Title: Dark Matter at Colliders

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Abstract: Although the fact that a large fraction of the matter in the universe is non-baryonic is beyond doubt, the exact composition of the dark matter is still shrouded in mystery. Using ultra-sensitive detectors in the deep underground laboratories, physicists are attempting to directly detect dark matter particles streaming from space. At colliders, physicists hope to manufacture large numbers of dark matter particles and study their properties. I will first use an effective field theory approach to demonstrate the power of colliders by comparing these two approaches. I will then describe the recent efforts on measuring dark matter properties at colliders and how imminent discoveries may change our fundamental understanding of physics and the universe.

Dark Matter at Colliders

Yang Bai

Theoretical Physics Group, SLAC National Accelerator Laboratory

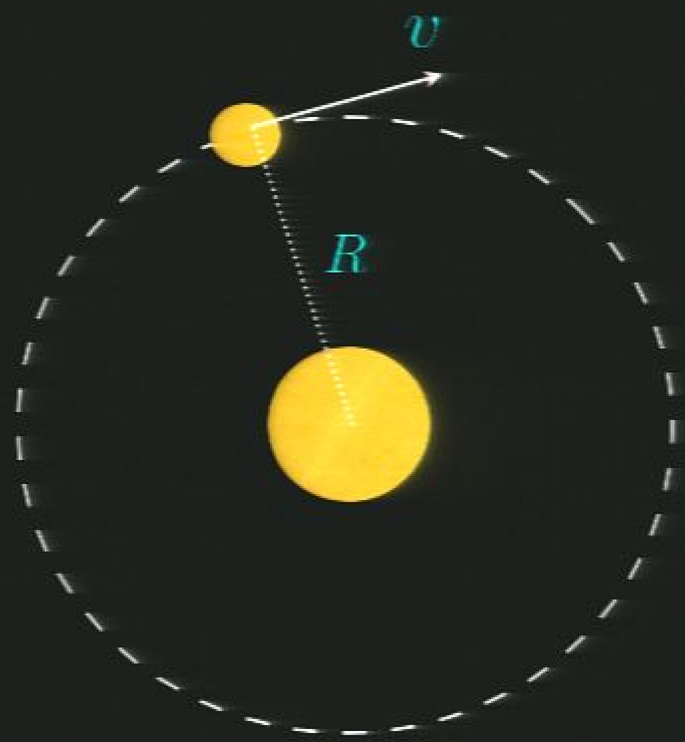
PI, Feb 11, 2011

Image Credit: NASA/Swift
Science Team/Stefan Immler

It seems that we can see just where the mass is

But, the truth is just the opposite

Using the Doppler shift, we can measure the galaxy 'rotation curve' $v(R)$

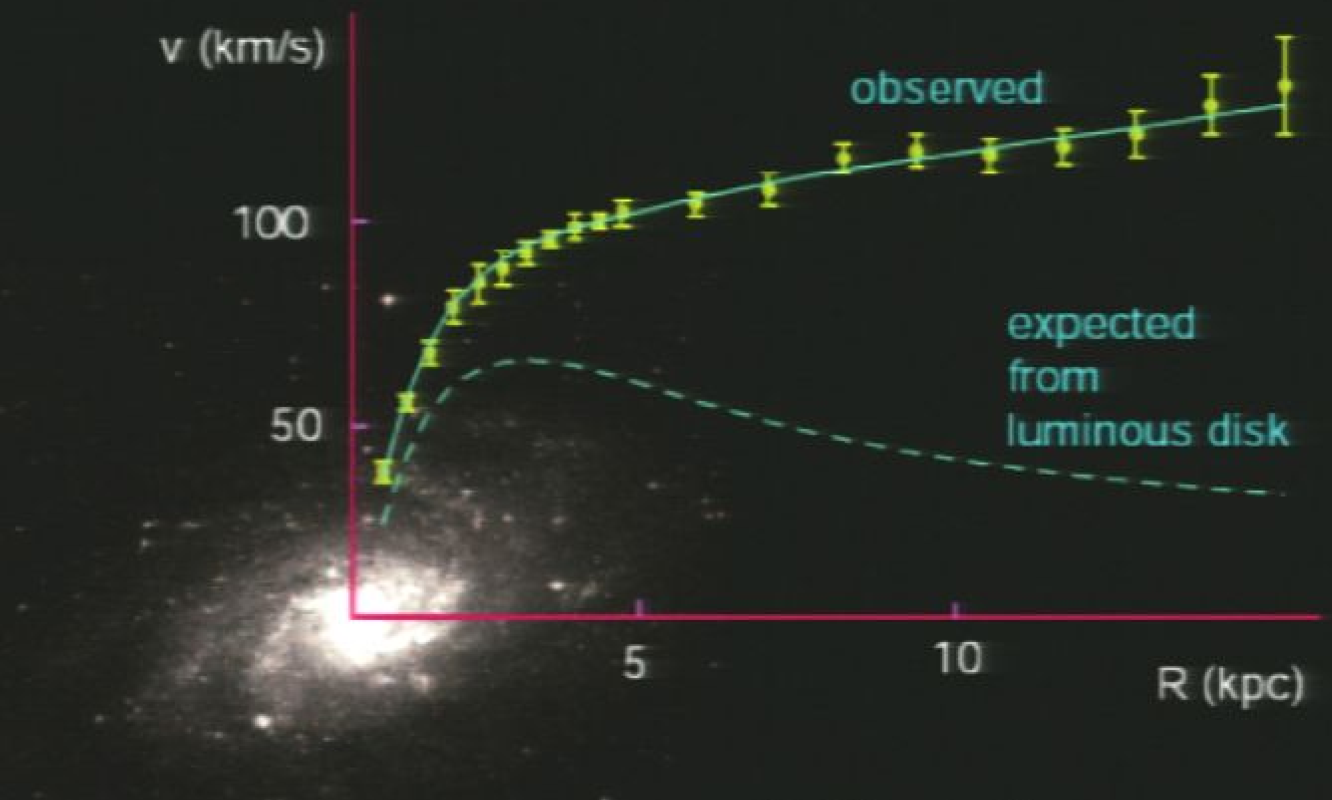


From Kepler's law, we expect

$$T^2 \sim R^3 \quad \text{or} \quad v \sim 1/\sqrt{R}$$

assuming all the mass of galaxies come from the region where stars are visible

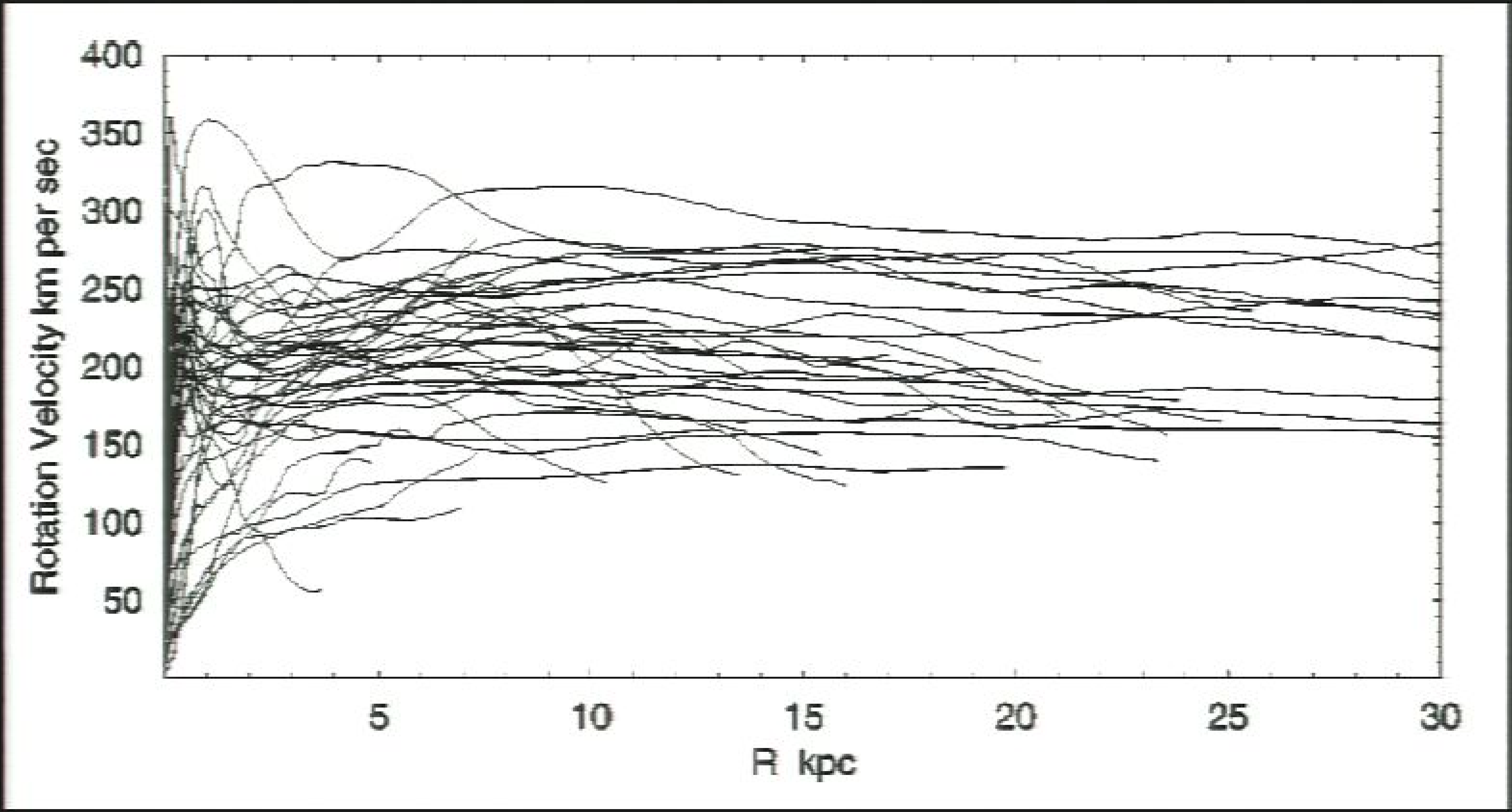
Galaxy Rotation Curve



M33 rotation curve

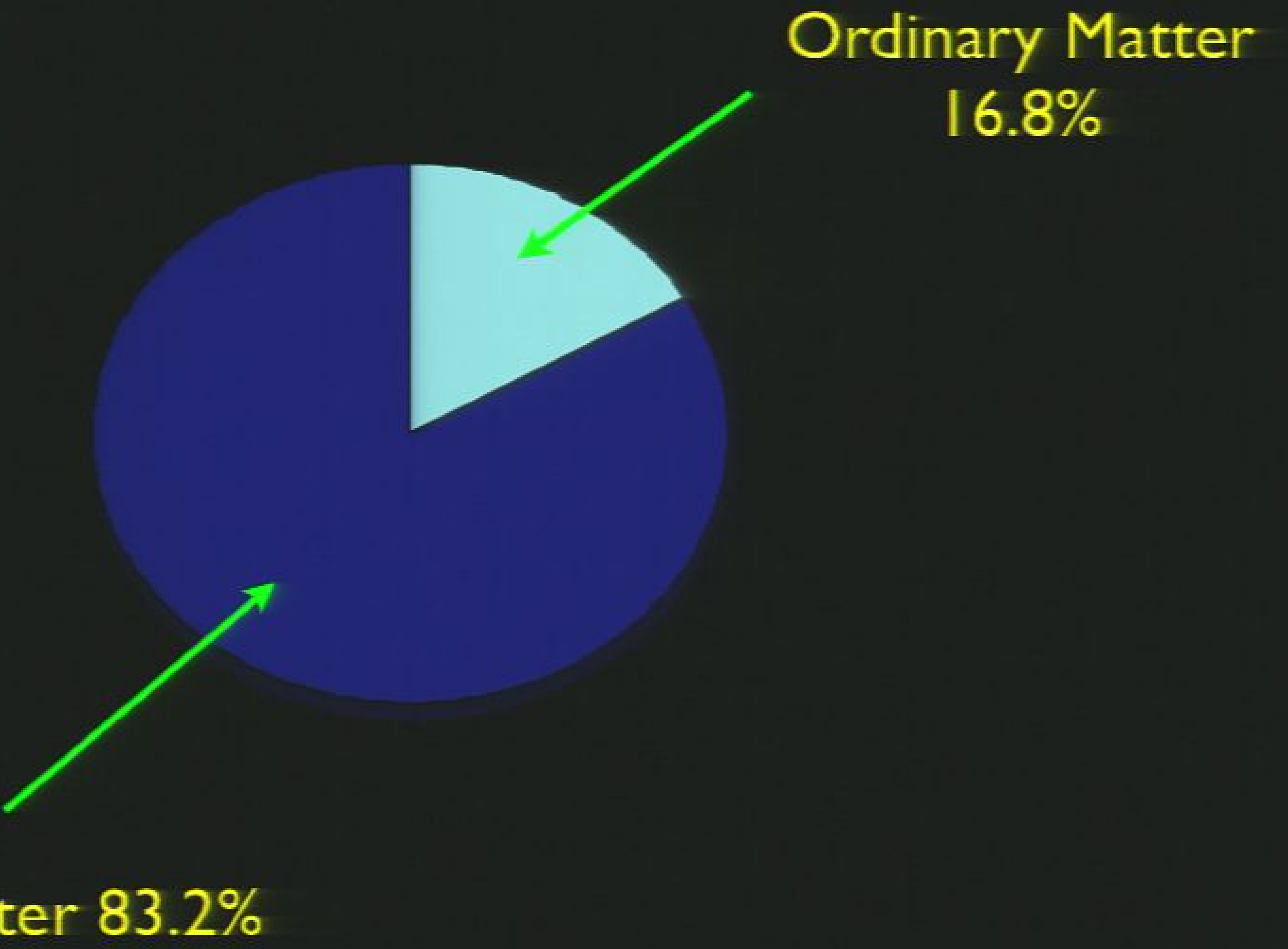
Missing matter exists beyond the visible star region

Here are rotation curves for more galaxies



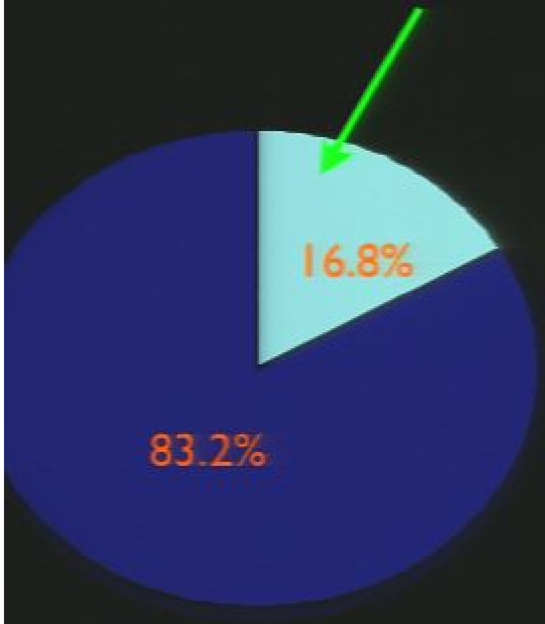
Sofue and Rubin

Quantitatively, we have the *matter* pie of our universe



From WMAP

molecular, atom, electron, nucleus, proton, neutron, quarks



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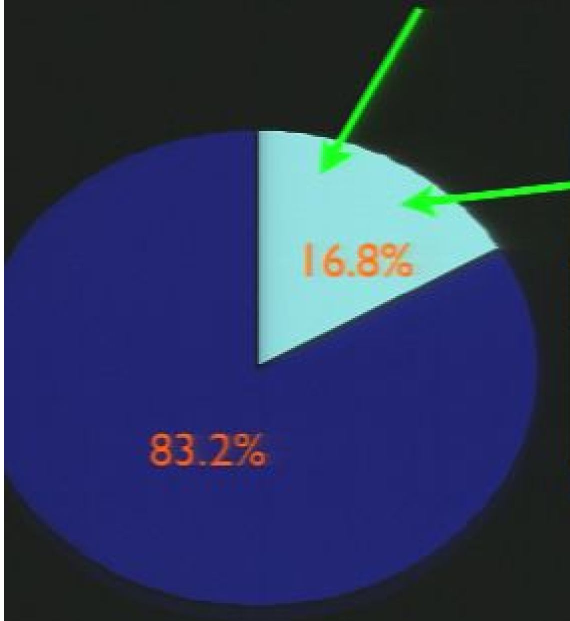
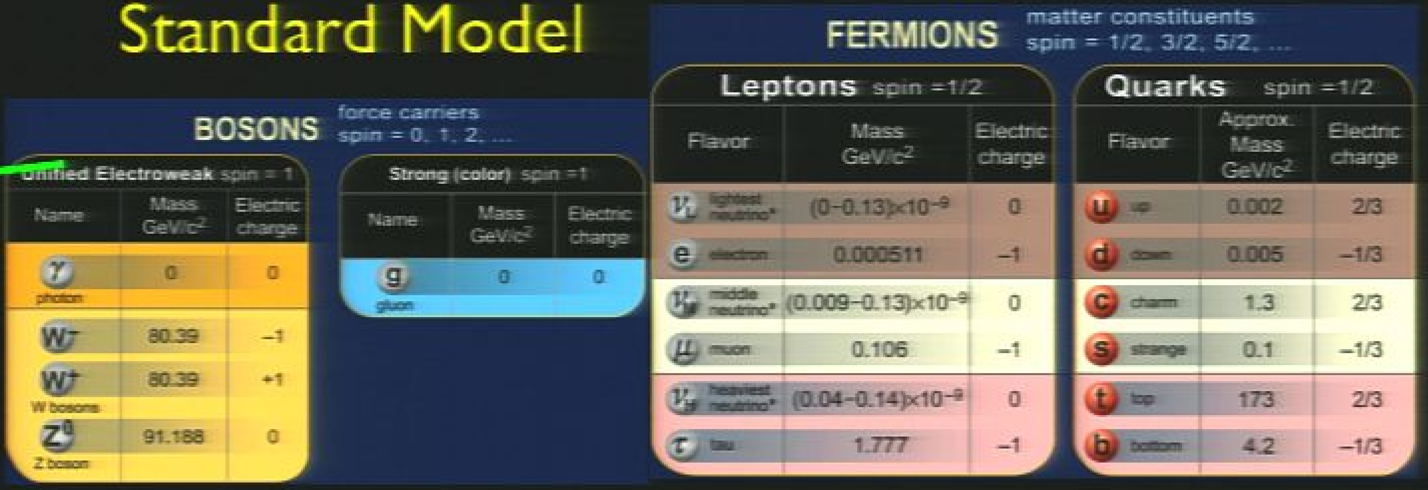


Standard Model



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

Unified Electroweak spin = 1

Name	Mass GeV/c^2	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/c^2	Electric charge
g gluon	0	0

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

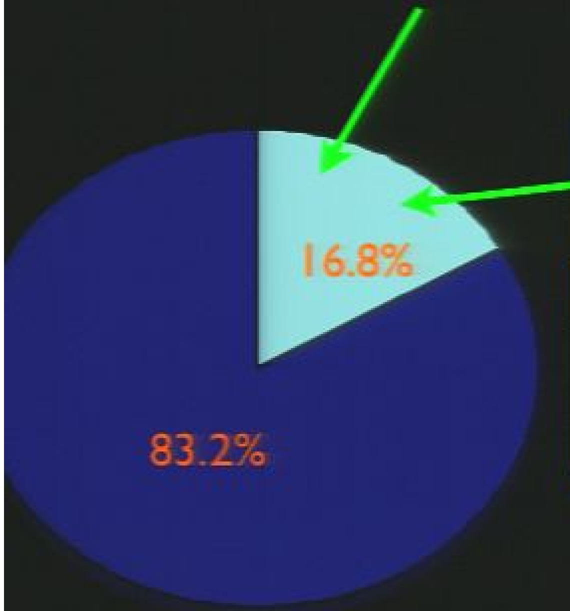
Leptons spin = 1/2

Flavor	Mass GeV/c^2	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/c^2	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

molecular, atom, electron, nucleus, proton, neutron, quarks



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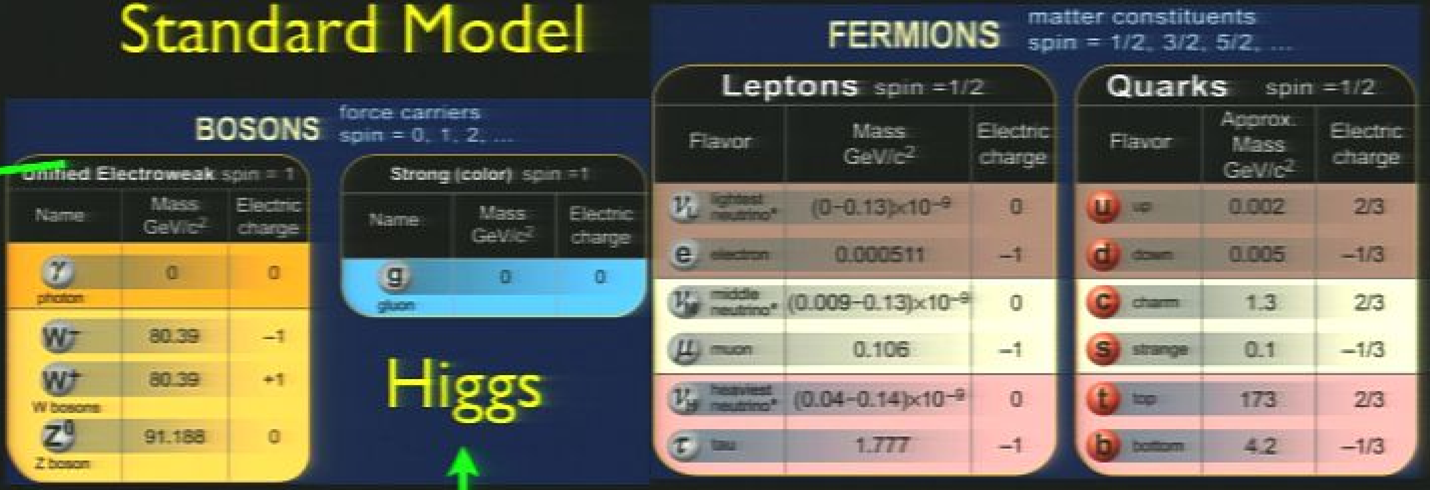

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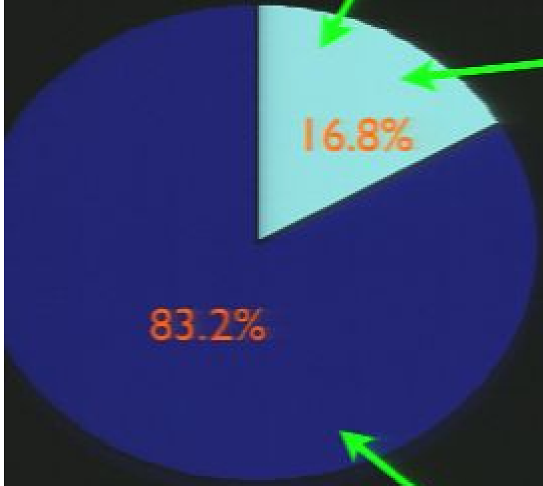
Higgs

electroweak symmetry breaking

molecular, atom, electron, nucleus, proton, neutron, quarks



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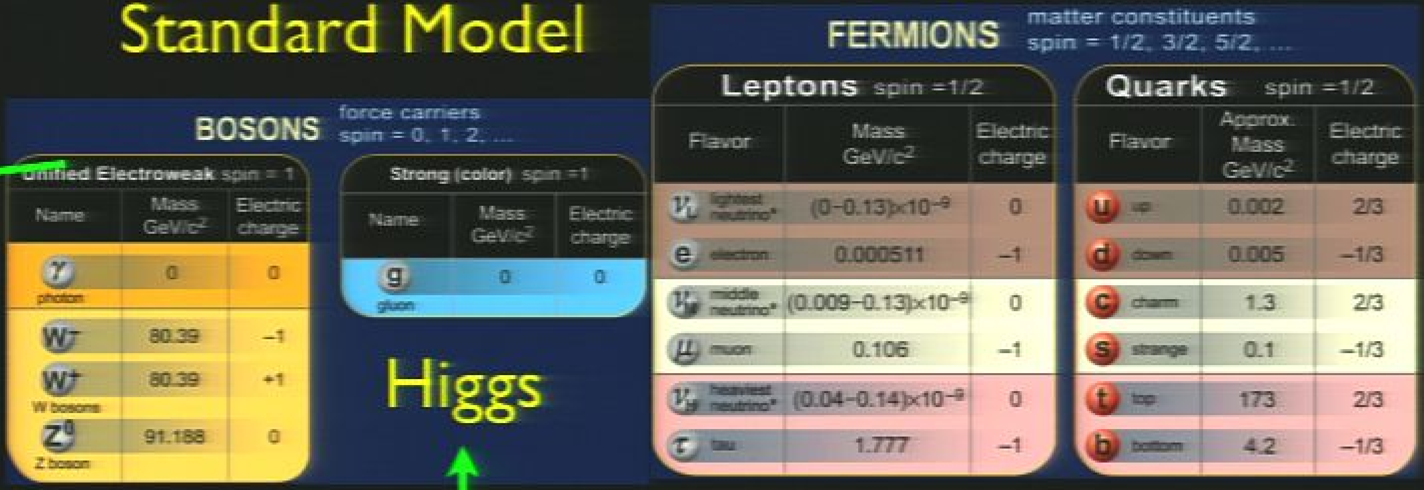

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Higgs

electroweak symmetry breaking

Dark Matter Sector ???

We have many fascinating questions to ask:

Is dark matter an elementary particle ?

Is the dark matter particle a fermion or a boson ?

How many particles in the dark matter sector ?

How does the dark matter particle interact with ordinary matter ?

Can we produce and store dark matter particles ?

……

To analyze those questions, we must first answer:

What particle is dark matter made of ?

