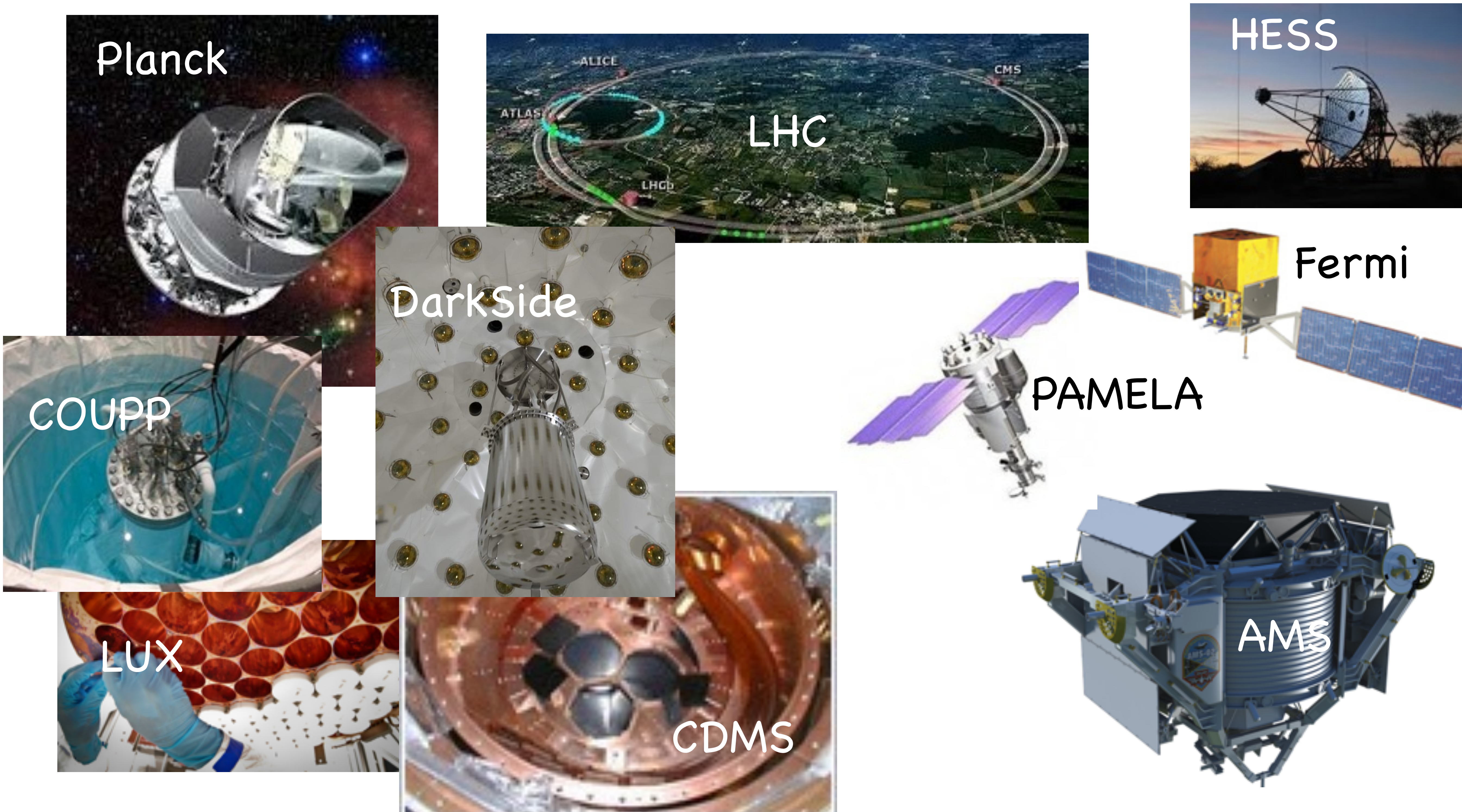
Fermilab

Status of Dark Matter Searches

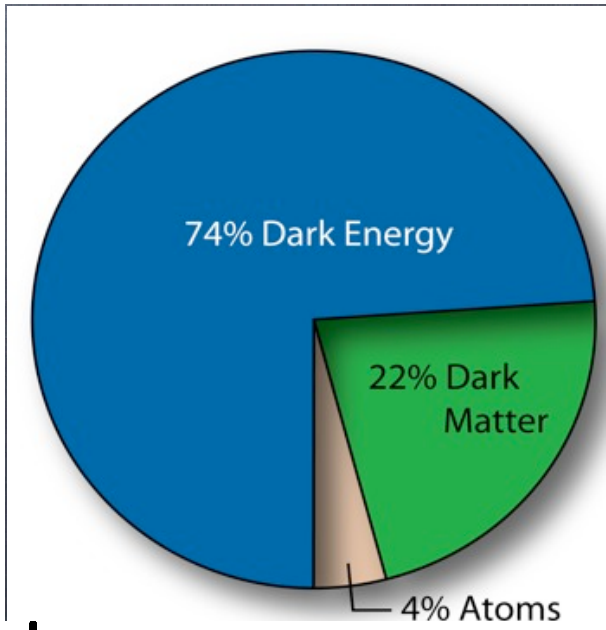


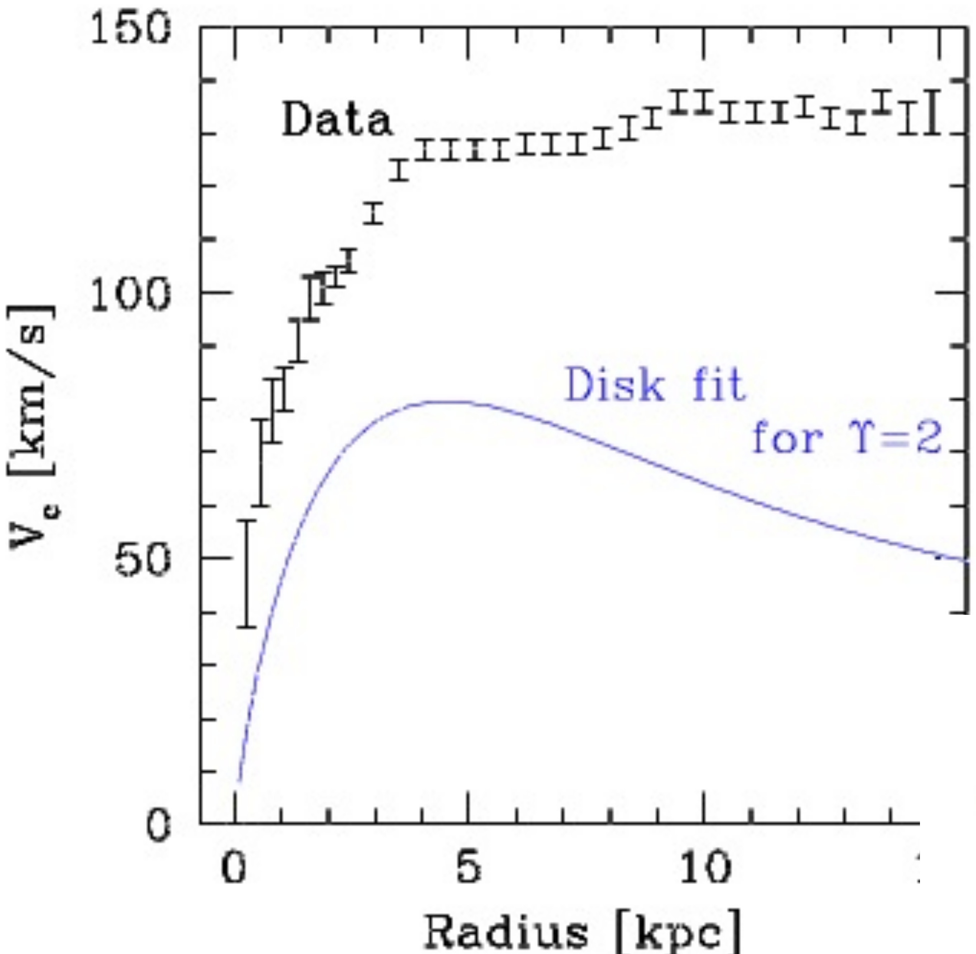
47th Fermilab Users Meeting

Ilias Cholis, 06/12/2014

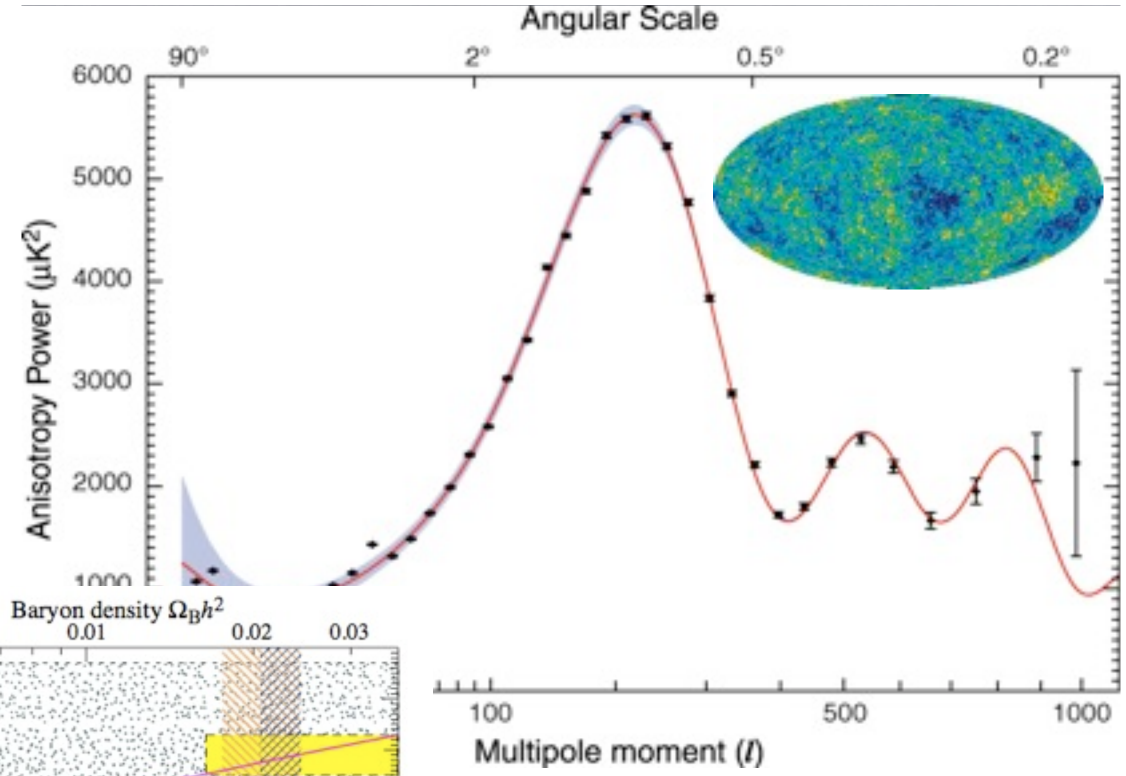
evidence for CDM

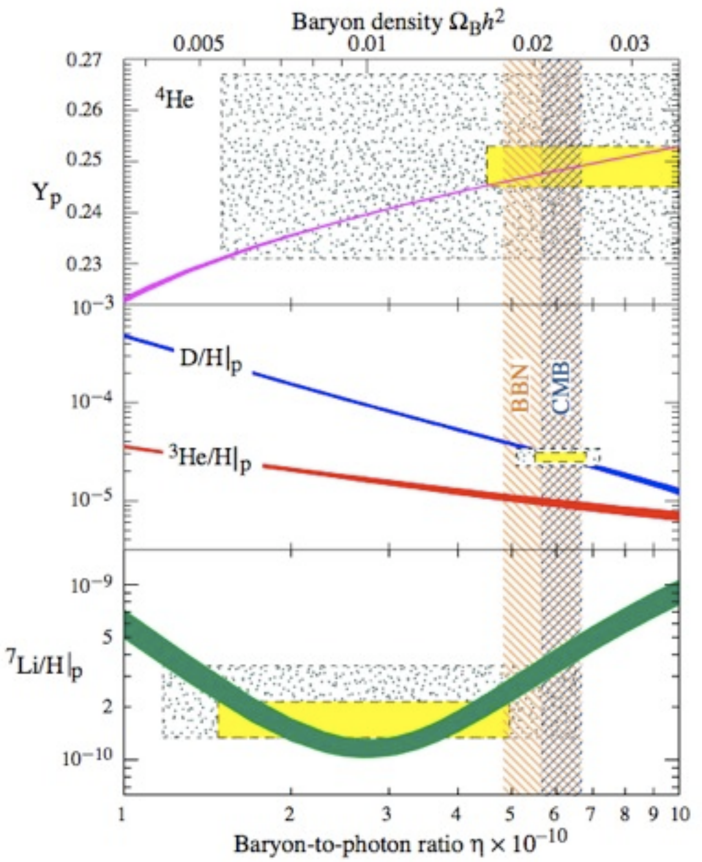
- galactic rotation curves
- velocity dispersion of galaxies in clusters
- CMB data and SN Ia data
- distribution of galaxies
- strong lensing measurements of background objects (usually galaxies)
- bullet cluster
- success of BBN (DM is non-baryonic)
- growth of structure (cold DM)

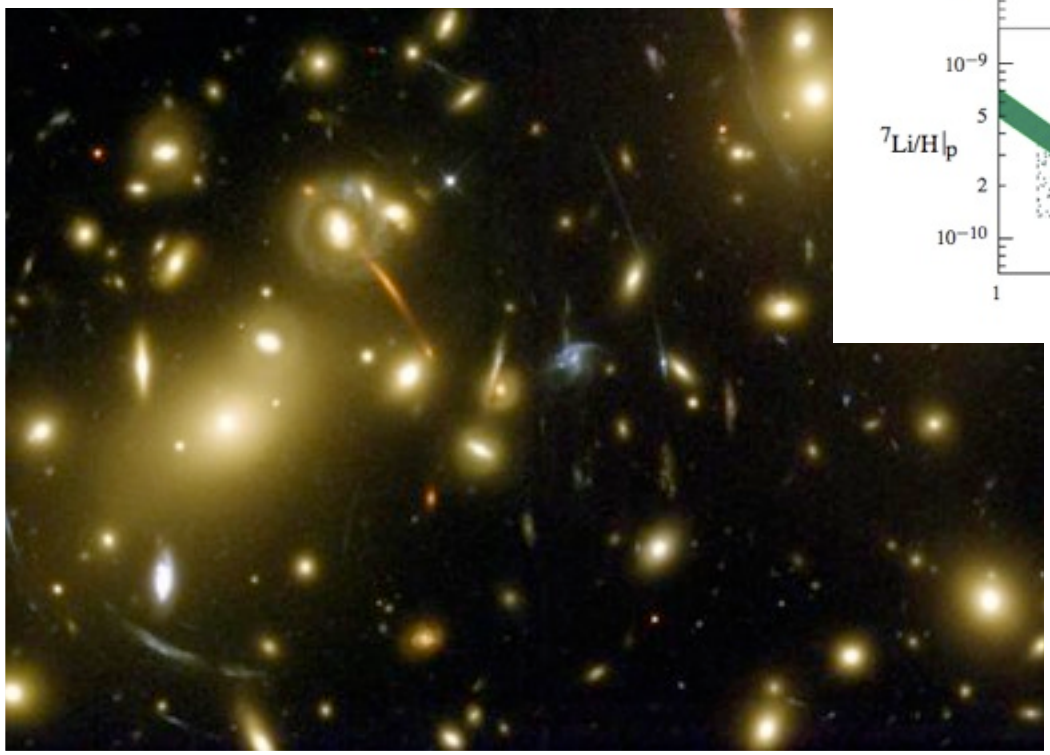


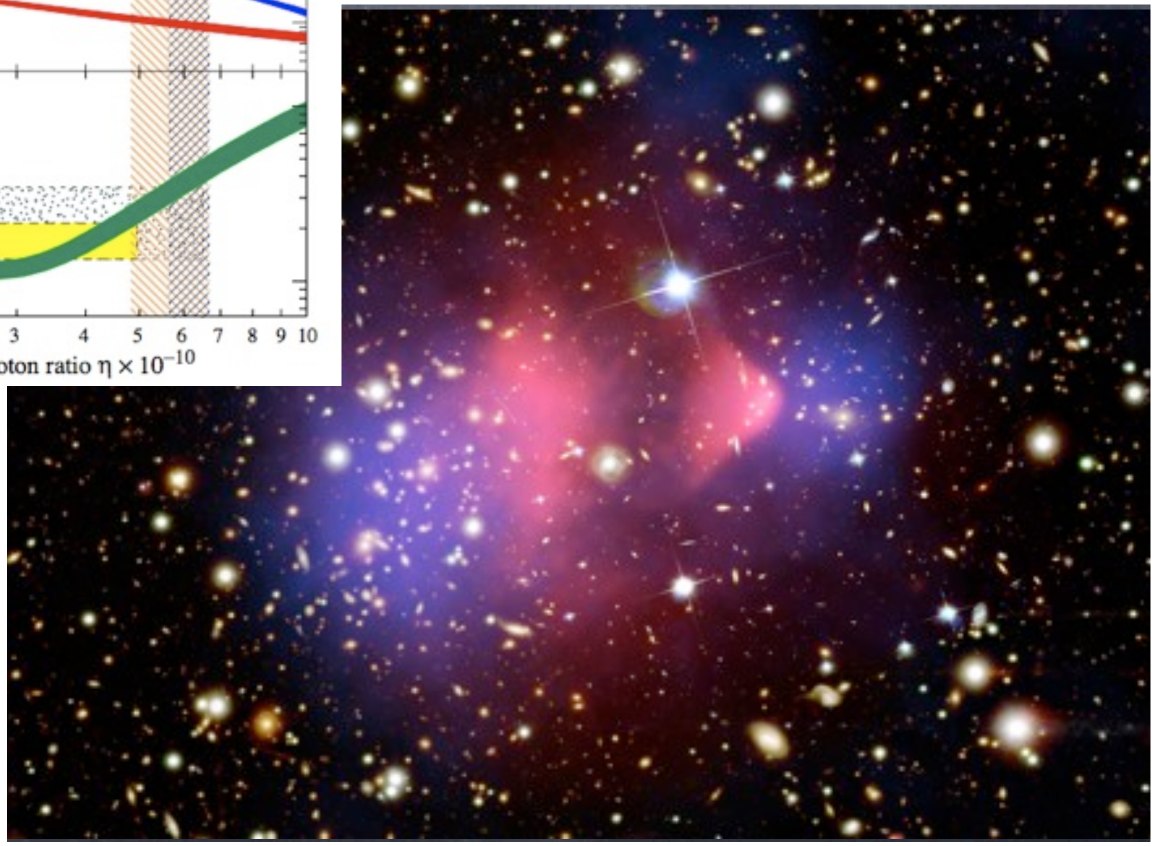


NGC 2403 rotation curve and model



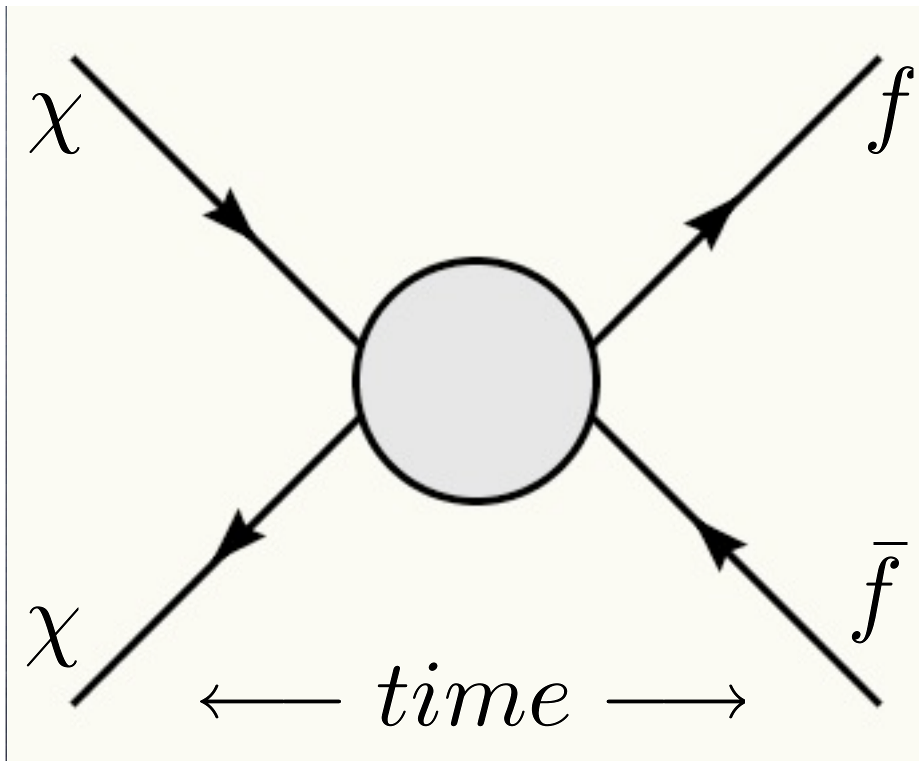






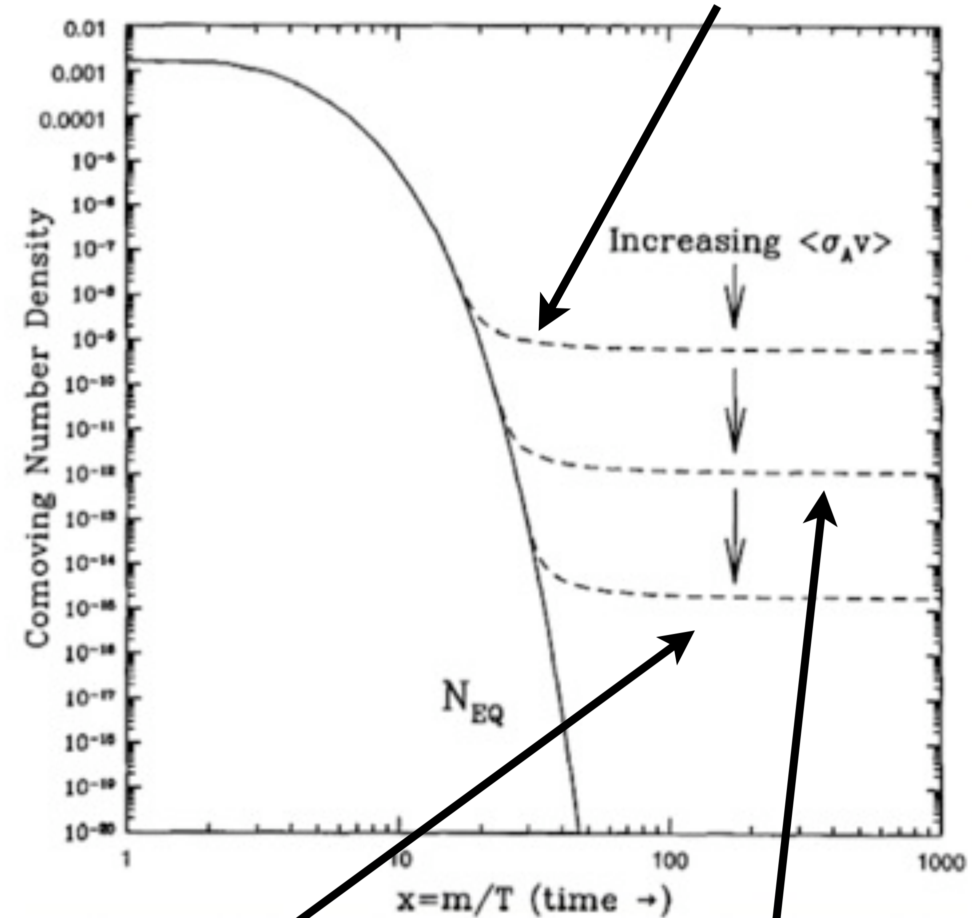
WIMP DM

Assuming thermal equilibrium:



For: $T \ll M_\chi$ $\qquad N_{eq} \propto e^{-M_\chi/T}$

Too much DM



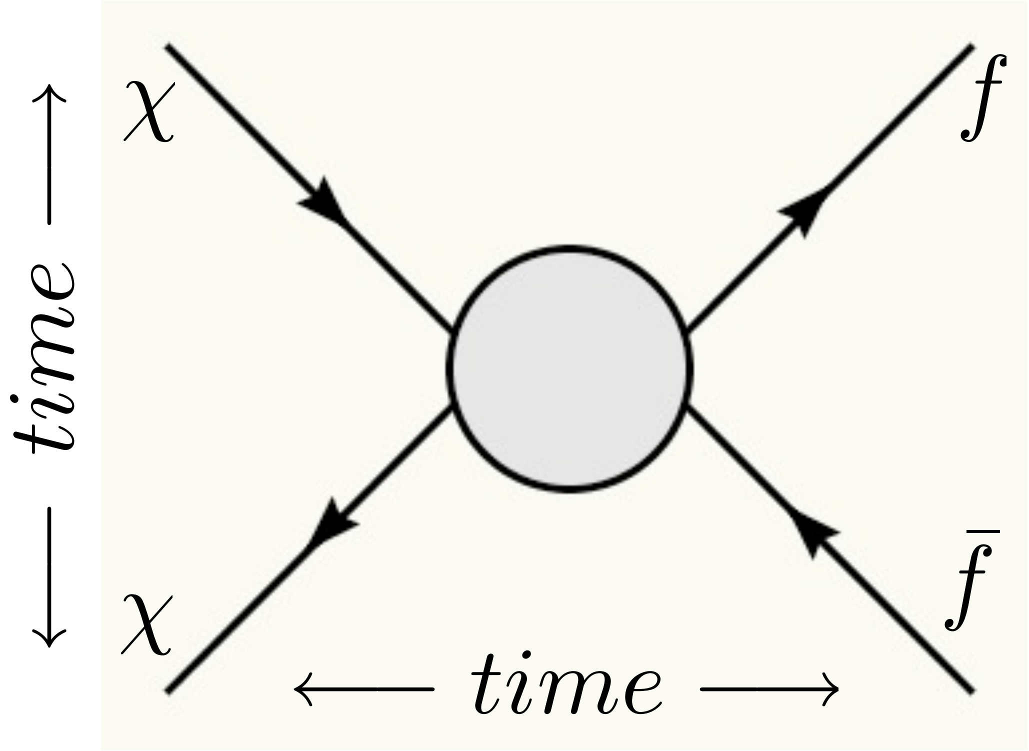
Too little DM

about right

$$\Omega h^2 \approx 0.1 \times \frac{3 \times 10^{-26} cm^3 s^{-1}}{\langle \sigma v \rangle} \quad \approx 0.1 \times \frac{\alpha^2/(100GeV)^2}{\langle \sigma v \rangle}$$

Thermal DM signals

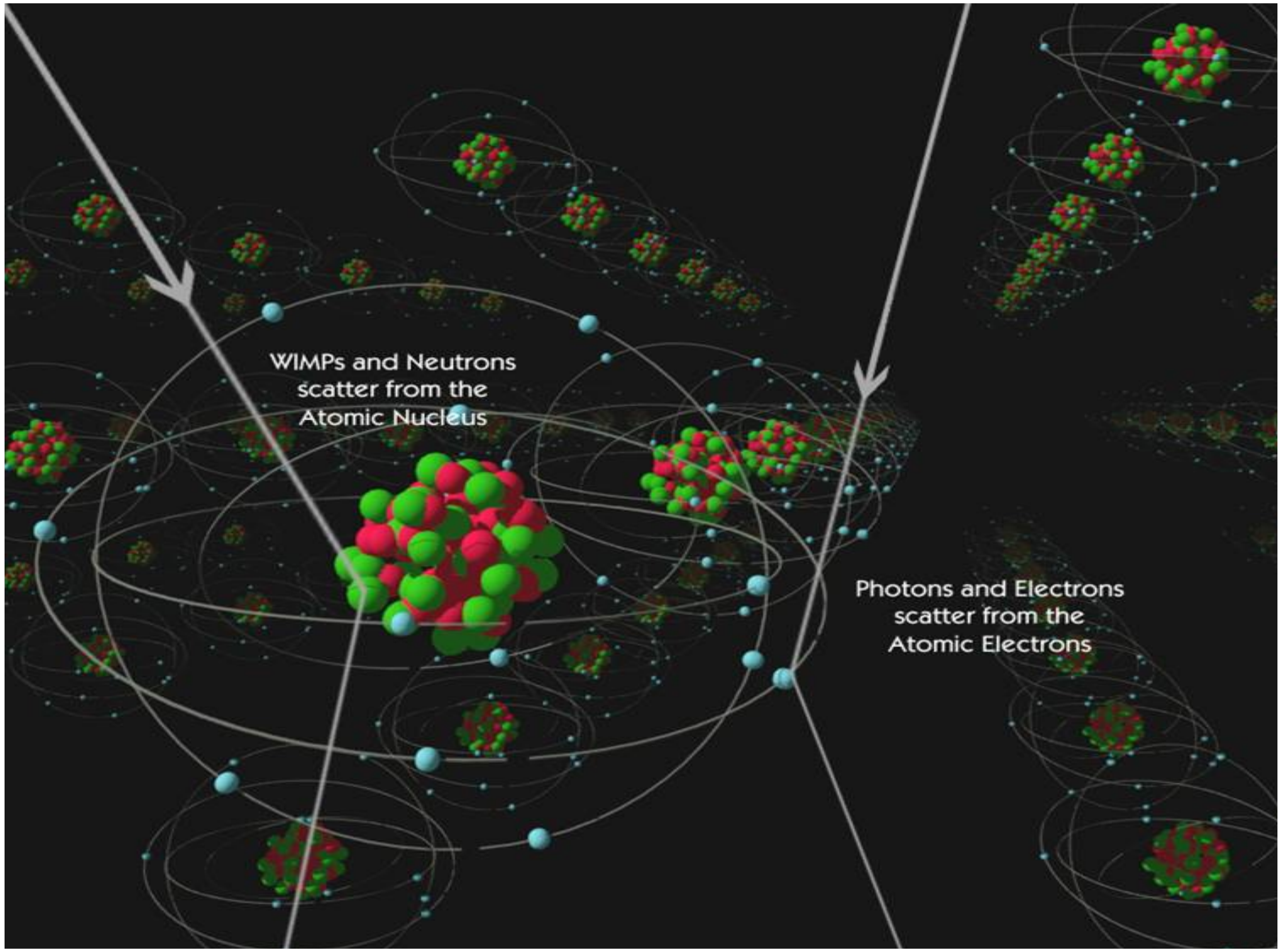
Direct Detection scattering off normal matter, Xe, Ar, Ge, Si:



Indirect detection: Dark matter annihilation into gamma-rays, cosmic rays, neutrinos

Dark matter production at colliders

Direct Detection:



