Fermion Portal Dark Matter

Yang Bai

Physics Department, Univ. of Wisconsin-Madison

@Experimental Physics Center of IHEP

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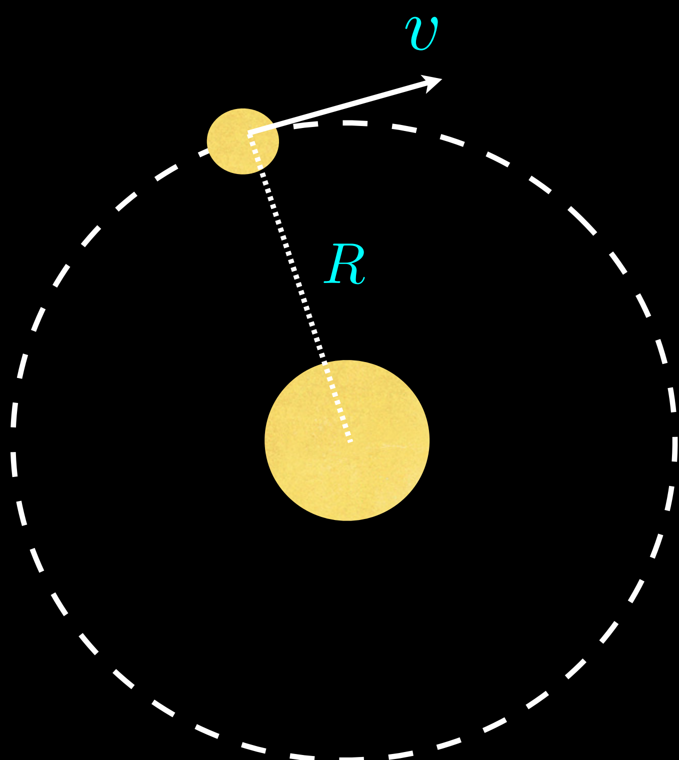
Outline

- Evidence of dark matter
- Methods to probe these interactions
- Simplified dark matter models
- Quark and lepton portal dark matter models
- Conclusion

Image Credit: NASA/Swift
Science Team/Stefan Immler

Newton's law

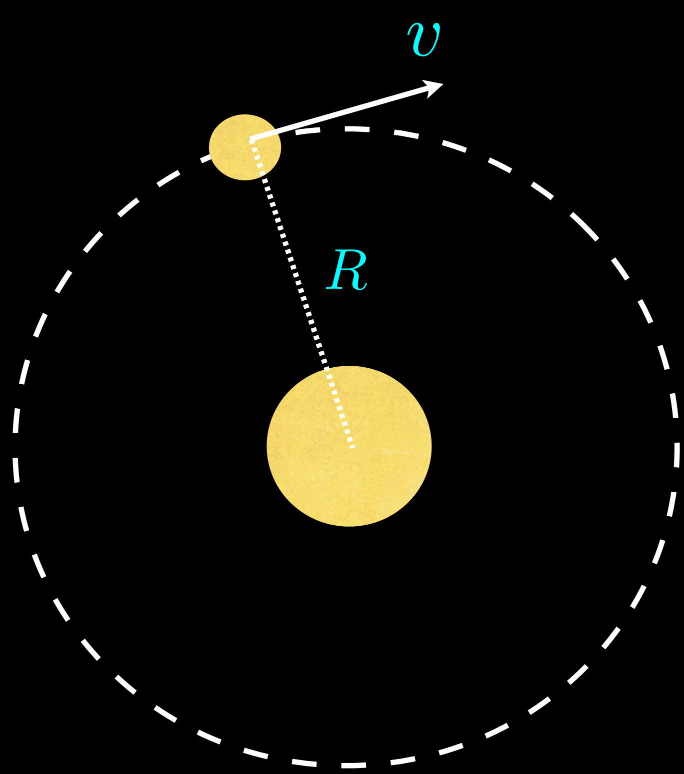


$$m\frac{v^2}{R} = G\frac{mM}{R^2}$$

$$v = \frac{\sqrt{GM}}{\sqrt{R}}$$

The physics law works independent of whether you can see the M matter or not

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

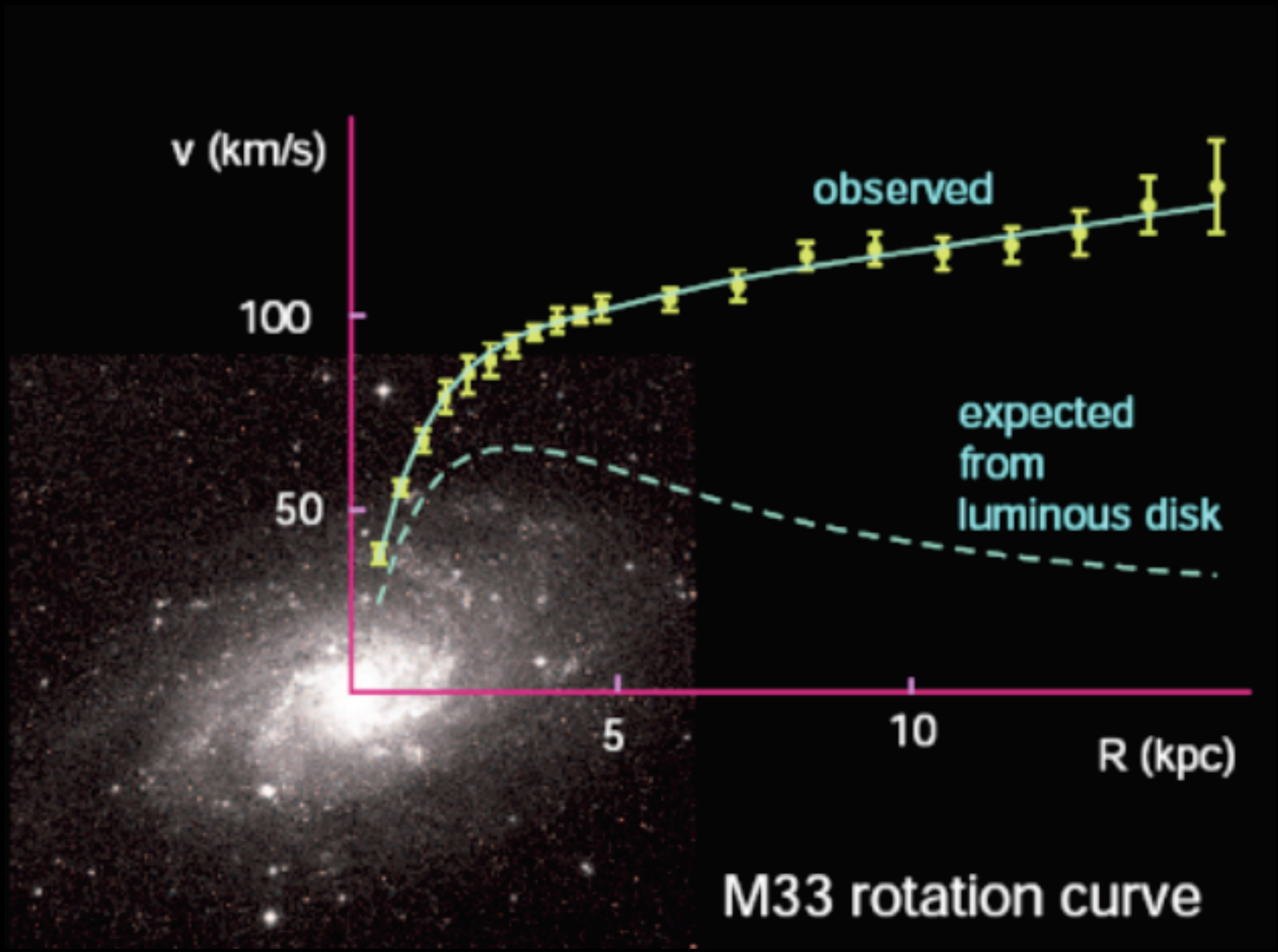


Assuming all the mass of galaxies come from the region where stars are visible

From Kepler's law, we expect

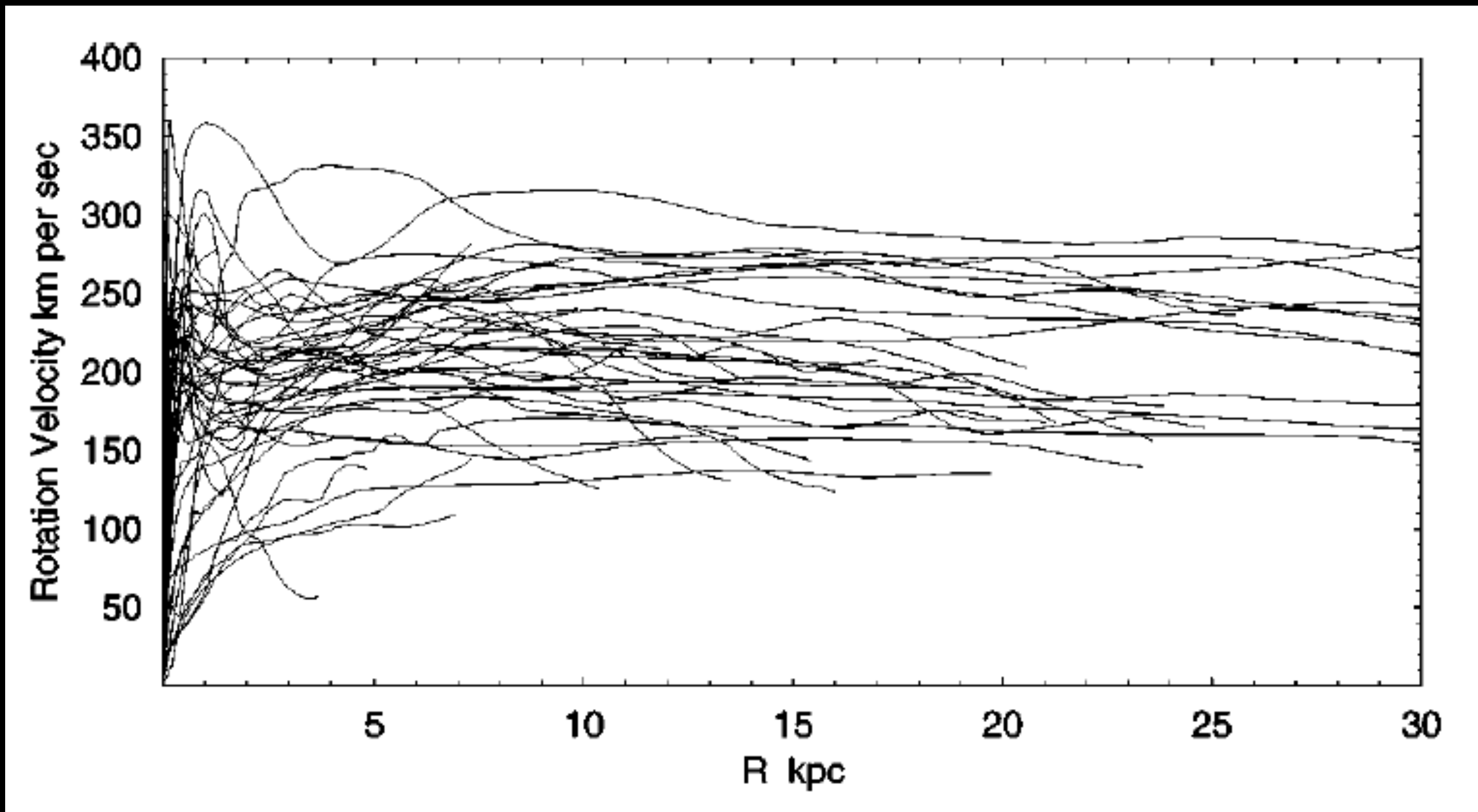
$$v \sim \frac{1}{\sqrt{R}}$$

Galaxy Rotation Curve



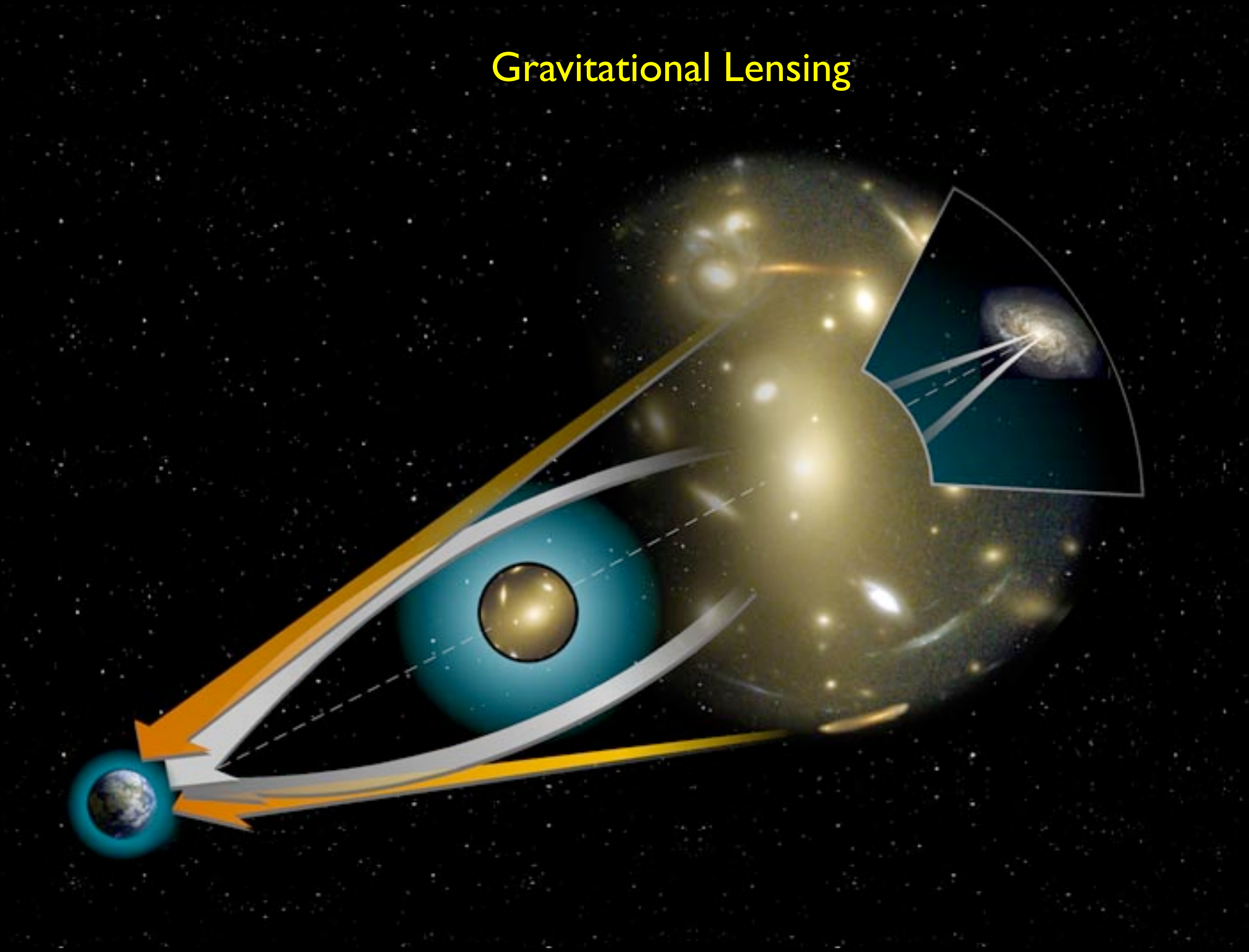
Missing matter exists beyond the visible star region

Here are rotation curves for more galaxies



Sofue and Rubin

More Evidence



More Evidence

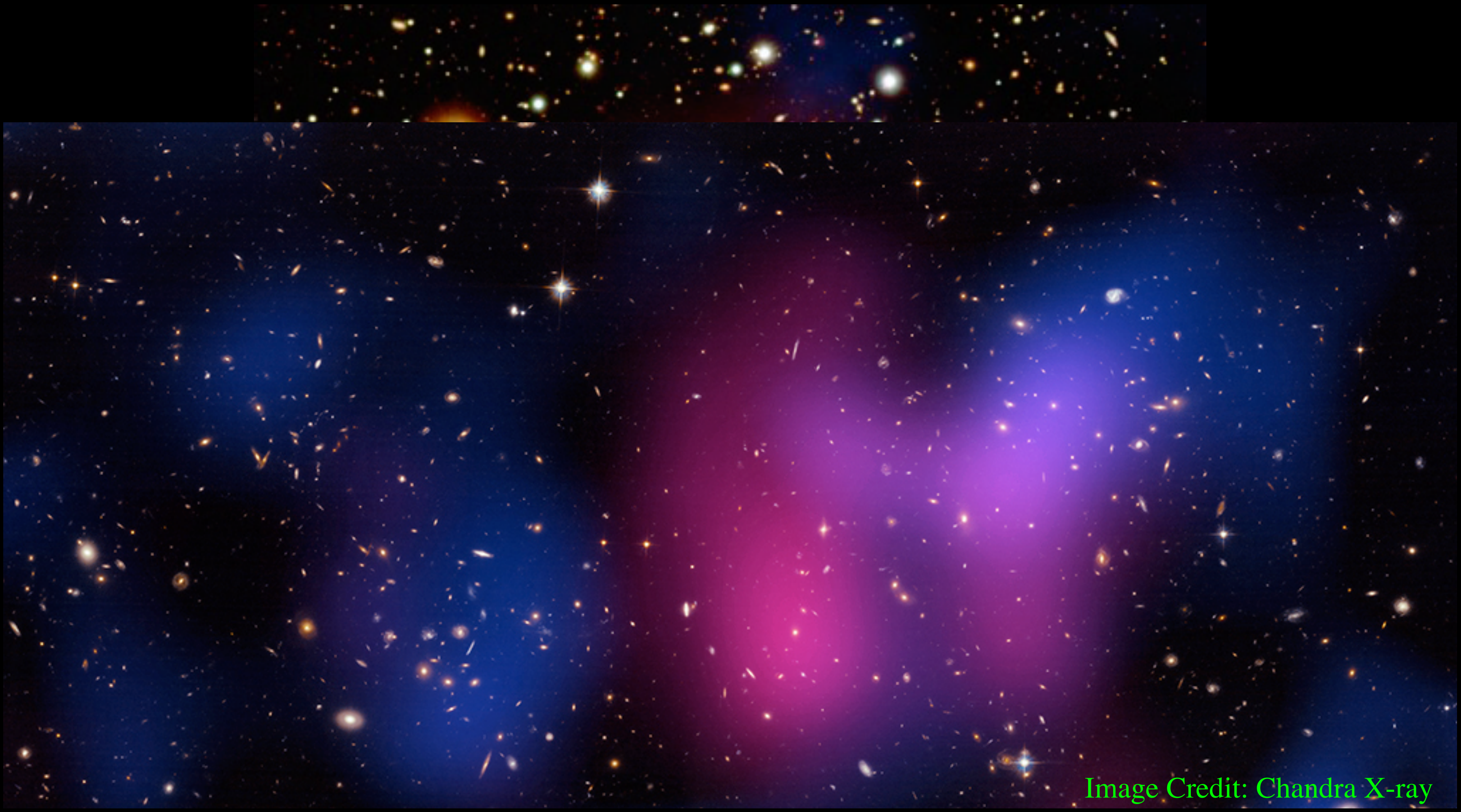
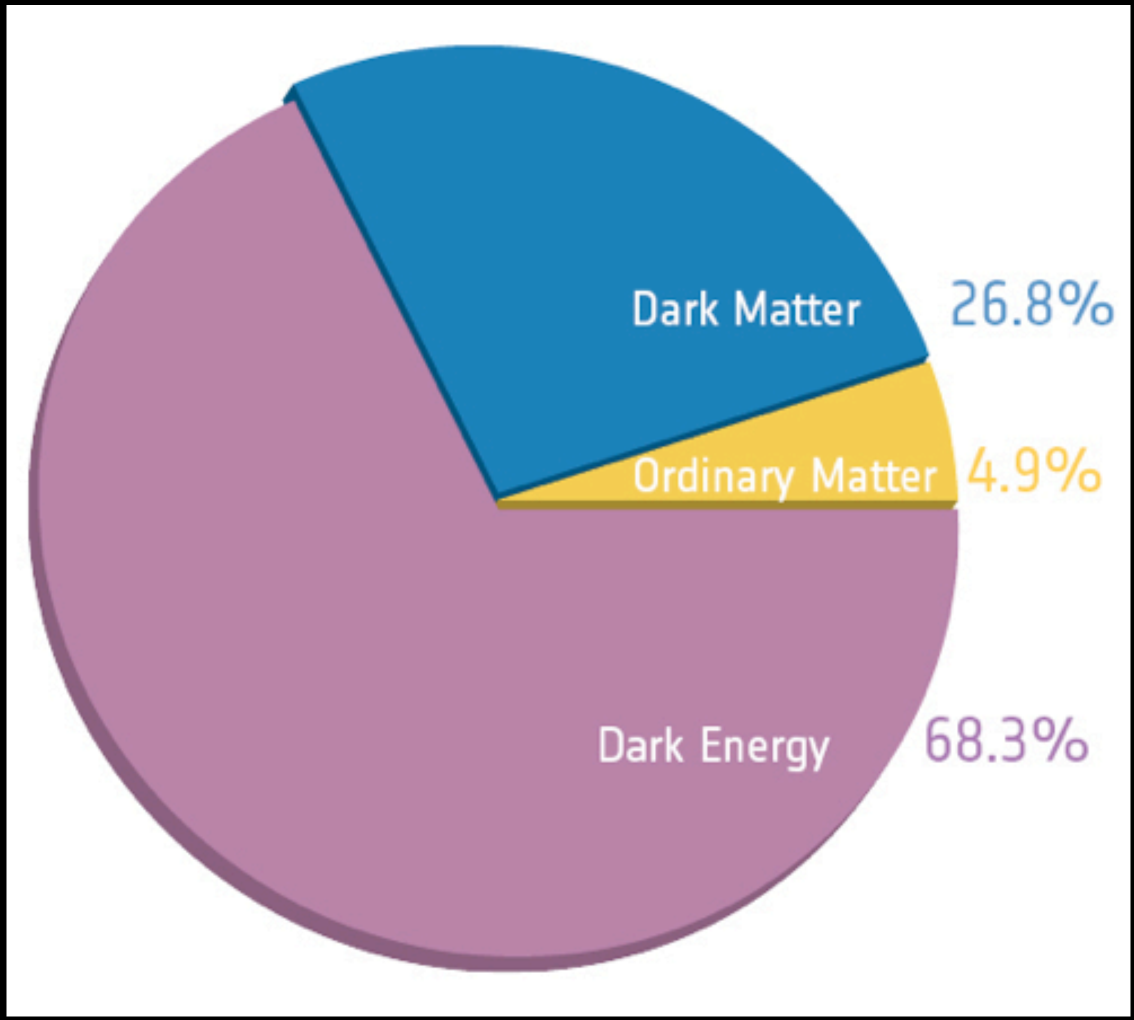


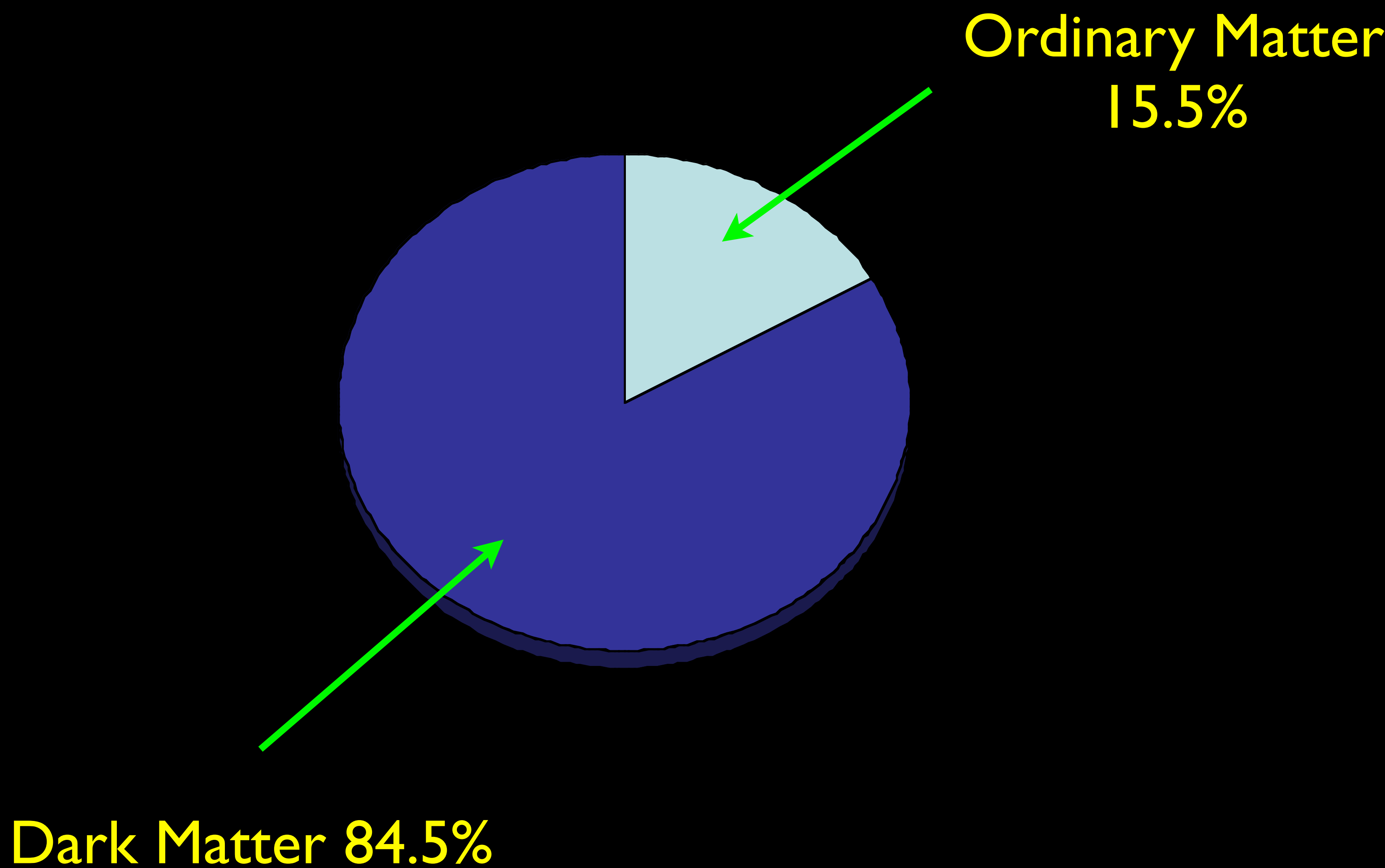
Image Credit: Chandra X-ray observatory

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



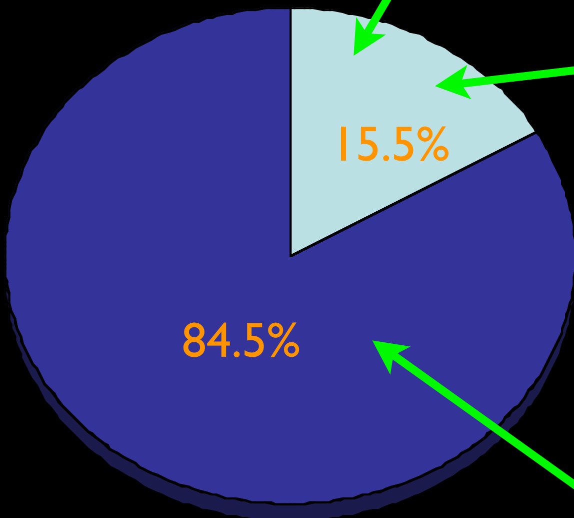
from PLANCK

and the *matter* pie of our universe



from PLANCK

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



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

Higgs

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

electroweak symmetry breaking

Dark Matter Sector ???

