Searching for 10GeV dark matter

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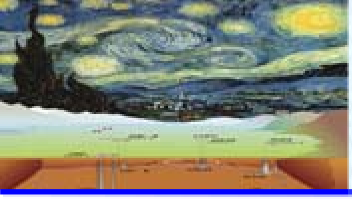


Hints for DM

photon

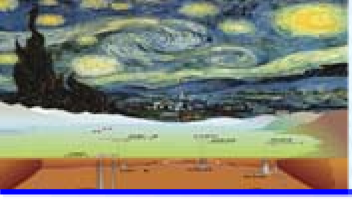
- 3.5 KeV line (KeV DM)
- 511 KeV line (MeV DM)
- GeV excess at GC and inner galaxy (GeV~O(10) GeV)
- Fermi 130 GeV line (~100 GeV DM)

Charged cosmic-ray

- Positron and electron excesses
  at 10GeV~TeV (TeV DM)
  PAMELA, ATIC, HESS, Fermi,
  AMS02…

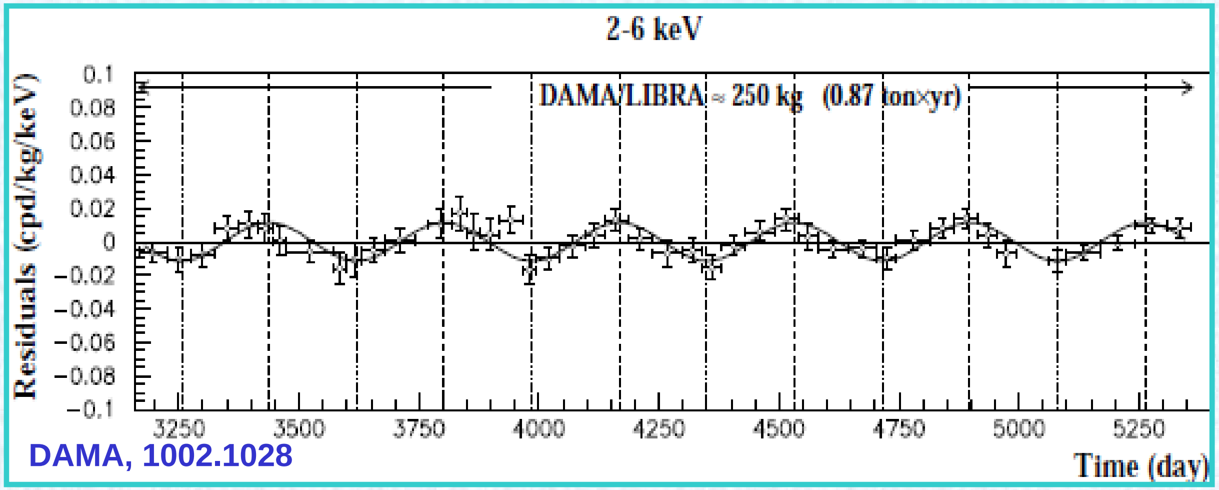
Direct detection

- Excess (GeV~10 DM), CoGeNT, CRESST, CDMS
  Modulation, DAMA, CoGeNT

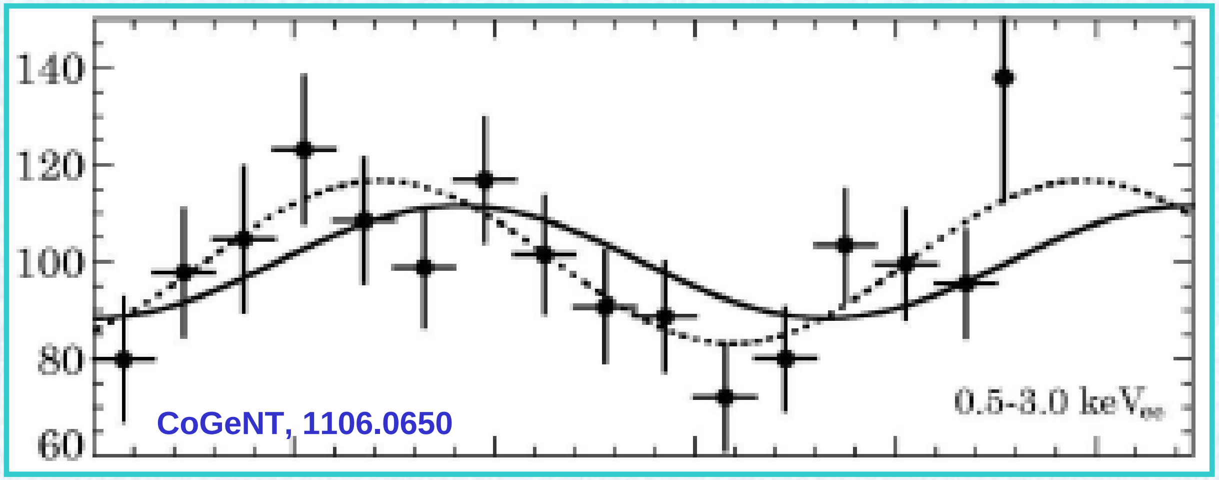


"Evidence" for 10GeV DM

- Modulation



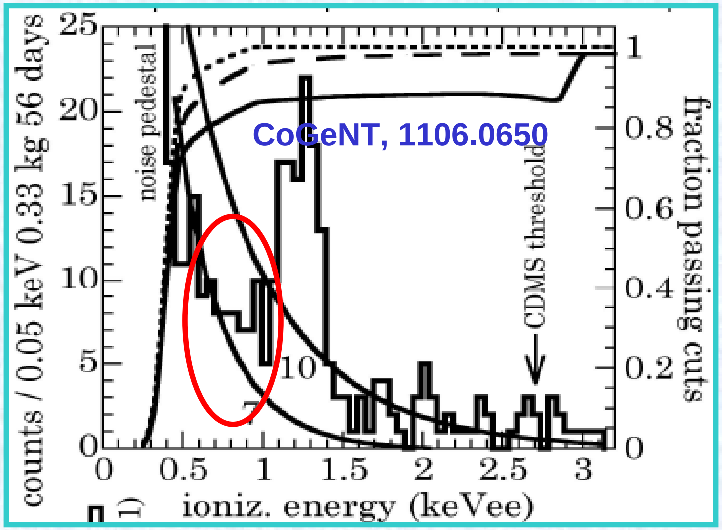
DAMA, 1002.1028

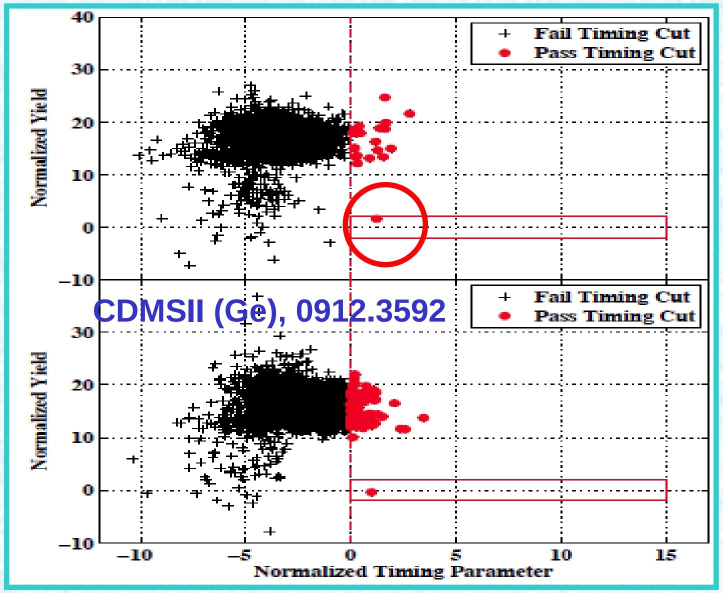


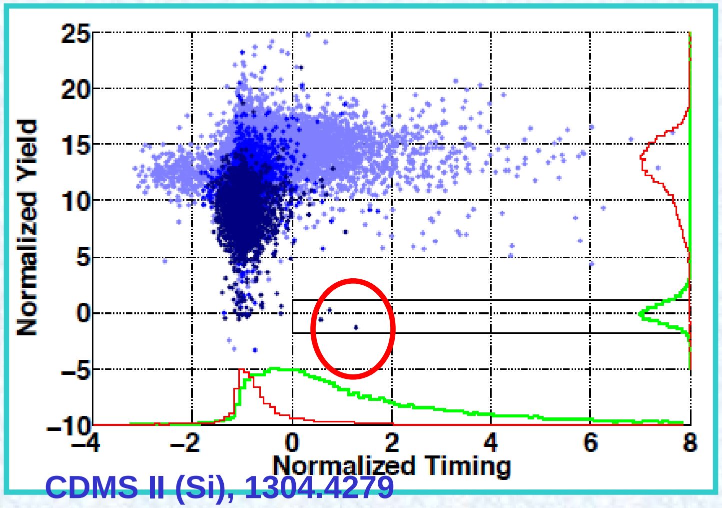
CoGeNT, 1106.0650

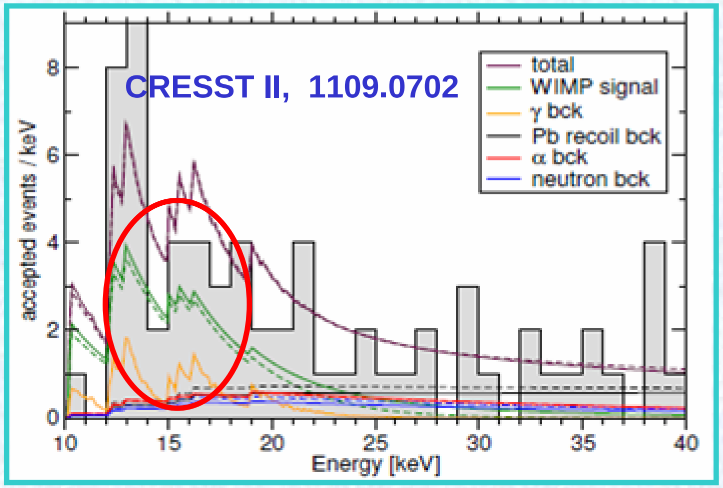
“Evidence” for 10GeV DM

- Event excess

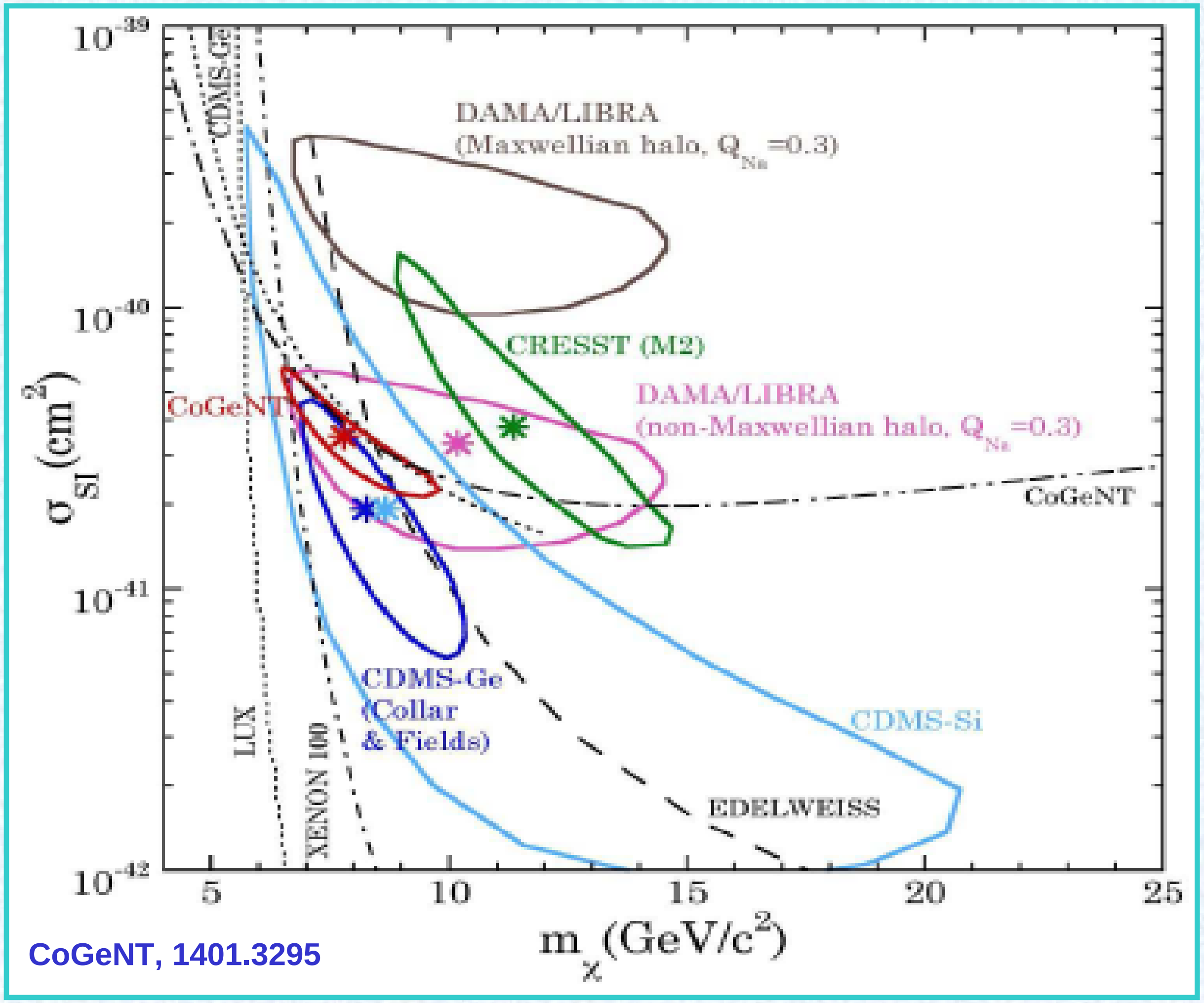








Parameter space for 10GeV DM

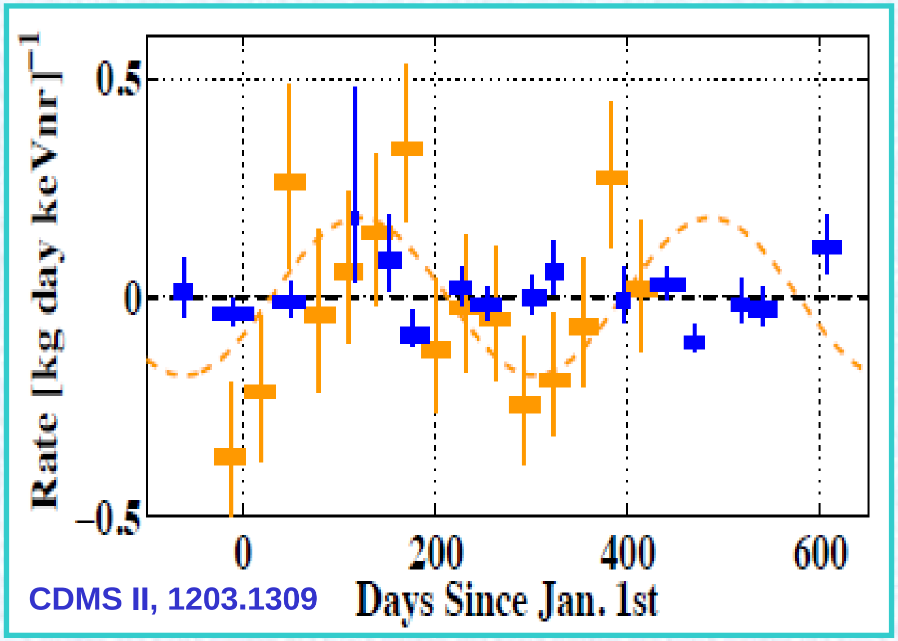


- Mass 5~15 GeV, Cross section (SI) 10^{-41}~10^{-40} cm^2 .

Results from other experiments

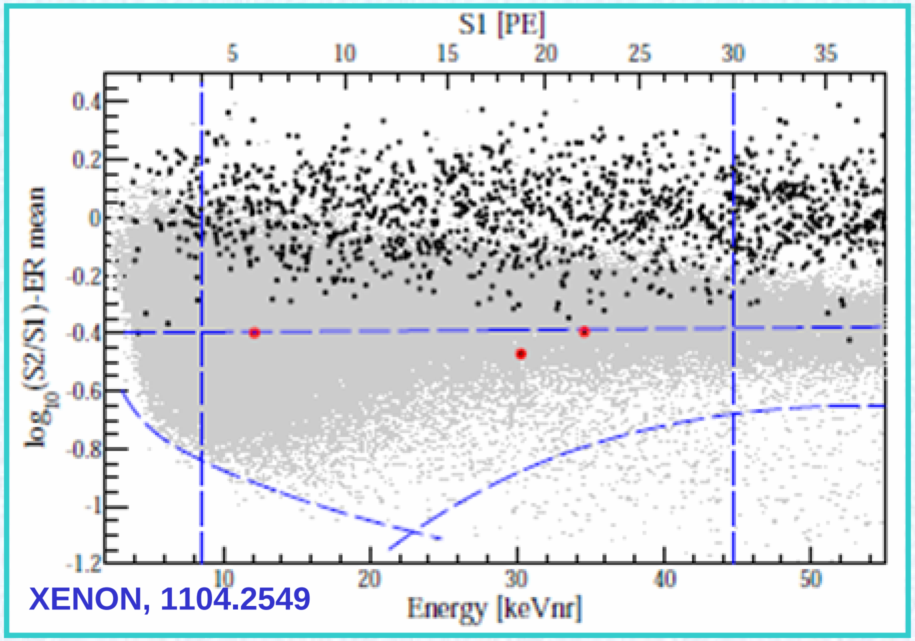
- **No** significant DM signal has been confirmed by many other experiments

- Modulation ?

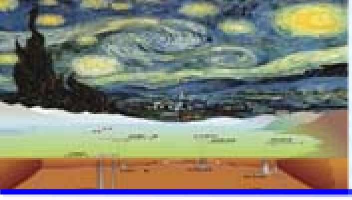


CDMS II, 1203.1309

- Event excess ?

