Outline

1. Brief review of what you need about cosmology
2. What we know or don't know about DM
3. Candidates for DM (Theory vs Anomaly Driven)
4. An oscillating scalar field as DM
5. Thermal relics
6. The canonical WIMP $(2^{+1/2}_{-1/2})$ Dirac fermion
   (aka "4th generation neutrino" or "Higgsino")
7. The "neutralino" (whatever that is)
8. Generic Signals of thermal WIMPs: direct, indirect, collider
9. Direct anomalies: DAMA
   - (a) Spin dependent?
   - (b) Inelastic?
   - (c) Light?
10. Direct anomalies: CoGeNT — ~~vs~~ other exps
11. Direct anomalies: CRESST - ?

(11) Indirect anomalies: INTEGRAL

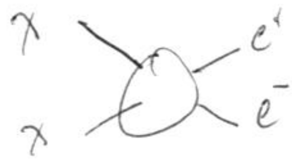
(12) Indirect anomalies: PAMELA/Fermi

(13) Indirect anomalies: "Haze"

(14) Dark forces + signals

Cheat Sheat for Early Universe

Key time $\Gamma^{-1} = H$ eg. equilibrium ends



$n\sigma v = H$ freezeout

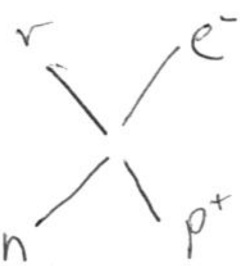
$$H = \frac{T^2}{M_{pl}} \quad \text{(rad domination)}$$

$$n_R \sim T^3$$

$$n_{NR} \sim (mT)^{3/2} e^{-m/T}$$ ← exponential!

$$H^2 = \frac{\rho}{M_{pl}^2}$$

e.g.



NB: TWO types of decoupling

chemical

kinetic

What we do and don't know about DM

The two key things to remember about dark matter

(1) No one knows anything about dark matter

(2) We already know a great deal about dark matter

Just remember these two things!

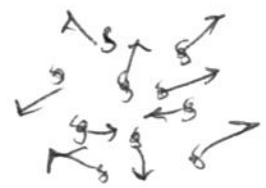
Our attitudes about DM historically

	Favored Candidate	Properties
(pre 1930s)	None	nothing
	Gas / Brown Dwarfs	Ordinary Matter
~80's	Neutrinos	weak interactions, light hot
90's +	Neutralinos ←	heavy, cold, really weakly interacting ← axions
→	?	?

Our ideas of what DM is evolve, what is unnatural today could be natural tomorrow.

Evidence for DM

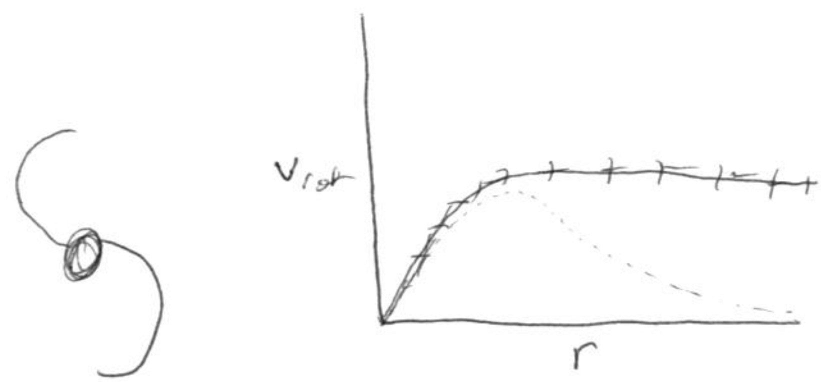
(1) Zwicky observes Coma cluster



$$mv^2 \sim V \sim \frac{GM_{TOT}}{\langle r \rangle} \Rightarrow V_{disp} \Leftrightarrow M_{TOT}$$

needs $O(10\times +)$ more mass

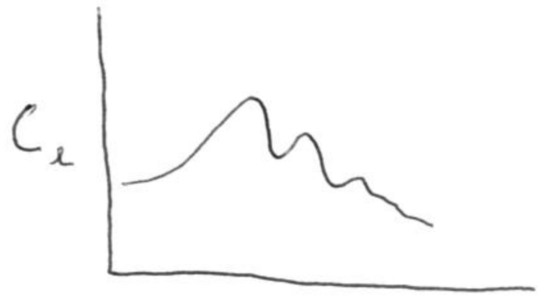
(2) Rubin radio measurements of rotation curves

