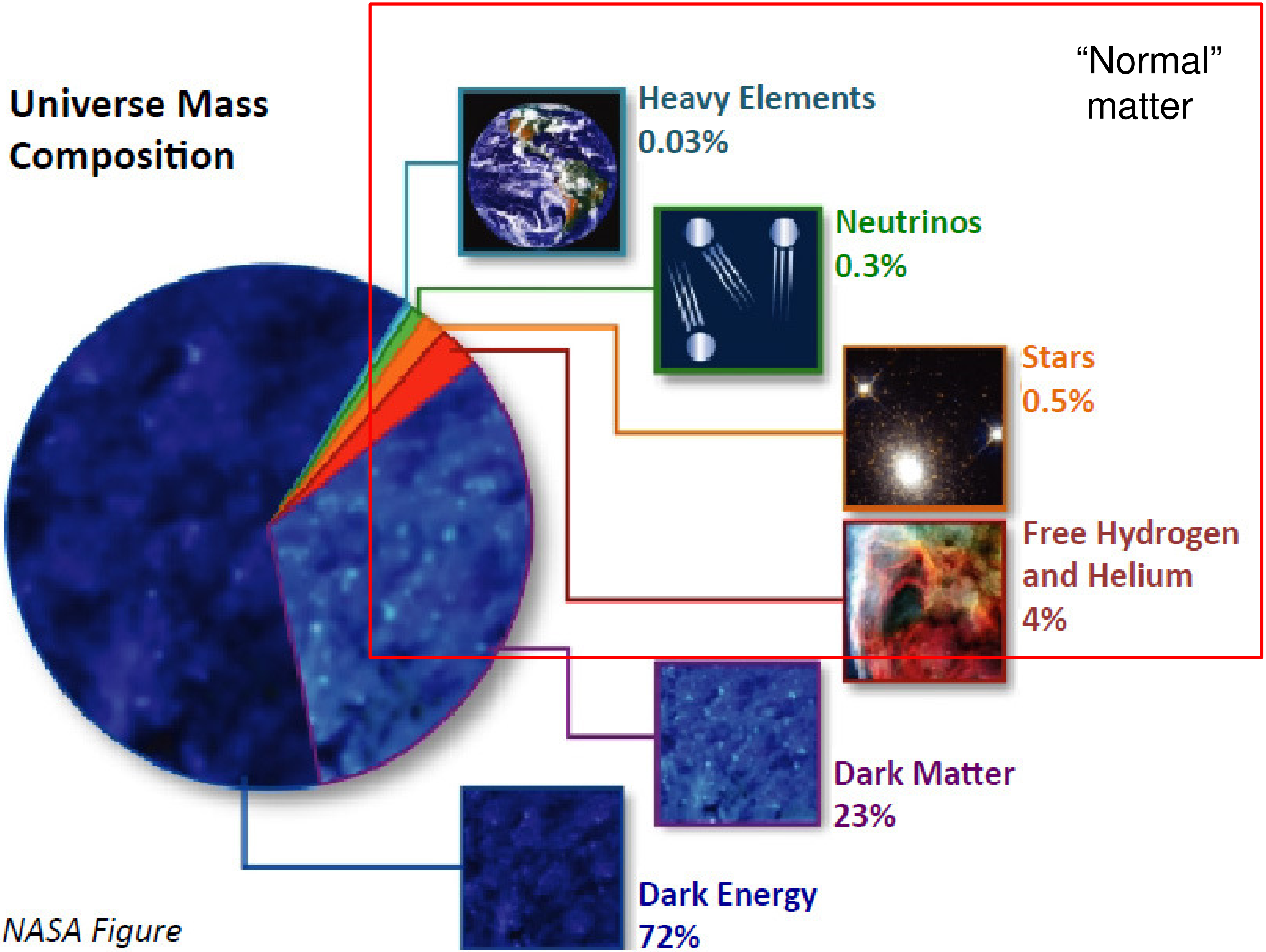
Part 2

Dark matter: what is it?

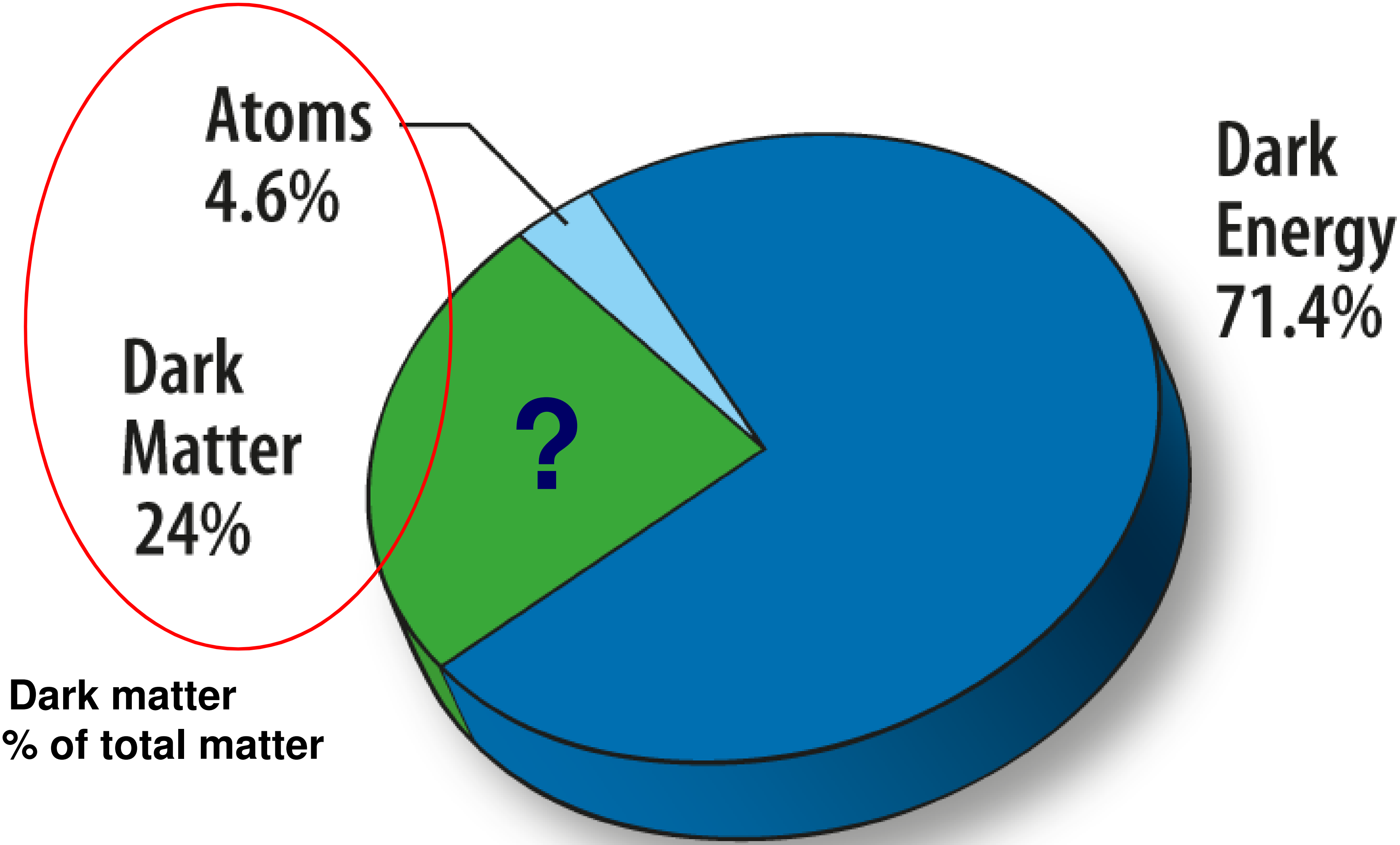
Overview of searches for dark matter


Universe Mass Composition
"Normal" matter
Heavy Elements 0.03%
Neutrinos 0.3%
Stars 0.5%
Free Hydrogen and Helium 4%
Dark Matter 23%
Dark Energy 72%

NASA Figure

Summary of dark matter evidence:
85% of matter in the universe is of unknown nature

Normal matter: ~15% of total matter



Dark matter
~85% of total matter

We know it is out there but we do not know what it is.

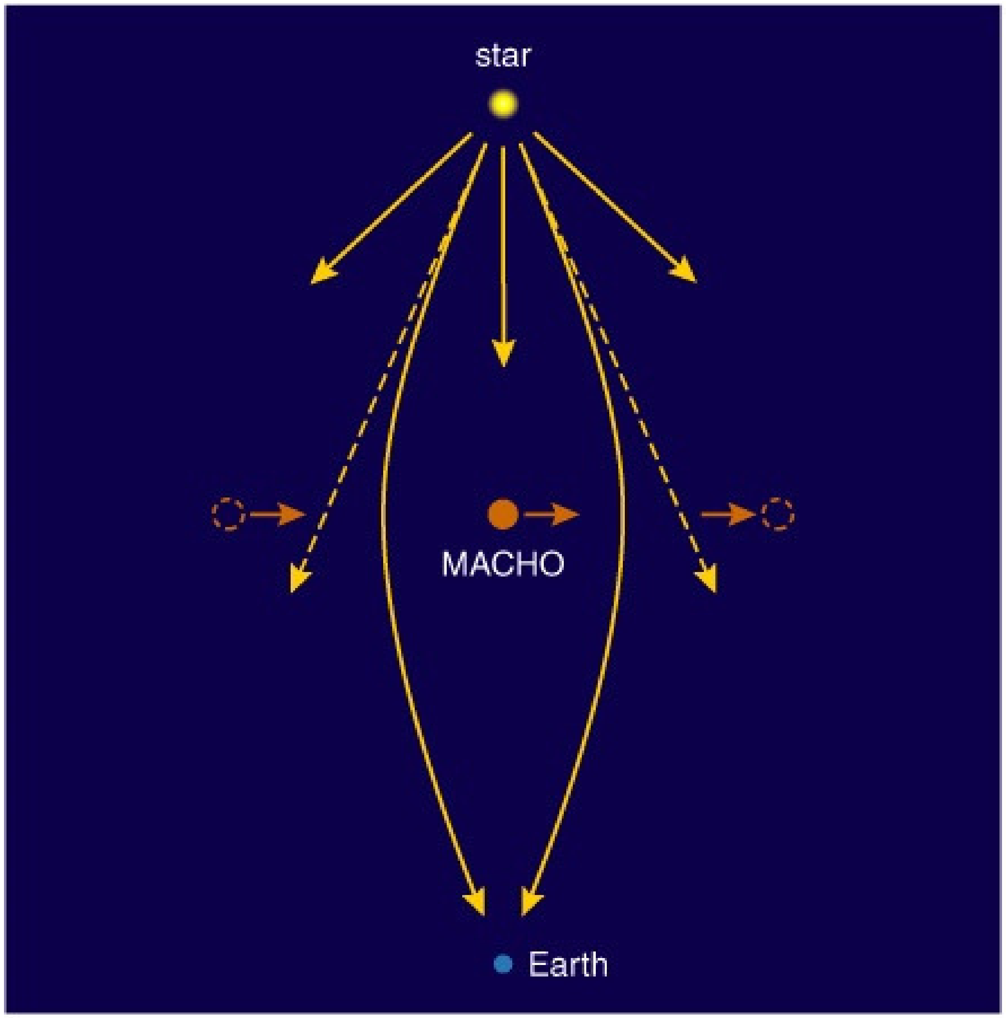
What dark matter is not:
MACHOS hypothesis have been ruled out

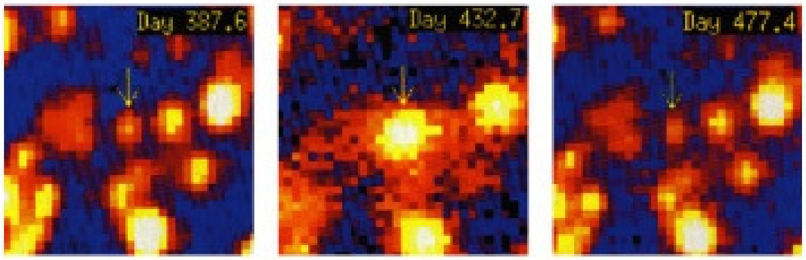
MACHOS: MAssive Compact Halo Objects:

dim stars (white dwarfs, drown dwarfs, neutron stars), black holes, and Jupiter-sized planets,

http://www.jcschroder.com/phy111/machos.htm

Searching for MACHOS with gravitational microlensing



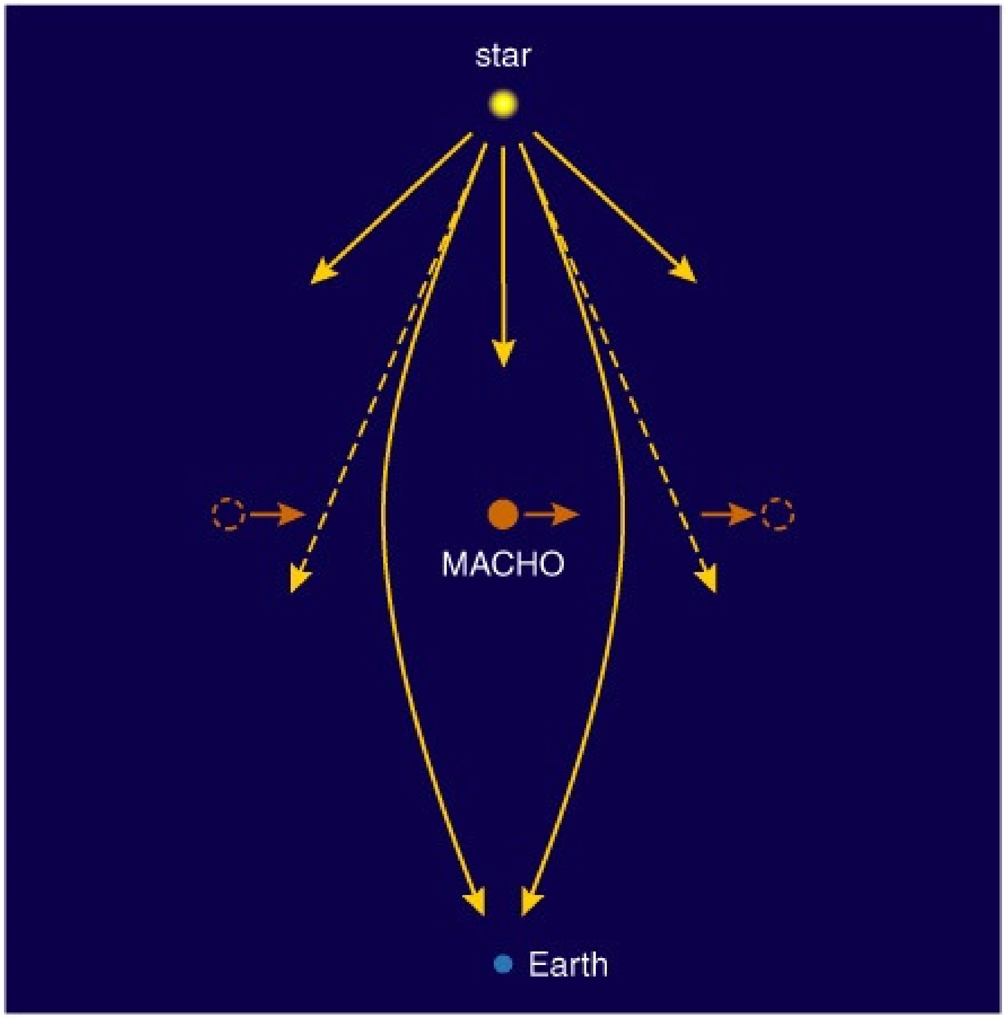

before

during

after

http://www.sjsu.edu/people/monika.kress/courses/sci255/

Searching for MACHOS with gravitational microlensing



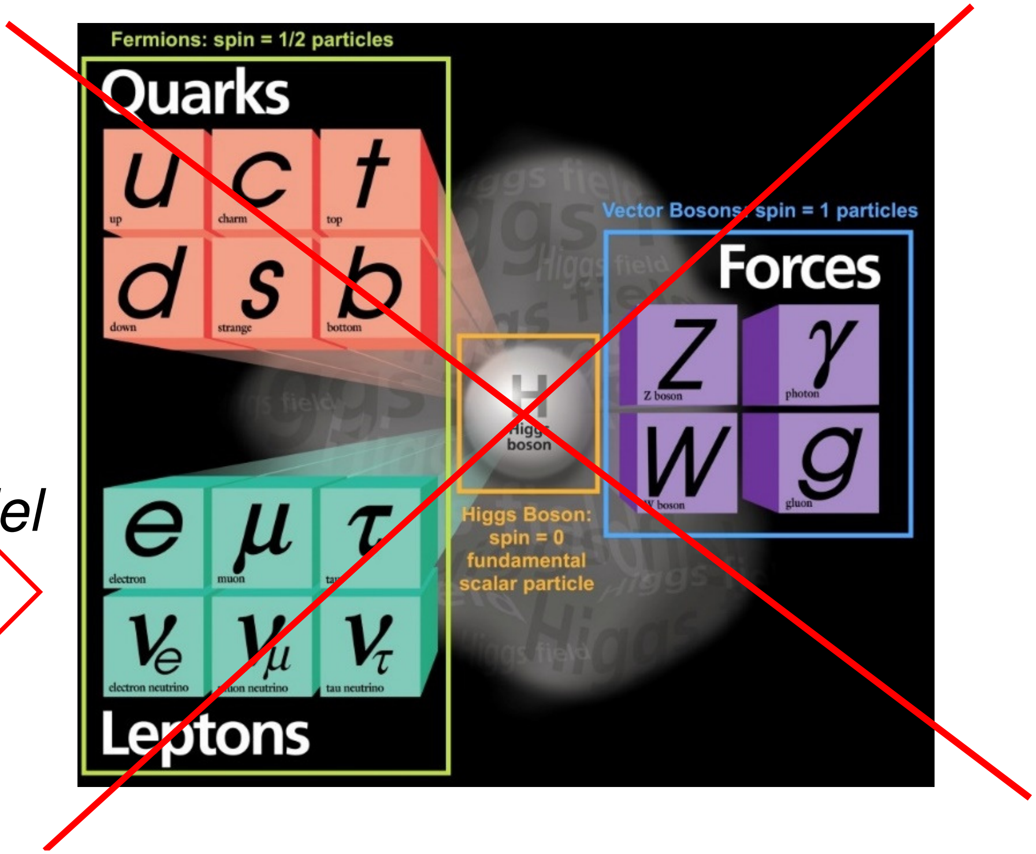
Results: not enough MACHOS to make dark matter

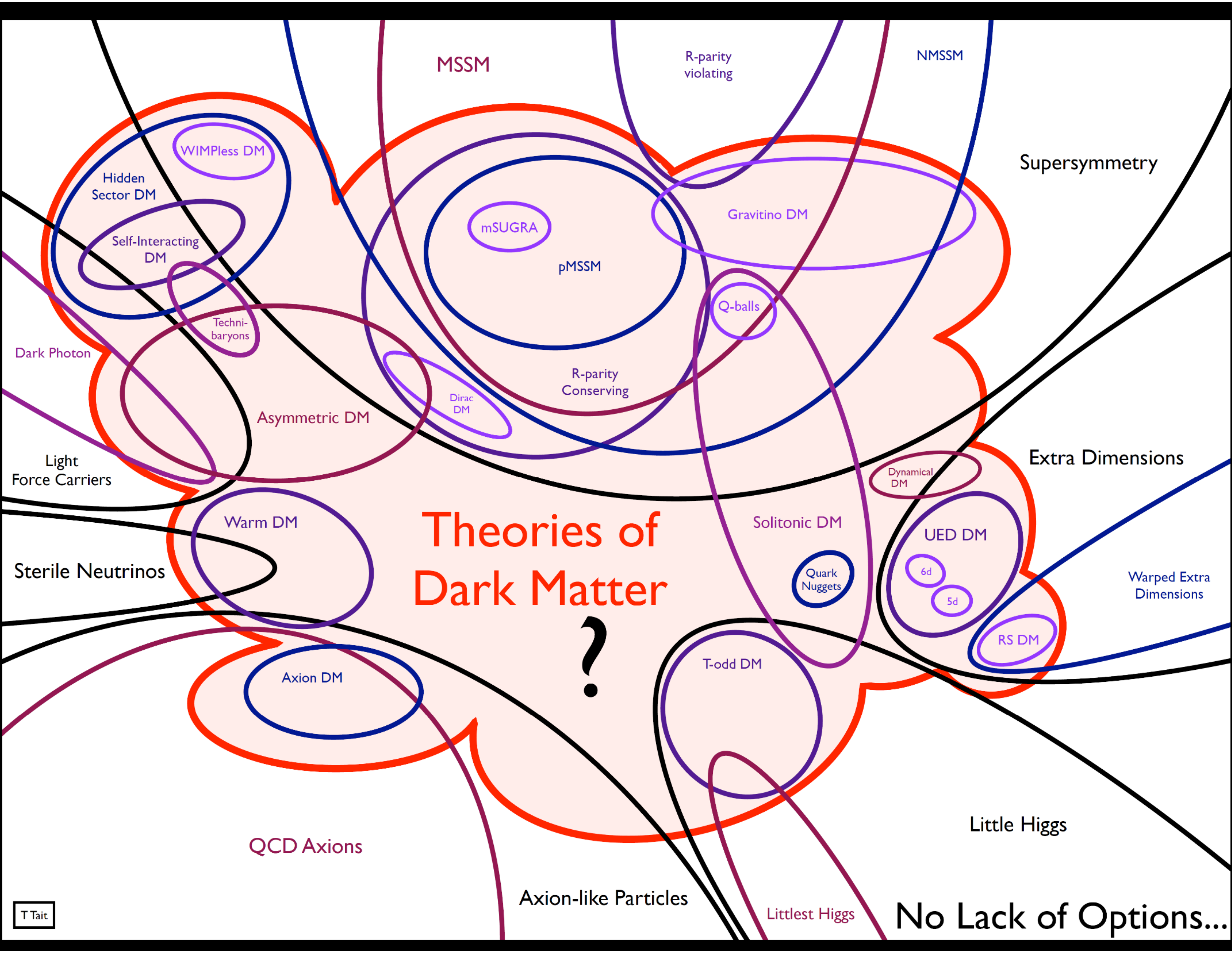
http://www.sjsu.edu/people/monika.kress/courses/sci255/

What do we know about dark matter?

Mostly have “negative” information from astrophysics and searches for new particles:

- No electric charge
- No colour charge (property of quarks and gluons that is related to the particles' strong interactions)
- No strong self-interaction
- Does not seem to decay: stable, or very long-lived
- *Not a particle in the Standard Model of particle physics*





Theories of Dark Matter ?

MSSM

R-parity violating

NMSSM

Supersymmetry

WIMPless DM

Hidden Sector DM

Self-Interacting DM

Techni-baryons

Dark Photon

mSUGRA

pMSSM

Gravitino DM

Q-balls

R-parity Conserving

Dirac DM

Asymmetric DM

Light Force Carriers

Extra Dimensions

Dynamical DM

Warm DM

Solitonic DM

UED DM

6d

5d

Quark Nuggets

Sterile Neutrinos

Warped Extra Dimensions

RS DM

Axion DM

T-odd DM

Little Higgs

QCD Axions

Axion-like Particles

Littlest Higgs

T Tait

No Lack of Options...

Approaching dark matter theories

Top down:
Begin with theory motivation (hierarchy problem, strong CP problem.) develop model (SUSY [supersymmetry], axion) look for stable, neutral particle (LSP [light supersymmetric particle], axion)

Bottom up:
Motivated often by specific experimental anomalies, theories constructed. Implications for other experiments (and often SUSY)

Phenomenological: Motivated by considering whether a viable and detectable model could exist of a certain type.

