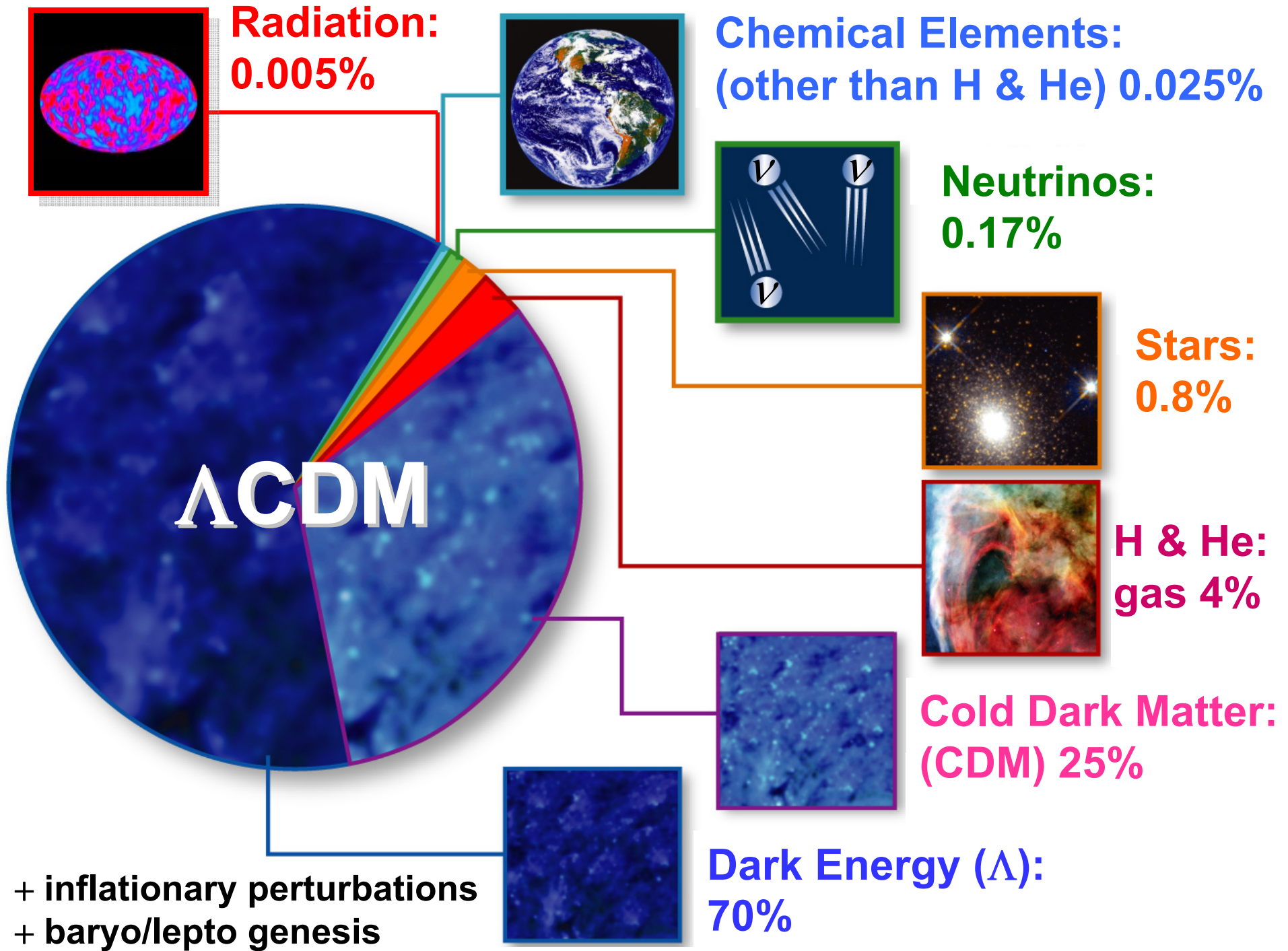


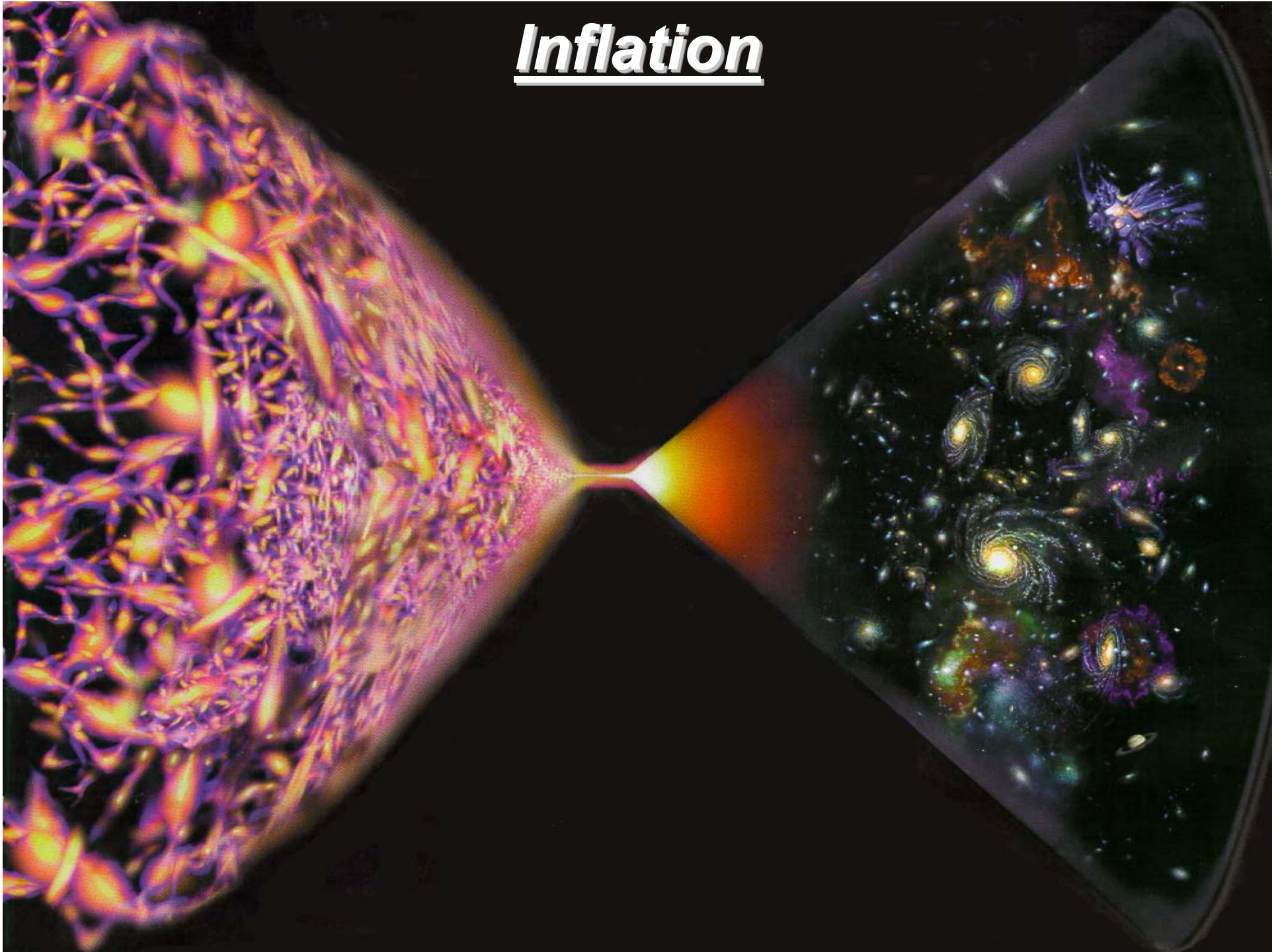
# ***The Dark Universe: Dark Matter and Dark Energy***

<b>Rocky I:</b>	<b>The Universe Observed</b>	<b>Monday</b>
<b>Rocky II:</b>	<b>Inflation</b>	<b>Tuesday</b>
<b>Rocky III:</b>	<b>Dark Matter</b>	<b>Wednesday</b>
<b>Rocky IV:</b>	<b>Dark Energy</b>	<b>Thursday</b>

