Dark matter: evidence and candidates

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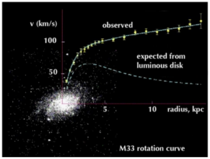
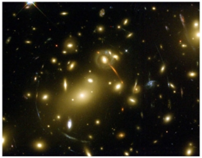
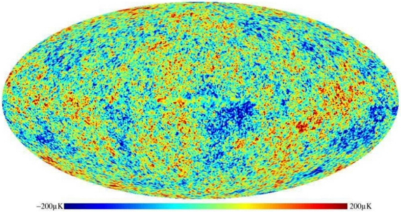
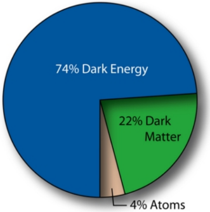
Dark matter (DM) in the Universe









Dark matter exists at various scales in the Universe.
(galaxies, clusters, large scale structures, cosmological scale)
However, its microscopic property remains unknown.

Coma cluster (后发座星系团)

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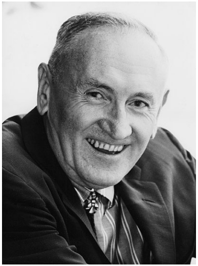

In 1933, Fritz Zwicky found that the **velocity dispersion** of galaxies in the Coma cluster was far too large to be supported by the luminous matter.

Mass-to-light ratio $\Upsilon_{\text{Coma}} \sim 260\Upsilon_\odot$

[Kent & Gunn, 1982]

Typical spiral galaxy: $\mathcal{O}(10)\Upsilon_\odot$

Spiral galaxies: rotation curves

In the 1970s, Vera Rubin and her collaborators measured the **rotation curves** of spiral galaxies and also found evidence for **non-luminous matter**.

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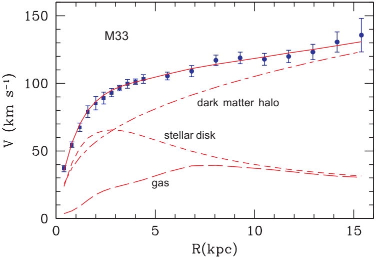
Triangulum galaxy M33



[Corbelli & Salucci, astro-ph/9909252]

Spiral galaxies: rotation curves

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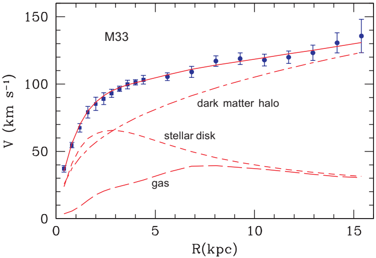
According to Newton's law, the relation between the rotation velocity v and the mass $M(r)$ within radius r should be

$$\boxed{\frac{v^2}{r} = \frac{G_N M(r)}{r^2}}$$

$$M(r) = \text{constant} \quad \Rightarrow \quad v \propto r^{-1/2}$$

$$M(r) \propto r \quad \Rightarrow \quad v = \text{constant}$$



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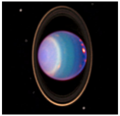
How can we explain an anomalous phenomenon?



Unexpected movement of **Uranus**

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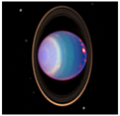

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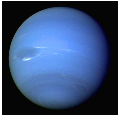
$\Downarrow$

Perturbed by **Neptune** (discovered in 1846)



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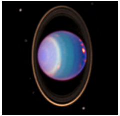

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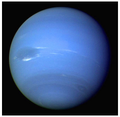

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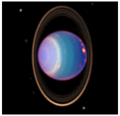

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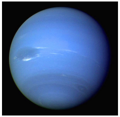

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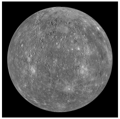

Anomalous perihelion precession of **Mercury**

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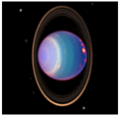

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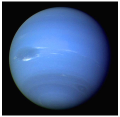

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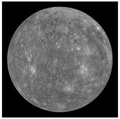

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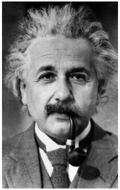
Update Newtonian mechanics to **general relativity**



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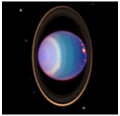

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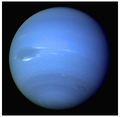

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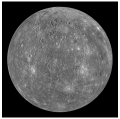

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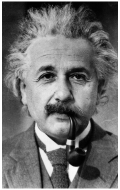

Modify known physical laws!

How about the anomalous phenomena here?

Modify physical laws $\Rightarrow$ **MOdified Newtonian Dynamics** (MOND)

[Milgrom, ApJ, 1983]

Difficult to coherently explain data at all scales with one model.

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Consider new objects $\Rightarrow$ **MAssive Compact Halo Objects** (MACHOs)

(**baryonic dark matter**: brown dwarfs, jupiters, stellar black-hole remnants, white dwarfs, neutron stars, ...)

MACHO fraction in the Galactic dark matter halo: $< 8\%$ (95% C.L.)

