DARK MATTER COLLOQUIUM

(MODERATOR ALEX KUSENKO)

EVIDENCE FOR DARK MATTER AND DARK MATTER CANDIDATES (MANOJ KAPLINGHAT)

DIRECT AND INDIRECT SEARCHES FOR DARK MATTER (DAN MCKINSEY AND JIM BUCKLEY)

PUTTING IT ALL TOGETHER: INFORMATION FROM COLLIDERS, SPACE AND UNDERGROUND (TIM TAIT)

DISCUSSION OF SOME TOUGH QUESTIONS (SPEAKERS ABOVE AND LIANTAO WANG)

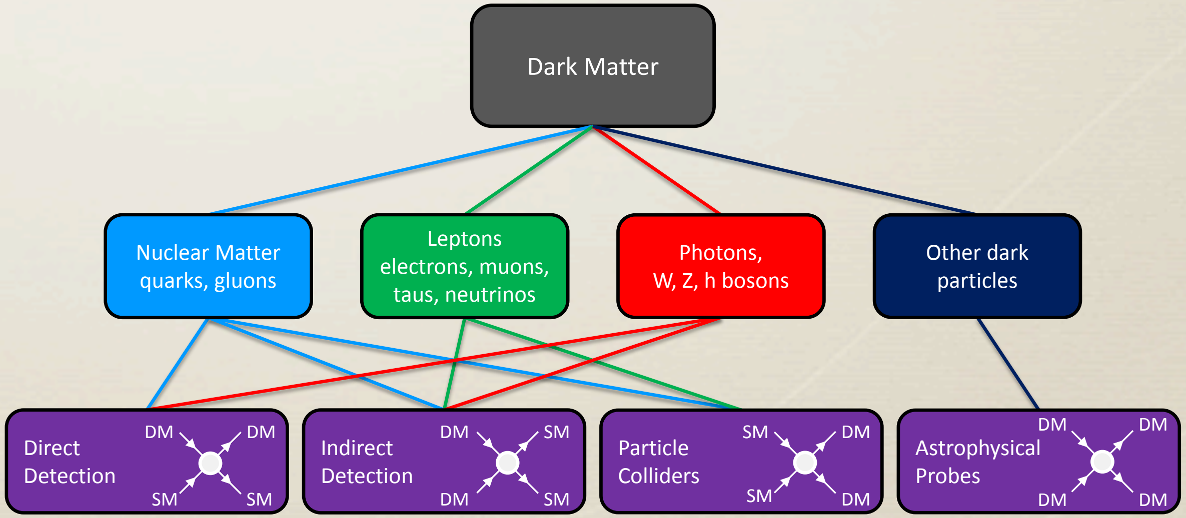
OPEN DISCUSSION

Dark matter and new physics

* Evidence from astronomy points to the presence of dark matter on kilo-parsec to horizon scales. **This evidence is summarized in the next few slides**.
* There is no stable, massive and neutral particle in the standard model that could be the dark matter.
* If dark matter is a new particle (which necessarily implies physics beyond the standard model), then the cosmological predictions match the large scale structure data beautifully.
* Models of new physics (such as Supersymmetry) typically have in their spectrum a new particle that could be the dark matter.

Dark matter and new physics

* Our knowledge of this dark sector is purely gravitational at present. In order to understand this sector we need to answer many questions, including:
  * How many particles make up the dark matter? What are their masses and spins? How do they couple to the standard model and to other dark sector particles?
* It is essential to attack the dark matter questions from multiple angles: colliders, direct searches, indirect searches and astrophysics. The short talks in this colloquium will serve to illustrate this using concrete examples.



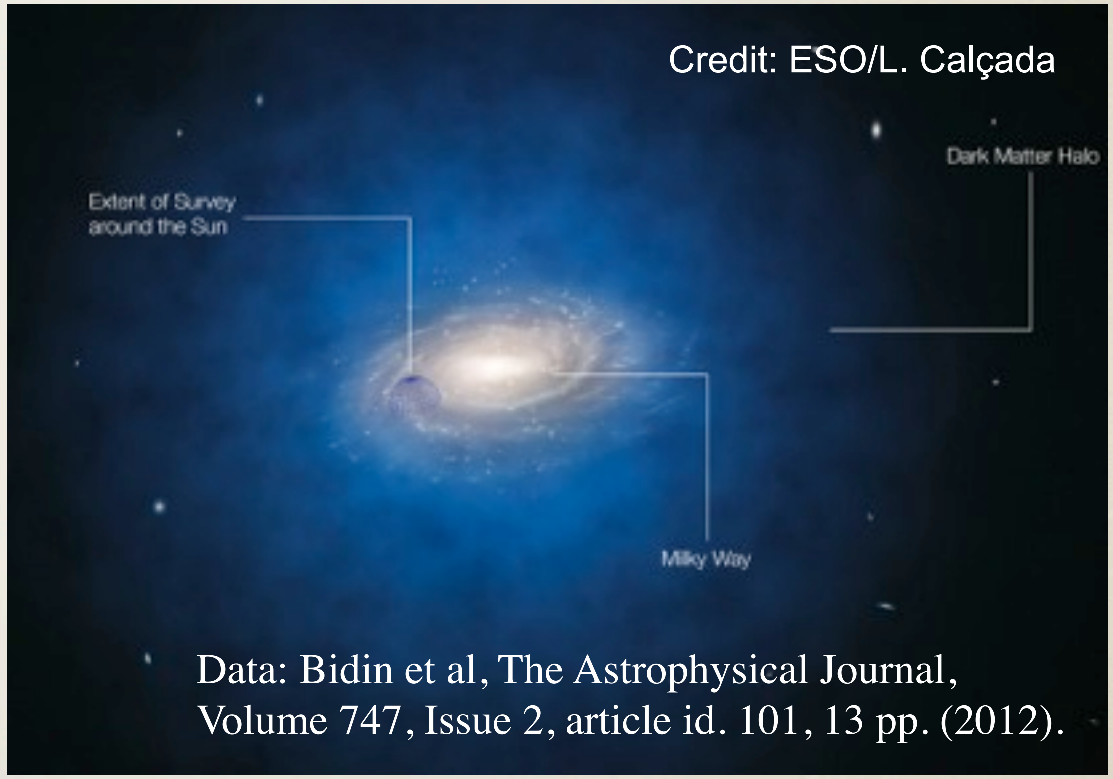
Local measurement of dark matter density

- Oort (1932) used motion of stars out of the plane of the disk to estimate the *total amount of matter, including dark matter,* locally.

J. H. Oort, Bulletin of the Astronomical Institutes of the Netherlands, Vol. 6, p.249 (1932)

- Most recent estimate gets local dark matter density 0.3+/- 0.1 Gev/cc

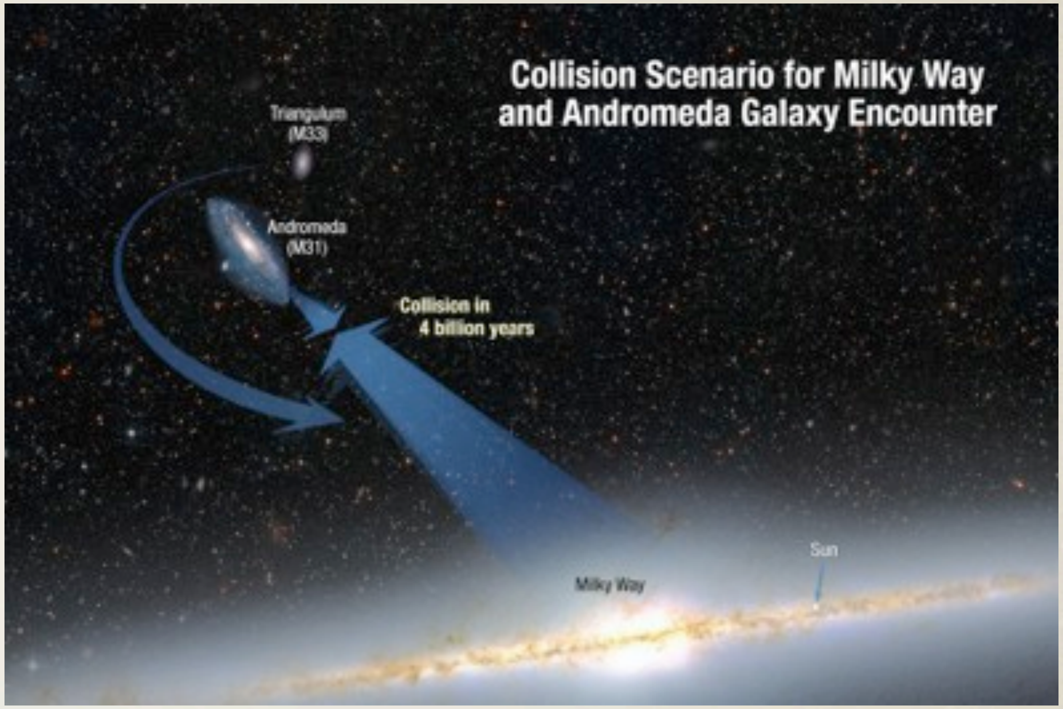
Bovy and Tremaine, The Astrophysical Journal, Volume 756, article id. 89, 6 pp. (2012)



Total mass of Andromeda and Milky Way from their relative motion

* Andromeda and Milky Way have turned around from the Hubble flow and are headed for collision. Kahn and Woltjer (1959) used this to bound the total mass of the local group from below.

Kahn and Woltjer, Astrophysical Journal, vol. 130, p.705, 1959

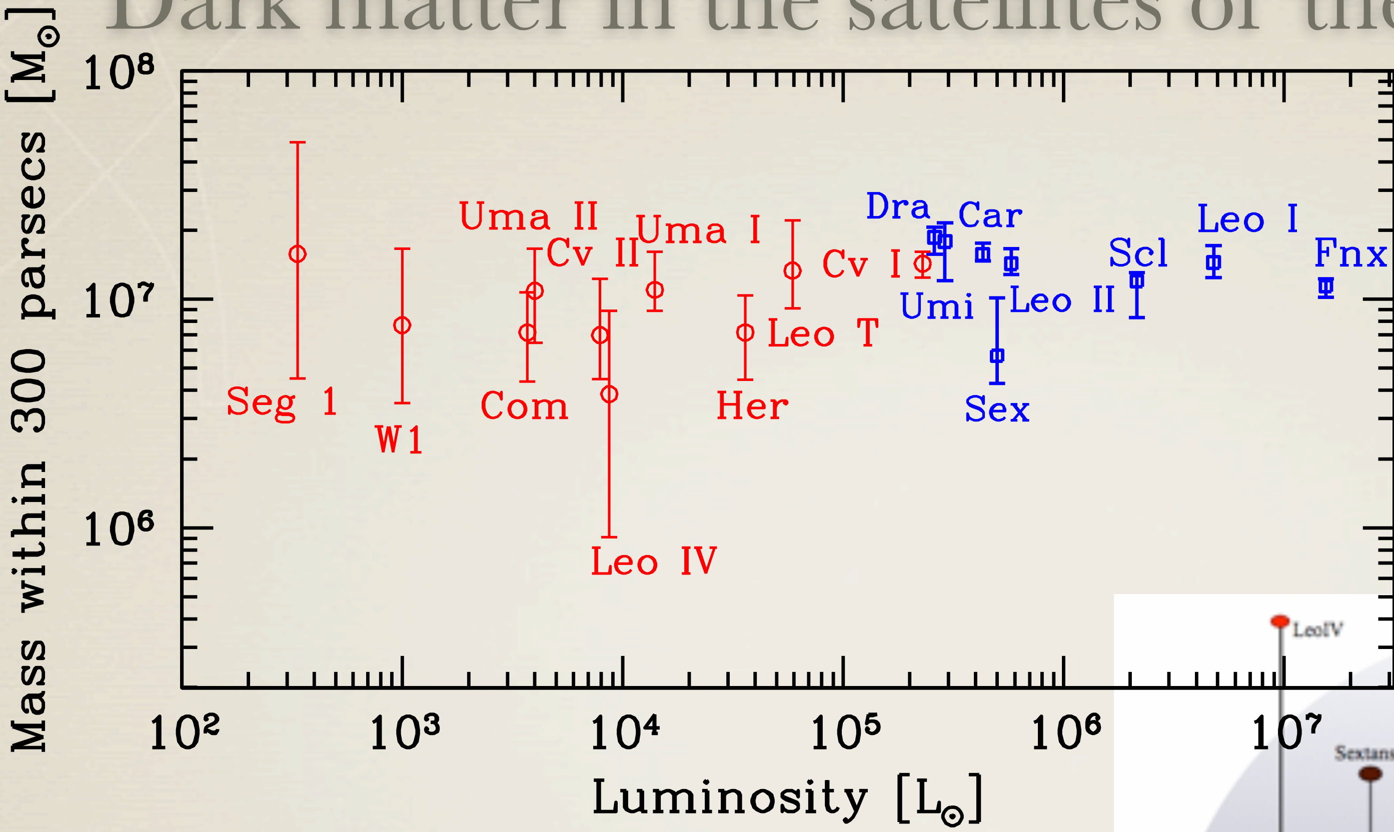


Credit: NASA; ESA; A. Feild and R. van der Marel, STScI

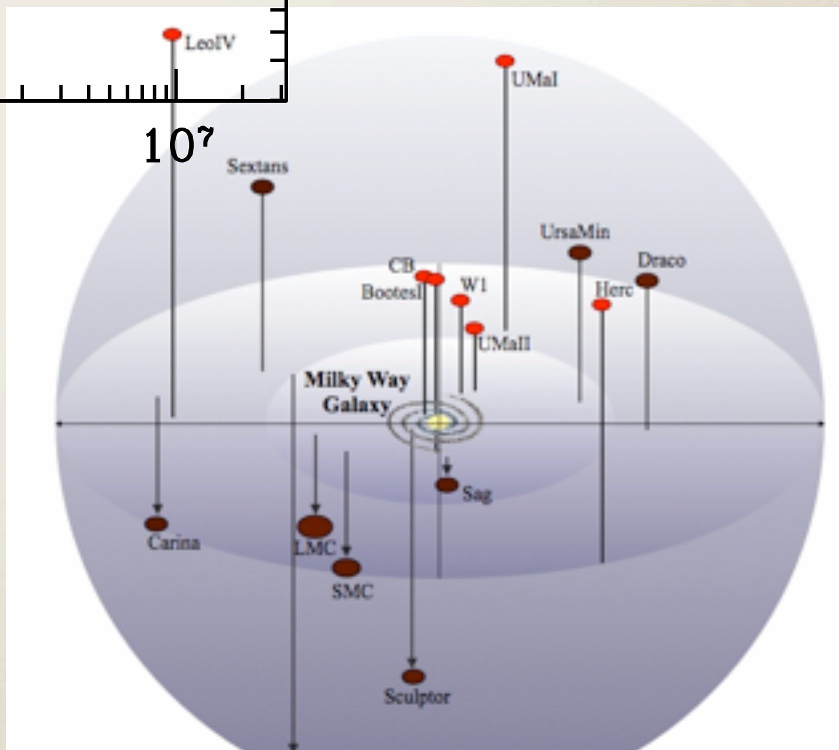
* Recent measurements show sum of virial masses of milky way and andromeda is 3.2×10^{12} M_{sun} with 20% error. Stars and gas ~10% of this mass.

Van der Marel et al, The Astrophysical Journal, Volume 753, Issue 1, article id. 8, 14 pp. (2012)

Dark matter in the satellites of the Milky Way



Strigari et al, Nature, Volume 454, pp. 1096-1097 (2008)



Bullock/Geha

Rotation speed and dark matter in galaxies

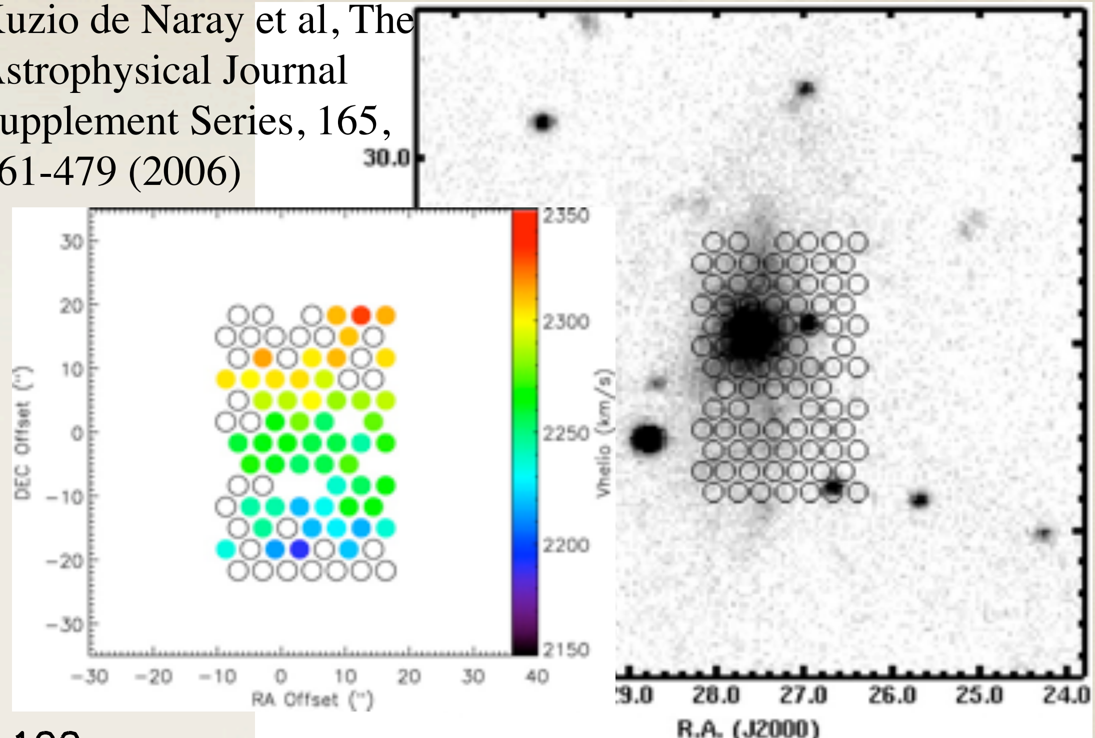
- The plateau in rotation speed as the distance from the center increases is the evidence for dark matter in spiral galaxies. The fact that spiral galaxies don't show a decline in rotation speed became widely accepted in the early 80's.

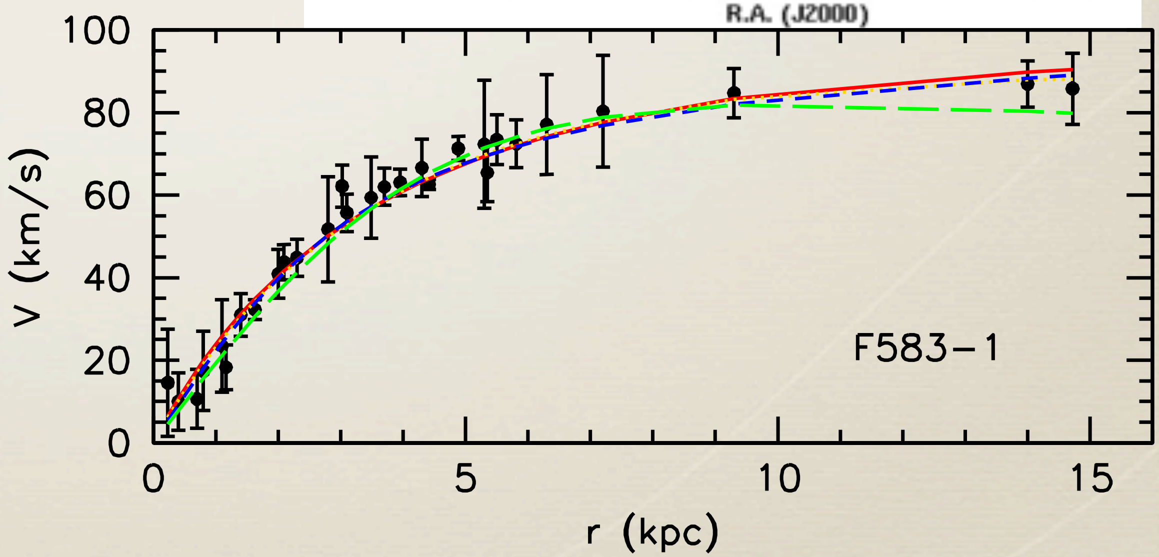
Bosma and van der Kruit, Astronomy and Astrophysics, vol. 79, Nov. 1979, p. 281-286

Rubin, Ford and Thonnard, Astrophysical Journal, vol. 238, June 1, 1980, p. 471-487

- To the right, velocity field and rotation curve of F583-1; this galaxy is 32 Mpc away and has low surface brightness (dark matter dominates).

Kuzio de Naray et al, The Astrophysical Journal Supplement Series, 165, 461-479 (2006)





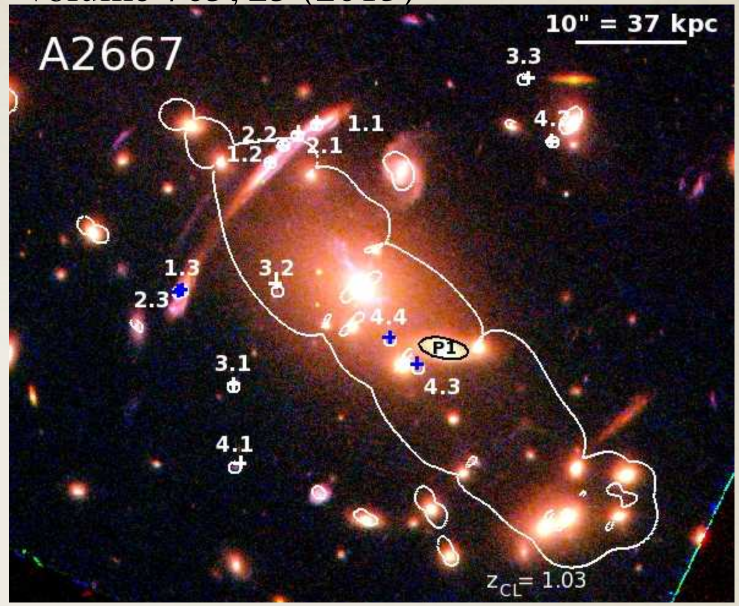
Kuzio de Naray et al, The Astrophysical Journal Letters, Volume 710, L161-L166 (2010)

Dark matter in clusters of galaxies

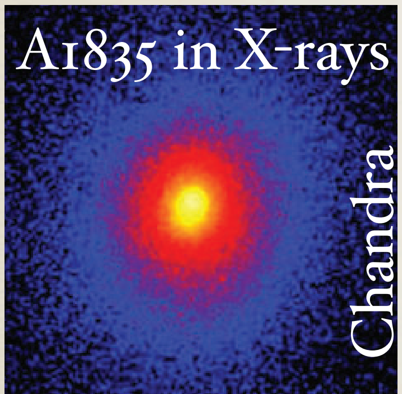
Zwicky (1937) used the velocity dispersion of galaxies in Coma to infer the dark matter

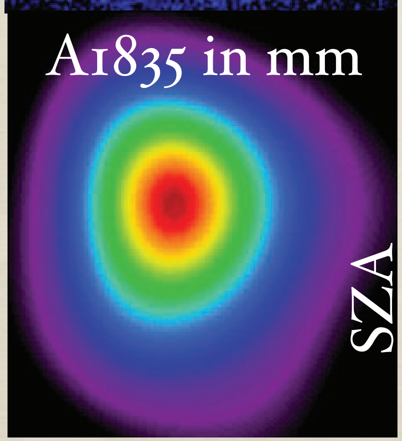
Zwicky, Astrophysical Journal, vol. 86, p.217 (1937)

Newman et al, The Astrophysical Journal, Volume 765, 25 (2013)



Lensing measures total mass.



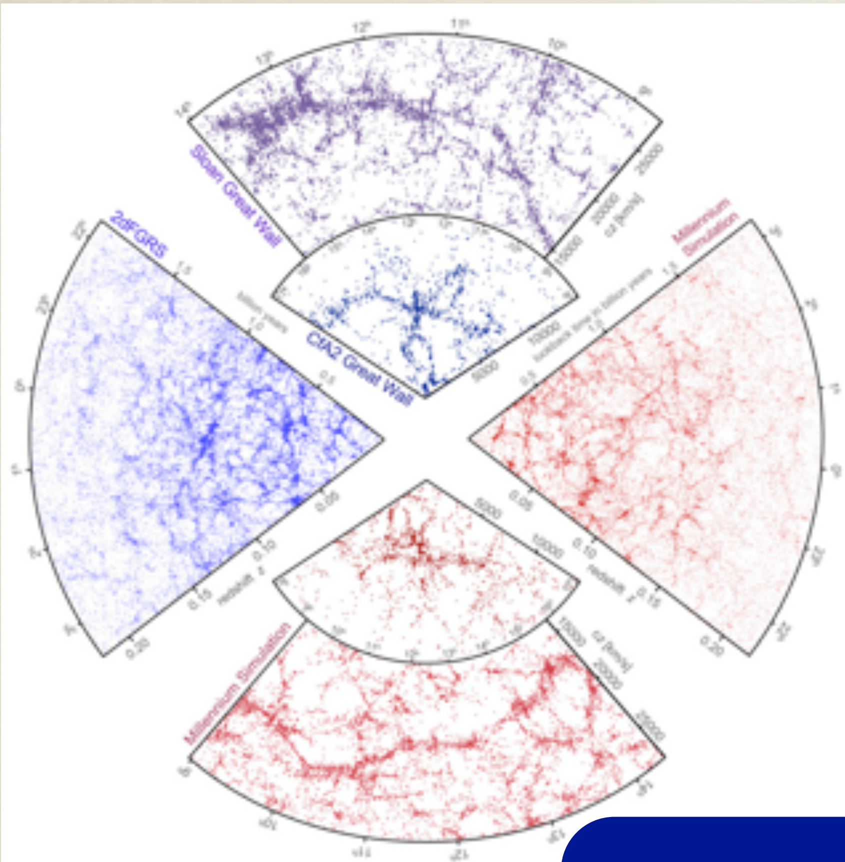


Clusters have a lot of gas, which can be inferred from X-ray and mm wavelength measurements. This allows us to measure the gravitational potential and hence the total mass as well as gas mass.

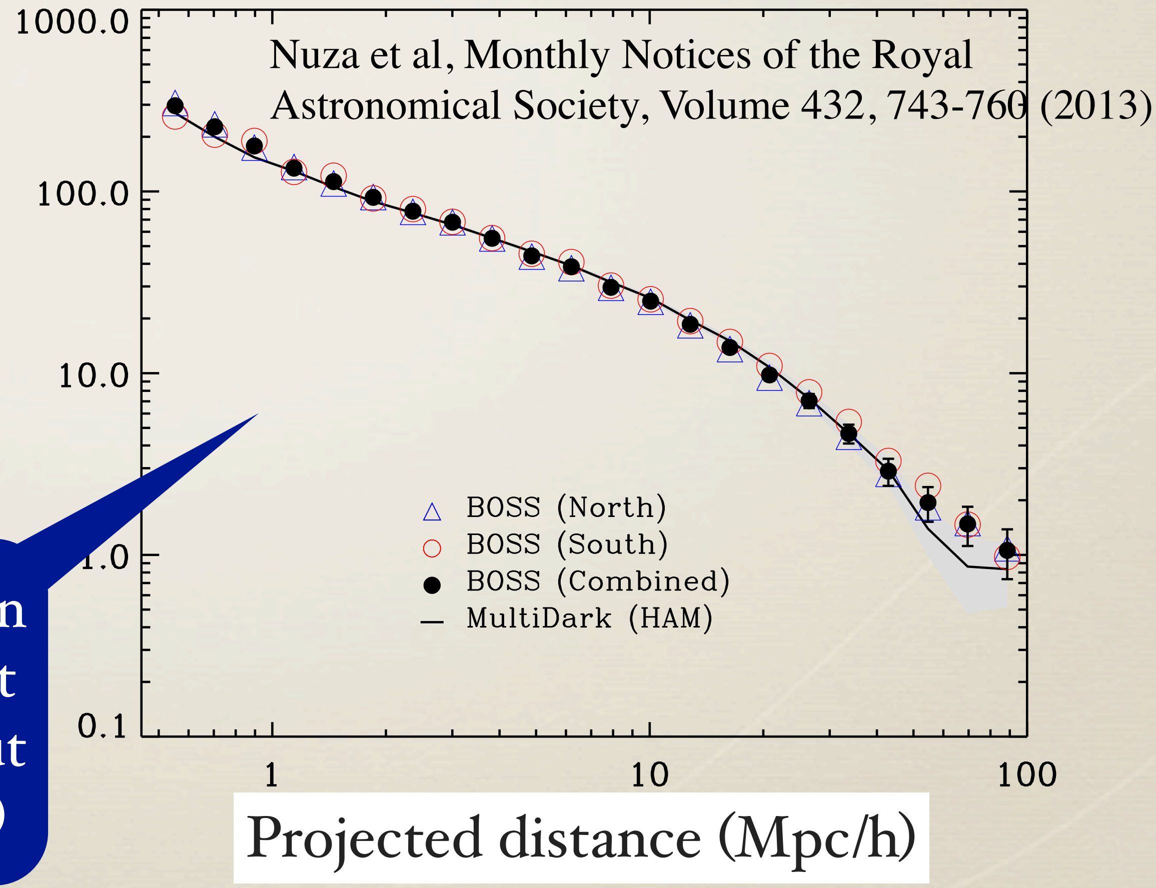
Markevitch et al, Clowe et al. (2004)

Cold dark matter on large scales

Blue: data (SDSS, 2dFGRS)
Red: Millennium simulation



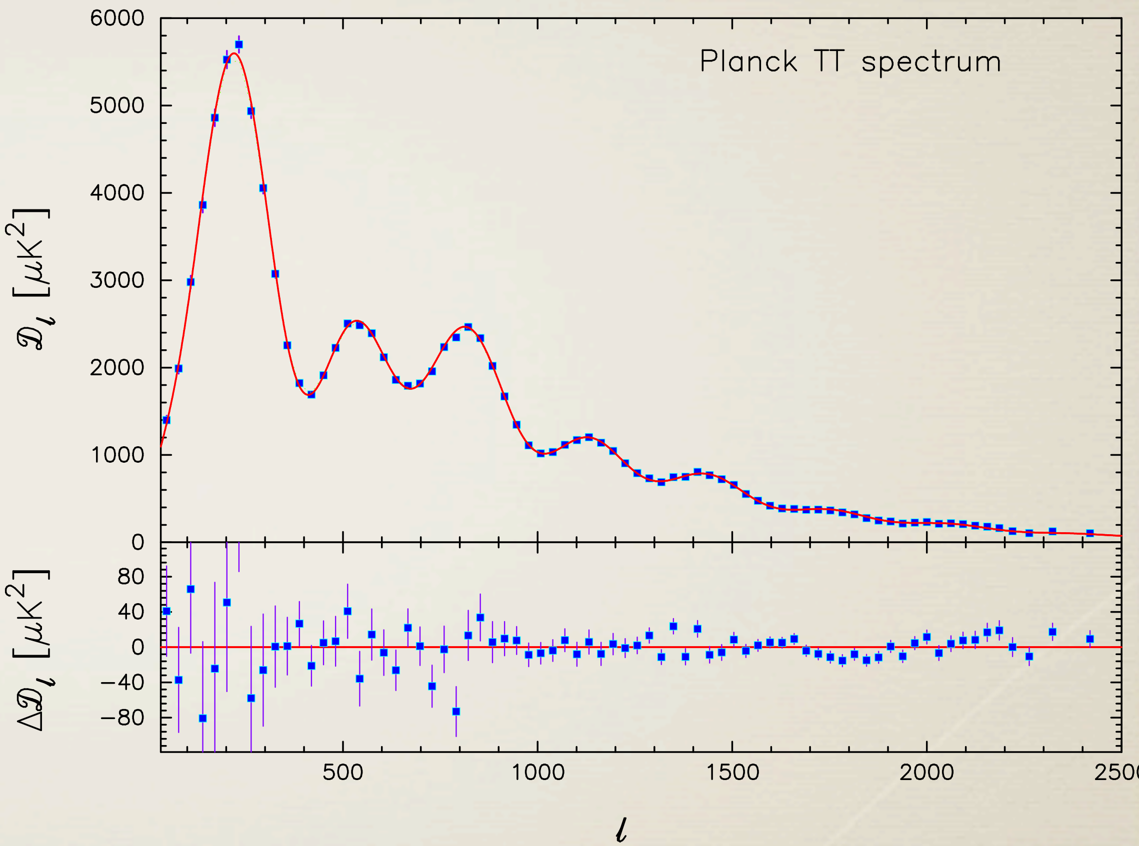
Great match to data on cosmological scales (CMB) down to scales of order Mega-parsec (Galaxies)



Correlation function at z~0.5 (about 5 Gyr ago)

Cosmic Microwave Background and the cosmological density of dark matter

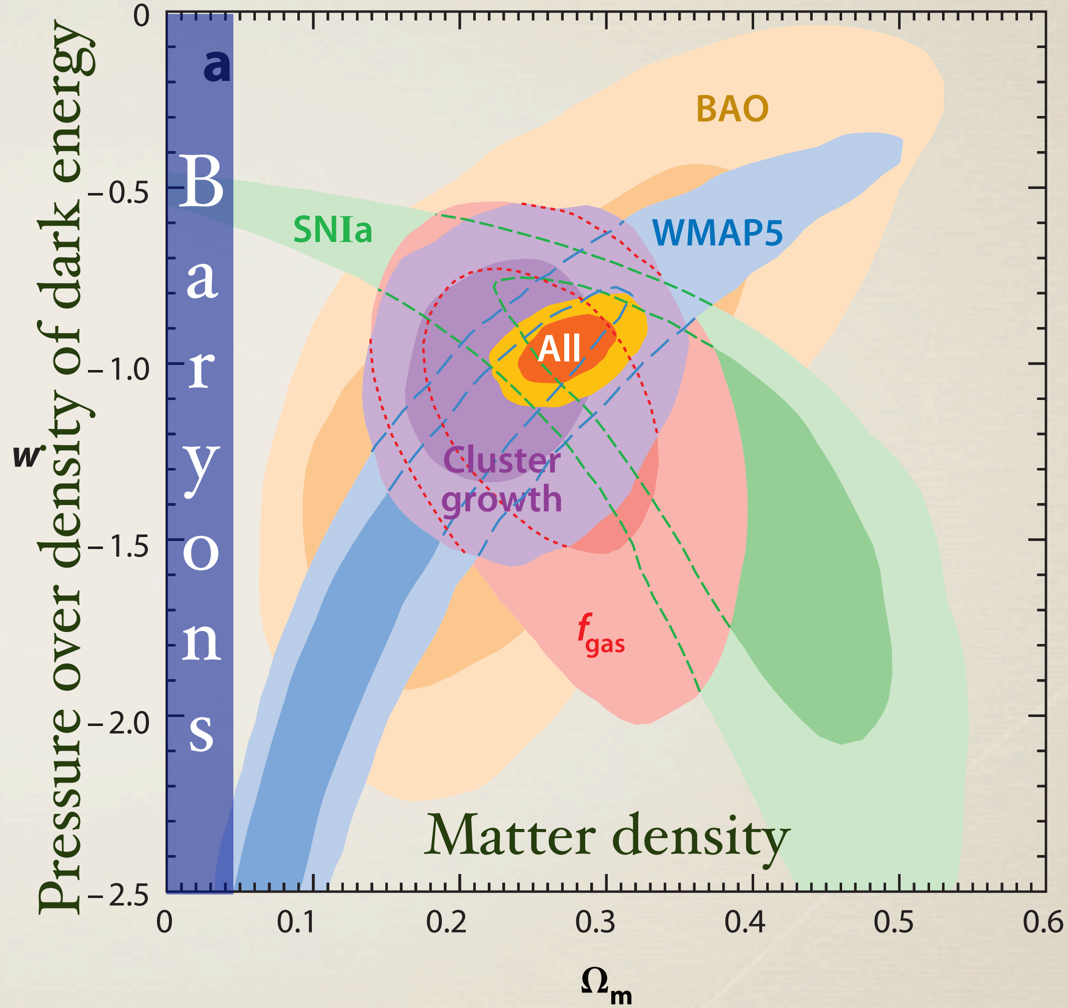
* Lower matter density leads to larger *change* of the gravitational potential wells, which *boosts* peak heights.
* *Higher* baryon density *increases* odd peak heights.
* $\Omega_{DarkMatter}h^2$=0.12 to about 2% where expansion rate today is 100h km/s/Mpc.



