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Part II:
Ideas Beyond the Standard Model

Outline

I. Standard Model Reminders
II. Grand Unified Theories
III. Supersymmetry

Many other BSM theories

Standard Model: Reminders

Passport

- Name: « Standard Model » of Particle Physics
- Date of Birth: 1967
- Parents: S. Glashow, A. Salam, S. Weinberg
  - Birth certificates:
    - Nucl. Phys 22 (1961) 579
    - Phys. Rev. Lett. 19 (1967) 1264
    - Conf. Proc. C 680519 (1968) 367
- Pediatricians: G. t'Hooft, M. Veltman
  - First pediatric examination: renormalizable (despite SSB)
- Particle Content:
  - Fermions: quarks & leptons (x3 generations)
  - Bosons:
    - Gauge: photon, W, Z, gluons
    - EWSB: Higgs
- External Symmetries:
  - Space-time structure: 3-D space, 1-D time, Minkowski metric
  - Poincaré group
    - Lorentz group: space-time rotation, boost
    - Space-time translation
- Discrete Symmetries: $C \cdot P \cdot T$
- Internal Symmetries:
  - Gauge group: $G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$
- Visa exemptions: particles dynamics from low energy up to the EWK scale

Grand Unified Theories

Passport

- Name: « Grand Unified Theories »
- Date of Birth: 1974
- Parents:
  - S. Glashow, H. Georgi
  - J. Pati, A. Salam, …
  - Birth certificates:
    - Phys. Rev. Lett. 32 (1974) 438,
    - Phys.Rev. D10 (1974) 275-289, …

- Particle Content:
  - Includes the SM
  - In addition:
    - Leptoquarks
    - Possible Z' and/or W'
    - Possible ν_R
- Internal Symmetries:
  - Ex. of Gauge groups:

$$G_{GUT} = E_6 \to SO(10)\times U(1)_\psi \to SU(5)\times U(1)_\psi \times U(1)_\chi$$
$$G_{SM} \hookleftarrow$$

$$G_{Pati-Salam} = SU(4)\times SU(2)_R \times SU(2)_L \to SU(3)_C \times SU(2)_R \times SU(2)_L \times U(1)_{B-L}$$
$$G_{SM} \times SU(2)_R \hookleftarrow$$

- Visa exemptions: particles dynamics from low energy up to the GUT scale

Grand Unified Theories

- Definition:
  - Beyond the Standard Model
  - Symmetry group (G_{GUT}) which unifies strong & EWK interactions
  - G_{GUT} must embed the SM group: $SU(3)_C$ x $SU(2)_L$ x $U(1)Y$
  - Examples: SU(5), SO(10), E_6,…

$$G = \begin{pmatrix} G_3+\frac{G_8}{\sqrt{3}}-\sqrt{\frac{2}{5}}B & G_1-iG_2 & G_4-iG_5 & X_1 & Y_1 \\ G_1+iG_2 & -G_3+\frac{G_8}{\sqrt{3}}-\sqrt{\frac{2}{5}}B & G_6-iG_7 & X_2 & Y_2 \\ G_4+iG_5 & G_6+iG_7 & -\frac{2}{\sqrt{3}}-\sqrt{\frac{2}{5}}B & X_3 & Y_3 \\ X_1 & X_2 & X_3 & \frac{W_3}{\sqrt{2}}+\sqrt{\frac{3}{10}}B & W^+ \\ Y_1 & Y_2 & Y_3 & W^- & -\frac{W_3}{\sqrt{2}}+\sqrt{\frac{3}{10}}B \end{pmatrix}$$

$$\Psi_R = \begin{pmatrix} d_1 \\ d_2 \\ d_3 \\ e^+ \\ -\bar{\nu}_e \end{pmatrix}_R \qquad \Psi_L = \begin{pmatrix} \bar{d}_1 \\ \bar{d}_2 \\ \bar{d}_3 \\ e^- \\ -\nu_e \end{pmatrix}_L \qquad \Psi_L = \begin{pmatrix} 0 & \bar{u}_3 & \bar{u}_2 & u_1 & d_1 \\ \bar{u}_3 & 0 & \bar{u}_1 & u_2 & d_2 \\ \bar{u}_2 & \bar{u}_1 & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^+ \\ -d_1 & -d_2 & -d_3 & -e^+ & 0 \end{pmatrix}_L$$

