Dark Matter in Particle Physics

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Outline

- Framework - General Relativity and Particle Physics
- Observed Universe and Inference
- Dark Energy, Dark Matter (DM)
- DM Candidates
- DM Direct Detection
- DM at Colliders

The Framework

- Einstein's **General Theory of Relativity** (GR)
- In GR 4 dim space-time is dynamical
- Mass/Energy curves space-time:
  Curvature $\propto$ Energy-density (ρ)
  Define $\Omega = \frac{\rho}{\rho_c}$ ρ_c is critical energy-density (a constant)
  All forms of matter/energy contributes to ρ - **Particle Physics**

The Standard Model of Particle Physics

Since $E = m\,c^2$, same unit for mass and energy: **eV** (set $c = 1$)

$$1\,GeV = 10^9\,eV$$

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Building blocks:

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c²	Electric charge
ν_L lightest neutrino*	$(0–0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009–0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04–0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c²	Electric charge
g gluon	0	0

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

Composites:

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
Baryons are fermionic hadrons.
These are a few of the many types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	antiproton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

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π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.776	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

[particleadventure.org]

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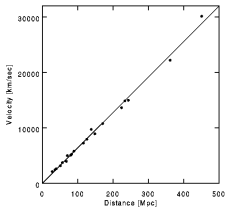
[particleadventure.org]

Big-Bang Neucleosynthesis (BBN)

explains element (D, He, Li, ...) abundances in the universe

The Observed Universe

- The universe is expanding [Hubble]



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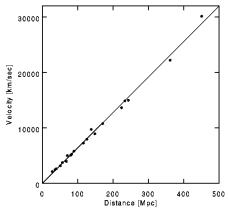

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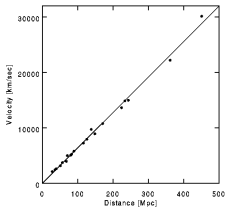

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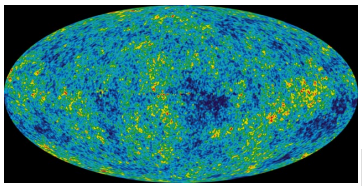
WMAP 
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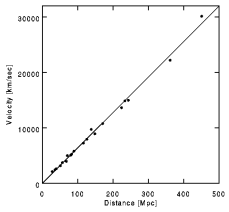

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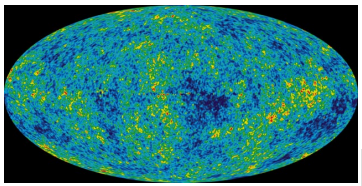
  WMAP 
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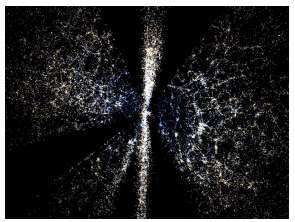
- Galaxy Clusters, Chandra, Ly α, 2dF, SDSS 

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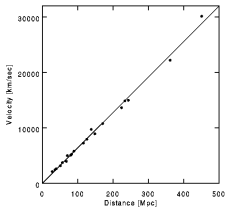

