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The Nature of Dark Matter: Where are we?

What has cosmology to say?

Remarkable with Lambda CDM
Potential problem: Dwarf galaxies

What can particle physics say?

(Neutrinos, Axions: no time)
Hierarchy Problem: Weakly Interacting Massive Particles (Higgs, Supersymmetry)
A complex dark matter sector?

Direct searches for Dark Matter Particles

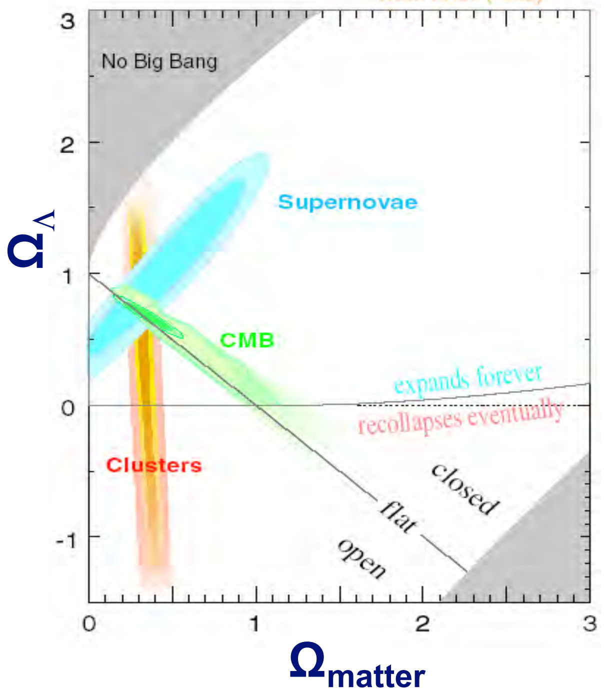
High mass region: situation and prospects
Low mass region: a 7 GeV WIMP?
What would it take to make a discovery?

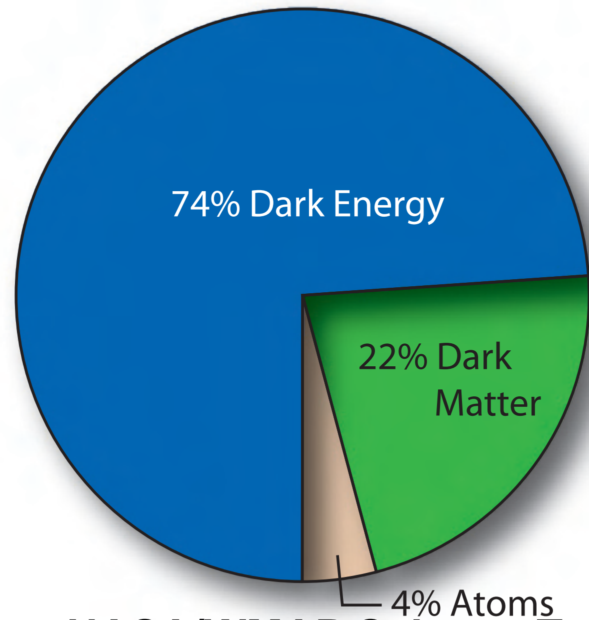
Indirect Searches

130 GeV?

Standard Model of Cosmology

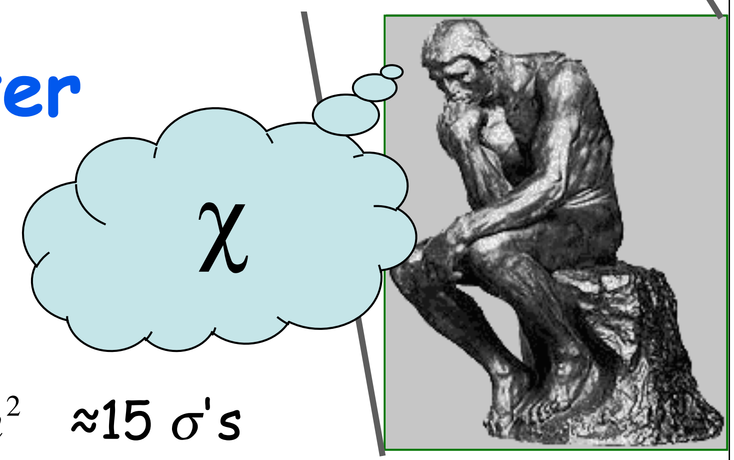
A surprising but consistent picture





Dark Matter is not ordinary matter (Baryons)

$\Omega_m >> \Omega_b = 0.047 \pm 0.006$ from Nucleosynthesis / WMAP

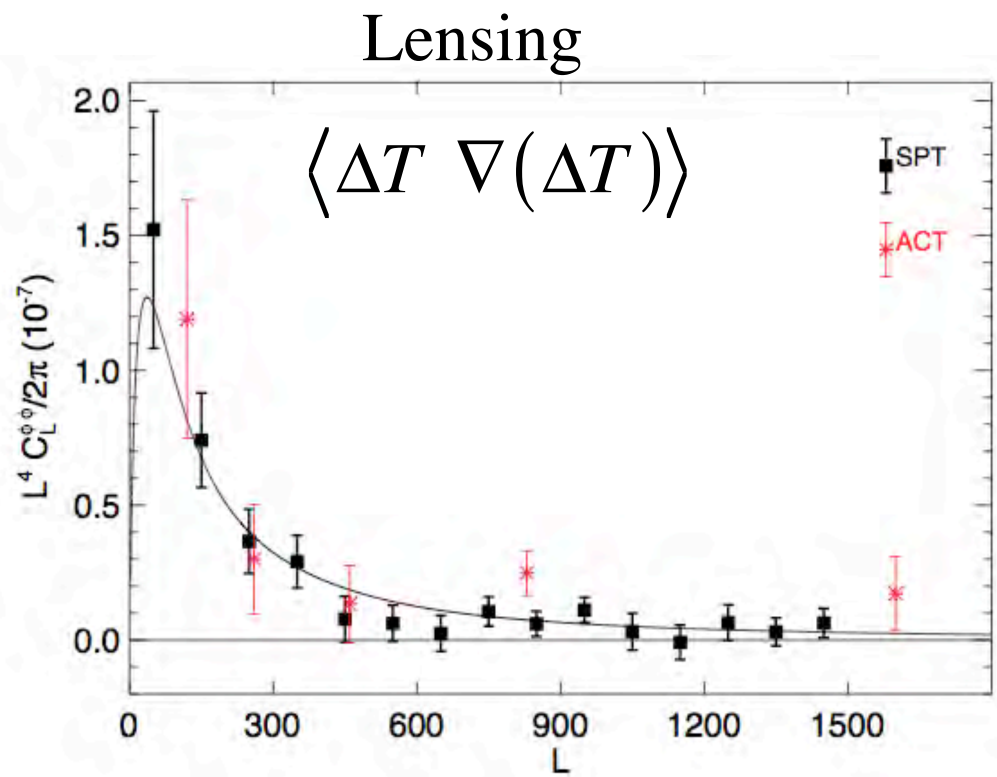


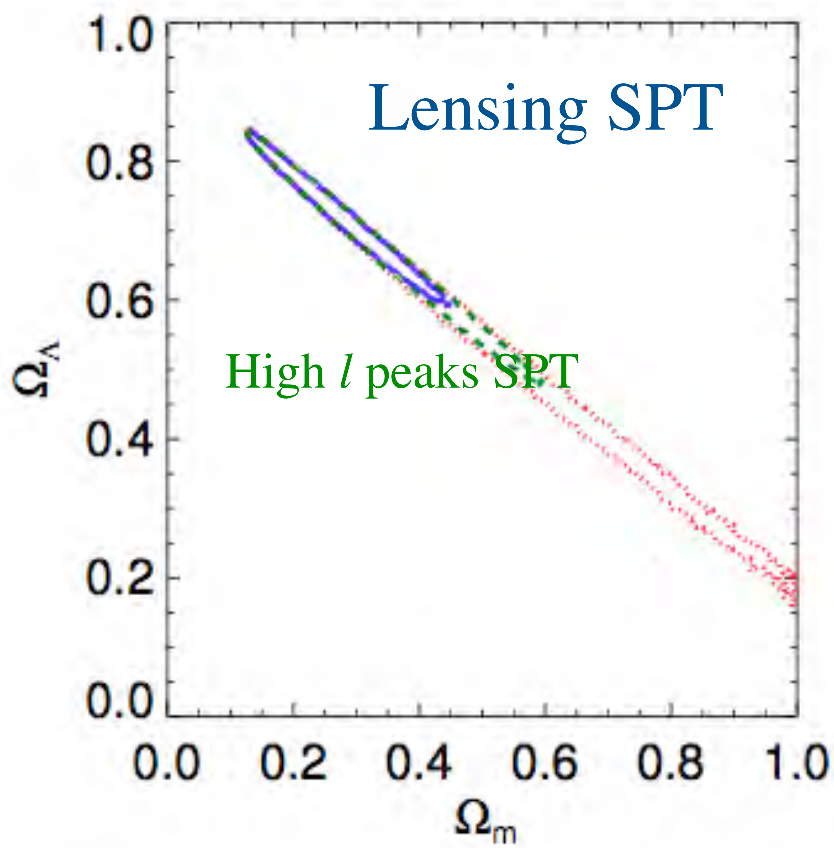
+ internally to WMAP $\Omega_m h^2 \neq \Omega_b h^2$ ≈15 σ's

=> Mostly cold: Not light neutrinos ≠ small scale structure

Lensing signal in CMBR

Independent confirmation of "dark energy": detection of gravitational lensing 2012

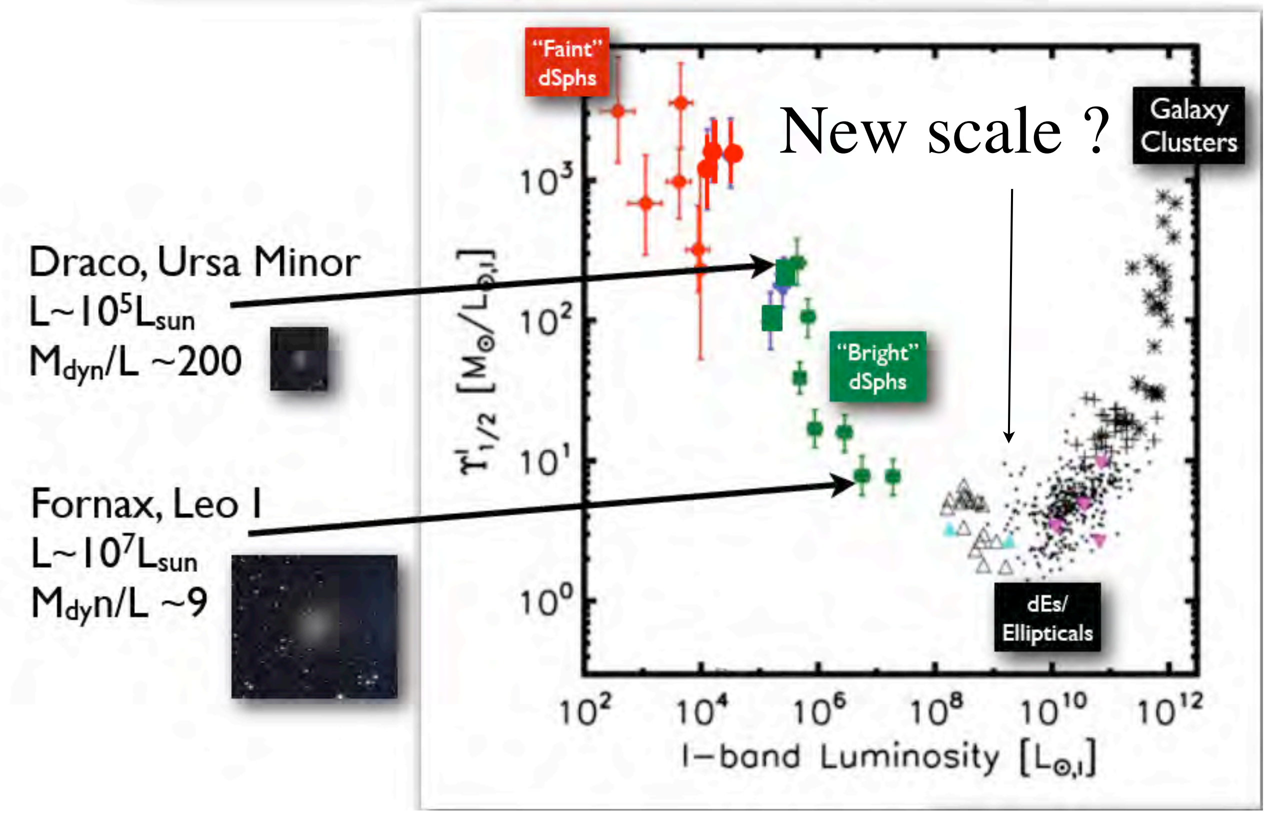




Recent Progress on Dark Matter

Remarkable agreement with Lambda CDM

Main difficulty: Dwarf Spheroidals, a new scale!



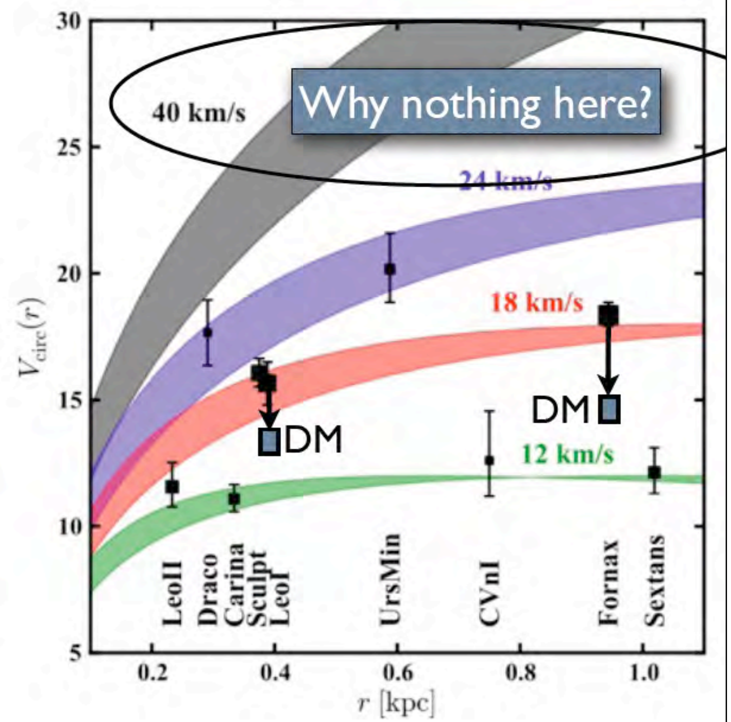
Dwarf Spheroidals

2 distinct problems

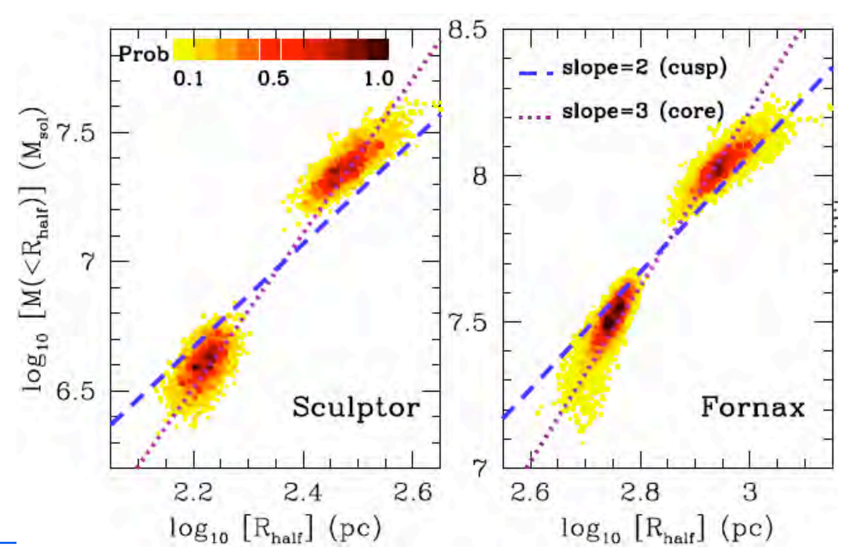
1) The number of satellites
but we keep discovering small ones

Not enough large mass satellites: Too big to fail

Frenk et al.
Bullock et al.



2) The density profile: NFW or core?
Basic degeneracy between velocity anisotropy and density profile
Walker and Penarrubia: break the degeneracy for Fornax and Sculptor with two populations of stars -> Core!



Is this the end of Lambda CDM?

2 ways to fix it?

