COSMOLOGY 101

3

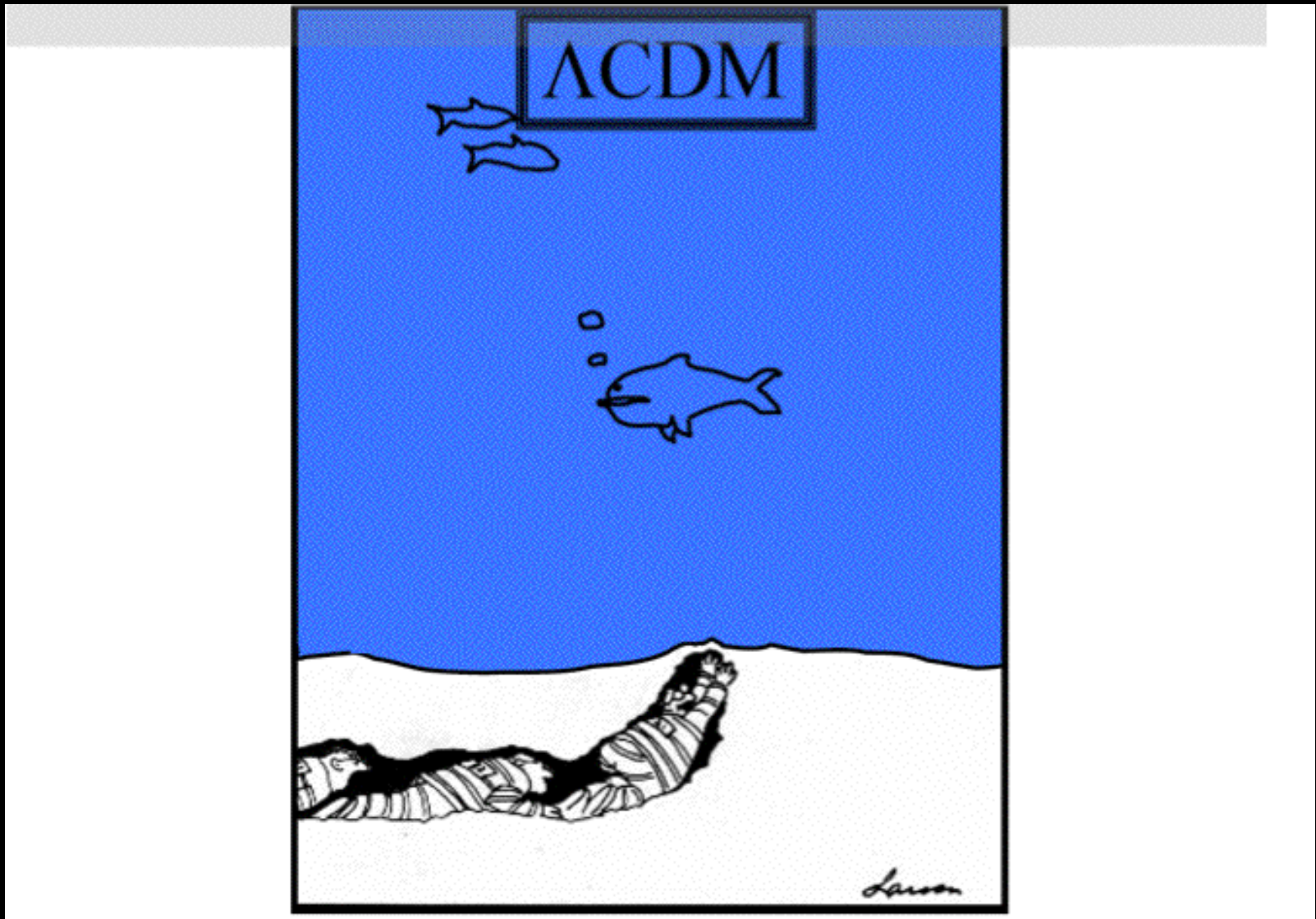
Chris Pearson : RAL Space

October 2015

COSMOLOGY

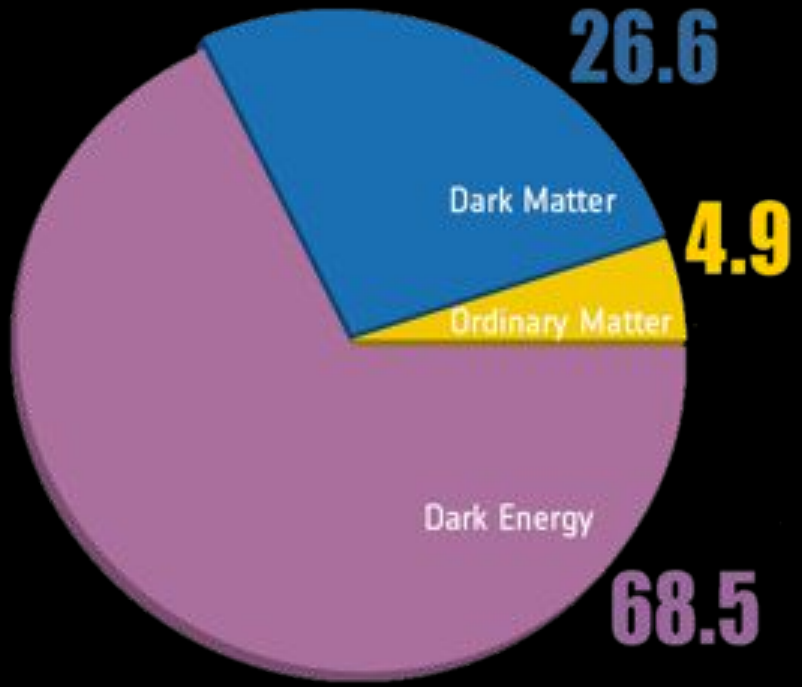
- How did the Universe Begin ?
- How old is the Universe ?
- How big is the Universe ?
- Where are we in the Universe ?
- What is the Universe made of ?
- Will the Universe end ?

Just when you thought it was safe …



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_o = 67.3 ± 0.012 km/s/Mpc

τ_{age} = 13.81 ± 0.05 Gyr

$\Omega_{\Lambda,o}$ = 0.685 ± 0.017

$\Omega_{m,o}$ = 0.315 ± 0.016

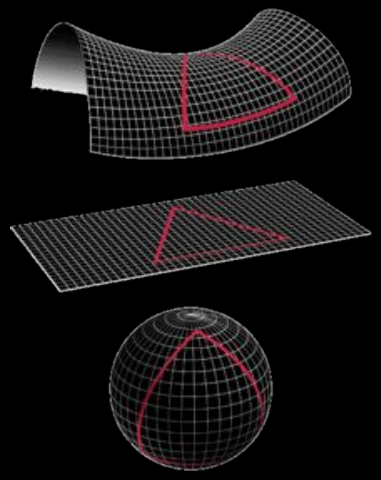
$\Omega_{DM,o}$ = 0.2662 ± 0.016

$\Omega_{b,o}$ = 0.0487 ± 0.00027

COSMOLOGY

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

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

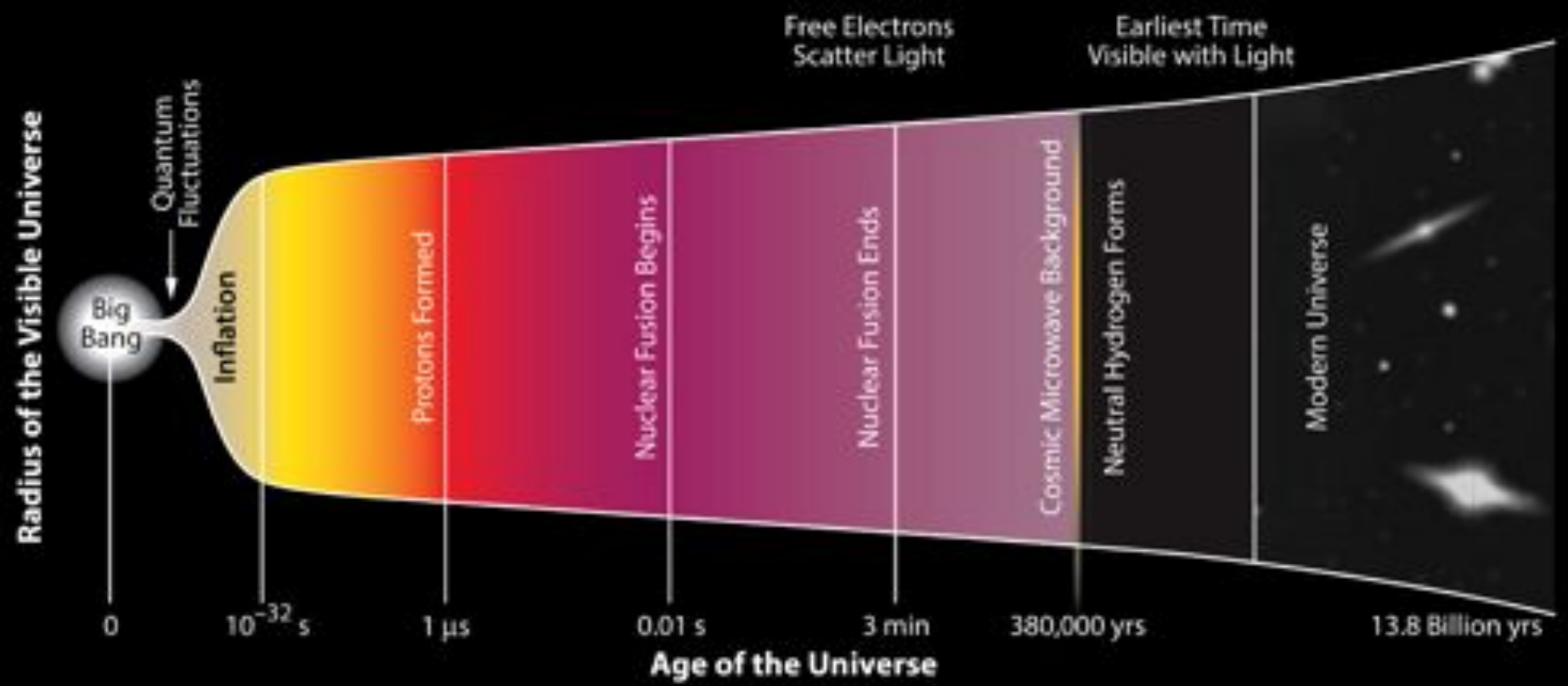


$\Omega < 1: \rho < \rho_{critical}$ **Universe expands**

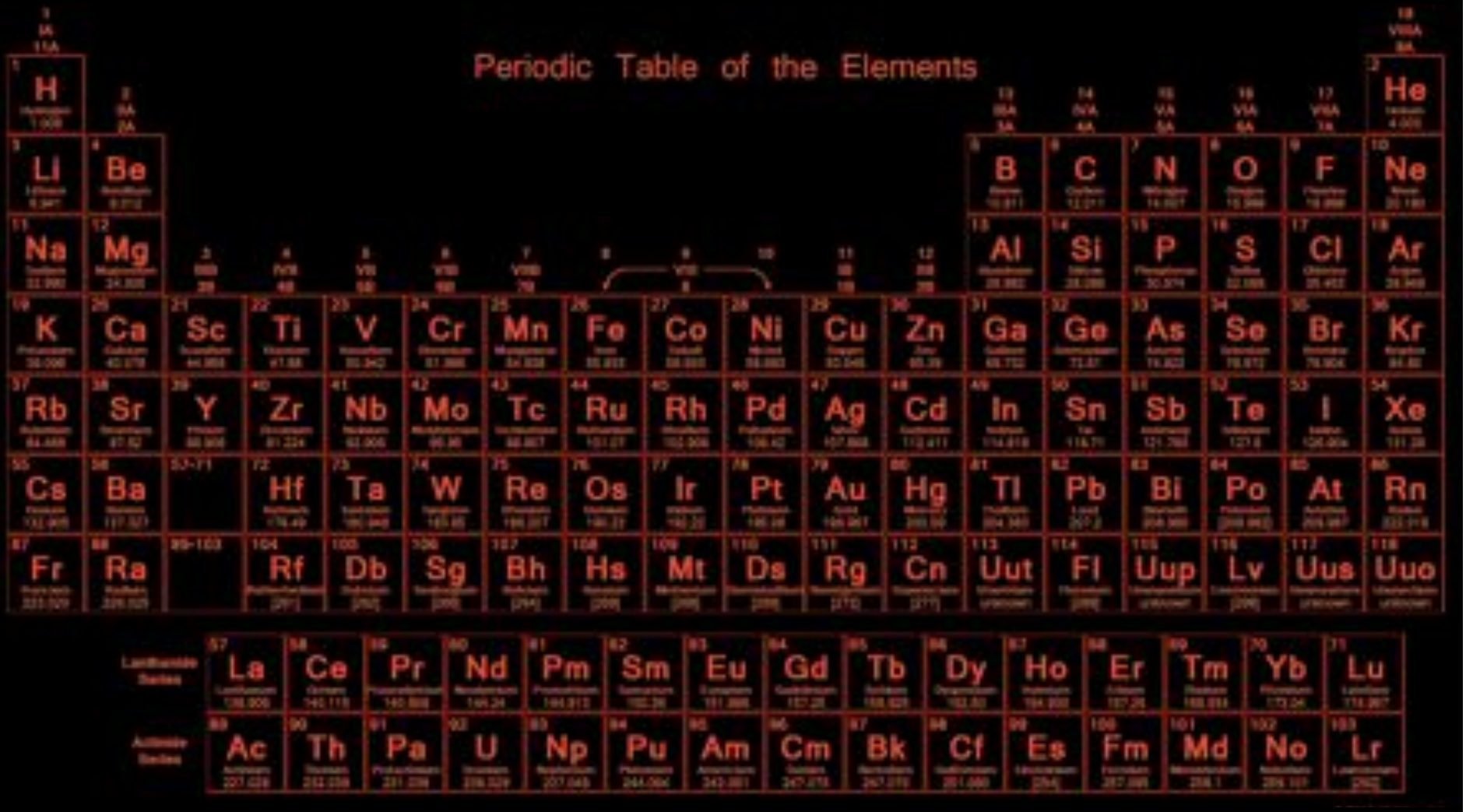
$\Omega = 1: \rho = \rho_{critical}$ **Critical value**

$\Omega > 1: \rho > \rho_{critical}$ **Universe contracts**

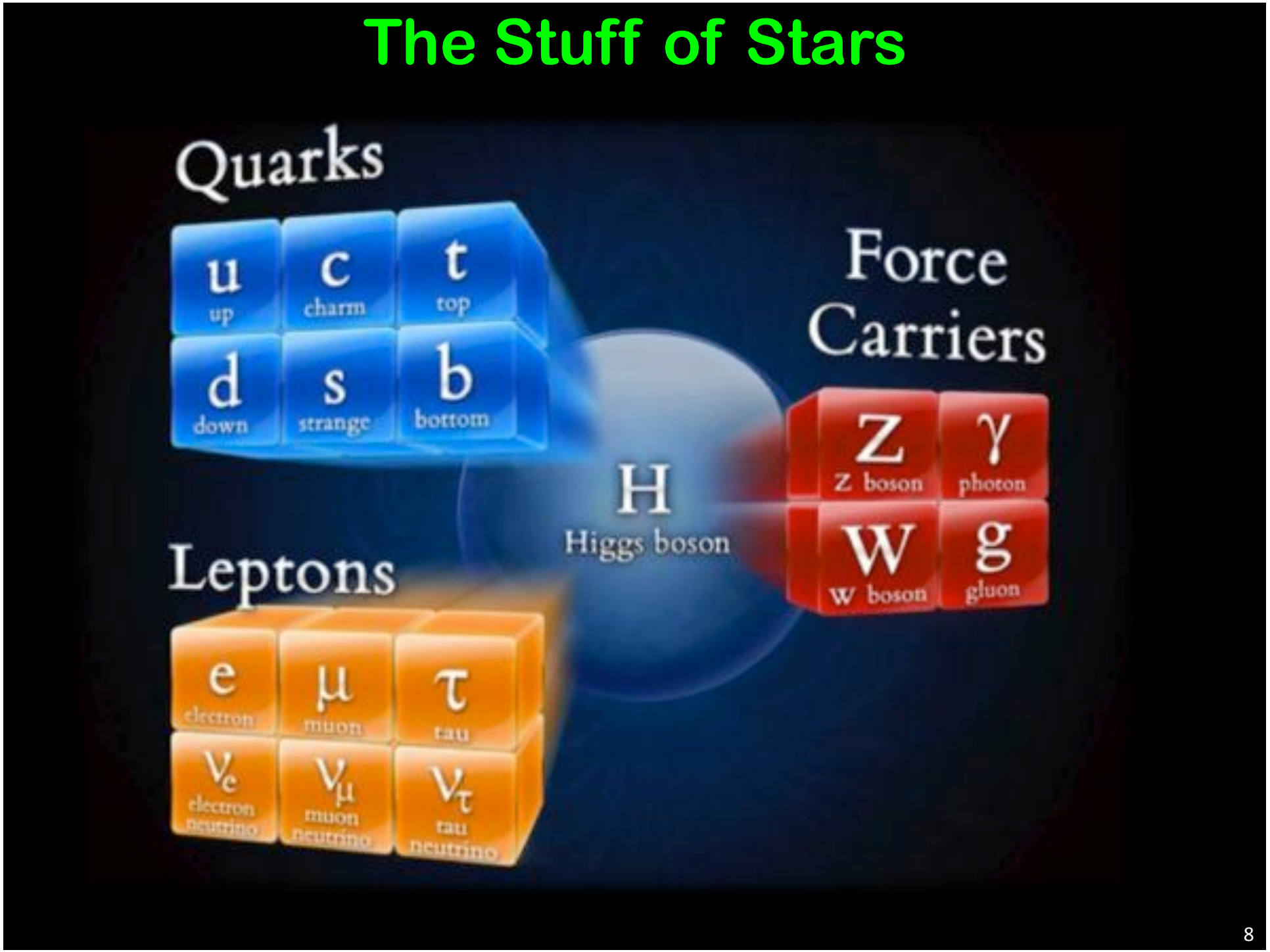
A Very Brief History of Time



The Stuff of Stars



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 ~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 memebers ~ 1000kms^{-1}

