

# COSMOLOGY 101

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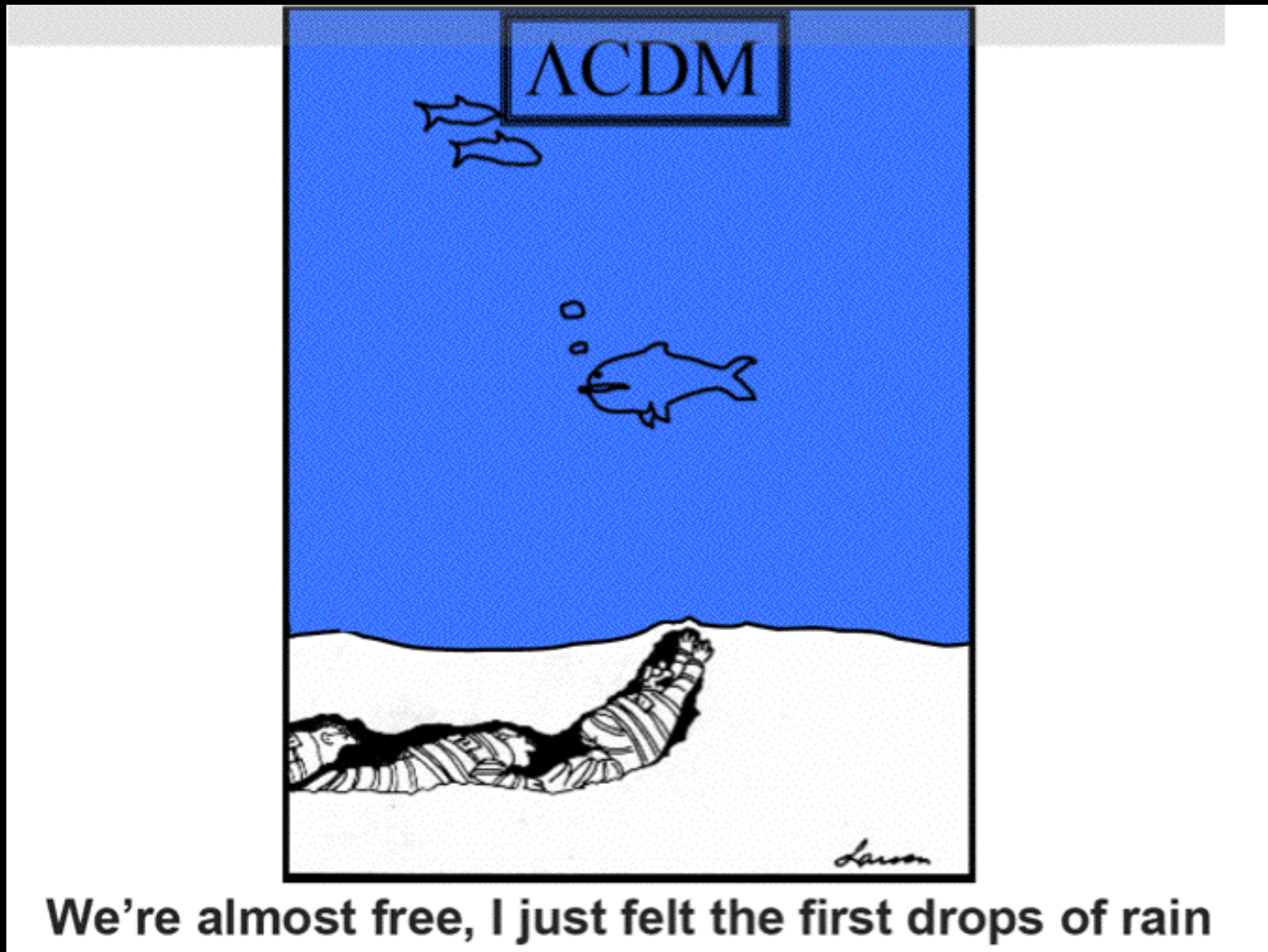
Chris Pearson : RAL Space

October 2015

# COSMOLOGY

- How did the Universe Begin ?
- How old is the Universe ?
- How big is the Universe ?
- Where are we in the Universe ?
- **What is the Universe made of ?**
- Will the Universe end ?

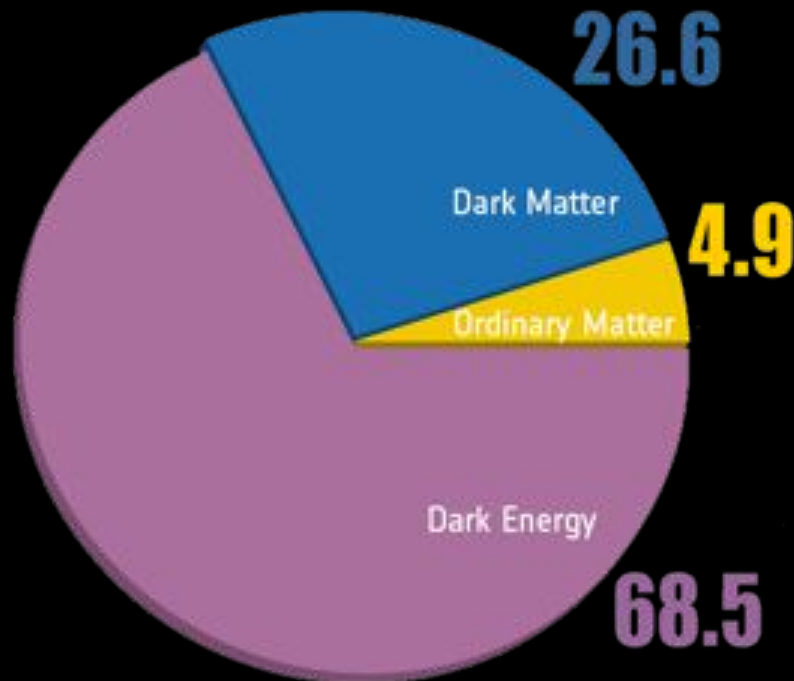
# Just when you thought it was safe ...



We're almost free, I just felt the first drops of rain

# COSMOLOGY

- Our Universe is flat and infinite
- The Universe is expanding
- The expansion of the Universe is accelerating
- The Universe began in a hot Big Bang



$$H_0 = 67.3 \pm 0.012 \text{ km/s/Mpc}$$

$$\tau_{\text{age}} = 13.81 \pm 0.05 \text{ Gyr}$$

$$\Omega_{\Lambda,0} = 0.685 \pm 0.017$$

$$\Omega_{m,0} = 0.315 \pm 0.016$$

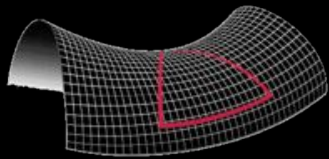
$$\Omega_{\text{DM},0} = 0.2662 \pm 0.016$$

$$\Omega_{b,0} = 0.0487 \pm 0.00027$$

# COSMOLOGY

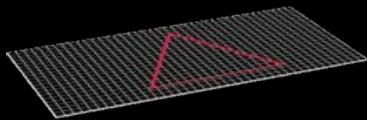
$$\Omega = \frac{\rho}{\rho_{critical}}$$

$$\rho_{critical} \approx 10^{-26} \text{ kg / m}^3$$



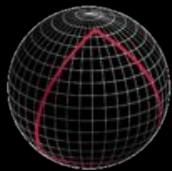
$$\Omega < 1: \rho < \rho_{critical}$$

Universe expands



$$\Omega = 1: \rho = \rho_{critical}$$

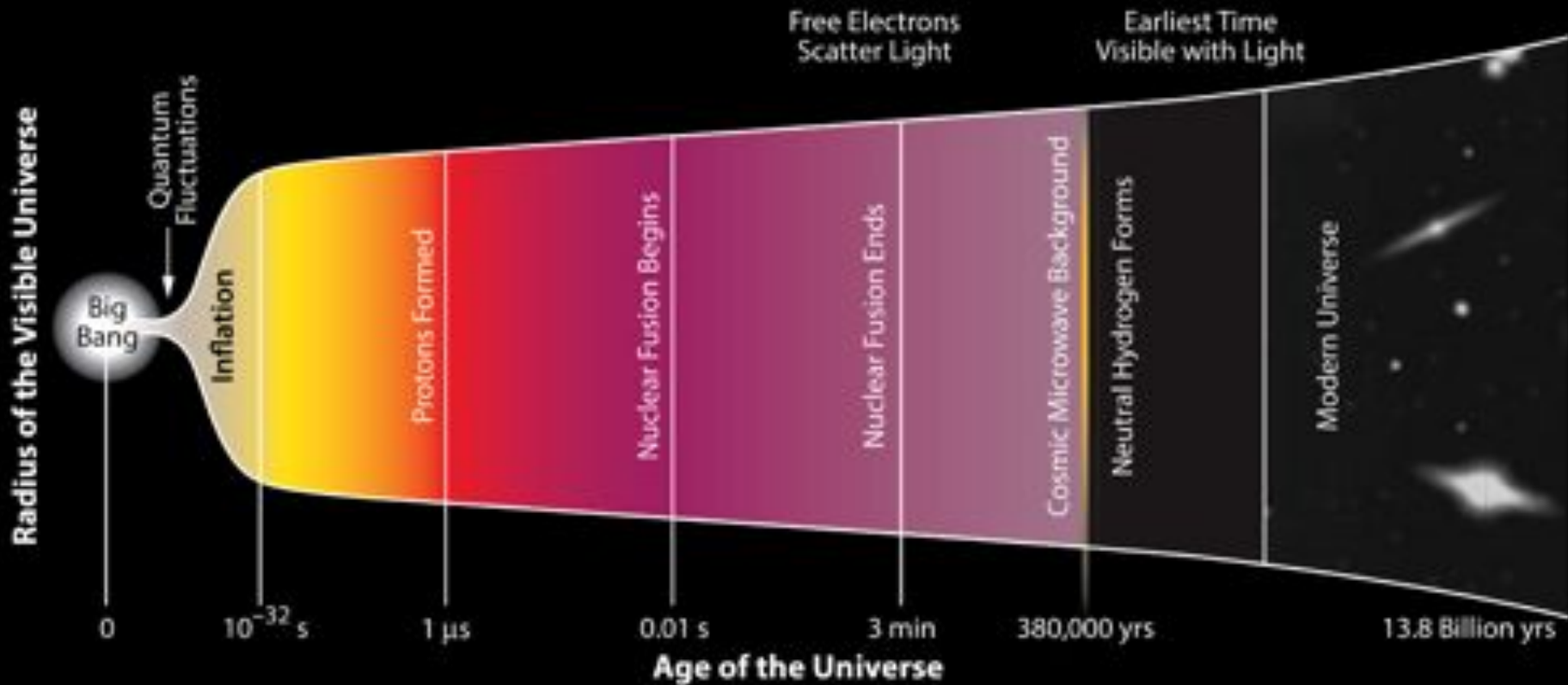
Critical value



$$\Omega > 1: \rho > \rho_{critical}$$

Universe contracts

# A Very Brief History of Time

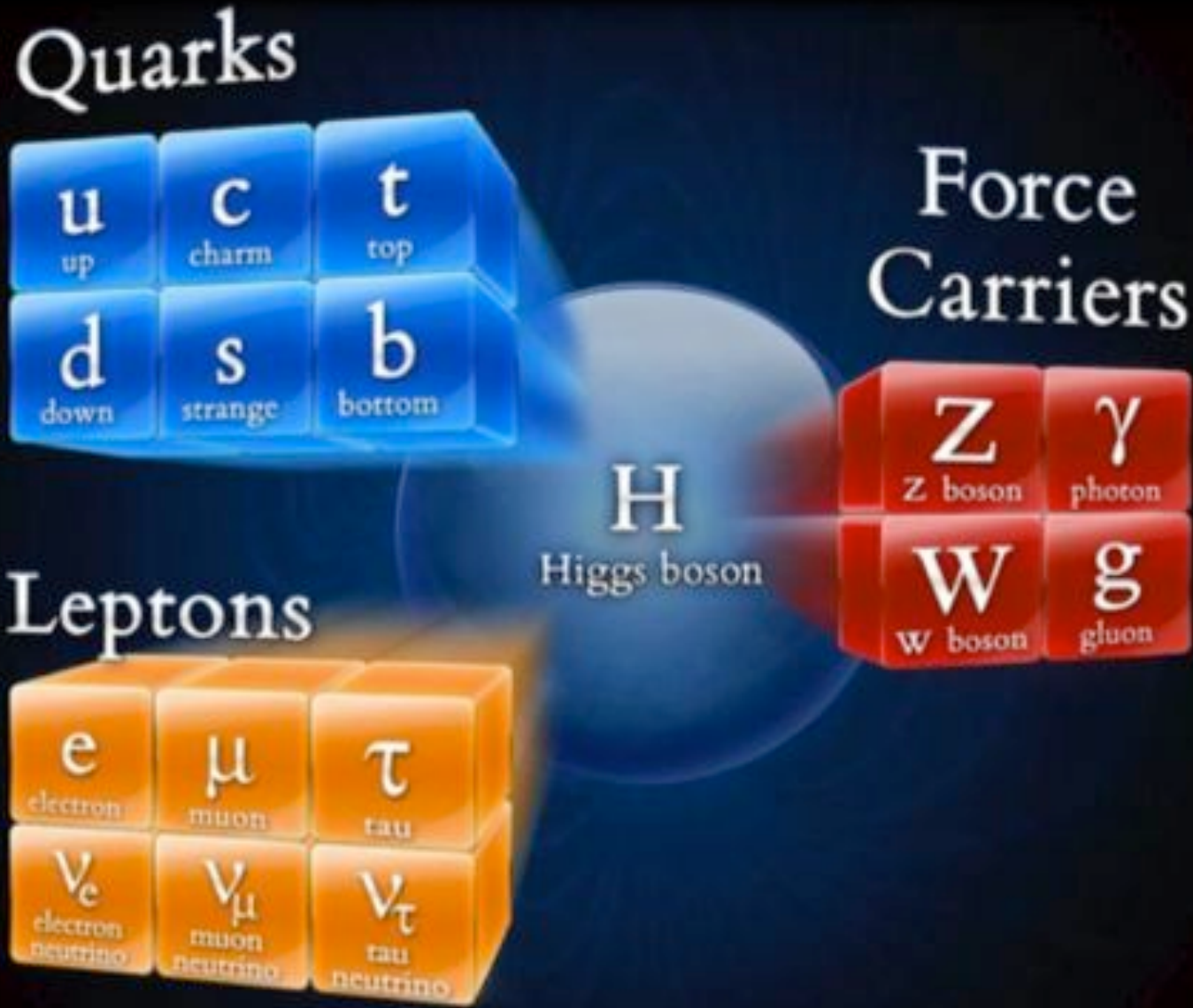


# The Stuff of Stars

Periodic Table of the Elements

1 IA 1A																	18 VIIIA 8A							
1 H Hydrogen 1.008																	2 He Helium 4.003							
3 IIA 2A	4 Li Lithium 6.941	5 Be Beryllium 9.012																	6 B Boron 10.811	7 C Carbon 12.011	8 N Nitrogen 14.007	9 O Oxygen 15.999	10 F Fluorine 18.998	11 Ne Neon 20.180
11 IIIA 3A	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948							
19 IVB 4B	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.63	33 As Arsenic 74.922	34 Se Selenium 78.972	35 Br Bromine 79.904	36 Kr Krypton 83.80							
37 VB 5B	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 101.07	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.757	52 Te Tellurium 127.6	53 I Iodine 126.905	54 Xe Xenon 131.29							
55 VIB 6B	56 Ba Barium 137.327	57-71 Lanthanide Series	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.387	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [209]	85 At Astatine [210]	86 Rn Radon [222]							
87 VIIA 7A	88 Ra Radium 226.025	89-103 Actinide Series	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [277]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [271]	111 Rg Roentgenium [272]	112 Cn Copernicium [285]	113 Uut Ununtrium [288]	114 Fl Flerovium [289]	115 Uup Ununpentium [288]	116 Lv Livermorium [293]	117 Uus Ununseptium [294]	118 Uuo Ununoctium [294]							
Lanthanide Series			57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.25	69 Tm Thulium 168.934	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.967							
Actinide Series			89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.073	97 Bk Berkelium 247.073	98 Cf Californium 251.080	99 Es Einsteinium [252]	100 Fm Fermium [257]	101 Md Mendelevium [258]	102 No Nobelium [259]	103 Lr Lawrencium [260]							

# The Stuff of Stars





# Weighing Up the Universe

- Directly measure what we see
- Measure the starlight from stars
- Assume some Mass/Light (M/L) ratio
- Our Sun  $M/L = 1$
- Local Solar neighbourhood  $M/L \sim 4$
- Corresponds to  $\Omega_* \sim 0.5\%$

# Evidence for Dark Matter

- **Galaxy Clusters**
- **Galaxy Rotation Curves**
- **Gravitational Lensing**
- **Big Bang Nucleosynthesis**
- **Cosmic Microwave Background**

# Evidence: Galaxy Clusters



# Evidence: Galaxy Clusters

Zwicky 1933: Coma Cluster

Virial Theorem to measure mas of astrophysical objects

$$KE = \frac{PE(\Phi)}{2}$$

$$K = \frac{1}{2} \sum_i^N m_i \dot{x}_i^2 = \frac{1}{2} M \langle v^2 \rangle$$

$$\Phi = \frac{-G}{2} \sum_{\substack{i,j \\ i \neq j}}^N \frac{m_i m_j}{|x_i - x_j|} \approx \frac{GM^2}{2R}$$

$$M = \frac{R \langle v^2 \rangle}{G}$$



# Evidence: Galaxy Clusters

Zwicky 1933: Coma Cluster

Radial velocities of cluster members  $\sim 1000 \text{ km s}^{-1}$

$$M = \frac{R \langle v^2 \rangle}{G} \approx 2 \times 10^{15} M_{\text{sun}}$$

Total Mass in Stars:  $M_{*} \sim 3 \times 10^{13} M_{\text{solar}}$

Total Mass in Gas:  $M_{\text{gas}} \sim 20 \times 10^{13} M_{\text{solar}}$

Not enough matter in luminous form

⇒ Cluster should be *flying apart* !!

