

# DARK ENERGY OR MODIFIED GRAVITY?

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Moscow, Russia*

*8 June 2011*

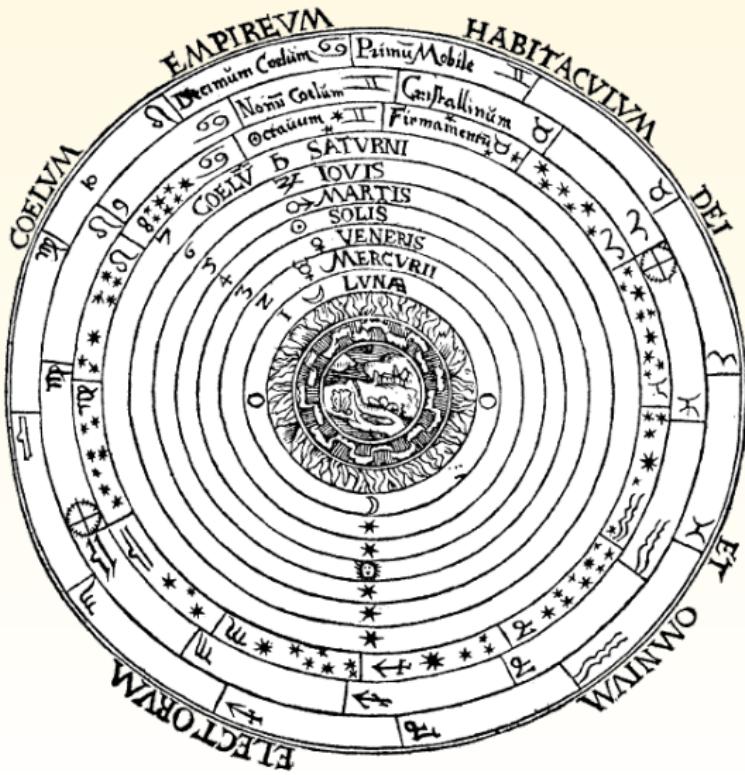
# A SKY ON A STARRY NIGHT...



*photo by Robert Reeves (2006)*

# NOT SO ANCIENT COSMOLOGY: PTOLEMAIC SYSTEM

Schema huius præmissæ diuisionis Sphærarum.



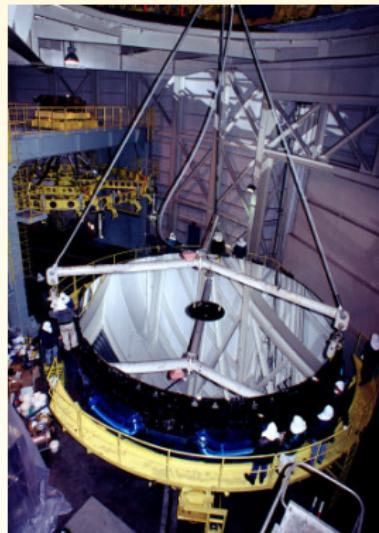
# WE LIVE IN A GOLDEN AGE OF ASTRONOMY!



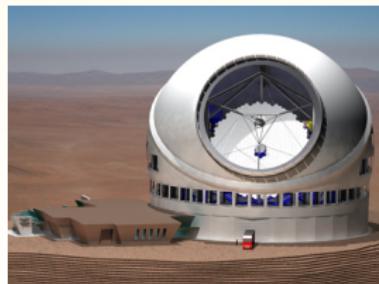
*Keck Telescope*



*Hubble Space Telescope*



*Subaru Primary Mirror*



*Plans for TMT*

# UNIVERSE IS BIG... AND IT IS GETTING BIGGER!



A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY  
AMONG EXTRA-GALACTIC NEBULAE

BY EDWIN HUBBLE

MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON

Communicated January 17, 1929

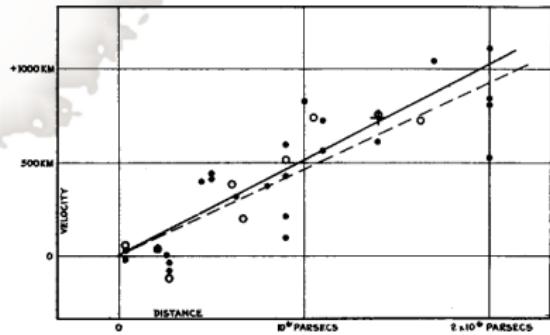


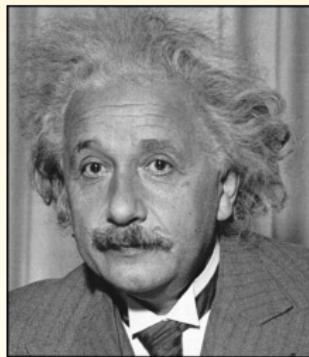
FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Radial velocities, corrected for solar motion, are plotted against distances estimated from involved stars and mean luminosities of nebulae in a cluster. The black discs and full line represent the solution for solar motion using the nebulae individually; the circles and broken line represent the solution combining the nebulae into groups; the cross represents the mean velocity corresponding to the mean distance of 22 nebulae whose distances could not be estimated individually.

