

*Direct Detection and Collider
Searches of Dark Matter
Lecture 4*

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Content of Lecture 4

- Halo-dependent and halo-independent direct detection data analysis.
- The future of direct dark matter detection.
- Introduction to search strategies at the LHC

Subject is very vast, so idiosyncratic choice of subjects + citations disclaimer

*Halo-dependent and halo-independent
direct detection data analysis*

Halo-Independent direct DM detection data comparison

Event rate: events/(unit mass of detector)/(keV of recoil energy)/day

$$\frac{dR}{dE_R} = \sum_T \int \frac{C_T}{M_T} \times \frac{d\sigma_T}{dE_R} \times n v f(\vec{v}, t) d^3 v$$

$$\frac{d\sigma_T}{dE_R} = \frac{\sigma_T(E_R) M_T}{2\mu_T^2 v^2} \quad \sigma_T(E_R) \sim \sigma_{ref}$$

$$\frac{dR}{dE_R} = \sum_T \frac{\sigma_T(E_R)}{2m\mu_T^2} \rho \eta(v_{min}, t) \quad \text{where} \quad \eta(v_{min}, t) = \int_{v > v_{min}} \frac{f(\vec{v}, t)}{v} d^3 v$$

$-\rho = nm$, $f(\vec{v}, t)$: local DM density and \vec{v} distribution depend on halo model.

Given $\rho \eta(v_{min})$ the plots are in the m, σ_{ref} plane: usual “Halo-Dependent”

NOTICE: $\tilde{\eta}(v_{min}) = \sigma_{ref} \rho \eta(v_{min})/m$ contains all the dependence of the rate on the halo and is common to all experiments! Fox, Liu, Weiner 1011.1915

Given m the plots are in the $v_{min}, \tilde{\eta}(v_{min})$ plane: “Halo-Independent”

Halo-Independent data comparison

Early versions of the method used the recoil spectrum dR/dE_R which is not directly accessible to experiments, and SI interactions [Fox, Liu, Weiner 1011.1915](#); [Frandsen et al 1111.0292](#)

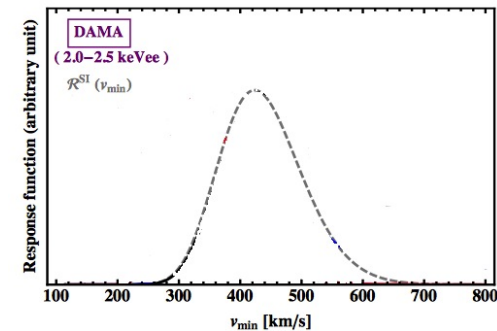
Halo Independent analysis for ANY interaction

[Gondolo-Gelmini 1202.6359](#); [Del Nobile, Gelmini, Gondolo and Huh, 1306.5273](#)

Using instead experimentally accessible quantities, including isotopic composition and energy resolution and efficiency with arbitrary energy dependence, we write the expected rate over a detected energy interval $[E'_1, E'_2]$ for any cross section as

$$R_{[E'_1, E'_2]} = \int_0^\infty dv_{min} \mathcal{R}_{[E'_1, E'_2]}(v_{min}) \tilde{\eta}(v_{min})$$

$\mathcal{R}_{[E'_1, E'_2]}$: EXPERIMENT AND INTERACTION
DEPENDENT response function non zero only
in an interval in v_{min} given an interval $[E'_1, E'_2]$
Every experiment is sensitive to a “window in velocity space”



Halo Independent analysis

Gondolo-Gelmini 1202.6359, Del Nobile, Gelmini, Gondolo and Huh, 1306.5273

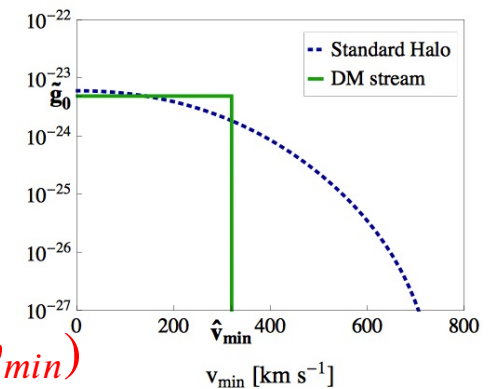
- **Rate measurements:** translated into weighted averages of the $\tilde{\eta}$ function:

$$R_{[E'_1, E'_2]}^{measured} = \overline{\eta}_{[E'_1, E'_2]} \int_0^\infty dv_{min} \mathcal{R}_{[E'_1, E'_2]}(v_{min})$$

$\overline{\eta}_{[E'_1, E'_2]}$: weighted average of $\tilde{\eta}$ with weight $\mathcal{R}_{[E'_1, E'_2]}(v_{min})$

Upper limits: $\tilde{\eta}$ is a non decreasing function of v_{min} : the smallest possible with value $\tilde{\eta}_0$ at $v_{min} = v_0$ is $\tilde{\eta}_0 \Theta(v_0 - v_{min}) \leq \tilde{\eta}$. Thus, compute the rate with this downward step function and ask for this rate to be at most equal to the measured limit for $\tilde{\eta}_0 = \tilde{\eta}_0^{lim}$.

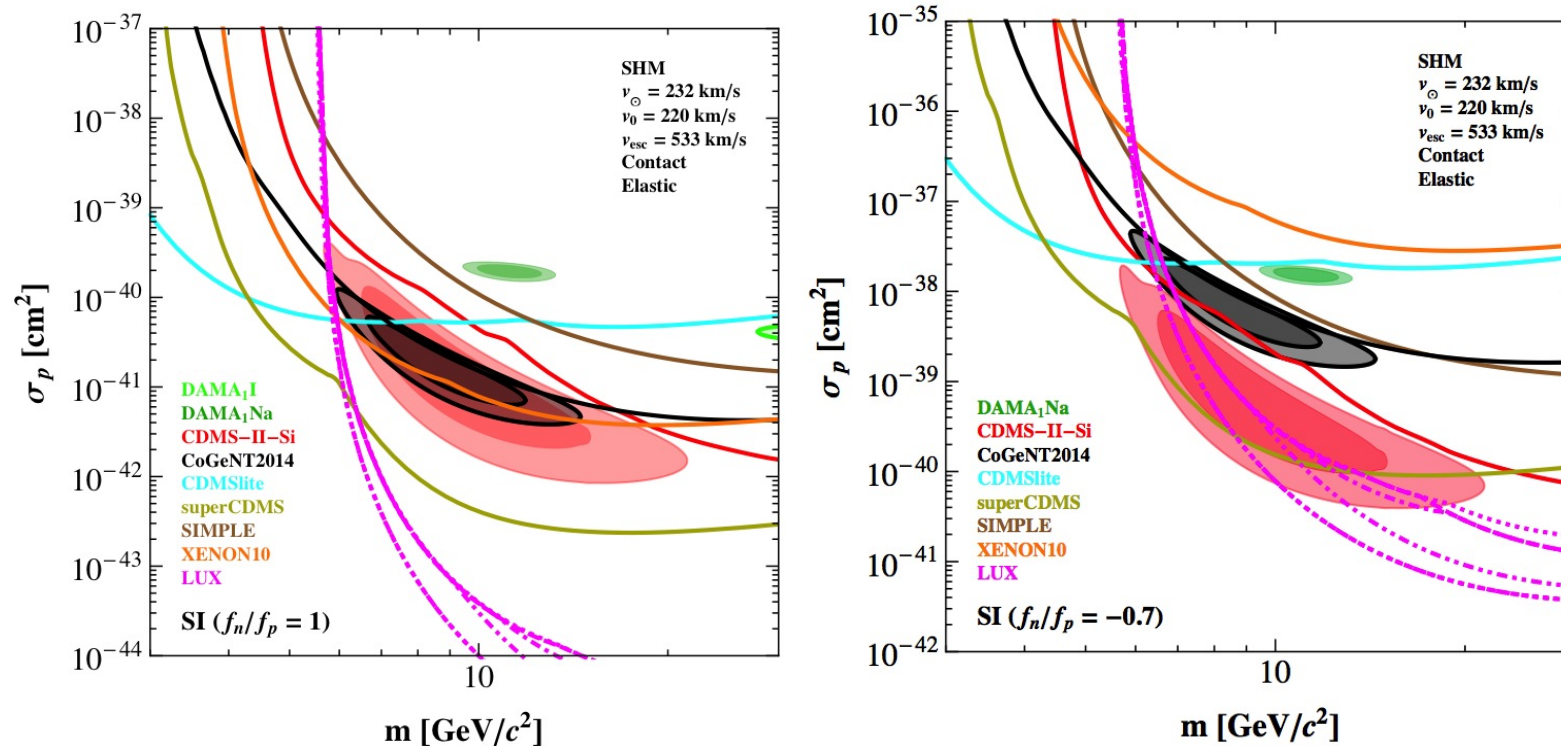
$$R_{[E'_1, E'_2]}^{limit} = \overline{\eta}_0^{limit}(v_0) \int_0^{v_0} dv_{min} \mathcal{R}_{[E'_1, E'_2]}^{SI}(v_{min})$$



Signals compatible with all limits? Assuming the SHM

Elastic contact Isospin Conserving (IC) or Violating (IV) Spin-Independent (SI)?

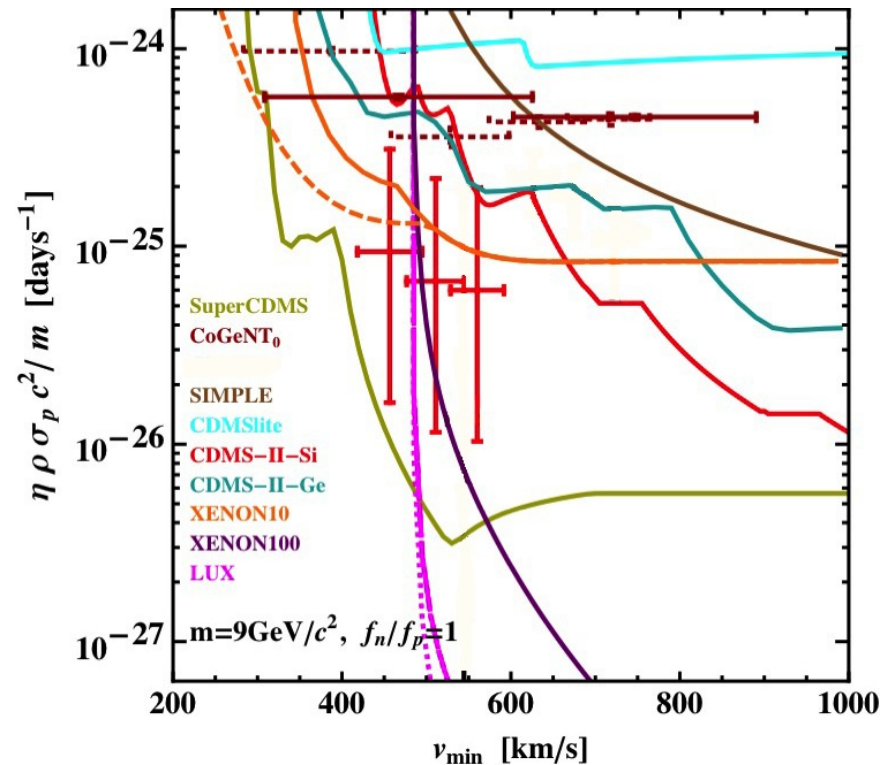
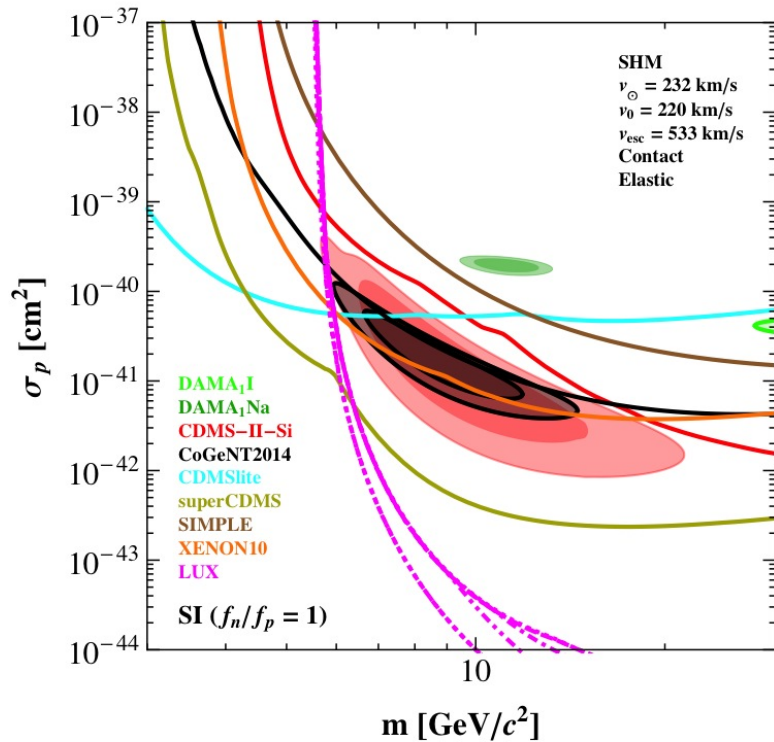
Figs. from Del Nobile, Gelmini, Gondolo, Huh 1405.5582 and Gelmini, Georgescu, Huh 1404.7484



