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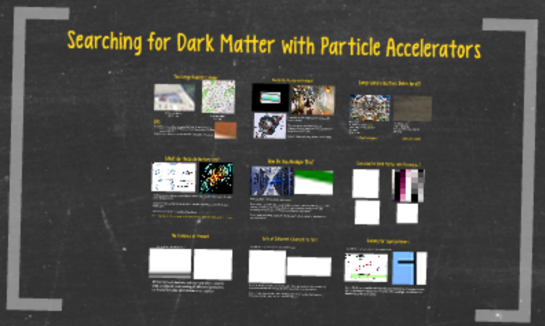
Finding Weakly Interacting Dark Matter:
Particle Accelerators and Direct Detection

Weakly Interacting Dark Matter

From Last Lecture



Searching for Dark Matter with Particle Accelerators

Direct Detection

Tim Linden

Lecture 6

Fall 2014 Compton Lectures

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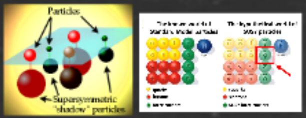
Weakly Interacting Dark Matter

From Last Lecture:

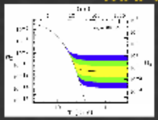
Supersymmetry



WIMP models are motivated by supersymmetry

The lightest supersymmetric particle is stable, and thus a good candidate to be the dark matter

WIMP Miracle



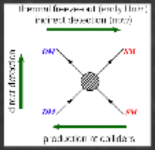
One question to answer:
Why nearly as much dark matter as regular matter?

Solution! Dark matter and regular matter interact in the early universe

Miracle! Letting dark matter and regular matter interact through the weak force gives us the correct density of dark matter today

Residual Interactions Today

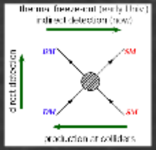
Remember: Any interaction that can happen WILL happen (maybe rarely)



We should be able to look for these interactions today!

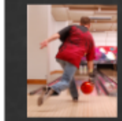
Residual Interactions Today

We don't know what happens in the center of this interaction!

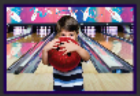


So we want to search for interactions occuring in every direction

It's called the weak force for a reason!



Early Universe



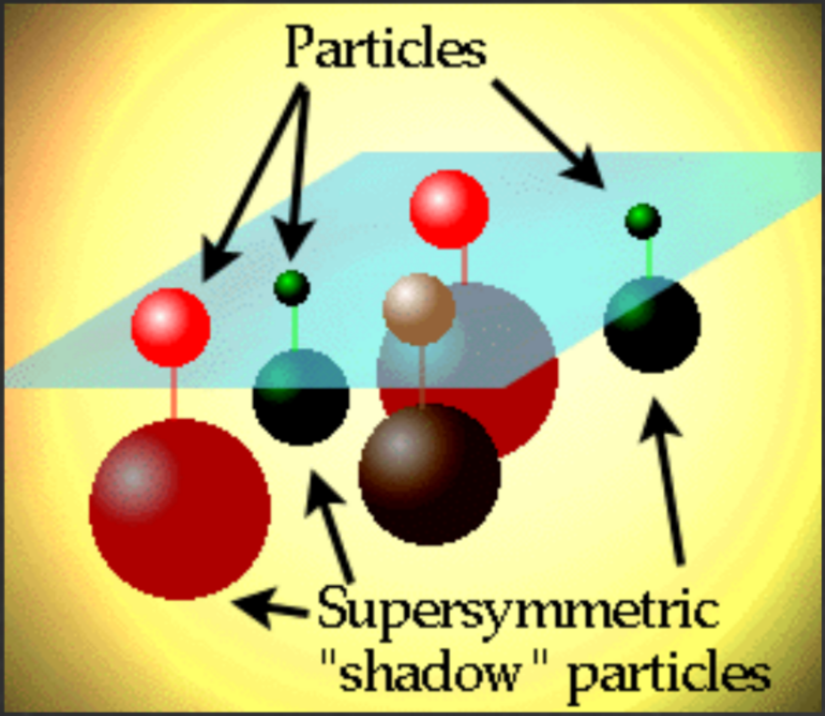
Now

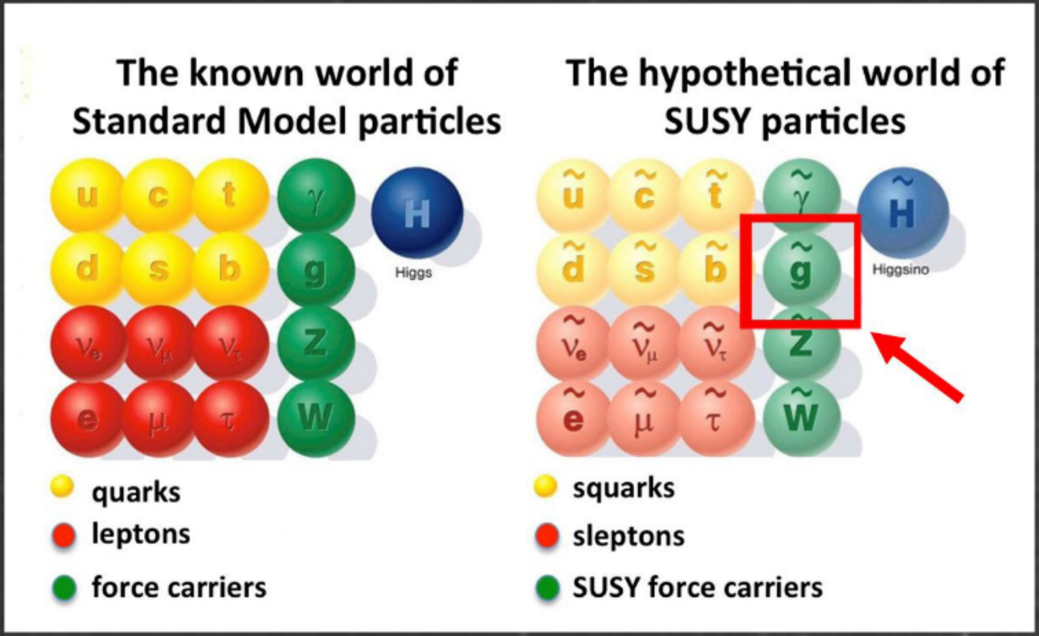
Solution, We need Sensitive Machines!

To Look for a Rare Interaction:

- Machine must be capable of seeing a single particle interaction, against a background where baryons might interact a lot
- Machine must be able to produce lots and lots of interactions

Supersymmetry





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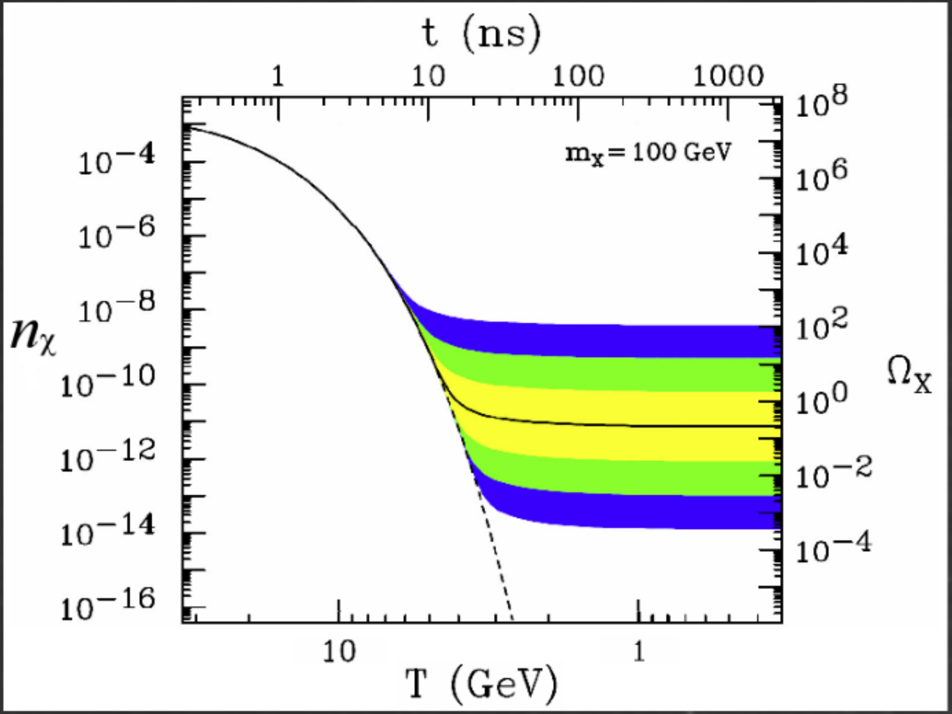

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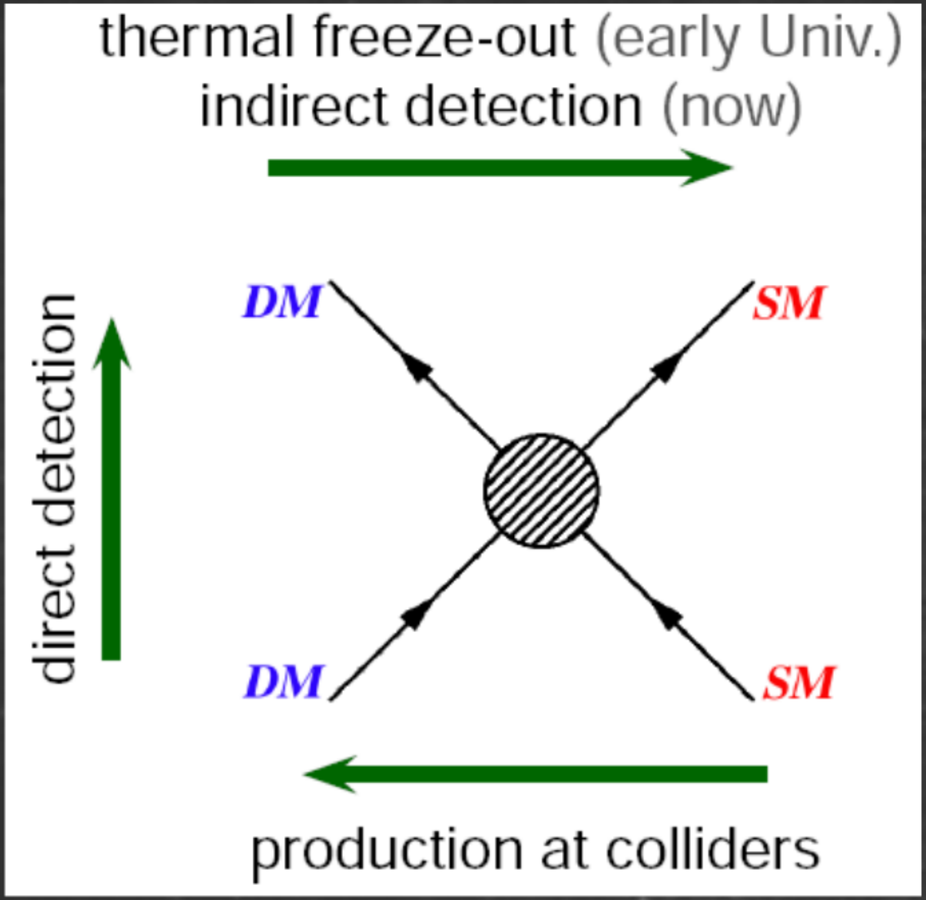

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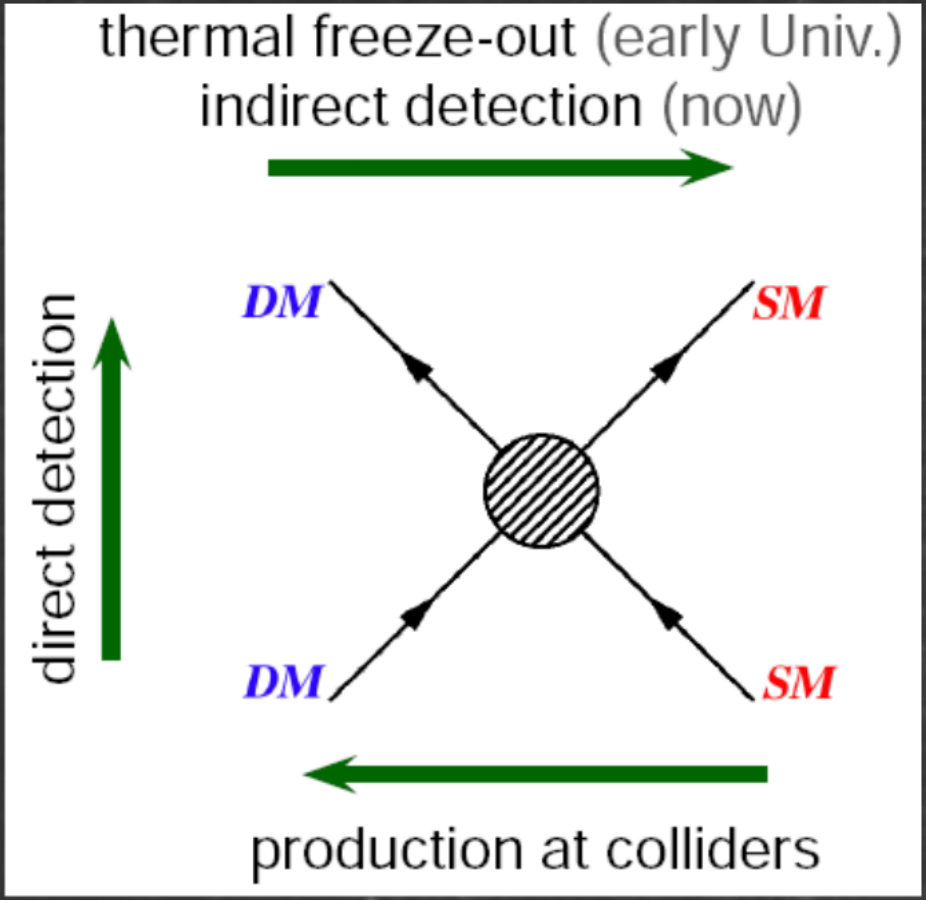

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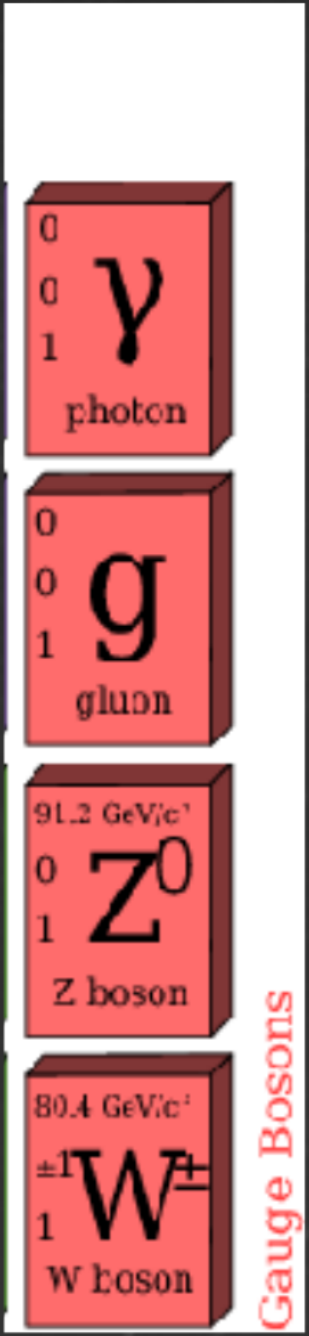

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The Large Hadron Collider

Tevatron - 4.26 Mile Ring
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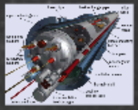
Large Hadron Collider
17 mile ring

LHC:

Maximum particle collision energy (8 TeV (original), 14 TeV (upgrade)
- Particles collide at 0.999999991c (3 m/s slower than c, or about 299792455 m/s)

Proton-Proton collider (as opposed to Proton/Antiproton at Tevatron)

How Do You Accelerate Protons?



1600 superconducting magnets are used (27 tonnes a piece)

These magnets need to be kept cool (superconducting) 100 Tonnes of Liquid Helium keeps them at (-271.5 C)

Largest superconducting structure in the world

Large (and sensitive) Detectors!!!!

ATLAS Detector
"A Toroidal LHC ApparatuS" Really!
46 meters long, 25 meters in diameter
7000 tonnes
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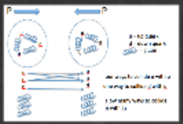

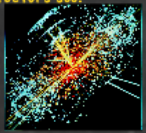

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Most of the times you are colliding two gluons.

Effect - If you have a 14 TeV collider (proton to proton), you don't actually know how energetic any given collision was

How Do You Analyze This?

Raw Data Rate = 100 Terabytes per second !

These events can't all be processed, much less stored. Hardware switches are used to remove 99.9999% of the events, which are not interesting, leaving about 100 interesting events (or about 3 billion interesting events per year).