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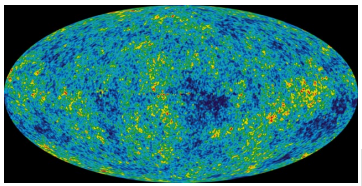
  WMAP 
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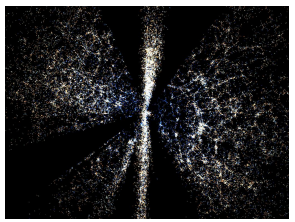
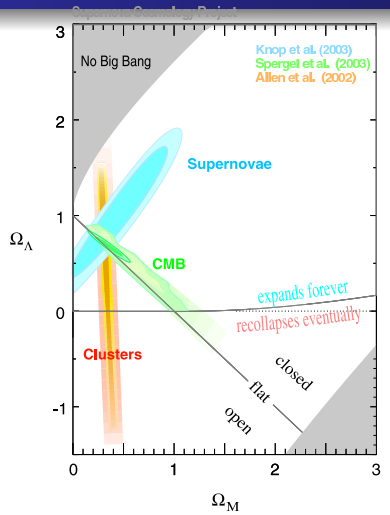
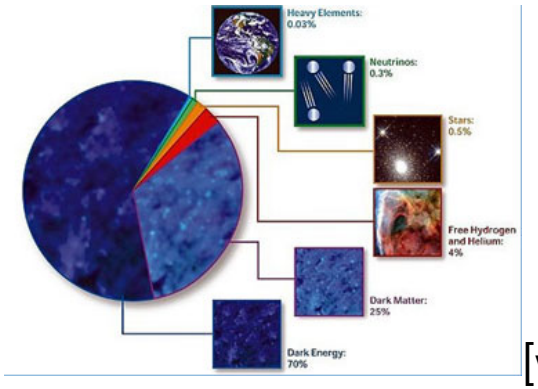
- Galaxy Clusters, Chandra, Ly α, 2dF, SDSS 
- Supernova Cosmology Project

Inference



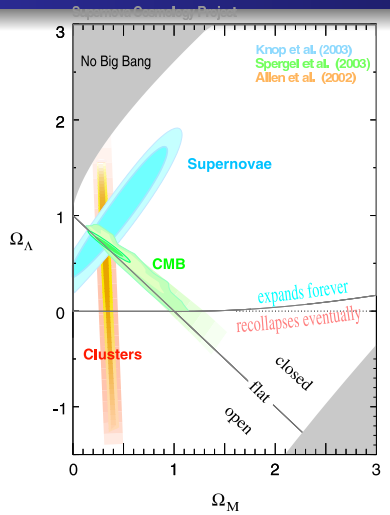


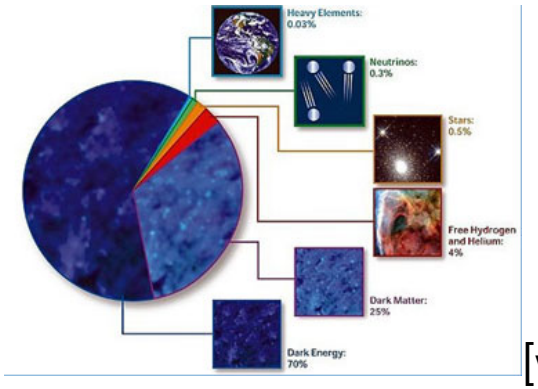
[wikipedia]

The universe

- **Flat** on large scales
- Expansion is **Accelerating**
- **95%** is unknown **dark matter** + **dark energy** - **What is it**??