# WHY DOES IT EXPAND? GRAVITY IS TO BLAME!

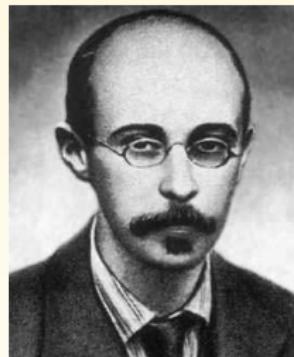
Einstein



de Sitter



Friedmann



Zwicky

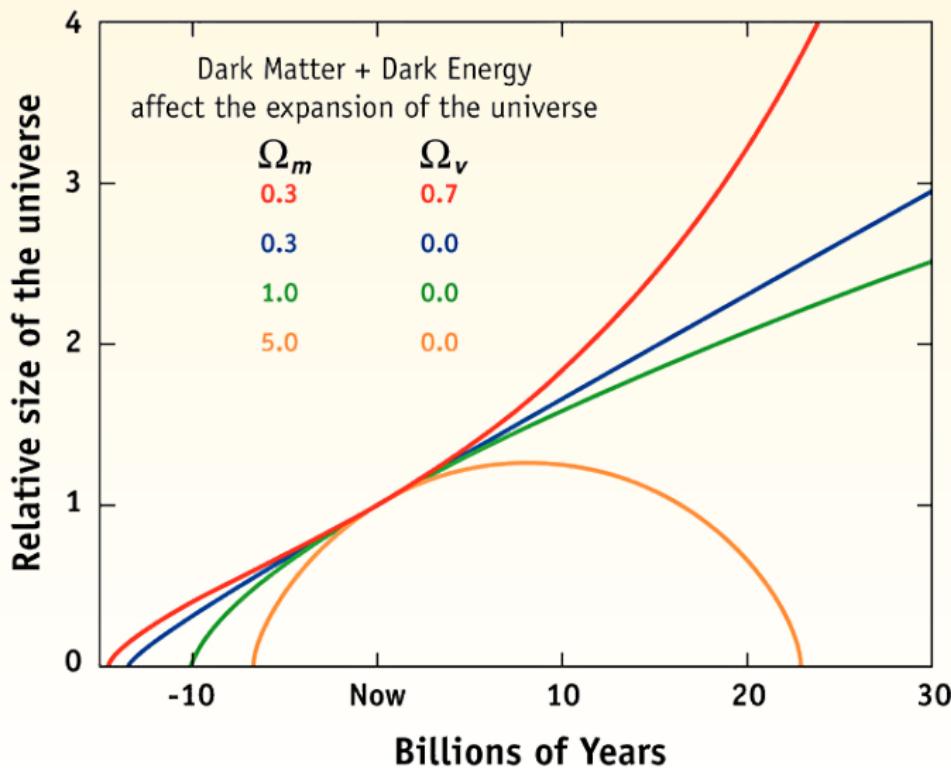


EINSTEIN'S GENERAL RELATIVITY DESCRIBES HOW UNIVERSE EXPANDS

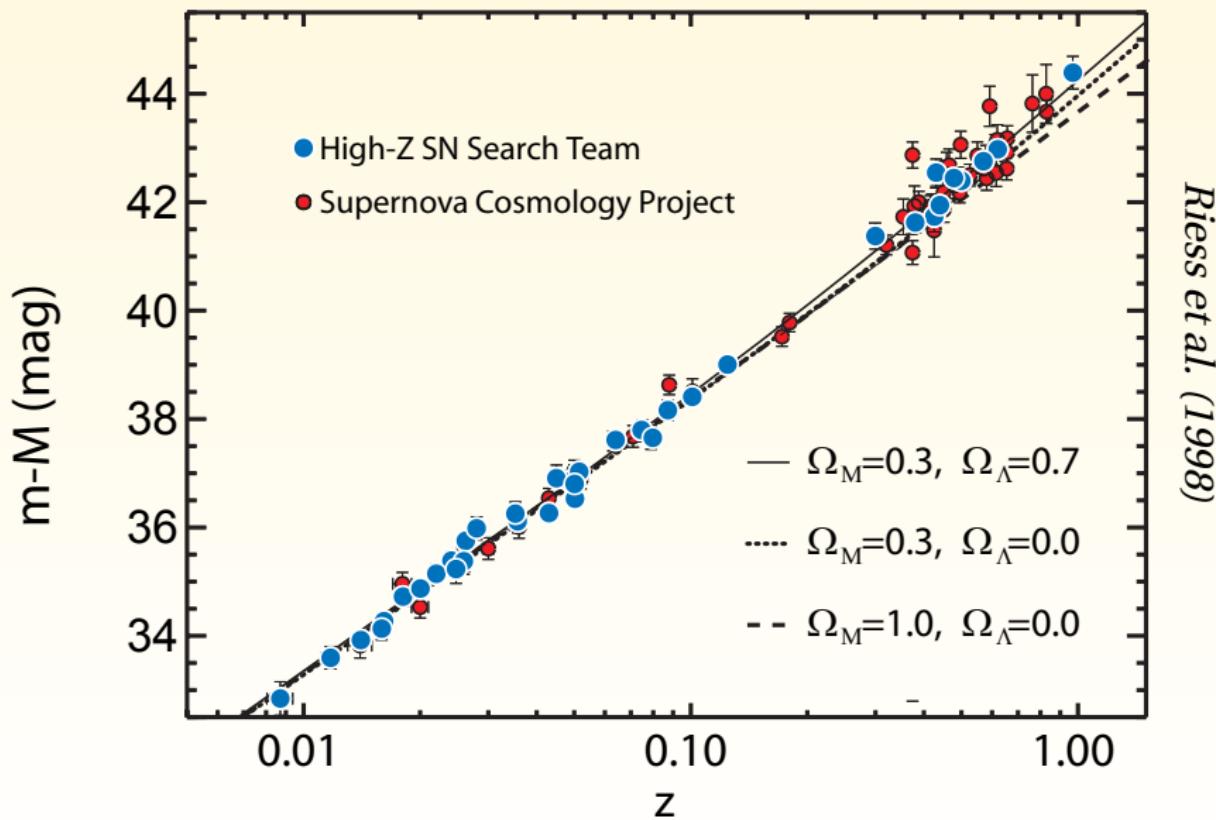
$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \quad \Rightarrow \quad \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3} \rho$$

# UNIVERSE EXPANSION IS DRIVEN BY MATTER

## EXPANSION OF THE UNIVERSE

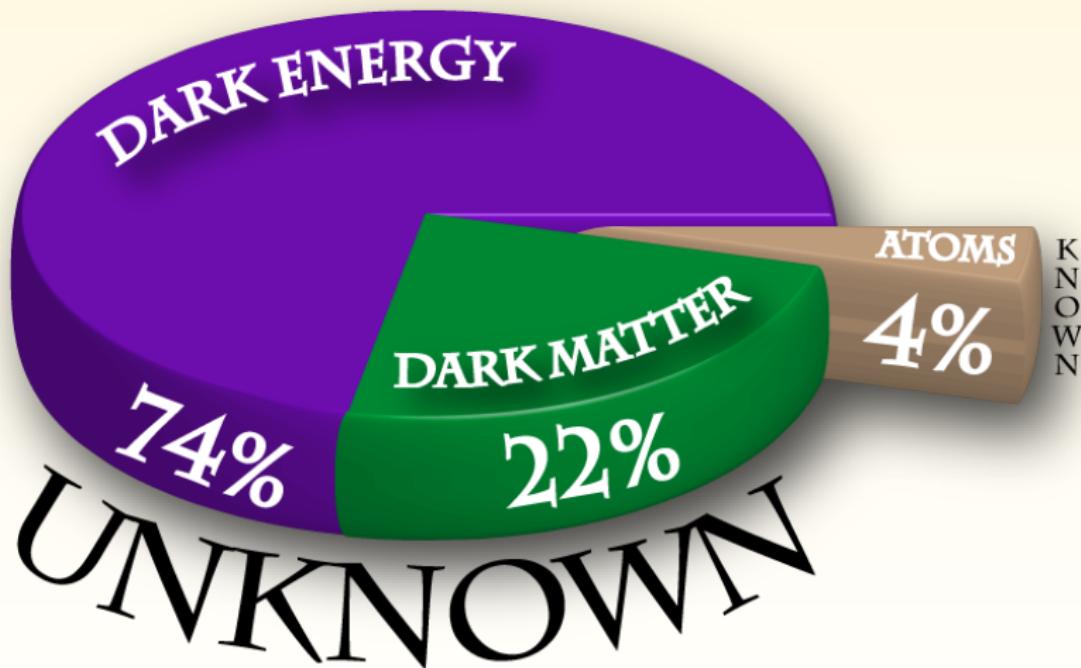


# MEASURE RATE OF EXPANSION VERY ACCURATELY...



Riess et al. (1998)

... AND KNOW WHAT THE UNIVERSE IS MADE OF?



# DARK MATTER: IT'S THERE, WE JUST DON'T SEE IT



Bradac et al. (2006)

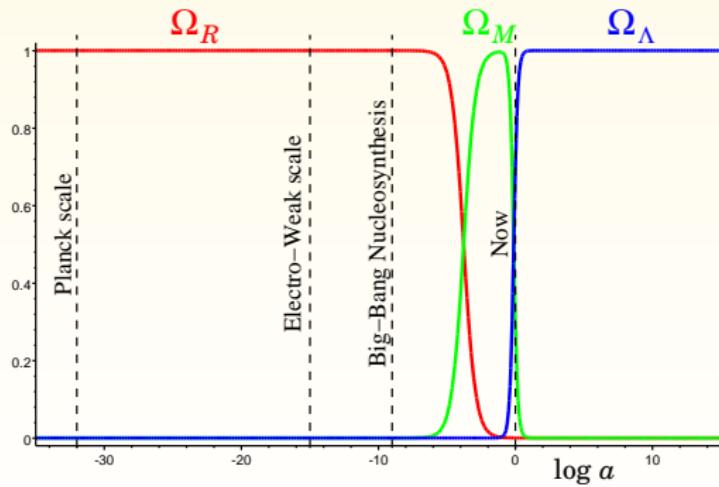
# DARK ENERGY: NO CLUE! JUST PROBLEMS...