Required “*dunkle materie*”



# Evidence: Galaxy Clusters



# Evidence: Galaxy Clusters



# Evidence: Galaxy Clusters



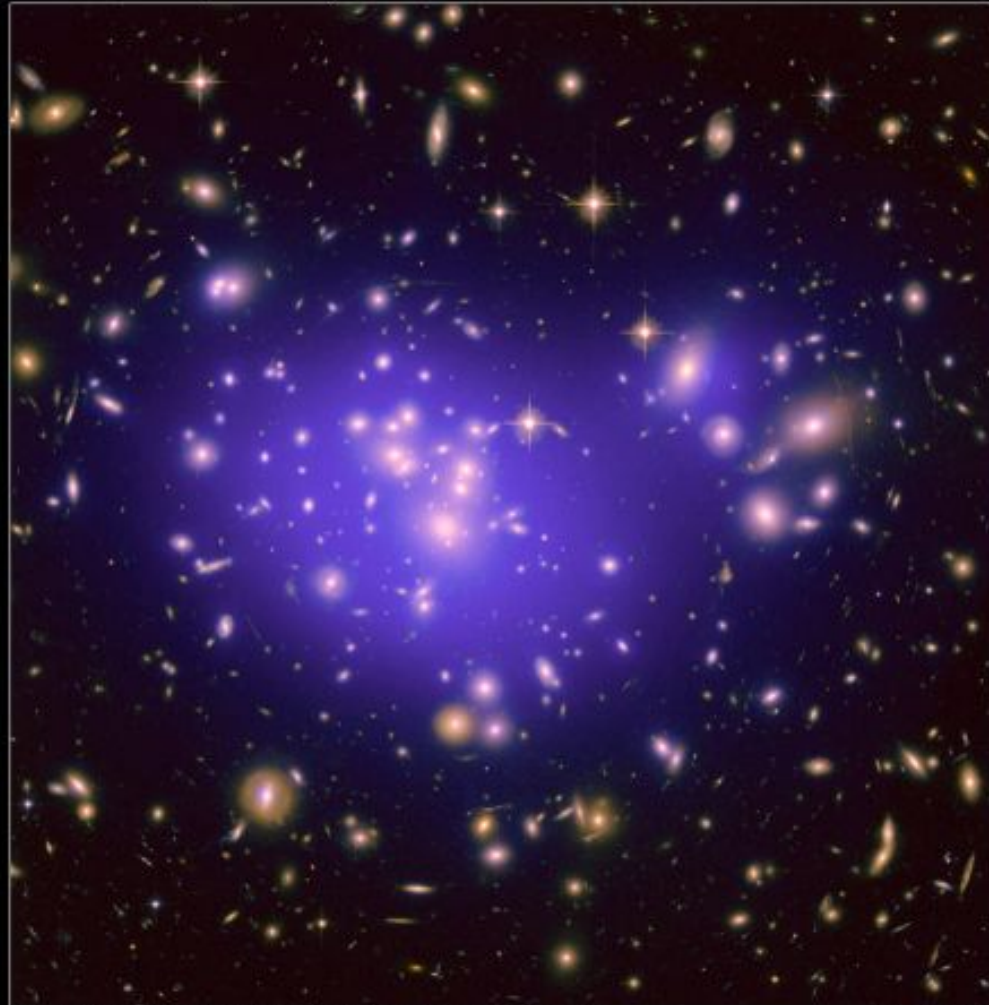


# Evidence: Galaxy Clusters

$$\Omega_{\text{clusters}} \approx 0.2 \quad (\Omega_{\text{hot gas}} \approx 0.02)$$

Dark Matter Map in Galaxy Cluster Abell 1689

HST ACS/WFC



NASA, ESA, E. Jullo (Jet Propulsion Laboratory), P. Natarajan (Yale University),  
and J.-P. Kneib (Laboratoire d'Astrophysique de Marseille, CNRS, France)

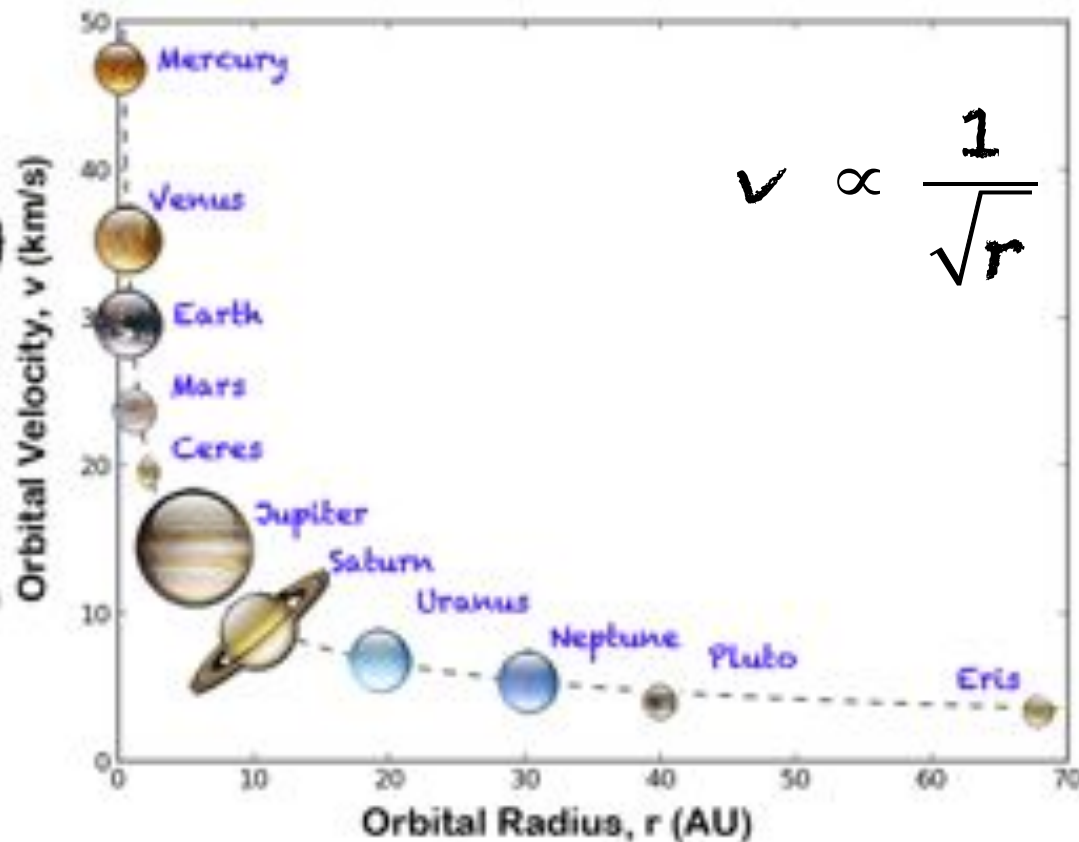
STScI-PRC10-28

# Evidence: Galaxy Rotation

Kepler's 3<sup>rd</sup> Law of Planetary Motion:

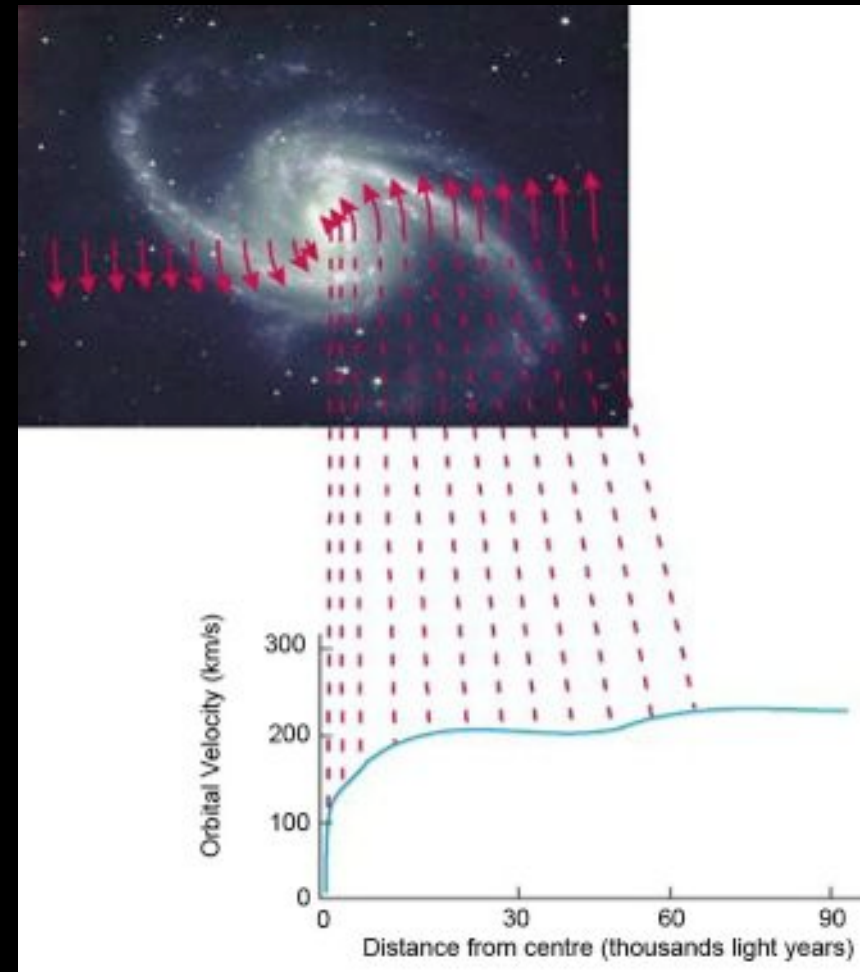
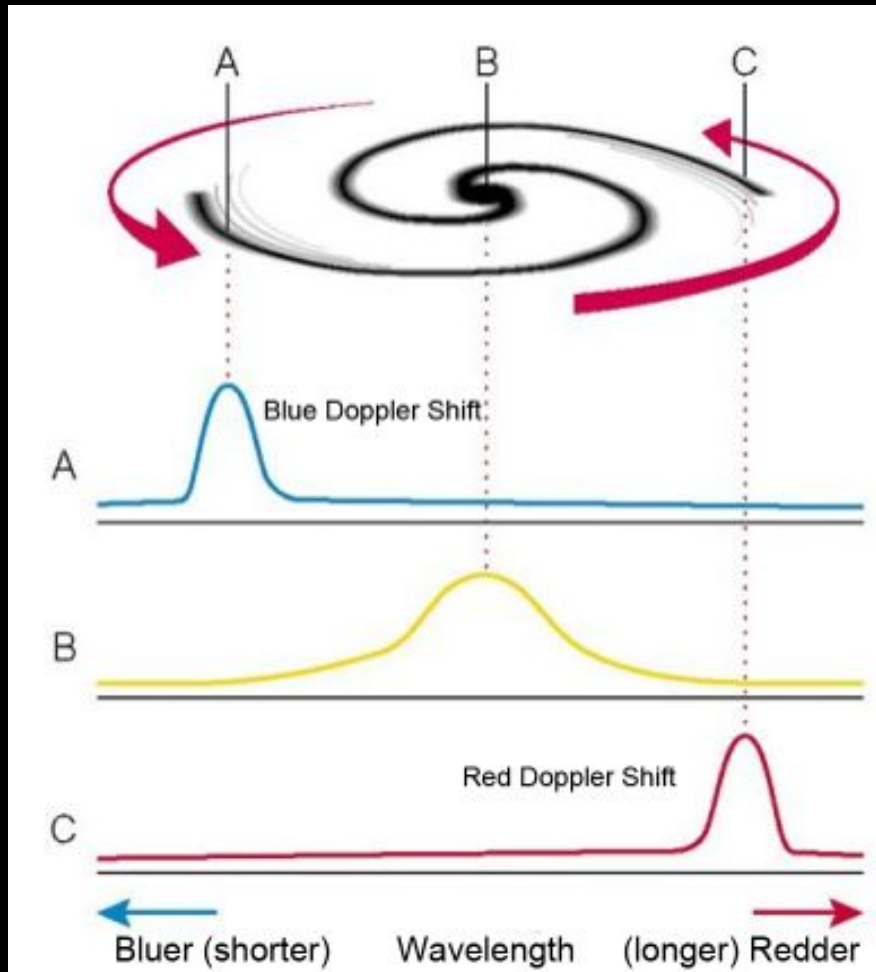
Orbital velocity is proportional to inverse square root of the distance

$$F = \frac{GMm}{r^2} = \frac{mv^2}{r} \Rightarrow v \propto r^{-1/2}$$



# Evidence: Galaxy Rotation

How do we weigh galaxies ?

