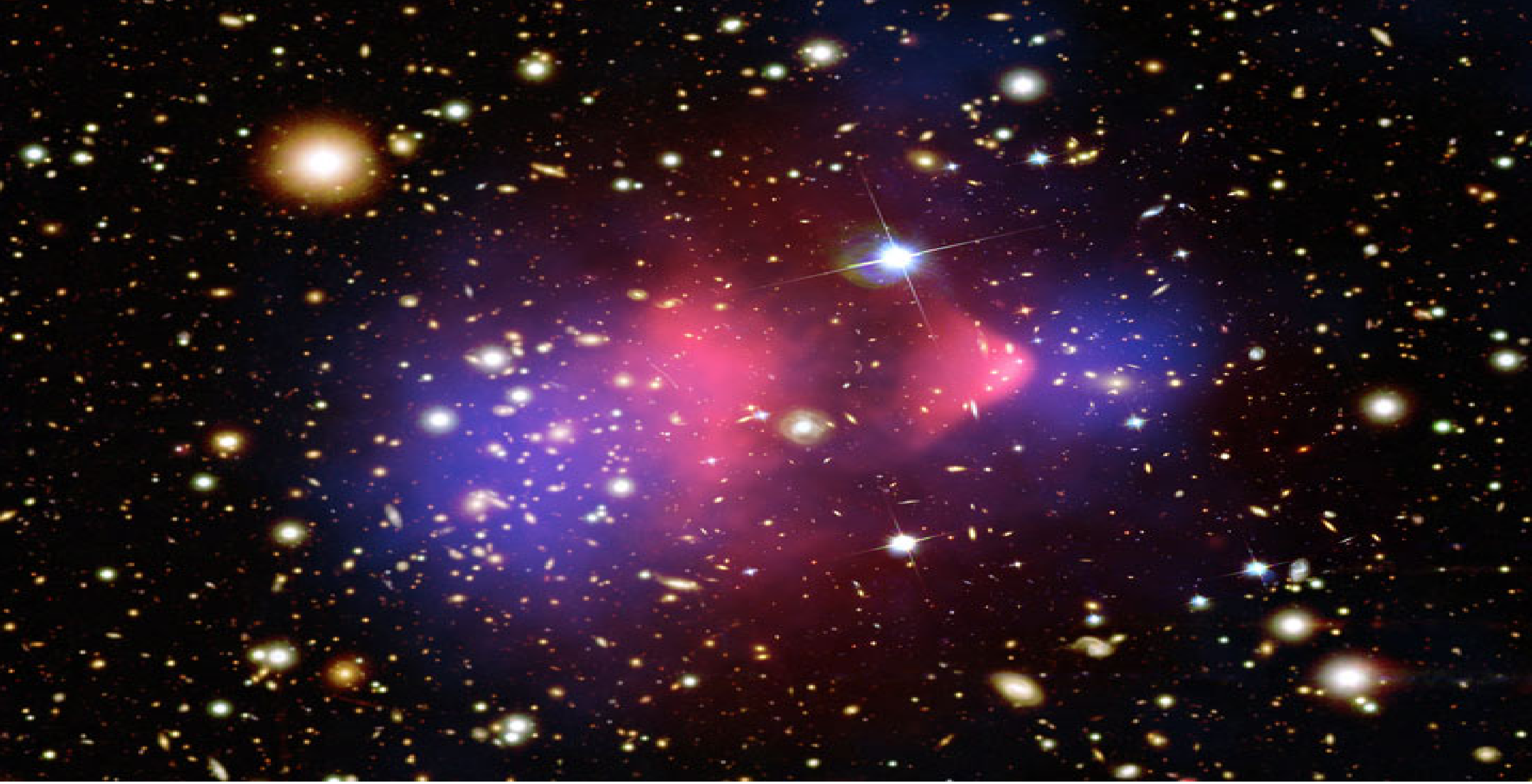


Chandra X-Ray Observatory

James Wells

CERN & U. Michigan

Exploring the Cosmos with the LHC

Humans in the Universe

Science has been mostly about our bodies.

What are we made of?

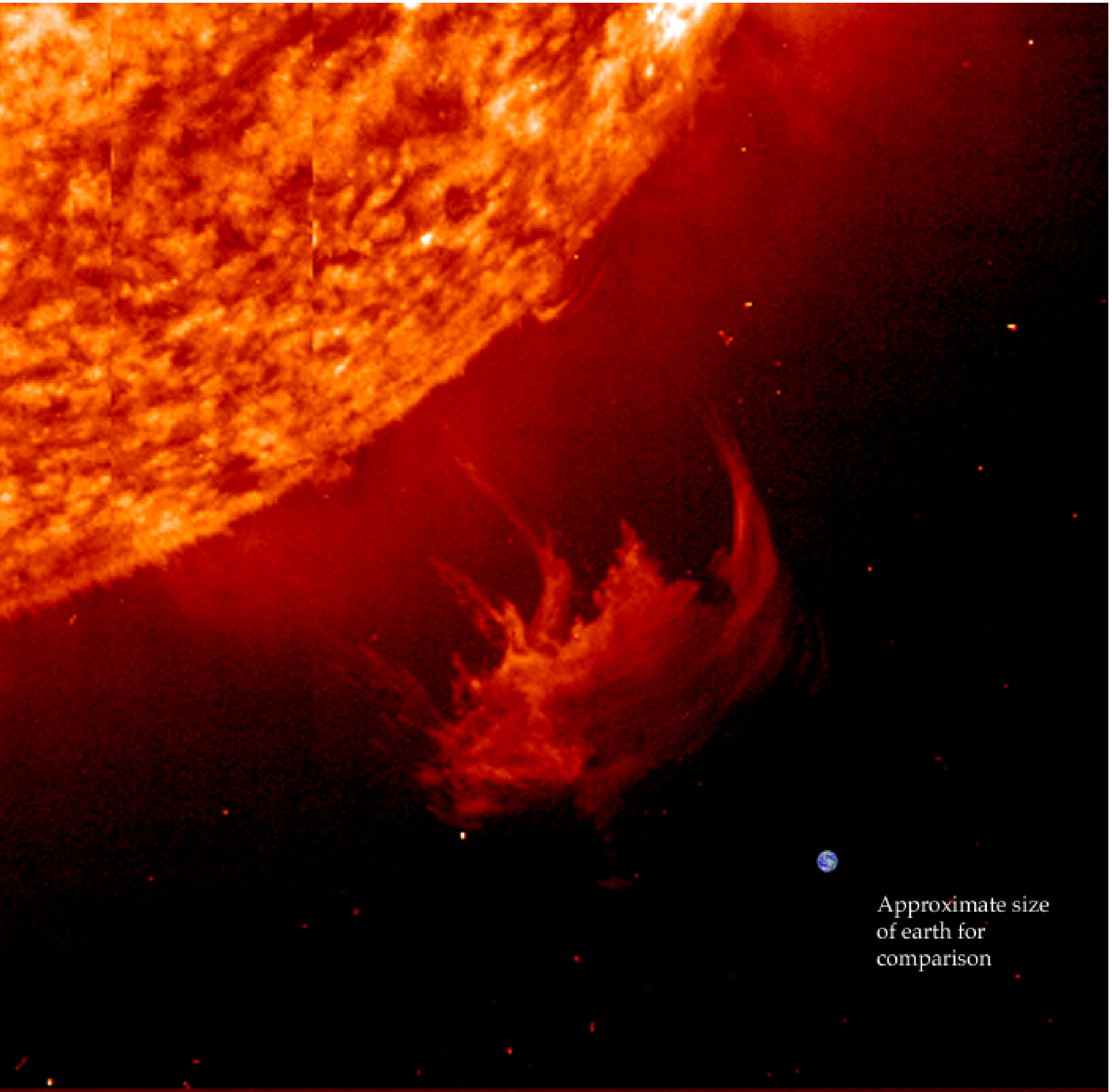
How do we interact with things?

www.minority-speak.com

Dr. Frankenstein in *Frankenstein (1931*)

Thread in history of science: human-centered science is less and less the full story of our universe.

