Gravitino - A Dark Matter Candidate

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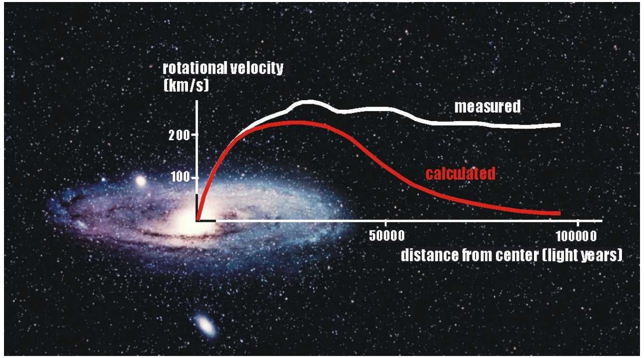
Introduction

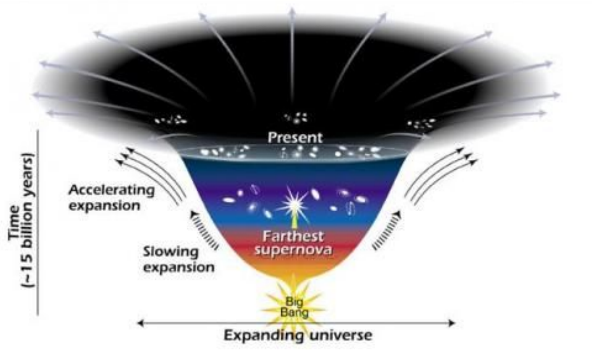
- First observed in the 1930s by astronomers Jan Oort and Fritz Zwicky due to inconsistencies with mass-to-light ratio and the rotational velocities of spiral arms

- Further measurements by Vera Rubin showed the velocity of objects in a galaxy as a function of radius from center is near constant, suggesting dark matter distribution differs from that of normal matter

- Continued measurements and improvements in metrology now tell us that dark matter contributes ~85% of the universe's matter (5% known matter, **27% dark matter**, 68% dark energy)

Credit: Queen's University Super CDMS Group





Credit: NASA

Relevance

Particle Physics

Finding a suitable candidate for dark matter is an open problem in particle physics. To find a suitable candidate we need to look outside the Standard Model and as such we look at exotic particles such as gravitinos and axions.

Cosmology

Dark matter makes up around **27% of the observable universe**.
Understanding dark matter is crucial in understanding the formative years of the universe. A particularly important topic is discussing the temperature of species of dark matter, whether it is ‘hot’, ‘warm’, or ‘cold’.

What makes a suitable candidate?

- Does not interact via electromagnetic force

- Must exist to this day* (**27% of energy**)