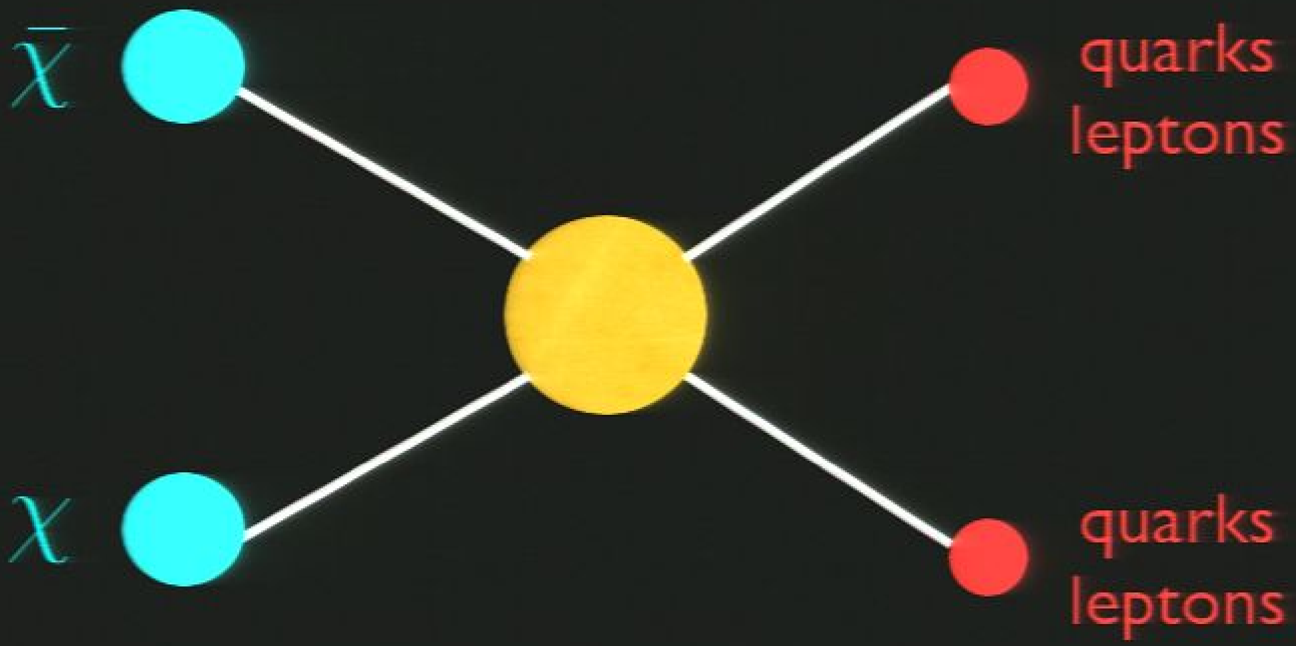
We need to have a particle that is:

- Dark: neutral; no electromagnetic charge
- Stable: has a lifetime of the age of our universe
- Heavy: relative to other elementary particles

Bahcall named this particle as

Weakly Interacting Massive Particle (WIMP)

I further add another property for WIMPs



We can then calculate the relic density of WIMPs

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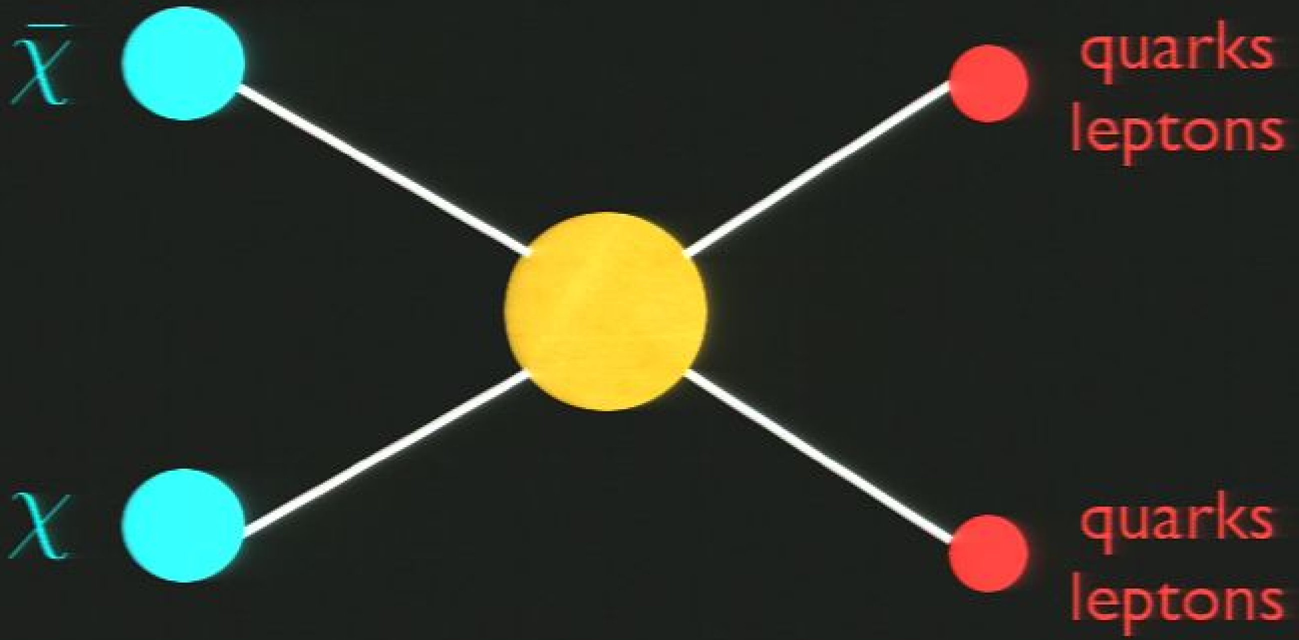
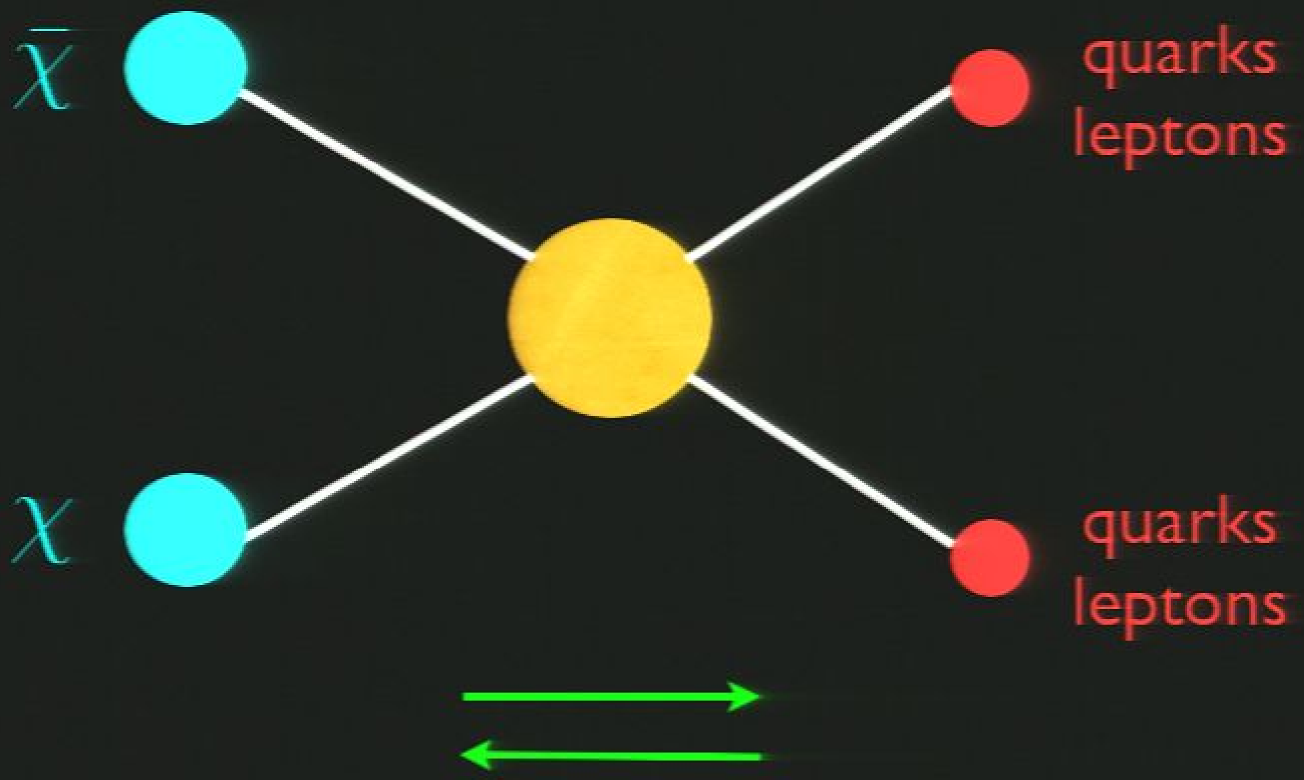
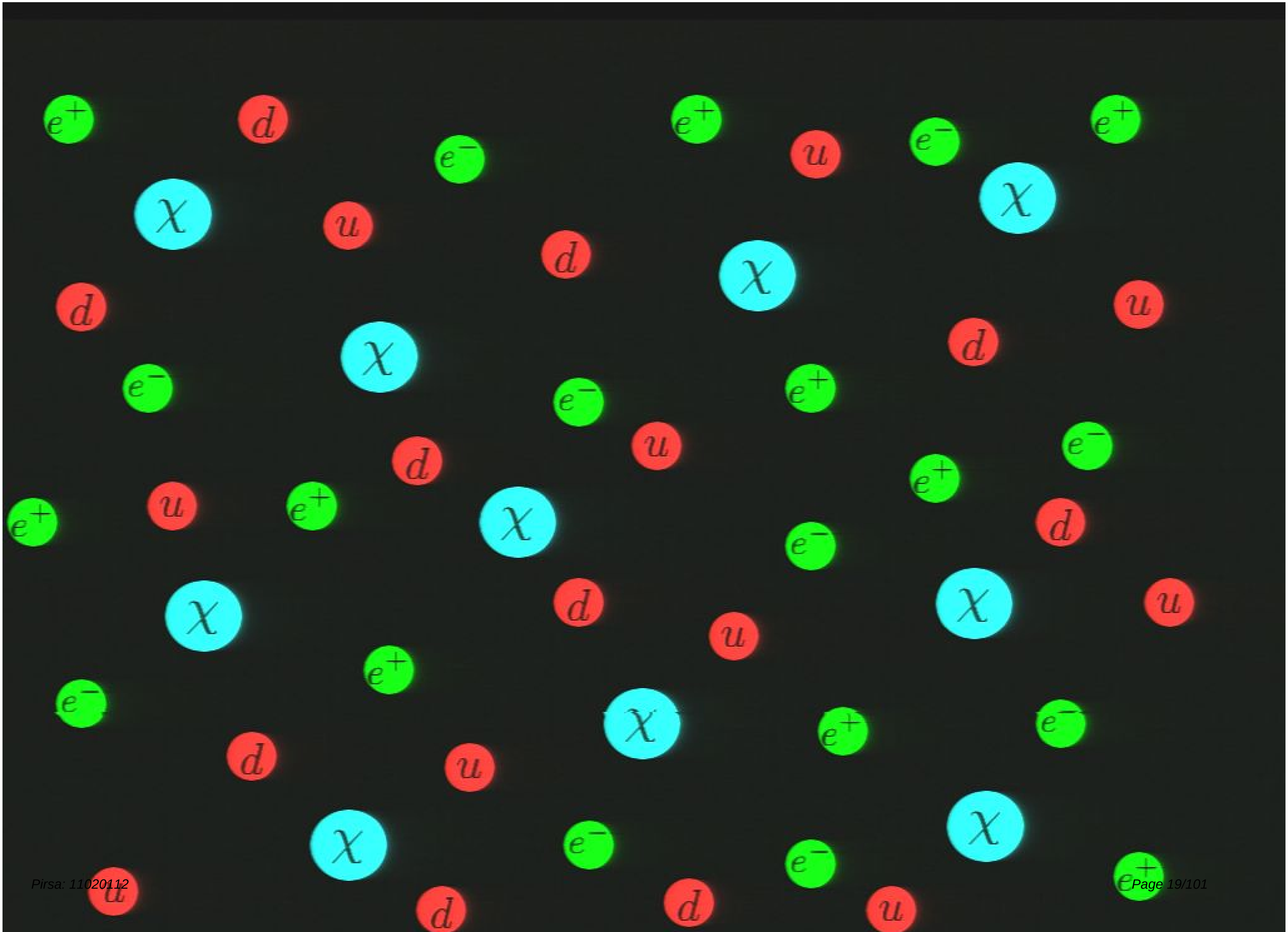


We can then calculate the relic density of WIMPs

Just after the Big Bang, dark matter were in thermal equilibrium with ordinary matter

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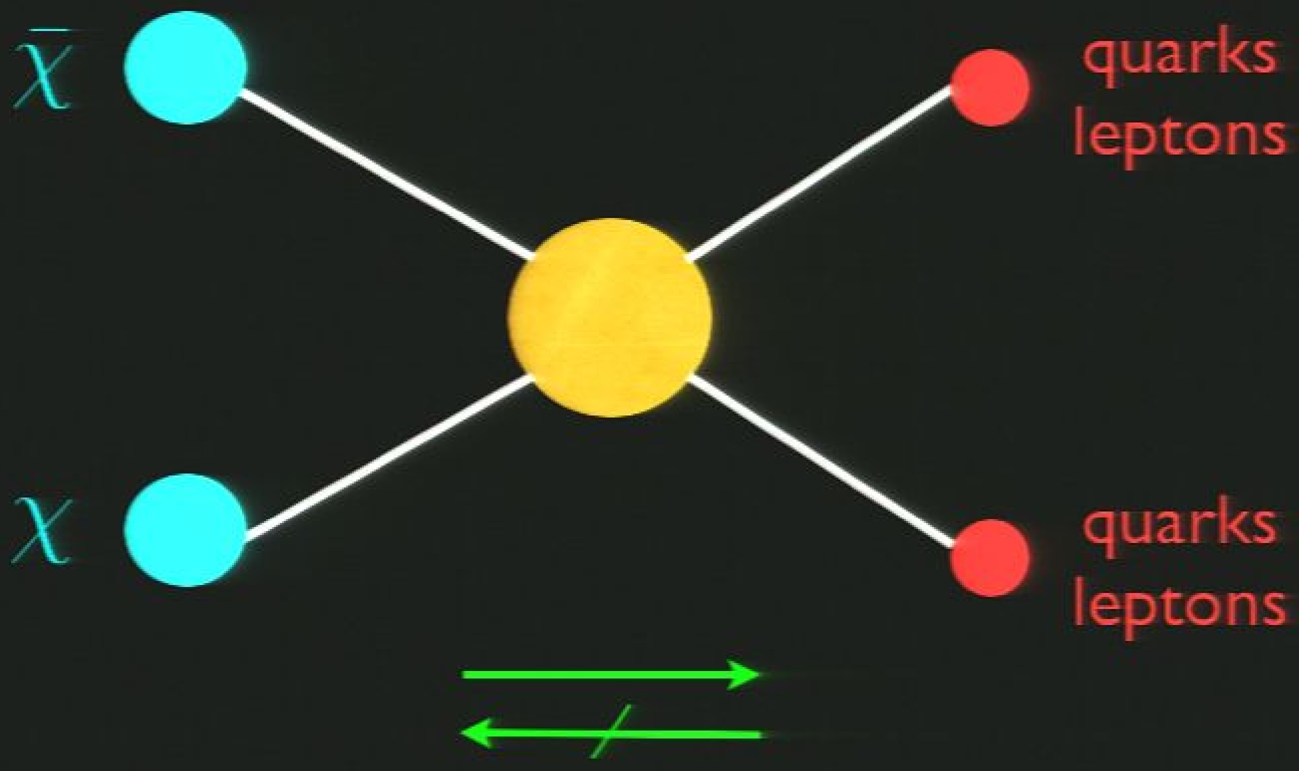
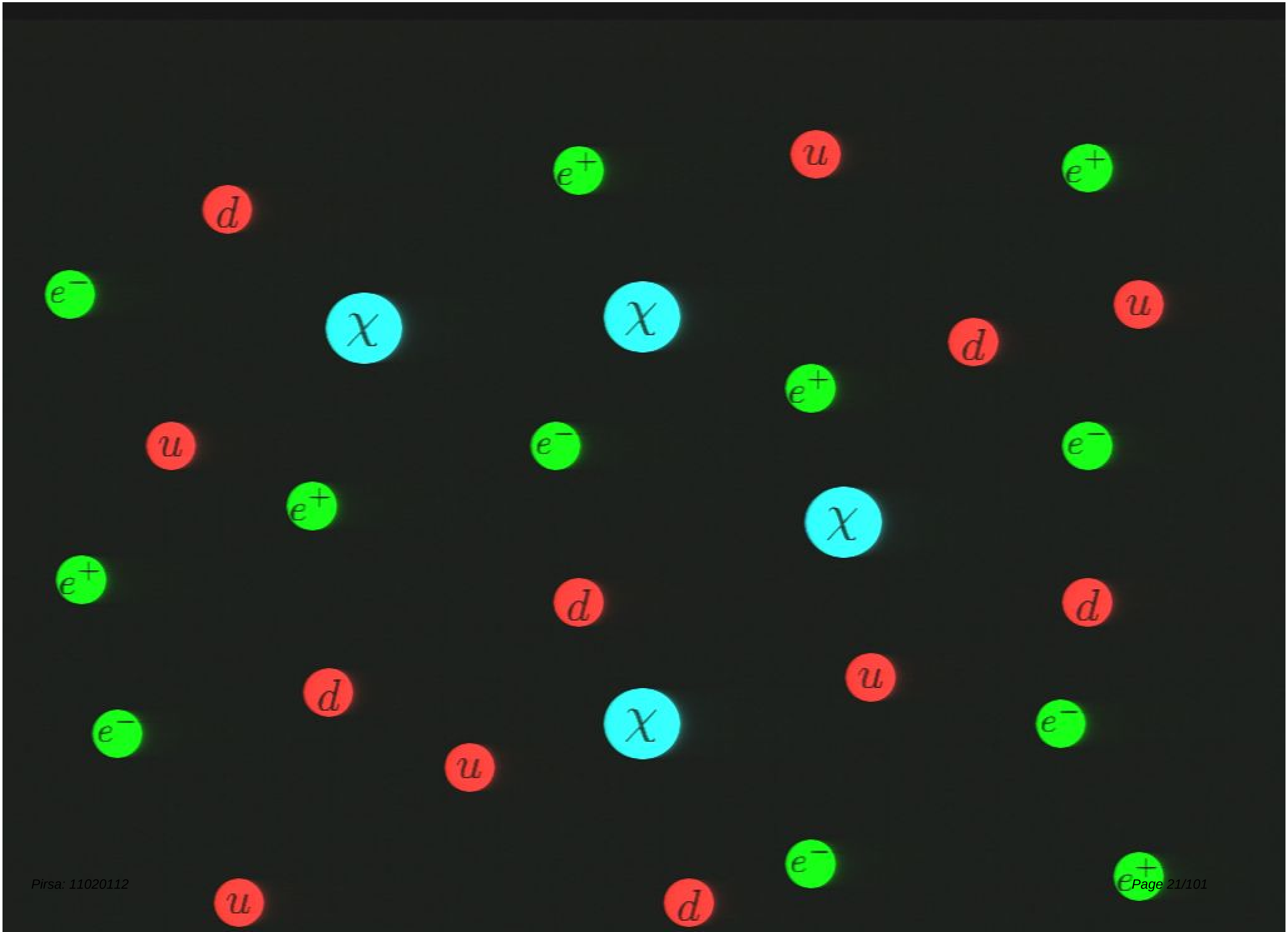
As the temperature drops below the WIMP mass



The WIMP number density follows the Boltzmann distribution:

$$n \sim \left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T}$$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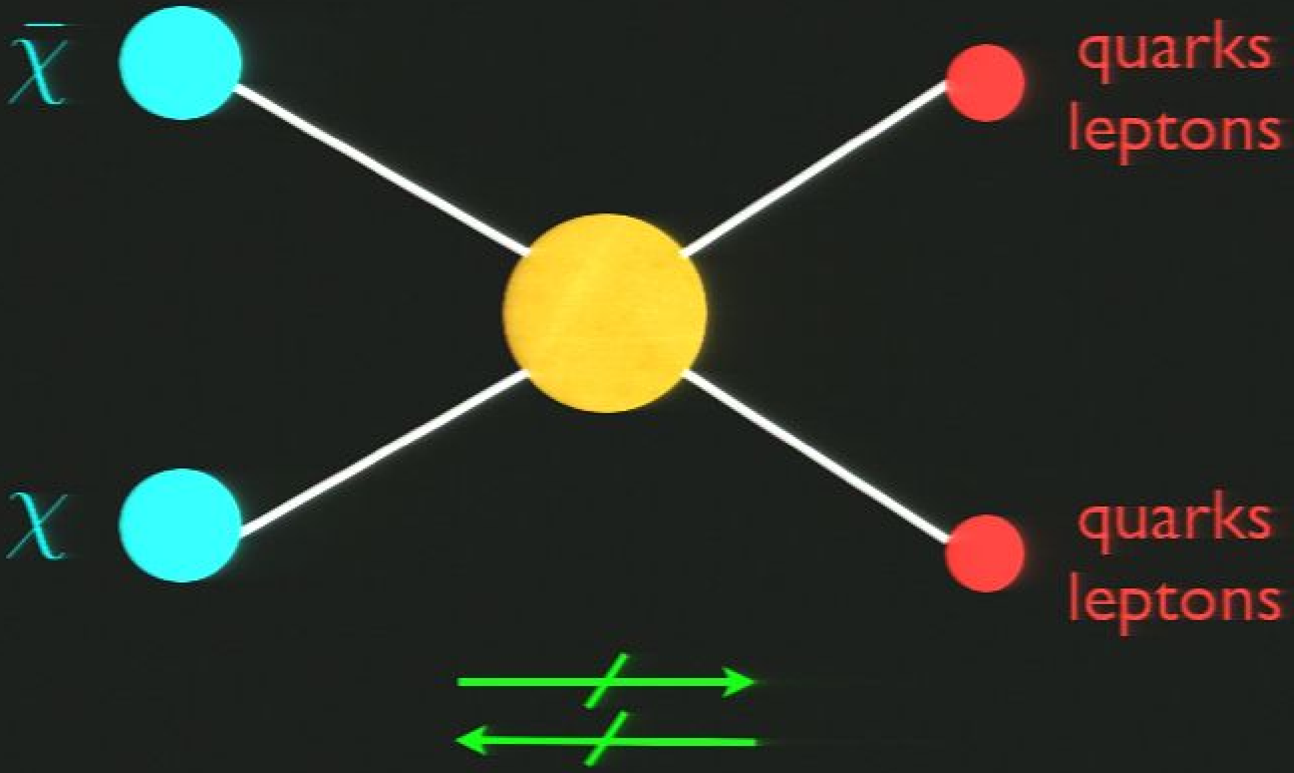
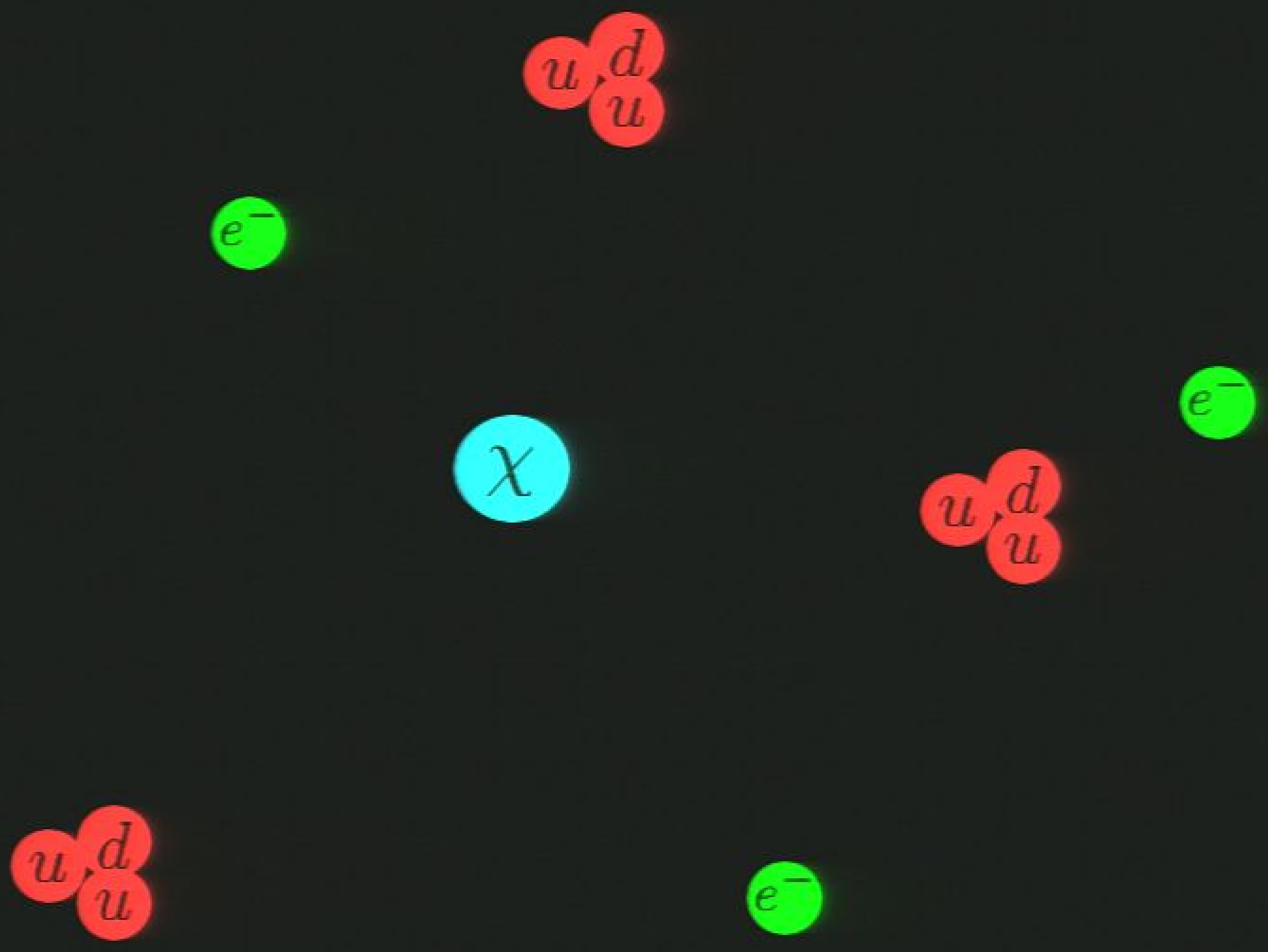
Eventually, as the universe expands, WIMPs can not find their partners to annihilate,



The WIMP relic density is 'frozen out'


u d u
e^-
e^-
χ
u d u
u d u
e^-

Quantitatively, solving the Boltzmann equation for the WIMP density, we have

$$\Omega_\chi = \frac{s_0}{\rho_c}\left(\frac{45}{\pi g_*}\right)^{1/2}\frac{x_f}{m_{\rm pl}}\frac{1}{\langle\sigma v\rangle}$$