Earth and our Solar System



Sun-Earth Distance = 1 AU

Sun-Pluto Distance = 40 AU

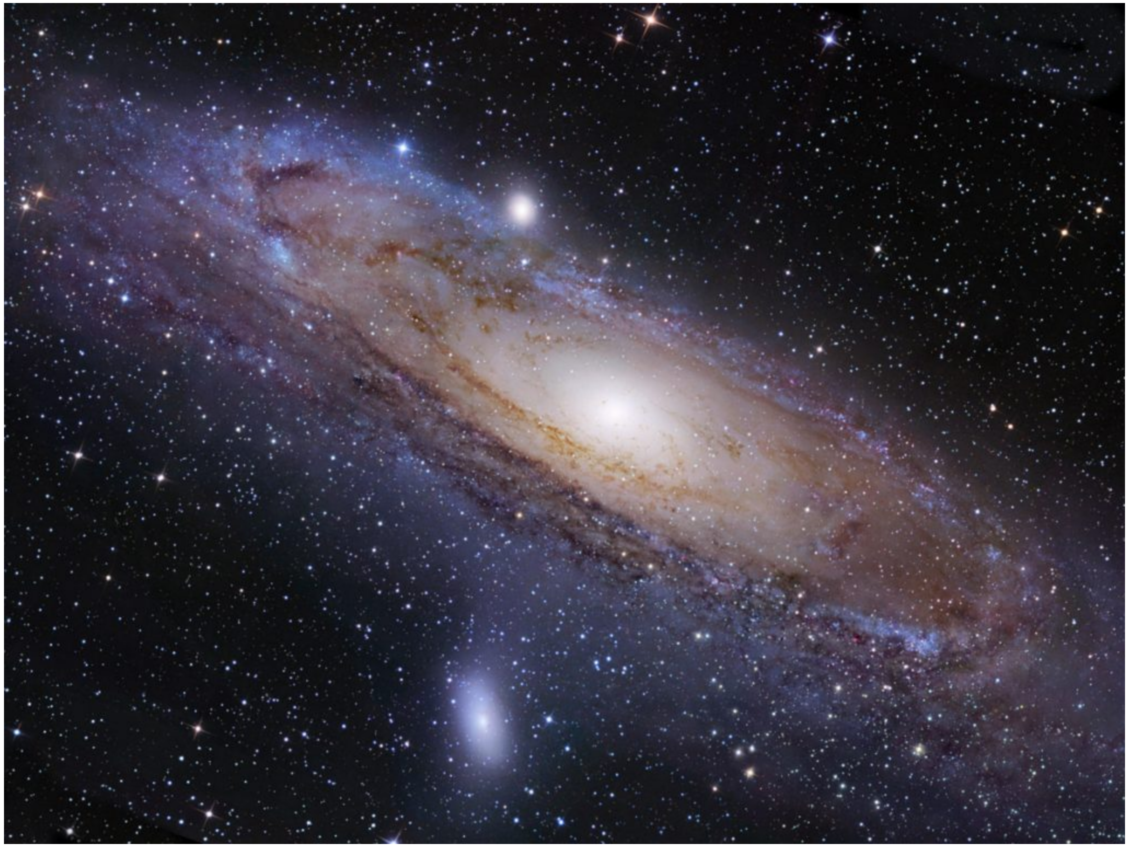
R_{sun} = 0.01 AU

1 AU = 150 million km = 8.3 light-minutes

1/8th sec for light to circumference of earth

NASA

Galaxy and Local Group

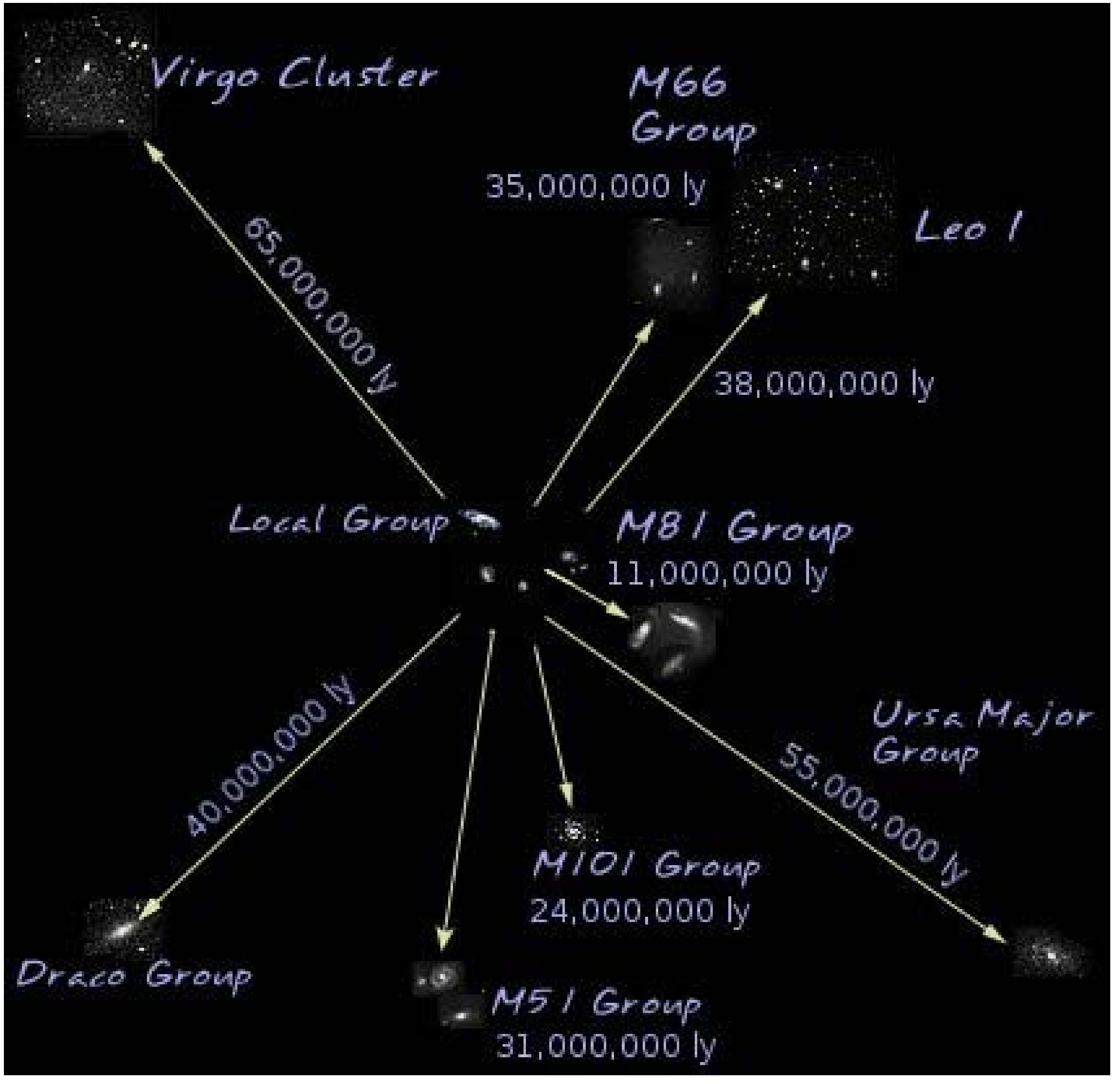


NASA

Andromeda is our closest galaxy neighbor, about 2.5 million light-years away (0.8 Mpc).

Andromeda is largest object in a small “Local Group” cluster that contains about 30 “nearby” galaxies, including Milky Way and Triangulum Galaxies, and the Large and Small Magellanic Cloud.

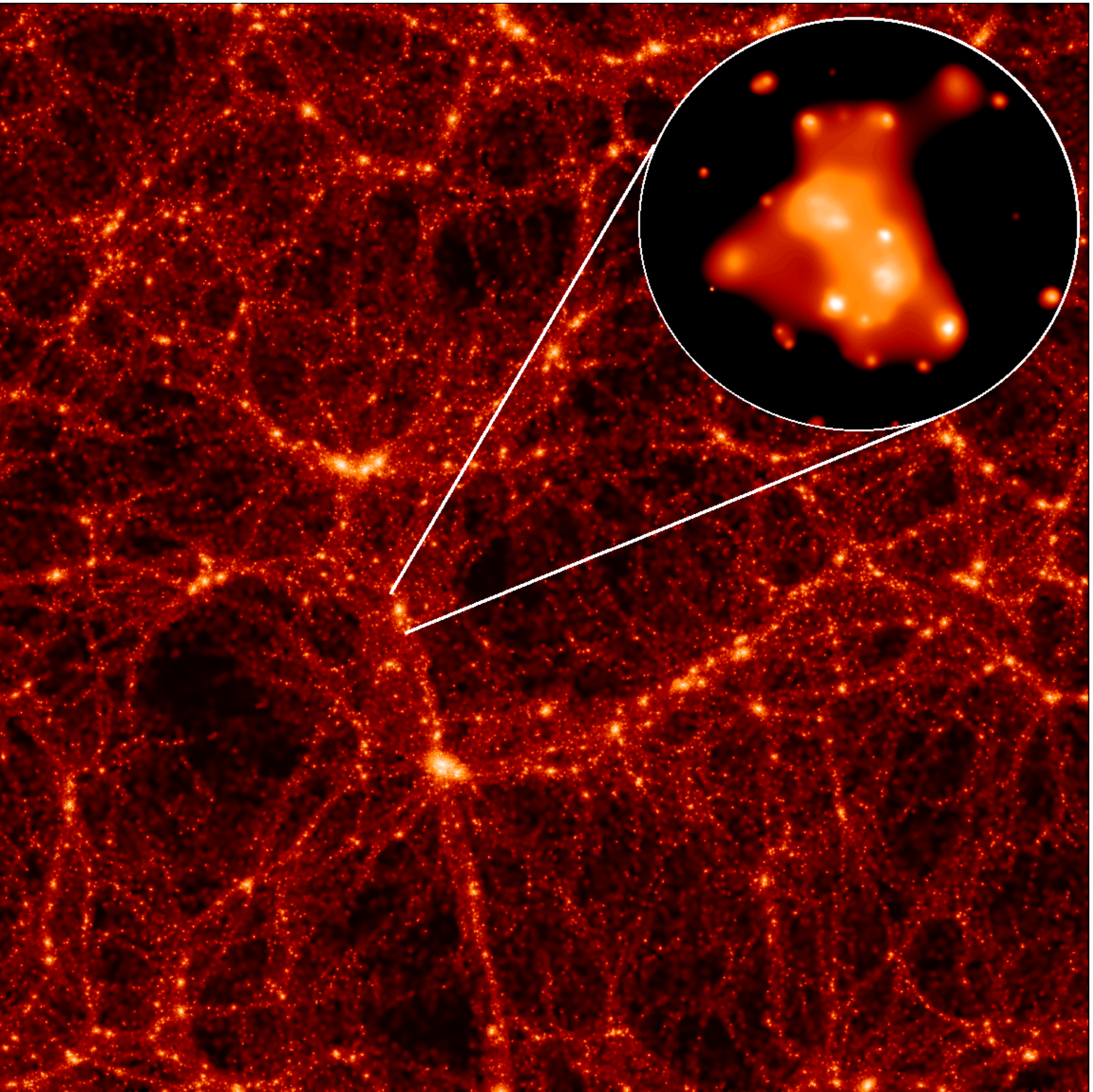
Virgo Supercluster



NASA Images

Simulation of Clustering

http://hea-www.harvard.edu/~bmaughan/scaling/sim0152.gif



Computer simulation of universe structure formation (Virgo consortium, Jenkins et al. 1998).

XMM-Newton X-ray image of a real galaxy cluster superimposed.

Evolution depends on relative composition of the universe (Dark matter, dark energy, matter, etc.).

Size of universe is about 150 billion light-years.

Ω Composition Fractions

Composition is given in terms of fraction of critical density of universe.

Illustrated later

ρ_c = critical density for flat universe
$= 3H^2/8\pi G \sim 10^{-29}$ grams/cm^3 (ρ_{water} = 1 gram/cm^3)

$\Omega_\Lambda = \rho_\Lambda/\rho_c$ = dark energy fraction
$\Omega_{DM} = \rho_{DM}/\rho_c$ = dark matter fraction
$\Omega_B = \rho_M/\rho_c$ = "normal matter" fraction
$\Omega_M = \Omega_{DM} + \Omega_B$ = total matter fraction

Overall Composition of Universe

Composition of body and earth: oxygen, hydrogen, nitrogen, etc.

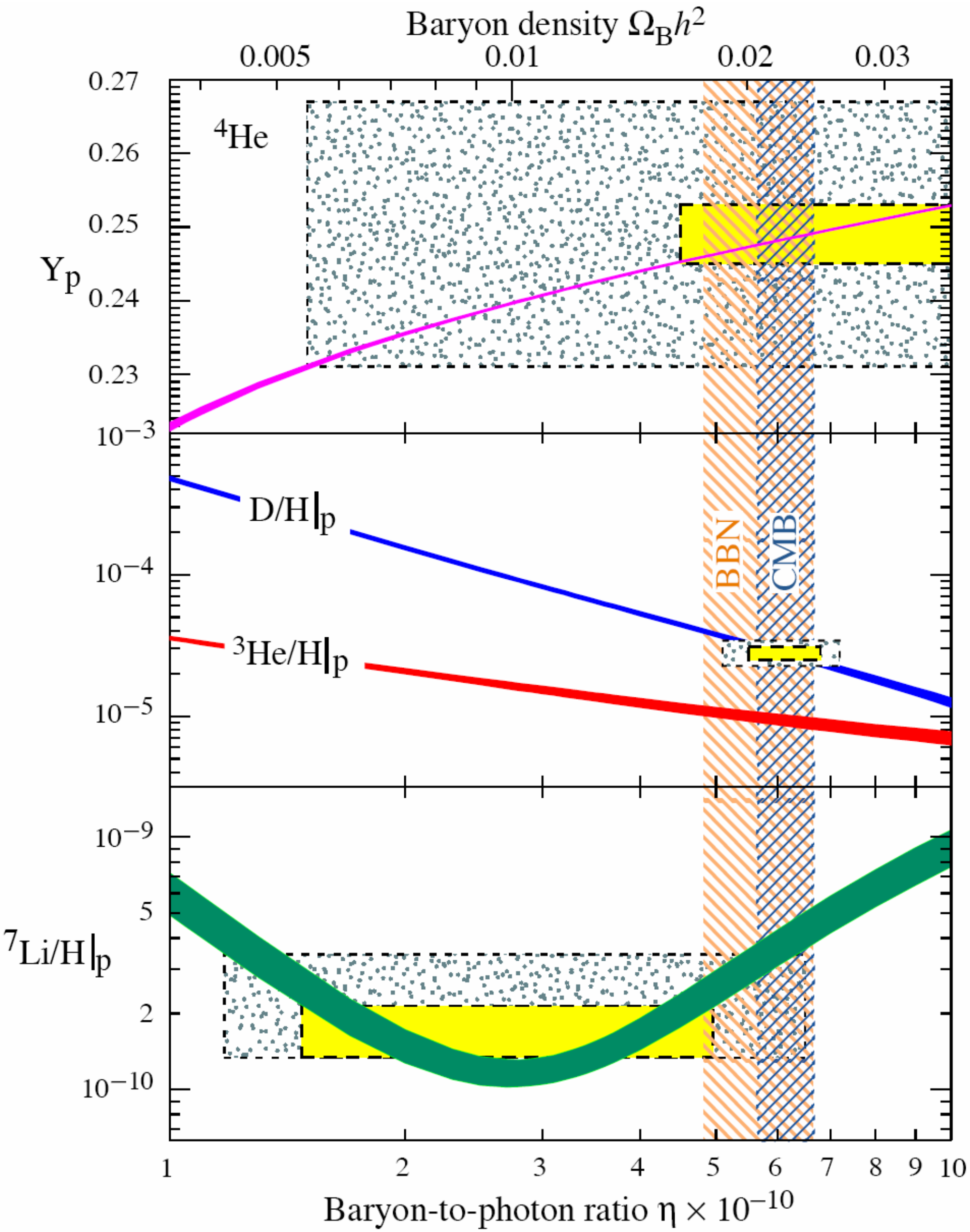
For the Universe, we need broader categories, not familiar in everyday life.

Baryonic matter: The stuff stars and planets and people are made of.

Dark Matter: Stable stuff we are not made of. Nothing like the particles we are used to.

Dark Energy: The vacuum energy of the Universe. Probably equivalent to Cosmological Constant in Einstein's Equation.

$$R_{\mu\nu} - \frac{1}{2}\mathcal{R}g_{\mu\nu} = 8\pi G T_{\mu\nu} + \Lambda g_{\mu\nu}$$



Fields & Sarkar, '06

"Big Bang Nucleosynthesis"

$n/p \sim \mathrm{Exp}[\, -(m_n - m_p)/T_f \,]$

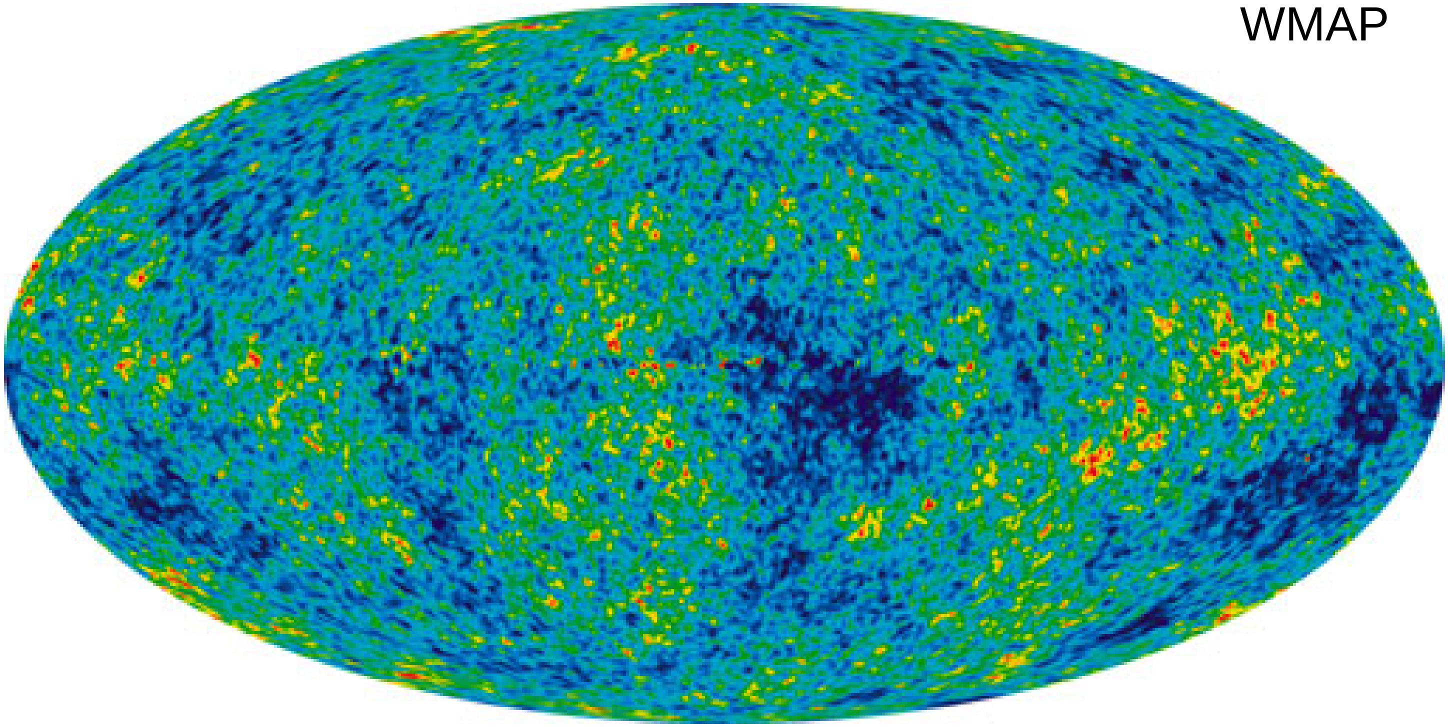
Taking into account β decay of neutrons, when nuclear reactions begin: n/p ~ 1/7 (sensitive to neutron lifetime)