IV makes **CDMS-II-Si** compatible with all 90%CL upper limits, not with **DAMA** or CoGeNT.

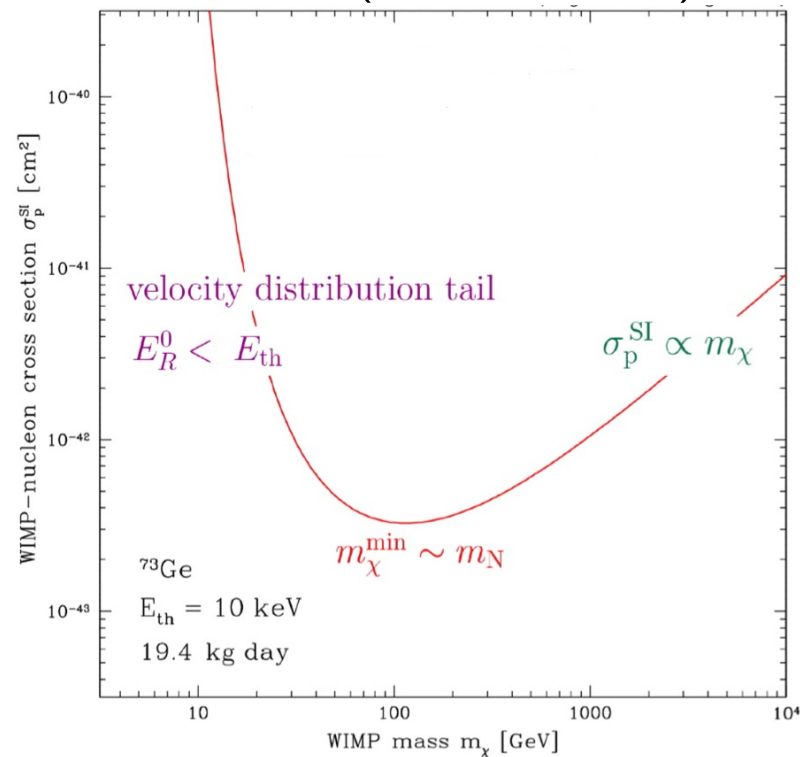
Halo Dependent vs Independent comparisons for elastic SI IC

Rate only crosses, $\tilde{\eta}_0$ Del Nobile, Gelmini, Gondolo, Huh 1304.6183, 1311.4247, 1405.5582



LEFT: **CDMS-II-Si** rejected by SuperCDSM bound in the SHM. RIGHT: $m = 9\text{GeV}$. **CDMS-II-Si rate (red) crosses** are forbidden by the SuperCDMS limit in any halo model.

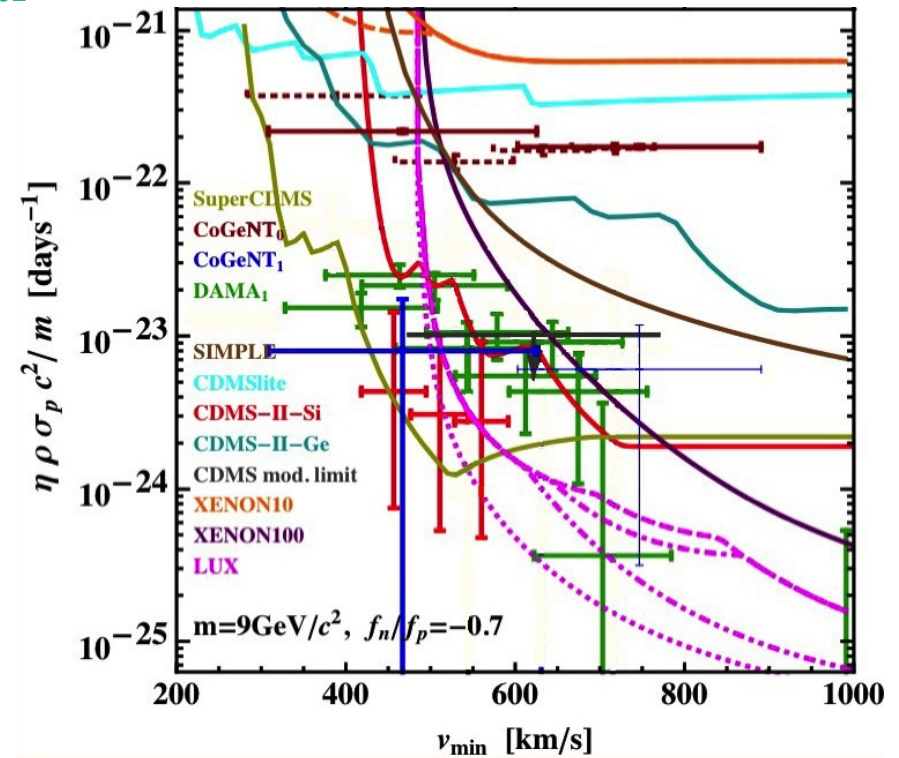
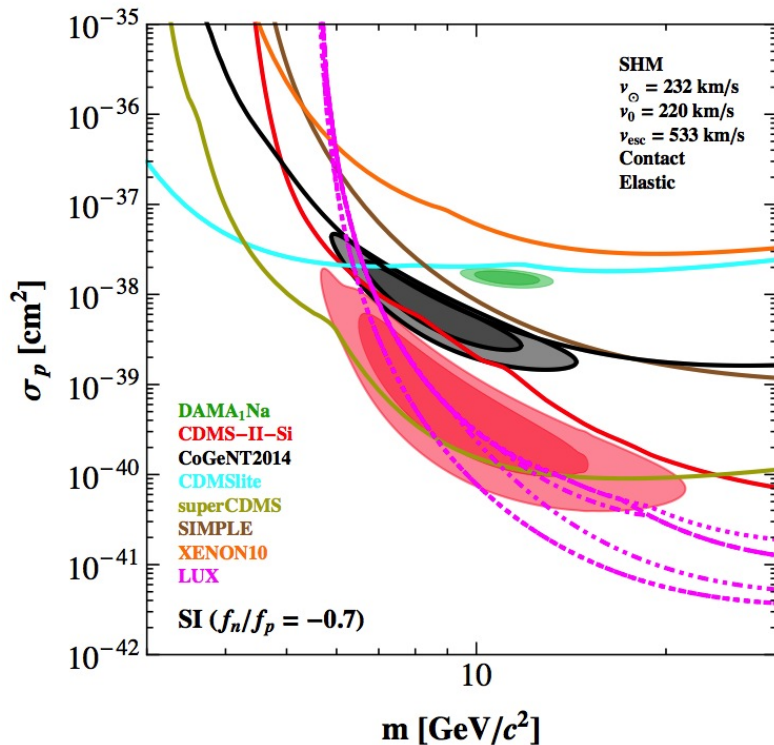
Halo Dependent and Independent upper limits Notice the shape of the limits. Generic Halo-Dependent limit (here the SHM):



What about a Halo-Independent limit?

Halo Dependent vs Independent comparison for elastic SI IV

Del Nobile, Gelmini, Gondolo, Huh 1304.6183, 1311.4247, 1405.5582

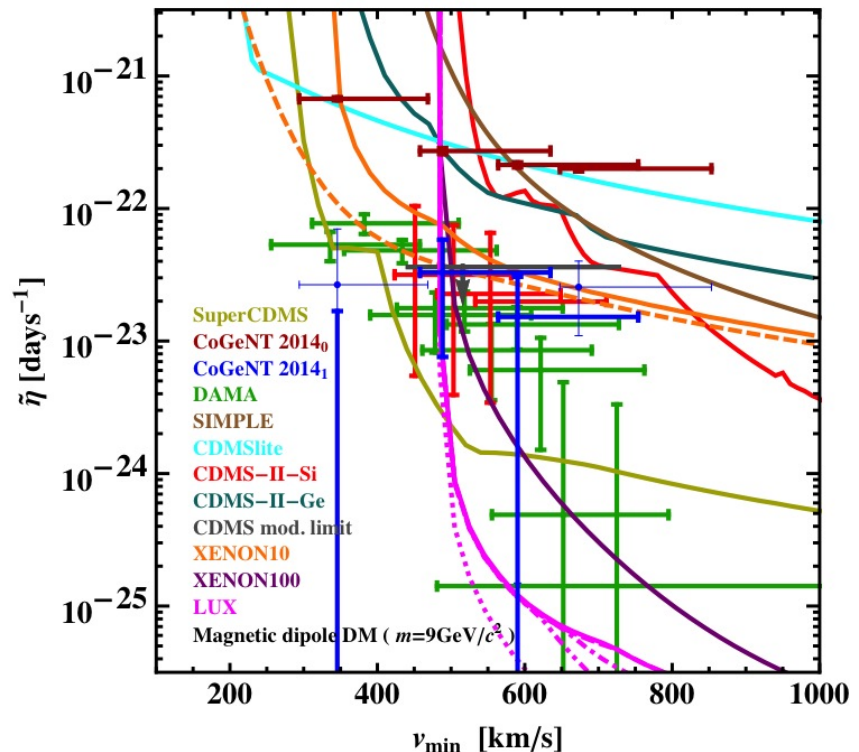
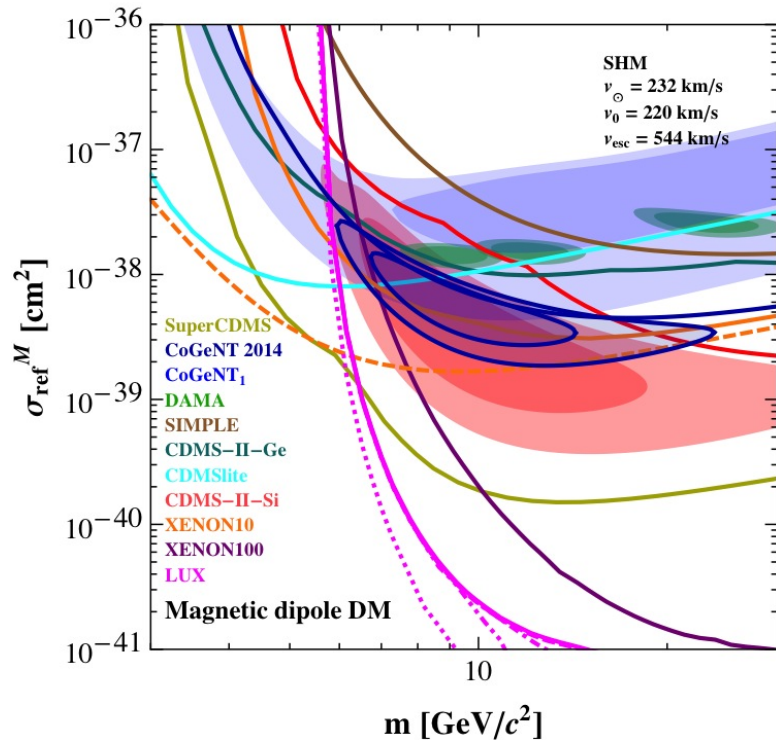


LEFT: Part of the 90%CL **CDMS-II-Si** region survives all 90%CL limits.

