Dark matter: candidates

Dark Matter (DM) candidates

- Baryonic Dark Matter
  - Cold molecular gas
  - Massive compact halo objects (MACHOs)
    - brown dwarfs, planets, (black holes)

- Non-baryonic Dark Matter
  - Thermal
    - neutrinos
    - weakly interacting massive particles (WIMPS)
    - gravitino
    - black holes
  - Non-thermal
    - axions

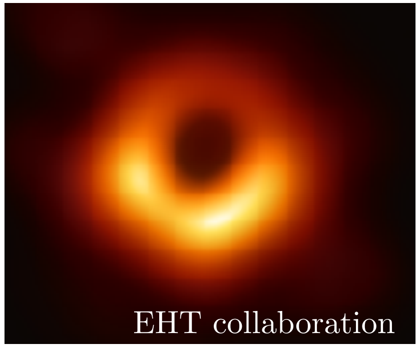
Baryonic dark matter

- **Cold molecular gas**
- must be cold (i.e. not emitting radiation) because they are not observed
- Many arguments against:
  - baryonic matter (in contradiction with CMB observations)
  - must be present in large quantities
  - would absorb light form distant objects

  ⇒ not a likely DM candidate

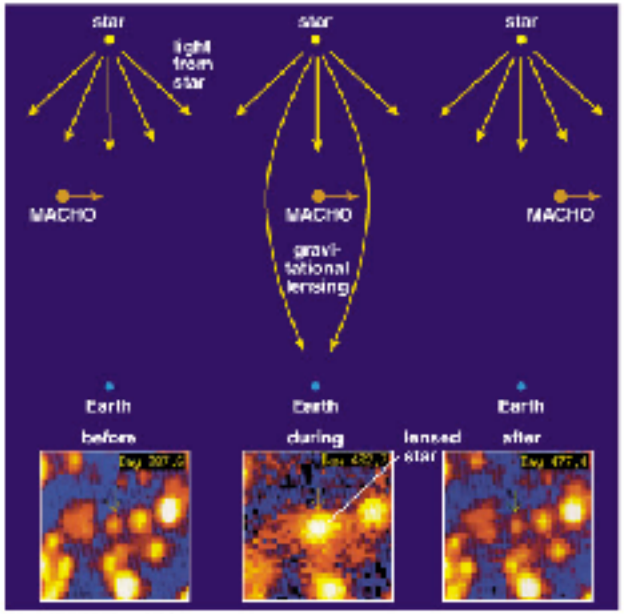
- **Primordial black holes (BH)**
- To be counted as DM, primordial BHs must have been formed before the Big Bang nucleosynthesis (otherwise they would have been counted in the baryonic matter Ω_b)
- Only very special models are allowed

⇒ BHs are not good candidates for DM



EHT collaboration

- **MACHOs**
  - Massive compact halo objects: brown dwarfs, black holes, planets
- Micro-lensing technique:
  - light amplification of distant star
  - duration $\approx (m_{\rm MACHO})^{1/2}$



Copyright © Addison Wesley.

- "MACHO" and "EROS" collaborations:
  - **MACHOs contribute to less than 8% of the halo mass**

Dark Matter "relic" particles

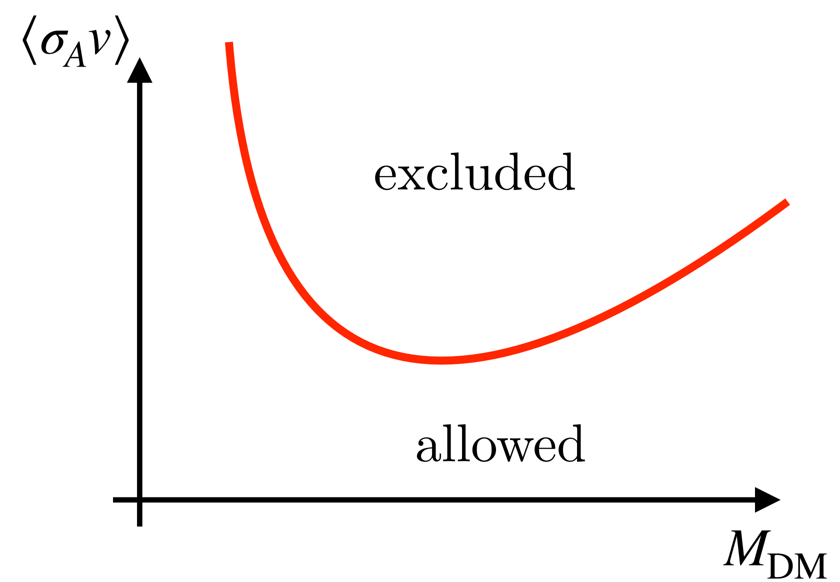
- Express the DM density Ω_{DM} as a function of annihilation cross section and mass

$$\Omega_{\mathrm{DM}} \propto \frac{M_{\mathrm{DM}}}{\langle \sigma_A v \rangle}$$

  - M_{DM} is the mass of the DM particle
  - $\langle \sigma_A v \rangle$ is the thermal-averaged annihilation cross section

- Both M_{DM} and σ are unknown
  $\Rightarrow$ present the experimental results in the $\langle \sigma_A v \rangle$ (or σ) versus M_{DM} plane

Example



- Direct detection from interaction with nuclei $\Rightarrow$ recoil $\Rightarrow$ low sensitivity for low M_{DM}
- At fixed Ω_{DM} (i.e. fixed density), the number of DM particles decreases for higher M_{DM} $\Rightarrow$ lower probability for interaction $\Rightarrow$ low sensitivity for high M_{DM}

Relic neutrinos

- Light neutrinos
  - constrained by structure formation
    - $\sum m_\nu < 0.5 - 1.0\,\text{eV}$
  - cannot contribute to more than $\Omega_\nu < 0.01$

- Heavy neutrinos
  - $m_\nu > m_Z/2$ (as required by LEP experiment)
  - must be "sterile" (to minimise interactions)
  - stable
    - why would a heavy neutrino be stable?
    - what quantum number could make it stable?
    - no obvious candidate...
  - too large mean free path to constitute galactic halo

Supersymmetry (SUSY)

- Supersymmetry:
  - relates fermions and bosons:
    - each SM fermion has a spin 1 SUSY partner:

      quarks (spin 1/2) $\rightarrow$ squarks (spin 1)

      leptons (spin 1/2) $\rightarrow$ sleptons (spin 1)
    - each SM boson has a spin 1/2 SUSY partner:

      gauge bosons (spin 1) $\rightarrow$ gauginos (spin 1/2)

      Higgs boson (spin 1) $\rightarrow$ Higgsino (spin 1/2)
  - $m_{\text{particle}} = m_{\text{sparticle}}$ if perfect symmetry

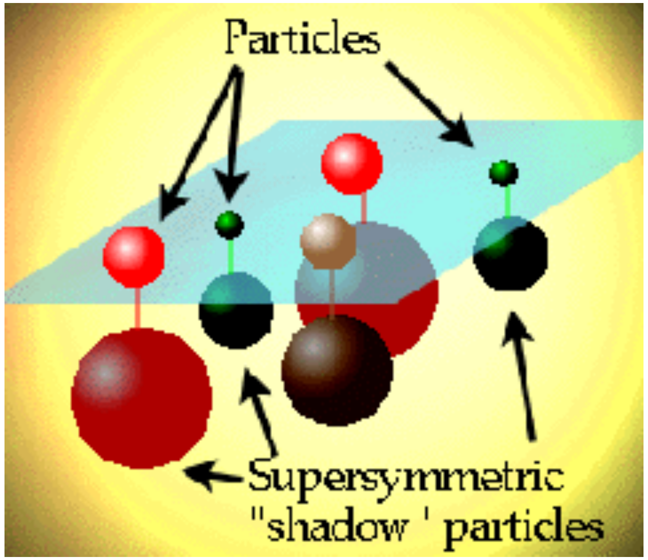
    $\Rightarrow$ SUSY is a broken symmetry at low energies
  - SUSY mass scales $\approx$ 1TeV

	SM	SUSY
Spin 1/2	quarks leptons	gauginos Higgsinos
Spin 1	gauge bosons Higgs boson	squarks sleptons

SUSY: R-parity

- R-parity:
  - $R = (-1)^{2J+3B+L}$
    $= +1$ for particles
    $= -1$ for sparticles
  - R must be conserved to avoid proton decay

	J	B	L	R
quarks	$\frac{1}{2}$	$\frac{1}{3}$	0	+1
leptons	$\frac{1}{2}$	0	1	+1
squarks	1	$\frac{1}{3}$	0	−1



The Particle Adventure

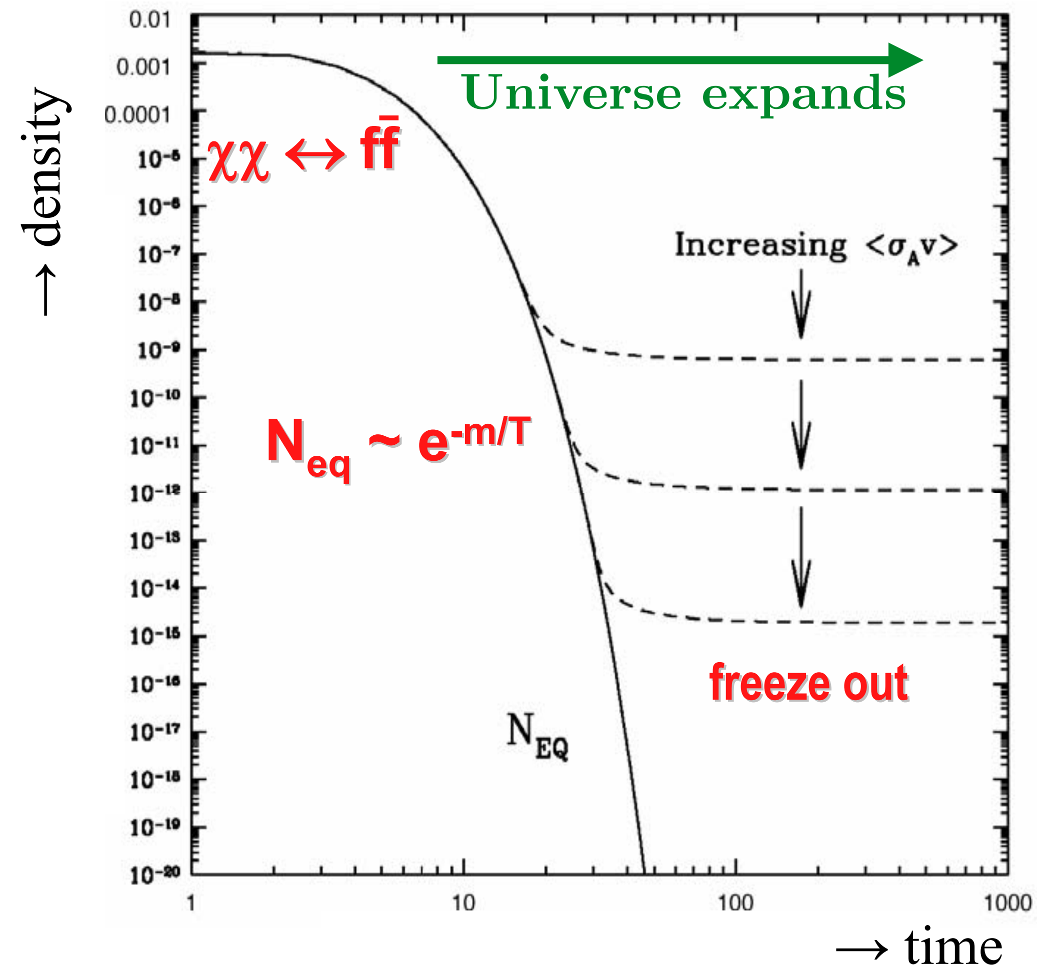
- Consequence of R-parity conservation:
  - sparticles are produced in pairs
  - Higgsino-gaugino mixing
    ⇒ eigenstates called neutralino (χ^0)

- The lightest neutralino χ_1^0 is stable, heavy, and it interacts weakly
  ⇒ excellent Dark Matter candidate

SUSY: Neutralino

- Relic neutralino density: $h^2\Omega_\chi \approx 0.1\,\mathrm{pb}/\langle\sigma\beta\rangle$

- If $m_\chi \approx 100\,\mathrm{GeV}$, and $\sigma \approx$ weak scale $\Rightarrow \Omega_\chi \approx \Omega_{\mathrm{DM}}$