**CERN Academic Training Lectures**      **January 2008**  
*Rocky Kolb*      *The University of Chicago*



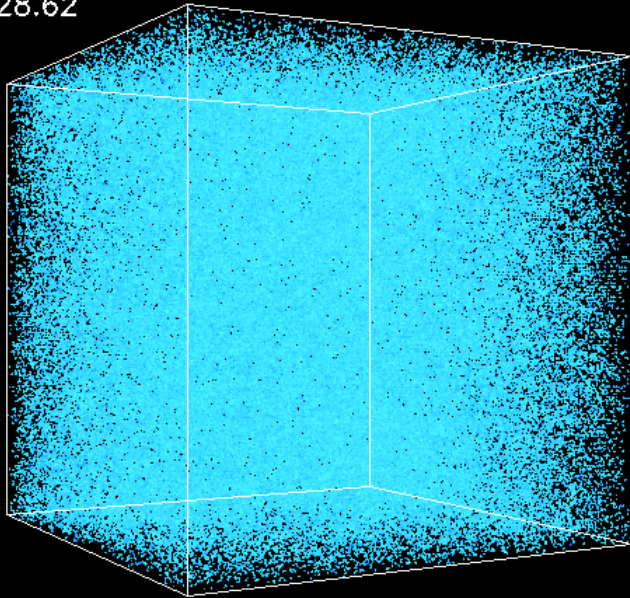
# Inflation



# The growth of cosmic seeds

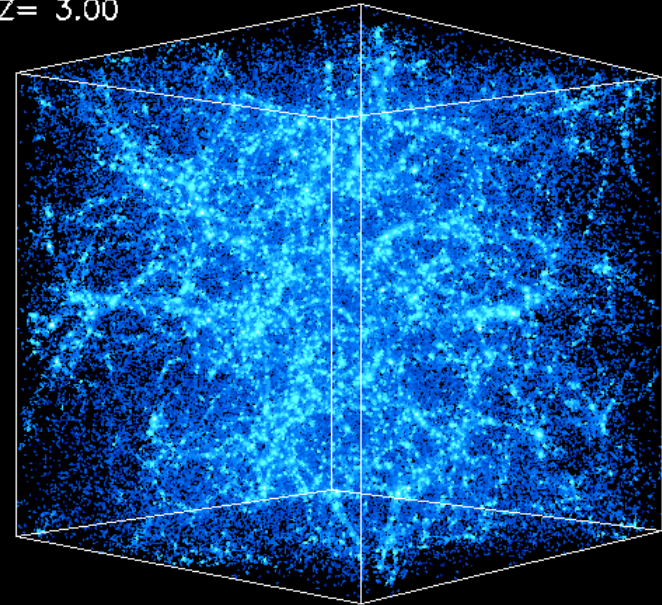
$Z=28.62$

100 Myr



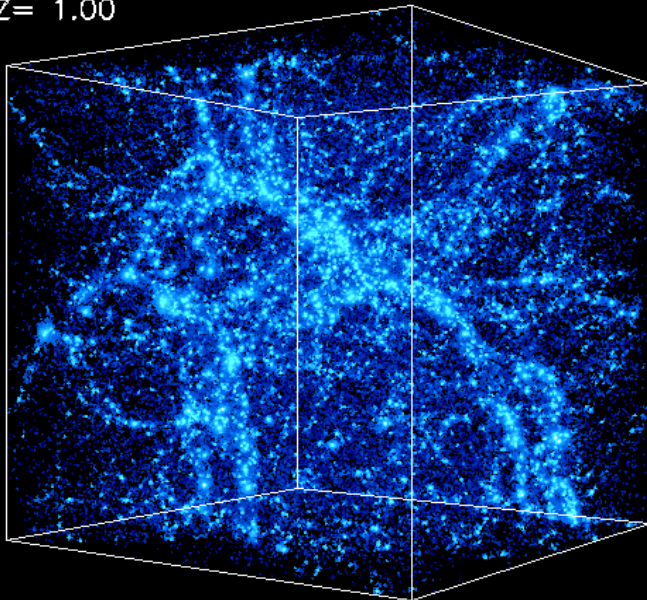
$Z= 3.00$

1 Gyr



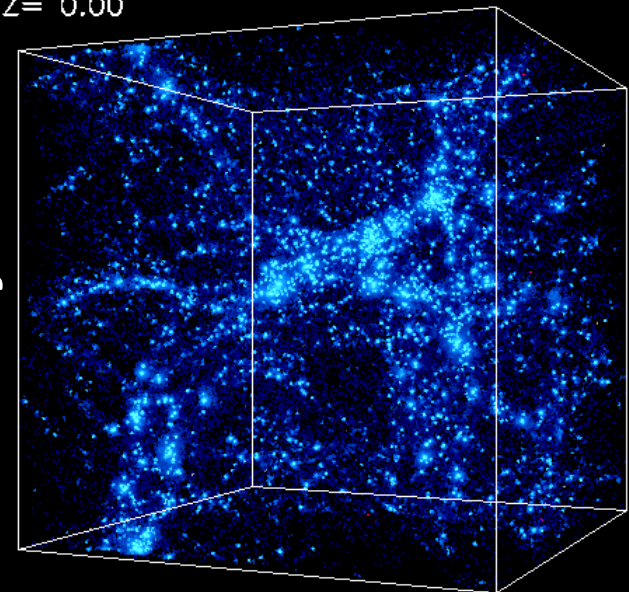
$Z= 1.00$

5 Gyr

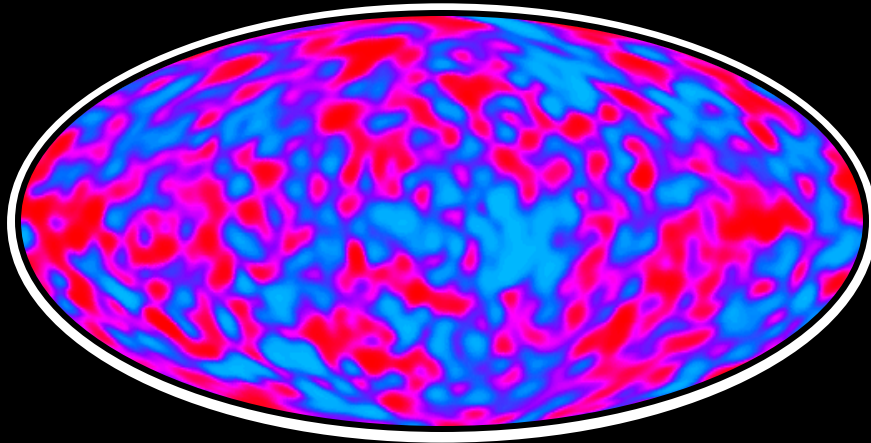


$Z= 0.00$

today



# Primordial Perturbations

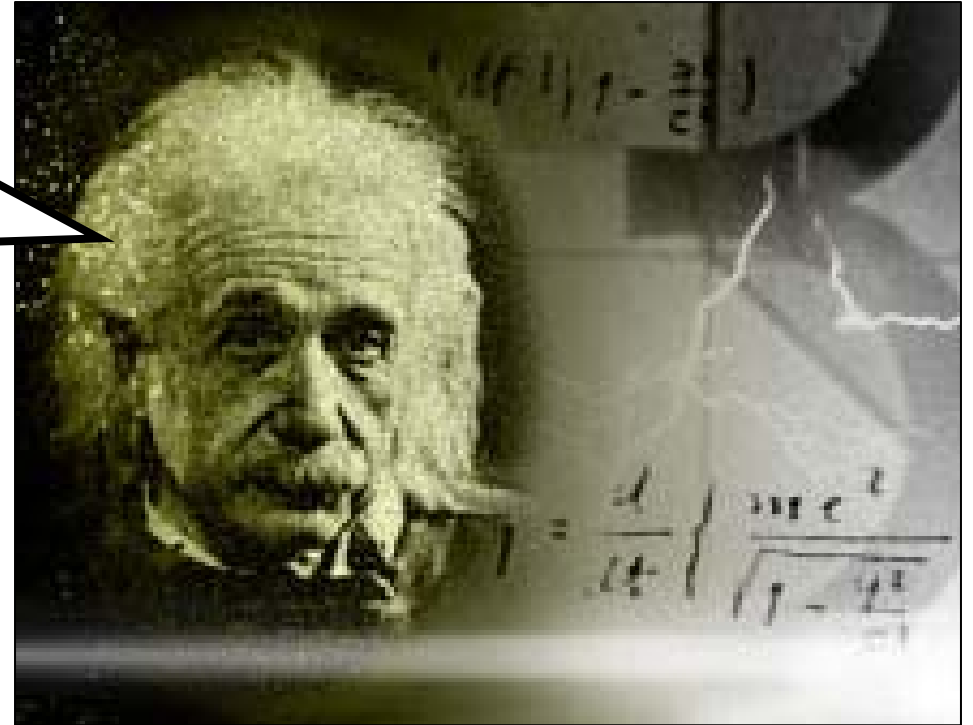
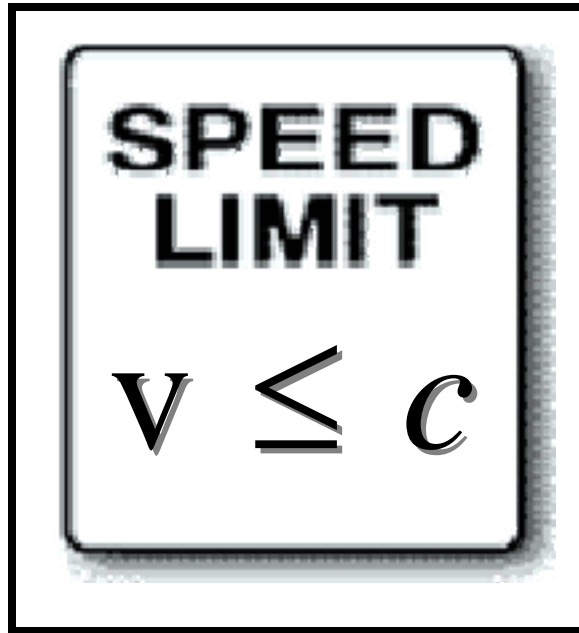


correlations on scales  
 $\gg 380,000$  light years

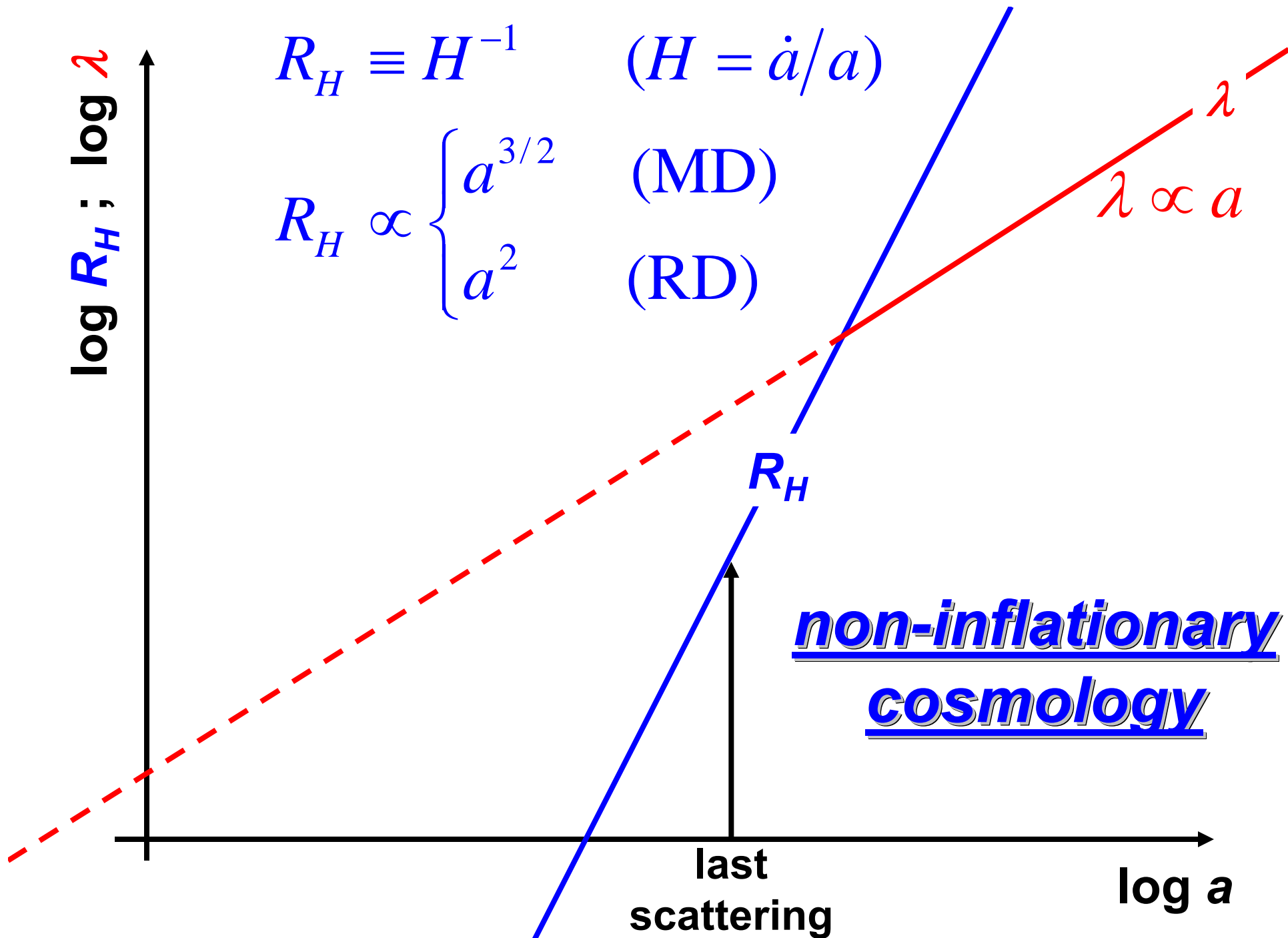
**CMB: a snapshot of the  
universe 380,000 AB**

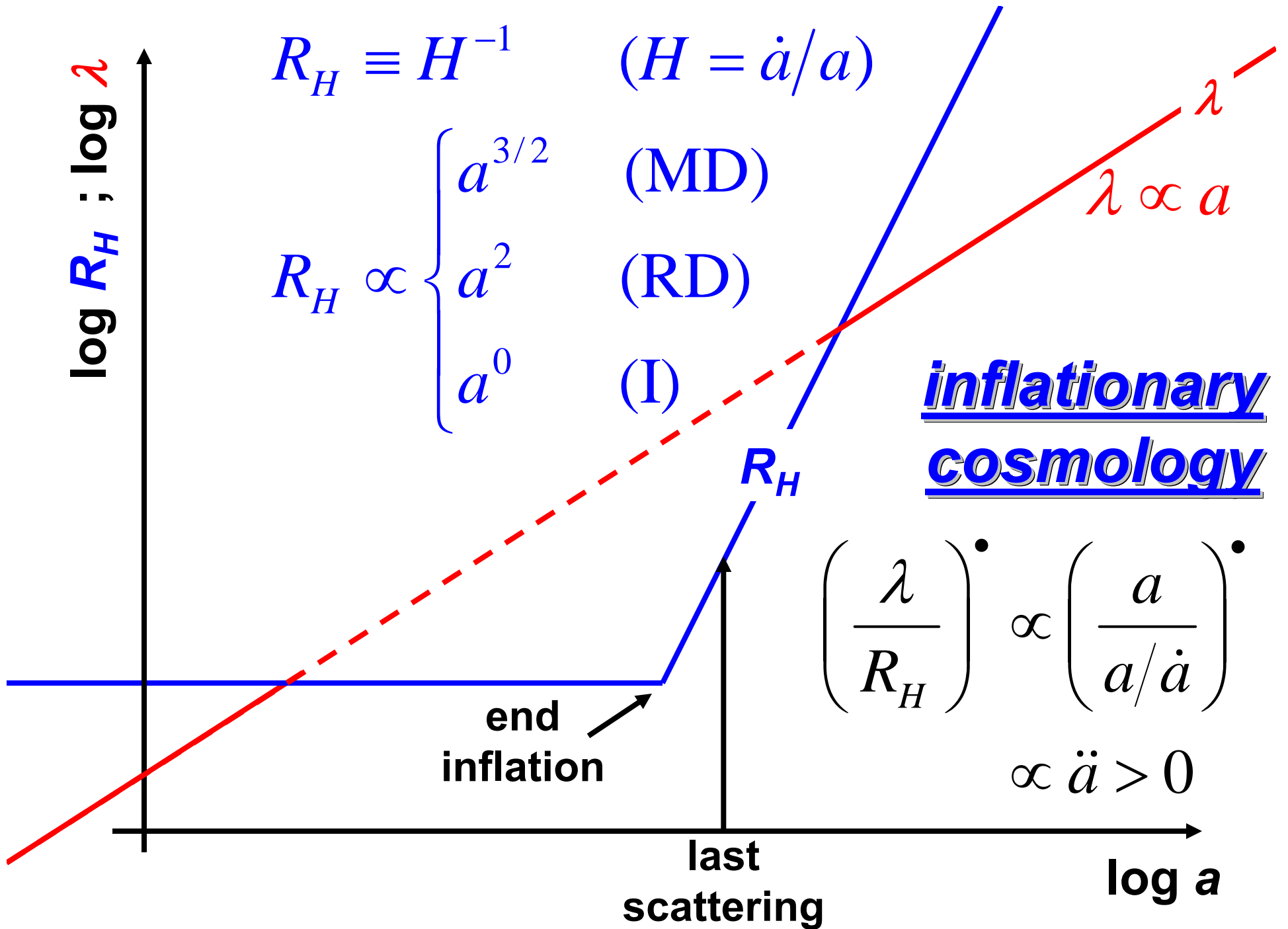


**More than 380,000 light years**  
**in less than 380,000 years?**

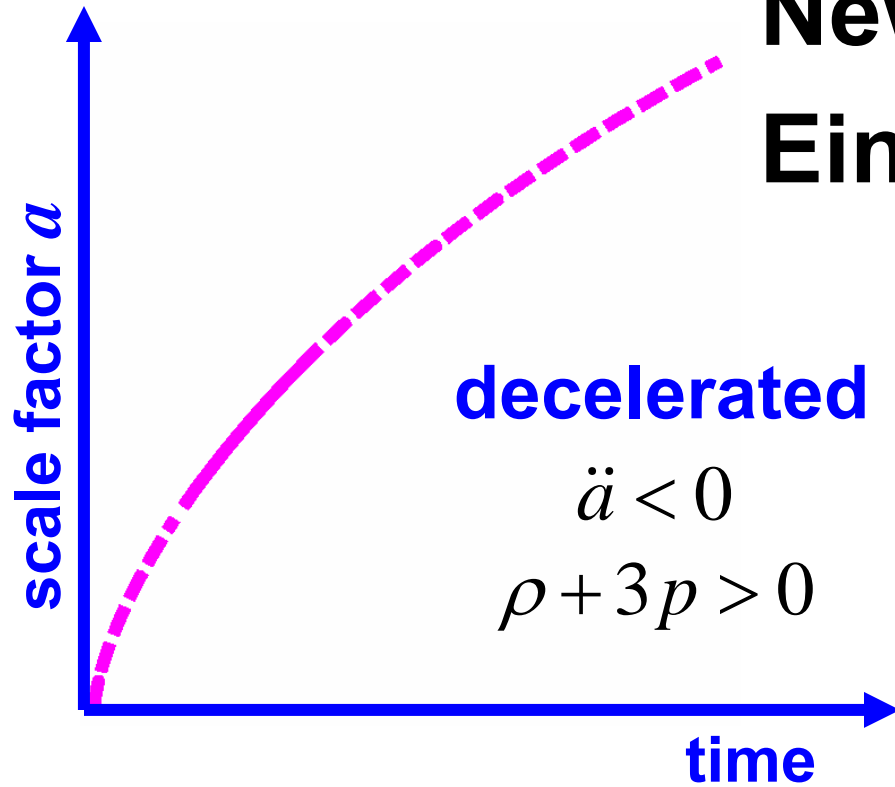


- $v \leq c$  for velocity through space
- no limit on expansion velocity of space
- “acausal” requires “accelerated” expansion