RIGHT: $m = 9\text{GeV}$. **CDMS-II-Si** rate small for **CoGeNT/DAMA** mod. **CoGeNT** annual mod. compatible with zero at $\simeq 1\sigma$, with best fit phase of DAMA- **Comparison of crosses and limits???**

Halo Dependent vs Halo Independent comparison for Magnetic Dipole DM

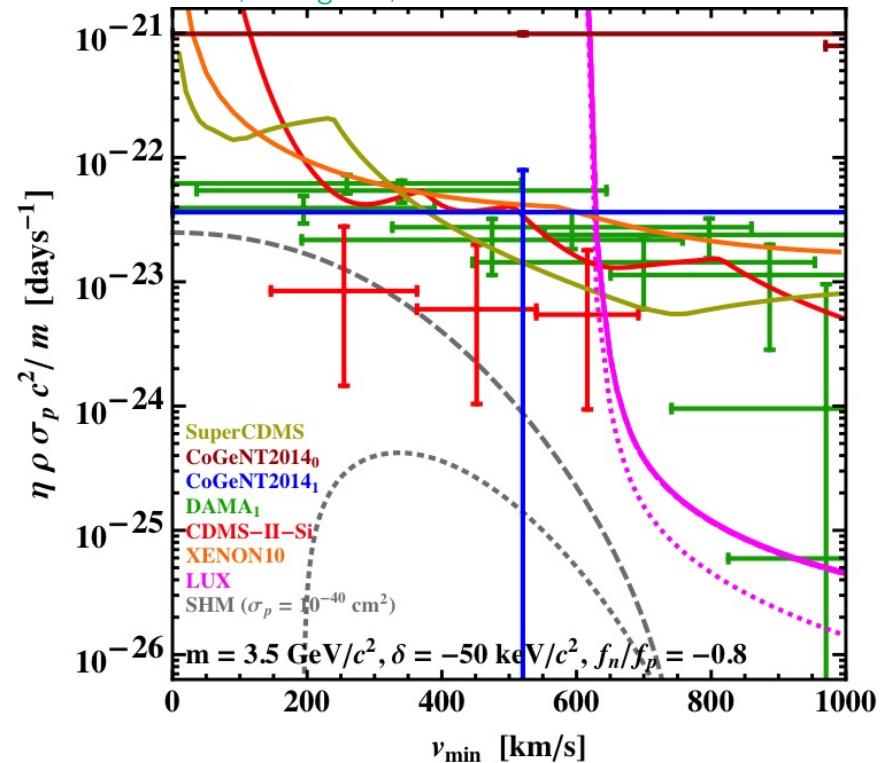
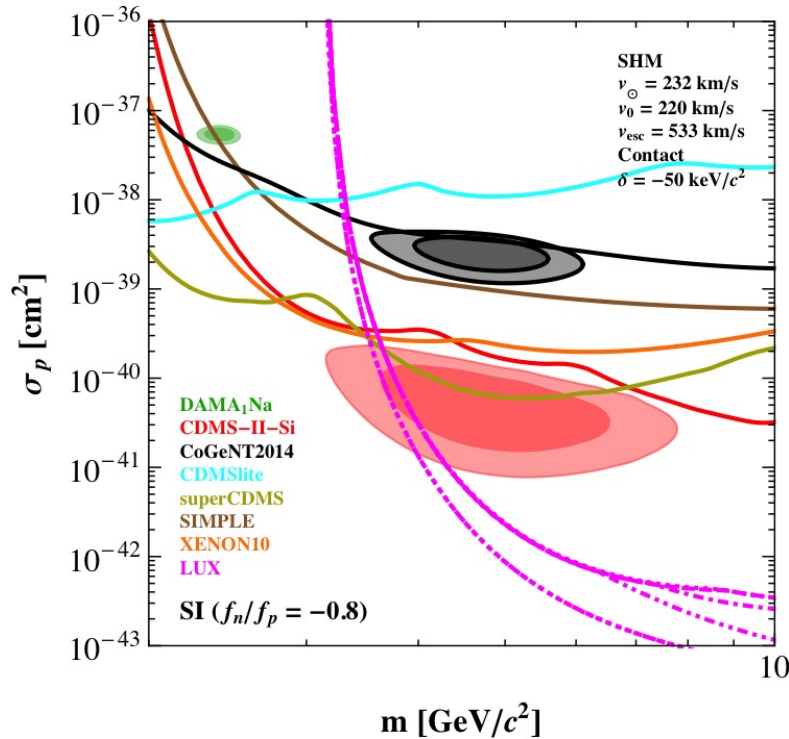
Del Nobile, Gelmini, Gondolo, Huh 1401.4508



LEFT: DAMA, CoGeNT and CDMS-Si overlap! RIGHT: CDMS-Si rate too small for CoGeNT/DAMA modulations. Both: rejected by SuperCDMS, but importance of CDMSLite limit depends on the halo model

Halo Dependent vs Independent comparison for Inelastic Exothermic SI “Ge-Phobic” DM

Gelmini, Georgescu, Huh 1404.7484



Exothermic $\delta = -50$ keV weakens Xe bounds, “Ge-Phobic” $f_n/f_p = -0.8$ weakens Ge bounds. LEFT: DAMA, CoGeNT and CDMS-SI disjoint! RIGHT: $m = 3.5$ GeV. CDMS-Si rate too small for CoGeNT and DAMA modulations (which overlap) Both: CDMS-Si allowed by all bounds

EHI- Extendent likelihood Halo Independent method Fox, Kahn and McCullough 1403.6830; Gelmini, Georgescu, Gondolo and Huh, 1507.03902

Comparing average $\tilde{\eta}(v_{min})$ values with upper bounds does not have a clear statistic meaning. With unbinned data (as in CDMS-II-Si) a statistically meaningful analysis can be made.

Starting with an **extended likelihood** for UNBINNED DATA

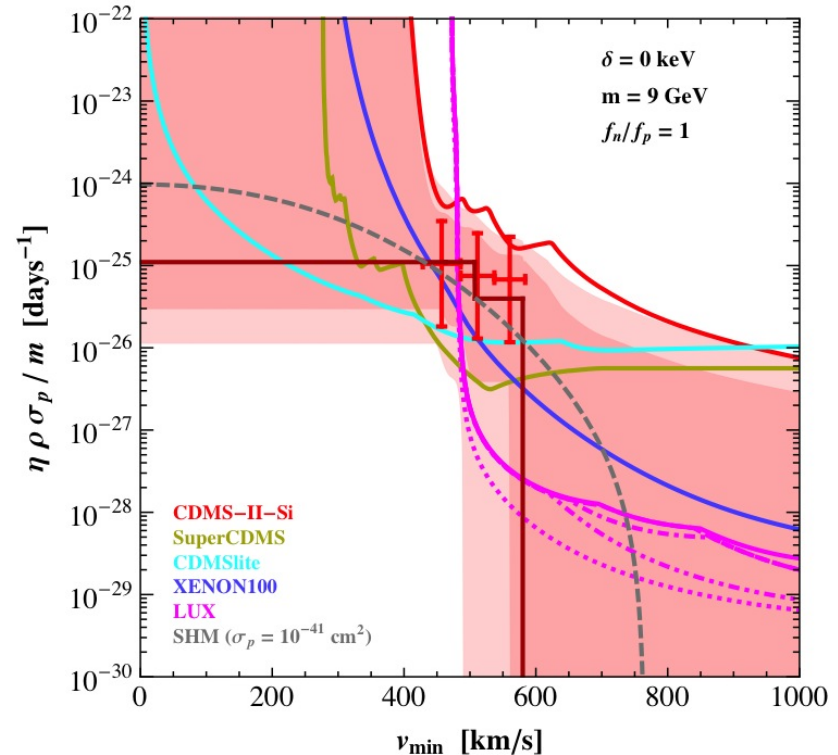
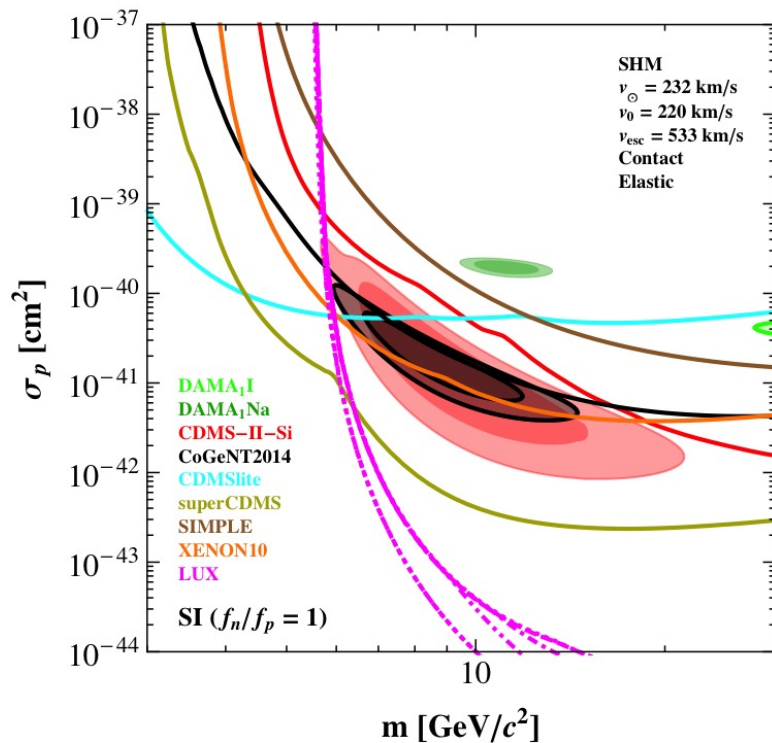
$$\mathcal{L}^{EHI}[\tilde{\eta}(v_{min})] \equiv e^{-N_E[\tilde{\eta}]} \prod_{a=1}^{N_O} MT \left. \frac{dR_{tot}}{dE'} \right|_{E'=E'_a}$$

one can find

- a **best fit $\tilde{\eta}(v_{min})$** , by extending to functionals the Karush-Kuhn-Tucker (KKT) maximization conditions, (Fox, Kahn and McCullough 1403.6830)
- a **statistically meaningful two-sided point-wise band** at a chosen CL. (Gelmini, Georgescu, Gondolo and Huh, 1507.03902)

EHI- Extendent likelihood Halo Independent method Fox, Kahn and McCullough 1403.6830; Gelmini, Georgescu, Gondolo and Huh, 1507.03902