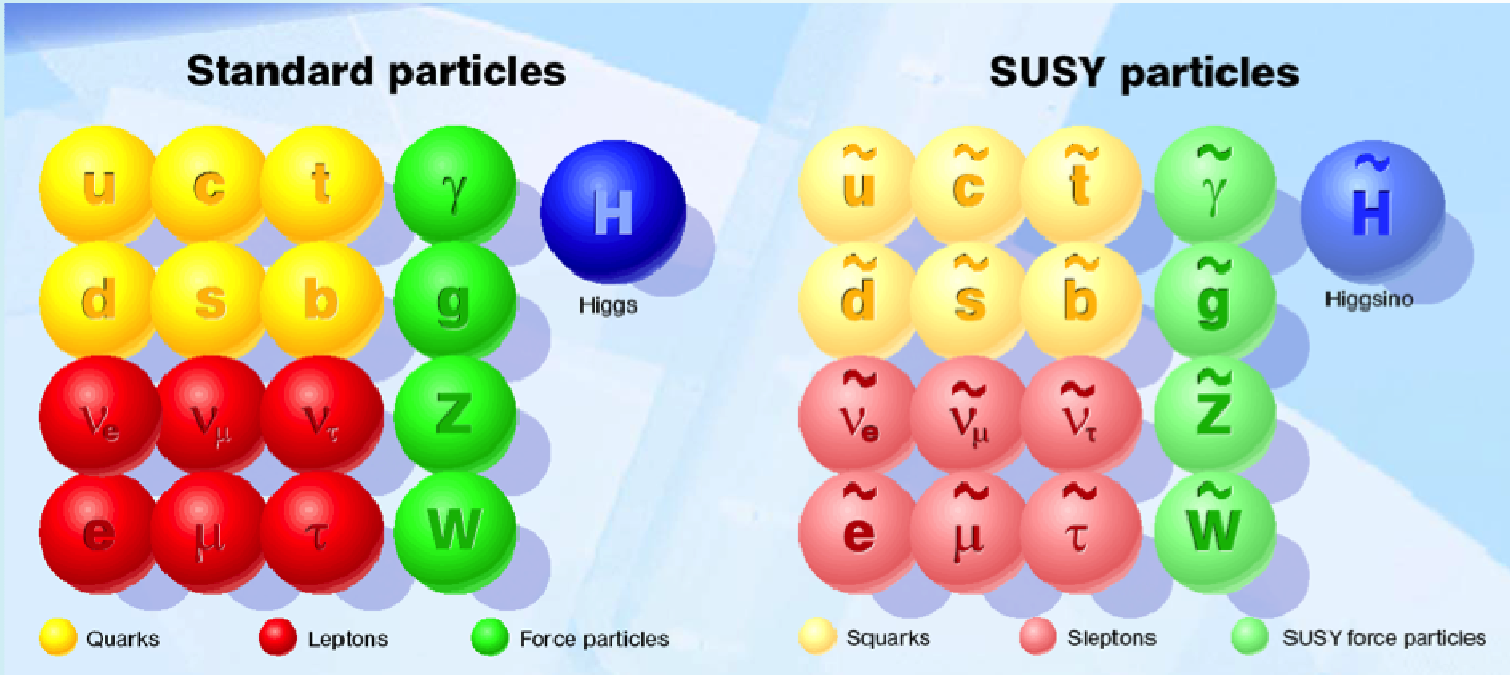
Supersymmetry

Passport

- Name: « Minimal Supersymmetric Standard Model » of Particle Physics
- Date of Birth: 1983s
- Grand Parents: Y. Golfand, E. Likhtman, D. Volkov,
V. Akulov, P. Ramond, P. Fayet, J. Iliopoulos,…
- Parents: H. Georgi, S. Dimopoulos
  - Birth certificate:
    - Nucl. Phys. B 193 (1983) 150
- 4-D Pediatricians: J. Wess, B. Zumino
- Particle Content:
  - Includes the SM (5 Higgs bosons)
  - Sfermions: squarks, sleptons
  - Gauginos: chargino, neutralinos, gluinos
  - SUGRA: graviton, gravitino
- Extended External Symmetries:
  - Space-time structure: 3-D space, 1-D time, Minkowski metric
  - Super-Poincaré group
    - Q: SUSY fermionic operators
    - Algebra w/ commuting & anti-commuting relations
- Internal Symmetries:
  - Low-E Gauge group: $G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$
  - High-E Gauge Group: $G_{GUT} = E_8 \; or \; E_6 \; or \; SO(10) \; or \; SU(5)$
- Visa exemptions: particles dynamics from low energy up to the GUT scale

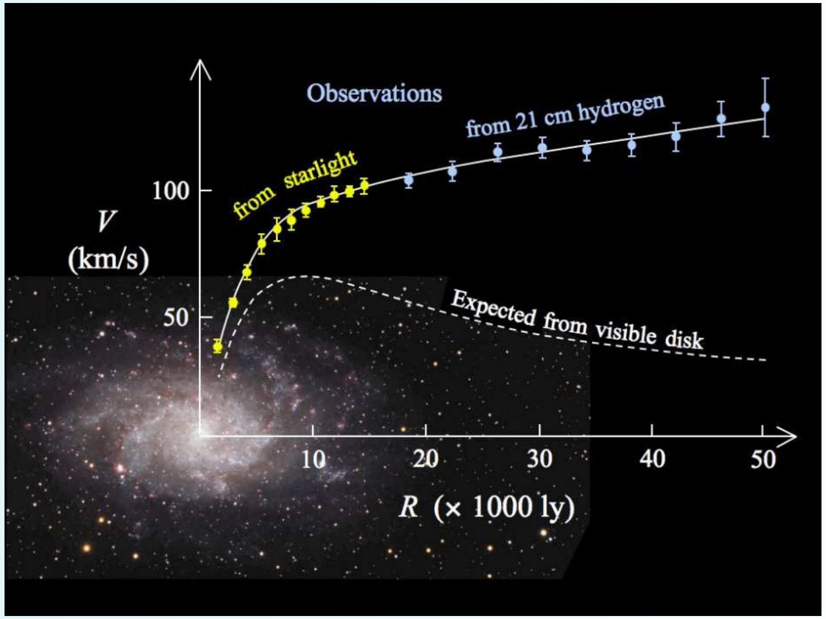
SUSY

- Definition:
  - Beyond the Standard Model
  - Symmetry between bosons and fermions
  - Extends the symmetry of space-time