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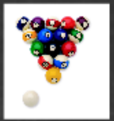
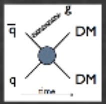
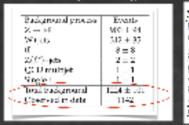
Searching for Dark Matter with Missing p_T

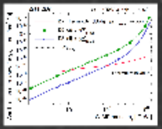




No Evidence at Present

Searches for Single Jets with Missing p_T





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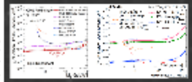

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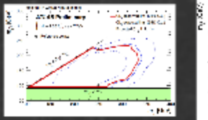

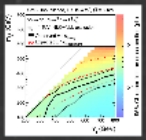

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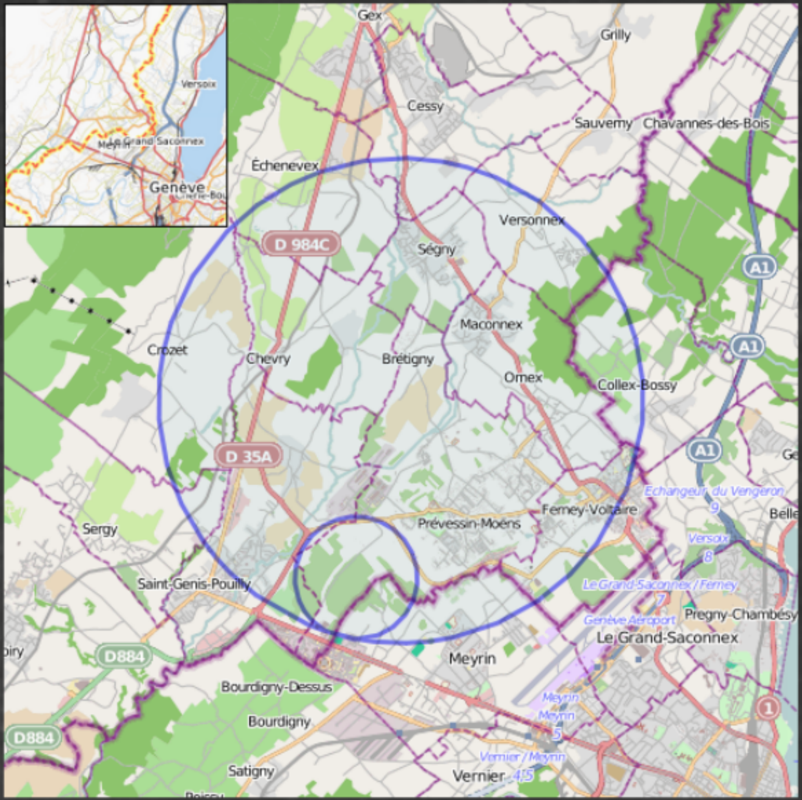

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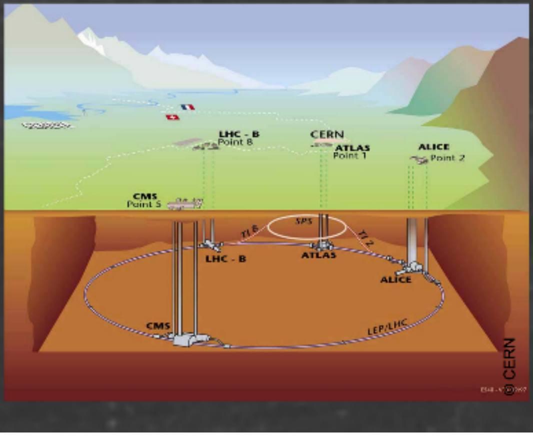

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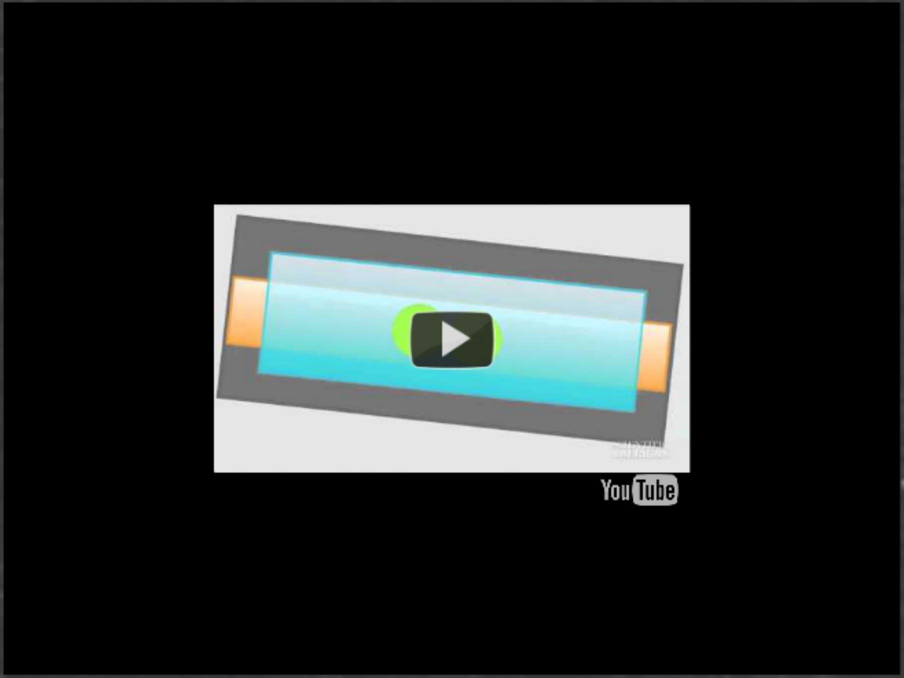

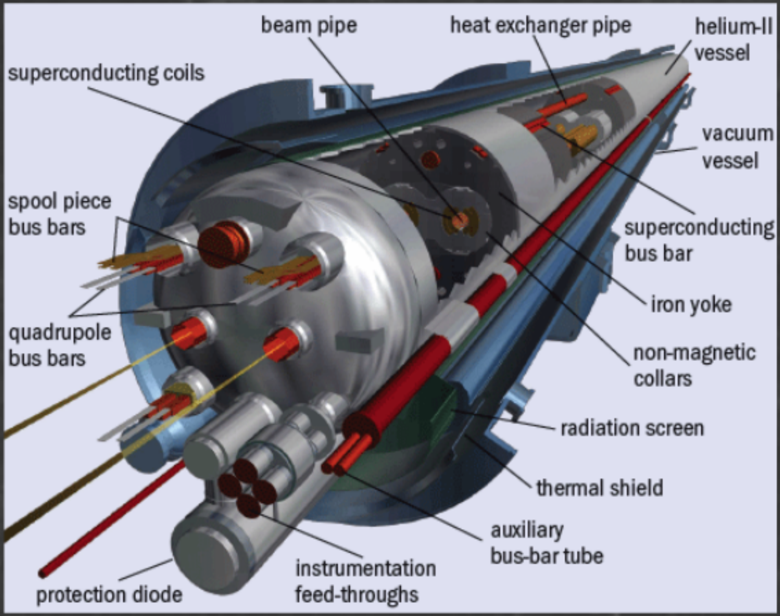

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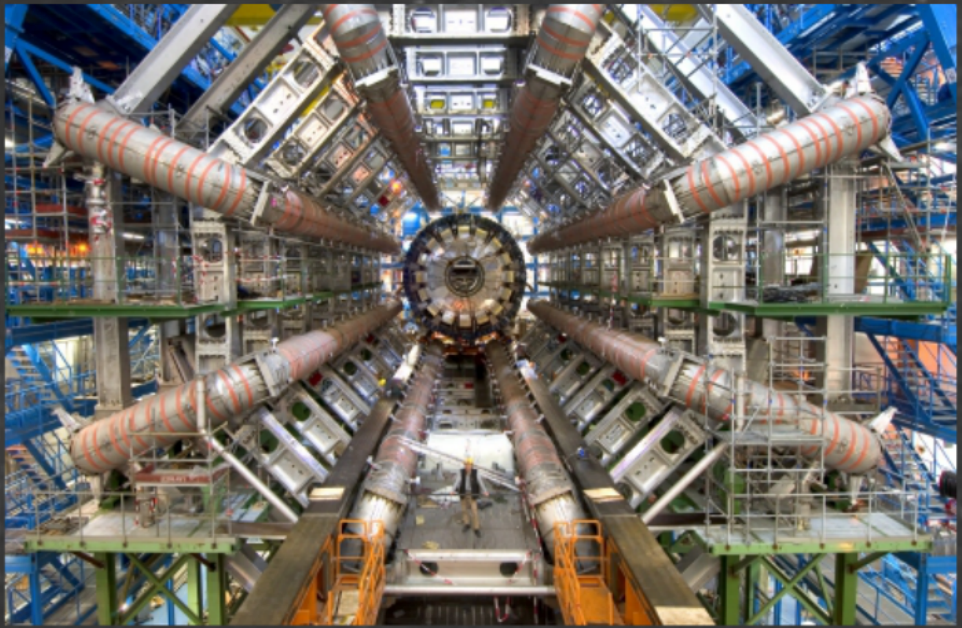

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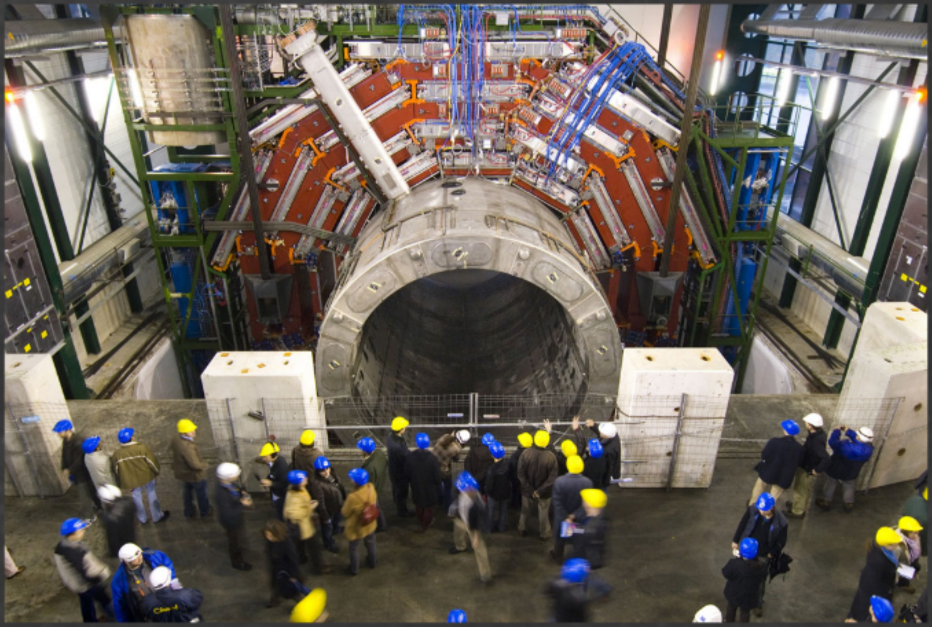

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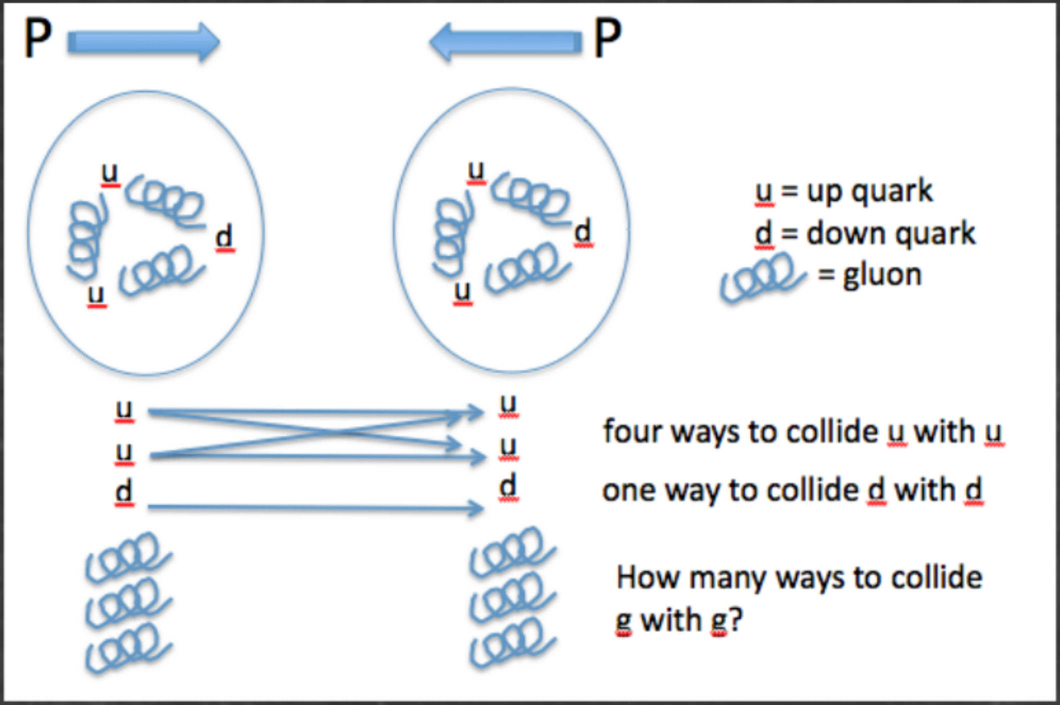
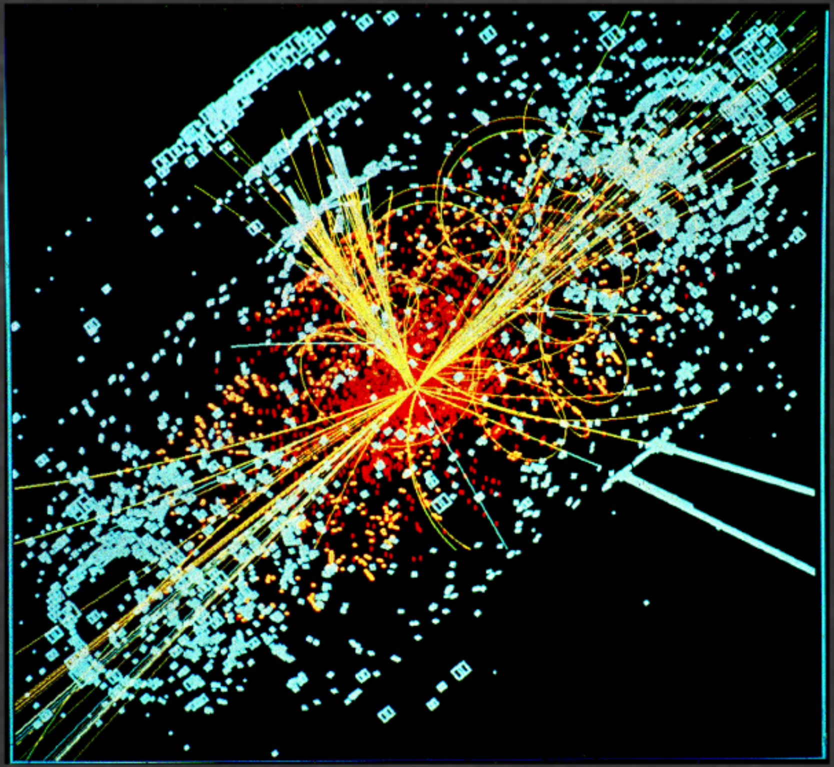


u = up quark
d = down quark
= gluon

four ways to collide u with u

one way to collide d with d

How many ways to collide g with g?



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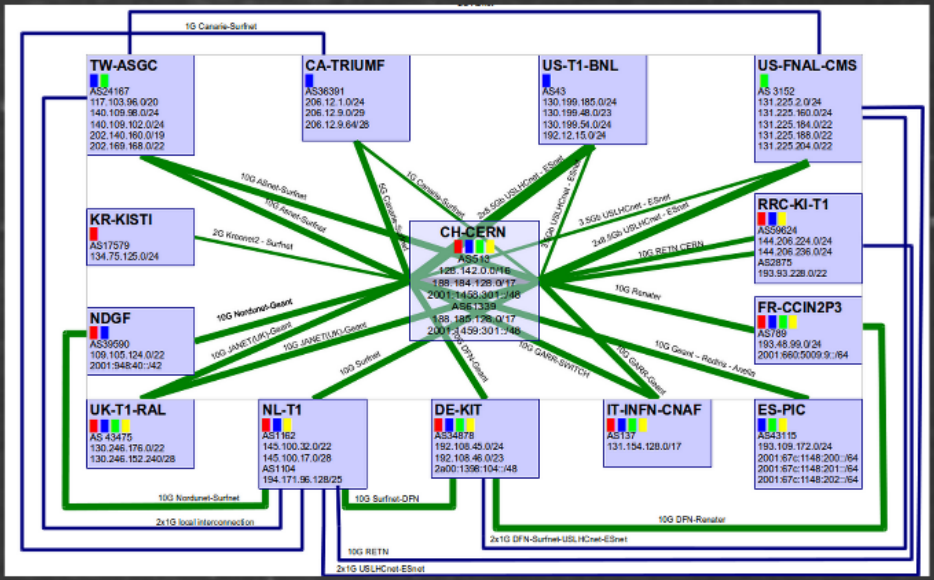

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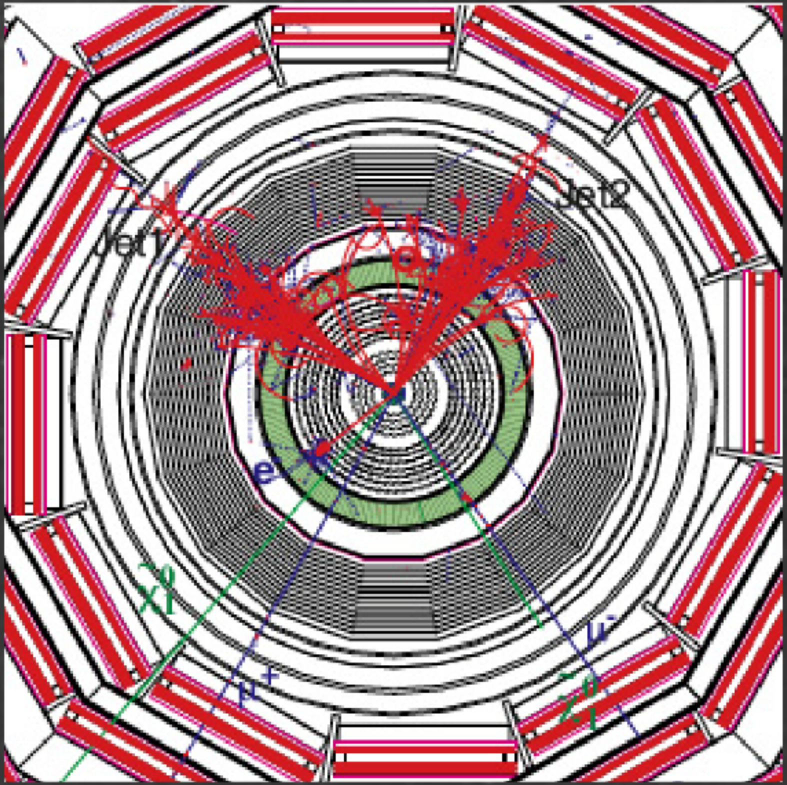