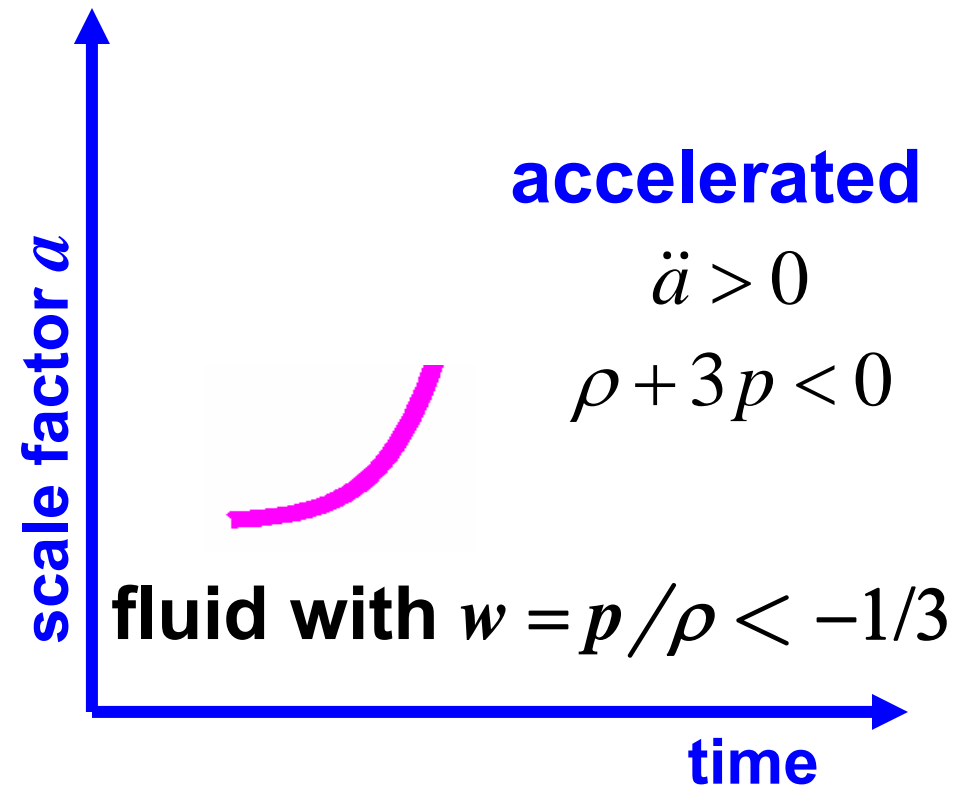


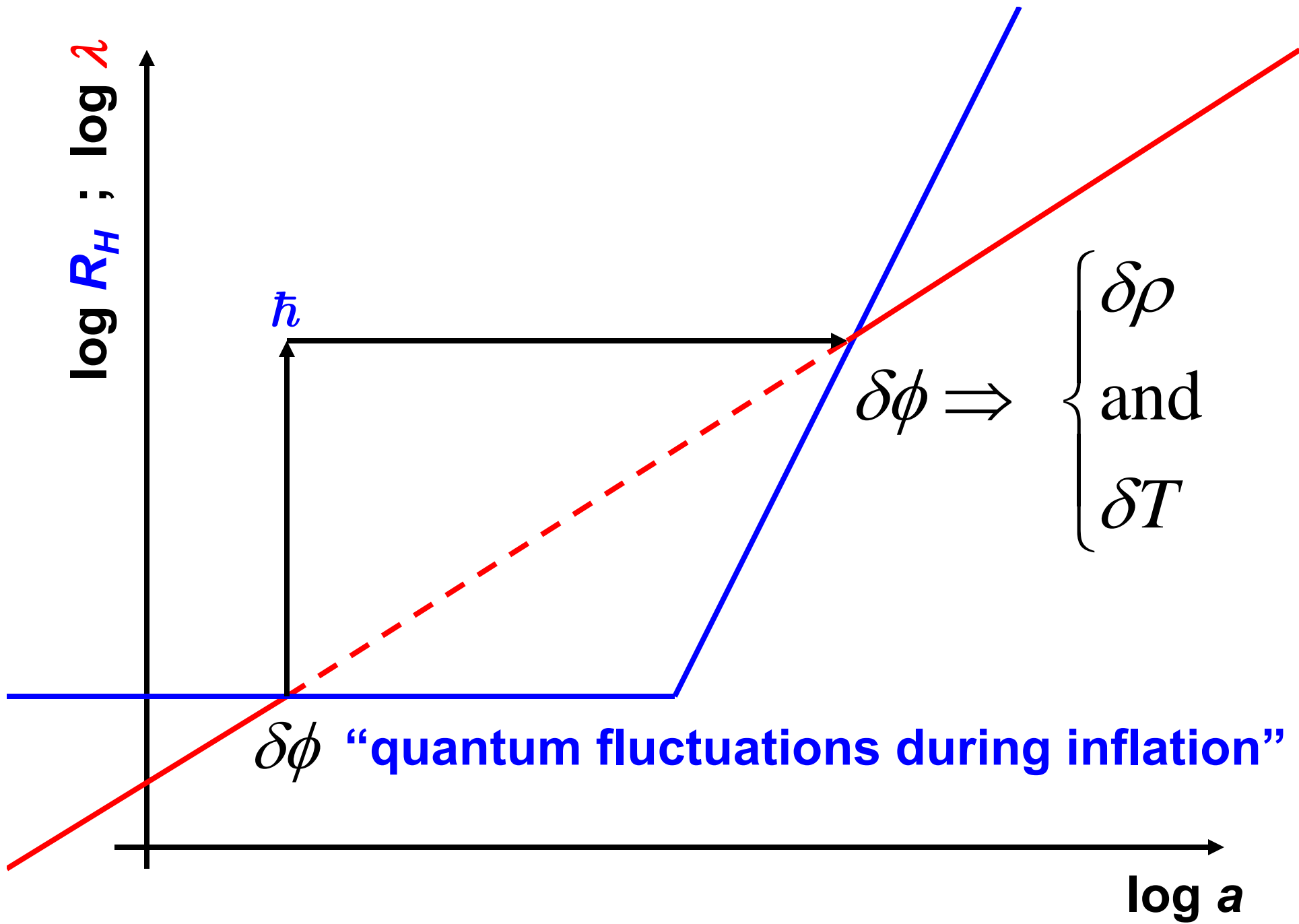




**Newton**  $\frac{\ddot{a}}{a} = -\frac{4\pi G}{3} (\rho + 3p)$

**Einstein**





# ***An Early Particle Cosmologist***

In mid-1930s, influenced by Eddington & Lemaître,



**Schrödinger turned to cosmological issues**

1938-1939: Graz → Vatican → Gent, Belgium → Dublin

# Proper Vibrations of the Expanding Universe

Erwin Schrödinger *Physica* 6, 899 (1939)

## Introduction:

“... proper vibrations [positive and negative frequency modes] cannot be rigorously separated in the expanding universe.

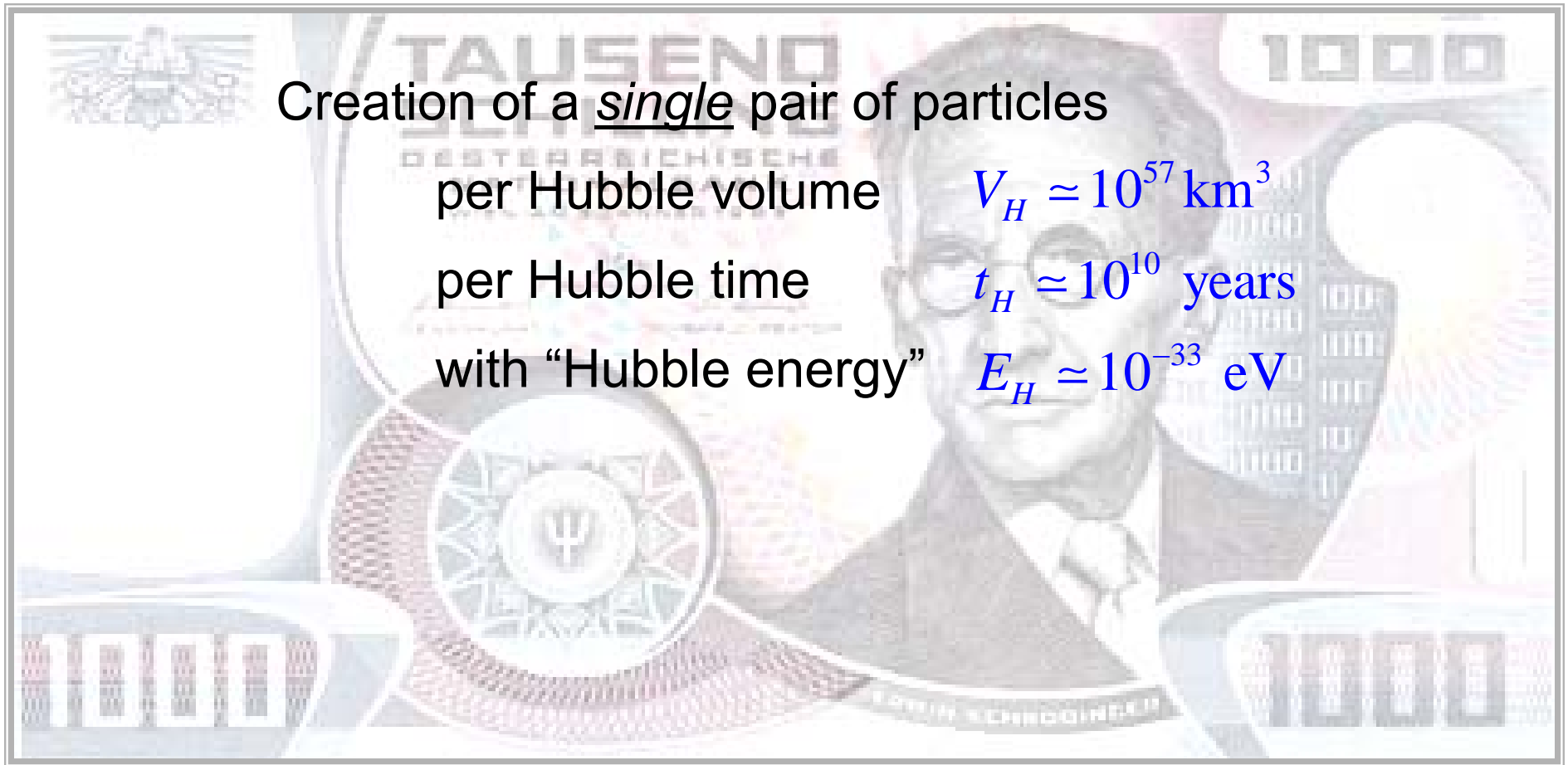
... this is a phenomenon of outstanding importance [density perturbations from inflation, WIMPZILLAS]. With particles it would mean production or annihilation of matter, merely by expansion,... Alarmed by these prospects, I have examined the matter in more detail.”

## Conclusion:

“... There will be a mutual adulteration of positive and negative frequency terms in the course of time, giving rise to ... the ‘alarming phenomenon’...”

# Proper Vibrations of the Expanding Universe

Erwin Schrödinger *Physica* 6, 899 (1939)



Creation of a single pair of particles  
per Hubble volume  $V_H \approx 10^{57} \text{ km}^3$   
per Hubble time  $t_H \approx 10^{10} \text{ years}$   
with “Hubble energy”  $E_H \approx 10^{-33} \text{ eV}$

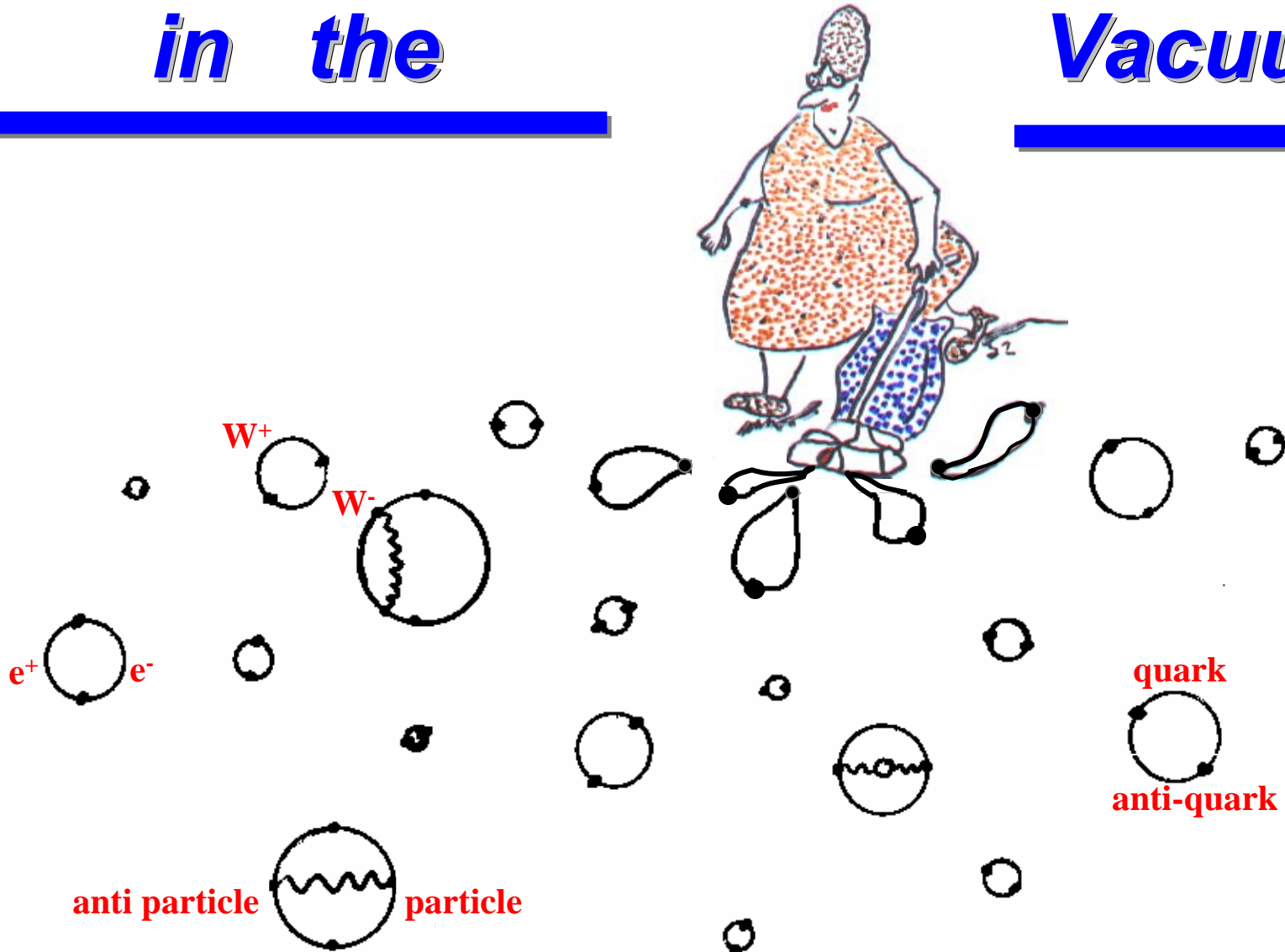
Alarming?