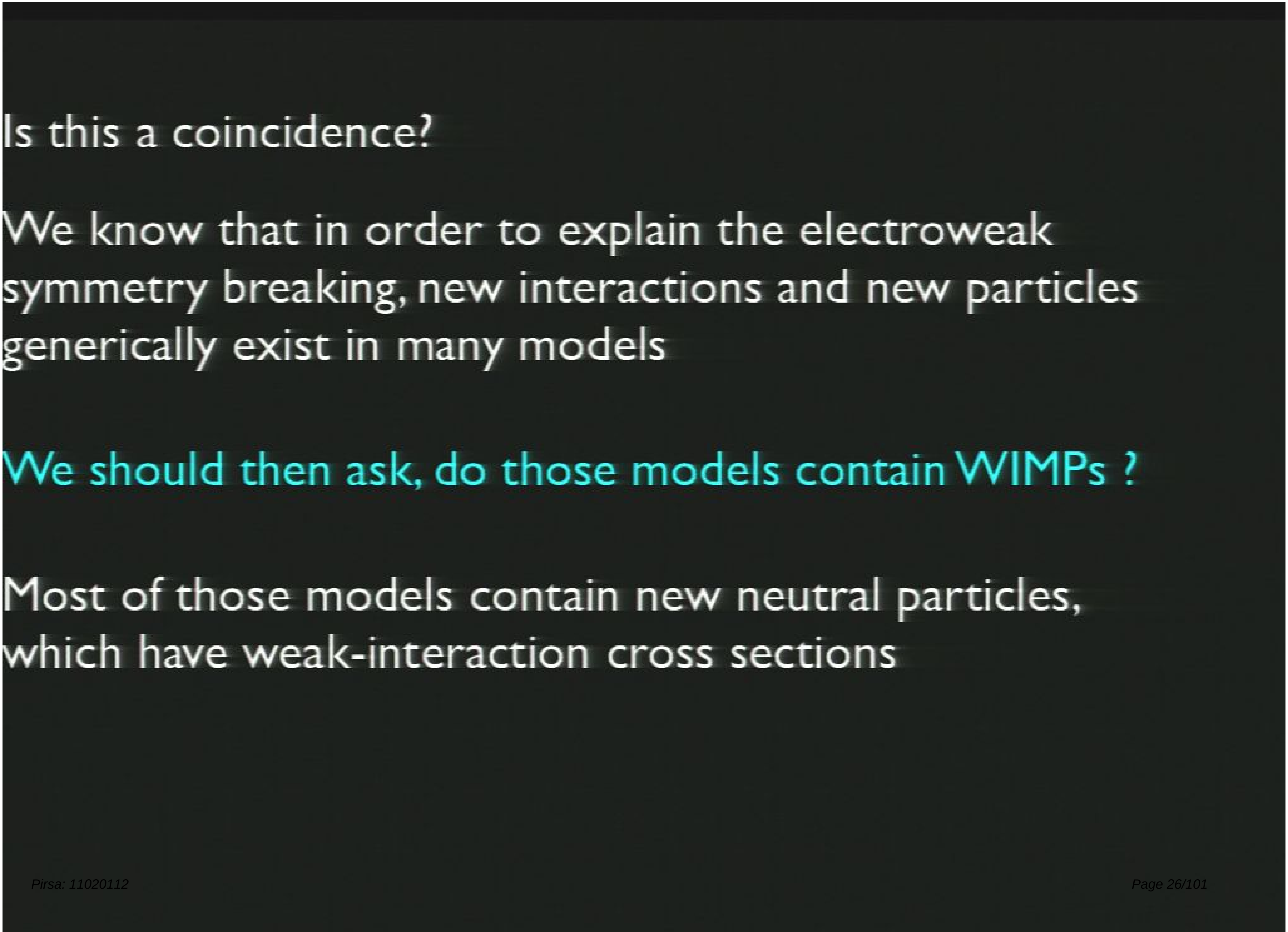
Putting in the numbers:

$$\langle\sigma v\rangle \approx 1\ \mathrm{pb} \approx \frac{\pi\alpha^2}{8m_\chi^2} \qquad \text{for } m_\chi = 100\ \mathrm{GeV}$$

This points to the length scale of weak interactions

Is this a coincidence?

We know that in order to explain the electroweak symmetry breaking, new interactions and new particles generically exist in many models



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We should then ask, do those models contain WIMPs ?

Most of those models contain new neutral particles, which have weak-interaction cross sections

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Our next question is whether there is a new stable neutral particle ?

Almost in every model of EWSB, there exists unbroken discrete symmetry to protect one neutral particle from decaying. Usually, such discrete symmetry is required for other reasons, e.g., to prevent rapid proton decay

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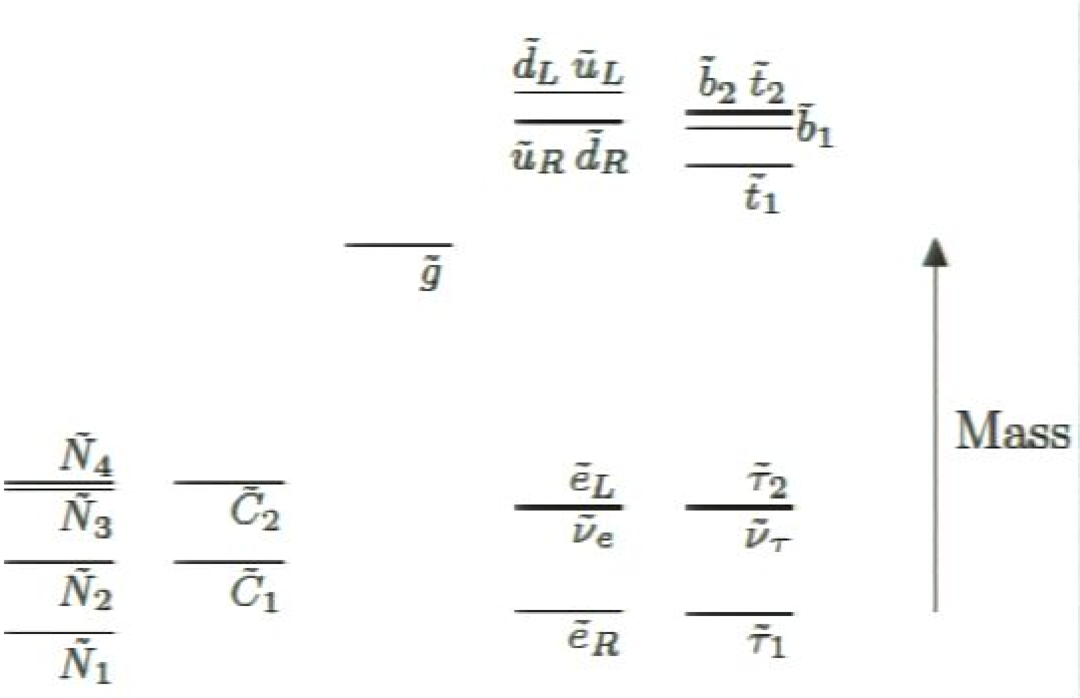
In the past few years, many new models based on extra dimension have been constructed. All of them also have WIMP candidates

As an elementary particle physicist, this is a fantastic news. We can then use the methods of particle physics to search for dark matter particles



However, without a specific mechanism to generate superparticle masses, there are hundreds of thousands of different spectra

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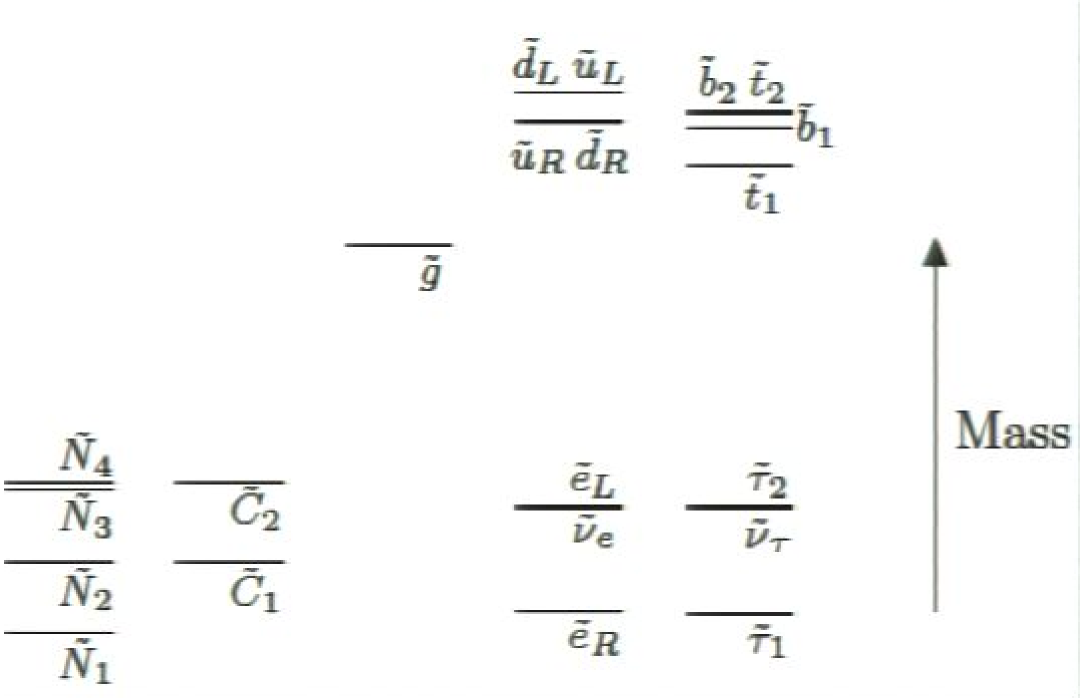

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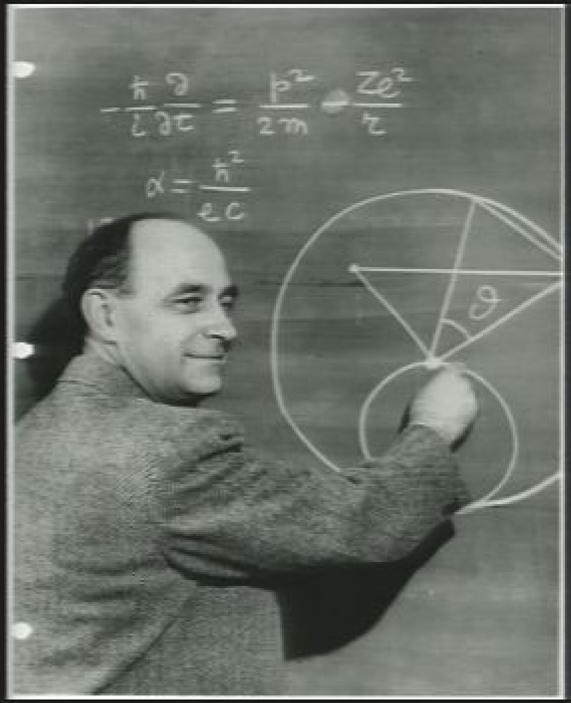
We need a better search strategy especially when the experimental probing energy is below or not too far above the dark matter mass

One lesson we can learn from the Fermi's theory of beta-decay

$$n \to p^{+} + e^{-} + \bar{\nu}_e$$



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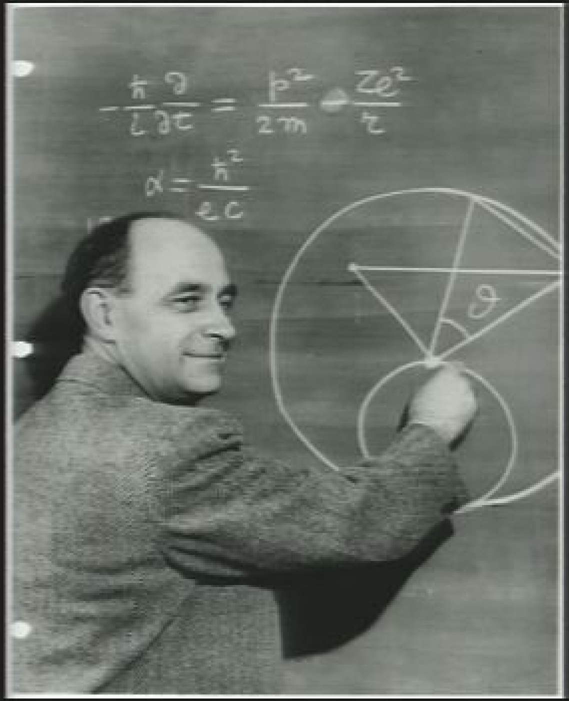
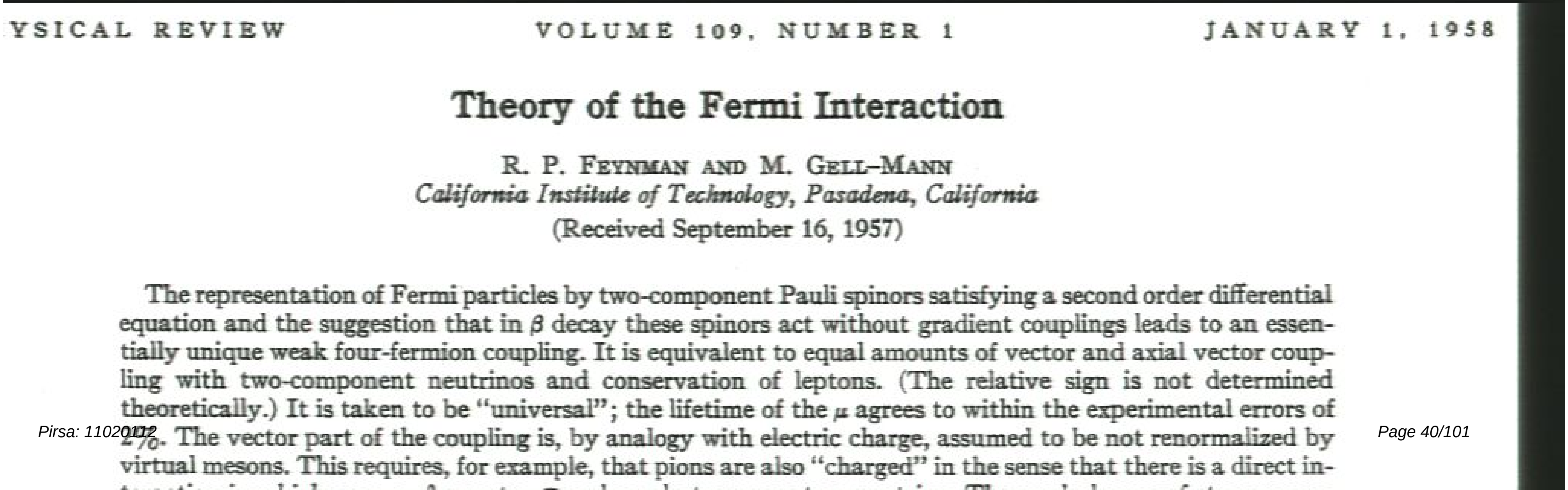
Feynman and Gell-Mann further deduced its V-A structure





YSICAL REVIEW VOLUME 109, NUMBER 1 JANUARY 1, 1958

Theory of the Fermi Interaction

R. P. Feynman and M. Gell-Mann
California Institute of Technology, Pasadena, California

(Received September 16, 1957)

The representation of Fermi particles by two-component Pauli spinors satisfying a second order differential equation and the suggestion that in β decay these spinors act without gradient couplings leads to an essentially unique weak four-fermion coupling. It is equivalent to equal amounts of vector and axial vector coupling with two-component neutrinos and conservation of leptons. (The relative sign is not determined theoretically.) It is taken to be "universal"; the lifetime of the μ agrees to within the experimental errors of 2%. The vector part of the coupling is, by analogy with electric charge, assumed to be not renormalized by virtual mesons. This requires, for example, that pions are also "charged" in the sense that there is a direct in-

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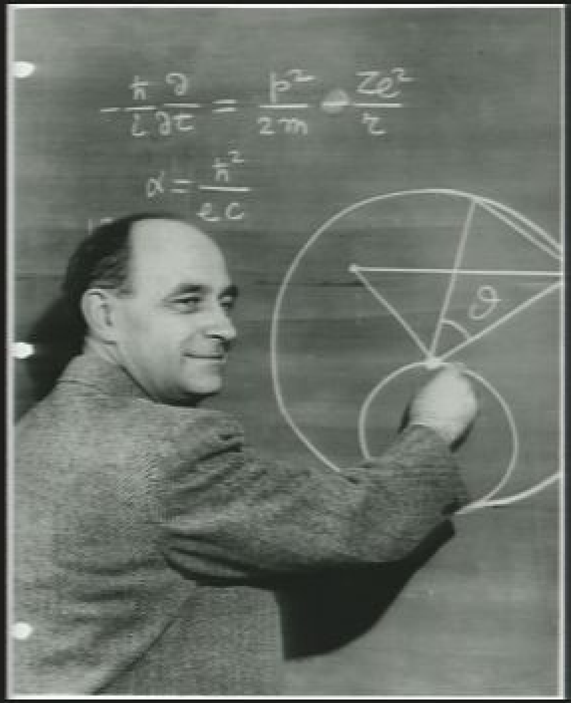

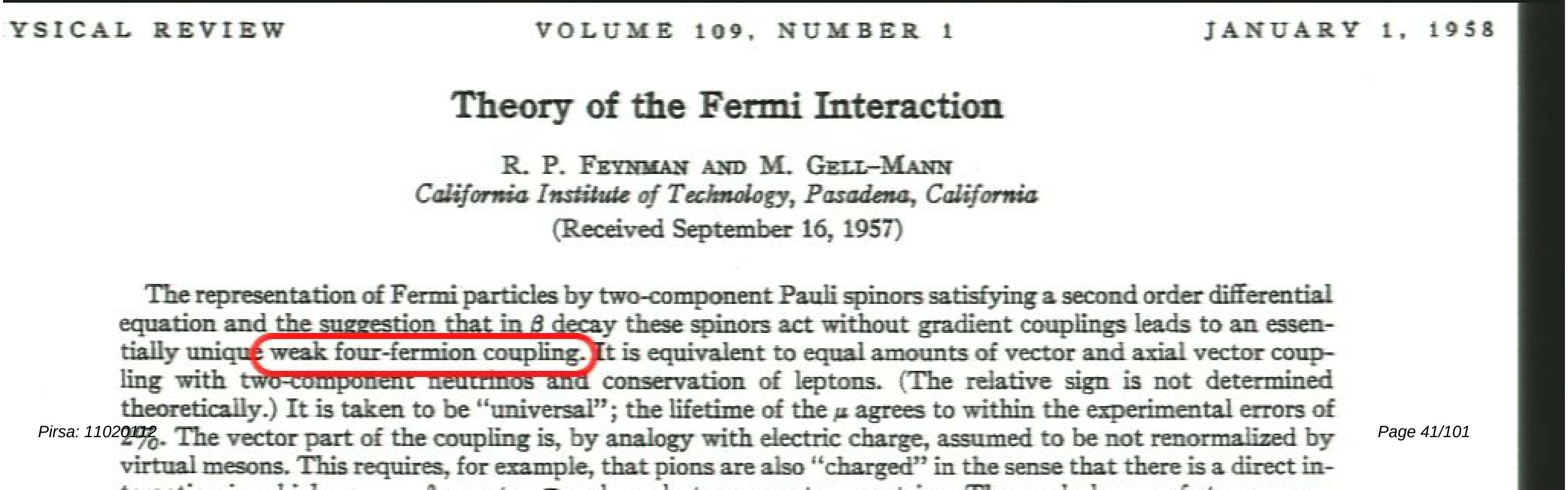

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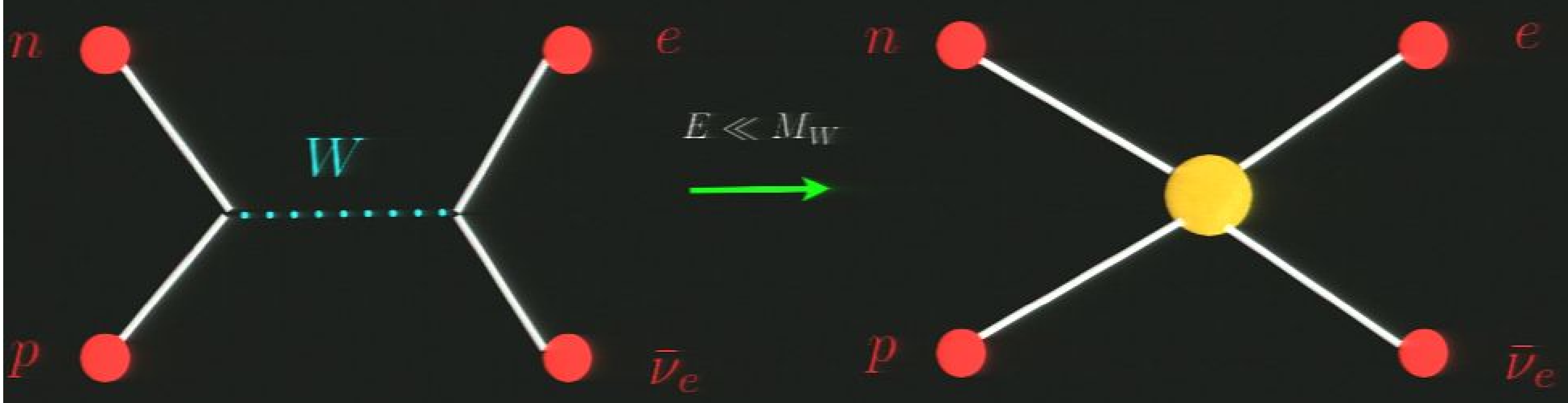
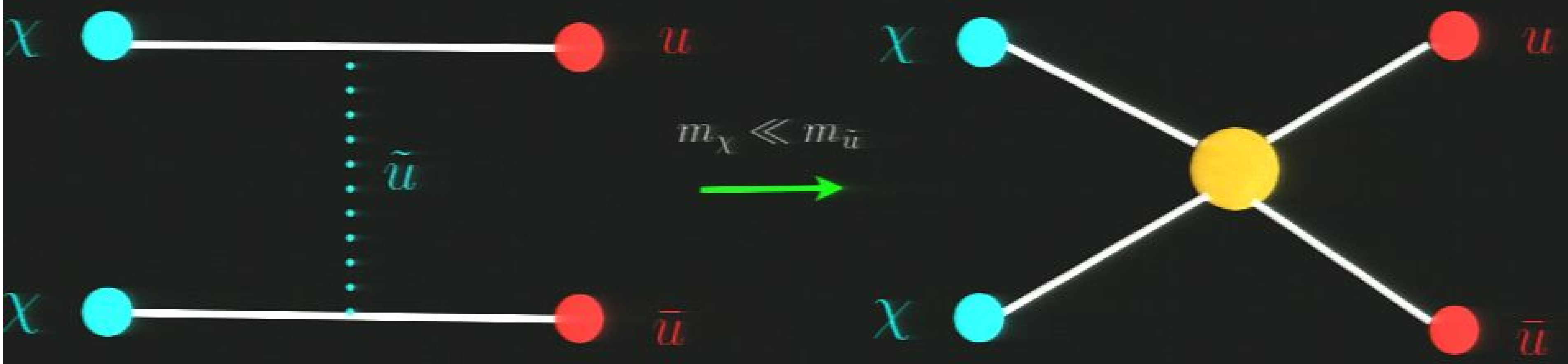
Now, we know that the beta decay is mediated by the weak interaction through exchanging of a W gauge boson



$$\frac{G_F}{\sqrt{2}}\bar{p}\gamma_\mu(g_V - g_A\gamma^5)n\,\bar{e}\gamma^\mu(1-\gamma^5)\nu_e$$

The coefficients have been measured from the angular correlations of decay products of various beta decays

Similarly, for dark matter interactions



We can write down a few operators to describe the effective interactions

$$\frac{1}{\Lambda^2}\bar{q}q\bar{\chi}\chi \qquad \frac{1}{\Lambda^2}\bar{q}\gamma_\mu q\,\bar{\chi}\gamma^\mu\chi \qquad \frac{1}{\Lambda^2}\bar{q}\gamma_\mu\gamma_5 q\,\bar{\chi}\gamma^\mu\gamma_5\chi$$

……

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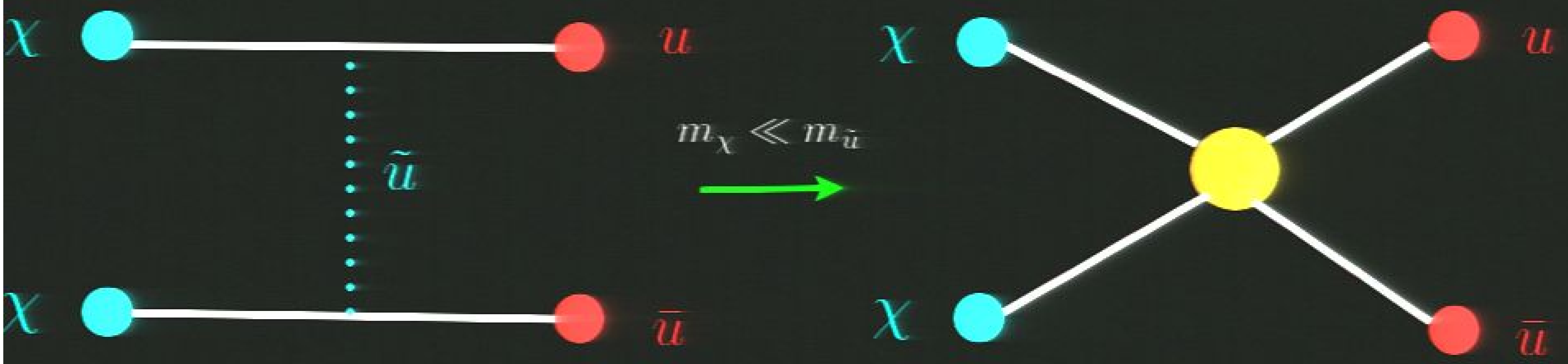