New scale provided by either astrophysics or particle physics

Astrophysics

Mass of the Milky Way: but other problems (M31, LMC,Leo proper motion)

Baryon ejection

- In practice very difficult to eject enough (energetics with current stars)
- Ejection early on?
- Relative velocity of dark matter and baryon

Particle Physics

- Heavy (≈ keV) sterile neutrino: but suppress the small guys first!
  The mass distribution is still cuspy

- Strongly interacting dark matter:

$$\frac{\sigma}{m} \approx 0.1 g / cm^2 \approx 0.18 \text{ barns/ GeV} \quad \text{OK} \quad \text{(Bullock's group)}$$

introduces core without other consequences (tri axiality OK, Bullet cluster OK)
"too big to fail" problem is alleviated indirectly

"The news of Lambda CDMS death may have been exaggerated"

Standard Model of Particle Physics

Fantastic success but Model is unstable

Why is W and Z at ≈100 M_p?

Need for new physics at that scale

supersymmetry

additional dimensions, global symmetries

In order to prevent the proton to decay, a new quantum number

=> Stable particles: Neutralino

Lowest Kaluza Klein excitation, little Higgs

Bringing both fields together: a remarkable concidence

Particles in thermal equilibrium
+ decoupling when nonrelativistic

Freeze out when annihilation rate ≈ expansion rate

$$\Rightarrow \Omega_x h^2 = \frac{3 \cdot 10^{-27} cm^3 / s}{\langle \sigma_A v \rangle} \Rightarrow \sigma_A \approx \frac{\alpha^2}{M_{EW}^2}$$

Cosmology points to W&Z scale

Inversely standard particle model requires new physics at this scale

=> significant amount of dark matter

Weakly Interacting Massive Particles

Dark Matter could be due to TeV scale physics

What Has Particle Physics to Offer?

But other possibilities! The Dark Matter sector could be complex e.g.,

Excited states

Weiner: now excluded

A mirror dark matter sector

May have interacted at high temperature

Maybe with matter-antimatter asymmetry

Would explain naturally why $\Omega_{DM} \approx 6\ \Omega_{baryon}$ if $M_{DM} \approx 6\ M_p$

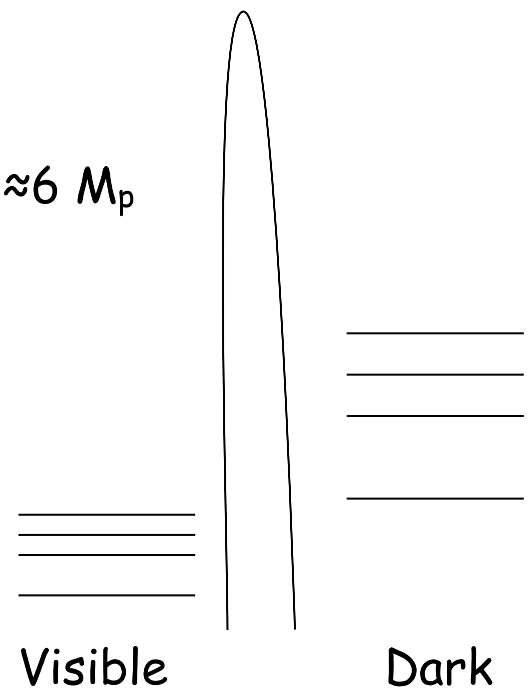
Could even be the origin of baryogenesis!

High cross sections within the dark matter sector?

cf.

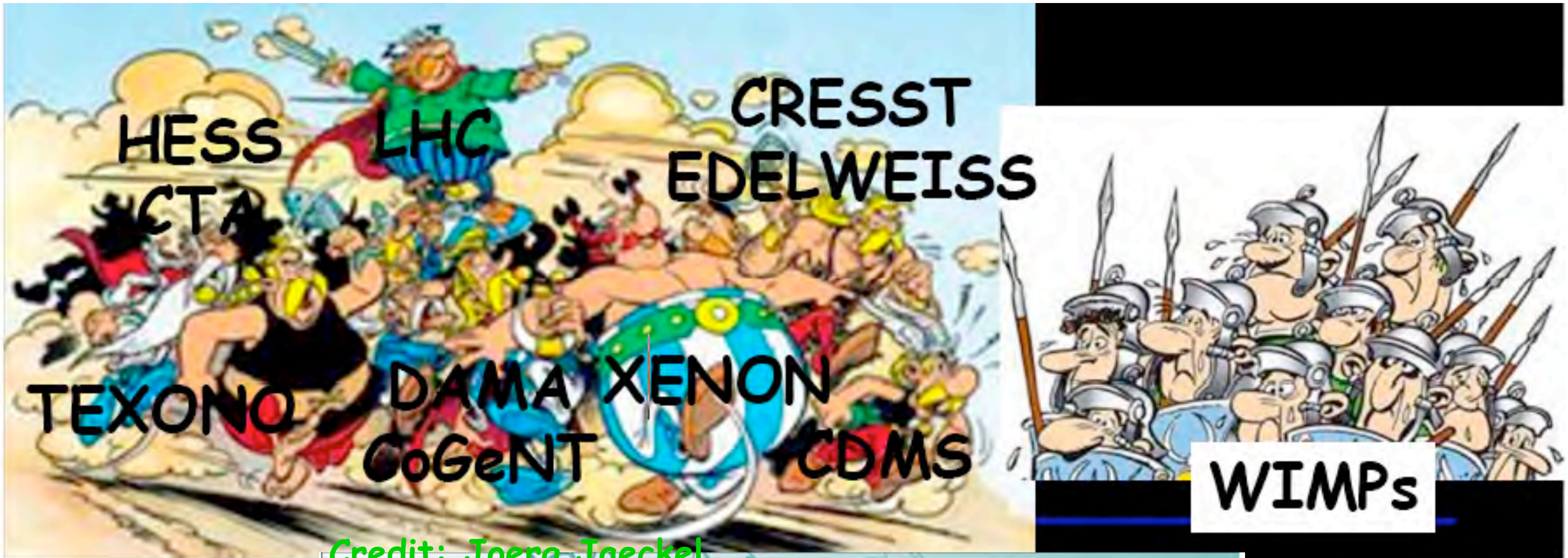
But no reason for weak-scale elastic cross section!

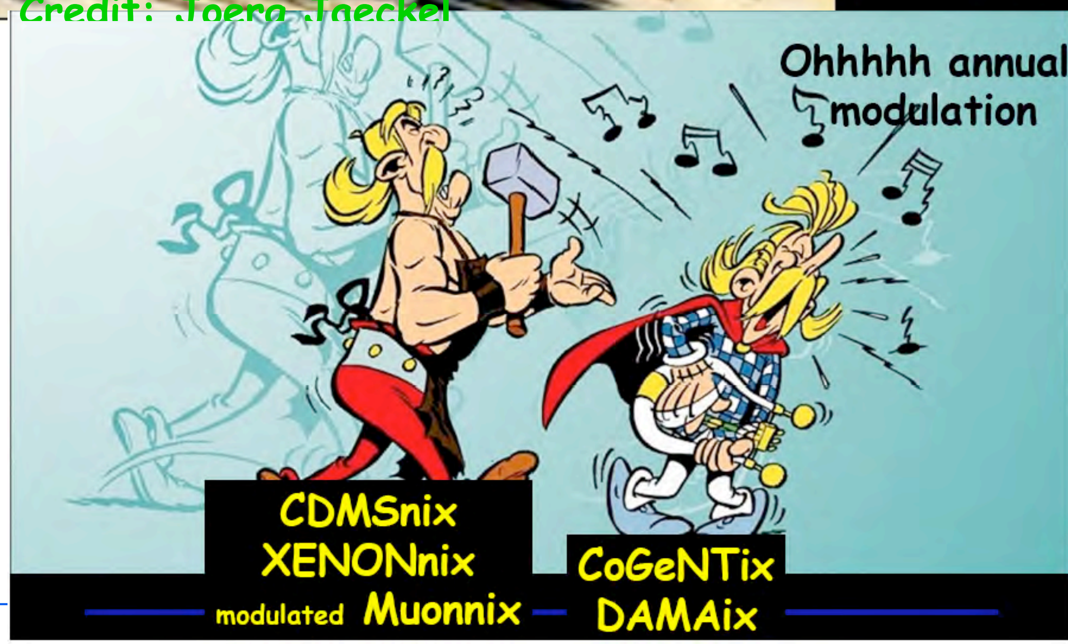
may be Higgs?



Dark Matter: An Exciting Time!

Credit: Joerg Jaeckel





LHC: Dependence on Model!

New data point m_h=125GeV/c^2

But no missing energy yet

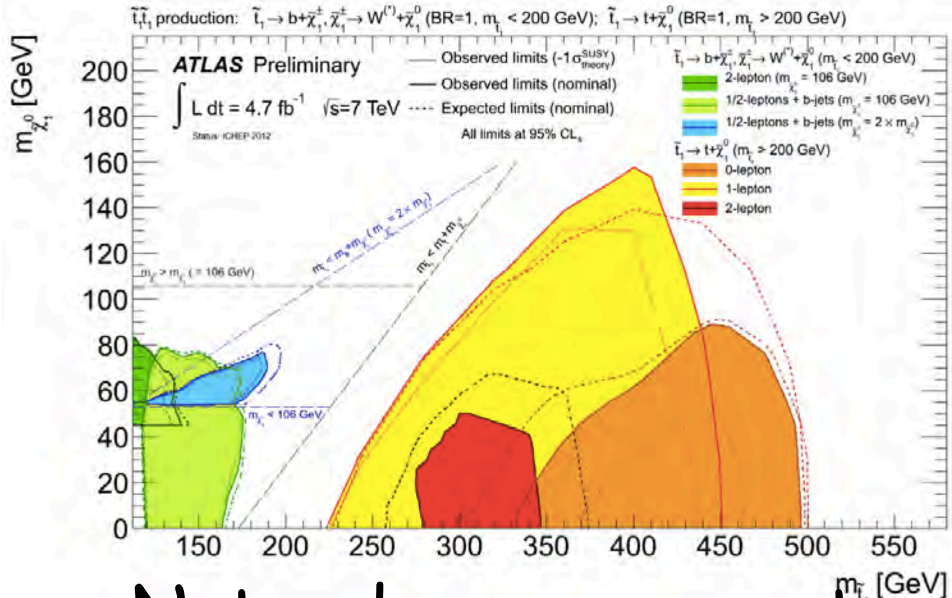
123 parameters in MSSM

=> Simplifications

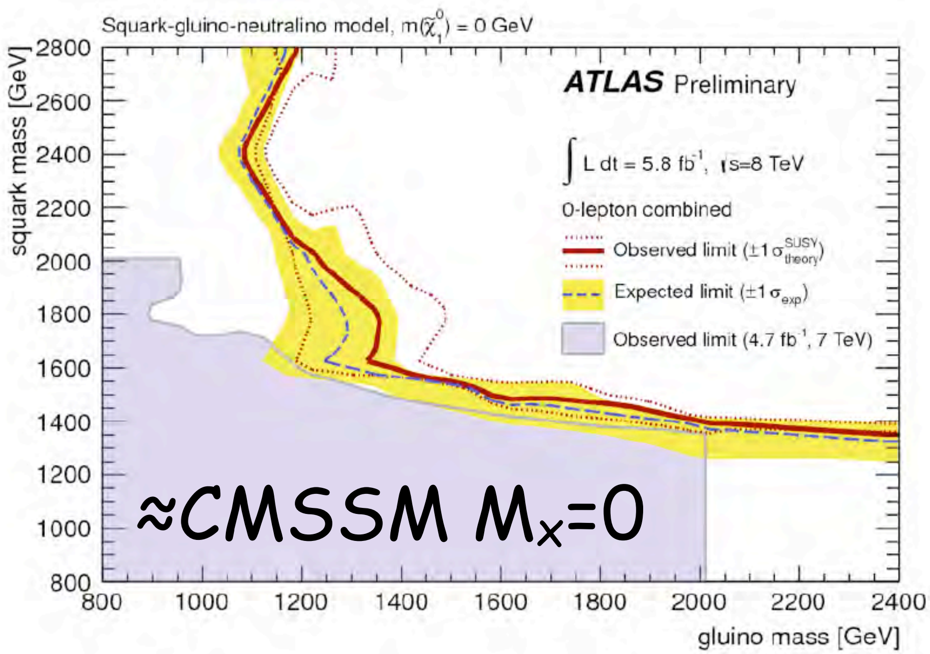
e.g. all bosons and all fermion masses equal at GUT scale: mSUGRA≈CMSSM

≠ what you really need to solve the hierarchy problem (light s-top)

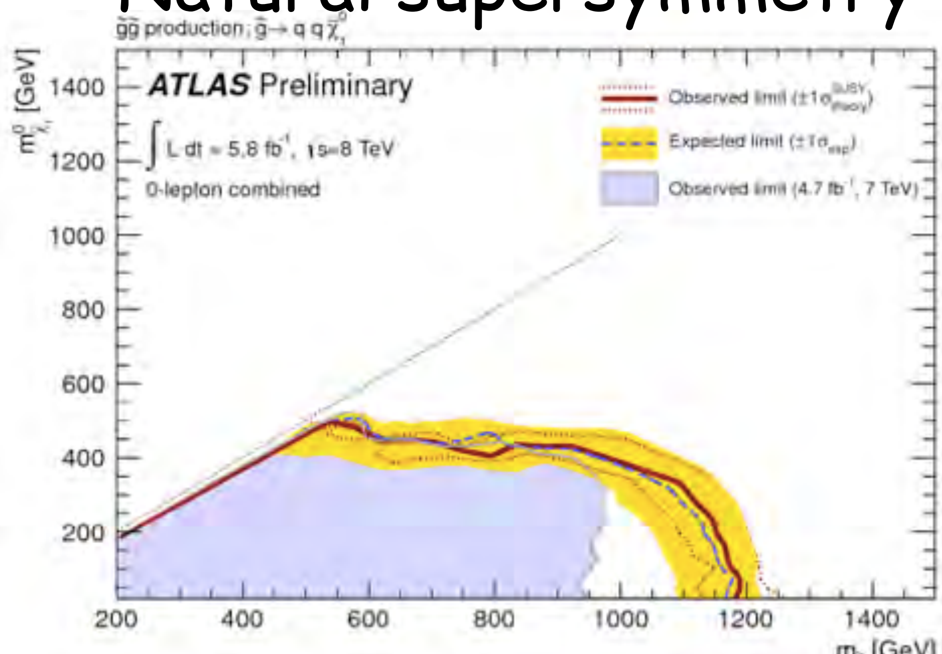
"Natural supersymmetry"



Natural supersymmetry



≈CMSSM M_χ=0



Current impact of LHC

Very active reformulation of simplified schemes

e.g. mSUGRA has to be finely tuned to get m_h=125 GeV/c^2

solution of hierarchy problem ≠ easy production at LHC

A generic region seems to attract attention

extension of "Focus" point region of mSUGRA/CMSSM
Heavy squarks and gluinos (may not be produced at LHC)
Some Higgsino component in neutralino to get the right relic density

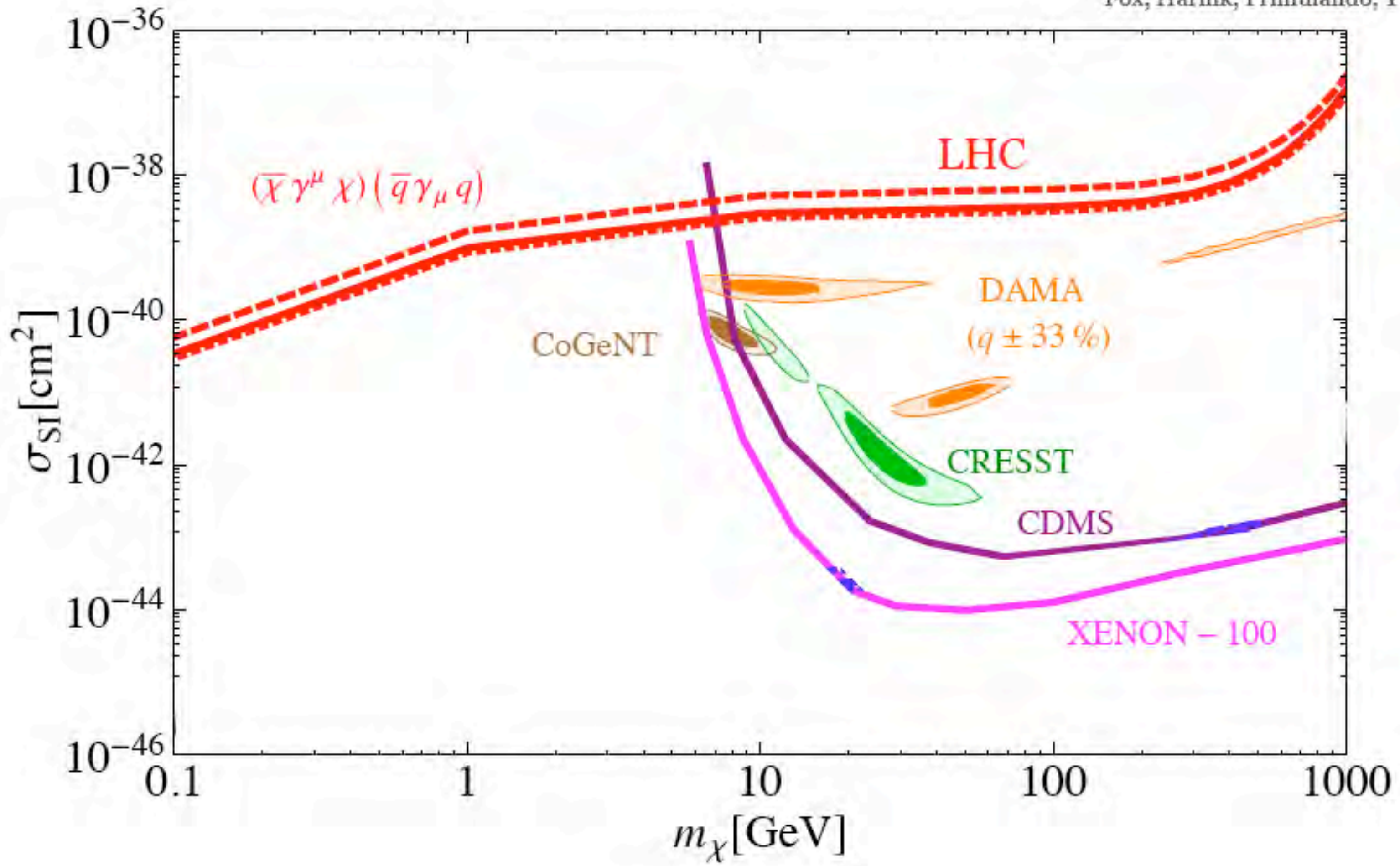
Relatively easy both for Direct Detection (≈10^{-45} cm^2/nucleon)
and Indirect Detection

