Dark Matter
Lecture 4

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DE-SC0009937

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Content:

- Direct dark matter searches (continuation)
  - Halo independent data analysis
  - News ideas for Light DM (LDM) searches

- Indirect dark matter searches
  - The GC GeV excess
  - The antiproton AMS-2 excess
  - The PAMELA-AMS-2 positron excess
  - Planck CMB limits
  - Indirect limits on DM annihilation cross-sections

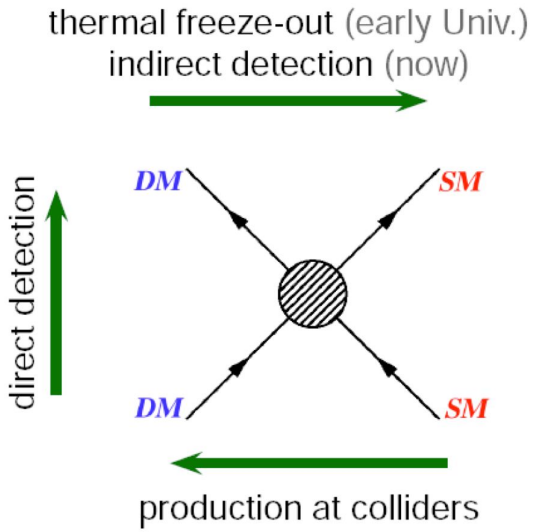
- LHC dark matter searches
  - A few comments on searches for simplified DM models

(Disclaimer: idiosyncratic choice of subjects-not complete lists of citations.)

WIMP DM searches:

- Direct Detection- looks for energy deposited within a detector by the DM particles in the Dark Halo of the Milky Way.

- Indirect Detection- looks for WIMP annihilation (or decay) products.



- At colliders (the LHC) as missing transverse energy, mono-jet or mono-photon events

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

$$\frac{dR}{dE_R} = \sum_T \int_{v>v_{min}} N_T \times \frac{d\sigma_T}{dE_R} \times n v f(\vec{v},t) d^3v$$

-E_R: nuclear recoil energy
- T: each target nuclide (elements and isotopes)
- $N_T = C_T/M_T =$ Number of nuclides T in the detector = (mass fraction × Number of nuclides T per unit target mass);
- $\mu_T = mM_T/(m+M_T)$, reduced mass
- v_{min} min WIMP speed to impart E_R to the target T

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

The recoil rate dR/dE_R is not directly accessible to experiments because experiments observe only a proxy E' for the recoil energy E_R with energy dependent energy resolutions and efficiencies.

Observed event rate:

$$\frac{dR}{dE'} = \varepsilon(E') \int_0^\infty dE_R \sum_T \frac{C_T}{M_T} G_T(E_R, E') \frac{dR_T}{dE_R}$$

- E': detected energy (in keVee or number of PE), C_T: mass fraction in target nuclide T;
- $\varepsilon(E')$: counting efficiency or cut acceptance; $G_T(E_R, E')$: energy response function

$$\frac{dR_T}{dE_R} = \int_{v>v_{min}} \frac{d\sigma_T}{dE_R} \times \frac{1}{m} \rho v f(\vec{v}, t) d^3v$$

Elements of the rate: Each with its own uncertainties

$$\left[\begin{array}{l}\text{Event}\\ \text{Rate}\end{array}\right] = \left[\begin{array}{l}\text{Detector}\\ \text{Response}\end{array}\right] \times \left[\begin{array}{l}\text{Cross}\\ \text{Section}\end{array}\right] \times \left[\begin{array}{l}\text{Halo}\\ \text{Model}\end{array}\right]$$

Elements of the Event Rate in Direct DM detection

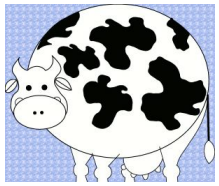
$$\left[\begin{array}{c}\text{Event}\\ \text{Rate}\end{array}\right] = \left[\begin{array}{c}\text{Detector}\\ \text{Response}\end{array}\right] \times \left[\begin{array}{c}\text{Cross}\\ \text{Section}\end{array}\right] \times \left[\begin{array}{c}\text{Halo}\\ \text{Model}\end{array}\right]$$

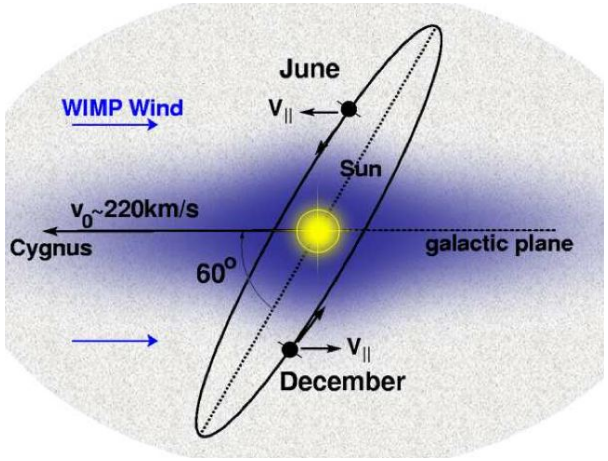
How many DM particles are passing through the detector and with which velocity distribution?

The usually assumed Standard Halo Model is a good first approximation but not expected to be correct. Uncertainty in measurements of key parameters, triaxiality, anisotropies and debris flows are found in simulations, and Earth could be within a DM clump, or DM stream, and maybe a Dark Disk...

Could we avoid using a halo model when comparing direct DM detection data?
Lots of work on "Halo-Independent" methods since 2010.

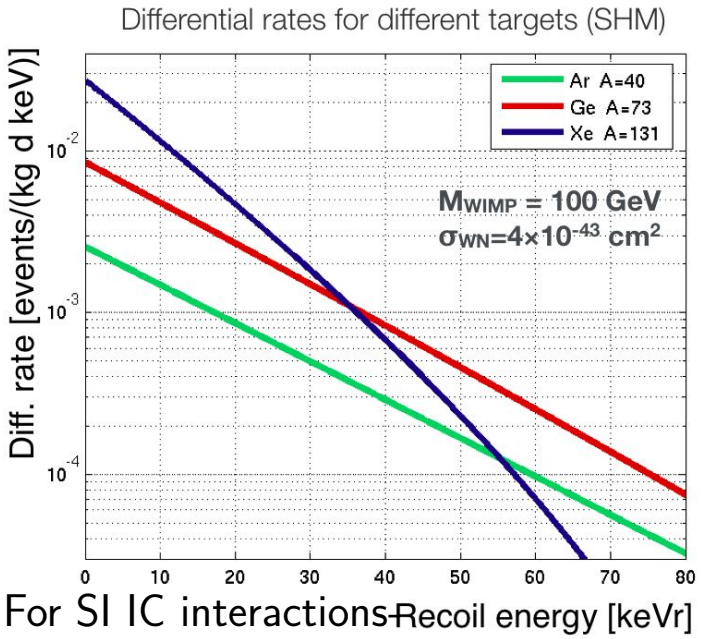
Standard Halo Model (SHM)

The  of halo models



- $\rho_{SHM} = 0.3^{+0.2}_{-0.1}$ GeV/cm^3
- $f(v,t)$: Maxwellian $\vec{v}$ distribution

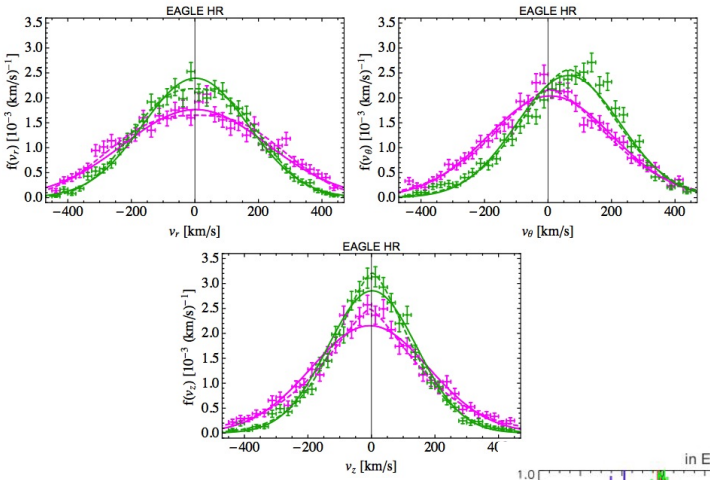
at rest with the Galaxy $v_\odot \simeq$220km/s (190 to 320km/s), $v_{esc} \simeq$500-650km/s

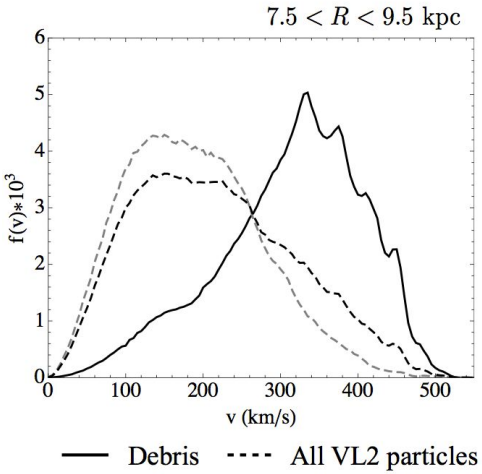


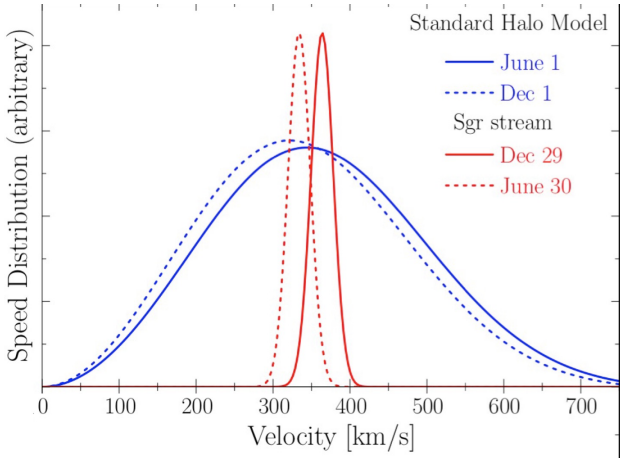
Expected annual modulation with max in late May-early June, min. in Dec. (unless gravitational focussing from the Sun is important) (Drukier, Freese, Spergel 1986)

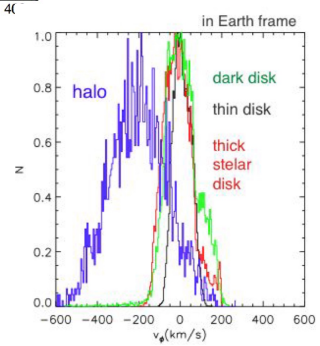
...but triaxiality, debris flows, streams, dark disk...