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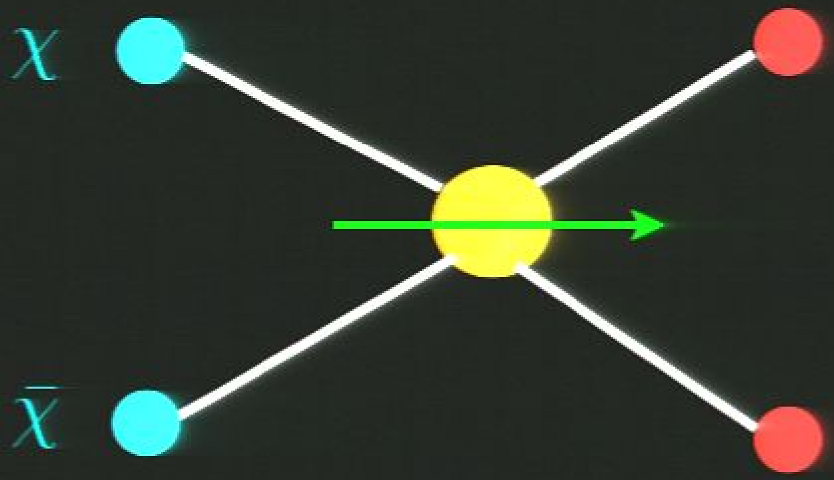
Having described the interactions of dark matter particles, we can test them from different experiments

Dark matter in the Universe can annihilate into ordinary matters and change the generic features of cosmic ray energy spectra



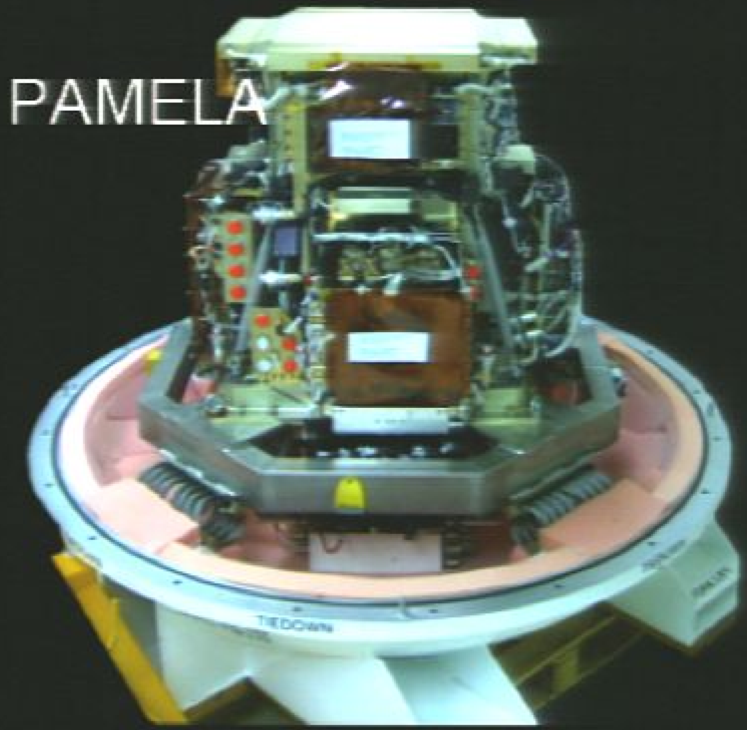
Positrons

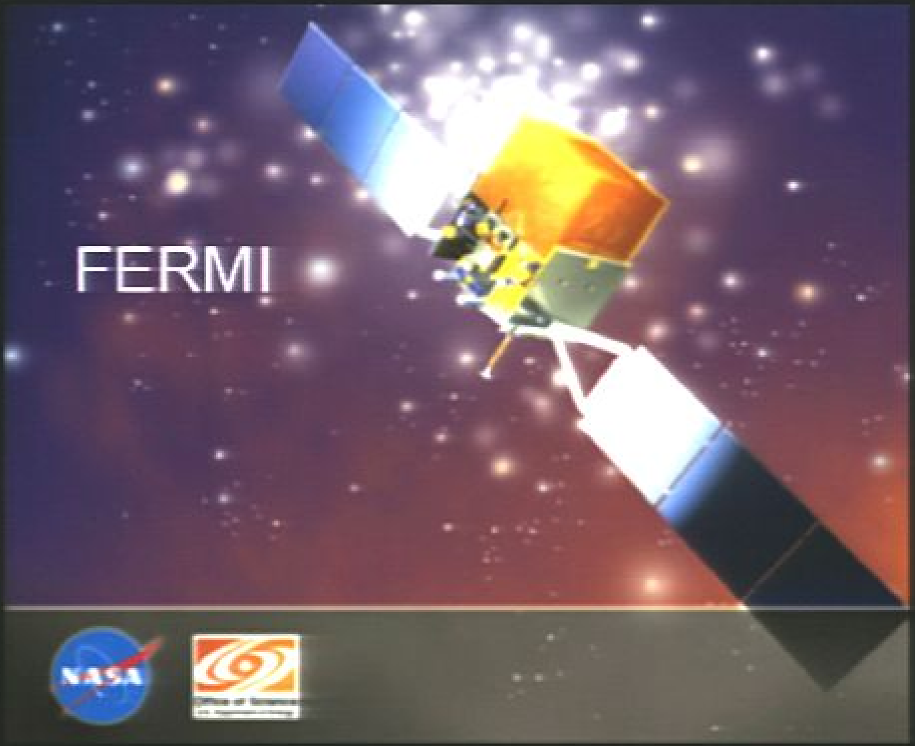
Anti-protons

Gamma rays

Neutrinos

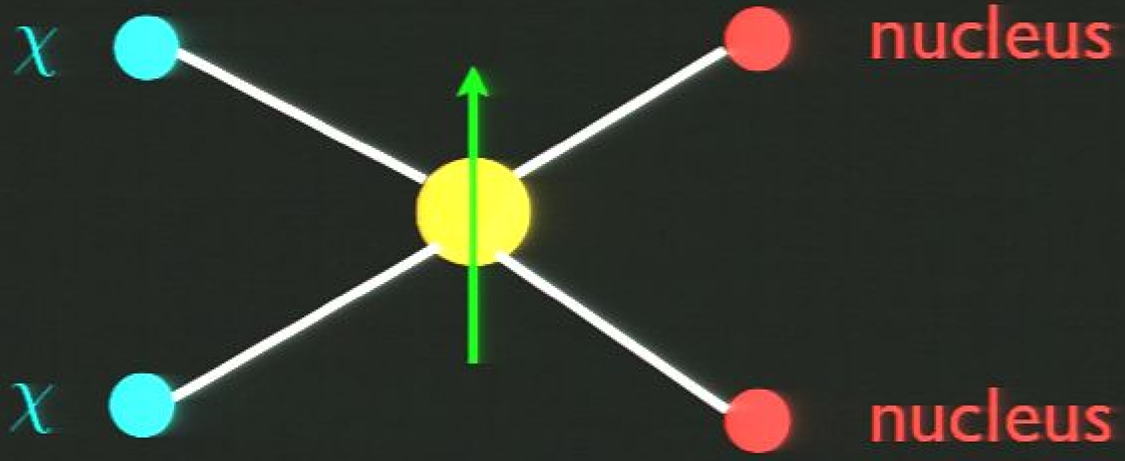
……


PAMELA


FERMI
NASA


HESS

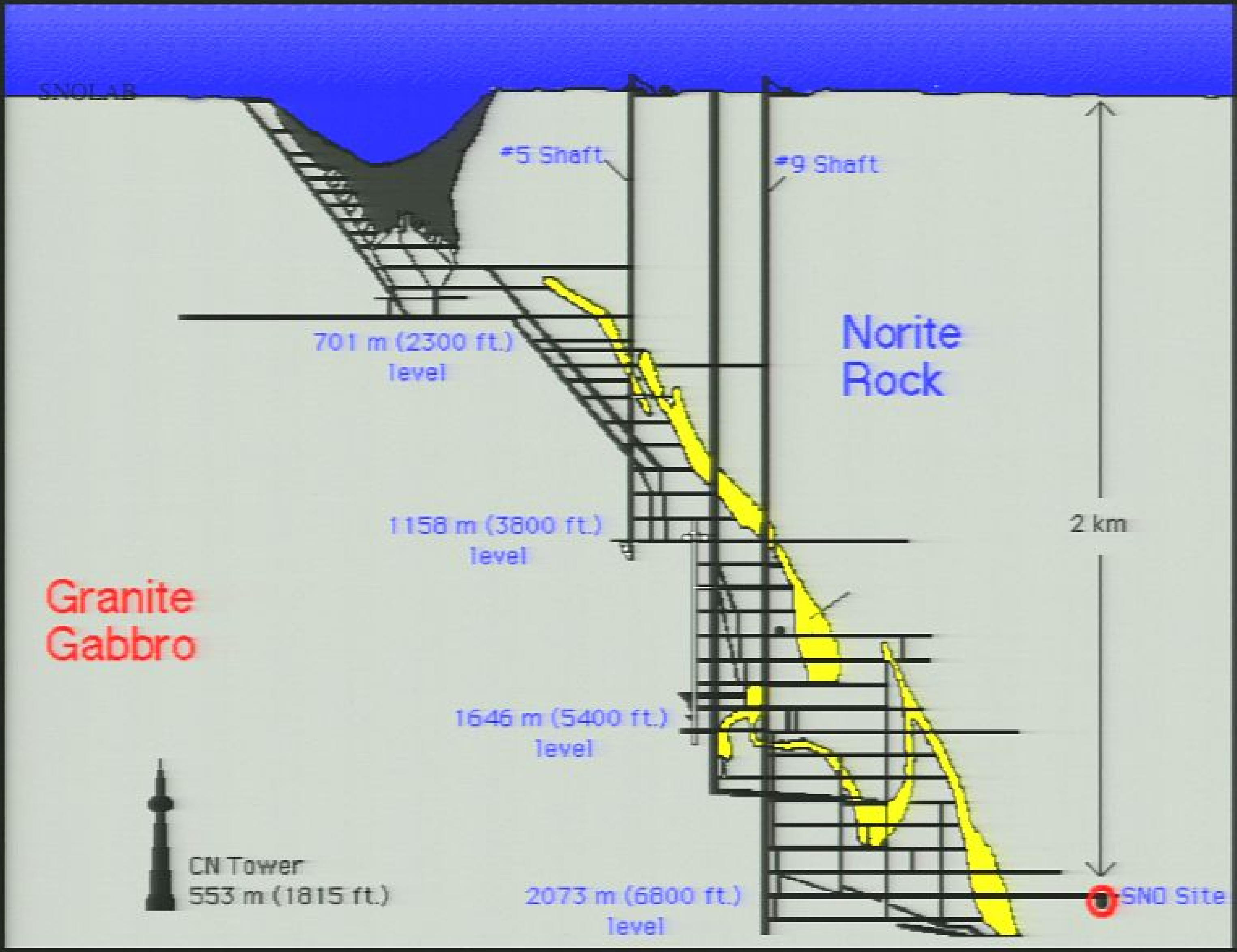
We can also wait for dark matter particles hitting the earth.



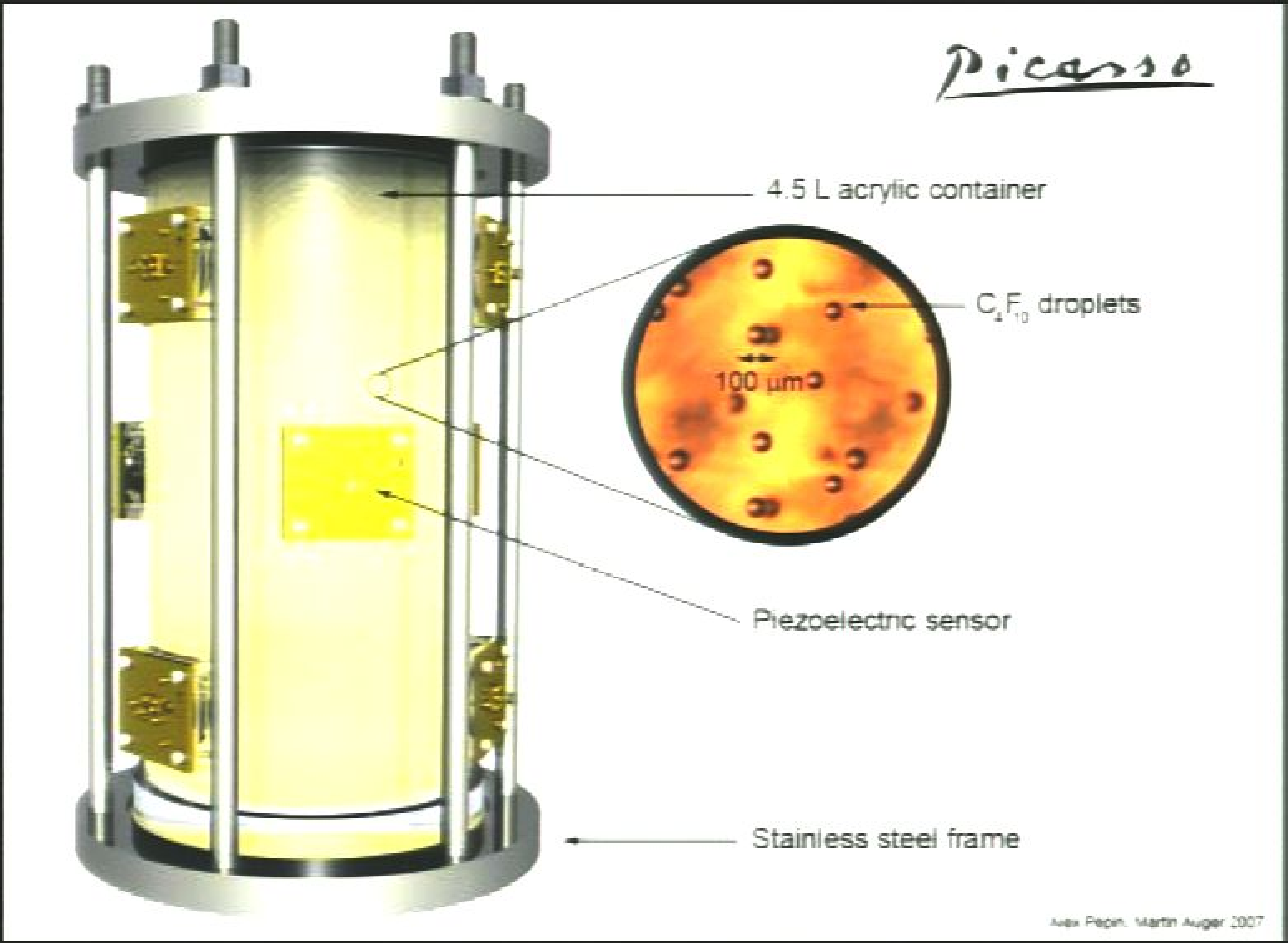
One dark matter particle hits a nucleus at one time, bounces off, and then departs

The deposited energy is typically tens of keV

We need a quiet place to measure such small energy



SNOLAB, Sudbury, Ontario



Alex Pepin, Martin Auger 2007

Project In CAnada to Search for Supersymmetric Objects

The nucleus F(9, 19) in PICASSO has one unpaired proton, and carries a large spin

It has a large spin-dependent cross section of dark matter scattering off the nucleus. Hence, it is sensitive to the following effective operator

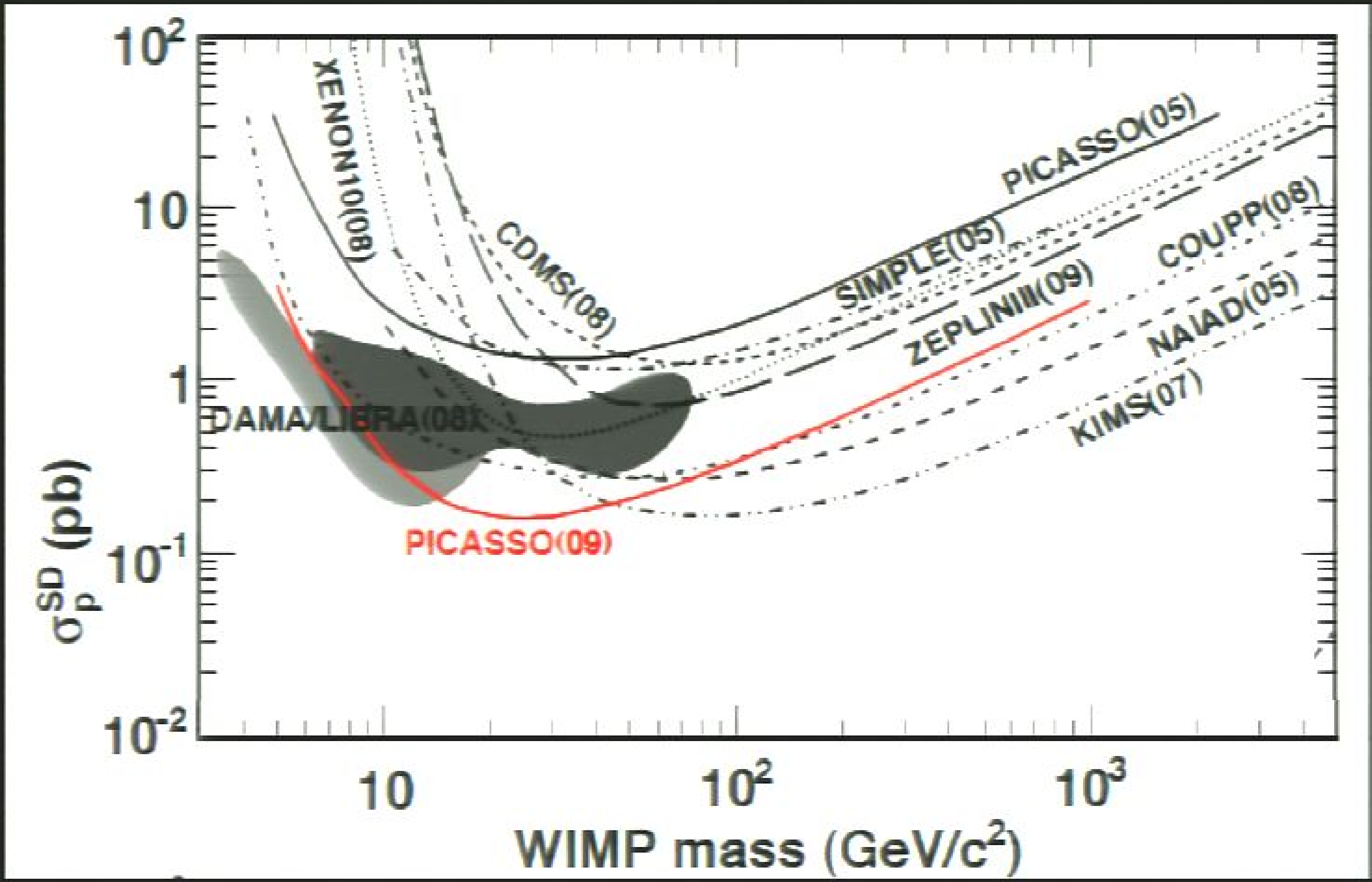
$$\frac{1}{\Lambda^2}\bar{q}\gamma_\mu\gamma_5 q\,\bar{\chi}\gamma^\mu\gamma_5\chi$$

The direct detection scattering cross section is

$$\sigma_p^{\rm SD} = \frac{3\,\mu_{\chi p}^2}{\pi\,\Lambda^4}\,(\Delta_q^p)^2$$

For a cutoff around 100 GeV, $\sigma_p^{\rm SD} \sim 1\ {\rm pb} = 10^{-36}\ {\rm cm}^2$

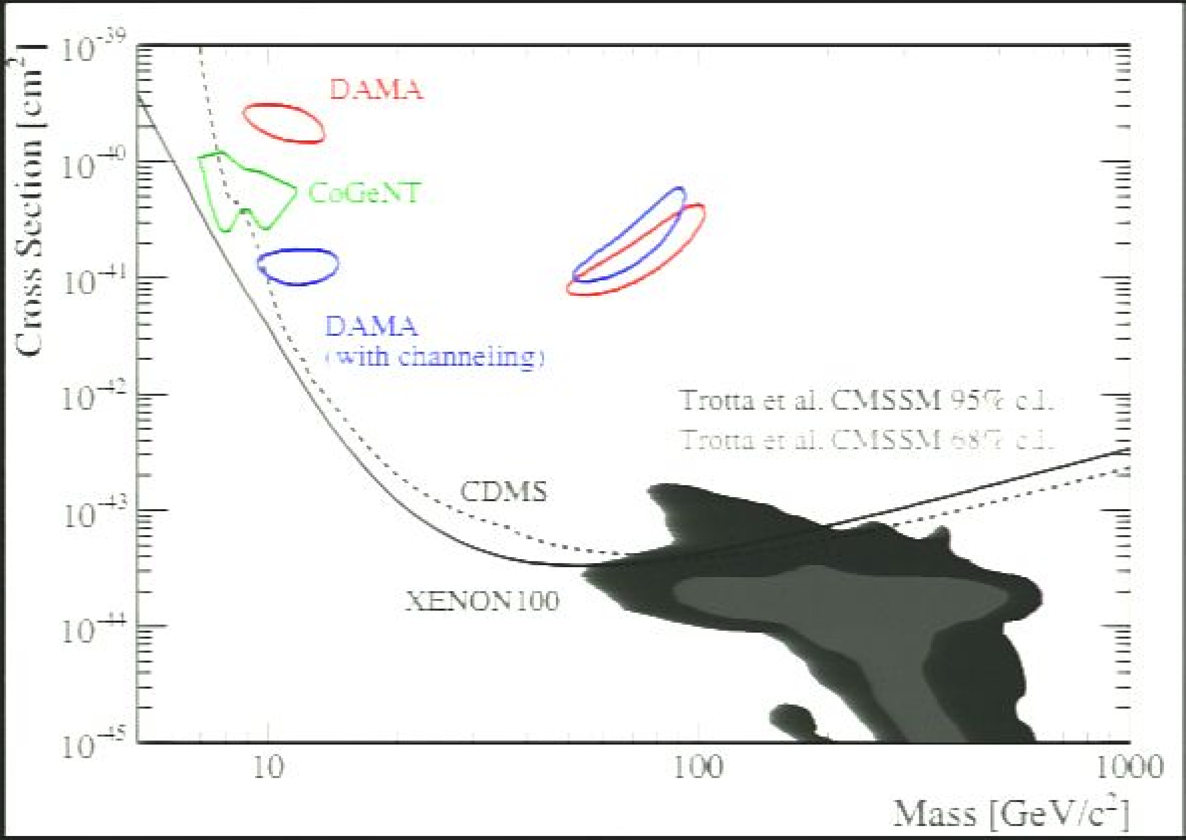
Since only “null results” have been observed so far, PICASSO can set a limit on the dark matter SD interaction strength



Similarly, for spin-independent cross sections

$$\frac{1}{\Lambda^2}\bar{q}q\bar{\chi}\chi$$

$$\frac{1}{\Lambda^2}\bar{q}\gamma_\mu q\,\bar{\chi}\gamma^\mu\chi$$



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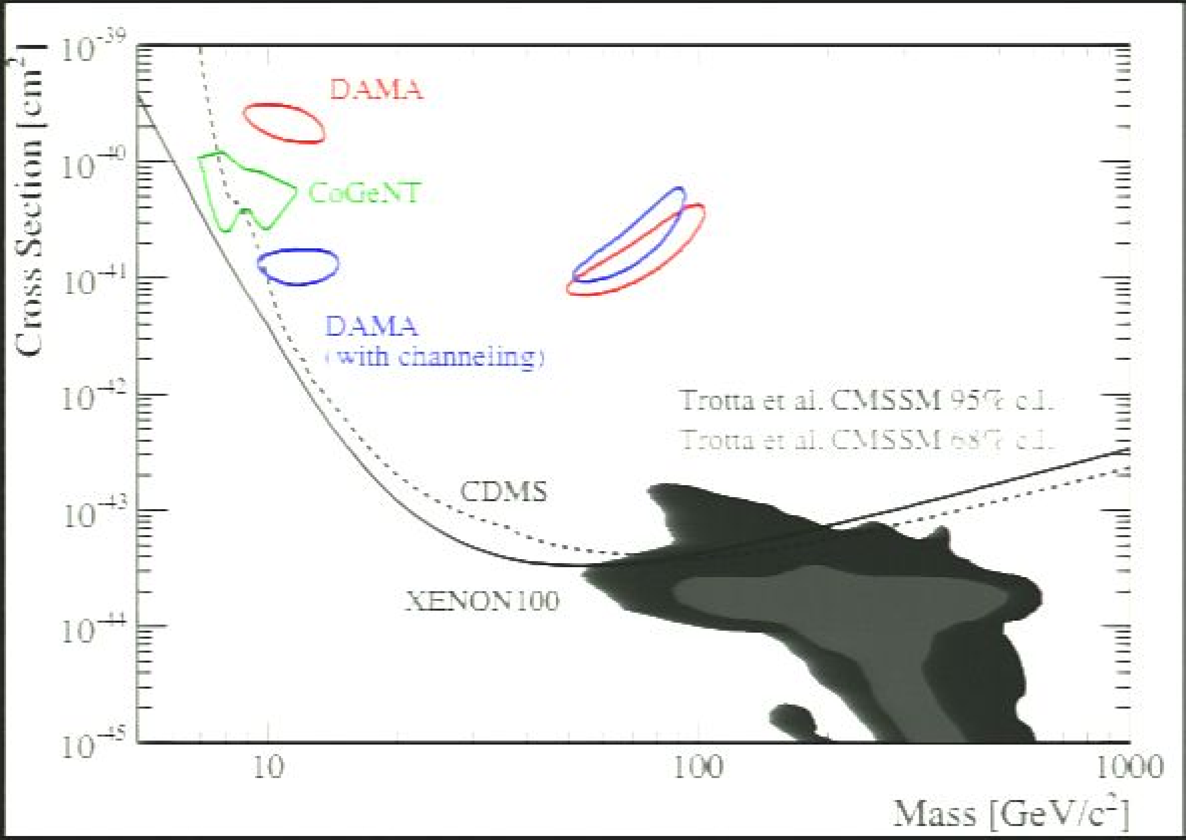

Explaining the DAMA modulation data goes beyond the EFT of a single dark matter particle

"Resonant Dark Matter", YB, Fox, JHEP, 0911, 052 (2009)