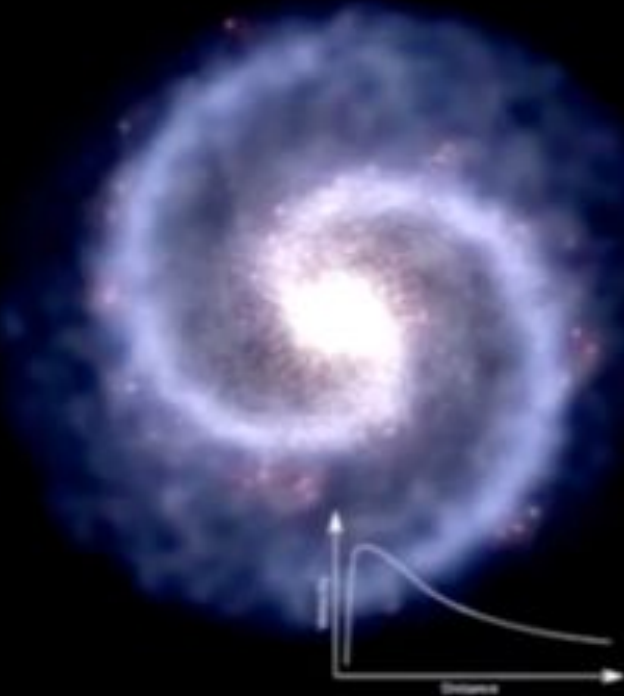


# Evidence: Galaxy Rotation

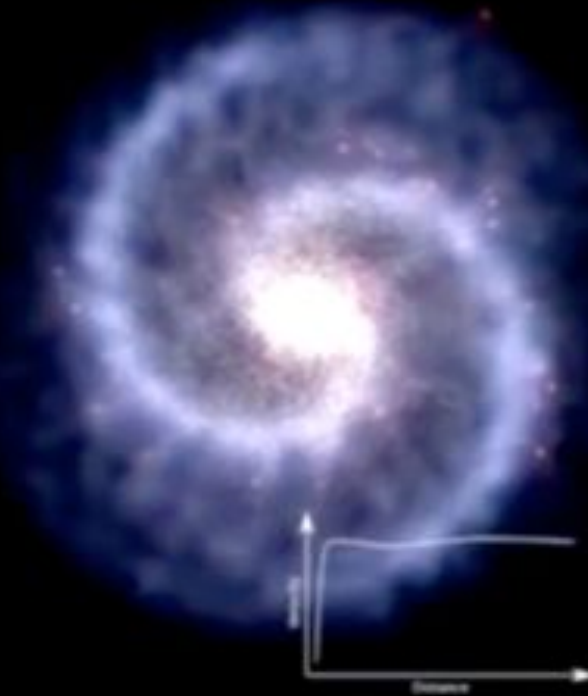
Rubin 1970s : Galaxy Rotation Curves



# Evidence: Galaxy Rotation



Galaxy Without Dark Matter



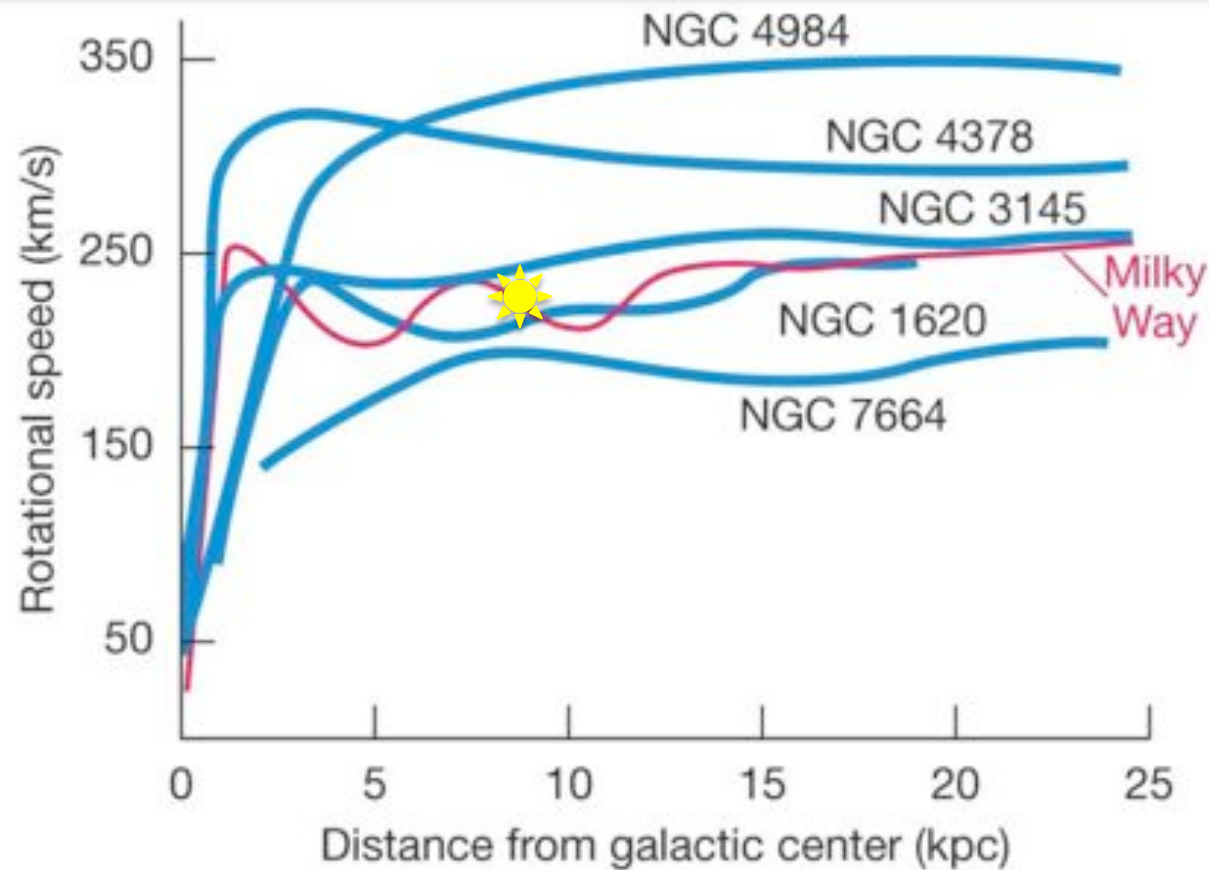
Galaxy With Dark Matter

# Evidence: Galaxy Rotation

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# Evidence: Galaxy Rotation

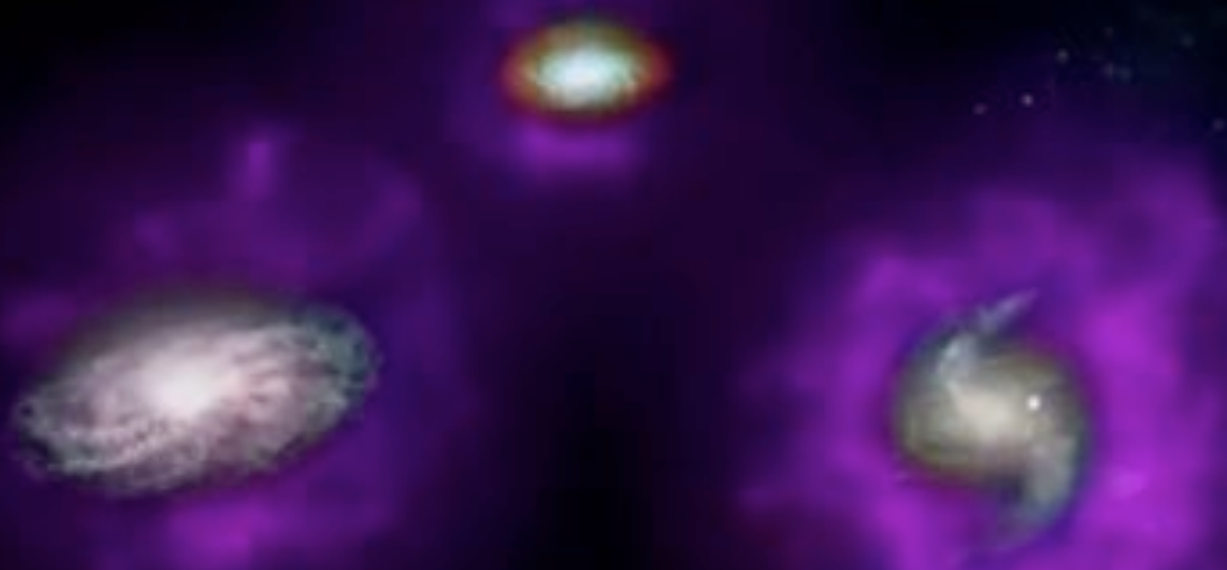
The Milky Way is surrounded by an enormous halo of nonluminous (dark) matter!



Luminous matter is concentrated at the center

# Evidence: Galaxy Rotation

The Problem of **MISSING MASS**  $\Rightarrow$  Giant Dark Spherical Halos



$$\Omega_{\text{halo}} \approx 0.08 - 0.16$$

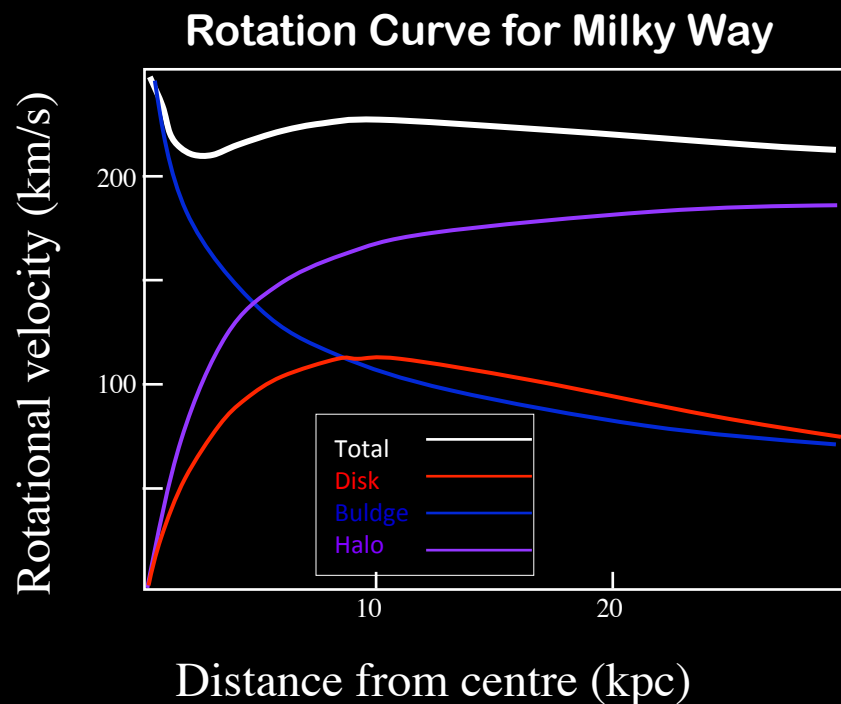


# Evidence: Galaxy Rotation

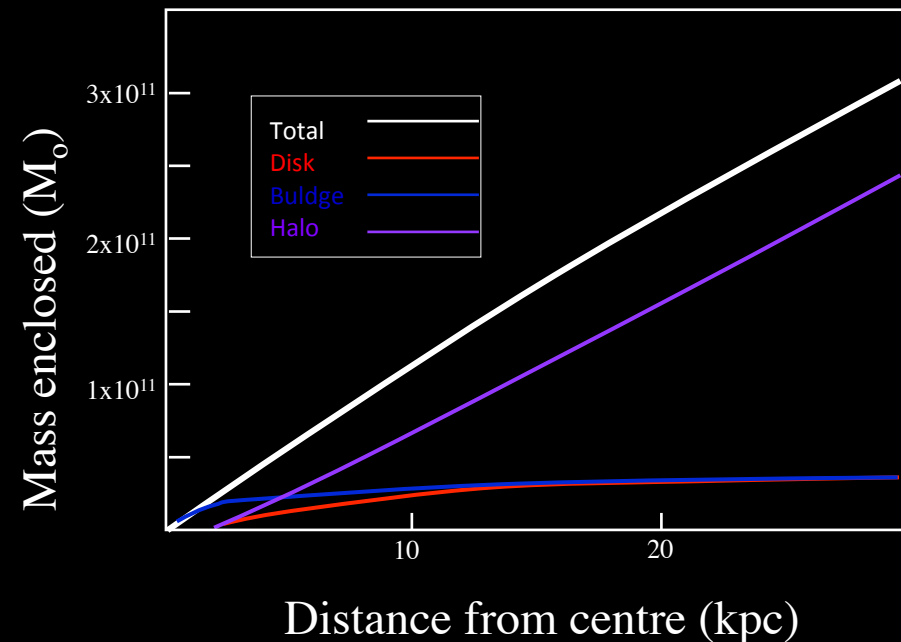
The Problem of **MISSING MASS ?**  $\Rightarrow$  rather **MISSING LIGHT !**

## Galaxy Rotation Curve

- The Disk Component
- The Buldge (+ stellar halo) Component
- Dark Matter Halo Component



## Mass Enclosed with distance for Milky Way



# Evidence: Gravitational MicroLensing

Searching for Dark Matter in the Galaxy Halo: **MA**ssive **C**ompact **H**alo **O**bject**S**

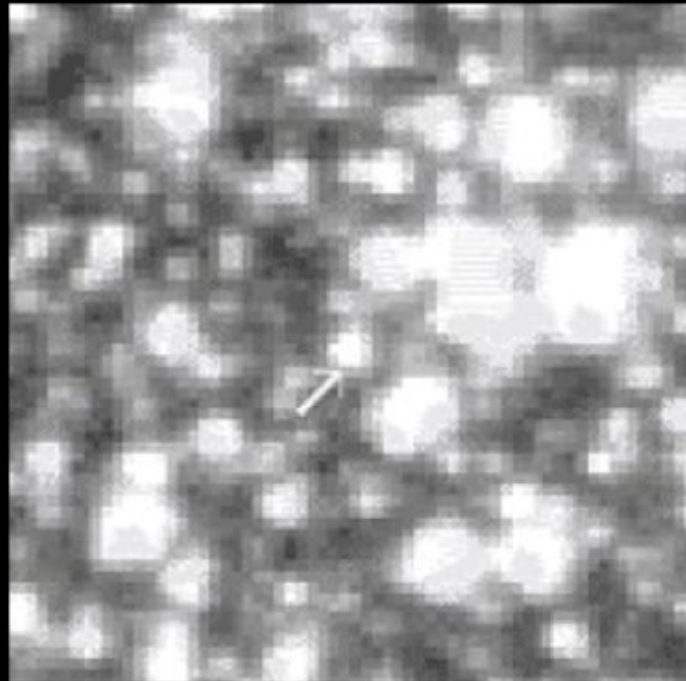


# Evidence: Gravitational MicroLensing

Searching for Dark Matter in the Galaxy Halo: **MA**ssive **C**ompact **H**alo **O**bject**S**