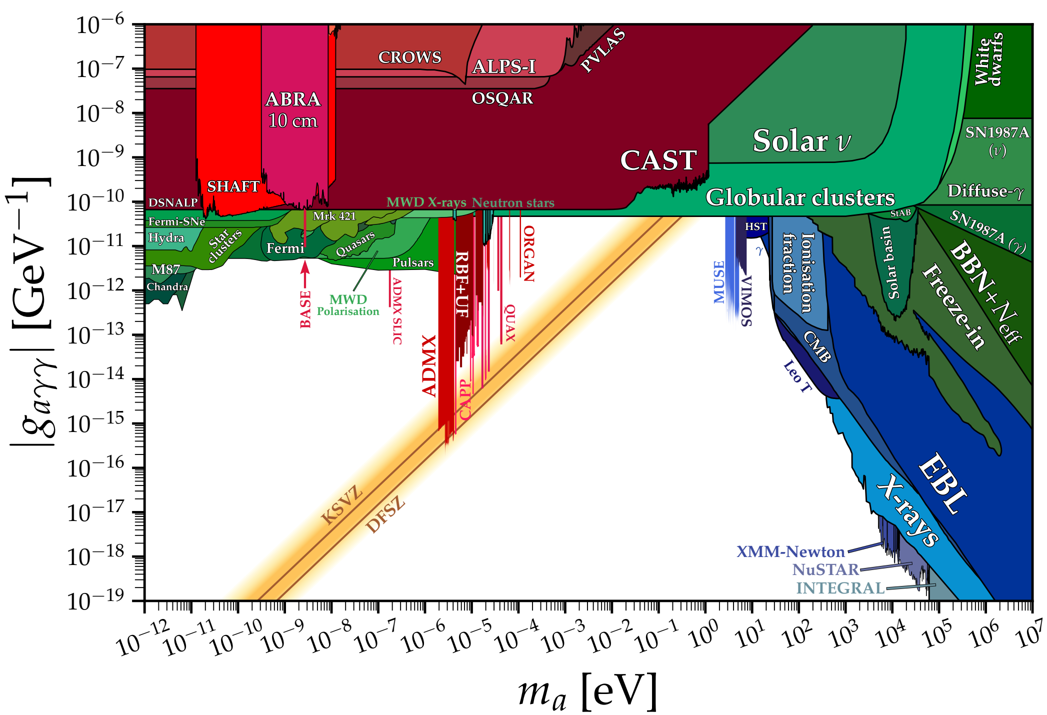
- The neutralino is a good DM candidate

Axions

- Axions were postulated to solve the strong *CP* problem:
  - strong interactions show no *CP* violation, while QCD has terms naturally violating *CP*
  - introduce a scalar field that has its minimum such that CP_{QCD} is conserved
  - new scalar field ⇒ new particle (axion)
  - mass of order $10^{-5} - 10^{-2}\,\mathrm{eV/c^2}$
  - sort of light π^0 , weakly coupling to photon pairs

- Axions are DM candidates
  - non-thermal (e.g. produced in particle decays)
  - axino (axion's SUSY partner) is also a DM candidate

- Several searches in terrestrial (red), astrophysical (green + blue) and QCD (orange)



Dark photons

- Dark photons V:
  - electrically neutral
  - vector bosons (spin 1)
  - mass $m_V < 2m_e \;\Rightarrow\;$ stable
- Production through multiple processes, e.g.
  - scattering: $\gamma e^{\pm} \to V e^{\pm}$
  - annihilation: $e^+ e^- \to V\gamma$
- Searches:
  - experiments sensitive to masses in the range $10^{-22} - 10^{-2}\,\mathrm{eV}$
  - direct detection via electromagnetic or gravitational interactions

Other DM candidates

- Most extensions of the SM have DM candidates
- Extra dimensions: unification of SM interactions and gravity ⇒ branes

  ⇒ Kaluza-Klein excitations lead to stable fields

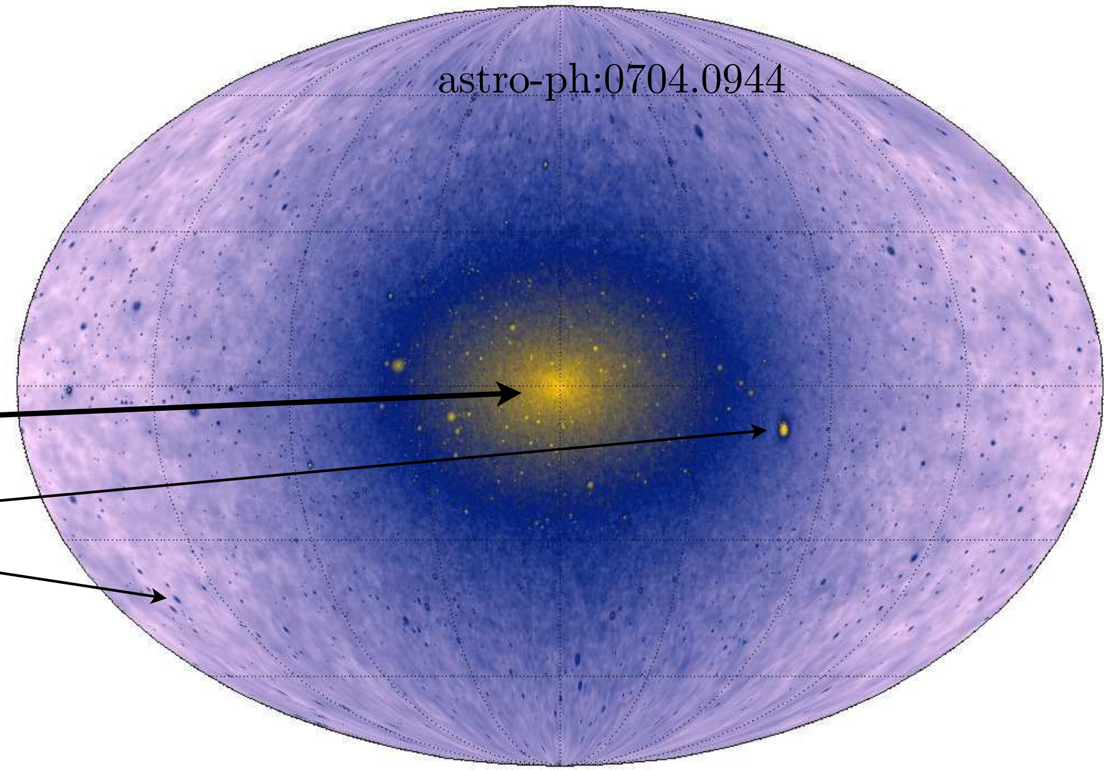
- Other exotic models:
  - topological solitons
  - gravitino (graviton's spin 3/2 partner)
    - difficult to test experimentally
  - modification of gravity
  - [and many more]

cf. PDG [pdg.lbl.gov]

Detection of dark matter

Galactic Dark Matter

- $\rho_{\text{DM}} \sim 1/r^2$ from galactic rotation curves
- DM galactic simulations:
  - central cusp
  - DM clumps
    - "hot spots" for signals

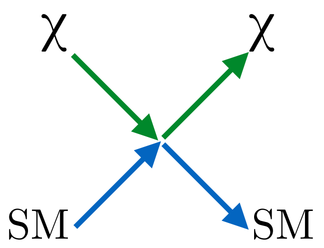


- DM could also accumulate gravitationally in stars after multiple scattering
- Isotropic DM velocity in galaxy
  $\Rightarrow$ annual modulation from Sun-Earth movement

Detection of Dark Matter

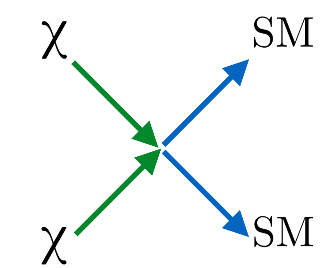
I. Direct detection

- interaction of halo DM in detectors
  - generally underground detectors



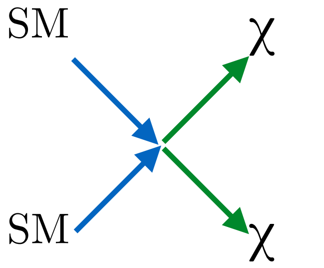
II. Indirect detection

- SM signals from the annihilation of DM particles (e.g. $\chi + \chi \rightarrow \gamma + \gamma$)



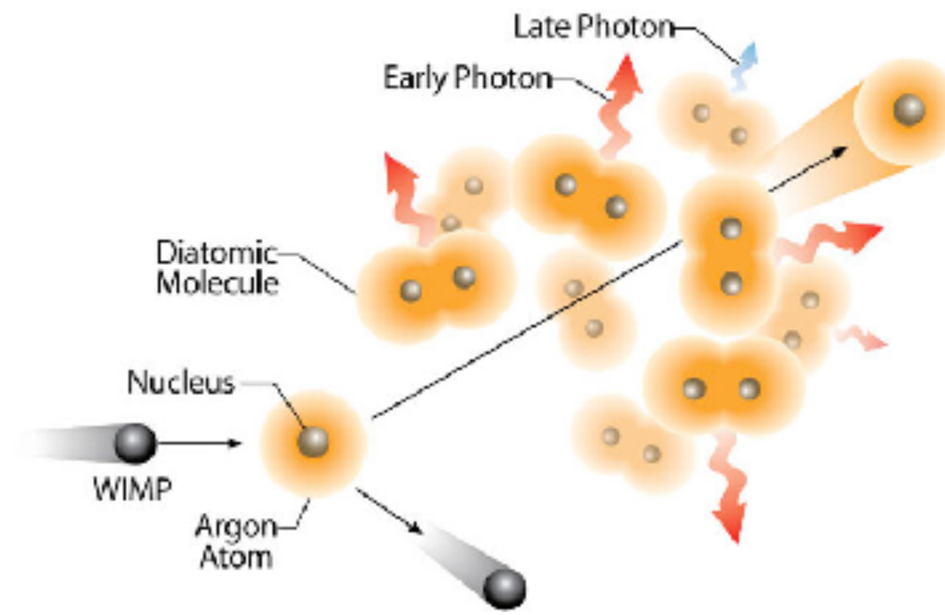
III. Creation of DM particle candidates at accelerators

- e.g. high-energy collisions producing SUSY

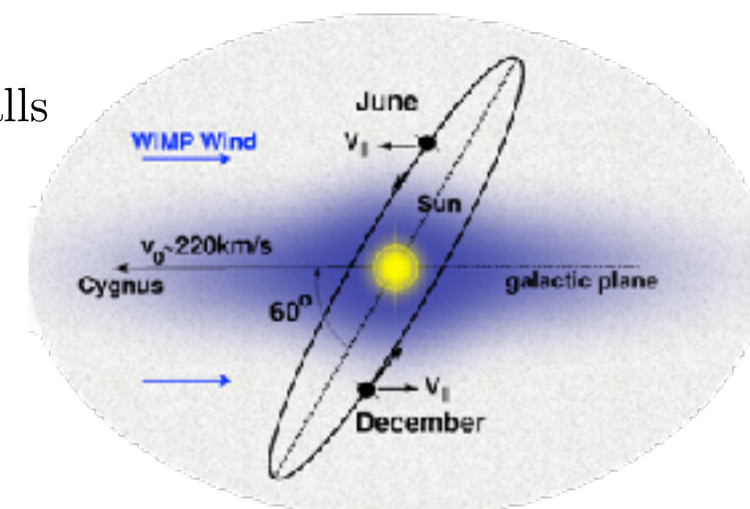


Direct detection experiments

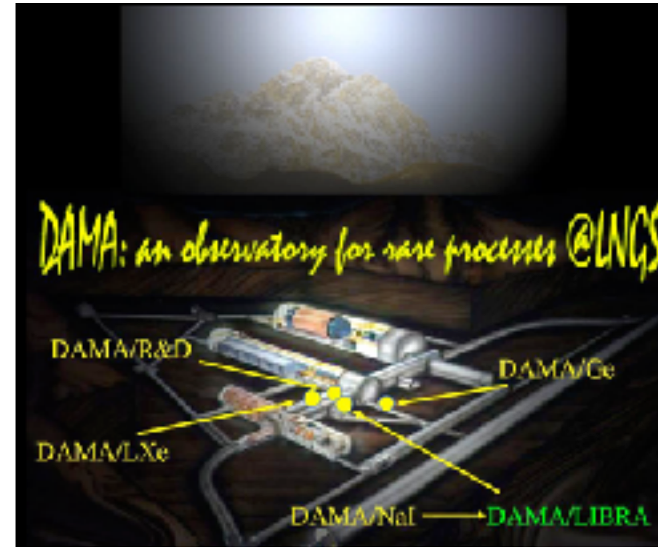
- WIMP interactions in the detector:
  - scattering on nucleus
    → 3 types of signals:
    - **ionisation** ⇒ electric pulse
    - **scintillating light** ⇒ photons
    - **emission of phonons**
      ⇒ detected as heat increase
      (≈10mK ⇒ necessity for cryogenics)



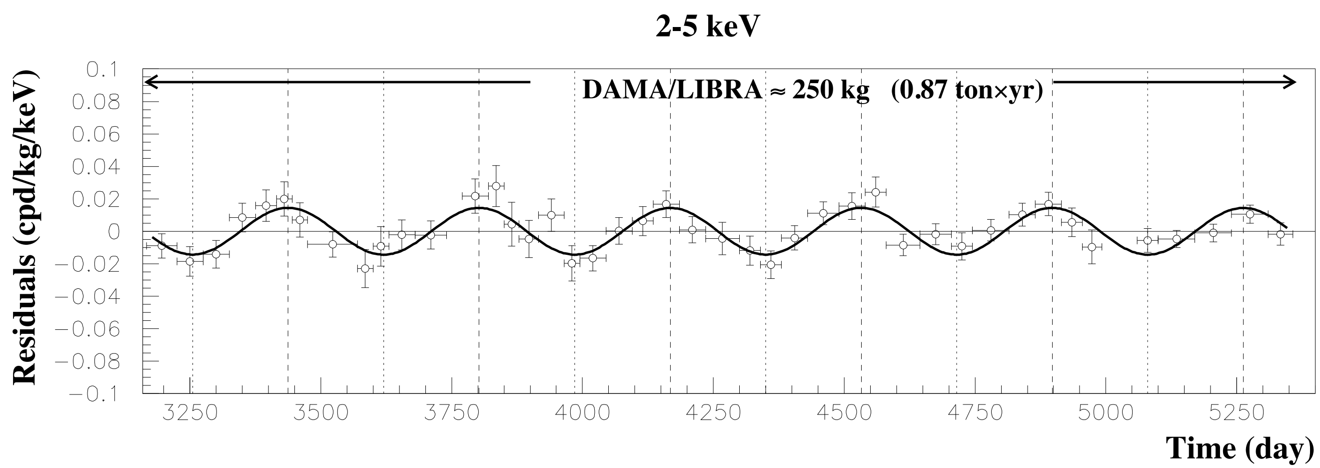
  - Background rejection:
    - deep underground to reject cosmic noise
    - reject neutrons and radioactivity with thick walls
    - use energy deposition topology to distinguish recoiling nuclei (signal) from recoiling electrons
    - annual modulation



DAMA/LIBRA



- Italy-China collaboration, at Gran Sasso
- 250kg NaI(Tl) crystals
  - highly radio-pure scintillators
- Significant annual modulation



- ...but controversial result:
  - questions about background control
  - not observed by other experiments... until...