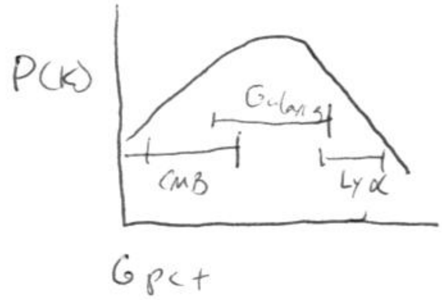


need additional matter

(3) Lensing Maps of DM (cf Bullet Cluster)

(4) Power Spectra CMB





amplitude + shape both point to DM

(5) BBN

Abundances of light elements $\Rightarrow B/\gamma \simeq 6\times10^{-9}$

$\Rightarrow \Omega \sim 0.04$

What do we know about DM?

Mostly negatives, i.e., what it is not

0) Massive

$w \simeq 0$ (pressureless) since $T \sim$ keV

[aside: $\rho \propto a^{-3(w+1)}$, thus $w = 0 \Rightarrow \rho \propto a^{-3}$]

0b) Neutral (it is "dark" matter, so doesn't couple to light)

From invisible Z width

$\Gamma_{inv} = 2.984 \pm 0.008\, \Gamma_\nu$ (PDG)

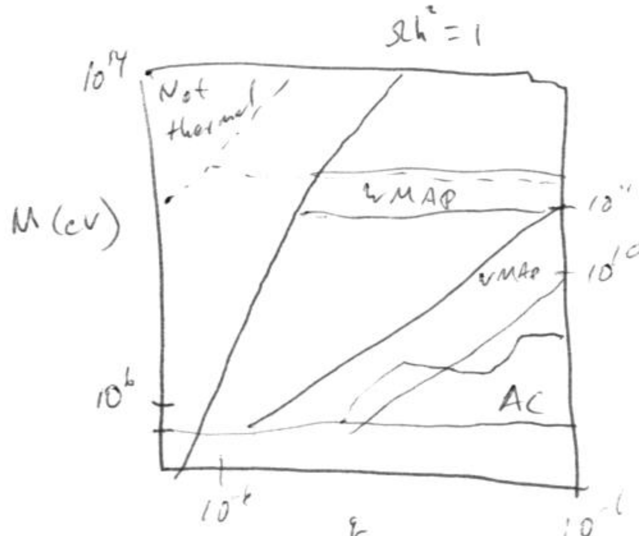
if $m < \frac{m_Z}{2}$ $\quad \sin\theta \sim 0.3\text{-}0.4$

If +1 charged

Heavy hydrogen $< 4\times10^{-14}$ for $5 < m_\chi < 1600\, m_p$

Millicharged limits

Dubovsky, Gorbunov, Rubtsov 0311189



0c) Not p/n/e: CMB + B/γ tell us it is something new (maybe black holes?)

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1. Cold

Hot DM washes out structure on small scales ⇒ "top down" structure formation

Cold DM has structure at small scales ⇒ "bottom up" hierarchical structure formation

But what do we mean "cold"?

Usually: means when DM decouples from SM it is non relativistic

Actually tested: DM was cold at $T \sim$ keV

Even neutrinos (at least some) are cold now!

(2) Non Interacting (i.e. collisionless)
What does this mean?