Planck collaboration, eprint arXiv:1303.5076

Consistency of different cosmological measures of the matter density

* The different measures of matter density from growth of clusters, fraction of gas in clusters, CMB, Supernova distances and Baryon acoustic oscillation all agree on a value for the matter density that is close to 25% of the critical density of the universe, which is about 6 times the density in baryons.



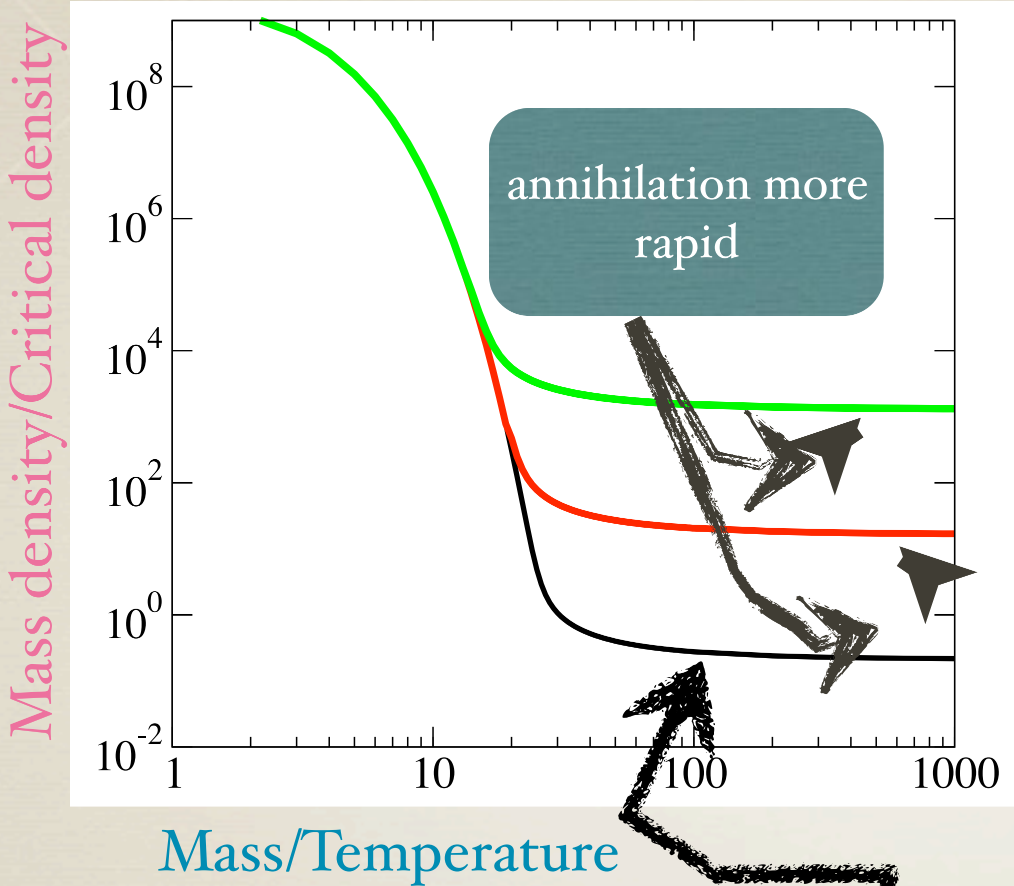
Allen et al, Annual Review of Astronomy and Astrophysics, vol. 49, pp. 409-470 (2011)

Mantz et al, Monthly Notices of the Royal Astronomical Society, Volume 406, Issue 3, pp. 1759-1772 (2010)

Motivations to search for a dark matter particle

- Observed large-scale structure reproduced by a model in which all of the dark matter is a cold collision-less particle.
- Models of new physics (such as Supersymmetry) have in their spectrum a new particle that could be the dark matter.
  - These dark matter candidates can be produced in quantities that are comparable to the measured cosmological density of dark matter. **We consider a few such examples next.**

Production through early universe freeze-out



$$\langle \sigma_{\rm ann} v \rangle = \pi \left(\frac{\alpha}{0.025}\right)^2 \left(\frac{\rm TeV}{m_X}\right)^2 2.3 \times 10^{-26} \frac{\rm cm^3}{s}$$

Example: Mass ~ 300 GeV,
Freeze out ~10 GeV (10 nano-second)

Candidates

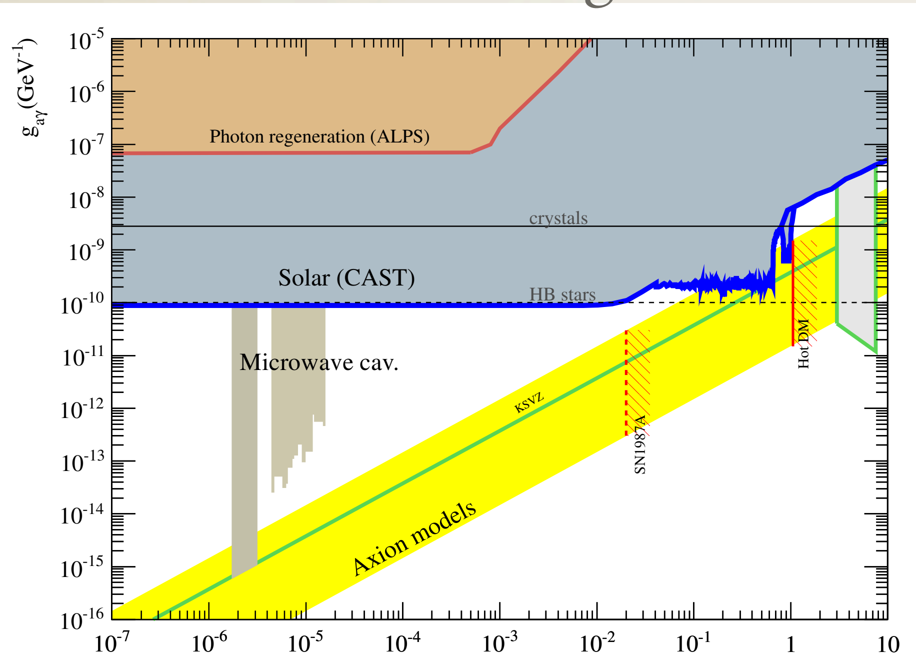
WIMP (SUSY neutralino, KK dark matter, ...): masses typically weak-scale (~100 GeV and larger) but could be smaller in non-minimal versions of SUSY.

WIMPless (LSP in hidden sector): masses could be much lower than weak-scale.

Phenomenological models with a light force carrier (hidden sector dark matter): masses in GeV-TeV range

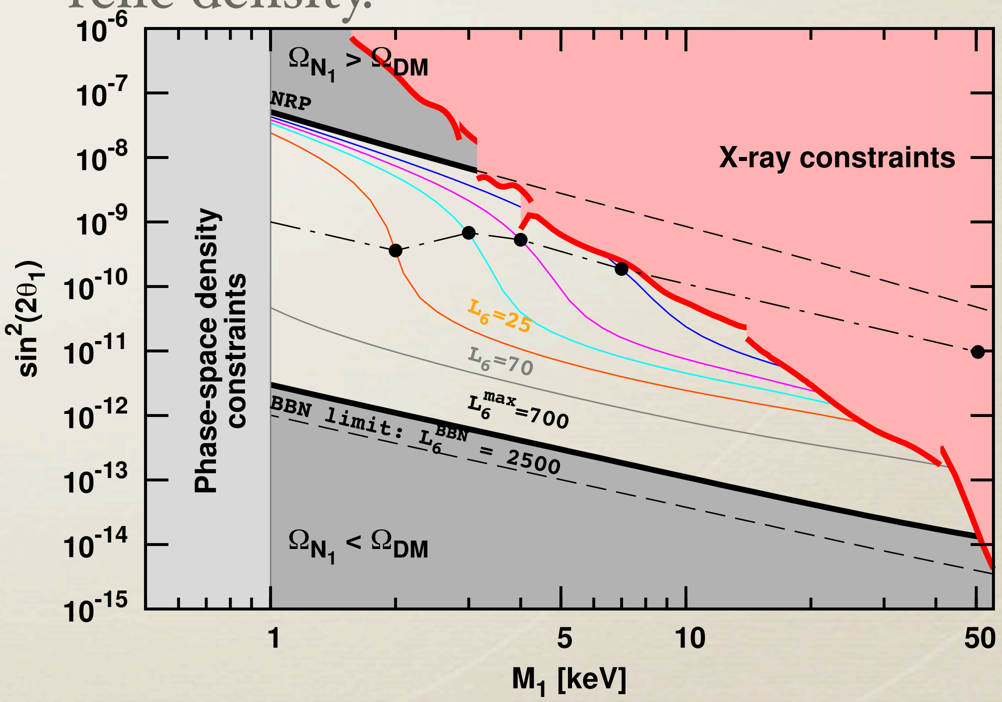
Production through non-thermal processes

Axions are pseudo-Goldstone bosons of a spontaneously broken global symmetry. A well-motivated example is the QCD axion in the Peccei-Quinn solution to the **strong CP problem**. It could be produced via a mis-alignment mechanism and could be all of the dark matter. It has been suggested that axions could form Bose-Einstein condensates in galaxies.



CAST collaboration, eprint arXiv:1209.6347

Right-handed or **sterile neutrinos** are motivated by the observation of non-zero neutrino masses, and for certain range of masses (1-100 keV), they may be dark matter. In a class of models (below), the mixing with active neutrinos and a significant lepton asymmetry determines the relic density.



Boyarsky et al, Ann.Rev.Nucl.Part.Sci.59:191-214,2009

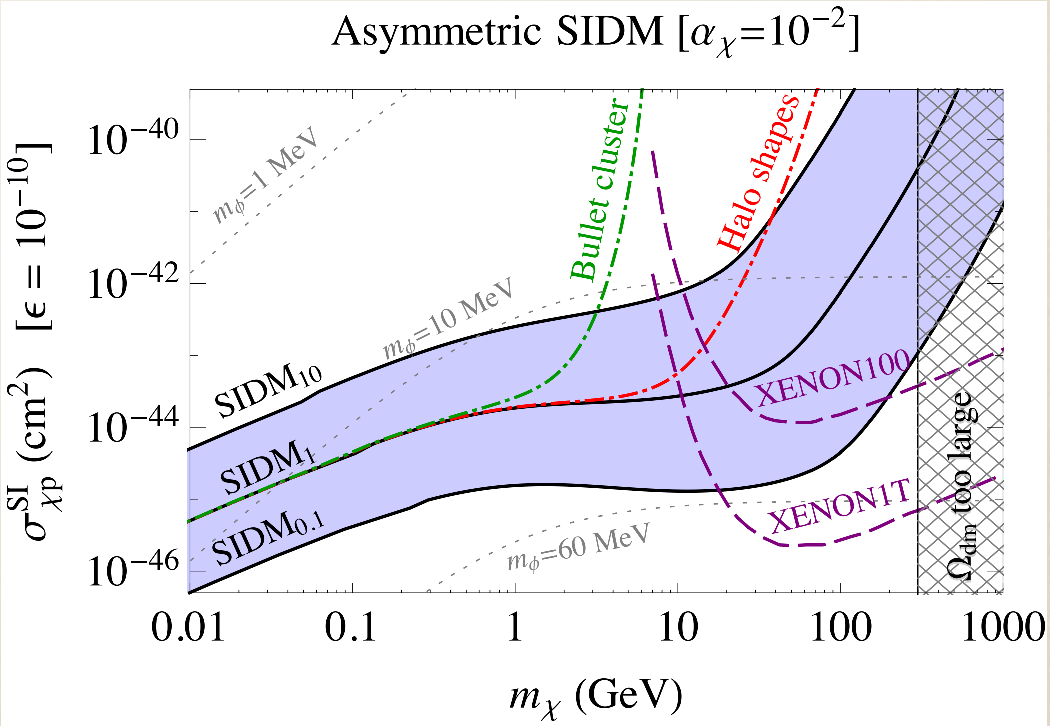
Production due to dark matter asymmetry

Asymmetric dark matter posits that the abundance of dark matter is set by the particle-antiparticle asymmetry in the dark sector.

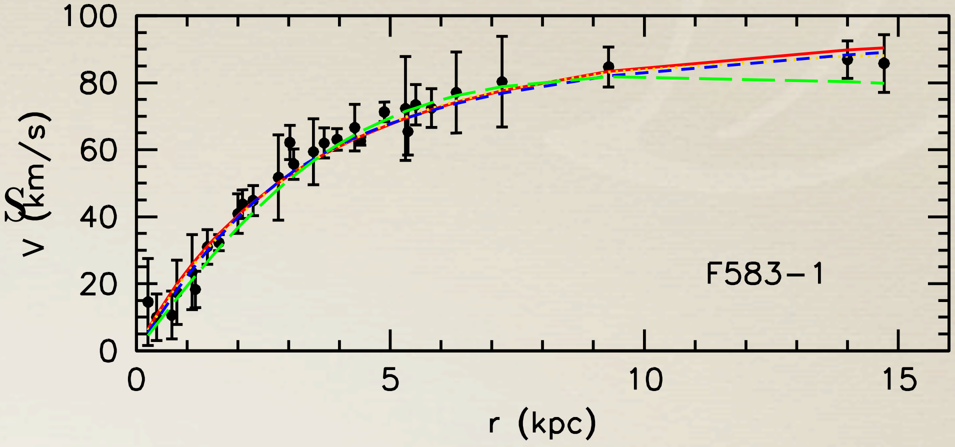
Annihilation cross section must be larger than the thermal relic cross section.

If the asymmetry in baryons is linked to the asymmetry in dark matter, then the dark matter masses must be ~ 10 GeV.

In simple models of asymmetric dark matter, there are fairly generic predictions for the scattering cross section with nucleons that also allow for dark matter self-interaction cross section which affects galaxies on observable scales.



Tough Question CF17: Is cold non-interacting dark matter in good agreement with observations of structure on all scales?



There are many puzzling aspects of structure formation on galactic and sub-galactic scales. Among these puzzles, one that is often discussed is the core-cusp issue or the related issue of densities that are lower than simple predictions for a **variety of galaxies**. An example is shown to the right.

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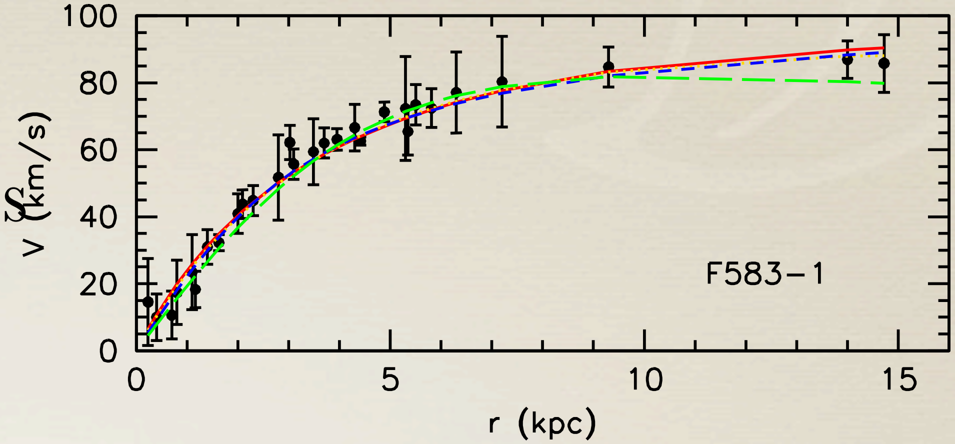

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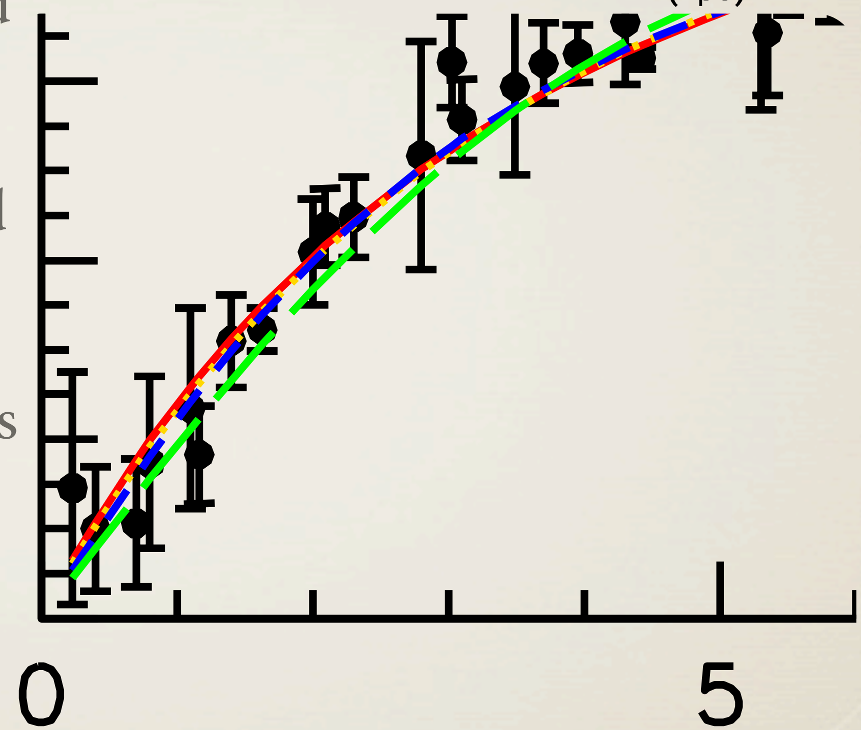

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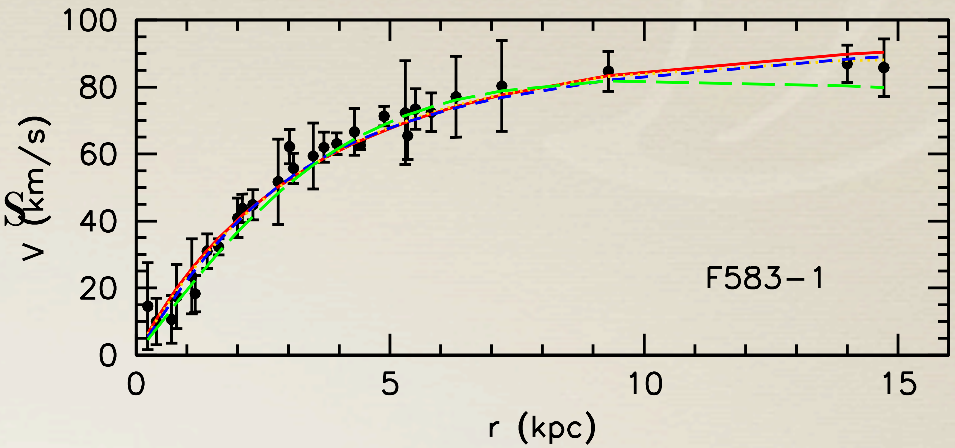

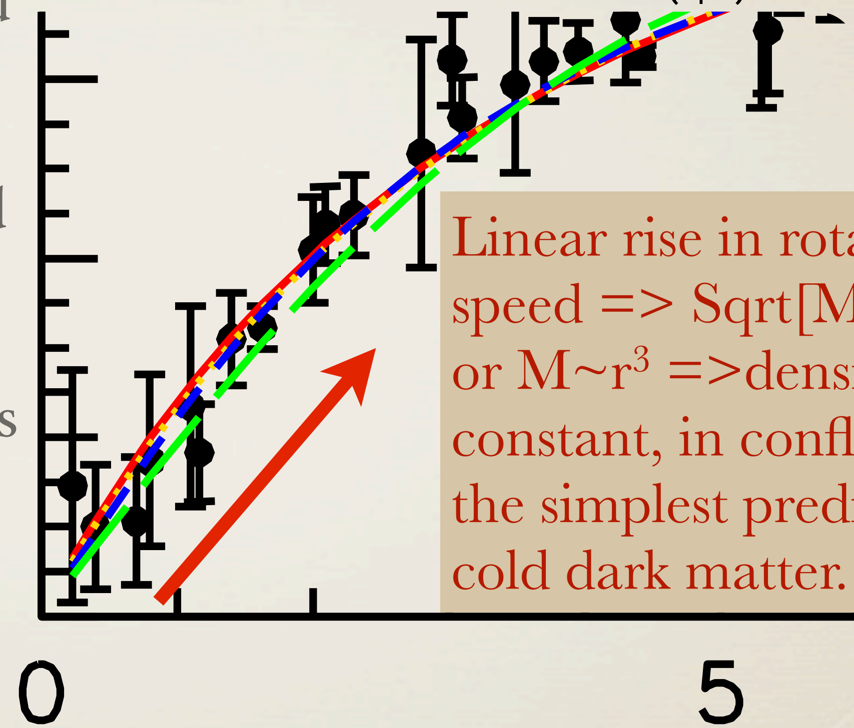

Linear rise in rotation speed => Sqrt[M/R] ~ r or $M \sim r^3$ =>density is constant, in conflict with the simplest predictions of cold dark matter.

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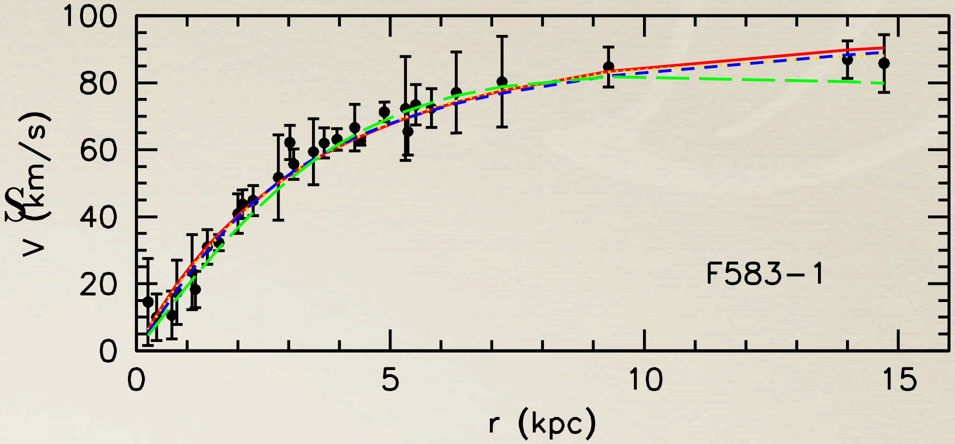

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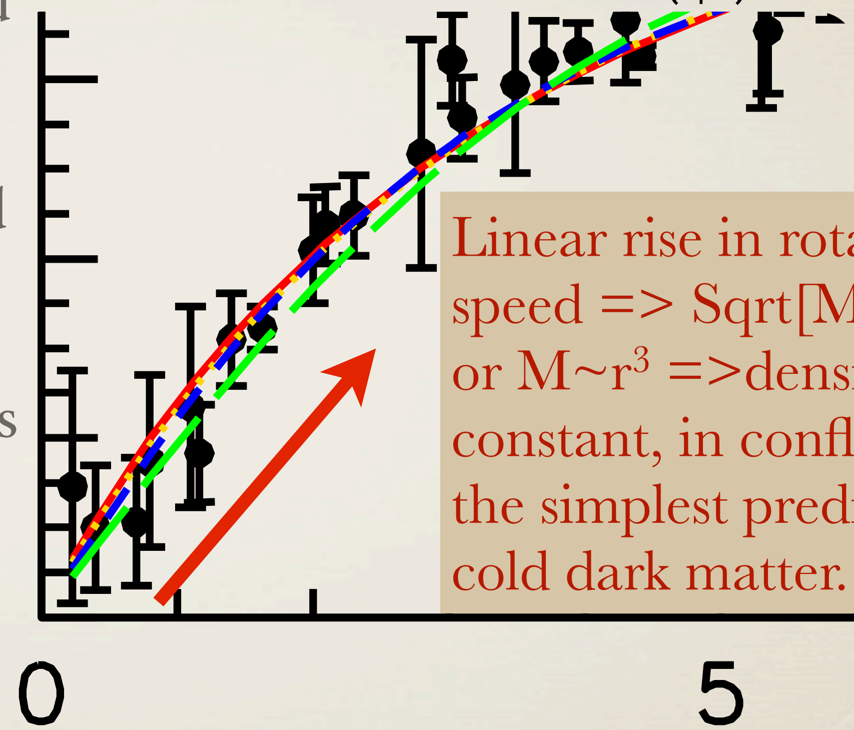
These puzzles provide good motivation for considering non-WIMP dark matter candidates.



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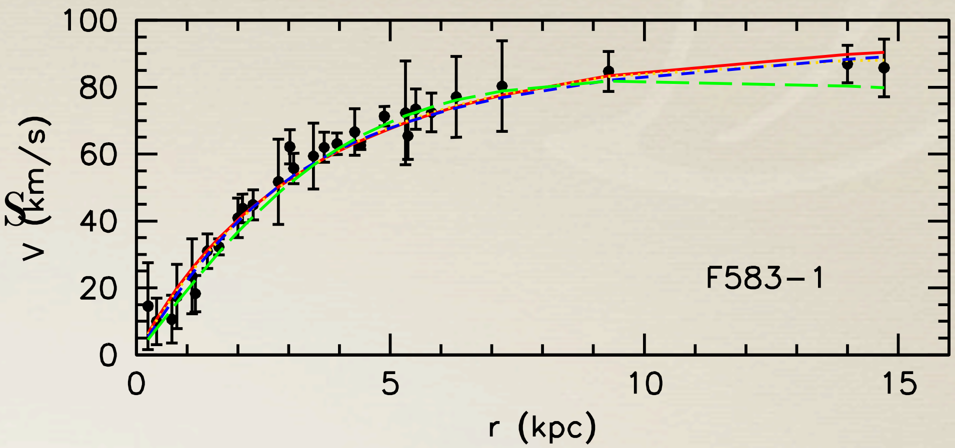

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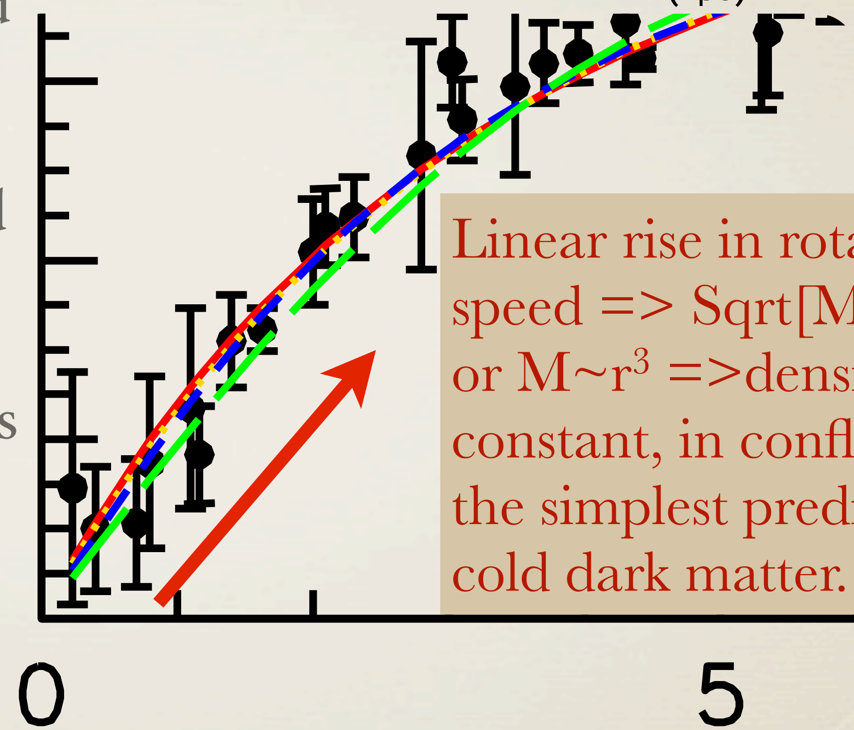

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In the last couple of years, cosmological simulations including baryons have reached the point where they can start to address this issue. Continued advances in computing are essential to this area. *Keep your ears open for progress on this front of galactic puzzles.*

Tough Question CF16: What are the prospects for determining the temperature of dark matter or self-interactions in the dark sector from astrophysics?

WIMP and axion dark matter are categorized as **cold non-interacting** dark matter.

The dominant form of dark matter could be **warm** (e.g., sterile neutrino, weak-scale gravitinos)

The dominant form of dark matter could have **large self-interactions** (e.g., hidden sector with light force carrier, asymmetric dark matter).

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Prospects

In the last few years, there has been great progress in simulating realistic galaxies with star formation. There has also been an explosion of high quality, high resolution data capable of peering closer than ever before into the centers of the least luminous galaxies to the brightest clusters of galaxies.

The puzzles have not vanished and it is reasonable to hope that further progress in numerical simulations and observations will sharpen or finally solve these puzzles.

If the dominant form of dark matter is warm or strongly self-interacting, does this mean that the SUSY framework is wrong?

No.

However, $\Omega_{\text{Neutralino}} << \Omega_{\text{Observed DM}}$, which is entirely natural. SUSY provides motivation for weak-scale cross sections but there is no strong argument to assert that $\Omega_{\text{Neutralino}} = \Omega_{\text{Observed DM}}$.

It should also be noted that examples of warm or self-interacting dark matter within the SUSY framework exist.

Direct Dark Matter Detection

Dan McKinsey
Yale University
July 29, 2013

WIMP Direct Detection

Look for anomalous nuclear recoils in a low-background detector.

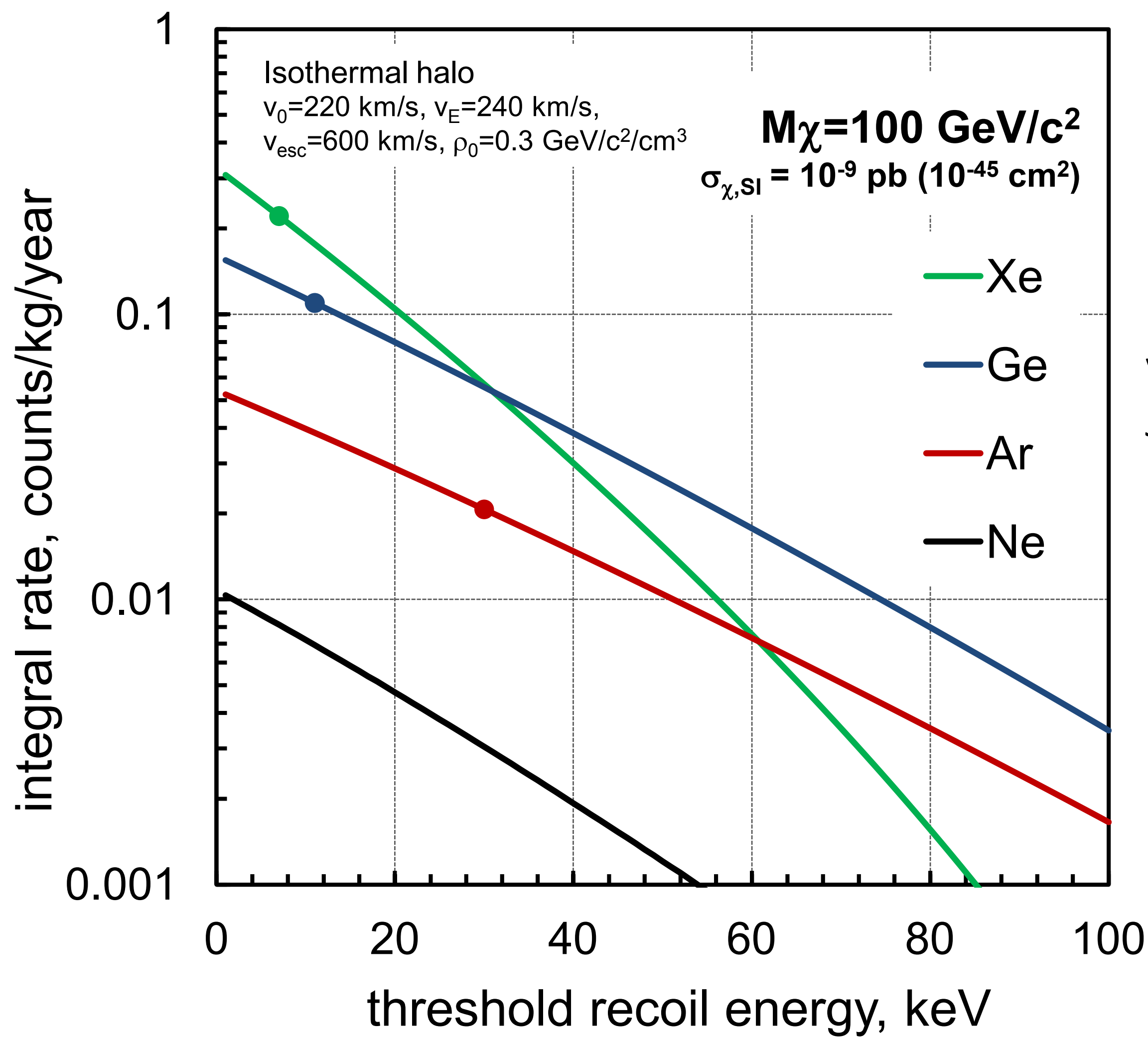
$R = N \rho \sigma \langle v \rangle$

From $\langle v \rangle$ = 220 km/s, get order of 10 keV deposited

Requirements:

- Low radioactivity
- Low energy threshold
- Gamma ray rejection
- Scalability

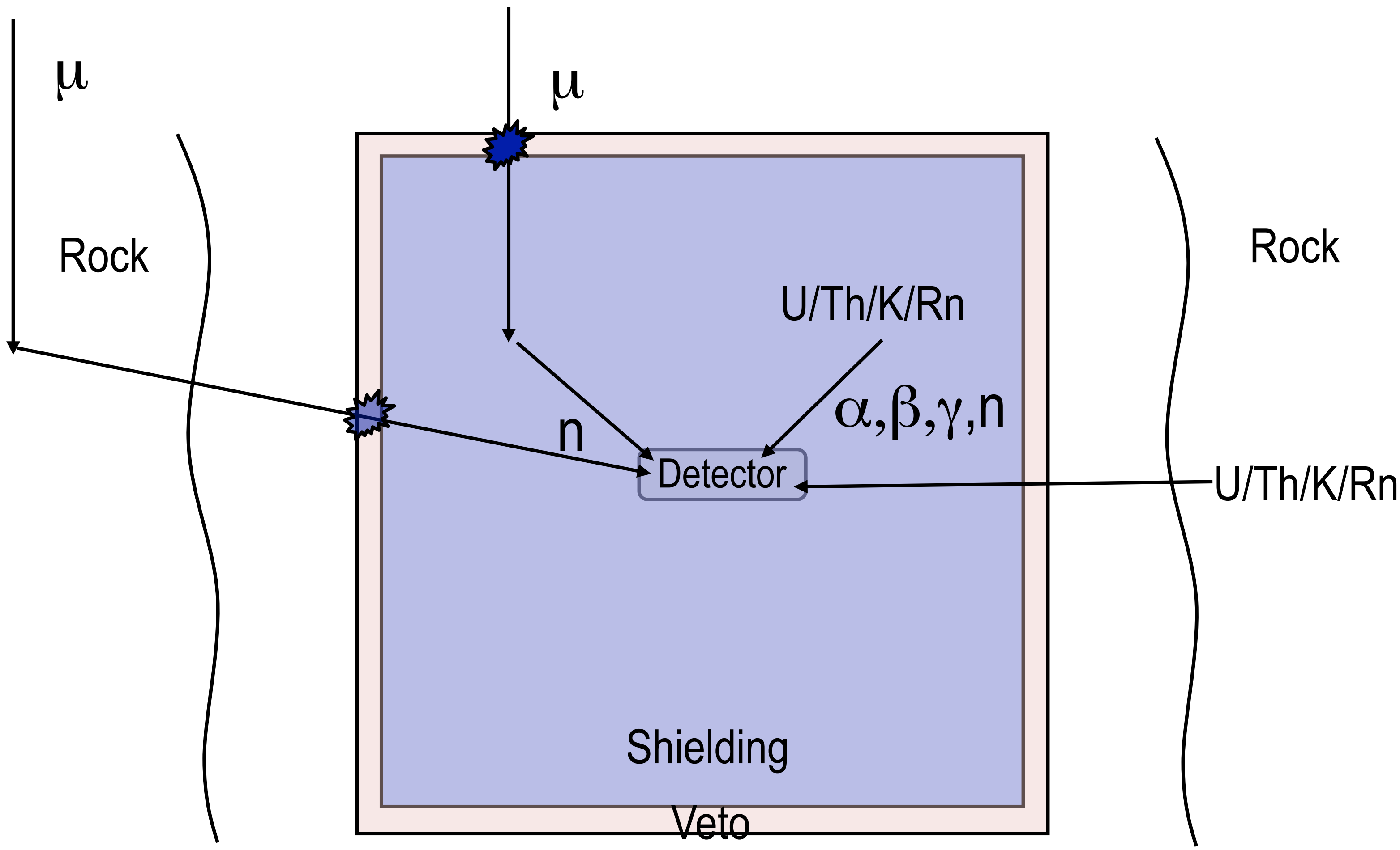
Predicted nuclear recoil spectra from WIMP-nucleus scattering



V. Chepel and H. Araujo, JINST 8, R04001 (2013).

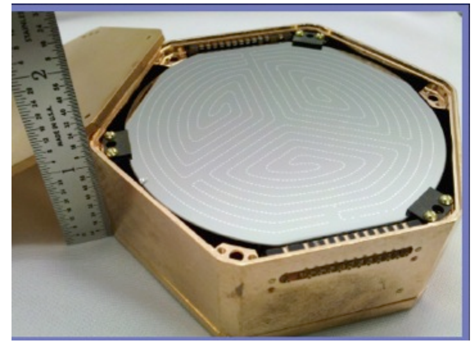
Background sources and shielding in a typical dark matter experiment.