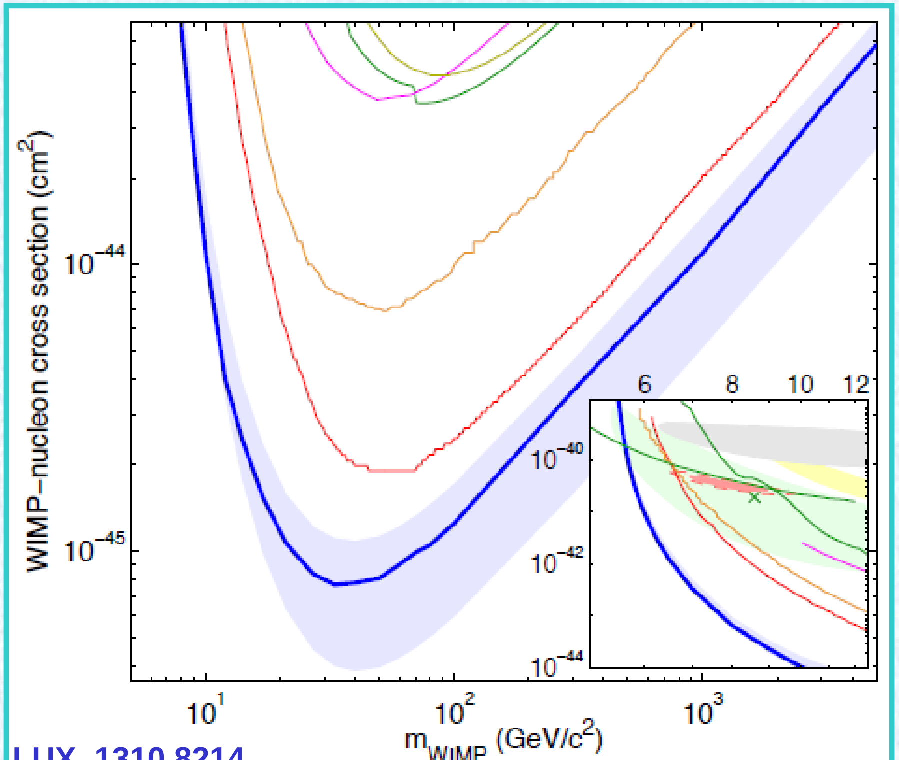


XENON, 1104.2549

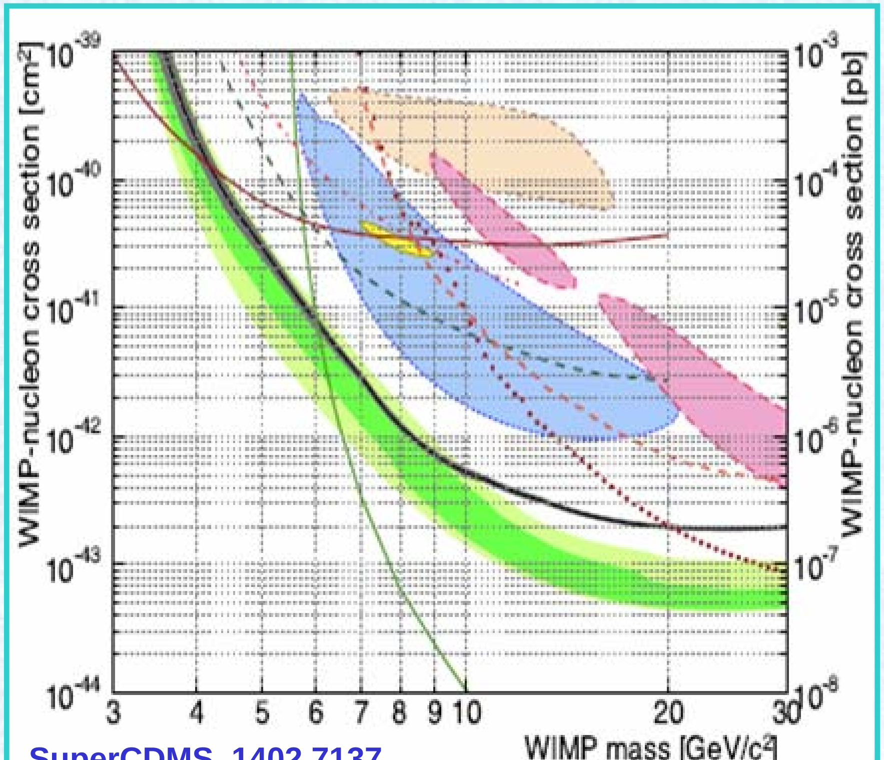


Results from LUX and SuperCDMS

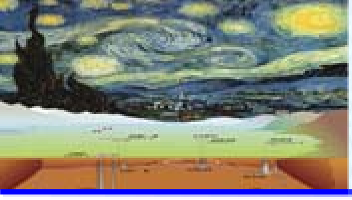
- **No** significant DM signal has been confirmed by many other experiments



LUX, 1310.8214



SuperCDMS, 1402.7137



To explain everything…

$$\frac{dR}{dE_{\text{det}}} = \int dE_R G(E_{\text{det}}, E_R)\sigma_0 F^2(q) \frac{\rho_\chi}{2m_\chi \mu^2} \int_{v_{\min}}^{v_{\max}} \frac{f(\vec{v})}{v} d^3v$$

- **Detector effect**

To modify the parameters of liquid noble detectors: light yield of xenon, scintillation efficiency, poisson fluctuations for threshold

- **Particle physics factor**

Isospin violation

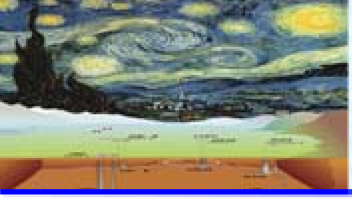
Inelastic scattering

Other interactions beyond SI

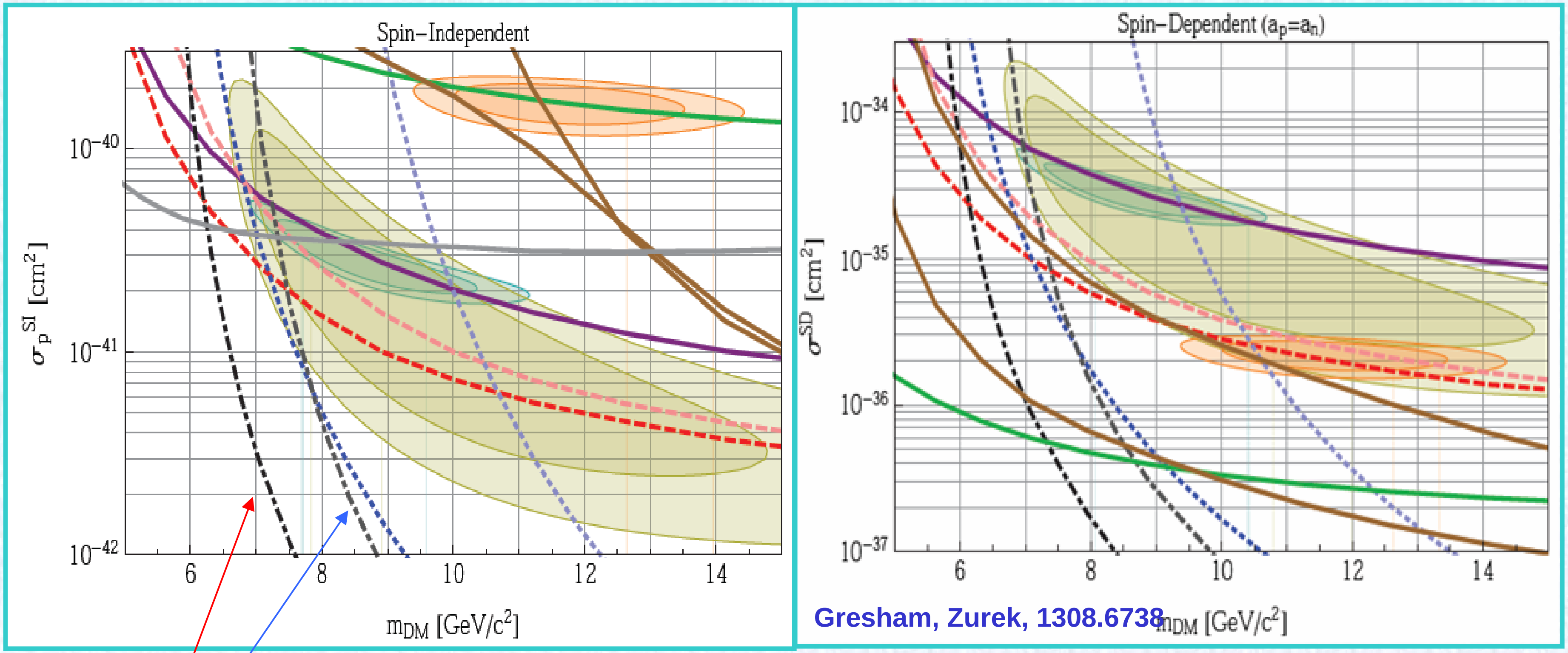
- **Astrophysics factor**

Non-standard velocity distribution

Gresham, Zurek, 1308.6738
Nobile et. al, 1322.4247
Fox et. al, 1401.0216



Parameter space for SI and SD

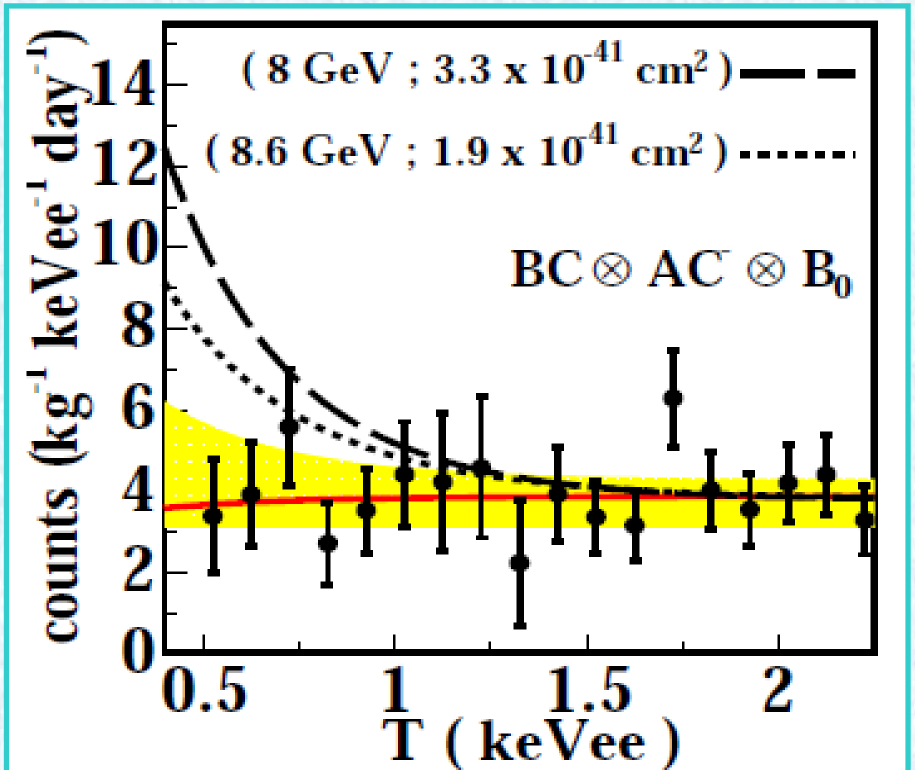


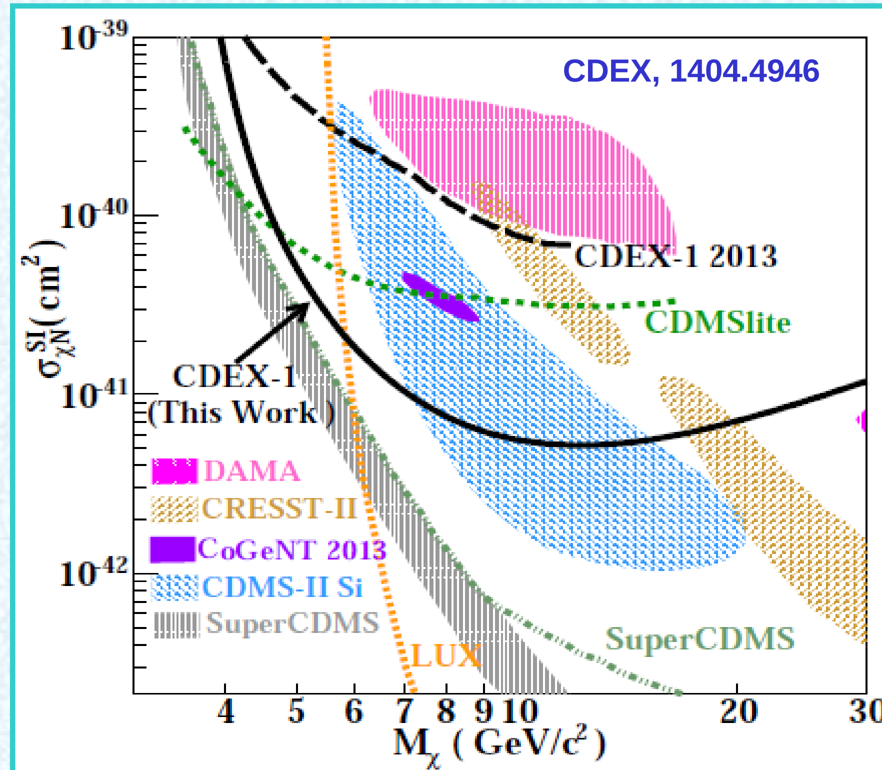
Gresham, Zurek, 1308.6738

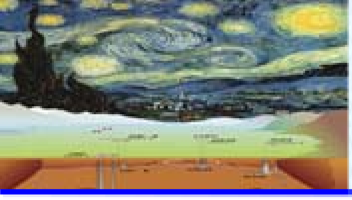
- LUX results almost exclude SI and SD interpretations for DAMA , CoGeNT and CDMS SI
- Modified scintillation efficiency can not relax the tensions between different experiments

Result from CDEX

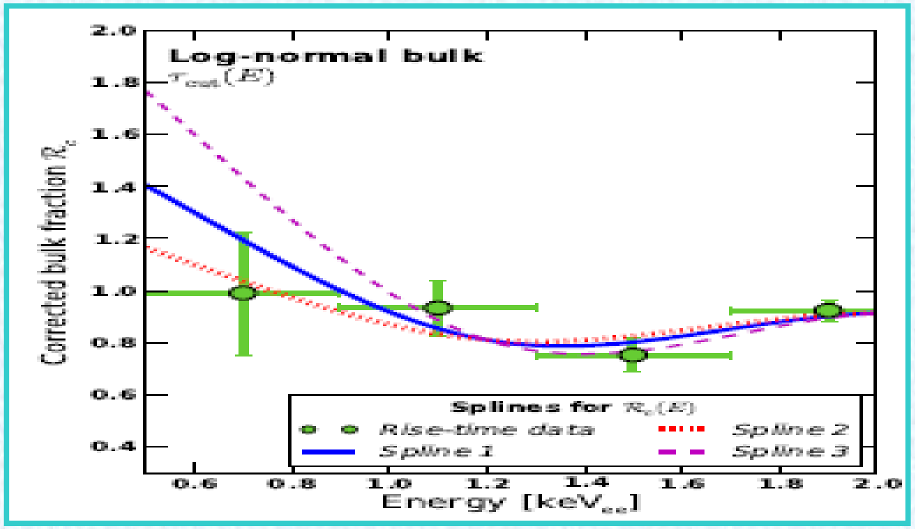
- Using the same material and technique as CoGeNT, CDEX (53.9 kg-days) does not observe excess events.

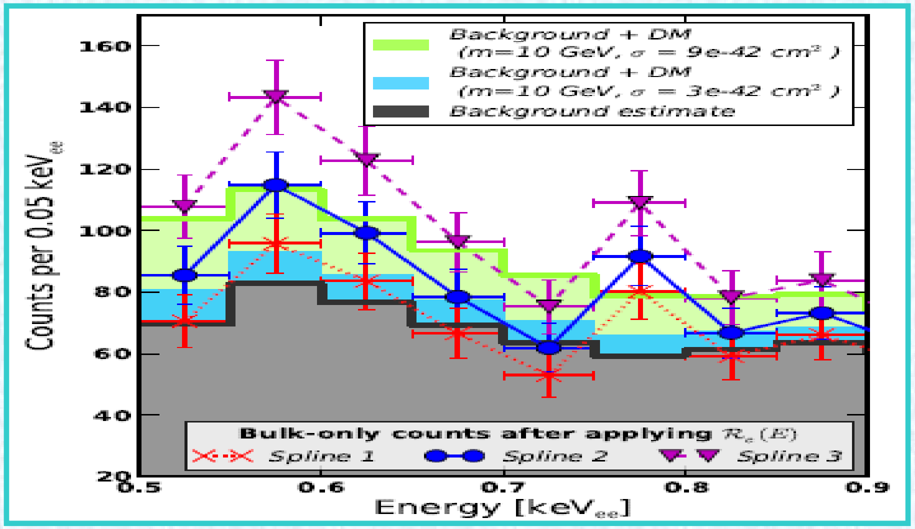


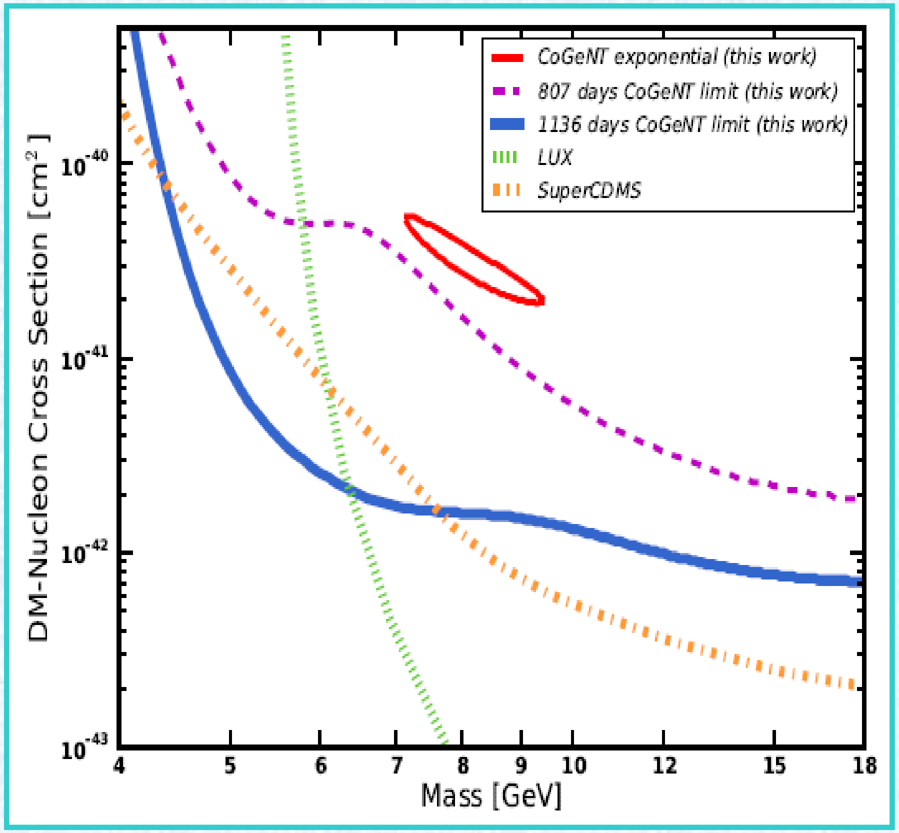




Reanalysis for CoGeNT result

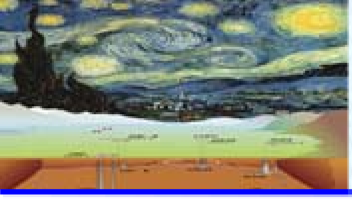




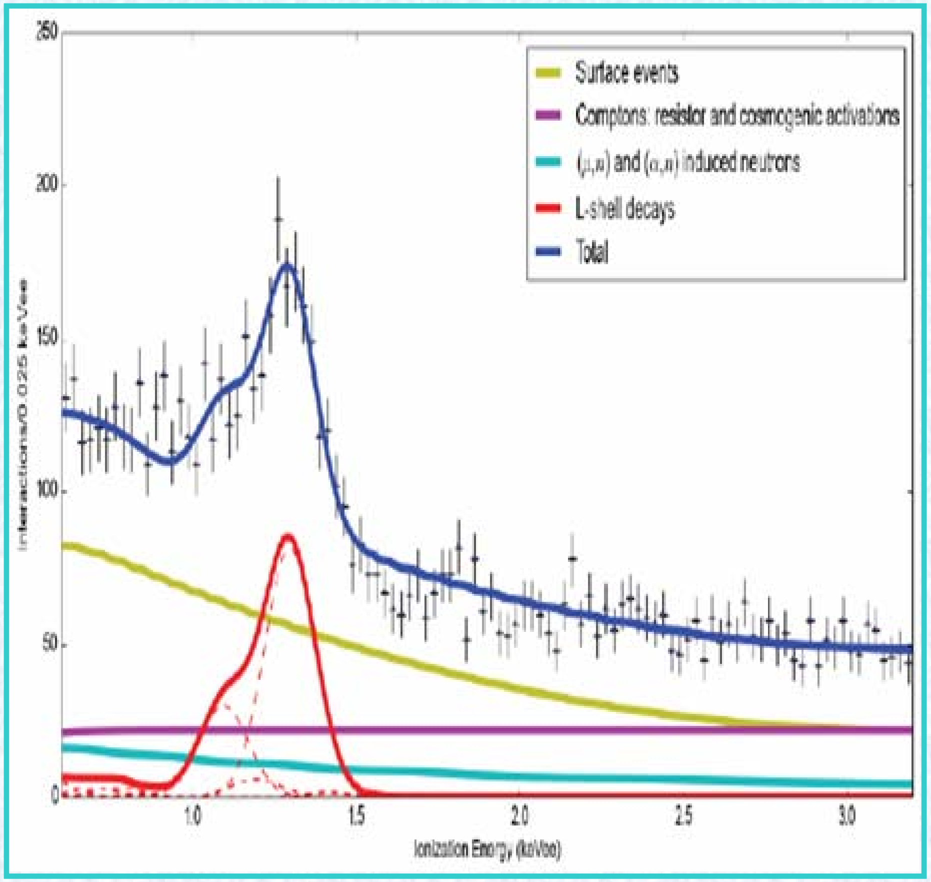


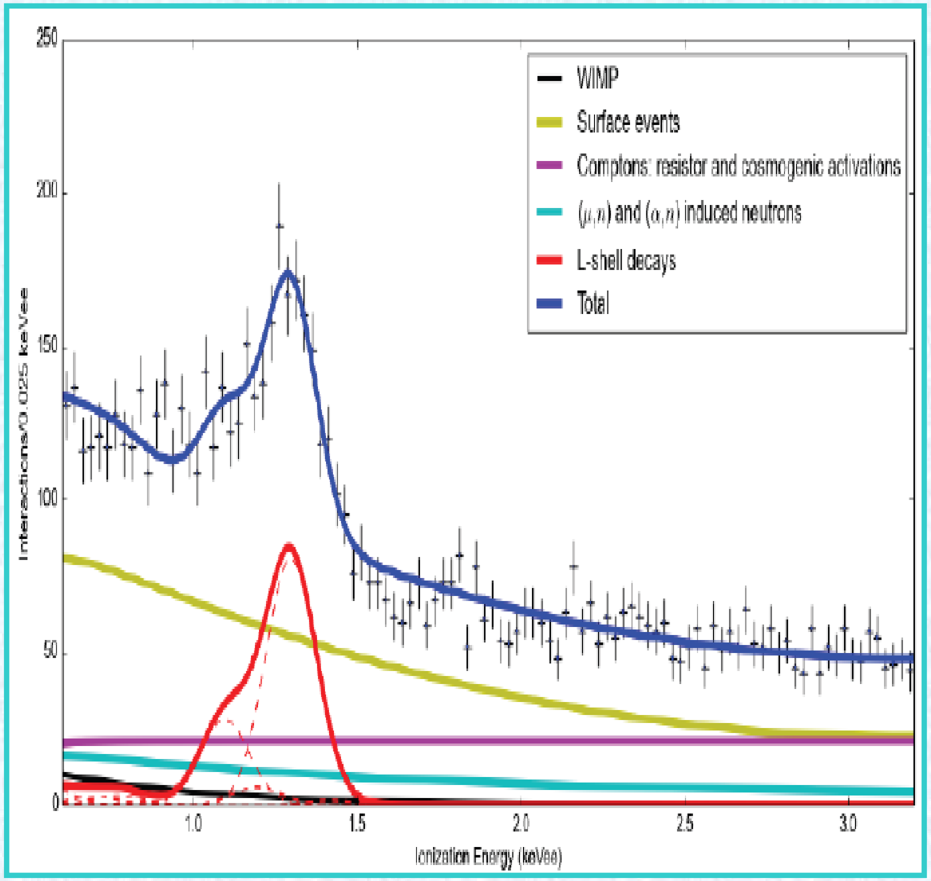
- An independent analysis indicate that the CoGeNT data show a preference for light DM signals at less than 1σ.

