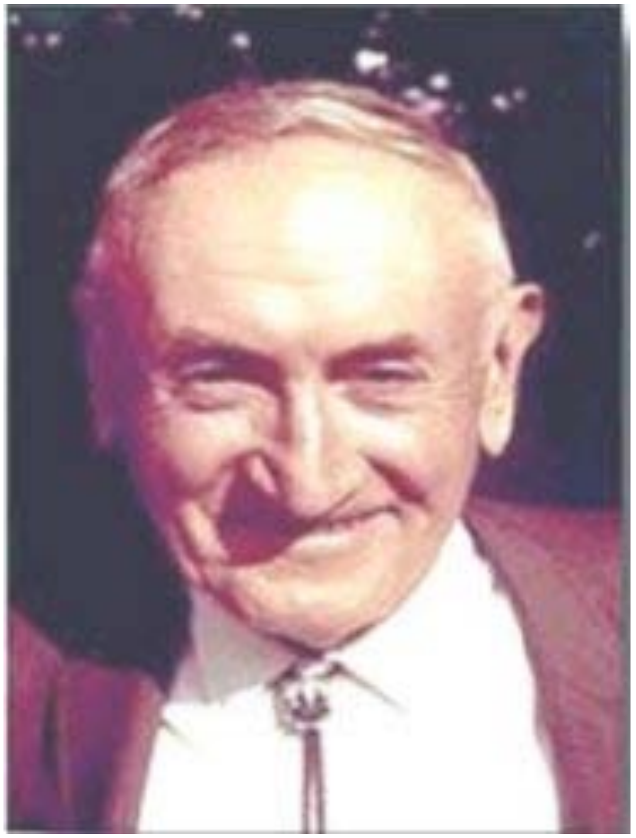
Shedding Light on Dark Matter from Deep Underground with XENON

Kaixuan Ni (Columbia)

University of Maryland, 11-25-2008

A well-known mystery for astronomers



Fritz Zwicky, The Astrophysical Journal, 85 (1937) 217

the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about 8.5×10^7 suns. According to (36), the conversion factor γ from luminosity to mass for nebulae in the Coma cluster would be of the order

$$\gamma = 500 , \tag{37}$$

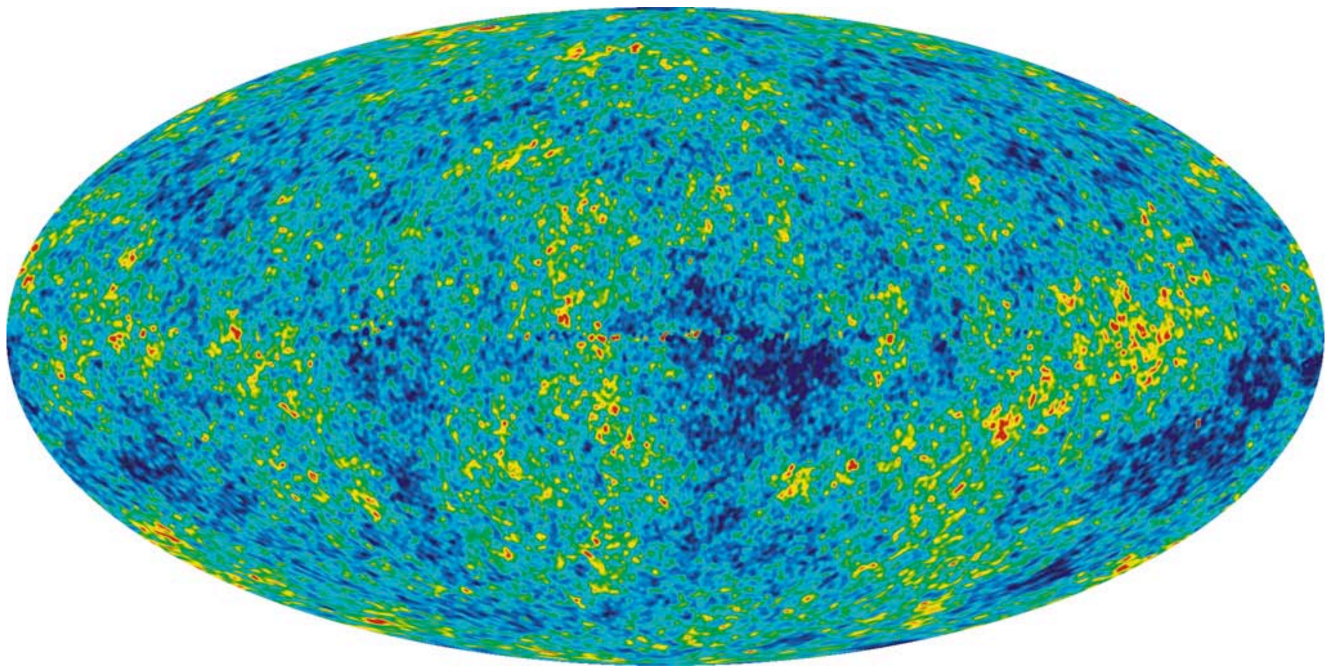
as compared with about $\gamma' = 3$ for the local Kapteyn stellar system. This discrepancy is so great that a further analysis of the problem is in order. Parts of the following discussion were published several

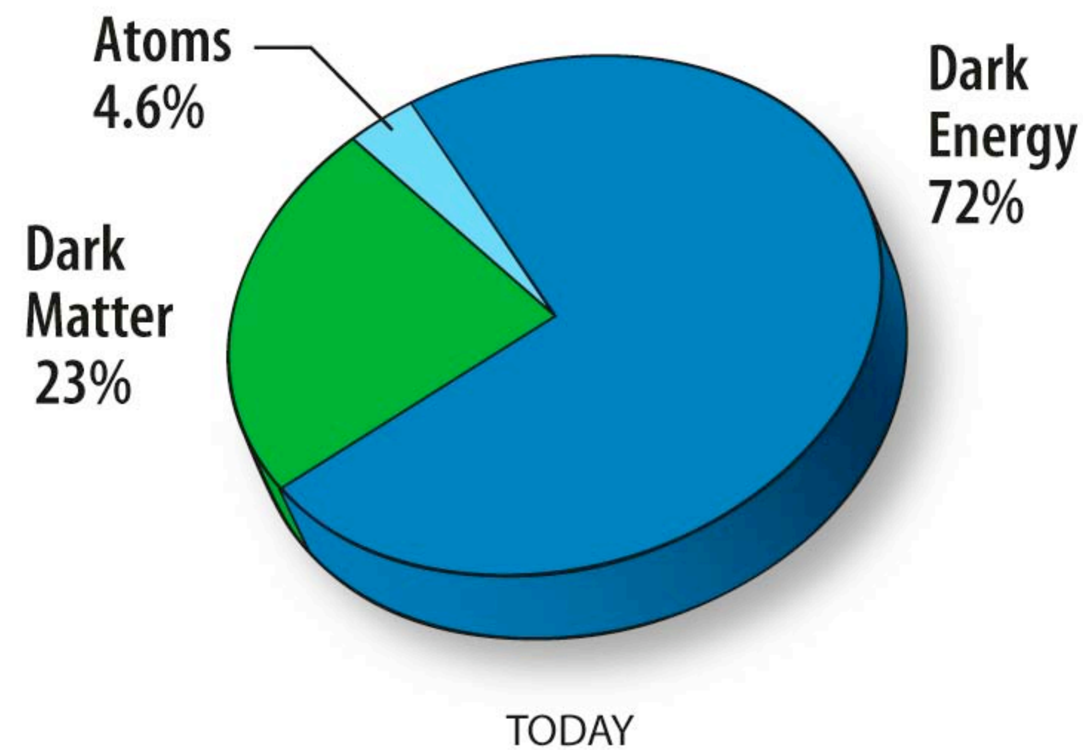
THE ASTROPHYSICAL JOURNAL, **238**:471–487, 1980 June 1

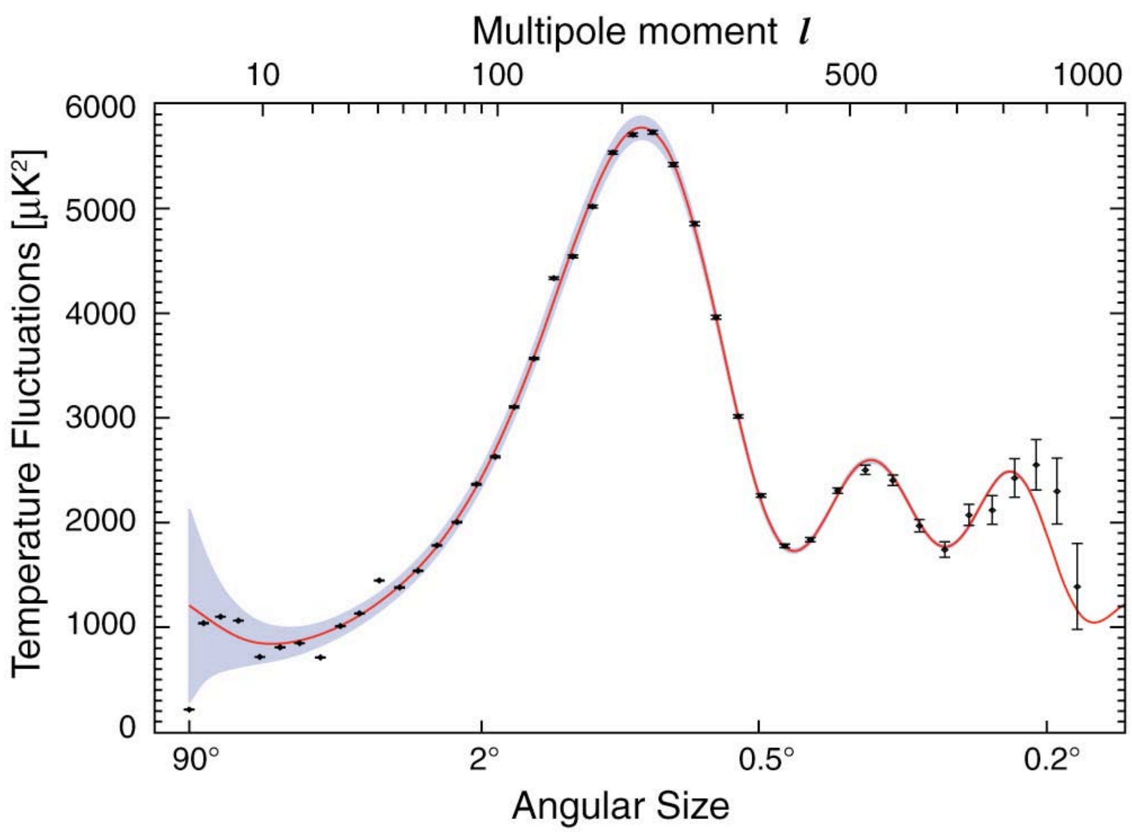
VERA C. RUBIN,[1,2] W. KENT FORD, JR.,[1] AND NORBERT THONNARD
Department of Terrestrial Magnetism, Carnegie Institution of Washington
Received 1979 October 11; accepted 1979 November 29

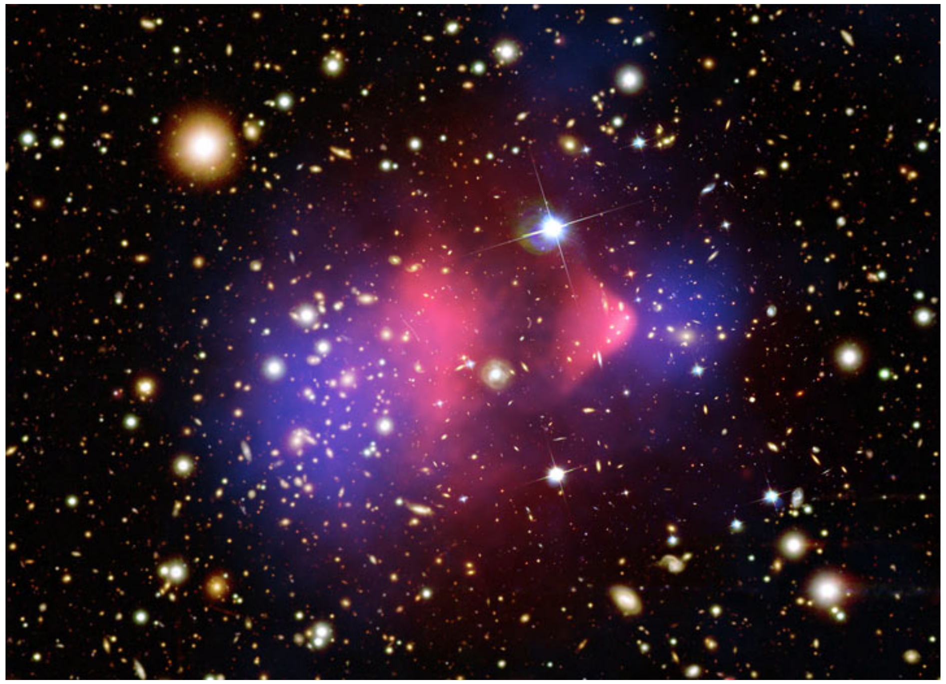
…All curves show a fairly rapid velocity rise to V ~ 125 km s^{-1} at R ~ 5 kpc, and a slower rise thereafter. Most rotation curves are rising slowly even at the farthest measured point. Neither high nor low luminosity Sc galaxies have falling rotation curves. Sc galaxies of all luminosities must have significant mass located beyond the optical image. …

Modern Precision Cosmology



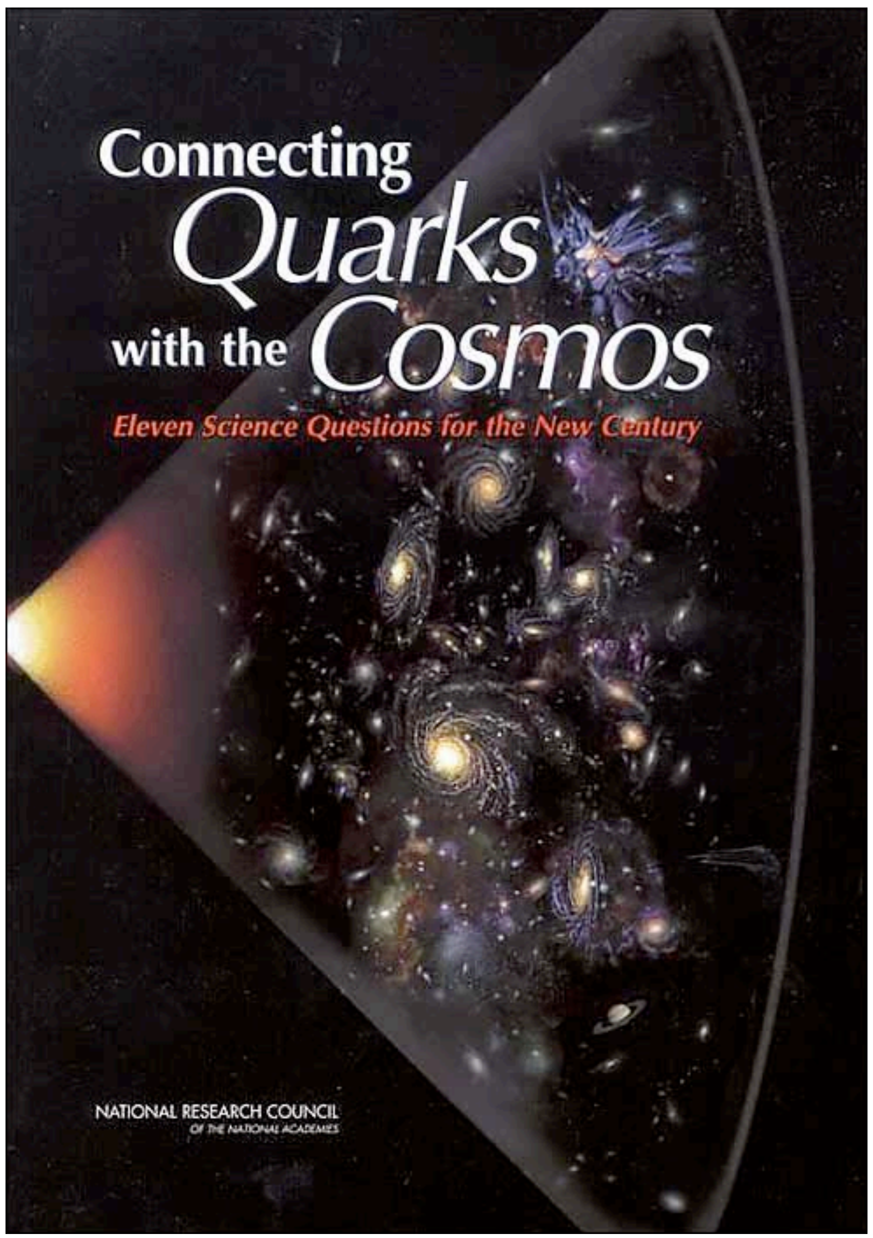






Question 1. What is Dark Matter?

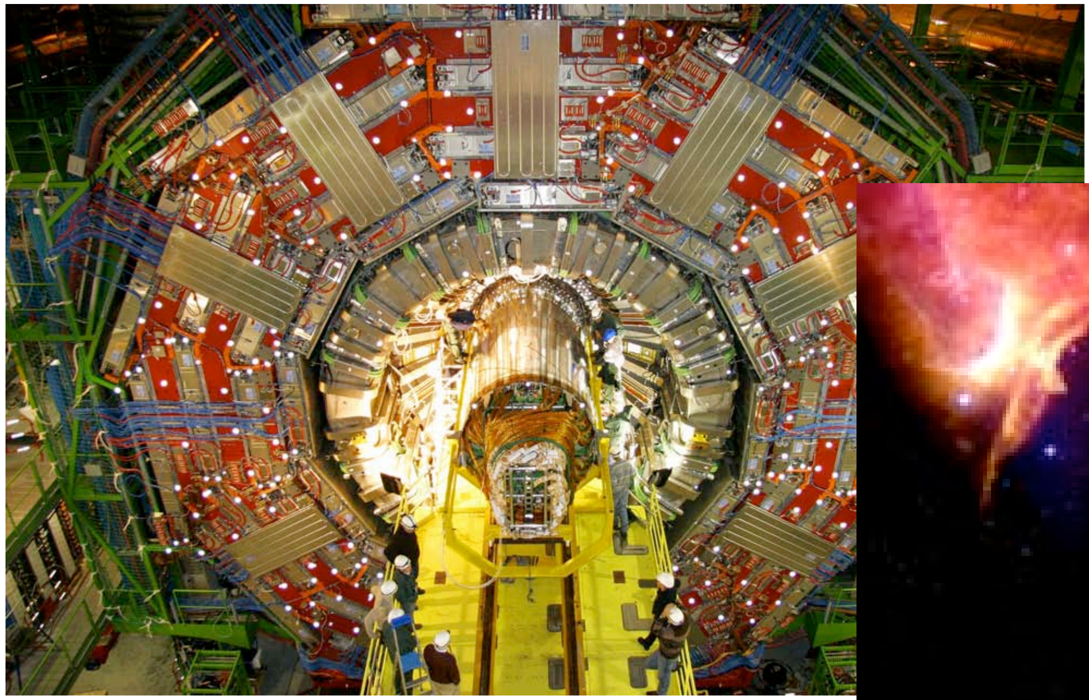
"Astronomers have shown that the objects in the universe from galaxies a million times smaller than ours to the largest clusters of galaxies are held together by a form of matter that is not what we are made of and that gives off no light. This matter probably consists of one or more as-yet-undiscovered elementary particles, and aggregations of it produce the gravitational pull leading to the formation of galaxies and large-scale structures in the universe. At the same time these particles may be streaming through our Earth-bound laboratories."



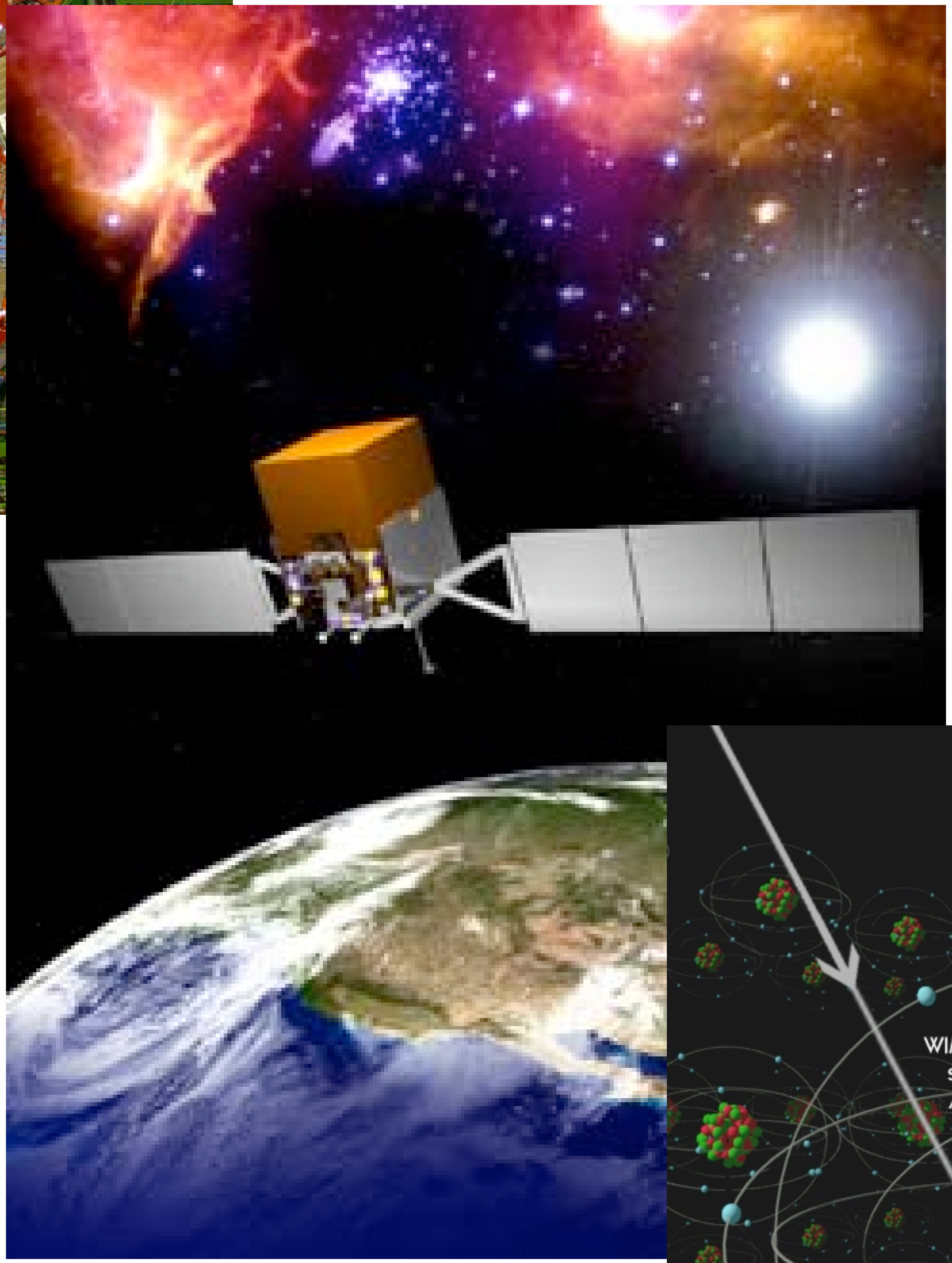
Dark Matter is a stable, neutral, and heavy particle that interacts very weakly, or only through gravity.

Leading DM candidates, such as neutralinos and axions, are from theories beyond the Standard Model!