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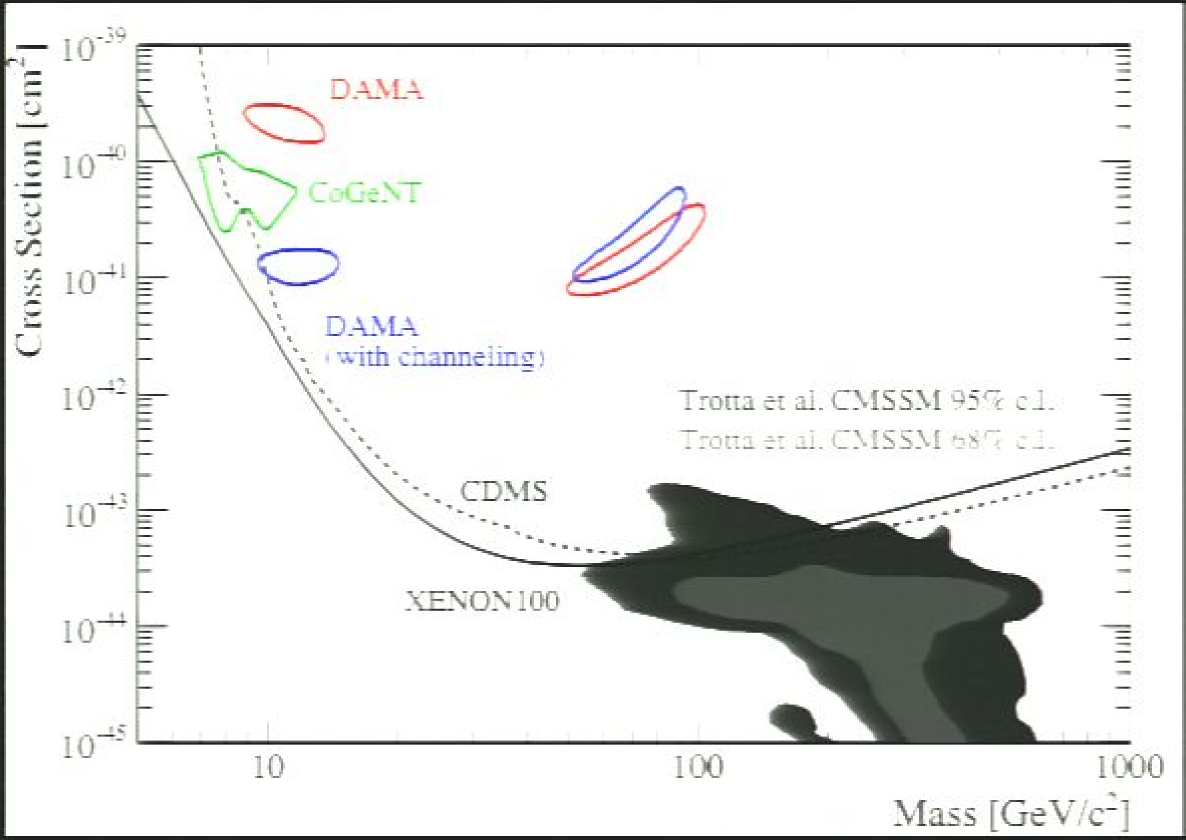
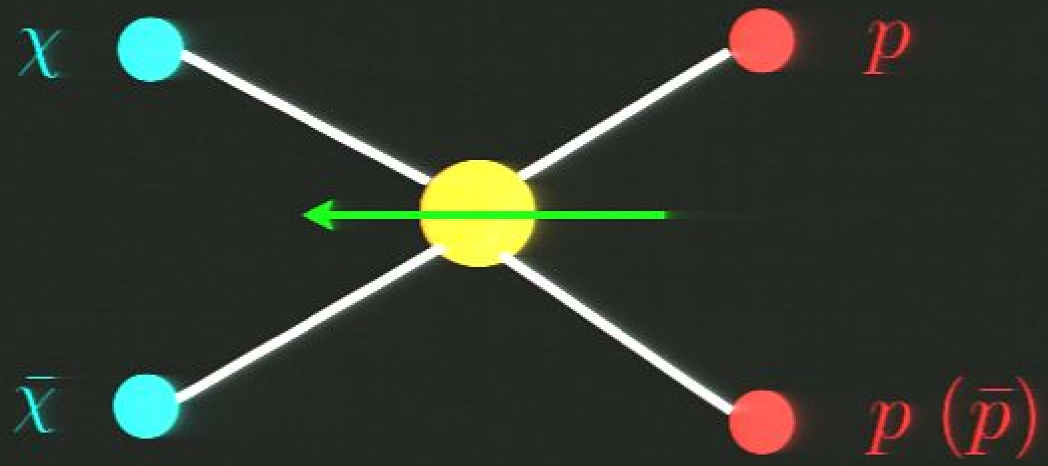


Explaining the DAMA modulation data goes beyond the EFT of a single dark matter particle

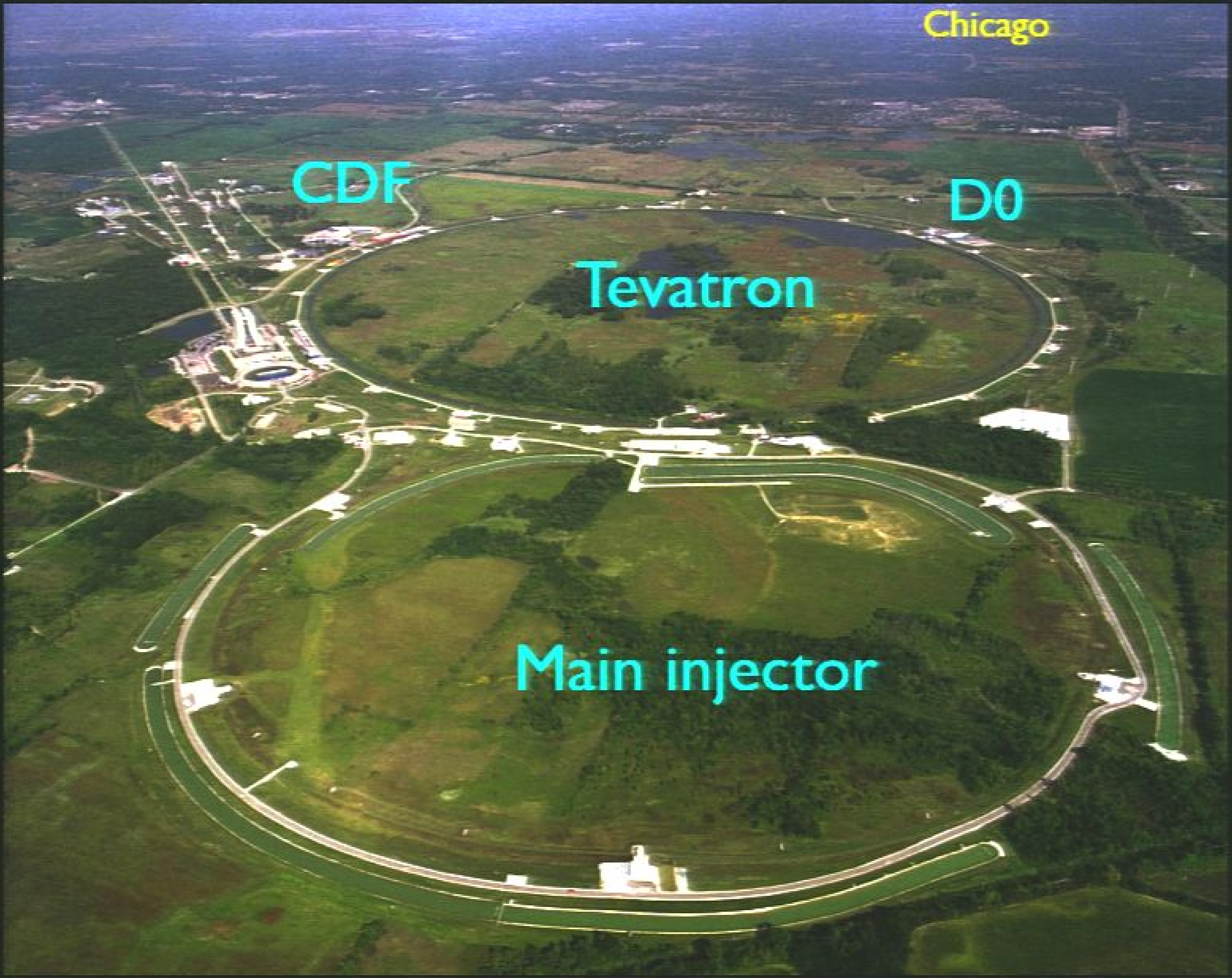
"Resonant Dark Matter", YB, Fox, JHEP, 0911, 052 (2009)

Direct detection probes the dark matter coupling to nucleons

In high energy physics, we build colliders and use proton or anti-proton collision to produce heavy particles



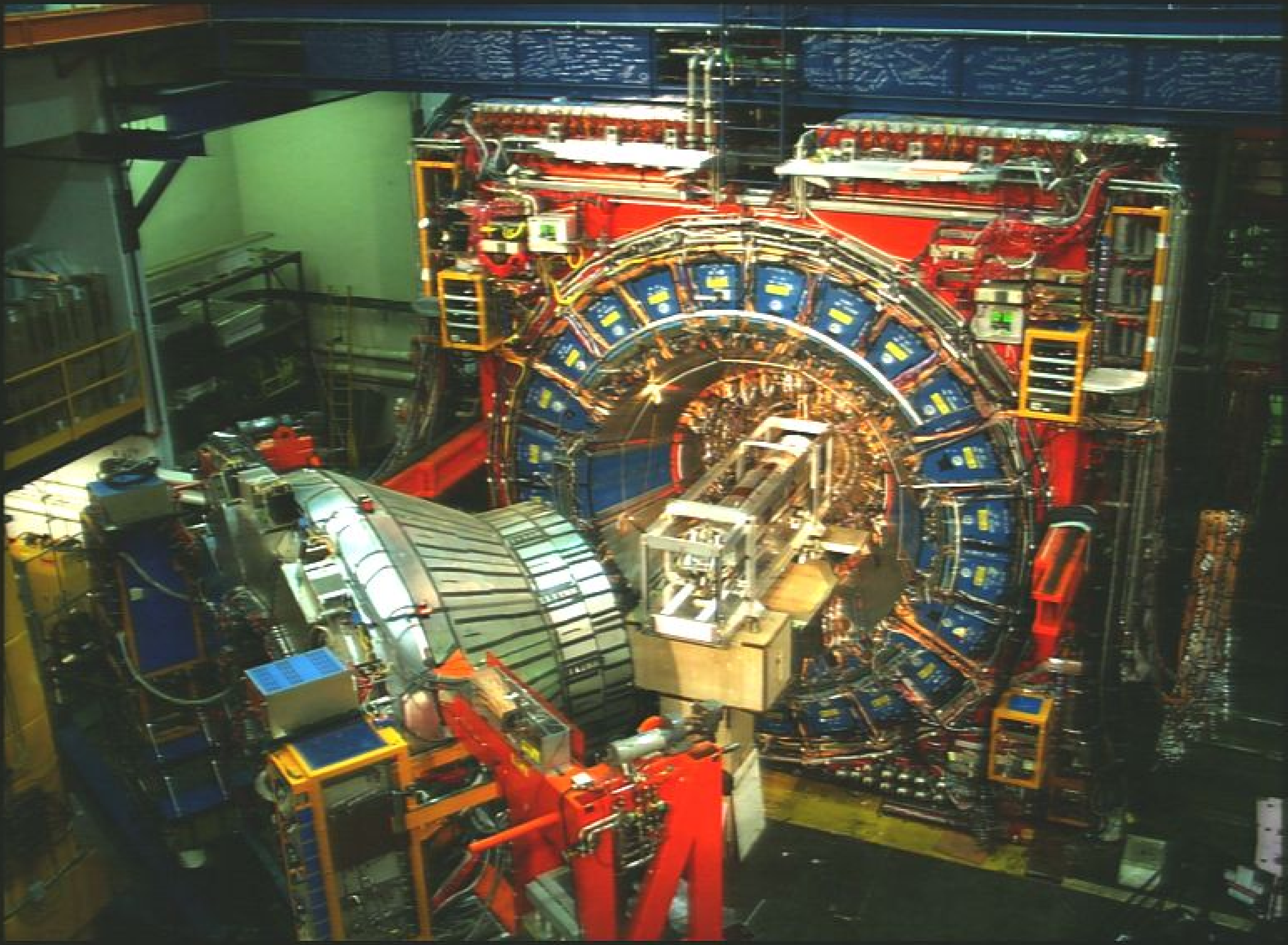
Why are there no bounds from colliders on this plot ?



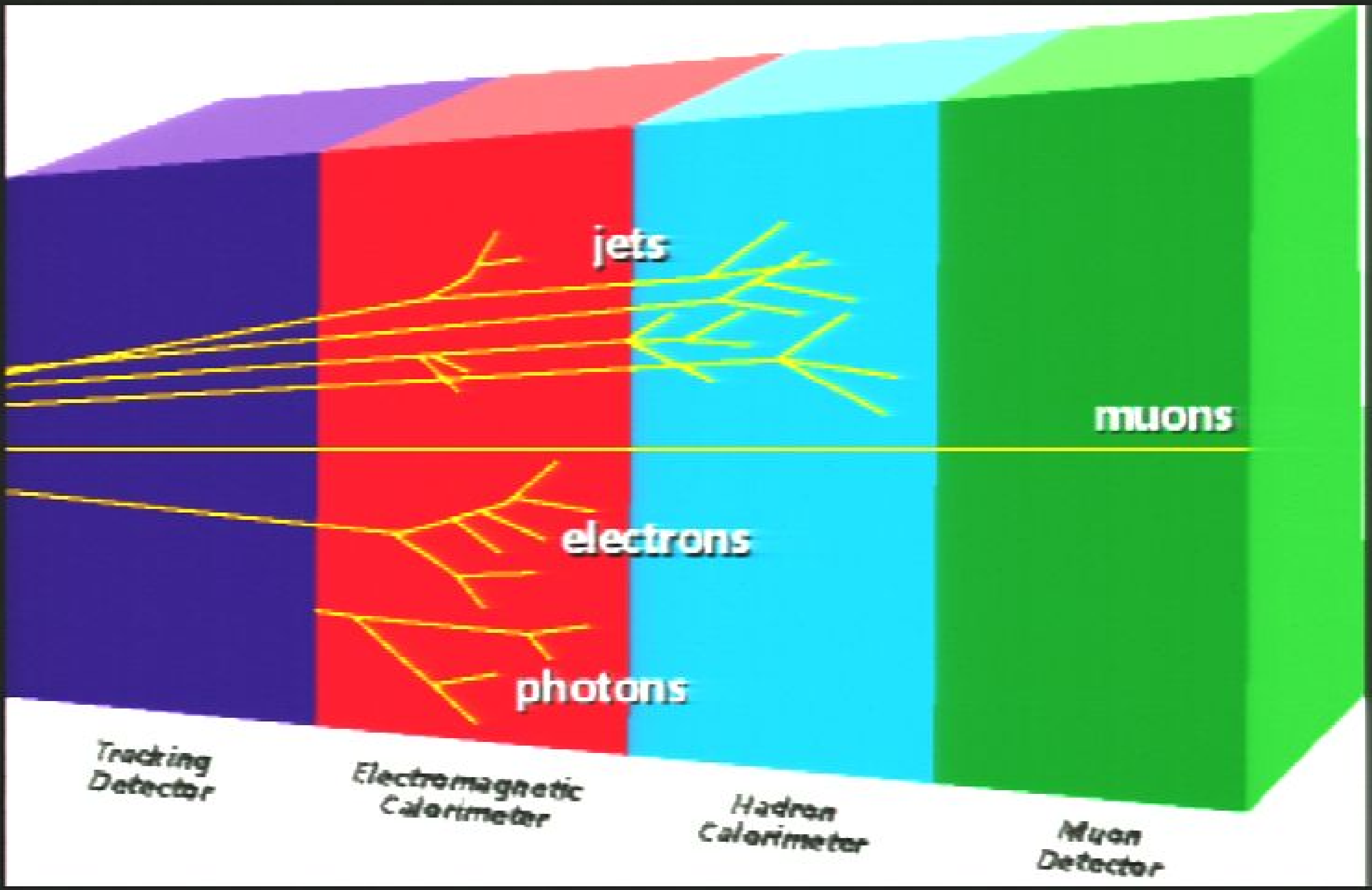
Tevatron at Fermilab

Proton-anti-proton

1.96 TeV 6 km



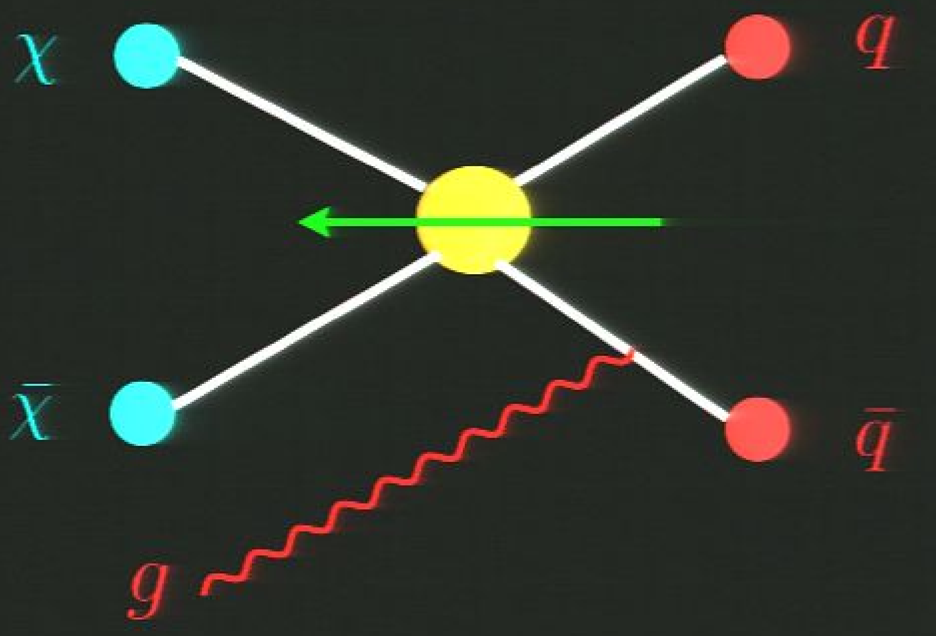
CDF detector



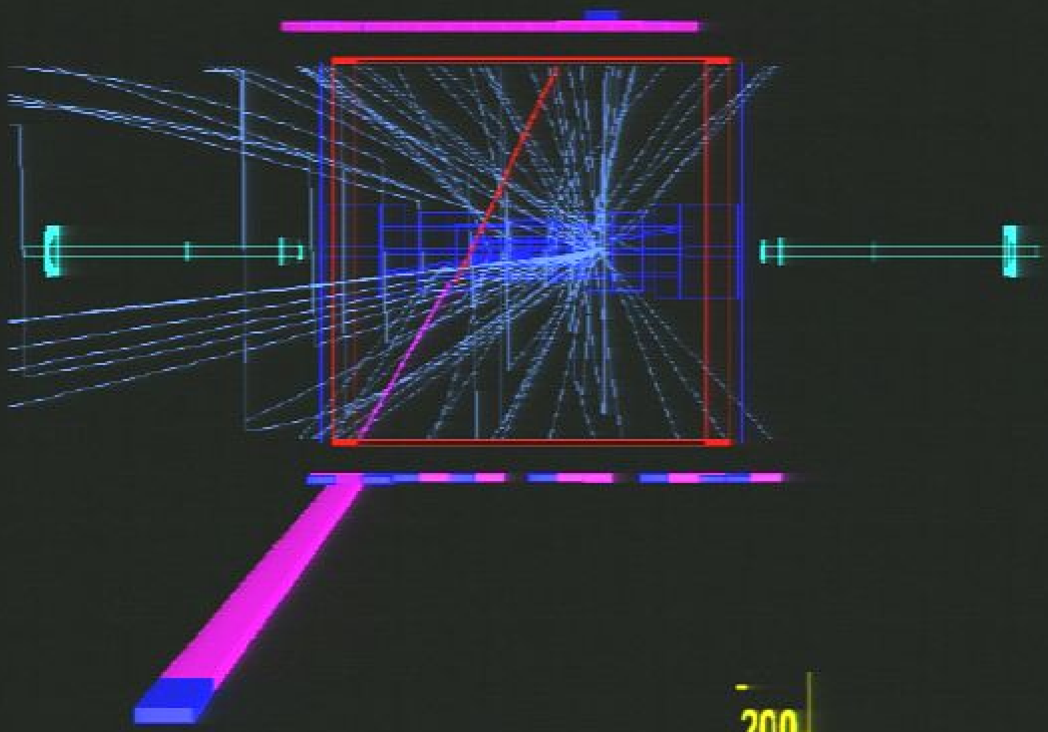
A dark matter particle produced at Tevatron will penetrate the detectors and escape, leaving no trace

If the collision final state only contains dark matter particles, we don't know when we should record the events

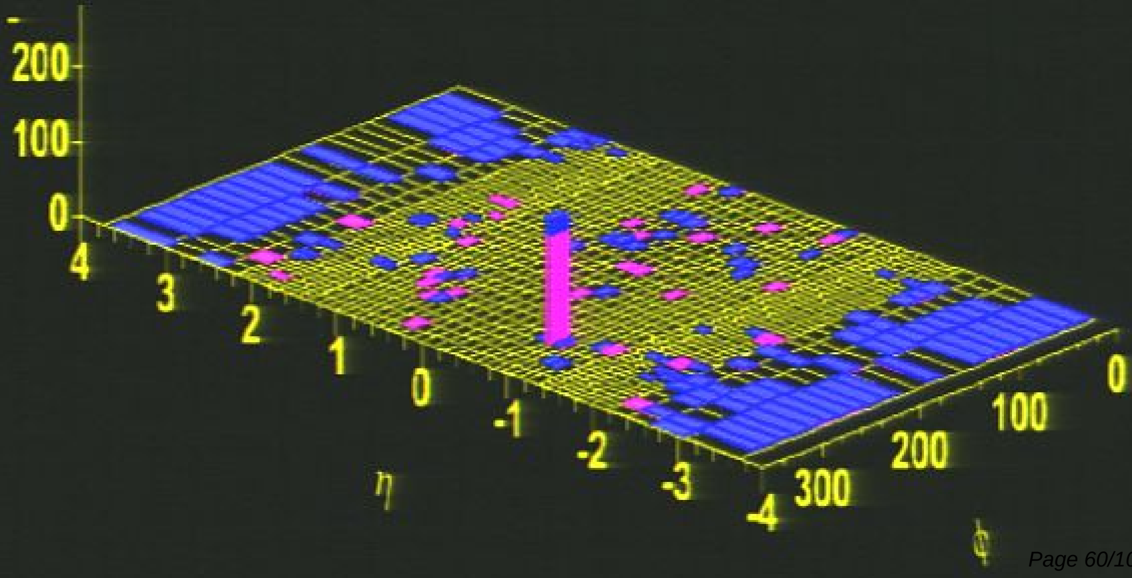
From QCD, the quarks inside the proton can radiate additional gluons



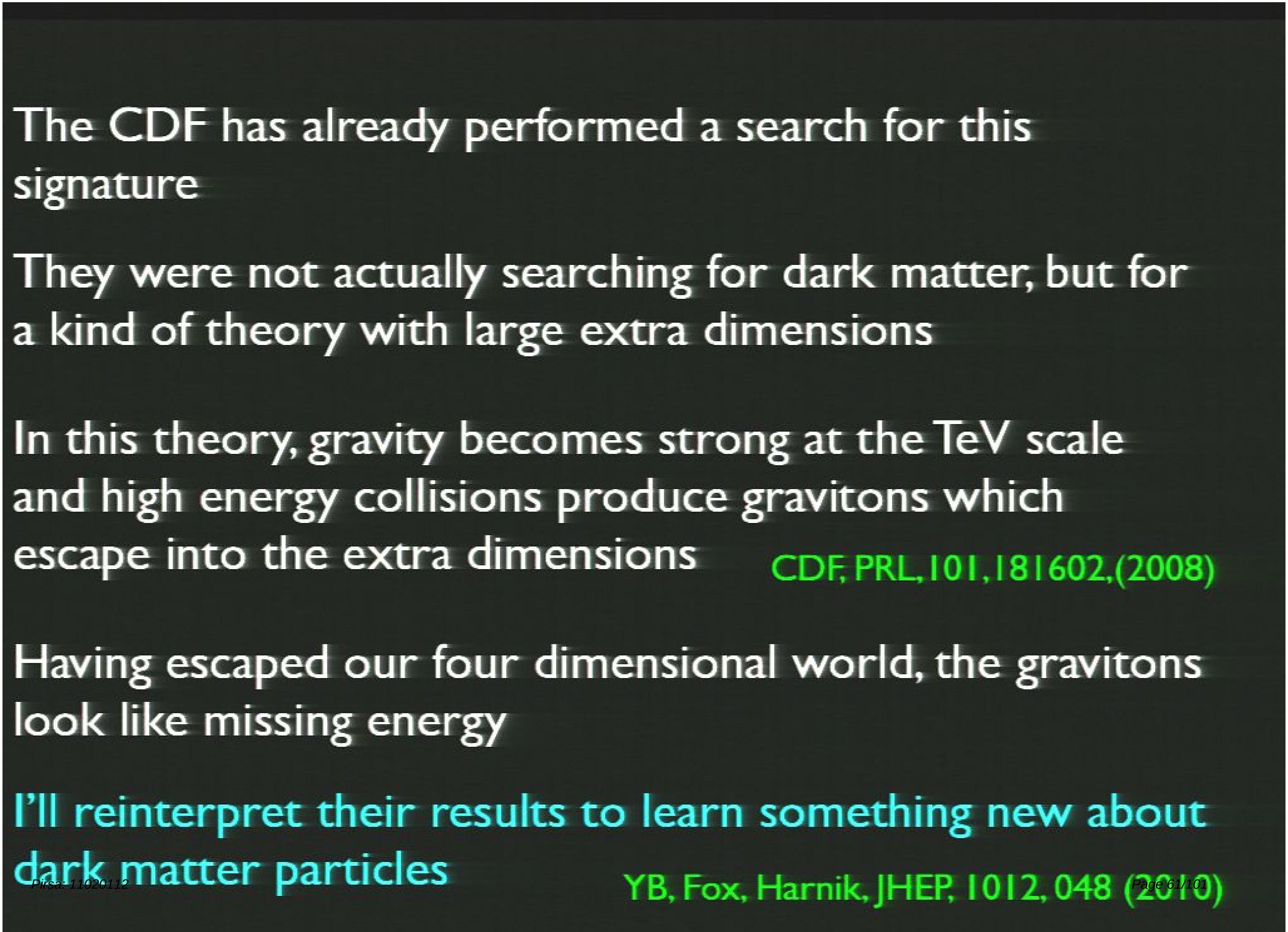
At least, we have one (visible) jet in the final state



Pt(jet)=175 GeV
MET=170 GeV



Monojet event



The CDF has already performed a search for this signature

They were not actually searching for dark matter, but for a kind of theory with large extra dimensions

In this theory, gravity becomes strong at the TeV scale and high energy collisions produce gravitons which escape into the extra dimensions

