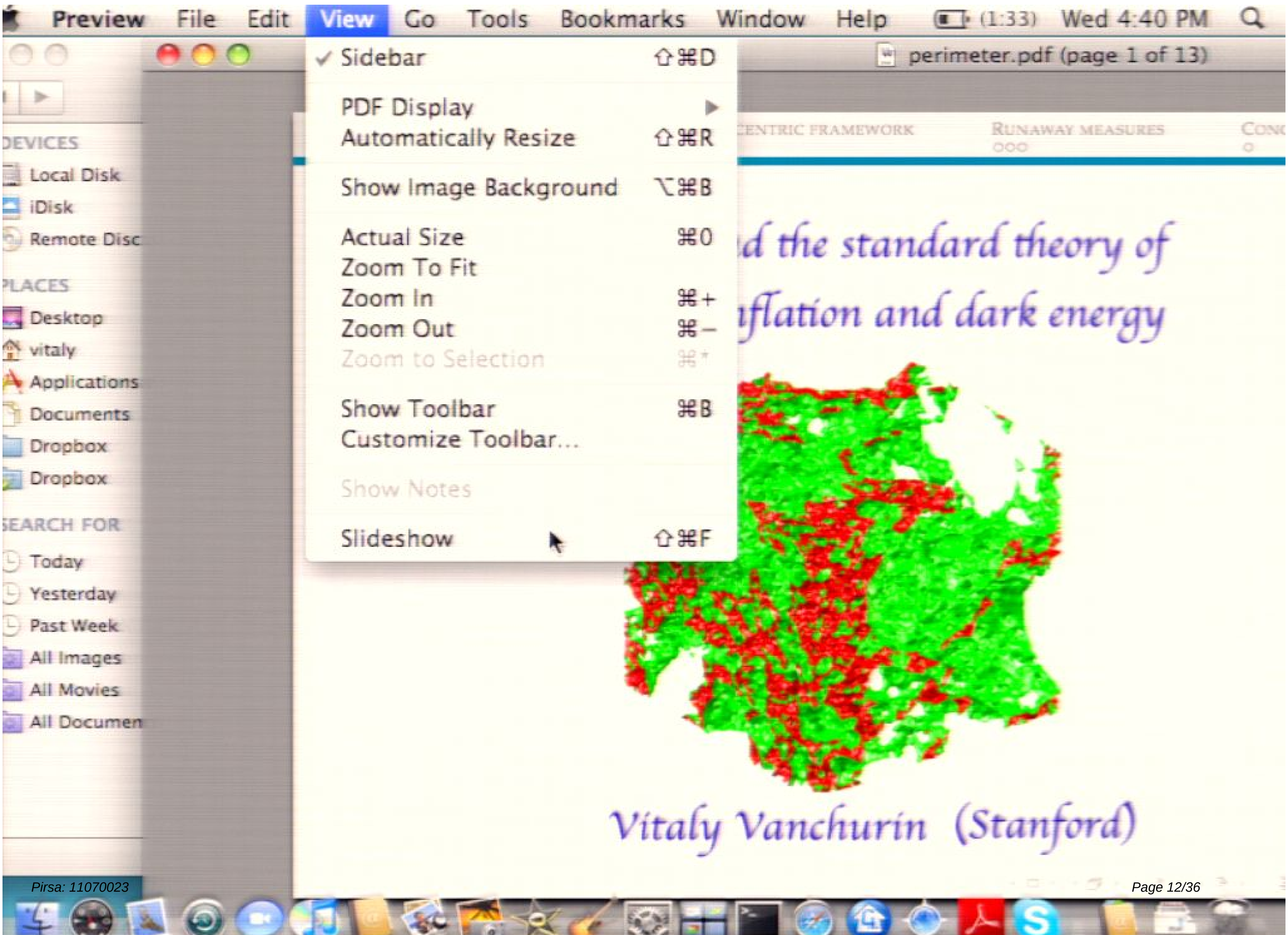
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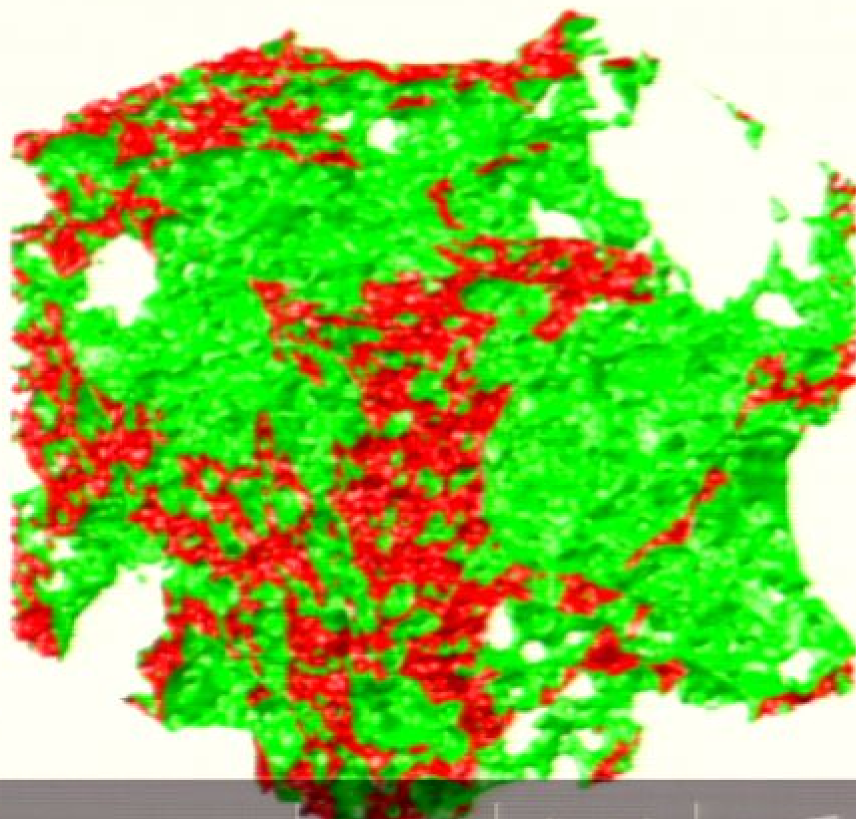