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

Total Mass in Stars: M_* ~ 3 x 10^{13} M_{solar}

Total Mass in Gas: M_{gas} ~ 20 x 10^{13} M_{solar}

Not enough matter in luminous form

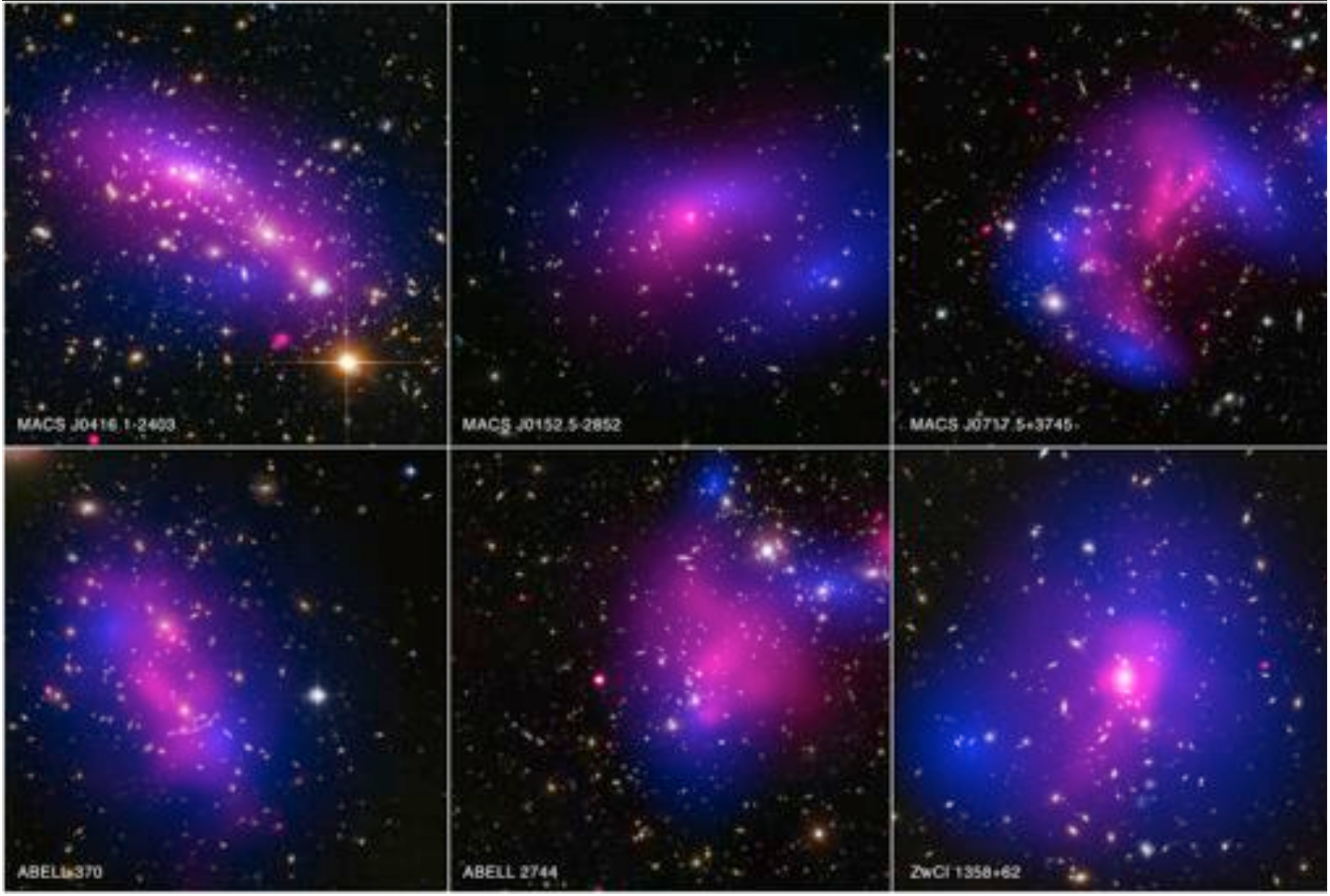
➠ Cluster should be *flying apart* !!

Required *"dunkle materie"*

Evidence: Galaxy Clusters

Evidence: Galaxy Clusters

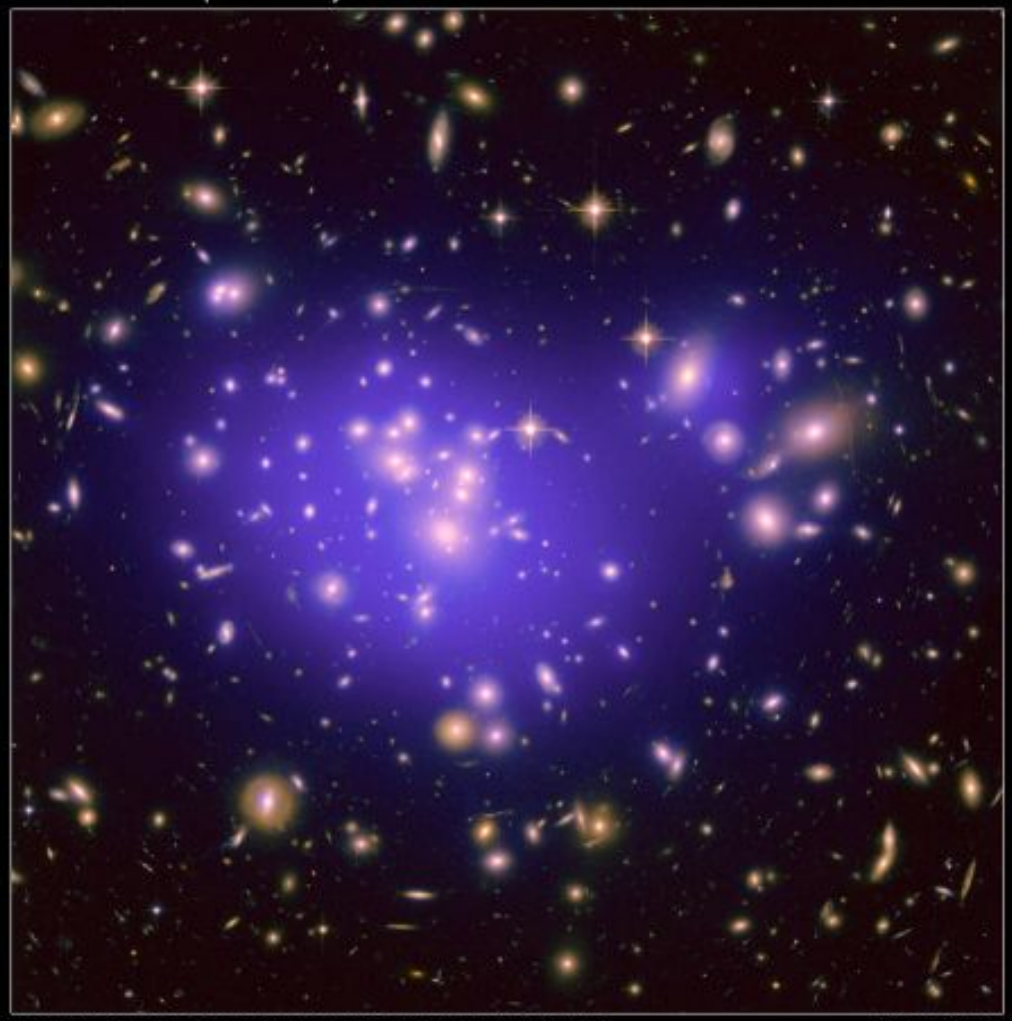
Evidence: Galaxy Clusters



Evidence: Galaxy Clusters

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

Dark Matter Map in Galaxy Cluster Abell 1689 *HST* ACS/WFC

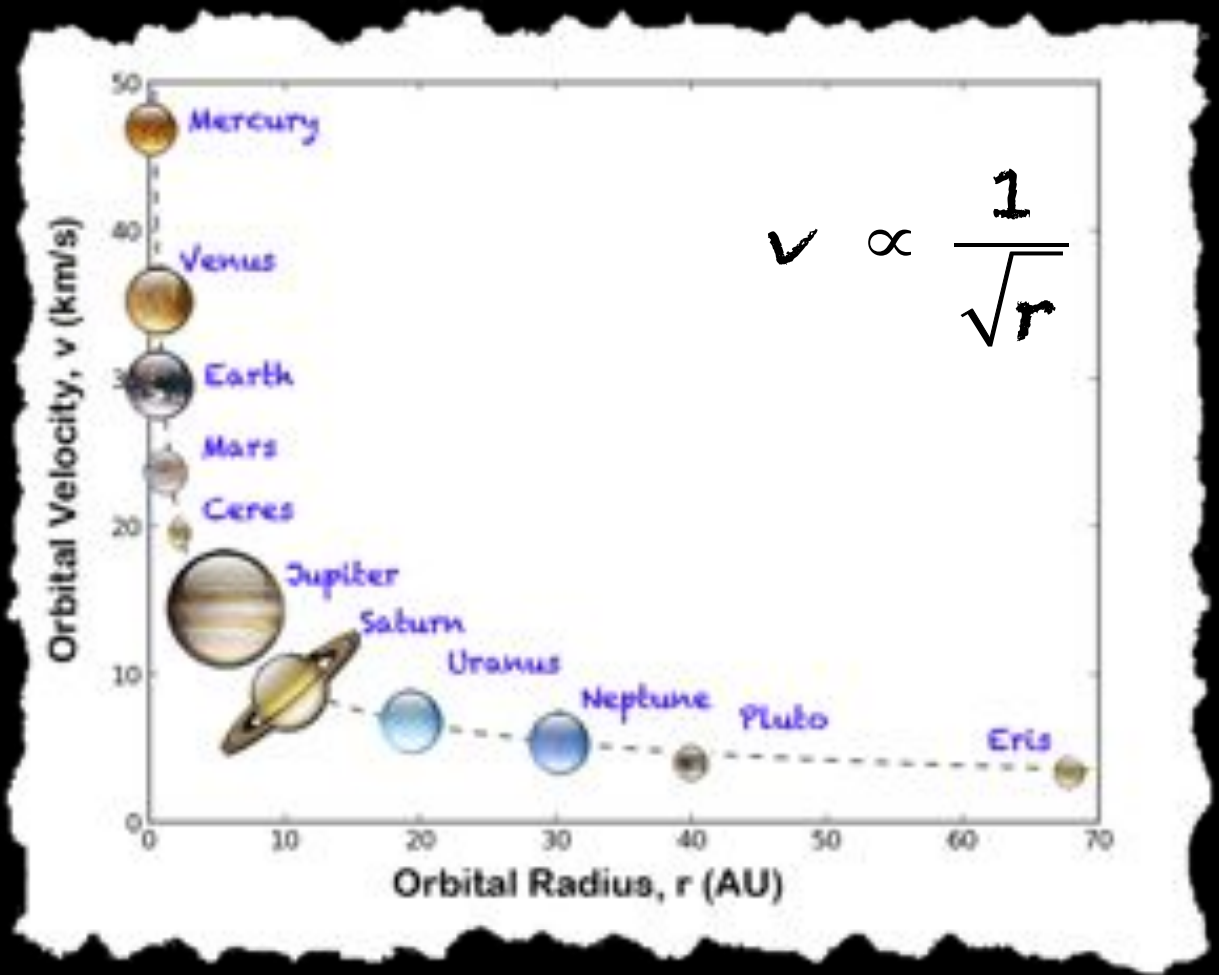


NASA, ESA, E. Jullo (Jet Propulsion Laboratory), P. Natarajan (Yale University), and J.-P. Kneib (Laboratoire d'Astrophysique de Marseille, CNRS, France) STScI-PRC10-28

Evidence: Galaxy Rotation

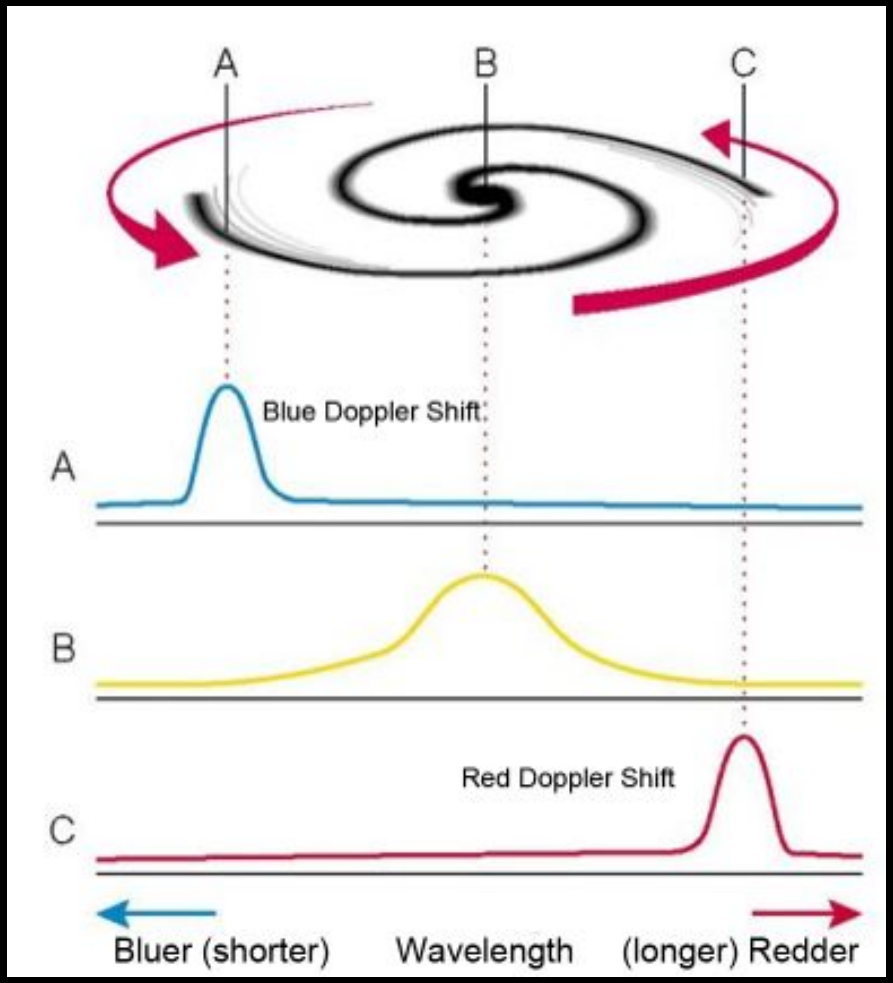
Kepler's 3rd Law of Planetary Motion:
Orbital velocity is proportional to inverse square root of the distance

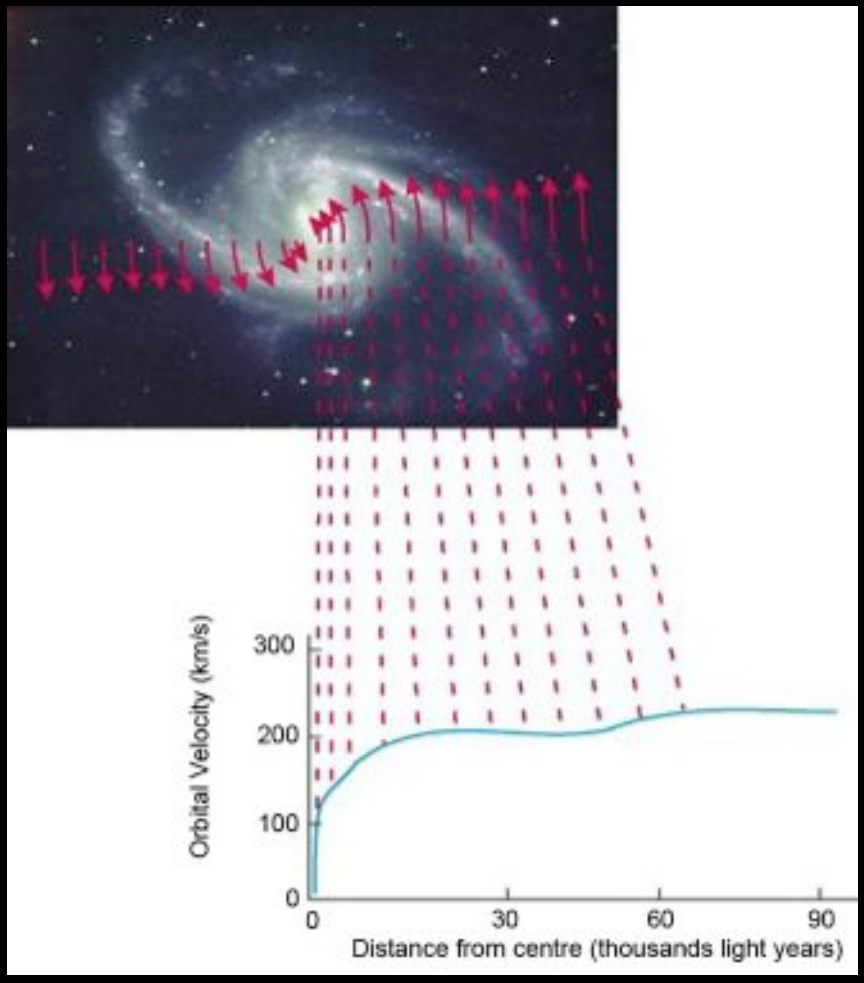
$$F = \frac{GMm}{r^2} = \frac{mv^2}{r} \Rightarrow v \propto r^{-1/2}$$



Evidence: Galaxy Rotation

How do we weigh galaxies ?