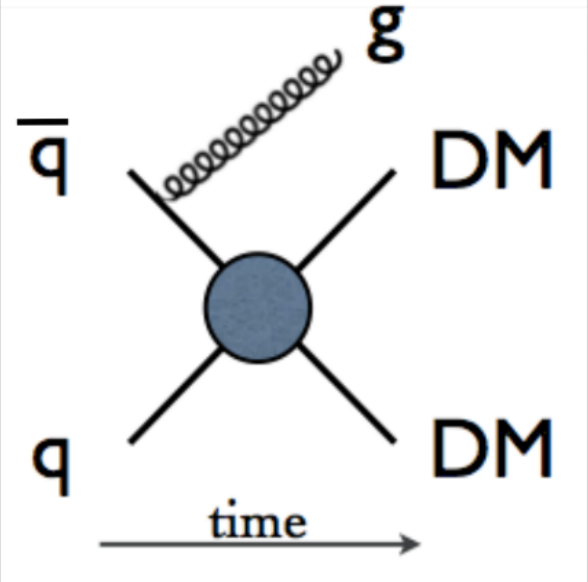

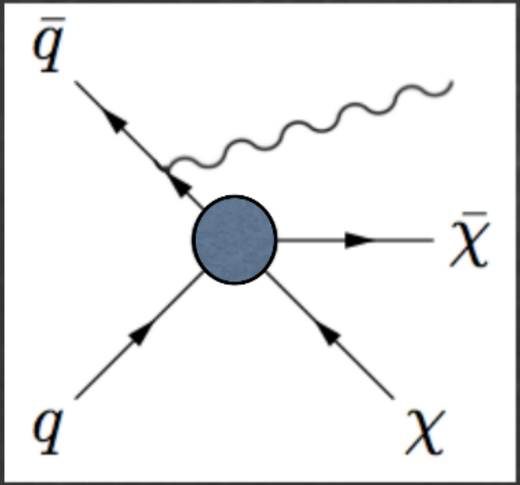

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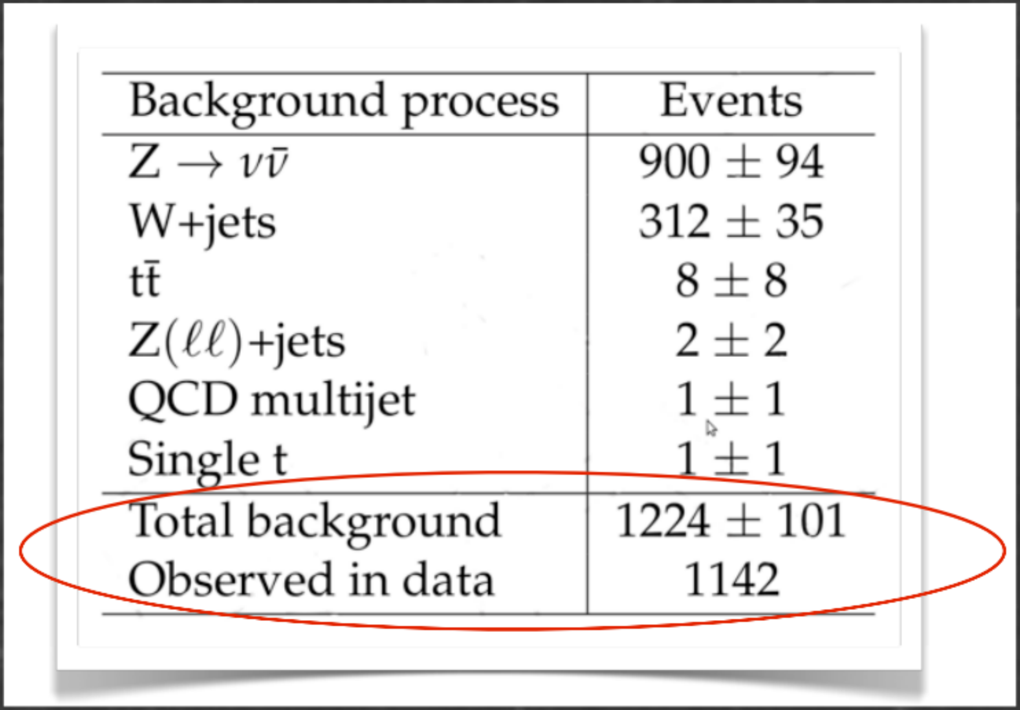
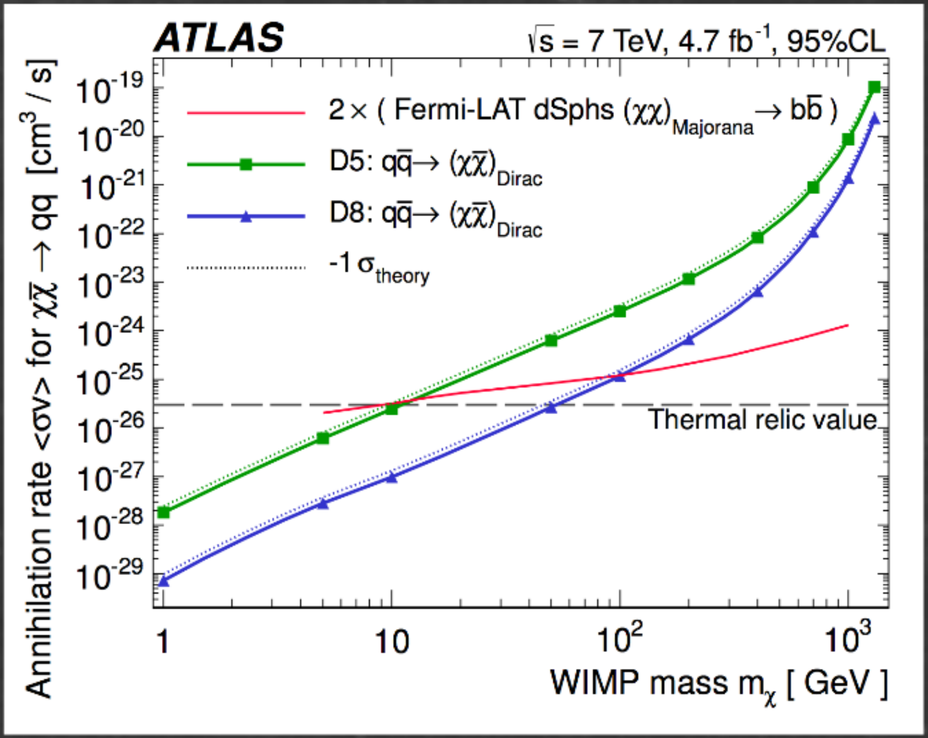


Background process	Events
$Z \to \nu\bar{\nu}$	900 ± 94
W+jets	312 ± 35
$t\bar{t}$	8 ± 8
$Z(\ell\ell)$+jets	2 ± 2
QCD multijet	1 ± 1
Single t	1 ± 1
Total background	1224 ± 101
Observed in data	1142



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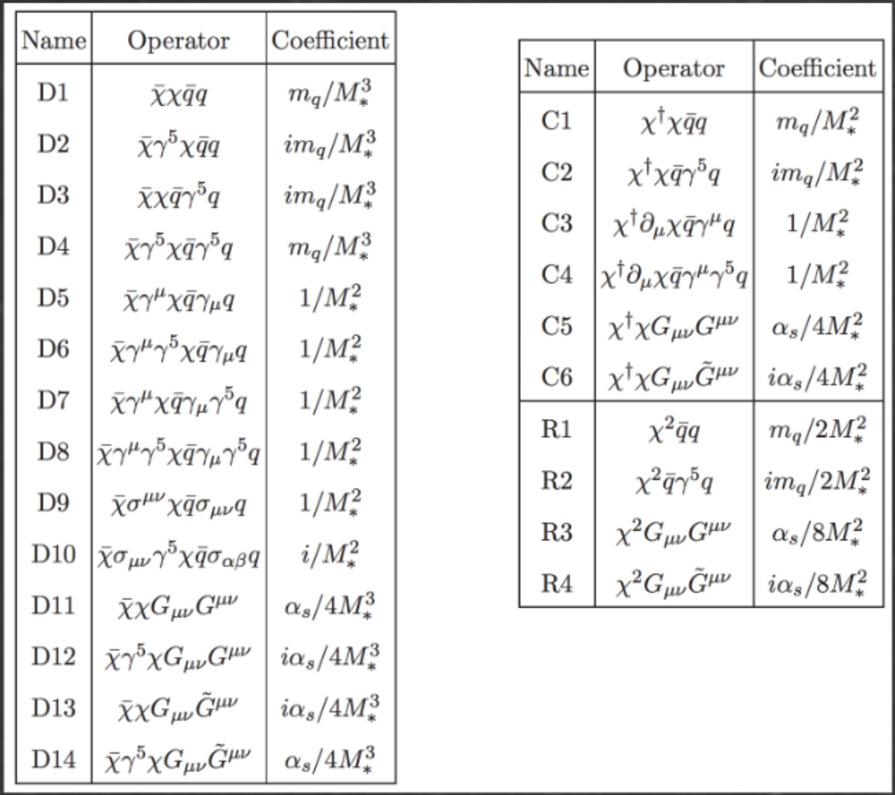

Name	Operator	Coefficient
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D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
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C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
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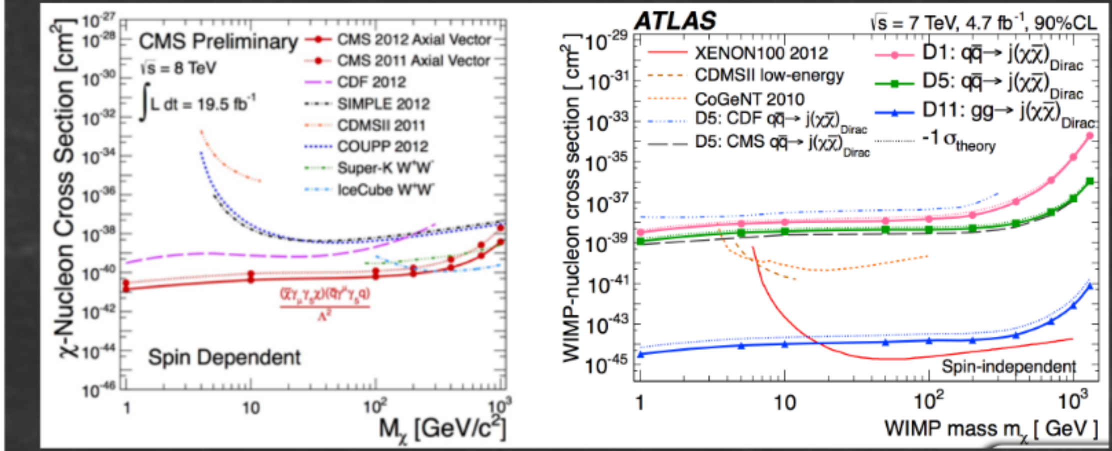
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$



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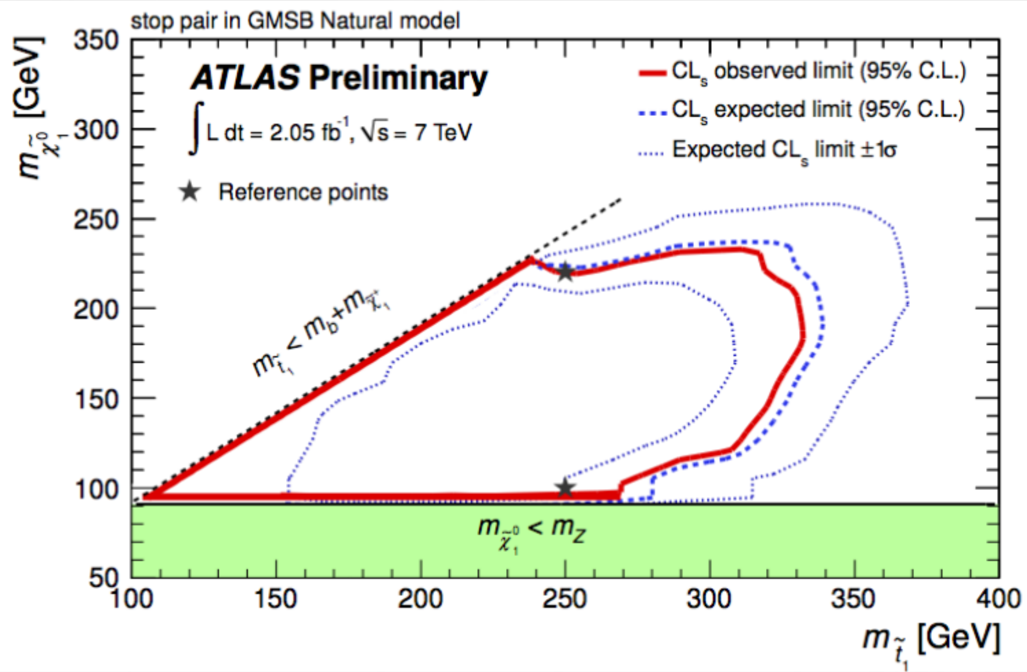

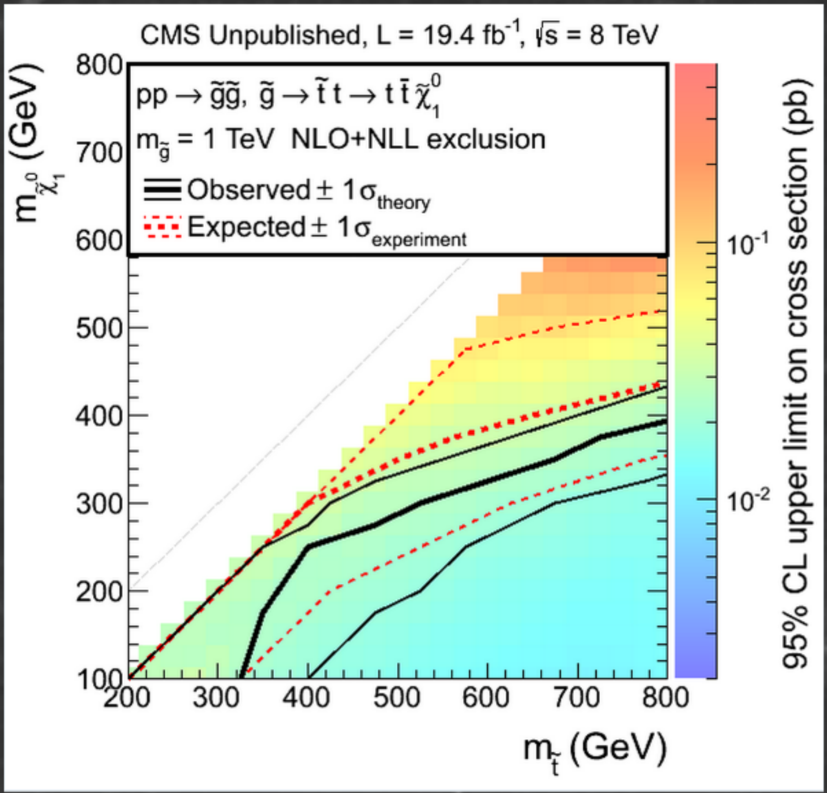

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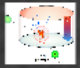
Direct Detection

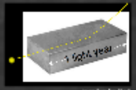
What are we looking for?



Dark Matter particle bumping off of standard model particles.

This is rare!

Luckily there are about 1 billion dark matter particles going through a square meter every second



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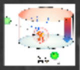
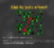
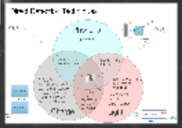


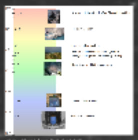
Can produce light, moving charge, or phonons



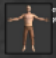


slide from Rick Gaitskell

Need to Get Rid of All Sources of Radiation



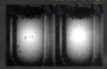
slide (photos) from Rick Gaitskell



emits 800 gamma rays per second

Archaeological Lead

Lots of Different Detectors!



Bubble Chamber
COUPP
PICO

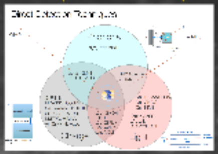
Liquid Xenon
XenonX
Xenon100
Xenon1T
LUX

Silicon
CDMS
CoGeNT

Silicon CCD
DAMIC

Sodium Iodide
DAMA/LIBRA

Different Experiments Use Different Techniques



slide from Laura Baudis

What Does a Silicon - Germanium Detector See?

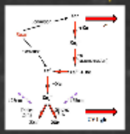
Dark Matter particle comes in and hits a Silicon or Germanium nucleus.

This produces a vibration inside the Si-Ge crystal

This vibration heats a Tungsten layer on the surface of the detector, which is being kept at the threshold of superconductivity. When superconductivity breaks, you detect a change in current across the tungsten layer

Layout of CDMS iZIP detector

What Does a Liquid Xenon Detector See?



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Also, can ionize (knock the outer electron) off the Xenon atom.

Voltage across the detector pushes electrons up to the top.

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Liquid Xenon - Able to scale up easily, bigger and bigger detectors use very similar technologies. Interior of detector continues to obtain lower backgrounds

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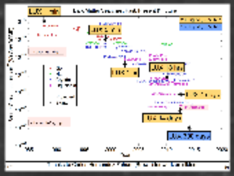
The Advancement of the Field



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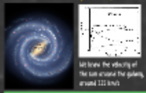
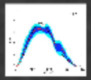
Important effect we have failed to discuss:

At What velocity can we expect a WIMP/collider interaction to occur?



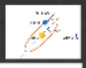
We know the velocity of the sun around the galaxy, around 220 km/s

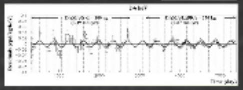
We can't directly measure the velocity of dark matter, since we haven't found it yet.