# Virtual Particles in the

---

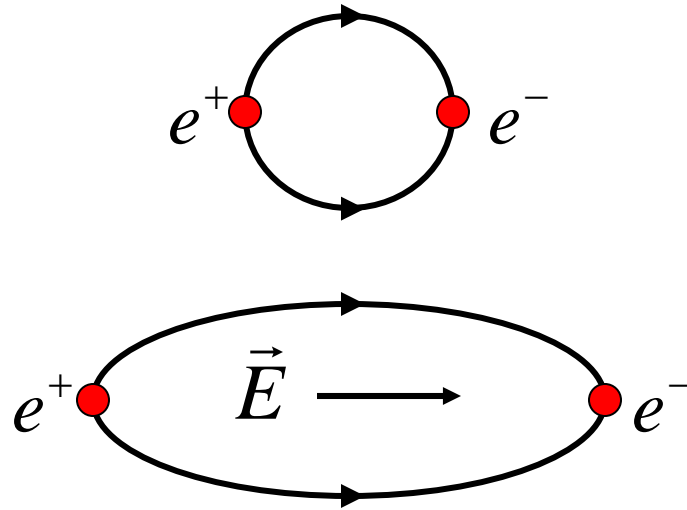
# Quantum Vacuum

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# *Disturbing the Vacuum*

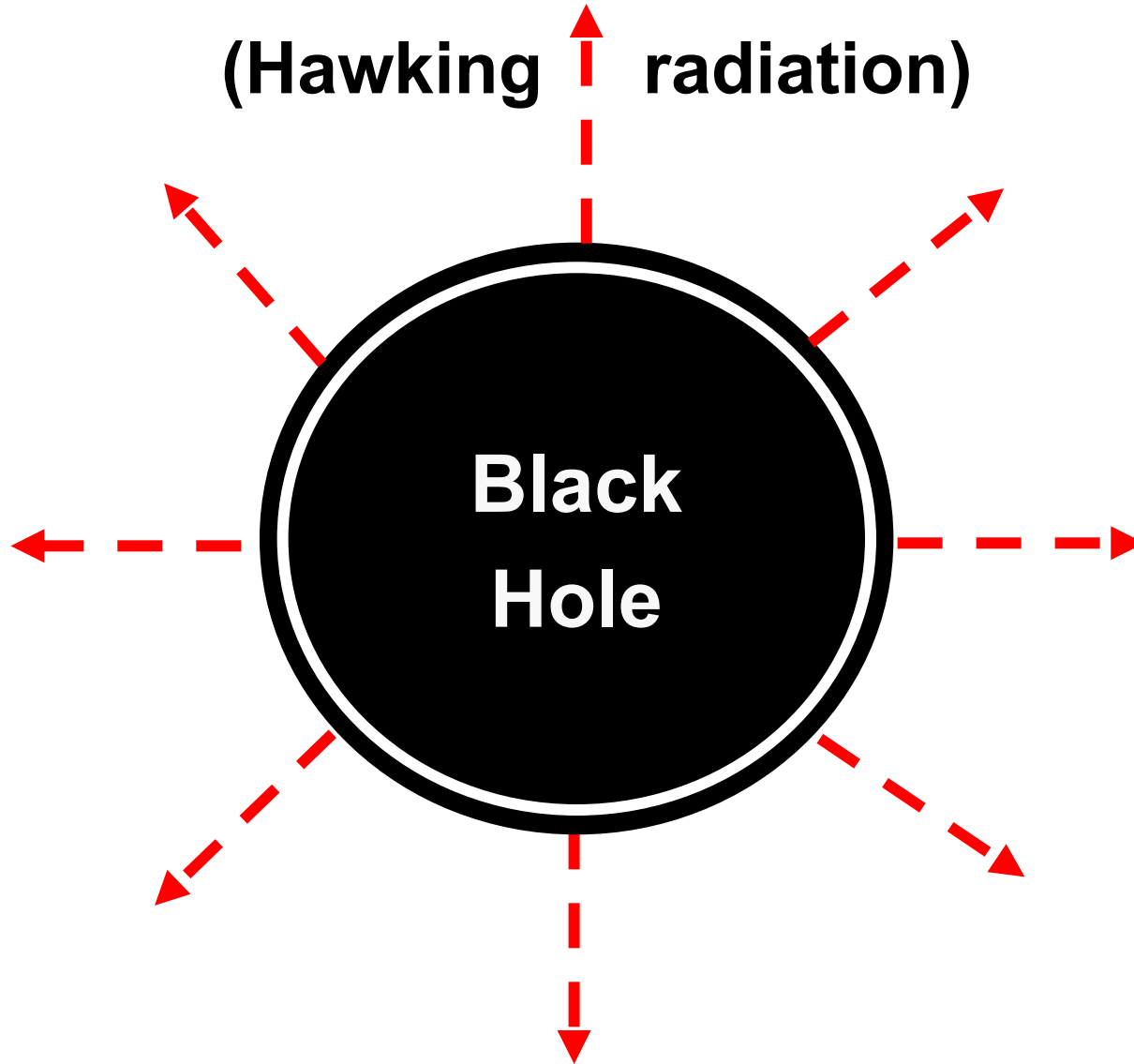
Particle creation in an external electric field



Particle creation if energy gained in acceleration over a Compton wavelength exceeds the particle's rest-mass

# *Disturbing the Vacuum*

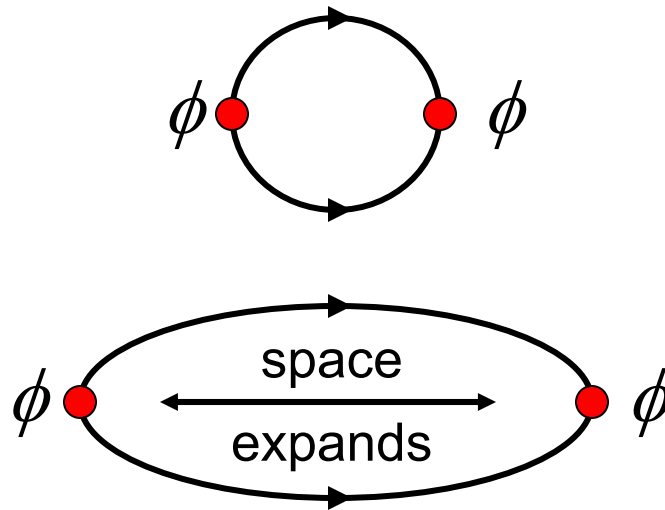
**Strong gravitational field** → **particle production**  
(Hawking radiation)





# *Disturbing the Vacuum*

Particle creation in the expanding universe



Particle creation if energy gained in expansion over a Compton wavelength exceeds the particle's rest-mass

# **Expanding Universe** **Particle Creation**

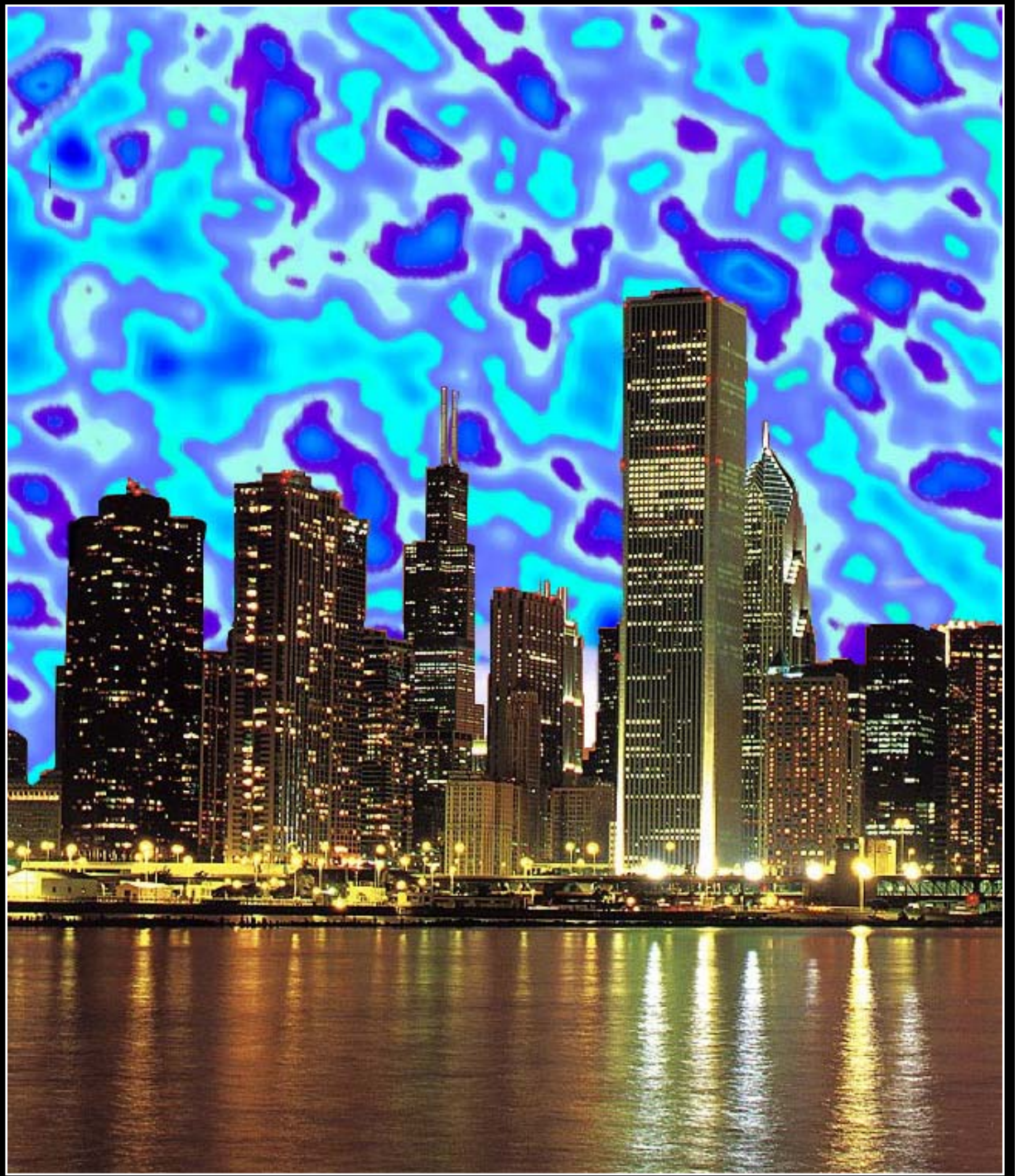
Discovery: Schrödinger (1939) *The Proper vibrations of the expanding universe*  
“the alarming phenomenon”

**It's a bug!**

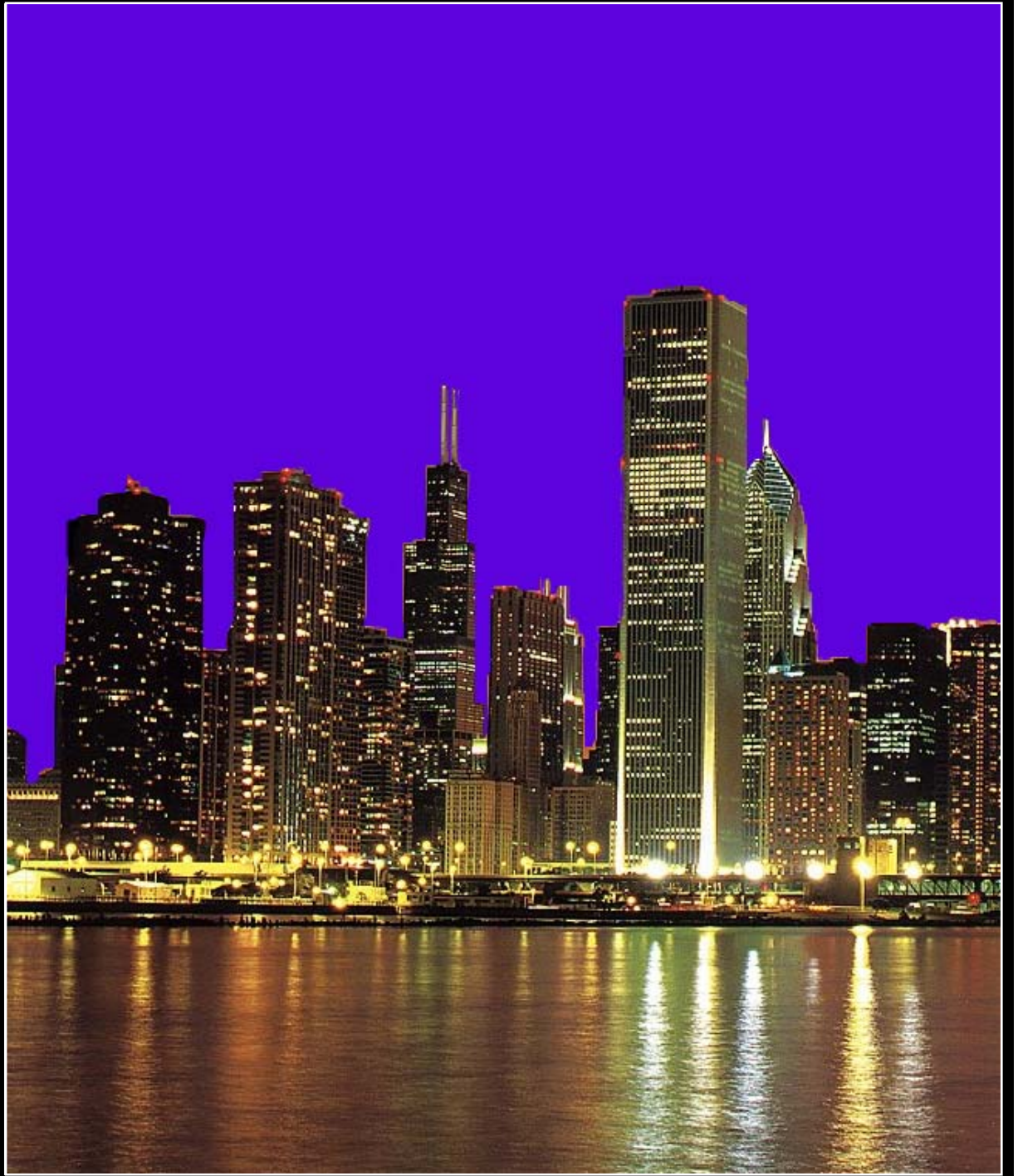
First application: density perturbations, gravitational waves from inflation

**1983—present: It's a feature!**

**A pattern  
of vacuum  
quantum  
fluctuations**



$$\hbar \rightarrow 0$$



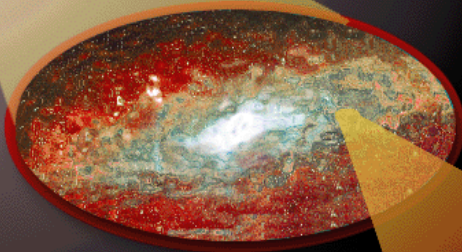
# Cosmic Symphony (Harmonice Mundi)

phase	tempo	duration	relic
string dominated $H \simeq ???$	pizzicato	$10^{-43}$ sec.??	????
vacuum dominated (inflation) $H \simeq a^0$	presto	$10^{-35}$ sec.?	seeds of structure gravitational waves CMB fluctuations

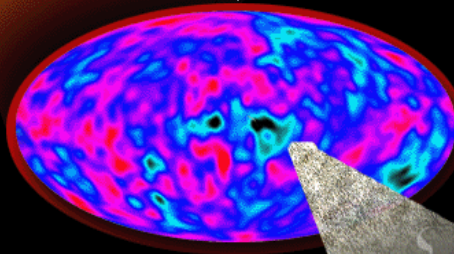
# Imprint of Inflation

*BIG BANG*

Inflation  
Big Bang plus  
 $10^{-35}$ ? seconds

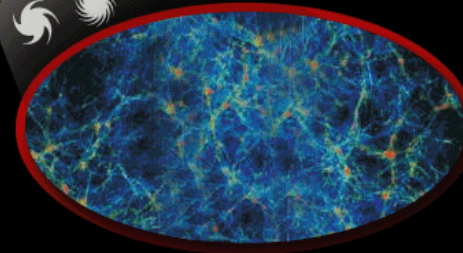


Big Bang plus  
380,000 Years



CMB fluctuations  
density perturbations  
gravitational waves

Big Bang plus  
14 Billion Years



# Cosmic Symphony (Harmonice Mundi)

phase	tempo	duration	relic
string dominated $H \simeq ???$	pizzicato	$10^{-43}$ sec.??	????
vacuum dominated (inflation) $H \simeq a^0$	presto	$10^{-35}$ sec.?	seeds of structure gravitational waves CMB fluctuations
radiation dominated $H \simeq a^{-2}$	allegro	earlier than 10,000 years	abundance of the light elements
matter dominated $H \simeq a^{-3/2}$	andante	later than 10,000 years	distant galaxies high- $z$ universe
vacuum dominated (inflation) $H \simeq a^0$	largo	day before yesterday	acceleration of the universe

# *Inflation, as a whole, can be divided into three parts*

## **1. Beginning**

*eternal inflation, wave function of the universe, did the universe have a beginning ????*