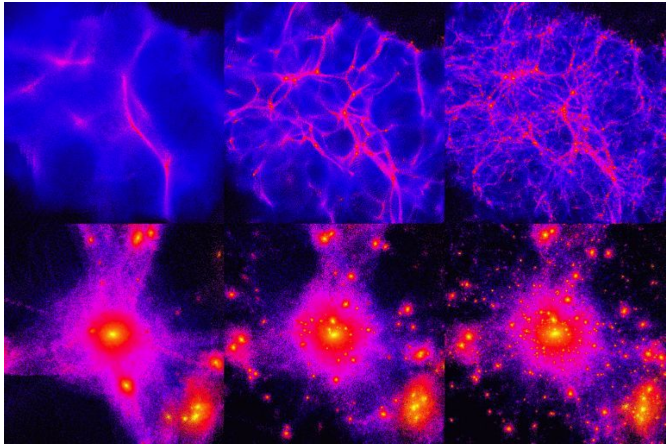
- Non-zero mass

- Few interactions with observable matter

Dark Matter Temperature

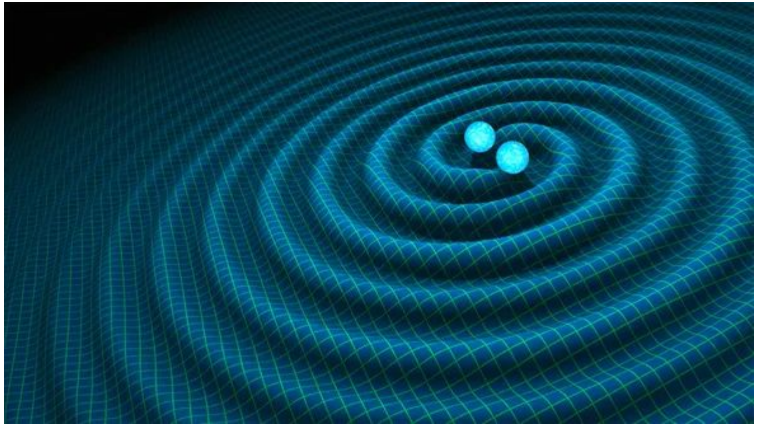
Image Credit: Ben Moore - University of Zurich

- Refers to velocity in a qualitative manner
  - Cold dark matter is non-relativistic today
  - Hot dark matter is relativistic
- Hotter dark matter requires more force to contain it meaning smaller clumps cease to form
- Different candidates have different temperatures
- Primary candidates for CDM are weakly interacting massive particles (WIMPs)
- ΛCDM



Gravitino - CDM Candidate?

Credit: Robert Hurt - Caltech



- Supersymmetric partner to the proposed quantum of gravity, the graviton

- Potential WIMP
  - Graviton suspected to be massless with few interactions with normal matter
  - Gravitino may be massive via symmetry breaking

We use Natural Units From Here On:

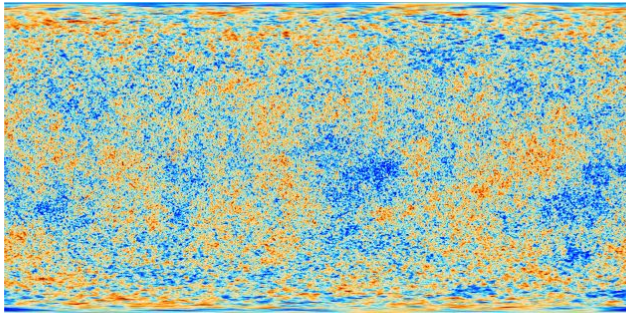
$$1 = c = \hbar = k_B$$

Equations from Cosmology

The Friedmann-Lemaître-Robertson-Walker metric describes the geometry of space-time in an **expanding universe**:

$$ds^2 = a^2(t)dr^2 - dt^2 \qquad H = \frac{\dot{a}}{a}$$

Credit: European Space Agency



In which entropy density of a comoving volume remains constant:

$$\frac{d(sa^3)}{dt} = 0$$

With this system we can derive the Friedmann equation

$$H^2 = \frac{8\pi^2}{3M_{PL}^2}(\rho_M + \rho_R) \rightarrow H^2 = \frac{2g_*}{M_{PL}^2}T^4$$

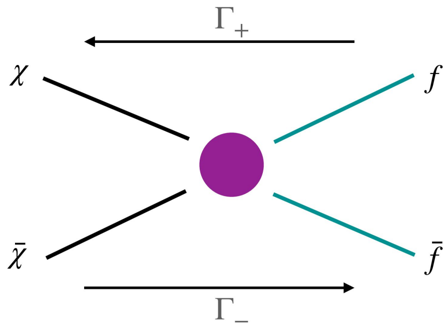
Number Density, Entropy Density, Abundance

$$\frac{dn}{dt} = \Gamma_+ - \Gamma_- \rightarrow \frac{d(na^3)}{dt} = (\Gamma_+ - \Gamma_-)a^3$$

$$\frac{dn}{dt} + 3Hn = -\langle\sigma v\rangle(n^2 - n_{eq}^2)$$

$$Y = \frac{n}{s}$$

$$\frac{dY}{dt} = -s\langle\sigma v\rangle(Y^2 - Y_{eq}^2)$$



Credit: Seyda Ipek

Number Density Equilibrium

$$n_{eq} = \frac{g}{(2\pi)^3} \int \frac{dp^3}{e^{\frac{E}{T}} \pm 1} \approx \frac{g}{(2\pi)^3} \int e^{-\frac{E}{T}} dp^3$$