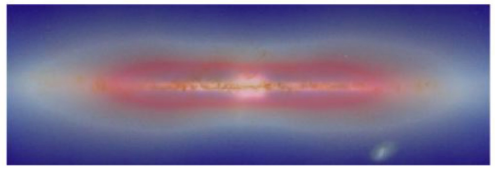
Distributions of radial, azimuthal, and vertical velocity components:











Could we avoid using a dark halo model to analyze Direct DM Detection data?
Could we use this data to predict the local characteristics of the dark halo instead?

"Halo-Independent": Recall the event rate:

For a WIMP-nucleus contact differential cross section (for momentum transfer and velocity-independent interaction operators) e.g. for Spin Independent interactions

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

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

- ρ, $f(\vec{v},t)$: local DM density, Earth's frame $\vec{v}$ distribution depend on halo model

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

"Halo-Independent": Given m, $d\sigma_T/dE_R$ plots in $(v_{min}, \tilde{\eta}(v_{min}))$ plane,

$$\tilde{\eta}(v_{min},t) = \frac{\sigma_{ref}}{m}\rho\eta(v_{min},t)$$

contains all halo dependence in ANY experiment!

Fox, Liu, Weiner 1011.1915; Frandsen et al 1111.0292; Gondolo-Gelmini 1202.6359...

"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

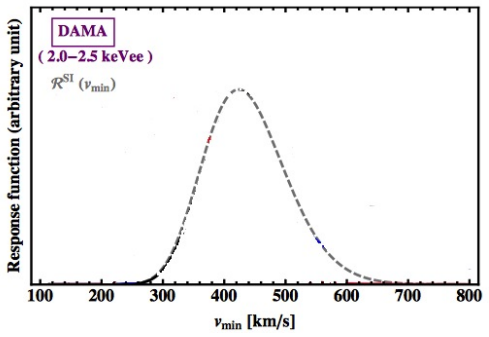
for ANY interaction, energy resolutions, efficiencies...

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

Use instead experimentally accessible quantities, including isotopic composition, energy resolutions and efficiencies, form factors with arbitrary energy dependence, and any interaction.
We write the predicted observable rate for any cross section as

$$R_{[E_1',E_2']} = \int_0^\infty dv_{min}\ \mathscr{R}_{[E_1',E_2']}(v_{min})\,\tilde{\eta}(v_{min})$$

$\mathscr{R}_{[E_1',E_2']}$: **experiment and interaction dependent response function**
(non zero only for an interval in v_{min} given a measured energy interval $[E_1', E_2']$)



"Halo Independent" data analysis

1- **Find the predictions of Direct Detection data for** $\tilde{\eta}(v_{min}, t)$, e.g. for the coefficients of the harmonic expansion of $\tilde{\eta}(v_{min}, t)$

2- **Compare data from different experiments by comparing their predictions for the halo**,
– putative detections translate into regions in the $(v_{min}, \tilde{\eta}(v_{min}))$ plane,
– upper limits on rates produce upper limits on $\tilde{\eta}(v_{min})$

Main Problem: Likelihoods are good for **parameter estimation**, **but here we want to find a function,** $\tilde{\eta}$**!** which the predicted rates depend on

$$R_{[E_1', E_2']} = \int_0^\infty dv_{min}\ \mathscr{R}_{[E_1', E_2']}(v_{min})\, \tilde{\eta}(v_{min})$$

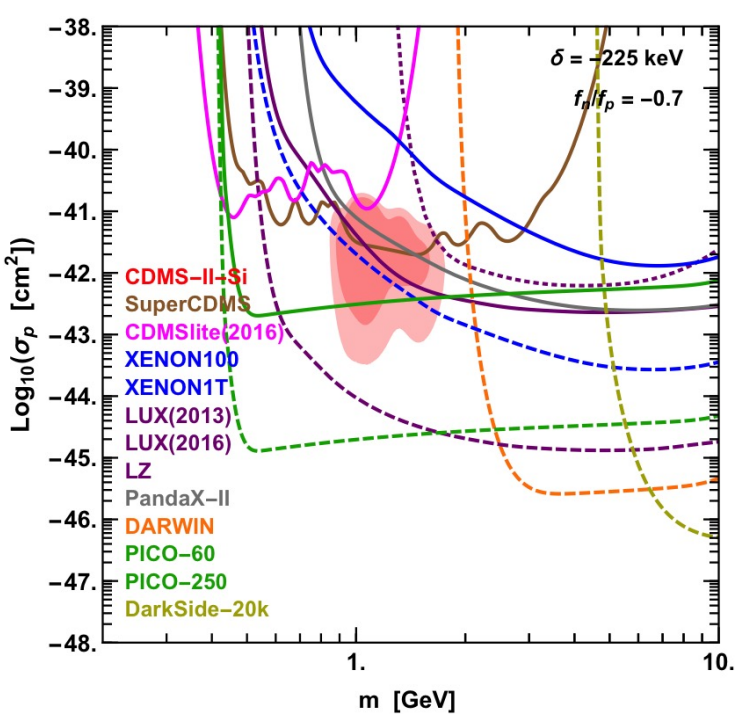
Inferred local DM speed distribution $\tilde{\eta}$

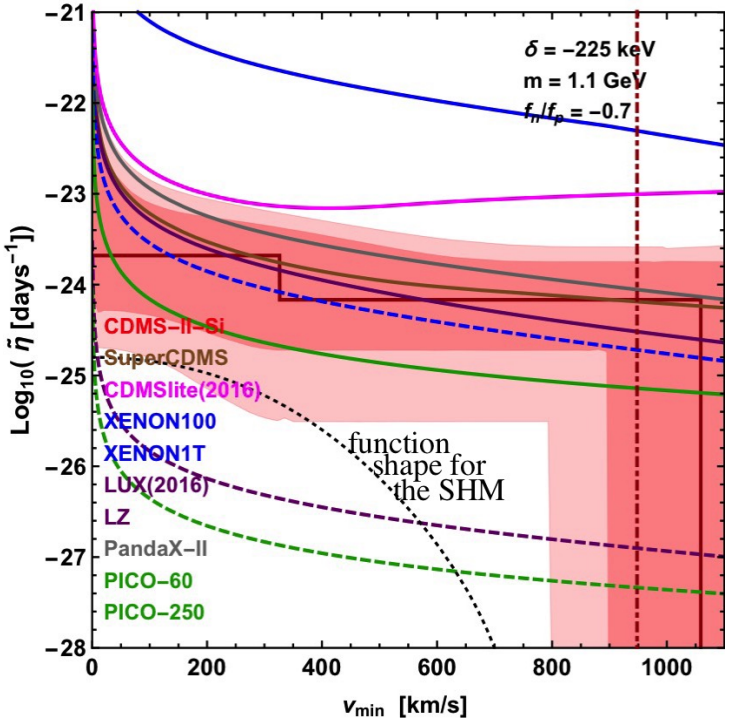
For a putative DM (time averaged) rate detection with unbinned data (e.g. CDMS-II-Si), using at least one extended likelihood, we found (Fox, Kahn and McCullough 1403.6830; Gelmini, Georgescu, Gondolo and Huh 1507.03902; Gelmini, Huh and Witte 1607.02445)

- a unique piecewise constant best fit $\tilde{\eta}(v_{min})$ with a number of downward steps $\leq$ number of data points, by extending to functionals the Karush-Kuhn-Tucker (KKT) maximization conditions (Fox, Kahn and McCullough 1403.6830), and a way to define

- statistically meaningful two-sided point-wise band at a chosen CL. (Gelmini, Georgescu, Gondolo and Huh, 1507.03902)

CDMS-II-Si candidate?: Inelastic exothermic DM with SI IV coupling Here $\delta = -225$ keV Gelmini, Georgescu, Gondolo and Huh, 1507.03902, Witte, Gelmini 1703.06892





LEFT: SHM RIGHT: Halo independent for m=1.1 GeV

Can be ruled out by an LZ or PICO-250 like experiment (not XENON1T)

A deeper understanding of Halo-Independent methods for all Likelihoods Gelmini, Huh and Witte 1707.07019

Why a piecewise constant best fit $\tilde{\eta}(v_{min})$ with the number of downward steps $\leq$ the number of data points (d)???

Well known theorems in convex geometry (Caratheodory, Fenchel-Eggleston) provide the answer: for d (time average) predicted rates the DM speed distribution $F(v)$, normalized to 1, is given by

$$F(v) = \sum_{n=1}^{d} F_n \, \delta(v - v_n)$$

with d= number of data points, which has at most 2d parameters F_n, v_n to estimate using the Likelihood.

Thus the integral $\tilde{\eta}(v_{min}) = const. \int_{v_{min}}^{\infty} dv \; F(v)/v$ is piecewise constant with at most d downward steps! (for the analysis of time dependent rates, go to galactic frame, where the velocity distribution is not time dependent, but the kernels are- see 1707.07019)

Prospects for DM direct detection-

In recent years we opened up to consider all possible DM-SM interactions and developed better ways to compare data from different experiments

"Halo-Independent" analysis is on firm mathematical ground..

