# Decaying Dark Matter, Bulk Viscosity, and Dark Energy

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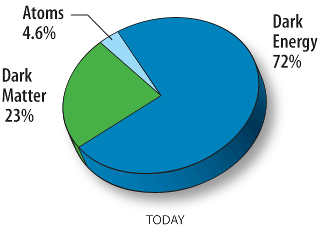
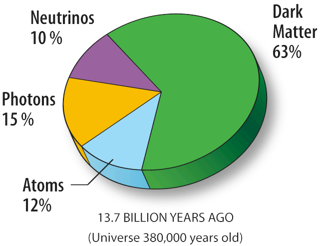
Dallas, SMU; April 5, 2010

# Outline



Atoms
4.6%
Dark
Energy
72%
Dark
Matter
23%
TODAY

Neutrinos
10 %
Dark
Matter
63%
Photons
15 %
Atoms
12%
13.7 BILLION YEARS AGO
(Universe 380,000 years old)

# Outline

- Standard Views Dark Matter
- Standard Views of Dark Energy
- Alternative Views of Dark Energy/Dark Matter

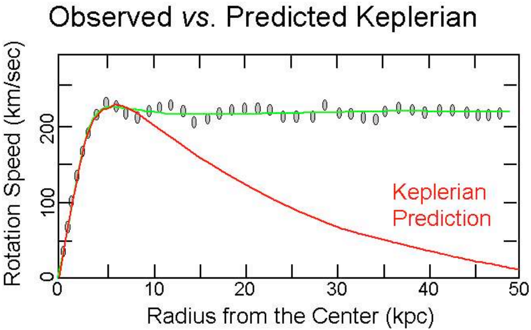
# Dark Matter

The evidence for dark matter very strong:

- Galactic rotation curves cannot be explained by the disk alone.
- Cosmic microwave background radiation.
- Gravitational lensing of background galaxies by clusters is so strong that it requires a significant dark matter component.
- Clusters are filled with hot X-ray emitting intergalactic gas (without dark matter, this gas would dissipate quickly).

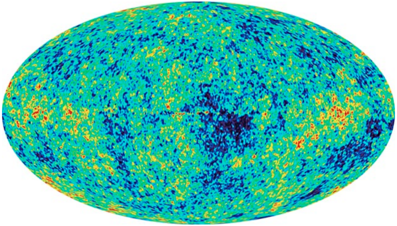
# Evidence for Dark Matter

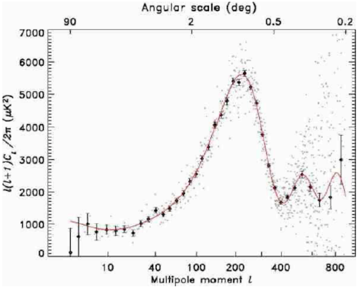
- Galactic rotation curves



# Evidence of Dark Matter

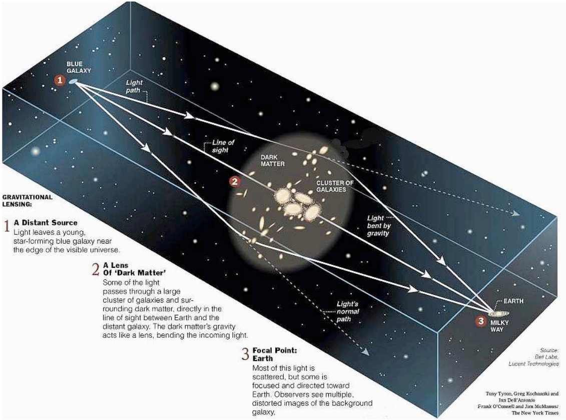
- Cosmic Microwave Background





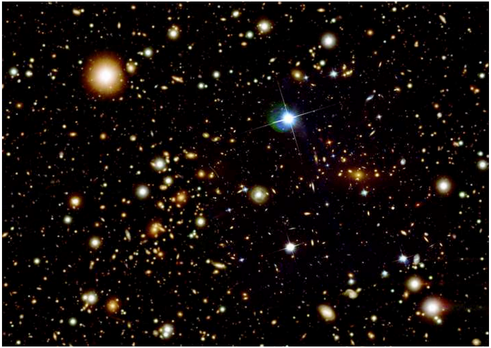
# Evidence of Dark Matter

- Gravitation lensing: seeing the invisible



# Evidence of Dark Matter

- Clusters are filled with hot X-ray emitting intergalactic gas
  Merging cluster: optical image