Almost all neutrons go into ^{4}He. Fraction is $Yp=2n/(n+p)=2(n/p)/(1+n/p) = 0.25$

Efficiency of forming other elements depend on nuclear interaction rates and the total nucleon density (I.e., baryon-to-photon ratio).

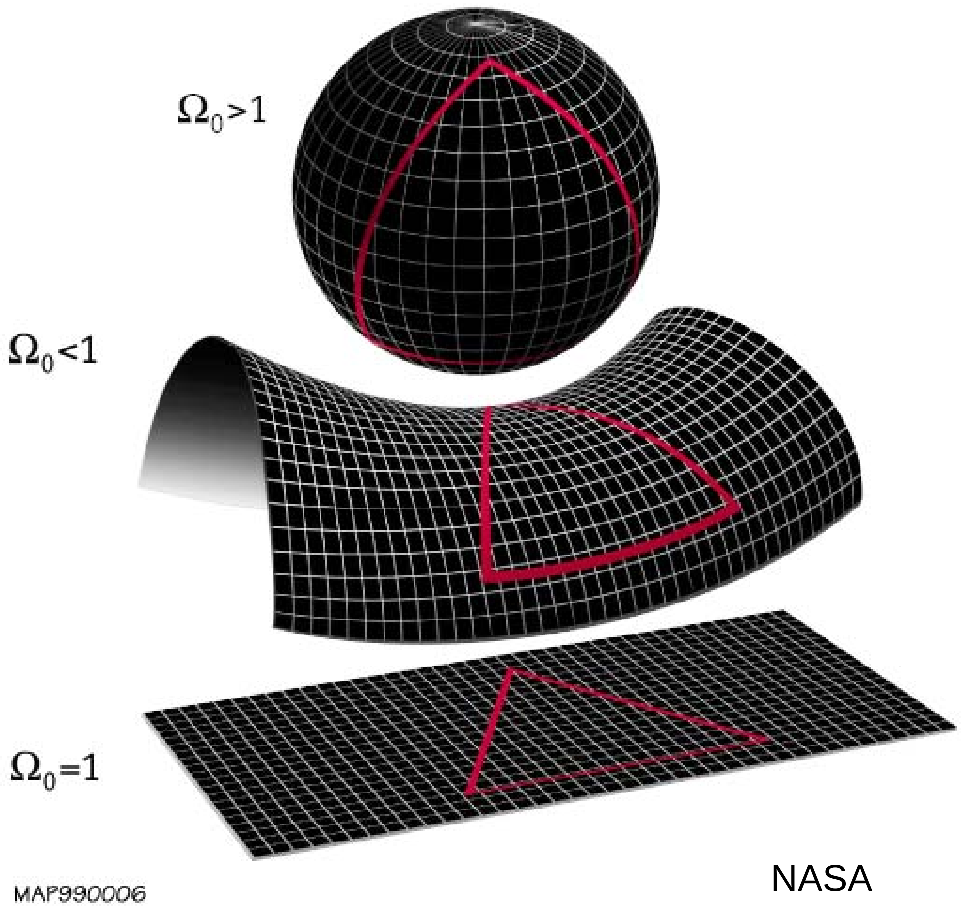
$\Omega_B h^2 \sim 0.02$ (small fraction of ρ_c)

Cosmic Microwave Background Radiation


WMAP

T_{cmb} = 2.725 K, with fluctuations of few x 10^{-3} K

Geometry of the Universe



NASA

Typical angle to bright spots:

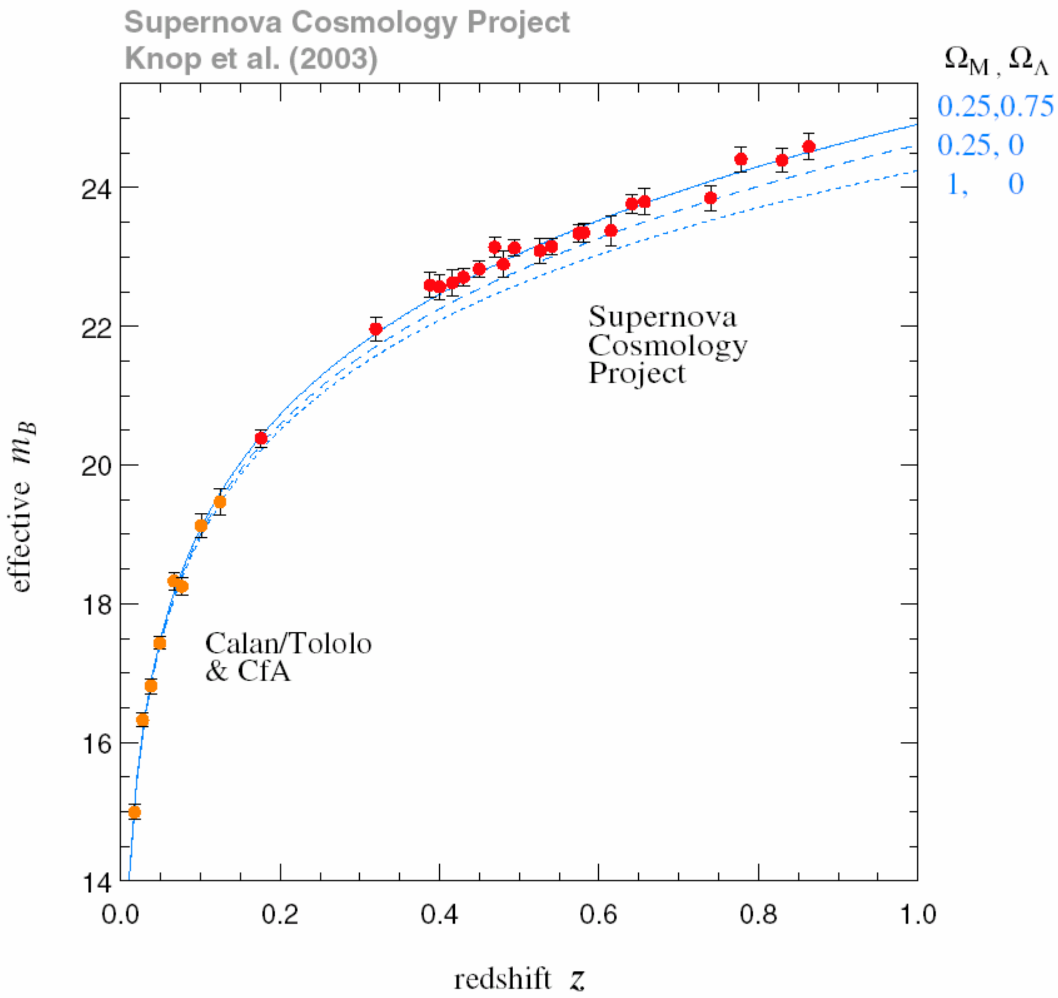
$\Omega>1$ (closed): 1 1/2 degrees

$\Omega<1$ (open): 1/2 degrees

$\Omega=1$ (flat): 1 degrees

WMAP sees 1 degree separation -- flat universe.

==> $\Sigma\, \Omega_i = \Omega_\Lambda + \Omega_M = 1$



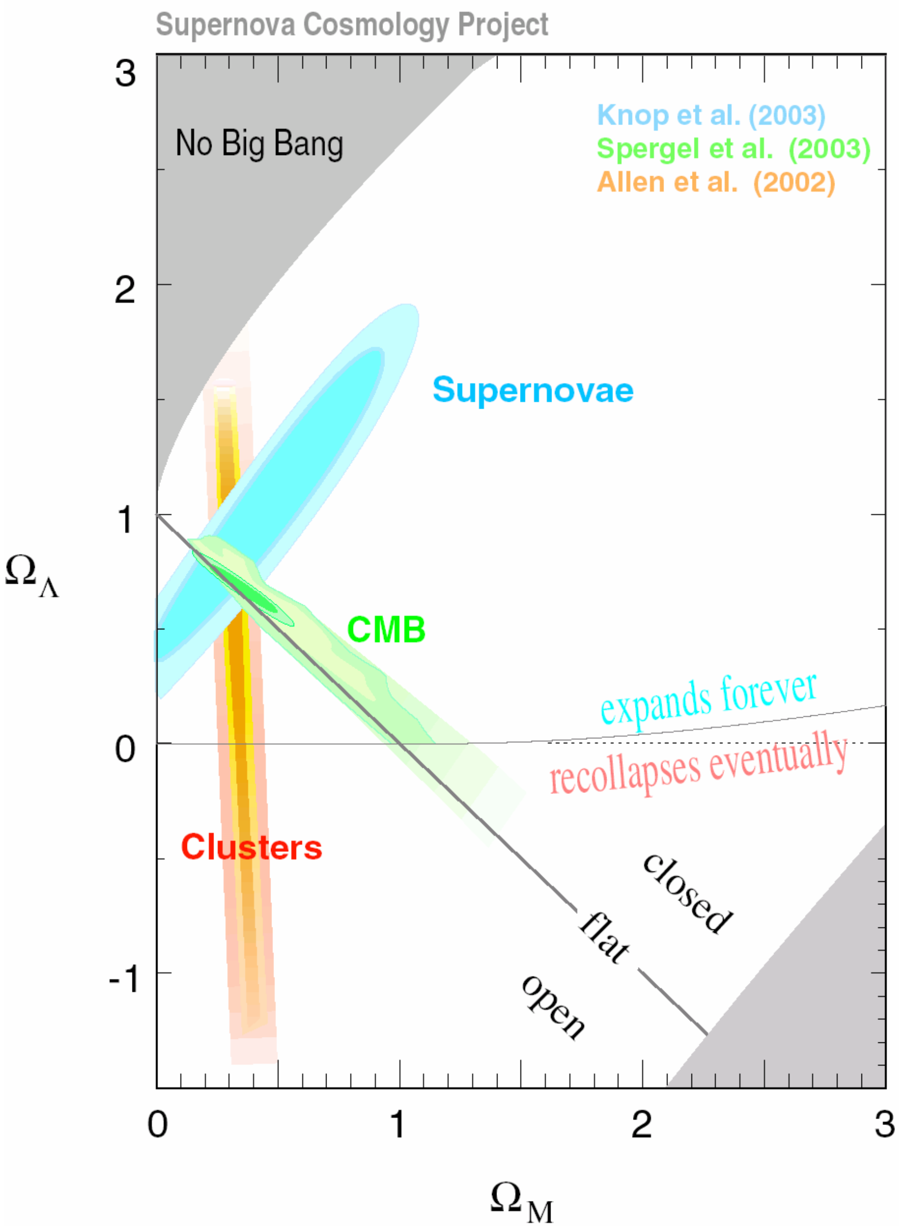
Vacuum Energy
Dark Energy

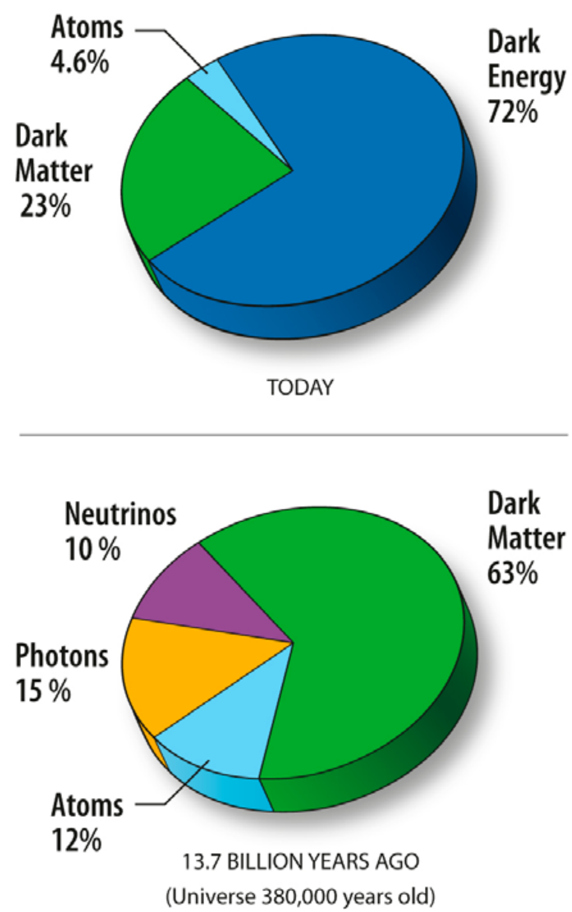
Vacuum energy changes expansion rate of the universe over time.