Other LHC input: "Monojets"

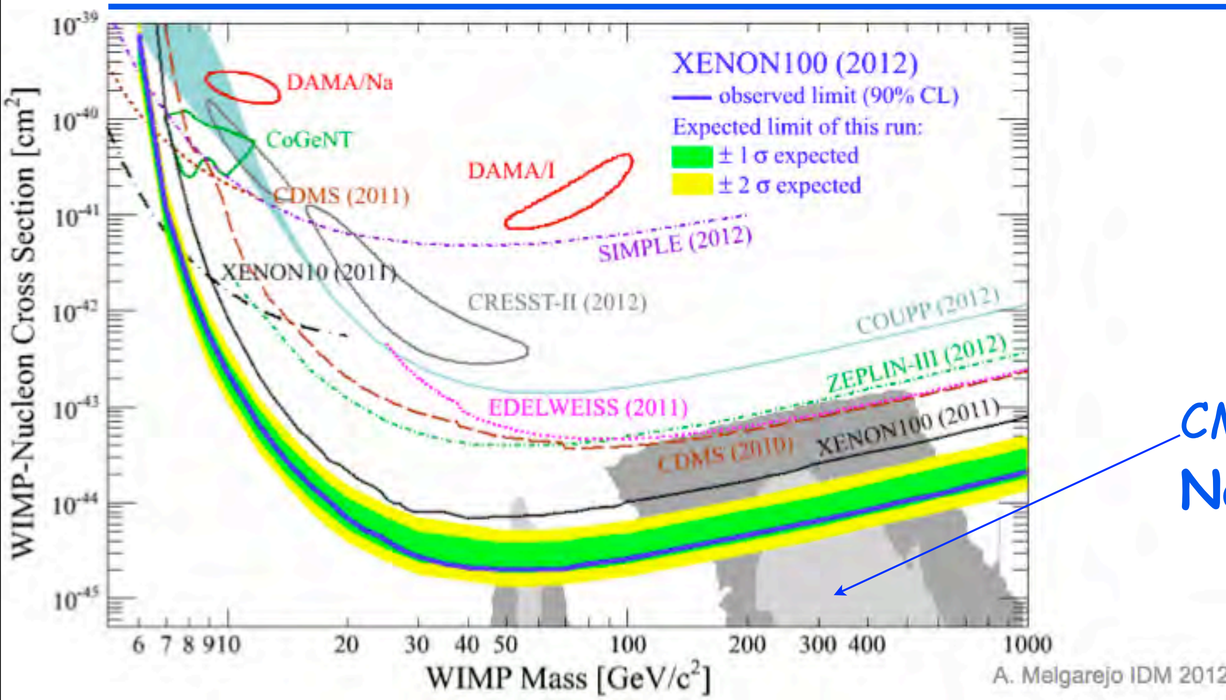
Instead of dealing with models, deal with operators

- Assume a heavy force mediator
- Not competitive at high mass for spin in dependent (but best for spin dependent)

Fox, Harnik, Primulando, Yu (2012)



High Mass Region

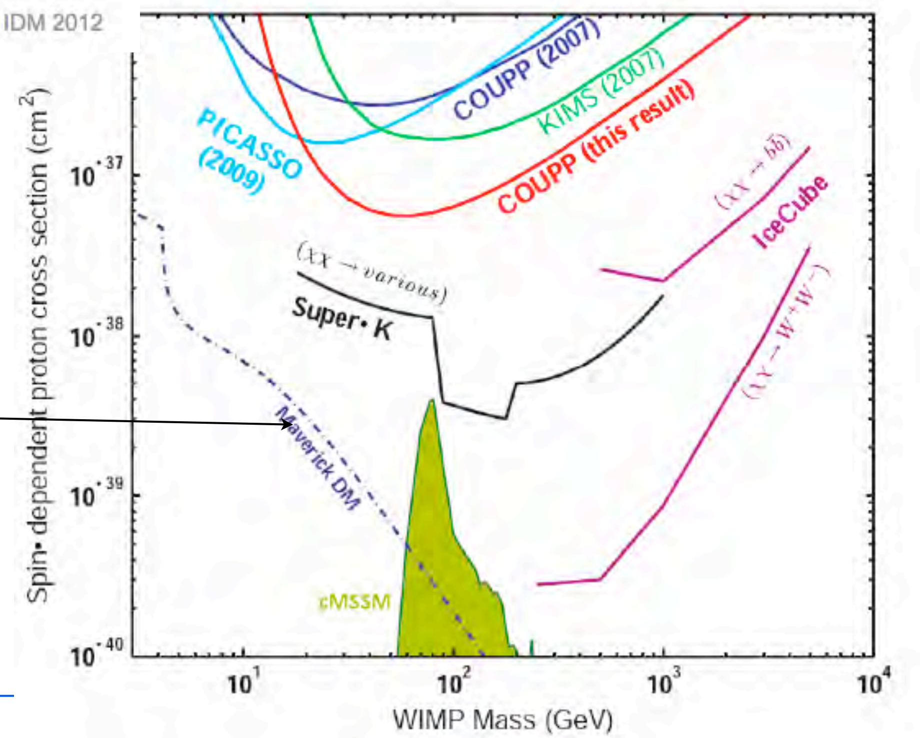


CMSSM≈mSUGRA Focal point region

No threshold for Direct Detection

LHC Monojets

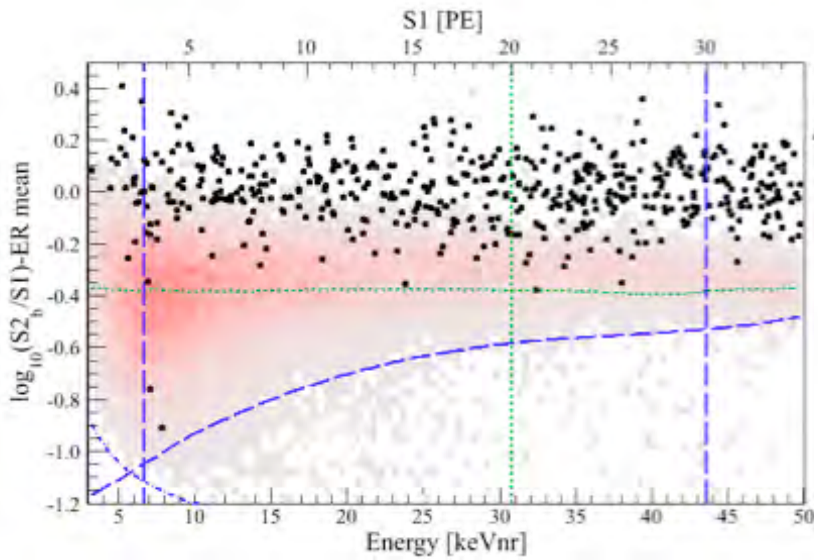
$$\left(\bar{\chi}\gamma_\mu\gamma_5\chi\right)\left(\bar{q}\gamma_\mu\gamma_5 q\right)$$

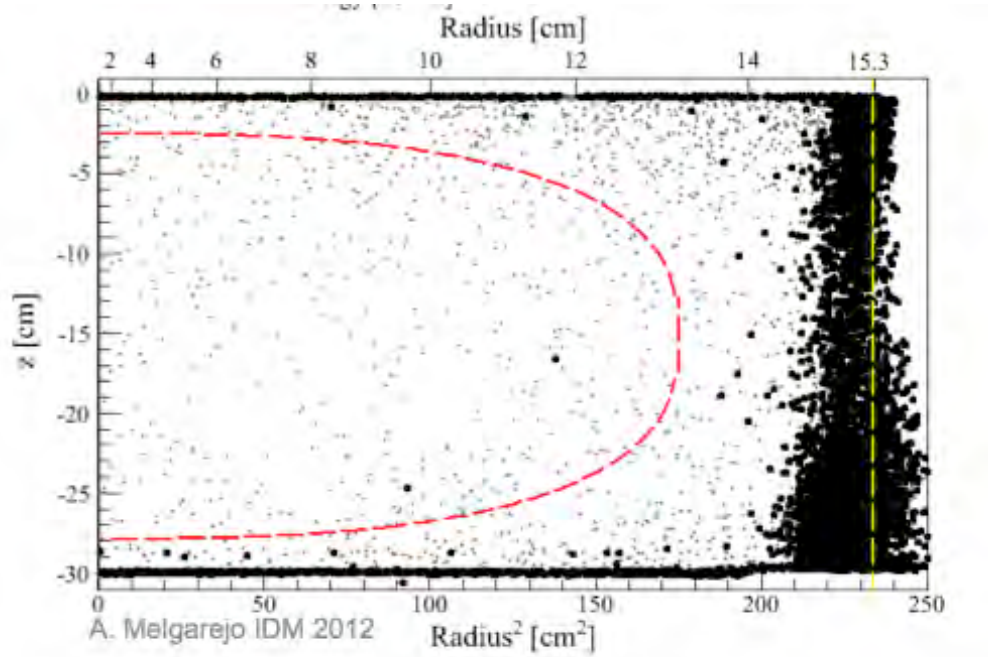


Xenon 100 Backgrounds

Much improvement on ^{85}Kr background

but still problem with purity of liquid (bad collection uniformity, evolving electron life time)





34kg fiducial, 225 days 2 events

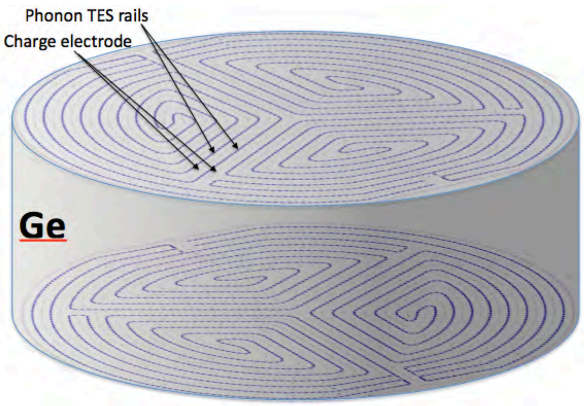
Abnormal S1/S2?

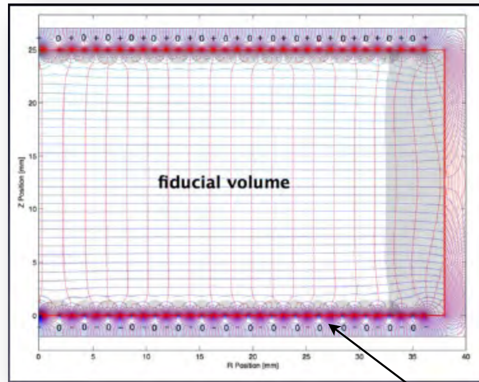
Needs additional purification or for 1 tonne scale

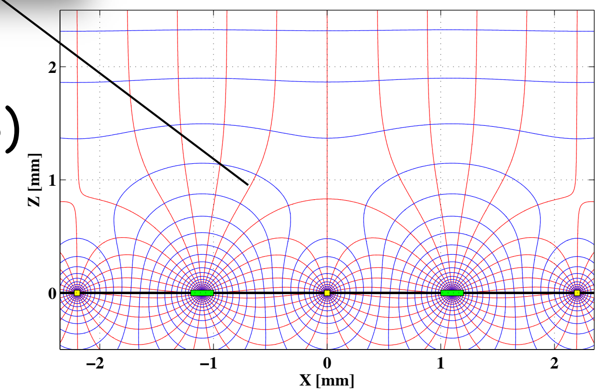
LUX results next Spring will also be important to judge potential of the technology: larger number of photoelectrons/ keV

Drawback of technology: Purity of liquid has to improve proportionally to sensitivity goals

Ge:Getting rid of the surfaces





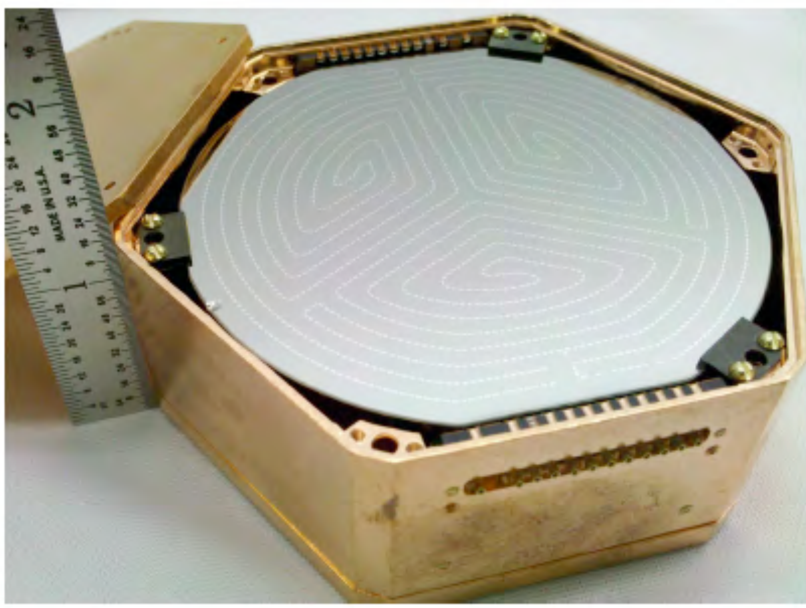


Interleaved electrodes

Reviving an idea of P. Luke (also used by EDELWEISS)