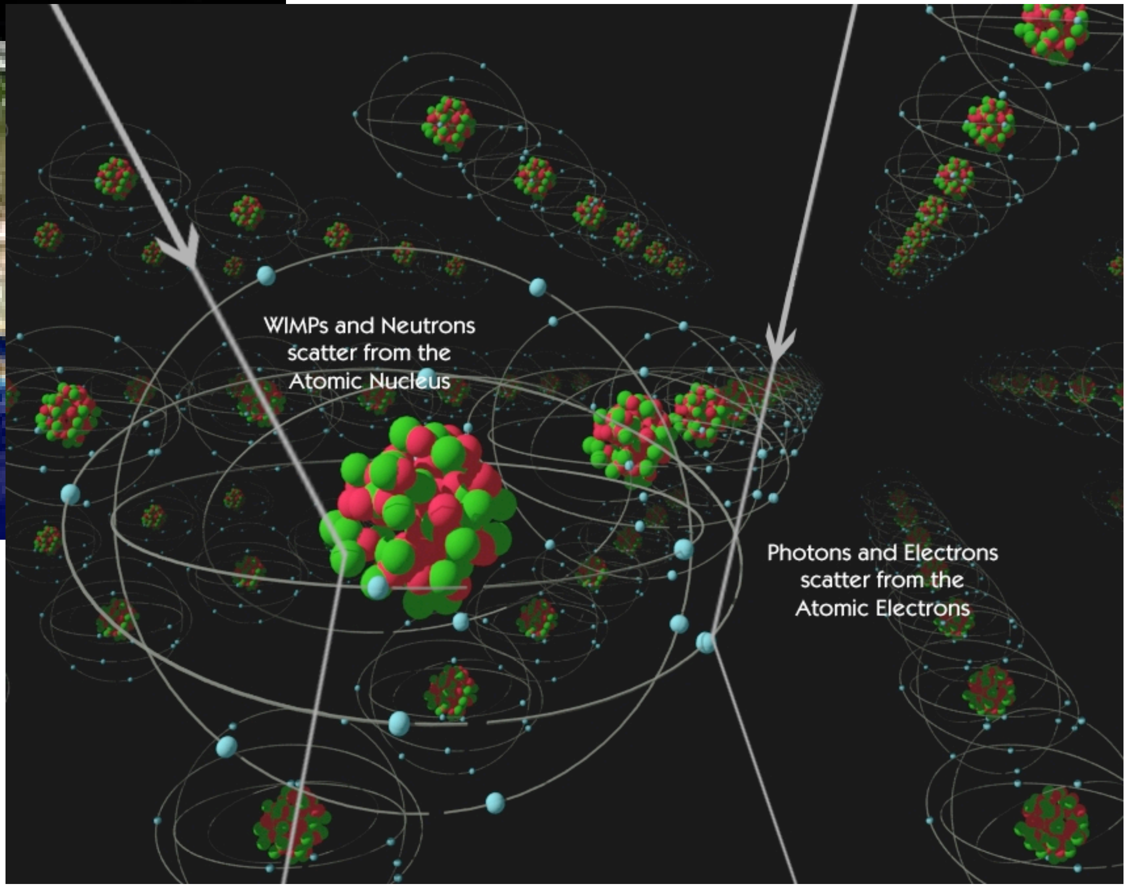
Three ways to probe the nature of dark matter



Indirectly search for DM annihilation products (gamma rays, neutrinos, electrons, positrons, etc.)



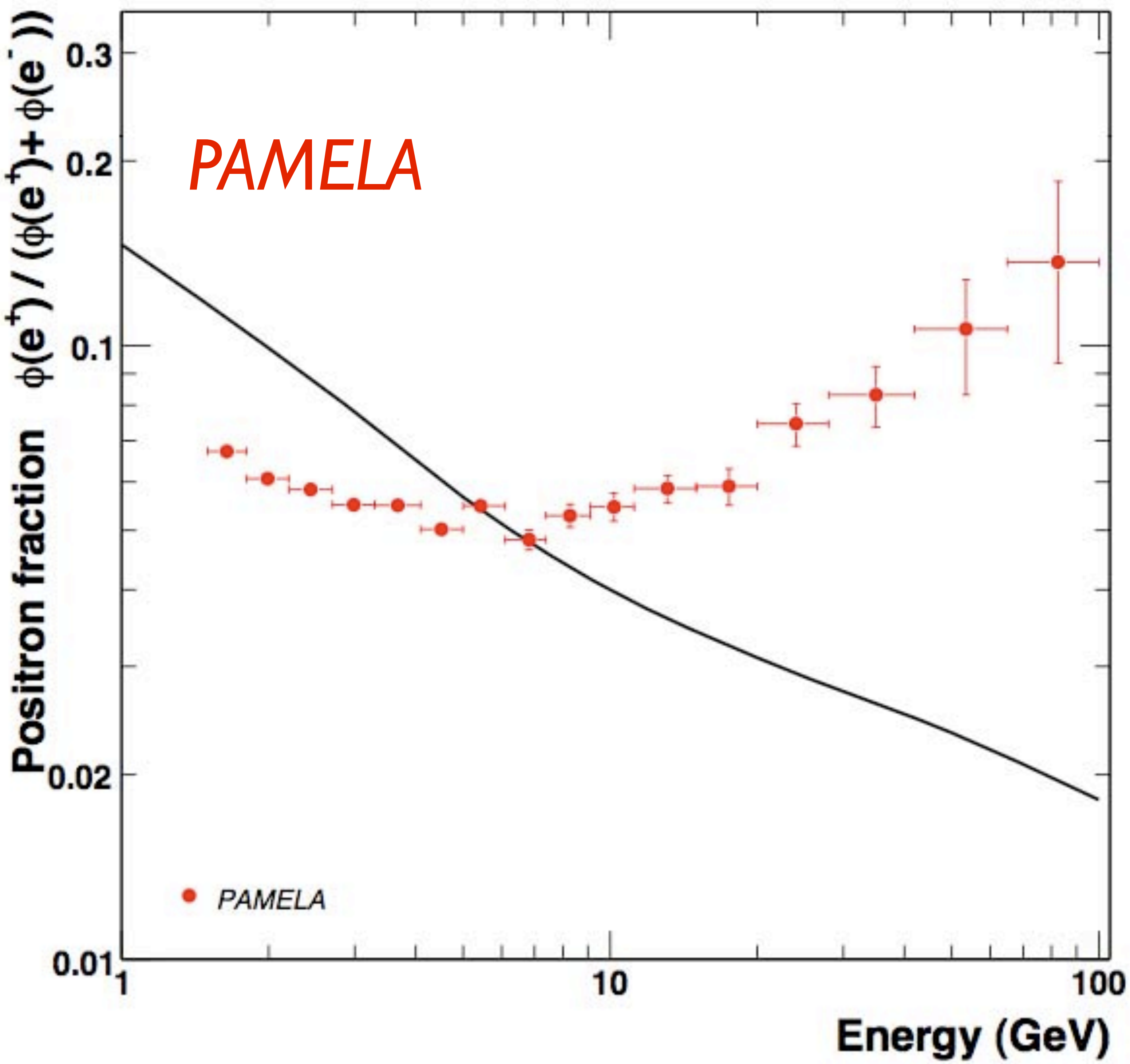
Produce dark matter in the Collider



Directly detect DM interacting with a terrestrial target

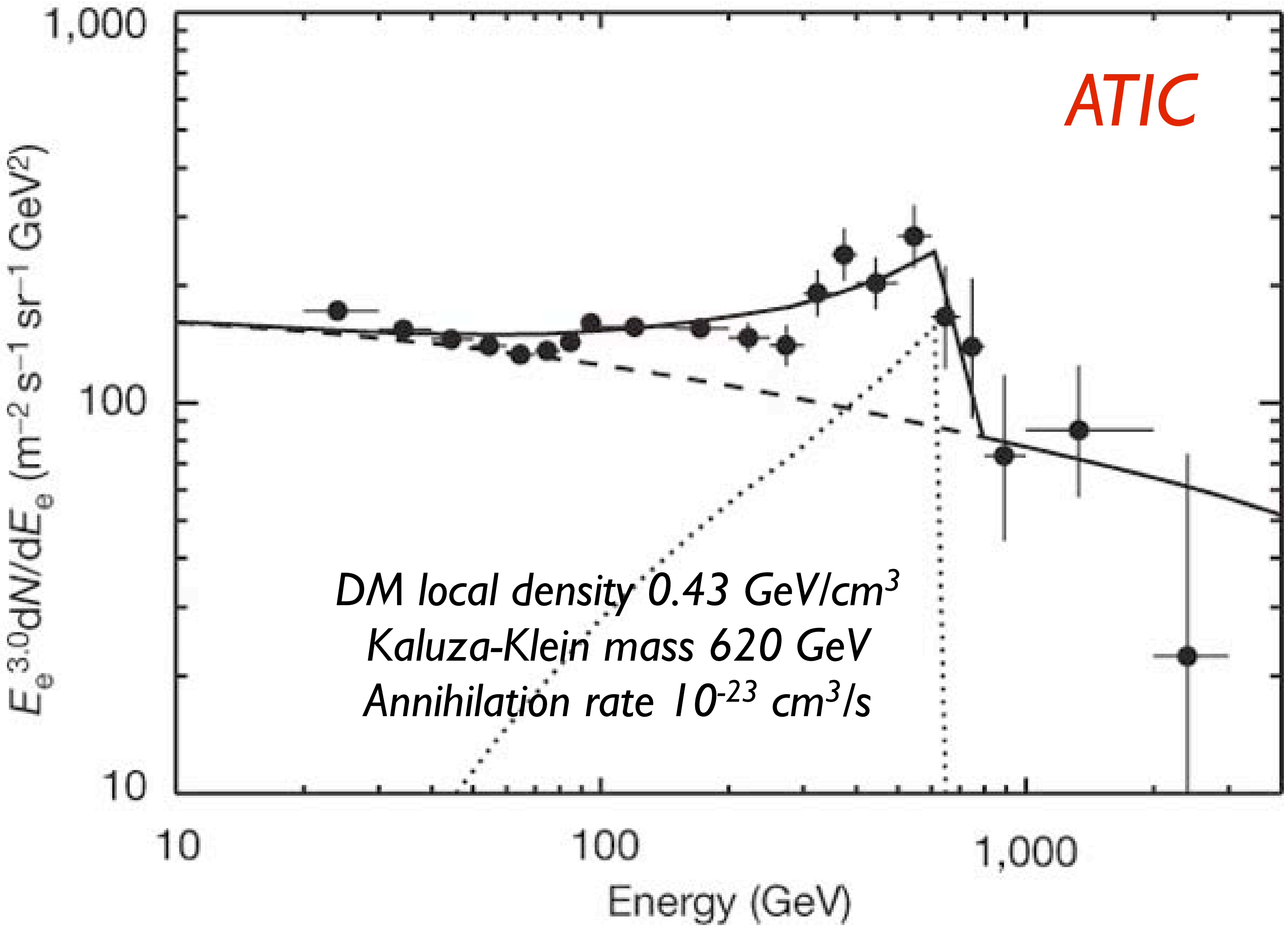
A fruitful year for indirect DM searches

Observation of an anomalous positron abundance in the cosmic radiation [arXiv:0810.4995]



A fruitful year for indirect DM searches

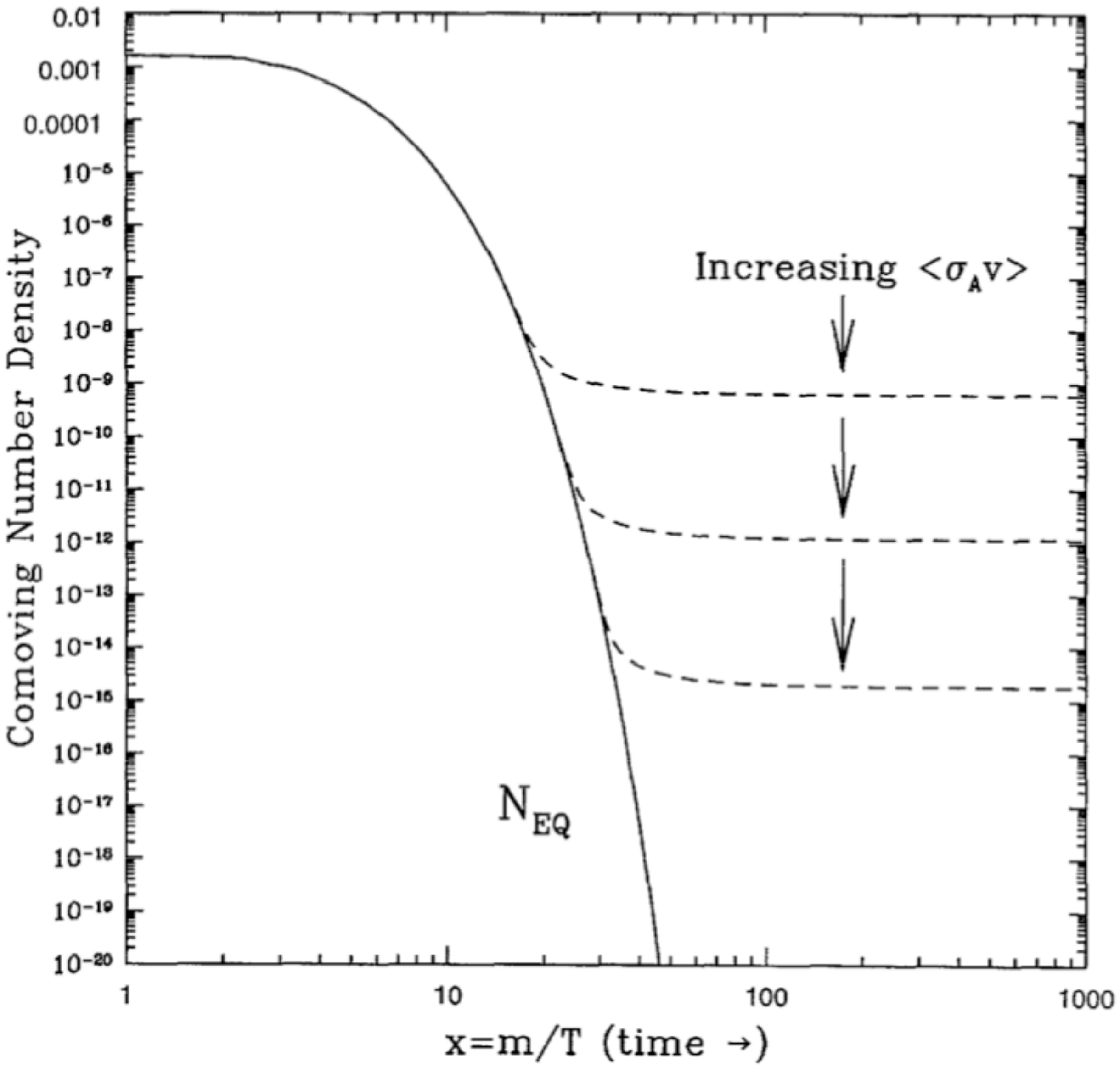
An excess of cosmic electrons.



J Chang *et al.* *Nature* **456**, 362-365 (2008) doi:10.1038/nature07477

Dark Matter Equation of State

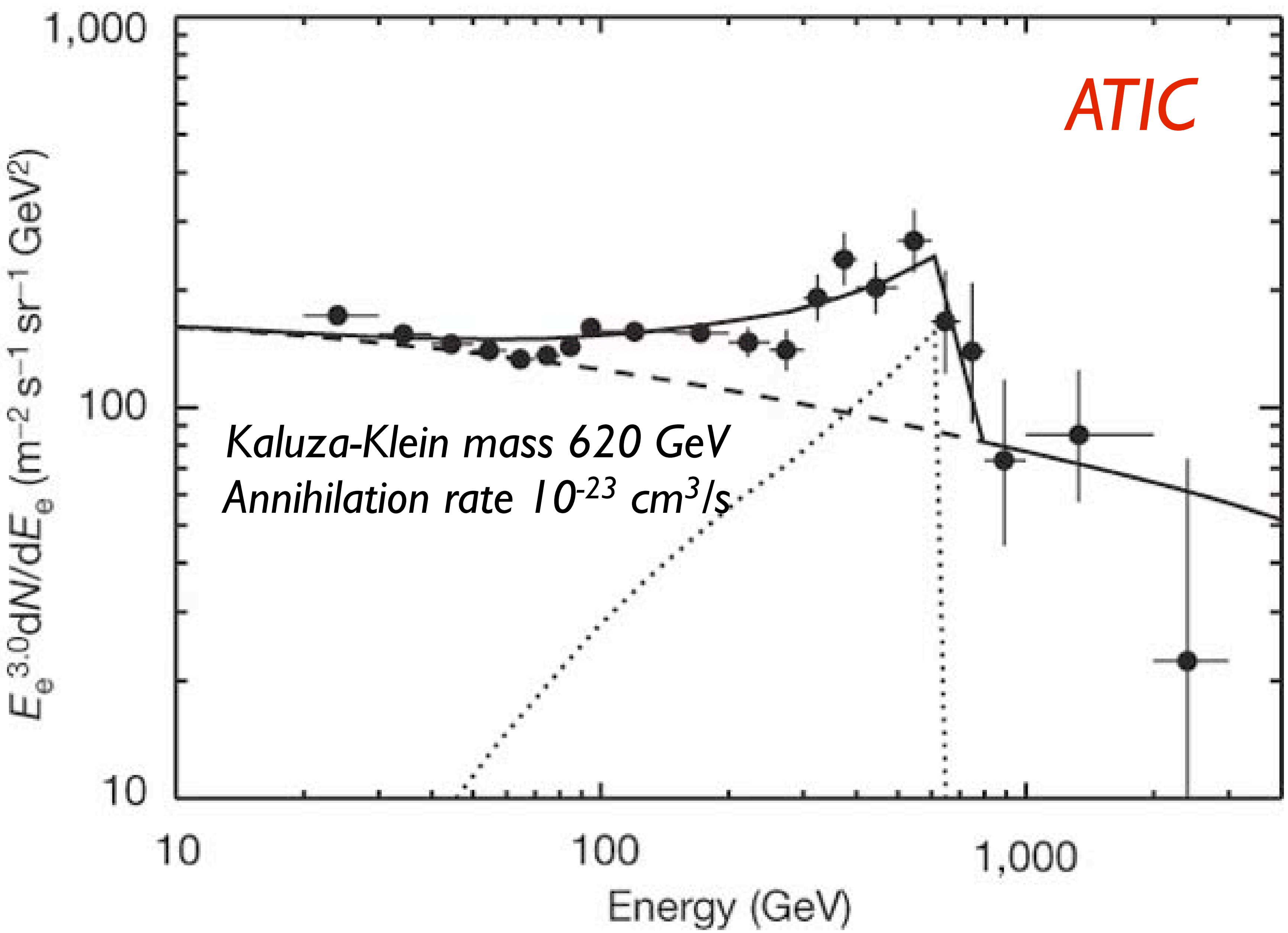
$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_{\rm A} v\rangle\left[(n_\chi)^2 - \left(n_\chi^{\rm eq}\right)^2\right]$$



$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} = \frac{3\times 10^{-27}\ {\rm cm}^3/{\rm s}}{\langle\sigma_{\rm A} v\rangle_{\rm freezout}}$$

$$\langle\sigma_{\rm A} v\rangle_{\rm freezout} = 3\times 10^{-26}\ {\rm cm}^3/{\rm s}$$

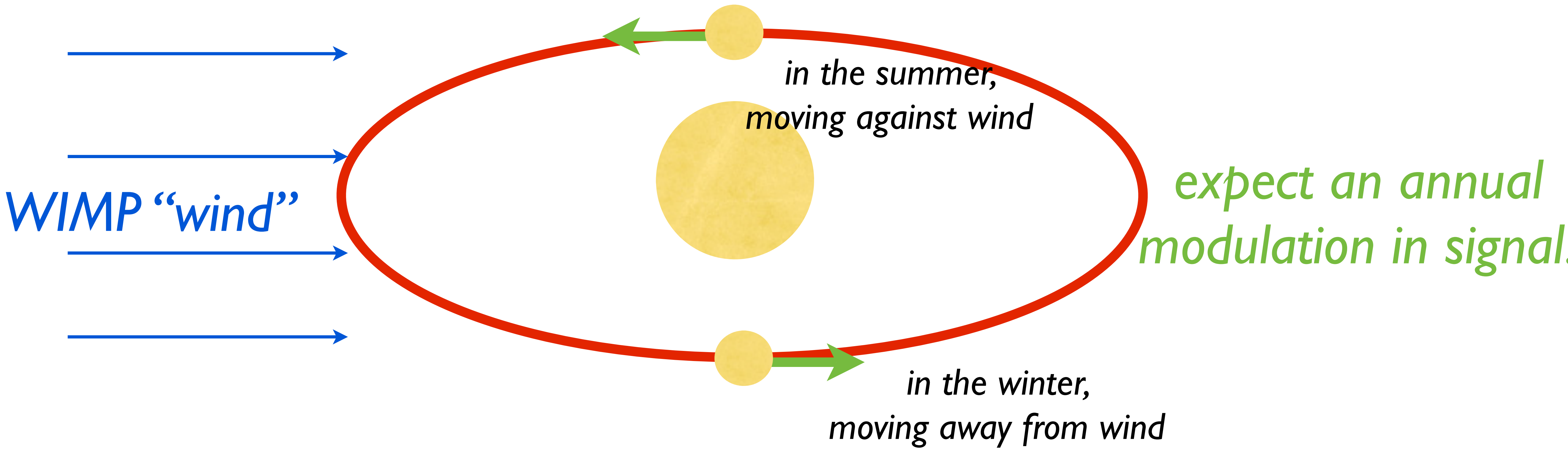
A fruitful year for indirect DM searches



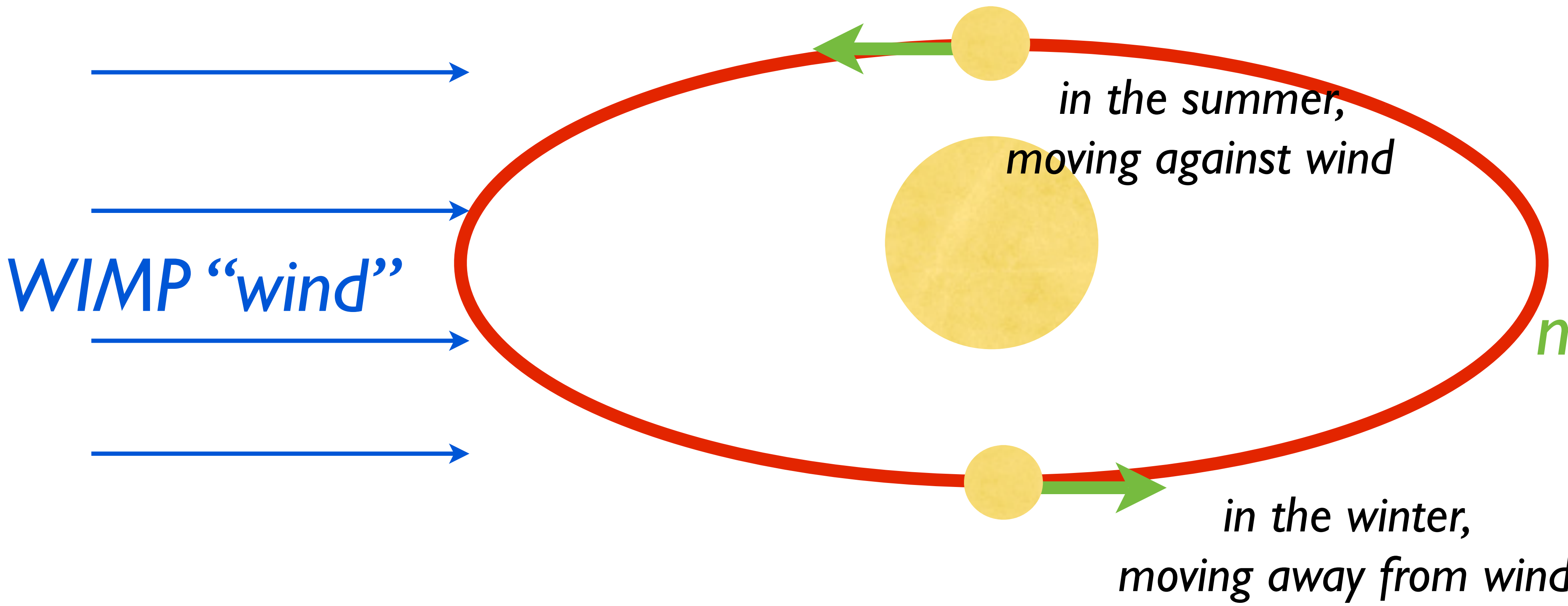
J Chang *et al. Nature* **456**, 362-365 (2008) doi:10.1038/nature07477