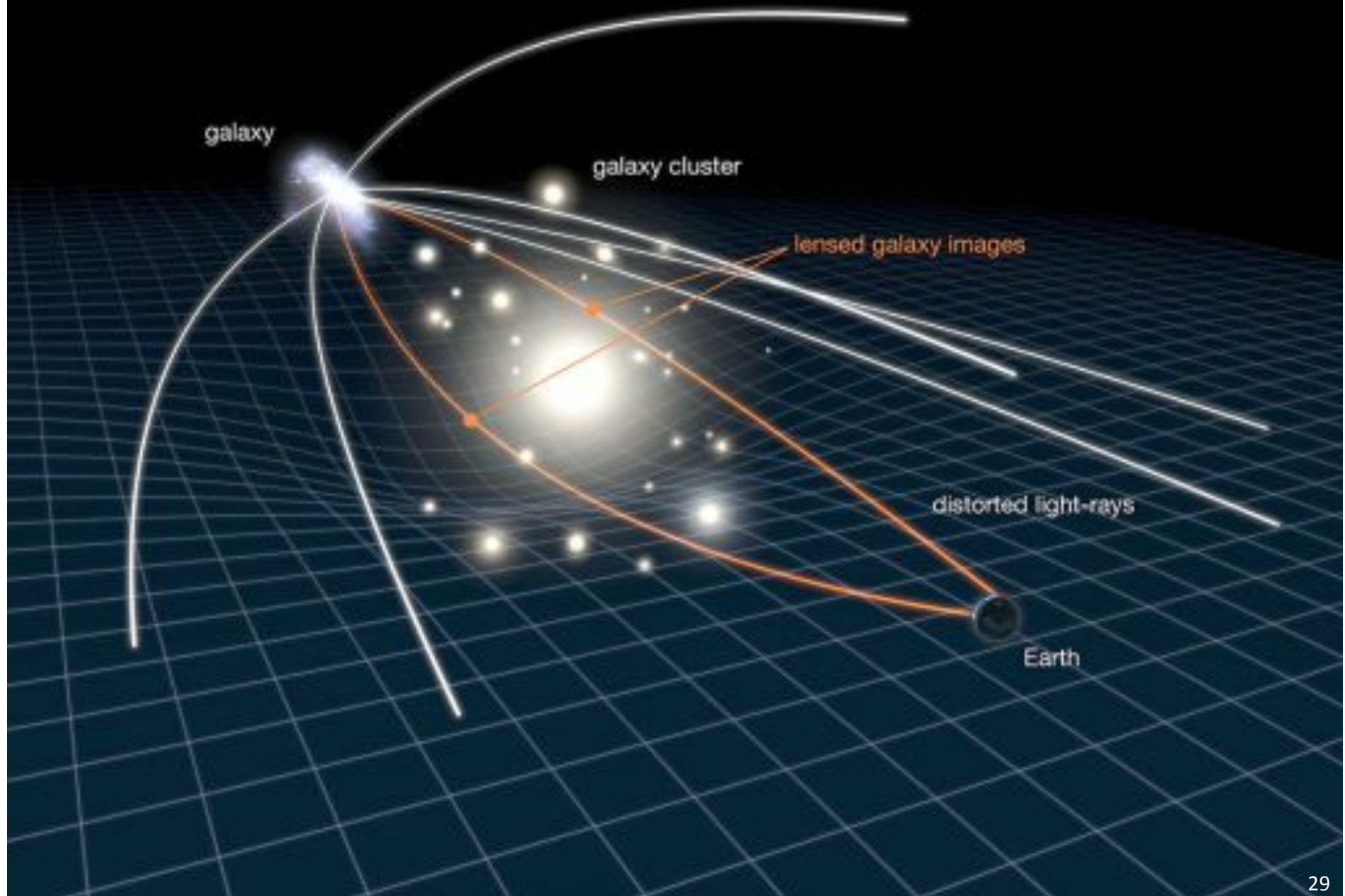
Observe amplification (brightening) of background star/galaxy as it is focused by halo object



# Mapping the Dark Matter: Gravitational Lensing

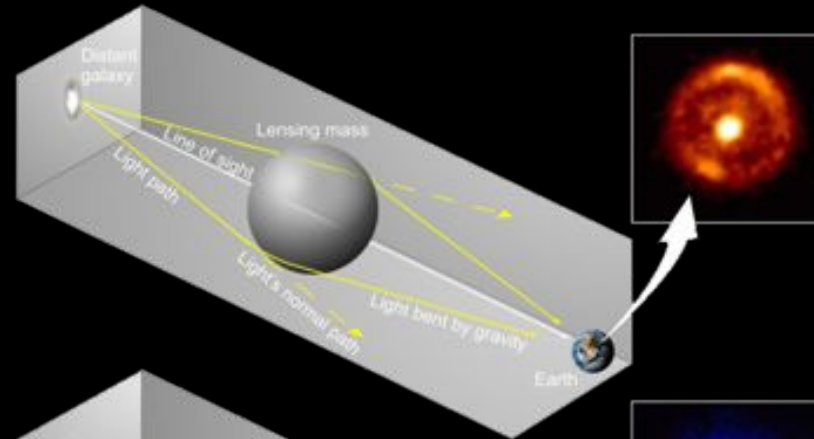


# Mapping the Dark Matter: Gravitational Lensing

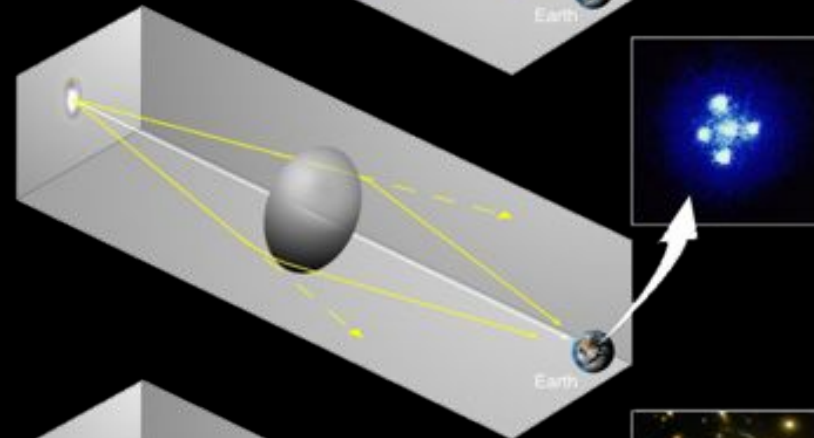


# Mapping the Dark Matter: Gravitational Lensing

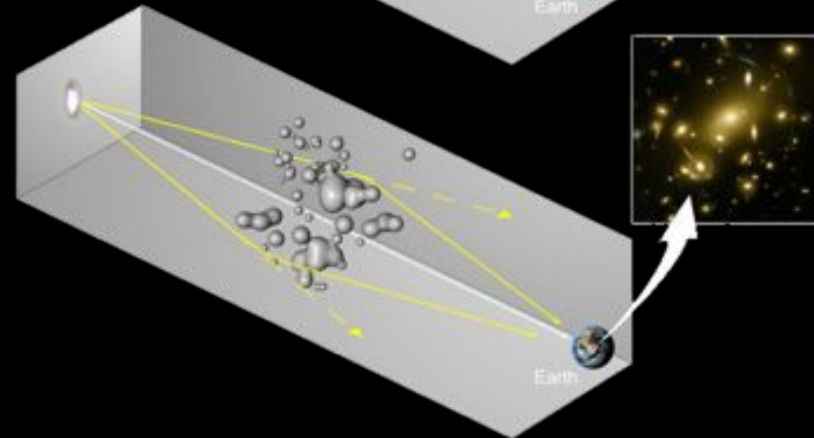
Spherical Lens: Einstein Ring



Oblate Lens: Einstein Cross



Clumpy Lens: Giant Arcs



# Mapping the Dark Matter: Gravitational Lensing

## Spherical Lens: Einstein Ring

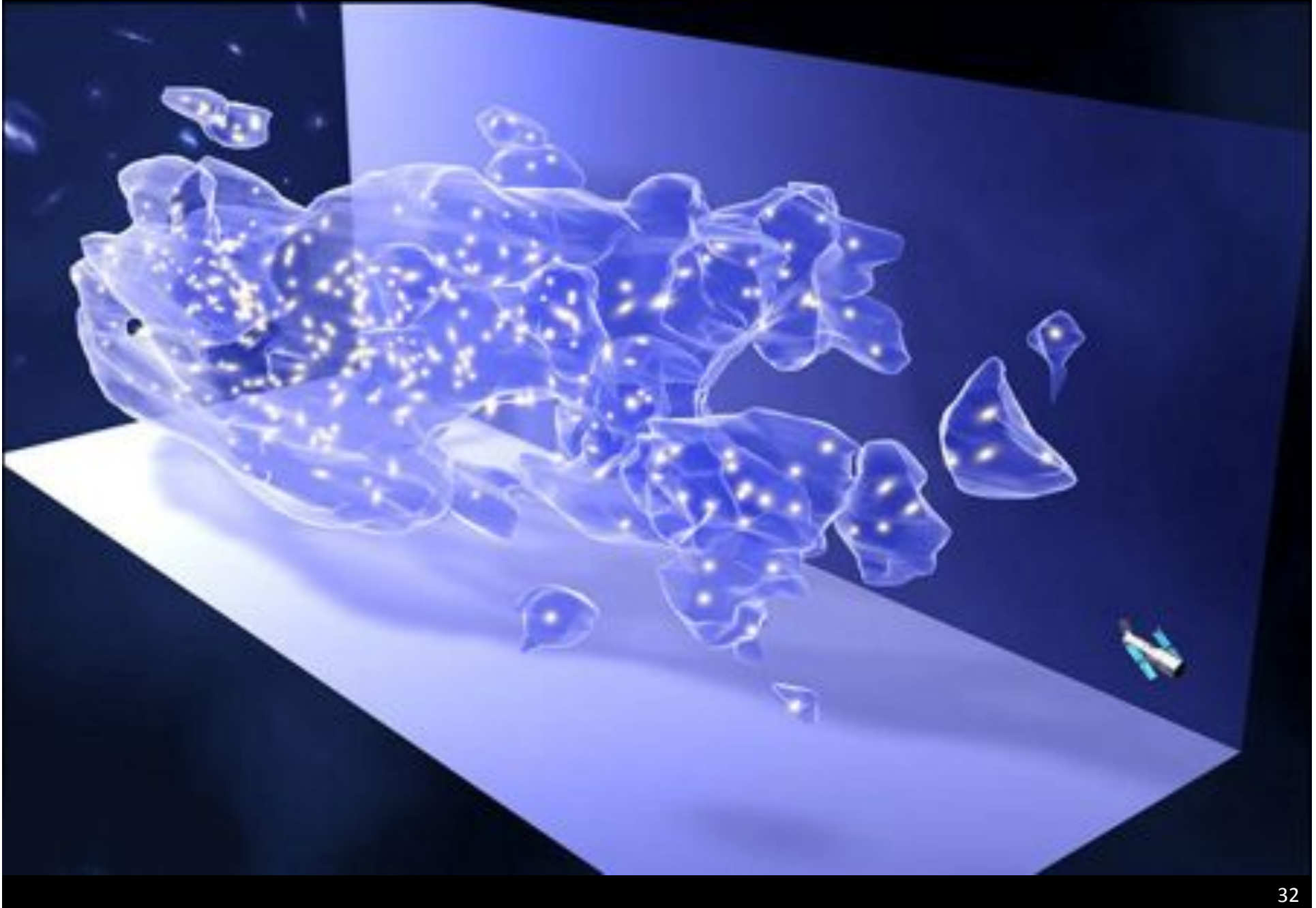
For a lens *halfway* between observe and source ( $d$  = lens distance)  
Einstein Ring Angular Radius ~

$$\theta_E \approx 0.5' \left( \frac{M}{10^{14} M_\odot} \right)^{1/2} \left( \frac{d}{1000 \text{ Mpc}} \right)^{-1/2}$$

Mass of Clusters estimated from gravitational lensing  
~ consistent with estimates of mass from Virial Theorem

$$\Omega_{\text{halo}} \approx 0.2$$

# Mapping the Dark Matter: Gravitational Lensing

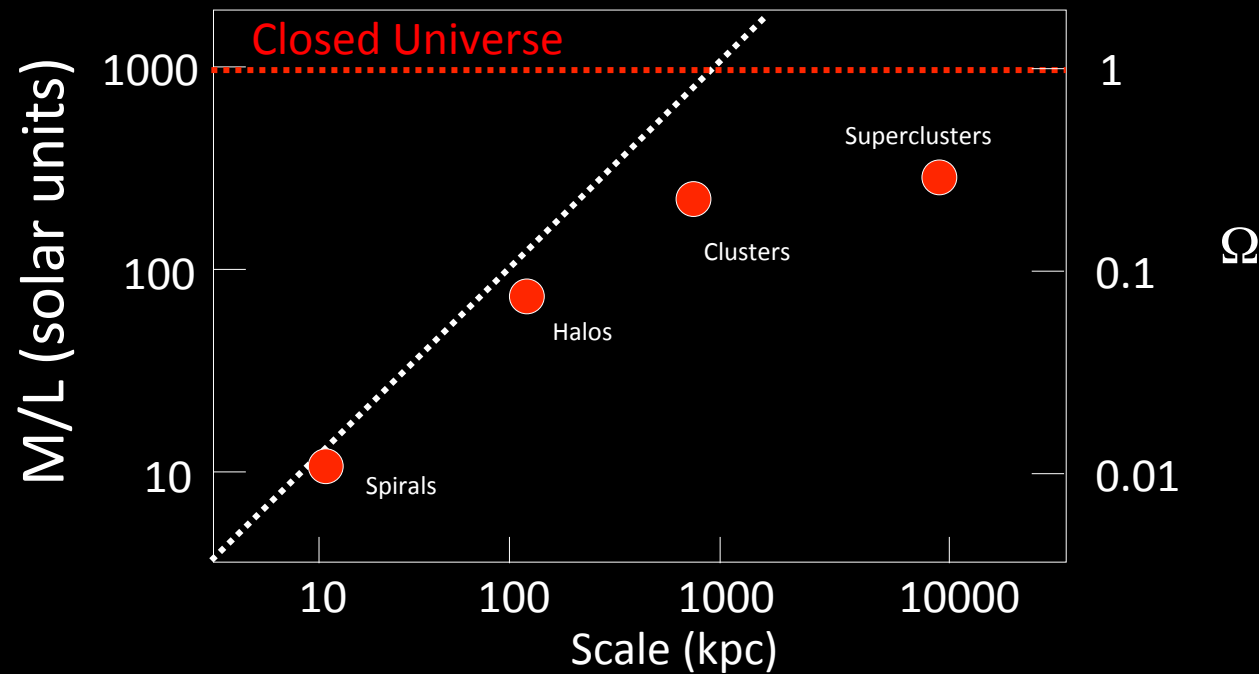




# Measured, Weighed ..... and found wanting

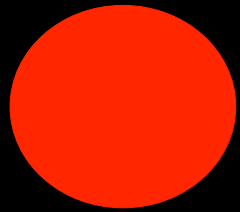
	M/L
Solar Neighbourhood	0.004
Galaxy Disk	10
Galaxy Halos	40-100
Galaxy Clusters	250

	$\Omega$
Solar Neighbourhood	0.004
Atomic/Molecular Gas	0.0008
Galaxy Halos	0.08-0.16
Galaxy Clusters	0.2



**Luminous matter cannot account for dynamics of structures on all scales !!!  
WHERE HAS ALL THE LIGHT GONE ???**

# Baryonic Dark Matter ?



Red Dwarf



Brown Dwarf



Black Dwarf



Black Hole

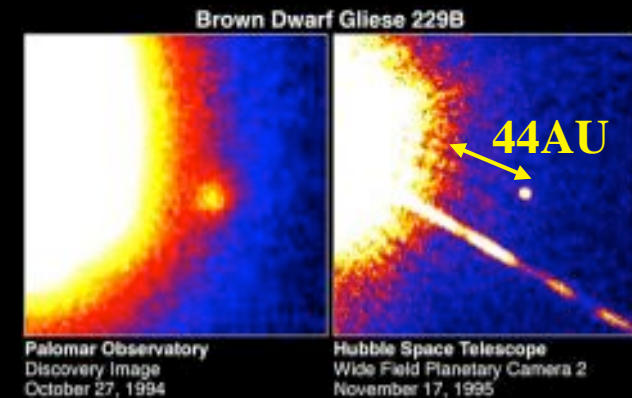


Neutron Star



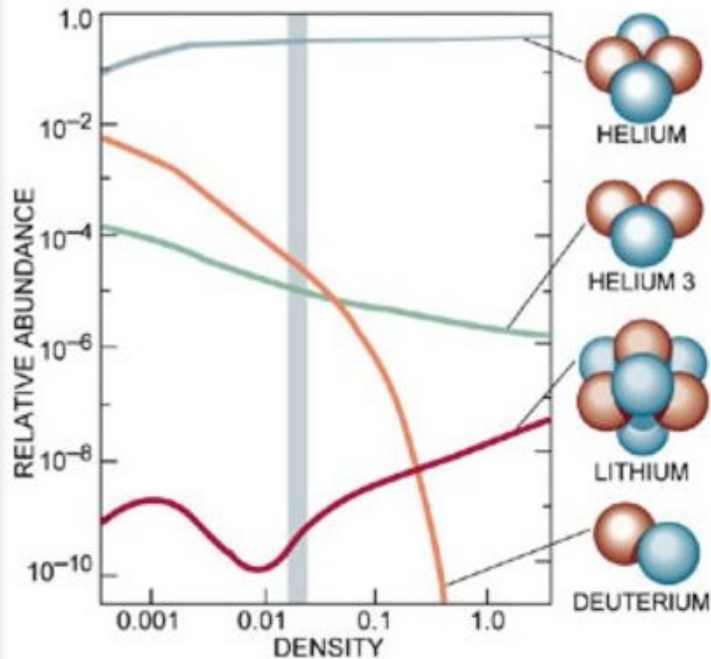
Jupiters/Planets

- 1. RED DWARF STARS  $< 1M_{\odot}$  ( $T^{\circ}\sim 2000\text{K}$ )**
  - Not enough detected
- 2. BROWN DWARF  $< 0.08M_{\odot}$  ( $T^{\circ}\sim 1000\text{K}$ ) - failed star**
  - Not enough detected
- 3. STELLAR REMNANTS (Black Dwarf, Neutron Stars, Black Holes)  $\sim 1M_{\odot}$** 
  - Universe too young for so many remnants to form
  - Universe too young for remnants to cool to Black Dwarf
- 4. JUPITERS / PLANETS / ROCKS  $\sim 0.001M_{\odot}$** 
  - Not Seen
  - Huge Numbers Required



# The Problem with the Baryons

Big Bang Nucleosynthesis ~ 3 minutes  $10^9$  K



Element abundance depends on Baryon photon ratio  $\eta$

$$\Omega_{\text{baryon}} \sim 3.7 \times 10^7 h^{-2} (T / 2.7)^3 \eta$$

- High baryon-photon ratio  $\Rightarrow$  higher density
- $\Rightarrow$  nucleosynthesis starts earlier (higher T)
- Helium production more efficient
- Less Deuterium (&  $^3\text{He}$ ) leftover

Observed abundance of Deuterium sets upper limit for primordial abundance

$$0.04 < \Omega_{\text{baryon}} < 0.05$$

# The Problem with the Baryons

$$0.04 < \Omega_{\text{baryon}} < 0.05$$

But .....