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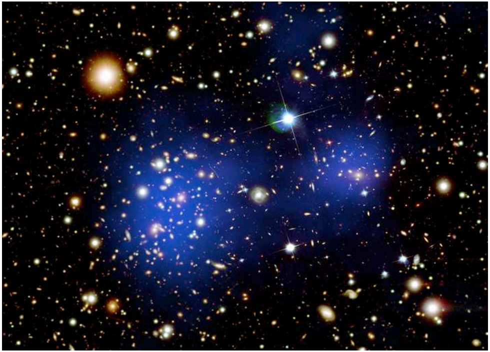

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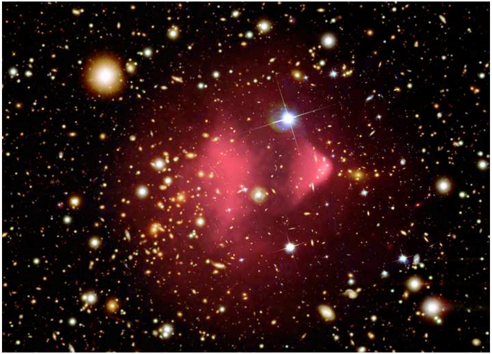

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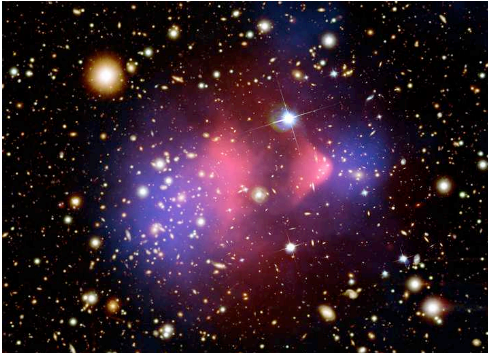
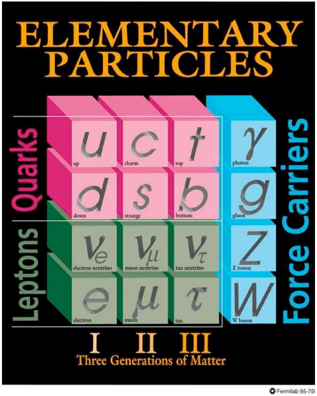


# Properties of the Dark Matter

- Nonrelativistic =>slow moving => cold/pressureless
- Weakly-interacting => only gravity, no electromagnetic or strong interactions
- Cold Dark Matter and Warm Dark Matter.

# Candidates for dark matter

- None of the known particles can be dark matter



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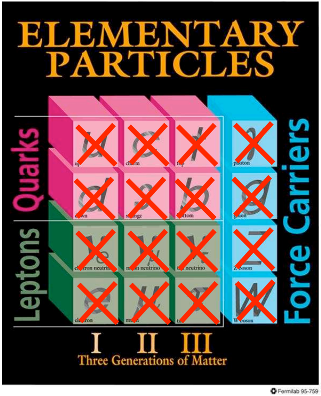


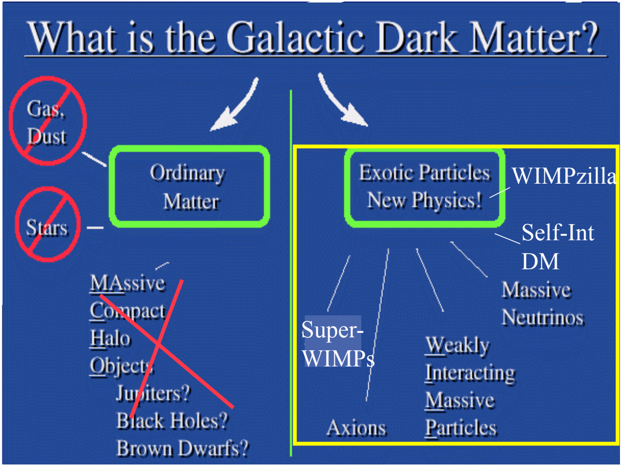
# Could the dark matter of galaxies be normal matter?

- MAssive Compact Halo Objects (MACHOs)
- Black Holes
- White Dwarfs
- Planets

# Candidates for Dark Matter

The SM offers no options for dark matter$\rightarrow$ Beyond standard model
There are two Higgs bosons: one is scalar and one is pseudoscalar particle having properties of candidates for Self Interacting dark matter (Warm Dark matter).( Lan and Long 2006).