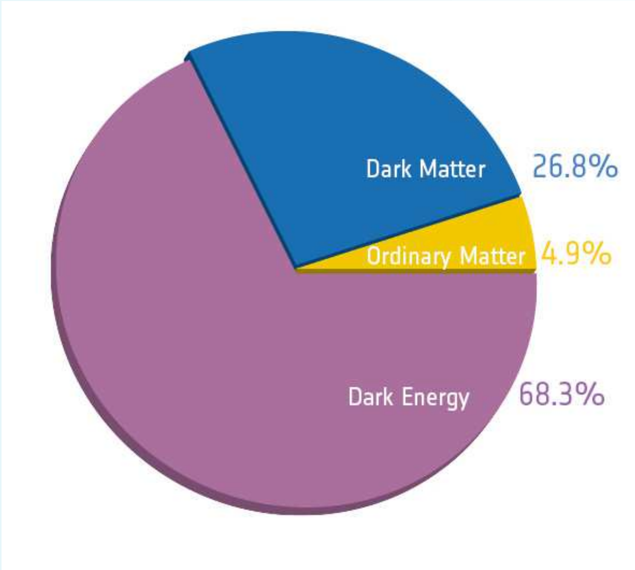


SUSY

- Cold Dark Matter:
  - Rotation curves of galaxies



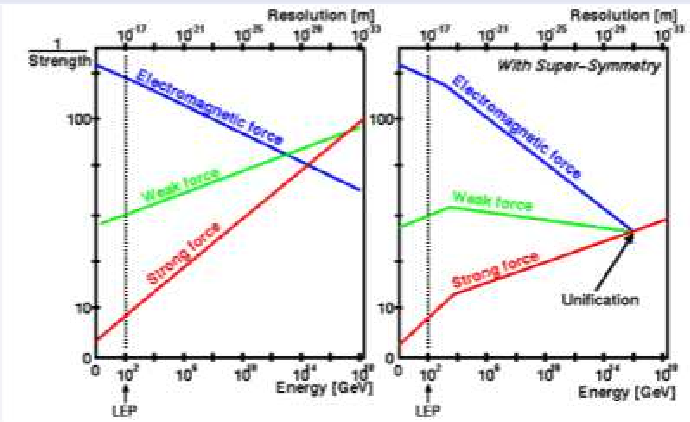
  - Fit to cosmological data:
  (Model: SM+GR)



SUSY

Assets

- Largest possible symmetry of S-matrix
- Local SUSY:
  - includes General Relativity (supergravity)
  - key ingredient for Superstrings & M-theory
- Grand Unification:

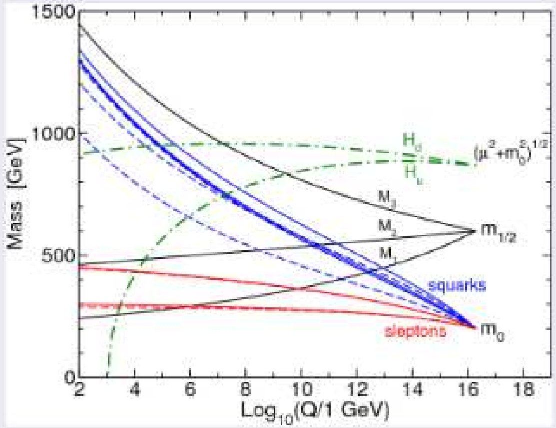


Assets

- $\tilde{\chi}_1^0$: often LSP $\Rightarrow$ good candidate for CDM
- MSSM predicted $M_h \lesssim 130$ GeV
- Solution to naturalness of Higgs:

$$\Delta M_h^2(Total) = \frac{\lambda_f^2 N_f}{4\pi^2}\left[(M_f^2 - M_S^2)Log(\frac{\Lambda}{M_f}) + 3M_f^2 Log(\frac{M_S}{M_f})\right]$$

- Radiative EWSB:



BACK-UP

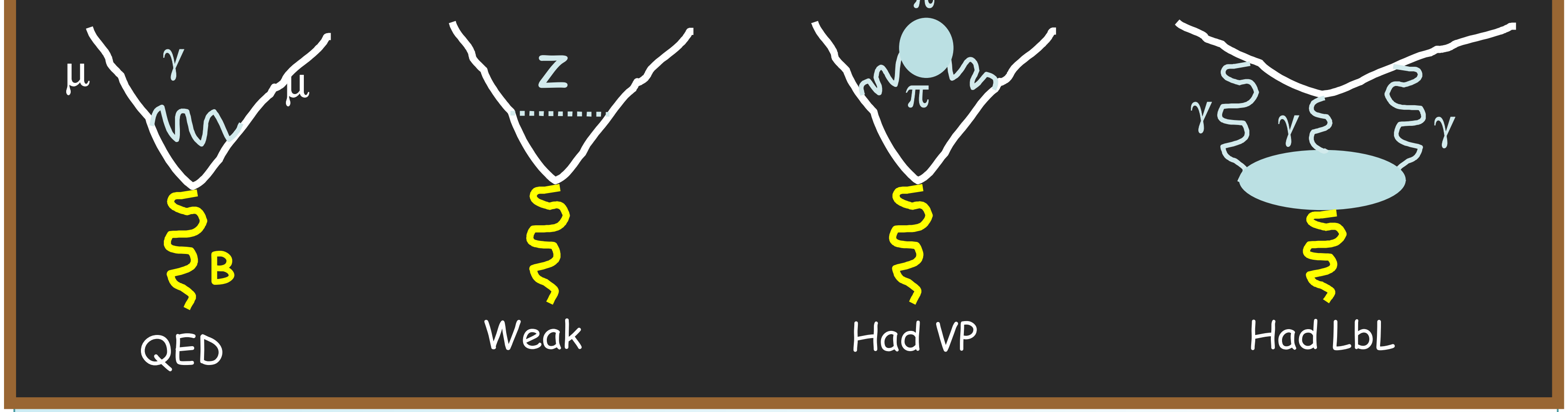
a_μ=1/2$(g-2)_\mu$ (1)
- Introduction -

- Magnetic dipole moment:
  - Charged particle w/ circular trajectory: $\vec{\mu}_L = \frac{e}{2mc}\vec{L}$ w/ $\vec{L} = \vec{r} \wedge \vec{p}$
  - This is due to spin: $\vec{\mu} = g_\ell \frac{e\hbar}{2m_\ell c}\vec{S}$
  - Dirac's theory predicts: $g_\ell = 2$
  - Precision measurements slightly differ: $g_\ell \approx 2.0024$
  - Anomalous magnetic moment: $a_\mu = \frac{1}{2}(g_\mu - 2)$
  - Measure it in: $\pi^\pm \to \mu^\pm + \nu_\mu$

    $e^\pm + \nu_e + \nu_\mu \hookleftarrow$
    - where muons are polarized
    - and decay to electrons carrying muon spin direction