In the near future: new data.

DAMA clearly sees an annual modulation at 12.9σ, DM or instrumental?

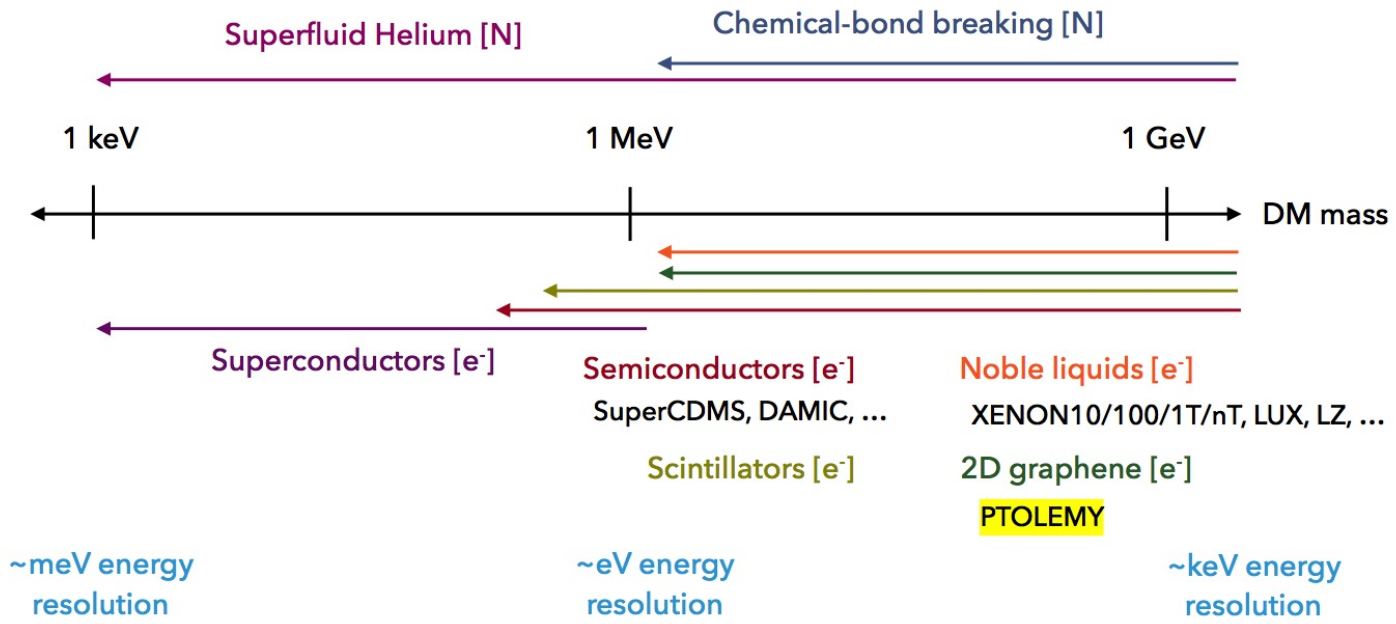
- "Global NaI(TI) Collaborative Effort": KIMS (52 kg) and DM-Ice (55 kg), in YangYang Lab. (S Korea), ANAIS (112 kg), in Canfranc Lab. (Spain) and SABRE (50 kg) in two sites, Gran Sasso Lab. (Italy) and Stawell Lab., Australia

Very important to check in the Southern Hemisphere!

- XENON1T, LZ, XENONnT, DarkSide20T, SuperCDMS, PICO...
- Further future: Directional Direct DM detectors (DRIFT, DMTPC)...?

Many ideas for sub-GeV "Light Dark Matter" (LDM) direct detection are being actively explored

"Dark Sector Workshop", 1608.08632, DOE workshop "U.S. Cosmic Visions: New Ideas in Dark Matter" in March of 2017



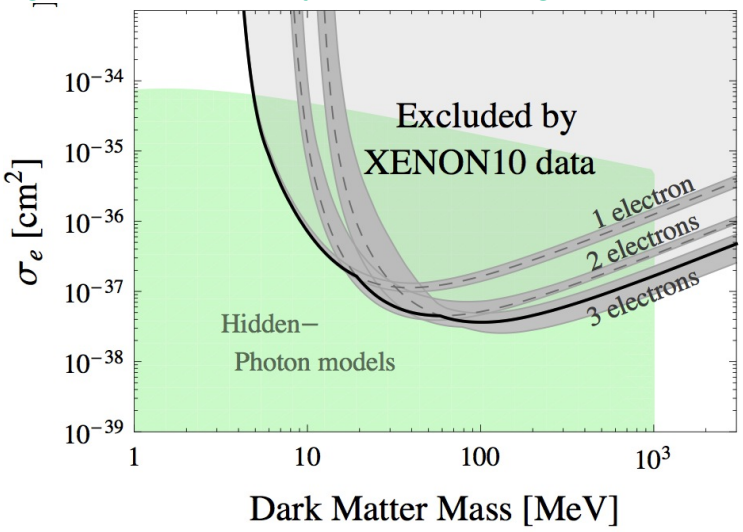
Materials that could be used to probe LDM, by scattering off electrons [e^-] or inelastic scattering nuclei [N] (photon emission in the nuclear recoil, breaking of chemical bonds in molecules or crystals, multi-phonon processes in superfluid helium or insulating crystals)

Sub-GeV "Light Dark Matter" (LDM)

$m \simeq$ keV to 0.1GeV$<<$ M, thus the maximum energy imparted in an elastic collision with the whole nucleus is below threshold for most experiments ($E_{thres} > 0.1$ keV)

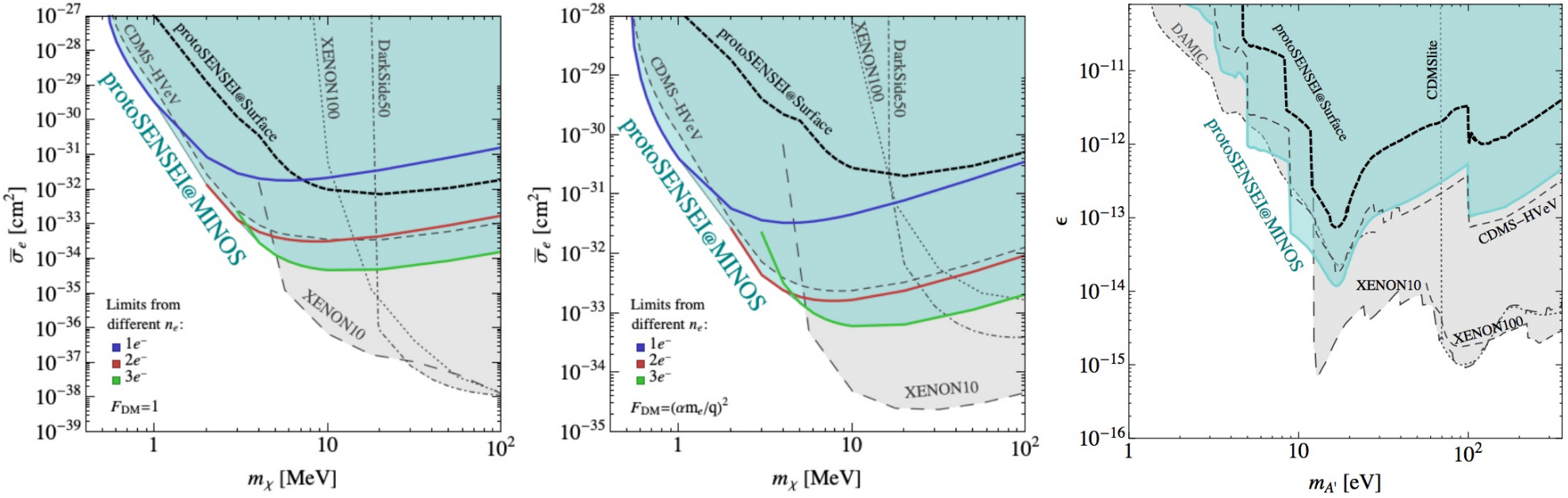
$$E_{max}^{elastic-Nuclei} \simeq 20eV \left(\frac{m}{100MeV}\right)^2 \left(\frac{10GeV}{M}\right)$$

but LDM could deposit enough energy, 1 to 10 eV, interacting with electrons (electron ionization, electronic excitation, molecular dissociation...) Bernabei et al. 0712.0562; Kopp et al. 0907.3159; Essig, Mardon & Volansky, 1108.5383; Essig et al. 1206.2644; Batell, Essig & Surujon 1406.2698



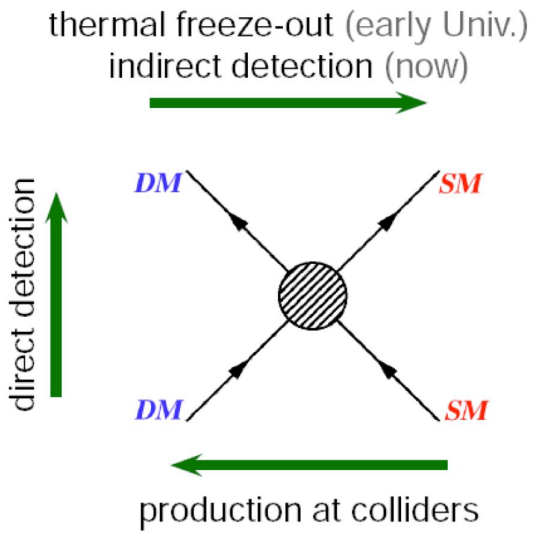
Many ideas for sub-GeV "Light Dark Matter" (LDM) direct detection are being actively explored

SENSEI "Direct-Detection Constraints on sub-GeV Dark Matter from a Shallow Underground Run Using a Prototype Skipper-CCD" LEFT: direct-detection constraints on eV-to-GeV dark matter interacting with electrons, exposure 0.177 gram-days 1901.10478



Right: limit on dark photon with mixing ε

WIMP DM searches:



- Direct Detection- looks for energy deposited within a detector by the DM particles in the Dark Halo of the Milky Way.