Dark Matter Debris

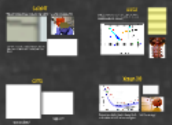
DAMA / LIBRA



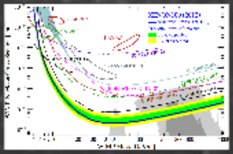


Different technique. Doesn't have a method for distinguishing background and signal, but looks for small annual modulations as the Earth orbits the sun

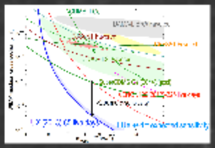
Other Signals! - But Also Constraints



Mess Plot

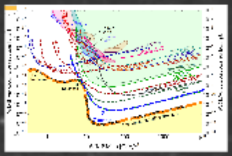


LUX

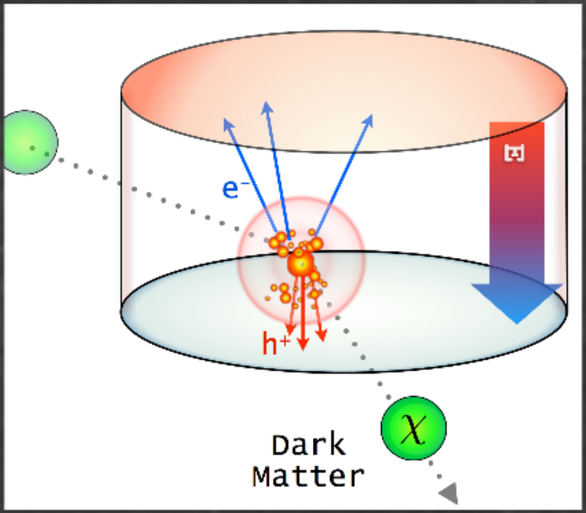


Results from LUX appear to have really cleaned out the low-mass WIMP window

Future



What are we looking for?



Dark Matter particle bumping off of standard model particles.

This is rare!

Luckily there are about 1 billion dark matter particles going through a square meter every second

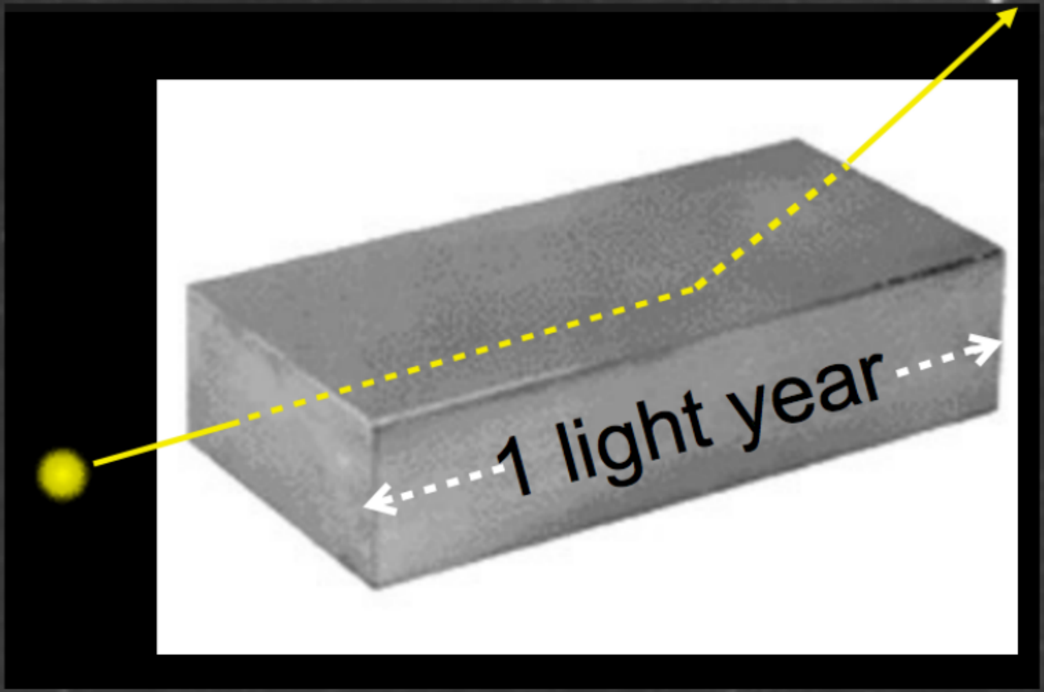


image from Dan Akerib

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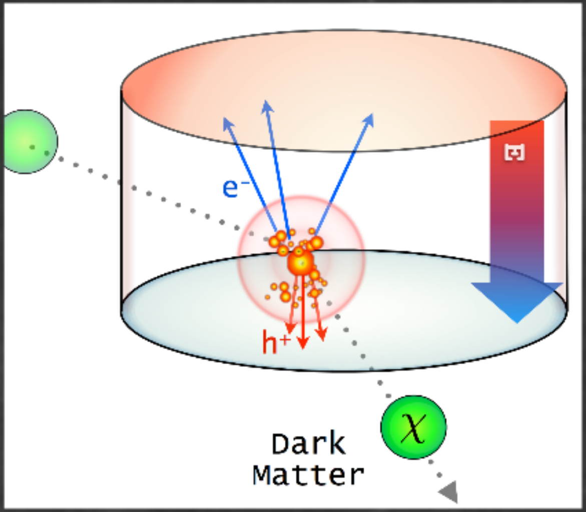
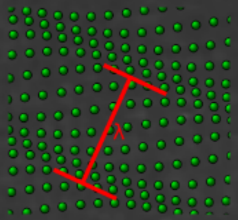


Can produce light, moving charge, or phonons

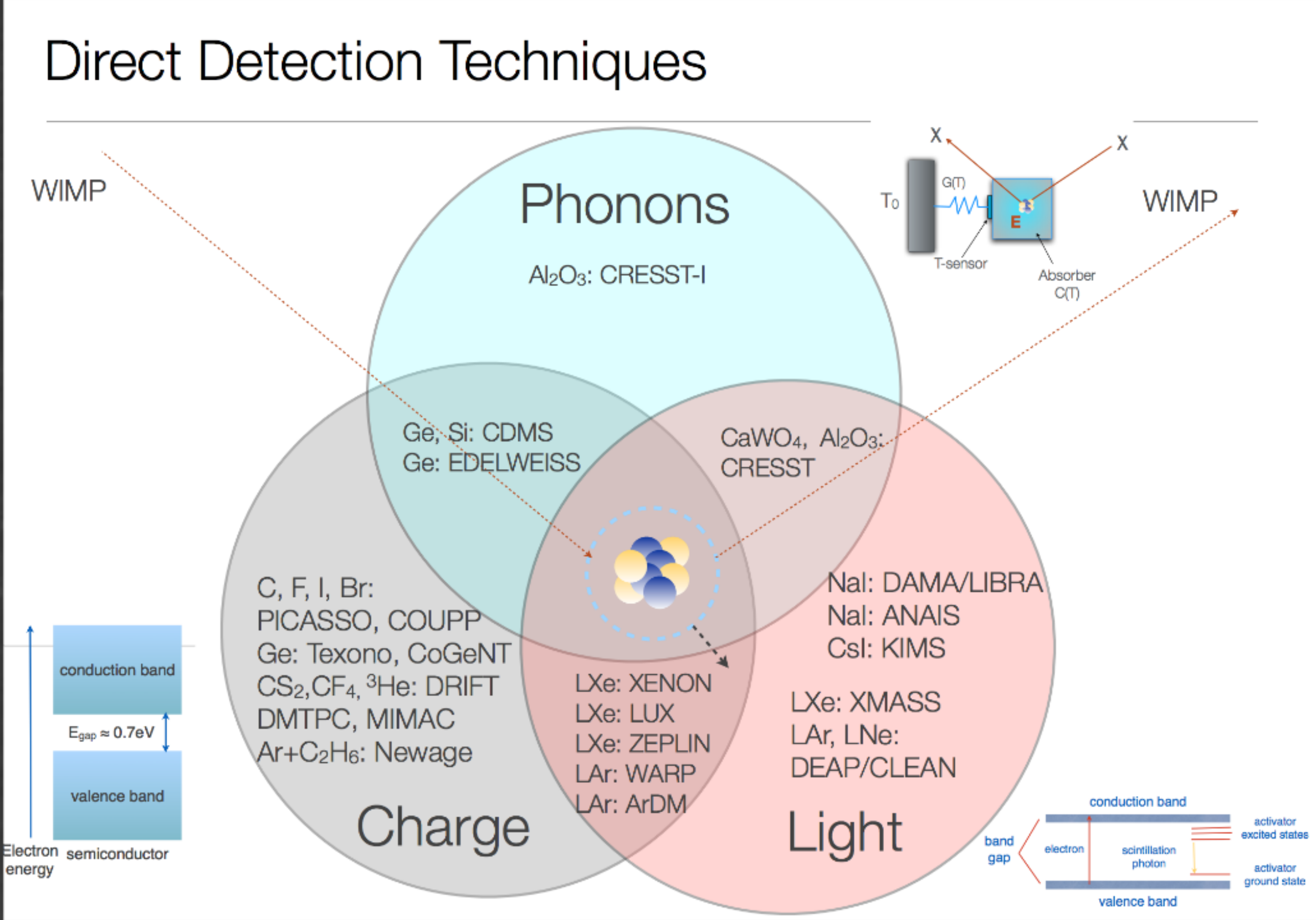
What the Heck is a Phonon?



A packet of vibrational energy in a medium.

Vibration states of molecules are quantized, and so, treated in quantum field theory, there is a "quasi-particle" of vibration

Direct Detection Techniques



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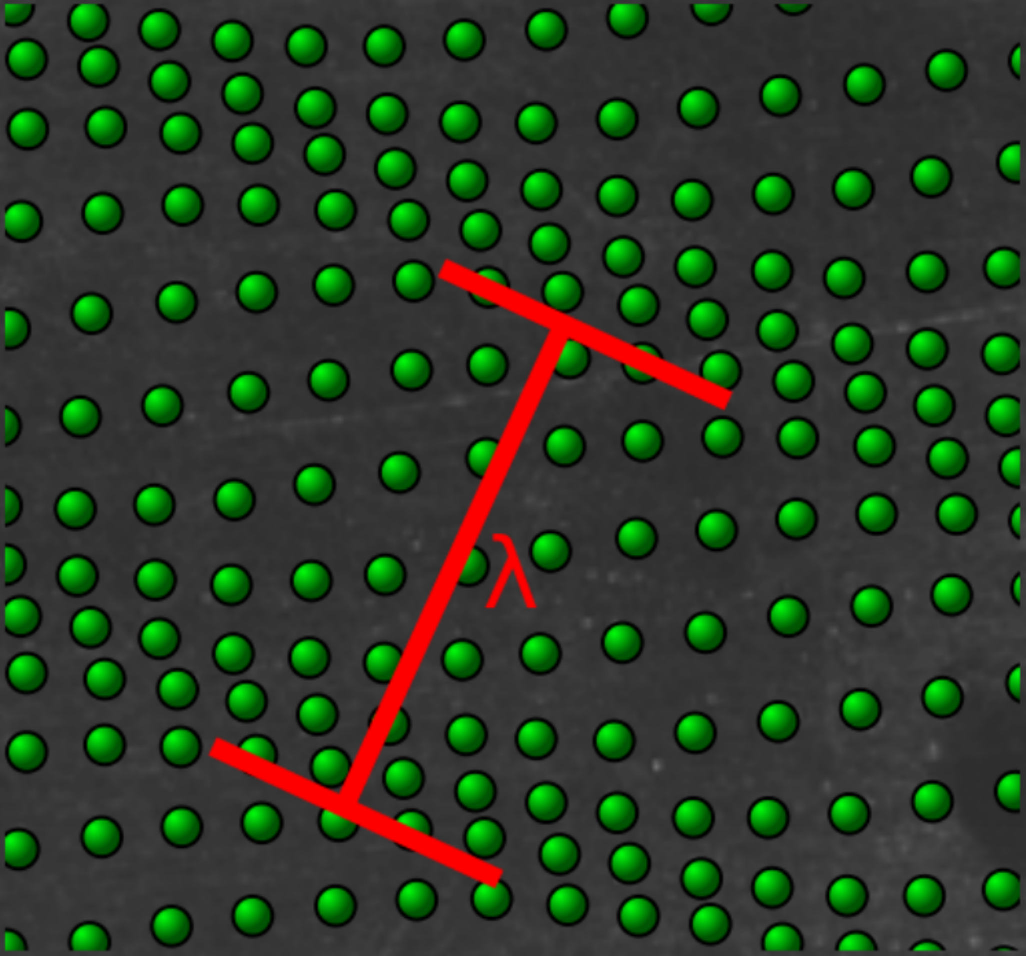

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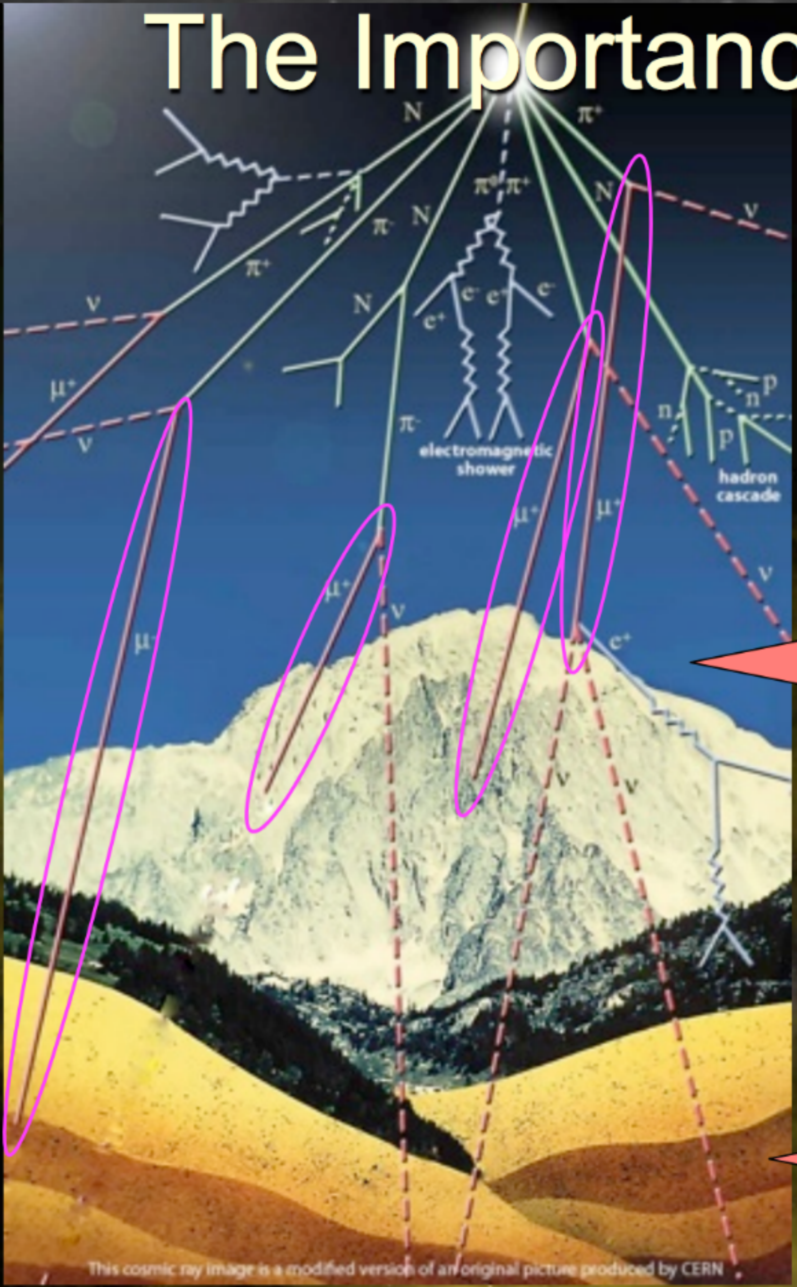
The Importance of Depth



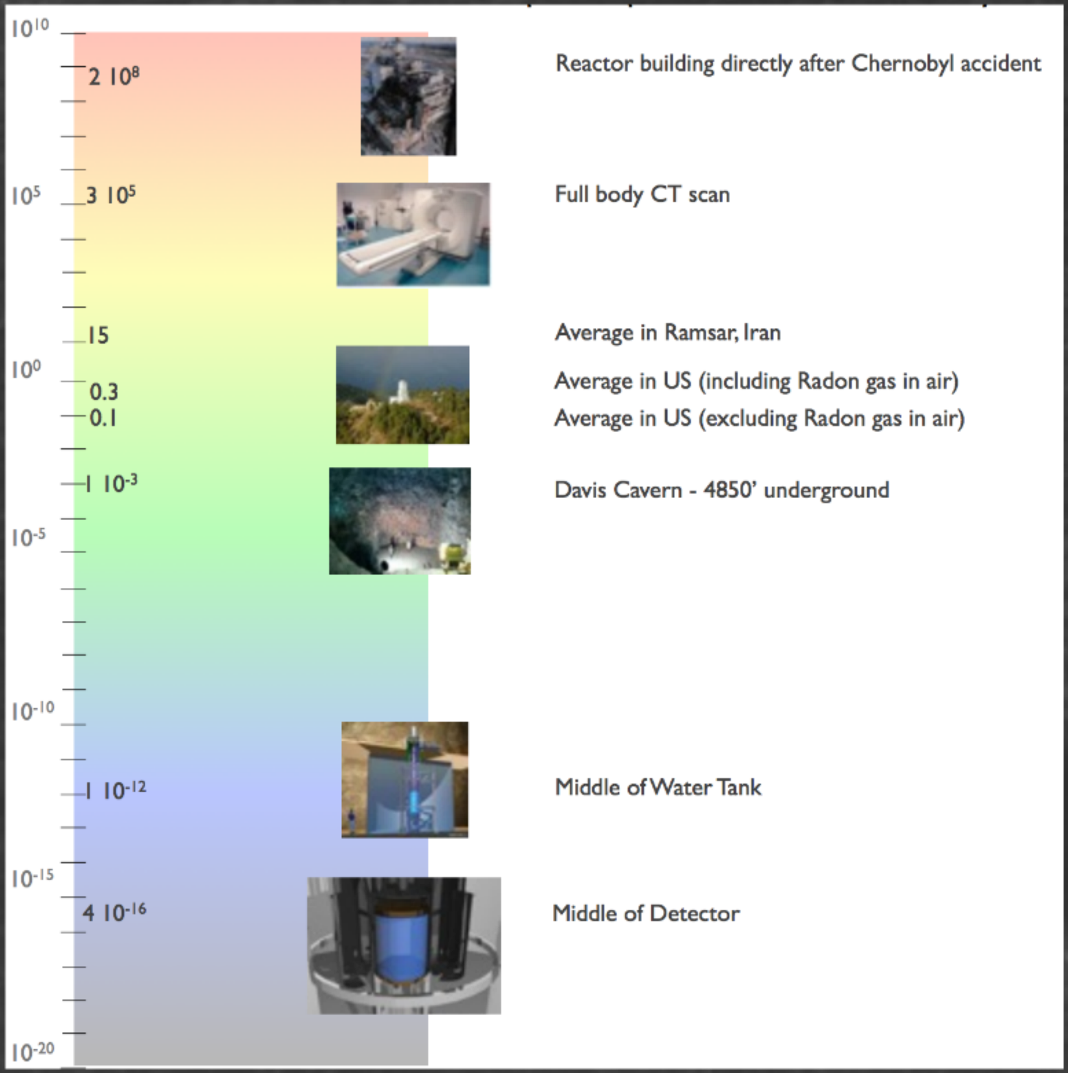
This cosmic ray image is a modified version of an original picture produced by CERN

