

Title: Introduction to Cosmology

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URL: <http://pirsa.org/08120041>

Abstract:

A Rear Window on the Universe



Claudia de Rham
McMaster / PI
YRC
December 9, 2008

Pirsa: 08120041



Early Cosmology



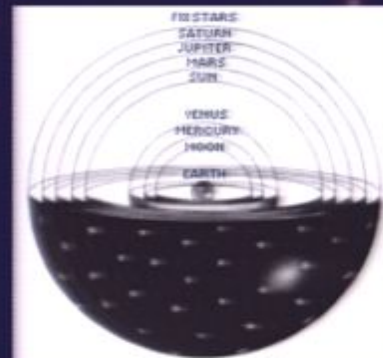
Itzam Nà, God of the Sky



Nut, Sky Goddess



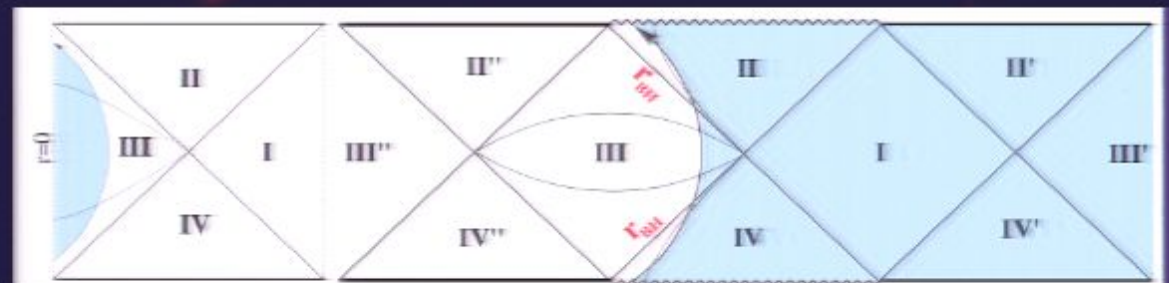
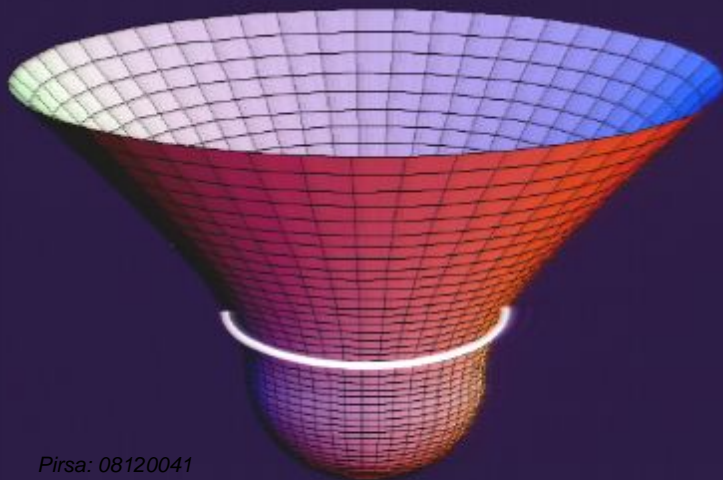
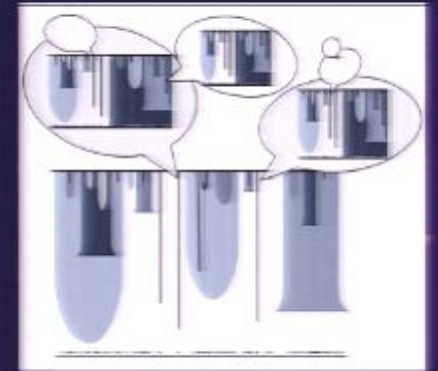
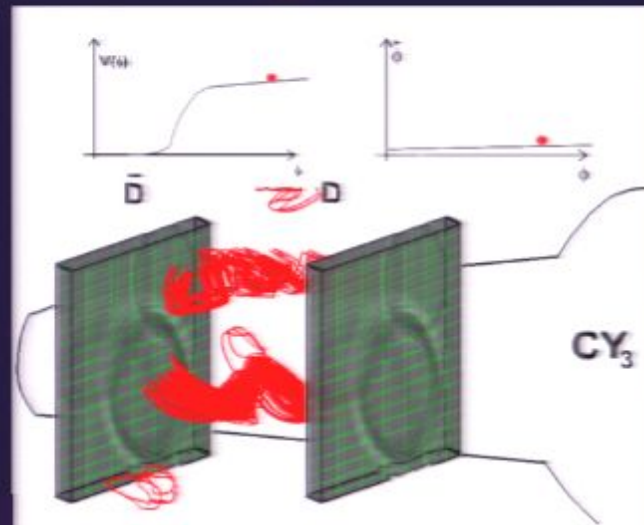
Shu, Holder of the Sky



Ptolemy

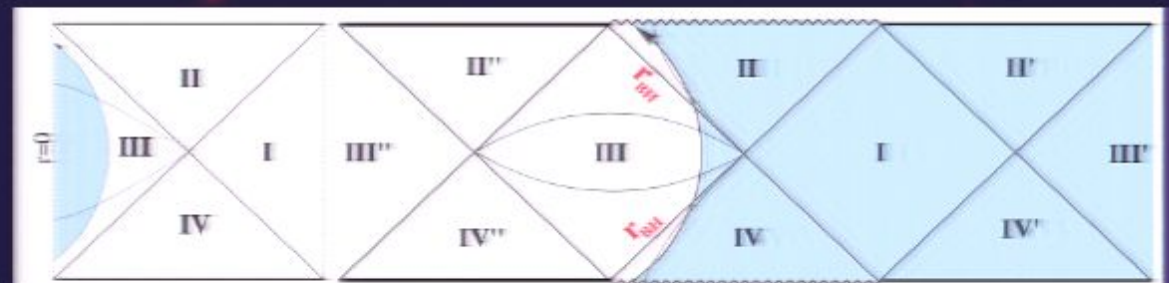
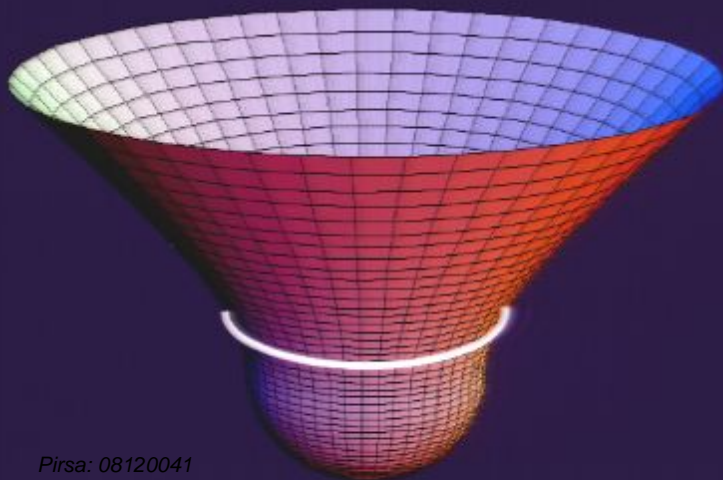
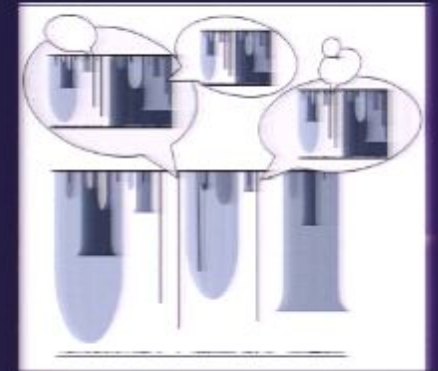
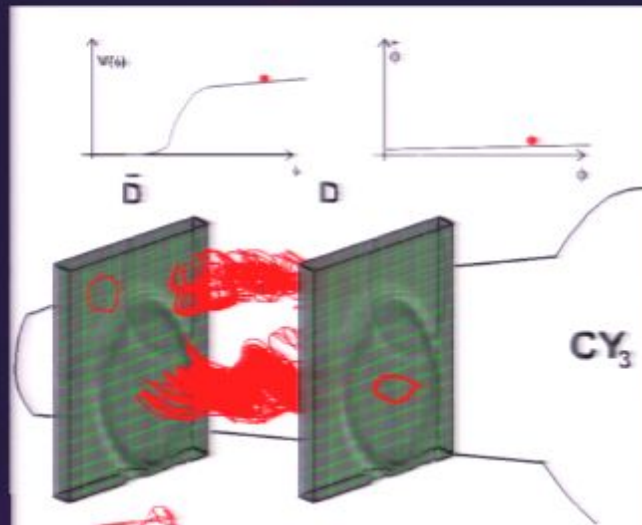


Modern Cosmology



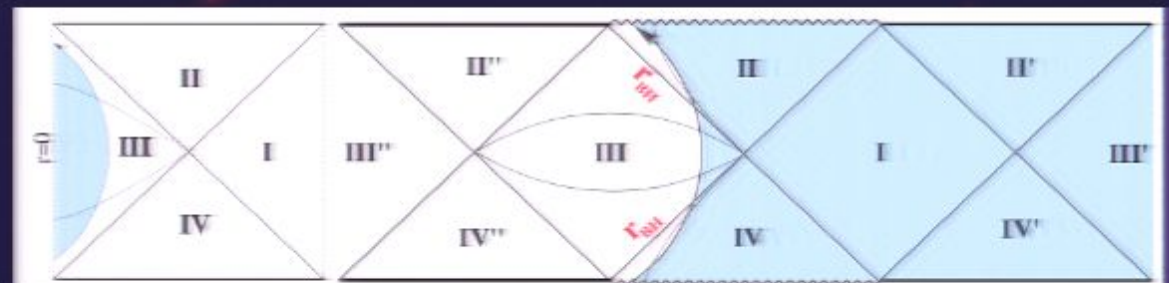
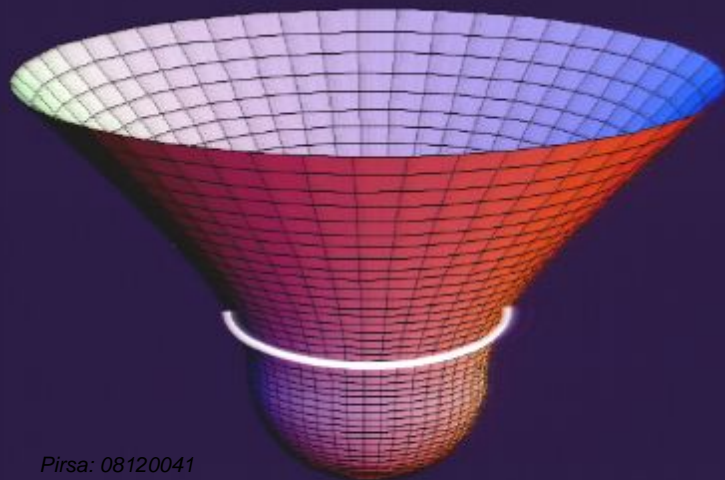
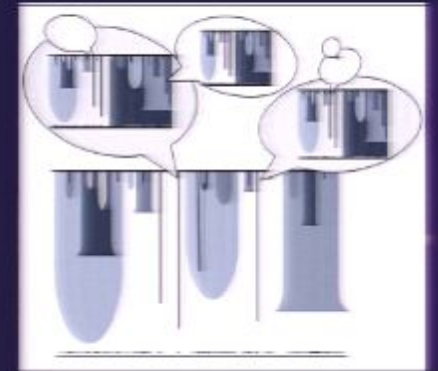
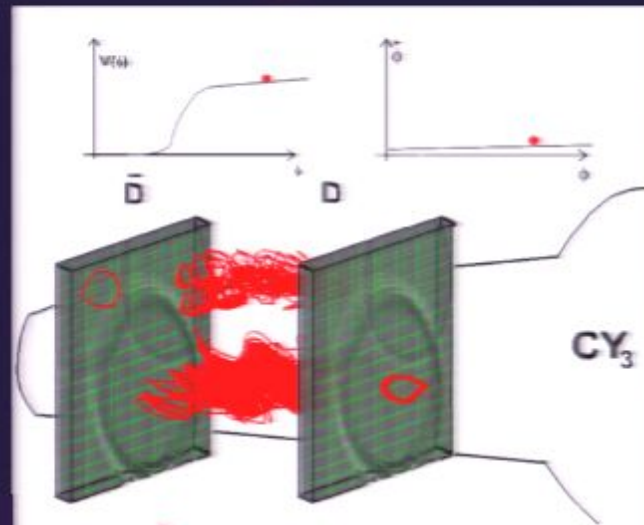


Modern Cosmology



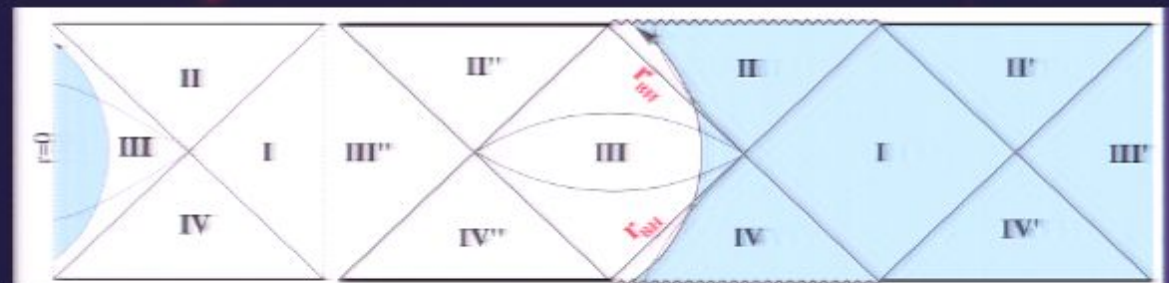
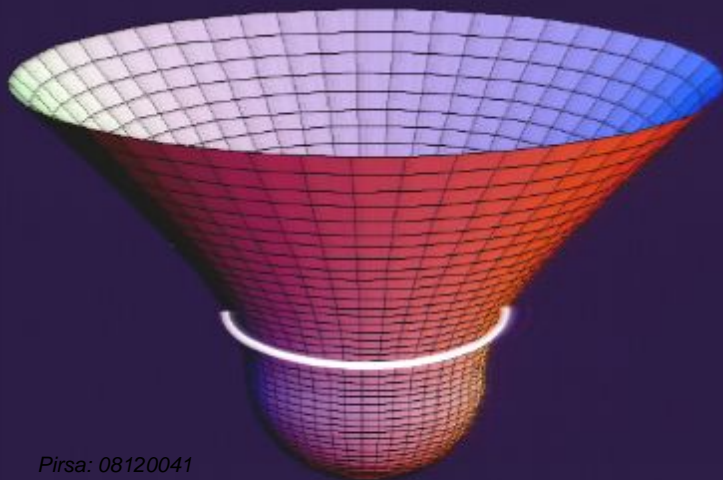
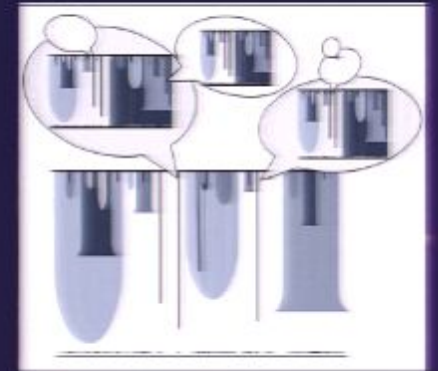
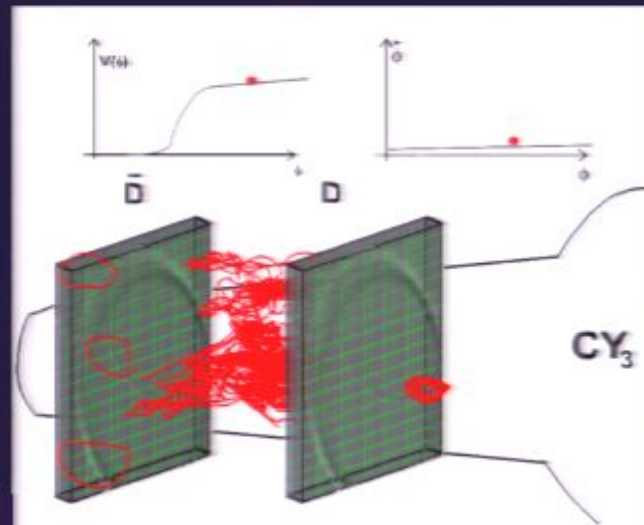


Modern Cosmology



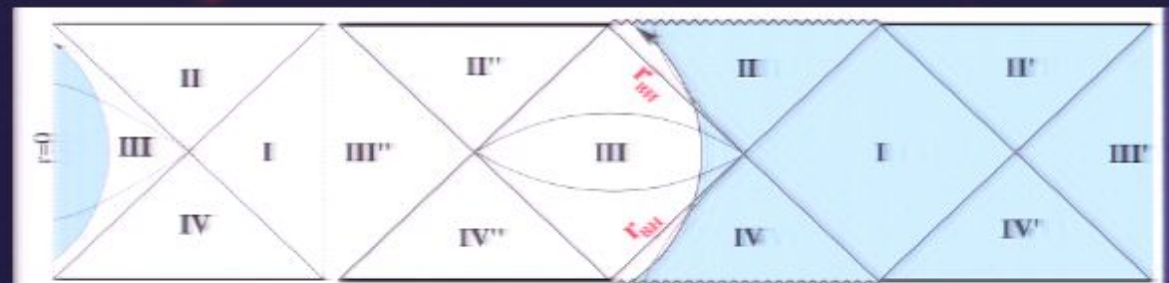
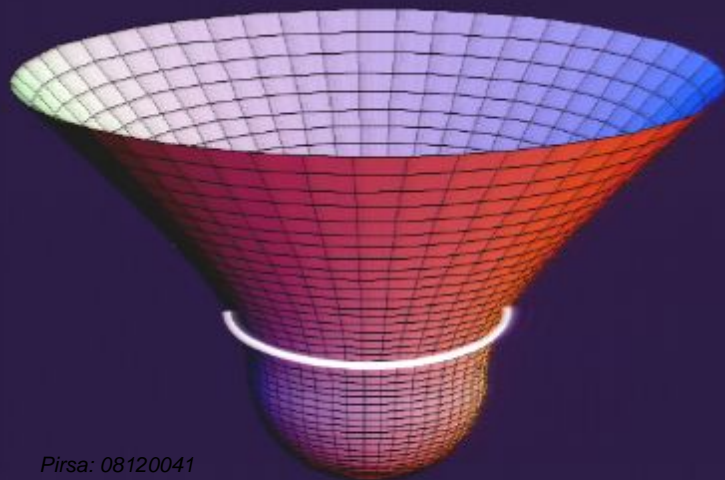
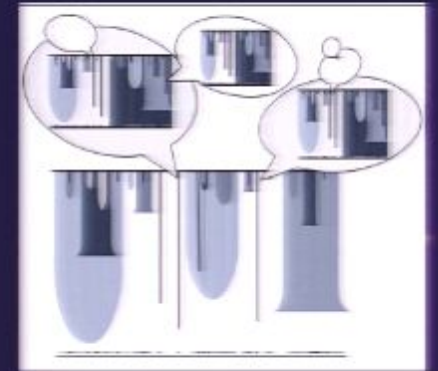
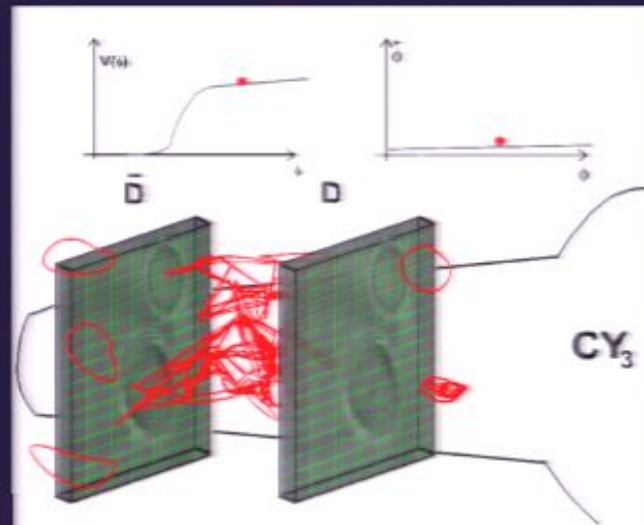