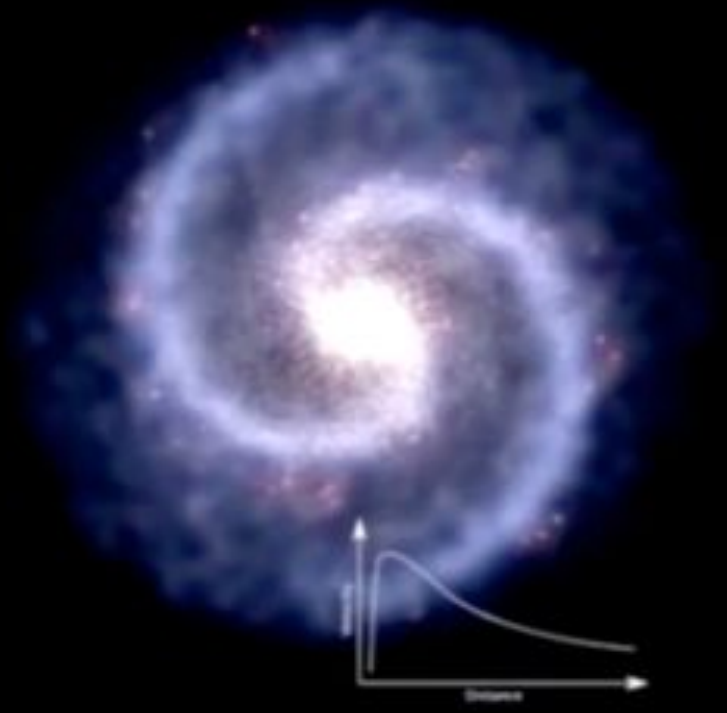




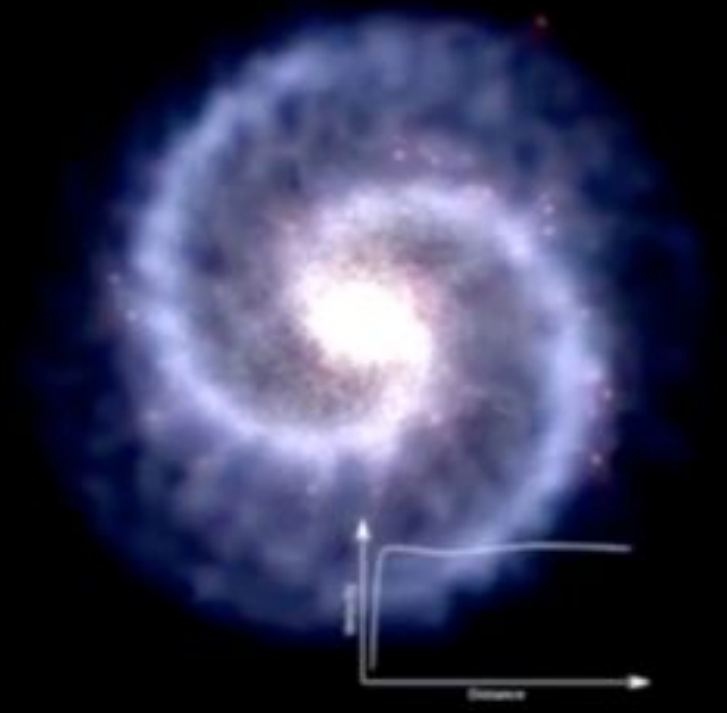
Evidence: Galaxy Rotation

Rubin 1970s : Galaxy Rotation Curves

Evidence: Galaxy Rotation



Galaxy Without Dark Matter

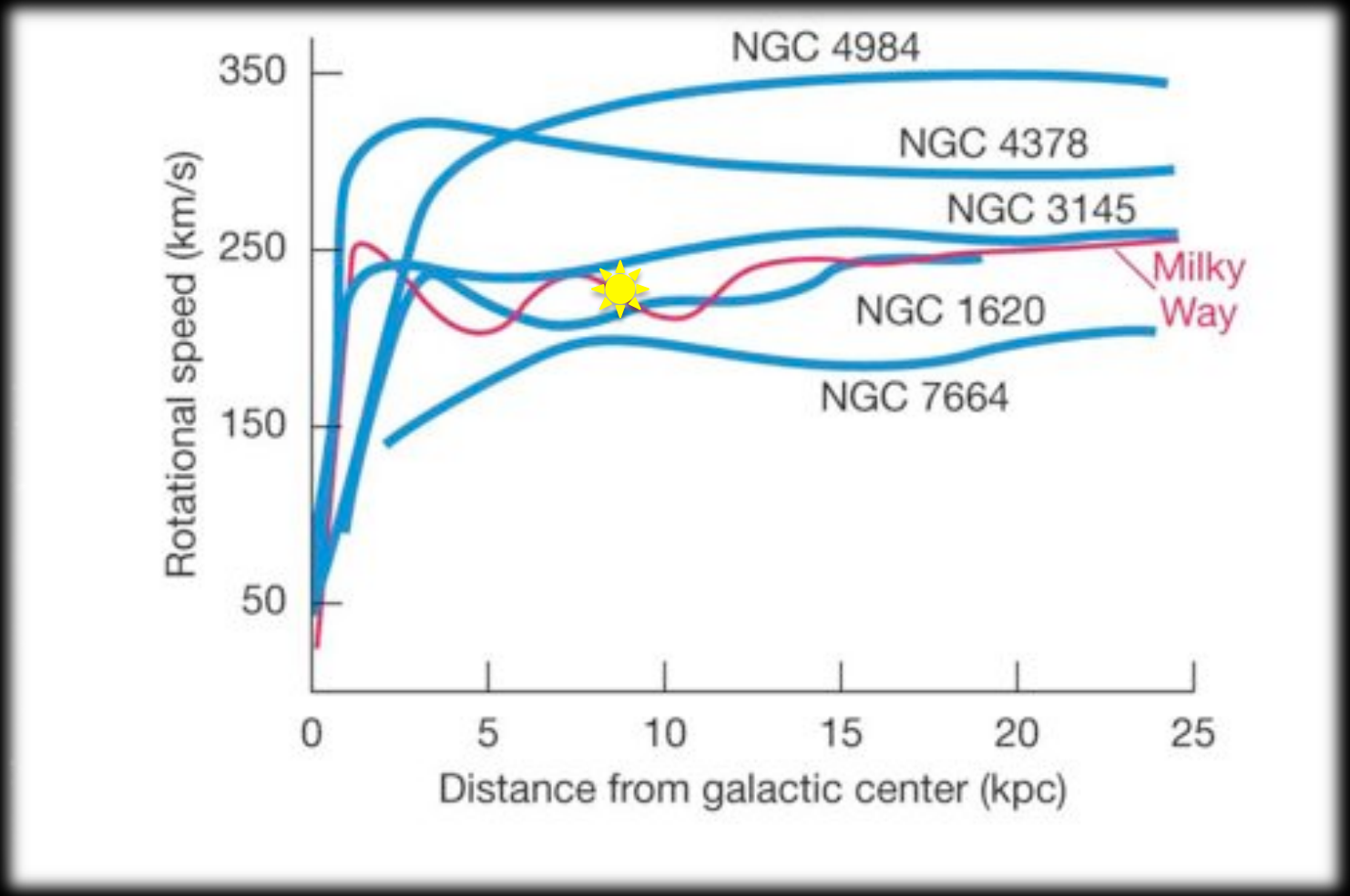


Galaxy With Dark Matter

Evidence: Galaxy Rotation

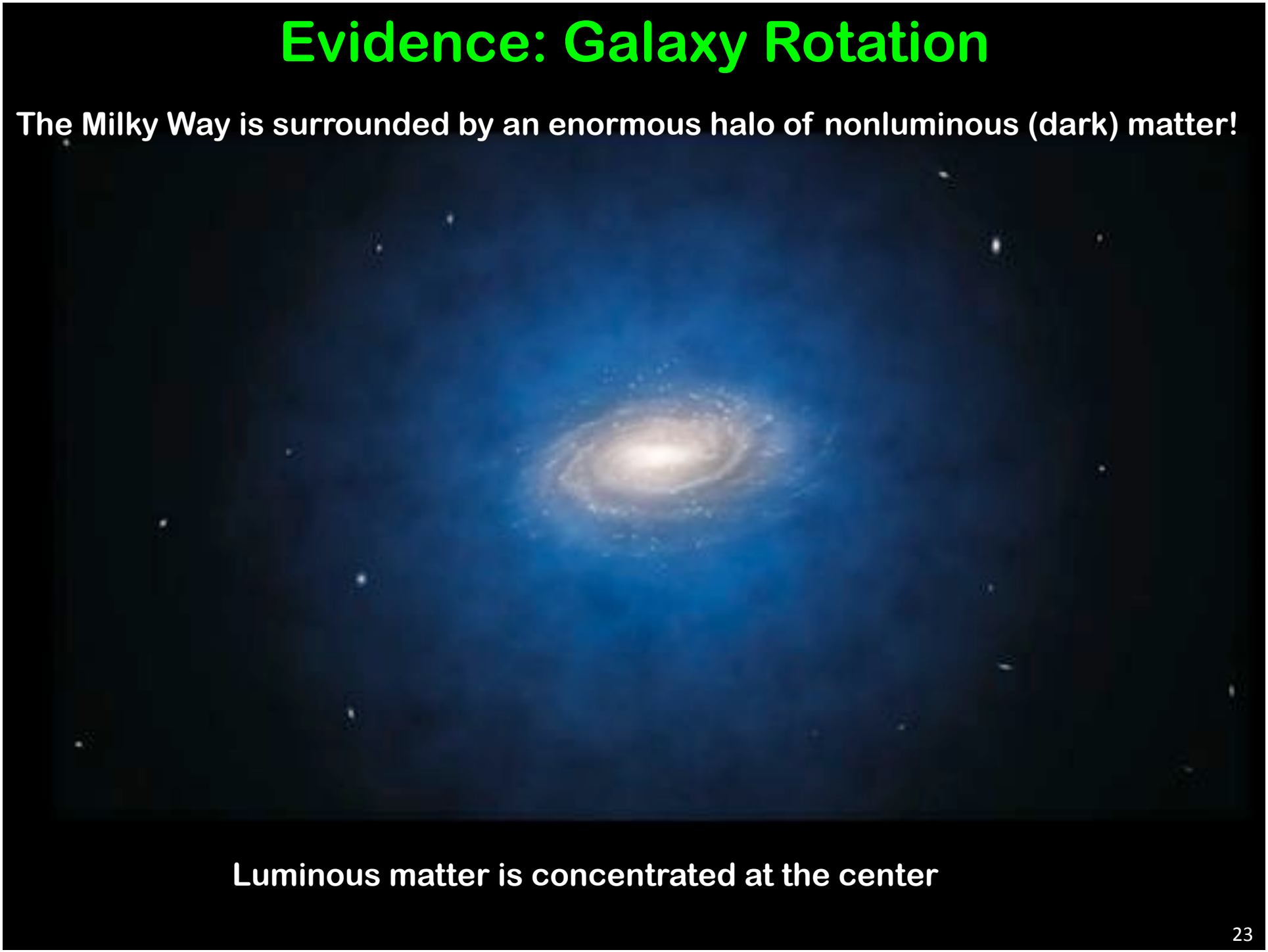
Kepler's Laws of Planetary Motion:
Orbital velocity is proportional to inverse square root of the distance

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



Evidence: Galaxy Rotation

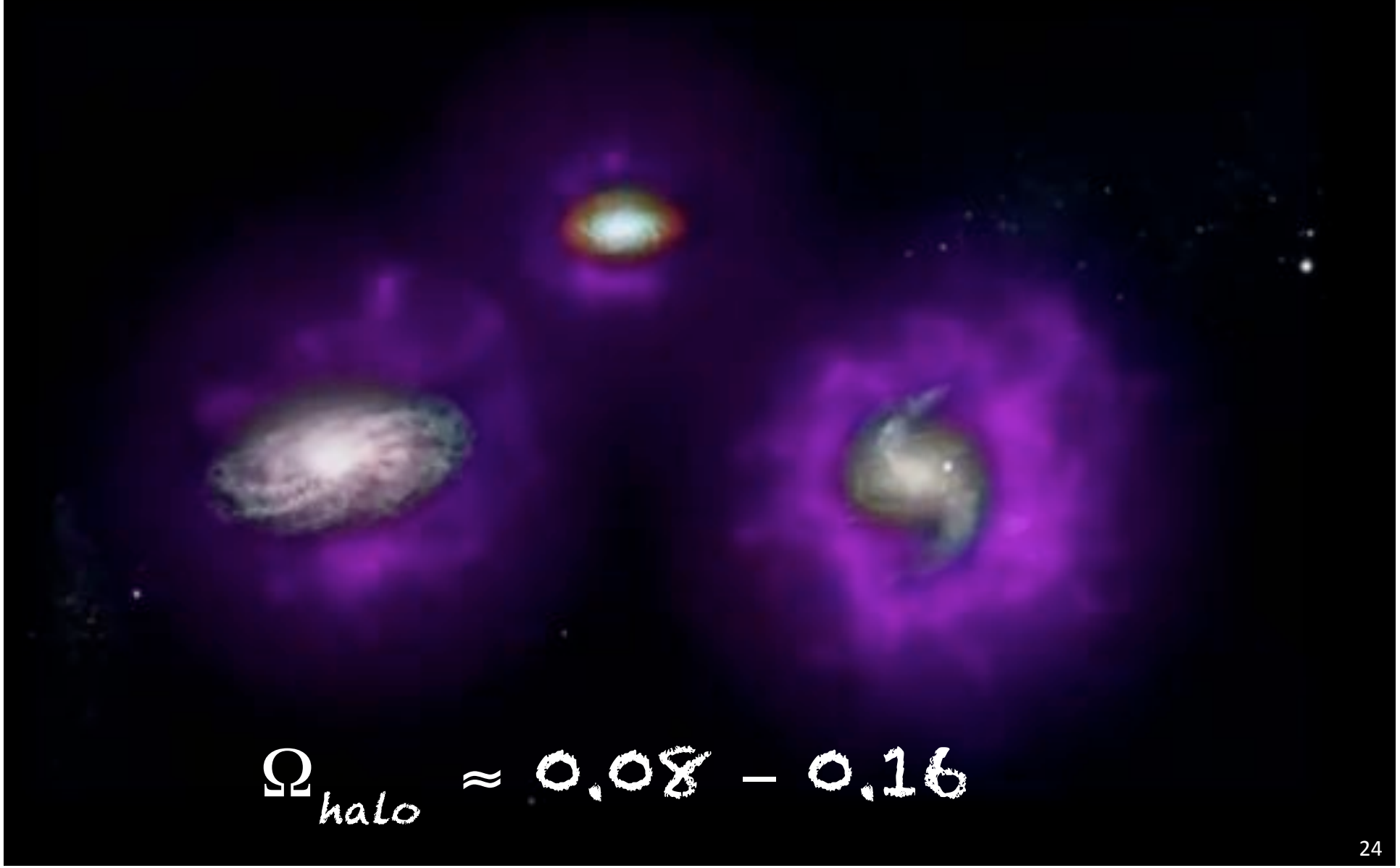
The Milky Way is surrounded by an enormous halo of nonluminous (dark) matter!



Luminous matter is concentrated at the center

Evidence: Galaxy Rotation

The Problem of MISSING MASS ➠ Giant Dark Spherical Halos



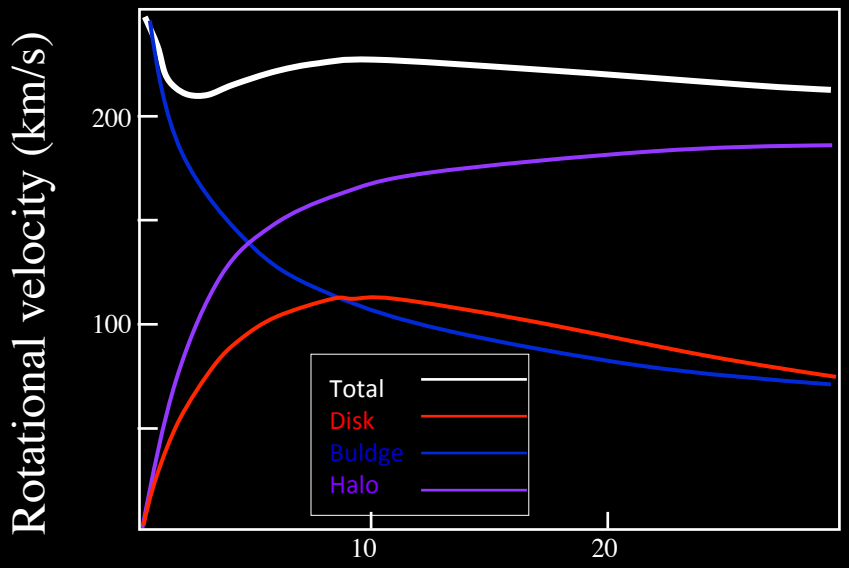
$$\Omega_{halo} \approx 0.08 - 0.16$$

Evidence: Galaxy Rotation

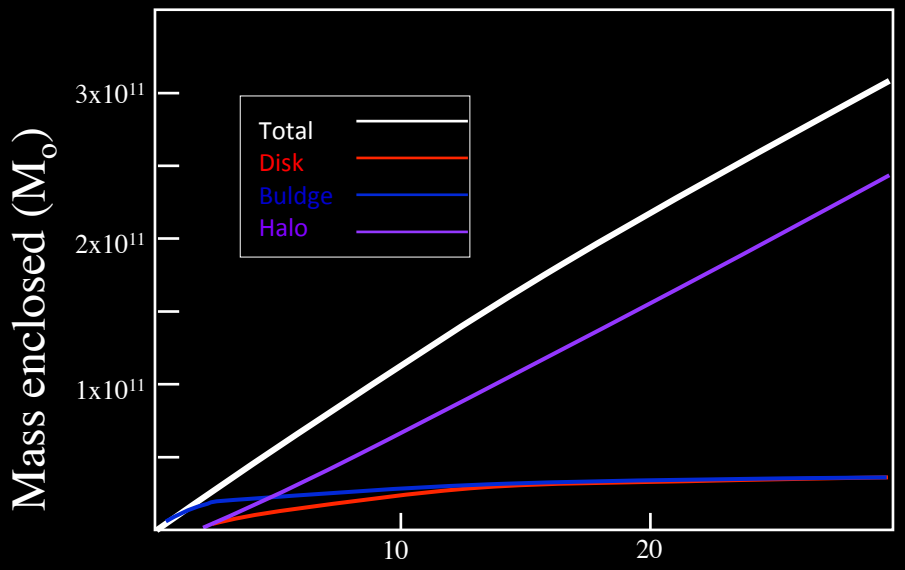
The Problem of MISSING MASS ? ➠ rather MISSING LIGHT !