Interpretations:

$m_\chi \simeq 50$GeV and $\sigma_{\chi p} \simeq 7\times10^{-6}$ pb

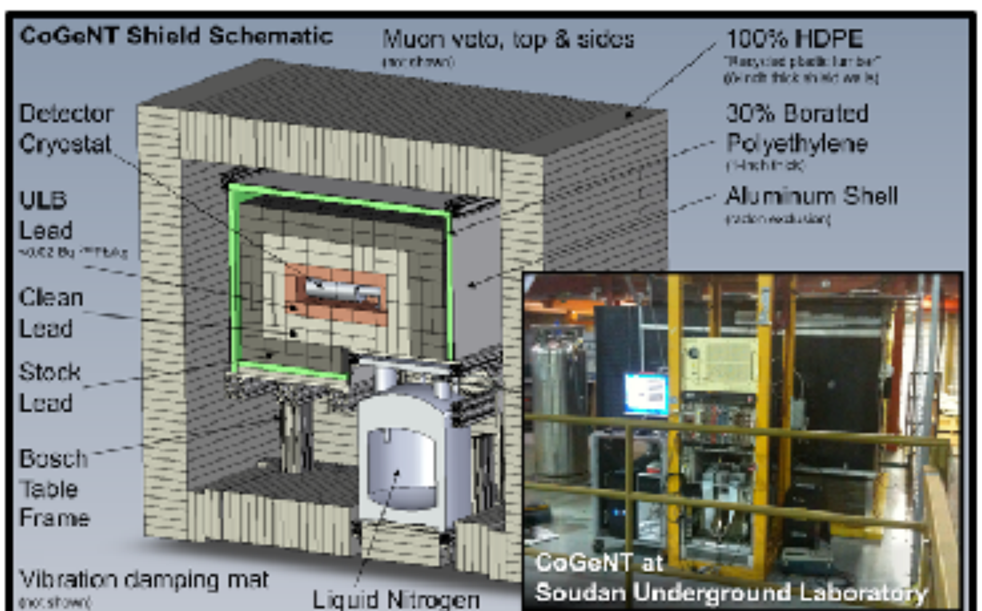
or

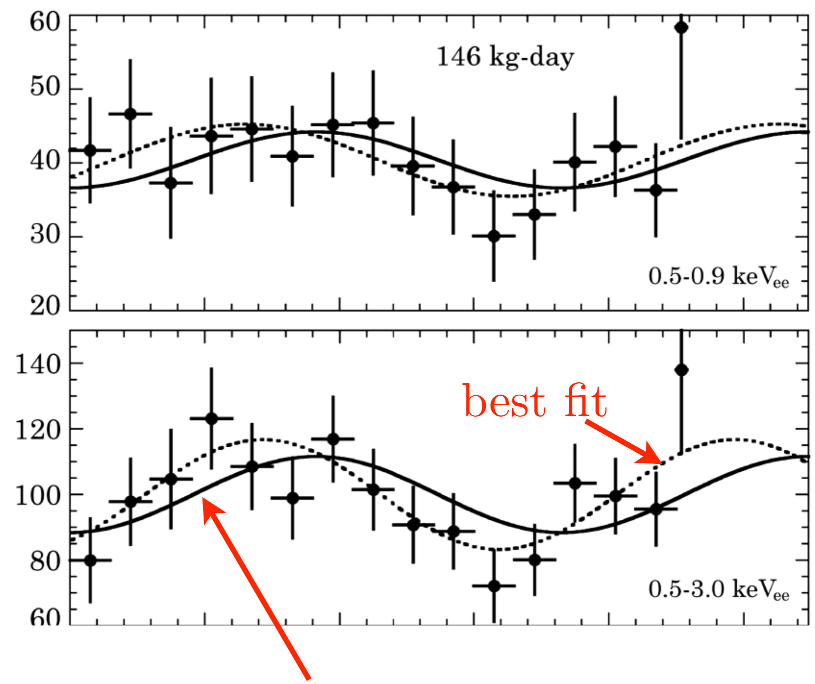
$m_\chi \simeq 6$–10GeV and $\sigma_{\chi p} \simeq 1\times10^{-3}$ pb

CoGeNT

- Dark matter search experiment at Soudan Lab (USA)
- Since December 2009
- A single high-purity 440g Germanium detector, operated at low temperature

- Unknown source, but incompatible with cosmic muons ⇒ ~7GeV Dark Matter candidate [?]

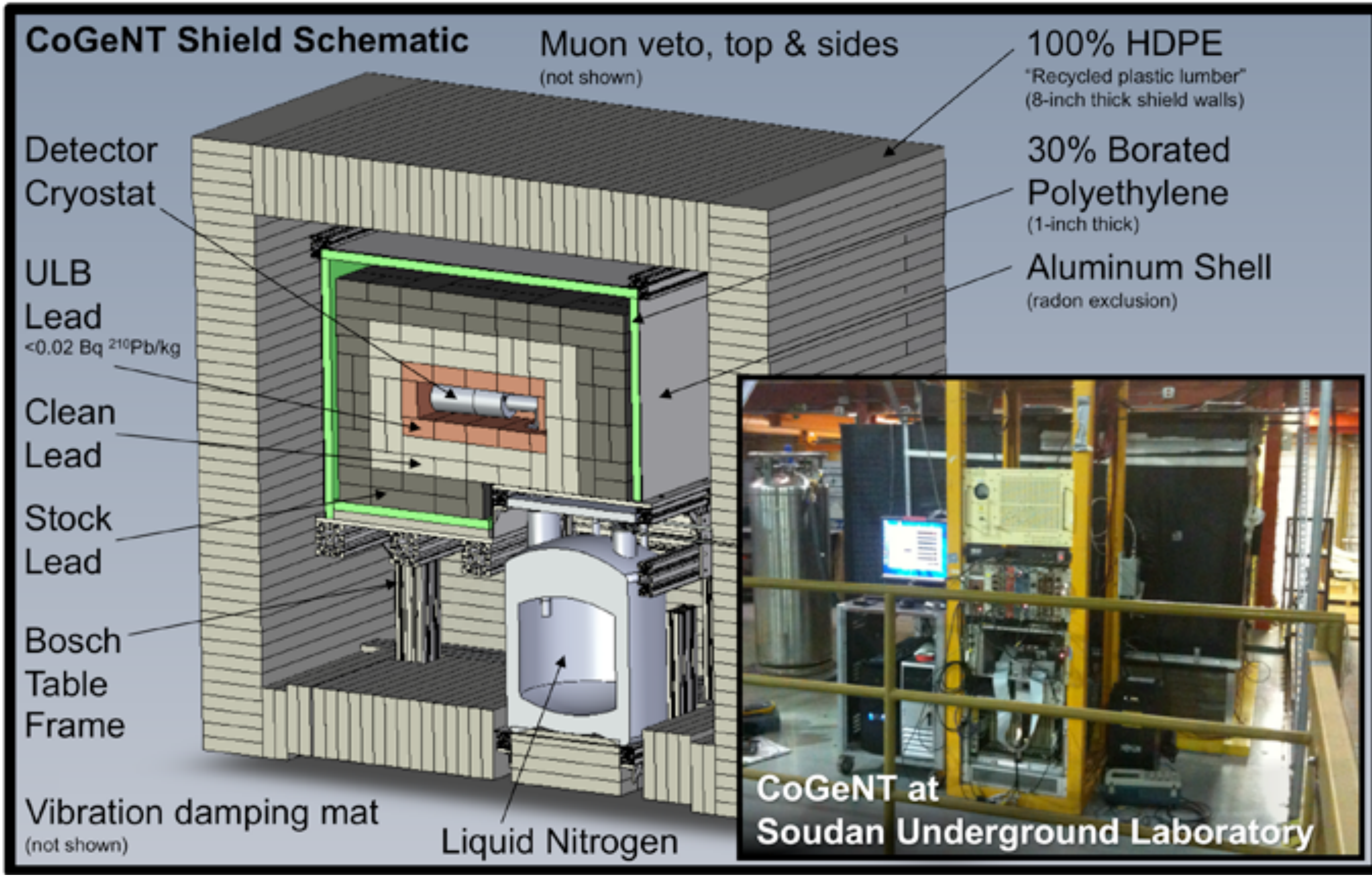




Phys. Rev. Lett. 107 (2011) 141301

modulation from simulation of 7GeV Dark Matter particles in the halo

CoGeNT

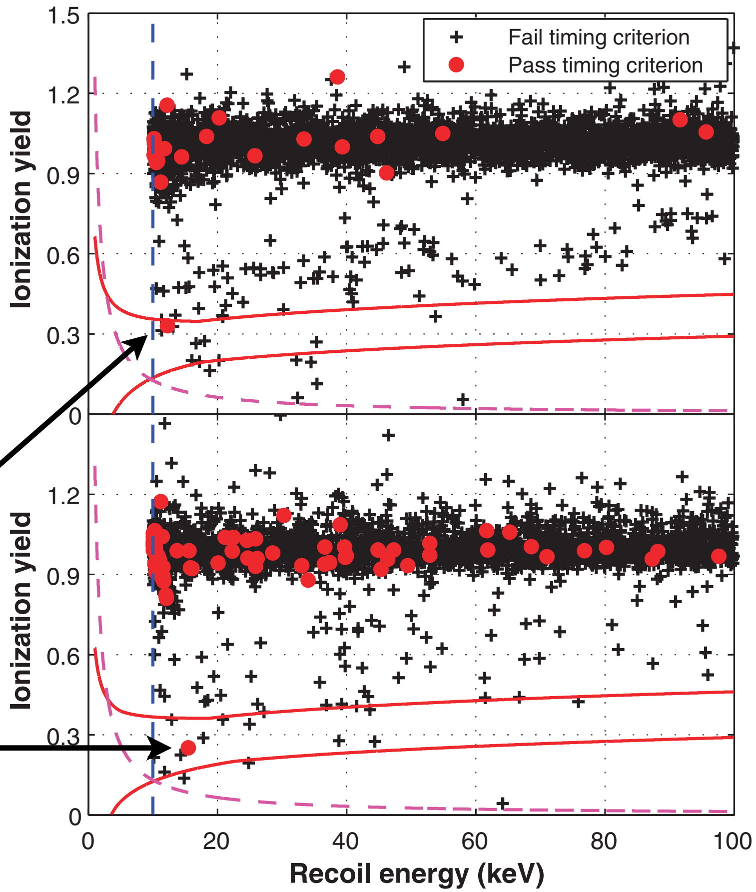

CoGeNT Shield Schematic
Muon veto, top & sides
(not shown)
100% HDPE
"Recycled plastic lumber"
(8-inch thick shield walls)
Detector
Cryostat
30% Borated
Polyethylene
(1-inch thick)
ULB
Lead
<0.02 Bq ²¹⁰Pb/kg
Aluminum Shell
(radon exclusion)
Clean
Lead
Stock
Lead
Bosch
Table
Frame
Vibration damping mat
(not shown)
Liquid Nitrogen
CoGeNT at
Soudan Underground Laboratory

CDMS

- Cryogenic Dark Matter Search (CDMS)
  - at Soudan mine (Minnesota)
  - Silicon and Germanium detector operated at low temperature
    - charge collection on one side
    - tungsten-based phonon detection on the other side (ΔT)

	recoiling particle	ionisation	phonons
WIMP	Nucleus	low	delayed
$e^{\pm}$, γ	$e^{\pm}$	high	fast

- Results [Science, 327 (2010) 1619]:
  - expect 0.9±0.2 background events
  - observe 2 WIMP candidates
    - not statistically significant yet

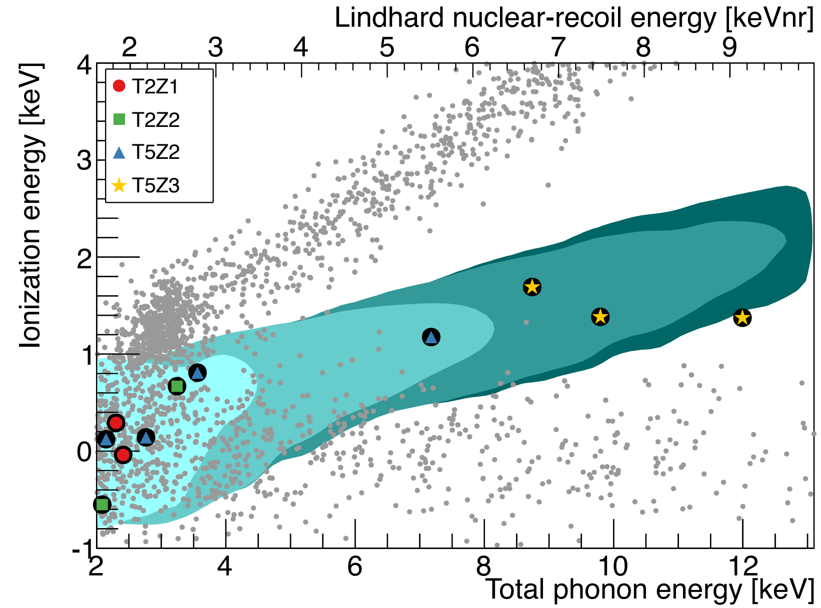


red points: phonon timing consistent with WIMPS
red lines: acceptable ionisation range