Need sensitivity of better than 1 event/100kg/year

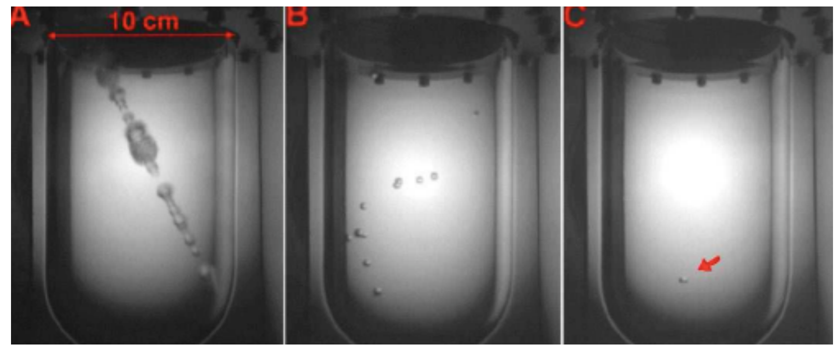


WIMP Direct Detection Technologies

- Cryogenic Ge detectors (CDMS, Edelweiss, CRESST): Excellent background rejection, low threshold and good energy resolution.



- Threshold detectors (COUPP, SIMPLE, PICASSO): Ultimate electron recoil rejection, inexpensive, easy to change target material for both SI and SD sensitivity.

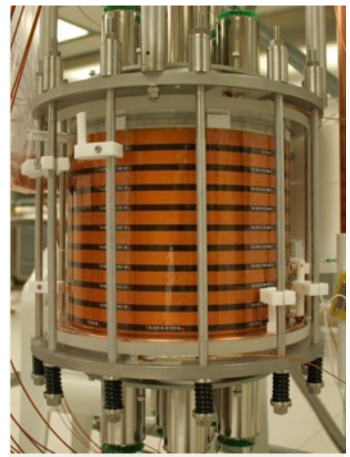


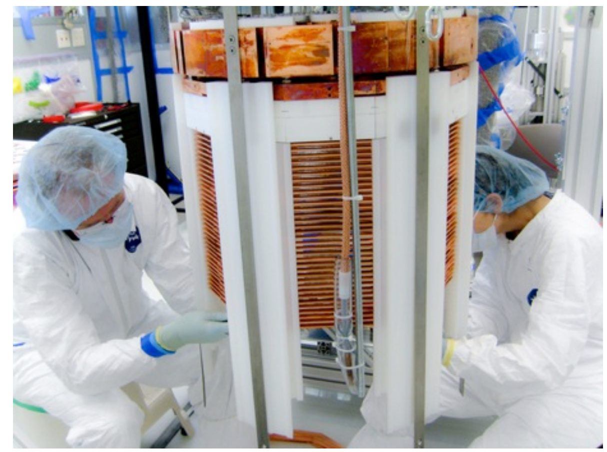
- Single-phase LAr, LXe (DEAP, CLEAN, XMASS): Simple and relatively inexpensive per tonne, pulse-shape discrimination and self-shielding.

WIMP Direct Detection Technologies

- Dual-phase Ar (DarkSide, ArDM): Excellent electron recoil rejection, position resolution.

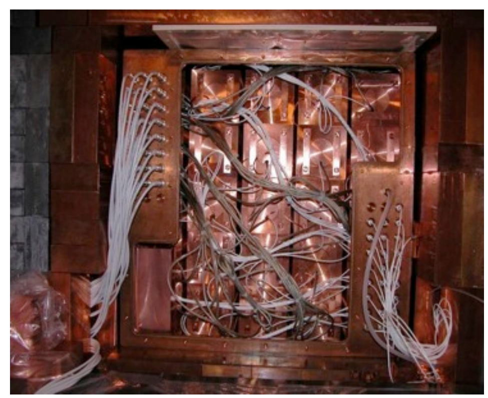
- Dual-phase Xe (XENON, LUX, Panda-X): Suitable target for both SI and SD, low energy threshold, excellent position resolution, self-shielding.

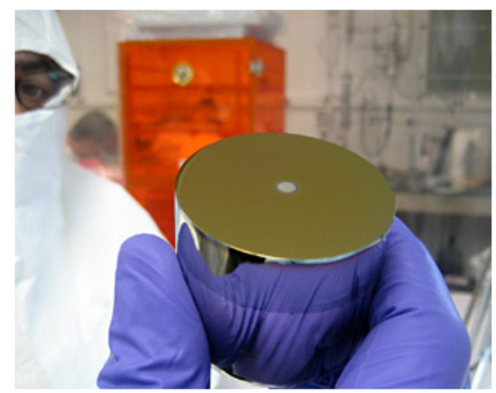




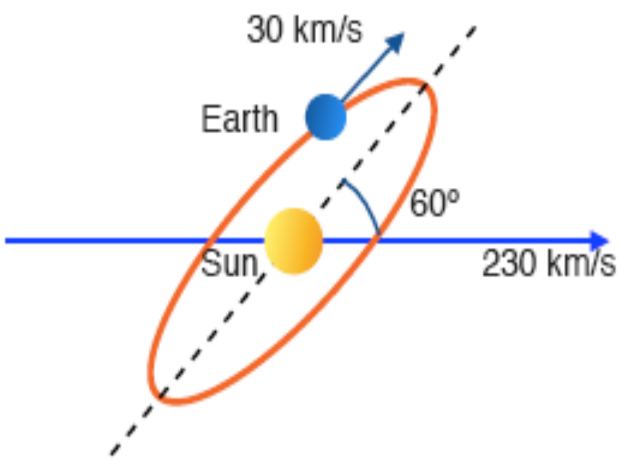
- Scintillating crystals (DAMA/LIBRA, KIMS): Annual modulation with large target mass.

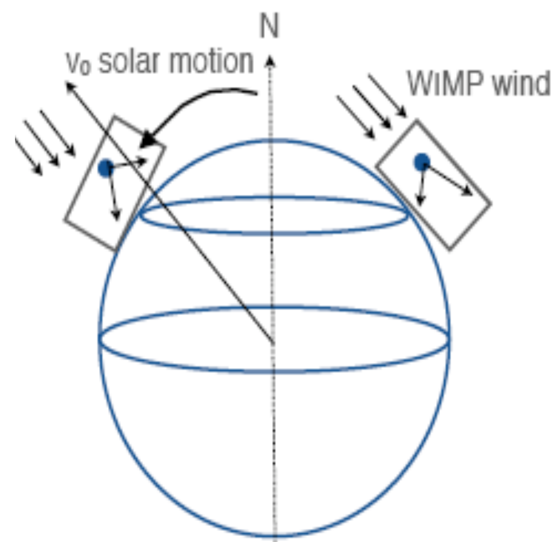
- Ionization detectors (CoGeNT, DAMIC): Very low energy threshold, good energy resolution.

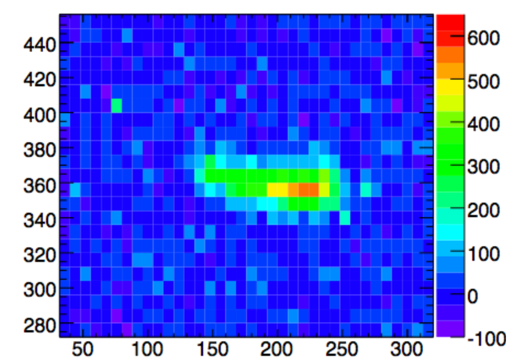




WIMP Directional Detectors
(DRIFT, DMTPC, D^3, MIMAC, NEWAGE, NEXT/Osprey)

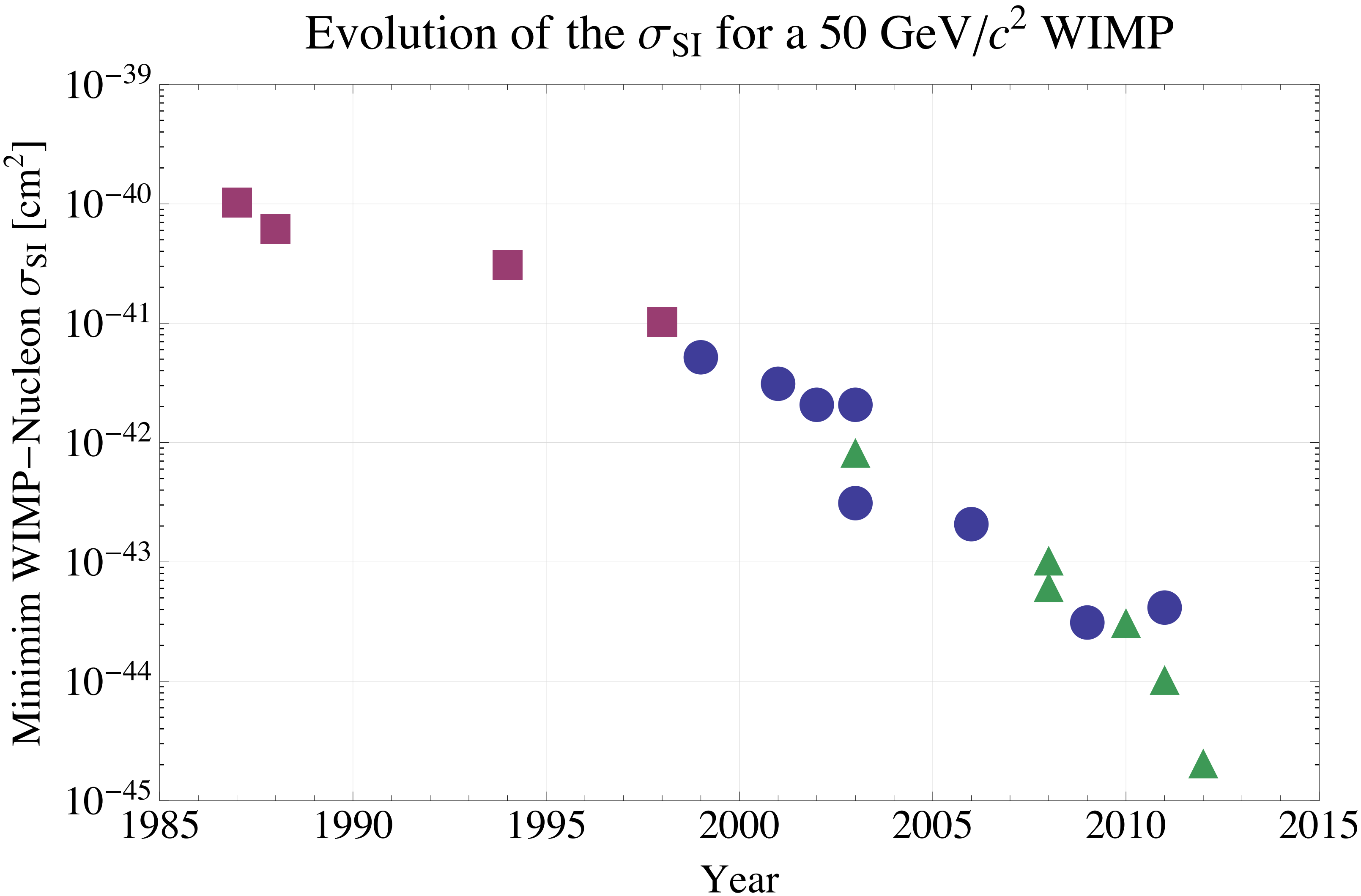




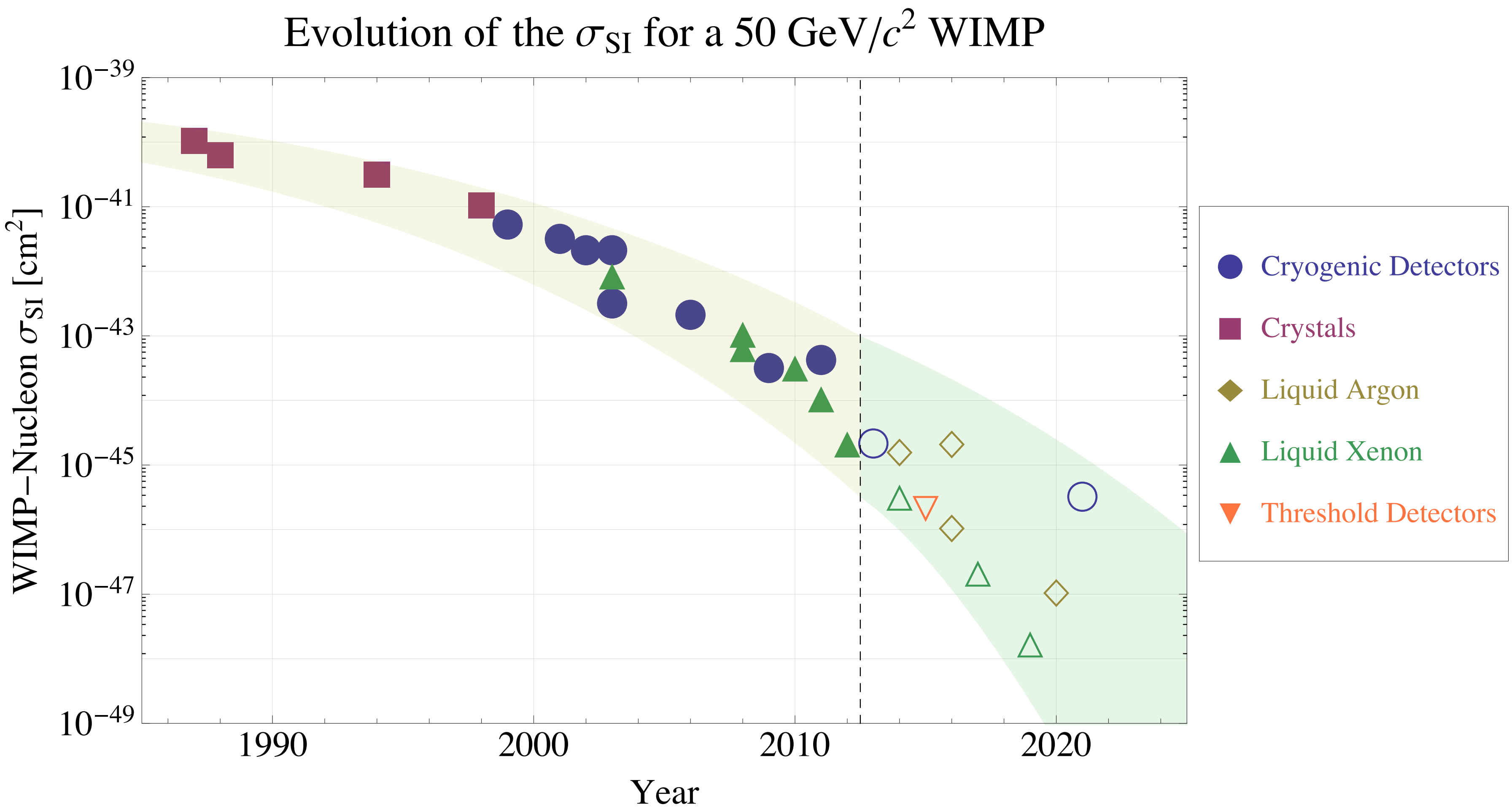


In the long run, directional detection will allow one to map out the velocity distribution of the dark matter in the galactic halo, and could serve as an important input to modeling of the detailed formation history and dynamics of the galaxy.

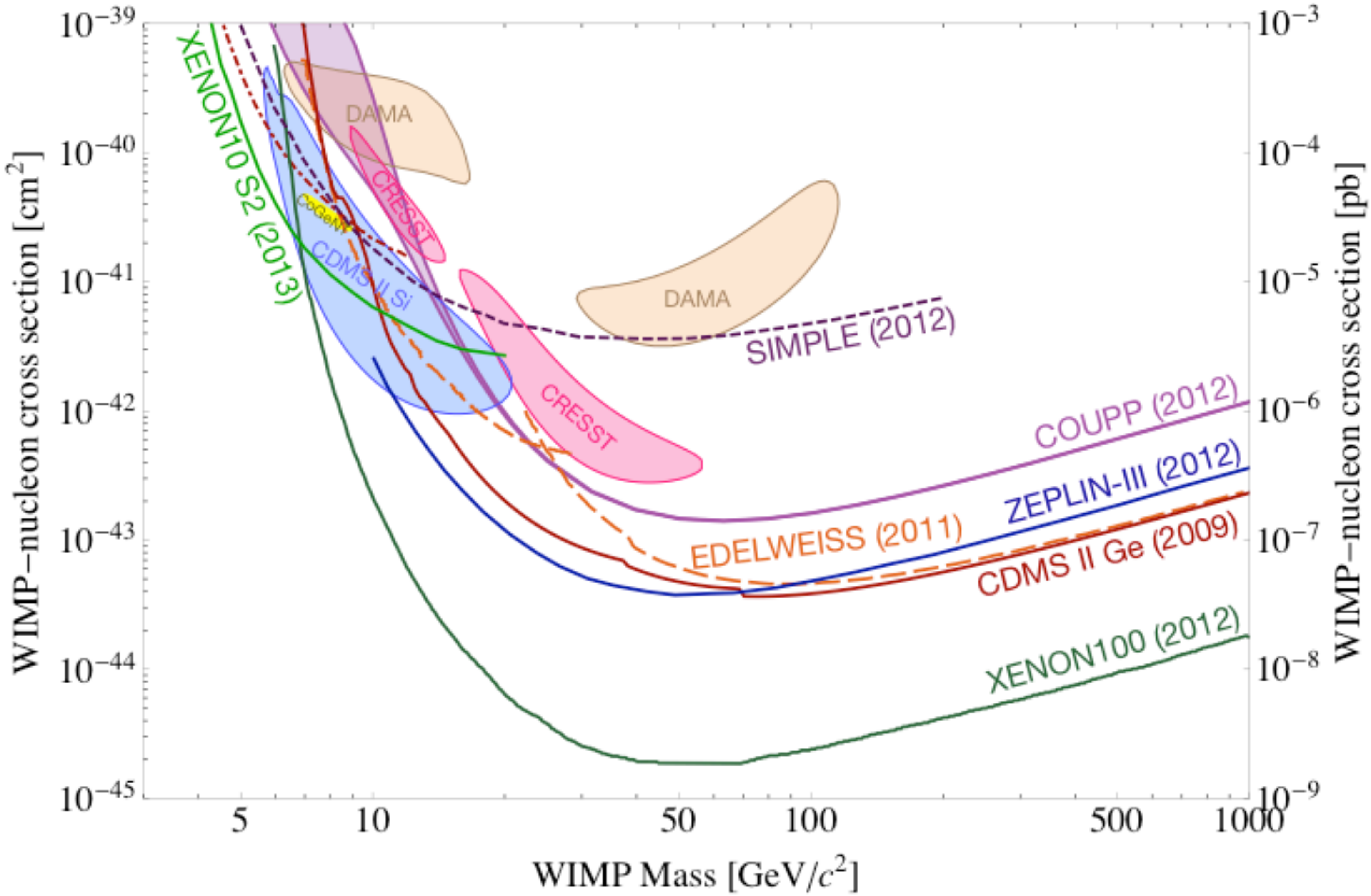
This field has seen tremendous progress over the past 25 years



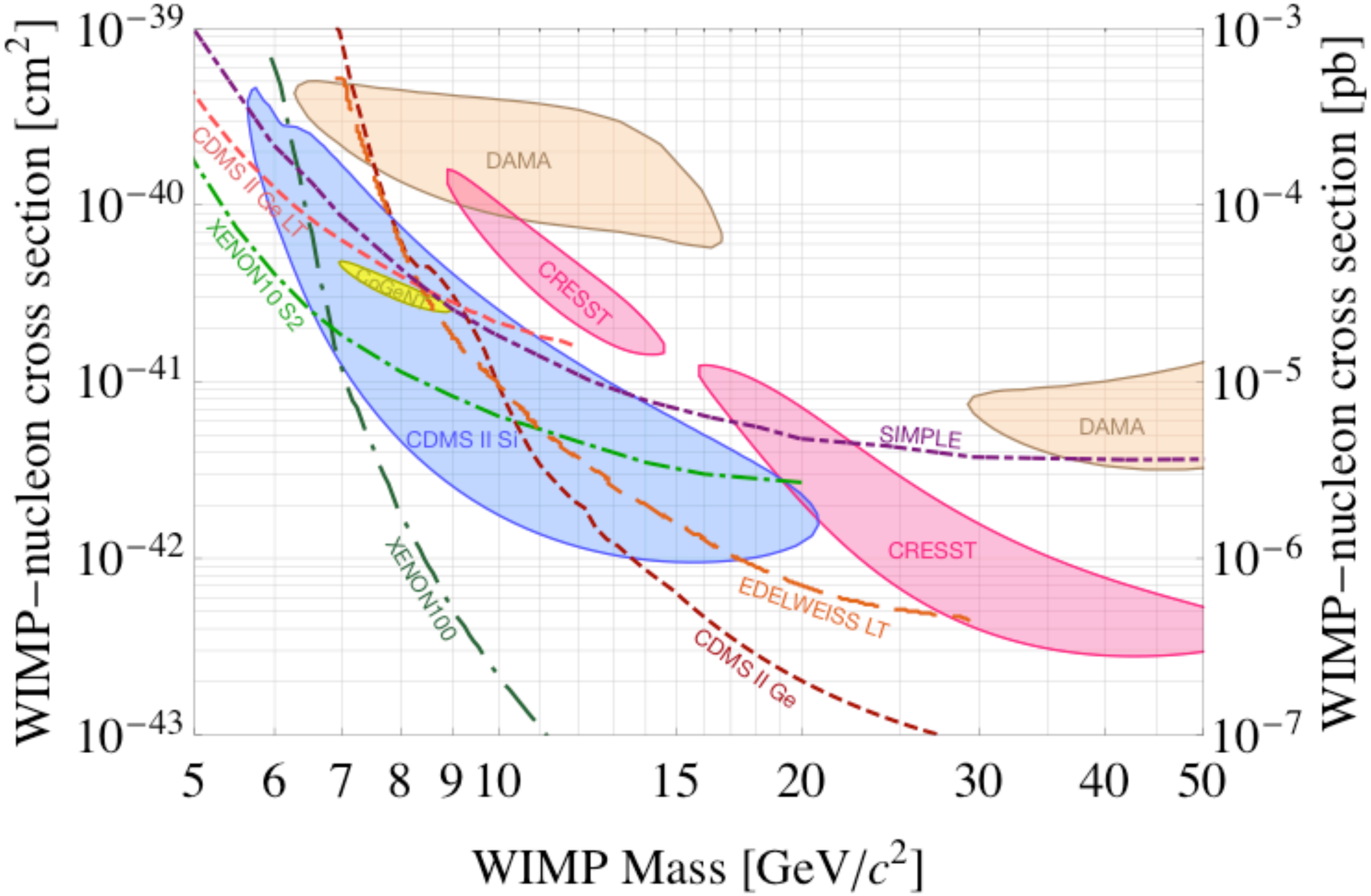
… and this progress is expected to continue.



Current limits

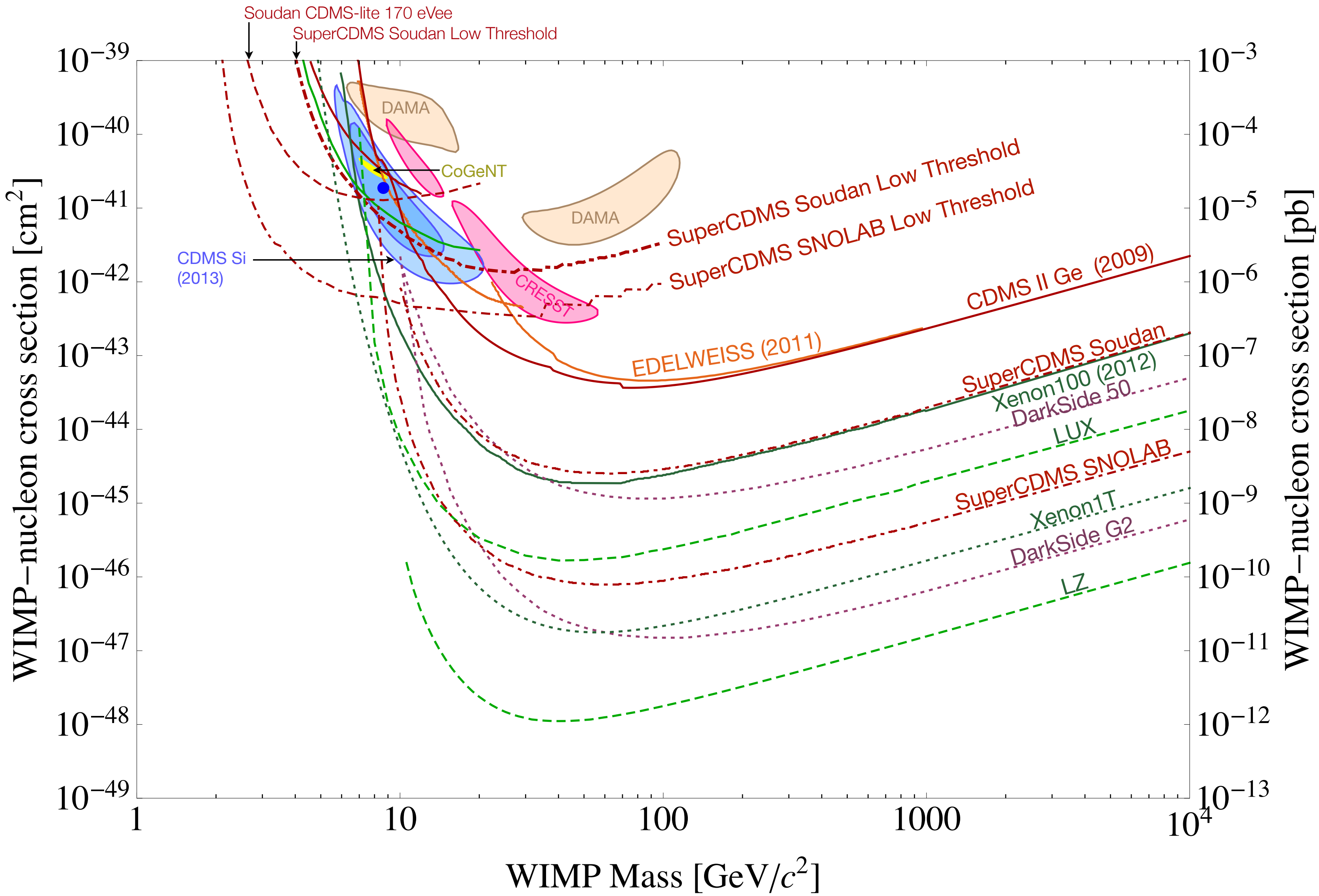


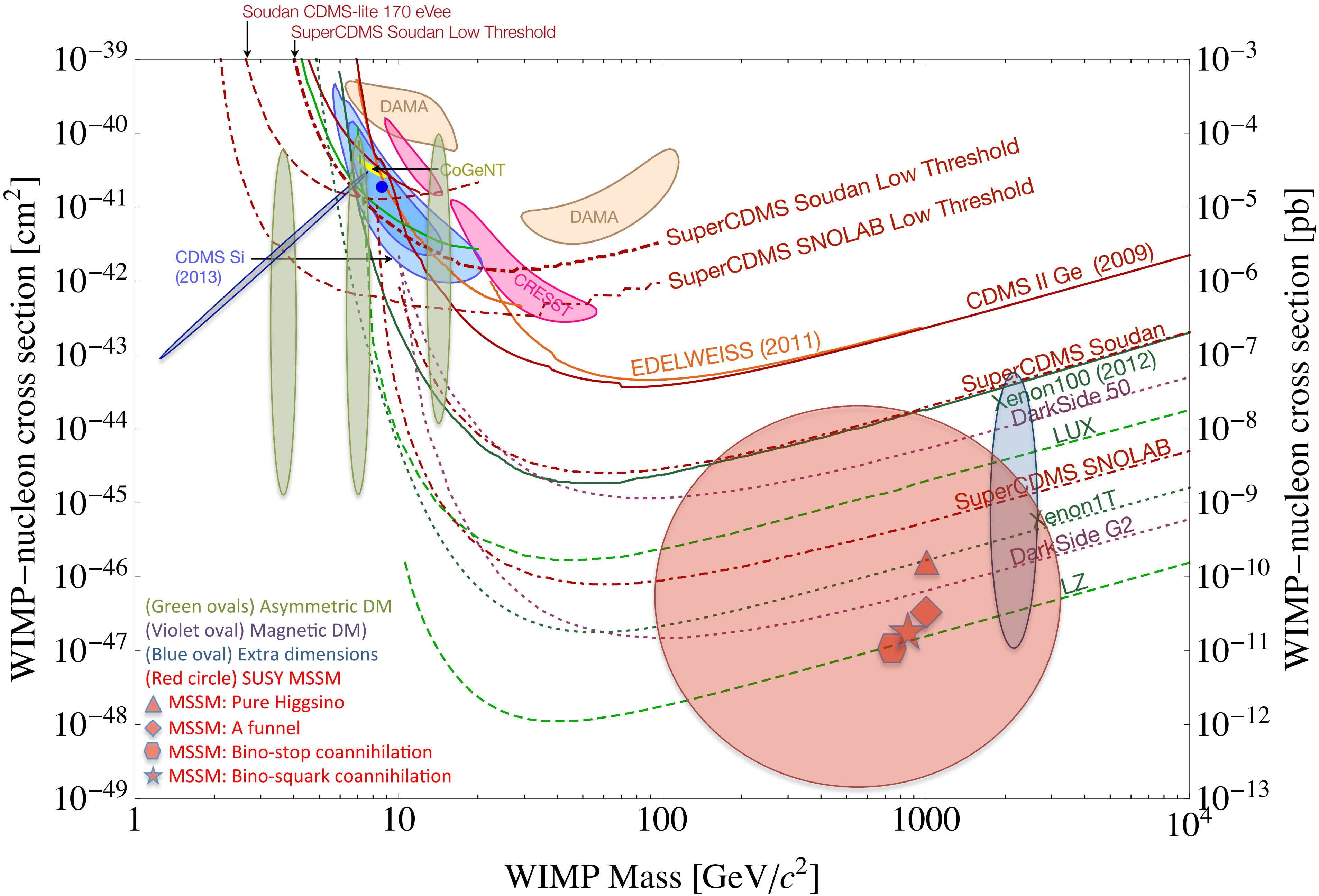
Low Mass WIMPs?



The resolution of these conflicts can only be achieved by observations with lower background, lower threshold, and higher discrimination detectors to either confirm or reject hints in the same target nuclei and then correlate with the magnitude of such signals in other targets. This will require improvement of existing detectors or development of new techniques.

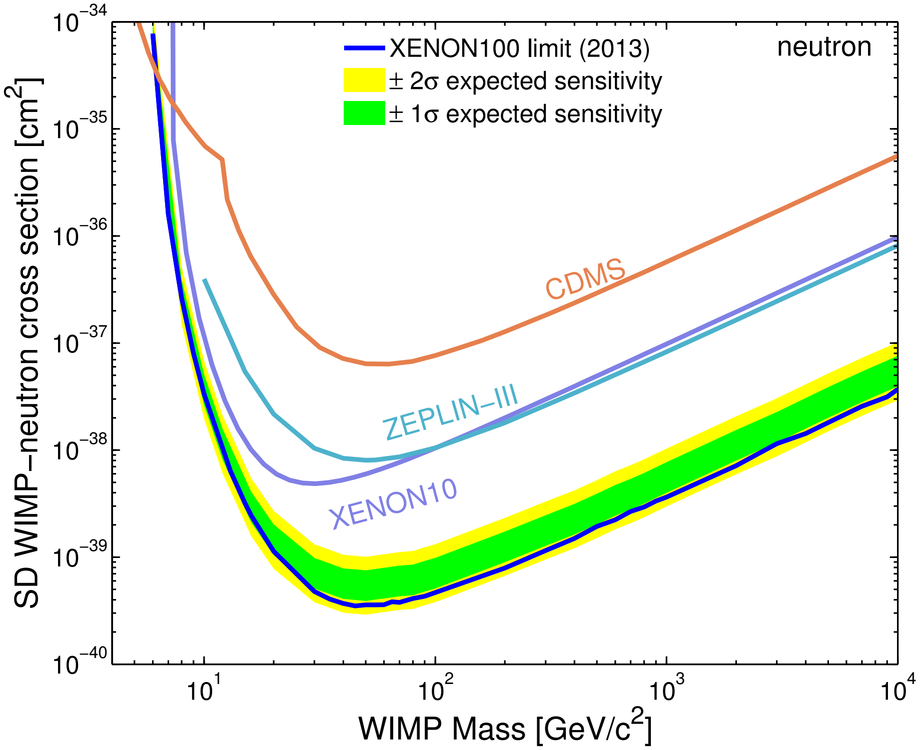
Existing and projected spin-independent cross-section limits

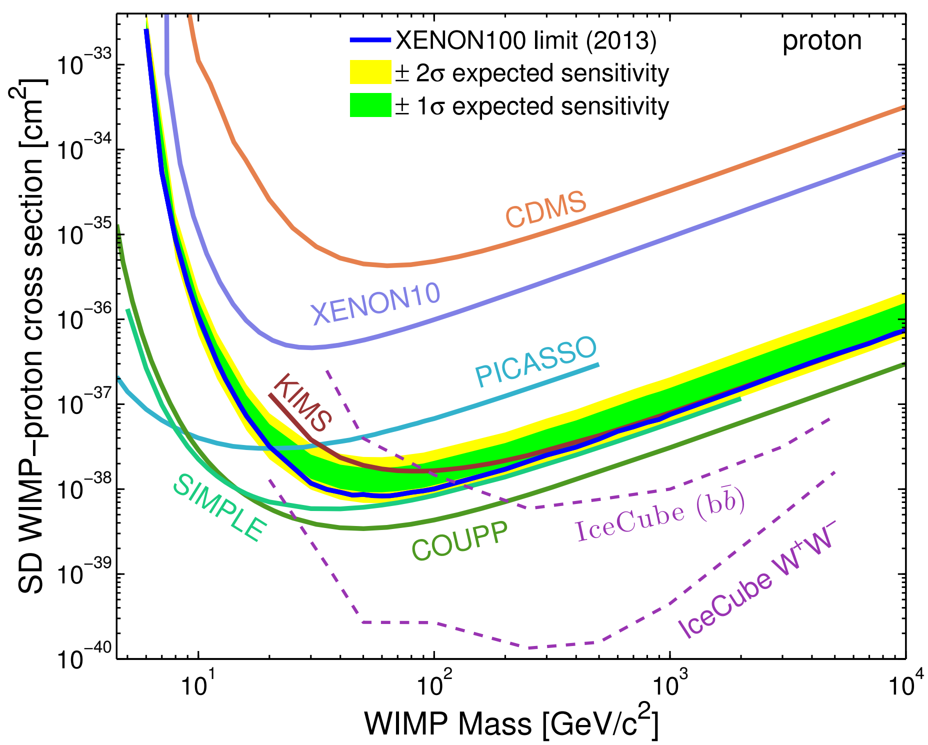



Soudan CDMS-lite 170 eVee
SuperCDMS Soudan Low Threshold
DAMA
DAMA
CoGeNT
CDMS Si
(2013)
SuperCDMS Soudan Low Threshold
SuperCDMS SNOLAB Low Threshold
CRESST
CDMS II Ge (2009)
EDELWEISS (2011)
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
SuperCDMS SNOLAB
Xenon1T
DarkSide G2
LZ
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM)
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation
WIMP–nucleon cross section [cm²]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c²]
1
10
100
1000
10⁴

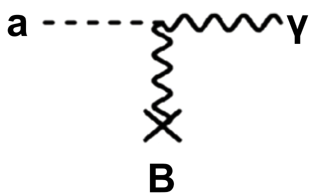
Spin-dependent cross-section limits

In spin-dependent coupling, the WIMP interacts with the free spin of the target, typically Parameterized as a neutron- or proton-spin dependent cross-section.