Inference





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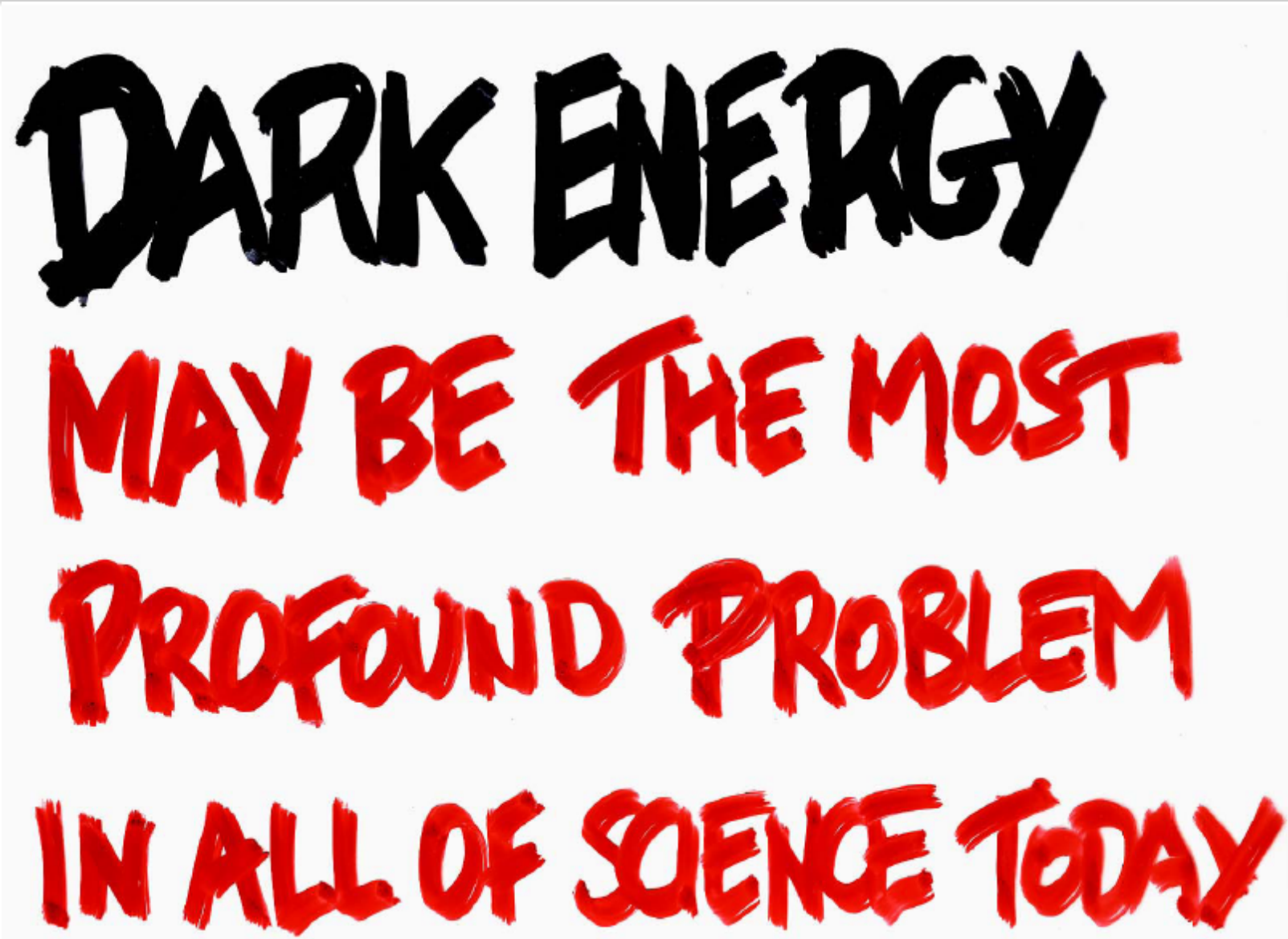
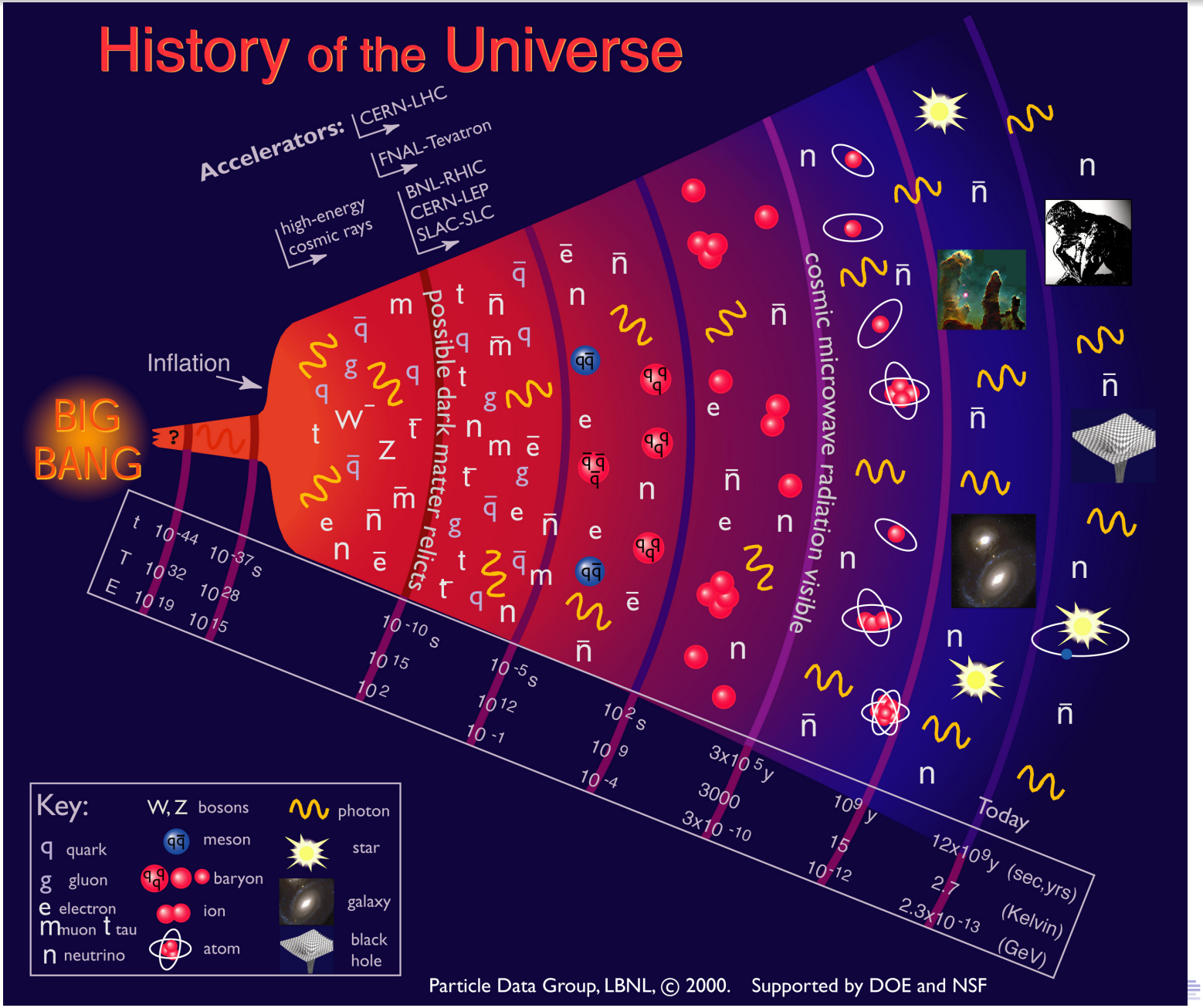
The DARK SIDE rules!!!