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

Rotation Curve for Milky Way



Mass Enclosed with distance for Milky Way

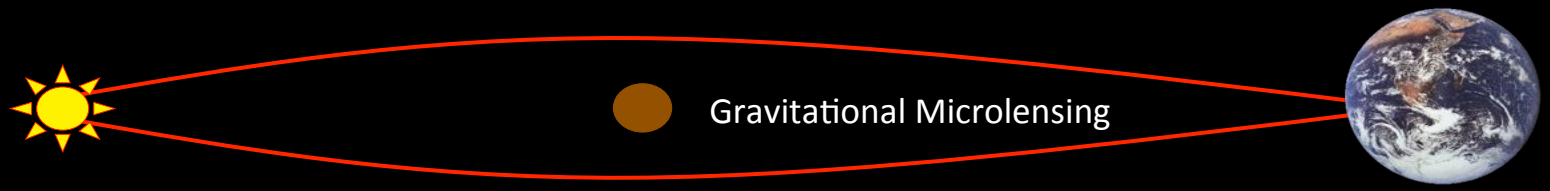


Evidence: Gravitational MicroLensing

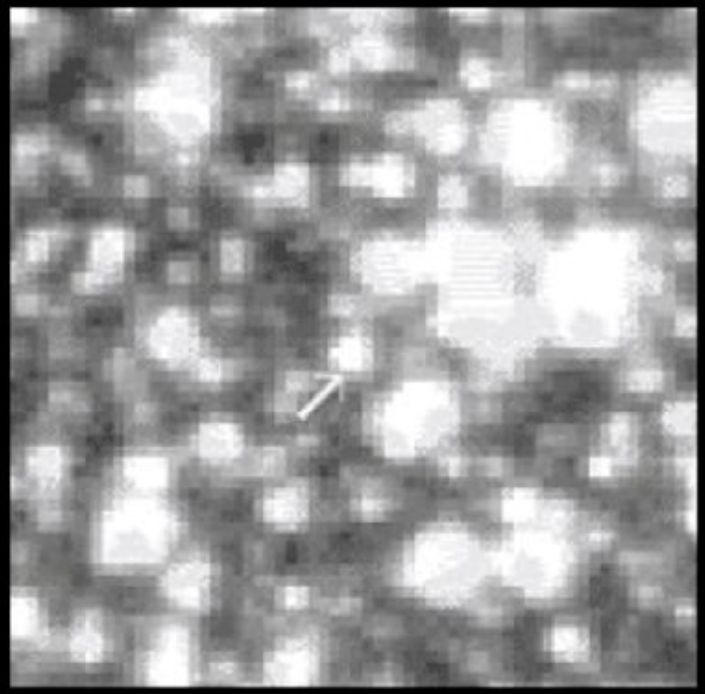
Searching for Dark Matter in the Galaxy Halo: **MA**ssive **C**ompact **H**alo **O**bject**S**

Evidence: Gravitational MicroLensing

Searching for Dark Matter in the Galaxy Halo: MAssive Compact Halo ObjectS

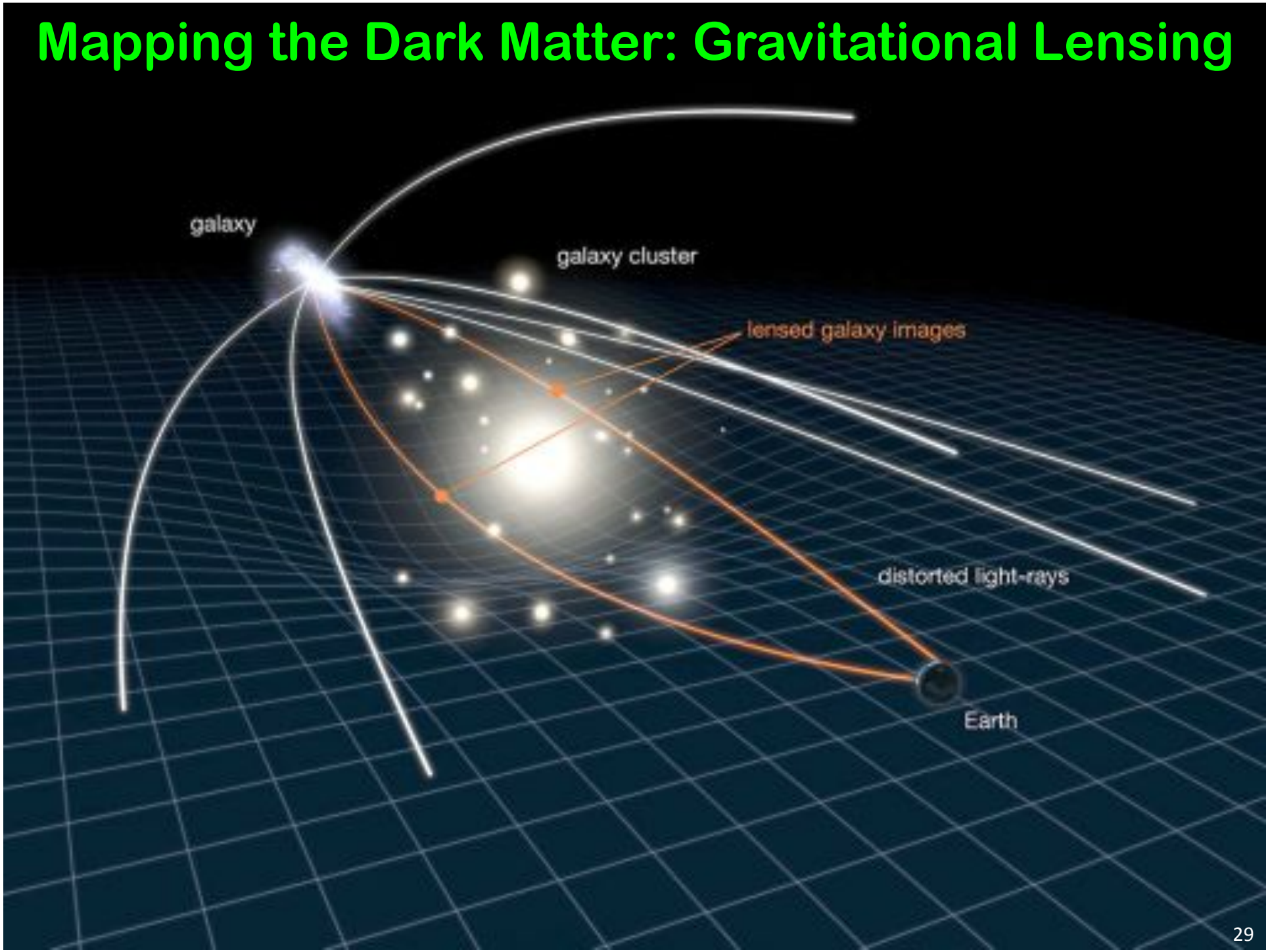


Observe amplification (brightening) of background star/galaxy as it is focused by halo object



Mapping the Dark Matter: Gravitational Lensing

Mapping the Dark Matter: Gravitational Lensing

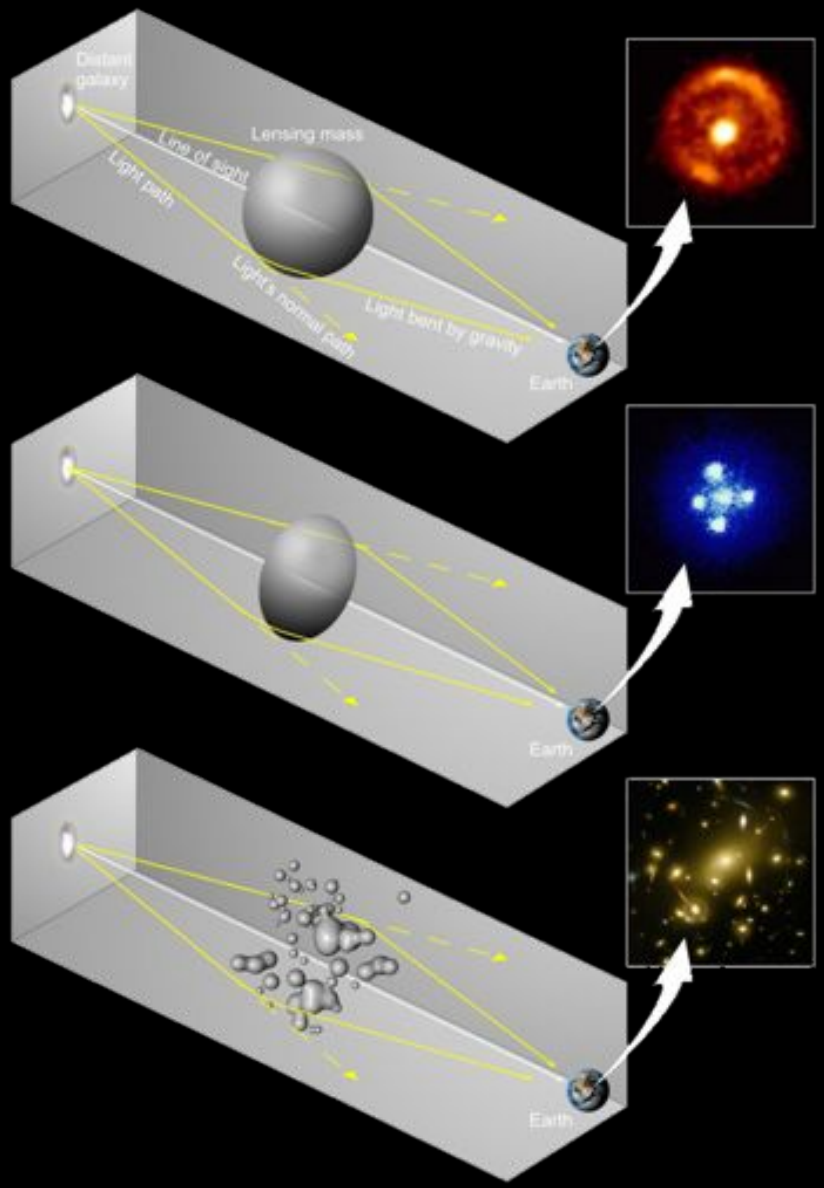


Mapping the Dark Matter: Gravitational Lensing

Spherical Lens: Einstein Ring

Oblate Lens: Einstein Cross

Clumpy Lens: Giant Arcs



Mapping the Dark Matter: Gravitational Lensing

Spherical Lens: Einstein Ring

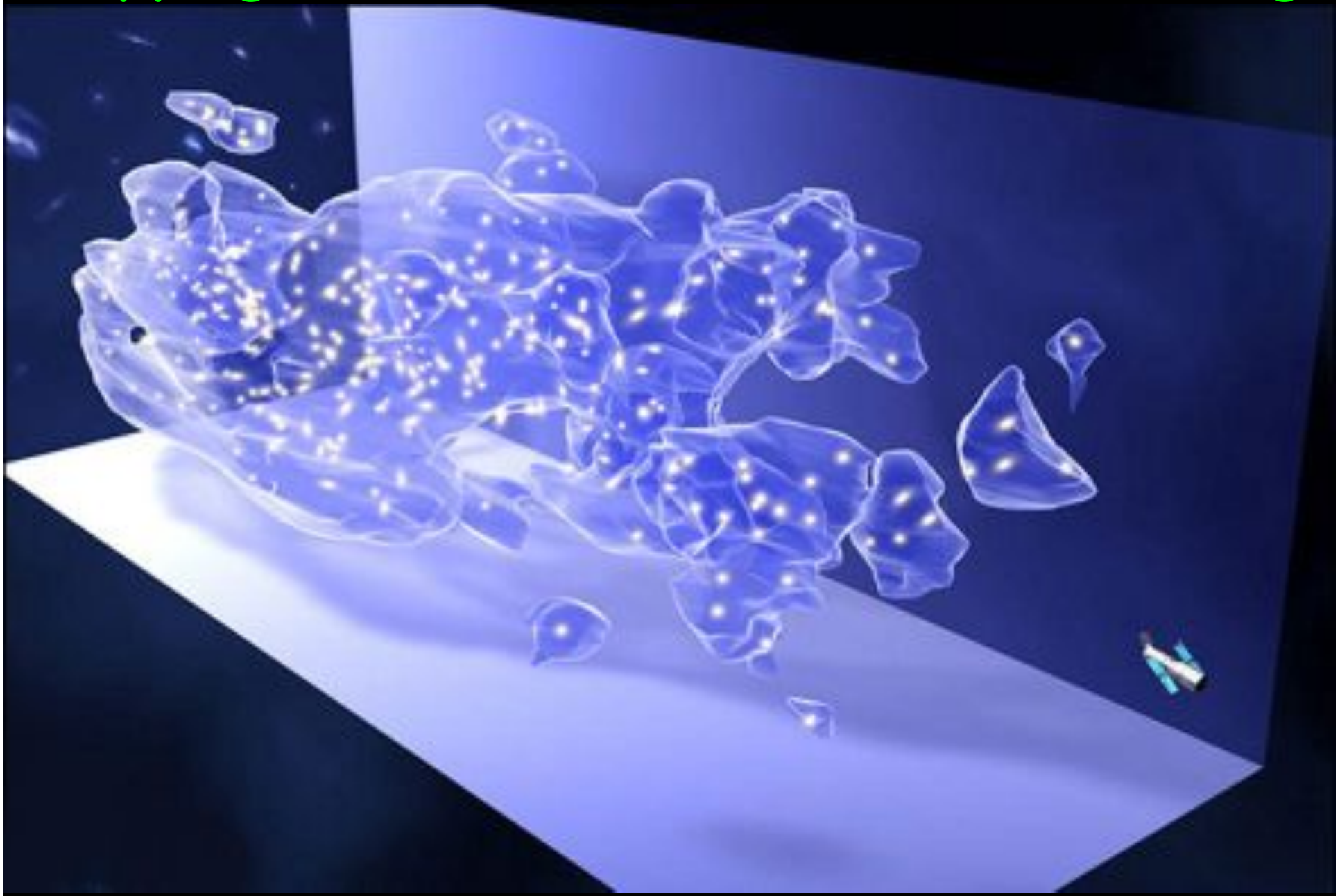
For a lens *halfway* between observe and source (d = lens distance)
Einstein Ring Angular Radius ~

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

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

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

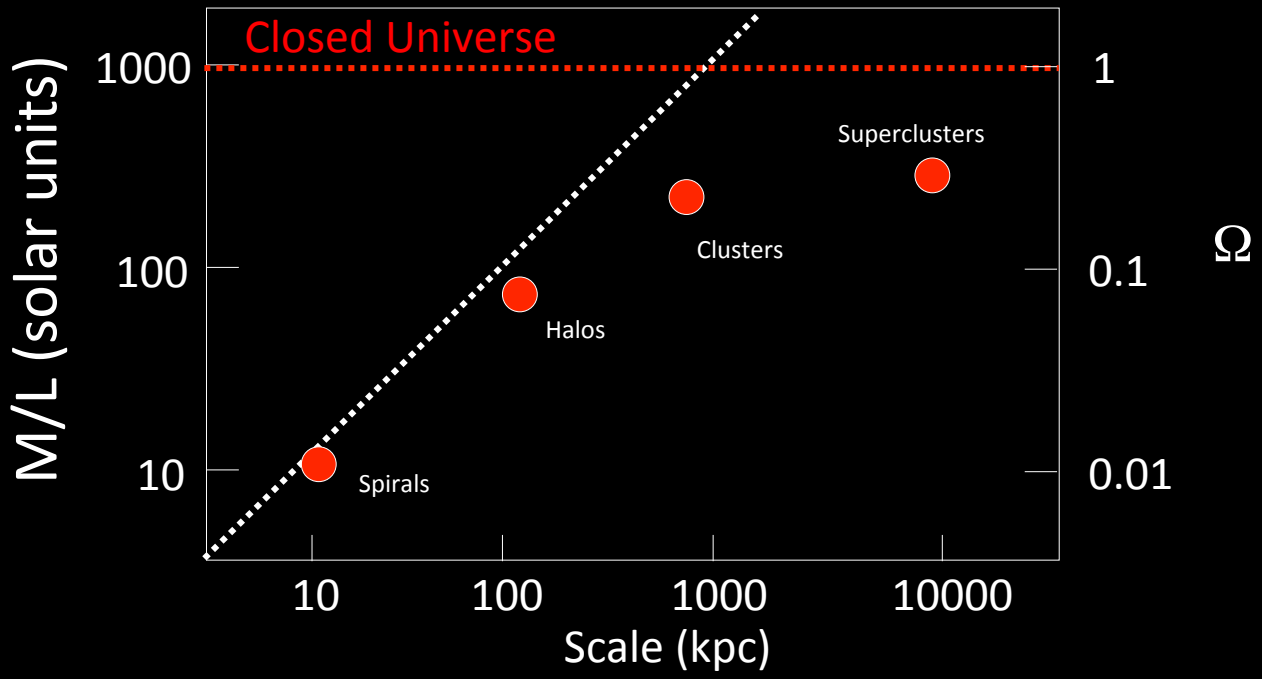
Mapping the Dark Matter: Gravitational Lensing



Measured, Weighed …… and found wanting

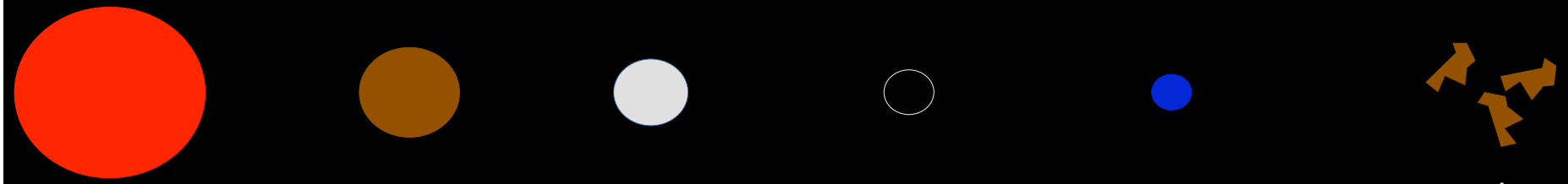
	M/L
Solar Neighbourhood	0.004
Galaxy Disk	10
Galaxy Halos	40-100
Galaxy Clusters	250

	Ω
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 ???