[EROS-2 coll., astro-ph/0607207]

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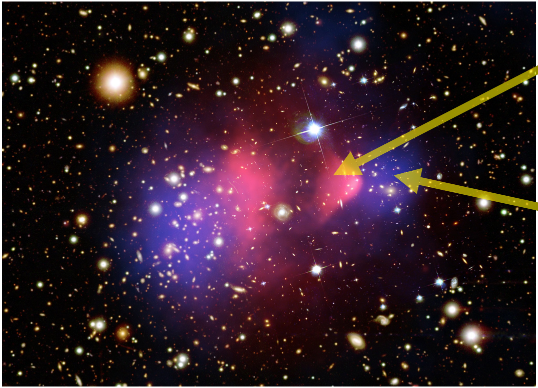
Consider new substances $\Rightarrow$ **Nonbaryonic Dark Matter**
(not constituted by baryons)

Bullet cluster: disfavor MOND



Fluid-like X-ray emitting plasma (visible matter)

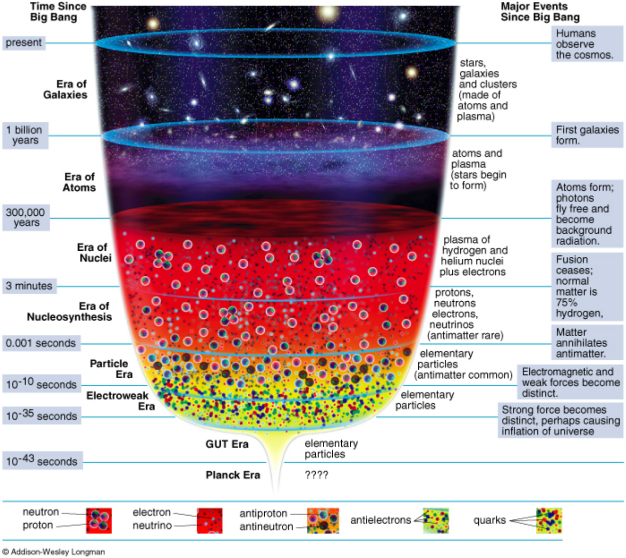
Mass distribution observed by weak gravitational lensing (DM dominated)

An 8σ significance **spatial offset** of the center of the **total mass** from the center of the **baryonic mass peaks** cannot be explained with an alteration of the gravitational force law. [Clowe *et al.*, astro-ph/0608407]

Big bang theory

According to the big bang theory, $\sim$ 13.8 billion years ago, the Universe was extremely **hot and dense**. Everything was in **thermal equilibrium** and interacted with each other.

As it expanded, the Universe cooled down. Its constituents **decoupled** from the thermal bath **one by one**.



Structure formation: hot, cold, and warm dark matter

Small initial fluctuations + Gravitational instability
$\Rightarrow$ Decoupled matter generates cosmological structures

Baryonic matter decoupled too late.
Only baryonic matter $\Rightarrow$ Galaxies would not be formed!
$\Rightarrow$ Needs **nonbaryonic dark matter** which decoupled much earlier

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Hot dark matter (such as neutrinos): **relativistic** when it decoupled

$\Rightarrow$ structure forms by fragmentation (top-down)

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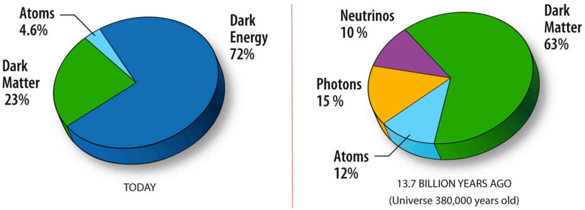
Milky Way dwarf satellites: ~ 20 (observed) vs. ~ 500 (CDM predicted)
"Missing satellites problem" $\Rightarrow$ **Warm** dark matter?

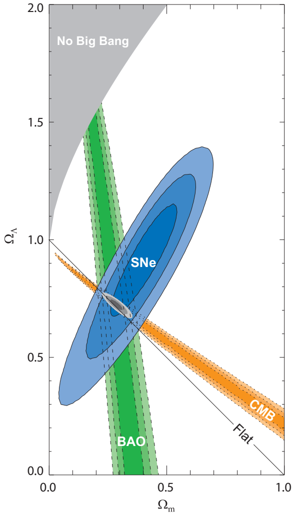
Standard cosmology: ΛCDM model

In the ΛCDM model, the Universe contains a **cosmological constant Λ** (dark energy) and **cold dark matter** (CDM).
The evolution of the Universe is governed by the **Friedmann equation**:

$$\frac{k}{H^2R^2} = \Omega_\Lambda + \Omega_m + \Omega_r - 1$$



[WMAP Science Team]



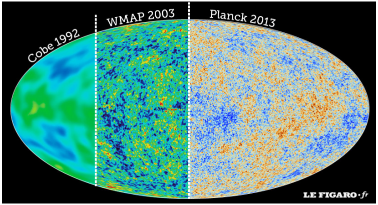
[Kowalski *et al.*, 0804.4142]

Cosmic microwave background (CMB)

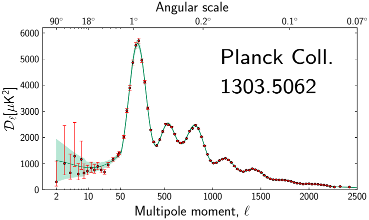
$t \sim 380\,000$ yr, $T \sim 3000$ K
Electrons + protons → hydrogen atoms
Photons decoupled

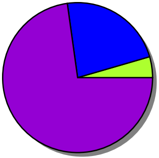
cools ⇓ down

Today, ~ 2.7 K microwave background



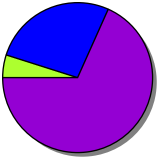
CMB anisotropies encode the information from the early Universe.
The shape of **anisotropy power spectrum** depends on cosmological parameters, such as Ω_Λ, Ω_m, Ω_b, ...