[Mike Turner, Neutrino 2006]


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Today
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Dark Matter candidates

Astrophysical objects - Disfavored

- MAssive Compact Halo Object (MACHO)
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Particle Dark Matter

- Axions
- Neutrinos
- Weakly Interacting Massive Particle (WIMP)
- Super-WIMP,E-WIMP,WIMPzilla
- LSP, LKP, LTP

Axions

- Strong interactions - Quantum Chromo Dynamics (QCD)
  Charge-Parity (CP) symmetry conserved - Why???
- Possible explanation - Axion [Peccei-Quinn]

$$\Omega_m = \left(\frac{10^{-5} eV}{m_a}\right)^{7/6} \qquad m_a = 6\, eV \left(\frac{10^6 GeV}{f_a}\right)$$

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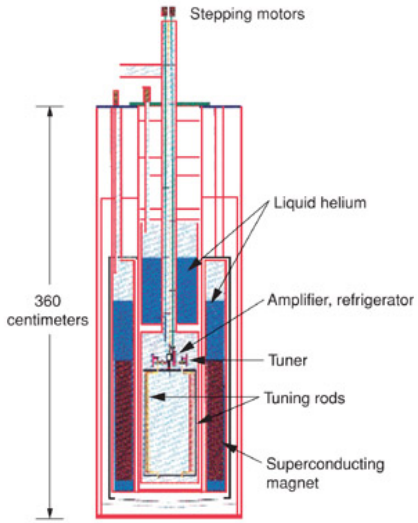

- Axion Dark Matter Expt. (ADMX)

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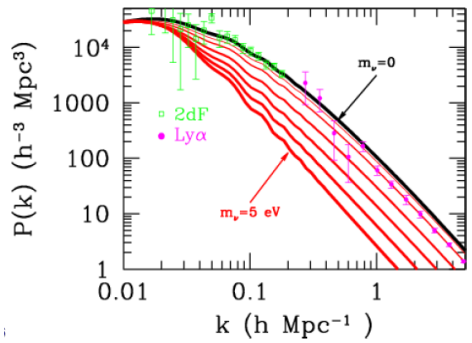

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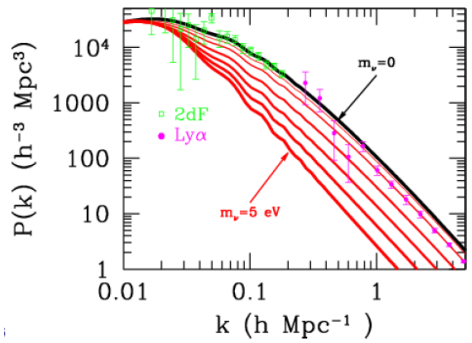

[Dodelson]

- Right-handed Neutrino (Sterile Neutrino) can be DM
  Warm Dark Matter
  Solves many puzzles : LSND, Small scale structure, etc.

Weakly Interacting Massive Particle (WIMP)

WIMP Cold dark matter - New particle

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Most studied extension of the SM - **Supersymmetry**

- Extension of space-time symmetry to Superspace
  Boson $\Longleftrightarrow$ Fermion symmetry.
  Every known particle has a **Superpartner**
- Lightest Supersymmetric Particle (LSP) can be stable
  LSP can be WIMP dark-matter. Eg. Neutralino

Other candidates

- SuperWIMP - Gravitino (partner of graviton)
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- Your candidate here

DM direct detection

- Cryogenic Dark Matter Search (CDMS), Soudan Mine, USA

Ge detector

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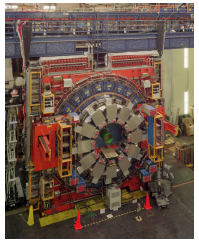
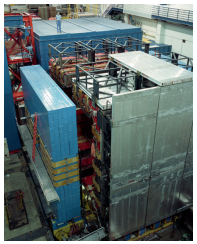
Ge detector

- DAMA, Gran Sasso, Italy. Detection claimed!!

NaI scintillators

DM at Colliders I

- Fermilab: Tevatron, CDF, D0

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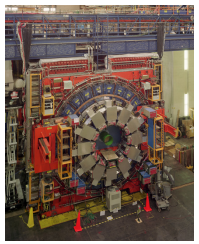
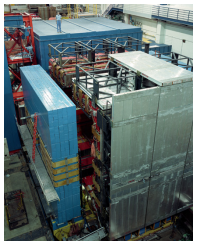