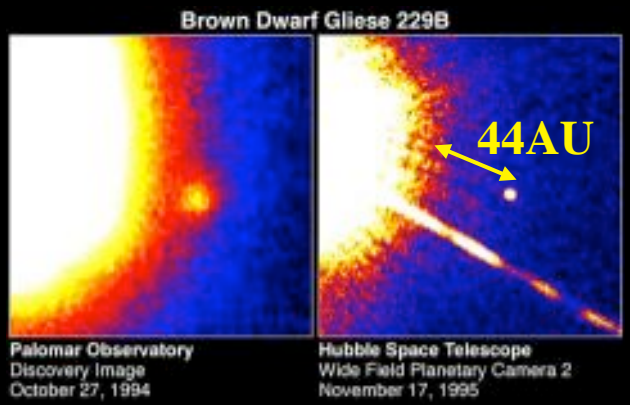
Baryonic Dark Matter ?



Red Dwarf Brown Dwarf Black Dwarf Black Hole Neutron Star Jupiters/Planets

1. **RED DWARF STARS < $1M_o$ (T^o~2000K)**
   - Not enough detected

2. **BROWN DWARF < $0.08M_o$ (T^o~1000K) - failed star**
   - Not enough detected

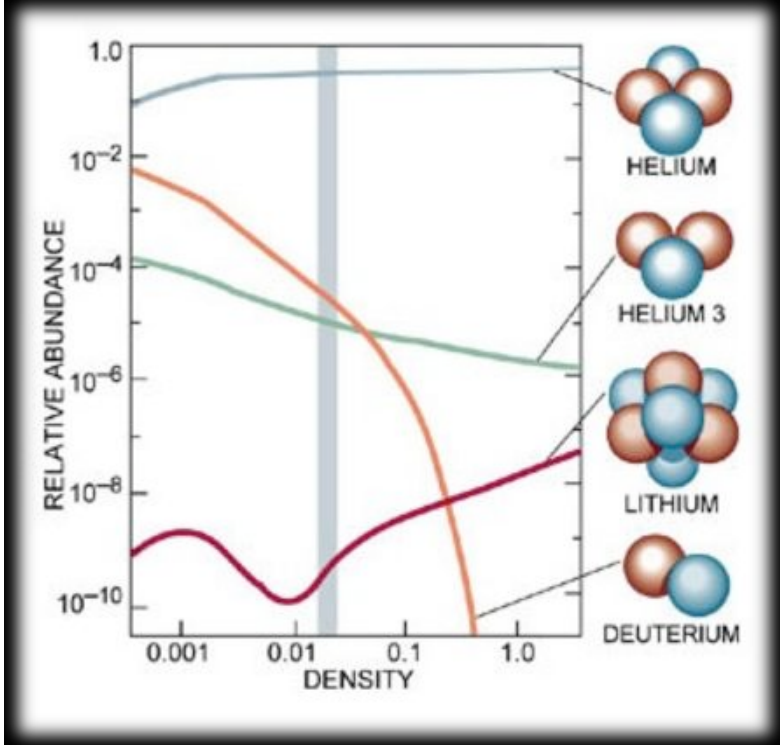


3. **STELLAR REMNANTS (Black Dwarf, Neutron Stars, Black Holes) ~ $1M_o$**
   - Universe too young for so many remnants to form
   - Universe too young for remnants to cool to Black Dwarf

4. **JUPITERS / PLANETS / ROCKS ~$0.001M_o$**
   - 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 η

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

- High baryon-photon rato ➠ higher density
- ➠ nucleosynthesis starts earlier (higher T)
- Helium production more efficient
- Less Deuterium (& ^{3}He) leftover

Observed abundance of Deuterium sets upper limit for primordial abundance

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

The Problem with the Baryons

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

But .....

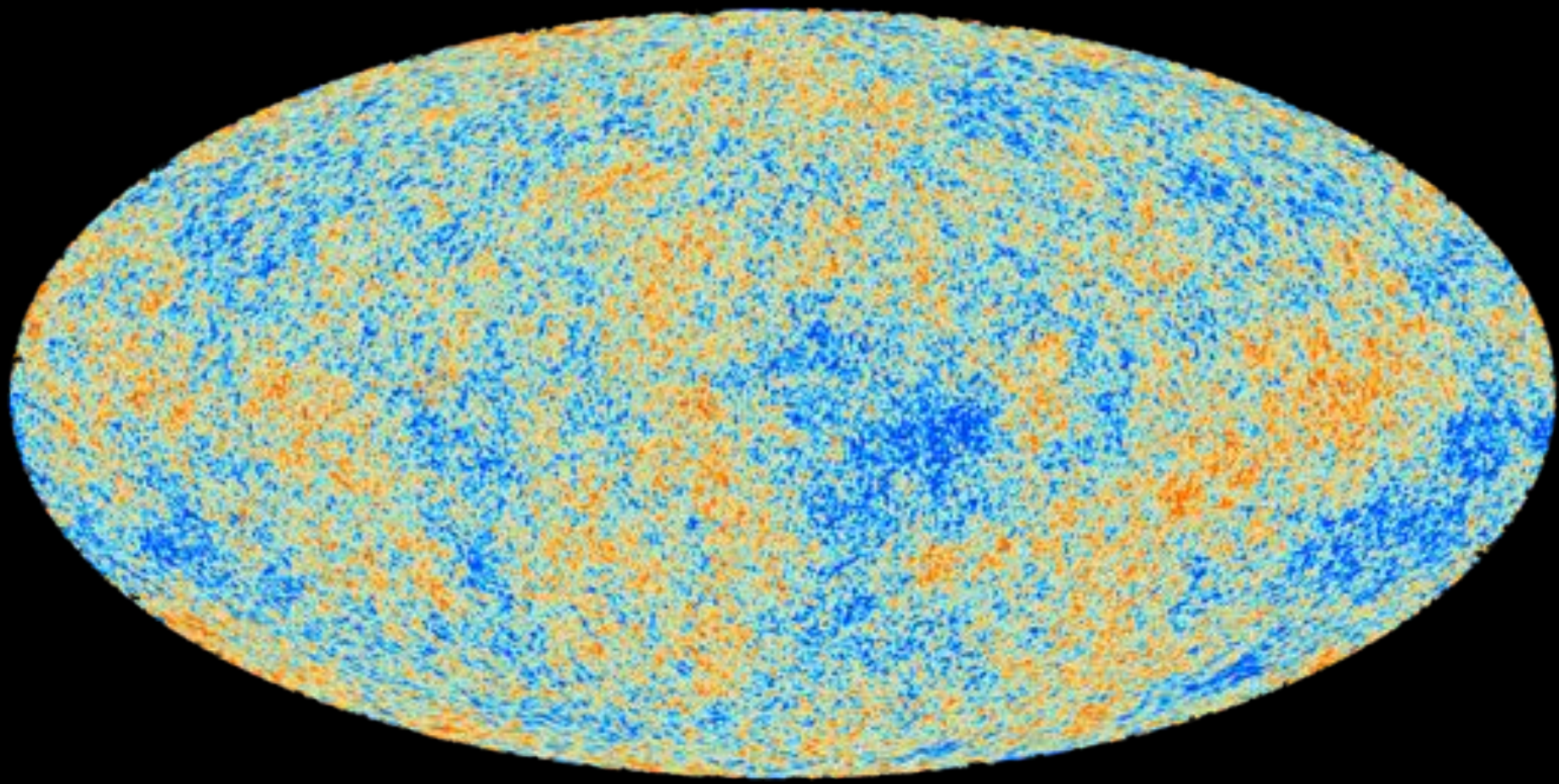
$$\Omega_{halo} \sim 0.16$$

$$\Omega_{clusters} > 0.2$$

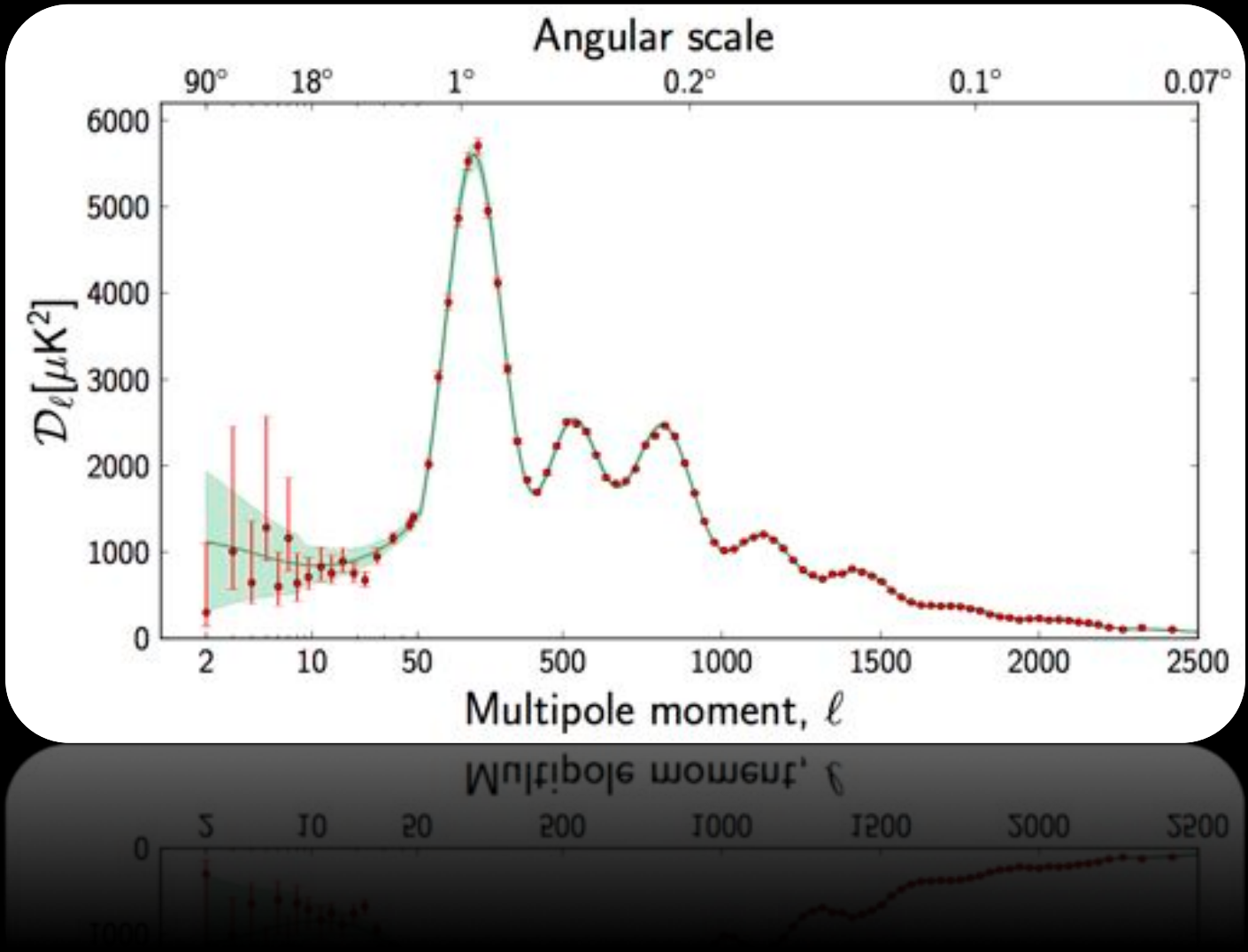
There is a factor 5 more dark matter than can be explained by the baryon abundance

majority of Dark matter most be non-baryonic

The Worst is yet to come !

