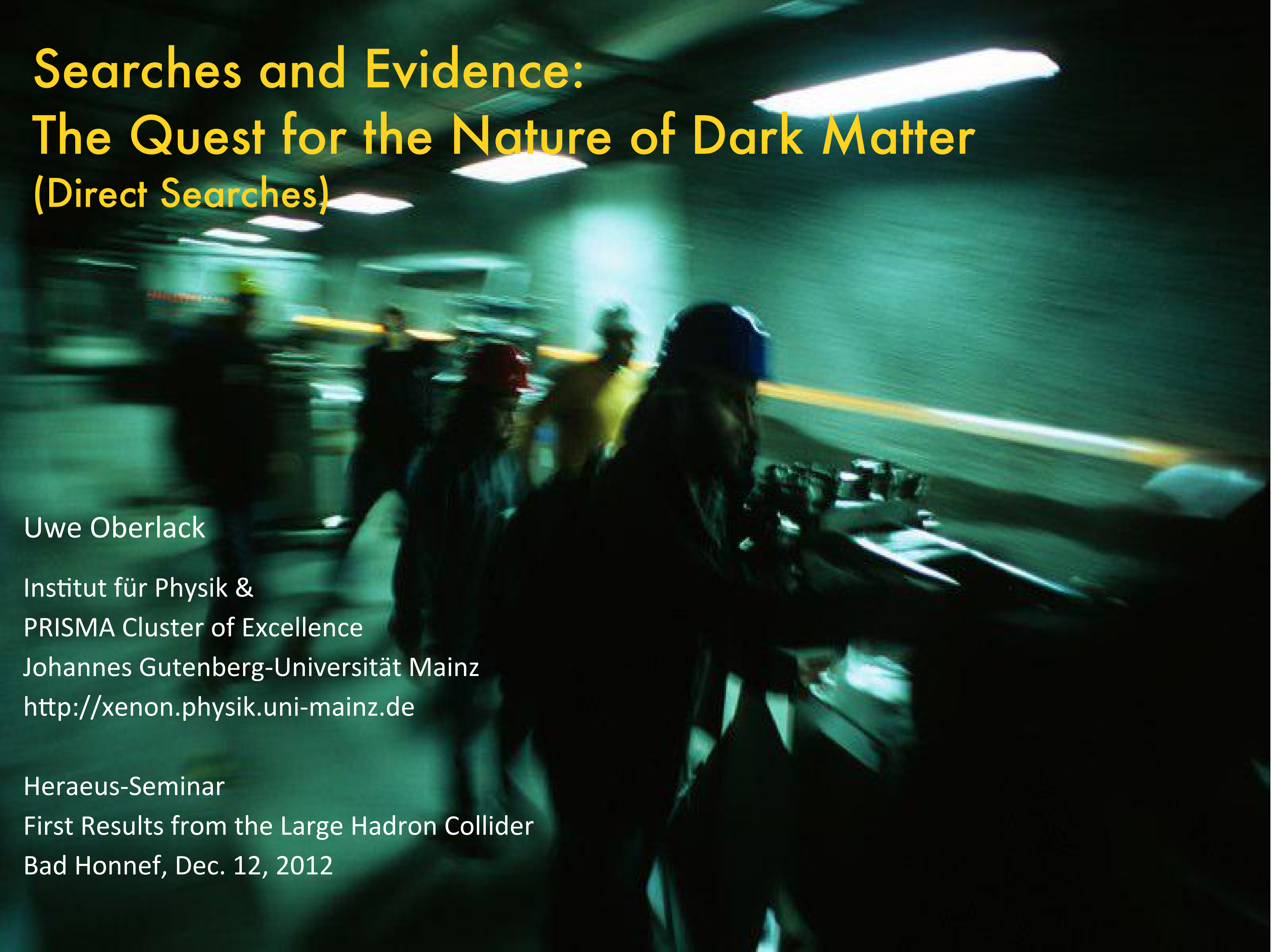


Searches and Evidence:
The Quest for the Nature of Dark Matter
(Direct Searches)

Uwe Oberlack

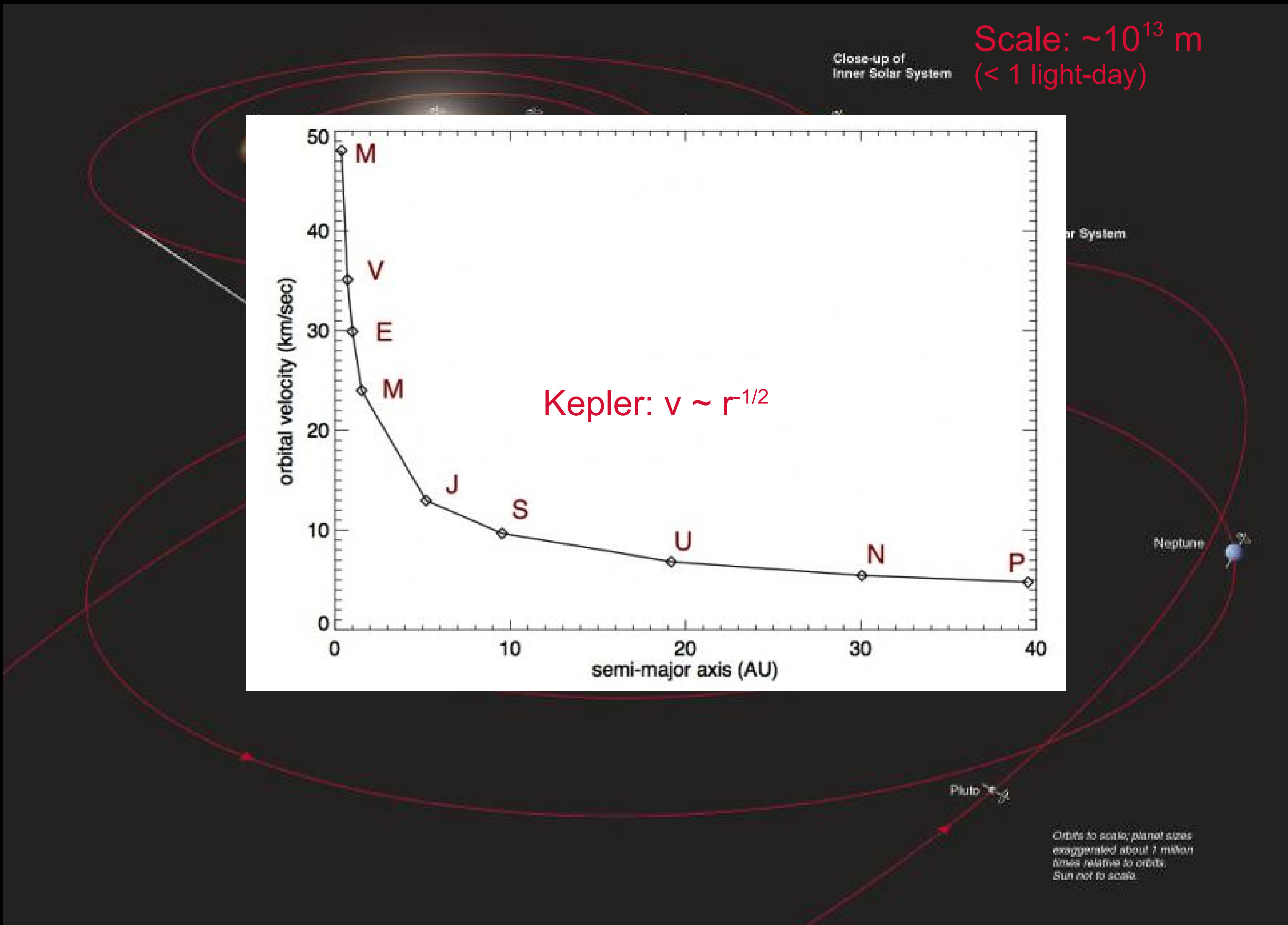
Institut für Physik &
PRISMA Cluster of Excellence
Johannes Gutenberg-Universität Mainz
http://xenon.physik.uni-mainz.de

Heraeus-Seminar
First Results from the Large Hadron Collider
Bad Honnef, Dec. 12, 2012

Outline

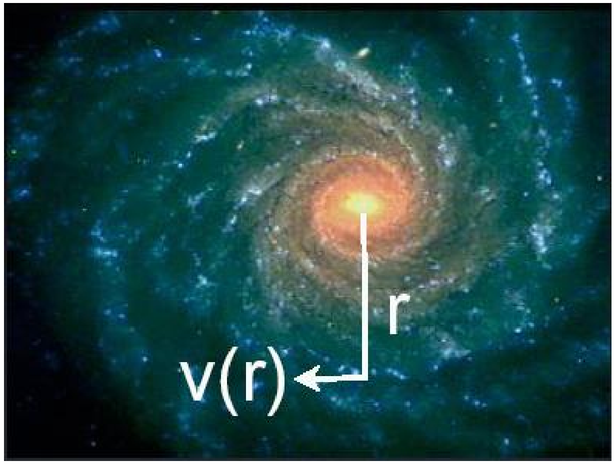
- Dark Matter: Evidence, Models, and the Magnificent WIMP
- Direct Detection Technique
- Status of WIMP DM Direct Detection
- XENON Dark Matter Search
- Future

Evidence for Dark Matter in the Solar System ?



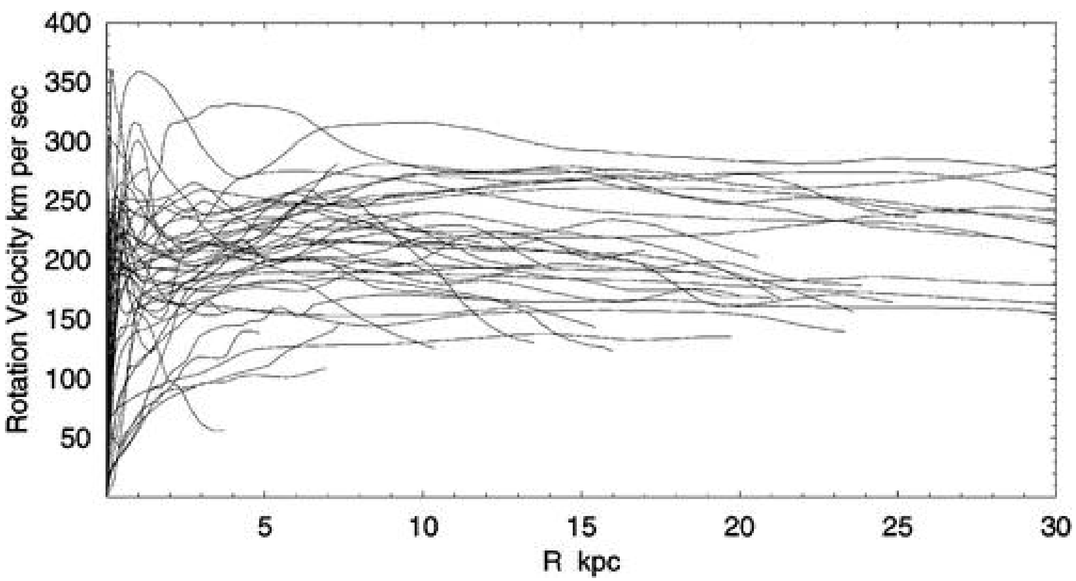
Evidence for Dark Matter in Spiral Galaxies

Scale: ~10^{21} m
(10^5 lightyears)

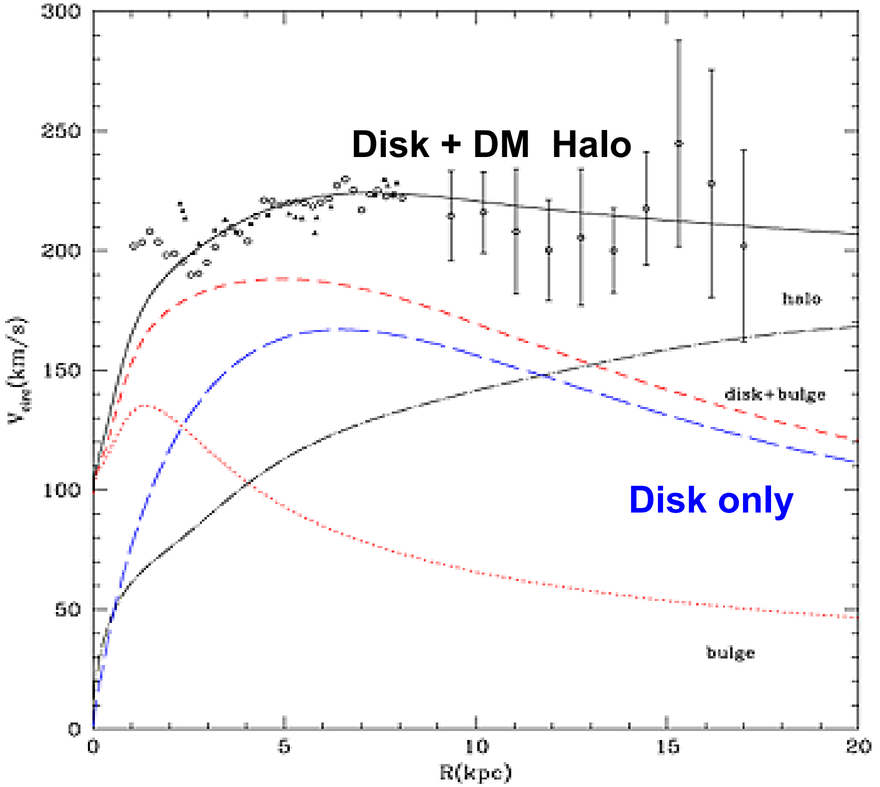


Rotation curves (orbital velocity vs. galactocentric radius) remain flat well beyond the edge of the visible disk in spiral galaxies.

$$\left.\begin{aligned} v(R) &= \sqrt{GM(R)/R} \\ v(R) &\approx const \end{aligned}\right\} \Rightarrow \left\{\begin{aligned} M(R) &\propto R \\ \rho(R) &\propto R^{-2} \end{aligned}\right.$$



Rotation curves of nearby galaxies
(Sofue & Rubin ARAA 2001)



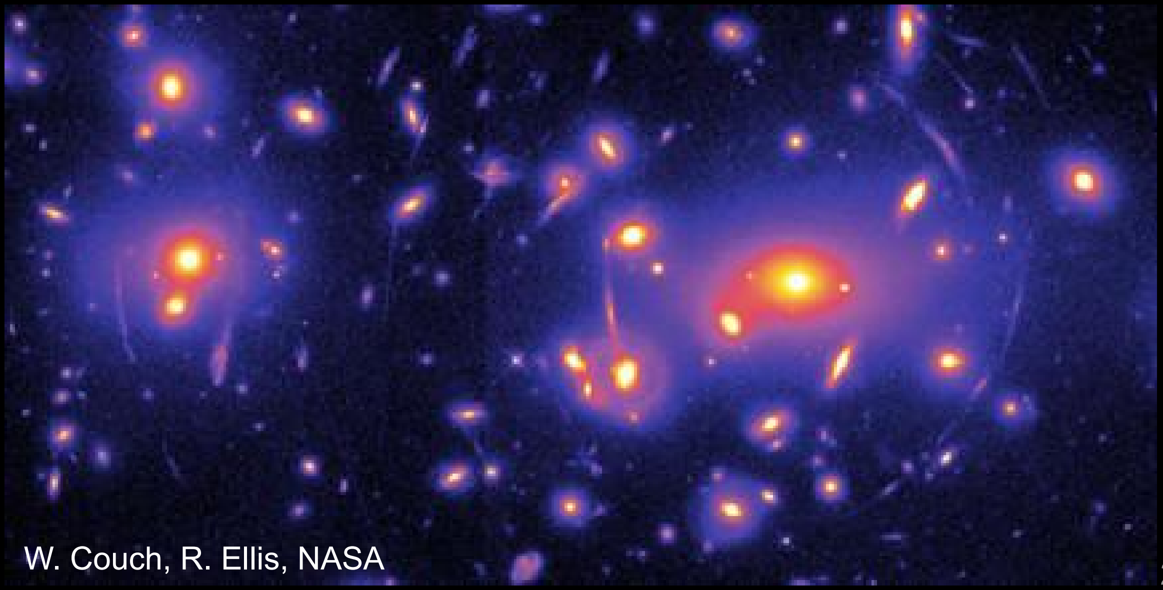
Rotation curve of the Milky Way
(A. Klypin et. al, ApJ. 573, 2002)

Evidence for Dark Matter in Galaxy Clusters

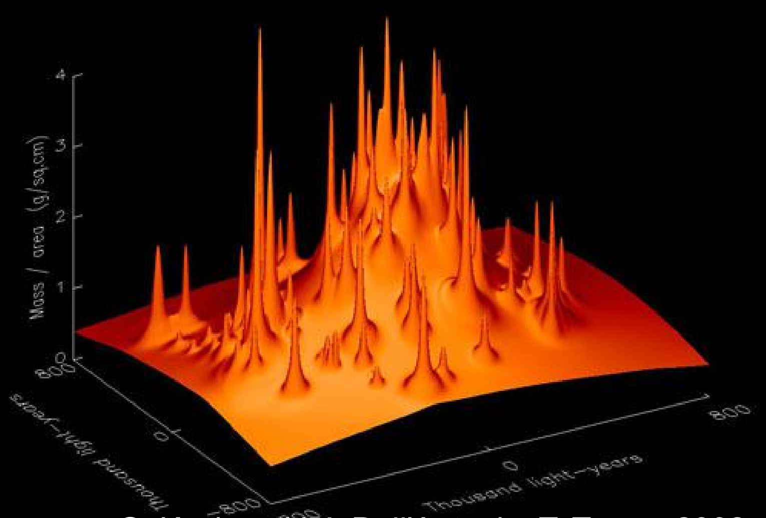
Scale: ~10^{22} m
(10^{6} lightyears)

- Orbital velocities of galaxies exceed escape velocity estimated from visible mass in galaxies (Zwicky 1933).
- X-ray gas: pressure too great for visible mass. Traces gravitational potential.
- Gravitational lensing: measures total mass distribution in galaxy clusters.

NOAO/Kitt Peak: Uson, Dale
NASA/CXC/IoA: Allen et al.



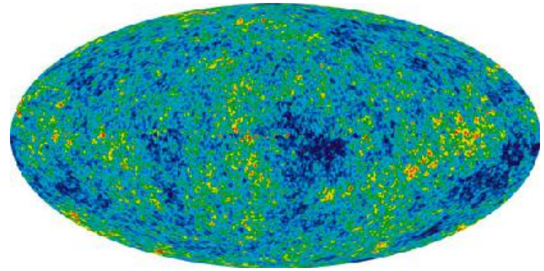
W. Couch, R. Ellis, NASA

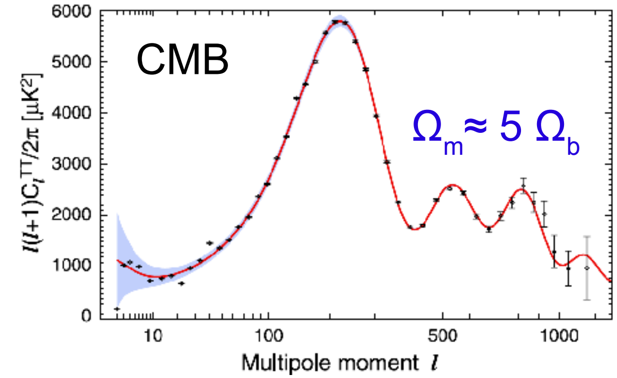


G. Kochanski, I. Dell'Antonio, T. Tyson, 2002

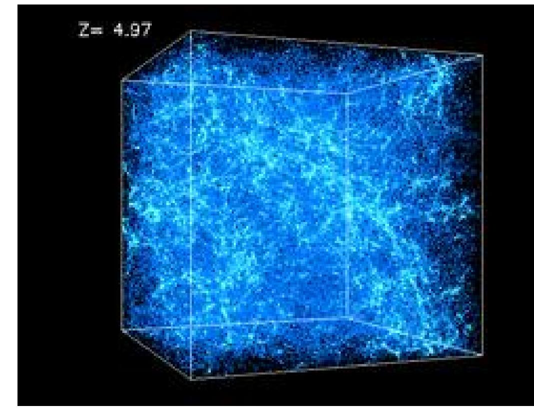
Evidence for Dark Matter from Cosmology

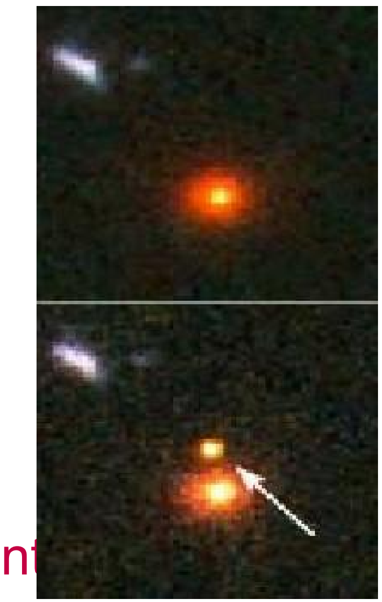
Scale: ~10^{26} m
(10^{10} lightyears)

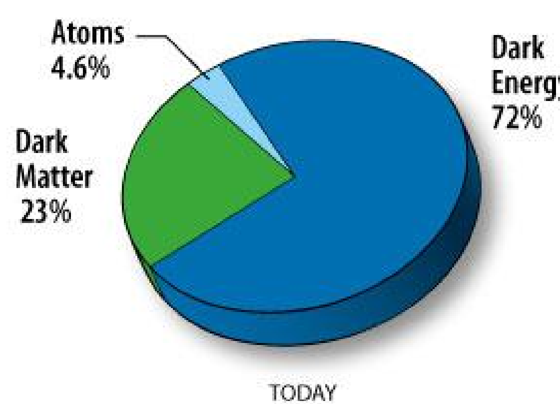


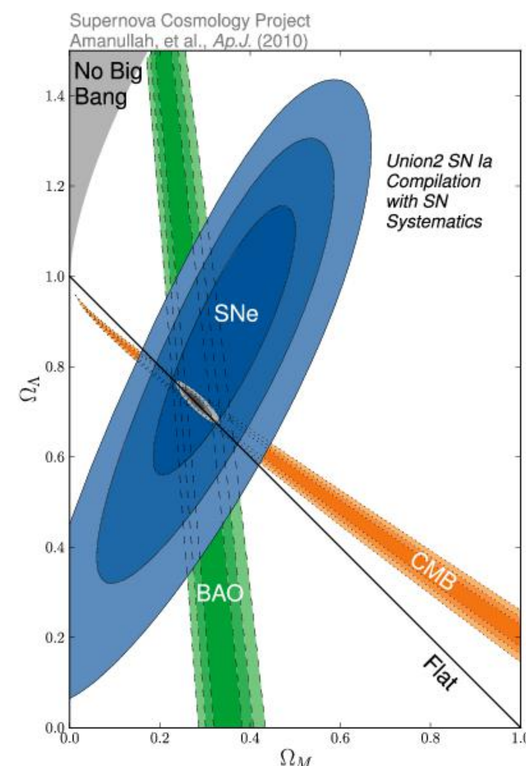


- Cosmic Microwave Background.
  - → Uniformity at age 380,000 yr.
  - → Flatness of the universe (with H_0)
  - → Baryon density, etc.
- Supernovae as standard candles.
  - → Expansion history of the universe.
- Galaxy surveys (wide or deep) and Simulations of structure formation.
  - → Large scale structure.
  - → Early structure formation. First stars. Quasars and galaxies.
- Big Bang Nucleosynthesis and light element abundances observed in the early universe.
  - → Limit on baryon density, consistent with CMB.
- Galaxy clusters
- Baryon Acoustic Oscillations
  - → standard ruler
- ...

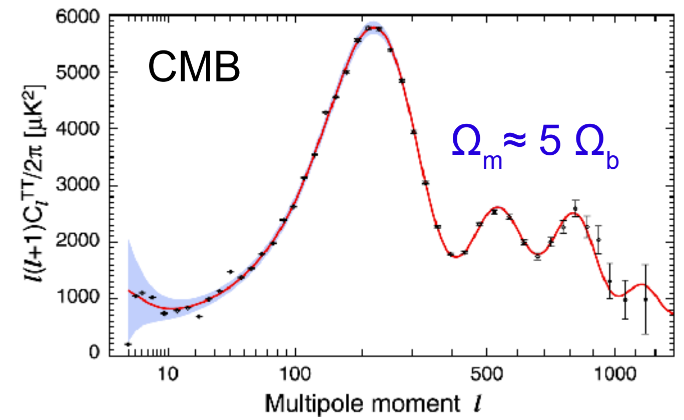






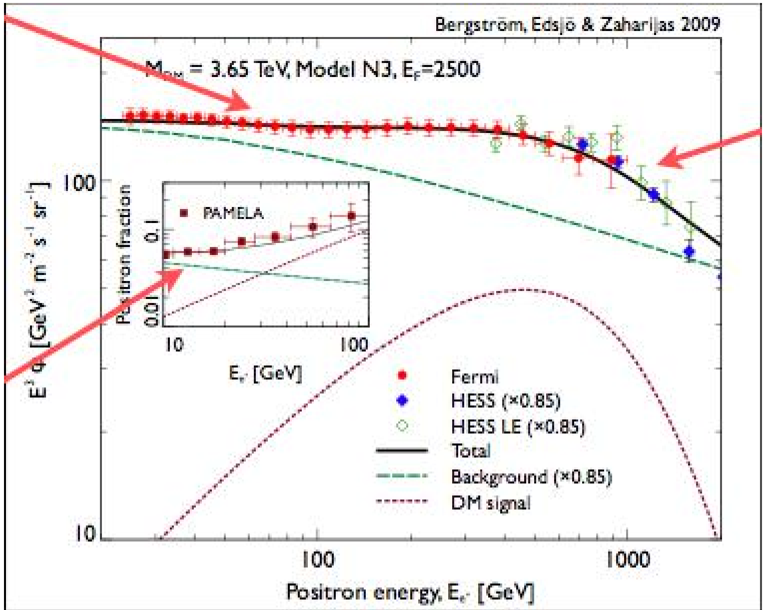


Dark Matter Detection Methods

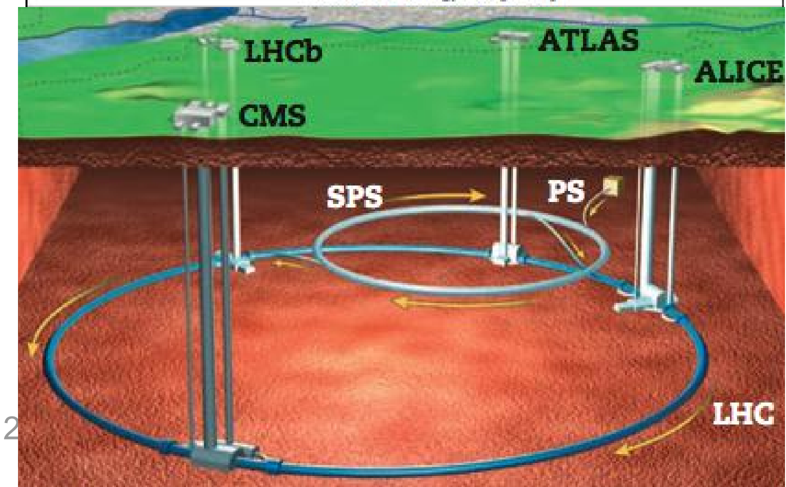


- Astrophysics / Cosmology:
  Gravitational Effects.
  - Rotation curves of spiral galaxies
  - Orbital velocities of galaxies in clusters (Zwicky 1933)
  - Colliding clusters (Bullet cluster)
  - CMB, large scale structure, lensing

- **Direct Detection:**
  - **WIMP scattering**
  - Axion searches, ...