Hard scattering

$$n \sigma v \tau = 1 \Rightarrow \frac{\sigma}{10^{-24} \mathrm{cm}^2} \lesssim \frac{\mathrm{TeV}}{M_{DM}}$$

What about gauge forces?
If massless $\alpha < 10^{-3}$ for $m_\chi \sim \mathrm{TeV}$
(Ackermann et al)

Long Range Forces ($\sim$ gravitation)
Equivalence Principle Violations
Kesden + Kamionkowski $\Rightarrow$ $B \lesssim 0.2$

Massive force carriers

Fox
Feng
$m_\varphi \gtrsim 50$ MeV

If neutral, stable, basically non-interacting and $\Omega h^2 \lesssim 0.1$ you're good to go!

What models of DM? (Theory driven)

Name	What is it?	Motivation	alive
axion	$(\bar{\Theta} + \frac{a}{f}) G\tilde{G}$ promote $\bar{\Theta}$ to dynamical variable to settle to 0 to explain why strong dynamics preserve CP	Strong CP problem	yes
neutralino	$\tilde{B} + \tilde{W}_3 + \tilde{H}_u + \tilde{H}_d$ actually four neutralinos different linear combinations of $\tilde{B}, \tilde{W}_3, \tilde{H}_u, \tilde{H}_d$	Hierarchy problem	yes
Sneutrino	$\tilde{\nu}$ s-partner of ν	Hierarchy problem	no* (direct detection) *non standard OK
LTOP	lightest t-odd particle	Hierarchy problem	Insofar as little Higgs models are alive
KKDM	$B^{(1)}, \nu^{(1)}$ higher dimension excitations of SM fields	Weak scale	Yes (has been already discovered at least once - ATIC)
axion	$\tilde{a}$ superpartner of a	Hierarchy problem + Strong CP problem	yes
gravitino	$\tilde{g}$ superpartner of g [superwimp]	Hierarchy problem and things falling	yes
inert doublet	$2^{\pm 1/2}$	Weak scale	if tweaked

In general LNSWP is a candidate

also: q balls, BHs, topological, whatever you're working on + I forgot to mention

NB: Many models in frameworks w/o names: dark forces, WIMPless...

Forming DM

Thermal	Non-thermal		
(i.e. DM was at one time in equilibrium)	Decay of other particle	Phase transition	incomplete $n\sigma v$

Canonical example 1

The oscillating scalar field.

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$ (KG eqn in expanding universe)

$$\phi \to \phi_0 e^{wt}$$

$$\Rightarrow w^2 + 3wH + m^2 = 0$$

$$\Rightarrow w = \frac{-3H \pm \sqrt{9H^2 - 4m^2}}{2}$$

if $m \gg H$

$$w = -\frac{3H}{2} \pm i m$$

$$\Rightarrow \quad \phi = \phi_0 e^{-\frac{3Ht}{2}} e^{\pm imt}$$

↑ decay ↑ oscillation

$$\dot{\phi}^2 + m^2\phi^2 \propto \langle \phi_0^2 \rangle m^2 e^{-3Ht} \qquad \text{(constant } H\text{)}$$

$$a = e^{Ht} a_0 \Rightarrow \rho \propto \rho_0 a^{-3}$$

$\Rightarrow$ depletes like volume

$\Rightarrow w = 0 \Rightarrow$ DM

$m \ll H$ $\qquad w = -3H, \quad -\frac{2m^2}{3H}$

↑ decays in 1 Hubble time

↖ stays for $t \sim \frac{H}{m^2} \gg H^{-1}$

NB $\quad \phi_0 \sim M_{pl} \qquad \langle \phi_0^2 \rangle m^2 = M_{pl}^2 m^2$

when $\quad H = m \Rightarrow H^2 = m^2 \qquad$ "comes inside the horizon"