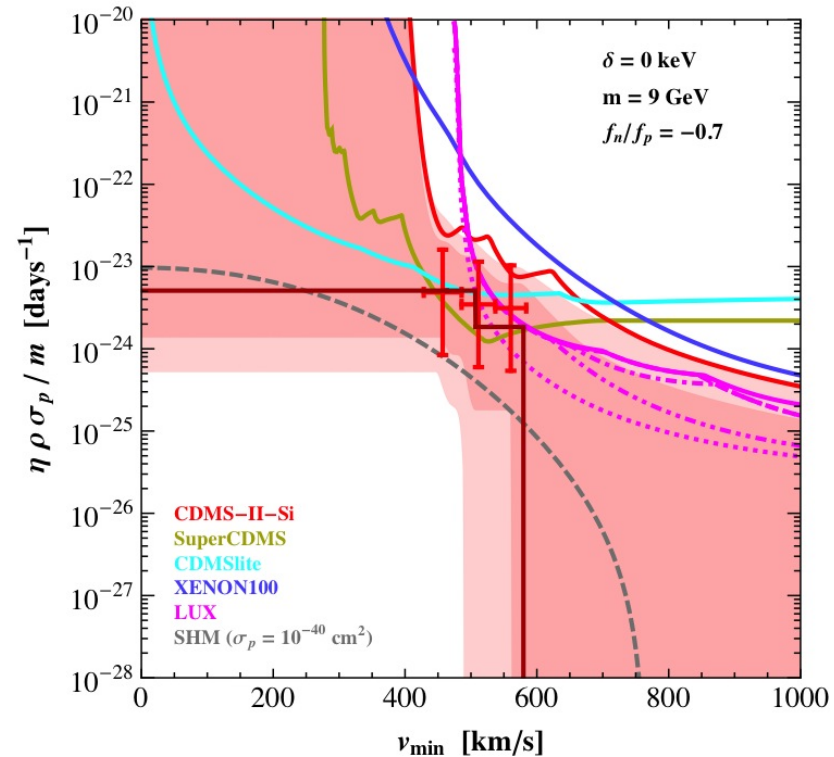
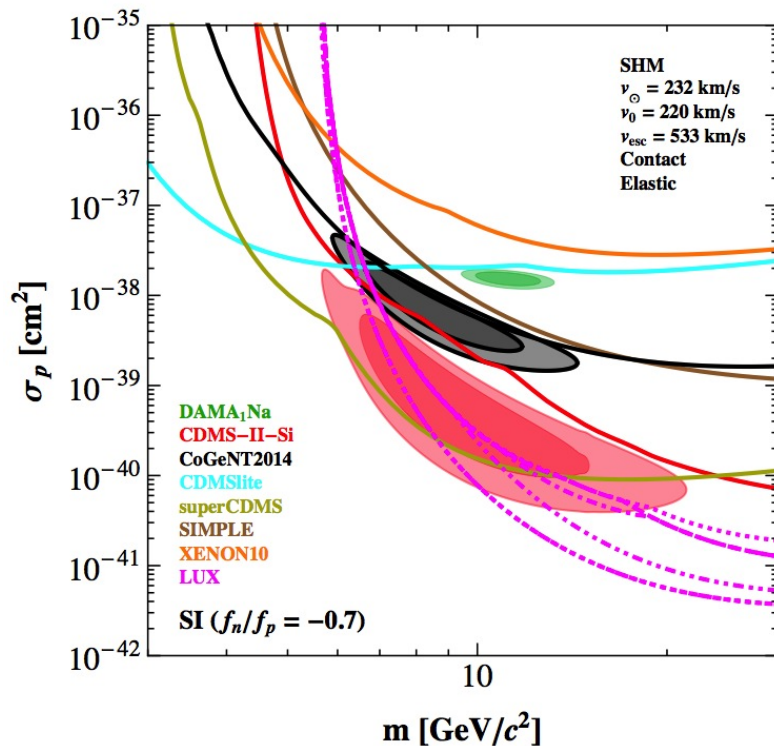
LEFT: halo dependent Figs. from Del Nobile, Gelmini, Gondolo, Huh 1405.5582 RIGHT: halo independent



90%CL bounds and the 68% and 90%CL regions (Left) and confidence confidence bands (Right) for CDMS-II-Si, $m = 9$ GeV elastic SI and $f_n/f_p = 1$. No continuous part of the bands allowed

EHI- Extendent likelihood Halo Independent method Fox, Kahn and McCullough 1403.6830; Gelmini, Georgescu, Gondolo and Huh, 1507.03902

LEFT: halo dependent Figs. from Gelmini, Georgescu, Huh 1404.7484 RIGHT: halo independent



90%CL bounds and the 68% and 90%CL regions and confidence bands for CDMS-II-Si, $m = 9$ GeV elastic SI $f_n/f_p = -0.7$. A continuous part of the bands (so any $\tilde{\eta}$ contained in it) is allowed

Outlook on halo-independent data comparison method

- The Halo Independent method to compare data of different direct DM searches is complementary to the usual comparison in the m, σ plane which must be done assuming a particular halo model. It shows when data cannot be made compatible with ANY choice of halo model- or not
- The Generalized Halo Independent method can be applied to ANY type of interaction, and not only to elastic but also to inelastic scattering (and can take fully into account all the characteristics of each experiment: energy resolutions, efficiencies etc)
- The way in which we compare data up to now for binned data, i.e. comparing averages over v_{min} intervals for putative DM signal with upper bounds of negative searches, does not have a clear statistical meaning- Our approach for unbinned data is better, but more work is necessary to understand how to do the halo independent comparison better.

The future of direct dark matter detection

Near Future experiments

In the future: new direct detection data.

DAMA clearly sees a modulation but is it DM or instrumental?

- DAMA/LIBRA changed its phototubes, so threshold from 2keVee to 1 keVee - results in 2017.
- “Global NaI(Tl) Collaborative Effort”: DM-Ice (55 kg-Yangyang), ANAIS (112kg, Canfranc), KIMS NaI (52 kg, Yangyang)) combined are comparable to DAMA \sim 220 kg. Start 2016

And many others... Xenon1T (about to start, later Xenon-nT), LUX (360kg running, later LZ, 7T, 2019?), PICO 60 (60liters running, later PICO-250?), EDELWEISS III (30kg), CRESST III (late 2016?), PandaX (still not competitive PandaX II, 0.5T, in 2017?), XMASS 1.5T (2017, later XMASS-7T 2019), DarkSide50 (50kg now- later to nT?), SuperCDMS-SNOLAB (up to 400kg, 2019?, was at Soudan, maybe later merge with Eureka), distant future Darwin? (30-50 tons)... still others, and directional detectors too

DAMA: DM signal or annually modulated backgrounds?

There have been many objections to the DAMA result over the years, none conclusive could they be observing annually modulated backgrounds?

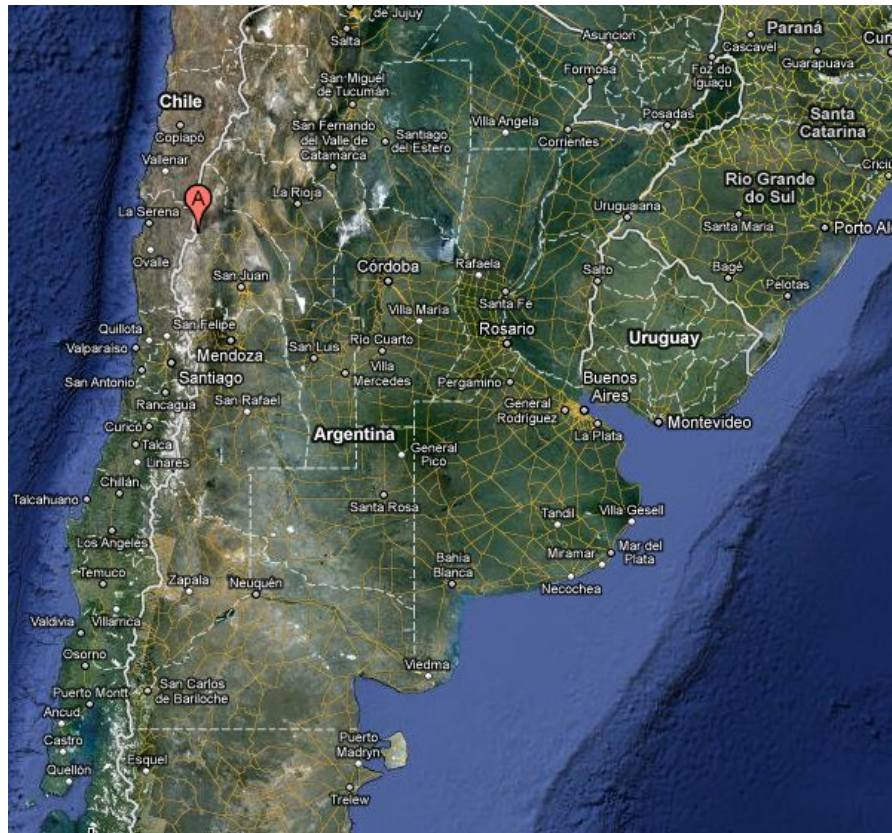
- $O(10 \text{ MeV})$ ambient neutrons at the LNGS or Soudan Mine (via scattering or neutron capture and activation- Auger electrons) J. P. Ralston [arXiv1006.5255](#)
- $> \text{TeV}$ cosmic ray μ 's which reach the LNGS or Soudan Mine underground facility and
 - either produce secondary neutrons via spallation in the detector or surrounding rock J. P. Ralston [arXiv1006.5255](#), K. Blum [arXiv1110.0857](#)
 - or deposit their energy directly into the detector D, Nygren [arXiv1102.0815 \(2011\)](#)
- DAMA refuted each claim...e.g. no modulation in multiple events (which n would produce)...
 phase of the modulation in DAMA is off with respect to the max T in the upper atmosphere
 S. Chang, J. Pradler and I. Yavin [arXiv:1111.4222](#) - Could muons + solar ν at the right depth produce the phase in DAMA? Jonathan Davis, [1407.1052](#) Idea rejected in [1409.3185](#) and [1409.3516](#)

DAMA: DM signal or annually modulated backgrounds?

A definitive way to eliminate the doubt that the annual modulation in a direct DM detector is due to seasonal backgrounds: make the experiments in the Southern Hemisphere. Problem is, all underground laboratories are in the North



Opportunity to build ANDES at the Agua Negra Tunnel



ANDES Laboratory concept

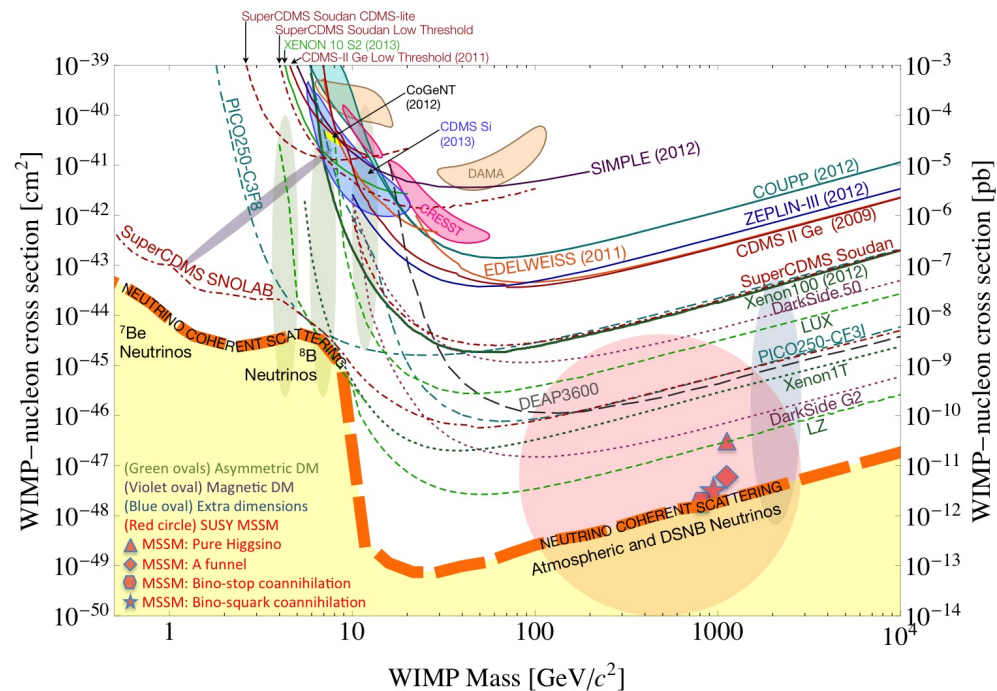


ANDES, an underground laboratory in the Agua Negra tunnel

- 2 tunnels, 12 m diameter, separated 60 m, 14 km long
- Argentinian side at about 400 km N of Pierre Auger
- Entry in Argentina (close to the city of San Juan) at altitude 4085m, in Chile at 3600 m (close to La Serena)
- Cavities at $\simeq 3700\text{m}$ altitude
- Deepest point from surface at $\simeq 4800$ mwe
- Rock: andesite, basalt, rhyolite; density $\simeq 2.7 \text{ g/cm}^3$
- Low radioactivity: 10^{-5} neutrons/kg s (Gran Sasso- 10^{-4} , Modane 10^{-5}); $1.08 \times 10^{-5} \mu\text{'s/ m}^2 \text{ sec}$; $T \simeq 30\text{-}40^\circ \text{ C}$
- Bidding finalized (in favor of Lombardi). Construction expected to start in 2015 and cavities will be ready within 2 years.