- Indirect Detection: from annihilation or decay
  - Cosmic rays
    PAMELA positrons?
    Fermi, ATIC, HESS electrons? Anti-deuterons?
  - Neutrinos
  - Gamma-rays

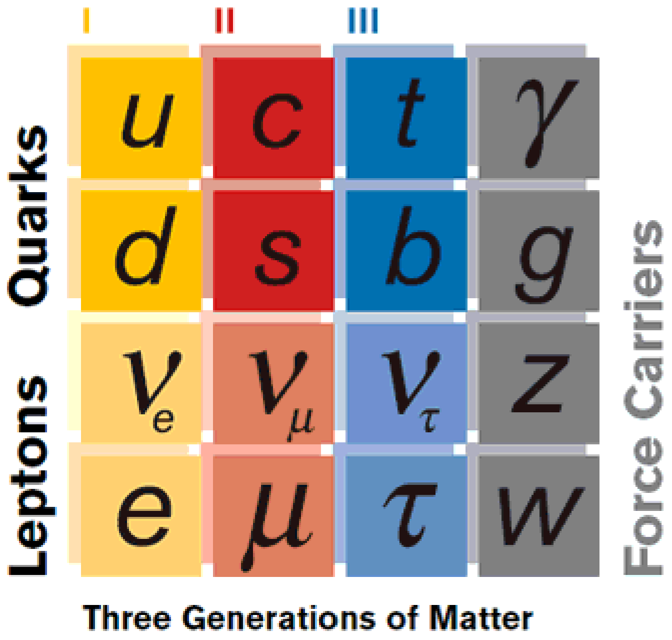


- Accelerator-based Creation and Measurement:
  - Missing energy / momentum (+ jets + lepton(s))
  - Search for (possibly) DM-related particles (SUSY, extra dimensions, dark photon)

What do we know about Dark Matter?

- Gravitationally interacting
  - How we know about Dark Matter
- Stable or long-lived
  - $\Omega_{DM} = 0.23$
- Cold or warm - not hot (relativistic)
  - Structure formation, CMB
- Non-baryonic
  - CMB, Big Bang nucleosynthesis
- Electrically neutral
  - Dark Matter

The Standard Model

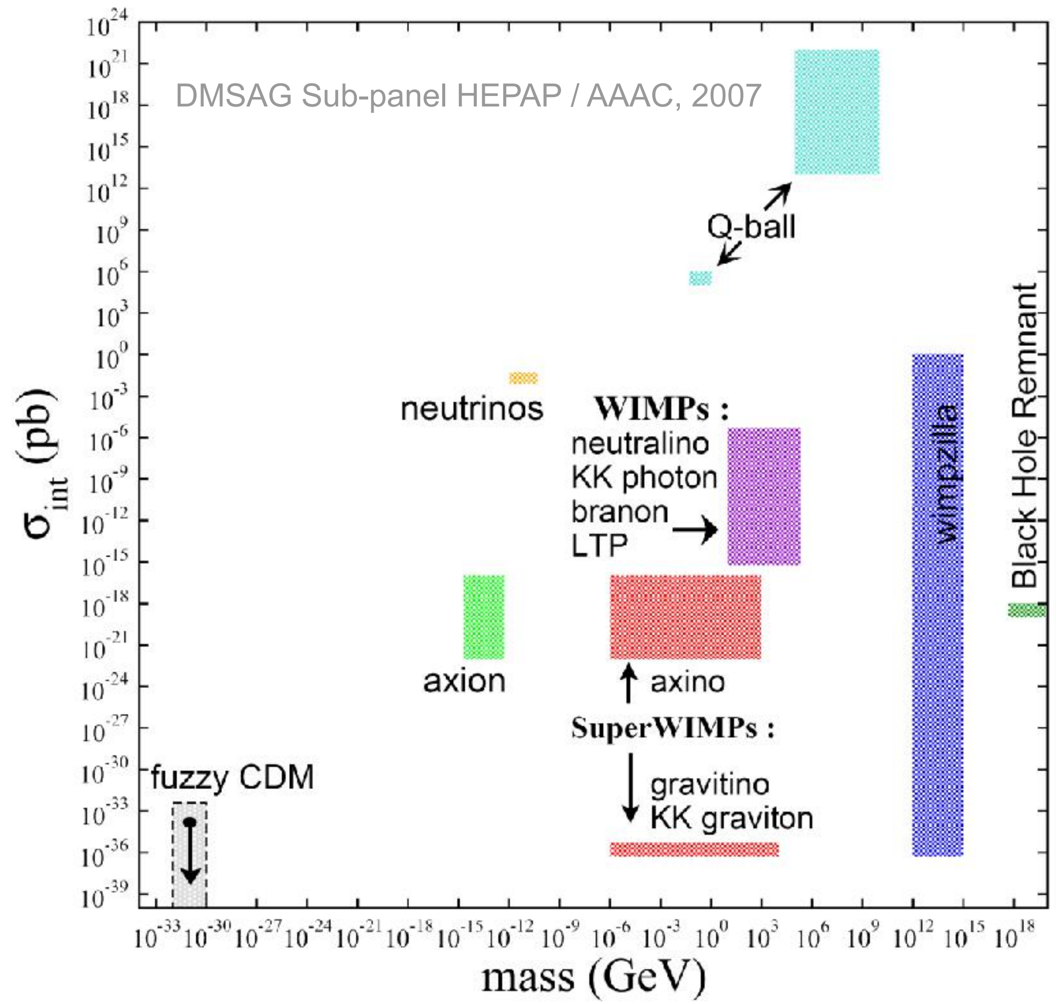


Dark Matter requires physics beyond the Standard Model.

What do we know about Dark Matter?

- Gravitationally interacting
  How we know about Dark Matter
- Stable or long-lived
  $\Omega_{DM} = 0.23$
- Cold or warm - not relativistic
  Structure formation, CMB
- Non-baryonic
  CMB, Big Bang nucleosynthesis
- Electrically neutral
  Dark Matter
- Additional constraints from accelerator searches, direct and indirect searches.

> 60 orders of magnitude



~ 50 orders of magnitude

This still leaves many options.

Where to start? Look for “well motivated” candidates.

Weakly Interacting Massive Particles (WIMPs): A thermal relic at just the right density

Boltzmann equation:

$$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle\sigma_{eff} v\rangle\left(n_\chi^2 - n_{\chi,eq}^2\right)$$

Decrease due to universe expansion

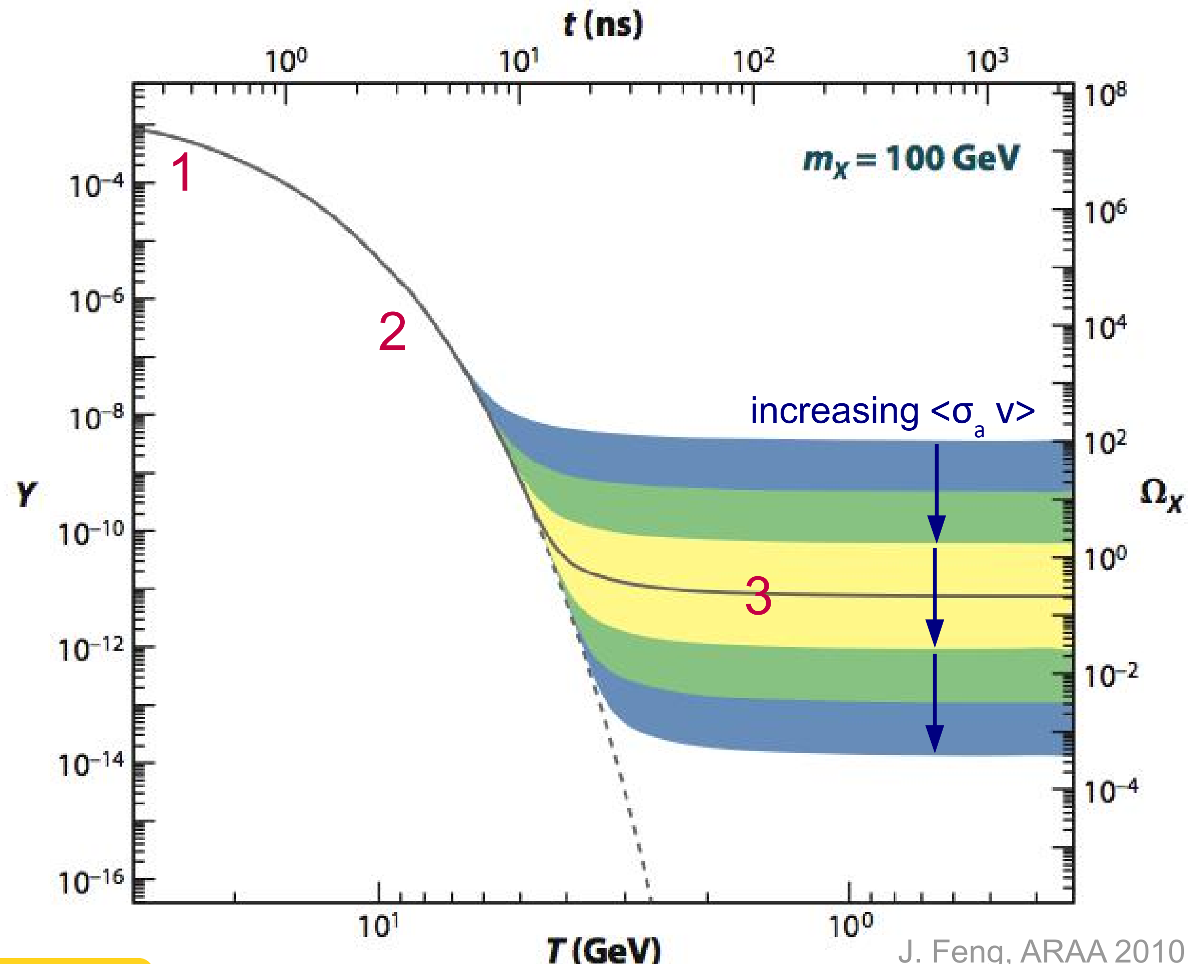
1 $kT \gg m_\chi c^2$: equilibrium of WIMP pair creation and annihilation

$\chi + \chi \leftrightarrow f + \bar{f}$ etc.

2 $kT < m_\chi c^2$: WIMP creation suppressed by factor $\exp(-kT/m_\chi c^2)$.

3 **Weakly Interacting**: **freeze out** when annihilation rate drops below expansion rate: $H > \Gamma_{ann} \sim n_\chi \langle\sigma_a v\rangle$

results in **relic density**: $\Omega_\chi h^2 \approx \frac{10^{-27} cm^3 s^{-1}}{\langle\sigma_a v\rangle}$



J. Feng, ARAA 2010
original plot much older, see Kolb & Turner 1990

If m_χ and σ_a related to the electroweak scale → $\Omega_\chi h^2 \sim O(0.1)$ ✓ → ***"WIMP miracle"***

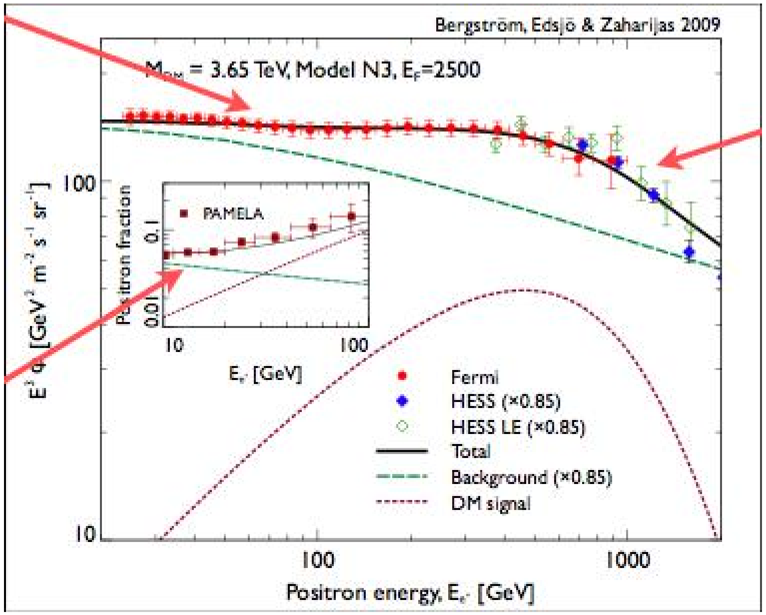
Massive particles: average WIMP velocity is non-relativistic. → **Cold Dark Matter**

A word on WIMPs

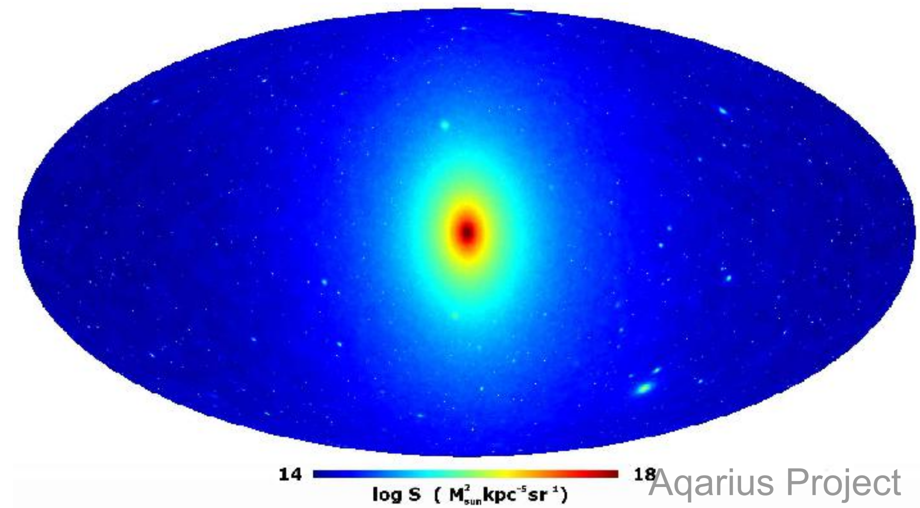
- Weakly interacting massive particles are just what the name says:
  - weakly interacting
  - massive
  - particles
- These are still quite generic properties and not tied to a specific model.
- The poster child and by far best studied WIMP has been a SUSY LSP in the form of a neutralino.
- However, one should not forget that there are other models that can produce WIMPs, e.g., Universal Extra Dimensions preserving Kaluza-Klein parity.

Indirect Dark Matter Searches
Tracing Products of DM Annihilation or Decay

Cosmic rays

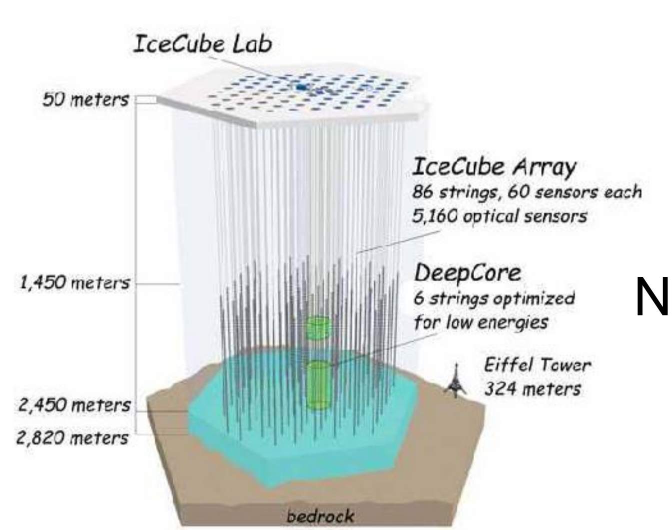


Gamma-rays

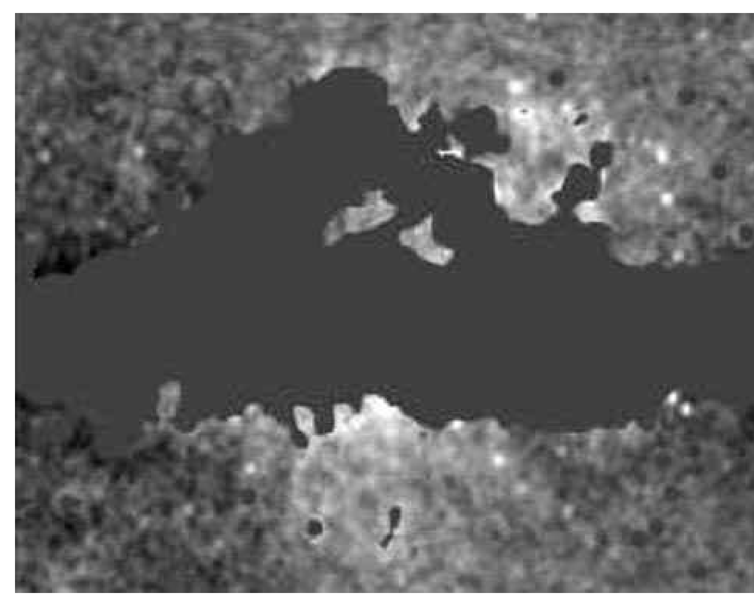


Aqarius Project

Other e.m. radiation



Neutrinos



WIMP Pair Annihilation Flux

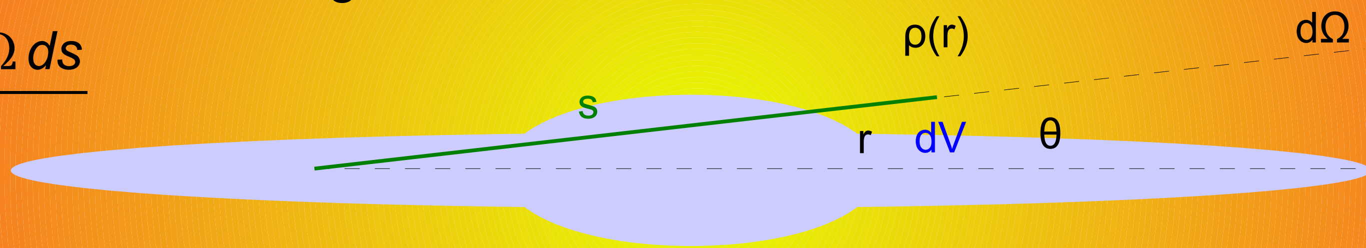
- Rate of WIMP annihilations in a volume

$$dV = s^2 d\Omega ds: \quad \langle \sigma_a v \rangle \frac{n_{DM}^2}{2} dV$$

Number of WIMP pairs in dV: $N(N-1)/2$

- leads to contribution in flux through an area dA perpendicular to the line of sight:

$$dF = \frac{\langle \sigma_a v \rangle n_{DM}^2 s^2 d\Omega ds}{8\pi s^2}$$



- Intensity (per unit area, time and solid angle): from integral along line of sight

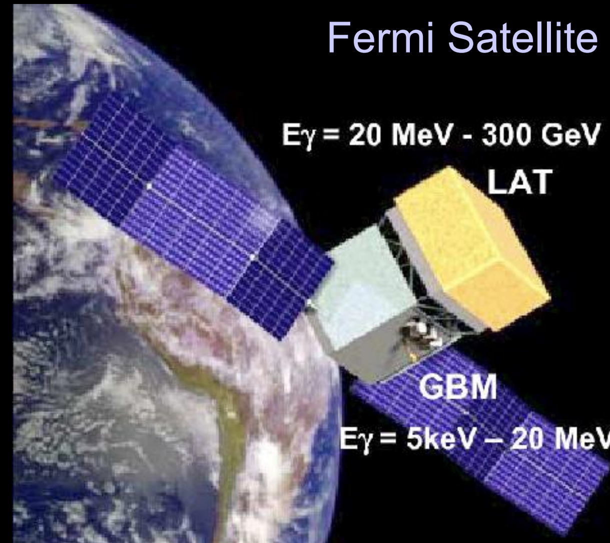
$$I(E,\theta) = \frac{\langle \sigma_a v \rangle}{8\pi m_{DM}^2} \frac{dN_\gamma}{dE} \int \rho_{DM}^2 ds$$

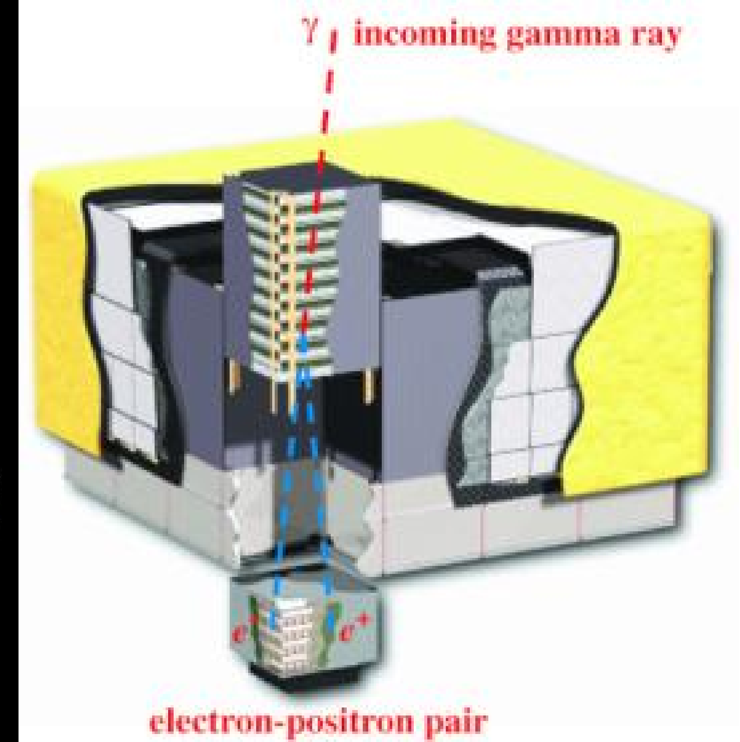
Number of photons per annihilation in Energieintervall *dE*:
(spectra from particle physics model):

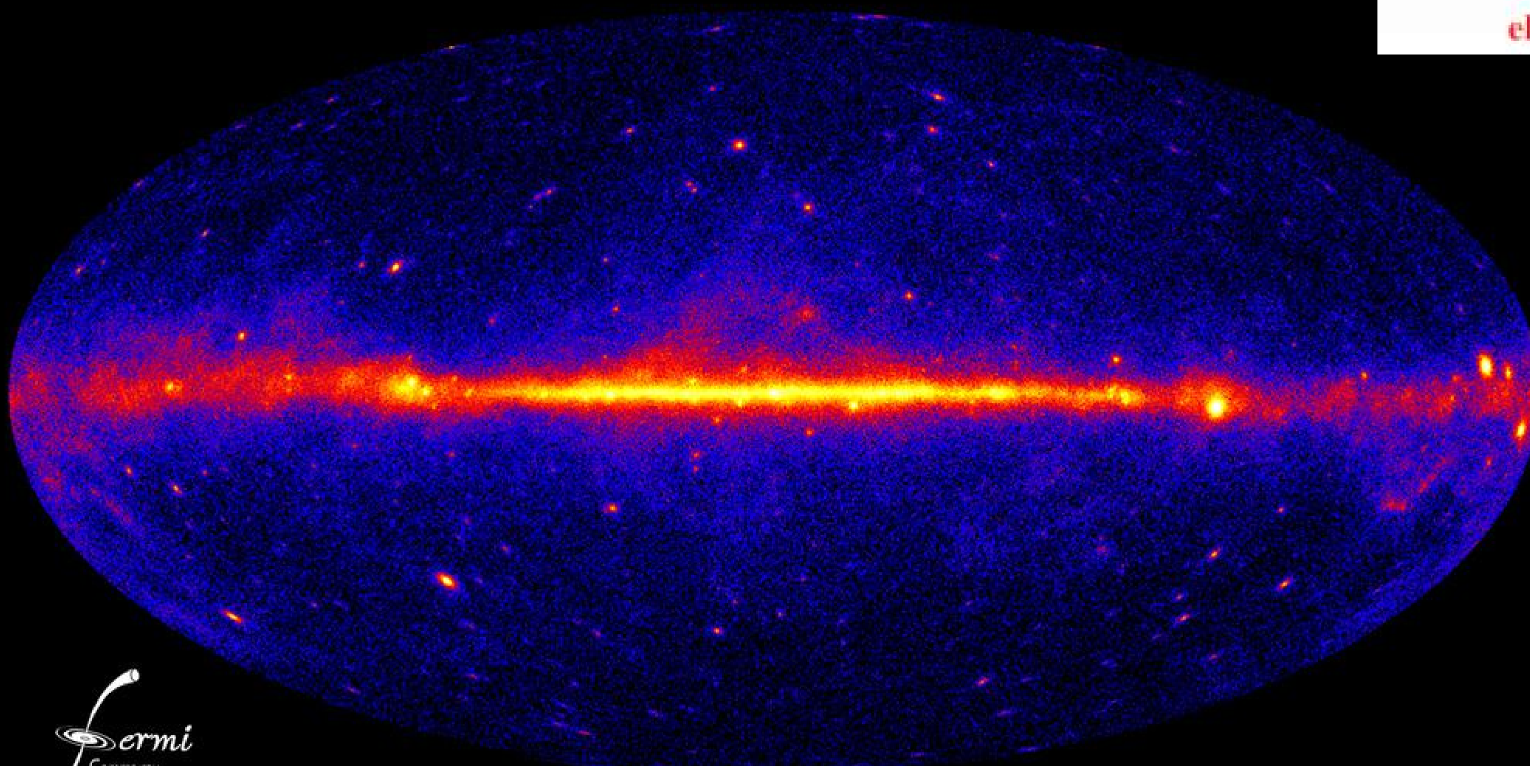
$$\frac{dN_\gamma}{dE} = \sum_f \frac{dN_f}{dE} b_f$$

sum over all pair annihilation final states with photon spectra $\frac{dN_f}{dE}$ and branching ratio b_f

Fermi: Gamma Radiation at GeV Energies



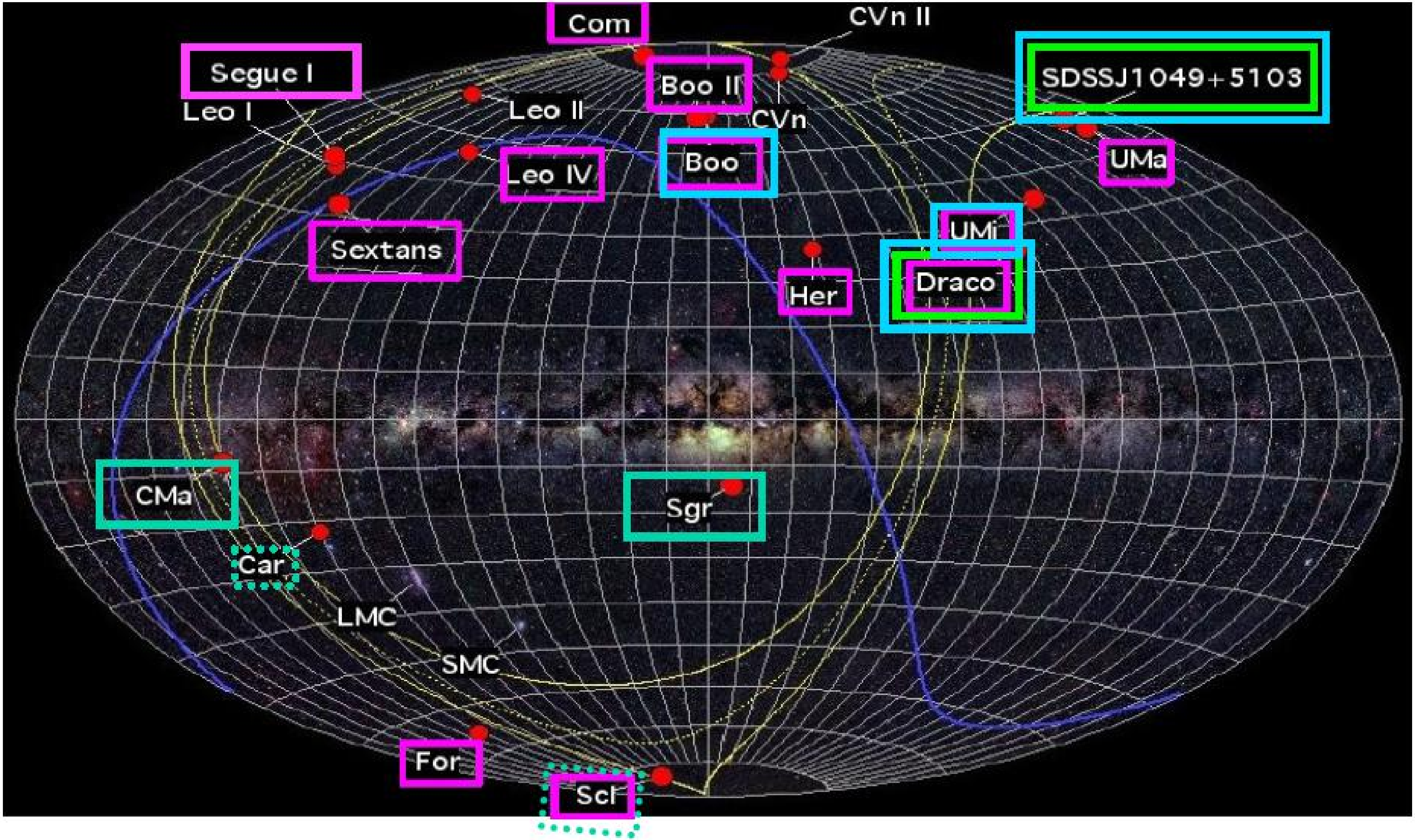




Fermi Gamma-ray Space Telescope

Dwarf Spheroids probed in Gamma-Rays

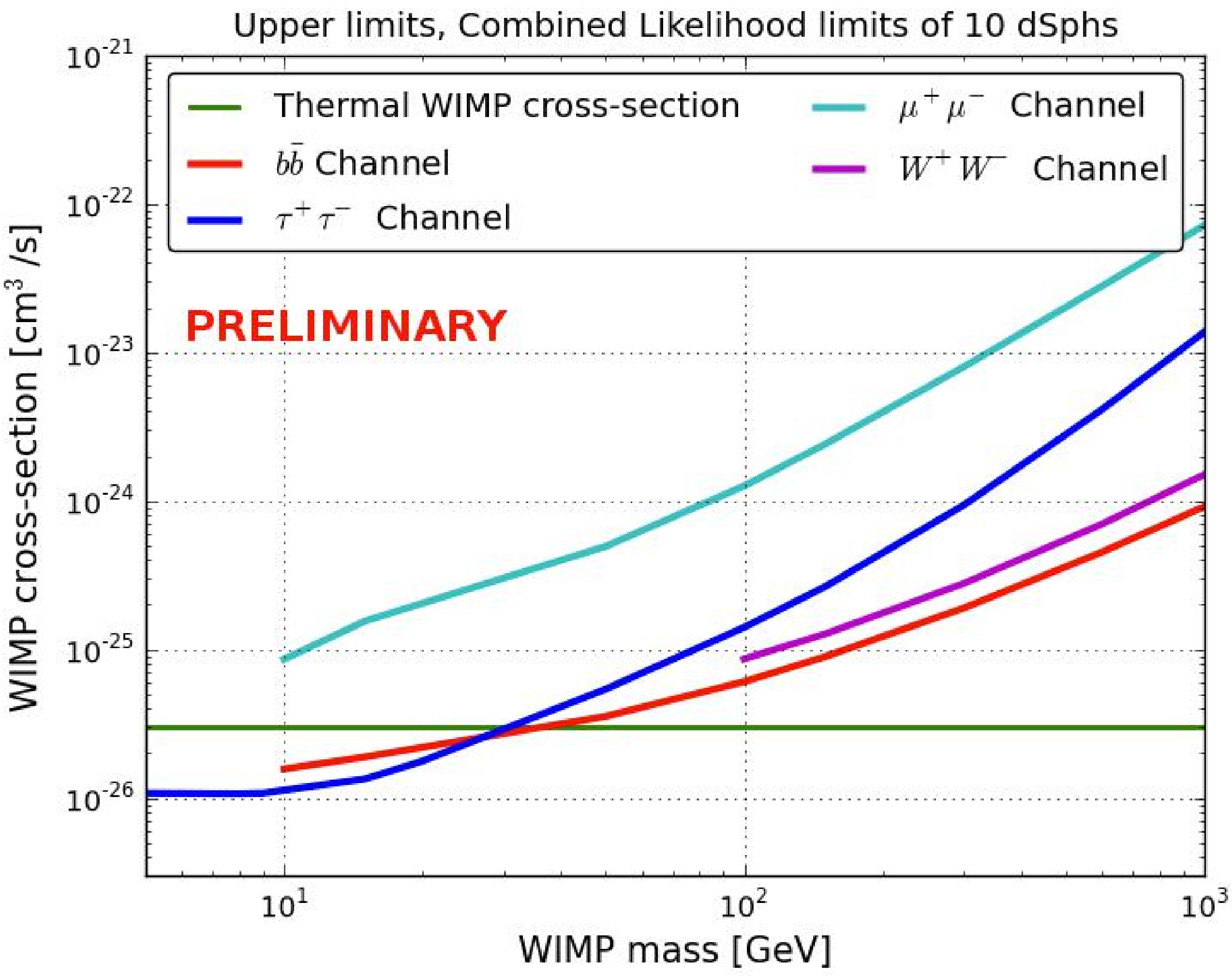
Fermi H.E.S.S. MAGIC Veritas



H.E.S.S. in prep.

