Particle Dark Matter

Tim Linden

Lecture 5

Fall 2014 Compton Lectures

http://chasm.uchicago.edu

From Last Lecture

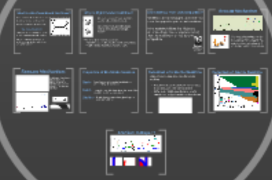
1.) Dark Matter explains how stars revolve around galaxies, and explains the growth of structure from the beginning of the universe to today

2.) Massive objects, modifications of gravity, and known particles have been ruled out as sources of dark matter

So what is the dark matter?

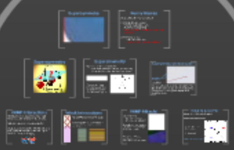
Sterile Neutrinos

The Heavier Cousin of Neutrinos



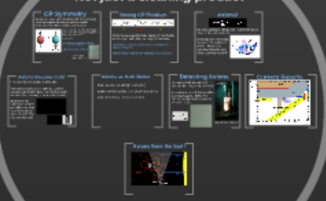
WIMPs

Weakly interacting massive particles



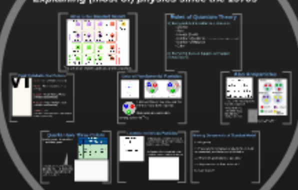
Axions

Not just a cleaning product



The Standard Model

Explaining (most of) physics since the 1970s



Something Else?

Lots of other ideas:

- Gravitinos
- CHAMPs
- SuperWIMPs
- WIMPZilla!

But - in the end, observations are the judge and jury!

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Properties of Dark Matter

1.) **Dark** - Doesn't interact with light

2.) **Stable** - Particle exists in Early Universe, and still exists today

3.) **Cold** - Particle is moving slowly, can fall into potential wells

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The Standard Model

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What is the Standard Model?

The set of all known particles and interactions

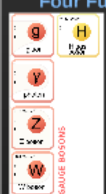
Rules of Quantum Theory

1.) Every particle interaction must conserve:

- Charge
- Spin
- Energy (mass)
- Number of Leptons (electron number, muon number, tau number)
- Number of Baryons
- Color

2.) Everything that can happen, will happen (maybe rarely)

Four Fundamental Forces



Gluon - Strong Nuclear Force (1)

Photon - Electromagnetic Force (0.001)

Z boson - Weak Nuclear Force (0.0000000000000001)

W boson - Weak Nuclear Force (0.0000000000000001)

Gravity - ???? (0.000000000000000000000000000000 00000000000001)

Lots of Fundamental Particles

Lots and lots of baryons can be formed from these quarks.

But most are not stable.

omega (8 x 10^{-11}s)

Also Antiparticles

proton u u d
neutron u d d
antiproton ū ū d̄
antineutron ū d̄ d̄

Every fundamental particle has an antiparticle

Antiparticle has the same mass, but opposite charge and spin

Quarks Have Three Colors

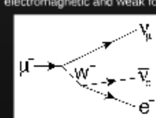
Quarks come in three colors: red, blue, green

Mesons and Hadrons must be colorless. It is impossible to observe something with color in nature.

Leptons: Colorless Particles

Unlike quarks, which have color and interact with the strong force, leptons are colorless

But leptons do interact with the electromagnetic and weak forces



Missing Components of Standard Model

1.) No gravity

2.) There are 19 numerical constants which must be measured, and have no a priori value.

3.) Why three generations of particles?

4.) Why more matter than antimatter?

5.) Dark Matter?

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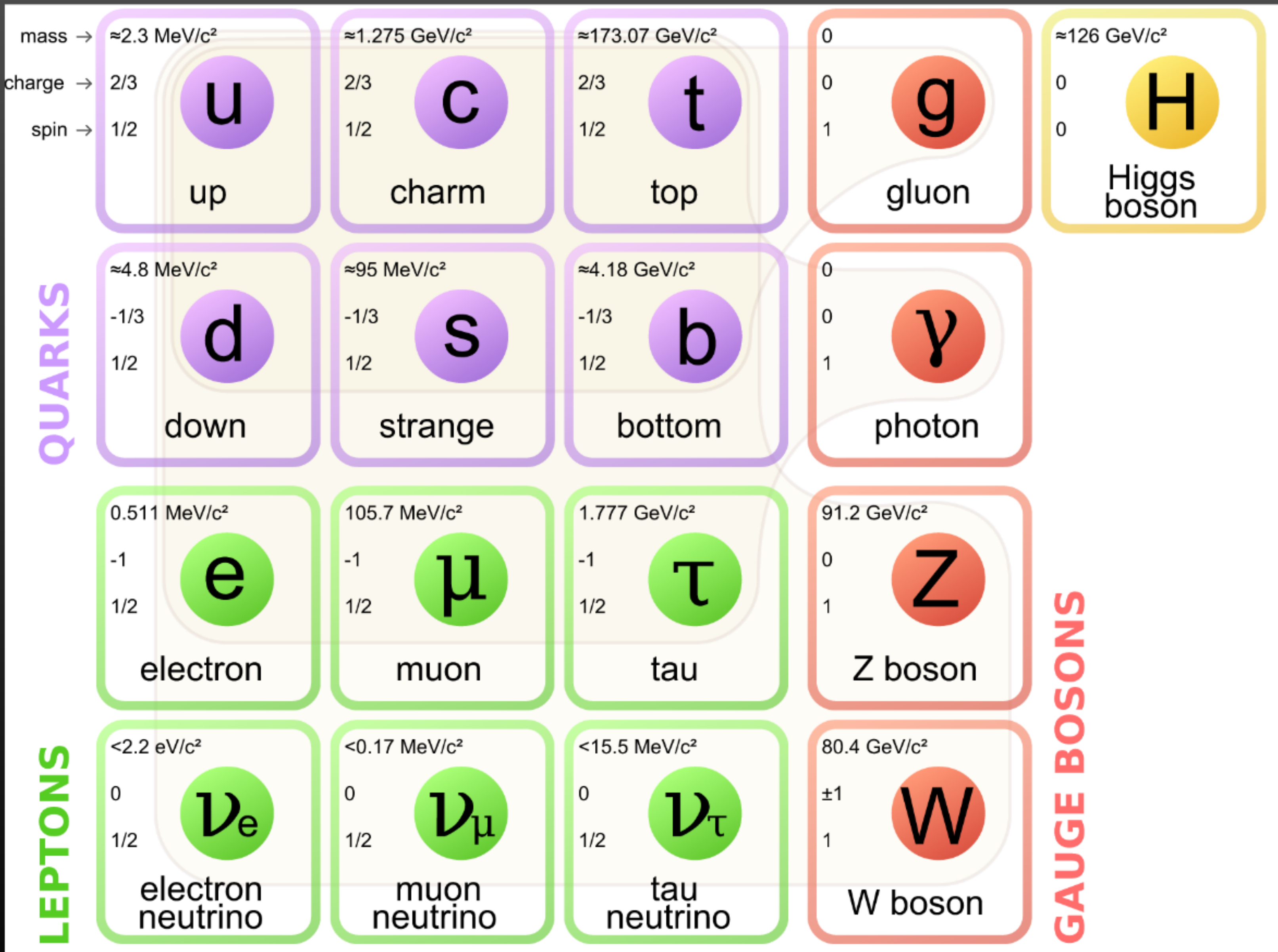

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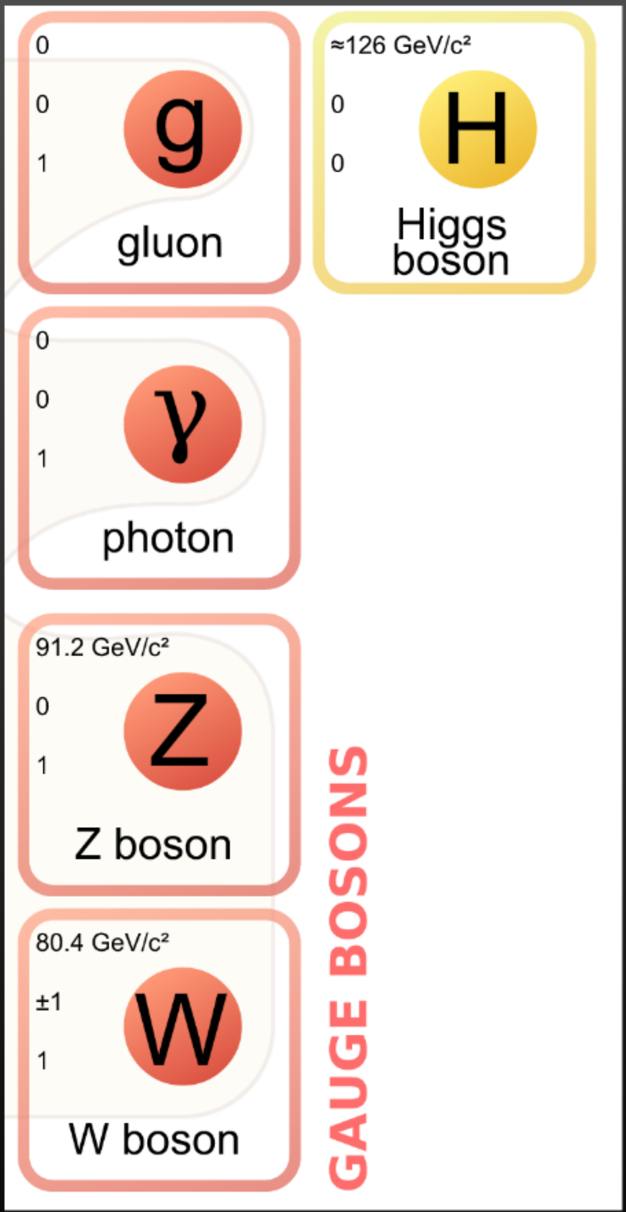

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Lots of Fundamental Particles

u up

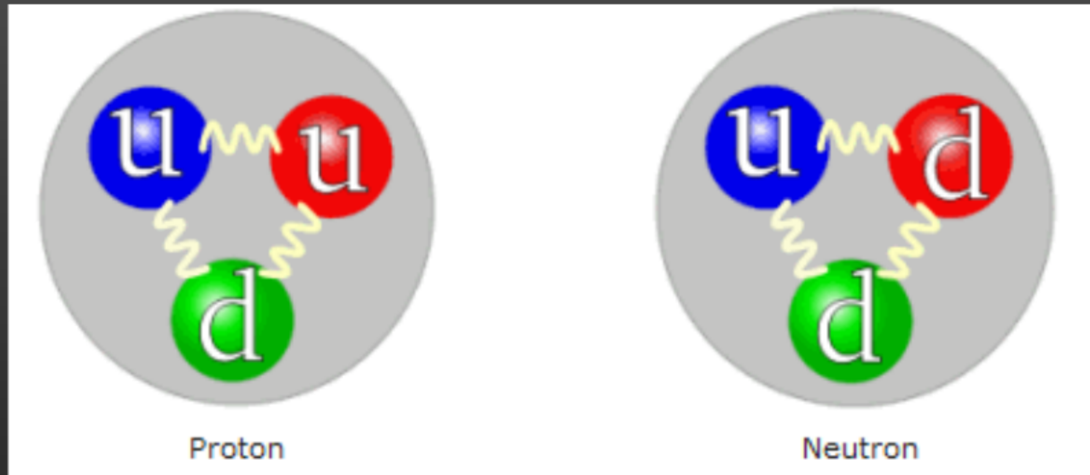
d down

c charm

s strange

t top

b bottom



Quark composition of a proton and a neutron (diagrams from *Wikipedia*)