A boost factor of ~200 is required

Also a busy year for direct DM searches

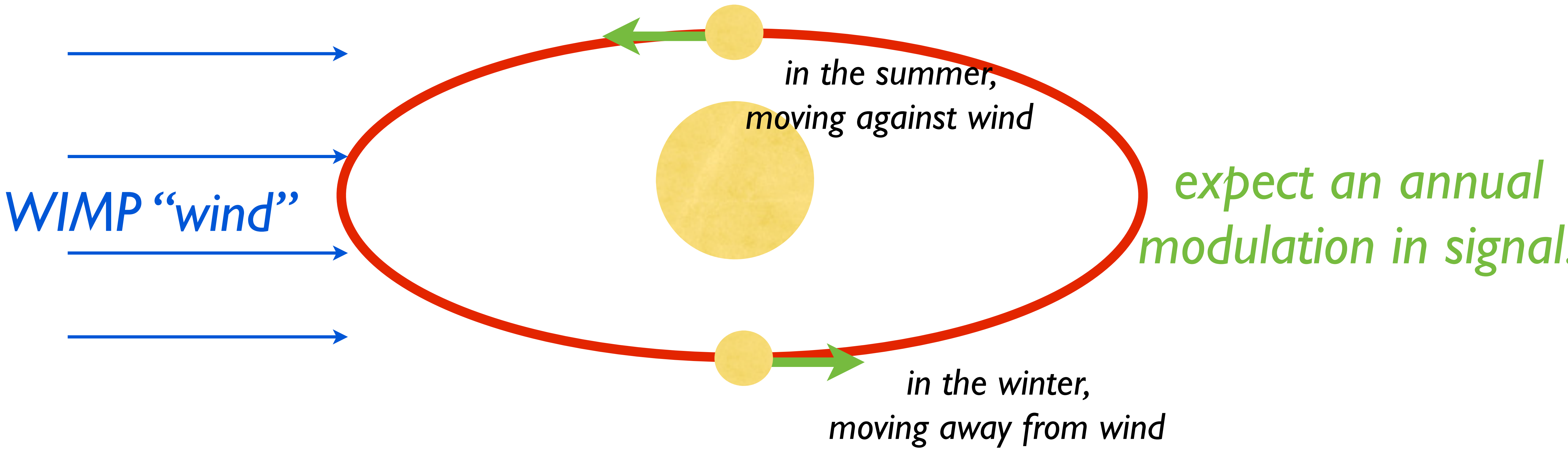


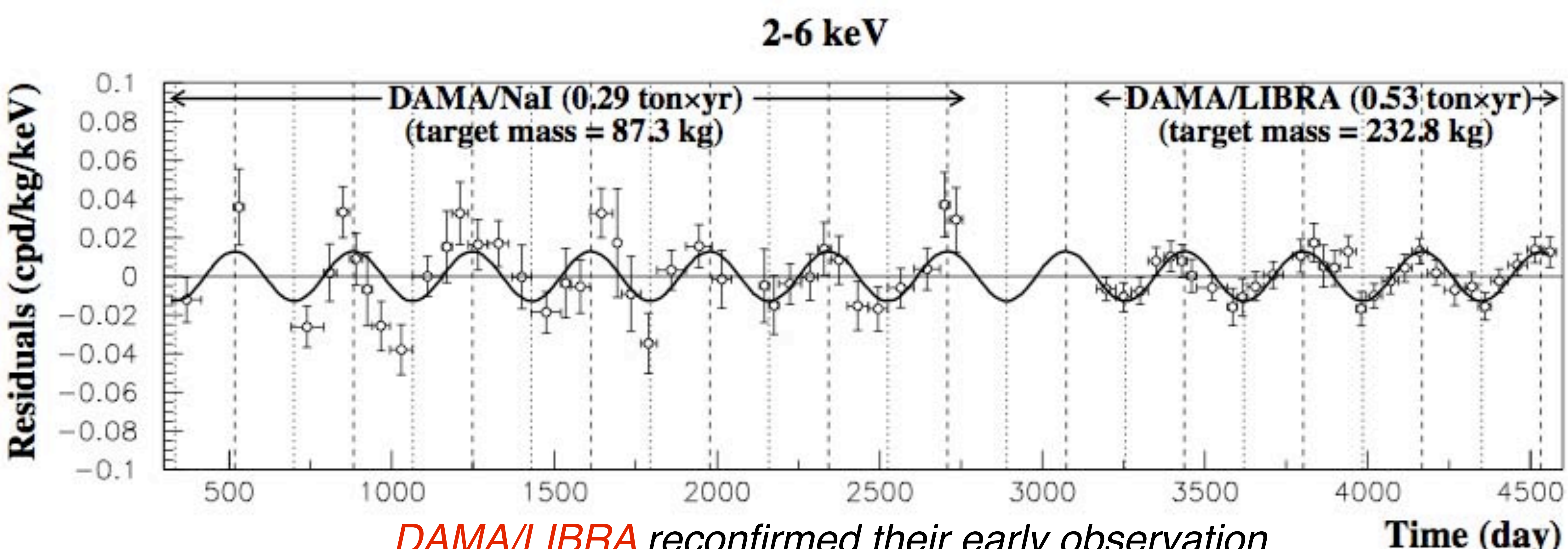
Also a busy year for direct DM searches



expect an annual modulation in signal!

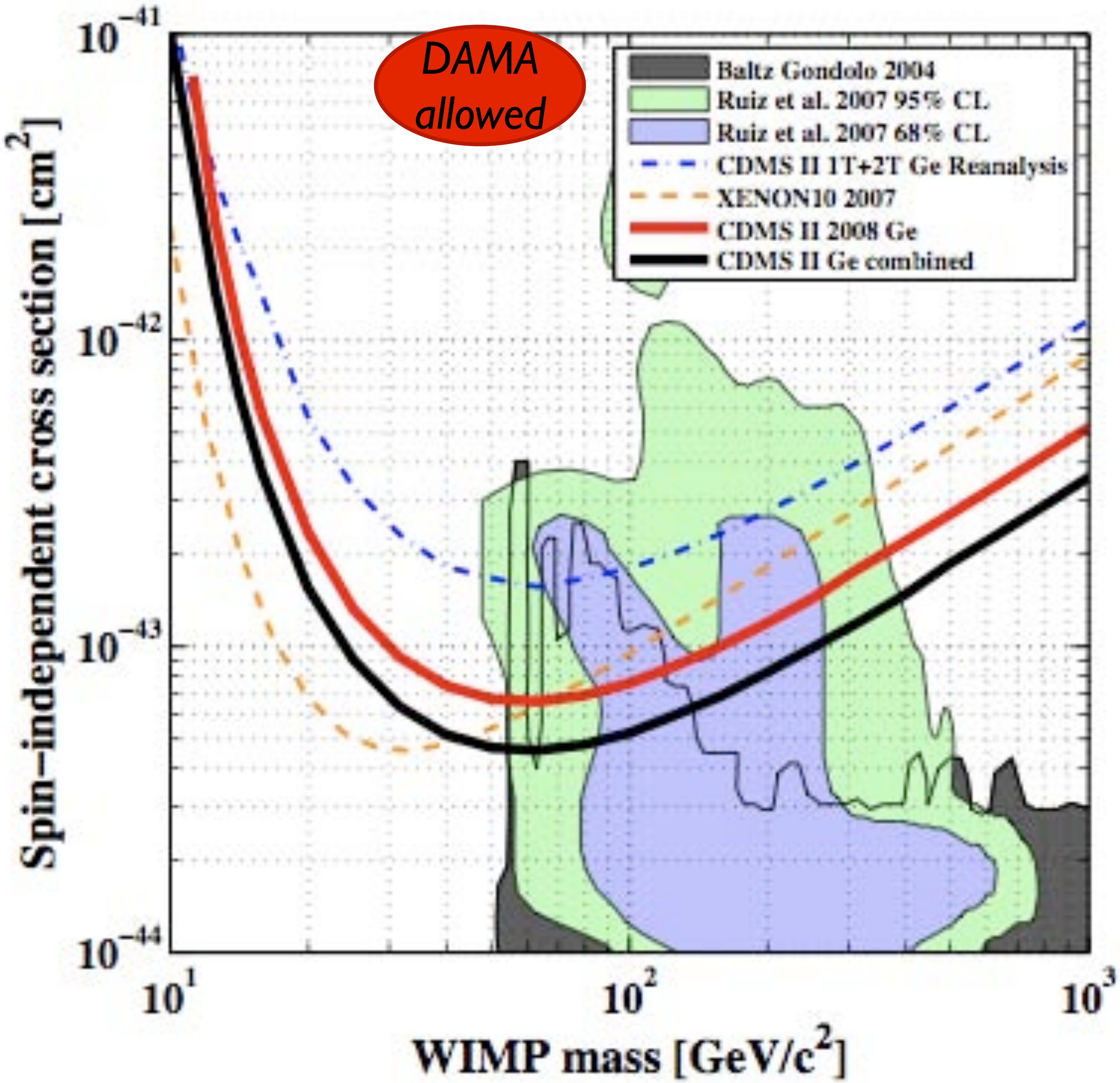
Also a busy year for direct DM searches





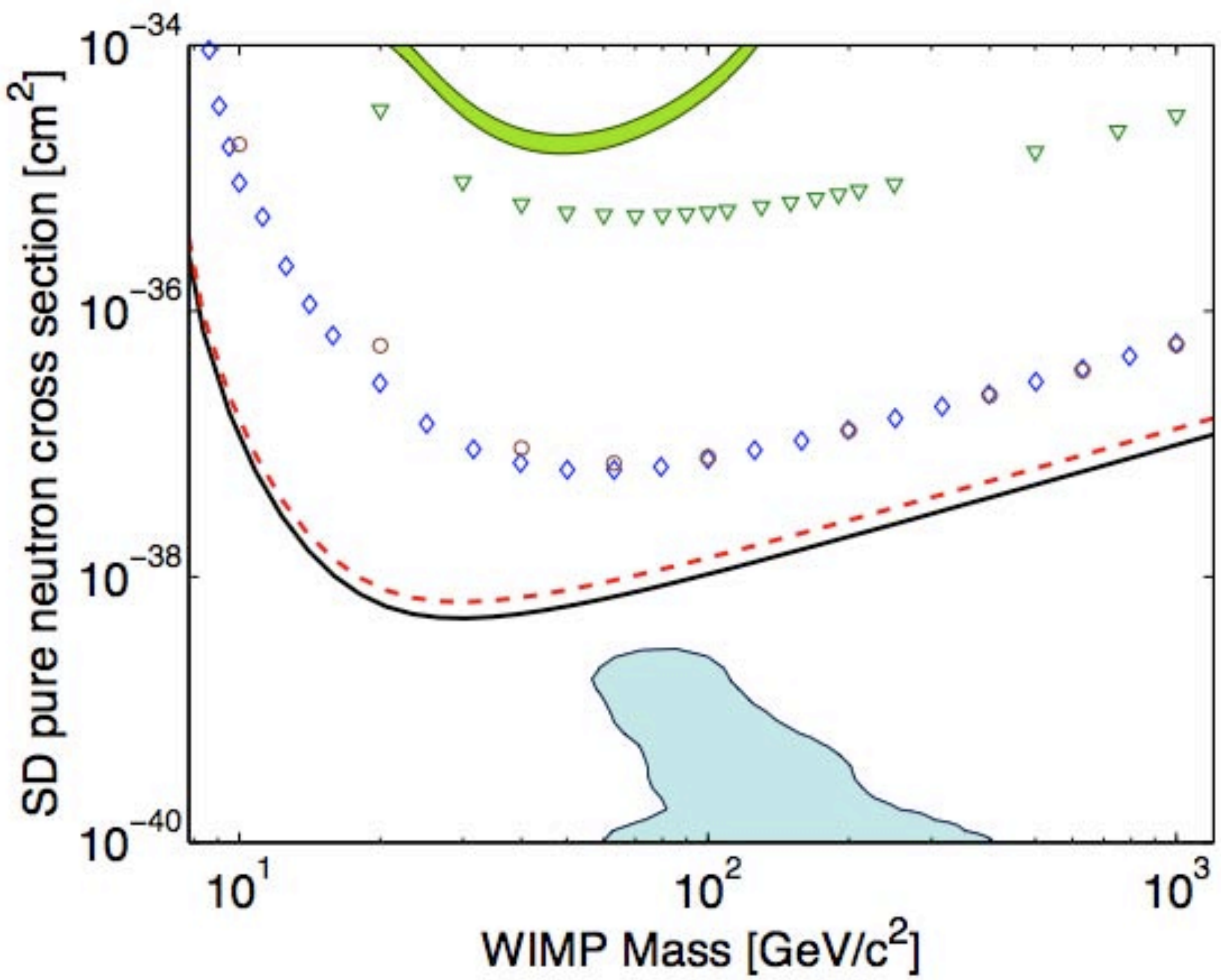
DAMA/LIBRA reconfirmed their early observation of annual modulation signal [arXiv:0804.2741]

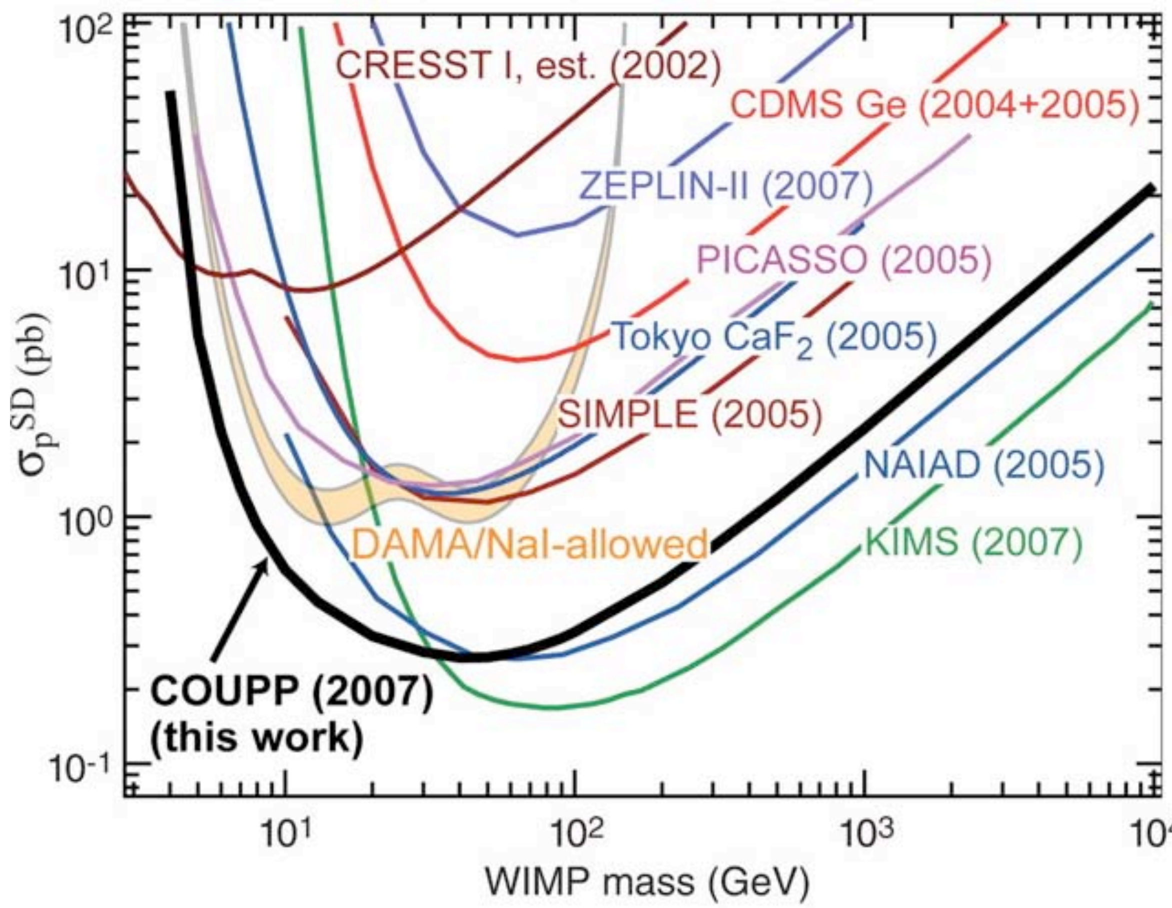
Also a busy year for direct DM searches



*CDMS further improves Spin-Independent after XENON10 [*arXiv:0802.3530*]*

Also a busy year for direct DM searches





XENON10 Spin-Dependent pure-neutron coupling [PRL 101, 091301 (2008)]

COUPP further improves Spin-dependent proton coupling [Science 319:933-936,2008]

arXiv:0810.0713

A Theory of Dark Matter

Nima Arkani-Hamed,[1] Douglas P. Finkbeiner,[2] Tracy R. Slatyer,[3] and Neal Weiner[4]

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[2] *Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138*

[3] *Physics Department, Harvard University, Cambridge, MA 02138*

[4] *Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003*

(Dated: October 31, 2008)

We propose a comprehensive theory of dark matter that explains the recent proliferation of unexpected observations in high-energy astrophysics. Cosmic ray spectra from ATIC and PAMELA require a WIMP with mass $M_\chi \sim 500 - 800\,\mathrm{GeV}$ that annihilates into leptons at a level well above that expected from a thermal relic. Signals from WMAP and EGRET reinforce this interpretation. Limits on $\bar{p}$ and π^0-γ's constrain the hadronic channels allowed for dark matter. Taken together, we argue these facts imply the presence of a new force in the dark sector, with a Compton wavelength $m_\phi^{-1} \gtrsim 1\,\mathrm{GeV}^{-1}$. The long range allows a Sommerfeld enhancement to boost the annihilation cross section as required, without altering the weak scale annihilation cross section during dark matter freezeout in the early universe. If the dark matter annihilates into the new force carrier ϕ, its low mass can make hadronic modes kinematically inaccessible, forcing decays dominantly into leptons. If the force carrier is a non-Abelian gauge boson, the dark matter is part of a multiplet of states, and splittings between these states are naturally generated with size $\alpha m_\phi \sim \mathrm{MeV}$, leading to the eXciting dark matter (XDM) scenario previously proposed to explain the positron annihilation in the galactic center observed by the INTEGRAL satellite; the light boson invoked by XDM to mediate a large inelastic scattering cross section is identified with the ϕ here. Somewhat smaller splittings would also be expected, providing a natural source for the parameters of the inelastic dark matter (iDM) explanation for the DAMA annual modulation signal. Since the Sommerfeld enhancement is most significant at low velocities, early dark matter halos at redshift ~ 10 potentially produce observable effects on the ionization history of the universe. Because of the enhanced cross section, detection of substructure is more probable than with a conventional WIMP. Moreover, the low velocity dispersion of dwarf galaxies and Milky Way subhalos can increase the substructure annihilation signal by an additional order of magnitude or more.

arXiv:0810.0713

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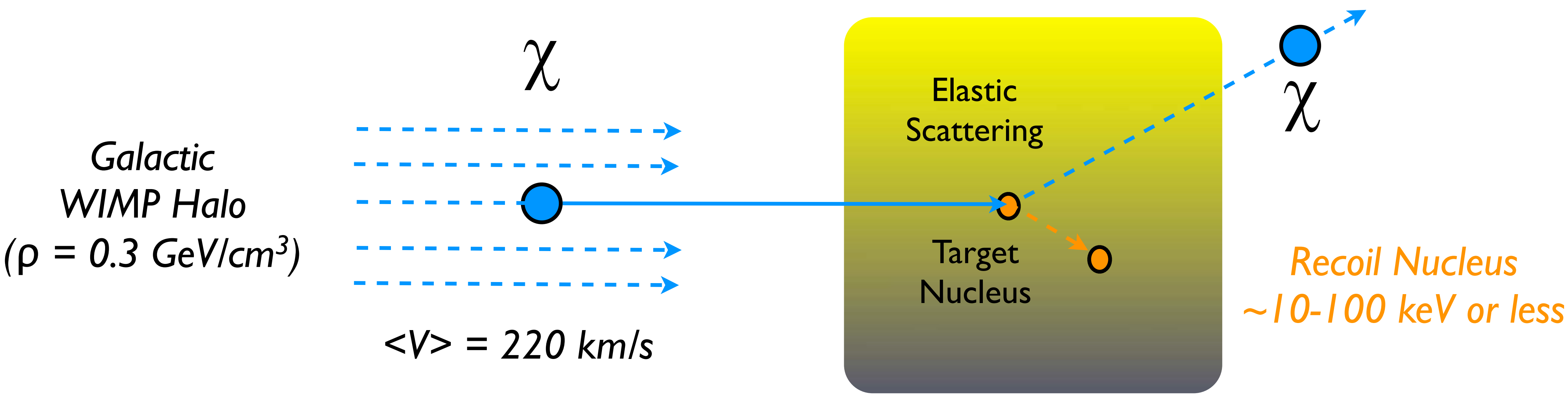
Are we at the edge of uncovering the nature of DM?