Brightness versus distance for "standard Candle" type Supernovae sensitive to expansion rate of the universe.

Measurements of non-zero vacuum energy Λ important discovery.

Composition of the Universe





Credit: NASA / WMAP Science Team

Dark Matter Necessary

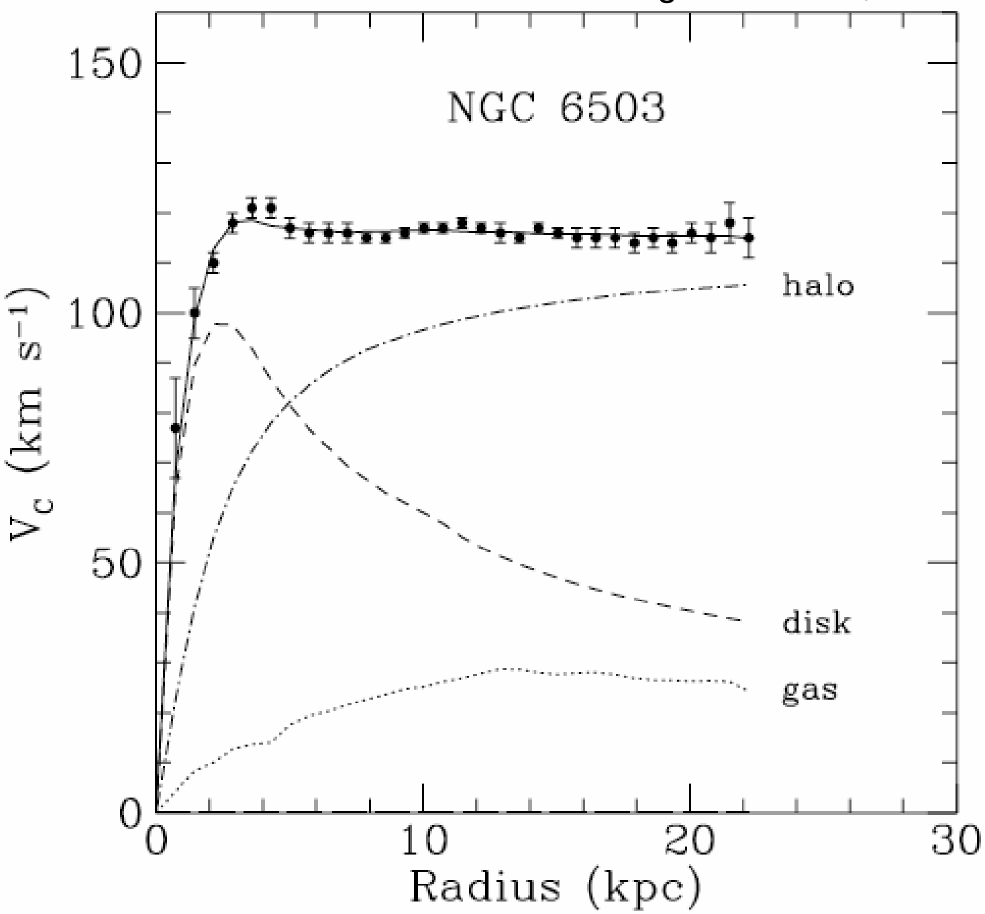
Cosmology appears to require existence of dark matter: a special type of matter dissimilar to our own.

These were all rather indirect inferences from early universe cosmology.

Are there more immediate and direct evidences for Dark Matter? Yes. Famous example is galaxy rotation profile.

Galaxy Rotation Curves

Begeman et al., '91



Lowell Observatory

$$v(r) = \sqrt{\frac{GM(r)}{r}} \rightarrow \frac{1}{\sqrt{r}}$$

Is expected, but instead get flat profile with r. DM Halo!

Bullet Cluster (galaxy clusters colliding)

QuickTime™ and a
Sorenson Video 3 decompressor
are needed to see this picture.

Blue =
Inferred DM
(from lensing of background objects)

Red =
Normal Hot gas
interacting electromag.

Simulation done by KIFAC.

Last picture is NASA -- color coding by inference

z=0.3 (1 Gpc)

What is the Dark Matter

Many ideas:

- Lightest Supersymmetric Particle (LSP)
- Lightest Kaluza-Klein Excitation of Extra Dimensions
- Technibaryons
- Singlet fermions
- Gravitinos
- Moduli fields
- Axions
- …

Particle Interpretation

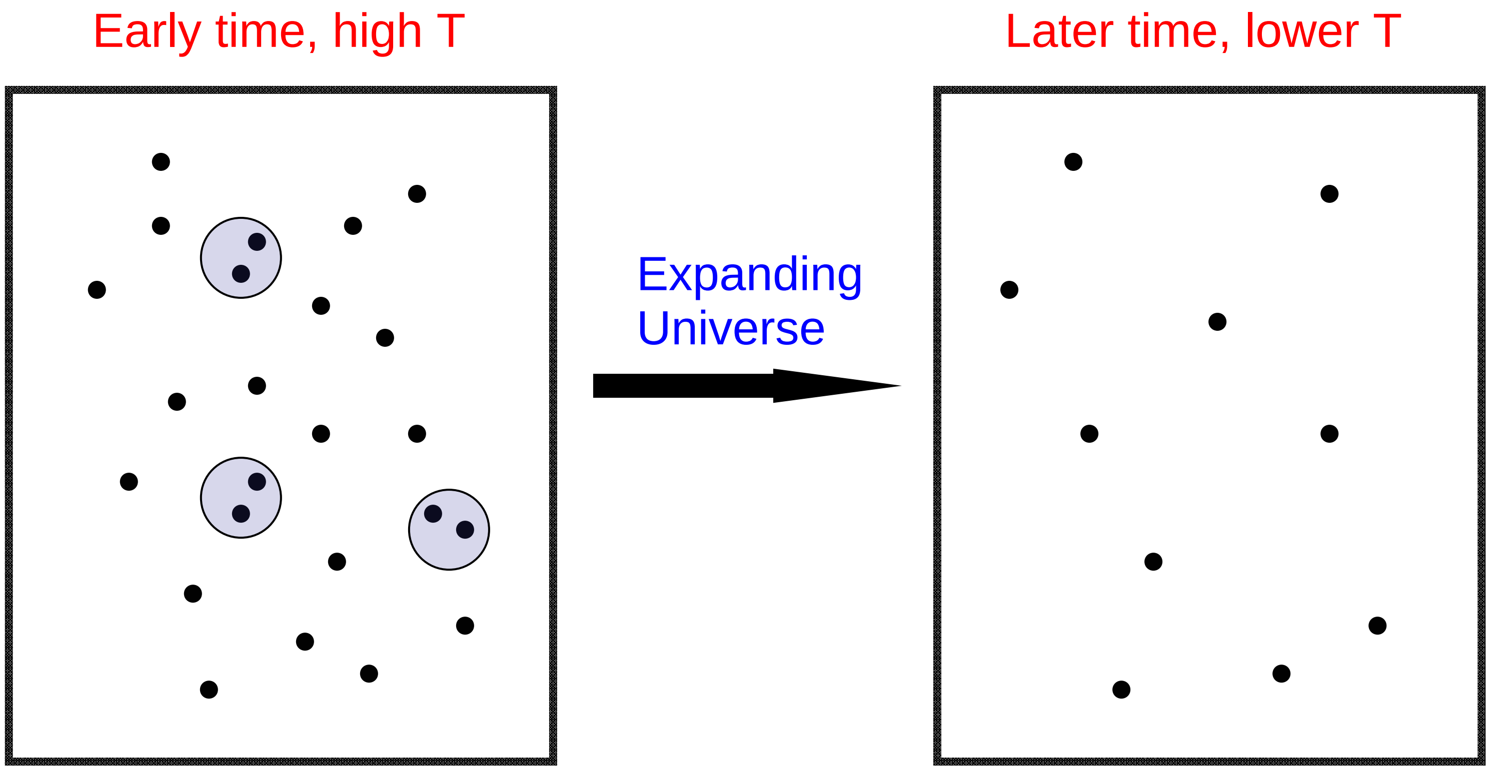
Particle Candidates must be Stable.

This usually means it is the lightest particle possessing a “quantum number”: an immutable quality about it.

Schoolyard example: give this apple to any boy you encounter who is shorter than you.

Every recess (“scattering event”), boys (“quantum number”) will hand apple to shorter boys (“decays”), ending with the same shortest (“lowest mass”) boy holding the apple forever after (“stable”).

Freeze-Out of Dark Matter

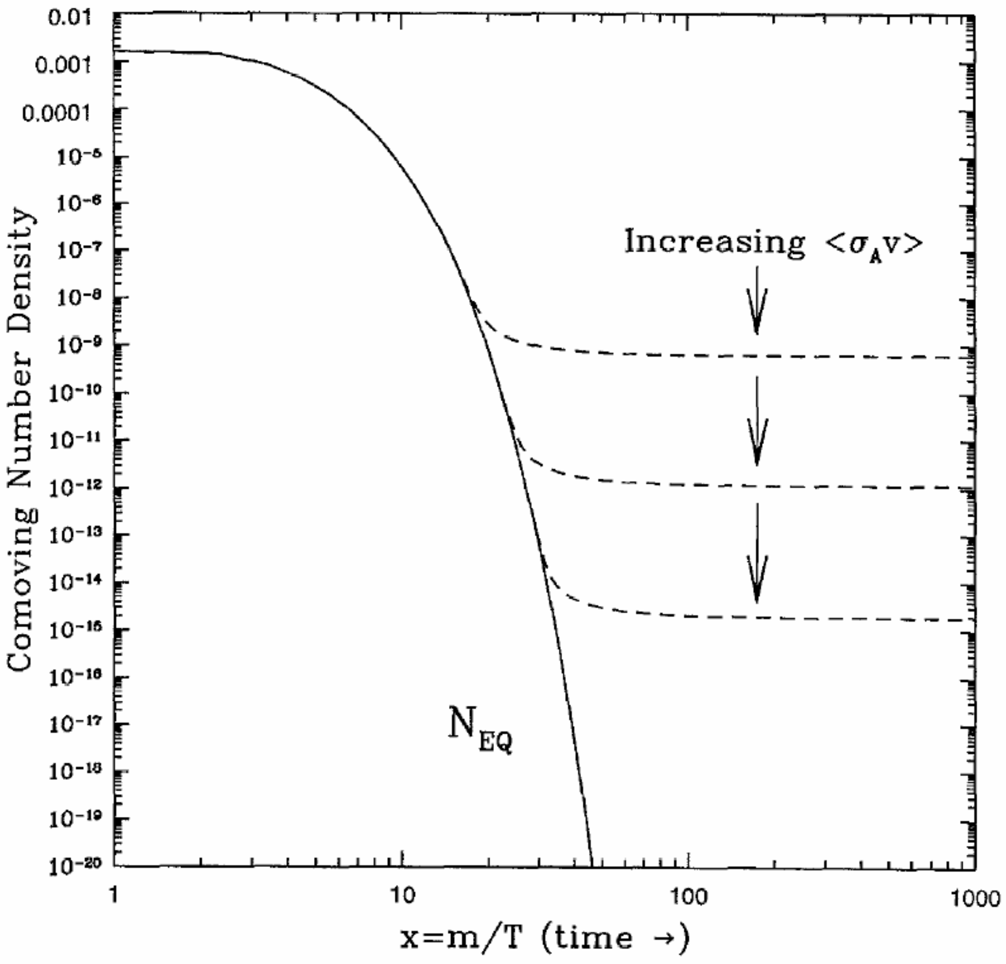


DM pairs come close enough to interact.

Never close enough to interact: “freeze-out”.