Modern Cosmology



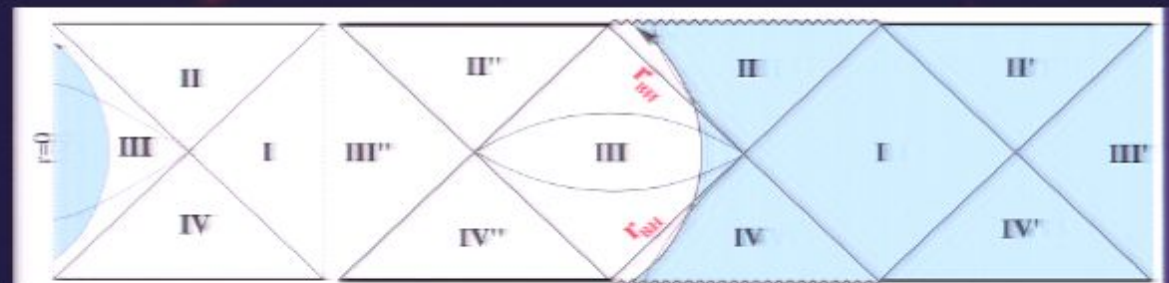
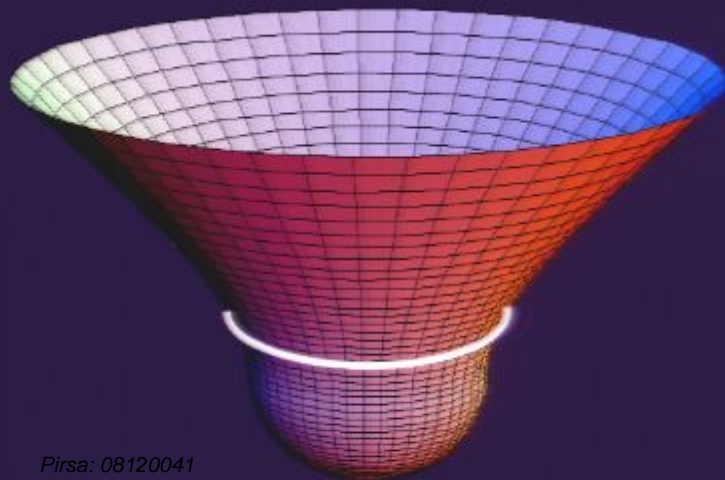
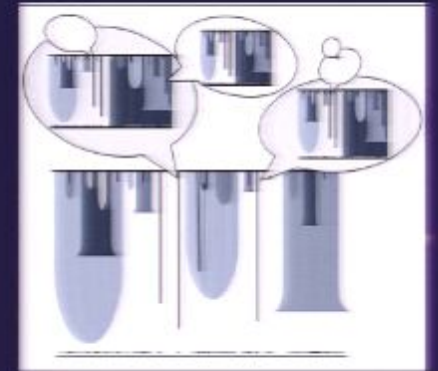
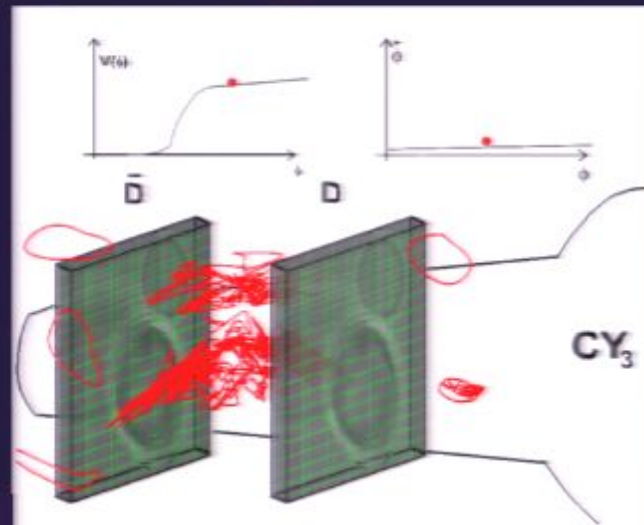


Modern Cosmology



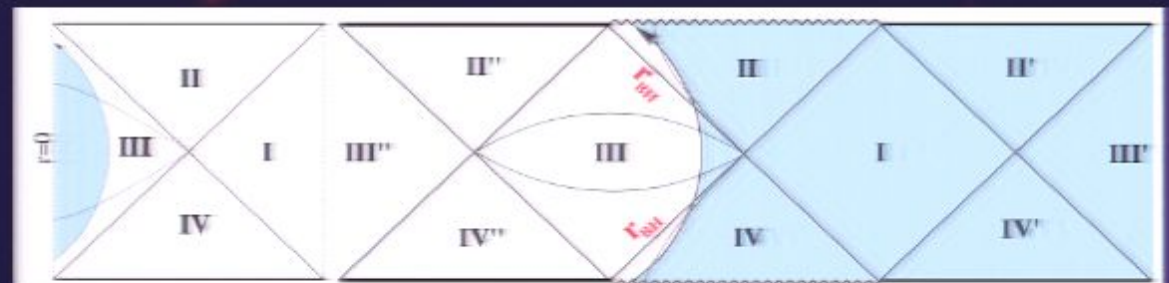
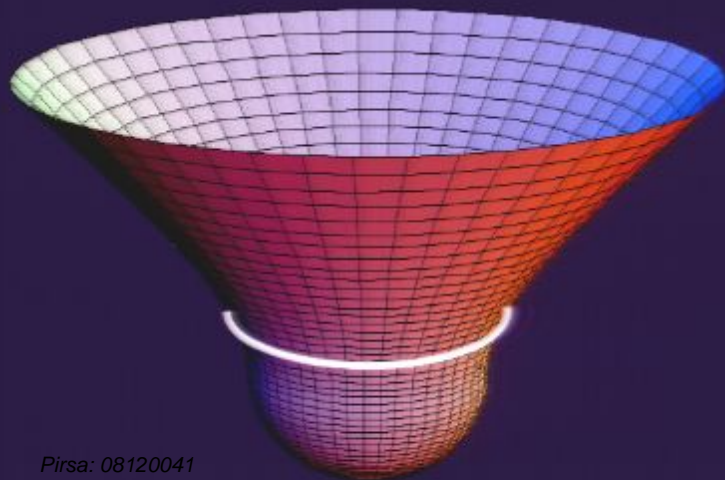
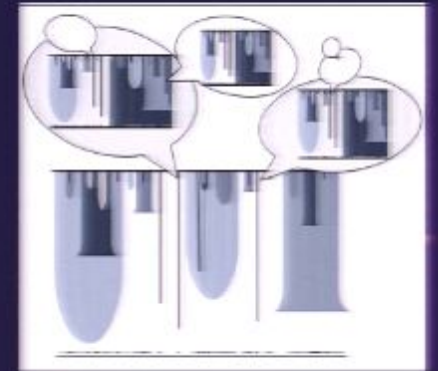
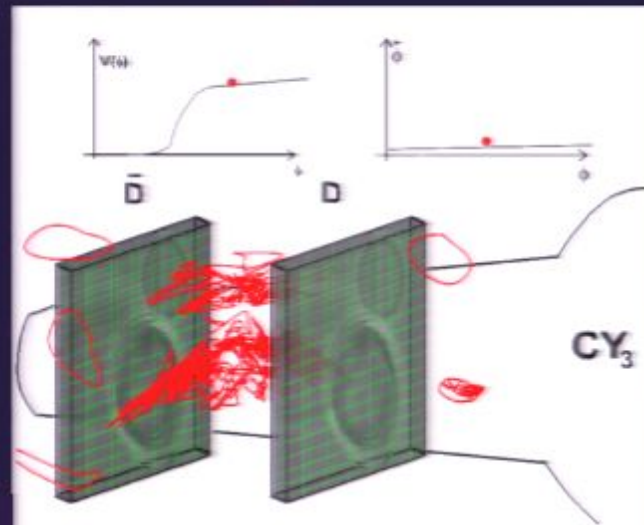


Modern Cosmology



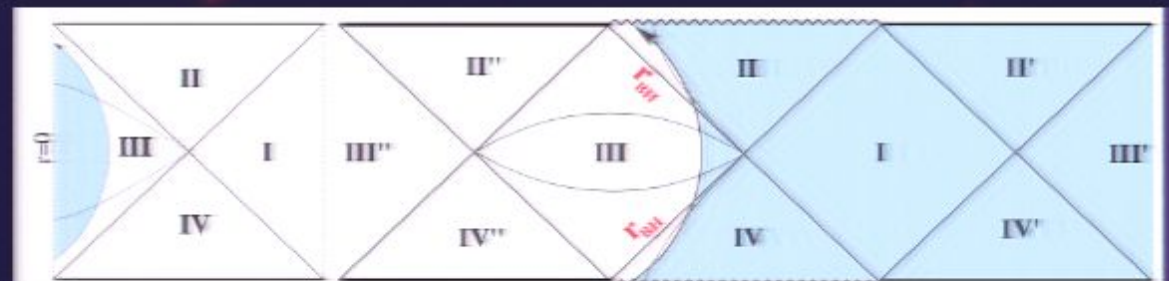
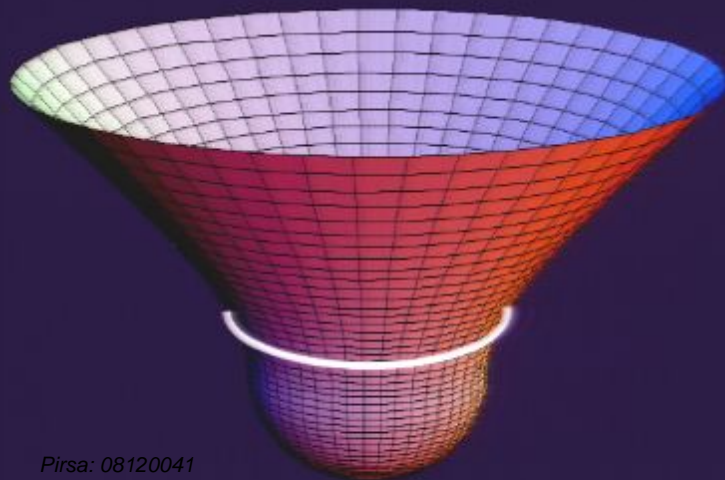
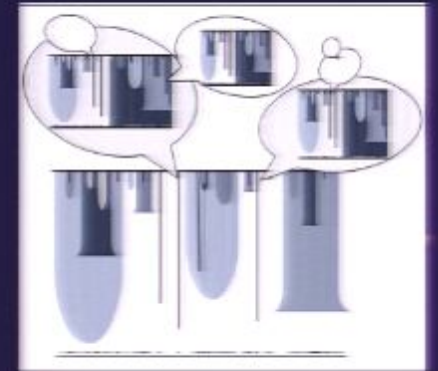
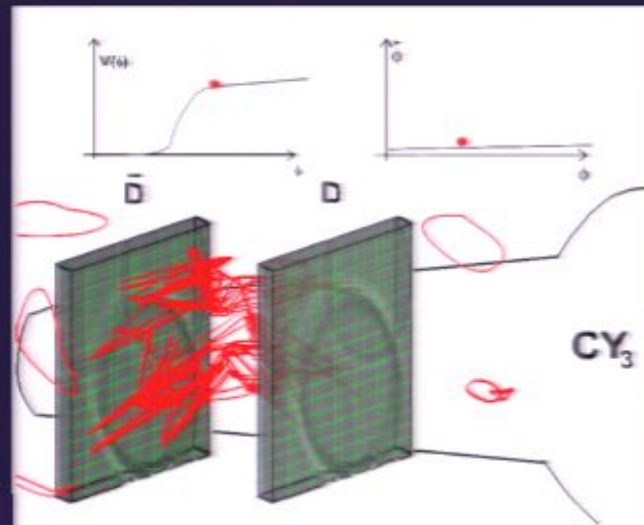


Modern Cosmology



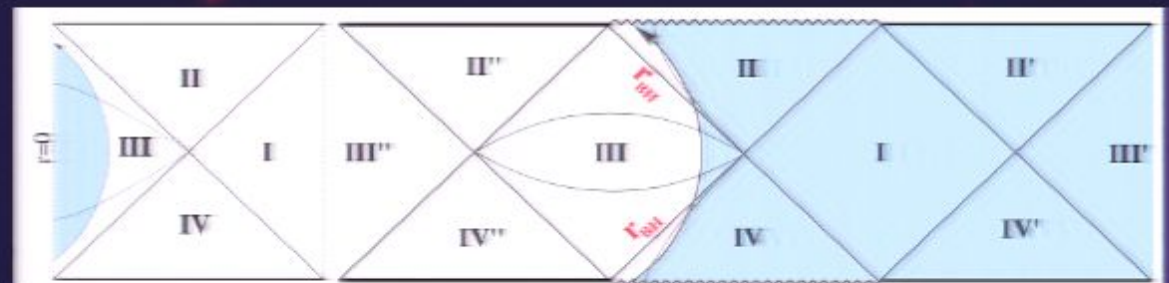
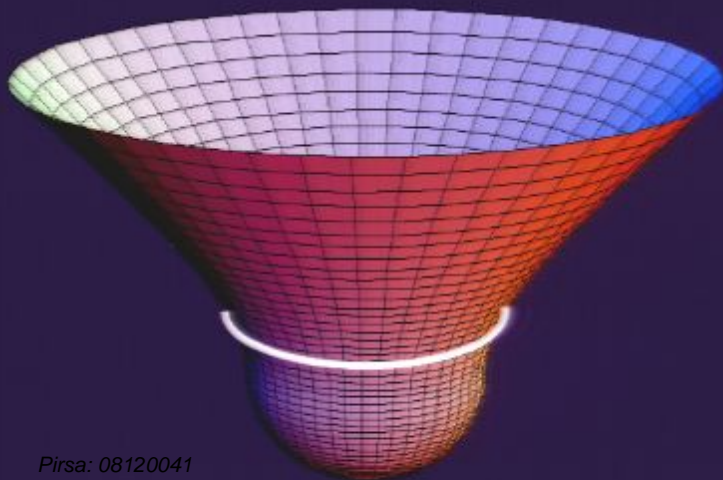
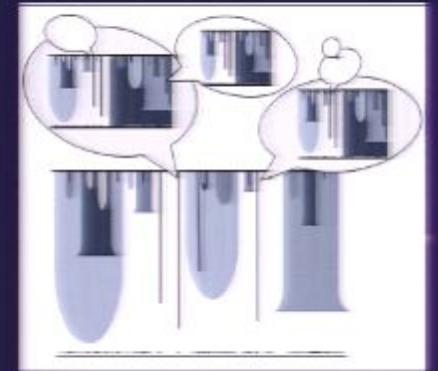
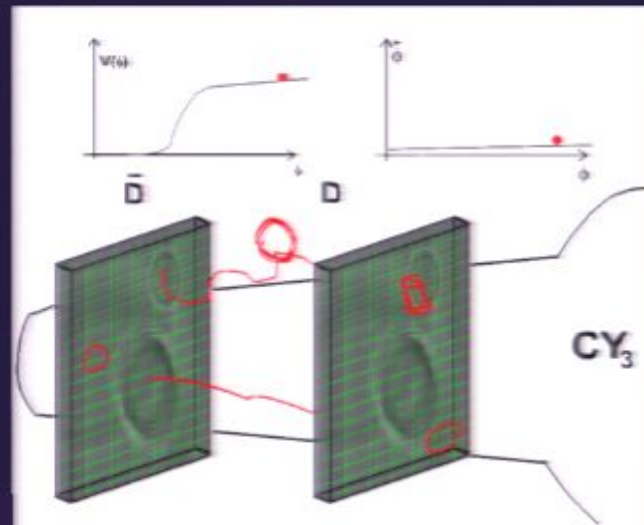


Modern Cosmology



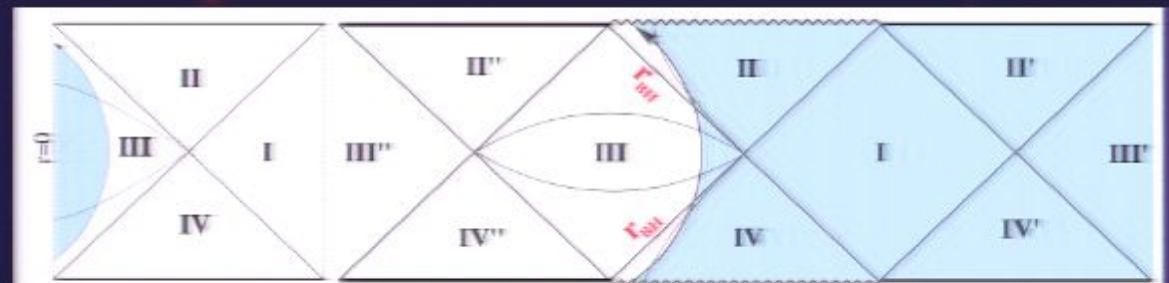
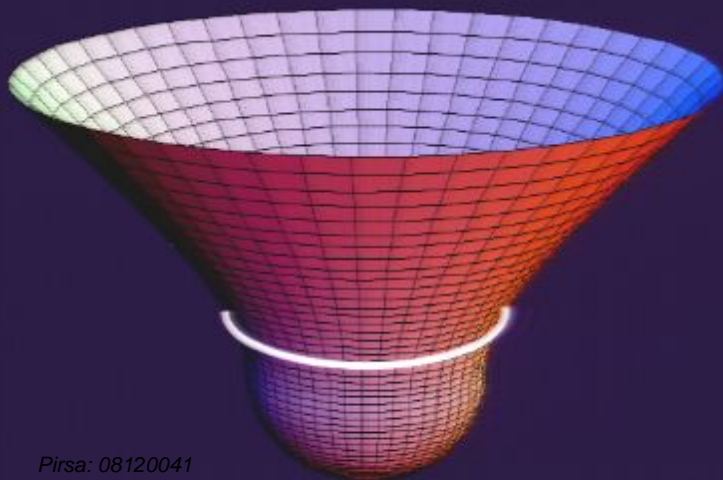
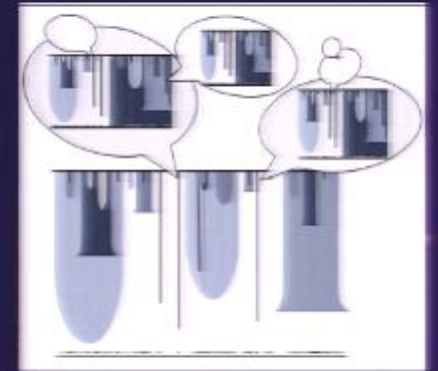
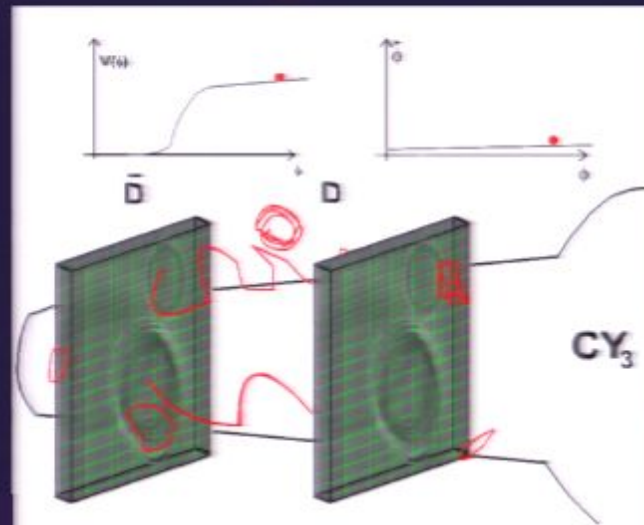