Notation/input:

$$\mu = \frac{m_\chi m_N}{m_\chi + m_N}$$

$$\rho_{local} = 0.3 GeV/cm^3$$

$$v_{rel} \approx \pm 240 km/s$$

$$v_{esc} \approx \pm 540 km/s$$

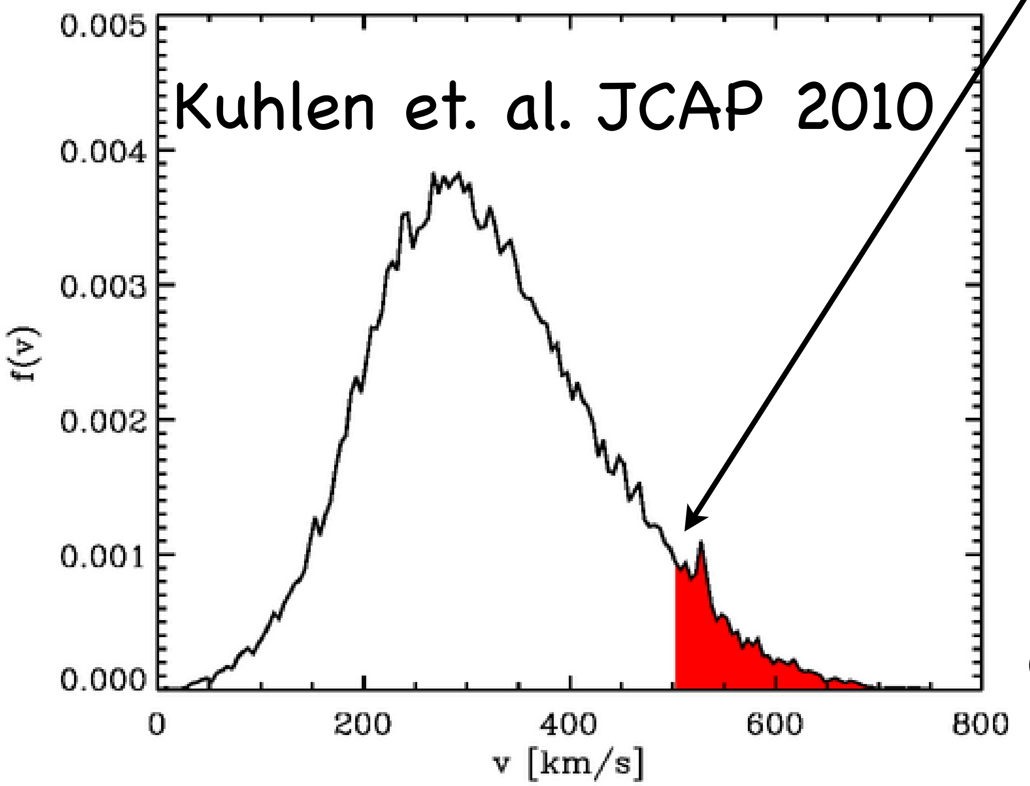
$$v_{mod} \approx \pm 30 km/s$$

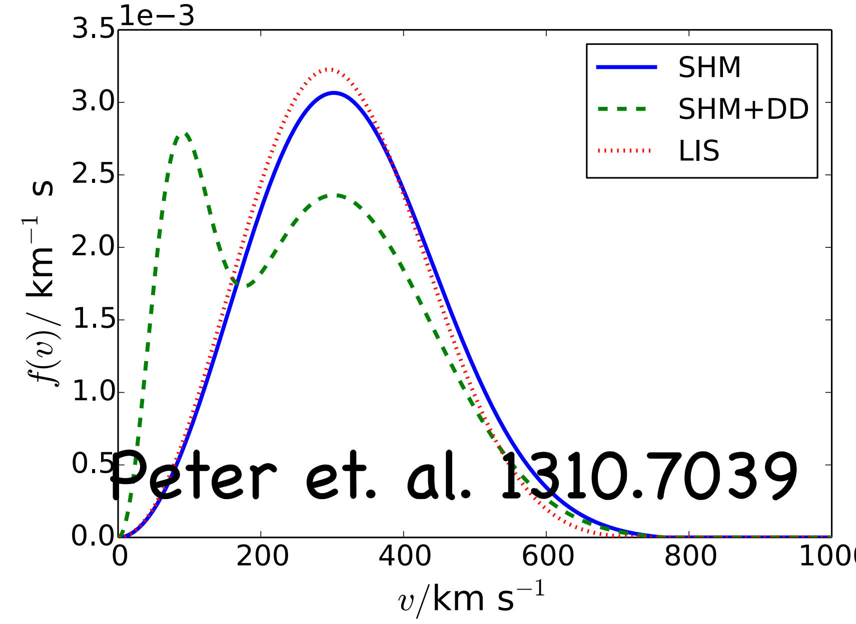
$$\text{Rate in} \frac{\text{events}}{\text{kg yr keV}} : \frac{dR}{dE_r} = \frac{\rho_{local}}{m_\chi} \int_{v_{min}}^{\infty} \frac{v f(v)}{m_N} \frac{d\sigma_{sc}}{dE_r} dv$$

recoil energy: $E_r = \frac{\mu^2 v^2 (1 - cos\theta)}{m_N}$

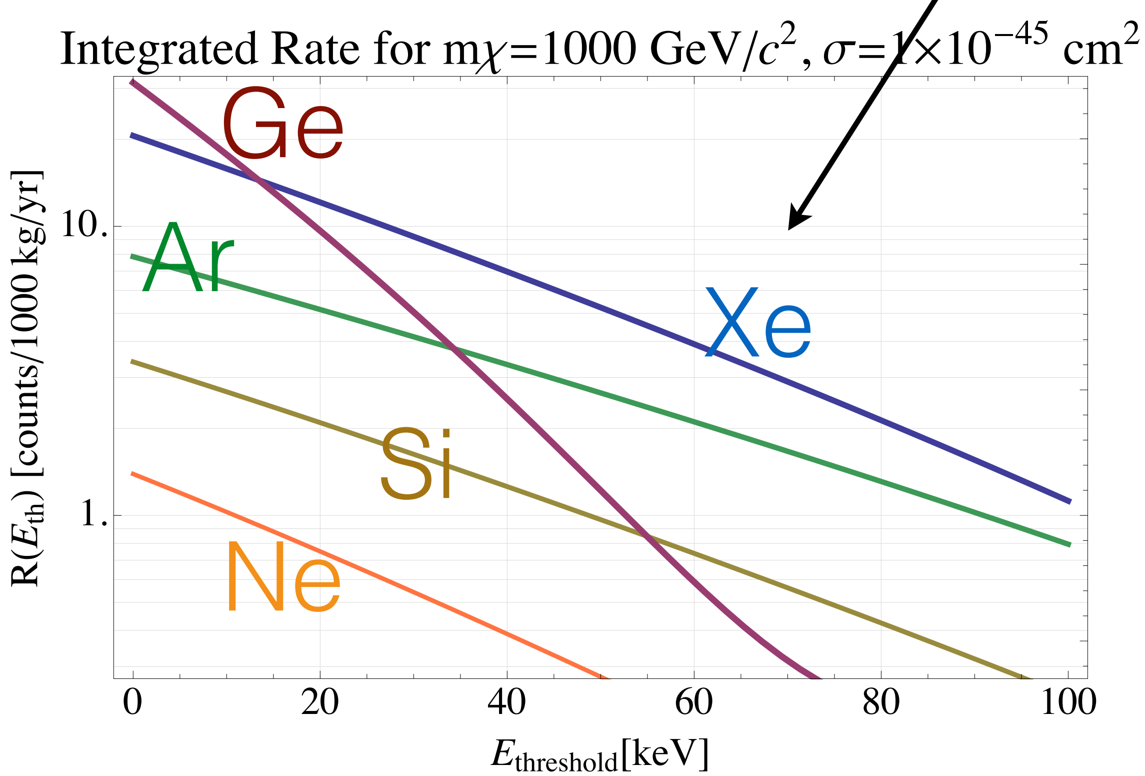
tot. diff. cross.-sec.: $\frac{d\sigma_{sc}}{dE_r} = \frac{m_N}{2\mu^2 v^2} (\sigma_{si} F_{si}^2(E_r) + \sigma_{sd} F_{sd}^2(E_r))$

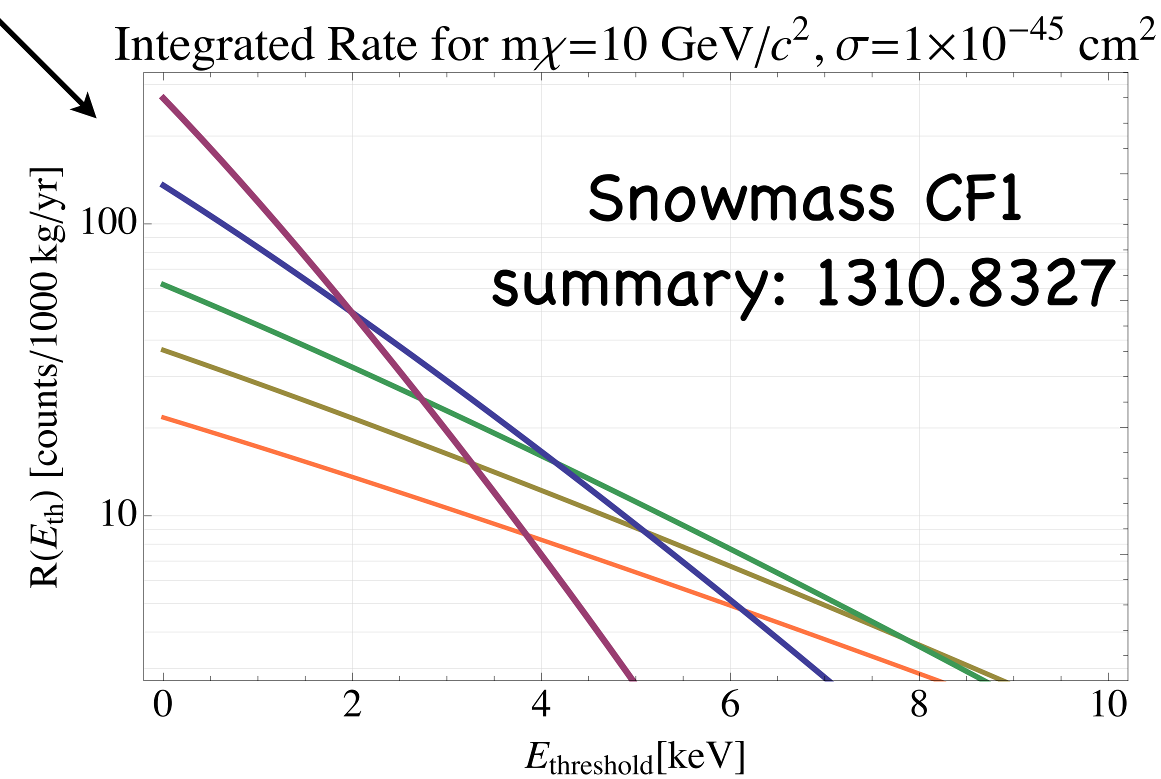
Minimum recoil velocity: $v_{min} = \sqrt{\frac{E_r m_N}{2\mu^2}}$





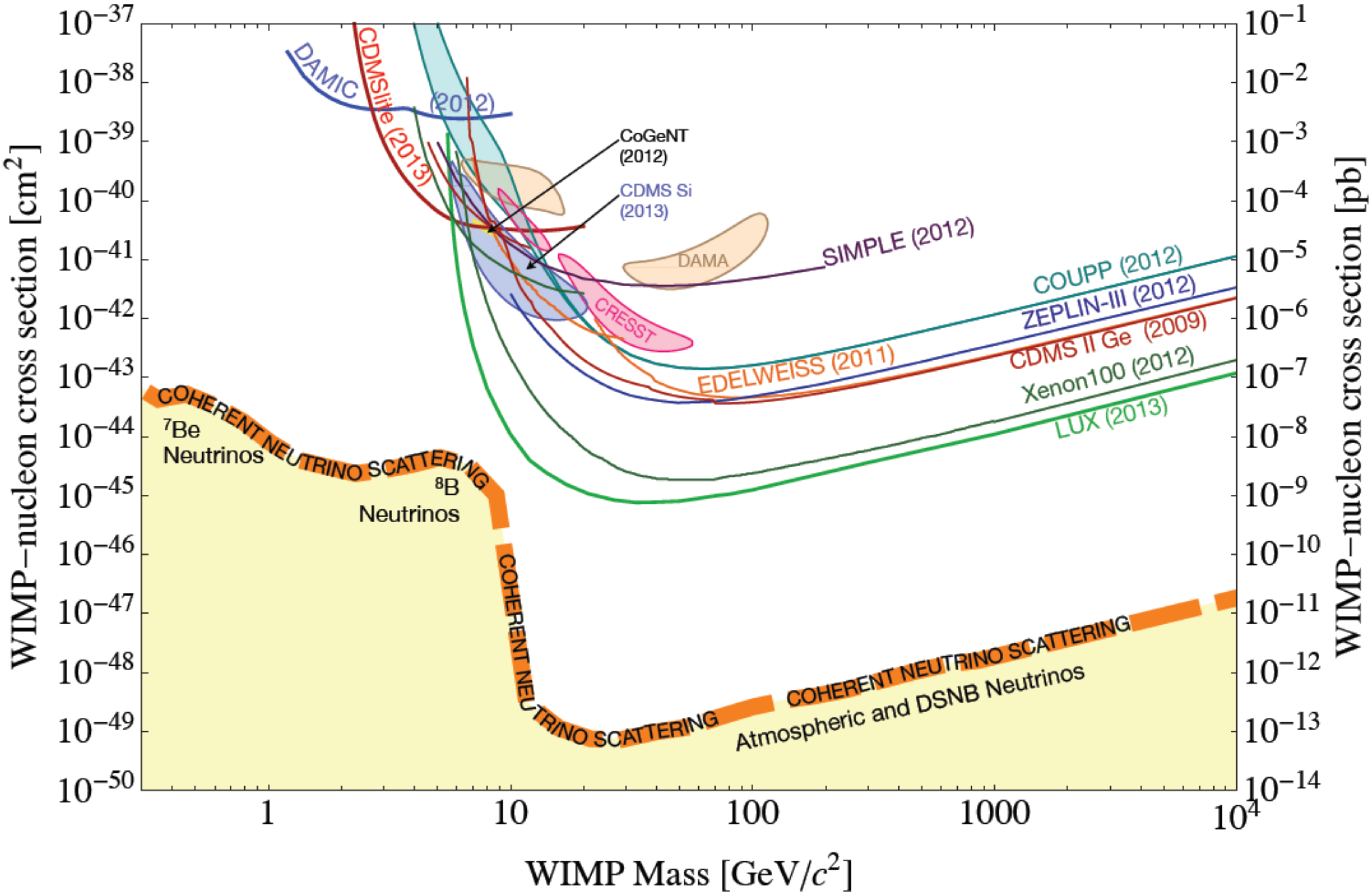
Thus, different targets provide best choice for different dark matter mass ranges(still unknown what's the right place to look). Also the exact assumptions on the velocity distribution and the significance of local sub-structure and streams can matter in some cases



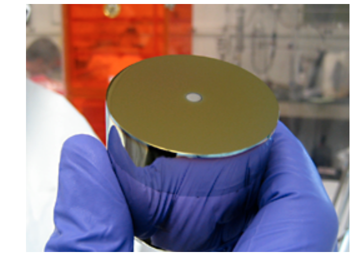


Direct Detection,

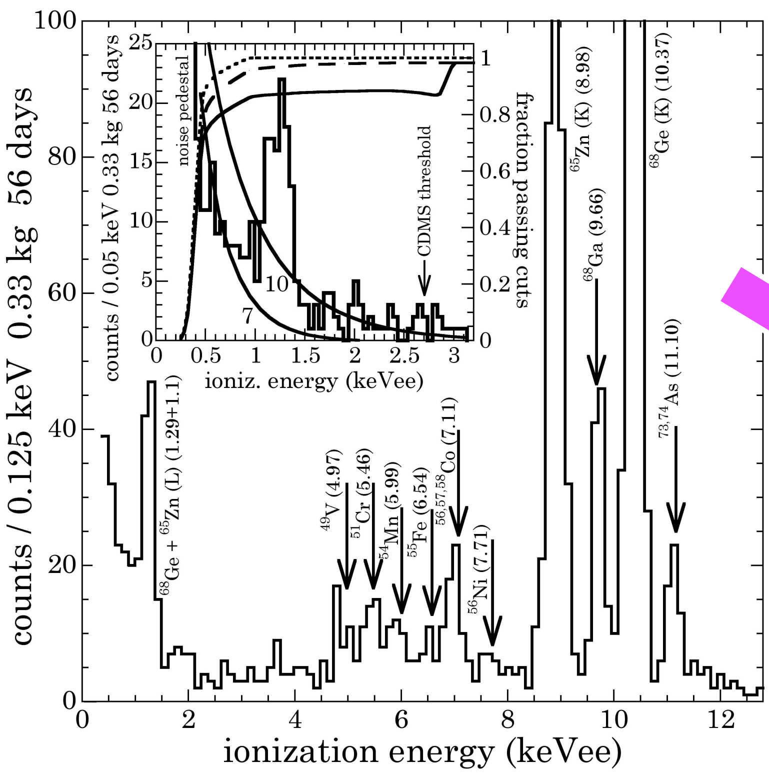
Spin-Independent Landscape

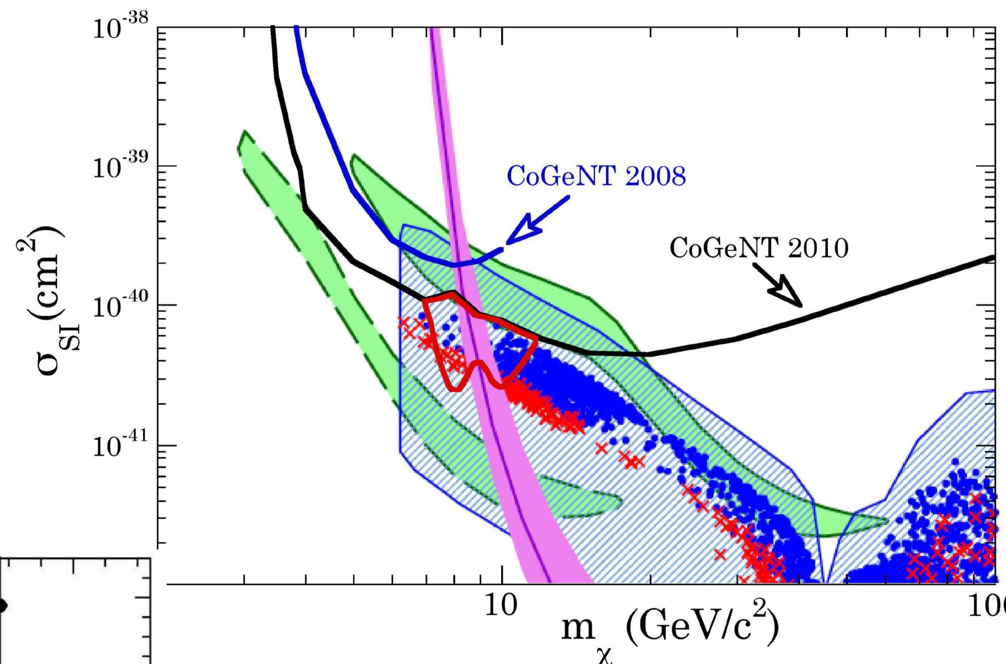


Update from **CoGeNT**

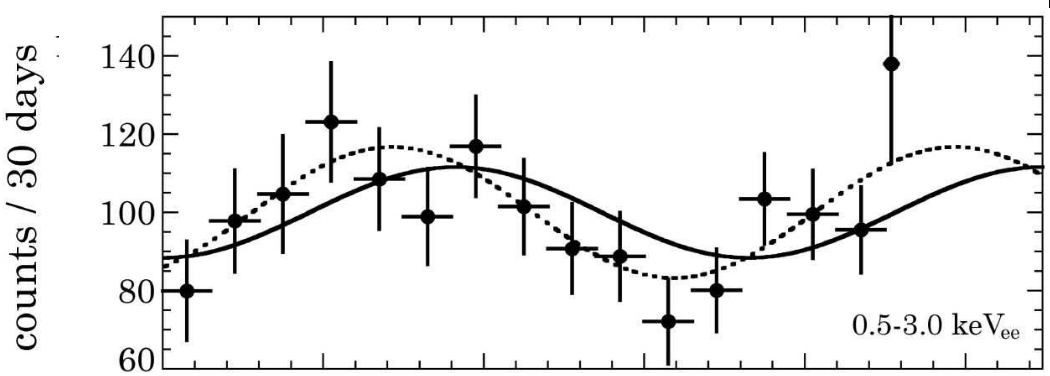


2010, excess:

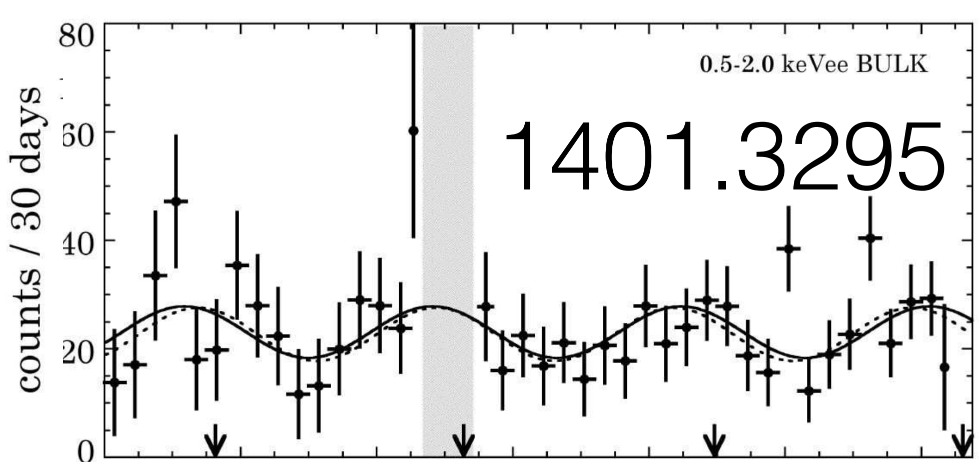




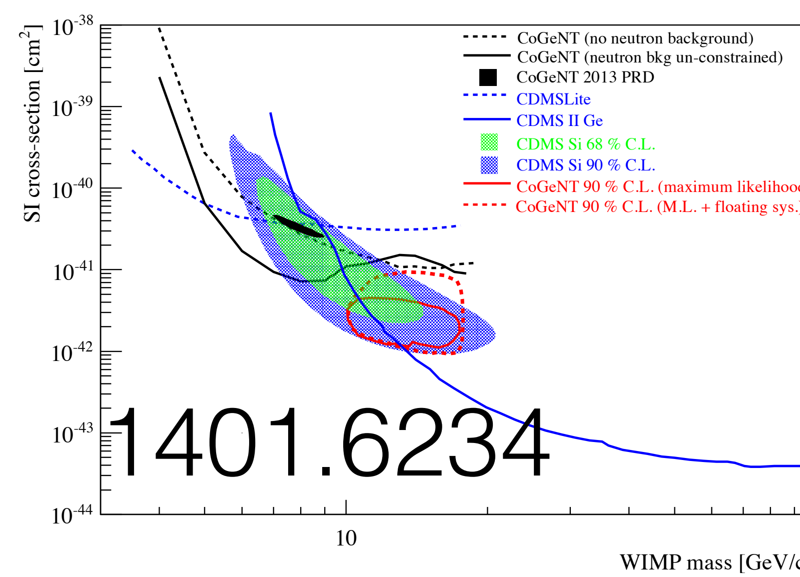
2011, hint of annual mod.:



2014, 2sigma hint of annual mod.:

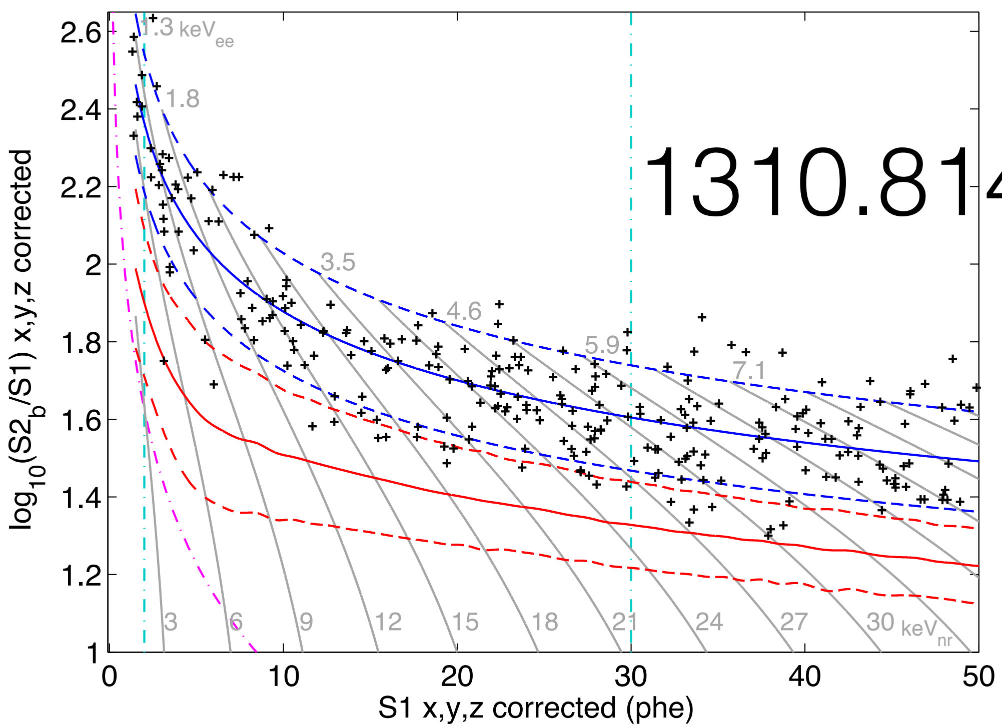


1401.3295



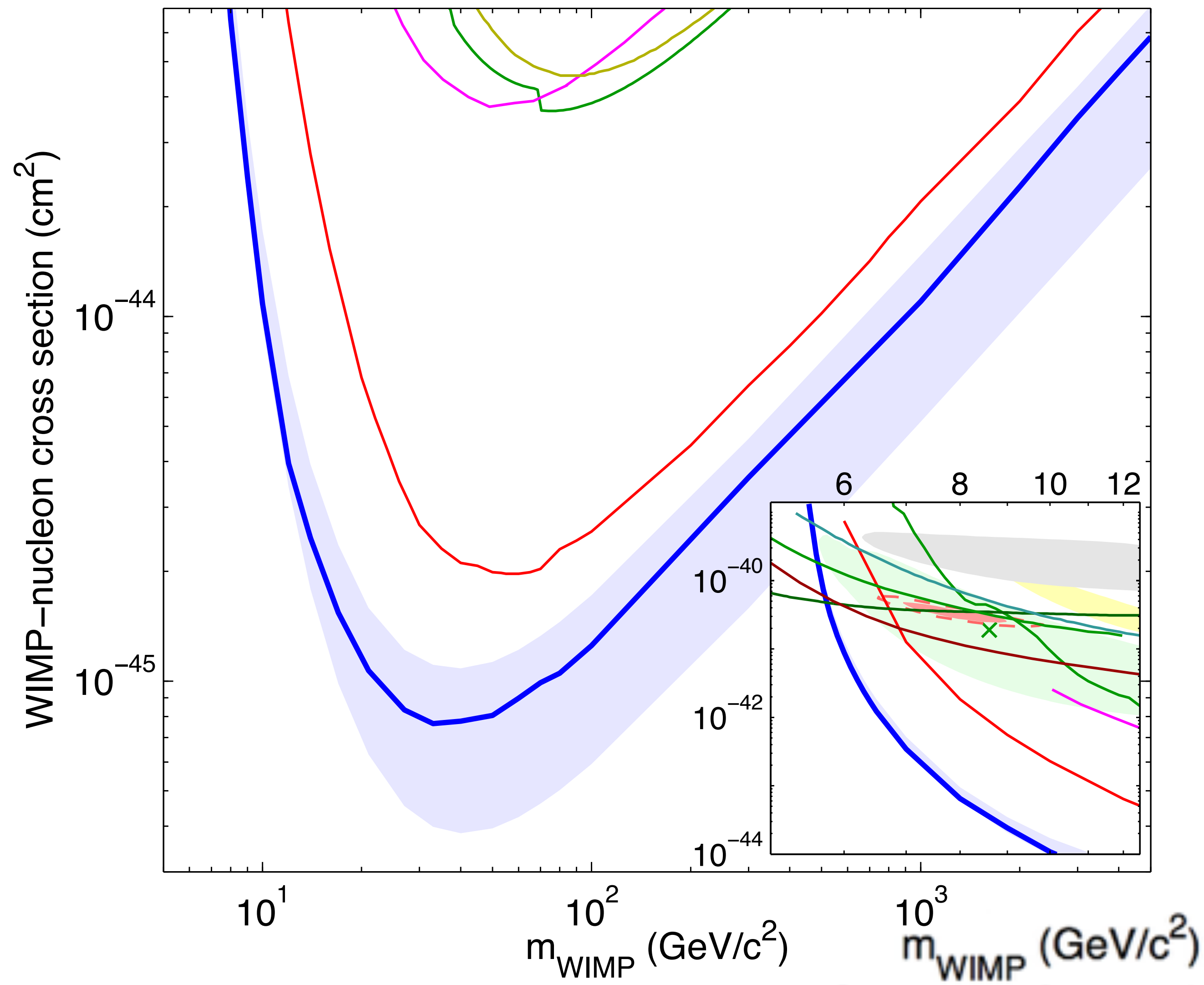
1401.6234

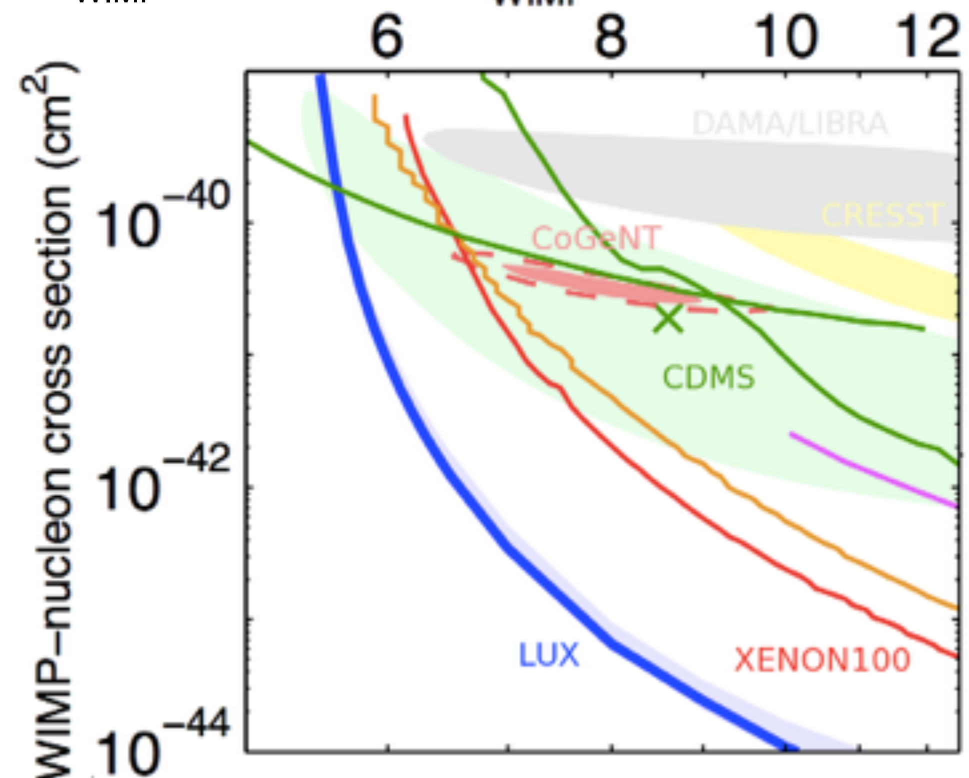
Update from **LUX**



1310.8142

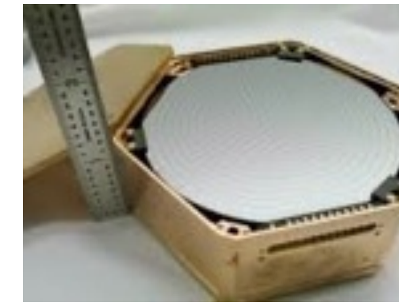
FIG. 4. The LUX WIMP signal region. Events in the 118 kg fiducial volume during the 85.3 live-day exposure are shown. Lines as shown in Fig. 3, with vertical dashed cyan lines showing the 2-30 phe range used for the signal estimation analysis.