Freeze-out process

Kolb & Turner, *Early Universe*



Freezeout when $n\langle\sigma v\rangle < H$

$$n_{eq} = g\left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T}$$

$$\Omega_{DM} \sim \frac{M_W^{-2}}{\langle\sigma v\rangle}$$

astrophysics

Particle physics

Tantalizing accident of scales…

Weakly Interacting Massive Particle: WIMP

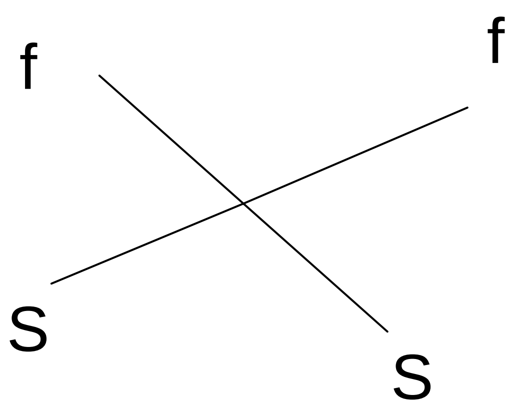
Simplest Example

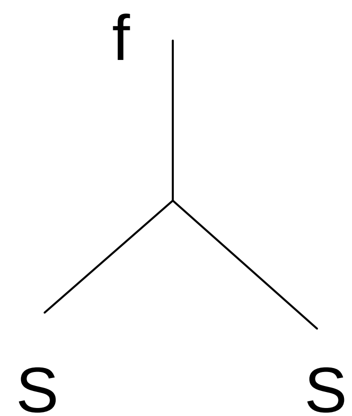
Particle: simple, real scalar field S.
Quantum Number: Z_2 charge invariance ("odd"=charged, "even"=no charge).

Silveira, Zee, '85
McDonald, '94
Burgess et al., '00

S is "odd" and all other Standard Model particles f={electron,photon,quark,…} are "even".

Invariant interactions: Any number of Standard Model particles, but only even number of S particles. S cannot decay -- it is stable.





Most Celebrated Example

Supersymmetry: Every particle of the Standard Model (electron, photon, etc.) has a superpartner (selectron, photino, etc.) separated by $\Delta s=1/2$.

Why Supersymmetry? Stabilizes the mass-giving Higgs boson to quantum corrections.

Quantum corrections under control if $\sim M_Z^2$

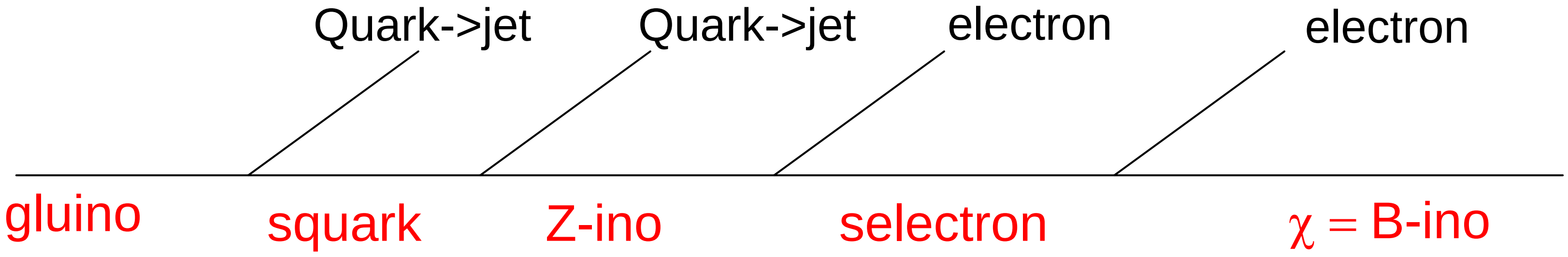
$$\Delta m_H^2 = \left\{ -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV}^2 \right\} + \left\{ \frac{|\lambda_f|^2}{8\pi^2}(\Lambda_{UV}^2 + M_{SUSY}^2) \right\} = \frac{|\lambda_f|^2}{8\pi^2} M_{SUSY}^2$$

Stability of Lightest Supersymmetric Particle

R-parity is a feature of most supersymmetric theories.

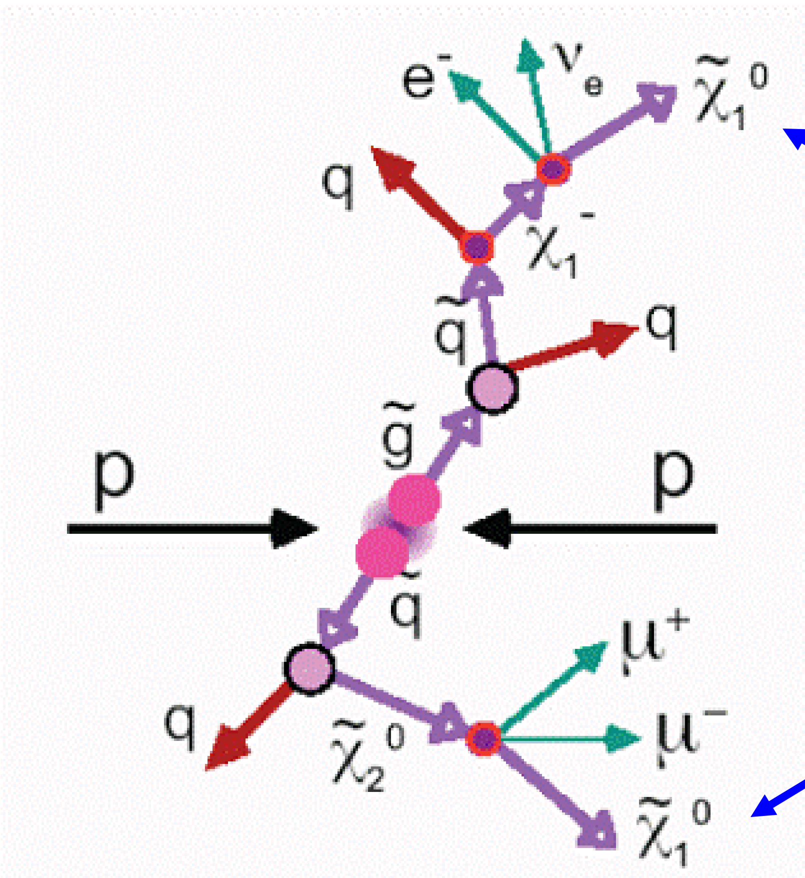
R-parity: A Z2 symmetry, where all Standard Model states are “even” and all superpartners are “odd”.

The lightest superpartner (χ or LSP) is stable.



Example cascade decay chain after making gluinos.

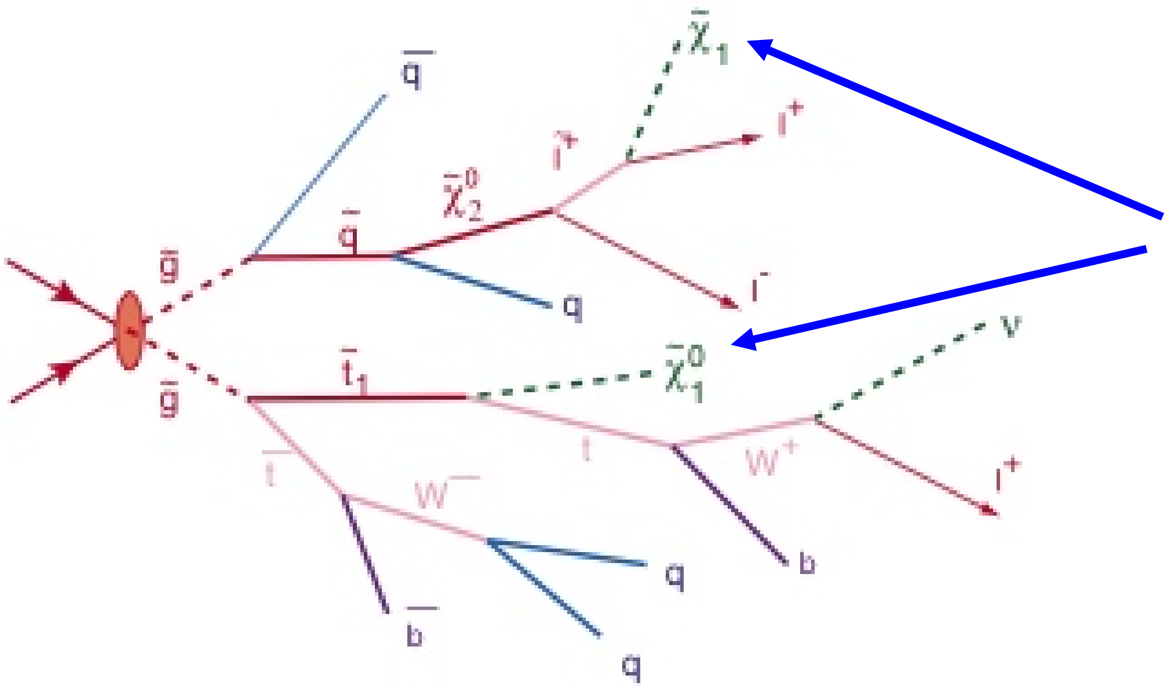
Example SUSY Event at LHC



LSP χ is source of much missing energy.

http://www.icepp.s.u-tokyo.ac.jp/~kenta/analysis.html

Another example

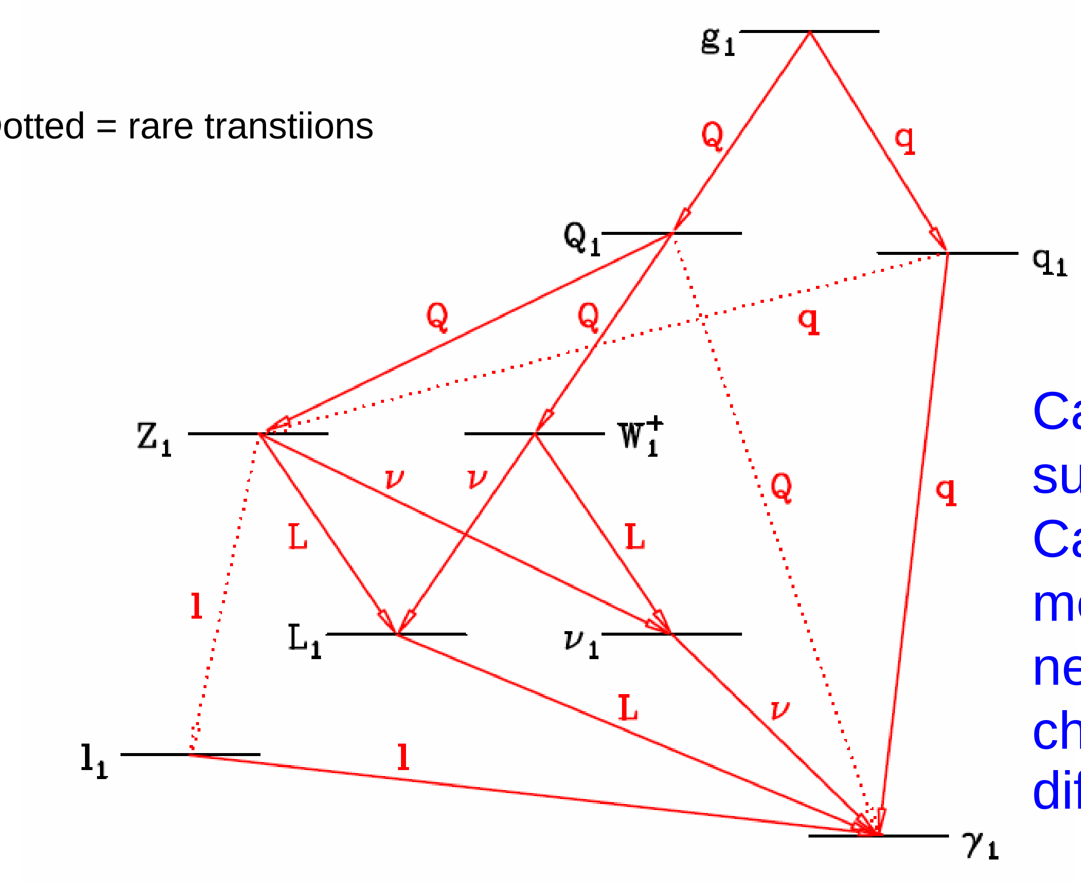


Large missing energy from cascade decays to LSP.