Davis et al, 1405.0495



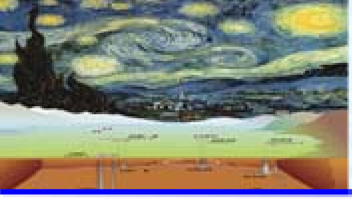
Reanalysis for CoGeNT result



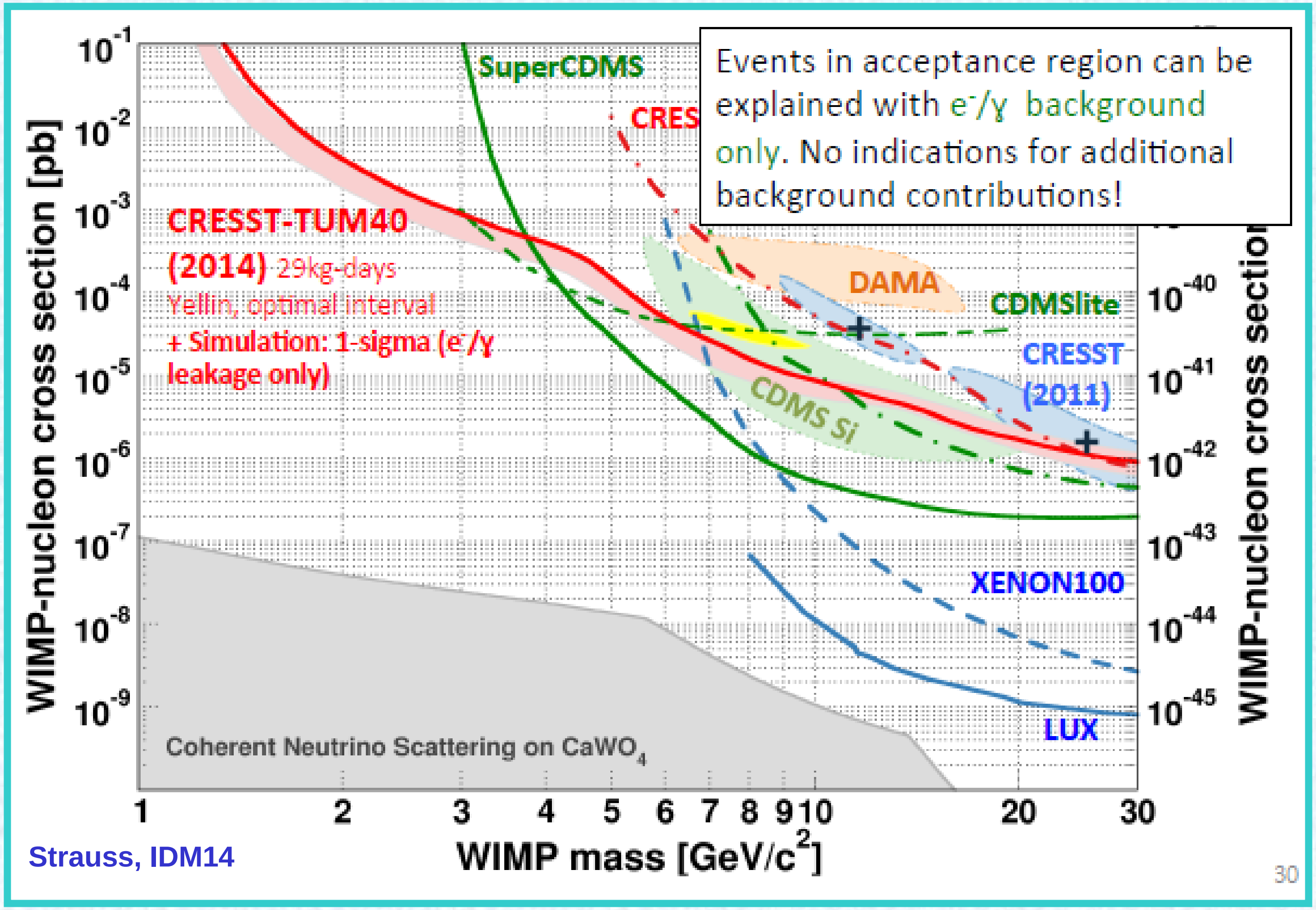


- Another re-analysis shows background model is a good fit to the CoGeNT data

Kelso et al, IDM14

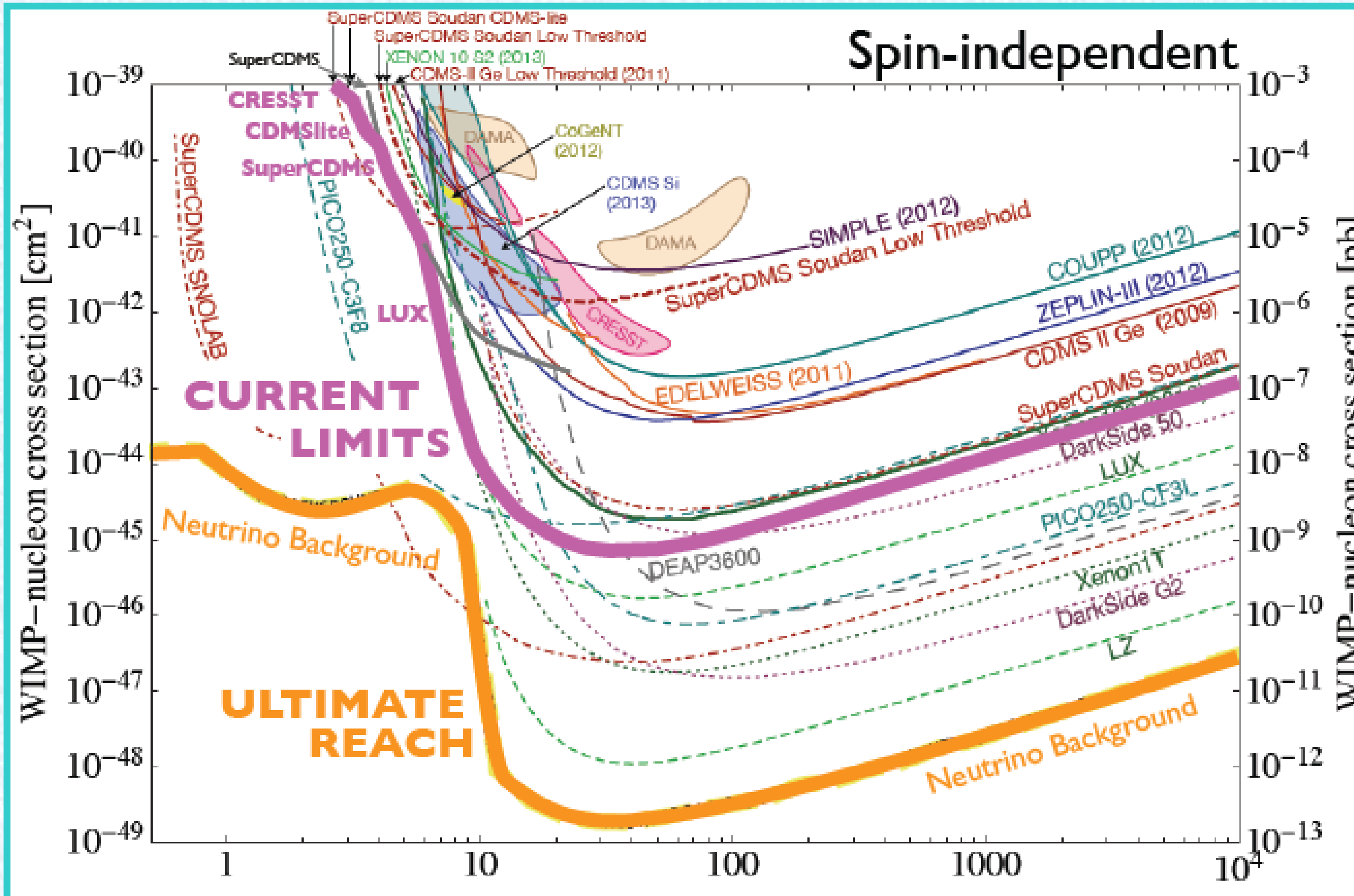


New result of CRESST

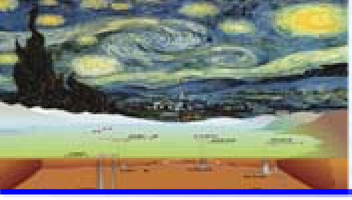


- Large parameter space for CRESSTII data in 2011 has been ruled out by the latest results

Current results for SI scattering



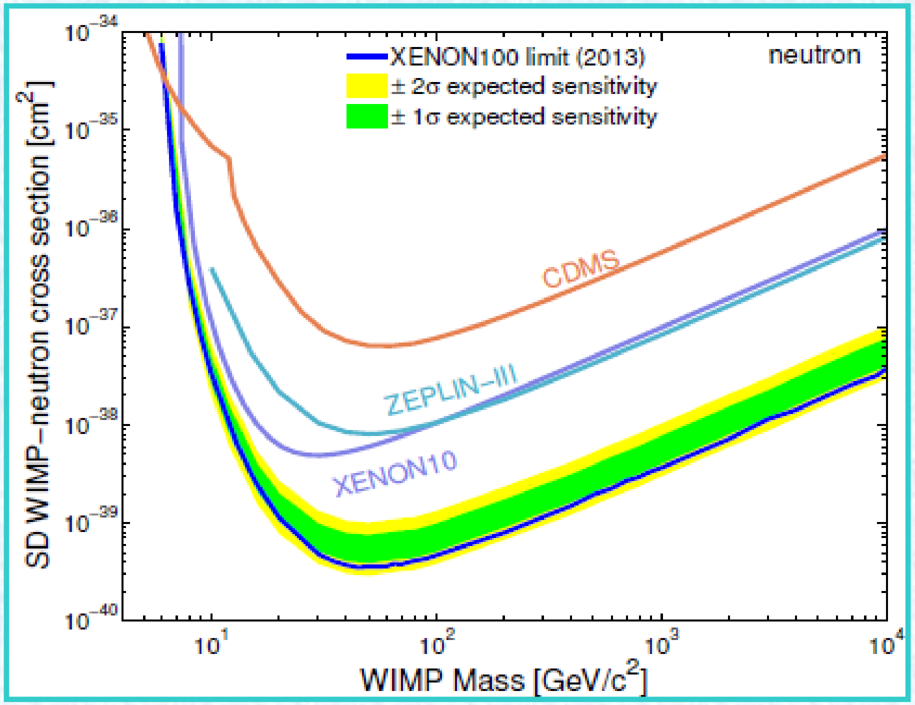
Snowmass 2013 et al

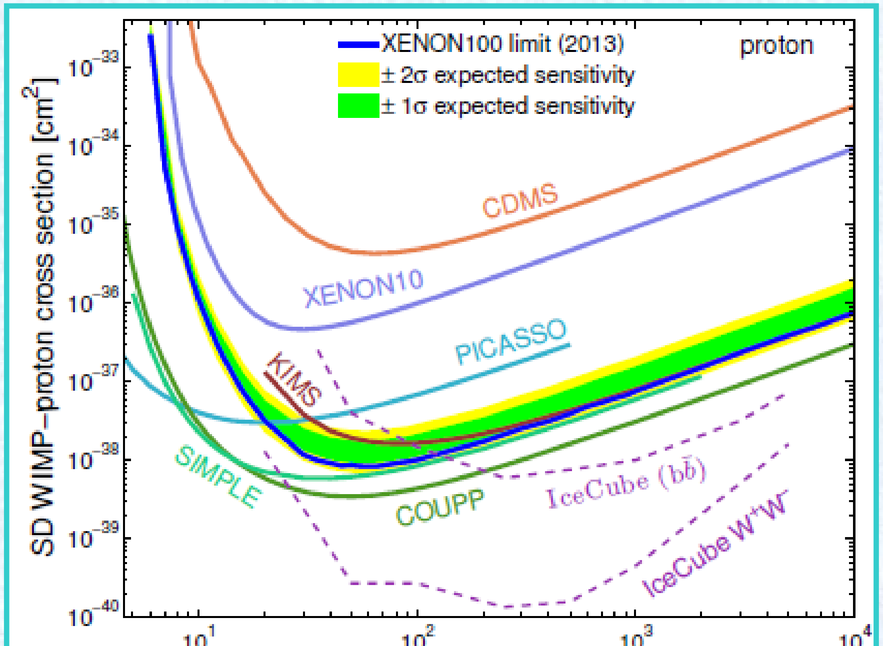


SD detection

- Axial- vector interaction
  Spin-dependent scattering

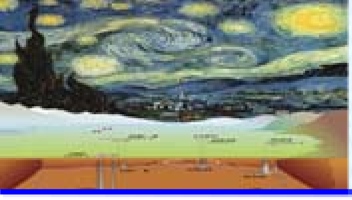
$$L_{SD} = \xi \bar{\psi}_\chi \gamma^5 \gamma_\mu \psi_\chi \bar{\psi}_N \gamma^5 \gamma^\mu \psi_N$$



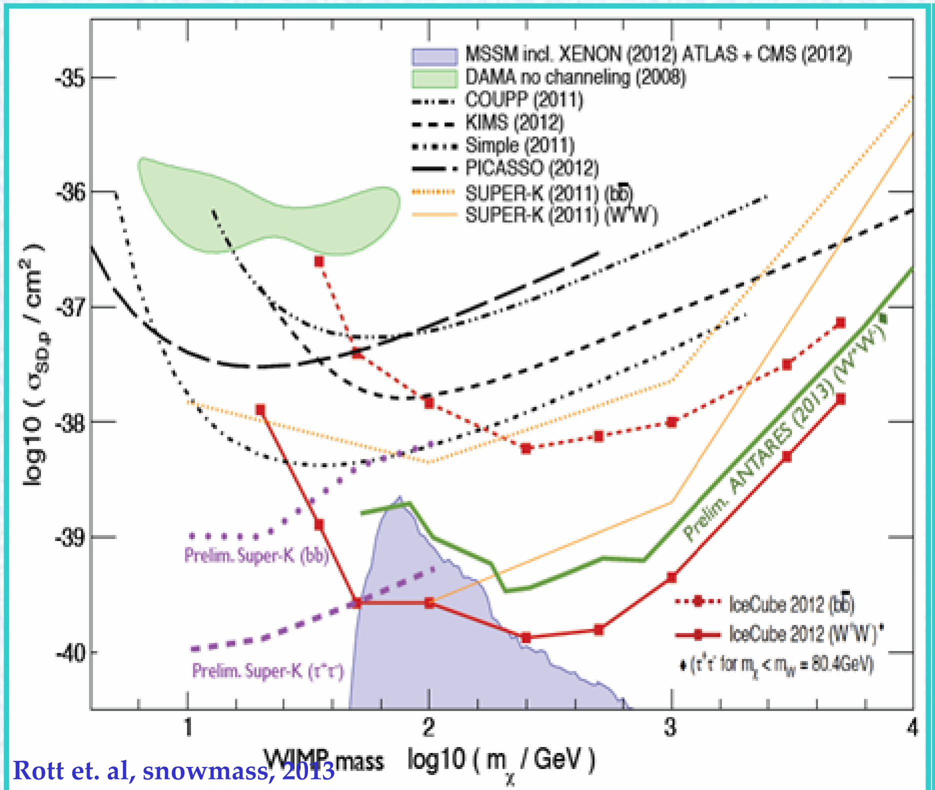


XENON 1301.6620

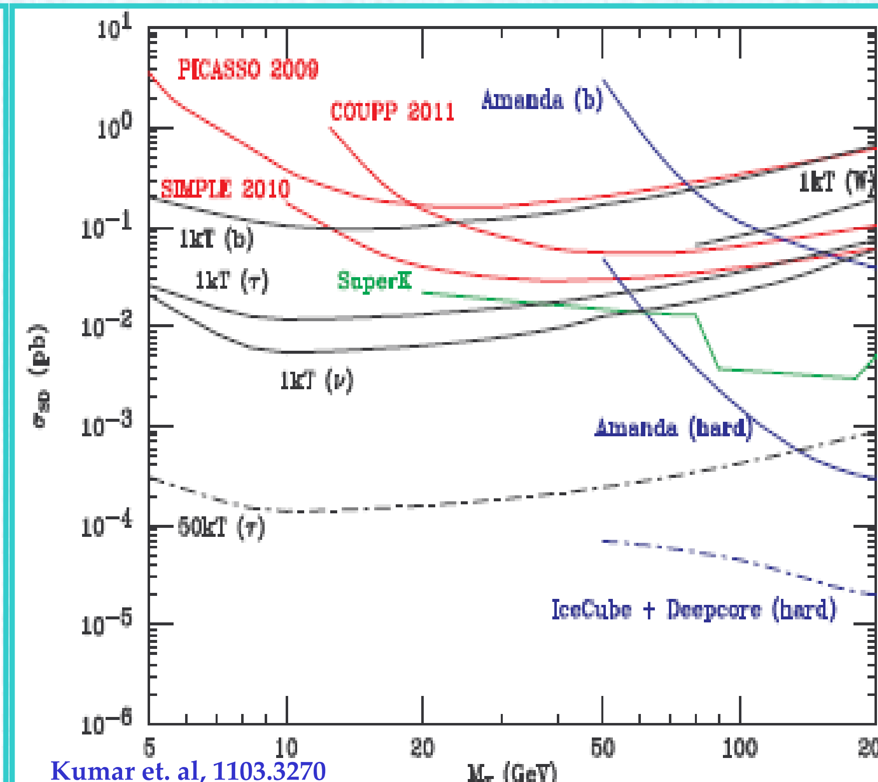
- Limits on SD interaction are weaker than that on SI interaction
- Depend on DM-proton or DM-nucleon interactions
- Neutrino detection depends on DM annihilation channels to neutrinos



Neutrino limit for light DM

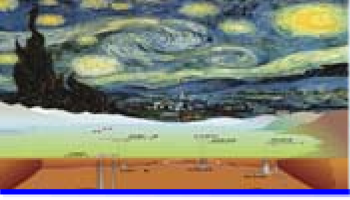


Rott et. al, snowmass, 2013

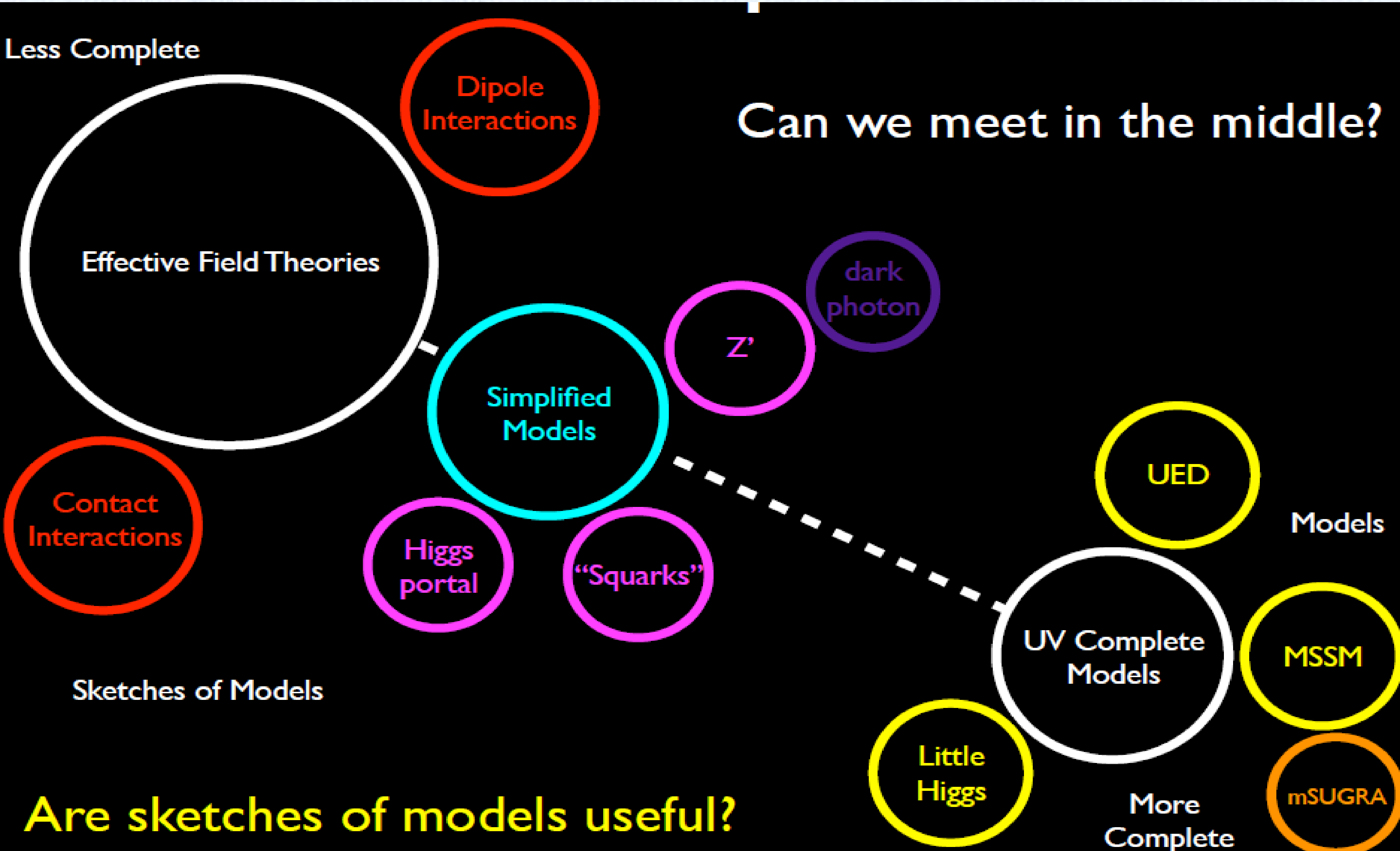


Kumar et. al, 1103.3270

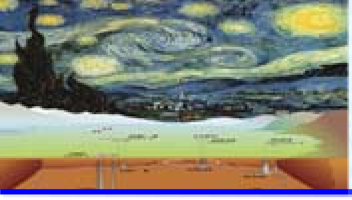
- Large Cerenkov detectors, such as ICeCube, are **difficult** to probe light DM due to high thresholds
- Super-K results can be used to search for light DM
- Future liquid scintillation detector has some advantages to search for electron-neutrinos induced by DM