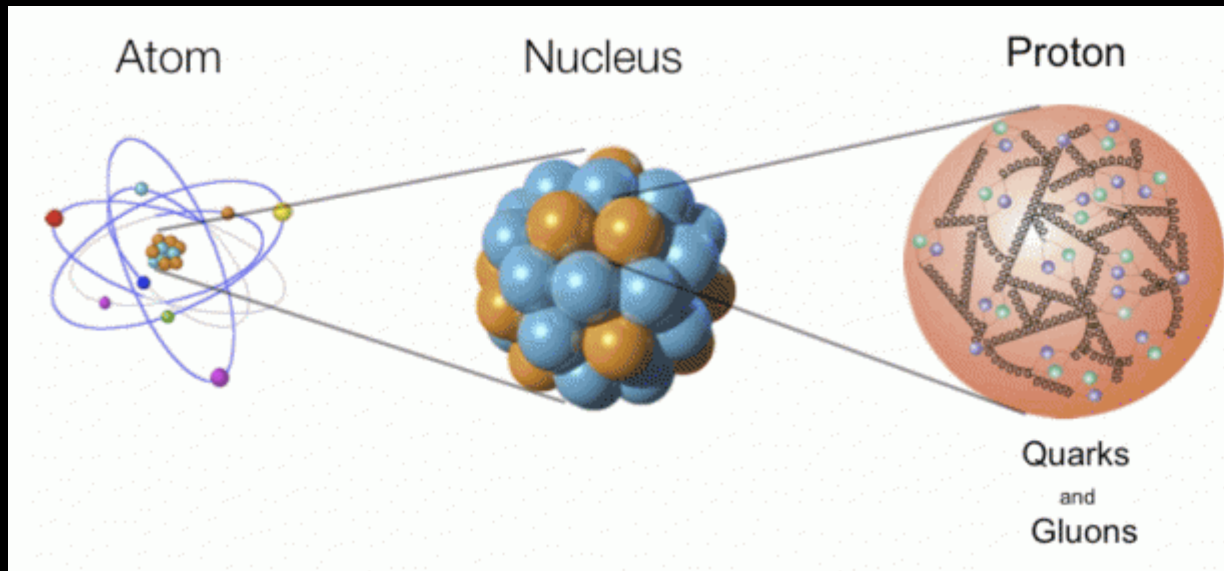
All evidence only requires the gravitational interaction between dark matter and ordinary matter

Why we care about its additional interactions?

- We don’t know its properties. For ordinary matter, we understand their particle properties
- It is non-trivial to have

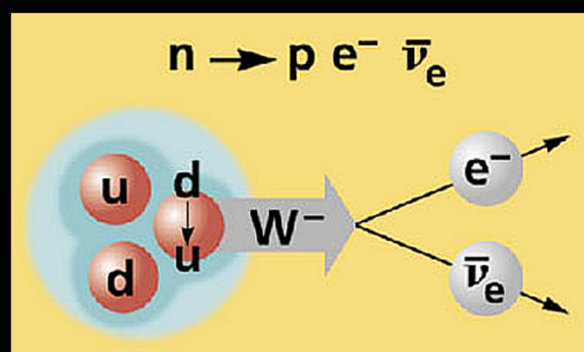
$$\frac{\text{Dark Matter} \quad (84.5\%)}{\text{Ordinary Matter } (15.5\%)} = 5.45$$

Ordinary Matter

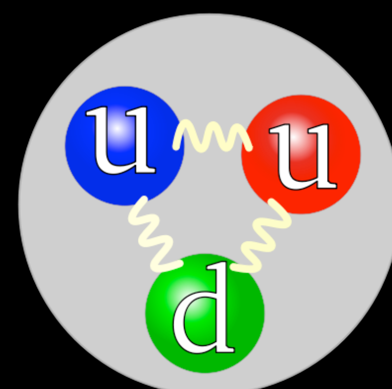


electromagnetic

weak



strong



Matter and anti-matter asymmetry

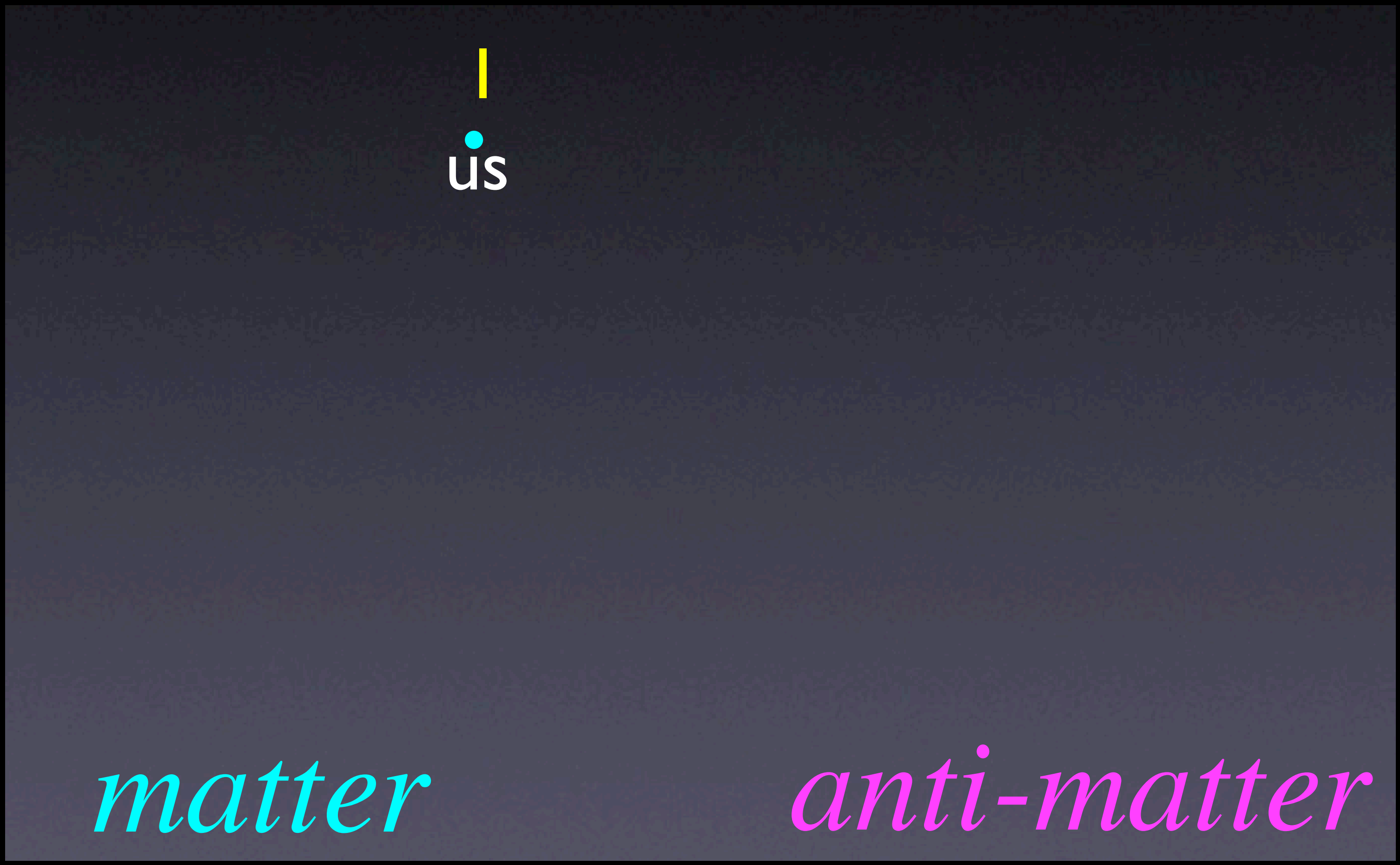
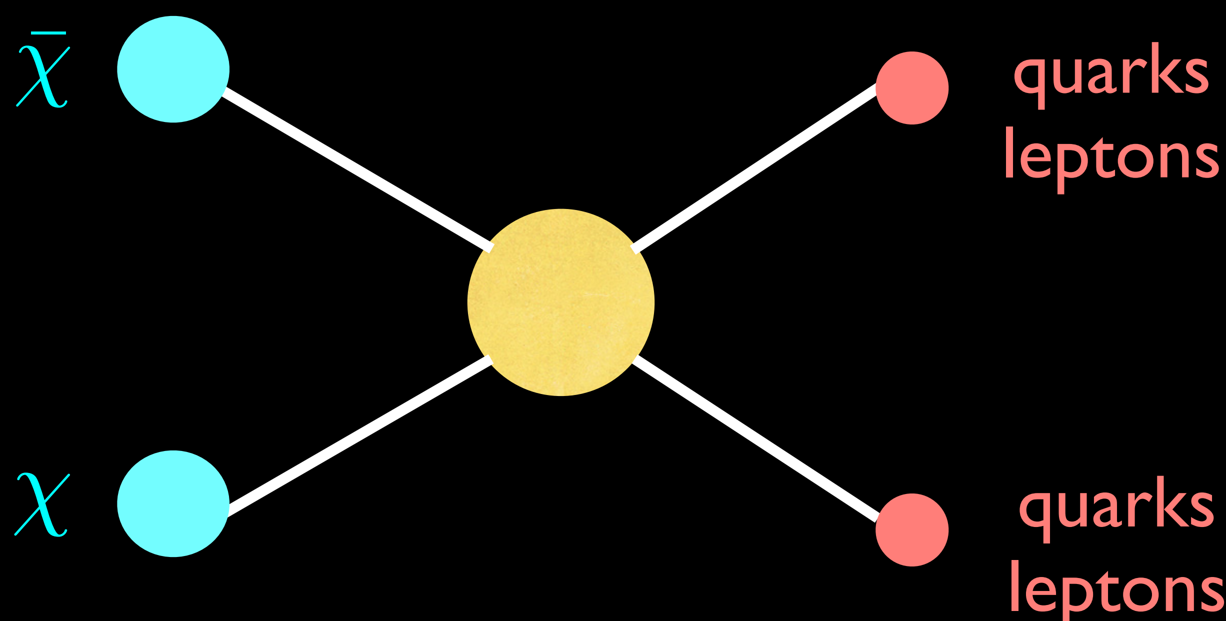


Image Credit:
Hitoshi Murayama

$$\frac{\text{Dark Matter (84.5\%)}}{\text{Ordinary Matter (15.5\%)}} = 5.45$$

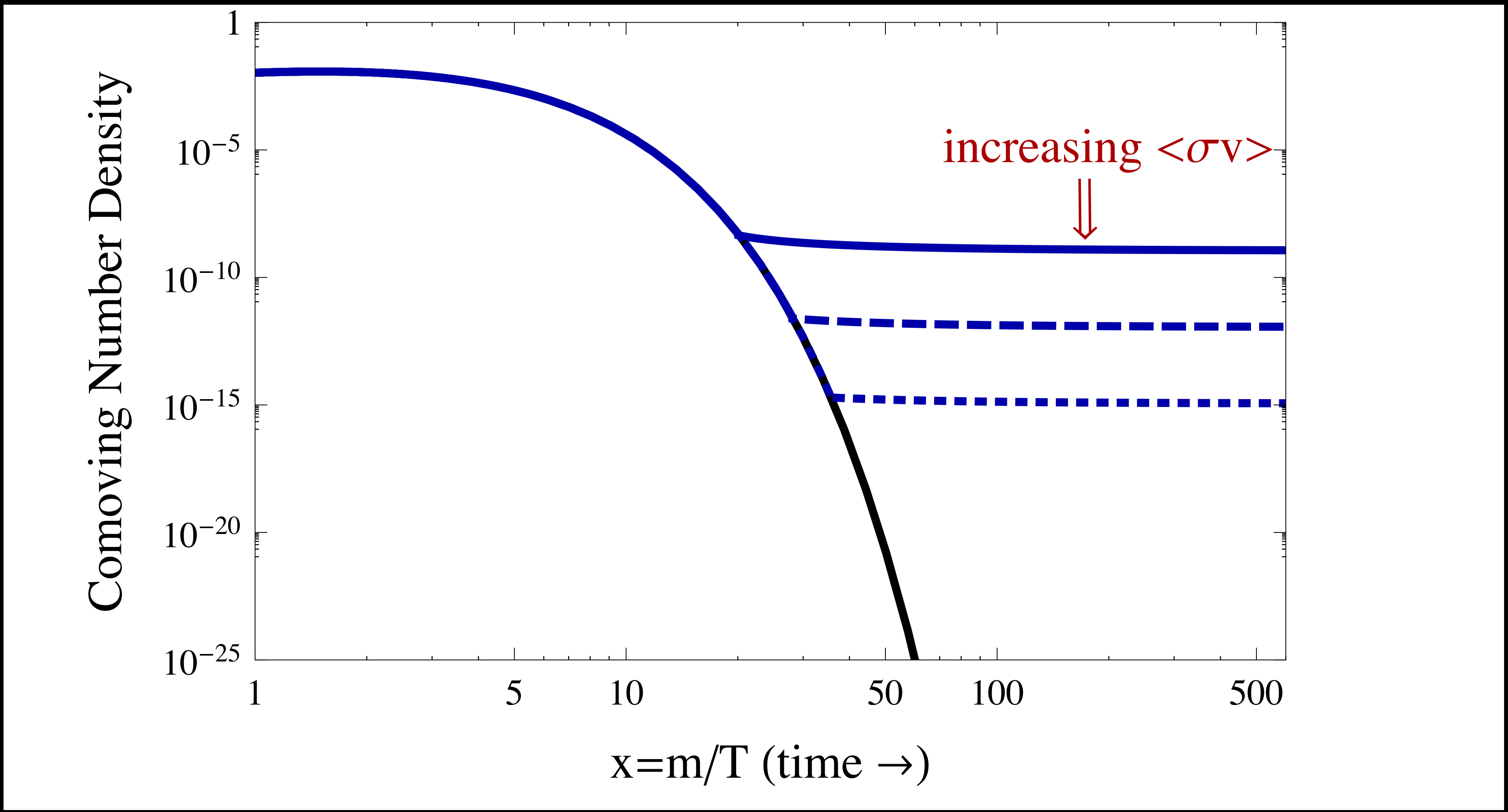
a deeper reason for relating the two kinds of matter?

simple and elegant: add other interactions



We can then calculate the relic density of dark matter

DM thermal relic abundance



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:

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

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

We should then ask, do those models contain WIMPs ?

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

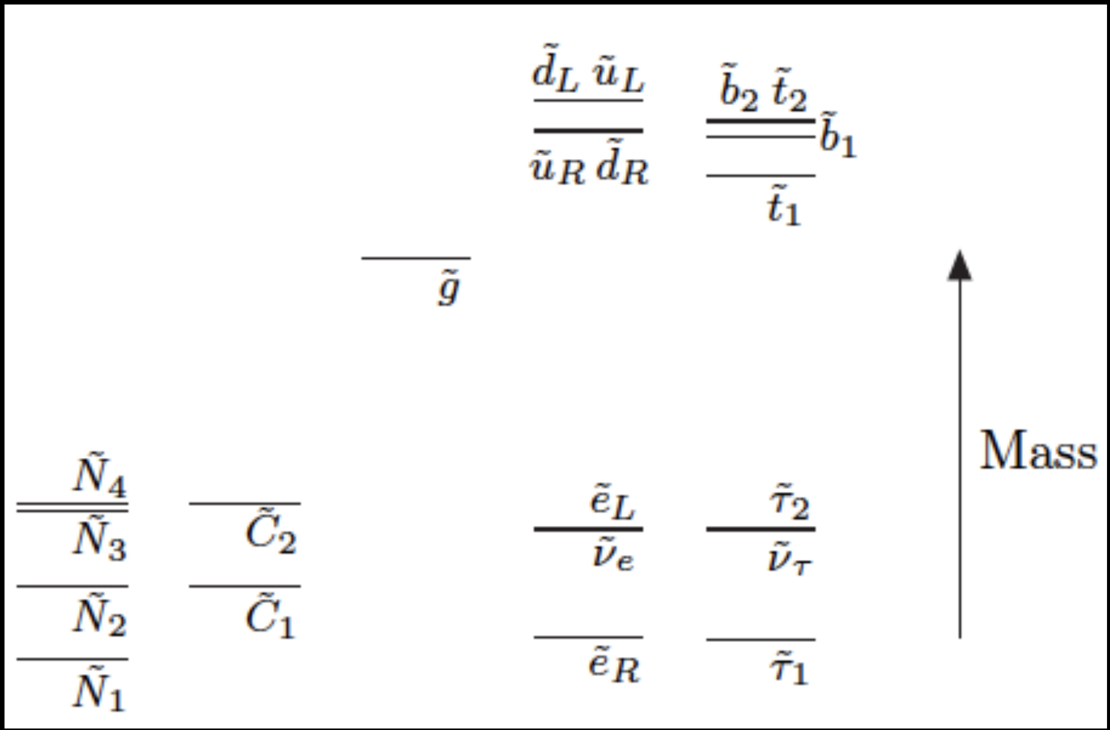
Our next question is whether there is a new stable neutral particle ?

Almost in every model of EWSB, there exists an 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

One example is the supersymmetry - the idea that all bosons and fermions in Nature have partners with opposite statistics. The fermionic photon, photino, is a plausible candidate of dark matter

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



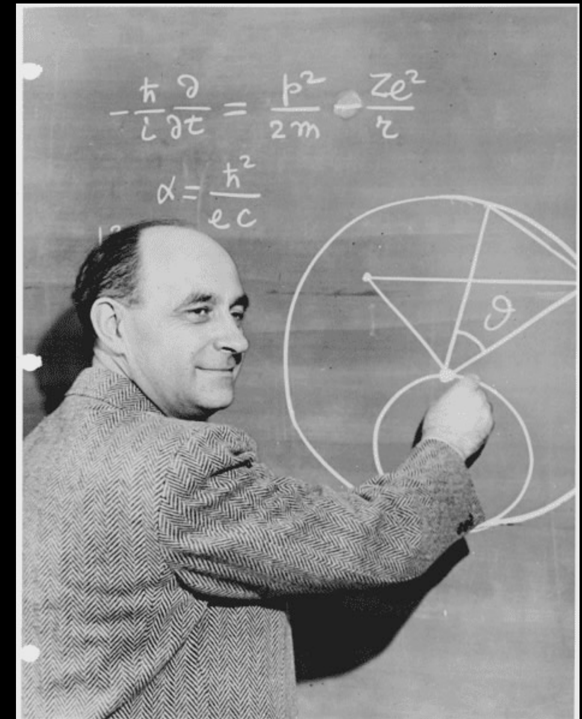
However, without a specific mechanism to generate superparticle masses, there are hundreds of thousands of different spectra

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

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

Sudarshan and Marshak, Feynman and Gell-Mann further deduced its V-A structure



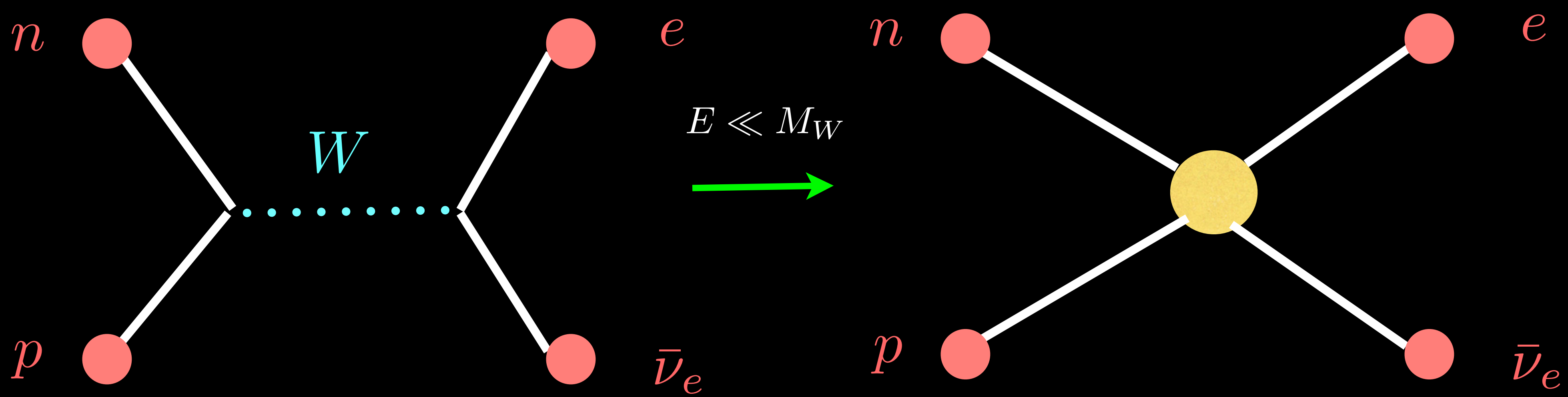
PHYSICAL REVIEW VOLUME 109, NUMBER 1 JANUARY 1, 1958

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 interaction in which, say, a π^0 goes to π^- and an electron goes to a neutrino. The weak decays of strange par-

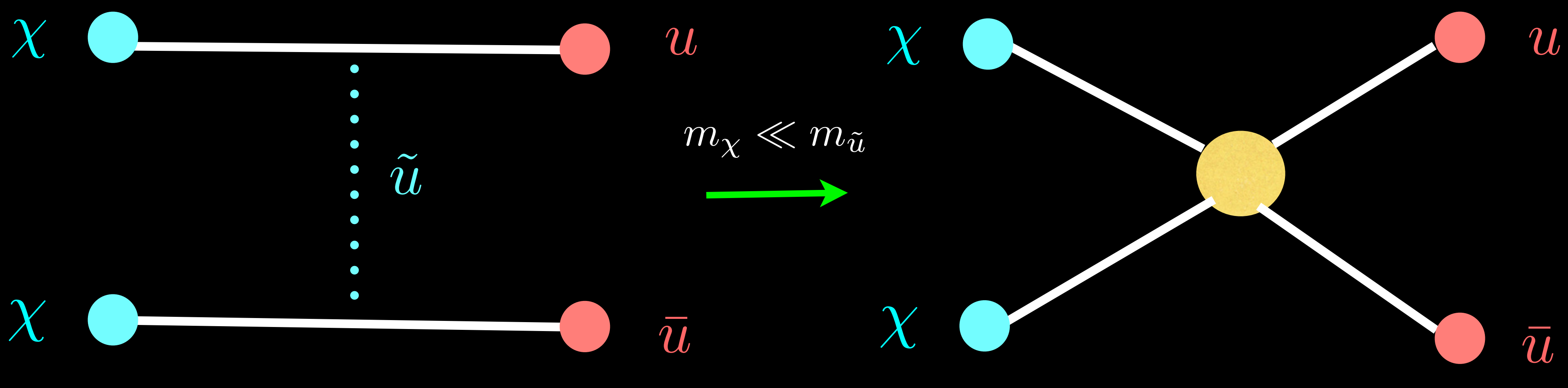
Now, we know that the beta decay is mediated by the weak interaction through exchanging of a W gauge boson



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

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

Similarly, for dark matter interactions

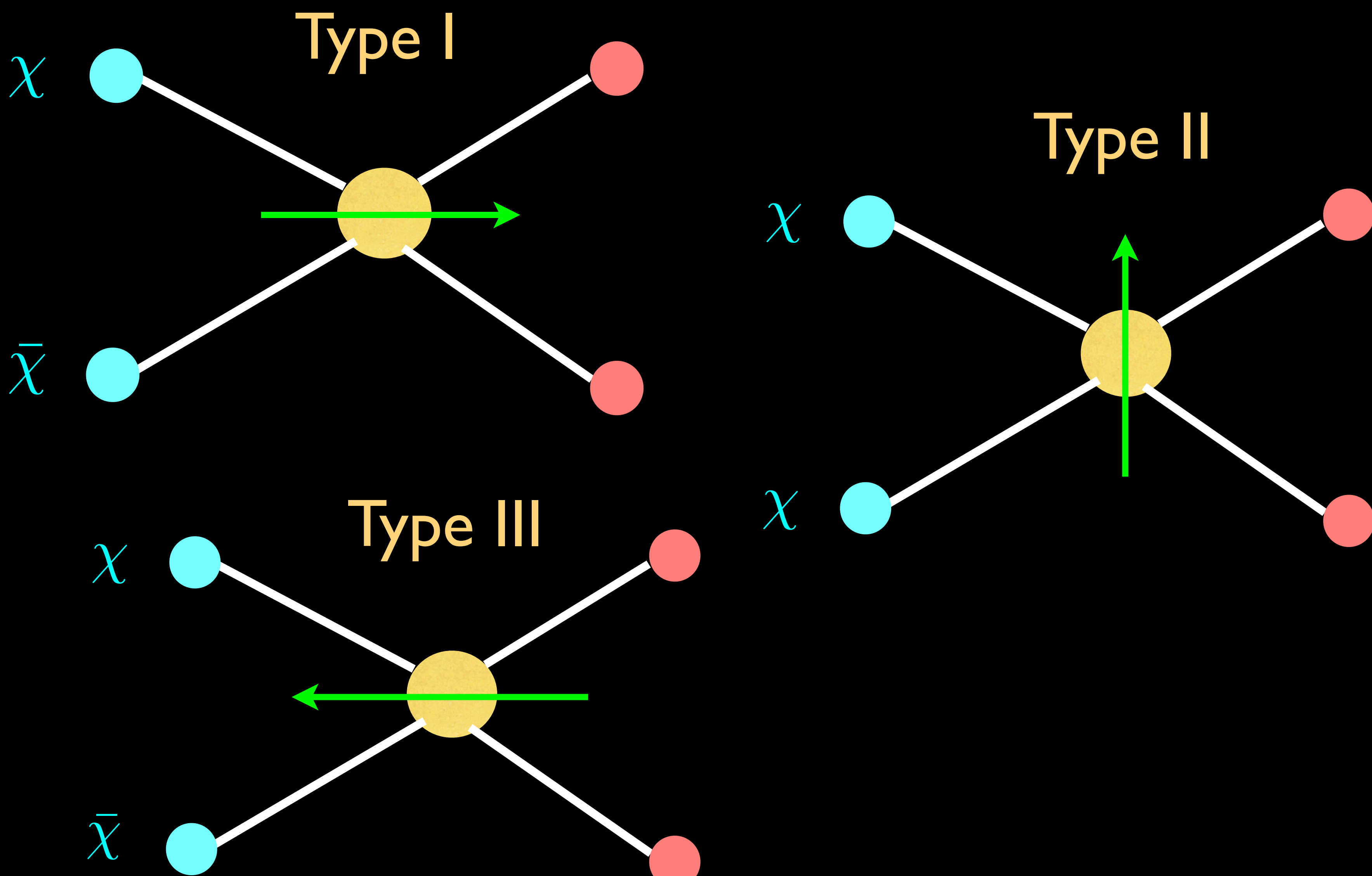


We can write down a few operators to describe the effective interactions

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

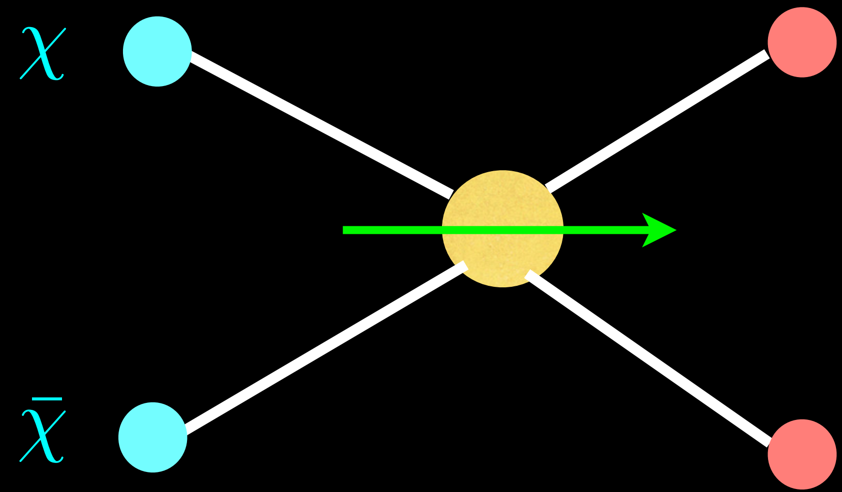
......