Our most conservative idea for dark matter:

Some exotic particle that we have not yet detected [note: it does not have to be just one particle]

Two most important parameters of such particles

(1) Mass

Measured in electron volts divided by c^2: [$1\text{eV}/c^2 = 1.782662\times10^{-36}$ kg]

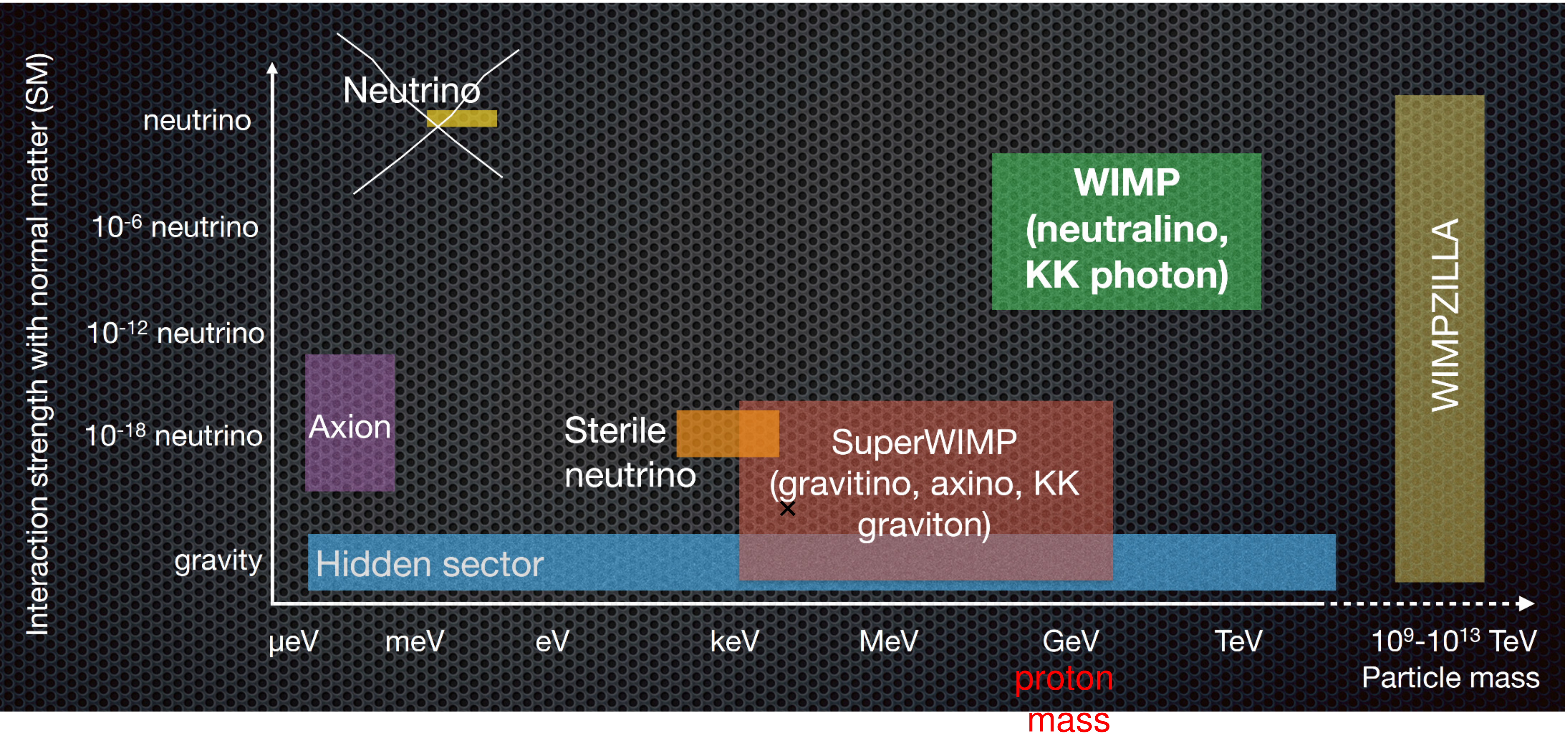
remember energy vs. mass $E = mc^2$, note that c^2 is usually omitted

Examples: mass of proton is 1.67×10^{-27} kg = 938×10^6eV= 938 MeV ~ 1GeV

mass of electron is 0.511 MeV

(2) Strength of interaction with normal matter

Dark matter candidate particle zoo



WIMP: Weakly **I**nteracting **M**assive **P**article

SuperWIMPS: superweakly-interacting massive particles produced in the late decays of other particles

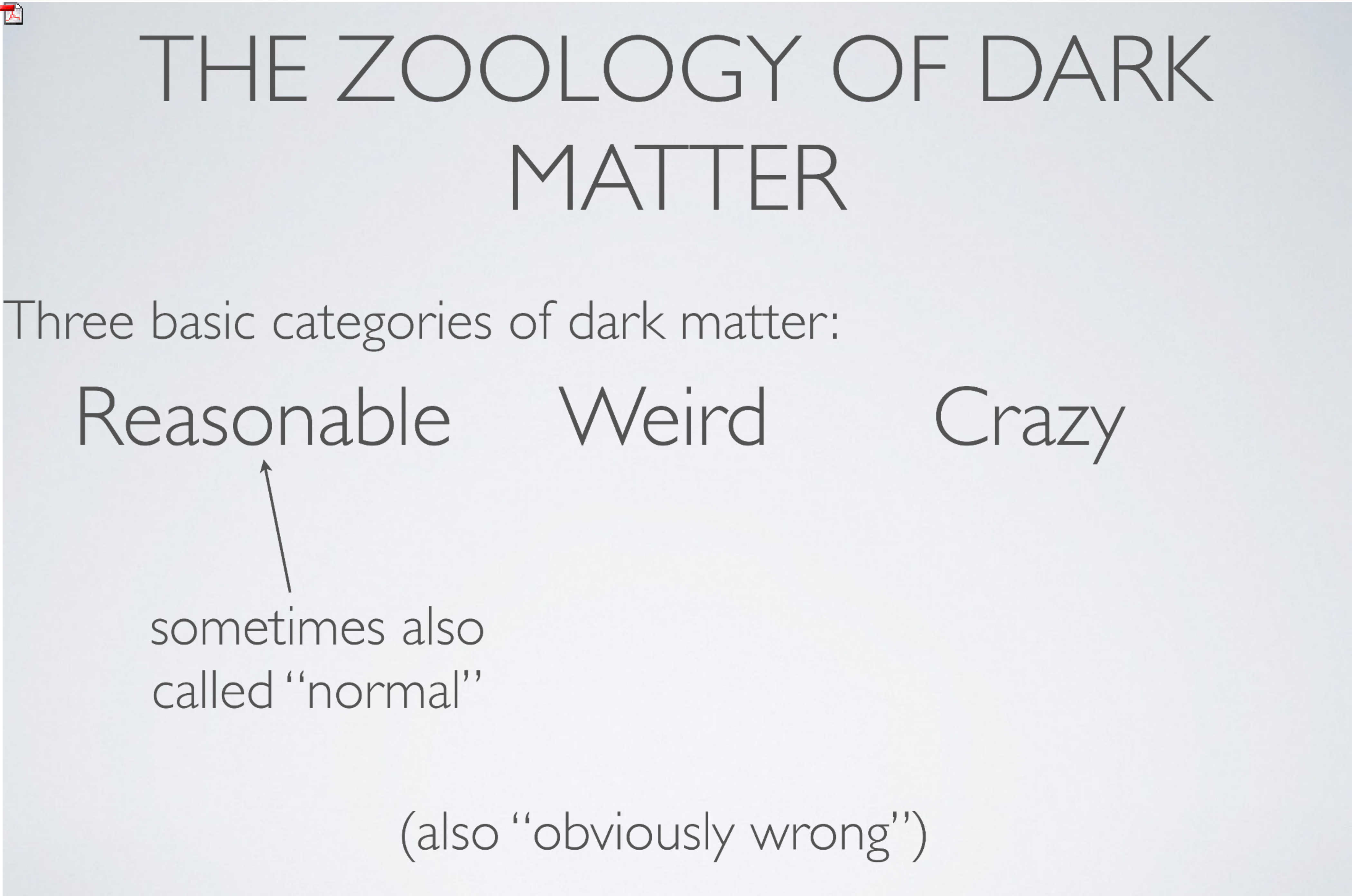
Axion, Peccei–Quinn symmetry

Kaluza-Klein (KK) photon and graviton are from universal extra dimension models

Neutralino and gravitino are particles of supersymmetric models

WIMPZILLA (nonthermal dark matter)

https://indico.in2p3.fr/event/10162/session/5/contribution/10/material/slides/0.pdf



THE ZOOLOGY OF DARK MATTER

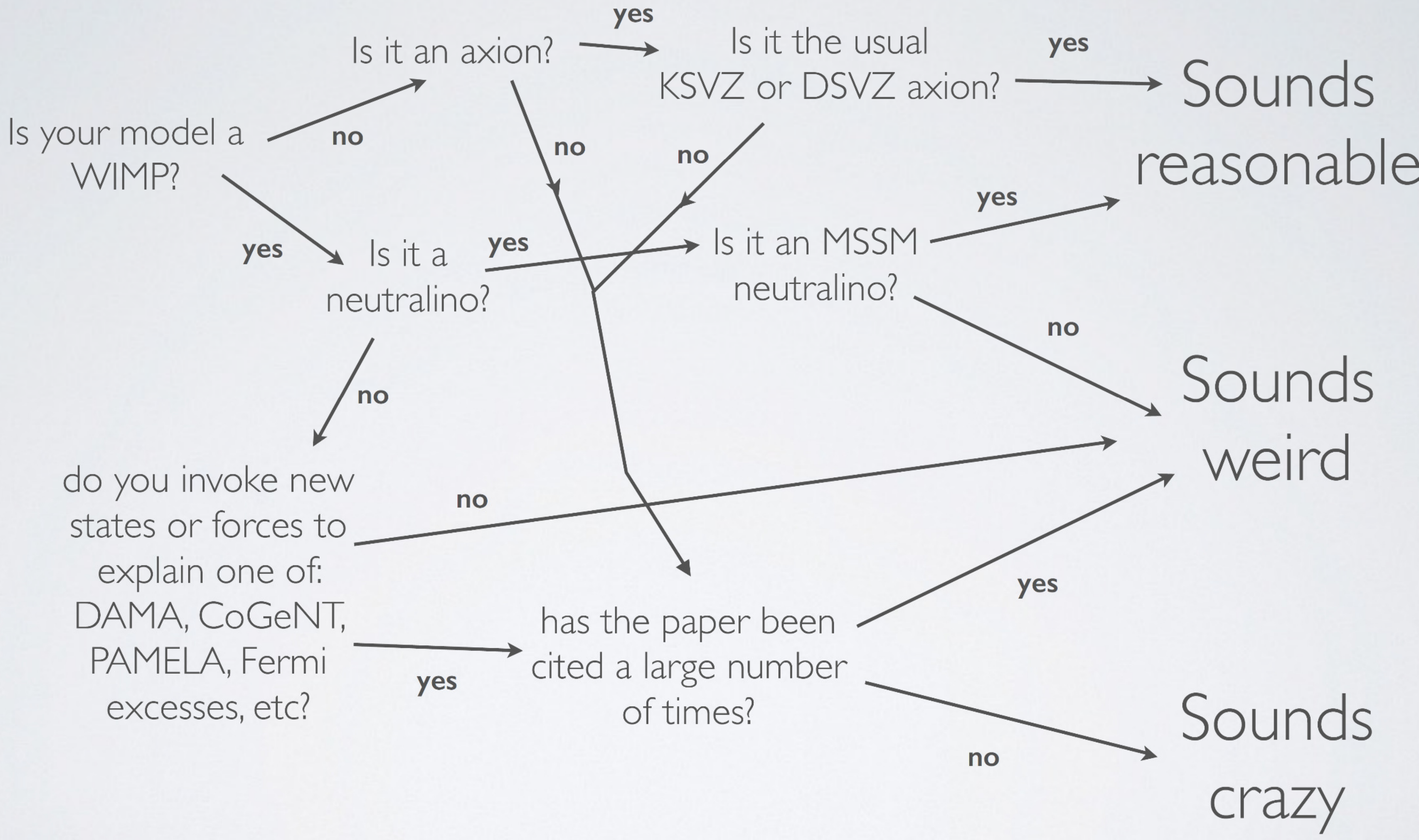
Three basic categories of dark matter:

Reasonable Weird Crazy

sometimes also called "normal"

(also "obviously wrong")

Slide from Neal Weiner's (New York University) review on dark matter at the 2015 Conference on the Intersections of Particle and Nuclear Physics



Is your model a WIMP?

no

Is it an axion?

yes

Is it the usual KSVZ or DSVZ axion?

yes

Sounds reasonable

no

no

yes

Is it a neutralino?

yes

Is it an MSSM neutralino?

yes

no

Sounds weird

no

do you invoke new states or forces to explain one of: DAMA, CoGeNT, PAMELA, Fermi excesses, etc?

no

yes

has the paper been cited a large number of times?

yes

no

Sounds crazy

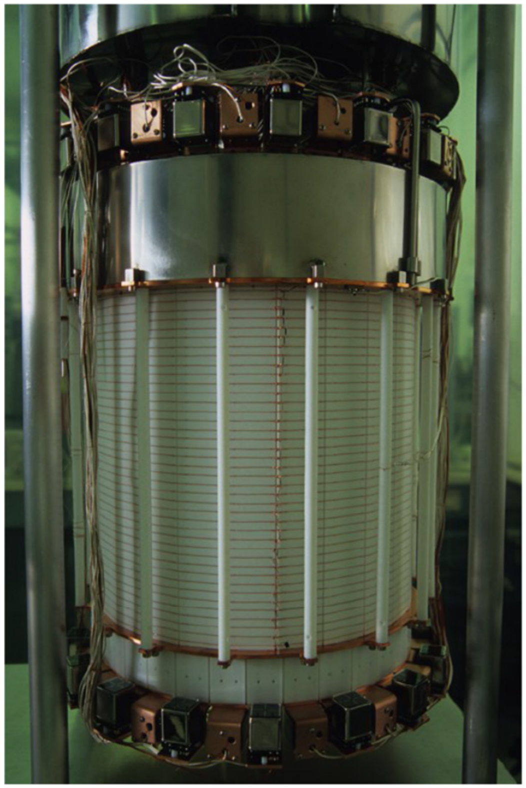
Neal Weiner, CIPANP 2015

How to search for dark matter particles

- Indirect detection

Search for things
dark matter can decay to
$\chi\chi \rightarrow e^+e^-, p\bar{p}$

- Direct detection



Build a trap for dark matter

$\chi\,\mathrm{N} \rightarrow \chi\,\mathrm{N}$

- Production at LHC

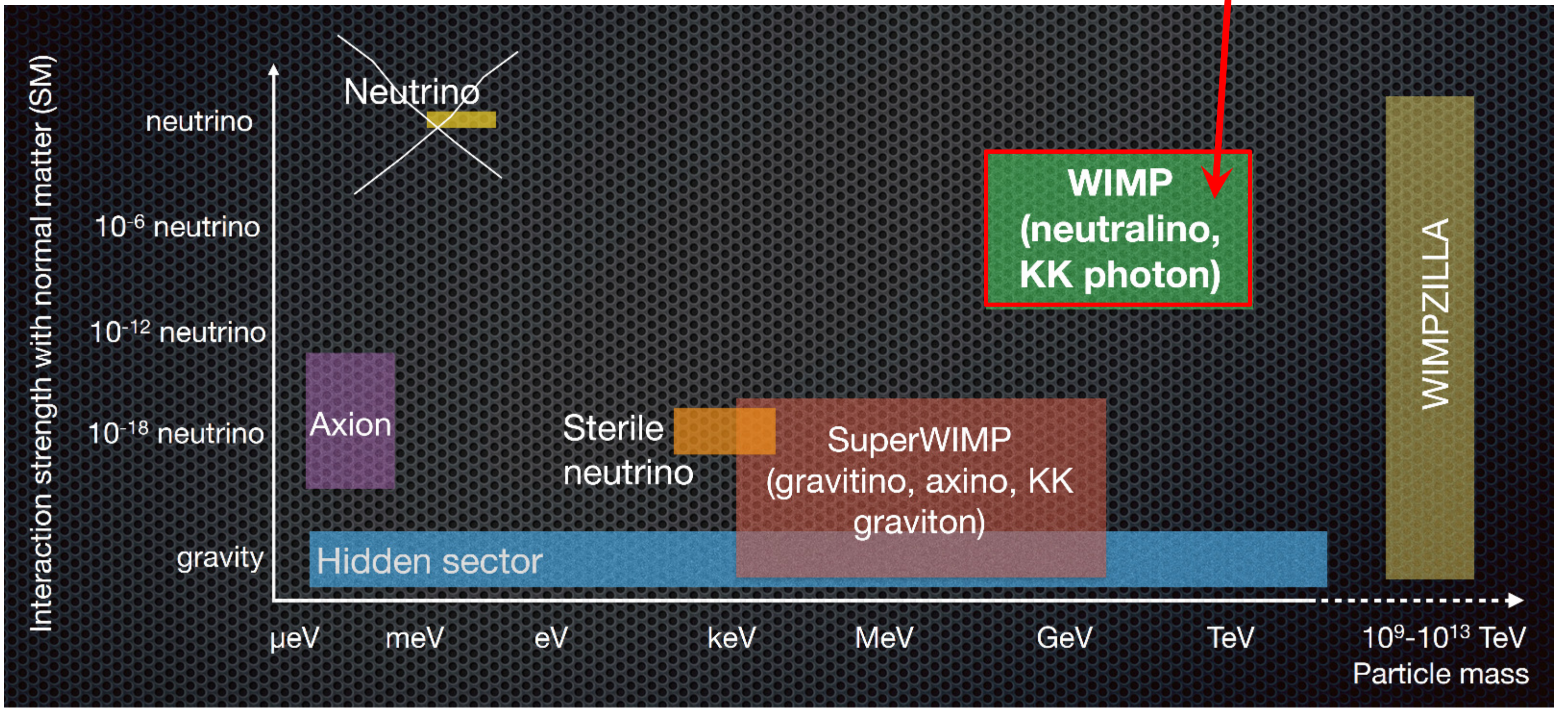
Make dark matter particles

$\mathrm{p} + \mathrm{p} \rightarrow \chi + \text{a lot}$

http://www.ippp.dur.ac.uk/~ross/invisibles13/talks/78-marrod_xe1n_undagoita/slides/78-0-Marrodan_Invis_Durham2013.pdf

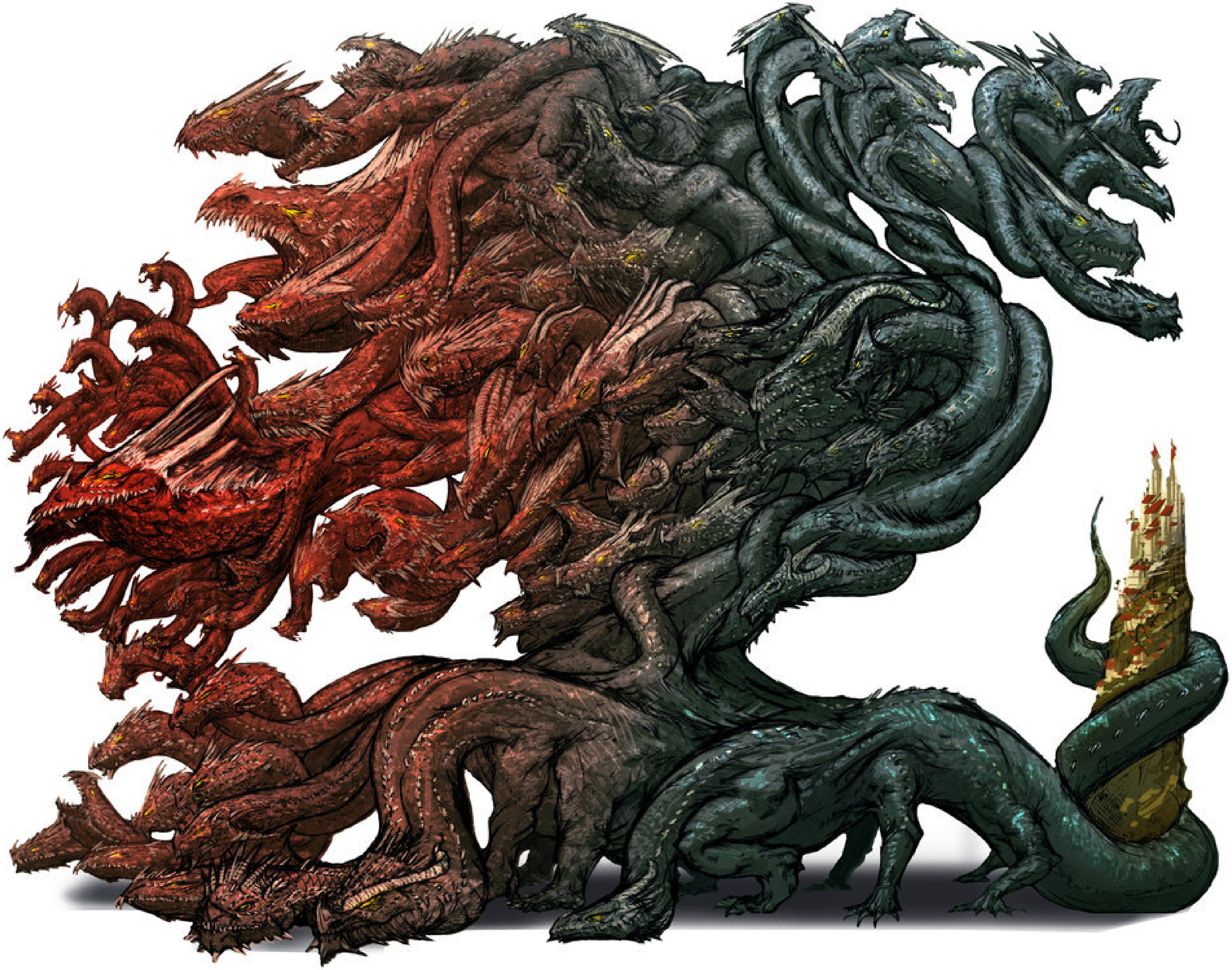
How to search for dark matter particles

1. Pick you favorite dark matter particle(s)
2. Decide how it can be detected (direct detection, indirect detection, produce the particle or a combination of these?)
3. Built your detector
4. Take measurements and see if you find it or rule it out the entire *“parameter space”*



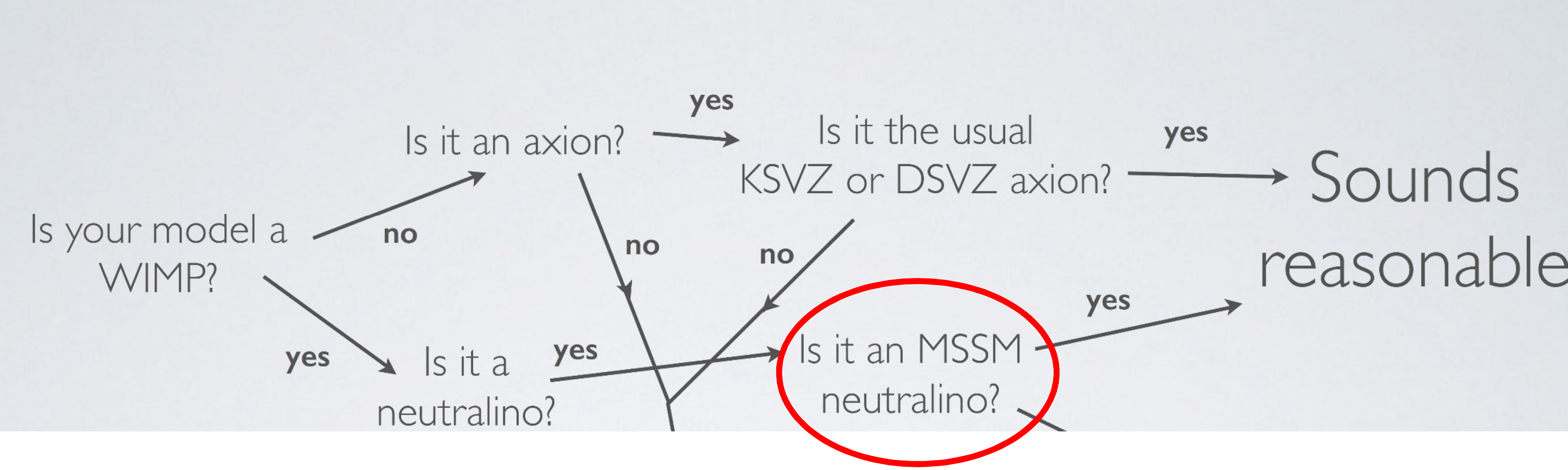
It is very difficult to completely rule out dark matter theories!