## Value problem:

expected  $\rho_\Lambda \sim M_{\text{Pl}}^4$   $\longleftrightarrow 10^{120} \longrightarrow \rho_\Lambda \sim \rho_M \neq 0$  observed

## Coincidence problem:

Now:  $\Omega_\Lambda = 0.7$       Before:  $\rho_\Lambda \propto a^0$        $\Omega_M = 0.3$        $\rho_M \propto a^{-3}$        $\Omega_R = 5 \cdot 10^{-5}$        $\rho_R \propto a^{-4}$



baryons

dark matter

UNKNOWN

dark energy

# MAYBE IT'S GRAVITY WE DON'T UNDERSTAND...

WHAT IF INSTEAD OF CURVATURE IN EINSTEIN-HILBERT ACTION WE HAD

$$S = \int \left\{ \frac{f(R)}{16\pi G} + \mathcal{L}_m \right\} \sqrt{-g} d^4x$$

UV MODIFICATION:

$$f(R) = R + \frac{R^2}{M^2}$$

Starobinsky (1980)

IR MODIFICATION:

$$f(R) = R - \frac{\mu^4}{R}$$

Capozziello et. al. [astro-ph/0303041]

Carroll et. al. [astro-ph/0306438]

FOR F(R) THEORY TO MAKE SENSE WE NEED:

- $f' > 0$  – otherwise gravity is a ghost
- $f'' > 0$  – otherwise gravity is a tachyon

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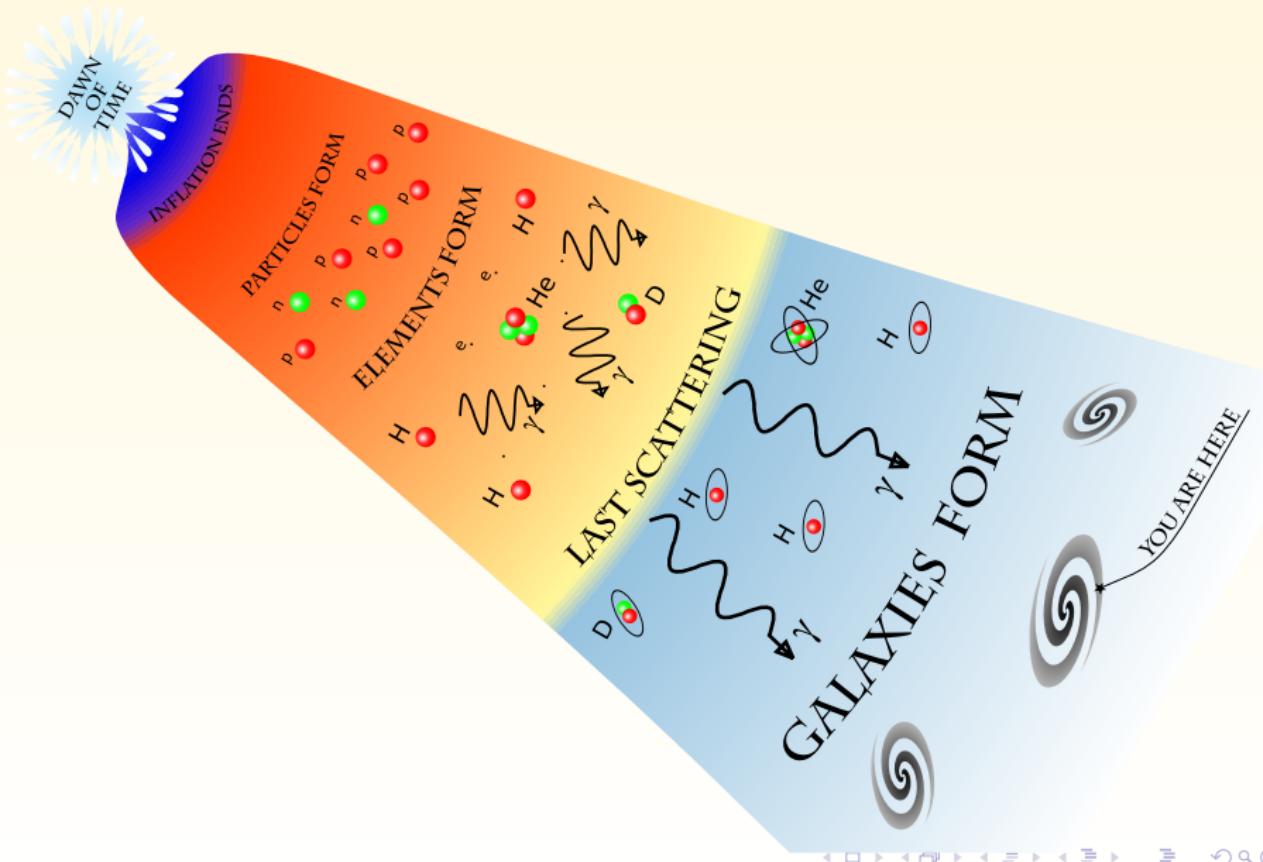
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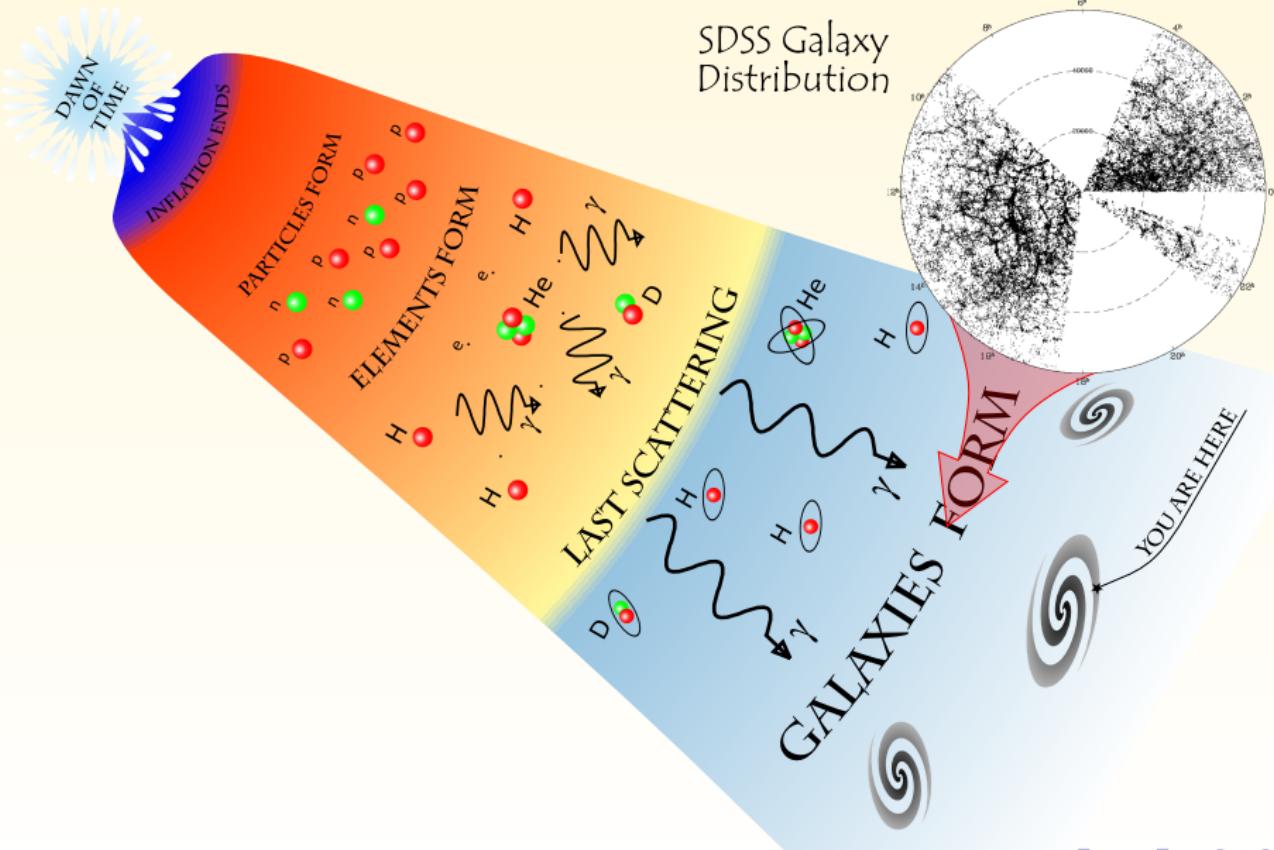
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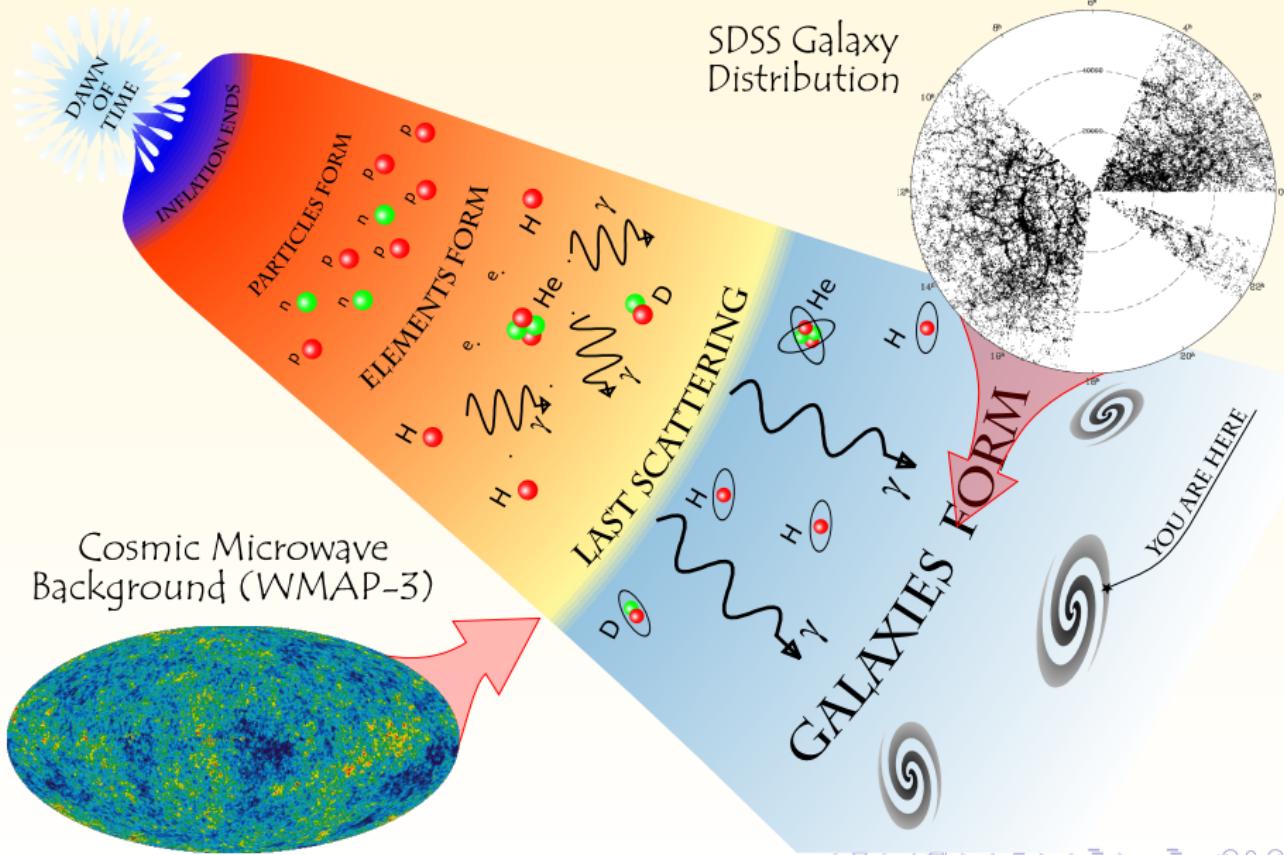
# BRIEF HISTORY OF THE UNIVERSE