Events close to the surface seen on one side

≠Events in the bulk seen on both sides

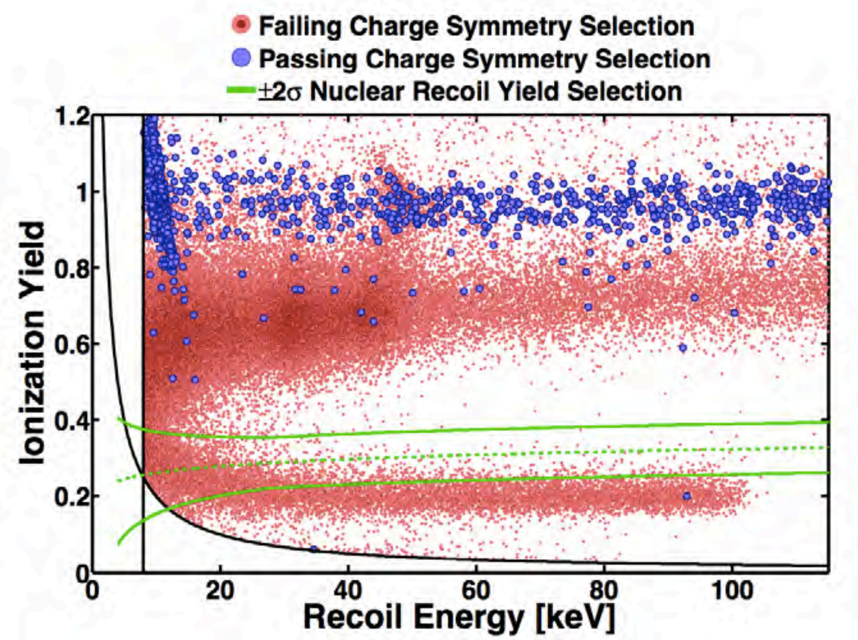


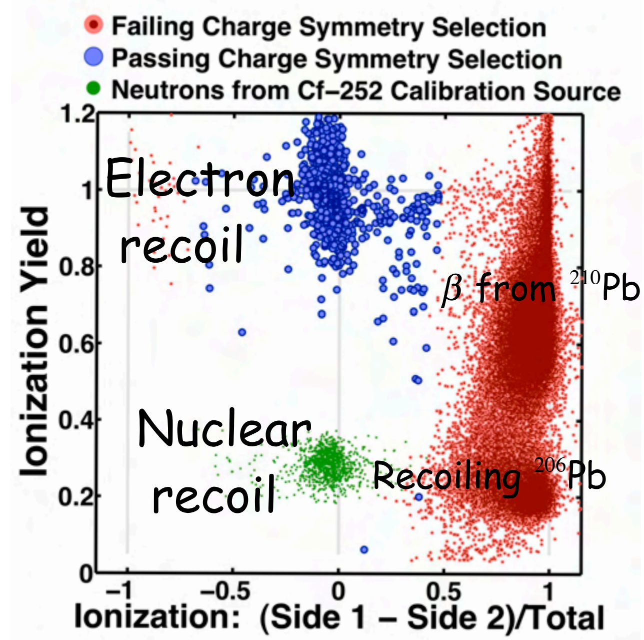
Ø 76mm thickness 25mm

Mass 630g

Exquisite Surface Rejection

Test with ^{210}Pb in low background environment





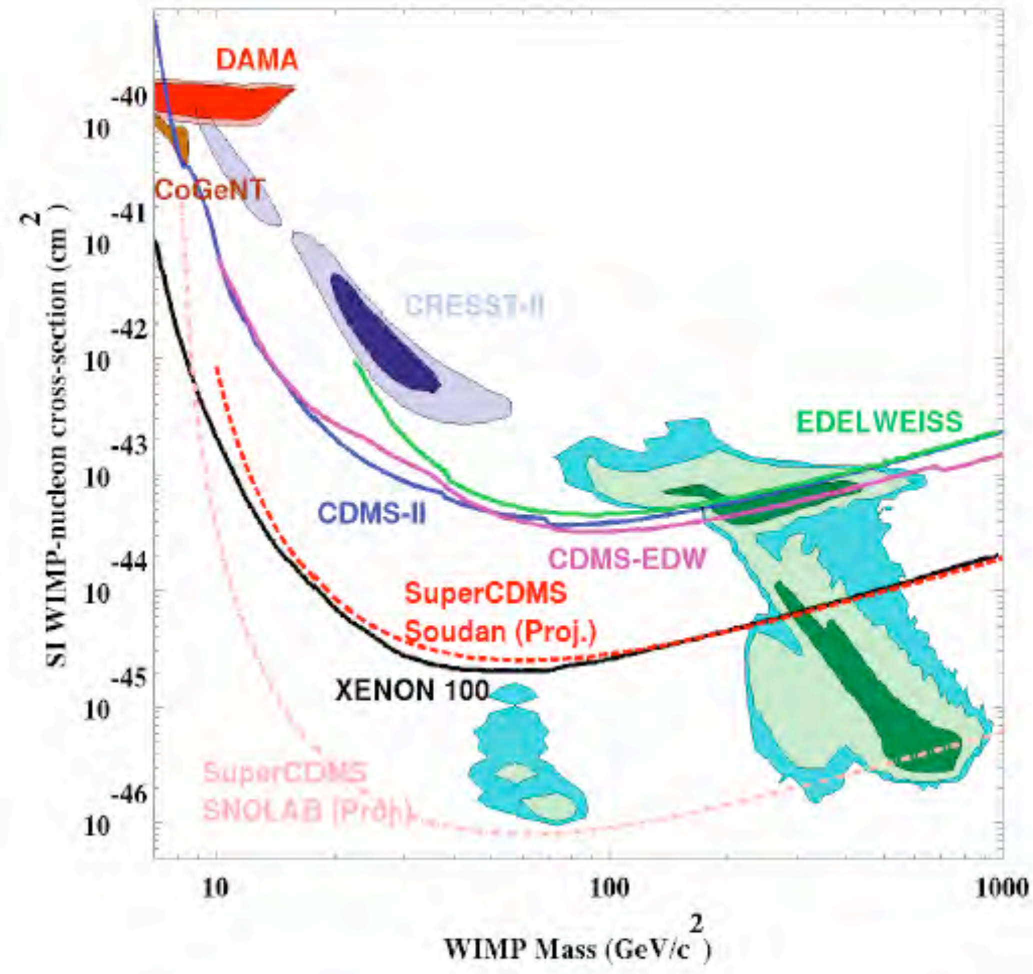
0/65,000 betas
0/15,000 ^{206}Pb recoils

More than sufficient for 200kg for 3 years (SNOLAB)

Large Mass Region: CDMS

CDMS reach 2015

Somewhat dependent on cosmogenic neutrons + purity of our shield



Technical progress

Super CDMS 10 kg running well at Soudan

8-> 3? 10^{-45} cm^2 depending on neutron background

Edelweiss III on its way to 32 kg

Liquid Xe

XMASS (800kg Xe)

first tests -> results at Japanese Physical Society meeting: background from Cu

LUX 350kg, successful tests at the surface -> underground this summer 2012

Xenon 2.4 tonne approved US +Europe

Panda X 1 tonne China +US

Liquid Ar:

MiniClean (180kg), Deep/Clean

WARP->Dark Side in Borexino CTF

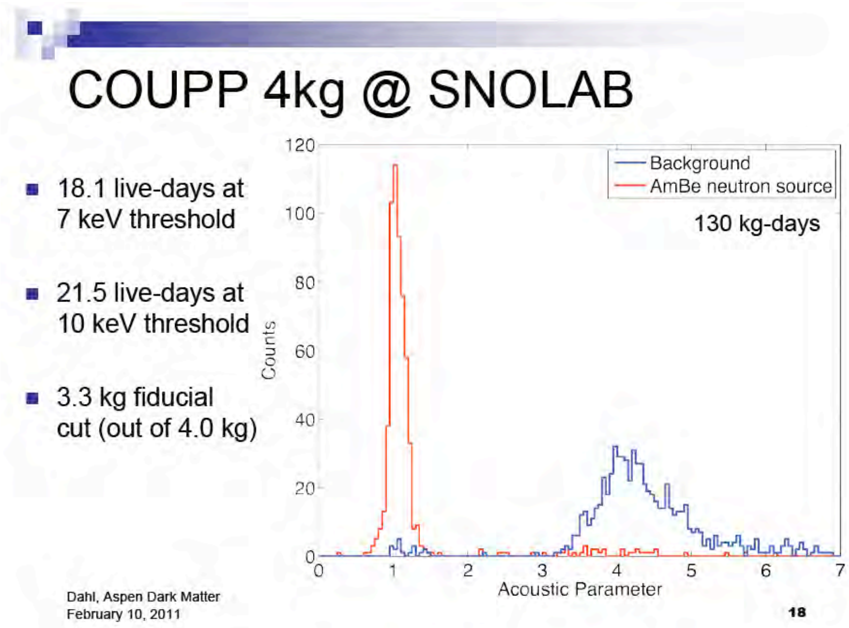
ArDM in Camfranc

COUPP 4kg at SNOLAB

Acoustic rejection of alphas

but neutrons due to detector components

-> SNOLAB

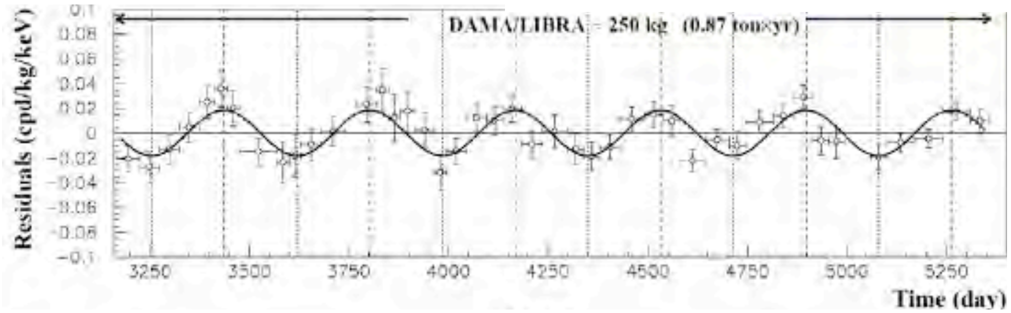


A Low Mass WIMP?

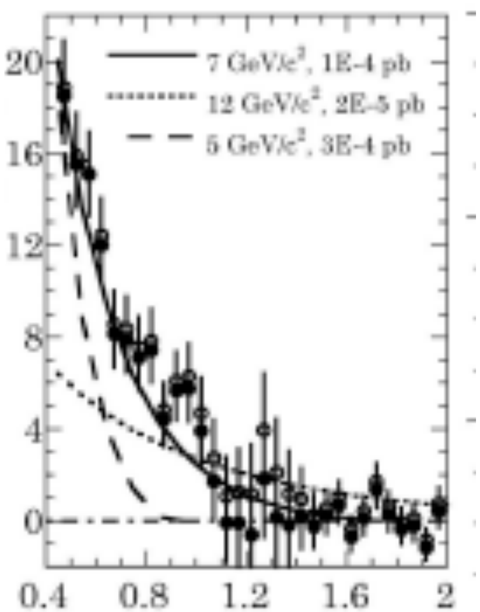
Experimental claims

DAMA (NaI)

Latest Princeton Nov 2010



CoGeNT (Ge)

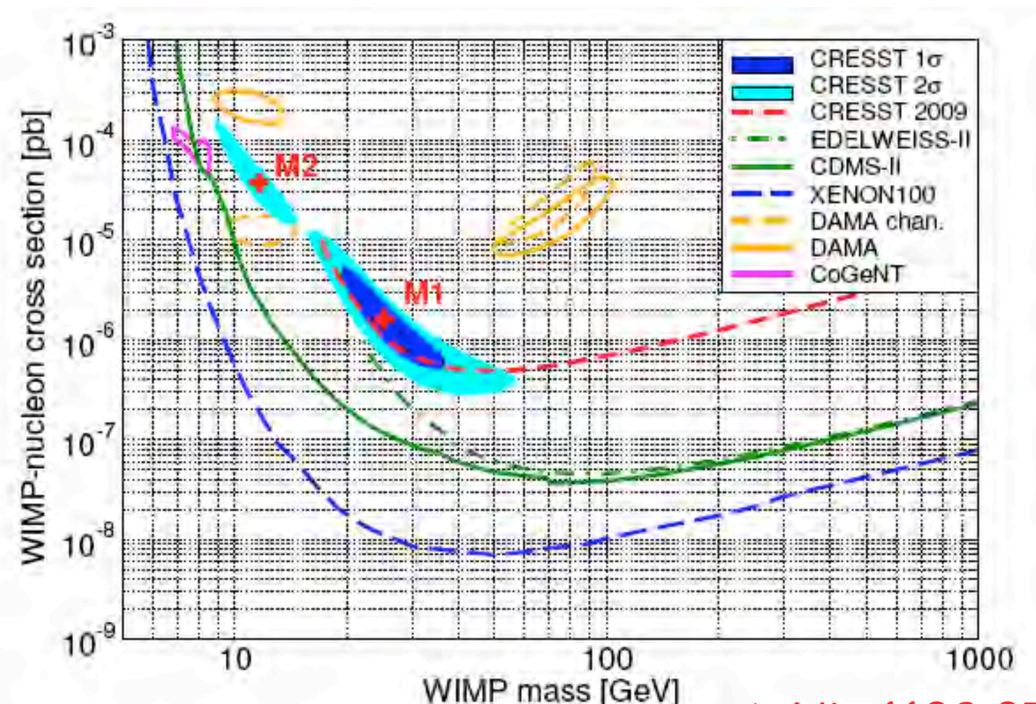


keV ee

Aalseth et al. ArXiv: 11060650

L X ray peak subtracted

CRESST (Ge)



ArXiv:1109.0702

A Low Mass WIMP?

3 questions

Can this be the results of experimental issues?

A lot of discussions DAMA e.g. Nygren

CoGeNT: Collar

Eventually, if no convergence, an independent group will have to repeat the experiment on same material

DM Ice at the South Pole (also KIMS ANAIS, Princeton)

How to make it compatible with CDMS and Xenon?

Can this be unified (Hooper,Collar)?

Hooper, Collar, Hall, McKinsey arXiv 1007.1005

Theory: very natural for asymmetric dark matter

dark matter ≠ anti dark matter (K. Zurek, L. Randal ...)

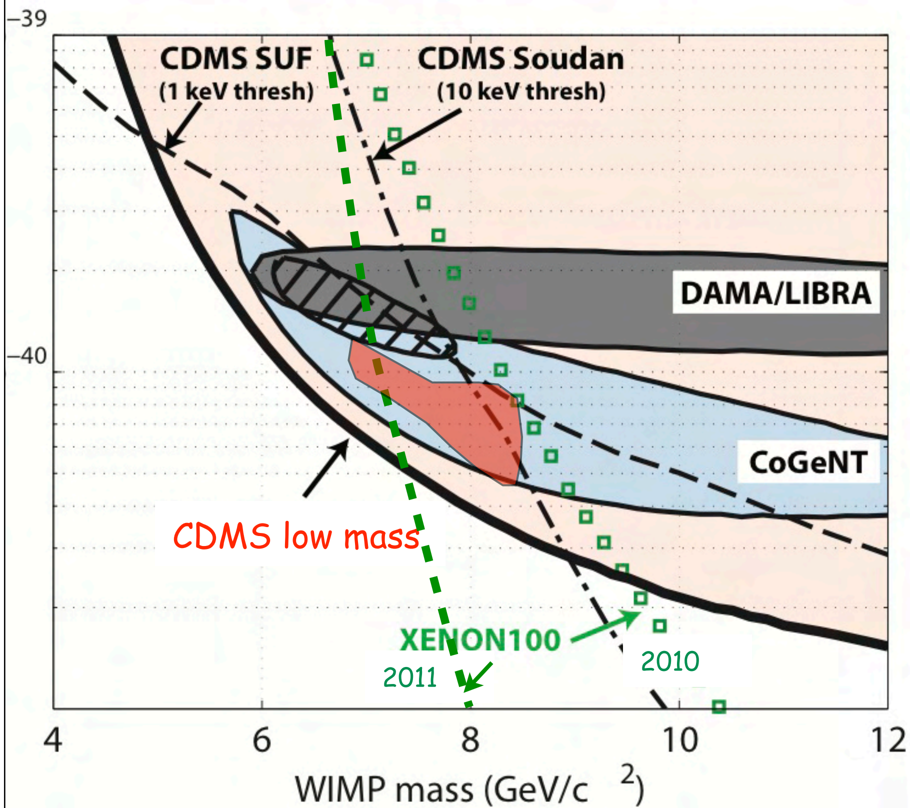
if baryon asymmetry coupled to dark matter asymmetry ≈ equal

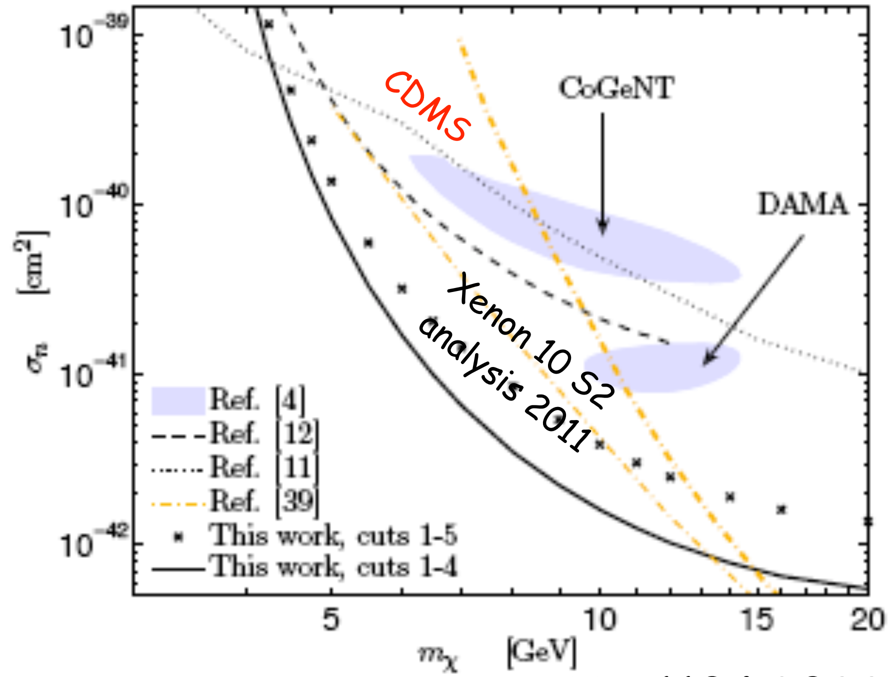
7 times more dark matter -> 7 GeV scale

Scattering through Higgs -> weak scale ????