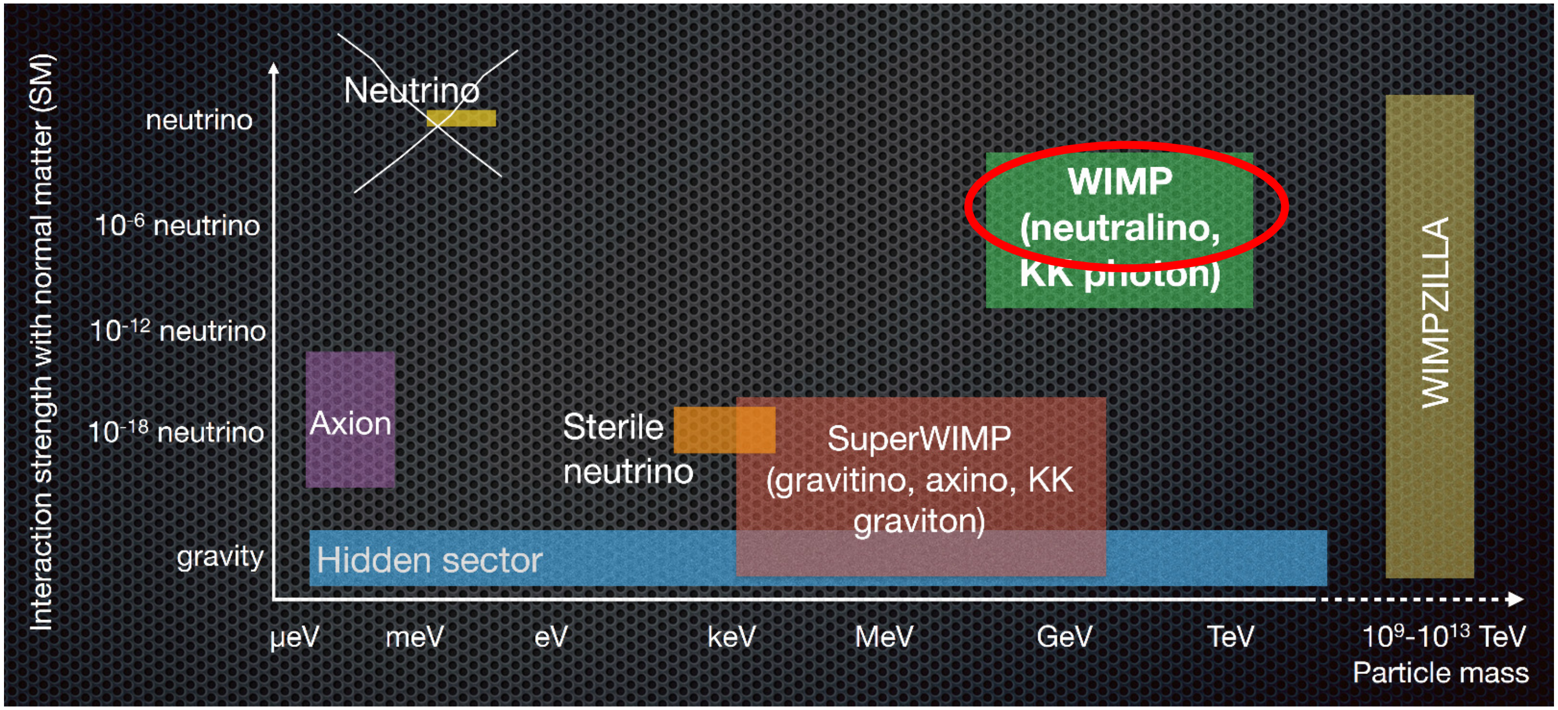
Ruled out theories produce more other theories!



http://westlylafleur.deviantart.com/art/Hundred-Headed-Dragon-328858556

Supersymmetry: WIMPs





Weakly Interacting Massive Particles (WIMPs)

A fraction of a second after the Big Bang the universe was so hot that new particles (and antiparticles) were created and destroyed all the time, just like in a particle accelerator.

As the universe expanded and cooled these particles were no longer created, and eventually the leftovers annihilated or decayed, clearing the universe of these exotic states.

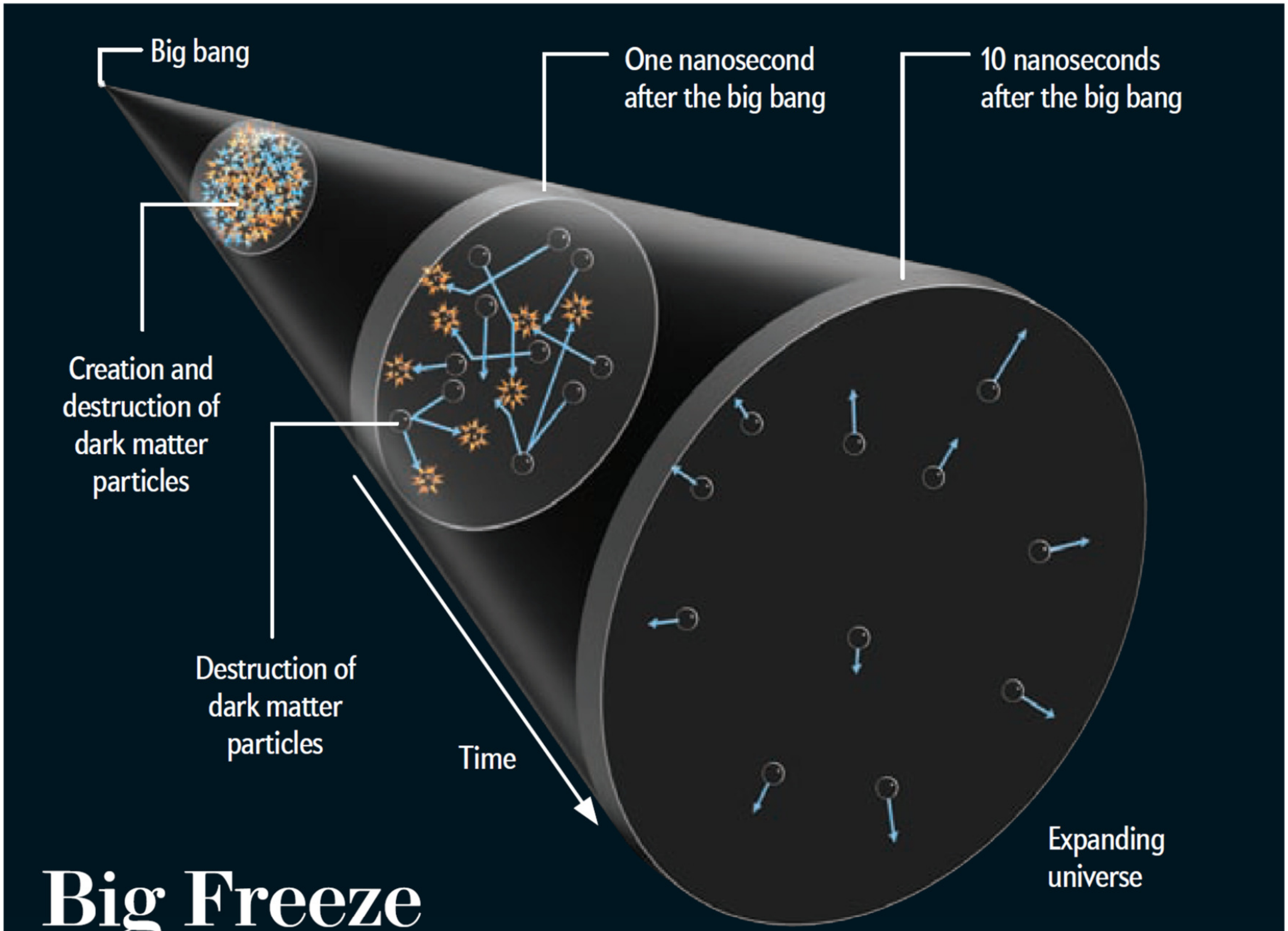
A weakly-interacting particle will not be able to completely annihilate and a residue of these particles will be left filling the universe.

It turns out that a stable particle of mass near 100 GeV and interacting via the weak force (just the kind of particle that particle physicists think exists anyway) will leave just about the right amount of "leftovers" to account for the observed dark matter density!

This class of natural dark matter candidates is generally called **weakly interacting massive particles (WIMPs)**.

http://cdms.berkeley.edu/Education/DMpages/essays/essays/essays/candidates.shtml

WHERE DARK MATTER CAME FROM



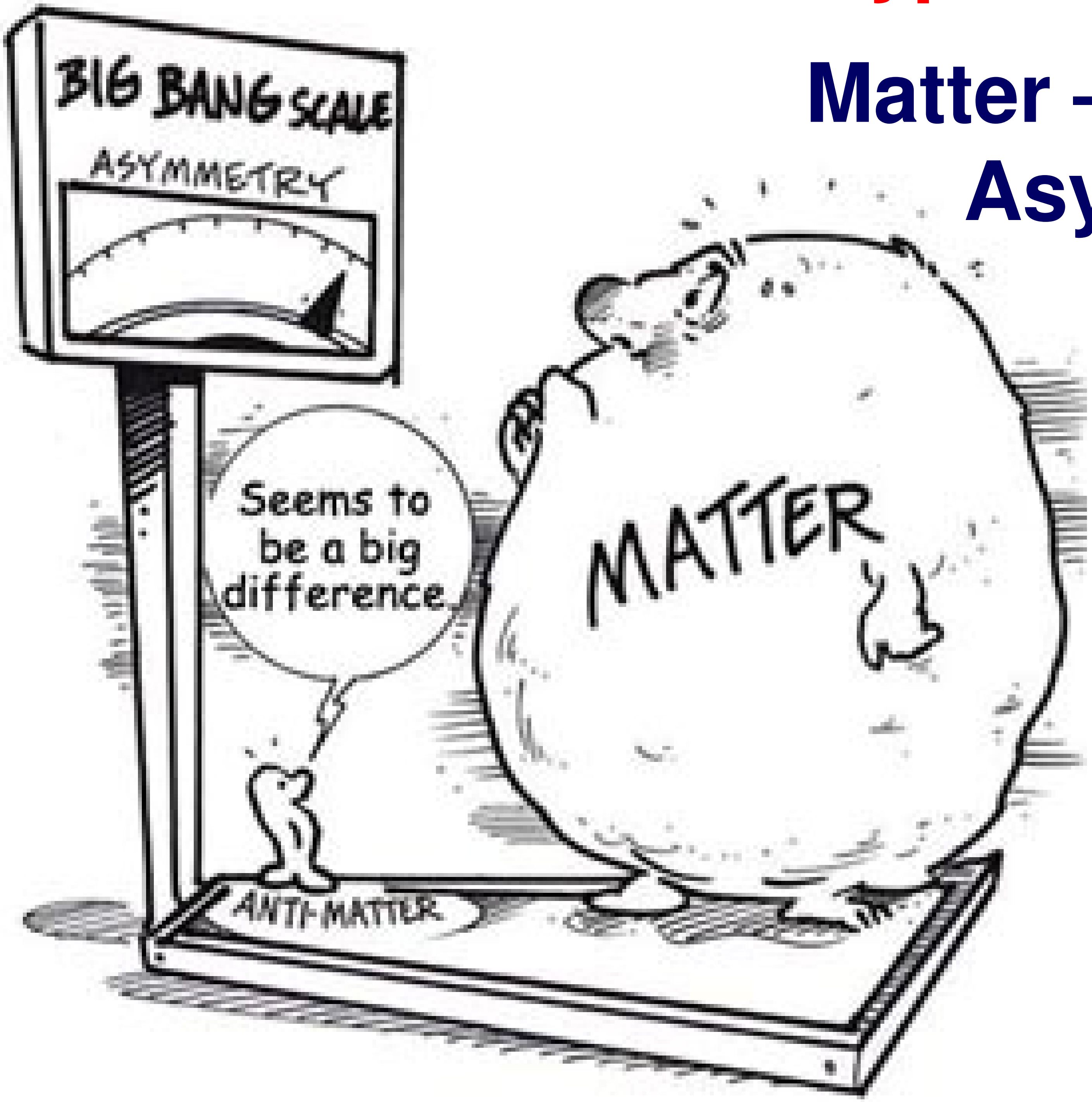
Big Freeze

In the hot, dense early universe, dark matter particles such as WIMPs were created and destroyed in a dynamic equilibrium. As the cosmos expanded, it cooled and eventually was no longer able to create new particles. Those left over became so spread out that they ceased colliding and getting destroyed. For WIMPs, theory makes a firm prediction for the amount of material that survived, which is consistent with observations.

Scientific American **23**, 44-51 (4 August 2014)

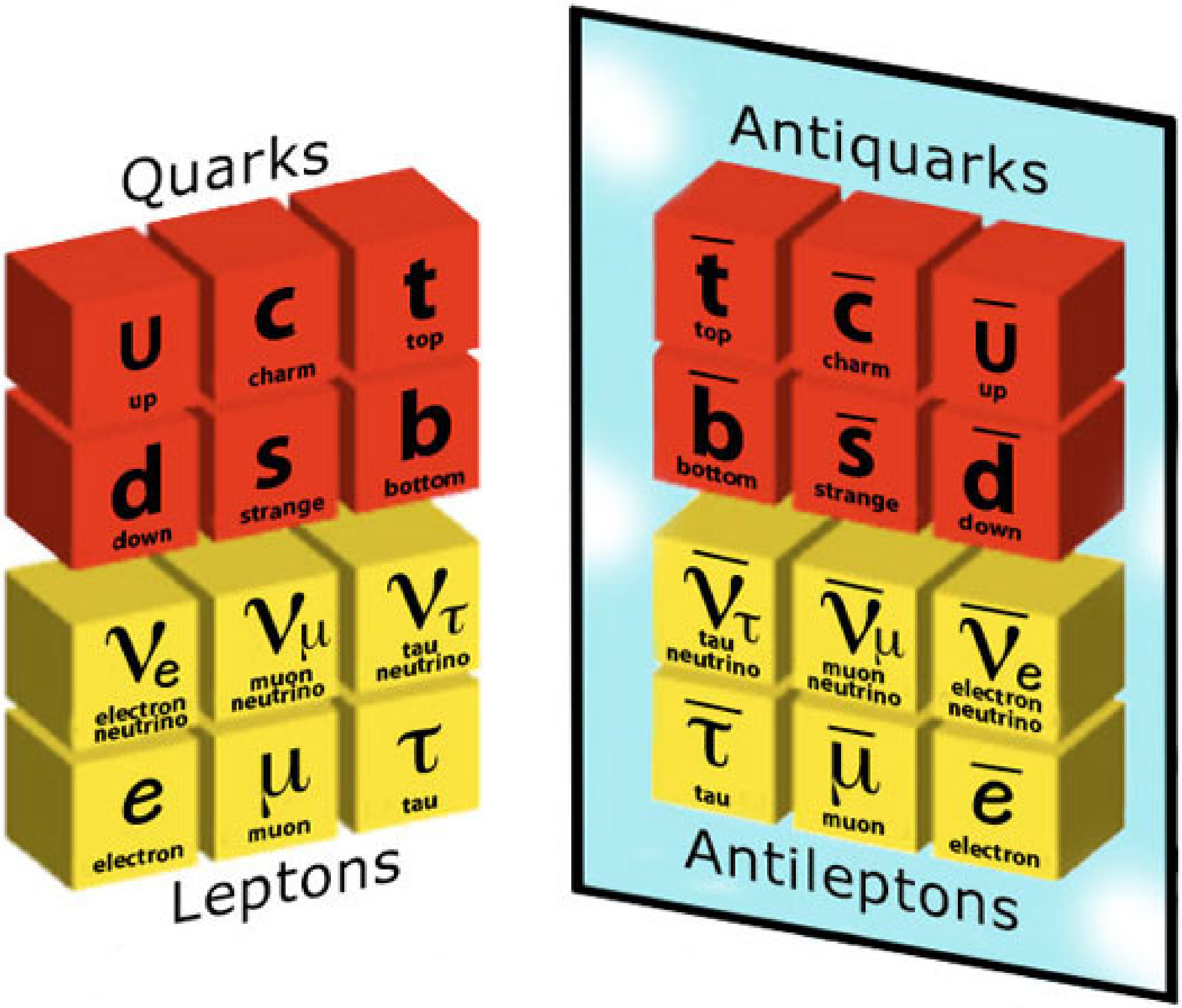
WIMPs and Sypersymmetry

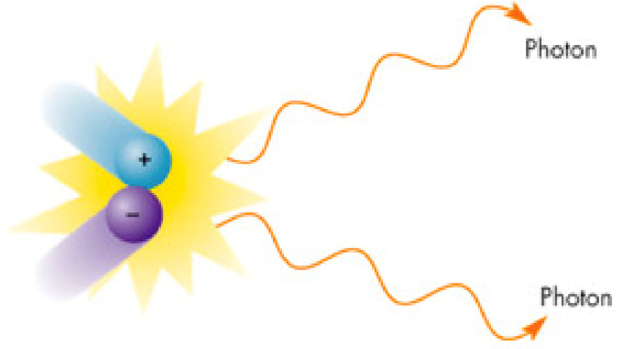
Matter – Antimatter Asymmetry

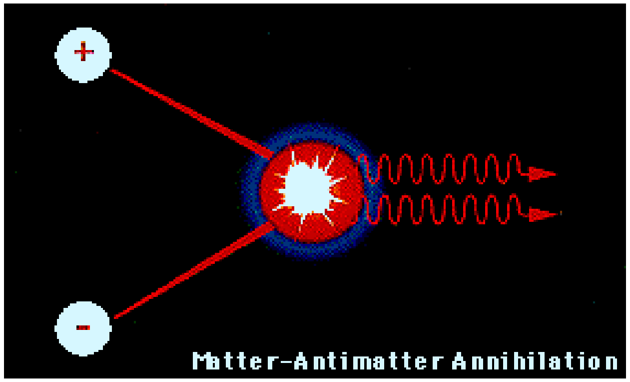


www.research.vt.edu

Matter-antimatter annihilation







http://imagine.gsfc.nasa.gov/science/toolbox/gamma_generation.html

https://www.learner.org/courses/physics/unit/text.html?unit=1&secNum=7

Charge

$$q \rightarrow -q$$

Parity

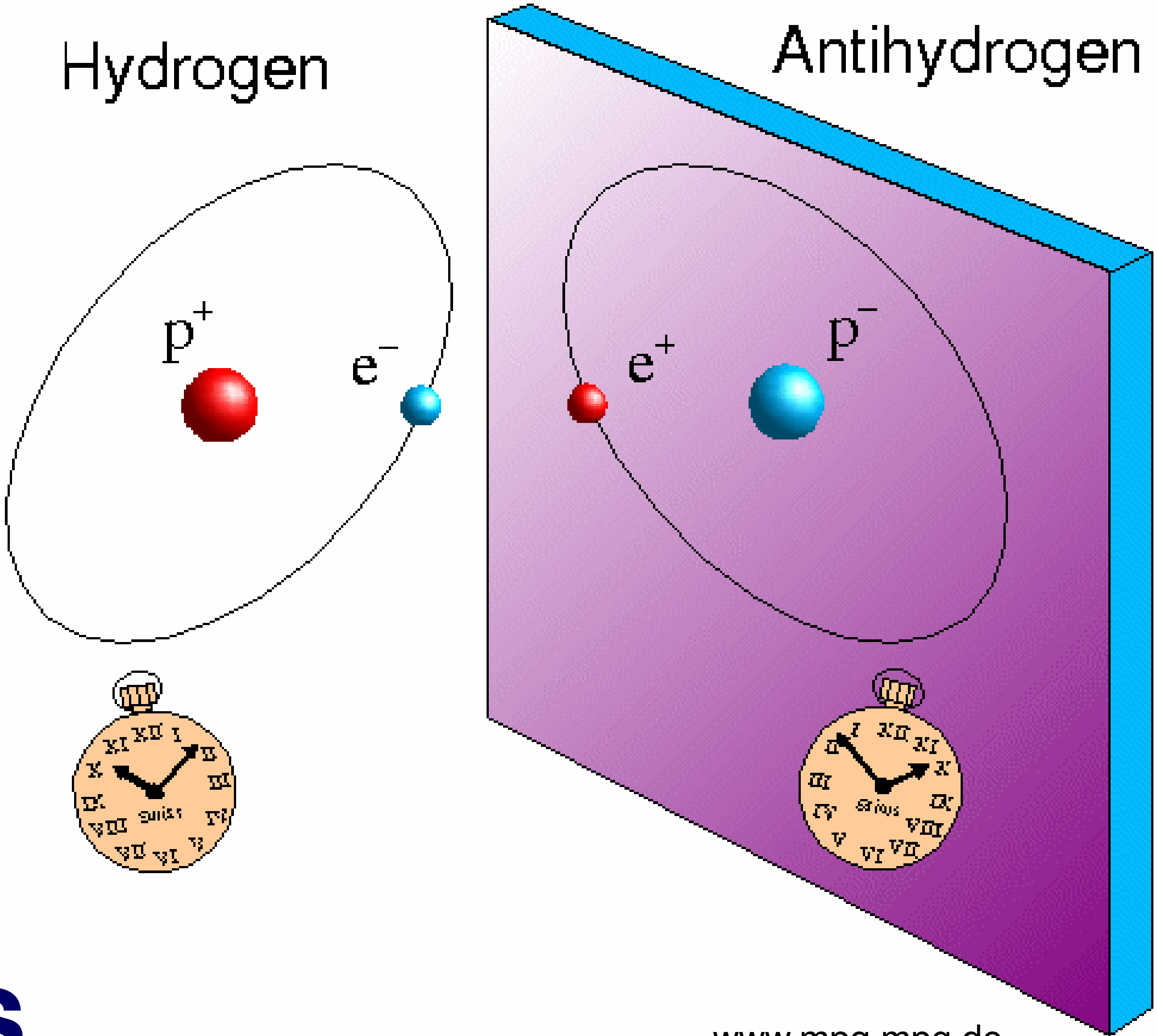
$$\vec{r} \rightarrow -\vec{r}$$

Time

$$t \rightarrow -t$$

Discrete Symmetries

If **CPT** symmetry holds, then
T-violation → CP-violation



www.mpq.mpg.de

Problems with the Standard Model:

Matter – Antimatter asymmetry

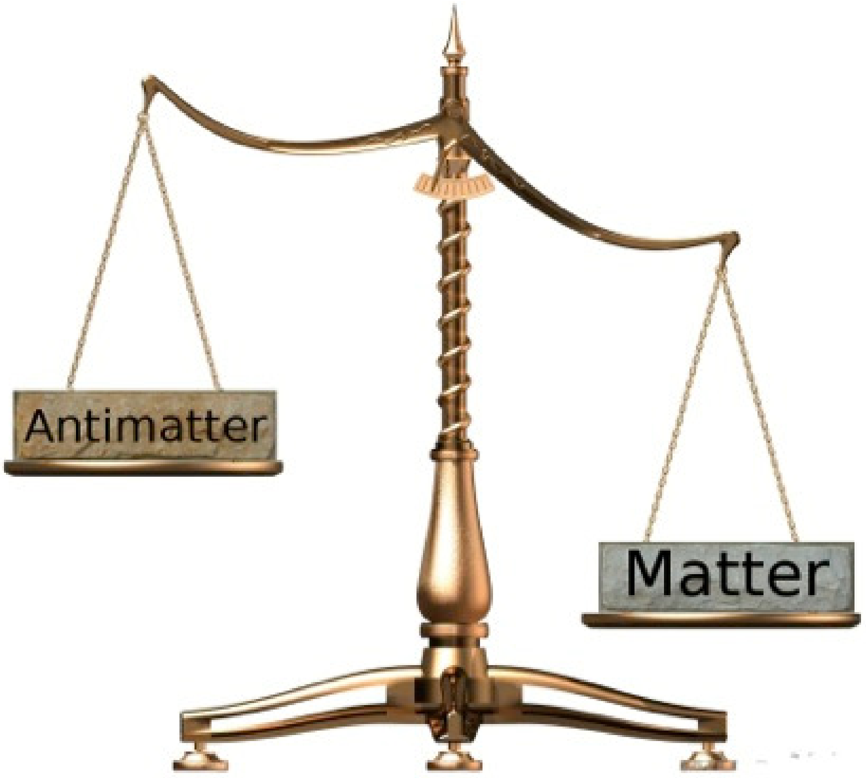
Andrei Sakharov (1967)