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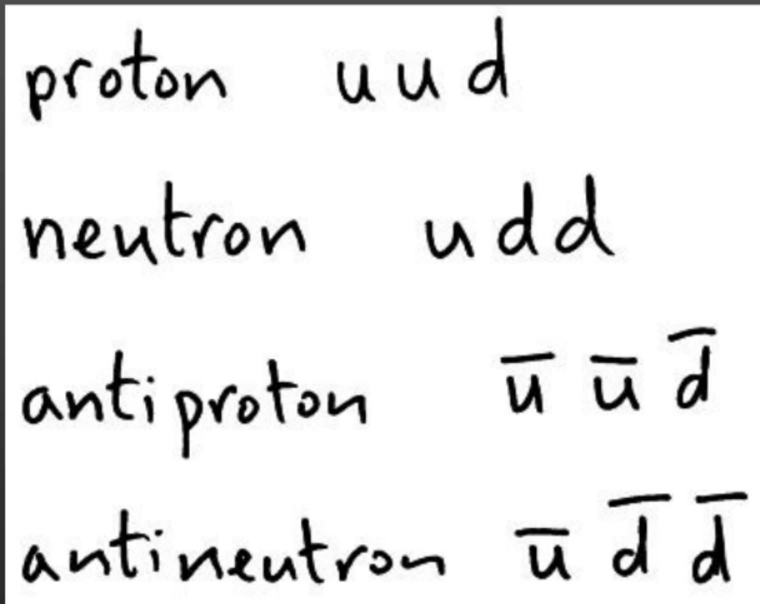
Also Antiparticles



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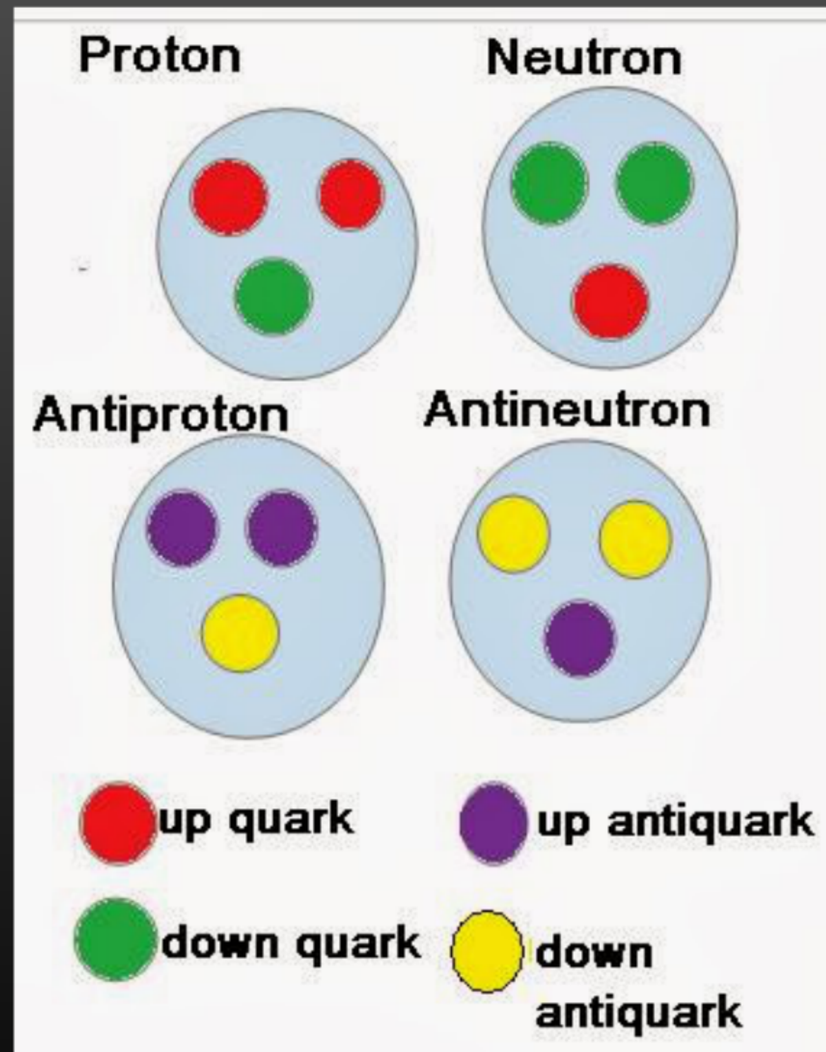
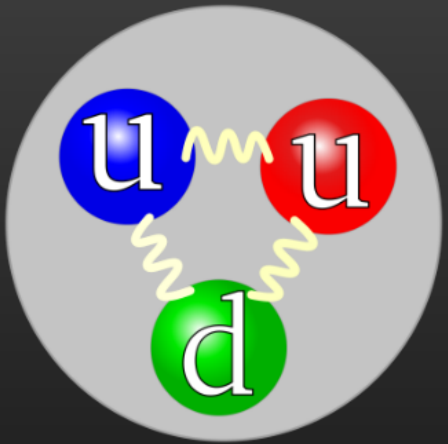
Antiparticle has the same mass, but opposite charge and spin



First predicted (positrons) by Paul Dirac in 1932

Quarks Have Three Colors

Quarks come in three colors:
red, blue, green



Mesons $q\bar{q}$					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Mesons and Hadrons must be colorless. It is impossible to observe something with color in nature.

Particle name	Symbol	Quark content	Rest mass (MeV/c^2)	I	J^P	Q (e)	S	C	B'	Mean lifetime (s)	Commonly decays to
nucleon/proton[7]	p / p^+ / N^+	uud	938.272 046(21)[a]	½	½+	+1	0	0	0	Stable[b]	Unobserved
nucleon/neutron[8]	n / n^0 / N^0	udd	939.565 379(21)[a]	½	½+	0	0	0	0	$(8.800 \pm 0.009) \times 10^2$[c]	$p^+ + e^- + \bar{\nu}_e$
Lambda[9]	Λ^0	uds	1 115.683 ±0.006	0	½+	0	–1	0	0	$(2.632 \pm 0.020) \times 10^{-10}$	$p^+ + \pi^-$ or $n^0 + \pi^0$
charmed Lambda[10]	Λ_c^+	udc	2 286.46 ±0.14	0	½+	+1	0	+1	0	$(2.00 \pm 0.06) \times 10^{-13}$	See Λ_c^+ decay modes
bottom Lambda[11]	Λ_b^0	udb	5 619.4 ±0.6	0	½+	0	0	0	–1	$(1.429 \pm 0.024) \times 10^{-12}$	See Λ_b^0 decay modes
Sigma[12]	Σ^+	uus	1 189.37 ±0.07	1	½+	+1	–1	0	0	$(8.018 \pm 0.026) \times 10^{-11}$	$p^+ + \pi^0$ or $n^0 + \pi^+$
Sigma[13]	Σ^0	uds	1 192.642 ±0.024	1	½+	0	–1	0	0	$(7.4 \pm 0.7) \times 10^{-20}$	$\Lambda^0 + \gamma$
Sigma[14]	Σ^-	dds	1 197.449 ±0.030	1	½+	–1	–1	0	0	$(1.479 \pm 0.011) \times 10^{-10}$	$n^0 + \pi^-$
charmed Sigma[15]	Σ_c^{++}	uuc	2 453.98 ±0.16	1	½+	+2	0	+1	0	$(2.91 \pm 0.32) \times 10^{-22}$[d]	$\Lambda_c^+ + \pi^+$
charmed Sigma[15]	Σ_c^+	udc	2 452.9 ±0.4	1	½+	+1	0	+1	0	$>1.43 \times 10^{-22}$[d]	$\Lambda_c^+ + \pi^0$
charmed Sigma[15]	Σ_c^0	ddc	2 453.74 ±0.16	1	½+	0	0	+1	0	$(3.05 \pm 0.37) \times 10^{-22}$[d]	$\Lambda_c^+ + \pi^-$
bottom Sigma[16]	Σ_b^+	uub	$5\,811.3^{+0.9}_{-0.8} \pm 1.7$	1	½+	+1	0	0	–1	$6.6^{+2.7}_{-3.5} \times 10^{-23}$[d]	$\Lambda_b^0 + \pi^+$
bottom Sigma†	Σ_b^0	udb	Unknown	1	½+	0	0	0	–1	Unknown	Unknown
bottom Sigma[16]	Σ_b^-	ddb	$5\,815.5^{+0.6}_{-0.5} \pm 1.7$	1	½+	–1	0	0	–1	$1.34^{+0.87}_{-1.15} \times 10^{-22}$[d]	$\Lambda_b^0 + \pi^-$
Xi[17]	Ξ^0	uss	1 314.86 ±0.20	½	½+	0	–2	0	0	$(2.90 \pm 0.09) \times 10^{-10}$	$\Lambda^0 + \pi^0$
Xi[18]	Ξ^-	dss	1 321.71 ±0.07	½	½+	–1	–2	0	0	$(1.639 \pm 0.015) \times 10^{-10}$	$\Lambda^0 + \pi^-$

Leptons: Colorless Particles

LEPTONS

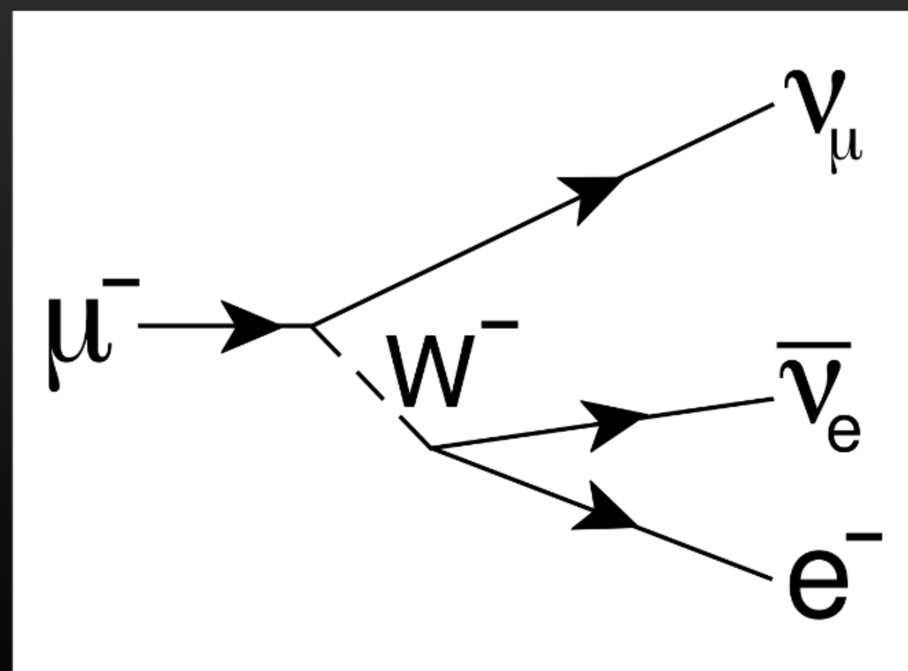
e^-	μ^-	τ^-
ν_e	ν_μ	ν_τ

ANTILEPTONS

e^+	μ^+	τ^+
$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$

Unlike quarks, which have color and interact with the strong force, leptons are colorless

But leptons do interact with the electromagnetic and weak forces



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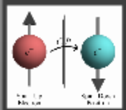
Axions

Not just a cleaning product

CP Symmetry

Most forces obey what physicists call "CP symmetry", that if we reverse the charge, and the spatial dimension, the laws of physics are invariant



If you turned the universe from matter to antimatter, and flipped all the spins, it should work the same

Experiment:

- Strong force and electromagnetic force obey CP symmetry

- Weak force does not (1964)

James Cronin
Nobel Prize 1980

Strong CP Problem

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{n_f g^2 \theta}{32\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - me^{i\theta'\gamma_5})\psi$$

CP — Not CP — CP

Strong force experimentally obeys CP symmetry, but the equations allow for large CP violation

Remember: Every interaction that can happen in physics happens.