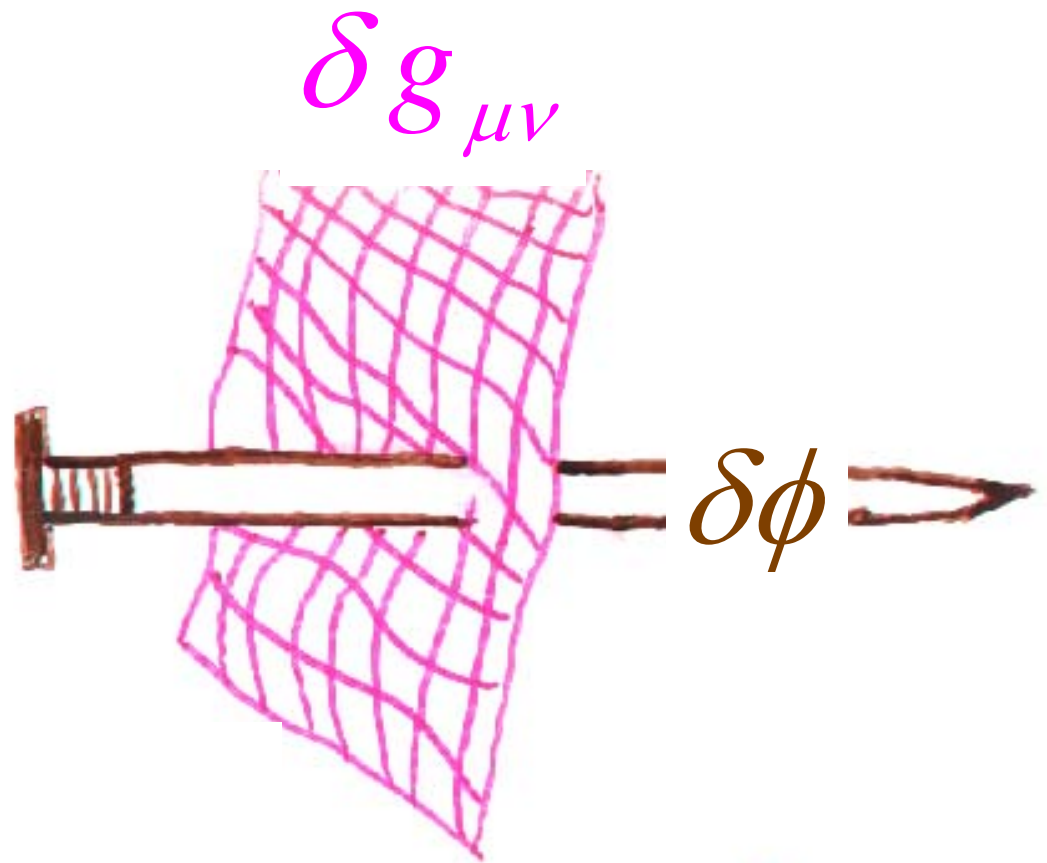
## **2. Middle**

*density perturbations, gravitational waves, (particle production in the expanding universe)*

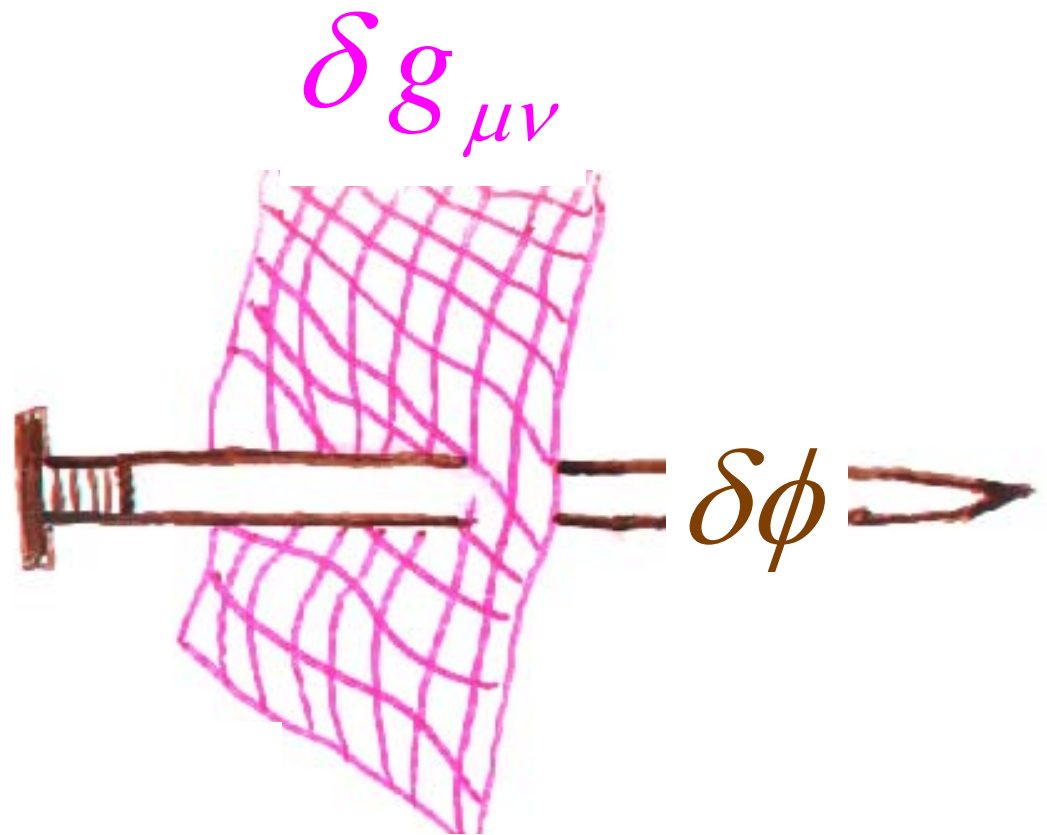
## **3. End**

*defrosting, heating, preheating, reheating, baryogenesis, phase transitions, dark matter, (particle production in the expanding universe)*





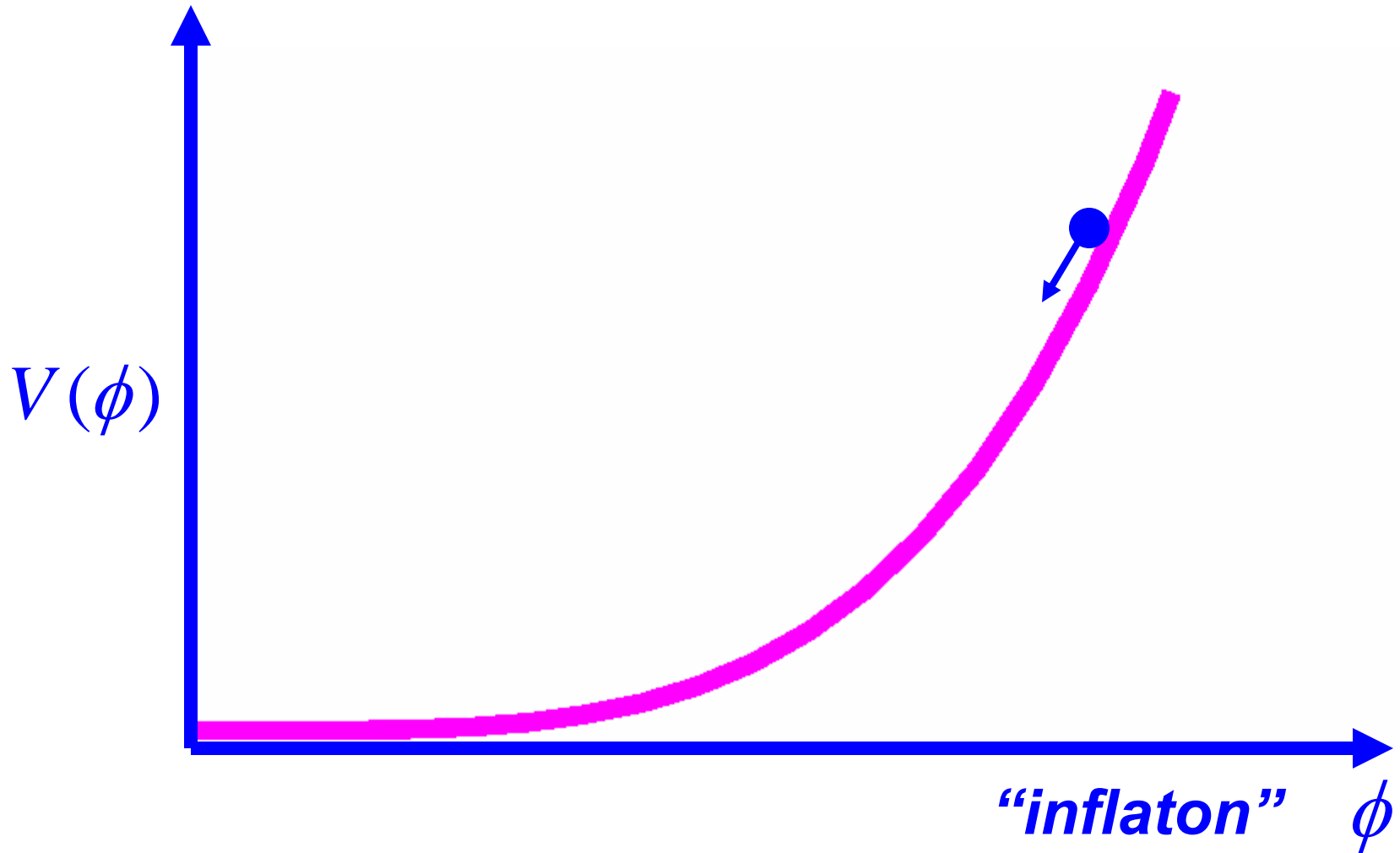
**Complete list of known fundamental  
scalar fields  
(from Particle Data Book):**



**(When a hammer is your only tool, everything looks like a nail.)**

**Potential energy: energy of  $\infty$ -wavelength mode**

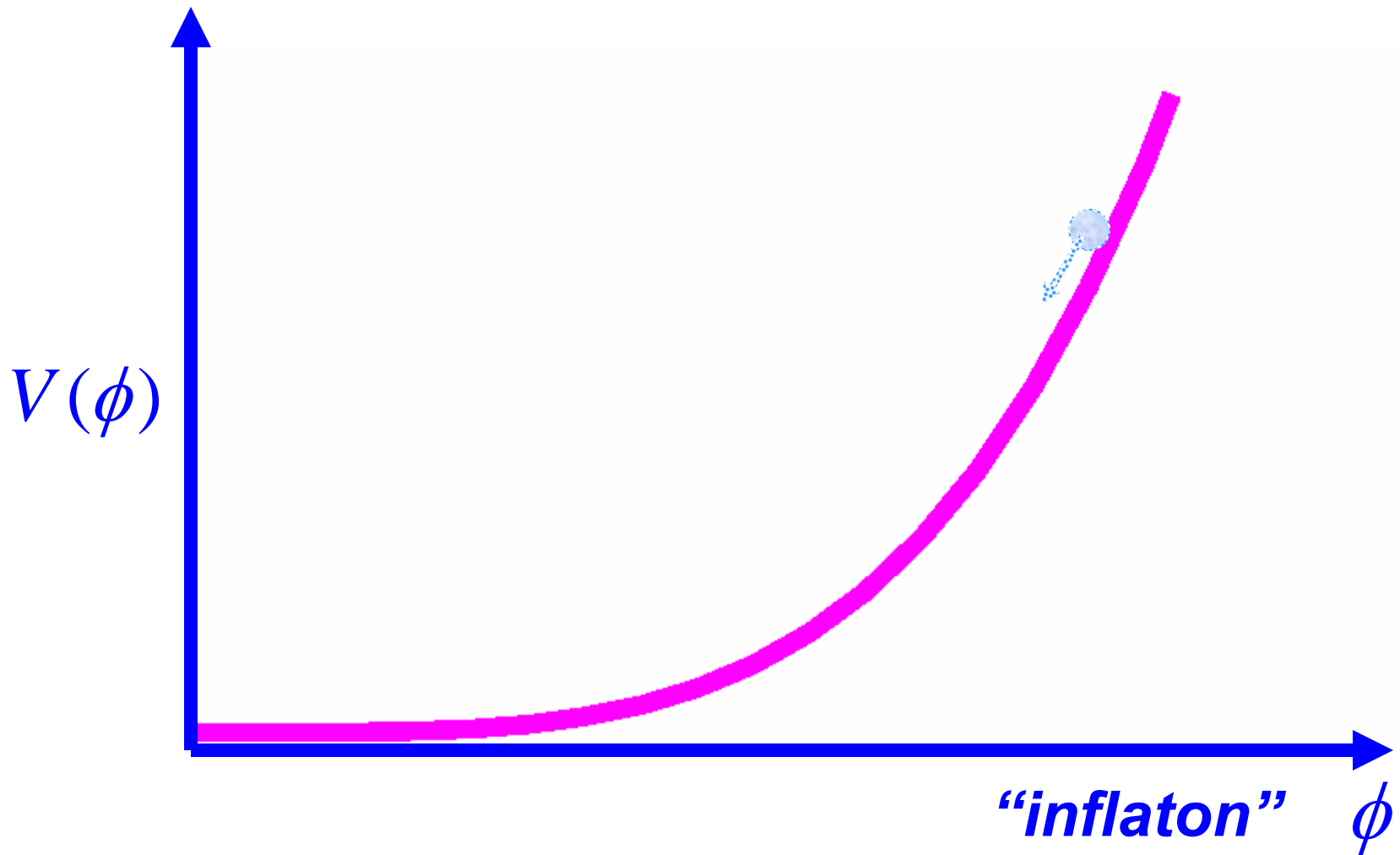
**Particle content: condensate of  $\infty$ -wavelength particles**