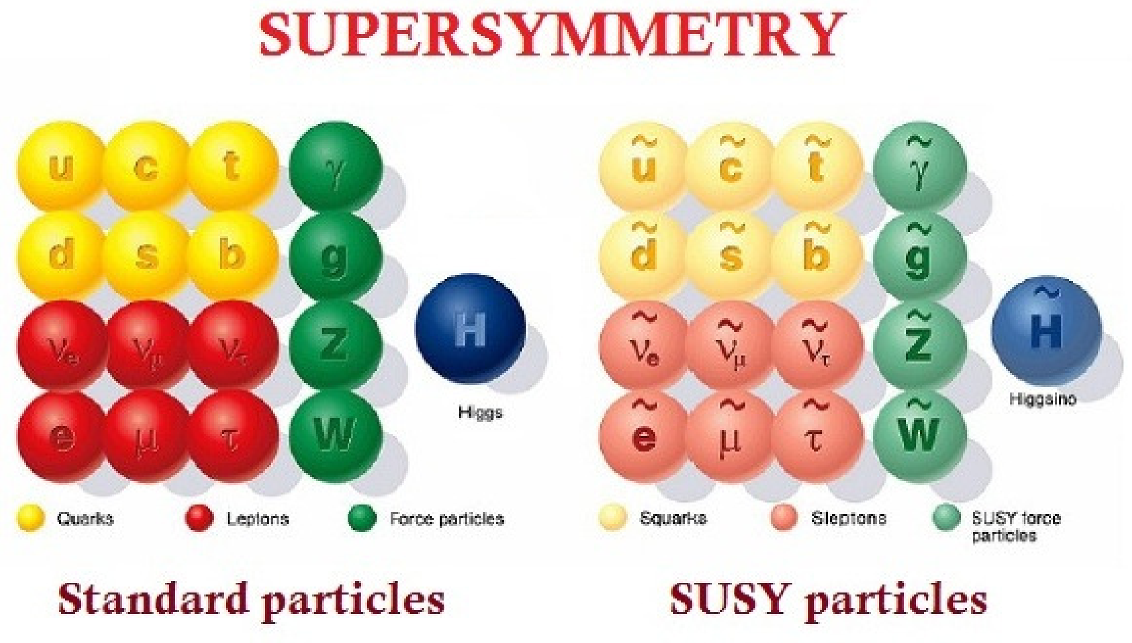
Need **CP-violation** for matter-antimatter asymmetry

Standard Model CP-violation **is insufficient** to generate observed matter – antimatter asymmetry.

www.research.vt.edu

Matter – Antimatter asymmetry:
Need new sources of CP- (T-) violation





Extended gauge symmetry

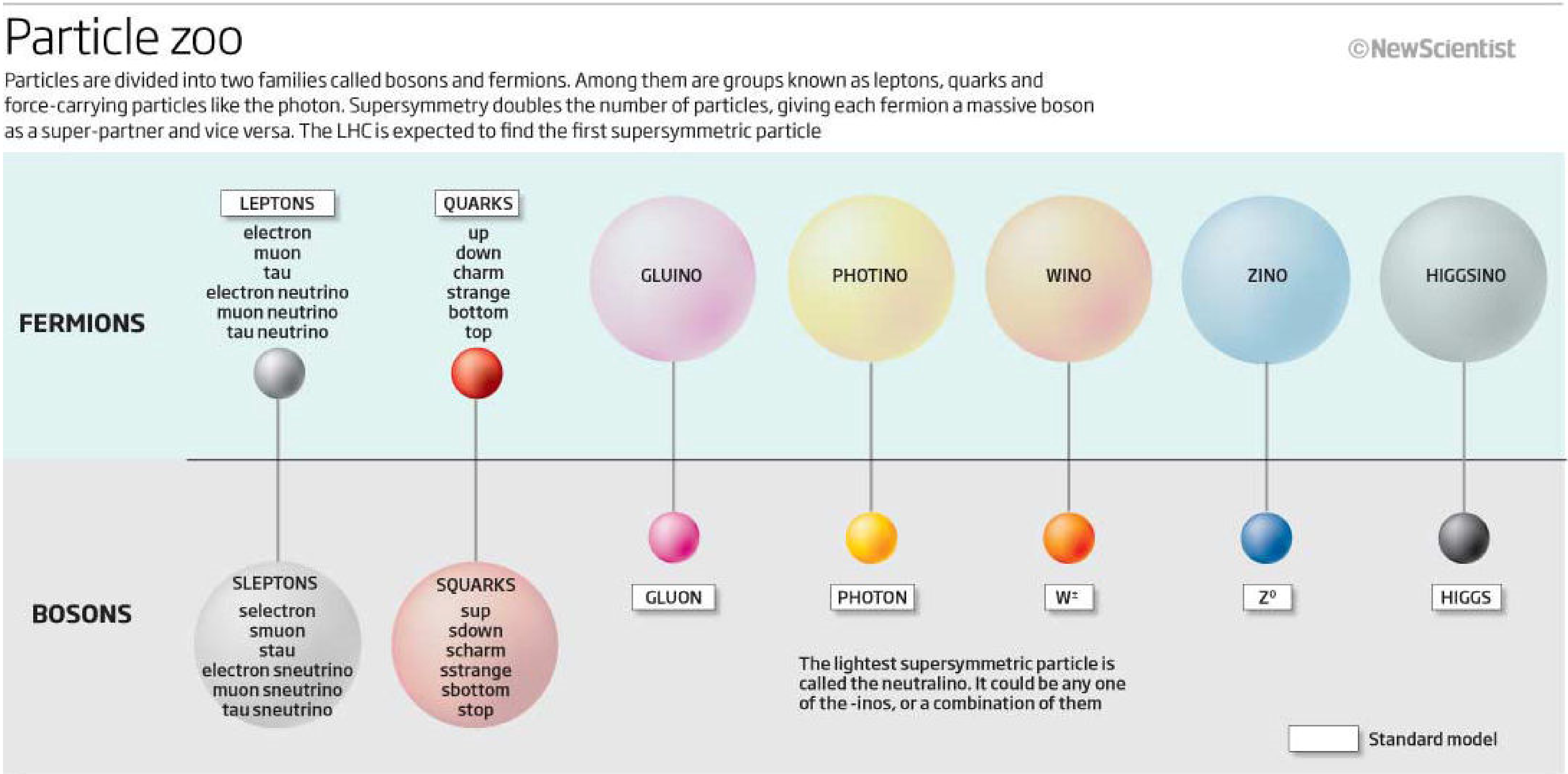
Additional spacetime dimensions

…….

www.simonsfoundation.org

Supersymmetry and WIMPs:

The lightest (stable) supersymmetries particle is your dark matter WIMP: neutralino (combination of –inos)

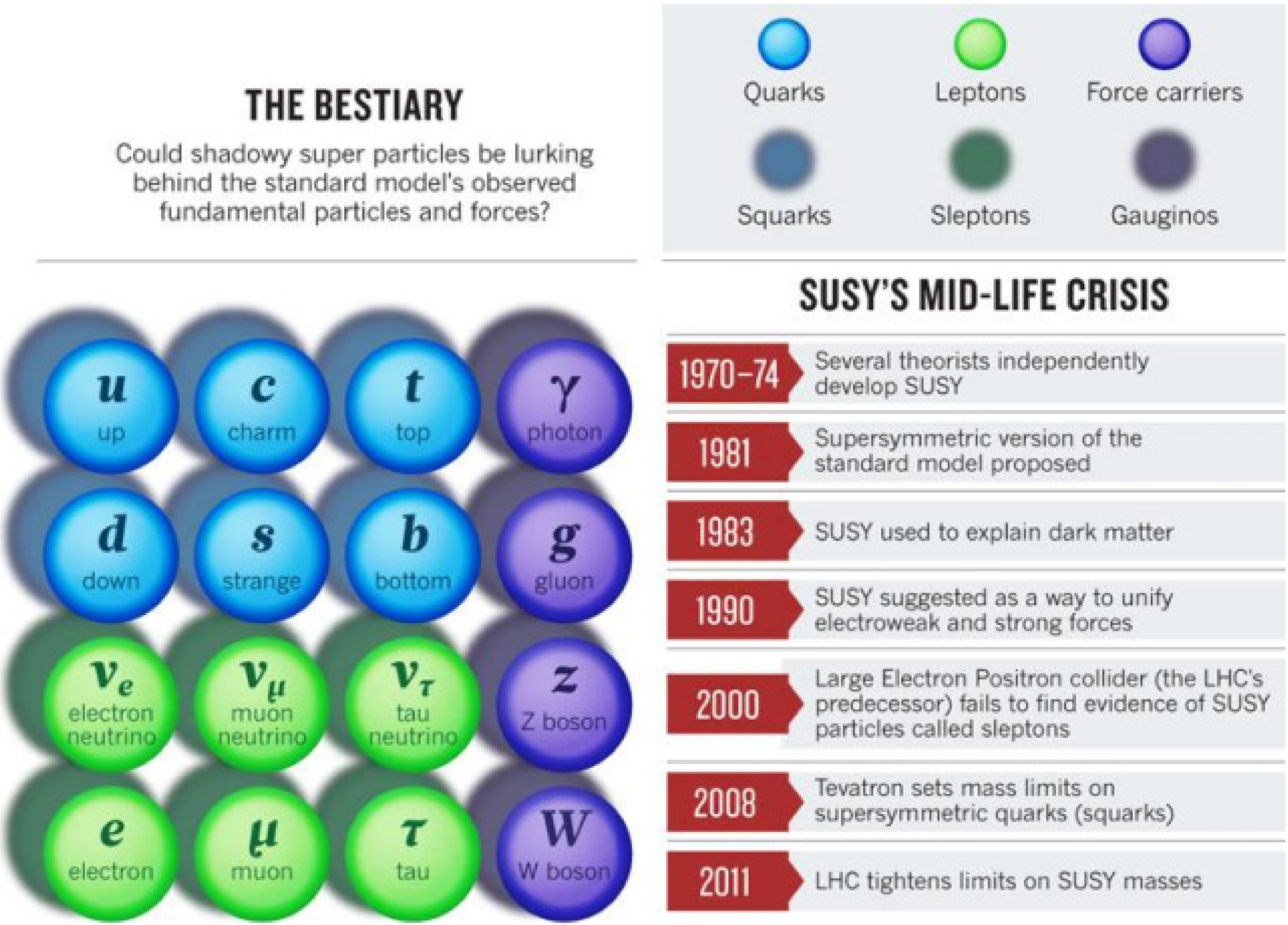


Particle zoo

©NewScientist

Particles are divided into two families called bosons and fermions. Among them are groups known as leptons, quarks and force-carrying particles like the photon. Supersymmetry doubles the number of particles, giving each fermion a massive boson as a super-partner and vice versa. The LHC is expected to find the first supersymmetric particle

The lightest supersymmetric particle is called the neutralino. It could be any one of the -inos, or a combination of them



THE BESTIARY

Could shadowy super particles be lurking behind the standard model's observed fundamental particles and forces?

SUSY'S MID-LIFE CRISIS

1970–74	Several theorists independently develop SUSY
1981	Supersymmetric version of the standard model proposed
1983	SUSY used to explain dark matter
1990	SUSY suggested as a way to unify electroweak and strong forces
2000	Large Electron Positron collider (the LHC's predecessor) fails to find evidence of SUSY particles called sleptons
2008	Tevatron sets mass limits on supersymmetric quarks (squarks)
2011	LHC tightens limits on SUSY masses

Image credit: Geoff Brumfiel from Nature

The Large Hadron Collider (LHC)

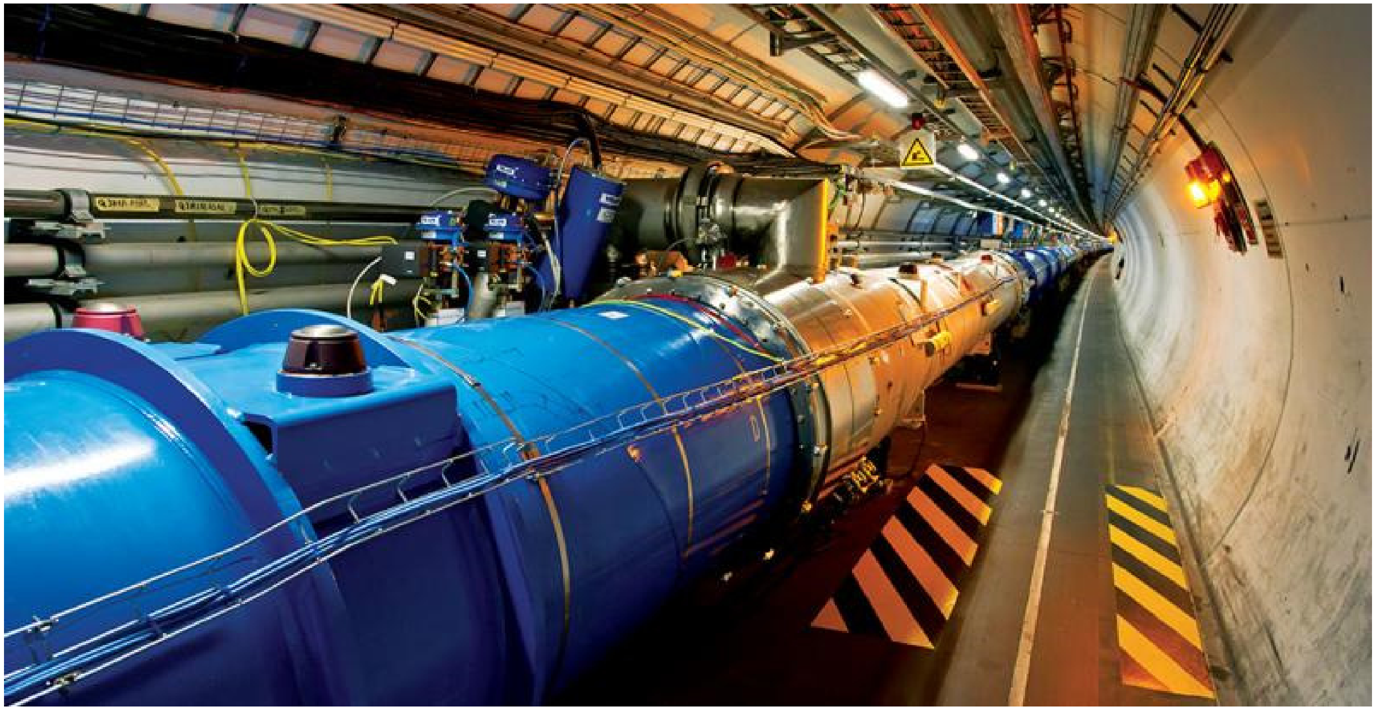
CERN (*Conseil Européen pour la Recherche Nucléaire)*

LHC: **27-kilometre ring** of superconducting magnets with a number of accelerating structures to boost the energy of the particles along the way.

The world's largest and most powerful particle collider: 13 TeV (10^{12} eV).
The largest, most complex experimental facility ever built.
The largest single machine in the world. Cost: 3 billion euro.

Credit: CERN

The Large Hadron Collider (LHC)



Inside the accelerator, two high-energy particle beams travel at close to the speed of light before they are made to collide.

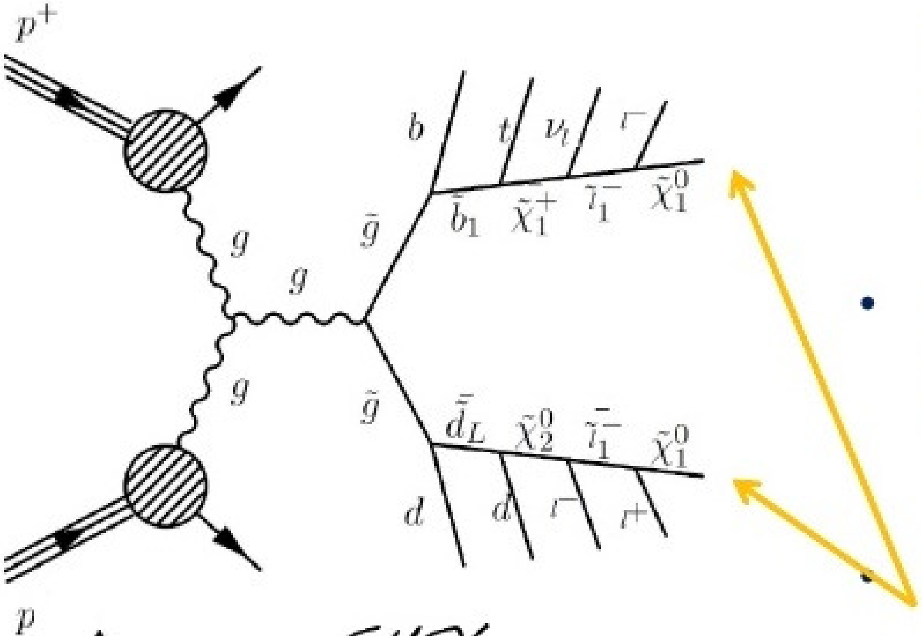
Kinetic energy of a proton (K)	Speed (%c)	Accelerator
50 MeV	31.4	Linac 2
1.4 GeV	91.6	PS Booster
25 GeV	99.93	PS
450 GeV	99.9998	SPS
7 TeV	99.9999991	LHC

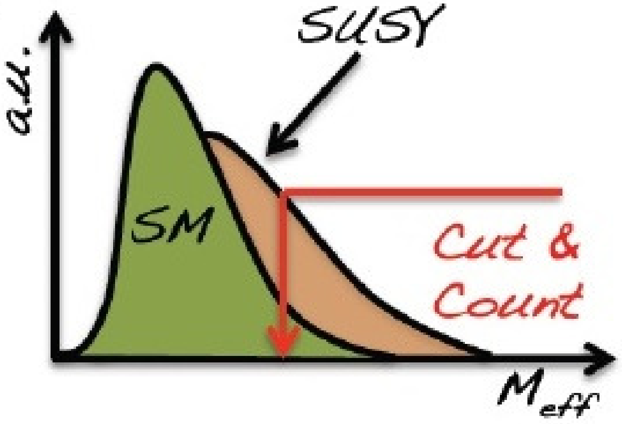
Relationship between kinetic energy and speed of a proton in the CERN machines. The rest mass of the proton is 0.938 GeV/c^2

Credit: CERN

Searches for SUSY at the LHC

Characteristic SUSY production and decay





- In R-parity is conserved, SUSY particles are produced in pairs and the lightest SUSY particle (LSP) becomes stable
  - $R=(-1)^{3(B-L)+2s}$
- No direct observation of SUSY particles, but only SM particles are reconstructed directly
  - No mass peaks
- LSP escapes the detector undetected producing a missing transverse energy (E_T^{miss})
- Evidence of SUSY is done by establishing an excess of events in some region of phase space
  - Crucial to understand the contribution from SM processes

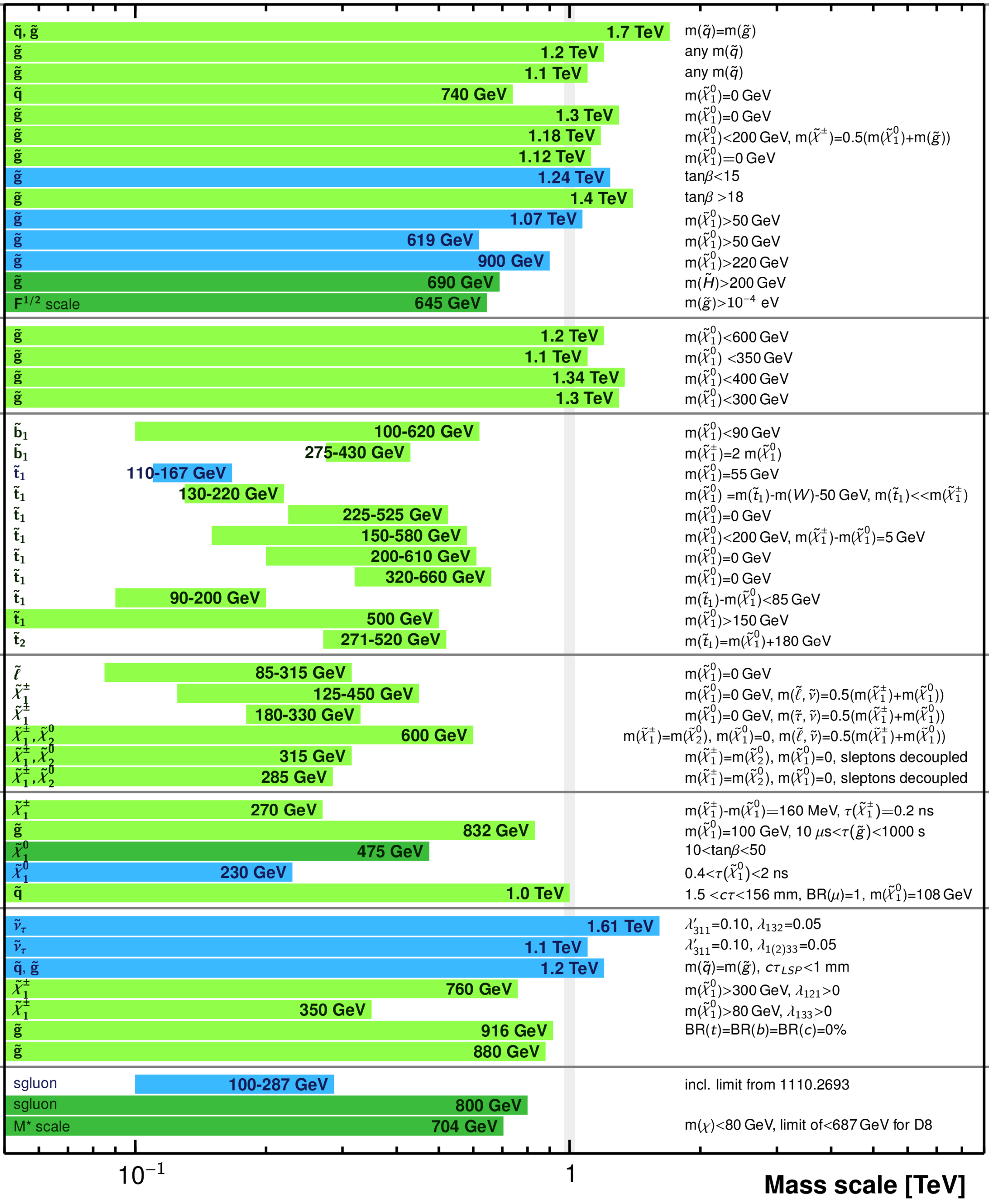
Slide from: T. Kono (ATLAS), BW2011 workshop

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

$\int \mathcal{L}\, dt$ = (4.6 - 22.9) fb^{-1} $\sqrt{s}$ = 7, 8 TeV



	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any $m(\tilde{q})$	1308.1841
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 740 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^{\pm})$=0.5($m(\tilde{\chi}_1^0)$+$m(\tilde{g})$)	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e, μ	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	tanβ<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	tanβ >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	4.8	$\tilde{g}$ 1.07 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	1209.0753
	GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	$m(\tilde{H})$>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	$m(\tilde{g})$>10^{-4} eV	ATLAS-CONF-2012-147
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.2 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	ATLAS-CONF-2013-061
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$ 275-430 GeV	$m(\tilde{\chi}_1^{\pm})$=2 $m(\tilde{\chi}_1^0)$	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-220 GeV	$m(\tilde{\chi}_1^0)$ =$m(\tilde{t}_1)$-$m(W)$-50 GeV, $m(\tilde{t}_1)$<<$m(\tilde{\chi}_1^{\pm})$	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e, μ	2 jets	Yes	20.3	$\tilde{t}_1$ 225-525 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-065
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20.7	$\tilde{t}_1$ 200-610 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$ 320-660 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-200 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$ 500 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$ 271-520 GeV	$m(\tilde{t}_1)$=$m(\tilde{\chi}_1^0)$+180 GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$ 85-315 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 125-450 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell}, \tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.7	$\tilde{\chi}_1^{\pm}$ 180-330 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau}, \tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 600 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell}, \tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 315 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e, μ	2 b	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 285 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-093
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 270 GeV	$m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$ 475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_{\tau} + X$, $\tilde{\nu}_{\tau}\to e + \mu$	2 e, μ	-	-	4.6	$\tilde{\nu}_{\tau}$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_{\tau} + X$, $\tilde{\nu}_{\tau}\to e(\mu) + \tau$	1 $e, \mu + \tau$	-	-	4.6	$\tilde{\nu}_{\tau}$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e, μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$ 1.2 TeV	$m(\tilde{q})$=$m(\tilde{g})$, $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_{\mu}$, $e\mu\tilde{\nu}_e$	4 e, μ	-	Yes	20.7	$\tilde{\chi}_1^{\pm}$ 760 GeV	$m(\tilde{\chi}_1^0)$>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e$, $e\tau\tilde{\nu}_{\tau}$	3 $e, \mu + \tau$	-	Yes	20.7	$\tilde{\chi}_1^{\pm}$ 350 GeV	$m(\tilde{\chi}_1^0)$>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t$, $\tilde{t}_1\to bs$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$ 880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e, μ (SS)	1 b	Yes	14.3	sgluon 800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