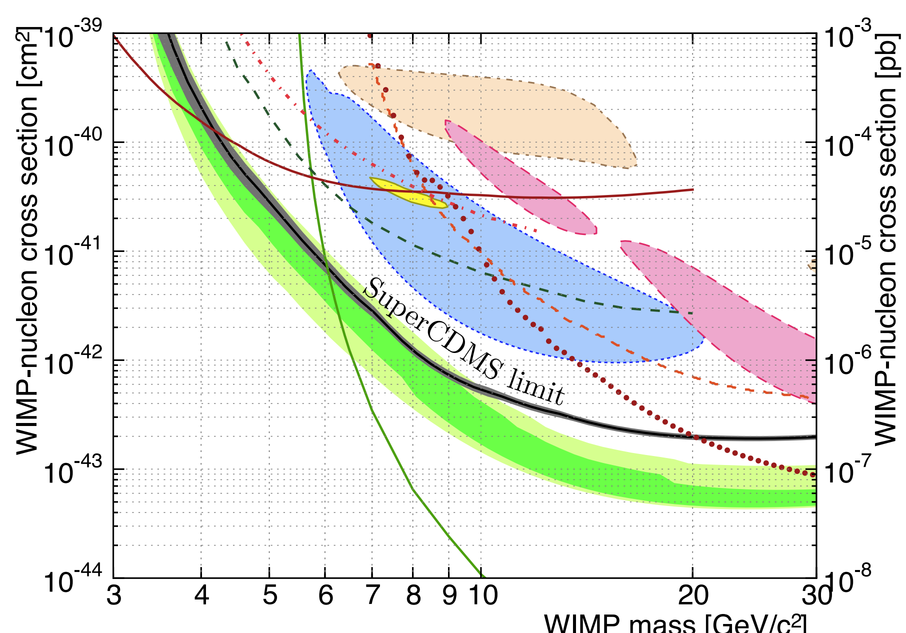
SuperCDMS

http://cdms.berkeley.edu

- Upgraded CDMS detector
  - 15 cylindrical Ge crystals
  - 0.6kg per crystal
  - 5 towers of 3 crystals
- Results based on 577 kg-day
- Optimised sensitivity for 5, 7, 10, and 15 GeV/c² WIMPs
- 11 candidates are selected (expected background: 6±1)



Detector	Candidate energies [keV_{nr}]	Expected background
T1Z1	—	$0.03^{+0.01}_{-0.01}$
T2Z1	1.7, 1.8	$1.4^{+0.2}_{-0.2}$
T2Z2	1.9, 2.7	$1.8^{+0.4}_{-0.3}$
T4Z2	—	$0.04^{+0.02}_{-0.02}$
T4Z3	—	$1.7^{+0.4}_{-0.3}$
T5Z2	5.8, 1.9, 3.0, 2.3	$1.1^{+0.3}_{-0.3}$
T5Z3	7.8, 9.4, 7.0	$0.13^{+0.06}_{-0.04}$

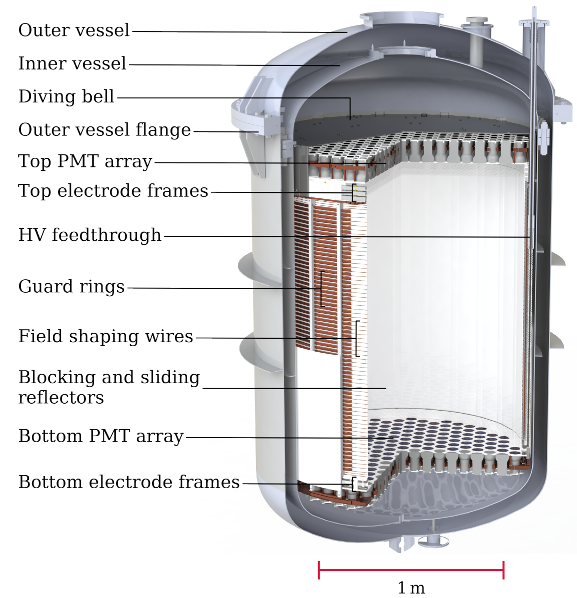


arXiv:1402.7137

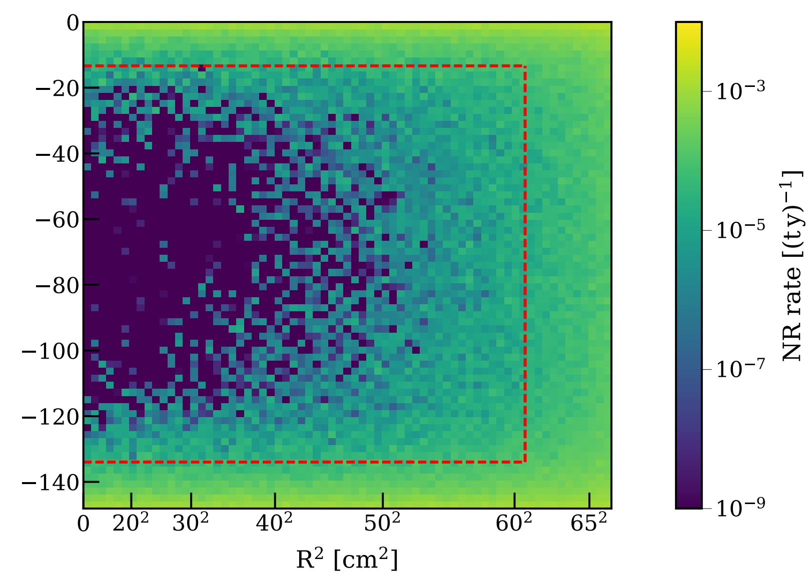
[update in arXiv:1708.08869]

XENONnT

- Dark matter search with liquid Xenon detector at Gran Sasso laboratory
- Detection principle of the XeTPC (Time Projection Chamber):
  - dark matter interactions with Xe atoms create primary **scintillation** light (S1) and **ionisation** of the Xe atoms
  - the electrons produce secondary **scintillation** light (S2)
  - S1 and S2 light detected by 494 photomultiplier tubes
  - combination of S1 and S2 intensities allows to separate signal from background

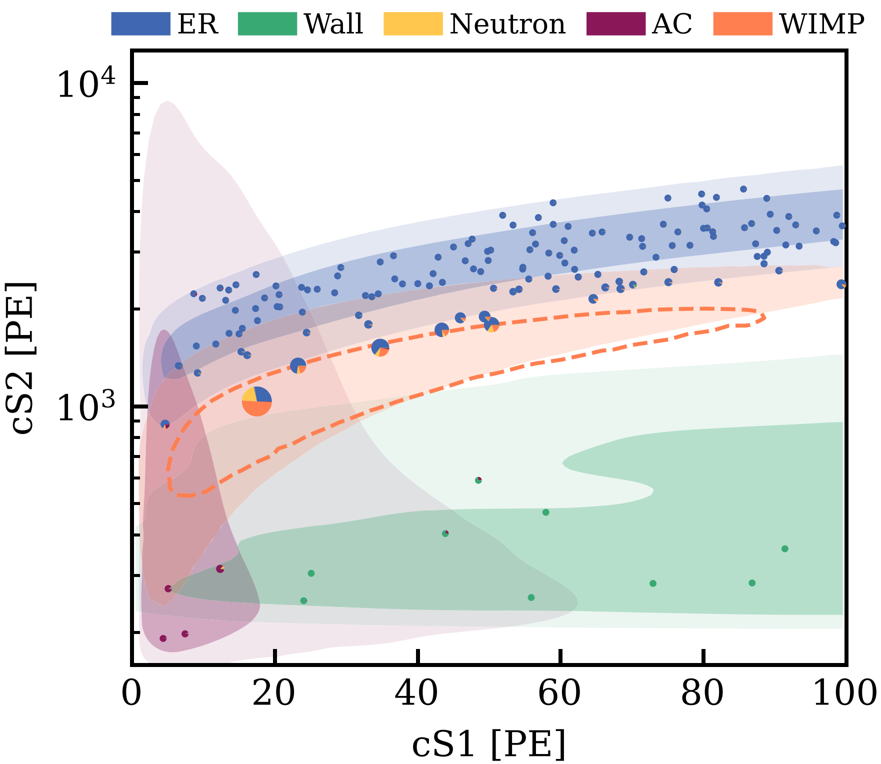


- Background
  - use outward-facing PMTs to veto background events produced outside the detector
  - simulation used to show the lowest background level is in the center of the detector volume (4t liquid Xe)



XENONnT: results

- Data taking during 95.1 days in 2021
  - exposure = $(1.09 \pm 0.03)\,\mathrm{t \cdot yr}$
  - expected background: 2.0 ± 0.2 events
  - observe 3 events in signal region



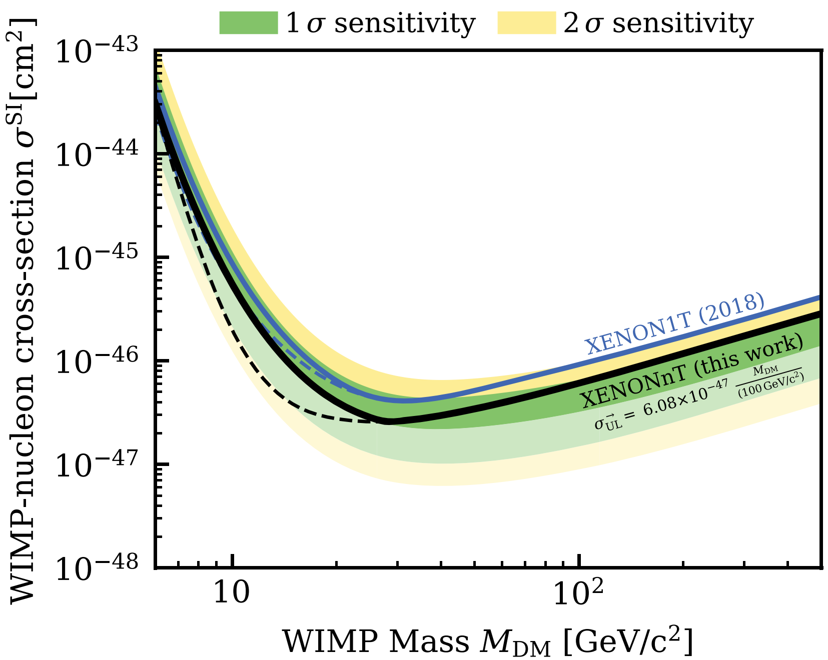
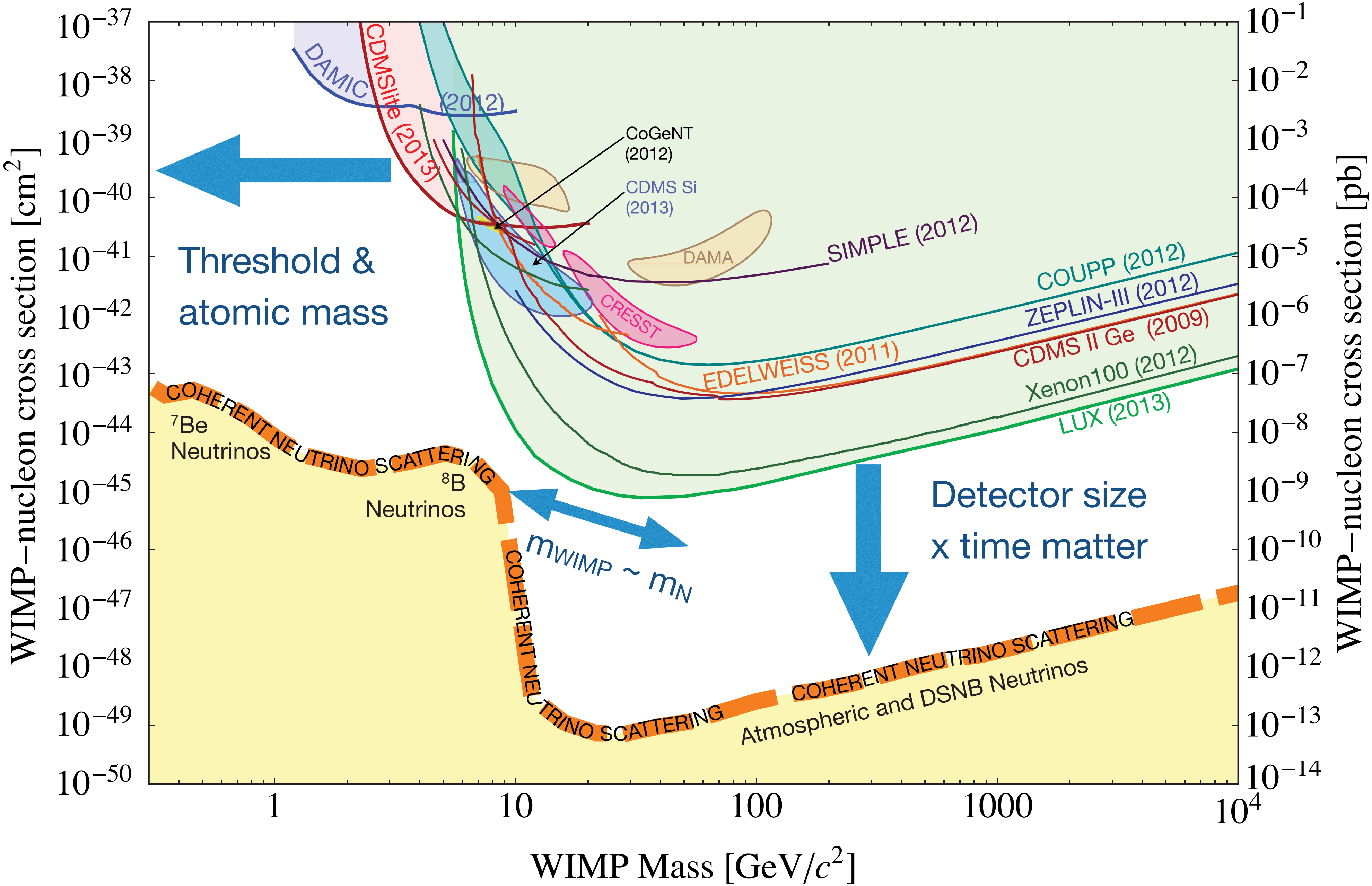


FIG. 4. Upper limit on spin-independent WIMP-nucleon cross section at 90% confidence level (full black line) as a function of the WIMP mass. A power constraint is applied to the limit to restrict it at or above the median unconstrained upper limit. The dashed lines show the upper limit without a power constraint applied. The 1σ (green) and 2σ (yellow) sensitivity bands are shown as shaded regions, with lighter colors indicating the range of possible downward fluctuations. The result from XENON1T [3] is shown in blue with the same power constraint applied. At masses above 100 GeV/c^2, the limit scales with mass as indicated with the extrapolation formula.