Modern Cosmology



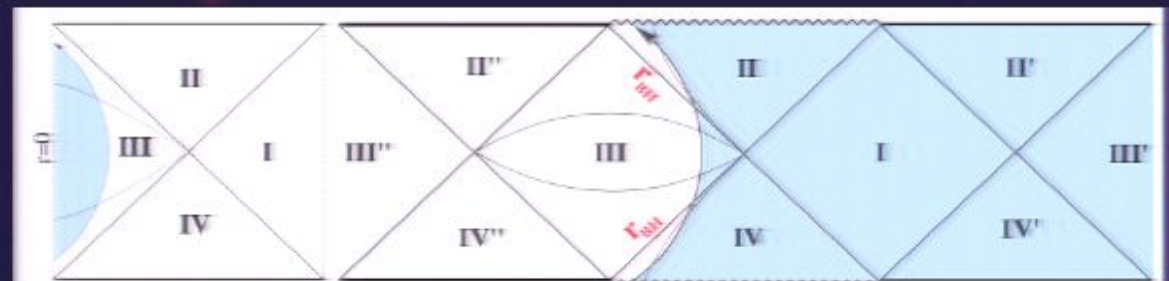
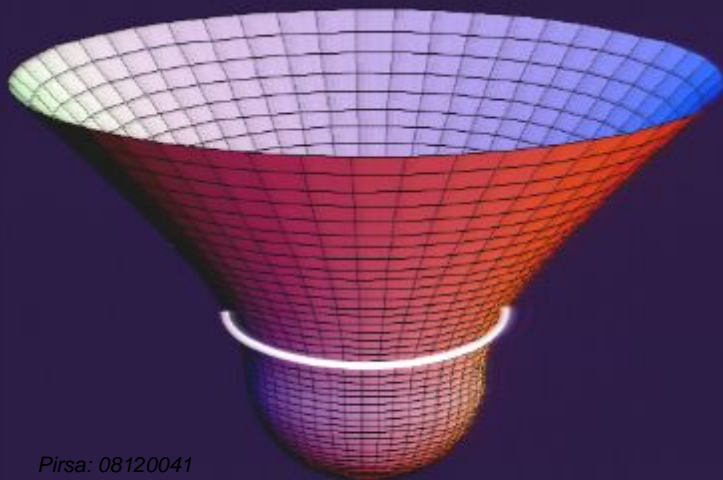
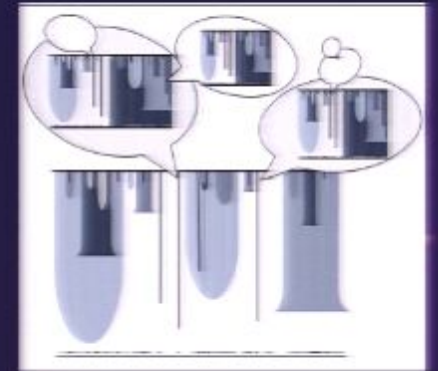
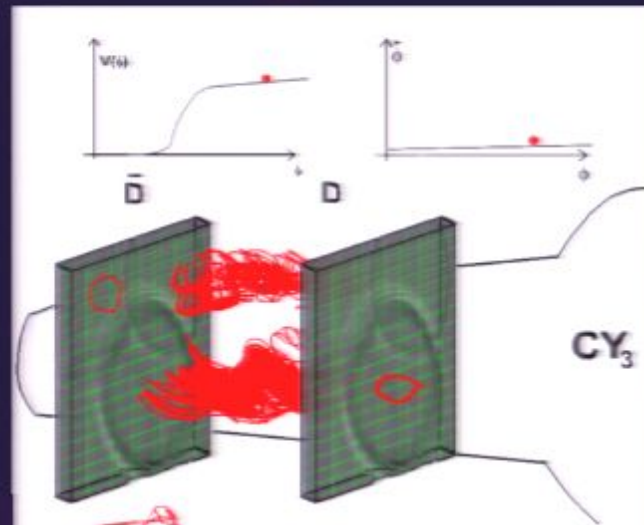


Modern Cosmology



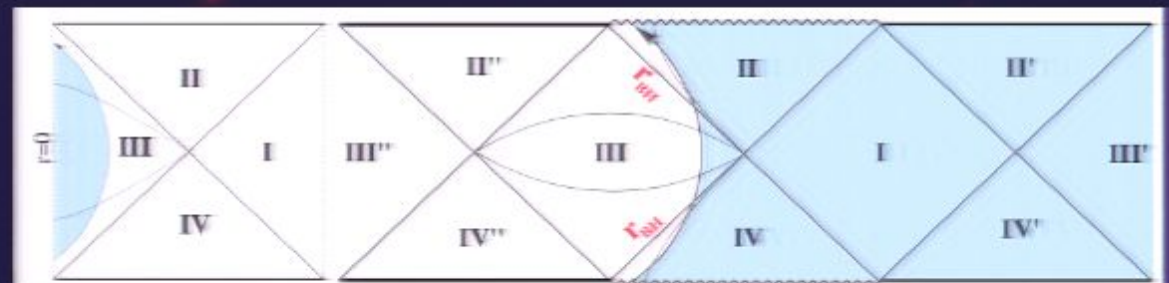
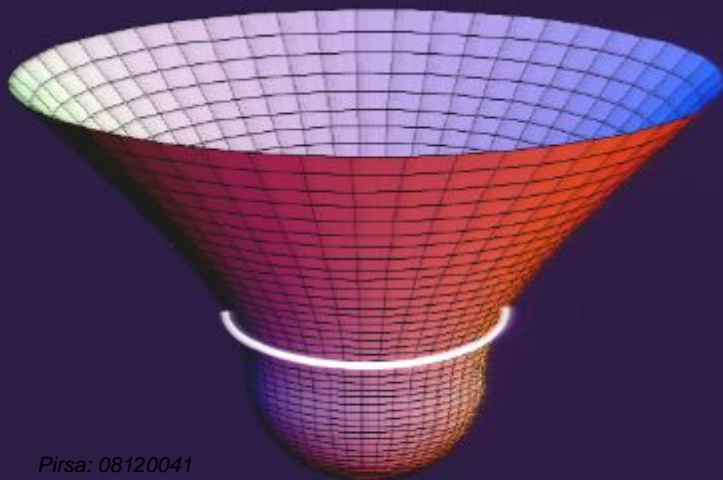
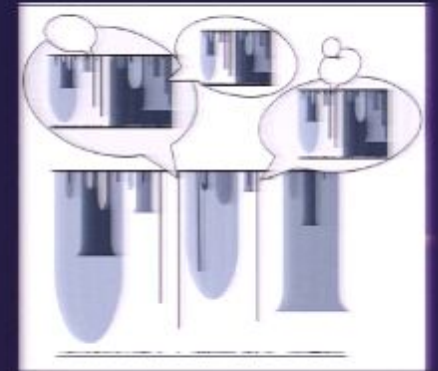
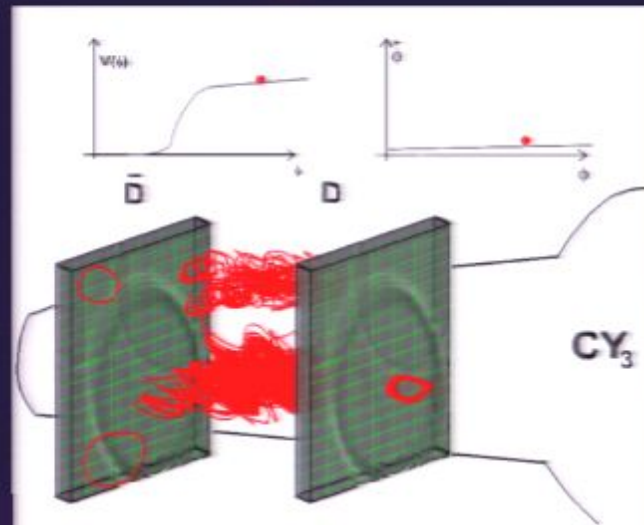


Modern Cosmology





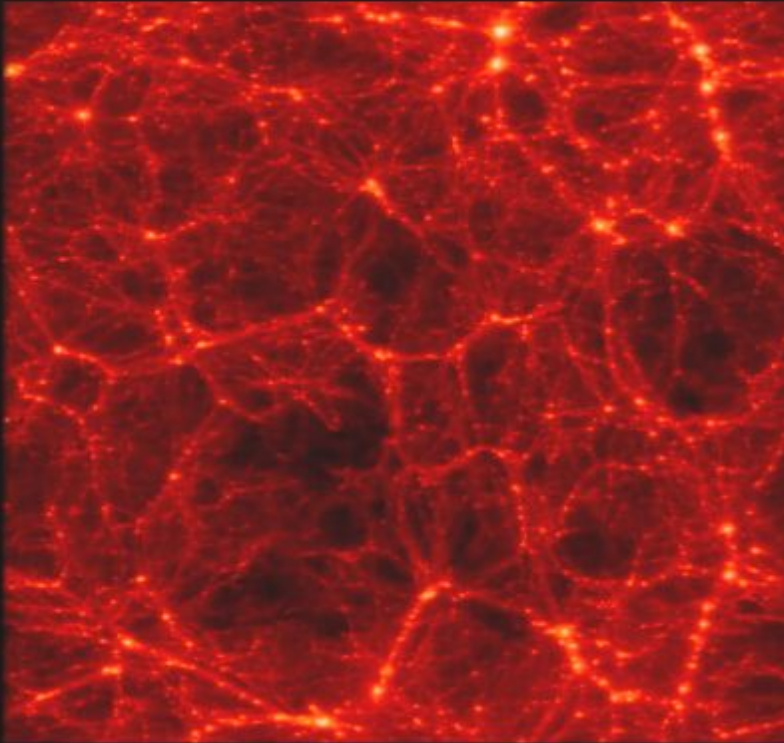
Modern Cosmology



Observations



Large Scale Structure



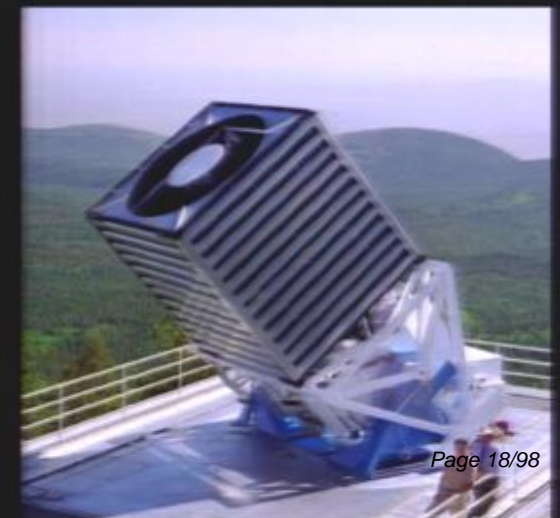
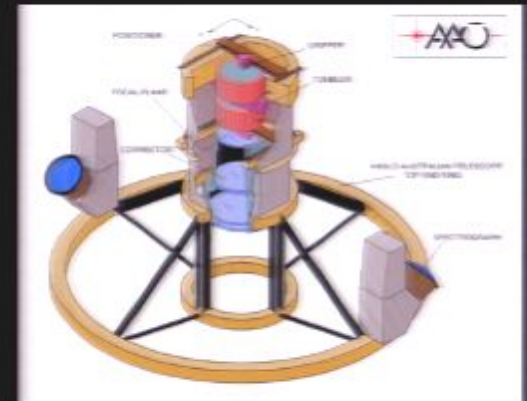
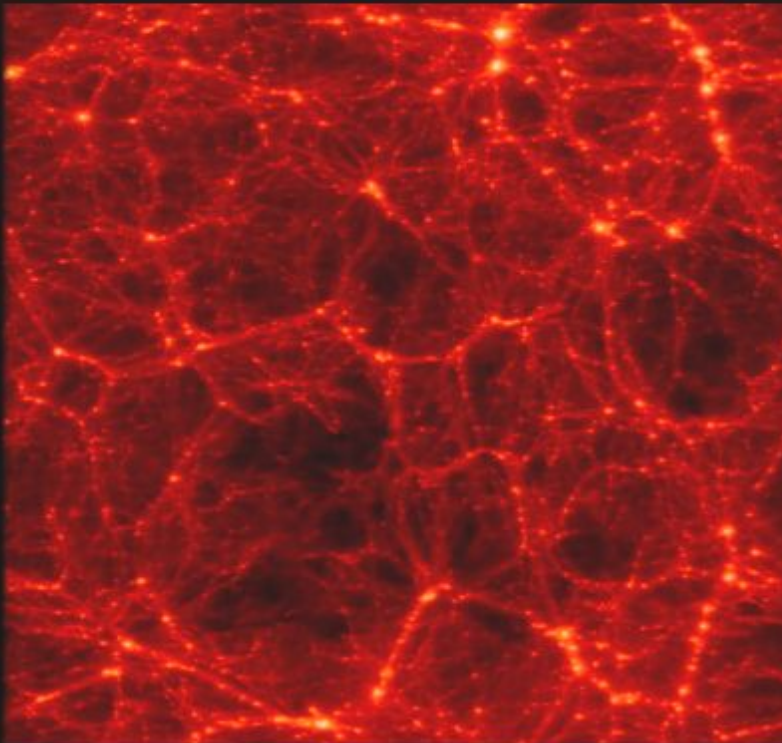
- ★ Measures:
 - the abundance of galaxy clusters
 - their size, etc ...
- ★ Tests:
 - the history of the Cosmic expansion
 - the growth of matter, structure formation, clustering

Large Scale Structure

★ Probes:

- 2dFGRS

- Sloan Digital Sky Survey



Type Ia Supernovae

- ★ Measures:

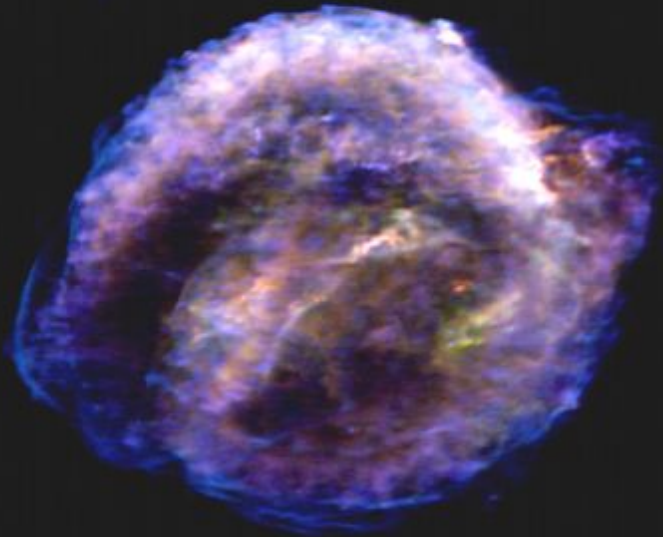
- the redshift of the supernovae

- ★ Tests:

- the expansion of the Universe

- ★ Probes:

CTIO, CFHT, ESO, HST,
VLT, Keck, UKIRT,
WIYN, APO, ...



Kepler

Type Ia Supernovae



- ★ Measures:
 - the redshift of the supernovae

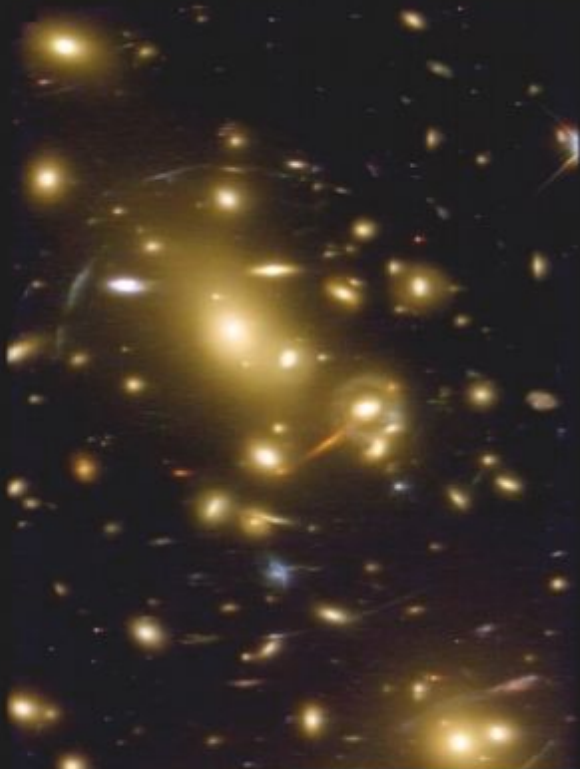


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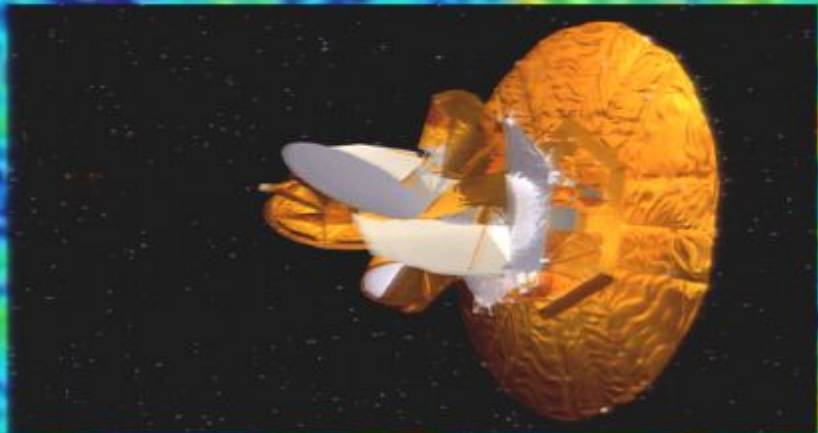
Gravitational Lensing



- ★ Measures:
 - matter density through its gravitational pull
- ★ Tests:
 - the composition of the Universe
- ★ Probes:
 - CFHT
 - William Herschel telescope