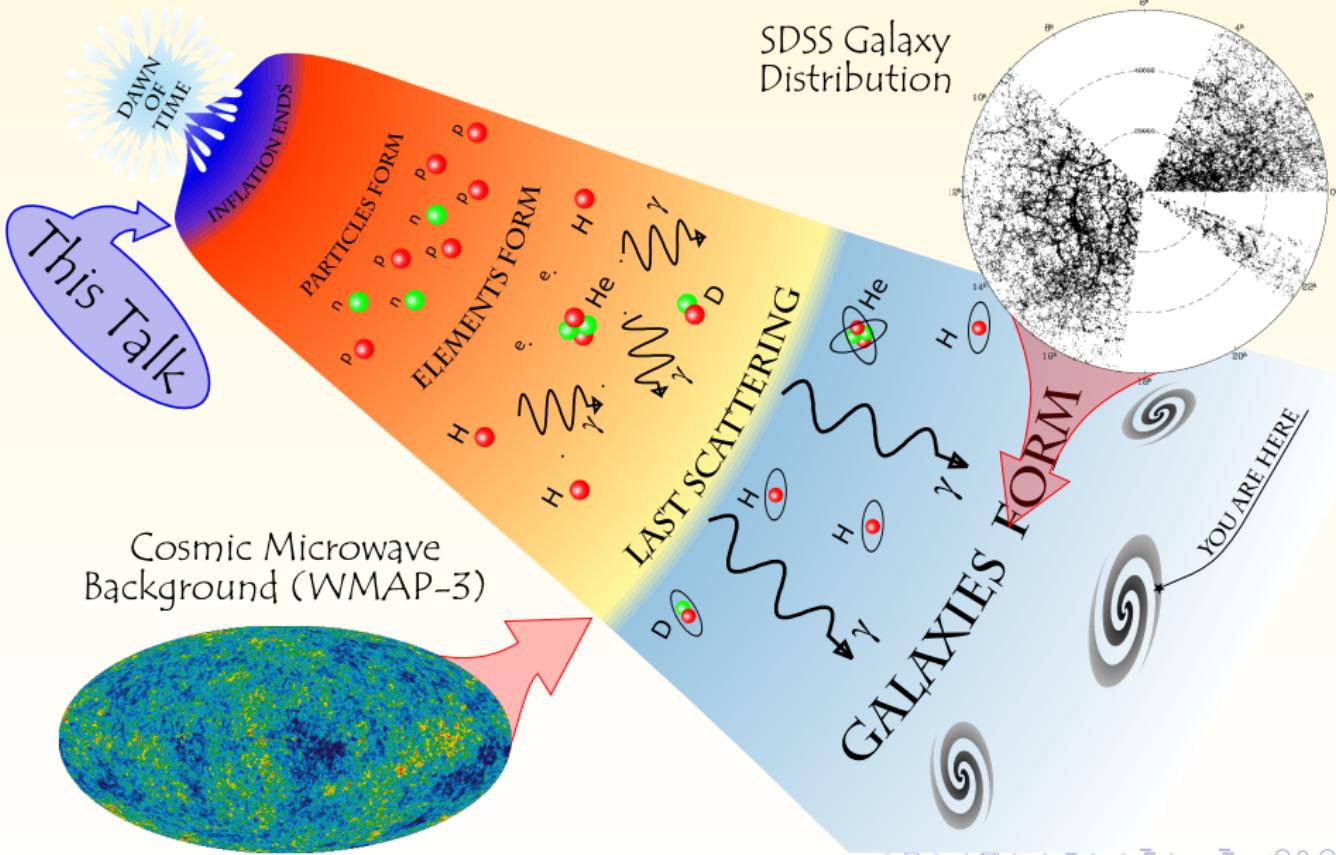
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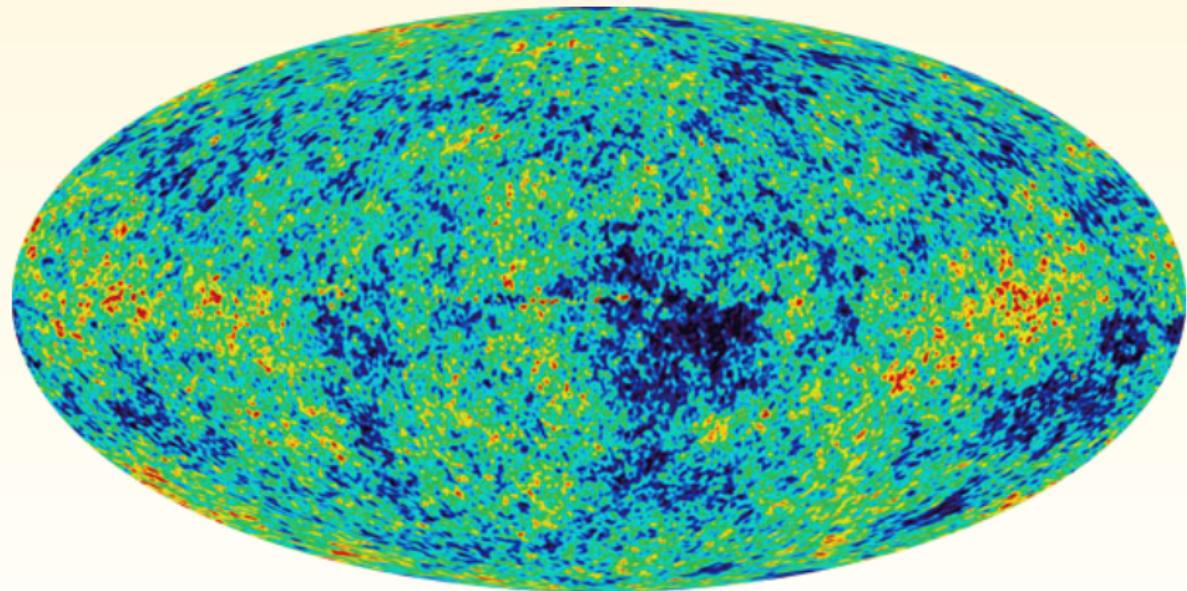
# BRIEF HISTORY OF THE UNIVERSE