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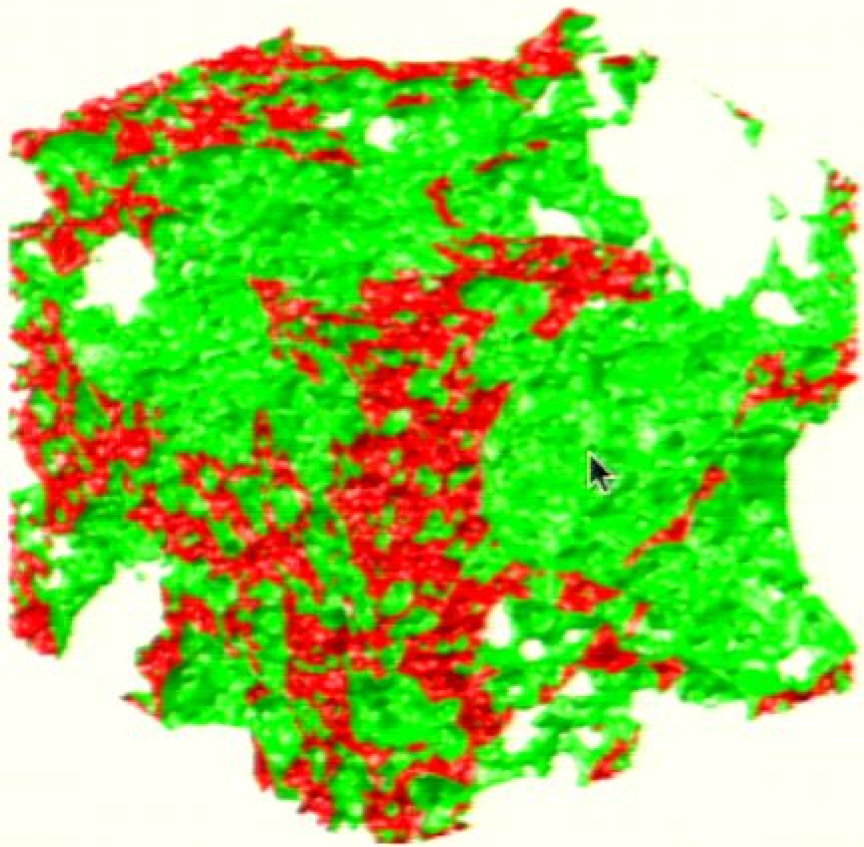