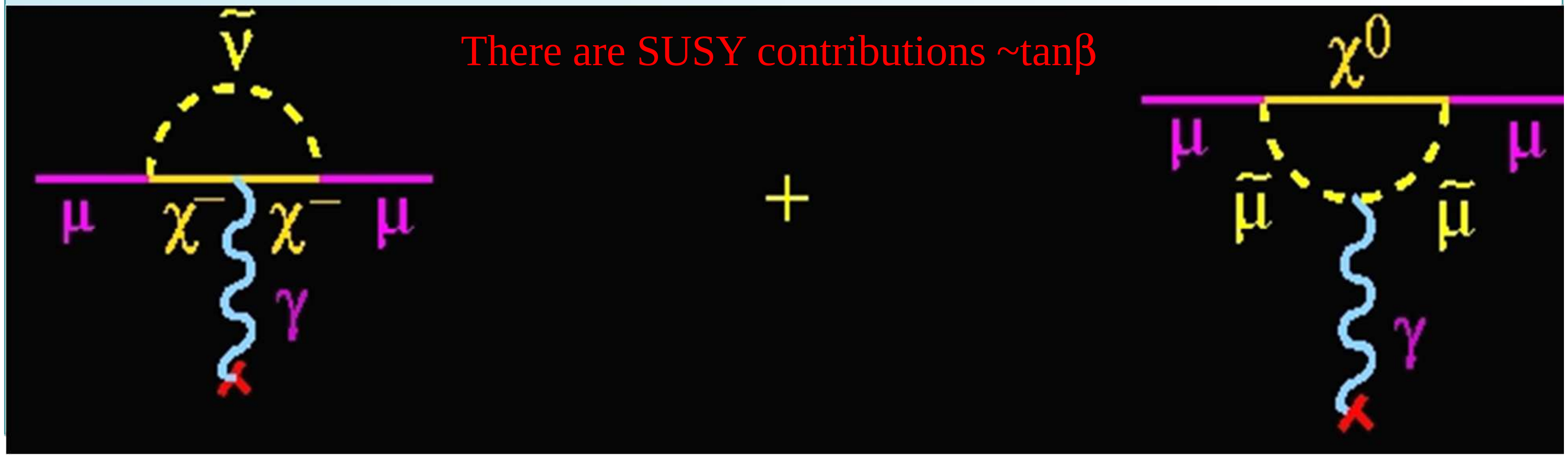
$a_\mu = 1/2(g-2)_\mu$
- Theoretical Predictions -