Theoretical approach



From Tim. Tait's talk



Effective field theory

- If the mediators are heavy enough to be integrated, interactions between DM and quarks and gluons can be described by several contact operators

- Spin independent: D1, 5, 11

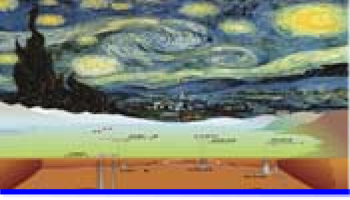
  Spin dependent: D8, 9

  Momentum dependent: D2, 3, 4, 6, 7, 10, 12, 13, 14

  Dipole: D15, 16

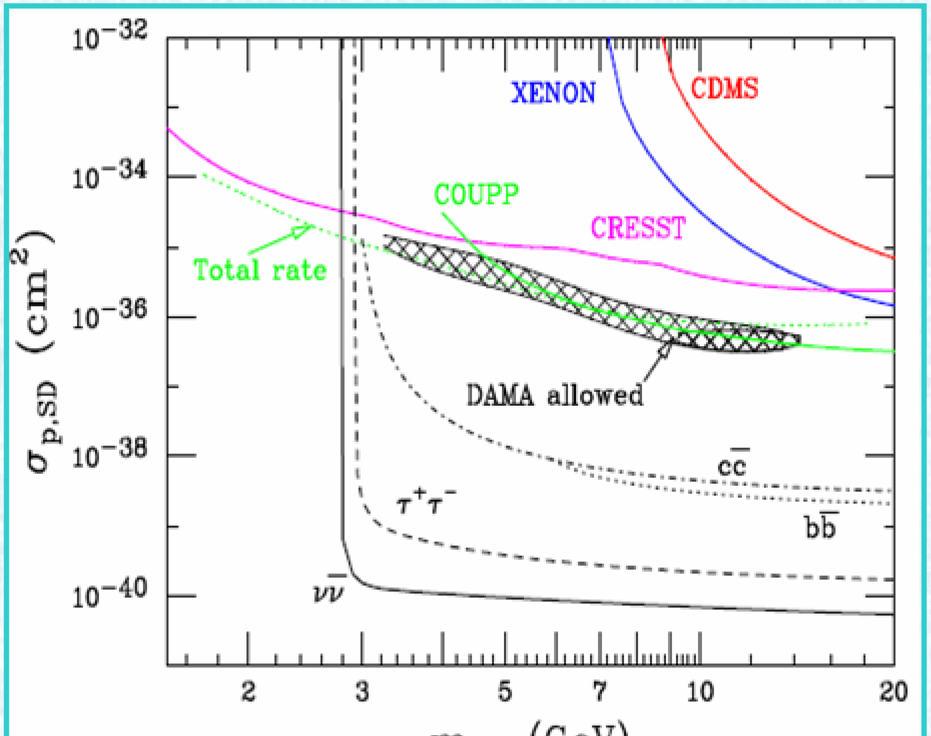
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$
D15	$\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$	M
D16	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi F_{\mu\nu}$	D

Goodman et. al, 1008.1783

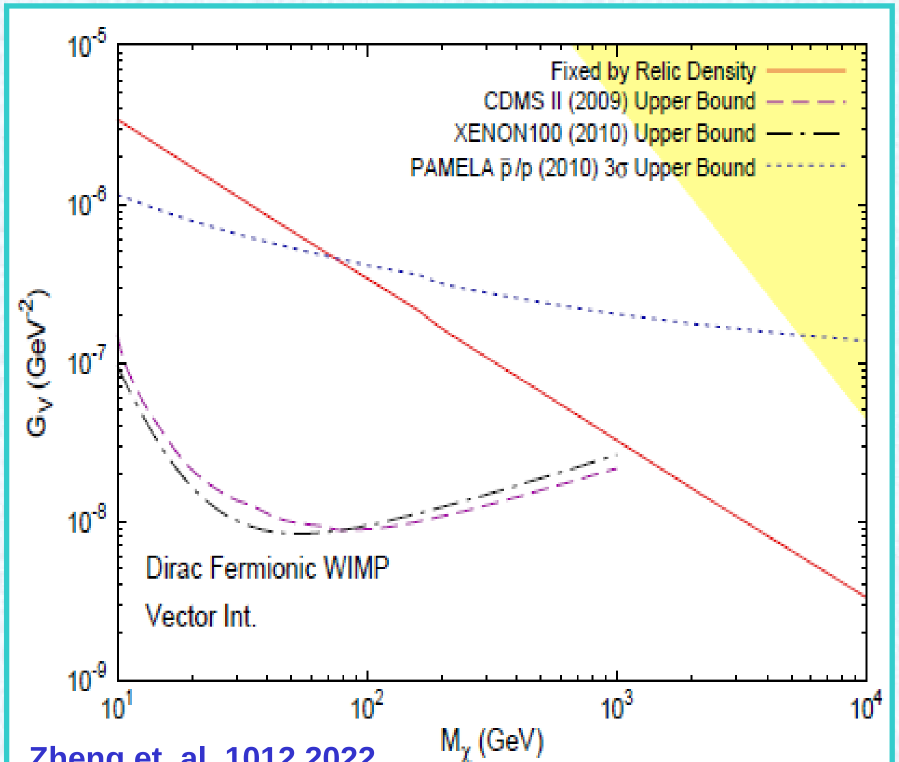


Indirect detection for EFT

- Three detections can be directly compared with each other in this context

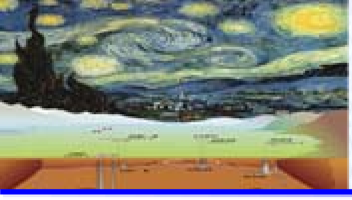


Hooper et. al, 0808.2464



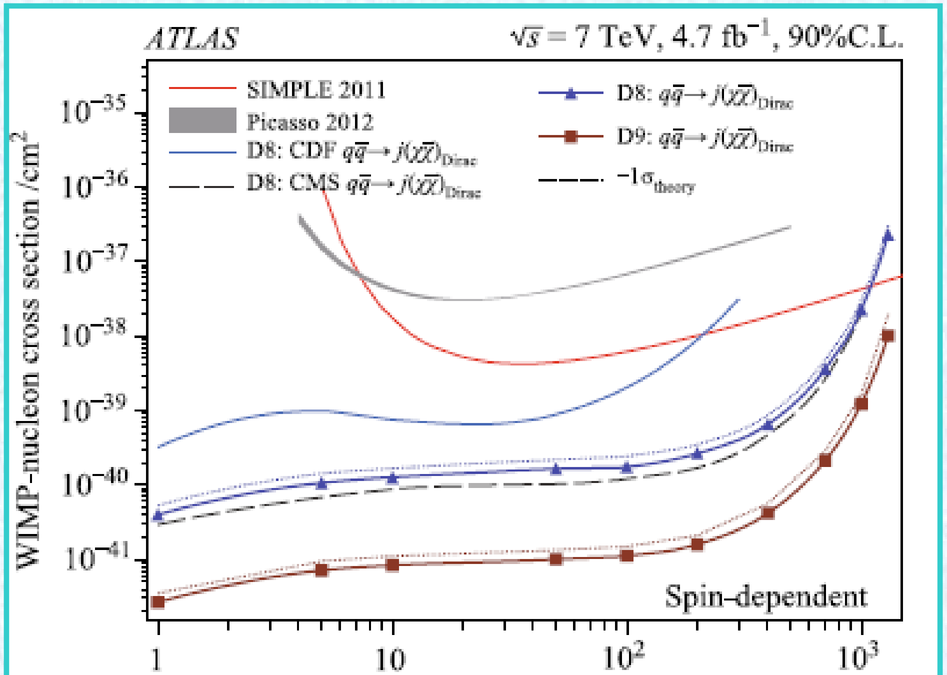
Zheng et. al, 1012.2022

- Interactions between DM and quarks will induce neutrinos and anti-protons

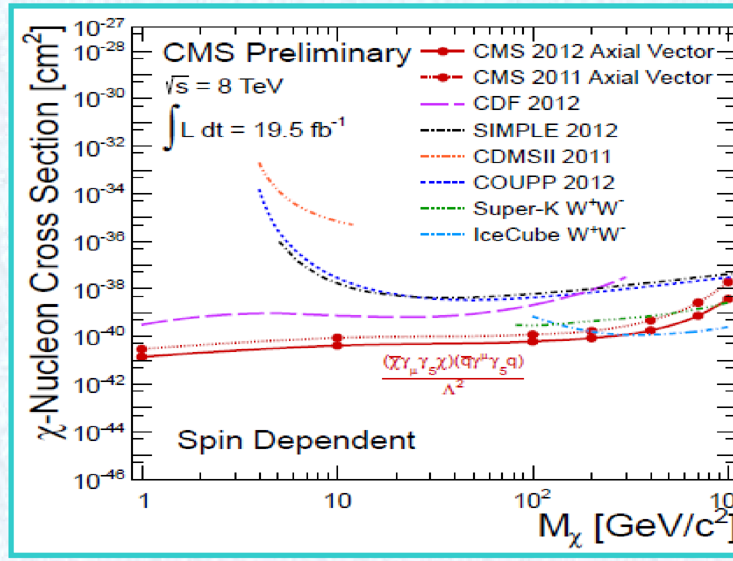


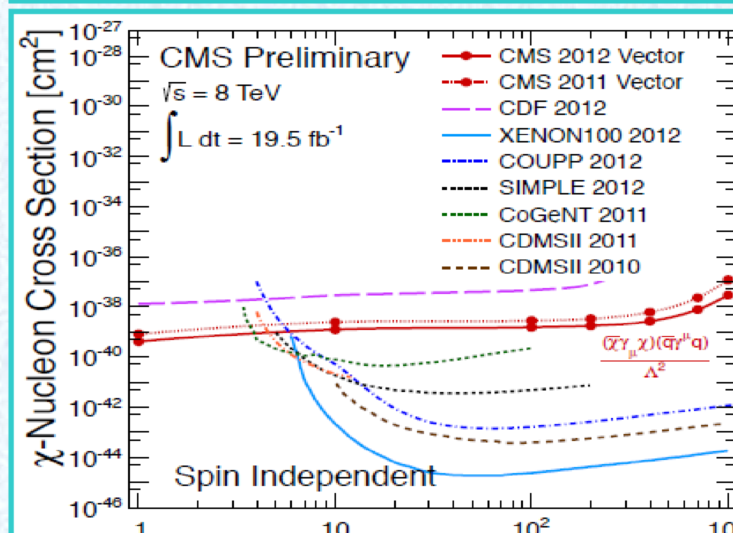
Collider detection for EFT

- If DM particles are directly produced by pp collisions, it requires a hard jet/photon from initial radiation to trigger the event
- Search for DM-quark/gluon effective theories



ATLAS, 1210.4491



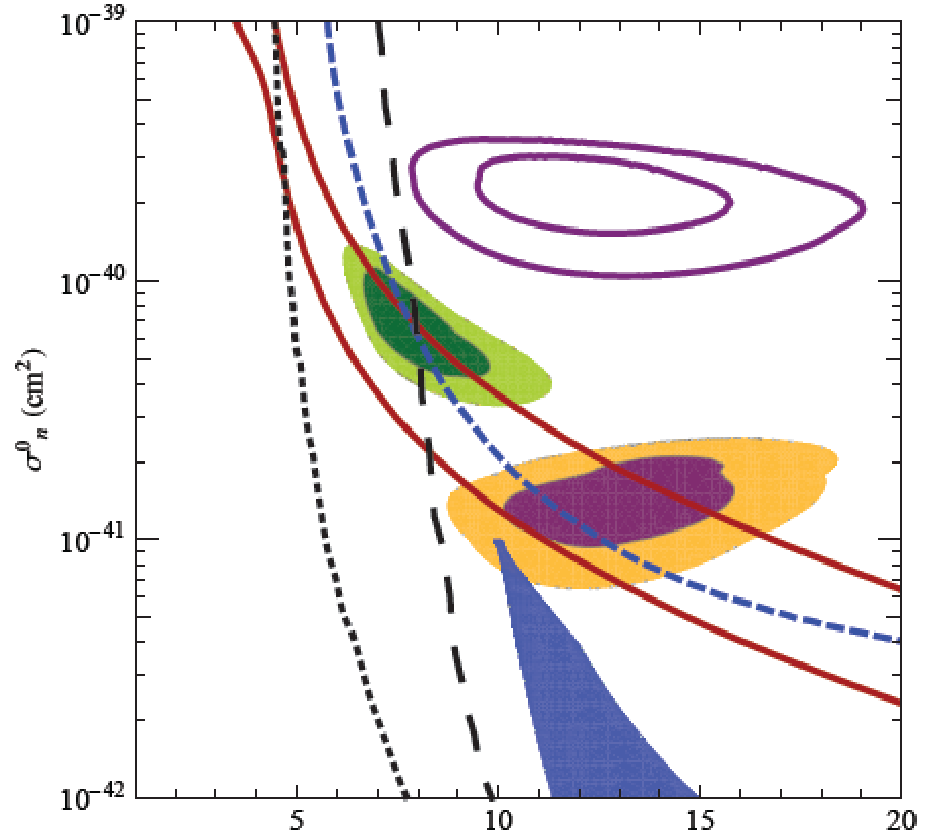


CMS-EXO-12-048

Simplified model: Higgs portal

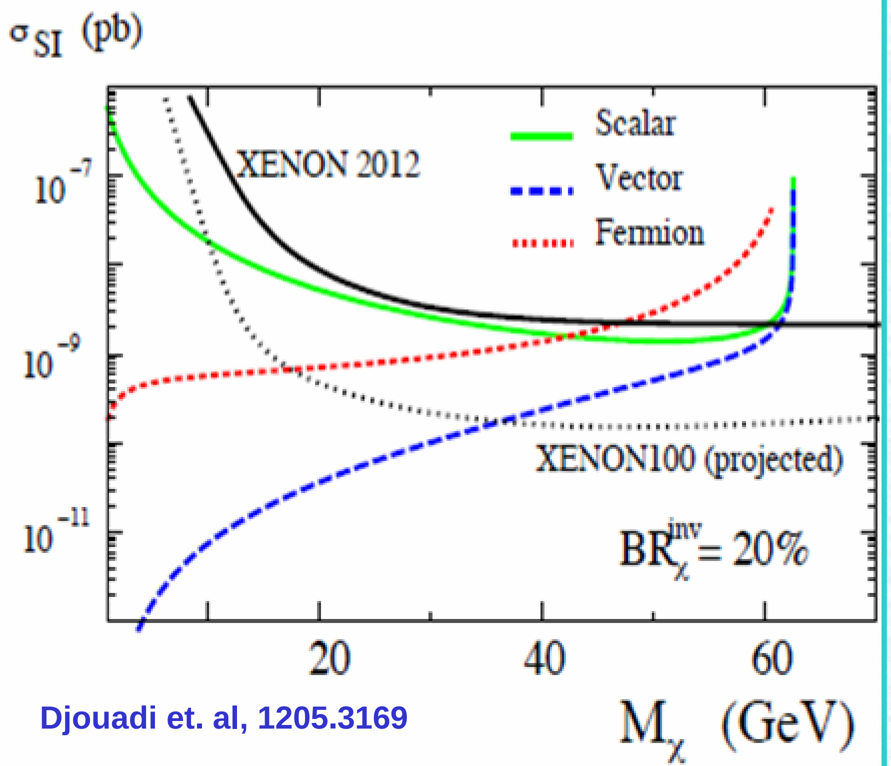
- Simple model with an extra singlet scalar

$$\mathcal{L} \ni \frac{1}{2}\partial^\mu S \partial_\mu S - \frac{1}{2}\mu_S^2 S^2 - \frac{\lambda_S}{4} S^4 - \lambda_L H^\dagger H S^2$$

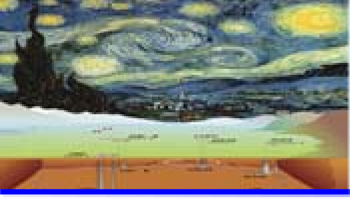


Andreas et. al, 1003.2595

- DM can interact with SM particles via the mixing between Higgs and new scalar
- Constrained by Higgs invisible decay

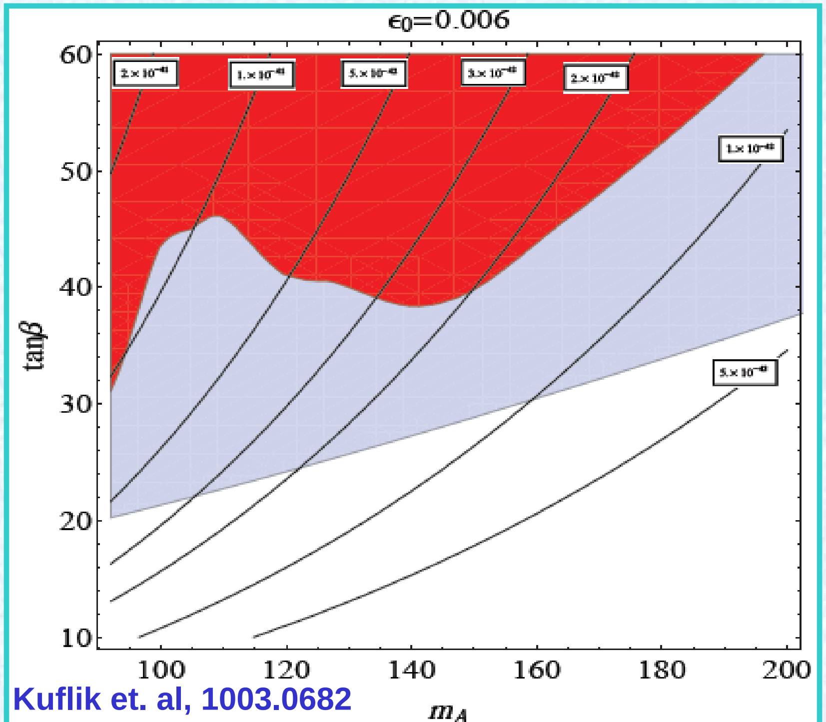


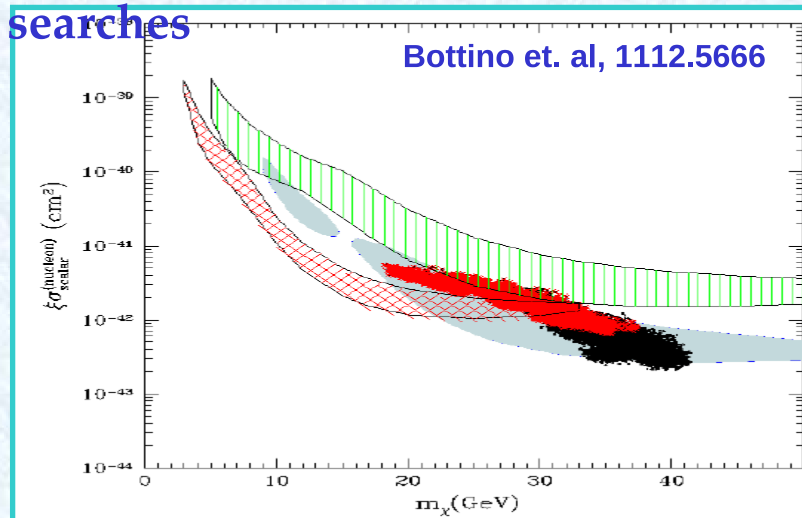
Djouadi et. al, 1205.3169

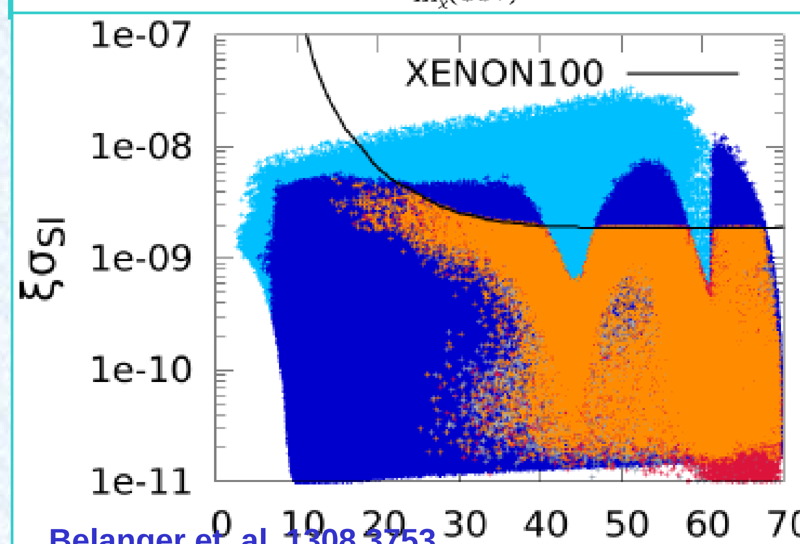


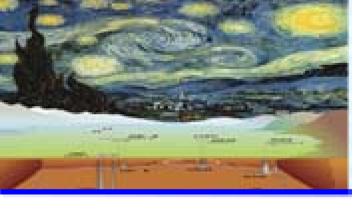
Complete theory: MSSM

- Neutralino in the MSSM is difficult to explain DAMA/CoGENT
- Constraints also from Higgs and flavor searches