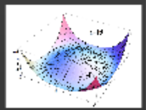
Need a reason that this CP violation does not occur

Axions!

$$\mathcal{L} = \frac{\theta g^2}{32\pi^2}G\tilde{G} - \frac{a}{f_a}g^2 G\tilde{G}$$

If a new particle is introduced, it fulfills the roll of theta in the early universe.

When the symmetry that produces the particle is broken, the particle becomes massive and theta becomes nearly 0



Axions Become Cold

The axion that is created is very light.

Remember last lecture, neutrinos couldn't become dark matter, because they were light, and thus "hot", moving at relativistic speeds

But axions are cooled via damped oscillations as they move through the potential well. Thus they are very cold

Axions as Dark Matter

- **Dark** (don't interact with light, commonly)

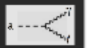
- **Stable** (very light particle, can't decay into anything)

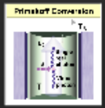
- **Cold** (driven to low velocities by friction)

Detecting Axions

The axion must also mix with photons (but very rarely, still dark)

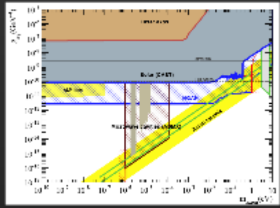
In an intense sea of photons (like a strong magnetic field). The photon energy must be tuned to the axion mass



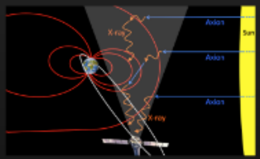


Axion Dark Matter eXperiment

Current Results



Axions from the Sun?



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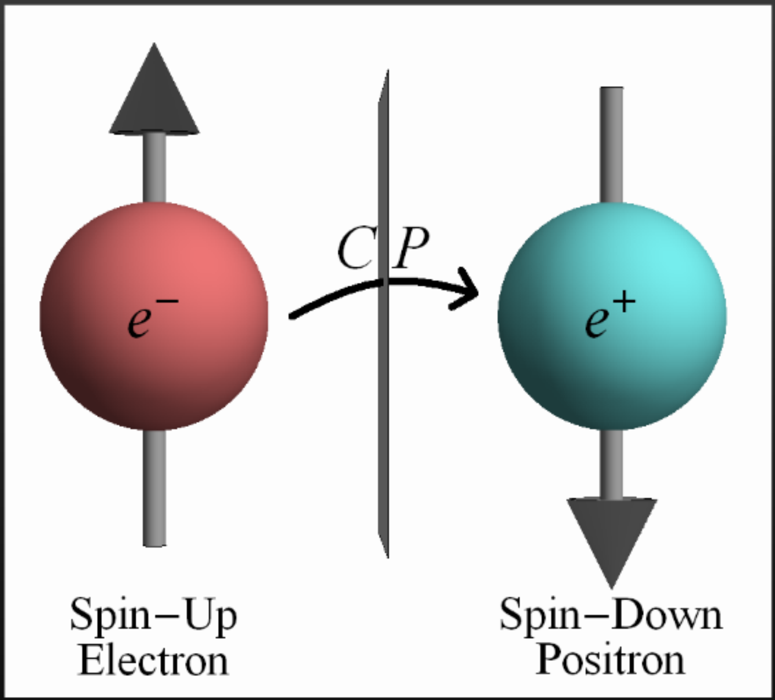

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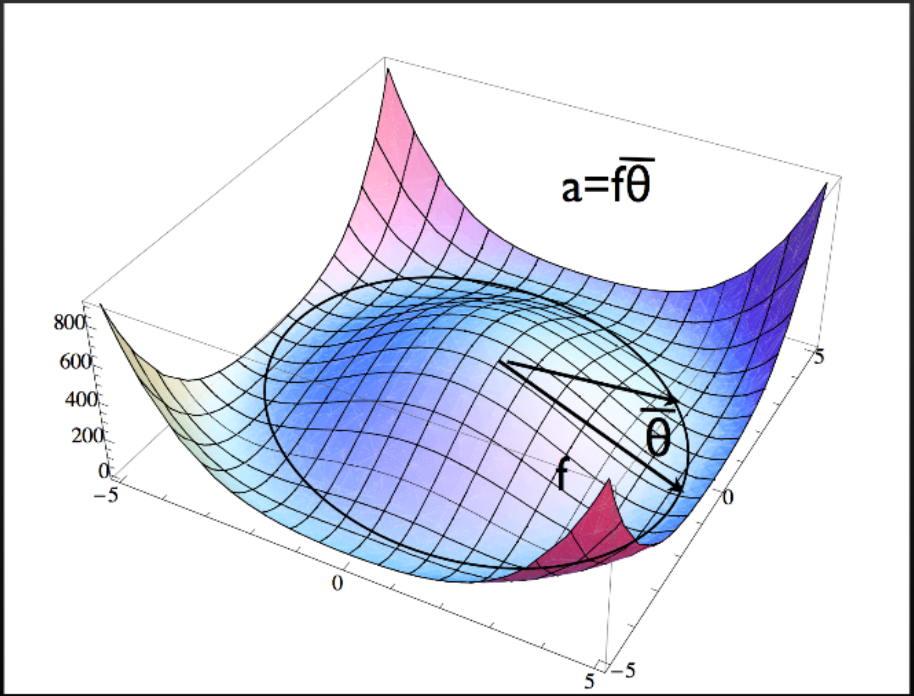

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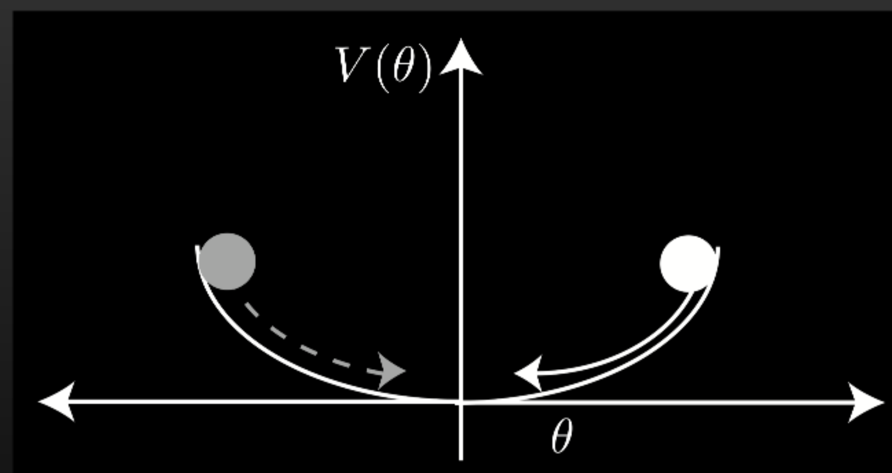

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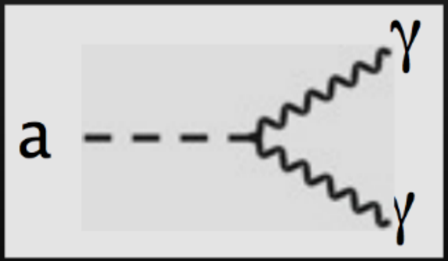