Direct Dark Matter Detection



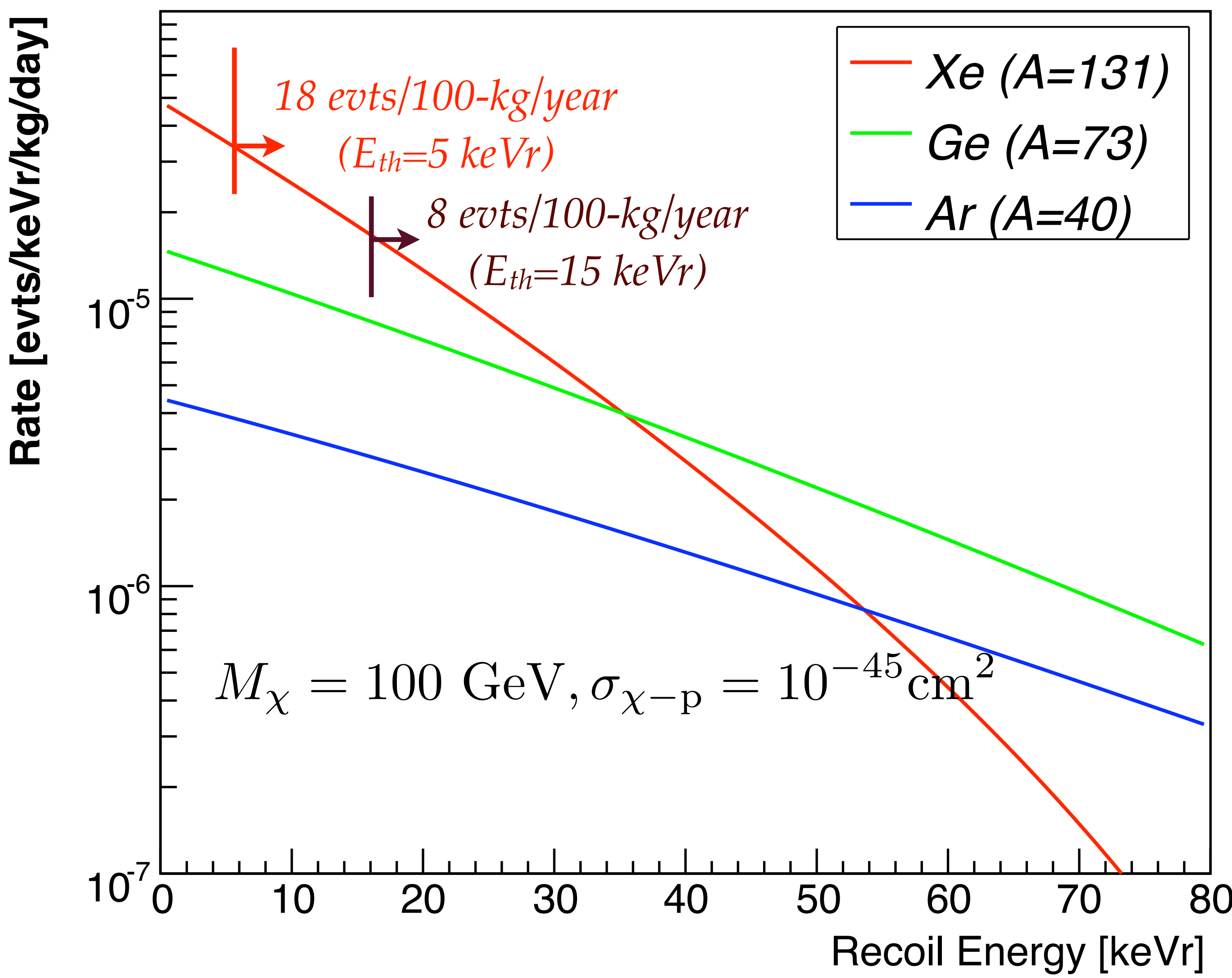
$\sigma_{\chi\text{-}p}$ *can be as low as* 10^{-46} *cm*^{2}

Goodman and Witten,
coherent scattering for WIMPs
Phys Rev D ***31****, 3059 (1985)*

The Challenges for Direct DM Detection

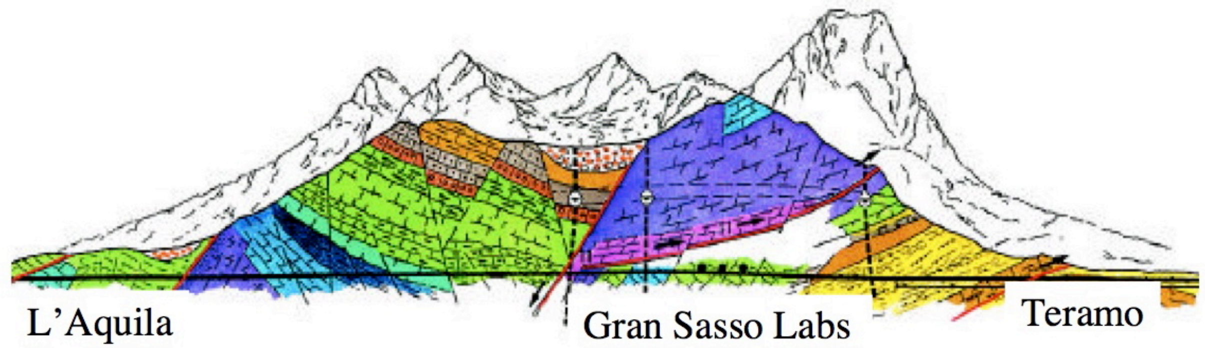
$$R \sim \frac{M_{det}}{M_\chi} \rho \sigma \langle v \rangle$$

WIMP Scattering Rates



- large mass (ton scale)
- low energy threshold (a few keV)
- background suppression
  - deep underground
  - passive shield
  - low intrinsic radioactivity
  - gamma background discrimination

Why do we need go to deep underground?



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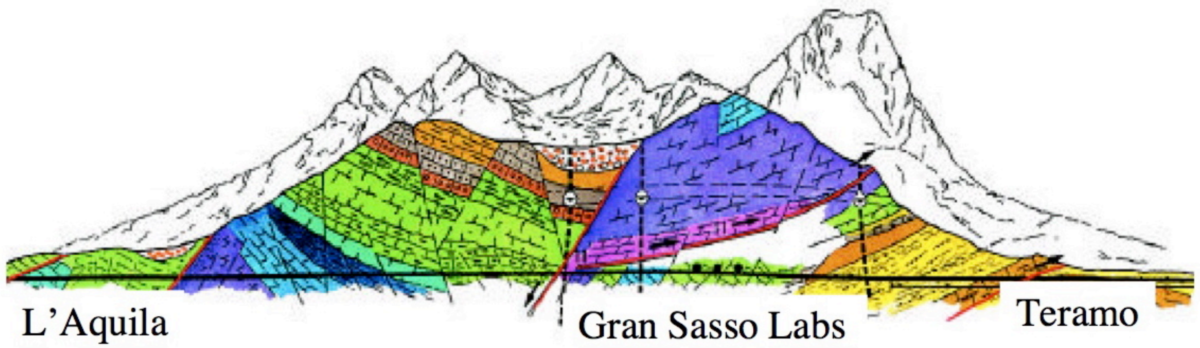

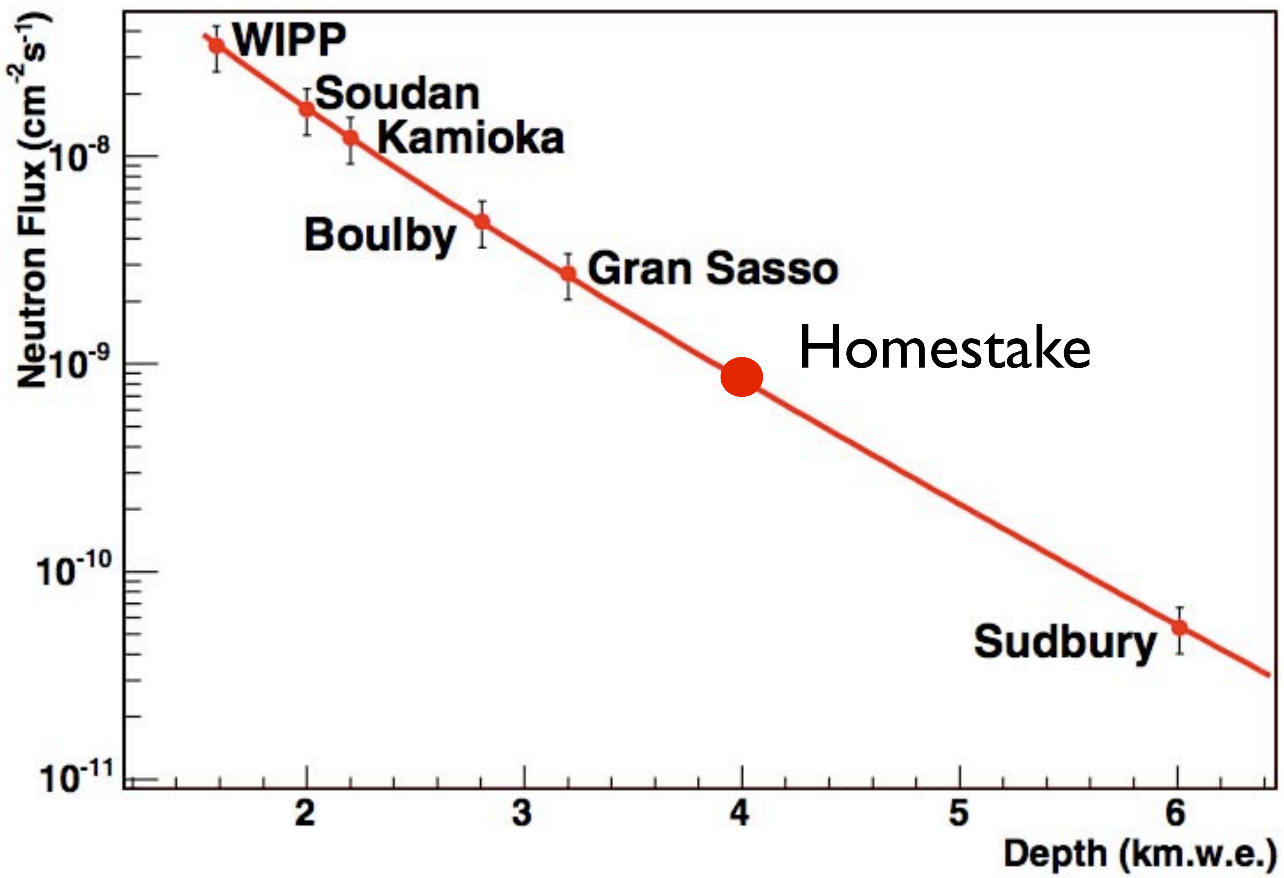

muon induced neutron flux

Mei and Hime, PRD (2006)

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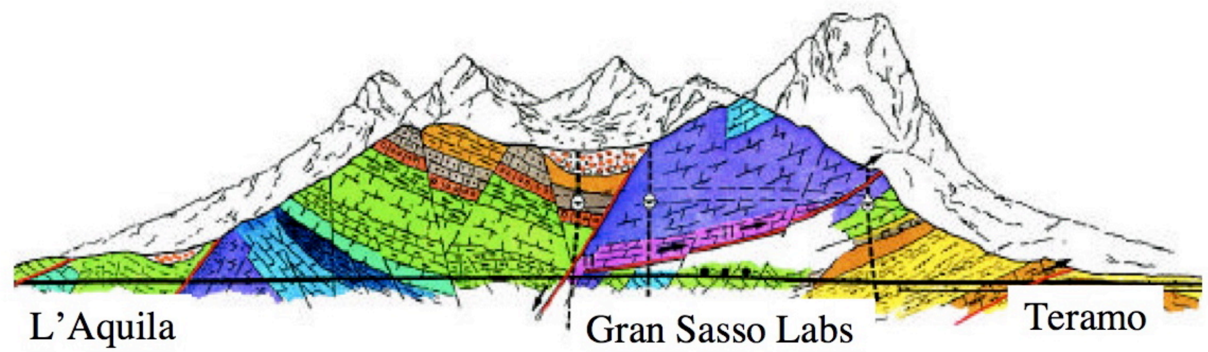
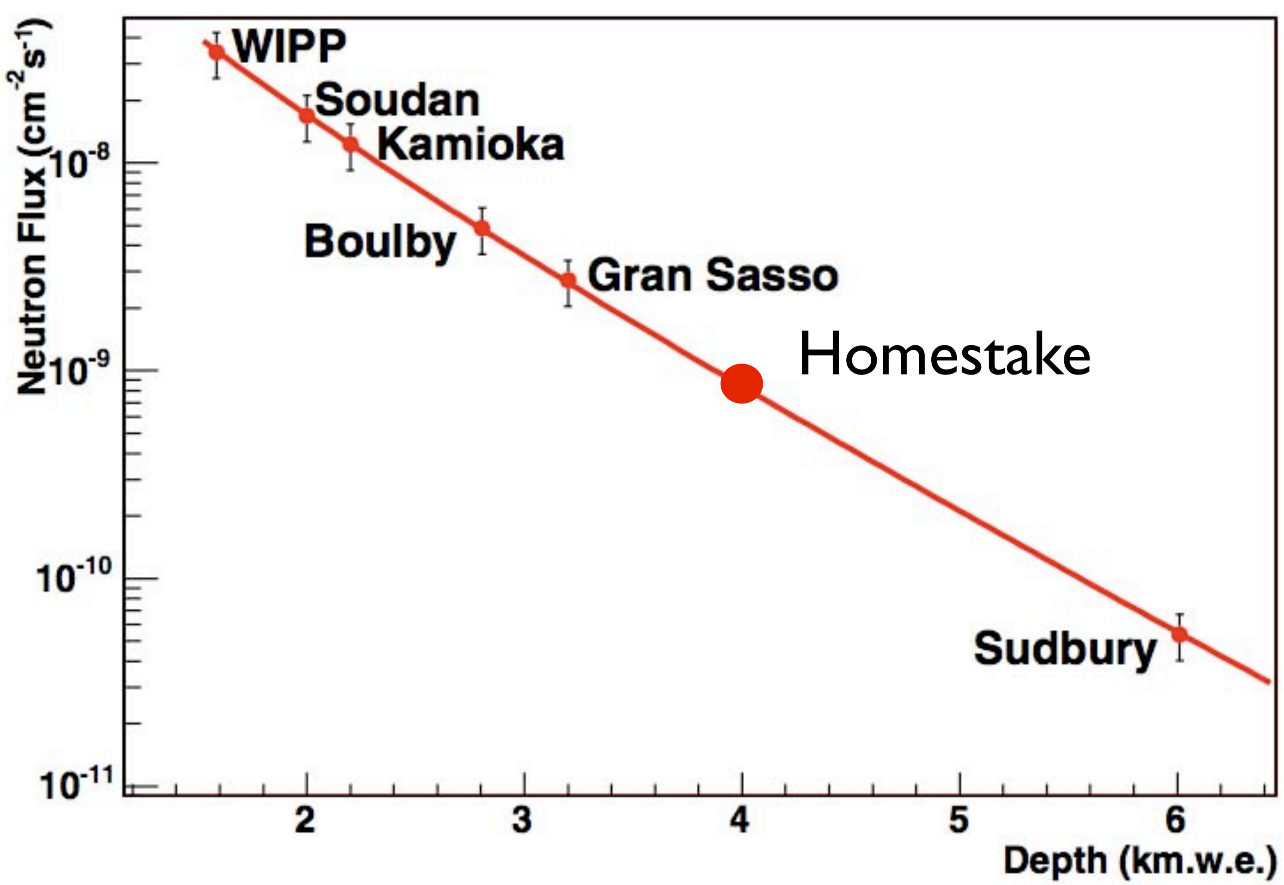
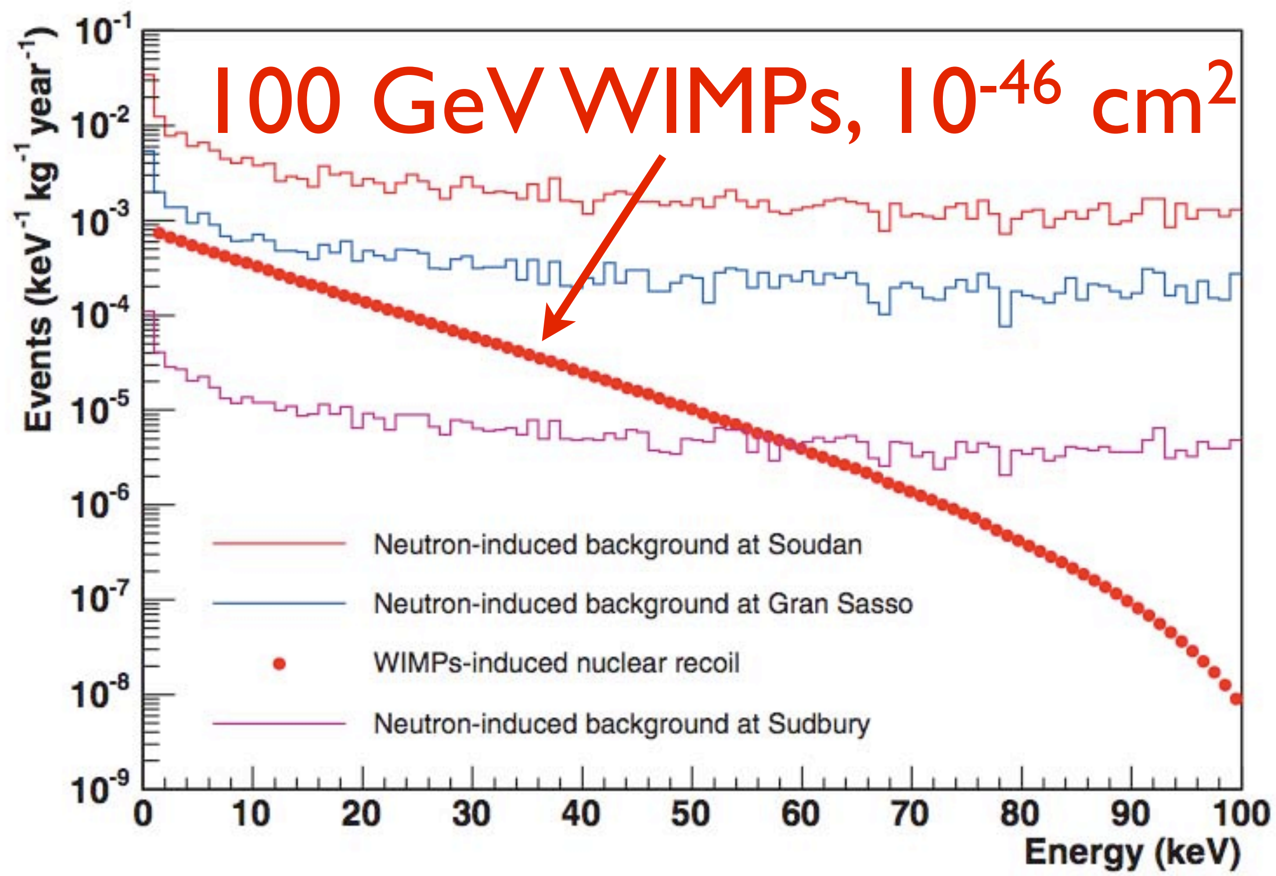




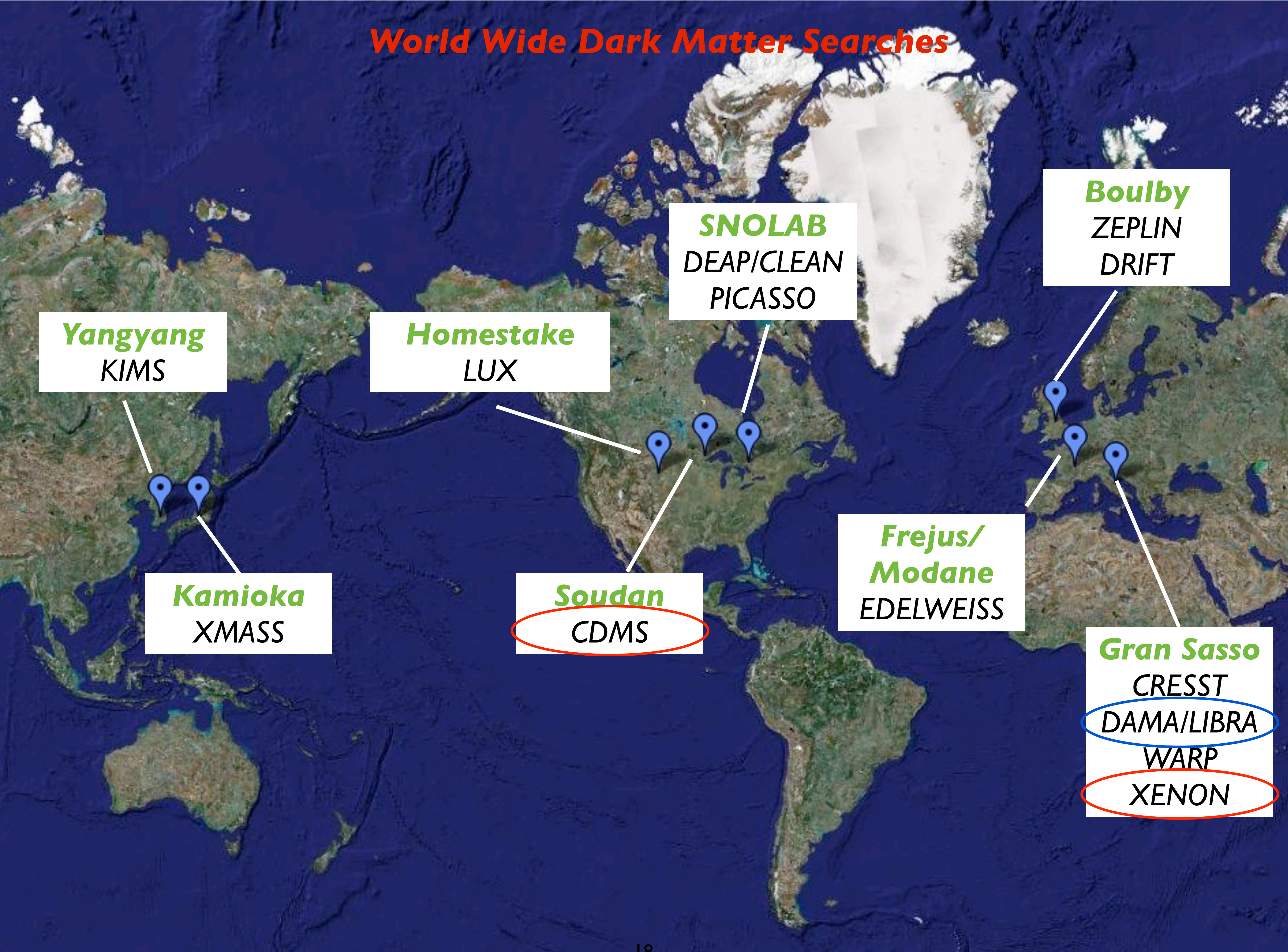
muon induced neutron flux



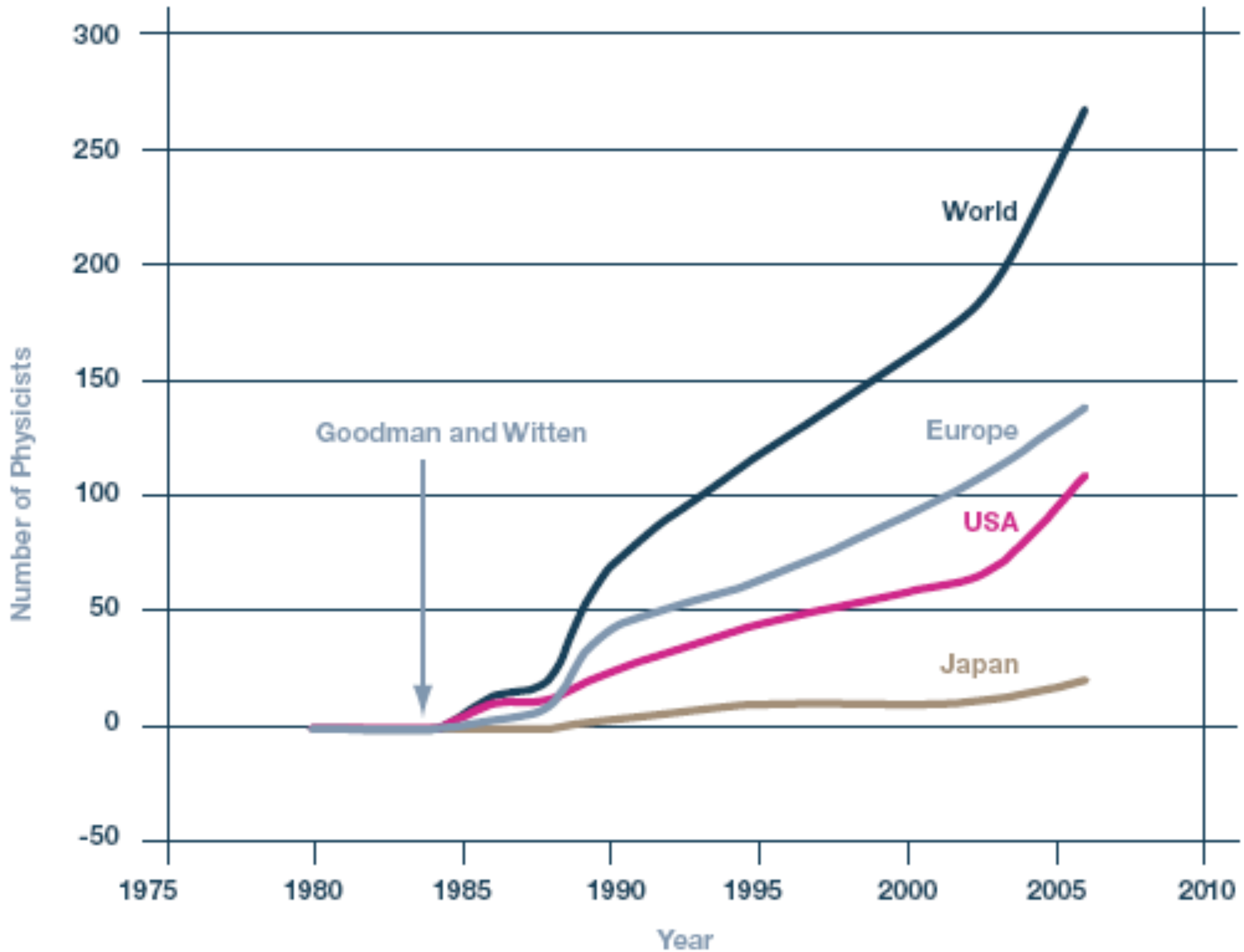
signal/background event rates

Mei and Hime, PRD (2006)