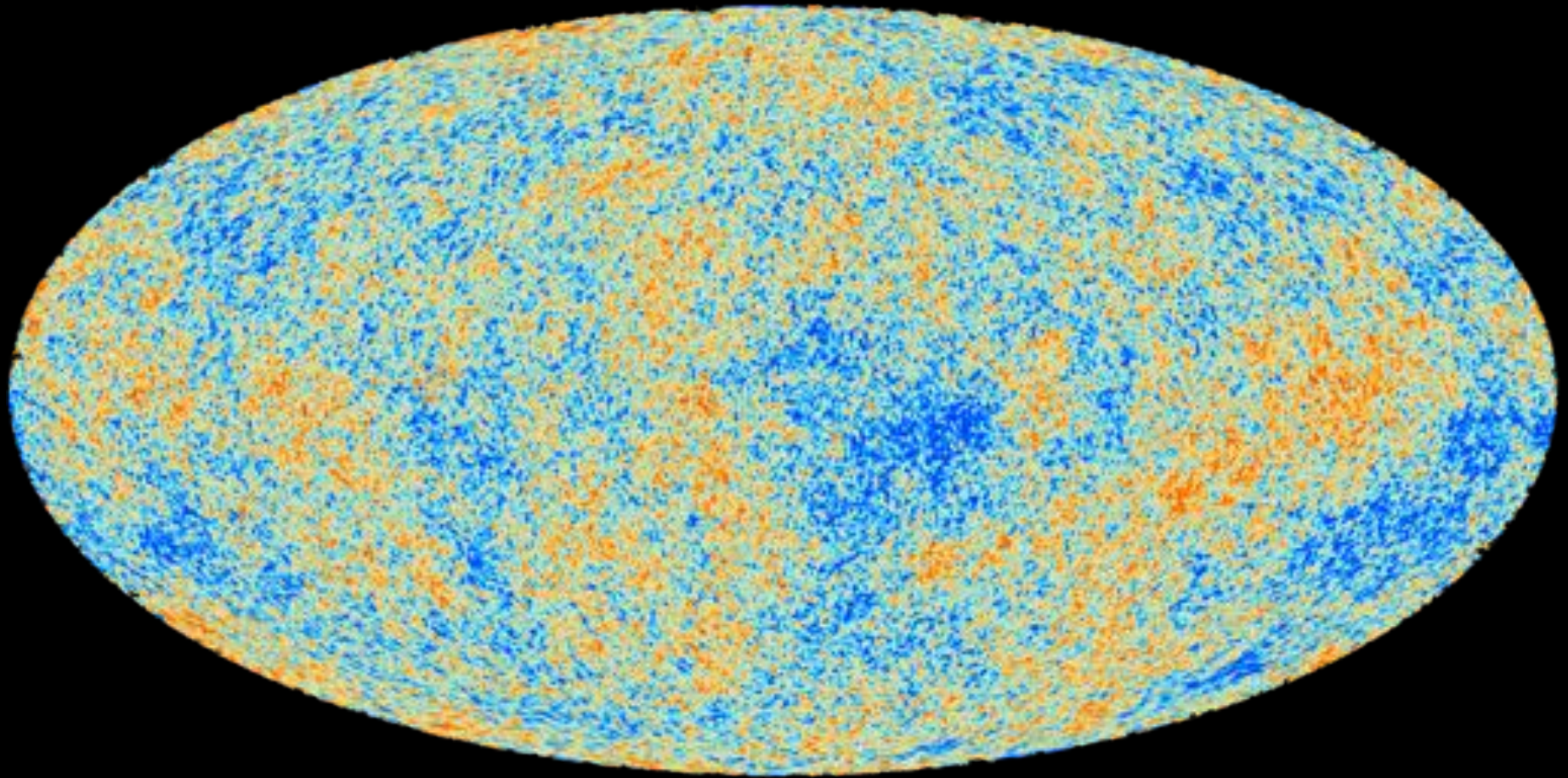
$$\Omega_{\text{halo}} \sim 0.16$$

$$\Omega_{\text{clusters}} > 0.2$$

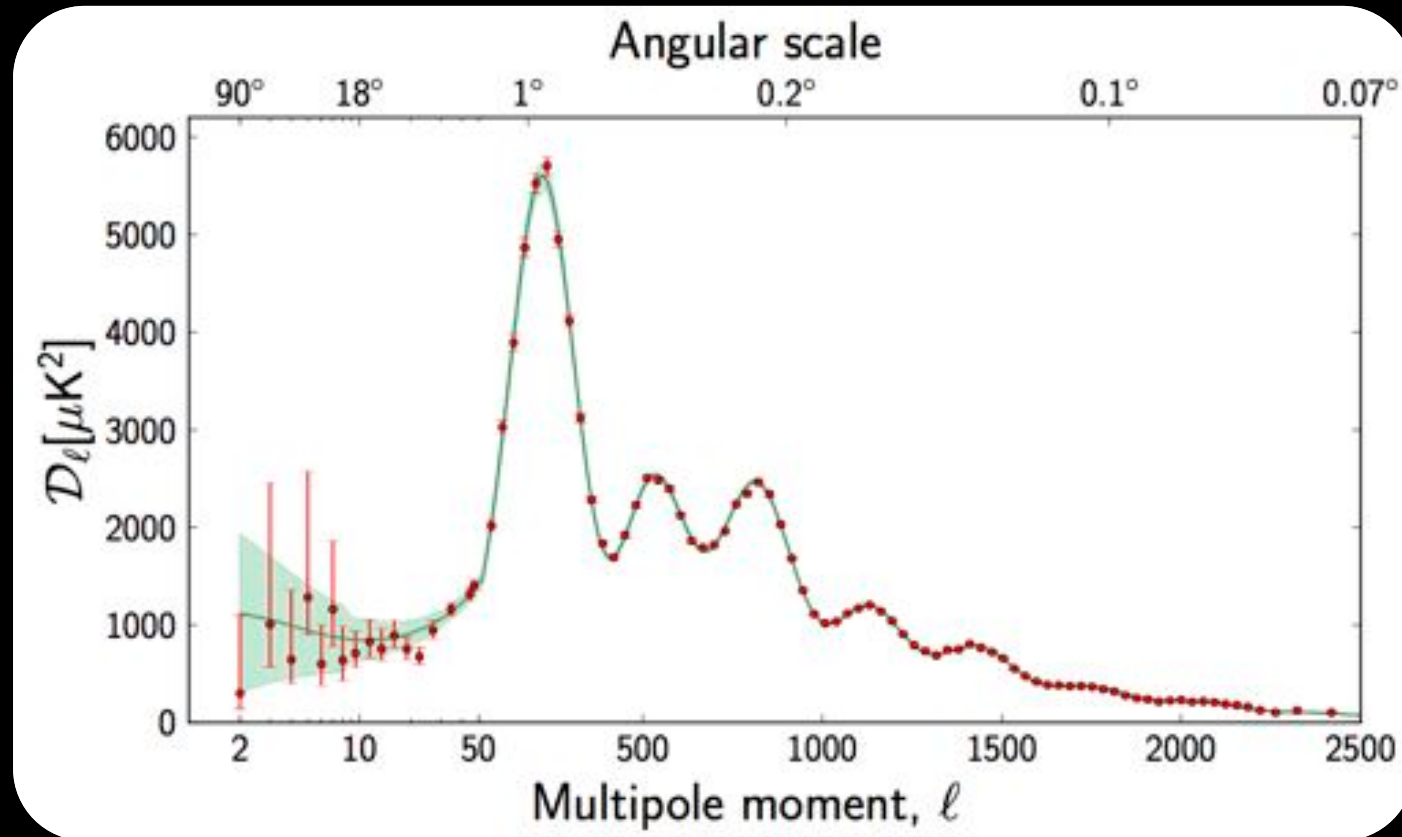
There is a factor 5 more dark matter than can be explained by the baryon abundance

majority of Dark matter most be non-baryonic

**The Worst is yet to come !**

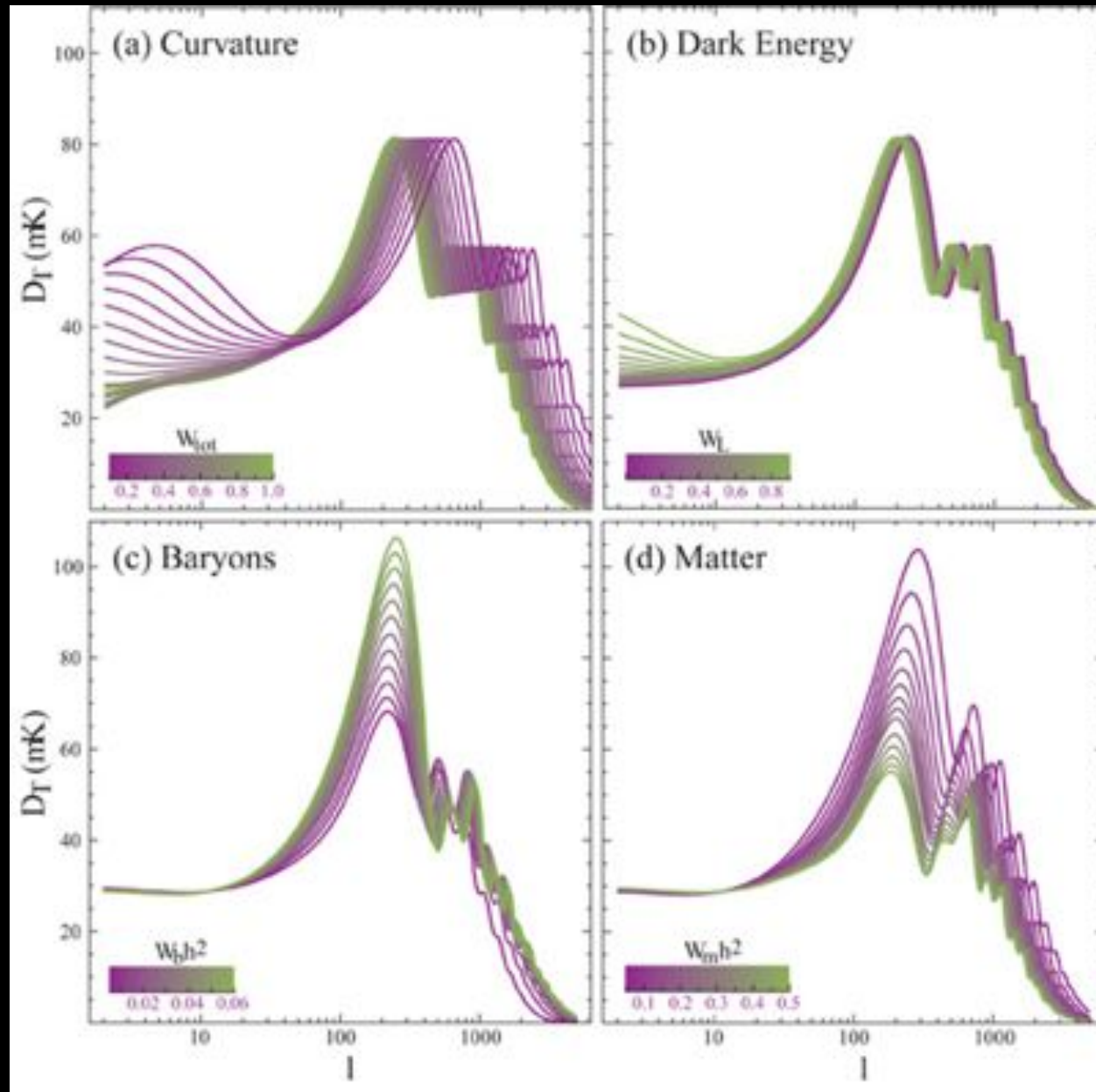


# Non-Baryonic Dark Matter



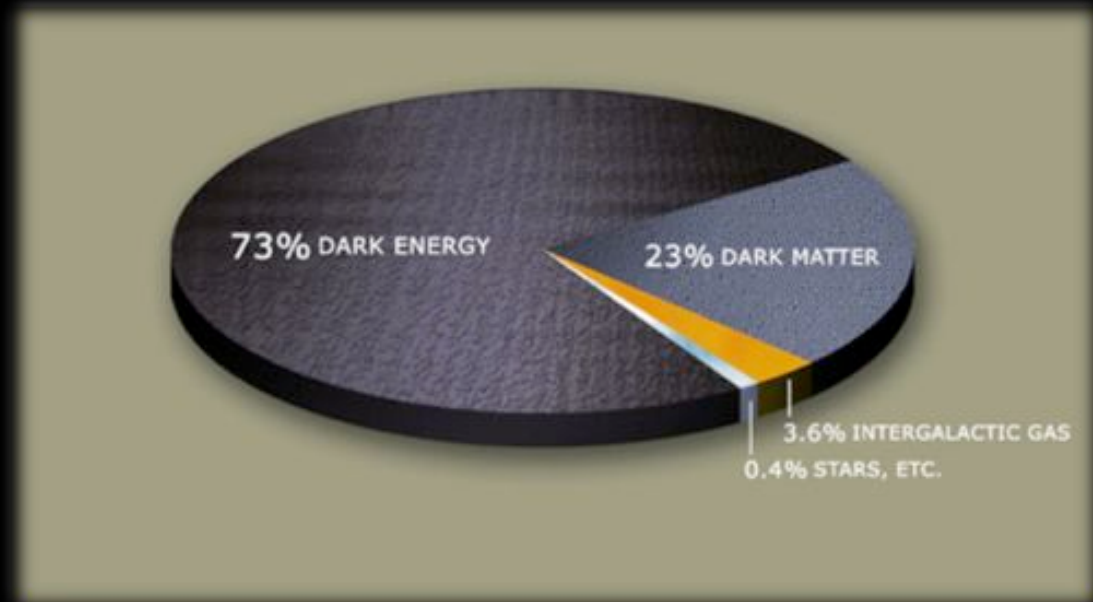
Consistent with  $\Omega_{\text{Total}} = 1$