- Results: upper limit at 90% C.L. on the nucleon scattering cross section of $2.58 \times 10^{-47}\,\mathrm{cm}^2$ at $28\,\mathrm{GeV/c}^2$

Phys. Rev. Lett. 130, 261002 (2023)

Limits on direct DM searches



Summary of experimental constraints

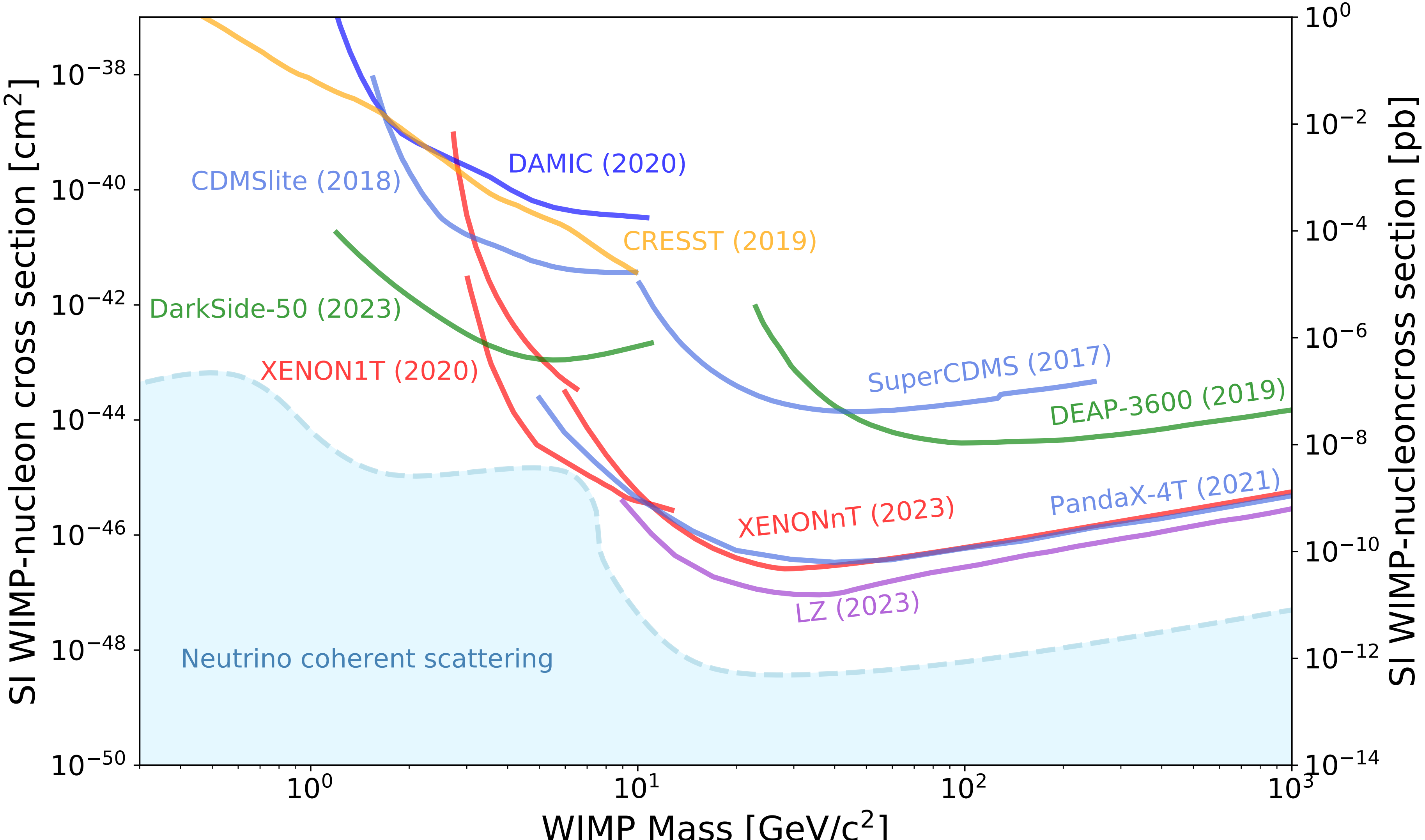
Table 27.1: Best constraints from direct detection experiments on the SI (at high >5 GeV and low < 5 GeV masses) and SD DM-nucleon couplings.

Experiment	Target	Fiducial mass [kg]	Cross section [cm^2]	DM mass [GeV]	Ref.
		Spin independent high mass (>5 GeV)			
LUX-ZEPLIN	Xe	5500	9.2×10^{-48}	36	[103]
PandaX-4T	Xe	2670	3.8×10^{-47}	40	[104]
XENONnT	Xe	4180	2.6×10^{-47}	30	[105]
SuperCDMS	Ge	12	1.0×10^{-44}	46	[106]
DarkSide-50	Ar	20	1.9×10^{-43}	10	[107]
DEAP-3600	Ar	2000	3.9×10^{-45}	100	[108]
		Spin independent low mass (<5 GeV)			
LUX (Migdal)	Xe	118	6.9×10^{-38}	2	[109]
XENON1T (Migdal)	Xe	1042	3×10^{-40}	2	[110]
XENON1T (ionisation only)	Xe	1042	3.6×10^{-41}	3	[111]
DarkSide-50 (ionisation only)	Ar	20	1.4×10^{-42}	2	[107]
SuperCDMS (CDMSlite)	Ge	0.6	2×10^{-40}	2	[112]
SuperCDMS (CDMSlite, Migdal)	Ge	0.6	6×10^{-38}	2	[113]
CRESST	$CaWO_4$ - O	0.024	1×10^{-39}	2	[114]
CRESST	Si	0.0035	4.5×10^{-32}	0.15	[115]
DAMIC	Si	0.3	1×10^{-40}	4	[116]
NEWS-G	Ne	0.3	1×10^{-38}	2	[117]
		Spin dependent proton			
PICO60	C_3F_8 - F	49	3.2×10^{-41}	25	[118]
PandaX-4T	Xe	2670	1.7×10^{-40}	40	[119]
LUX-ZEPLIN	Xe	5500	4.2×10^{-41}	32	[103]
XENONnT	Xe	4180	1.4×10^{-40}	30	[105]
		Spin dependent neutron			
PandaX-4T	Xe	2670	5.8×10^{-42}	40	[119]
LUX-ZEPLIN	Xe	5500	1.5×10^{-42}	30	[103]
XENONnT	Xe	4180	4.3×10^{-42}	30	[105]

PDG, 2023

Summary direct searches

- No unambiguous WIMP direct observation
- Newest limits reduce the allowed theoretical phase space



PDG, 2023

Detection of Dark Matter

I. Direct detection

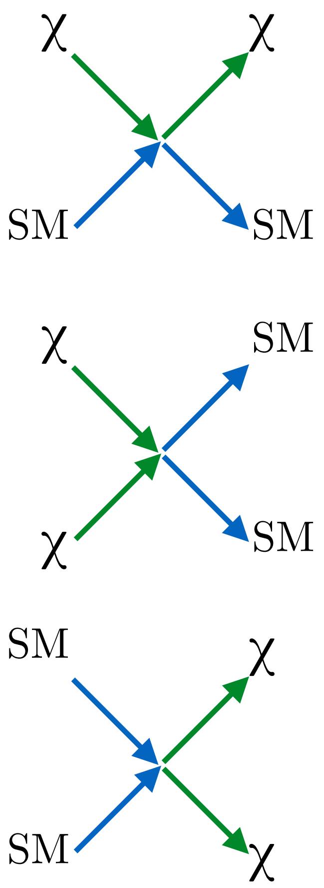
- interaction of halo DM in detectors
    - generally underground detectors

II. Indirect detection

- SM signals from the annihilation of DM particles (e.g. $\chi + \chi \rightarrow \gamma + \gamma$)

III. Creation of DM particle candidates at accelerators

- e.g. high-energy collisions producing SUSY



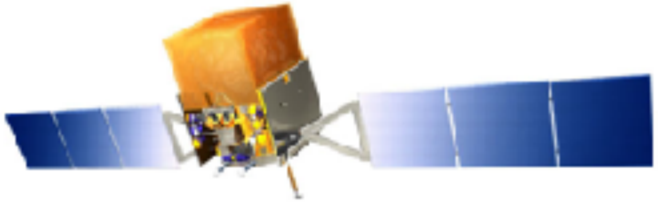
Indirect detection of DM

- Search for signature of annihilation of DM particles
  - highest probability from regions with highest DM density

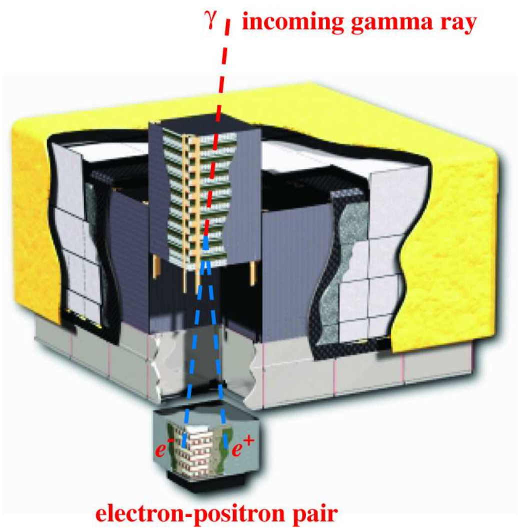
- Signal could come from
  - center of stars (or from Earth!)
  - halo DM clumps

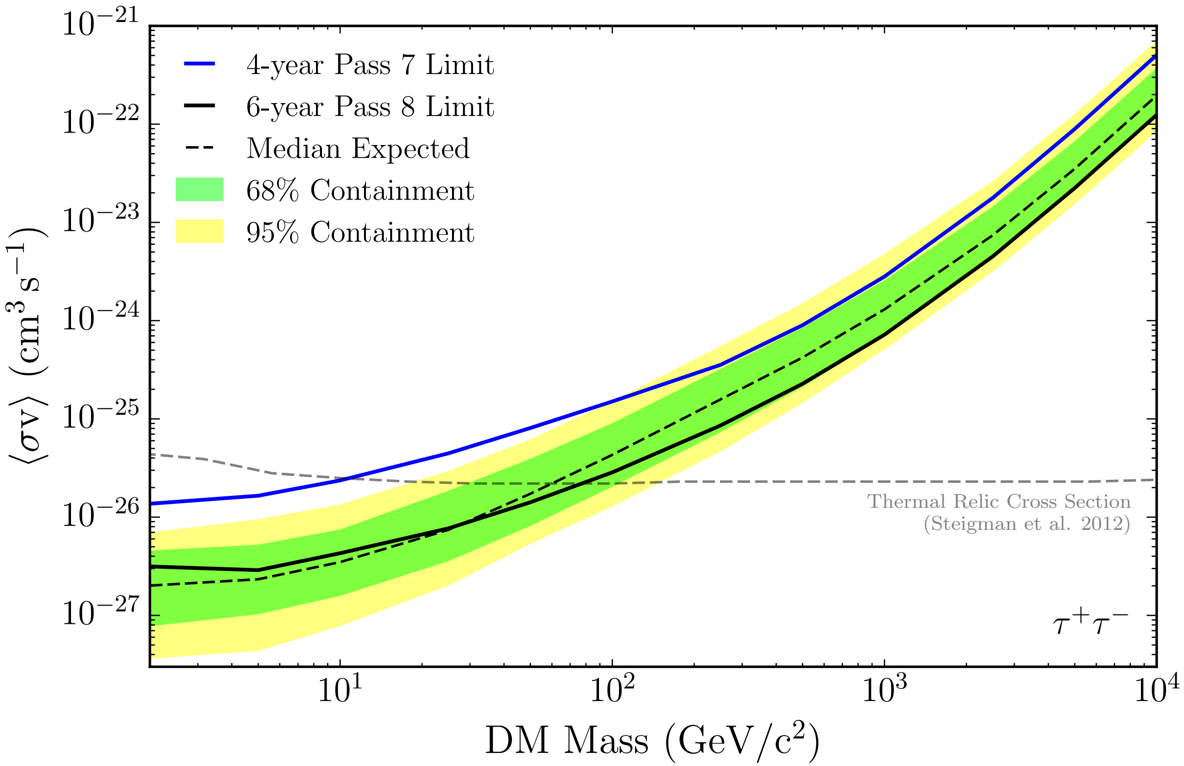
- Possible signals:
  - monoenergetic photons from $\chi\chi \rightarrow \gamma\gamma \quad or\ \chi\chi \rightarrow Z\gamma$
    - Experiments: HESS, GLAST/Fermi
  - monoenergetic neutrinos from $\chi\chi \rightarrow \nu\nu$
    - Experiments: neutrino telescopes (e.g. Ice Cube)