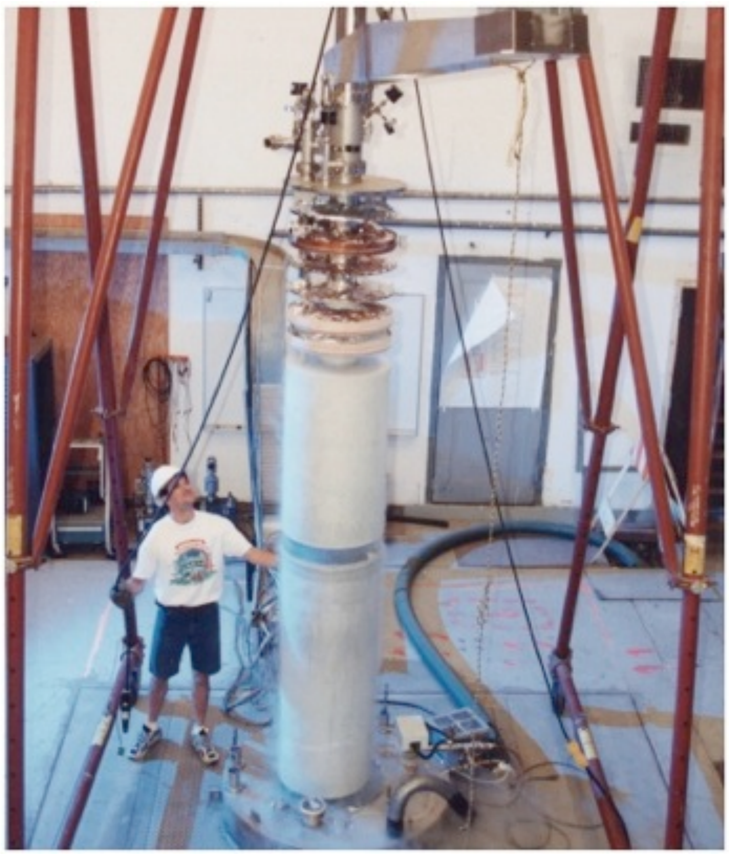


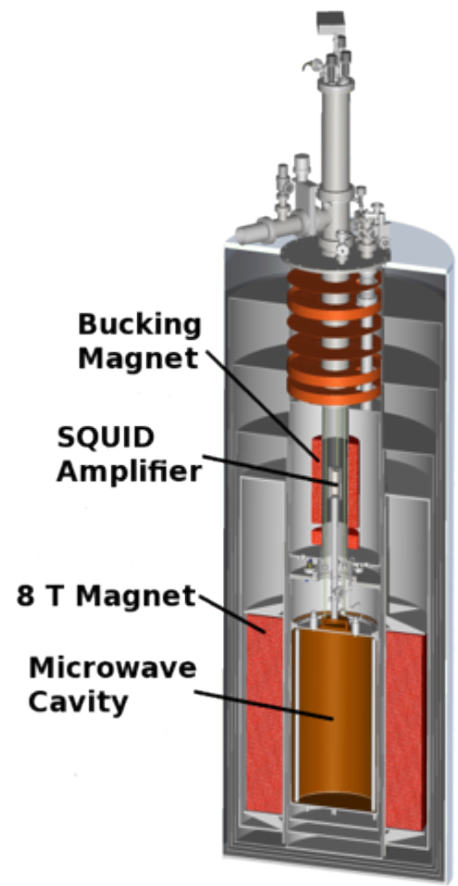


Axion Detection

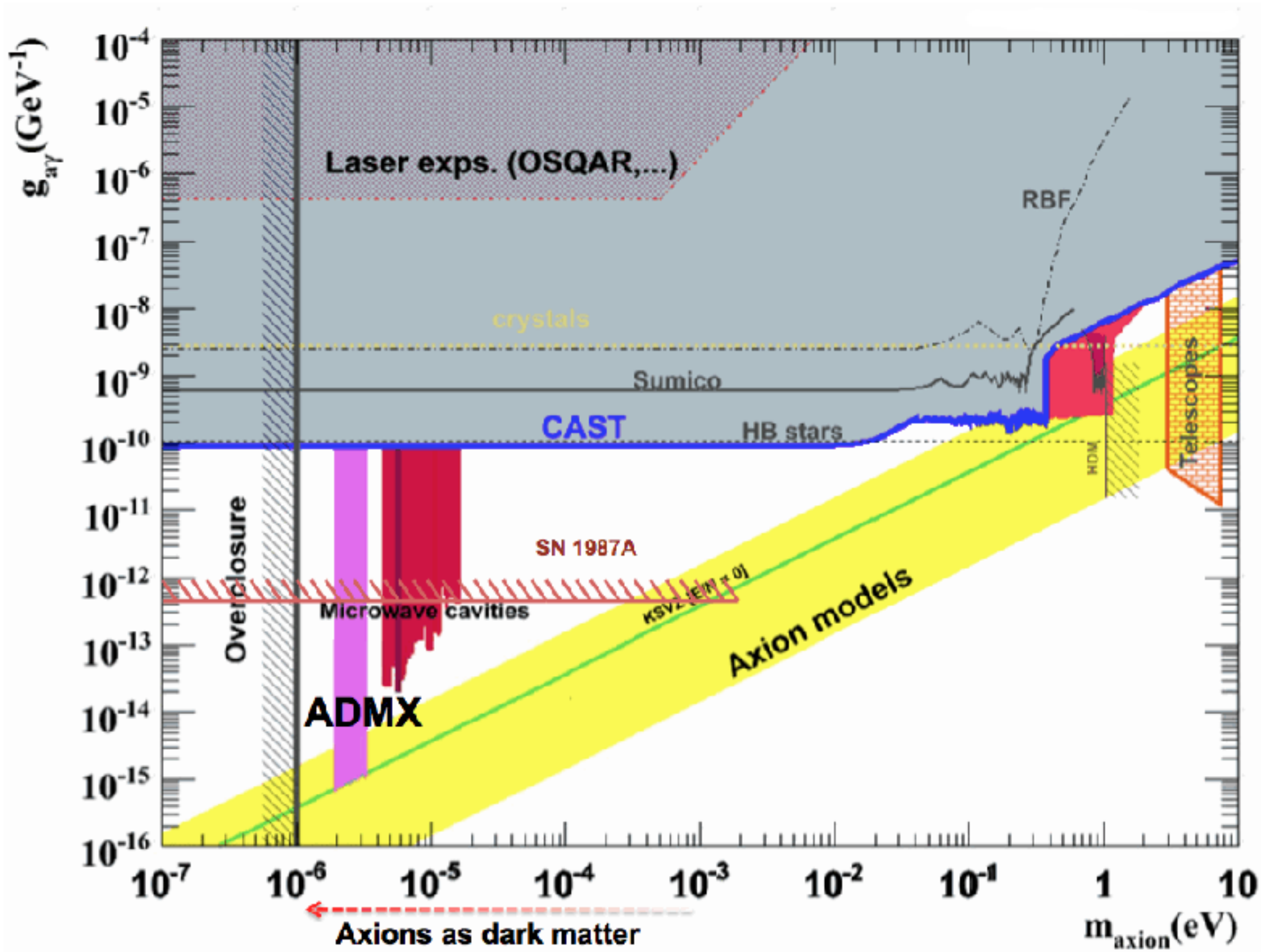


Dark matter axions may be converted into photons in a high magnetic field. ADMX (a resonant cavity axion detector) is sensitive to axions in the mass range 1 μeV to 100 μeV. Ongoing R&D to push to higher mass (higher frequency cavities)





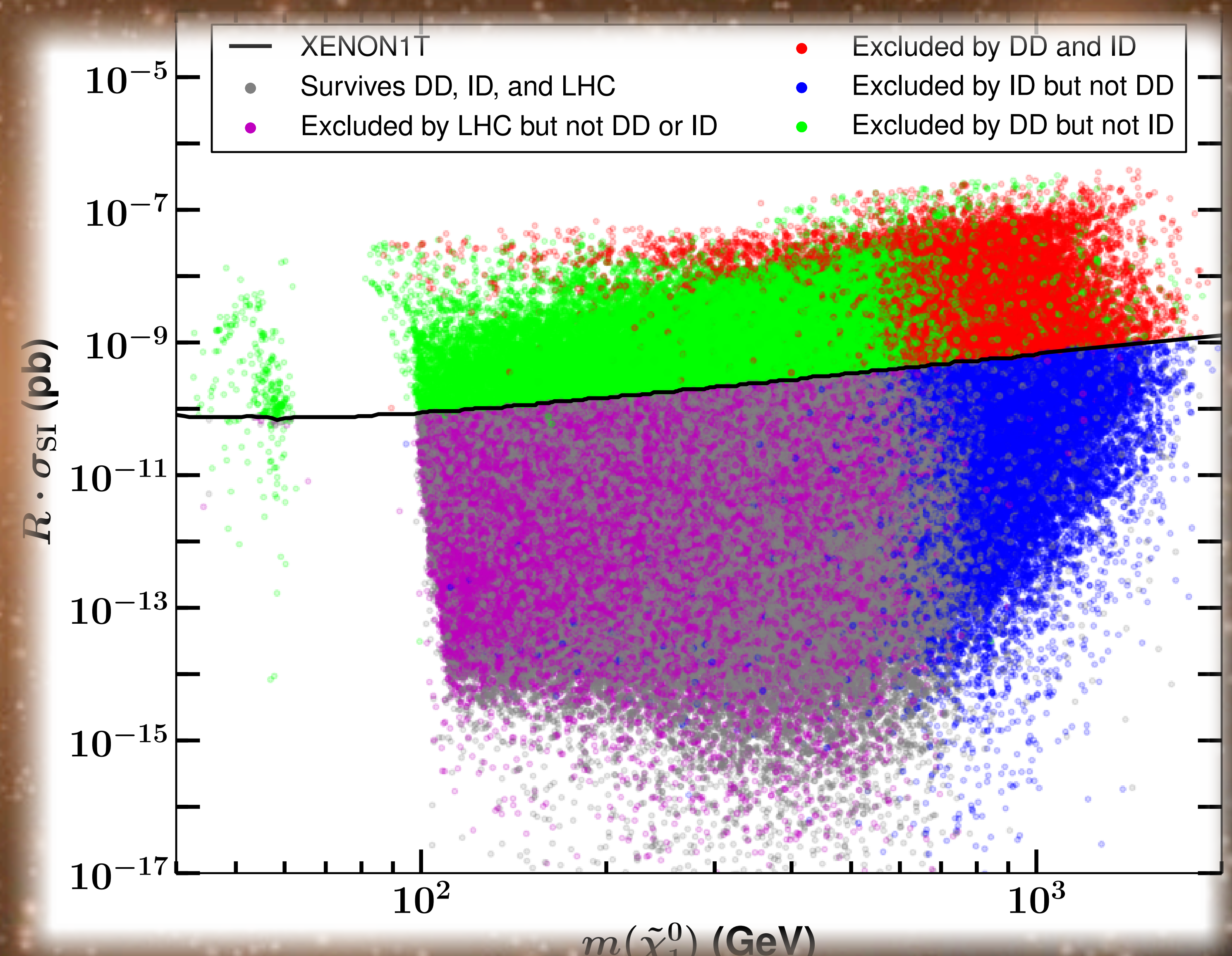
Axion detection: existing limits and future projections



Indirect Detection Experiments

Jim Buckley

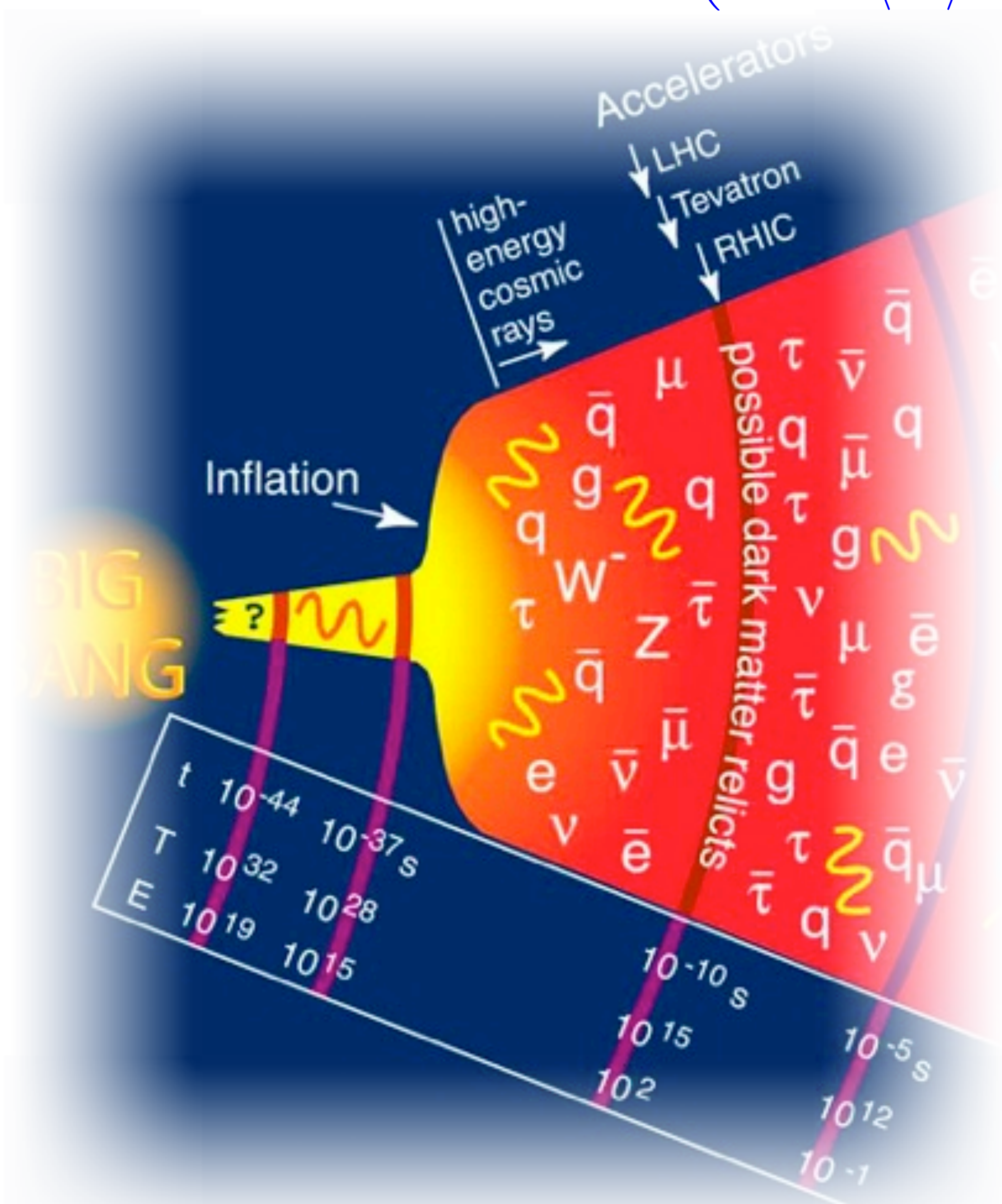
for the CF2 working group

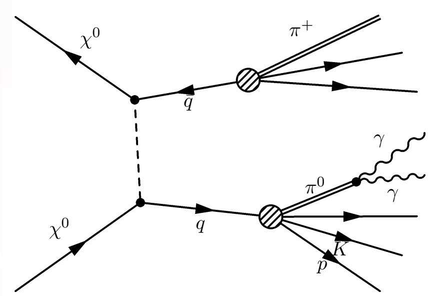


M. Cahill-Rowley, R. Cotta, A. Drlica-Wagner, S. Funk, J. Hewett, A. Ismail, T. Rizzo and M. Wood (SLAC and Irvine Particle Theory groups)

Indirect Detection Cross Section

DM relic abundance : $\Omega_\chi \approx \frac{0.1}{h^2}\left(\frac{3\times10^{-26}\mathrm{cm}^3\mathrm{sec}^{-1}}{\langle\sigma v\rangle}\right)$





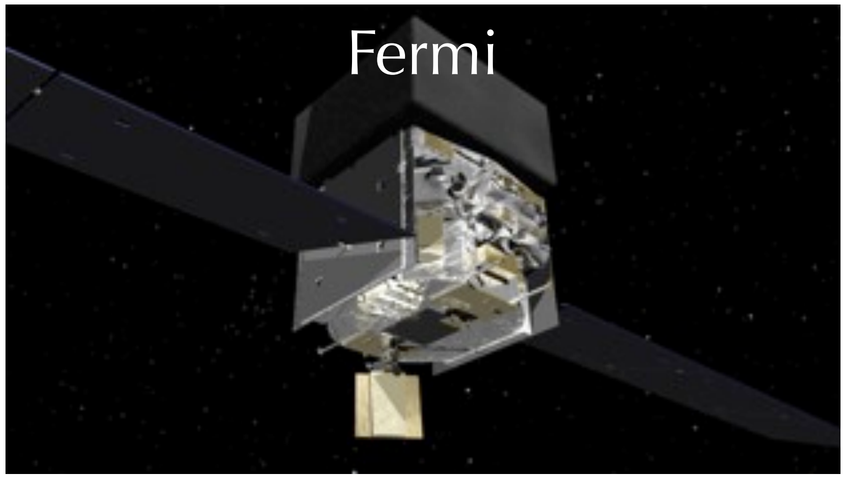
Annihilation Channel	Secondary Processes	Signals
$\chi\chi \to q\bar{q},\ gg$	$p, \bar{p}, \pi^\pm, \pi^0$	p, e, ν, γ
$\chi\chi \to W^+W^-$	$W^\pm \to l^\pm\nu_l,\ W^\pm \to u\bar{d} \to \pi^\pm,\ \pi^0$	p, e, ν, γ
$\chi\chi \to Z^0Z^0$	$Z^0 \to l\bar{l},\ \nu\bar{\nu},\ q\bar{q} \to$ pions	p, e, γ, ν
$\chi\chi \to \tau^\pm$	$\tau^\pm \to \nu_\tau e^\pm \nu_e,\ \tau \to \nu_\tau W^\pm \to p, \bar{p}$, pions	
$\chi\chi \to \mu^+\mu^-$		e, γ
$\chi\chi \to \gamma\gamma$ $\chi\chi \to Z^0\gamma$	Z^0 decay	γ γ
$\chi\chi \to e^+e^-$		e, γ

- The same interactions of WIMPs with standard model particles in the early universe (holding WIMPs in thermal equilibrium) imply interactions in the current universe.

- While the cross-section for a specific interaction (e.g., scattering off a nucleon) or annihilation channel is indirectly related to this decoupling cross section, *almost all annihilation channels produce photons and the total annihilation rate to photons is closely related to the decoupling cross section:* $\sim n_\chi^2\langle\sigma v\rangle$

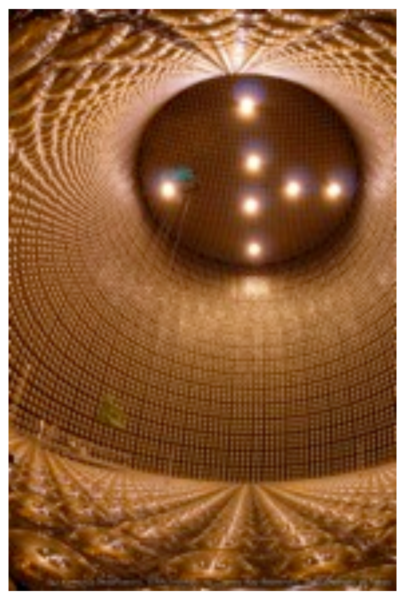
** Gamma-ray production by annihilation in the present universe is closely related to the decoupling cross section in the early universe with a natural scale* $\langle\sigma v\rangle \approx 3\times10^{-26}\mathrm{cm}^3\mathrm{sec}^{-1}$

Indirect Detection

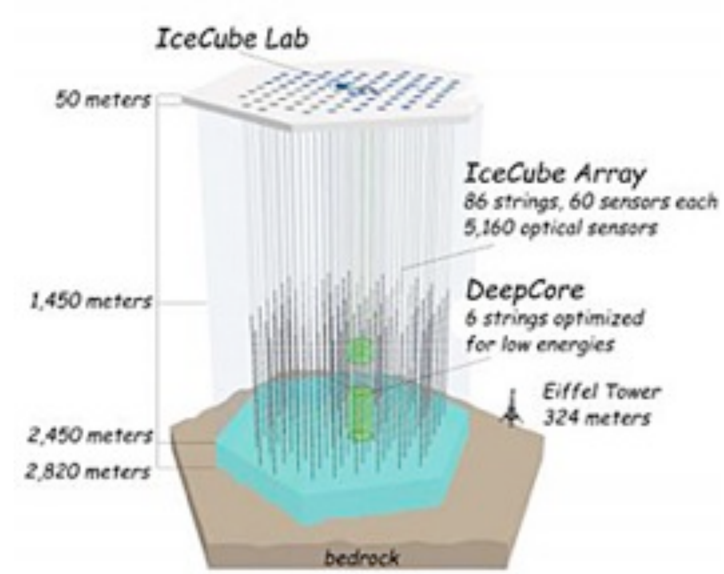


γ

Super-K

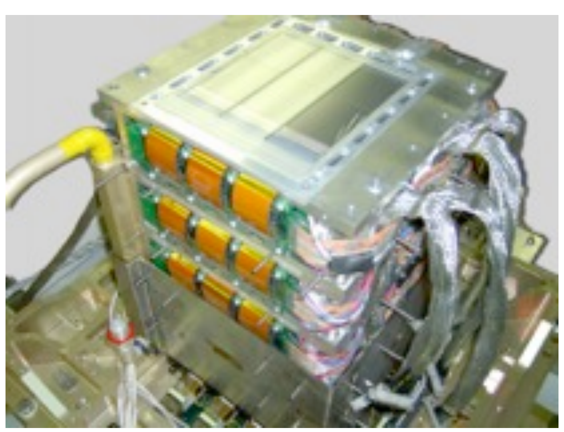


ν



ICECUBE

PAMELA



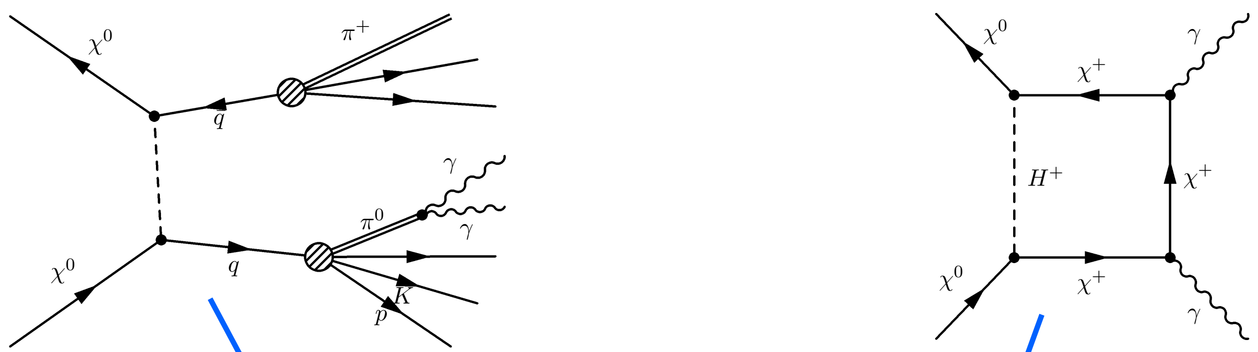
$$e^-, e^+, p, \bar{p}$$

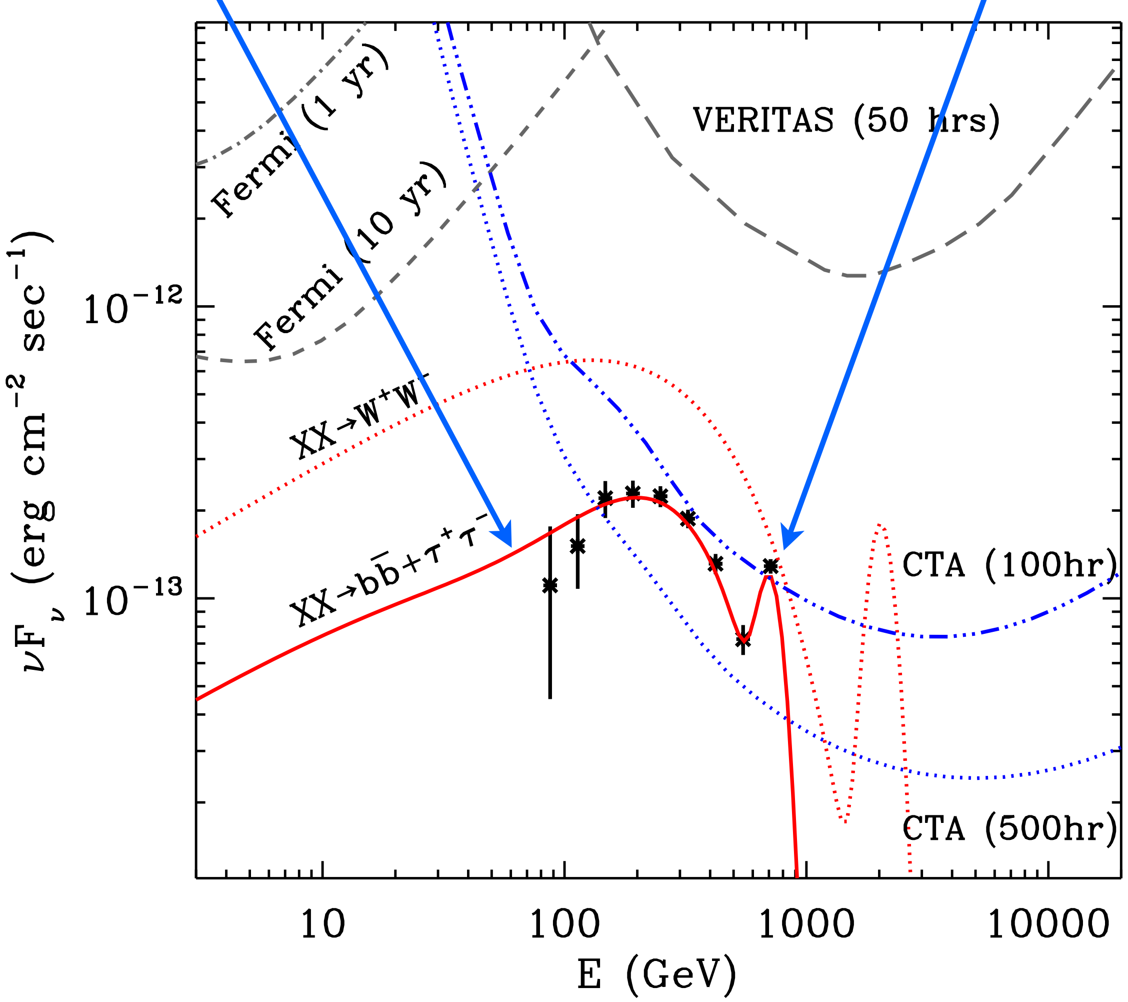
AMS

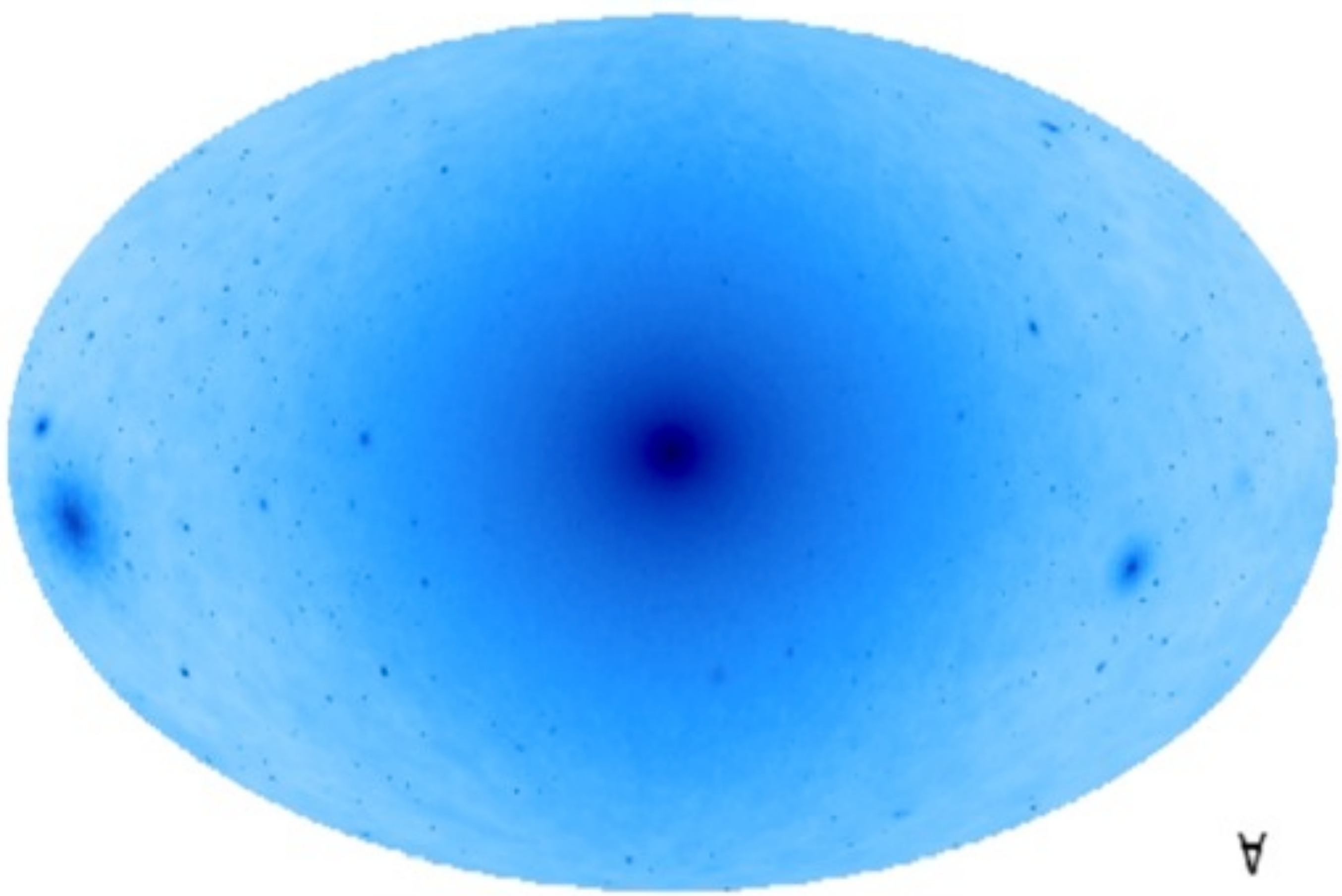
Gamma Rays from DM Annihilation

$$E_\gamma \Phi_\gamma(\theta) \approx 10^{-10} \underbrace{\left(E_{\gamma,\mathrm{TeV}} \frac{dN}{dE_{\gamma,\mathrm{TeV}}}\right)\left(\frac{\langle \sigma v\rangle}{10^{-26}\mathrm{cm^{-3}s^{-1}}}\right)\left(\frac{100\,\mathrm{GeV}}{M_\chi}\right)^2}_{\text{Particle Physics Input}} \underbrace{J(\theta)} \;\mathrm{erg\,cm^{-2}s^{-1}sr^{-1}}$$

$$J(\theta) = \underbrace{\frac{1}{8.5\,\mathrm{kpc}}\left(\frac{1}{0.3\,\mathrm{GeV/cm^3}}\right)^2 \int_{\text{line of sight}} \rho^2(l)dl(\theta)}_{\text{Astrophysics/Cosmology Input}}$$



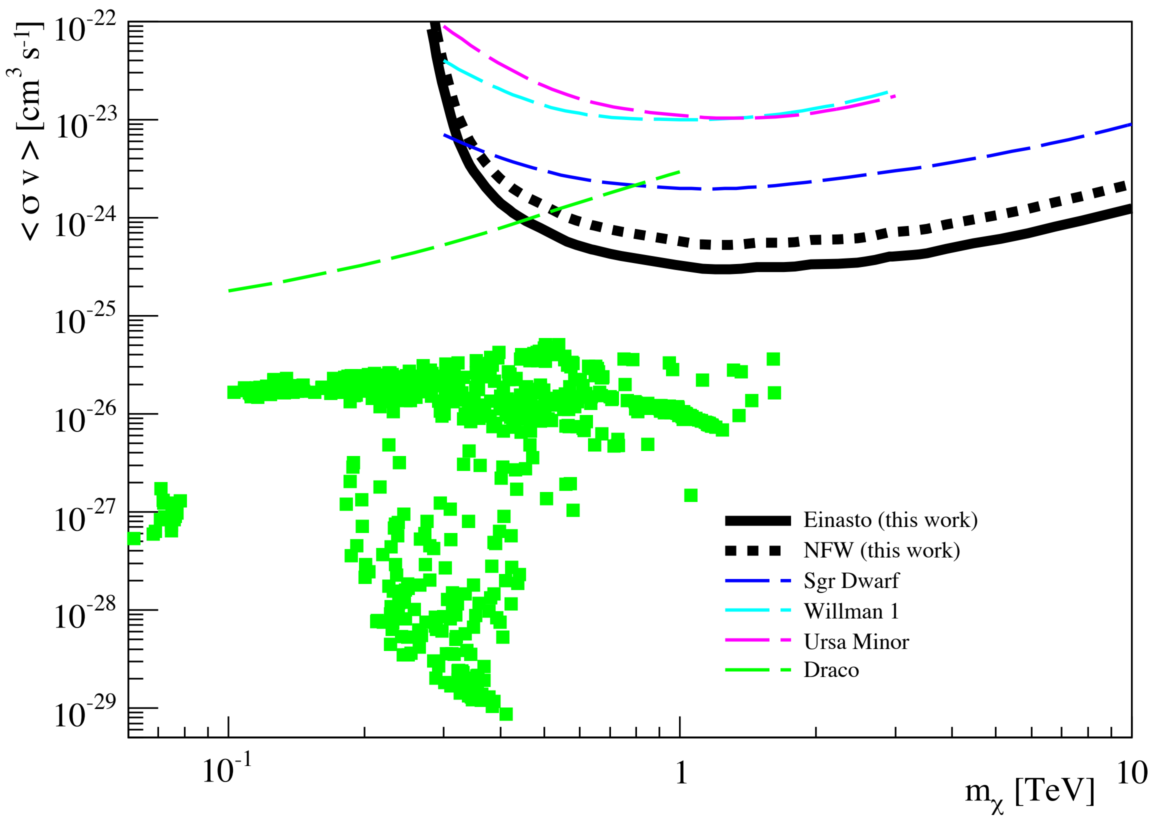




Line-of-sight integral of ρ^2 for a Milky-Way-like halo in the VL Lactea II ΛCDM N-body simulations (Kuhlen et al.)