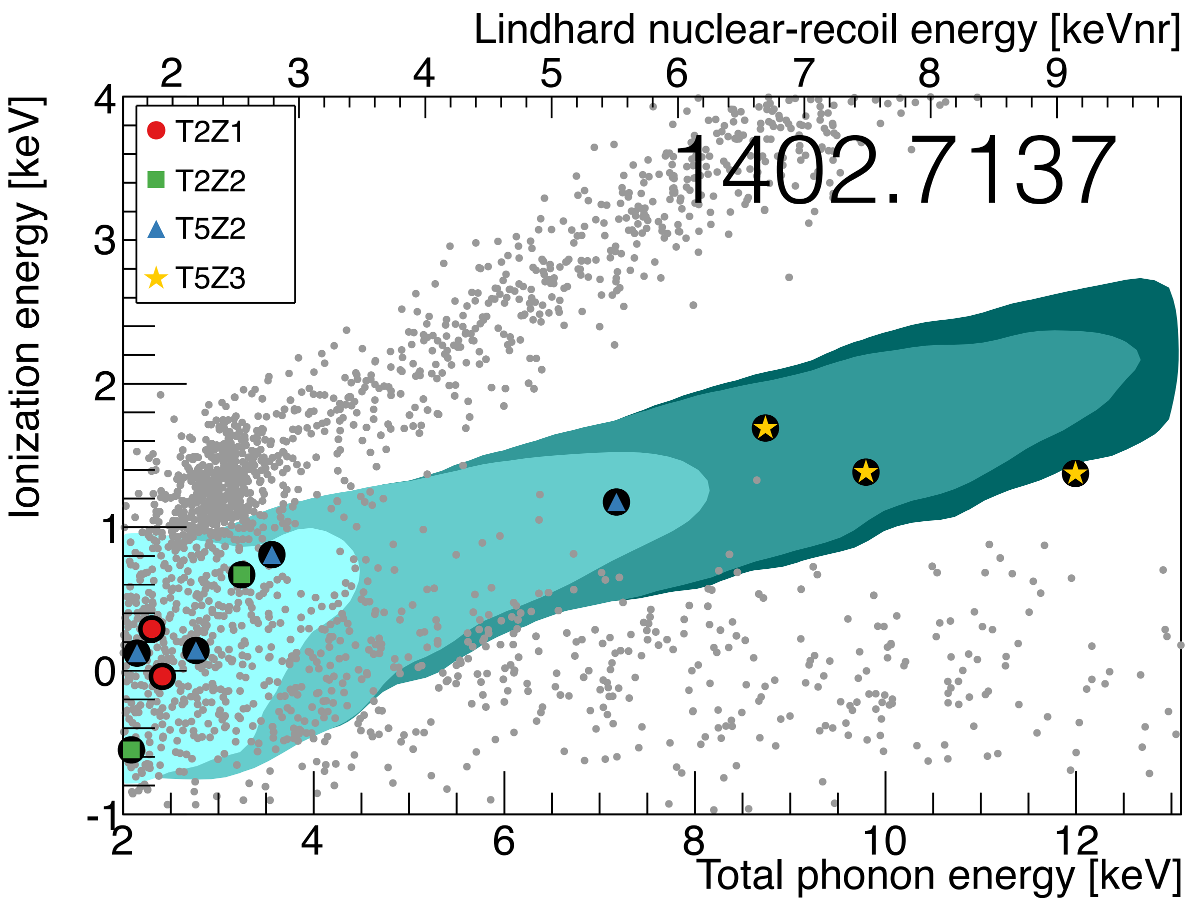


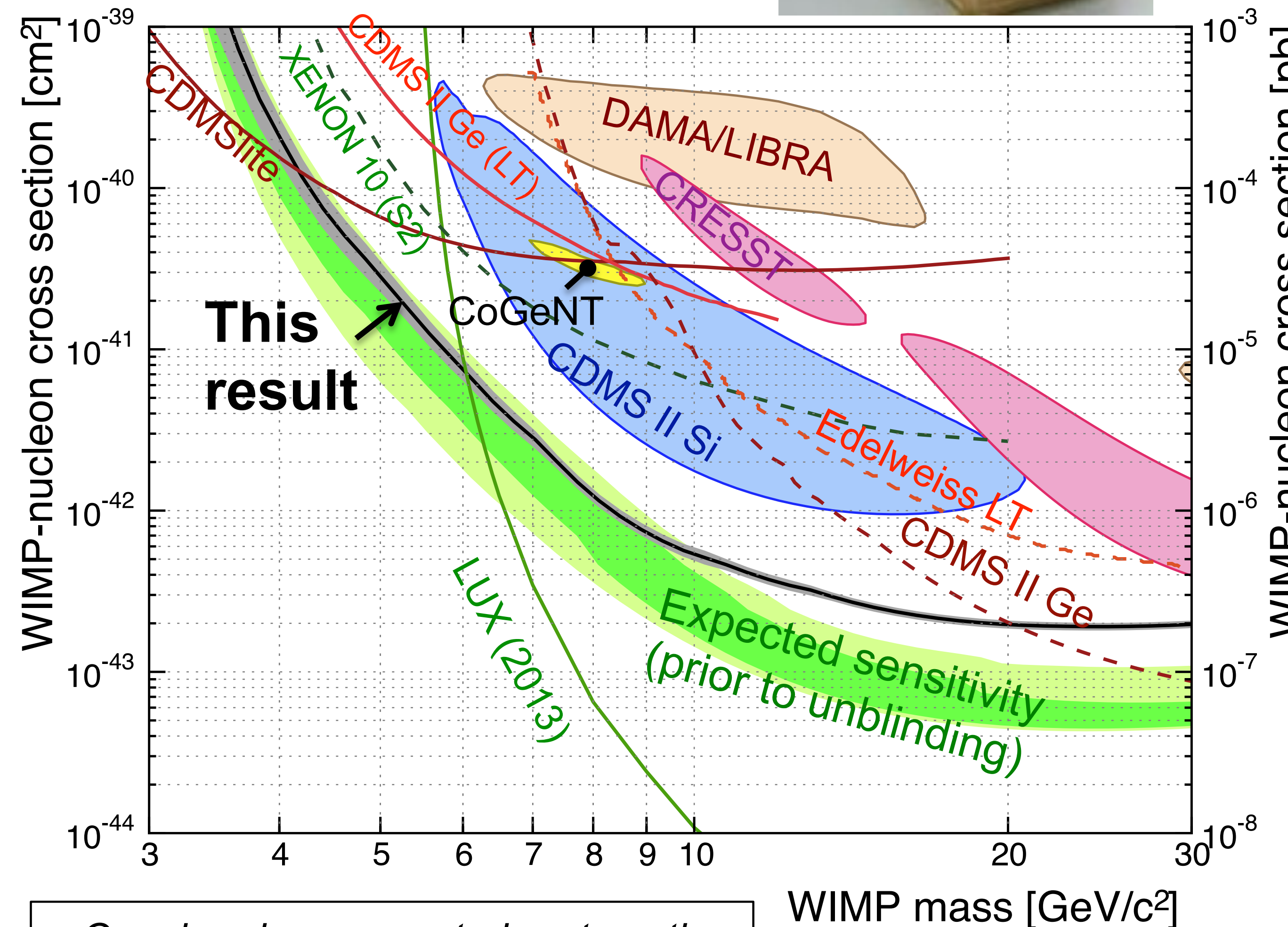


The strongest limit in a very wide mass range (factor of 20 stronger than Xenon100). Energy scale calibration and velocity profile can still affect the limits at the lower mass range.

Update from **SuperCDMS**







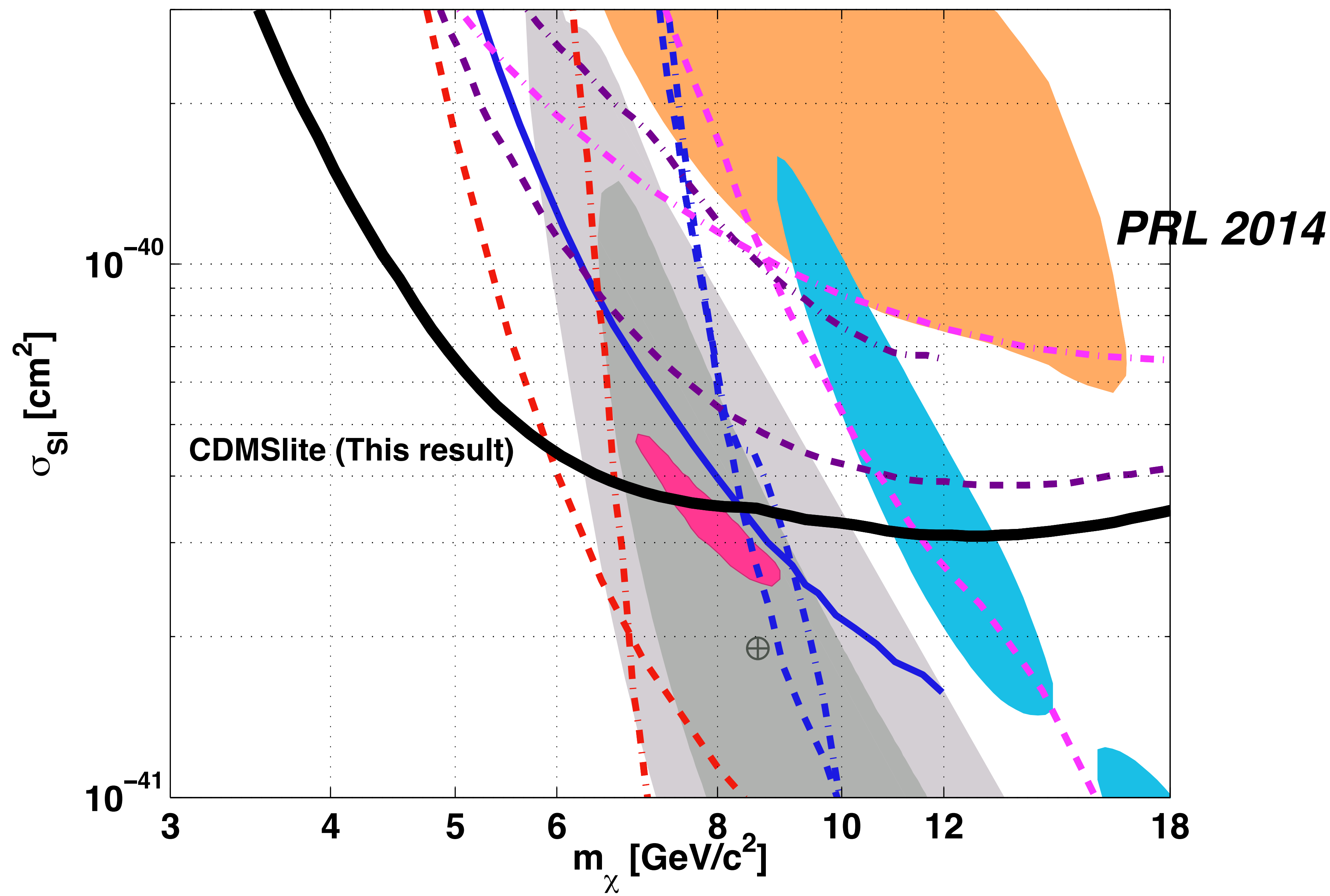
Gray bands: propagated systematic unc. from fiducial volume + nuclear recoil energy scale + trigger efficiency

Fermilab W&C, March 2014

Disfavors CoGeNT and CDMS Si.
Strong Limits for m<6GeV.
Weaker limits than expected for m>20 GeV (but already excluded by earlier CDMS Ge results)

Lauren Hsu talk at Fermilab

CDMSlite result:

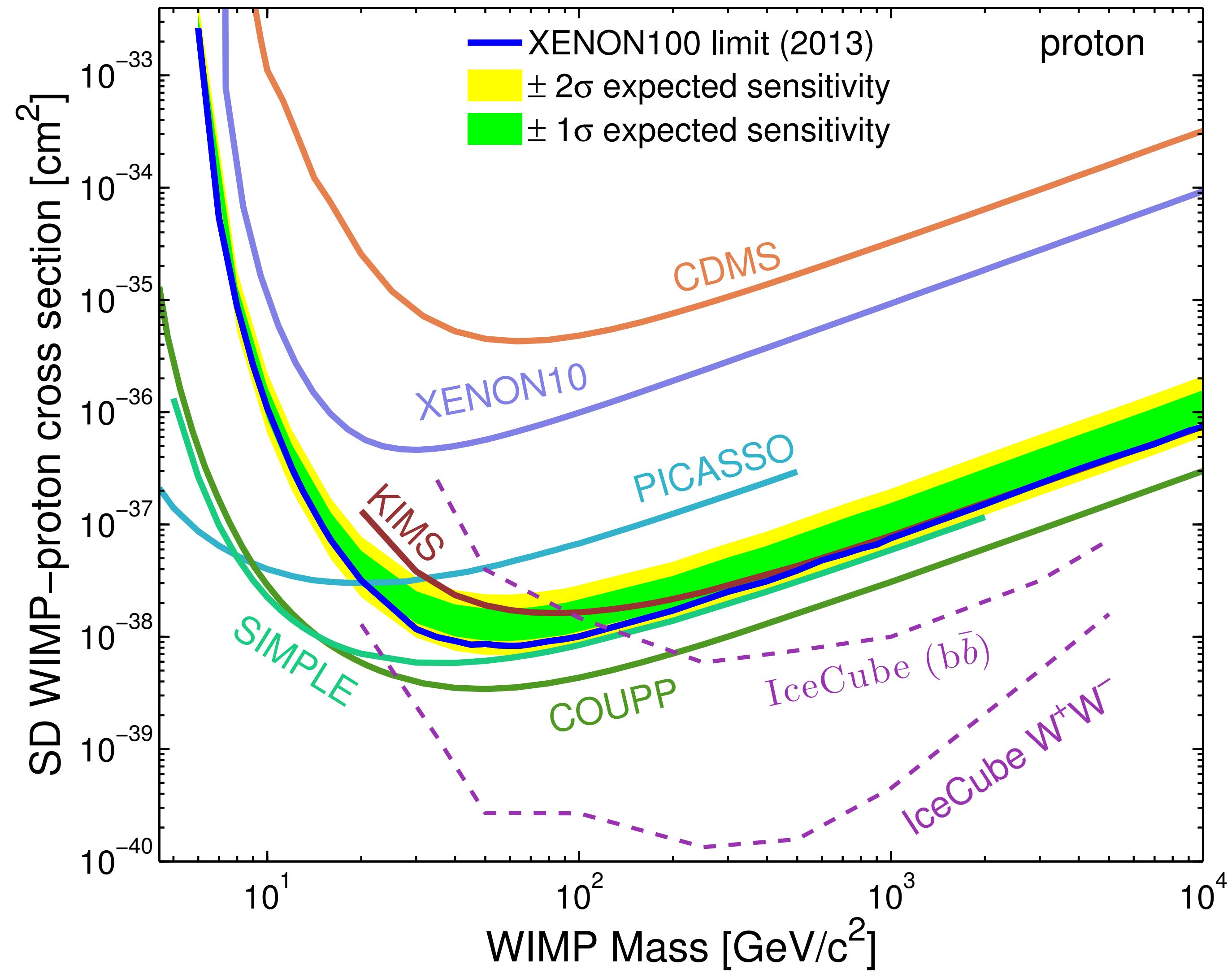


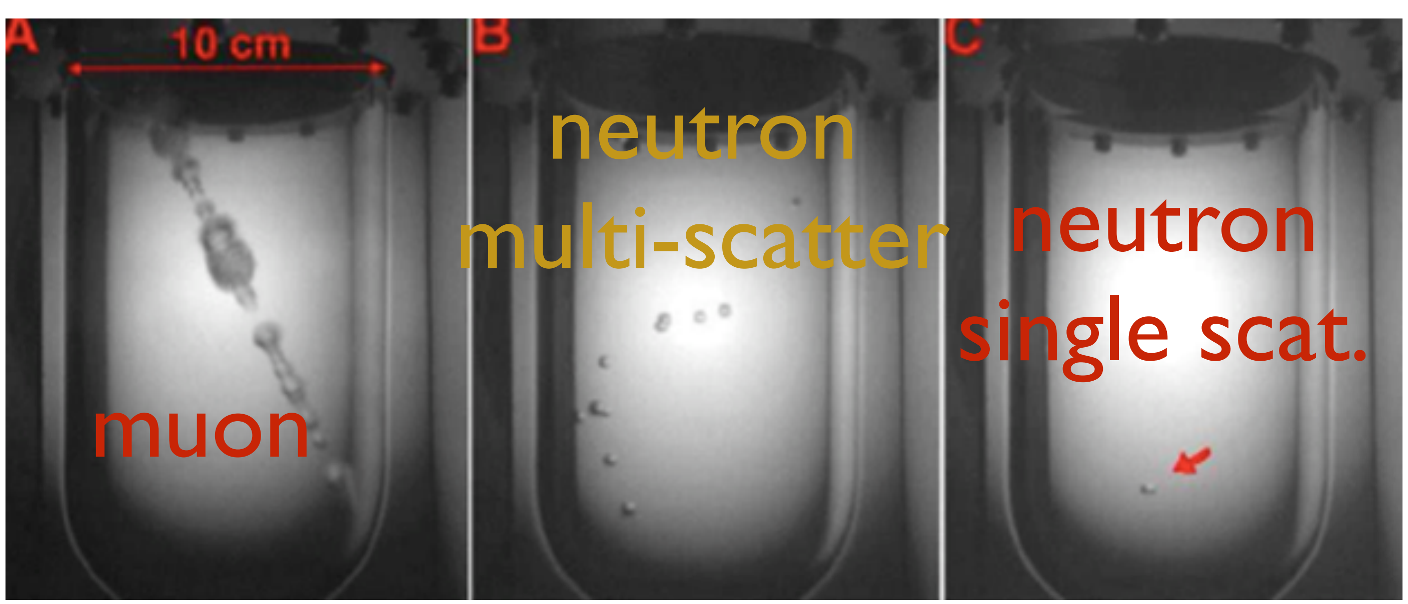
Best Current limit bellow 4 GeV (surpassed by SuperCDMS results at the >4 GeV)

Update from **COUPP-> PICO**

Currently 60 kg of CF_3I

With PICASSO (PICO) 4kg of C_3F_8





Snowmass CF1 summary: 1310.8327

very good position measurement

DarkSide

1. Argon TPC

~ 50 kg of liquid argon in
19 PMTs at top and bottom

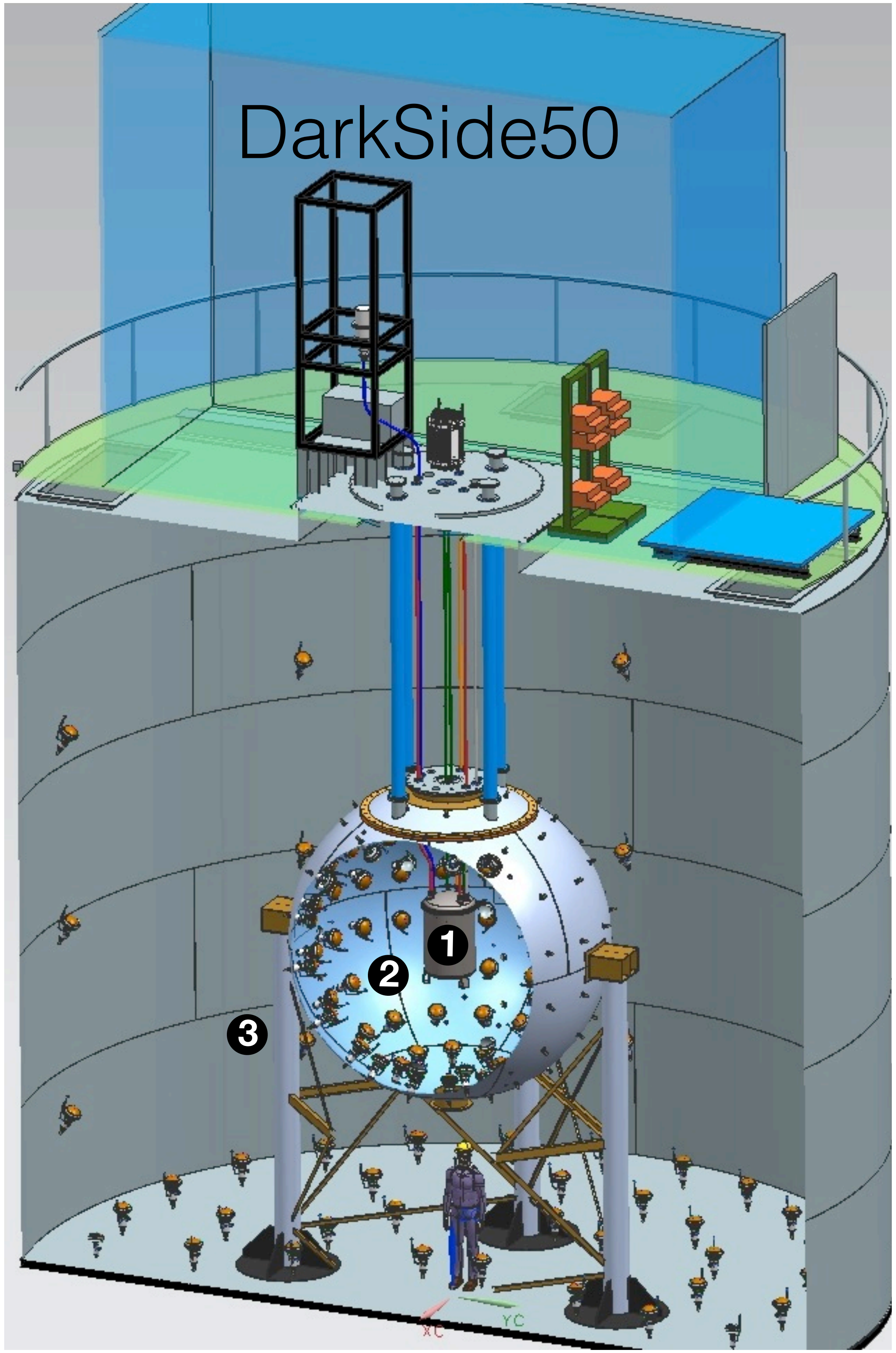
Background rejection through: i) pulse shape discrimination, ii) ionization to scintillation ratio and iii) 3D position reconstruction.

2. Neutron Veto

Ensures large capture cross-section of n on B. Captured neutrons produce alpha particles that are easy to detect. Also provides in-situ measurement of neutron background.

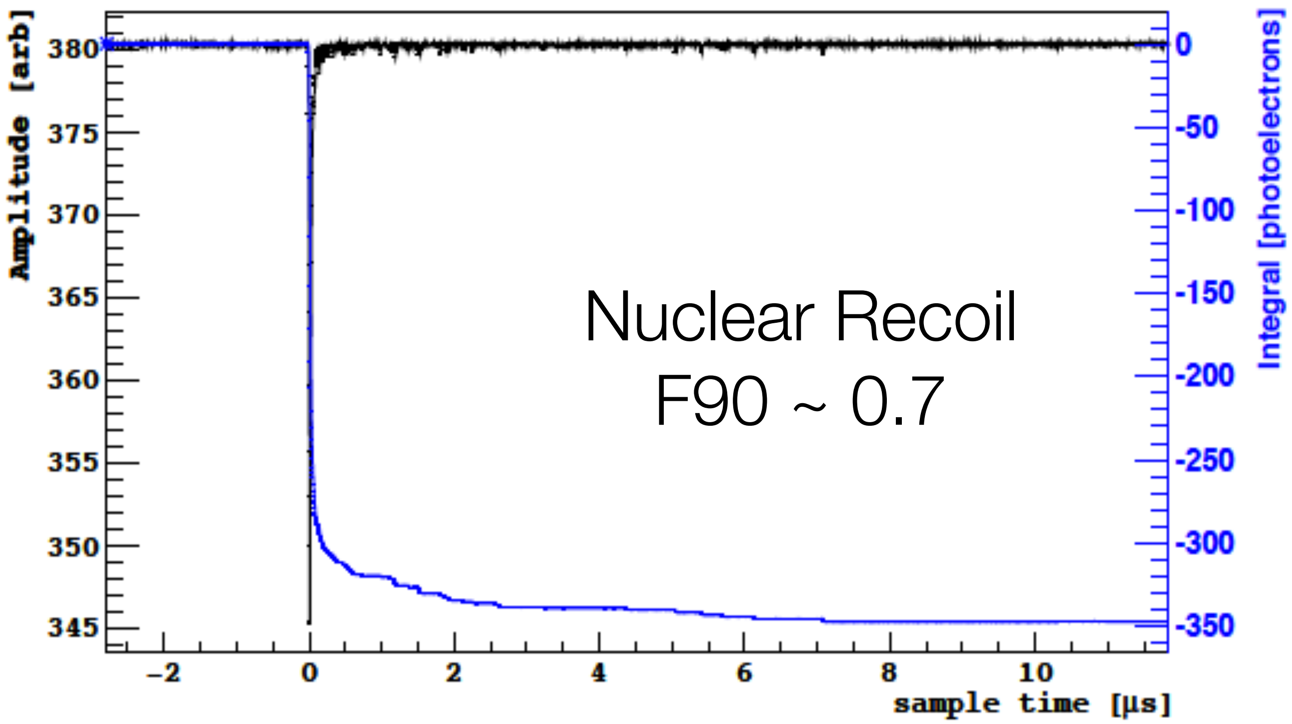
3. Muon Veto

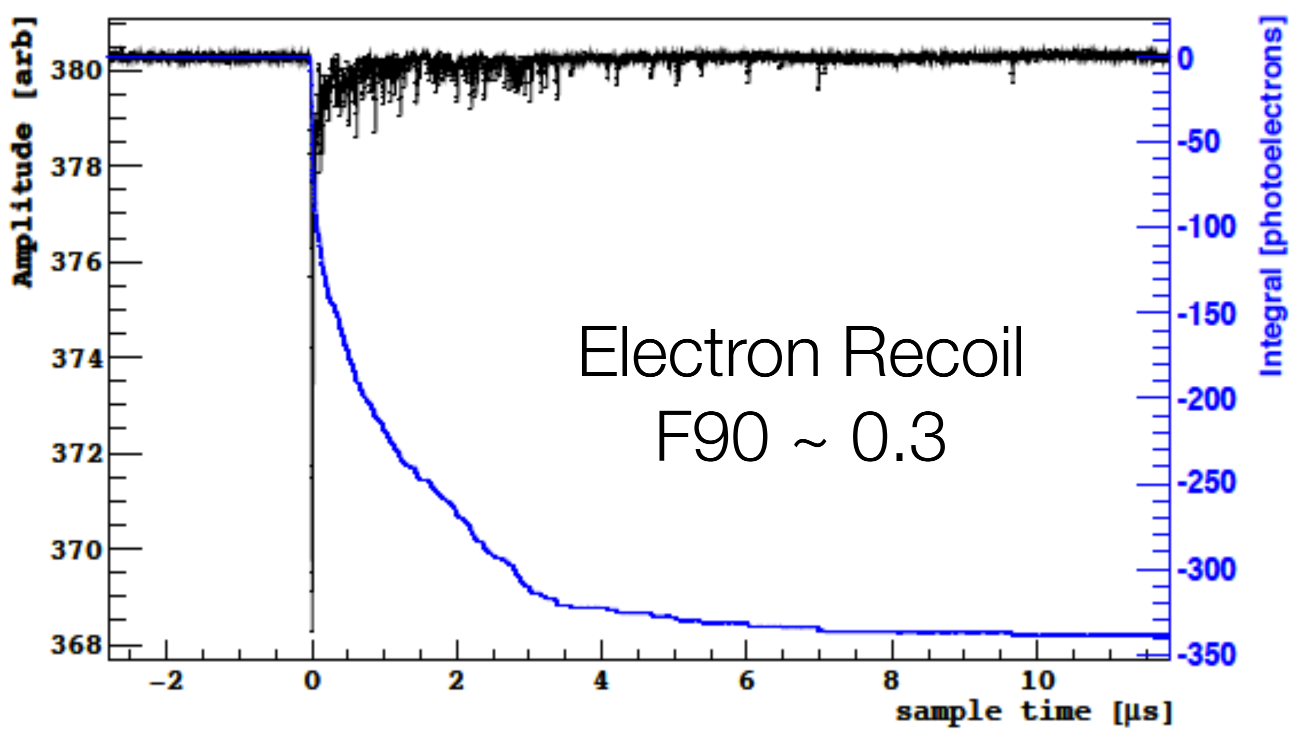
Water tank surrounding neutron veto and providing active rejection of cosmogenic induced backgrounds as well as shielding gamma-rays for neutron veto.