World Wide Dark Matter Searches



Dark Matter physicists



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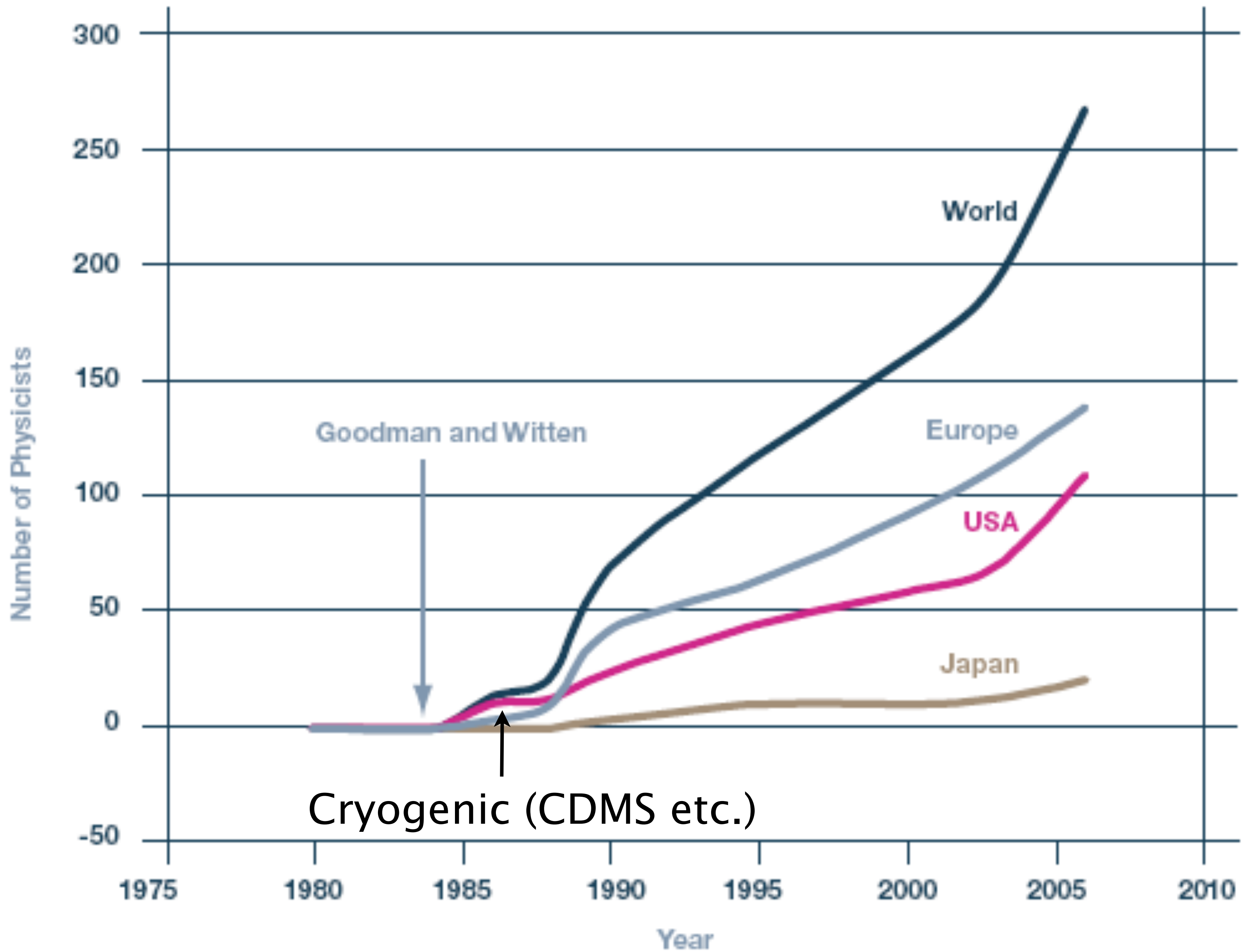

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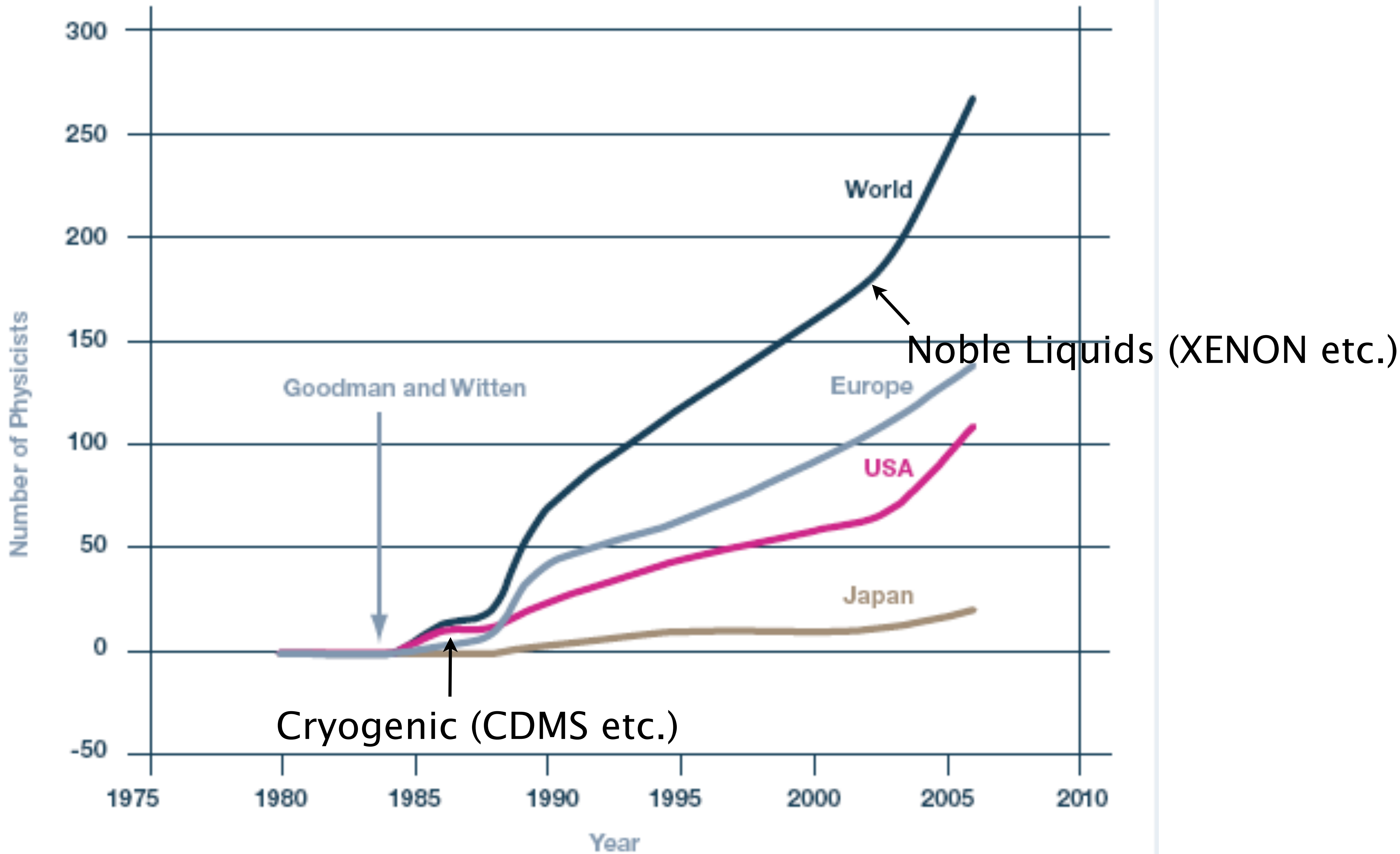
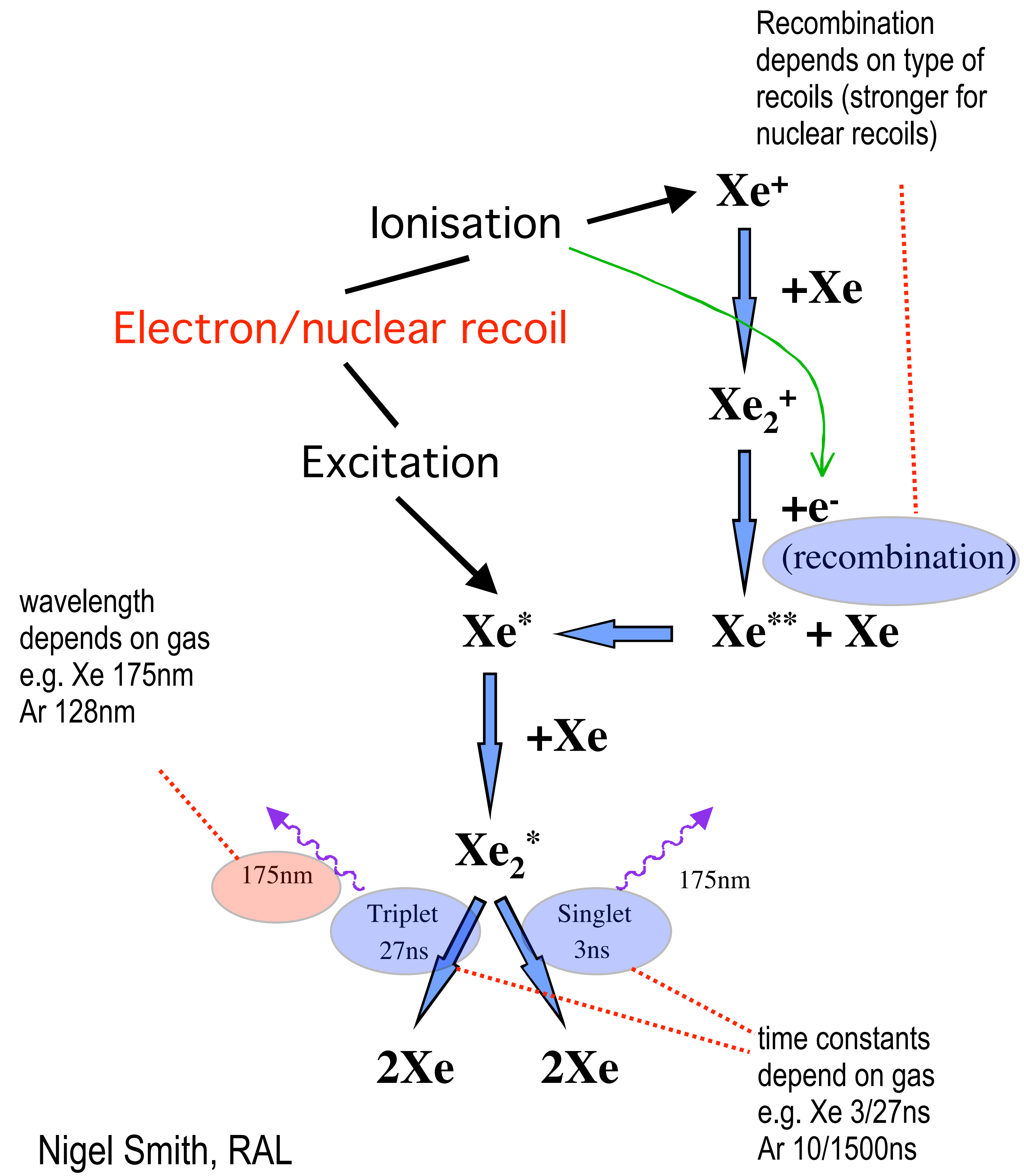


The Merits of Noble Liquids for Dark Matter Detection

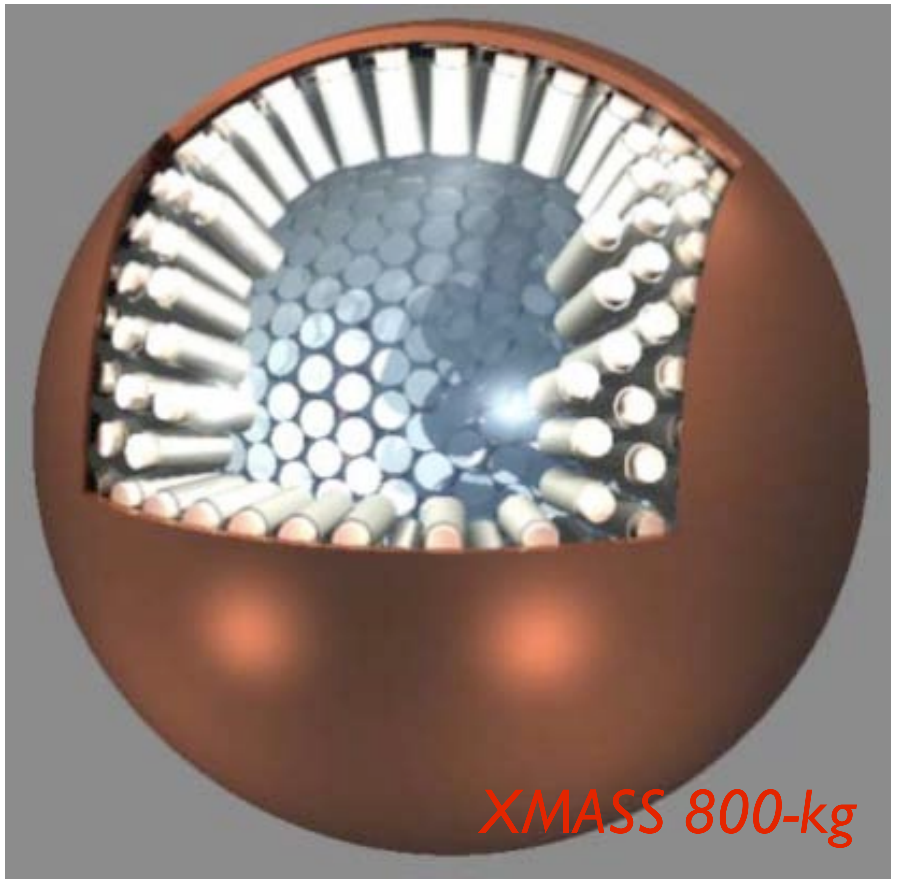
- *scalability : relatively cheap and "easy" cryogenics at 170 K (LXe), 87 K (LAr)*
- *bkg reduction: via self-shielding*
- *low threshold : high scintillation yield*
- *gamma rejection: electron and nuclear recoil discrimination*

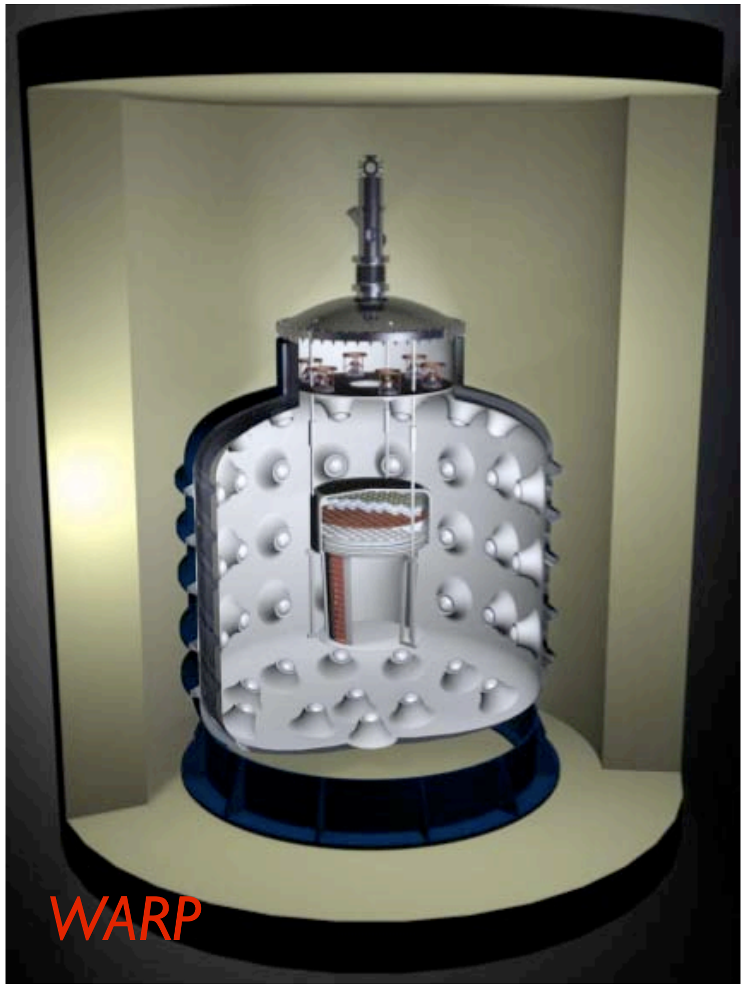


Nigel Smith, RAL

The Noble Liquid Revolution

- *Noble liquids (LAr, LXe) are relatively inexpensive, easy to scale up*
- *Self-shielding reduce external background*
- *Excellent gamma background rejection (pulse-shape, or ionization/scintillation)*





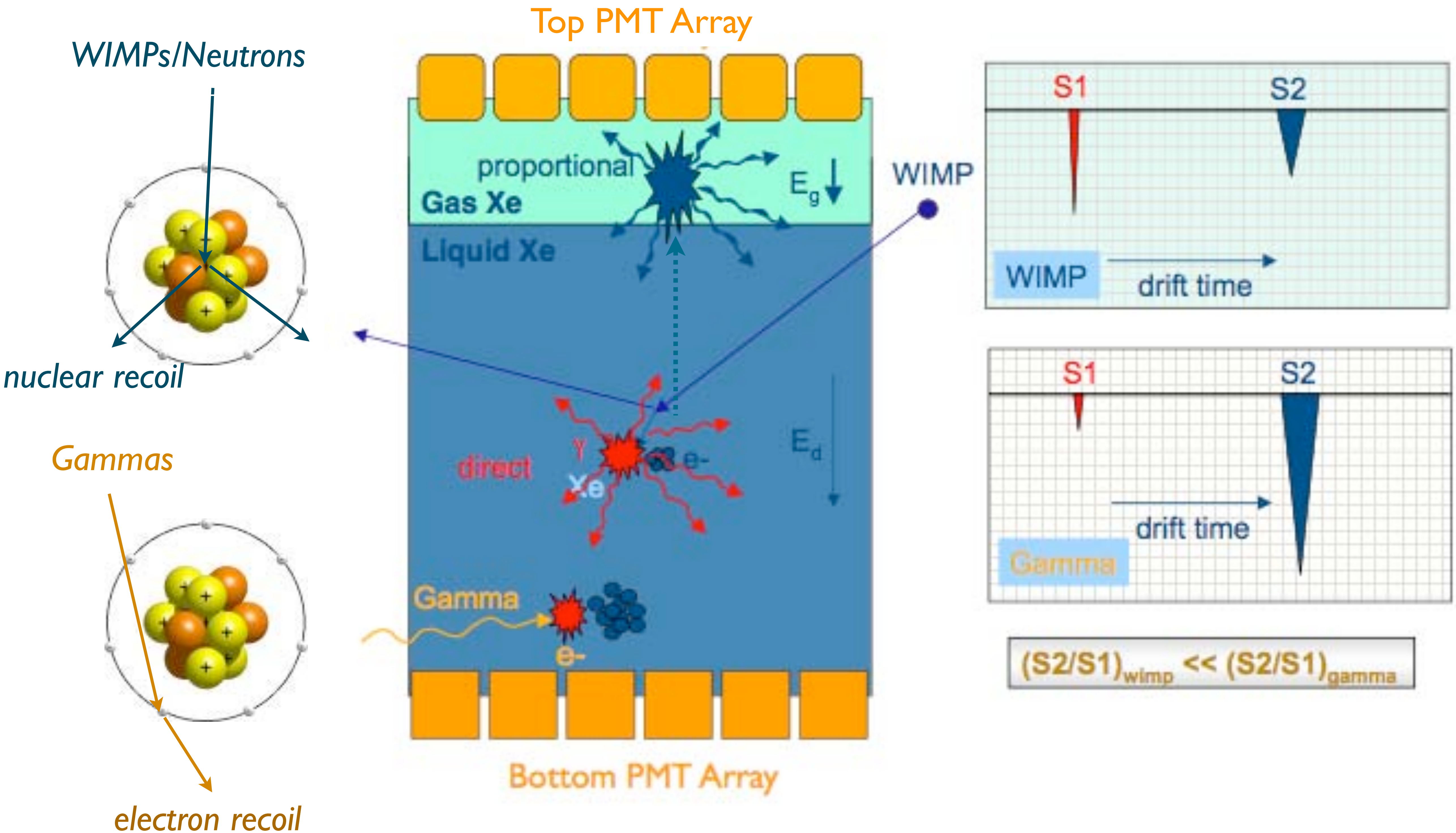
Single Phase

(XMASS, CLEAN/DEAP)

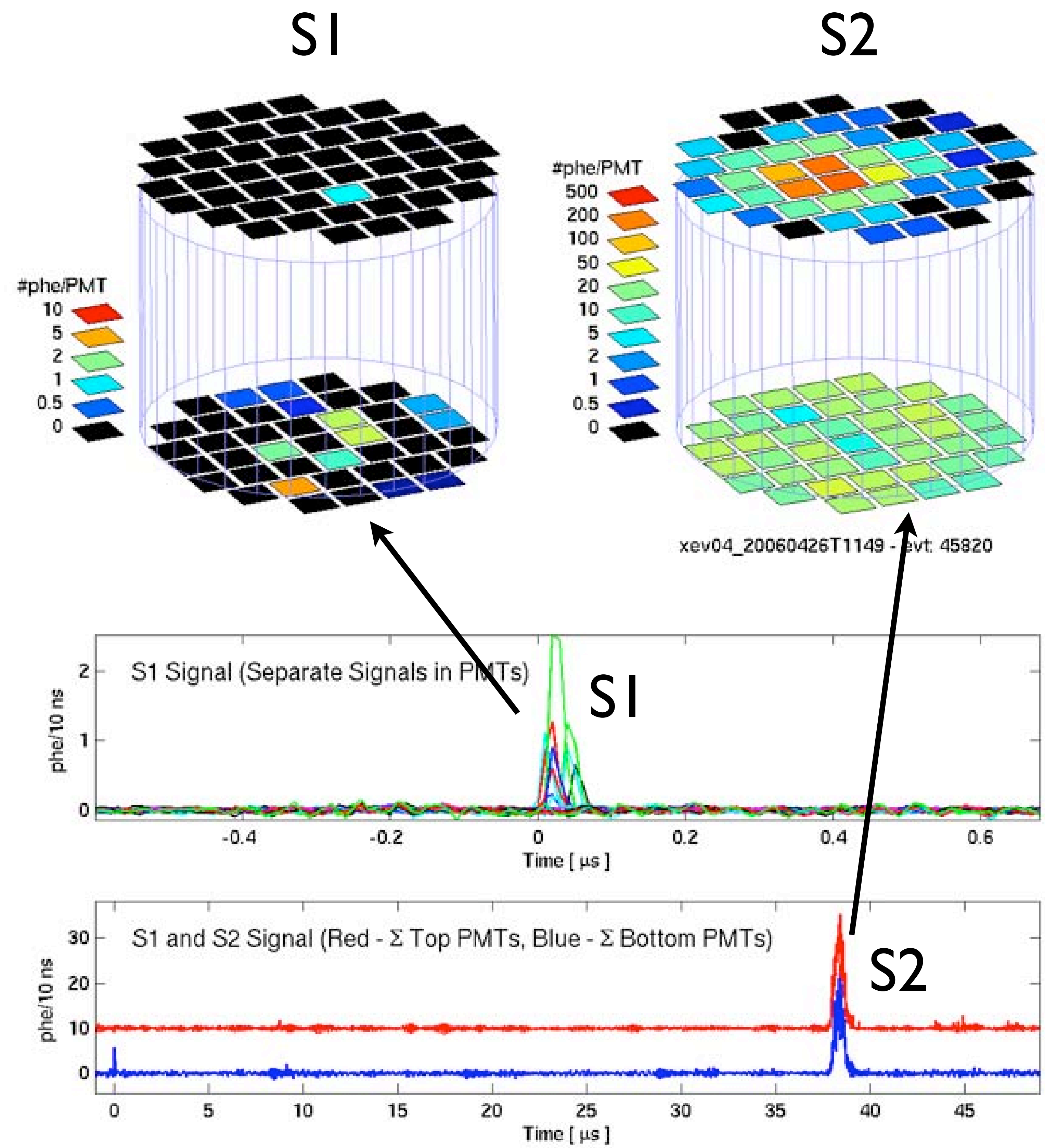
Two Phase

(**XENON**,LUX,ZEPLIN II/III,WARP,ArDM.)