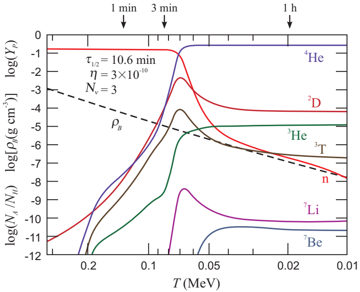
WMAP

	WMAP	Planck
Dark matter	22.7%	26.8%
Ordinary matter	4.5%	4.9%
Dark energy	72.8%	68.3%

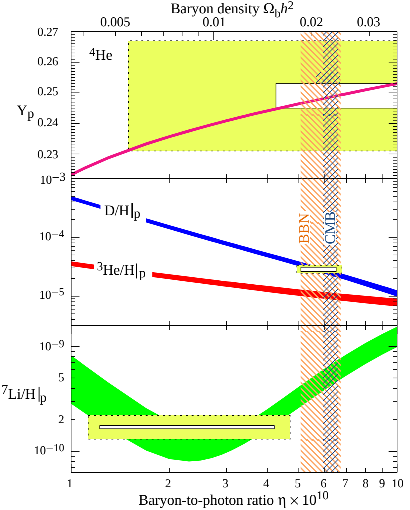


Planck

Big bang nucleosynthesis (BBN): $t \sim 1$ sec $-$ 1 hour



[Kolb & Turner, *The Early Universe*]



[Cyburt *et al.*, 0808.2818]

Primordial abundances of light elements

$\Downarrow$

Baryon density Ω_b

(consistent with CMB observations)

$\Downarrow$

The majority of matter is **nonbaryonic**

Inferred properties of dark matter

- **Dark (electrically neutral):** no light emitted from it
- **Nonbaryonic:** BBN & CMB observations
- **Long lived:** survived from early eras of the Universe to now
- **Colorless:** otherwise, it would bind with nuclei
- **Cold:** structure formation theory
- **Abundance:** more than 80% of all matter in the Universe

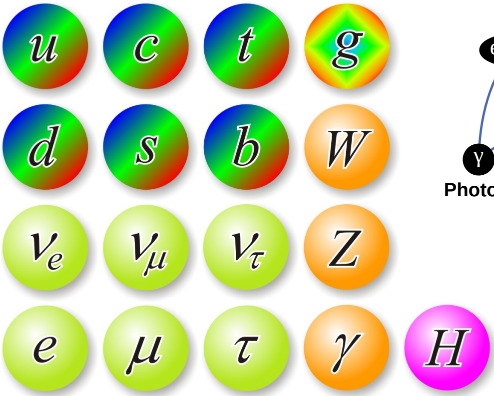
$$\rho_{\mathrm{DM}} \sim 0.4\ \mathrm{GeV/cm^3}\ \text{near the earth}$$

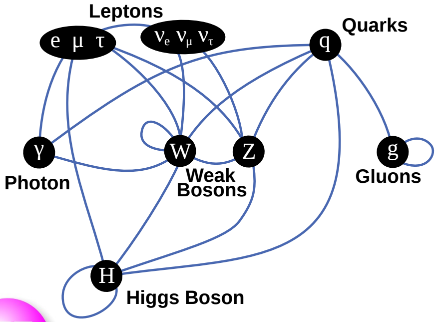
Standard model (SM) of particle physics

$SU(3)_C \times SU(2)_L \times U(1)_Y$ **gauge symmetry**

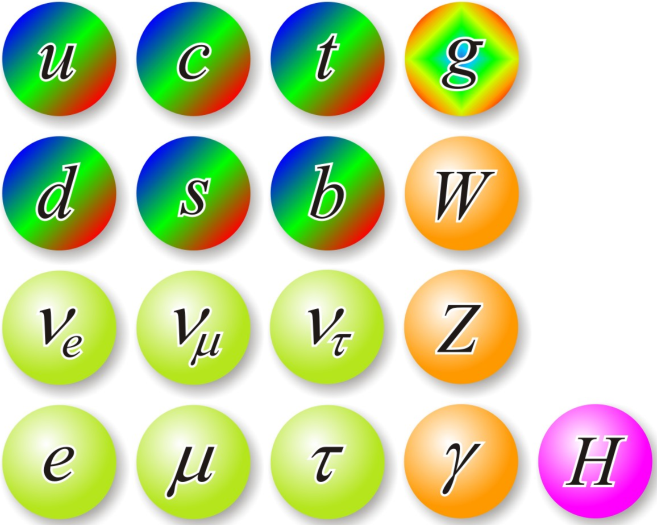
Spontaneous symmetry breaking of the Higgs field

$\Rightarrow$ Electroweak symmetry breaking & generating fermion masses





Are there dark matter candidates in the standard model?