The future of Direct DM detection (IC SI interactions and SHM)

several ton-scale detectors will start seeing neutrinos. Some extend to low masses



Defining the “neutrino floor” to assume subtraction by a factor ~ 20 none of these experiments reach the it. ^8B neutrino scattering would be a very interesting proof of sensitivity and observation of Coherent Neutrino Scattering

Further future Experiment to reach the “neutrino floor”

Ideas for high WIMP mass:

Need greater target mass but with appropriate reduction of the background

Large liquid noble gases experiments: **Darwin (50 T Xe+ 50T Ar) ?**

Larger superheated fluid: **PICO (250 liters)?**

Ideas for low WIMP mass:

Much larger Ge low threshold detectors: **Ton-scale SuperCDM + Edelweiss** (but need to reduce backgrounds)

Even further future

Directional direct Dark Matter detectors:

If WIMP is at high mass: 10 tons of low pressure gas (100 torr)=10,000m with cubic mm pixels (following DRIFT, DMTPC)

Detection of LDM (Light Dark Matter) 1 keV to 10's MeV

via interaction with electrons: electron ionization or electronic excitation or molecular dissociation, breaking Cooper Pair in superconductors (“Dark Sectors 2016

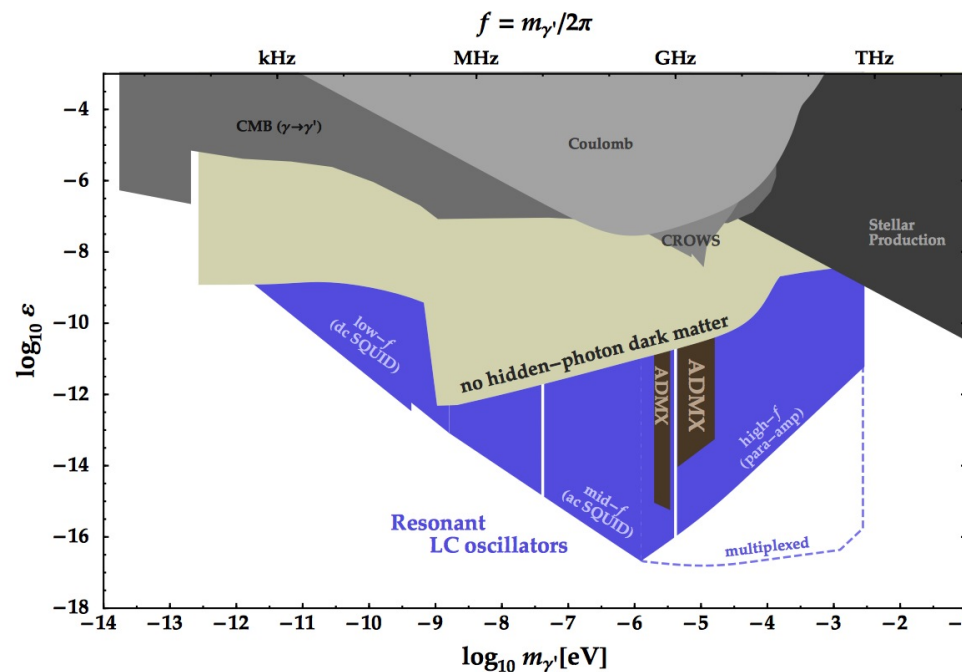
Workshop” 1608.08632)

Dark Photons as Dark Matter?

E.g. Chaudhuri, Graham, Irwin, Mardon, Rajendran & Zhao “A radio for Hidden Electric dark matter detection” 1411.7382:

Dark Photons as Dark Matter? E.g. Chaudhuri, Graham, Irwin, Mardon, Rajendran & Zhao “A radio for Hidden Electric dark matter detection” 1411.7382

Hidden-photon DM is a weakly coupled “hidden electric field” oscillating at a frequency fixed by the mass, and able to penetrate any shielding. An observable effect is a real, oscillating magnetic field. They propose a tunable, resonant circuit to couple to this magnetic field.



Present directional direct Dark Matter detectors

A recent review: F. Mayet et al 1602.03781

Directional detectors can measure both the energy and direction of the WIMP-induced recoils. They are at present very small:

Exp.	V (L)	Gas	P (mbar)	Drift	Threshold (keV)	Location	Ref.
DRIFT	800	73% CS ₂ + 25% CF ₄ + 2% O ₂	55	ion, 50 cm	20 [24]	Boulby	[29]
MIMAC	5.8	70 % CF ₄ + 28 % CHF ₃ + 2 % C ₄ H ₁₀	50	e ⁻ , 20 cm	2	Modane	[86]
NEWAGE	37	CF ₄	100	e ⁻ , 41 cm	50	Kamioka	[87]
DMTPC	1000	CF ₄	40	e ⁻ , 27 cm	20	SNOLAB	[91, 93]

Cubic meter scale has been operated by DRIFT and DMTPC (both low-pressure gas TPC) but significantly larger directional detectors must be constructed to reach leading sensitivity.

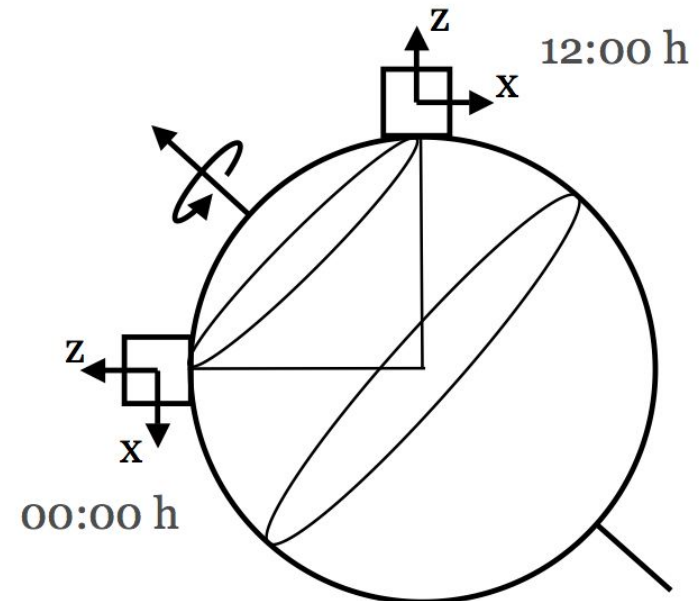
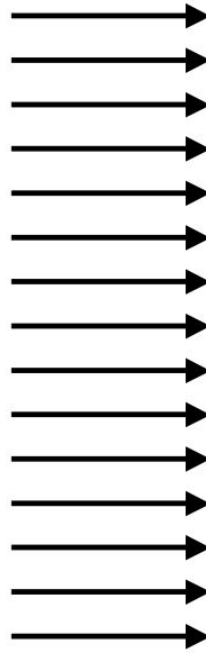
Present directional direct Dark Matter detectors

low density gas TPCs Measure direction of recoil- track reconstructed through drift of e



Directional direct DM detectors: daily modulation

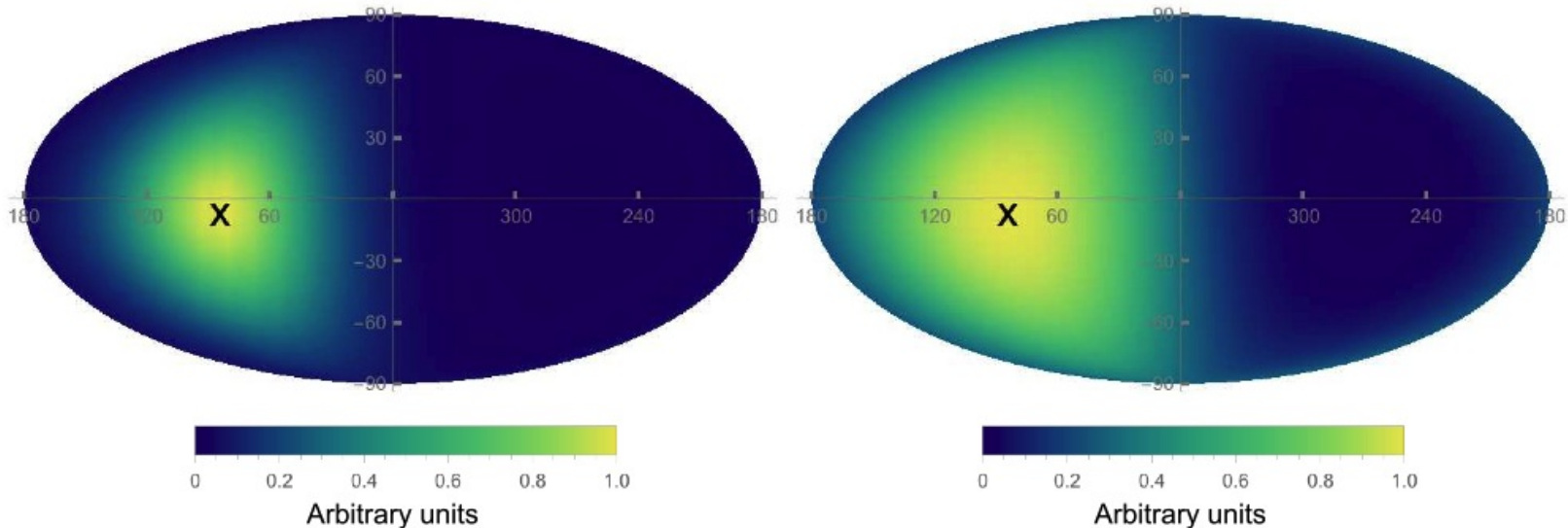
Because of the Earth's rotation, the peak recoil direction in the lab frame varies over the course of a day: daily modulation



Directional direct DM detectors, dipole feature

Left: Flux of 100 GeV WIMPs with $v > v_{min}$ for $E_R = 25$ keV F recoils arriving on Earth.

Right: Angular distribution of the energy differential recoil rate in F for WIMP $m = 100$ GeV, $E_R = 25$ keV. Maps are incoming direction of WIMP-induced recoils in Mollweide equal-area projections, in Galactic coordinates.



A few dozen events would be enough to detect the dipole feature. Unmistakeable DM signature: no known backgrounds can mimic this directional signature!