GLAST/Fermi



- Fermi gamma-ray space telescope
  - detector for e^+e^- pairs from γ conversions with a silicon-strip tracker + calorimeter
  - covers 20MeV → 300GeV range
- No significant signal



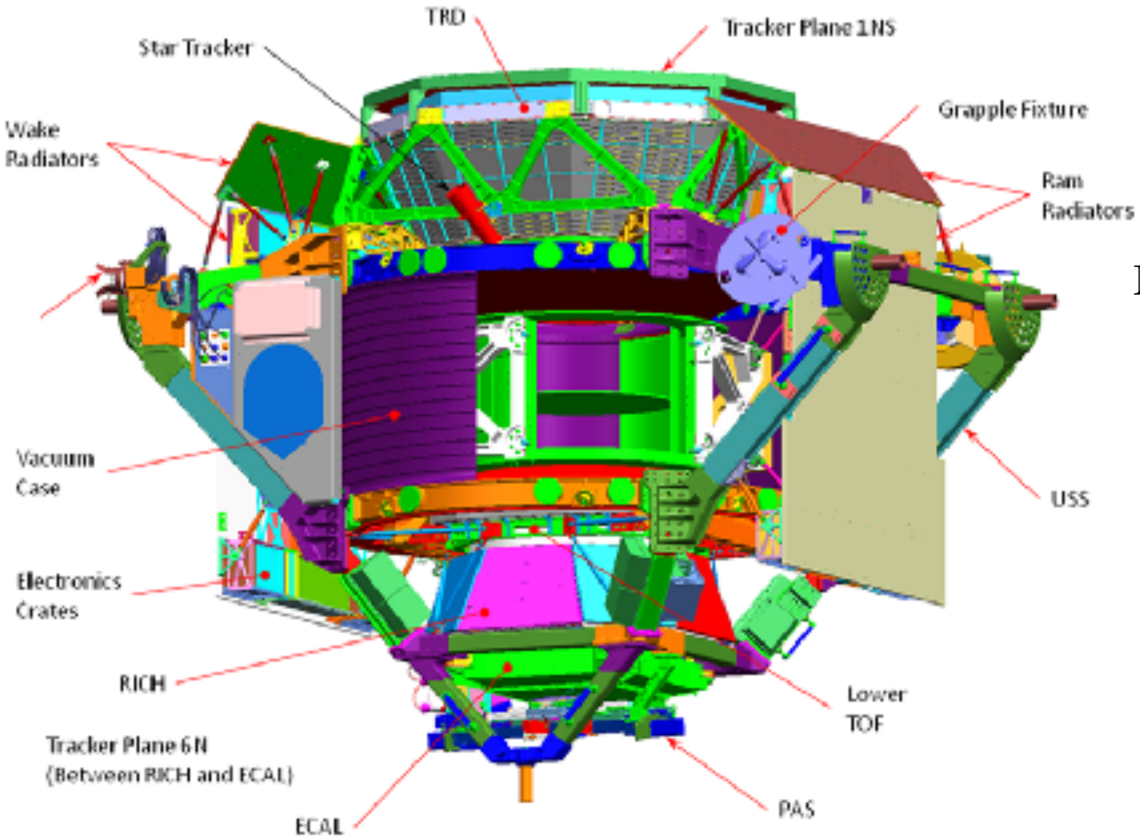


arXiv:1503.02641

http://www-glast.stanford.edu

Alpha Magnetic Spectrometer (AMS-02)

- Charged particle detector in space
- Installed on the ISS since 2011
- Operated from CERN
- Scientific output since 2013

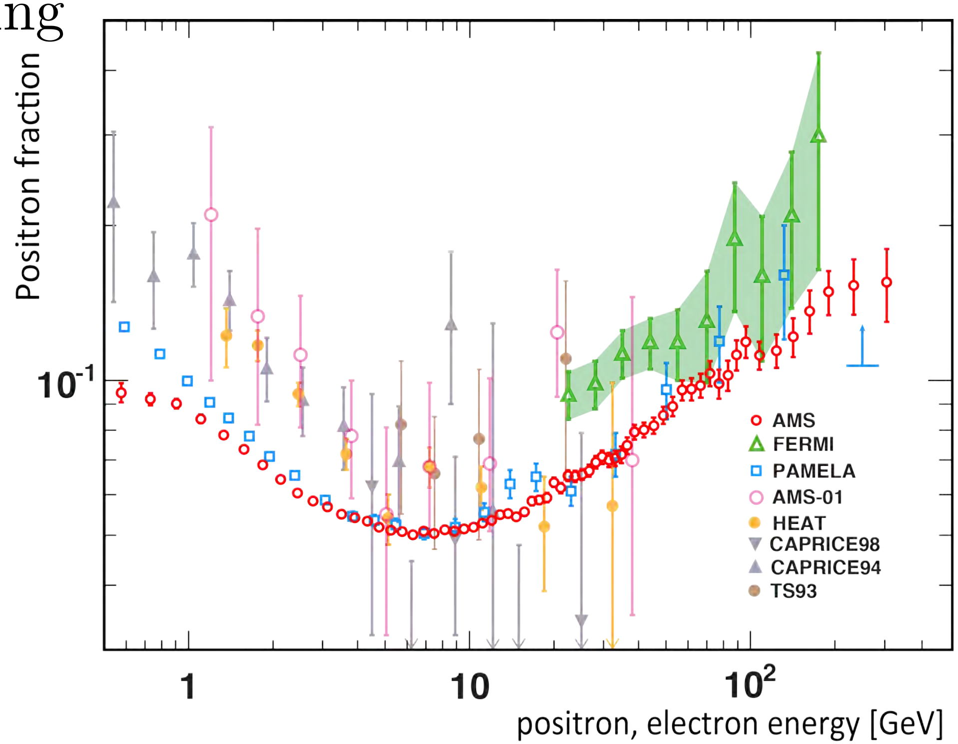


Main detector components:

- **Silicon Tracker + permanent magnet**: momentum and charge identification
- **Transition Radiation Detector**: $e^{\pm}$ identification
- **Time of Flight**: particle velocity ⇒ identification
- **Cherenkov Detector**: particle ID
- **Electromagnetic calorimeter**: energy

Alpha Magnetic Spectrometer (AMS-02)

- Results from 18 months of data taking
  - 25×10^9 cosmic ray particles
  - 6.8×10^6 electrons/positrons
  - measure e^+/e^- fraction as a function of energy $(0.5 - 350\,\text{GeV})$



- Results:
  - confirms previous observations
  - spectrum is isotropic and stable in time (no yearly modulation)
  - spectrum is compatible with the sum of a diffuse component plus a common $e^{\pm}$ source component

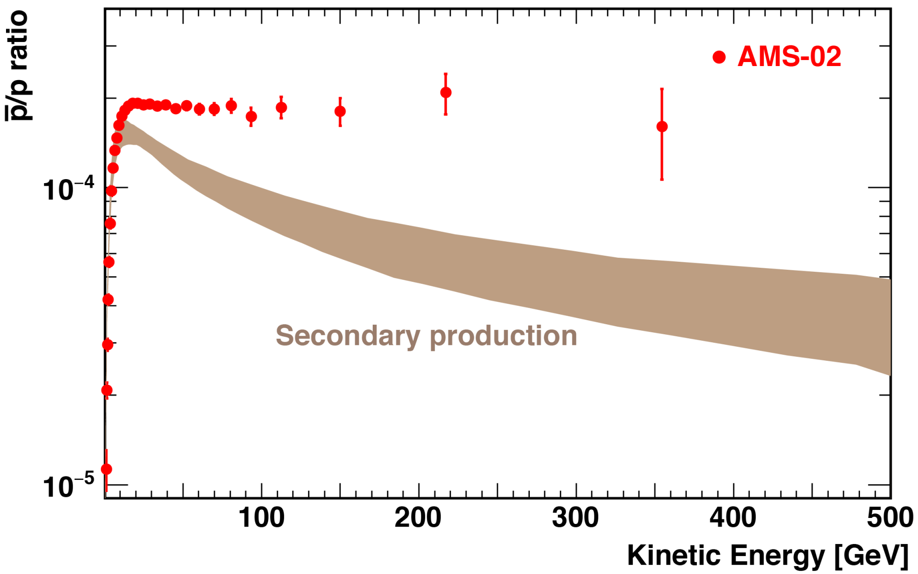
$\Rightarrow$ potentially indication of a DM source $(\chi\chi \to e^+e^-)$

$\Rightarrow$ need results at higher energies (up to 1 TeV)

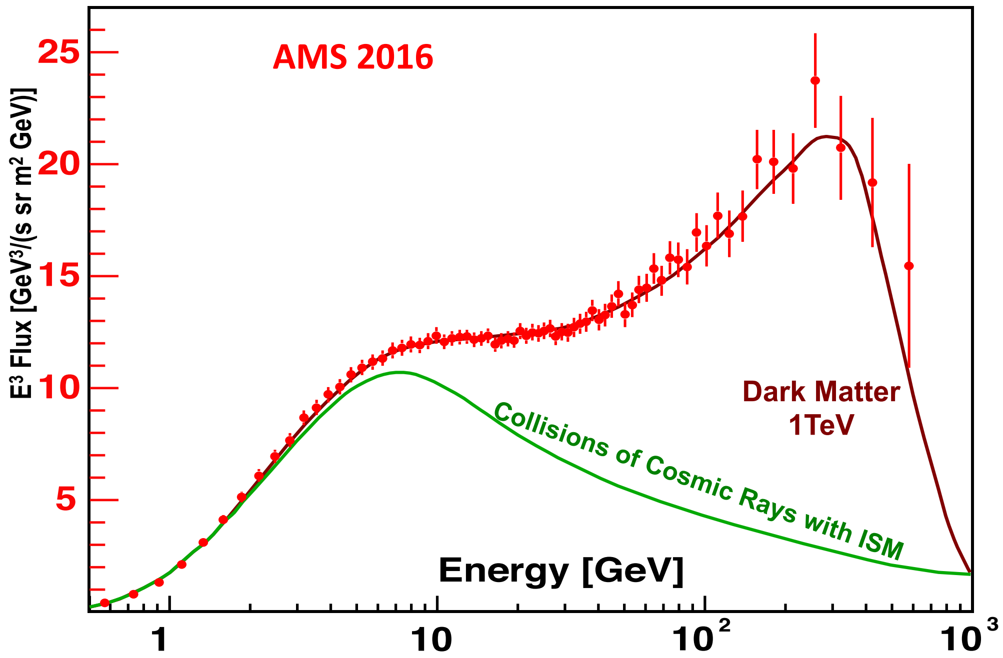
AMS-02: results after 5 years

- Results from 5 years of data taking
  - 90×10^9 cosmic ray particle
  - from sample of 300×10^6 protons, study anti-proton / proton ratio
    - flat distribution up to 400GeV
    - cannot be explained by secondary production of anti-protons
      $\Rightarrow$ dark matter source (annihilation)?
  - positron spectrum shows excess at about 1 TeV
    $\Rightarrow$ is it a sign of DM?