- Supersymmetric Dark Matter?
- Extra-Dimensional Particles



What is the Galactic Dark Matter?
Gas, Dust
Stars
Ordinary Matter
MAssive Compact Halo Objects
Jupiters?
Black Holes?
Brown Dwarfs?
Exotic Particles New Physics!
WIMPzilla
Self-Int DM
Massive Neutrinos
Super-WIMPs
Weakly Interacting Massive Particles
Axions

# Evidence for Dark Energy

- Cosmic Acceleration
- Supernovae are great distance indicators
- Supernovae determine expansion rate in the past
  The expansion rate depends on the content:
  - Mass slows the expansion
  - Dark energy accelerates the expansion

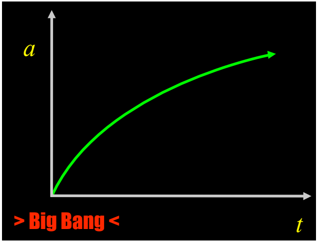
# Evidence for Dark Energy

The Friedman equation with matter and radiation:

$$H^2 = (\frac{\dot{a}}{a})^2 = \frac{8\pi G}{3}(\frac{\rho_{M0}}{a^3} + \frac{\rho_{R0}}{a^4}) - \frac{k}{a^2} \qquad (1)$$

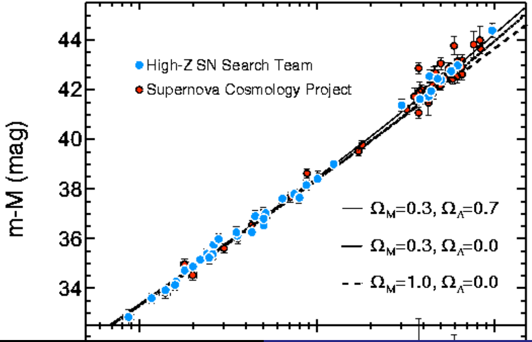
Multiply by $a^2$ to get: $\dot{a}^2 \propto \frac{\rho_{M0}}{a} + \frac{\rho_{R0}}{a^2} + const$

If a is increasing, each team on the right is decreasing; we therefore predict the universe should be decelerating



# Evidence for Dark Energy

Two groups went out to look for the decelerationof the universe, using type Ia supernovae as standardizable candles.Result: supernovae are dimmer than expected. The universe is not decelerating at all, its accelerating. Cant be explained by matter and radiation.



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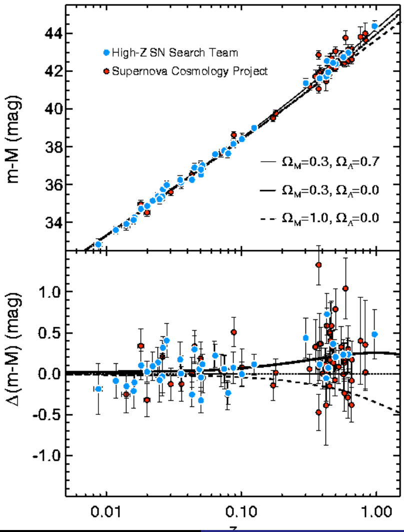
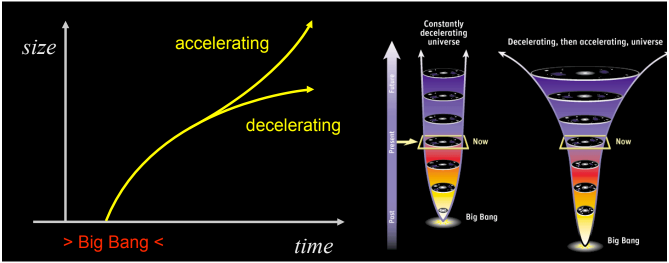


# Evidence for Dark Energy

What could make the universe accelerate? From the Friedmann equation, we need something that doesnt dilute away as the universe expands. Call it Dark Eenergy.

$\dot{a}^2 \propto \frac{\rho_{M0}}{a} + \frac{\rho_{R0}}{a^2} + a^2 \rho_{DE} + const$

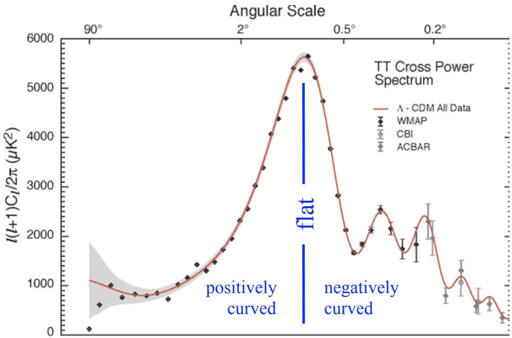


# Evidence for Dark Energy

The expansion rate is described by the Hubble constant, H, relating the distance of a galaxy to its velocity. $v = Hd$ (Hubble law) $H^2 = (\frac{8\pi G}{3})\rho$ The Hubble constant (squared) is proportional to the energy density $\rho$. So if $\rho$ is constant, H will be constant. But the distance d to some particular galaxy will be increasing, so from Hubble law its apparent velocity will go up: it will accelerate away from us.