http://www.pha.jhu.edu/~morris

Extra Dimensions Example

Dotted = rare transtiions

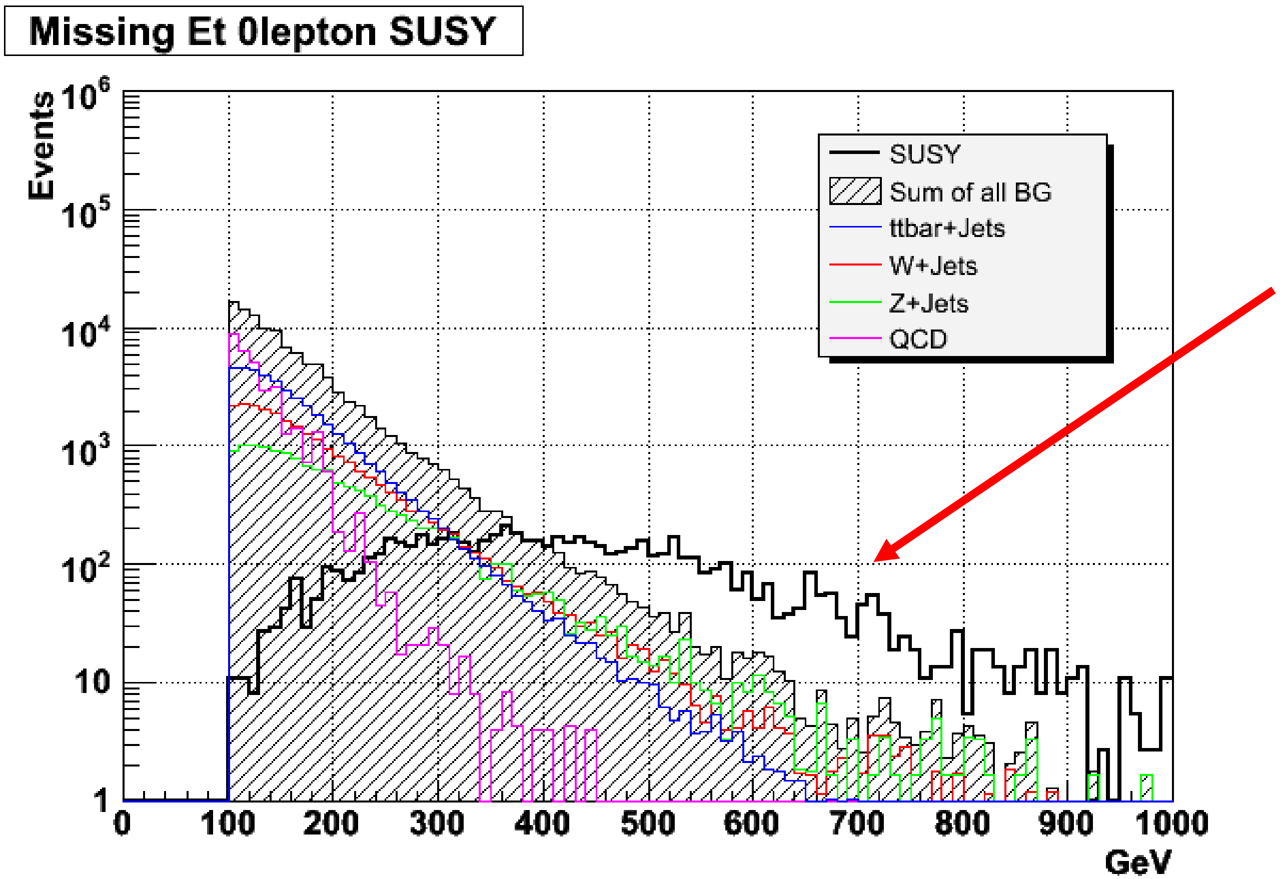


KK Spectrum and their decays.

Can mimic supersymmetry! Careful measurements needed in all channels to tell the difference.

Matchev, Schmaltz, ‘02

Inferring Dark Matter



http://www.icepp.s.u-tokyo.ac.jp/~kenta/analysis.html

This tail in large missing energy at the collider infers existence of dark matter.

Many other channels confirm it, and confirm LSP from supersymmetry is the dark matter.

Not so fast!

Can the SUSY LSP found at the LHC really be the Dark Matter?

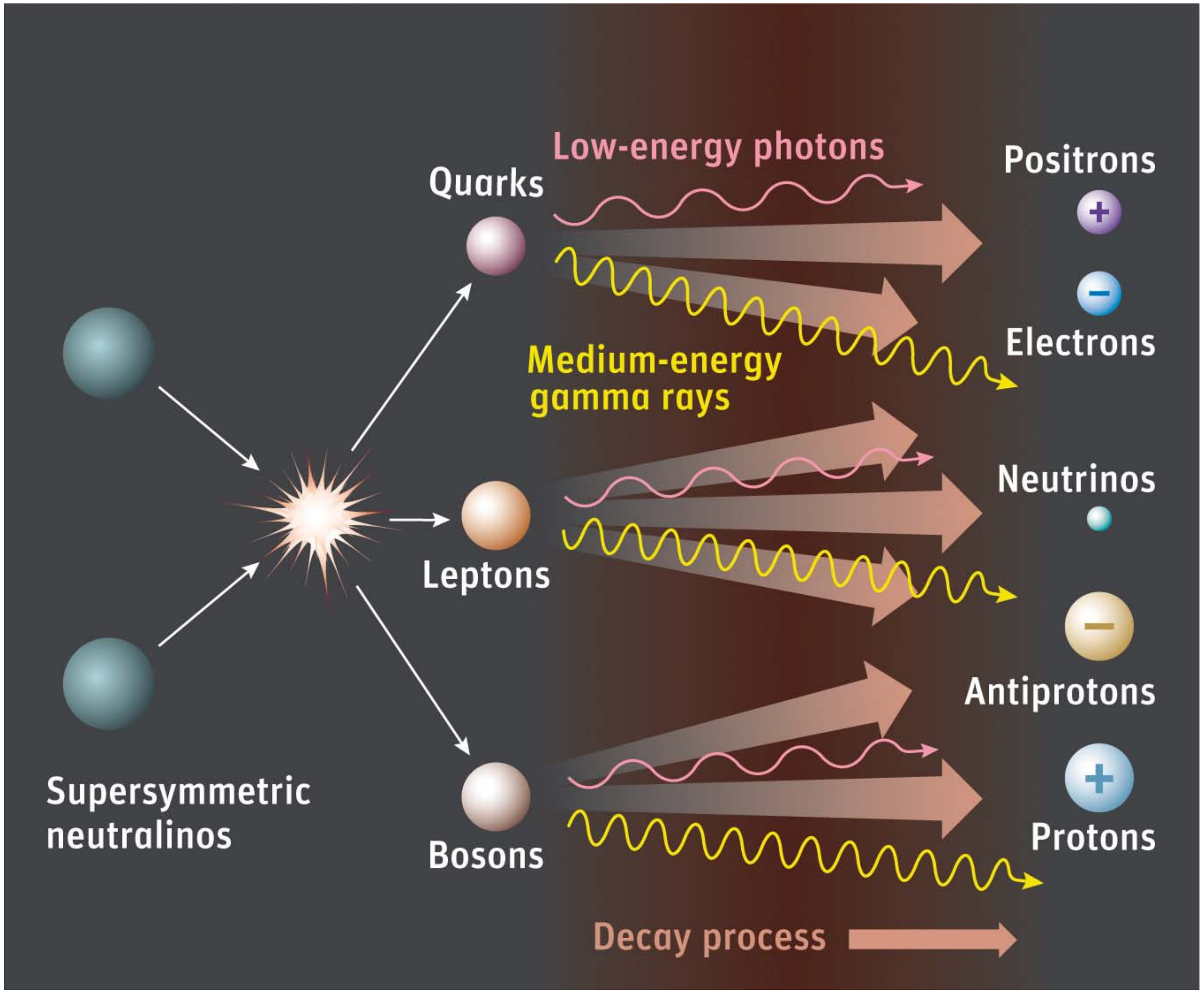
Interrelated issues involved:

- Is it stable on cosmological scales and not just $c\tau$~20 meters?

- Are its couplings consistent with proper relic abundance, Ω_M=23%?

Are there other experimental opportunities to confirm?

Confirming Evidence



Lots of dark matter particles floating around in our galaxy.

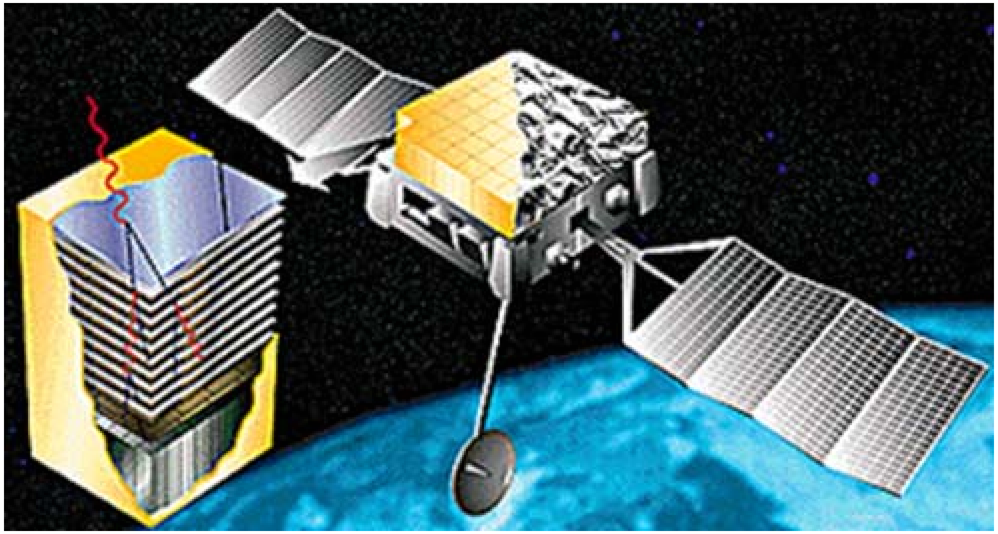
Sometimes they find each other and annihilate, producing positrons, antiprotons and photons (gamma rays).

Telescope / Gregg Dinderman

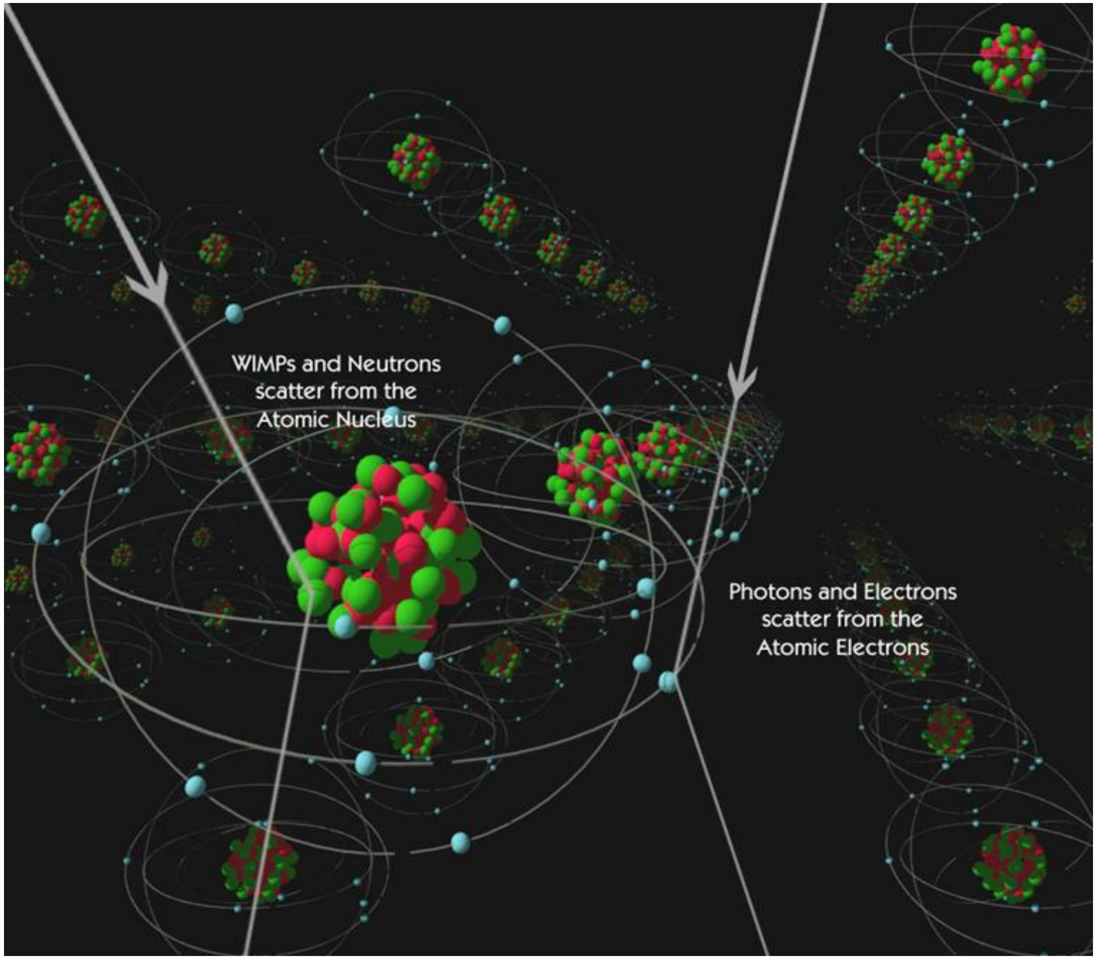
Annihilation into Photons

Launch any day now on Delta II rocket.

NASA/DOE/GLAST



Earth-based Direct Detection



CDMS is located more than 2000 ft below ground in Soudan Underground Laboratory in Minnesota.