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Paradoxes with Cutoff Measures

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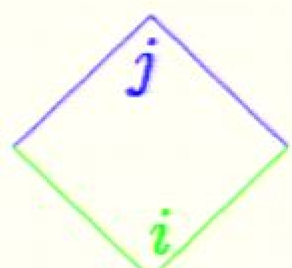

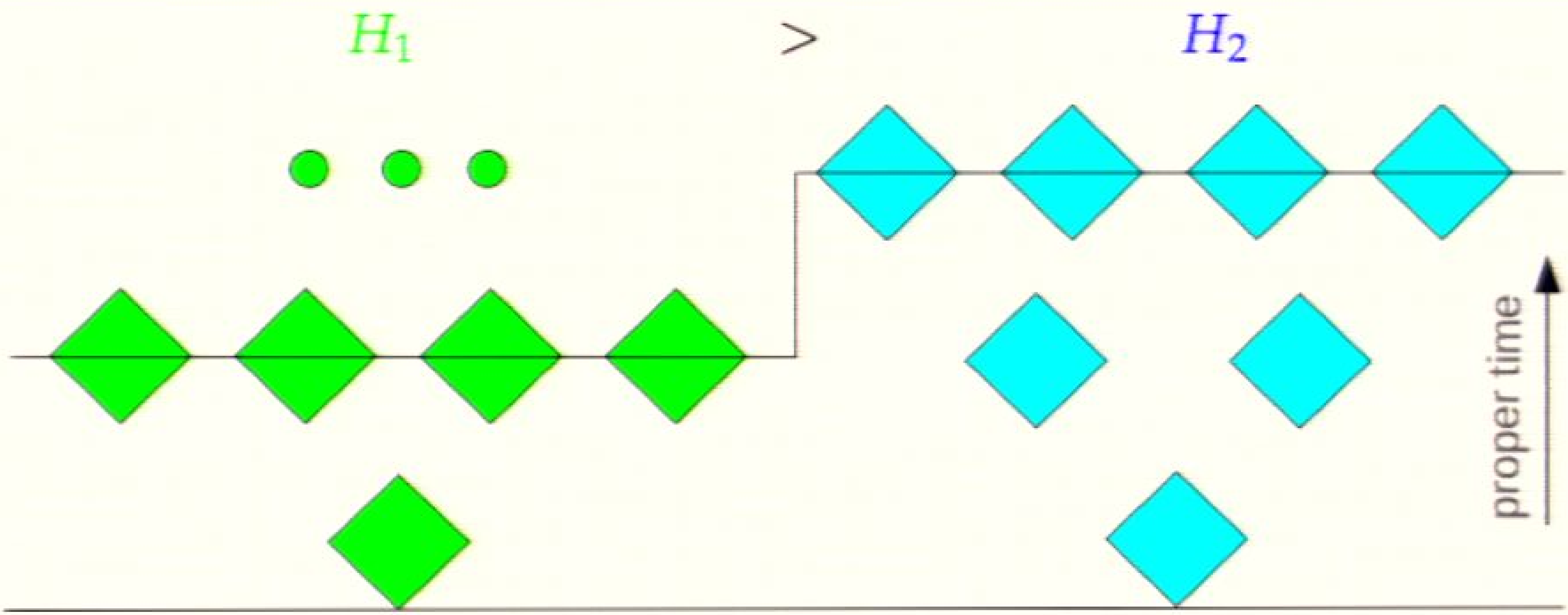

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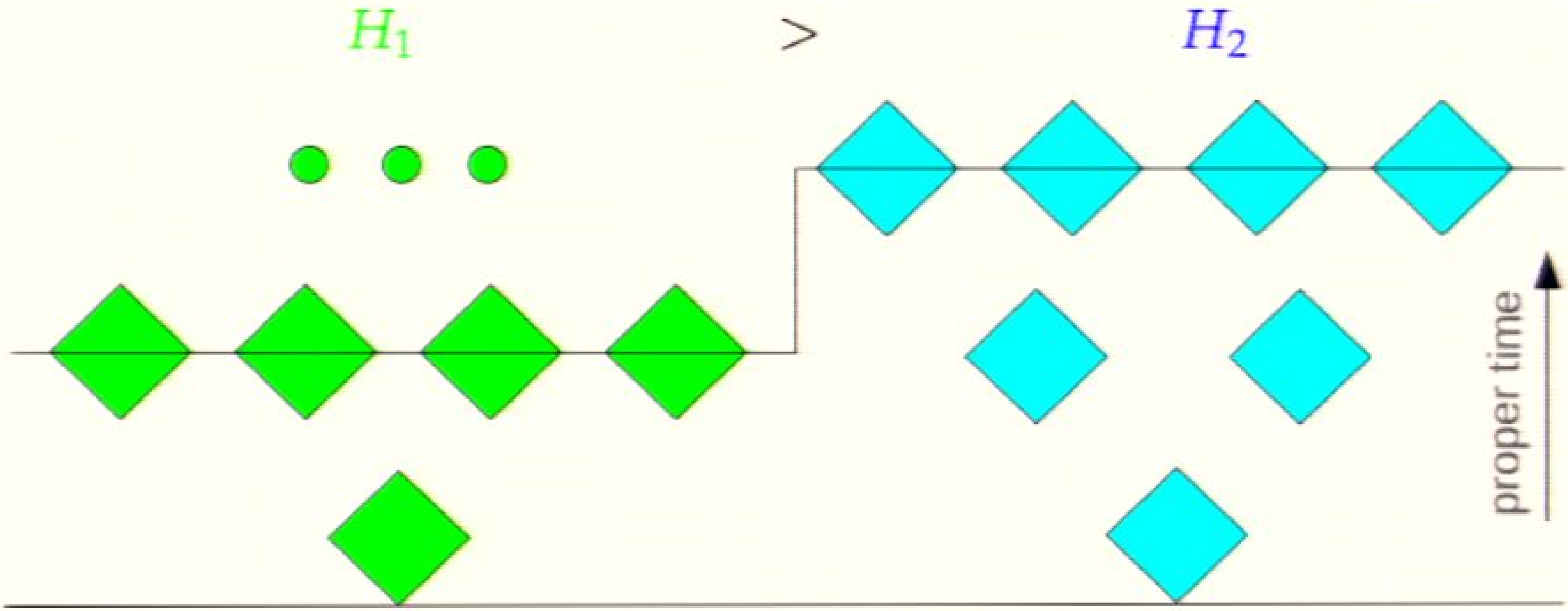
$$\frac{1}{5} = \frac{N_\Diamond(1)}{N_\vee(1)} \neq \frac{N_\Diamond(2)}{N_\vee(2)} = \frac{3}{7}$$

- Bayes rule fails!
- Exceptions: Proper time cutoff, Stationary measure.

POSSIBLE RESOLUTIONS

- Absolute cutoff interpretation [Olum] [Bousso, Freivogel, Leichenauer, Rosenhaus (2010)]
  - End of time?
  - Mechanism is needed...
- Multiversal arXivist interpretation [Guth, V.V., (2011+ε)]
  - Guth-Vanchurin paradox.
  - Changing probabilities.
- Geocentric interpretation [Noorbala, V.V. (2010)]
  - Use the cutoff measure only once to determine $M(i)$.
  - ... related to proper time cut-off and stationary measures.