Indirect detection: gamma-ray

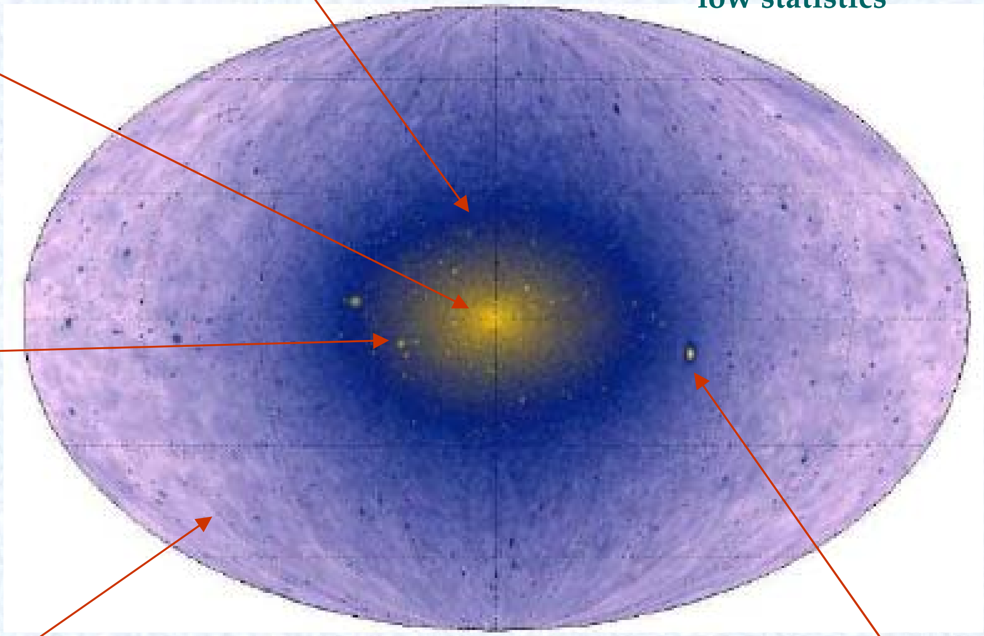
- Detecting target: dense DM region

$$\phi(E,\psi) = \rho^2 R \times \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_D^2}\frac{dN}{dE}\times\frac{1}{\rho^2 R}\int_{LOS}\rho^2(l)dl$$

Galactic halo
large statistics galactic background

Galaxy cluster
low background, good source id
low statistics

Galactic center
Good statistics
Astrophysical source and
confusion/diffusion background



Massive subhalo
low background
low statistics, position unknown

Extra-galactic
large statistics
extra-galactic/galactic background

Satellite galaxy
low background, good source id
low statistics

Jeltema/Hooper, IPMU, 2009.12

Probe DM in the Galactic Center

- Large DM annihilation rate at the GC due to large DM density

$$\Phi_\gamma \propto J = \frac{1}{\Delta\Omega}\int d\Omega \int_{\mathrm{l.o.s.}} \rho^2(l)\,dl(\psi)$$

- Typical J factors ($\log_{10}$ GeV^2 cm^{-5})
  - Dwarfs: e.g. Ursa Major II 19.6, Coma 19, Draco 18.8
  - Clusters: e.g. Fornax 17.8, M49 17.6
  - GC: 21.0 for a region within O(1)^o

  Linden, CFW, 2013

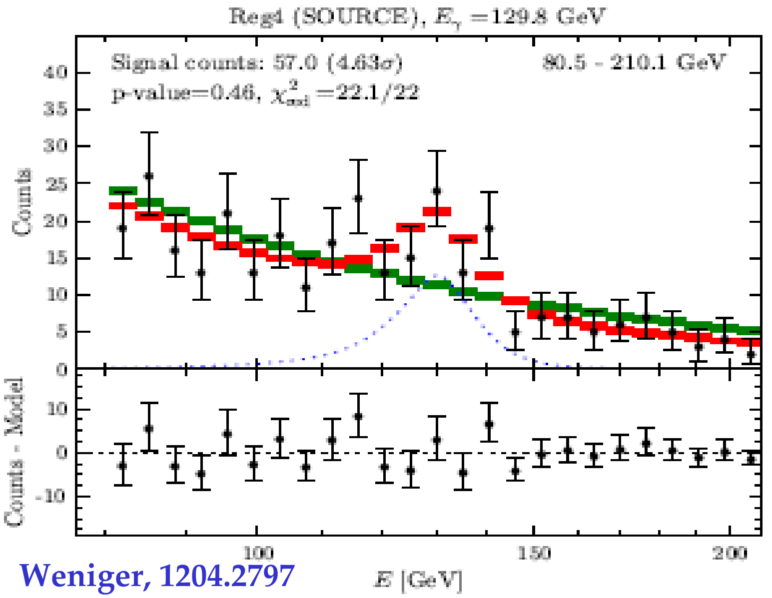
- Very complicated astrophysical environment

  point source, stars, pulsars, gas….

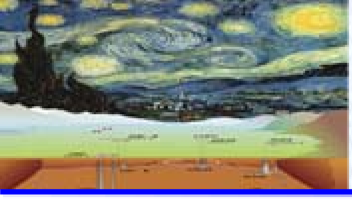
- Some hints…

  130 GeV gamma-ray line ?

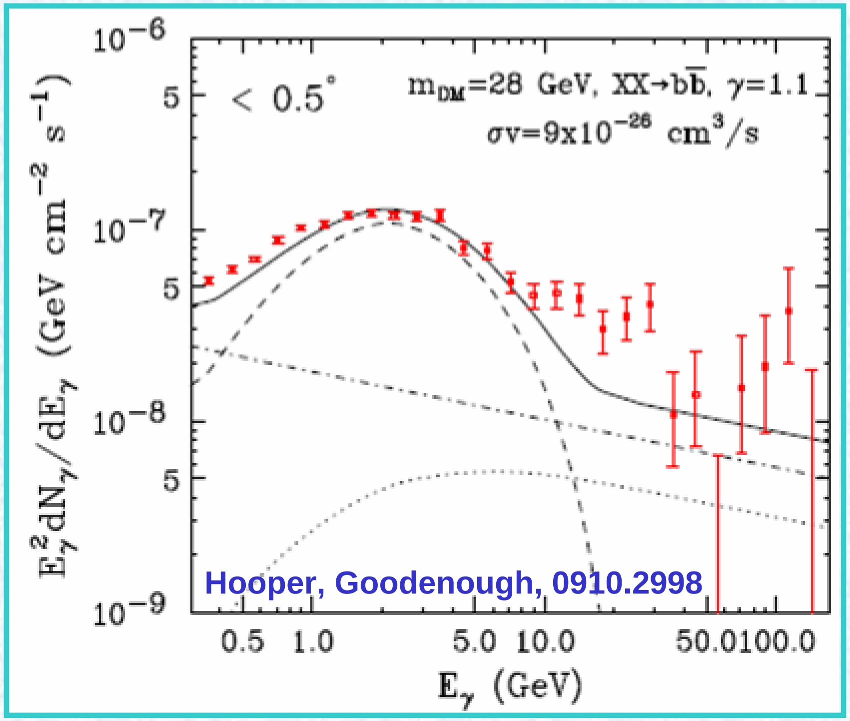
  May go away now…



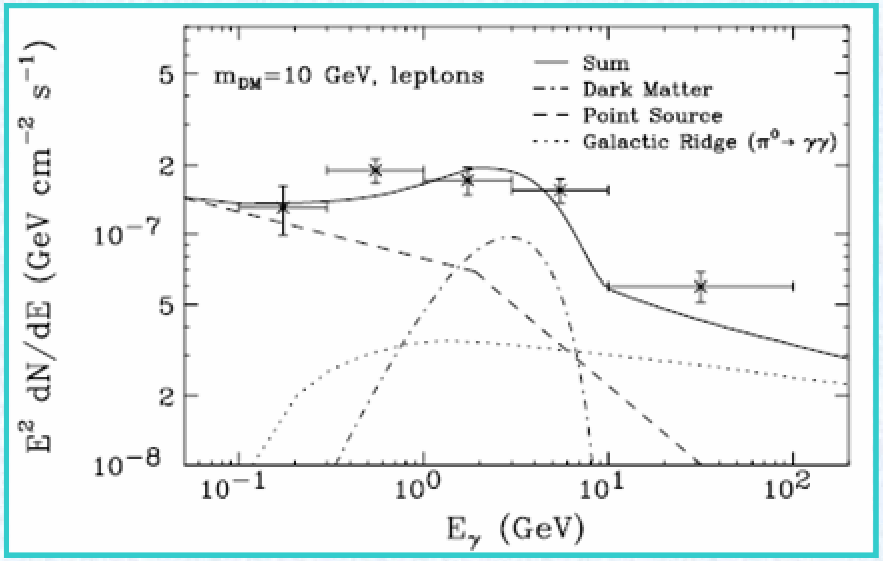
Weniger, 1204.2797

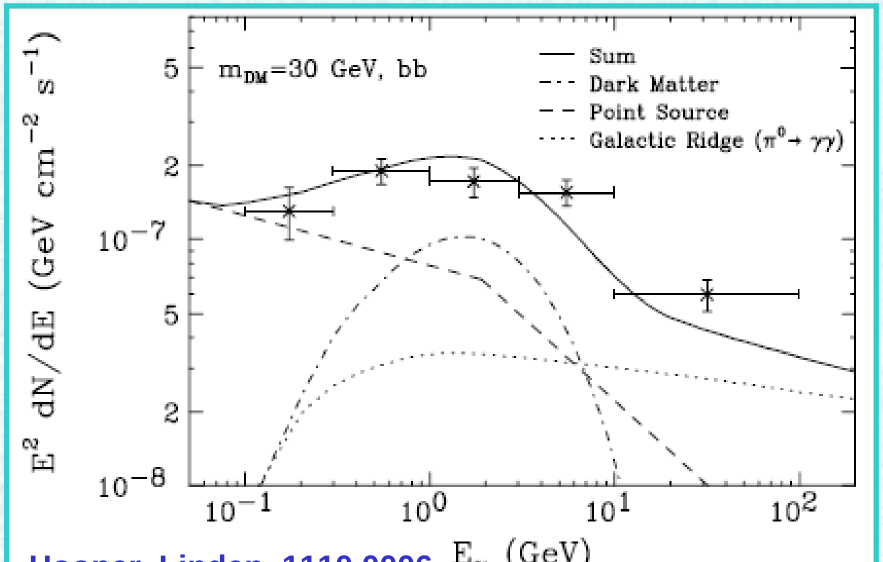


GeV gamma-ray excess in the GC



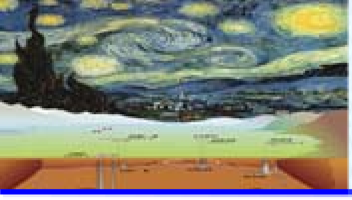
Hooper, Goodenough, 0910.2998



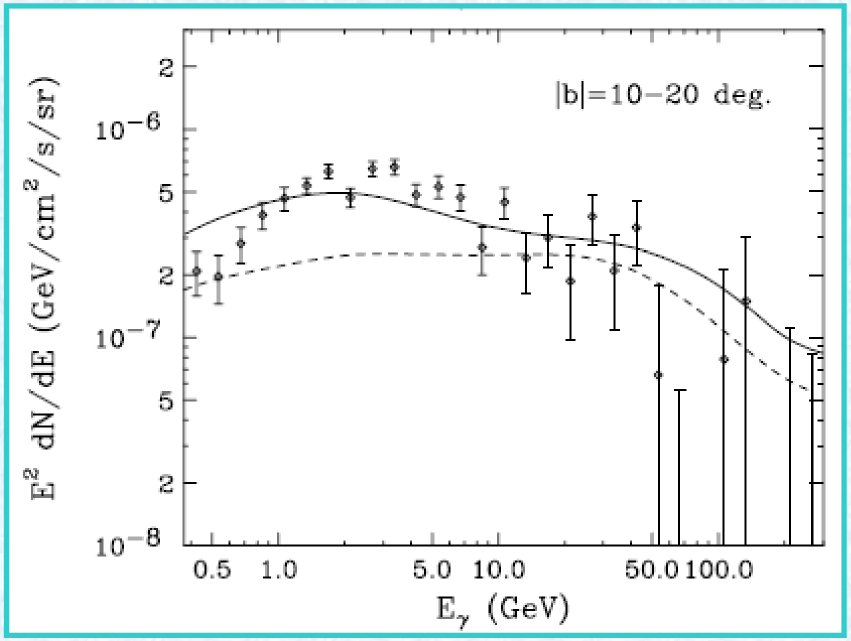


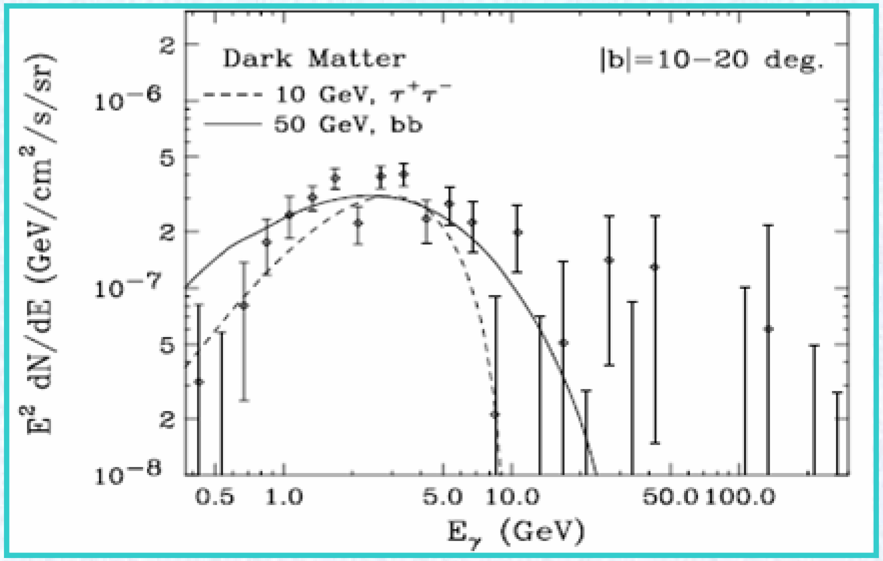
Hooper, Linden, 1110.0006

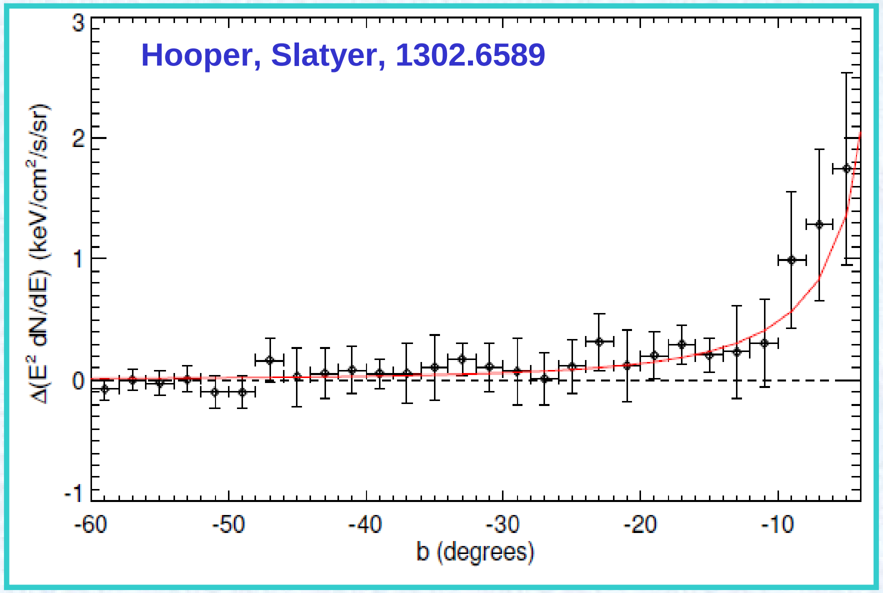
- Possible GeV gamma-ray excess in the small region of the GC
- DM annihilation signal ?
- 30 GeV to bb, 10GeV to ττ, σv~10^{-26}-10^{-27}
- Cusp density distribution



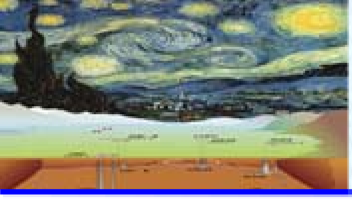
GeV gamma-ray excess in the inner Galaxy?