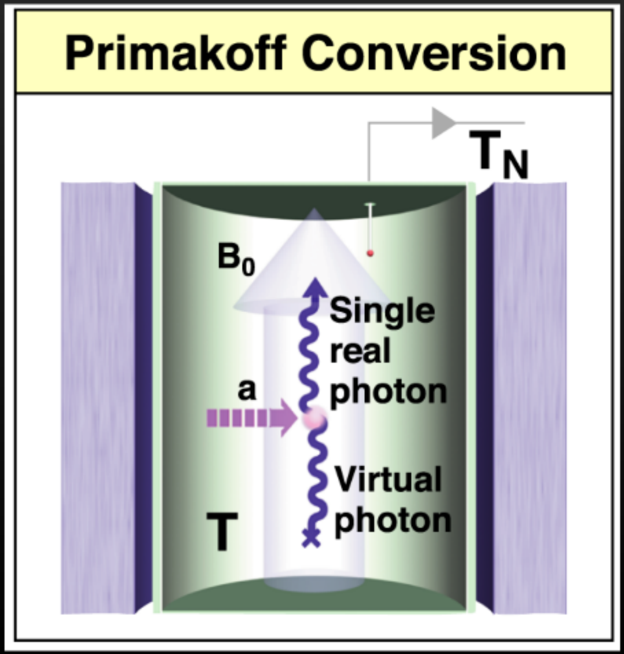

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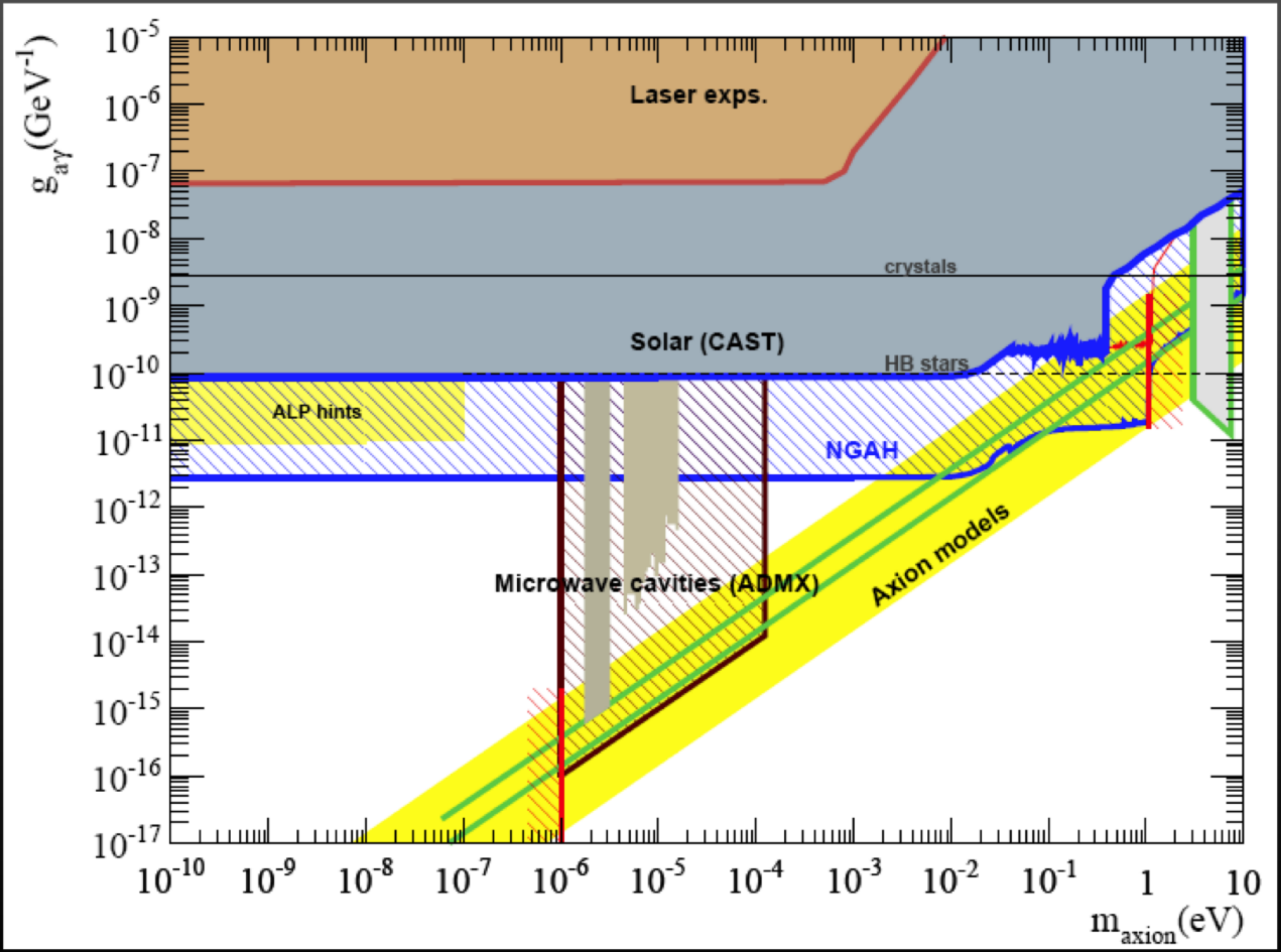

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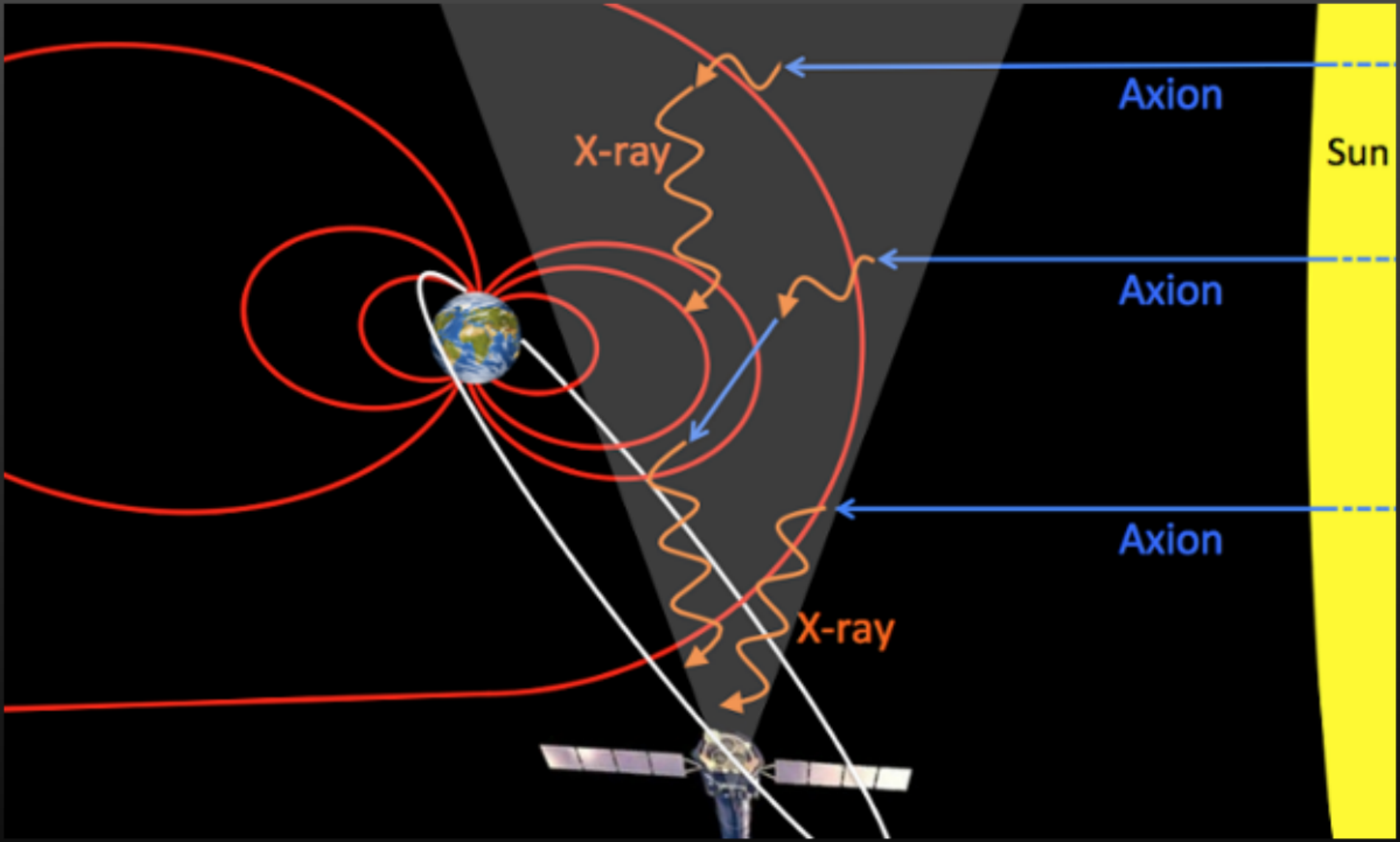


Sterile Neutrinos

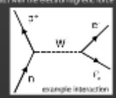
The Heavier Cousin of Neutrinos

What Do We Know About Neutrinos?

Known standard model particle that doesn't interact with the electromagnetic force

But neutrinos do interact with the weak force

Proposed in the 1930 and discovered in 1956

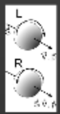


Two Interesting Facts:

All neutrinos are left-handed, while all anti-neutrinos are right handed

Neutrino masses are at least 6 orders of magnitude smaller than any other particle

Why no Right Handed Neutrinos?



All other standard model particles can be left and right handed.

But all neutrinos are left-handed, and all anti-neutrinos are right handed

Two ideas (not mutually exclusive):

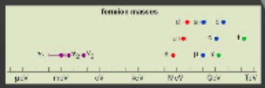
- Neutrinos are majorana (their own antiparticle)
- Right handed neutrinos are very heavy

Are Neutrinos Their Own Antiparticle?

Neutrinos are not charged, and neutrinos have the opposite spin as anti-neutrinos.

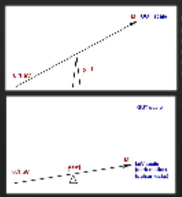
If the neutrino follows the Majorana equation (lingo: has a majorana mass) then the neutrino might be its own antiparticle

Seesaw Mechanism



If the mass of the neutrinos was able to mix with the sterile neutrinos, the seesaw mechanism can dynamically make the left-handed neutrinos light, and the right handed ones very heavy

Seesaw Mechanism



Unfortunately, this doesn't directly allow us to determine the sterile neutrino mass from the masses of the observed neutrinos

Properties of the Sterile Neutrino

Dark - Doesn't interact with standard model particles (except mixing with neutrinos)

Cold - Actually, warm-ish (depends on the mass of the neutrino) Possible way to detect

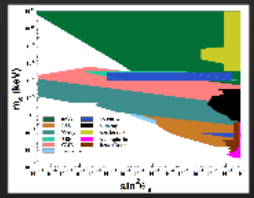
Stable - Rarely decays, except through mixing with standard neutrinos.

Detection of a Sterile Neutrino

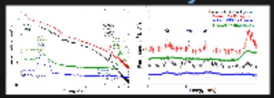
Mass of sterile neutrinos can be almost anything

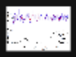
- If neutrino mass is above the weak force mass they are very hard to detect
- Otherwise, might see decay of sterile neutrinos into light neutrinos plus photon

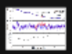
Detection of Sterile Neutrino

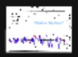


3.57 keV X-Rays !?









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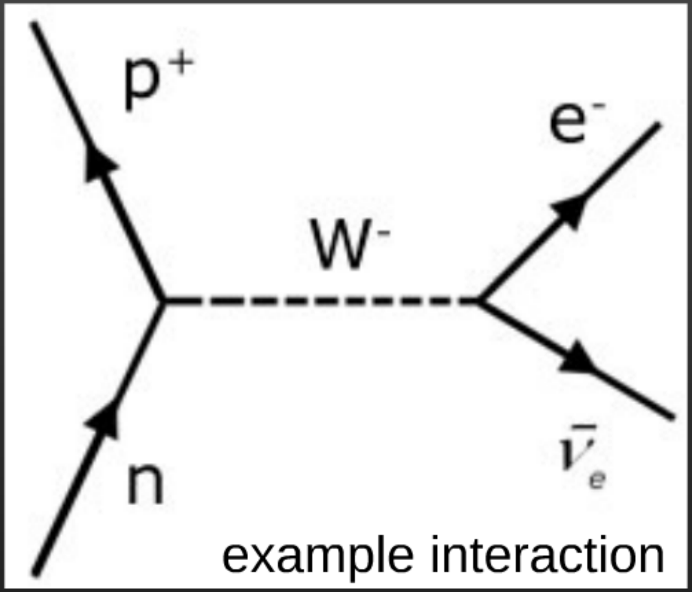
But neutrinos do interact with the weak force

Proposed in the 1930 and discovered in 1956

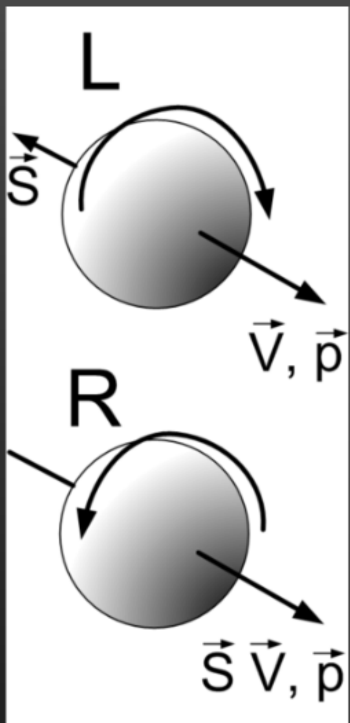


Two Interesting Facts:

All neutrinos are left-handed, while all anti-neutrinos are right handed

Neutrino masses are at least 6 orders of magnitude smaller than any other particle

Why no Right Handed Neutrinos?