Combined analysis of Milky Way satellites with Fermi

Maja Llena Garde, Fermi Symp. 2011



3 x 10^{-26} cm^3/s

- Relevante Grenzen bei niedrigen WIMP-Massen für zwei Zerfallskanäle

Indirect Searches – Upper Limits

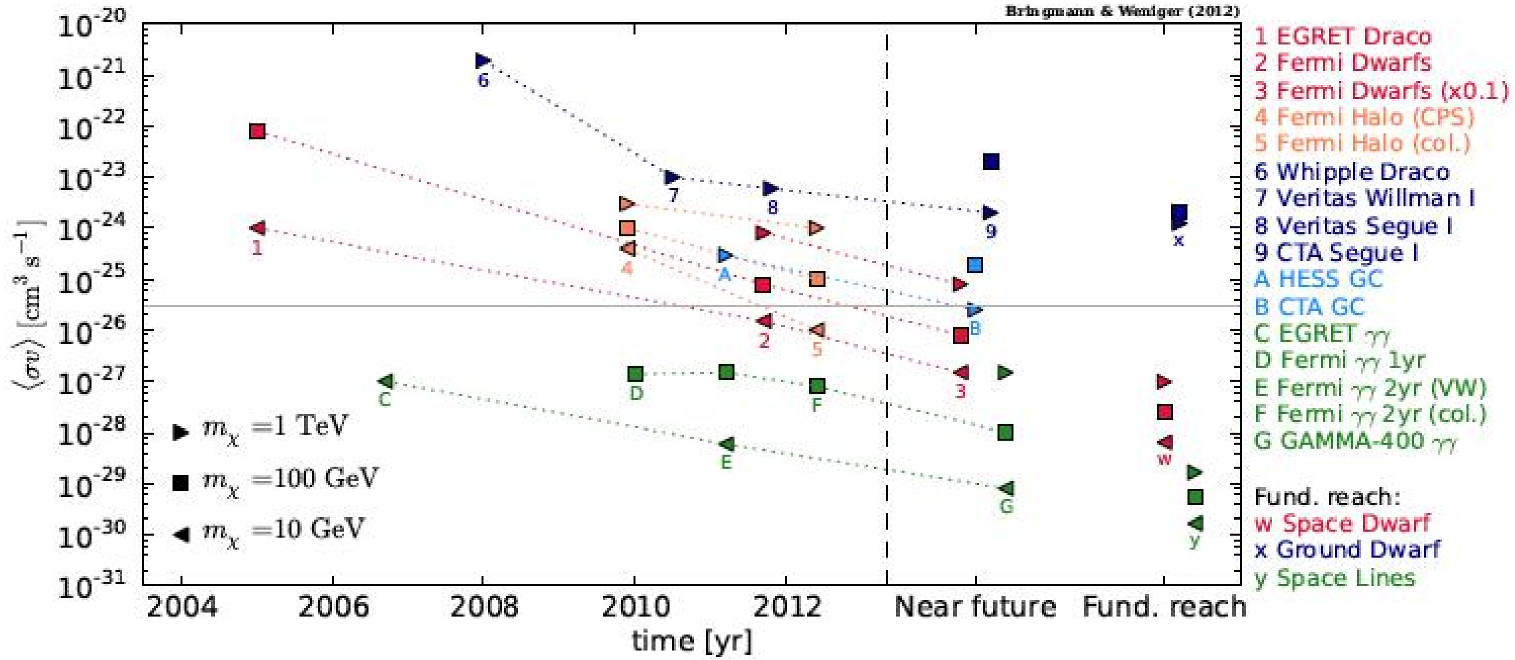
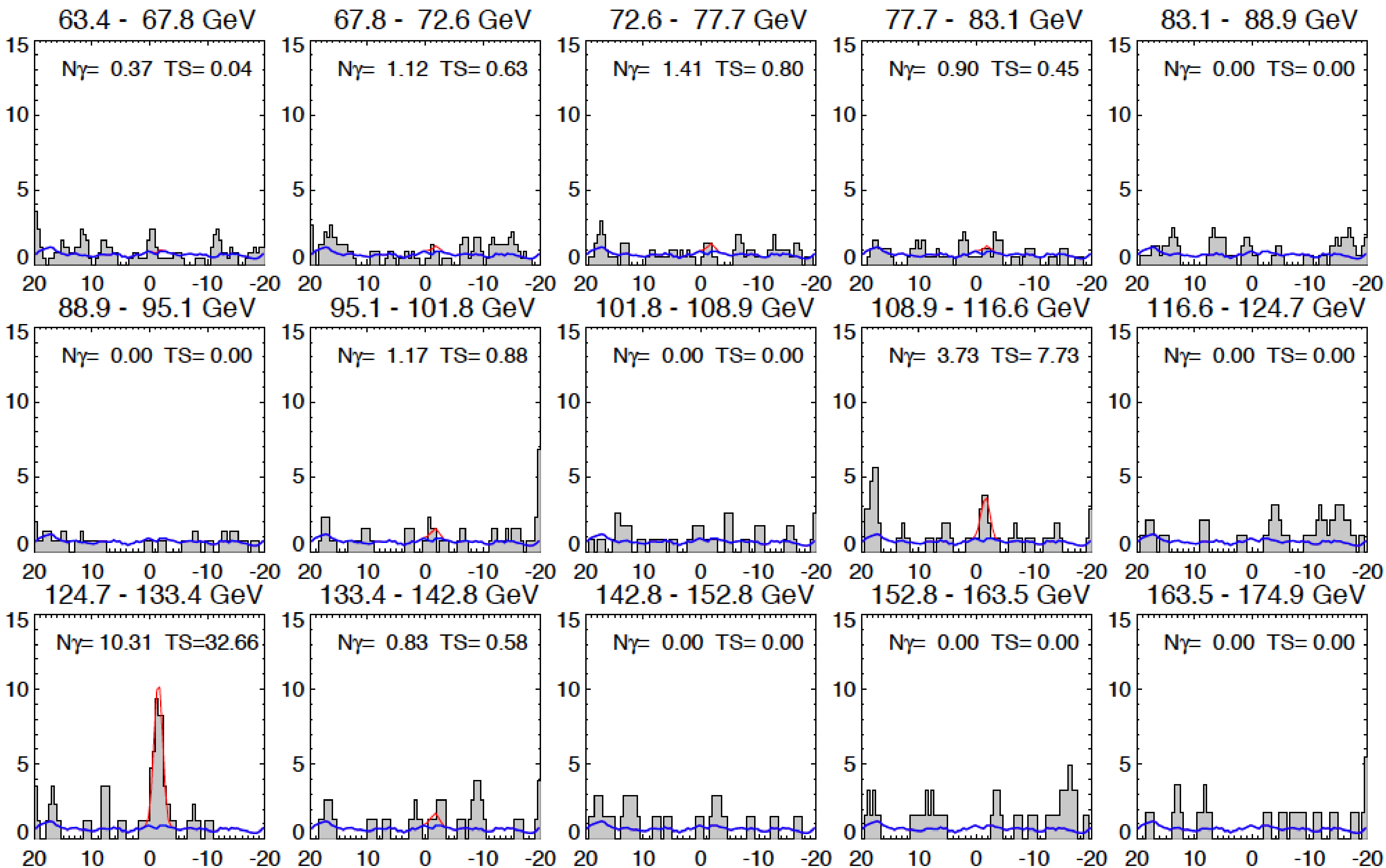


Figure 6: Time evolution of limits. References: EGRET Draco [196]; Fermi Dwarfs [85]; Fermi Halo (CPS) [95]; Fermi Halo (col.) [118]; Whipple Draco [105]; Veritas Willman I [111]; Veritas Segue I [197]; CTA Segue I and GC [195]; HESS GC [115]; EGRET $\gamma\gamma$ [123]; Fermi $\gamma\gamma$ 1yr [124]; Fermi $\gamma\gamma$ 2yr (VW) [125]; Fermi $\gamma\gamma$ 2yr (col.) [126]; GAMMA-400 [35].

Torsten Bringmann, Christoph Weniger
arXiv:1208.5481

Indirect Searches – The Fermi "130 GeV Line"



M. Su, D. P. Finkbeiner
arXiv:1206.1616

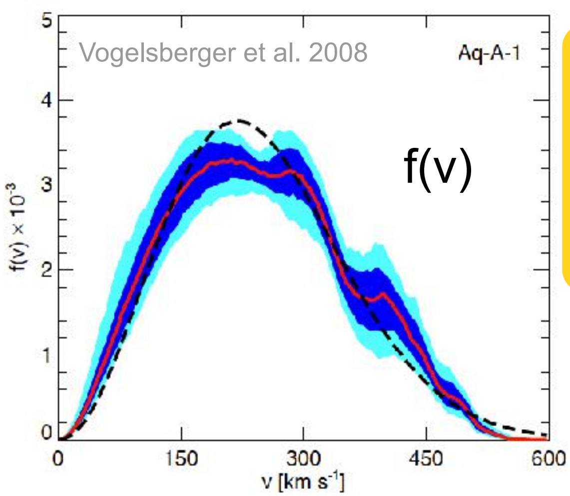
Outline

- Dark Matter: Evidence, Models, and the Magnificent WIMP
- Direct Detection Technique
- Status of DM Direct Detection
- XENON Dark Matter Search
- Future


z=0.0
Via Lactea 2 (2008)
http://www.ucolick.org/~diemand/vl
Galactic Dark Matter
Observer
80 kpc

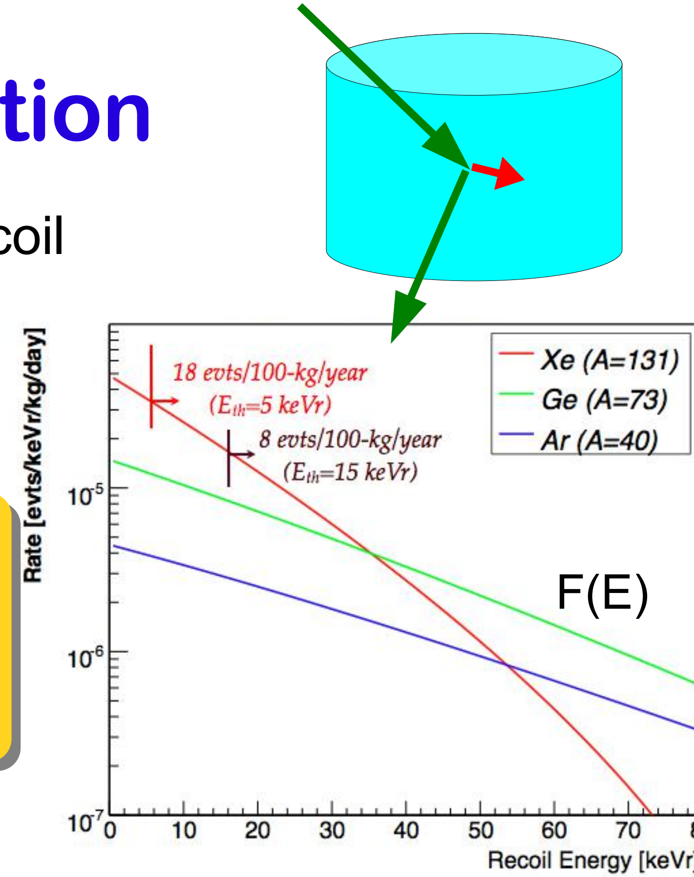
WIMP Dark Matter Direct Detection

- Scattering of WIMPs χ off of nuclei A. → nuclear recoil
  - elastic or inelastic?
  - spin-independent (~A^2) or spin-dependent?
- Energy spectrum:



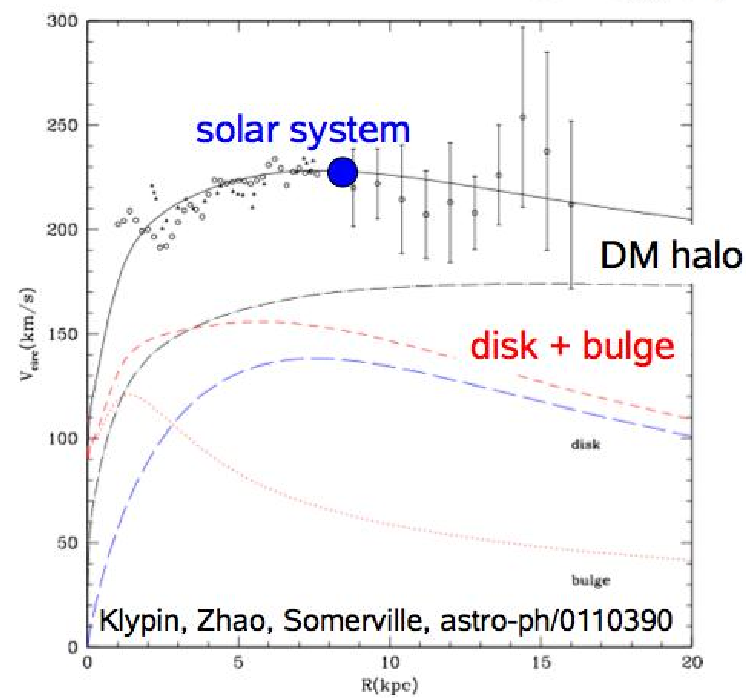
$$\frac{dR}{dE} = \frac{\rho_\chi \, \sigma_s}{2\, m_\chi \, \mu^2} \left|F(E)\right|^2 \int_{v_{min}}^{v_{esc}} \frac{f(\mathbf{v},t)}{v} \, d^3 v$$

$$f(\mathbf{v},t) \propto \exp\left(\frac{-(\mathbf{v}+\mathbf{v}_E(t))^2}{2\,\sigma_v^2}\right)$$



- m_χ ~ 10 - 10^4 GeV/c^2, $\mu = (m_\chi m_n)/(m_\chi + m_n)$
- v_χ ~ 230 km/s
- "Standard" spherical halo:
  Featureless recoil spectrum <E> ~ O(10 keV)
- ρ_χ/m_χ: local number density of WIMPs
  ρ_χ ~ 0.3 GeV/c^2/cm^3, $\rho_\chi/m_\chi \lesssim$ 10 / L
- σ_s cross section per nucleus.

Typical rate < 10^{-3} events / kg / day



WIMP-Nucleon Scattering, Nuclear Form Factor

Spin-independent scattering

Zero momentum transfer:

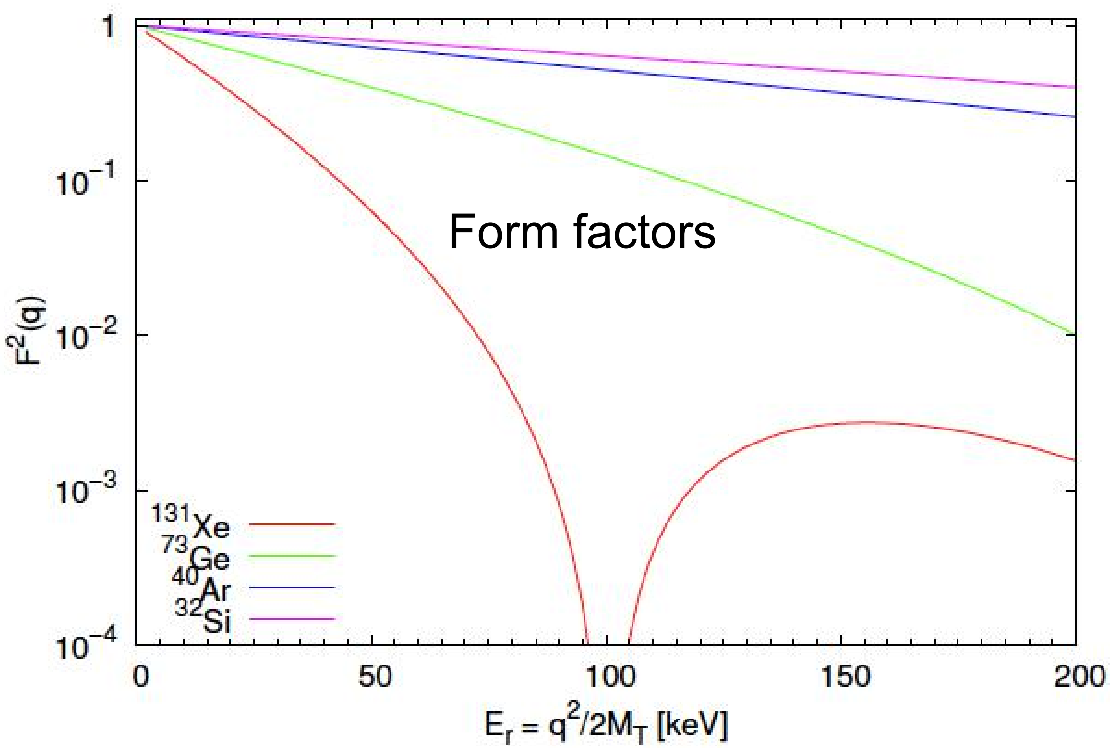
$$\sigma = \frac{4\,\mu^2}{\pi}\left[Z\,f_p + (A-Z)\,f_n\right]^2$$

coherent scattering

reduced mass $\mu = \frac{m_\chi\, m_N}{m_\chi + m_N}$ $\quad m_\chi \ll m_N : \mu \approx m_\chi$ $\quad m_\chi \gg m_N : \mu \approx m_N$

f_p , f_n : scattering amplitudes protons, neutrons

usually: $f_p \approx f_n \Rightarrow \sigma \propto A^2$



Finite momentum transfer:
Form factor ↔
Fourier transform of nuclear density

$$F^2(q) = \left| \int \rho(r) \exp\left\{ i\,\frac{\vec{q}\cdot\vec{r}}{\hbar} \right\} dr \right|^2 = \left(\frac{3\, j_1(qR_1)}{(q\,R_1)} \right)^2 \exp\left[-(qs)^2\right]$$

Momentum transfer: $q = \sqrt{s\; m_N\, E_r}$

j_1 : first spherical Bessel function

$R_1 = \sqrt{R_0^2 - 5\,s^2}$, $R_0 \approx 1.2\ \text{fm}\ A^{1/3}$, $s \approx 1$ fm

Helms form factor density profile

$$\rho(r) = \int_{\text{volume}} \rho_0(\mathbf{r}')\rho_1(\mathbf{r}-\mathbf{r}')d^3x'$$

$$\rho_0(r) = \begin{cases} \frac{3}{4\pi r_n^3} & r < r_n \\ 0 & r > r_n\,, \end{cases}$$

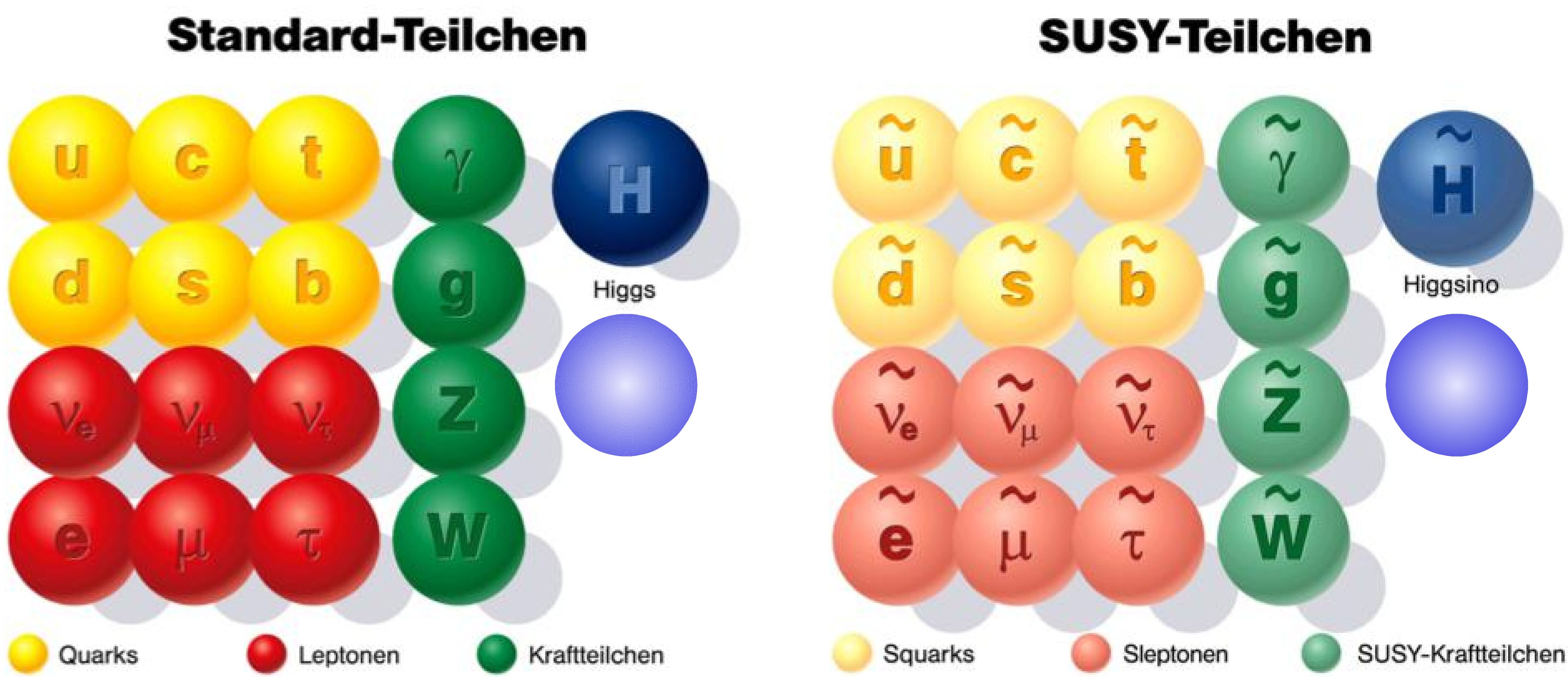
$$\rho_1(r) = \frac{1}{(2\pi s^2)^{\frac{3}{2}}} e^{-r^2/2s^2}\,.$$

SUSY – MSSM

WIMPs have been most extensively studied in the SUSY framework, but numerous other theories can provide WIMPs too.