How do you naturally have enough annihilation to wipe out the symmetric component?

Compatibility with other experiments with CoGeNT original "claim"





Xenon 10 S2 Analysis ArXiv:1104.3088
1 electron sensitivity level

Ahmed et al ArXiv:1011.2482
Very robust
Same material as CoGeNT

Collar: arXiv:1106.0653 still excessive sensitivity to calibration especially at few (5) electrons level

CoGent is shifting!

2/3 of events are surface events.

Why not 100%?

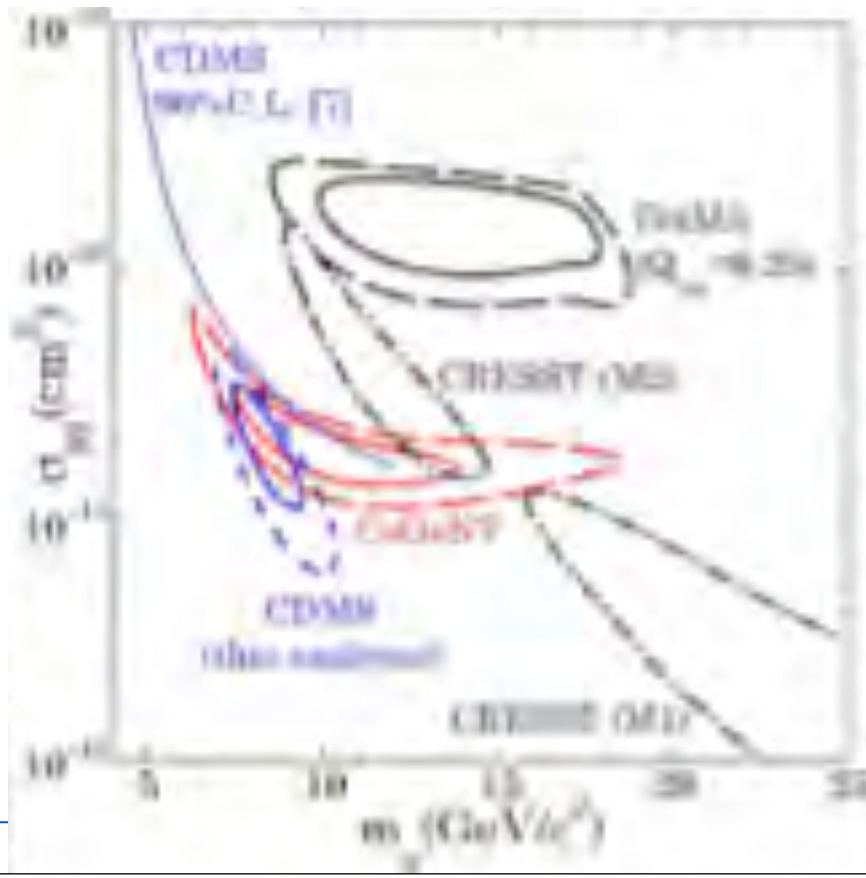
anomaly drifts drastically down

Potential problem: rise time Monte Carlo does not fit data

CDMS not incompatible with 2 10^{-41} cm^2/nucleon signal

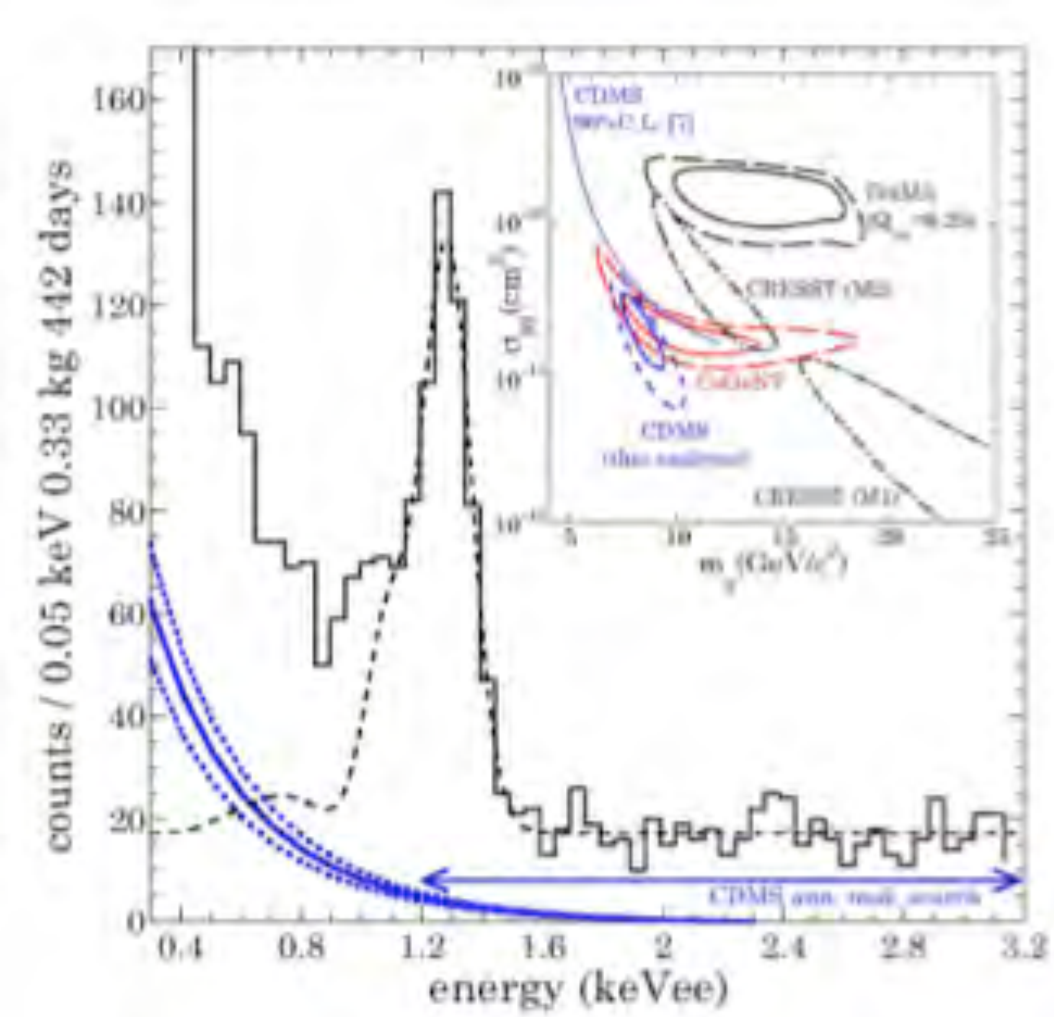
In latest paper, CoGeNTollaboration does not claim any WIMP signal

No more unification with DAMA but maybe with CRESST

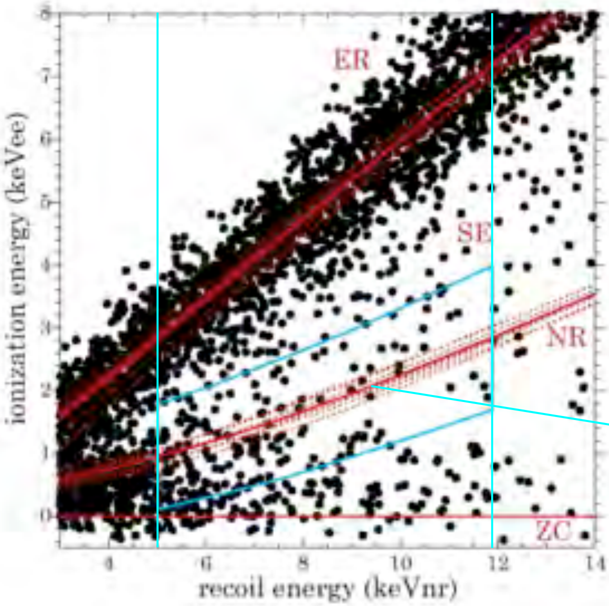


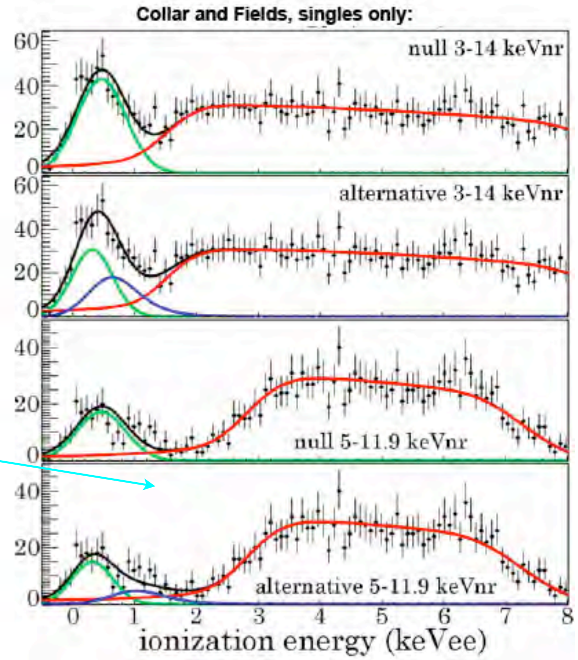
Juan Strikes Back!

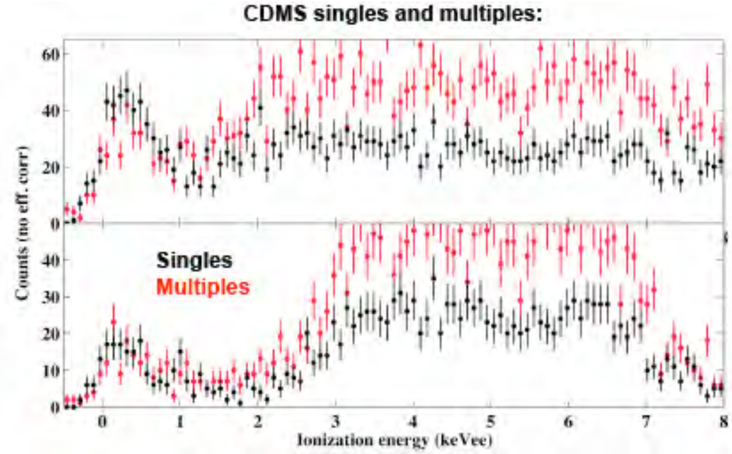
A signal in CDMS Data?

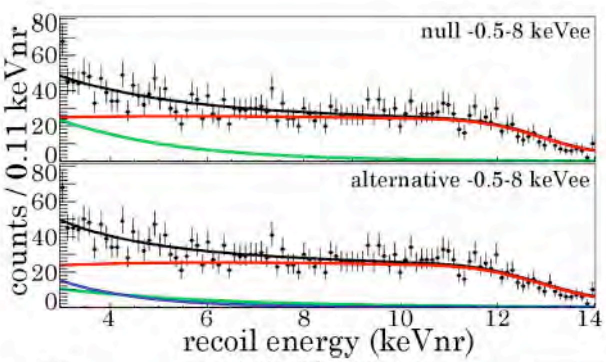


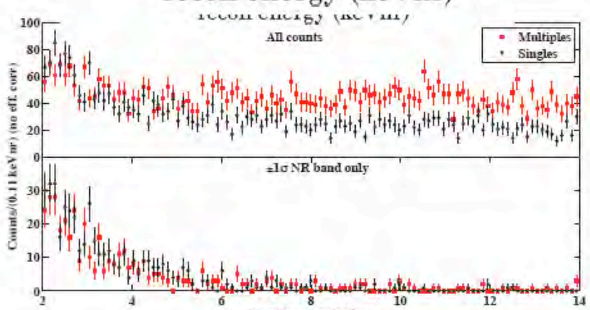
The CDMS "Signal"











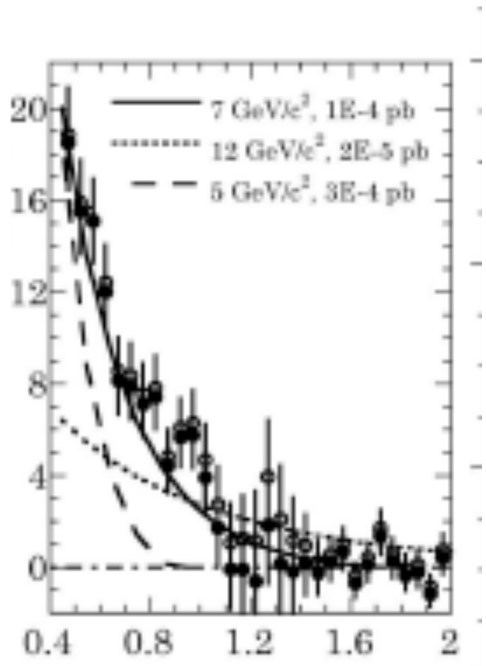
No significant difference between singles and multiples

We are doing our own analysis

Modulation?

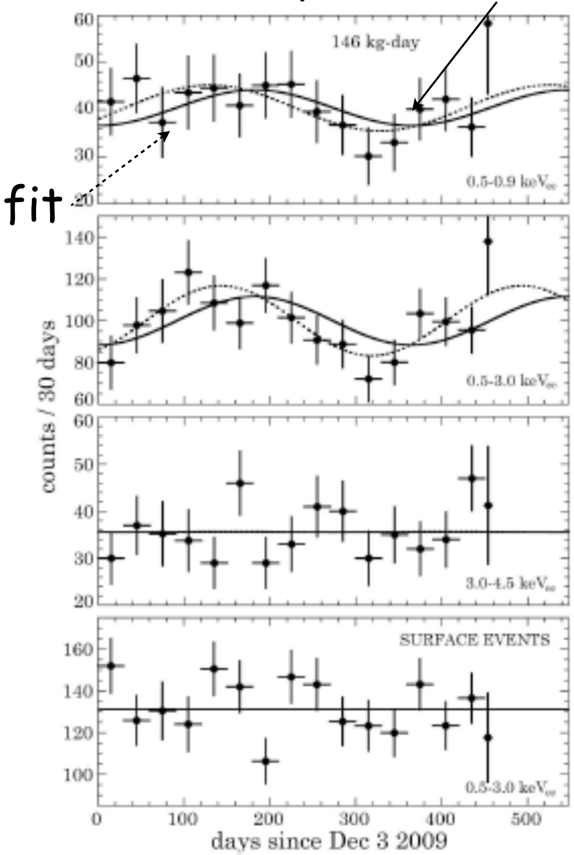
Aalseth et al. ArXiv: 11060650

Modulation appears larger 0.9-3keV
where there are very few events



Expected modulation

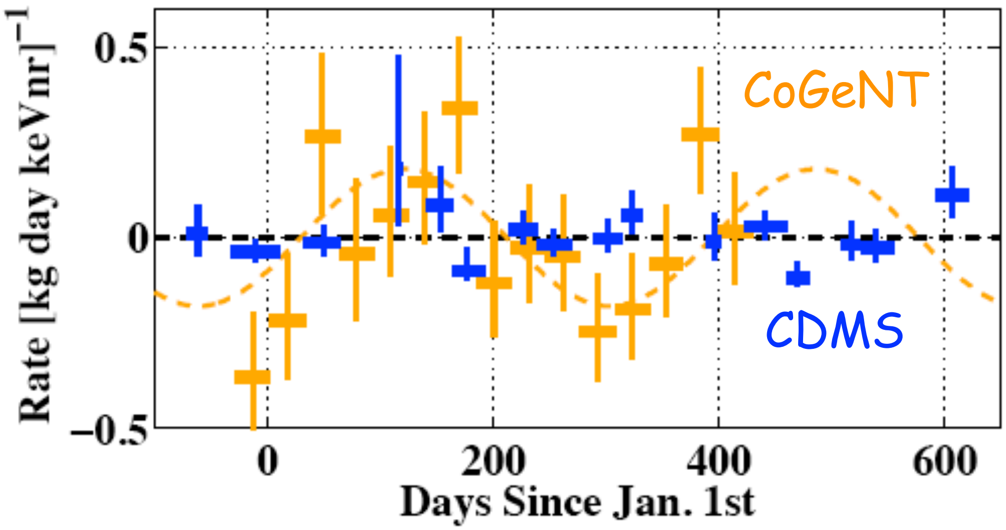
Best fit

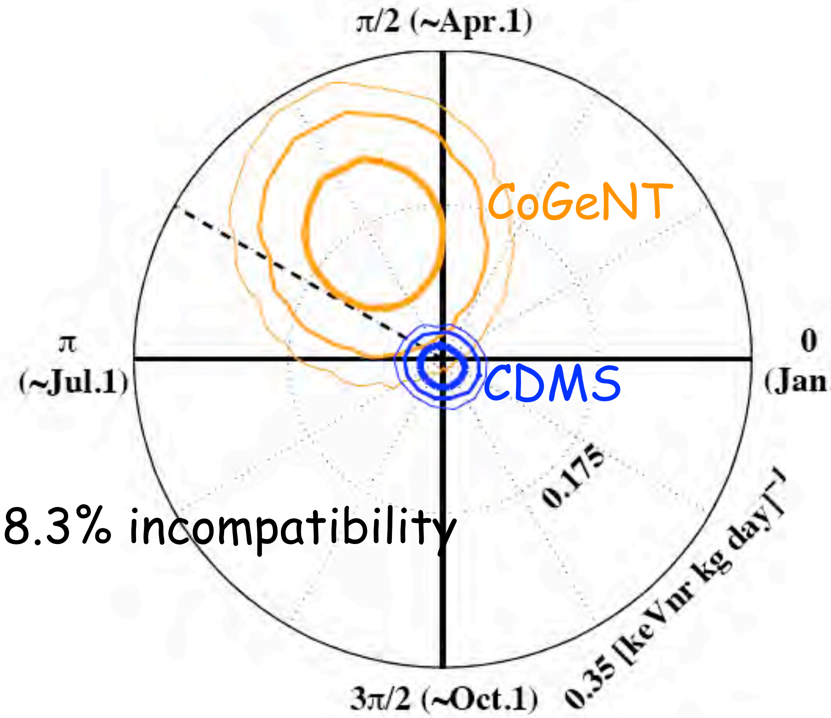


CDMS (Marina del Rey)