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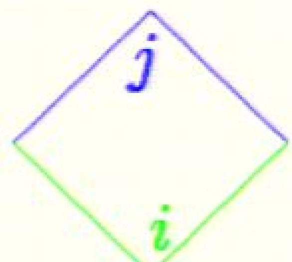

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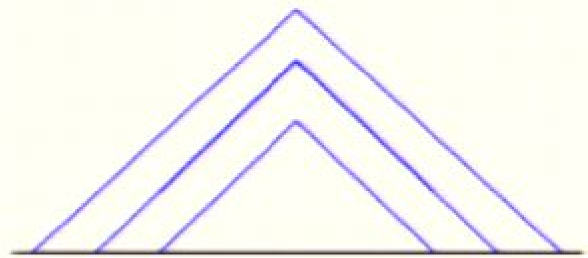
Basic setup

- After all, we are dealing with probabilities on the space of outcomes of experiments: $W(i)$, $W(j,i)$, $W(k,j,i)$,...
- So let us concentrate on the final result regardless of where it comes from, and demand that it satisfy some constraints
  - 1) Bayes rule: $W(k,j,i) = W(k|j,i)W(j,i)$, etc.
  - 2) Markov property (in time): $W(k|j,i) = W(k|j)$, etc.
- This reduces all W's to only two functions:
  - $\mu(i) \equiv W(i)$ (on initial conditions) and
  - $W(j|i)$ (the transition probabilities).
- $\mu(i)$ can be computed from a cutoff measure as $\mu(i) = M(i)$,
- or written down with no reference to any cutoff measure.
- same true for $W(j|i)$ ...

- $W(j|i)$ can be verified by repeated experiments as usual.
- $\mu(i)$ can be verified by exploring more of the initial surface of the local lab.



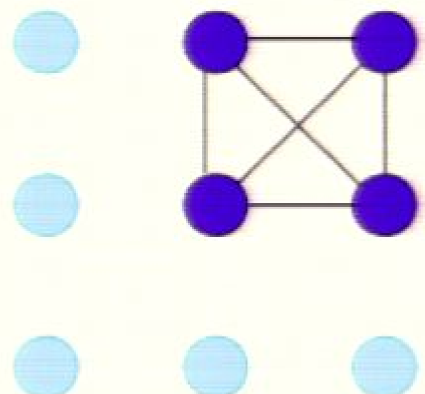
- In the case that the initial condition is a 3d field configuration: $i \longmapsto \phi(x), \dot{\phi}(x)$ (or perhaps $A_\mu(x), \dot{A}_\mu(x)$)
- Example: Thermal distribution of CMB photons observed on the initial surface of the lab [Penzias, Wilson (1964)]:
  - $\mu \approx \exp(-H_{\rm EM}/T)$ with $T = 2.7$K.
  - Anisotropies? Acoustic peaks? Interaction terms; counterpart of inflation.

Need a slowly scrambling state...

FURTHER SIMPLIFYING CONSTRAINT

- 3) Markov property in space: ϕ is a Markov random field and $\mu[\phi]$ is its probability distribution.
- ϕ outside any region depends on ϕ inside only through its boundary: $\mu(\phi_{\text{in}}, \phi_\partial, \phi_{\text{out}}) = \mu(\phi_{\text{out}}|\phi_\partial) \cdot \mu(\phi_{\text{in}}, \phi_\partial)$.

- Neighborhood of points is defined via a graph.
- According to the Hammersley-Clifford theorem μ factorizes into cliques of the graph:



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(In the above example, $L = L(\phi, \nabla\phi)$).

- It follows that any measure satisfying the spatial Markov property corresponds to a local 3d Lagrangian.

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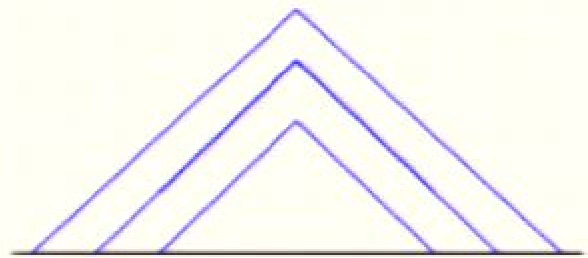

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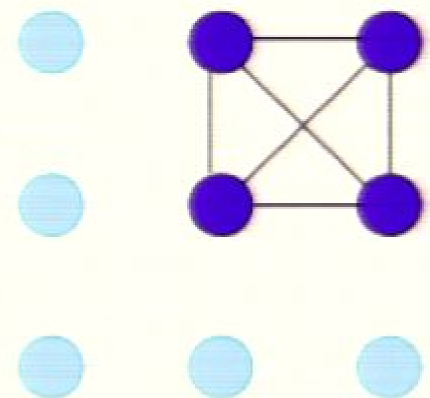