All other standard model particles can be left and right handed.

But all neutrinos are left-handed, and all anti-neutrinos are right handed

Two ideas (not mutually exclusive):

- Neutrinos are majorana (their own antiparticle)
- Right handed neutrinos are very heavy

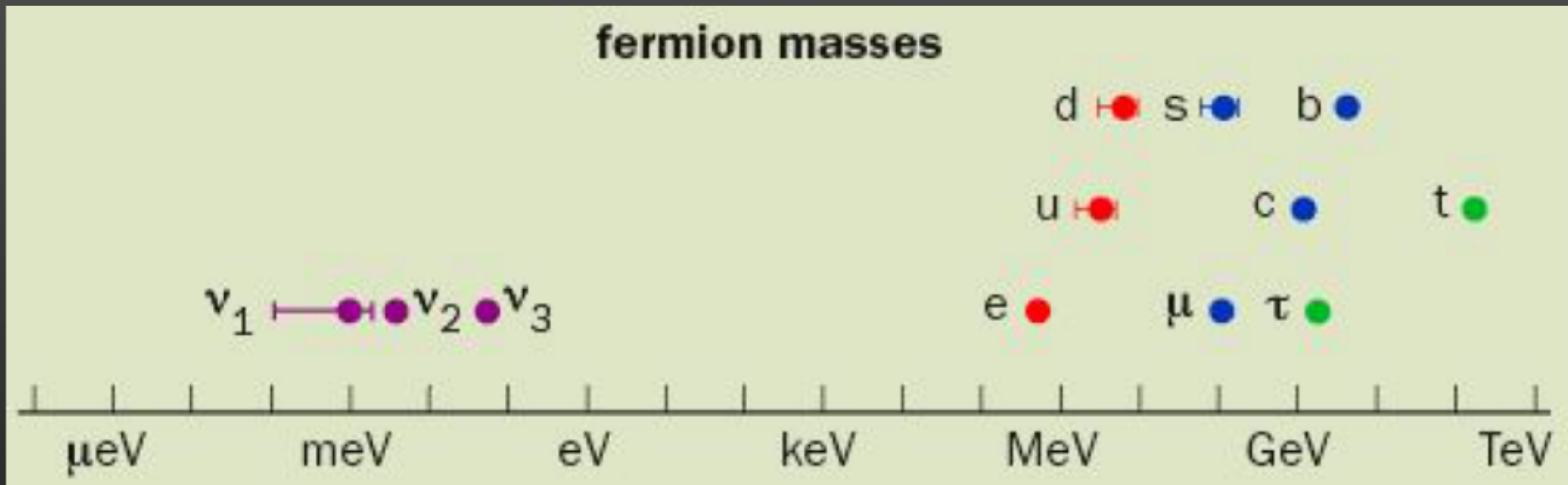
Are Neutrinos Their Own Antiparticle?

Neutrinos are not charged, and neutrinos have the opposite spin as anti-neutrinos.

If the neutrino follows the Majorana equation (lingo: has a majorana mass) then the neutrino might be its own antiparticle

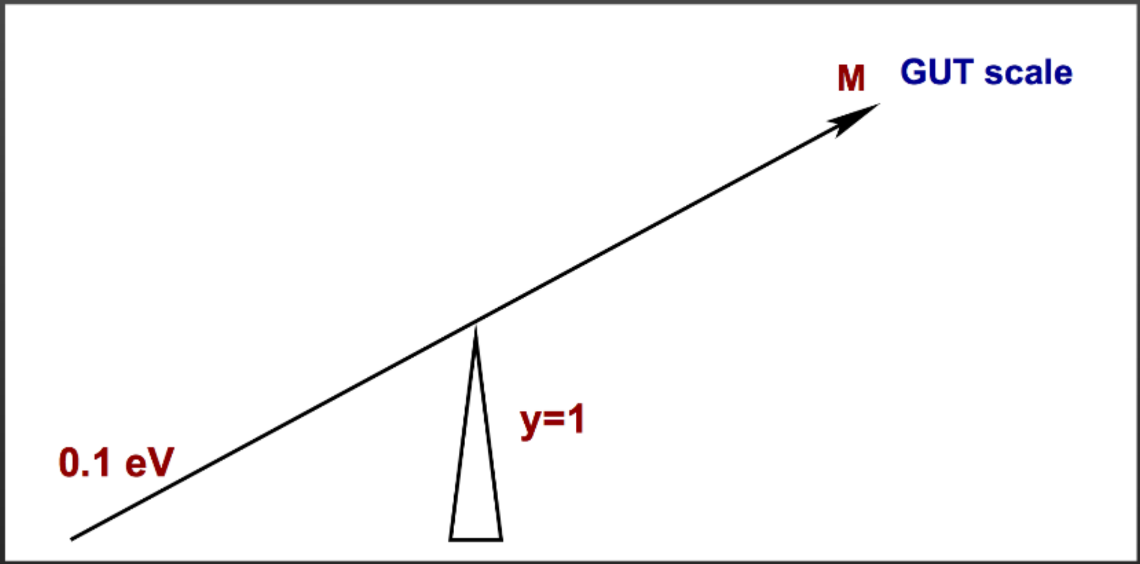
Ettore Majorana
(1906-1938?)

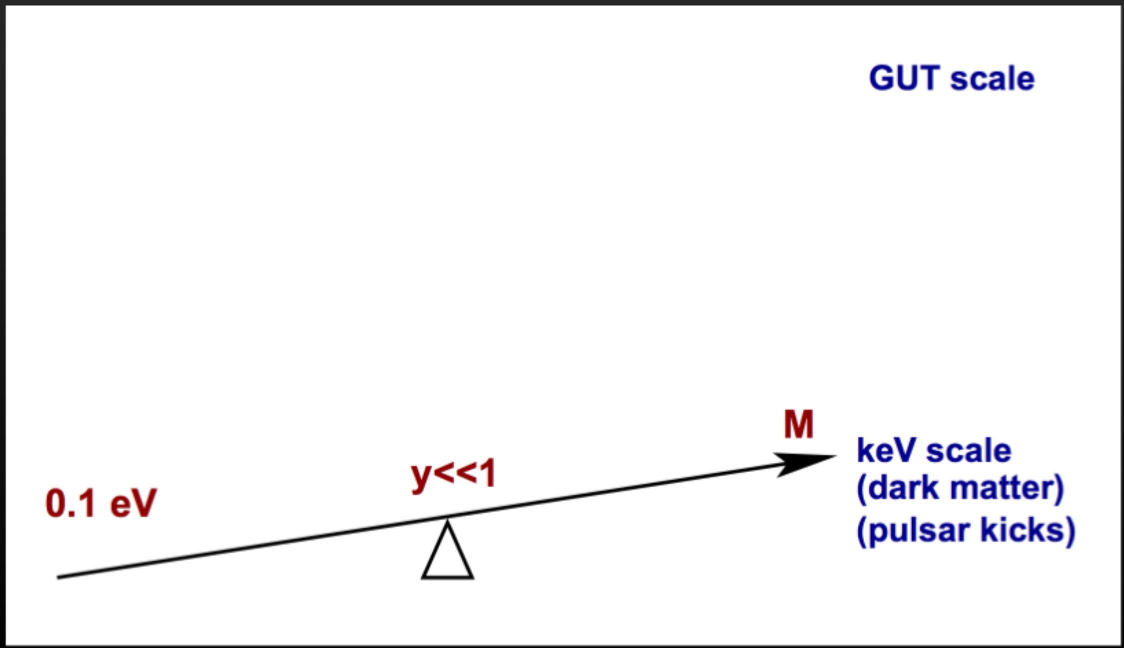
Seesaw Mechanism



If the mass of the neutrinos was able to mix with the sterile neutrinos, the seesaw mechanism can dynamically make the left-handed neutrinos light, and the right handed ones very heavy

Seesaw Mechanism





Unfortunately, this doesn't directly allow us to determine the sterile neutrino mass from the masses of the observed neutrinos

$$A = \begin{pmatrix} 0 & M \\ M & B \end{pmatrix},$$

$$\lambda_{\pm} = \frac{B \pm \sqrt{B^2 + 4M^2}}{2}.$$

Properties of the Sterile Neutrino

Dark - Doesn't interact with standard model particles (except mixing with neutrinos)

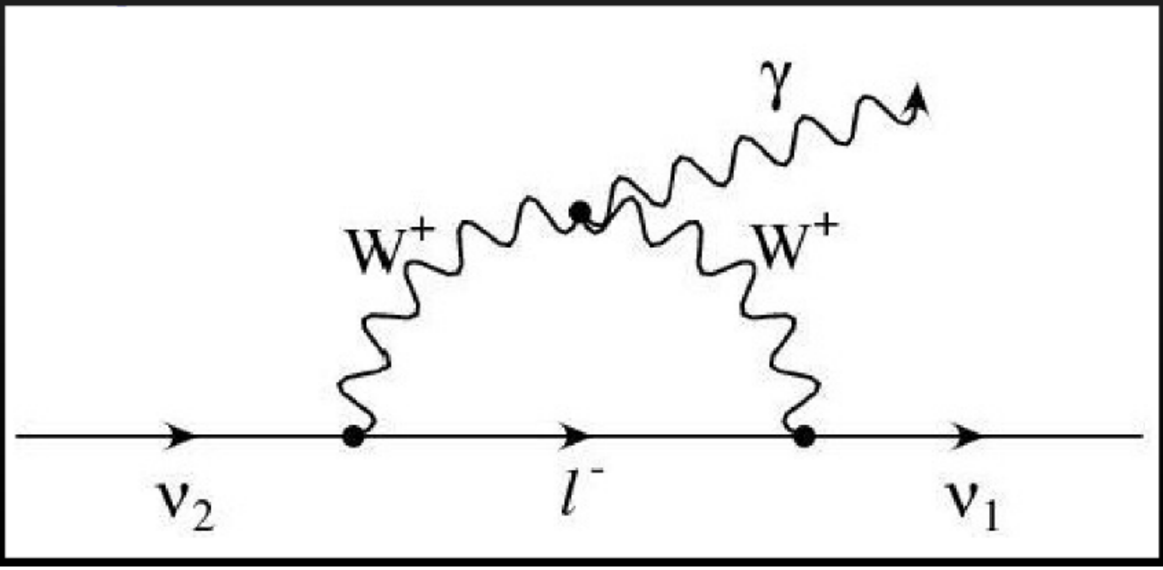
Cold - Actually, warm-ish (depends on the mass of the neutrino) Possible way to detect

Stable - Rarely decays, except through mixing with standard neutrinos.