5 keV-11.9 keV nuclear recoil:

arXiv:1203.1309

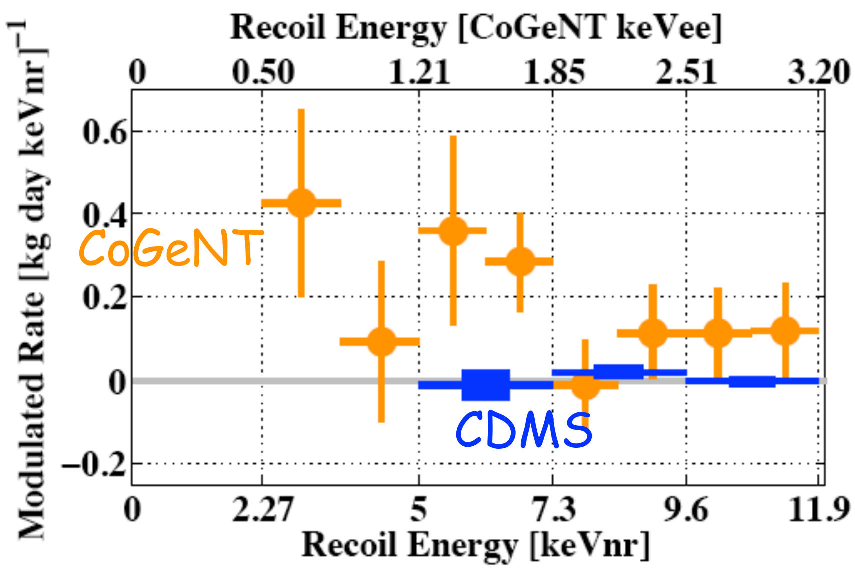




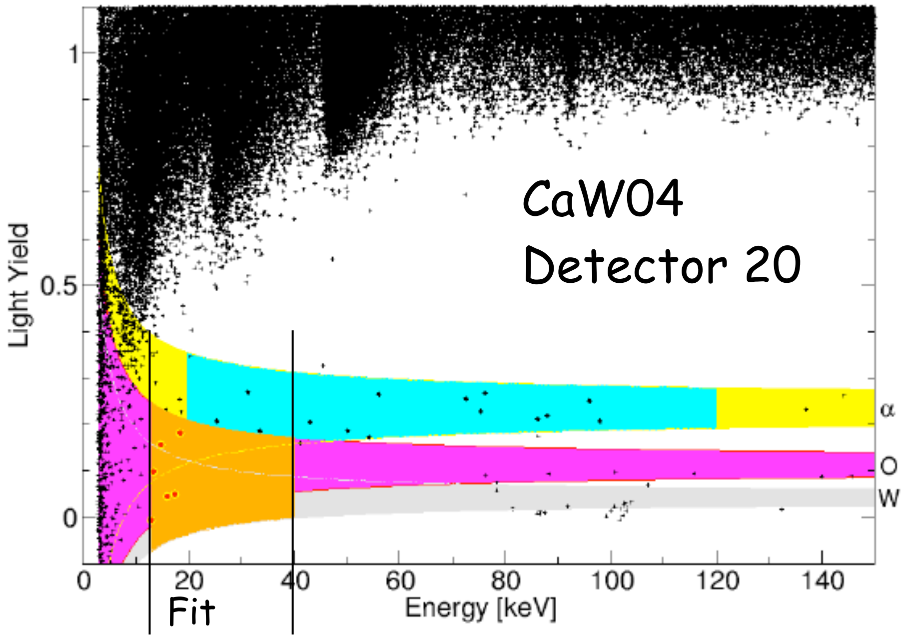
98.3% incompatibility

We are of course looking at lower energy

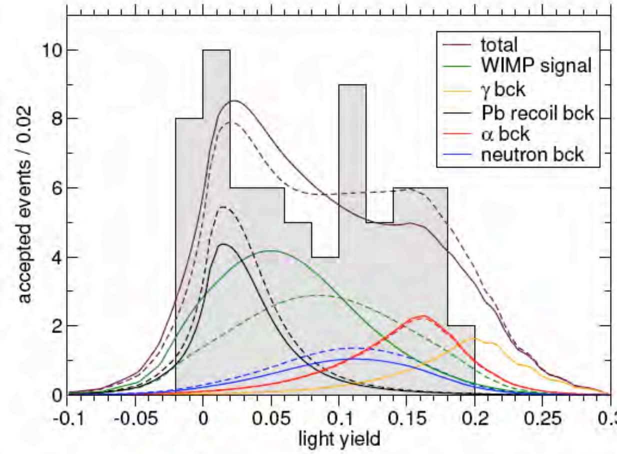
Hope to have a solid result at lower energy soon!

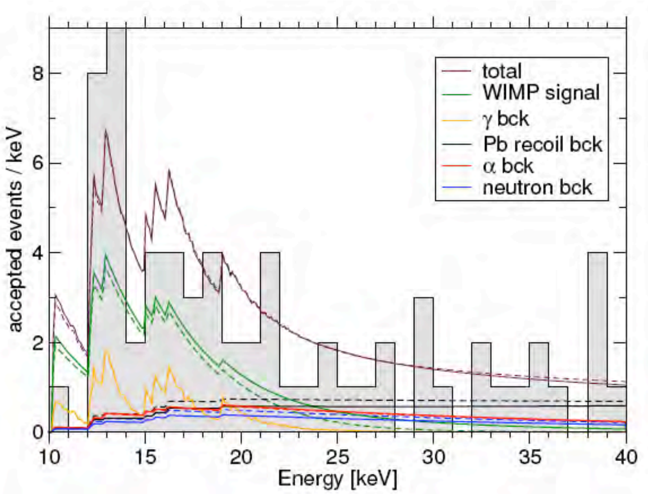


CRESST (1109.0702)



Detailed fit of recoil energy and scintillation distributions + multiplicity (neutrons)





Claim >4 σ ≠ rest of field

But 42-47 background, 29-24 signal Evts

Maximum likelihood notoriously sensitive to assumed functional forms!

What if the shape assumed for the background is slightly wrong?

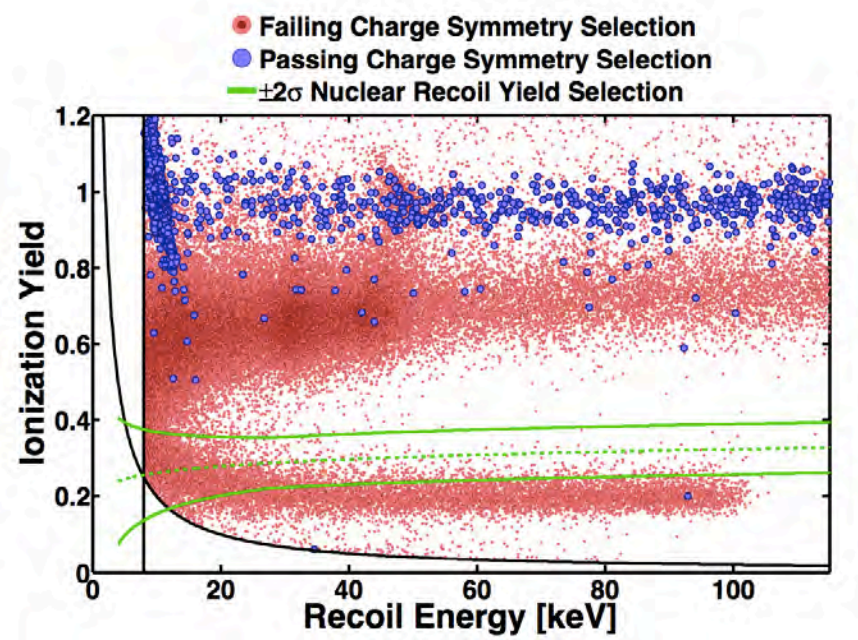
CRESST Most Likely Explanation

^{206}Pb recoils

Possibility of a low energy excess due to spallation from alpha and ^{206}Pb rough surface (Kuzniak, Boulay,Pollmann arXiV:1203.1576)

Cf. Edelweiss Domange's Thesis

Also CDMS where we can measure directly the ^{206}Pb



Low Mass CDMS

2 modes

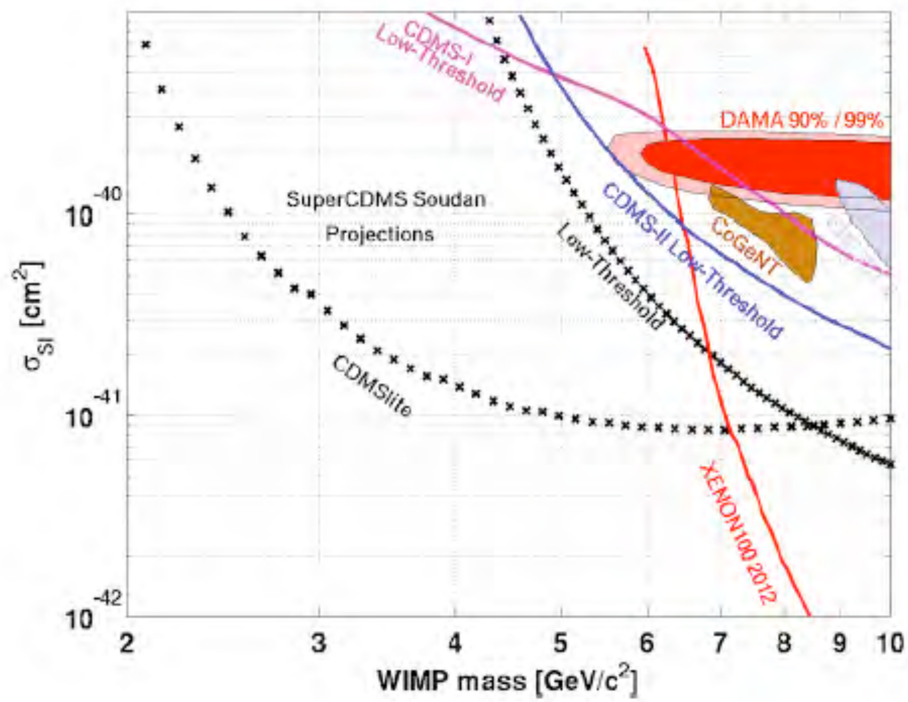
- "Low Threshold" : we measure the phonon energy and correct for the phonon emission from carrier drift in the electric field (Luke Neganov Effect) with the ionization yield of a nuclear recoil (15% correction)

- "CDMS Lite": take one or two detectors, apply ≈60V => measure the ionization with the phonon => 100eV threshold

in either case, no discrimination

rapidly background limited

=> result in coming year



What Would It Take?

Internal to one experiment

Rigorous statistical treatment

Number equivalent to "5 sigmas"   ≈6 events for background of 0.4 events
Fold in uncertainty on background..
Blind (at least 90%)

Energy scale calibration

Nuclear recoil yield (=demonstration of sensitivity)

Behaves like dark matter

Unique signature: Single Nuclear recoils
Distribution within fiducial volume, time (if modulation is small)

Clear separation from background

≠unexpected tail of a distribution
Enough signal to noise
Multidimensional information

=>Protection against outliers

Significant calibration with radioactive sources
+ calibrated Monte Carlos

What Would It Take?

Complementary experiments

At least two experiments

Each with blind analysis, high level of discrimination, understanding of backgrounds

Better: very different technologies, different types of backgrounds

Should be fully statistically compatible.

But we may need to have two experiments with the same target

There could be non trivial dependence on nucleus (e.g. isospin)

Clearly, as a community, we should have done this for DAMA. Attempt to do it now!

Problem: expensive, difficult to justify in a budget limited environment.

Maybe natural internationally.

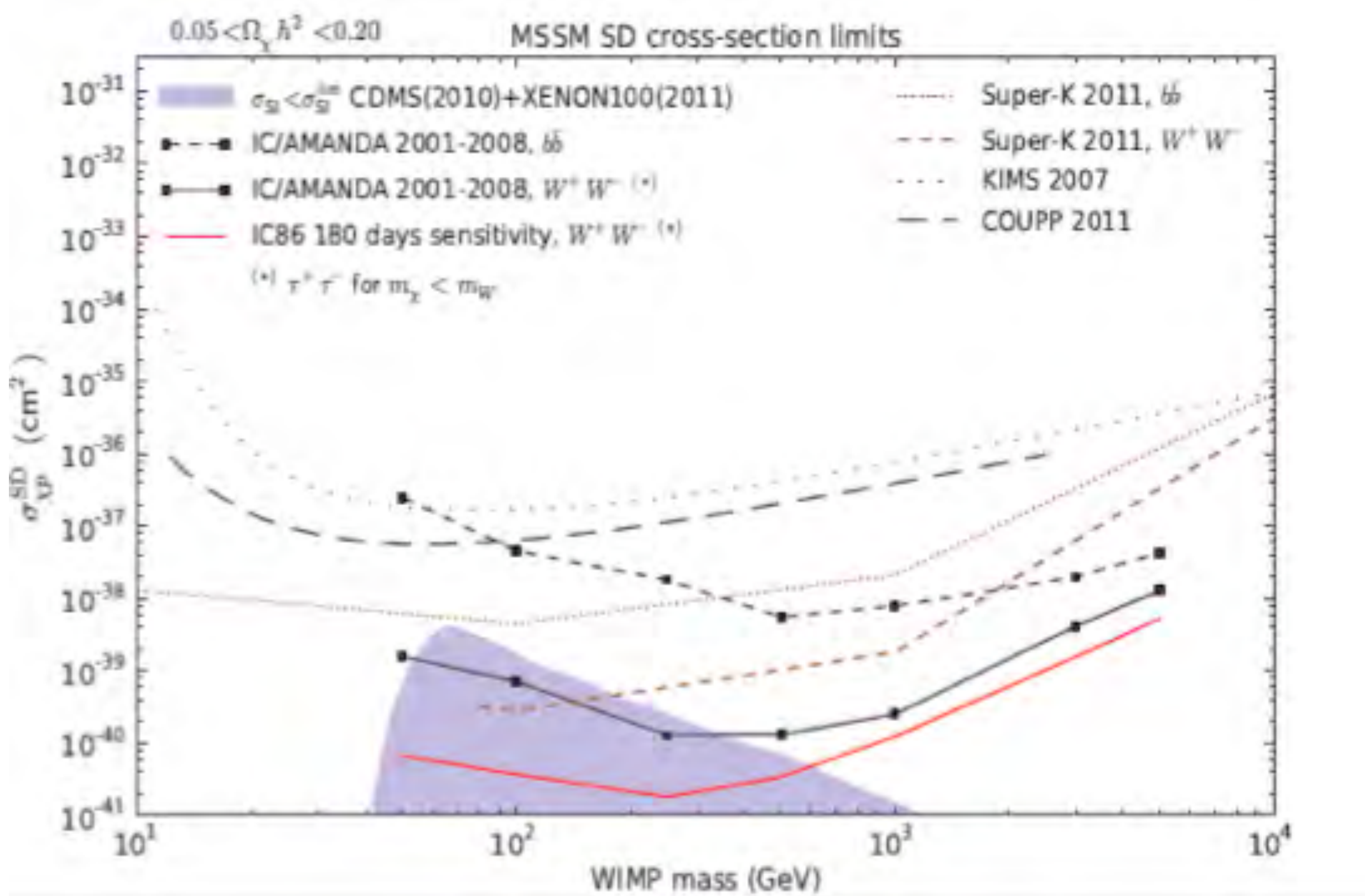
A convincing claim may speed up the next generation.