At the earth’s surface cosmic ray muons pass through your hand at more than 1 every second

At a depth of 4850 ft underground in Sanford Lab, the rock overburden reduces the flux of cosmic muons through your hand to around 1 per year

slide from Rick Gaitskell

Need to Get Rid of All Sources of Radiation



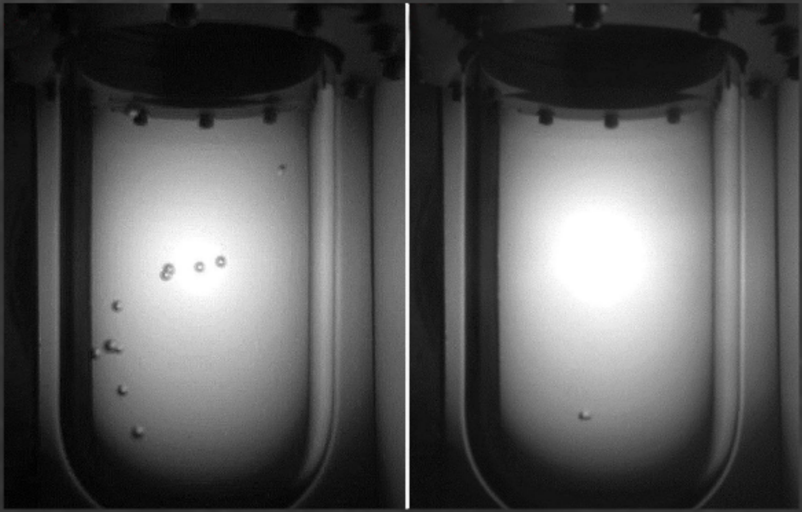
$2\ 10^{8}$	Reactor building directly after Chernobyl accident
$3\ 10^{5}$	Full body CT scan
15	Average in Ramsar, Iran
0.3	Average in US (including Radon gas in air)
0.1	Average in US (excluding Radon gas in air)
$1\ 10^{-3}$	Davis Cavern - 4850' underground
$1\ 10^{-12}$	Middle of Water Tank
$4\ 10^{-16}$	Middle of Detector

slide pilfered from Rick Gaitskell

emits 1000 gamma-rays per second

Archaelogical Lead

Lots of Different Detectors!



Bubble Chamber:
COUPP
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Liquid Xenon:
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Silicon:
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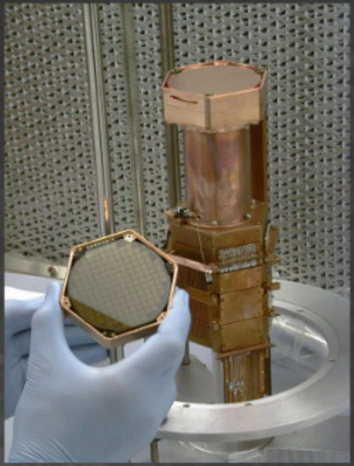
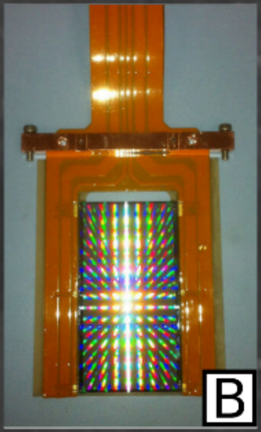
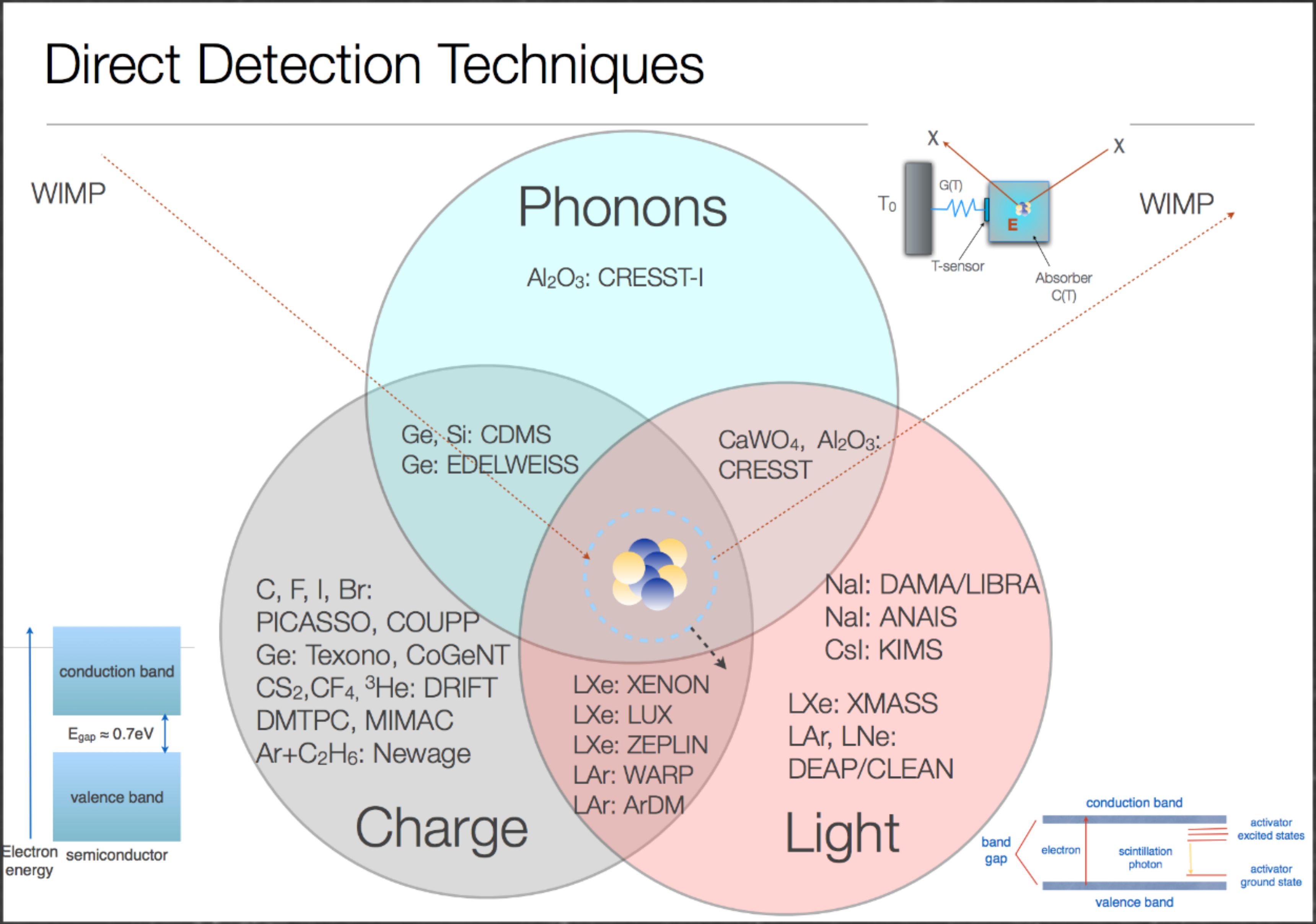




Silicon CCD:
DAMIC

Sodium Iodide:
DAMA/LIBRA

Different Experiments Use Different Techniques



Direct Detection Techniques

Phonons

Al_2O_3: CRESST-I

Ge, Si: CDMS
Ge: EDELWEISS

$CaWO_4$, Al_2O_3: CRESST

Charge

C, F, I, Br: PICASSO, COUPP
Ge: Texono, CoGeNT
CS_2, CF_4, ^3He: DRIFT
DMTPC, MIMAC
$Ar+C_2H_6$: Newage

LXe: XENON
LXe: LUX
LXe: ZEPLIN
LAr: WARP
LAr: ArDM

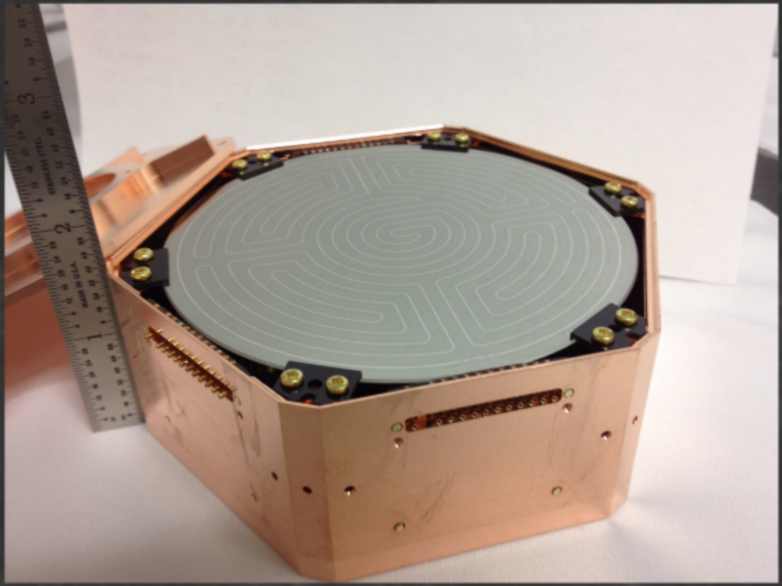
Light

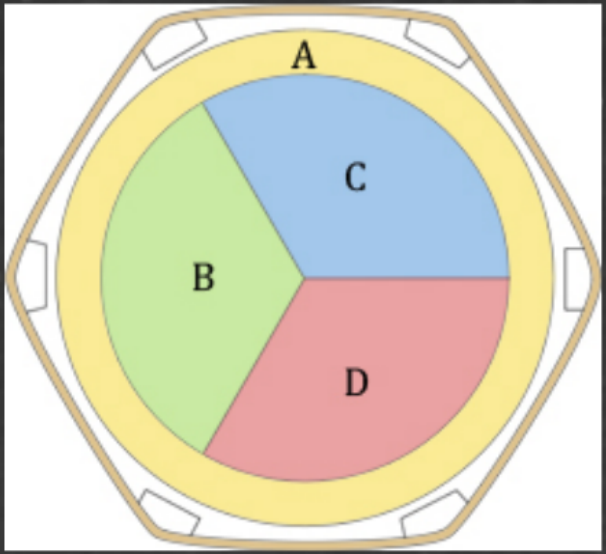
NaI: DAMA/LIBRA
NaI: ANAIS
CsI: KIMS

LXe: XMASS
LAr, LNe: DEAP/CLEAN

slide from Laura Baudis

What Does a Silicon - Germanium Detector See?





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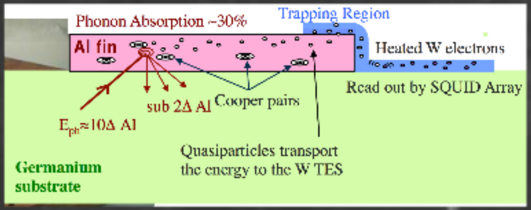

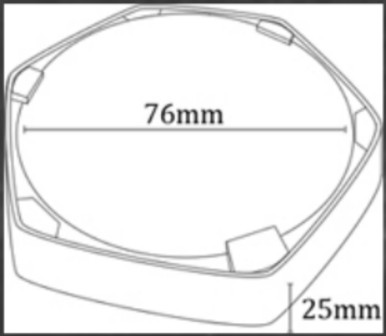

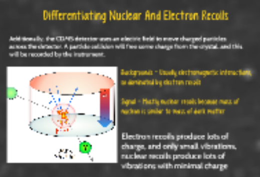

Differentiating Nuclear And Electron Recoils

Additionally, the CDMS detector uses an electric field to move charged particles across the detector. A particle collision will free some charge from the crystal, and this will be recorded by the instrument.

Electron recoils produce lots of charge, and only small vibrations, nuclear recoils produce lots of vibrations with minimal charge

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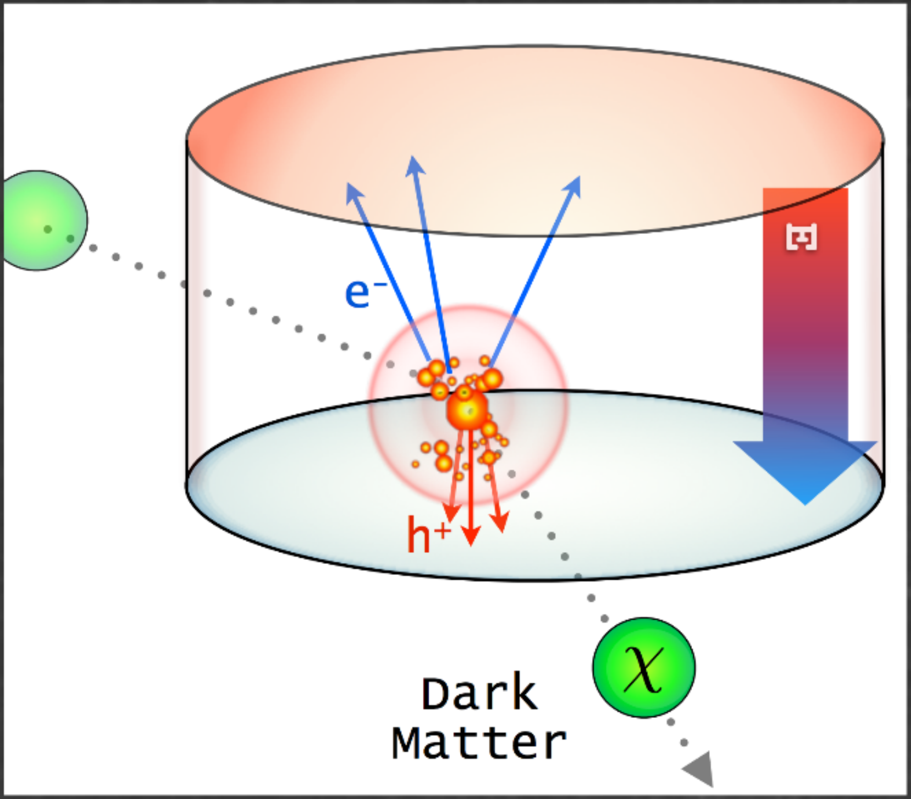

Backgrounds - Usually electromagnetic interactions, so dominated by electron recoils

Signal - Mostly nuclear recoils because mass of nucleon is similar to mass of dark matter

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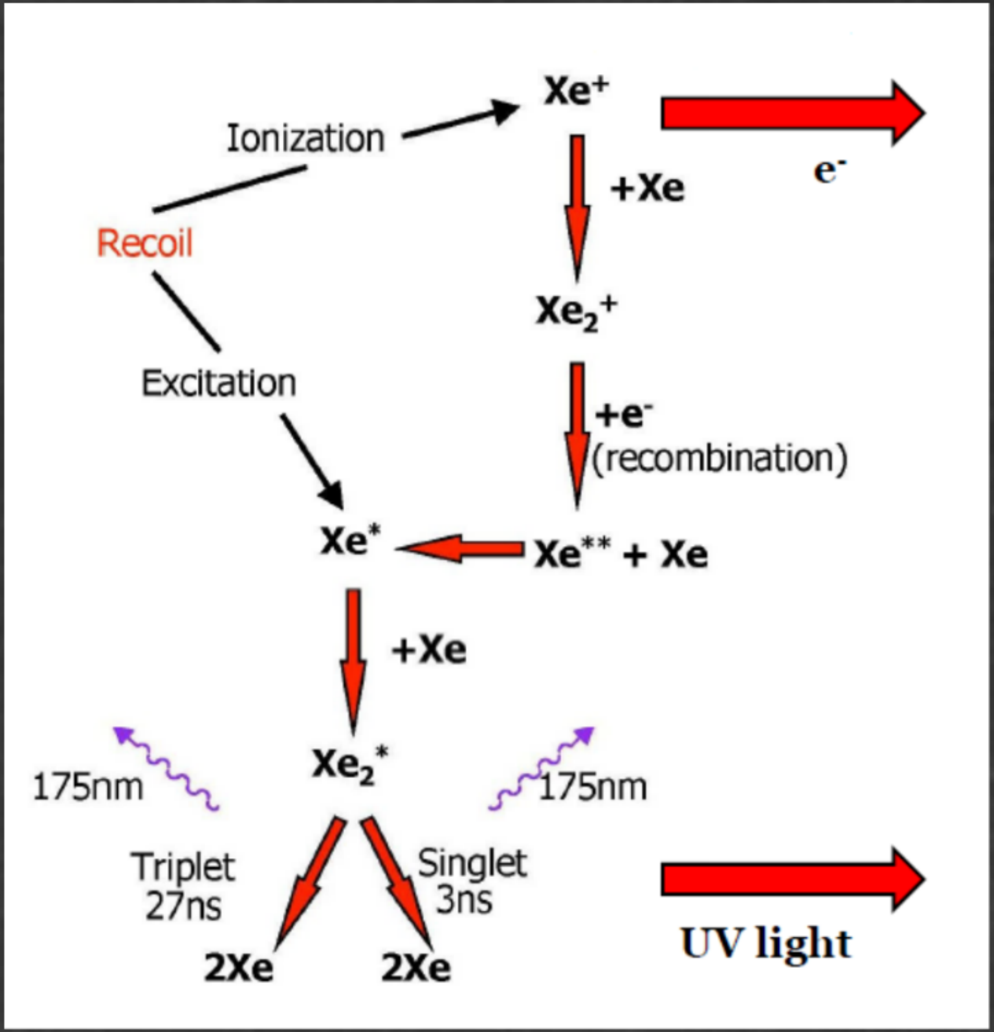
What Does a Liquid Xenon Detector See?