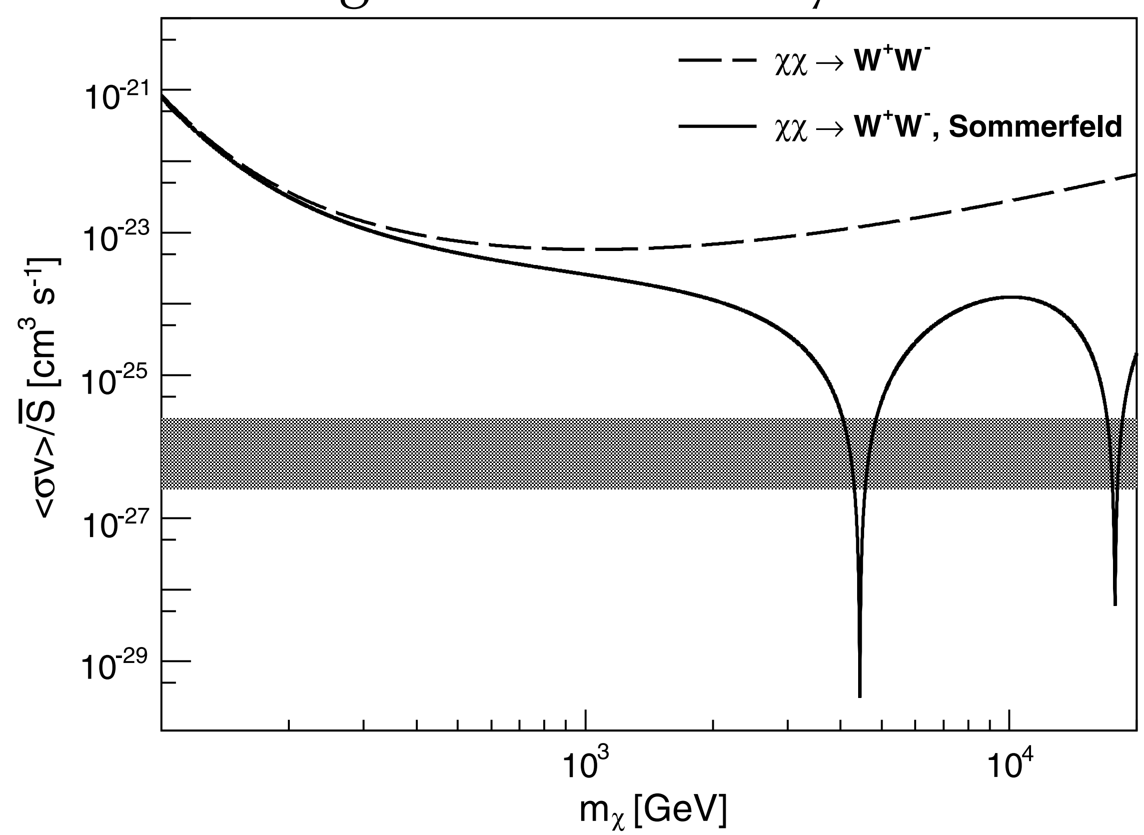
ACT DM Constraints

GC Limits



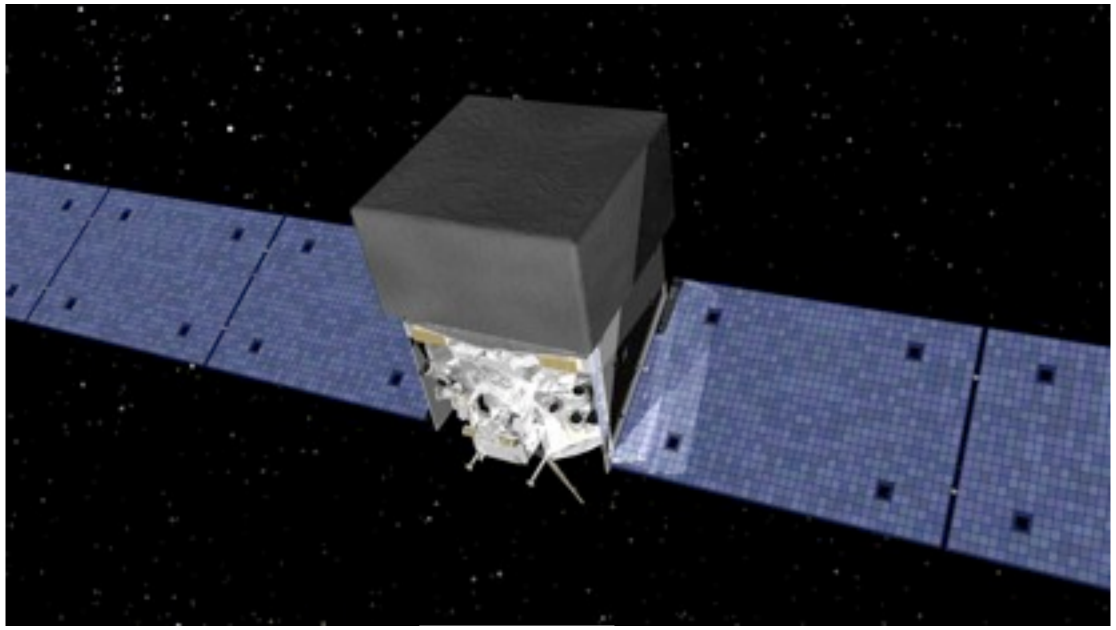
(Aharonian et al. for the HESS collaboration, PRL 106, 1301)

Segue Dwarf Galaxy Limits

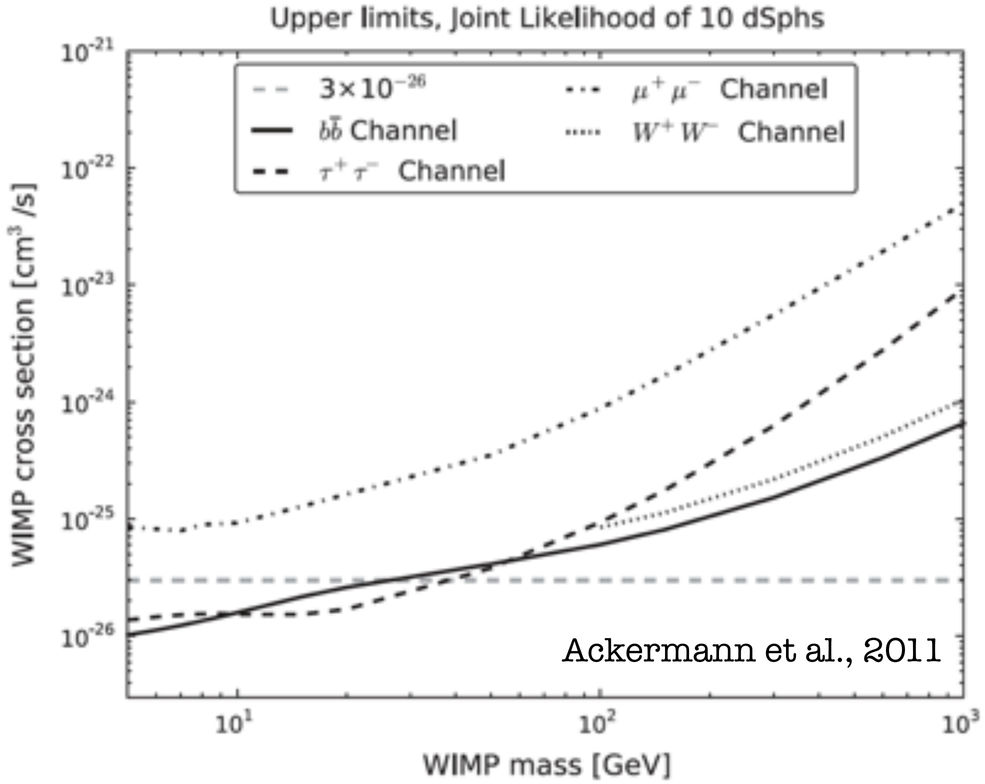


(Aliu et al. for the VERITAS collaboration, PRD 85, 062001)

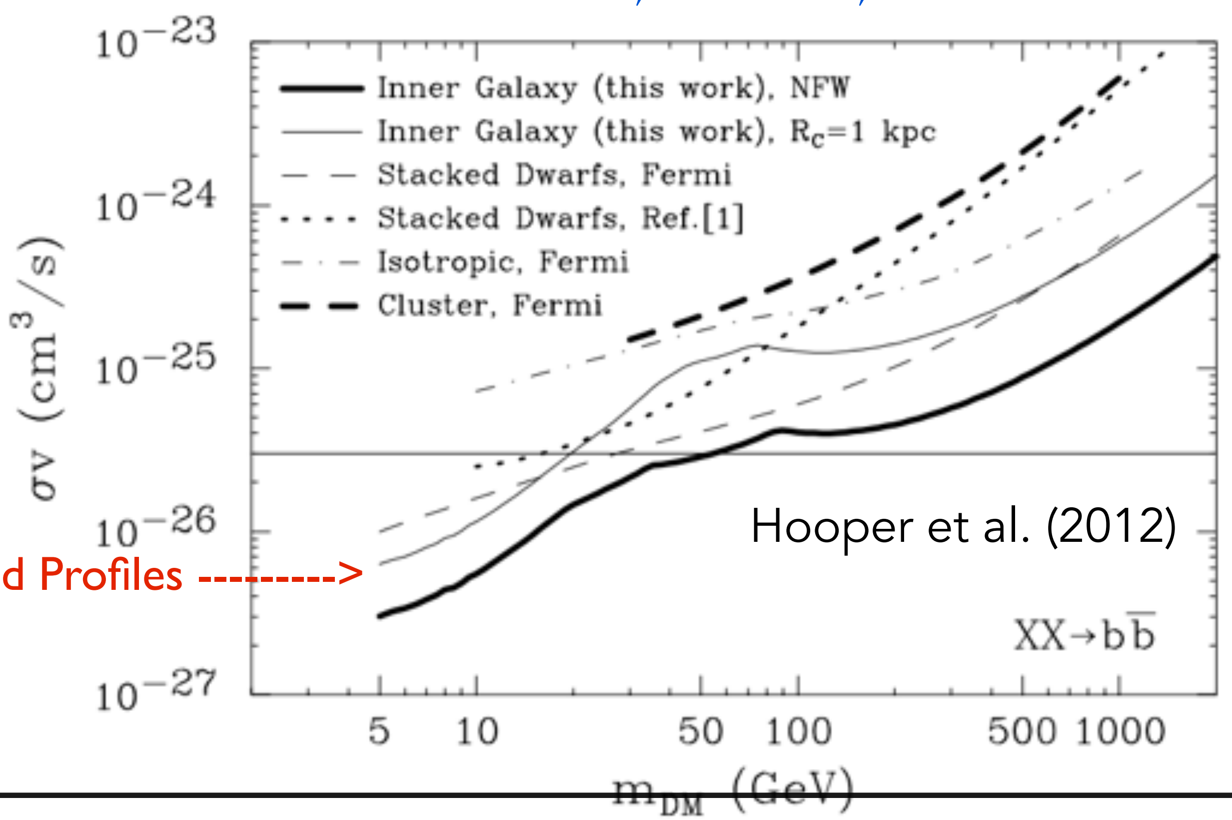
Fermi LAT DM Constraints



Dwarf Constraints

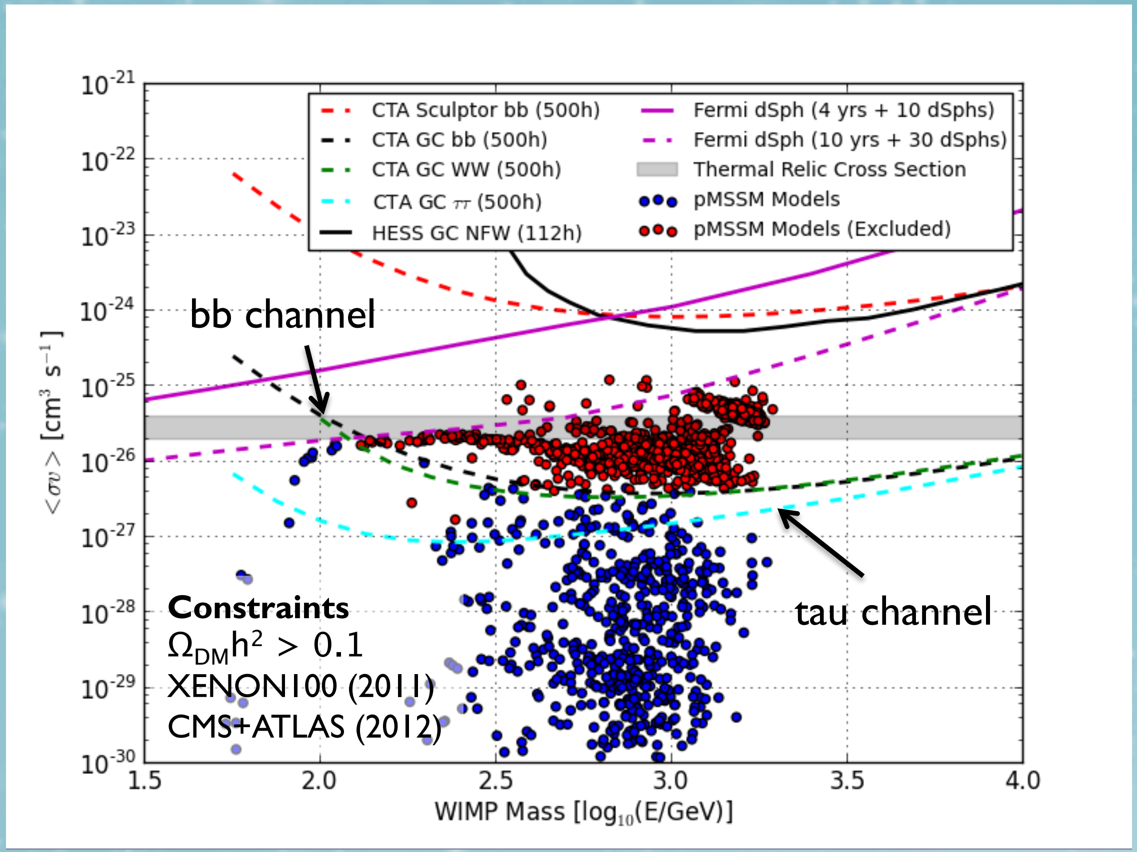


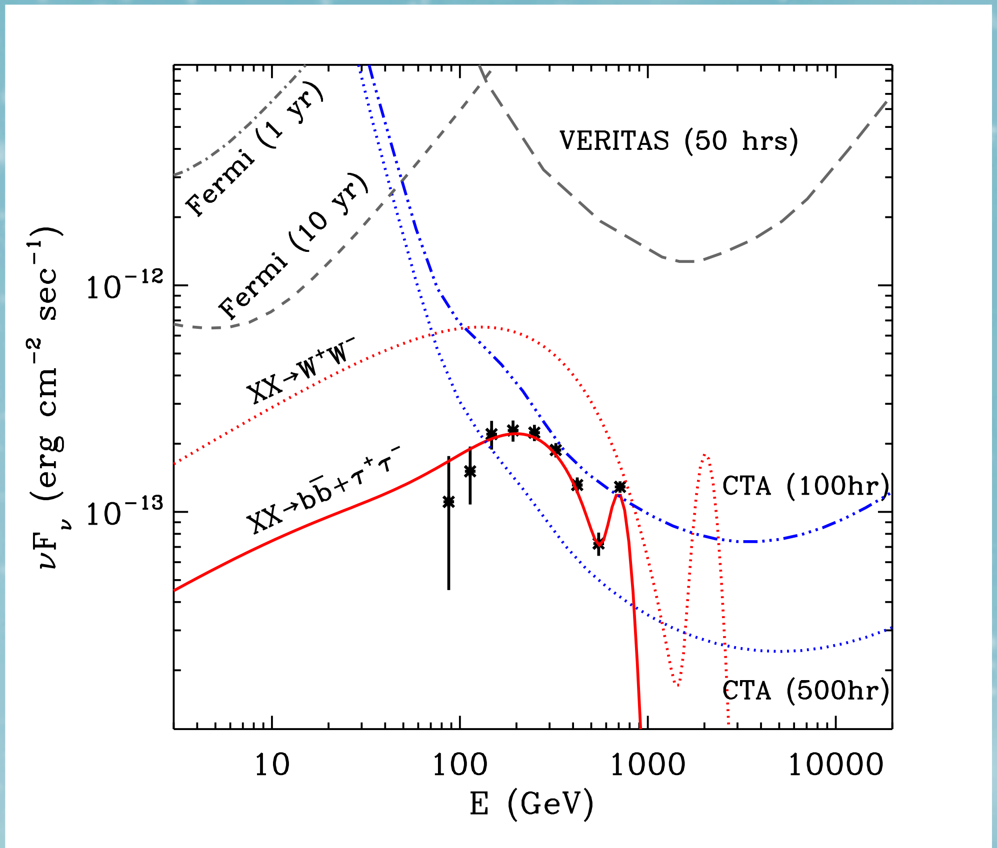
GC, Cluster, Constraints

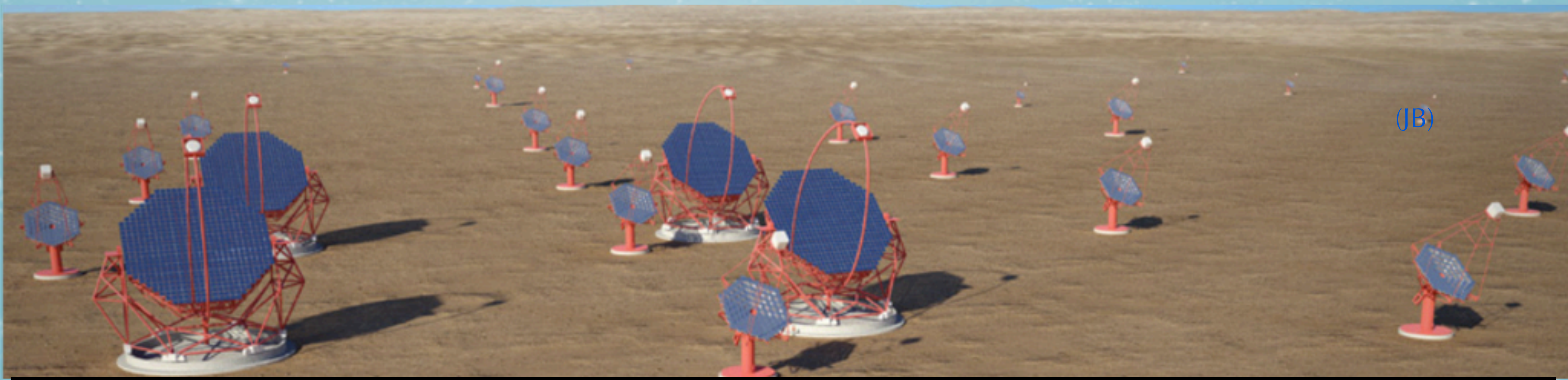


Enormous progress since last Snowmass meeting! We are beginning to probe natural cross section at low mass (<20 GeV) and pull within 1-2 orders of magnitude for 100GeV-1TeV WIMPs.

CTA

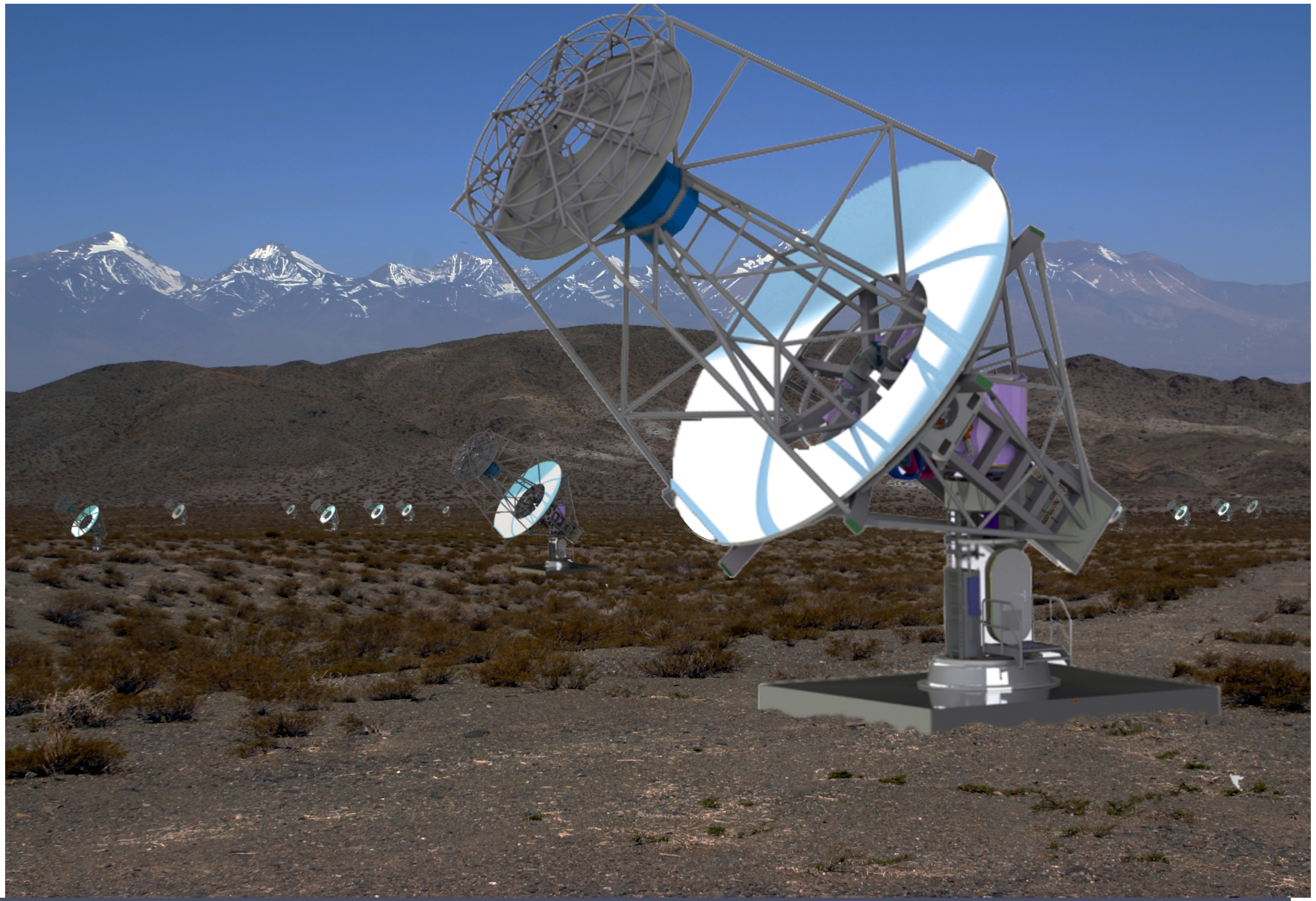


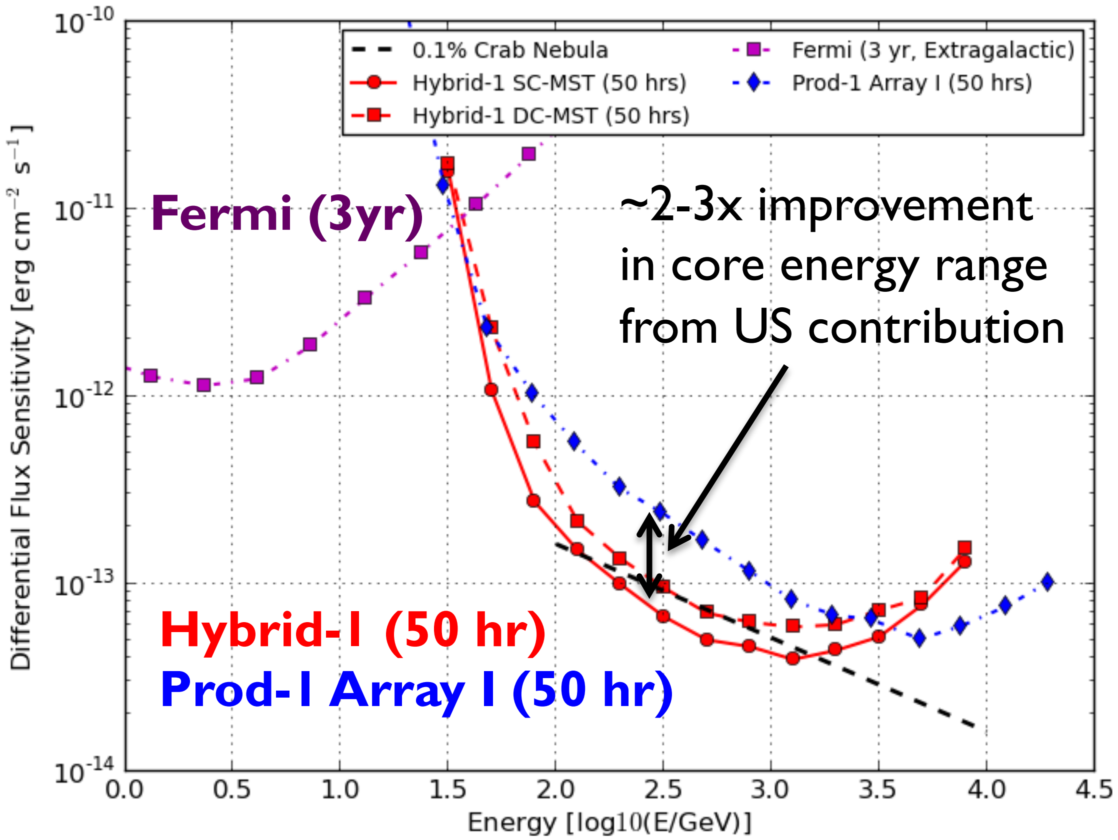




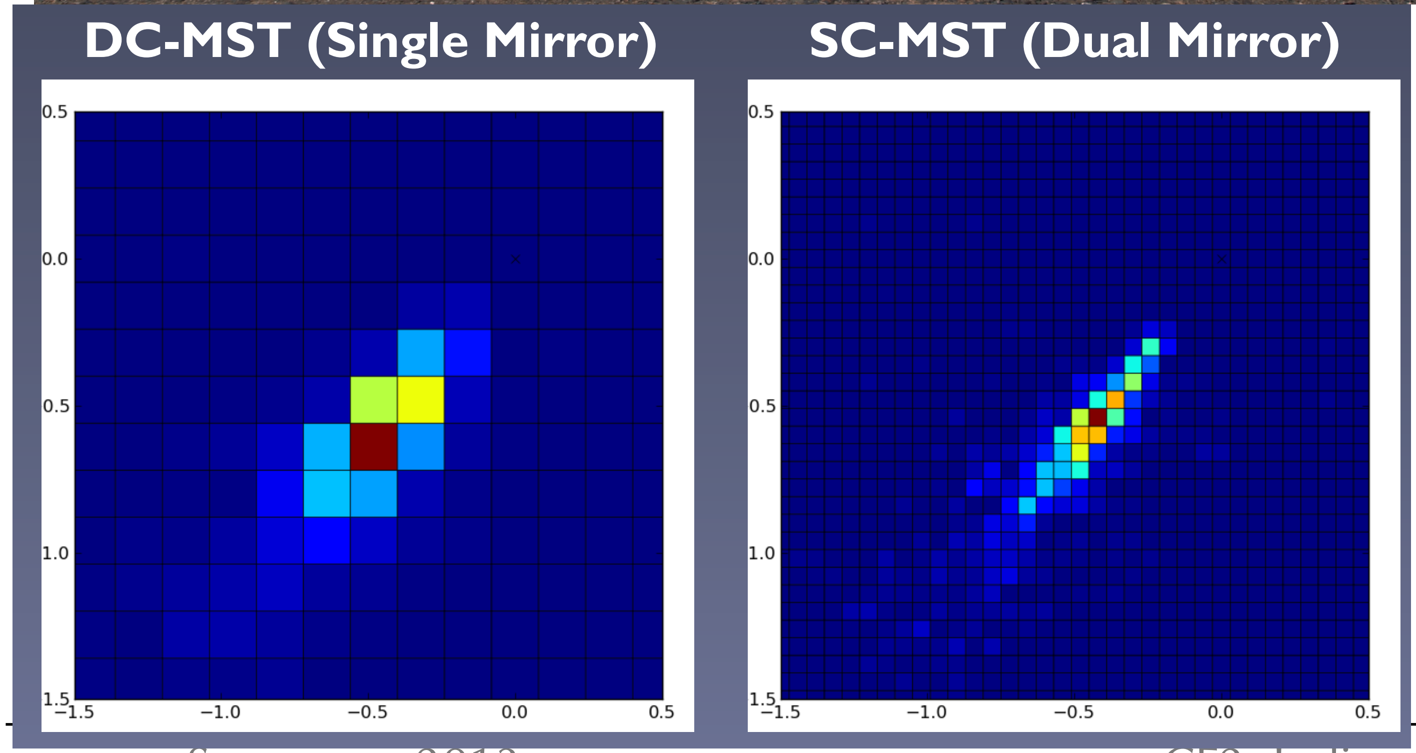
** A CTA like instrument with ~60 Mid-sized telescopes has the sensitivity to probe the natural cross section for WIMP annihilation from 100 GeV to 10 TeV - But this requires a US contribution*

CTA-US

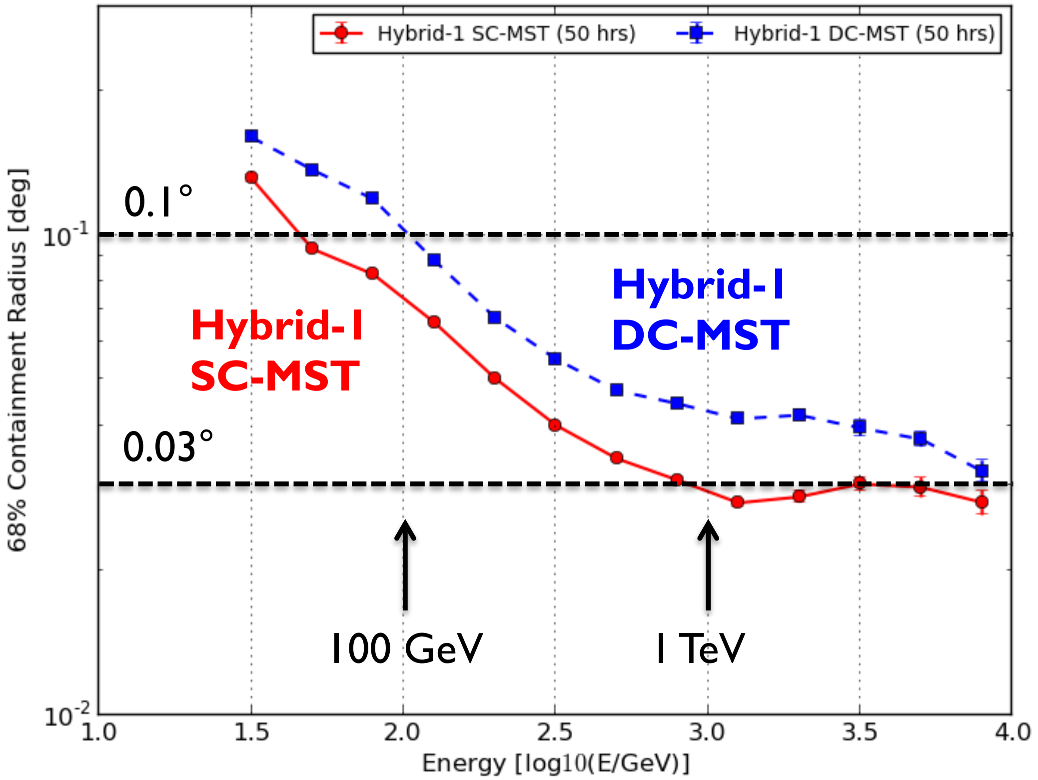




0.1% Crab Nebula
Hybrid-1 SC-MST (50 hrs)
Hybrid-1 DC-MST (50 hrs)
Fermi (3 yr, Extragalactic)
Prod-1 Array I (50 hrs)
Fermi (3yr)
~2-3x improvement in core energy range from US contribution
Hybrid-1 (50 hr)
Prod-1 Array I (50 hr)
Differential Flux Sensitivity [erg cm^{-2} s^{-1}]
Energy [log10(E/GeV)]

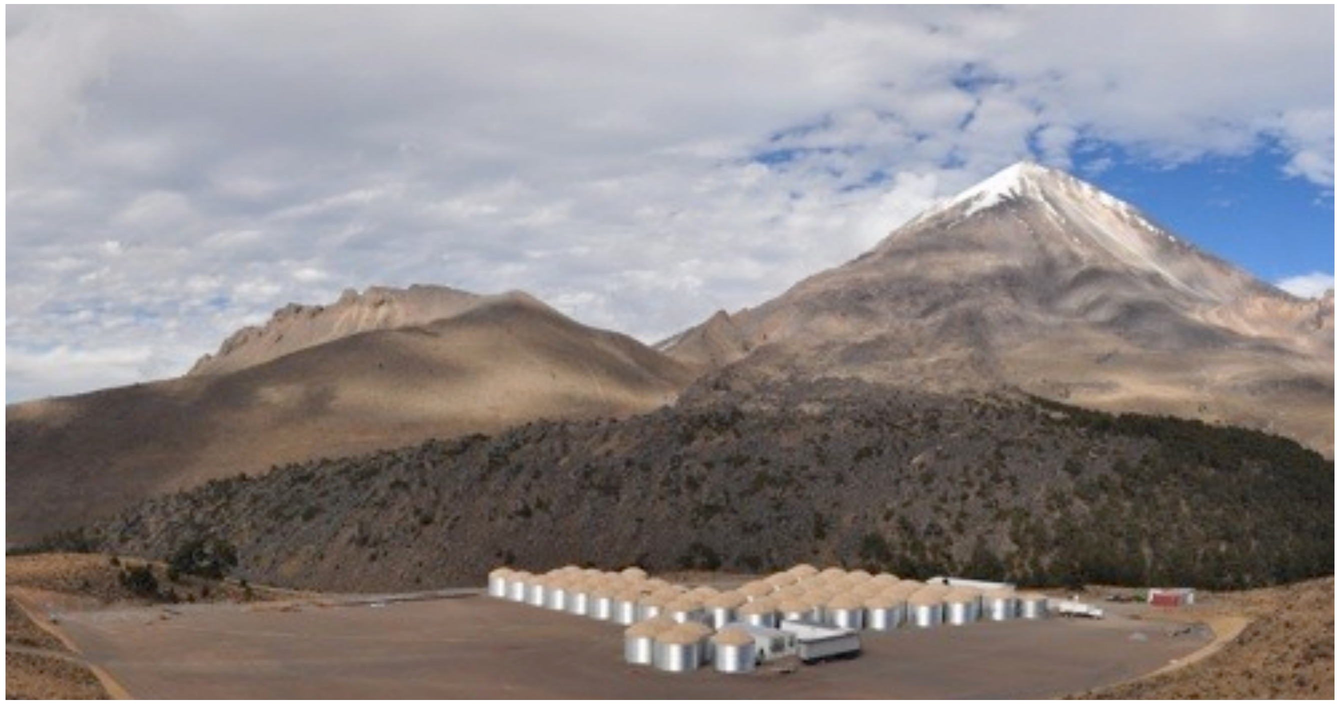


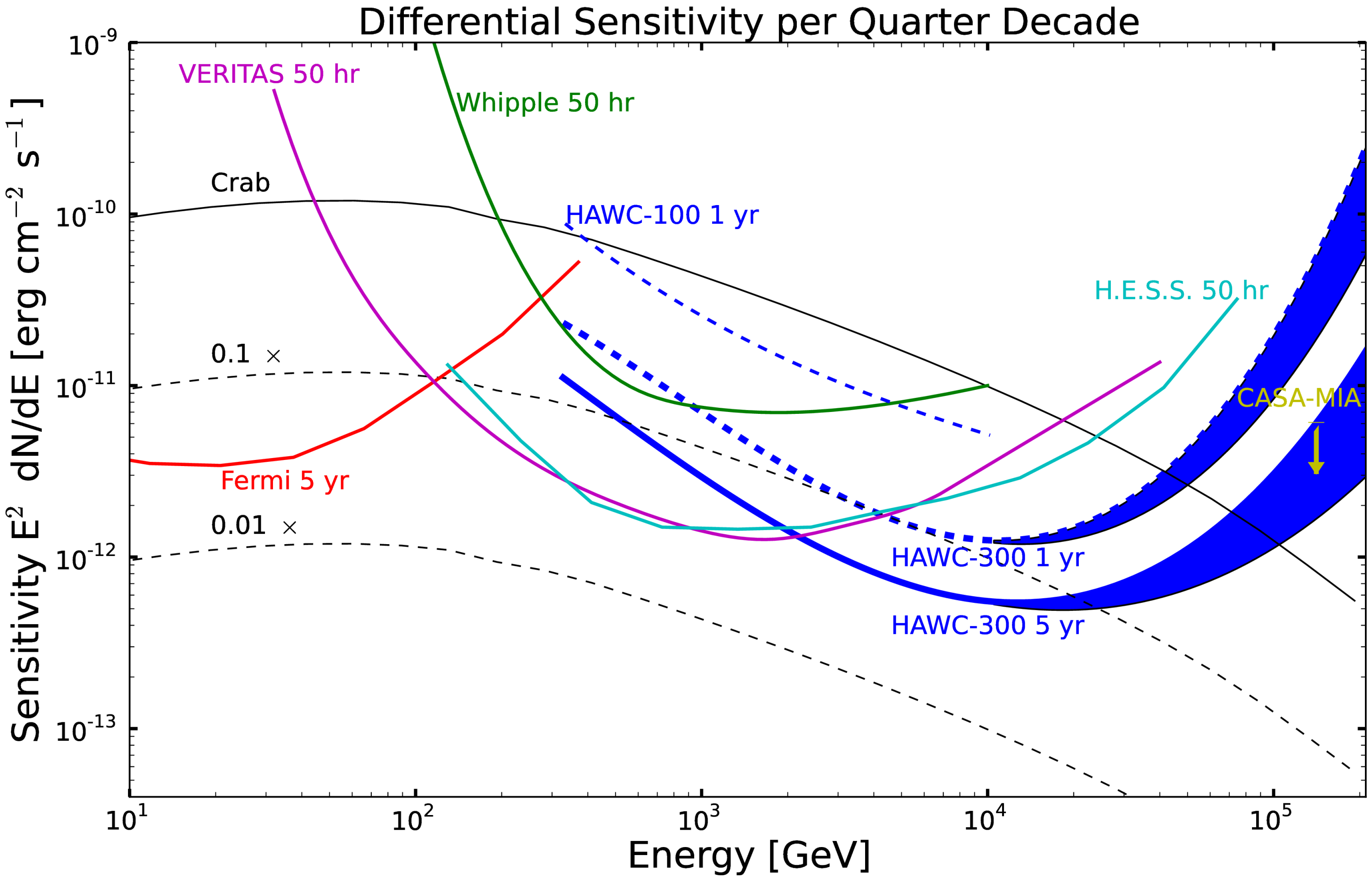
DC-MST (Single Mirror)
SC-MST (Dual Mirror)