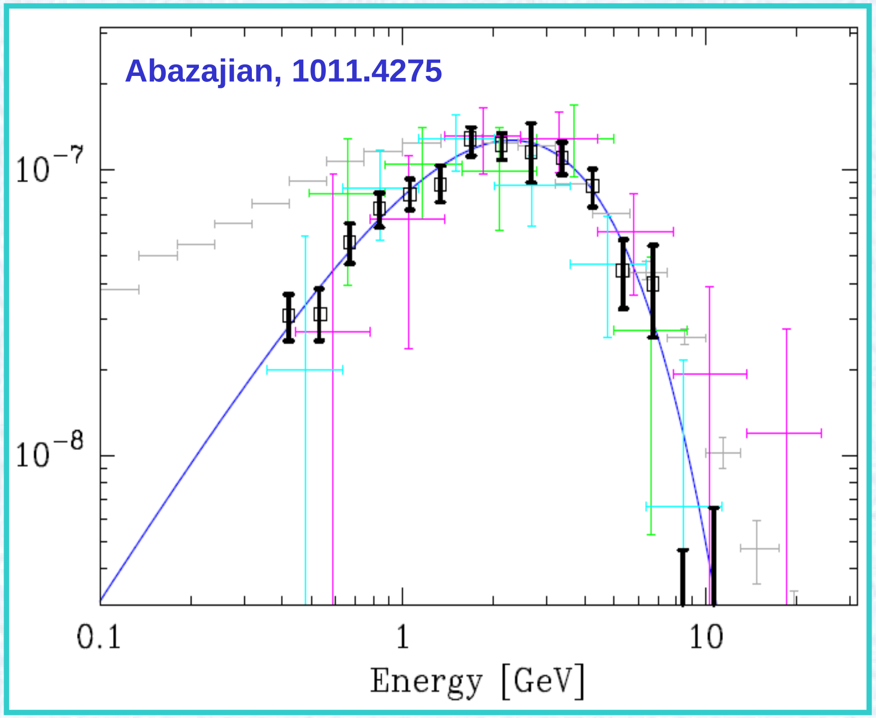


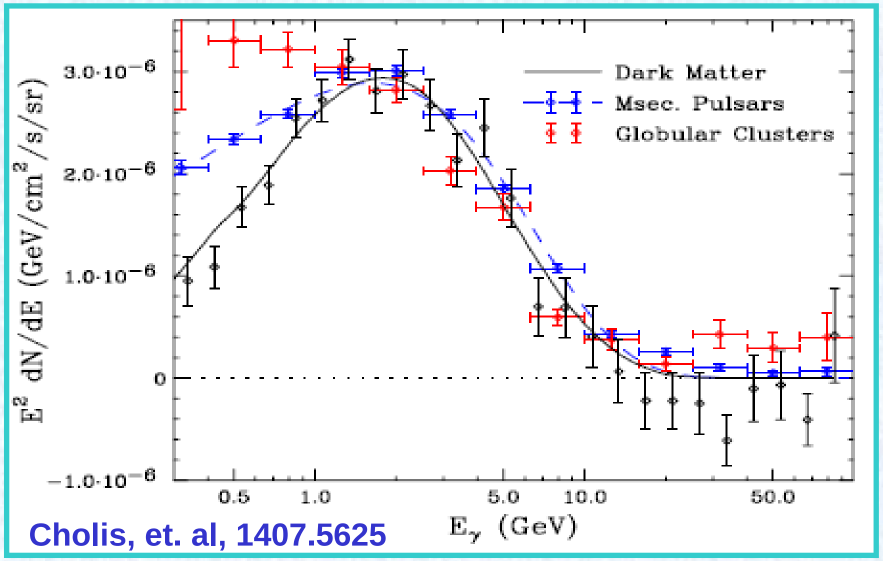


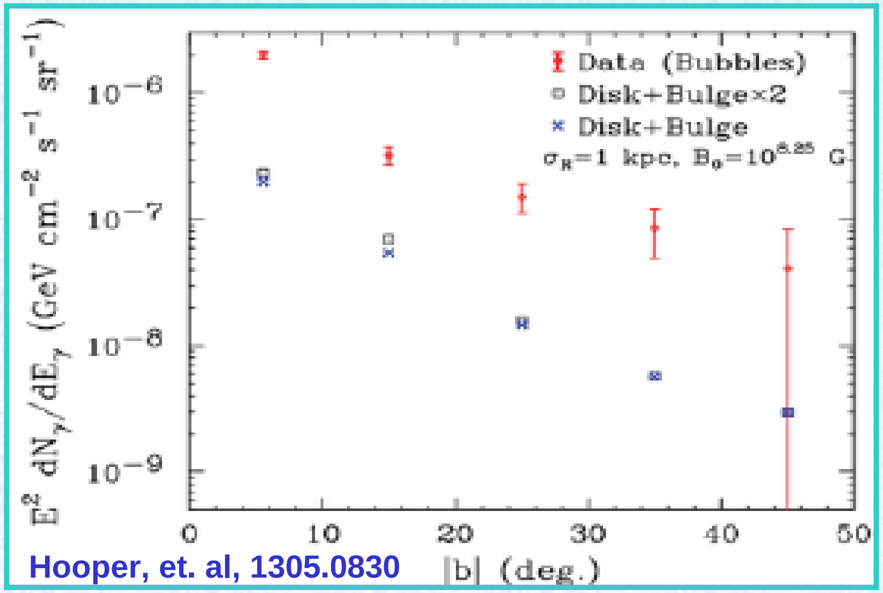
- Possible GeV gamma-ray excess in the region ~2-3 kpc from the GC
- Consistent with NFW distribution



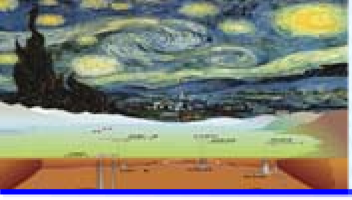
Millisecond pulsars?



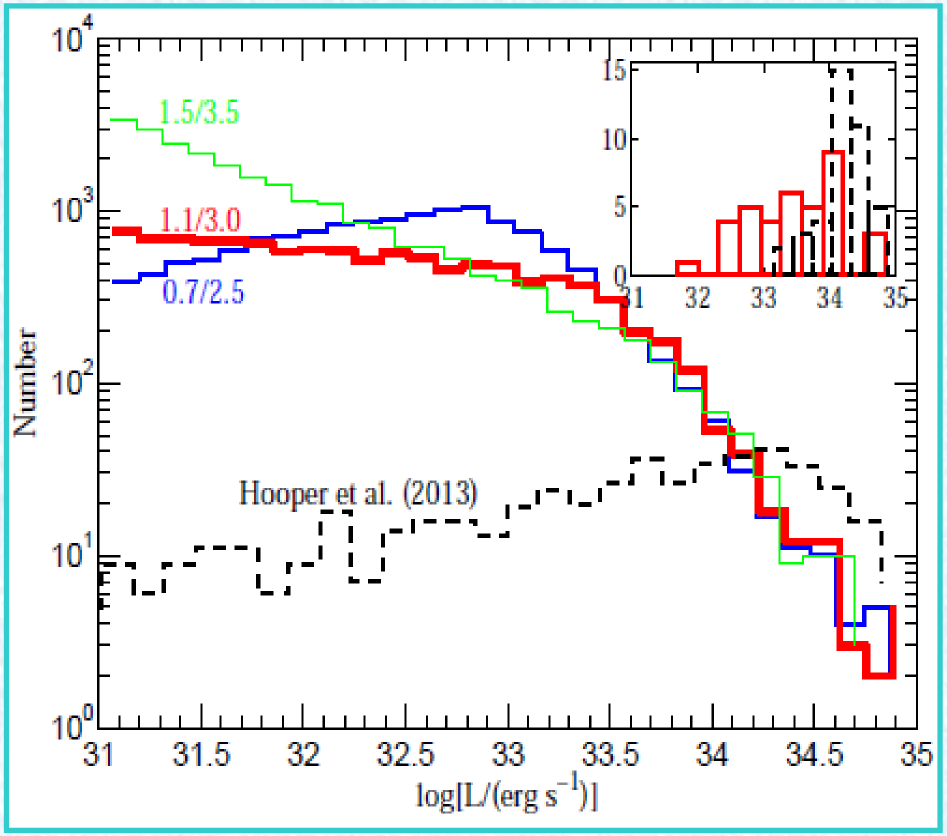


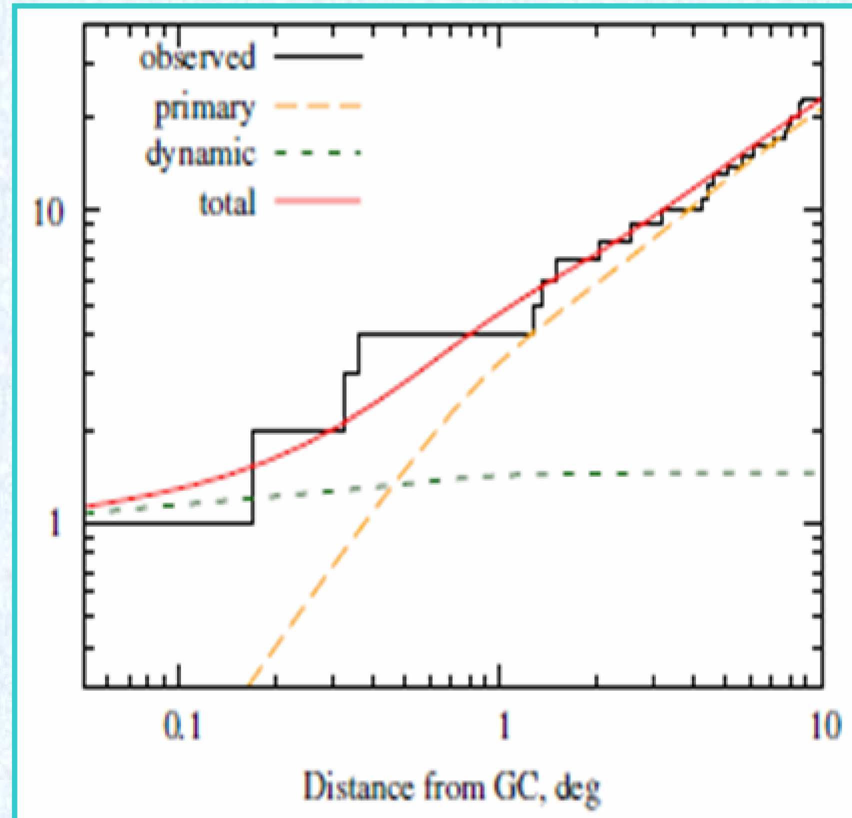


- May be produced by many MSPs ~O(10^3)
- However, require harder spectrum at E<1GeV
- Flux is not sufficient?
- Distribution of MSP is not consistent?



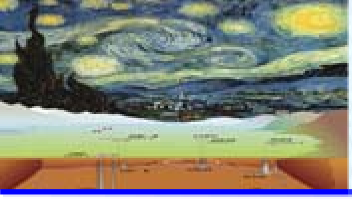
Millisecond pulsars?



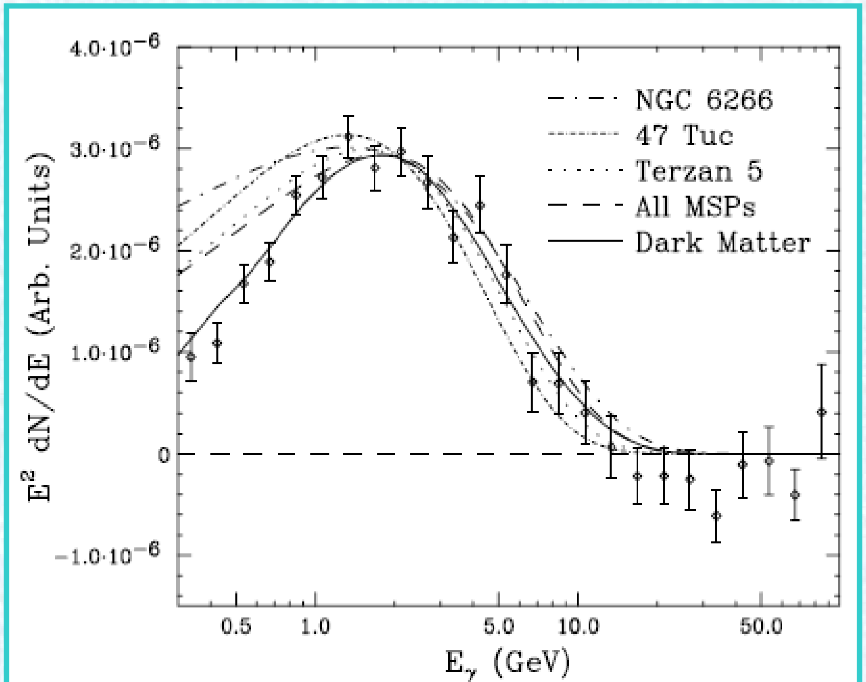


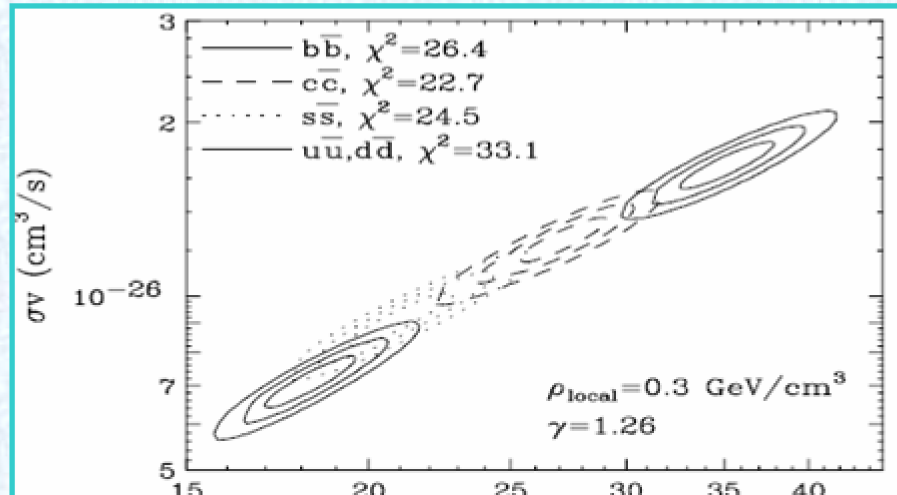
- Spectrum: systematic (theoretical and experiemental) uncertainties at E<1GeV?
- Flux: how to derive a correct luminosity function?
- Spatial distribution: LMXB (tracer of MSP?) seems to r $^{-(2-3)}$ in the galaxy
- MSP interpretation is still debatable

Yuan, Zhang, 1404.2318

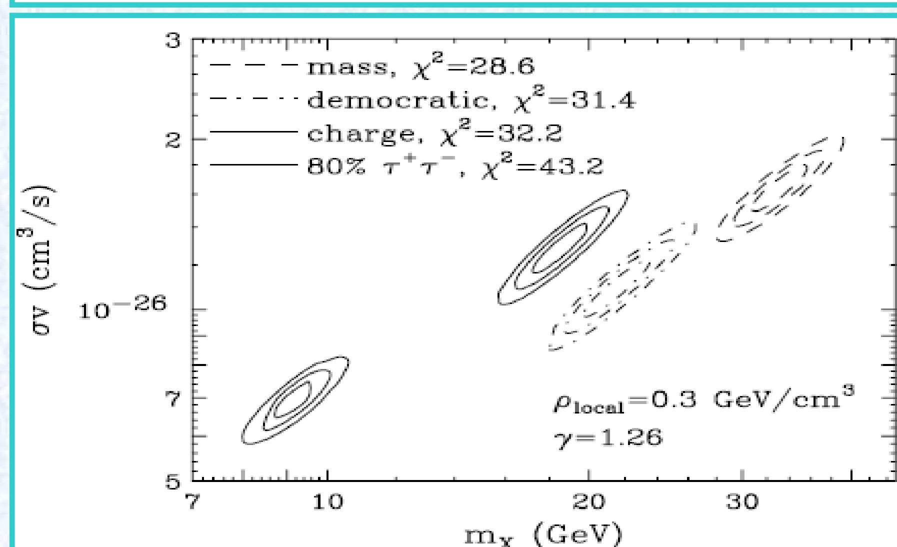


10GeV DM again ?

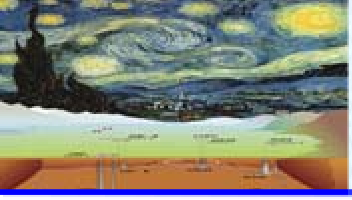




Daylan, 1402.6703



- **Different features compared to models that can interpret anomalous direct detection results**

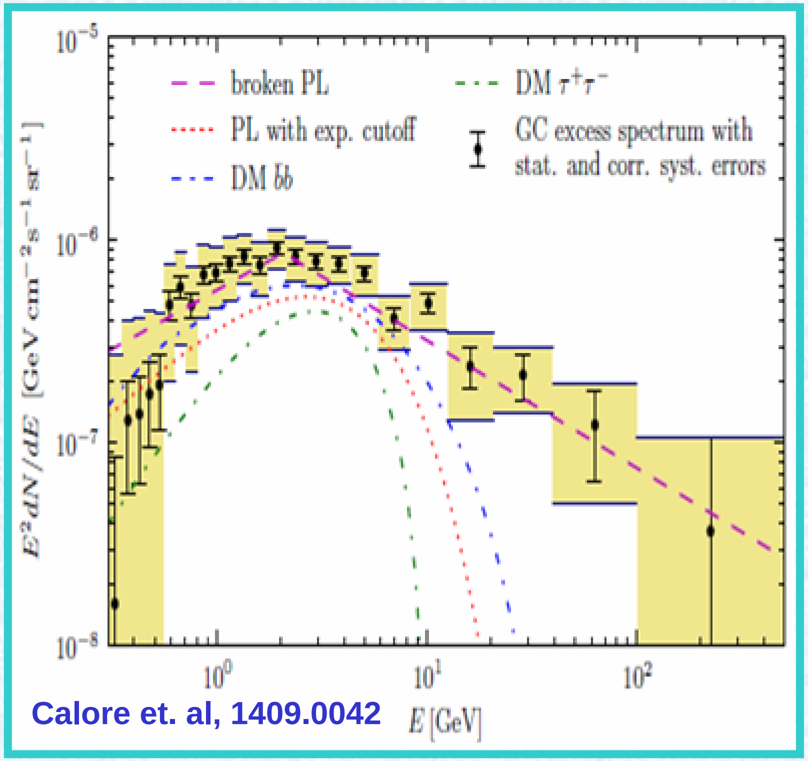


How to acquire a DM component?

- In a chosen region and each energy bin, fit the data with a set of templates
  - Diffuse gamma-ray: pi and bremsstrahlung
  - Diffuse gamma-ray: inverse Compton radiation
  - Point sources
  - Fermi-bubbles
  - Isotropic component
  - Excess component: e.g. NFW distribution
- The main components of data are diffuse gamma-rays which needed to be determined by the interactions between cosmic rays and gas/ISRF.

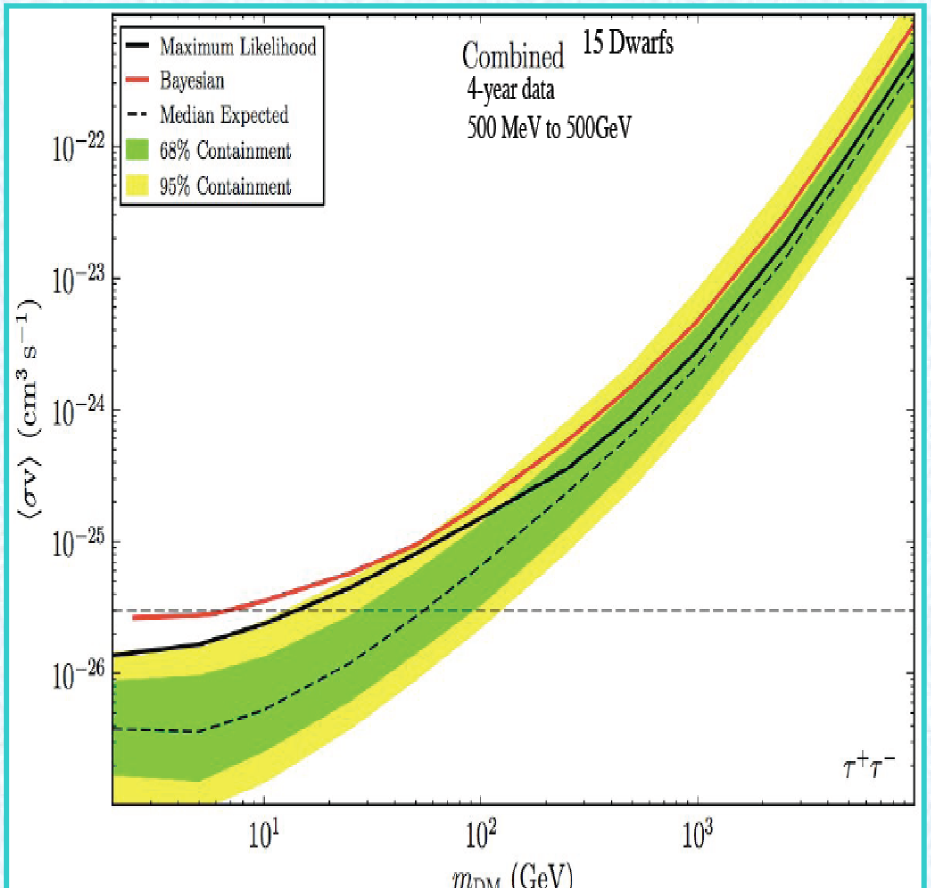
  Large uncertainties from the cosmic-ray models, unknowns about interstellar gas, unresolved point sources etc…

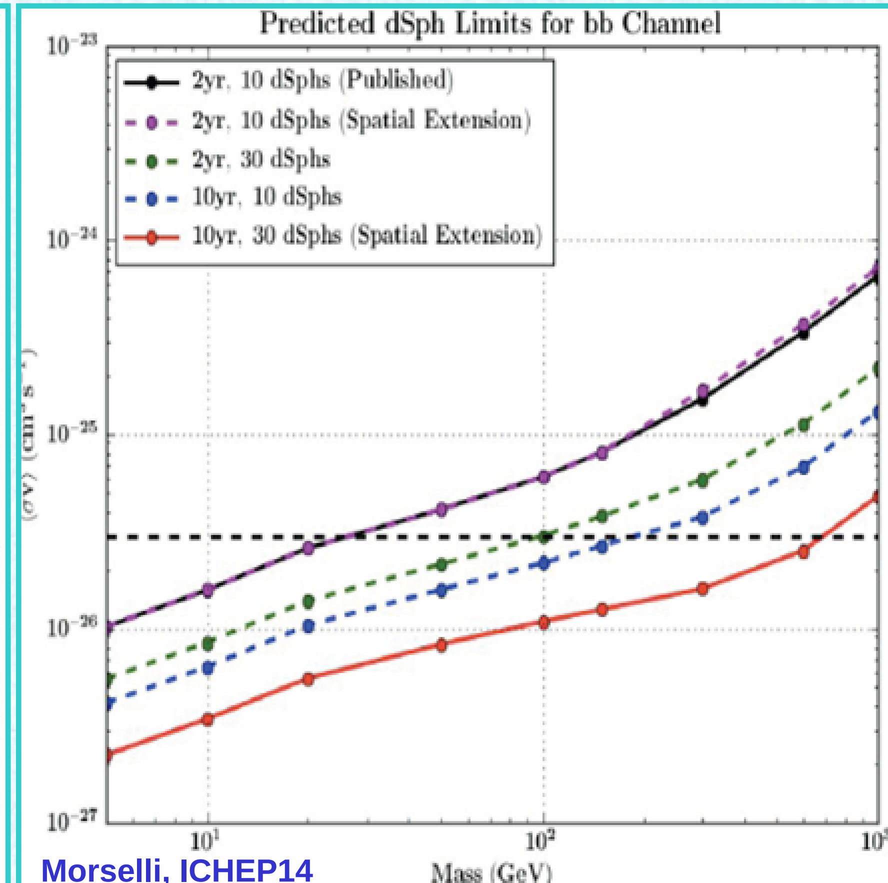
- Excess ~1-10GeV seems to exist … but the spectrum is not clearly confirmed