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



Type I -- Indirect Detection

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



Positrons

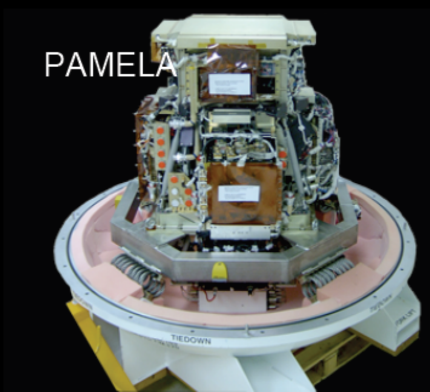
Anti-protons

Gamma rays

Neutrinos

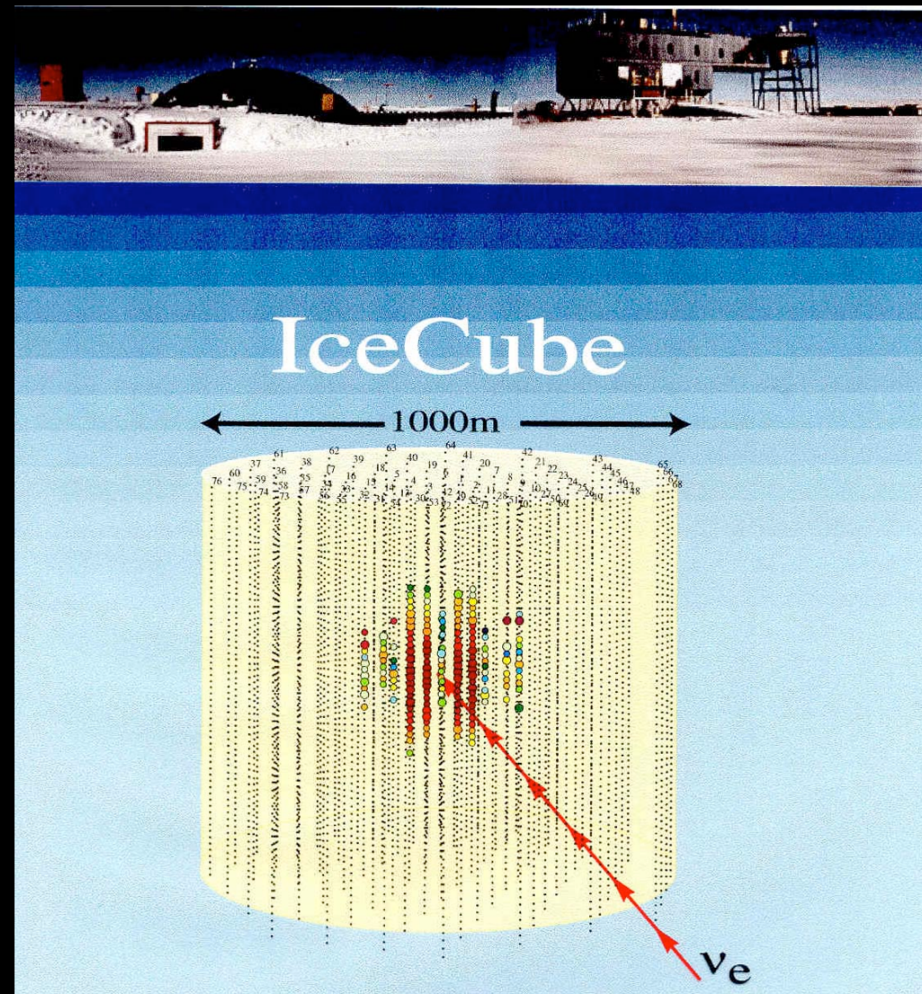
......

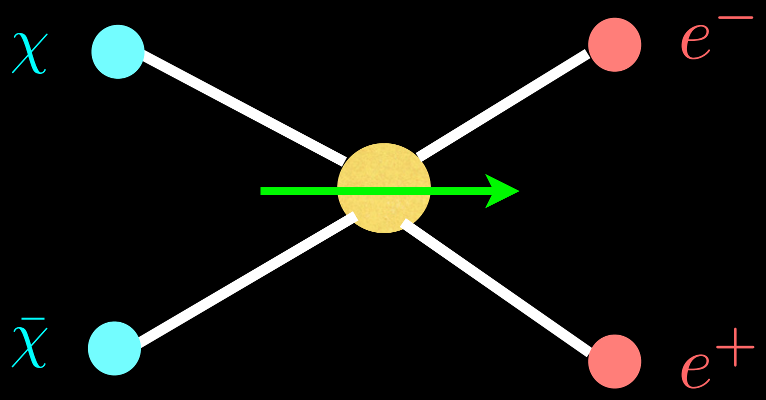

AMS


PAMELA

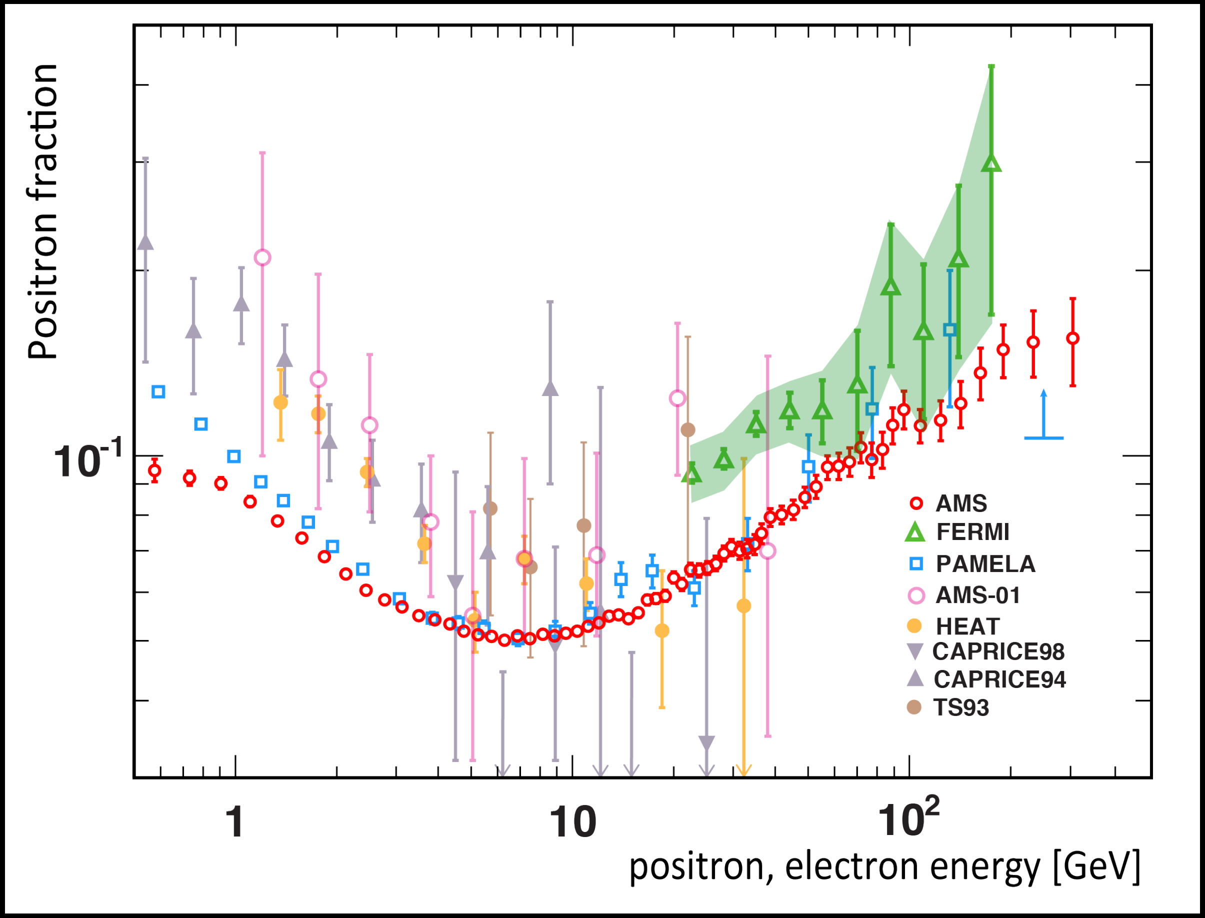

FERMI
NASA


HESS

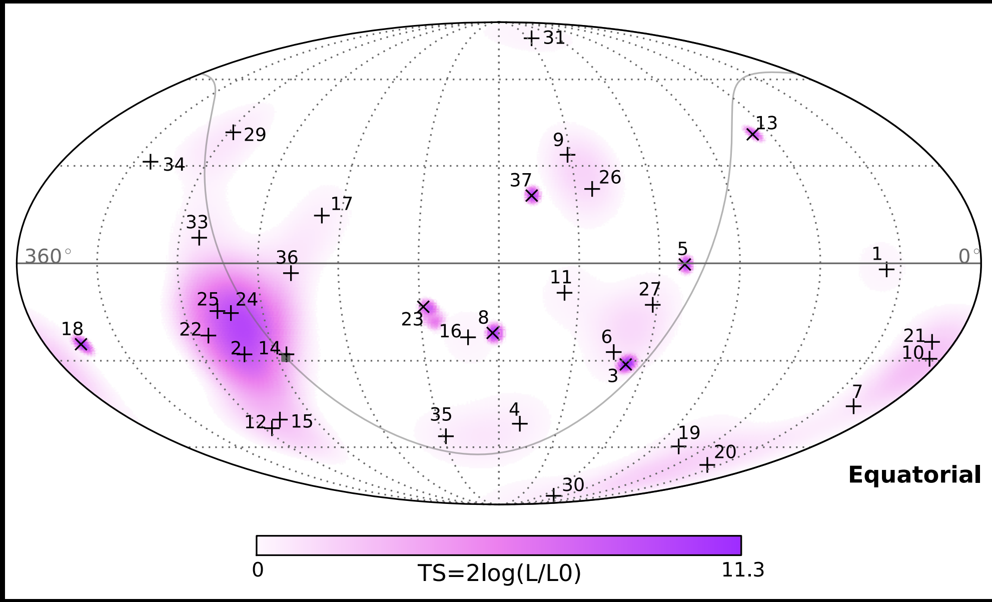

IceCube
1000m
ν_e



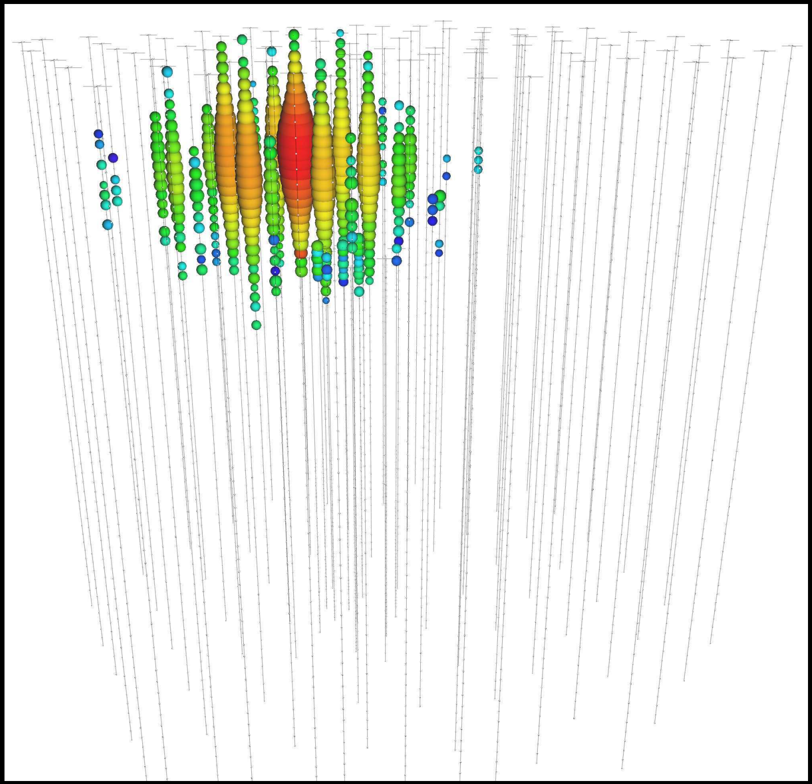
χ
$\bar{\chi}$
e^-
e^+

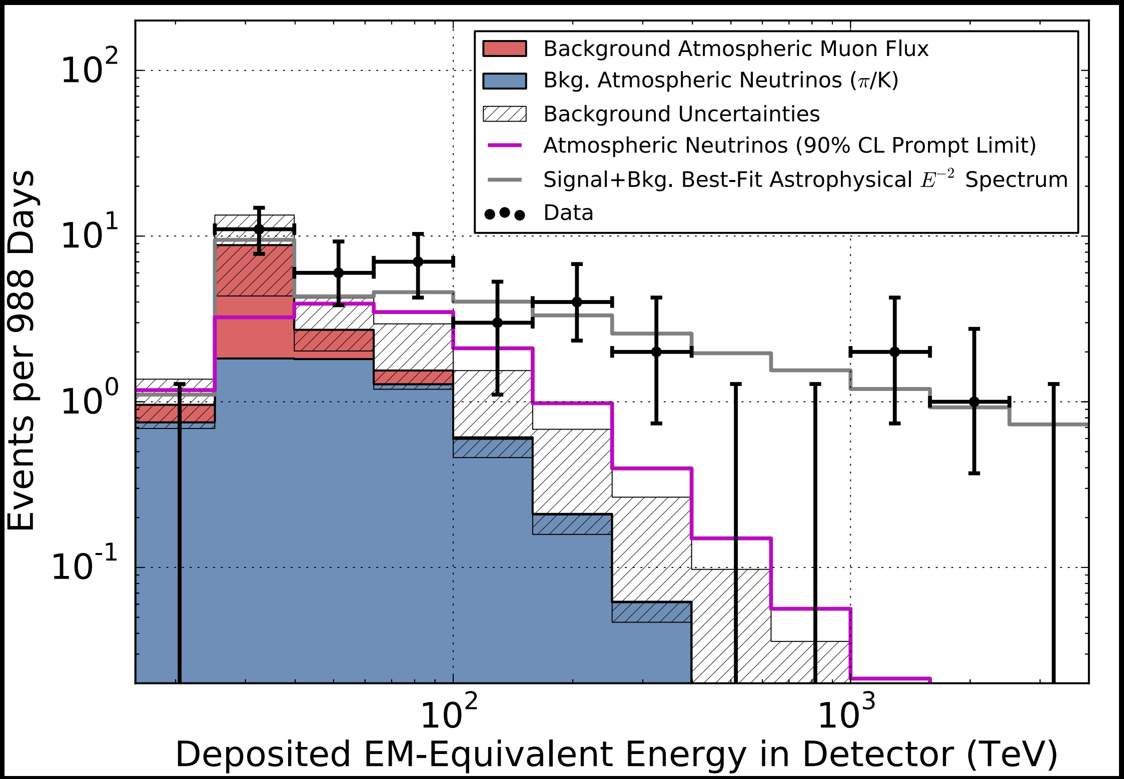


Positron fraction
10^{-1}
1
10
10^2
positron, electron energy [GeV]
AMS
FERMI
PAMELA
AMS-01
HEAT
CAPRICE98
CAPRICE94
TS93



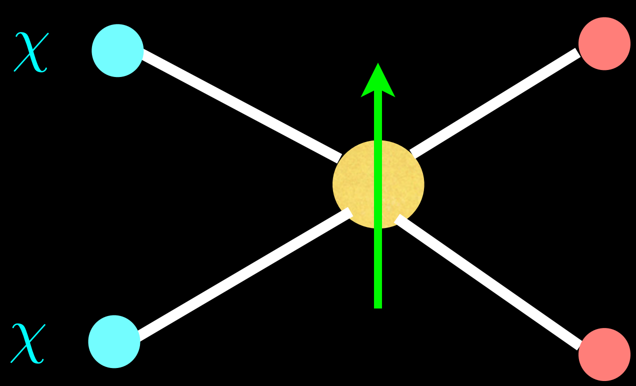
IceCube: 1405.5303

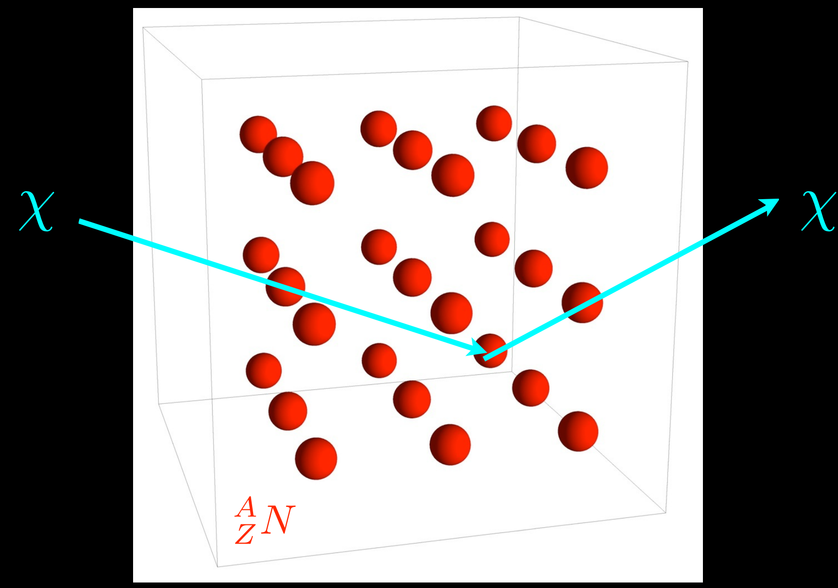




Type II -- Direct Detection

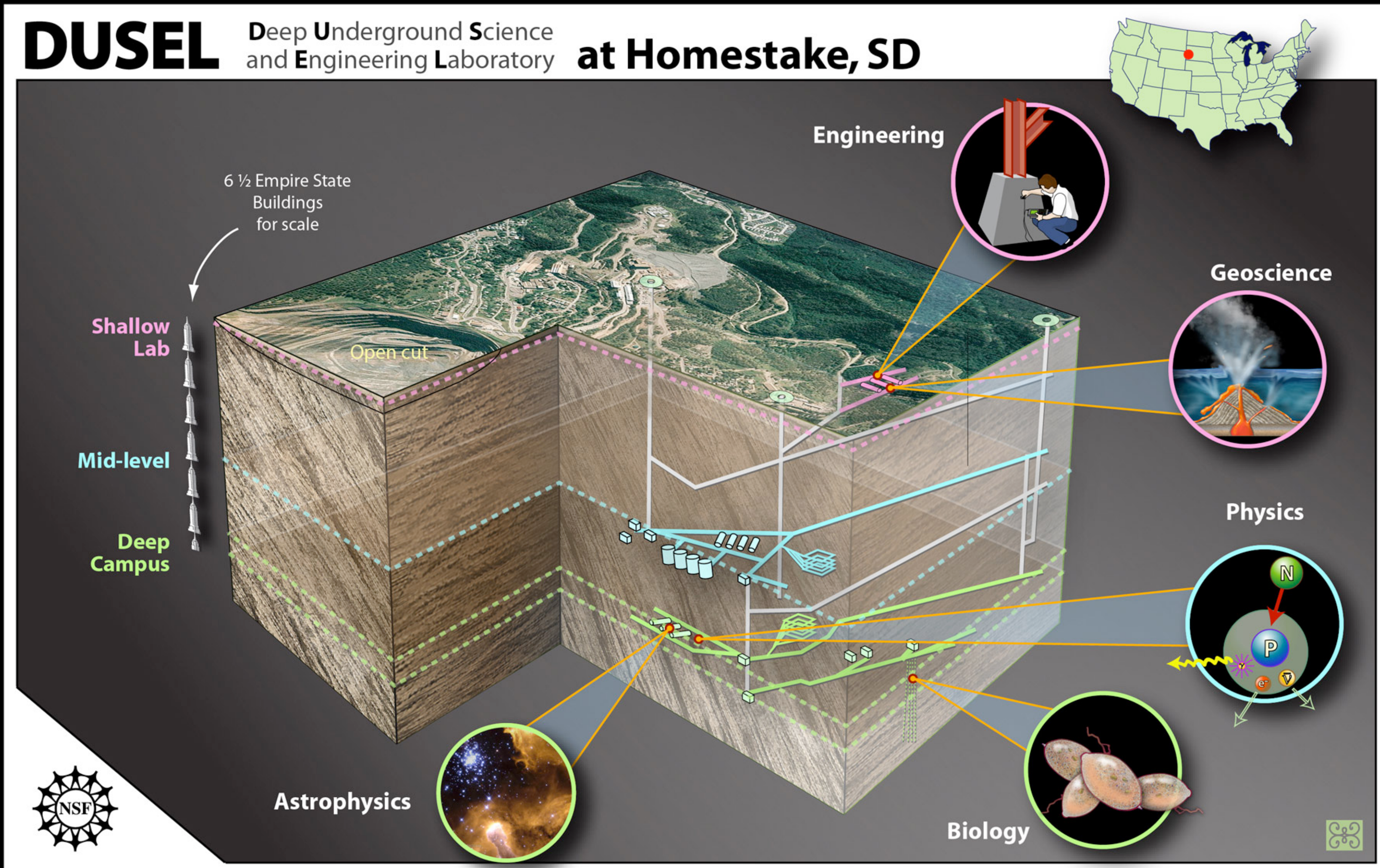
We can also wait for dark matter particles hitting the earth





The deposited energy is typically tens of keV

We need a quiet place to measure such small energy

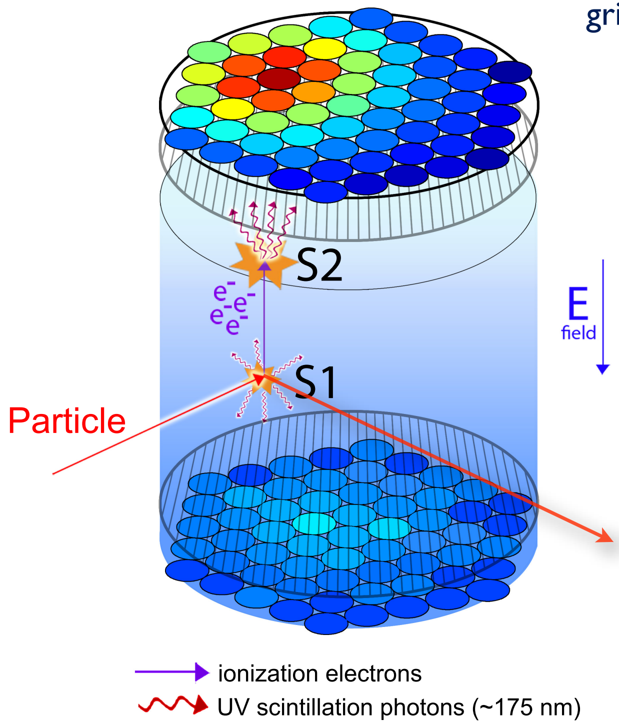

DUSEL
Deep Underground Science and Engineering Laboratory
at Homestake, SD
6 ½ Empire State Buildings for scale
Shallow Lab
Mid-level
Deep Campus
Open cut
Engineering
Geoscience
Physics
Astrophysics
Biology
NSF