g!=2 because of some virtual effects that can be calculated precisely



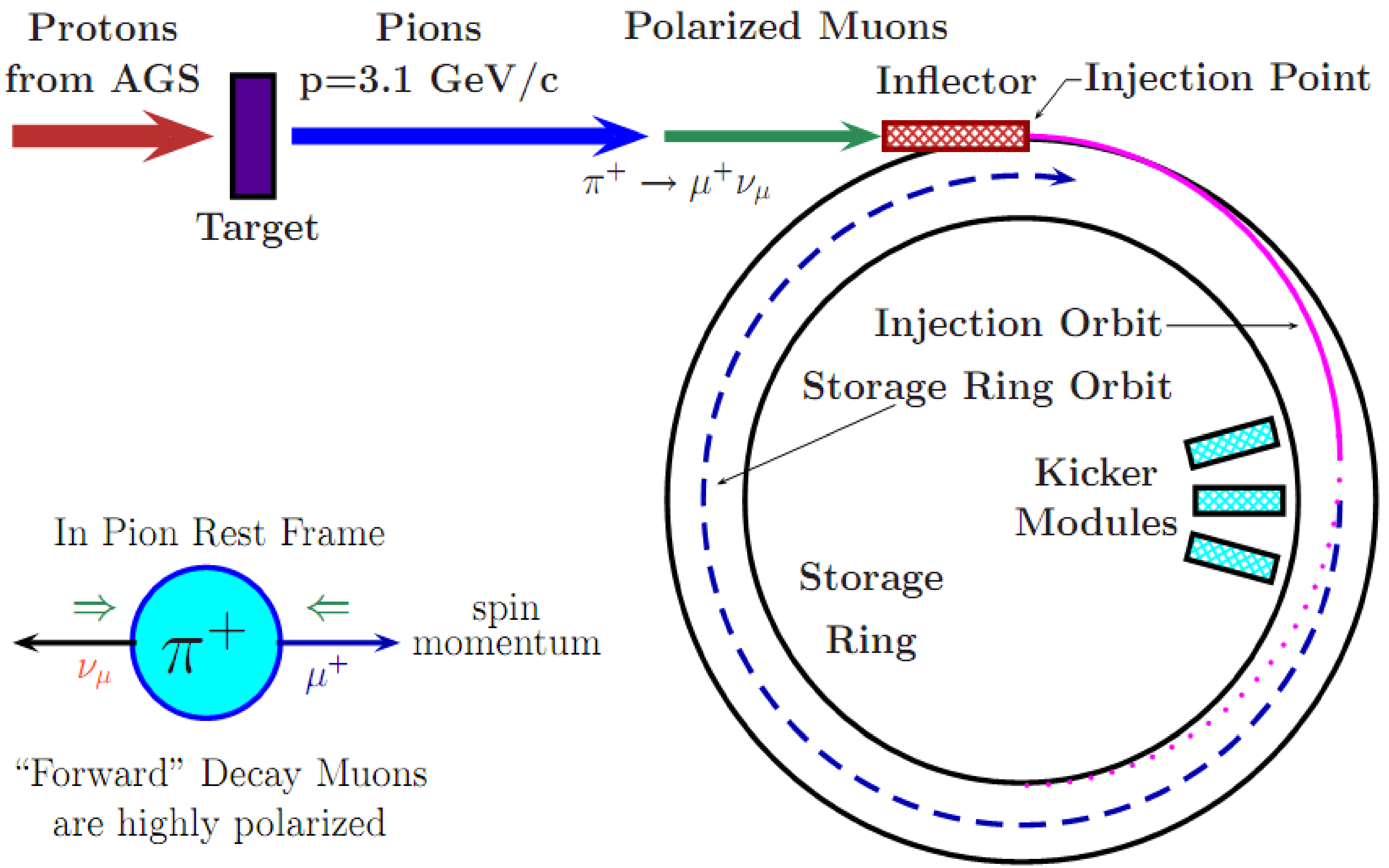
Full: up-to 4-loops
Partial: 5-loop

Full: up-to 2-loops

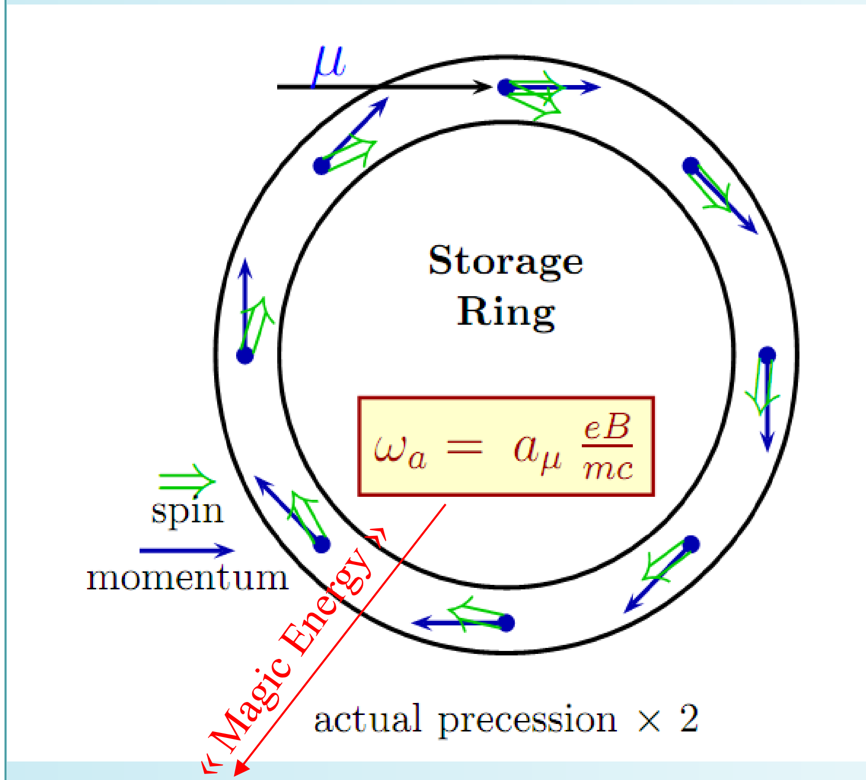


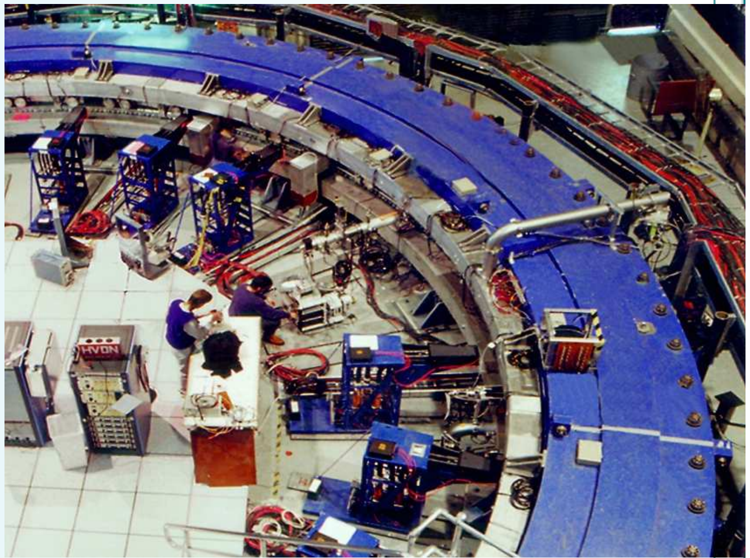
$a_\mu = 1/2(g-2)_\mu$
- Experimental Setup -

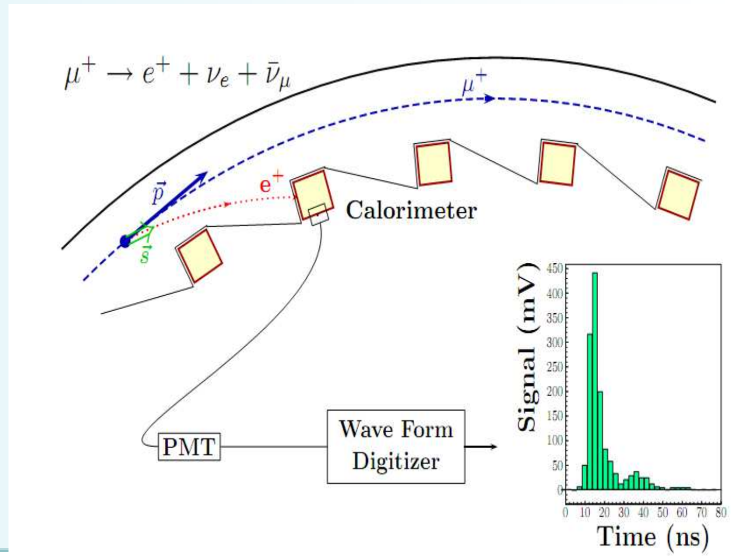
E821 at BNL (1998-2001)



a_μ=1/2(g-2)$_\mu$
- Measurement Technique -







$p(\mu^{\pm}) = 3.094\,GeV$

Larmor Precession angle : ≈ 12°

$R = 7.112\,m$

Larmor Precession frequency : ω_a

$B = 1.45\,T$ (constant)