**Classical equations of motion**

$$V(\phi) \neq 0 \longrightarrow V(\phi) = 0$$

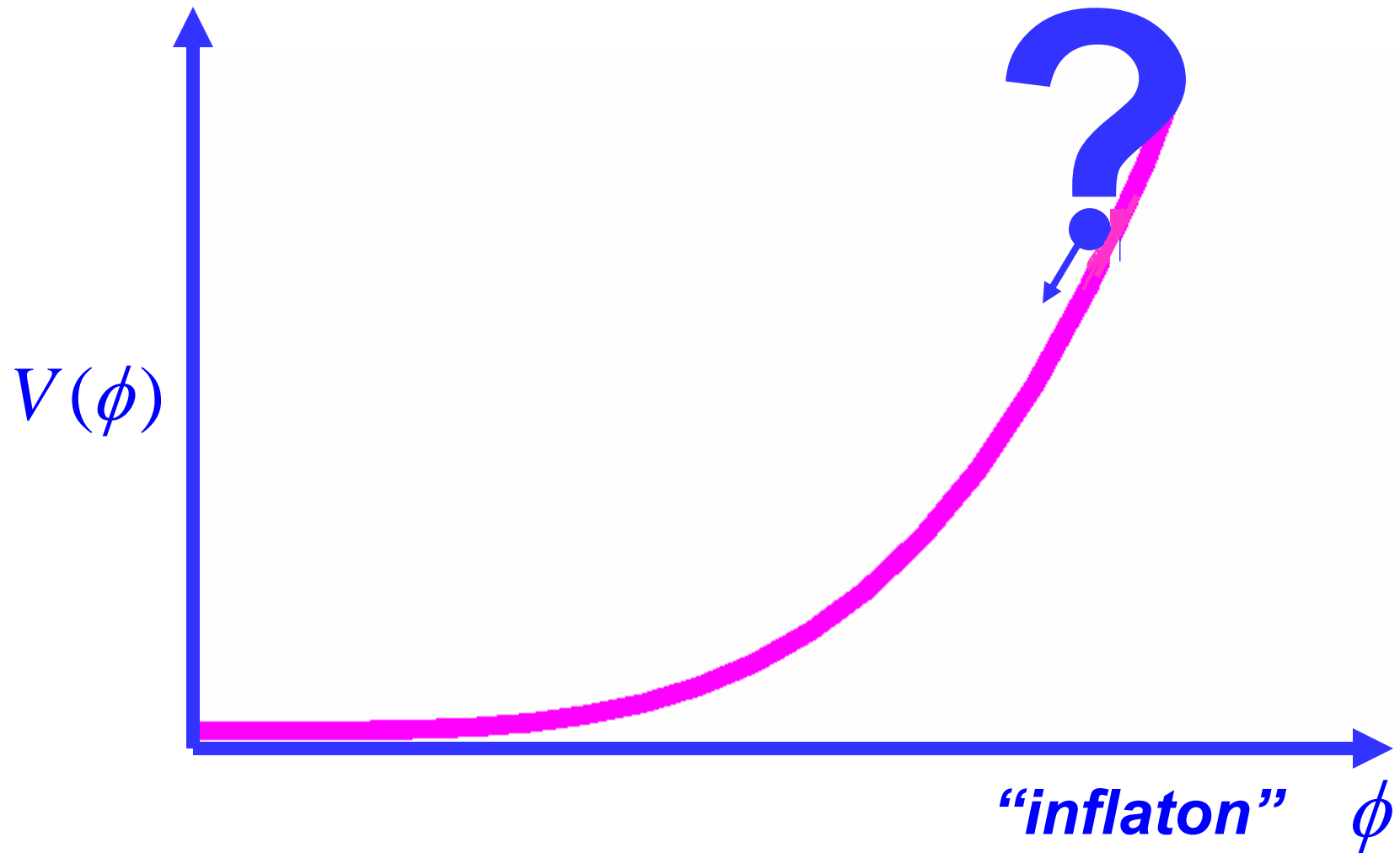
Particle creation: finite-wavelength modes  
→  $\phi$  not smooth



Quantum fluctuations

$$\delta\phi \longrightarrow \delta\rho \longrightarrow \delta T$$

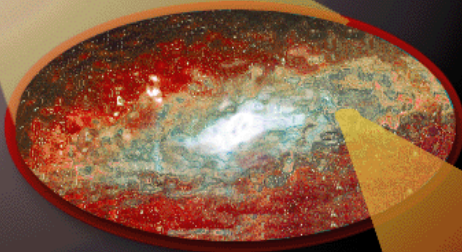
# *Who is the inflaton?*



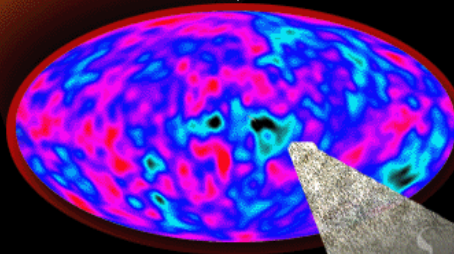
# Imprint of Inflation

*BIG BANG*

Inflation  
Big Bang plus  
 $10^{-35}$ ? seconds

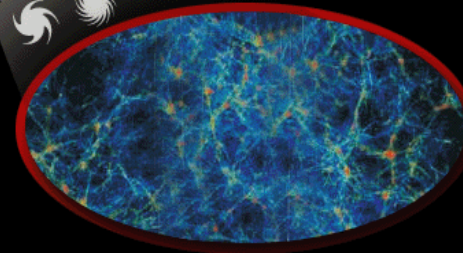


Big Bang plus  
380,000 Years



CMB fluctuations  
density perturbations  
gravitational waves

Big Bang plus  
14 Billion Years



# Quantum Generation of Perturbations:

- Perturbations are a model-dependent function of  $H$  and how  $H$  changes during inflation:  $V(\phi) \leftrightarrow H(\phi)$ .

	density perturbations	gravitational waves
amplitude @ $k = k_*$	$P_{\mathcal{R}}(k_*)$	$P_{\mathcal{T}}(k_*)$
spectral index	$n \equiv \frac{d \ln P_{\mathcal{R}}(k_*)}{d \ln k}$	$n_T \equiv \frac{d \ln P_{\mathcal{T}}(k_*)}{d \ln k}$
running of index	$\frac{dn}{d \ln k}$	$\frac{dn_T}{d \ln k}$



# *Inflation Generalities*

- The inflaton scalar potential must be “flat”
- Scalar perturbations depend on  $V(\phi)$  and  $V'(\phi)$
- Tensor perturbations (gravitational waves) depend only on  $V(\phi)$
- Many, many models of inflation

# ***Models of Inflation***

**old, new, pre-owned,  
chaotic, quixotic, ergodic,  
ekpyrotic, autoerotic,  
faith-based, free-based,  
D-term, F-term, summer-term,  
brane, braneless, brainless,  
supersymmetric, supercilious,  
natural, supernatural, *au natural*,  
hybrid, low-bred, white-bread,  
one-field, two-field, left-field,  
eternal, internal, infernal,  
self-reproducing, self-promoting,  
dilaton, dilettante, .....**

# ***Model Classification\****

**Type I:** single-field, slow-roll models  
(or models that can be expressed as such)

**Type II:** anything else  
(branes, pre-big-bang, etc.)

---

*\*Used for superstrings, supernovae, superconductors, ...*

The nature of inflation is a complex natural phenomenon.

Single-field, slow-roll inflation is a simple, elegant, compelling explanation.

**“For every complex natural phenomenon there is a simple, elegant, compelling, but wrong explanation.”**

***- Tommy Gold***

# ***Model Classification\****

**Type I:** single-field, slow-roll models  
(or models that can be expressed as such)

**Type Ia:** large-field models

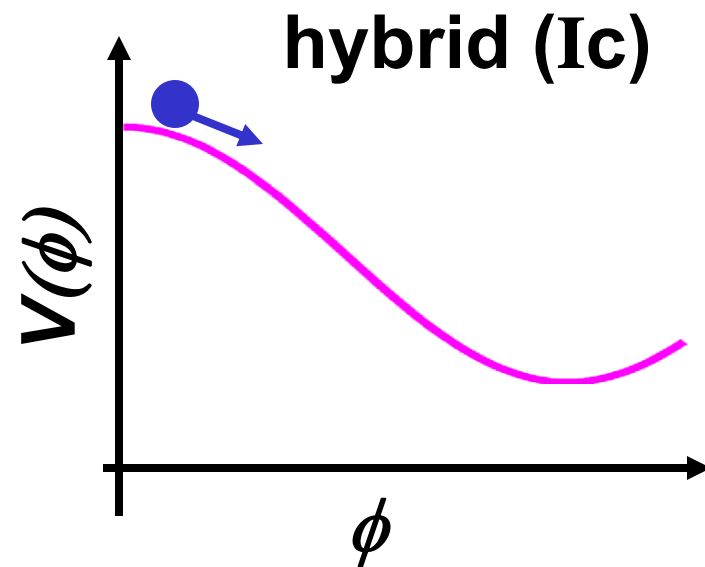
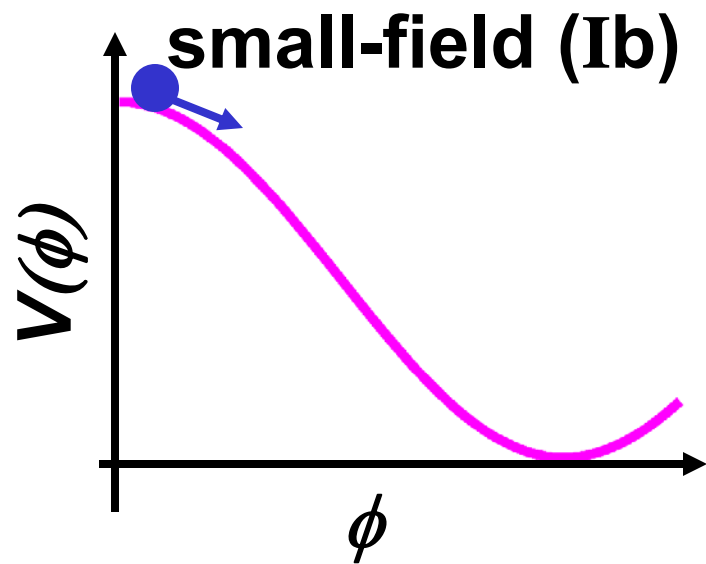
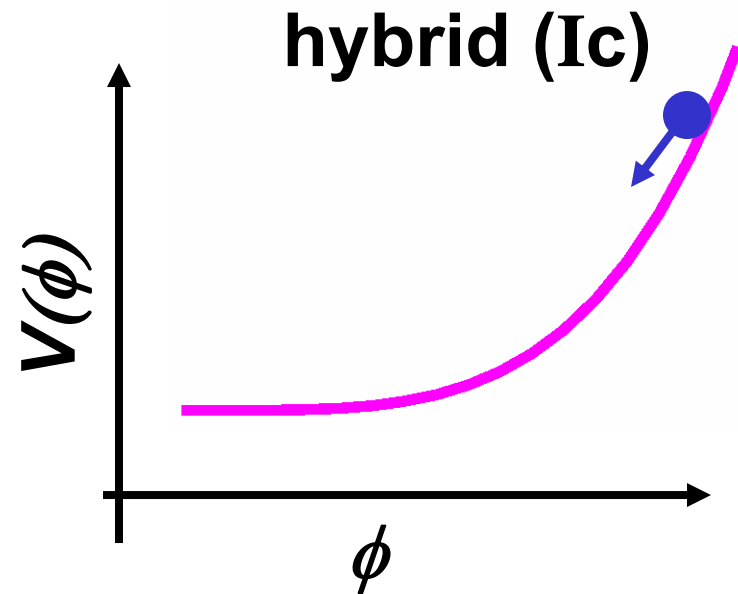
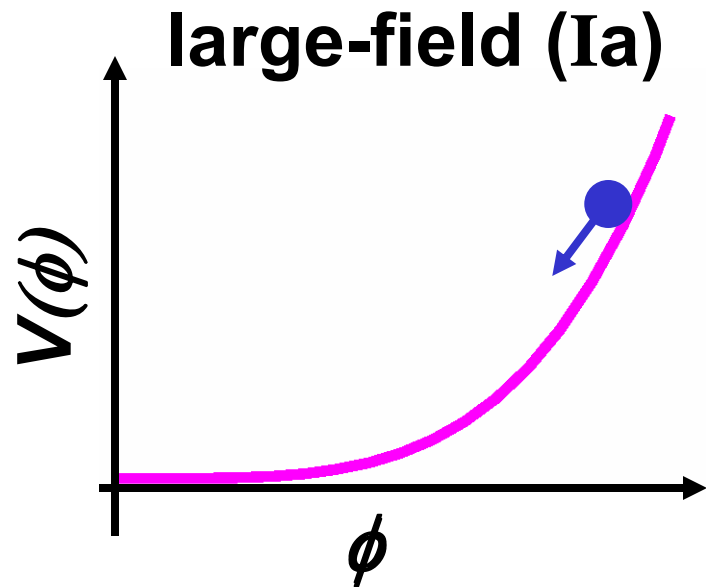
**Type Ib:** small-field models

**Type Ic:** hybrid models

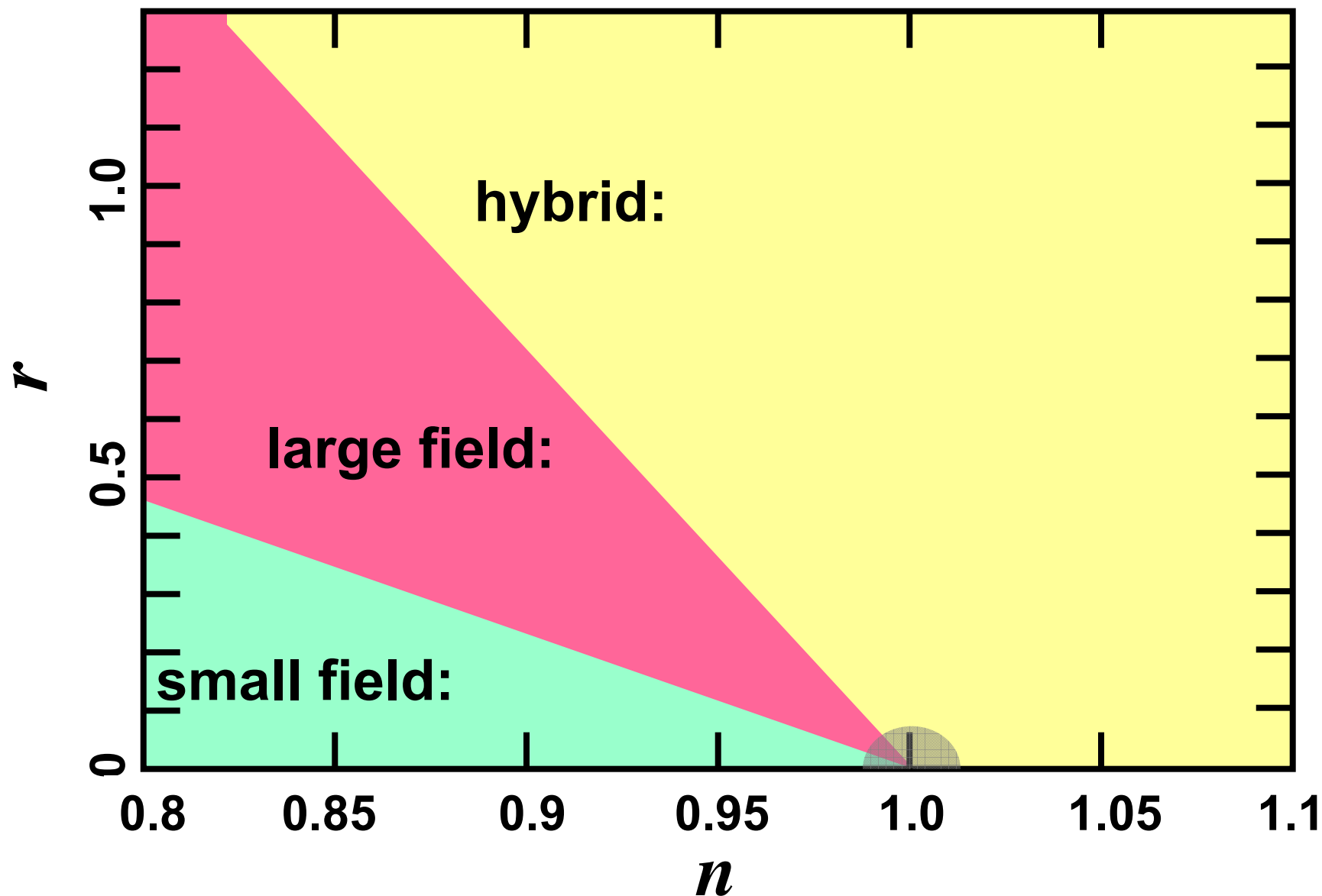
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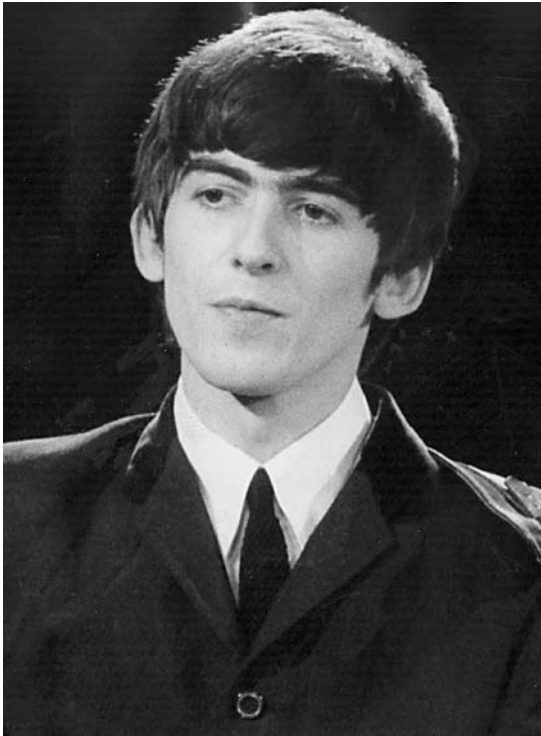
Dodelson, Kinney, Kolb 1997