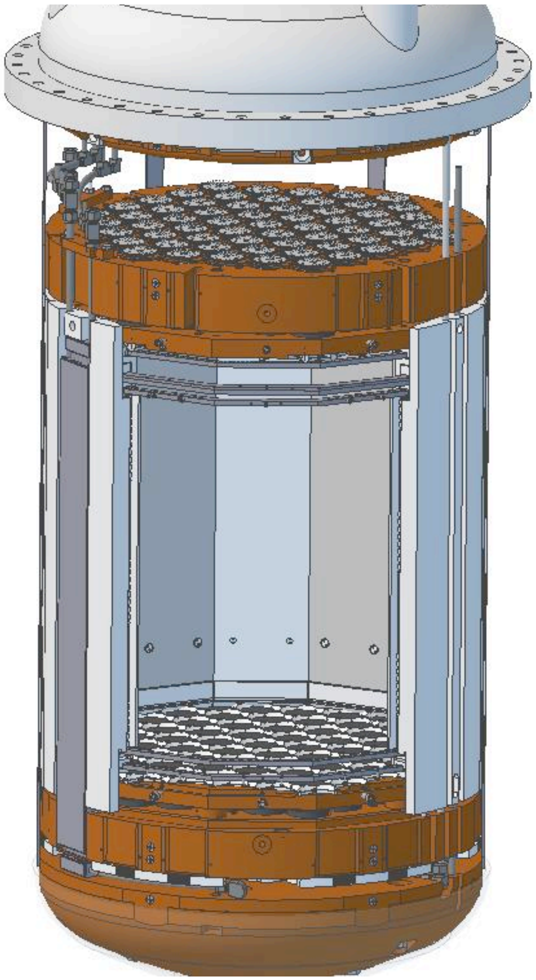
LUX

A Liquid Xenon TPC

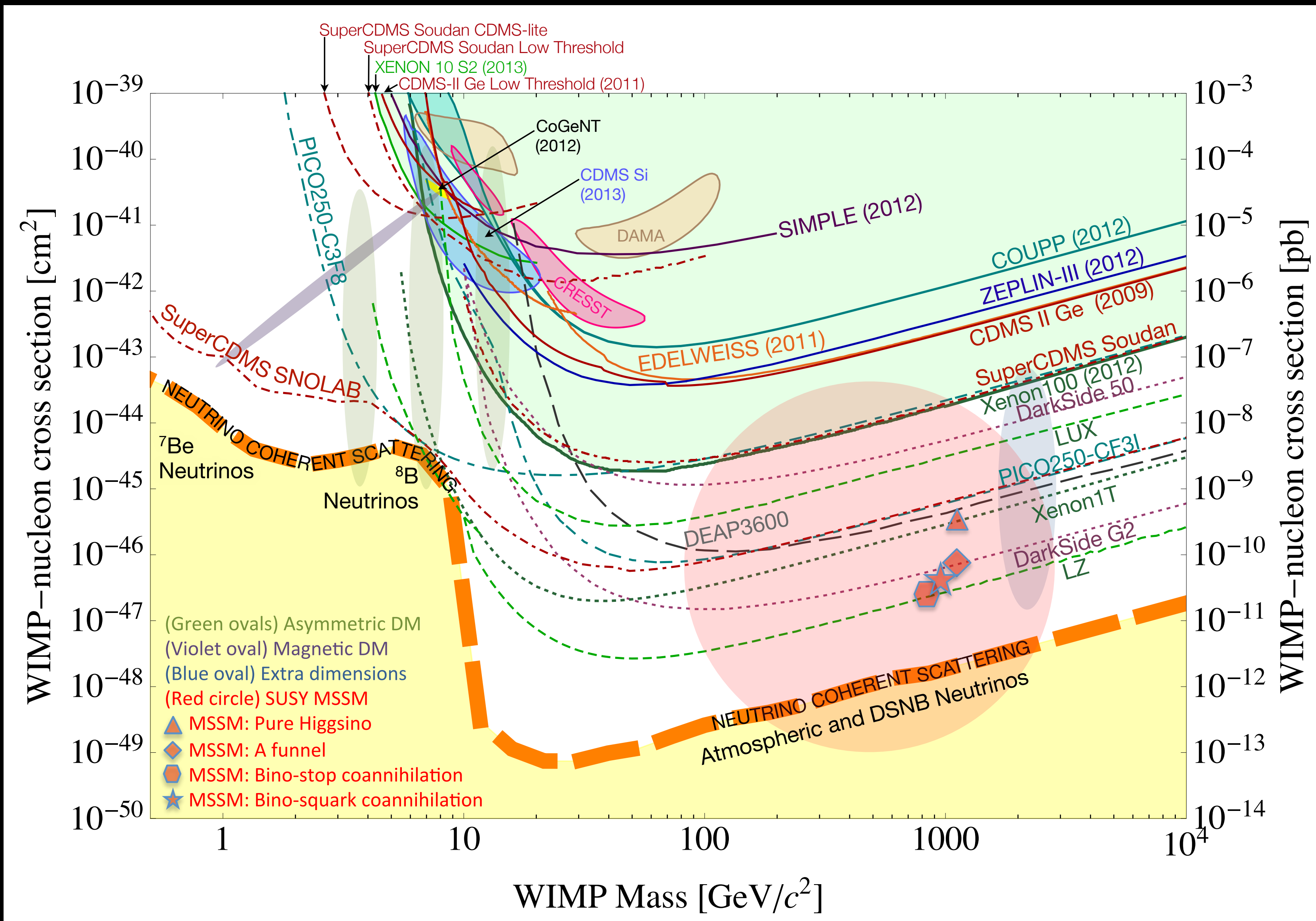
- 365 kg/300 kg active
- Dual-phase TPC
- 122 PMTs

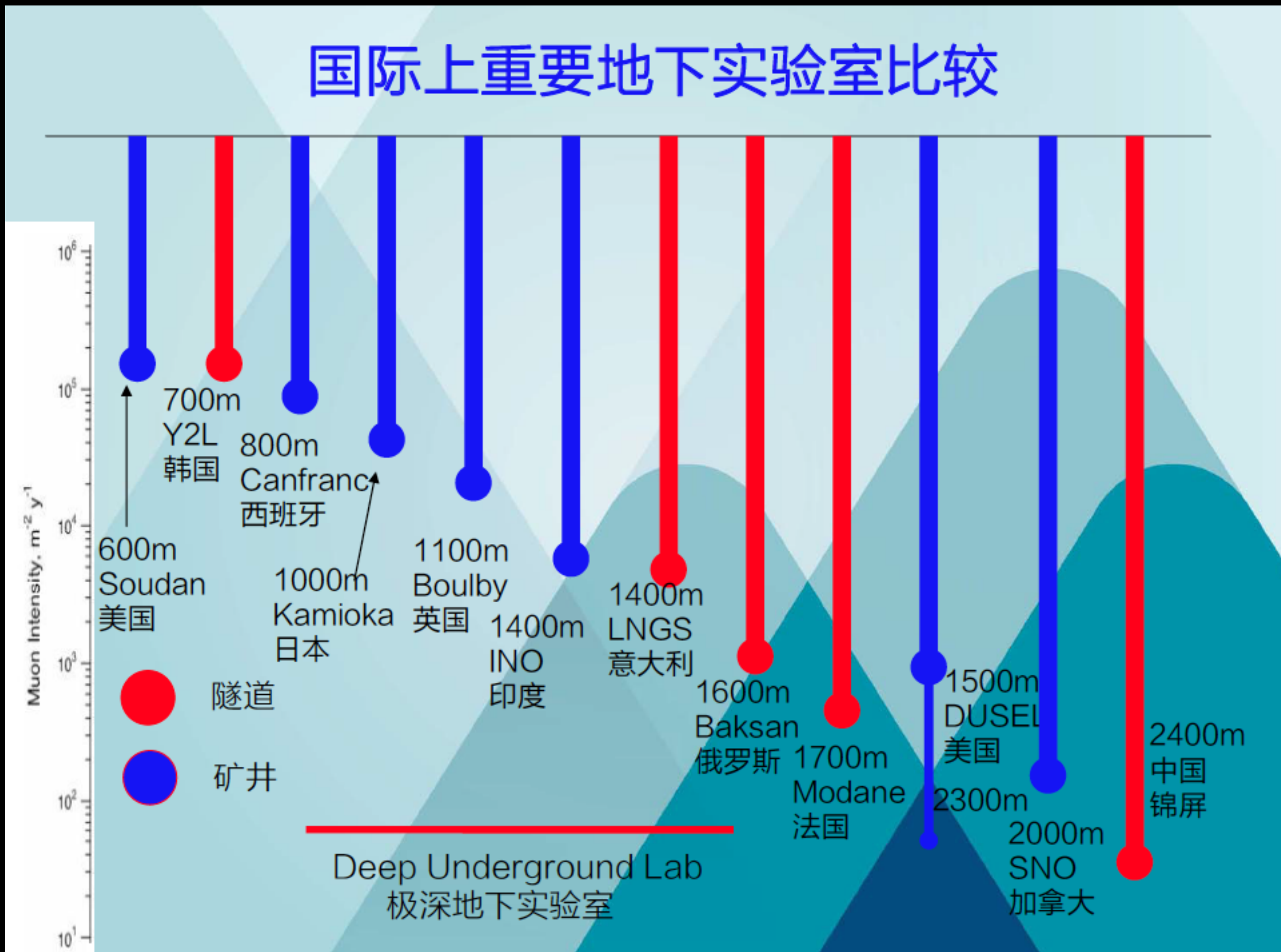
Over 200 sensors
temperatures
heater powers
liquid levels
flow rates
pmt currents
grid currents



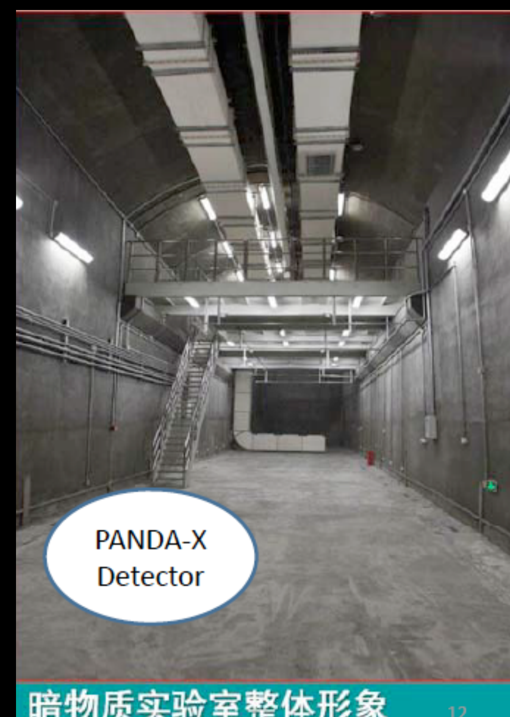


current limits: < 0.1 events/kg/year




国际上重要地下实验室比较
Muon Intensity, m^{-2} y^{-1}
10^6
10^5
10^4
10^3
10^2
10^1
600m
Soudan
美国
700m
Y2L
韩国
800m
Canfranc
西班牙
1000m
Kamioka
日本
1100m
Boulby
英国
1400m
INO
印度
1400m
LNGS
意大利
1600m
Baksan
俄罗斯
1700m
Modane
法国
1500m
DUSEL
美国
2300m
2000m
SNO
加拿大
2400m
中国
锦屏
隧道
矿井
Deep Underground Lab
极深地下实验室

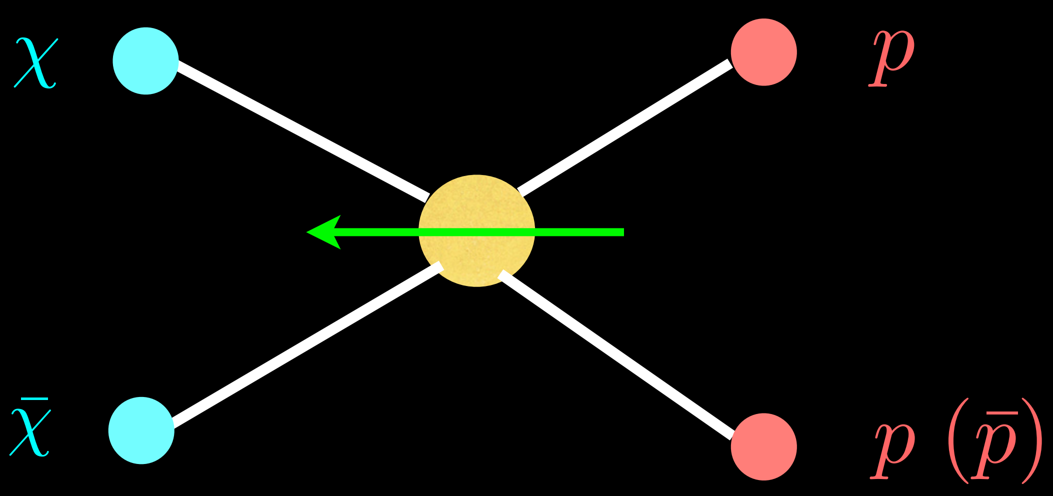

CJPL
中国锦屏地下实验室
China Jinping Underground Laboratory
CDEX整体屏蔽结构
空气
岩石
混凝土 50cm
聚乙烯 1m
铅 20cm
支撑结构 15cm
含硼聚乙烯 20cm
高纯无氧铜 10cm
反符合探测系统
高纯锗探测器
工作空间


PANDA-X
Detector
暗物质实验室整体形象
12

Type III -- Collider Searches

Direct detection probes the dark matter coupling to nucleons

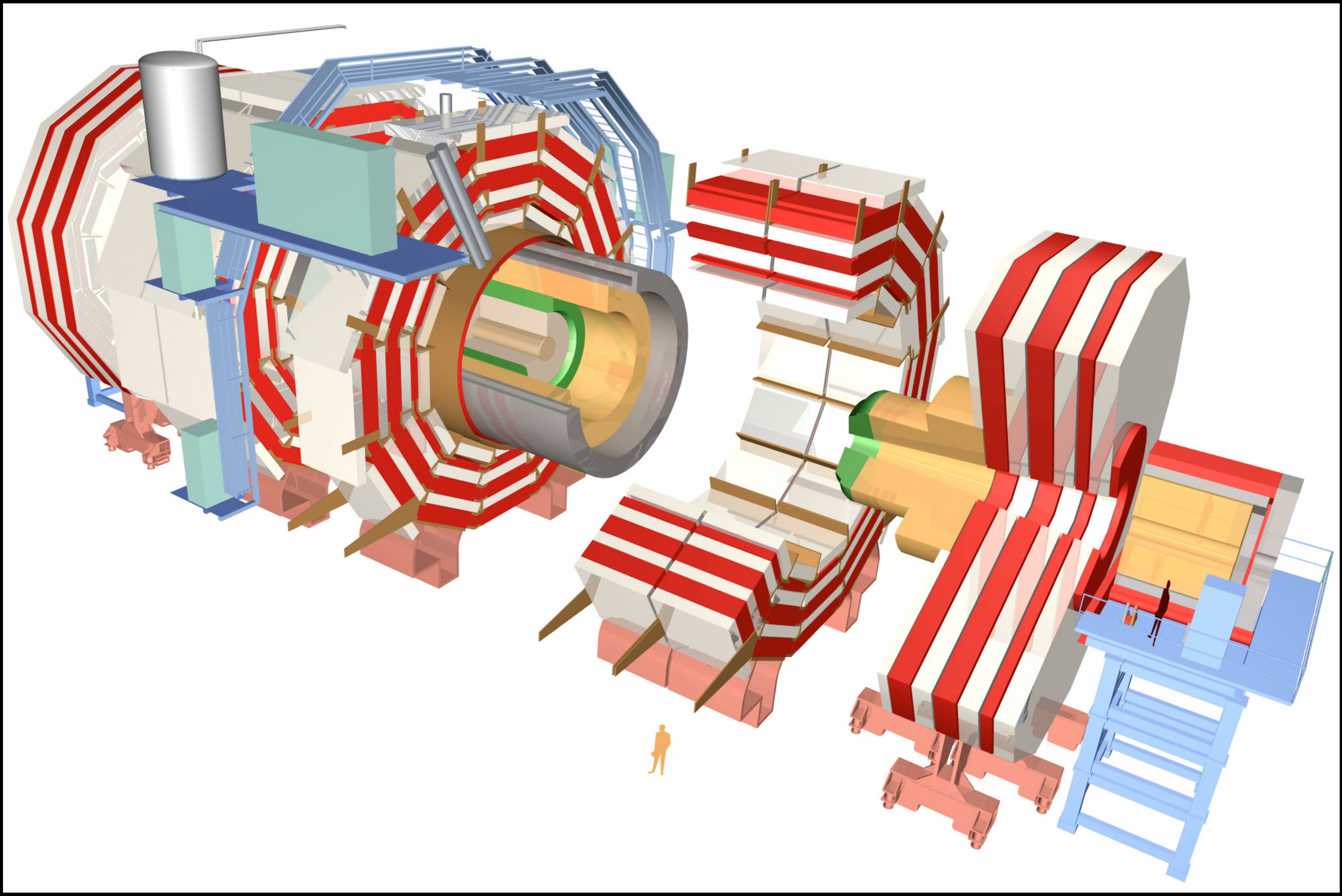
In high energy physics, we build colliders and use proton or anti-proton collision to produce heavy particles

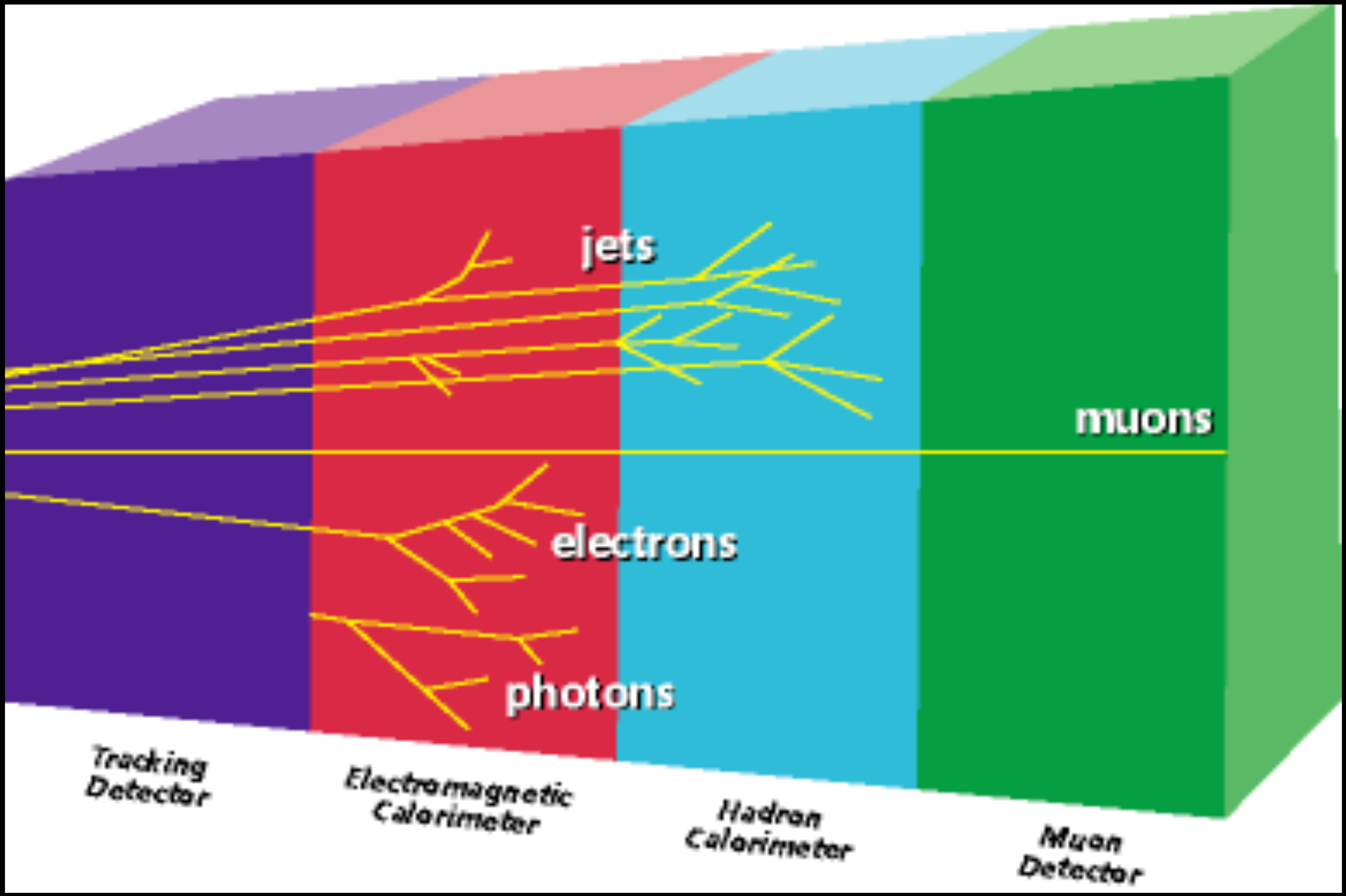


they discovered
the Higgs boson

LHC at CERN

Proton-proton
7, 8, 13, 14 TeV 27 km

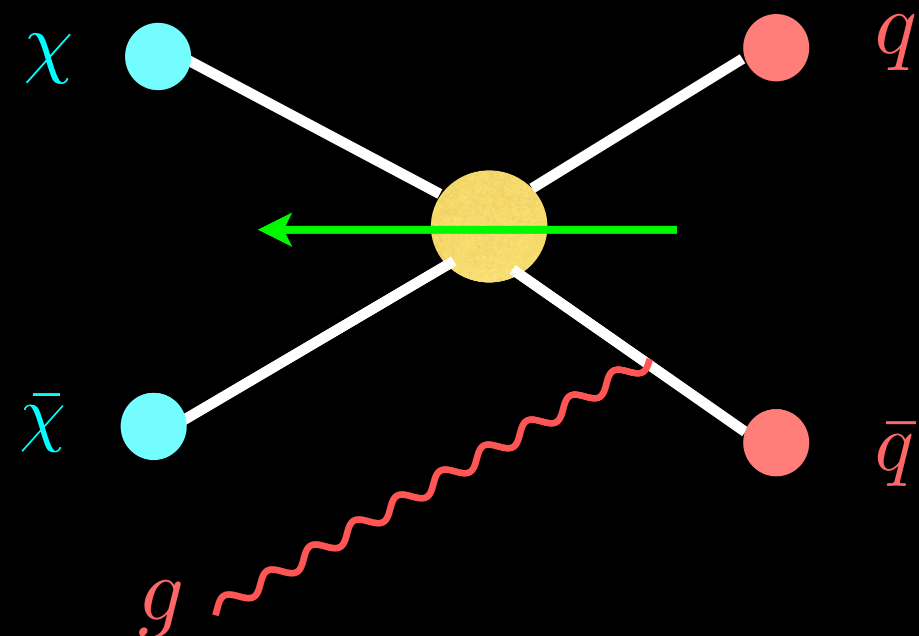




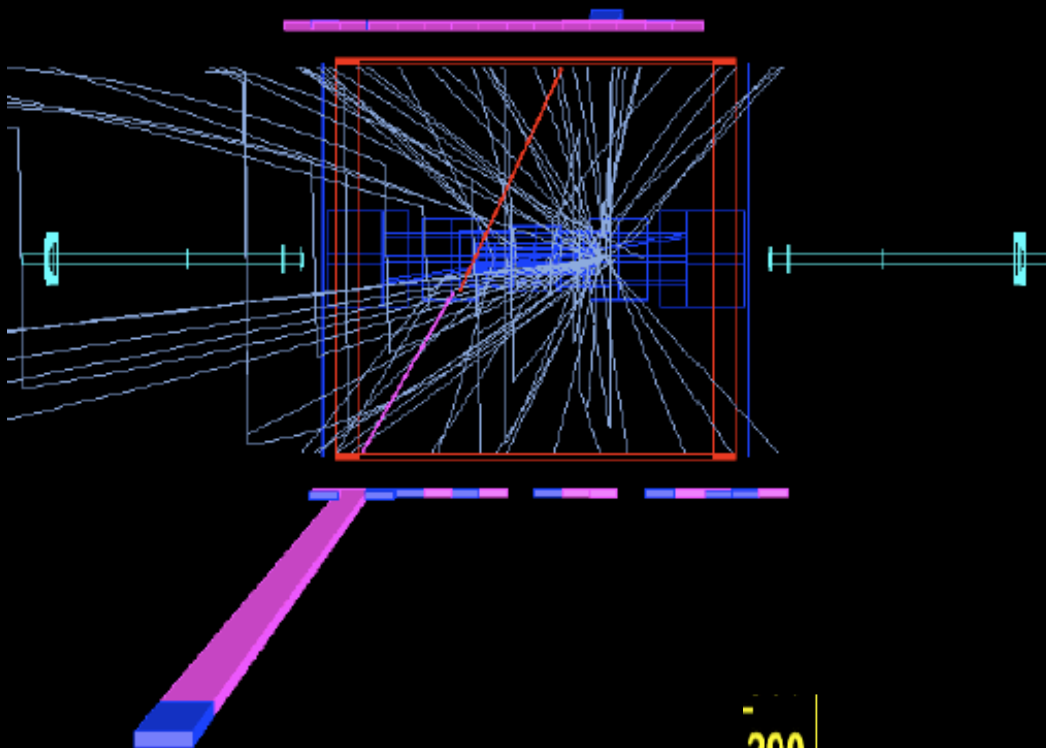
- A dark matter particle produced at the LHC will penetrate the detectors and escape, leaving no trace

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

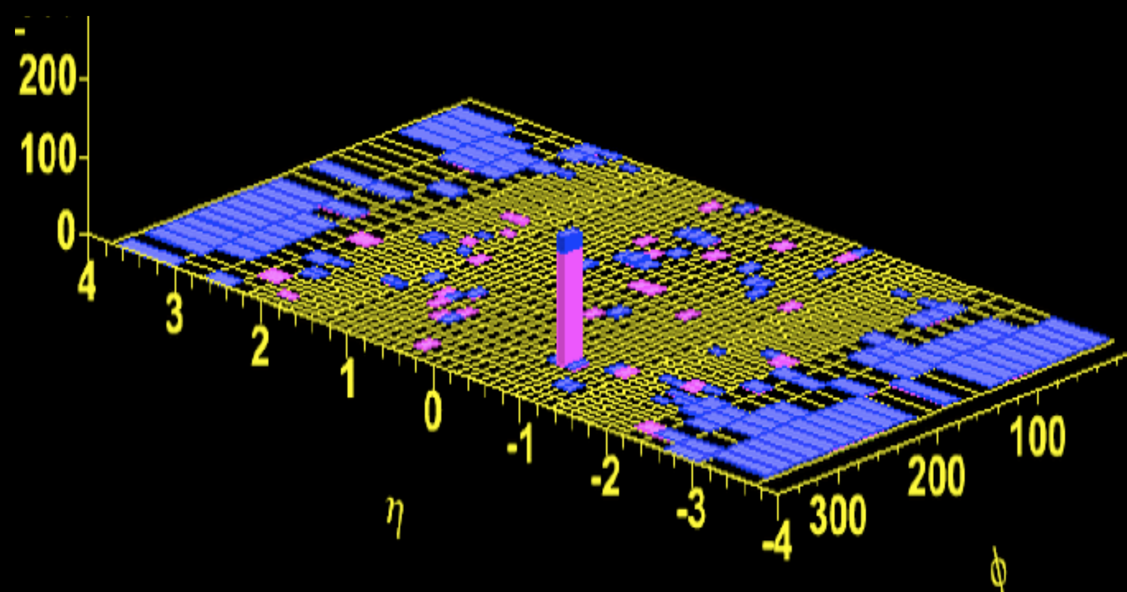
From QCD, the quarks inside the proton can radiate additional gluons