- Indirect Detection- looks for WIMP annihilation (or decay) products.
  Caveat: DM may not annihilate or decay

- At colliders (the LHC) as missing transverse energy, mono-jet or mono-photon events

Indirect detection through γ and anomalous cosmic rays

Main detectors: PAMELA, AMS, Fermi ST, HESS, VERITAS, CANGAROO, MAGIC

Look for an excess of γ, e^+, $\bar{p}$ over expected, and a bump at $E \sim m$

(Fig. from G. Gondolo)

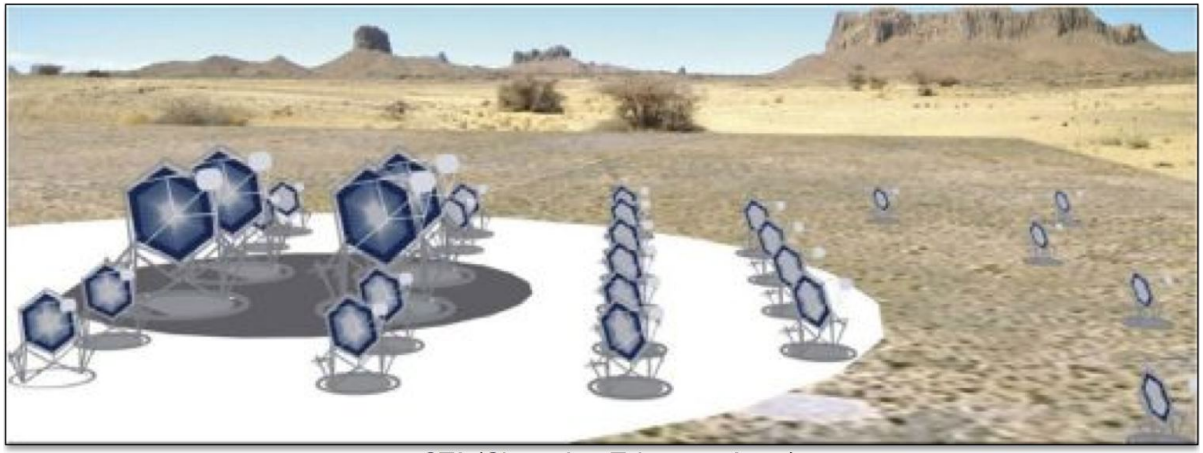
PAMELA

AMS

Fermi-LAT (Fermi Large Area Telescope)

H.E.S.S. & H.E.S.S.-2

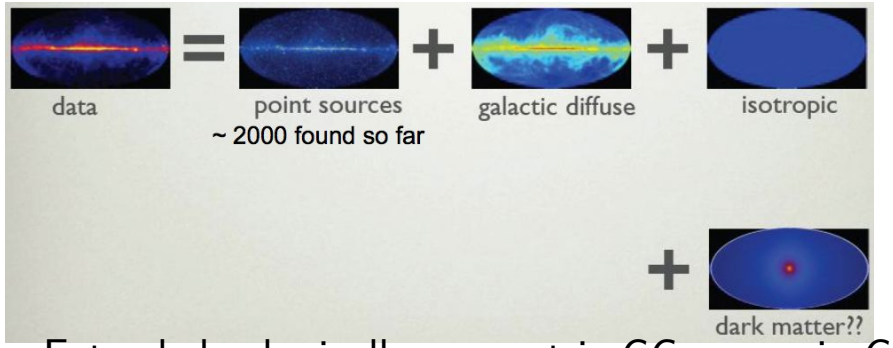
In planning stage

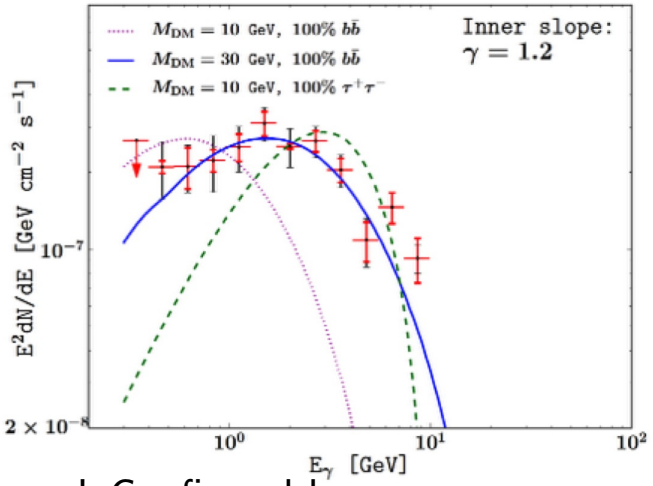


CTA (Cherenkov Telescope Array)

Light WIMPs in the sky too?

GeV γ's from extended region at the Galactic Center and Inner Galaxy. From annihilation of DM with m =7-10GeV into $\tau^+\tau^-$ or 30-45GeV into $q\bar{q}$? Goodenough& Hooper 0910.2998, Hooper& Goodenough 1010.2752, Hooper& Linden 1110.0006; Hooper 1201.1303; Abazajian& Kaplinghat 1207.6047, Hooper etal 1305.0830, Macias& Gordon, 1306.5725, Abazajian et al. 1402.4090, Dayland et al. 1402.6703, Cholis, Hooper& Linden 1407.5625, Calore, Cholis& Weniger 1409.0042, Bartels, Krishnamurthy& Weniger 1506.05104, Lee et al. 1506.05124, Hooper&Mohlabeng 1512.04966, Fermi-LAT 1511.02938 and 1704.03910, ...



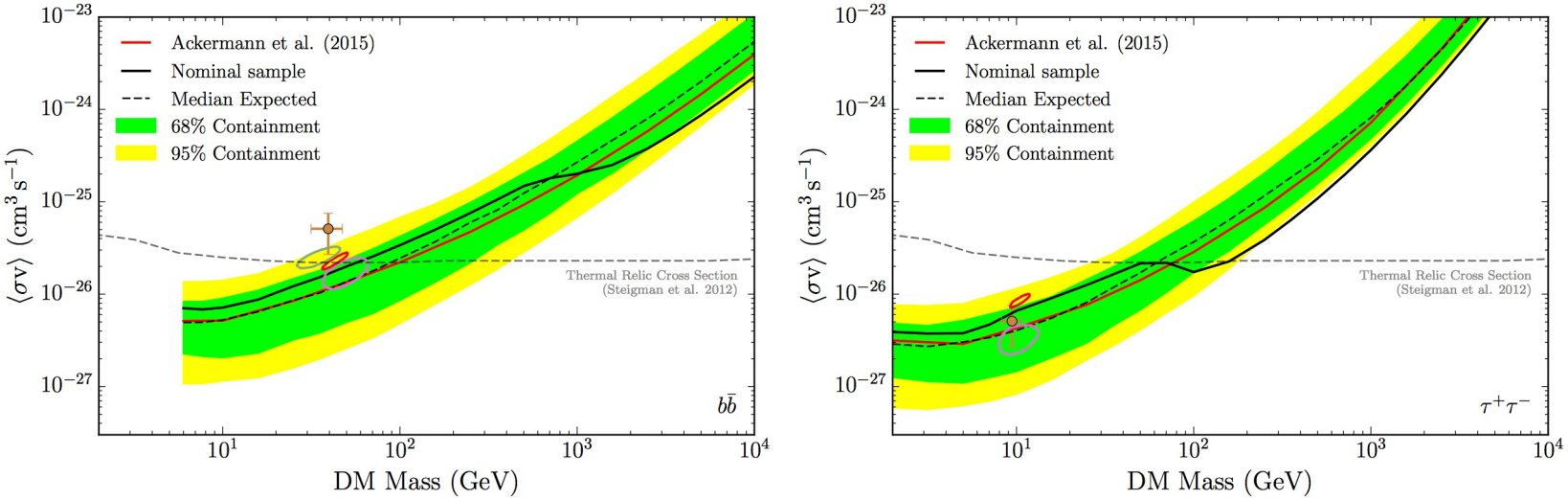


Extended spherically symmetric GC excess in GeV's gamma rays! Confirmed by many groups..

DM annihilation or astrophysical? Unresolved millisecond pulsars: why so many and why spherically distributed? For DM GC excess is in considerable tension with combined dwarf galaxy Fermi-LAT analyses. Abazajian&Keeley 1512.04966, Fermi LAT 1503.0264

Upper limit on annihilating DM from Fermi ST 95% CL upper limits, 6 y of

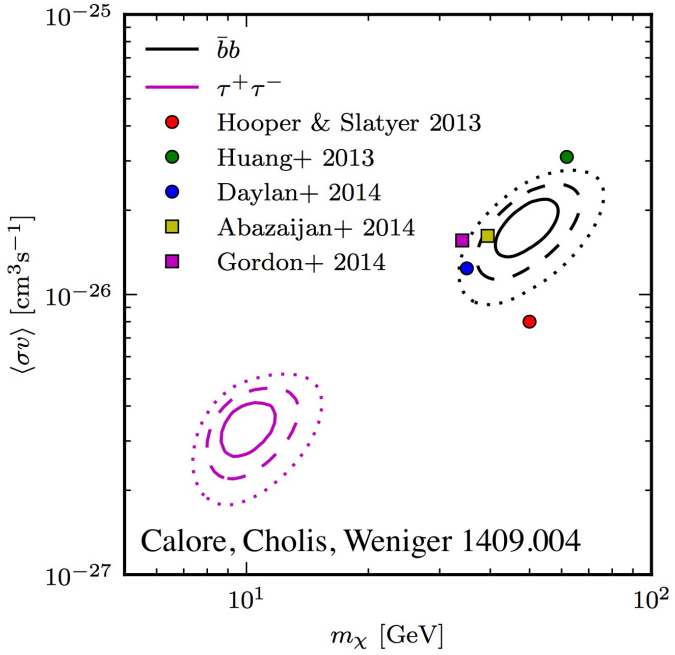
Fermi Large Area Telescope (LAT)- 15 stacked dwarfs 1611.03184



Shown are to the GC excess. They are in tension with the upper limit.