# WMAP: A SATELLITE MISSION TO MEASURE CMB

# CMB: LOOKING AS FAR BACK AS WE CAN SEE

# UNIVERSE STARTS OUT VERY HOMOGENEOUS!



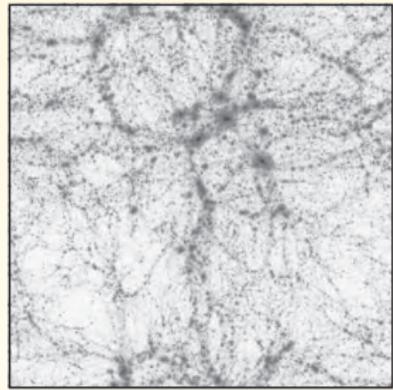
CMB is homogeneous at 10 part per million level!

# GRAVITY MAKES LARGE SCALE STRUCTURE GROW!

# N-BODY SIMULATIONS WITH F(R) DARK ENERGY

density:

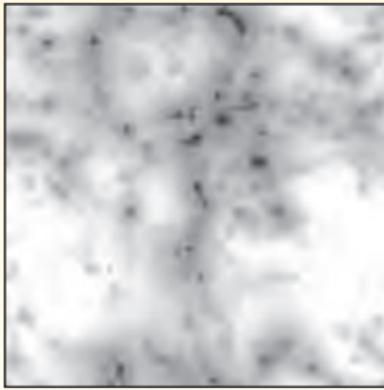
$$\max[\ln(1+\delta)]$$



$$\min[\Psi]$$

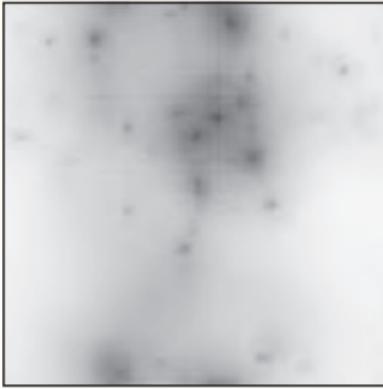
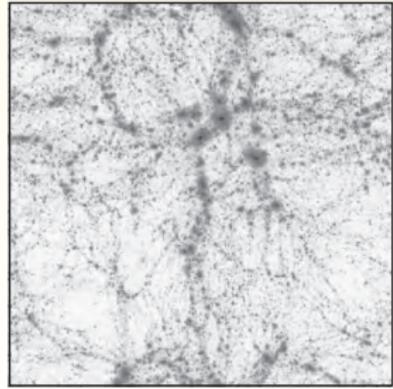


$$\min[f_R/f_{R0}]$$



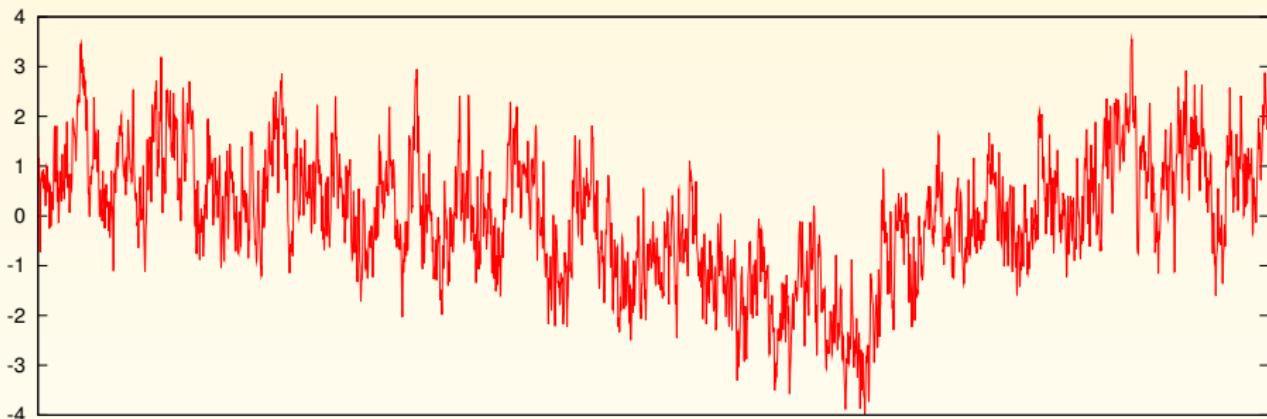
density:

$$\max[\ln(1+\delta)]$$



Oyaizu, Lima & Hu (0807.2462)