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

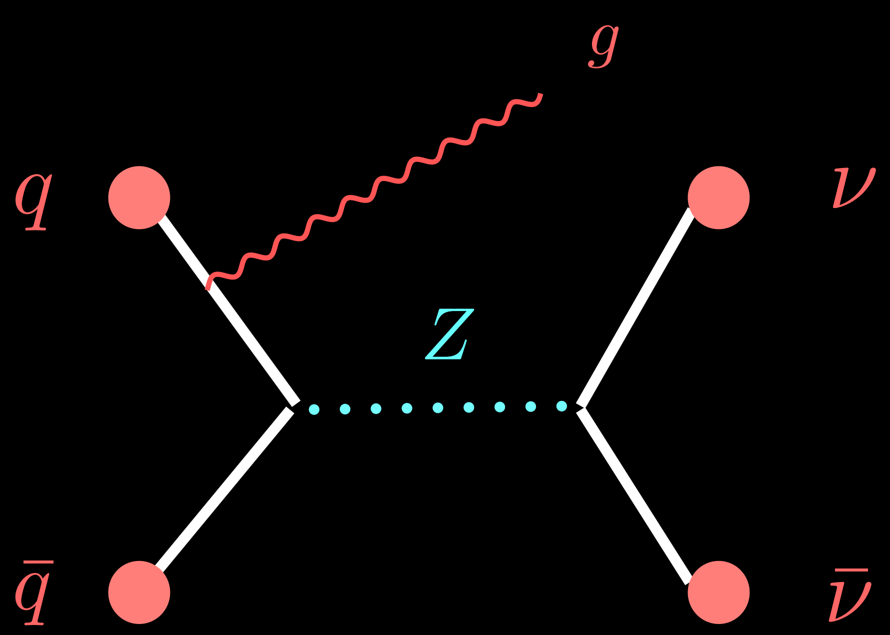


Pt(jet)=175 GeV
MET=170 GeV



Monojet event

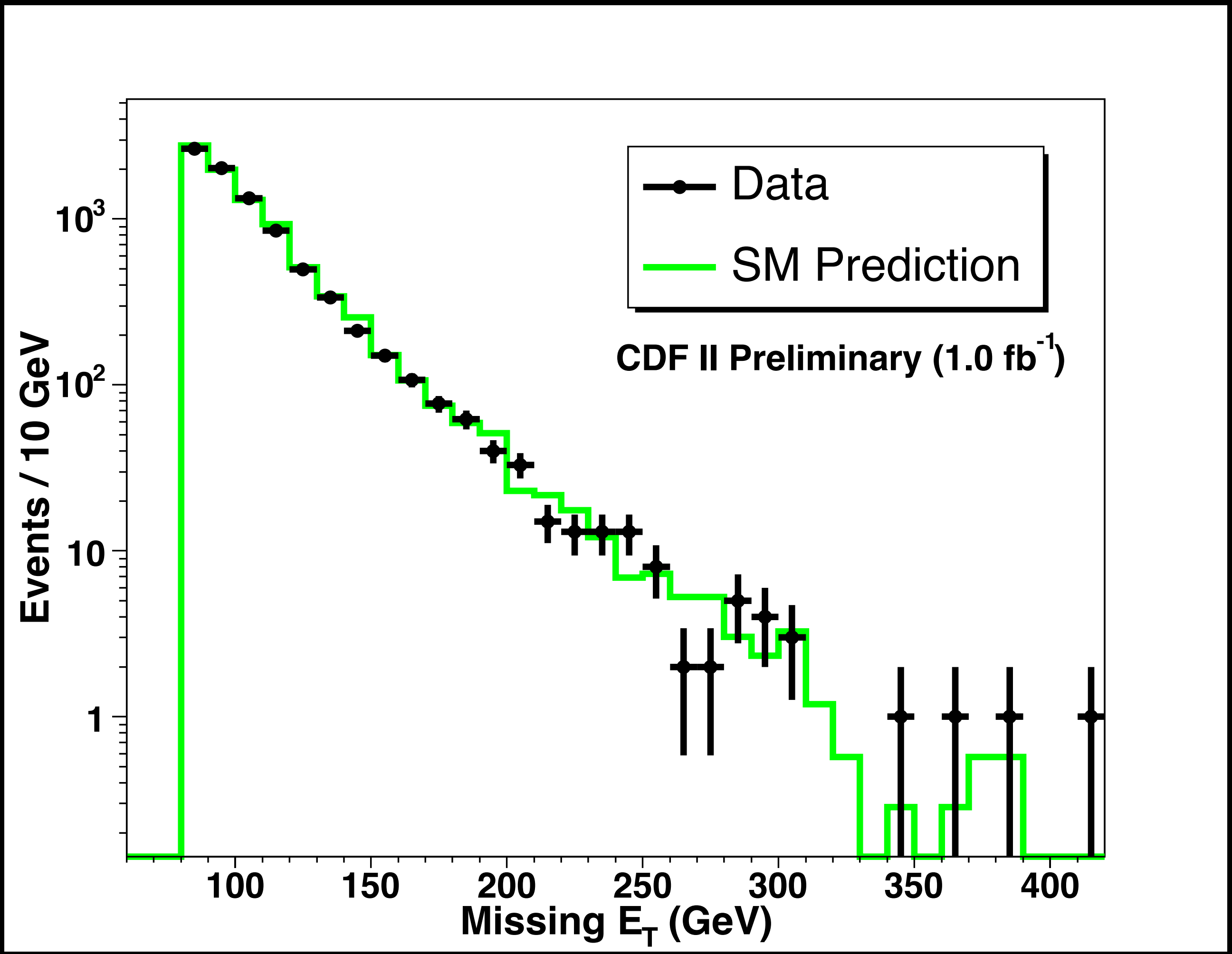
Monojet plus MET events also appear from other ways



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

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

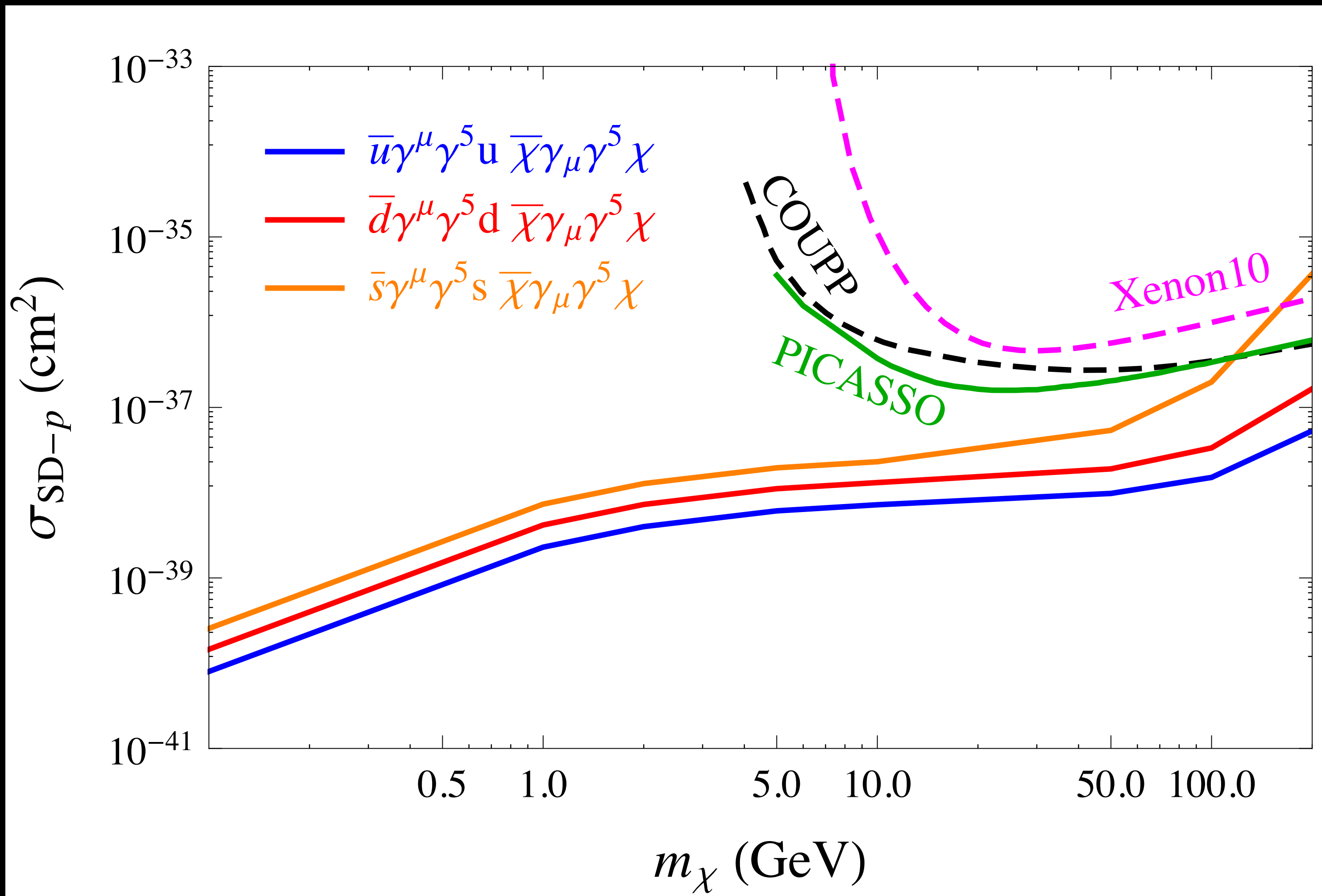
The "null result" sets a lower bound on the cutoff

Recall the formula for the direct detection scattering cross section

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

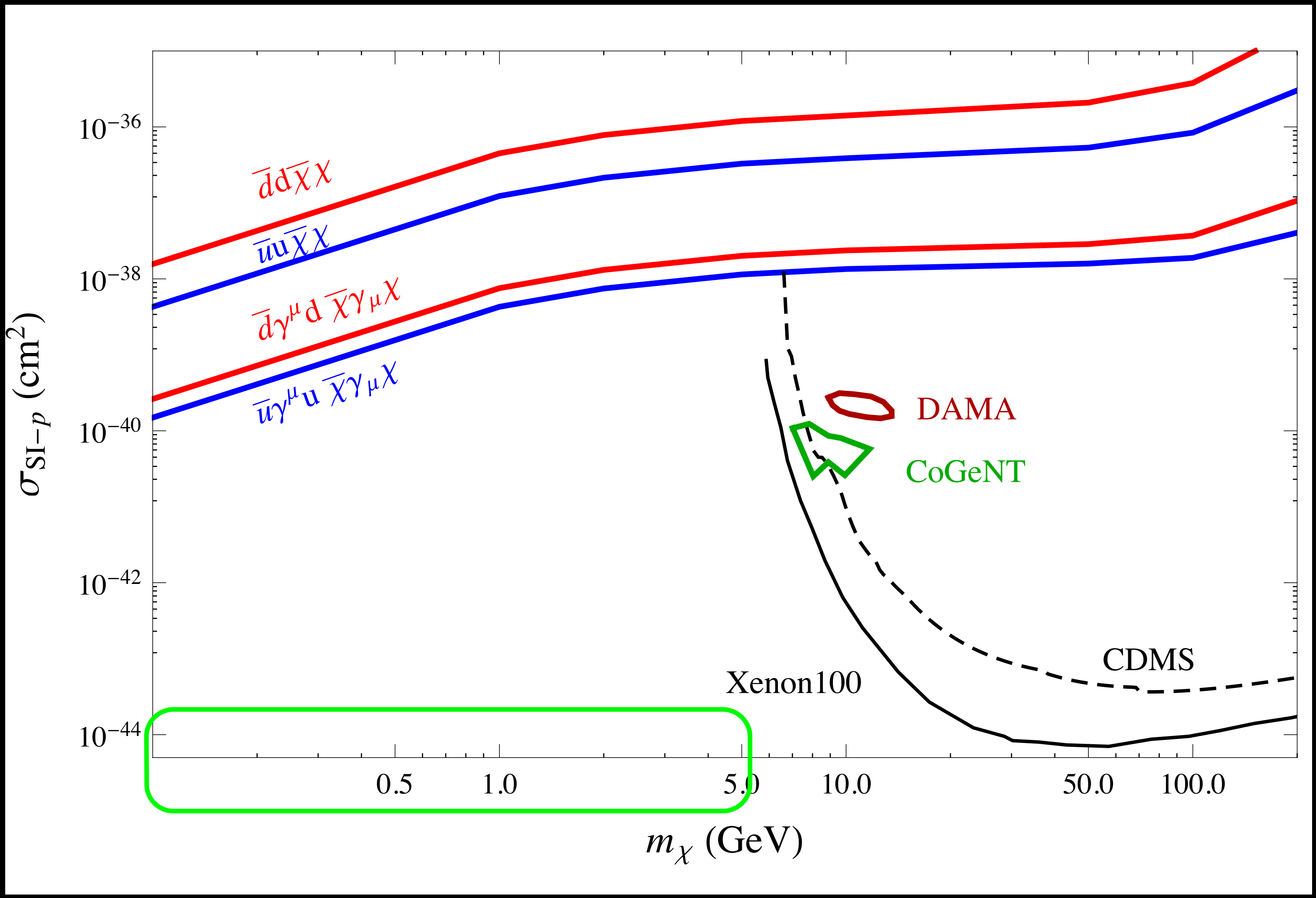
So, we can set an upper bound on the scattering cross section from monojet searches

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



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

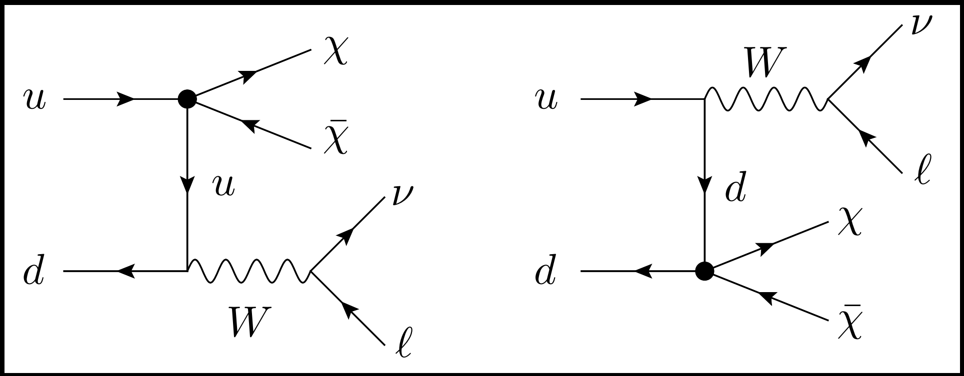
Bai, Fox, Harnik, JHEP, 1012, 048 (2010)

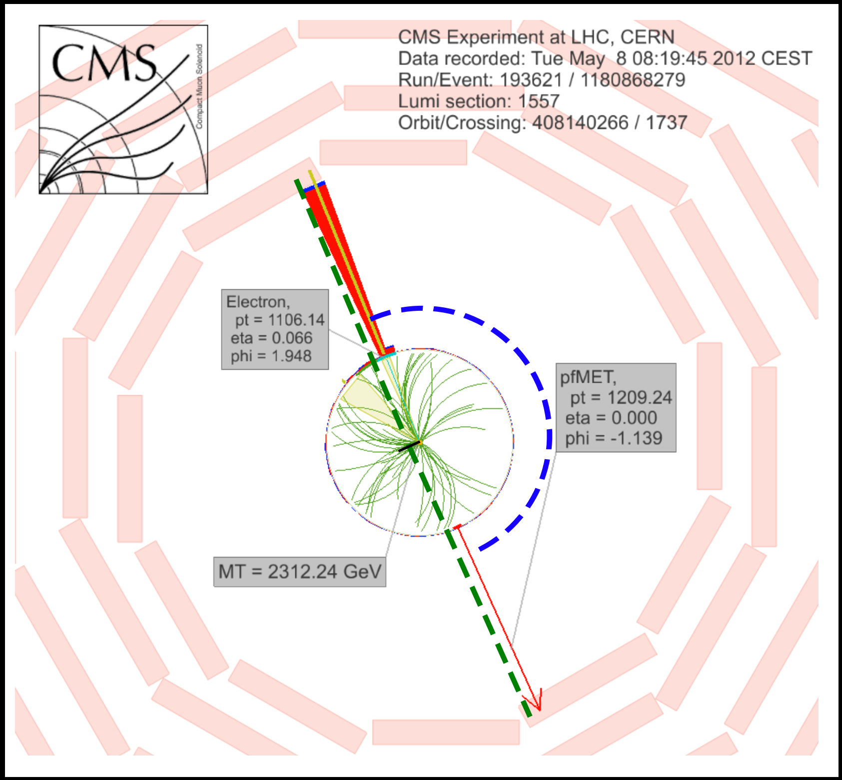


World's best spin-independent limit for light dark matter

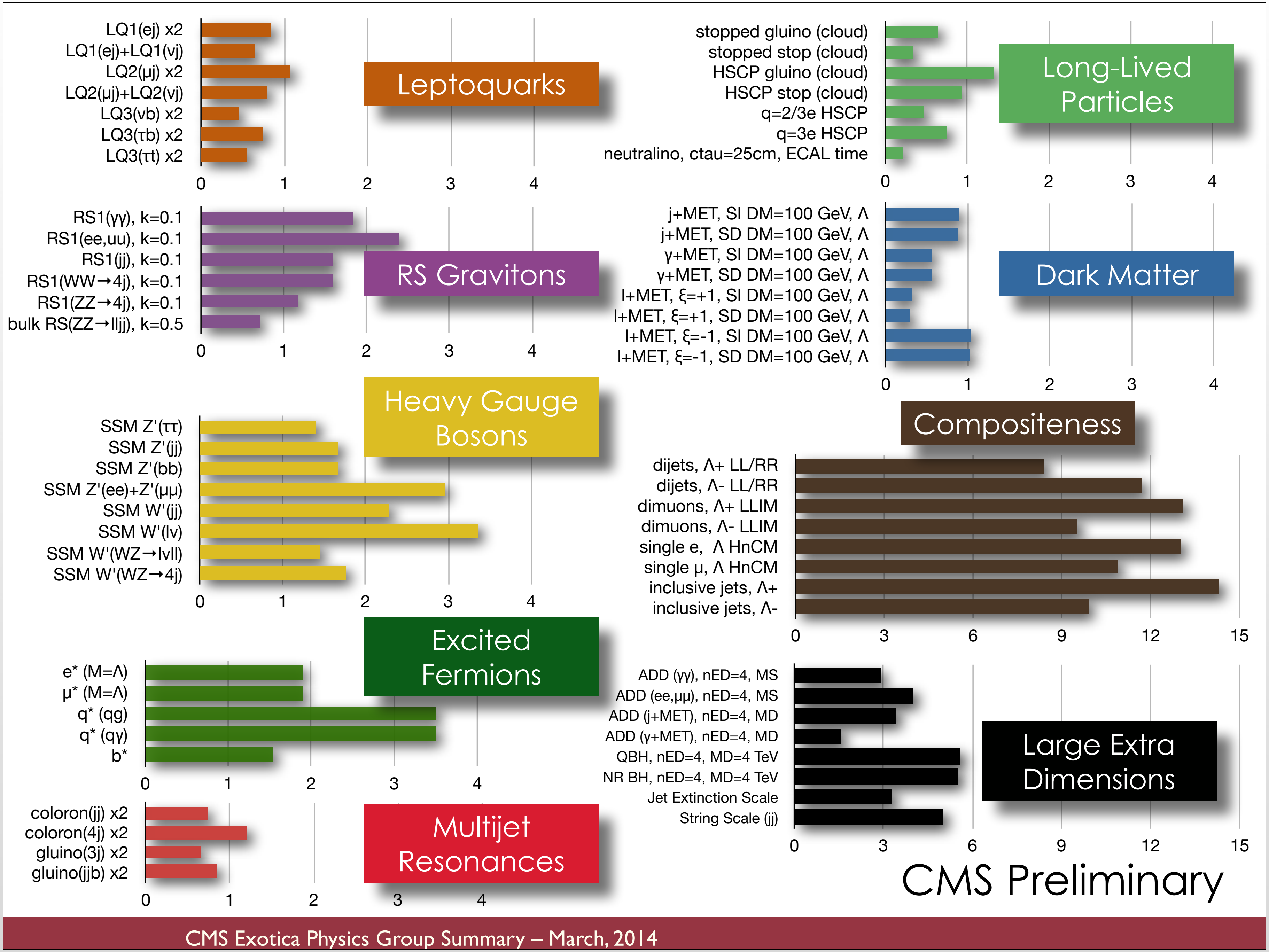
Mono-lepton

Bai and Tait, 1208.4361





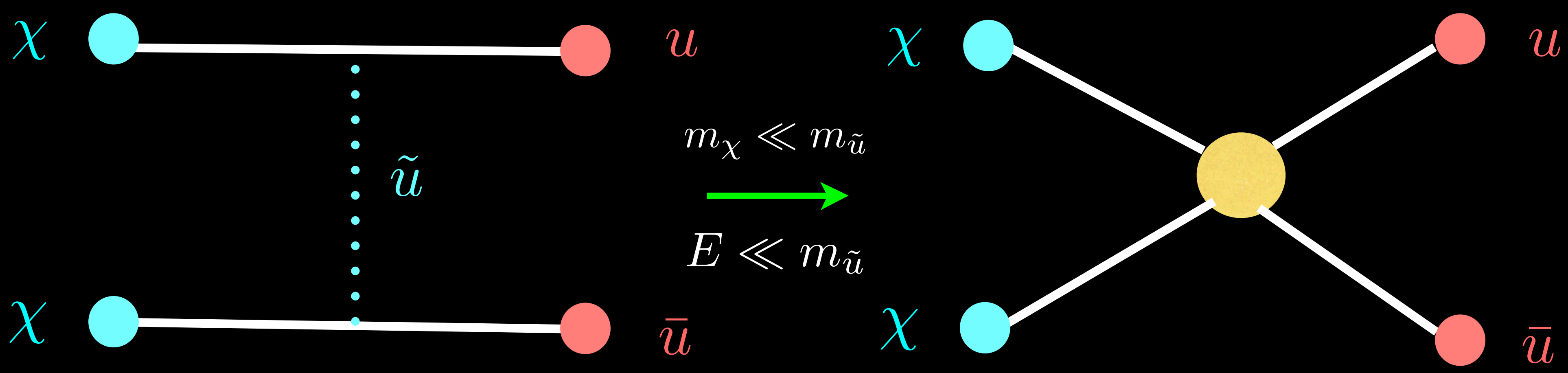
Mono-X: mono-photon, mono-higgs, mono-top ……



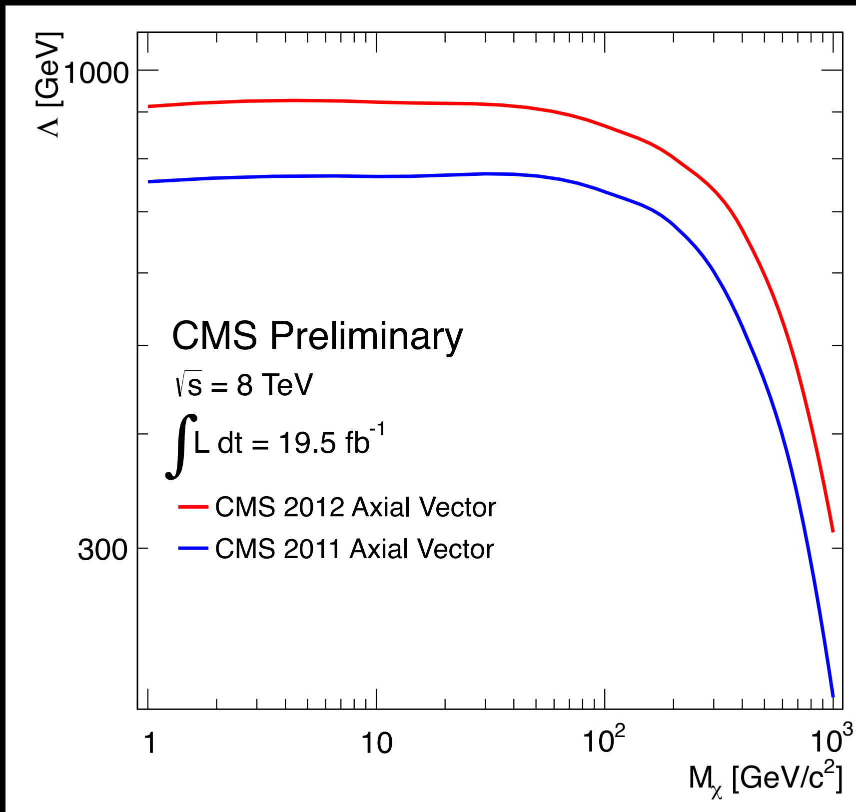
Leptoquarks
LQ1(ej) x2
LQ1(ej)+LQ1(vj)
LQ2(μj) x2
LQ2(μj)+LQ2(vj)
LQ3(vb) x2
LQ3(τb) x2
LQ3(ττ) x2
0 1 2 3 4
Long-Lived Particles
stopped gluino (cloud)
stopped stop (cloud)
HSCP gluino (cloud)
HSCP stop (cloud)
q=2/3e HSCP
q=3e HSCP
neutralino, ctau=25cm, ECAL time
0 1 2 3 4
RS Gravitons
RS1(γγ), k=0.1
RS1(ee,uu), k=0.1
RS1(jj), k=0.1
RS1(WW→4j), k=0.1
RS1(ZZ→4j), k=0.1
bulk RS(ZZ→lljj), k=0.5
0 1 2 3 4
Dark Matter
j+MET, SI DM=100 GeV, Λ
j+MET, SD DM=100 GeV, Λ
γ+MET, SI DM=100 GeV, Λ
γ+MET, SD DM=100 GeV, Λ
l+MET, ξ=+1, SI DM=100 GeV, Λ
l+MET, ξ=+1, SD DM=100 GeV, Λ
l+MET, ξ=-1, SI DM=100 GeV, Λ
l+MET, ξ=-1, SD DM=100 GeV, Λ
0 1 2 3 4
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(bb)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lv)
SSM W'(WZ→lvll)
SSM W'(WZ→4j)
0 1 2 3 4
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
0 3 6 9 12 15
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ)
b*
0 1 2 3 4
Large Extra Dimensions
ADD (γγ), nED=4, MS
ADD (ee,μμ), nED=4, MS
ADD (j+MET), nED=4, MD
ADD (γ+MET), nED=4, MD
QBH, nED=4, MD=4 TeV
NR BH, nED=4, MD=4 TeV
Jet Extinction Scale
String Scale (jj)
0 3 6 9 12 15
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
0 1 2 3 4
CMS Preliminary
CMS Exotica Physics Group Summary – March, 2014