Look for Dark Matter particle collisions with nuclei.

http://cdms.berkeley.edu

ROM2F/2008/07
April 2008

First results from DAMA/LIBRA and the combined results with DAMA/NaI

R. Bernabei [a,b], P. Belli [b], F. Cappella [c,d], R. Cerulli [e], C.J. Dai [f], A. d'Angelo [c,d], H.L. He [f], A. Incicchitti [d], H.H. Kuang [f], J.M. Ma [f], F. Montecchia [a,b], F. Nozzoli [a,b], D. Prosperi [c,d], X.D. Sheng [f], Z.P. Ye [f,g]

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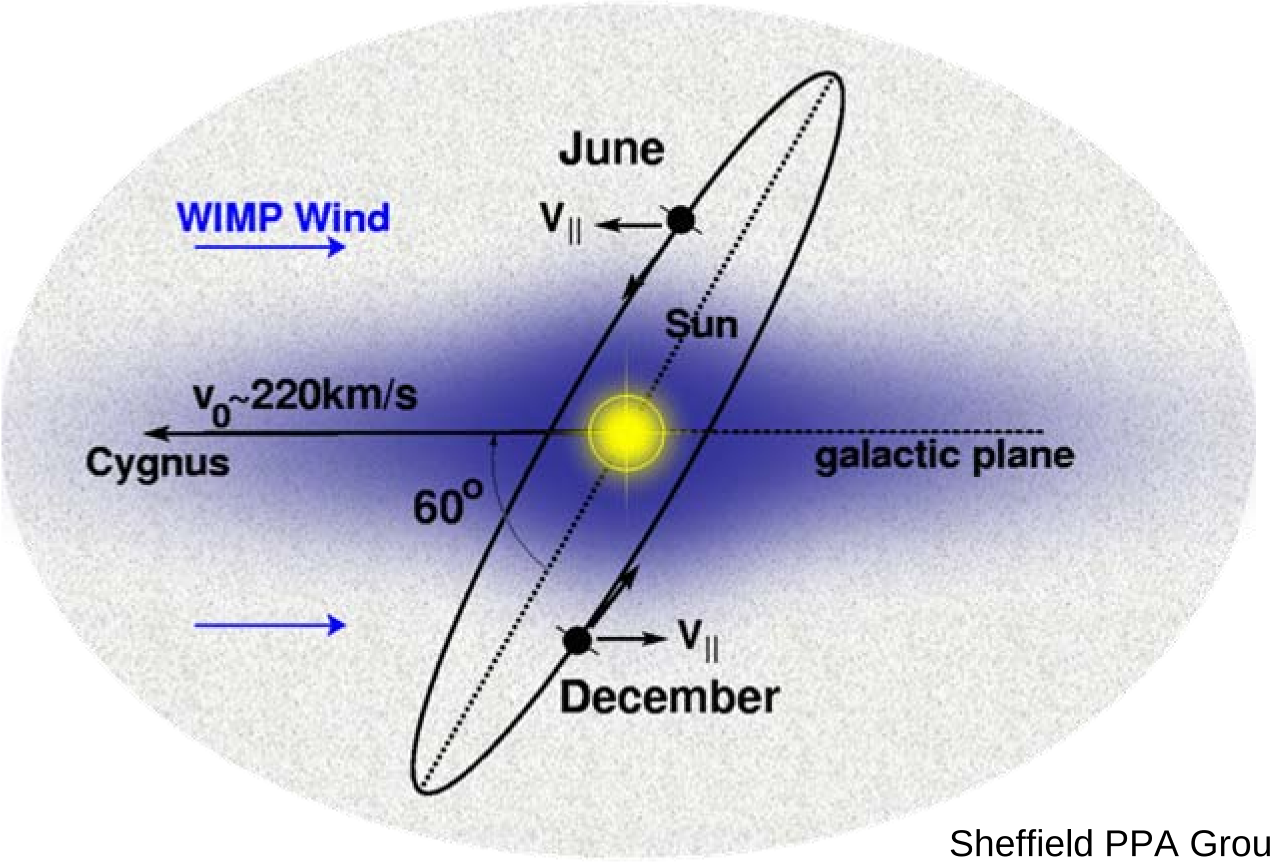
[g] *University of Jing Gangshan, Jiangxi, China*

Abstract

The highly radiopure $\simeq$ 250 kg NaI(Tl) DAMA/LIBRA set-up is running at the Gran Sasso National Laboratory of the I.N.F.N.. In this paper the first result obtained by exploiting the model independent annual modulation signature for Dark Matter (DM) particles is presented. It refers to an exposure of 0.53 ton$\times$yr. The collected DAMA/LIBRA data satisfy all the many peculiarities of the DM annual modulation signature. Neither systematic effects nor side reactions can account for the observed modulation amplitude and contemporaneously satisfy all the several requirements of this DM signature. Thus, the presence of Dark Matter particles in the galactic halo is supported also by DAMA/LIBRA and, considering the former DAMA/NaI and the present DAMA/LIBRA data all together (total exposure 0.82 ton$\times$yr), the presence of Dark Matter particles in the galactic halo is supported at 8.2 σ C.L..

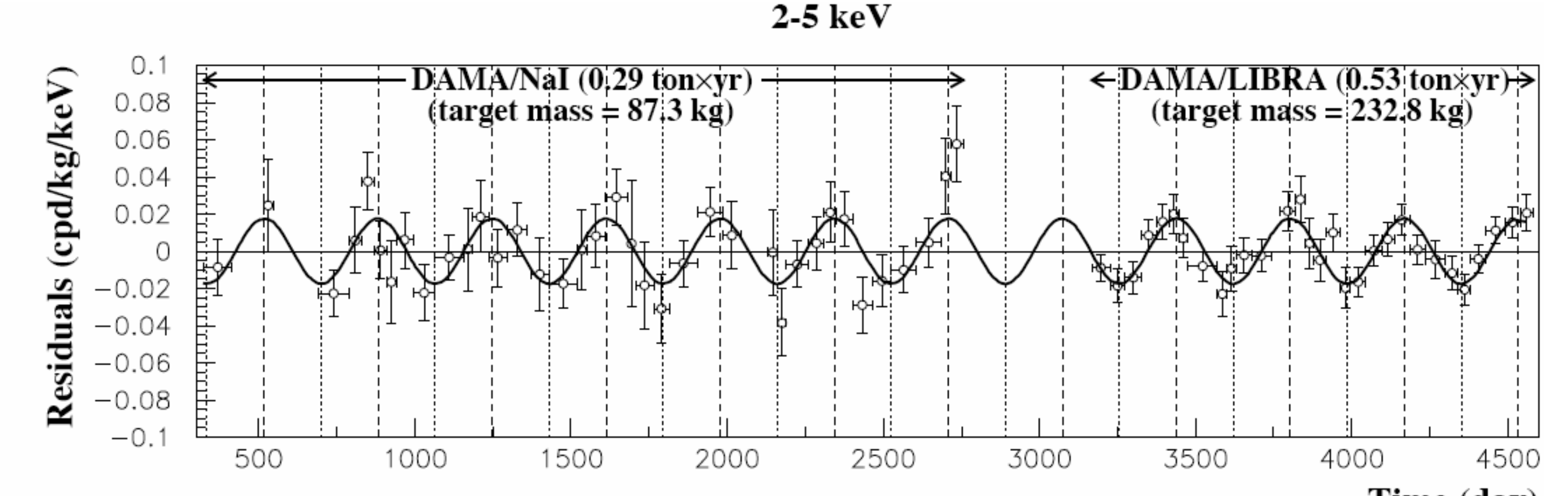
Annual Modulation of Signal



Sheffield PPA Group

Flux for interaction is different when earth traveling against or with the “WIMP wind”.

DAMA Data



Bernabei et al., ‘08

Controversial because hard to mesh with other non-signals (CDMS, etc), and no separation of nuclei recoil from atomic interactions.

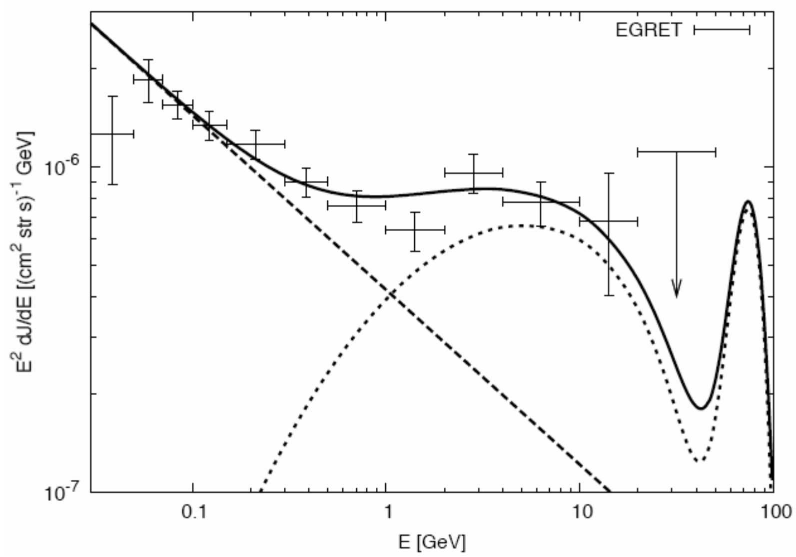
Gravitino Dark Matter

DAMA is not the only “anomaly” in experiment.

Previous photon and positron experiments also are challenging to explain purely by regular astrophysics.

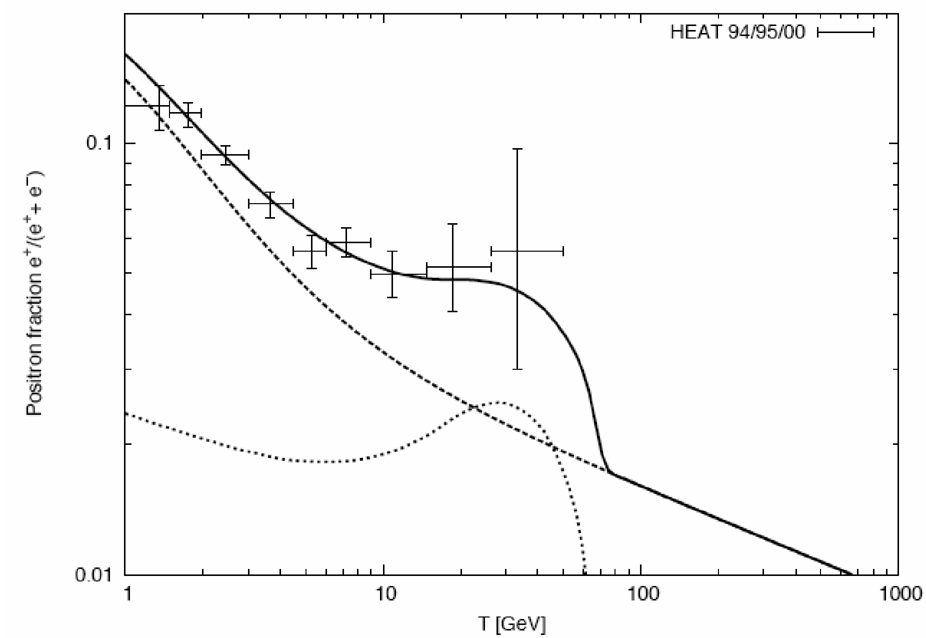
New supersymmetry idea by Buchmueller, Covi, Hamaguchi, Ibarra, and Yanagida: heavy gravitino dark matter.

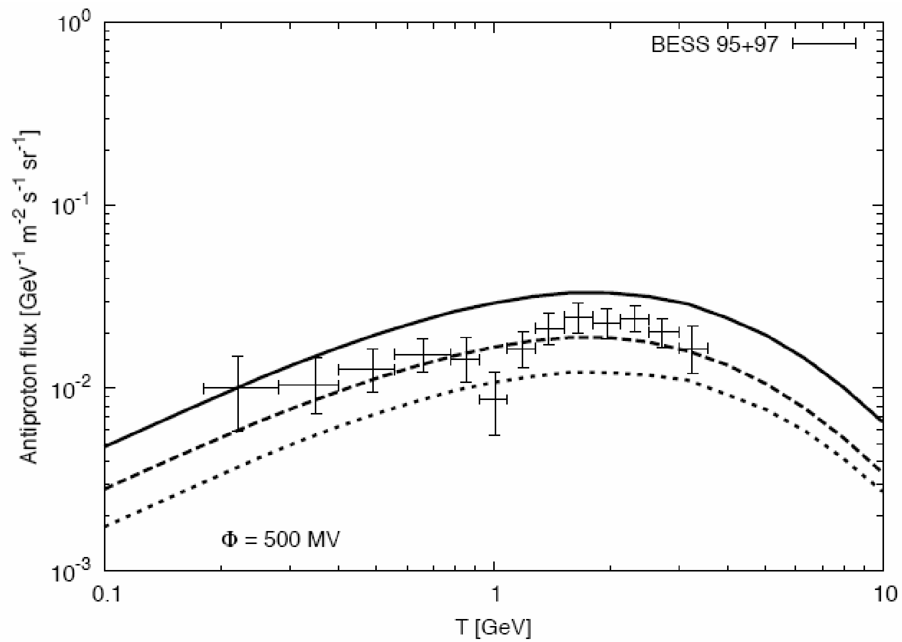
Gravitino -> $Z\nu$, W^+e^- and W^-e^+ (lifetime greater than age of the universe -- gravitino is dark matter).



Indirect Detection

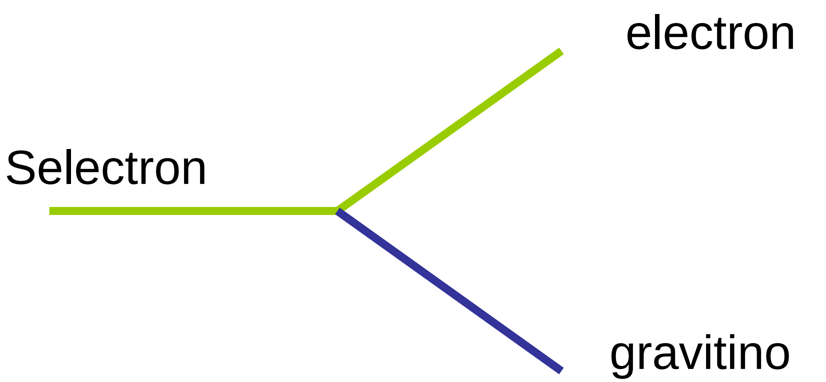
Gravitino decays to $Z\nu$, W^+e^- and W^-e^+ lead to many photons and anti-matter (positrons and antiprotons).