Calore et. al, 1409.0042

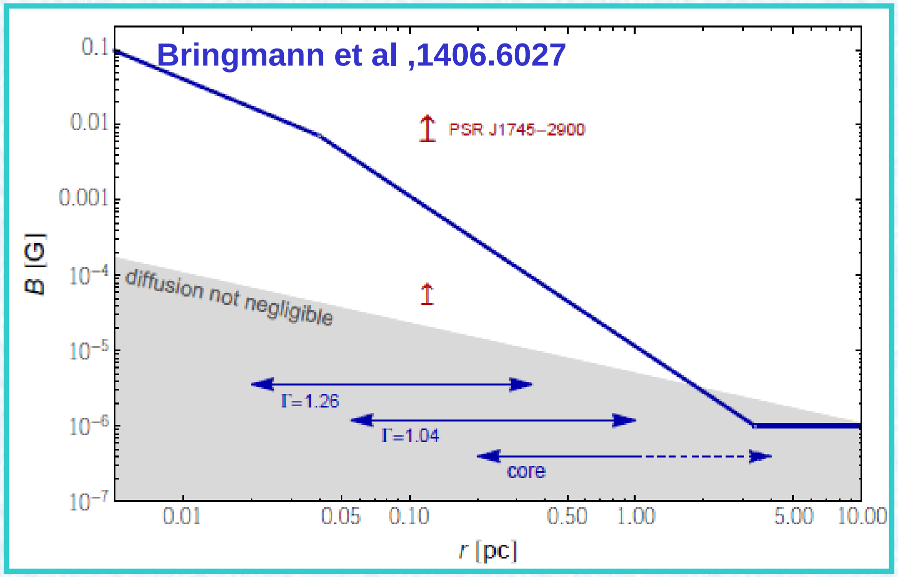
Constraints from dwarf galaxies

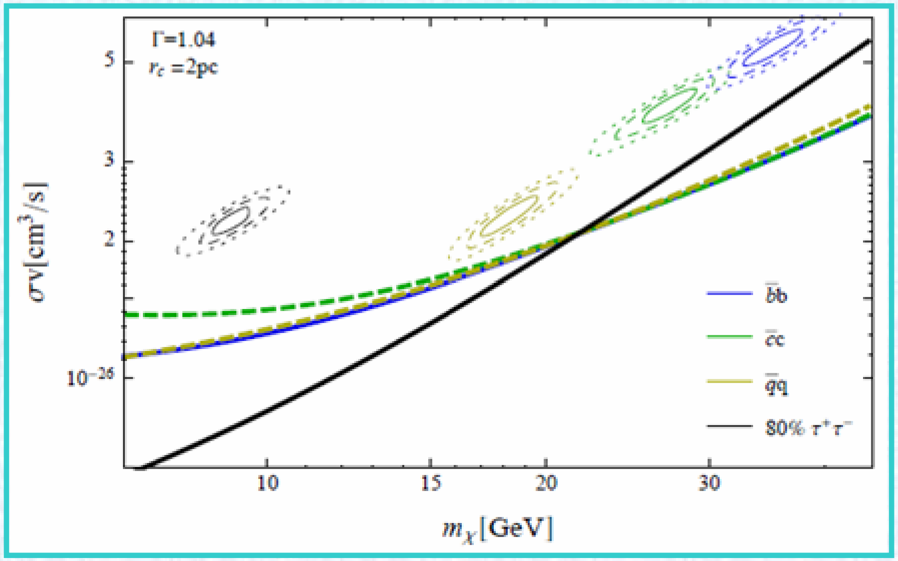


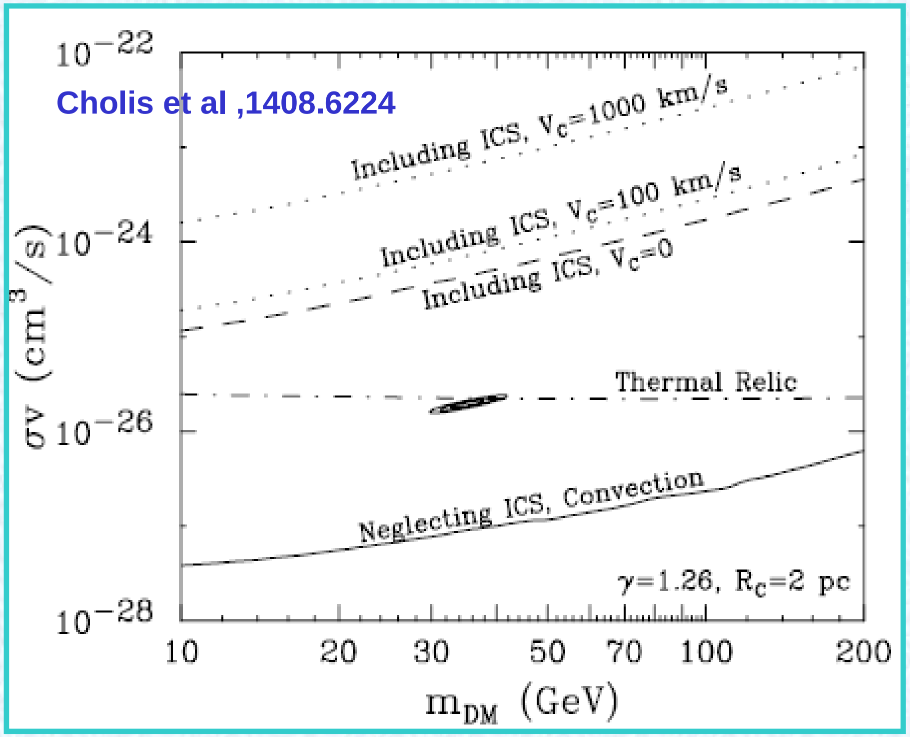


- **If the GC excess is induced by DM annihilations, the observations of dwarf spheroidal galaxies should also detect the signals at GeV scale**

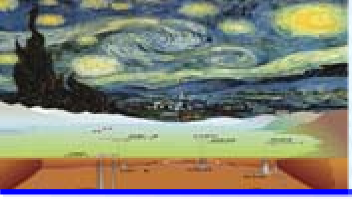
Constraint from radio observation



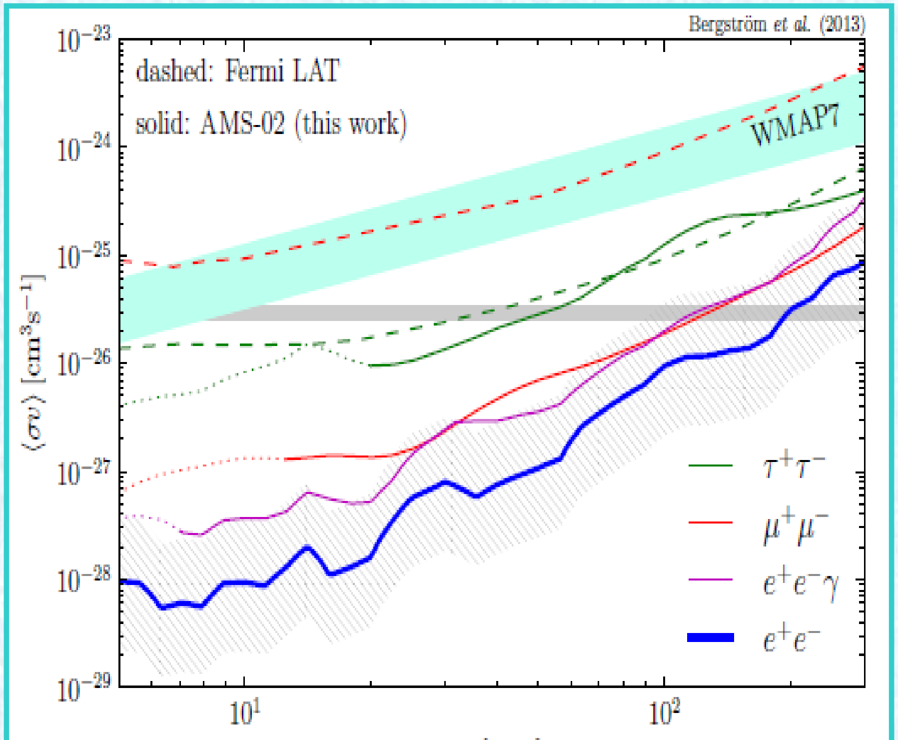




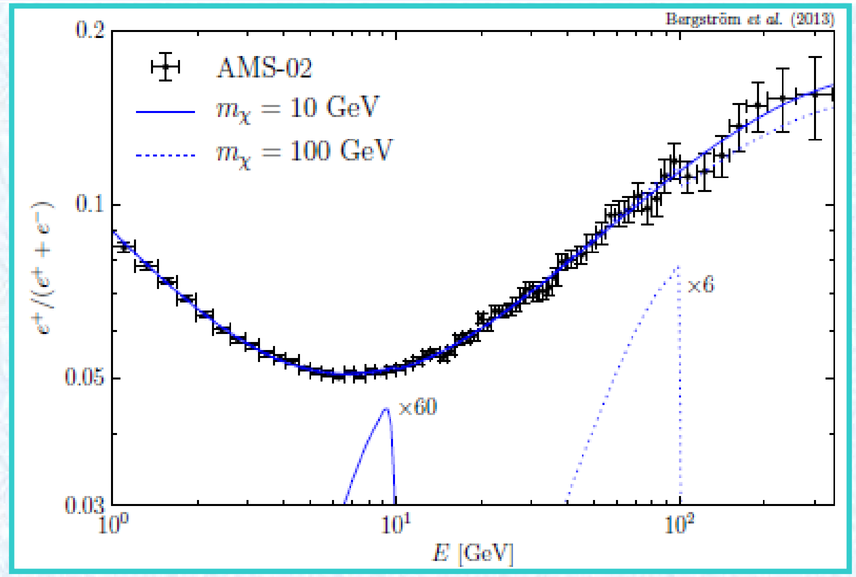
- Null results for 408Mhz radio signals from a 4″ area around the GC
- Constraints depend on magnetic field distribution model and DM profile at the GC
- Considering the ICS and convection effects would loose the constraint

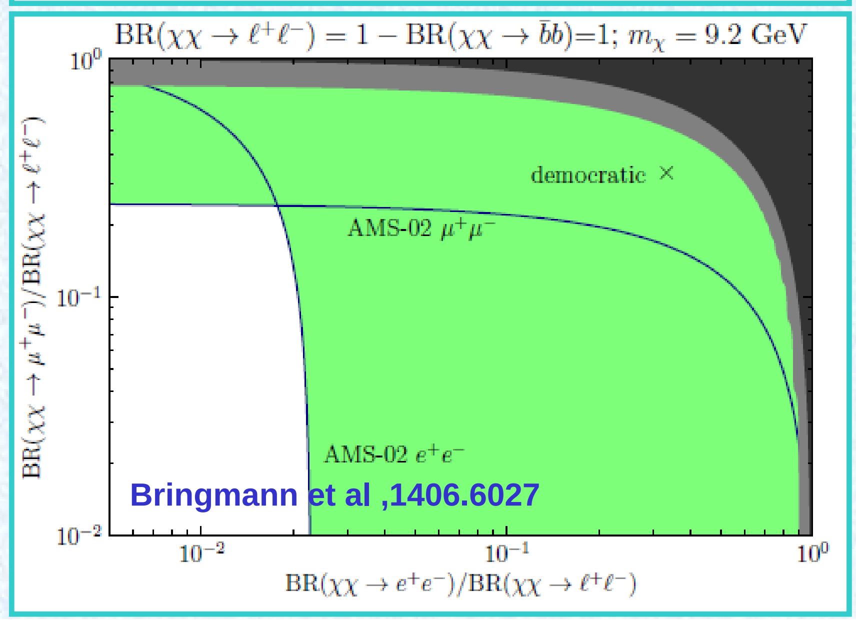


Constraint from positrons



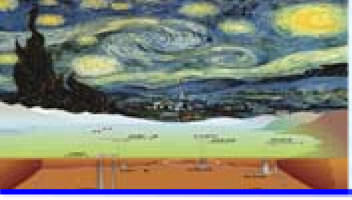
Bergstrom et al ,1306.3983



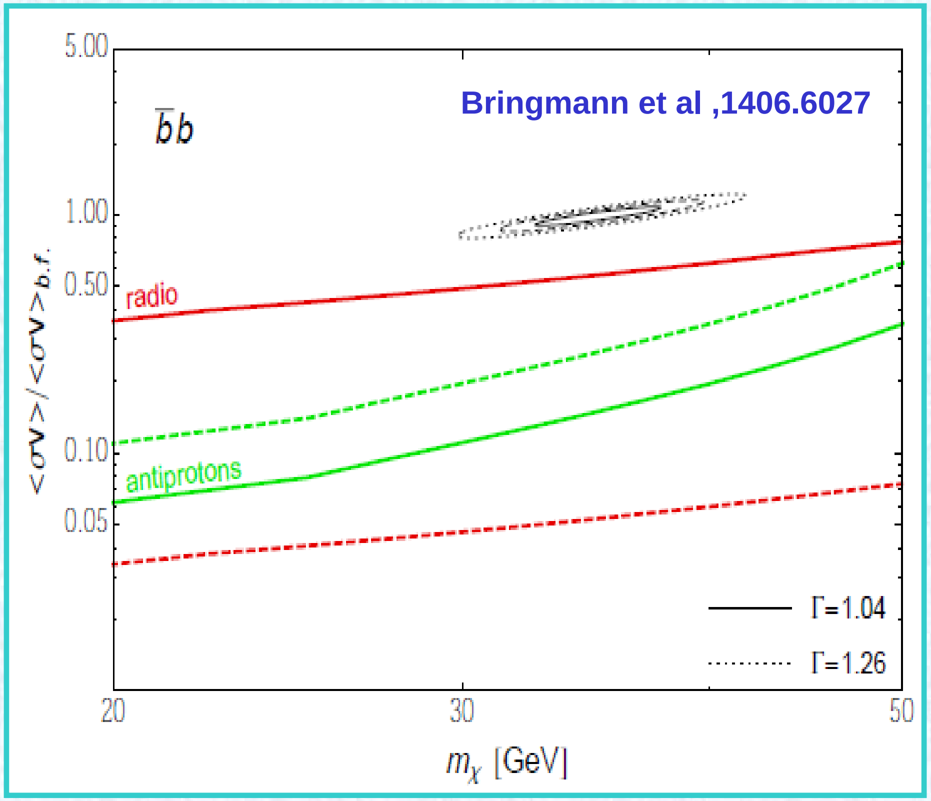


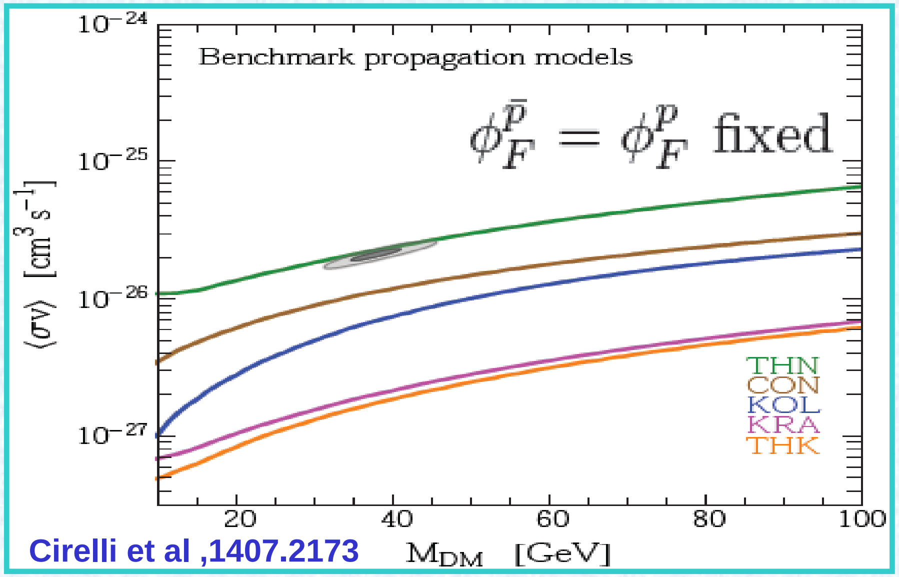
Bringmann et al ,1406.6027

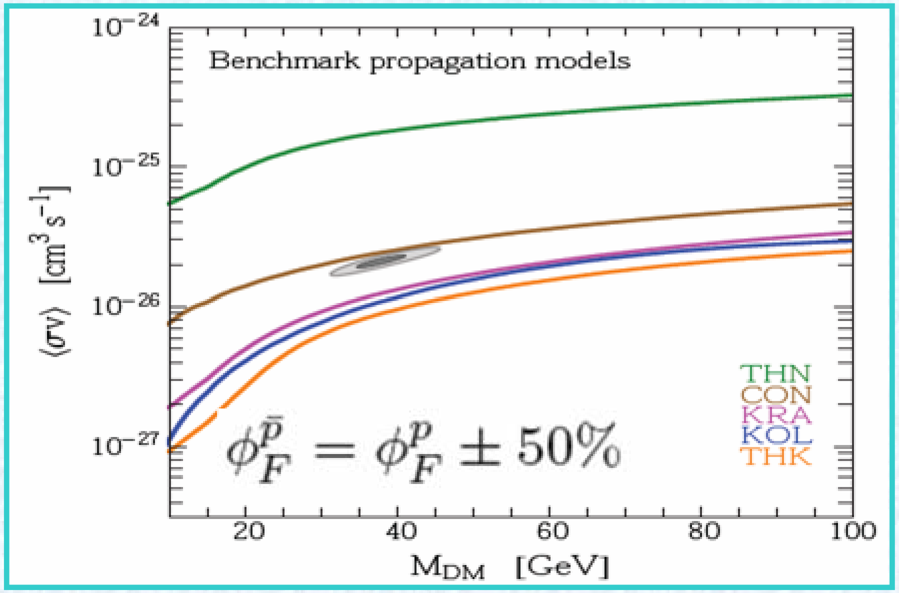
- How to understand the contributions from astrophysical sources ?
- It seems that DM annihilating to light leptons has been excluded



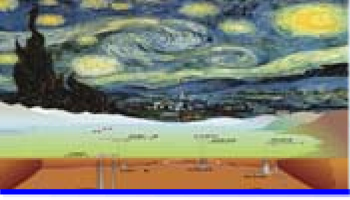
Constraints from anti-protons





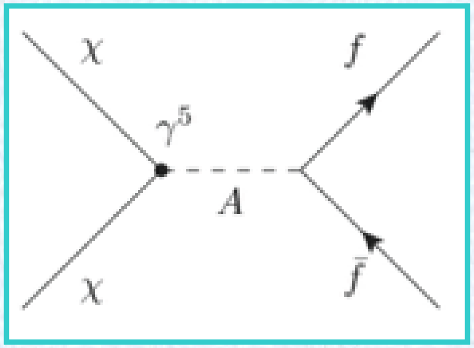


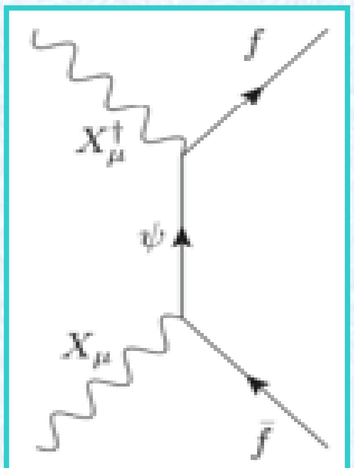
- If DMs annihilate into bb, the anti-proton data set stringent constraints
- Constraints may be relax due to uncertainties from propagation model and solar modulation model



Simplified models

Berlin et al, 1404.0022



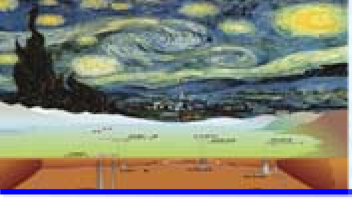


Model Number	*DM*	*Mediator*	*Interactions*	Elastic Scattering	Near Future Reach?	
					Direct	LHC
1	Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
1	Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
2	Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
2	Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
3	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi$, $\bar{b}\gamma_\mu b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Maybe
4	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$ or $\sigma_{\rm SD} \sim (q/2m_\chi)^2$	Never	Maybe
5	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
5	Majorana Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
6	Complex Scalar	Spin-0	$\phi^\dagger\phi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Real Scalar	Spin-0	ϕ^2, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Complex Vector	Spin-0	$B_\mu^\dagger B^\mu$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Real Vector	Spin-0	$B_\mu B^\mu$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
7	Dirac Fermion	Spin-0 (t-ch.)	$\bar{\chi}(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
7	Dirac Fermion	Spin-1 (t-ch.)	$\bar{\chi}\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
8	Complex Vector	Spin-1/2 (t-ch.)	$X_\mu^\dagger\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
8	Real Vector	Spin-1/2 (t-ch.)	$X_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes