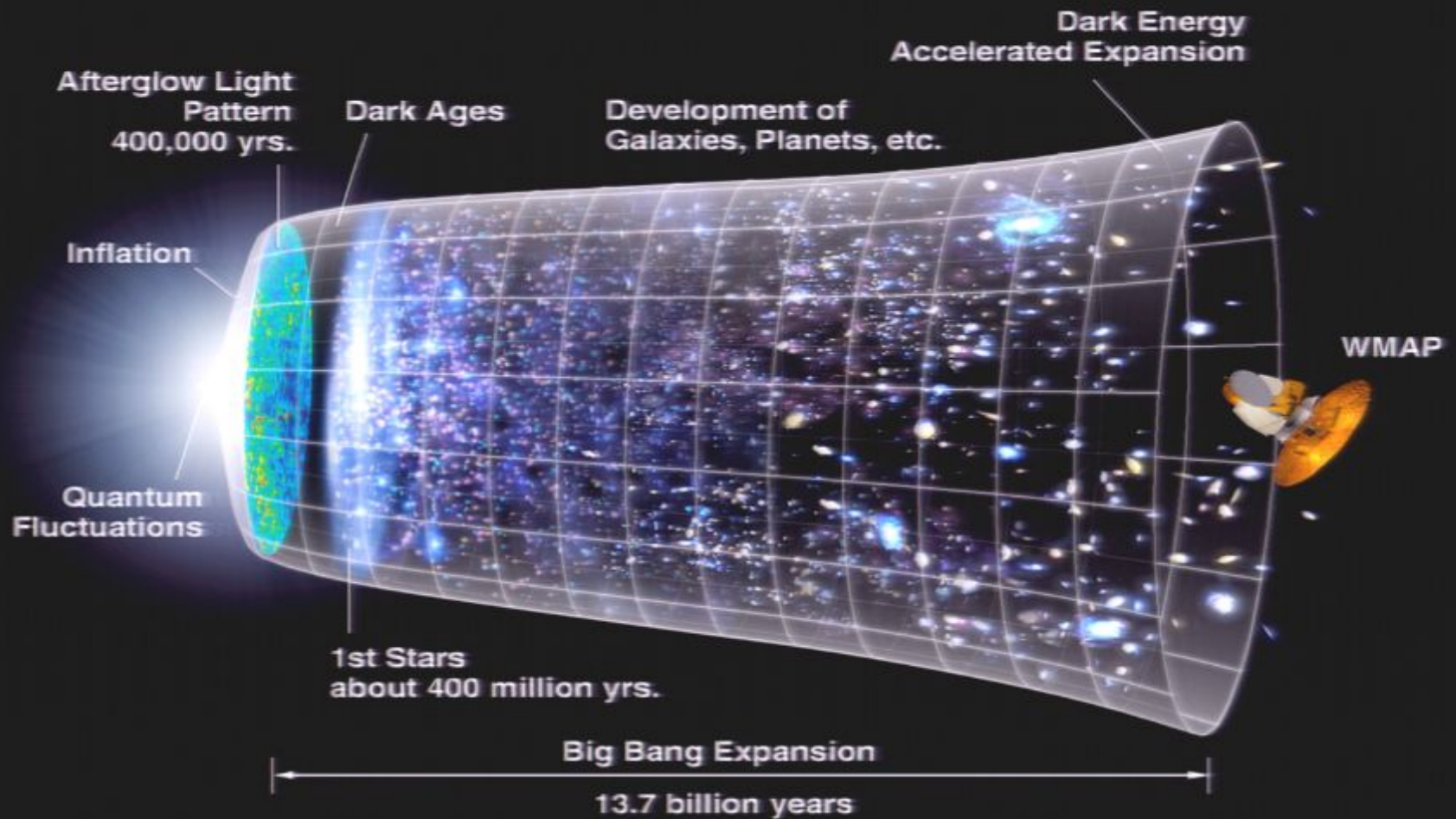


Cosmic Microwave Background



- ★ Measures:
 - the radiation emitted at the period of last scattering
- ★ Tests:
 - the cosmic expansion history
 - the composition of the Universe
- ★ Probes:
 - COBE, WMAP, Planck
 - balloons (BOOMERanG, MAXIMA, ...)
 - ground (Tenerife, South Pole, Saskatoon, ...)

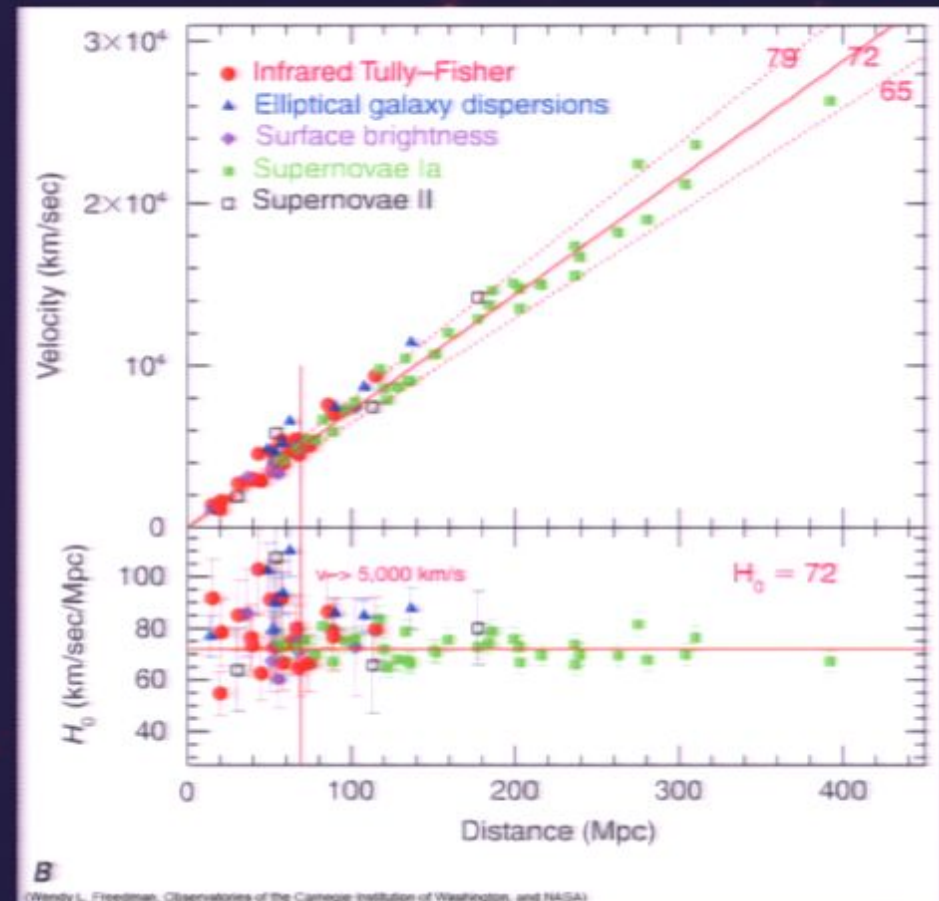
The standard model of Cosmology



WMAP 2006 press release

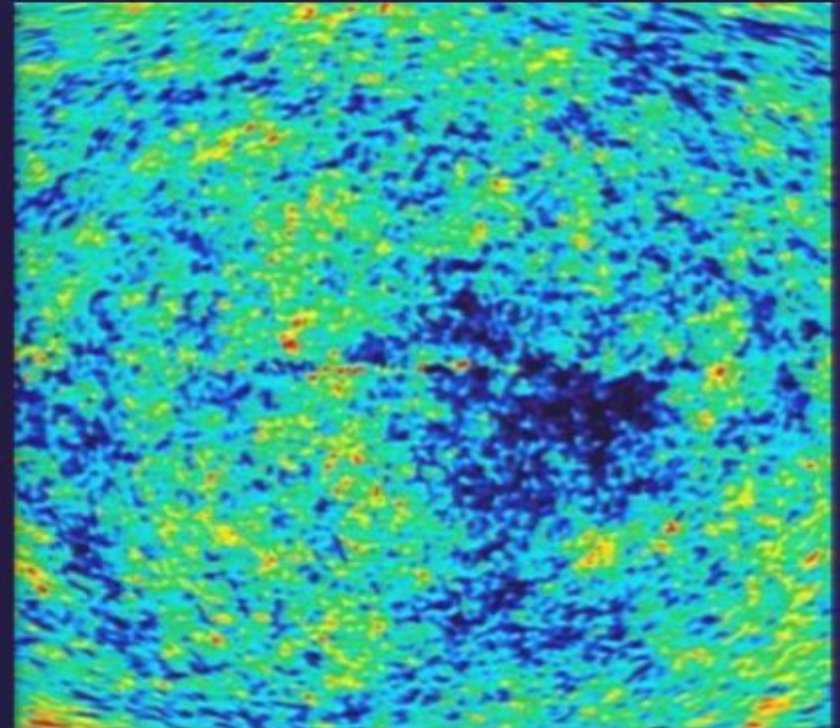
An expanding Universe

- ★ Observations show that the Universe is **expanding**,
- ★ and must have started with a **Hot Big Bang**



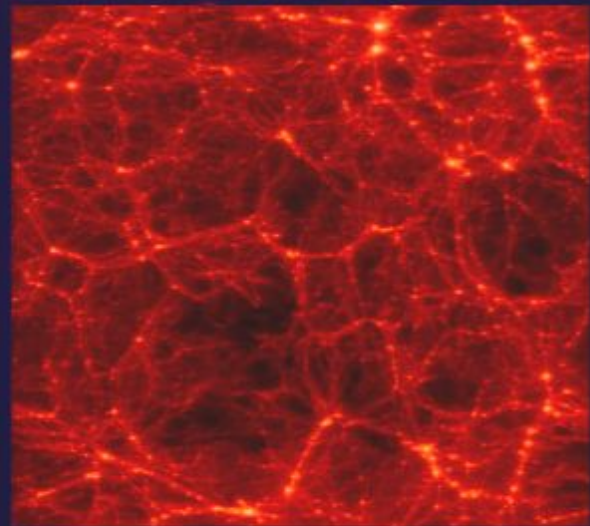
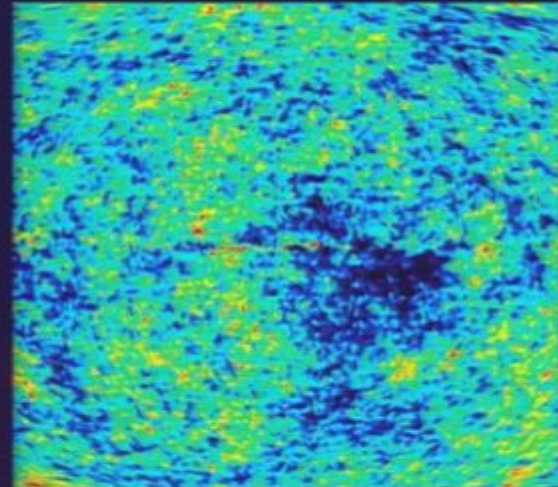
An expanding Universe

- ★ Observations show that the Universe is **expanding**,
- ★ and must have started with a **Hot Big Bang**.
- ★ Today, the Universe appears extremely **homogeneous** and **isotropic** on large scales.



An expanding Universe

- ★ The evolution of the early Universe is **dominated by** one or more **fields**,
- ★ whose **quantum fluctuations** seed the **large scale structure** of the current Universe

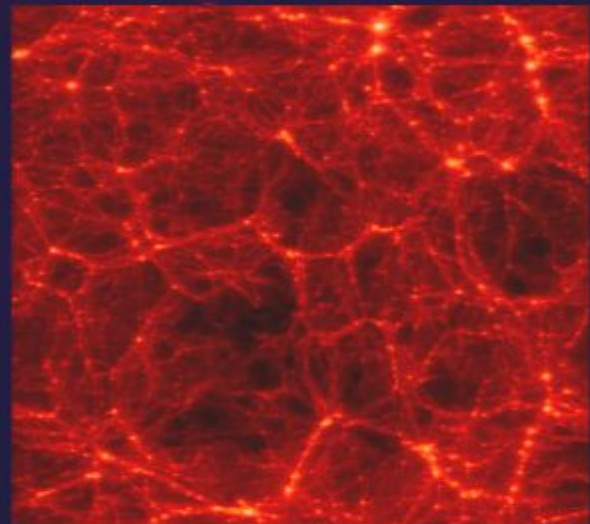
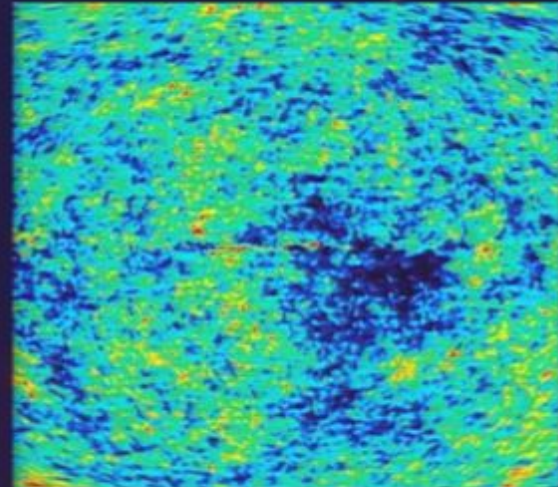


$$\zeta \sim \frac{\delta T}{T} \sim \frac{\delta \rho}{\rho}$$

spatial curvature perturbations

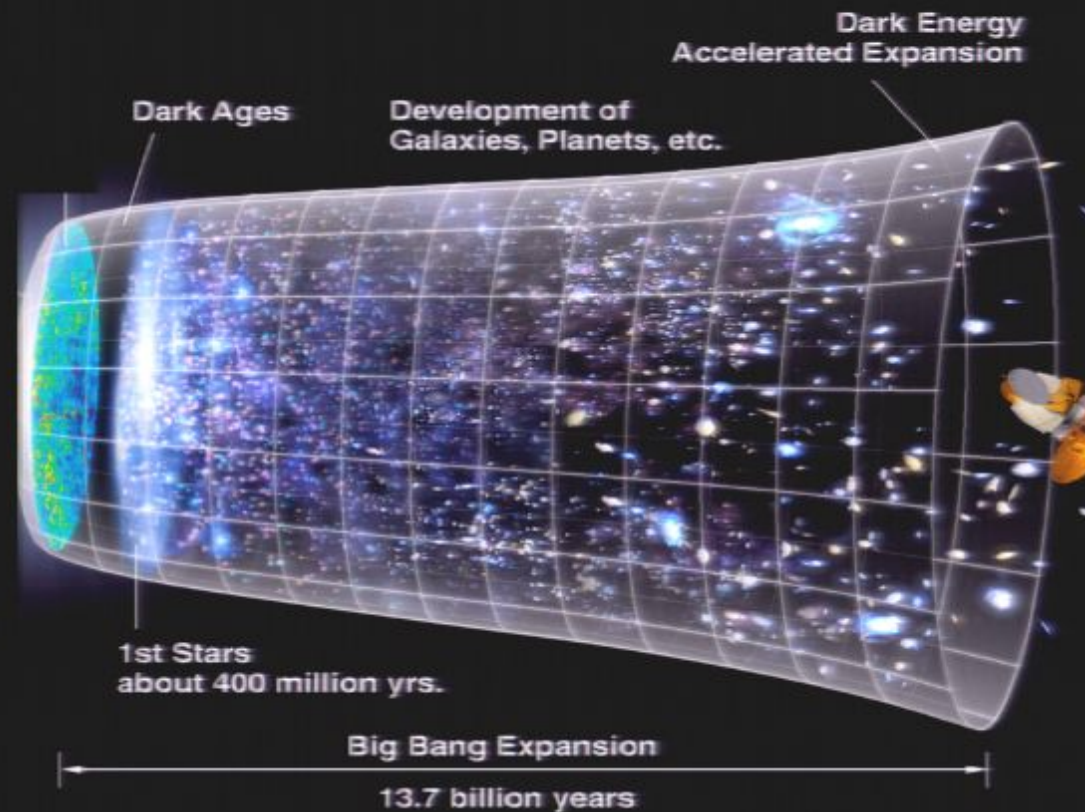
An expanding Universe

- ★ The evolution of the early Universe is **dominated by** one or more **fields**,
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- ★ Matter is then created at **reheating** when the energy of the driving field is transferred to the matter.

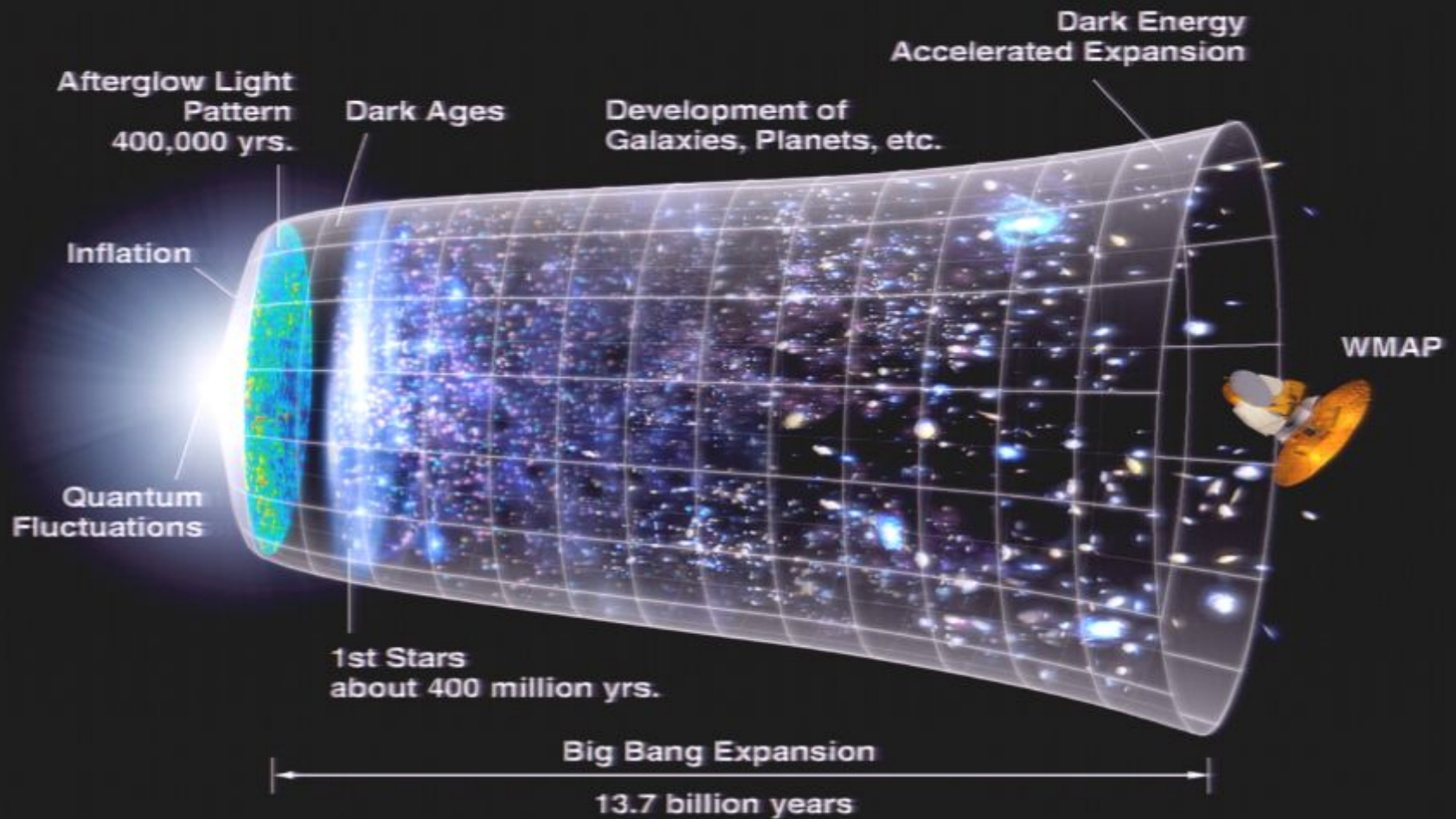


The standard model of Cosmology

- ★ As the Universe expands, the photons **decouple** from the plasma of hydrogen and helium: **period of last scattering**.
- ★ Large scale structure starts forming and give birth to first galaxies
- ★ The current Universe accelerating and is composed of
 - 5% **Matter**
 - 25% **Dark Matter**
 - 70% **Dark Energy**