MSSM: Minimal Supersymmetric Standard Model

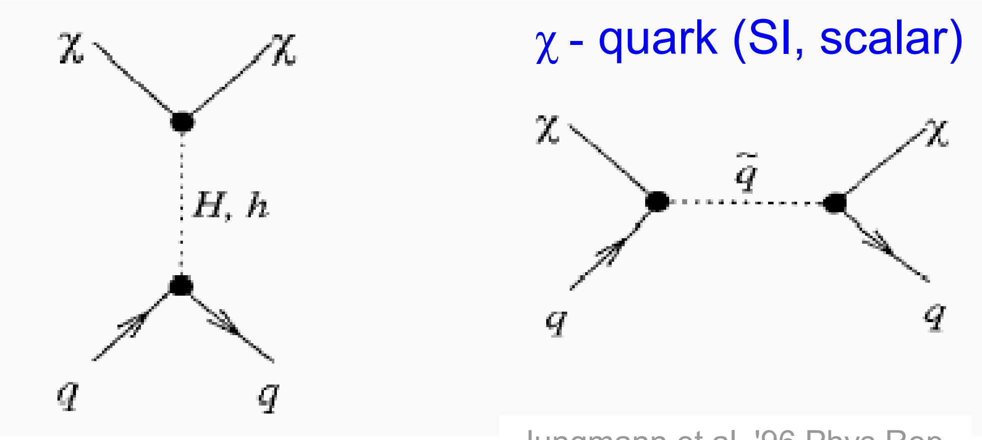
- 105 (!) additional physical parameters: (e.g., PDG http://pdg.lbl.gov/, Supersymmetry Part I)
  - Masses (scalar masses, gauginos)
  - Requires (at least) 2 Higgs bosons in the SM + 2 Higgsinos
  - CP phases
  - Mixing angles (e.g., for neutralinos & charginos), …



WIMP Scattering Cross Sections

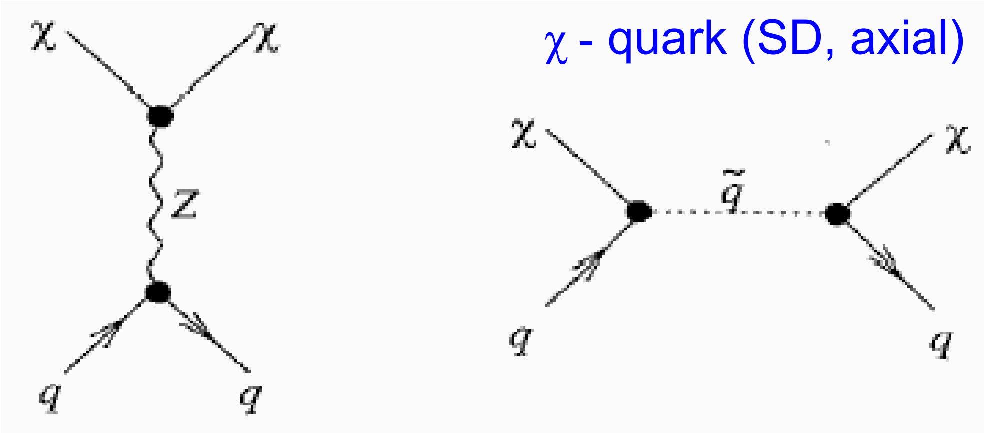
Example SUSY (direct searches are sensitive to other models as well)

- Cross sections χ – quark and χ – gluon with various SUSY models cover large parameter space: constrained by accelerator and direct search experiments, and cosmology.
- **Spin-independent** interactions: coupling to mass of nucleus.
  Coherence $\rightarrow \sigma \propto A^2$

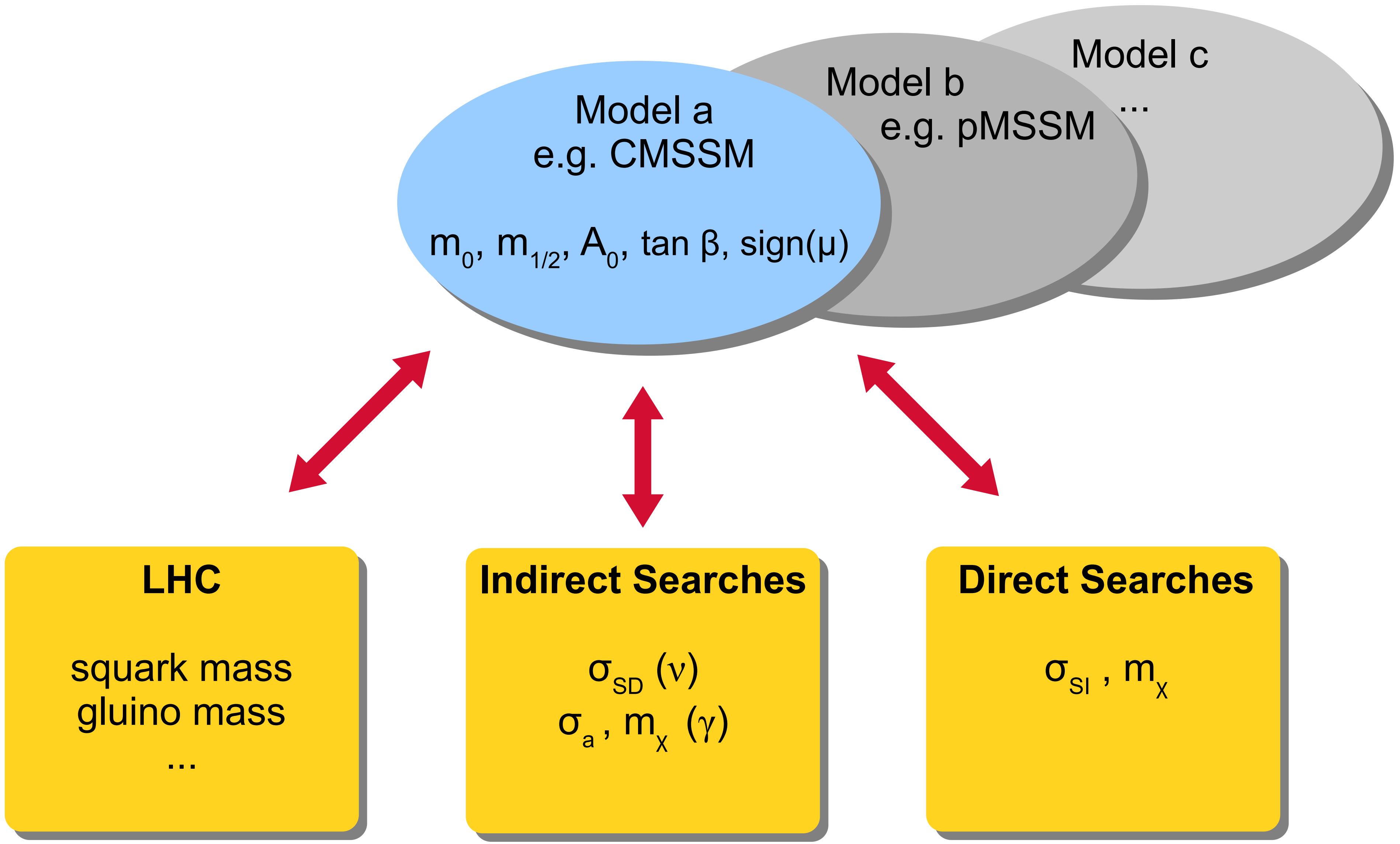


Jungmann et al. '96 Phys.Rep.

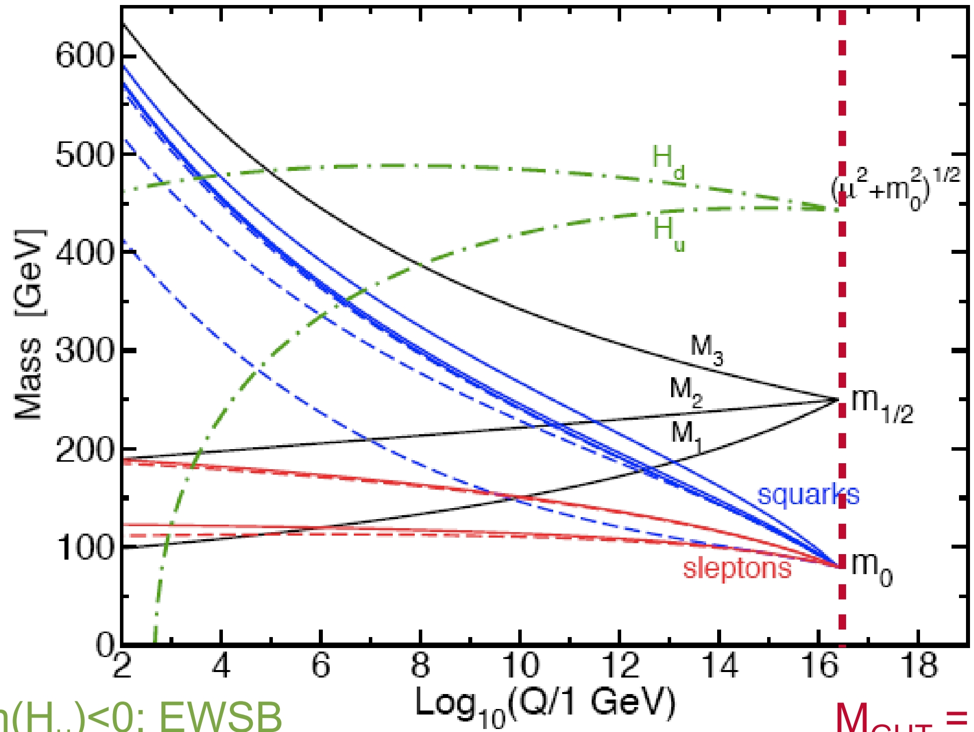
- **Spin-dependent** interactions: coupling of spins of nucleus and neutralino.Interactions with paired nucleons in the same energy state cancel.
  $\rightarrow$ no A^2 enhancement
  $\sigma \propto (J+1)/J$



Complementarity in Dark Matter Searches:
Direct Searches, Indirect Searches, and the LHC



Constrained Minimal Supersymmetric Standard Model CMSSM / mSUGRA

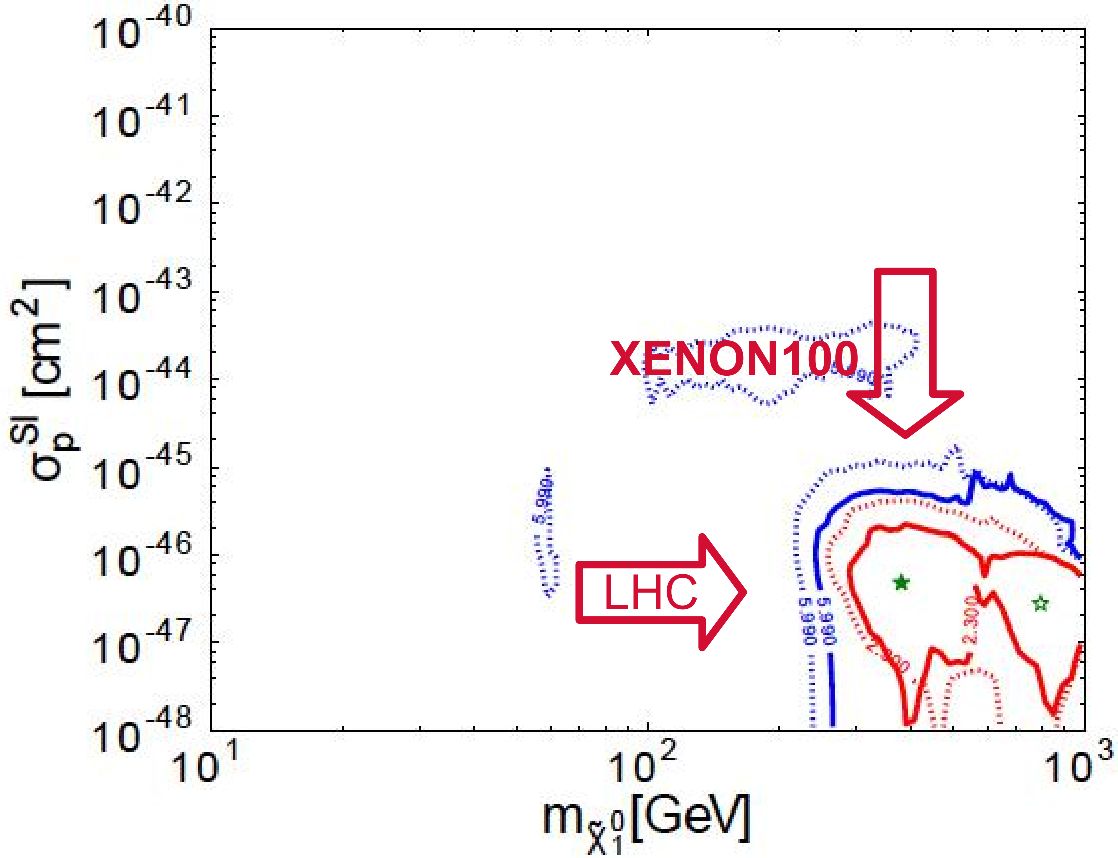


m(H_u)<0: EWSB

$M_{GUT} = 2.5\times10^{16}$ GeV

- Reduction to 5 additional parameters defined at the GUT scale (~10^{16} GeV):
  - m_0: universal supersymmetry-breaking scalar mass
  - $m_{1/2}$: universal supersymmetry-breaking gaugino mass
  - A_0: universal supersymmetry-breaking trilinear scalar interaction
  - tan β: ratio of vacuum expectation values of two (required) Higgs doublet
  - sign(μ). μ: mass of supersymmetric higgsinos.
    Value(μ) determined by electroweak symmetry breaking (EWSB)
- Renormalization group equations determine sparticle mass spectrum at low energies.

Direct Searches and the LHC in the CMSSM



"Consequently, looking beyond the CMSSM and NUHM1, ..., not only seems timely now, but mandatory."

O. Buchmueller et al.
arXiv:1207.7315

Naturalness of SUSY WIMPs

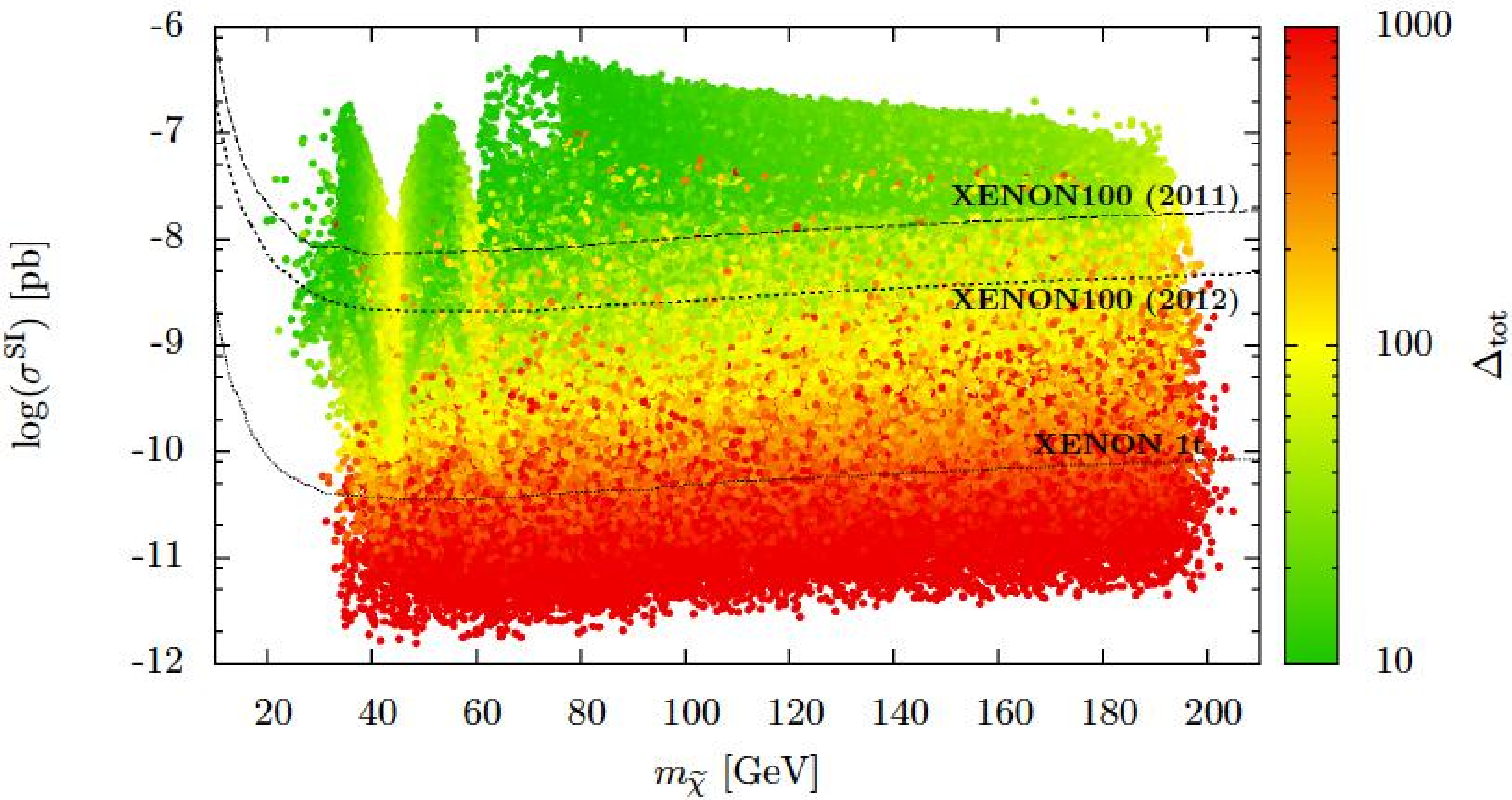
Ph. Grothaus, Manfred Lindner, Y. Takanishi,
arXiv:1207.4434

- pMSSM with 11 free parameters: $\tan\beta\,,\, M_1\,,\, M_2\,,\, M_3\,,\, M_A\,,\, \mu\,,\, m_{\tilde{\ell}_L}\,,\, m_{\tilde{\ell}_R}\,,\, m_{\tilde{q}_{1,2}}\,,\, m_{\tilde{q}_3}\,,\, a_0$
- Measure for naturalness: Δ_{tot}

$$\Delta_{\rm tot} \equiv \sqrt{\sum\nolimits_{p_i=\mu^2,b,m_{H_u}^2,m_{H_d}^2} \{\Delta p_i\}^2}$$

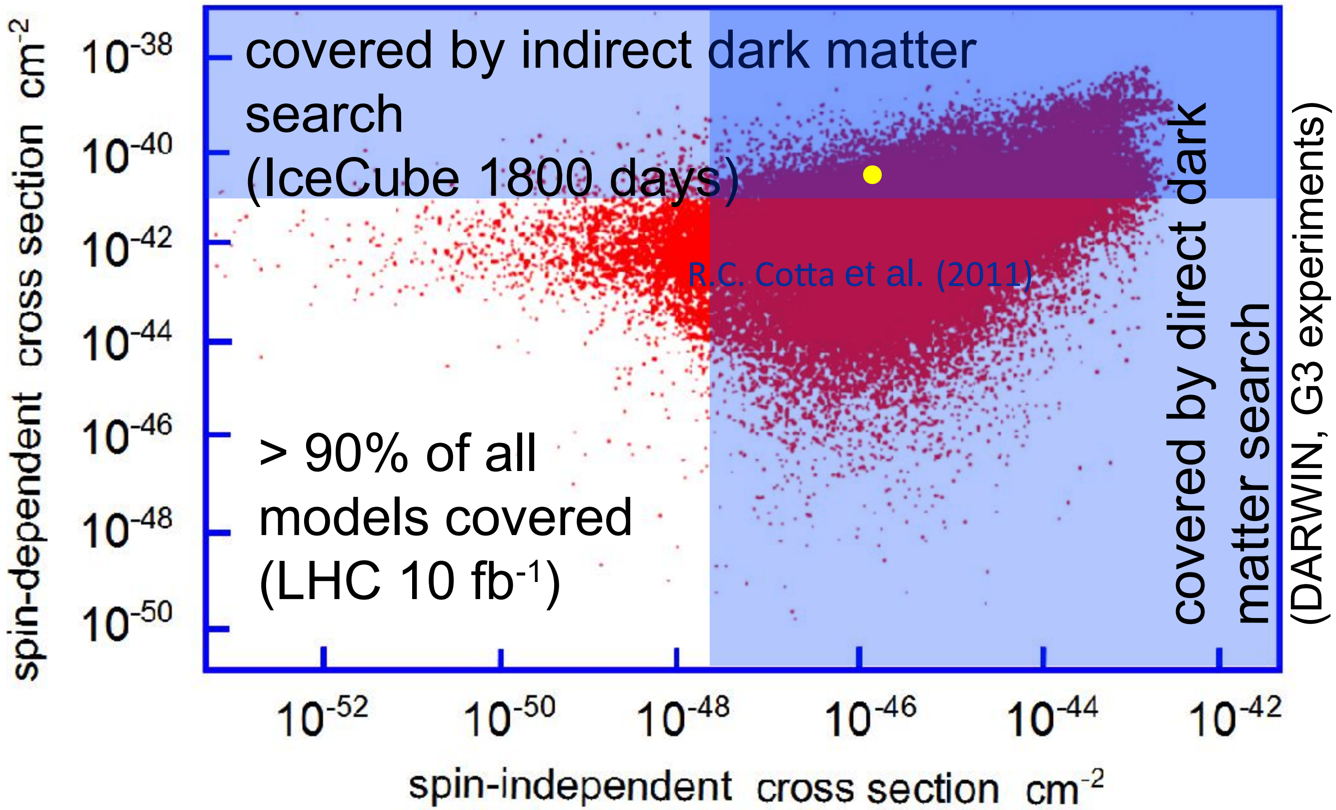
$$m_Z^2 = \frac{|m_{H_d}^2 - m_{H_u}^2|}{\sqrt{1-\sin^2 2\beta}} - m_{H_u}^2 - m_{H_d}^2 - 2|\mu|^2$$

$$\Delta p_i \equiv \left|\frac{p_i}{M_Z^2}\frac{\partial M_Z^2(p_i)}{\partial p_i}\right| = \left|\frac{\partial \ln M_Z^2(p_i)}{\partial \ln p_i}\right|$$



Complementarity in the pMSSM

- **pMSSM:** "SUSY without prejudice": 19 free parameters at the weak scale
- **Spin-dependent scattering** cross section (indirect search with neutrinos, direct search)
- **Spin-independent scattering** cross section (direct search)
- **Test of models beyond the SM** (accelerator search)



- plus: **Annihilation / Decay** (indirect searches γ, ν, CR)

When DM is discovered:

- Independent measurements for confirmation.
- Measurements of properties: understanding its nature.

Backgrounds in Direct DM Search

Cross-sections are *very* small: <10^{-44} cm^2 or 10^{-8} pb (spin-independent)

Without background, sensitivity $\propto$ (mass × exposure time)$^{-1}$

With background subtraction $\propto$ (M t)$^{-1/2}$
until limited by systematics.

Backgrounds:

Gamma-rays & beta decays:

- ~100 events/kg/day
- Need very good β and γ background discrimination.
- Shielding: low-activity lead, water, noble liquids (active), liquid N_2, ...

Neutrons from (α, n) and spontaneous fission (concrete, rock, etc.):

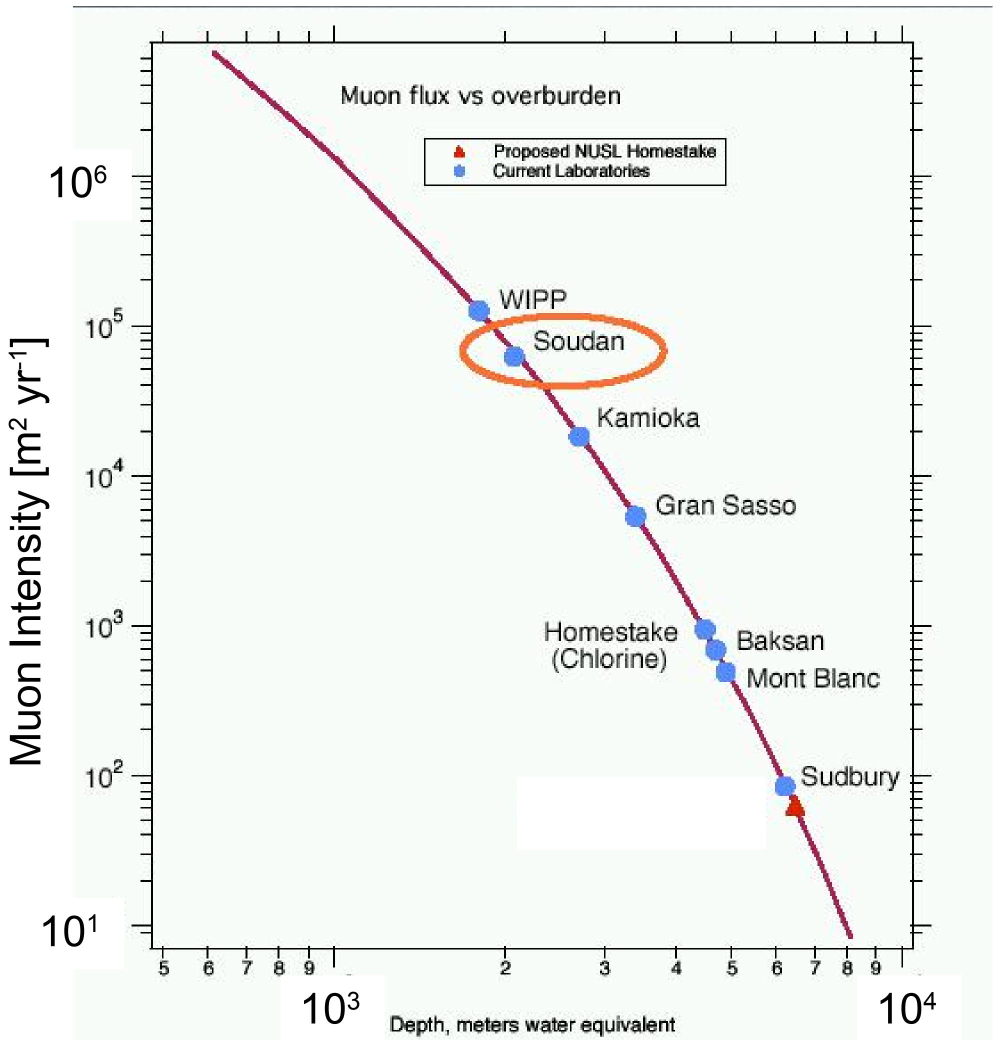
- ~ 1 event/kg/day (LNGS)
- Neutron moderator (polyethylene, paraffin, ...)

Neutrons from CR muons:

- Rate depending on depth.
- μ-veto, n-veto, shielding

α decays from natural decay chains

- surface effects, recoiling nucleus



Depth [meters water equivalent]

DM Detector Overview
Detection Principles

Bubble Formation
COUPP, PICASSO, SIMPLE

Tracking
Drift, DM-TPC, MIMAC, NIT

Ionization
CoGeNT

CDMS-II, Super-CDMS
Edelweiss-2

LAr: WARP, ArDM
LXe: **XENON**, LUX, Zeplin

Phonons

CRESST-II, ROSEBUD, **EURECA**

Scintillation
DAMA/LIBRA
KIMS, XMASS, DEAP/CLEAN

Outline

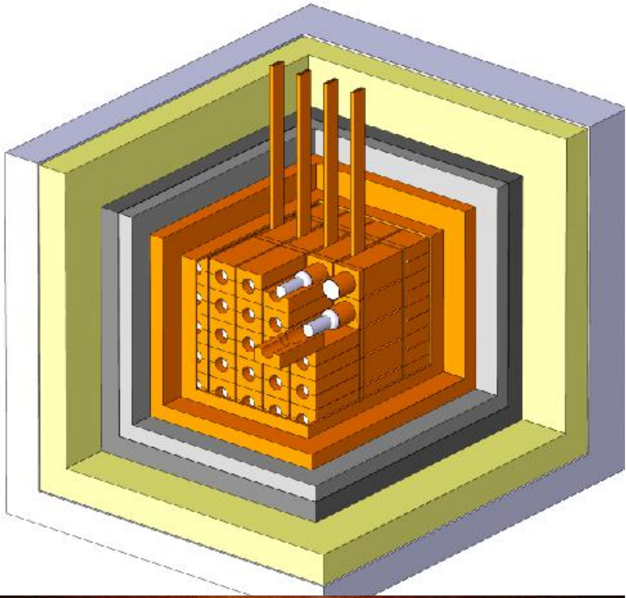
- Dark Matter: Evidence, Models, and the Magnificent WIMP
- Direct Detection Technique
- Status of DM Direct Detection
- XENON Dark Matter Search
- Future

Have we detected Dark Matter?