$$r = (\text{tensor/scalar})_{l=2}$$

$n = \text{scalar spectral index}$

# Harrison-Zel'dovich Spectrum ?



$$n \equiv 1?$$

$$n' \equiv 0?$$

$$r \equiv 0?$$



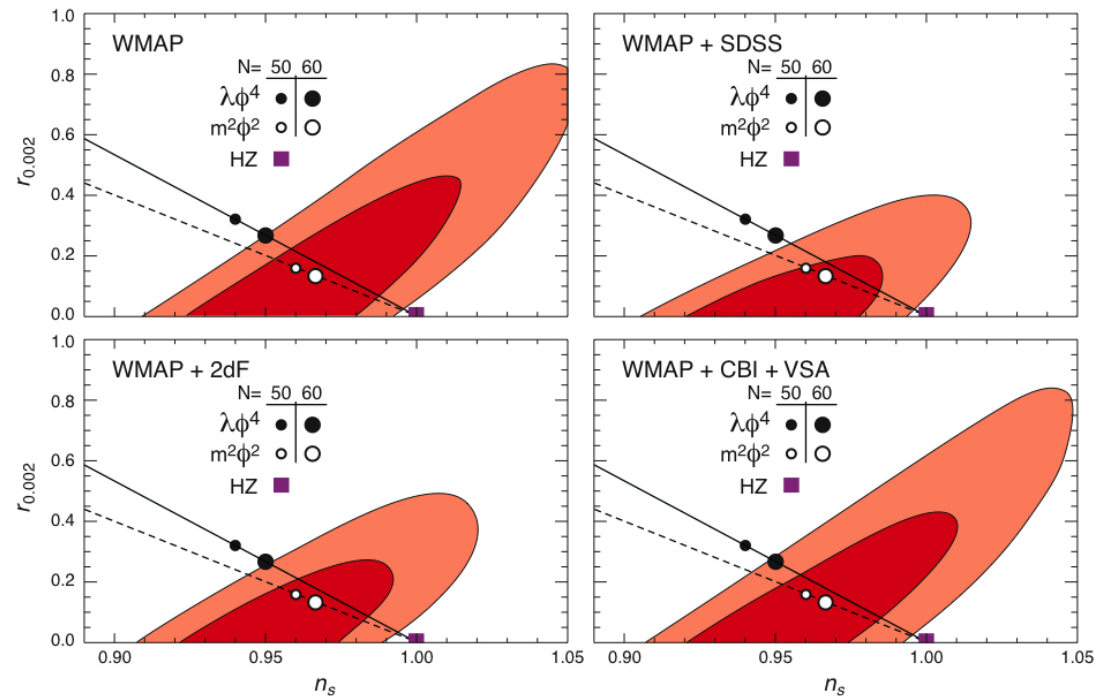
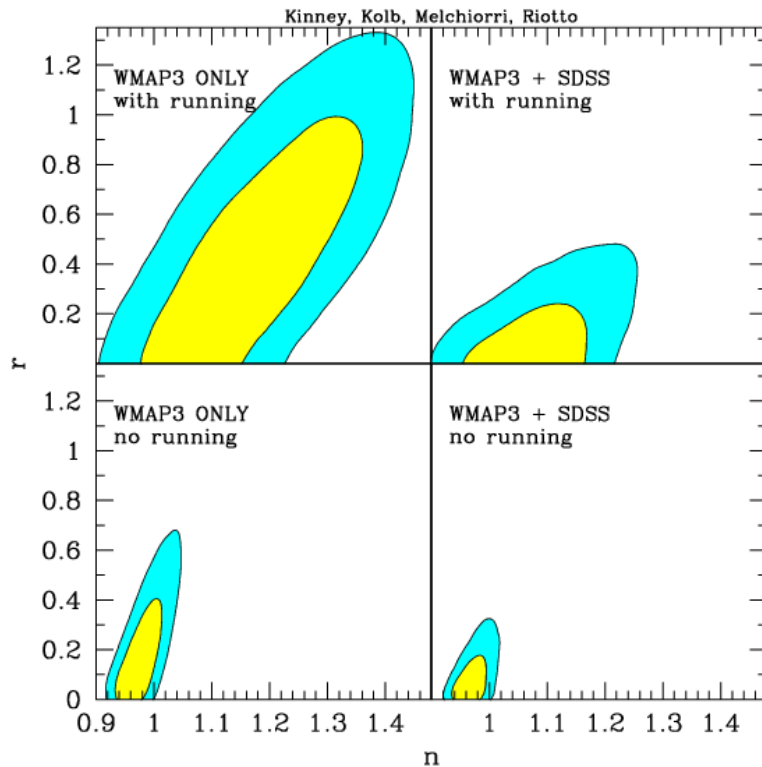
**Fixed point of ignorance**

- **Observational question: Combine CMB & LSS?**
- **Theoretical question: What if exact Harrison-Zel'dovich**



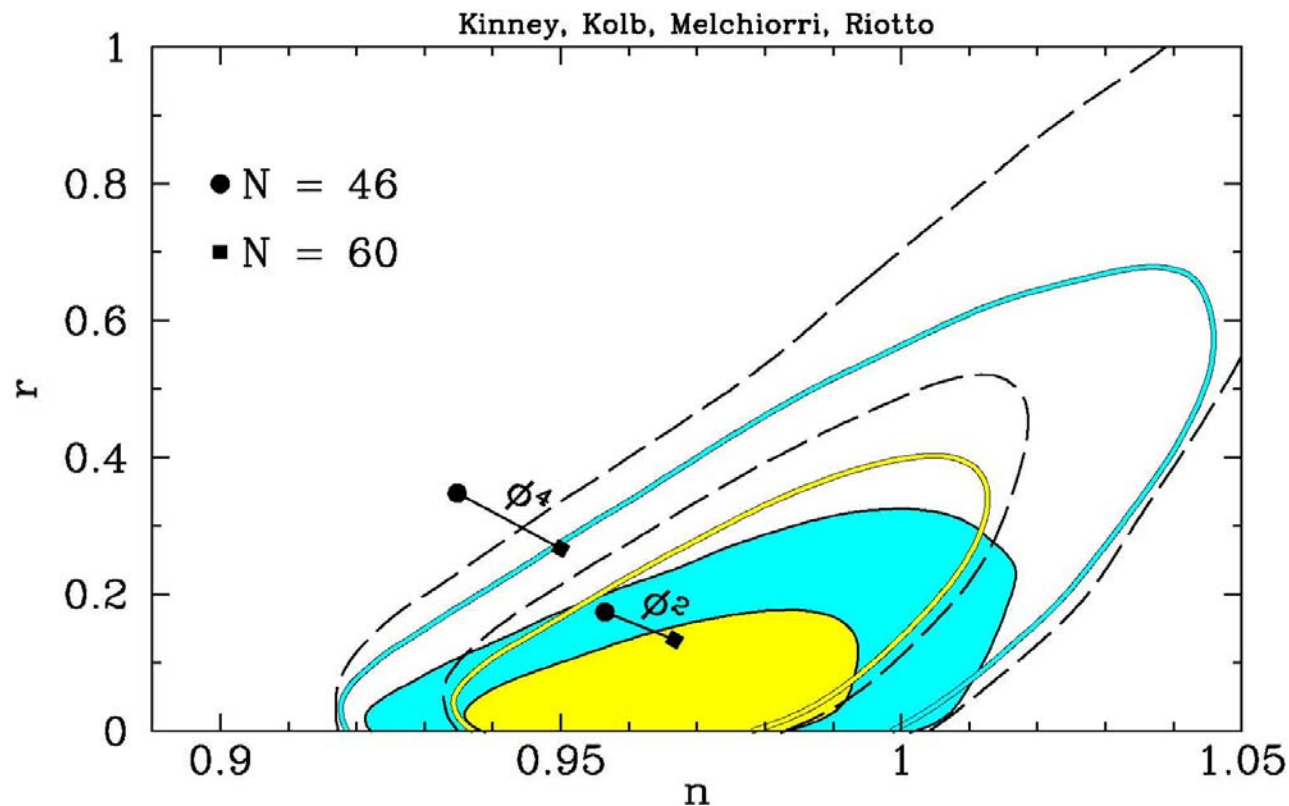
# Harrison-Zel'dovich Spectrum ?

1. Harrison—Zel'dovich ruled out at about 95%C.L.
2. Find  $r \lesssim 1 \rightarrow V \lesssim 10^{15}$  GeV
3. Prefer red spectrum if no running, blue spectrum if running
4. Information of  $\phi^2$  and  $\phi^4$  models
5. Find  $r$  can be quite small



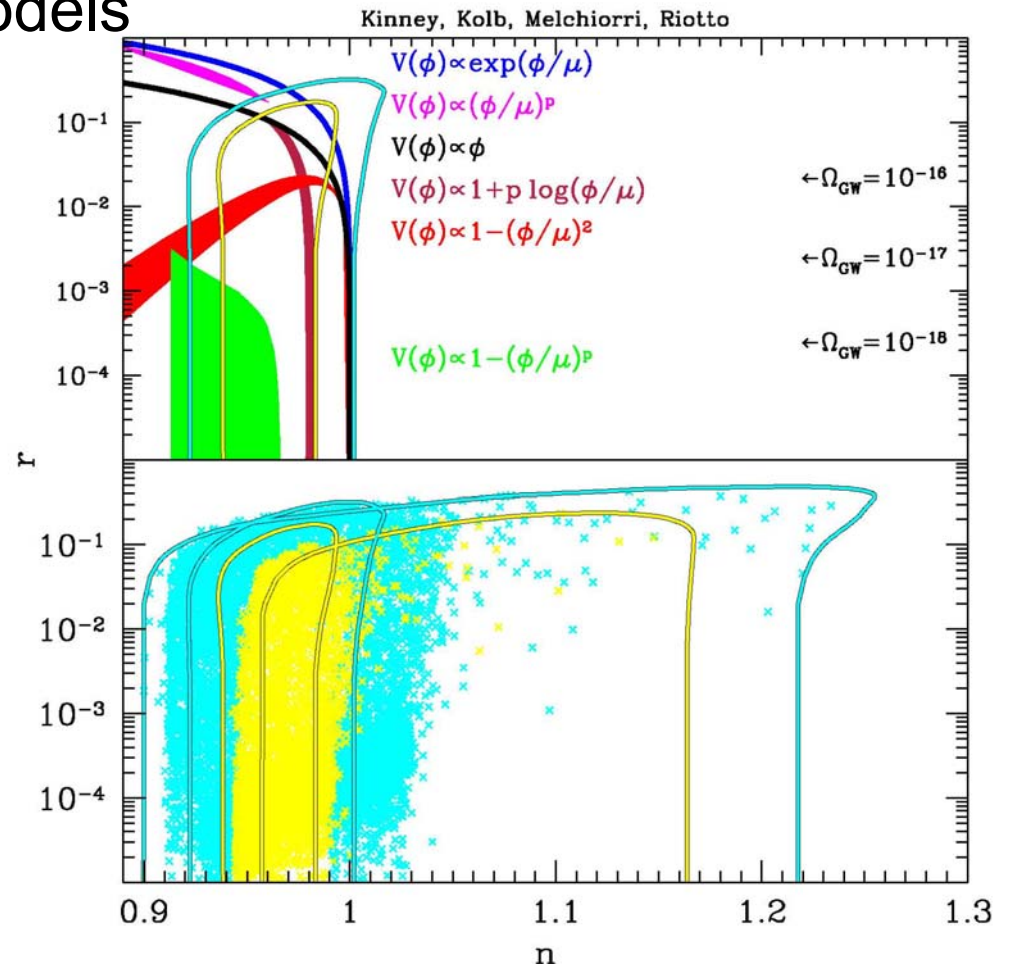
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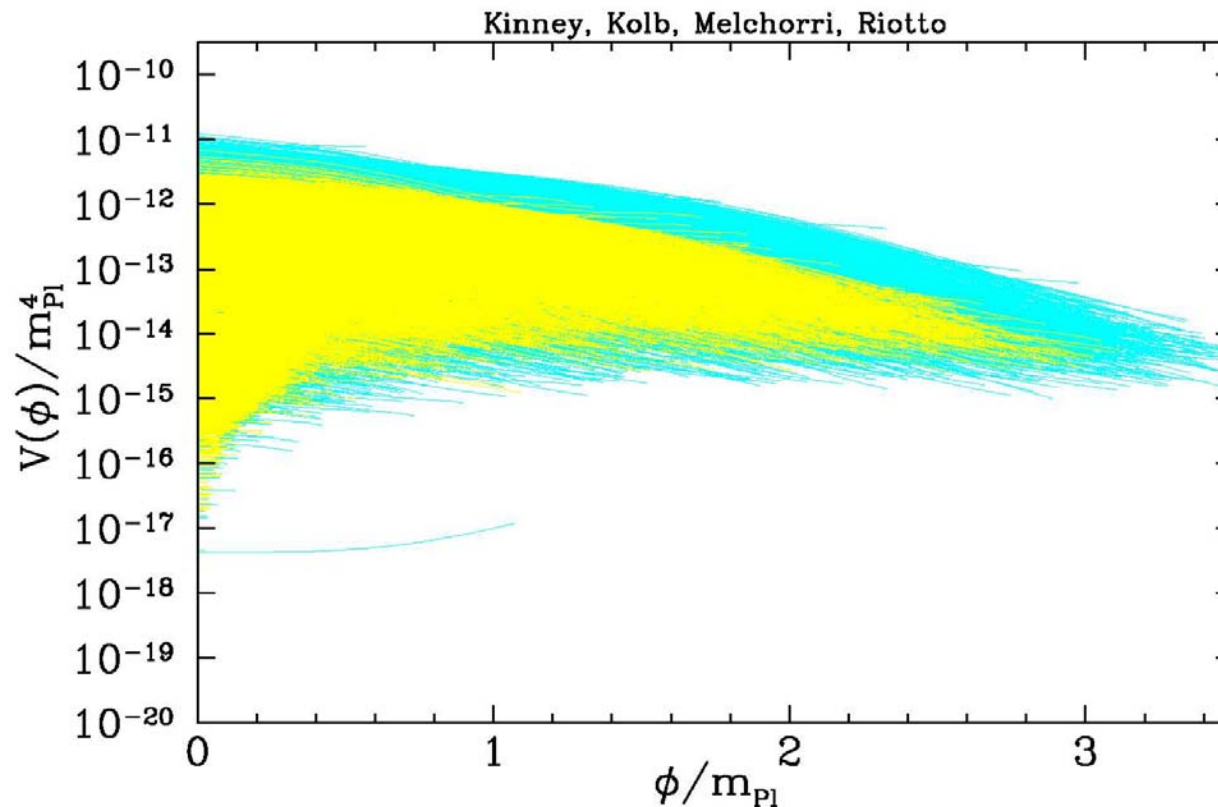
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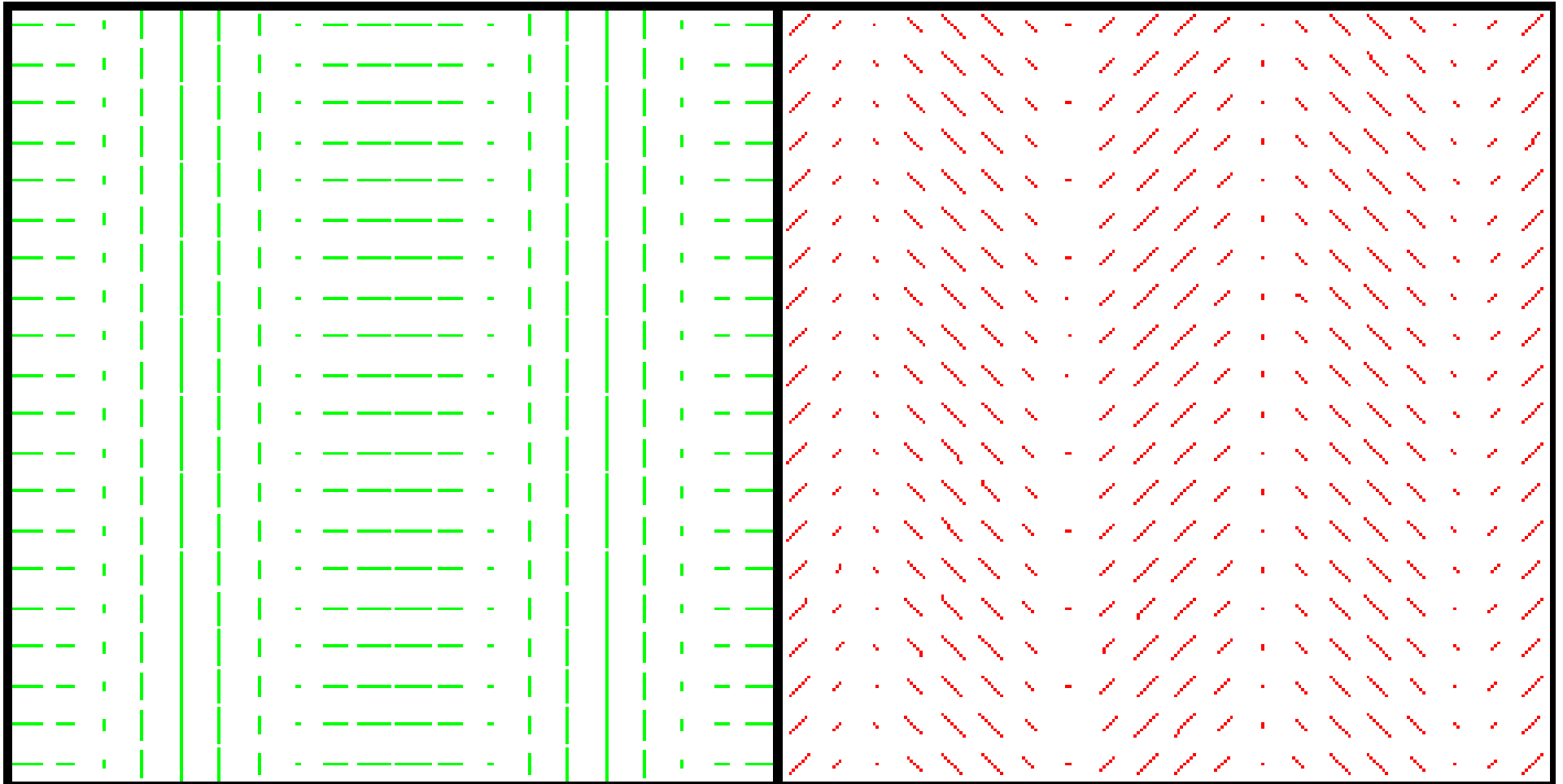
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5. Find  $r$  can be quite small