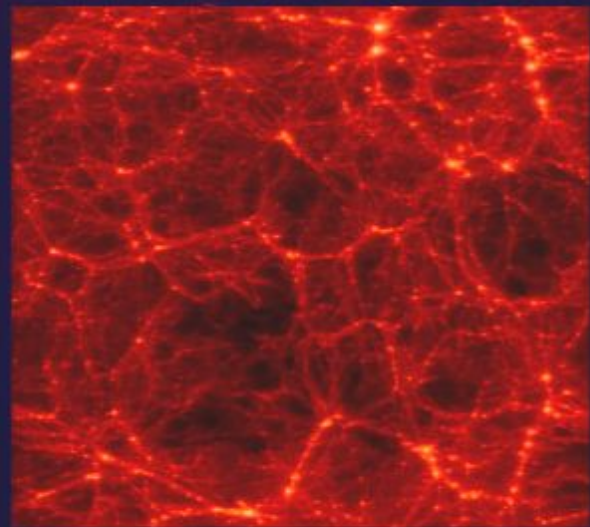
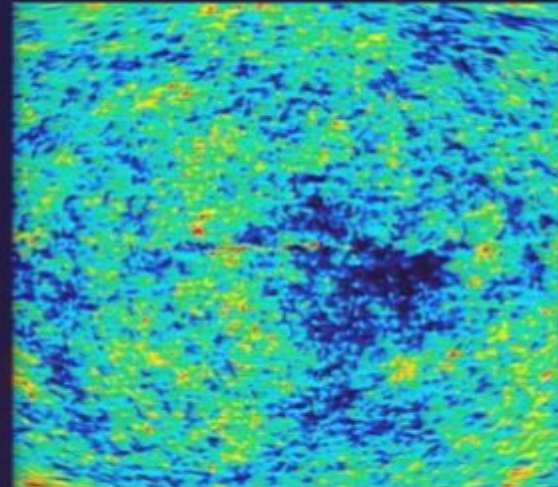
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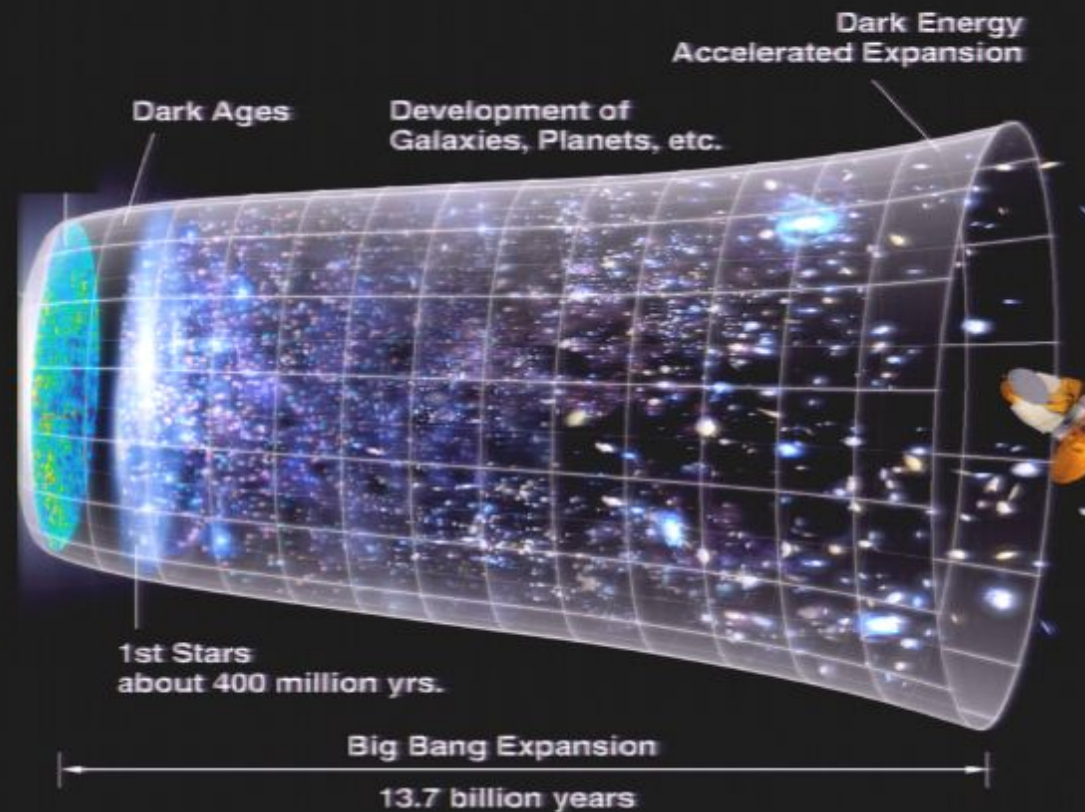


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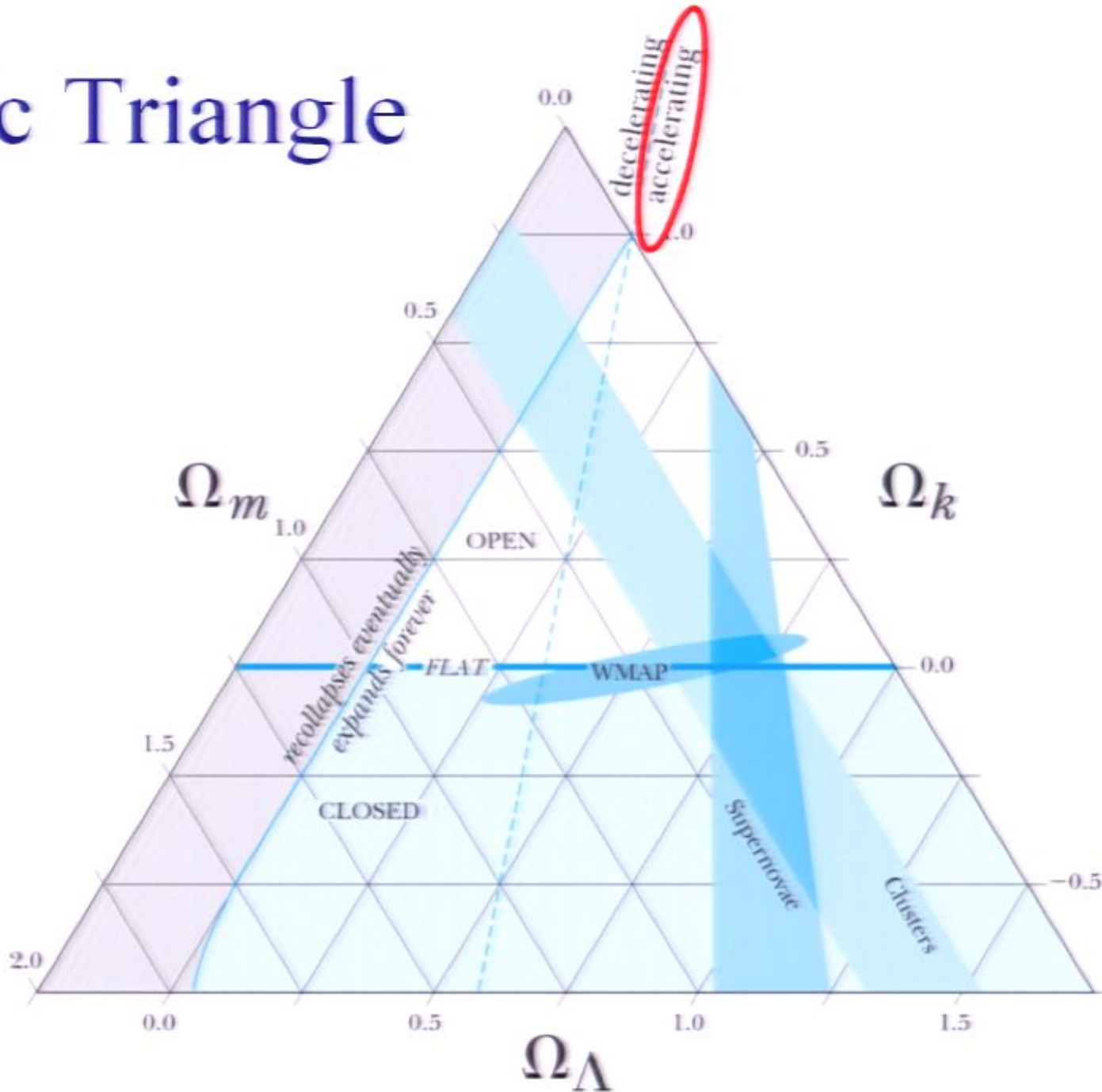
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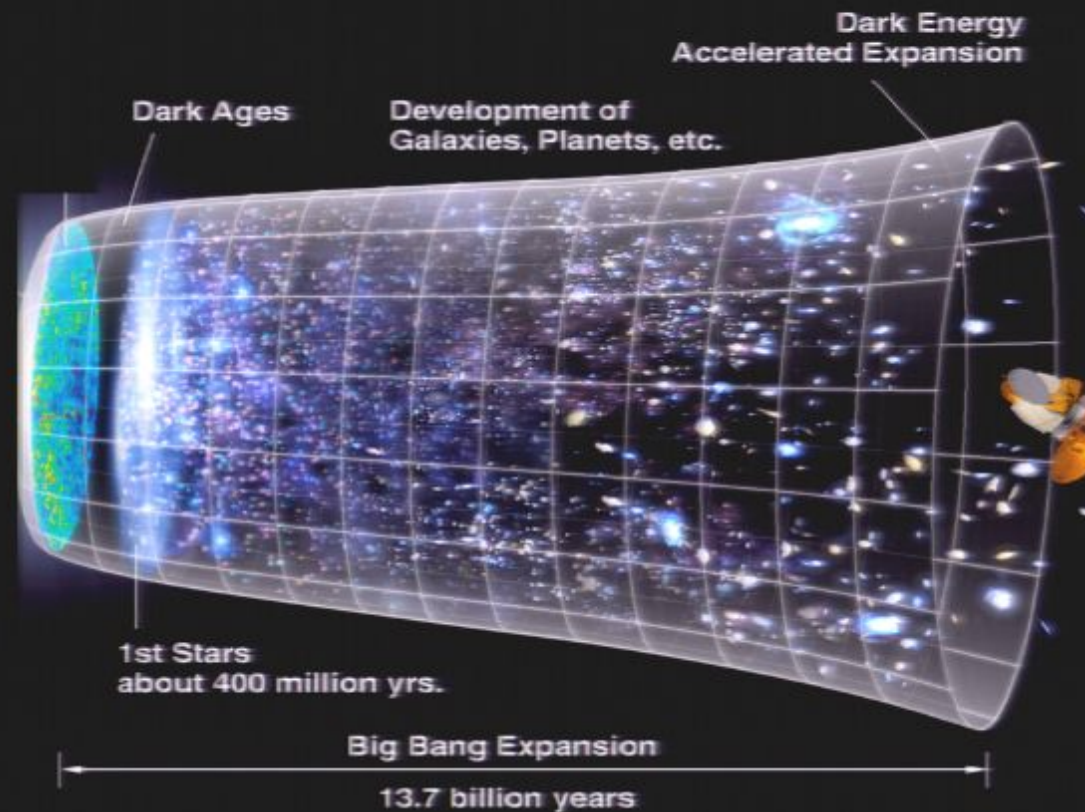


Cosmic Triangle

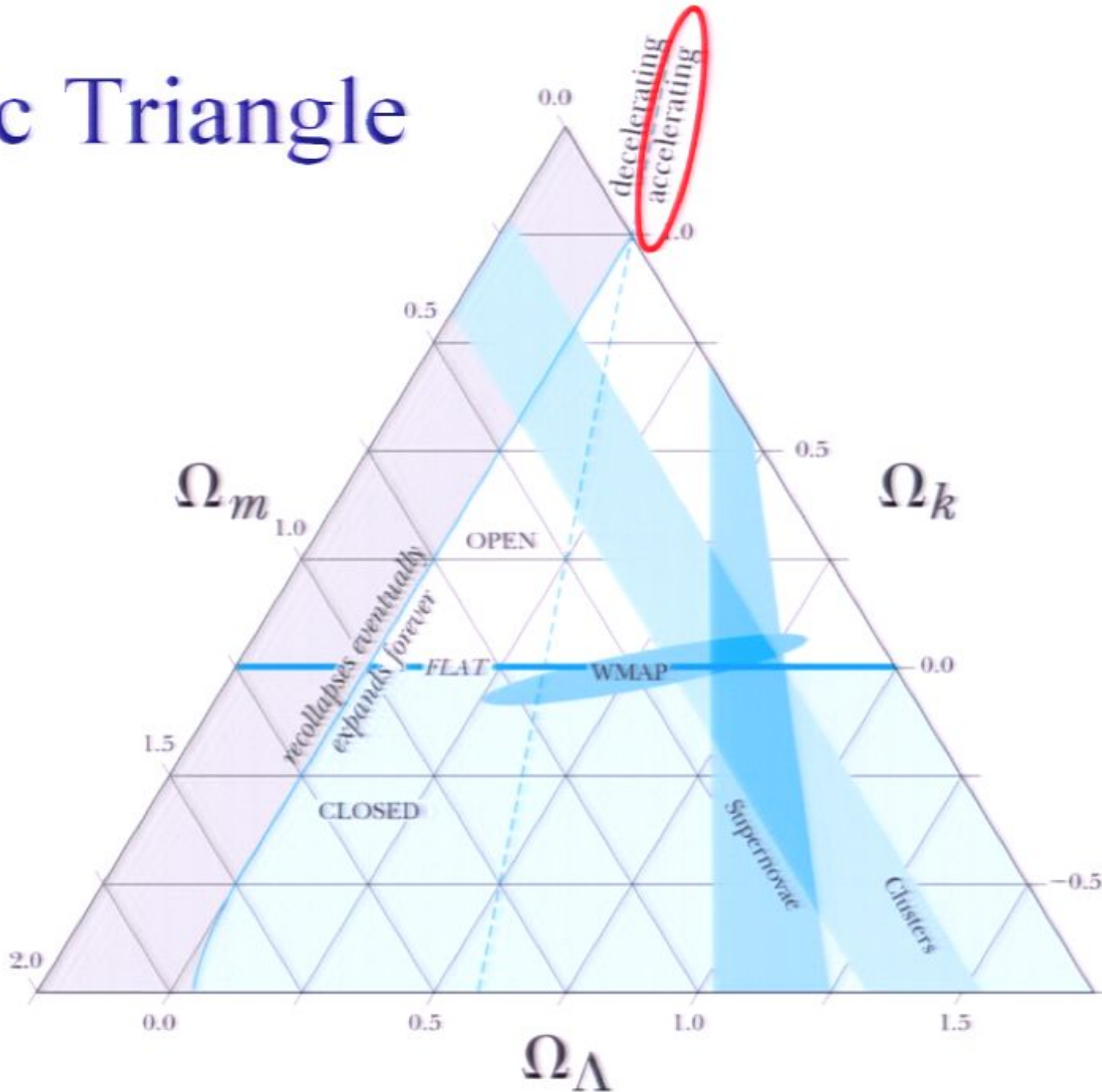


The standard model of Cosmology

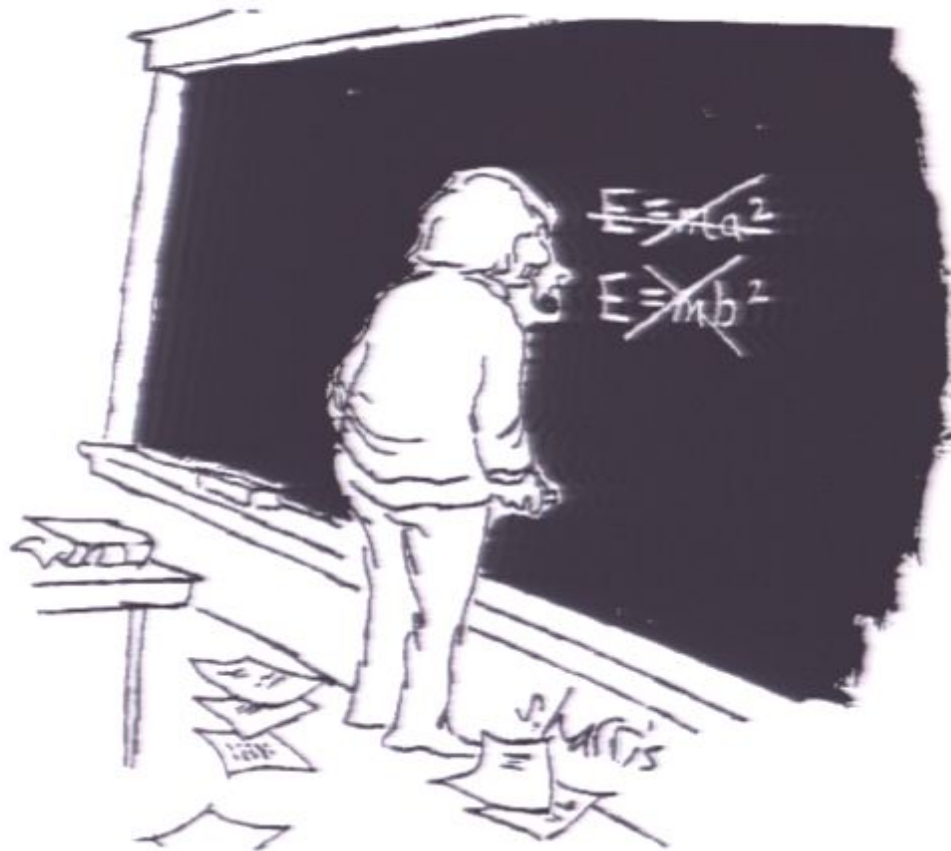
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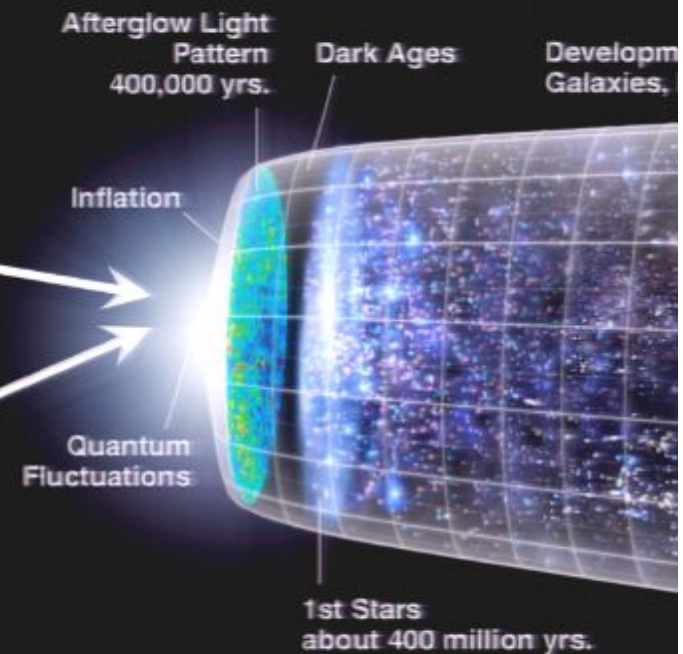


Cosmological Puzzles



1. What happened at the Big Bang?

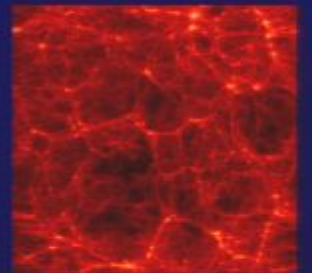
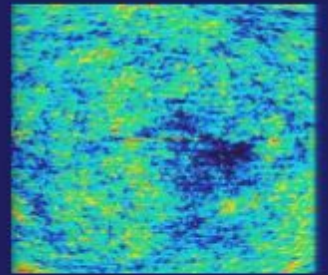
- ★ What is the BB?
- ★ What created it?
- ★ What are the implications for Planck scale physics?
- ★ Did time begin?
- ★ Is there anything before the BB?



quantum gravity, string theory

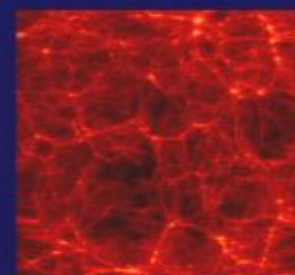
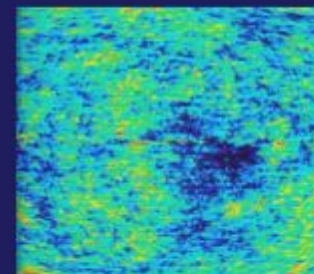
2. What generated the large scale structure?