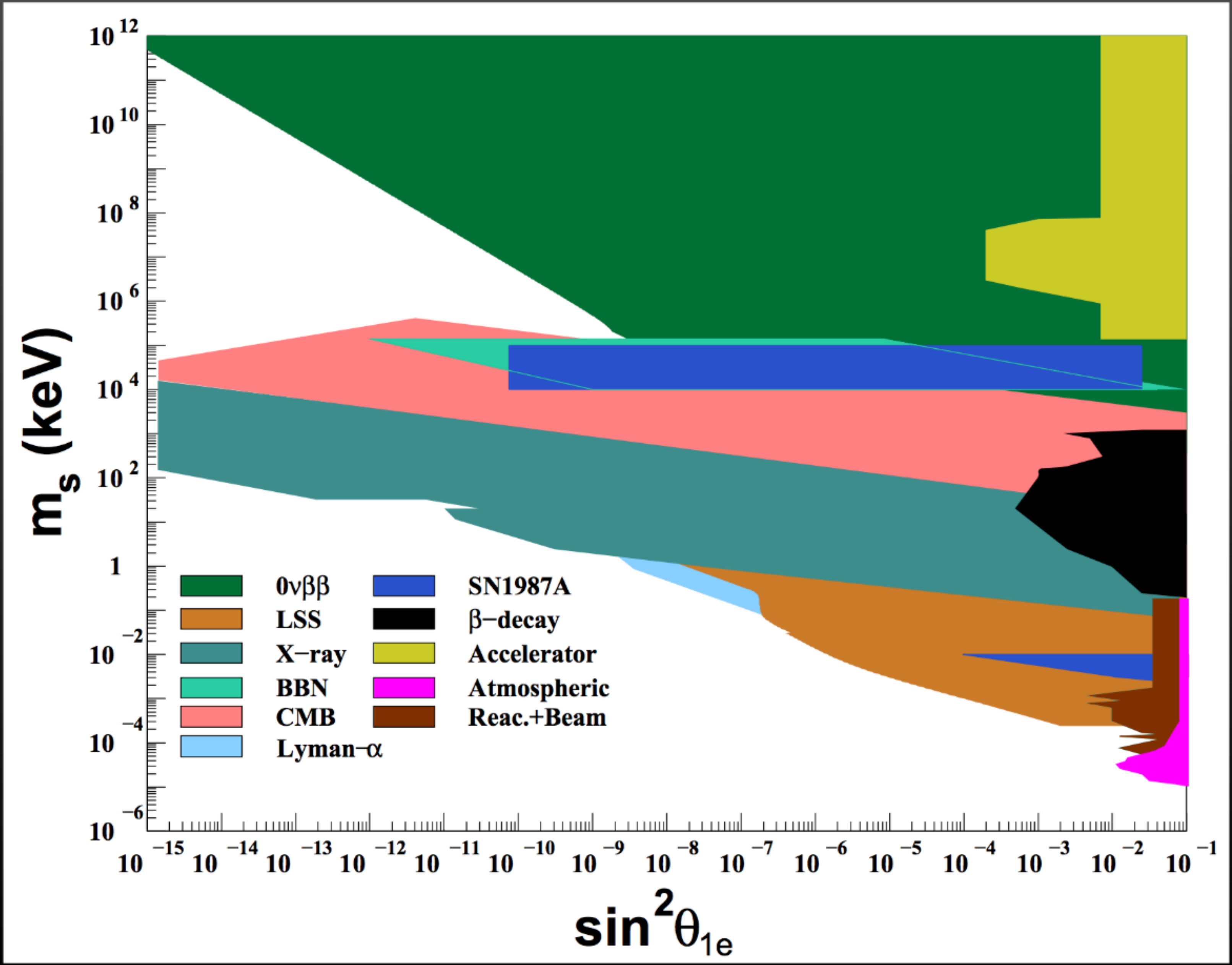
Detection of a Sterile Neutrino

Mass of sterile neutrinos can be almost anything

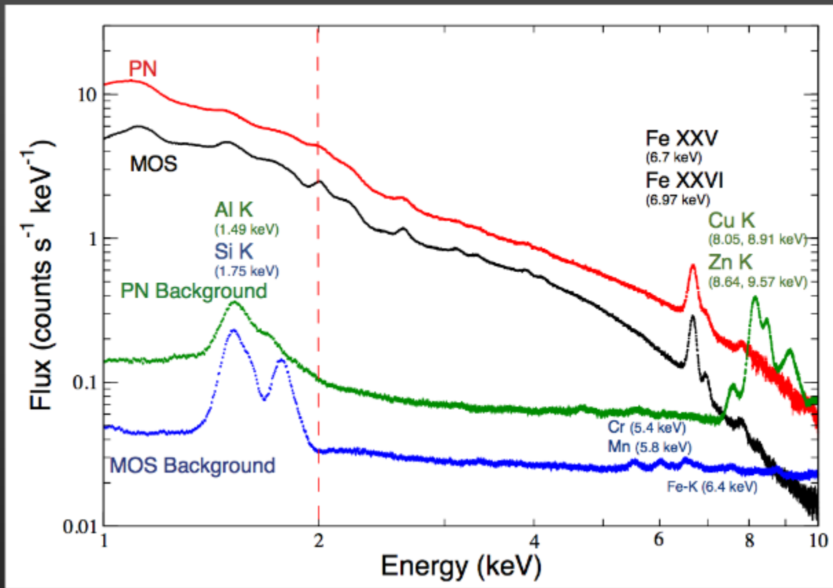
- If neutrino mass is above the weak force mass they are very hard to detect
- Otherwise, might see decay of sterile neutrinos into light neutrinos plus photon

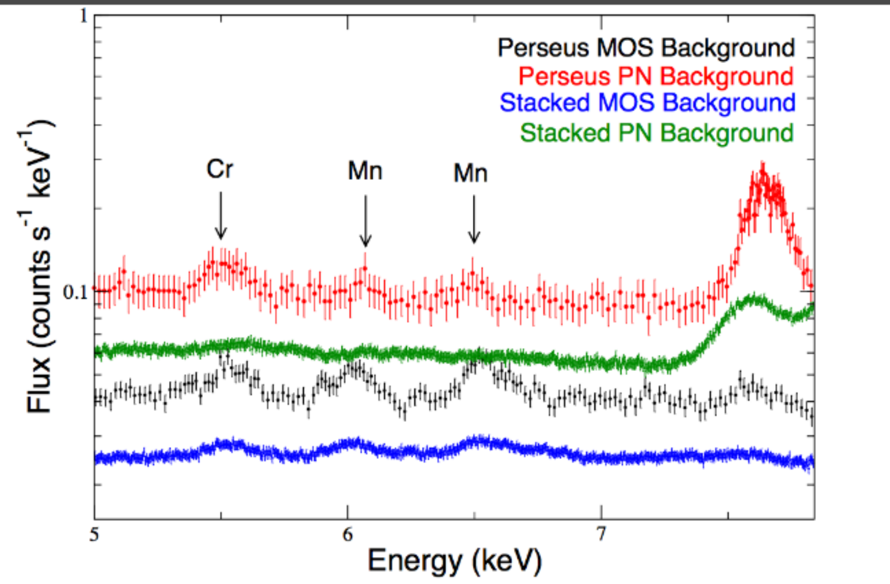


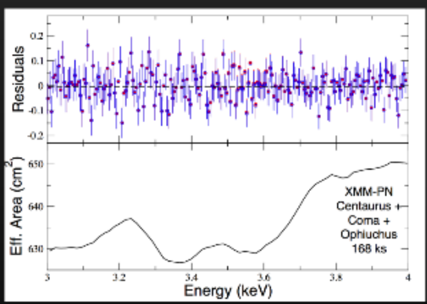
Detection of Sterile Neutrino

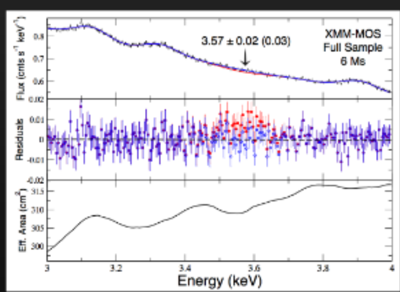


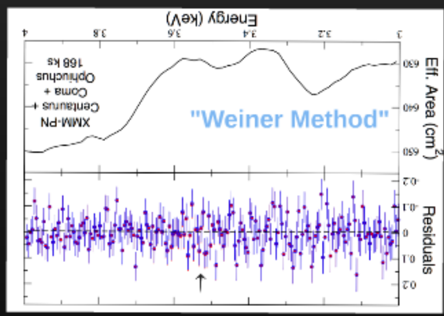
3.57 keV X-Rays !?







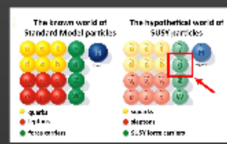




WIMPs

Weakly interacting massive particles

Supersymmetry



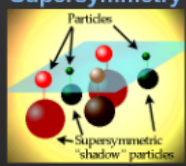
Funny Names

Superparticle Naming Convention:

1.) For quarks and leptons:
- Take Normal particle name
- Add "s" at the beginning
- squarks, sleptons, sneutrinos, staus, stops, selections

2.) For force carriers
- add "ino" to the end
- Higgsino, wino, gravitino, neutralino

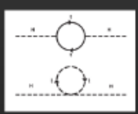
Supersymmetry



Supersymmetry

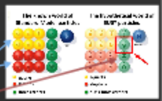
Why do we want supersymmetry?
- **Hierarchy problem** - why is the mass of the Higgs boson smaller than the Planck Mass?

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}[\Lambda_{UV}^2 + ...]$$



To make the Higgs boson mass equal to experiments, need to cancel this divergence

Supersymmetry and Dark Matter?



If superparticles have some quantum number that is different than standard model particles (R-parity), then the lightest superparticle would be stable

WIMP Interactions

We know there is about 5x as much dark matter as baryonic matter in the universe.

Why not 1000000x, or 0.000000001x?

Suggests some interaction which produces a near equilibrium of dark matter and regular matter in the early universe.

Weak Interactions

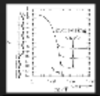
Let this supersymmetric particle interact with standard particles via the weak force

In the early universe, the weak force is strong, and these particles can reach equilibrium

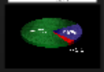
WIMP Miracle!

A particle with a:
- Weak cross-section
- Weak mass (~100 GeV)

Naturally provides a particle with the correct observed dark matter density.



This is why WIMPs are considered the best candidates for the dark matter.



What to Look For

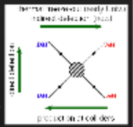
Mass: 10 - 10000 GeV (broadly)

Interaction: Weak Force

Weak force interactions are hard to see today.

But not impossible.