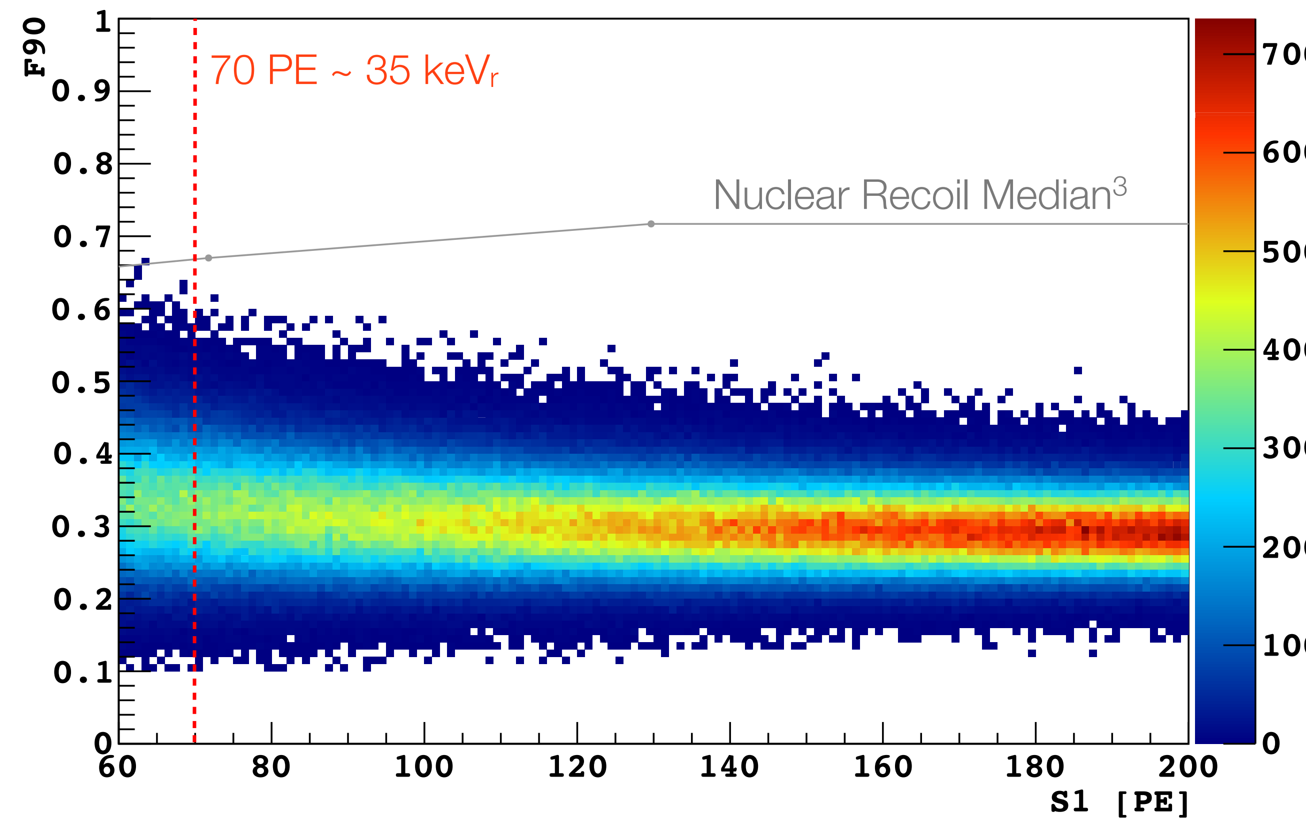


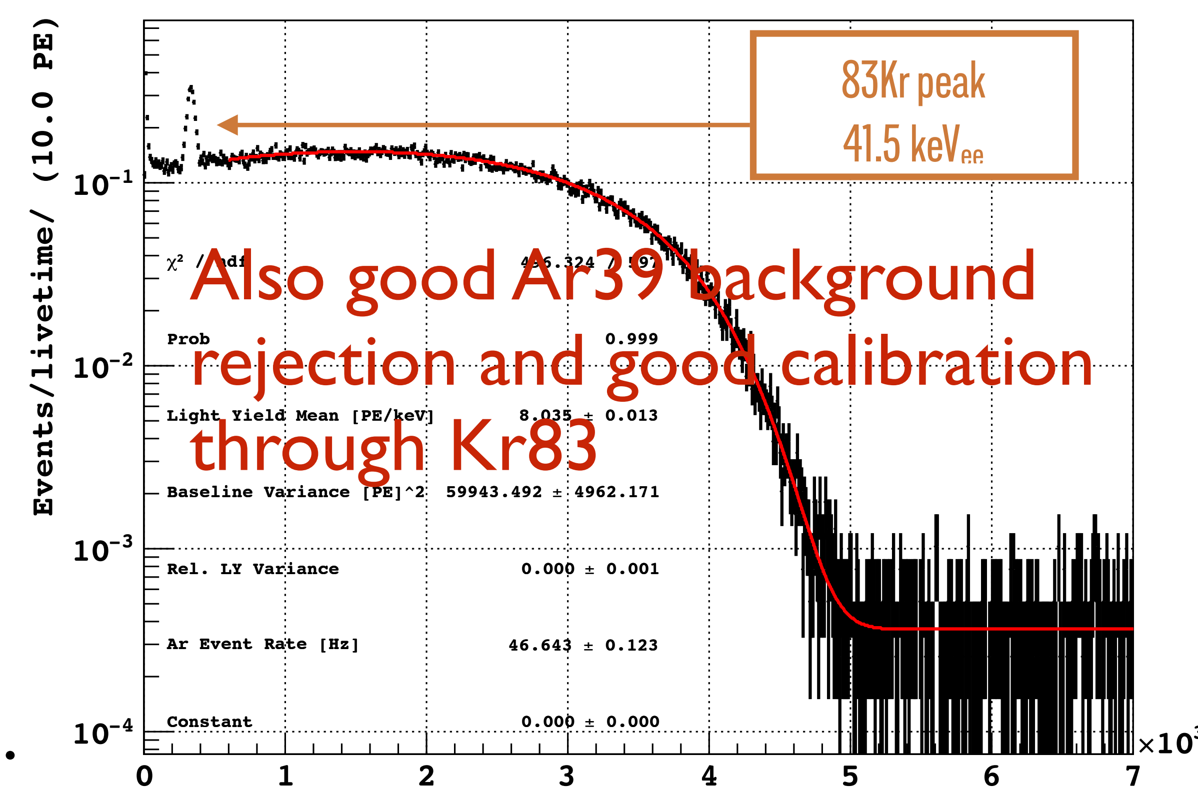
Special thanks to
Y. Guardincerri & S.Pordes

Pulse Shape Discrimination in Argon: electrons and nuclear recoils create different excitation densities in Ar ->different densities of singlet and triplet excited states. Those states have large difference in lifetimes (7ns for singlet and 1.6 mus for triplet) leading to very different scintillation time profiles





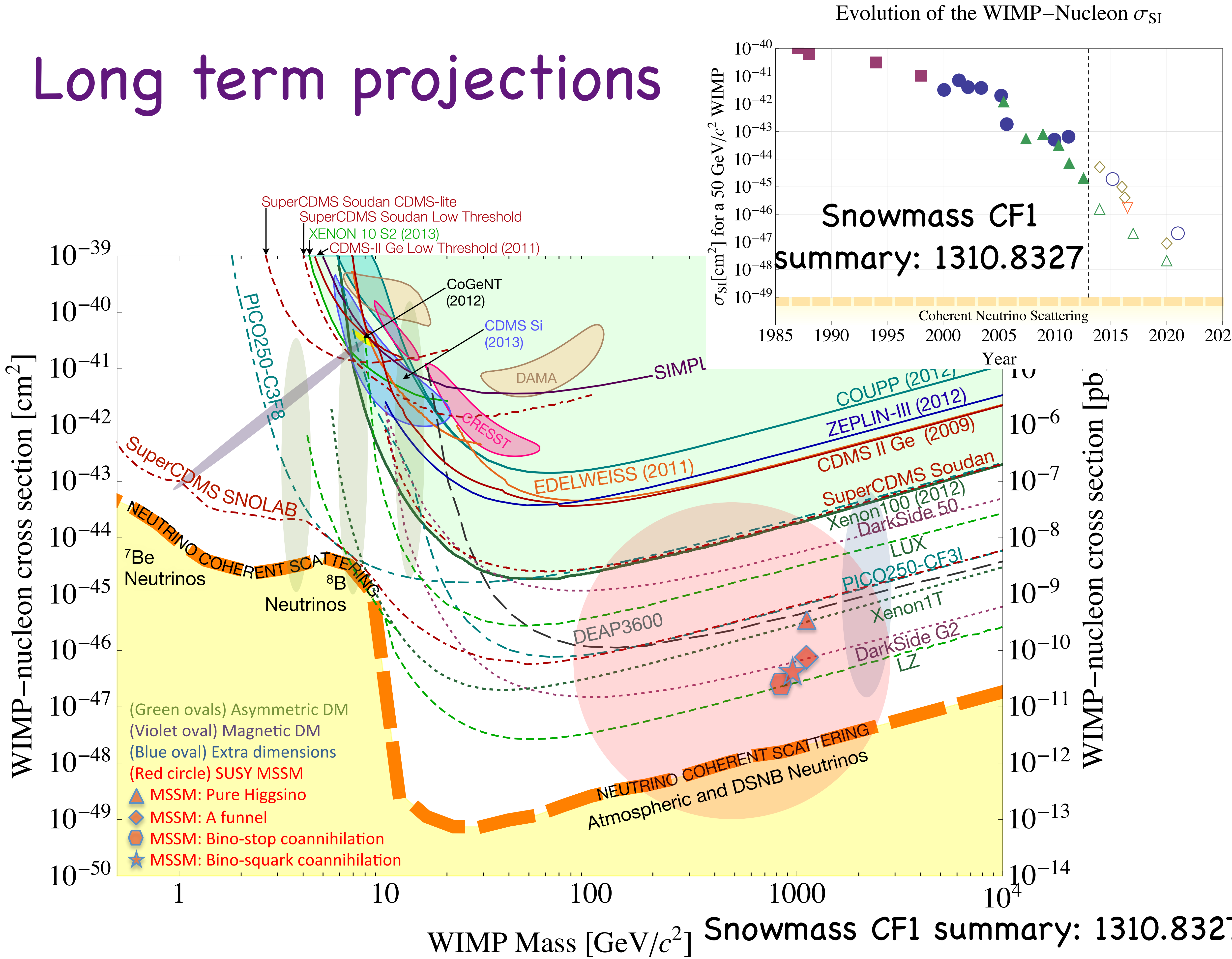




Also good Ar39 background rejection and good calibration through Kr83

F90 is the the fraction of light in the first 90 ns.

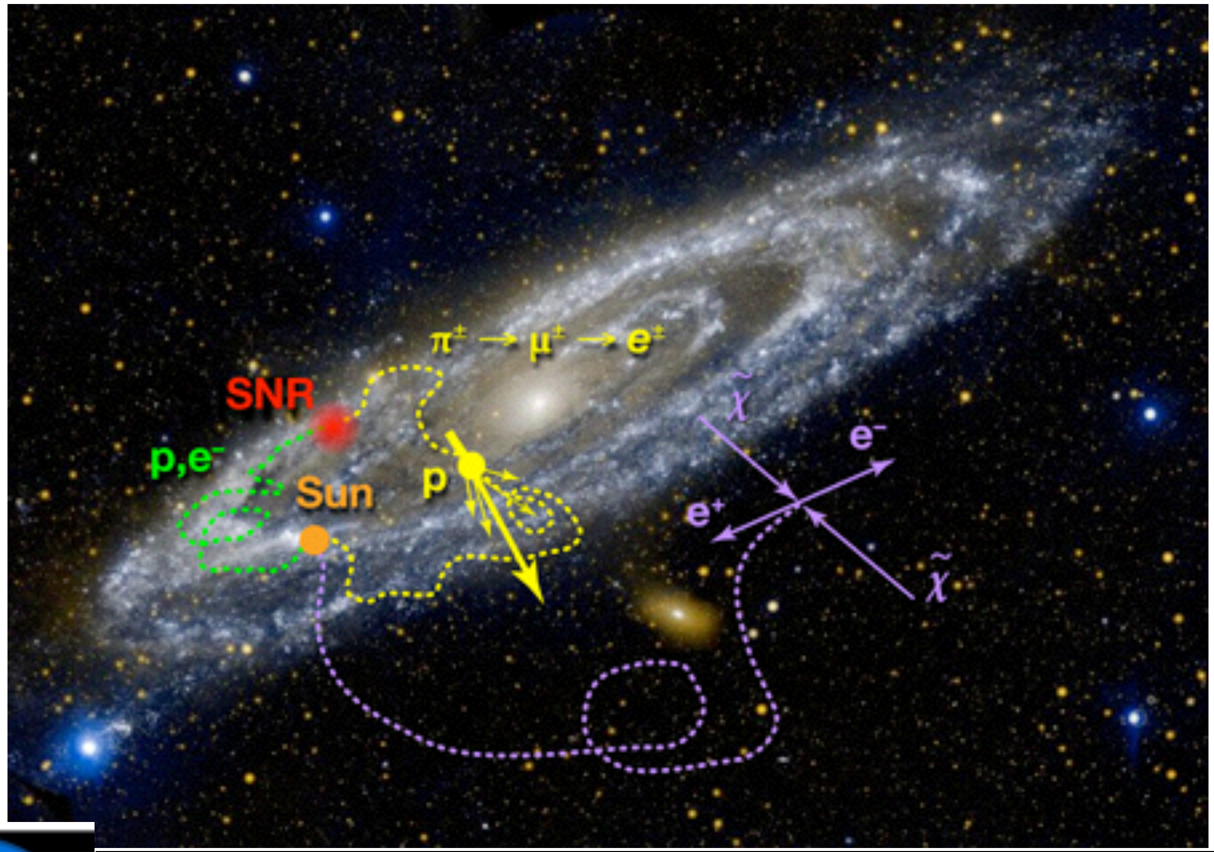
Long term projections

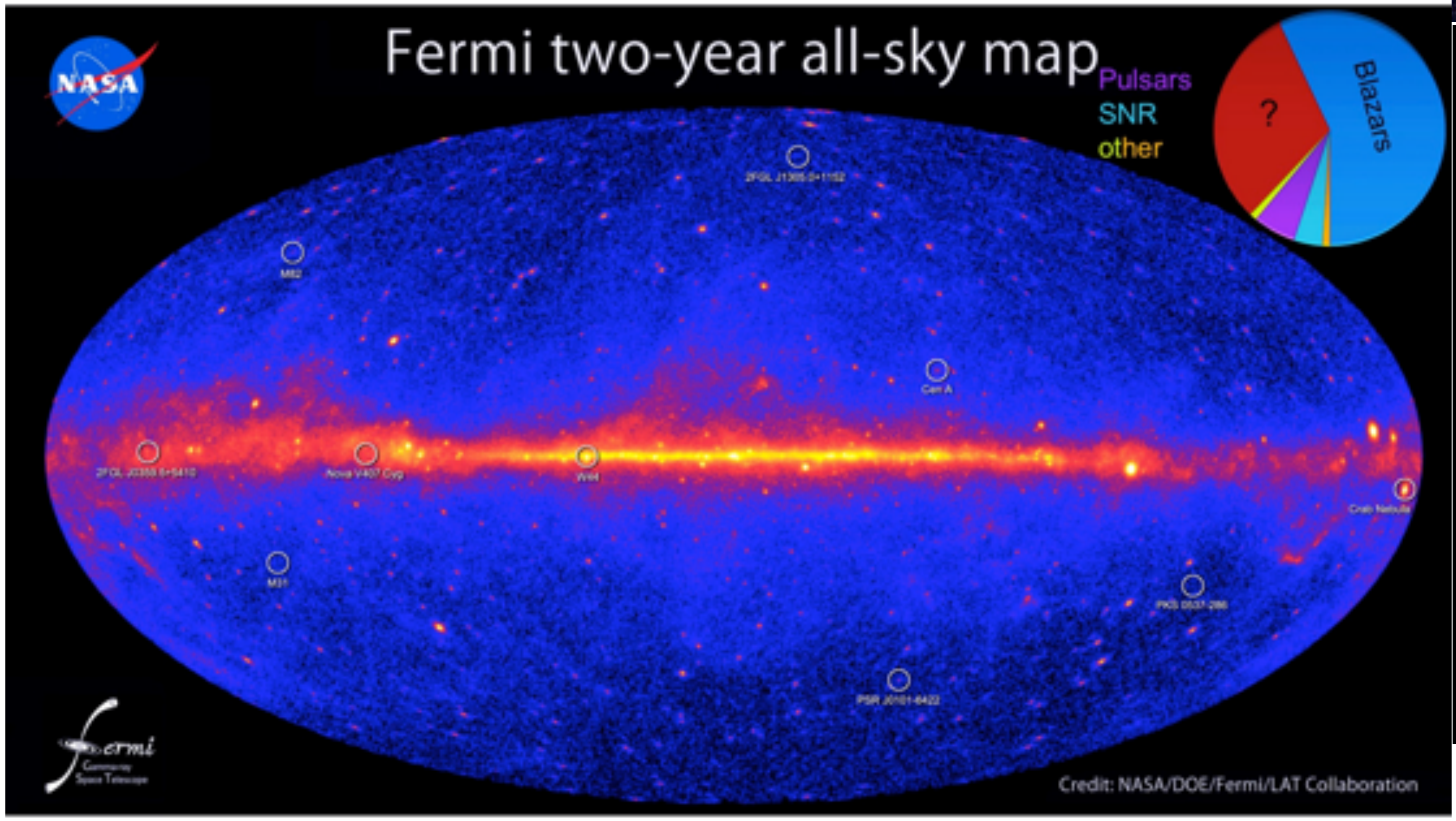


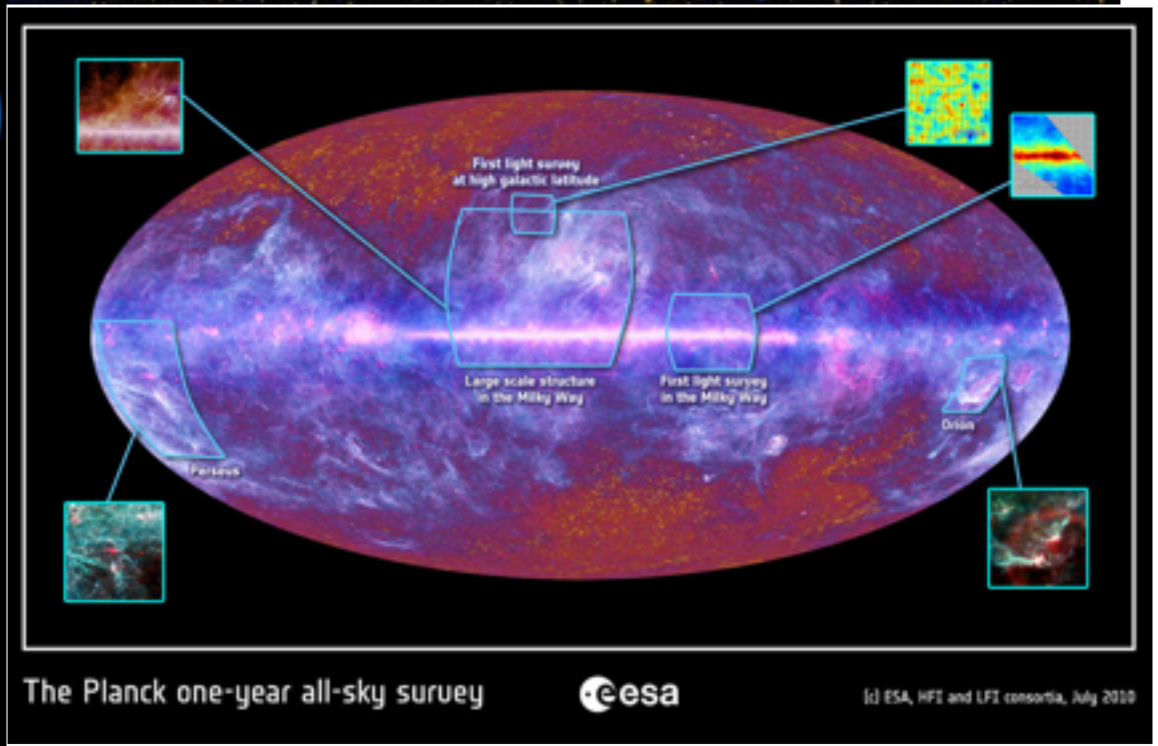
Snowmass CF1 summary: 1310.8327

Indirect detection: Cosmic-rays, gamma-rays and multi-wavelength approach

With CR spectral measurements we can understand the properties of the ISM, and probe sources of high energy CRs. Antimatter CRs indirectly also probe DM. Combine with gamma-ray and radio observations. Look for a DM signal.



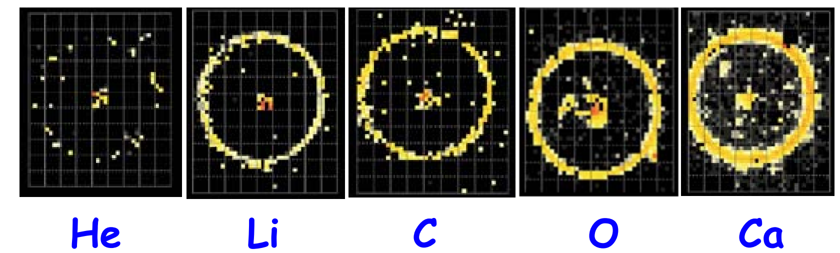


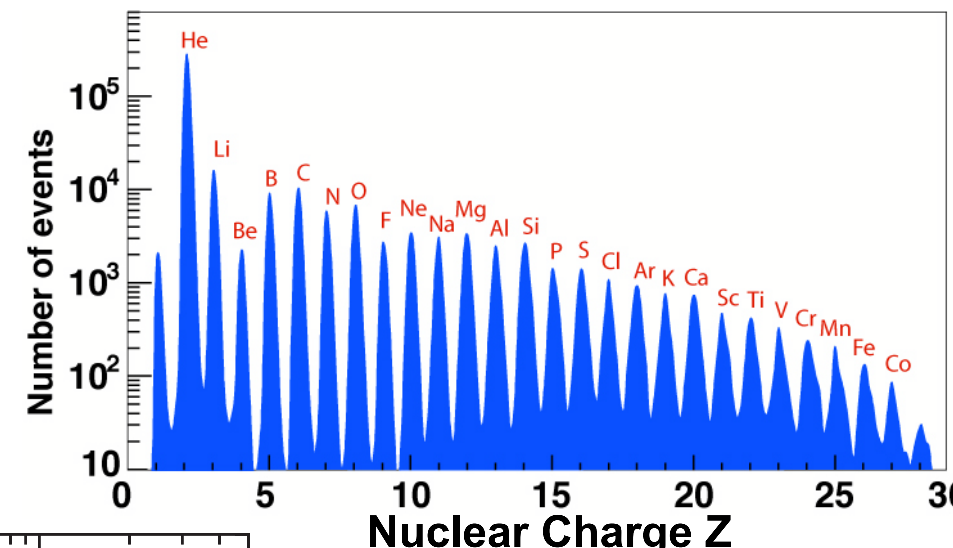


A great new Era for CRs:The AMS-02

Lunched on May 2011, will collect data for 20 yrs.
Will measure all CR nuclei species up to Ni.

positron fraction,
positrons,electrons
spectra,
antiproton/proton
B/C, Be10/Be9





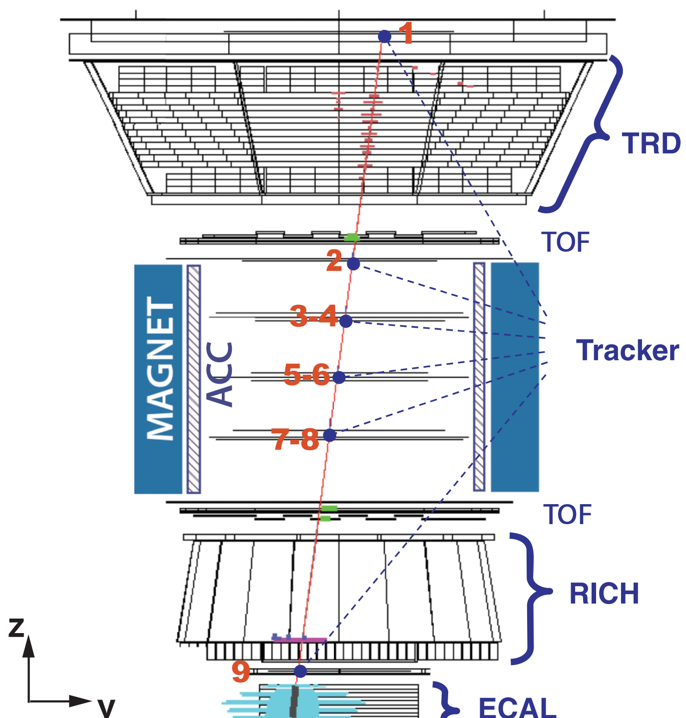
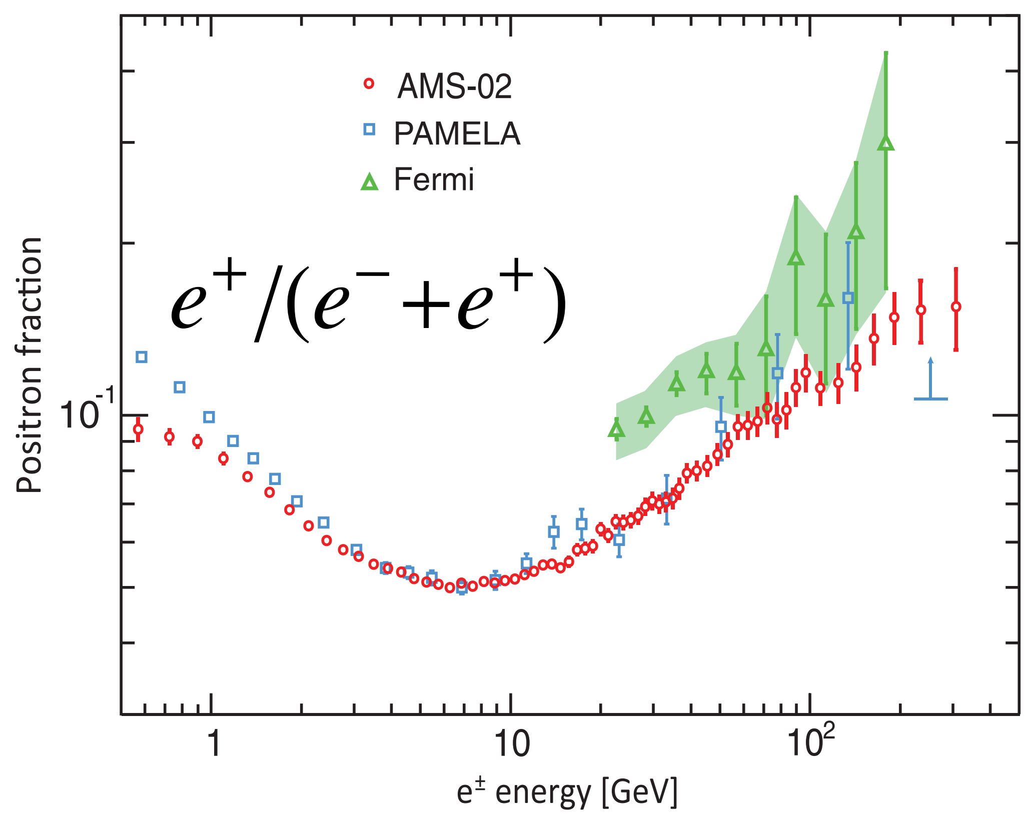


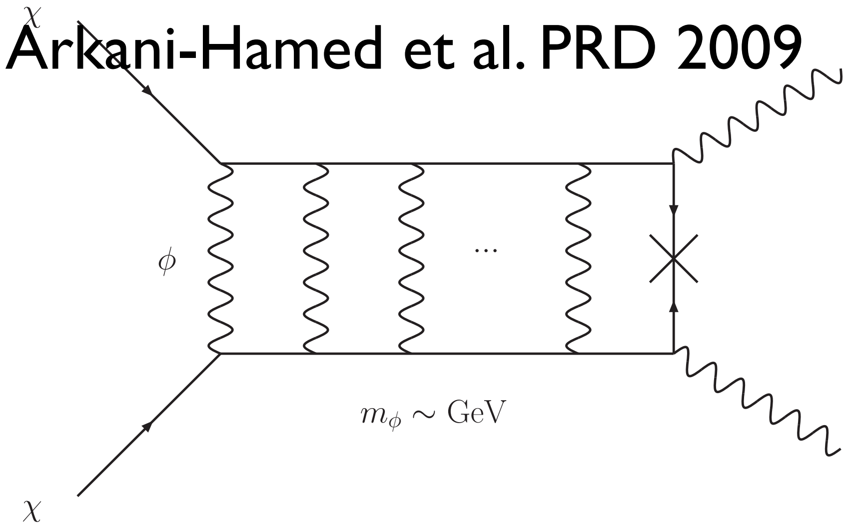
FIG. 1 (color). A 1.03 TeV electron event as measured by the AMS detector on the ISS in the bending (*y-z*) plane. Tracker planes 1–9 measure the particle charge and momentum. The TRD identifies the particle as an electron. The TOF measures the charge and ensures that the particle is downward-going. The RICH independently measures the charge and velocity. The ECAL measures the 3D shower profile, independently identifies the particle as an electron, and measures its energy. An electron is identified by (i) an electron signal in the TRD, (ii) an electron signal in the ECAL, and (iii) the matching of the ECAL shower energy and the momentum measured with the tracker and magnet.