# Non-Baryonic Dark Matter



# Non-Baryonic Dark Matter

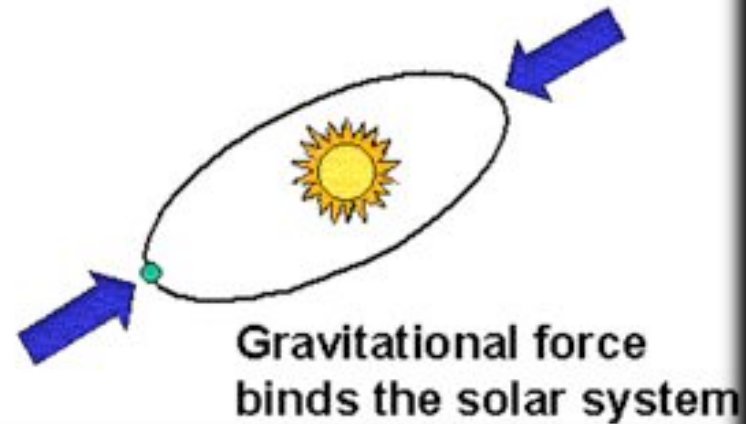
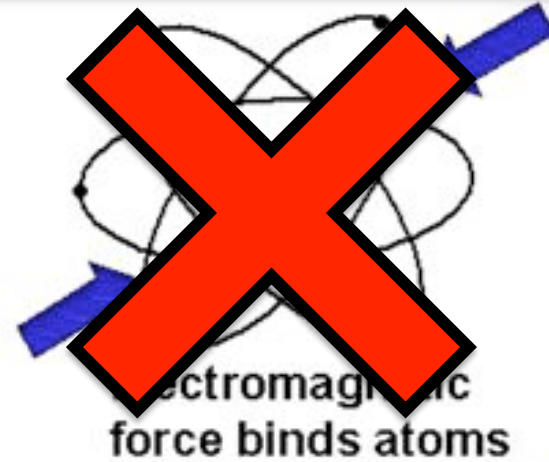
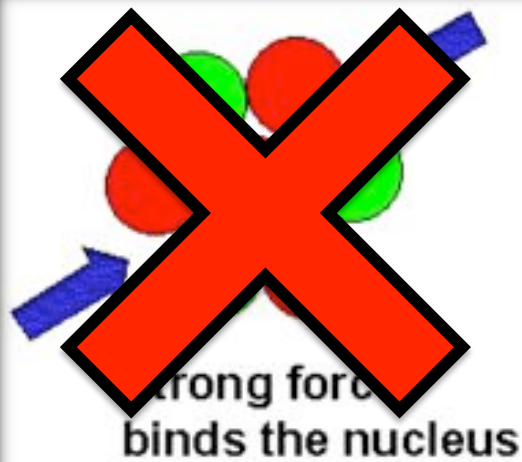
	$\Omega$
Solar Neighbourhood	0.004
Hot Gas in clusters	0.02
Galaxy Halos	0.08-0.16
Galaxy Clusters	0.2
Baryon Nucleosynthesis	0.04
CMB Inflation	1
CMB Dark Matter	0.23
CMB Dark Energy	0.73



- Baryonic matter consistent with local solar neighbourhood and intracluster medium
- Some of Halo mass possibly dark baryons - **BARYONIC DARK MATTER**
- Majority of Halo and Cluster dark matter  $\Rightarrow$  **NON BARYONIC DARK MATTER**
- 73% of Universe is **DARK ENERGY**



# Non-Baryonic Dark Matter



# Non-Baryonic Dark Matter

Three generations of matter (fermions)

	I	II	III		
mass →	2.4 MeV/c <sup>2</sup>	1.27 GeV/c <sup>2</sup>	171.2 GeV/c <sup>2</sup>	0	7 GeV/c <sup>2</sup>
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
name →	<del>u</del> up	<del>c</del> charm	<del>t</del> top	<del>γ</del> photon	<del>H</del> Higgs boson
Quarks	4.8 MeV/c <sup>2</sup>	104 MeV/c <sup>2</sup>	4.2 GeV/c <sup>2</sup>	0	
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	<del>d</del> down	<del>s</del> strange	<del>b</del> bottom	<del>g</del> gluon	
Leptons	<2.2 eV/c <sup>2</sup>	<0.17 MeV/c <sup>2</sup>	<15.5 MeV/c <sup>2</sup>	91.2 GeV/c <sup>2</sup>	
	0	0	0	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	<del>ν<sub>e</sub></del> electron neutrino	<del>ν<sub>μ</sub></del> muon neutrino	<del>ν<sub>τ</sub></del> tau neutrino	<del>Z</del> Z boson	
	0.511 MeV/c <sup>2</sup>	105.7 MeV/c <sup>2</sup>	1.777 GeV/c <sup>2</sup>	80.4 GeV/c <sup>2</sup>	
	-1	-1	-1	±1	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	<del>e</del> electron	<del>μ</del> muon	<del>τ</del> tau	<del>W<sup>±</sup></del> W boson	
					Gauge bosons

**Baryons**  
(strong Force)

**Charged**  
(Electromagnetism)

**Decays**

# Non-Baryonic Dark Matter

To be born Dark, to become dark, to be made dark, to have darkness

**COLD DARK MATTER**

Non Relativistic at decoupling

Heavy Neutrino

SUSY Particles

Axions

} WIMPs

**HOT DARK MATTER**

Relativistic at decoupling

Light Neutrino

**COSMIC RELICS**

Symmetry Defects

Monopoles

Cosmic Strings

Cosmic Textures

# Hot Dark Matter: Neutrinos

The ONLY Dark Matter Candidate known to exist

Neutrino density from big bang  $\sim 330 /\text{cm}^3$  (compare with radiation)  $410 /\text{cm}^3$

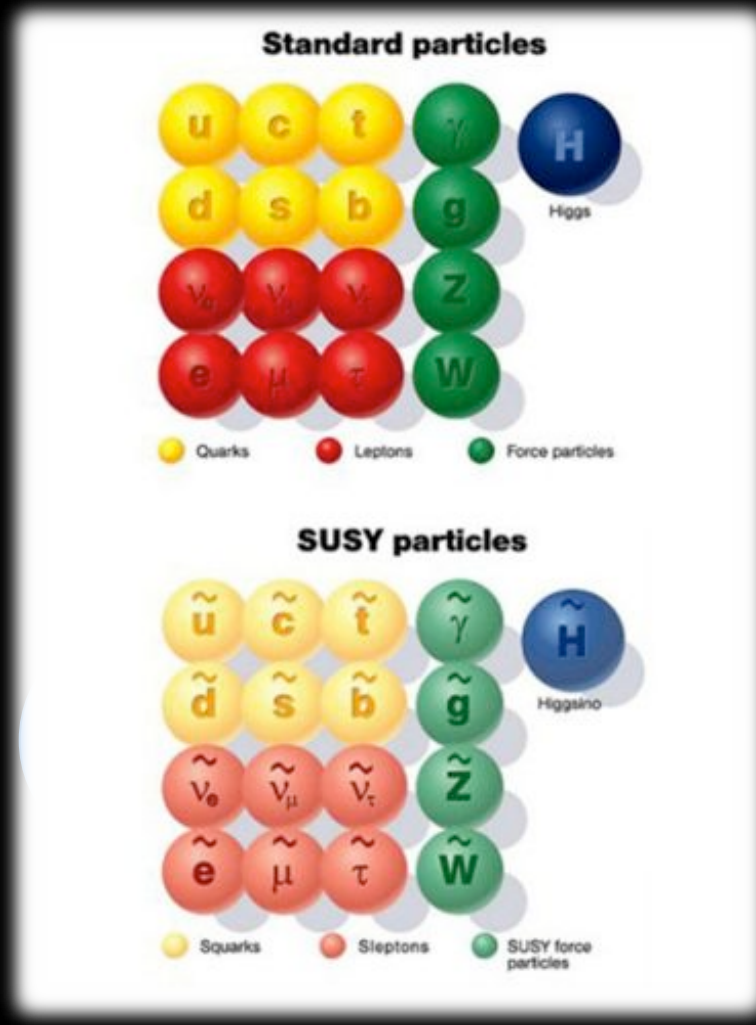
In order to contribute ALL Dark Matter require  $m_{\text{neutrino}} \sim 4\text{eV}$



# Cold Dark Matter: WIMPS

Weakly Interacting Massive Particles (opposite to MACHOS !!)

Supersymmetry: higher order symmetry connecting: Fermions  $\leftrightarrow$  Bosons



Particle	spin	SUSY partner	spin
quark	1/2	squark	0
lepton	1/2	slepton	0
photon	1	photino	1/2
gluon	1	gluino	1/2
W/Z	1	zino / wino	1/2
graviton	2	gravitino	3/2
Higgs	0	Higgsino	1/2
axion	0	axino	1/2

# Cold Dark Matter: WIMPS

Weakly Interacting Massive Particles (opposite to MACHOS !!)

SUSY models: R-parity

All Standard Model particles have R-parity of +1

All supersymmetric particles have R-parity of  $-1$ .

R-parity preserved  $\Rightarrow$  the lightest supersymmetric particle (**LSP**) cannot decay.

**LSP WIMP: strong candidate for cold dark matter**

⇒ CHARGED PARTICLES

(selectron, squark, smuon, wino, charged Higgsino) RULED OUT

$$m_{\text{sneutrino}} > m_{\text{sleptons}}$$

gravitino - self annihilates too slowly ⇒ too high abundance

Photino mass  $\sim 0.5\text{GeV}$  ⇒ Possible candidate for LSP

Stranger possibilities - neutralino - mixing state of photino, higgsino, wino states?

# Cold Dark Matter: WIMPS

Weakly Interacting Massive Particles

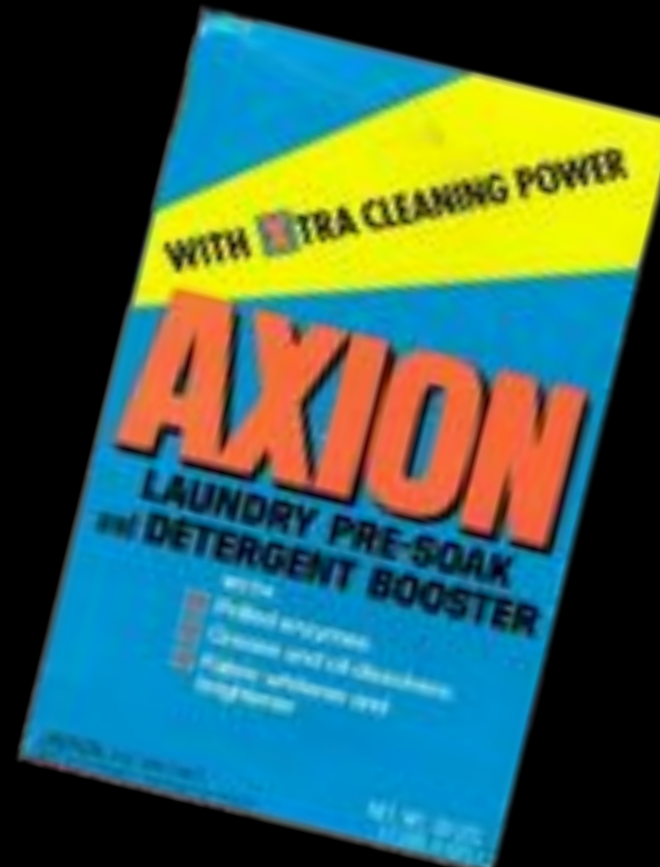


the expected WIMP flux at Earth is enormous,  $10^7 m_{\text{WIMP}}/\text{cm}^2$ ,  
( $m_{\text{WIMP}}$  = WIMP mass in GeV).

However, WIMP-nucleon scattering cross sections  $< 10^{-41} \text{ cm}^2$   
-> expected WIMP-nuclear scattering rate  $\sim 0.001$  to  $1$  event /kg

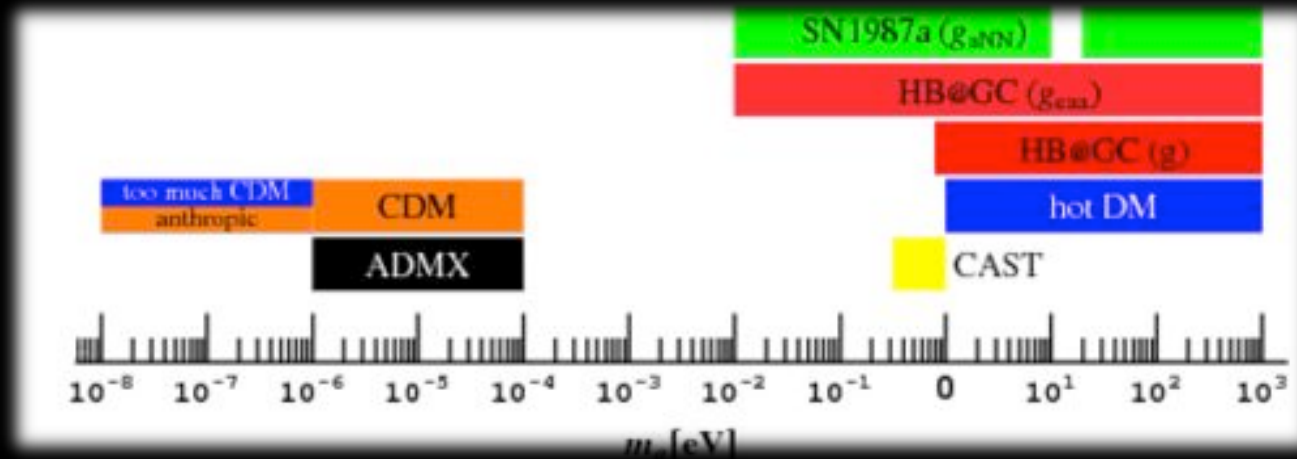
# Cold Dark Matter: Axions

- Solution for *mending* the strong QCD CP problem
- CP violation predicted but not observed on order of  $10^{-8}$  (c.f. flatness problem in inflation)
- 1978: Peccei-Quinn Constraint - Introduce Spin 0 pseudoscalar boson  
→ suppress Strong CP violation
- Requires symmetry breaking on GUT scales with particle mass





# Cold Dark Matter: Axions



Stellar core constraints

Stars radiate axions  $\rightarrow$  decay into photons

$$10^{-5} \text{ eV} < m_{axion} < 6 \times 10^{-3} \text{ eV}$$

$\Omega < 1$  lighter axion greater energy density

- Axions created abundantly in the Big Bang
- Coupling to inflation field  
 $\rightarrow$  dynamical friction strips primordial axions of their kinetic energy
- Axions are light but still **cold** (non-relativistic when decouple)

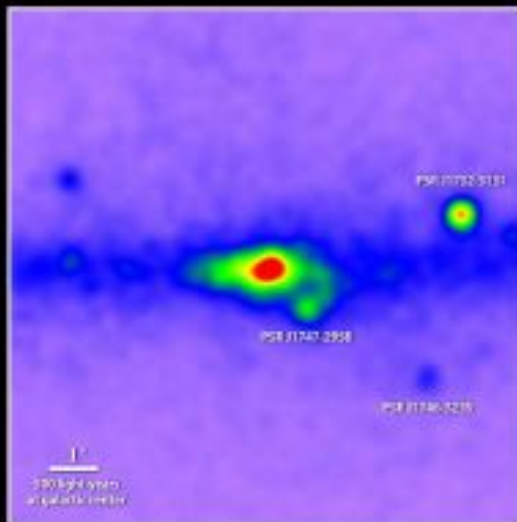
# Dark Matter Candidate Identity Parade

Candidate	Mass	
Neutrino	4 eV	Hot Dark Matter
Axion	$10^{-5}$ eV	Cold Dark Matter
Photino	0.5 GeV	LSP
Neutralino	10 GeV	LSP
Axino	~ keV	LSP
Cosmion	5-10 GeV	Created by $P\bar{p}$ annihilation, useful for Solar Neutrino Problem
Quark Nuggets	~ $10^{15}$ kg	Created in initial stages of Big Bang but predicted flux of $10^6$ kg yr <sup>-1</sup> not detected
Shadow Matter	~ GeV	Predicted by E8xE8 Superstring Theories, Decouples $10^{-43}$ s after Big Bang
Primordial Black Holes	$>10^{12}$ kg	Collapse of Space time on scales of Horizon due to fluctuations
Relics	??	Monopoles, Strings, Textures

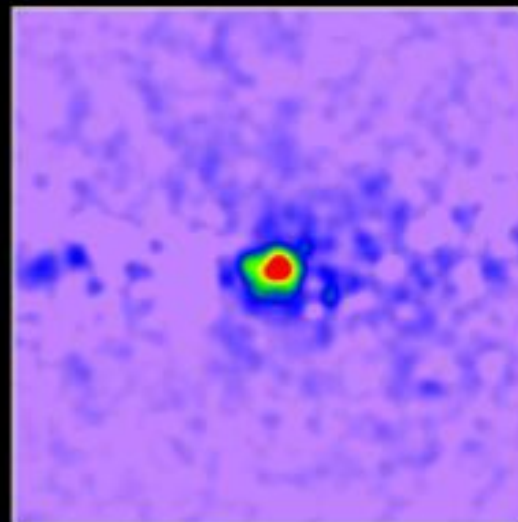
# Dark Matter Candidate Detection

- Excess of gamma-rays in direction of the Galactic Center ?
- Dark matter particle of mass  $\sim 35.25$  GeV WIMP annihilating ?