# Polarization Pattern

Stebbins, Kosowsky, Kamionkowski

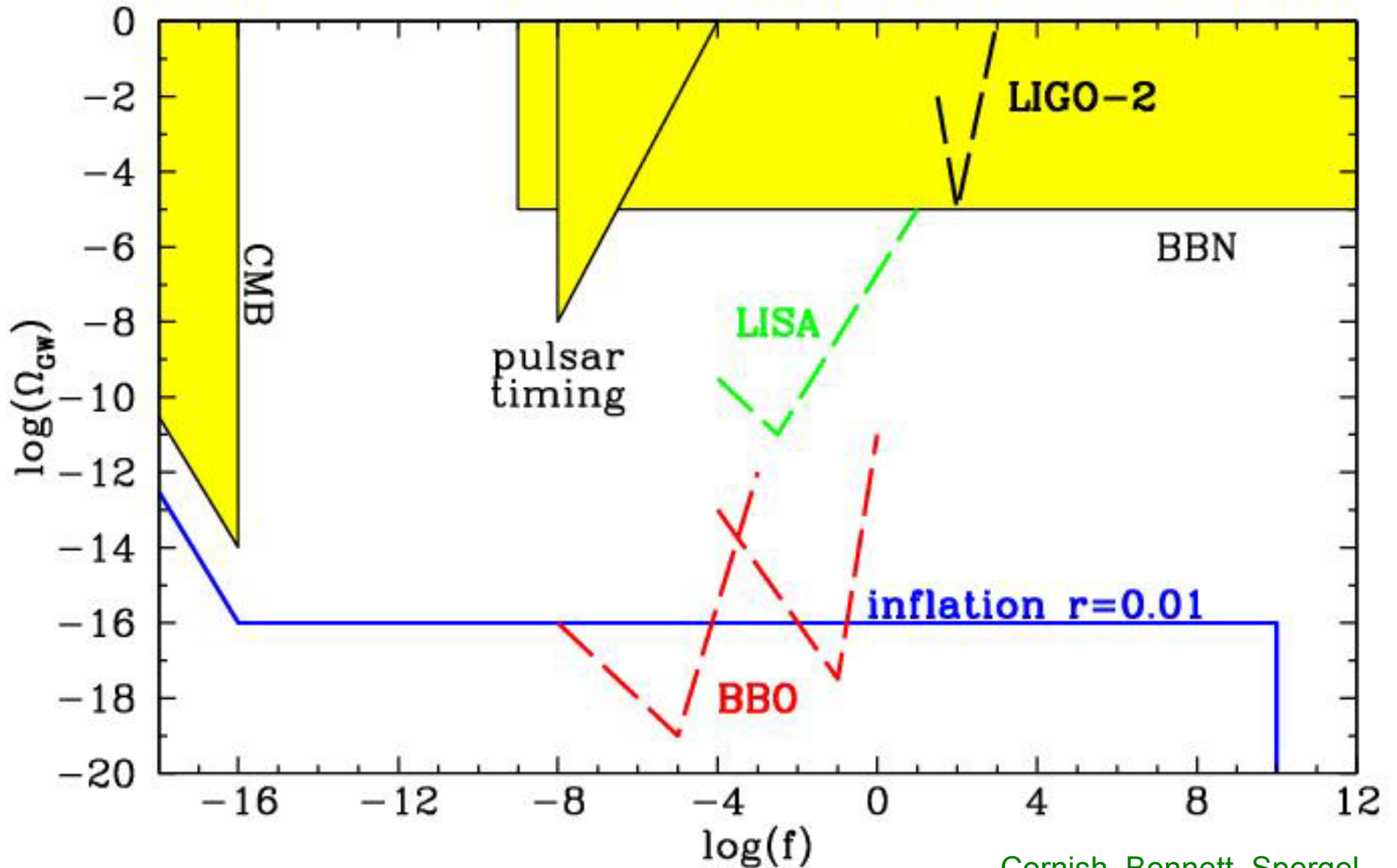
Seljak & Zaldarriaga



**E modes**

**B modes**  
**(gravitational waves)**

# LIGO/VIRGO → LISA → BBO



Cornish, Bennett, Spergel

# *Inflation and SUSY*

- The inflaton scalar potential must be flat–stable to radiative corrections
- SUSY to the rescue?
- Not so fast ... (see Lyth & Riotto, Phys. Rep. 1999)
- Many models give  $V(\phi) \sim A + \ln\phi$  “hybrid” models
- But no general prediction for
  - scalar spectral index  $n$ , but expect  $n - 1$  small, say  $O(\epsilon \sim 0.05)$
  - running of  $n$  [say  $n' \sim (n-1)^2$ ]
  - amplitude of gravitational wave background [say  $r \sim (n-1)^2$ ]
- Need observational guidance

# *Inflation and Strings/Branes*

- Inflation and strings were made for each other (Burgess)
- Most stringy/braney models can be expressed in terms of an effective field theory—phenomenological approach useful
- Heavy states seem to decouple ( $H_I \ll M_{\text{STRING}}$ )
- Some models lead to relic (super)strings, some (DBI) to non-Gaussian signals.
- Naturalness
- No general distinctive signature



## Comparison to observation:

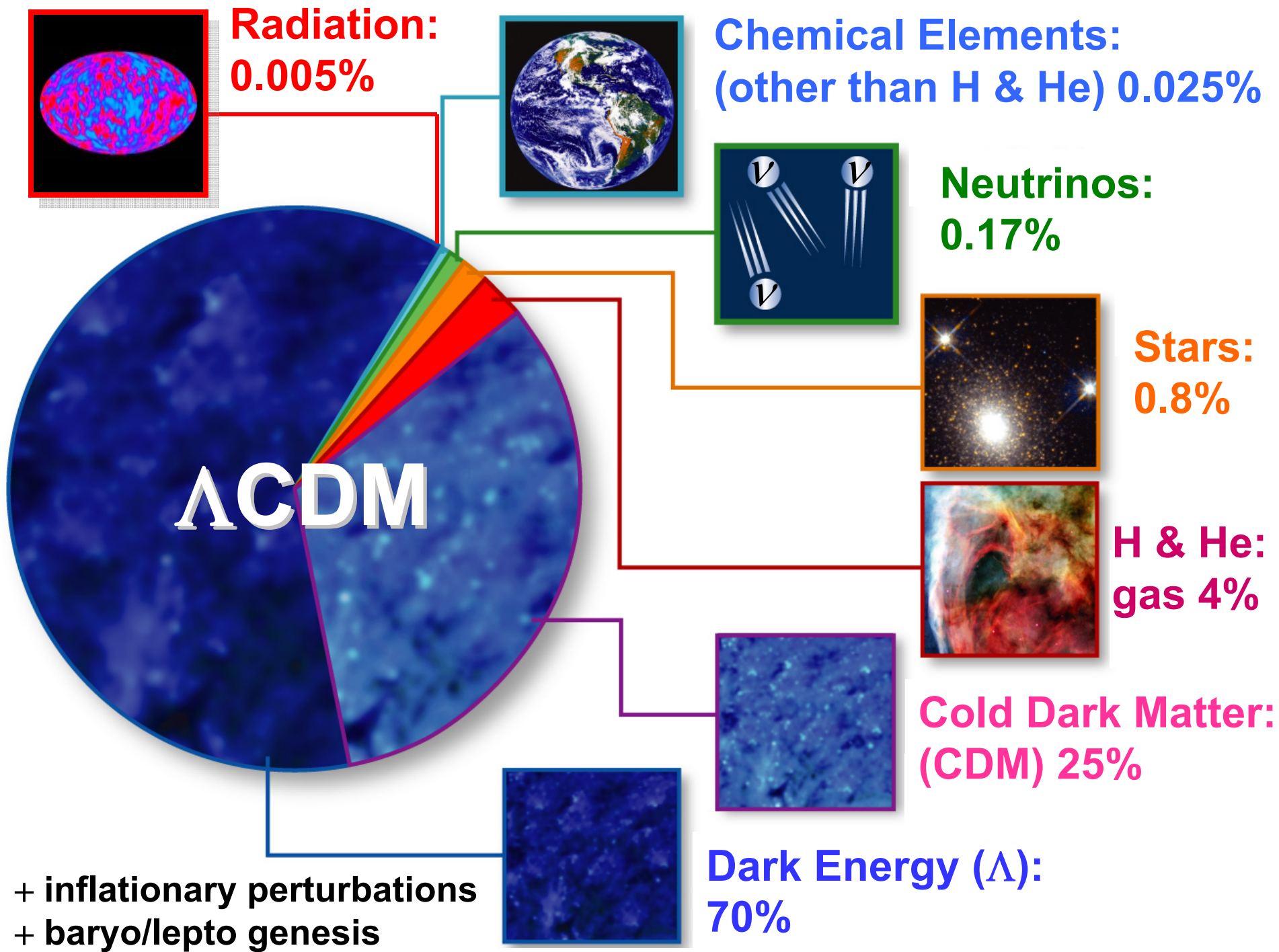
- ✓ 1. a (nearly exact) power-law
- ✓ 2. spectrum of gaussian
- ✓ 3. super-Hubble-radius
- ✓ 4. scalar perturbations (seeds of structure) &
- 5. tensor perturbations (gravitational waves)
- 6. related by a consistency relation
- ✓ 7. in their growing mode
- ✓ 8. in a spatially flat universe.

## *Some Simple Questions:*

1. Was inflation “normal” (i.e., 3-D FRW)?
2. Can dynamics of inflation be described in terms of a single scalar field?
3. What was the expansion rate during inflation?
4. What was the general shape of the inflaton potential?
5. What was the more or less exact shape of the inflaton potential?
6. Did the perturbations arise from fluctuations in the inflaton?
7. Can inflation tell us anything about physics at very high energy scales (unification, string, Planck)?
8. Any indication of isocurvature fluctuations?
9. Any indications of non-Gaussian perturbations?

# Issues

1. Transplanckian physics
  - probe of short-distance physics?
2. Defrosting
  - preheating, reheating, ....
3. Particle production
  - WIMPZILLAS, gravitons, ....
4. Why only one field?
  - isocurvature perturbations
5. Extra dimensions, brane, bulk, etc.?
  - new dynamics



## Suggested reading:

Lectures on Cosmic Inflation and its Potential Stringy Realizations.

C.P. Burgess

Class.Quant.Grav.24:S795, 2007. arXiv:0708.2865 [hep-th]

Particle physics models of inflation and the cosmological density perturbation.

David H. Lyth, Antonio Riotto

Phys.Rept.314:1-146,1999. hep-ph/9807278

*Cosmological Inflation and Large-Scale Structure*, Liddle & Lyth

# ***The Dark Universe: Dark Matter and Dark Energy***

<b>Rocky I:</b>	<b>The Universe Observed</b>	<b>Monday</b>
<b>Rocky II:</b>	<b>Inflation</b>	<b>Tuesday</b>
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**CERN Academic Training Lectures**      **January 2008**  
*Rocky Kolb*      *The University of Chicago*