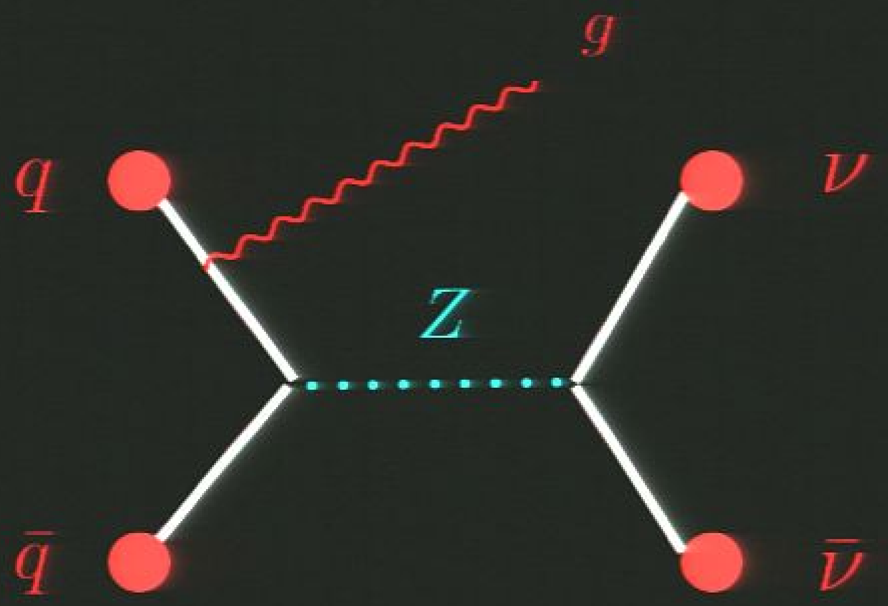
CDF, PRL, 101, 181602, (2008)

Having escaped our four dimensional world, the gravitons look like missing energy

I'll reinterpret their results to learn something new about dark matter particles

YB, Fox, Harnik, JHEP, 1012, 048 (2010)

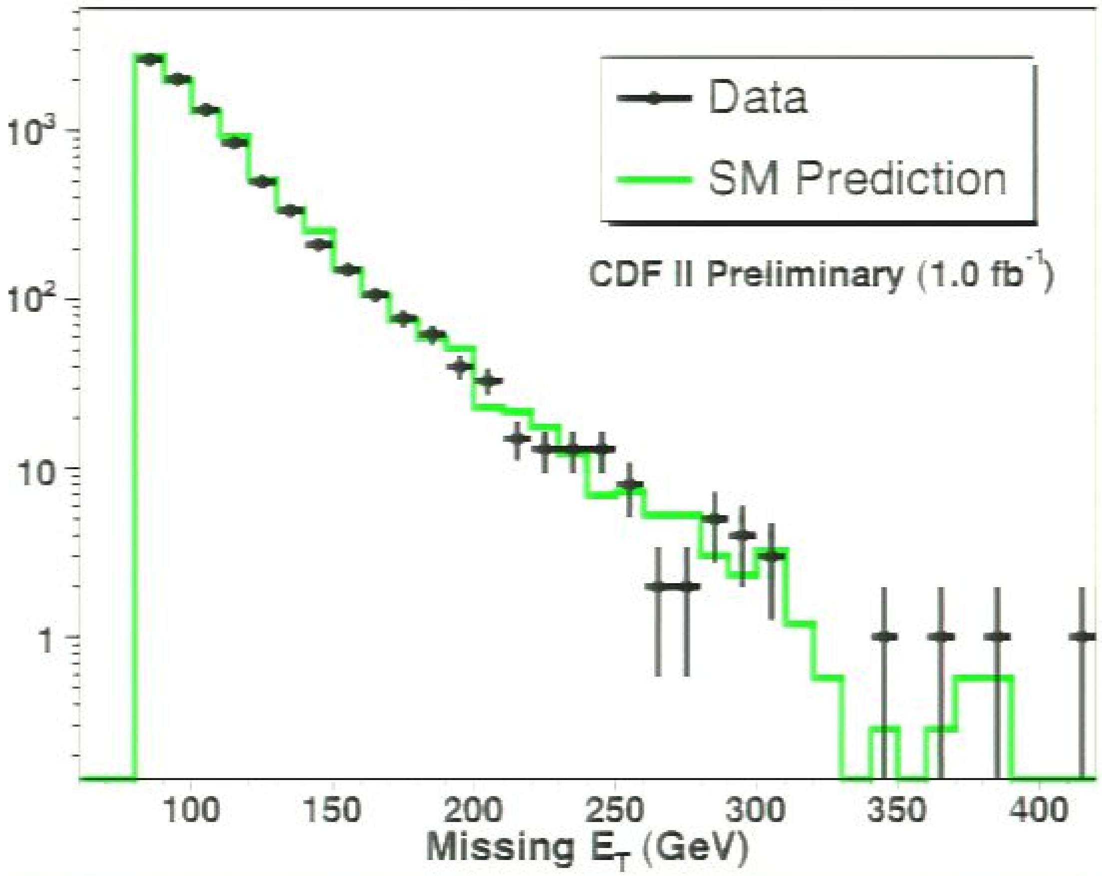
Monojet plus MET events also appear from other ways



Before we can make a claim for the discovery of extra dimension or dark matter particles at colliders,

we need to check whether the observables can be explained by the standard model first

Here is what CDF observed



expect: 8663 ± 332

observe: 8449

Consistent with the standard model prediction so far

Come back to our effective operator: $\frac{1}{\Lambda^2}\bar{q}\gamma_\mu\gamma_5 q\,\bar{\chi}\gamma^\mu\gamma_5\chi$

The monojet+MET production cross section is

$$\sigma_{1j} = c\,\alpha_s\,\frac{p_T^2(1j)}{\Lambda^4}$$

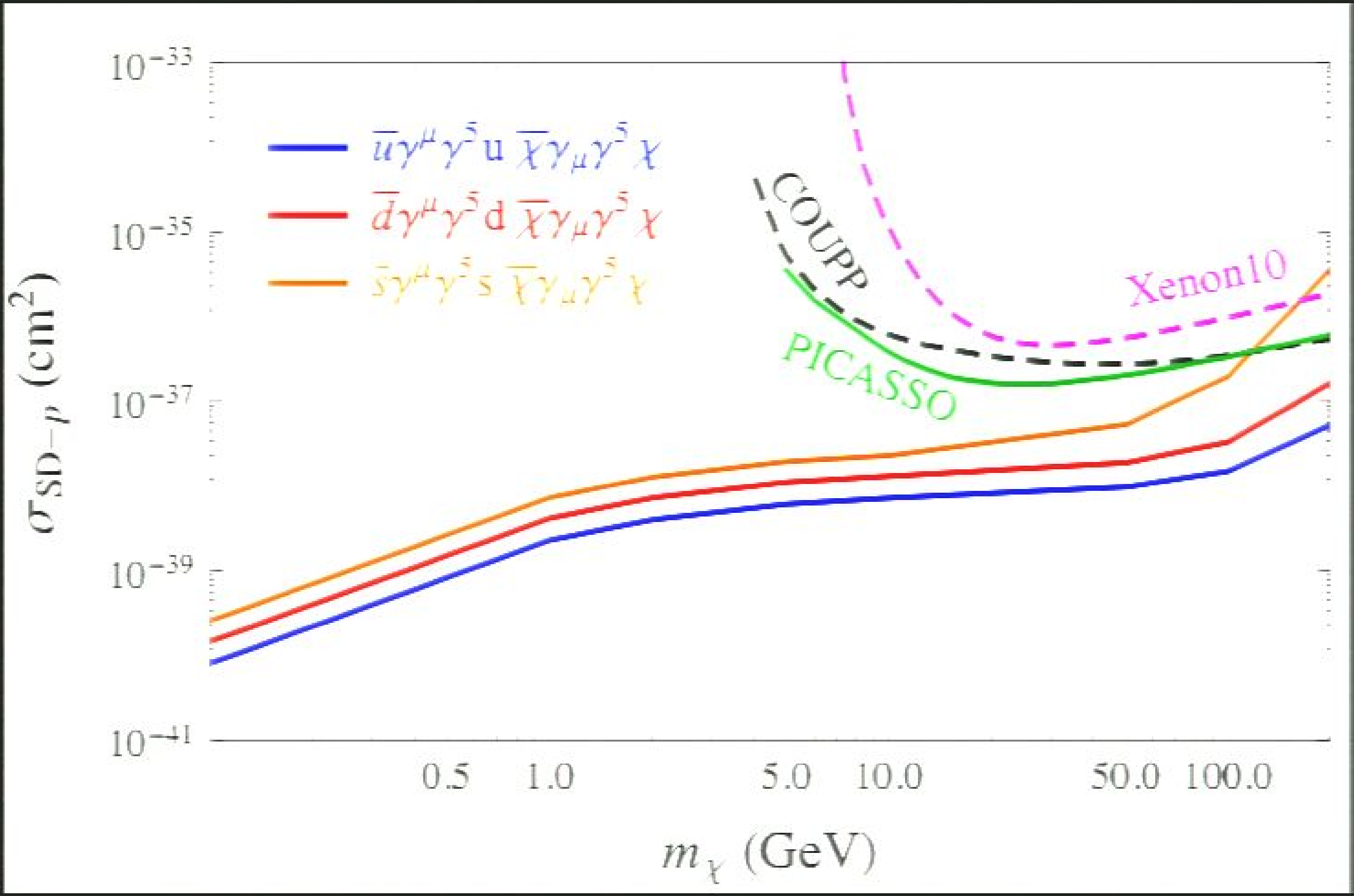
The "null result" sets an lower bound on the cutoff

Recall the formula for the direct detection scattering cross section

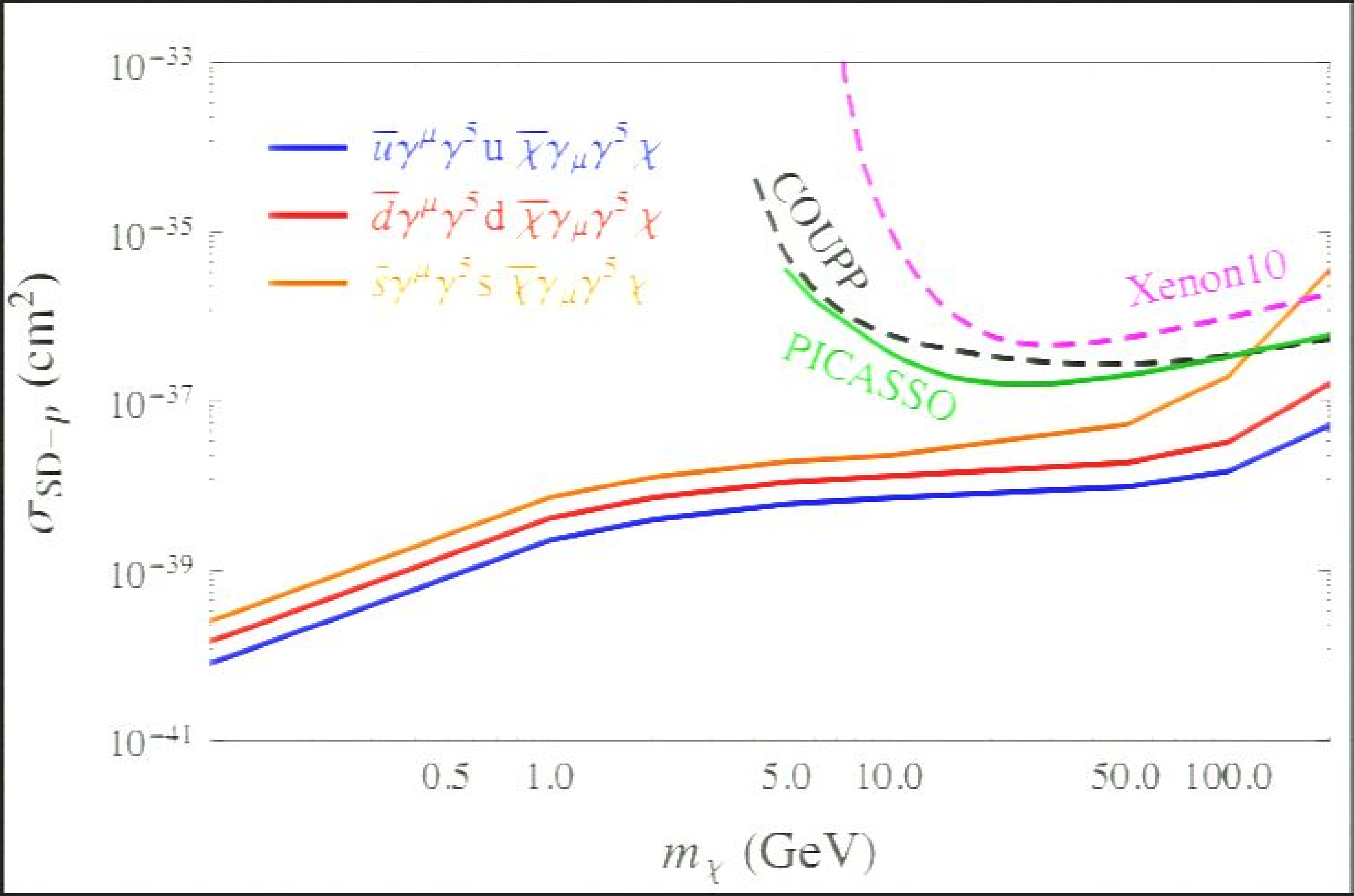
$$\sigma_p^{\rm SD} = \frac{3\,\mu_{\chi p}^2}{\pi\,\Lambda^4}\left(\Delta_q^p\right)^2$$

So, we can set an upper bound on the scattering cross section from monojet searches

YB, Fox, Harnik, JHEP, 1012, 048 (2010)

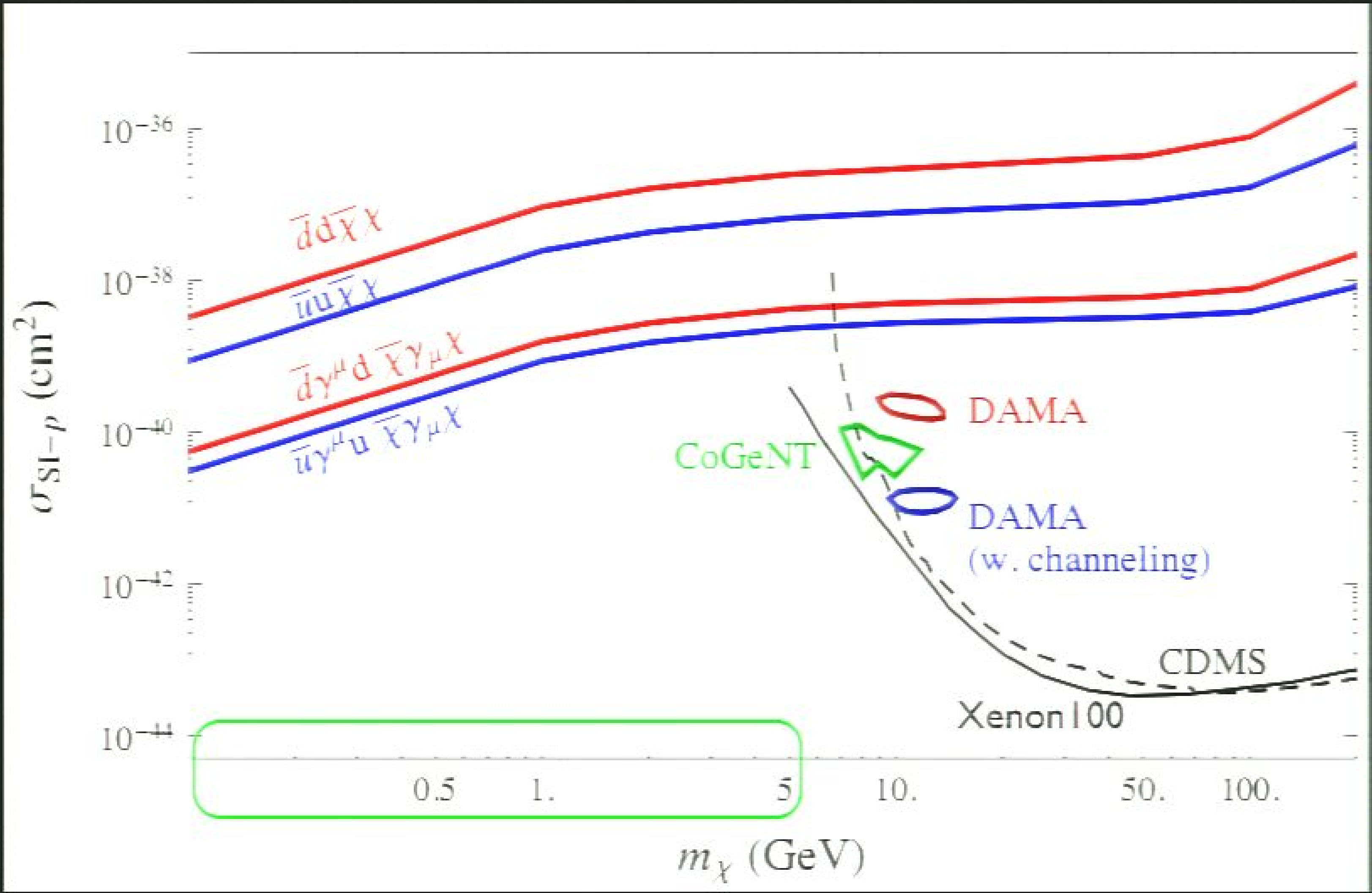


YB, Fox, Harnik, JHEP, 1012, 048 (2010)



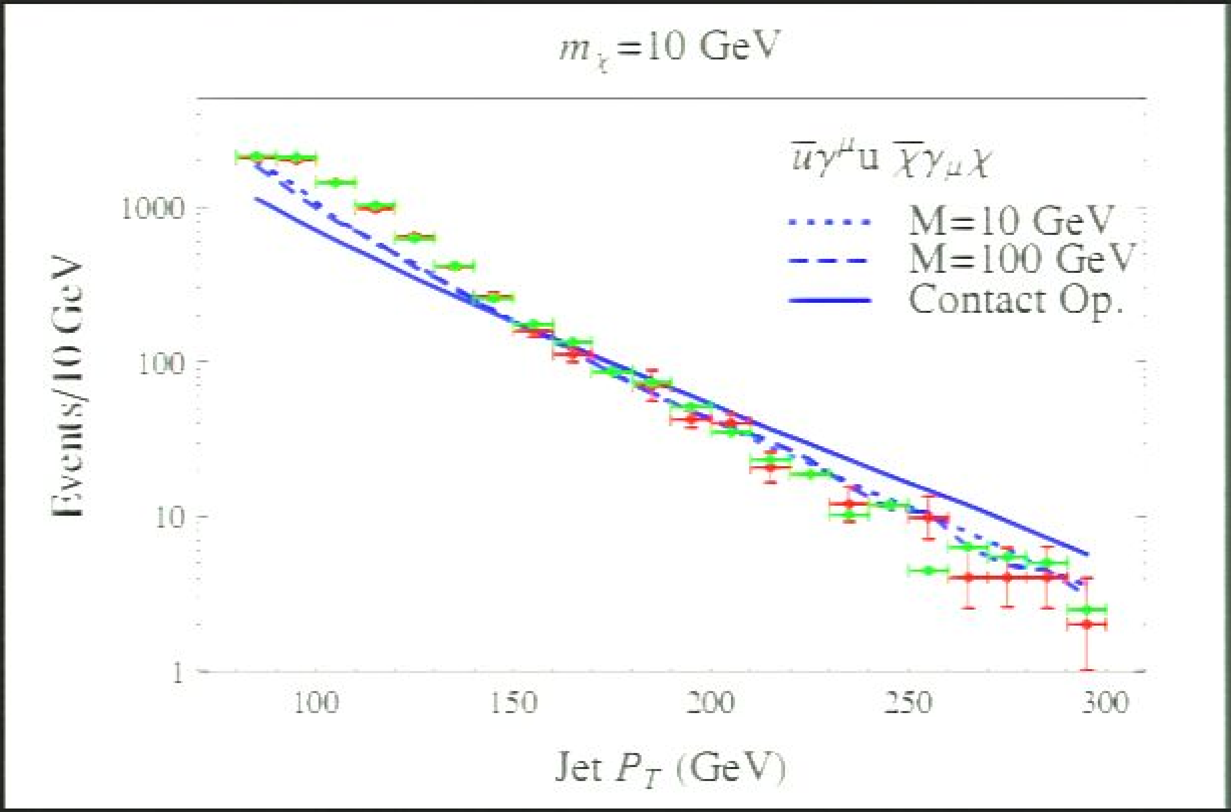
World's best spin-dependent limit up to 100 GeV

YB, Fox, Harnik, JHEP, 1012, 048 (2010)



World's best spin-independent limit for light dark matter

With more data collected at CDF, we can improve the limits



use the shape difference to cut backgrounds

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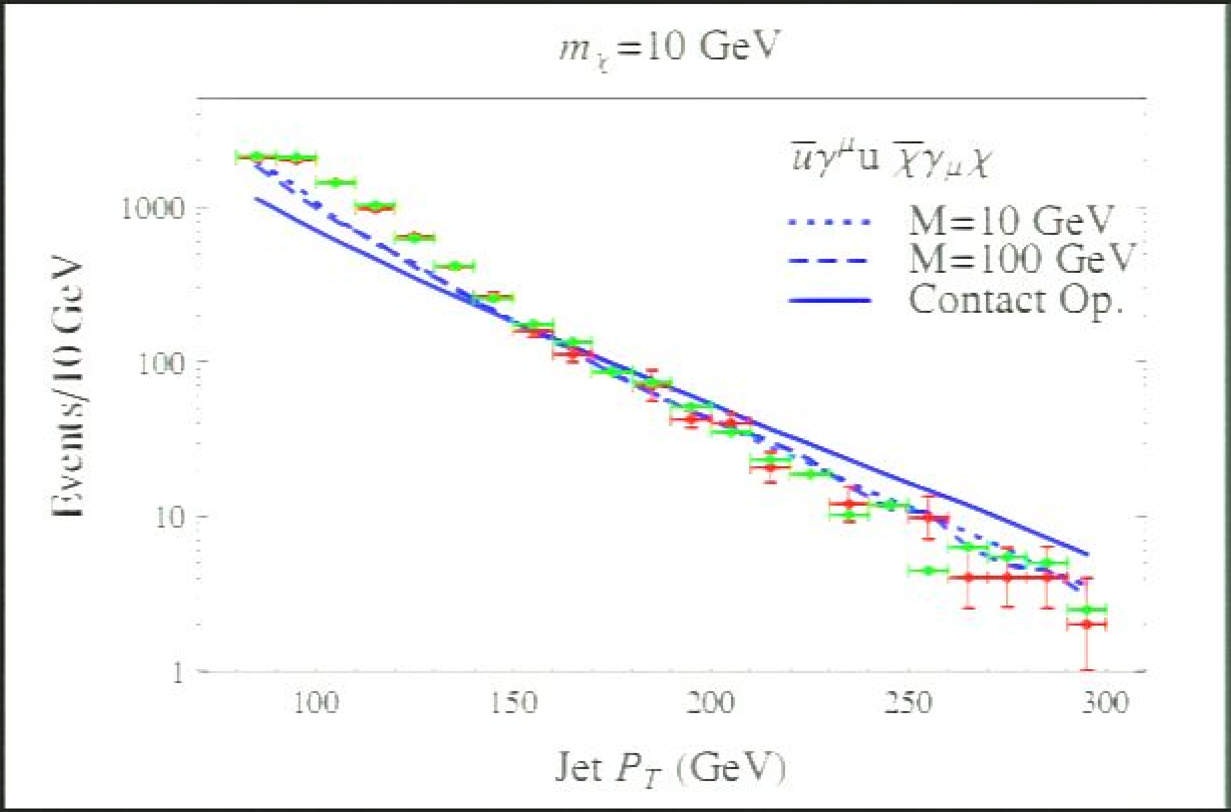

use the shape difference to cut backgrounds

CDF + YB, Fox, Harnik are using the current data to set limits on WIMP direct detection cross sections

Since colliders are so powerful to test the WIMP scenario, we can even ask the following to-do list

- Measure the masses of dark matter and other particles in the dark sector
- Measure the spin of dark matter
- Measure the couplings of dark matter to visible particles
- Calculate the dark matter annihilation cross section
- Confirm or disprove the WIMP coincidence

It is not obvious that all of these can be done

We do not know the momenta of quarks that initiate the reaction

We do not observe the two outgoing dark matter particles

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We do not know the momenta of quarks that initiate the reaction

We do not observe the two outgoing dark matter particles

But, we can gather more information about dark matter from the observed final-state particles

We need to go beyond the EFT of dark matter. We can hope to produce other heavier particles in the dark sector. The final state from heavier particle decays contains a rich feature with more jets or leptons

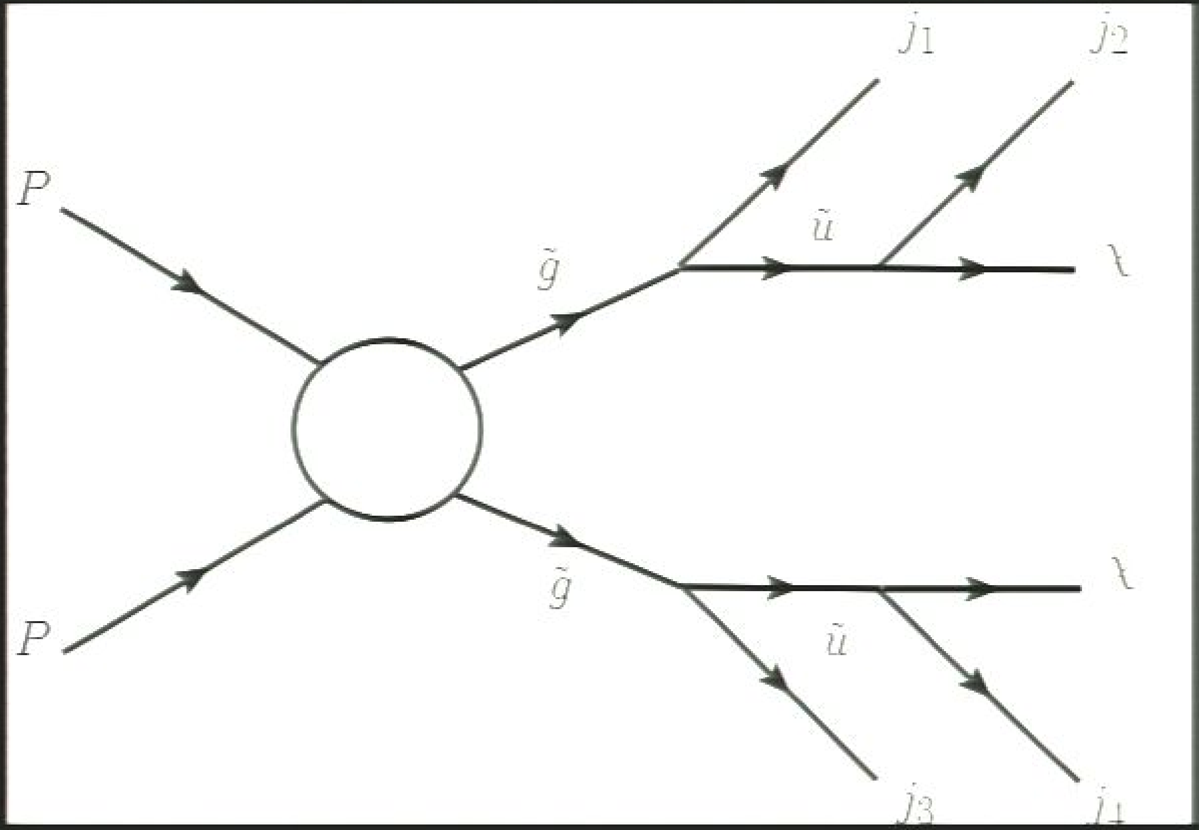
Fortunately, we have another collider with a arger center-of-mass energy