This analyses rules out the "WIMP miracle" benchmark annihilation cross section ($< \sigma_{annih} v > \simeq 2 \times 10^{-26}$ cm^3/s) for masses up to $\simeq$60 GeV for s-wave annihilation, i.e. v-independent $\sigma_{annih} v$. For p-wave annihilation $\sigma_{annih} v \sim v^2$, so it is 10^5 times larger at WIMP decoupling ($v \simeq 0.3$c) than in the galaxy ($v \simeq 10^{-3}$c)

GC GeV excess

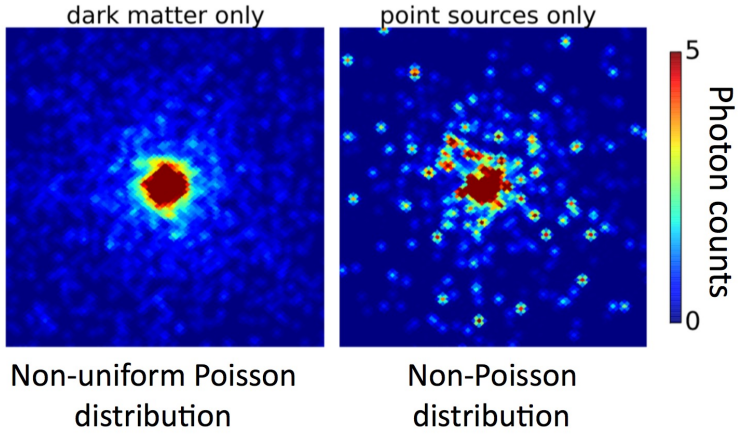


Given the astrophysics uncertainties this signal could at most constitute a confirmation of a DM discovery somewhere else.

Potential astrophysical sources of the GC excess:

- Past activity of the Galactic center Carlson & Profumo 1405.7685, Petrovic, Serpico &Zaharijas1405.7928
- Series of leptonic cosmic-ray outbursts Cholis et al. 1506.05119
- Molecular Clouds in the disk De Boer et al. arXiv:1610.08926
- Stellar population of the X-bulge and the nuclear bulge Macias et al. 1611.06644
- Unresolved millisecond pulsars Abazajian 1011.4275, Bartels, Krishnamurthy & Weniger 1506.05104

Differences in the statistics of the photon counts can be quantified - tentative evidence of an unresolved point source population found Lee et al 1506.05124, Bartels et al 1506.05104 or small scale structure of the diffuse background? Horiuchi, Kaplinghat & Kwa 1604.01402

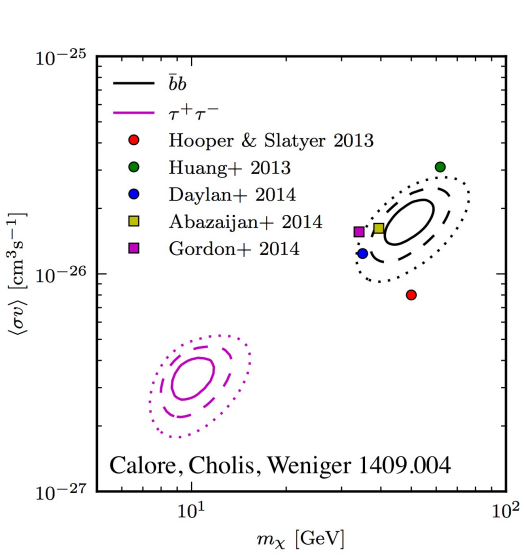


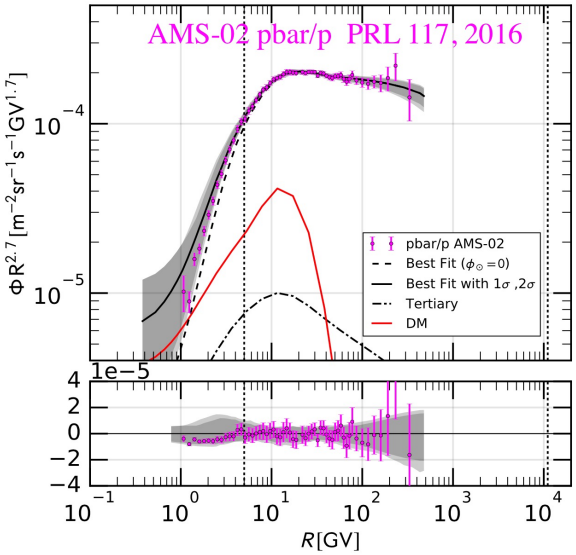
Still jury is out on the origin of the GC excess:

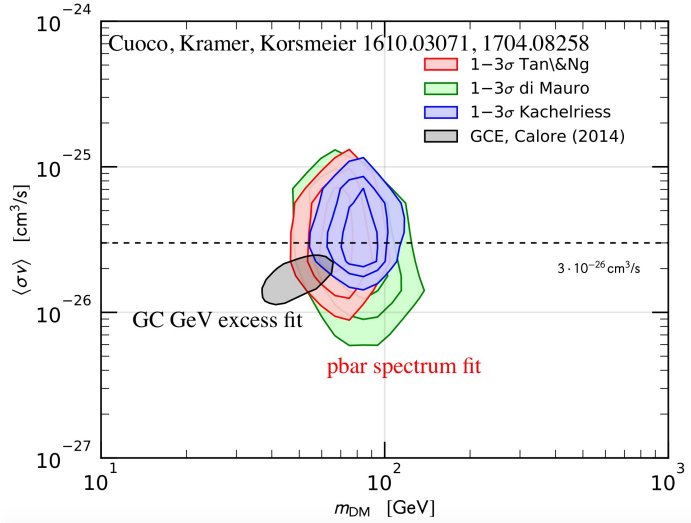
"DM Strikes back": Statistical evidence suggested that the GC excess originates from point sources. But, unmodeled sources in the Fermi Bubbles can lead to a DM signal being misattributed to point sources Leane and Slatyer 1904.08430

- GC excess traces the stellar over-density of the Galactic bulge ("Boxy Bulge" due to the bar in our galaxy), so no more room for DM Macias et al 1901.03822

GC GeV excess and AMS-02 $\bar{p}$ spectrum?



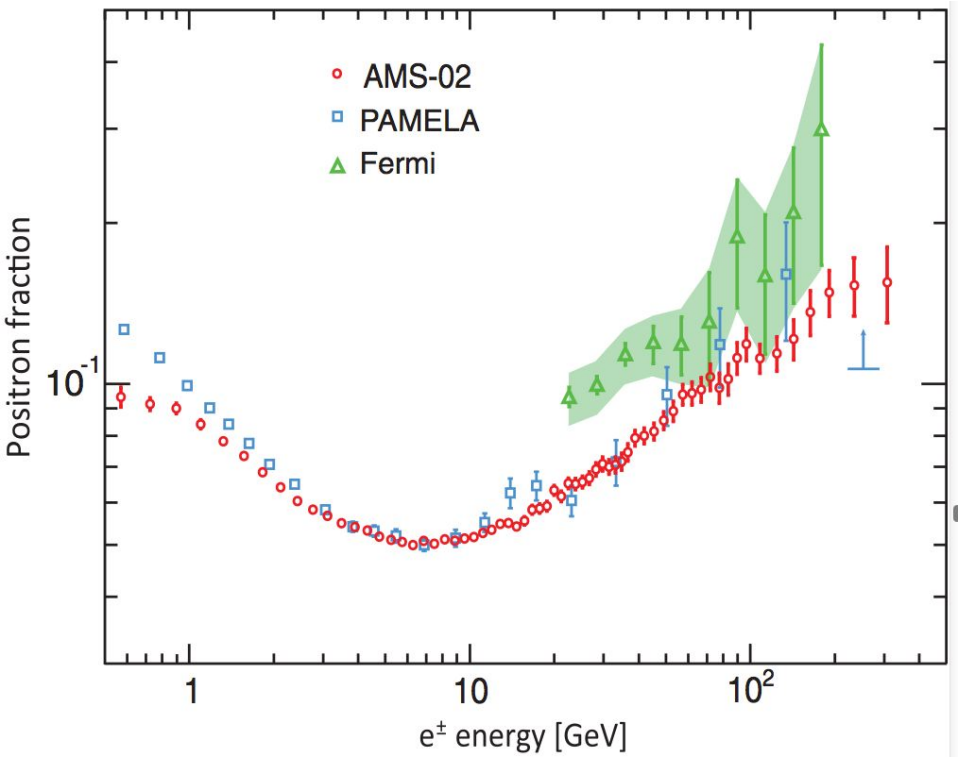


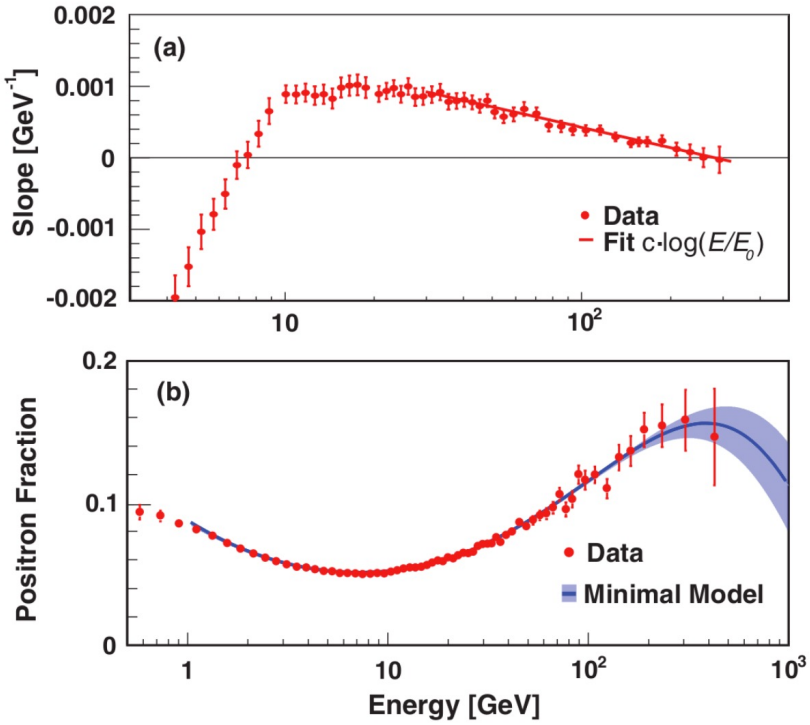


LEFT: some fits to the GC excess, MIDDLE: Cosmic-ray $\bar{p}/p$ ratio as a function of rigidity measured by AMS-02 compared to that predicted from standard secondary production in the interstellar medium. Excess appears at energies between 10 and 20 GeV (but large systematic uncertainties in $\bar{p}$ production cross section, solar modulation and cosmic-ray transport make significance difficult to assess. RIGHT: Fits to $\bar{p}/p$ excess compared with GC excess fits