Low particle density limit

$$n_{eq} = g \begin{cases} \left(\frac{mT}{2\pi}\right)^{3/2} e^{-\frac{m}{T}} & T << m \\ \frac{T^3}{\pi^2} & T >> m \end{cases}$$

Entropy Density

$$S = \frac{U + PV}{T} \leftrightarrow s = \frac{\rho + P}{T}$$

$$s = \frac{4\rho}{3T} = \frac{4}{3T} g_* \int Ef(p)dp^3$$

$$s = 4n$$

Abundance

$$Y_{eq} = \frac{n_{eq}}{s} = \sqrt{\pi}\left(\frac{g}{g_*}\right)\left(\frac{m}{2T}\right)^{\frac{3}{2}} e^{-\frac{m}{T}}$$

$$= \sqrt{\pi}\left(\frac{g}{g_*}\right)\left(\frac{x}{2}\right)^{\frac{3}{2}} e^{-x}, \qquad x = \frac{m}{T}$$

$$\frac{d(sa^3)}{dt} = 0 \rightarrow \frac{d(aT)}{dt} = 0 \rightarrow \frac{dx}{dt} = Hx$$

$$\frac{dY}{dx} = -\frac{s\langle\sigma v\rangle}{Hx}(Y^2 - Y_{eq}^2)$$

Abundance Cont.

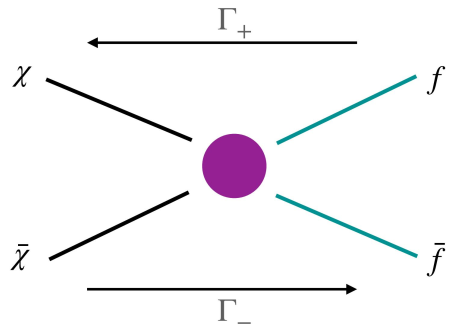
$$\frac{dY}{dx} = -\sqrt{\frac{g_*}{2}}\frac{mM_{PL}\langle\sigma v\rangle}{\pi^2 x^2}\left(Y^2 - \left(\sqrt{\pi}\frac{g}{g_*}\left(\frac{x}{2}\right)^{\frac{3}{2}}e^{-x}\right)^2\right)$$

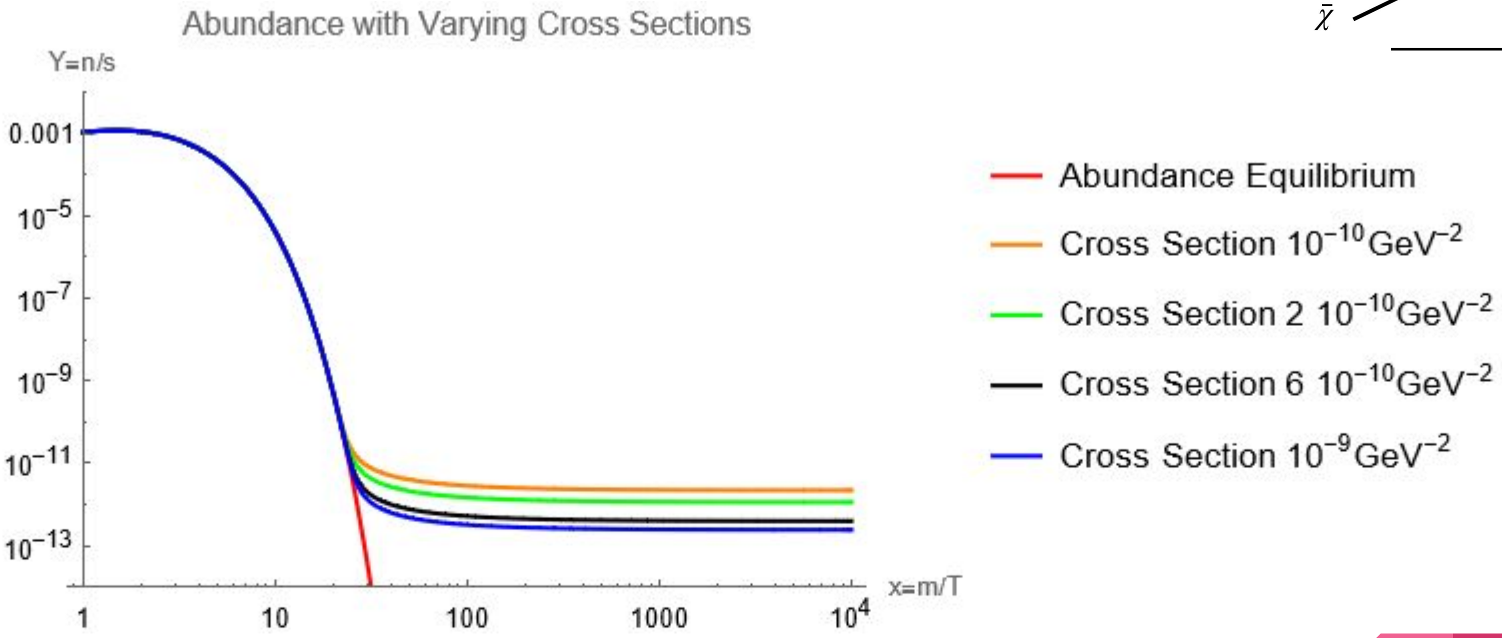
Unitless (in natural units) equation with terms of variable magnitudes.