- ★ Strong evidence that the primordial power spectrum is very close to
 - gaussian
 - scale invariant $n_s = 0.95 \pm 0.015$



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- ★ Strong evidence that the primordial power spectrum is very close to
 - **gaussian**
 - **scale invariant** $n_S = 0.95 \pm 0.015$
- ★ The most commonly “accepted” hypothesis is that the Universe underwent a period of “**inflation**” dominated by the **potential energy** of one or several scalar field(s) in an **expanding Universe**.



$$\omega = \frac{p}{\rho} \gtrsim -1 \quad n_S - 1 \simeq \frac{V'(\phi)}{V(\phi)}$$

2. What generated the large scale structure?

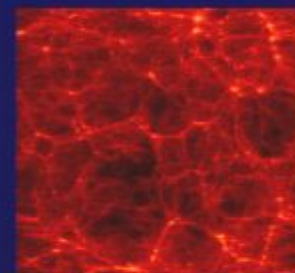
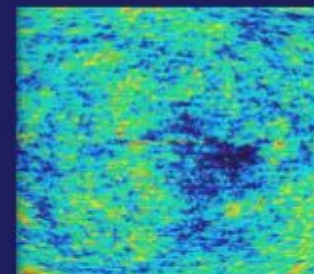
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- ★ **What is the inflaton scalar field?**



Inflation from String Theory

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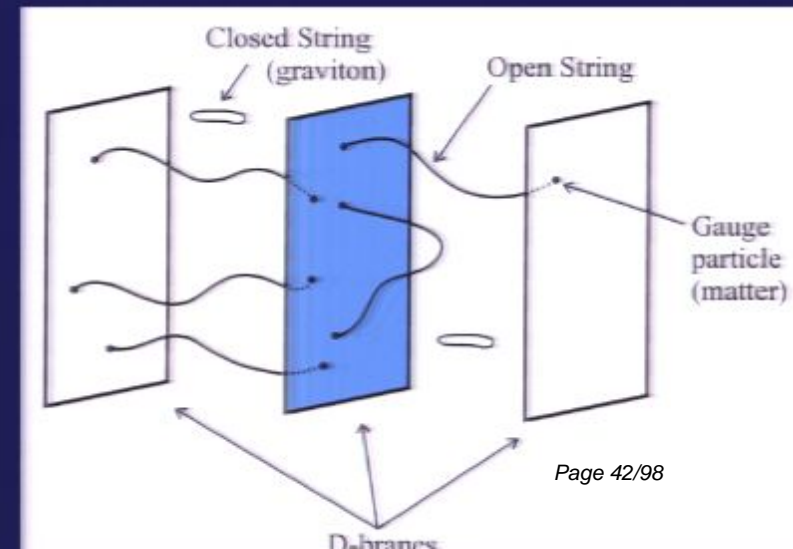
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- ST implies the presence of **branes**, on which matter fields can be localized


→ D-brane inflation



D-Brane Inflation

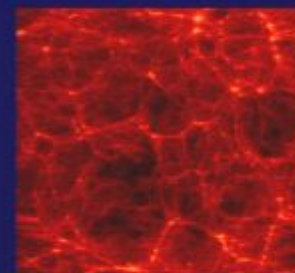
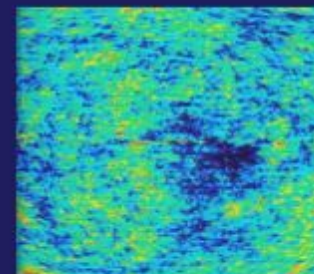
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 can be used as **inflaton candidates**.

- ★ D-branes are charged objects
 D-branes and anti D-branes attract each other
- ★ When the branes are far away, the interaction is weak giving rise to a **naturally slow-rolling potential**
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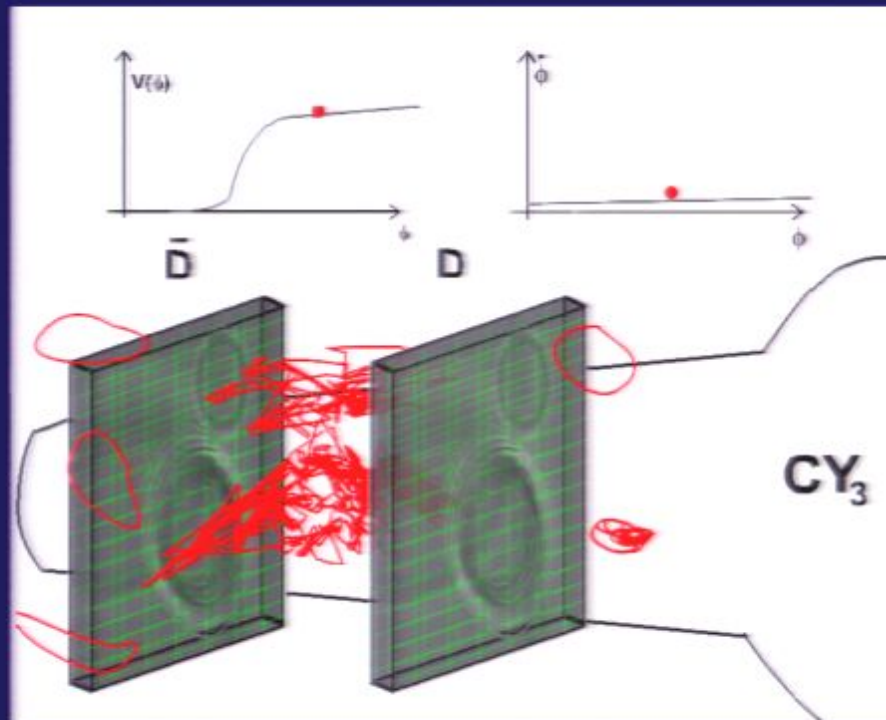
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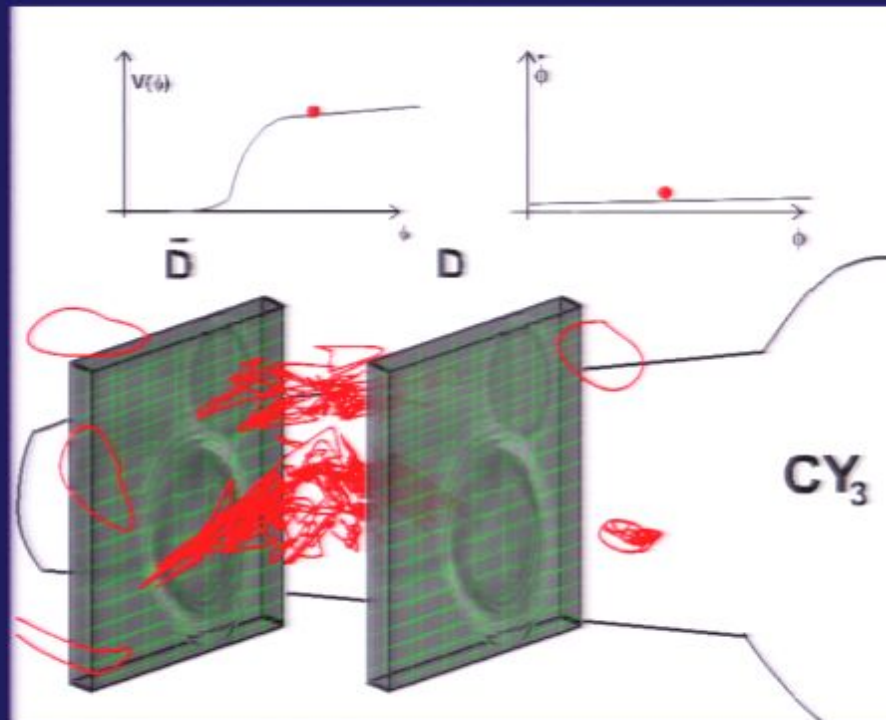
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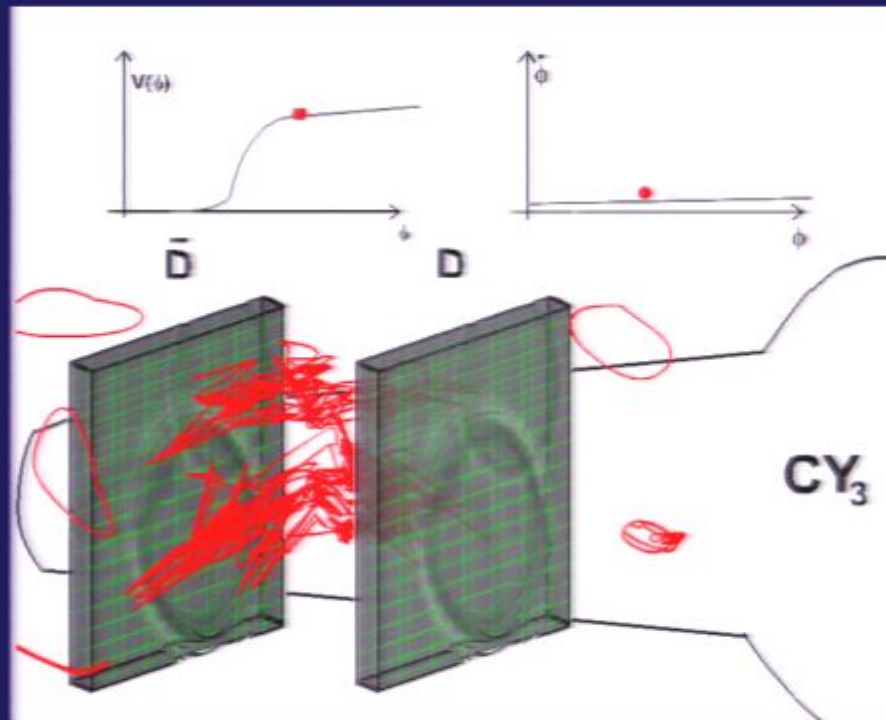
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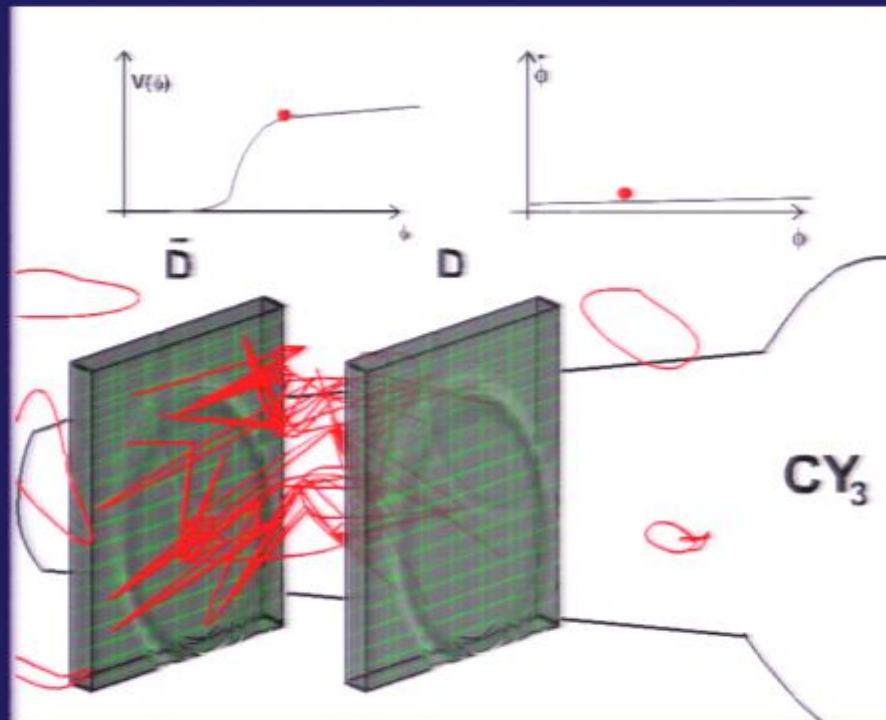
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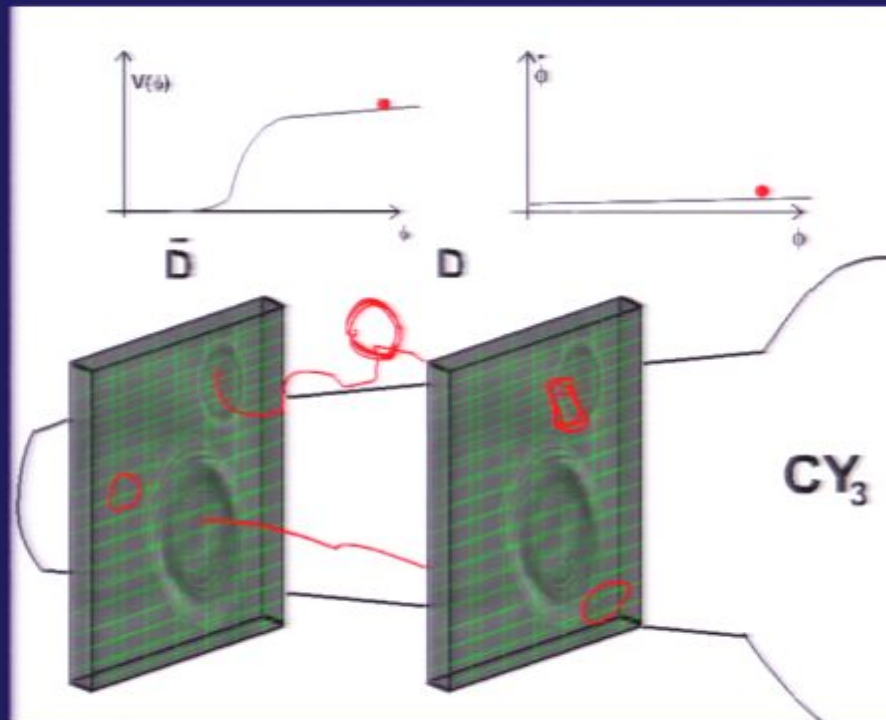
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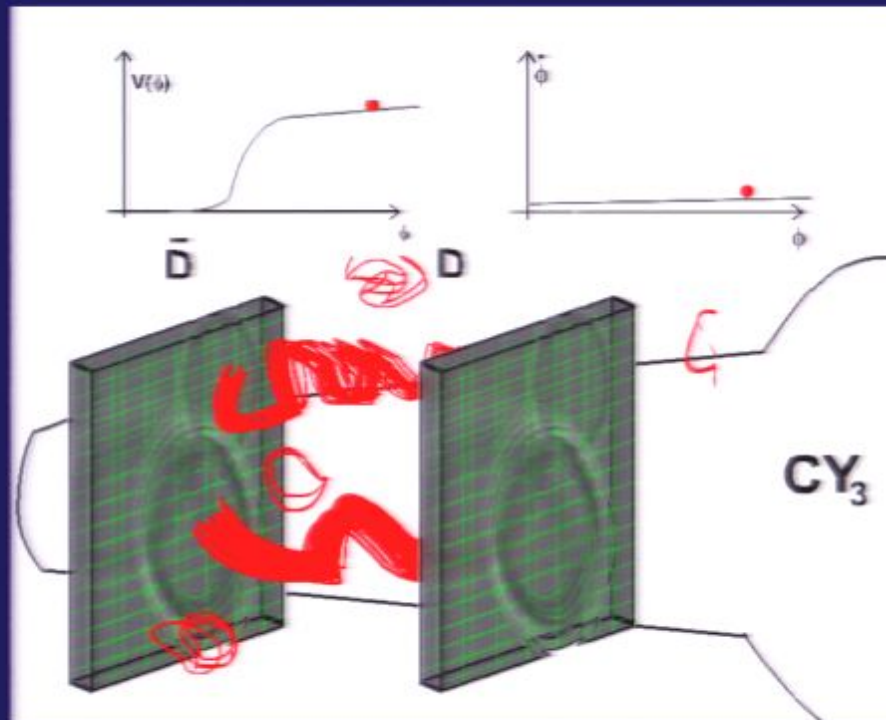
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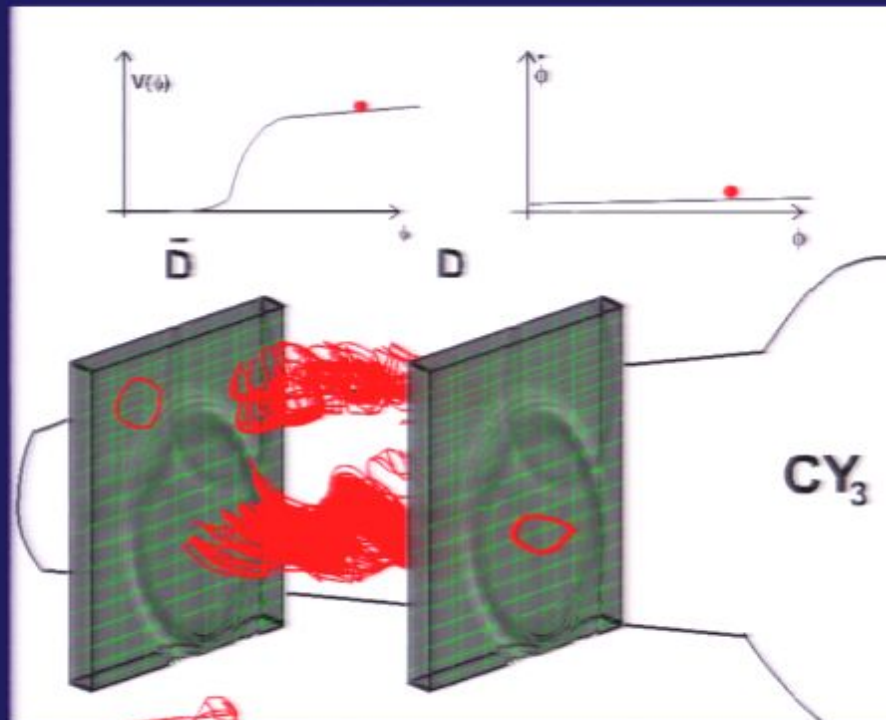
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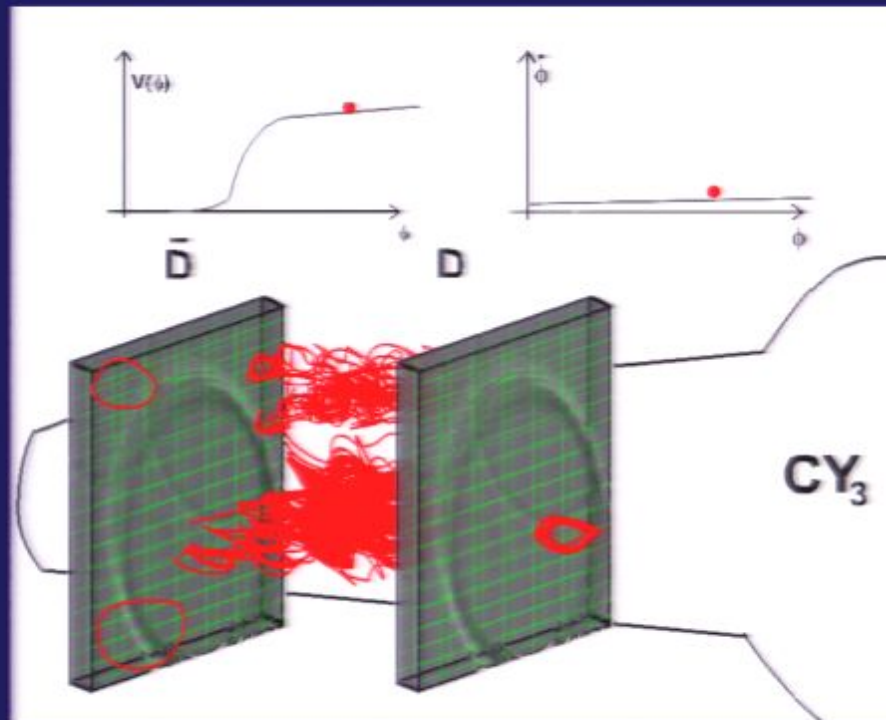
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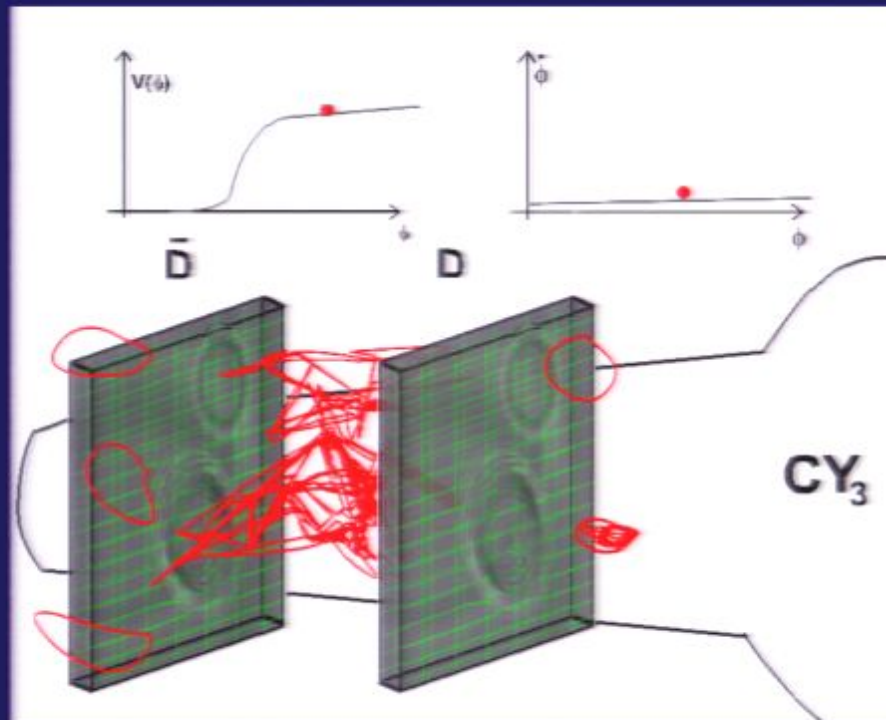
- ★ The brane can be evolving very **fast** down the throat, $\dot{\phi} \lesssim 1$ and still produce a **nearly scale invariant power spectrum**