# PRESS-SCHECHTER FORMALISM



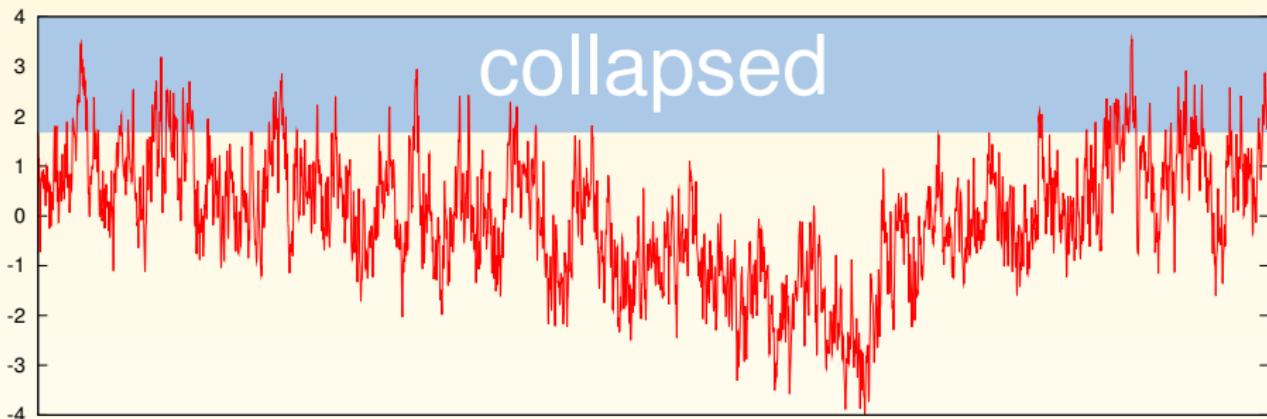
Linear density perturbation are a Gaussian Random Field,  
described by variance  $\sigma^2 \equiv \langle \delta^2 \rangle$  and spectrum  $P(k)$

(above picture shows scale-invariant fluctuations, actual ones have different spectrum)

Overdense regions with  $\delta > \delta_c = \frac{3}{20} (12\pi)^{\frac{2}{3}} \simeq 1.69$  are fully collapsed!

Density distribution is very clumpy, smooth on scale  $R$   
to look for objects of mass  $M = \frac{4\pi}{3} R^3 \bar{\rho}$

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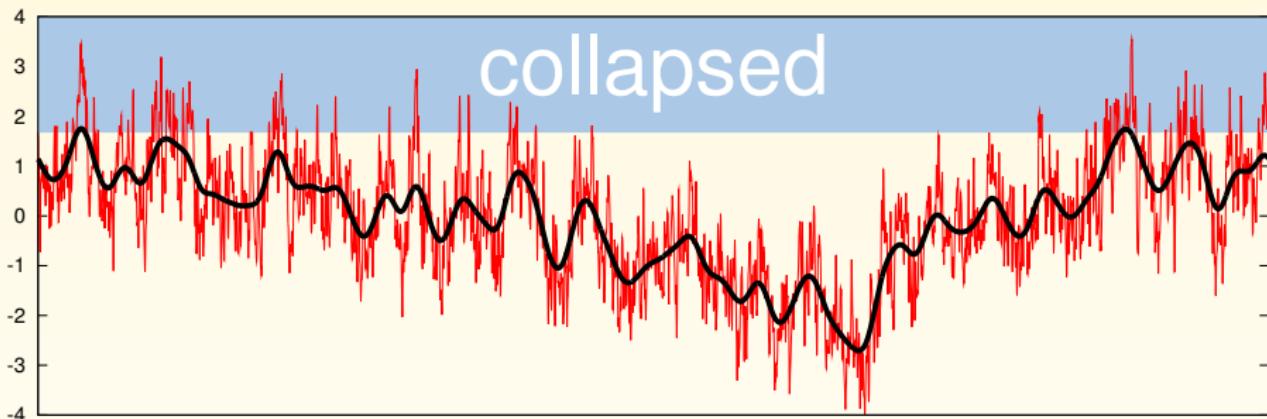
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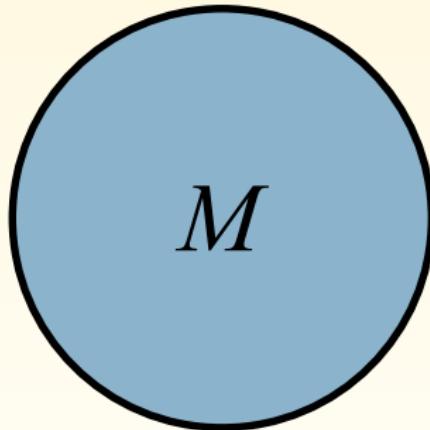
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# WARM-UP: NEWTONIAN COLLAPSE OF A DUST BALL



$$\ddot{r} = -G \frac{M}{r^2}$$

$$E = \frac{\dot{r}^2}{2} - G \frac{M}{r} = \text{const, say} = 0$$

$$\dot{r} = - \left( \frac{r_g}{r} \right)^{\frac{1}{2}}, \quad r_g \equiv 2GM$$

$$\int r^{\frac{1}{2}} dr = - \int r_g^{\frac{1}{2}} dt$$

Outer shell of radius  $r$   
collapses under the  
gravitational pull of  
mass  $M$  in the interior

$$r = \left( \frac{3}{2} r_g^{\frac{1}{2}} (t_* - t) \right)^{\frac{2}{3}}$$

# SPHERICAL SOLUTIONS IN F(R) GRAVITY

We need to solve a non-linear differential equation:

$$\square\phi = -\frac{8\pi}{3} G(\rho - 3p) + V'(\phi)$$

How do we understand its solutions?

“EQUILIBRIUM” REGIME:

$$V'(\phi) = \frac{8\pi}{3} G(\rho - 3p)$$

chameleon mechanism

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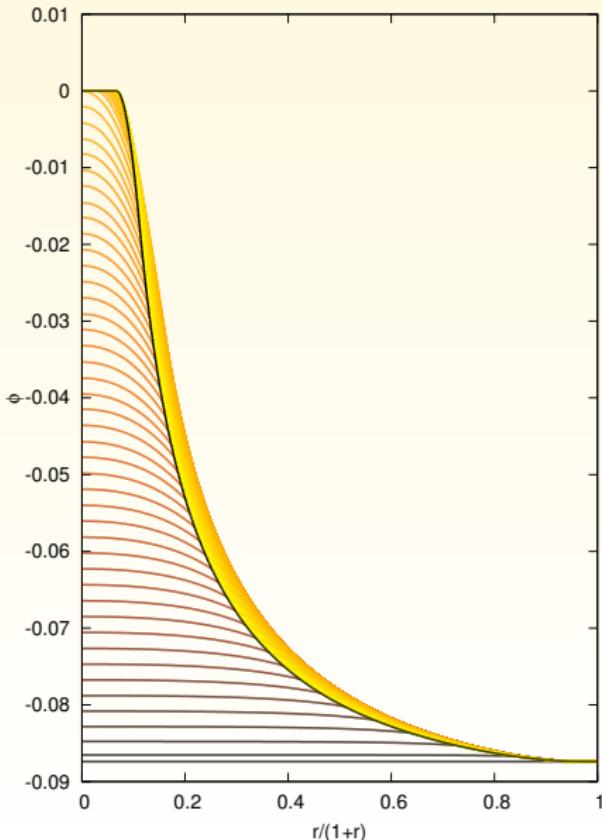
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# QUASI-STATIC BALL COLLAPSE IN F(R) GRAVITY



Potential well of  
a compact object:

$$\Delta\phi = -\frac{8\pi}{3}G\rho + \underbrace{V'(\phi)}_{\text{negligible?}}$$