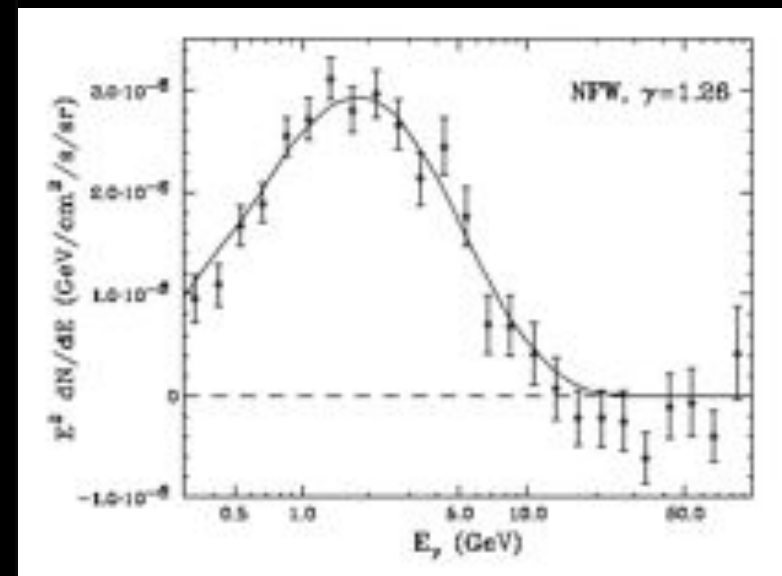
Uncovering a gamma-ray excess at the galactic center



Unprocessed map of 1.0 to 3.16 GeV gamma rays

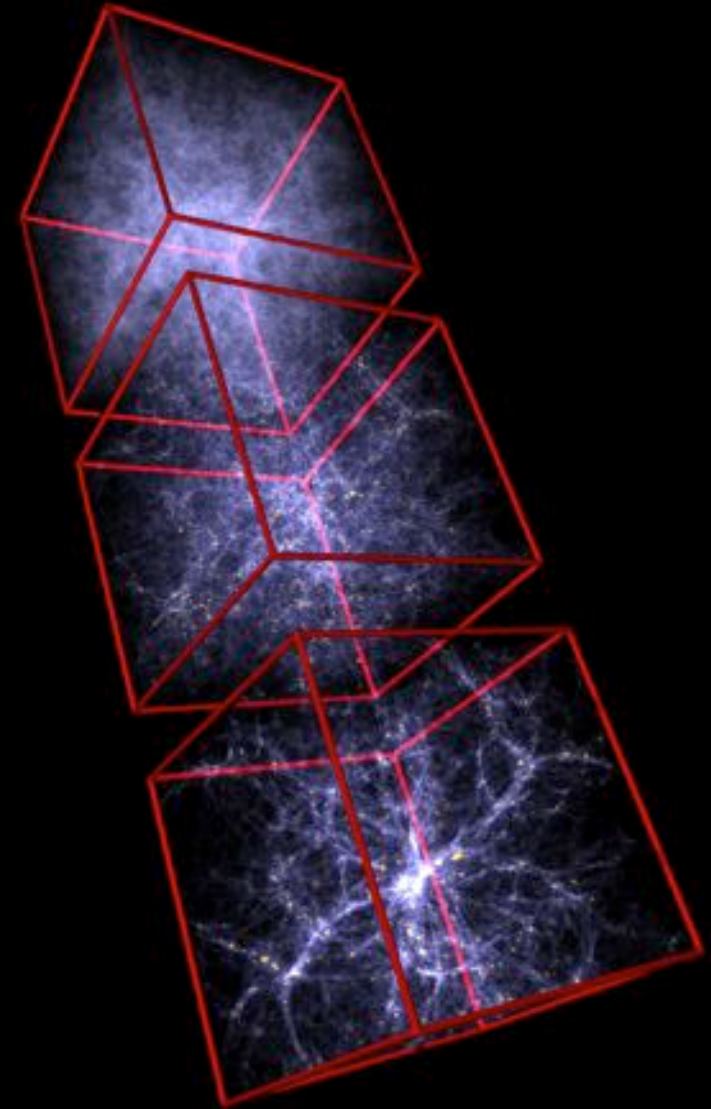
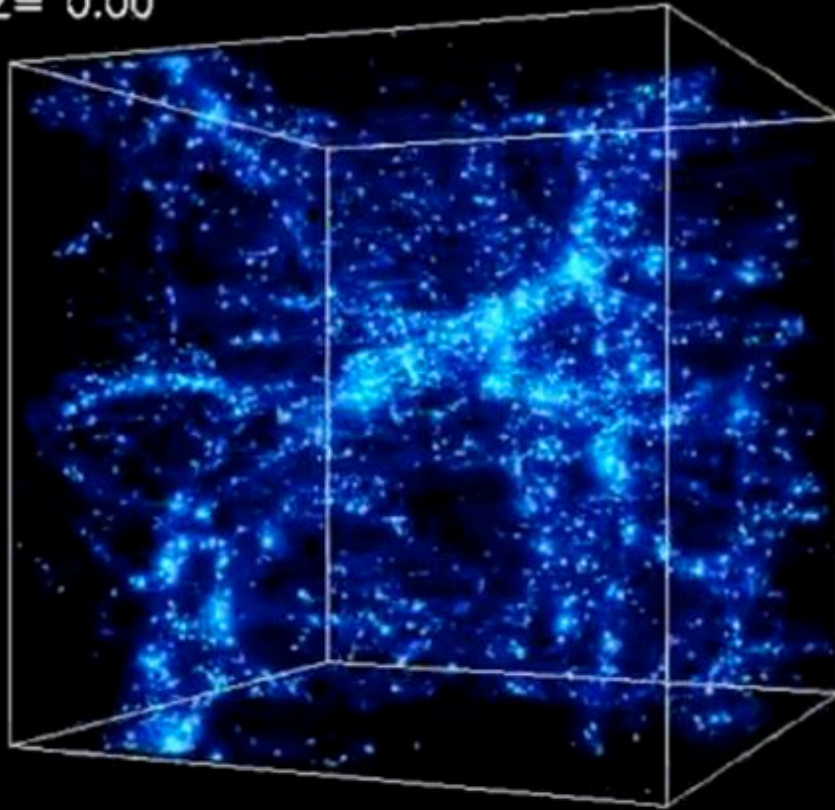


Known sources removed



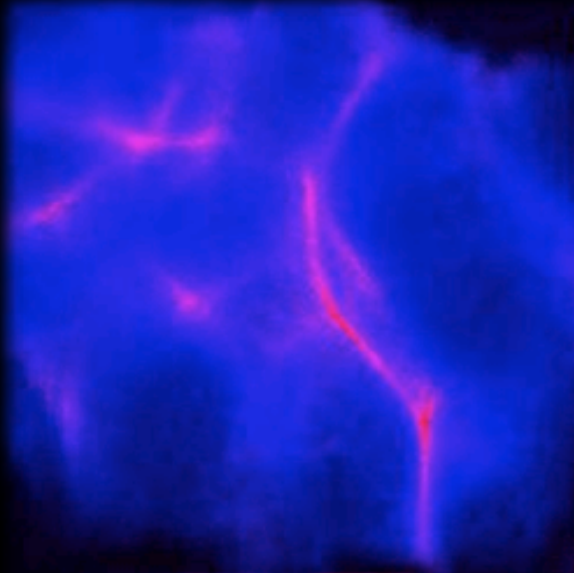
# Structure Formation in a Dark Matter Universe

$Z = 0.00$

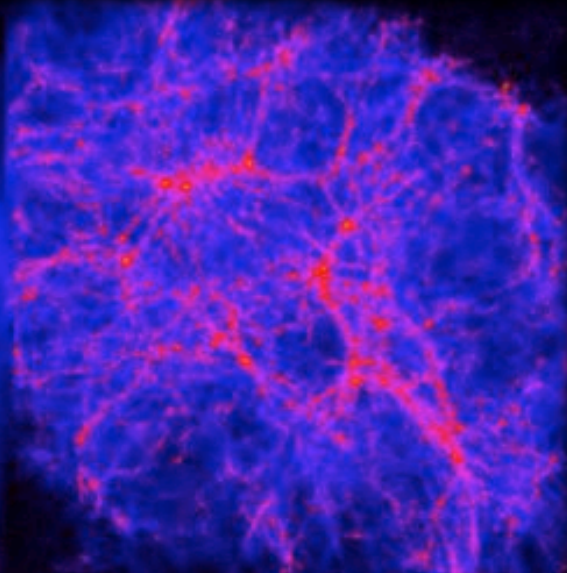


# Structure Formation in a Dark Matter Universe

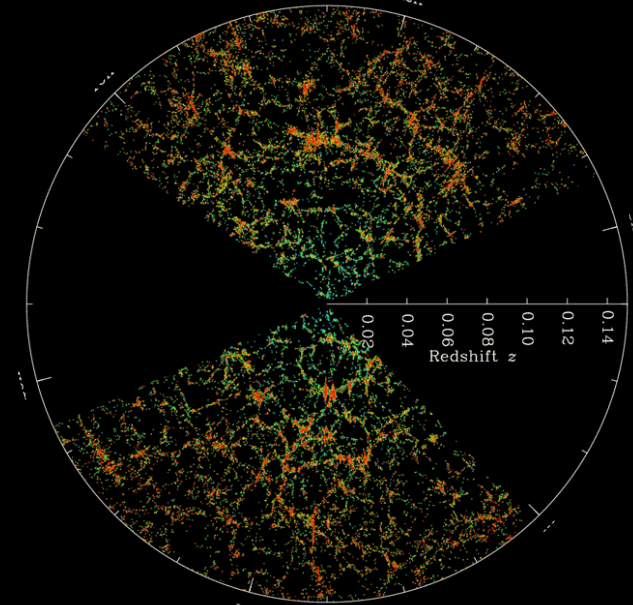
HOT DARK MATTER



COLD DARK MATTER

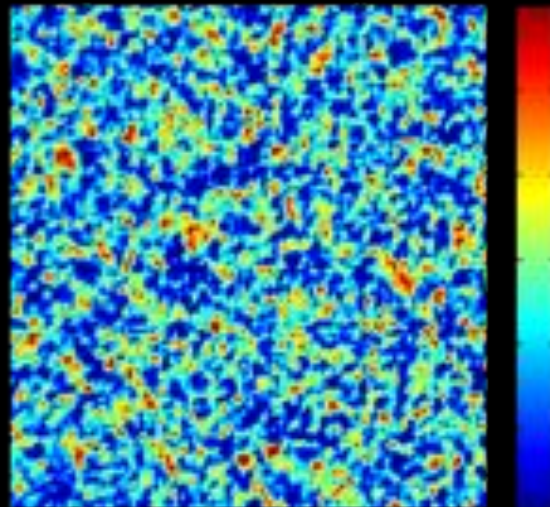
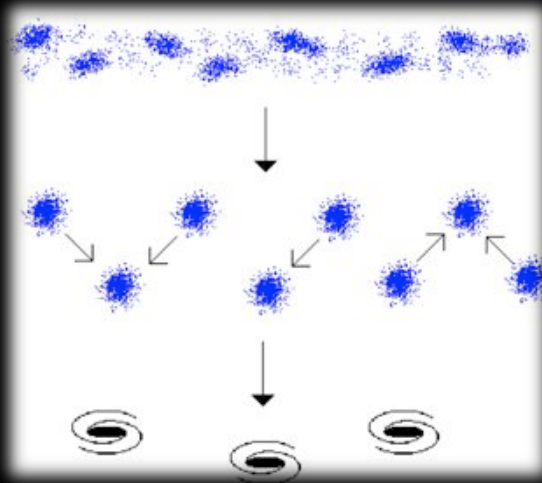


THE REAL UNIVERSE

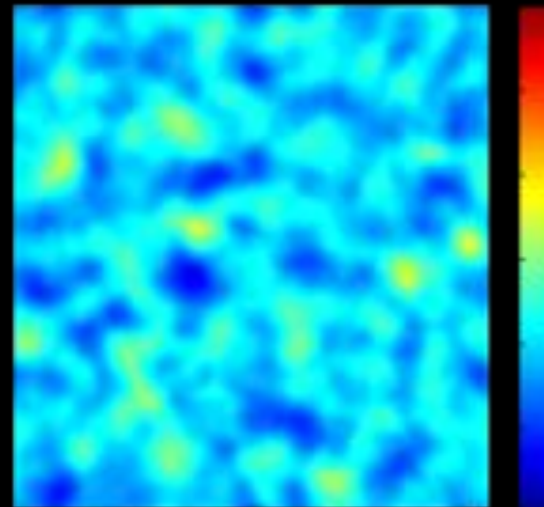
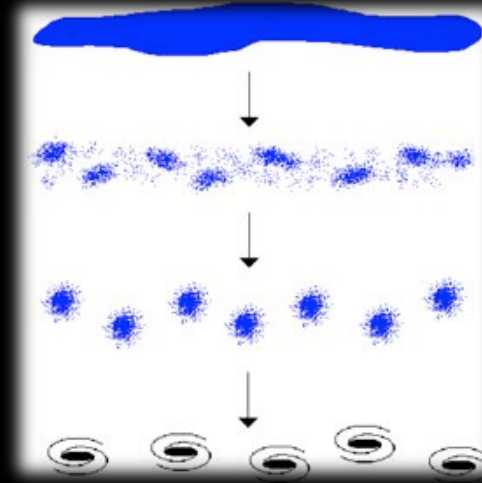