Directional recoil rate

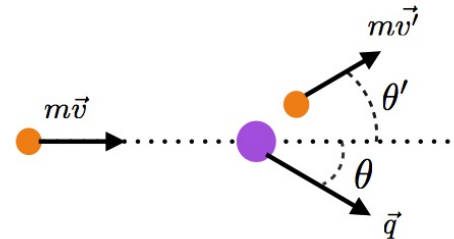
- The double differential event rate per unit detector mass as a function of both the **recoil energy** and **direction** is given by:

$$\frac{d^2 R}{dE d\Omega} = \frac{\rho}{mM} \int_{v > v_m} d^3 v \left(\frac{d^2 \sigma}{dE d\Omega} \right) v f(\mathbf{v})$$

$d\Omega$: infinitesimal solid angle around the recoil direction.

- Azimuthal symmetry of the scattering around the WIMP arrival direction:

$$d\Omega = 2\pi d \cos \theta$$



Directional recoil rate

- Recall:

$$E = \frac{2\mu^2 v^2}{M} \cos^2 \theta$$

which gives:

$$\cos \theta = \frac{v_m}{v}$$

- Impose this relation through a Dirac delta function:

$$\begin{aligned} \frac{d^2\sigma}{dE d\Omega} &= \frac{d\sigma}{dE} \frac{1}{2\pi} v \delta(v \cos \theta - v_m) \\ &= \frac{d\sigma}{dE} \frac{1}{2\pi} v \delta(\mathbf{v} \cdot \hat{\mathbf{q}} - v_m) \end{aligned}$$

Directional recoil rate

- Remember the energy differential cross section for standard contact interactions:

$$\frac{d\sigma}{dE} = \frac{M}{2\mu^2 v^2} \sigma_0 F^2(E)$$

- We have:

$$\frac{d^2 R}{dE d\Omega} = \frac{\rho \sigma_0 F^2(E)}{4\pi m \mu^2} \hat{f}(v_m, \hat{\mathbf{q}})$$

$\hat{f}(v_m, \hat{\mathbf{q}})$ is the three-dimensional *Radon transform* of the velocity distribution: **[Gondolo, hep-ph/0209110]**

$$\hat{f}(v_m, \hat{\mathbf{q}}) = \int d^3 v \delta(\mathbf{v} \cdot \hat{\mathbf{q}} - v_m) f(\mathbf{v})$$

Johan Radon, austrian mathematician, proposed Radon transform in 1917. Used in tomography where f is density and \hat{f} scatt. data output; etc

Directional recoil rate

- Using the Radon transform, one can evaluate the event rate analytically for most halo models.
- For the SHM with a truncated Maxwellian velocity distribution, the Radon transform in the lab frame is:

$$\hat{f}(v_m, \hat{\mathbf{q}}) \propto \left(\exp \left[-\frac{(v_m + \hat{\mathbf{q}} \cdot \mathbf{v}_{\text{lab}})^2}{2\sigma_v^2} \right] - \exp \left[-\frac{v_{\text{esc}}^2}{2\sigma_v^2} \right] \right)$$

if $v_m + \hat{\mathbf{q}} \cdot \mathbf{v}_{\text{lab}} < v_{\text{esc}}$, and zero otherwise.

\mathbf{v}_{lab} : velocity of the lab with respect to the Galaxy.

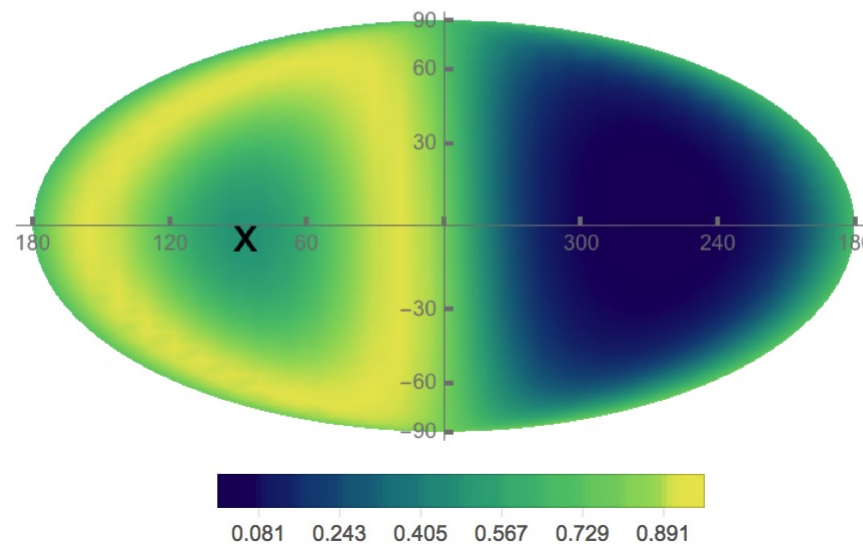
Directional recoil rate

$$\hat{f}(v_m, \hat{\mathbf{q}}) \propto \left(\exp \left[-\frac{(v_m + \hat{\mathbf{q}} \cdot \mathbf{v}_{\text{lab}})^2}{2\sigma_v^2} \right] - \exp \left[-\frac{v_{\text{esc}}^2}{2\sigma_v^2} \right] \right)$$

- Two regimes of interest:
 - If $v_m > v_{\text{lab}}$, argument of first exponential minimized when $\hat{\mathbf{q}}$ is in the opposite direction of \mathbf{v}_{lab} . \rightarrow *dipole feature*
 - If $v_m < v_{\text{lab}}$, i.e. for **low recoil energies** and **large WIMP masses**, maximum of the Radon transform happens at an angle between $\hat{\mathbf{q}}$ and \mathbf{v}_{lab} . \rightarrow *ring-like feature* in the recoil map. [Bozorgnia, Gelmini, Gondolo, IJGPP.6361]

Directional recoil rate

- Differential directional recoil rate in fluorine, assuming 5 keV recoil energy and 100 GeV WIMP.



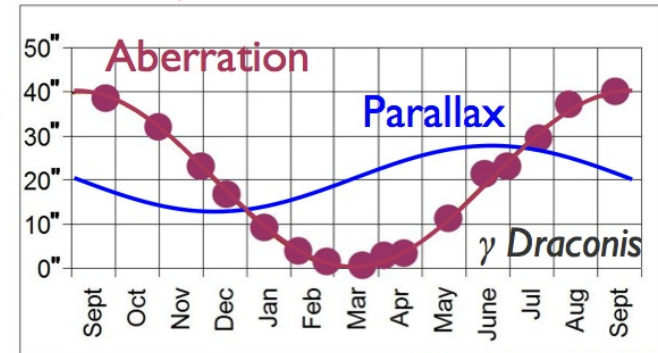
Once this can be detected, we will be in there real of WIMP astronomy!