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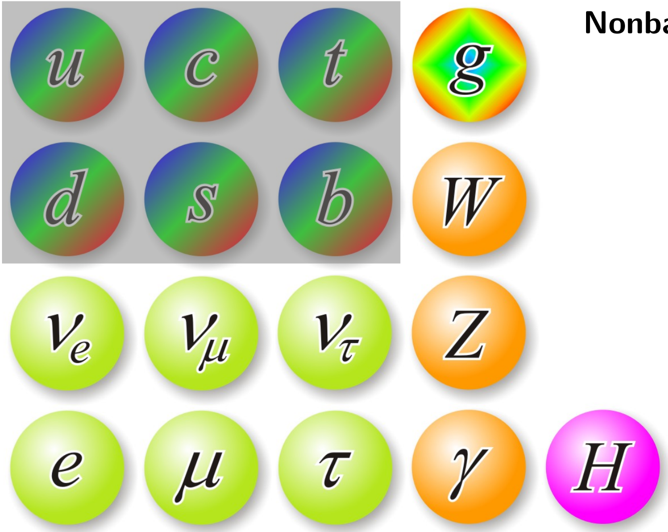

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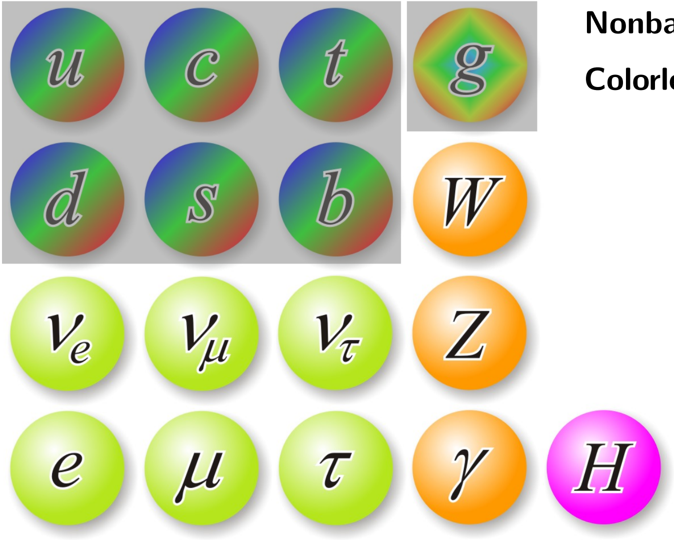

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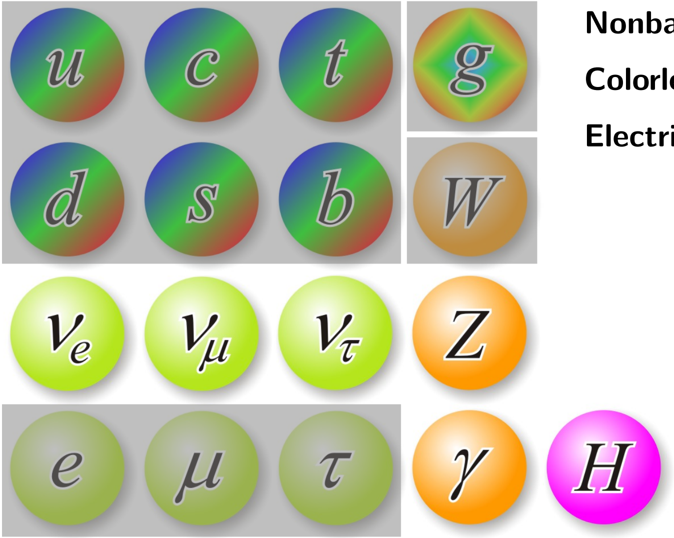

Nonbaryonic

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Electrically neutral

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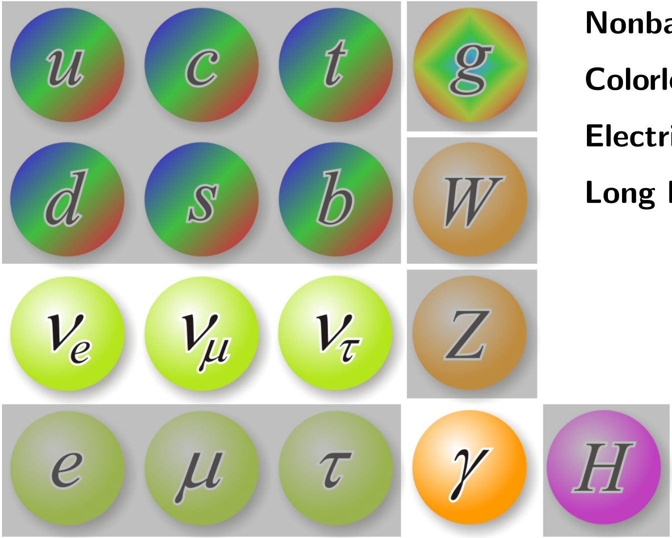