DAMA/LIBRA

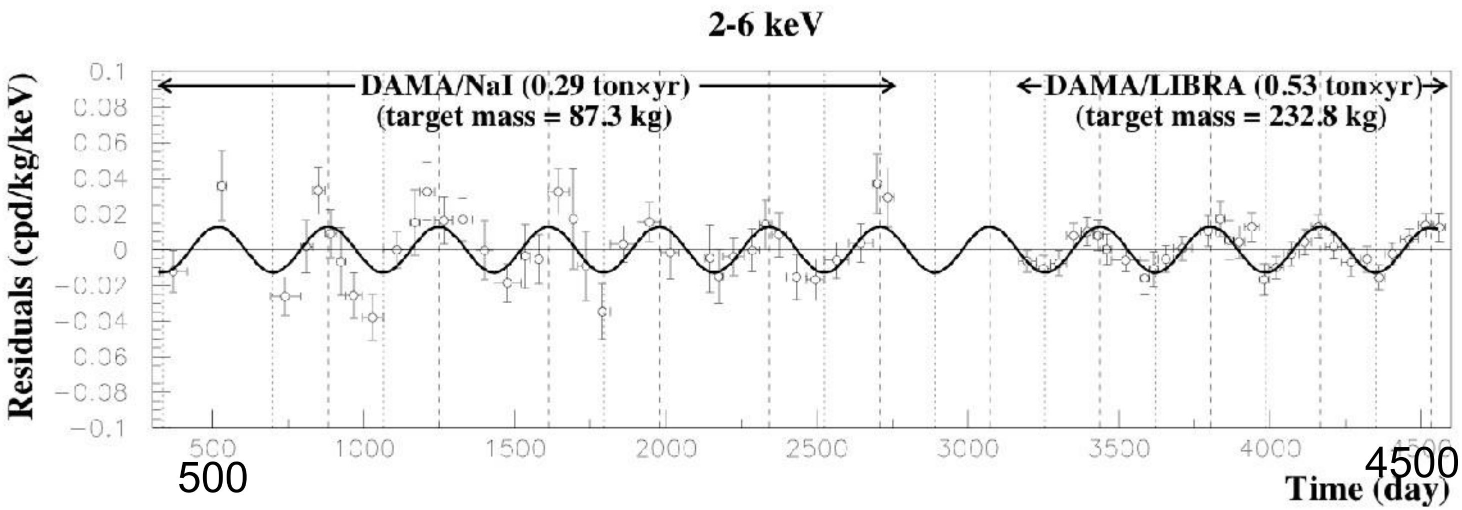
R. Bernabei et al. arXiv:0804.2738, arxiv:1002.1028

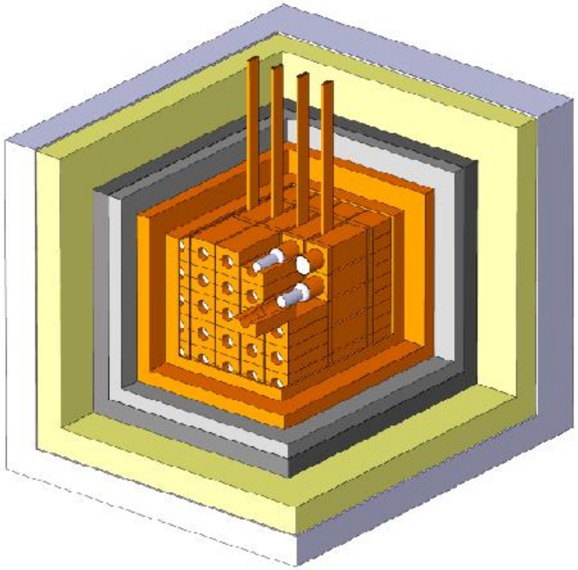
- Successor of DAMA/NaI experiment
- 5x5 array of 9.7 kg NaI(Tl) crystals viewed by 2 PMTs each.
- PMTs with single photoelectron threshold, operating in coincidence.
- Total mass:
  - DAMA/NaI 1996-2002: ~100 kg
  - DAMA/LIBRA 2003-2008: 232.8 kg
  - DAMA/LIBRA: since 11/2008: 242.5 kg
- Heavy shield:
  >10 cm of Cu, 15 cm of Pb + Cd foils,
  10/40 cm PE/paraffin, ~1 m concrete
- Radon sealing



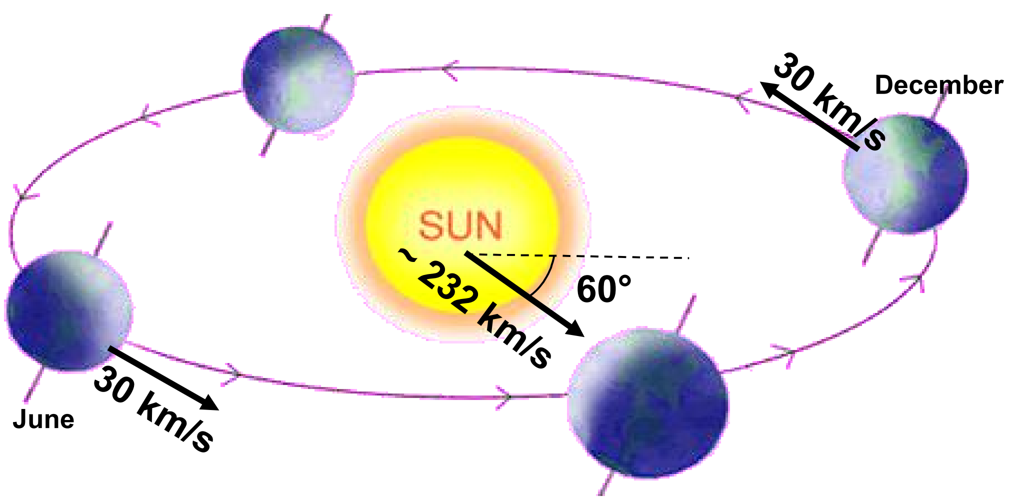
DAMA/LIBRA Annual Modulation

R. Bernabei et al. EPJ C 56, 333 (2008), arxiv:0804.2741
EPJ C 67, 39 (2010), arxiv:1002.1028





- ~250 kg of NaI counters
- 1.17 ton-year exposure (2010)



Drukier, Freese, Spergel PRD 86
Freese et al. PRD 88

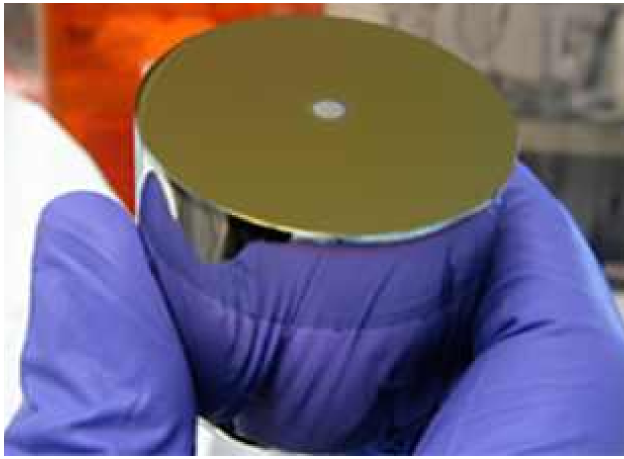
- Modulation in 2-6 keV single hits: 8.9 σ
- Mostly in 2-4 keV, ~0.02 cts/d/kg/keV
- Total single rate ~1 cts/d/kg/keV
- Standard DM distribution: < ~5% modulation
- Period & phase about right for DM.
- No annual modulation in 6-14 keV.
- No annual modulation in multiple hits. (which?)
- **DM detection?**
- Conflict with other experiments in standard scenarios that test the larger steady state effect.

Low Mass WIMPs?
Inelastic Dark Matter?
Luminous DM?

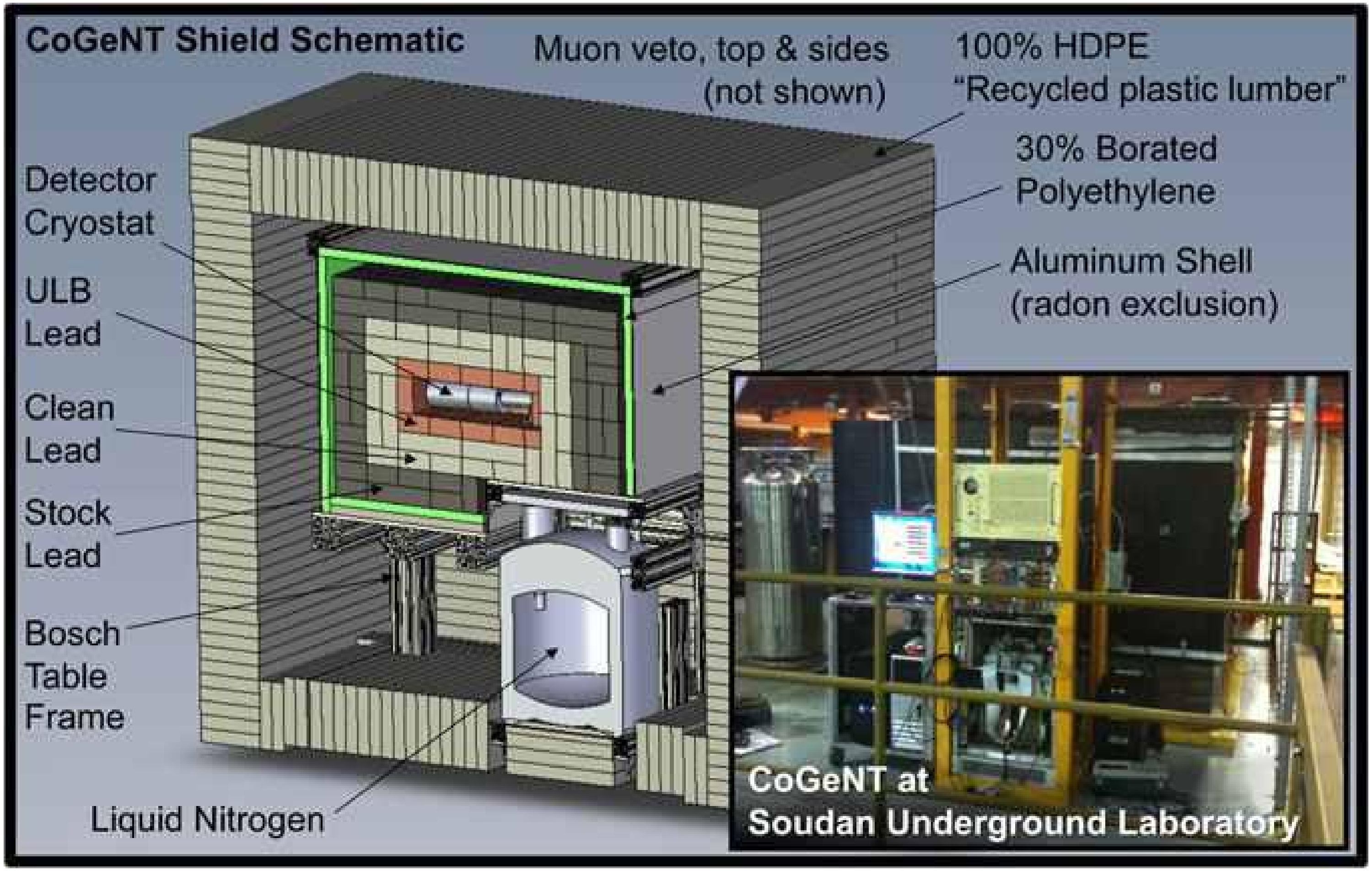
…

… or some yet to be understood detector or background effect?

CoGeNT

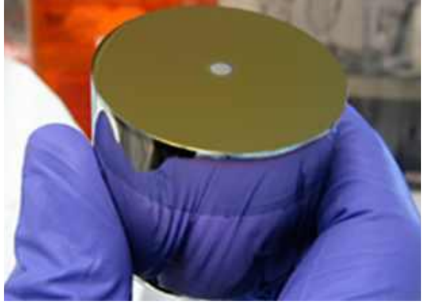


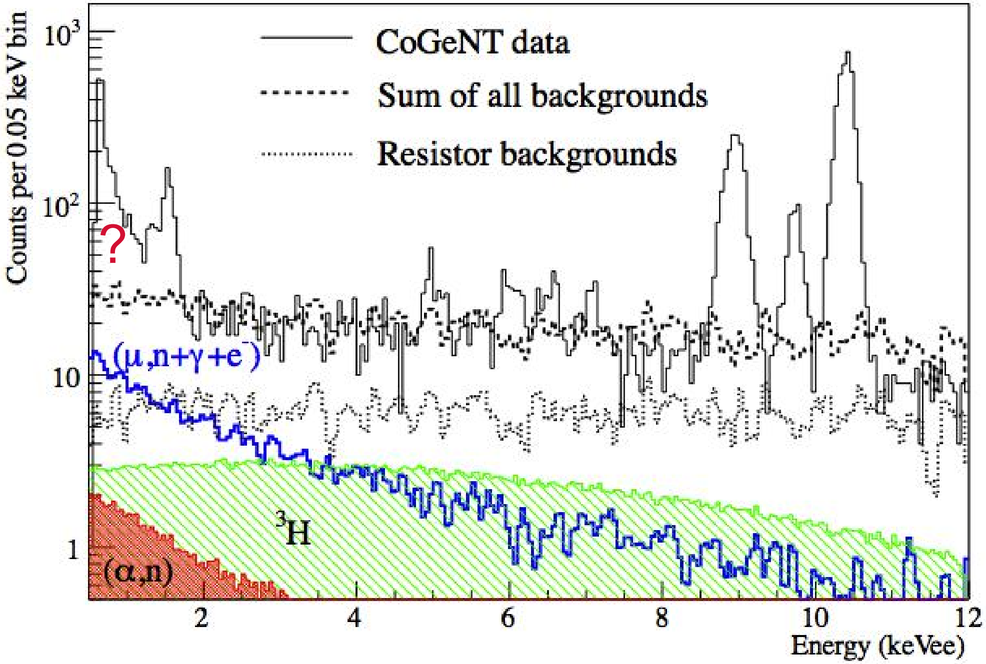
- Single P-type point contact (PPC) Germanium detector:
  440 g mass, 330 g fiducial (CDMS: 250 g per detector)
  Low electronic noise, hence low threshold (0.4 keVee)
- Located in Soudan mine (2100 mwe)
- Passive shield + Muon veto



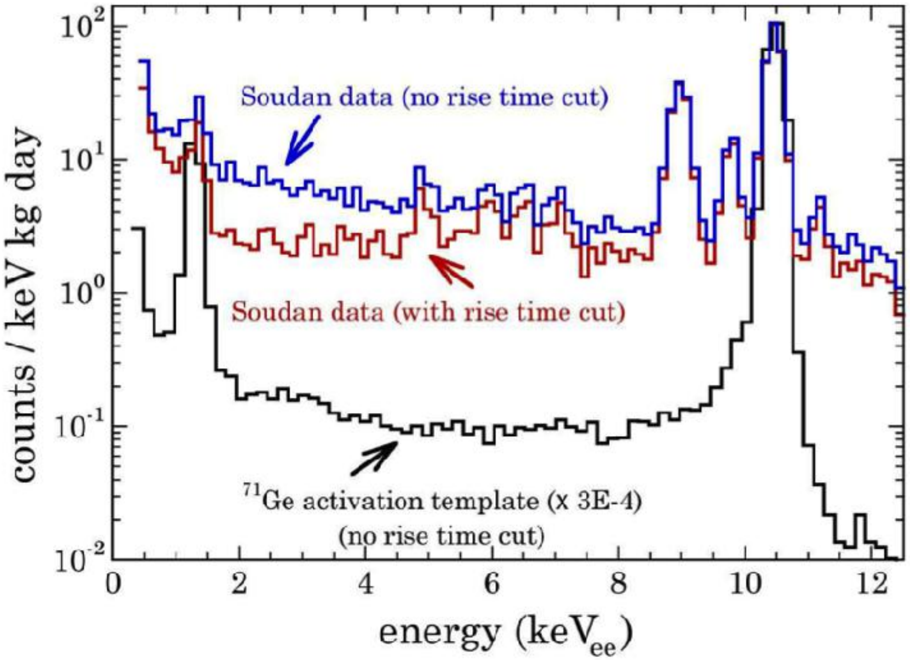
CoGeNT: What are these low-energy events?

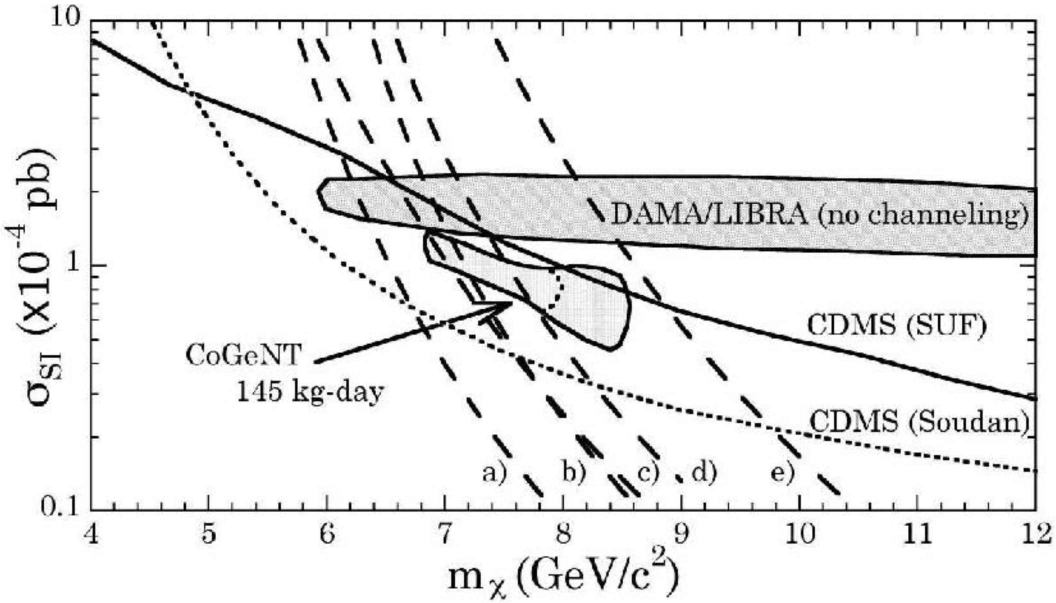
arxiv:1106.0650, arxiv:1208.5737





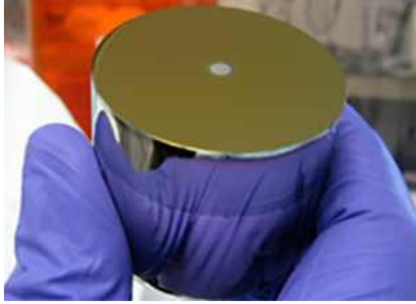
- 145 kg day exposure
- Fire in mine stopped data taking.
- meanwhile additional exposure collected

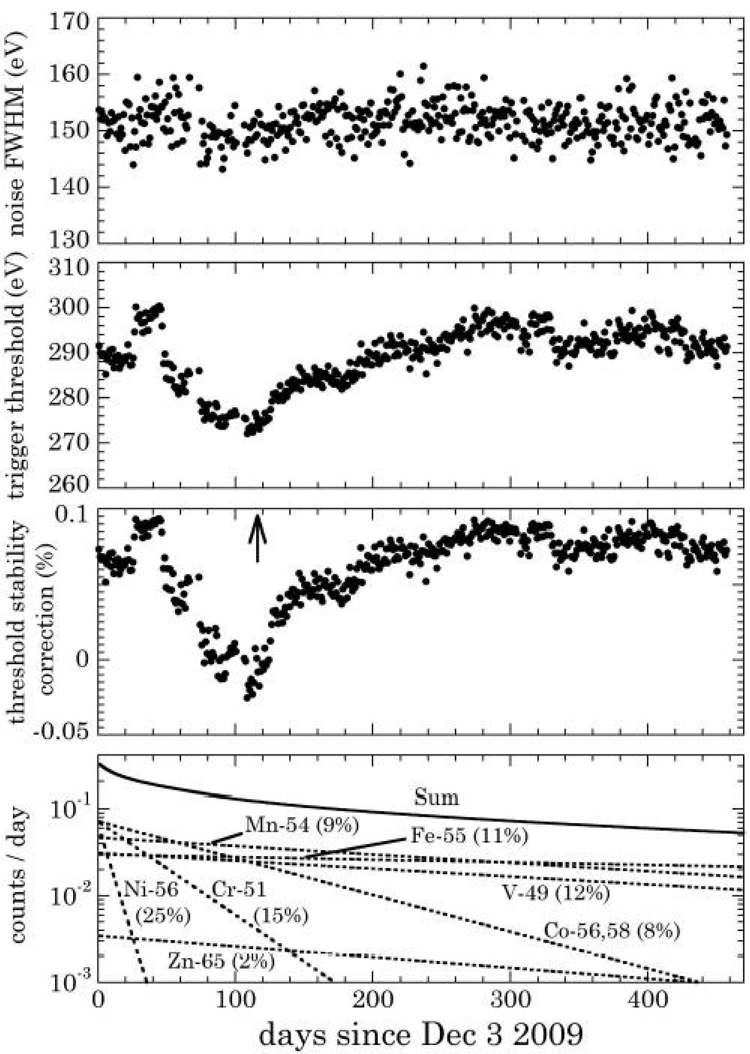




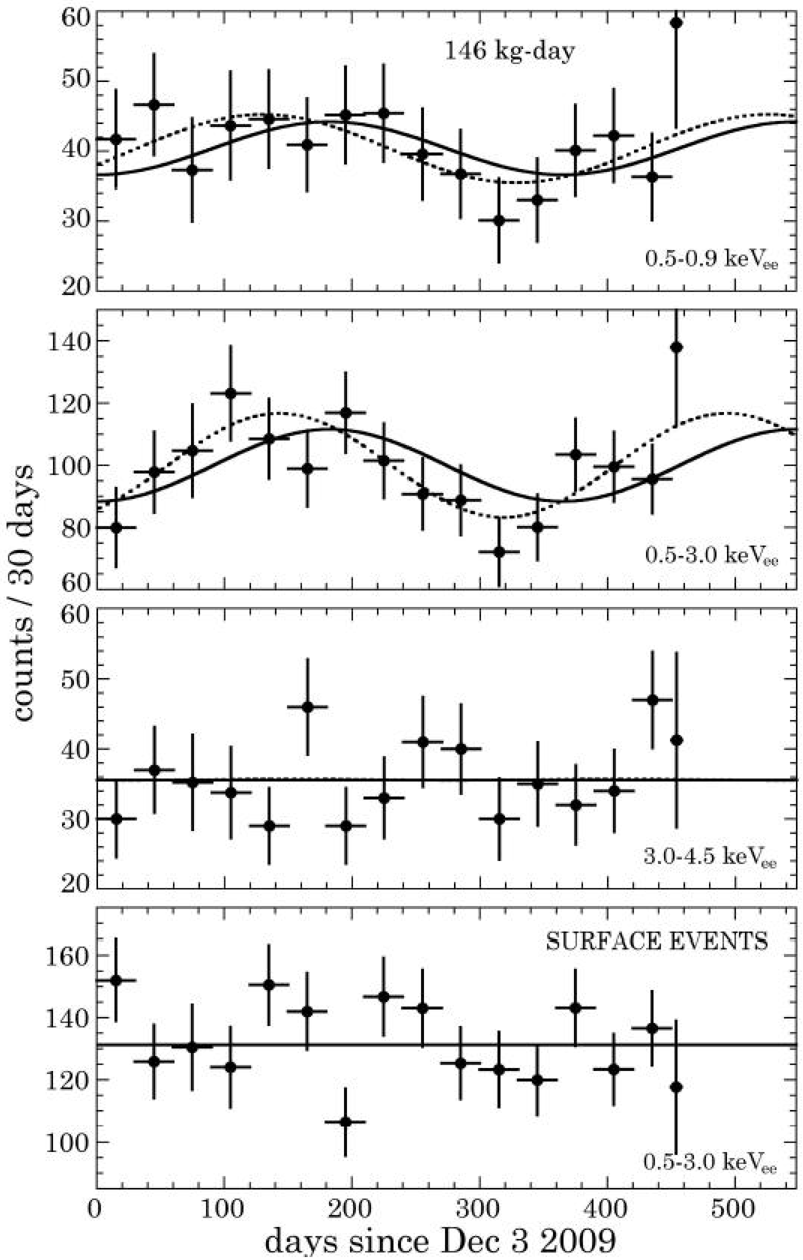
CoGeNT: Annual Modulation?

arxiv:1106.0650





Electronic noise and threshold stability



- 145 kg day exposure
- ~2.8 σ effect
- solid line: expected DM phase
- dotted line: best fit

CRESST II: Phonons + Scintillation

CRESST

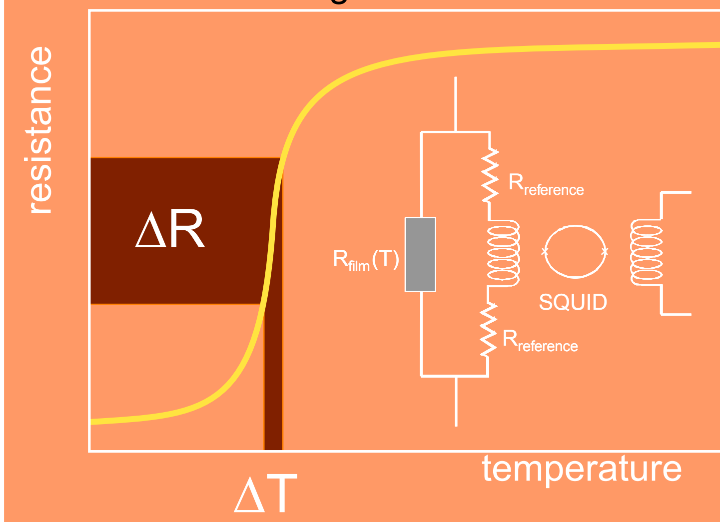
Cryogenic Rare Event Search with Superconducting Thermometers

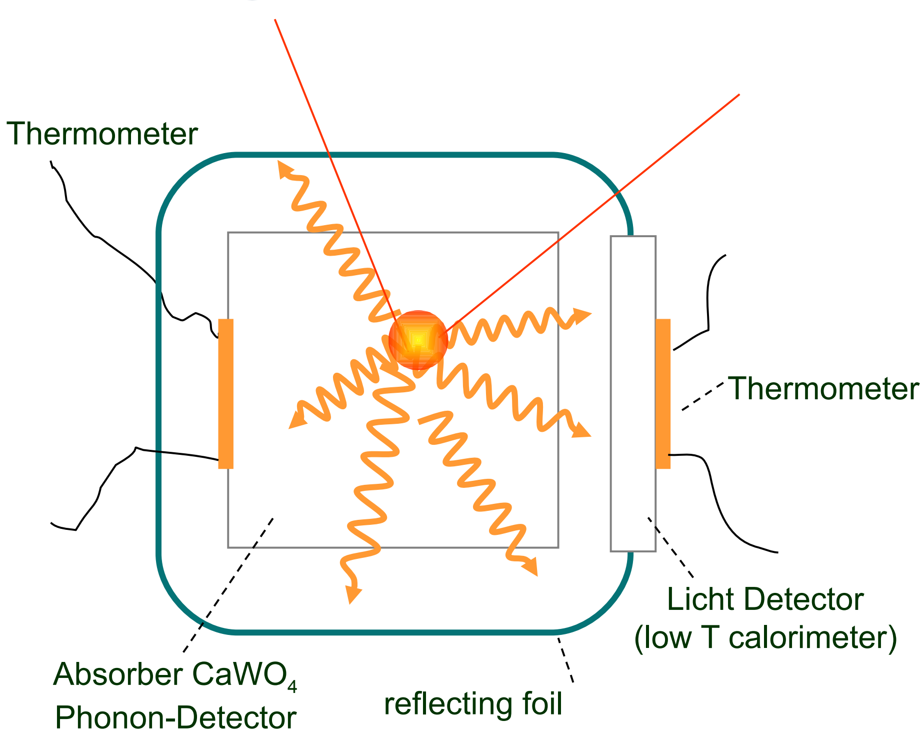
light + phonons (scintillating crystals)

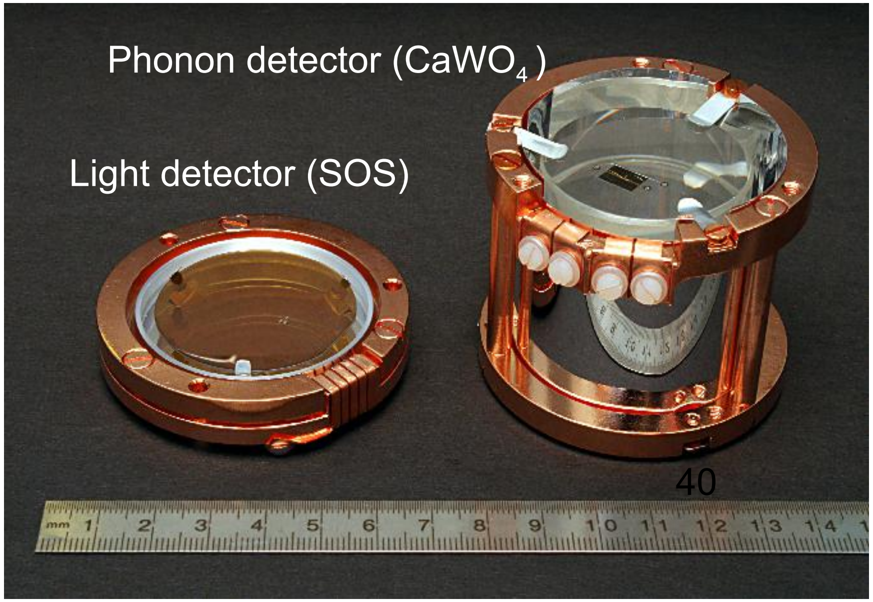
Max-Planck-Institut München, TU München
Universität Tübingen, Oxford University, Gran Sasso

Transition Edge Sensors (TES)