Topic of the next 4 lectures



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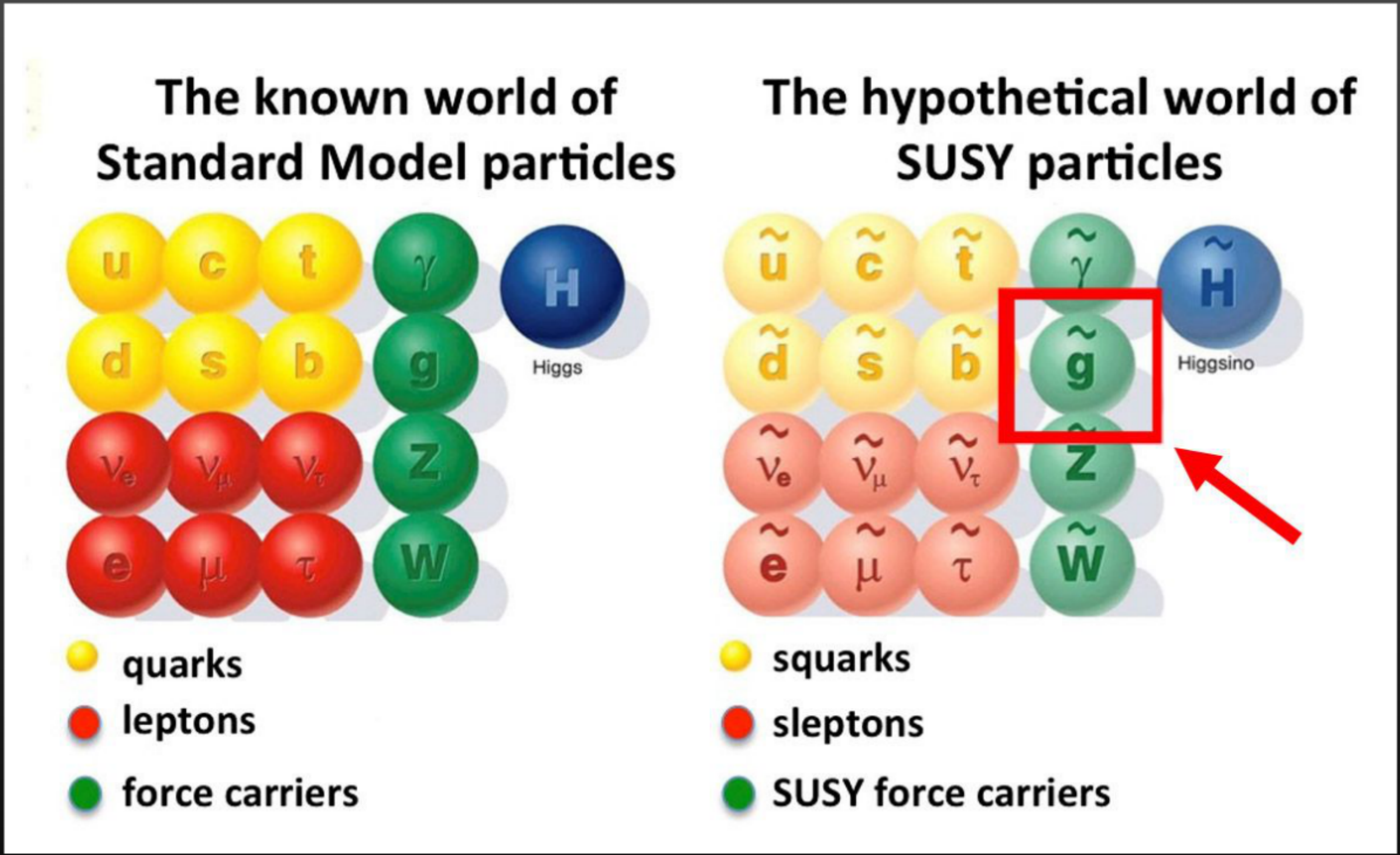

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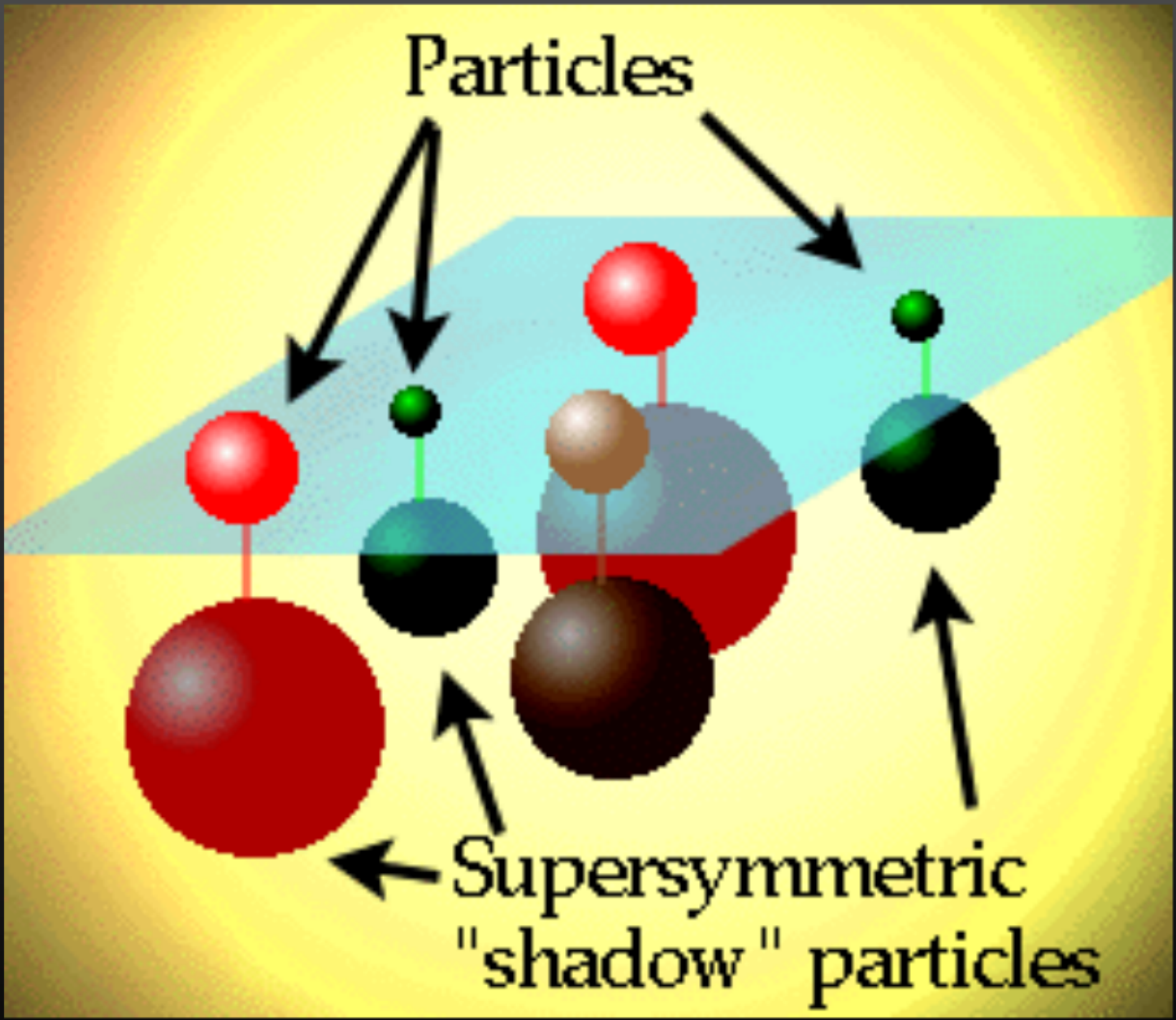

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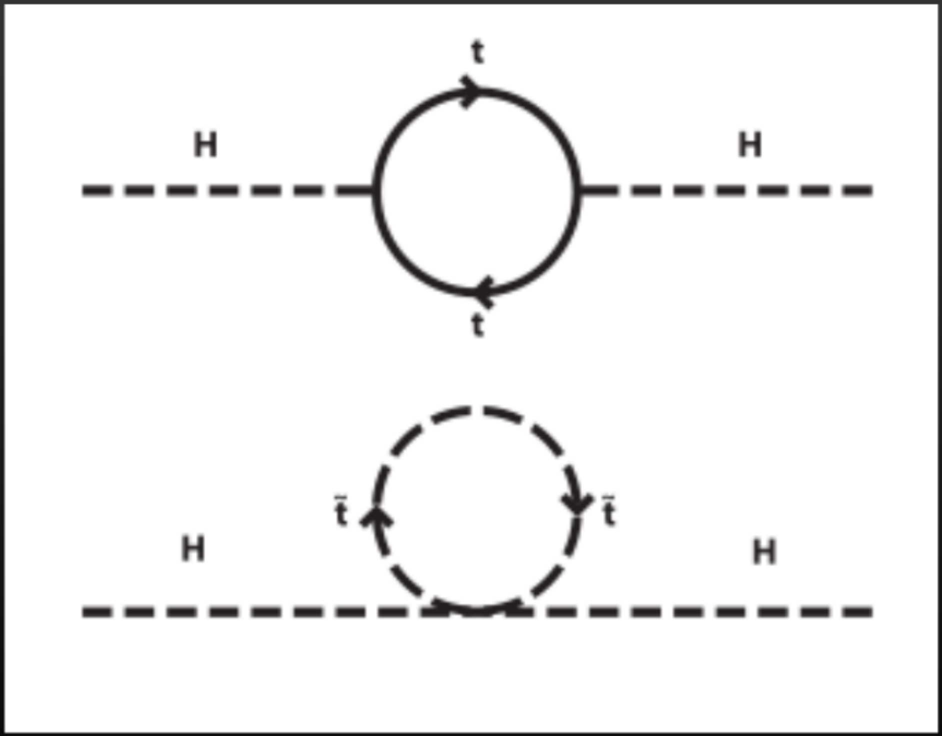

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Stable

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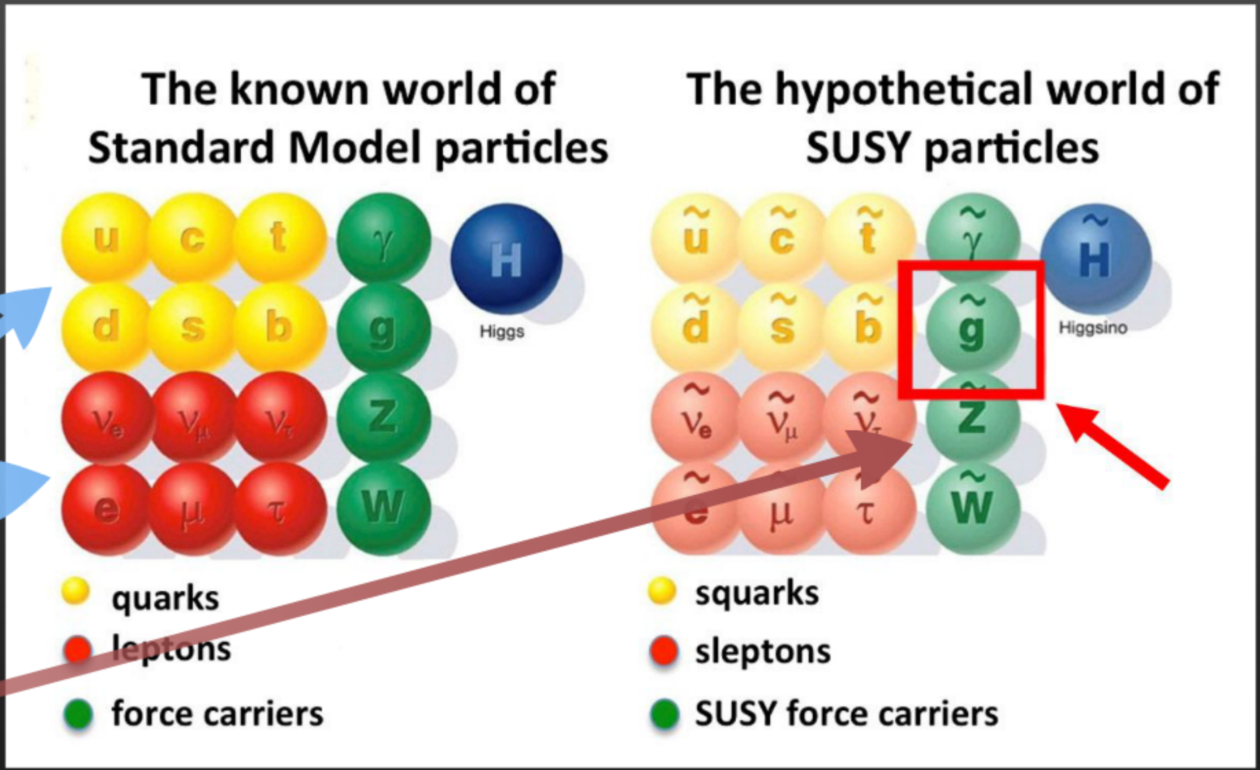