AMS press release April 2015



AMS press release December 2016



Ice Cube Dark Matter search

- Ice Cube searched for DM annihilation signals into neutrino pairs
- Data from IC-79 dataset
- Limit: $\langle \sigma_A v \rangle \leq 10^{-41} \langle \sigma_A v \rangle \leq 10^{-22}$ cm^{3}s^{-1}

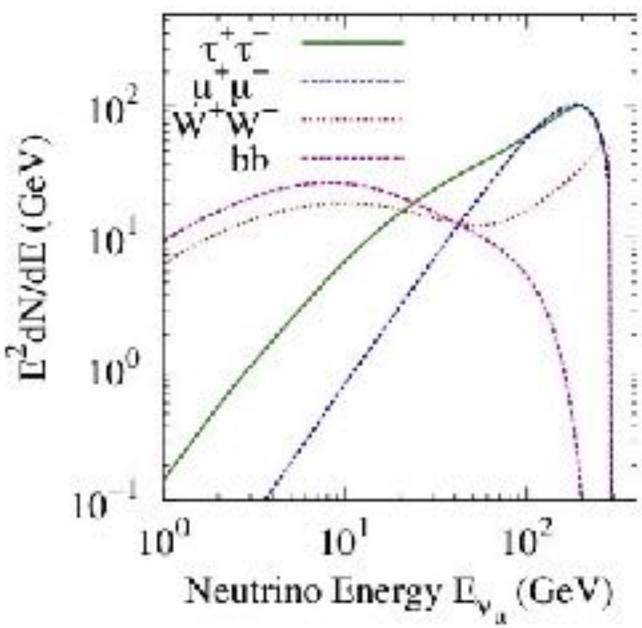
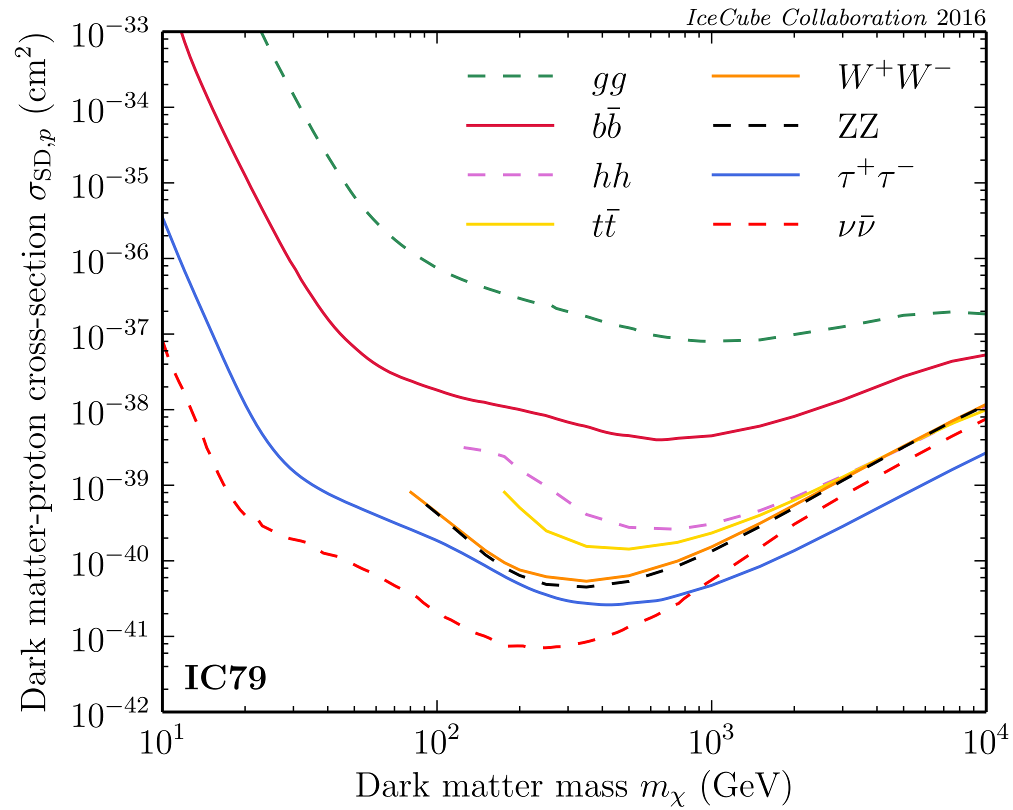


FIG. 3. Differential muon neutrino energy spectrum per annihilation, taking neutrino oscillations into account. In this example we assume a WIMP mass of 300 GeV and 100% branching fraction into the corresponding annihilation channel.



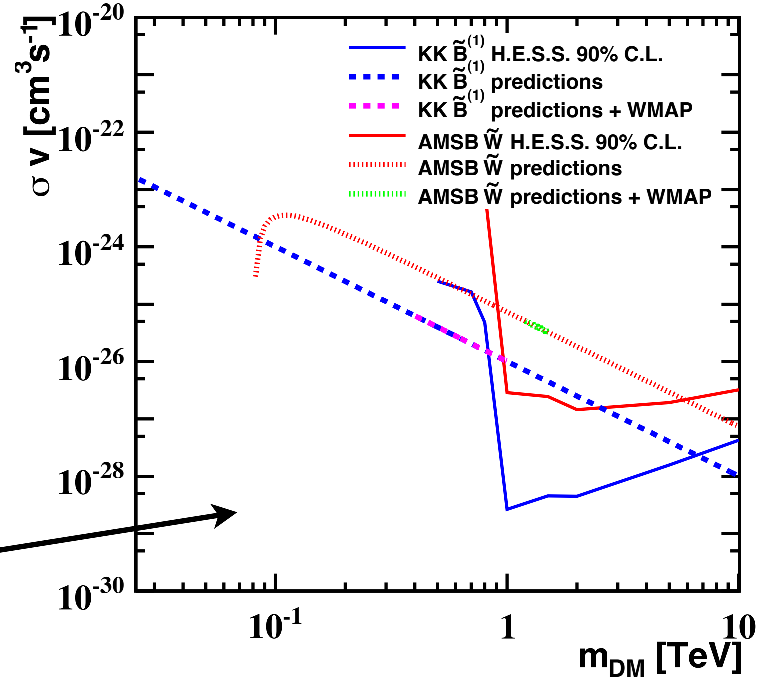
arXiv:1601.00653

Cherenkov telescopes

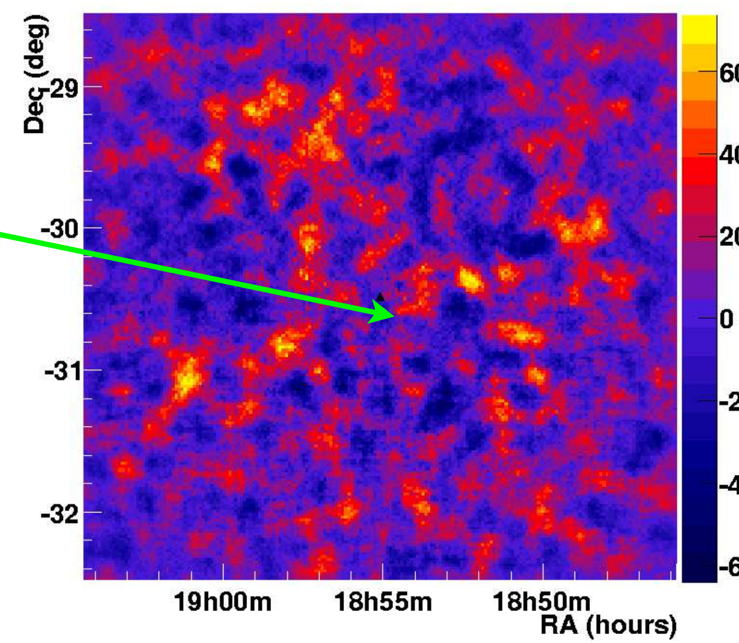
- Use atmosphere as Cherenkov radiator for cosmic particles

- HESS (High energy stereoscopic system)
  - search for DM near high-density objects:
    - black holes
    - galactic center
    - dwarf galaxy:

      no γ signal at expected location
    - Canis Major overdensity

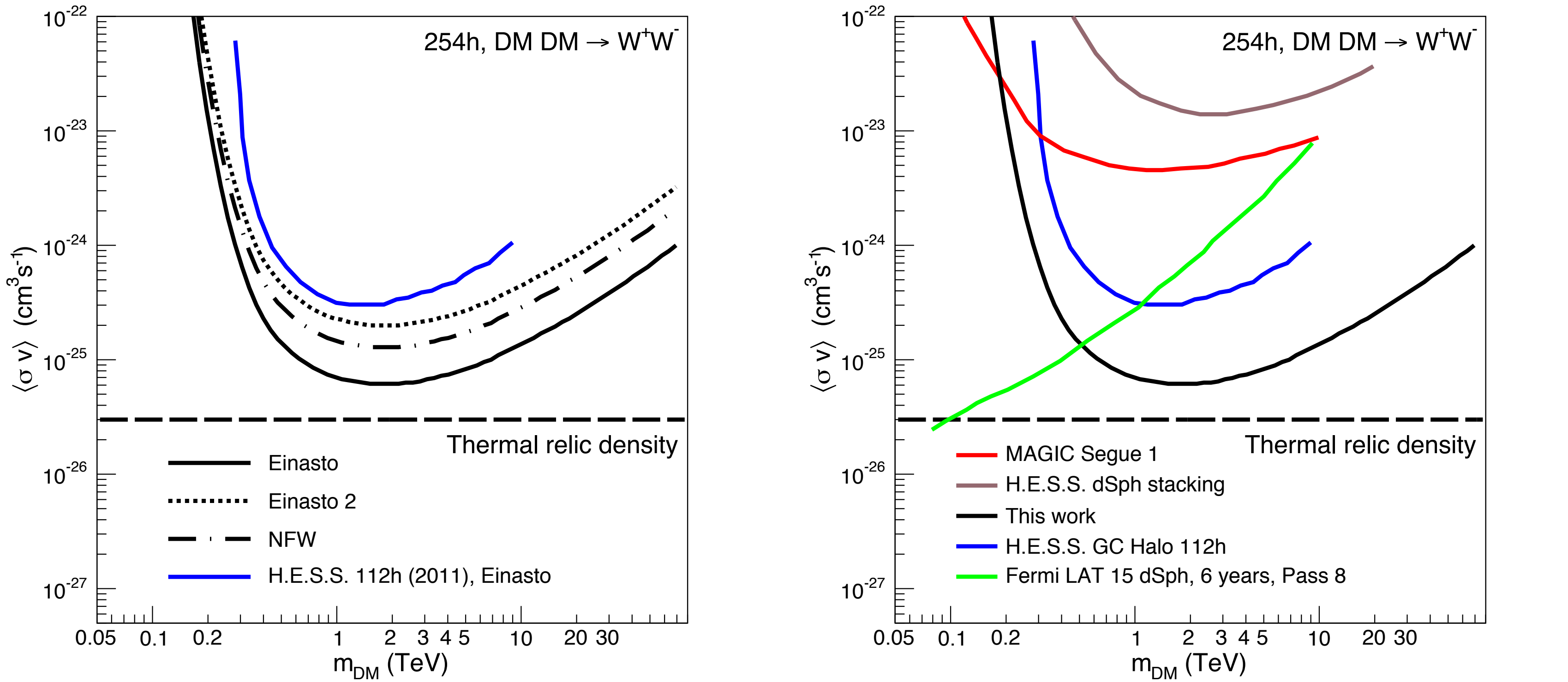


astro-ph/0806.2981



astro-ph/0711.2369

H.E.S.S. (10 years results)



Phys. Rev. Lett. 117 (2016) 111301

FIG. 2: Left: Impact of the DM density distribution on the constraints on the velocity-weighted annihilation cross section $\langle\sigma v\rangle$. The constraints expressed in terms of 95% C. L. upper limits are shown as a function of the DM mass m_{DM} in the W^+W^- channels for the Einasto profile (solid black line), another parametrization of the Einasto profile (dotted black line), and the NFW profile (long dashed-dotted black line), respectively. Right: Comparison of constraints on the W^+W^- channels with the previous published H.E.S.S. limits from 112 hours of observations of the GC [10] (blue line), the limits from the observations of 15 dwarf galaxy satellites of the Milky Way by the Fermi satellite [23] (green line), the limits from 157 hours of observations of the dwarf galaxy Segue 1 [24] (red line), and the combined analysis of observations of 4 dwarf galaxies by H.E.S.S. [25] (brown line).

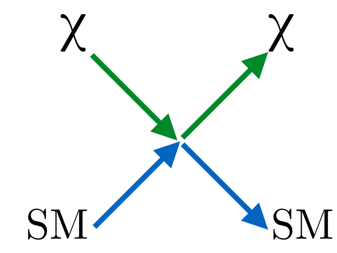
Summary indirect searches

- Several experimental techniques
- Several independent results
- Many hints but no significant or unambiguous signal
- Very active field:
  - many more results expected in the coming years

<u>Detection of Dark Matter</u>

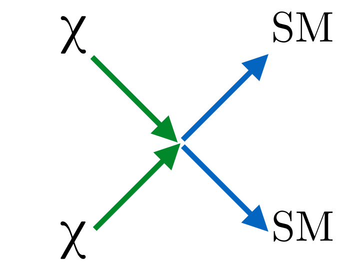
I. Direct detection

- interaction of halo DM in detectors
    - generally underground detectors



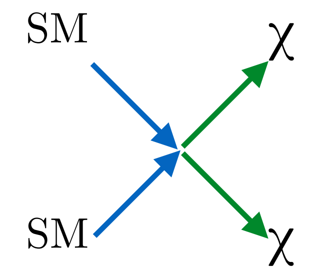
II. Indirect detection

- SM signals from the annihilation of DM particles (e.g. $\chi + \chi \rightarrow \gamma + \gamma$)



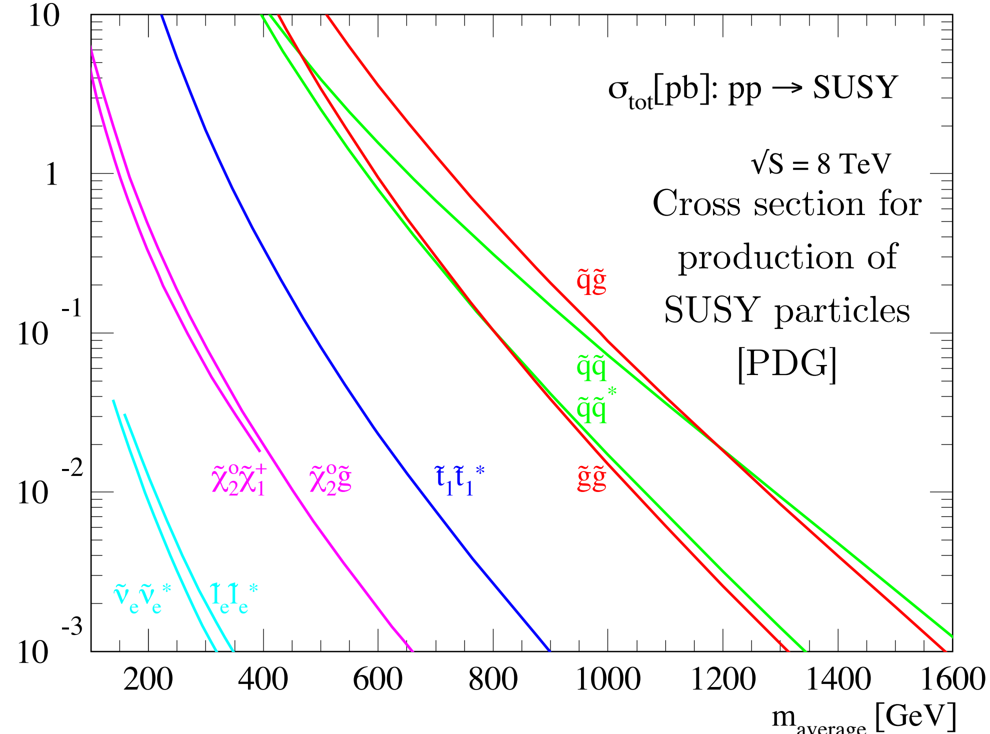
III. Creation of DM particle candidates at accelerators