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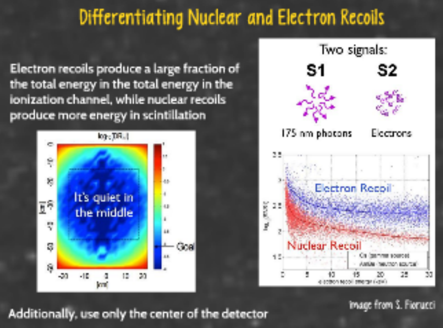
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Additionally, use only the center of the detector

Image from S. Fiorucci

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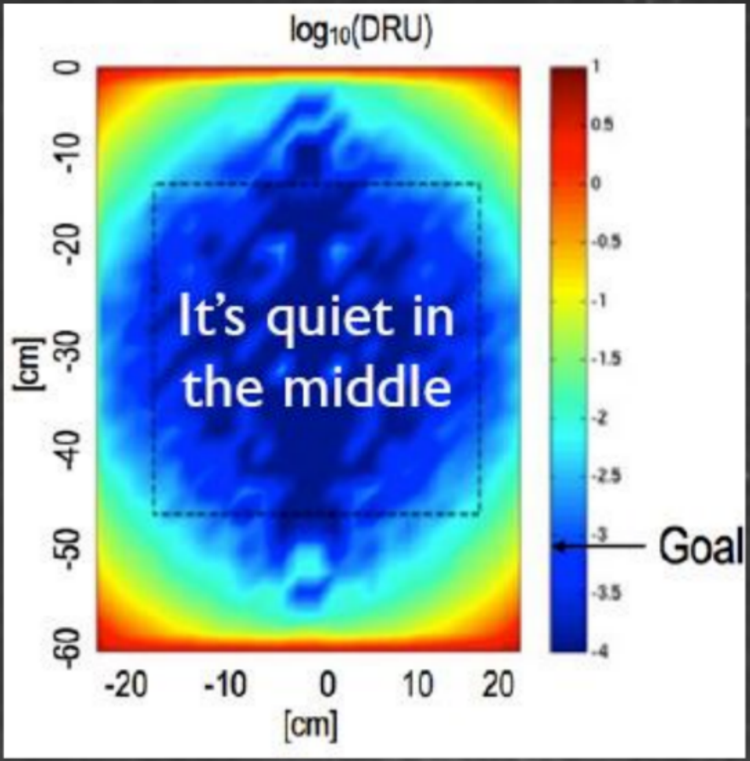

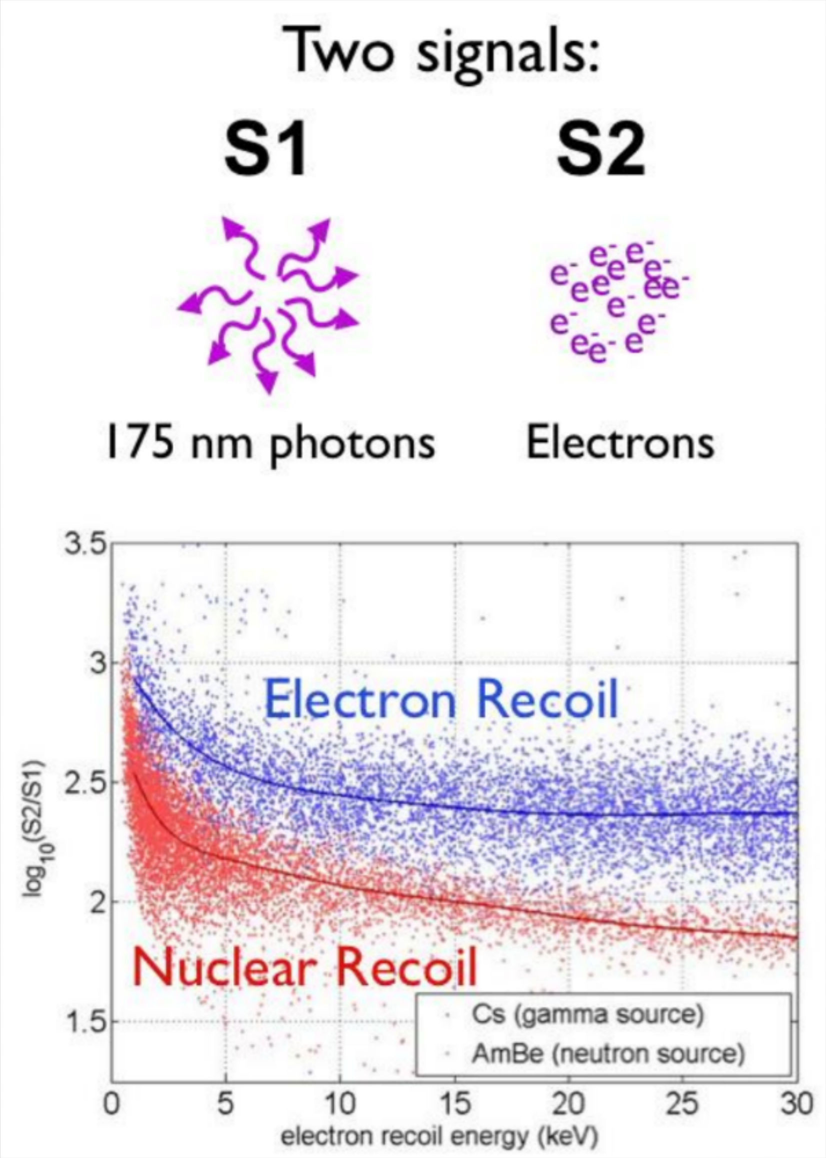

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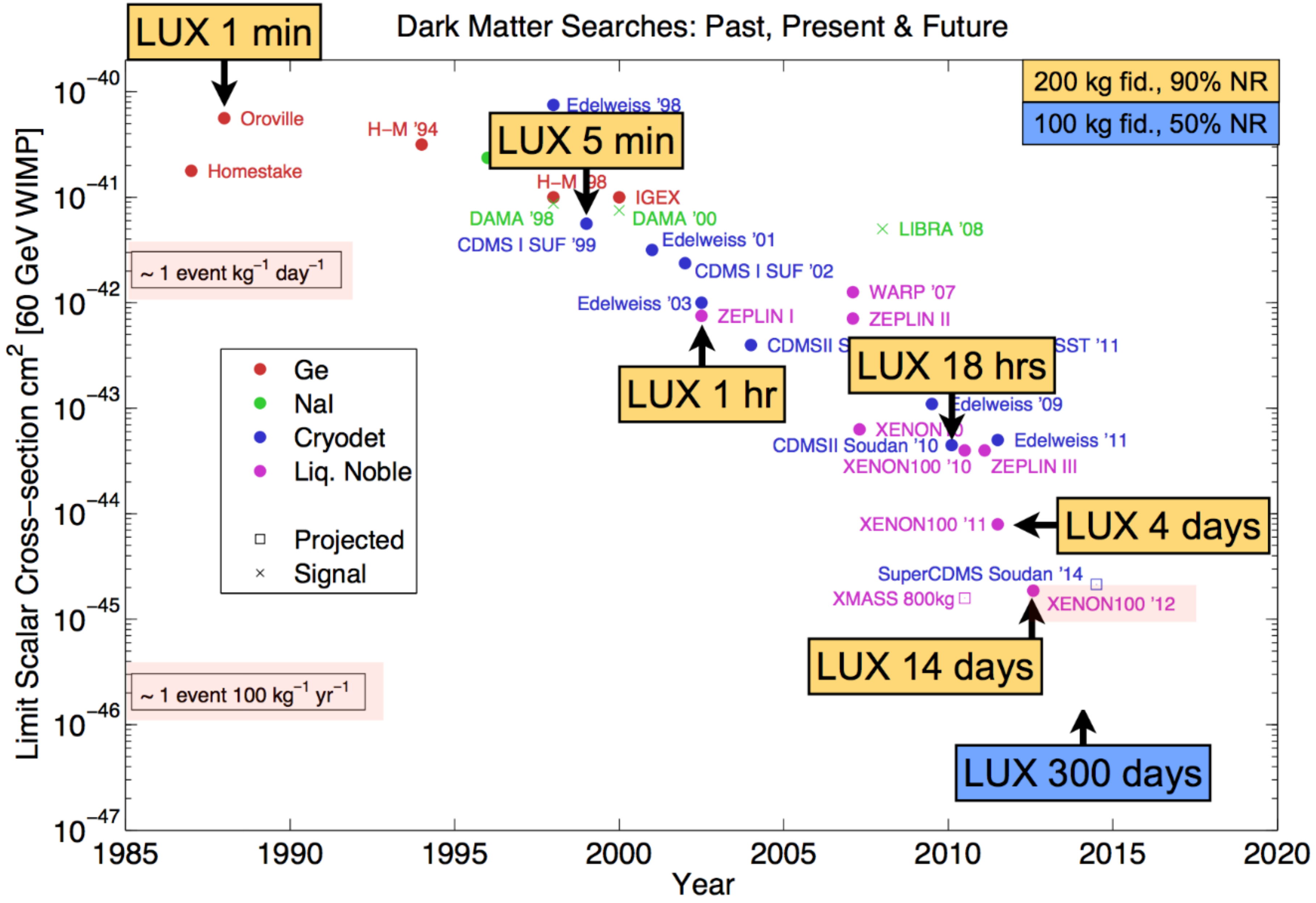
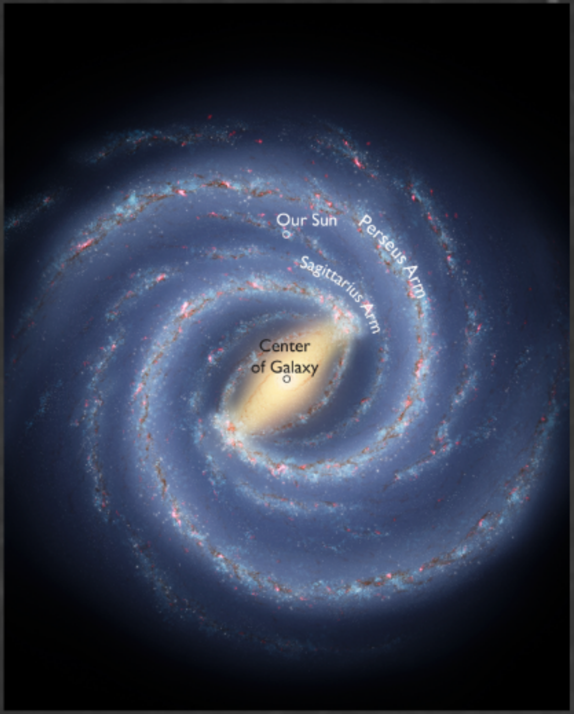


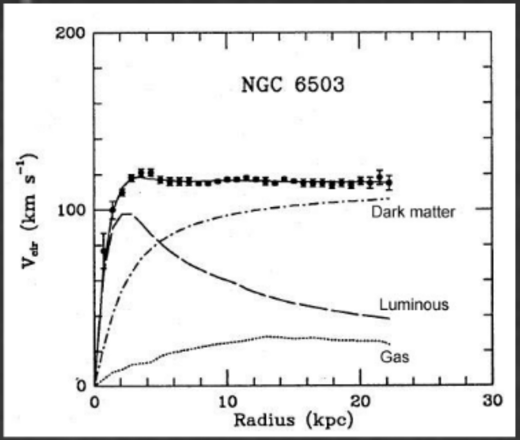
Thanks to Carlos Hernandez Faham (Brown) for work on slides

The WIMP Wind

Important effect we have failed to discuss:

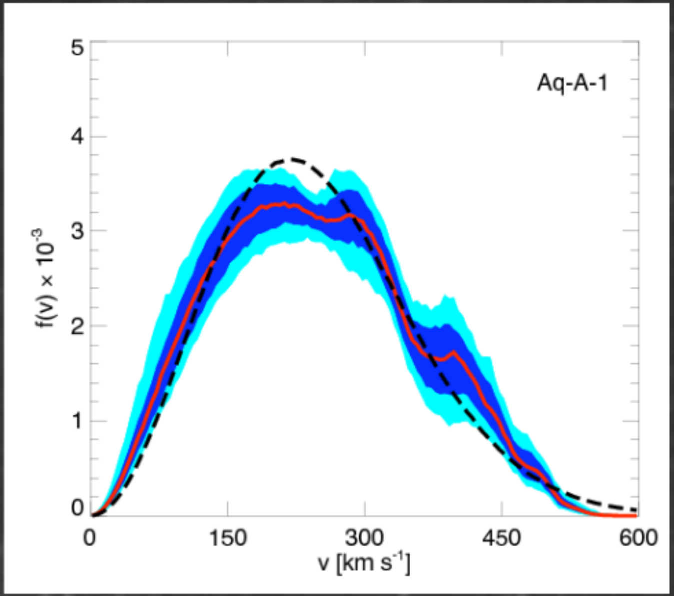
At What velocity can we expect a WIMP/collider interaction to occur?





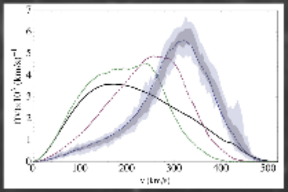
We know the velocity of the sun around the galaxy, around 225 km/s

We can't directly measure the velocity of dark matter, since we haven't found it yet.



Dark Matter Debris

Additional subhalos falling into the Milky Way (possibly due to previous interactions between our galaxy and others) can produce a significant high velocity tail.



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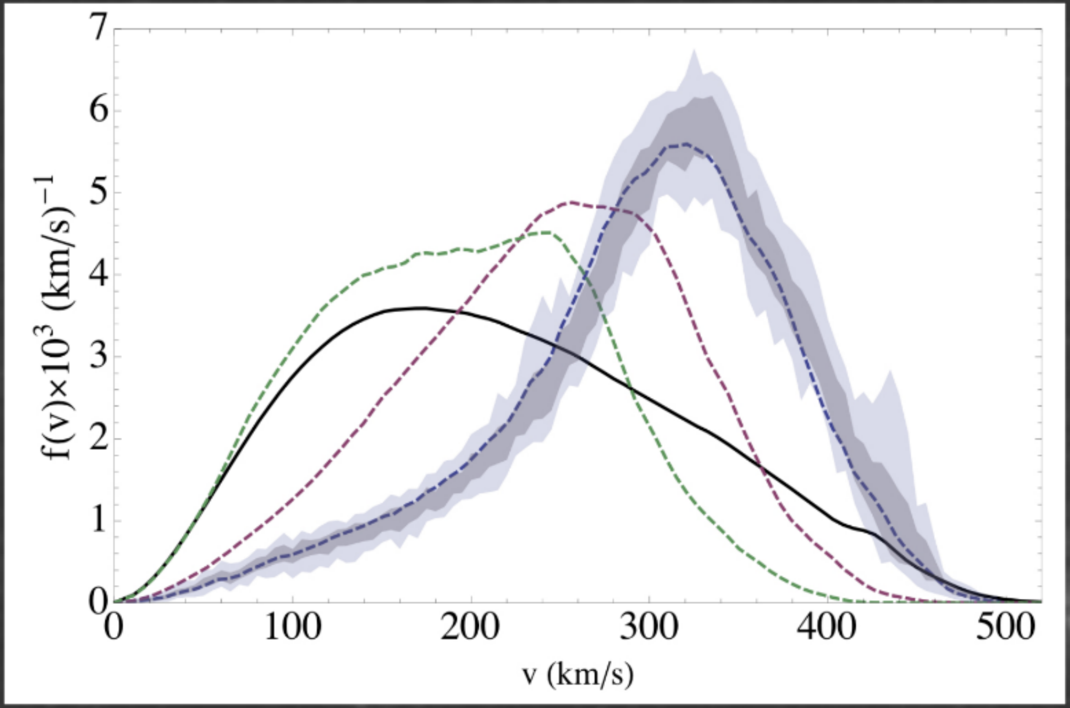

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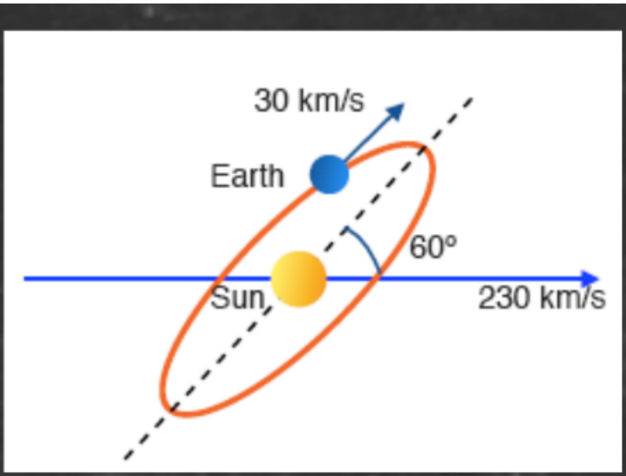
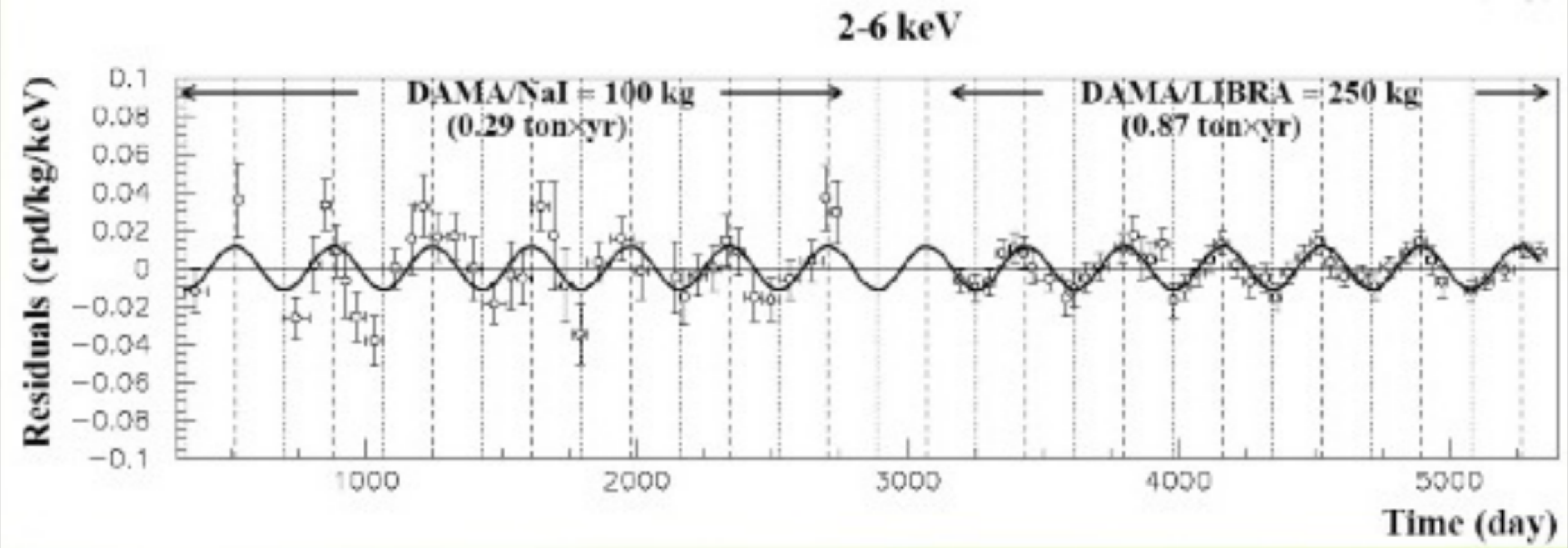
DAMA / LIBRA