Two-phase Xenon Detectors for Dark Matter Detection

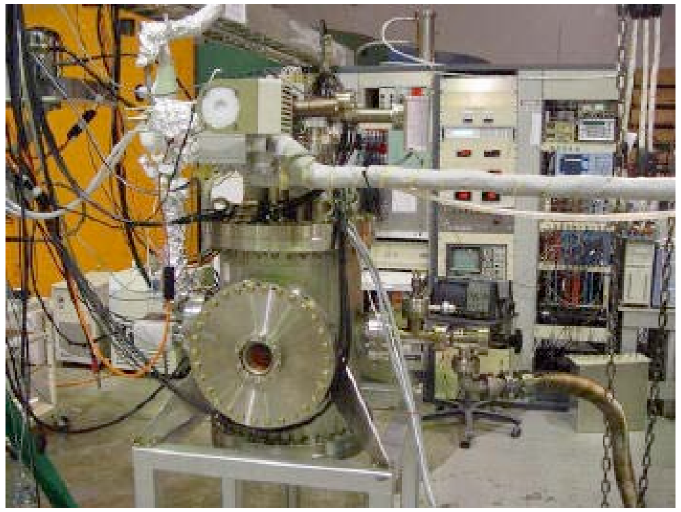


Signals from XENON10



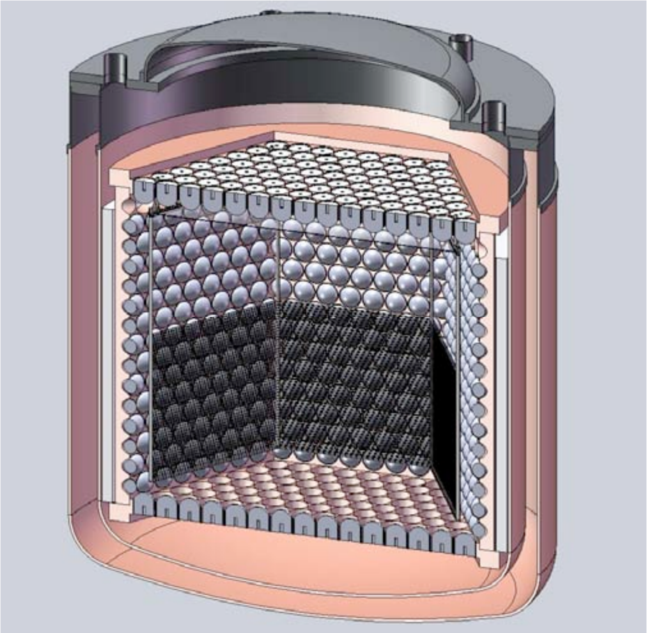
The Phased XENON Program

XENON R&D
(2001-2005)



XENON10
(2006-2007)

XENON100
(2007-2012)

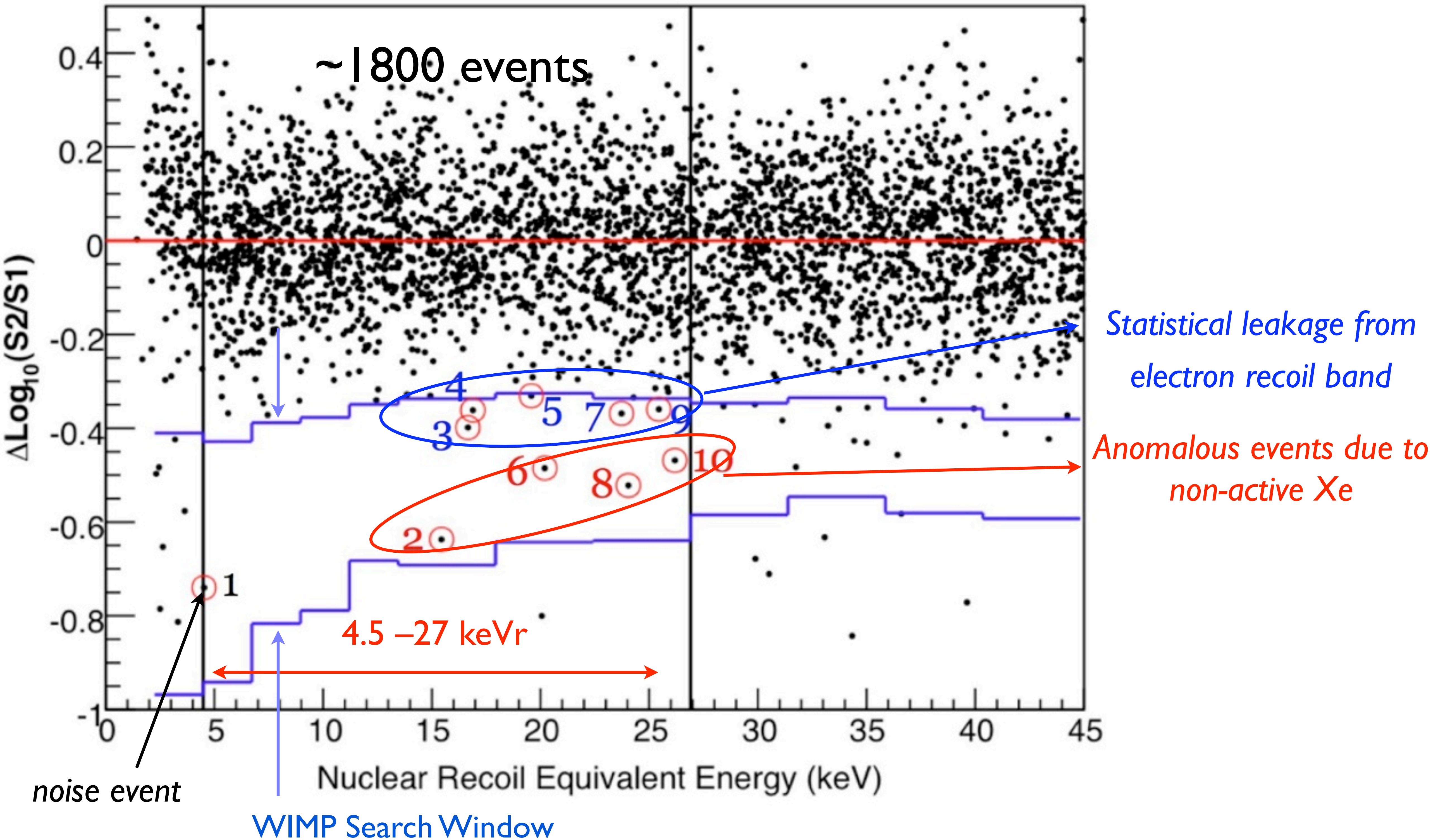


XENON1T
(2012)

XENON10 WIMP Search Data

136 kg-days Exposure= 58.6 live days x 5.4 kg x 0.86 (ε) x 0.50 (50% NR)

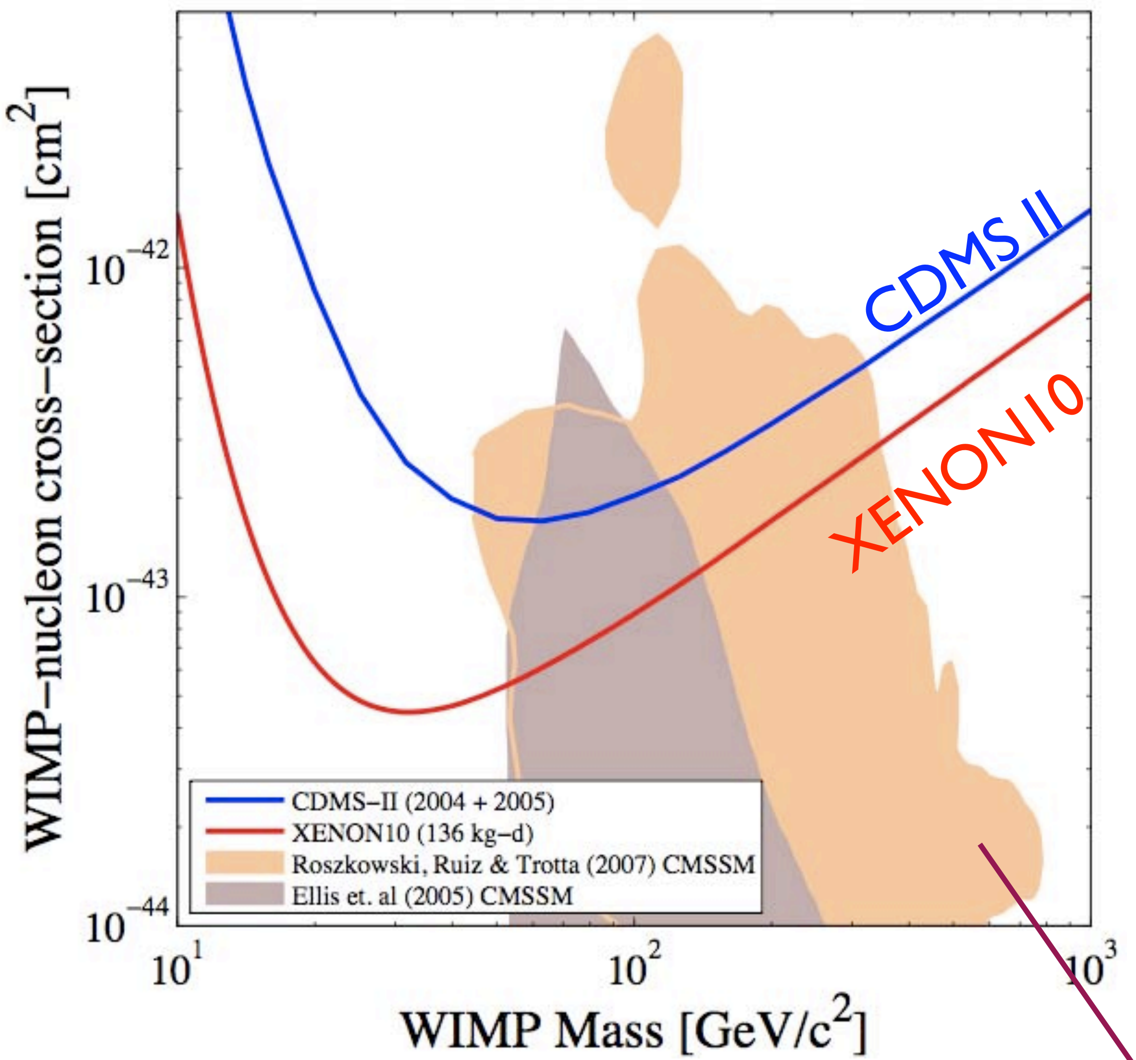
(data collected between Oct.2006 and Feb.2007)

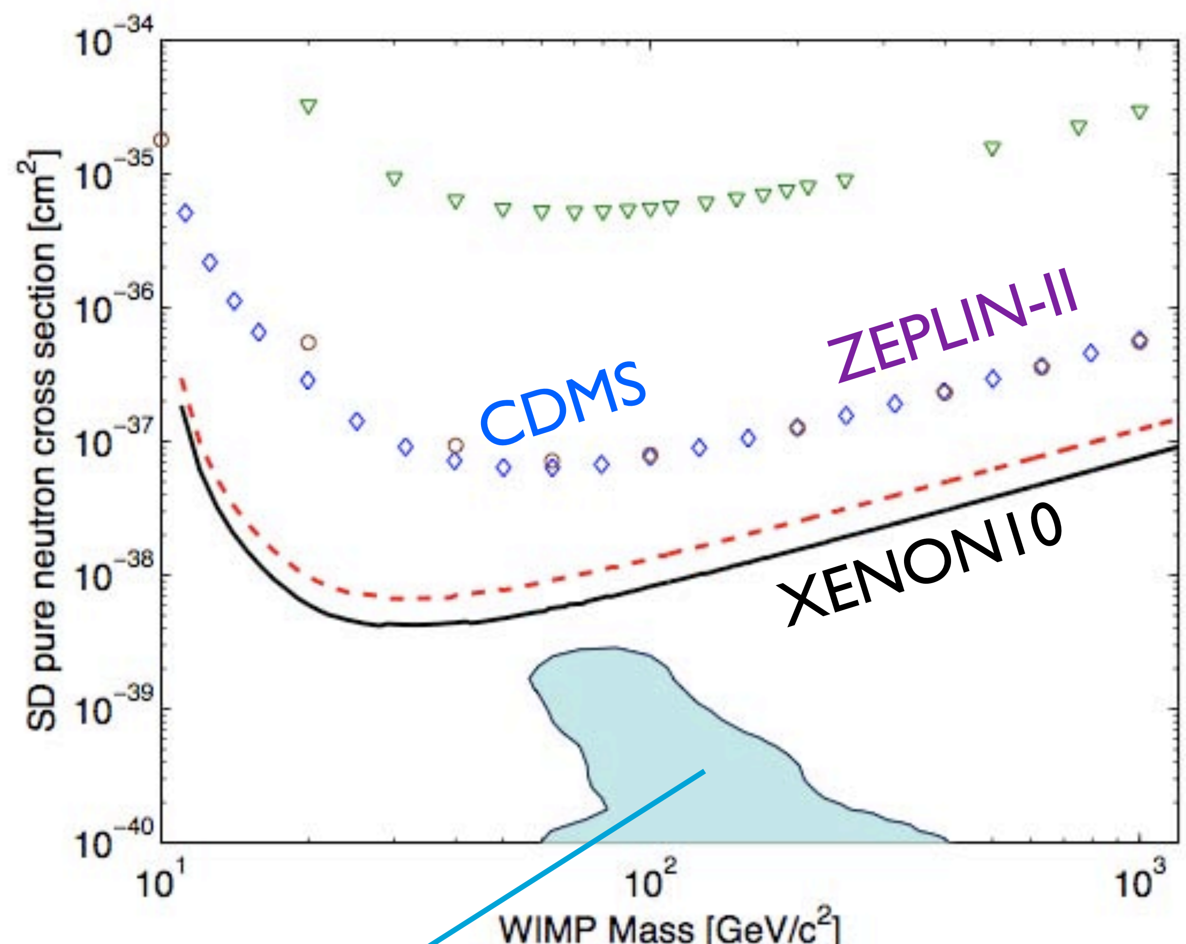


XENON10 WIMP-Nucleon Cross-Section Upper Limits

Spin-independent
Phys. Rev. Lett. **100**, 021303 (2008)

Spin-dependent
Phys. Rev. Lett. **101**, 091301 (2008)





(NO BKG SUBTRACTION)
8.8×10^{-44} cm^2 at 100 GeV
4.5×10^{-44} cm^2 at 30 GeV

Constrained Minimal Supersymmetric Model

(NO BKG SUBTRACTION)
6×10^{-39} cm^2 at 30 GeV

inelastic Dark Matter (iDM)

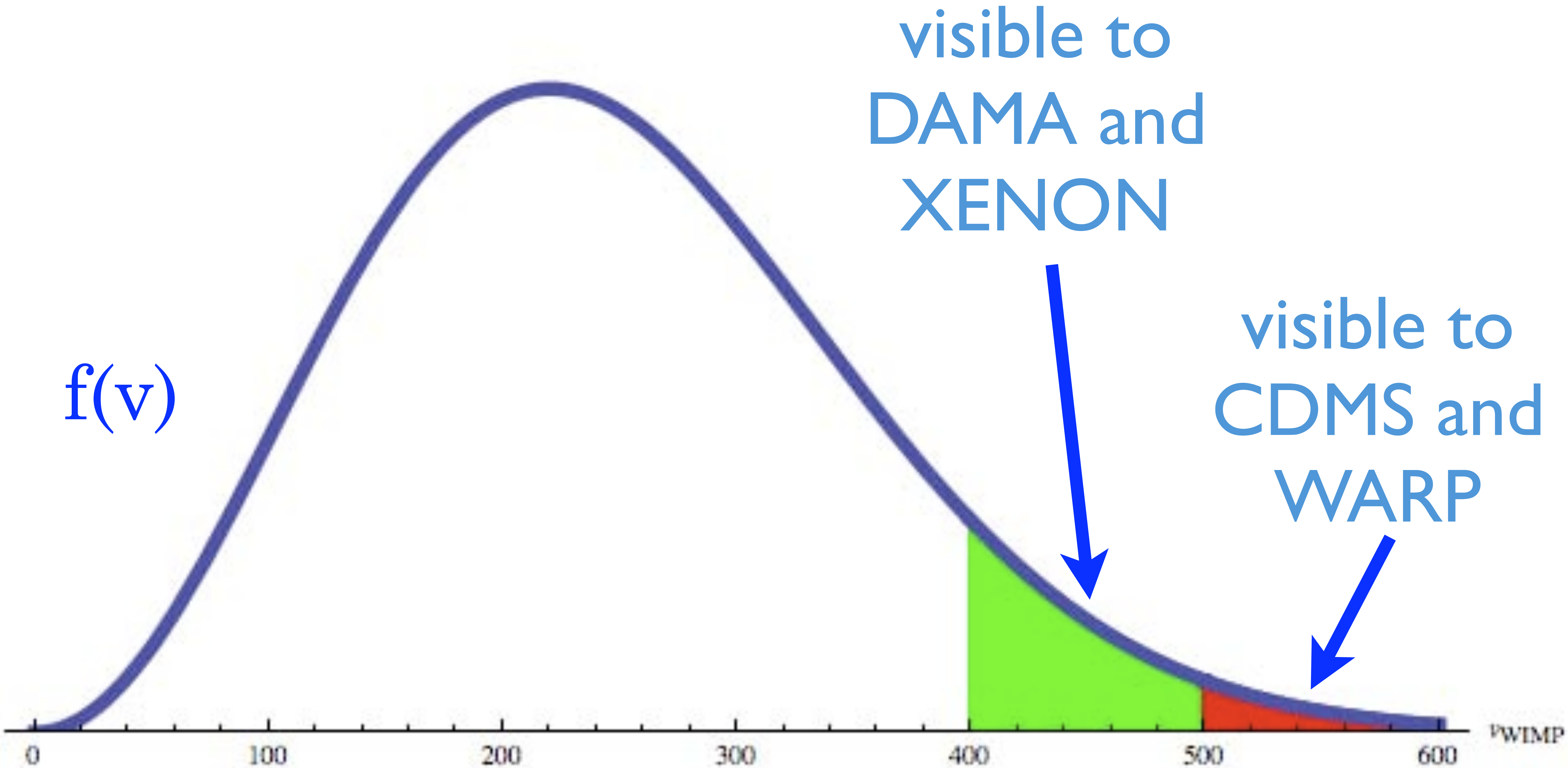
Spencer Chang, Graham D. Kribs, David Tucker-Smith, Neal Weiner
[arXiv:0807.2250]

No longer elastic scattering.
If dark matter can only scatter off of a nucleus by transitioning to an excited state, the kinematics are changed dramatically

$$\delta \leq \frac{1}{2}\mu\beta^2 c^2 \approx 100 \text{ keV}$$

$$\mu = \frac{M_\chi M_N}{M_\chi + M_N}$$

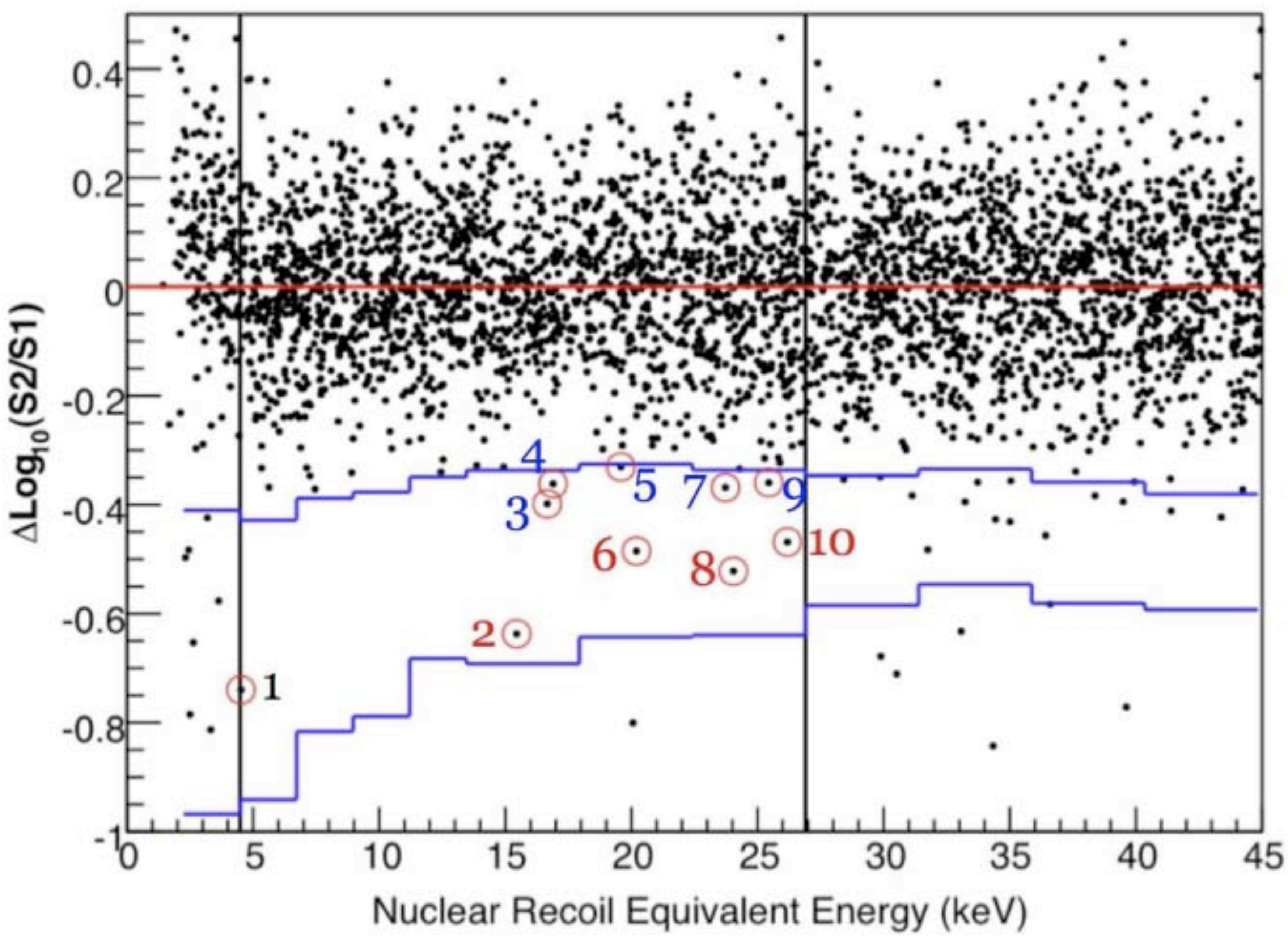
must have enough kinetic energy to scatter