$\sqrt{s}$ = 7 TeV full data

$\sqrt{s}$ = 8 TeV partial data

$\sqrt{s}$ = 8 TeV full data

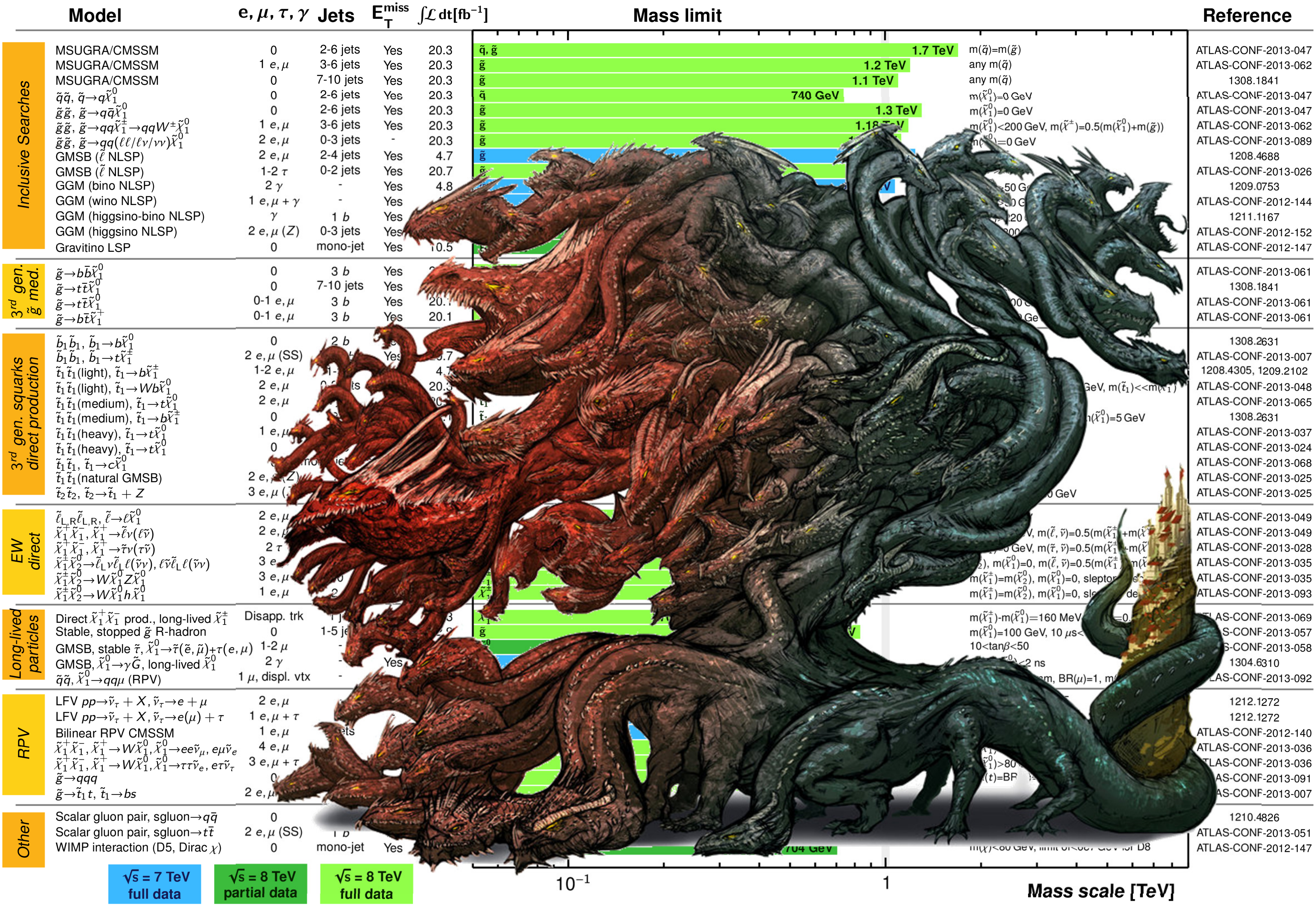
**Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.*

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

$\int\mathcal{L}\,dt$ = (4.6 - 22.9) fb^{-1} $\sqrt{s}$ = 7, 8 TeV



	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}$, $\tilde{g}$ 1.7 TeV	m($\tilde{q}$)=m($\tilde{g}$)	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any m($\tilde{q}$)	1308.1841
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 740 GeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^\pm_1\to qqW^\pm\tilde{\chi}^0_1$	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	m($\tilde{\chi}^0_1$)<200 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}^0_1$)+m($\tilde{g}$))	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}^0_1$	2 e, μ	0-3 jets	-	20.3	$\tilde{g}$	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$		1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$		ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	4.8			1209.0753
	GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes				ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes				1211.1167
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes				ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5			ATLAS-CONF-2012-147
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}^0_1$	0	3 b	Yes				ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0	7-10 jets	Yes				1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e, μ	3 b	Yes	20.1			ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}^+_1$	0-1 e, μ	3 b	Yes	20.1			ATLAS-CONF-2013-061
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_1$	0	2 b					1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}^\pm_1$	2 e, μ (SS)		Yes				ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	1-2 e, μ			4.7			1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}^0_1$	2 e, μ			20.3		m($\tilde{t}_1$)<<m($\tilde{\chi}_1$)	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}^0_1$	2 e, μ				$\tilde{t}_1$		ATLAS-CONF-2013-065
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	0				$\tilde{t}_1$	($\tilde{\chi}^0_1$)=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}^0_1$	1 e, μ						ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}^0_1$	0						ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$							ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,						ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + Z$	3 e, μ					0 GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e, μ						ATLAS-CONF-2013-049
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,					V, m($\tilde{\ell}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}$	ATLAS-CONF-2013-049
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ					GeV, m($\tilde{\tau}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}$	ATLAS-CONF-2013-028
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e					), m($\tilde{\chi}^0_1$)=0, m($\tilde{\ell}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}$	ATLAS-CONF-2013-035
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1 Z\tilde{\chi}^0_1$	3 e, μ					m($\tilde{\chi}^\pm_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, slepton	ATLAS-CONF-2013-035
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1 h\tilde{\chi}^0_1$	1 e, μ	2			$\tilde{\chi}^\pm_1$	m($\tilde{\chi}^\pm_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, sl	ATLAS-CONF-2013-093
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 j			$\tilde{\chi}^\pm_1$	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=160 MeV	AS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 je			$\tilde{g}$	m($\tilde{\chi}^0_1$)=100 GeV, 10 μs<	S-CONF-2013-057
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}^0_1\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-				10<tanβ<50	S-CONF-2013-058
	GMSB, $\tilde{\chi}^0_1\to\gamma\tilde{G}$, long-lived $\tilde{\chi}^0_1$	2 γ	-	Yes			<2 ns	1304.6310
	$\tilde{q}\tilde{q}$, $\tilde{\chi}^0_1\to qq\mu$ (RPV)	1 μ, displ. vtx	-				BR(μ)=1	AS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau + X$, $\tilde{\nu}_\tau\to e + \mu$	2 e, μ						1212.1272
	LFV $pp\to\tilde{\nu}_\tau + X$, $\tilde{\nu}_\tau\to e(\mu) + \tau$	1 $e, \mu + \tau$						1212.1272
	Bilinear RPV CMSSM	1 e, μ	ets					ATLAS-CONF-2012-140
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to ee\tilde{\nu}_\mu$, $e\mu\tilde{\nu}_e$	4 e, μ						ATLAS-CONF-2013-036
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to\tau\tau\tilde{\nu}_e$, $e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$					($\tilde{\chi}^0_1$)>80	TLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0					(t)=BR	AS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t$, $\tilde{t}_1\to bs$	2 e, μ						AS-CONF-2013-007
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0						1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e, μ (SS)	1 b					ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes		704 GeV	m(χ)<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

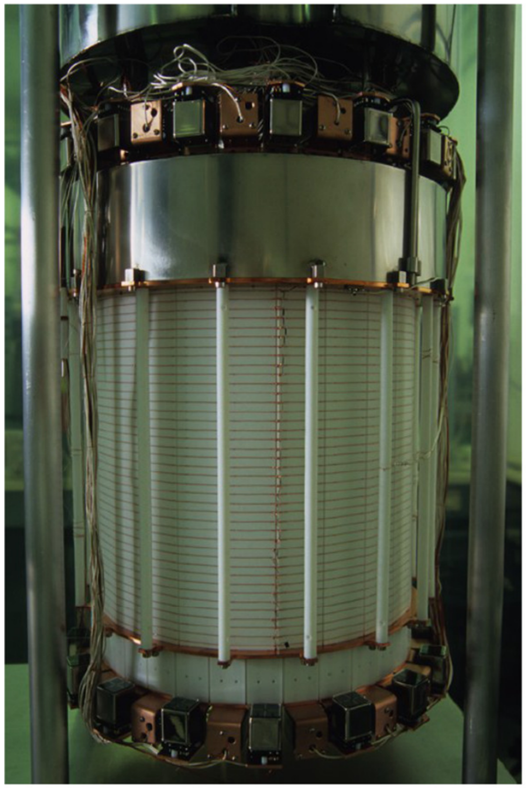
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

How to search for dark matter particles

- Indirect detection

Search for things
dark matter can decay to
$\chi\chi \rightarrow e^+e^-, p\bar{p}$

- Direct detection



Build a trap for dark matter

$\chi \mathrm{N} \rightarrow \chi \mathrm{N}$

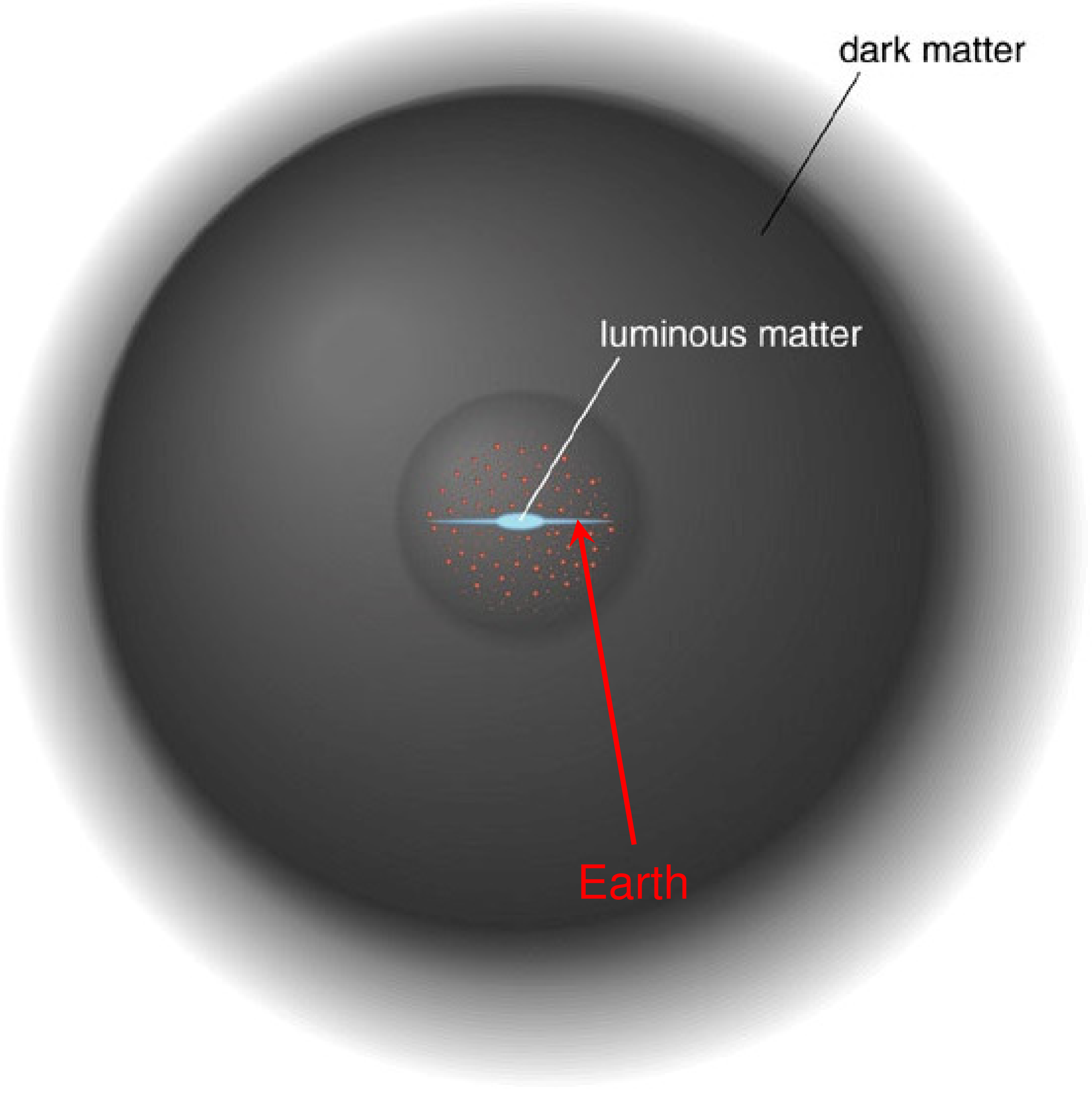
- Production at LHC

Make dark matter particles

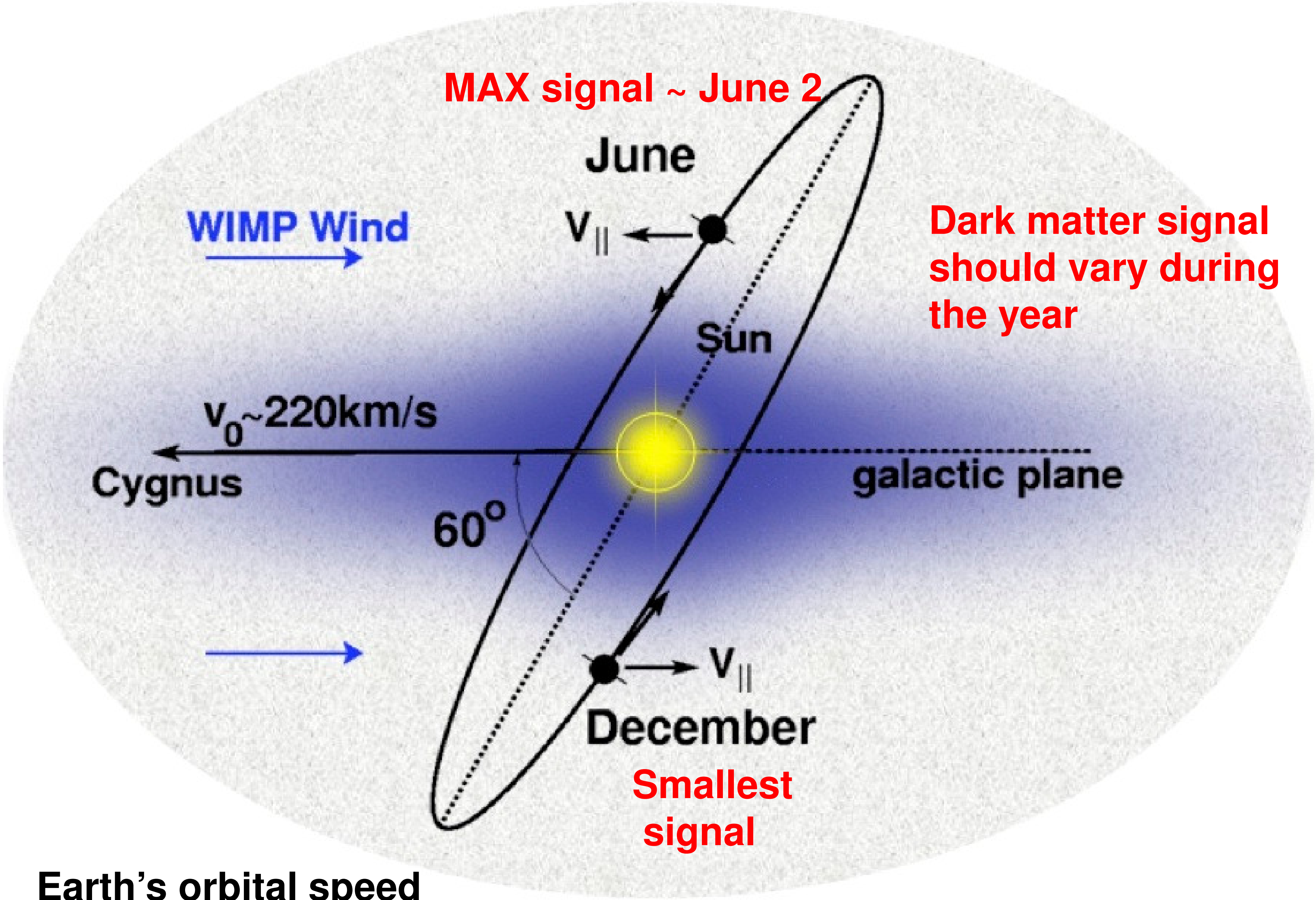
$\mathrm{p} + \mathrm{p} \rightarrow \chi$ + a lot

http://www.ippp.dur.ac.uk/~ross/invisibles13/talks/78-marrod_xe1n_undagoita/slides/78-0-Marrodan_Invis_Durham2013.pdf

There should be dark matter on Earth for us to detect



Earth is moving through dark matter halo (dark matter not moving)



MAX signal ~ June 2

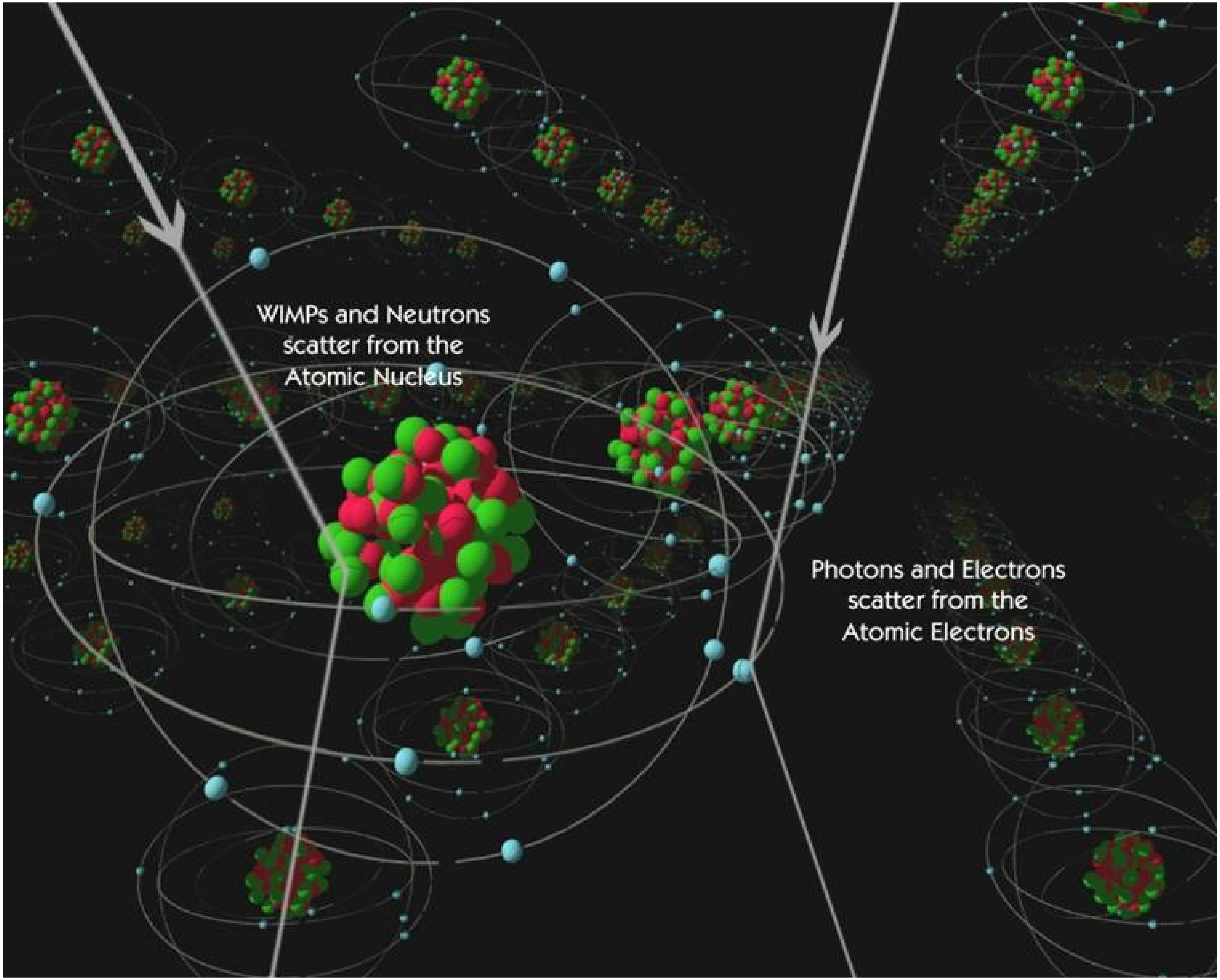
Dark matter signal should vary during the year

Smallest signal

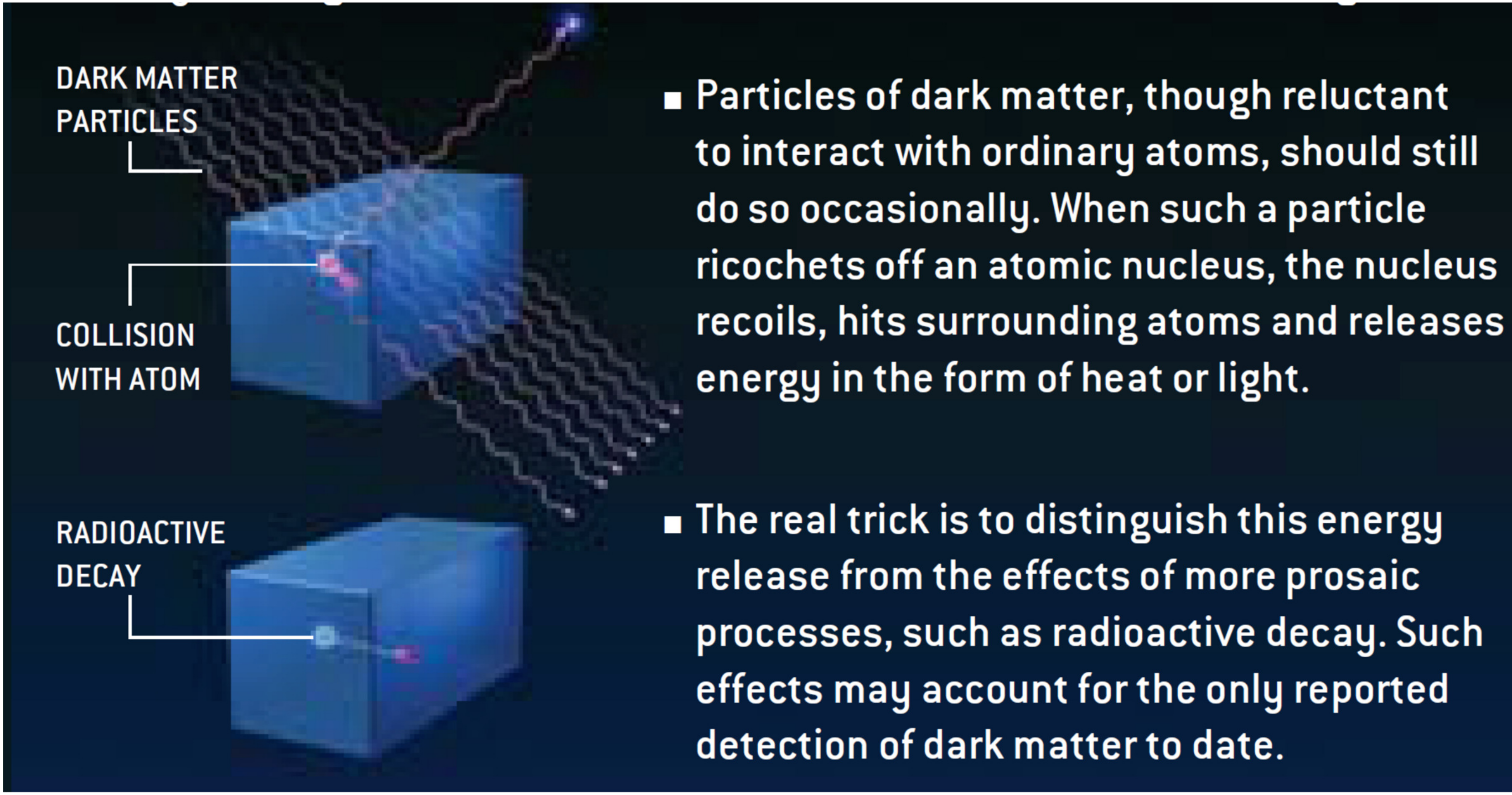
Earth's orbital speed around the Sun is 30 km/s

http://www.hep.ucl.ac.uk/darkMatter/

Direct detection: How to detects WIMPs?



http://cdms.berkeley.edu/Education/DMpages/essays/essays/essays/science/images/NucRecoilAtoms.jpg



- Particles of dark matter, though reluctant to interact with ordinary atoms, should still do so occasionally. When such a particle ricochets off an atomic nucleus, the nucleus recoils, hits surrounding atoms and releases energy in the form of heat or light.
- The real trick is to distinguish this energy release from the effects of more prosaic processes, such as radioactive decay. Such effects may account for the only reported detection of dark matter to date.