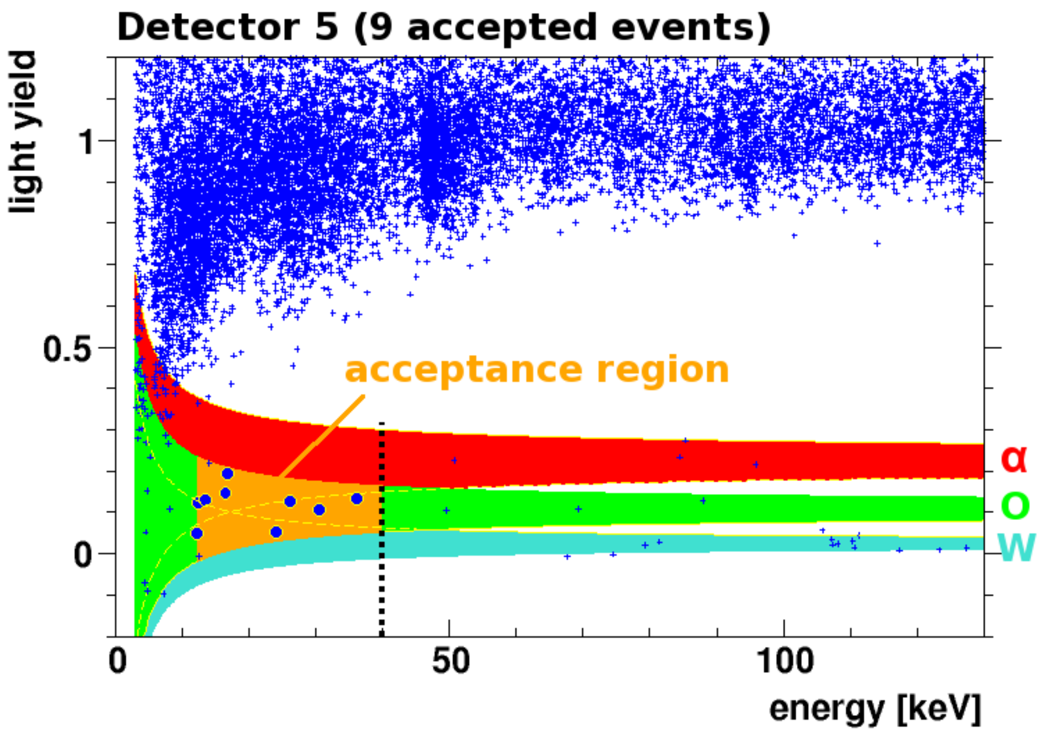
superconducting phase-transition-thermometer tungsten Tc≈15mK

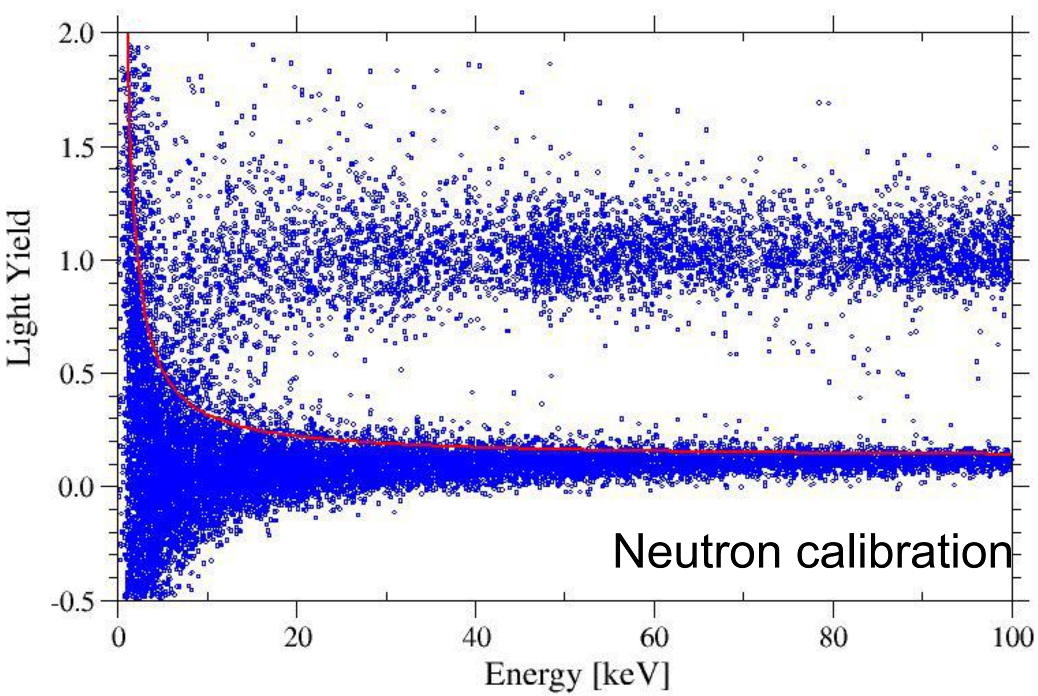






CRESST II: What are these excess counts?





- Data from 9 $CaWO_4$ detectors
- Exposure: 730 kg d
- 57 events observed in O-band (in allen Detektoren)
- Acceptance region (detector specific): O-band in ~10-40 keV

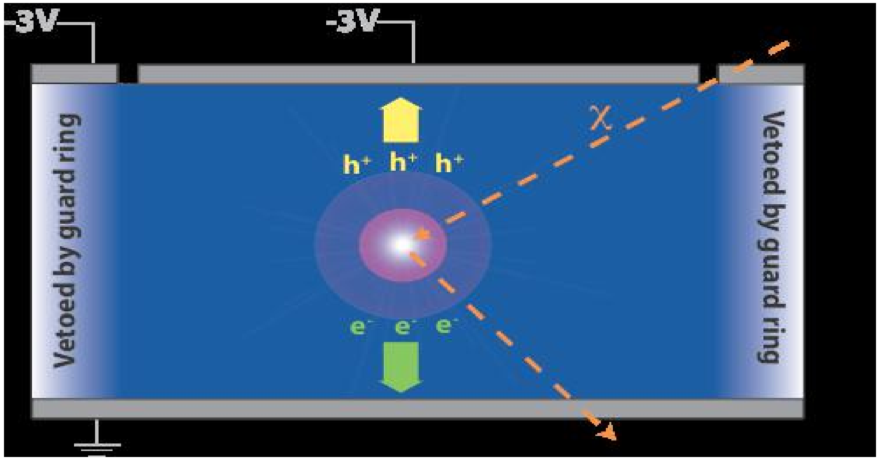
- Background estimated from sidebands:
  - α-events: 9.3
  - neutrons (generate mostly O-recoils): 17.3
  - e/γ leakage: 9.0
- Excess events not explained by modeled background: 4.6 σ (?)
- Hint of low-mass WIMPs?
  - best fit: $M_\chi \sim 13$ GeV/c^2, $\sigma \sim 3\times10^{-5}$ pb = 3×10^{-41} cm^2
  - confidence region?
- Systematic background uncertainty?
- Further background reduction

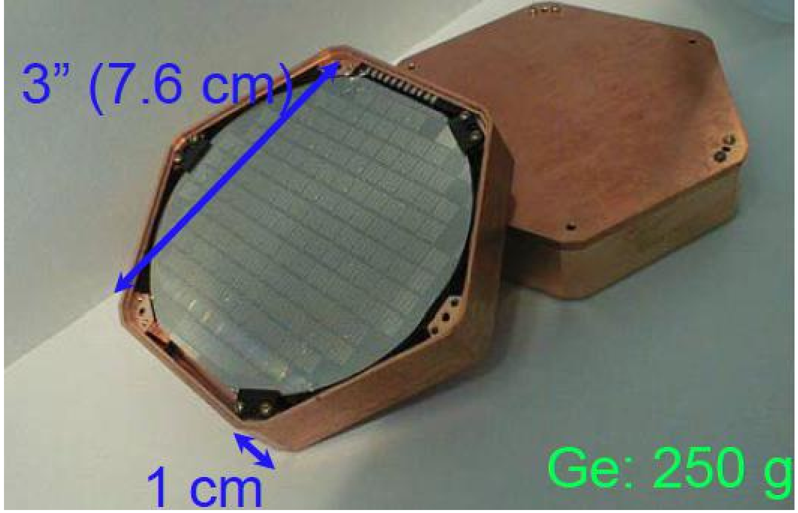
Low Mass WIMPs?

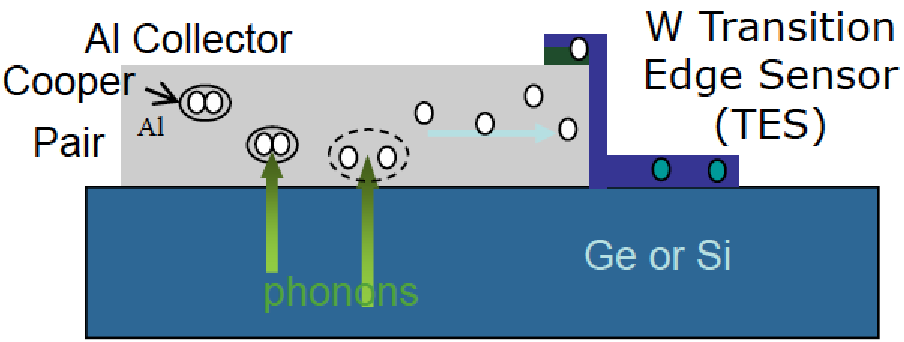
… or yet to be understood detector or background effects?

Spoiling the party: Limits

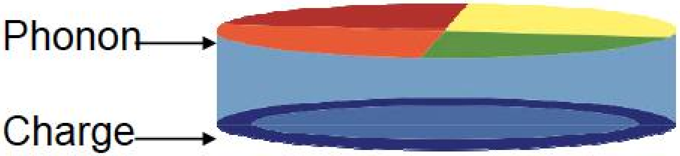
CDMS-II: Phonons + Charge
(Cryogenic Germanium)

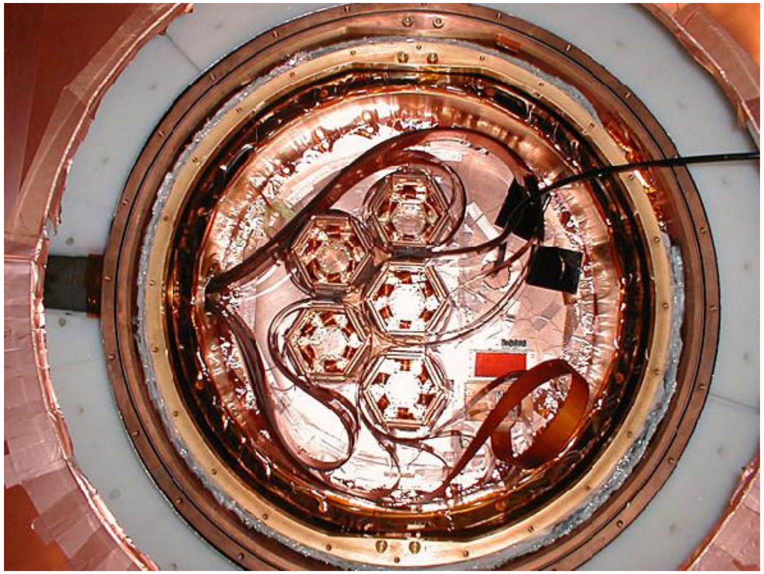






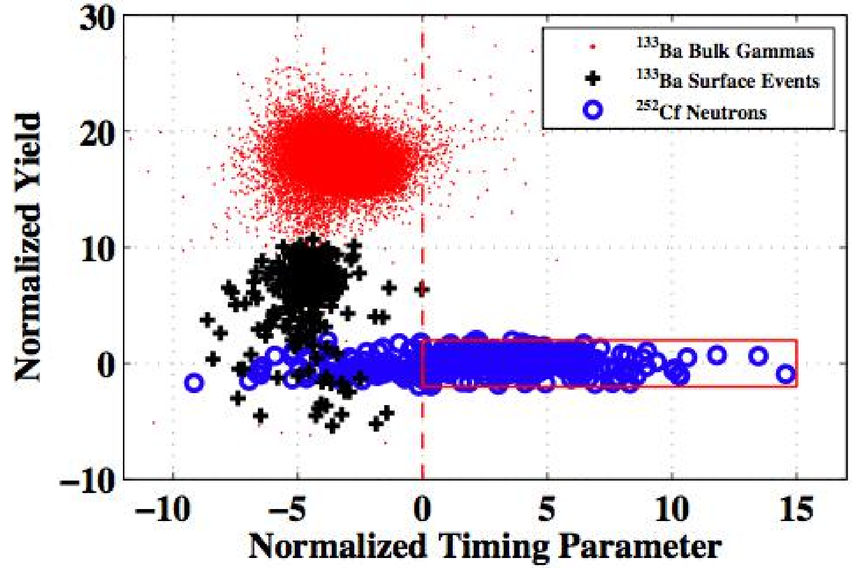
- Located at Soudan mine (Minnesota)
- Ge crystals operated at ~40 mK
- Fast phonon read-out with Tungsten Transition-edge sensors (TES)
  - direct measurement of nuclear recoil energy
  - SQUID Readout
- Low-voltage drift for charge read-out
  - e.m. background suppression with charge / phonon ratio
- Suppression of surface events with phonon timing signal

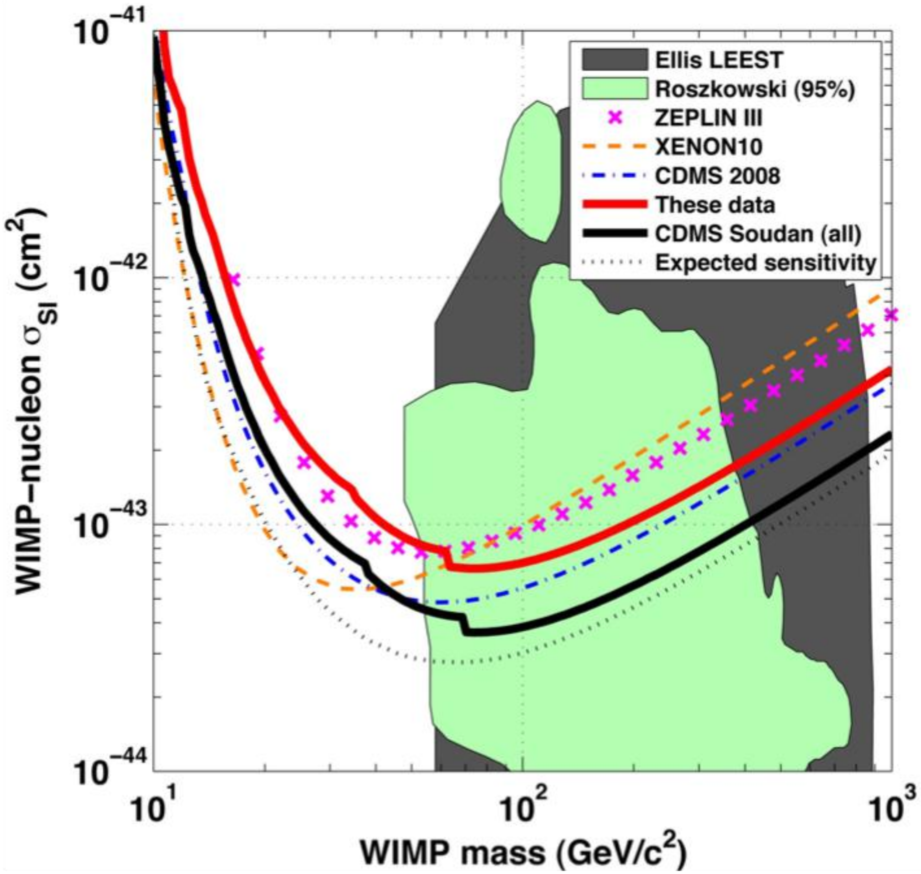




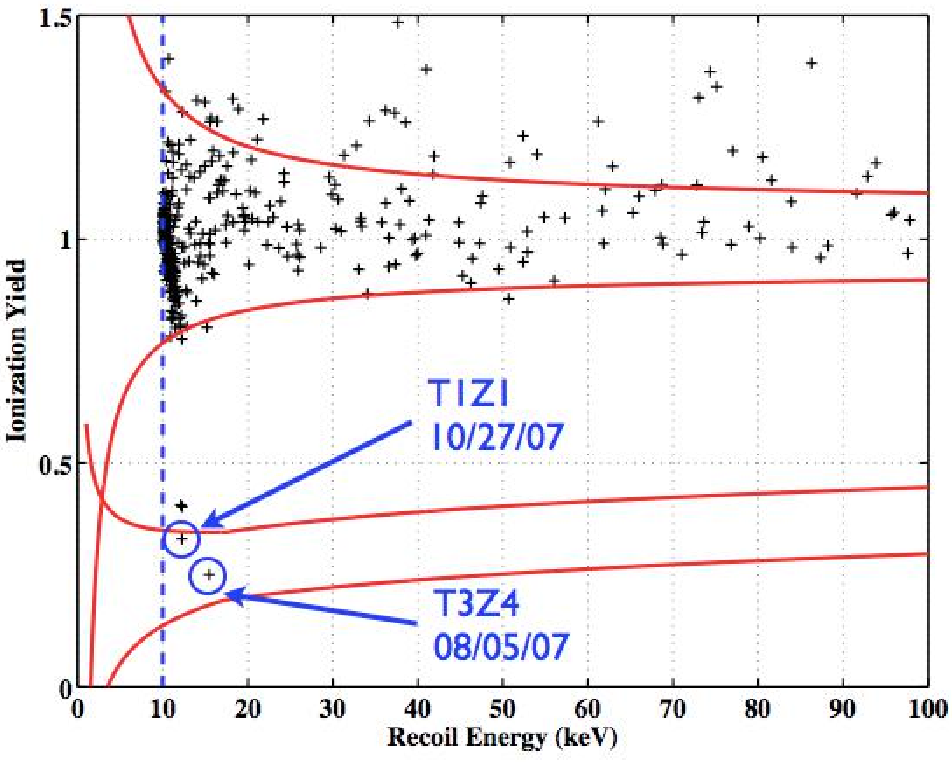
CDMS-II
Spin-Independent Limit

- 2 events observed after all cuts.
- Pre-opening background estimate: 0.6 events
- Revised estimate: 0.8 +/- 0.1 events
- 23% chance for background.
- CDMS-II completed.
- Next phase: Super-CDMS (15 kg) at Soudan mine construction and first operation in parallel



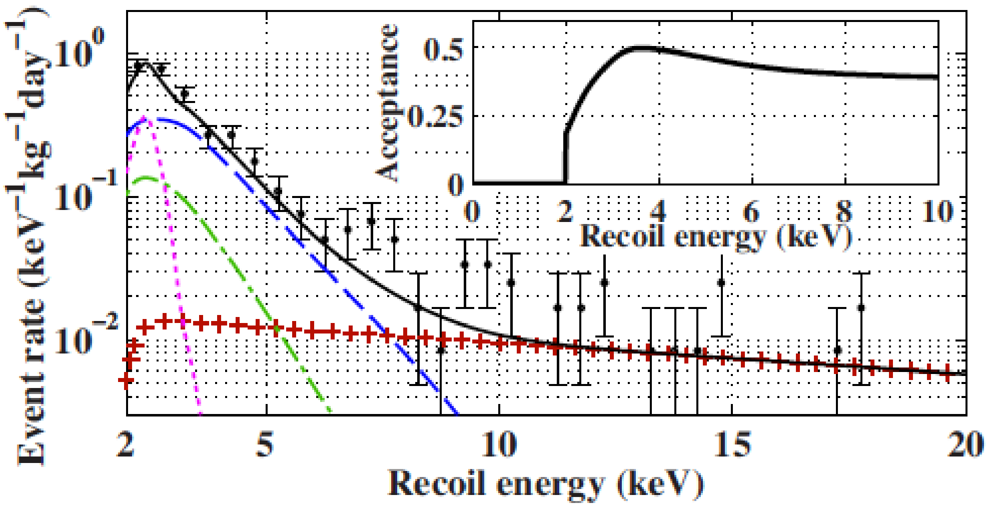


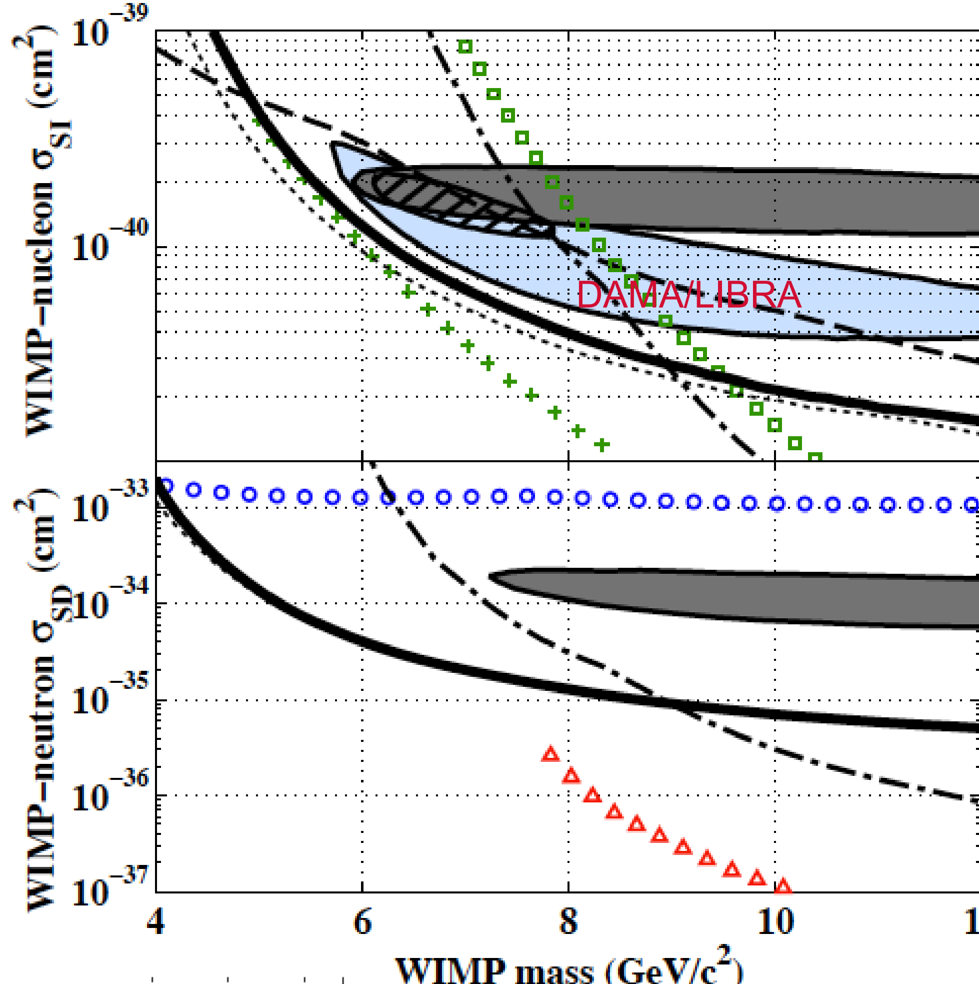
Science 327, Issue 5973, 1619 (2010)



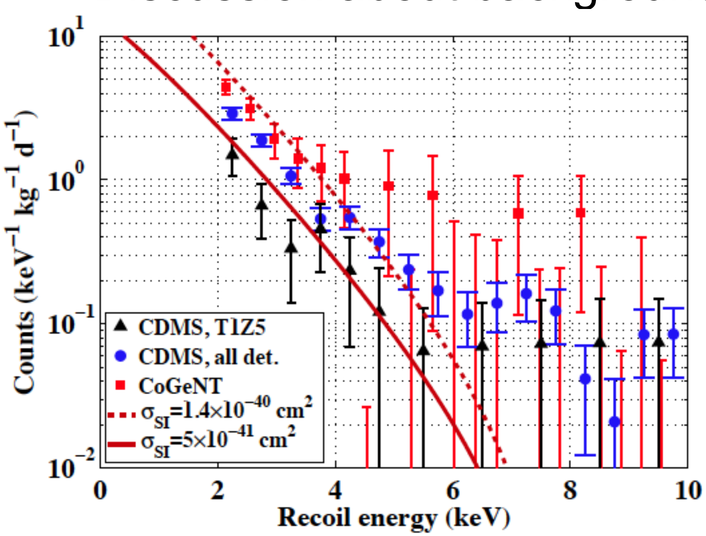
CDMS Low Threshold Limit

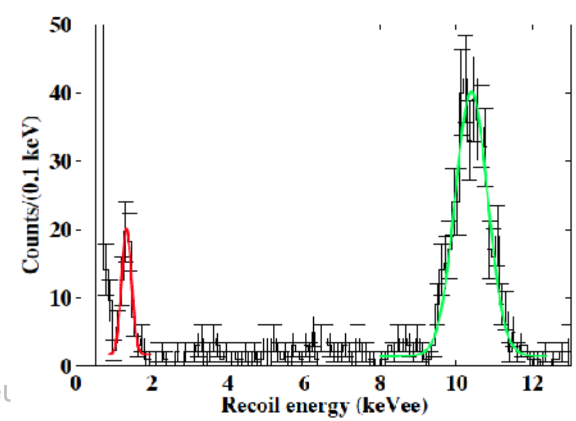
PRL 106, 131302 (2011), arXiv:1011.2482





- Strong tension with low mass WIMP interpretation of CoGeNT & DAMA/LIBRA results
- Discussion about background





Outline

- Dark Matter: Evidence, Models, and the Magnificent WIMP
- Direct Detection Technique
- Status of DM Direct Detection
- XENON Dark Matter Search
- Future

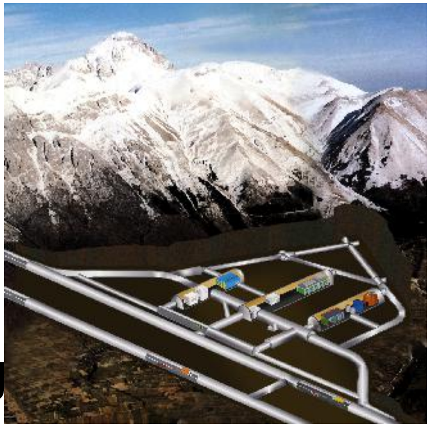
The XENON Collaboration

USA, Switzerland, Portugal, Italy, France, Germany, Israel, Netherlands, China (Xe100 only)

Columbia | Rice | UCLA | Zürich | Coimbra | LNGS | SJTU (Xe100)

Mainz | Bologna | Subatech | Münster | Nikhef | Heidelberg | Weizman

The XENON Program



GOAL: Explore WIMP Dark Matter with a sensitivity of $\sigma_{SI} \sim 10^{-47}$ cm^2.

Requires ton-scale fiducial volume with extremely low background.

CONCEPT:

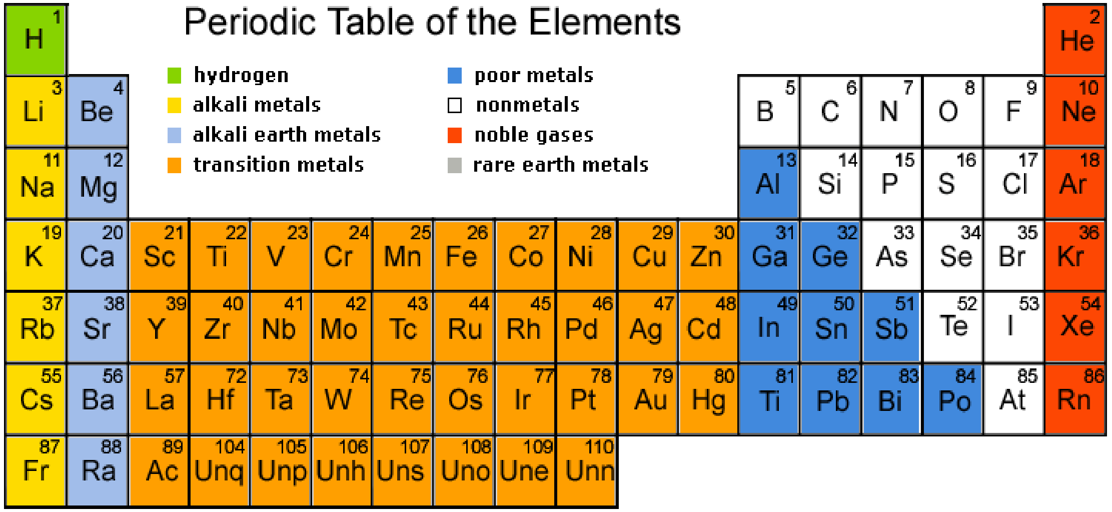
- Target LXe: excellent for DM WIMPs scattering.
  Sensitive to both axial and scalar coupling.
- Detector: two-phase LXeTPC: 3D position sensitive, self-shielding
- Background discrimination: simultaneous charge & light detection.
- PMT readout with >3 pe/keV.
  Low energy threshold for nuclear recoils (~6-8 keV).