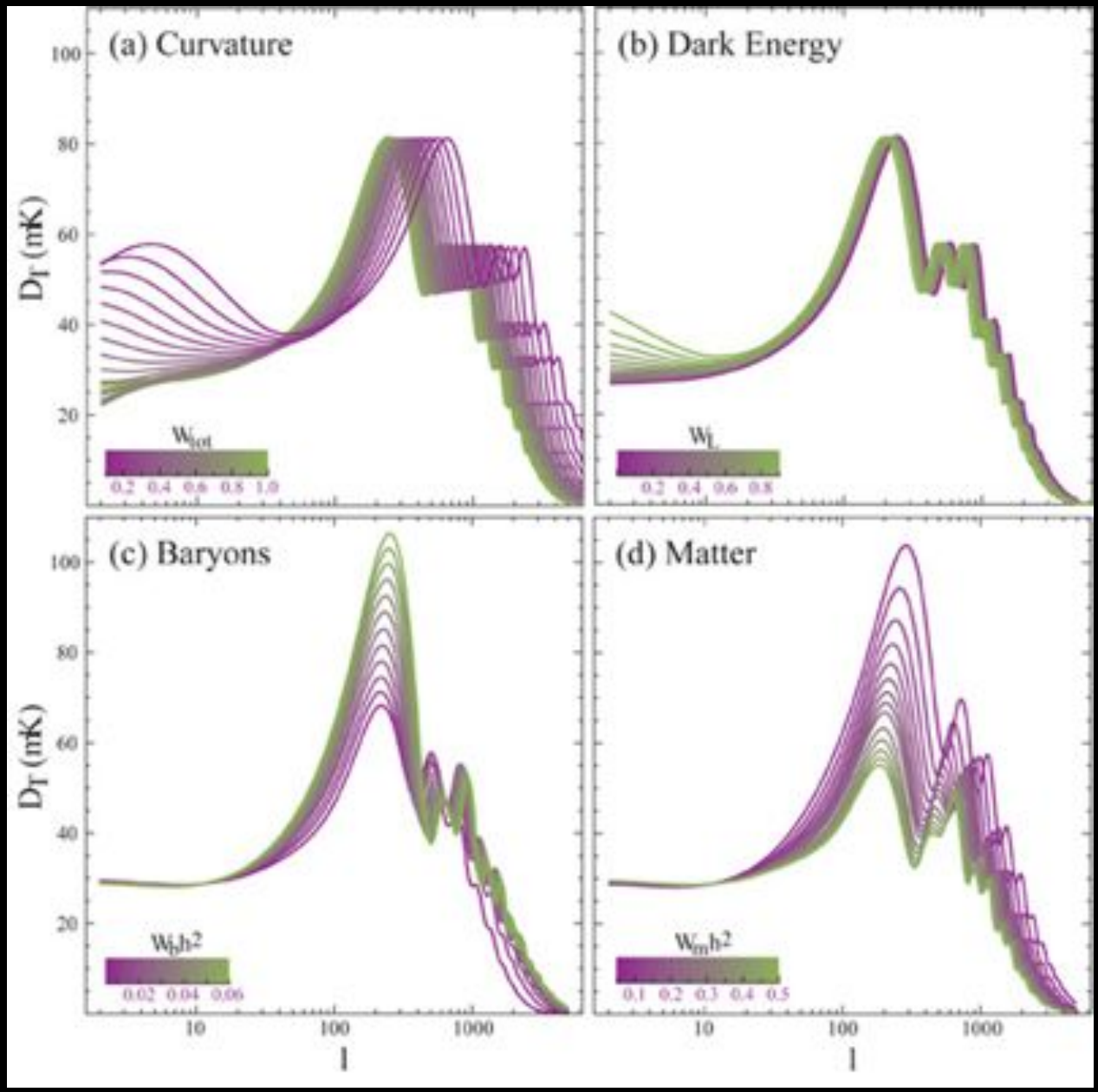


Non-Baryonic Dark Matter



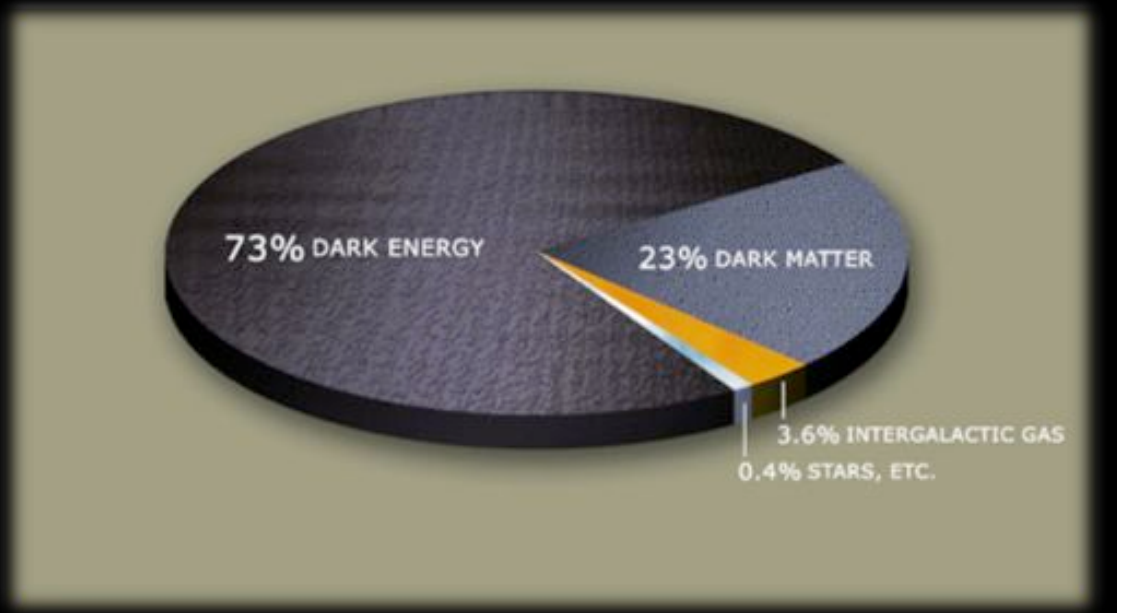
Consistent with $\Omega_{Total} = 1$

Non-Baryonic Dark Matter



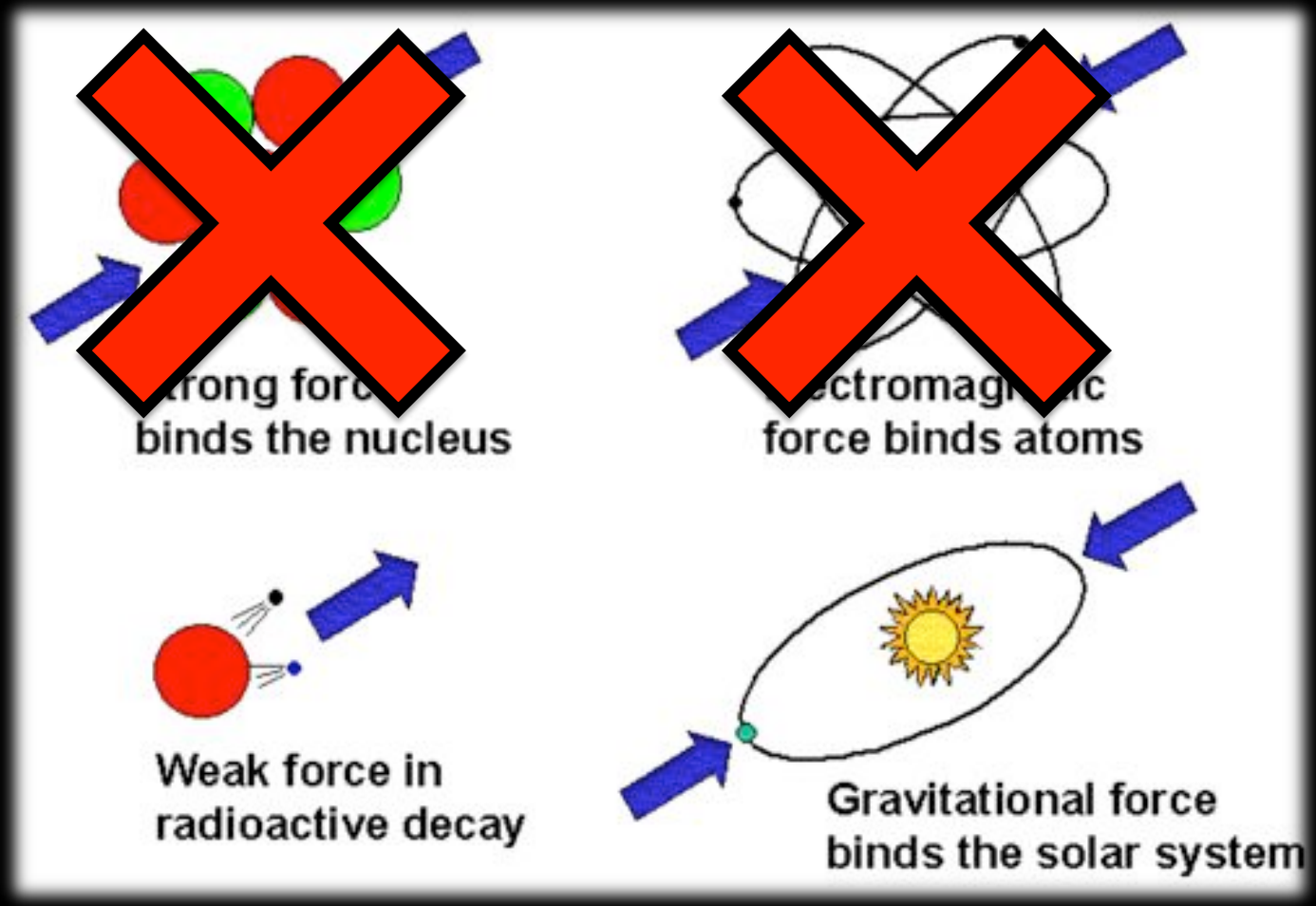
Non-Baryonic Dark Matter

	Ω
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

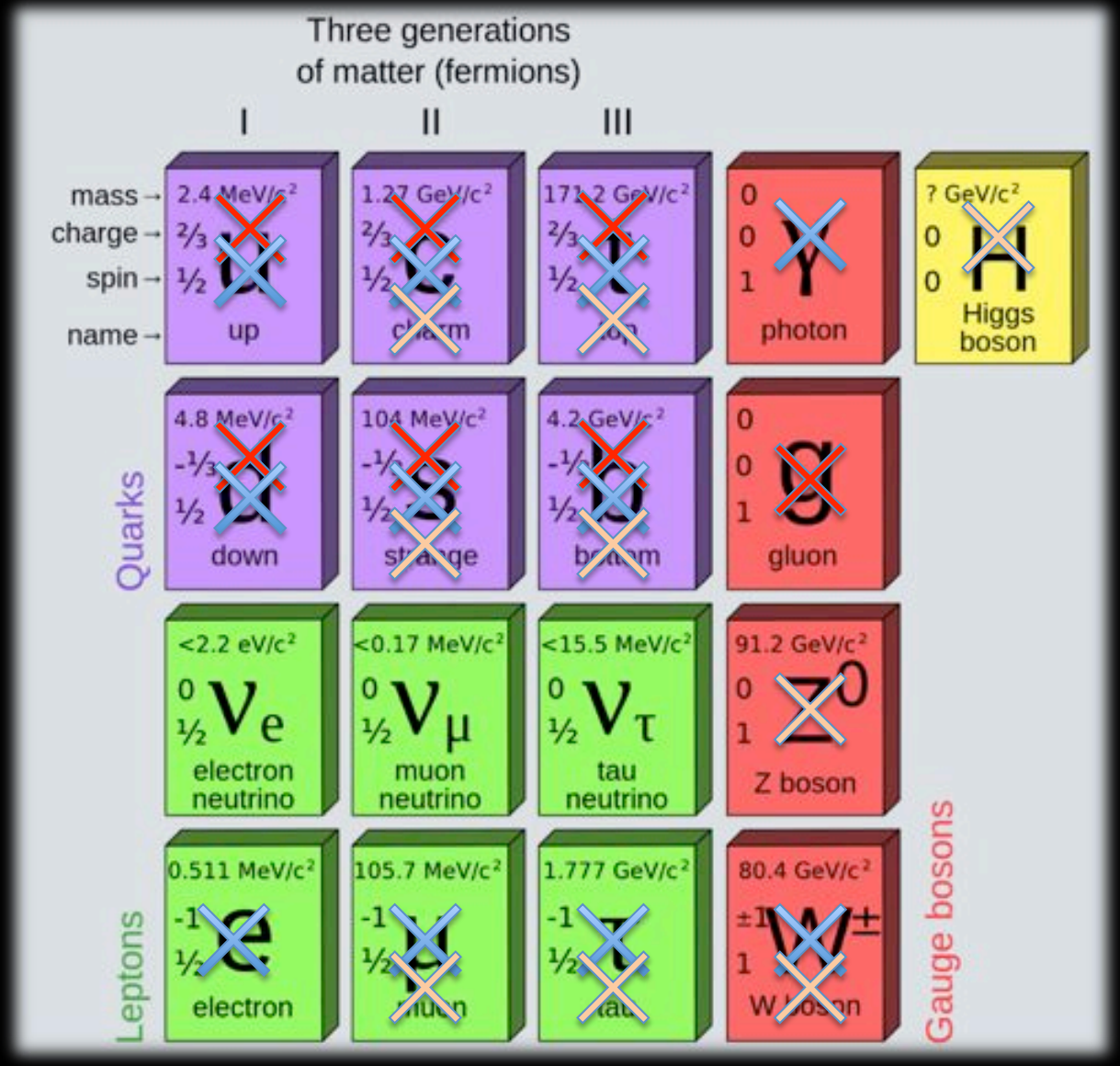


- **Baryonic matter consistent with local solar neighbourhood and intracluster medium**
- **Some of Halo mass possibly dark baryons - BARYONIC DARK MATTER**
- **Majority of Halo and Cluster dark matter ➠ NON BARYONIC DARK MATTER**
- **73% of Universe is DARK ENERGY**

Non-Baryonic Dark Matter



Non-Baryonic Dark Matter



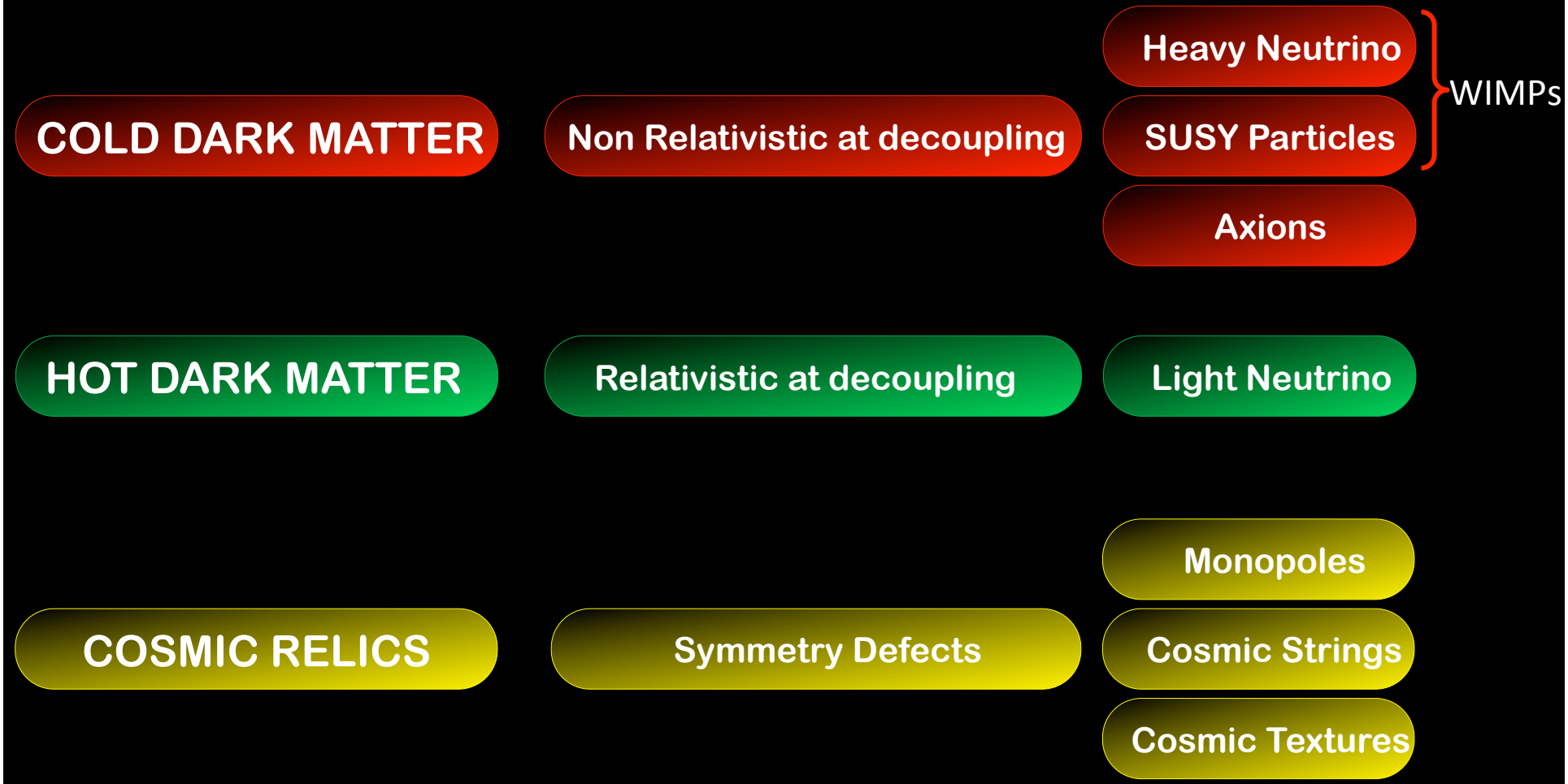
Baryons
(strong Force)

Charged
(Electromagnetism)

Decays

Non-Baryonic Dark Matter

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



Hot Dark Matter: Neutrinos

The ONLY Dark Matter Candidate known to exist

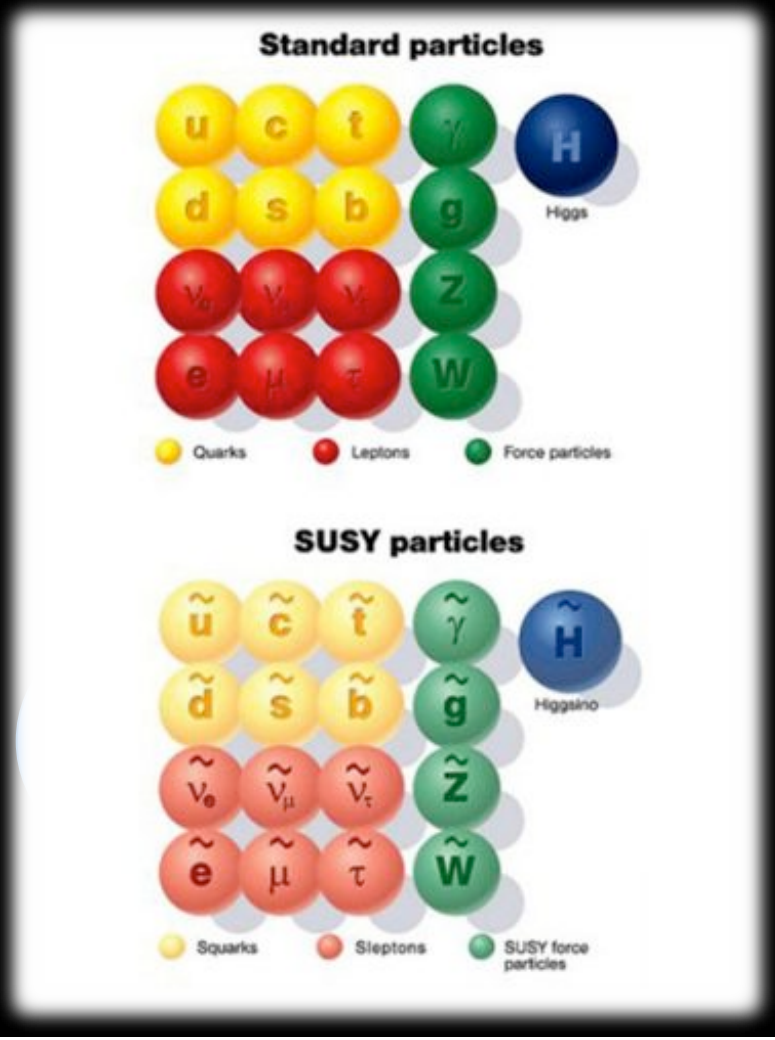
Neutrino density from big bang ~ 330 /cm^3 (compare with radiation) 410 /cm^3

In order to contribute ALL Dark Matter require $m_{neutrino}$ ~ 4eV

Cold Dark Matter: WIMPS

Weakly Interacting Massive Particles (opposite to MACHOS !!)

Supersymmetry: higher order symmetry connecting: Fermions ⇔ 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 ⇒ 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

$m_{sneutrino} > m_{sleptons}$

gravitino - self annihilates too slowly ➠ too high abundance

Photino mass ~ 0.5GeV ➠ Possible candidate for LSP

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

Cold Dark Matter: WIMPS

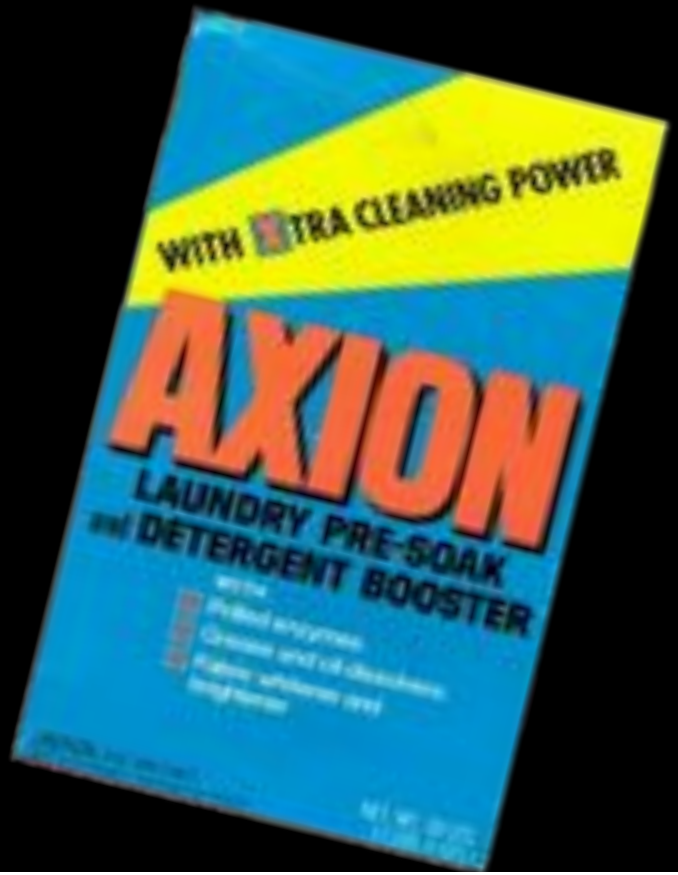
Weakly Interacting Massive Particles

the expected WIMP fl ux at Earth is enormous, $10^7\ m_{WIMP}/cm2$,
(m_{WIMP} = WIMP mass in GeV).