Hybrid-1 SC-MST (50 hrs)
Hybrid-1 DC-MST (50 hrs)
0.1°
0.03°
Hybrid-1 SC-MST
Hybrid-1 DC-MST
100 GeV
1 TeV
68% Containment Radius [deg]
Energy [log10(E/GeV)]

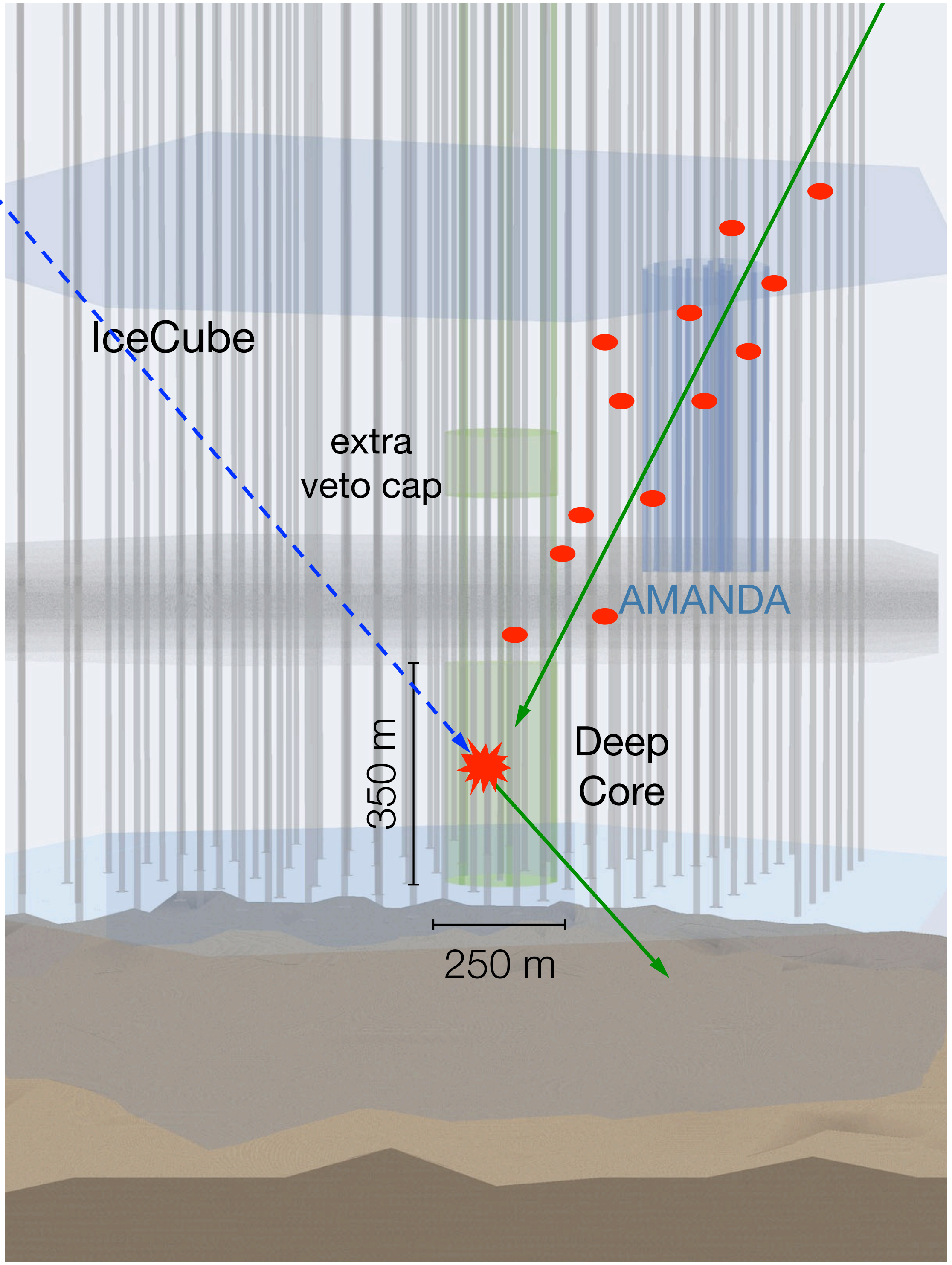
HAWC

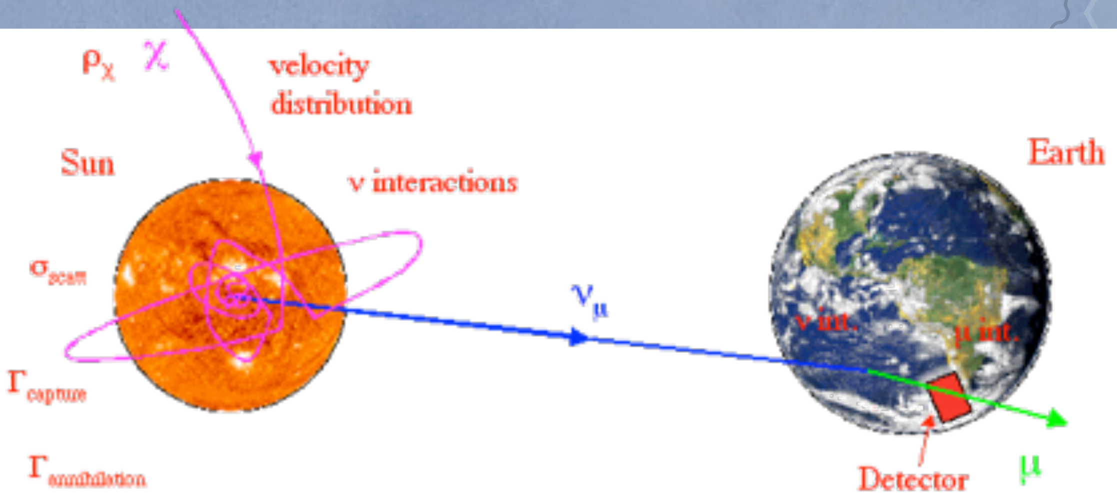




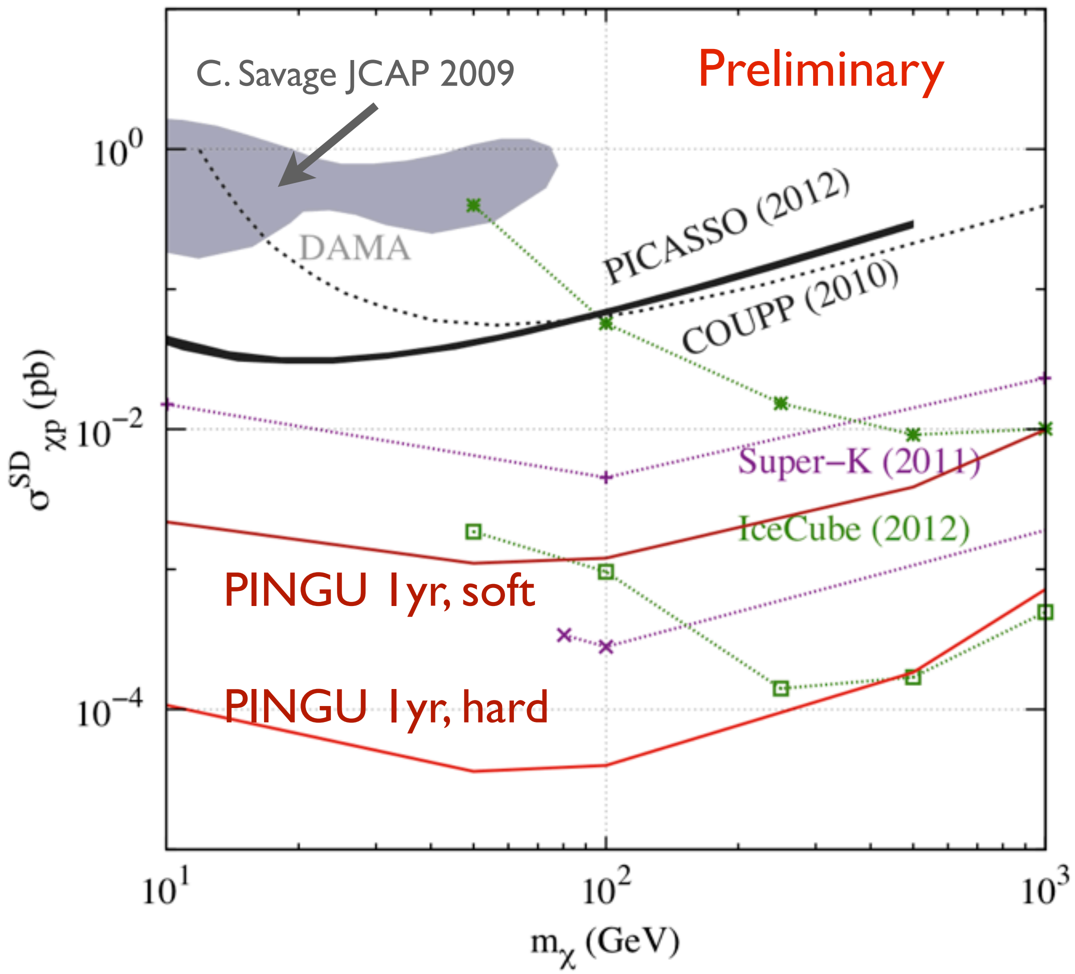
Differential Sensitivity per Quarter Decade
Sensitivity E2 dN/dE [erg cm−2 s−1]
Energy [GeV]
VERITAS 50 hr
Whipple 50 hr
Crab
HAWC-100 1 yr
H.E.S.S. 50 hr
0.1 ×
CASA-MIA
Fermi 5 yr
0.01 ×
HAWC-300 1 yr
HAWC-300 5 yr

Future Neutrino Detectors



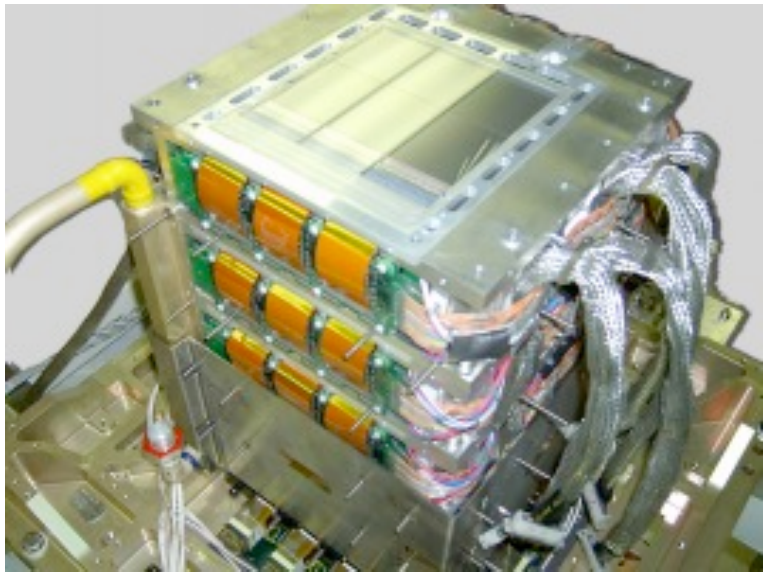


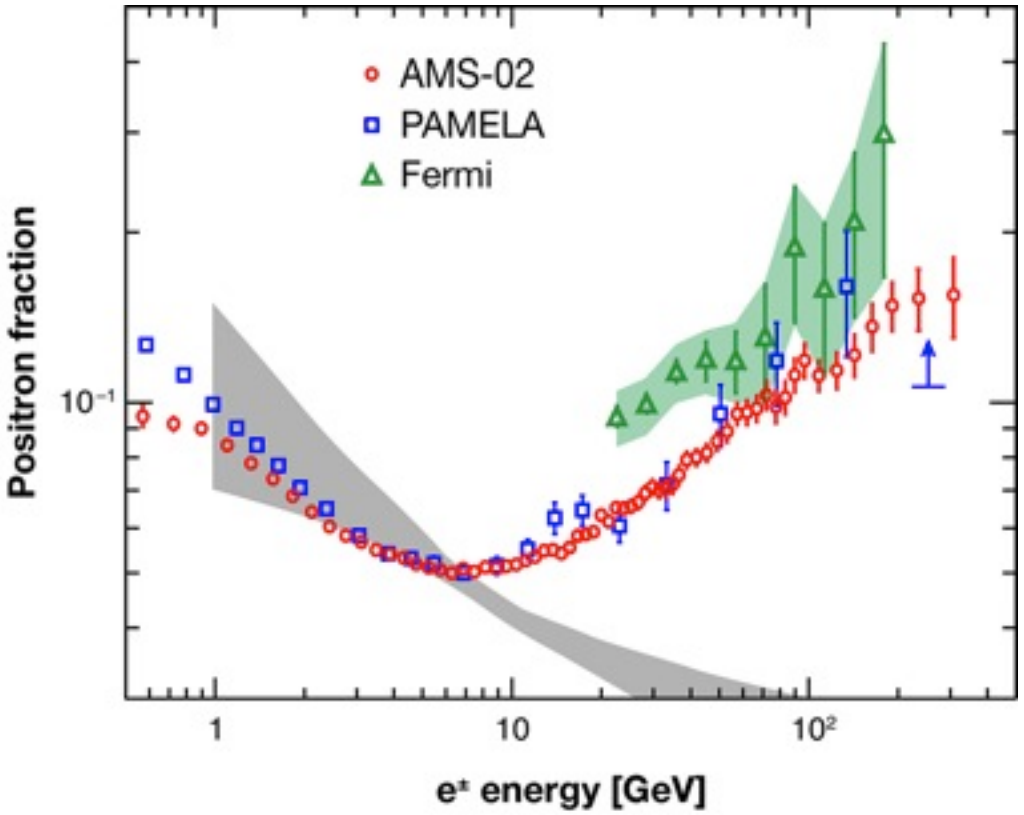
Adapted Rott, Tanaka, Itow JCAP09(2011)029 to



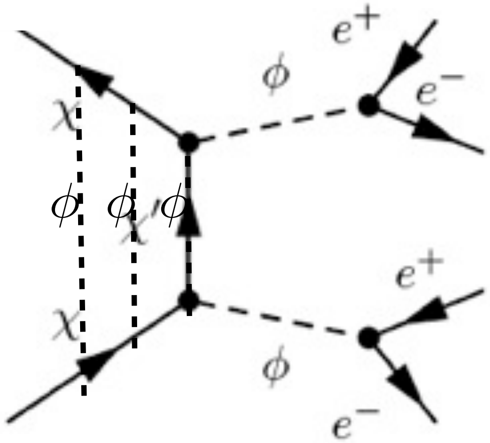
** Future Neutrino experiments like the PINGU enhancement to IceCube/DeepCore offer the possibility of discovery of a smoking-gun signal (high energy neutrinos from the sun), and may provide some of the best constraints on spin dependent cross sections.*

Positron Results



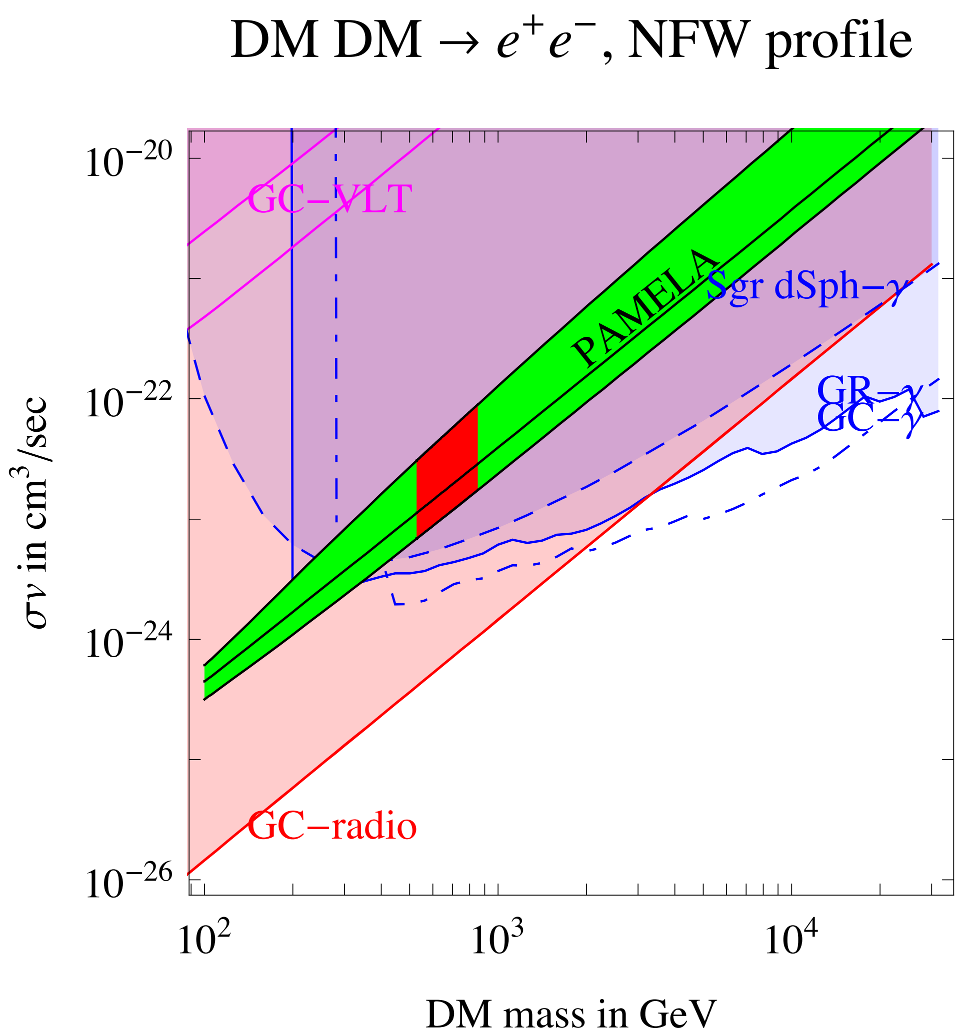


New dark sector force carrier giving a Sommerfeld enhancement, hadronic channels kinematically inaccessible (e.g., Arkani-Hamed, Finkbeiner, Slayter and Weiner, 1999, PRD 79, 015014)



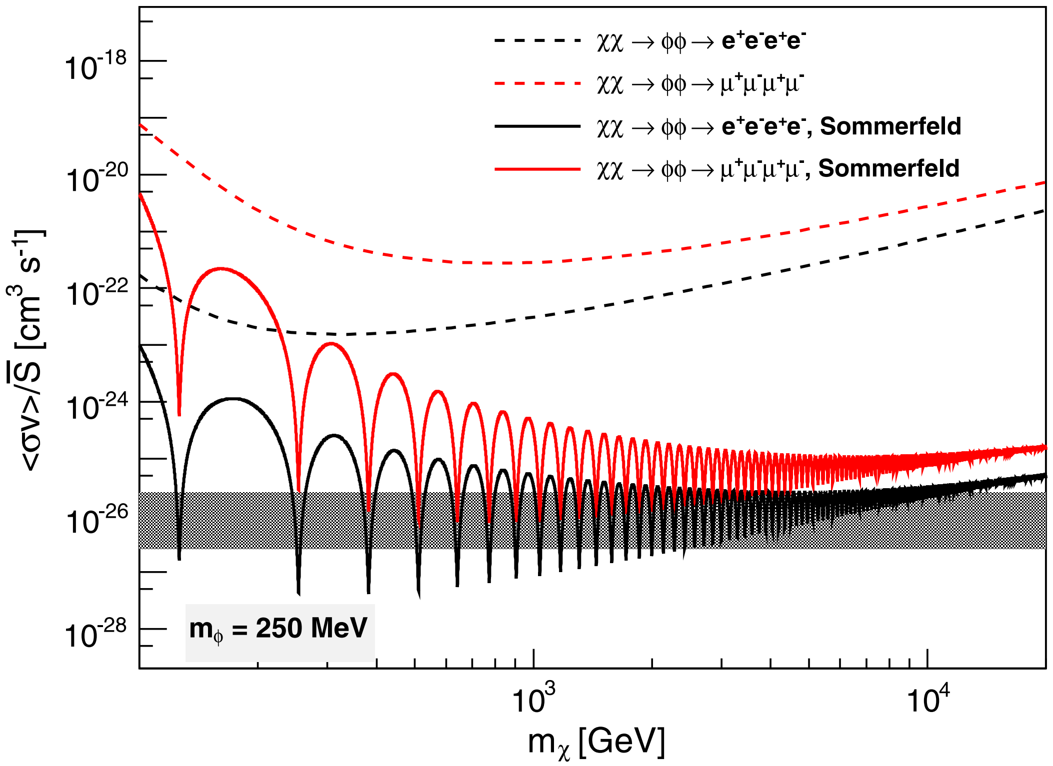
- Pamela results on positron excess are now confirmation by Fermi (using geomagnetic field) and AMS result.
- Signal may also be explained by some cosmic-ray propagation models, or by astrophysical sources such as pulsars.
- A DM interpretation requires a combined astrophysical/particle physics boost of 100 or more.

Shedding Light on Positrons



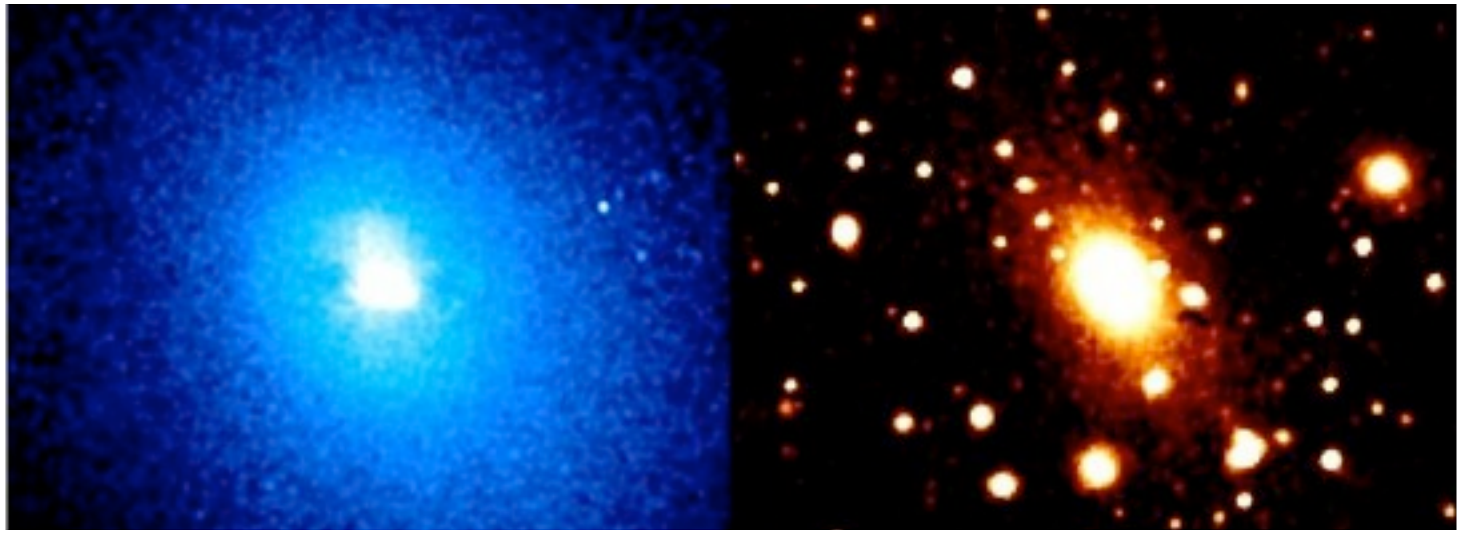
Radio Synchrotron and gamma-ray IC limits for Pamela scenario (Bertone, Cirelli, Strumia and Taoso, arXiv:0811.2744v3). *Note: Radio bounds are sensitive to assumptions about B-fields and diffusion, may be optimistic.*

VERITAS Segue Limits with Sommerfeld Enhancement

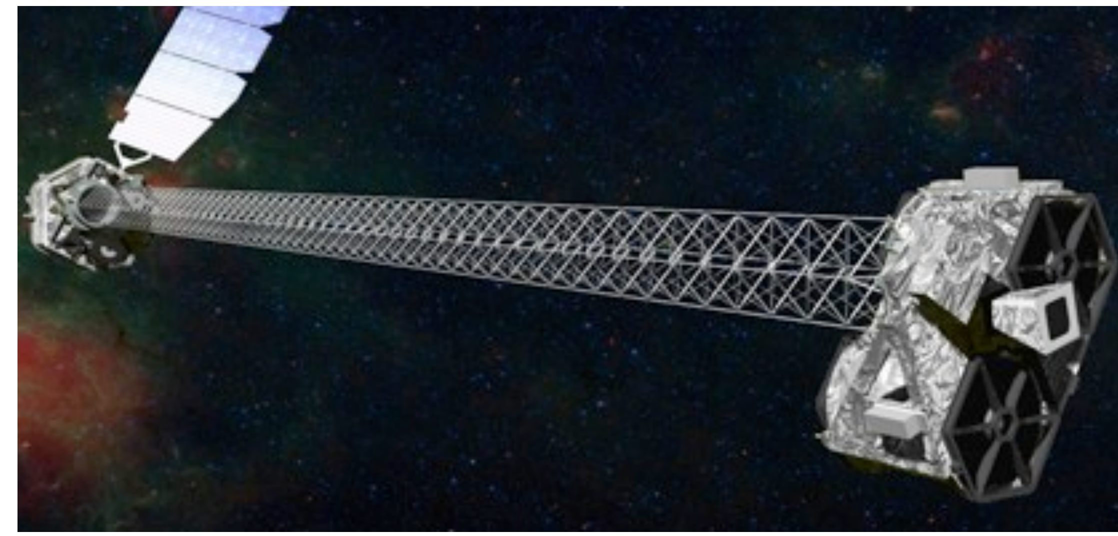


- Pamela excess implies a large radio synchrotron and inverse Compton signal, and a boost in secondary gammas from the GC that are not observed.

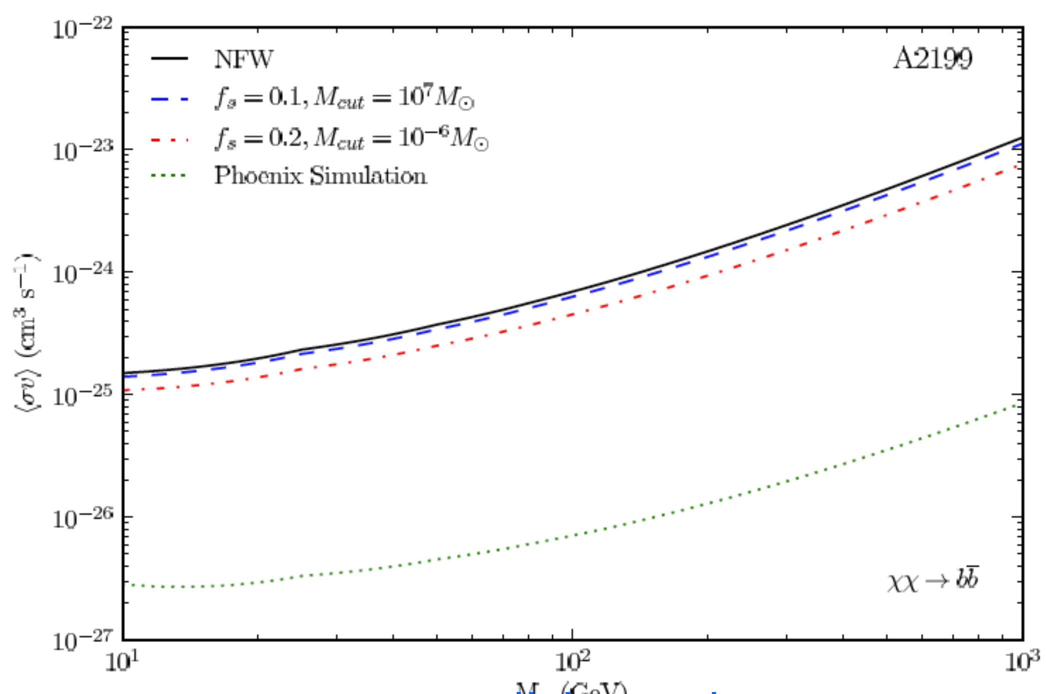
Astrophysical Constraints



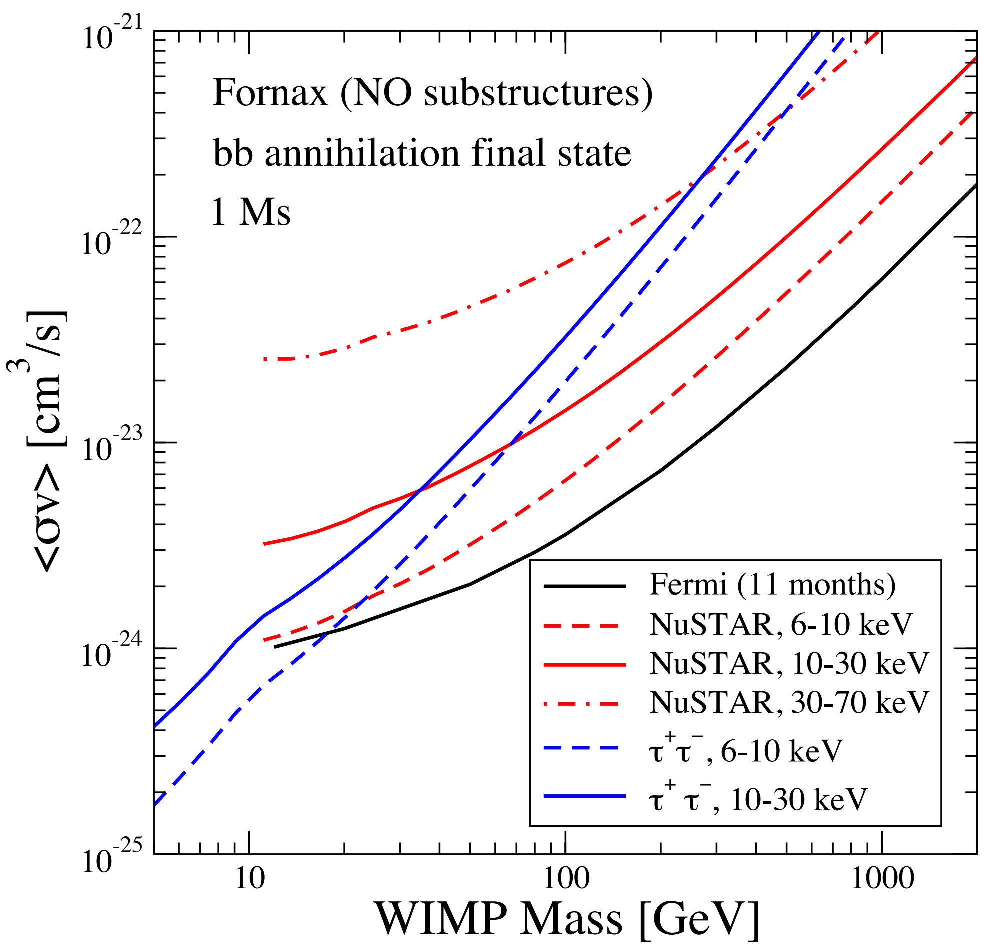
X-Ray (NuSTAR) constraints on Fornax cluster compared with Fermi gamma-ray constraints



Radio Constraints on Galaxy Cluster (A2199)



(SLAC CF Talk by T. Jeltema)