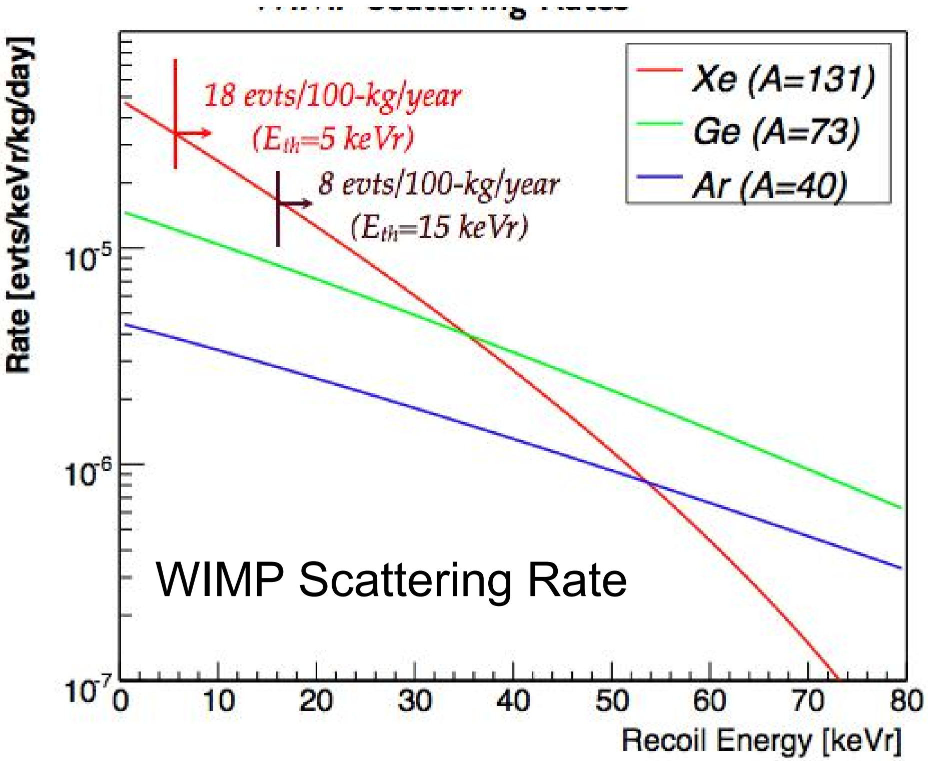
PHASES:

R&D	XENON10	XENON100	XENON1T
Start: 2002	2005-2007	2007 → ...	2011 → DM search 2015
	Proof of concept. Total mass: 14 kg 15 cm drift. Best limit in '07: $\sigma_{SI} \sim 10^{-43}$ cm^2	Ongoing DM search. Total mass: 170 kg 30 cm drift. Best limit in '11, '12: 2012: $\sigma_{SI} \sim 2 \times 10^{-45}$ cm^2	Technical design studies. Total mass: ~ 3 t 1 m drift. Goal: $\sigma_{SI} \sim 2 \times 10^{-47}$ cm^2

Liquid Xenon for Dark Matter Search

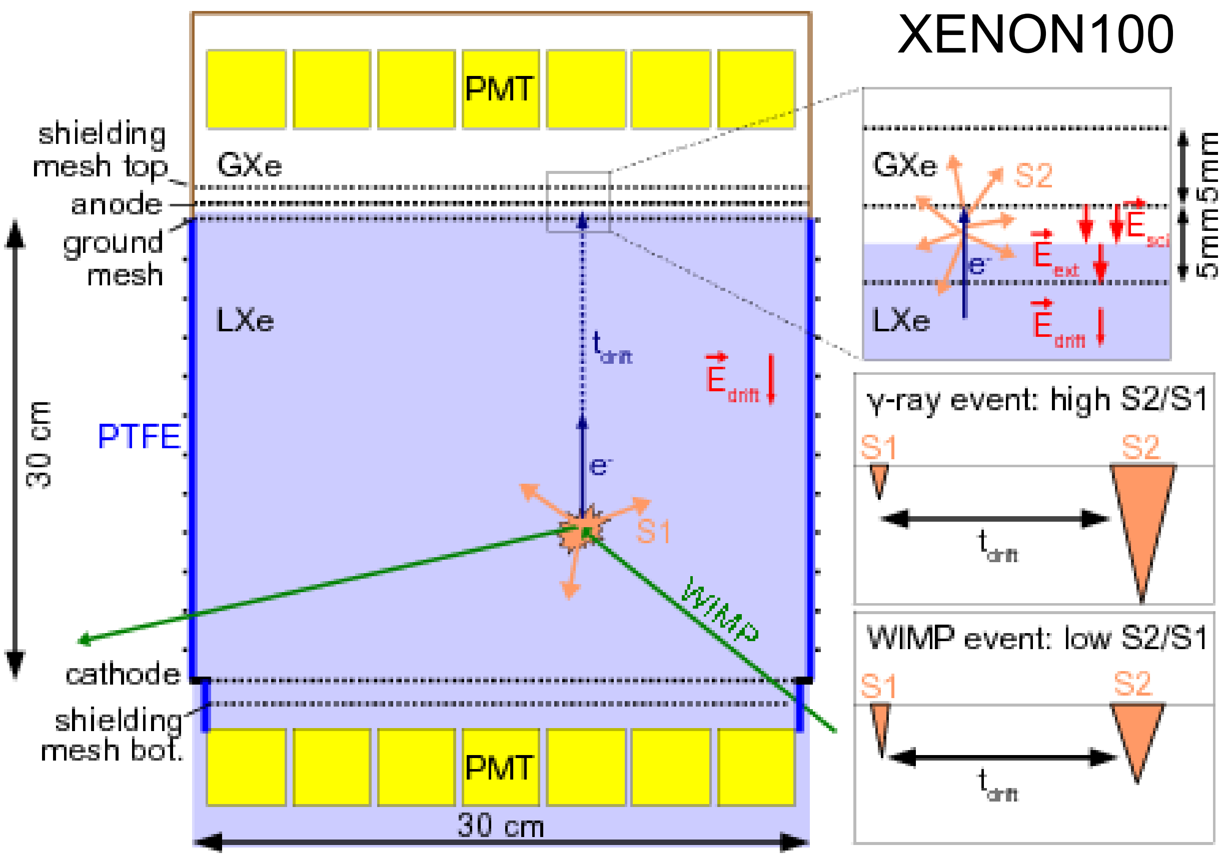
- Large atomic number A~131 best for SI interactions ($\sigma \sim A^2$).
  Need low threshold.
- ~50% odd isotopes: SD interactions
  If DM detected: probe physics with the same detector using isotopically enriched media.
- No long-lived isotopes.
  Proven Kr-85 reduction to ppt level.
- High Z (54) and density:
  compact & self-shielding
- Scalability to large mass for $\sigma \sim 10^{-47}$ cm^2 ~ 1 evt/ton/yr.
- "Easy" cryogenics (-100°C).
- Efficient and fast scintillator.
- Background discrimination in TPC.
  - Ionization/Scintillation
  - 3D imaging of TPC





The Liquid Xenon Dual Phase TPC
Ionization + Scintillation

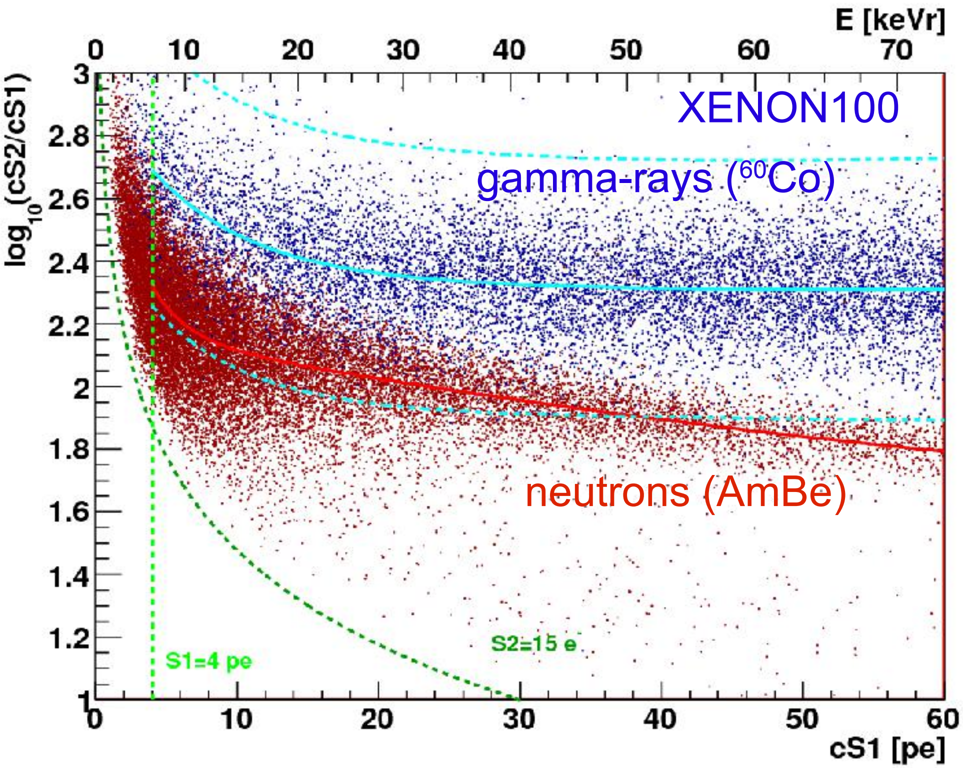
- Wimp recoil on Xe nucleus in dense liquid (2.9 g/cm^3) → Ionization + UV Scintillation
- Detection of primary scintillation light (S1) with PMTs.
- Charge drift towards liquid/gas interface.
- Charge extraction liquid/gas at high field between ground mesh (liquid) and anode (gas)
- Charge produces proportional scintillation signal (S2) in the gas phase (10 kV/cm)



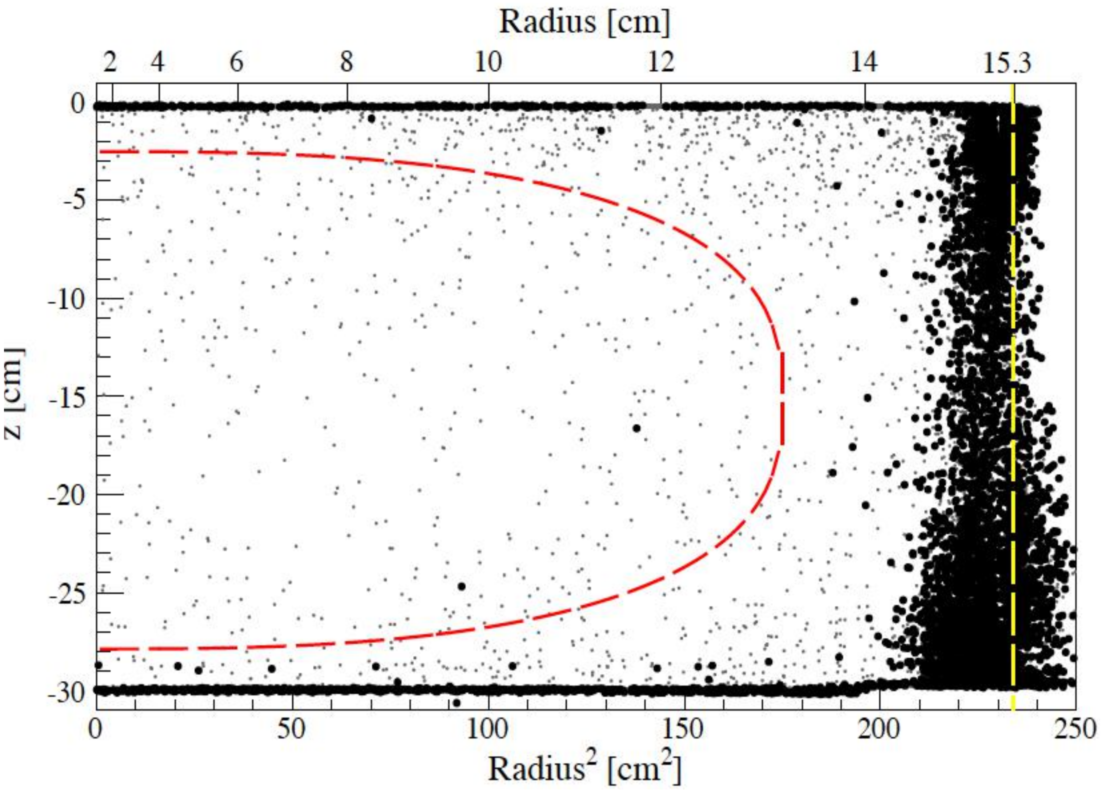
- 3D position measurement:
  X/Y from S2 signal. Resolution few mm.
  Z from electron drift time (~1 mm).

Background Discrimination in Dual Phase Liquid Xenon TPC's

Ionization/Scintillation Ratio S2/S1



3D Position Resolution: fiducial cut, singles/multiples



XENON100 (2007 –)

- 100 times lower background than XENON10
  - Material screening
  - Active LXe Veto
  - Low activity stainless steel
  - LXe self-shielding
  - Upgrade of XENON10 shield (Cu, water)
  - Cryocooler/Feedthroughs outside shield

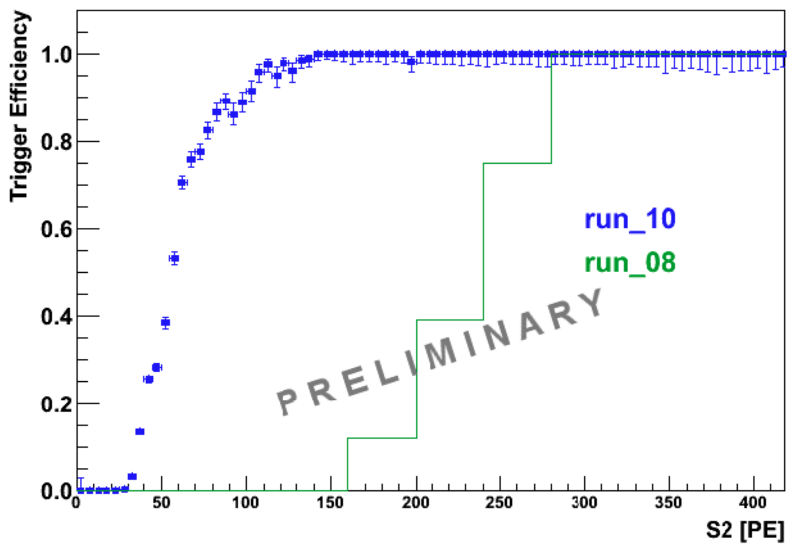
- ~7 times larger target mass
  62 kg LXe target, 165 kg total
- New PMTs with lower activity and high QE
  total: 248 PMTs

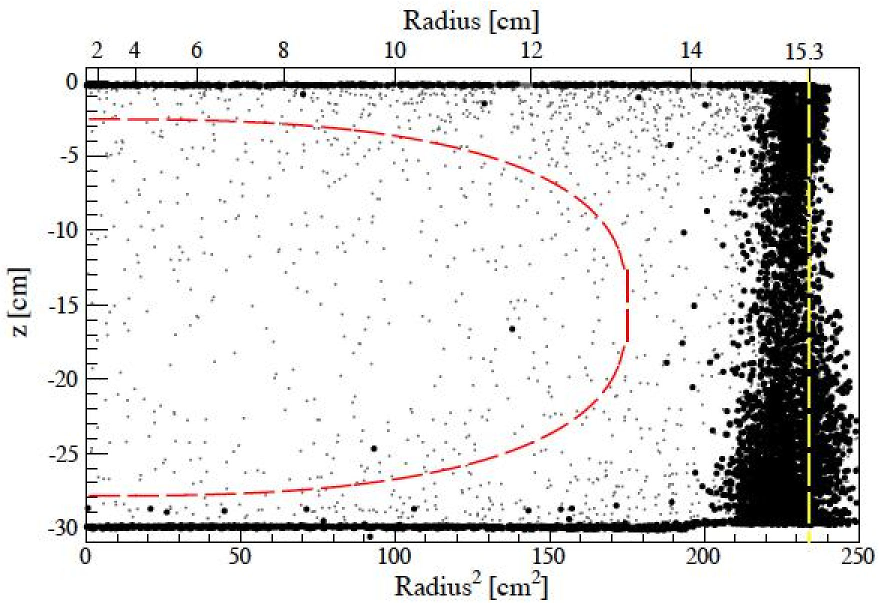
PRL 107, 131302 (2011)

- Improved electronics, grids, ...
- 100 live days DM search Jan – June 2010 PRL 107, 131302 (2011)
  225 live days DM search Feb 2011 – Mar 2012

XENON100 2012 Result

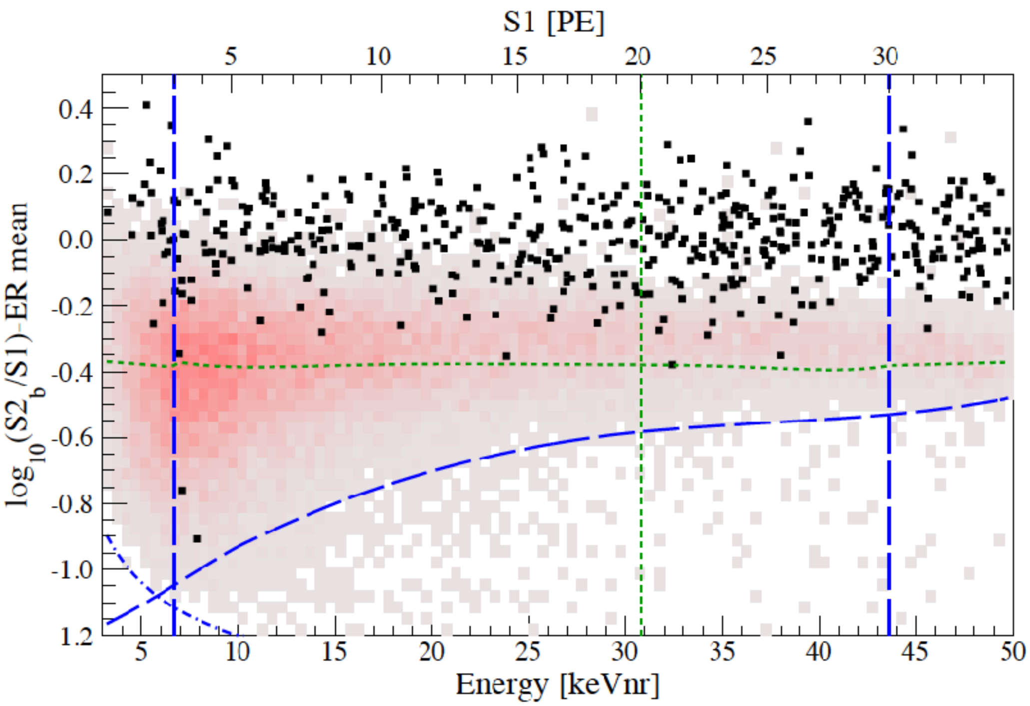
Reduced trigger threshold





Comparison with 2011 result:

- Factor ~2.5 live time: 225 d
- reduced trigger threshold
  lower energy threshold: 8.4 → 6.6 keV_{nr}
- reduced ^{85}Kr background
  400 ppt → 19±4 ppt
  dominant bgd in 2011, now negligible



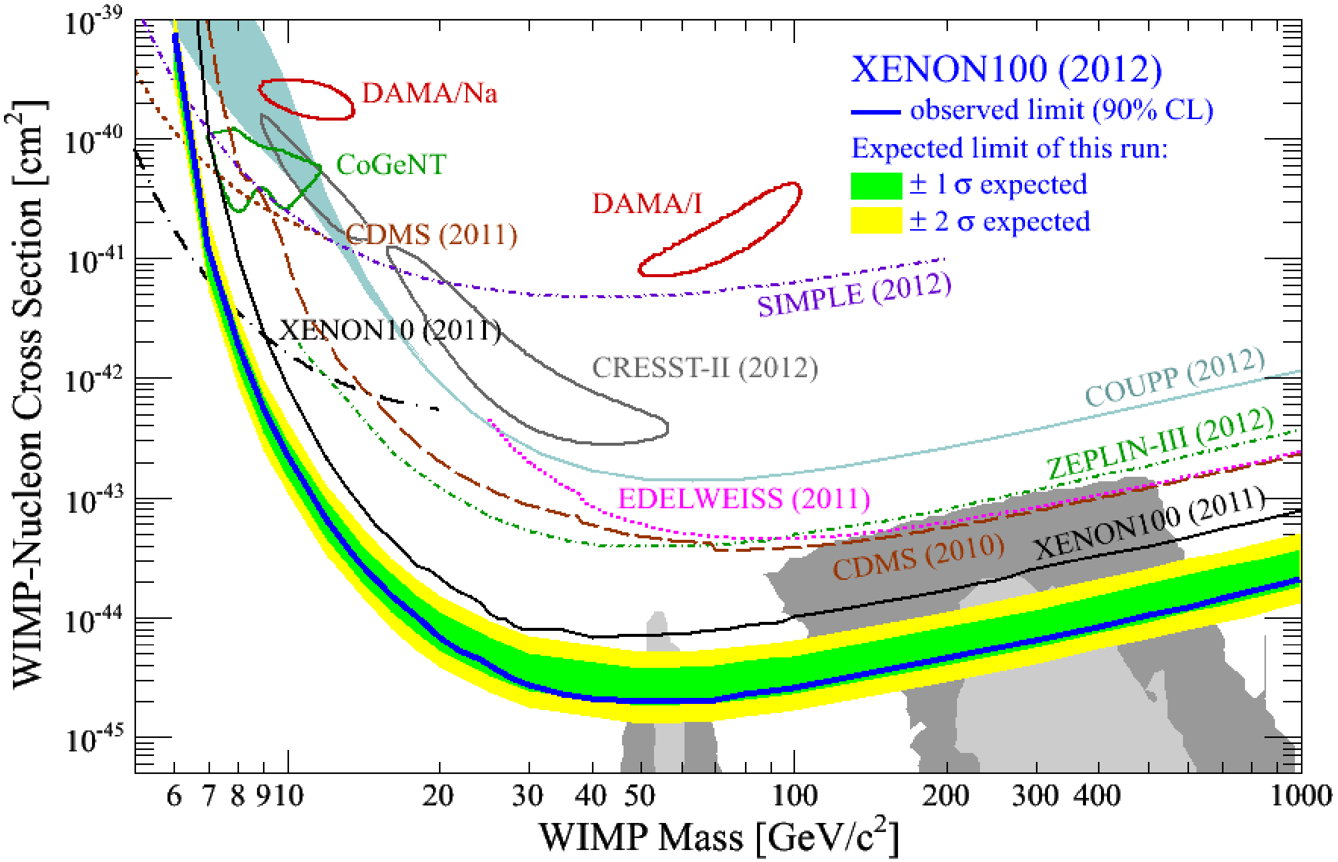
XENON100 – 2012 Result

arXiv:1207.5988
PRL 109, 181301 (2012)
2011 result: PRL 107, 131302

- 224.6 live days, fiducial mass 34 kg. → raw exposure: 7636 kg×d
- Energy window: 3 – 30 PE S1 / 6.6 – 43.3 keVnr
- Profile Likelihood limit based on side-bands from calibration. Blind analysis.
- Extremely low electromag. background: $(5.3\pm0.6)\times10^{-3}$ events/(keVee kg day) in DM region
- Best SI upper limit. $\sigma_{SI} = 2.0\times10^{-45}$ cm^2 @ 55 GeV/c^2 (90% CL)
- SUSY (CMSSM) parameter space further constrained in updated models incl. LHC limits.
- Strong tension with low mass WIMP interpretation for DAMA, CoGeNT, CRESST

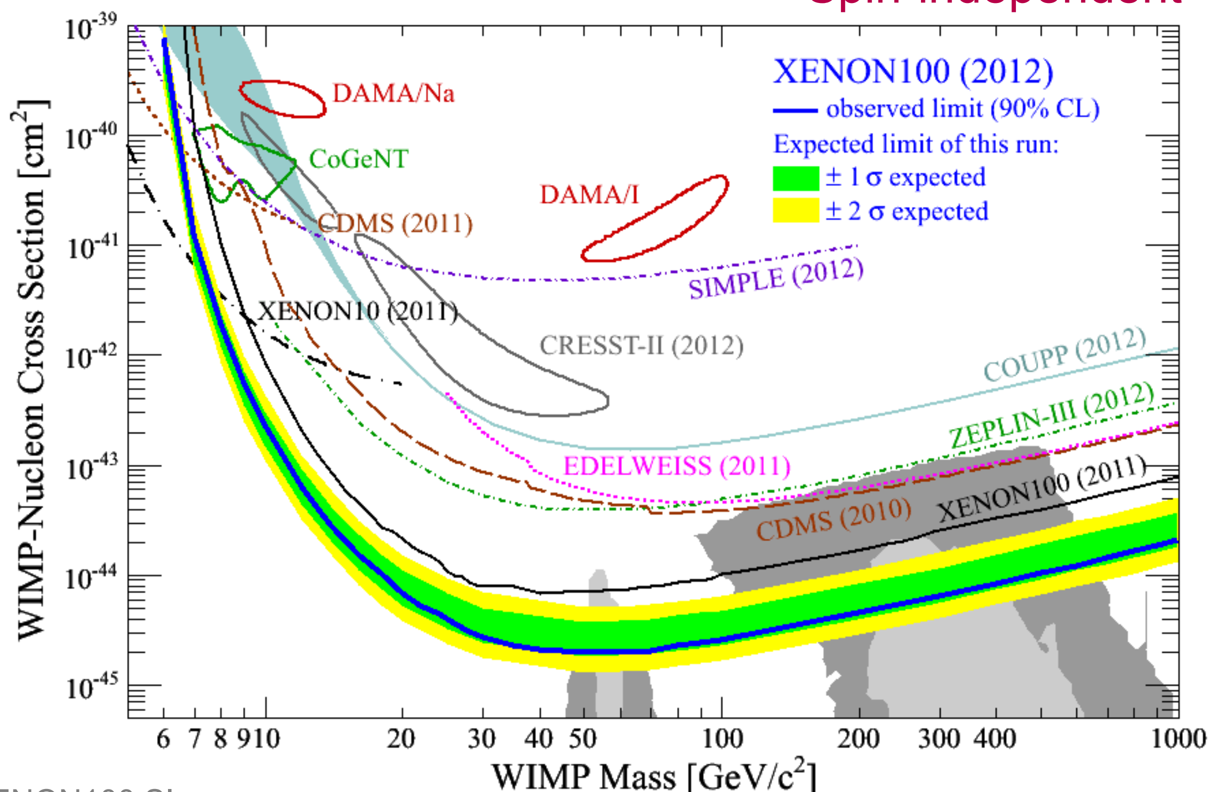
Comparison with cuts-based analysis: 3-20 PE

- Observed after all cuts: 2 events.
  Expected background: (1.0 ± 0.2) events.
- Weighted effective exposure for 100 GeV WIMP:

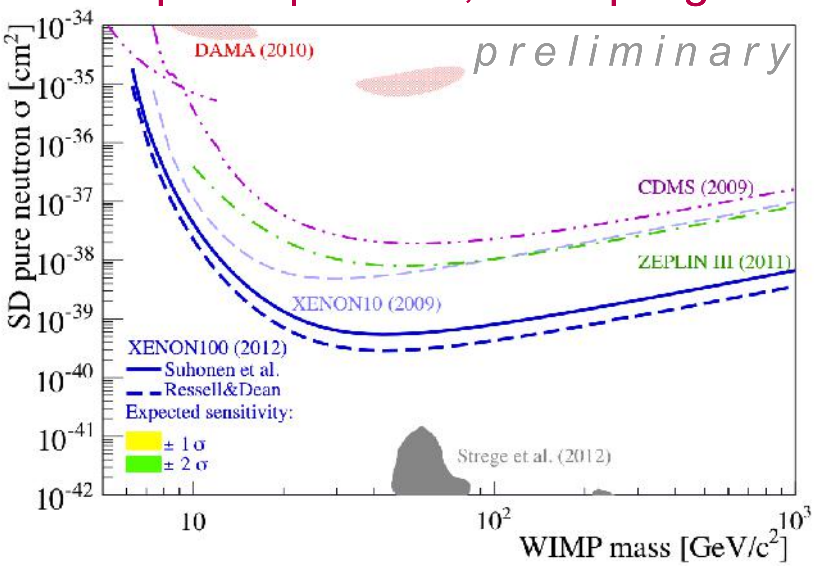


Status in WIMP DM Sensitivities (2012)

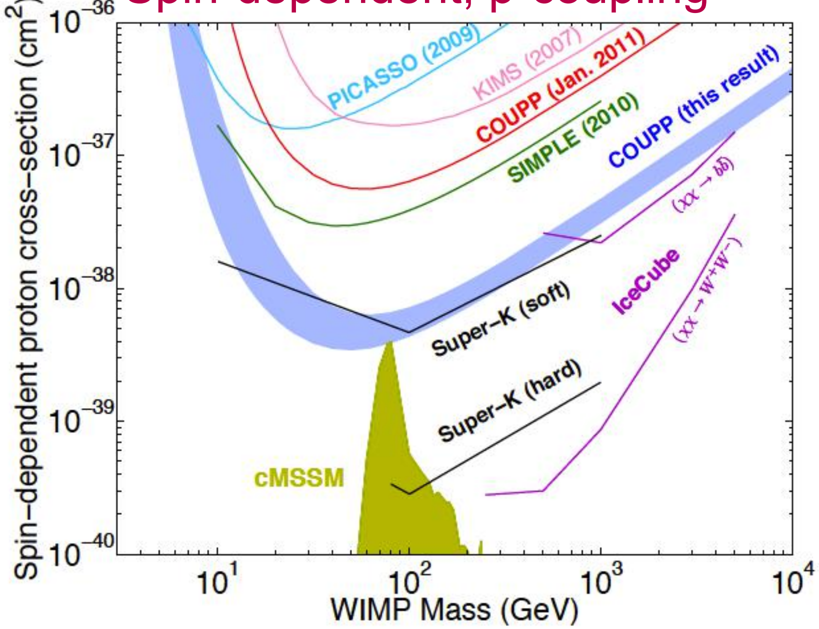
Spin-independent



Spin-dependent, n-coupling



Spin-dependent, p-coupling



XENON100 SI,
2010 PRL 105, 131302
2011 PRL 107, 131302
2012 PRL 109, 181301

CDMS-II SI, 2010
Science 327, 1619

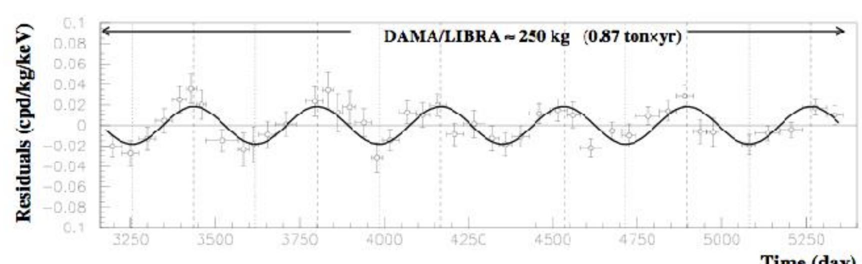
EDELWEISS-II SI, 2011
Phys. Lett. B 702, 329

CoGeNT SI,
PRL 106 (2011) 131301
2011b: arxiv:1106.0650

COUPP SD:
2012: arXiv:1204.3094

PICASSO SD, 2012
arxiv:1202.1240

Annual modulation – DM?