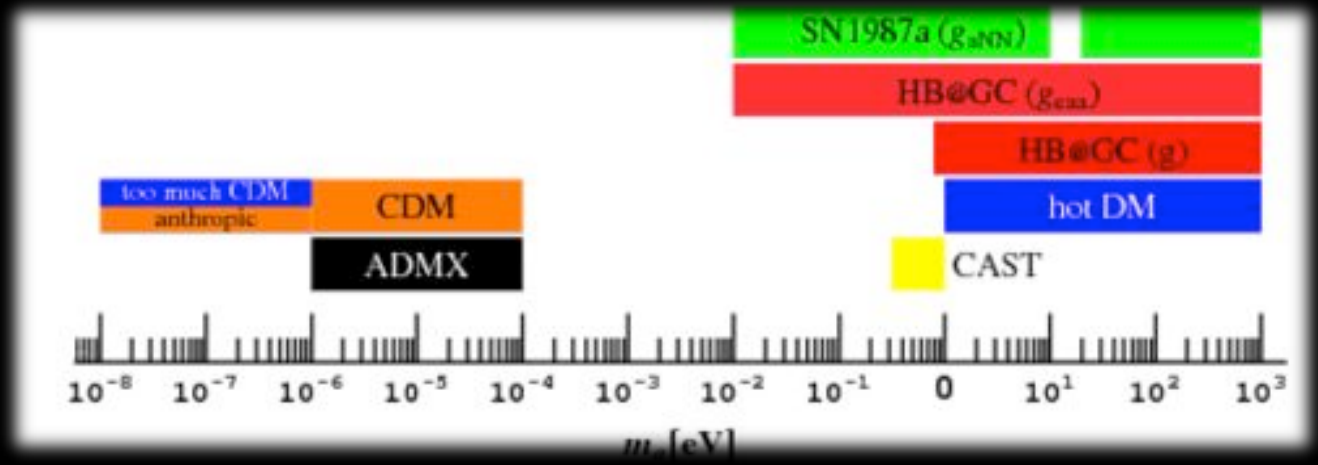
However, WIMP-nucleon scattering cross sections < $10^{-41}\ cm^2$
-> expected WIMP-nuclear scattering rate ~0.001 to 1 event /kg

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 -> decay into photons

$$10^{-5}\ eV < m_{axion} < 6x10^{-3}\ eV$$

Ω<1 lighter axion greater energy density

- Axions created abundantly in the Big Bang

- Coupling to inflation field
  -> dynamical friction strips primordial axions of their kinetic energy

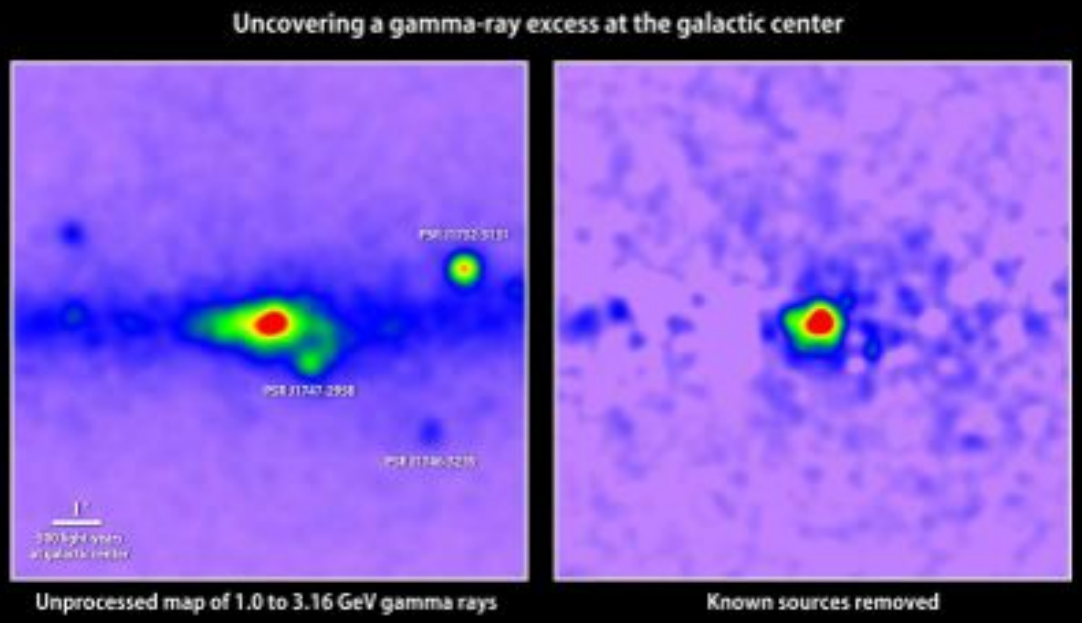
- Axions are light but still **cold** (non-relativistic when decouple)

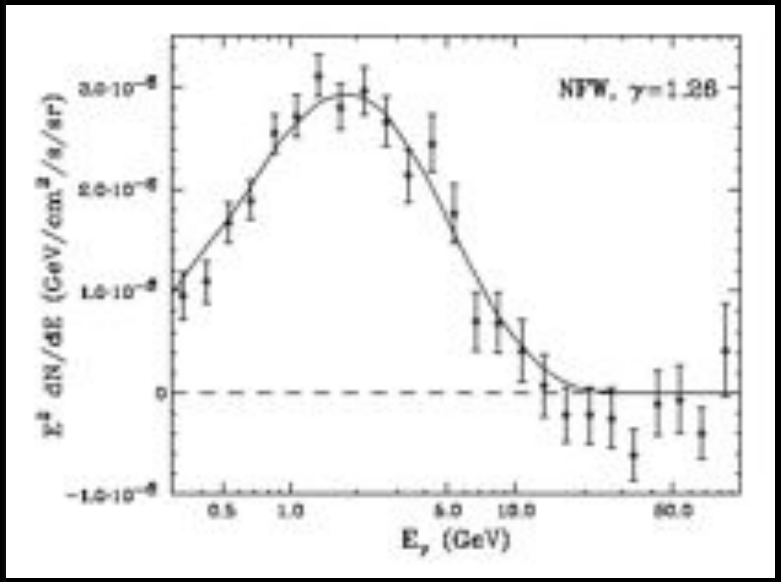
Dark Matter Candidate Identity Parade

Candidate	Mass	
Neutrino	4 eV	Hot Dark Matter
Axion	10^{-5} eV	Cold Dark Matter
Photino	0.5 GeV	LSP
Neutralino	10GeV	LSP
Axino	~ keV	LSP
Cosmion	5-10 GeV	Created by $P^{\pm}$ 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^{-1} 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

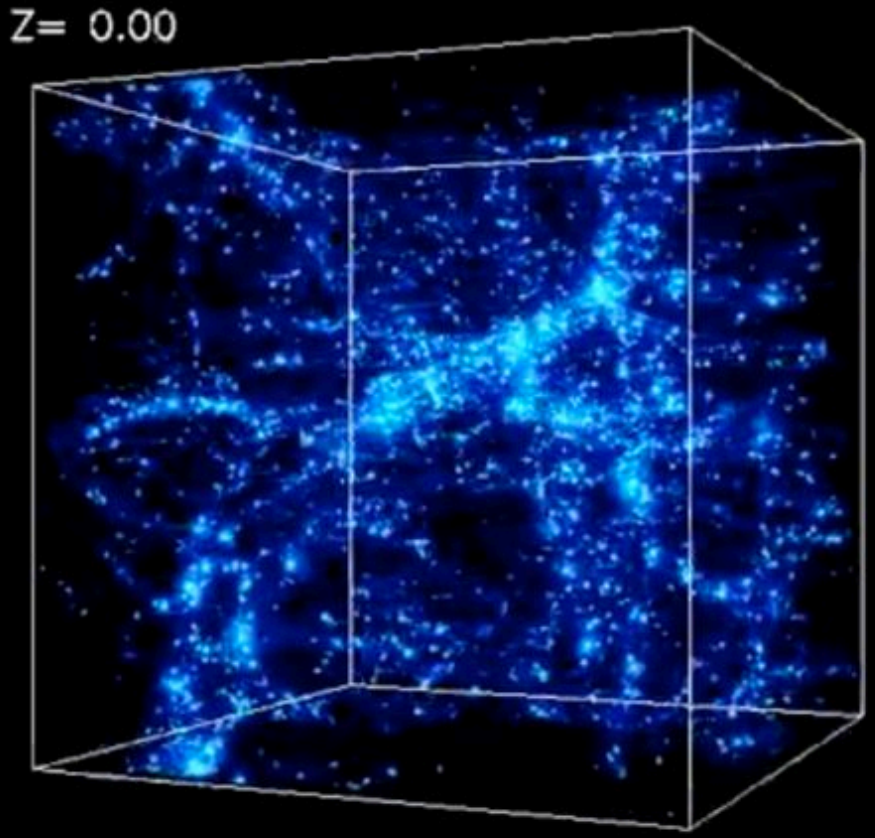
Dark Matter Candidate Detection

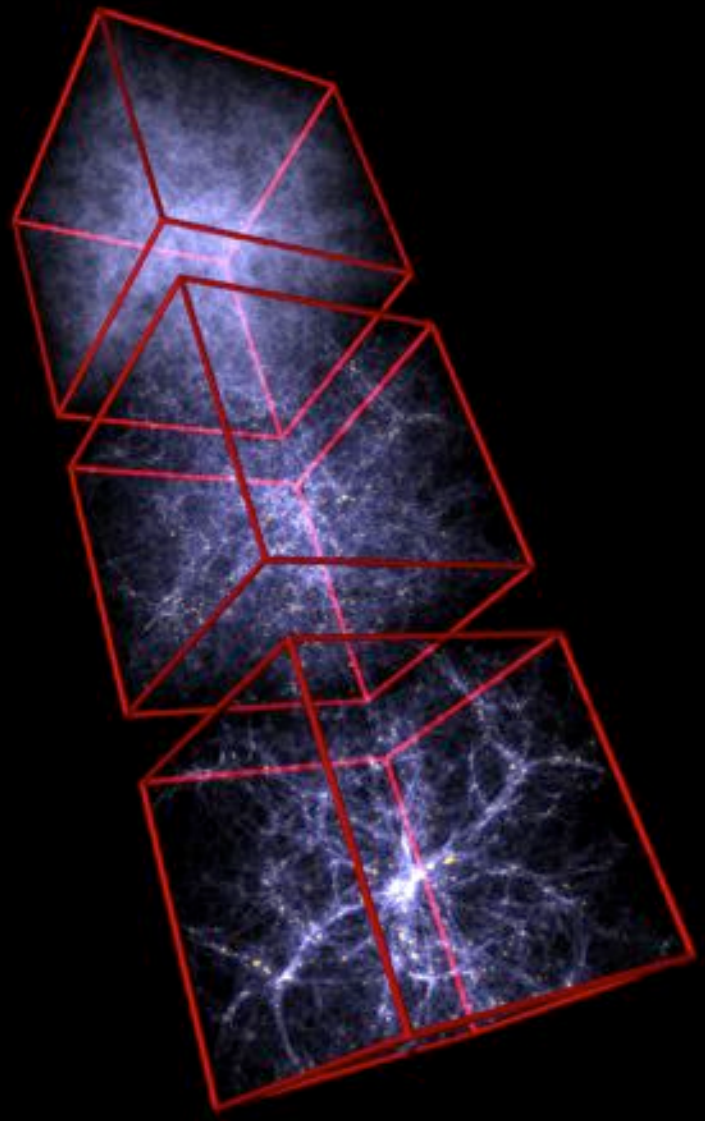
- Excess of gamma-rays in direction of the Galatic Center ?
- Dark matter particle of mass ~35.25 GeV WIMP annihilating ?





Structure Formation in a Dark Matter Universe



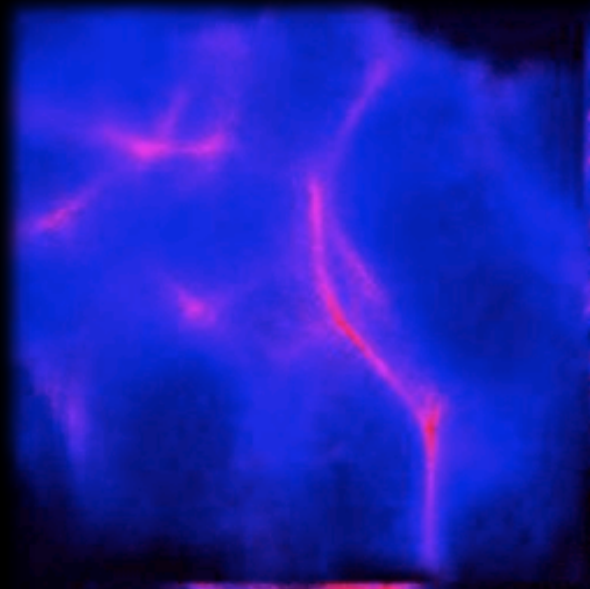


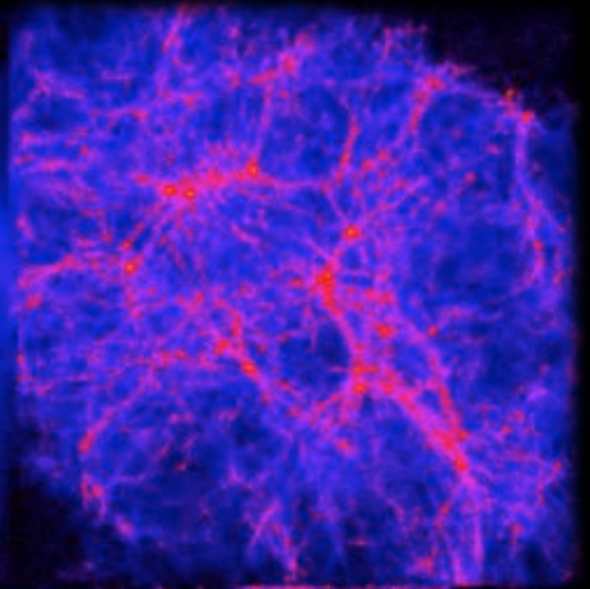
Structure Formation in a Dark Matter Universe

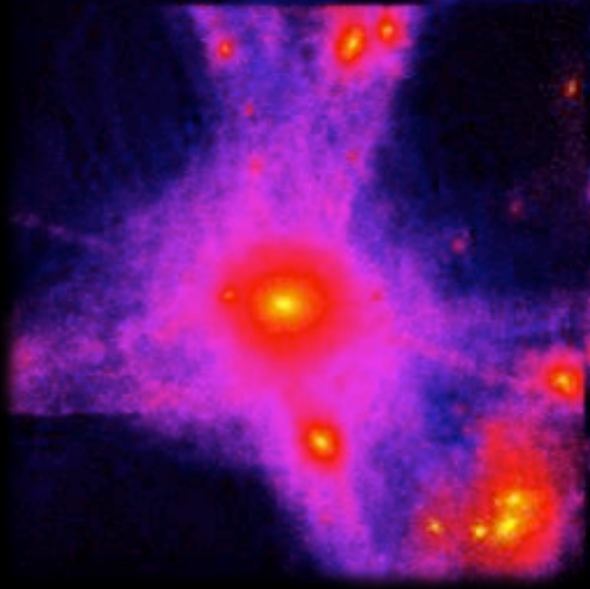
HOT DARK MATTER

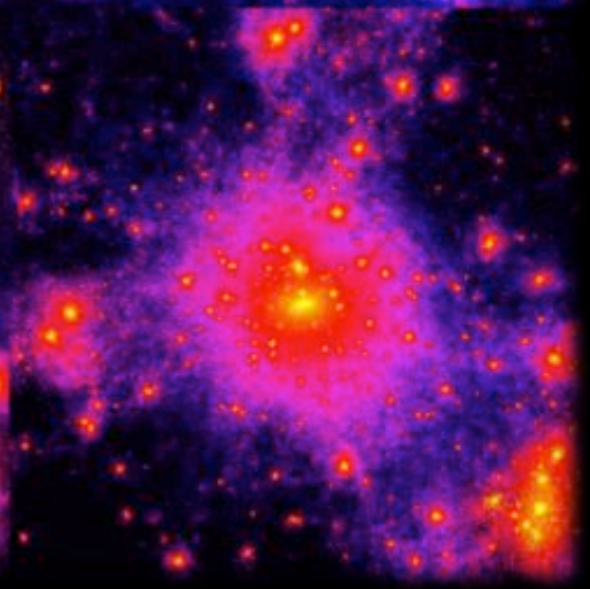
COLD DARK MATTER

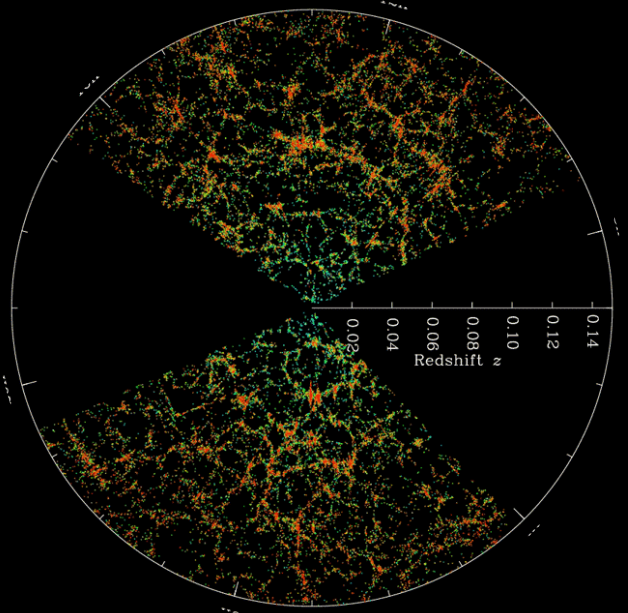
THE REAL UNIVERSE







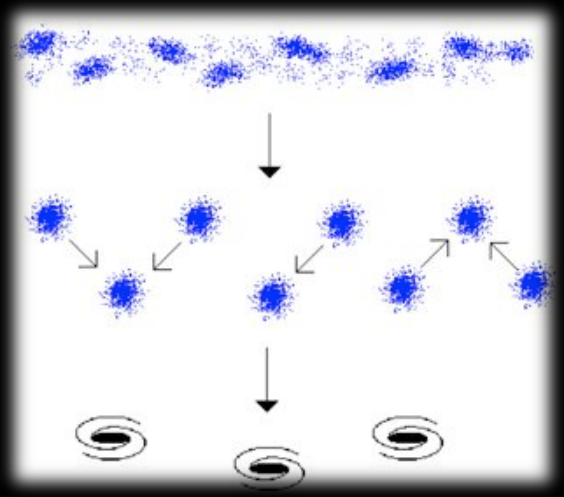


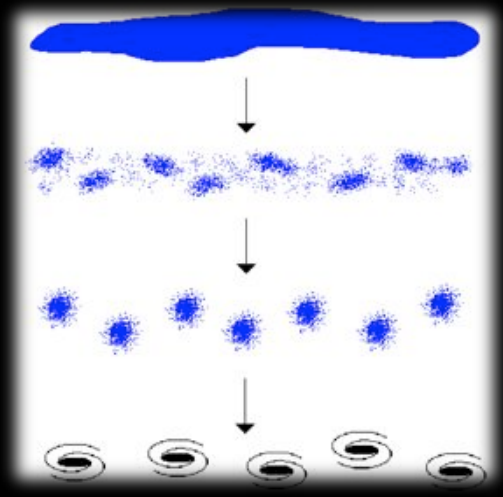


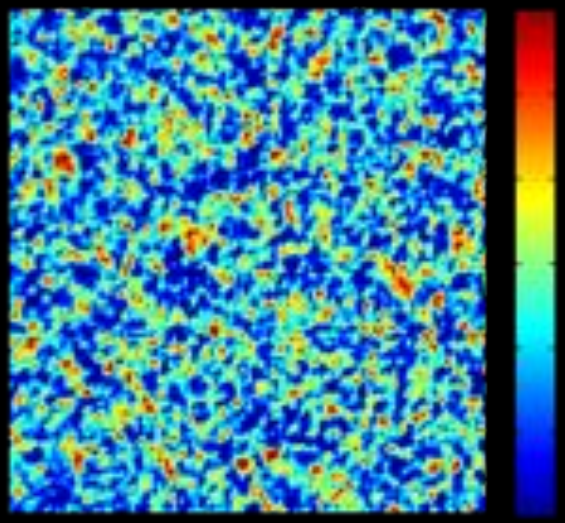
Structure Formation in a Dark Matter Universe