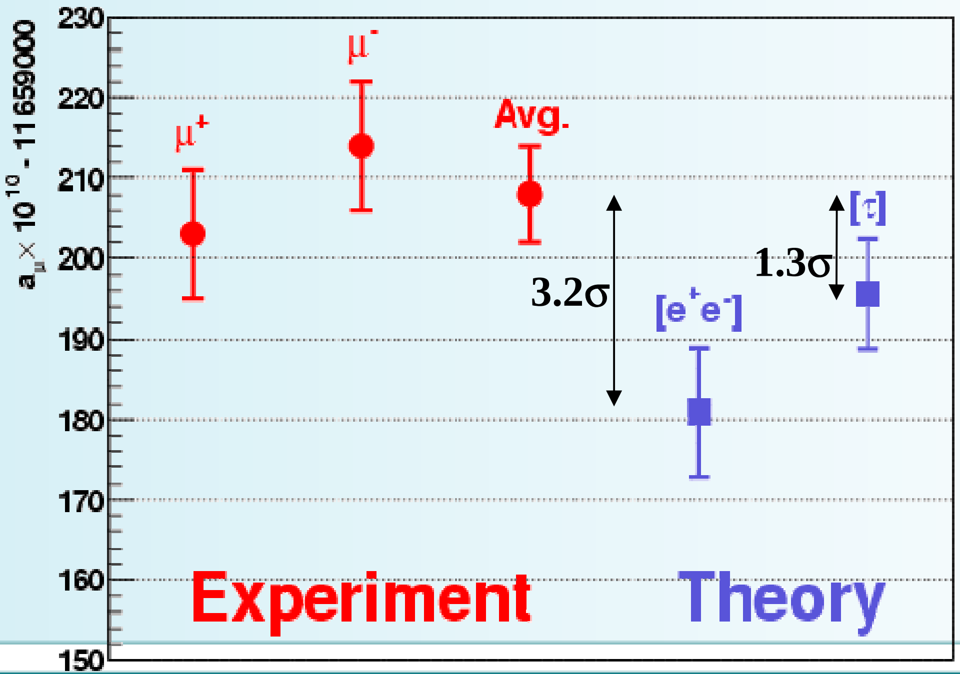
$a_\mu = 1/2(g-2)_\mu$
- Final Results -

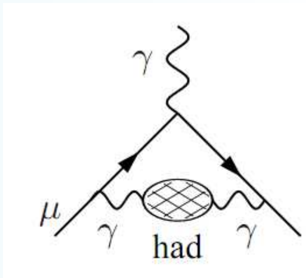
One of the most precise measurements in particle physics: 0.54 ppm !

$$a_\mu^{\rm exp} = 1.16592080(63) \times 10^{-3}$$

$$a_\mu^{\rm the} = 1.16591793(68) \times 10^{-3}$$

Ref: G.W. Bennett et al., PRD73 (2006) 072003





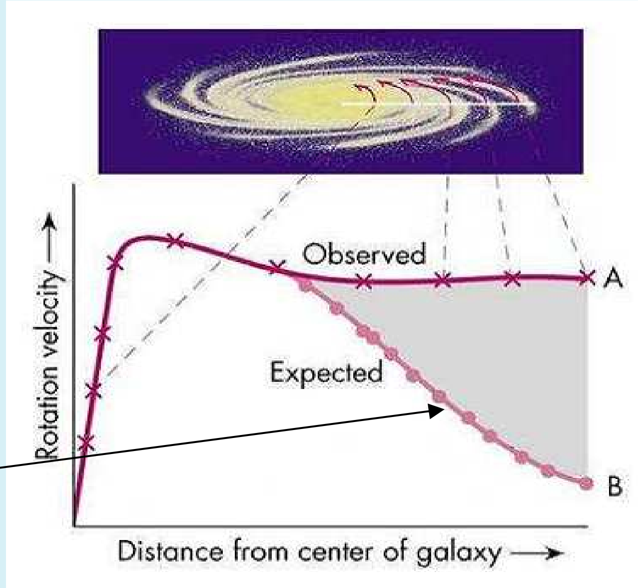
LO hadronic vacuum polarization

Evidence for Dark Matter

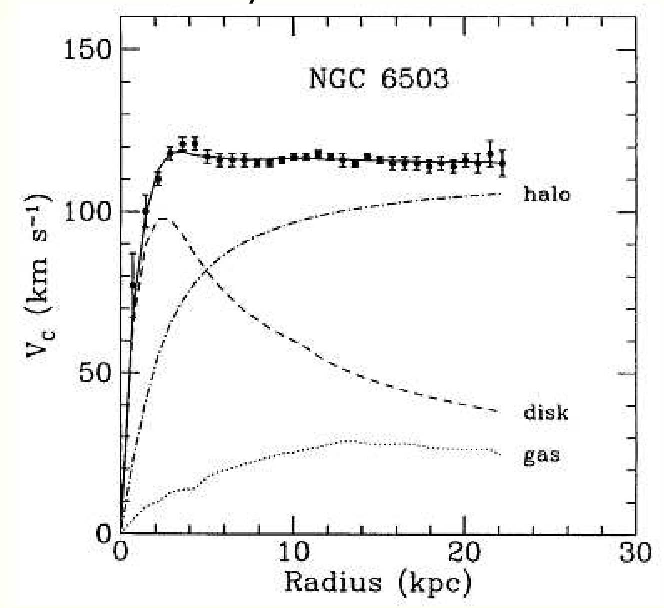
• Spiral galaxy rotation curves are incompatible w/ only visible matter contributions

Ref: F. Zwicky, Helv Phys Acta 6(2) (1933) 110-127

$$v = \sqrt{\frac{GM(r)}{r}}$$



Galaxy Rotaion Curve



• Other indications:

  • Clusters and Super-Clusters (gravitational lensing, X-rays,…)
  • Large Scale Structures (formation)
  • …

Main Properties of Dark Matter

- Its composition cannot be explained by SM particles

- Features of the « Usual Suspect »:
  - Massive: compatible w/ measured Ω_m, « Cold Dark Matter »: $\beta < 0.1$
  - No electric charge (Dark)
  - No color charge (no bound states found in exotic nuclei or atoms)
  - Only interactions: Weak & Gravitational
  - So-called WIMP: « Weakly Interacting Massive Particle »

Dark Matter Candidates

- SM Particles:
  - Neutrinos:
    - Hot Dark Matter (β>0.95): not suitable to explain properties of galaxies

- SUSY Particles:
  - Gravitino: when LSP: in general too light => Hot Dark Matter
  - Sneutrino: large annihilation σ (=> mass > 500 GeV), too σ_{el}(sneutrino+N)~O(fb)
  - Lightest Neutralino: ideal candidate
  - or even Axion, Axino (SO(10)-inspired)