PAMELA excess 10 to 100's GeV (old "HEAT excess") from the halo

Confirmed by the Fermi Space Telescope-LAT and AMS (Alpha Magnetic Spectrometer) in 2013 (LEFT) and as of 2016 (RIGHT)





DM explanation of the PAMELA/AMS e^+ excess? Would require a very weird DM particle. Meade et al 0905.0480, Cirelli, Panci,Serpico 0912.0663 and others; Cholis, Hooper, 1304.2417

- No $\bar{p}$ excess: "Leptophilic DM"
- No bump in spectrum seen by Fermi and HESS: m_{dm} >TeV.
- Annihilation: not to e^+e^- (would produce sharp peak) but mostly to $\tau^+\tau^-$ or $e^+e^-e^+e^-$ (lead to low mass scale mediators φ, so that $\chi\chi \to \varphi\varphi$ and then $\varphi \to e^+e^-$ Arkani-Hamed, Finkbeiner, Slatyer and Weiner 0810.0713)- And with "boost factor" B $\simeq 10^2 - 10^3$ of the annihilation rate

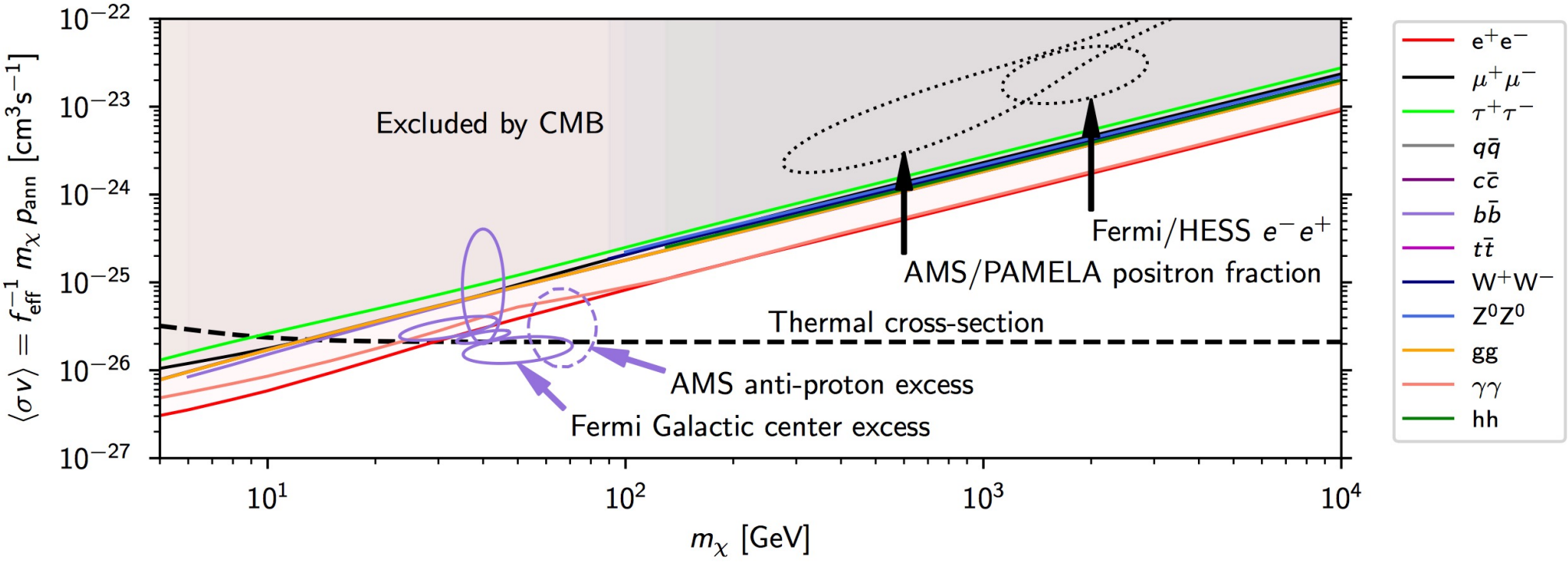
Requires relatively small amount of DM in the GC (cored profiles) to escape GC limits.

- Decay: would need $\tau \simeq 10^{26}$ s. FermiLAT galaxy clusters and extragalactic background data practically exclude this lifetime (limits from our galaxy and from CMB are not competitive for decaying DM).

Otherwise astrophysical origin: "mature" pulsars within a few kpc

In 2017, HAWC first measurements 1702.02992 of the very high-energy (multi-TeV) γ-ray emission from the Geminga and Monogem pulsars- show they inject a flux of e^+ into the local interstellar medium as necessary to account for the observed e^+ excess. This strongly favors nearby pulsars as the origin Hooper et al 1702.08436.

CMB limits on DM annihilation cross sections Planck 2018, 1807.06209



DM annihilations which would heat up the Universe close to recombination would leave an imprint in the CMB- Limits due to the total electromagnetic power injected, so they extend to lower masses too

Indirect limits on DM annihilation cross sections

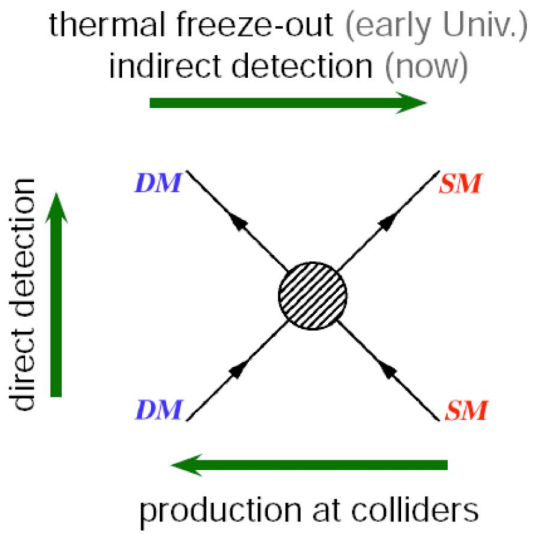
1- CMB anisotropy precision measurements (Planck and others) Constrain DM annihilations (or decays) at recombination or after

2- FermiLAT observations of stacked dwarf galaxies Constrain annihilation at present of DM particles bound to galactic haloes

3- Positron spectrum measured by AMS-02 (more precise that earlier measurements) Constrain annihilation at present of DM particles close to Earth

They all imply $< \sigma v >< 3 \times 10^{-26}$ cm^3/s $= \sigma_{th} v$ for WIMP $m < O(10)$ GeV (exact limit depends on annih. mode). $\sigma_{th} v$ is the upper limit of thermal WIMPs (so $\Omega \leq \Omega_{DM}$). This rejects thermal WIMPs $m < O(10)$ GeV if annihilation is in s-wave:$< \sigma v >$ is v independent, but not constraining for p-wave annihilation: $< \sigma v > \sim v^2$. This is so because at freeze-out $v \simeq c/3$ and it is much smaller at recombination and within galaxies.

WIMP DM searches:



- Direct Detection- looks for energy deposited within a detector by the DM particles in the Dark Halo of the Milky Way.

- Indirect Detection- looks for WIMP annihilation (or decay) products.

- At colliders (the LHC) as missing transverse energy, mono-jet or mono-photon events

  A few comments on LHC searches using simplified DM models.

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.

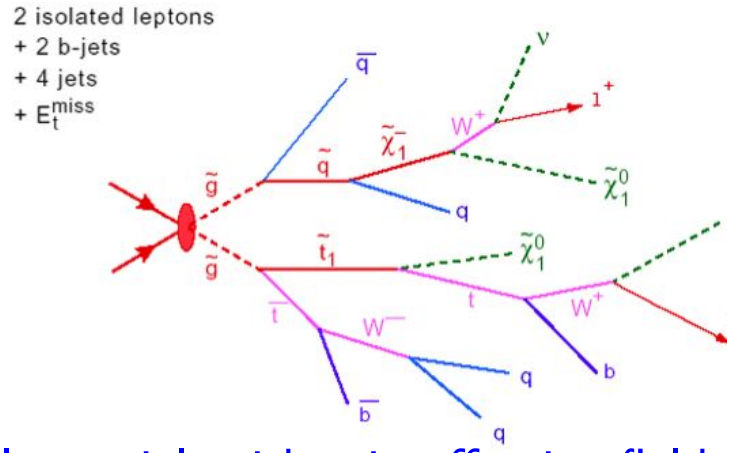
- A DM signal may be hidden by backgrounds.