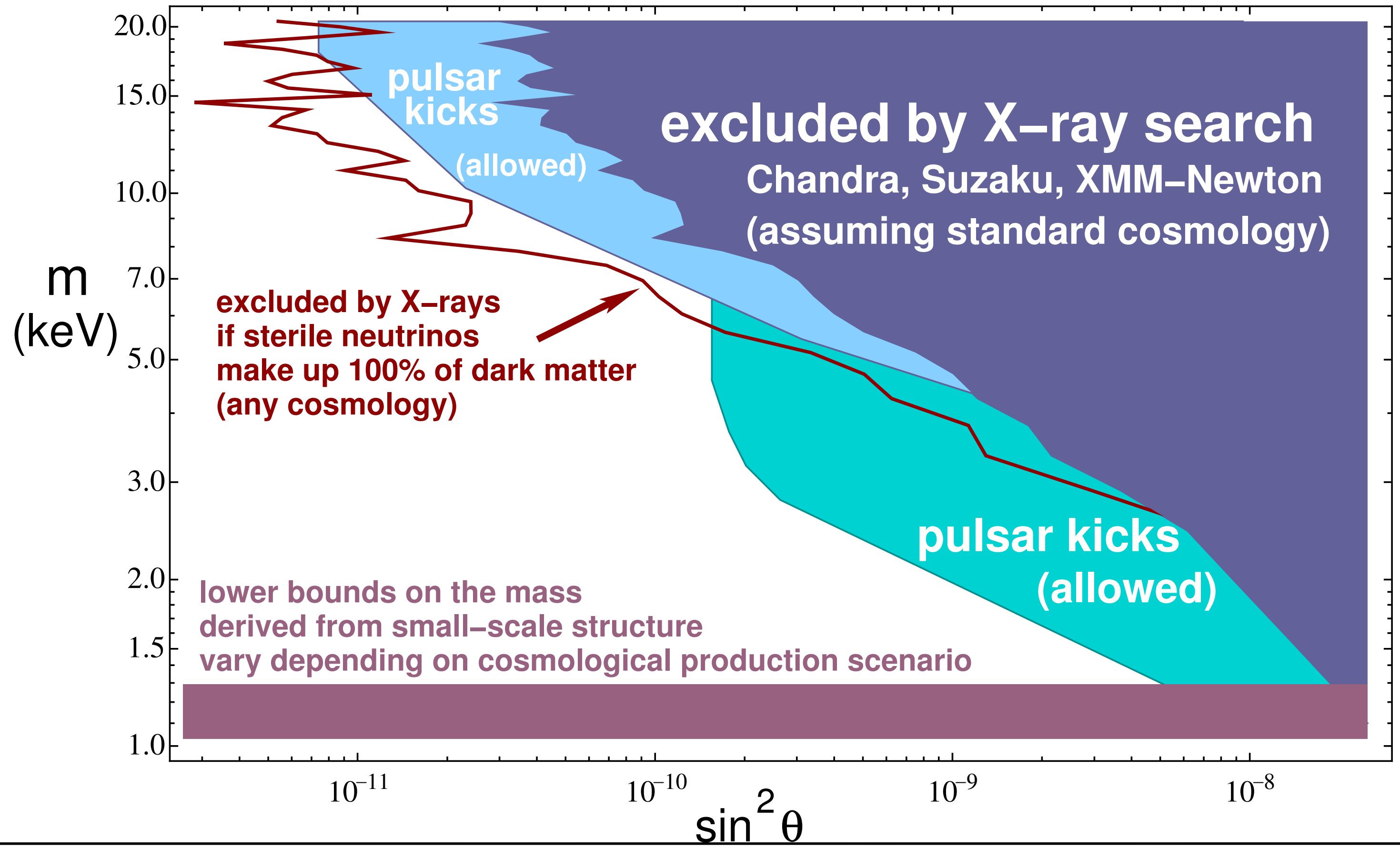
- When the magnetic field and diffusion are understood, radio constraints on DM can be important.
- Electrons up-scatter CMB photons, producing a measurable X-ray signal and DM constraints

Sterile Neutrinos

Chandra

Suzaku

XMM/Newton

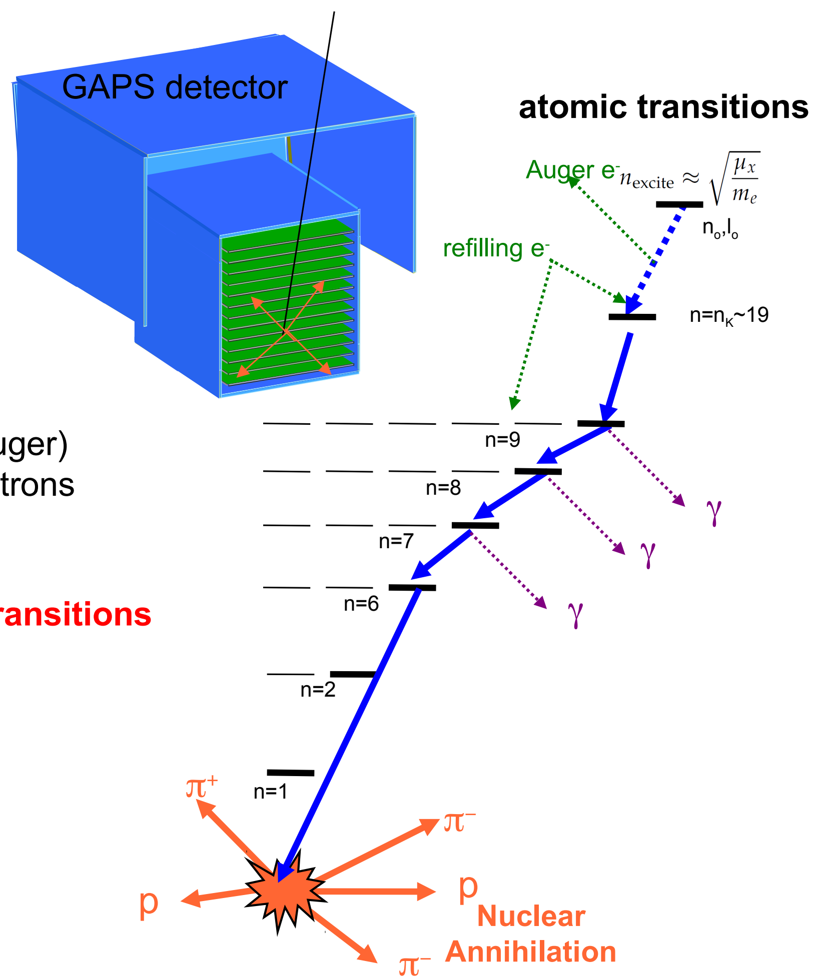


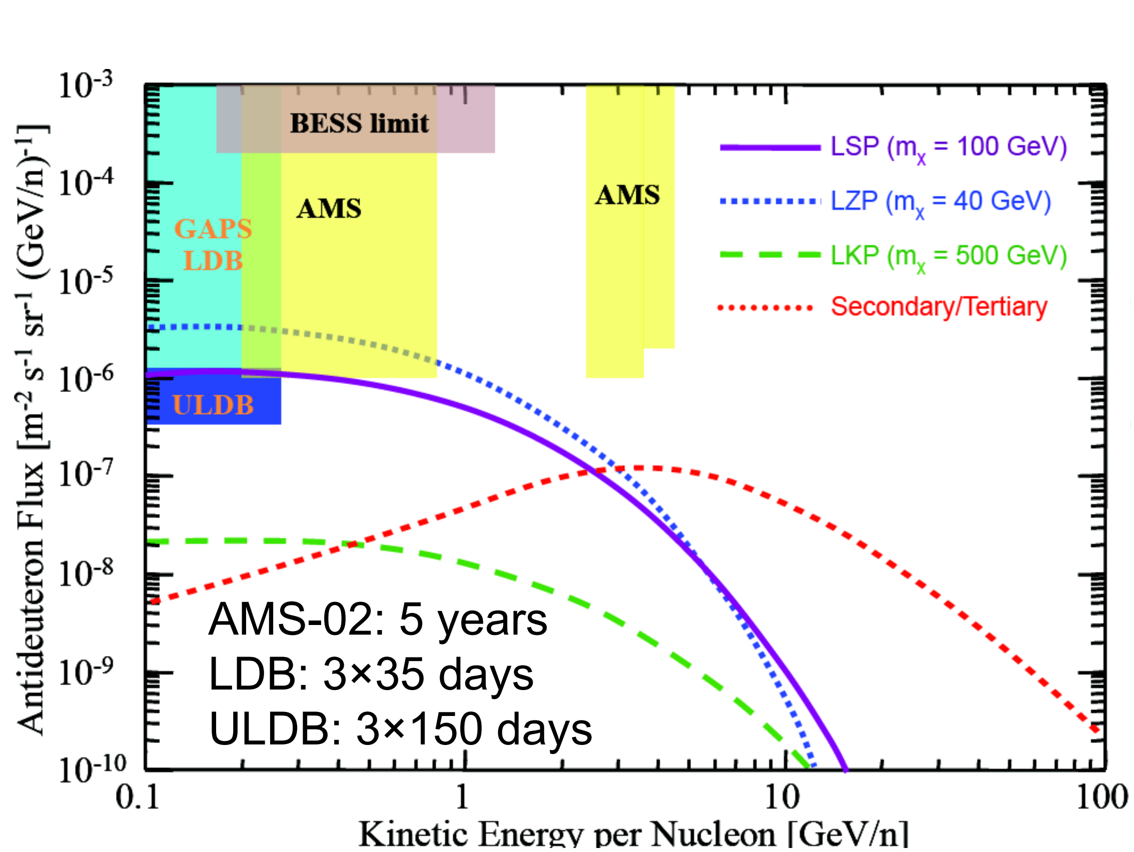
(Loewenstein et al, Astrophys.J. 700 (2009) 426-435; Astrophys.J. 714 (2010) 652-662; Astrophys.J. 751 (2012) 82; Kusenko, Phys.Rept. 481 (2009) 1-28)

GAPS

Novel approach for antideuteron identification

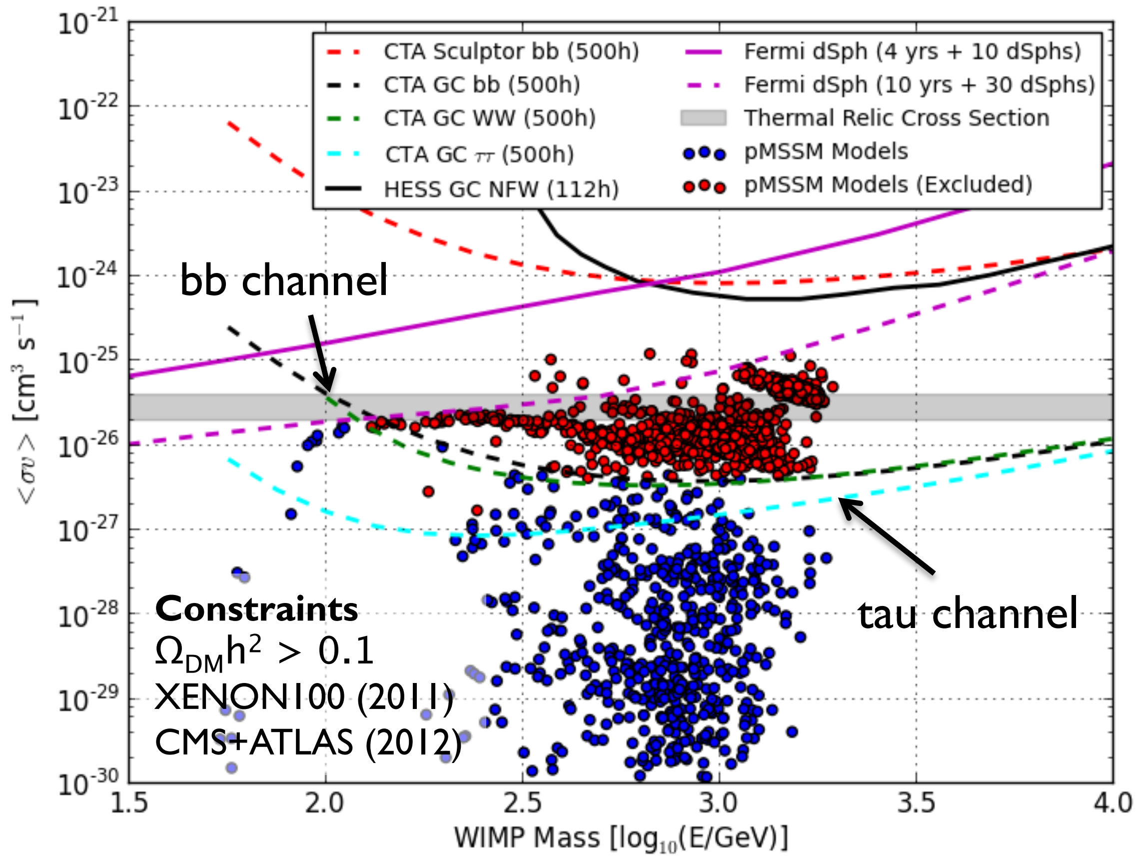
- antideuteron slows down and stops in material
- large chance for creation of an excited exotic atom ($E_{kin} \sim E_l$)
- deexcitation:
  - fast ionisation of bound electrons (Auger) → complete depletion of bound electrons
  - Hydrogen-like exotic atom (nucleus+antideuteron) deexcites via **characteristic X-ray transitions**
- nucleus-antideuteron annihilation: **pions and protons**
- exotic atomic physics understood (tested in KEK 2004/5 testbeam)

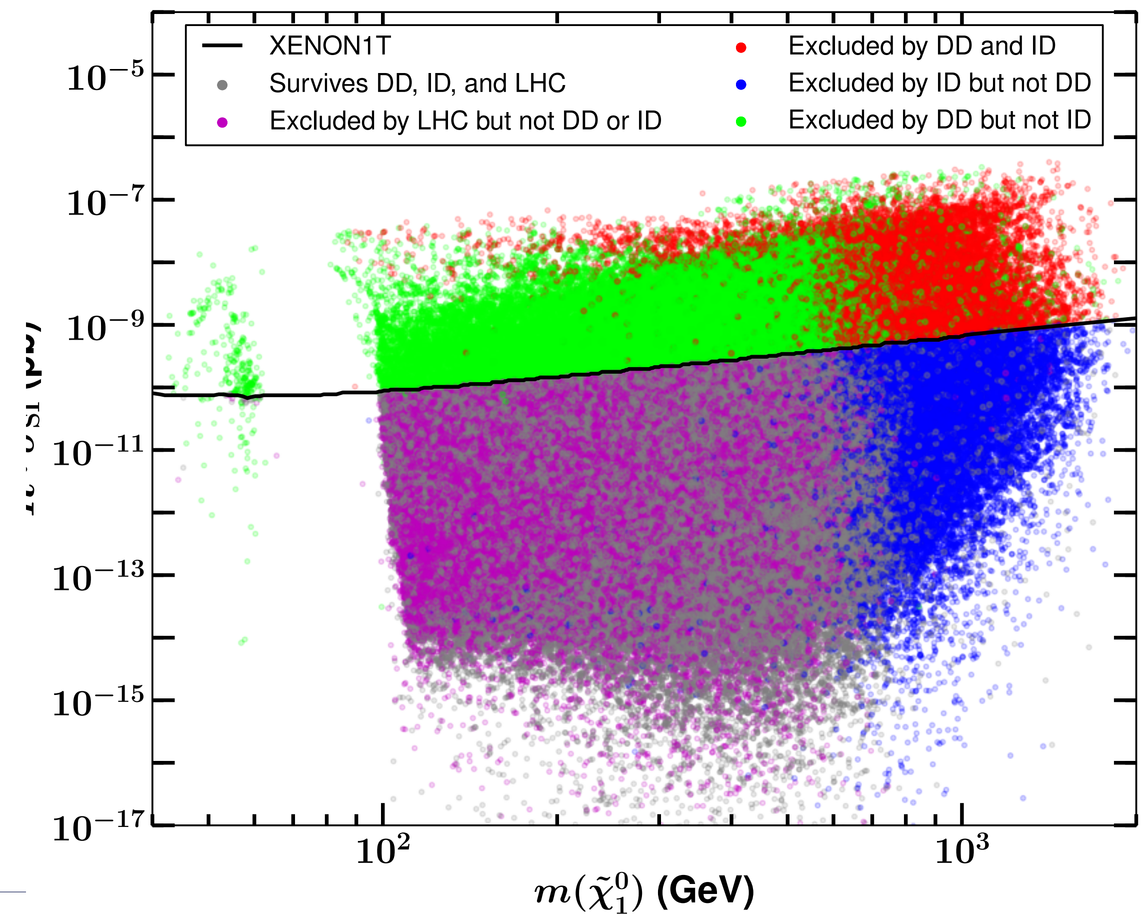




Ph. von Doetinchem | **GAPS** | March 13 - p6

CF2 Key Findings





- CTA, with the U.S. enhancement, would provide a powerful new tool for searching for WIMP dark matter. The angular distribution would determine the distribution of dark matter in halos, and the universal spectrum would be imprinted with information about the mass and annihilation channels needed to ID the WIMP.
- Future Neutrino experiments like the PINGU enhancement to IceCube/DeepCore offer the possibility of a smoking-gun signal (high energy neutrinos from the sun), and may provide some of the best constraints on spin dependent cross sections.
- Other astrophysical constraints such as low-frequency radio (synchrotron from electrons) or X-rays (inverse Compton scattering by electrons, sterile neutrino decay) can provide very powerful tests for DM annihilation for certain annihilation channels and provide constraints on decaying dark matter.
- Detailed theoretical studies with PMSSM, contact operators, realistic halo models are resulting in quantitative estimates of sensitivity, showing the complementary reach of different techniques.

Assembling a Theory of Dark Matter

Tim M.P. Tait
University of California, Irvine

Snowmass
July 29, 2013

What is Dark Matter?

“Cold Dark Matter: An Exploded View” by Cornelia Parker

The Dark Matter Questionnaire

- ☐ Mass
- ☐ Spin
- ☐ Stable?
  - ☐ Yes ☐ No

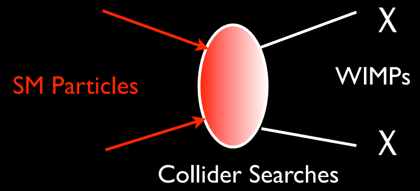
Couplings:

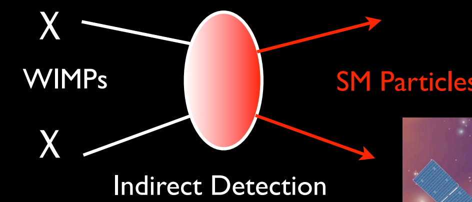
- ☑ Gravity
- ☐ Weak Interaction?
- ☐ Higgs?
- ☐ Quarks / Gluons?
- ☐ Leptons?

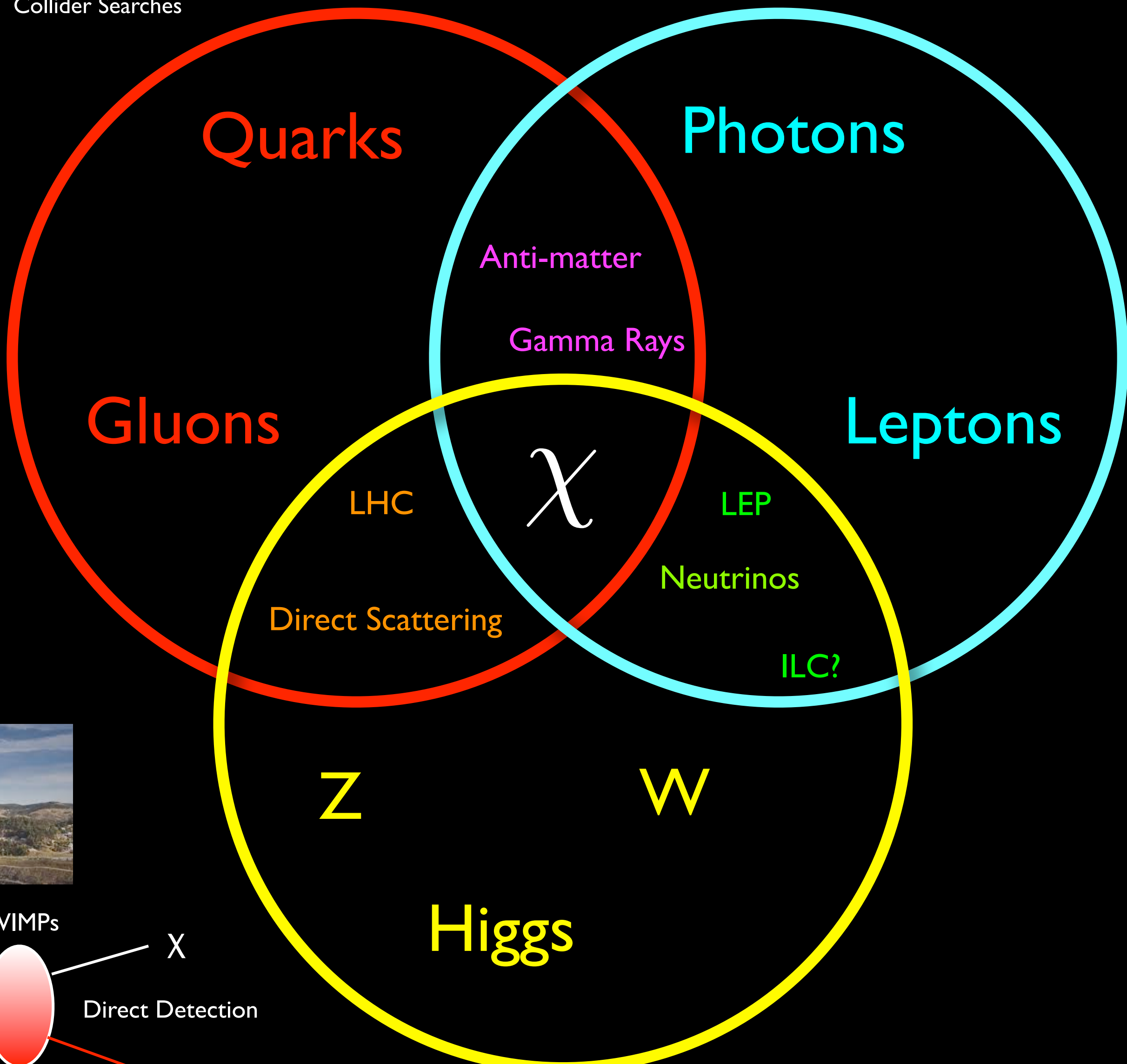
Thermal Relic?

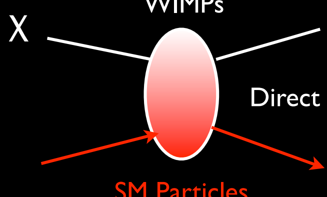
- ☐ Yes ☐ No

Map of DM-SM Interactions





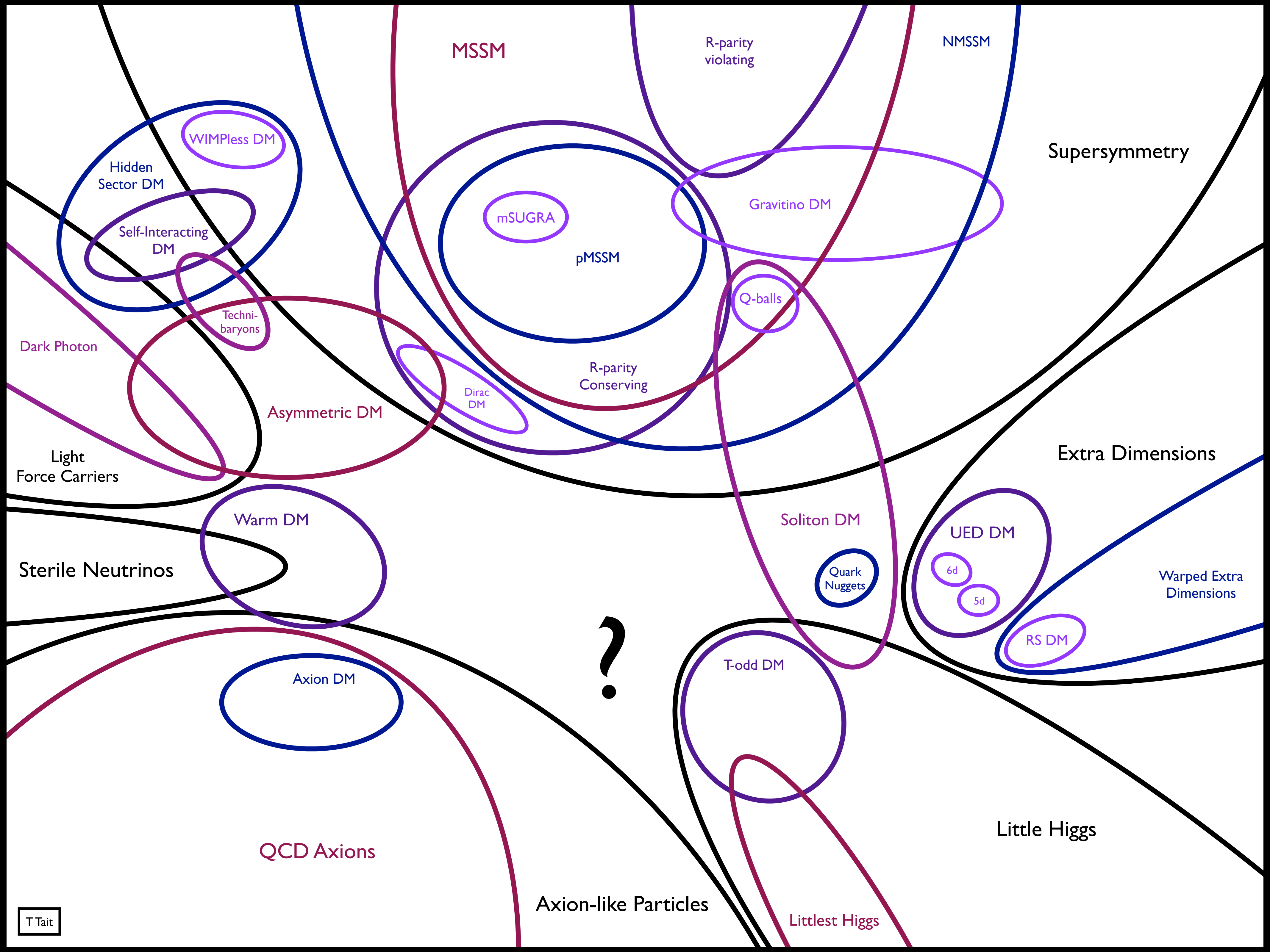


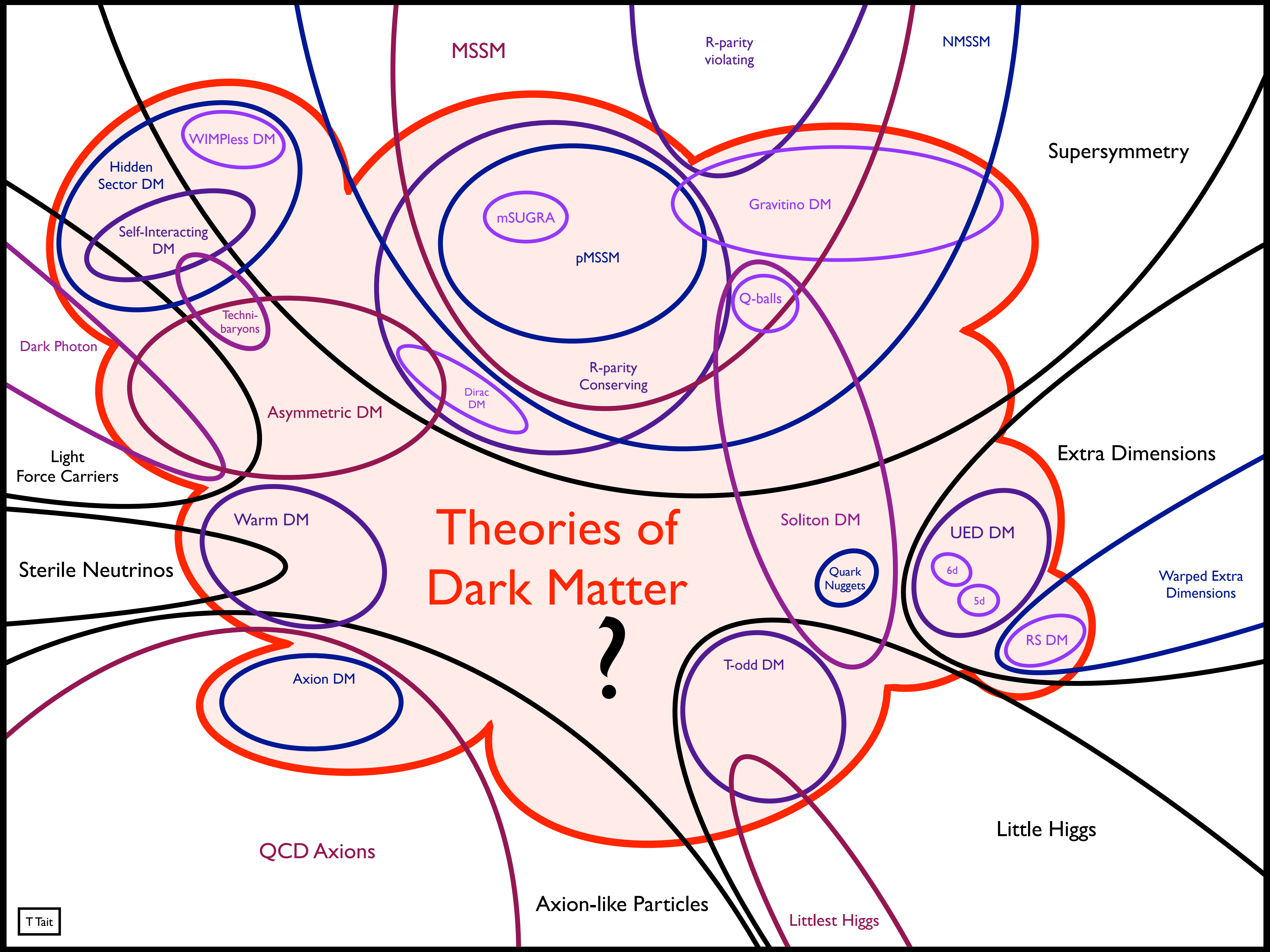


Ultimately, we need to fill out the questionnaire experimentally. But as we try to relate the results of experiments to one another and unravel the deeper theoretical underpinning, we need at least some kind of theoretical framework in which to cast our progress.

What could the theory be?

No lack of possibilities...


MSSM
R-parity
violating
NMSSM
WIMPless DM
Hidden
Sector DM
Supersymmetry
Self-Interacting
DM
mSUGRA
Gravitino DM
pMSSM
Q-balls
Techni-
baryons
Dark Photon
R-parity
Conserving
Dirac
DM
Asymmetric DM
Light
Force Carriers
Extra Dimensions
Warm DM
Soliton DM
UED DM
Sterile Neutrinos
Quark
Nuggets
6d
Warped Extra
Dimensions
5d
?
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait



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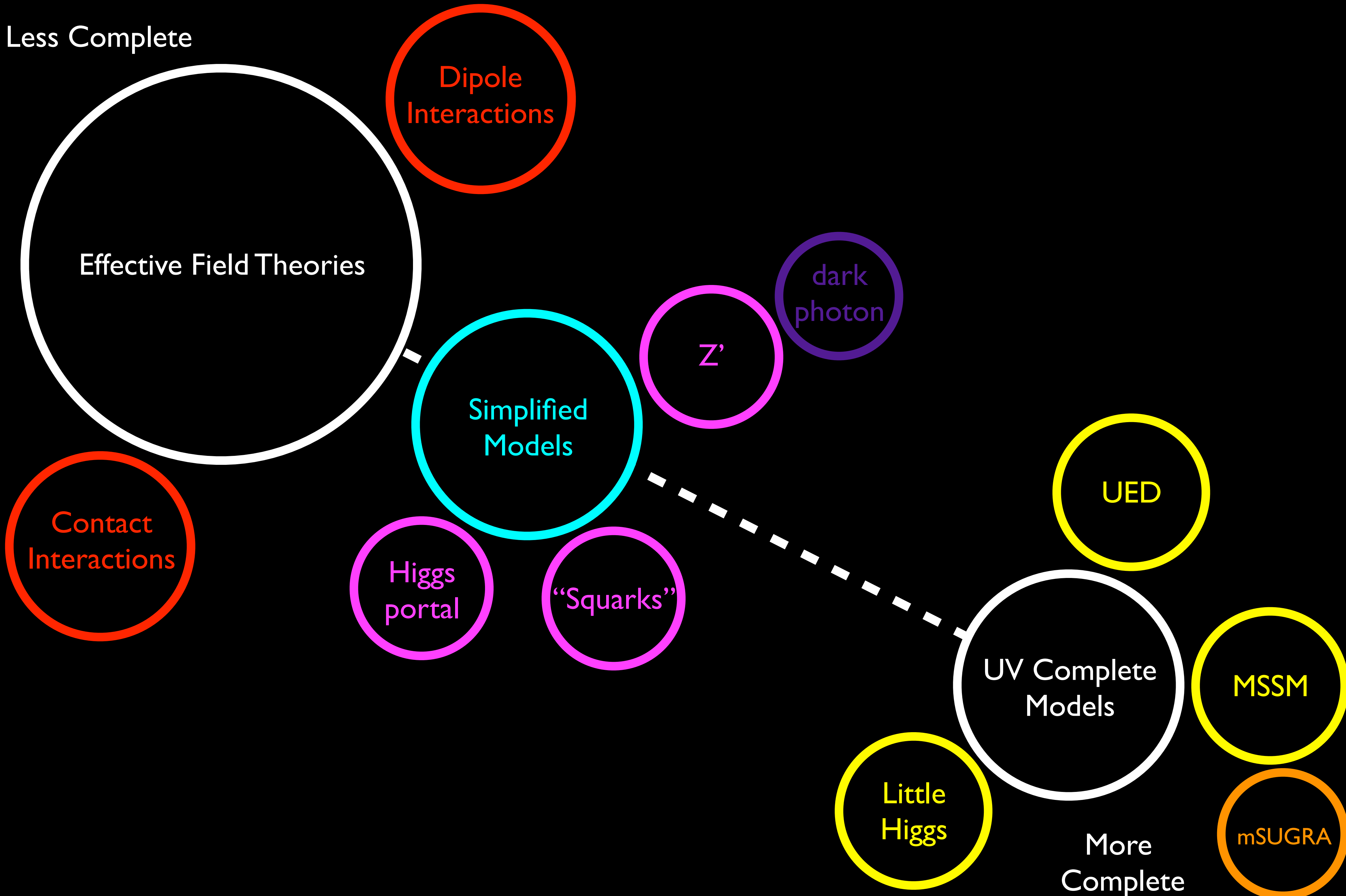
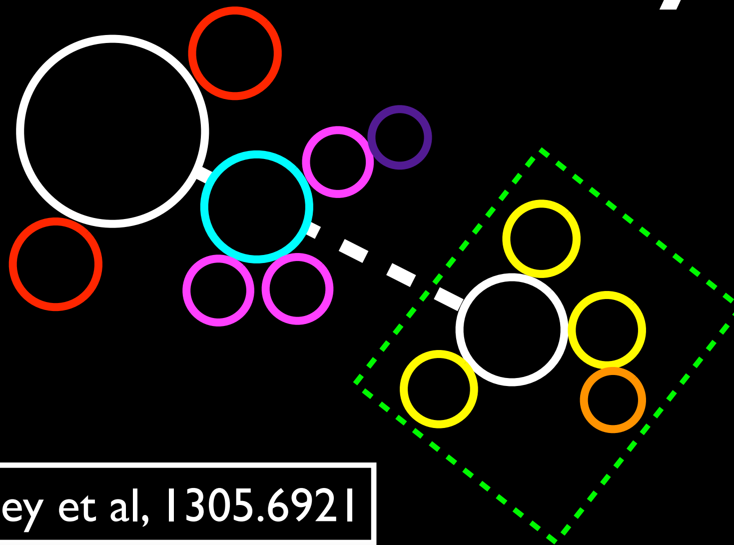
Spectrum of Theory Space

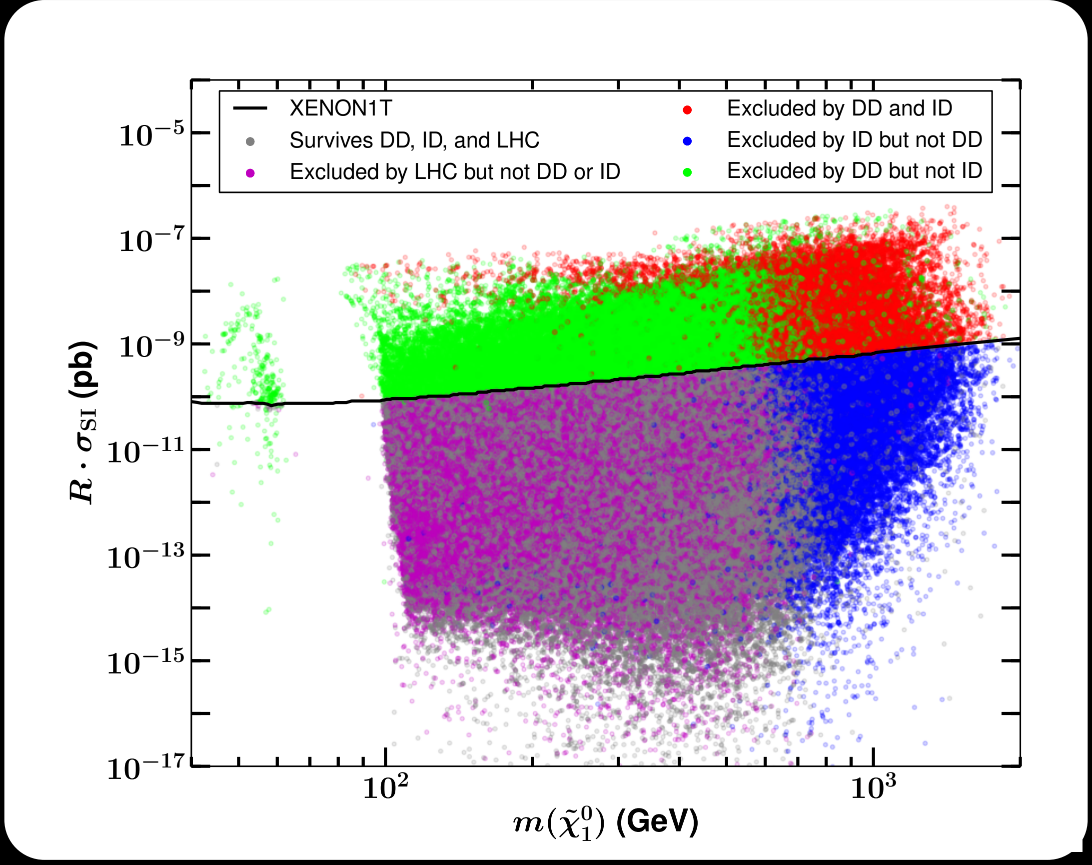


The Most Complete Theory

- On the "complete" end of the spectrum is our favorite theory: the MSSM.
- Reasonable phenomenological models have ~20 parameters, leading to rich and varied visions for dark matter.
- This plot shows a scan of the `pMSSM' parameter space in the plane of the WIMP mass versus the SI cross section.
- The colors indicate which (near) future experiments can detect this model: LHC only, Xenon 1ton only, CTA only, both Xenon and CTA, or can't be discovered.
- It is clear that just based on which experiments see a signal, and which don't, that there could be (potentially soon) suggestions of favored parameter space(s) from data.