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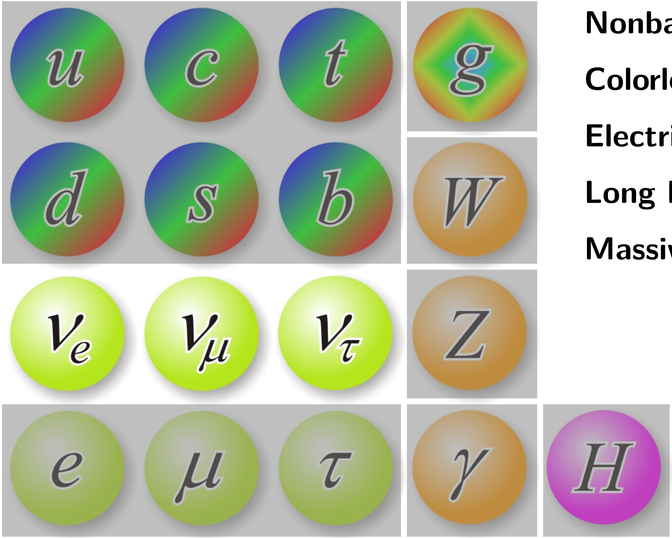

Nonbaryonic

Colorless

Electrically neutral

Long lived

Massive

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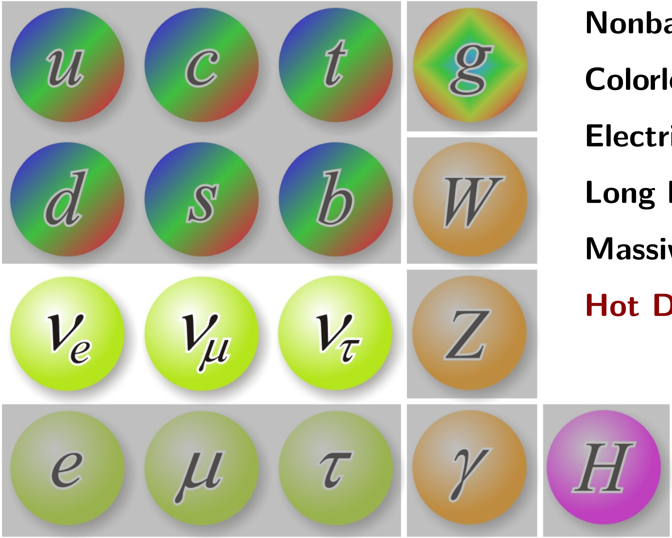

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Hot DM: neutrinos

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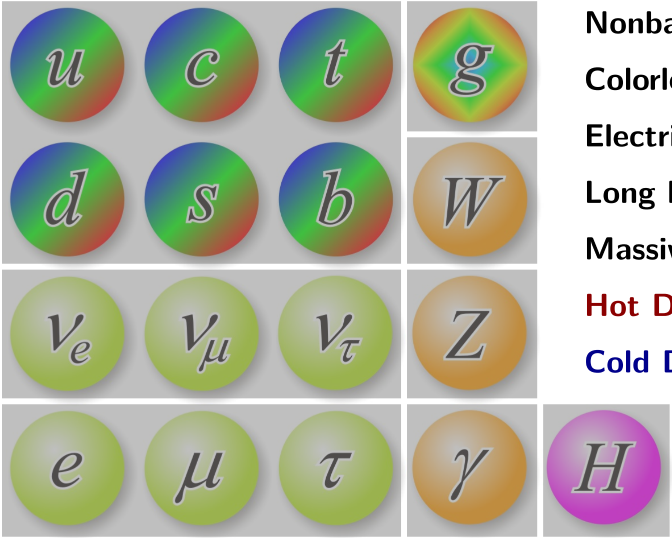

Nonbaryonic

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Electrically neutral

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Massive

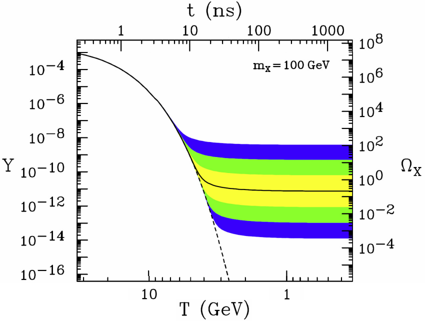
Hot DM: neutrinos

Cold DM: none

WIMP miracle

The **relic density** of dark matter can be calculated by the Boltzmann equation:
$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma_{\rm ann}v\rangle\,[n_\chi^2 - (n_\chi^{\rm EQ})^2]$$

$$\Rightarrow \qquad \Omega_\chi h^2 \simeq \frac{3\times10^{-27}\ \mathrm{cm^3\ s^{-1}}}{\langle\sigma_{\rm ann}v\rangle}$$



[Feng, arXiv:1003.0904]