DAMA/LIBRA, 2010 arxiv:1002.1028

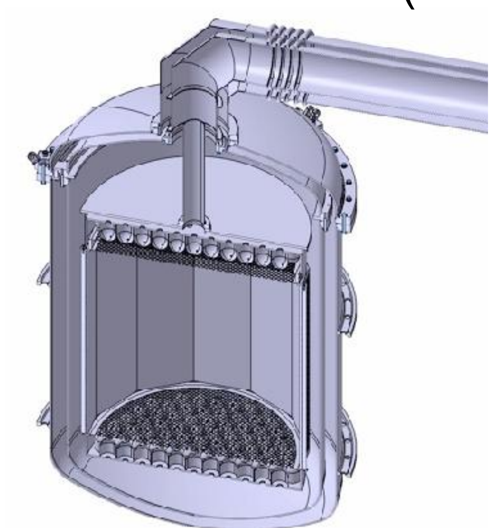
Outline

- Dark Matter: Evidence, Models, and the Magnificent WIMP
- Direct Detection Technique
- Status of DM Direct Detection
- XENON Dark Matter Search
- Future

Future Developments

Noble Liquids

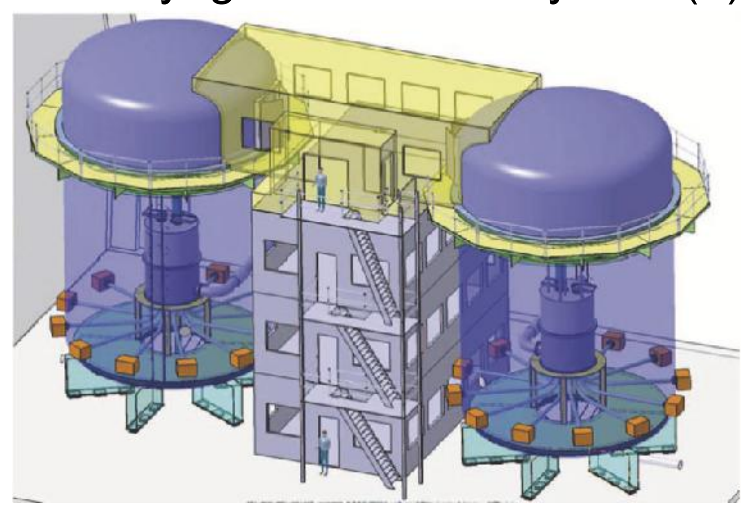
- **LXe:**
  XENON100 (taking data)
  XMASS (scintillation only, construction completed)
  LUX (commissioning)
  XENON1T (start construction 2012)



- **LAr:**
  ArDM (commissioning underground)
  Mini-Clean (scint., under construction)
  DEAP-3600 (under construction)
  DarkSide-50 (under construction)
- **LXe & LAr Generation 3**: DARWIN (R&D)

Cryogenic Germanium

- USA:
  Super-CDMS (under construction)
  GeoDM (R&D)
- Europe:
  Edelweiss-3 (under construction)
  EURECA (R&D)
  cryogenic Ge and crystals (?)

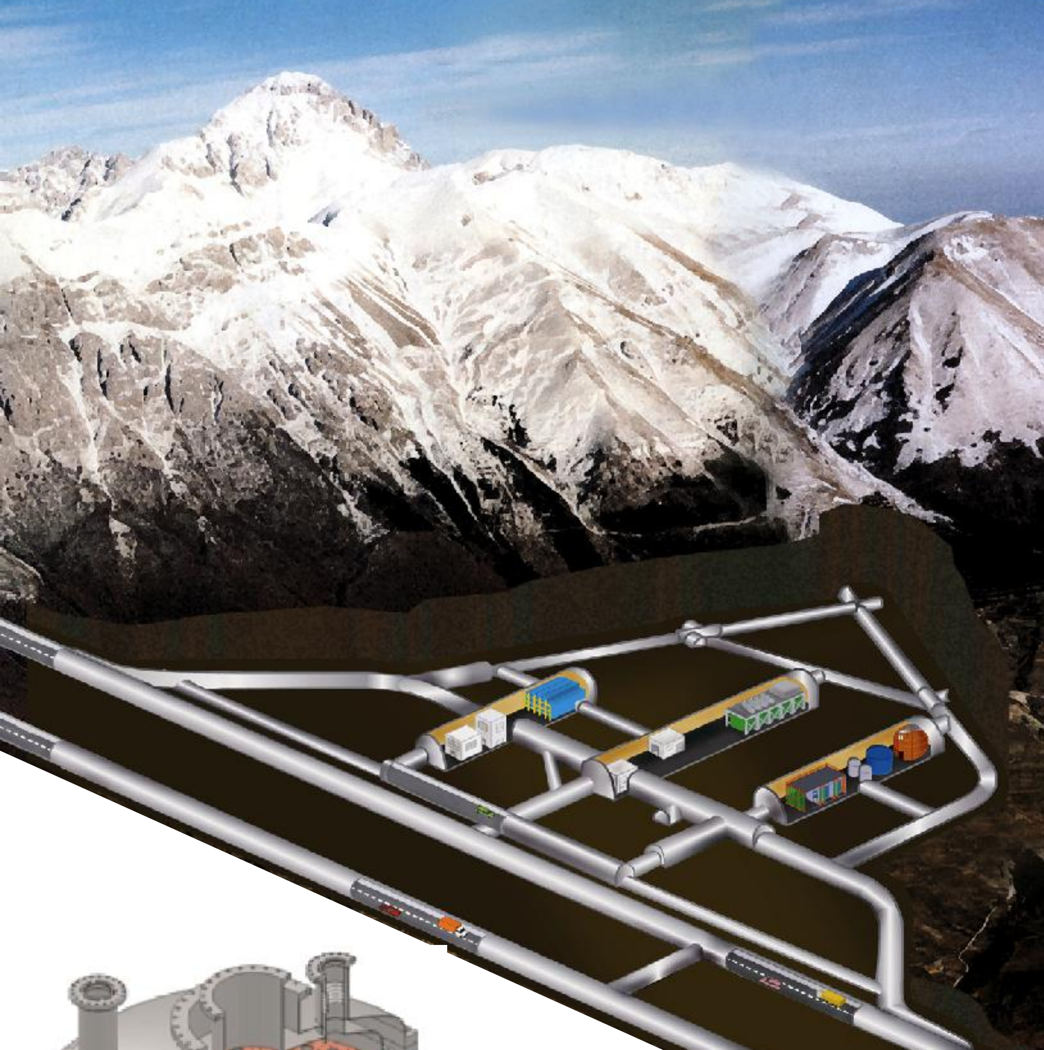


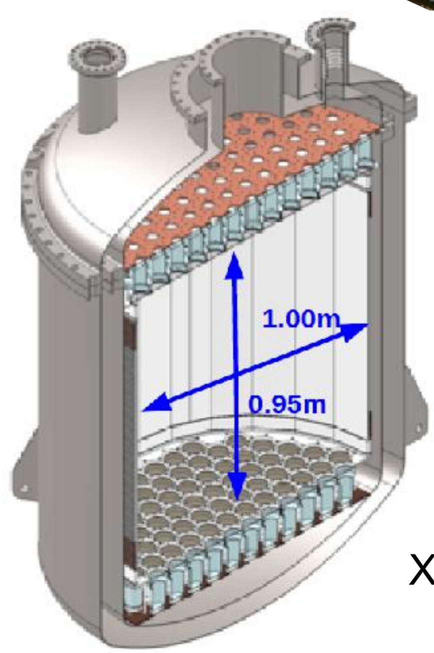
Superheated liquids

COUPP (60 kg under construction)
PICASSO

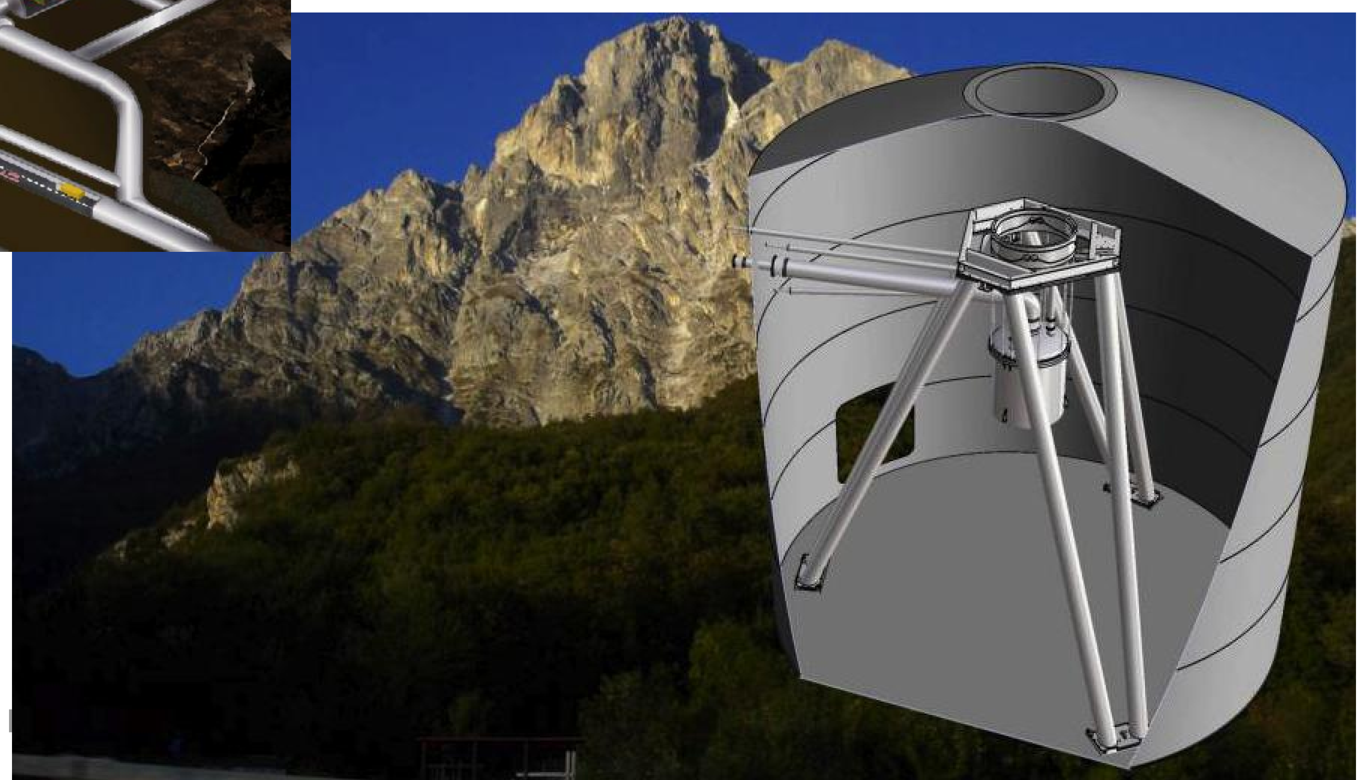
XENON1T (2011-2015)

- Liquid xenon TPC to explore σ ~ 2×10^{-47} cm^2
- Detector size:
  1 m^3, 3 t LXe, 1 t fiducial mass
  300 PMTs (3”)
- Water Cherenkov Muon Veto
- Hall B @ LNGS, Italy, approved by INFN
- Funded
- Construction start: fall 2012 very soon!
- First Dark Matter results expected in 2015



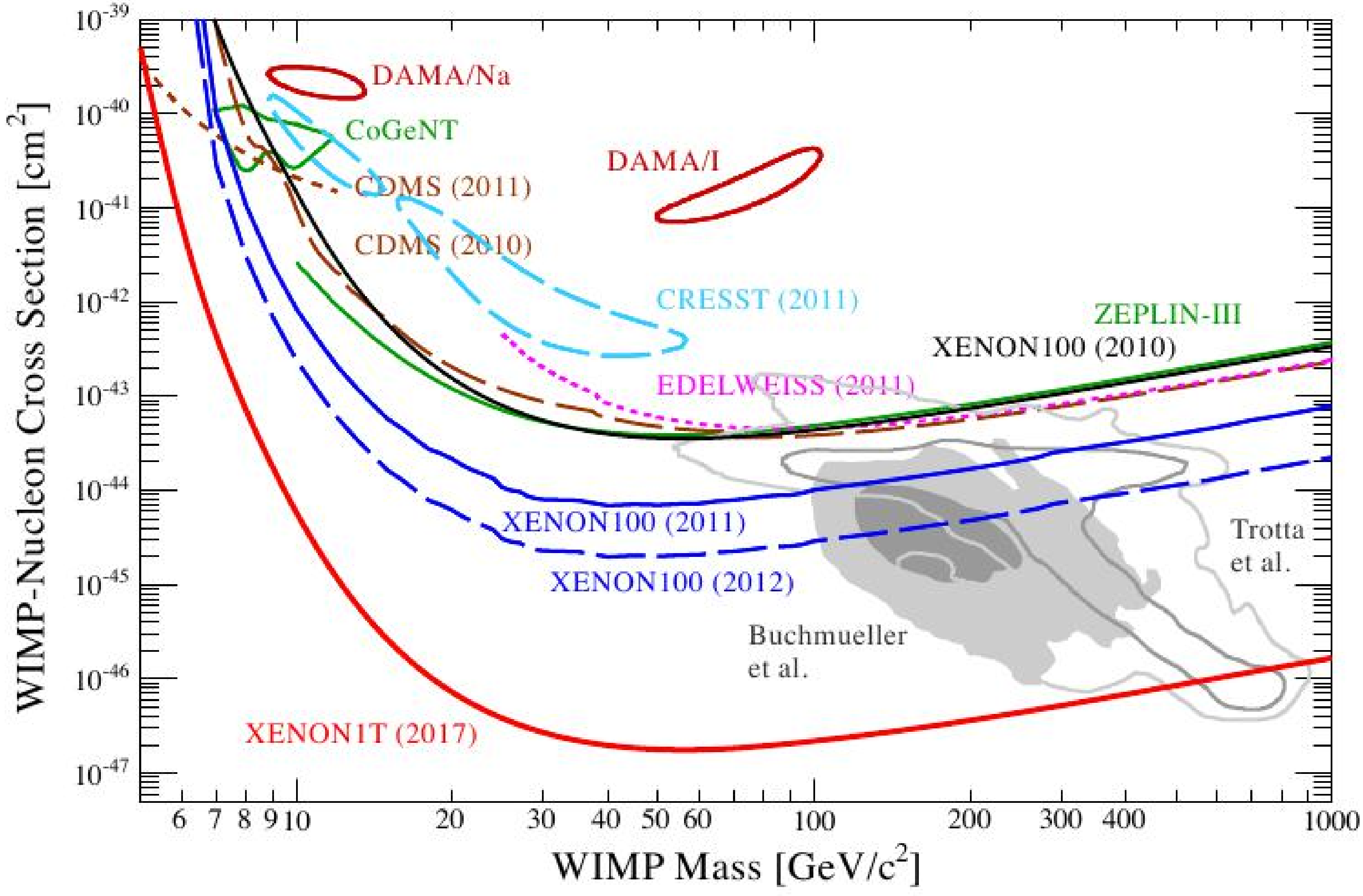


XENON1T TPC



The Future of Direct Dark Matter Searches
(next ~5 years)

Spin-independent sensitivity



DARWIN

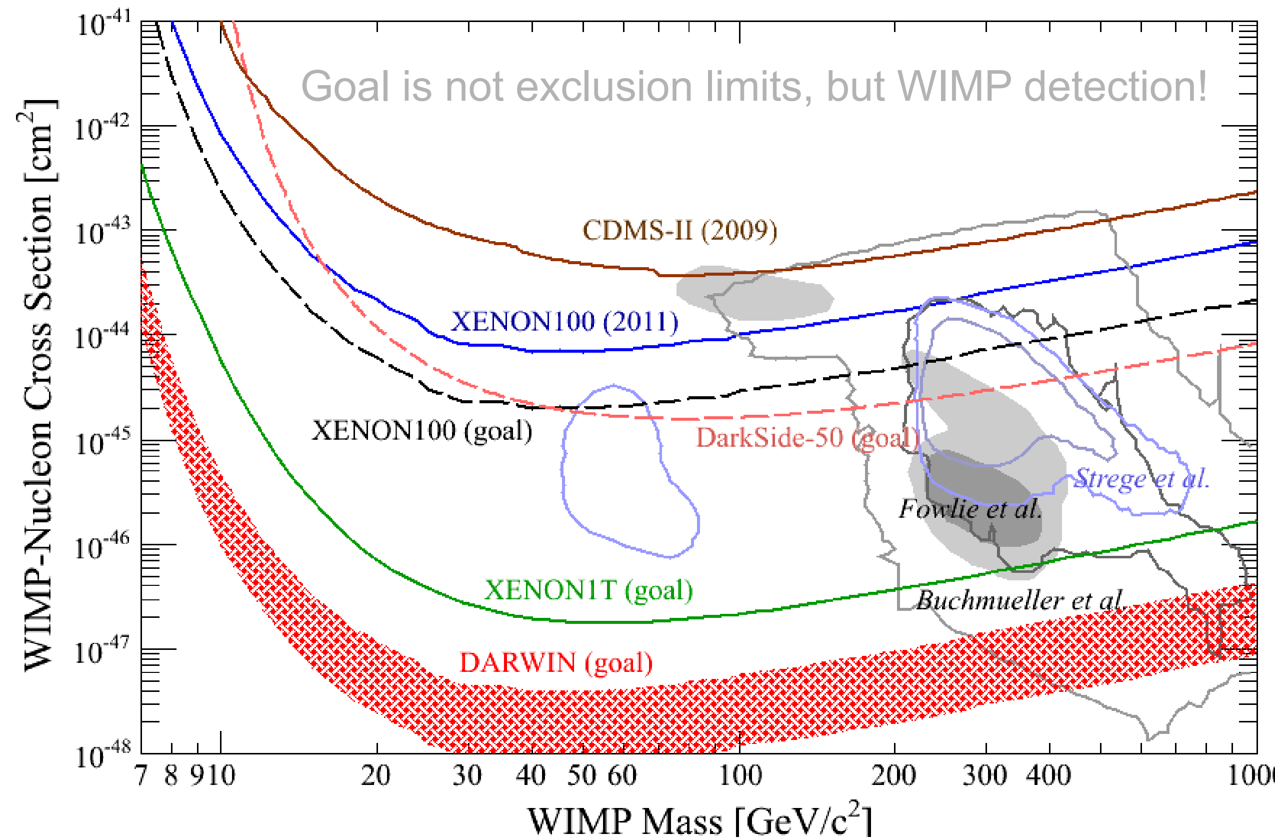
Dark Matter WIMP Search with Noble Liquids

R&D and design study for an “ultimate” noble liquid Dark Matter facility in Europe

Goal:
Measurement of DM properties with sensitivity of ~10^{-48} cm^2
- limited by solar neutrinos

→ Measurement of p-p neutrinos with % precision
(factor 200 NR/ER suppression)

Requirements:
^{85}Kr (^{nat}Kr < 0.1 ppt)
^{222}Rn < 0.1 µBq/kg



25 groups from ArDM, DarkSide, WARP, XENON

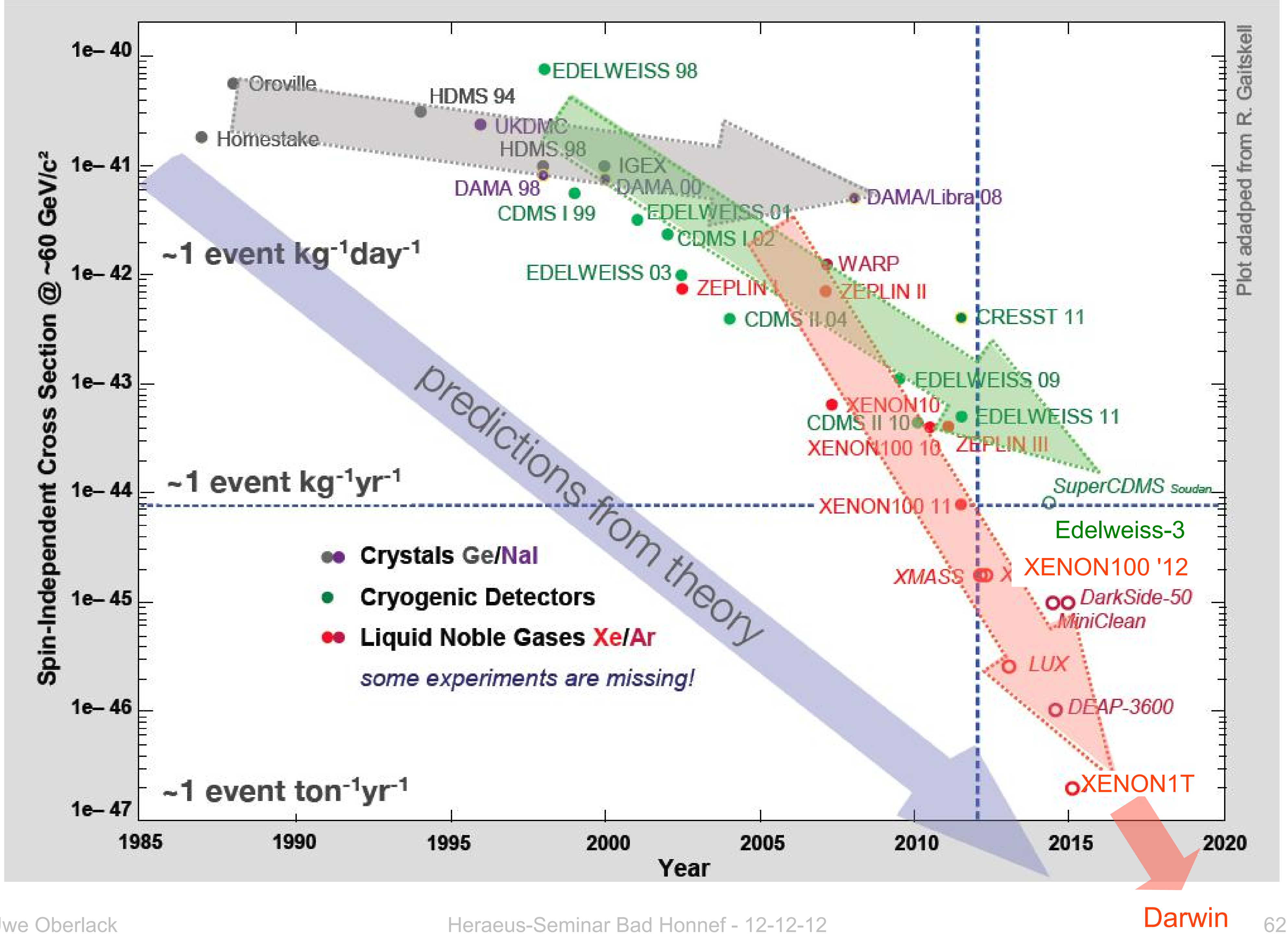
Europe: UZH, INFN, ETHZ, Subatech, Nikhef

Germany: Dresden, KIT, Mainz, MPIK, Münster

Israel: WIS USA: Columbia, Princeton, UCLA, Arizona SU

darwin.physik.uzh.ch

Outlook



Spin-Independent Cross Section @ ~60 GeV/c²
1e−40
1e−41
1e−42
1e−43
1e−44
1e−45
1e−46
1e−47
1985
1990
1995
2000
2005
2010
2015
2020
Year
Plot adadped from R. Gaitskell
~1 event kg⁻¹day⁻¹
~1 event kg⁻¹yr⁻¹
~1 event ton⁻¹yr⁻¹
predictions from theory
Oroville
Homestake
HDMS 94
UKDMC
HDMS 98
EDELWEISS 98
DAMA 98
CDMS I 99
IGEX
DAMA 00
EDELWEISS 01
CDMS I 02
EDELWEISS 03
ZEPLIN I
CDMS II 04
DAMA/Libra 08
WARP
ZEPLIN II
CRESST 11
EDELWEISS 09
XENON10
CDMS II 10
XENON100 10
ZEPLIN III
EDELWEISS 11
SuperCDMS Soudan
XENON100 11
Edelweiss-3
XMASS
XENON100 '12
DarkSide-50
MiniClean
LUX
DEAP-3600
XENON1T
Crystals Ge/NaI
Cryogenic Detectors
Liquid Noble Gases Xe/Ar
some experiments are missing!
Darwin

Summary

- **Rapid progress in Dark Matter direct searches:**
  - Sensitivity advanced by 3 orders of magnitude in the last decade, increasing pace.
  - Noble liquid detectors now setting the pace in sensitivity.
- **Confusing results in direct searches in the last couple of years**:
  - CoGeNT, CRESST excess events & DAMA/LIBRA annual modulation: Low mass WIMPs? Or poorly understood backgrounds?
- **XENON100: world-leading sensitivity.**
  - Upper limit on (spin-independent) WIMP-nucleon cross-section $\sigma_s = 2.0\times10^{-45}$ cm^2 @ 50 GeV/c^2 (90% CL)
  - 2012: Factor 3.5 improvement over previous XENON100 limit, factor 20 over other experiments.
  - XENON100 (& others) in conflict with the low mass WIMP interpretation.
  - Inelastic DM (nearly) ruled out as explanation for annual modulation in DAMA/LIBRA.
  - New SD limit (world-best for pure neutron coupling)
- **The future looks exciting:**
  - New experiments in direct searches on the horizon. XENON1T starting construction. Pushing another 2 orders of magnitude in sensitivity.
  - Rapid progress at the LHC: Limits on new physics improving fast. No hint for SUSY yet. CMSSM feeling the heat.
  - New results in indirect searches: hints and limits. Fundamental problems of background subtraction remain.
  - *If DM consists of WIMPs we will likely find hints of them within the next 5 years.*

Thank you for your attention!