- Other BSM candidates:
  - LKP (ED), LTP (LH), branons, black holes,…

Universe Expansion

Density for species i

$$\Omega_i \equiv \frac{\rho_i}{\rho_c}$$

Critical density

$$\rho_c \equiv \frac{3H^2}{8\pi G_N}$$

$$\rho_c \approx 1.88\times10^{-29} h^2 \cdot g \cdot cm^{-3}$$

$$H \approx 71 \text{ km} \cdot \text{s}^{-1} \cdot \text{Mpc}^{-1}$$

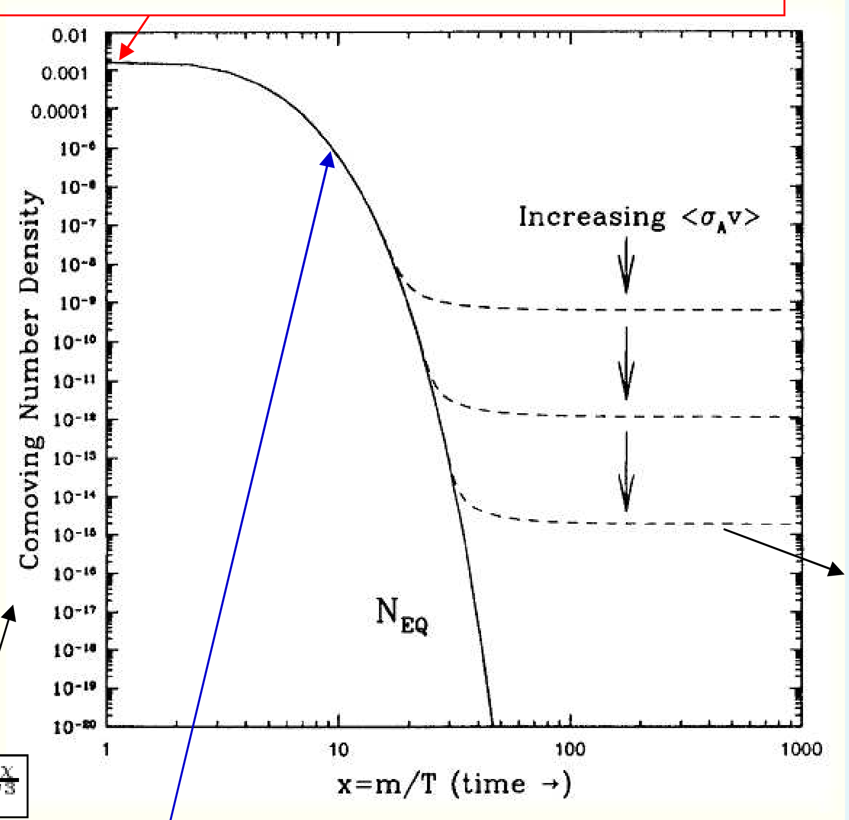
(Hubble param. today)

$\rho < \rho_c$	$\Omega < 1$	$k = -1$	Open
$\rho = \rho_c$	$\Omega = 1$	$k = 0$	Flat
$\rho > \rho_c$	$\Omega > 1$	$k = 1$	Closed

Dark Matter Relic Density

$\tilde{\chi}_1^0 + \tilde{\chi}_1^0 \leftrightarrow f + \bar{f}$ thermal equilibrium

$T \gg m_\chi$ $n_\chi \propto T^3$ (hot universe)



$f_\chi = \frac{n_\chi}{T^3}$

freeze-out:
interaction rate <
expansion rate

$T \ll m_\chi$ $n_\chi \propto \exp^{-m_\chi/T}$ (universe cools down)

Boltzmann equation

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{annih} v_{rel} \rangle (n^2 - n_{equil}^2)$$

decrease due to expansion

variation due to annihil. into SM particles

- n: actual neutralino density
- n_{equil}: neutralino density at thermal equilibrium
- σ_{annih}: annihiliation cross section
- v_{rel}: relative velocity

solution

$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} \simeq \frac{3 \times 10^{-27} cm^3/s}{\langle \sigma_{ann} v \rangle}$$