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Observed relic density

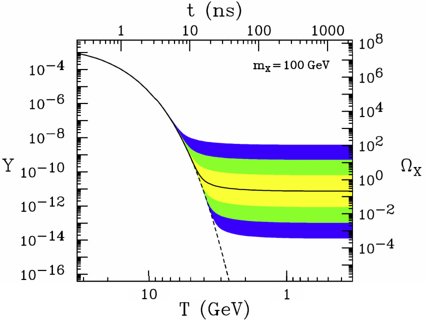
$\Downarrow$

$\langle\sigma_{\rm ann}v\rangle \sim \mathcal{O}(10^{-26})\ \mathrm{cm}^3\ \mathrm{s}^{-1}$

Typical value of weak interactions

$\Downarrow$

Weakly interacting massive particles (WIMPs) are wonderful candidates



[Feng, arXiv:1003.0904]

Problem of the standard model

A ∼125 GeV Higgs boson has been discovered at the LHC

[ATLAS Coll., 1207.7214; CMS Coll., 1207.7235]

In the standard model, the quantum correction of the Higgs boson mass Δm_H^2 suffers from the quadratic divergence

$\Downarrow$

Hierarchy problem

$\Downarrow$

New physics at the TeV scale

(Supersymmetry, extra dimensions, little Higgs, ...)

$\Downarrow$

New physics models often involve candidates for **WIMP dark matter**

Supersymmetry (SUSY)

A symmetry between fermions and bosons

$e,\ \mu,\ \tau$	leptons $\longleftrightarrow$ sleptons	$\tilde{e},\ \tilde{\mu},\ \tilde{\tau}$
$\nu_e,\ \nu_\mu,\ \nu_\tau$	neutrinos $\longleftrightarrow$ sneutrinos	$\tilde{\nu}_e,\ \tilde{\nu}_\mu,\ \tilde{\nu}_\tau$
$d,\ u,\ s,\ c,\ b,\ t$	quarks $\longleftrightarrow$ squarks	$\tilde{d},\ \tilde{u},\ \tilde{s},\ \tilde{c},\ \tilde{b},\ \tilde{t}$
g	gluon $\longleftrightarrow$ gluino	$\tilde{g}$
$W^\pm,\ H^\pm$	charged bosons $\longleftrightarrow$ charginos	$\tilde{\chi}_1^\pm,\ \tilde{\chi}_2^\pm$
$B,\ W^3,\ H_1^0,\ H_2^0$	neutral bosons $\longleftrightarrow$ neutralinos	$\tilde{\chi}_1^0,\ \tilde{\chi}_2^0,\ \tilde{\chi}_3^0,\ \tilde{\chi}_4^0$

Supersymmetry (SUSY)

A symmetry between fermions and bosons

$e,\ \mu,\ \tau$	leptons $\longleftrightarrow$ sleptons	$\tilde{e},\ \tilde{\mu},\ \tilde{\tau}$
$\nu_e,\ \nu_\mu,\ \nu_\tau$	neutrinos $\longleftrightarrow$ sneutrinos	$\tilde{\nu}_e,\ \tilde{\nu}_\mu,\ \tilde{\nu}_\tau$
$d,\ u,\ s,\ c,\ b,\ t$	quarks $\longleftrightarrow$ squarks	$\tilde{d},\ \tilde{u},\ \tilde{s},\ \tilde{c},\ \tilde{b},\ \tilde{t}$
g	gluon $\longleftrightarrow$ gluino	$\tilde{g}$
$W^\pm,\ H^\pm$	charged bosons $\longleftrightarrow$ charginos	$\tilde{\chi}_1^\pm,\ \tilde{\chi}_2^\pm$
$B,\ W^3,\ H_1^0,\ H_2^0$	neutral bosons $\longleftrightarrow$ neutralinos	$\tilde{\chi}_1^0,\ \tilde{\chi}_2^0,\ \tilde{\chi}_3^0,\ \tilde{\chi}_4^0$

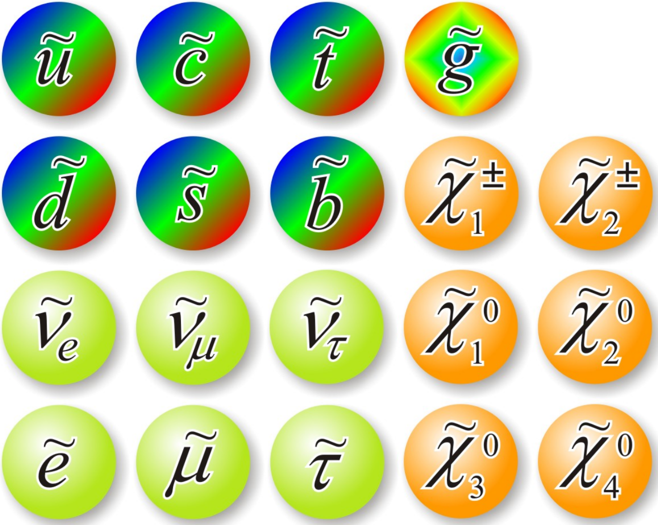
Not to violate baryon number B or lepton number L