- e.g. high-energy collisions producing SUSY



WIMPs at accelerators

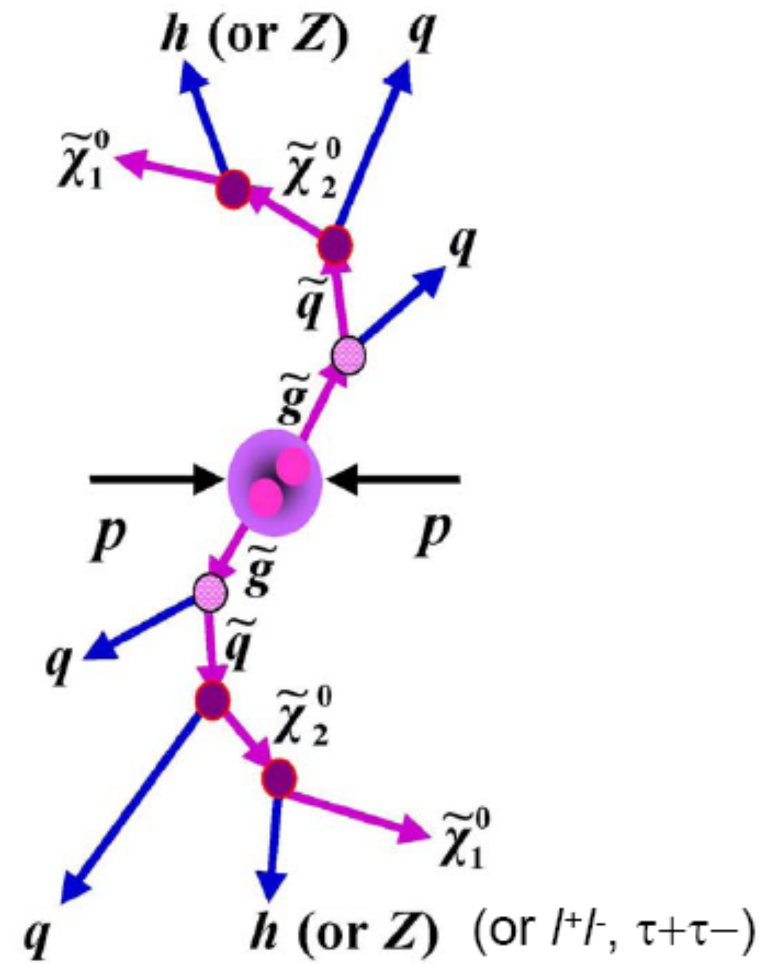
- For some models, DM particles are produced at accelerators
- SUSY neutralino is (still!) a candidate for discovery
  - it has a mass accessible to the LHC (100GeV–1TeV)
  - it has a predicted signature that can distinguish it from other processes



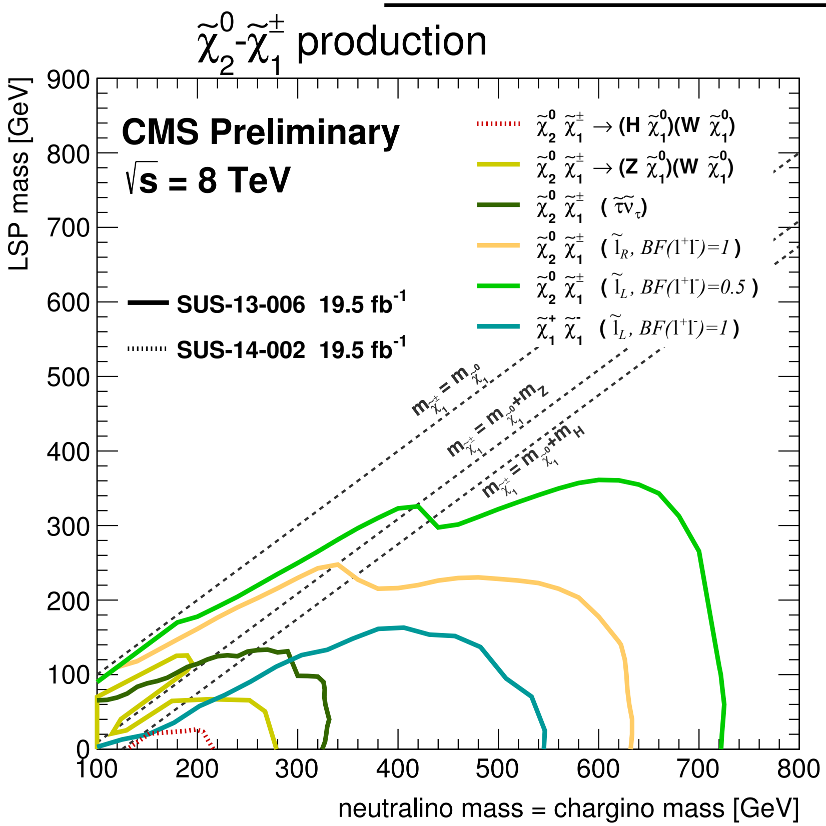
- Caution:
  - even if discovered at an accelerator, a new stable particle is only a DM <u>candidate</u>
  - its properties must then be studied to check they satisfy the requirements for being dark matter
  - ultimately, we will want to observe it directly!

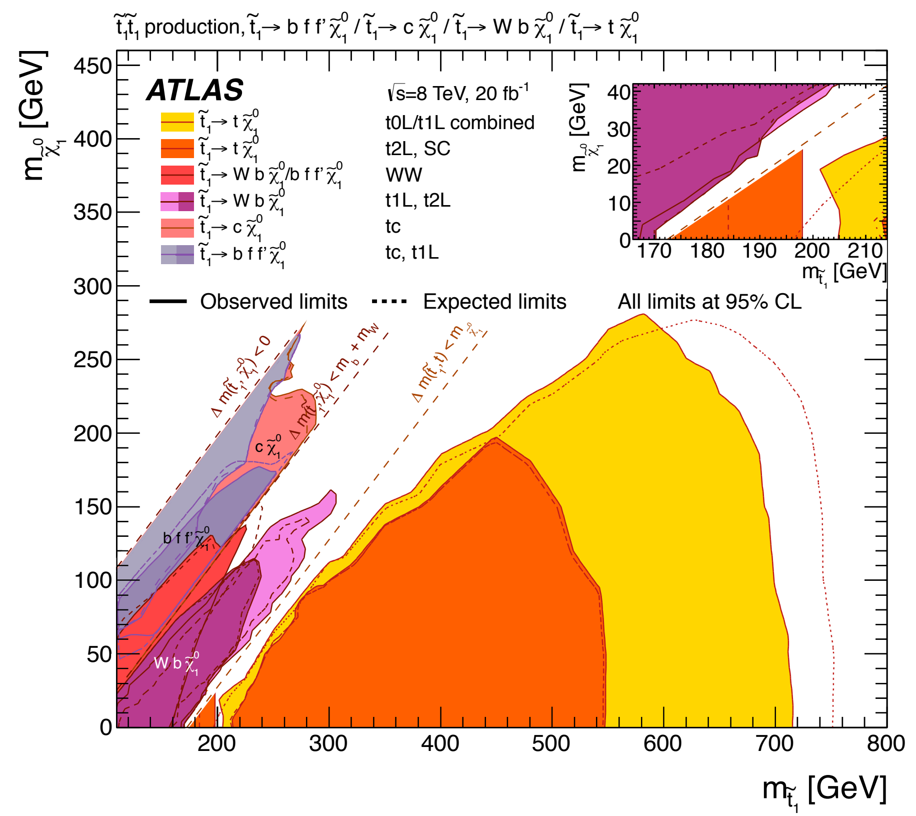
SUSY: experimental method

- Identification:
  - a neutralino would be associated with production of jets and photons
  - the missing mass is the χ^0 mass
- Interpretation:
  - the production rate can be associated to the annihilation cross section $\langle \sigma v \rangle$
  - $\langle \sigma v \rangle$ and $m_\chi \Rightarrow$ DM properties
- Finally, compare with cosmological constraints!



SUSY: results from LHC

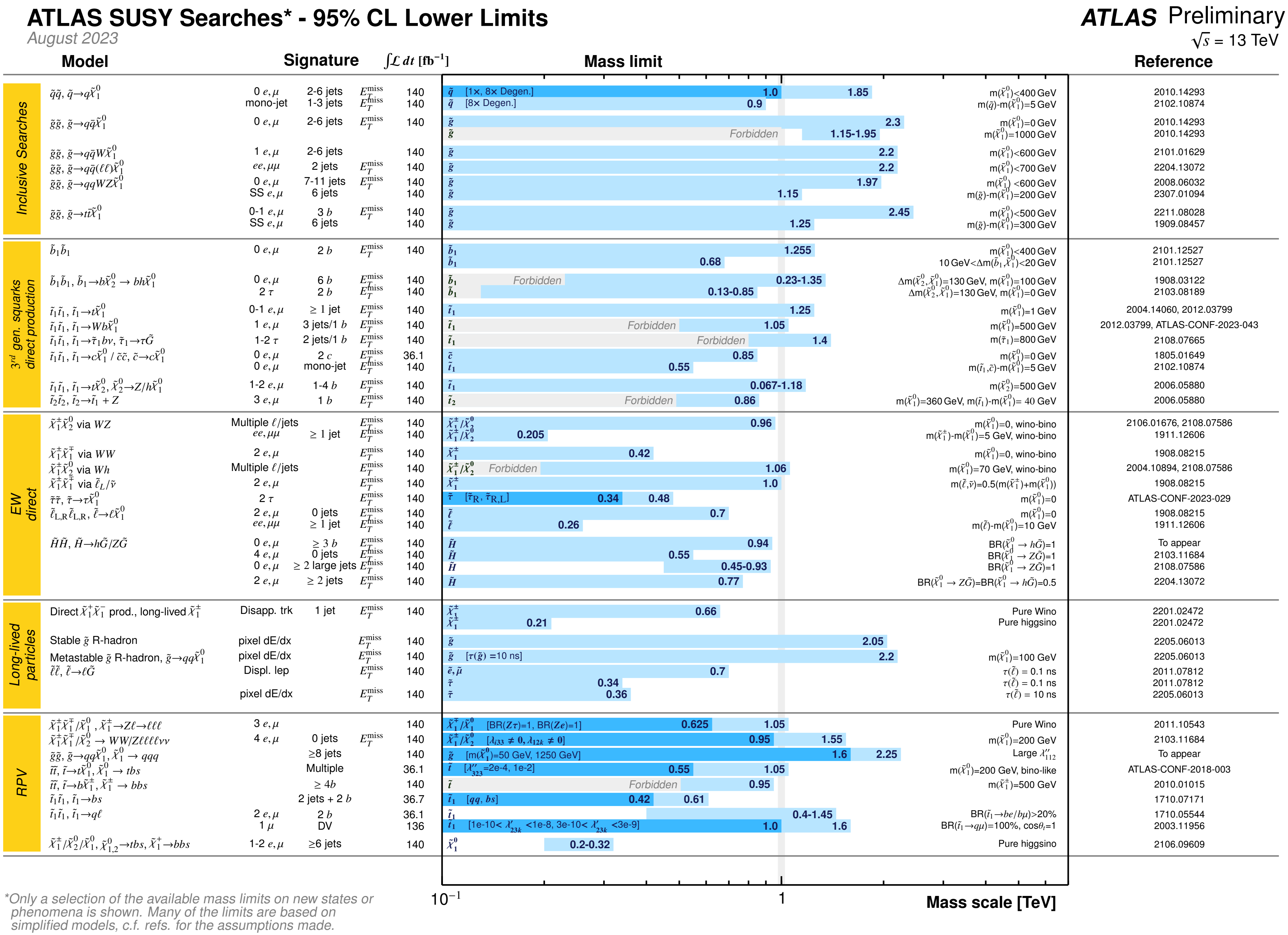




- First LHC results (7–8 TeV)
  - direct search by ATLAS and CMS $\Rightarrow$ $M_{\mathrm{SUSY}} > O(1)$ TeV
  - indirect search at LHCb $\Rightarrow$ $M_{\mathrm{SUSY}} > O(10)$ TeV

$\Rightarrow$ no indication for DM candidate at accelerators...

Limits on the masses of sparticles



Summary on Dark Matter

- Strong evidence for Dark Matter and Dark Energy from cosmological observations
- Several DM candidates, among which the SUSY particles are (were?) the most promising
- Several experiments:
  - hints of direct observation of a DM particle
  - hints of indirect observation through DM annihilation

  $\Rightarrow$ no unambiguous DM signature

- Hopefully will soon get direct and/or indirect evidence, and possibly production of DM candidates at accelerators!