# Structure Formation in a Dark Matter Universe

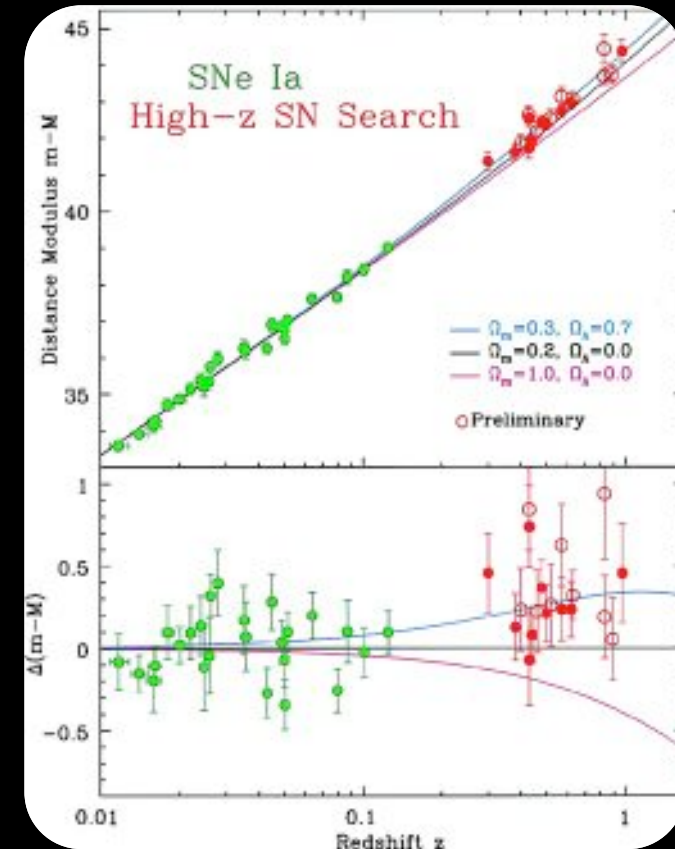
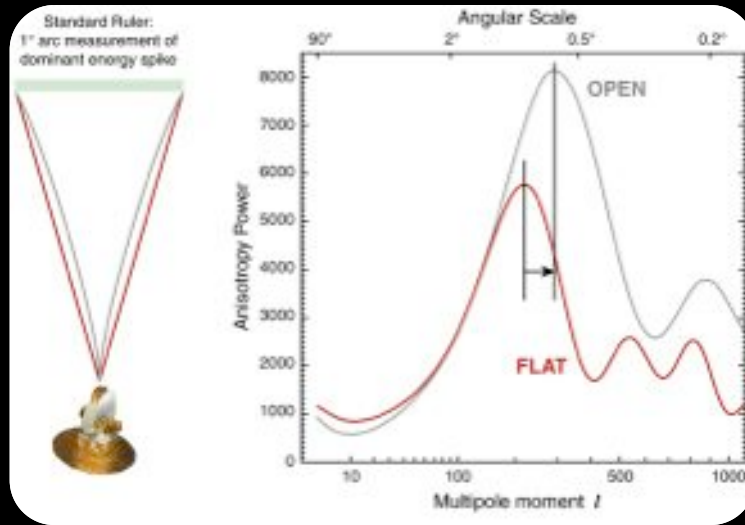
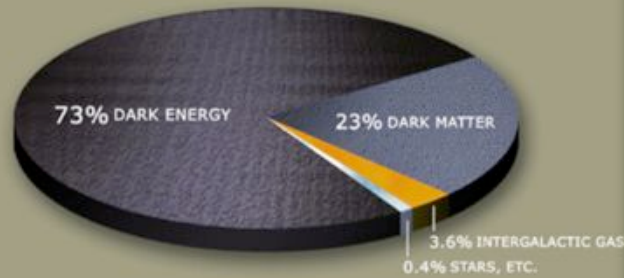
**Cold Dark Matter  
Bottom-Up Hierarchical Scenario**



**Hot Dark Matter  
Top-Down Pancake Scenario**



# Dark Energy



Our Universe is accelerating due to a repulsive force equivalent to  $\Omega_{\Lambda,0} = 0.7$

# Structure Formation in a Dark Matter Universe

## Cosmological Constant ?

Einsteins greatest blunder?

$$G_{ik} = R_{kl} - \frac{1}{2}g_{ik}R - \Lambda g_{ik} = \frac{8\pi G}{c^4} T_{ik}$$

$$\dot{R}^2 = \frac{8\pi G\rho}{3}R^2 - kc^2 + \frac{\Lambda R^2}{3}$$

## Vacuum Energy ?

Cosmic Cashmir effect ?

Problem:  $\sim 10^{120}$  smaller than predicted by quantum theory

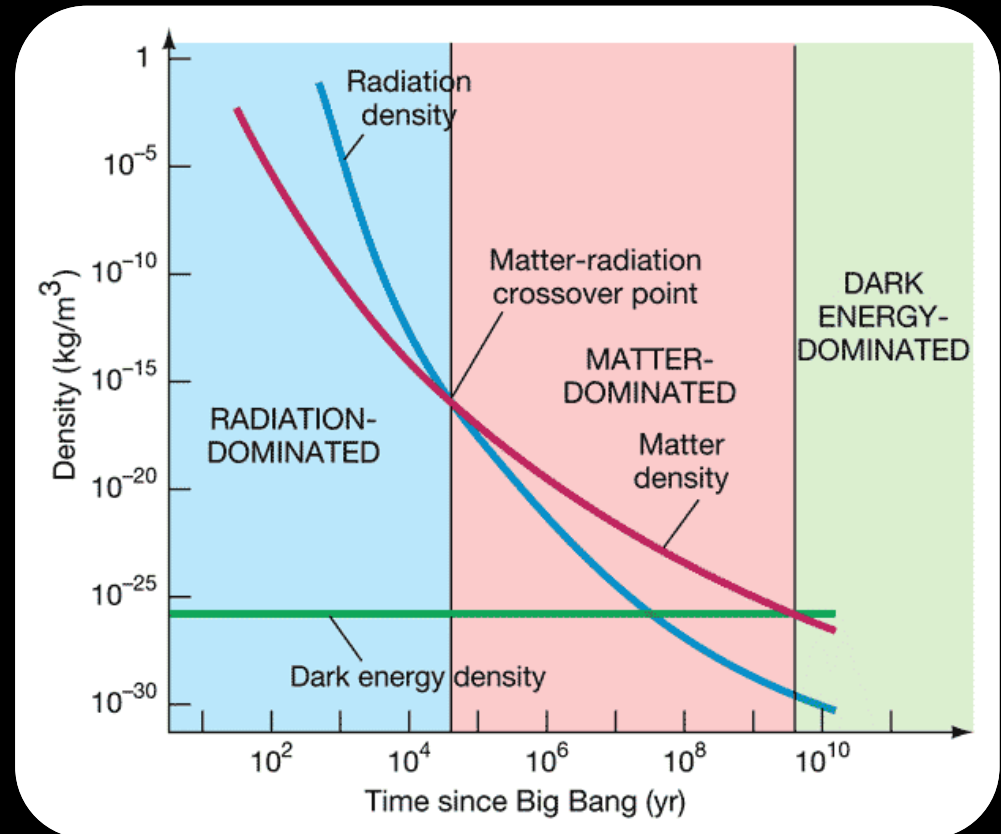
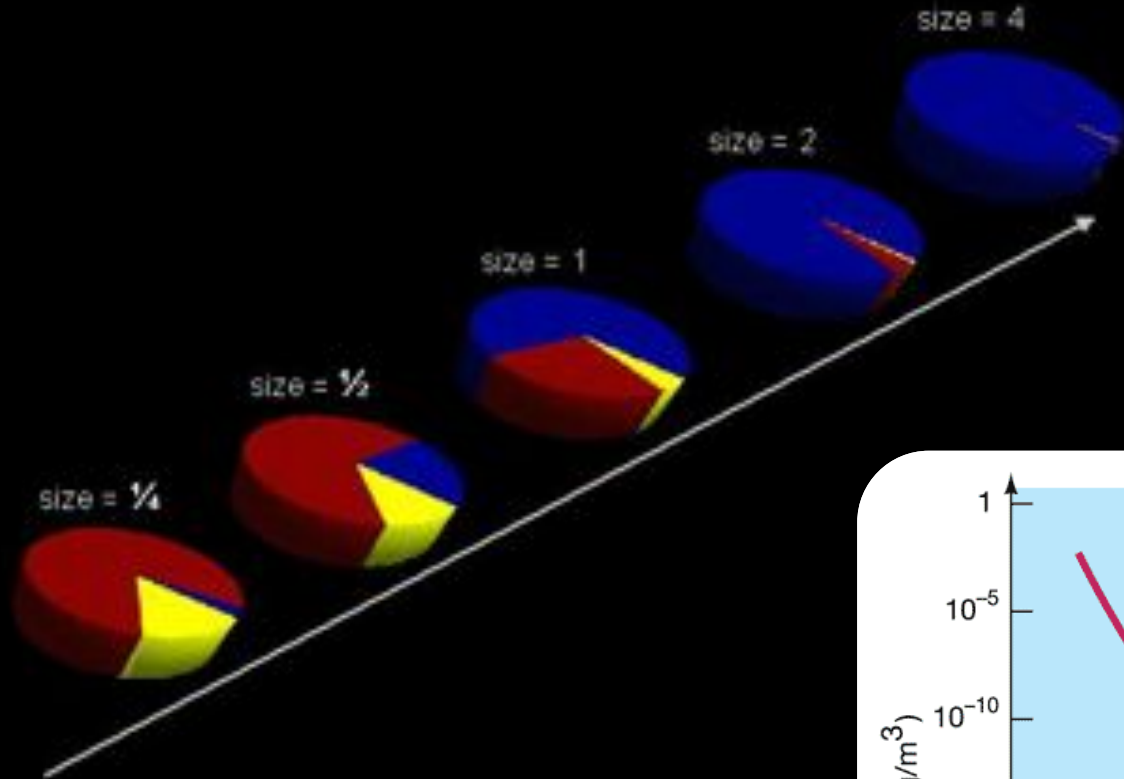
## Quintessence ?

Scalar field / fifth fundamental force ?

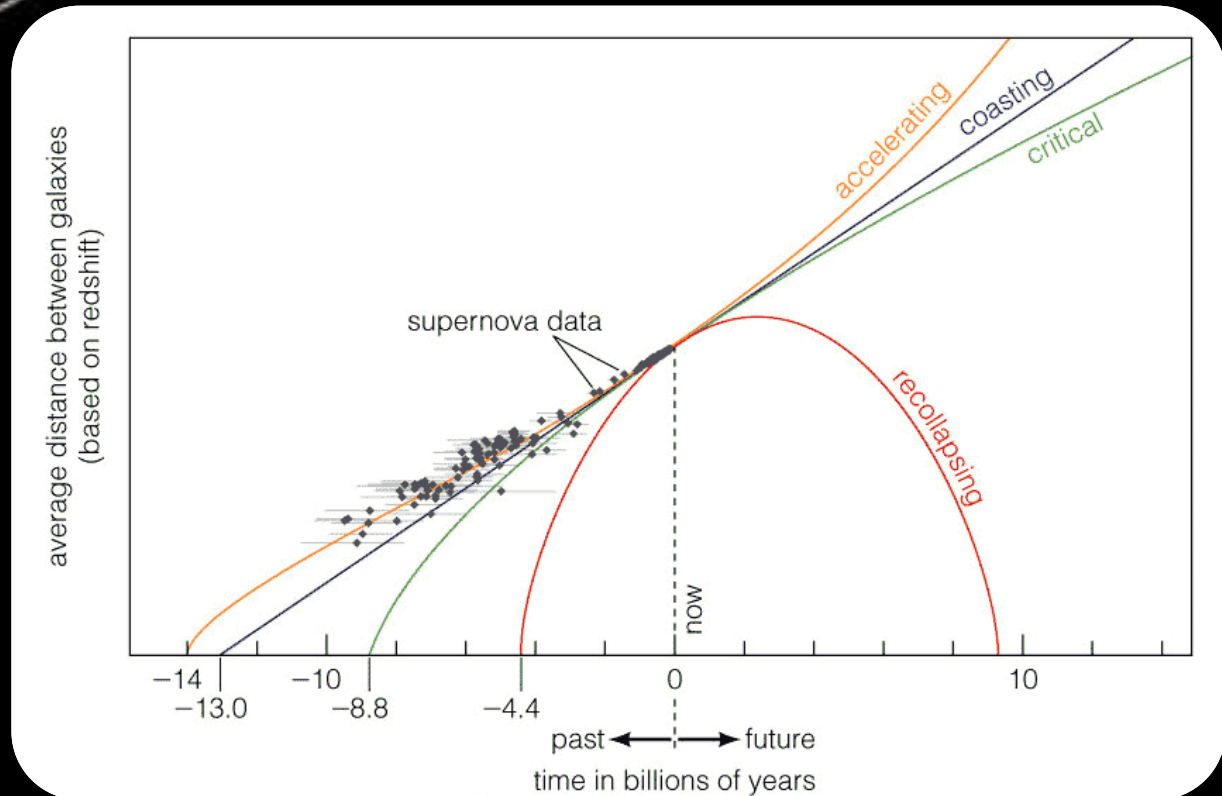
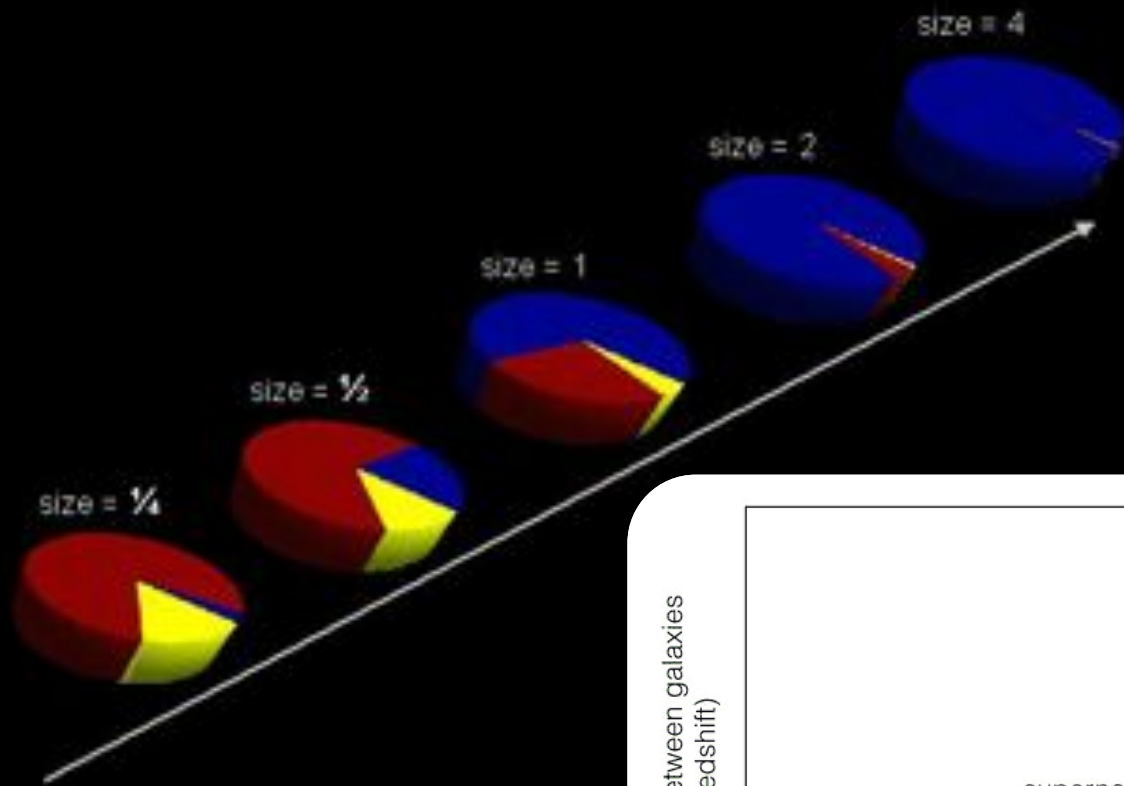
Evolves with time



# Structure Formation in a Dark Matter Universe



# Structure Formation in a Dark Matter Universe



# Our Universe

- began in a Big Bang event ~ 13.7 Billion Years ago
  - has been expanding ever since
  - started accelerating about 4 billion years ago
- 
- contains 6x as much Dark (non-baryonic) matter than normal matter
  - and is dominated by a Dark Energy 3x greater than the dark matter
  - so we don't really know what 96% of our Universe is made of