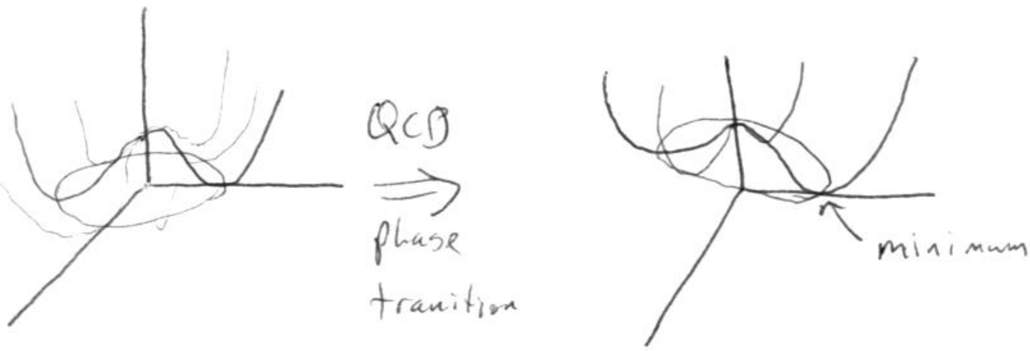
$$\frac{\rho}{M_{pl}^2} = m^2$$

$$\Rightarrow \rho \simeq m^2 M_{pl}^2 \simeq \langle \phi_0^2 \rangle m^2$$

$\Rightarrow$ matter dominated as soon as $H \sim m$

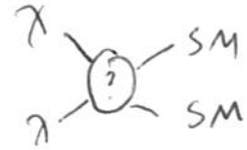
<u>Bad</u> DM candidate (no structure growth before MD)

Loosely the axion is this sort of model

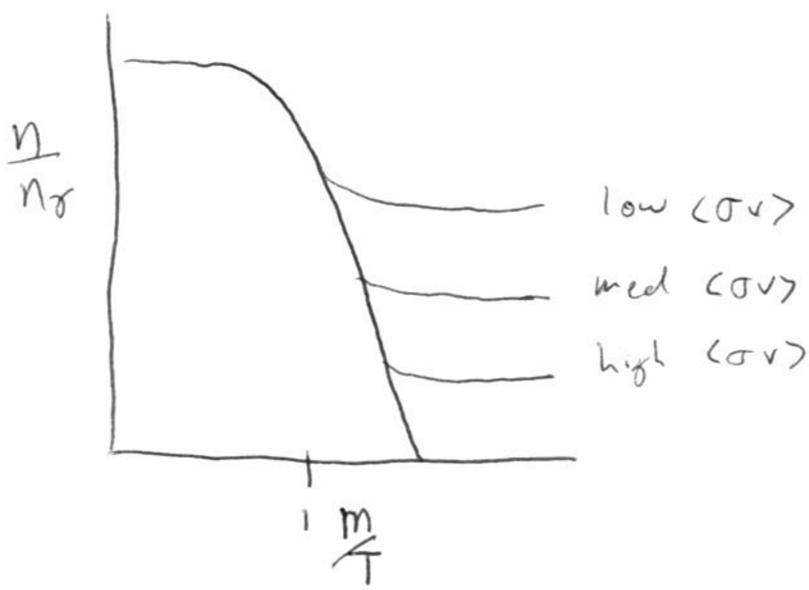


The thermal WIMP

Assume



when $T < m_\chi$ number density is suppressed



$n\sigma v = H$ (assume)

$\Rightarrow n = \frac{H}{\sigma v}$; assume freezeout at $x_f = \frac{m}{T_f}$

NB $x_f << \infty$! $\Rightarrow x_f \sim 1$ (really ~ 20)

$n_{now} = n_f \times \left(\frac{T_{now}}{T_f}\right)^3 \times$ entropy $\quad H_{freezeout} = \frac{T_f^2}{M_{pl}} = \frac{m^2}{M_{pl} x_f^2}$

$\rho_{now} = m\, n_{now} = m\, n_f \left(\frac{T_{now}}{T_f}\right)^3$

$= m \times \frac{m^2}{M_{pl} x_f^2} \times \frac{T_{now}^3 x_f^3}{m^3 \langle\sigma v\rangle} \times \text{entropy} = \frac{T_{now}^3 x_f}{\langle\sigma v\rangle M_{pl}} \times \text{entropy}$