Mathematica does not like this equation, we rescale it:

$$\zeta = \sqrt{\frac{g_*}{2}}\frac{mM_{PL}\langle\sigma v\rangle}{\pi^2 x^2}Y \qquad \frac{d\zeta}{dx} = -\frac{1}{x^2}(\zeta^2 - \zeta_{eq}^2)$$

Resulting Plot





Problems with this Model

- Only considers radiation dominant universe

- It gives little information about the formative period of dark matter

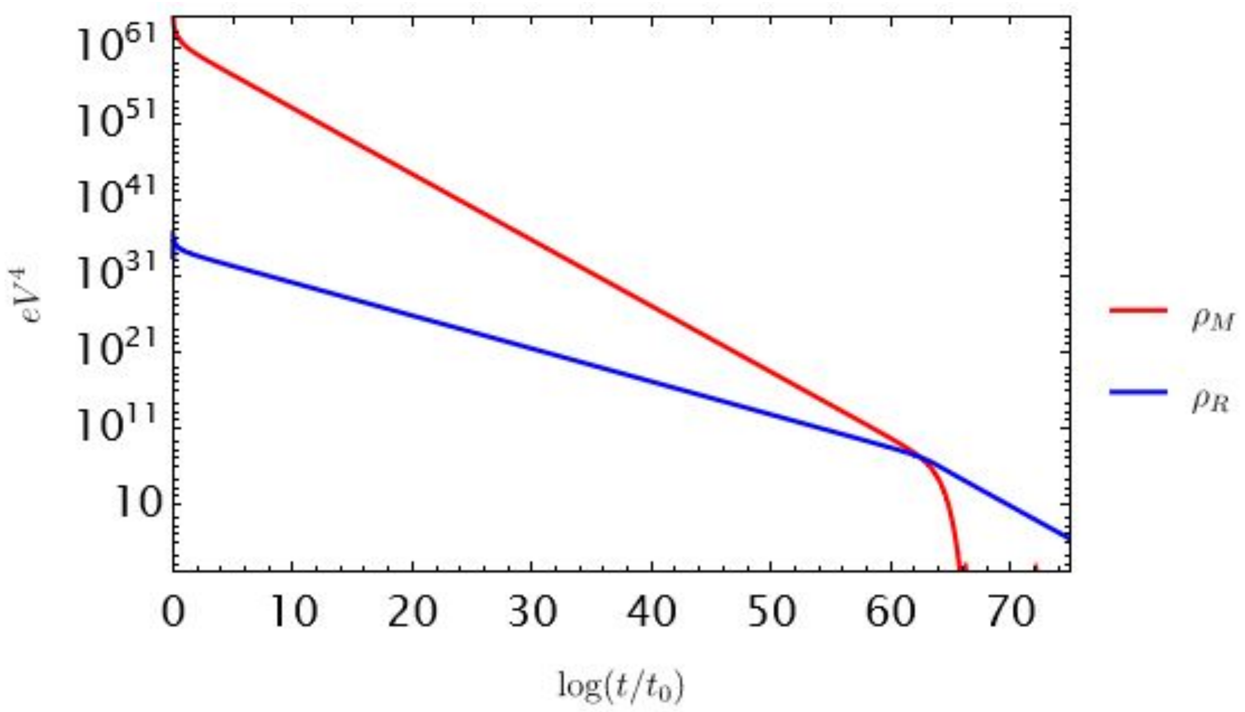
More Complicated System to Solve

$$\frac{d(na^3)}{dt} = \sum \text{Production} - \sum \text{Annihilation} \pm \sum \text{Decay}$$