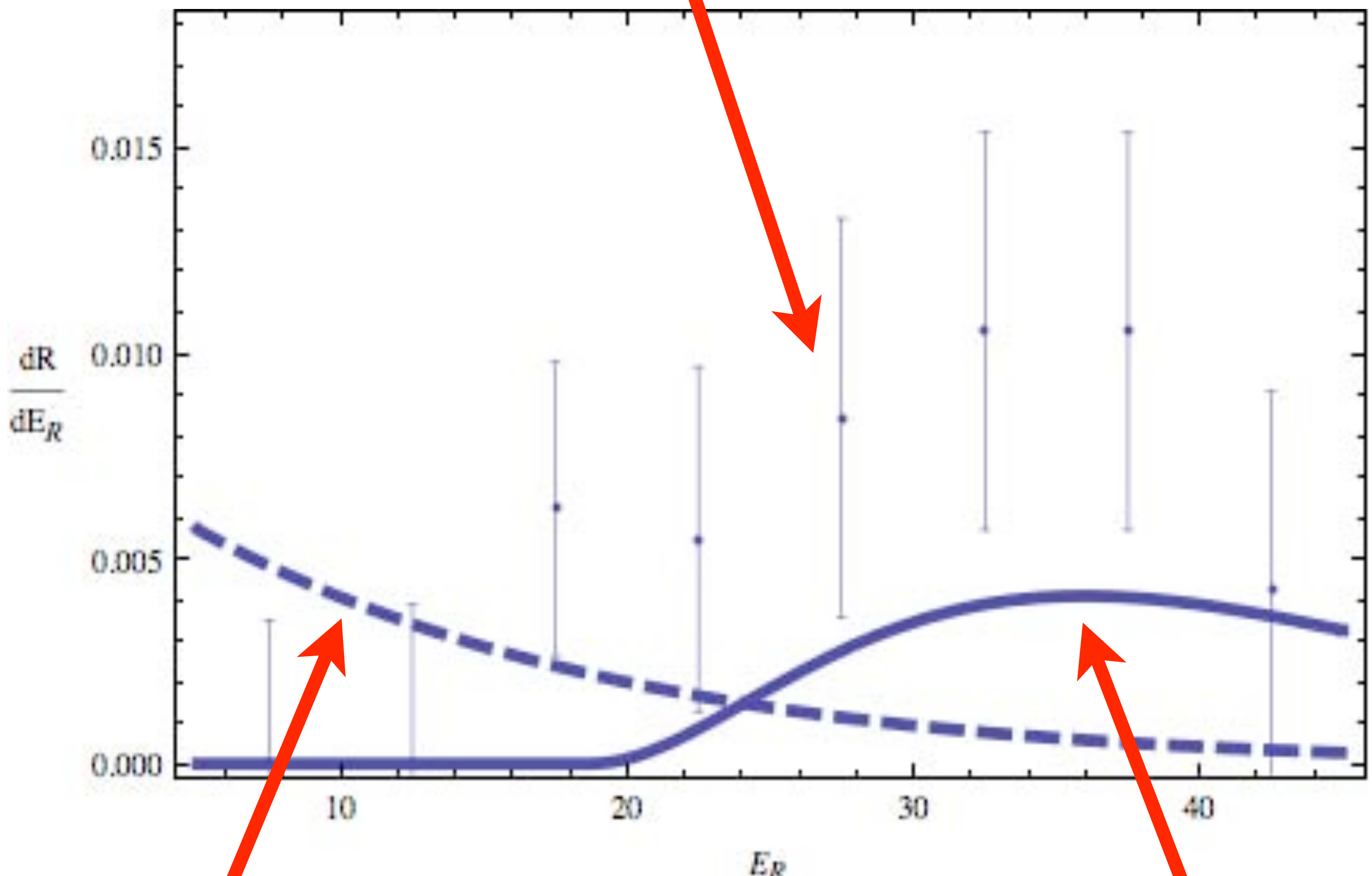
modulation is also significantly enhanced

N. Weiner

Spectrum is dramatically modified Standard WIMPs have a spectrum that peaks at low energies



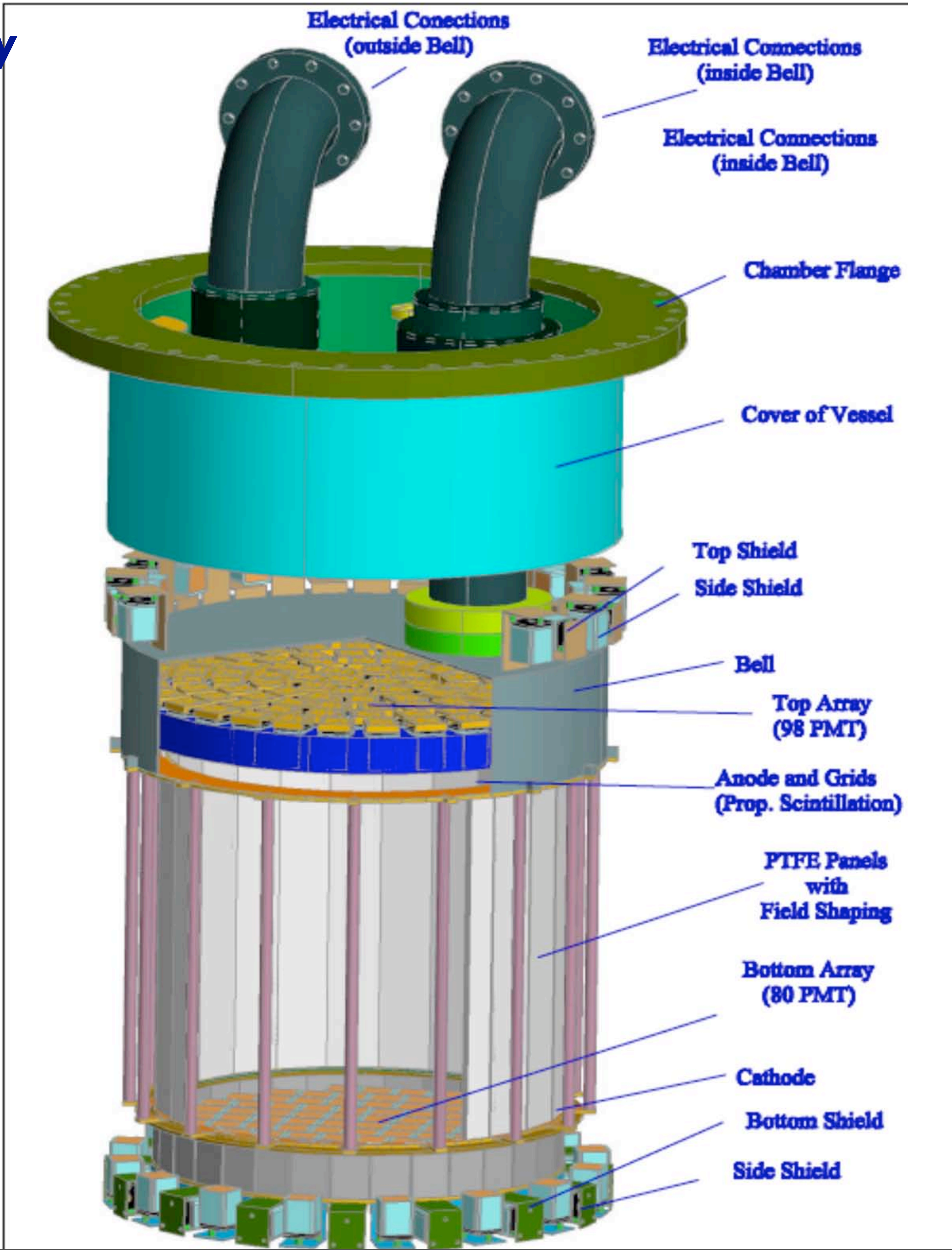
XENON10 “background” data adjusted for efficiencies (taking unpublished acceptance x efficiency = 0.3, error bars estimated)



M_X=100 GeV, δ=0 keV, normalized to inelastic XENON10 signal

M_X=100 GeV, δ = 120 keV, normalized to DAMA 2-6 keV

XENON100: The TPC Assembly



XENON100 Collaboration

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An international collaboration of 46 physicists from 9 institutions

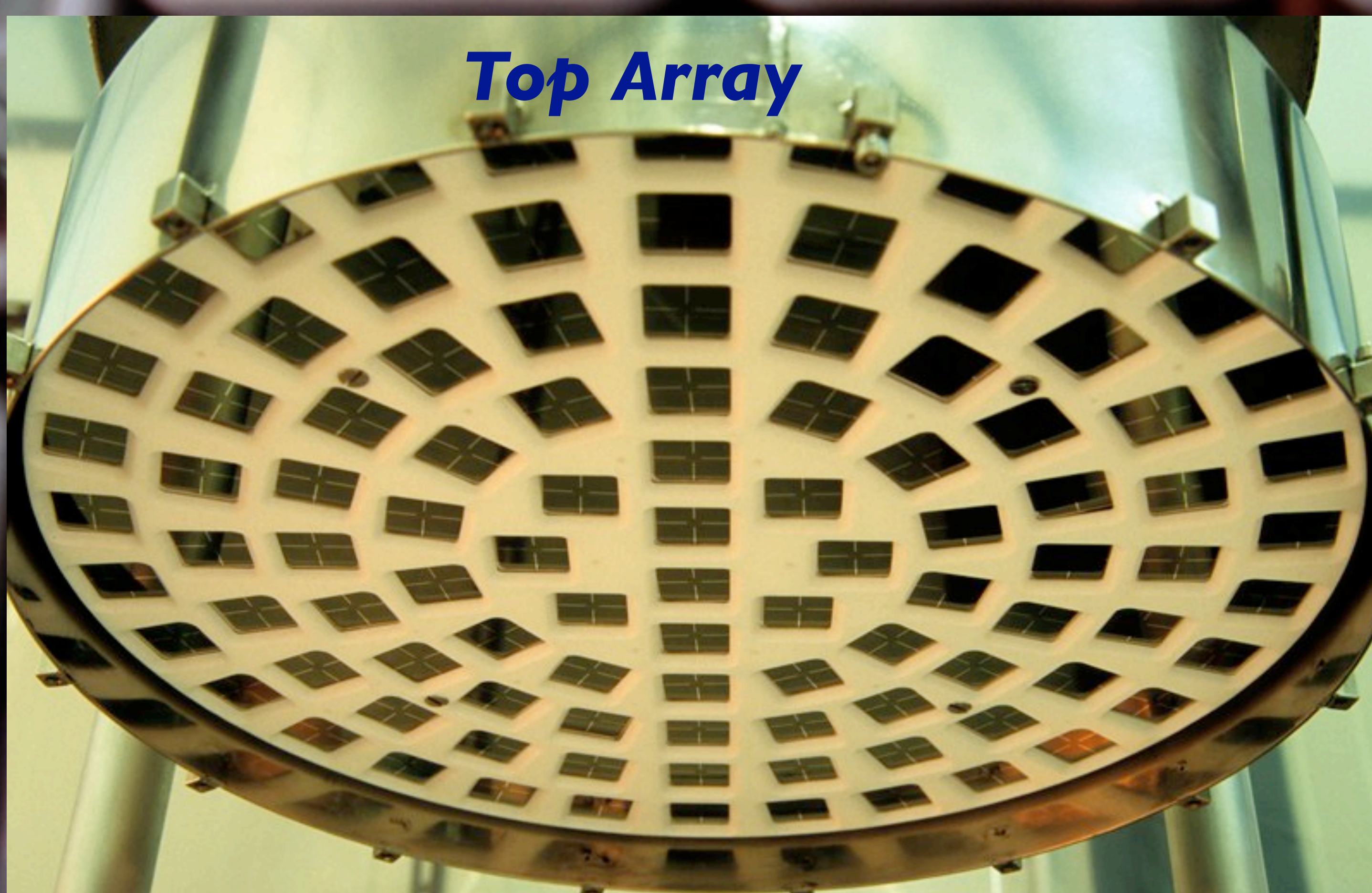
Laboratori Nazionali del Gran Sasso, Italy

XENON100 Underground at the Laboratori Nazionali del Gran Sasso

LNGS: 1.4km rock (3100 mwe)

XENON100: The PMTs

- 242 PMTs (Hamamatsu R8520-06-Al)
- 1 “ square metal channel developed for XENON
- Low radioactivity (<1 mBq U/Th per PMT)
- 80 PMTs for bottom array (33% QE)
- 98 PMTs for top array (23% QE)
- 64 PMTs for top/bottom/side Veto (23% QE)



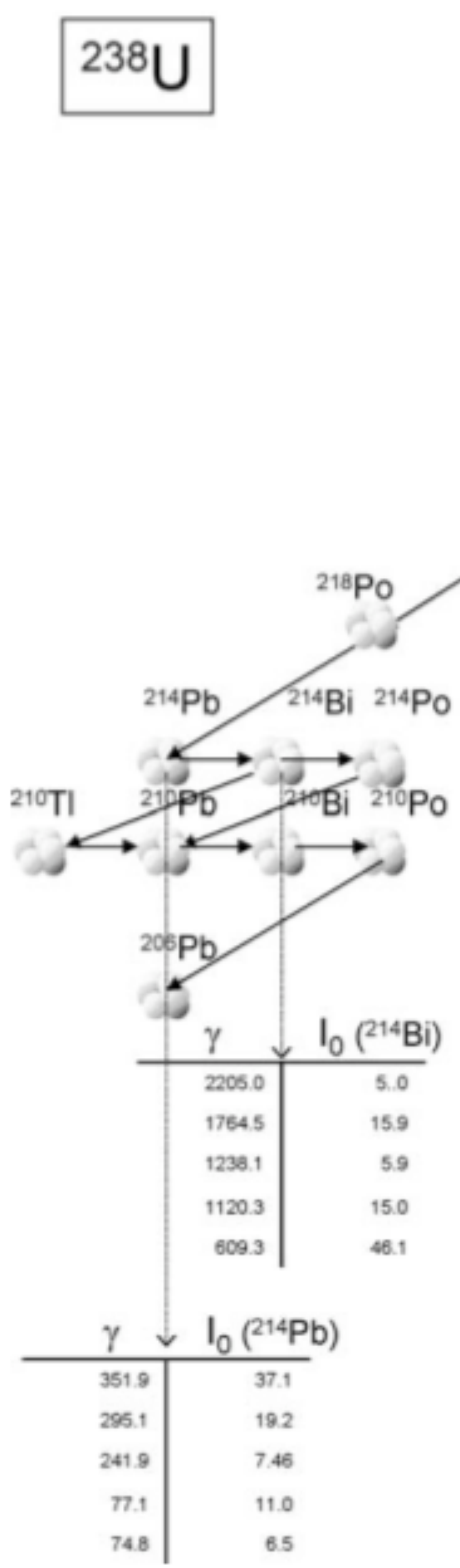
Ultra-low radioactive material selection

All materials used in XENON100 detector were selected based on low radioactivity

TPC Material	Unit	Quantity used	^{238}U [mBq/unit]	^{232}Th [mBq/unit]	^{40}K [mBq/unit]	^{60}Co [mBq/unit]	^{210}Pb [Bq/unit]
R8520 PMTs	PMT	242	0.15 ± 0.02	0.17 ± 0.04	9.15 ± 1.18	1.00 ± 0.08	
PMT bases	base	242	0.16 ± 0.02	0.07 ± 0.02	< 0.16	< 0.01	
Stainless steel	kg	70	< 1.7	< 1.9	< 9.0	5.5 ± 0.6	
PTFE	kg	10	< 0.31	< 0.16	< 2.2	< 0.11	
QUPID	QUPID	-	<0.49	<0.40	<2.4	<0.21	
Shield Material							
Copper	kg	1600	< 0.07	< 0.03	<0.06	<0.0045	
Polyethylene	kg	1600	< 3.54	< 2.69	< 5.9	< 0.9	
Inner Pb (5 cm)	kg	6300	< 6.8	< 3.9	< 28	< 0.19	17 ± 5
Outer Pb (15 cm)	kg	27200	< 5.7	< 1.6	14 ± 6	< 1.1	516 ± 90

Table 1: Radioactivity of XENON100 materials: Average values are given if different activities were obtained for different material samples, such as different batches of PMTs and stainless steel. Upper limits are given if no activity above background was found. Radioactivity from other components, such as screws and cables, are negligible (at least a factor of 10 lower compared to those in the table).

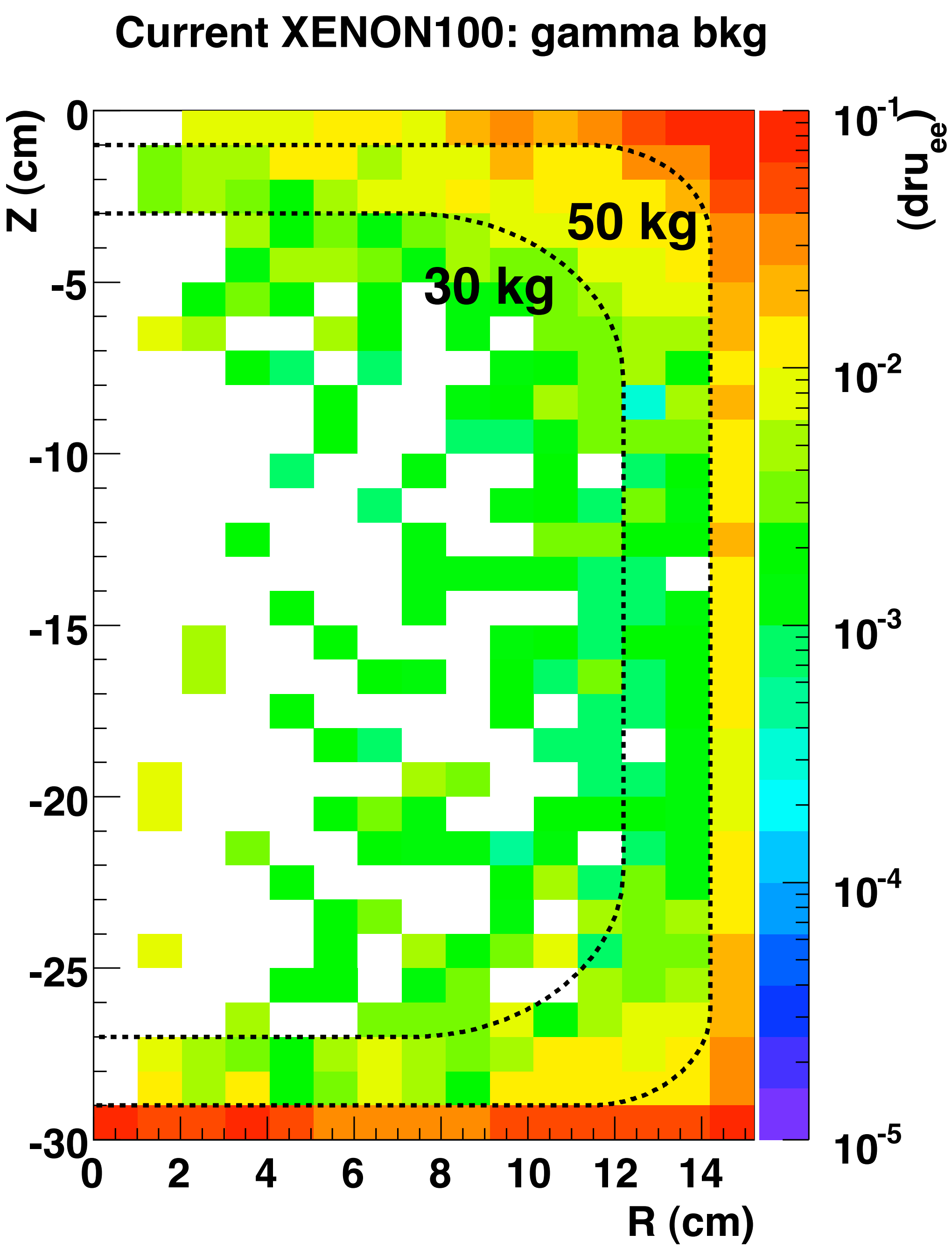
Background simulation



- *0.15 mBq/PMT x 242 PMTs gives 3000 ^{238}U decays/day*
- *Each ^{238}U decay produces 15 gammas and 9 alphas*
- *16M gamma/year*
- *(alpha,n) reaction results 7 neutron/year*

A realistic model based on Geant4 was constructed to propagate all the gammas/neutrons to simulate the background rate.