Searches at the LHC

- Either in complete theories

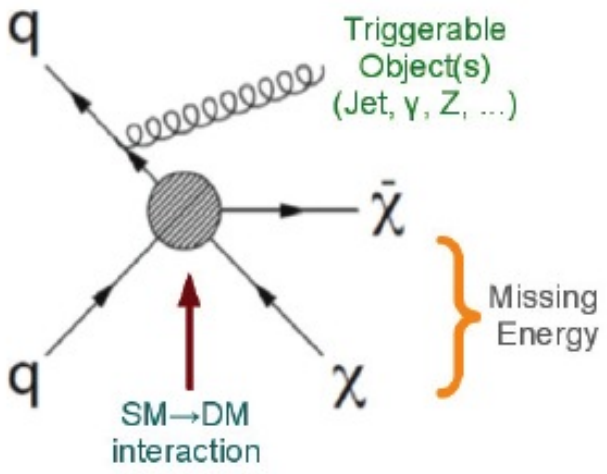
DM through known decay chain

(specific UV complete models e.g. SUSY, or simplified topologies)

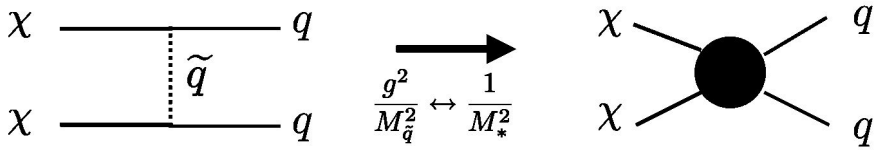


- Or direct DM production plus a visible particle either in effective field theories (EFT) or simplified DM models

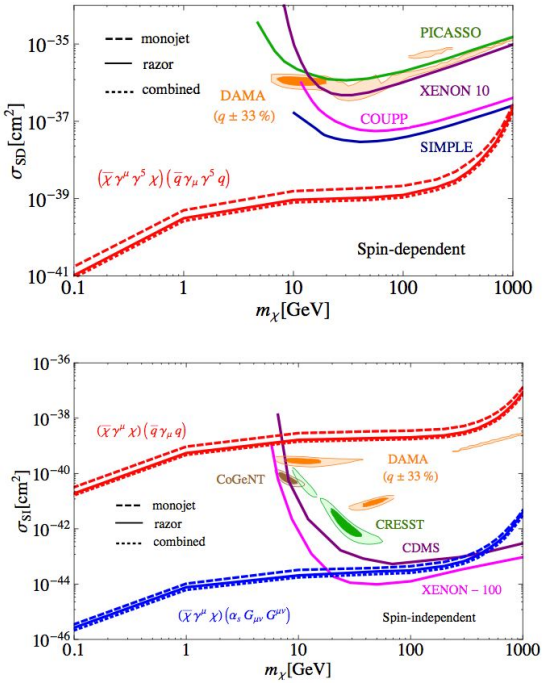
photon or gluon ("monophoton" or "monojet" signal) or mono-W's (leptons), mono-Z's (dileptons), or mono-Higgses.

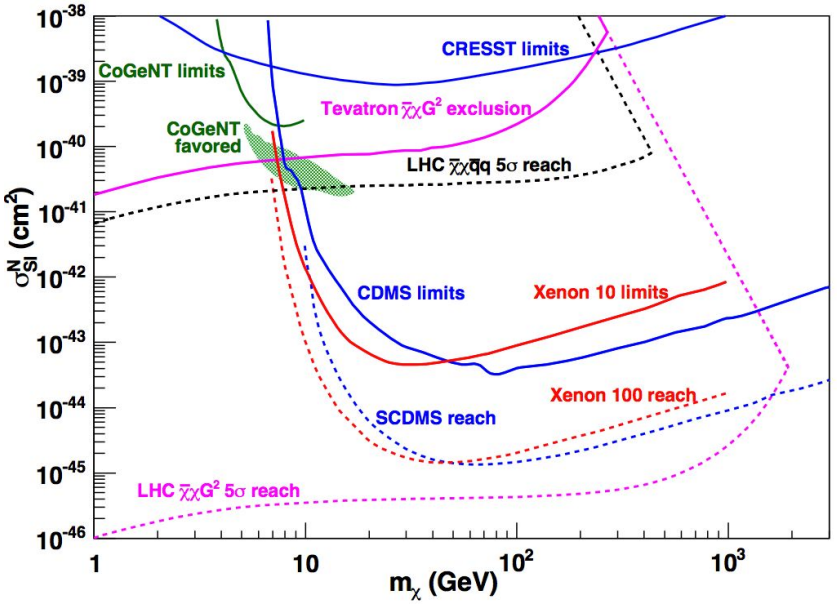


Initially done only for EFT



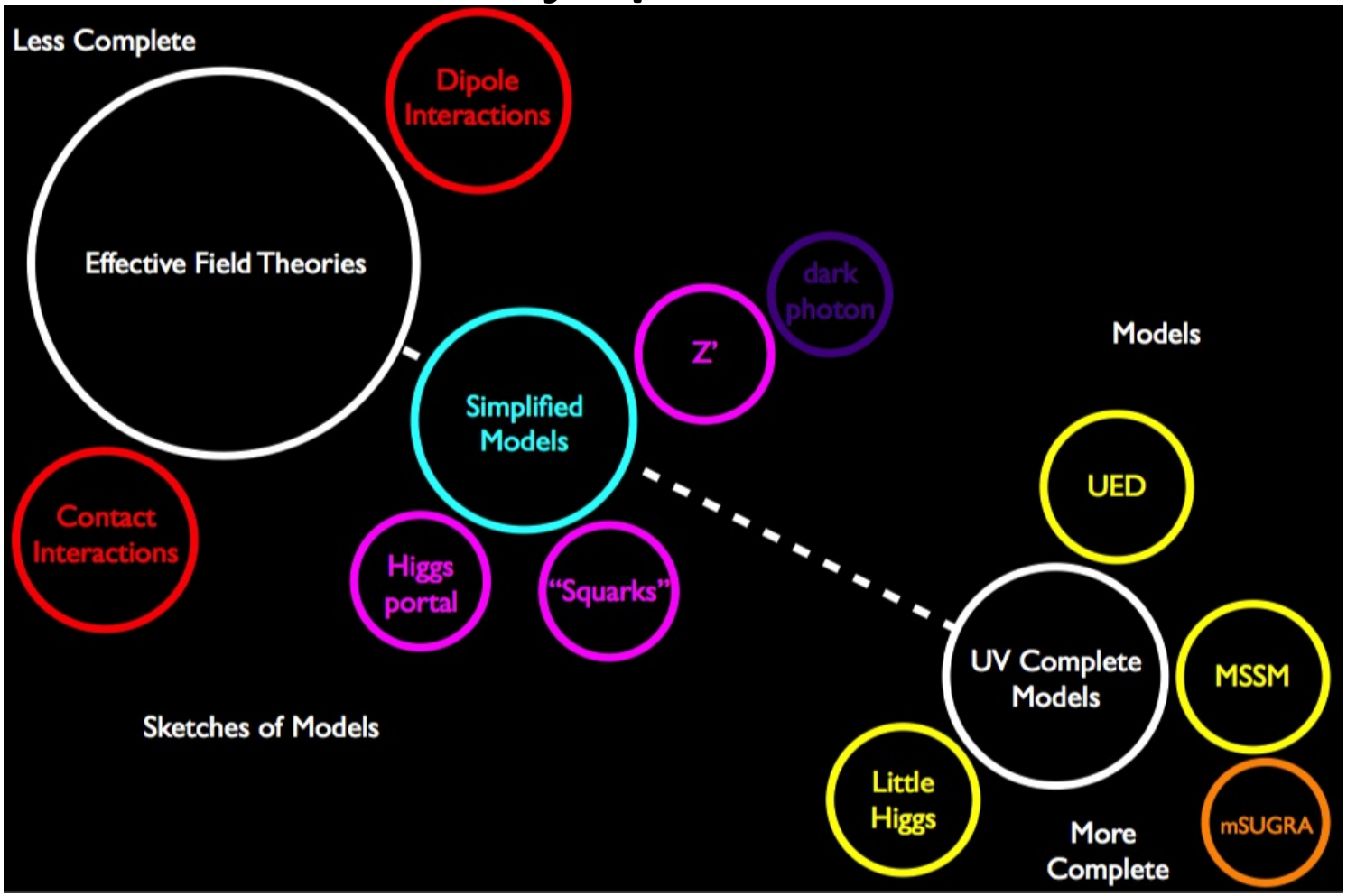
Searches at the LHC direct production plus a photon or gluon (monophoton-monojet signal) for CONTACT interactions Beltran et al 1002.4137; Fox et al 1203.1662





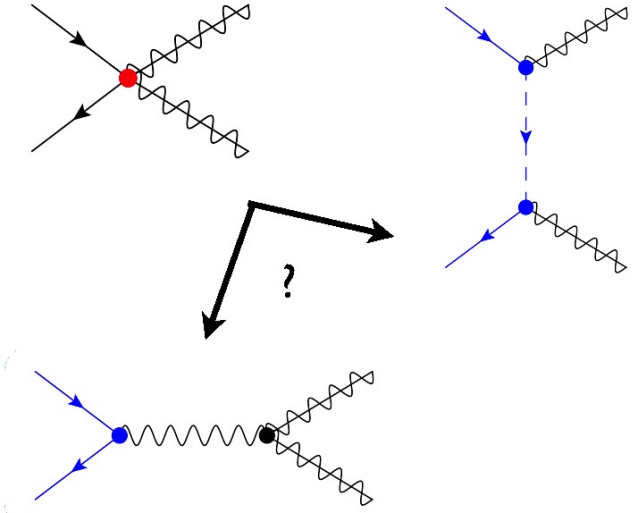
Caveat: in direct DM "contact interaction" if mediator M > q > MeV but here mediators mass > 100's GeV- Problem: for accessible cross sections, LHC can resolve the vertex