$$\frac{d(\rho_M a^3)}{dt} = -\Gamma_M \rho_M a^3$$

$$\frac{d(\rho_R a^4)}{dt} = \Gamma_M \rho_M a^4$$

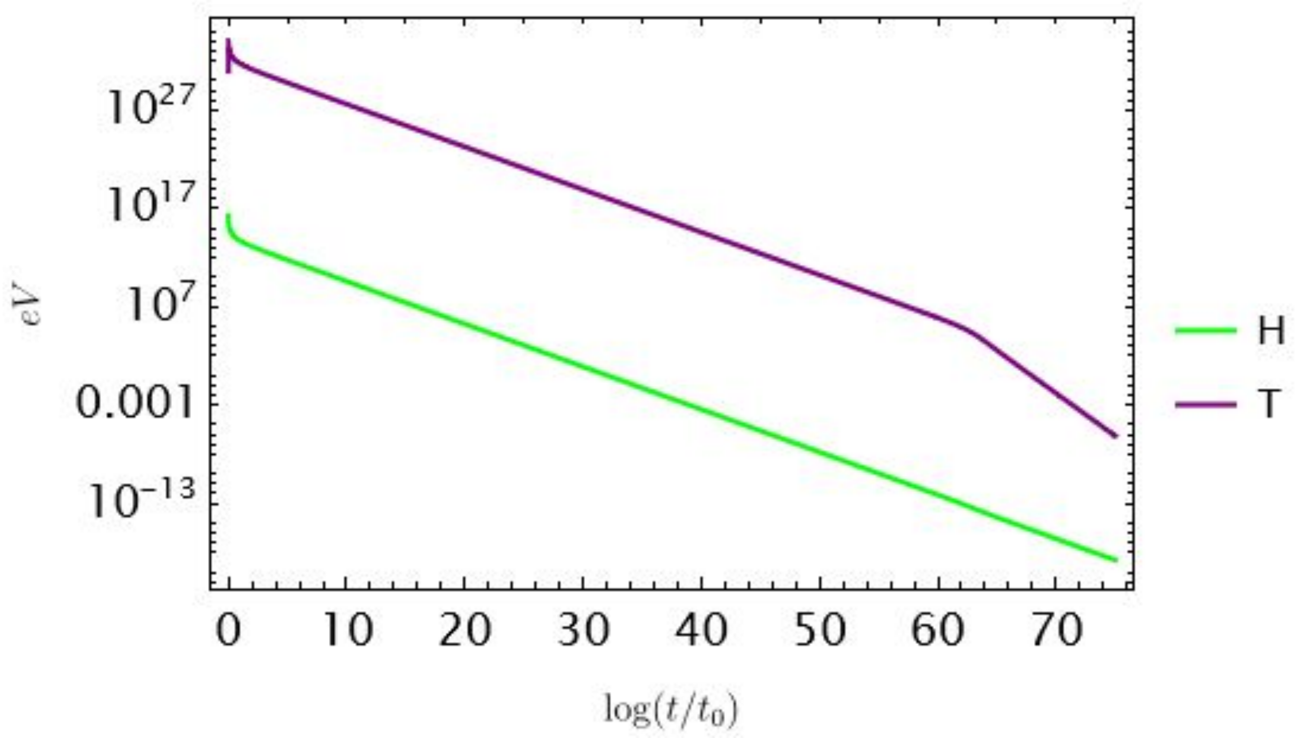
Matter and Radiation Energy Density Post-Inflation



Matter Energy Density

Radiation Energy Density

Hubble Parameter and Temperature Post-Inflation




Thank You!