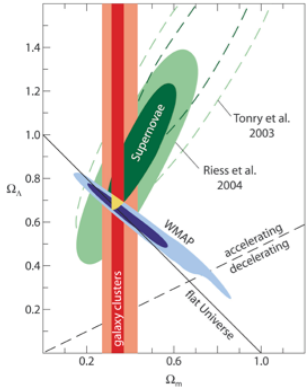
# Evidence for Dark Energy

Density parameter, $\Omega = \frac{8\pi G}{3H^2}\rho = 1 + \frac{k}{a^2H^2}$ The geometry of space depend on $\Omega$ and k. From the CMB temperature anisotropies $\Omega_{tot} = [\theta_{(peak)}]^{-\frac{1}{2}}$ we know that $\Omega_{tot} = 1$, the Universe is flat. Matter (Ordinary+dark) and radiation only accounts for 0.3



# Cosmic Concordance

- $\Omega_B = 0.04, \Omega_\gamma = 0.001, \Omega_{DM} = 0.23, \Omega_\Lambda = 0.73$




Constraining the Cosmological Parametres

# Evidence for Dark Energy

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Evidence for acceleration leads us to the Dark Energy

# Unified Models Dark matter produces Dark Energy

- Appearing Dark Matter
  *Umezu, Ichiki, Kajino, Mathews, Yashiro(2006)*

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- Decaying Dark Matter
- Relativistic Corrections to Freadman Cosmology
  *Kolb, Matarrese, Rioto(2005)*

# Bulk Viscosity and Decaying Dark Matter

*Mathews, Lan, Kolda(2008)*

- Decaying dark matter leads to dissipative bulk viscosity in the cosmic fluid
- This viscosity may account for some or all of the apparent cosmic acceleration

# Viscous Dark matter

- Bulk Viscosity

$$T^{\mu\nu} = (\rho + p)U^\mu U^\nu + g^{\mu\nu} p + \Delta T^{\mu\nu} \quad (2)$$

$$\Delta T^{\mu\nu} = -\zeta 3 \frac{\dot{a}}{a} \left( g^{\mu\nu} + U^\mu U^\nu \right) \quad (3)$$

$$T^{\mu\nu} = \left( \rho + p - \zeta 3 \frac{\dot{a}}{a} \right) U^\mu U^\nu + g^{\mu\nu} \left( p - \zeta 3 \frac{\dot{a}}{a} \right) \quad (4)$$

- Negative pressure $\longrightarrow$ Dark Energy
  The effect of bulk viscosity is to replace the fluid pressure with an effective pressure given by,

$$p_{\mathrm{eff}} = p - \zeta 3 \frac{\dot{a}}{a} \quad (5)$$

# Cosmological Model

- Flat cosmology k = 0, $\Lambda = 0$ in a comoving FRW metric

$$g_{\mu\nu} dx^{\mu} dx\nu = -dt^2 + a(t)^2[dr^2 + r^2 d\theta^2 + r^2 sin^2\theta d\phi^2] \quad (6)$$

- Total mass energy density

$$\rho = \rho_{DM} + \rho_b + \rho_h + \rho_r \quad (7)$$

- In the FRW frame, the energy momentum tensor can reduces to $T_{00} = \rho$, $T_{0i} = 0$
  $T_{eft} = (p - 3\zeta H)g =>$ Bulk Viscosity enter as an effective negative pressure in the energy momentum tensor but the Friedmann equation does not depend upon the effective pressure and it is exactly the same as for a non-dissipative cosmology
  $H^2 = \frac{\dot{a}}{a}^2 = \frac{8}{3}\pi G\rho$

- Conservation equation => energy density in matter and radiation:
  $\rho_h = \frac{\rho_{m0} e^{-\frac{t}{\tau}}}{a^3}$
  $\rho_l = \frac{1}{a^4}[\rho_{l0} + \frac{\rho_{h0}}{\tau} + \rho_{BV}]$
- $\rho_{BV}$ is the dissipated energy in light relativistc specied due to the cosmic bulk viscosity => total density include term from dissipated energy density in bulk viscosity.