Expected Background and Sensitivity Reach



dru$_{ee}$ = evts/keVee/kg/day

	Current XENON100			
Fiducial Mass	50 kg		30 kg	
Background Units [a]	ER $[10^{-3} dru_{ee}]$	NR $[10^{-7} dru_{nr}]$	ER $[10^{-3} dru_{ee}]$	NR $[10^{-7} dru_{nr}]$
PMTs and bases	4.91	3.25	<1.4	2.87
QUPIDs	–	–	–	–
Stainless steel	<2.01	<2.01	<0.35	<1.66
PTFE	<0.18	<6.99	<0.03	<5.04
Copper Cryostat	–	–	–	–
Polyethylene	<2.50	<5.37	<1.2	<4.73
^{85}Kr/U/Th [b]	<0.2	–	<0.2	–
Concrete/Rocks[c]	–	1.34	–	1.11
μ-induced n in shield	–	33	–	33
μ-induced n in rock	–	< 3.7	–	< 3.7
Total Bkg	<9.8	<55.7	<3.2	<52.1
Run Time	40 days		200 days	
Raw Exposure	2000 kg-day		6000 kg-day	
Total Bkg events	<1.0		<1.2	
# of WIMP events[e]	3.9		11.8	
SI $\sigma_{\chi-p}$ reach	6×10^{-45} cm^2 (early 2009)		2×10^{-45} cm^2 (end 2009)	

[e] *assume cross section 10^{-44} cm^2*

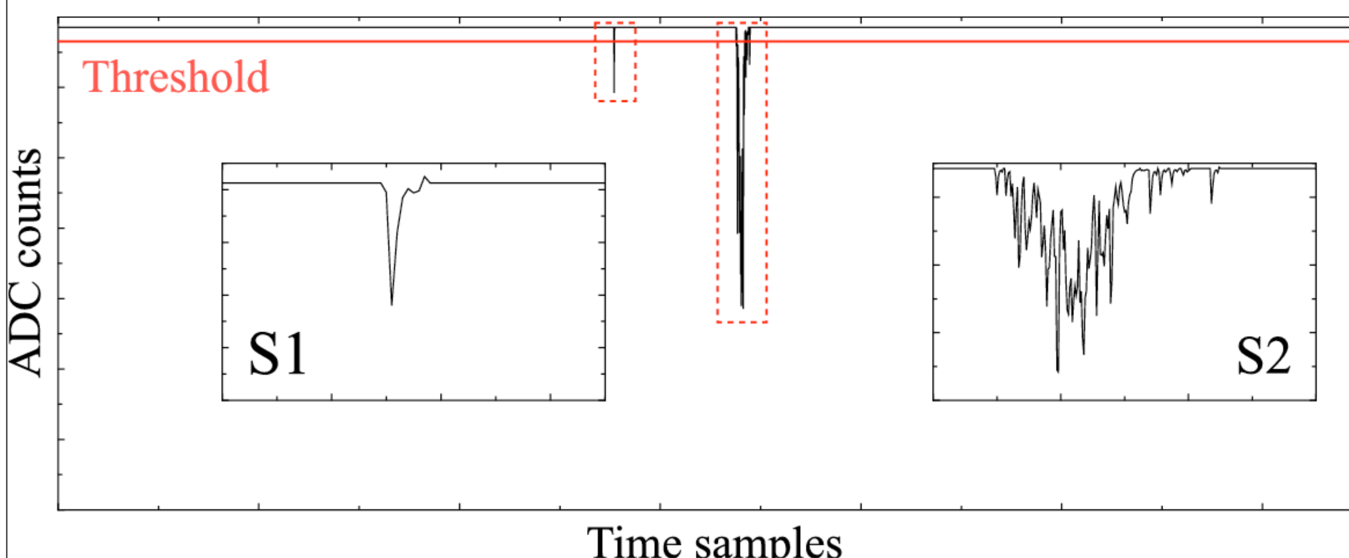
XENON100: Data Acqusition System

Requirements:

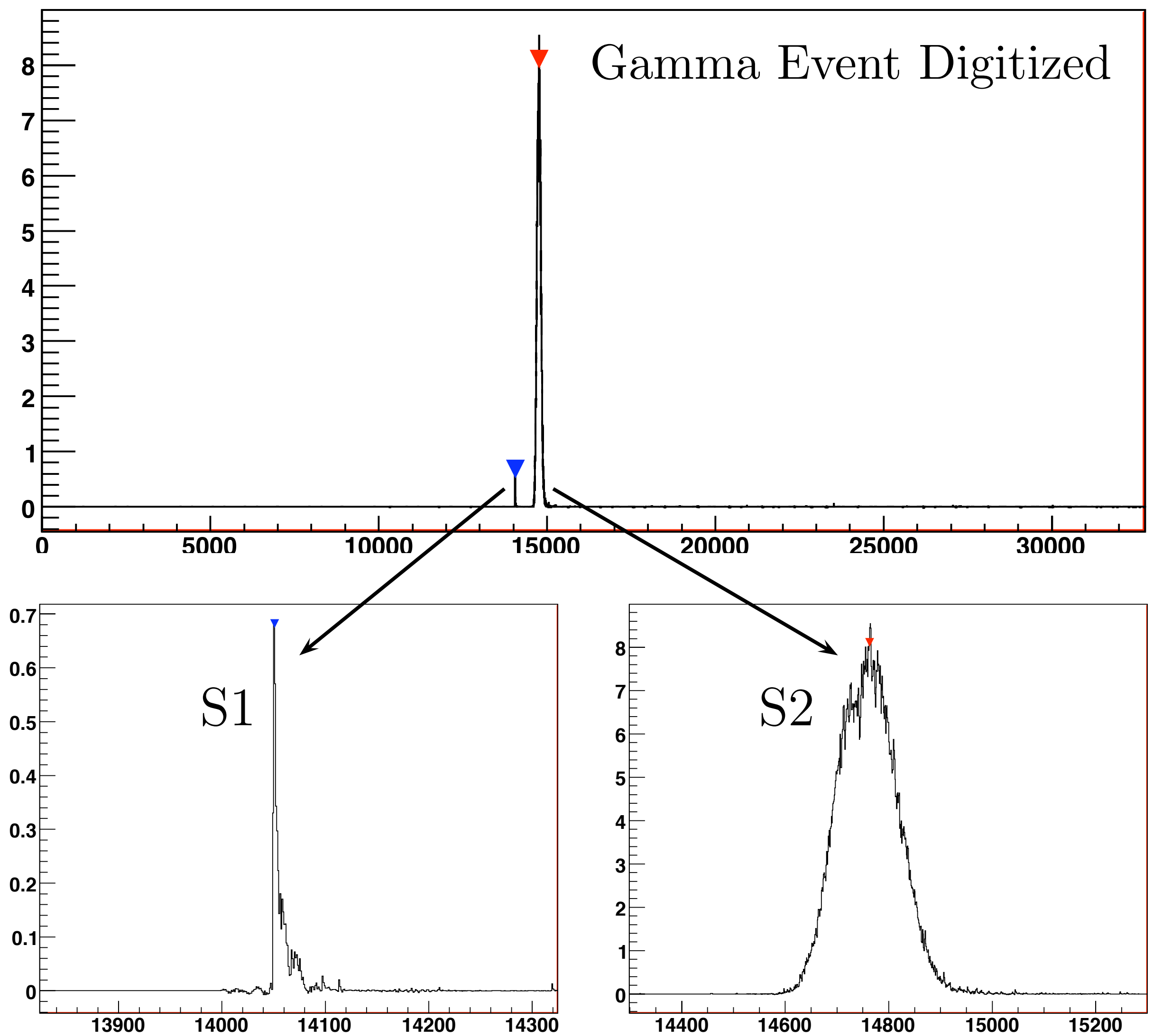
digitize full waveform (320μs) of 242 PMTs
with no deadtime and with
high rate capability for calibration

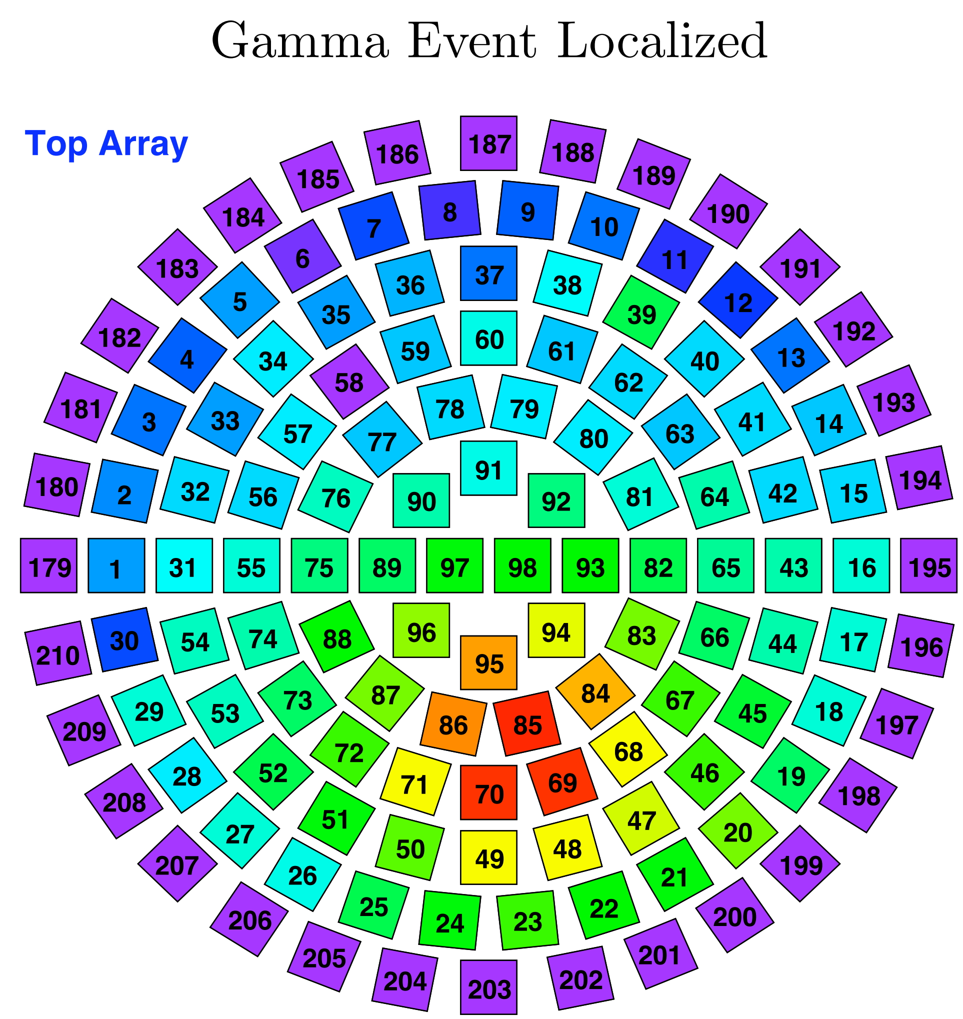
CAEN V1724 Flash ADC: 14bit, 100MHz

circular buffer: no deadtime
on board FPGA: *Zero Length Encoding*
only relevant signal portion transferred from ADC
to DAQ computer to allow faster event transfer rates
>60 Hz in calibration mode



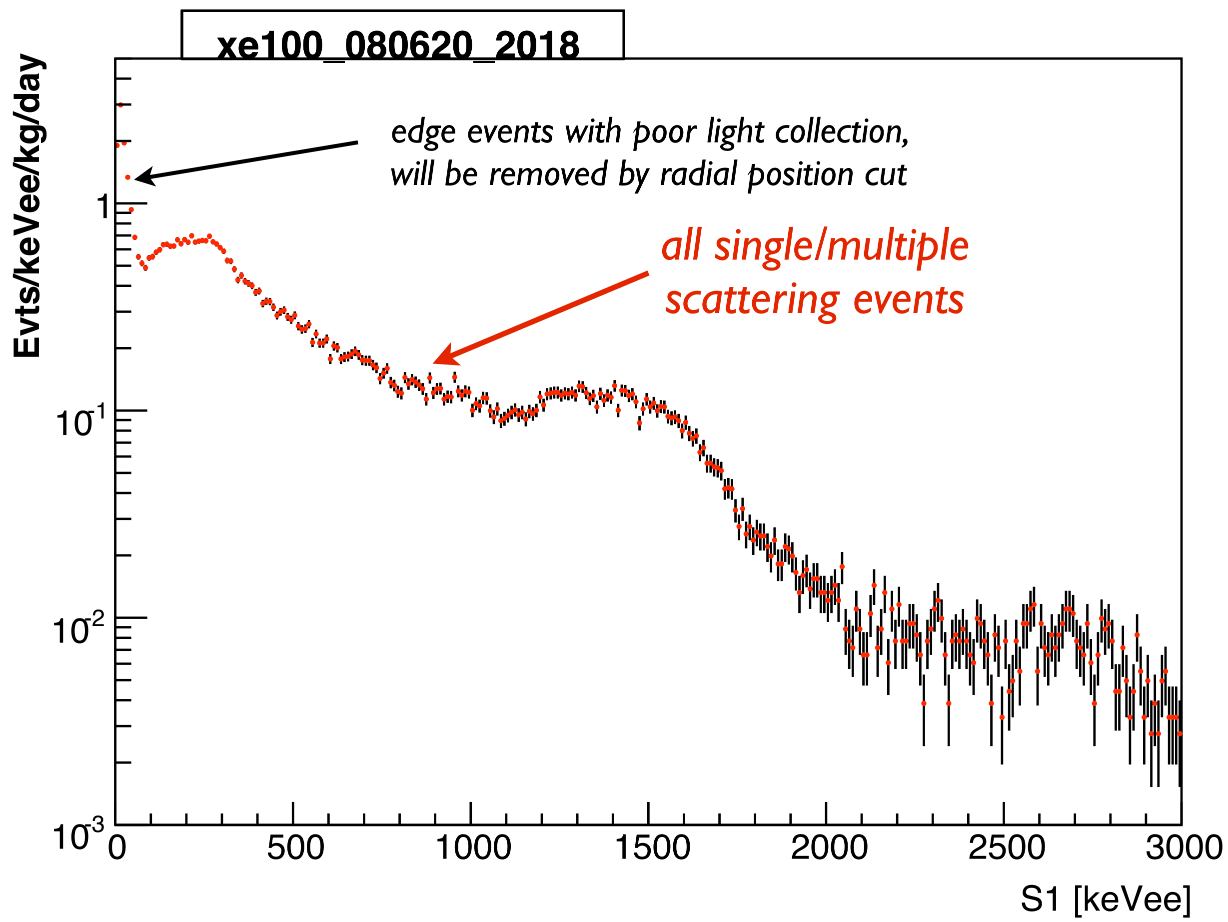
First signals from XENON100



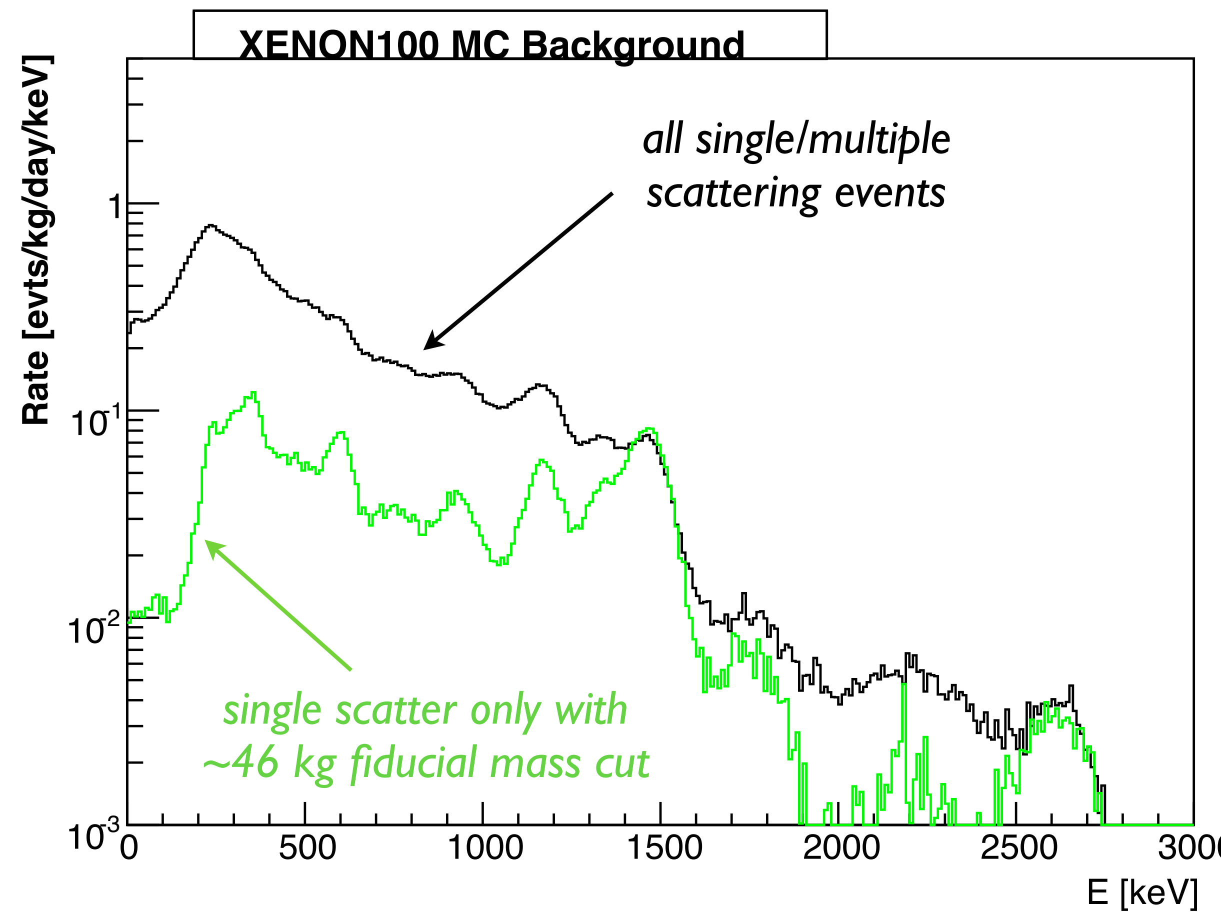


XENON100 background run

data



Simulation

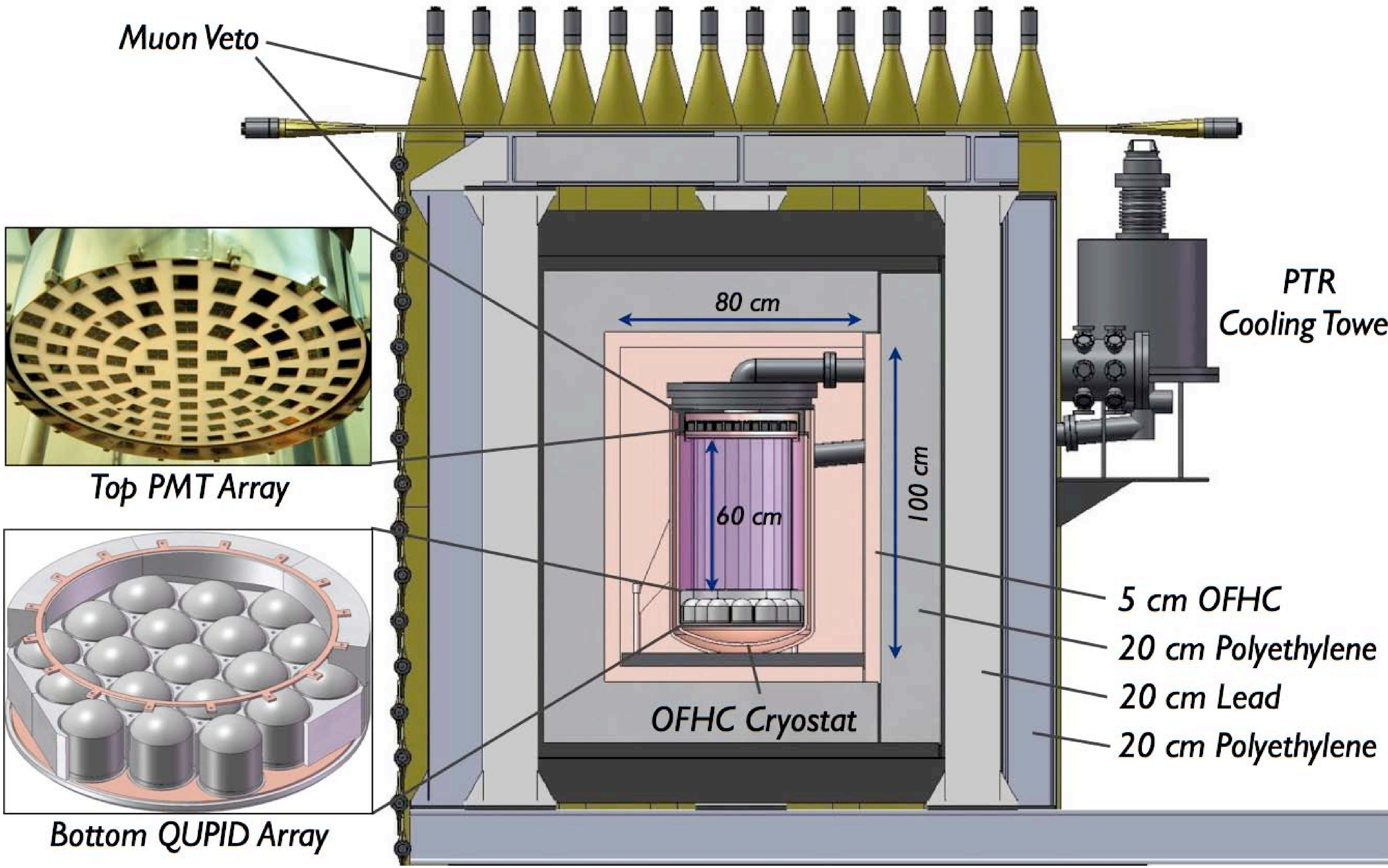


Detector has been fully filled with liquid xenon.

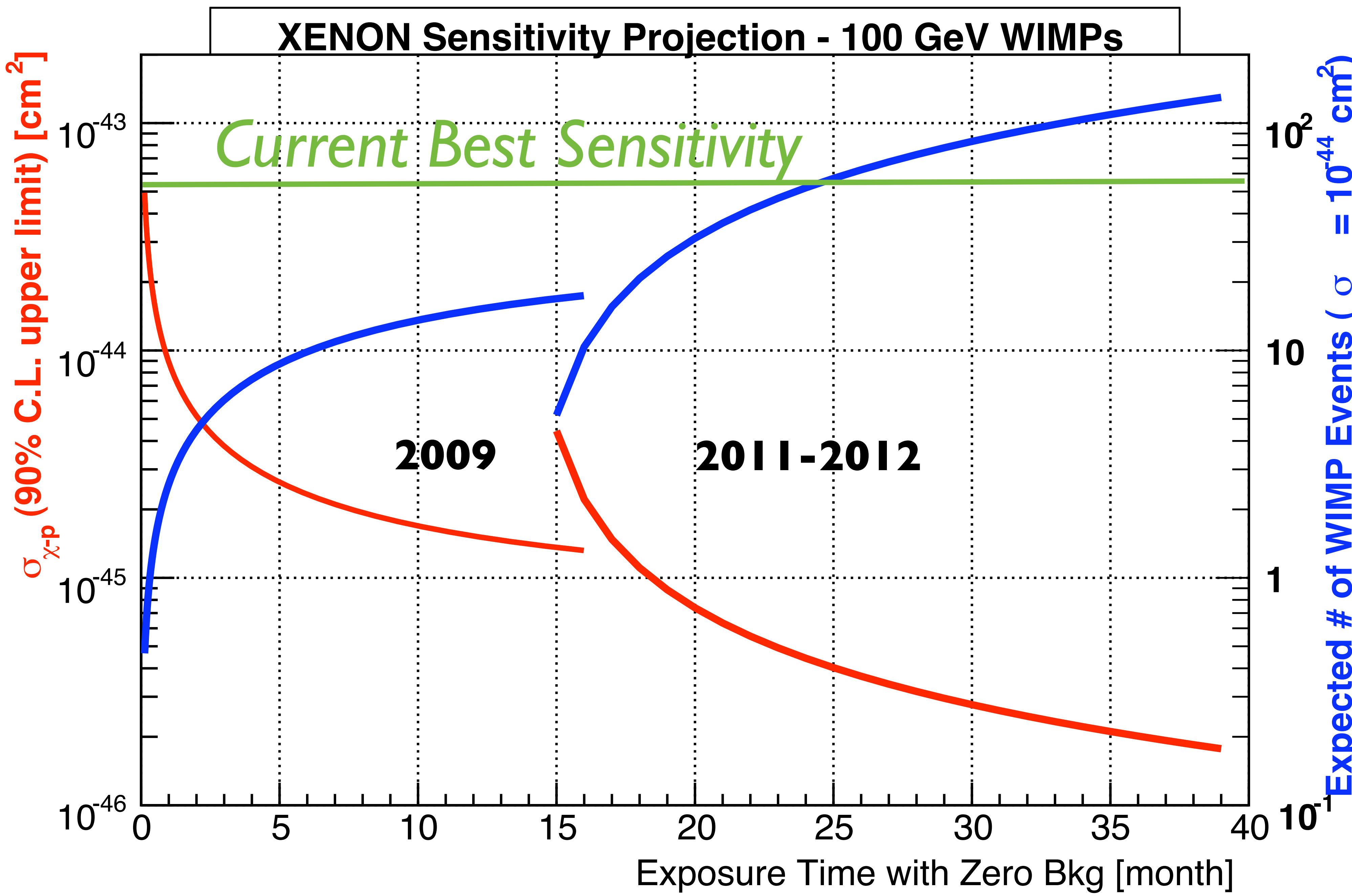
First Measured background Spectrum in good agreement with MC prediction!

WIMP search run is planned to start in April 2009.

A proposal to upgrade XENON100 (2009-2012)



Sensitivity Reach of the XENON100 Program



Multi-ton scale XENON Detector for DUSEL (beyond 2012)

- *Explore the full region/accumulate WIMP statistics*
- *New design with full coverage of ultra-low background photodetectors and cryostat*
- *Larger International Collaboration*
- *Total project cost: $50M-$100M*
- *neutrinoless double beta decay*
- *pp solar neutrinos*