Spectrum of DM Theory Space Fig. from T. Tait



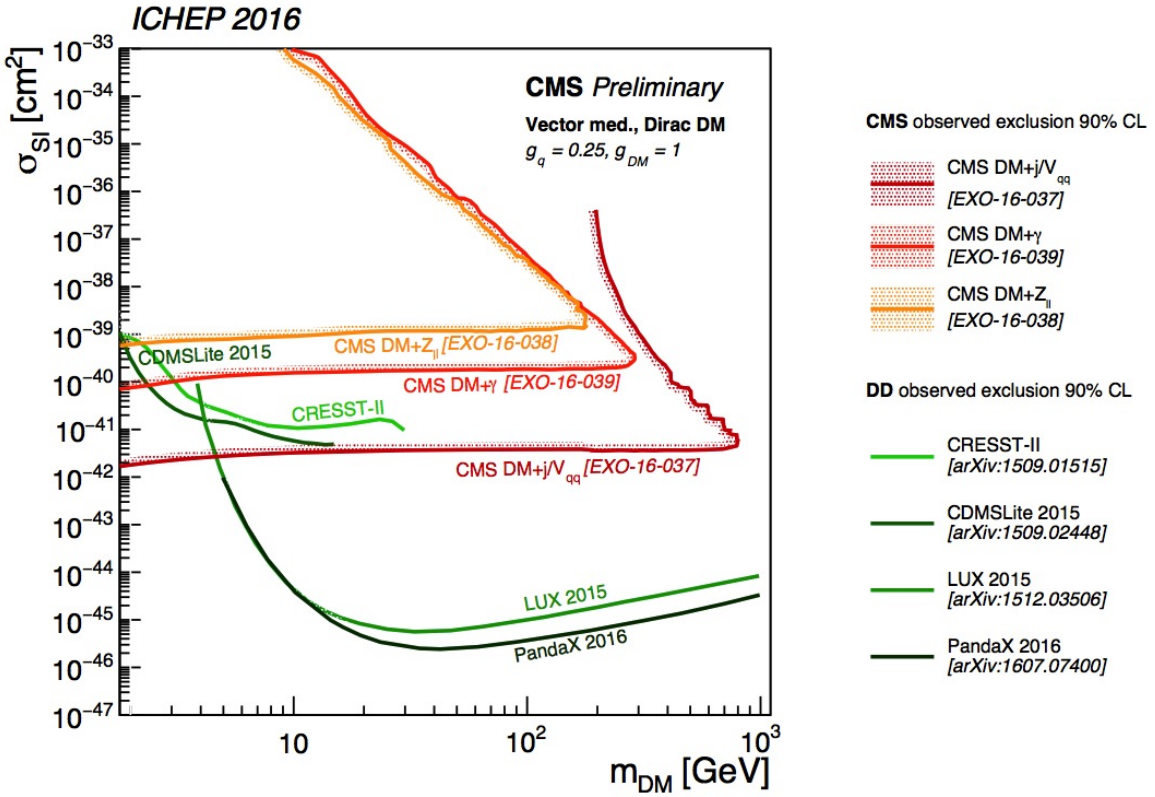
EFT vs "simplified model"

• Many different FT couplings have the same EFT limit! Many, many models to study. How to classify them?



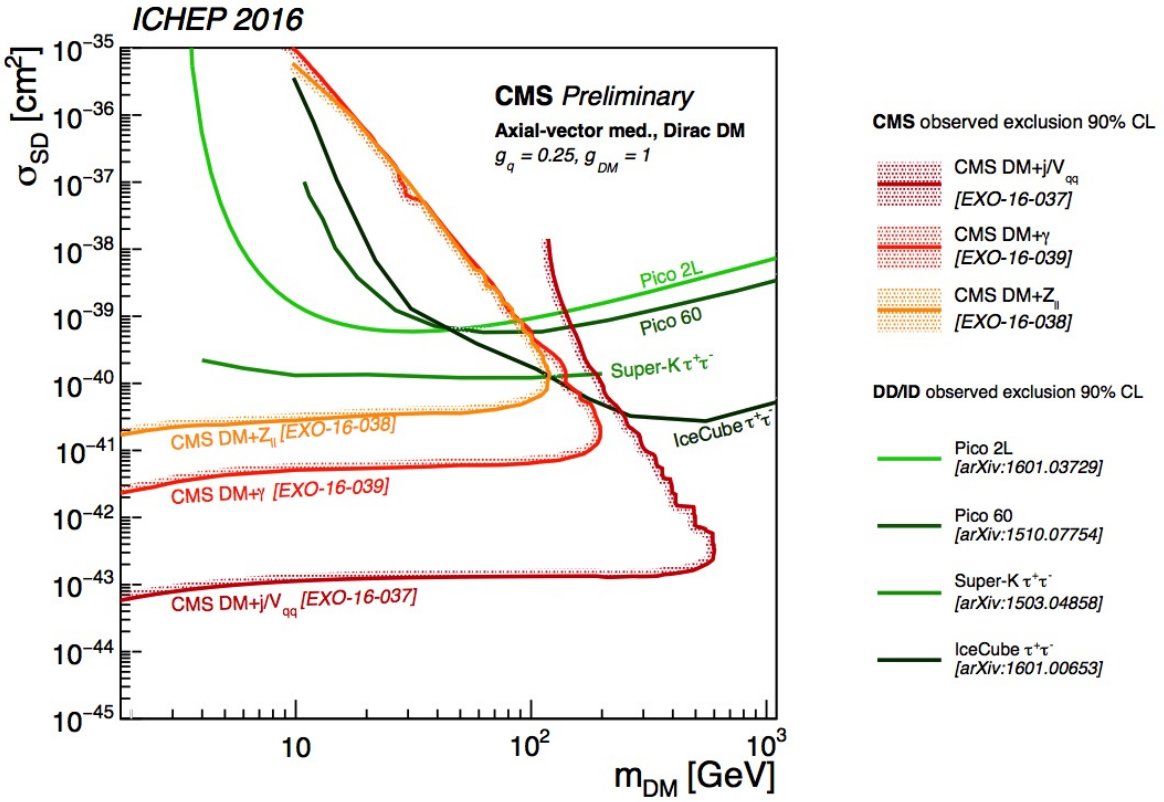
• For light enough mediators, limits on them are important. The mediators themselves can be created at the LHC and other accelerators. Four parameters: $m_{DM}, M_{mediator}, g_q, g_{DM}$.

Simplified Models "Mono" searches - SI vector mediator



Notice large assumed couplings $g_q = 0.25$ $g_{DM} = 1$

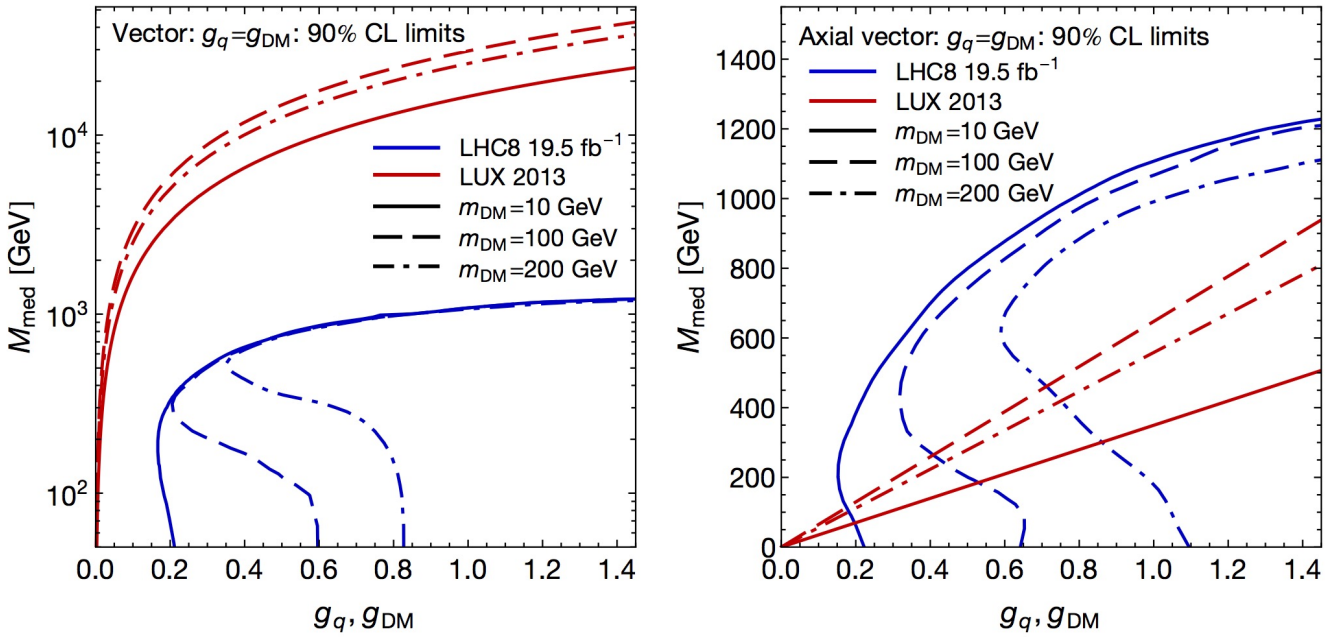
Simplified Models "Mono" searches
SD axial-



If couplings are $\simeq 0.1$ or less LHC limits disappear. E.g. $g_q = g_{DM} < 0.1$

Buchmuller, Dolan, Malik and Mc Cabe, 1407.8257

Simplified Models "Mono" searches limits Buchmuller, Dolan, Malik and Mc Cabe, 1407.8257



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Outlook

DM searches are advancing fast in all fronts, direct and indirect detection, the LHC, astrophysical observations and modeling. Lots of data necessarily lead to many hints. Hopefully at some point several of them will point to the same DM candidate.

Motto attributed to Einstein:

"Make things as simple as possible, but not simpler.