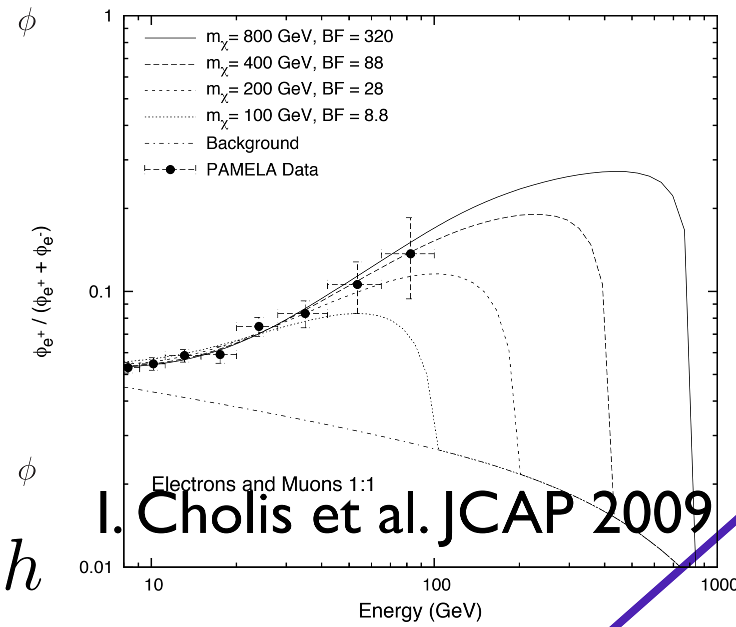


Annihilating Dark Matter Interpretation Models

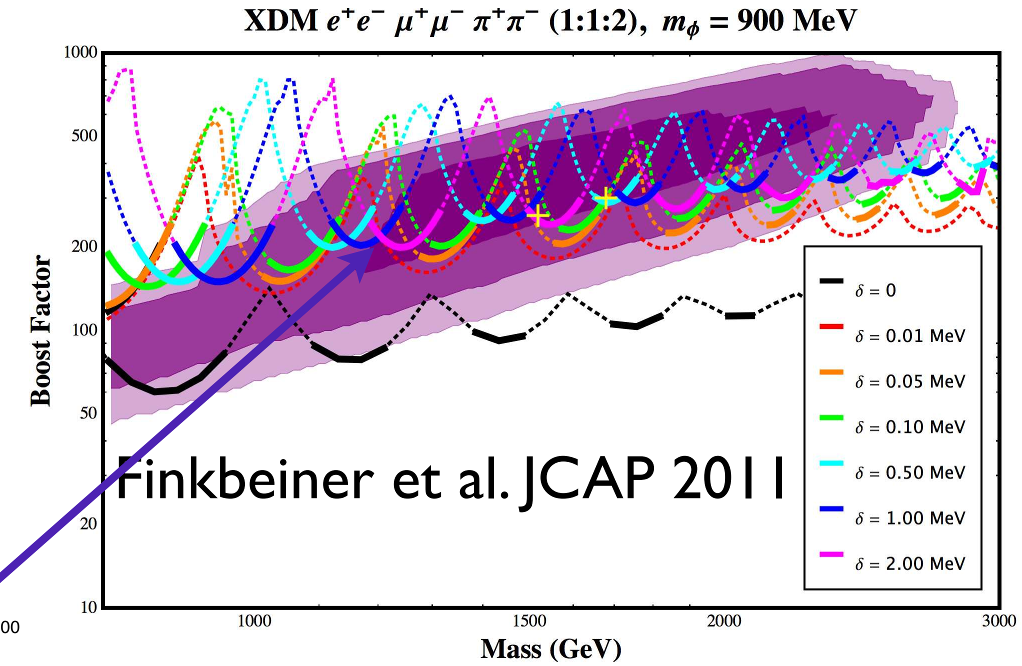
Physical models that work with all data; leptons/ antiprotons/ gamma-rays/ microwave (Models with Sommerfeld enhancement)

Arkani-Hamed et al. PRD 2009





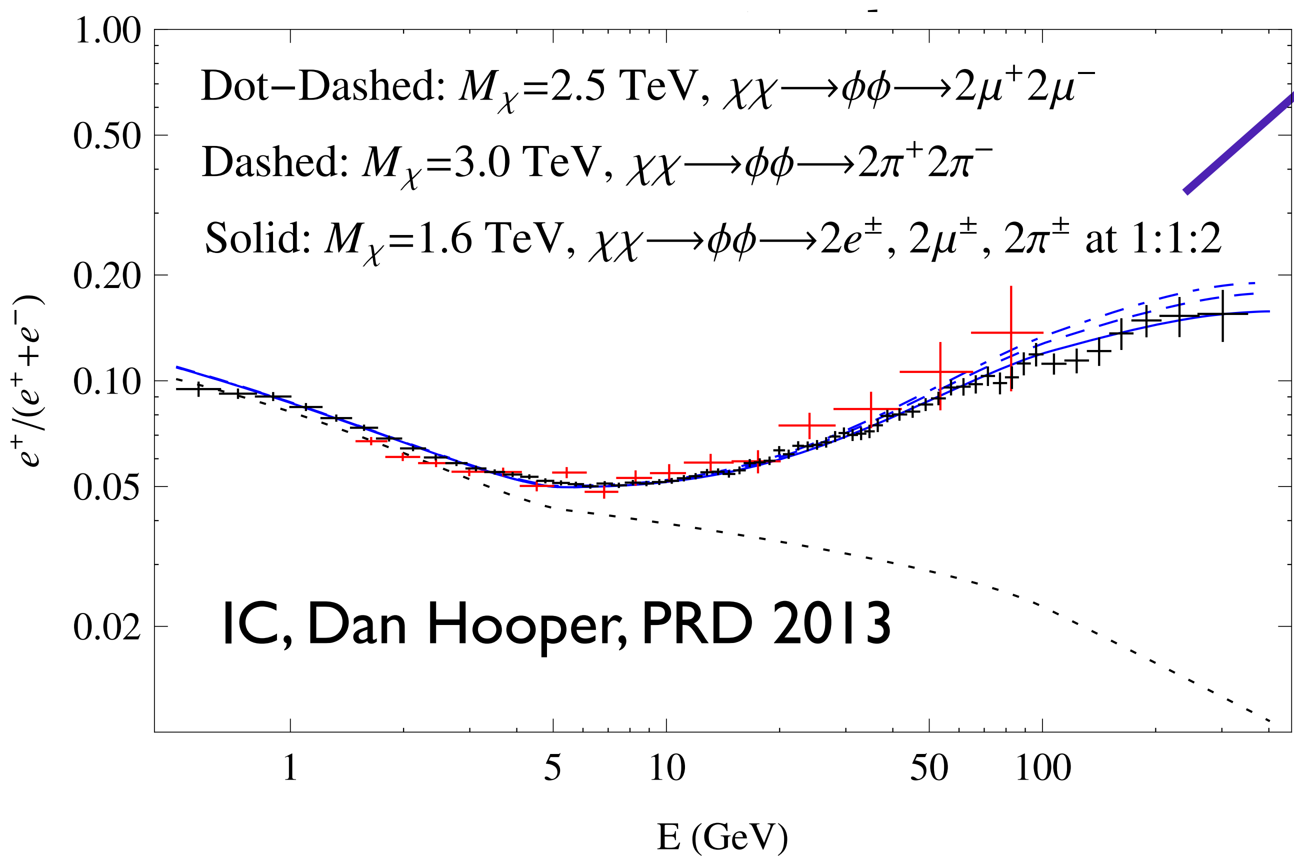
I. Cholis et al. JCAP 2009



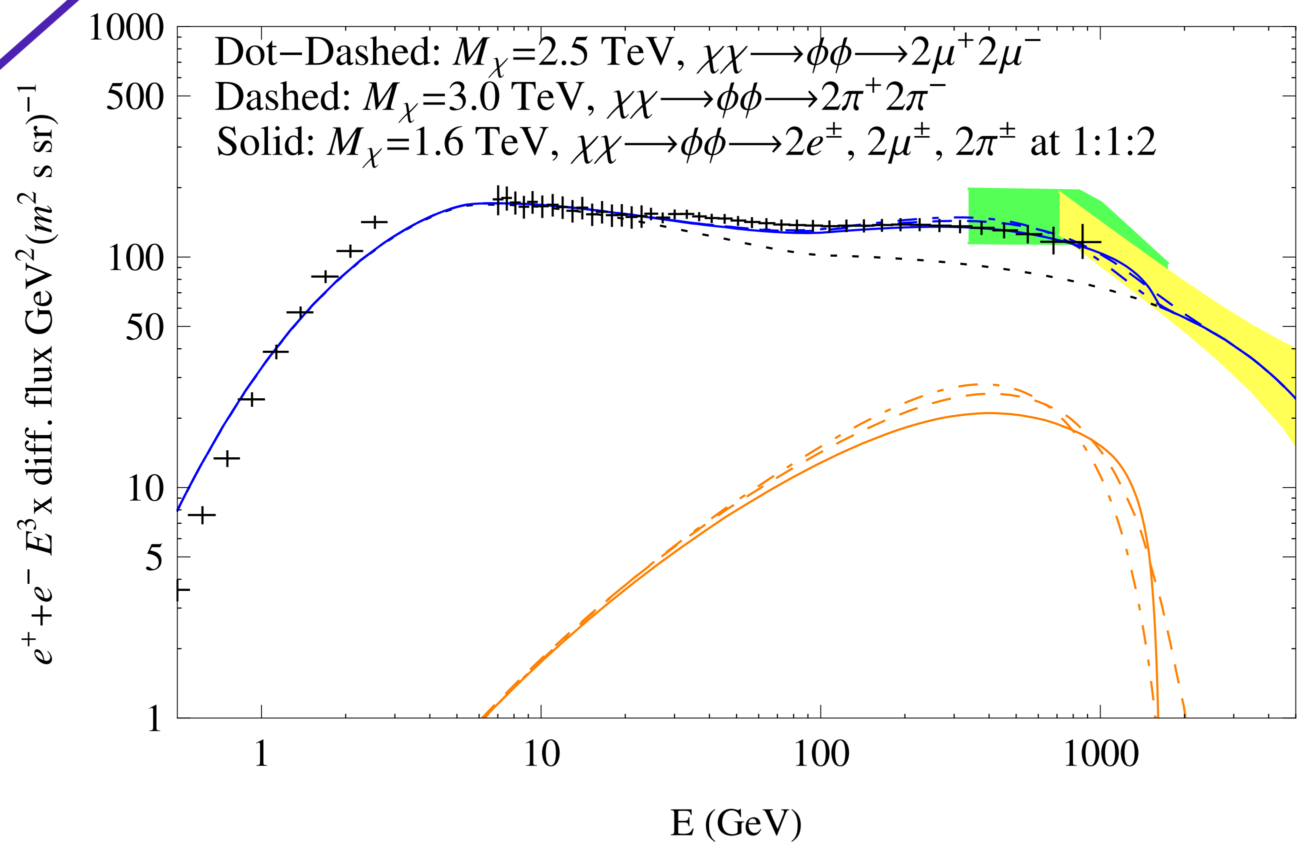
Finkbeiner et al. JCAP 2011

phi mixing with the SM higgs $\kappa \phi^2 h^\dagger h$

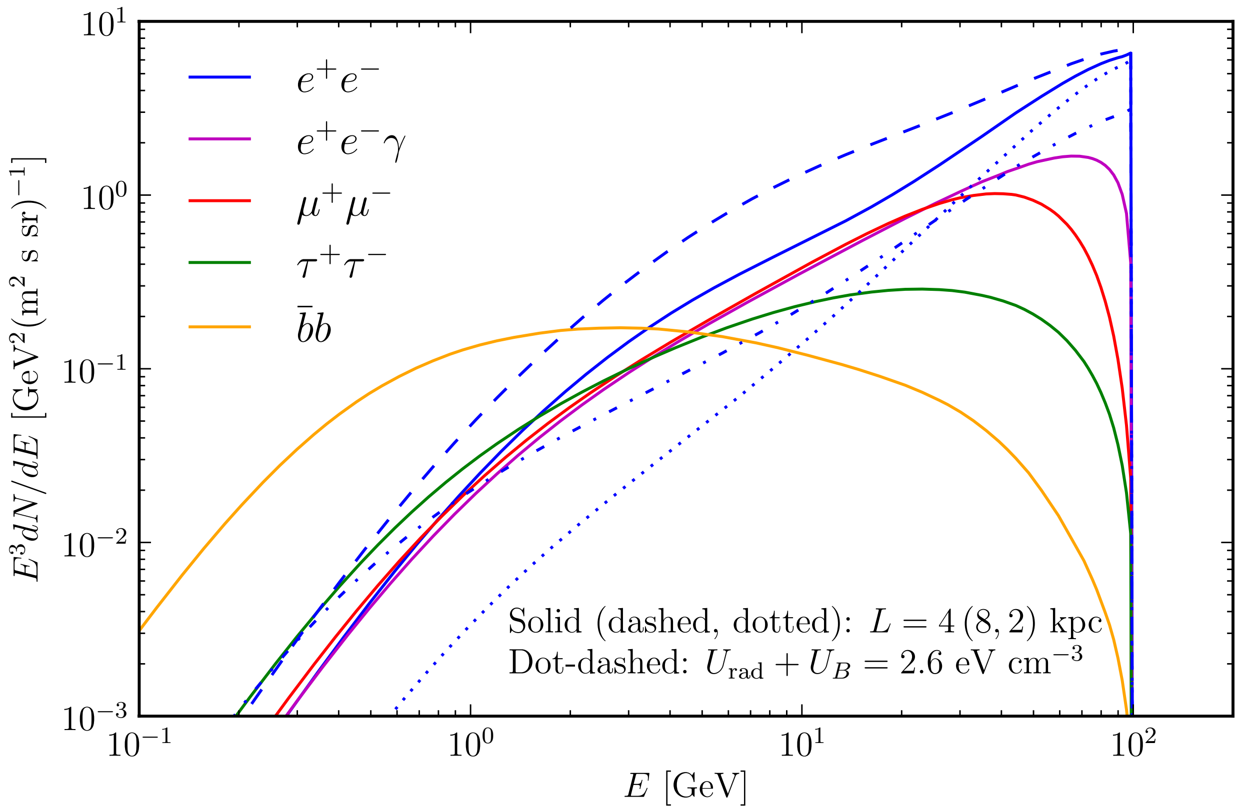
$\langle \phi \rangle \sim m_\phi$ OR mix with EM $F'_{\mu\nu} F^{\mu\nu}$



IC, Dan Hooper, PRD 2013

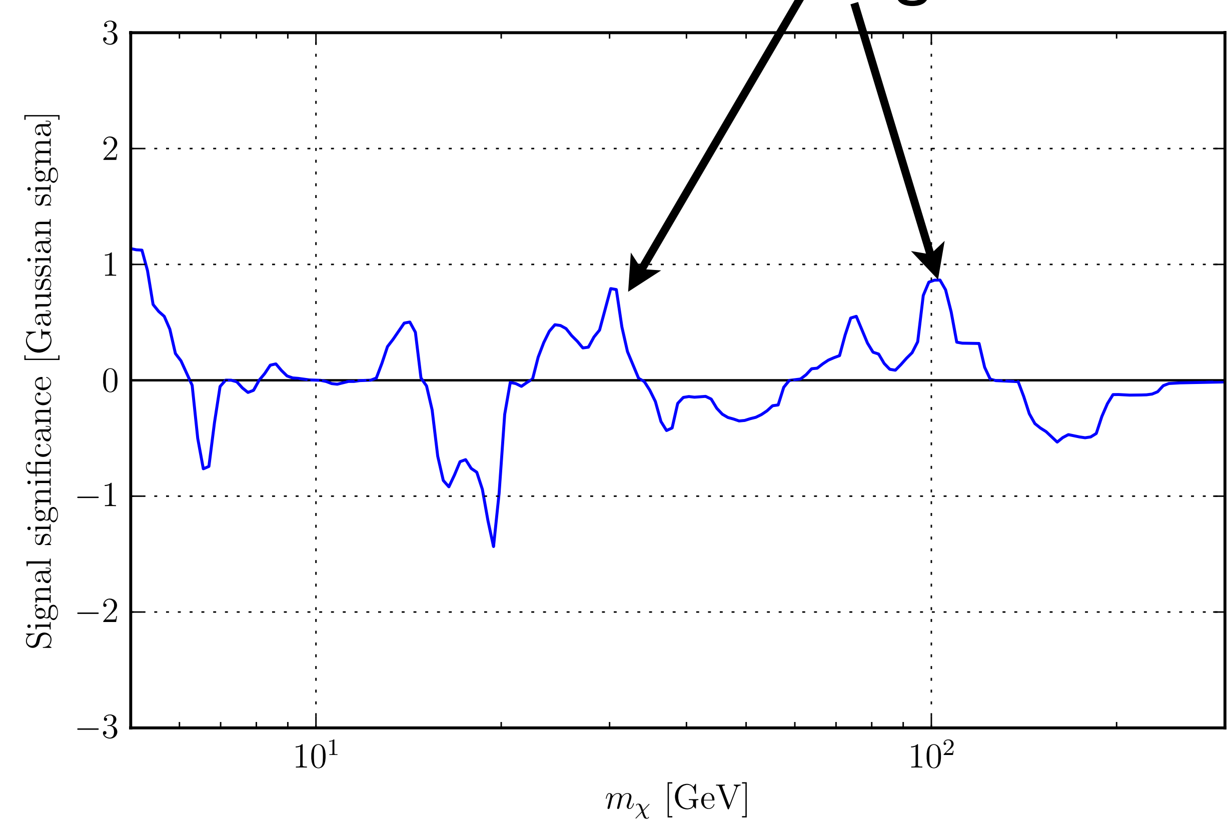


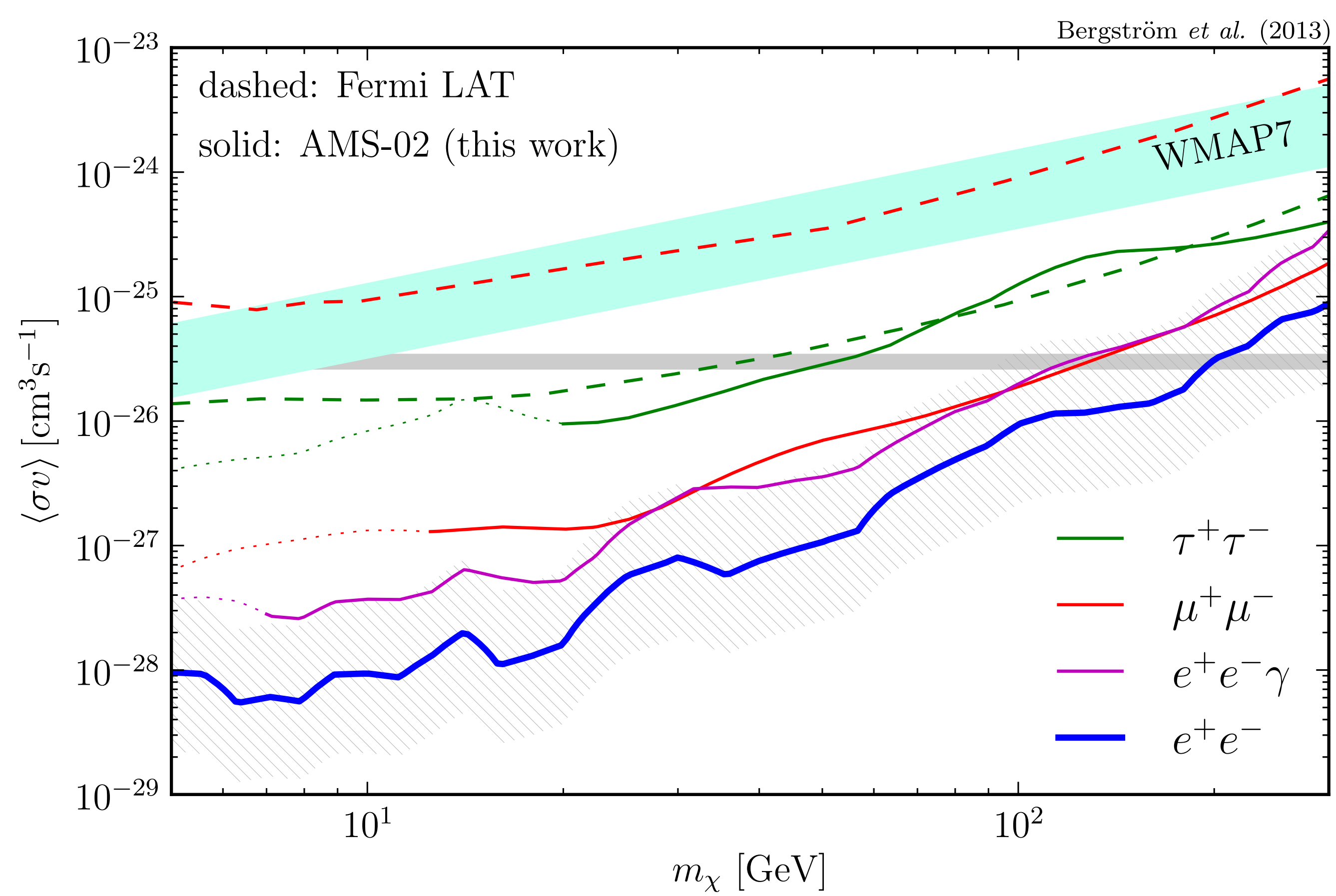
Lack of spectral features in the positron fraction: LIMITS on lighter WIMPs



Lars Bergstrom, Torsten Bringmann, IC, Dan Hooper, Christoph Weniger, PRL 2013 (arXiv:1306.3983)

Less than 1 sigma

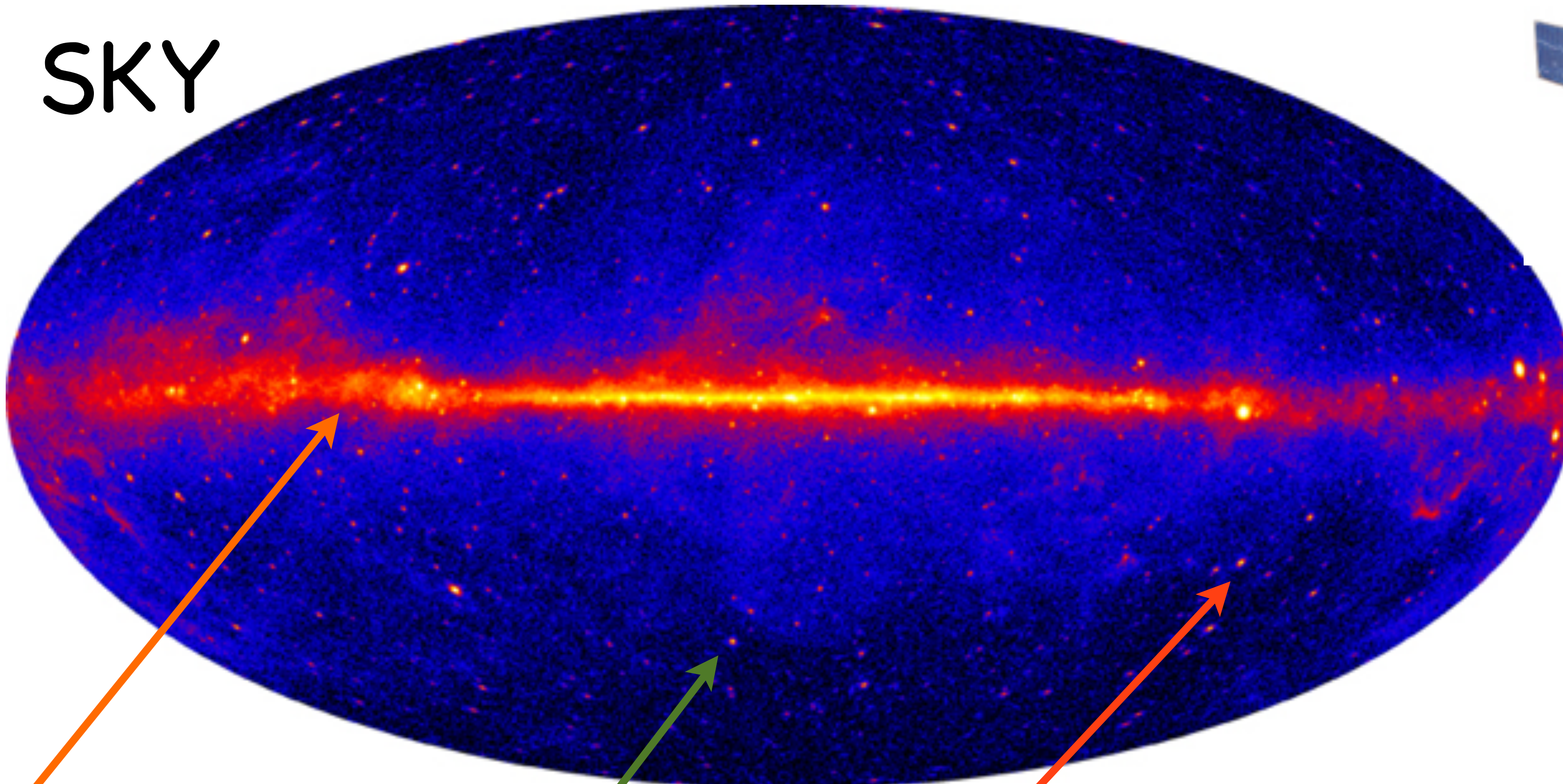


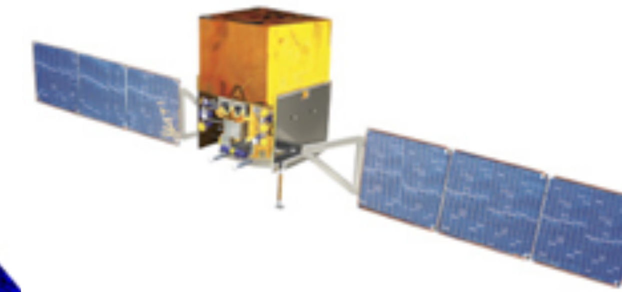


The absence of spectral features in the AMS positron fraction gives limits on light leptophilic DM that are 10-100 times stronger than current limits from CMB, or from dSph (similarly for the GC)

Gamma-rays

Fermi SKY





Known sources for the observed gamma-rays are:

i)Galactic Diffuse: decay of pi0s (and other mesons) from pp (NN) collisions (CR nuclei inelastic collisions with ISM gas), bremsstrahlung radiation off CR e, Inverse Compton scattering (ICS): up-scattering of CMB and IR, optical photons from CR e

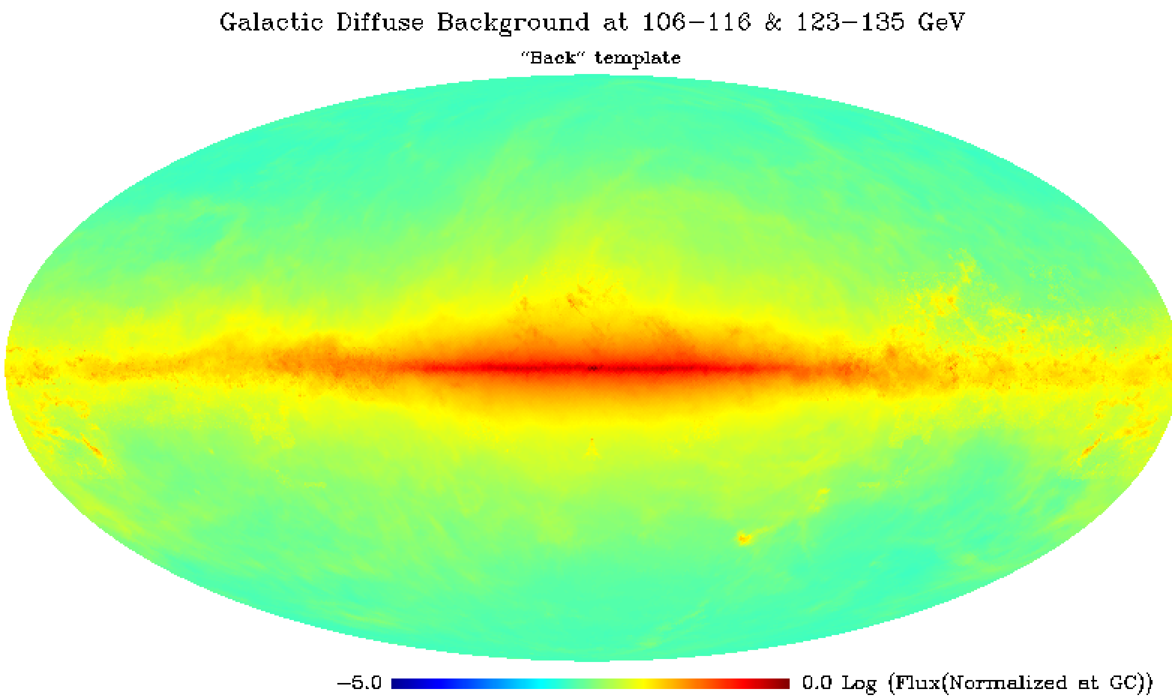
ii)from point sources (galactic or extra galactic) (1873 detected in the first 2 years)

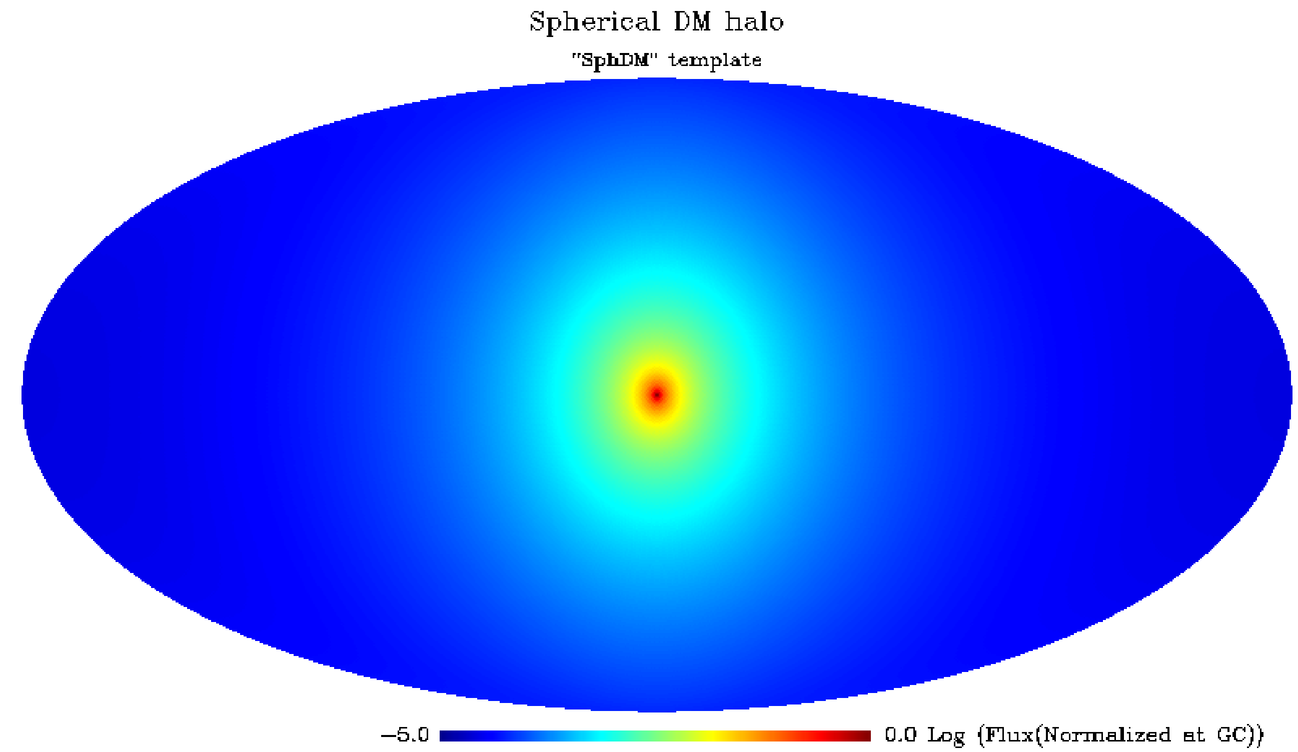
iii)Extragalactic Isotropic

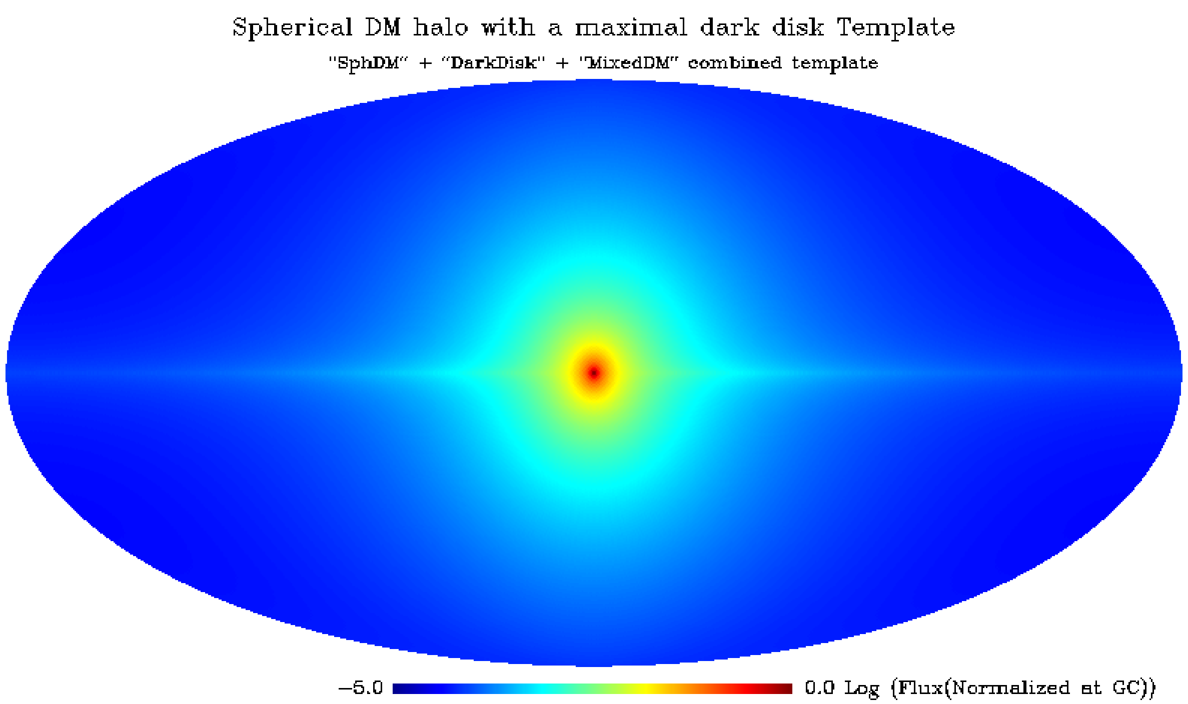
iv)"extended sources"