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RUNAWAY MEASURES

- Assumption #1: The fundamental theory (e.g. string theory) possess only a finite number N of vacuum solutions, landscape of vacua, with probability distribution of observable parameters among vacua described by a normalizable function $P(\Lambda, H_I, N_e...)$.
- Assumption #2: The correct cosmological measure can be described by a positive definite weighting function $w(\Lambda, H_I, N_e...)$ with an exponential dependence in at least one but possibly many observable parameters (e.g. Q-catastrophe [Garriga, Vilenkin (2005)]).
- For example:

$$w(\mathbf{x} \equiv (a, b, c...)) \propto e^{\frac{A}{a}+\frac{B}{b}+\frac{C}{c}+...}$$

where $A \geq B \geq C....$

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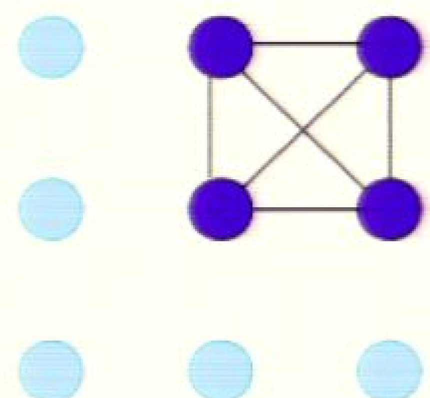

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LANDSCAPE STATISTICS [LINDE, V.V. (2010)]

- Ideally:

$$\langle \mathbf{x} \equiv (a, b, c...) \rangle = \frac{\sum_{i=1...N} \mathbf{x}_i w(\mathbf{x}_i)}{\sum_{i=1...N} w(\mathbf{x}_i)}. \quad (1)$$

- In reality:

$$\langle \mathbf{x} \rangle = \int d\mathbf{x}_1 P(\mathbf{x}_1) ... \int d\mathbf{x}_N P(\mathbf{x}_N) \frac{\sum_{i=1...N} \mathbf{x}_i w(\mathbf{x}_i)}{\sum_{i=1...N} w(\mathbf{x}_i)}. \quad (2)$$

- But not:

$$\langle \mathbf{x} \rangle = \frac{\int d\mathbf{x} w(\mathbf{x}) P(\mathbf{x}) \mathbf{x}}{\int d\mathbf{x} w(\mathbf{x}) P(\mathbf{x})}. \quad (3)$$

- Two important conclusions in large N limit :
  - 1) only $\langle a \rangle$ is obtained from runaway behavior of $w(\mathbf{x})$.
  - 2) all other observables (i.e. $b, c, ...$) are determined by $P(\mathbf{x})$.

PHENOMENOLOGY

- CC seems to be the best candidate for a runaway, but then
- all other constants should derivable from first principles!
- Examples:
  - Hawking's distribution:

$$w(\Lambda) \sim e^{S(\Lambda)} = \exp\left(24\pi^2/\Lambda\right) . \tag{4}$$

  - Baby universes:

$$w(\Lambda) \sim e^{e^{S(\Lambda)}} = \exp\left(\exp\left(24\pi^2/\Lambda\right)\right) . \tag{5}$$