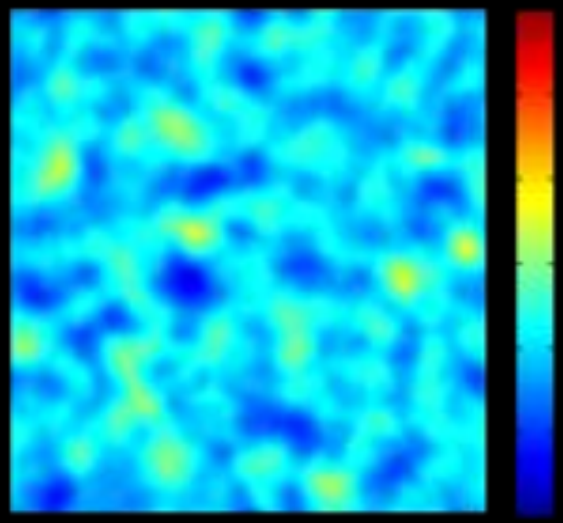
Cold Dark Matter
Bottom-Up Hierarchical Scenario

Hot Dark Matter
Top-Down Pancake Scenario

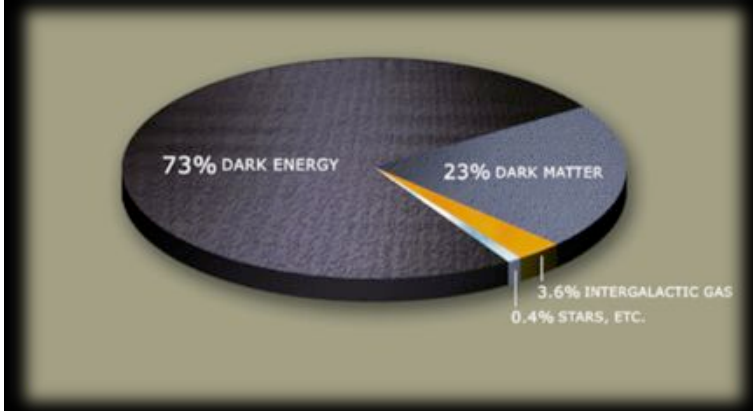


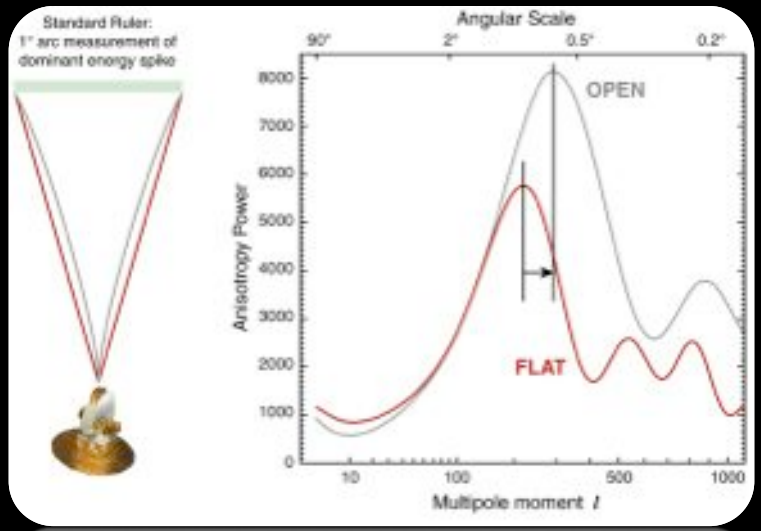


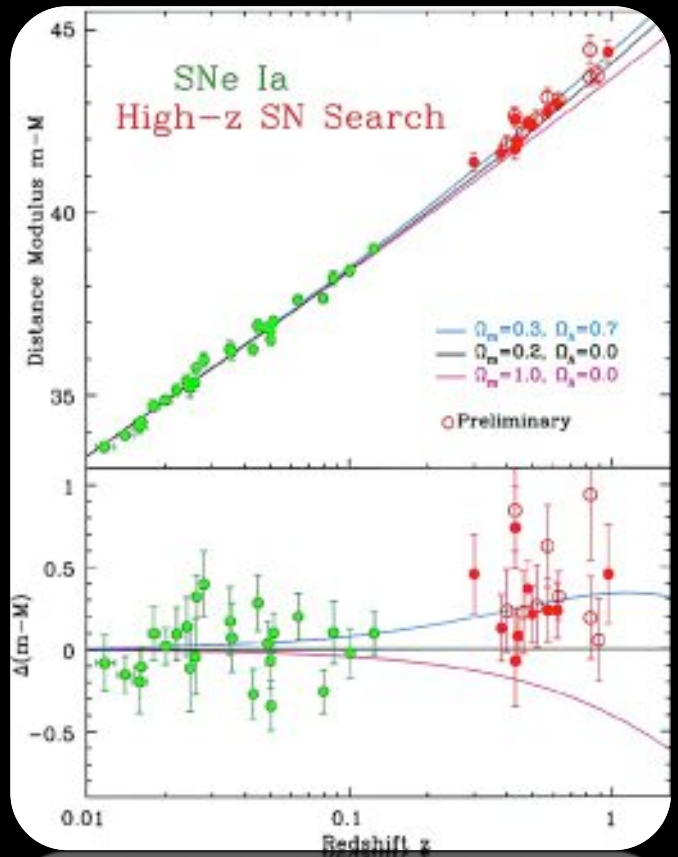




Dark Energy







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

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 ?

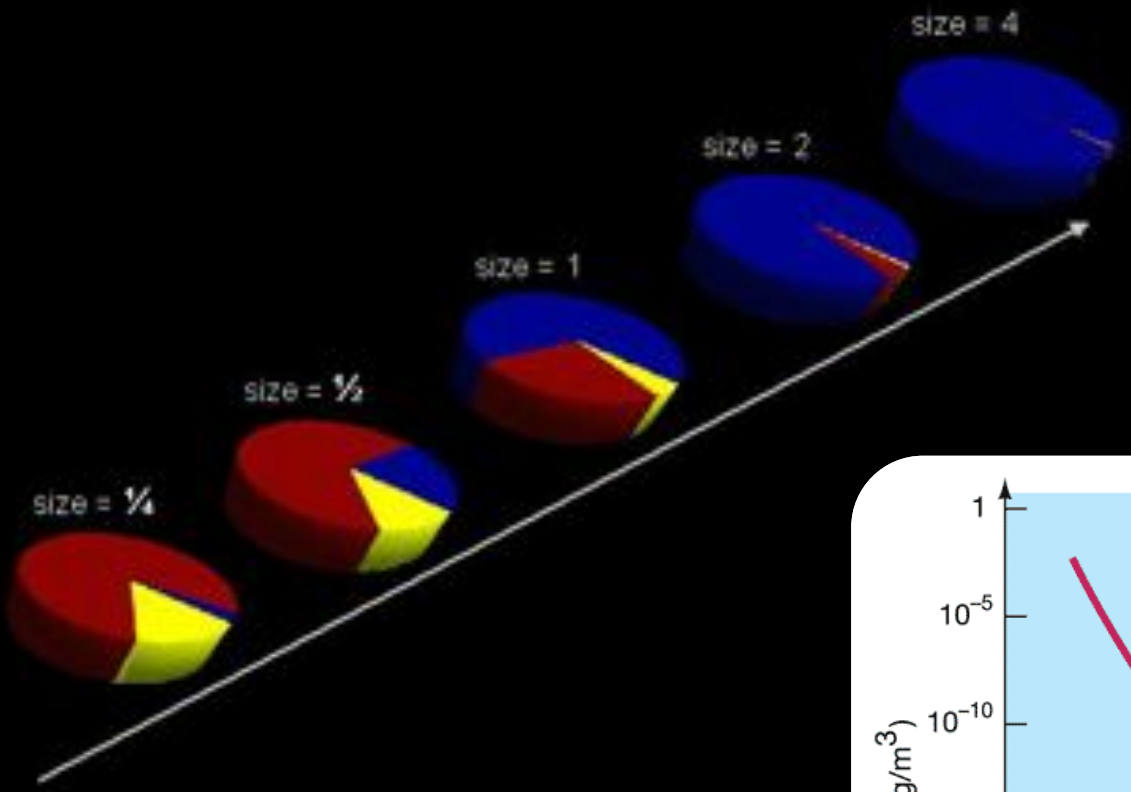
Problem: ~ 10^{120} smaller than predicted by quantum theory

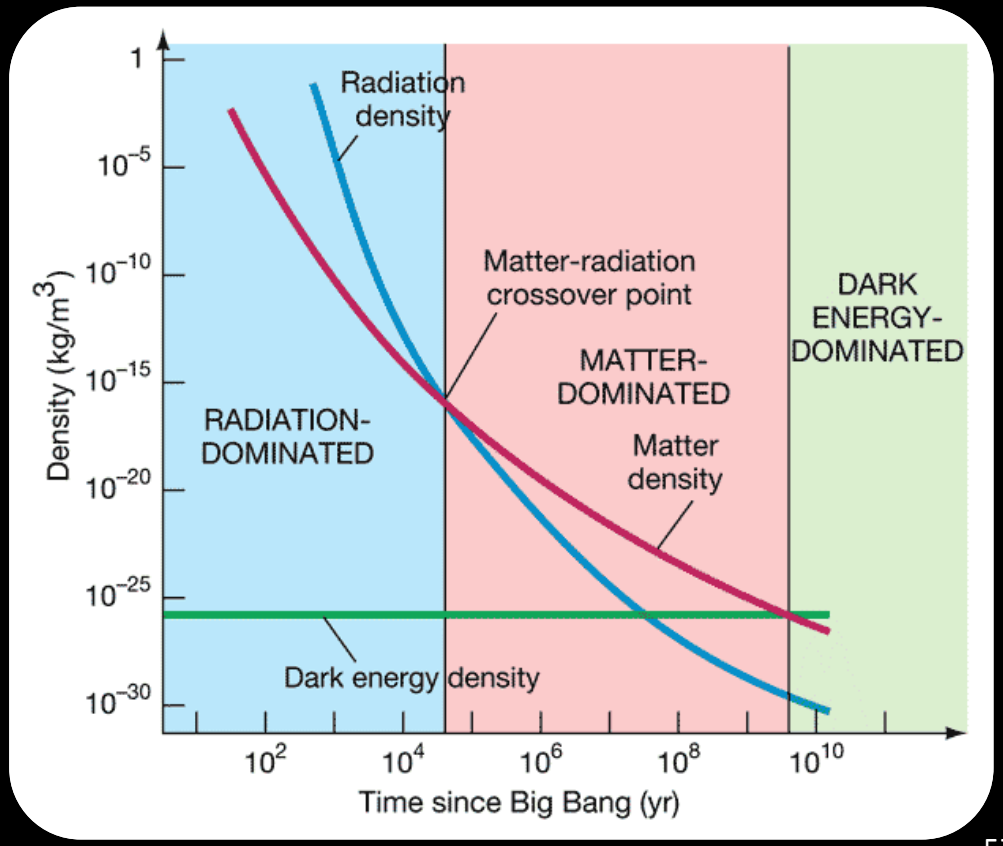
Quintessence ?

Scalar field / fifth fundamental force ?

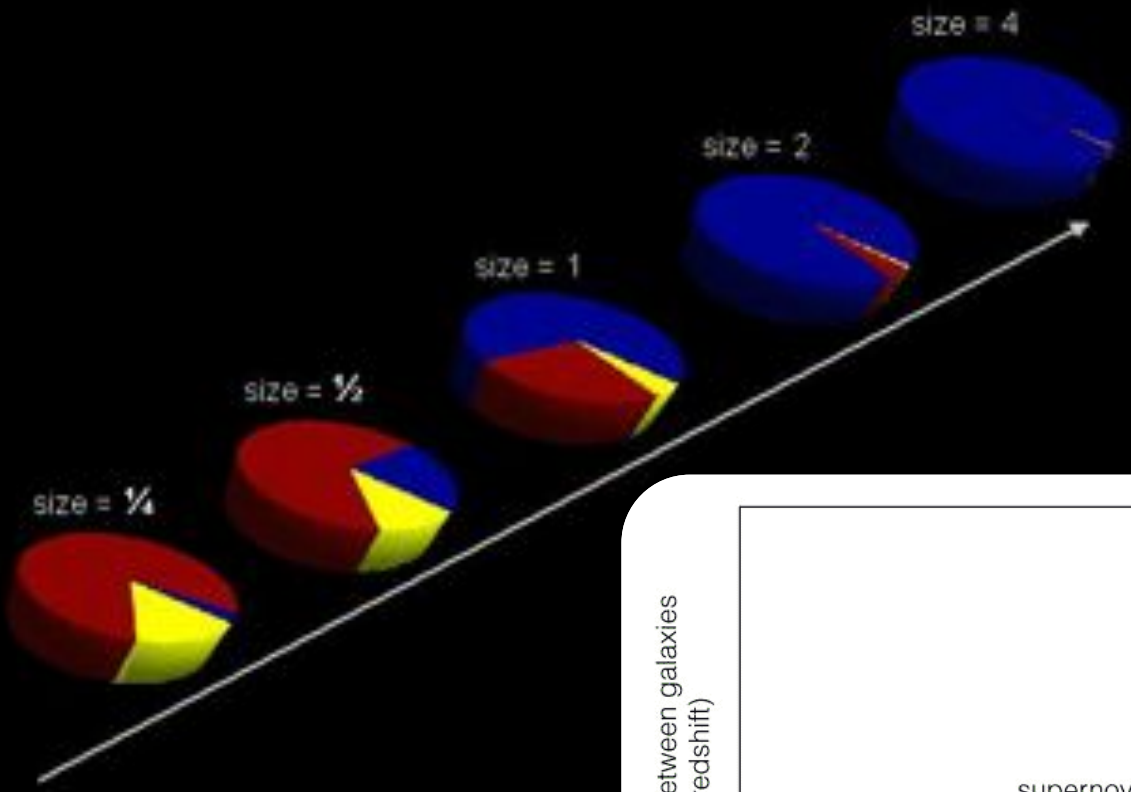
Evolves with time

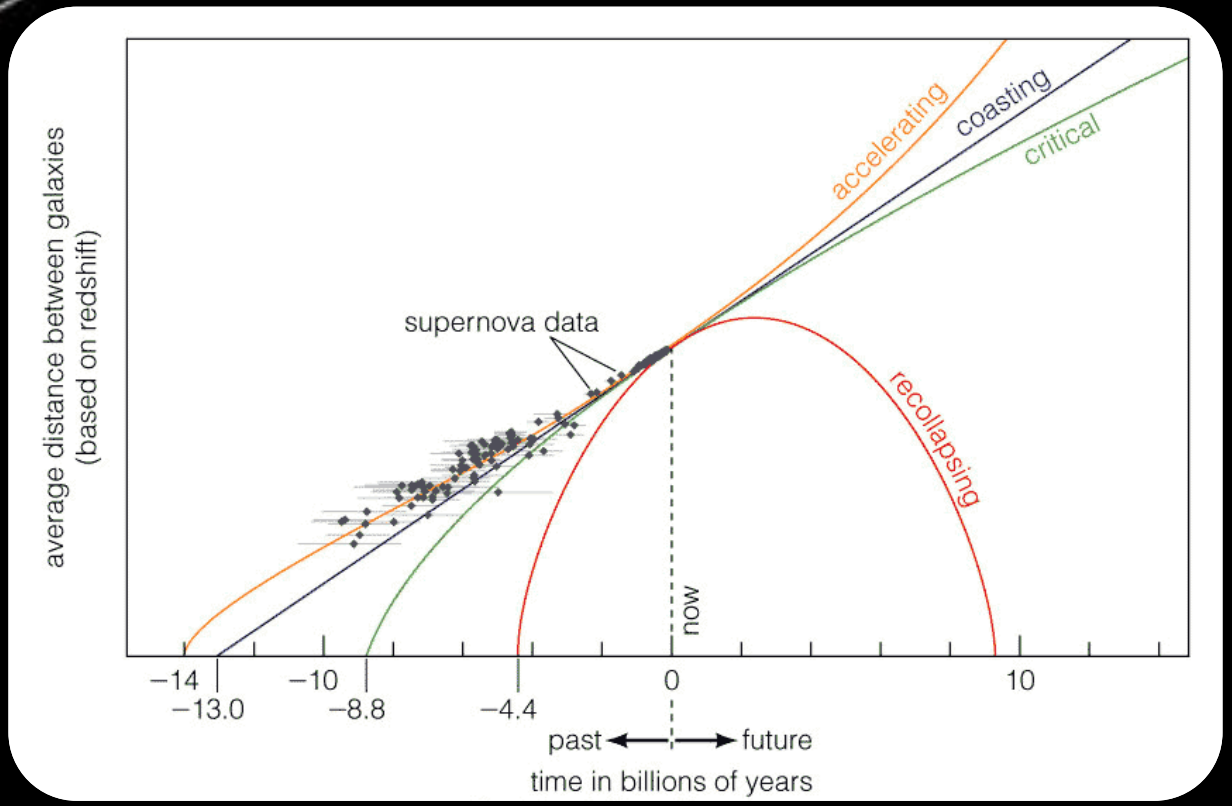
Structure Formation in a Dark Matter Universe





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