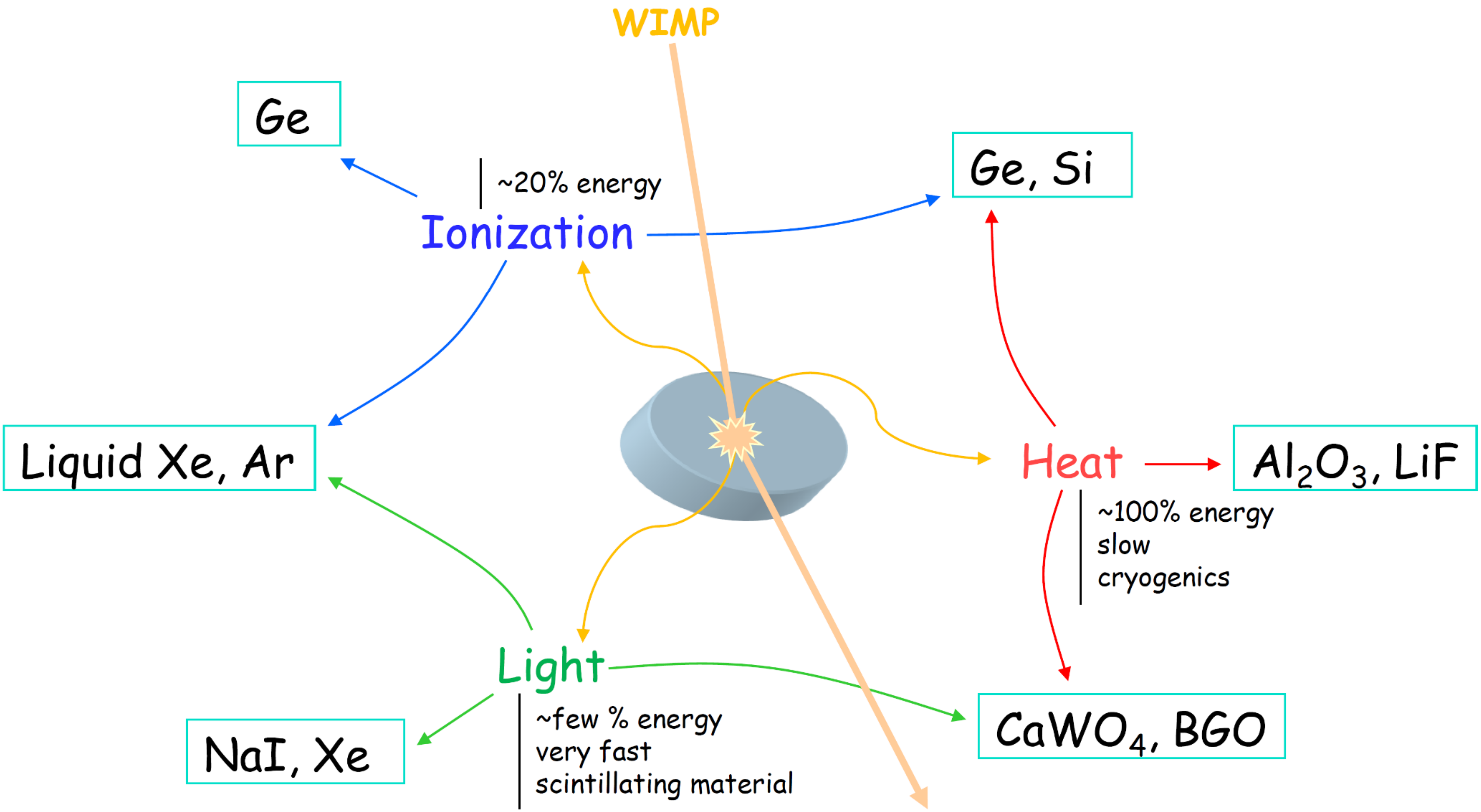
Detection principle:

Measure the recoil energy imparted to detector nuclei through WIMP-nucleon collisions.

Scientific American **288**, 50-59 (March 2003)

Direct detection possibilities

Selection of detection material



WIMP

Ge

~20% energy

Ionization

Ge, Si

Liquid Xe, Ar

Heat

Al_2O_3, LiF

~100% energy
slow
cryogenics

Light

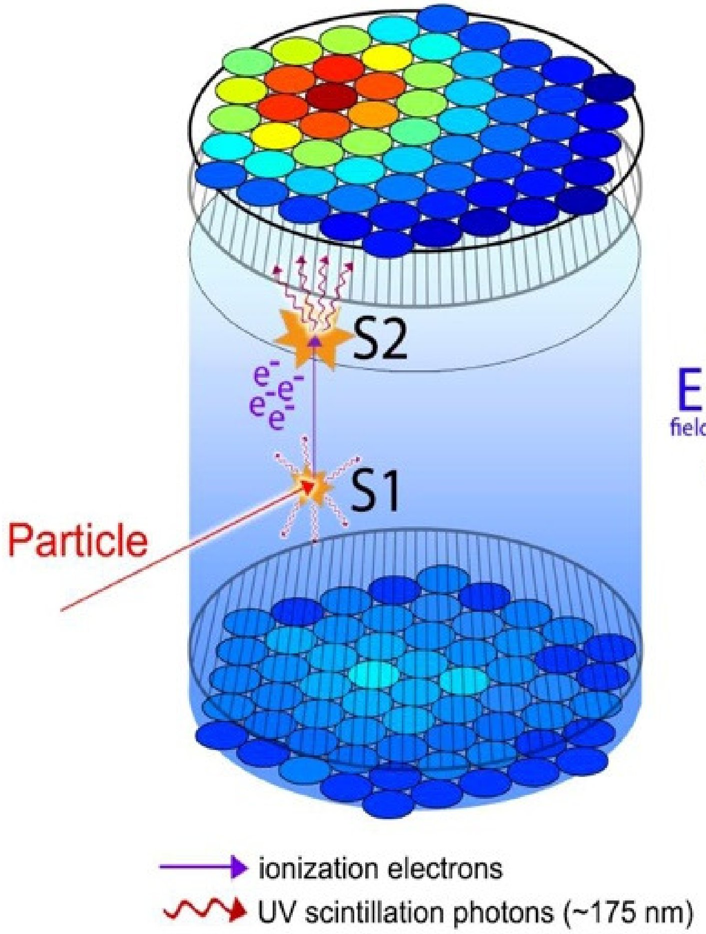
~few % energy
very fast
scintillating material

NaI, Xe

$CaWO_4$, BGO

http://luxdarkmatter.org/talks/20120919_Dark_Matter_LUX_Outreach_Fiorucci.pdf

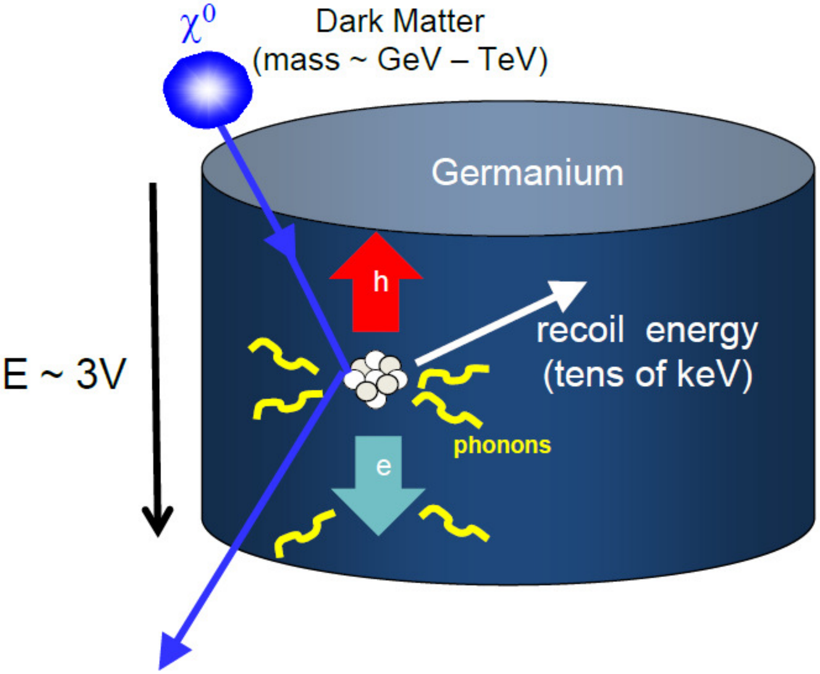
Scintillation detectors



Principle: Looks for slight pulses of light triggered by dark matter passing through, liquid xenon or argon

LUX: http://www.hep.ucl.ac.uk/darkMatter/

Cryogenic detectors



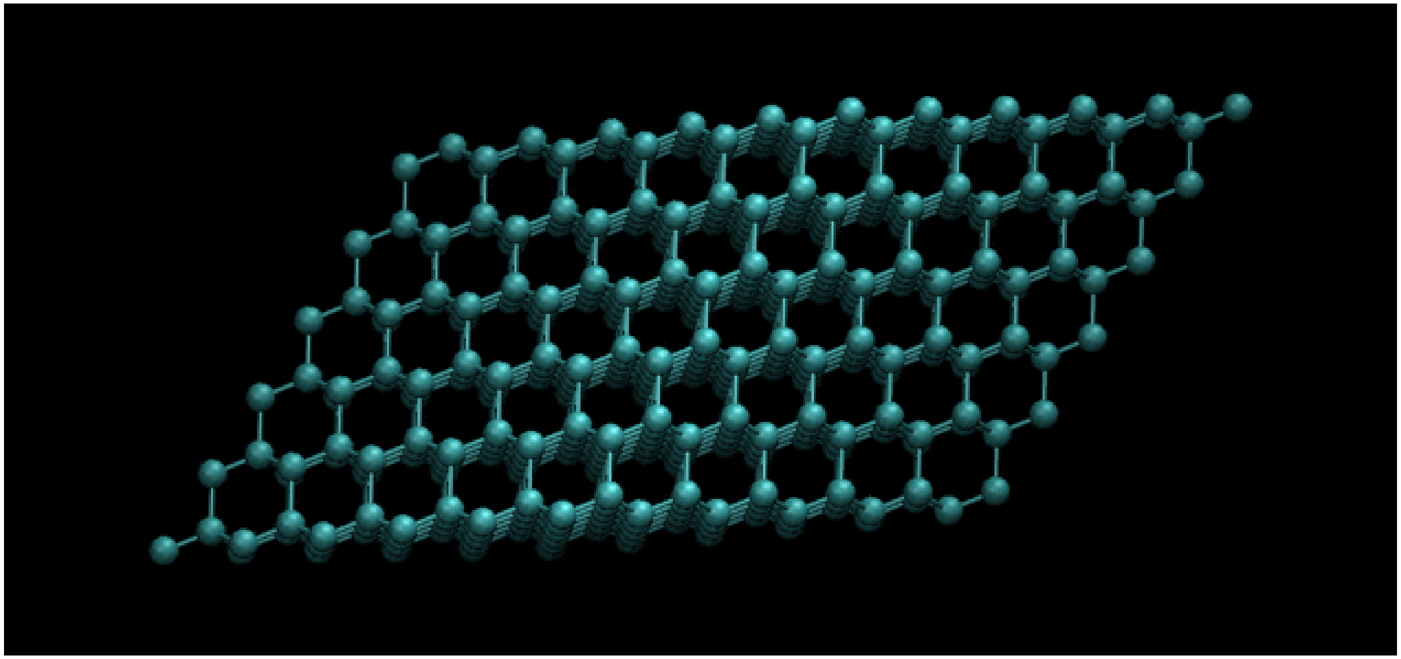
Principle: Looks for slight pulses of heat generated by dark matter passing through a supercooled crystal.

CDMS: https://www.slac.stanford.edu/exp/cdms/

To understand how heat spreads through a material, consider that heat — as well as sound — is actually the motion or vibration of atoms and molecules.

Low-frequency vibrations correspond to sound, while higher frequencies correspond to heat. At each frequency, quantum mechanics principles dictate that the vibrational energy must be a multiple of a basic amount of energy, called a quantum, that is proportional to the frequency.

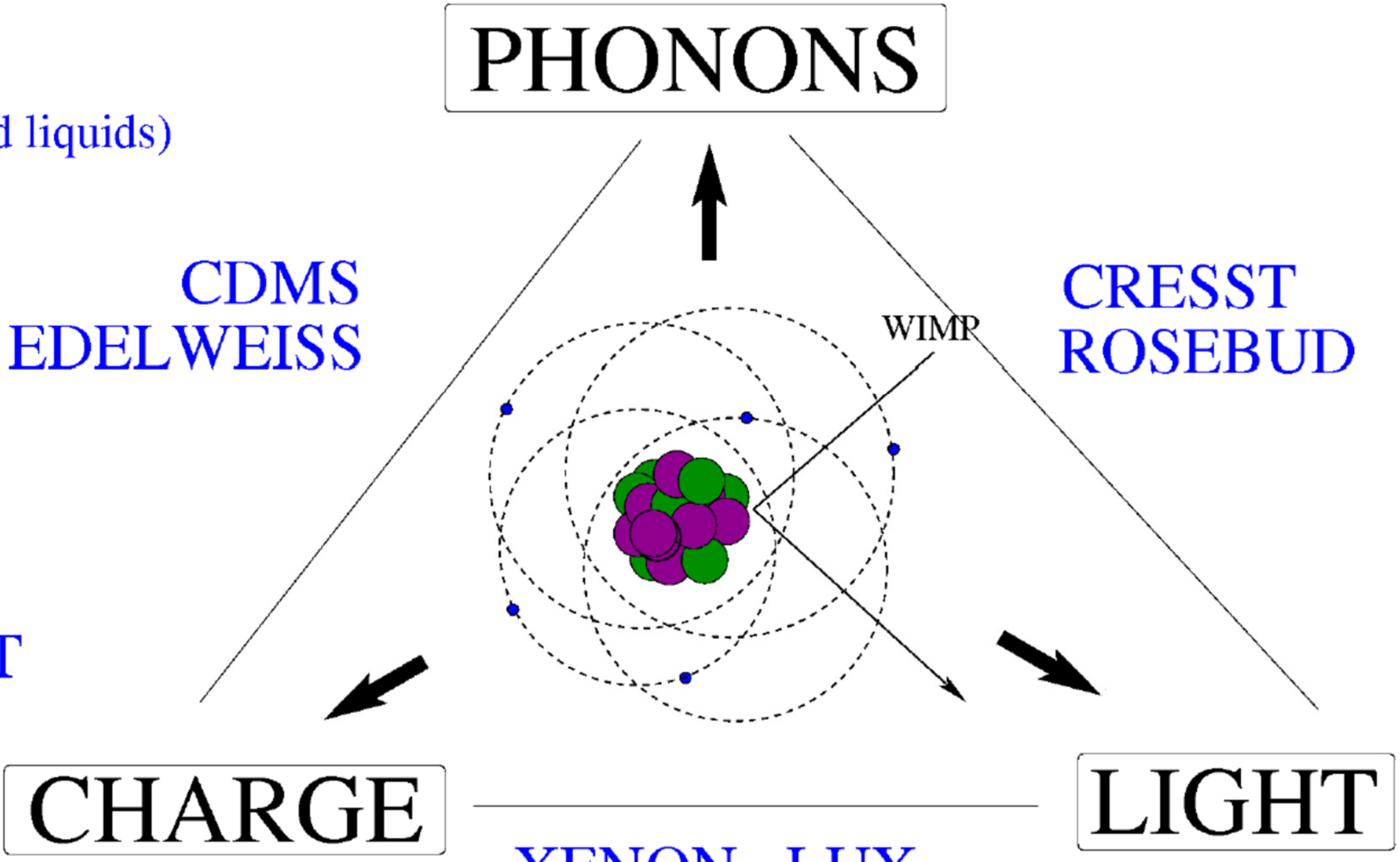
A **phonon** is a definite discrete unit or quantum of vibrational mechanical energy, just as a photon is a quantum of electromagnetic or light energy.



http://news.mit.edu/2010/explained-phonons-0706

http://exciting-code.org/boron-animate-phonons

Direct detection experiments



CRESST I
CUORE

PHONONS

PICASSO
COUPP
SIMPLE
(Superheated liquids)

CDMS
EDELWEISS

CRESST
ROSEBUD

CoGeNT
CDEX
Texono

CHARGE

LIGHT

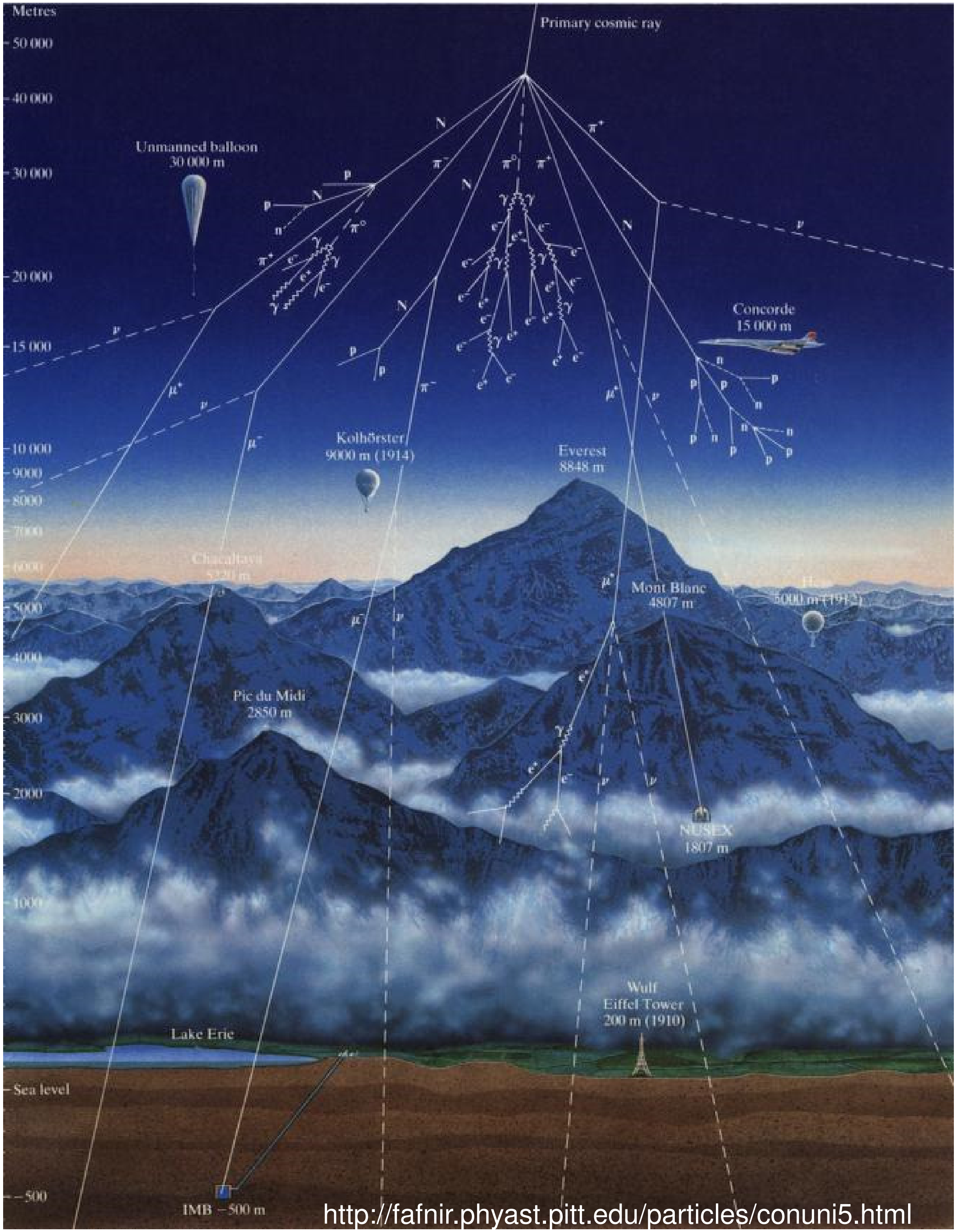
DAMA
KIMS
DM–Ice

DRIFT DMTPC
MIMAC NEWAGE
(Directional)