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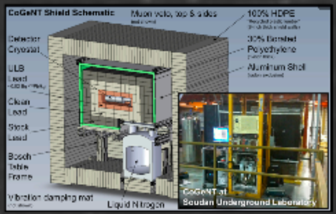
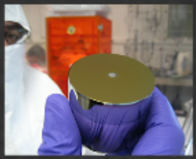
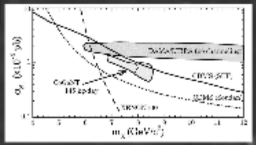
CoGeNT

440g Germanium/Silicon Detector (like CDMS) - located in Soudan, MN



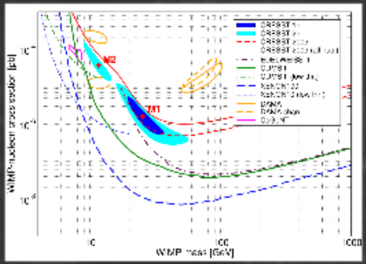


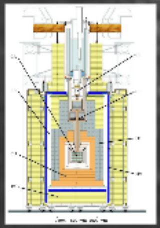


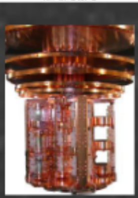
CoGeNT collaboration found a hint of dark matter with a cross-section similar to that reported by DAMA

CRESST

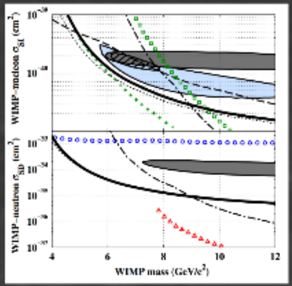
A Cryogenic Dark Matter Detector, uses supercooled liquid (superconducting) and detects voltage jumps due to energy deposited during nuclear interactions



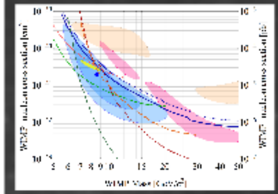




CDMS

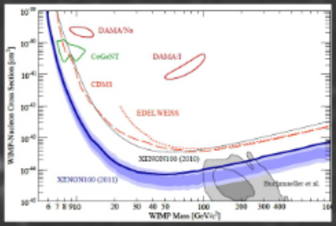


Constraints!



Signal ?!

Xenon 100



Xenon producing very strong limits - but the energy calibration is hard at low energies

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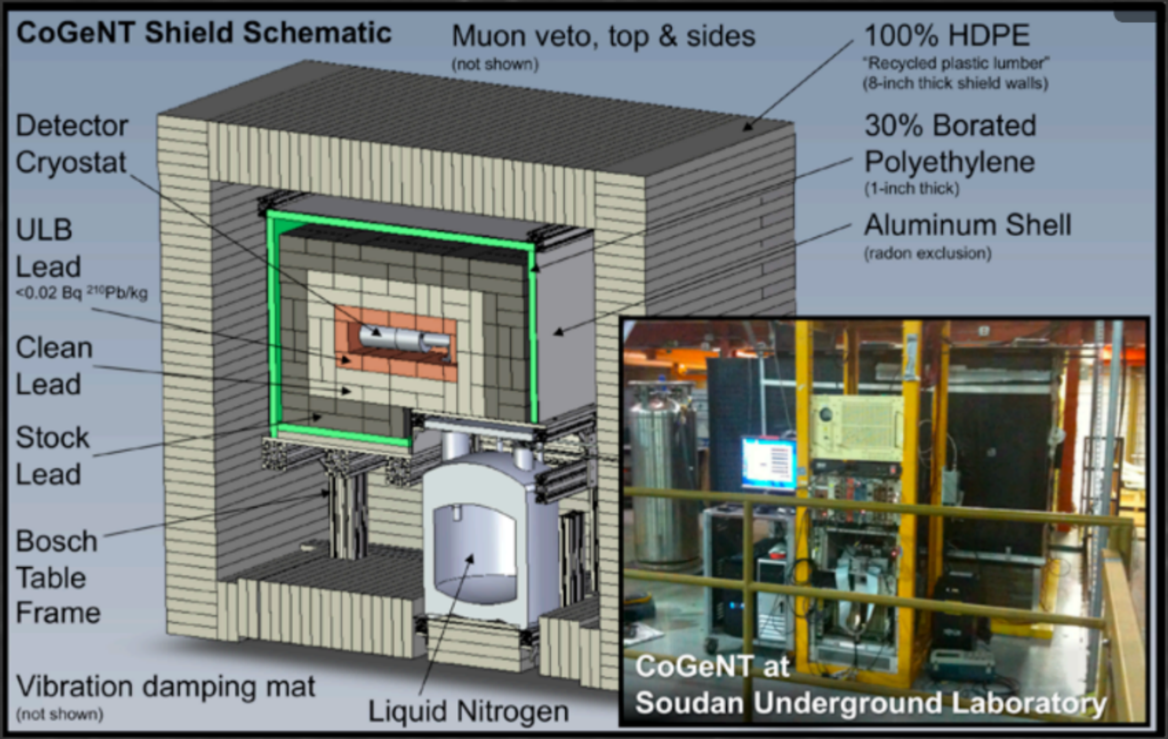

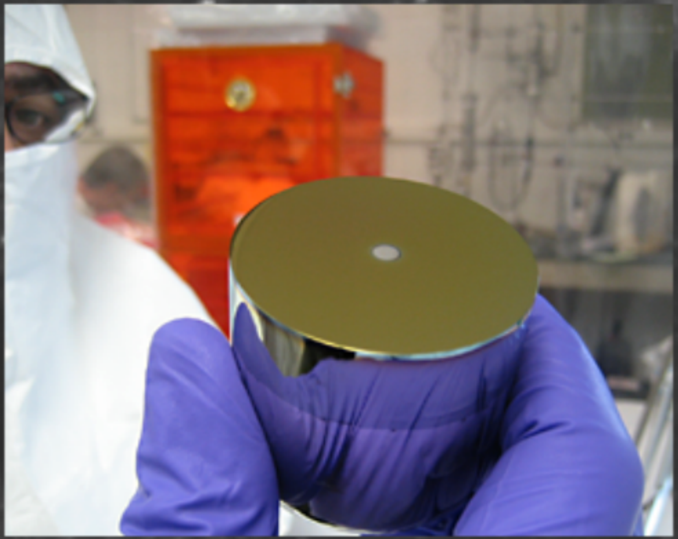

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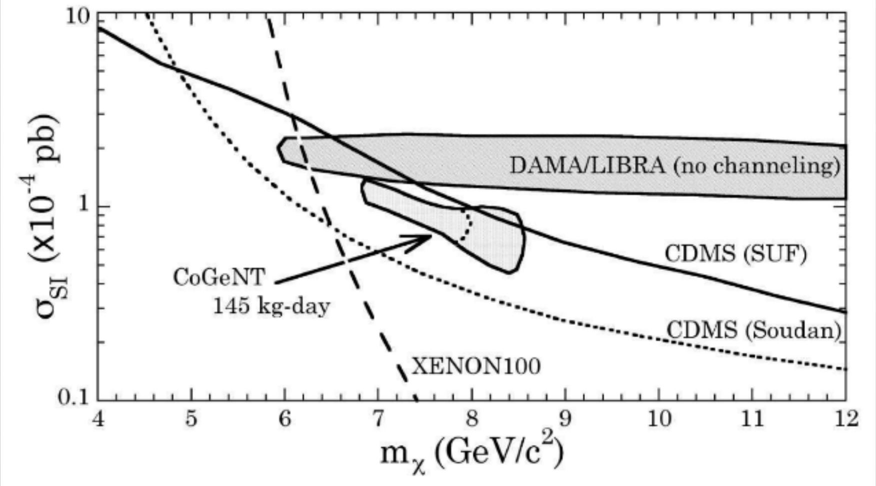
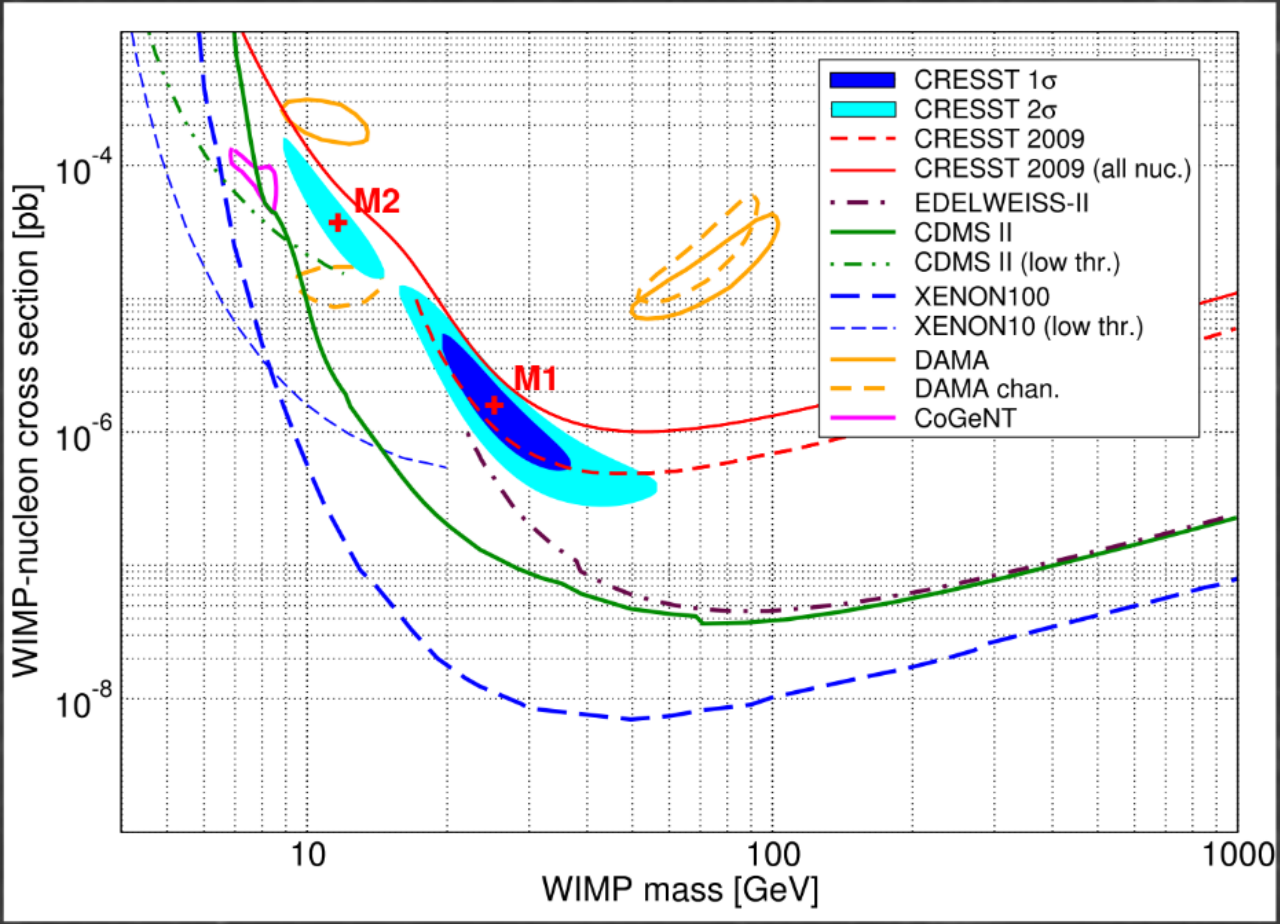
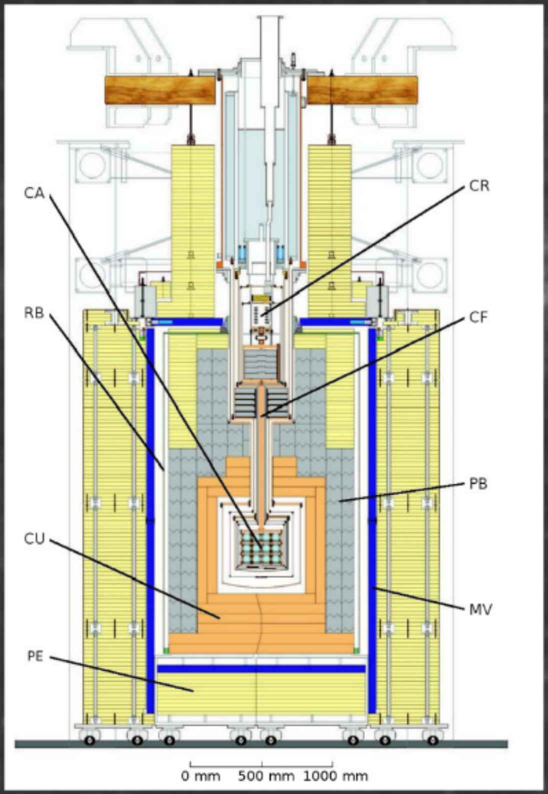


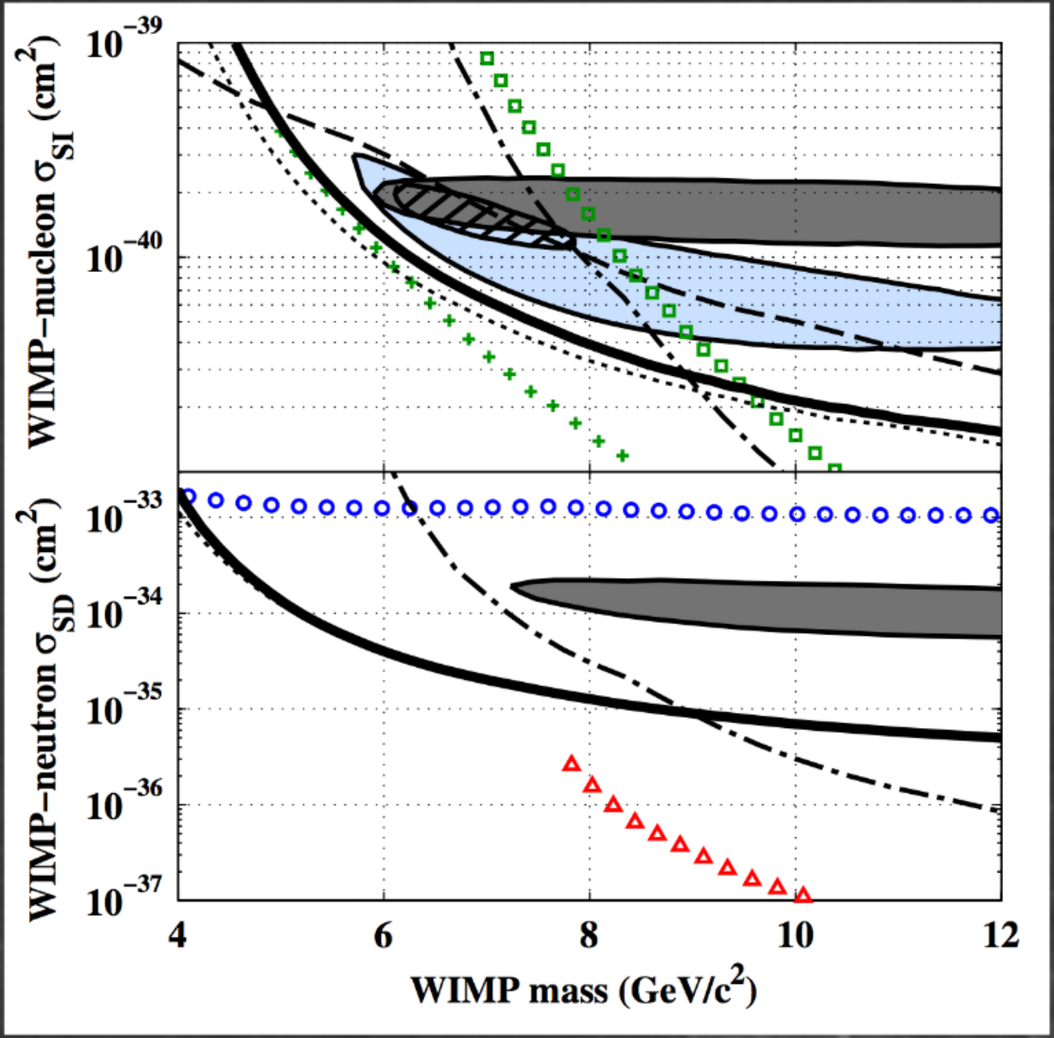
CRESST

A Cryogenic Dark Matter Detector, uses supercooled liquid (superconducting) and detects voltage jumps due to energy deposited during nuclear interactions