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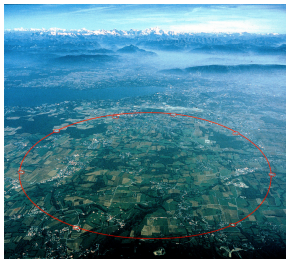
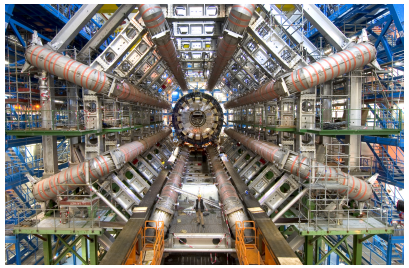
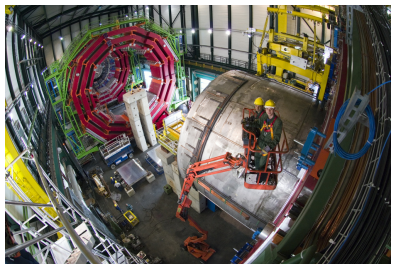

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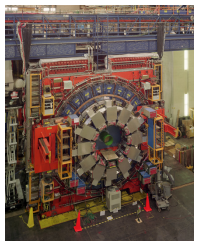
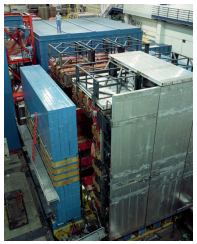

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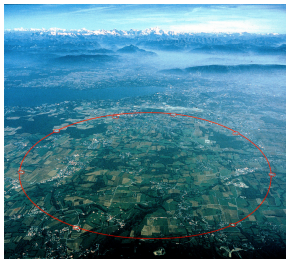
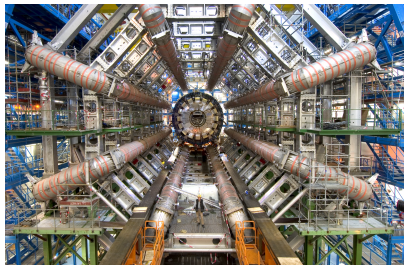
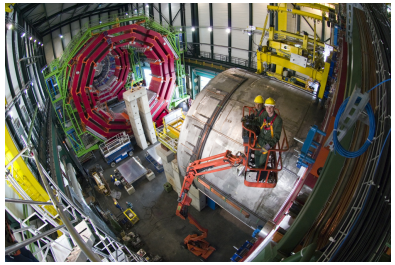
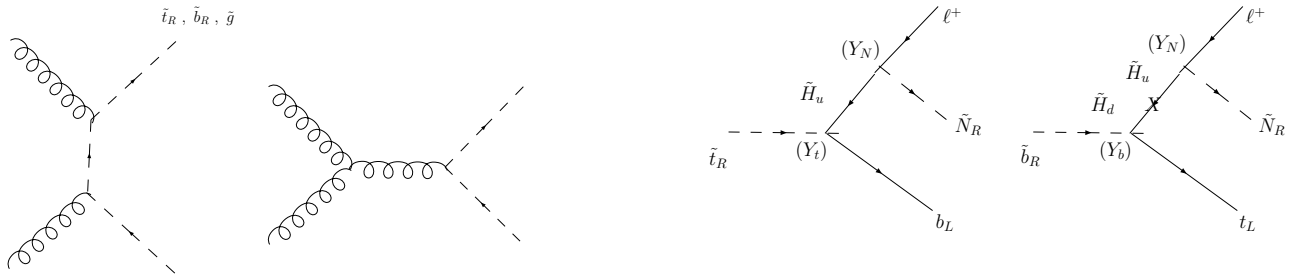




- The Future: Linear Collider:

DM at Colliders II

- Example: Supersymmetry



- LSP leads to "missing momentum"

Final Thoughts

- What is Dark Energy and Dark Matter???
- Many Candidates, Mass range 10^{-5}eV - 10^{12}GeV
- Vigorous search underway - Direct and Collider
- Exciting times! We might discover DM particle soon
- Dark Energy - Only for the brave!