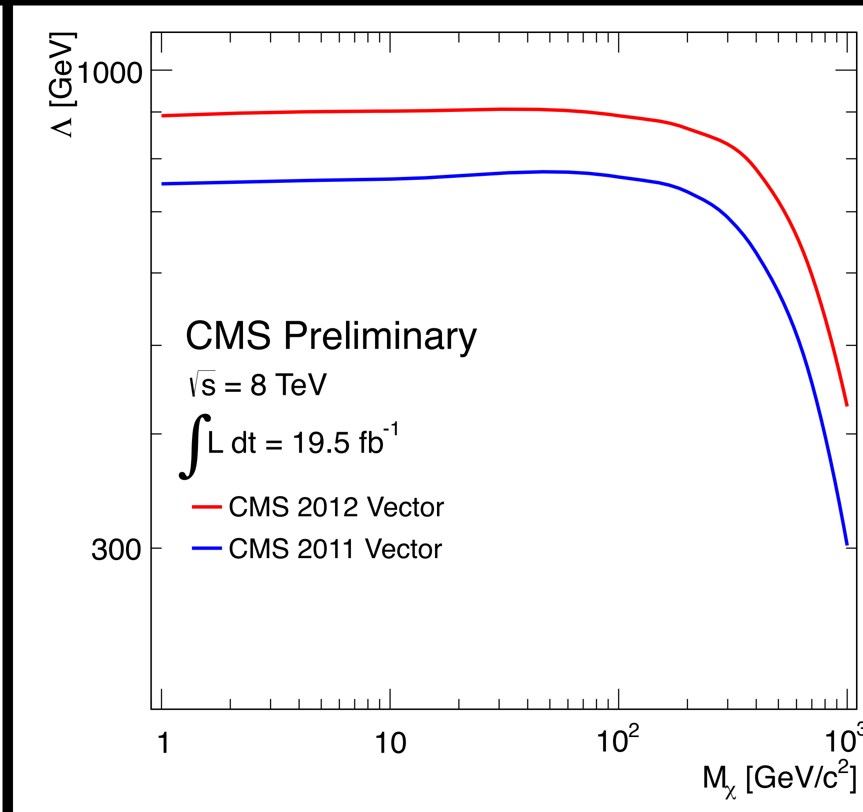
What is next for LHC Run2 ?

we have concentrated on EFT



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





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

The above description does not work well if the collider energy is far about the cutoff $E > \Lambda$

A UV model is necessary for a robust description

Mediators

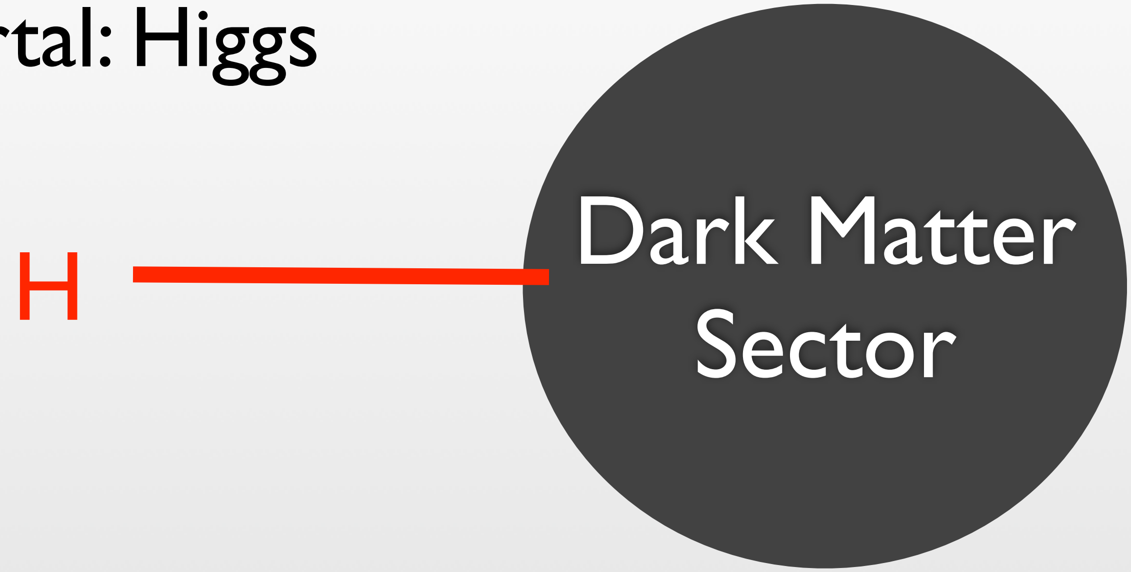
Standard Model

Dark Matter Sector

- ★ Graviton
- ★ Z boson
- ★ Higgs boson
- ★ Z', dilaton, radion ...

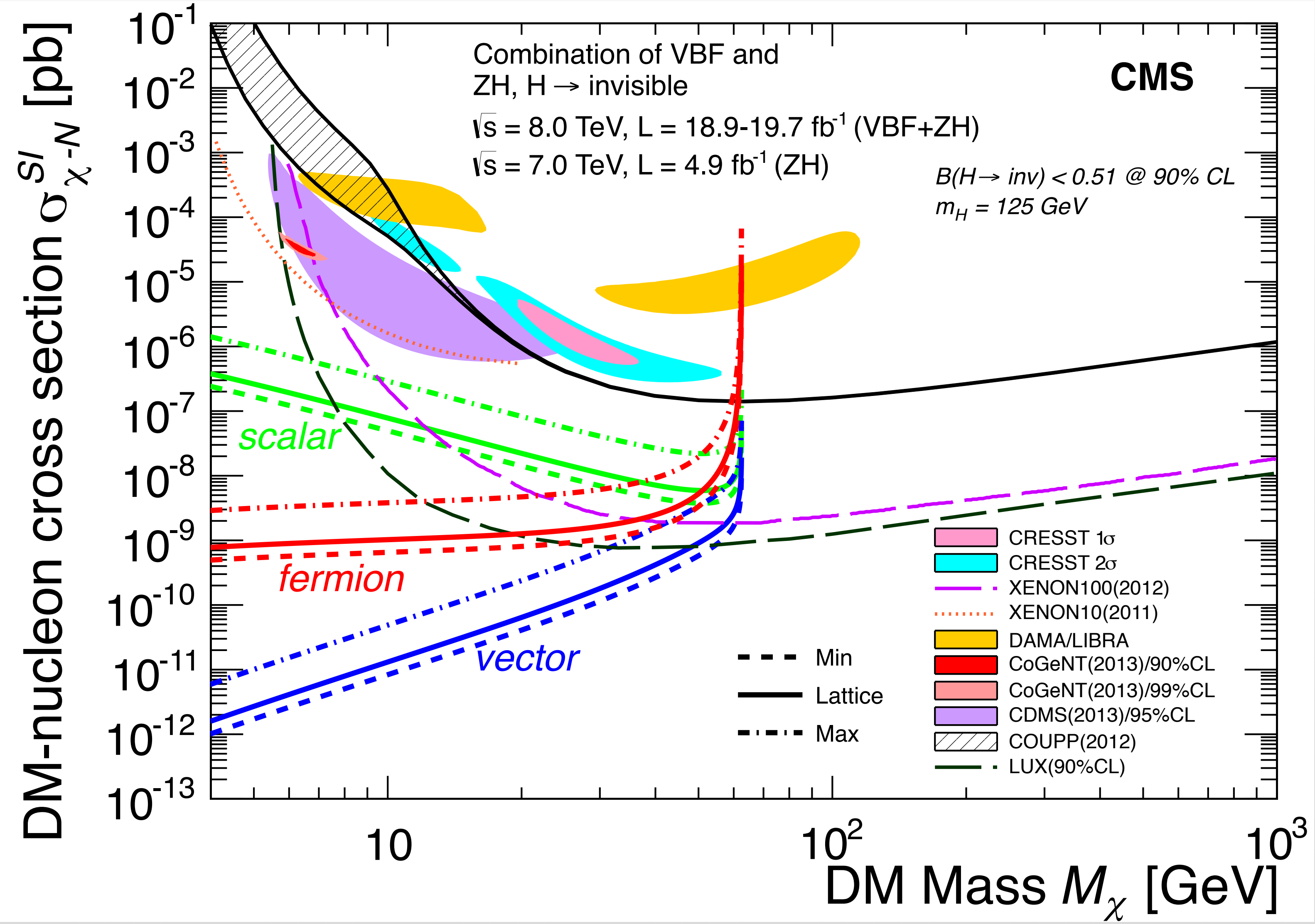
Simplified Dark Matter Models

★ Boson portal: Higgs portal



★ Fermion portal

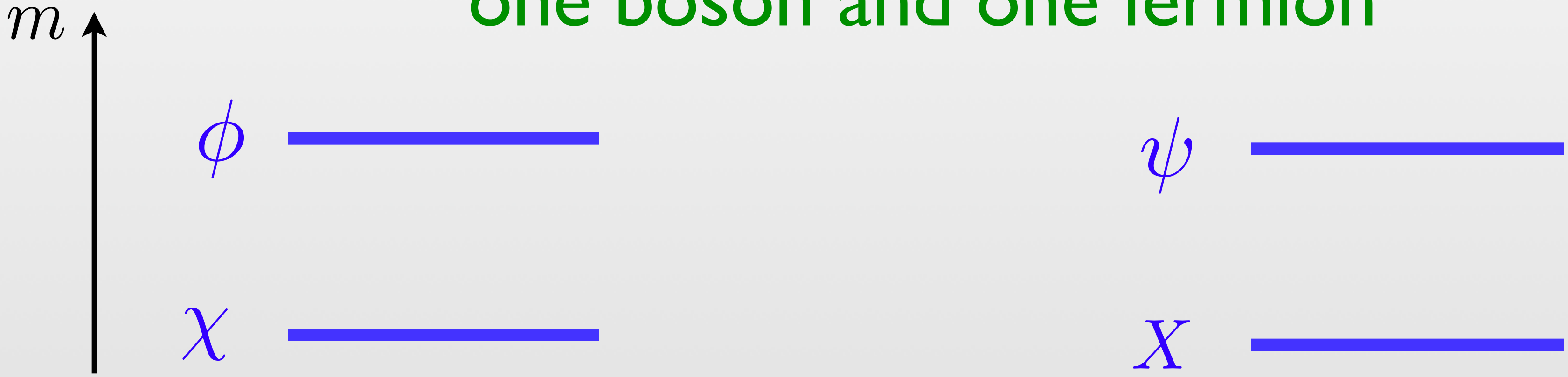
Higgs Portal Dark Matter



Fermion Portal Dark Matter

Conserving the Lorentz symmetry, at least two particles in the dark matter sector are required

one boson and one fermion

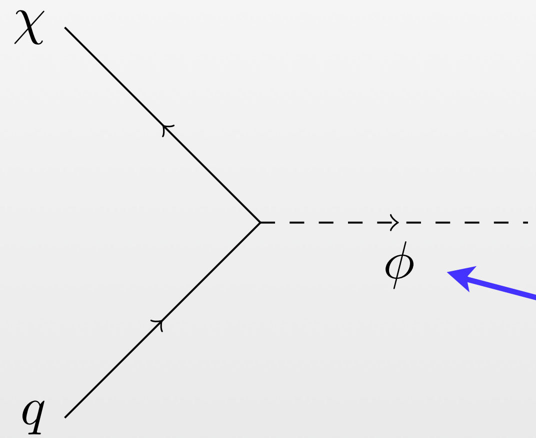


a Majorana or Dirac Fermion or a scalar dark matter

$\boxed{\text{Fermion Portal DM at the LHC has “signatures” beyond the simplified SUSY DM}}$

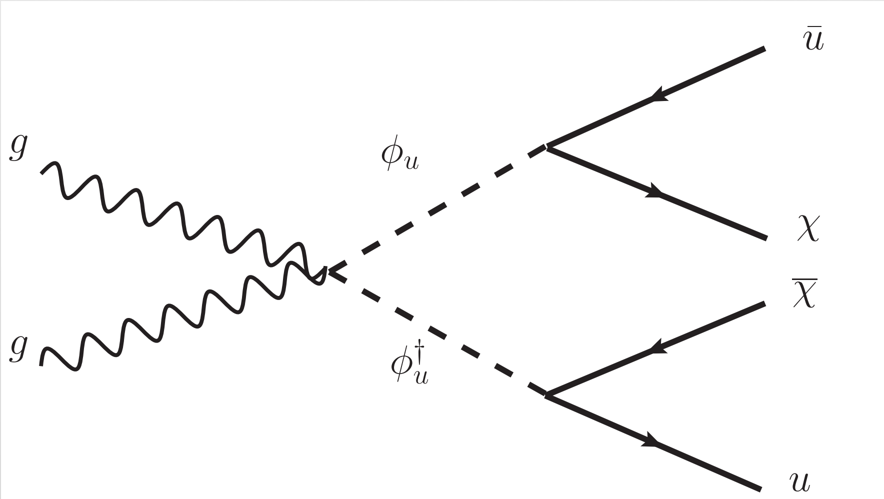
Quark Portal Dark Matter

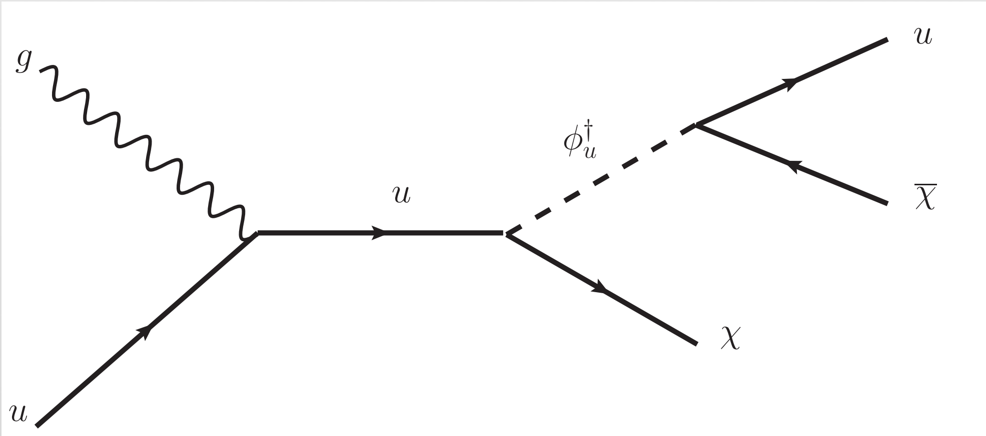
$$\mathcal{L}_{\text{fermion}} \supset \lambda_{u_i}\phi_{u_i}\overline{\chi}_L u^i_R + \lambda_{d_i}\phi_{d_i}\overline{\chi}_L d^i_R + \text{h.c.}$$



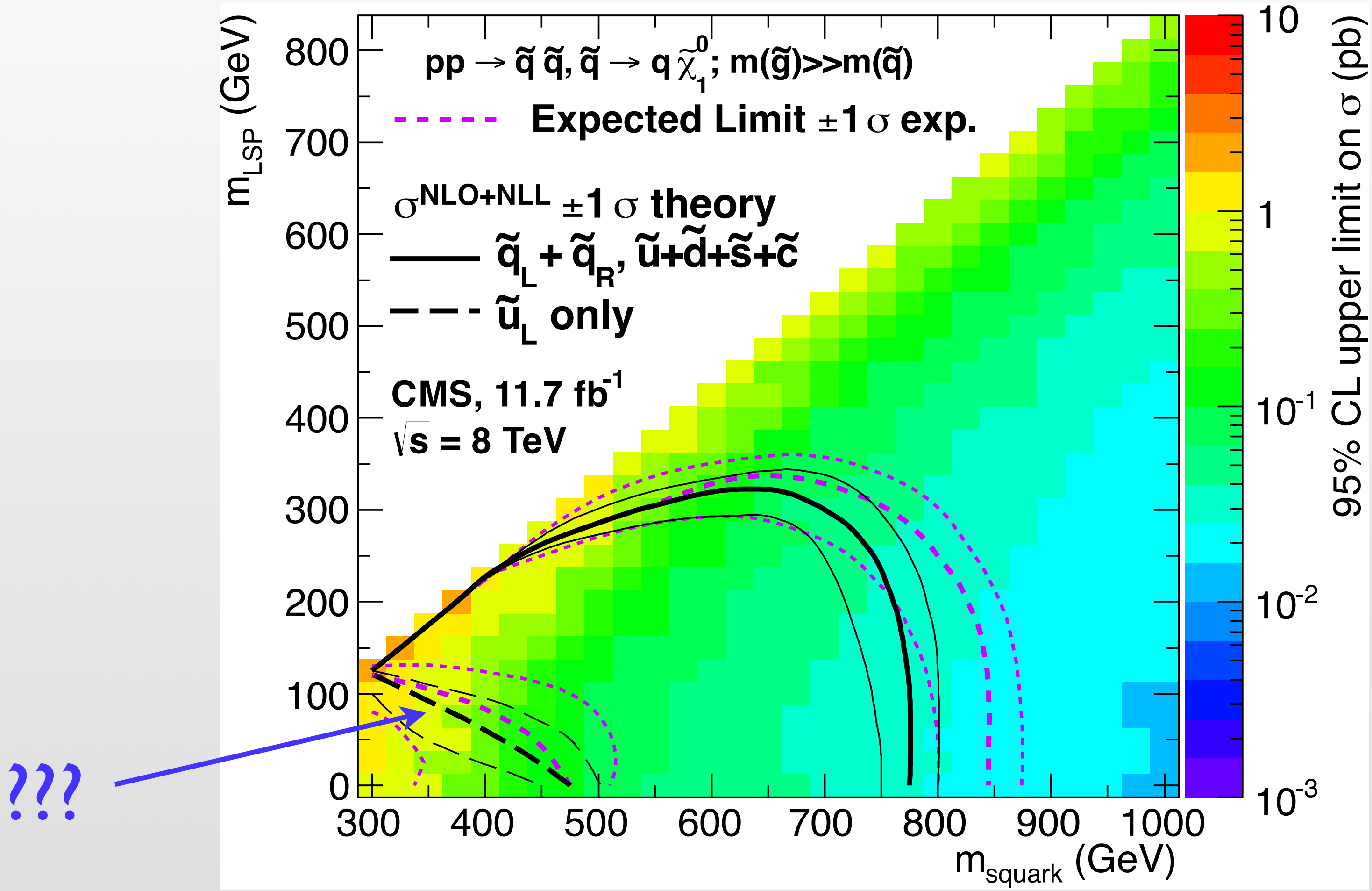
QCD triplet

at the LHC



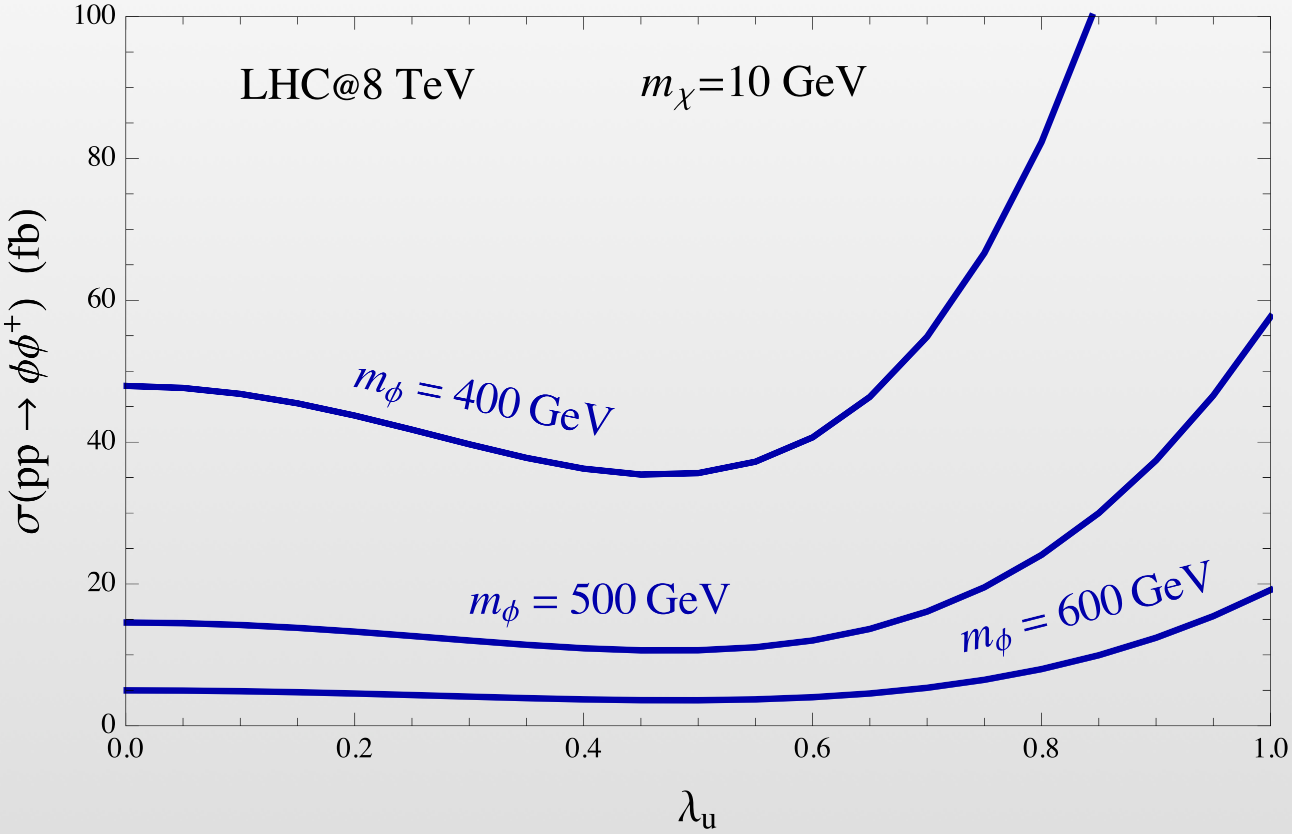


Quark Portal Dark Matter



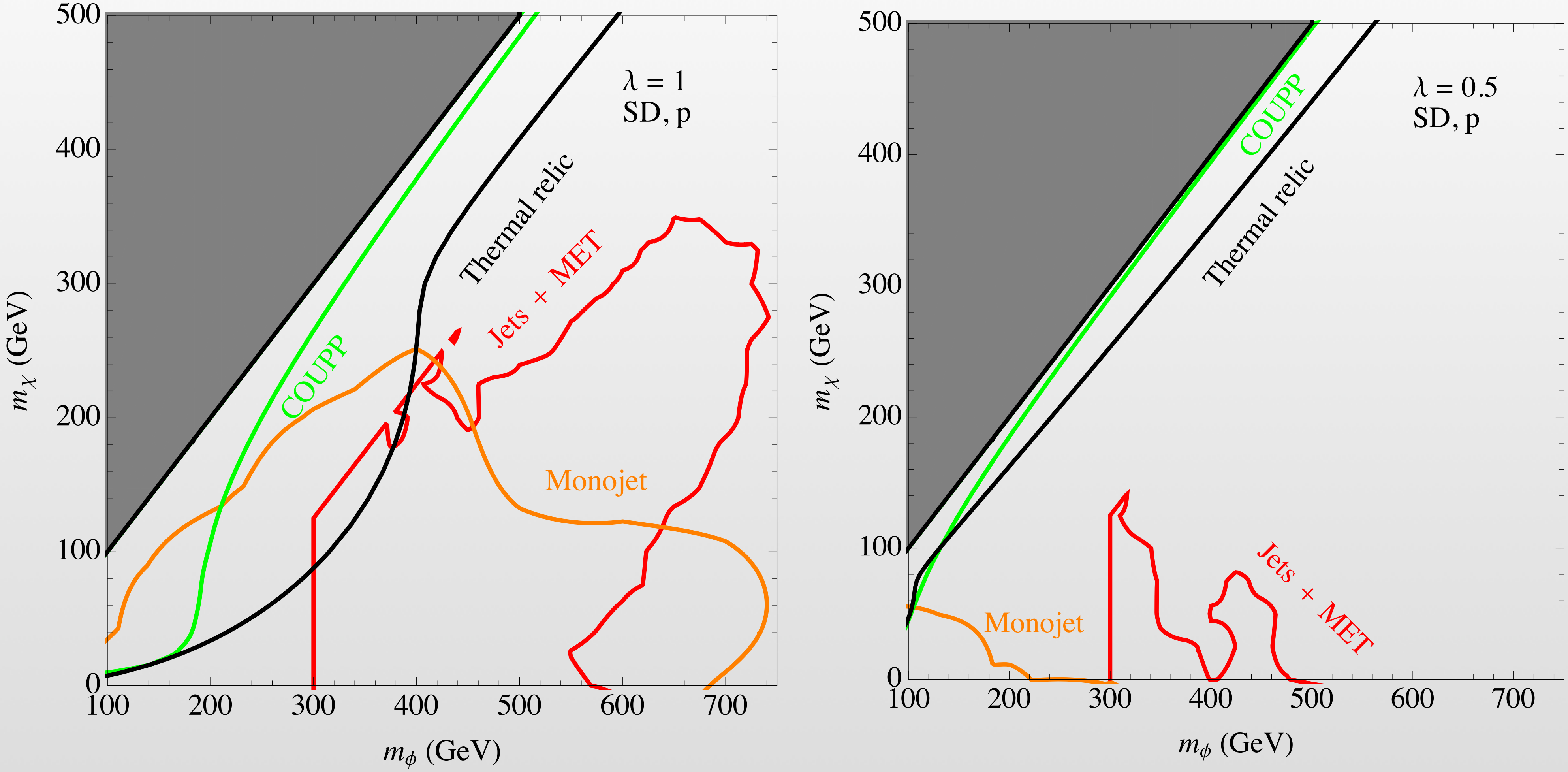
two jets + MET

QCD and Yukawa Interference



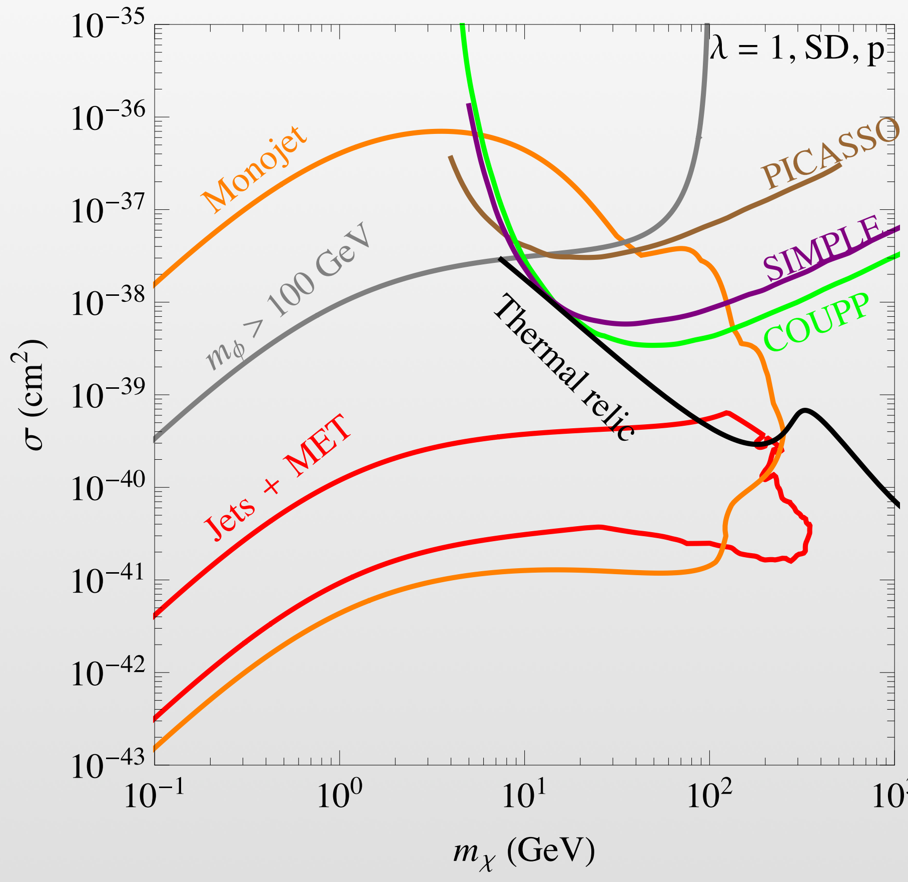
interesting deconstructive interference region