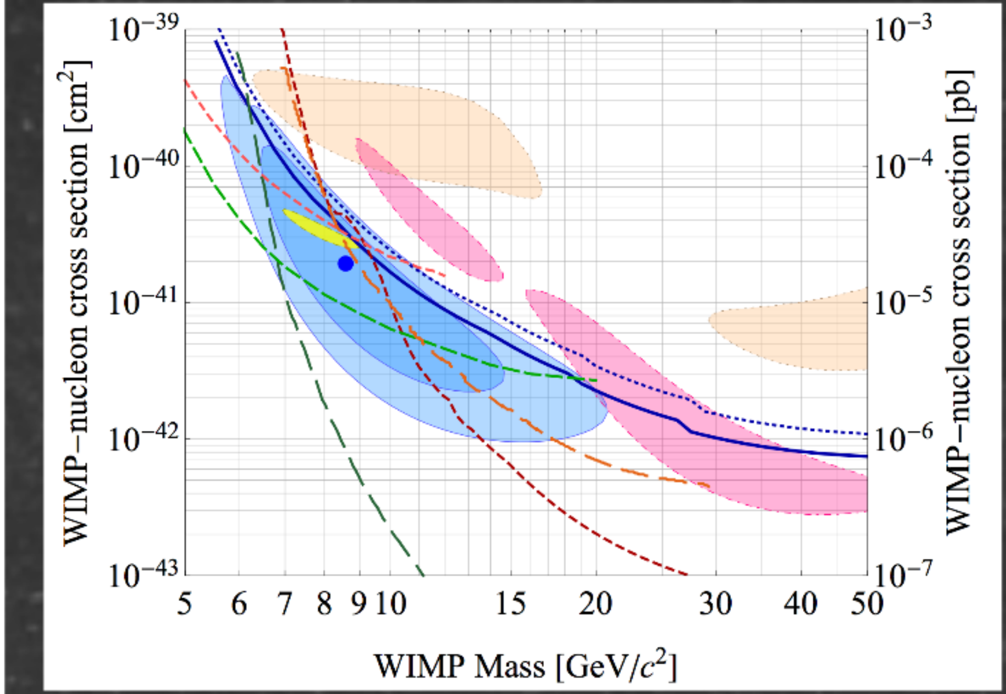




CDMS

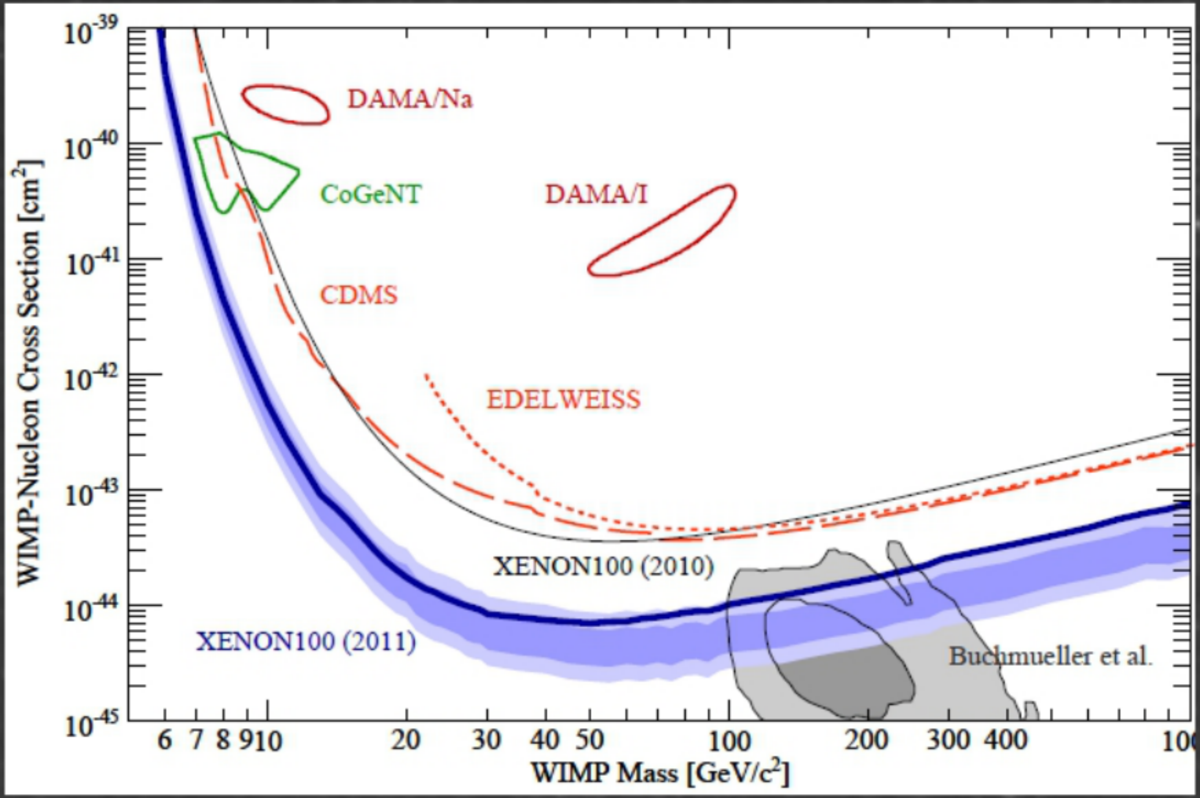


Constraints!



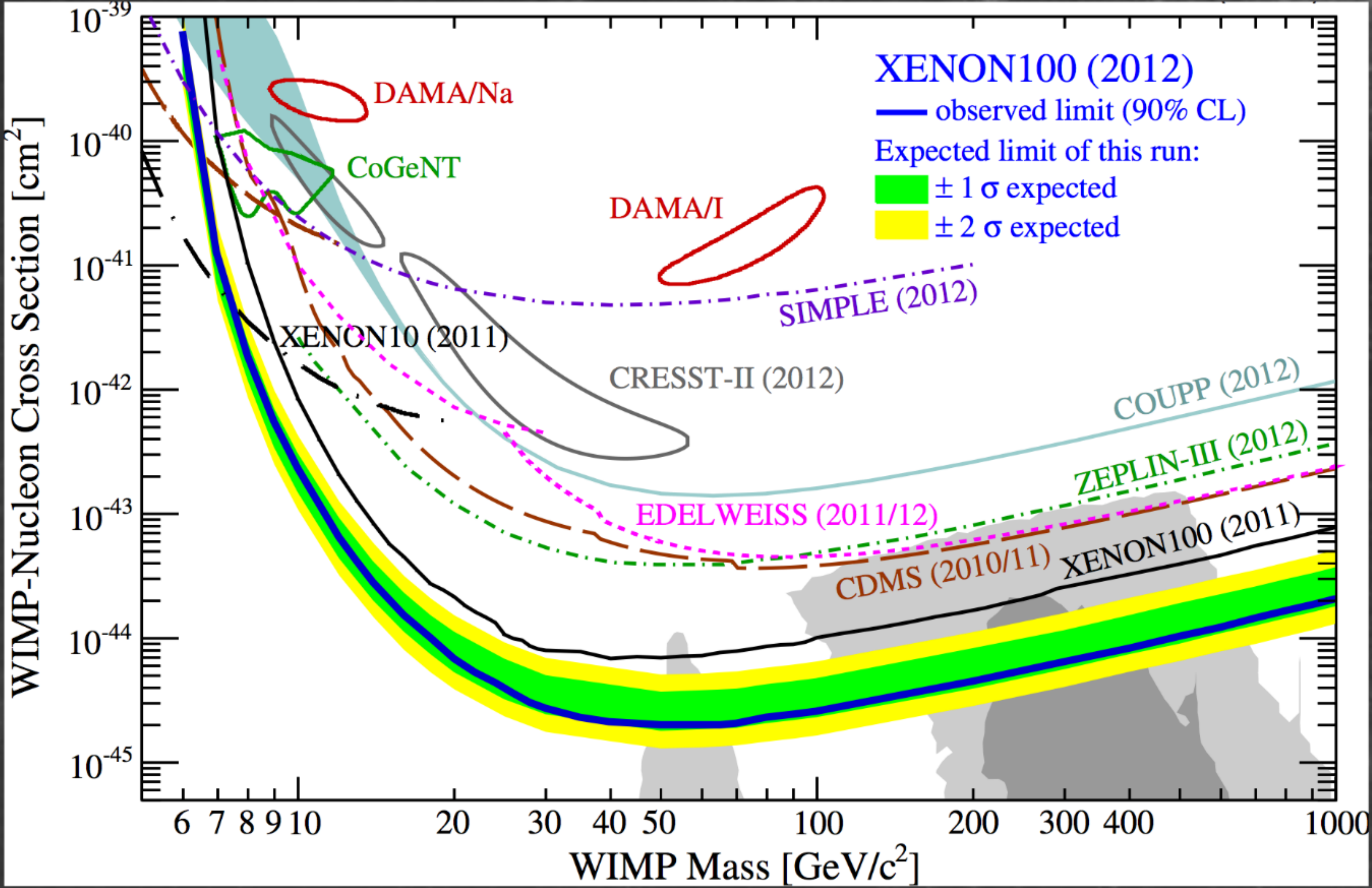
Signal ?!

Xenon 100

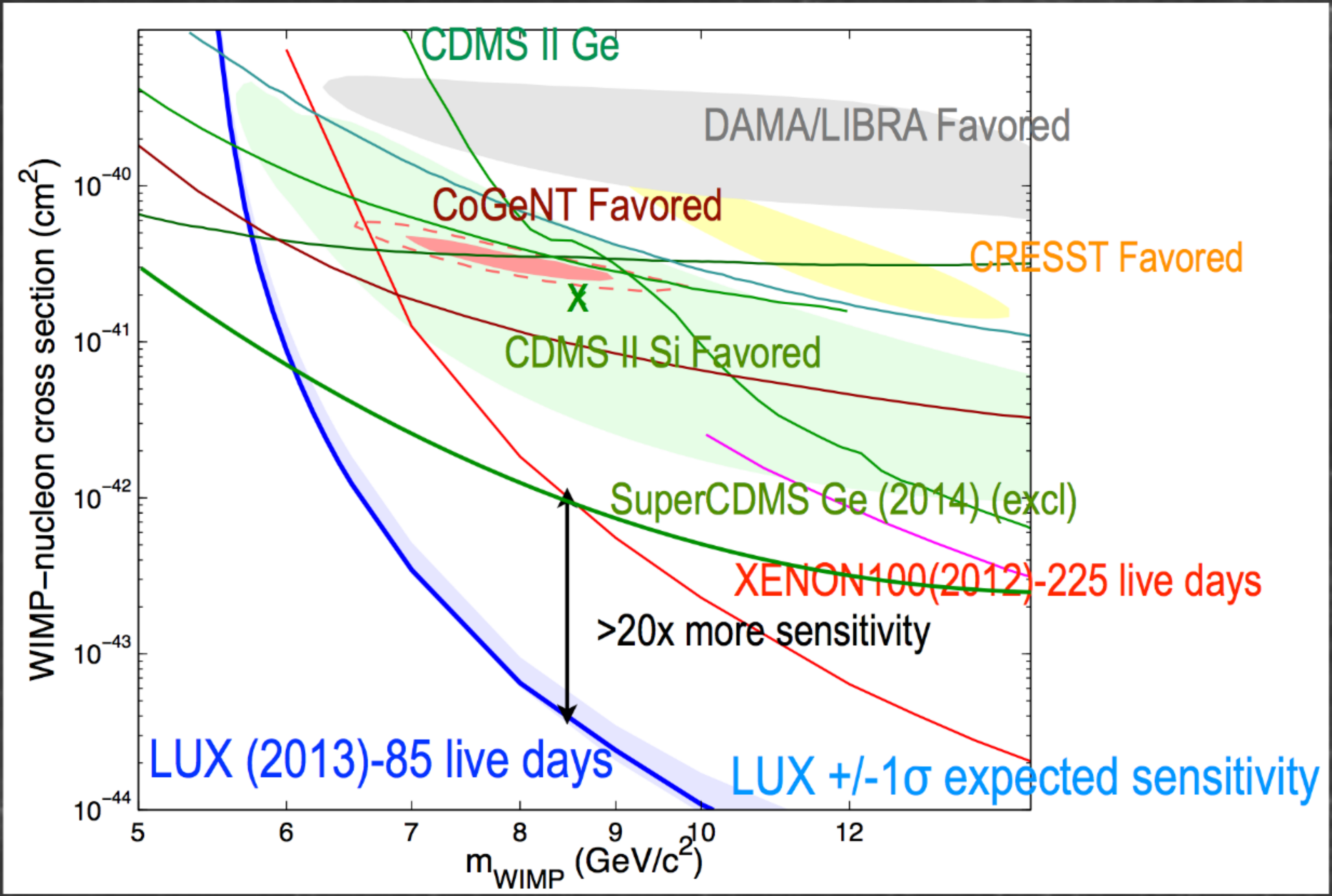


Xenon producing very strong limits - but the energy calibration is hard at low energies

Mess Plot

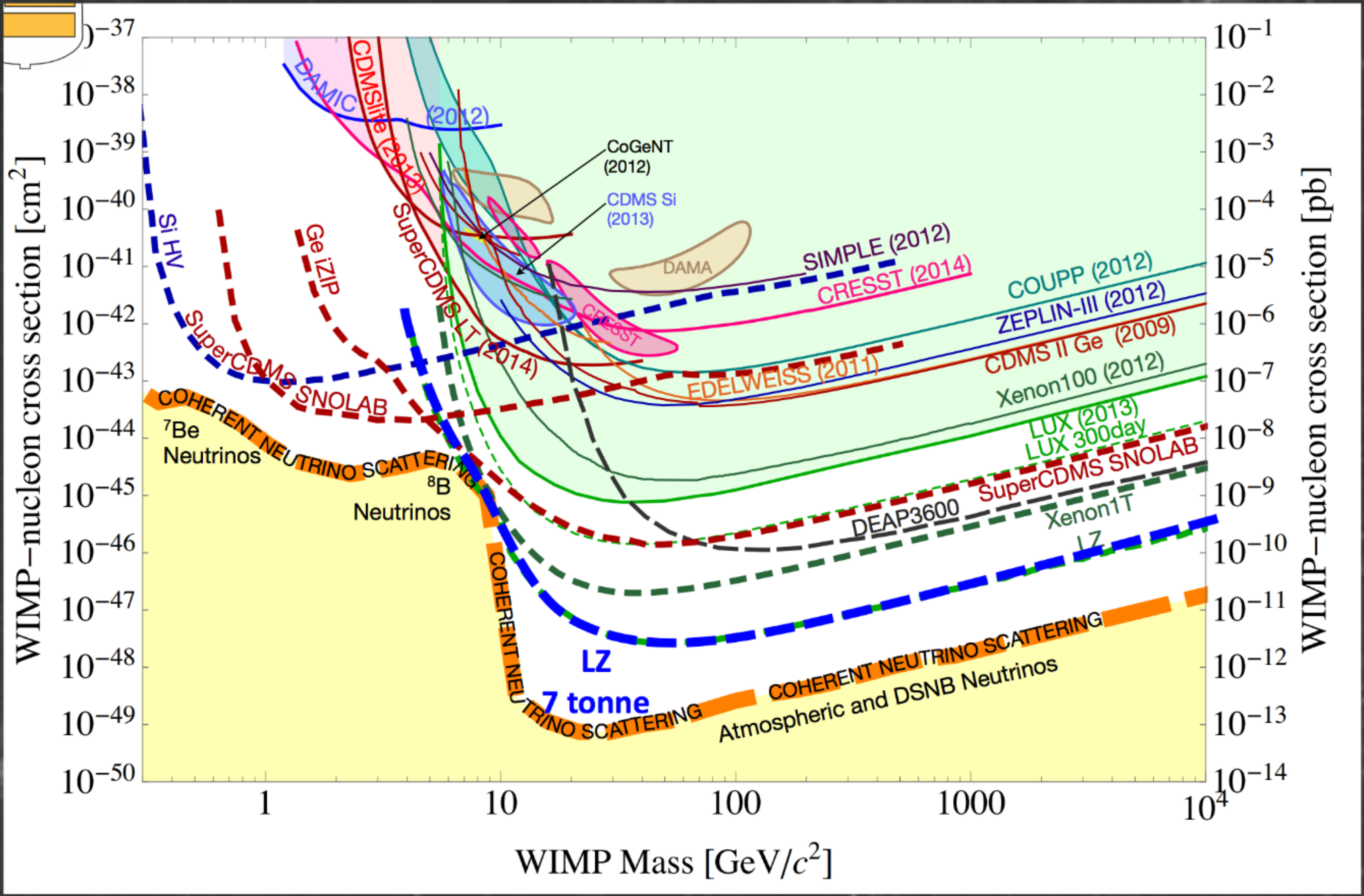

XENON100 (2012)
observed limit (90% CL)
Expected limit of this run:
± 1 σ expected
± 2 σ expected
DAMA/Na
CoGeNT
DAMA/I
SIMPLE (2012)
XENON10 (2011)
CRESST-II (2012)
COUPP (2012)
ZEPLIN-III (2012)
EDELWEISS (2011/12)
CDMS (2010/11)
XENON100 (2011)
10^-39
10^-40
10^-41
10^-42
10^-43
10^-44
10^-45
WIMP-Nucleon Cross Section [cm^2]
6
7
8
9
10
20
30
40
50
100
200
300
400
1000
WIMP Mass [GeV/c^2]

LUX



Results from LUX appear to have really cleaned out the low-mass WIMP window

Future


WIMP–nucleon cross section [cm^2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c^2]
$)^{-37}$
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
1
10
100
1000
10^4
DAMIC
(2012)
CDMSlite (2013)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
CRESST (2014)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
Xenon100 (2012)
EDELWEISS (2011)
CRESST
SuperCDMS LT (2014)
Si HV
Ge iZIP
SuperCDMS SNOLAB
LUX (2013)
LUX 300day
SuperCDMS SNOLAB
DEAP3600
Xenon1T
LZ
LZ
7 tonne
COHERENT NEUTRINO SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
COHERENT NEUTRINO SCATTERING
COHERENT NEUTRINO SCATTERING
Atmospheric and DSNB Neutrinos

chasm.uchicago.edu

Finding Weakly Interacting Dark Matter: Particle Accelerators and Direct Detection

Tim Linden

Lecture 6

Fall 2014 Compton Lectures