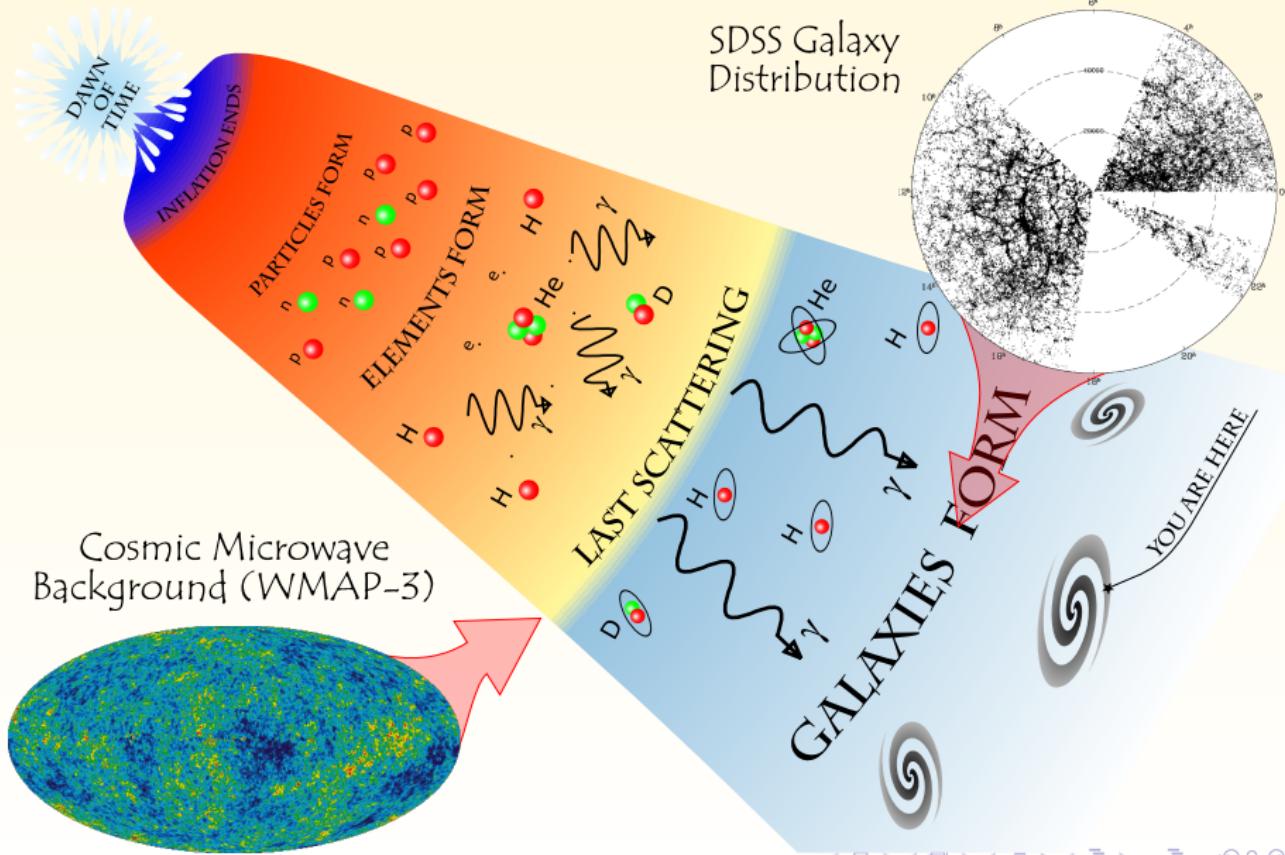
$$\Delta\Phi = 4\pi G\rho$$

Excitations of  $f(R)$  degree of freedom  $\phi$   
and Newtonian potential  $\Phi$  are related:

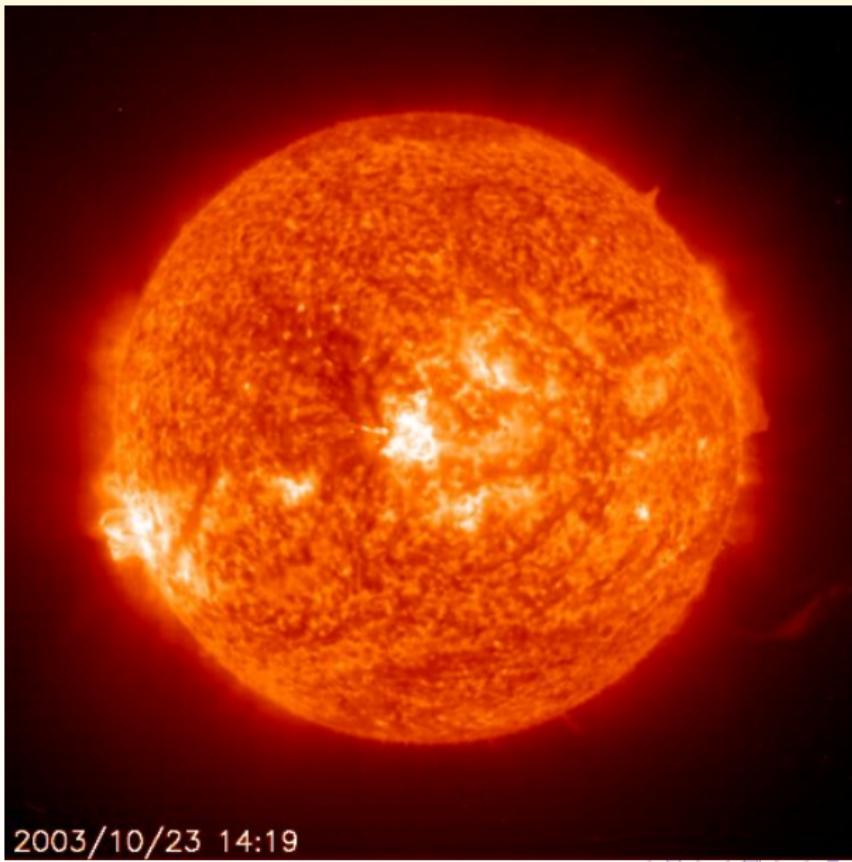
$$\phi \approx \phi_* - \frac{2}{3}\Phi$$

Effective Newton's constant  
changes (non-linearly)!

# BACK TO THE HISTORY OF THE UNIVERSE...



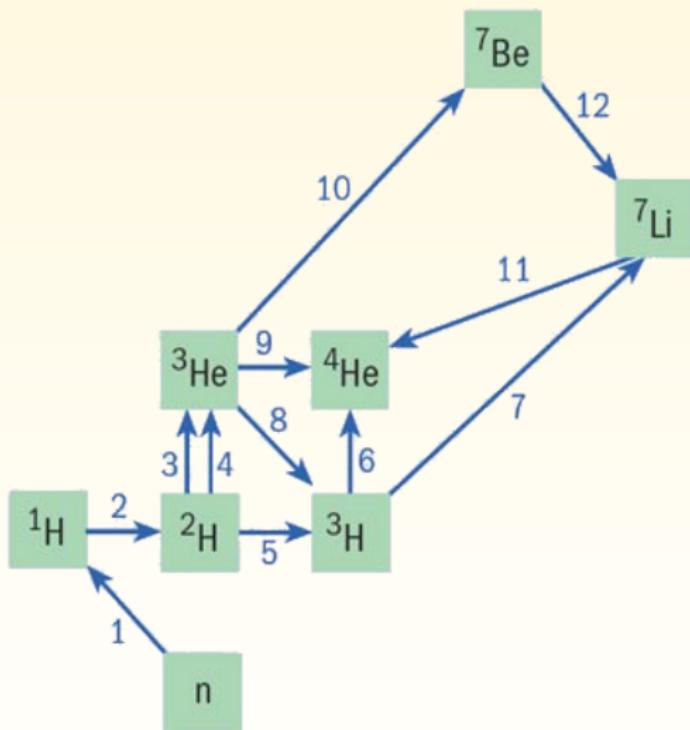
# How Do WE SEE PAST OPAQUE PLASMA?