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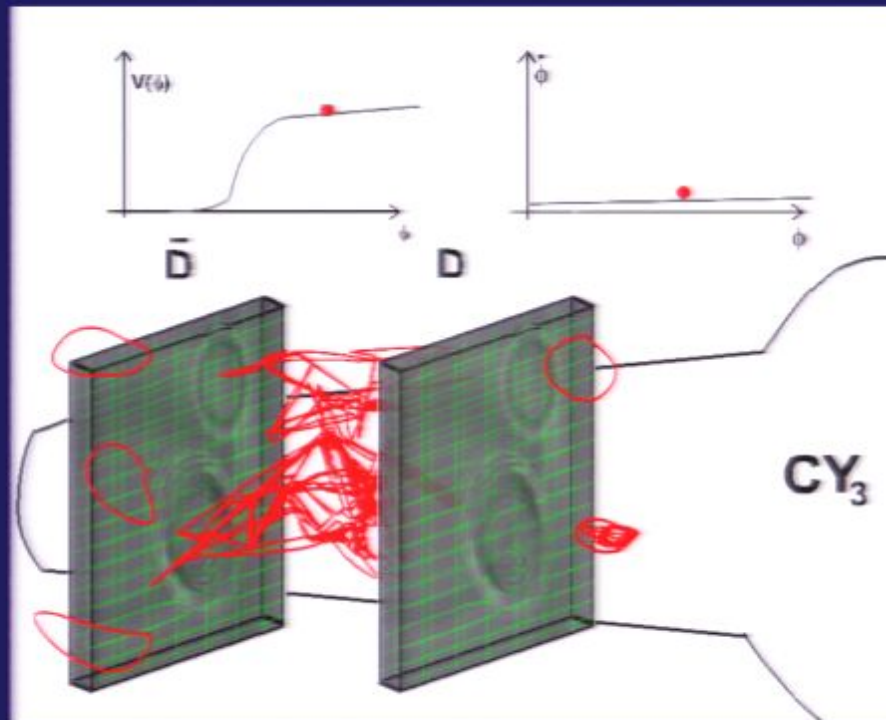
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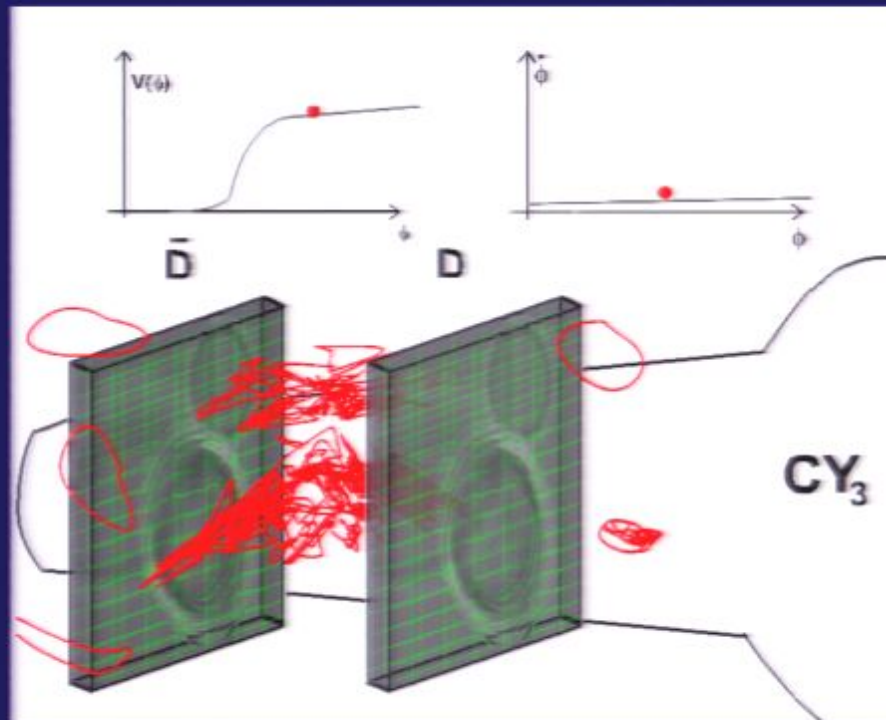
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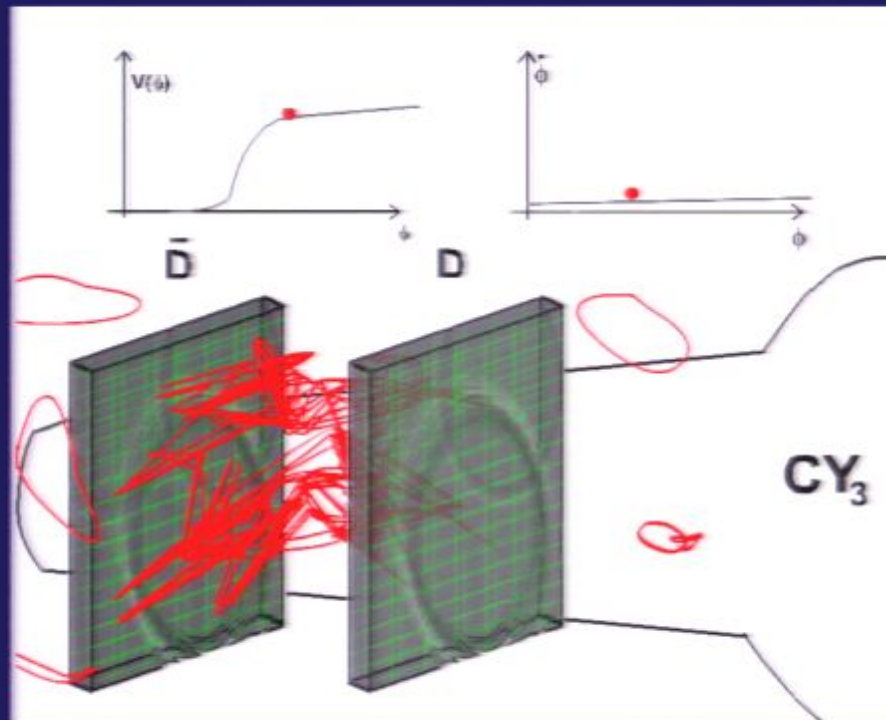
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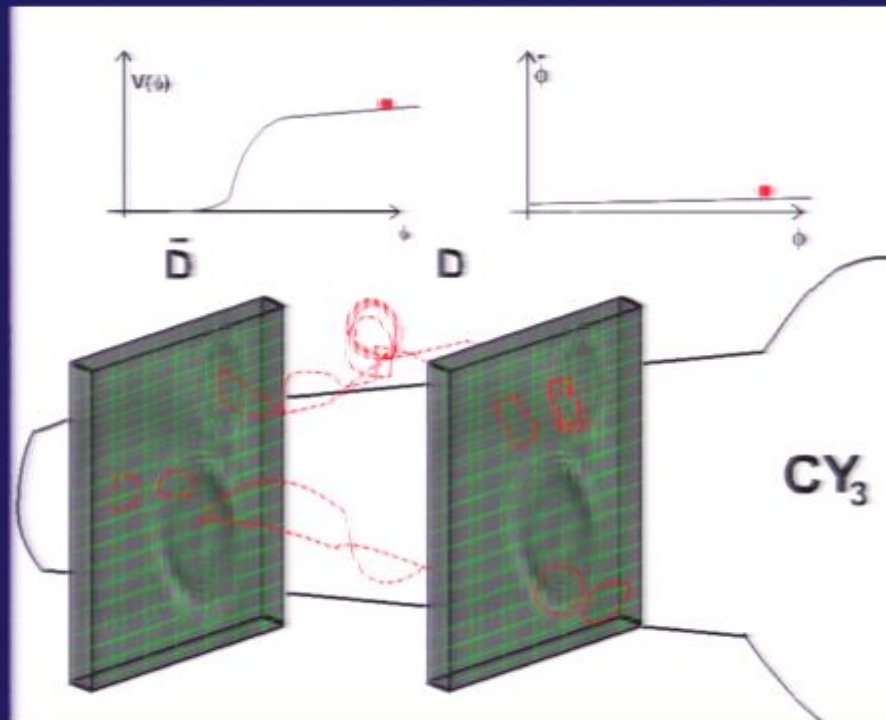
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Alternatives to inflation

★ Pre-Big-Bang scenario

M. Gasperini
G. Veneziano

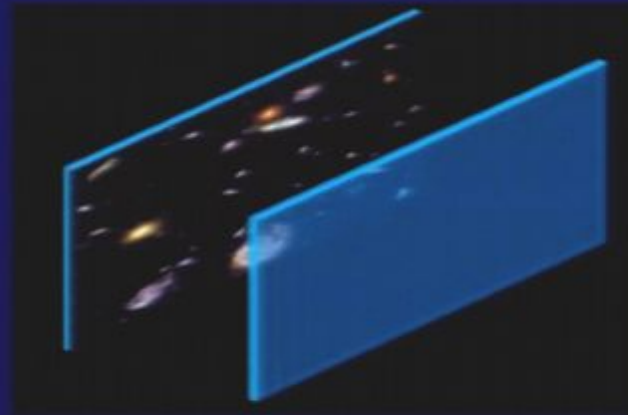
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- singularity at strong coupling (large $g_s = e^\phi$) $\omega \gg 1$

★ Ekpyrotic scenario

- singularity at weak coupling (α' important)

J. Khoury, B. Ovrut, P. Steinhardt, N. Turok



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★ Hagedorn phase

- expanding phase in Einstein frame, evolution driven by string gas.

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Signatures of Inflation and alternative scenarios

1. Departure from scale invariance

$$\langle \zeta(\vec{k}_1) \zeta(\vec{k}_2) \rangle \sim k_1^{n_S - 4} \delta^{(3)}(\vec{k}_1 + \vec{k}_2)$$

power spectrum

$$P(k) \sim k^{n_S - 1}$$

amount of power on each scale

observed value: $n_S = 0.95 \pm 0.015$

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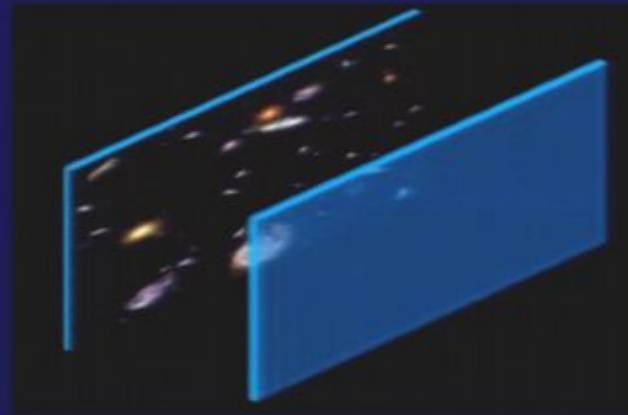
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- ★ Measuring the 3-pt function gives some insight on the departure from gaussianity.

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- ★ In momentum space, the 3-pt function depends on 3 vectors that add up to zero \rightarrow triangles.

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(squeezed)



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- ★ If $n\text{G}$ generated at **horizon crossing**

$$k_1 \sim k_2 \sim k_3 \sim aH$$

→ dominant contribution in **equilateral triangle**

Case for single field **DBI inflation**

- ★ If $n\text{G}$ generated at **superhorizon scale**

spatial gradients are negligible

→ local shape in real space

large contribution in the **local (squeezed) triangle**

Case for **multifield scenarios** (eg. curvaton, ekpyrosis)

- ★ **However, initial conditions** can give large contributions in other shapes as well (eg. **flat triangles for excited states**) !