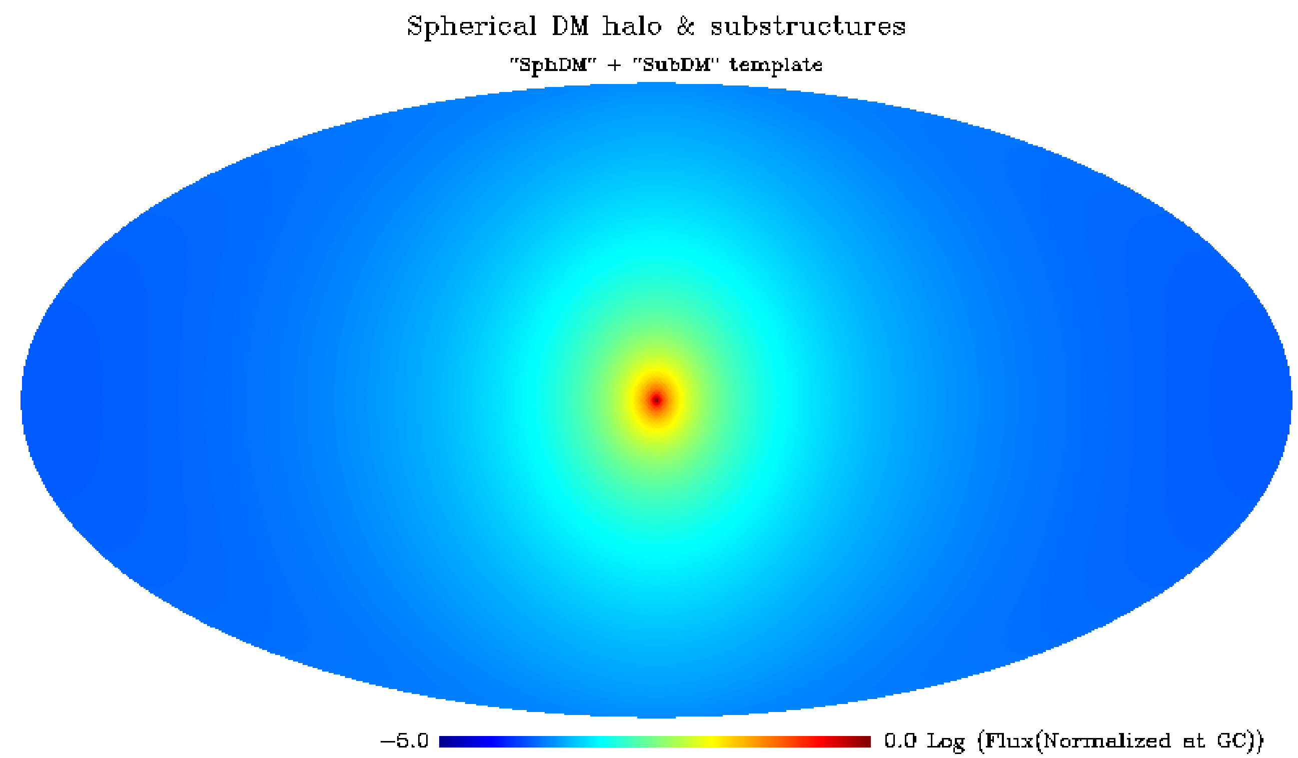
iv)misidentified CRs (isotropic dew to diffusion of CRs in the Galaxy)

Diffuse Gamma-Ray maps, examples









$$\rho_{sph}(r) = \rho_{Ein} \exp\left\{-\frac{2}{\delta}\left[\left(\frac{r}{r_c}\right)^{\delta} - 1\right]\right\}$$

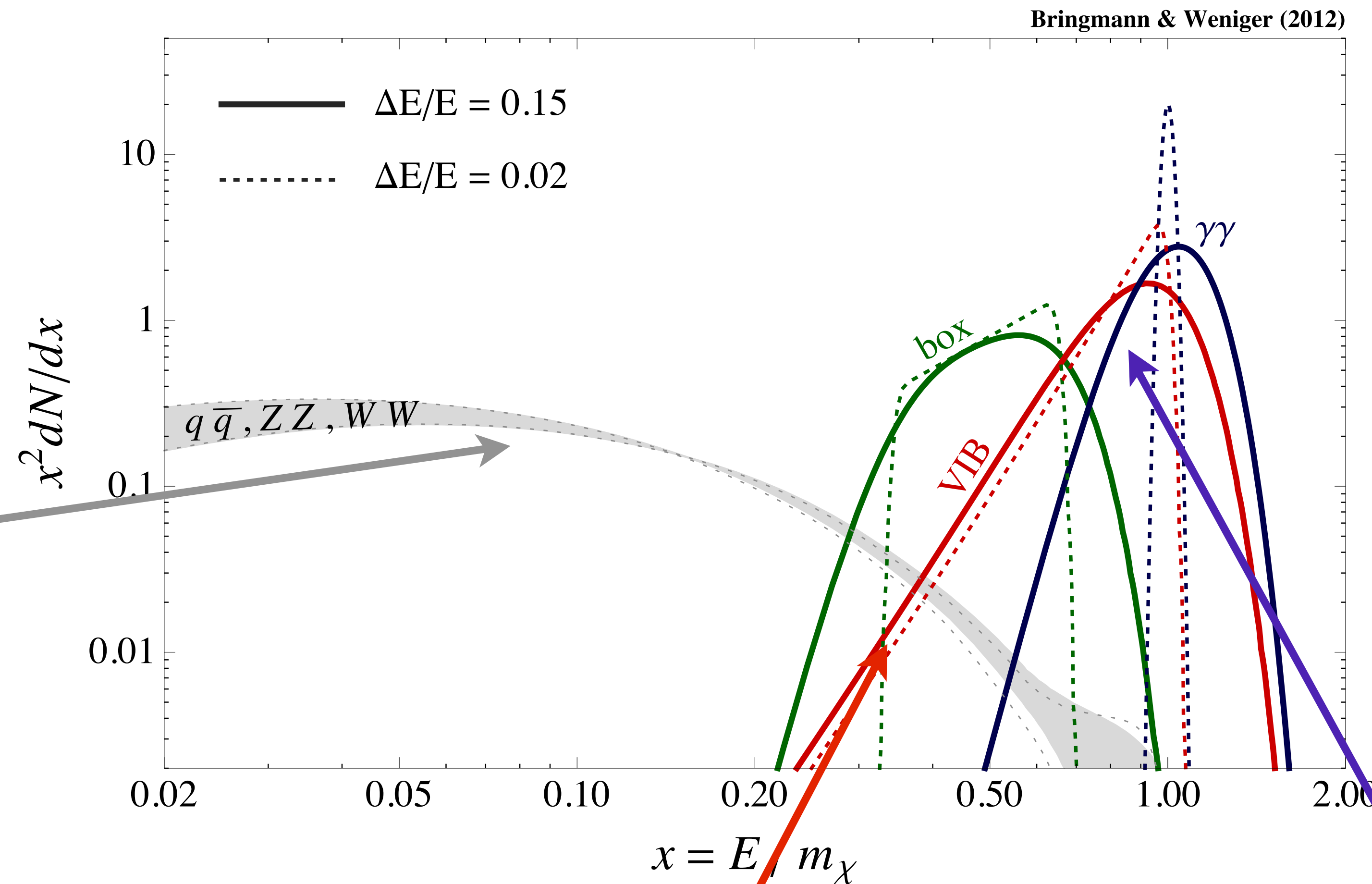
$$\rho_{DD}(R, z) = \rho_{0_{DD}} \exp\left[\frac{1.68\,(R_\odot - R)}{R_{1/2}}\right] \exp\left[-\frac{0.693\,|z|}{z_{1/2}}\right]$$

Looking for DM annihilation signals

For a DM annihilation signal
We want to observe: $$\frac{d\Phi_\gamma}{dE} = \int\int \frac{\langle \sigma v \rangle}{4\pi} \frac{dN_\gamma}{dE}_{DM} \frac{\rho^2_{DM}(l,\Omega)}{2\, m^2_\chi} dl d\Omega$$

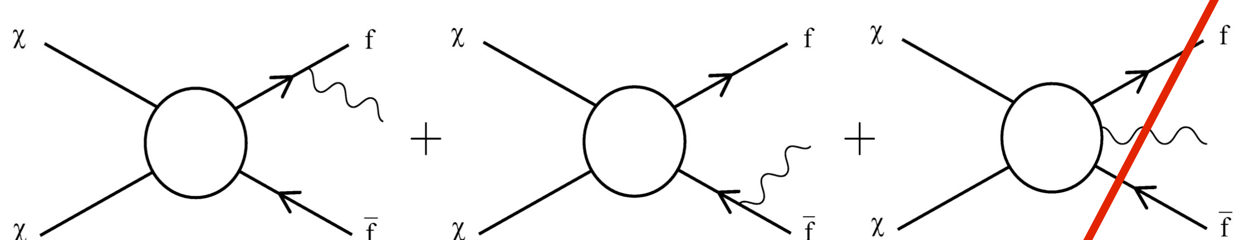
- Hardening of a spectrum without a clear cut-off localized in a certain region (Fermi haze->Fermi bubbles)
- Hardening of a spectrum with a clear cut-off: ~10 GeV DM claims towards the Galactic Center (GC) inner few degrees
- Line or lines
- One of the most likely targets is the GC (though backgrounds also peak), others are the known substructure (dSphs) or Galaxy clusters

DM annihilation spectra

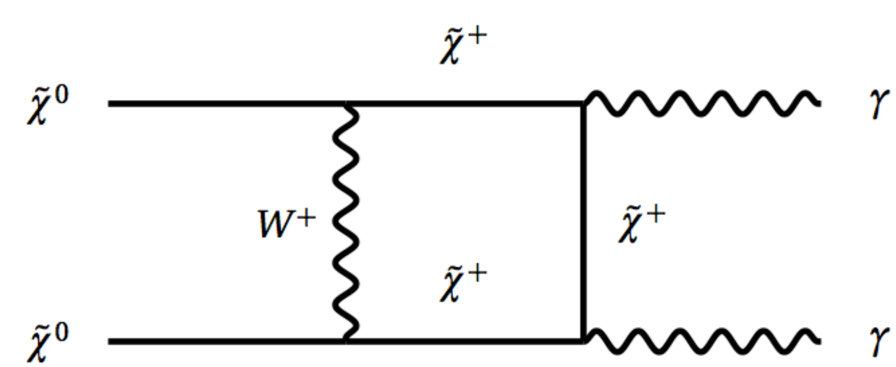


Continuum emission, tree level, relatively hard spectrum, but featureless

Two body annihilation to photons. Almost monochromatic Line, but suppressed at O(a^2).



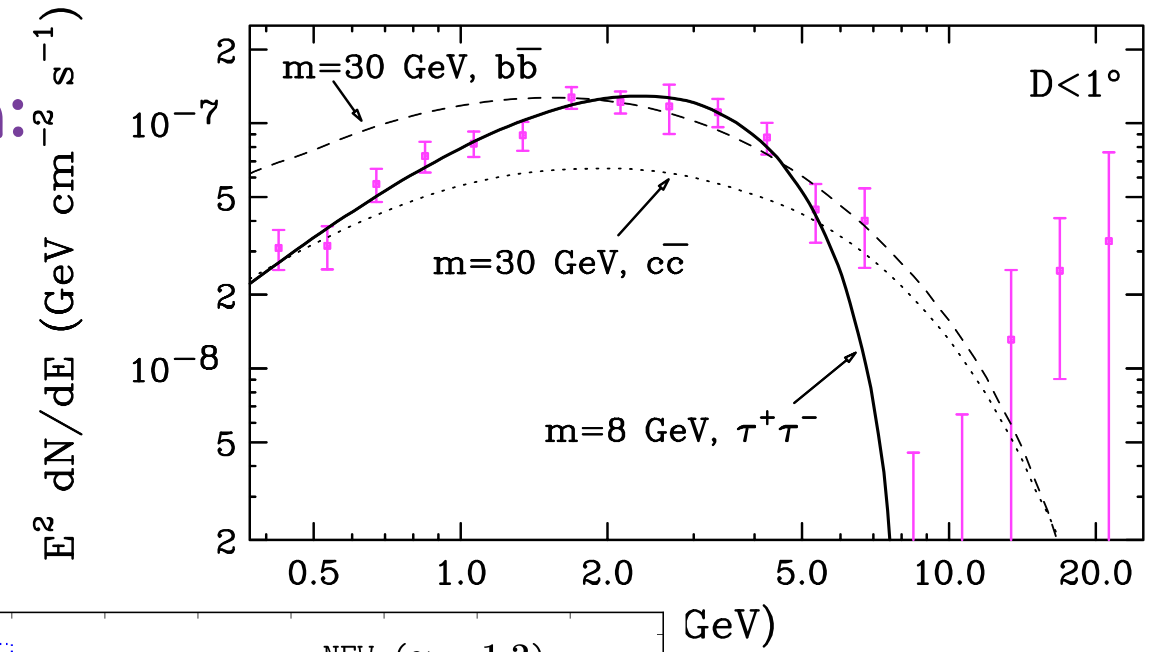
Final state radiation Virtual Internal Bremss.



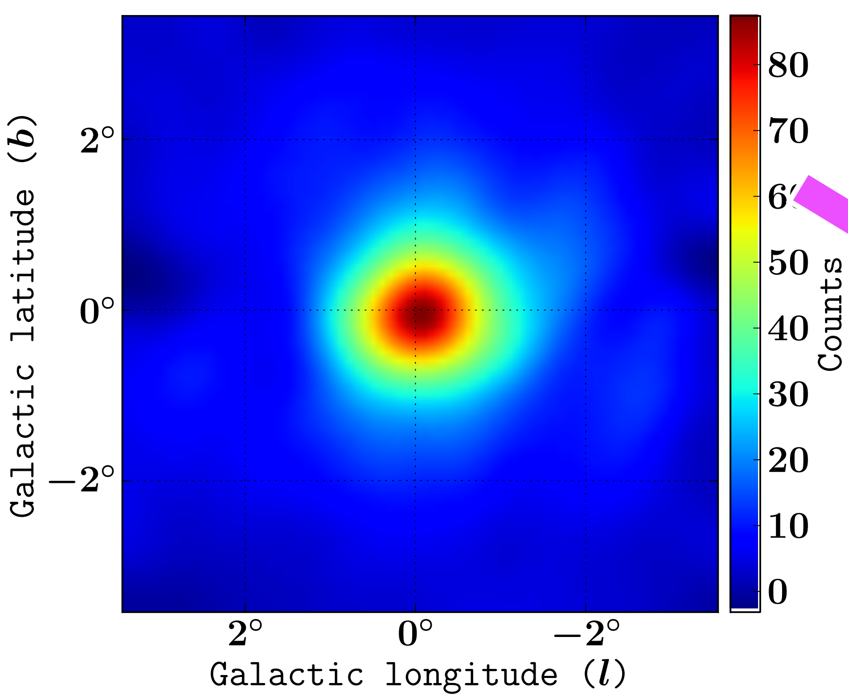
Comes from radiative corrections to processes with charged particles. Suppressed by O(a), but with a much harder spectrum; FSR has an additional suppression factor of (mf/Mchi)^2

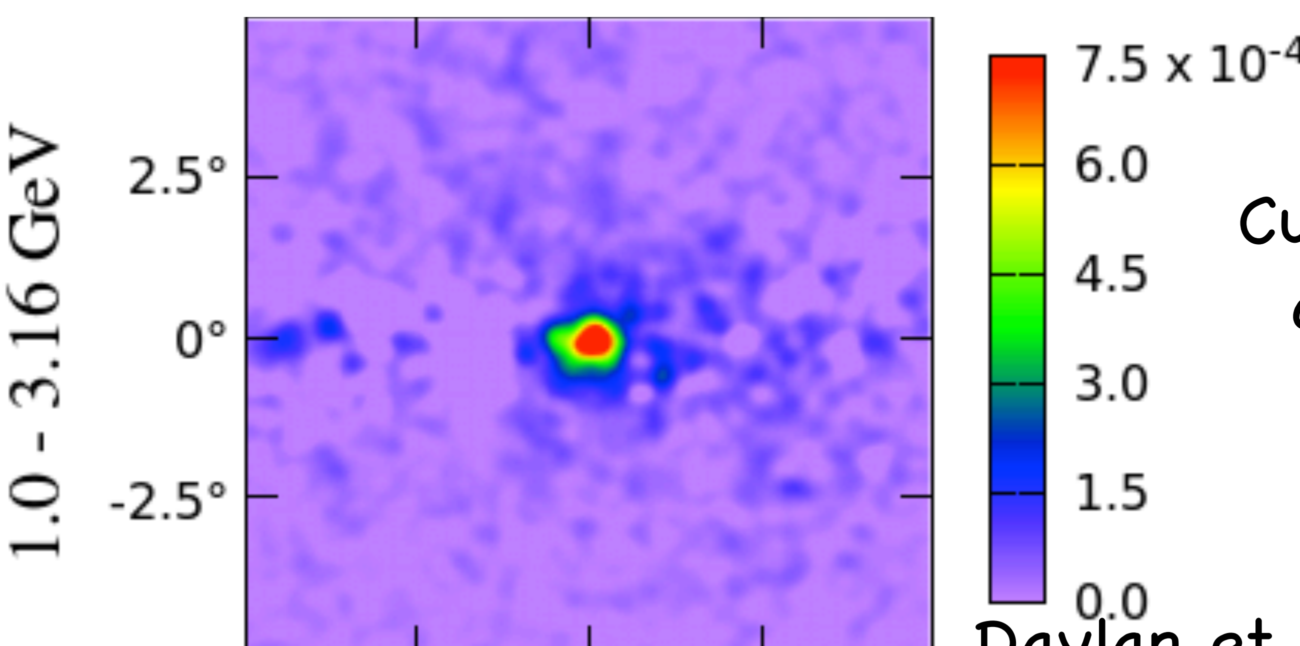
A possible DM signal from the GC? (GeV excess)

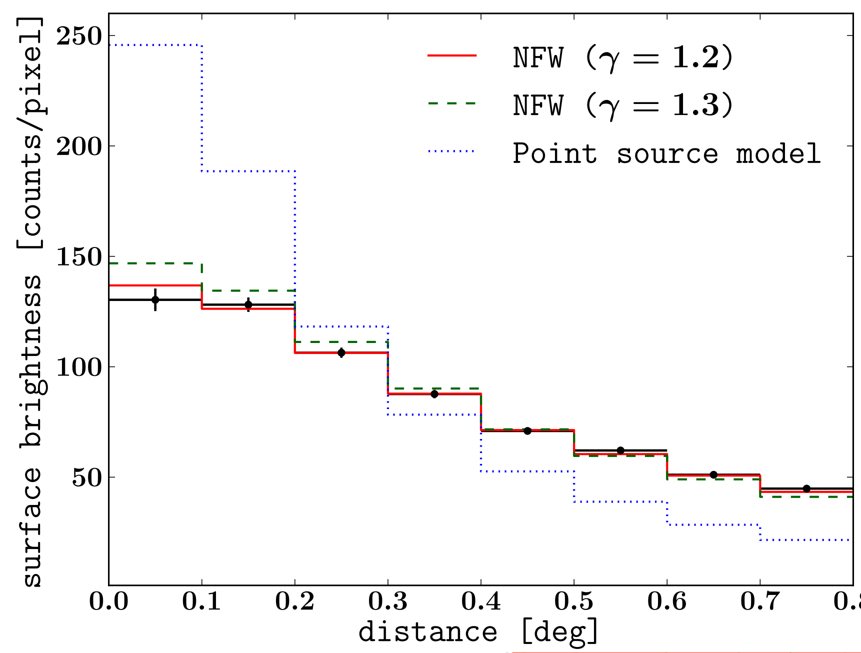
The First studies: Hooper & Goodenough:
(arXiv:0910:2998 & 1010.2752)

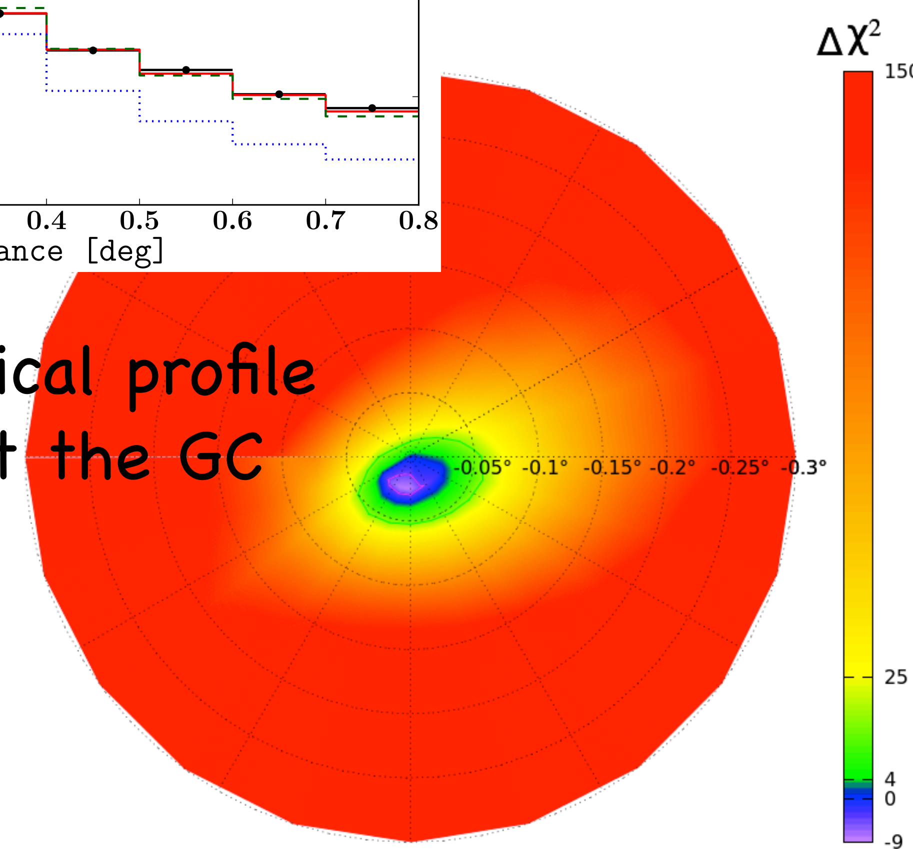


Gordon & Macias (1306.5725)





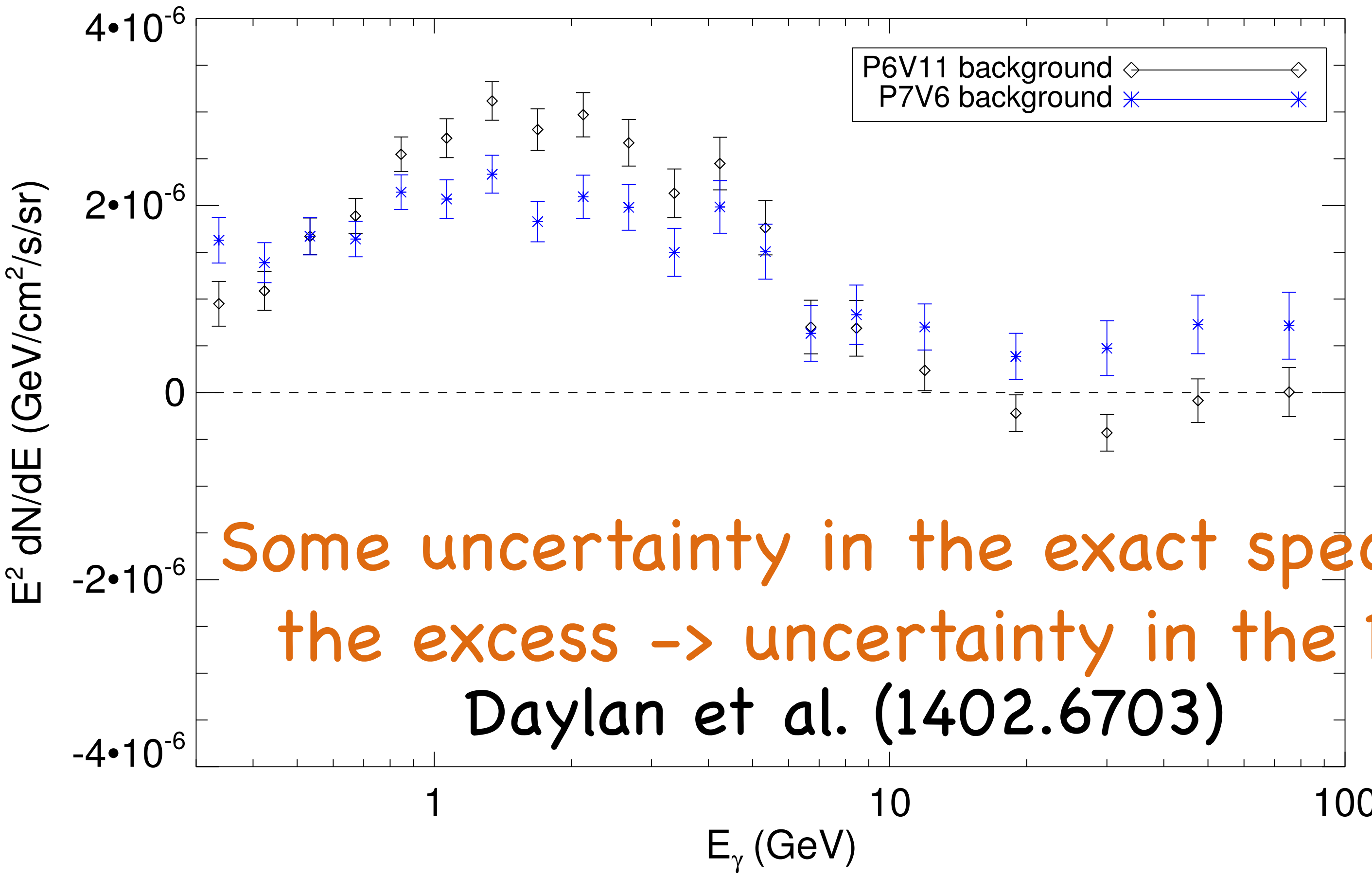


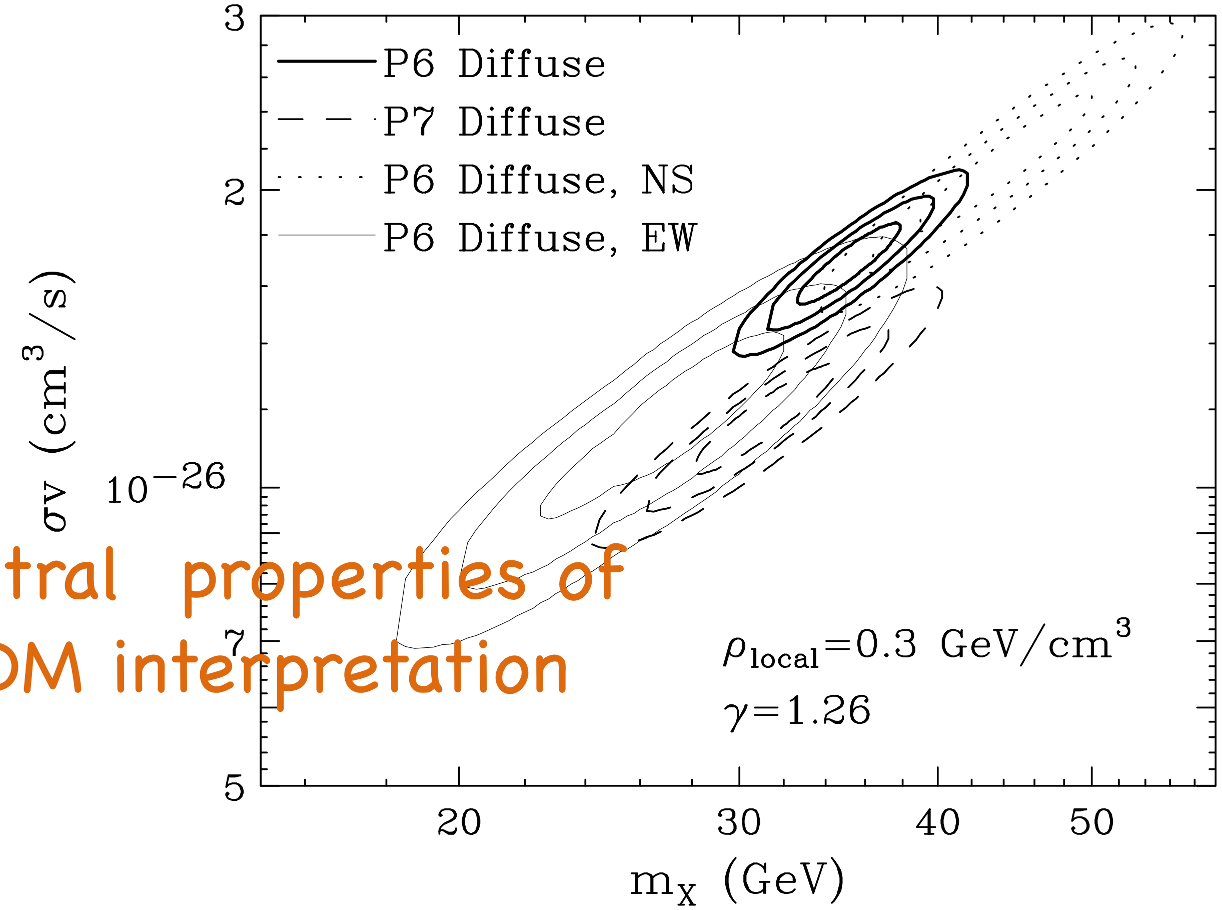


Cuspy morphological profile and centered at the GC

Daylan et al. (1402.6703)