- **DM-quark interaction will induce signals at the direct detection and LHC**
- **The Light mediator can be checked at the LHC**
- **Many models are still safe**

For **discussions in complete models, see**

Cheung et. al, 1406.6372, Guo et. al, 1409.7864
Cao et. al, 1410.3239



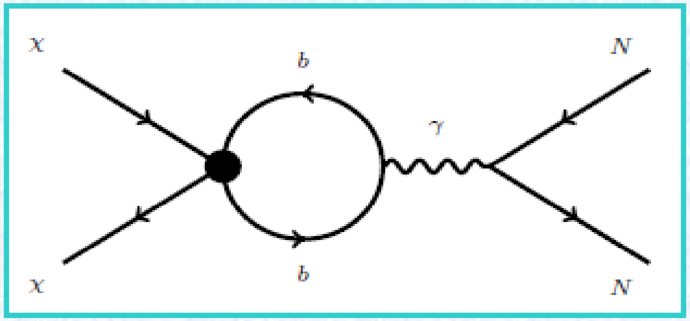
Some examples of simplified model

- Consider interactions which are not velocity suppressed

$$\mathcal{L}_U = (g_\chi \bar{\chi}\gamma^\mu\gamma^5\chi + g_b \bar{b}\gamma^\mu\gamma^5 b)\, U_\mu \quad ,$$
$$\mathcal{L}_V = (g_\chi \bar{\chi}\gamma^\mu\chi + g_b \bar{b}\gamma^\mu b)\, V_\mu \quad ,$$
$$\mathcal{L}_a = i\,(g_\chi \bar{\chi}\gamma^5\chi + g_b \bar{b}\gamma^5 b)\, a \quad ,$$

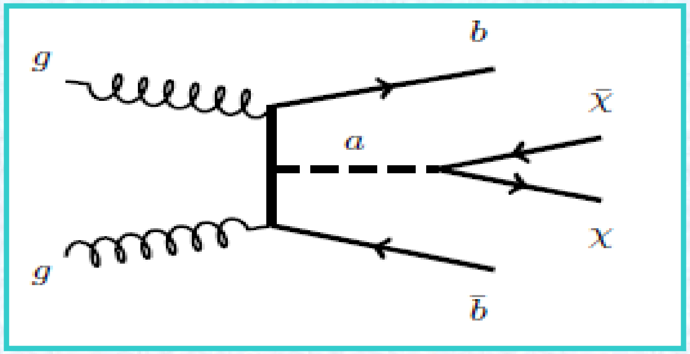
$$\mathcal{L} \supset \frac{\lambda_b}{2}\left[\bar{b}(1-\gamma_5)\chi_b\phi + \bar{\chi}_b(1+\gamma_5)b\,\phi^\dagger\right]$$

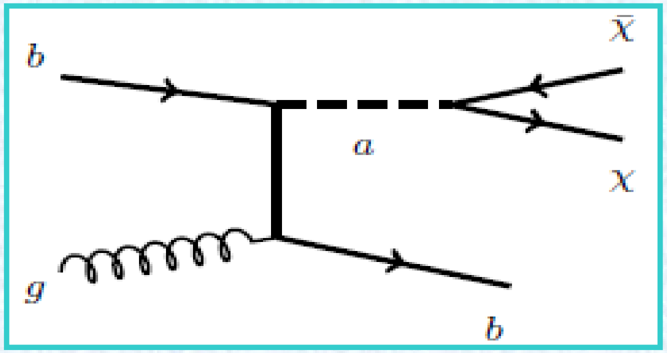
- Induce DM-nucleon interaction at the loop level

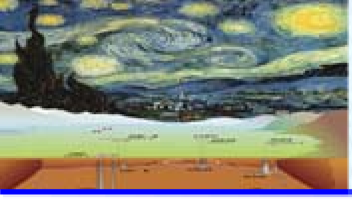


Agrawal et al,1404.1373
Izaguirre et. al, 1404.2018
Bottino et. al, 1112.5666

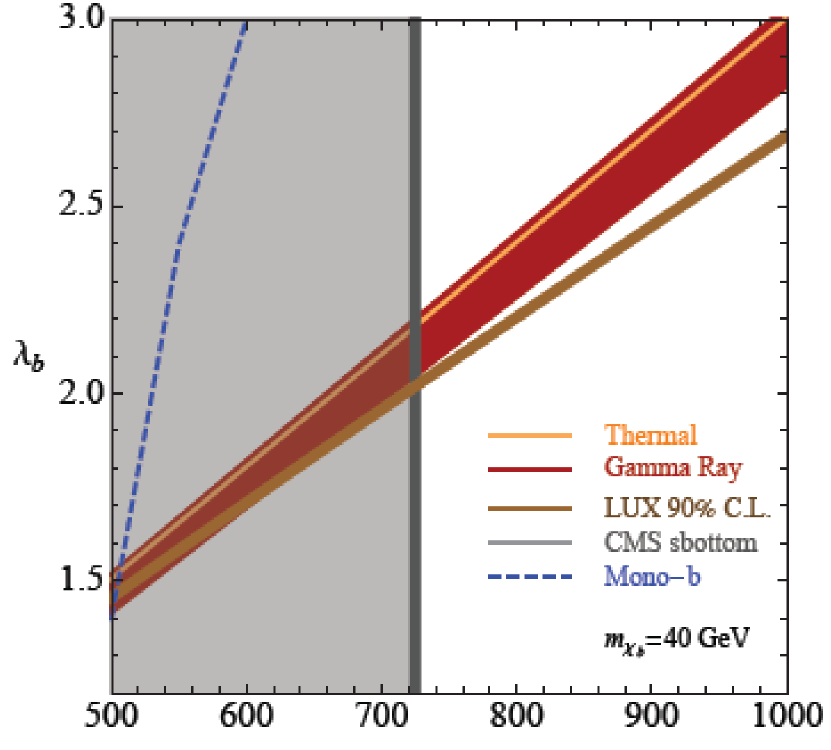
- Produce b-jets +MET at the LHC



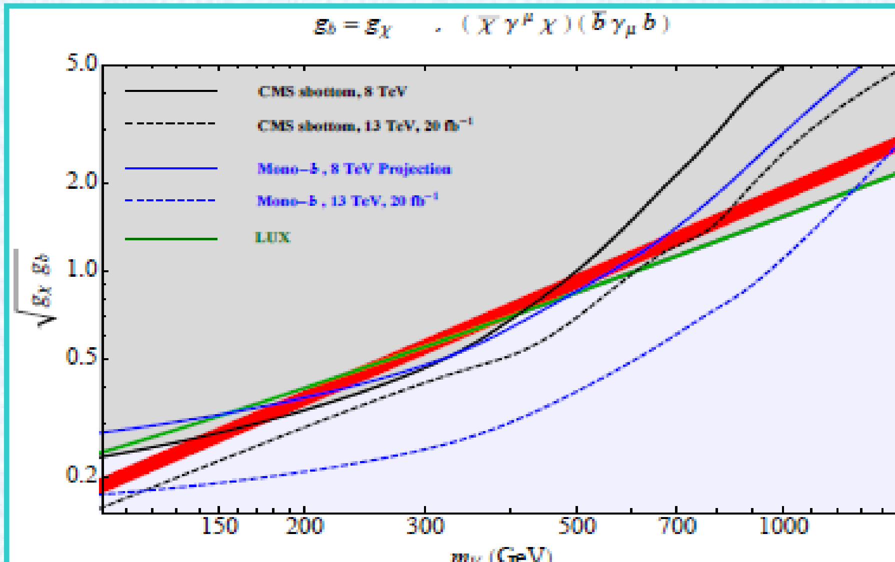


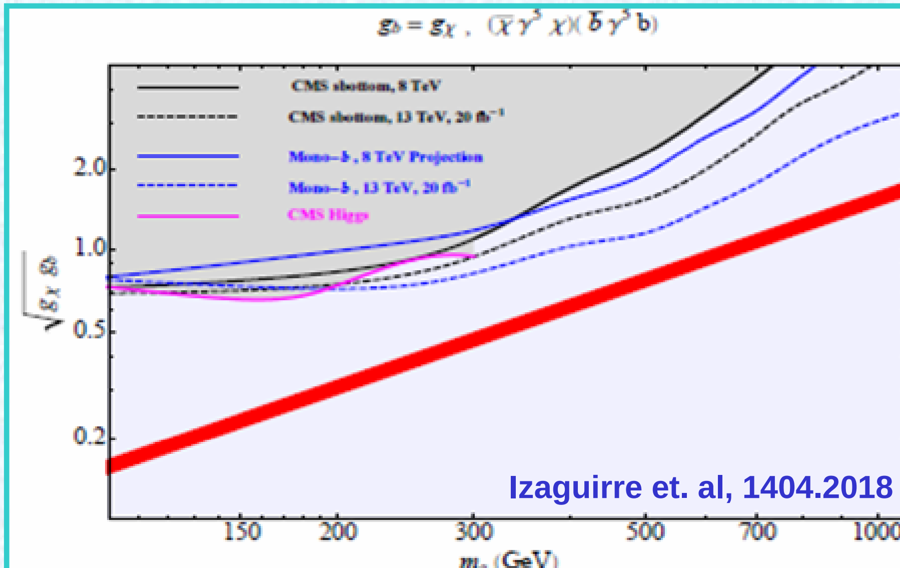


Constraints from direct detections and LHC



Agrawal et al,1404.1373





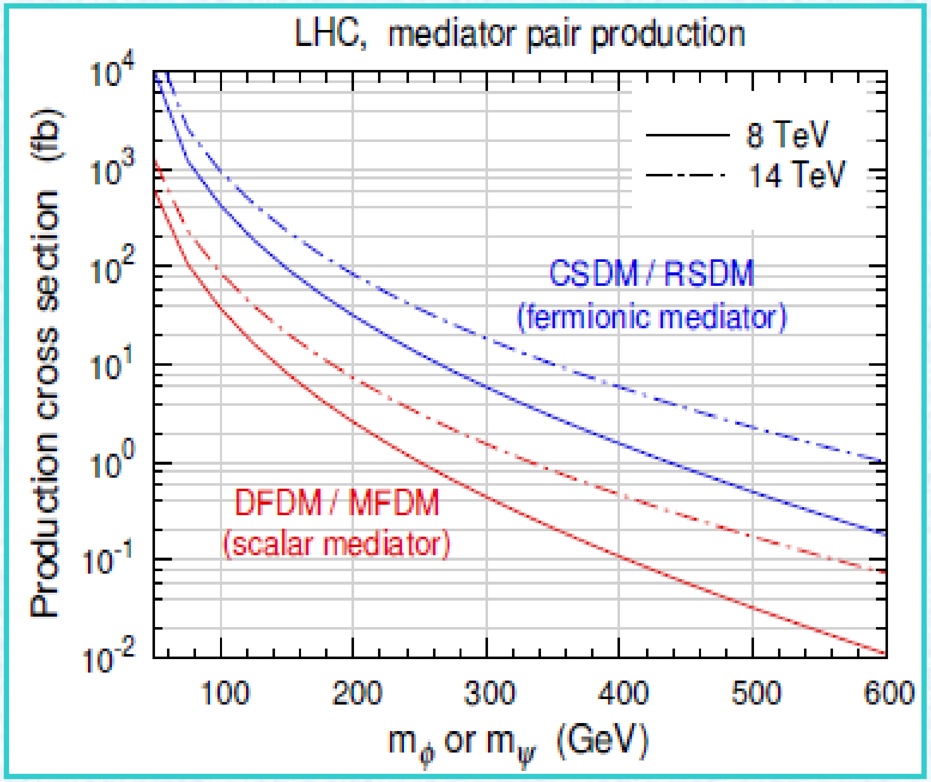
Izaguirre et. al, 1404.2018

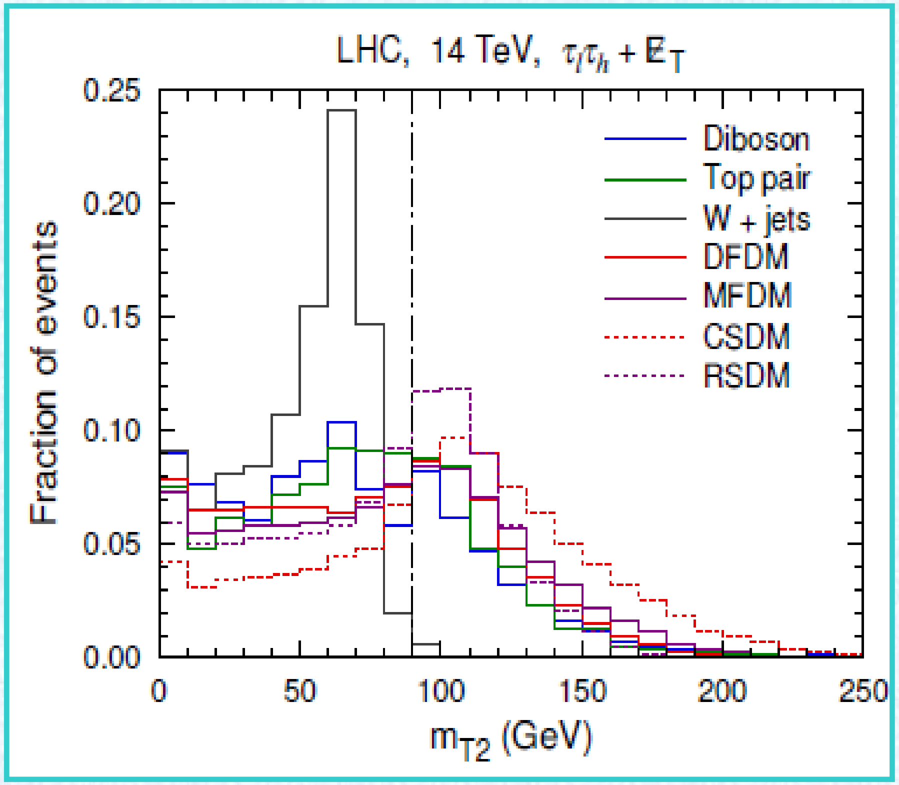
Tau portal DM

- Assume DM particles dominantly couple to taus.
- No anti-proton constraint and very weak positron constraint.
- Best fit for gamma-ray excess m_{DM}~10GeV, weak constraints from direct detection in this mass region.
- If DM annihilate into taus via s-channel, the mediator would be radiated from taus at colliders. The production cross section is very small.
- If DM annihilate into taus via t-channel, the mediator is similar as stau in the SUSY. The mediators can be directly produced in pair at colliders.

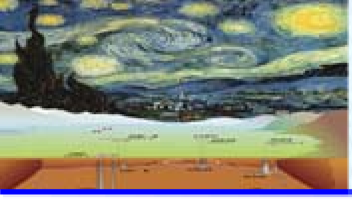
Yu, Bi, Yan, Yin, 1410.3347

Searching for mediators

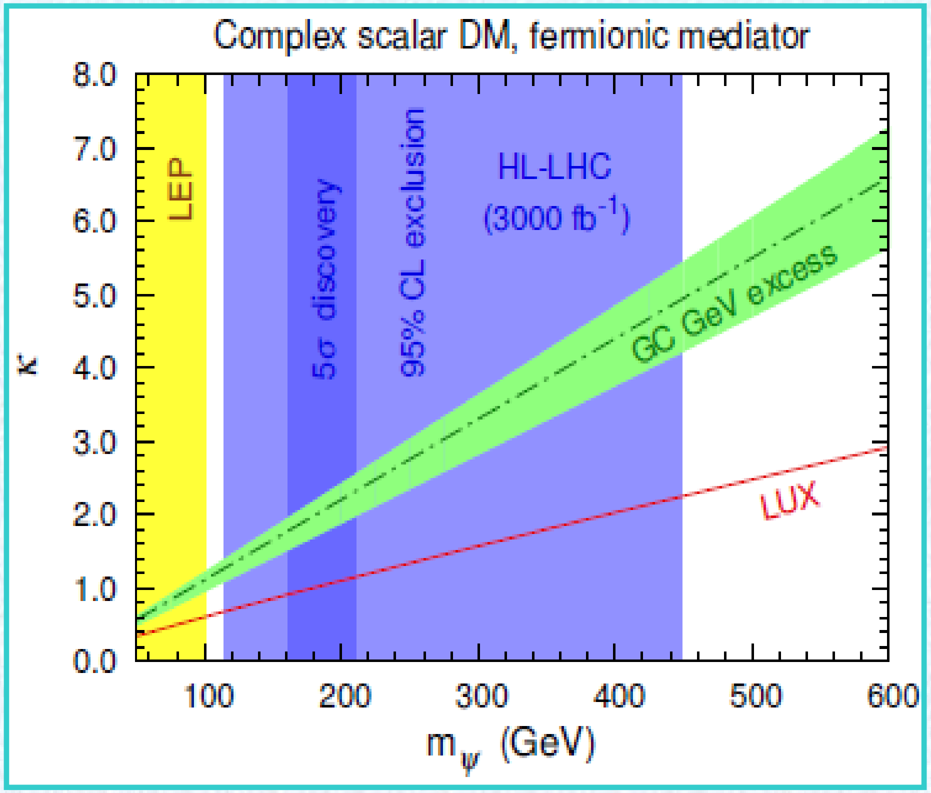


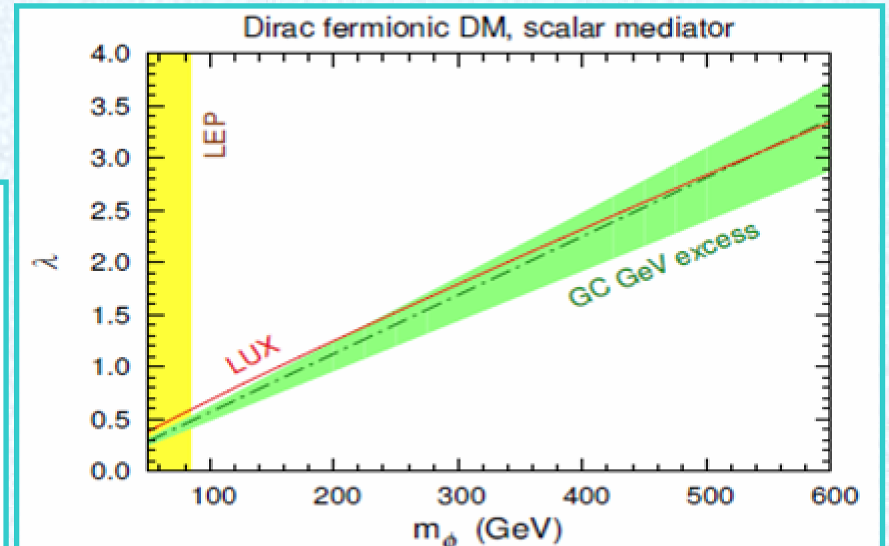


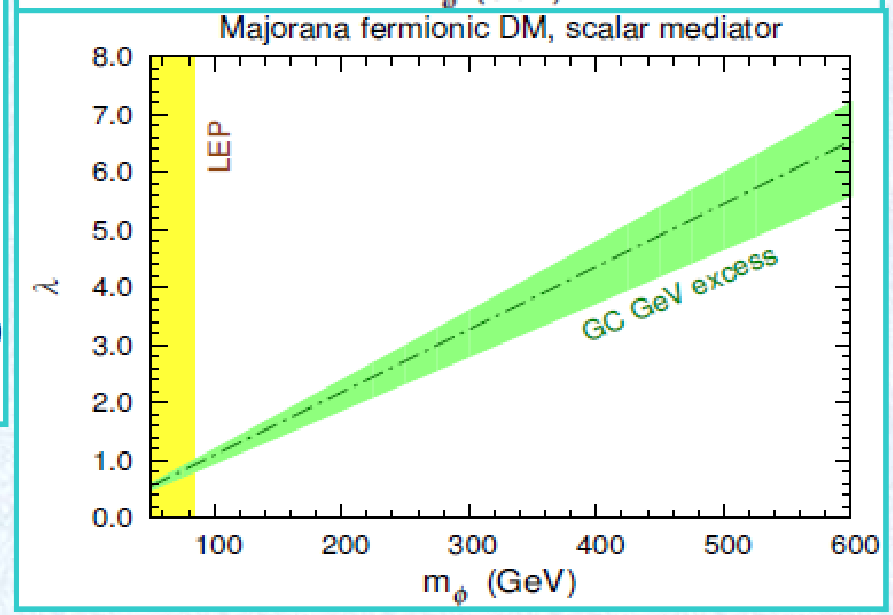
- The signal is 2τ+MET
- Consider three combinations of tau decay modes $2\tau_h$, $\tau_h\tau_l$, $2\tau_l$
- Use MT2 varible to suppress backgrounds from di-boson, top pair and W+jets. This method is adopted in LHC SUSY analyses, see ATLAS-CONF-2013-064

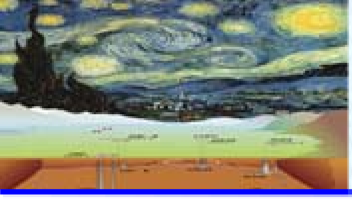


Sensitivities from direct detections and colliders









Summary

- Some direct detections provided possible evidences for light DM
- Many other direct detections only give constraints
- GeV gamma ray excess in the GC and inner Galaxy also indicates the existence of light DM
- Combining results from all the DM detections are crucial
- Tau portal DM is not stringently constrained/hard to be tested