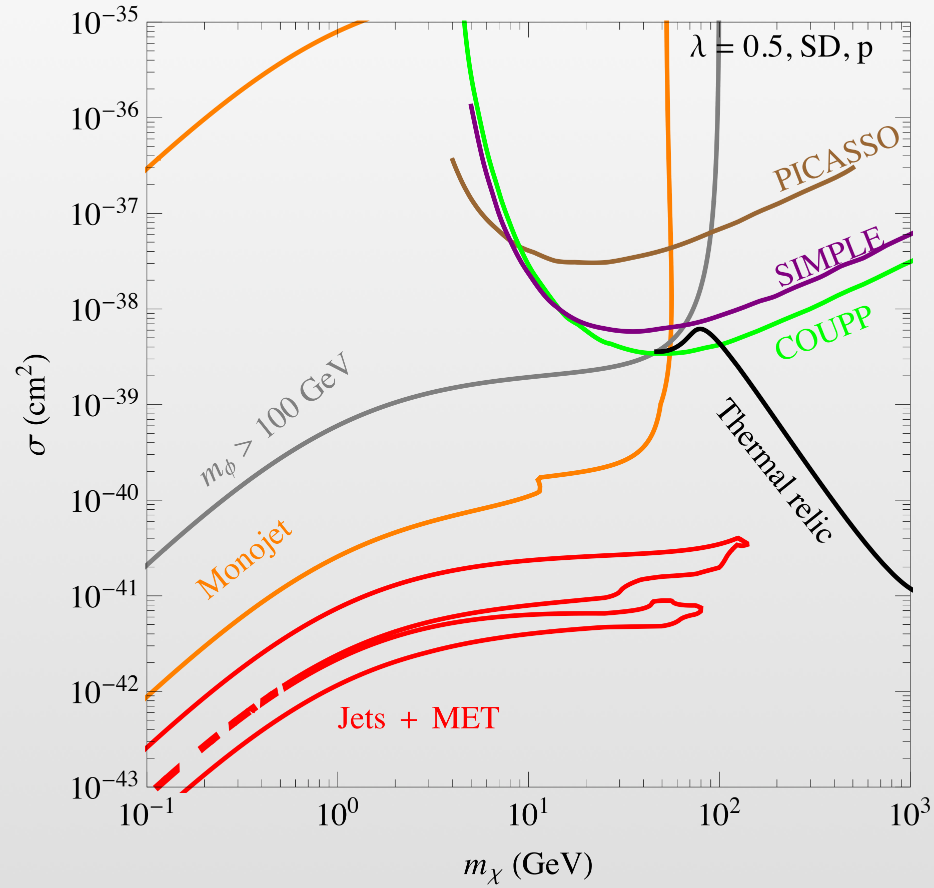
Current Allowed Parameter Space



Majorana fermion dark matter up-quark

Compare to Direct Detection

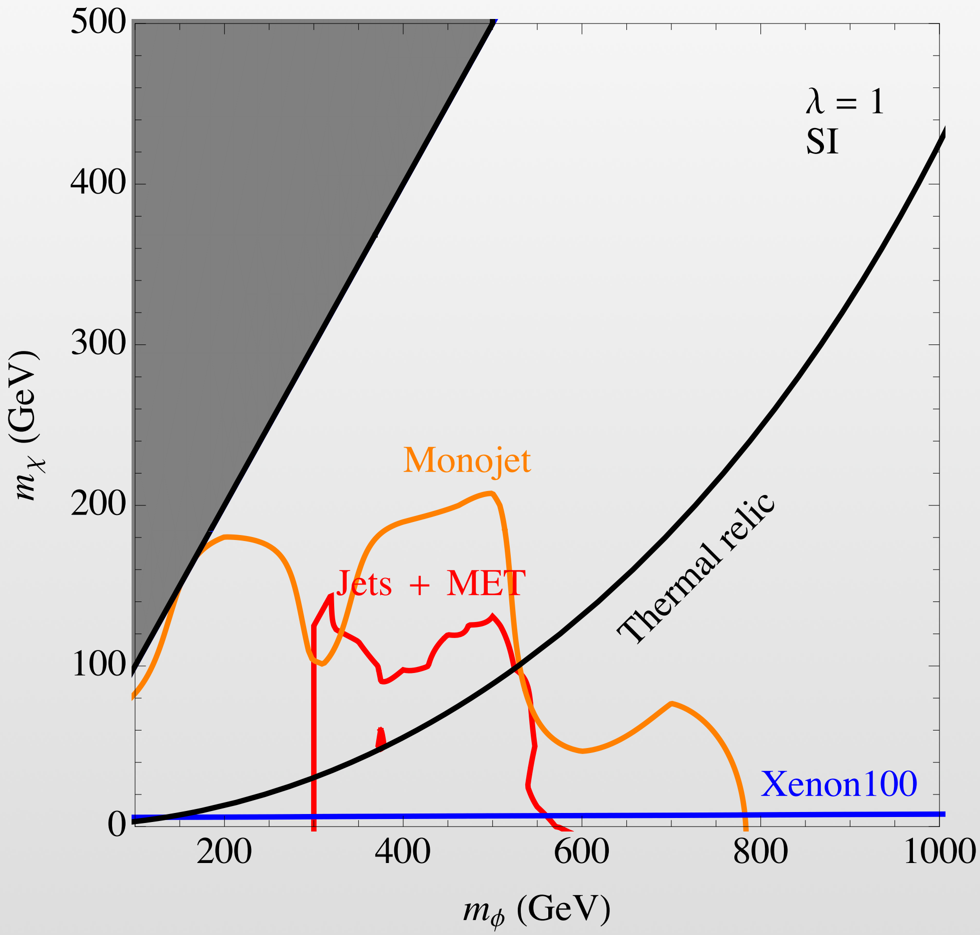


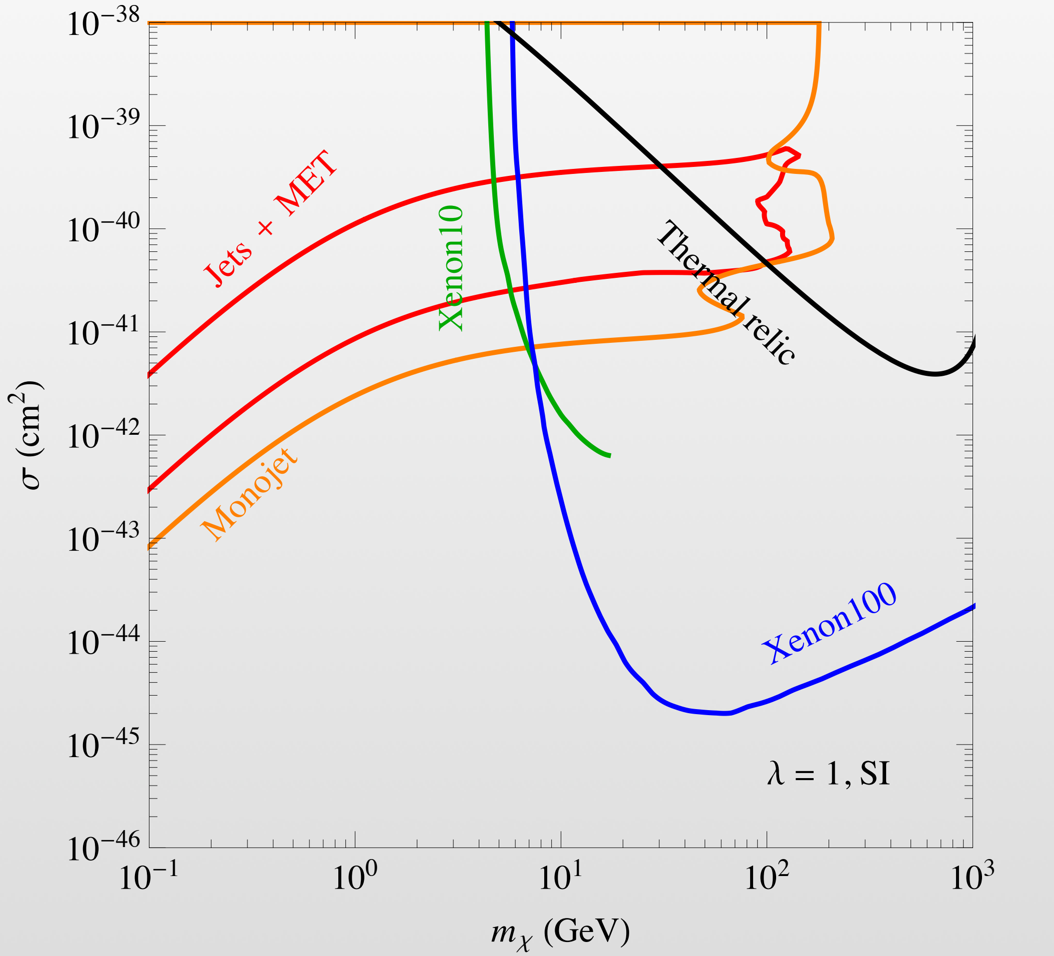


Majorana fermion dark matter

up-quark

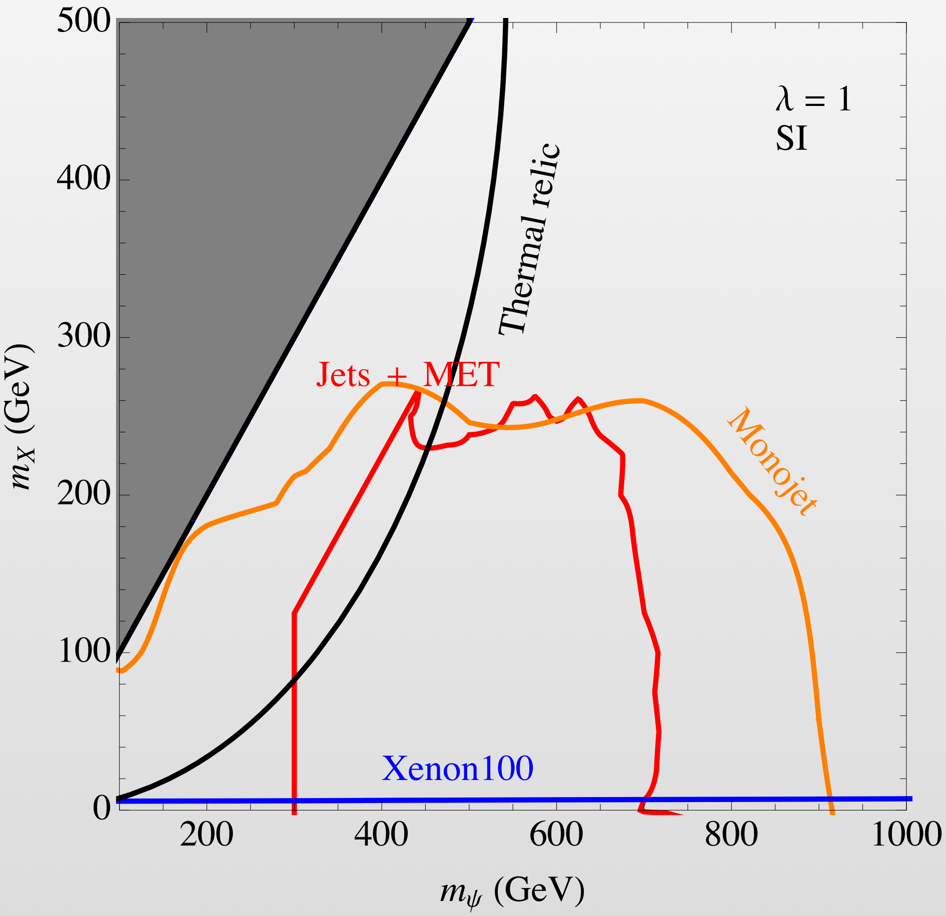
Dirac Fermion Dark Matter

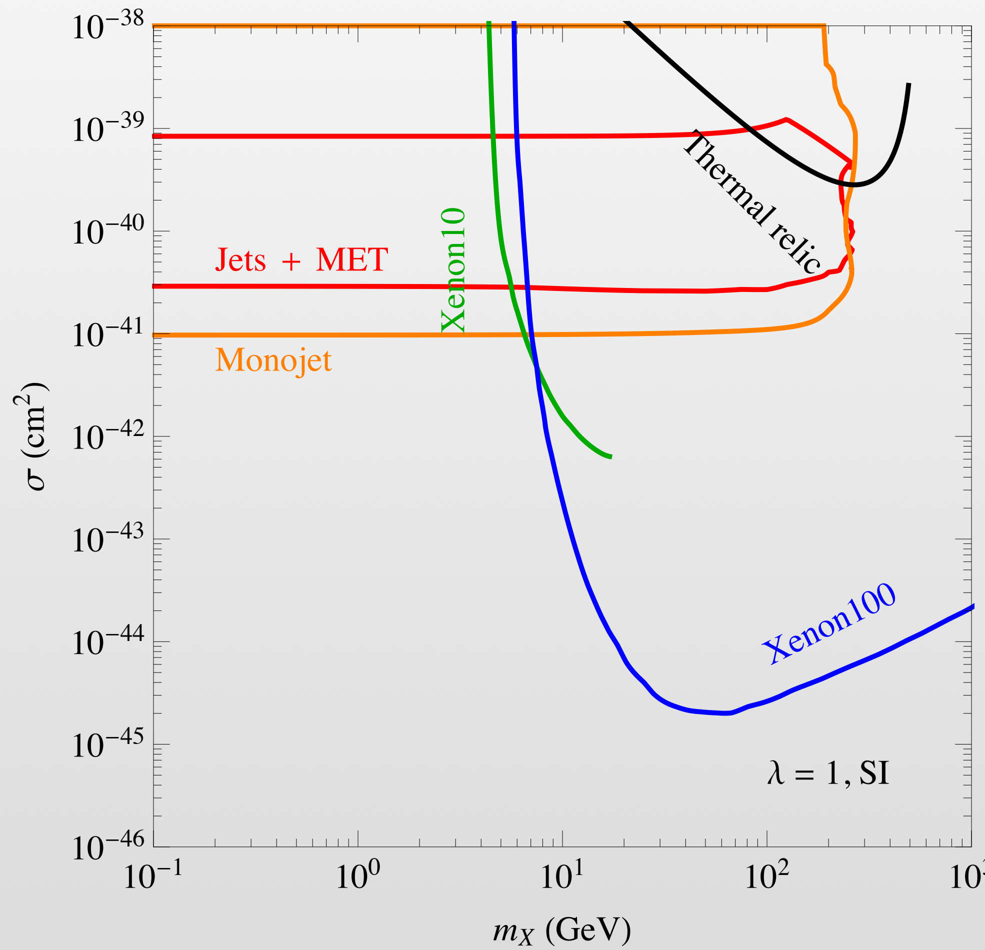




up-quark

Complex Scalar Dark Matter

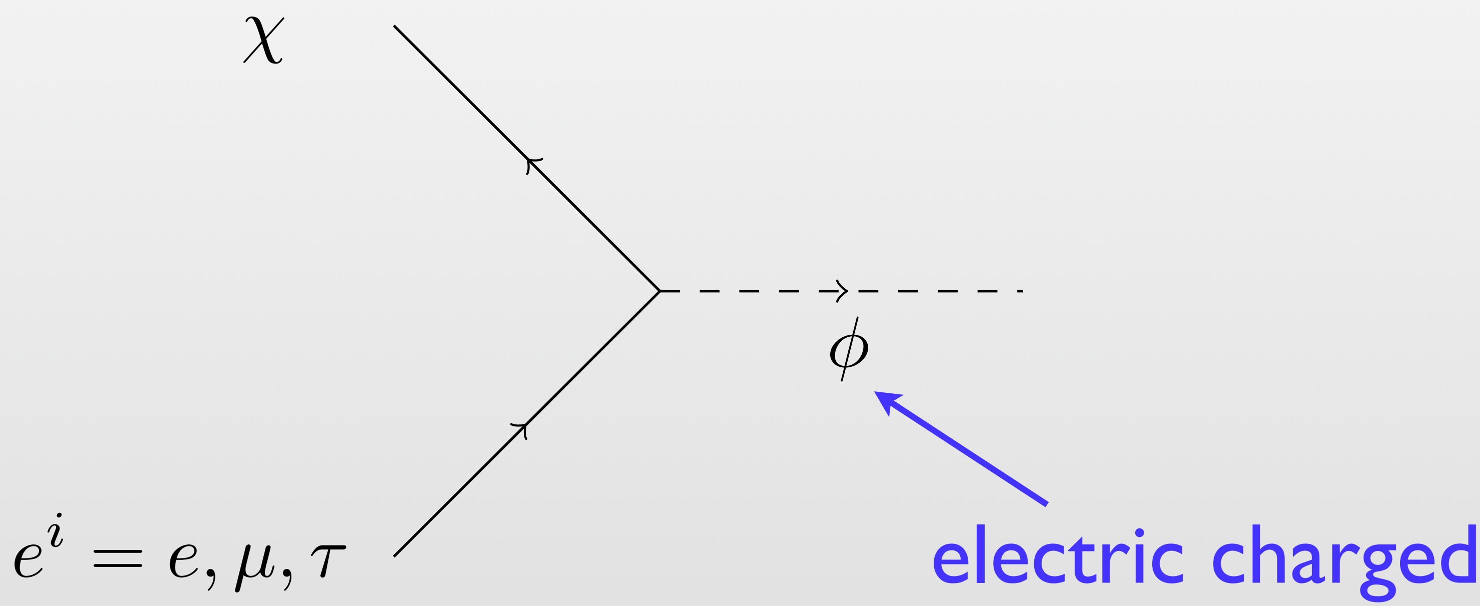




up-quark

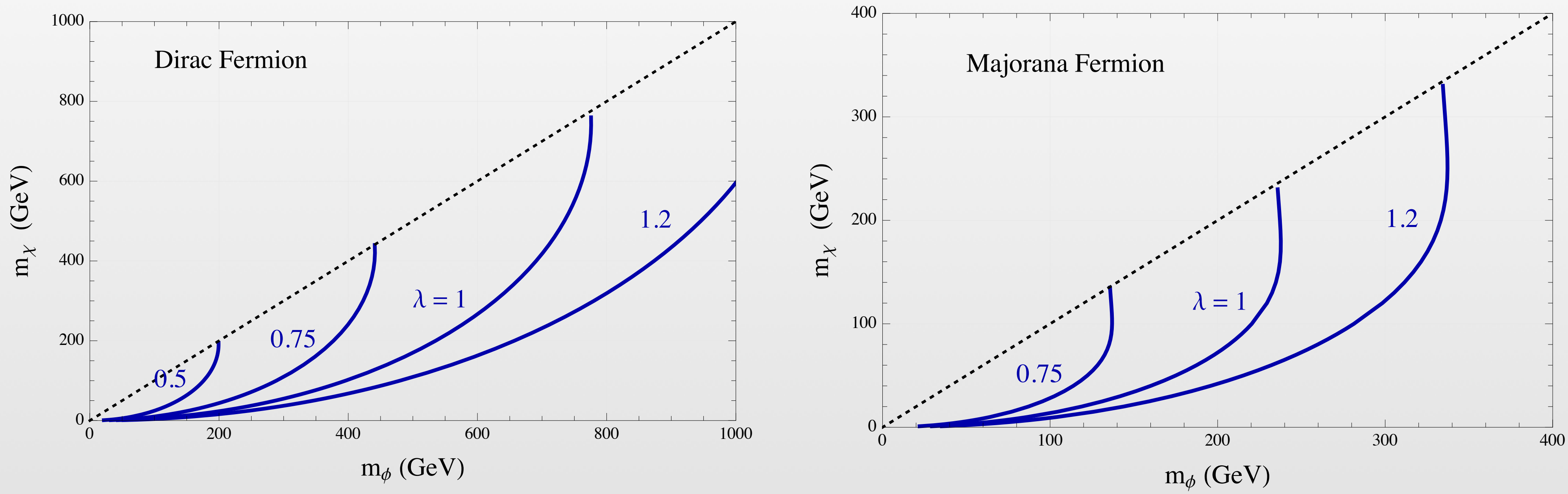
Lepton Portal Dark Matter

$$\mathcal{L}_{\text{fermion}} \supset \lambda_i \phi_i \overline{\chi}_L e_R^i + \text{h.c.}\,,$$



- ★ we will consider flavors one by one for Dirac fermion, Majorana fermion and complex scalar dark matter

Thermal Relic Abundance

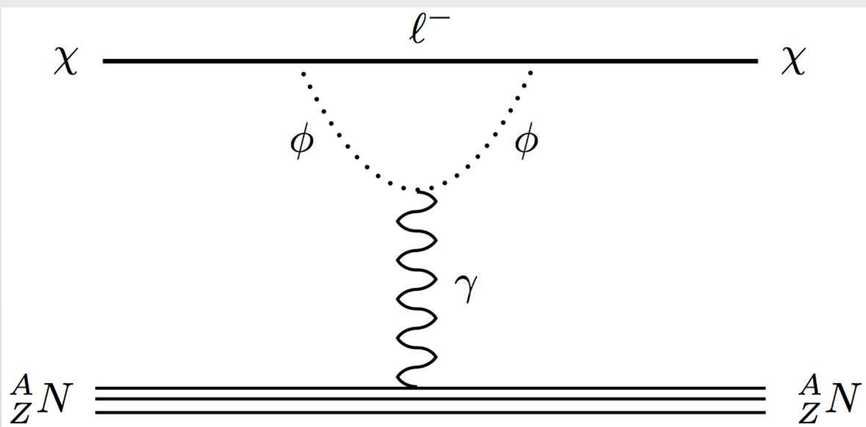


★ the degenerate region (the diagonal line) requires more a careful co-annihilation calculation, which has been ignored here

Dark Matter Direct Detection

★ scattering off electrons at the target is suppressed by the electron wave function

★ scattering off nucleons requires one-loop process



$$\mathcal{O}_1^{\rm Dirac} = \left[\overline{\chi}\gamma^\mu(1-\gamma^5)\partial^\nu\chi + \text{h.c.}\right] F_{\mu\nu}$$

$$\mathcal{O}_2^{\rm Dirac} = \left[i\,\overline{\chi}\gamma^\mu(1-\gamma^5)\partial^\nu\chi + \text{h.c.}\right] F^{\alpha\beta}\epsilon_{\mu\nu\alpha\beta}$$

charge+magnetic dipole

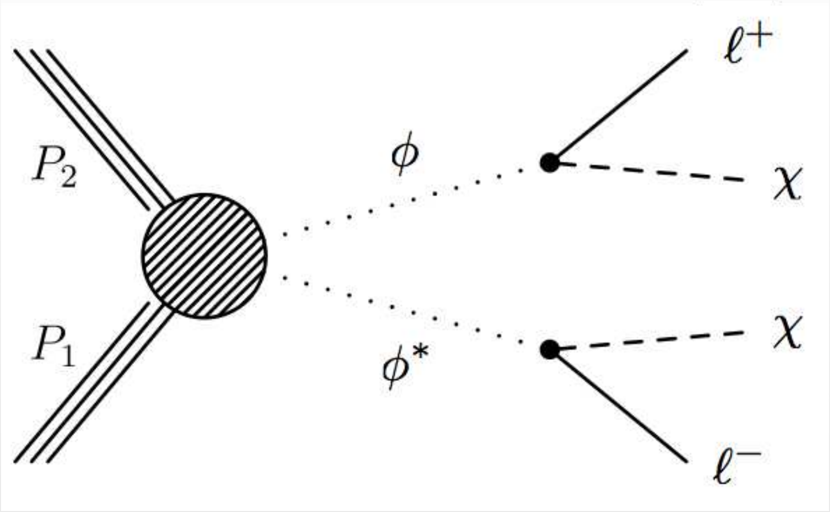
$$\mathcal{O}_1^{\rm Majorana} = \left[-\overline{\chi}\gamma^\mu\gamma^5\partial^\nu\chi + \text{h.c.}\right] F_{\mu\nu}$$