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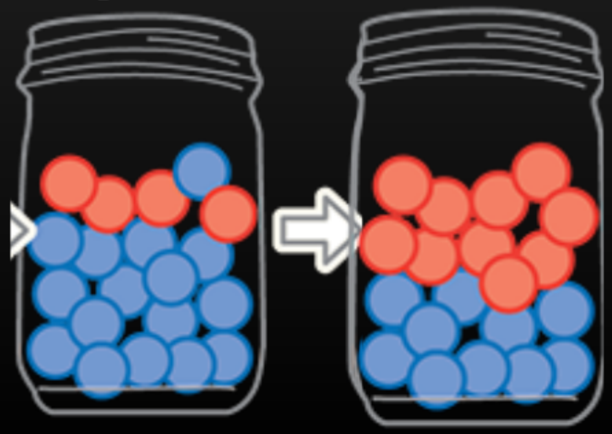

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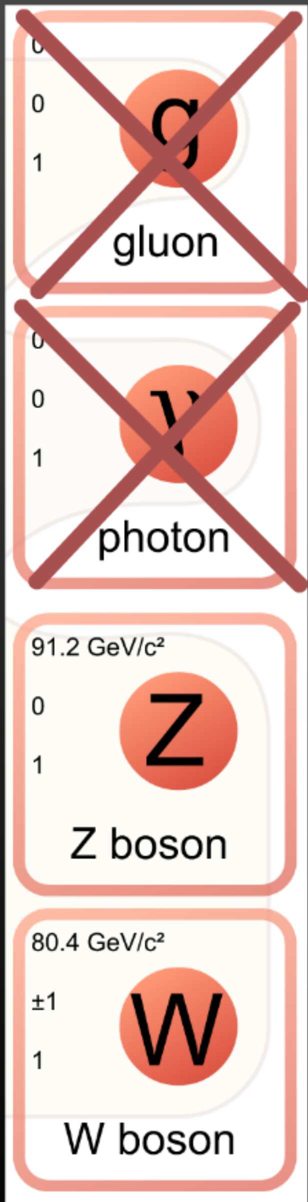

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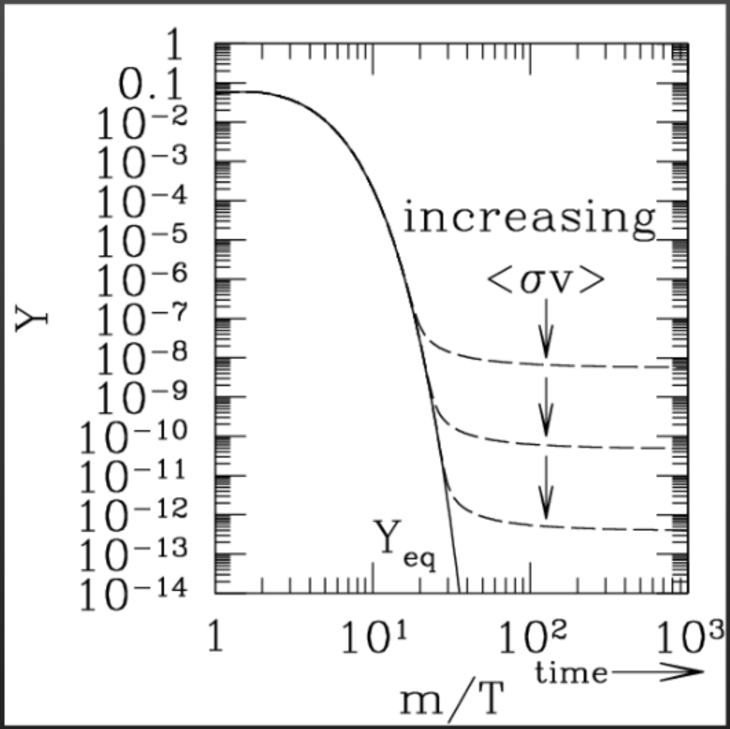

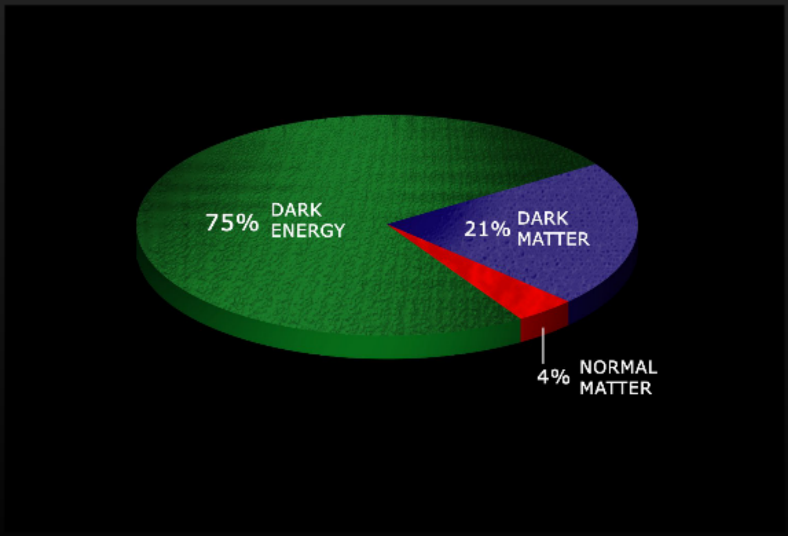

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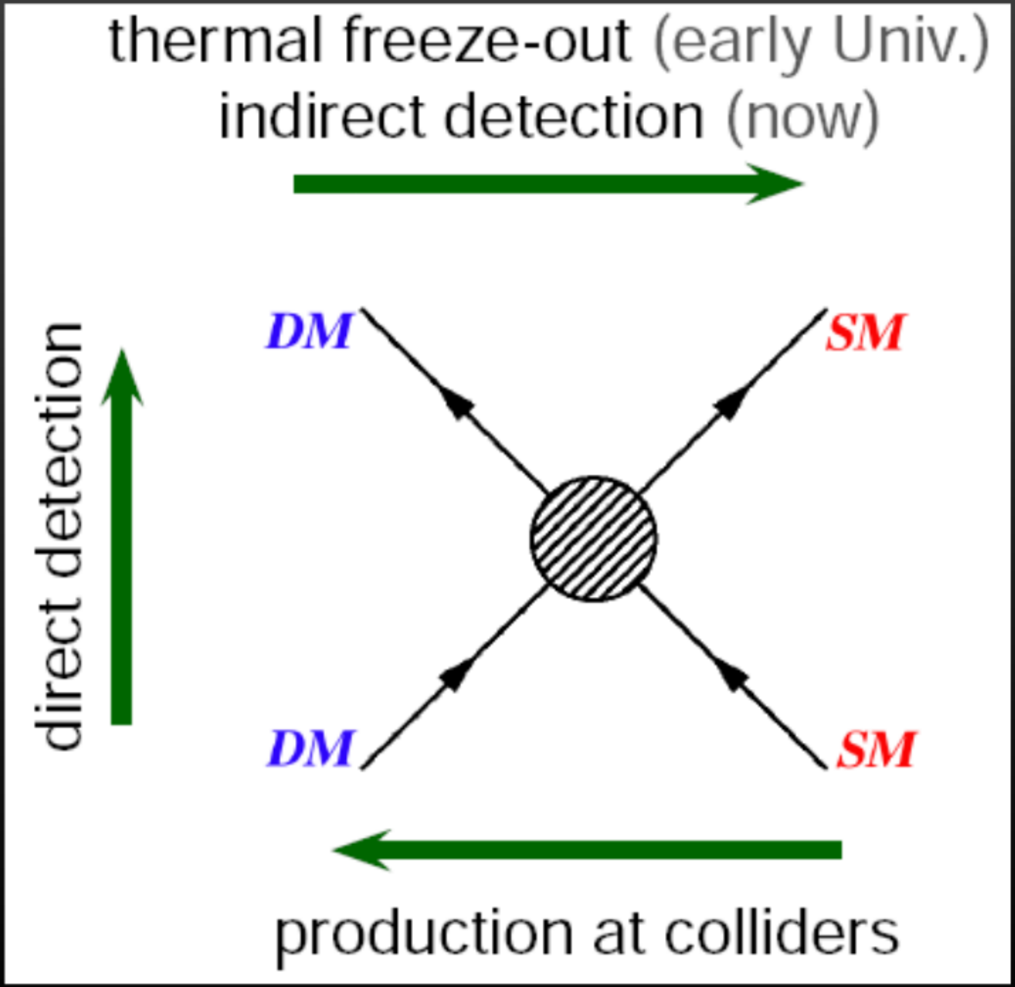

Something Else?

Lots of other ideas:

- Gravitinos
- CHAMPs
- SuperWIMPs
- WIMPZilla!

Roderick Redman (1905-1975)

Redman's Theorem - Any competant theorist can fit any theory to any set of facts.

But - in the end, observations are the judge and jury!

Conclusion

Remember there are no standard model particles that have the properties necessary to be the dark matter

However, several simple extensions of the standard model produce particles that naturally explain the dark matter properties.

These extensions were invented for reasons independent of dark matter

But this is not an exhaustive list, still reasons to think of new extensions to the standard model http://chasm.uchicago.edu

Sterile Neutrinos
The Heavier Cousin of Neutrinos

WIMPs
Weakly interacting massive particles

Axions
Not just a cleaning product

From Last Lecture

1.) Dark Matter explains how stars revolve around galaxies, and explains the growth of structure from the beginning of the universe to today

2.) Massive objects, modifications of gravity, and known particles have been ruled out as sources of dark matter

So what is the dark matter?

Something Else?

Lots of other ideas:
- Gravitinos
- CHAMPs
- SuperWIMPs
- WIMPZilla!

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The Standard Model
Explaining (most of) physics since the 1970s

Particle Dark Matter

Tim Linden

Lecture 5

Fall 2014 Compton Lectures