$\Rightarrow$ **R-parity conserved SUSY** $[P_R = (-1)^{3(B-L)+2s}]$

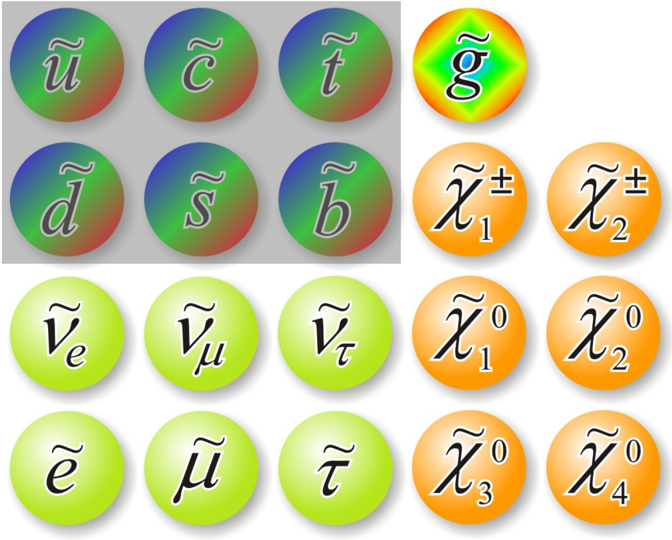
$\Rightarrow$ The **lightest SUSY particle (LSP)** is stable