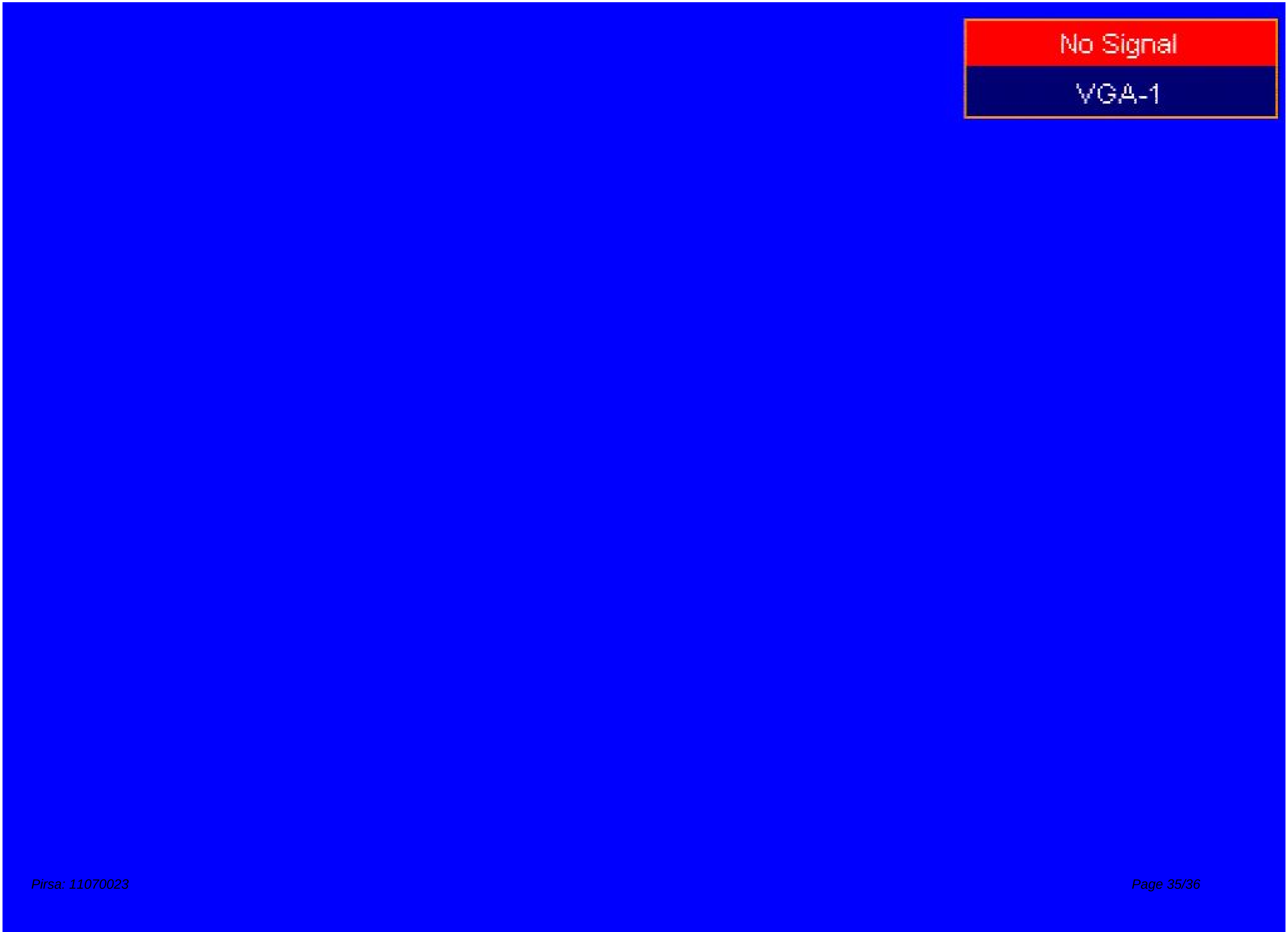
  - Observable universes [Linde, V.V. (2009)]:

$$w(\Lambda, H_I) \sim \exp\left(H_I^{\frac{3}{2}} |\Lambda|^{-\frac{3}{4}}\right) , \tag{6}$$

- Runaway naturally explain hierarchy between H_I and $|\Lambda|^{\frac{1}{2}}$.
- Note: H_I cannot be too large, but $|\Lambda|$ has to be the smallest.

CONCLUSIONS

- Standard theory of inflation and dark energy is great, but extrapolation to higher energy scales requires new physics
- Paradoxes of eternal inflation guide us in this search
  - Holographic cosmology is one directions to proceed
  - Mathematical limit interpretation is another direction
  - Geocentric framework perhaps also worth exploring
- Runaway measures and landscape of vacua
  - provide a mechanism for hierarchy between inflation & CC
  - suggest that some problems could be measure independent.
  - We might even return to Einstein's dream of a final theory.
- Some "simple" things to do:
  - geocentric 3D Lagrangian awaits to be discovered
  - measure independent $P(\Lambda, H_I, ...)$ needs to be derived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