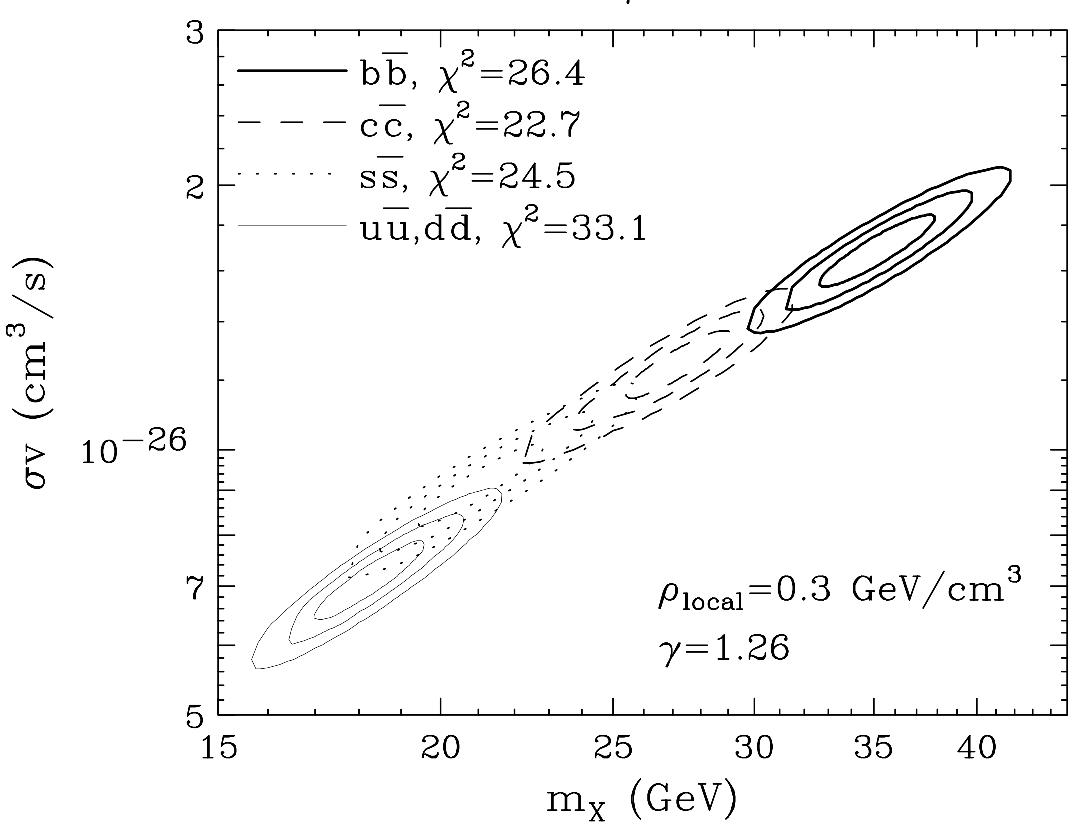
Spectrum has a sharp spectral cut-off:





Some uncertainty in the exact spectral properties of the excess -> uncertainty in the DM interpretation

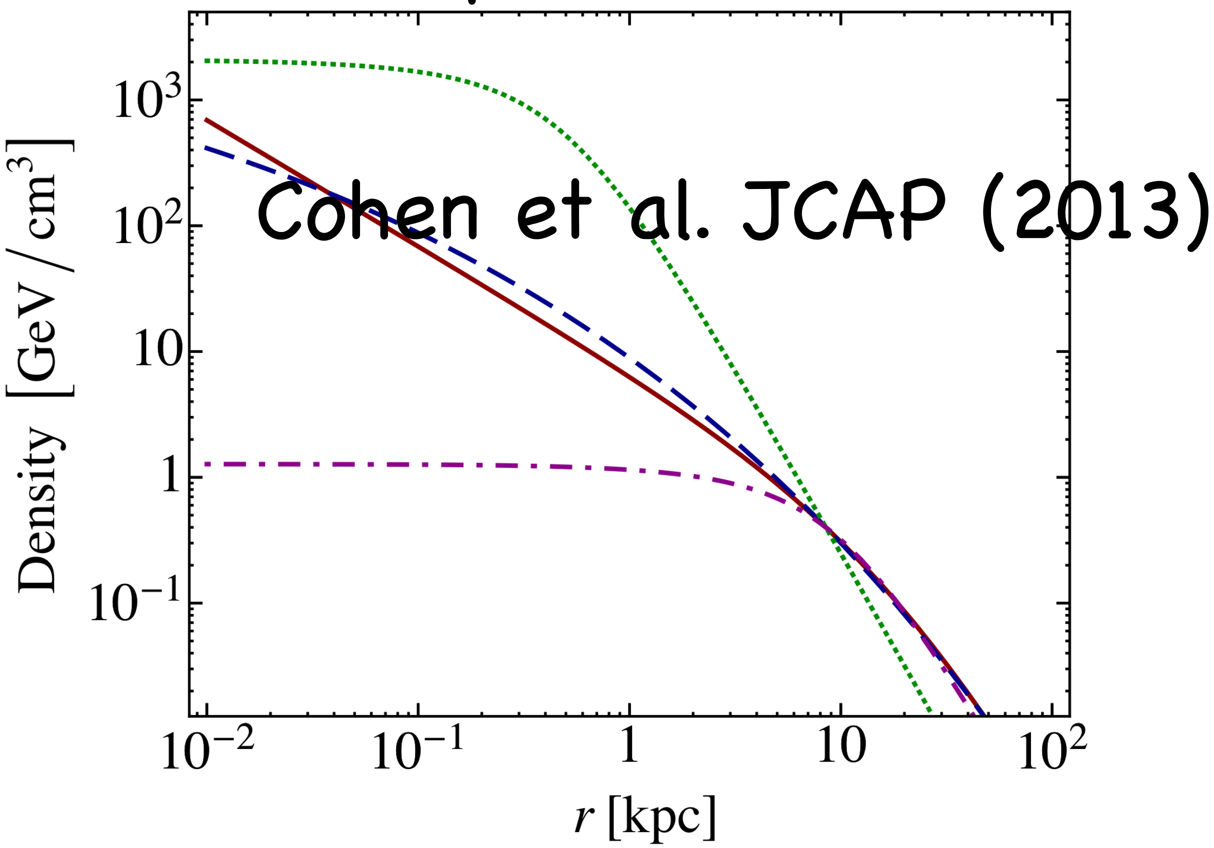
Daylan et al. (1402.6703)



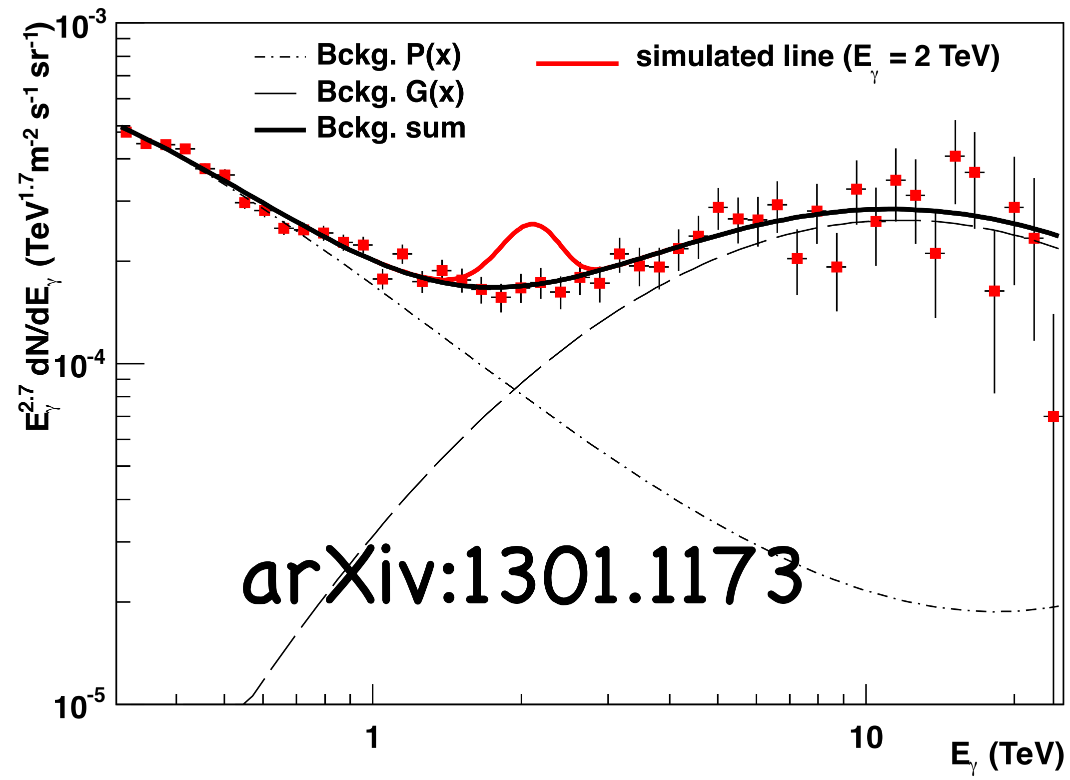
Degeneracy with respect to the DM annihilation "channel" (describes the SM products of annihilation)

The case of a gamma-ray line at the galactic center

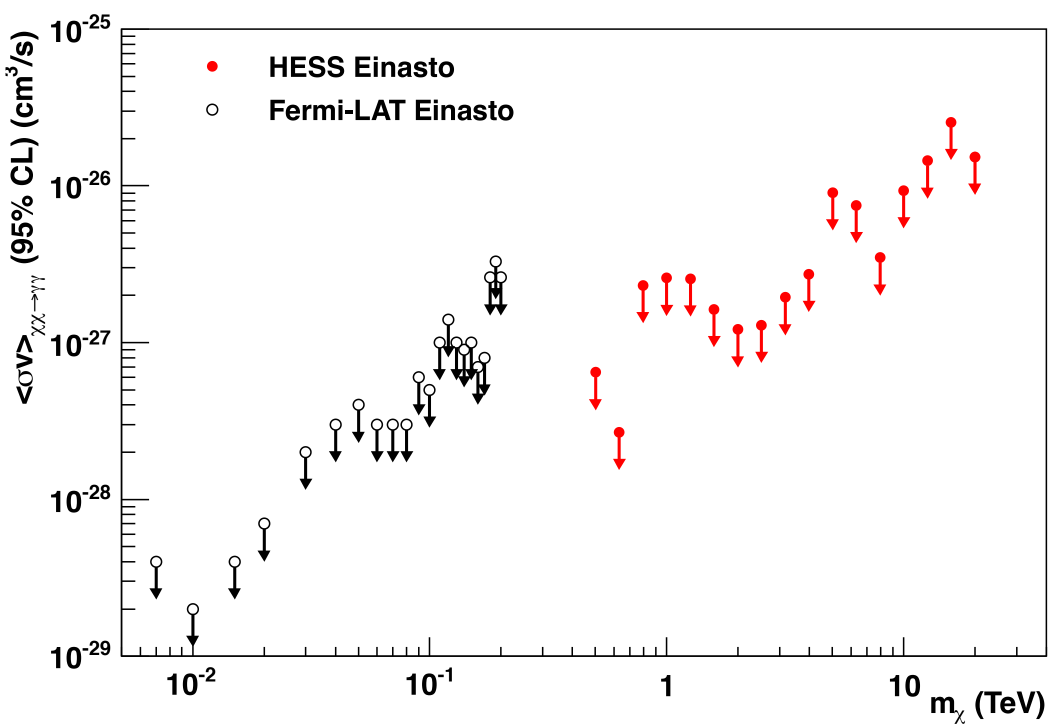
The DM profile:



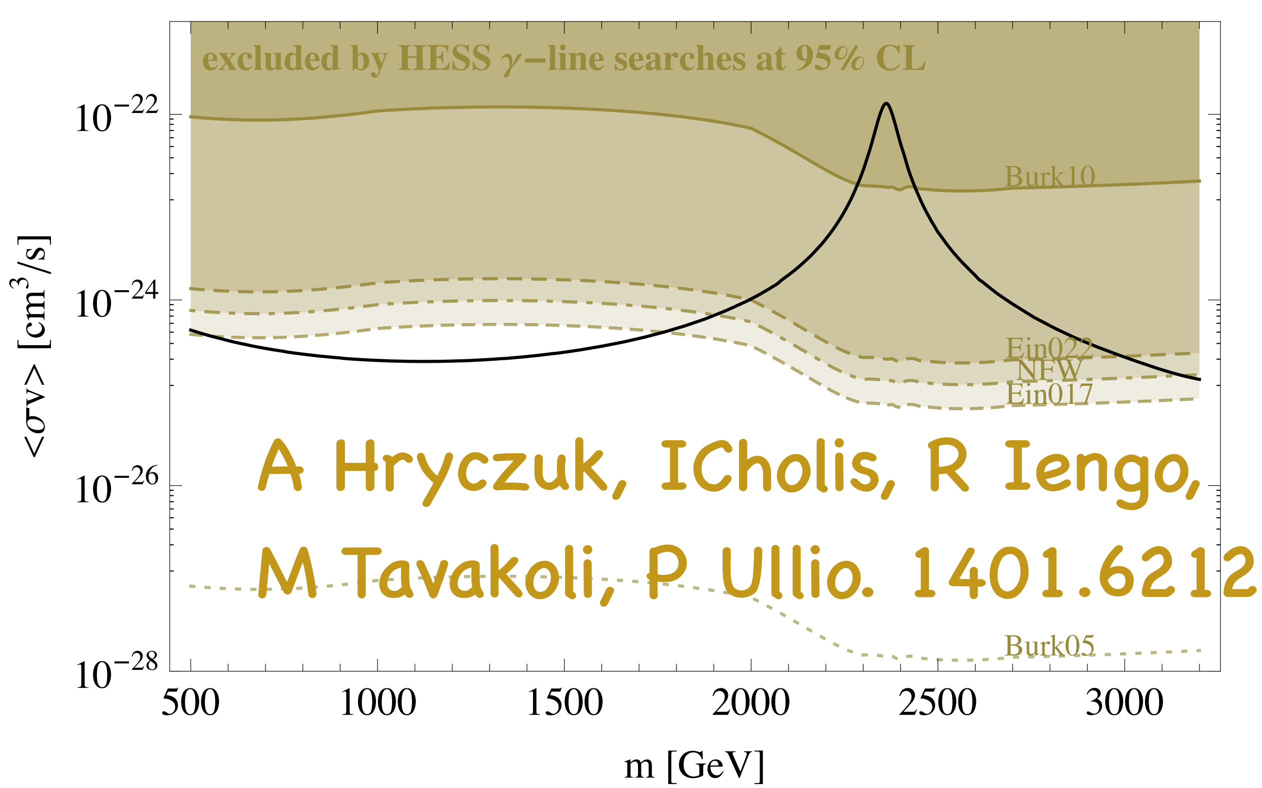
Looking for spectral features (HESS):



The Limits on spectral features:

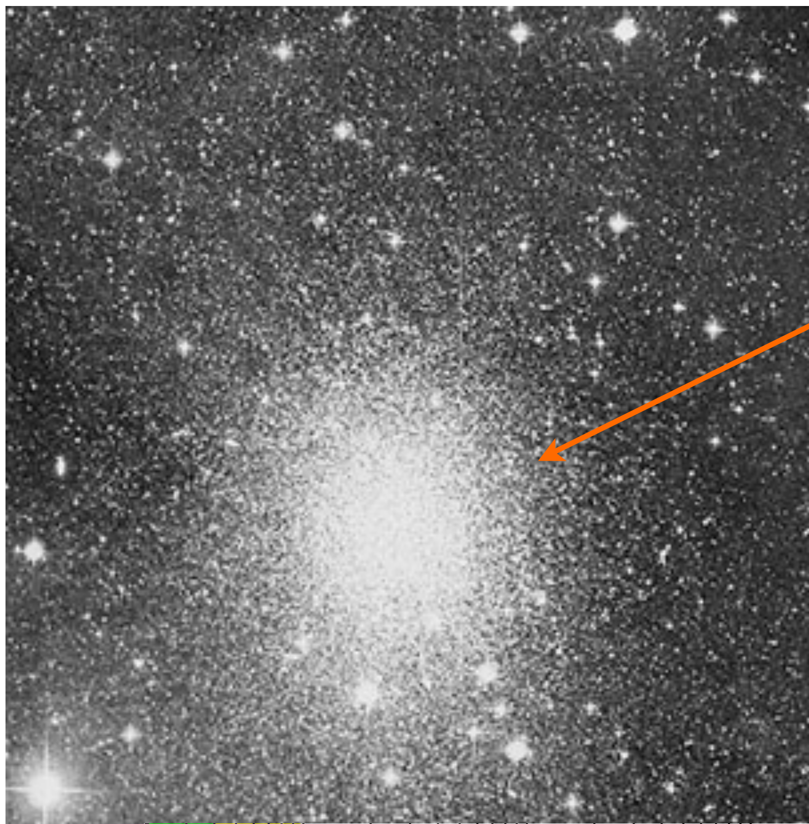


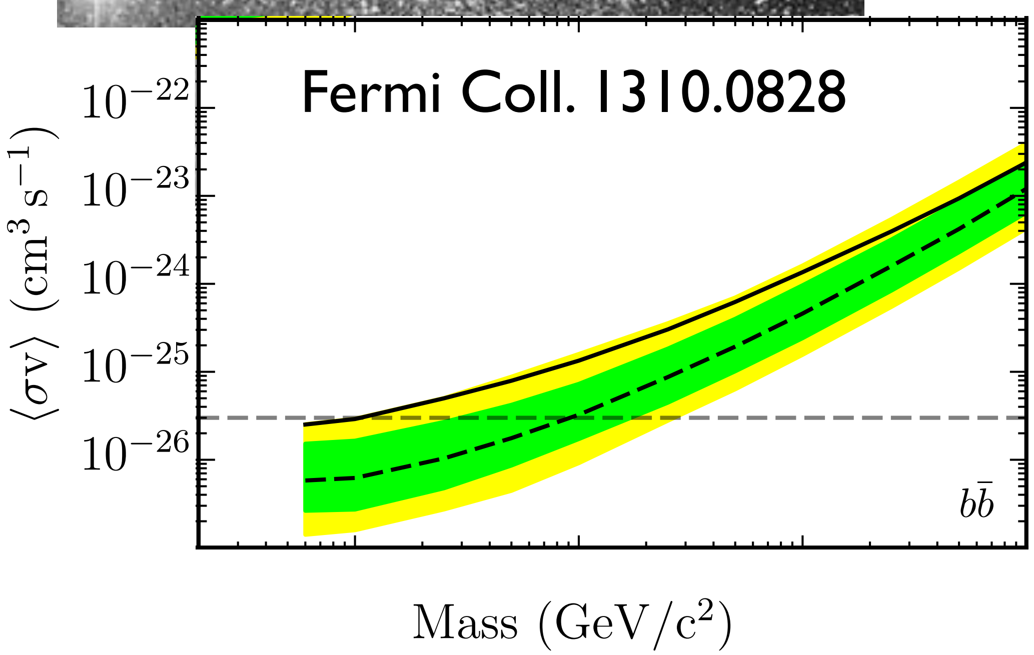
Wino Limits:



Significance of dwarf spheroidal galaxies for Dark Matter annihilation signal searches

Sculptor





dwarf Spheroidal galaxies are low luminosity galaxies (spheroidal in shape) containing ~10-100 million stars with the observed ones being companions to our Galaxy or to Andromeda. Their typical mass is ~ 100 times smaller than our galaxy.

Why we care:

among the most dark matter-dominated galaxies with very low baryonic gas densities, and suppressed star formation rates ->

flux of gamma-rays from individual sources and CRs interacting with local medium is low (small backgrounds in gammas),

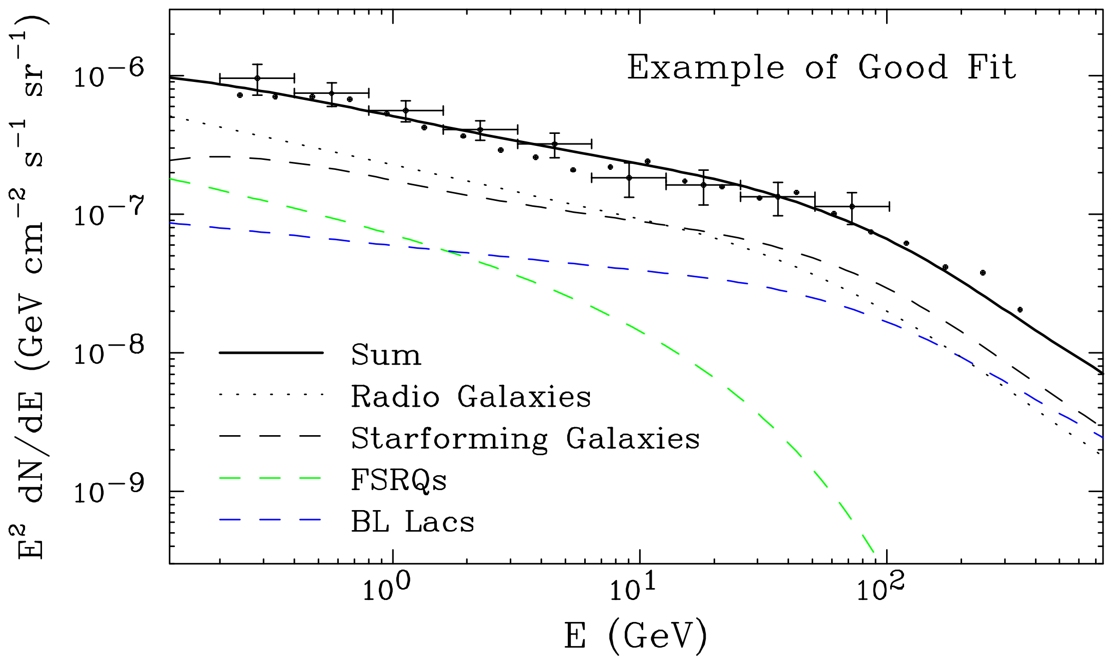
thus a "good" target to look for a DM signal in gamma-rays, especially for detectors as the

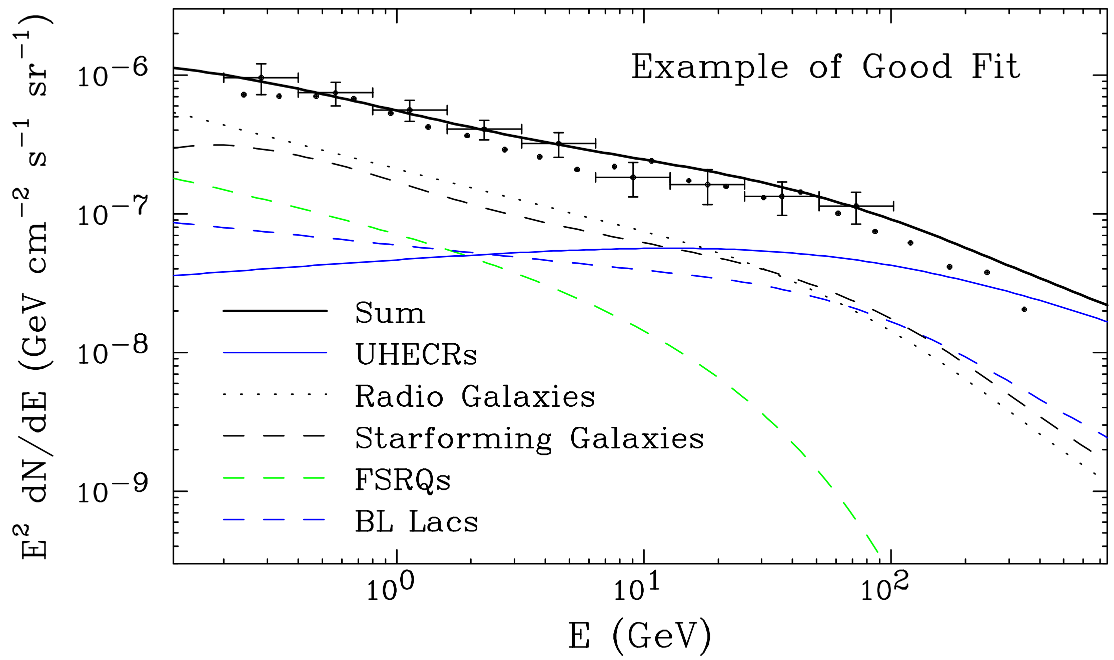
Fermi-LAT, Air-Cherenkov telescopes

(Evans,Ferrer&Sarkar 04, Colafrancesco,Profumo,Ullio 07, Strigari, Koushiappas, Bullok, Koplinghat 07, ...)

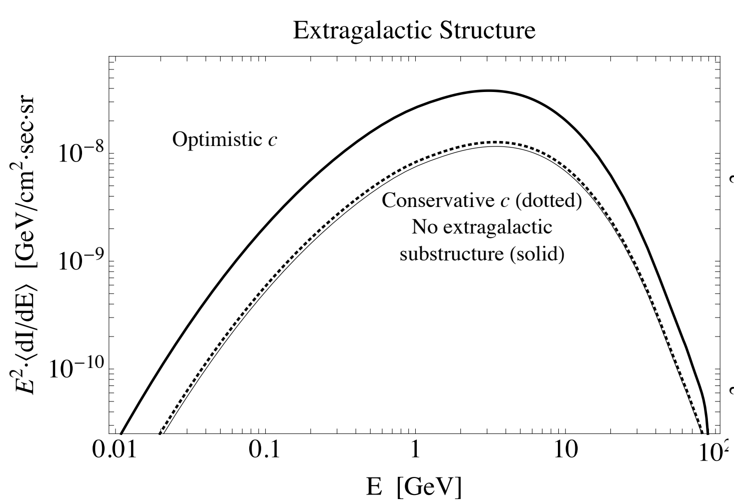
Constraints from High Latitudes (mainly extragalactic)

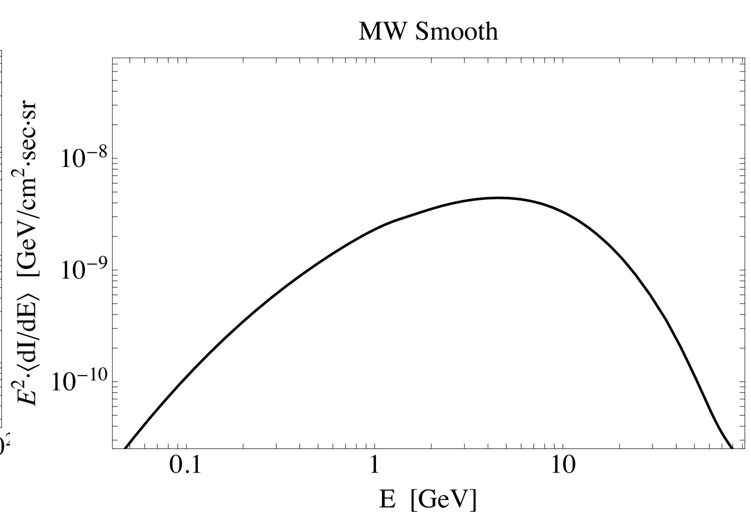
Extragalactic diffuse gamma-rays are isotropically distributed. There are many astrophysical sources that suffer from relatively large uncertainties. Correlating to radio we can extract some of their properties and model them out. —> Build models for the non-DM contribution and derive limits on DM.