So, we may directly produce heavier particles in the dark matter sector

Proton-proton
7, 14 TeV 27 km

LHC at CERN

Using SUSY as an example



There are four jets plus missing energy in the final state

Simply from energy and momentum conservation, we have two observations

The two jets from the same decay chain should have invariant masses bounded by the gluino mass

$$m_{j_1 j_2}^{\max} = m_{\tilde{g}} - m_{\chi} \quad \text{or} \quad (m_{j_1 j_2}^{\max})^2 = \frac{(m_{\tilde{g}}^2 - m_{\tilde{u}}^2)(m_{\tilde{u}}^2 - m_{\chi}^2)}{m_{\tilde{u}}^2}$$

If we know the momentum of each dark matter particle (we only know the sum of two dark matter particle transverse momenta), we can determine the gluino and neutralino masses

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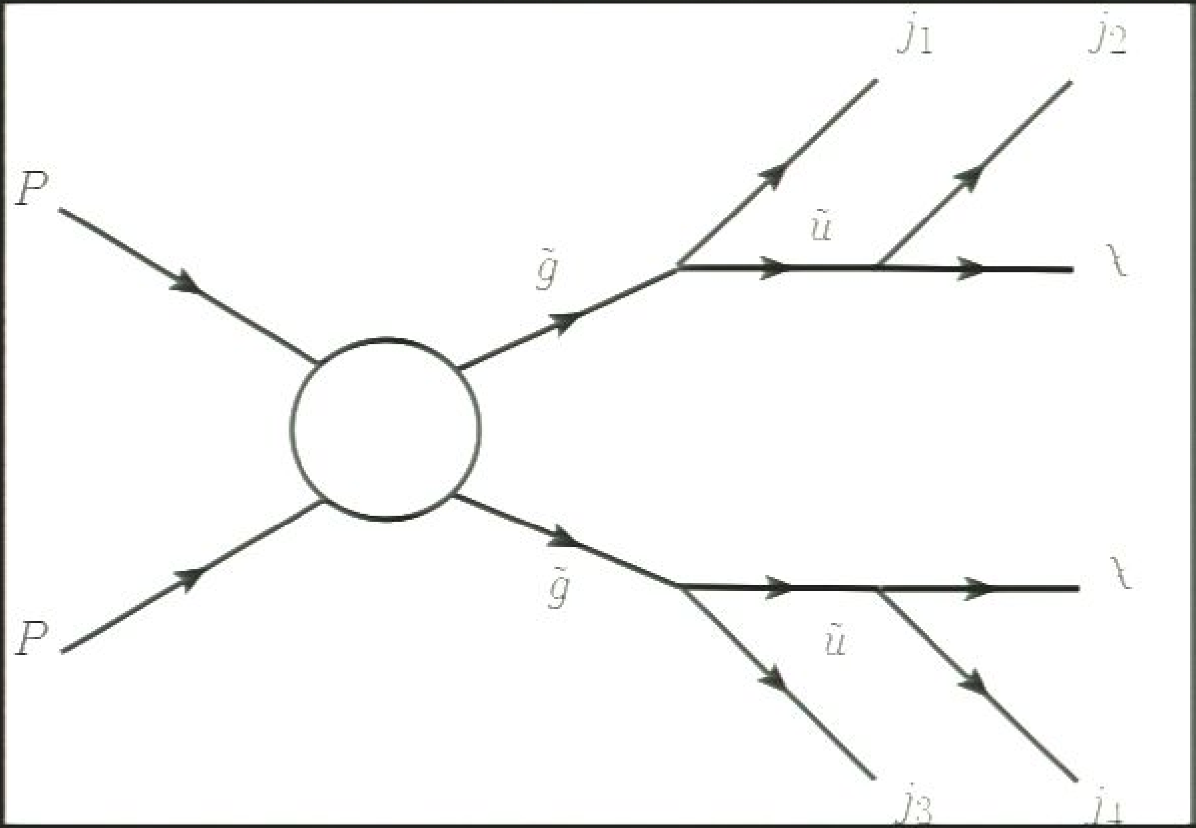

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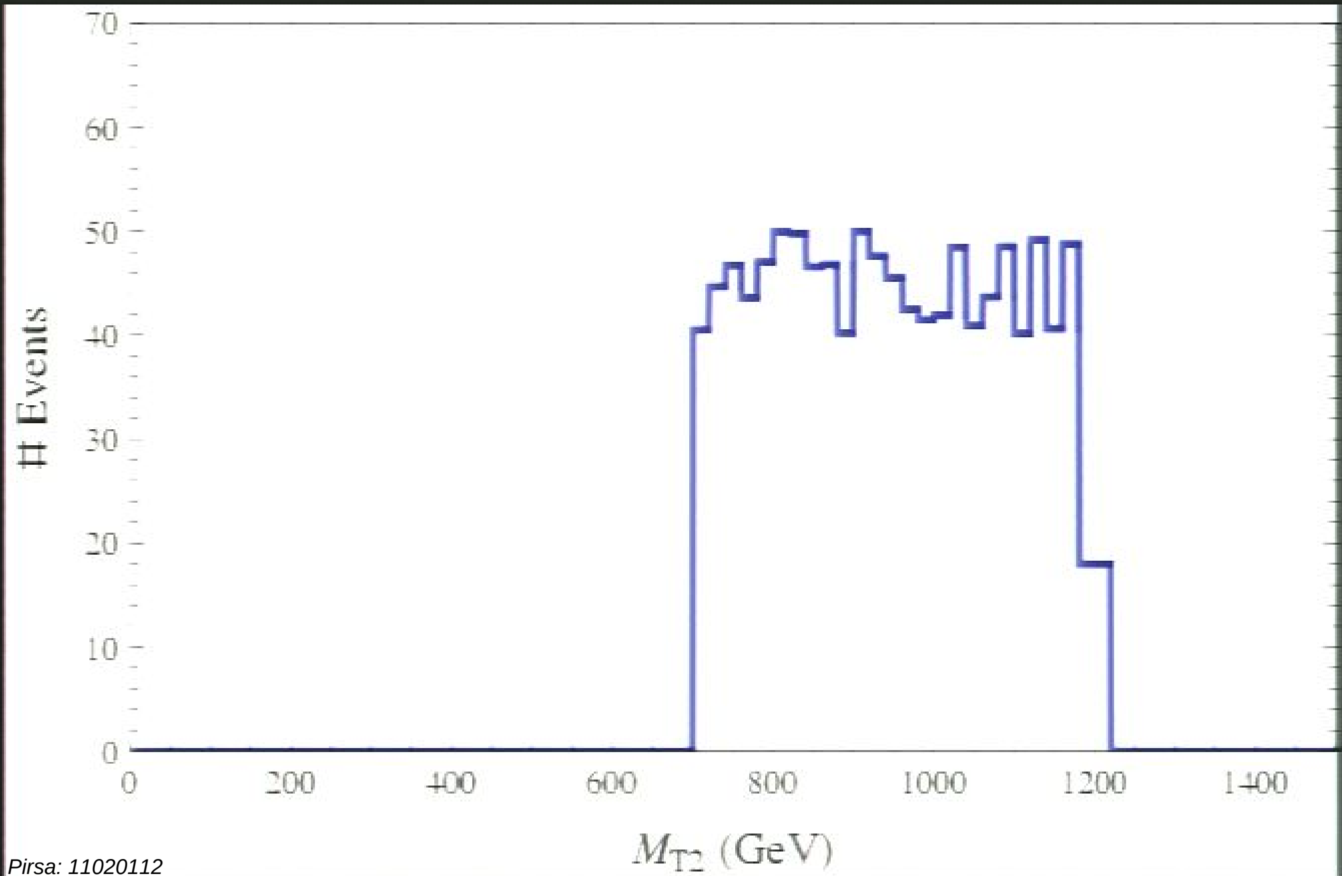
Statistically, one can use the following variable to increase the probability to have the true combination

$$M_{T2}(\mu_\chi) \equiv \min_{p_T^{\chi_1}+p_T^{\chi_2}=\not{p}_T} \left[\max[M_T(j1, j2, \chi_1 : \mu_\chi), M_T(j3, j4, \chi_2 : \mu_\chi)]\right]$$

Lester and Summers '03



$m_{\tilde{g}} = 1.2$ TeV

$m_{\tilde{u}} = 1.0$ TeV

$m_\chi = 700$ GeV

$\mu_\chi = 700$ GeV

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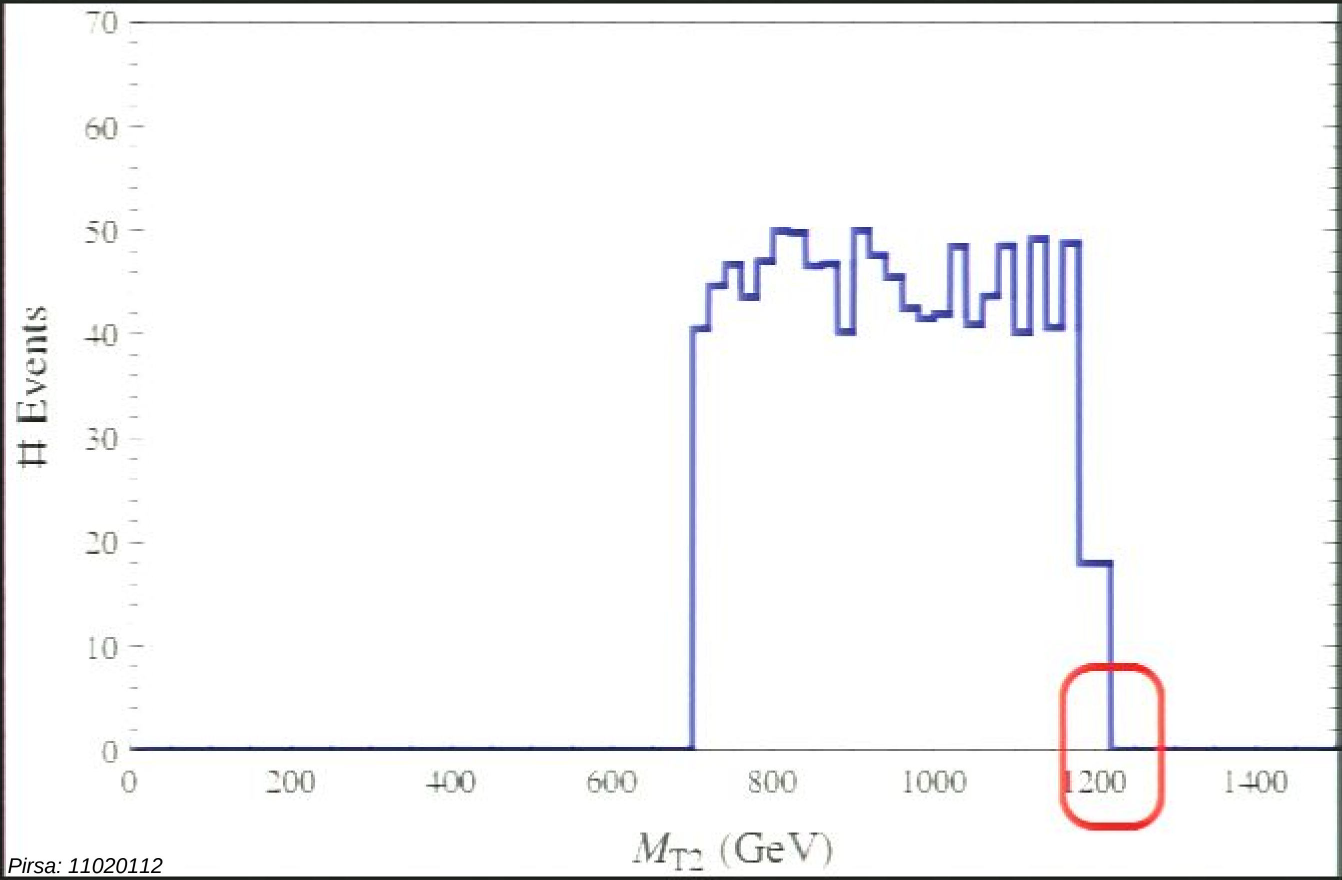

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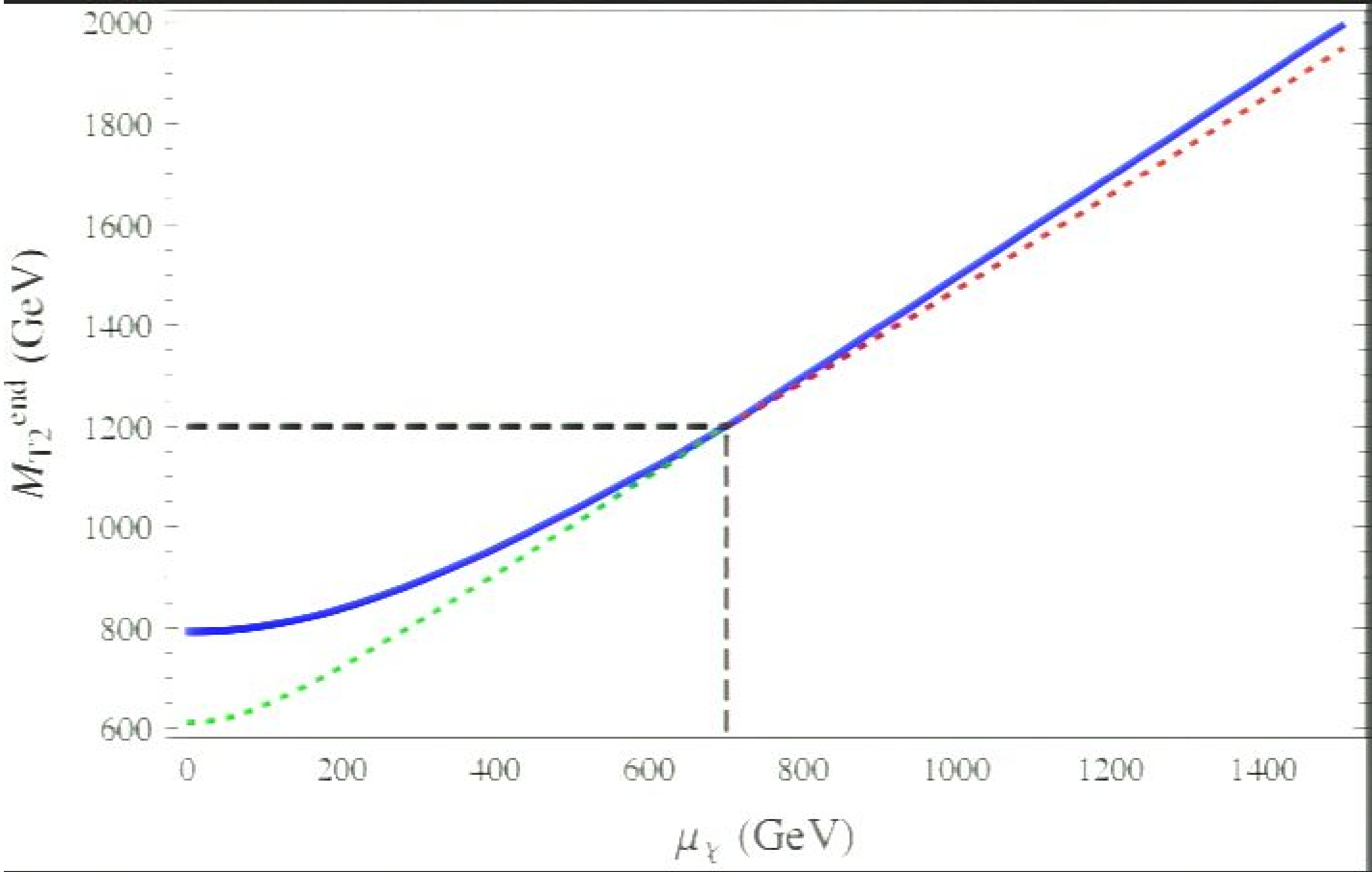
$m_\chi = 700$ GeV

$\mu_\chi = 700$ GeV

The kink structure can further determin the dark matter mass

Cho, Choi, Kim, Park '07



$m_{\tilde{g}} = 1.2$ TeV

$m_{\tilde{u}} = 1.0$ TeV

$m_\chi = 700$ GeV

When varying the trial dark matter mass from below to above the true value, the MT2 curve changes the slope

This sounds very nice. But, if LHC sees excess in this channel, one should first determine the dark matter event topologies before perform mass measurements

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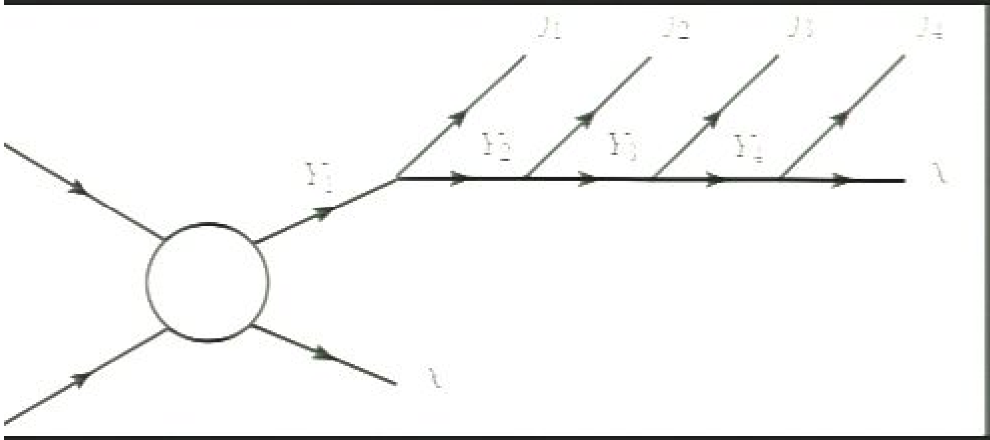
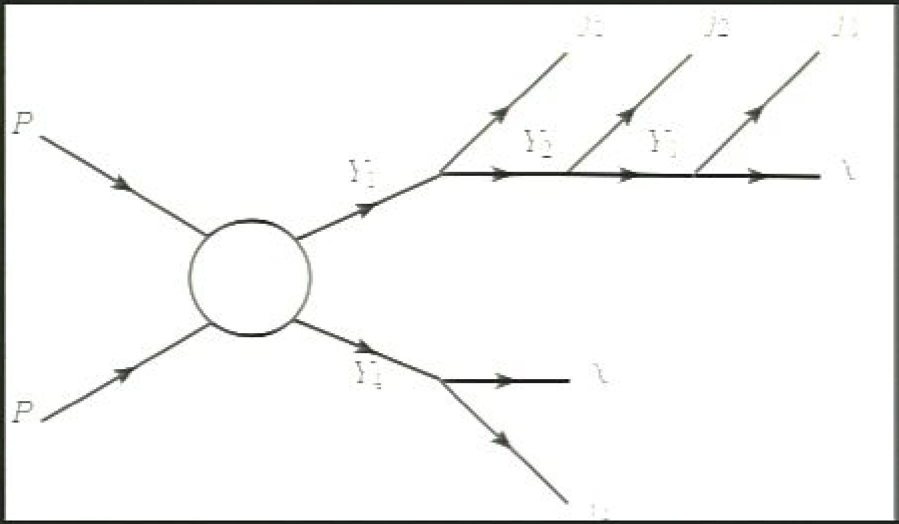
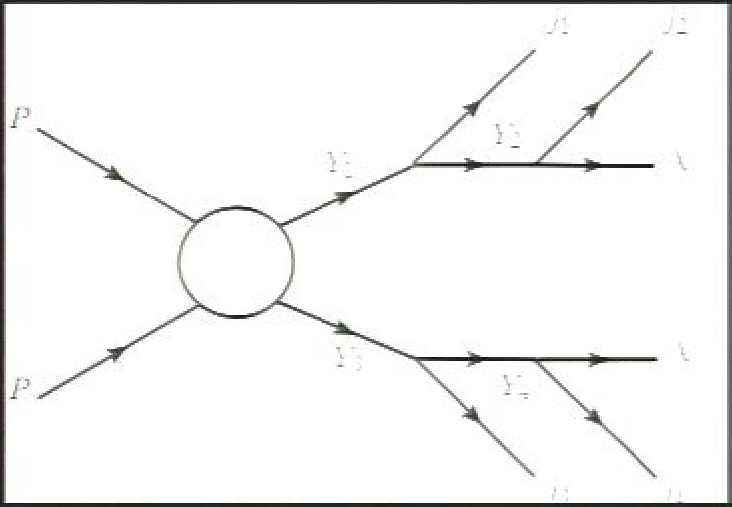


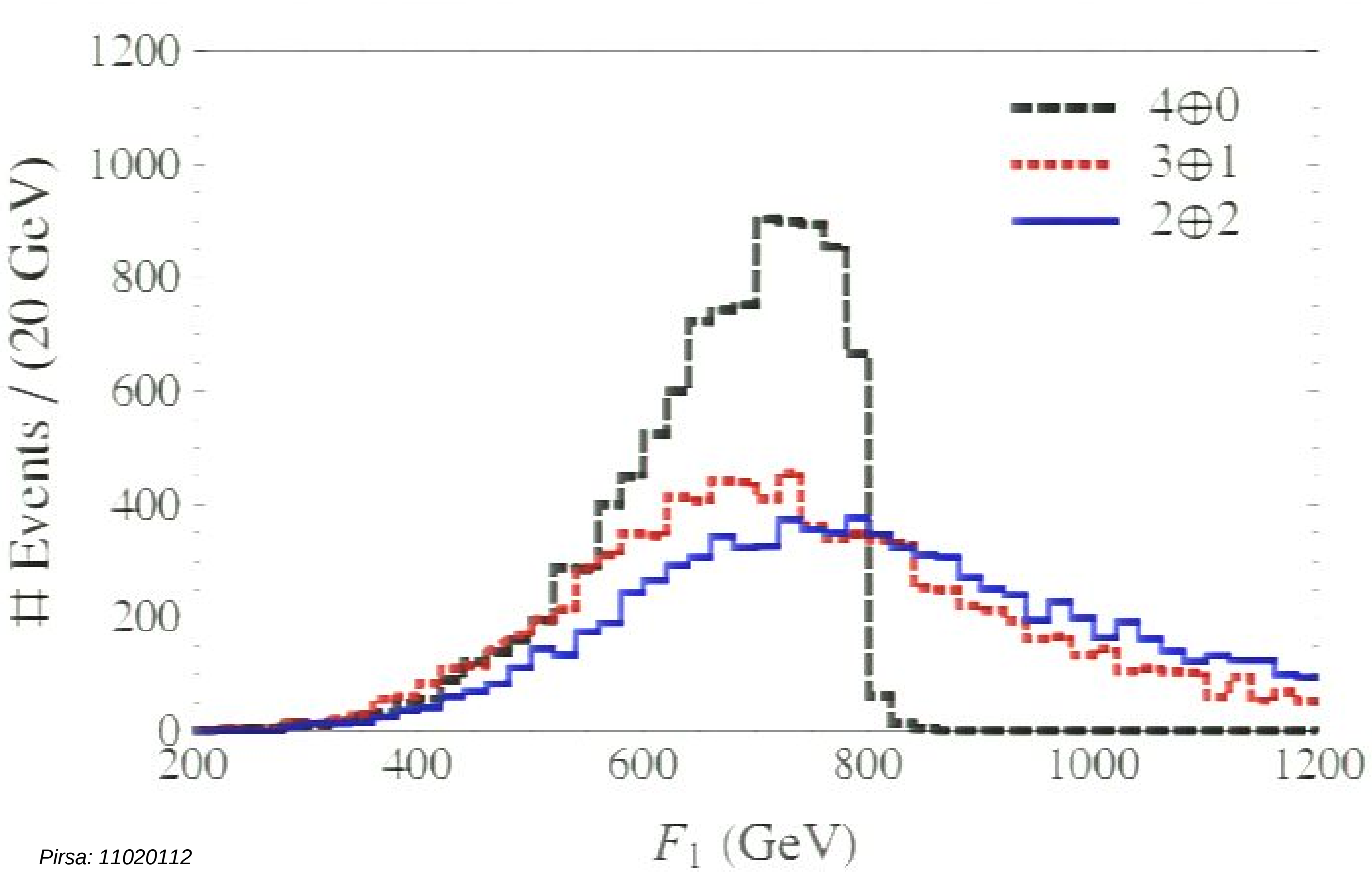




YB, Cheng, 2010, submitted to JHEP

The invariant mass of the visible particles on the same chain have an end-point

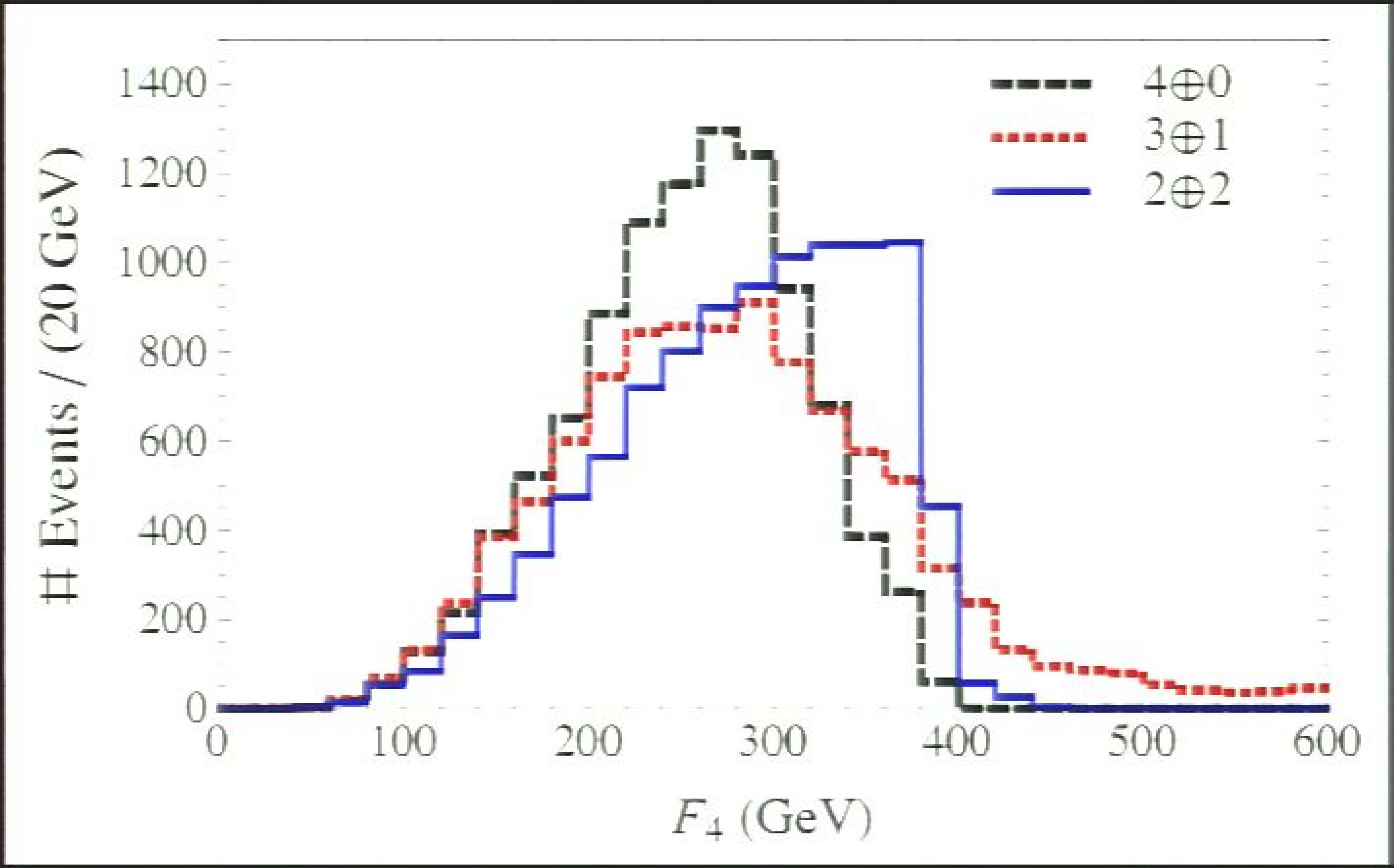
$$F_1(p_1, p_2, p_3, p_4) = \mathrm{inv}[p_1, p_2, p_3, p_4]$$



theory level or parton level

YB, Cheng, 2010, submitted to JHEP

$$F_4(p_1, p_2, p_3, p_4) = \min\Big[\bigcup_{i,j} \max\big(\mathrm{inv}[i,j], \mathrm{inv}[k,l]\big)\Big] \quad \text{for} \quad \epsilon^{klij} \neq 0$$