Indirect Detection

Ice Cube

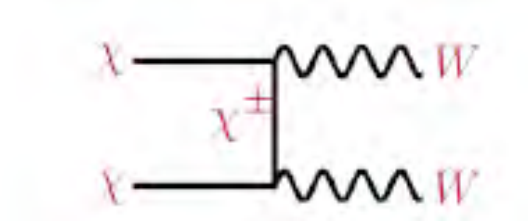
86 strings 180 days

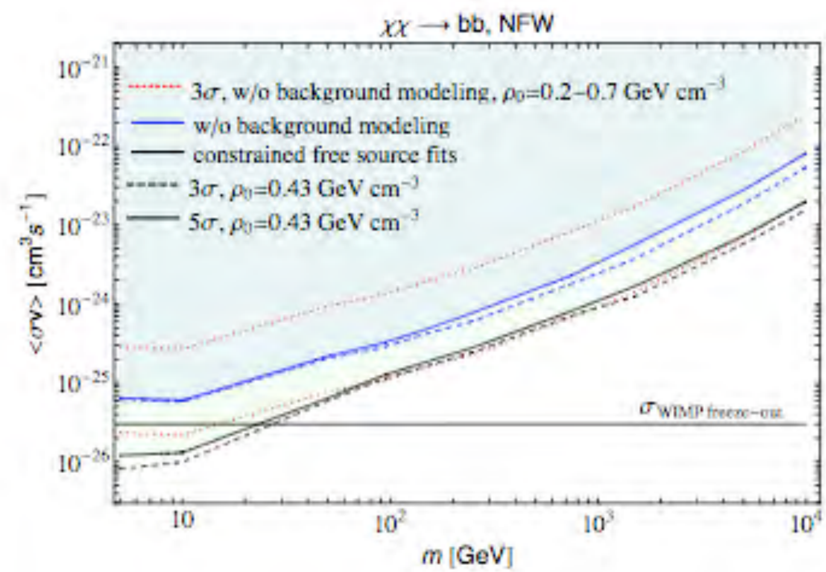
Starts to provide complementary limits to direct detection for spin dependent



Indirect Detection Fermi

Continuum Photons



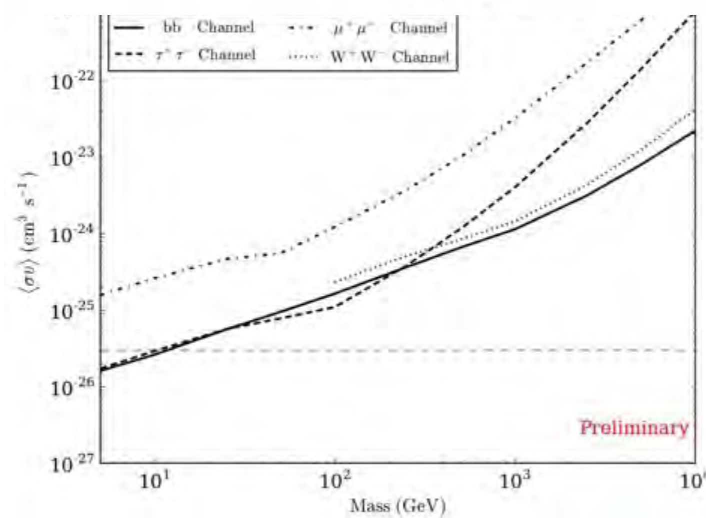


Fermi: Nothing so far

Halo

arXiv:1205.6474

but uncertainty on density



Dwarfs: combined analysis /not sensitive to exact profile

Fermi symposium

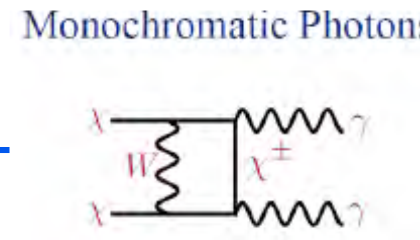
less exclusion than arXiv: 1108.3546

Note: in realistic models not 100% branching ratio!

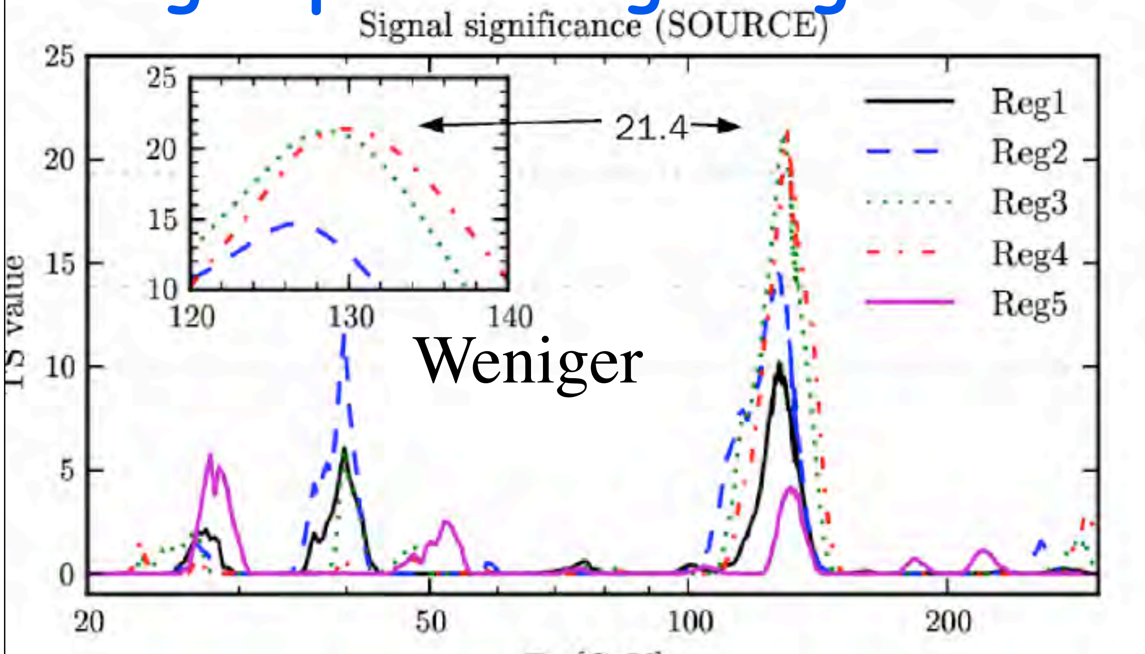
Some significant soft component

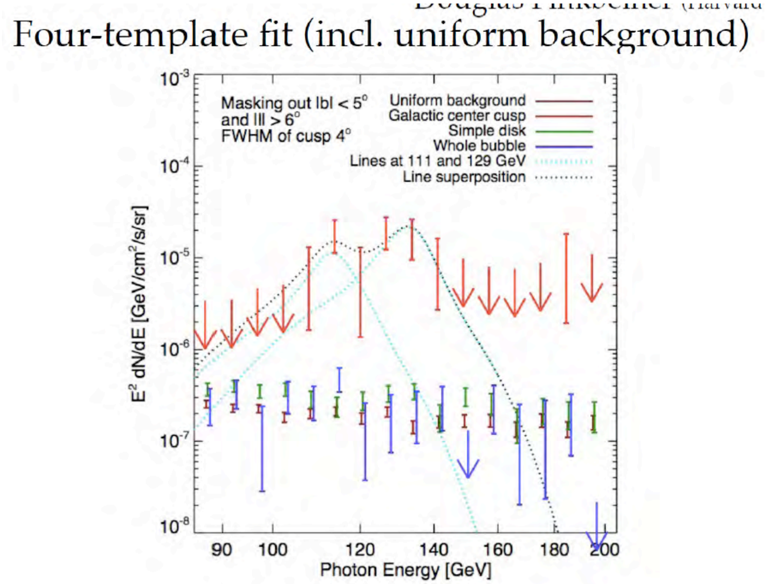
=> limit on mass would be weaker

Monochromatic line ?



2 groups claiming a signal in Fermi LAT data!





Su and Finkbeiner

$$E_\gamma = 129.8 \pm 2.4^{+7}_{-13}\,\mathrm{GeV}$$

$$\chi\chi \rightarrow \begin{matrix}\gamma\gamma \\ \gamma Z\end{matrix}$$

Assuming Einasto profile with 0.4 GeV/cm³ local density:

$$\langle\sigma v\rangle_{\chi\chi\rightarrow\gamma\gamma} = 1.27 \pm 0.32^{+0.18}_{-0.28} \times 10^{-27}\,\mathrm{cm}^3/\mathrm{s}$$ $\leftarrow$ 3.3σ $\uparrow 5.1\sigma$ After trials

Fermi LAT team:

They see it, but less significance (3.35 sigma local, 2 global): 135GeV with new calibration

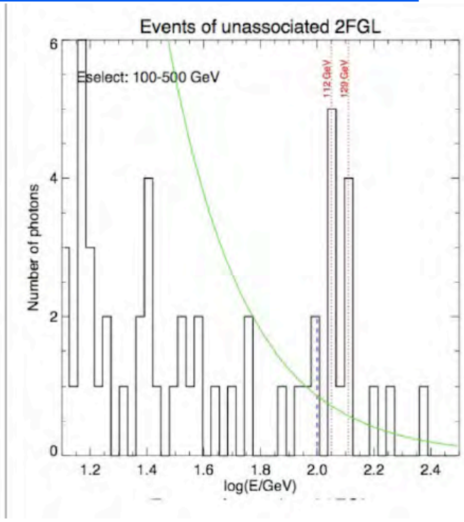
135 GeV?

Other information:

Seems to be resolved

Not centered on galactic center by ≈ 1 degree

Possibly seen in other systems ???



What could it be?

An artifact e.g. from limb of the earth

Current conclusion: apparently not

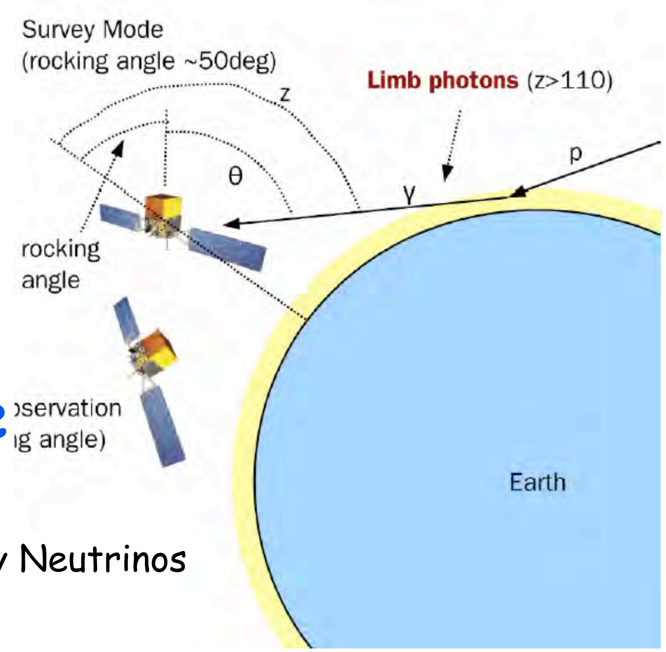
Astrophysics Source?

Aharonian et al. IC by Extra cold electron wind

But resolved.

Dark Matter?

Offset OK



But cross section very large

No continuum

Very peculiar model: e.g. Right Handed Heavy Neutrinos

=> bad news for direct detection

Note: Hooper Linden etc. claim excess at few

Conclusions

1) A lot action and controversies!

2) What seems to be established

Non baryonic dark matter

Dark Energy

General features of Lambda CDM as an excellent first approximation

Particle Physics Standard Model

Higgs-like particle at 125 GeV/c^2

But the hierarchy problem remains!

3) Potentially disruptive

Challenge to lambda CDM by the dwarf spheroidals: A new scale

Is this due to astrophysics or particle physics?

Sterile neutrinos?

What mass, mixing?

No sign of supersymmetry yet at LHC!

But challenge only to the simplest models

Some unusual dark matter properties: light dark matter, large modulations

Current claims do not pass the bar

The 130 GeV lines

Need confirmation

=> the next few years are very important

complementarity between cosmology, direct detection, indirect and LHC

Sterile Neutrinos?

Anomalies

LSND antineutrino

MiniBoone

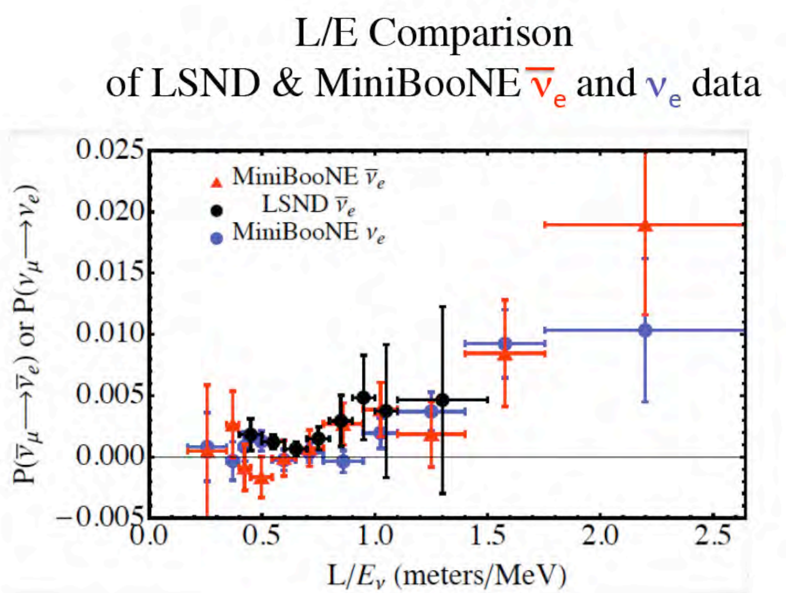
antineutrinos now similar to neutrinos

twice as much statistic

less fluctuation up in high energy

Now compatible with LSND

3.6 sigma



Deficit of reactor antineutrinos

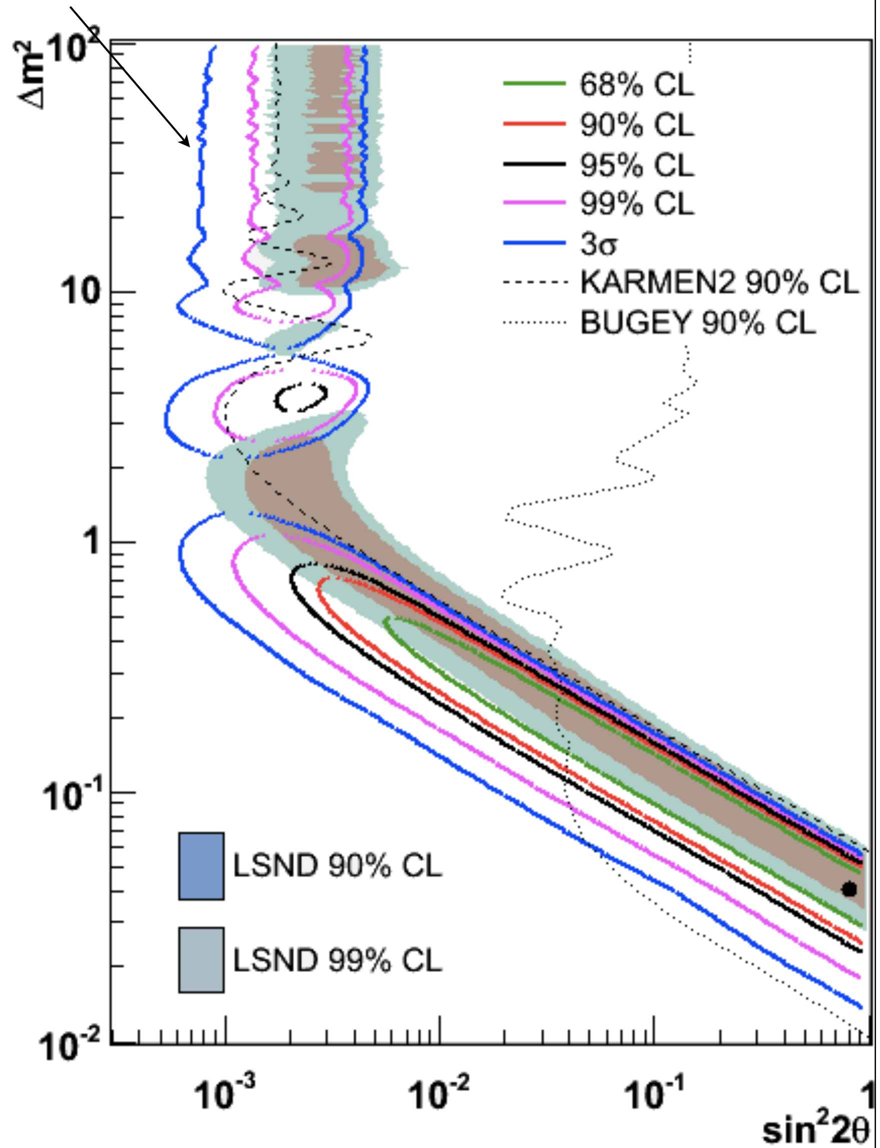
Sage-Gallex

Tension with μ disappearance

We need probably ≥2 sterile neutrinos

Note: Karmen excludes large DM^2

not keV neutrino! Best fit ≈ 1 eV



Neutrinos From Cosmology

Three pieces of information

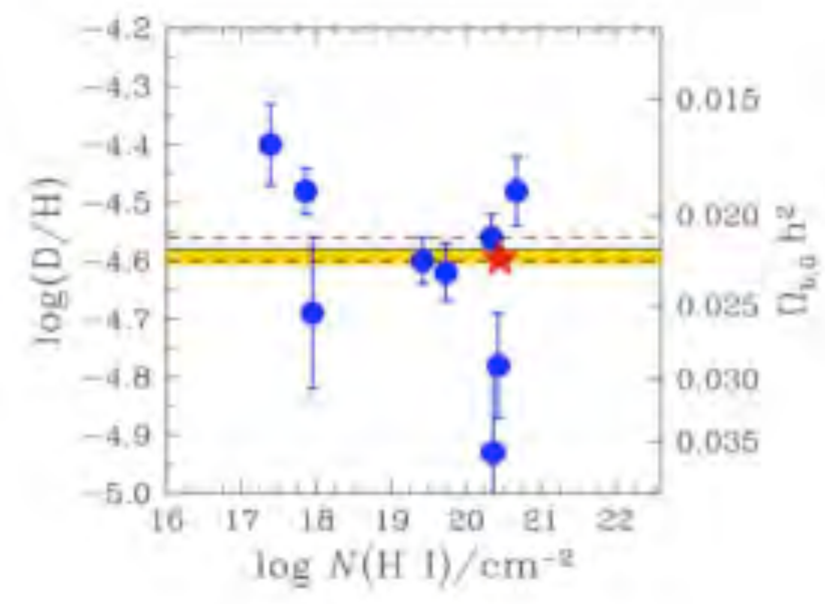
1 Density of the universe

For thermal neutrinos: $\Omega_\nu h^2 = 0.0106 \frac{m_\nu}{eV}$

Sterile neutrinos are sterile if $\sin^4\theta > \frac{3\times 10^{-6}\,\mathrm{eV}^2}{\Delta m^2}$