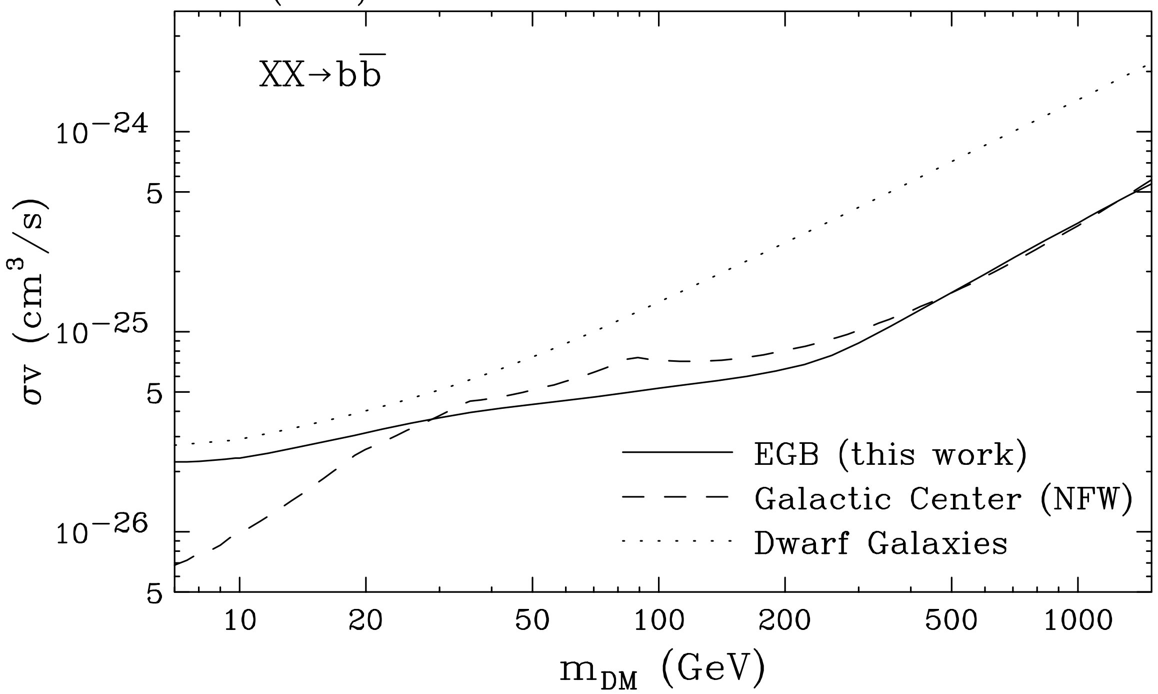




I.C., S. McDermott, D. Hooper, JCAP 1402 (2014)

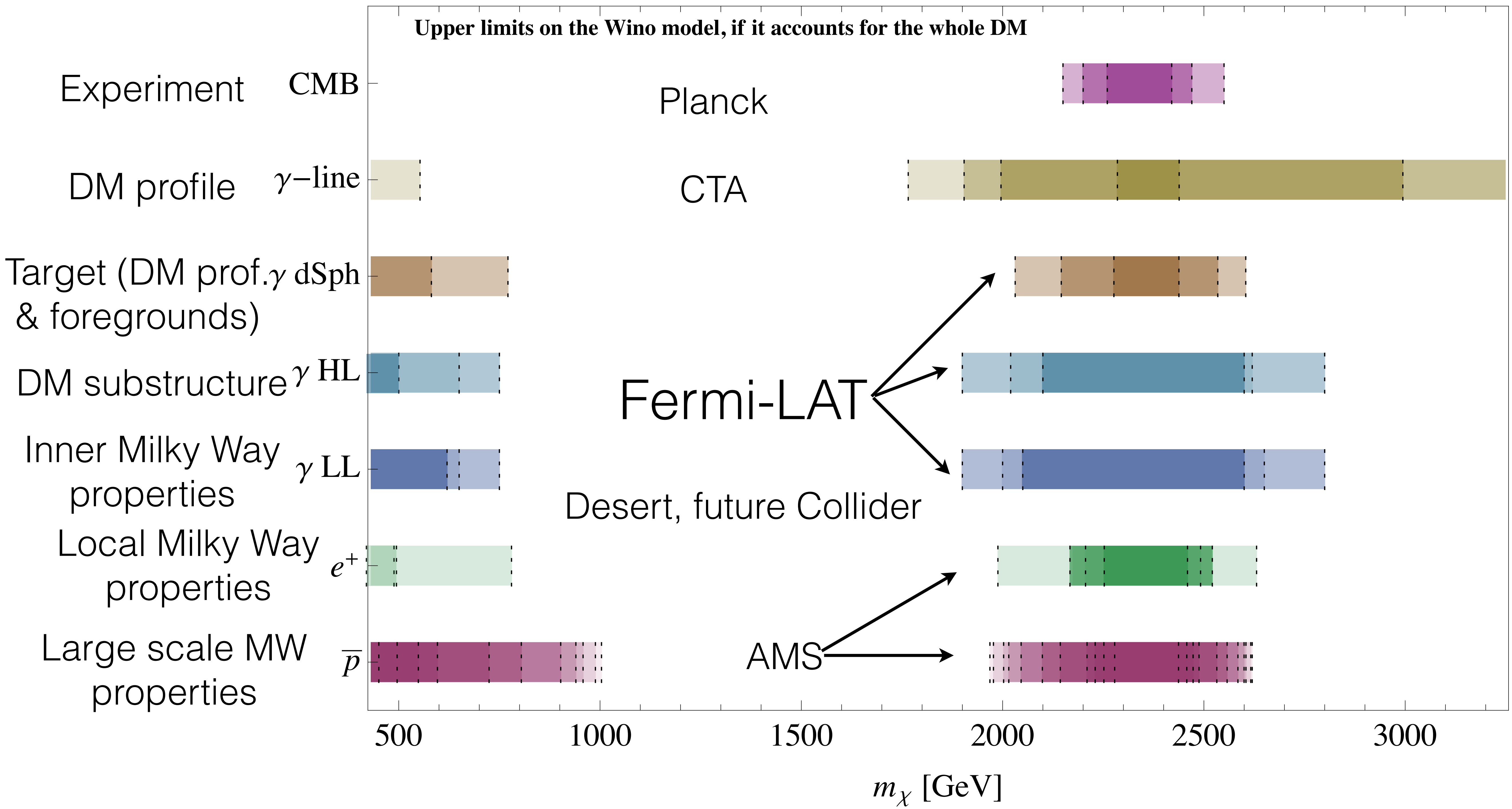






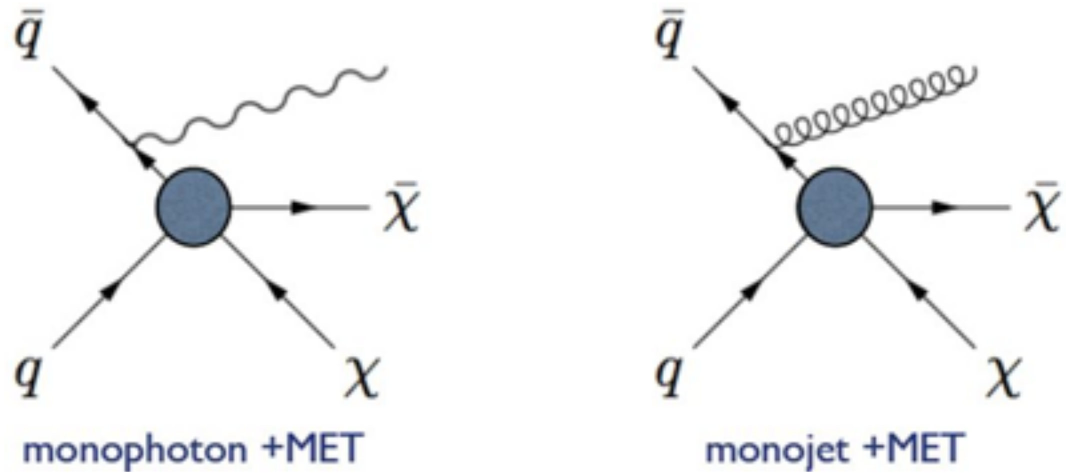
An example of indirect detection limits: Wino DM

95% CL upper limits:



Andrzej Hryczuk, IC, Roberto Iengo, Maryam Tavakoli, Piero Ullio. 1401.6212

Collider Searches



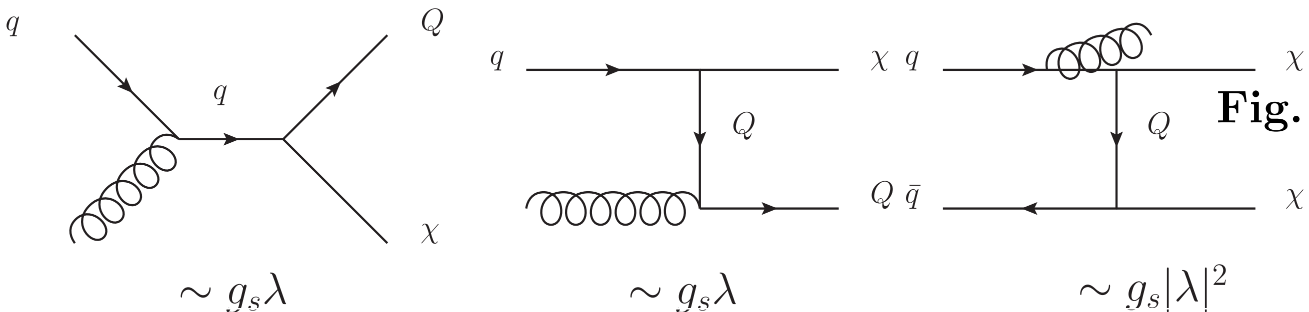


Fig. 2. Feynman diagrams contributing to monojet signals at a hadron collider.

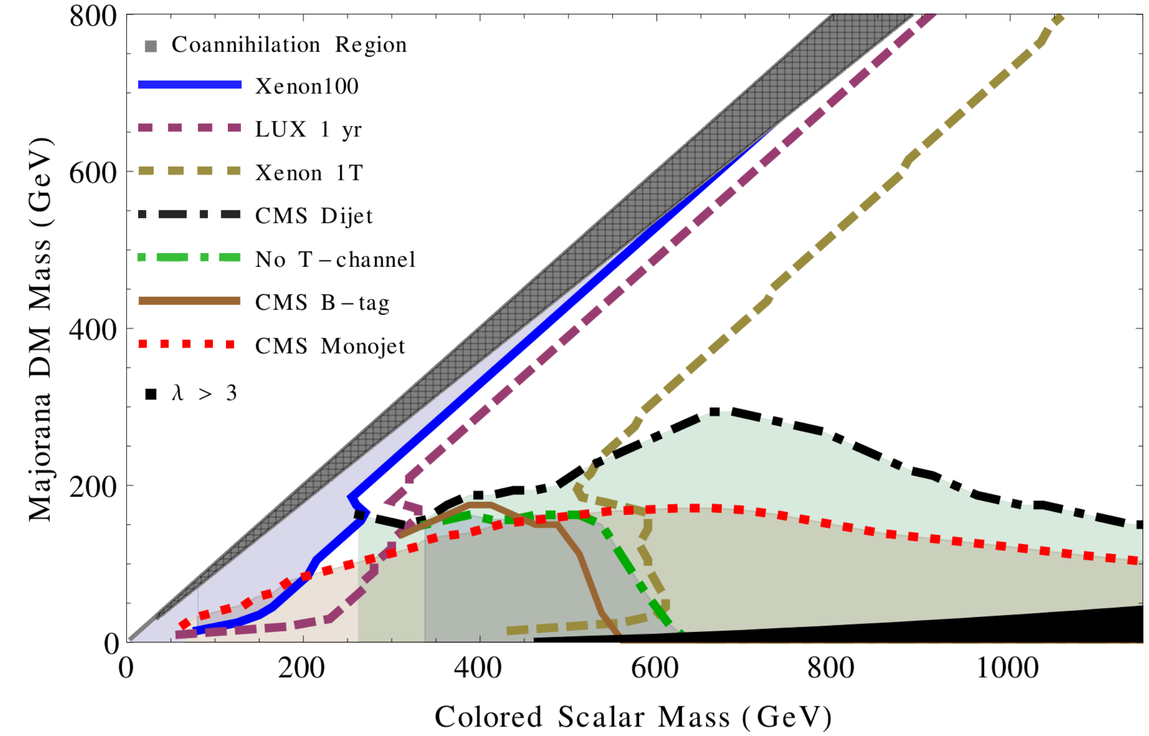
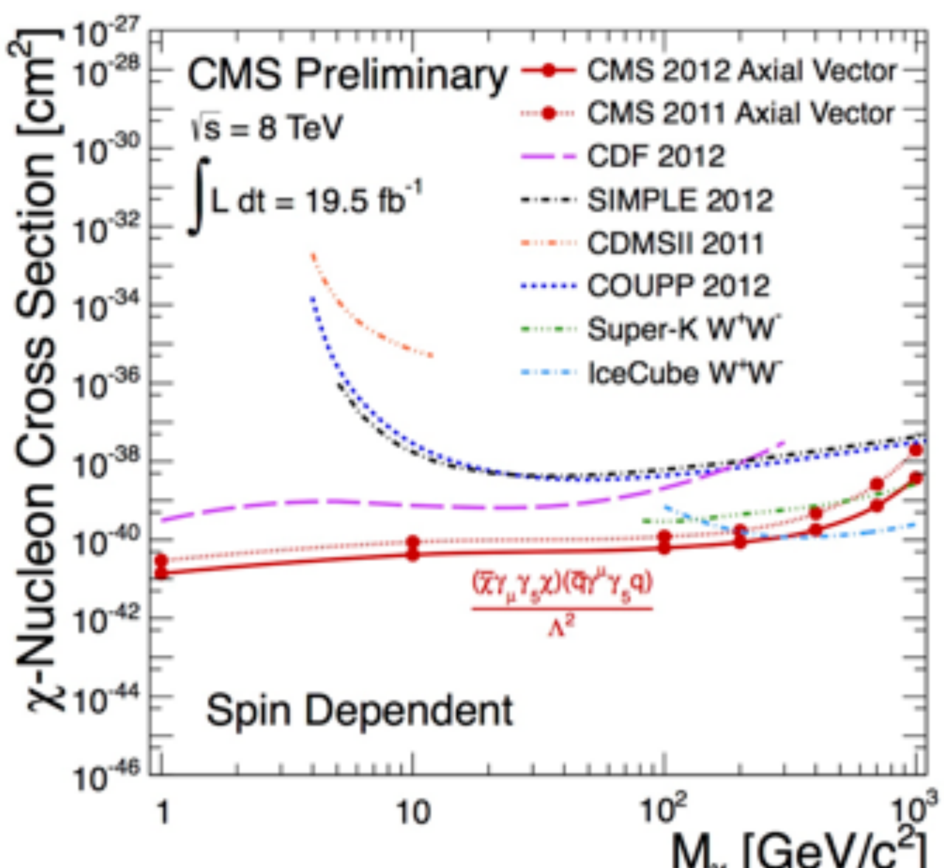
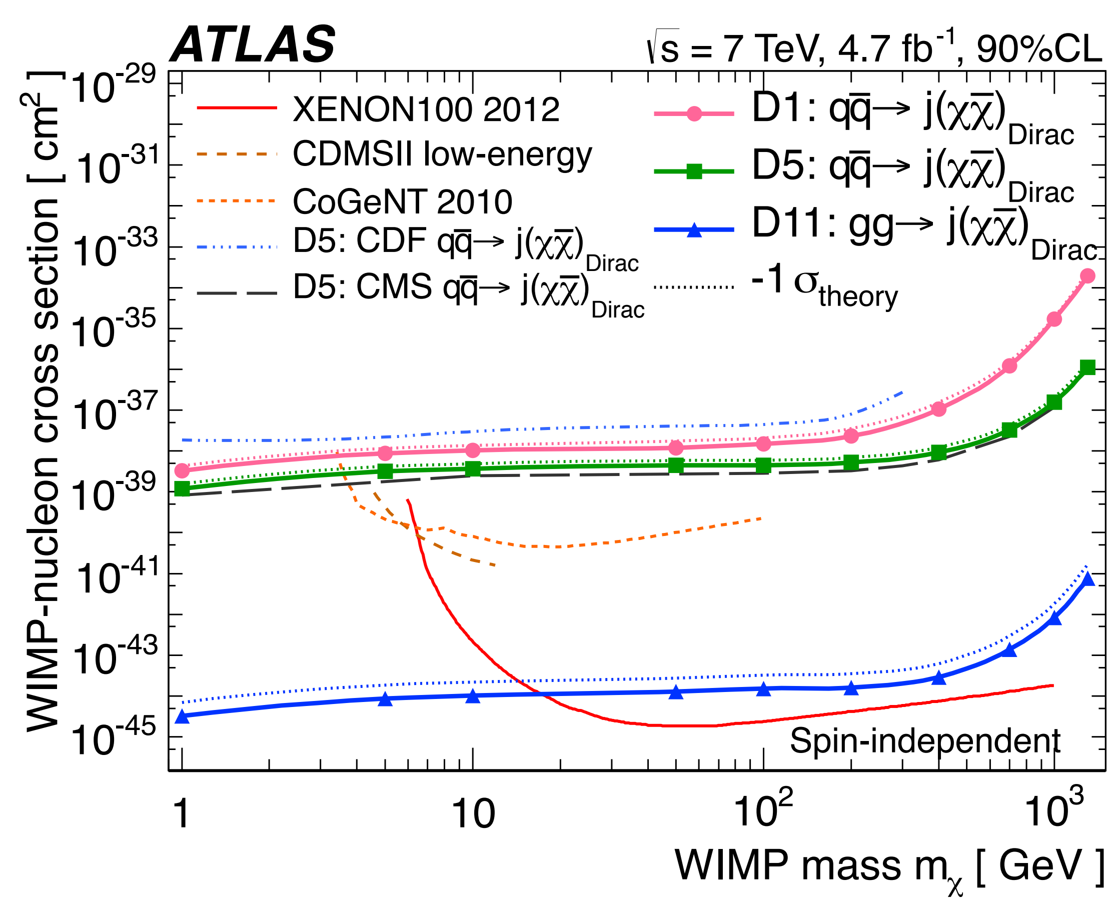


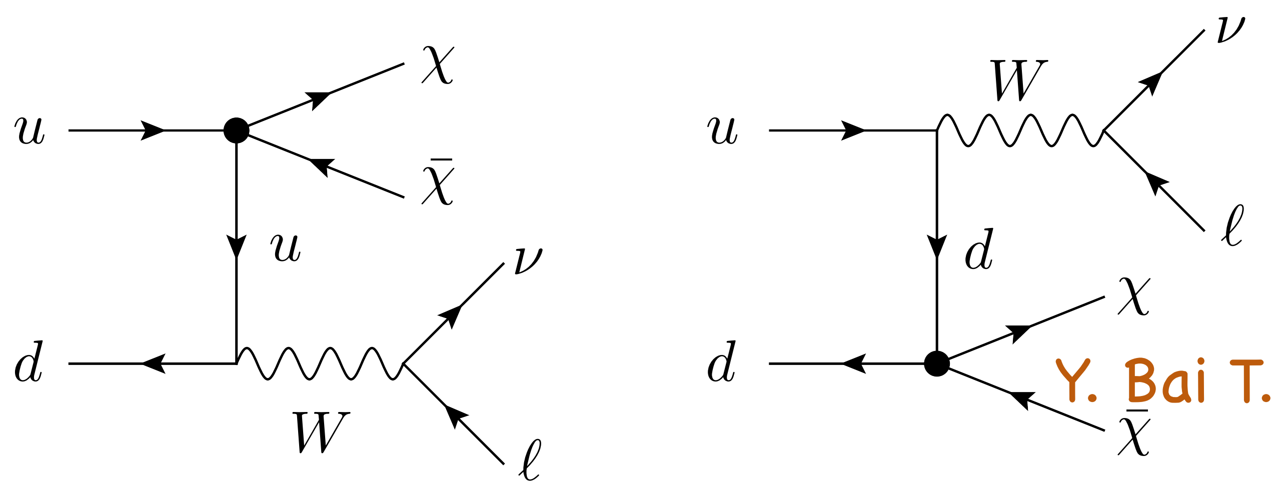
Fig. 4. Limits on Majorana dark matter coupling to all generations.

S. Chang et al. 1307.8120





Going beyond mono jets and mono-photons. e.g. similar searches involving other SM particles: mono-W, mono-Z



Y. Bai T.M.P Tait PLB (2013)

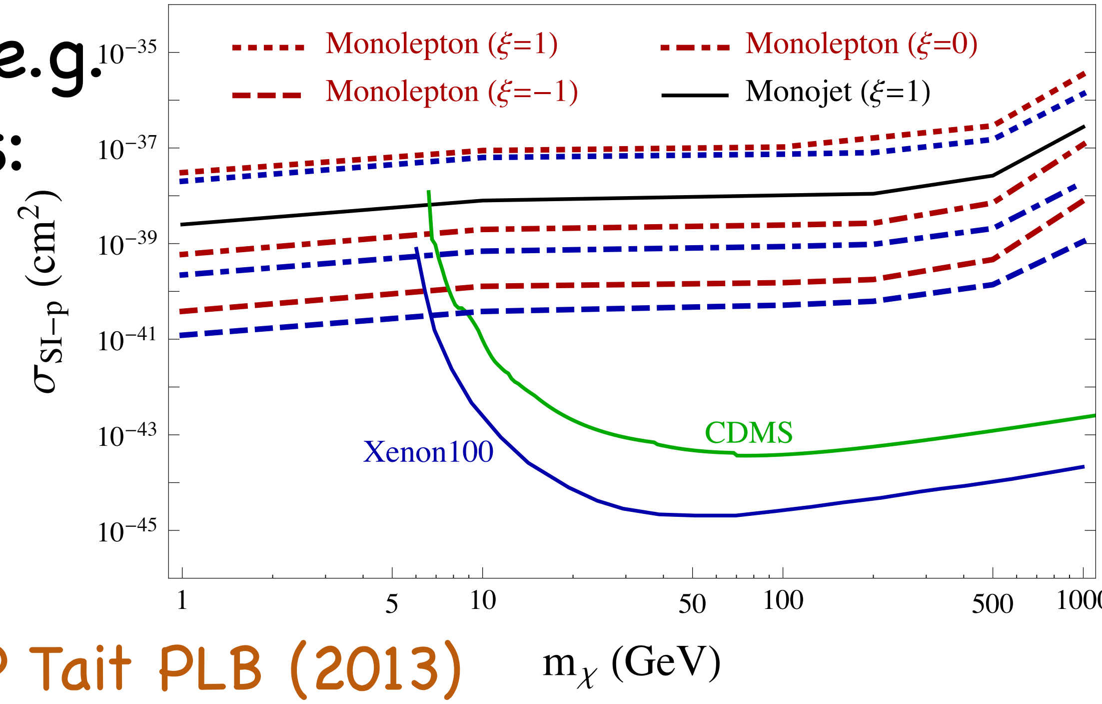
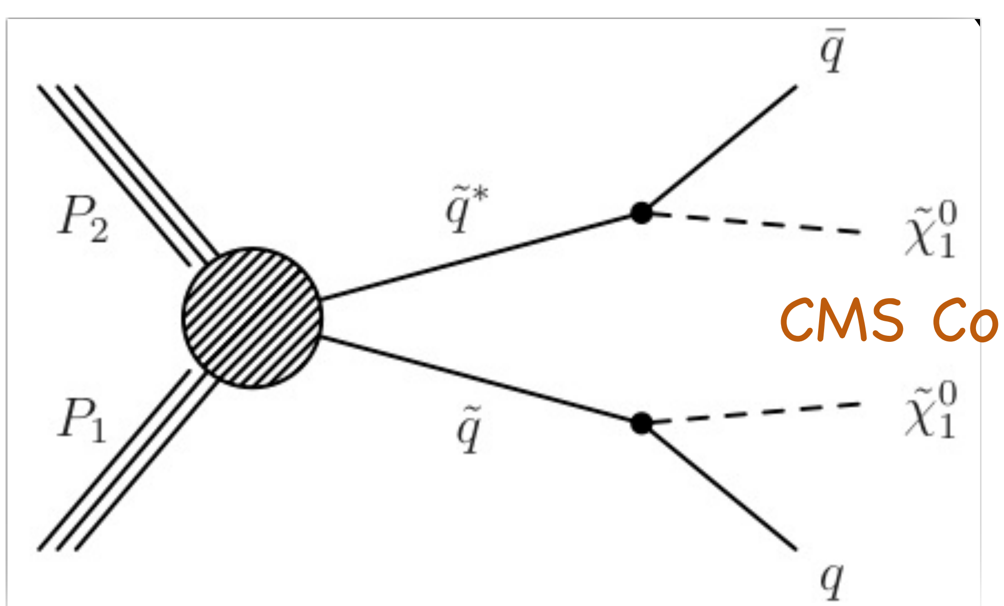
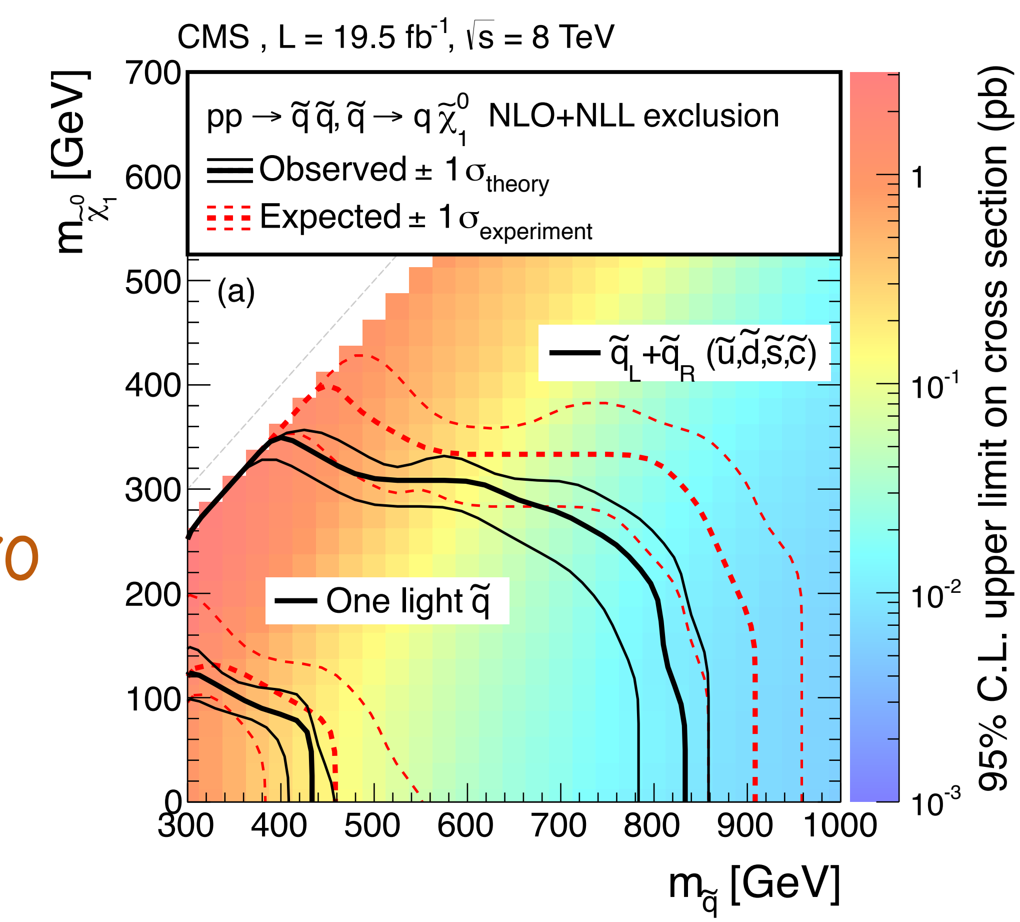


FIG. 4: Mono-lepton bounds and bounds from direct detection projected into the plane of the WIMP mass and the spin-independent cross section with protons. The red and blue lines are from CMS 5 fb^{-1} data at 7 TeV and 20 fb^{-1} data at 8 TeV, respectively.

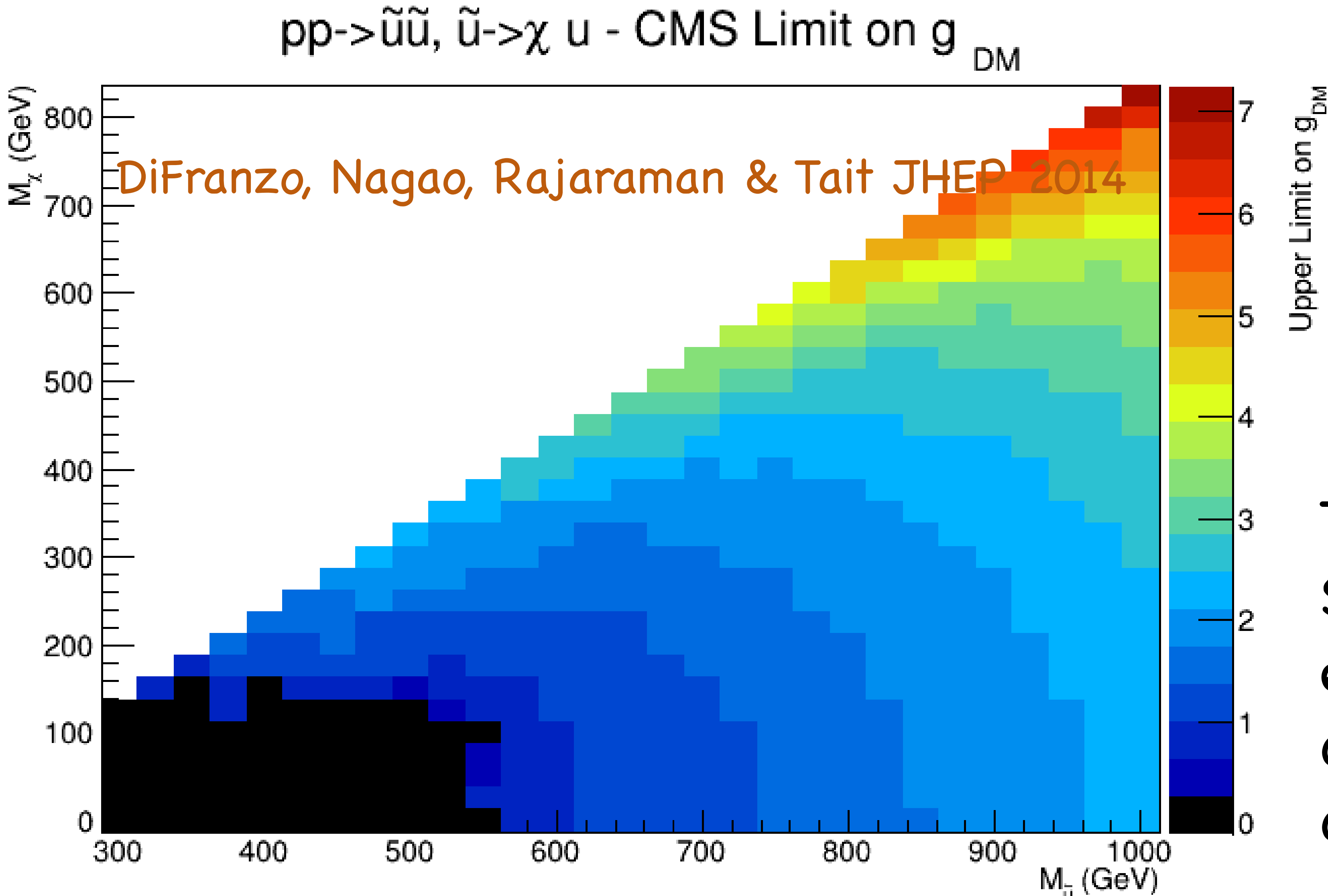
Multi-jets and missing ET:



CMS Coll. 1402.4770

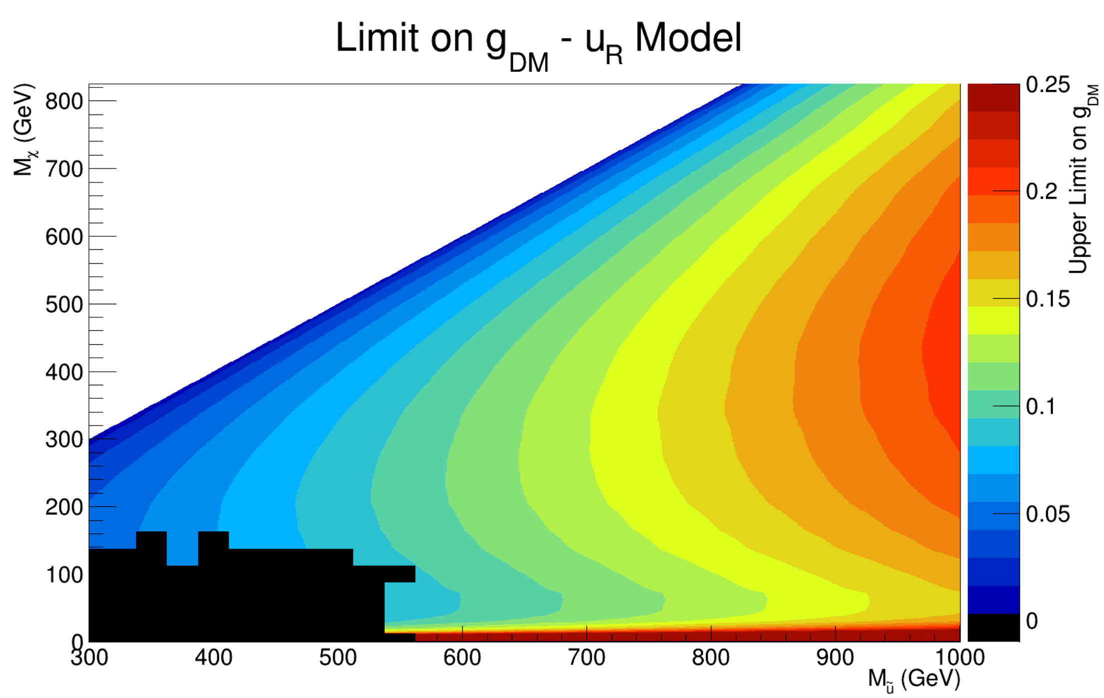


A model: Dirac DM coupling to right-handed up quark (uR model):



Limit on the coupling strength in the plane of dark matter mass and the mediators.

This DM particle has also SI scat. No mass range is entirely ruled out but current limits on the couplings are stronger.



See also works from, P. Agrawal & V. Rentala: 1304.3068, H. An, L-T Wang, H. Zhang: 1308.0592, Y. Bai & J. Berger: 1308.0612 among others.

Thank you