After detector simulation, one can use a function to fit the distribution and obtain the slope or the sharpness of the end point

For around 1000 signal events, one can use the existence of end-points to identify the dark matter event topologies

We can then measure the dark matter mass, spin, couplings, calculate its relic abundance and confirm the WIMP coincidence

YB, Cheng, 2010, submitted to JHEP

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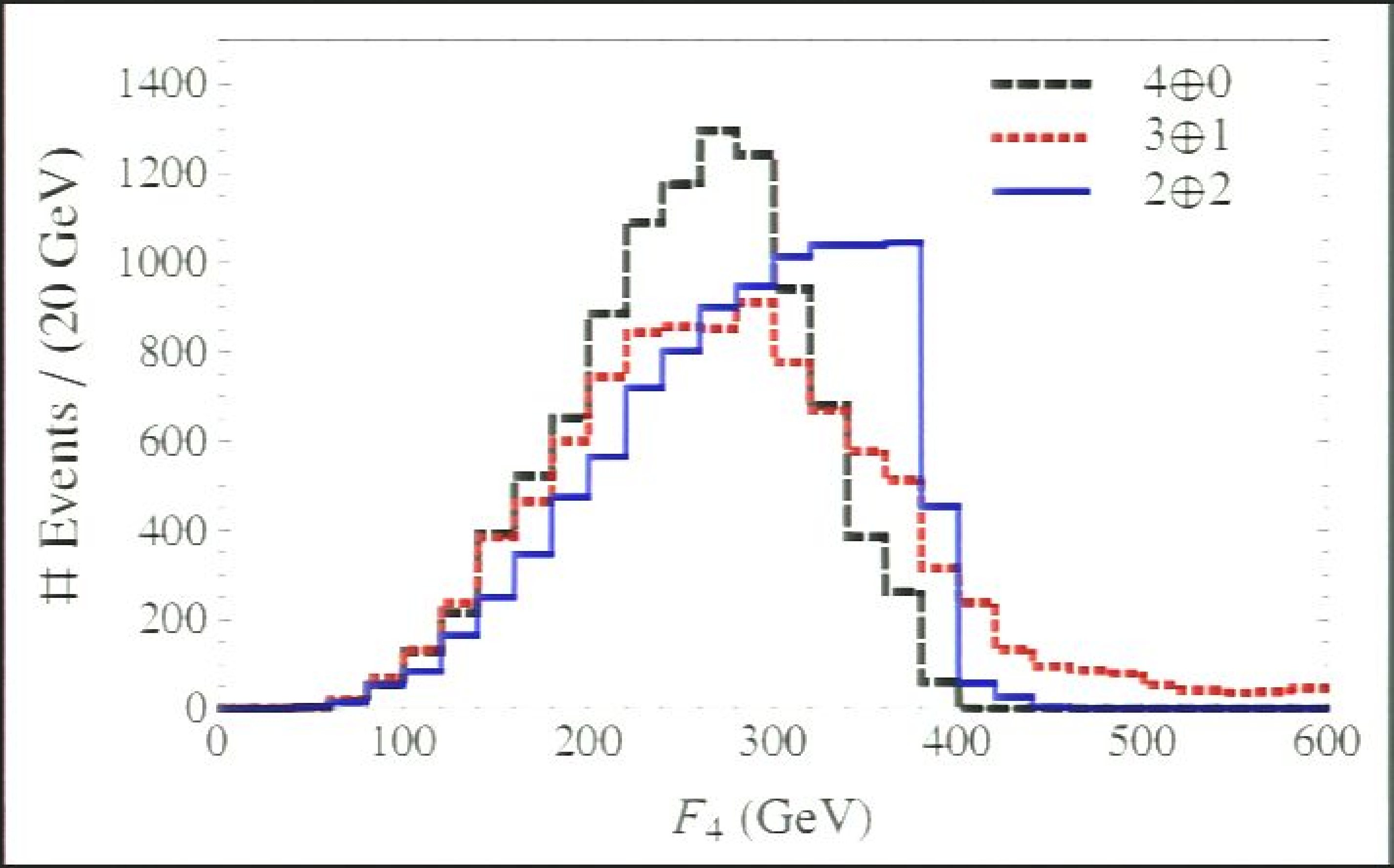

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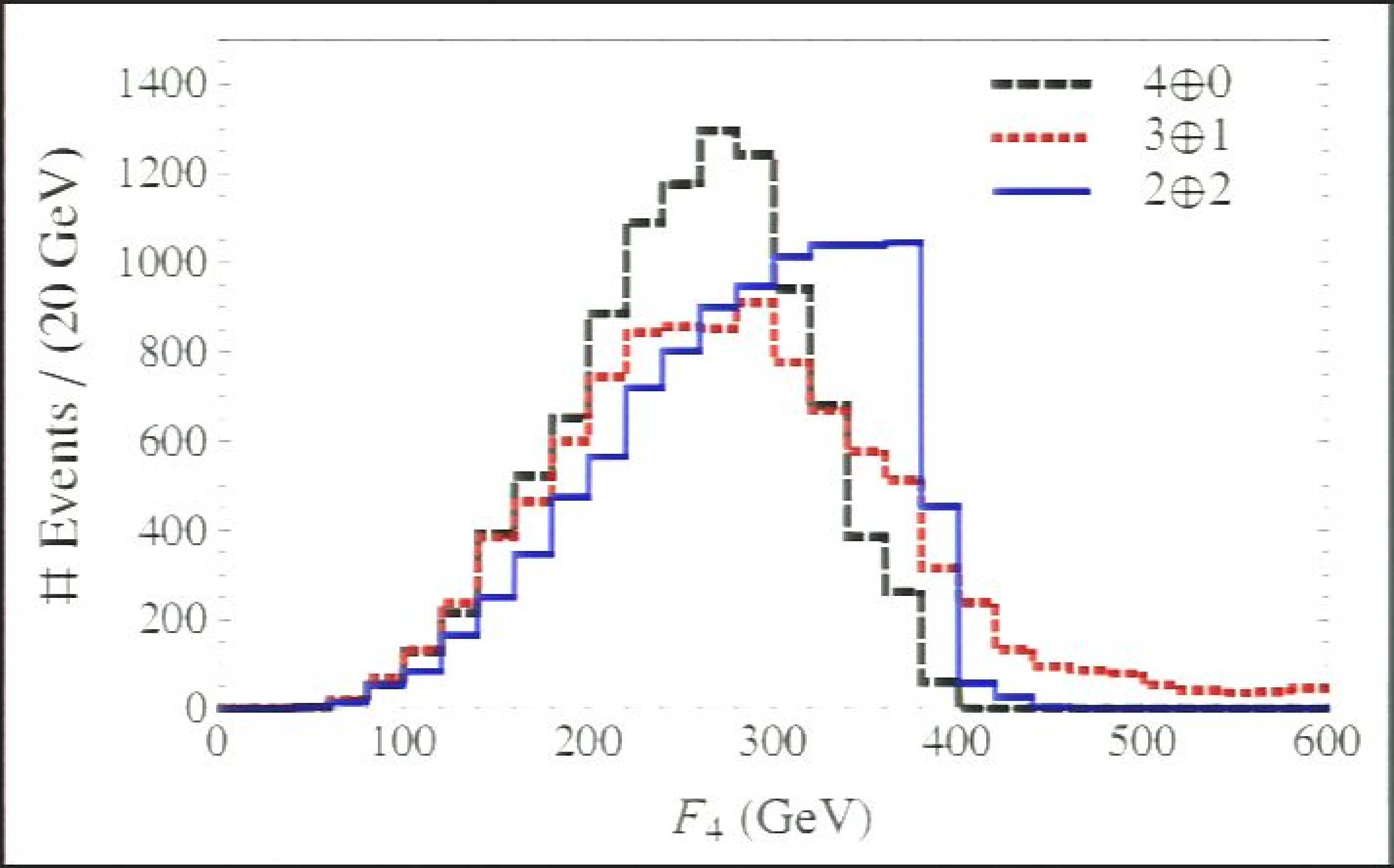

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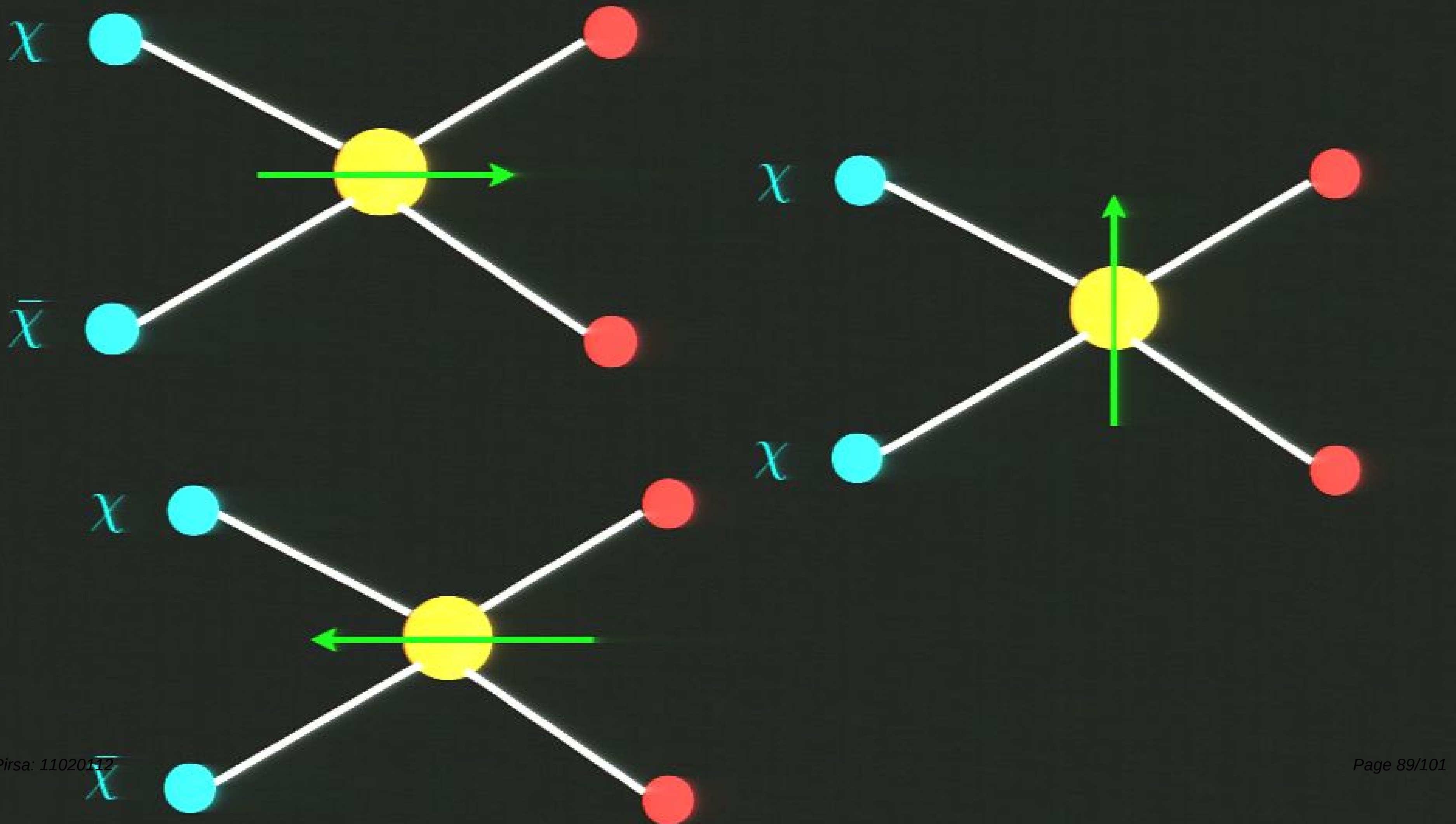
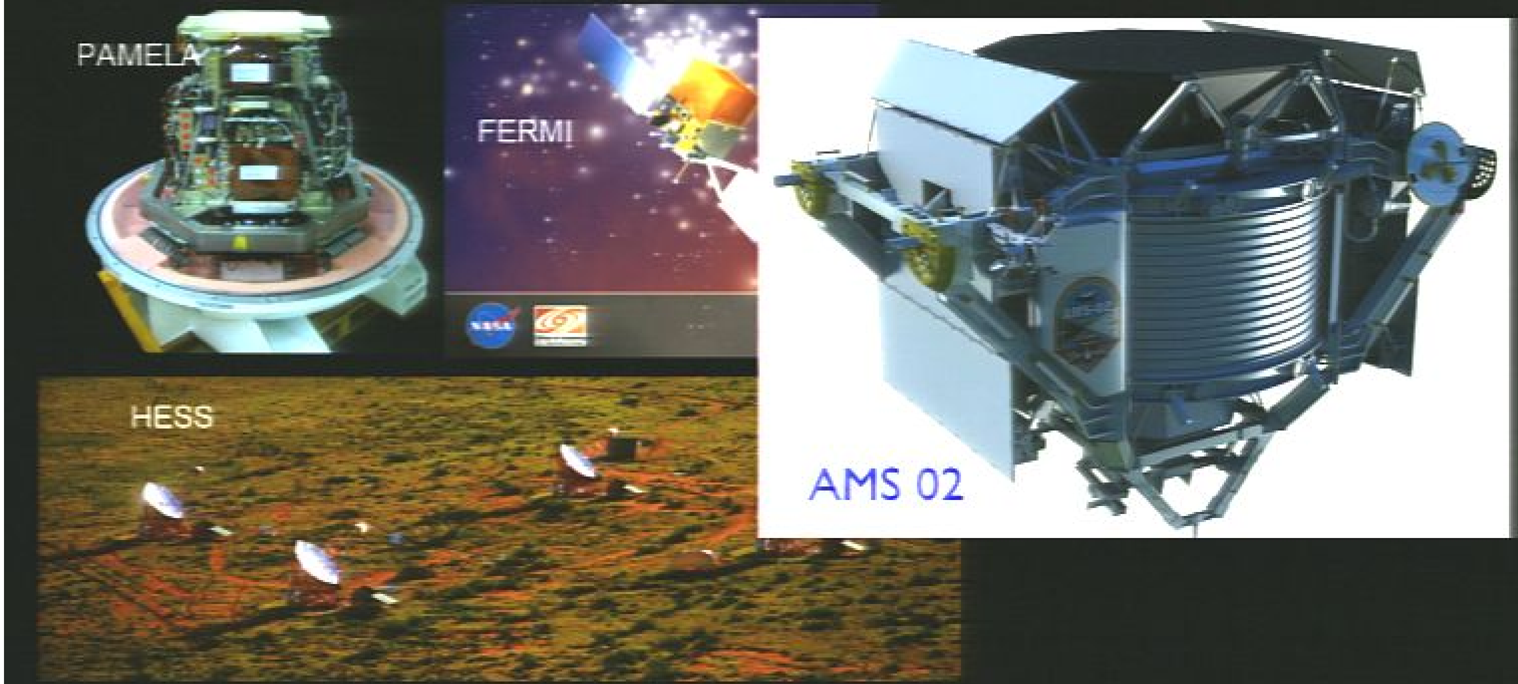
We need the synergy of three experimental approaches to understand the complete story of the dark matter sector



Outlook

Outlook



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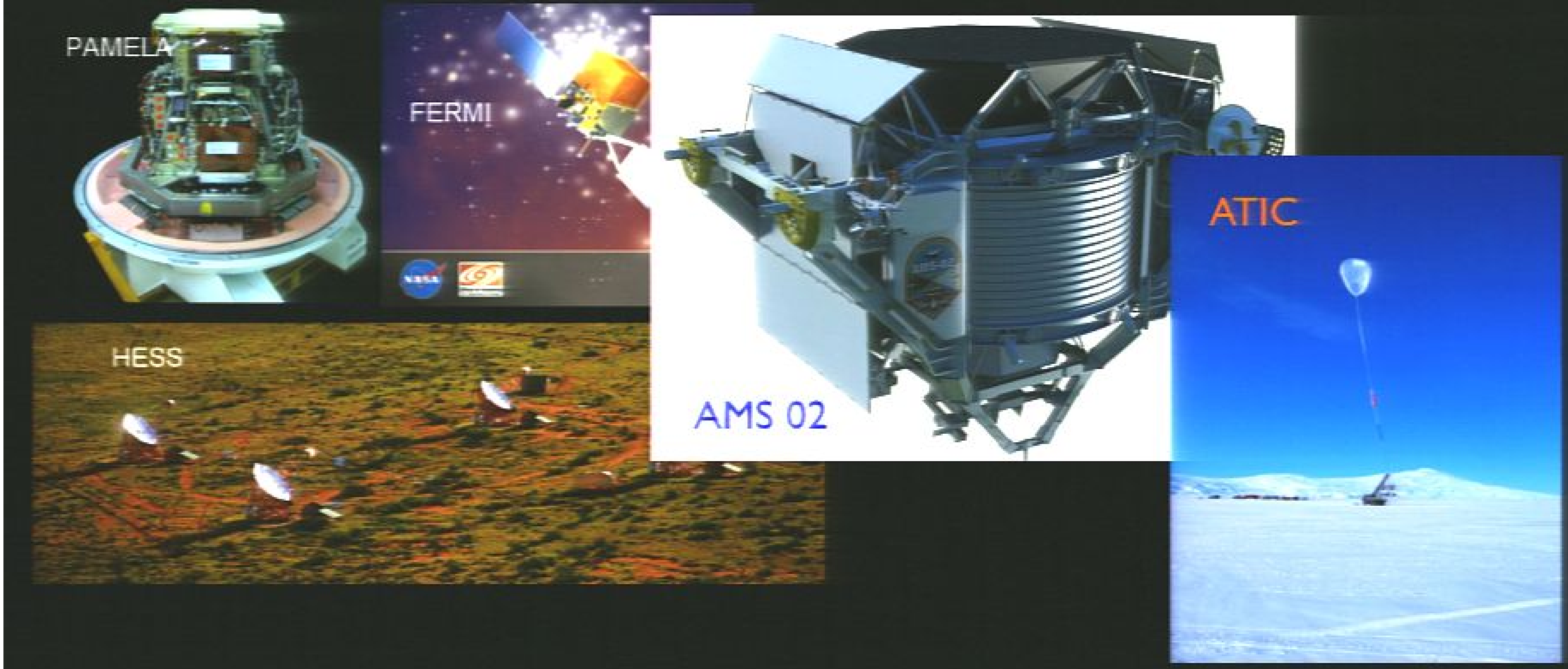

Outlook

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PAMELA
FERMI
AMS 02
ATIC
HESS
IceCube
1000m
ν_e
SNO+
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Outlook


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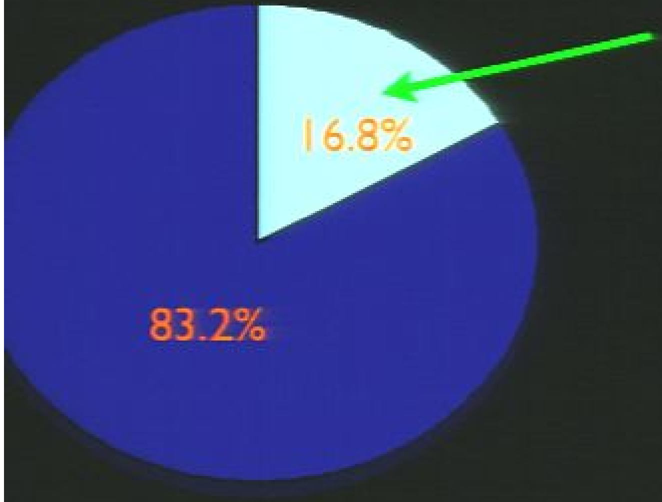
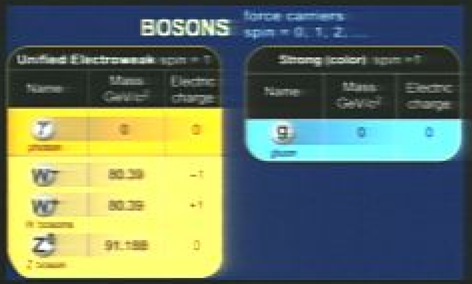


Standard Model



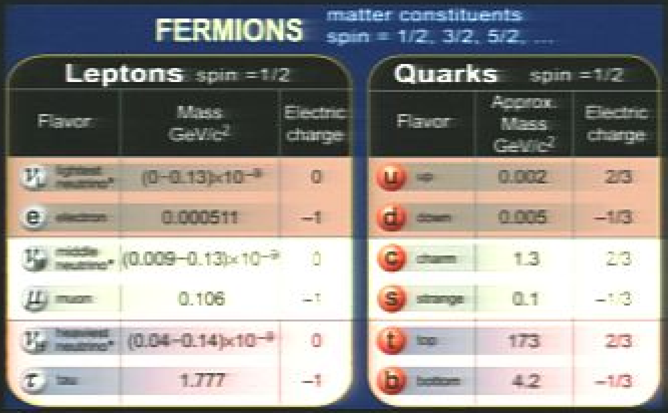
BOSONS force carriers spin = 0, 1, 2, …

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



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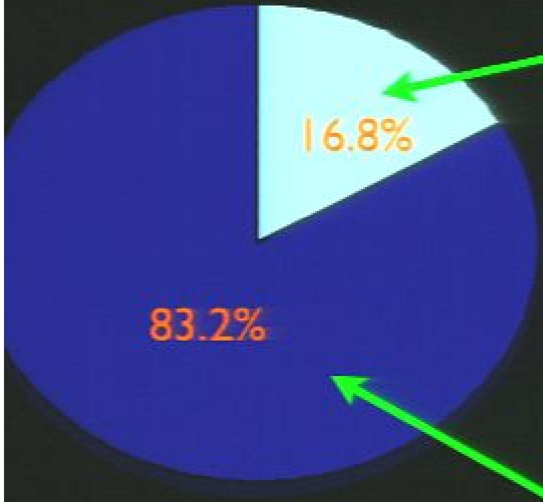
Leptons spin = 1/2

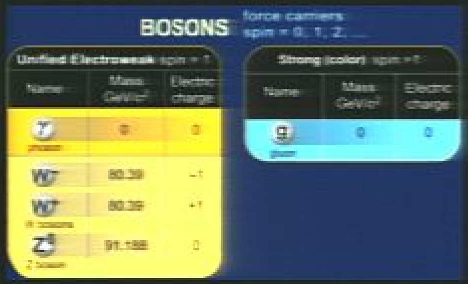
Flavor	Mass GeV/c²	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	−1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	−1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	−1

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

Standard Model





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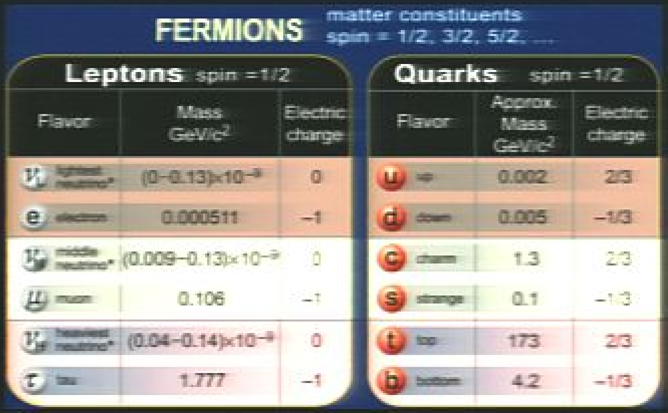

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ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	−1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	−1

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

Standard Dark Model

Thanks