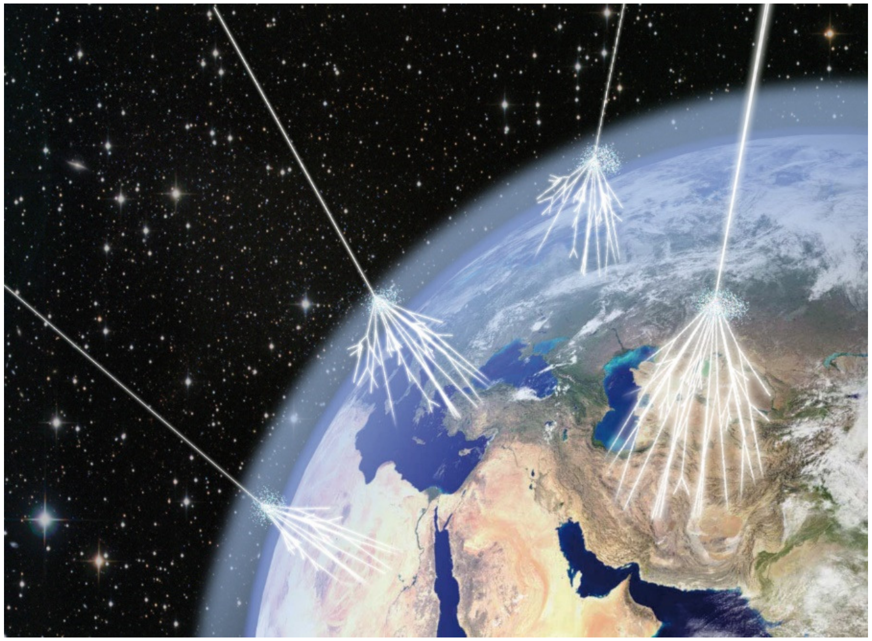
XENON LUX
ZEPLIN PandaX
DarkSide ArDM

XMASS
DEAP/CLEAN

Slide from: Teresa Marrodan Undagoitia Invisibles Workshop, Durham, 2013

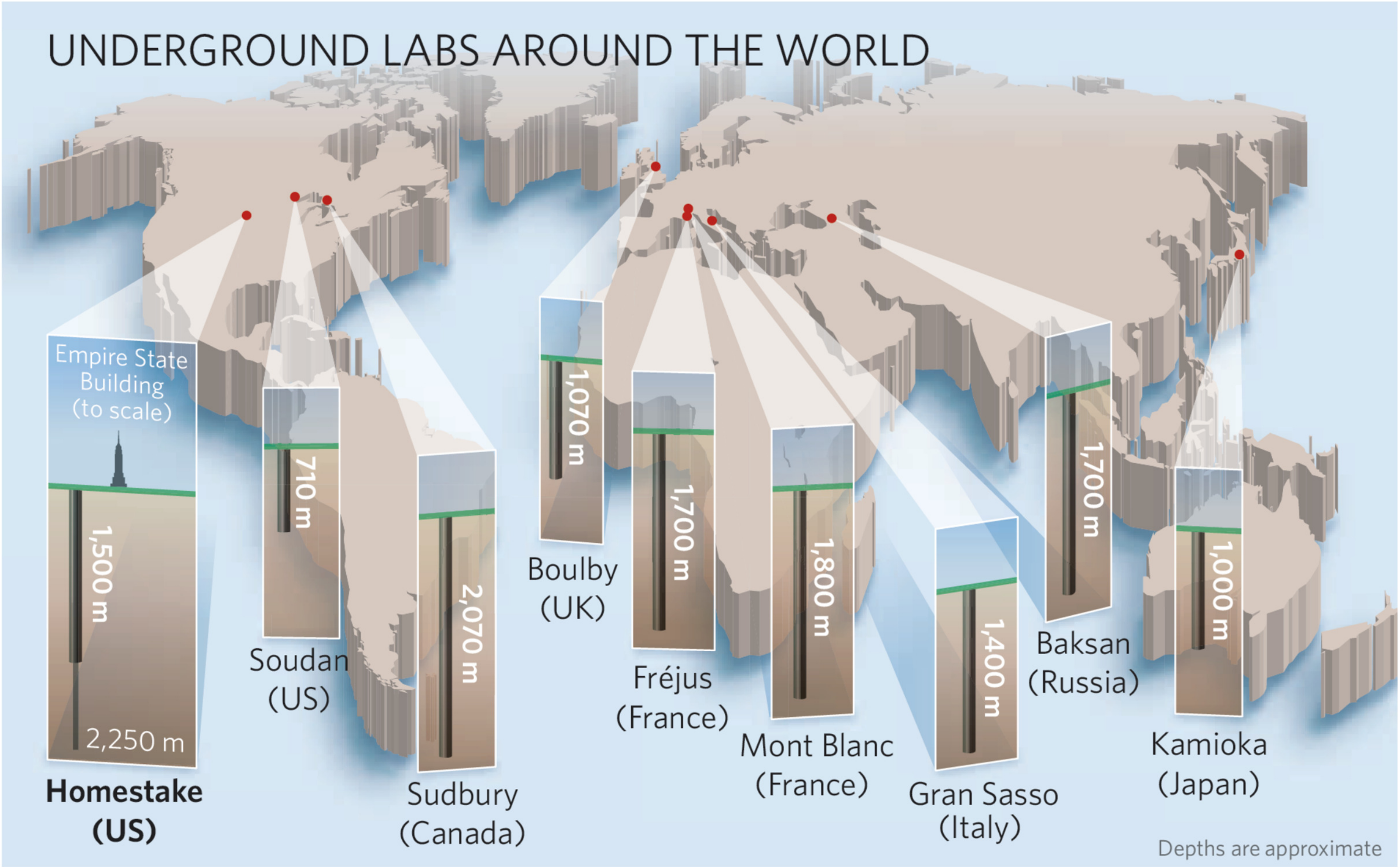


http://fafnir.phyast.pitt.edu/particles/conuni5.html



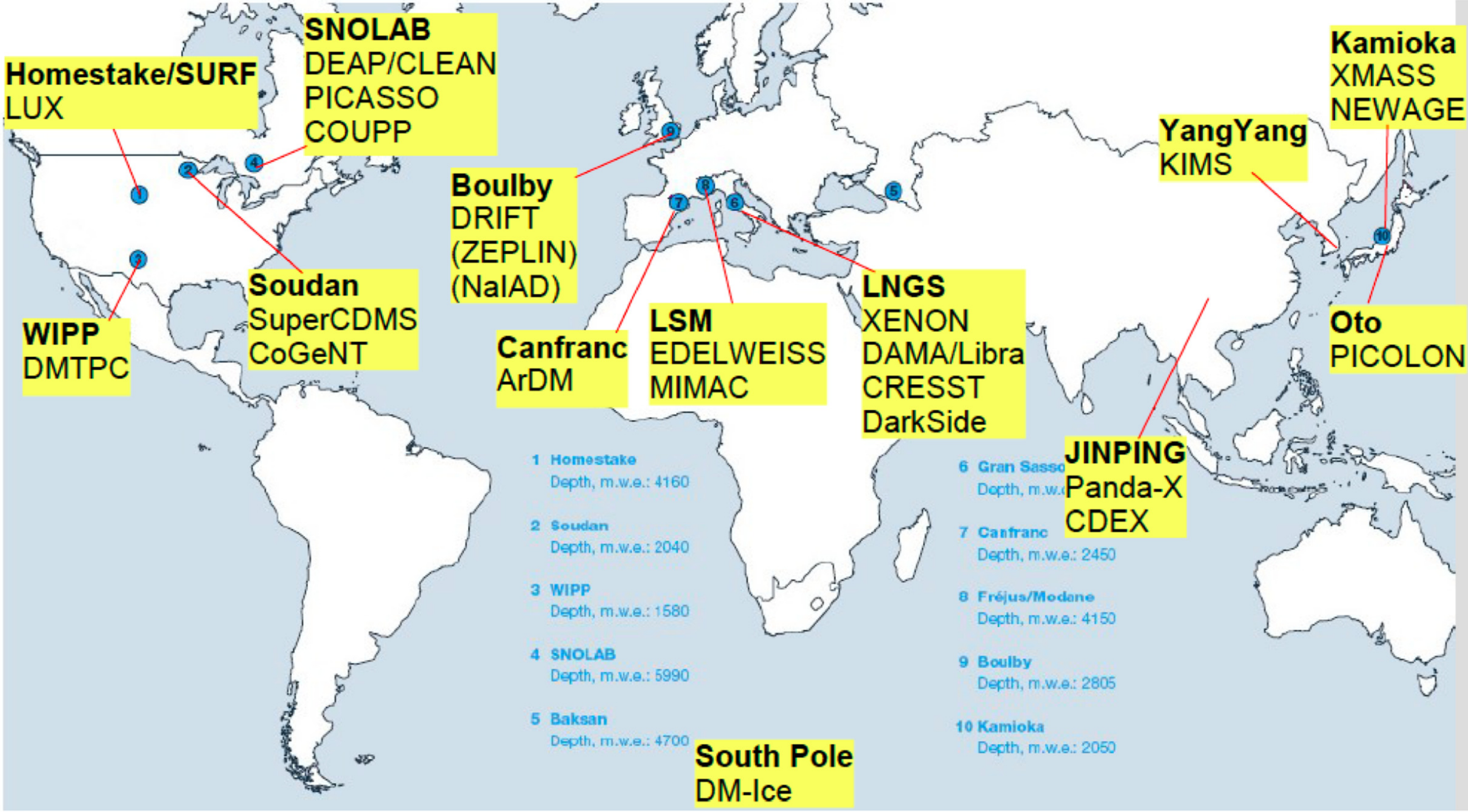
Need to shield dark matter detector from cosmic rays:

Go really deep underground.



http://www.nature.com.udel.idm.oclc.org/nature/journal/v448/n7151/full/448232a.html

Underground laboratories



Homestake/SURF
LUX

SNOLAB
DEAP/CLEAN
PICASSO
COUPP

Boulby
DRIFT
(ZEPLIN)
(NaIAD)

Soudan
SuperCDMS
CoGeNT

WIPP
DMTPC

Canfranc
ArDM

LSM
EDELWEISS
MIMAC

LNGS
XENON
DAMA/Libra
CRESST
DarkSide

YangYang
KIMS

Kamioka
XMASS
NEWAGE

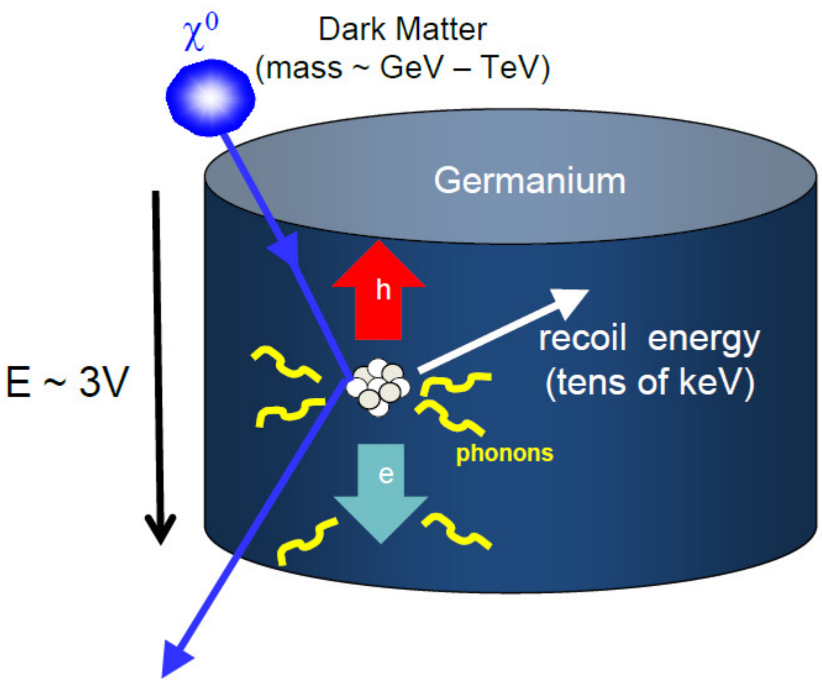
Oto
PICOLON

JINPING
Panda-X
CDEX

South Pole
DM-Ice

Slide from: Teresa Marrodan Undagoitia Invisibles Workshop, Durham, 2013

Cryogenic Dark Matter Search (CDMS)



The CDMS experiment has pioneered the use of cryogenic silicon and germanium detectors to perform sensitive searches for dark matter.

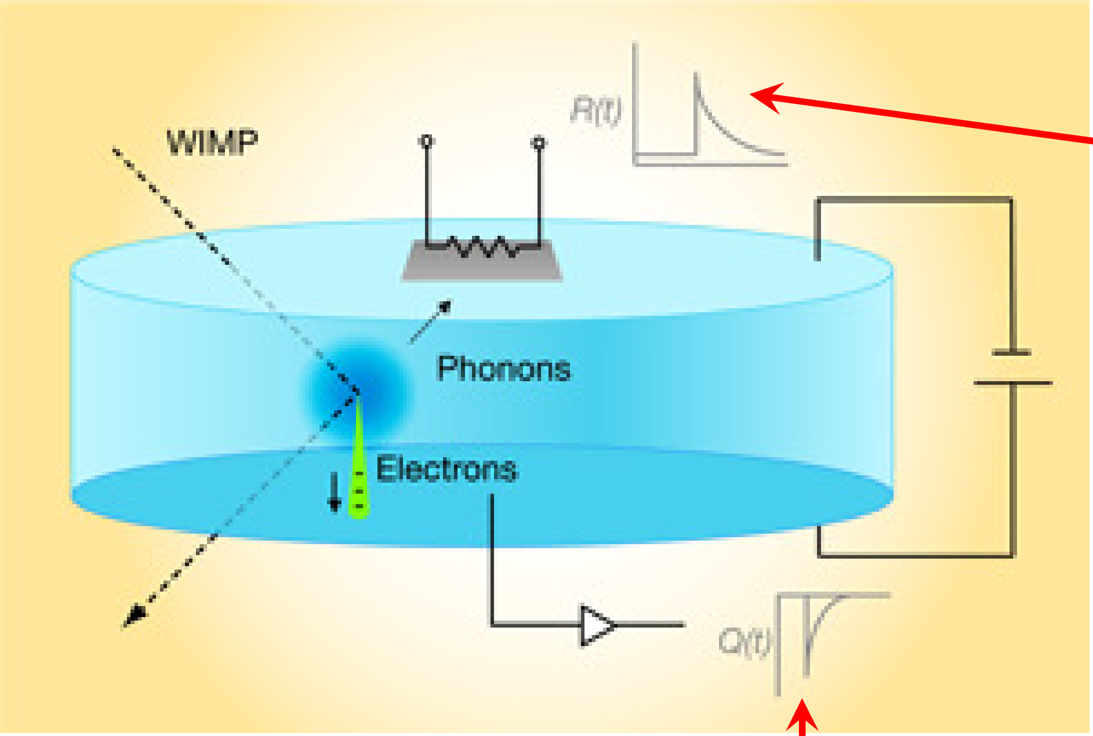
The recoiling nucleus from a dark matter interaction produces crystal lattice vibrations (phonons) and also electron-hole pairs (“e” and “h”).

The phonon and charge signals are captured by electrodes applied to the face of the crystal using photolithography.

These detectors provide unique capabilities for background rejection and offer unmatched sensitivity for the very small energy deposits associated with low-mass dark matter interactions.

https://www.slac.stanford.edu/exp/cdms/

Cryogenic Dark Matter Search (CDMS)



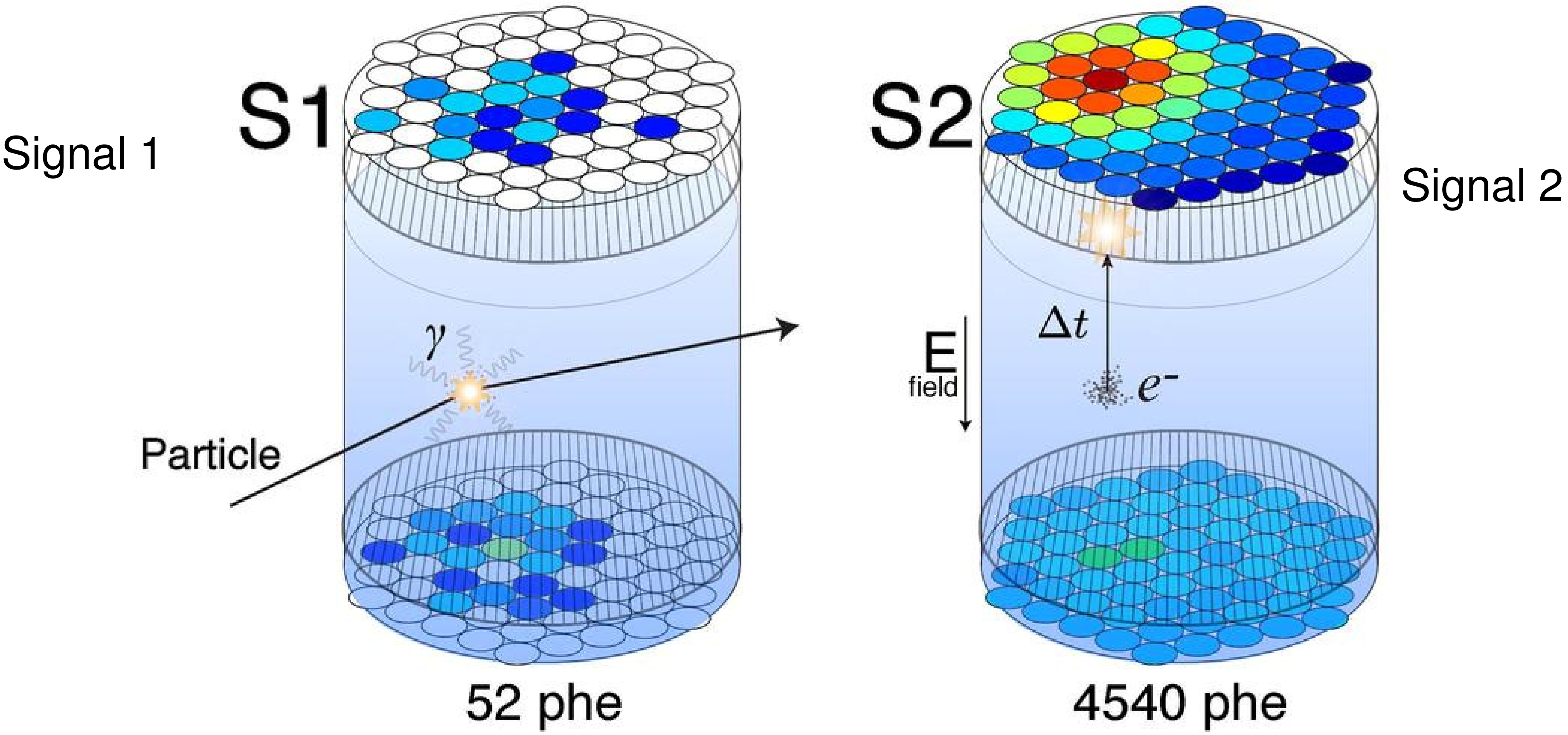
Phonons reaching one face of the detector face break Cooper pairs (weakly bound electron pairs) in a thin superconducting aluminum layer; the resulting quasiparticles heat a transition-edge sensor bonded to the aluminum layer, causing a measurable momentary change in its resistance R(t).

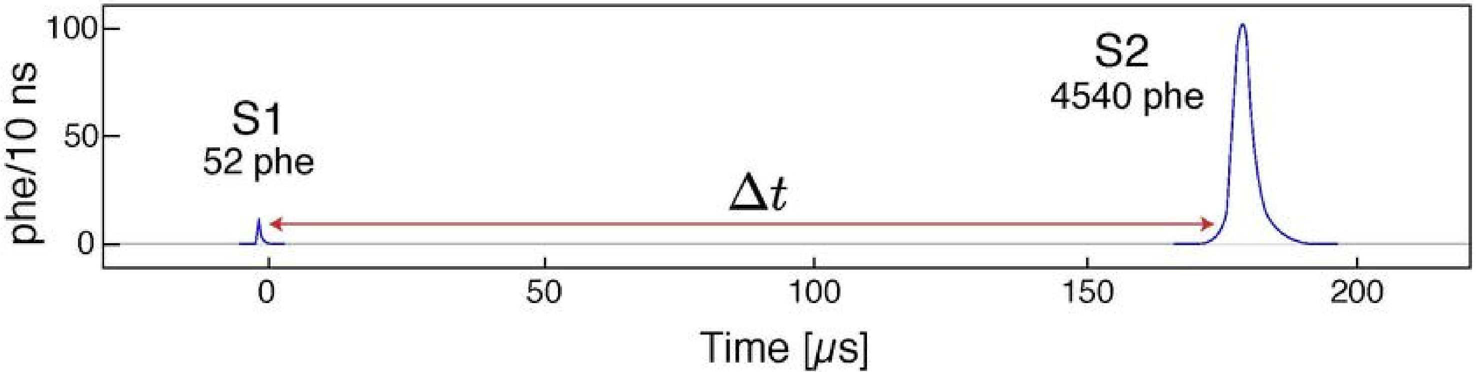
Charge carriers drift out to one face of the detector under the influence of a small electric field, and are detected with a sensitive amplifer [signal shown as Q(t)].

In reality, the readout elements on both sides are highly segmented, and the relative timing of the ionization and phonon signals recorded, to provide good event localization.

http://physics.aps.org/articles/v2/2

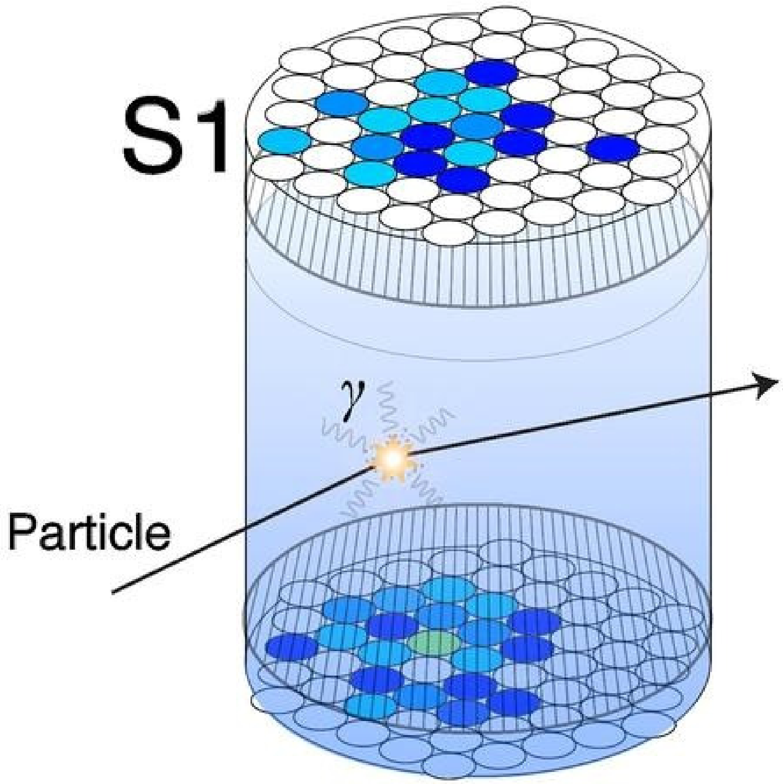
Scintillation detectors
The Large Underground Xenon (LUX) Experiment





https://en.wikipedia.org/wiki/File:LUXEvent.pdf

The Large Underground Xenon (LUX) Experiment

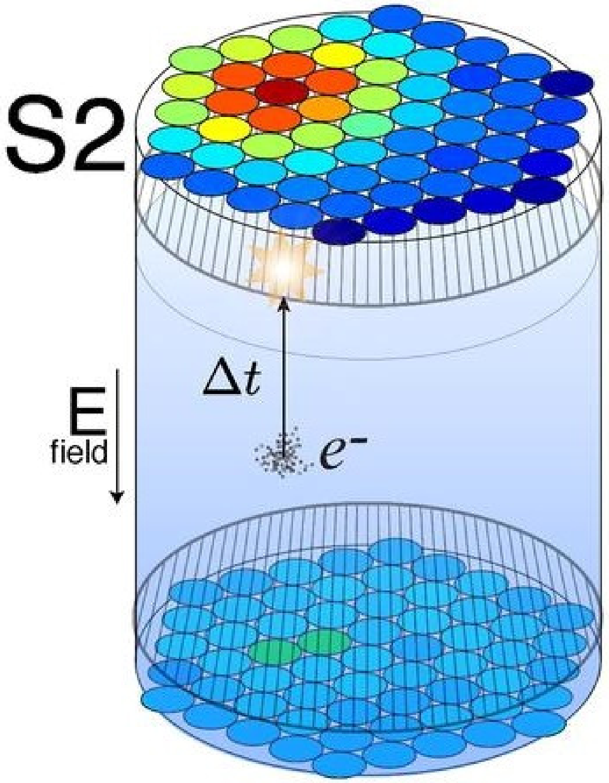


Particle interactions inside the LUX detector produce 175 nm ultraviolet photons and electrons.

The photons (γ), moving at the speed of light, are quickly detected by the photomultiplier tubes. This photon signal is called S1.

https://en.wikipedia.org/wiki/File:LUXEvent.pdf

The Large Underground Xenon (LUX) Experiment



An electric field in the liquid xenon drifts the electrons towards the liquid surface.

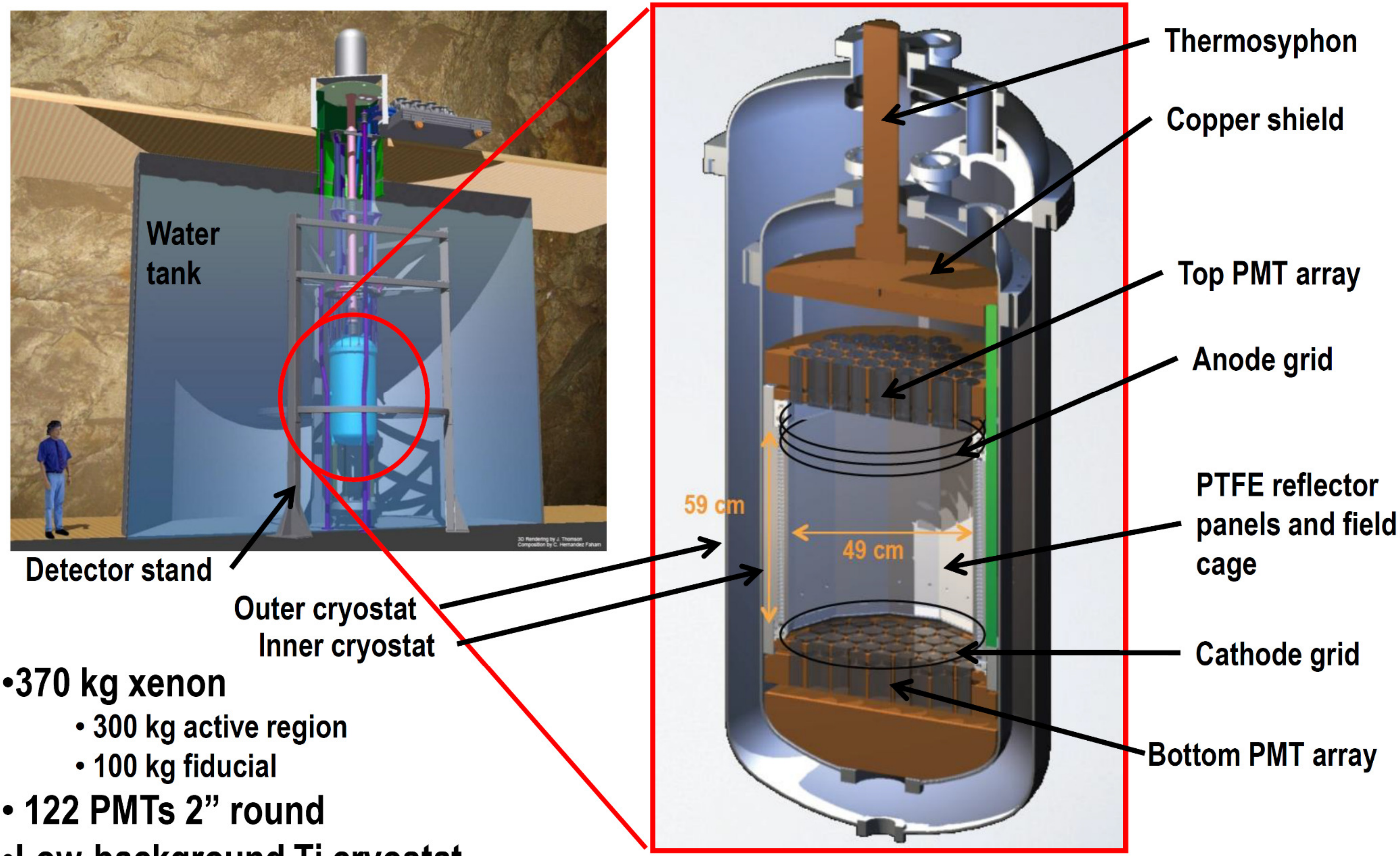
A much higher electric field above the liquid surface pulls the electrons out of the liquid and into the gas, where they produce electroluminescence photons (in the same way that neon sign produces light).