In the distant future: WIMP astronomy Fig. from Gondolo

Aberration of WIMPs

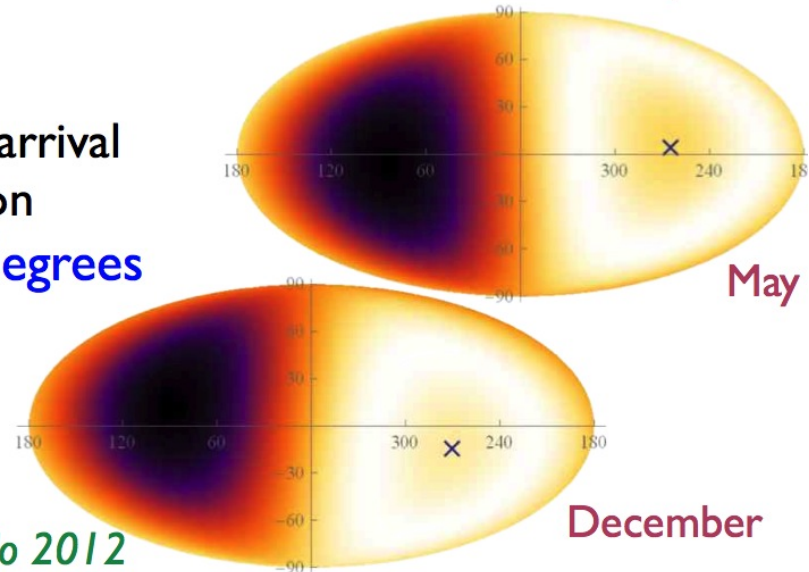


Photon arrival direction
20 arcsec



Bradley 1725

WIMP arrival direction
10 degrees

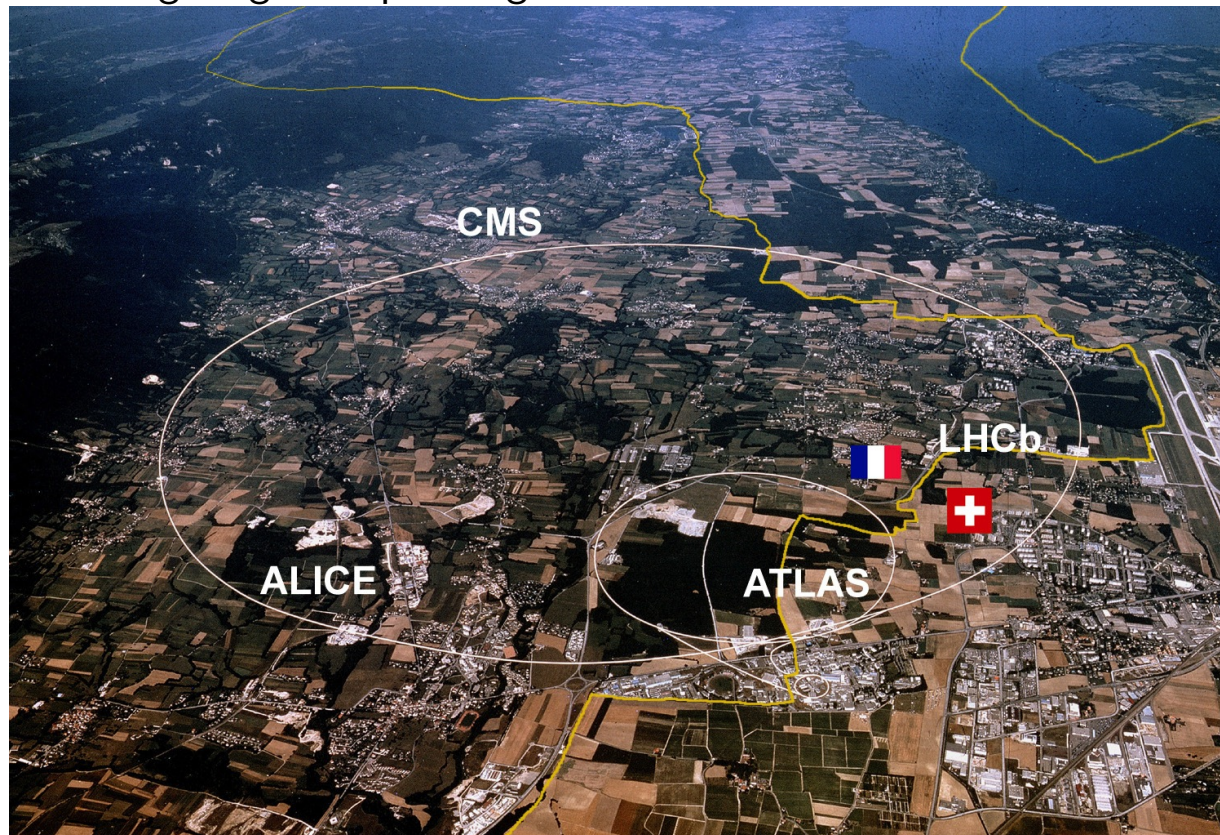


Bozorgnia, Gelmini, Gondolo 2012

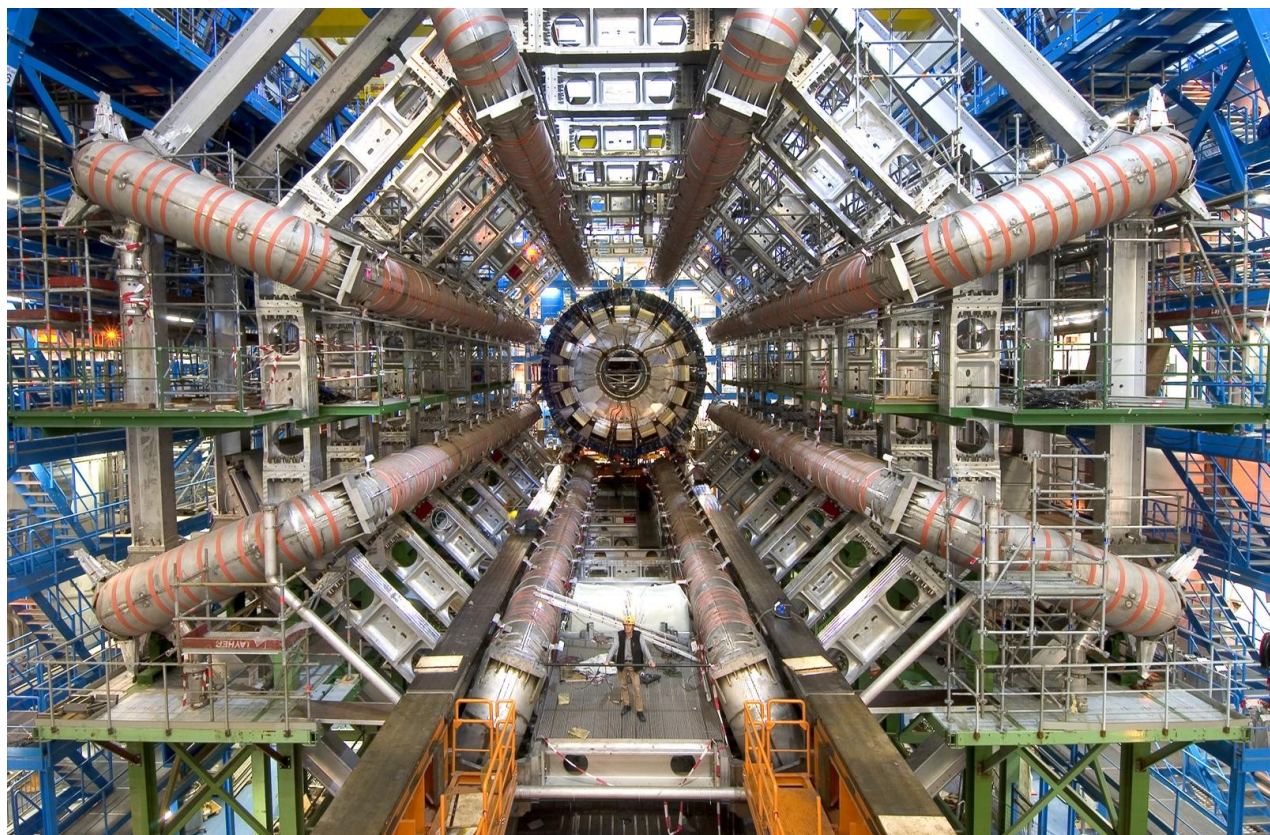
DM search strategies at the LHC

The Large Hadron Collider (LHC)

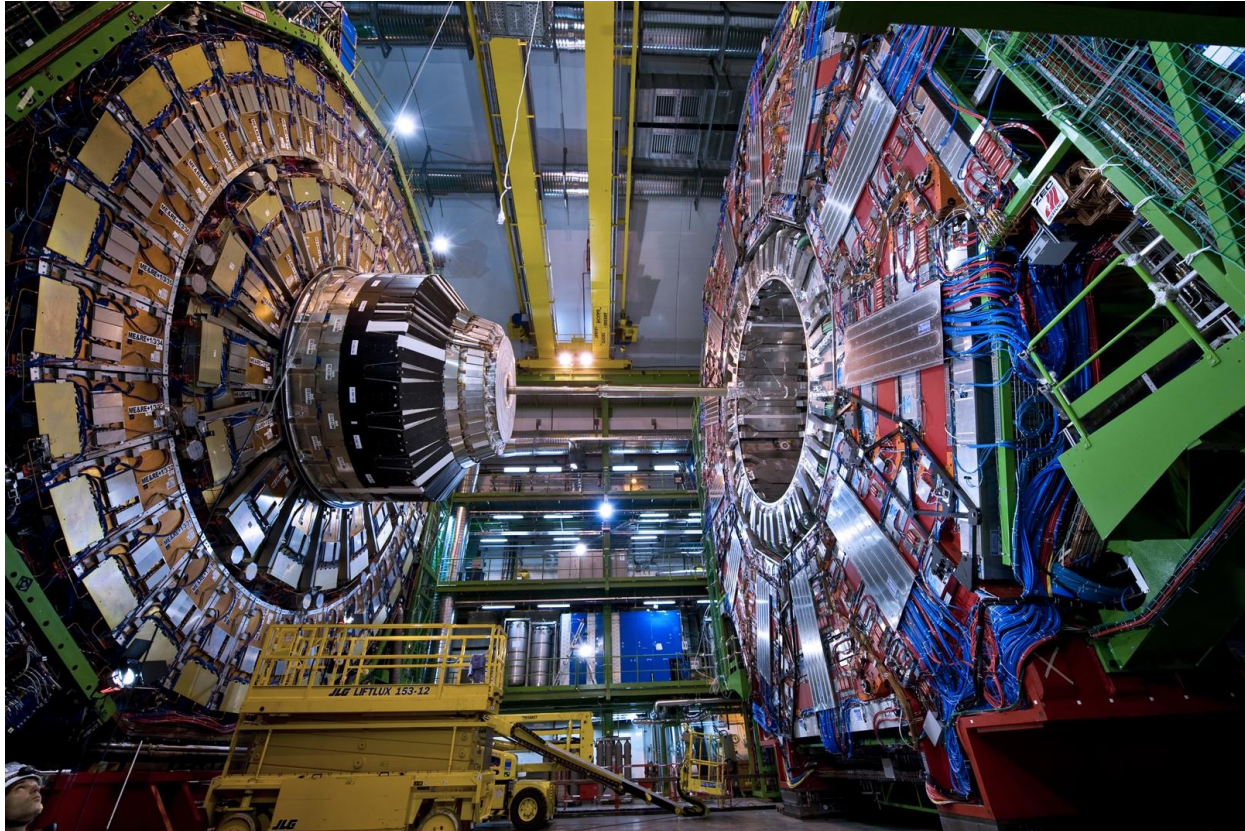
- The most powerful particle accelerator in the world, 27 km around, 100 m below ground
- 1600 superconducting magnets operating at 1.9 K



ATLAS



CMS

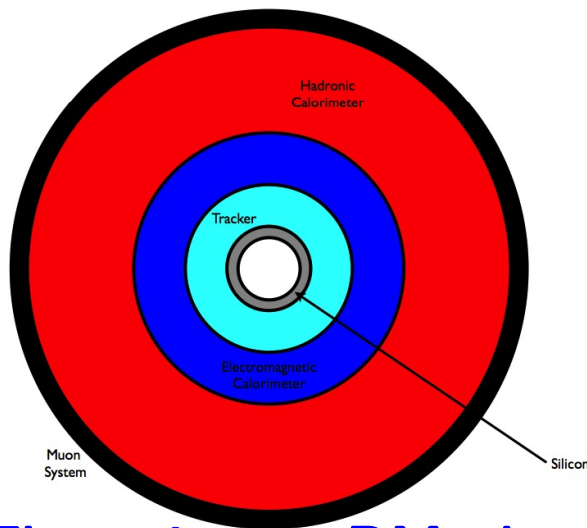


LHC multipurpose experiments: ATLAS and CMS



Are very large and very complicated detectors!!

Theorist version of an LHC detector



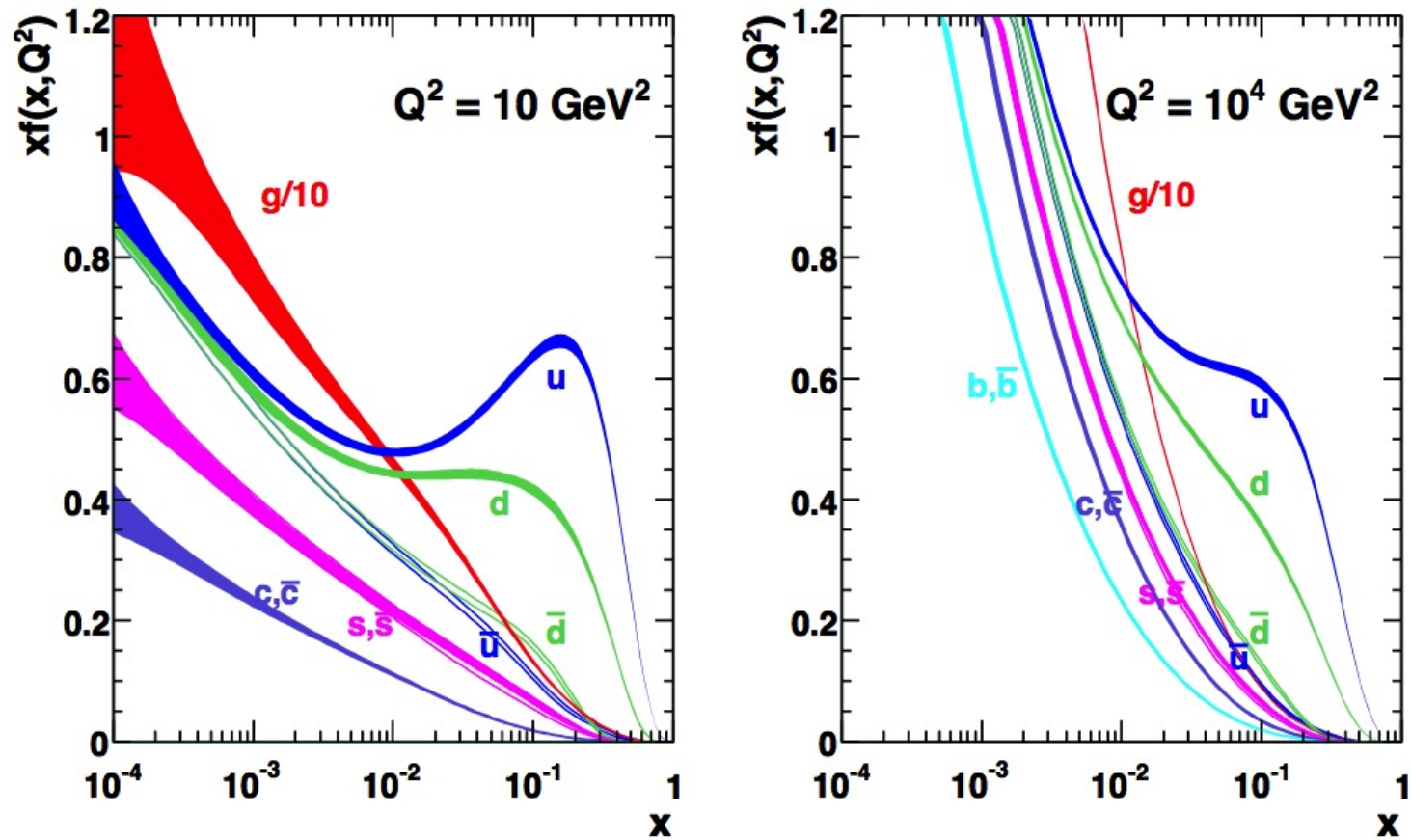
- Inner layer of silicon detectors: displaced vertices
- EM tracker: path of charged particles
- Calorimeters: stop e , γ and hadrons
- Outer radius of μ detectors: muon momenta
- Magnetic fields bend charged particle paths: measure momentum

There is no DM detector! DM signal is missing energy and momentum, actually MET (p_T). But so is for neutrinos!