# Need a Physical model for Bulk Viscosity

- If a gas is out of pressure equilibrium as it expands or contracts a bulk viscosity is generated
  $3\zeta H = \triangle p$
  $\triangle p$ is the different between the constant volume equilibrium pressure and the actual fluid pressure

# Decaying Dark Matter Produces Bulk Viscosity

- Particle decays lead to heating and pressure from the relativistic decay products
- This increase in heating is inevitably associated with an increase in entropy $\triangle S = \frac{\triangle Q}{T}$
- Entropy will be evidenced in a dissipation of energy $=>$ Dissipation $=>$ Bulk Viscosity

# Particle decay

Pressureless DM => relativistic particles $p = \rho/3$

- out of temperature and pressure equilibrium
- dissipation and bulk viscosity

During decay matter and relativistic particles are out of pressure and temperature equilibrium (Weinberg)

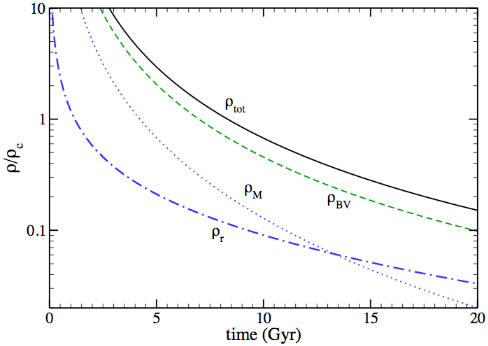
- $\triangle p = (\frac{4}{3})\rho_h \tau_{eq}[1 - 3\frac{\partial p}{\partial \rho}](\frac{\partial U^\alpha}{\partial x \alpha})$
  Equilibration $\tau_{eq} = \frac{\tau}{1-3\tau H}$ Need $\frac{\partial p}{\partial \rho} \sim \frac{p}{\rho} \neq \frac{1}{3}$
  $p = \frac{\rho_l + \rho_\gamma}{3}$
- $=> \zeta = \rho_h \tau_{eq}[1 - \frac{\rho_l + \rho_\gamma}{3}]^2$

# Candidates for Decaying Dark Matter

- Sneutrinos mix in vacuum with active neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$=> WDM and CDM
- Parameters: Sterile neutrino mass $m_s$ and mixing angle $\theta$
- For $m_s < 10MeV \Rightarrow \nu_s \rightarrow \gamma + \nu$

# Why this does not work

Acceleration $=> H^2 = \frac{8}{3}\pi G\rho =$ constant $=> \rho =$constant

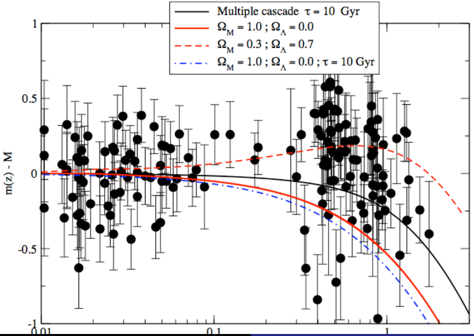


# How to fix this

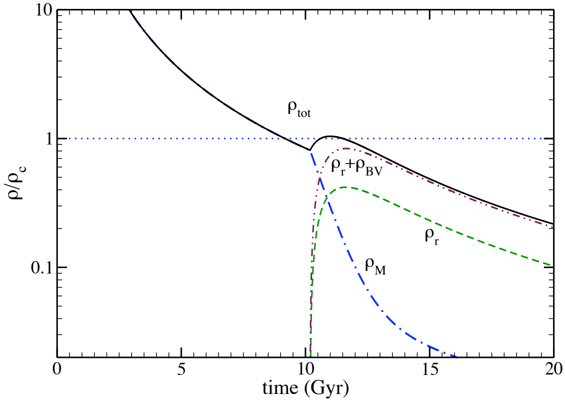
Need much larger BV coefficient

Cascading decays: Sterile neutrinos

$\nu_1 \longrightarrow \nu_2 \longrightarrow \nu_3 \longrightarrow \nu_4 \longrightarrow \nu_5 \longrightarrow \nu_6 \longrightarrow$regular neutrinos or Late decays due to time varying mass or a late phase transition



Late decaying DM with bulk viscosity can produce cosmic acceleration without Dark Energy or a Cosmological constant



# Conclusion

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- Can account for some dark energy if the appearance of the particle decays is delayed by a cascade

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- Can account for some dark energy if the appearance of the particle decays is delayed by a cascade
- **Can account for all dark energy if there is a late phase transition possibly caused by a time-dependent mass**

Thank you for your attention!

In collaboration with H. N. Long, G. Mathews, C. Kolda, and M. Giovannini