The electroluminescence photons are detected by the photomultiplier tubes as the S2 signal.

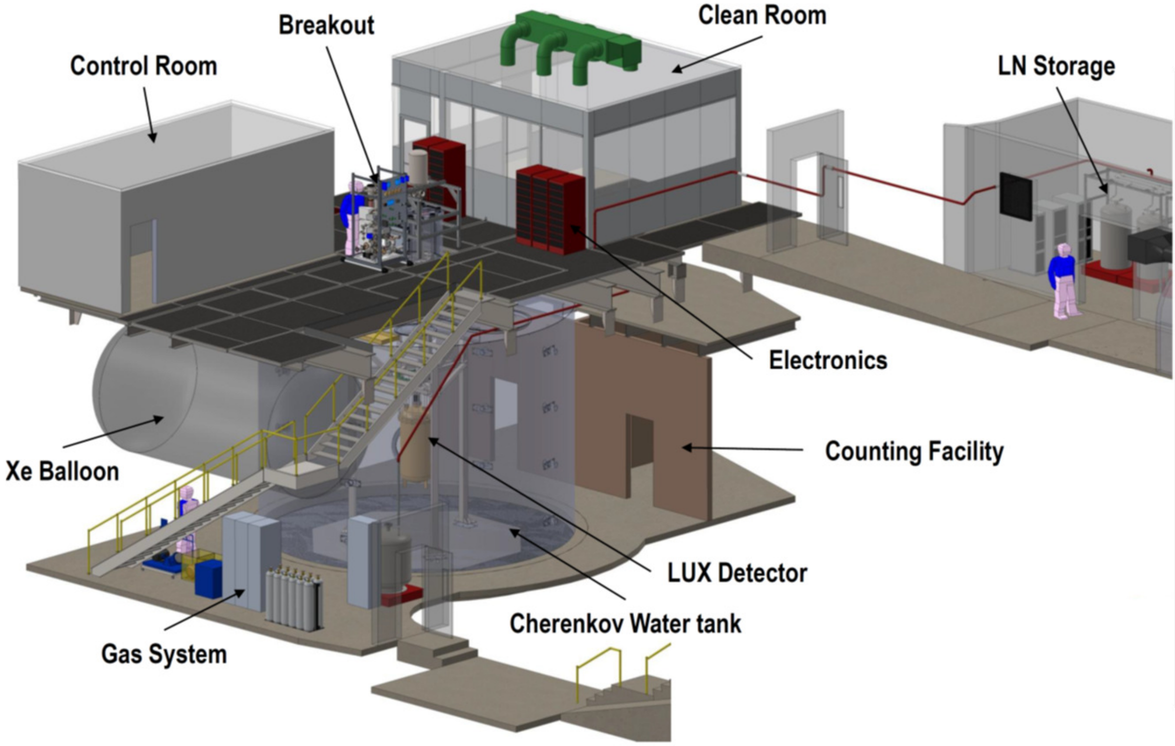
A single particle interaction in the liquid xenon can be identified by the pair of an S1 and an S2 signal. The detector is isolated from background particles by a surrounding water tank and above earth shielding that reduce cosmic rays and radiation interacting with the xenon.

https://en.wikipedia.org/wiki/File:LUXEvent.pdf

The LUX Experiment



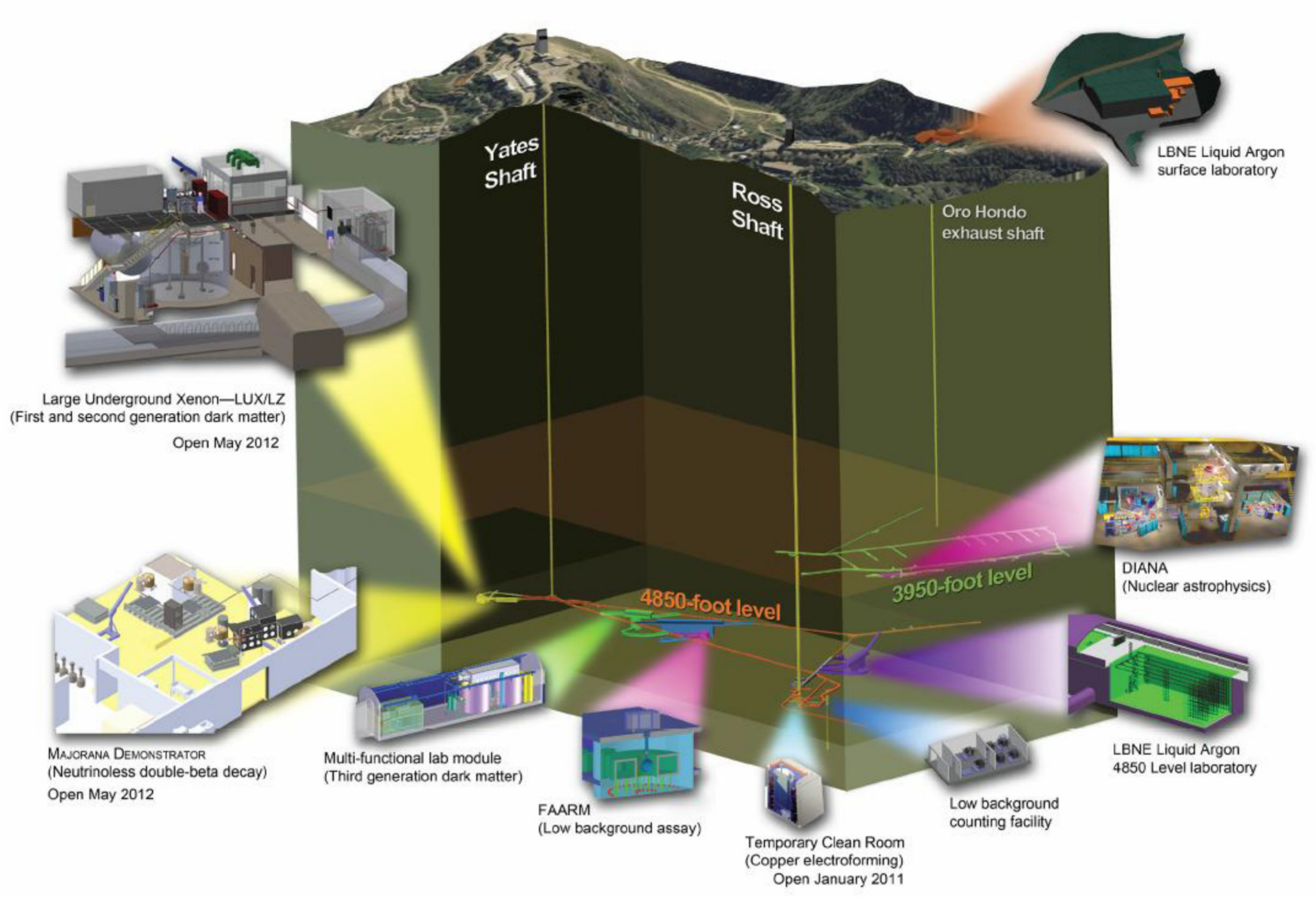
- 370 kg xenon
  - 300 kg active region
  - 100 kg fiducial
- 122 PMTs 2” round
- Low-background Ti cryostat



Access Tunnel to the Davis Underground Laboratory, Dec 2011

http://luxdarkmatter.org/talks/20120919_Dark_Matter_LUX_Outreach_Fiorucci.pdf

Future of Sanford Lab



Background sources

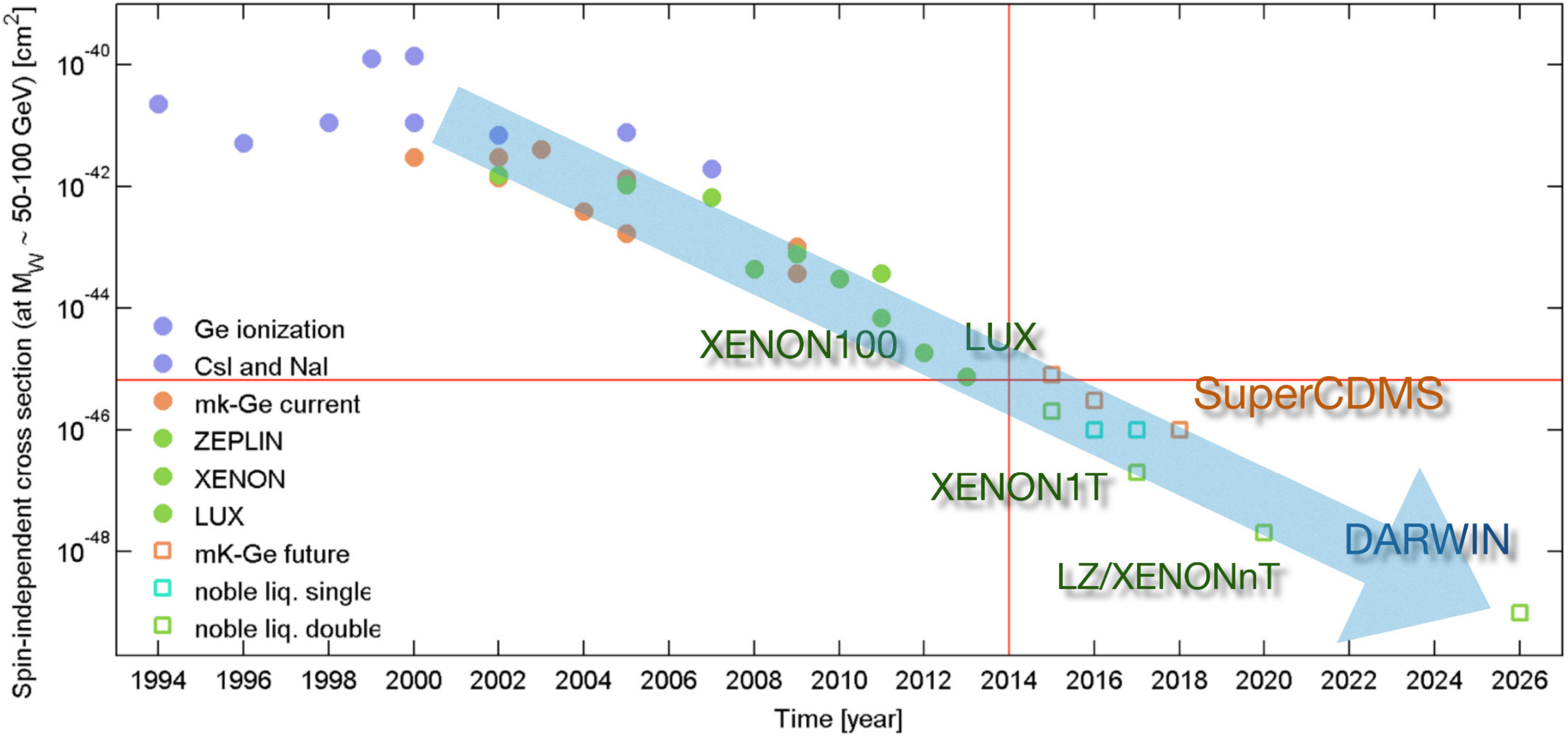
- Natural **U**, **Th** chains and ^{40}**K**
  - Electronic recoils: β's and γ's
  - α's: high energy but still BG in some experiments
- **Neutrons** → nuclear recoils
  - (α, n) reactions and spontaneous fission
  - From muon showers after a spallation process
- **Rn** and ^{85}**Kr**
  - Rn emanation from various detector materials
  - Kr from the air (^{85}Kr produced at nuclear power plants)

→ **Background suppression/removal** 1 part per quadrillion 10^{15} pure Xe!

- Material screening and selection
- Removal of Kr or Rn with dedicated devices
- Shielding (underground lab, detector shield, active veto)

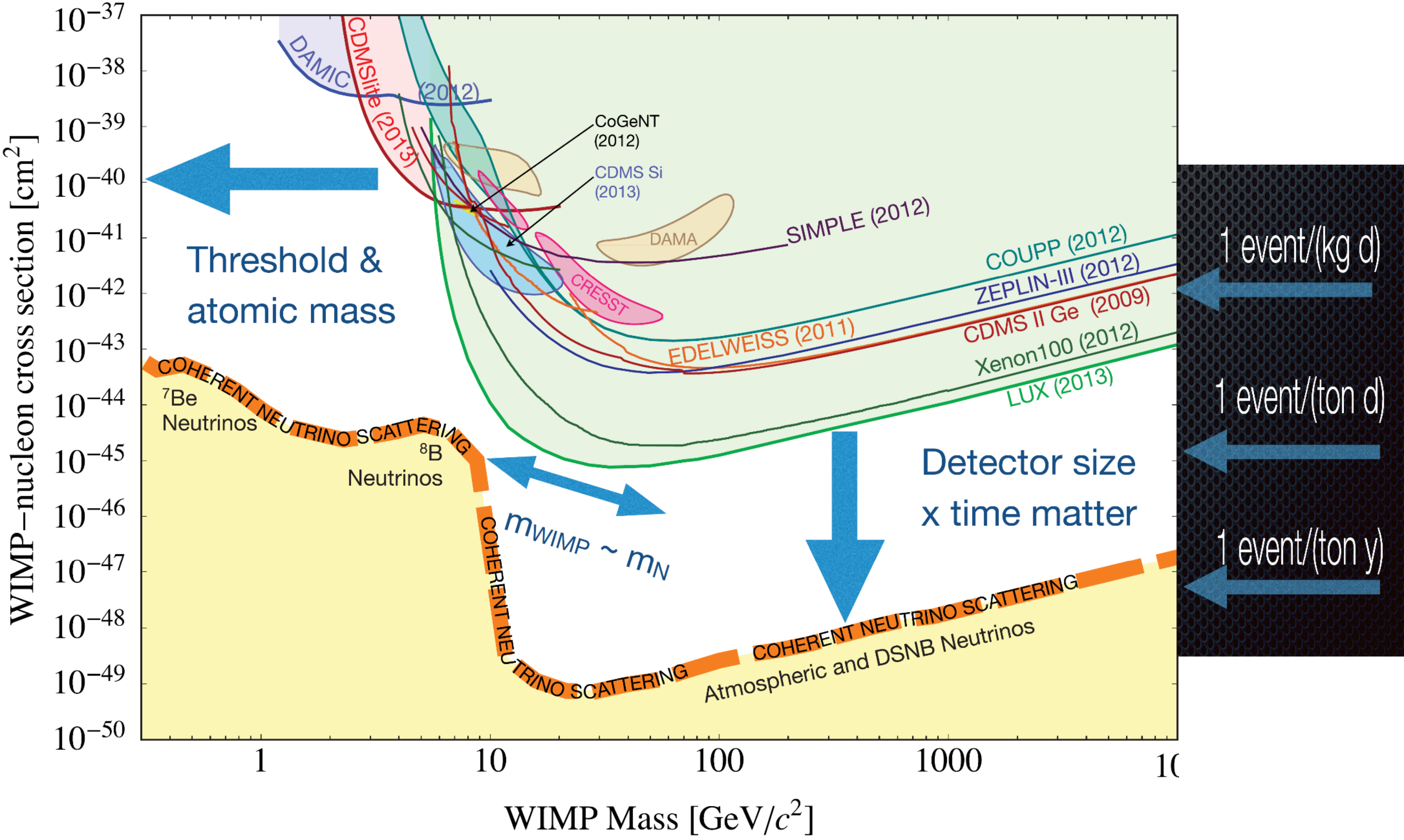
Slide from: Teresa Marrodan Undagoitia Invisibles Workshop, Durham, 2013

A history and future projections of direct detection limits



LB, Physics of the Dark Universe 4, 2014

How to improve WIMP direct detection experiments?



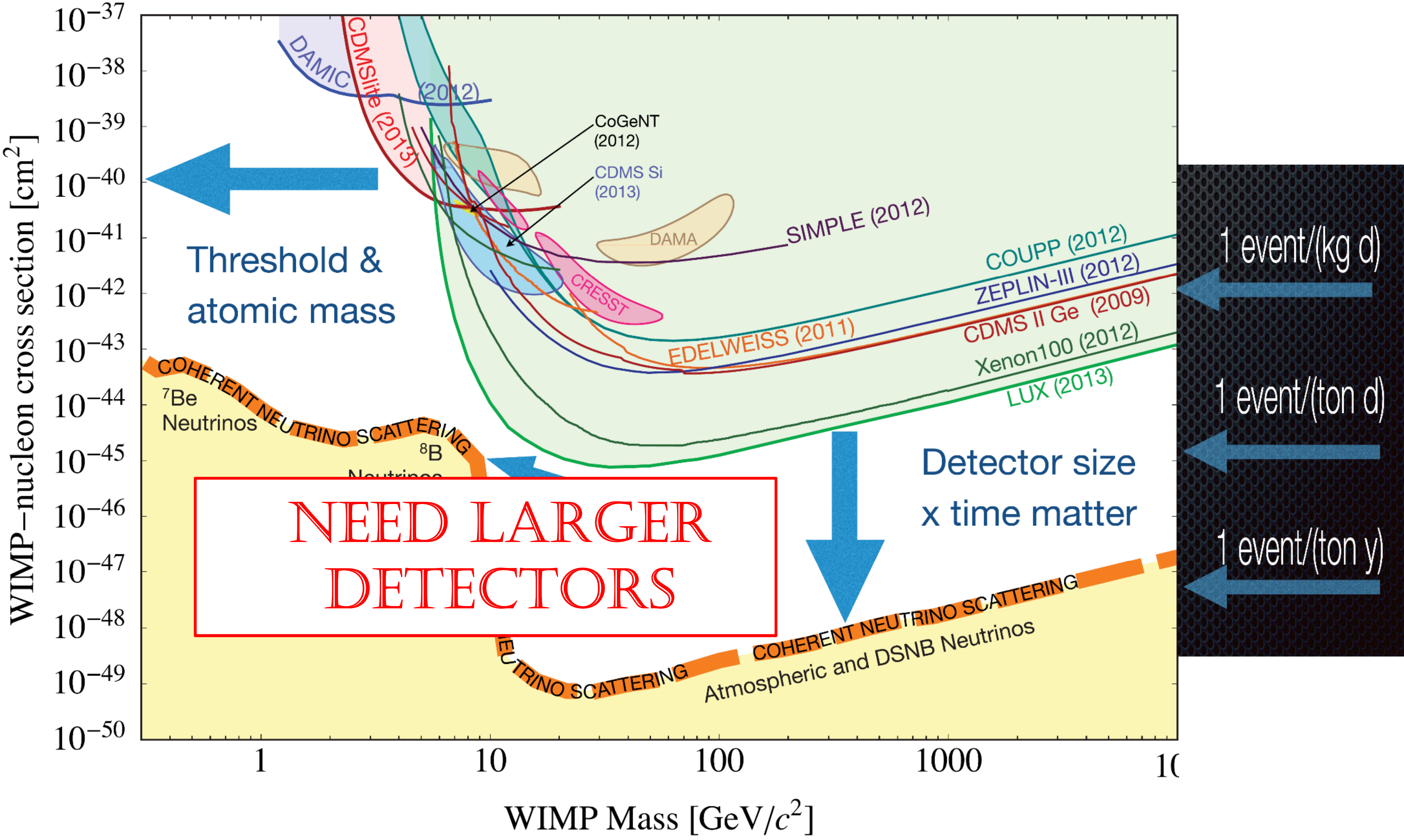
Threshold & atomic mass

$m_{WIMP} \sim m_N$

Detector size x time matter

https://indico.in2p3.fr/event/10162/session/5/contribution/10/material/slides/0.pdf

How to improve WIMP direct detection experiments?



Threshold & atomic mass

Detector size x time matter

1 event/(kg d)

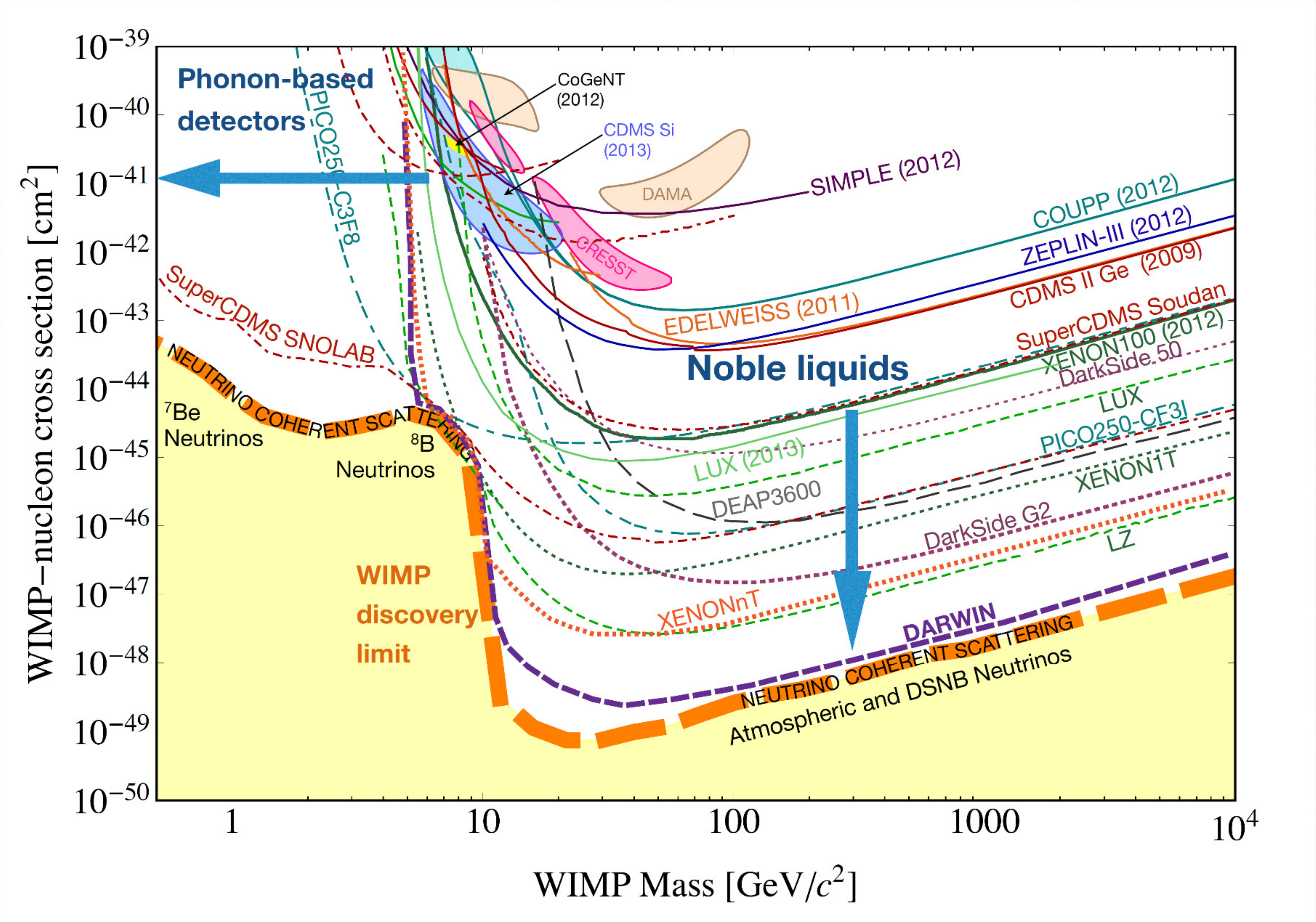
1 event/(ton d)

1 event/(ton y)

NEED LARGER DETECTORS

https://indico.in2p3.fr/event/10162/session/5/contribution/10/material/slides/0.pdf

The WIMP landscape: prospects



https://indico.in2p3.fr/event/10162/session/5/contribution/10/material/slides/0.pdf