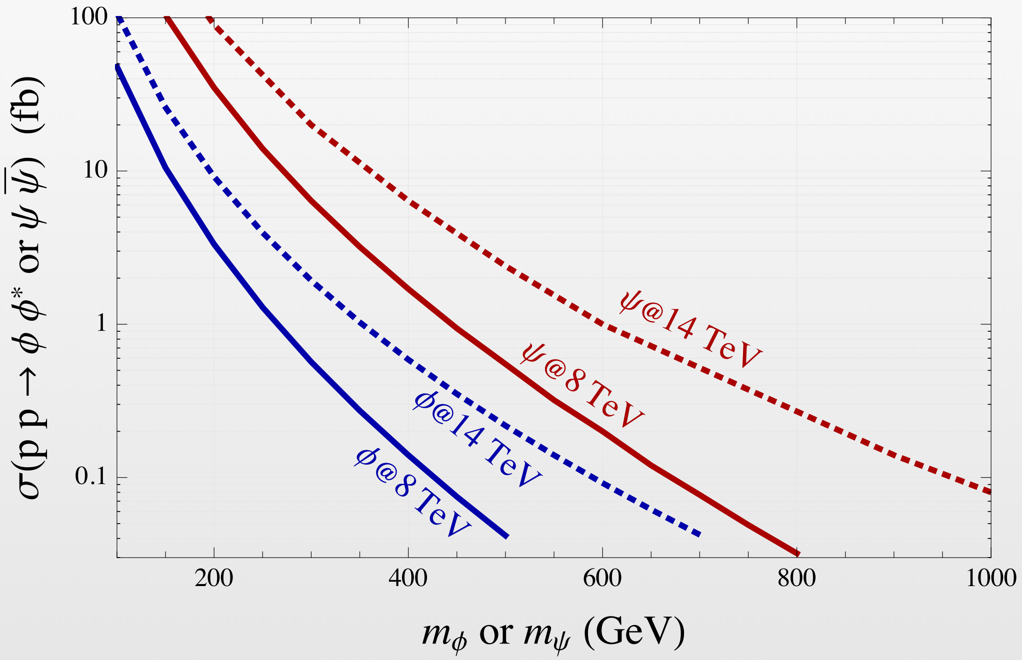
anapole moment

$$\mathcal{O}_1^{\rm Complex} = \partial^\mu X \partial^\nu X^\dagger F_{\mu\nu}$$

charge radius

Production at the LHC

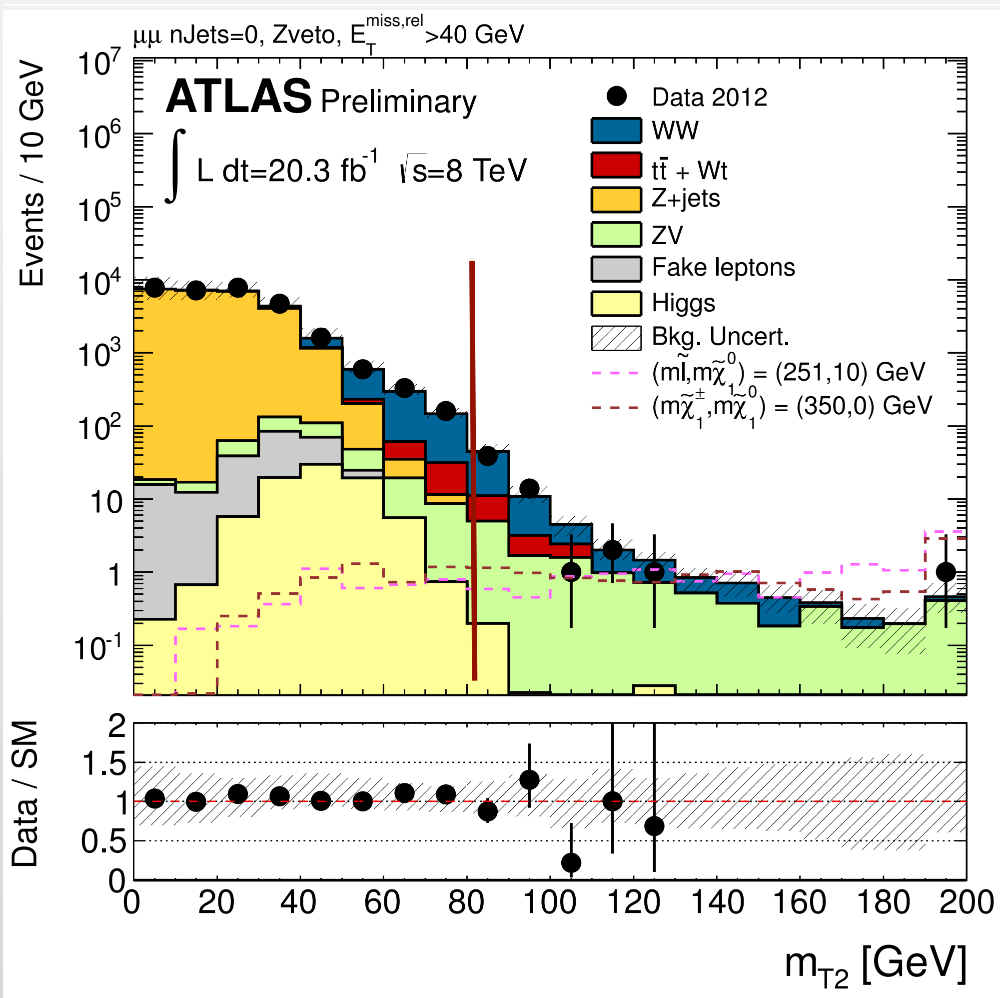




- ★ Fermion DM: the complex scalar mediator production (the same as the right-handed selectron one in SUSY)
- ★ Complex scalar DM: vector-like fermion mediators with larger cross sections

Lepton MT2

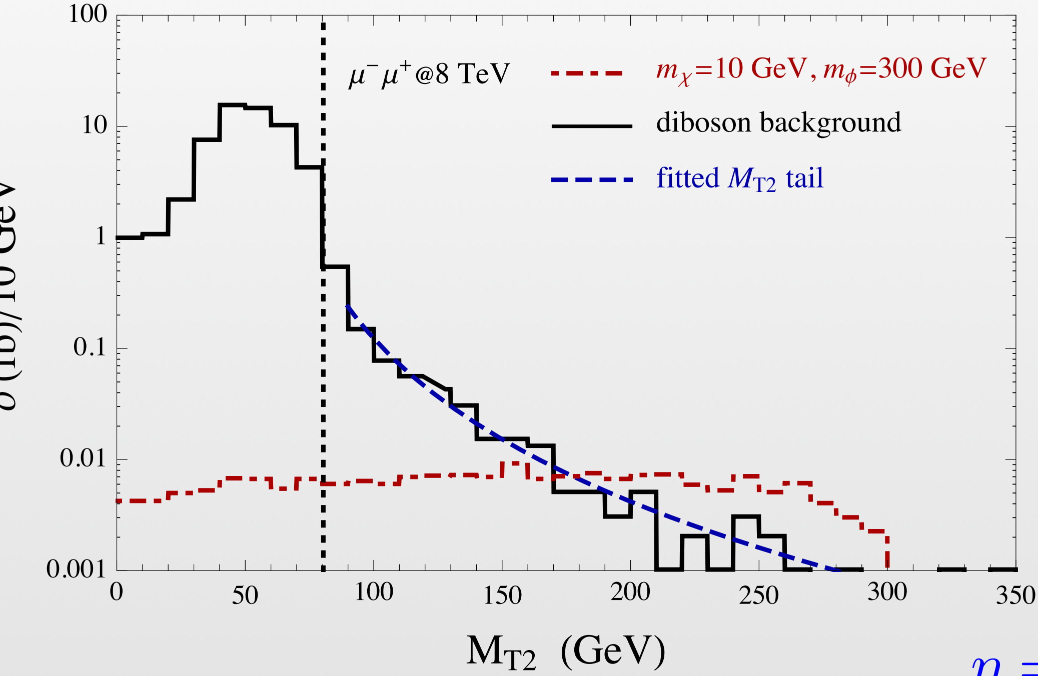
$$M_{T2} = \min \left\{ \bigcup_{\vec{p}_1^T + \vec{p}_2^T = \vec{E}_T^{\text{miss}}} \max \left[M_T(\vec{p}_{\ell_1}, \vec{p}_1^T), M_T(\vec{p}_{\ell_2}, \vec{p}_2^T) \right] \right\}$$

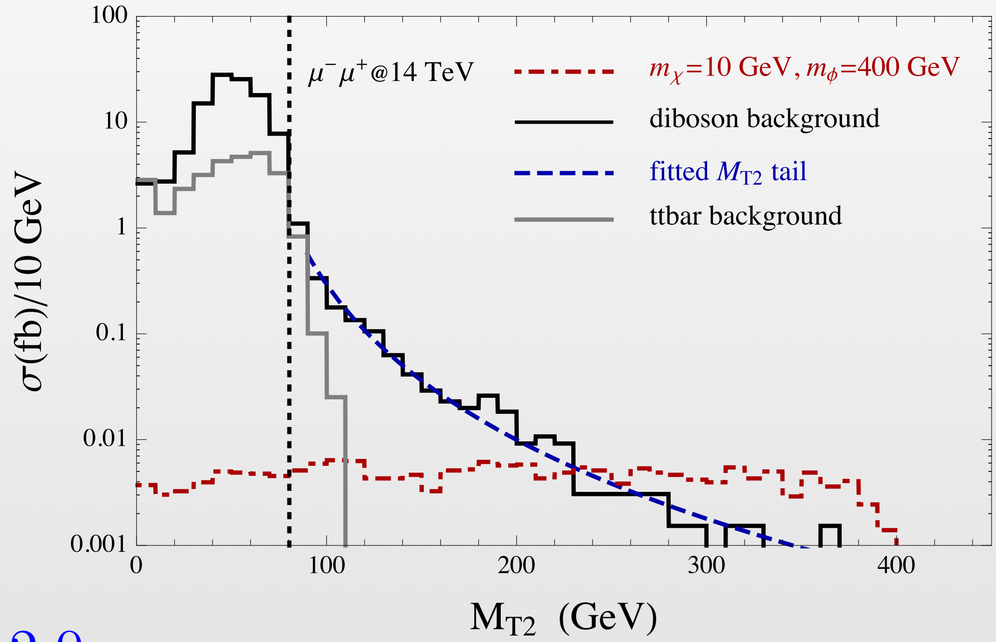


pt(j) > 20 GeV

jet veto

Tail of the Leptonic MT2



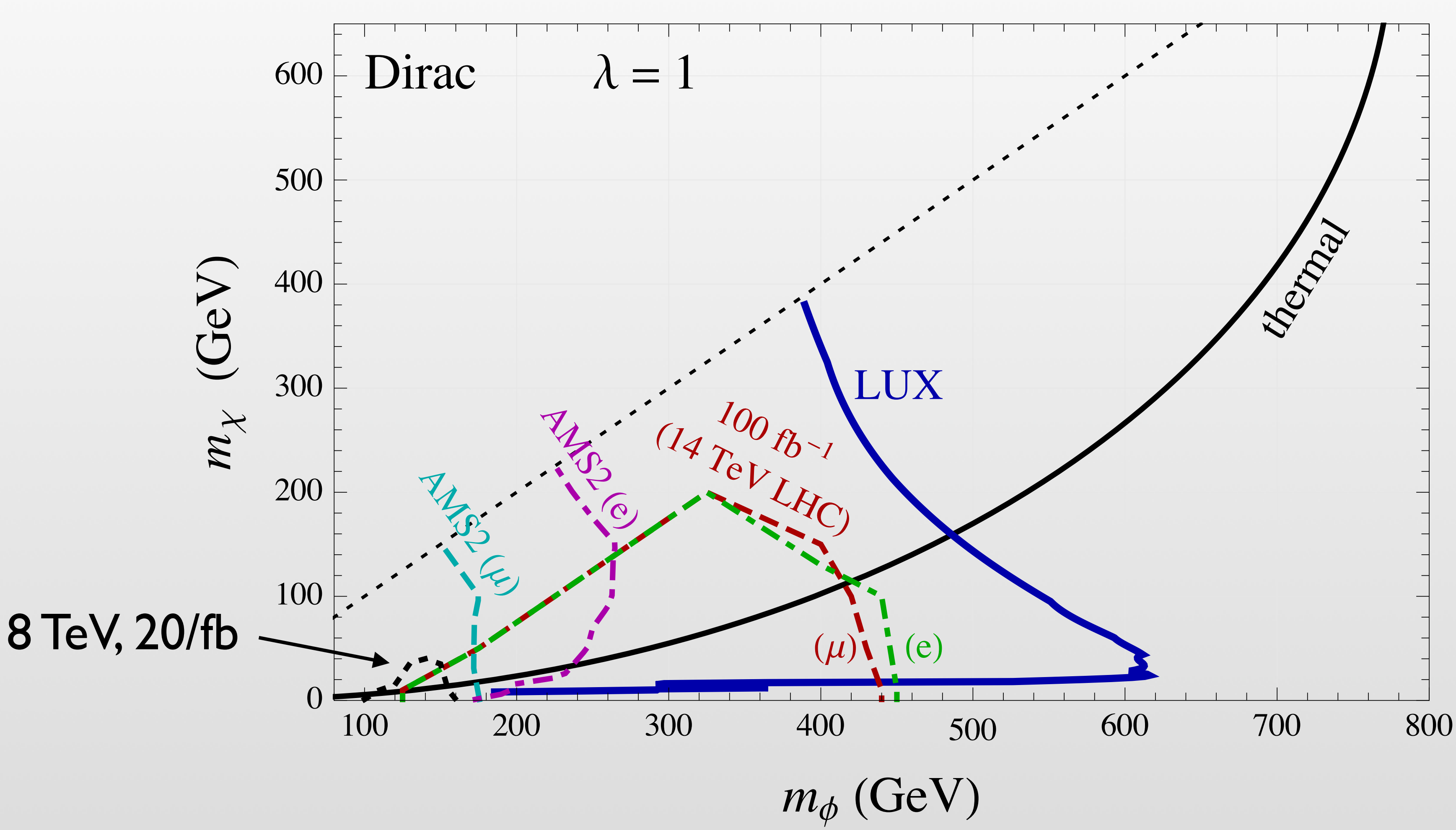


$$\eta = 2.0$$

$$F\left(M_{T2}\right) = \frac{N_0}{\left[\eta M_{T2}^2 - M_W^2\right]^2 + \eta^2 M_{T2}^4 \Gamma_W^2 / M_W^2}$$

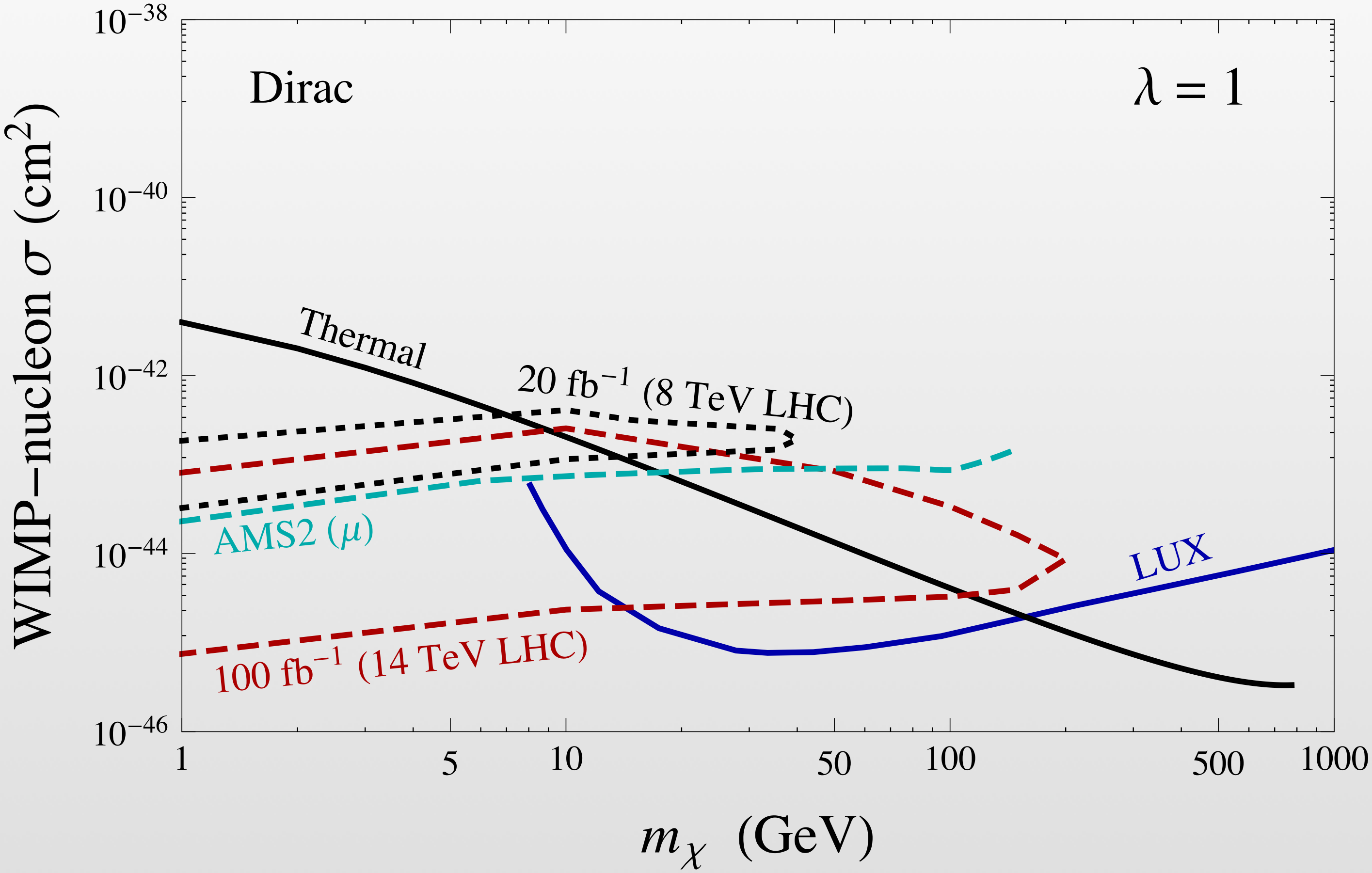
★ the tail can be fitted by a Breit-Wigner formula

Status of Fermion DM



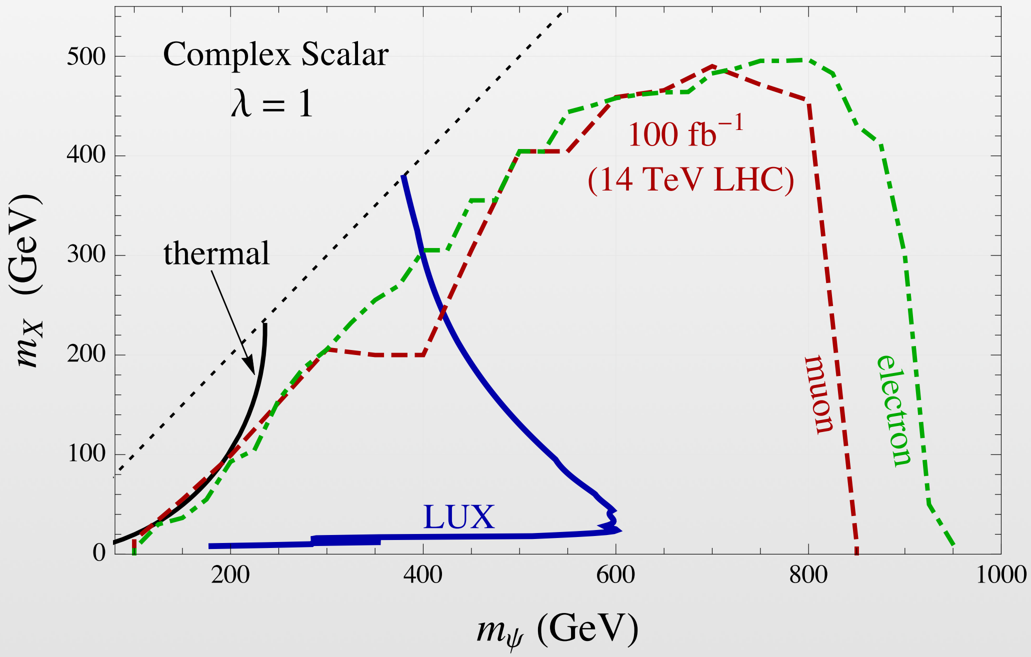
$\tau^+\tau^- + \mathrm{MET}$ should also be searched for

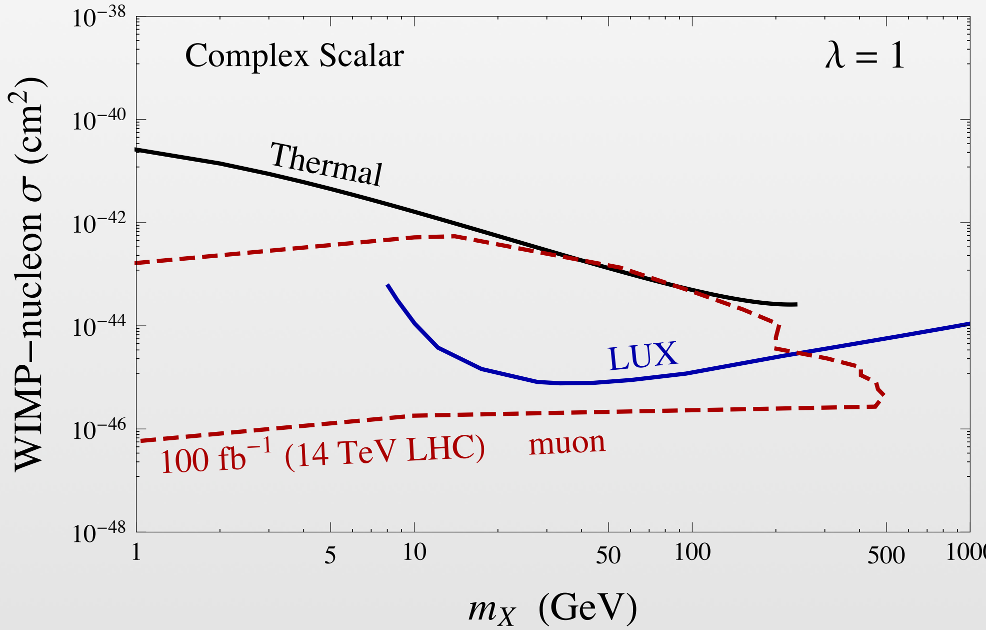
Status of Fermion DM



Majorana fermion DM has suppressed direct detection cross sections due to the anapole moment

Status for Complex Scalar DM





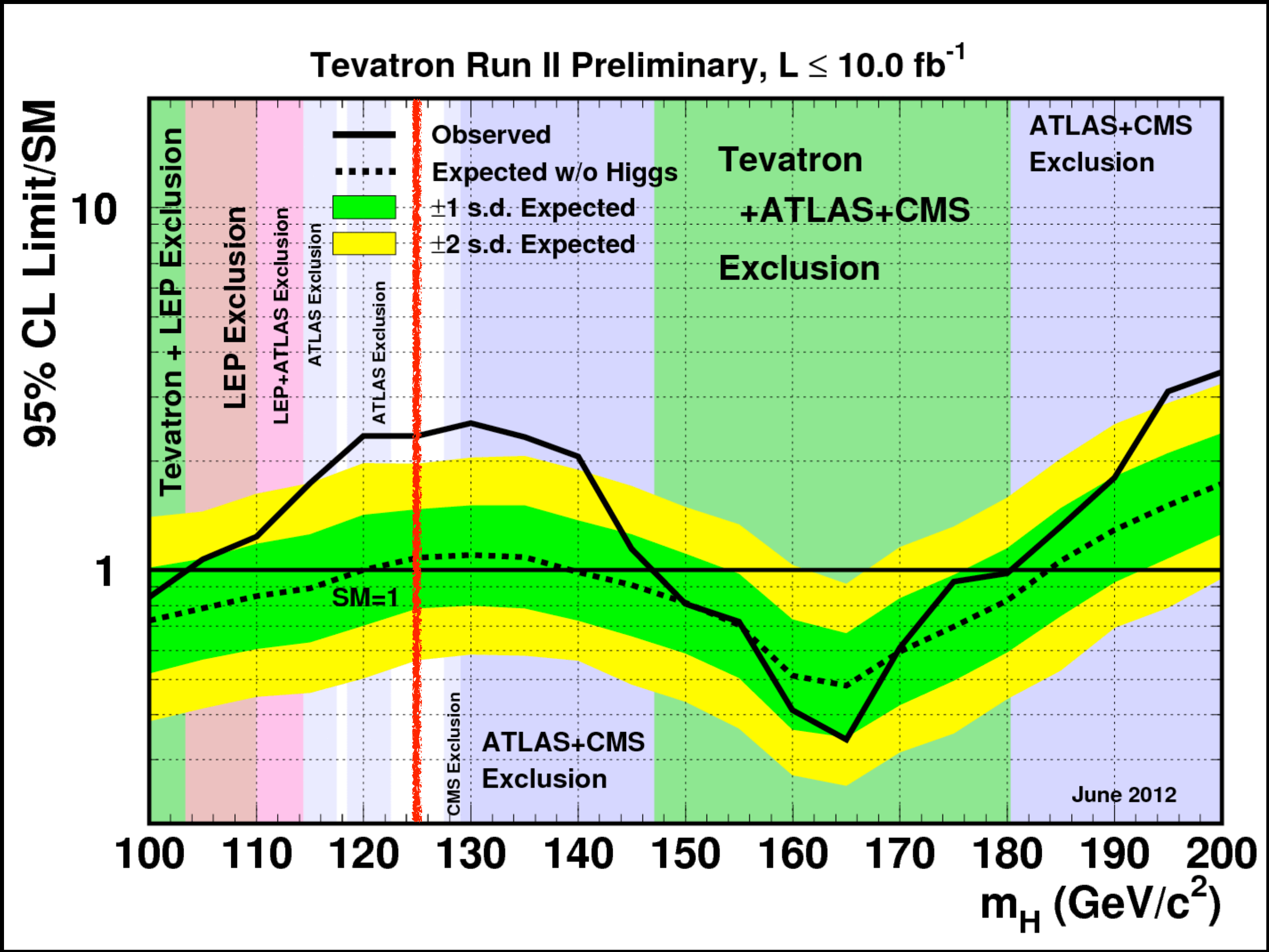
- ★ the indirect detection is also p-wave suppressed
- ★ much wider range of parameter space to be explored by the 14 TeV LHC

Conclusion

- We know the existence of the dark matter gravitational interaction
- We have not yet proved any additional interactions at the current moment
- More searches for simplified dark matter models should be performed at the LHC
- The LHC Run2 has a good coverage of fermion portal dark matter models

Discovery History of the Higgs Boson

just one month before the discovery



谢谢！

Thanks