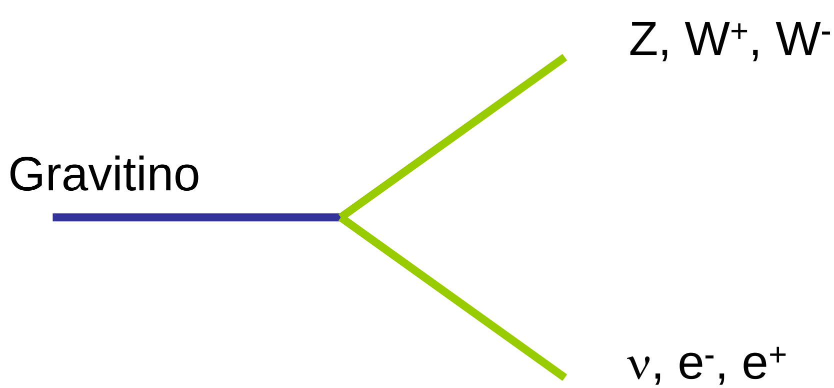


Ibarra, Tran, '08

Important Decays for Colliders

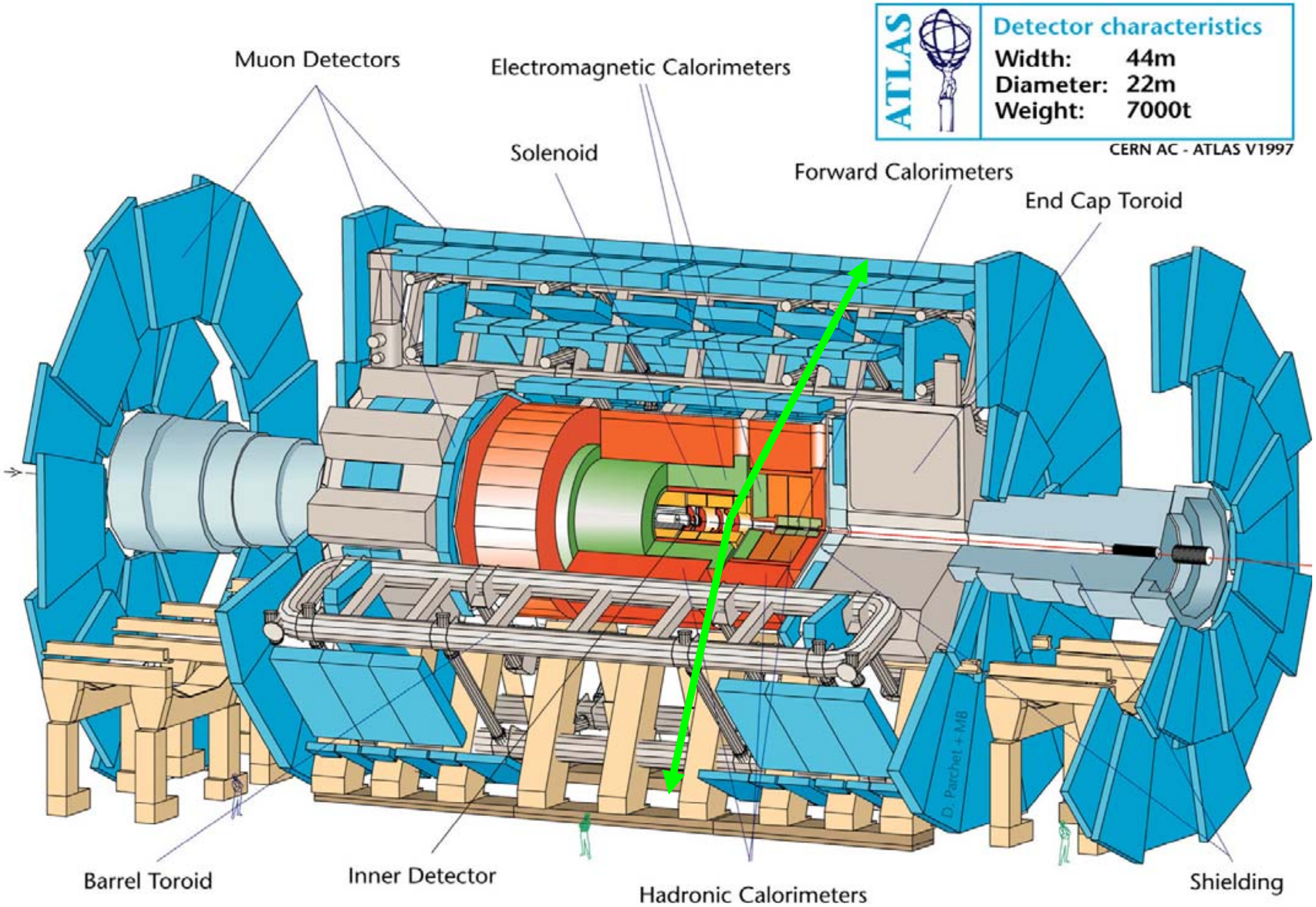


Lifetime of this decay can be greater than the detector size, but is smaller than age of universe.



Lifetime of this decay is much longer than the age of the universe -- gravitinos can be the dark matter.

Sleptons Traversing Detector



Very massive, slow moving, objects.

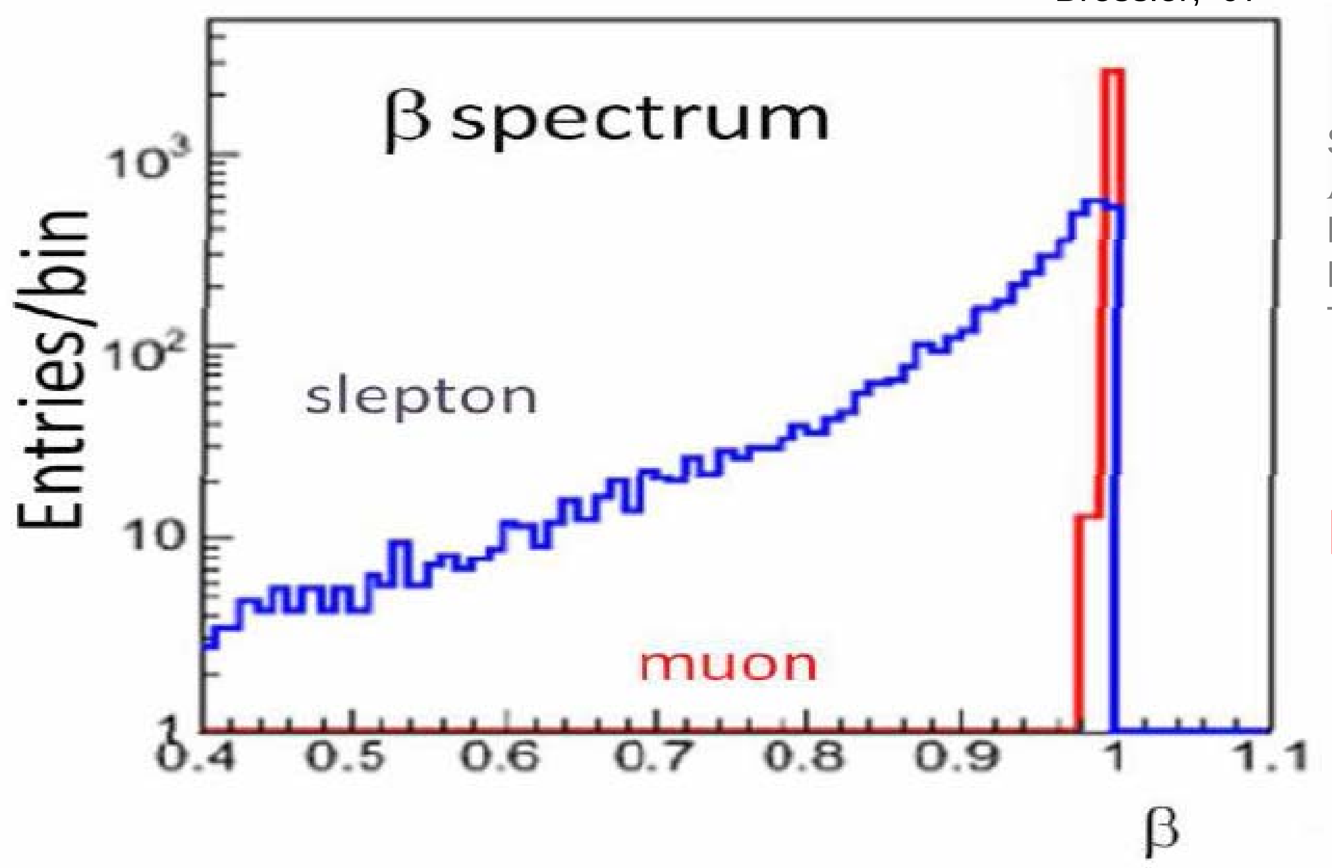
Takes "long time" to get out to the muon chamber.

Keep track of timing.

Collisions every 25ns (7.5 meters) -- 3 events in detector at any given time.

Slowness of Sleptons

Bressler, '07



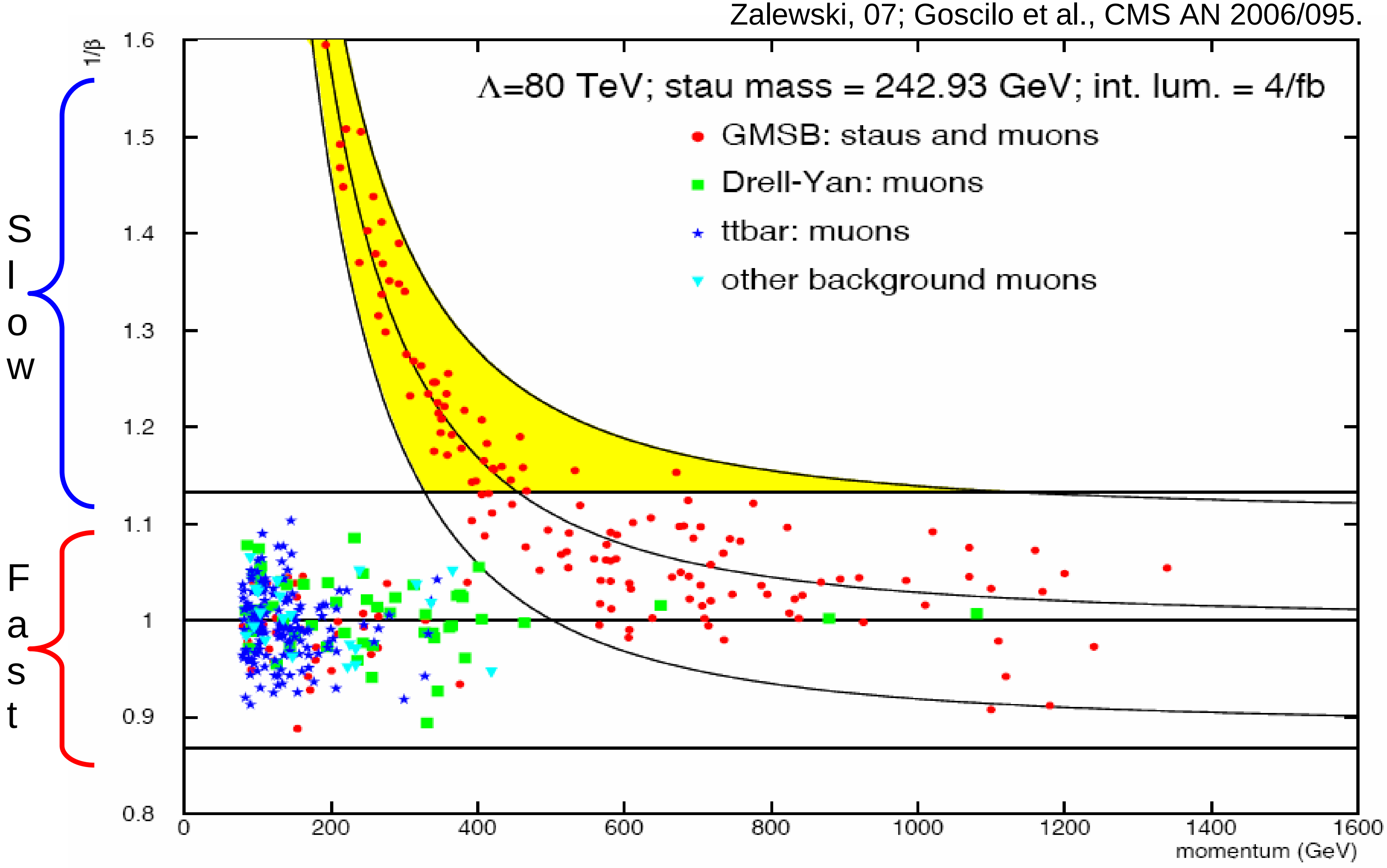
Sign(μ)=+
Λ=30 TeV
M=250 TeV
N_5=3
Tanβ=5

$M_{slepton}$~100 GeV

β is velocity in "units of c", where β=1 means speed of light.

Measured 1/β distributions

Zalewski, 07; Goscilo et al., CMS AN 2006/095.



Discovery estimated within 670 pb^{-1} (1 year)