2 Number of relativistic species

Big Bang Nucleosynthesis
He: 2 values
New result from Pettini and Cookes
Combined with CMB: N_ν=3.0±0.5
Microwave background
Power spectrum + 3 point correlation
B mode in polarization



3 Large scale structure

Light neutrinos (normal + sterile): not a solution to the dark matter problem

Axions

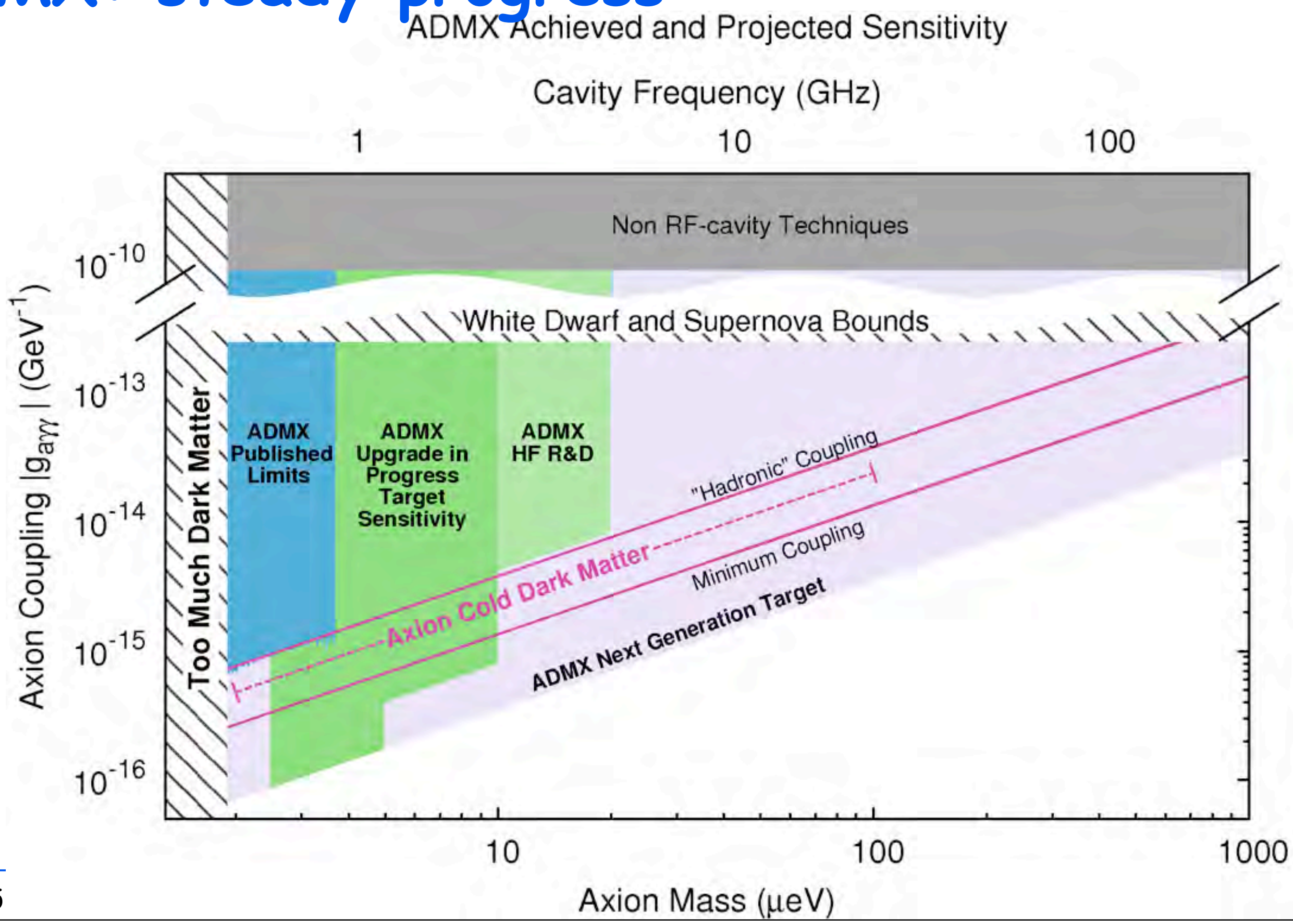
CP problem

QCD violate CD

One way out: Peccei Quinn axions which restore CP dynamically.

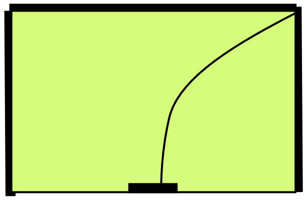
If exist have to be cosmologically significant!

ADMX: steady progress

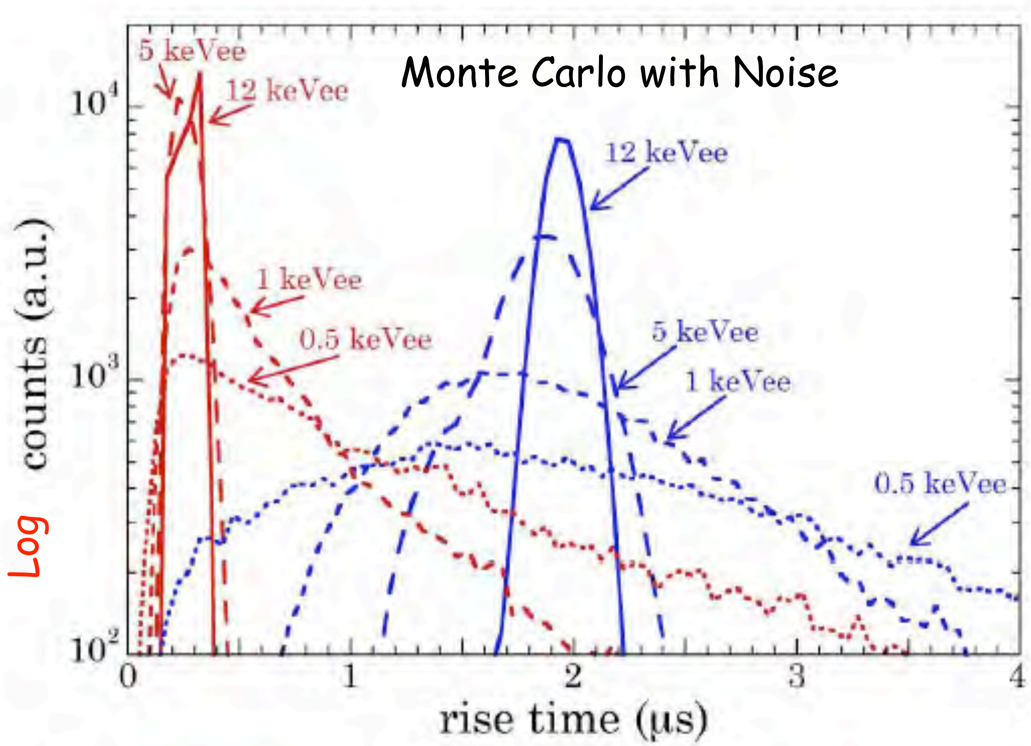


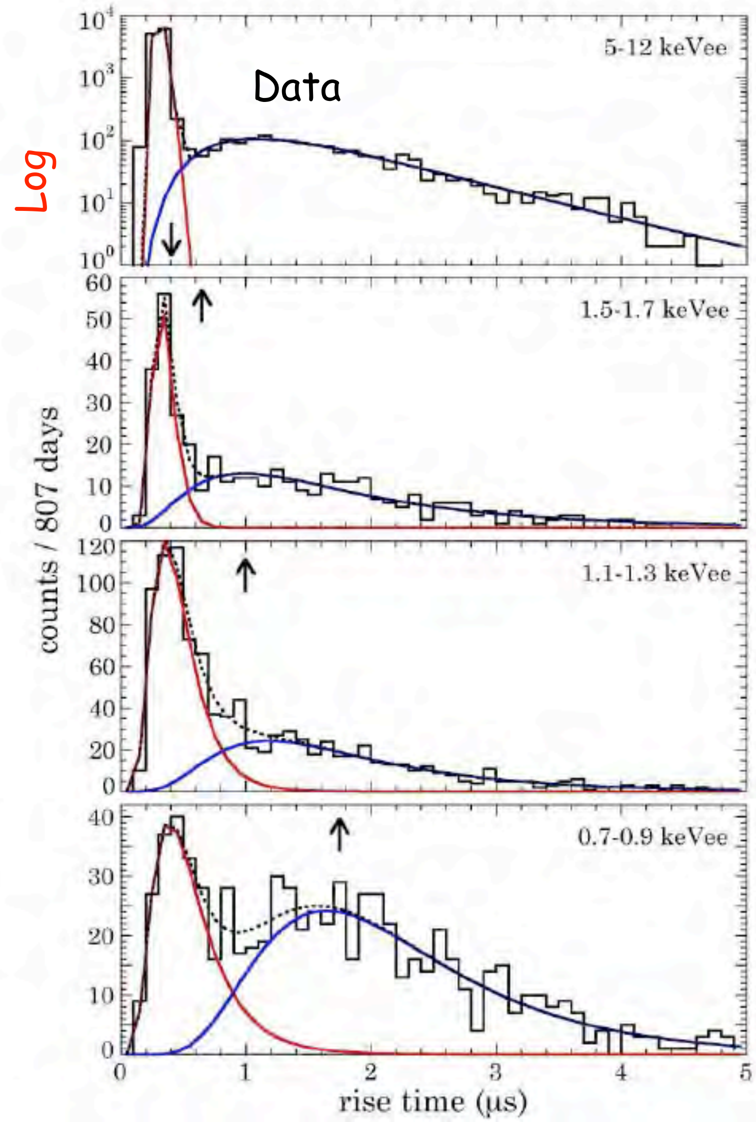
CoGeNT

Problem: events from surface



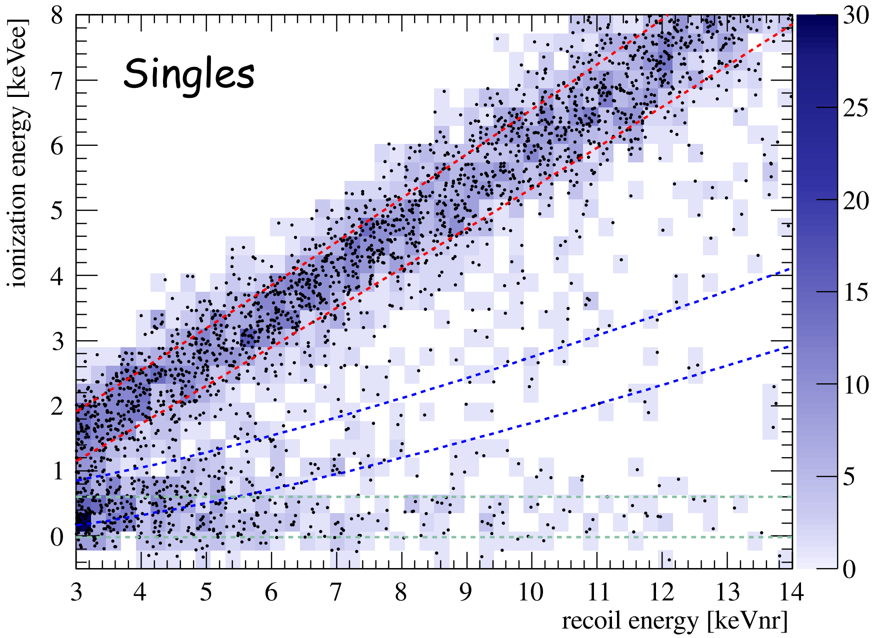
Monte Carlo remains qualitative

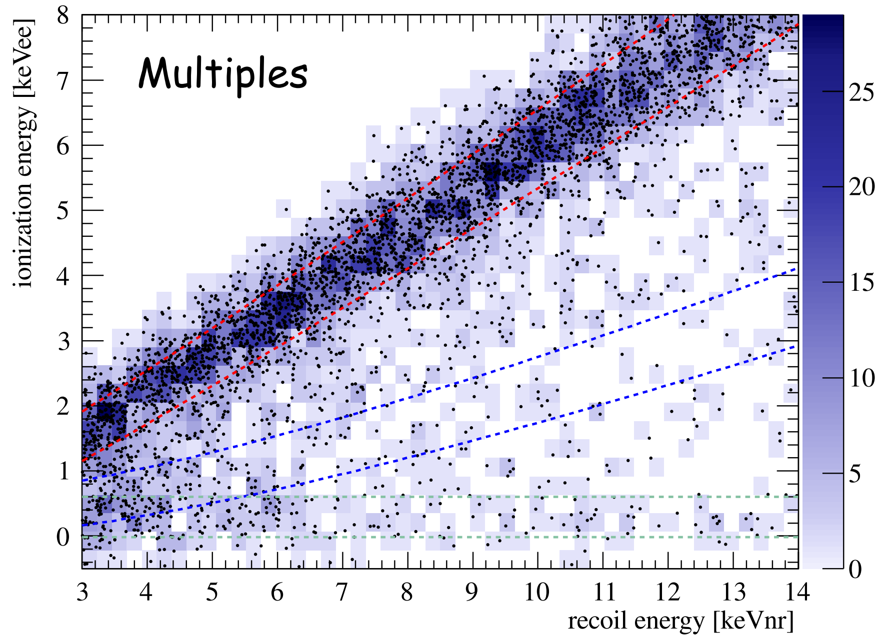


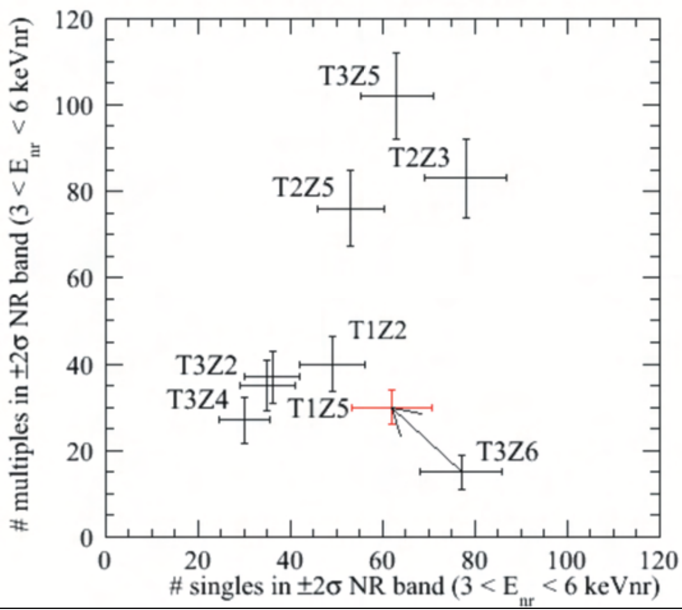


Low Mass CDMS

Multiples look very similar to singles







Hopes and Progress