2003/10/23 14:19

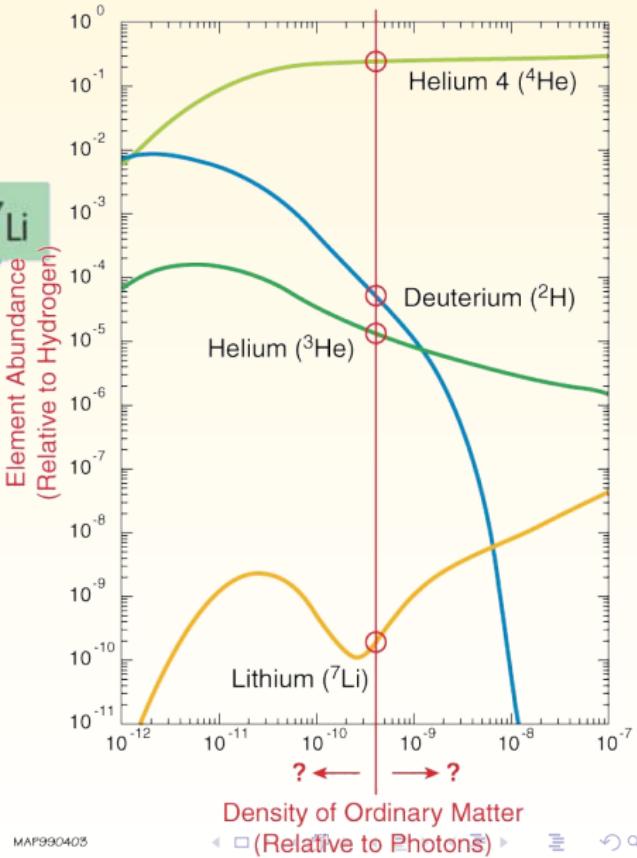
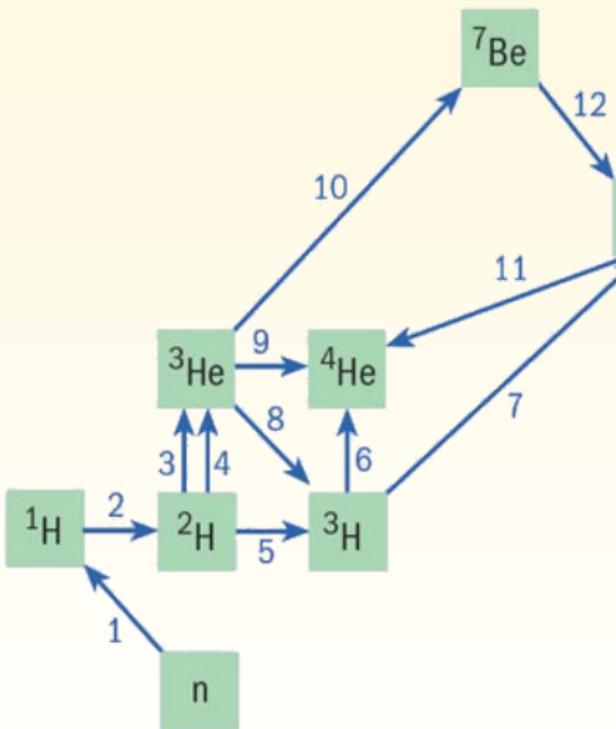


# BIG BANG NUCLEOSYNTHESIS



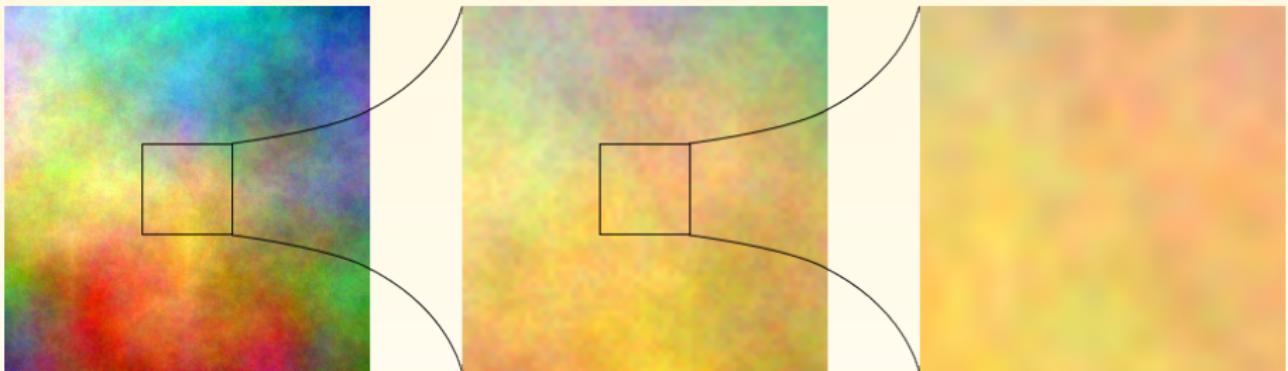
- 1  $n \rightarrow ^1H + e^- + \bar{\nu}$
- 2  $^1H + n \rightarrow ^2H + \gamma$
- 3  $^2H + ^1H \rightarrow ^3He + \gamma$
- 4  $^2H + ^2H \rightarrow ^3He + n$
- 5  $^2H + ^2H \rightarrow ^3H + ^1H$
- 6  $^2H + ^3H \rightarrow ^4He + n$
- 7  $^3H + ^4He \rightarrow ^7Li + \gamma$
- 8  $^3He + n \rightarrow ^3H + ^1H$
- 9  $^3He + ^2H \rightarrow ^4He + ^1H$
- 10  $^3He + ^4He \rightarrow ^7Be + \gamma$
- 11  $^7Li + ^1H \rightarrow ^4He + ^4He$
- 12  $^7Be + n \rightarrow ^7Li + ^1H$

# BIG BANG NUCLEOSYNTHESIS



MAP990403

# INFLATION: AN ANSWER TO COSMIC CONSPIRACY?



inflation wipes the slate clean and re-seeds the structure

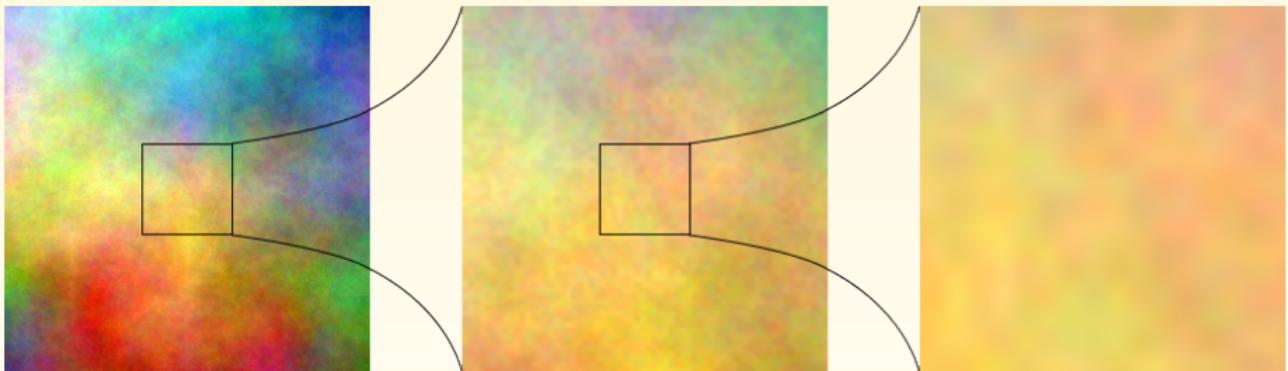
... but inflation has to end eventually!

Inflation  
is cold

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Big Bang  
is hot

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**Inflation  
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# CMB RIPPLES CARRY LOTS OF INFORMATION!

# STILL UNANSWERED: HOW DOES INFLATION END?

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# INSTEAD OF A CONCLUSION