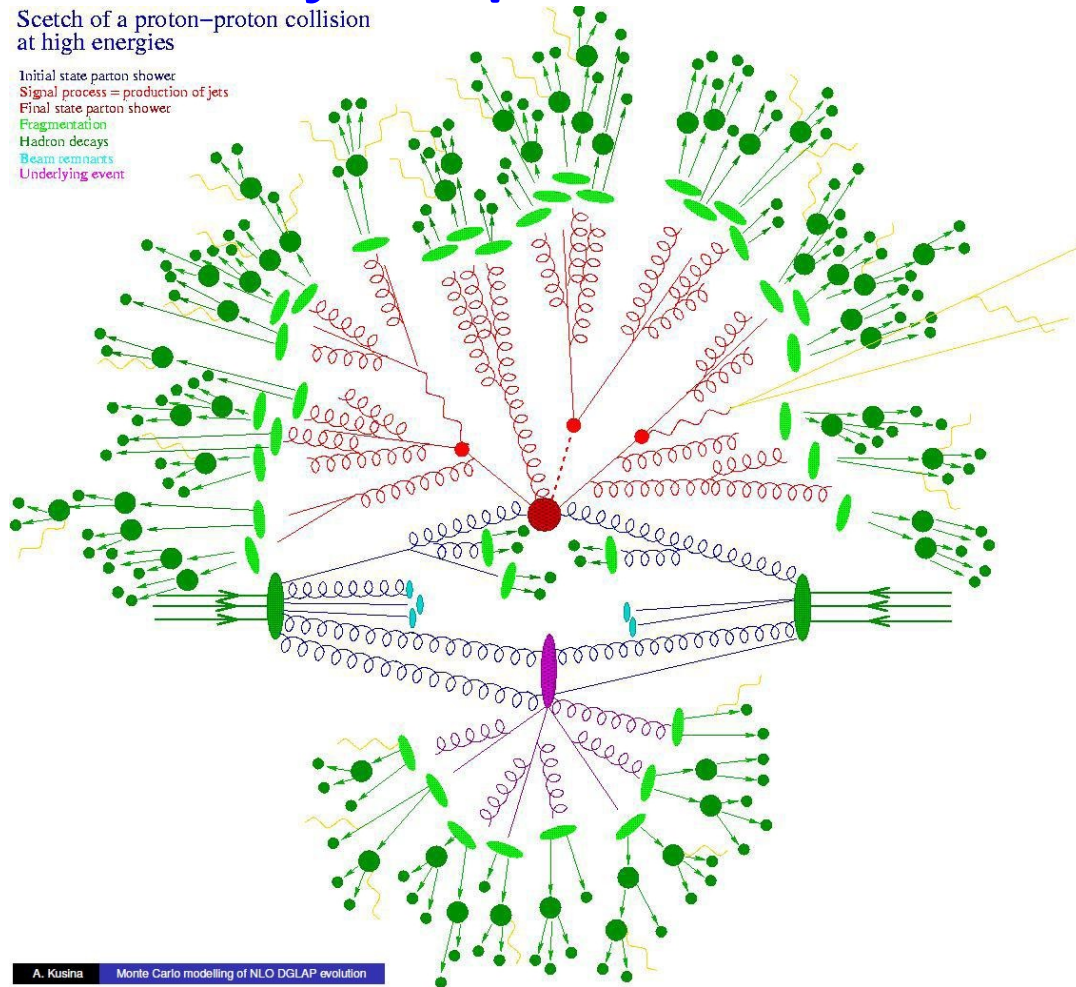
In hadron colliders, the initial momentum along the beam axis $x p_{had}$ of the colliding partons is not known so the amount of TOTAL missing energy/momentum cannot be determined. However, the initial partonic momentum transverse to the beam axis $p_T = 0$, so any net momentum in the transverse plane indicates Missing Transverse Energy (MET) really p_T (advantage of lepton colliders: can measure the total missing energy/momentum)

Protons are bags of patrons

MSTW 2008 NLO PDFs (68% C.L.)



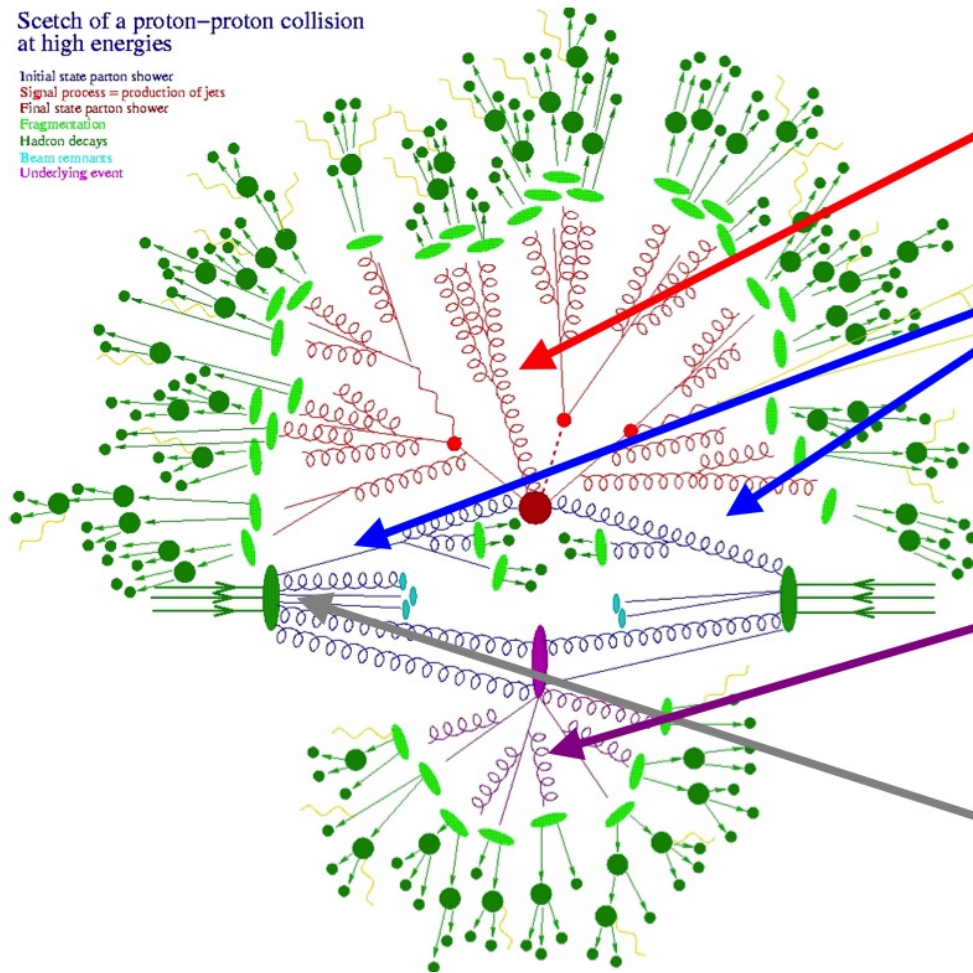
p-p collisions are very complicated



p-p collisions are very complicated Fig. from T. Tait

Sketch of a proton-proton collision at high energies

Initial state parton shower
Signal process = production of jets
Final state parton shower
Fragmentation
Hadron decays
Beam remnants
Underlying event



Outgoing partons fragment and hadronize into jets.

Energetic partons participate in the hard scattering (controlled by PDFs).

Proton remnants leave behind hadronic debris.

Protons come in as color singlets.

DM searches at the LHC

Main signature:

DM particles escape detection at colliders, thus they are characterized by **missing transverse energy (missing E_T , MET)** in collider events.

Caveats:

- The DM particles may be too heavy to be produced (above a few TeV).
- A signal produced by a particle escaping the detectors with lifetime $\simeq 100$ ns cannot be distinguished from one with lifetime $> 10^{17}$ s as required for DM particles.
- Hadron colliders are relatively insensitive to DM that interacts only with leptons.
- A DM signal may be hidden by backgrounds.

Main backgrounds for DM MET search

- “QCD background”

Measuring MET is difficult because one need to measure accurately EVERYTHING VISIBLE. Missmeasurement of jet energies is a fake source of missing momentum.

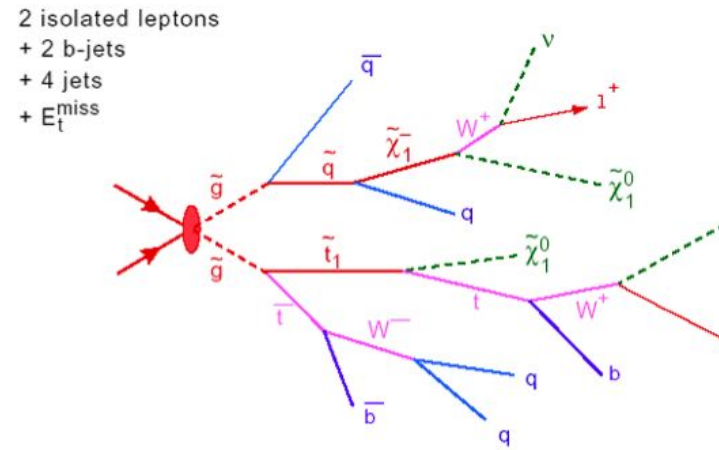
- Neutrinos are a background if they cannot be identified

- $Z \rightarrow \nu\nu$ 20% of the time - look like DM MET.
- $W \rightarrow \nu\ell$, if the charged lepton ℓ is missed, ν cannot be identified and looks like DM MET.
- Same for τ decays, also produce ν 's and ℓ 's

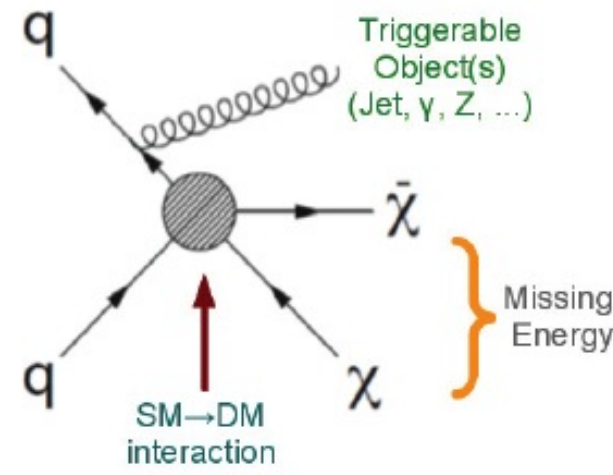
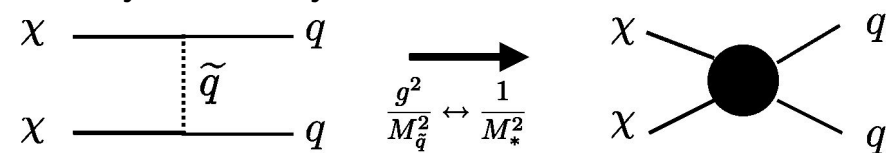
Searches at the LHC

- Either in complete theories
DM through known decay chain
(specific UV complete models e.g. SUSY,
or simplified topologies)

- Or direct DM production plus a visible particle either in effective field theories
(EFT) or simplified DM models
photon or gluon (“monophoton” or “monojet”
signal) or mono-W’s (leptons), mono-Z’s
(dileptons), or mono-Higgses.



Initially done only for EFT



Spectrum of DM Theory Space Fig. from T. Tait