$\Rightarrow$ An attractive candidate for **non-baryonic dark matter**

SUSY particles

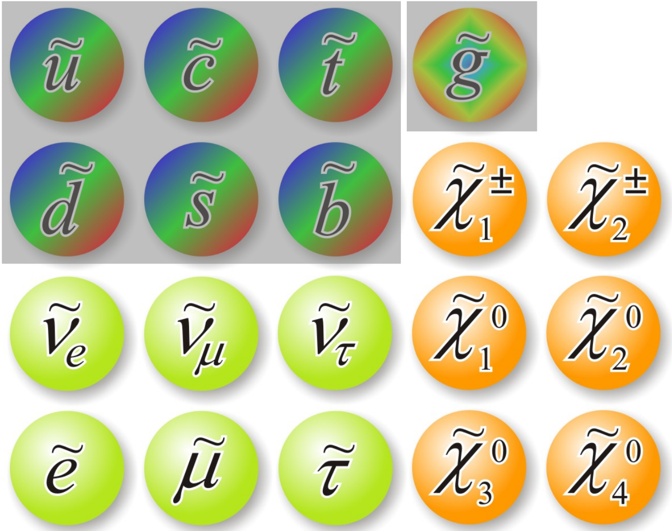


SUSY particles



Nonbaryonic

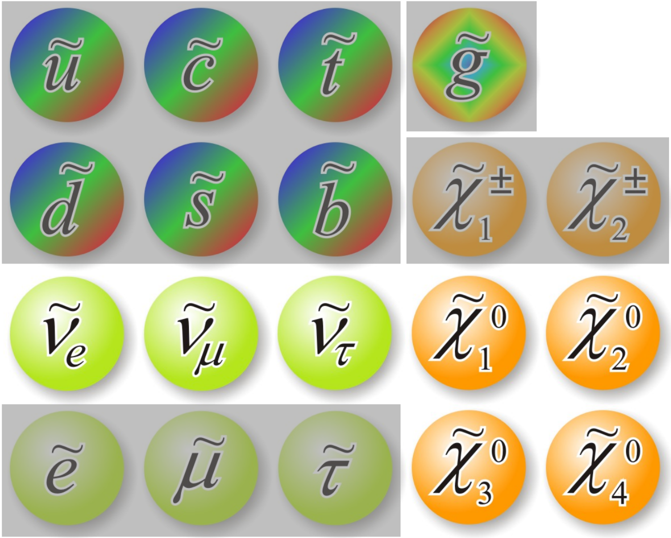
SUSY particles



Nonbaryonic

Colorless

SUSY particles

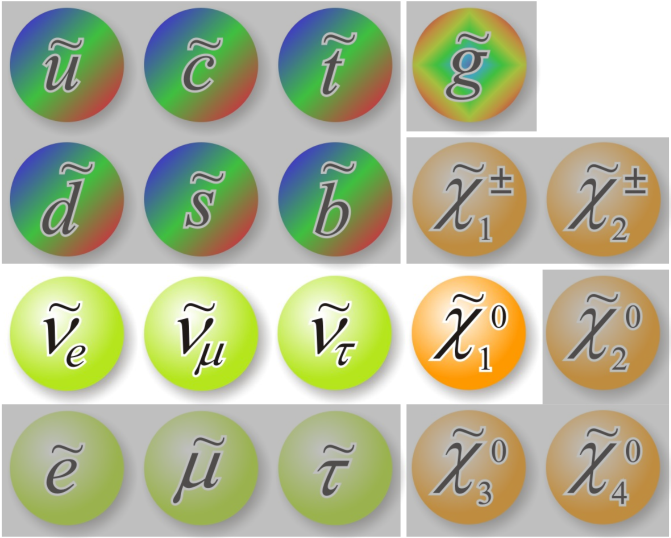


Nonbaryonic

Colorless

Electrically neutral

SUSY particles



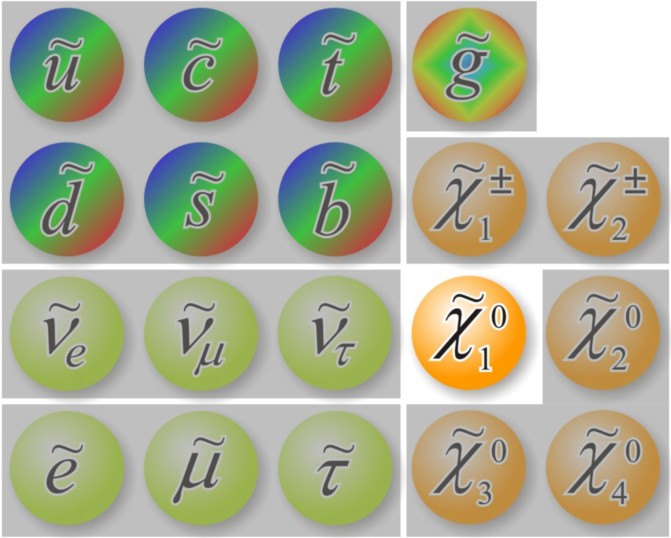
Nonbaryonic

Colorless

Electrically neutral

Long lived

SUSY particles



Nonbaryonic

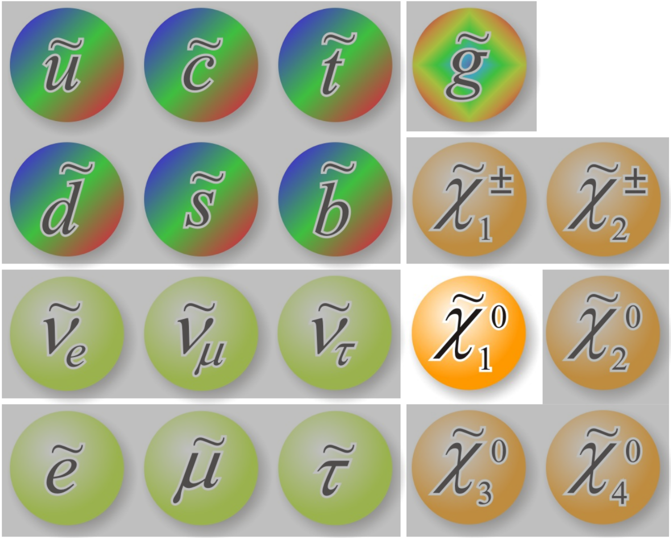
Colorless

Electrically neutral

Long lived

Not excluded by experiment

SUSY particles



Nonbaryonic

Colorless

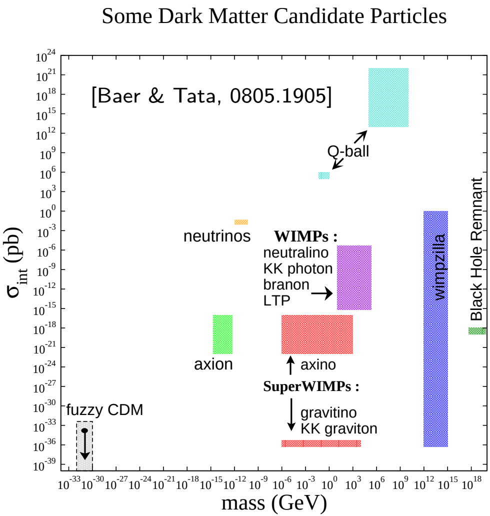
Electrically neutral

Long lived

Not excluded by experiment

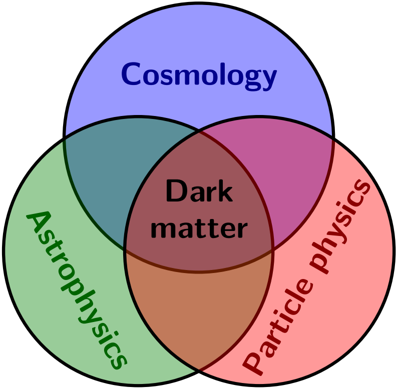
Cold DM: χ_1^0
(the lightest neutralino)

More candidates



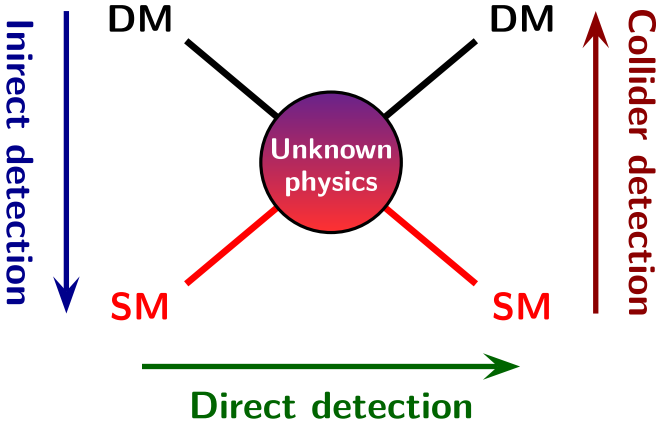
Conclusions and discussions

Dark matter connects our knowledge of the Universe from the largest to the smallest scales.



Conclusions and discussions

Current and near future dark matter searching experiments are promising to solve the mystery of dark matter.



Thanks for your attentions!