Backup Slides

Backup Slides

Ω_m

WMAP result (2003) $\Omega_m h^2 = 0.135\ ^{+0.008}_{-0.009}$; $h^2 \approx 0.5$

Thermal History of the Universe

Big Bang $\longrightarrow$ Inflation $\longrightarrow \cdots \longrightarrow$ BBN $\longrightarrow$ Today

Hubble rate:

$$H \equiv \frac{\dot{a}}{a}\,; \quad H^2 = \frac{8\pi G}{3}\rho$$

$$H = 1.66\sqrt{g_*}\frac{T^2}{M_{Pl}} \quad (\text{Rad Dom})$$

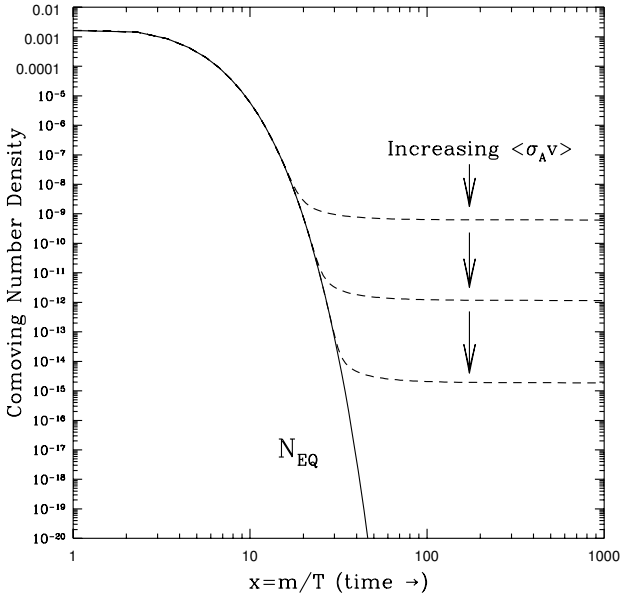
Boltzmann Equation

Big Bang $\longrightarrow$ Inflation $\longrightarrow \cdots \longrightarrow$ BBN $\longrightarrow$ Today

$$\frac{d}{dt} n_{\tilde{\nu}_0} = -3Hn_{\tilde{\nu}_0} - \langle \sigma v \rangle_{SI} \left(n^2_{\tilde{\nu}_0} - n^2_{\tilde{\nu}_0\, eq} \right) - \langle \sigma v \rangle_{CI} \left(n_{\tilde{\nu}_0} n_\phi - n_{\tilde{\nu}_0\, eq} n_{\phi\, eq} \right) + C_\Gamma$$

Thermal equilibrium if $\langle \sigma v \rangle_{SI}\, n_{\tilde{\nu}_0} > 3H$; $\langle \sigma v \rangle_{CI}\, n_\phi > 3H$

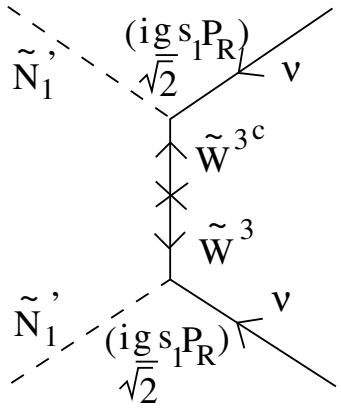
Freeze-out



[Kolb & Turner, Early Universe]

$$\Omega_0 \equiv \frac{n_0 M}{\rho_c} \approx 4 \times 10^{-10} \left(\frac{\mathrm{GeV}^{-2}}{\langle \sigma v \rangle} \right)$$

Mixed $\tilde{\nu}_0$ Dark Matter



$$\Omega_0 h^2 = \frac{10^{-4}}{s_1^4} \left\{ \left[g^2 \left(\frac{100\ \text{GeV}}{M_{\tilde{W}}} \right) + g'^2 \left(\frac{100\ \text{GeV}}{M_{\tilde{B}}} \right) \right]^2 \right\}^{-1}$$

$\therefore s_1 \approx 0.2$ results in observed relic density