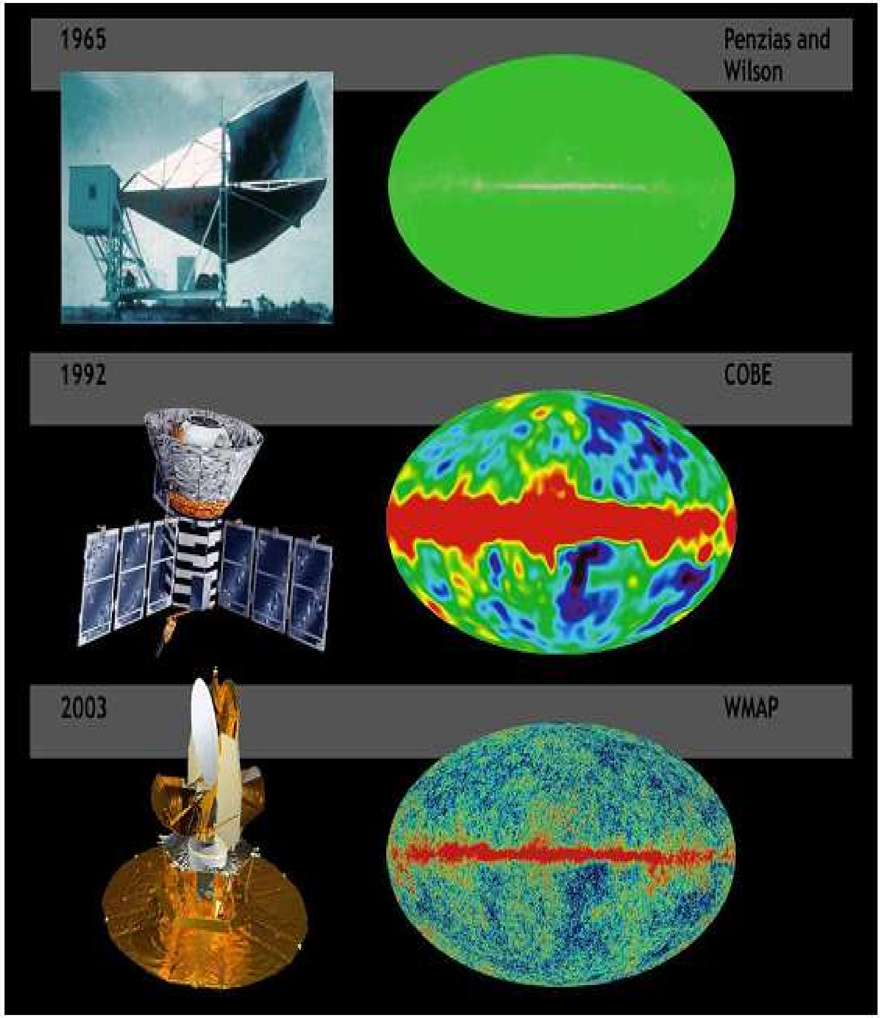
w/ WMAP =>

$$\langle \sigma_{ann} v \rangle \simeq 3 \times 10^{-26} \text{ cm}^3/\text{s}$$

typical for weak interactions!

Cosmic Microwave Background

- Very isotropical photon radiation at T = 2.7°K
- Relic radiation from the Big Bang
- Predicted by G. Gamow, R. Alpher, R. Herman, in 1948



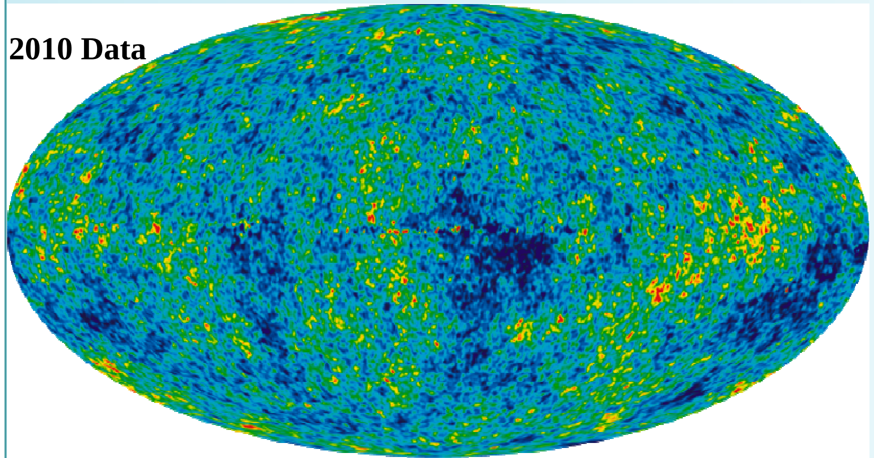
Discovered in 1964
Using a radio-telescope

COBE: « COsmic Background Explorer »
Satellite expt launched in 19??

WMAP: « Wilkinson Microwave Anisotropy Probe »
Satellite expt launched in 2001

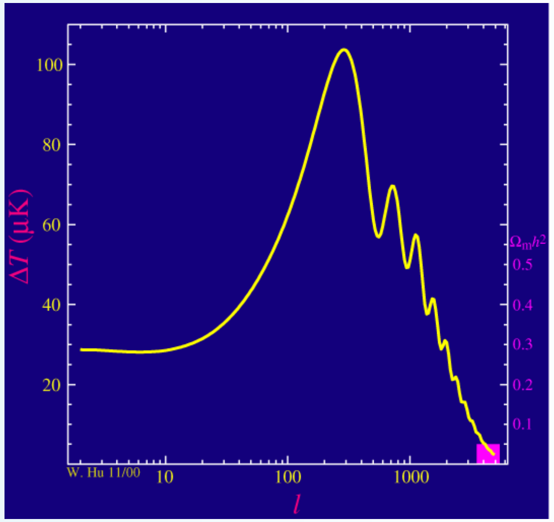
⟵ Need accuracy of $\Delta T/T \sim 10^{-5}$

Cosmology Precision Measurements



Anisotropies measured by the WMAP satellite exp[t]

Ref: C.L. Bennett et al., Astrophys J Suppl 148 (2003) 1

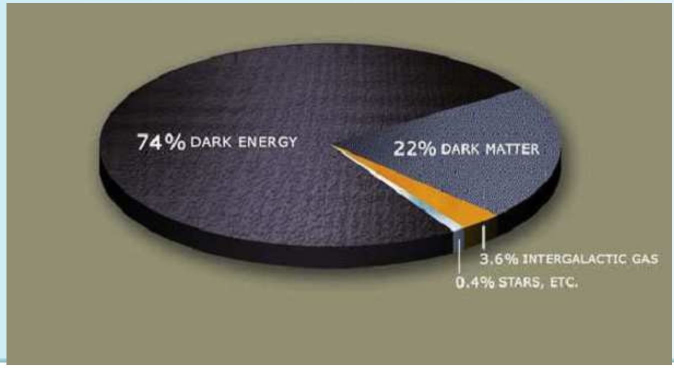


CMB: Angular Power Spectrum

Positions & rel. heights of acoustic peaks

=> infos about geometry & composition of the universe

Combined w/ other measurements (supernovae, galaxy clusters,...):



$$\begin{cases} \Omega_{baryon} h^2 = 0.02267 \begin{cases} +0.00058 \\ -0.00059 \end{cases} \\ \Omega_\Lambda h^2 = 0.726 \pm 0.015 \\ \Omega_\nu h^2 \approx 0.005 \end{cases}$$

$$\Omega_{CDM} h^2 = \Omega_{Matter} h^2 - \Omega_{Baryon} h^2 = 0.1126 \begin{cases} +0.0081\,(0.0161) \\ -0.0090\,(0.0181) \end{cases}$$

68% CL   95% CL

=> $\Omega_{\tilde{\chi}_1} h^2 < 0.129$ 95% CL