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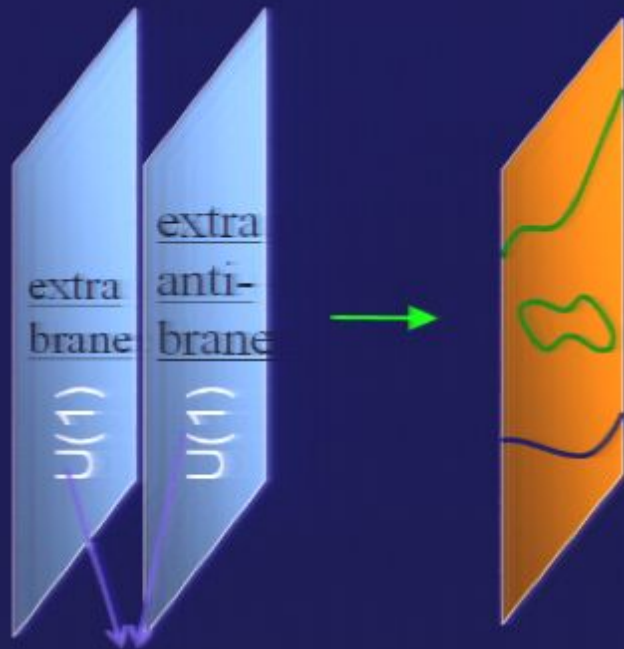
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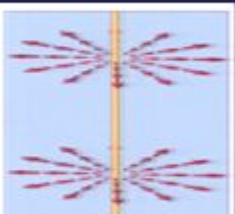
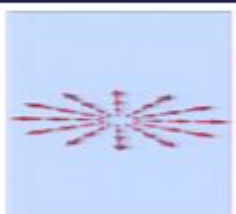
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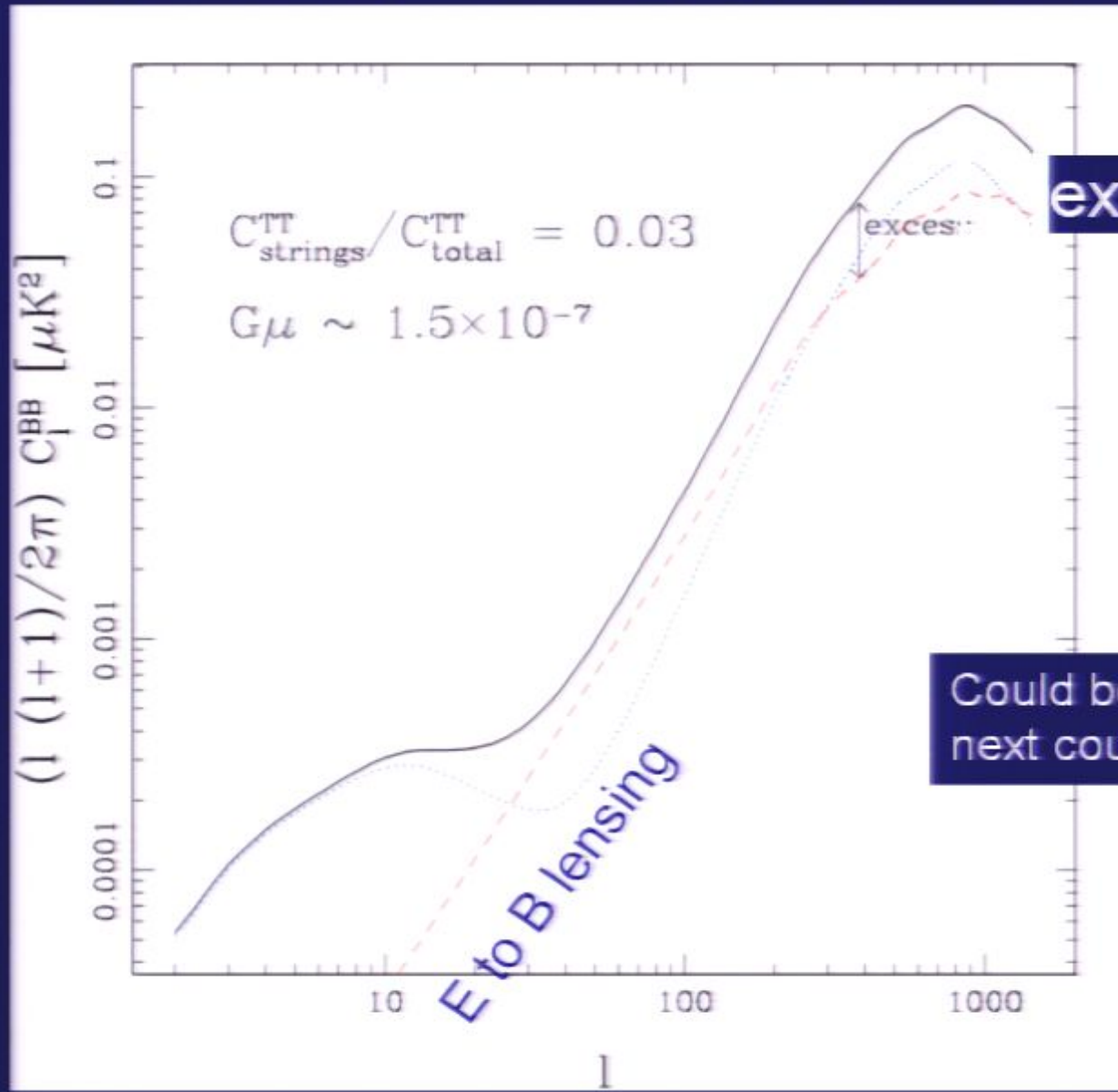
Brane inflation: New source for cosmic strings



- Annihilation of inflating branes can produce **strings** (actual 1-D objects or “wrapped” higher-D objects)
- Predicts $10^{-11} < G\mu < \text{few} \times 10^{-7}$
- caveat: possible stability problems
- Not ruled out; potentially detectable



A possible observable: source of CMB B-modes!



Other Cosmological Puzzles

- ★ What happened at the Big Bang?
- ★ What generated the large scale structure?
- ★ What is 95% of the current Universe made off?

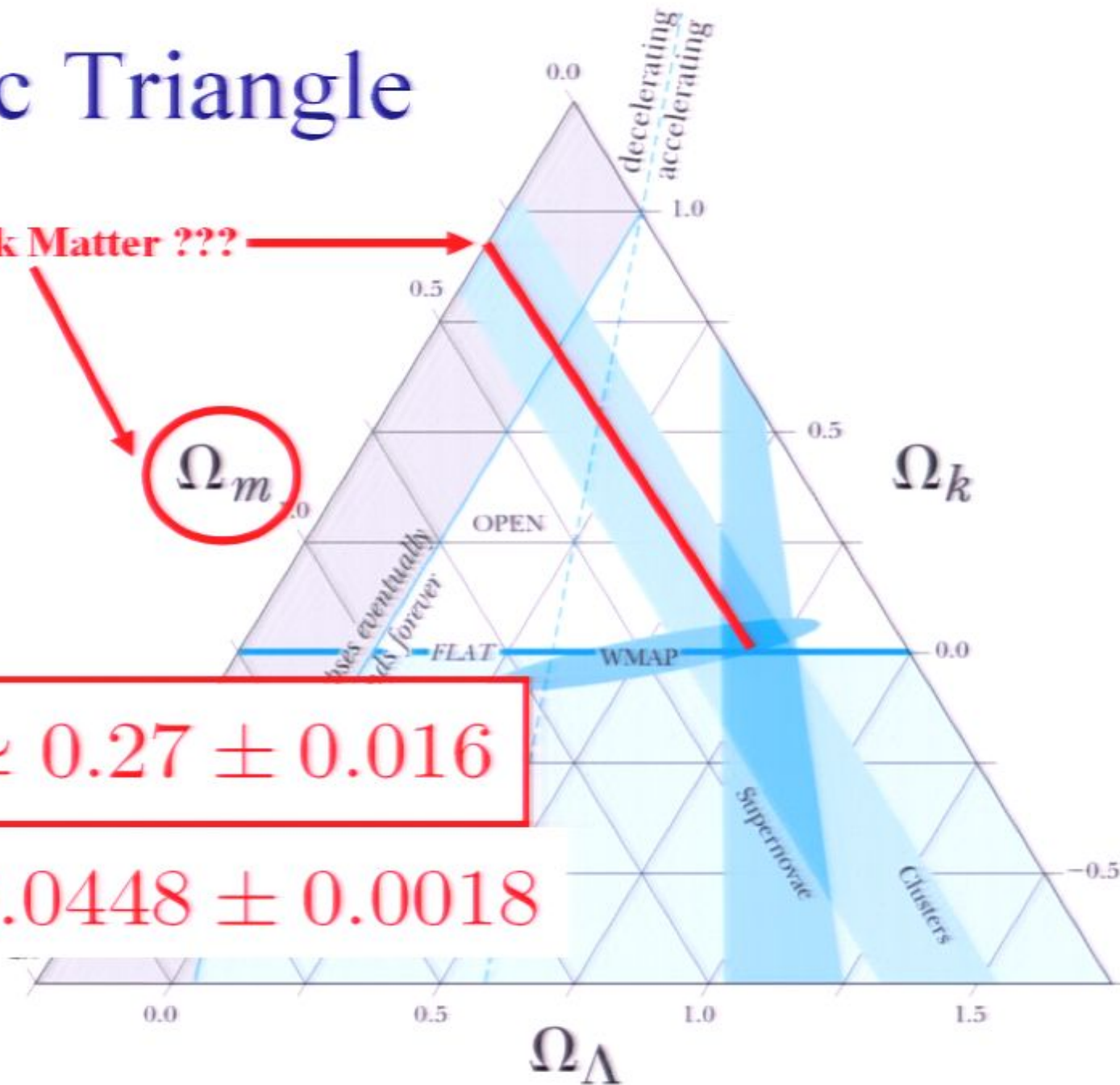
Cosmic Triangle

What is Dark Matter ???

Ω_m

$$\Omega_m \simeq 0.27 \pm 0.016$$

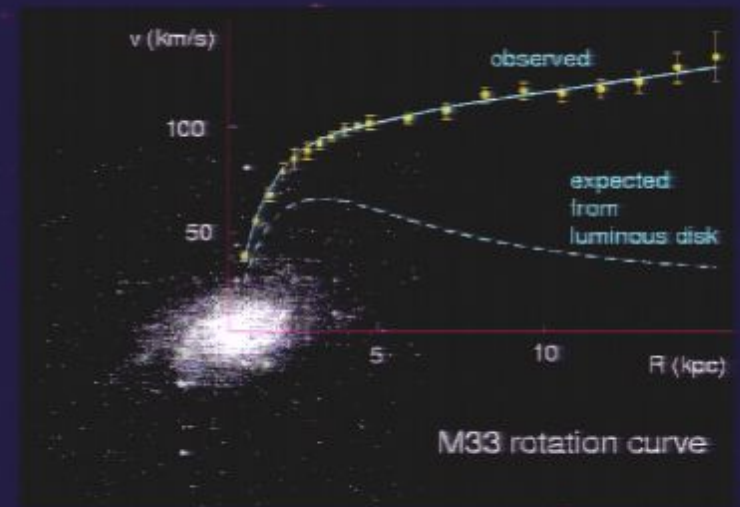
$$\Omega_b \simeq 0.0448 \pm 0.0018$$



Dark Matter

also supported by:

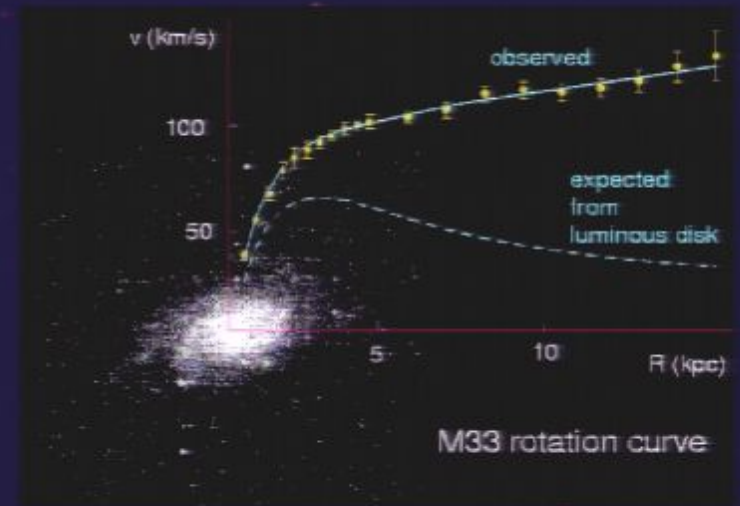
- CMB data
- Distance-luminosity for supernovae type I A
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- Abundance of light elements (BBN)



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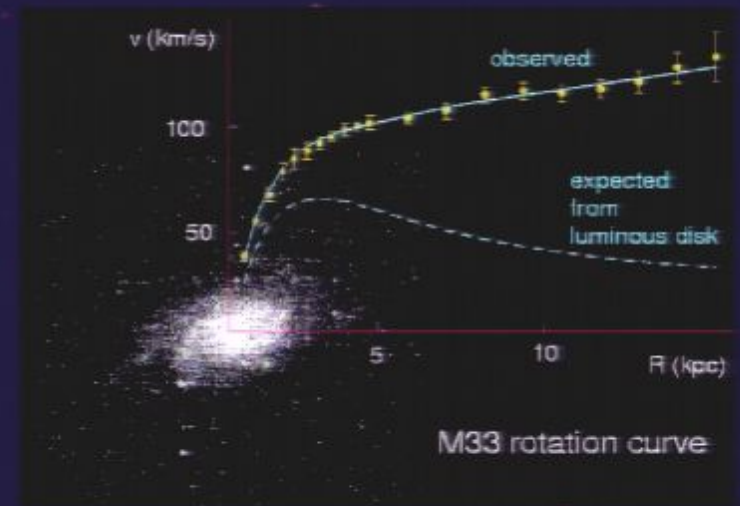


- ★ Is it physics beyond the **Standard Model of Particle Physics** ?
- ★ Or physics beyond **General Relativity** ?

Dark Matter

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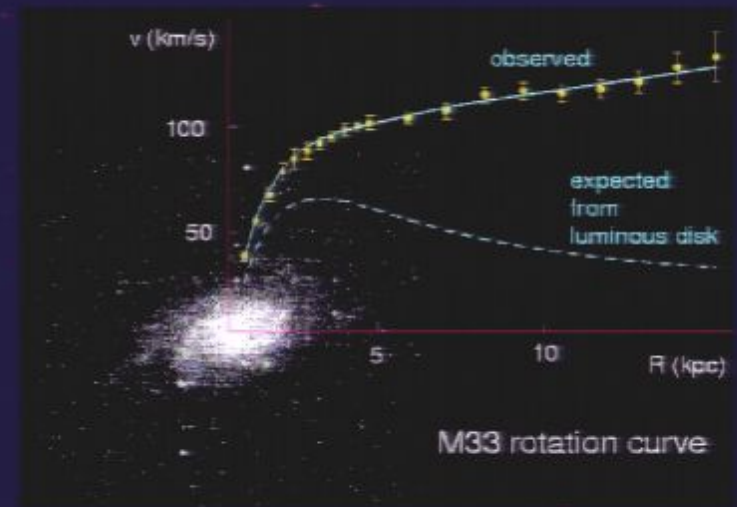
★ Is it physics beyond the **Standard Model of Particle Physics** ?

- Neutrinos, but would not contribute enough
- LSP
- Axions
- Wimpzillas
- Solitons
- Self-interacting dark matter
- Kaluza-Klein dark matter, etc.

Dark Matter

also supported by:

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M. Milgrom, J. Bekenstein

- **MO**dified **N**ewtonian **D**ynamics (MOND)
- **T**ensor **V**ector **S**calar theory (TeVeS)
- Bigravity (Eddington-Born-Infeld gravity)
- ...

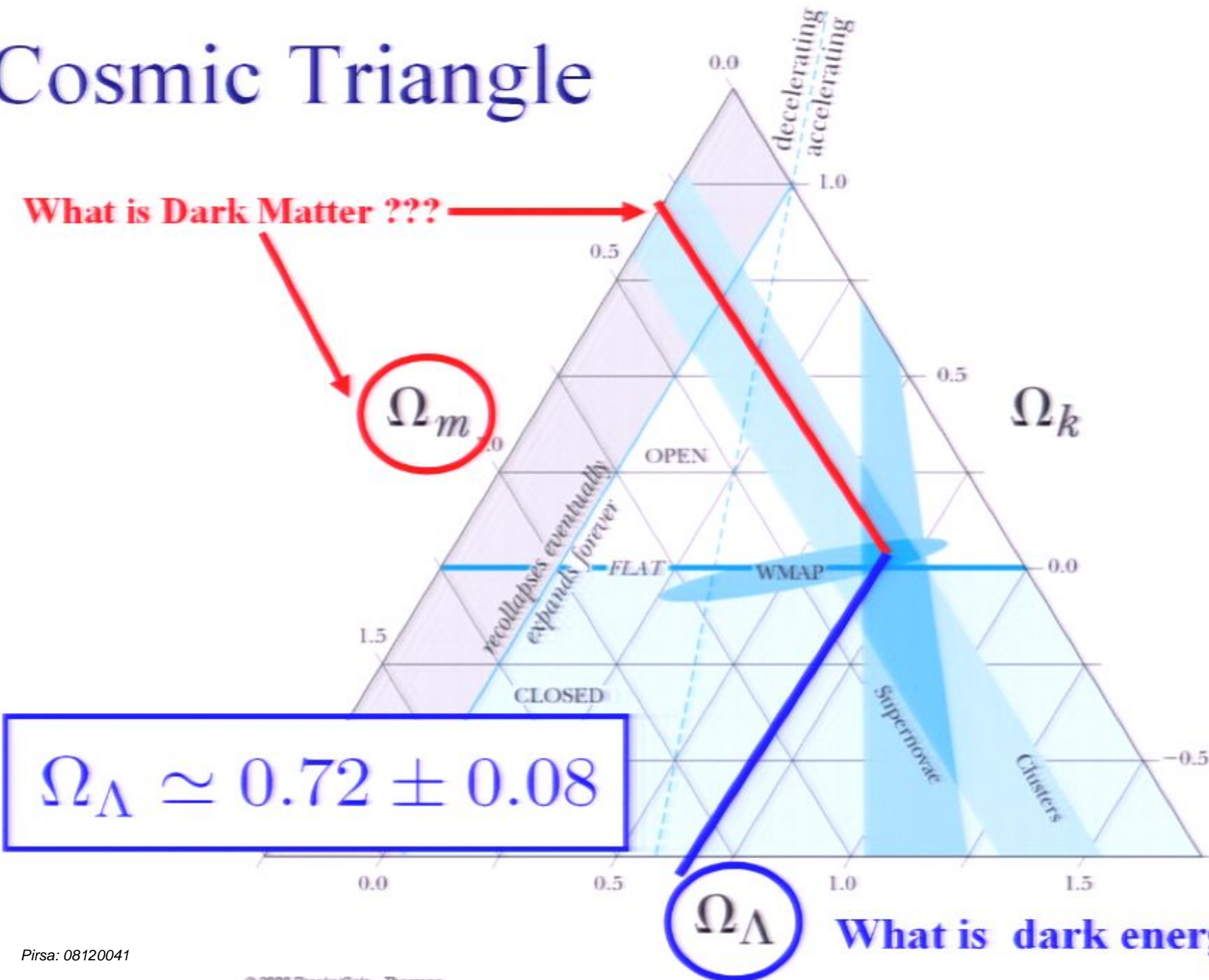
John Moffat

Fabian Schmidt

Constantinos Skordis

Cosmic Triangle

What is Dark Matter ???



What is dark energy ???

Dark Energy

1. “Dynamical solutions”,

The acceleration is driven by another degree of freedom (eg. **scalar field**), eg.

- quintessence tackles the **coincidence problem**
(why is dark energy starting to dominate *now*)
- $f(R)$ gravity

- often requires a hidden fine-tuning
- strong constraints from fifth force experiments

Dark Energy

1. “Dynamical solutions”

2. **Backreaction**

The acceleration is driven by the **inhomogeneities** of the Universe

→ natural explanation to the **coincidence problem**

Dark Energy

1. “Dynamical solutions”,

The acceleration is driven by another degree of freedom (eg. **scalar field**), eg.

- quintessence tackles the **coincidence problem**
(why is dark energy starting to dominate *now*)
- $f(R)$ gravity

- often requires a hidden fine-tuning
- strong constraints from fifth force experiments

Dark Energy

1. “Dynamical solutions”

2. **Backreaction**

The acceleration is driven by the **inhomogeneities** of the Universe

→ natural explanation to the **coincidence problem**

Dark Energy

1. “Dynamical solutions”
2. Backreaction
3. Vacuum Energy

→ face with the **Cosmological Constant Problem**

(why is the vacuum energy 10^{120} times smaller than expected from particle physics)

- **Landscape**: The fundamental theory as a very large number of possible vacua ($\sim 10^{500}$) with with different vacuum energy.

We live in a vacuum with tiny vacuum energy

→ relies on the **anthropic principle**

Niayesh Afshordi
Ghazal Geshnizjani
Justin Khoury
Andrew Tolley
Mark Wyman
Tom Giblin
CdR

Dark Energy

1. “Dynamical solutions”
2. Backreaction
3. Vacuum Energy

→ face with the **Cosmological Constant Problem**

(why is the vacuum energy 10^{120} times smaller than expected from particle physics)

- **Landscape**

- **Degravitation**: The vacuum energy really is that big, but gravitate very weakly on the geometry



gravity should be modified in the Infrared,
theory of massive gravity



No Signal

VGA-1

No Signal

VGA-1

No Signal

VGA-1

No Signal

VGA-1