Cahill-Rowley et al, 1305.6921



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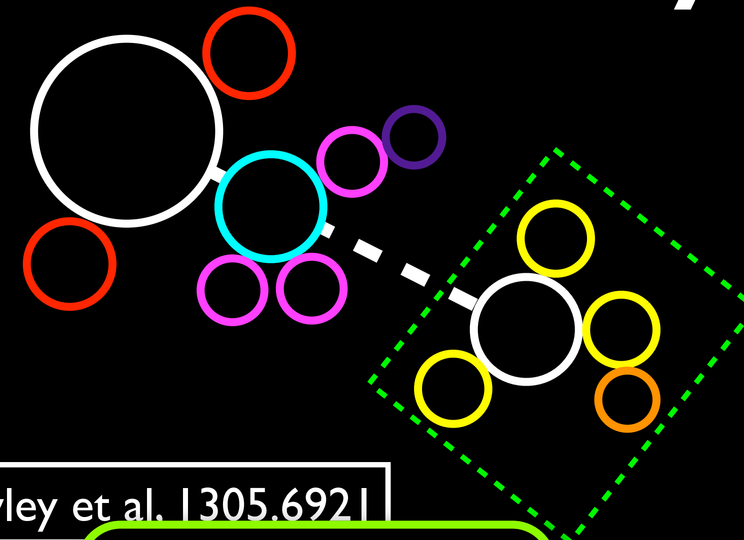

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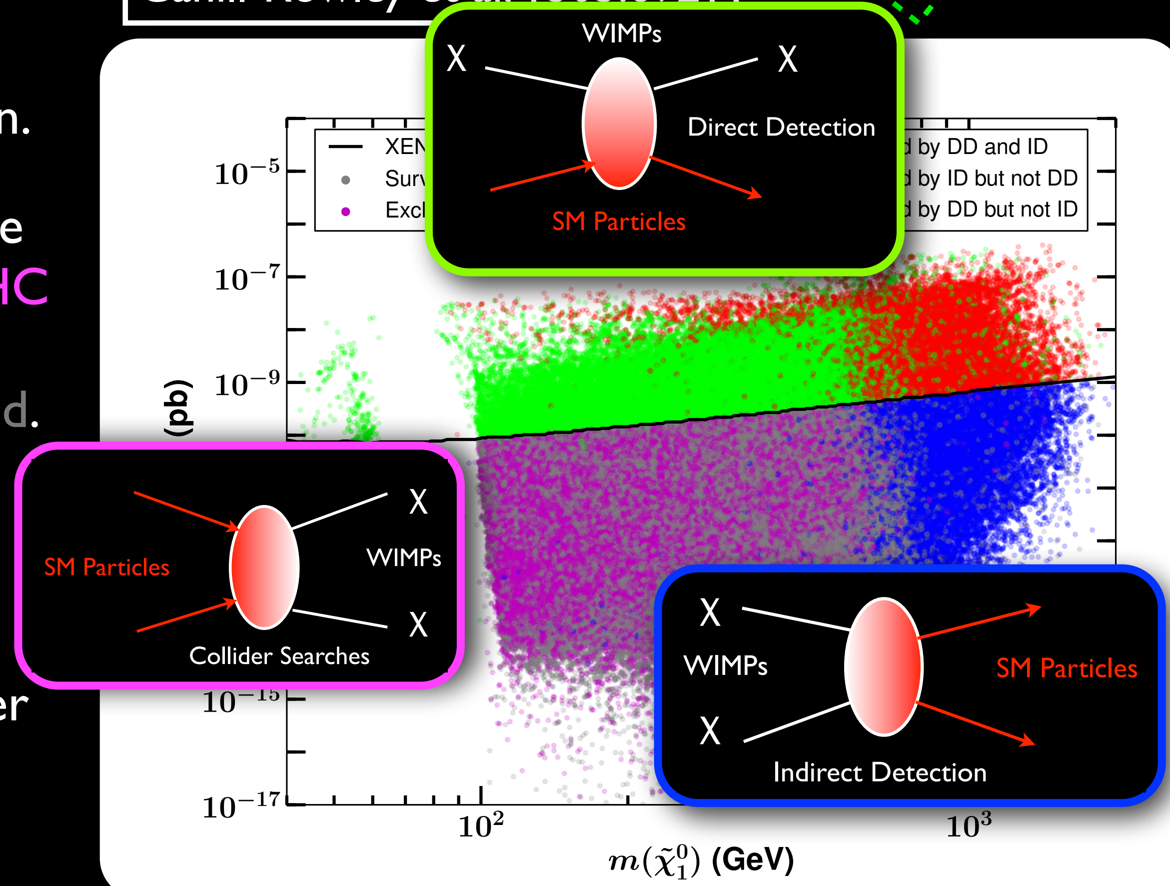
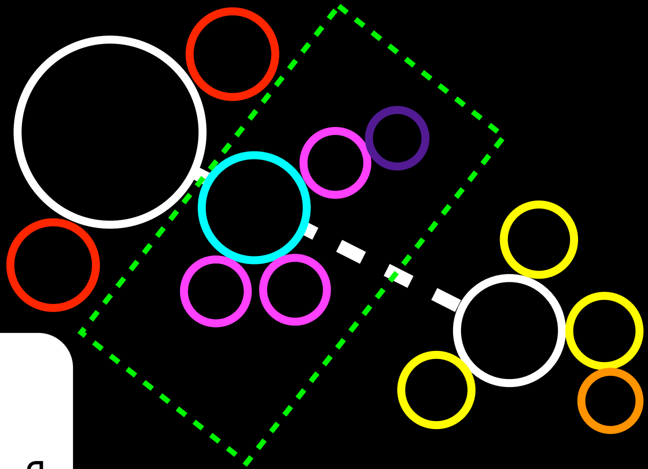
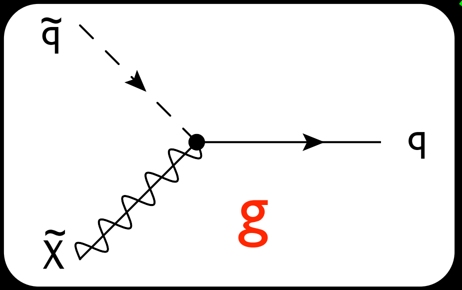
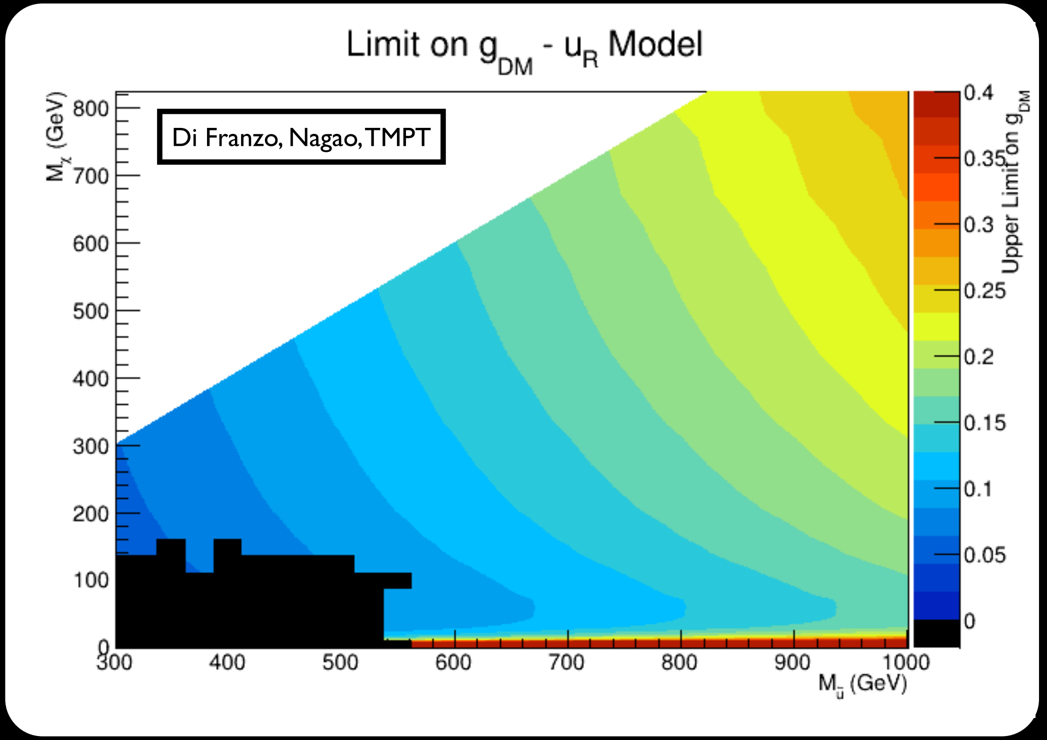


Simplified Models

- Moving away from complete theories, we come to simplified models.
- These contain the dark matter, and some of the particles which allow it to talk to the SM, but are not meant to be complete pictures.
- As a simple example, we can look at a theory where the dark matter is a Dirac fermion which interacts with a quark and a (colored) scalar mediating particle.
- There are three parameters: the DM mass, the mediator mass, and the coupling g.
- These are like the particles of the MSSM, but with subtle differences in their properties and more freedom in their interactions.
- Just like the MSSM was one example of a complete theory, this is only one example of a "partially complete" one.







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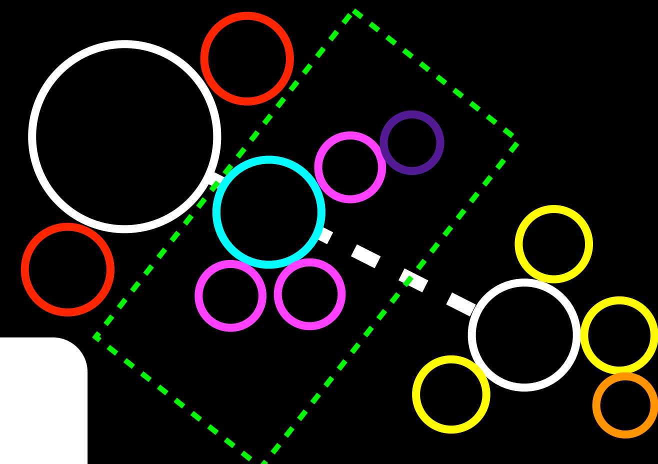
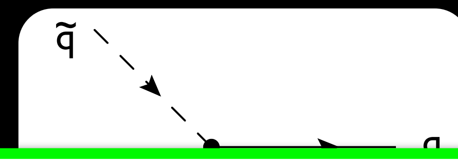
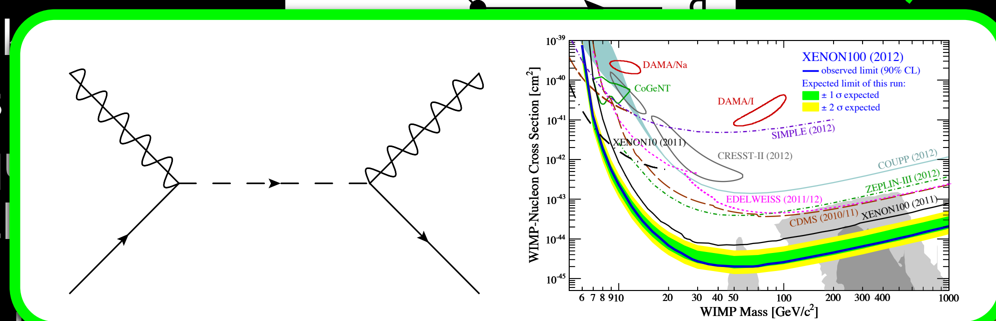
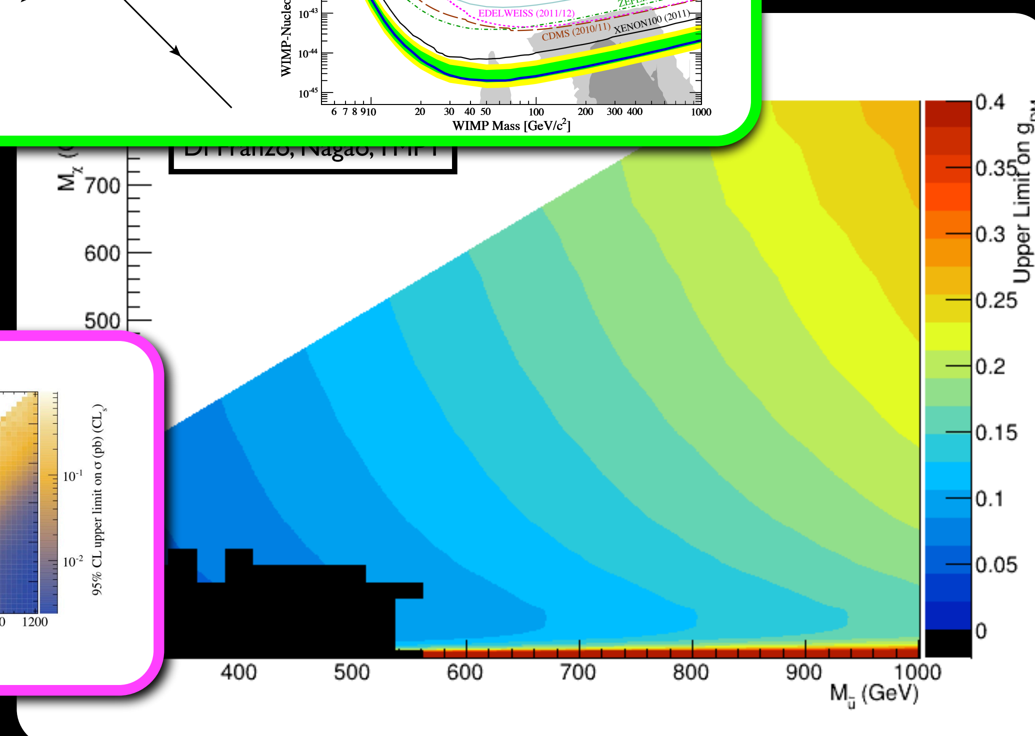
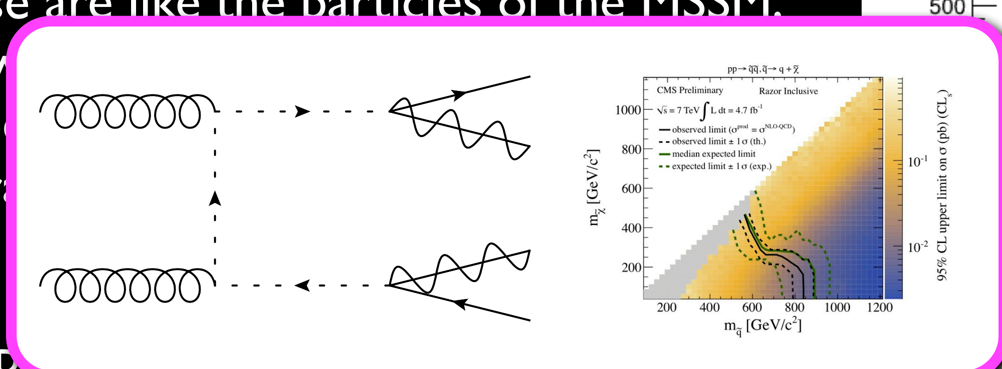


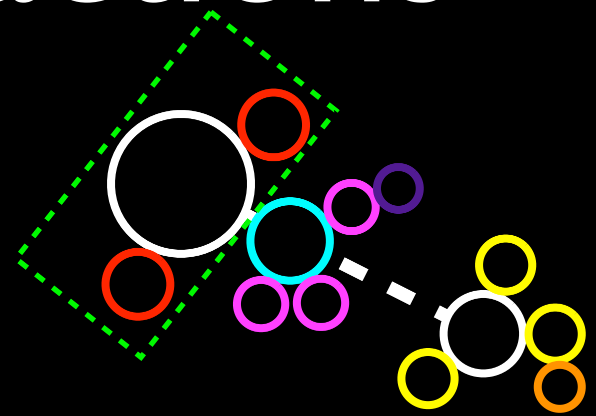




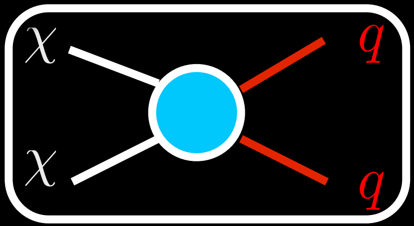


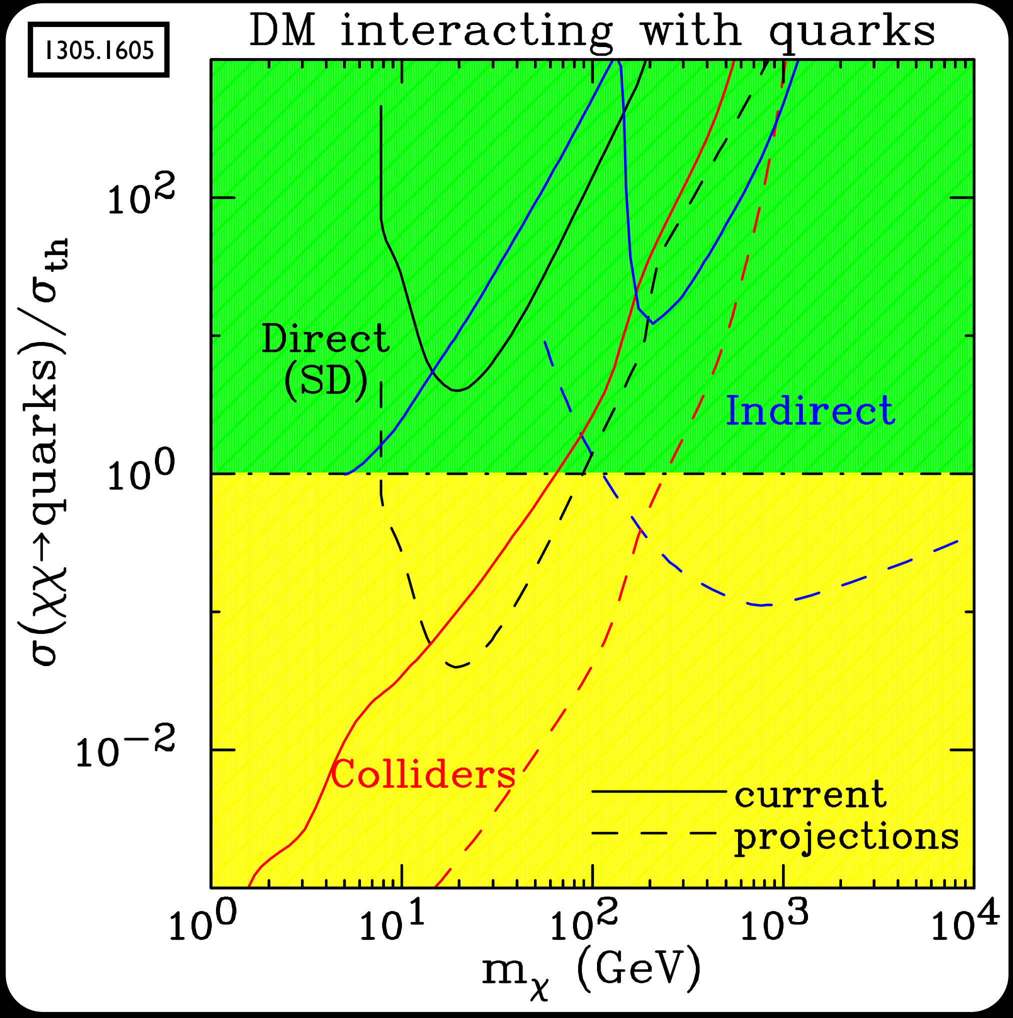


Contact Interactions



- In the limit where the mediating particles are heavy compared to all energies of interest, we are left with a theory containing the SM, the dark matter, and nothing else.
- The residual effects of the mediators are left behind as what look like non-renormalizable interactions between DM and the SM.





- These are the simplest and least complete description of dark matter we can imagine.
- For any particular choice of interaction type, there are two parameters: the DM mass and the strength of that interaction.

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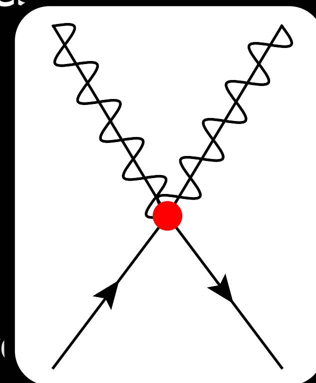

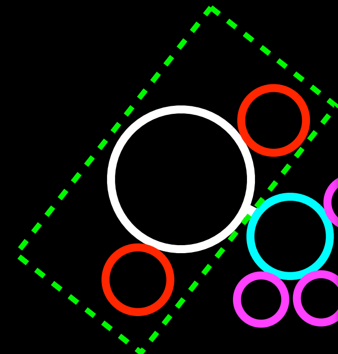

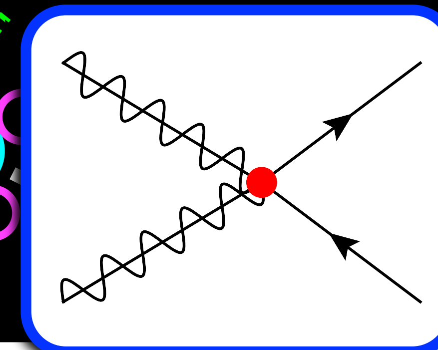

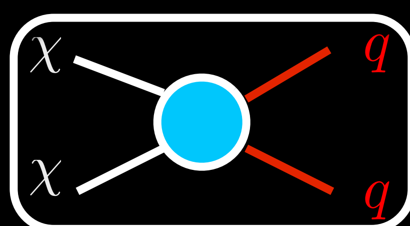

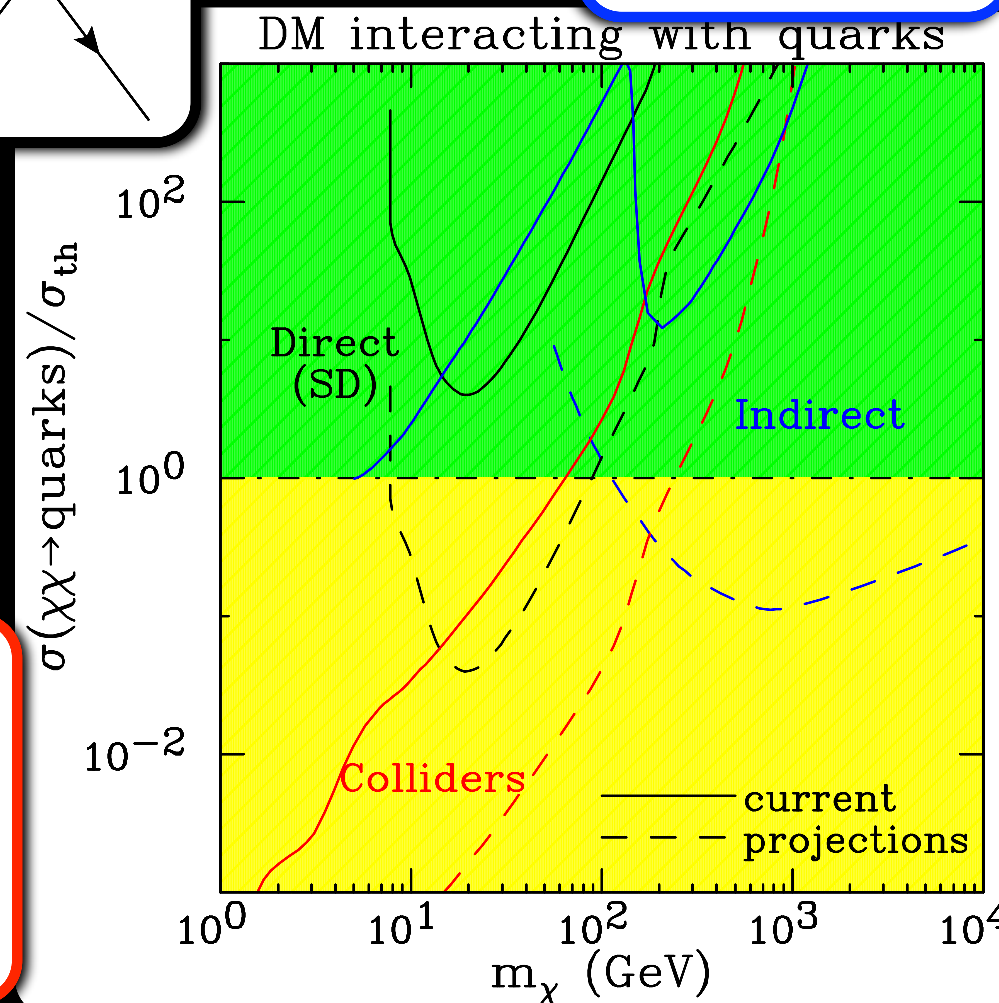

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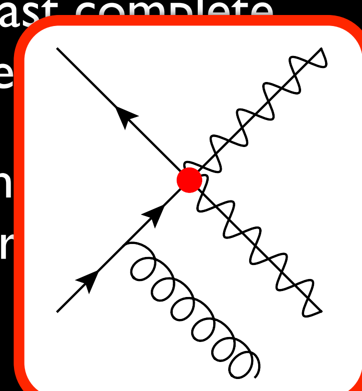
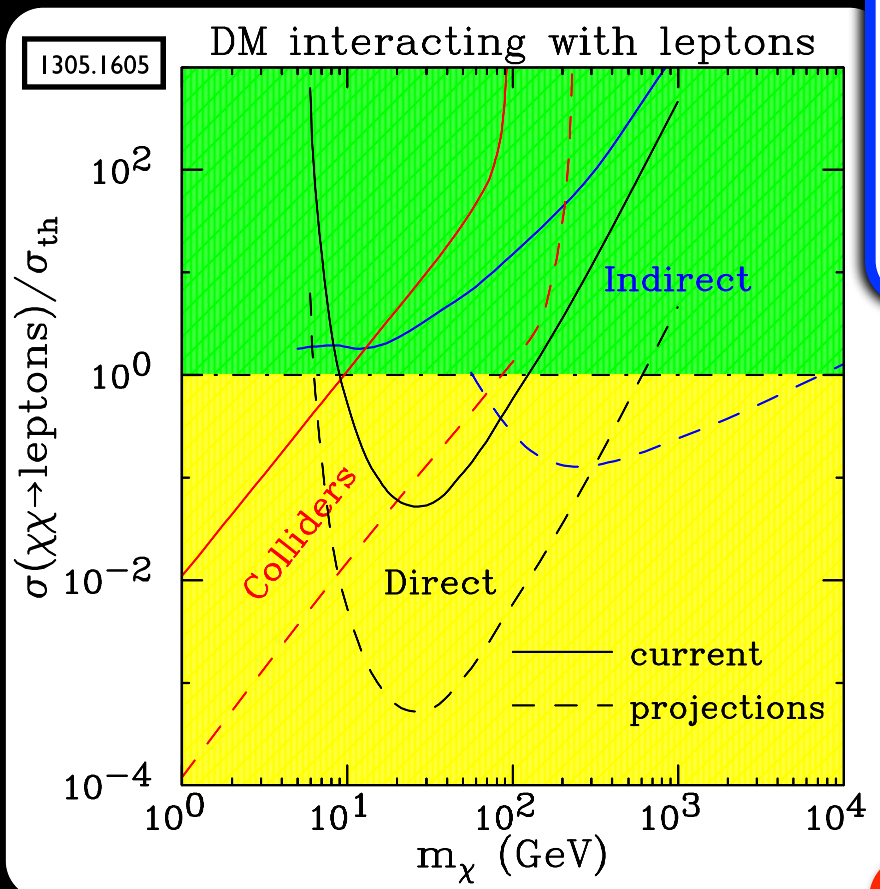
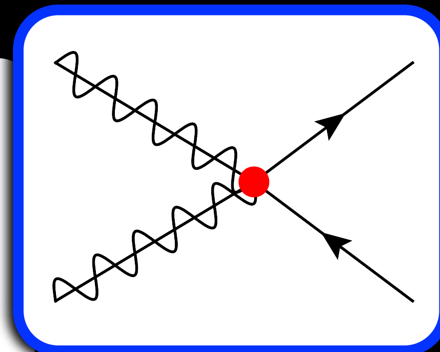
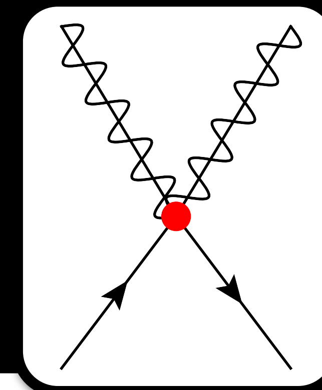
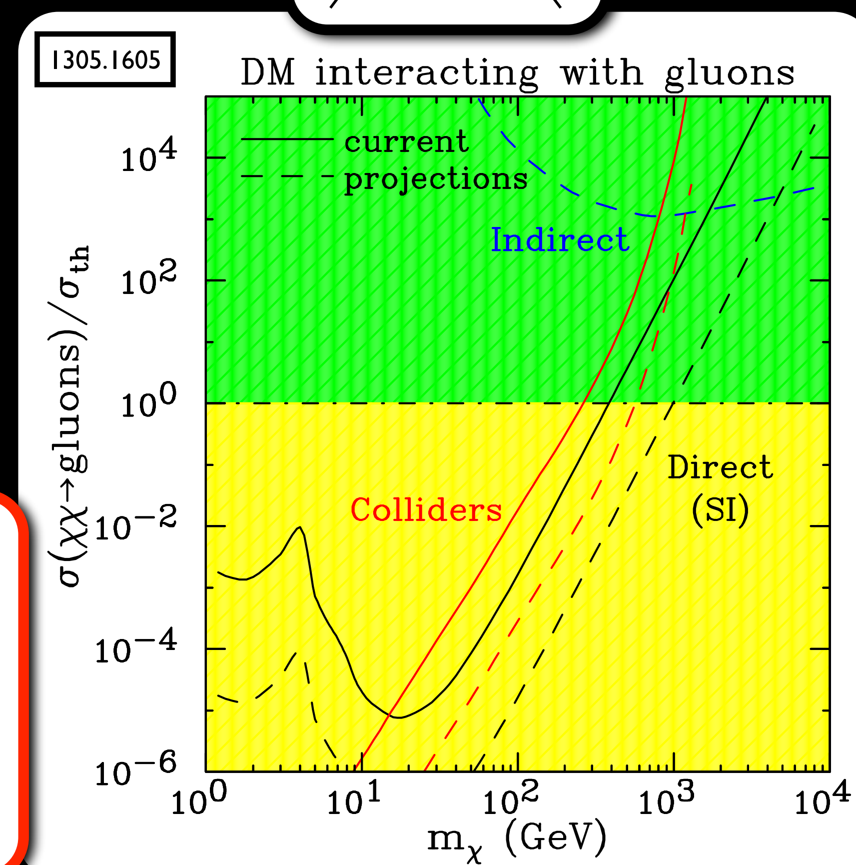


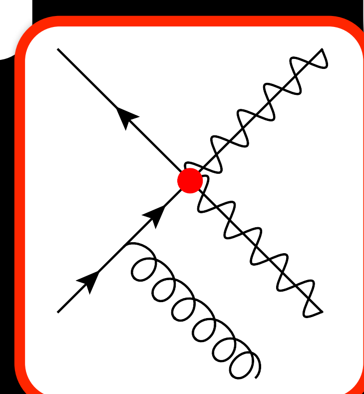
Lepton/Gluon Interactions











A Possible Timeline

2013

2014

LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.

2015

2016

2017

2018

- [?] Mass: < 200 GeV
- [ ] Spin
- [ ] Stable?

Couplings:

- [x] Gravity
- [ ] Weak Interaction?
- [ ] Higgs?
- [x] Quarks / Gluons?
- [ ] Leptons?
- [ ] Thermal Relic?

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LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.

Fermi observes a faint gamma ray line at 150 GeV from the galactic center.

- ☑ Mass: 150 +/- 15 GeV
- ☐ Spin
- ☐ Stable?

Couplings:

- ☑ Gravity
- ☐ Weak Interaction?
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A Possible Timeline

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YOU ARE HERE

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Two LHC experiments see a significant excess of leptons plus missing energy.

Xenon sees a similar signal.

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No jets + MET

Neutrinos are seen coming from the Sun by IceCube.

- ☑ Mass: 150 +/- 15 GeV
- ☑ Spin: > 0
- ☐ Stable?

Couplings:

- ☑ Gravity
- ☒ Weak Interaction?
- ☐ Higgs?
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A Possible Timeline

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YOU ARE HERE

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A positive signal of axion conversion is observed at an upgraded ADMX.

Two LHC experiments see a si... lept...

Fermi observes a faint gamma ray line at 150 GeV from the galactic center.

☑ Mass: 150 +/- 15 GeV	☑ Mass: 20 μeV
☑ Spin: > 0	☑ Spin: 0
☐ Stable?	☐ Stable?
Couplings:	Couplings:
☑ Gravity	☑ Gravity
☒ Weak Interaction?	☑ Weak Interaction
☐ Higgs?	☐ Higgs?
☑ Quarks / Gluons	☐ Quarks / Gluons?
☑ Leptons	☐ Leptons?
☐ Thermal Relic?	☒ Thermal Relic?

A Possible Timeline

2013

YOU ARE HERE

2014

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2018

????

☑ Mass: 150 +/- 0.1 GeV	☑ Mass: 20 μeV
☑ Spin: > 0	☑ Spin: 0
☐ Stable?	☐ Stable?
Couplings:	Couplings:
☑ Gravity	☑ Gravity
☒ Weak Interaction?	☑ Weak Interaction
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A multi-pronged search strategy identifies a mixture of dark matter which is 50% classic WIMP and 50% axion.

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Outlook

- Putting together a detailed particle description of dark matter will necessarily involve many experimental measurements.
- Important details such as the mass and spin will hopefully come along as part of that program.
- The three traditional pillars of dark matter searches: direct, indirect, and collider, naturally probe different parts of the space of DM-SM couplings.
  - They are highly complementary to one another in terms of discovery potential.
  - Together they can probe a large fraction of the space of interesting WIMP models in the near future.
  - Input from all of them is likely to be necessary to reconstruct enough of the couplings to be able to firmly understand the dark matter relic density.

" Ωh^2 or bust! "